Dramatic Climate Transition Precludes the Potential Habitability of Icy Planets and Moons. Jun Yang[1], Feng Ding[2], Ramses M. Ramirez[3], W. R. Peltier[4], and Yongyun Hu[1], [1]Laboratory for Climate and Atmosphere-Ocean Studies, Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing, China (J.Y., junyang@pku.edu.cn, and Y.H., yyhu@pku.edu.cn); [2]Department of the Geophysical Sciences, University of Chicago, Chicago, IL, USA (fding.dfdfdf@gmail.com); [3]Carl Sagan Institute, Department of Astronomy, Cornell University, Ithaca, NY, USA; [4]Department of Physics, University of Toronto, Ontario, Canada.

[Abstract] Identifying possibly habitable planets beyond our solar system is one of the most intriguing scientific targets for on-going and future space missions. The habitability of a planet is determined not only by its current stellar insolation and atmospheric properties, but also by its evolution history. Previous studies[1,2] suggested that when host stars brighten, icy planets and moons would become habitable after their initial ice shield melts. Here we show that this conclusion is invalid for planets and moons having low concentrations of greenhouse gases, such as Europa, Enceladus, and icy exoplanets orbiting G and F stars. Using global climate models, we find that the melting of snowball planets requires stellar fluxes that exceed the moist or even runaway greenhouse limit, due to the high albedo of ice/snow and weak greenhouse effect. After the ice melts, such planets directly enter a moist or runaway greenhouse state; in either state, water loss from the ocean(s) is significant. This dramatic climate transition and the post-snowball moist or runaway greenhouse climate are hard limits for most types of life and its evolution, especially for complex life. The number of potentially habitable exoplanets should therefore be less than that previously estimated.

References [1] Shields, A. L., Bitz, C. M., Meadows, V. S., Joshi, M. M. & Robinson T. D. Spectrum-driven planetary deglaciation due to increases in stellar luminosity. *Astrophys. J. Lett.* 785, L9 (2014). [2] Ramirez, R. M. & Kaltenegger L. Habitable zones of post-main sequence stars. *Astrophys. J.* 823, 6 (2016).

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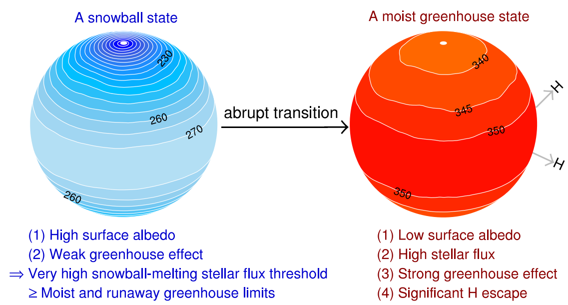

Figure 1. Schematic illustration of the climate transition and underlying physical mechanisms. The climate transition from a snowball state to a moist greenhouse state (or a runaway greenhouse state) is abrupt. The contour lines are surface temperatures right before the snowball melting (left) and after the snowball melting (right), with a contour interval of 5 K.