

RESEARCH ARTICLE SUMMARY

CORONAVIRUS

Autoantibodies against type I IFNs in patients with life-threatening COVID-19

Paul Bastard*† and Lindsey B. Rosen† *et al.*

INTRODUCTION: Interindividual clinical variability is vast in humans infected with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), ranging from silent infection to rapid death. Three risk factors for life-threatening coronavirus disease 2019 (COVID-19) pneumonia have been identified—being male, being elderly, or having other medical conditions—but these risk factors cannot explain why critical disease remains relatively rare in any given epidemiological group. Given the rising toll of the COVID-19 pandemic in terms of morbidity and mortality, understanding the causes and mechanisms of life-threatening COVID-19 is crucial.

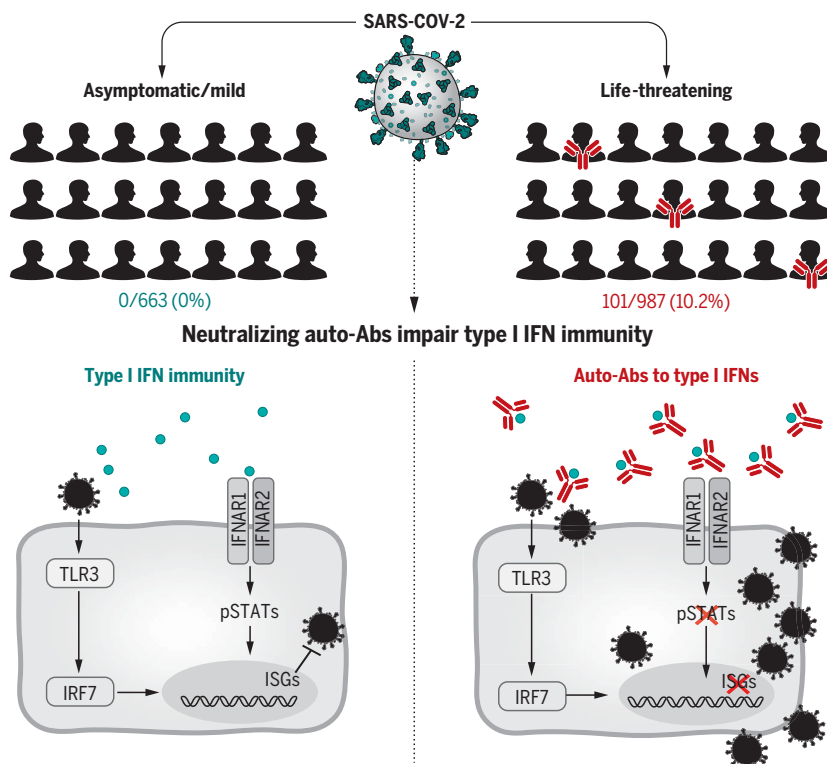
RATIONALE: B cell autoimmune infectious phenocopies of three inborn errors of cyto-

kine immunity exist, in which neutralizing autoantibodies (auto-Abs) against interferon- γ (IFN- γ) (mycobacterial disease), interleukin-6 (IL-6) (staphylococcal disease), and IL-17A and IL-17F (mucocutaneous candidiasis) mimic the clinical phenotypes of germline mutations of the genes that encode the corresponding cytokines or receptors. Human inborn errors of type I IFNs underlie severe viral respiratory diseases. Neutralizing auto-Abs against type I IFNs, which have been found in patients with a few underlying noninfectious conditions, have not been unequivocally shown to underlie severe viral infections. While searching for inborn errors of type I IFN immunity in patients with life-threatening COVID-19 pneumonia, we also tested the hypothesis that neutralizing auto-Abs against type I IFNs

may underlie critical COVID-19. We searched for auto-Abs against type I IFNs in 987 patients hospitalized for life-threatening COVID-19 pneumonia, 663 asymptomatic or mildly affected individuals infected with SARS-CoV-2, and 1227 healthy controls from whom samples were collected before the COVID-19 pandemic.

RESULTS: At least 101 of 987 patients (10.2%) with life-threatening COVID-19 pneumonia had neutralizing immunoglobulin G (IgG) auto-Abs against IFN- ω (13 patients), against the 13 types of IFN- α (36), or against both (52) at the onset of critical disease; a few also had auto-Abs against the other three individual type I IFNs. These auto-Abs neutralize high concentrations of the corresponding type I IFNs, including their ability to block SARS-CoV-2 infection *in vitro*. Moreover, all of the patients tested had low or undetectable serum IFN- α levels during acute disease. These auto-Abs were present before infection in the patients tested and were absent from 663 individuals with asymptomatic or mild SARS-CoV-2 infection ($P < 10^{-16}$). They were present in only 4 of 1227 (0.33%) healthy individuals ($P < 10^{-16}$) before the pandemic. The patients with auto-Abs were 25 to 87 years old (half were over 65) and of various ancestries. Notably, 95 of the 101 patients with auto-Abs were men (94%).

CONCLUSION: A B cell autoimmune phenocopy of inborn errors of type I IFN immunity accounts for life-threatening COVID-19 pneumonia in at least 2.6% of women and 12.5% of men. In these patients, adaptive autoimmunity impairs innate and intrinsic antiviral immunity. These findings provide a first explanation for the excess of men among patients with life-threatening COVID-19 and the increase in risk with age. They also provide a means of identifying individuals at risk of developing life-threatening COVID-19 and ensuring their enrolment in vaccine trials. Finally, they pave the way for prevention and treatment, including plasmapheresis, plasmablast depletion, and recombinant type I IFNs not targeted by the auto-Abs (e.g., IFN- β). ■



Neutralizing auto-Abs to type I IFNs underlie life-threatening COVID-19 pneumonia. We tested the hypothesis that neutralizing auto-Abs against type I IFNs may underlie critical COVID-19 by impairing the binding of type I IFNs to their receptor and the activation of the downstream responsive pathway. Neutralizing auto-Abs are represented in red, and type I IFNs are represented in blue. In these patients, adaptive autoimmunity impairs innate and intrinsic antiviral immunity. ISGs, IFN-stimulated genes; TLR, Toll-like receptor; IFNAR, IFN- α/β receptor; pSTAT, phosphorylated signal transducers and activators of transcription; IRF, interferon regulatory factor.

The full author list and the list of author affiliations is available in the full article online.

*Corresponding authors: Jean-Laurent Casanova (jean-laurent.casanova@rockefeller.edu); Paul Bastard (paul.bastard@institutimagine.org)

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<https://doi.org/10.1126/science.abd4585>

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Autoantibodies against type I IFNs in patients with life-threatening COVID-19

Paul Bastard^{1,2,3,*}†, Lindsey B. Rosen⁴†, Qian Zhang³†, Eleftherios Michailidis⁵†, Hans-Heinrich Hoffmann⁵†, Yu Zhang⁴†, Karim Dorgham⁶†, Quentin Philippot^{1,2}†, Jérémie Rosain^{1,2}†, Vivien Béziat^{1,2,3}†, Jérémy Manry^{1,2}, Elana Shaw⁴, Liis Haljasmägi⁷, Pärt Peterson⁷, Lazaro Lorenzo^{1,2}, Lucy Bizien^{1,2}, Sophie Trouillet-Assant^{8,9}, Kerry Dobbs⁴, Adriana Almeida de Jesus⁴, Alexandre Belot^{10,11,12}, Anne Kallaste¹³, Emilie Catherinot¹⁴, Yacine Tandjaoui-Lambiotte¹⁵, Jeremie Le Pen⁵, Gaspard Kerner^{1,2}, Benedetta Bigio³, Yoann Seeleuthner^{1,2}, Rui Yang³, Alexandre Bolze¹⁶, András N. Spaan^{3,17}, Ottavia M. Delmonte⁴, Michael S. Abers⁴, Alessandro Aiuti¹⁸, Giorgio Casari¹⁸, Vito Lampasona¹⁸, Lorenzo Piemonti¹⁸, Fabio Ciceri¹⁸, Kaya Bilguvar¹⁹, Richard P. Lifton^{19,20,21}, Marc Vasse²², David M. Smadja²³, Mélanie Migaud^{1,2}, Jérôme Hadjadj²⁴, Benjamin Terrier²⁵, Darragh Duffy²⁶, Lluís Quintana-Murci^{27,28}, Diederik van de Beek²⁹, Lucie Roussel^{30,31}, Donald C. Vinh^{30,31}, Stuart G. Tangye^{32,33}, Filomeen Haerynck³⁴, David Dalmau³⁵, Javier Martinez-Picado^{36,37,38}, Petter Brodin^{39,40}, Michel C. Nussenzweig^{41,42}, Stéphanie Boisson-Dupuis^{1,2,3}, Carlos Rodríguez-Gallego^{43,44}, Guillaume Vogt⁴⁵, Trine H. Mogensen^{46,47}, Andrew J. Oler⁴⁸, Jingwen Gu⁴⁸, Peter D. Burbelo⁴⁹, Jeffrey I. Cohen⁵⁰, Andrea Biondi⁵¹, Laura Rachele Bettini⁵¹, Mariella D'Angio⁵¹, Paolo Bonfanti⁵², Patrick Rossignol⁵³, Julien Mayaux⁵⁴, Frédéric Rieux-Laucat²⁴, Eystein S. Husebye^{55,56,57}, Francesca Fusco⁵⁸, Matilde Valeria Ursini⁵⁸, Luisa Imberti⁵⁹, Alessandra Sottini⁵⁹, Simone Paghera⁵⁹, Eugenia Quiros-Roldan⁶⁰, Camillo Rossi⁶¹, Riccardo Castagnoli⁶², Daniela Montagna^{63,64}, Amelia Licari⁶², Gian Luigi Marsegli⁶², Xavier Duval^{65,66,67,68,69}, Jade Ghosn^{68,69}, HGID Lab§, NIAID-USUHS Immune Response to COVID Group§, COVID Clinicians§, COVID-STORM Clinicians§, Imagine COVID Group§, French COVID Cohort Study Group§, The Milieu Intérieur Consortium§, CoV-Contact Cohort§, Amsterdam UMC Covid-19 Biobank§, COVID Human Genetic Effort§, John S. Tsang^{70,71}, Raphaela Goldbach-Mansky⁴, Kai Kisand⁷, Michail S. Lionakis⁴, Anne Puel^{1,2,3}, Shen-Ying Zhang^{1,2,3}, Steven M. Holland⁴¶, Guy Gorochoff^{6,72}¶, Emmanuelle Jouanguy^{1,2,3}¶, Charles M. Rice⁵¶, Aurélie Cobat^{1,2,3}¶, Luigi D. Notarangelo⁴¶, Laurent Abel^{1,2,3}¶, Helen C. Su⁴¶, Jean-Laurent Casanova^{1,2,3,42,73}¶#

Interindividual clinical variability in the course of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection is vast. We report that at least 101 of 987 patients with life-threatening coronavirus disease 2019 (COVID-19) pneumonia had neutralizing immunoglobulin G (IgG) autoantibodies (auto-Abs) against interferon- ω (IFN- ω) (13 patients), against the 13 types of IFN- α (36), or against both (52) at the onset of critical disease; a few also had auto-Abs against the other three type I IFNs. The auto-Abs neutralize the ability of the corresponding type I IFNs to block SARS-CoV-2 infection in vitro. These auto-Abs were not found in 663 individuals with asymptomatic or mild SARS-CoV-2 infection and were present in only 4 of 1227 healthy individuals. Patients with auto-Abs were aged 25 to 87 years and 95 of the 101 were men. A B cell autoimmune phenocopy of inborn errors of type I IFN immunity accounts for life-threatening COVID-19 pneumonia in at least 2.6% of women and 12.5% of men.

Myobacteriosis, staphylococcosis, and candidiasis can be driven by monogenic inborn errors of interferon- γ (IFN- γ), interleukin-6 (IL-6), and IL-17A and IL-17F, respectively, or they can be driven by their genetically driven autoimmune phenocopies, with the production of neutralizing autoantibodies (auto-Abs) against these cytokines (1–8). Type I IFNs, first described in 1957, are ubiquitously expressed cytokines that contribute to both innate immunity (through their secretion by plasmacytoid dendritic cells and other leukocytes) and cell-intrinsic immunity (in most if not all cell types) against viral infections (9–13). Their receptors are ubiquitously expressed and trigger the induction of IFN-stimulated genes (ISGs) via phosphorylated STAT1-STAT2-IRF9

trimers (STAT, signal transducers and activators of transcription; IRF, interferon regulatory factor) (14). Neutralizing immunoglobulin G (IgG) auto-Abs against type I IFNs can occur in patients treated with IFN- α 2 or IFN- β (15) and exist in almost all patients with autoimmune polyendocrinopathy syndrome type I (APS-1) (16). They are also seen in women with systemic lupus erythematosus (17).

These patients do not seem to suffer from unusually severe viral infections, although human inborn errors of type I IFNs can underlie severe viral diseases, both respiratory and otherwise (18). In 1984, Ion Gresser described a patient with unexplained auto-Abs against type I IFNs suffering from severe chickenpox and shingles (19, 20). More recently, auto-Abs against type I IFNs have been found in a few

patients with biallelic, hypomorphic *RAG1* or *RAG2* mutations and viral diseases including severe chickenpox and viral pneumonias (21). Our attention was drawn to three patients with APS-1, with known preexisting anti-type I IFN auto-Abs, who had life-threatening coronavirus disease 2019 (COVID-19) pneumonia (22) (see detailed case reports in Methods). While searching for inborn errors of type I IFNs (18, 23), we hypothesized that neutralizing auto-Abs against type I IFNs might also underlie life-threatening COVID-19 pneumonia.

Auto-Abs against IFN- α 2 and/or IFN- ω in patients with critical COVID-19

We searched for auto-Abs against type I IFNs in 987 patients hospitalized for life-threatening COVID-19 pneumonia. We also examined 663 individuals infected with severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) presenting asymptomatic infection or mild disease and 1227 healthy controls whose samples were collected before the COVID-19 pandemic. Plasma or serum samples were collected from patients with critical COVID-19 during the acute phase of disease. Multiplex particle-based flow cytometry revealed a high fluorescence intensity (FI) (>1500) for IgG auto-Abs against IFN- α 2 and/or IFN- ω in 135 patients (13.7%) with life-threatening COVID-19 (Fig. 1A). We found that 49 of these 135 patients were positive for auto-Abs against both IFN- α 2 and IFN- ω , whereas 45 were positive only for auto-Abs against IFN- α 2, and 41 were positive only for auto-Abs against IFN- ω .

We also performed enzyme-linked immunosorbent assay (ELISA), and the results obtained were consistent with those obtained with Luminex technology (fig. S1A). We found that 11 and 14 of 23 patients tested had low levels of IgM and IgA auto-Abs against IFN- ω and IFN- α 2, respectively (Fig. 1B and fig. S1B). Auto-Abs against type I IFNs were detected in two unrelated patients for whom we had plasma samples obtained before SARS-CoV-2 infection, which indicates that these antibodies were present before SARS-CoV-2 infection and were not triggered by the infection. As a control, we confirmed that all 25 APS-1 patients tested had high levels of auto-Abs against IFN- α 2 and IFN- ω (fig. S1C). Overall, we found that 135 of 987 patients (13.7%) with life-threatening COVID-19 pneumonia had IgG auto-Abs against at least one type I IFN.

The auto-Abs neutralize IFN- α 2 and IFN- ω in vitro

We then tested whether auto-Abs against IFN- α 2 and IFN- ω were neutralizing in vitro. We incubated peripheral blood mononuclear cells (PBMCs) from healthy controls with 10 ng/mL IFN- α 2 or IFN- ω in the presence of plasma from healthy individuals or from patients with auto-Abs. A complete abolition of STAT1 phosphorylation was observed in 101 patients

with auto-Abs against IFN- α 2 and/or IFN- ω (table S1). The antibodies detected were neutralizing against both IFN- α 2 and IFN- ω in 52 of these 101 patients (51%), against only IFN- α 2 in 36 patients (36%), and against only IFN- ω in 13 patients (13%) at the IFN- α 2 and IFN- ω concentrations tested (Fig. 1, C and D). IgG depletion from patients with auto-Abs restored normal pSTAT1 induction after IFN- α 2 and IFN- ω stimulation, whereas the purified IgG fully neutralized this induction (Fig. 1C and fig. S1D). Furthermore, these auto-Abs neutralized high amounts of IFN- α 2 (fig. S1E) and were neutralizing at high dilutions (Fig. 1E and fig. S1F). Notably, 15 patients with life-threatening COVID-19 and auto-Abs against IFN- α 2 and/or IFN- ω also had auto-Abs against other cytokines [IFN- γ , granulocyte-macrophage colony-stimulating factor (GM-CSF), IL-6, IL-10, IL-12p70, IL-22, IL-17A, IL-17F, and/or tumor necrosis factor- β (TNF β)], only three of which (IL-12p70, IL-22, and IL-6) were neutralizing (in four patients) (fig. S2, A to C). Similar proportions were observed in the other cohorts (fig. S2, D to L).

We also analyzed ISG induction after 2 hours of stimulation with IFN- α 2, IFN- β , or IFN- γ in

the presence of plasma from healthy individuals or from patients with auto-Abs. With plasma from eight patients with auto-Abs against IFN- α 2, the induction of ISG CXCL10 was abolished after IFN- α 2 stimulation but maintained after stimulation with IFN- γ (Fig. 1F). We then found that plasma from the five patients with neutralizing auto-Abs neutralized the protective activity of IFN- α 2 in Madin-Darby bovine kidney (MDBK) cells infected with vesicular stomatitis virus (VSV) (table S2). Overall, we found that 101 of 987 patients (10.2%)—including 95 men (94%)—with life-threatening COVID-19 pneumonia had neutralizing IgG auto-Abs against at least one type I IFN. By contrast, auto-Abs were detected in only 4 of 1227 healthy controls (0.33%) (Fisher exact test, $P < 10^{-16}$) and in none of the 663 patients with asymptomatic or mild SARS-CoV-2 infection tested (Fisher exact test, $P < 10^{-16}$).

Auto-Abs against all 13 IFN- α subtypes in patients with auto-Abs to IFN- α 2

We investigated whether patients with neutralizing auto-Abs against IFN- α 2 only or those with neutralizing auto-Abs against IFN- α 2 and IFN- ω also had auto-Abs against the other 15

type I IFNs. ELISA showed that all patients tested ($N = 22$) with auto-Abs against IFN- α 2 also had auto-Abs against all 13 IFN- α subtypes (IFN- α 1, - α 2, - α 4, - α 5, - α 6, - α 7, - α 8, - α 10, - α 13, - α 14, - α 16, - α 17, and - α 21), whereas only 2 of the 22 patients tested had auto-Abs against IFN- β , 1 had auto-Abs against IFN- κ , and 2 had auto-Abs against IFN- ϵ (Fig. 2A). The auto-Abs against IFN- β had neutralizing activity against IFN- β (Fig. 1D). We confirmed that all of the patients had auto-Abs against all 13 subtypes of IFN- α by testing the same samples using luciferase-based immunoprecipitation assay (LIPS) (Fig. 2B). For IFN- β , we also screened the whole cohort in a multiplex assay. We found that 19 of 987 (1.9%) patients had auto-Abs against IFN- β and that all of them were in our cohort of severe COVID-19 individuals with neutralizing auto-Abs against IFN- α and/or IFN- ω . Of these patients with auto-Abs against IFN- β , only two were neutralizing against IFN- β (Fig. 1, D and F).

Ten of the 17 genes encoding type I IFNs (IFN- α 2, - α 5, - α 6, - α 8, - α 13, - α 14, - α 21, - β , - ω , and - κ), have undergone strong negative selection, which suggests that they play an essential role in the general population. By contrast, the

¹Laboratory of Human Genetics of Infectious Diseases, Necker Branch, INSERM U1163, Necker Hospital for Sick Children, Paris, France. ²University of Paris, Imagine Institute, Paris, France.

³St. Giles Laboratory of Human Genetics of Infectious Diseases, Rockefeller Branch, The Rockefeller University, New York, NY, USA. ⁴Laboratory of Clinical Immunology and Microbiology, Division of Intramural Research, National Institute of Allergy and Infectious Diseases (NIAID), National Institutes of Health (NIH), Bethesda, MD, USA. ⁵Laboratory of Virology and Infectious Disease, The Rockefeller University, New York, NY, USA. ⁶Sorbonne Université, INSERM, Centre d'Immunologie et des Maladies Infectieuses, (CIMI-Paris), Paris, France. ⁷Institute of Biomedicine and Translational Medicine, University of Tartu, Tartu, Estonia. ⁸Hospices Civils de Lyon, Lyon Sud Hospital, Pierre-Bénite, France. ⁹International Center of Research in Infectiology, Lyon University, INSERM U1111, CNRS UMR 5308, ENS, UCBL, Lyon, France. ¹⁰International Center of Research in Infectiology, Lyon University, INSERM U1111, CNRS UMR 5308, ENS, UCBL, Lyon, France. ¹¹National Reference Centre for Rheumatic and Autoimmune and Systemic Diseases in Children (RAISE), Lyon, France. ¹²Lyon Immunopathology Federation (LIFE), Hospices Civils de Lyon, Lyon, France. ¹³Internal Medicine Clinic, Tartu University Hospital, Tartu, Estonia. ¹⁴Pneumology Department, Foch Hospital, Suresne, France. ¹⁵Avicenne Hospital, Assistance Publique Hôpitaux de Paris (AP-HP), Bobigny, INSERM U1272 Hypoxia and Lung, Bobigny, France. ¹⁶Helix, San Mateo, CA, USA. ¹⁷Department of Medical Microbiology, University Medical Center Utrecht, Utrecht, Netherlands. ¹⁸IRCCS San Raffaele Hospital and Vita-Salute San Raffaele University, Milan, Italy. ¹⁹Department of Genetics, Yale University School of Medicine, New Haven, CT, USA. ²⁰Yale Center for Genome Analysis, Yale University School of Medicine, New Haven, CT, USA. ²¹Laboratory of Human Genetics and Genomics, The Rockefeller University, New York, NY, USA. ²²Service de Biologie Clinique and UMR-S 1176, Hôpital Foch, Suresnes, France. ²³INSERM UMR-S 1140, Biosurgical Research Laboratory (Carpentier Foundation), Paris University and European Georges Pompidou Hospital, Paris, France. ²⁴Laboratory of Immunogenetics of Pediatric Autoimmune Diseases, INSERM UMR 1163, University of Paris, Imagine Institute, Paris, France. ²⁵Department of Internal Medicine, National Referral Center for Rare Systemic Autoimmune Diseases, Assistance Publique Hôpitaux de Paris-Centre (APHP-CUP), University of Paris, Paris, France. ²⁶Translational Immunology Laboratory, Institut Pasteur, Paris, France. ²⁷Human Evolutionary Genetics Unit, Institut Pasteur, CNRS UMR 2000, 75015, Paris, France. ²⁸Human Genomics and Evolution, Collège de France, Paris, France. ²⁹Amsterdam UMC, University of Amsterdam, Department of Neurology, Amsterdam Neuroscience, Amsterdam, Netherlands. ³⁰Department of Medicine, Division of Infectious Diseases, McGill University Health Centre, Montréal, Québec, Canada. ³¹Infectious Disease Susceptibility Program, Research Institute, McGill University Health Centre, Montréal, Québec, Canada. ³²Garvan Institute of Medical Research, Darlinghurst 2010, NSW, Sydney, Australia. ³³St Vincent's Clinical School, Faculty of Medicine, University of New South Wales Sydney, Darlinghurst 2010, NSW, Australia. ³⁴Department of Paediatric Immunology and Pulmonology, Centre for Primary Immunodeficiency Ghent (CPIG), PID Research Laboratory, Jeffrey Modell Diagnosis and Research Centre, Ghent University Hospital, Ghent, Belgium. ³⁵Infectious Diseases and HIV Service, Hospital Universitari Mutua Terrassa, Universitat de Barcelona, Fundació Docència i Recerca Mutua Terrassa, Terrassa, Barcelona, Catalonia, Spain. ³⁶IrsiCaixa AIDS Research Institute and Institute for Health Science Research Germans Trias i Pujol (IGTP), Badalona, Spain. ³⁷Infectious Diseases and Immunity, Centre for Health and Social Care Research (CESS), Faculty of Medicine, University of Vic-Central University of Catalonia (UVic-UCC), Vic, Spain. ³⁸Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain. ³⁹Science for Life Laboratory, Department of Women's and Children's Health, Karolinska Institutet, Karolinska, Sweden. ⁴⁰Department of Pediatric Rheumatology, Karolinska University Hospital, Karolinska, Sweden. ⁴¹Laboratory of Molecular Immunology, The Rockefeller University, New York, NY, USA. ⁴²Howard Hughes Medical Institute, New York, NY, USA. ⁴³Department of Immunology, Hospital Universitario de Gran Canaria Dr. Negrín, Canarian Health System, Las Palmas de Gran Canaria, Spain. ⁴⁴Department of Clinical Sciences, University Fernando Pessoa Canarias, Las Palmas de Gran Canaria, Spain. ⁴⁵Neglected Human Genetics Laboratory, INSERM, University of Paris, Paris, France. ⁴⁶Department of Infectious Diseases, Aarhus University Hospital, Skejby, Denmark. ⁴⁷Department of Biomedicine, Aarhus University, Aarhus, Denmark. ⁴⁸Bioinformatics and Computational Biosciences Branch, Office of Cyber Infrastructure and Computational Biology, NIAID, NIH, Bethesda, MD, USA. ⁴⁹Division of Intramural Research, National Institute of Dental Craniofacial Research (NIDCR), NIH, Bethesda, MD, USA. ⁵⁰Laboratory of Infectious Diseases, Division of Intramural Research, NIAID, NIH, Bethesda, MD, USA. ⁵¹Pediatric Department and Centro Tettamanti-European Reference Network PaedCan, EuroBloodNet, MetabERN-University of Milano-Bicocca-Fondazione MBBM-Ospedale, San Gerardo, Monza, Italy. ⁵²Department of Infectious Diseases, San Gerardo Hospital - University of Milano-Bicocca, Monza, Italy. ⁵³University of Lorraine, Plurithematic Clinical Investigation Centre INSERM CIC-P 1433, INSERM U1116, CHRU Nancy Hôpitaux de Brabois, F-CRIN INI-CRCT (Cardiovascular and Renal Clinical Trials), Nancy, France. ⁵⁴Intensive Care Unit, Pitié-Salpêtrière Hospital, Paris University, AP-HP, Paris, France. ⁵⁵Department of Clinical Science and K.G. Jebsen Center for Autoimmune Disorders, University of Bergen, Bergen, Norway. ⁵⁶Department of Medicine, Haukeland University Hospital, Bergen, Norway. ⁵⁷Department of Medicine (Solna), Karolinska Institutet, Stockholm, Sweden. ⁵⁸Human Molecular Genetics Laboratory, Institute of Genetics and Biophysics, "A. Buzzati-Traverso" Consiglio Nazionale delle Ricerche, Naples, Italy. ⁵⁹Centro di Ricerca Emato-oncologica AIL (CREA) Laboratory, Diagnostic Department, ASST Spedali Civili di Brescia, Brescia, Italy. ⁶⁰Department of Infectious and Tropical Diseases, University of Brescia and ASST Spedali di Brescia, Brescia, Italy. ⁶¹Direzione Sanitaria, ASST Spedali Civili di Brescia, Brescia, Italy. ⁶²Department of Pediatrics, Fondazione IRCCS Policlinico San Matteo, University of Pavia, Pavia, Italy. ⁶³Laboratory of Immunology and Transplantation, Fondazione IRCCS Policlinico San Matteo, Pavia, Italy. ⁶⁴Department of Clinical, Surgical, Diagnostic and Pediatric Sciences, University of Pavia, Pavia, Italy. ⁶⁵INSERM CIC 1425, Paris, France. ⁶⁶AP-HP, University Hospital of Bichat, Paris, France. ⁶⁷University Paris Diderot, Paris 7, UFR de Médecine-Bichat, Paris, France. ⁶⁸Infection, Antimicrobials, Modelling, Evolution (IAME), INSERM, UMR1137, University of Paris, Paris, France. ⁶⁹AP-HP, Bichat Claude Bernard Hospital, Infectious and Tropical Diseases Department, Paris, France. ⁷⁰Center for Human Immunology, NIH, Bethesda, MD, USA. ⁷¹Multiscale Systems Biology Section, Laboratory of Immune System Biology, NIAID, NIH, Bethesda, MD, USA. ⁷²Département d'Immunologie, AP-HP, Hôpital Pitié-Salpêtrière, Paris, France. ⁷³Pediatric Hematology and Immunology Unit, Necker Hospital for Sick Children, AP-HP, Paris, France.

*Corresponding author. Email: jean-laurent.casanova@rockefeller.edu (J.-L.C.); paul.bastard@institutimagine.org (P.B.)

†These authors contributed equally to this work.

‡These authors contributed equally to this work.

§All collaborators and their affiliations appear at the end of this paper.

¶These authors contributed equally to this work.

#These authors contributed equally to this work.

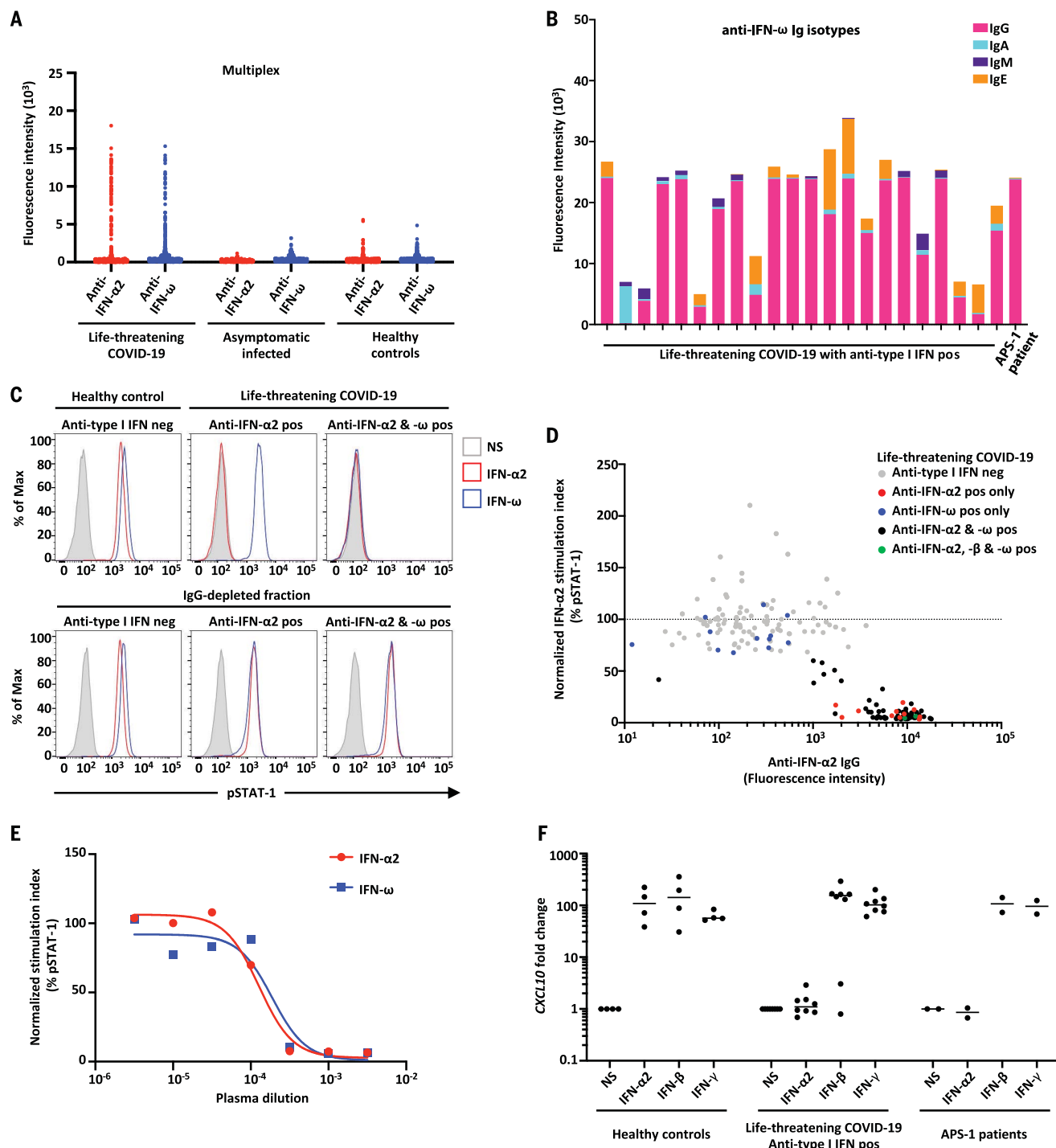


Fig. 1. Neutralizing auto-Abs against IFN- $\alpha 2$ and/or IFN- ω in patients with life-threatening COVID-19. (A) Multiplex particle-based assay for auto-Abs against IFN- $\alpha 2$ and IFN- ω in patients with life-threatening COVID-19 ($N = 782$), in patients with asymptomatic or mild SARS-CoV-2 infection ($N = 443$), and in healthy controls not infected with SARS-CoV-2 ($N = 1160$). (B) Anti-IFN- ω Ig isotypes in 23 patients with life-threatening COVID-19 and auto-Abs to type I IFNs. (C) Representative fluorescence-activated cell sorting (FACS) plots depicting IFN- $\alpha 2$ - or IFN- ω -induced pSTAT1 in healthy control cells (gated on CD14 $^{+}$ monocytes) in the presence of 10% healthy control or anti-IFN- $\alpha 2$ or anti-IFN- ω auto-Abs-containing patient plasma (top panel) or an IgG-depleted plasma fraction (bottom panel). Max, maximum; neg, negative; pos, positive; NS, not stimulated. (D) Plot of anti-IFN- $\alpha 2$ auto-Ab levels against their

neutralization capacity. The stimulation index (stimulated over unstimulated condition) for the plasma from each patient was normalized against that of healthy control plasma from the same experiment. Spearman's rank correlation coefficient = -0.6805 ; $P < 0.0001$. (E) Median inhibitory concentration (IC_{50}) curves representing IFN- $\alpha 2$ - and IFN- ω -induced pSTAT1 levels in healthy donor cells in the presence of serial dilutions of patient plasma. The stimulation index (stimulated over unstimulated condition) for patient plasma was normalized against that of 10% healthy control plasma. IFN- $\alpha 2$: $IC_{50} = 0.016\%$, $R^2 = 0.985$; IFN- ω : $IC_{50} = 0.0353\%$, $R^2 = 0.926$. R^2 , coefficient of determination. (F) Neutralizing effect on CXCL10 induction, after stimulation with IFN- $\alpha 2$, IFN- β , or IFN- γ , in the presence of plasma from healthy controls ($N = 4$), patients with life-threatening COVID-19 and auto-Abs against IFN- $\alpha 2$ ($N = 8$), and APS-1 patients ($N = 2$).

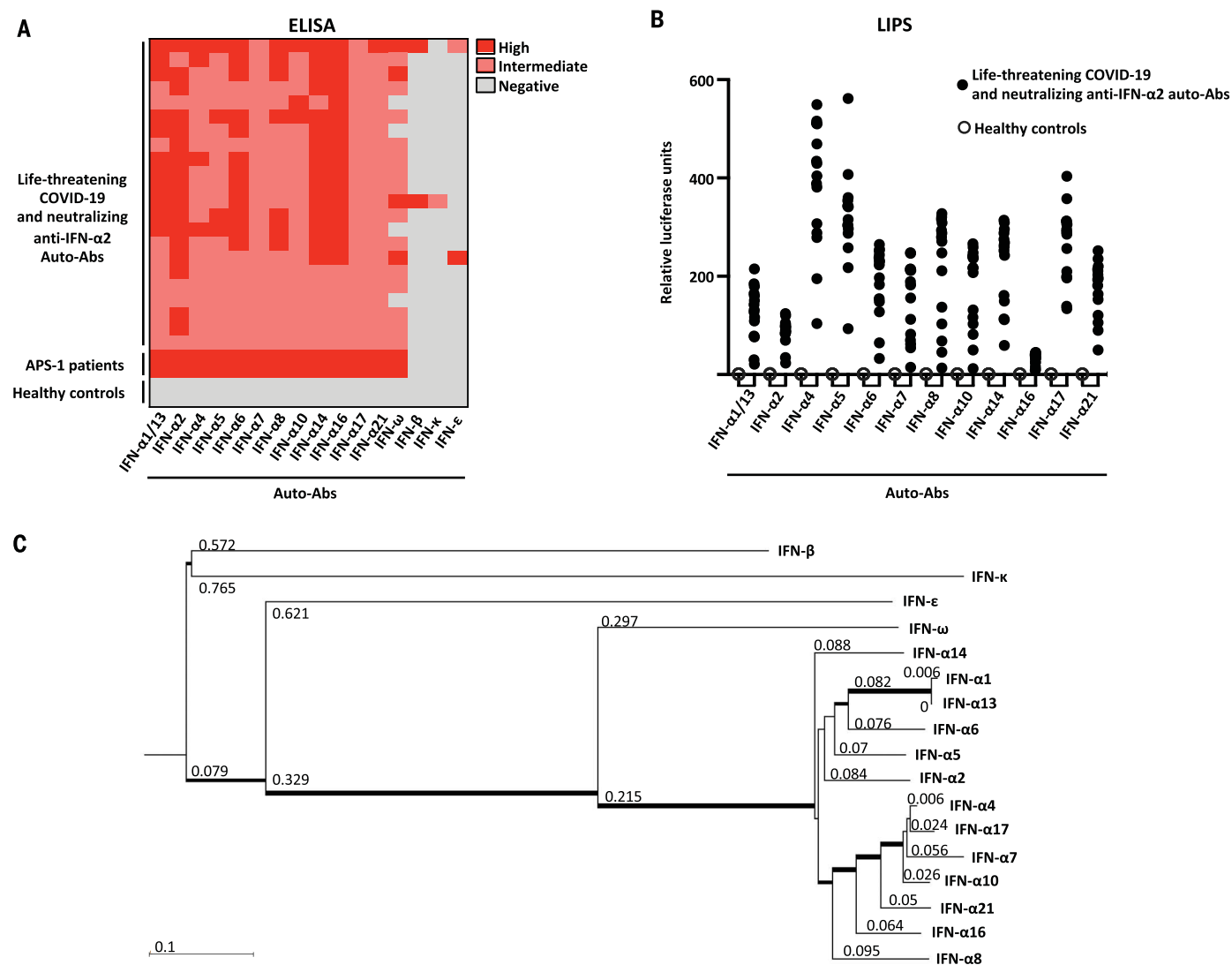


Fig. 2. Auto-Abs against the different type I IFN subtypes. (A) ELISA for auto-Abs against the 13 different IFN-α subtypes, IFN-ω, IFN-β, IFN-κ, and IFN-ε in patients with life-threatening COVID-19 and auto-Abs against IFN-α2 ($N = 22$), APS-1 patients ($N = 2$), and healthy controls ($N = 2$). (B) LIPS for the 12 different IFN-α subtypes tested in patients with auto-Abs against IFN-α2 ($N = 22$) and

healthy controls ($N = 2$). (C) Neighbor-joining phylogenetic tree of the 17 human type I IFN proteins. Horizontal branches are drawn to scale (bottom left, number of substitutions per site). Thinner, intermediate, and thicker internal branches have bootstrap support of <50 , ≥ 50 , and $>80\%$, respectively. The bootstrap value for the branch separating IFN-ω from all IFN-α subtypes is 100%.

other seven IFN loci in the human genome often carry loss-of-function alleles (24). Moreover, the 13 IFN-α subtypes and IFN-ω are more closely related to each other than they are to the other three IFNs (IFN-β, IFN-ε, and IFN-κ), which are structurally and phylogenetically more distant (Fig. 2C). Thus, all patients with neutralizing auto-Abs against IFN-α2 that we tested ($N = 22$) had auto-Abs against all 13 IFN-α subtypes, and 3 of the 22 patients tested (14%) had auto-Abs against 14 or more type I IFNs.

The auto-Abs neutralize IFN-α2 against SARS-CoV-2 in vitro and IFN-α in vivo

Plasma from eight patients with neutralizing auto-Abs against type I IFN also neutralized the ability of IFN-α2 to block the infection of

Huh7.5 cells with SARS-CoV-2 (Fig. 3A). Plasma from two healthy controls or from seven SARS-CoV-2-infected patients without auto-Abs did not block the protective action of IFN-α2 (Fig. 3A and fig. S3A). These data provide compelling evidence that the patients' blood carried sufficiently large amounts of auto-Abs to neutralize the corresponding type I IFNs and block their antiviral activity in vitro, including that against SARS-CoV-2.

We also found that all 41 patients with neutralizing auto-Abs against the 13 types of IFN-α tested had low (one patient) or undetectable (40 patients) levels of the 13 types of IFN-α in their plasma during the course of the disease (Fig. 3B) (25, 26). Type I IFNs may be degraded and/or bound to the corresponding circulating auto-Abs. The presence of circulating neutral-

izing auto-Abs against IFN-α is, therefore, strongly associated with low serum IFN-α levels (Fisher exact test, $P < 10^{-6}$). Consistently in patients with neutralizing auto-Abs against IFN-α2, the baseline levels of type I IFN-dependent transcripts were low, whereas they were normal for nuclear factor κB (NF-κB)-dependent transcripts (Fig. 3C and fig. S3B). Overall, our findings indicate that the auto-Abs against type I IFNs present in patients with life-threatening COVID-19 were neutralizing in vitro and in vivo.

Pronounced excess of men in patients with auto-Abs against type I IFNs

There was a pronounced excess of male patients (95 of 101; 94%) with critical COVID-19 pneumonia and neutralizing auto-Abs against type I

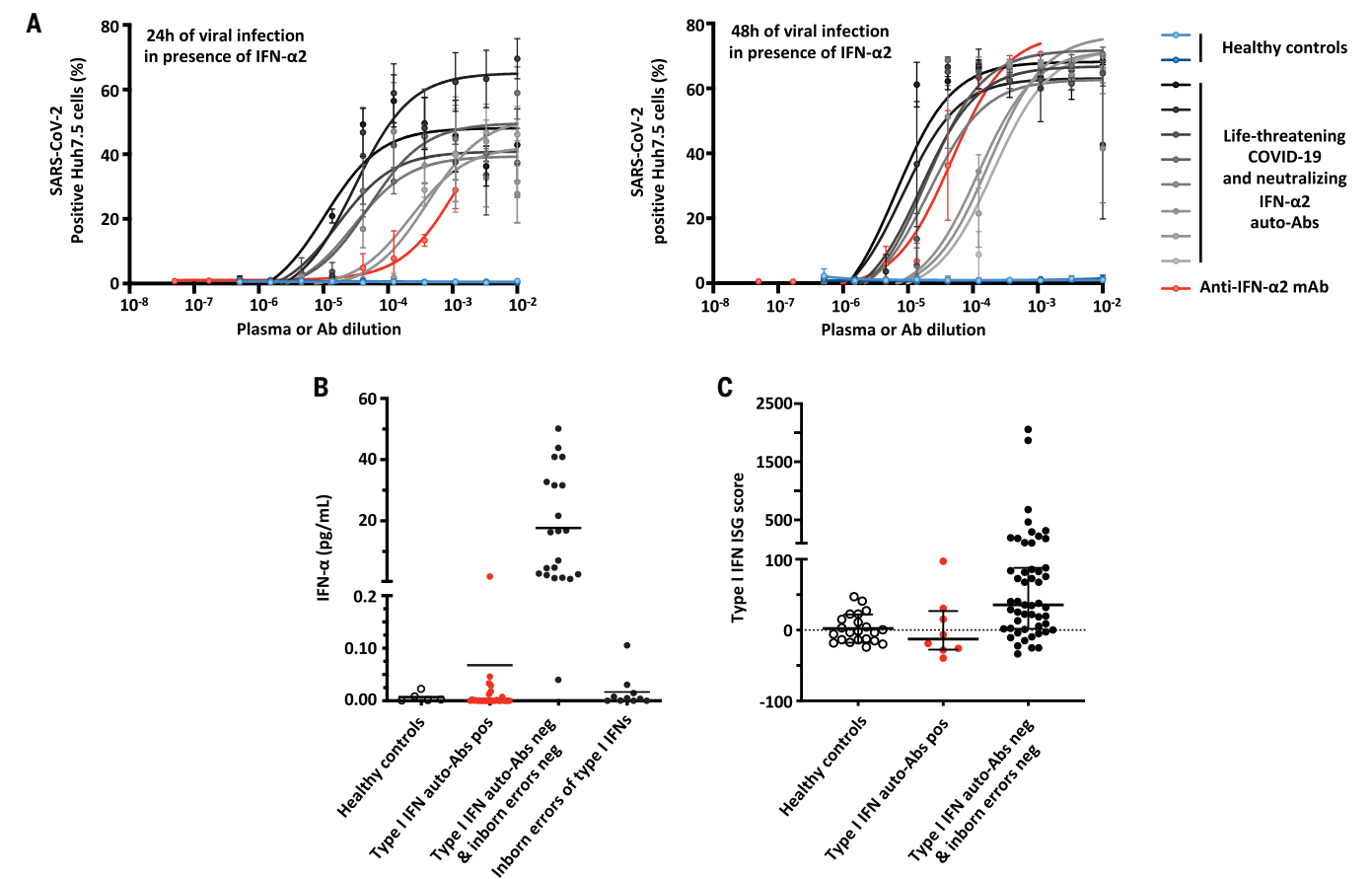


Fig. 3. Enhanced SARS-CoV-2 replication, despite the presence of IFN-α2, in the presence of plasma from patients with auto-Abs against IFN-α2 and low in vivo levels of IFN-α. (A) SARS-CoV-2 replication—measured 24 hours (left) and 48 hours (right) after infection—in Huh7.5 cells treated with IFN-α2 in the presence of plasma from patients with life-threatening COVID-19 and neutralizing auto-Abs against IFN-α2 (*N* = 8); a commercial anti-IFN-α2 antibody; or control plasma (*N* = 2). (B) IFN-α levels in the plasma or serum of patients with neutralizing auto-Abs

(*N* = 41), healthy controls (*N* = 5), COVID-19 patients without auto-Abs (*N* = 21), and patients with life-threatening COVID-19 and loss-of-function (LOF) variants (*N* = 10), as assessed by Simoa ELISA. (C) z-scores for type I IFN gene responses in whole blood of COVID-19 patients with (*N* = 8) or without (*N* = 51) neutralizing auto-Abs, or healthy uninfected controls (*N* = 22). The median ± interquartile range is shown. z-scores were significantly lower for patients with neutralizing auto-Abs compared with patients without auto-Abs (Mann-Whitney test, *P* = 0.01).

Table 1. Sex and age distribution of patients with critical COVID-19 with and without auto-Abs. Ages and sexes of the patients and controls and information about auto-Abs against IFN-α2 and IFN-α, presented by age and sex. Dashes in rightmost column indicate data not available. OR, odds ratio; CI, confidence interval.				
Life-threatening COVID-19	<i>N</i> total	<i>N</i> auto-Abs positive (percentage)	OR [95% CI]	<i>P</i> value*
Sex				
Female	226	6 (2.6%)	1	—
Male	761	95 (12.5%)	5.22 [2.27 – 14.80]	2.5 × 10 ⁻⁶
Age				
<65 years	602	51 (8.5%)	1	—
≥65 years	385	50 (13.0%)	1.61 [1.04 – 2.49]	0.024

**P* values were derived from Fisher's exact test, as implemented in R (<https://cran.r-project.org/>).

IFNs. This proportion of males was higher than that observed in patients with critical COVID-19 without auto-Abs (75%; Fisher exact test, *P* = 2.5 × 10⁻⁶), and the proportion was much higher than that in male patients in the asymptomatic

or pauci-symptomatic cohort (28%; Fisher exact test, *P* < 10⁻⁶) (Table 1, Fig. 4A, and fig. S4A). Further evidence for X-chromosome linkage was provided by the observation that one of the seven women with auto-Abs and life-

threatening COVID-19 had X chromosome-linked incontinentia pigmenti (IP), in which cells activate only a single X chromosome (cells having activated the X chromosome bearing the null mutation in *NEMO* dying in the course of development) (27). The prevalence of auto-Abs against type I IFNs in the general population was estimated at 0.33% (0.015 to 0.67%) in a sample of 1227 healthy individuals—a value much lower than that in patients with life-threatening COVID-19 pneumonia, by a factor of at least 15. The patients with auto-Abs were also slightly older than the rest of our cohort (49.5% of patients positive for auto-Abs were over 65 years of age versus 38% for the rest of the cohort; *P* = 0.024), which suggests that the frequency of circulating anti-type I IFNs auto-Abs increases with age (Table 1 and Fig. 4B). However, auto-Abs were found in patients aged from 25 to 87 years (fig. S4B). Principal components analysis (PCA) was performed on data from

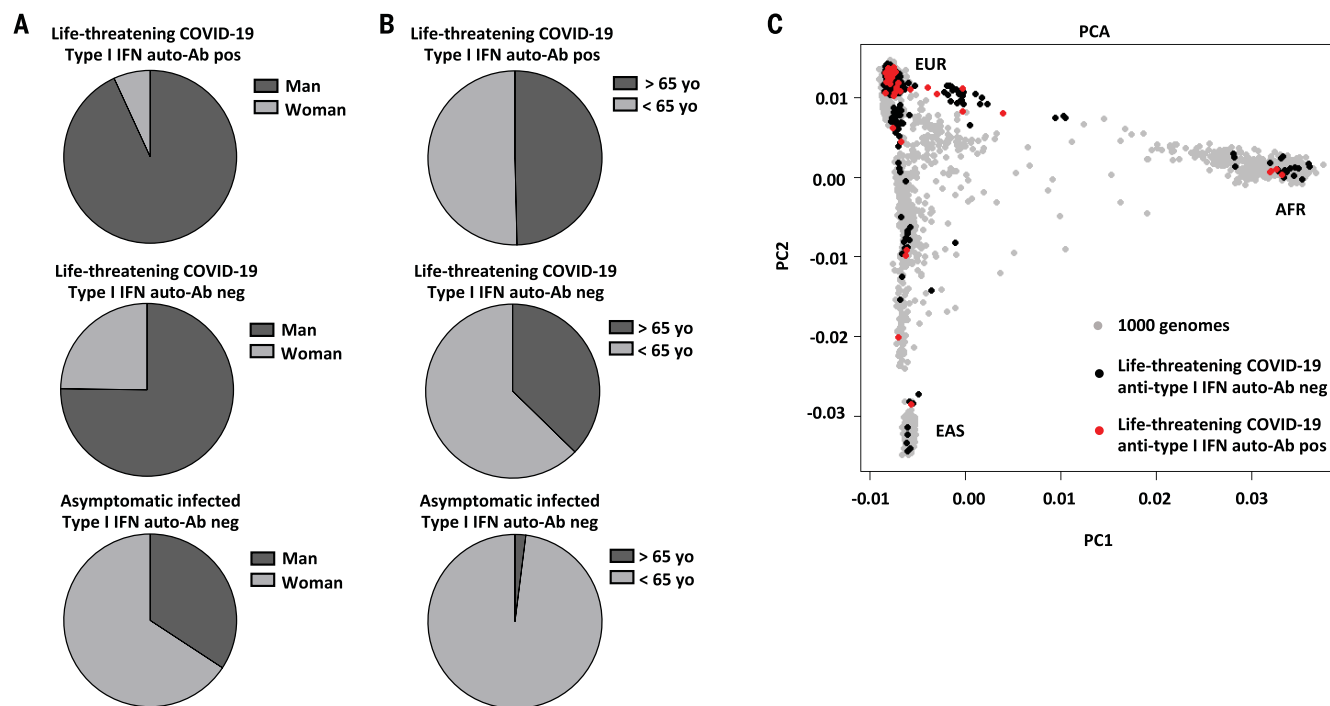


Fig. 4. Demographic and ethnic information about the patients and controls. (A) Gender distribution in patients with life-threatening COVID-19 and auto-Abs to type I IFNs, patients with life-threatening COVID-19 and without auto-Abs to type I IFNs, and individuals with asymptomatic or mild SARS-CoV-2. (B) Age distribution in patients with life-threatening COVID-19

and auto-Abs to type I IFNs, patients with life-threatening COVID-19 and without auto-Abs to type I IFNs, and individuals with asymptomatic or mild SARS-CoV-2. yo, years old. (C) PCA on 49 patients with life-threatening COVID-19 and auto-Abs against type I IFNs. EUR, Europeans; AFR, Africans; EAS, East-Asians.

49 patients: 34 Europeans, 5 North Africans, 4 sub-Saharan Africans, 2 patients from the Middle East, 2 South Asians, 1 East Asian, and 1 South American (Fig. 4C). Large-scale studies will be required to determine the frequency of such auto-Abs in humans of different sexes, ages, and ancestries. Finally, the presence of auto-Abs was associated with a poor outcome, with death occurring in 37 of the 101 patients (36.6%) (table S1).

Neutralizing auto-Abs to type I IFNs are causative of critical COVID-19

There are multiple lines of evidence to suggest that the neutralizing auto-Abs against type I IFNs observed in these 101 patients preceded infection with SARS-CoV-2 and accounted for the severity of disease. First, the two patients for whom testing was performed before COVID-19 were found to have auto-Abs before infection. Second, three patients with APS-1 known to have neutralizing auto-Abs against type I IFN immunity before infection also had life-threatening COVID-19 (22) (supplementary methods). Third, we screened a series of 32 women with IP and found that a quarter of them had auto-Abs against type I IFNs, including one who developed critical COVID-19 (fig. S1C). Fourth, there is a marked bias in favor of men, which suggests that the production of auto-Abs against type I IFNs—whether

driven by germ line or somatic genome—may be X chromosome-linked and therefore pre-existing to infection.

Moreover, IFN- α subtypes were undetectable during acute disease in the blood of patients with auto-Abs against IFN- α , which suggests a preexisting or concomitant biological impact in vivo. It is also unlikely that patients could break self-tolerance and mount high titers of neutralizing IgG auto-Abs against type I IFN within only 1 or even 2 weeks of infection. Finally, inborn errors of type I IFNs underlying life-threatening COVID-19 in other previously healthy adults—including autosomal recessive IFN- α/β receptor subunit 1 (IFNAR1) deficiency—have also been reported in an accompanying paper (18). Collectively, these findings suggest that auto-Abs against type I IFNs are a cause and not a consequence of severe SARS-CoV-2 infection, although their titers and affinity may be enhanced by the SARS-CoV-2-driven induction of type I IFNs. They also provide an explanation for the major sex bias seen in patients with life-threatening COVID-19 and perhaps also for the increase in risk with age.

Conclusion

We report here that at least 10% of patients with life-threatening COVID-19 pneumonia have neutralizing auto-Abs against type I IFNs. With our accompanying description of patients

with inborn errors of type I IFNs and life-threatening COVID-19 (18), this study highlights the crucial role of type I IFNs in protective immunity against SARS-CoV-2. These auto-Abs against type I IFNs were clinically silent until the patients were infected with SARS-CoV-2—a poor inducer of type I IFNs (28)—which suggests that the small amounts of IFNs induced by the virus are important for protection against severe disease. The neutralizing auto-Abs against type I IFNs, like inborn errors of type I IFN production, tip the balance in favor of the virus, which results in devastating disease with insufficient, and even perhaps deleterious, innate and adaptive immune responses.

Our findings have direct clinical implications. First, SARS-CoV-2-infected patients can be screened to identify individuals with auto-Abs at risk of developing life-threatening pneumonia. Such patients recovering from life-threatening COVID-19 should also be excluded from donating convalescent plasma for ongoing clinical trials, or at least they should be tested before their plasma donations are accepted (29). Second, this finding paves the way for preventive or therapeutic intervention, including plasmapheresis, monoclonal Abs depleting plasmablasts, and the specific inhibition of type I IFN-reactive B cells (30). Finally, in this patient group, early treatment with IFN- α is unlikely to be beneficial; however, treatment

with injected or nebulized IFN- β may have beneficial effects, as auto-Abs against IFN- β appear to be rare in patients with auto-Abs against type I IFNs.

Materials and methods

Subjects and samples

We enrolled 987 patients with proven life-threatening (critical) COVID-19, 663 asymptomatic or pauci-symptomatic individuals with proven COVID-19, and 1227 healthy controls in this study. All subjects were recruited following protocols approved by local Institutional Review Boards (IRBs). All protocols followed local ethics recommendations and informed consent was obtained when required.

COVID-19 disease severity was assessed in accordance with the Diagnosis and Treatment Protocol for Novel Coronavirus Pneumonia. The term life-threatening COVID-19 pneumonia describes pneumonia in patients with critical disease, whether pulmonary, with mechanical ventilation [continuous positive airway pressure (CPAP), bilevel positive airway pressure (BiPAP), intubation, or high-flow oxygen], septic shock, or damage to any other organ requiring admission in the intensive care unit (ICU). The individuals with asymptomatic or mild SARS-CoV-2 infection were individuals infected with SARS-CoV-2 who remained asymptomatic or developed mild, self-healing, ambulatory disease with no evidence of pneumonia. The healthy controls were individuals who had not been exposed to SARS-CoV-2.

Plasma and serum samples from the patients and controls were frozen at -20°C immediately after collection. The fluid-phase LIPS assay was used to determine the levels of antibodies against the SARS-CoV-2 nucleoprotein and spike protein, as has been previously described (31).

Detection of anti-cytokine auto-Abs

Multiplex particle-based assay

Serum and plasma samples were screened for auto-Abs against 18 targets in a multiplex particle-based assay, in which magnetic beads with differential fluorescence were covalently coupled to recombinant human proteins. Patients with an FI of >1500 for IFN- $\alpha 2$ or IFN- β or >1000 for IFN- ω were tested for blocking activity, as were patients positive for another cytokine.

ELISA

ELISA was performed as previously described (5). In brief, ELISA plates were coated with recombinant human interferon- α (rhIFN- α) or rhIFN- ω and incubated with 1:50 dilutions of plasma samples from the patients or controls. A similar protocol was used when testing for 12 subtypes of IFN- α .

LIPS

Levels of auto-Abs against IFN- α subtypes were measured with LIPS, as previously described

(32). IFN- $\alpha 1$, IFN- $\alpha 2$, IFN- $\alpha 4$, IFN- $\alpha 5$, IFN- $\alpha 6$, IFN- $\alpha 7$, IFN- $\alpha 8$, IFN- $\alpha 10$, IFN- $\alpha 14$, IFN- $\alpha 16$, IFN- $\alpha 17$, and IFN- $\alpha 21$ sequences were transfected in HEK293 cells, and the IFN- α -luciferase fusion proteins were collected in the tissue culture supernatant. For autoantibody screening, serum samples were incubated with protein G agarose beads, and we then added 2×10^6 luminescence units (LU) of antigen and incubated. Luminescence intensity was measured. The results are expressed in arbitrary units (AU), as a fold-difference relative to the mean of the negative control samples.

Functional evaluation of anti-cytokine auto-Abs

The blocking activity of anti-IFN- α and anti-IFN- ω auto-Abs was determined by assessing STAT1 phosphorylation in healthy control cells after stimulation with the appropriate cytokines in the presence of 10% healthy control or patient serum or plasma.

We demonstrated that the IFN- α and IFN- ω blocking activity observed was due to auto-Abs and not another plasma factor, by depleting IgG from the plasma with a protein G column. Without eluting the IgG, the flow-through fraction (IgG-depleted) was then collected and compared with total plasma in the phospho-STAT1 assay.

The blocking activity of anti-IFN- γ , -GM-CSF, -IFN- $\lambda 1$, -IFN- $\lambda 2$, -IFN- $\lambda 3$, -IL-6, -IL-10, -IL-12p70, -IL-22, -IL-17A, -IL-17F, -TNF α , and -TNF β antibodies was assessed with the assays outlined in table S3, as previously reported (21).

For the neutralization of ISG induction, PBMCs were left unstimulated or were stimulated for 2 hours with 10 ng/mL IFN- α or 10 ng/mL IFN- γ in a final volume of 100 μL . Real-time quantitative polymerase chain reaction (RT-qPCR) analysis was performed with Applied Biosystems Taqman assays for CXCL10, and the β -glucuronidase (GUS) housekeeping gene for normalization. Results are expressed according to the $\Delta\Delta\text{Ct}$ method, as described by the manufacturer's kit.

Phylogenetic reconstruction

Protein sequences were aligned with the online version of MAFFT v7.471 software (33), using the L-INS-i strategy (34) and the BLOSUM62 scoring matrix for amino acid substitutions. Phylogenetic tree reconstruction was performed by the neighbor-joining method (35) with the substitution model (36). Low-confidence branches ($<50\%$) are likely to be due to gene conversion events between IFNA genes, as previously reported (24, 37). The tree was then visualized (38). Very similar results were obtained with the corresponding DNA sequences (37, 39).

Statistical analysis

Comparison of proportions were performed using a Fisher exact test, as implemented in R

(<https://cran.r-project.org/>). PCA was performed with Plink v1.9 software on whole-exome and whole-genome sequencing data with the 1000 Genomes (1kG) Project phase 3 public database as a reference.

Simoa

Serum IFN- α concentrations were determined with Simoa technology, as previously described (40, 41), with reagents and procedures obtained from the Quanterix Corporation.

VSV assay

The seroneutralization assay was performed as previously described (42). In brief, the incubation of IFN- $\alpha 2$ with MDBK cells protects the cultured cells against the cytopathic effect of VSV. The titer of anti-IFN- α antibodies was defined as the last dilution causing 50% cell death.

SARS-CoV-2 experiment

SARS-CoV-2 strain USA-WA1/2020 was obtained from BEI Resources and amplified in Huh7.5 hepatoma cells at 33°C . Viral titers were measured on Huh7.5 cells in a standard plaque assay. Plasma samples or a commercial anti-IFN- $\alpha 2$ antibody were serially diluted and incubated with 20 pM recombinant IFN- $\alpha 2$ for 1 hour at 37°C (starting concentrations: plasma samples = 1/100 and anti-IFN- $\alpha 2$ antibody = 1/1000). The cell culture medium was then removed and replaced with the plasma- or antibody-IFN- $\alpha 2$ mixture. The plates were incubated overnight, and the plasma- or antibody-IFN- $\alpha 2$ mixture was removed by aspiration. The cells were washed once with phosphate-buffered saline (PBS) to remove potential anti-SARS-CoV-2 neutralizing antibodies, and fresh medium was then added. Cells were then infected with SARS-CoV-2 by directly adding the virus to the wells. Cells infected at a high multiplicity of infection (MOI) were incubated at 37°C for 24 hours, whereas cells infected at a low MOI were incubated at 33°C for 48 hours. The cells were fixed with 7% formaldehyde, stained for SARS-CoV-2 with an anti-N antibody, imaged, and analyzed as previously described (43).

Nanostring

For the NanoString assay, total RNA was extracted from whole blood samples collected in PaxGene tubes. The expression of selected genes was determined by NanoString methods and a 28-gene type I IFN score was calculated (44).

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ACKNOWLEDGMENTS

We thank the patients, their families, and healthy donors for placing their trust in us. We thank the French Incontinentia pigmenti association for their help and support. We thank Y. Nemirovskaya, D. Papandrea, M. Woollett, D. Liu, C. Rivalain, and C. Patissier for administrative assistance; D. Kapogiannis (National Institute on Aging) for providing healthy donor samples; and S. Xirasager, J. Barnett, X. Cheng, S. Weber, J. Danielson, B. Garabedian, and H. Matthews for their assistance in this study. We also thank R. Apps, B. Ryan, and Y. Belkaid of the CHI for their assistance. We thank the CRB-Institut Jérôme Lejeune, CRB-BioLeL, Paris, France, for their assistance. We thank

M. C. García Guerrero; I. Erkiiza; E. Grau; M. Massanella from IrsiCaixa AIDS Research Institute, Badalona, Spain; and J. Guitart from the Department of Clinical Genetics, University Hospital Germans Trias i Pujol, Badalona, Spain, for providing samples. We also thank J. Dalmau from IrsiCaixa for assistance. **Funding:** The Laboratory of Human Genetics of Infectious Diseases is supported by the Howard Hughes Medical Institute, The Rockefeller University, the St. Giles Foundation, the National Institutes of Health (NIH) (R01AI088364), the National Center for Advancing Translational Sciences (NCATS), NIH Clinical and Translational Science Award (CTSA) program (UL1 TR001866), a Fast Grant from Emergent Ventures, the Mercatus Center at George Mason University, the Yale Center for Mendelian Genomics and the GSP Coordinating Center funded by the National Human Genome Research Institute (NHGRI) (UM1HG006504 and U24HG008956), the French National Research Agency (ANR) under the Investments for the Future program (ANR-10-IAHU-01), the Integrative Biology of Emerging Infectious Diseases Laboratory of Excellence (ANR-10-LABX-62-IBED), the French Foundation for Medical Research (FRM) (EQU201903007798), the FRM and ANR GENCOV project (ANRS-COV05), the Square Foundation, Grandir – Fonds de solidarité pour l'enfance, the SCOR Corporate Foundation for Science, the Institut National de la Santé et de la Recherche Médicale (INSERM), and the University of Paris. Samples from San Raffaele Hospital were obtained through the Covid-BioB project and by healthcare personnel of San Raffaele Hospital, San Raffaele Telethon Institute for Gene Therapy (SR-TIGET) clinical laboratory and clinical research unit, funded by the Program Project COVID-19 OSR-UniSR and Fondazione Telethon. The French COVID Cohort Study Group was sponsored by INSERM and supported by the REACTing consortium and by a grant from the French Ministry of Health (PHRC 20-0424). The Cov-Contact Cohort was supported by the REACTing consortium, the French Ministry of Health, and the European Commission (RECOVER WP 6). The Milieu Intérieur Consortium was supported by the French Government's Investissement d'Avenir program, Laboratoire d'Excellence Milieu Intérieur grant (ANR-10-LABX-69-01) (primary investigators: L.Q.-M. and D.Du.). The Simoa experiment was supported by the PHRC-20-0375 COVID-19 grant "DIGITAL COVID" (primary investigator: G.G.). S.G.T. is supported by a Leadership 3 Investigator Grant awarded by the National Health and Medical Research Council of Australia and a COVID19 Rapid Response Grant awarded by UNSW Sydney. C.R.-G. and colleagues were supported by the Instituto de Salud Carlos III (COV20-10333 and COV20-10334, Spanish Ministry of Science and Innovation RTC-2017-6471-1; AEI/FEDER, UE) and Cabildo Insular de Tenerife (CGIEU0000219140 and "Apuestas científicas del ITER para colaborar en la lucha contra la COVID-19"). S.T.-A. and A.B. were supported by ANR-20-COVI-0064 (primary investigator: A.Be.). This work is supported by the French Ministry of Health "Programme Hospitalier de Recherche Clinique Inter régional 2013" by the Contrat de Plan Etat-Lorraine and FEDER Lorraine, and by a public grant overseen by the French National Research Agency (ANR) as part of the second Investissements d'Avenir program FIGHT-HF (reference no. ANR-15-RHU-0004) and by the French PIA project "Lorraine Université d'Excellence" (reference no. ANR-15-IDEX-04-LUE) (45); and biobanking is performed by the Biological Resource Center Lorrain BB-0033-00035. This study was supported by the Fonds IMMUNOV, for Innovation in Immunopathology; by a grant from the Agence Nationale de la Recherche (ANR-flash Covid19 "AIROCovid" to F.R.-L.); and by the FAST Foundation (French Friends of Sheba Tel Hashomer Hospital). Work in the Laboratory of Virology and Infectious Disease was supported by NIH grants P01AI138398-S1, 2U19AI111825, and R01AI091707-10S1; a George Mason University Fast Grant; and the G. Harold and Leila Y. Mathers Charitable Foundation. The Amsterdam UMC Covid-19 Biobank was supported by grants from the Amsterdam Corona Research Fund, the Dr. C.J. Vaillant Fund, and the Netherlands Organization for Health Research and Development [ZonMw; NWO-Vici-Grant (grant no. 918-19-627 to D.v.d.B.)]. This work was also supported by the Division of Intramural Research of the National Institute of Dental Craniofacial Research and the National Institute of Allergy and Infectious Diseases, National Institutes of Health, and by Regione Lombardia, Italy (project "Risposta immune in pazienti con COVID-19 e comorbidità"). The opinions and assertions expressed herein are those of the author(s) and do not necessarily reflect the official policy or position of the Uniformed Services University or the Department of Defense. J.H. holds an Institut Imagine M.D.-Ph.D. fellowship from the Fondation Bettencourt Schueller. J.R. is supported by the INSERM Ph.D. program ("poste d'accueil Inserm"). P.Ba. was supported by the French Foundation for Medical Research (FRM, EA20170638020) and the M.D.-Ph.D. program

of the Imagine Institute (with the support of the Fondation Bettencourt-Schueller). We thank the Association "Turner et vous" for their help and support. Sample processing at IrsiCaixa was possible thanks to the crowdfunding initiative YoMeCorono. D.C.V. is supported by the Fonds de la recherche en santé du Québec clinician-scientist scholar program. K.K. was supported by the Estonian Research Council grant PUT1367. We thank the GEN-COVID Multicenter Study (<https://sites.google.com/dbm.unisi.it/gen-covid>). We thank the NIAID Office of Cyber Infrastructure and Computational Biology, Bioinformatics and Computational Biosciences Branch (contract no. HHSN316201300006W/HHSN27200002 to MSC, Inc.), the Operations Engineering Branch for developing the HGRRepo system to enable streamlined access to the data, and the NCI Advanced Biomedical Computational Science (ABCS) for data transformation support. Biomedical Advanced Research and Development Authority was supported under contract no. HHS010201600031C (to J.H.). Financial support was provided by the National Institute of Allergy and Infectious Diseases (NIAID) K08AI135091; the Burroughs Wellcome Fund CAMS; the Clinical Immunology Society; and the American Academy of Allergy, Asthma, and Immunology. **Author contributions:** P.Ba., L.B.R., Q.Z., E.M., H.-H.H., Y.Z., K.Dor., Q.P., J.R., V.B., J.Ma., E.S., L.H., P.P., L.L., L.B., S.T.-A., K.Dob., A.A.d.J., A.Be., L.P., D.D., E.S.H., J.S.T., R.G.-M., K.K., A.P., S.-Y.Z., S.M.H., G.G., E.J., C.M.R., L.D.N., H.C.S., and J.-L.C. performed or provided supervision of experiments, generated and analyzed data, and contributed to the manuscript by providing figures and tables. J.L.P., G.K., B.B., Y.S., R.Y., A.B., K.B., R.P.L., M.M., A.C., and L.A. performed computational analysis of data. P.Ba., A.K., E.C., Y.T.-L., A.N.S., O.M.D., M.S.A., A.A., G.C., V.L., F.C., M.V., D.M.S., J.H., B.T., D.Du., L.Q.-M., D.v.d.B., L.R., D.C.V., S.G.T., F.H., D.Da., T.H.M., P.Br., J.M.-P., M.C.N., S.B.-D., C.R.-G., G.V., A.J.O., J.Gu., P.D.B., J.I.C., A.B., L.R.B., M.D.A., P.Ba., P.R., F.R.-L., F.F., M.V.U., L.I., A.S., S.P., E.Q.-R., C.R., R.C., D.M., A.L., G.L.M., X.D., J.Gh., M.S.L., and G.G. evaluated and recruited patients to COVID and/or control cohorts of patients. P.Ba. and J.-L.C. wrote the manuscript. J.-L.C. supervised the project. All authors edited the manuscript. **Competing interests:** H.C.S. is adjunct faculty at the University of Pennsylvania. J.-L.C. is listed as an inventor on patent application U.S. 63/055,155 filed by The Rockefeller University that encompasses aspects of this publication. R.P.L. is a nonexecutive director of Roche and its subsidiary Genentech. The authors declare no other competing interests. **Data and materials availability:** All data are available in the manuscript or in the supplementary materials. Plasma, cells, and genomic DNA are available from J.-L.C. or D.C.V. under a material transfer agreement with The Rockefeller University and the Research Institute-McGill University Health Centre. Huh7.5 cells are available on request from C.M.R. under a material transfer agreement with The Rockefeller University and Apath, LLC. Materials and reagents used are almost exclusively commercially available and nonproprietary. Requests for materials derived from human samples may be made available, subject to any underlying restrictions on such samples. J.-L.C. can make material transfer agreements available through The Rockefeller University. This work is licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>. This license does not apply to figures/photos/artwork or other content included in the article that is credited to a third party; obtain authorization from the rights holder before using such material.

SUPPLEMENTARY MATERIALS

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Supplementary Materials and Methods

Figs. S1 to S4

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Data S1

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HGID Lab Andrés Augusto Arias^{1,3}, Bertrand Boisson^{1,2}, Soraya Bouchier², Jacinta Bustamante^{1,2}, Marwa Chbihi², Jie Chen¹, Maya Chrabieh², Tatiana Kochetkov¹, Tom Le Voyer², Dana Liu¹, Yelena Nemirovskaya², Masato Ogishi¹, Dominick Papandrea², Cécile Patissier², Franck Rapoport¹, Manon Roynard², Natasha Vladikine², Mark Woollett¹, Peng Zhang¹

¹St. Giles Laboratory of Human Genetics of Infectious Diseases, Rockefeller Branch, The Rockefeller University, New York, NY, USA.

²Laboratory of Human Genetics of Infectious Diseases, Necker

Branch, INSERM U1163, Necker Hospital for Sick Children, Paris, France. ³School of Microbiology and Group of Primary Immunodeficiencies, University of Antioquia UdeA, Medellín, Colombia.

NIAID-USUHS Immune Response to COVID Group Anuj Kashyap¹, Li Ding¹, Marita Bosticardo¹, Qinlu Wang², Sebastian Ochoa⁴, Hui Liu¹, Samuel D. Chauvin³, Michael Stack¹, Galina Koroleva⁴, Neha Bansal⁵, Clifton L. Dalgard^{6,7}, Andrew L. Snow⁸

¹Laboratory of Clinical Immunology and Microbiology, Division of Intramural Research, NIAID, NIH, Bethesda, MD, USA. ²Bioinformatics and Computational Biosciences Branch, NIAID Office of Cyber Infrastructure and Computational Biology, NIAID, NIH, Bethesda, MD, USA. ³Laboratory of Immune System Biology, Division of Intramural Research, NIAID, NIH, Bethesda, MD, USA. ⁴NIH Center for Human Immunology, NIH, Bethesda, MD, USA. ⁵Multiscale Systems Biology Section, Laboratory of Immune System Biology, NIAID, NIH, Bethesda, MD, USA. ⁶PRIMER, Uniformed Services University of the Health Sciences, Bethesda, MD, USA. ⁷Department of Anatomy, Physiology & Genetics, Uniformed Services University of the Health Sciences, Bethesda, MD, USA. ⁸Department of Pharmacology & Molecular Therapeutics, Uniformed Services University of the Health Sciences, Bethesda, MD, USA.

COVID Clinicians Jorge Abad¹, Sergio Aguilera-Albesa², Ozge Metin Akcan³, Ilad Alavi Darazam⁴, Juan C. Alkane⁵, Miquel Alfonso Ramos⁵, Seyed Alireza Nadiji¹, Gulsun Altan⁸, Jerome Allardet-Servent⁹, Luis M. Allende¹⁰, Laia Alsina¹¹, Marie-Alexandra Alyanikian¹², Blanca Amador-Borrero¹³, Zahir Amoura¹⁴, Arnau Antolín¹⁵, Sveklet Arslan¹⁶, Sophie Assant¹⁷, Terese Auguet¹⁸, Axelle Azot¹⁹, Fanny Bajolle²⁰, Aurélie Baldoli²¹, Maite Ballester²², Hagit Baris Feldman²³, Benoit Barrou²⁴, Alexandra Beuron²⁵, Agurtzane Bilbao²⁶, Geraldine Blanchard-Rohner²⁷, Ignacio Blanco¹, Adeline Blandinières²⁸, Daniel Blazquez-Garnier²⁹, Marketa Bloomfield³⁰, Mireia Bolivar-Prados³¹, Raphael Borie³², Ahmed A. Boufhiha³³, Claire Bouvattier³⁴, Oksana Boyarchuk³⁵, Maria Rita P. Bueno³⁶, Jacinta Bustamante²⁰, Juan José Cáceres Agra³⁷, Semra Calimli³⁸, Ruggero Capra³⁹, Maria Carrabba⁴⁰, Carlos Casanovas⁴¹, Marion Caseris⁴², Martin Castella⁴³, Francesco Castelli⁴⁴, Martín Castillo de Vera⁴⁵, Mateus V. Castro⁴⁶, Emilie Catherine⁴⁶, Martin Chalumeau⁴⁷, Bruno Charbit⁴⁸, Matthew P. Cheng⁴⁹, Pèrè Clavé⁵¹, Bonaventura Clotet⁵⁰, Anna Codina⁵¹, Fatih Colkesen⁵², Fatma Colkesen⁵³, Roger Colobran⁵⁴, Cléo Comarmond⁵⁵, Angelo G. Corsico⁵⁶, David Dalmau⁵⁷, David Ross Darley⁵⁸, Nicolas Dauby⁵⁹, Stéphane Dauter⁶⁰, Loïc de Pontual⁶¹, Amin Dehban⁶², Geoffroy Delplanq⁶³, Alexandre Demoule⁶⁴, Antonio Di Sabatino⁶⁵, Jean-Luc Diehl⁶⁶, Stephanie Dobbela⁶⁷, Sophie Durand⁶⁸, Waleed Eldars⁶⁹, Mohamed Elgamal⁷⁰, Marwa H. Elmagdy⁷¹, Melike Emiroglu⁷², Emine Hafize Erdeniz⁷³, Selma Erol Aytakin⁷⁴, Romain Euvard⁷⁵, Repec Evcen⁷⁶, Giovanna Fabio⁴⁰, Laurence Faivre⁷⁷, Antonin Falck⁴², Muriel Fartoukh⁷⁸, Morgane Faure⁷⁹, Miguel Fernandez Arquer⁸⁰, Carlos Flores⁸¹, Bruno Francois⁸², Victoria Fumadó⁸³, Francesca Fusco⁸⁴, Blanca Garcia Solis⁸⁵, Pascale Gausse⁸⁶, Juana Gil-Herrera⁸⁷, Laurent Gilardin⁸⁸, Monica Girona Alarcon⁸⁹, Mónica Girona-Alarcón⁸⁹, Jean-Christophe Goffard⁹⁰, Funda Gök⁹¹, Rafaela González-Montelongo⁹², Antoine Guerdier⁹³, Yahya Gül⁹⁴, Sukru Nail Guner⁹⁴, Marta Gut⁹⁵, Jérôme Hadjadj⁹⁶, Filomena Haerynck⁹⁷, Rabih Halwan⁹⁸, Lennart Hammarström⁹⁹, Nevin Hatipoglu¹⁰⁰, Elisa Hernandez-Brito¹⁰¹, Maria Soledad Holanda-Peña¹⁰², Juan Pablo Horcajada¹⁰³, Sami Iraiech¹⁰⁴, Linda Humbert¹⁰⁵, Alejandro D. Iglesias¹⁰⁶, Antonio Íñigo-Campos⁹², Matthieu Jamme¹⁰⁷, Maria Jesús Arranz¹⁰⁸, Iolanda Jordan¹⁰⁹, Fikret Kanat¹¹⁰, Hasan Kapakli¹¹¹, Iskender Kara¹¹², Adem Karbuz¹¹³, Kadriye Kart Yasar¹¹⁴, Sevgi Keles¹¹⁵, Yasemin Kendir Demirkol¹¹⁶, Adam Klocperk¹¹⁷, Zbigniew J. Król¹¹⁸, Paul Kuentz¹¹⁹, Yat Wah M. Kwan¹²⁰, Jean-Christophe Lagier¹²¹, Yu-Lung Lau¹²², Fleur Le Bourgeois⁶⁰, Yee-Sin Leo¹²³, Rafael Leon Lopez¹²⁴, Daniel Leung¹²², Michael Levin¹²⁵, Michael Levy⁶⁰, Romain Lévy²⁰, Zhi Li⁴⁸, Agnes Linglart¹²⁶, José M. Lorenzo-Salazar⁹², Céline Louapre¹²⁷, Catherine Lubetzki¹²⁷, Charles-Edouard Luyt¹²⁸, David C. Lye¹²⁹, Davood Mansour¹³⁰, Majid Marjani¹³¹, Jesus Marquez Pereira¹³², Andrea Martin¹³³, David Martínez Pueyo¹³⁴, Javier Martínez-Picado¹³⁵, Iciar Marzana¹³⁶, Alexis Mathian¹⁴, Larissa R. B. Matos³⁶, Gail V. Matthews¹³⁷, Julien Mayaux¹³⁸, Jean-Louis Mége¹³⁹, Isabelle Melki¹⁴⁰, Jean-François Meritet¹⁴¹, Ozge Metin¹⁴², Isabelle Meyts¹⁴³, Mehdi Mezidi¹⁴⁴, Isabelle Migeotte¹⁴⁵, Maude Millereux¹⁴⁶, Tristan Miralet¹⁴⁷, Clotilde Mircher¹⁴⁸, Mehdi Mirsaedi¹⁴⁸, Abián Montesdeoca Melián¹⁴⁹, Antonio Morales Martínez¹⁵⁰, Pierre Morange¹⁵¹, Clémence Mordacq¹⁰⁵, Guillaume Morelle¹⁵², Stéphane Mouly¹³, Adrián Muñoz-Barrera⁹², Cyrill Nafati¹⁵³, João Farelá Neves¹⁵⁴, Lisa F. P. Ng¹⁵⁵

Yeray Novoa Medina¹⁵⁶, Esmeralda Nuñez Cuadros¹⁵⁷, J. Gonzalo Ochoa-Vinyals¹⁵⁸, Zerrin Orbak¹⁵⁹, Mehdi Qualha²⁰, Tayfun Özçelik¹⁶⁰, Qiang Pan Hammarström¹⁶¹, Christophe Parizot¹⁶², Tiffany Pascreau¹⁶², Estela Paz-Artal¹⁶³, Rebeca Pérez de Diego⁸⁵, Aurélien Philippe¹⁶⁴, Quentin Philippot⁷⁸, Laura Planas-Serra¹⁶⁵, Dominique Parot¹⁶⁶, Julien Poissy¹⁶⁷, Géraldine Poncelet⁴², Marie Pouletty¹⁶⁸, Paul Quentric¹³⁸, Didier Raoult¹³⁹, Anne-Sophie Rebillat¹⁶⁸, Ismail Reisli¹⁶⁹, Pilar Ricart¹⁷⁰, Jean-Christophe Richard¹⁷¹, Nadia Rivet²⁸, Jacques G. Rivière¹⁷², Gemma Rocamora Blanchi¹⁵, Carlos Rodrigo¹, Carlos Rodríguez-Gallego¹⁷³, Agustí Rodríguez-Palmero¹⁷⁴, Carolina Soledad Romero¹⁷⁵, Anya Rothenbuhler¹⁷⁶, Flore Rozenberg⁷⁷, Maria Yolanda Ruiz del Prado⁷⁸, Joan Sabater Riera¹⁵, Oliver Sanchez¹⁷⁹, Silvia Sánchez-Ramón¹⁸⁰, Agatha Schluter¹⁸¹, Matthieu Schmidt¹⁸¹, Cyril E. Schweitzer¹⁸², Francesco Scolari¹⁸³, Anna Sediva¹⁸⁴, Luis M. Seijó¹⁸⁵, Damien Sene¹³, Sevtpat Senoglu¹¹⁴, Mikko R. J. Seppänen¹⁸⁶, Alex Serra Illovis¹⁸⁷, Mohammad Shahrooei⁶², David Smadja¹⁸⁸, Ali Sobh¹⁸⁹, Xavier Solanich Moreno¹⁵, Jordi Solé-Violán¹⁹⁰, Catherine Soler¹⁹¹, Pere Soler-Palacín¹³³, Yuri Stepanovskiy¹⁹², Annabelle Stoclin¹⁹³, Fabio Taccone¹⁴⁵, Yacine Tandjaoui-Lambiotte¹⁹⁴, Jean-Luc Taupin¹⁹⁵, Simon J. Tavernier¹⁹⁶, Benjamin Terrier¹⁹⁷, Caroline Thumerelle¹⁰⁵, Gabriele Tomasoni¹⁹⁸, Julie Toubiana⁴⁷, Josep Trenado Alvarez¹⁹⁹, Sophie Trouillet-Assant²⁰⁰, Jesús Troya²⁰¹, Alessandra Tucci²⁰², Matilde Valeria Ursini⁸⁴, Yurdağul Uzunhan²⁰³, Pierre Vabres²⁰⁴, Juan Valencia-Ramos²⁰⁵, Ana Maria Van Den Rym¹⁸¹, Isabelle Vandernoot²⁰⁶, Hulya Vatansev²⁰⁷, Valentina Vélaz-Danarmaria⁴¹, Sébastien Viel¹⁶⁶, Cédric Vianin²⁰⁸, Marie E. Vilaire⁶⁸, Audrey Vincent³⁴, Guillaume Voiriot²⁰⁹, Fanny Vuotto¹⁰⁵, Alper Yosunkaya⁹¹, Barnaby E. Young¹²³, Fatih Yucel¹⁰, Faiez Zannad¹¹¹, Mayana Zatz²⁶, Alexandre Belot^{212*}

¹University Hospital and Research Institute "Germans Trias i Pujol", Badalona, Spain. ²Navarra Health Service Hospital, Pamplona, Spain. ³Division of Pediatric Infectious Diseases, Necmettin Erbakan University, Meram Medical Faculty, Konya, Turkey. ⁴Department of Infectious Diseases, Loghman Hakim Hospital, Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁵Hospital Nacional Edgardo Rebagliati Martins, Lima, Peru. ⁶Parc Sanitari Sant Joan de Déu, Sant Boi de Llobregat, Barcelona, Spain. ⁷Virology Research Center, National Institutes of Tuberculosis and Lung diseases, Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁸Division of Pediatric Infectious Diseases, Faculty of Medicine, Selçuk University, Konya, Turkey. ⁹Intensive Care Unit, Hôpital Européen, Marseille, France. ¹⁰Immunology Department, University Hospital 12 de Octubre, Research Institute imas12, Complutense University, Madrid, Spain. ¹¹Hospital Sant Joan de Déu, Barcelona, Spain. ¹²Department of Biological Immunology, Necker Hospital for Sick Children, APHP and INEM, Paris, France. ¹³Internal Medicine Department, Hôpital Lariboisière, APHP; Université de Paris, Paris, France. ¹⁴Internal Medicine Department, Pitié-Salpêtrière Hospital, Paris, France. ¹⁵Hospital Universitari de Bellvitge, Barcelona, Spain. ¹⁶Division of Clinical Immunology and Allergy, Necmettin Erbakan University, Meram Medical Faculty, Konya, Turkey. ¹⁷Joint Research Unit, Hospices Civils de Lyon-bio Mérieux, Hospices Civils de Lyon, Lyon Sud Hospital, Lyon, France. ¹⁸Hospital Universitario de Tarragona Joan XXIII, Universitat Rovira i Virgili (URV), IISPV, Tarragona, Spain. ¹⁹Private practice, Paris, France. ²⁰Necker Hospital for Sick Children, AP-HP, Paris, France. ²¹Department of Infectious Diseases, CHU de Caen, Caen, France. ²²Consorcio Hospital General Universitario, Valencia, Spain. ²³The Genetics Institute, Tel Aviv Sourasky Medical Center and Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel. ²⁴Department of Urology, Nephrology, Transplantation, APHP-SU, Sorbonne Université, INSERM U 1082, Paris, France. ²⁵Service de Médecine Intensive-Réanimation et Pneumologie, APHP Hôpital Pitié-Salpêtrière, Paris, France. ²⁶Cruces University Hospital, Bizkaia, Spain. ²⁷Paediatric Immunology and Vaccinology Unit, Geneva University Hospitals and Faculty of Medicine, Geneva, Switzerland. ²⁸Hematology, Georges Pompidou Hospital, APHP, Paris, France. ²⁹Pediatric Infectious Diseases Unit, Instituto de Investigación 12 de Octubre (imas12), Hospital Universitario 12 de Octubre, Madrid, Spain. ³⁰Department of Immunology, Motol University Hospital, 2nd Faculty of Medicine, Charles University, Department of Pediatrics, Thomayer's Hospital, 1st Faculty of Medicine, Charles University, Prague, Czech Republic. ³¹Centro de Investigación Biomédica en Red de Enfermedades Hepáticas y Digestivas (Ciberhd), Hospital de Mataró, Consorcio Sanitari del Maresme, Mataró, Spain. ³²Service de Pneumologie, Hôpital Bichat, APHP, Paris, France. ³³Clinical Immunology Unit, Pediatric Infectious Disease Department, Faculty of Medicine and Pharmacy, Averroes University Hospital, LICIA Laboratoire d'immunologie clinique, d'inflammation et d'allergie, Hassan II University, Casablanca, Morocco. ³⁴Endocrinology Unit, APHP Hôpitaux

- Universitaires Paris-Sud, Le Kremlin-Bicêtre, France. ³⁵Department of Children's Diseases and Pediatric Surgery, I.Horabachevsky Ternopil National Medical University, Ternopil, Ukraine. ³⁶Human Genome and Stem-Cell Research Center, University of São Paulo, São Paulo, Brazil. ³⁷Hospital Insular, Las Palmas de Gran Canaria, Spain. ³⁸Division of Critical Care Medicine, Department of Anesthesiology and Reanimation, Konya State Hospital, Konya, Turkey. ³⁹MS Center, Spedali Civili, Brescia, Italy. ⁴⁰Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico, Milan, Italy. ⁴¹Bellvitge University Hospital, L'Hospitalet de Llobregat, Barcelona, Spain. ⁴²Hôpital Robert Debré, Paris, France. ⁴³Pediatric Immunohematology Unit, Necker Enfants Malades Hospital, AP-HP, Paris, France. ⁴⁴Department of Infectious and Tropical Diseases, University of Brescia, ASST Spedali Civili di Brescia, Brescia, Italy. ⁴⁵Doctoral Health Care Center, Canarian Health System, Las Palmas de Gran Canaria, Spain. ⁴⁶Hôpital Foch, Suresnes, France. ⁴⁷Necker Hospital for Sick Children, Paris University, AP-HP, Paris, France. ⁴⁸Pasteur Institute, Paris, France. ⁴⁹McGill University Health Centre, Montreal, Canada. ⁵⁰University Hospital and Research Institute "Germans Trias i Pujol", IrsiCaixa AIDS Research Institute, UVic-UCC, Badalona, Spain. ⁵¹Clinical Biochemistry, Pathology, Paediatric Neurology and Molecular Medicine Departments and Biobank, Institut de Recerca Sant Joan de Déu and CIBERER-ISCIII, Espilugues, Spain. ⁵²Division of Clinical Immunology and Allergy, Department of Internal Medicine, Necmettin Erbakan University, Meram Medical Faculty, Konya, Turkey. ⁵³Department of Infectious Diseases and Clinical Microbiology, Konya Training and Research Hospital, Konya, Turkey. ⁵⁴Hospital Universitari Vall d'Hebron, Barcelona, Spain. ⁵⁵Pitié-Salpêtrière Hospital, Paris, France. ⁵⁶Respiratory Diseases Division, IRCCS Policlinico San Matteo Foundation and University of Pavia, Pavia, Italy. ⁵⁷Fundació Docència i Recerca Mútua Terrassa, Barcelona, Spain. ⁵⁸UNSW Medicine, St Vincent's Clinical School; Department of Thoracic Medicine, St Vincent's Hospital Darlinghurst, Sydney, Australia. ⁵⁹CHU Saint-Pierre, Université Libre de Bruxelles (ULB), Brussels, Belgium. ⁶⁰Pediatric Intensive Care Unit, Robert-Debré University Hospital, APHP, Paris, France. ⁶¹Sorbonne Paris Nord, Hôpital Jean Verdier, APHP, Bondy, France. ⁶²Specialized Immunology Laboratory of Dr. Shahrooei, Sina Medical Complex, Ahvaz, Iran. ⁶³Centre de génétique humaine, CHU Besançon, Besançon, France. ⁶⁴Sorbonne Université Médecine and APHP Sorbonne Université site Pitié-Salpêtrière, Paris, France. ⁶⁵Department of Internal Medicine, Fondazione IRCCS Policlinico San Matteo, University of Pavia, Pavia, Italy. ⁶⁶Intensive Care Unit, Georges Pompidou Hospital, APHP, Paris, France. ⁶⁷Department of Pneumology, AZ Delta, Roeselare, Belgium. ⁶⁸Institut Jérôme Lejeune, Paris, France. ⁶⁹Department of Microbiology and Immunology, Faculty of Medicine, Mansoura University, Mansoura, Egypt. ⁷⁰Department of Chest, Faculty of Medicine, Mansoura University, Mansoura, Egypt. ⁷¹Department of Medical Biochemistry and Molecular Biology, Faculty of Medicine, Mansoura University, Mansoura, Egypt. ⁷²Faculty of Medicine, Division of Pediatric Infectious Diseases, Selcuk University, Konya, Turkey. ⁷³Division of Pediatric Infectious Diseases, Ondokuz Mayıs University, Samsun, Turkey. ⁷⁴Necmettin Erbakan University, Meram Medical Faculty, Division of Pediatric Allergy and Immunology, Konya, Turkey. ⁷⁵Centre Hospitalier Fleury, Bourg-en-Bresse, France. ⁷⁶Division of Clinical Immunology and Allergy, Department of Internal Medicine, Necmettin Erbakan University, Meram Medical Faculty, Konya, Turkey. ⁷⁷Centre de Génétique, CHU Dijon, Dijon, France. ⁷⁸APHP Tenon Hospital, Paris, France. ⁷⁹Sorbonne Universités, UPMC University of Paris, Paris, France. ⁸⁰Department of Clinical Immunology, Hospital Clínico San Carlos, Madrid, Spain. ⁸¹Genomics Division, Instituto Tecnológico y de Energías Renovables (ITER), Santa Cruz de Tenerife, Spain; CIBER de Enfermedades Respiratorias, Instituto de Salud Carlos III, Madrid, Spain; Research Unit, Hospital Universitario N.S. de Candelaria, Santa Cruz de Tenerife, Spain; Instituto de Tecnologías Biomédicas (ITB), Universidad de La Laguna, San Cristóbal de La Laguna, Spain. ⁸²CHU Limoges and Inserm CIC 1435 & UMR 1092, Limoges, France. ⁸³Infectious Diseases Unit, Department of Pediatrics, Hospital Sant Joan de Déu, Barcelona, Spain; Institut de Recerca Sant Joan de Déu, Spain; Universitat de Barcelona (UB), Barcelona, Spain. ⁸⁴Institute of Genetics and Biophysics 'Adriano Buzzati-Traverso', IGB-CNR, Naples, Italy. ⁸⁵Laboratory of Immunogenetics of Human Diseases, IdiPAZ Institute for Health Research, La Paz Hospital, Madrid, Spain. ⁸⁶Hematology, APHP, Hôpital Européen Georges Pompidou and Inserm UMR-S1140, Paris, France. ⁸⁷Hospital General Universitario and Instituto de Investigación Sanitaria "Gregorio Marañón", Madrid, Spain. ⁸⁸Bégin military Hospital, Bégin, France. ⁸⁹Pediatric Intensive Care Unit, Hospital Sant Joan de Déu, Barcelona, Spain. ⁹⁰Department of Internal Medicine, Hôpital Erasme, Université Libre de Bruxelles, Brussels, Belgium. ⁹¹Division of Critical Care Medicine, Department of Anesthesiology and Reanimation, Necmettin Erbakan University, Meram Medical Faculty, Konya, Turkey. ⁹²Genomics Division, Instituto Tecnológico y de Energías Renovables (ITER), Santa Cruz de Tenerife, Spain. ⁹³Assistance Publique Hôpitaux de Paris, Paris, France. ⁹⁴Division of Allergy and Immunology, Necmettin Erbakan University, Meram Medical Faculty, Konya, Turkey. ⁹⁵CNAG-CRG, Centre for Genomic Regulation (CRG), Barcelona Institute of Science and Technology (BIST); Universitat Pompeu Fabra (UPF), Barcelona, Spain. ⁹⁶Department of Internal Medicine, National Reference Center for Rare Systemic Autoimmune Diseases, AP-HP, APHP-CUP, Hôpital Cochin, Paris, France. ⁹⁷Ghent University Hospital, Ghent, Belgium. ⁹⁸Sharjah Institute of Medical Research, College of Medicine, University of Sharjah, Sharjah, United Arab Emirates. ⁹⁹Department of Biosciences and Nutrition, SE14183, Huddinge, Karolinska Institutet, Stockholm, Sweden. ¹⁰⁰Pediatric Infectious Diseases Unit, Bakirkoy Dr. Sadi Konuk Training and Research Hospital, University of Health Sciences, Istanbul, Turkey. ¹⁰¹Department of Immunology, Hospital Universitario de Gran Canaria Dr. Negrín, Canarian Health System, Las Palmas de Gran Canaria, Spain. ¹⁰²Intensive Care Unit, Marqués de Valdecilla Hospital, Santander, Spain. ¹⁰³Hospital del Mar, Parc de Salut Mar, Barcelona, Spain. ¹⁰⁴Intensive Care Unit, APHM, Marseille, France. ¹⁰⁵CHU Lille, Lille, France. ¹⁰⁶Department of Pediatrics, Columbia University, New York, NY, USA. ¹⁰⁷Centre Hospitalier Intercommunal Poissy Saint Germain en Laye, Poissy, France. ¹⁰⁸Fundació Docència i Recerca Mútua Terrassa, Barcelona, Spain. ¹⁰⁹Hospital Sant Joan de Déu, Kids Corona Platform, Barcelona, Spain. ¹¹⁰Selcuk University, Faculty of Medicine, Chest Diseases Department, Konya, Turkey. ¹¹¹Division of Allergy and Immunology, Balıkesir Atatürk City Hospital, Balıkesir, Turkey. ¹¹²Division of Critical Care Medicine, Selcuk University, Faculty of Medicine, Konya, Turkey. ¹¹³Division of Pediatric Infectious Diseases, Prof. Dr. Cemil Tascioglu City Hospital, Istanbul, Turkey. ¹¹⁴Departments of Infectious Diseases and Clinical Microbiology, Bakirkoy Dr. Sadi Konuk Training and Research Hospital, University of Health Sciences, Istanbul, Turkey. ¹¹⁵Meram Medical Faculty, Necmettin Erbakan University, Meram Medical Faculty, Konya, Turkey. ¹¹⁶Health Sciences University, Umraniye Education and Research Hospital, Istanbul, Turkey. ¹¹⁷Department of Immunology, 2nd Faculty of Medicine, Charles University and University Hospital in Motol, Prague, Czech Republic. ¹¹⁸Central Clinical Hospital of Ministry of the Interior and Administration in Warsaw, Warsaw, Poland. ¹¹⁹Oncobiologie Génétique Bioinformatique, PC Bio, CHU Besançon, Besançon, France. ¹²⁰Paediatric Infectious Disease Unit, Hospital Authority Infectious Disease Center, Princess Margaret Hospital, Hong Kong (Special Administrative Region), China. ¹²¹Aix Marseille Univ, IRD, MEPIH, IHU Méditerranée Infection, Marseille, France. ¹²²Department of Paediatrics and Adolescent Medicine, The University of Hong Kong, Hong Kong, China. ¹²³National Centre for Infectious Diseases, Singapore. ¹²⁴Hospital Universitario Reina Sofía, Cordoba, Spain. ¹²⁵Imperial College, London, UK. ¹²⁶Endocrinology and diabetes for children, AP-HP, Bicêtre Paris-Saclay Hospital, Le Kremlin-Bicêtre, France. ¹²⁷Neurology Unit, APHP Pitié-Salpêtrière Hospital, Paris University, Paris, France. ¹²⁸Intensive Care Unit, APHP Pitié-Salpêtrière Hospital, Paris University, Paris, France. ¹²⁹National Centre for Infectious Diseases; Tan Tock Seng Hospital; Yong Loo Lin School of Medicine; Lee Kong Chian School of Medicine, Singapore. ¹³⁰Department of Clinical Immunology and Infectious Diseases, National Research Institute of Tuberculosis and Lung Diseases, Shahid Beheshti University of Medical Sciences, Tehran, Iran. ¹³¹Clinical Tuberculosis and Epidemiology Research Center, National Research Institute of Tuberculosis and Lung Diseases (NRITLD), Shahid Beheshti University of Medical Sciences, Tehran, Iran. ¹³²Hospital Sant Joan de Déu and University of Barcelona, Barcelona, Spain. ¹³³Pediatric Infectious Diseases and Immunodeficiencies Unit, Hospital Universitari Vall d'Hebron, Vall d'Hebron Research Institute, Vall d'Hebron Barcelona Hospital Campus, Universitat Autònoma de Barcelona (UAB), Barcelona, Spain. ¹³⁴Hospital Universitari Mútua de Terrassa, Universitat de Barcelona, Barcelona, Spain. ¹³⁵IrsiCaixa AIDS Research Institute, ICREA, UVic-UCC, Research Institute "Germans Trias i Pujol", Badalona, Spain. ¹³⁶Department of Laboratory, Cruces University Hospital, Barakaldo, Bizkaia, Spain. ¹³⁷University of New South Wales, Darlinghurst, NSW, Australia. ¹³⁸APHP Pitié-Salpêtrière Hospital, Paris, France. ¹³⁹Aix-Marseille University, APHM, Marseille, France. ¹⁴⁰Robert Debré Hospital, Paris, France. ¹⁴¹APHP Cochin Hospital, Paris, France. ¹⁴²Necmettin Erbakan University Meram Faculty of Medicine Department of Pediatric Infectious Diseases, Konya, Turkey. ¹⁴³University Hospitals Leuven, Leuven, Belgium. ¹⁴⁴Hospices Civils de Lyon, Hôpital de la Croix-Rousse, Lyon, France. ¹⁴⁵Hôpital Erasme, Brussels, Belgium. ¹⁴⁶CH Gonesse, Gonesse, France. ¹⁴⁷Vascular Medicine, Georges Pompidou Hospital, APHP, Paris, France. ¹⁴⁸Division of Pulmonary and Critical Care, University of Miami, Miami, FL, USA. ¹⁴⁹Guanarteme Health Care Center, Canarian Health System, Las Palmas de Gran Canaria, Spain. ¹⁵⁰Regional University Hospital of Málaga, Málaga, Spain. ¹⁵¹Aix-Marseille Université, Marseille, France. ¹⁵²Department of General Paediatrics, Hôpital Bicêtre, AP-HP, University of Paris Saclay, Le Kremlin-Bicêtre, France. ¹⁵³CHU de La Timone, Marseille, France. ¹⁵⁴Centro Hospitalar Universitário de Lisboa Central, Lisbon, Portugal. ¹⁵⁵Infectious Diseases Horizontal Technology Centre, A*STAR; Singapore Immunology Network, A*STAR, Singapore. ¹⁵⁶Department of Pediatrics, Complejo Hospitalario Universitario Insular-Materno Infantil, Canarian Health System, Las Palmas de Gran Canaria, Spain. ¹⁵⁷Regional University Hospital of Málaga, Málaga, Spain. ¹⁵⁸Hospital Universitario Marqués de Valdecilla, Santander, Spain. ¹⁵⁹Ataturk University Medical Faculty, Erzurum, Turkey. ¹⁶⁰Bilkent University, Department of Molecular Biology and Genetics, Ankara, Turkey. ¹⁶¹Department of Laboratory Medicine, Karolinska Institutet, SE14186, Stockholm, Sweden. ¹⁶²Hôpital Foch, Suresnes, France. ¹⁶³Department of Immunology, Hospital Universitario 12 de Octubre, Instituto de Investigación Sanitaria Hospital 12 de Octubre (imas12), Madrid, Spain. ¹⁶⁴APHP Hôpitaux Universitaires Paris-Sud, Le Kremlin-Bicêtre, France. ¹⁶⁵Neuro-metabolic Diseases Laboratory, IDIBELL-Hospital Duran i Reynals, Barcelona; CIBERER U759, ISCIII, Madrid, Spain. ¹⁶⁶Hospices Civils de Lyon, Lyon, France. ¹⁶⁷Université de Lille, Inserm U1285, CHU Lille, Paris, France. ¹⁶⁸Department of General Pediatrics, University Hospital Robert Debré, APHP, Paris, France. ¹⁶⁹Necmettin Erbakan University, Konya, Turkey. ¹⁷⁰Germans Trias i Pujol Hospital, Badalona, Spain. ¹⁷¹Medical Intensive Care Unit, Hôpital de la Croix-Rousse, Hospices Civils de Lyon, Lyon, France. ¹⁷²Pediatric Infectious Diseases and Immunodeficiencies Unit, Hospital Universitari Vall d'Hebron, Vall d'Hebron Research Institute, Vall d'Hebron Barcelona Hospital Campus, Barcelona, Spain. ¹⁷³Department of Immunology, Hospital Universitario de Gran Canaria Dr. Negrín, Canarian Health System, Las Palmas de Gran Canaria, Spain; University Fernando Pessoa Canarias, Las Palmas de Gran Canaria, Spain. ¹⁷⁴Neurometabolic Diseases Laboratory, IDIBELL-Hospital Duran i Reynals, Barcelona, Spain. ¹⁷⁵Consorcio Hospital General Universitario, Valencia, Spain. ¹⁷⁶APHP Hôpitaux Universitaires Paris-Sud, Paris, France. ¹⁷⁷Virology Unit, Université de Paris, Cochin Hospital, APHP, Paris, France. ¹⁷⁸Hospital San Pedro, Logroño, Spain. ¹⁷⁹Respiratory medicine, Georges Pompidou Hospital, APHP, Paris, France. ¹⁸⁰Department of Immunology, Hospital Clínico San Carlos, Madrid, Spain. ¹⁸¹Service de Médecine Intensive Réanimation, Institut de Cardiologie, Hôpital Pitié-Salpêtrière, Paris, France. ¹⁸²CHRU de Nancy, Hôpital d'Enfants, Vandœuvre, France. ¹⁸³Chair of Nephrology, University of Brescia, Brescia, Italy. ¹⁸⁴Department of Immunology, 2nd Faculty of Medicine, Charles University and Motol University Hospital, Prague, Czech Republic. ¹⁸⁵Clinica Universidad de Navarra, Madrid, Spain. ¹⁸⁶HUS Helsinki University Hospital, Children and Adolescents, Rare Disease Center, and Inflammation Center, Adult Immunodeficiency Unit, Majakka, Helsinki, Finland. ¹⁸⁷Fundació Docència i Recerca Mútua Terrassa, Terrassa, Spain. ¹⁸⁸Hôpital Européen Georges Pompidou, Paris, France. ¹⁸⁹Department of Pediatrics, Faculty of Medicine, Mansoura University, Mansoura, Egypt. ¹⁹⁰Critical Care Unit, Hospital Universitario de Gran Canaria Dr. Negrín, Canarian Health System, Las Palmas de Gran Canaria, Spain. ¹⁹¹CHU de Saint Etienne, Saint-Priest-en-Jarez, France. ¹⁹²Shupky National Medical Academy for Postgraduate Education, Kiev, Ukraine. ¹⁹³Gustave Roussy Cancer Campus, Villejuif, France. ¹⁹⁴Intensive Care Unit, Avicenne Hospital, APHP, Bobigny, France. ¹⁹⁵Laboratory of Immunology and Histocompatibility, Saint-Louis Hospital, Paris University, Paris, France. ¹⁹⁶Department of Internal Diseases and Pediatrics, Primary Immune Deficiency Research Laboratory, Centre for Primary Immunodeficiency Ghent, Jeffrey Modell Diagnosis and Research Centre, Ghent University Hospital, Ghent, Belgium. ¹⁹⁷Department of Internal Medicine, Université de Paris, INSERM, U970, PARCC, F-75015, Paris, France. ¹⁹⁸First Division of Anesthesiology and Critical Care Medicine, University of Brescia, ASST Spedali Civili di Brescia, Brescia, Italy. ¹⁹⁹Intensive Care Department, Hospital Universitari Mútua Terrassa, Universitat Barcelona, Terrassa, Spain. ²⁰⁰Hospices Civils de Lyon, Lyon Sud Hospital, Lyon, France. ²⁰¹Infanta Leonor University Hospital, Madrid, Spain. ²⁰²Hematology Department, ASST Spedali Civili di Brescia, Brescia, Italy. ²⁰³Pneumology, Hôpital Avicenne, APHP, INSERM U1272, Université Sorbonne Paris Nord, Bobigny, France. ²⁰⁴Dermatology Unit, Laboratoire GAD, INSERM UMR1231 LNC, Université de Bourgogne, Dijon, France. ²⁰⁵University Hospital of Burgos, Burgos, Spain. ²⁰⁶Center of Human Genetics, Hôpital Erasme, Université Libre de Bruxelles, Brussels, Belgium. ²⁰⁷Department of Chest Diseases, Necmettin Erbakan University,

Meram Medical Faculty, Konya, Turkey. ²⁰⁸CHU de Caen, Caen, France. ²⁰⁹Sorbonne Université, Service de Médecine Intensive Réanimation, Hôpital Tenon, Assistance Publique-Hôpitaux de Paris, Paris, France. ²¹⁰General Intensive Care Unit, Konya Training and Research Hospital, Konya, Turkey. ²¹¹CHU de Nancy, Nancy, France. ²¹²University of Lyon, CIRI, INSERM U1111, National Referee Centre RAISE, Pediatric Rheumatology, HFME, Hospices Civils de Lyon, Lyon, France. *Leader of the COVID-Clinicians group.

COVID-STORM Clinicians Giuseppe Foti¹, Giacomo Bellani¹, Giuseppe Citerio¹, Ernesto Contro¹, Alberto Pesci², Maria Grazia Valsecchi³, Marina Cazzaniga⁴

¹Department of Emergency, Anesthesia and Intensive Care, School of Medicine and Surgery, University of Milano-Bicocca, San Gerardo Hospital, Monza, Italy. ²Department of Pneumology, School of Medicine and Surgery, University of Milano-Bicocca, San Gerardo Hospital, Monza, Italy. ³Center of Bioinformatics and Biostatistics, School of Medicine and Surgery, University of Milano-Bicocca, San Gerardo Hospital, Monza, Italy. ⁴Phase I Research Center, School of Medicine and Surgery, University of Milano-Bicocca, San Gerardo Hospital, Monza, Italy.

Imagine COVID Group Christine Bole-Feyso¹, Stanislas Lyonnet^{1*}, Cécile Masson¹, Patrick Nitschke¹, Aurore Pouliet¹, Yoann Schmitt¹, Frederic Tores¹, Mohammed Zarhrate¹

¹Imagine Institute, Université de Paris, INSERM UMR 1163, Paris, France. *Leader of the Imagine COVID Group.

French COVID Cohort Study Group Laurent Abel¹, Claire Andrejak², François Angoulvant³, Delphine Bachelet⁴, Romain Basmaci⁵, Sylvie Behillini⁶, Marine Beluze⁷, Dehbia Benkerrouf⁸, Krishna Bhavsar⁴, François Bompard⁹, Lila Bouadma⁴, Maude Bouscambert¹⁰, Mireille Caralp¹¹, Minerva Cervantes-Gonzalez¹², Anissa Chair⁴, Alexandra Coelho¹³, Camille Couffignal⁴, Sandrine Couffin-Cadiegues¹⁴, Eric D'ortenzio¹², Charlene Da Silveira⁴, Marie-Pierre Debray⁴, Dominique Deplanque¹⁵, Diane Descamps¹⁶, Mathilde Desvallées¹⁷, Alpha Diallo¹⁸, Alphonsine Diout¹³, Céline Dorival⁸, François Dubos¹⁹, Xavier Duval⁴, Philippine Eloy⁴, Vincent V. E. Enouf²⁰, Hélène Esperou²¹, Marina Esposito-Farese⁴, Manuel Etienne²², Nadia Ettalhoui⁴, Nathalie Gault⁴, Alexandre Gaymar⁴⁰, Jade Ghosn⁴, Tristan Gigante²³, Isabelle Gorenne⁴, Jérémie Guedj²⁴, Aurélie Hocht¹³, Isabelle Hoffmann⁴, Salma Jaafoura²¹, Ouifia Kafif⁴, Florentia Kaguelidou²⁵, Sabina Kali⁴, Antoine Khalil⁴, Coralie Khan¹⁷, Cédric Laouénan⁴, Samira Laribi⁴, Minh Le⁴, Quentin Le Hingrat⁴, Soizic Le Mestre¹⁸, Hervé Le Nagard²⁴, François-Xavier Lescuré⁴, Yves Lévy²⁶, Claire Levy-Marchal²⁷, Bruno Lina¹⁰, Guillaume Lingas²⁴, Jean Christophe Lucet⁴, Denis Malvy²⁸, Marina Lambert¹³, France Mentré⁴, Noémie Mercier¹⁸, Amina Meziiane⁸, Hugo Mouquet²⁰, Jimmy Mullaert⁴, Nadège Neant²⁴, Marion Noret²⁹, Justine Pages³⁰, Aurélie Papadopoulos²¹, Christelle Paul¹⁸, Nathan Peiffer-Smadja⁴, Ventislava Petrov-Sanchez³¹, Gilles Peytavin⁴, Olivier Picone³¹, Oriane Puéchal¹², Manuel Rosa-Caltava¹⁰, Bénédicte Rossignol²³, Patrick Rossignol³², Carine Roy⁴, Marion Schneider⁴, Caroline Semaille¹², Nassima Si Mohammed⁴, Lysa Tagheret⁴, Coralie Tardivon⁴, Marie-Capucine Tellier⁴, François Téoulé⁸, Olivier Terrier¹⁰, Jean-François Timsit⁴, Théo Treoux⁴, Christelle Tual³³, Sarah Tubiana⁴, Sylvie van der Werf³⁴, Noémie Vanel³⁵, Aurélie Veisliger³³, Benoît Visseaux¹⁶, Aurélie Wiedemann²⁶, Yazdan Yazdanpanah³⁶

¹Inserm UMR 1163, Paris, France. ²CHU Amiens, Amiens, France. ³Hôpital Necker, Paris, France. ⁴Hôpital Bichat, Paris, France. ⁵Hôpital Louis Mourrier, Colombes, France. ⁶Institut Pasteur, Paris, France. ⁷F-CRIN Partners Platform, AP-HP, Université de Paris, Paris, France. ⁸Inserm UMR 1136, Paris, France. ⁹Drugs for Neglected Diseases Initiative, Geneva, Switzerland. ¹⁰Inserm UMR 1111, Lyon, France. ¹¹Inserm Transfert, Paris, France. ¹²REACTing, Paris, France. ¹³Inserm UMR 1018, Paris, France. ¹⁴Inserm, Pôle Recherche Clinique, France. ¹⁵CIC 1403 Inserm-CHU Lille, Paris, France. ¹⁶Université de Paris, IAME, INSERM UMR 1137, AP-HP, University Hospital Bichat Claude Bernard, Virology, F-75018 Paris, France. ¹⁷Inserm UMR 1219, Bordeaux, France. ¹⁸ANRS, Paris, France. ¹⁹CHU Lille, Lille, France. ²⁰Pasteur Institute, Paris, France. ²¹Inserm sponsor, Paris, France. ²²Rouen - SMIT, France. ²³FCRIN INI-CRCT, Nancy, France. ²⁴Inserm UMR 1137, Paris, France. ²⁵Centre d'Investigation Clinique, Inserm CIC1426, Hôpital Robert Debré, Paris, France. ²⁶Inserm UMR 955, Créteil, France; Vaccine Research Institute (VRI), Paris, France. ²⁷F-CRIN INI-CRCT, Paris, France.

²⁸Bordeaux - SMIT, France. ²⁹RENARCI, Annecy, France. ³⁰Hôpital Robert Debré, Paris, France. ³¹Colombes - Louis Mourier - Gynécologie, Paris, France. ³²University of Lorraine, Plurithematic Clinical Investigation Centre Inserm CIC-P: 1433, Inserm U1116, CHRU Nancy Hopitaux de Brabois, F-CRIN INI-CRCT; (Cardiovascular and Renal Clinical Trialists), Nancy, France. ³³Inserm CIC-1414, Rennes, France. ³⁴Institut Pasteur, UMR 3569 CNRS, Université de Paris, Paris, France. ³⁵Hôpital A timone, Marseille, France. ³⁶Paris - Bichat - SMIT, France.

The Milieu Intérieur Consortium Laurent Abel¹, Andres Alcover², Hugues Aschard², Kalla Astrom³, Philippe Bousso², Pierre Bruhns², Ana Cumano², Caroline Demangel², Ludovic Deriano², James Di Santo², Françoise Dromer², Gérard Eberl², Jost Enninga², Jacques Fellay⁴, Ivo Gomperts-Boneca², Milena Hasan², Serge Herberg², Olivier Lantz⁶, Hugo Mouquet², Etienne Patin², Sandra Pellegrini², Stanislas Pol², Antonio Rausell⁸, Lars Rogge², Anavaj Sakuntabhai², Olivier Schwartz², Benno Schwickowski², Spencer Shorte², Frédéric Tangy², Antoine Toubert², Mathilde Tournier¹⁰, Marie-Noëlle Ungeheuer², Matthew L. Albert^{11*}, Darragh Duffy^{2*}, Lluís Quintana-Murci^{2*}

¹INSERM U1163, University of Paris, Imagine Institute, Paris, France. ²Pasteur Institute, Paris, France. ³Lund University, Lund, Sweden. ⁴EPFL, Lausanne, Switzerland. ⁵Université Paris 13, Paris, France. ⁶Curie Institute, Paris, France. ⁷Cochin Hospital, Paris, France. ⁸INSERM UMR 1163 - Institut Imagine, Paris, France. ⁹Hôpital Saint-Louis, Paris, France. ¹⁰Sorbonne Paris Nord University, Inserm U1153, Inrae U1125, Cnam, Nutritional Epidemiology Research Team (EREN), Bobigny, France. ¹¹In Situ, San Francisco, CA, USA. *Co-coordinators of The Milieu Intérieur Consortium. Additional information can be found at: www.milieuinterieur.fr/en.

CoV-Contact Cohort Loubna Alavoine¹, Karine K. A. Amat², Sylvie Behillini³, Julia Bielicki⁴, Patricia Bruining⁵, Charles Burdet⁶, Eric Caumes⁷, Charlotte Charpentier⁸, Bruno Coignard⁹, Yolande Costa¹, Sandrine Couffin-Cadiegues¹⁰, Florence Diamond⁸, Aline Dechanet¹¹, Christelle Delmas¹⁰, Diane Descamps⁸, Xavier Duval¹, Jean-Luc Ecobichon¹, Vincent Enouf³, Hélène Espérou¹⁰, Wahiba Frezouls¹, Nadhira Houhou¹, Emilia Ilic-Habensuss¹, Ouifia Kafif¹, John Kikoine¹¹, Quentin Le Hingrat⁸, David Lebeaux²², Anne Lerclercq³, Jonathan Lecauch¹, Sophie Letrou¹, Bruno Lina¹³, Jean-Christophe Lucet⁴, Denis Malvy¹⁵, Pauline Manchon¹¹, Milica Mandic¹, Mohamed Meghadecha¹⁶, Justina Motiejunaite¹⁷, Mariama Nouroudine¹, Valentine Piquard¹¹, Andrea Postolache¹¹, Caroline Quintin¹, Jade Rexach¹, Layidé Roufai¹⁰, Zaven Terzian¹¹, Michael Thy¹⁸, Sarah Tubiana⁴, Sylvie van der Werf³, Valérie Vignati¹, Benoît Visseaux⁸, Yazdan Yazdanpanah¹⁴

¹Centre d'Investigation Clinique, Inserm CIC 1425, Hôpital Bichat Claude Bernard, APHP, Paris, France. ²MEA Fondation Léon M¹Ba, Paris, France. ³Institut Pasteur, UMR 3569 CNRS, Université de Paris, Paris, France. ⁴University of Basel Children's Hospital, Basel, Switzerland. ⁵Julius Center for Health Sciences and Primary Care, University Medical Center Utrecht, Utrecht, Netherlands. ⁶Université de Paris, IAME, Inserm UMR 1137, F-75018, Paris, France. ⁷Hôpital Bichat Claude Bernard, APHP, Paris, France. ⁸Hôpital Pitié Salpêtrière, APHP, Paris, France. ⁹Université de Paris, IAME, INSERM UMR 1137, AP-HP, University Hospital Bichat Claude Bernard, Virology, F-75018 Paris, France. ¹⁰Santé Publique France, Saint Maurice, France. ¹¹Pole Recherche Clinique, Inserm, Paris, France. ¹²Hôpital Bichat Claude Bernard, APHP, Paris, France. ¹³APHP, Paris, France. ¹⁴Virpath Laboratory, International Center of Research in Infectiology, Lyon University, INSERM U1111, CNRS UMR 5308, ENS, UCBL, Lyon, France. ¹⁵IAME Inserm UMR 1138, Hôpital Bichat Claude Bernard, APHP, Paris, France. ¹⁶Service des Maladies Infectieuses et Tropicales, Groupe Pellegrin, Place Amélie-Raba-Léon, Bordeaux, France. ¹⁷Hôpital Hotel Dieu, APHP, Paris, France. ¹⁸Service des explorations fonctionnelles, Hôpital Bichat - Claude Bernard, APHP, Paris, France. ¹⁹Center for Clinical Investigation, Assistance Publique-Hôpitaux de Paris, Bichat-Claude Bernard University Hospital, Paris, France.

Amsterdam UMC Covid-19 Biobank Michiel van Agtmael¹, Anna Geke Algera², Frank van Baarle², Diane Bax³, Martijn Beudel⁴, Harm Jan Bogaard⁵, Marije Bomers¹, Lieuwke Bos², Michela Botta², Justin de Brabander⁶, Godelieve Bree⁶, Matthijs C. Brouwer⁴, Sanne de Bruin⁷, Marianna Bugiani⁸, Esther Bulle², Osoul Chouchane¹, Alex Cloberty³, Paul Elbers², Lucas Fleuren², Suzanne Geerlings¹, Bart Geerts⁸, Theo Geijtenbeek⁹, Armand Girbes², Bram Goorhuis¹, Martin P. Grobusch¹, Florianne Hafkamp¹, Laura Hagens², Jorg Hamann¹⁰, Vanessa Harris¹, Robert Hemke¹¹, Sabine M. Hermans¹,

Leo Heunks², Markus W. Hollmann⁸, Janneke Horn², Joppe W. Hovius¹, Menno D. de Jong¹², Rutger Koning⁴, Niels van Mourik¹, Jeanine Nellen¹, Frederique Paulus², Edgar Peters¹, Tom van der Pol¹, Benedikt Preckel⁸, Jan M. Prins¹, Jorinde Raasveld², Tom Reijnders¹, Michiel Schinkel¹, Marcus J. Schultz², Alex Schuurman¹³, Kim Sigaloff¹, Marry Smit², Cornelis S. Stijns¹, Willemke Stijlma², Charlotte Teunissen¹⁴, Patrick Thorat², Anissa Tsonas², Marc van der Valk¹, Denise Veelo⁸, Alexander P. J. Vlaar¹⁵, Heder de Vries², Michèle van Vugt¹, W. Joost Wiersinga¹, Dorien Wouters¹⁶, A. H. (Koos) Zwiderman¹⁷, Diederik van de Beek^{18*}

¹Department of Infectious Diseases, Amsterdam UMC, Amsterdam, Netherlands. ²Department of Intensive Care, Amsterdam UMC, Amsterdam, Netherlands. ³Experimental Immunology, Amsterdam UMC, Amsterdam, Netherlands. ⁴Department of Neurology, Amsterdam UMC, Amsterdam Neuroscience, Amsterdam, Netherlands. ⁵Department of Pulmonology, Amsterdam UMC, Amsterdam, Netherlands. ⁶Department of Infectious Diseases, Amsterdam UMC, Amsterdam, Netherlands. ⁷Department of Pathology, Amsterdam UMC, Amsterdam, Netherlands. ⁸Department of Anesthesiology, Amsterdam UMC, Amsterdam, Netherlands. ⁹Department of Experimental Immunology, Amsterdam UMC, Amsterdam, Netherlands. ¹⁰Amsterdam UMC, Netherlands Biobank Core Facility, Amsterdam UMC, Amsterdam, Netherlands. ¹¹Department of Radiology, Amsterdam UMC, Amsterdam, Netherlands. ¹²Department of Medical Microbiology, Amsterdam UMC, Amsterdam, Netherlands. ¹³Department of Internal Medicine, Amsterdam UMC, Amsterdam, Netherlands. ¹⁴Neurochemical Laboratory, Amsterdam UMC, Amsterdam, Netherlands. ¹⁵Department of Intensive Care, Amsterdam UMC, Amsterdam, Netherlands. ¹⁶Department of Clinical Chemistry, Amsterdam UMC, Amsterdam, Netherlands. ¹⁷Department of Clinical Epidemiology, Biostatistics and Bioinformatics, Amsterdam UMC, Amsterdam, Netherlands. ¹⁸Department of Neurology, Amsterdam UMC, Amsterdam, Netherlands. *Leader of the AMC consortium.

COVID Human Genetic Effort Laurent Abel¹, Alessandro Aiuti², Saleh Al Muhisen³, Fahd Al-Mulla⁴, Mark S. Anderson⁵, Andrés Augusto Arias⁶, Hagit Baris Feldman⁷, Dusan Bogunovic⁸, Alexandre Bolze⁹, Anastasiia Bondarenko¹⁰, Ahmed A. Boustifha¹¹, Petter Brodin¹², Yenan Bryceson¹², Carlos D. Bustamante¹³, Manish Butte¹⁴, Giorgio Casari¹⁵, Samya Chakravarty¹⁶, John Christodoulou¹⁷, Elizabeth Cirulli¹⁸, Antonio Condino-Neto¹⁸, Megan A. Cooper¹⁹, Clifton L. Dalgard²⁰, Joseph L. deRisi²¹, Murkesh Desai²², Beth A. Droleat²³, Sara Espinosa²⁴, Jacques Fellay²⁵, Carlos Flores²⁶, Jose Luis Franco²⁷, Peter K. Gregersen²⁸, Filomena Haerynck²⁹, David Hagin³⁰, Rabi Halwani³¹, Jim Heath³², Sarah E. Henrickson³³, Elena Hsieh³⁴, Kohsuke Imai³⁵, Yuval Itan³⁶, Timokratas Karamitros³⁶, Kai Kisand³⁷, Cheng-Lung Ku³⁸, Yu-Lung Lai³⁹, Yun Ling⁴⁰, Carrie L. Lucas⁴¹, Tom Mariatis⁴², Davoud Mansouri⁴³, Laszlo Marodi⁴⁴, Isabelle Meys⁴⁵, Joshua D. Milner⁴⁶, Kristina Mironska⁴⁷, Trine Mogensen⁴⁸, Tomohiro Morio⁴⁹, Lisa F. P. Ng⁵⁰, Luigi D. Notarangelo⁵¹, Giuseppe Novelli⁵², Antonio Novelli⁵³, Cliona O'Farrelly⁵⁴, Satoshi Okada⁵⁵, Tayfun Ozcelik⁵⁶, Rebecca Perez de Diego⁵⁷, Anna M. Planas⁵⁸, Carolina Prando⁵⁹, Aurora Pujol⁶⁰, Lluís Quintana-Murci⁶¹, Laurent Renia⁶², Alessandra Renier⁶³, Carlos Rodriguez-Gallego⁶⁴, Vanessa Sancho-Shimizu⁶⁵, Vijay Sankaran⁶⁶, Kelly Schiabor Barrett⁹, Mohammed Shahrooei⁶⁷, Andrew Snow⁶⁸, Pere Soler-Palacin⁶⁹, Andrés N. Spaan⁷⁰, Stuart Tangye⁷¹, Stuart Turvey⁷², Furkan Uddin⁷³, Mohammed J. Uddin⁷⁴, Diederik van de Beek⁷⁵, Sara E. Vazquez⁷⁶, Donald C. Vinh⁷⁷, Horst von Bernuth⁷⁸, Nicole Washington⁹, Pawel Zawadzki⁷⁹, Helen C. Su^{31*}, Jean-Laurent Casanova^{80*}

¹INSERM U1163, University of Paris, Imagine Institute, Paris, France. ²San Raffaele Telethon Institute for Gene Therapy, IRCCS Ospedale San Raffaele, Milan, Italy. ³King Saud University, Riyadh, Saudi Arabia. ⁴Dasman Diabetes Institute, Department of Genetics and Bioinformatics, Dasman, Kuwait. ⁵University of California, San Francisco, San Francisco, CA, USA. ⁶Universidad de Antioquia, Group of Primary Immunodeficiencies, Antioquia, Colombia. ⁷The Genetics Institute, Tel Aviv Sourasky Medical Center and Sackler Faculty of Medicine, Tel Aviv University, Tel Aviv, Israel. ⁸Icahn School of Medicine at Mount Sinai, New York, NY, USA. ⁹Helix, San Mateo, CA, USA. ¹⁰Shupky National Medical Academy for Postgraduate Education, Kiev, Ukraine. ¹¹Clinical Immunology Unit, Pediatric Infectious Disease Department, Faculty of Medicine and Pharmacy, Averroes University Hospital, LICIA Laboratoire d'immunologie clinique, d'inflammation et d'allergie, Hassani li University, Casablanca, Morocco. ¹²Karolinska Institute, Stockholm, Sweden. ¹³Stanford University, Stanford, CA, USA. ¹⁴University of California, Los Angeles, CA, USA. ¹⁵Medical

- Genetics, IRCCS Ospedale San Raffaele, Milan, Italy. ¹⁶Department of Pediatrics and Children's Healthcare of Atlanta, Emory University, Atlanta, GA, USA. ¹⁷Murdoch Children's Research Institute, Victoria, Australia. ¹⁸University of São Paulo, São Paulo, Brazil. ¹⁹Washington University School of Medicine, St. Louis, MO, USA. ²⁰The American Genome Center; Uniformed Services University of the Health Sciences, Bethesda, MD, USA. ²¹University of California San Francisco; Chan Zuckerberg Biohub, San Francisco, CA, USA. ²²Bai Jerbai Wadia Hospital for Children, Mumbai, India. ²³School of Medicine and Public Health, University of Wisconsin, Madison, WI, USA. ²⁴Instituto Nacional de Pediatría (National Institute of Pediatrics), Mexico City, Mexico. ²⁵Swiss Federal Institute of Technology Lausanne, Lausanne, Switzerland. ²⁶Research Unit, Hospital Universitario Nuestra Señora de Candelaria, Canarian Health System, Santa Cruz de Tenerife, Spain. ²⁷University of Antioquia, Medellín, Colombia. ²⁸Feinstein Institute for Medical Research, Northwell Health USA, Manhasset, NY, USA. ²⁹Department of Paediatric Immunology and Pulmonology, Centre for Primary Immunodeficiency Ghent (CPiG), PID Research Laboratory, Jeffrey Modell Diagnosis and Research Centre, Ghent University Hospital, Edegem, Belgium. ³⁰The Genetics Institute Tel Aviv Sourasky Medical Center, Tel Aviv, Israel. ³¹Sharjah Institute of Medical Research, College of Medicine, University of Sharjah, Sharjah, United Arab Emirates. ³²Institute for Systems Biology, Seattle, WA, USA. ³³Children's Hospital of Philadelphia, Philadelphia, PA, USA. ³⁴Anschutz Medical Campus, Aurora, CO, USA. ³⁵Riken, Tokyo, Japan. ³⁶Hellenic Pasteur Institute, Athens, Greece. ³⁷University of Tartu, Tartu, Estonia. ³⁸Chang Gung University, Taoyuan County, Taiwan. ³⁹The University of Hong Kong, Hong Kong, China. ⁴⁰Shanghai Public Health Clinical Center, Fudan University, Shanghai, China. ⁴¹Yale School of Medicine, New Haven, CT, USA. ⁴²New York Genome Center, New York, NY, USA. ⁴³Shahid Beheshti University of Medical Sciences, Tehran, Iran. ⁴⁴Semmelweis University Budapest, Budapest, Hungary. ⁴⁵KU Leuven, Department of Immunology, Microbiology and Transplantation, Leuven, Belgium. ⁴⁶Columbia University Medical Center, New York, NY, USA. ⁴⁷University Clinic for Children's Diseases, Skopje, North Macedonia. ⁴⁸Aarhus University, Aarhus, Denmark. ⁴⁹Tokyo Medical & Dental University Hospital, Tokyo, Japan. ⁵⁰Singapore Immunology Network, Singapore. ⁵¹National Institute of Allergy and Infectious Diseases, National Institutes of Health, Bethesda, MD, USA. ⁵²Department of Biomedicine and Prevention, University of Rome "Tor Vergata," Rome, Italy. ⁵³Bambino Gesù Children's Hospital, Rome, Italy. ⁵⁴Trinity College, Dublin, Ireland. ⁵⁵Hiroshima University, Hiroshima, Japan. ⁵⁶Bilkent University, Ankara, Turkey. ⁵⁷Laboratory of Immunogenetics of Human Diseases, Innate Immunity Group, IdiPAZ Institute for Health Research, La Paz Hospital, Madrid, Spain. ⁵⁸IBB-CSIC, IDIBAPS, Barcelona, Spain. ⁵⁹Faculdades Pequeno Príncipe e Instituto de Pesquisa Pelé Pequeno Príncipe, Curitiba, Brazil. ⁶⁰Neurometabolic Diseases Laboratory, IDIBELL - Hospital Duran I Reynals; Catalan Institution for Research and Advanced Studies (ICREA); CIBERER U759, ISCIII Madrid Spain, Barcelona, Spain. ⁶¹Institut Pasteur (CNRS UMR2000) and Collège de France, Paris, France. ⁶²Infectious Diseases Horizontal Technology Center and Singapore Immunology Network, Agency for Science Technology (A*STAR), Singapore. ⁶³Medical Genetics, University of Siena, Italy; Genetica Medica, Azienda Ospedaliero-Universitaria Senese, GEN-COVID Multicenter Study, Italy. ⁶⁴Hospital Universitario de Gran Canaria Dr Negrín, Canarian Health System, Canary Islands, Spain. ⁶⁵Imperial College London, London, UK. ⁶⁶Boston Children's Hospital, Harvard Medical School, Boston, MA, USA. ⁶⁷Saeed Pathobiology and Genetic Laboratory, Tehran, Iran. ⁶⁸Uniformed Services University of the Health Sciences (USUHS), Bethesda, MD, USA. ⁶⁹Hospital Universitari Vall d'Hebron, Barcelona, Spain. ⁷⁰University Medical Center Utrecht, Amsterdam, Netherlands. ⁷¹Garvan Institute of Medical Research, Sydney, Australia. ⁷²The University of British Columbia, Vancouver, Canada. ⁷³Holy Family Red Crescent Medical College; Centre for Precision Therapeutics, NeuroGen Children's Healthcare; Genetics and Genomic Medicine Centre, NeuroGen Children's Healthcare, Dhaka, Bangladesh. ⁷⁴Mohammed Bin Rashid University of Medicine and Health Sciences, College of Medicine, Dubai, United Arab Emirates; The Centre for Applied Genomics, Department of Genetics and Genome Biology, The Hospital for Sick Children, Toronto, Ontario, Canada. ⁷⁵Amsterdam UMC, University of Amsterdam, Department of Neurology, Amsterdam Neuroscience, Amsterdam, Netherlands. ⁷⁶University of California, San Francisco, San Francisco, CA, USA. ⁷⁷McGill University Health Centre, Montreal, Canada. ⁷⁸Charité - Berlin University Hospital Center, Berlin, Germany. ⁷⁹Molecular Biophysics Division, Faculty of Physics, A. Mickiewicz University, Uniwersytetu Poznańskiego 2, Poznań, Poland. ⁸⁰The Rockefeller University, Howard Hughes Medical Institute, Necker Hospital, New York, NY, USA. *Leaders of the COVID Human Genetic Effort.

22 June 2020; accepted 16 September 2020
Published online 24 September 2020
10.1126/science.abd4585

Autoantibodies against type I IFNs in patients with life-threatening COVID-19

Paul Bastard, Lindsey B. Rosen, Qian Zhang, Eleftherios Michailidis, Hans-Heinrich Hoffmann, Yu Zhang, Karim Dorgham, Quentin Philippot, Jérémie Rosain, Vivien Béziat, Jérémy Manry, Elana Shaw, Liis Haljasmägi, Pärt Peterson, Lazaro Lorenzo, Lucy Bizien, Sophie Trouillet-Assant, Kerry Dobbs, Adriana Almeida de Jesus, Alexandre Belot, Anne Kallaste, Emilie Catherinot, Yacine Tandjaoui-Lambiotte, Jeremie Le Pen, Gaspard Kerner, Benedetta Bigio, Yoann Seeleuthner, Rui Yang, Alexandre Bolze, Andrés N. Spaan, Ottavia M. Delmonte, Michael S. Abers, Alessandro Aiuti, Giorgio Casari, Vito Lampasona, Lorenzo Piemonti, Fabio Ciceri, Kaya Bilguvar, Richard P. Lifton, Marc Vasse, David M. Smadja, Mélanie Migaud, Jérôme Hadjadj, Benjamin Terrier, Darragh Duffy, Lluís Quintana-Murci, Diederik van de Beek, Lucie Roussel, Donald C. Vinh, Stuart G. Tangye, Filomeen Haerynck, David Dalmau, Javier Martinez-Picado, Petter Brodin, Michel C. Nussenzweig, Stéphanie Boisson-Dupuis, Carlos Rodríguez-Gallego, Guillaume Vogt, Trine H. Mogensen, Andrew J. Oler, Jingwen Gu, Peter D. Burbelo, Jeffrey I. Cohen, Andrea Biondi, Laura Rachele Bettini, Mariella D'Angio, Paolo Bonfanti, Patrick Rossignol, Julien Mayaux, Frédéric Rieux-Laucat, Eystein S. Husebye, Francesca Fusco, Matilde Valeria Ursini, Luisa Imberti, Alessandra Sottini, Simone Paghera, Eugenia Quiros-Roldan, Camillo Rossi, Riccardo Castagnoli, Daniela Montagna, Amelia Licari, Gian Luigi Marseglia, Xavier Duval, Jade Ghosn, HGID Lab, NIAID-USUHS Immune Response to COVID Group, COVID Clinicians, COVID-STORM Clinicians, Imagine COVID Group, French COVID Cohort Study Group, The Milieu Intérieur Consortium, CoV-Contact Cohort, Amsterdam UMC Covid-19 Biobank, COVID Human Genetic Effort, John S. Tsang, Raphaela Goldbach-Mansky, Kai Kisand, Michail S. Lionakis, Anne Puel, Shen-Ying Zhang, Steven M. Holland, Guy Gorochov, Emmanuelle Jouanguy, Charles M. Rice, Aurélie Cobat, Luigi D. Notarangelo, Laurent Abel, Helen C. Su and Jean-Laurent Casanova

Science **370** (6515), eabd4585.

DOI: 10.1126/science.abd4585originally published online September 24, 2020

The genetics underlying severe COVID-19

The immune system is complex and involves many genes, including those that encode cytokines known as interferons (IFNs). Individuals that lack specific IFNs can be more susceptible to infectious diseases. Furthermore, the autoantibody system dampens IFN response to prevent damage from pathogen-induced inflammation. Two studies now examine the likelihood that genetics affects the risk of severe coronavirus disease 2019 (COVID-19) through components of this system (see the Perspective by Beck and Aksentijevich). Q. Zhang *et al.* used a candidate gene approach and identified patients with severe COVID-19 who have mutations in genes involved in the regulation of type I and III IFN immunity. They found enrichment of these genes in patients and conclude that genetics may determine the clinical course of the infection. Bastard *et al.* identified individuals with high titers of neutralizing autoantibodies against type I IFN- α 2 and IFN- ω in about 10% of patients with severe COVID-19 pneumonia. These autoantibodies were not found either in infected people who were asymptomatic or had milder phenotype or in healthy individuals. Together, these studies identify a means by which individuals at highest risk of life-threatening COVID-19 can be identified.

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