Implications of Long-Term Changes in Solar Luminosity for Habitability and Climate Dynamics

Georg Feulner, Mona Bukenberger & Stefan Petri

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Potsdam Institute for Climate Impact Research

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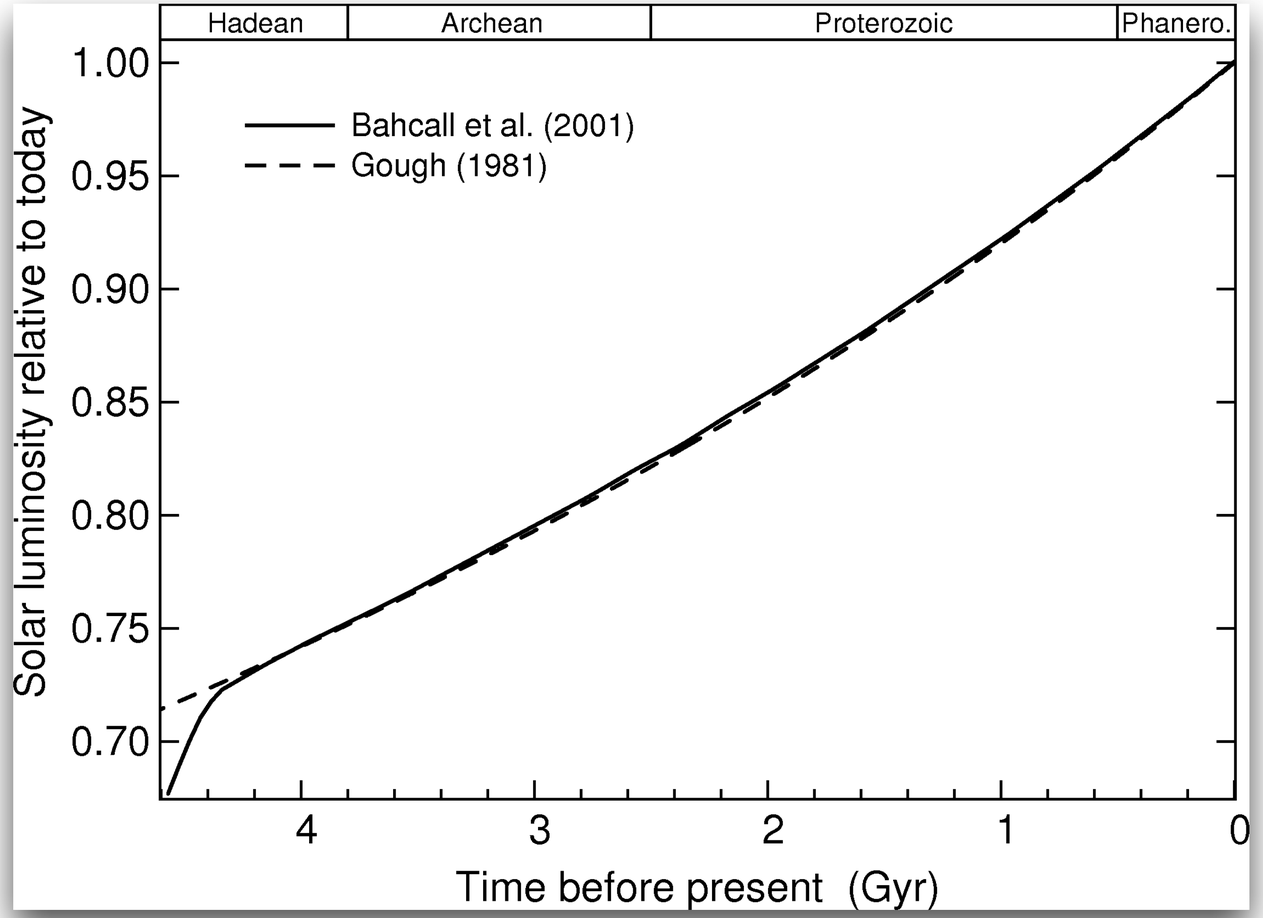
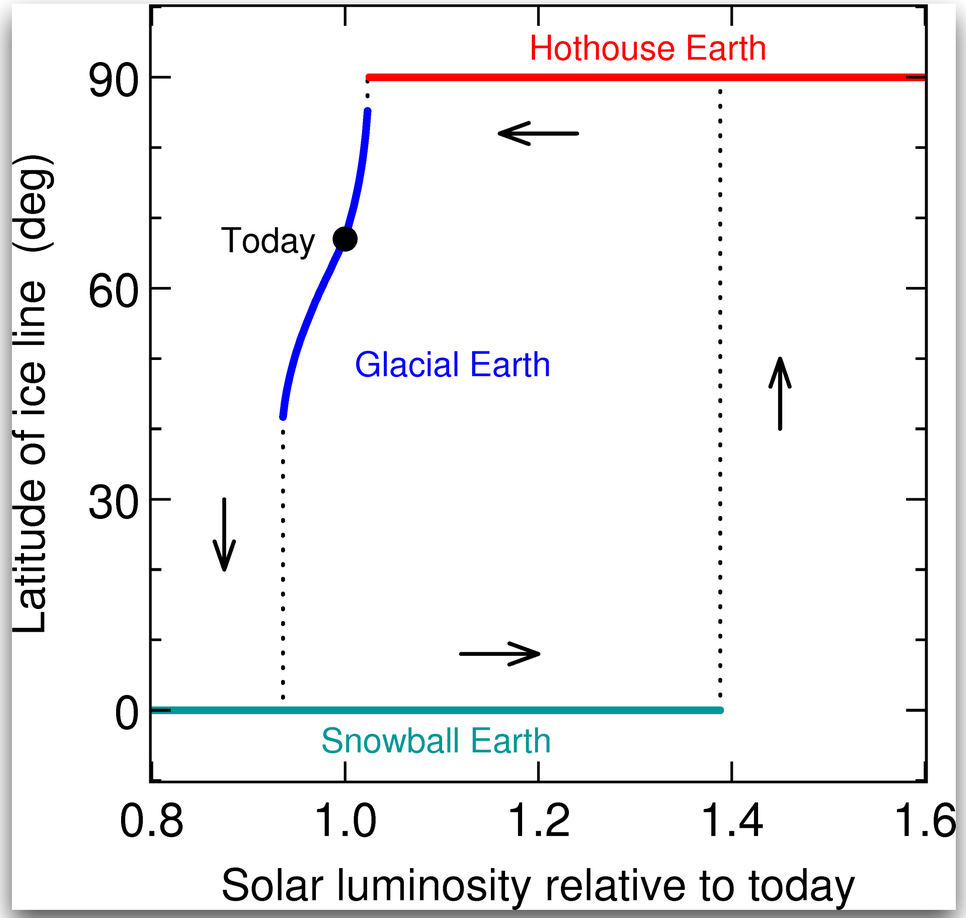
Long-Term Evolution of Solar Luminosity

Sun getting steadily brighter



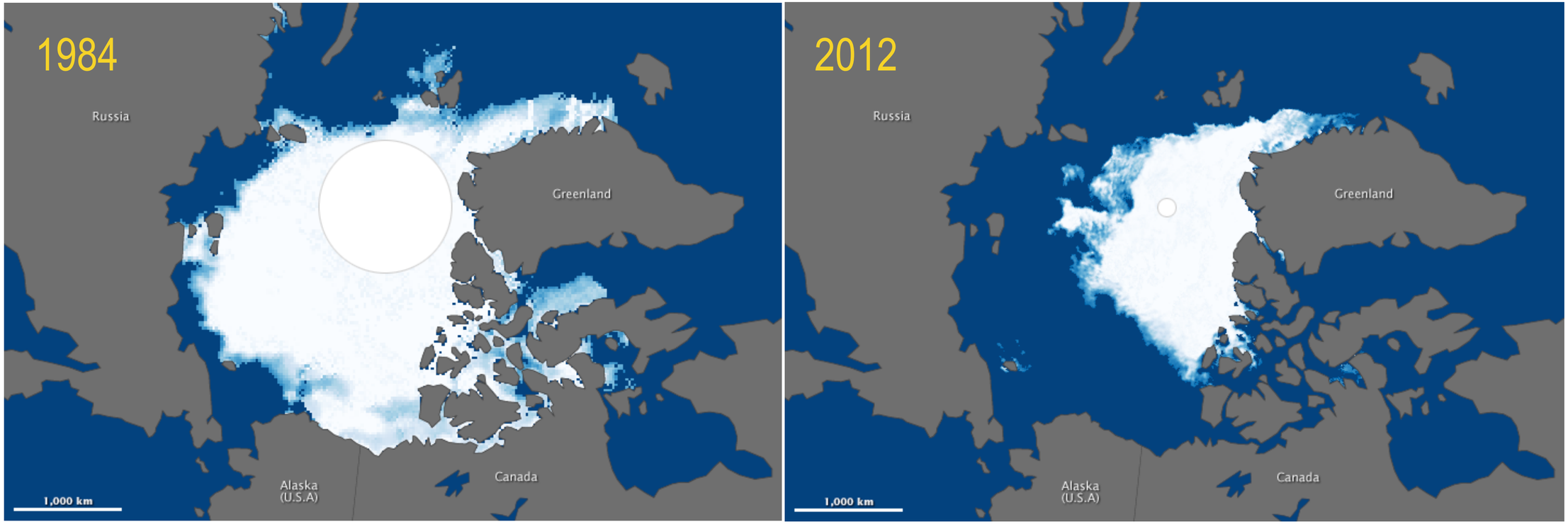
Global glaciation below ~ 0.9 S/S_0



Feulner (2012, Rev. Geophys., 50, RG2006); Feulner (2017)

Fundamental Cause: Ice–Albedo Feedback

Lower temperature ⇒ more ice and snow ⇒ higher albedo ⇒
increased reflection of solar radiation ⇒ lower temperature



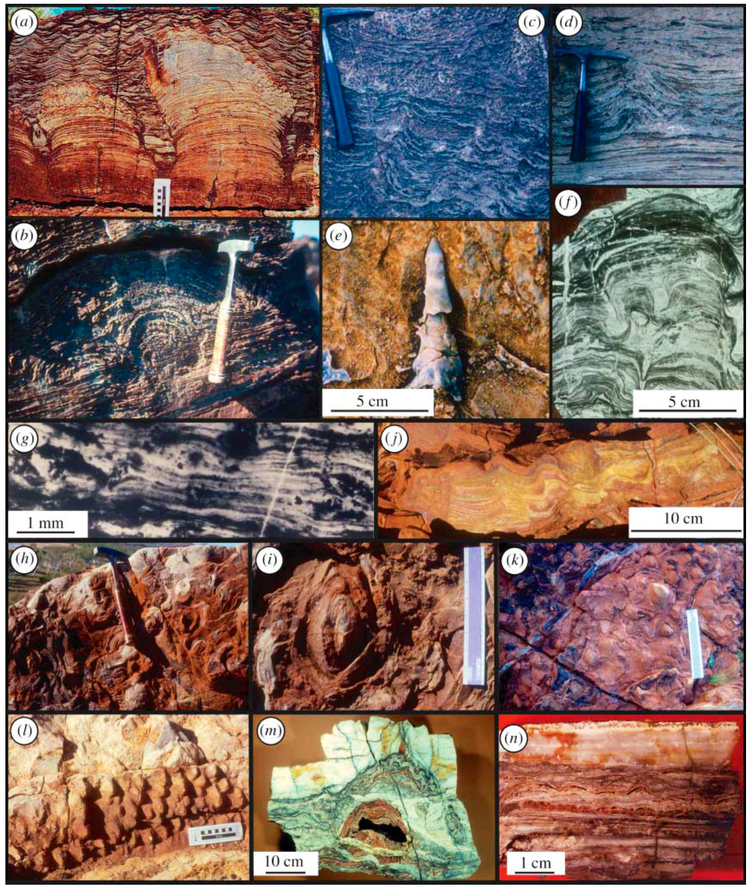
Feulner (2012, Rev. Geophys., 50, RG2006); Feulner (2017)

“Faint Young Sun Paradox”

- Schwarzschild (1957): “Can this change in brightness of the Sun have had some geophysical or geological consequences that might be detectable?”
- Ringwood (1961): “Other factors being equal, [...] the surface of the Earth during the period of its birth, 4.5 billion years ago, and 3 billion years ago, would have passed through an intense ice age.”

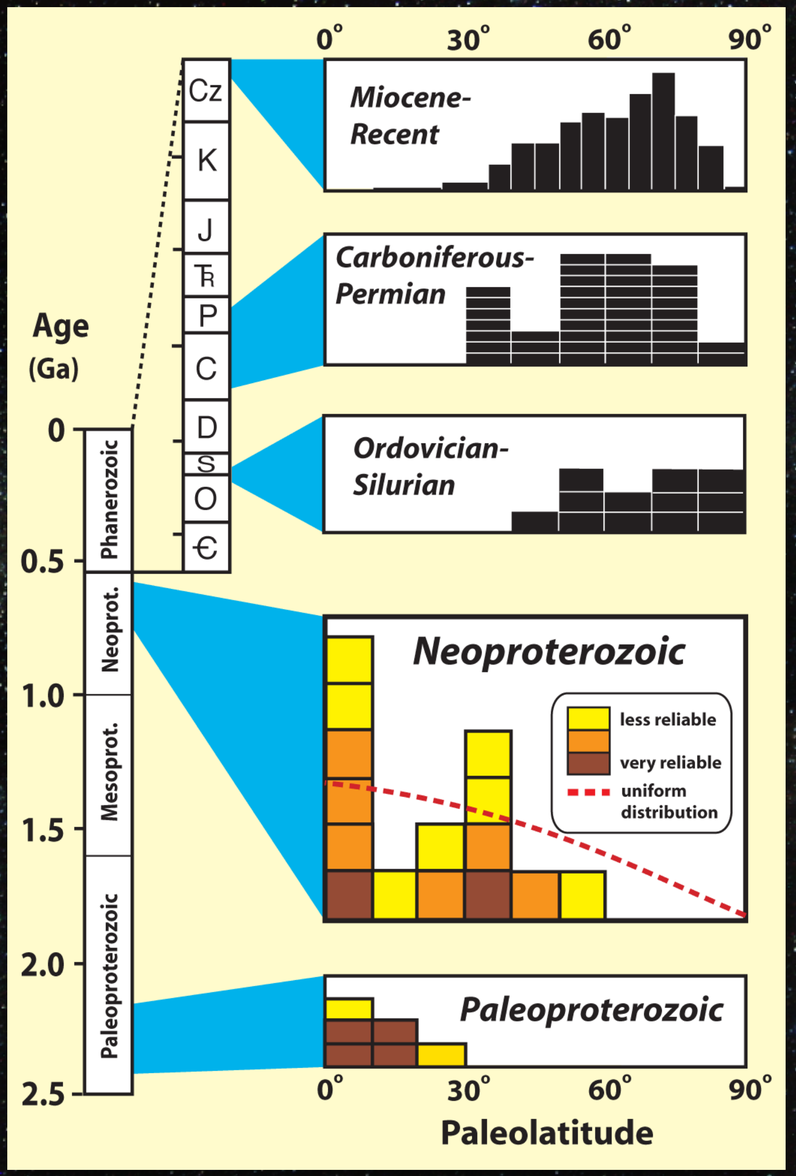
“Faint Young Sun Paradox”

Ample geological evidence for liquid water on early Earth despite low solar luminosity



Graeme Churchard; Schopf (2006)

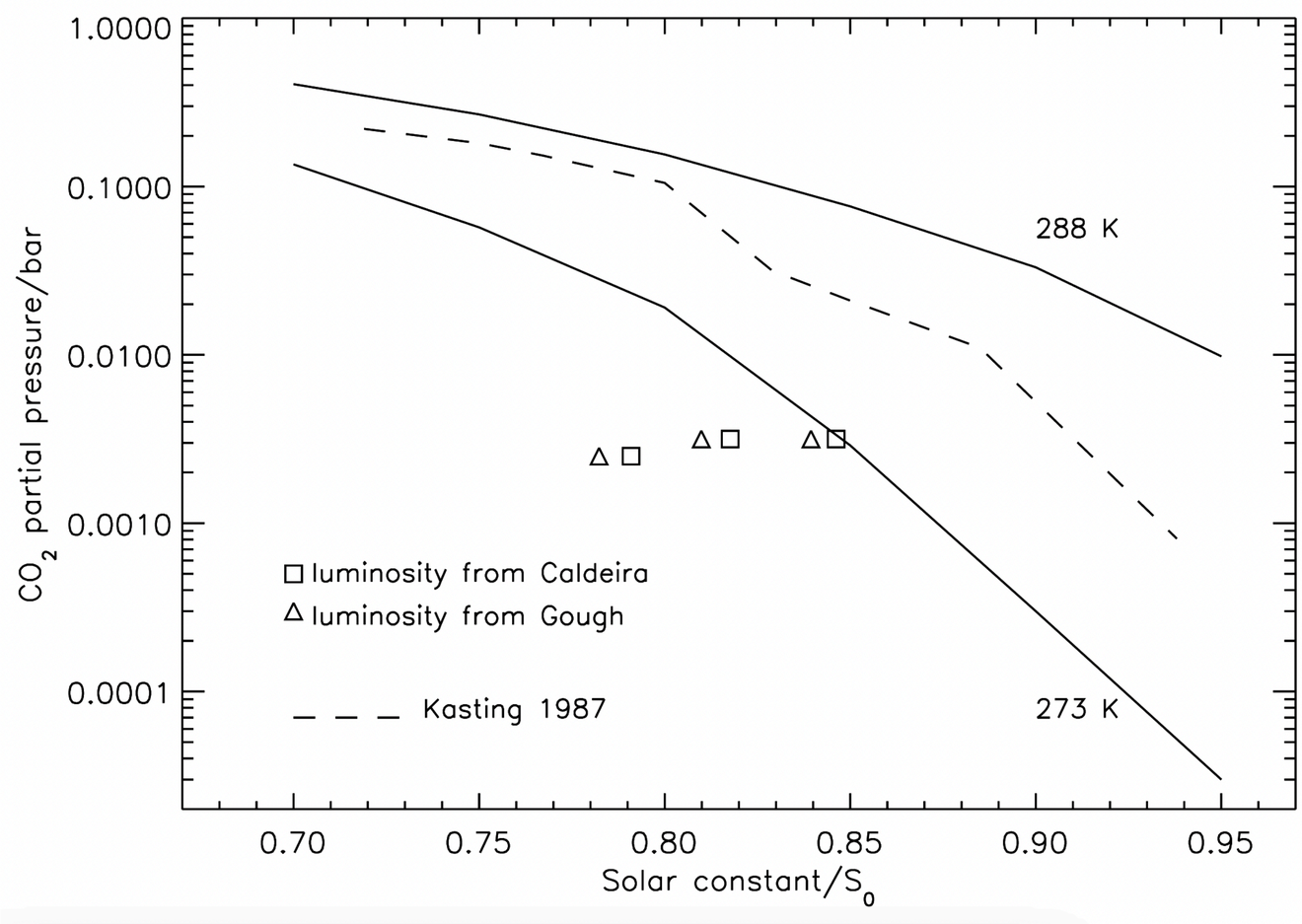
But: Three Episodes of Global Glaciation



äquinoktium/Wikimedia Commons; Mikkel Juul; www.snowballearth.org, nach Evans (2003)

CO_2 Required to Prevent Snowball State

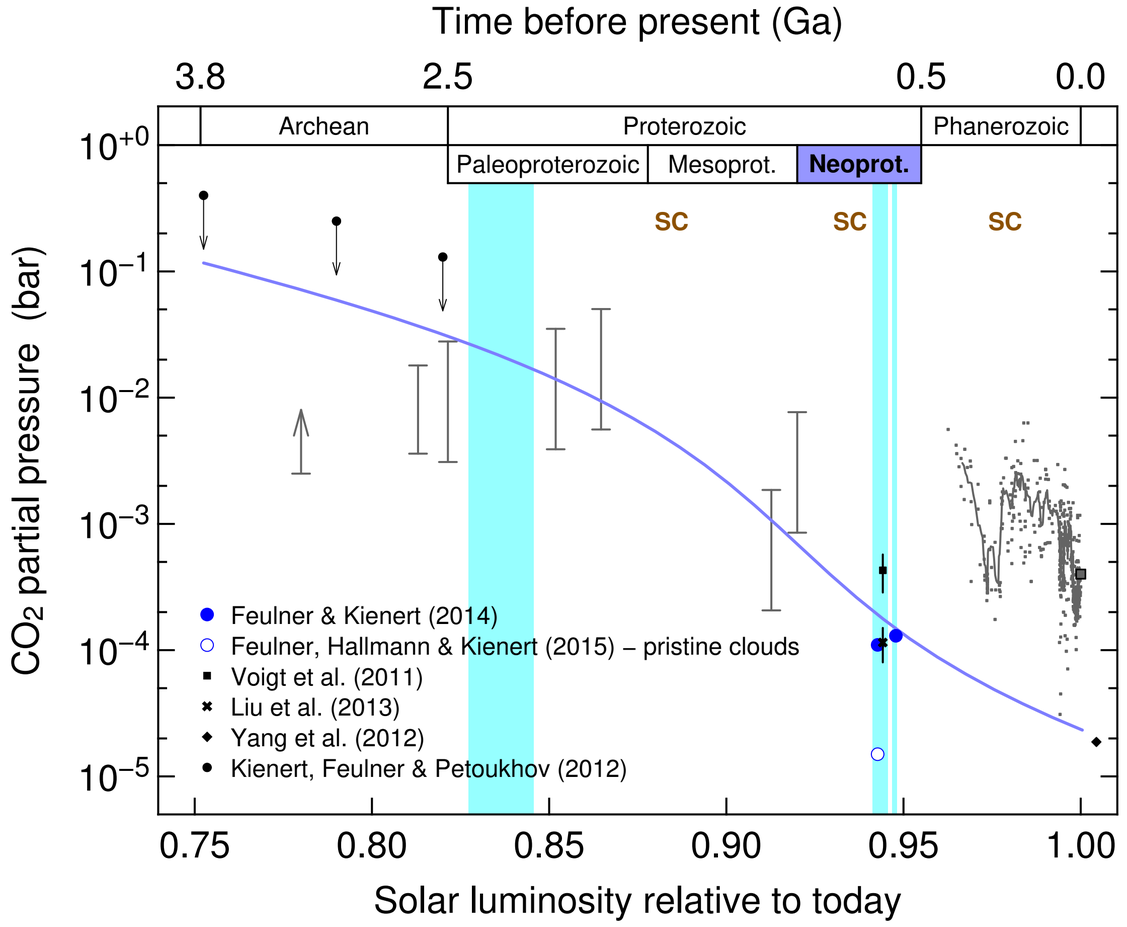
Investigated using simple models without ice–albedo feedback – unsatisfactory!



von Paris et al. (2008)

Strange Behaviour of a Simple Model

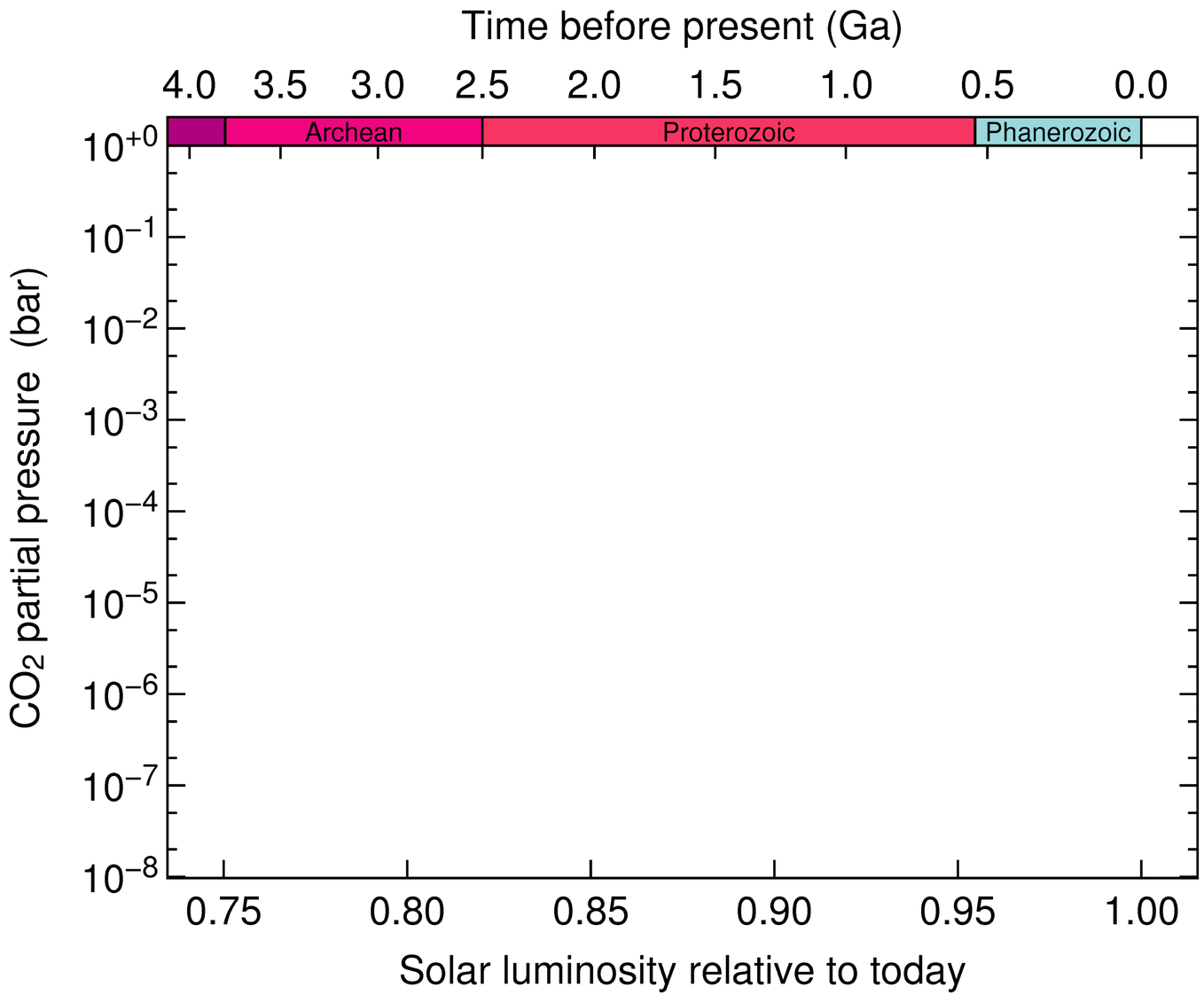
1D energy balance model – shape due to distributions of solar vs. longwave radiation?



Similar behaviour in 3D models?

Feulner (2017)

Building a Synthesis Diagram



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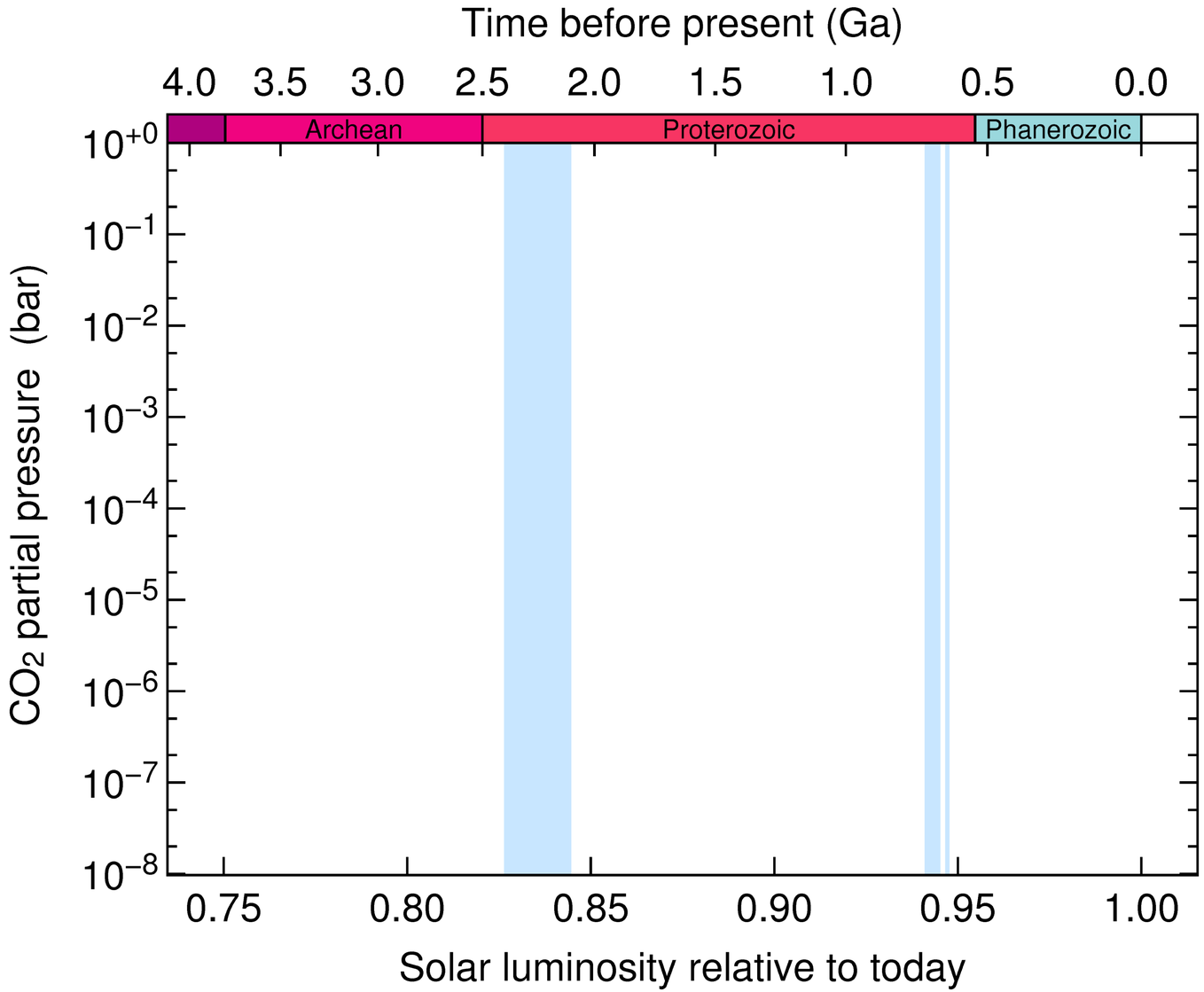
Building a Synthesis Diagram



\+ past global glaciations

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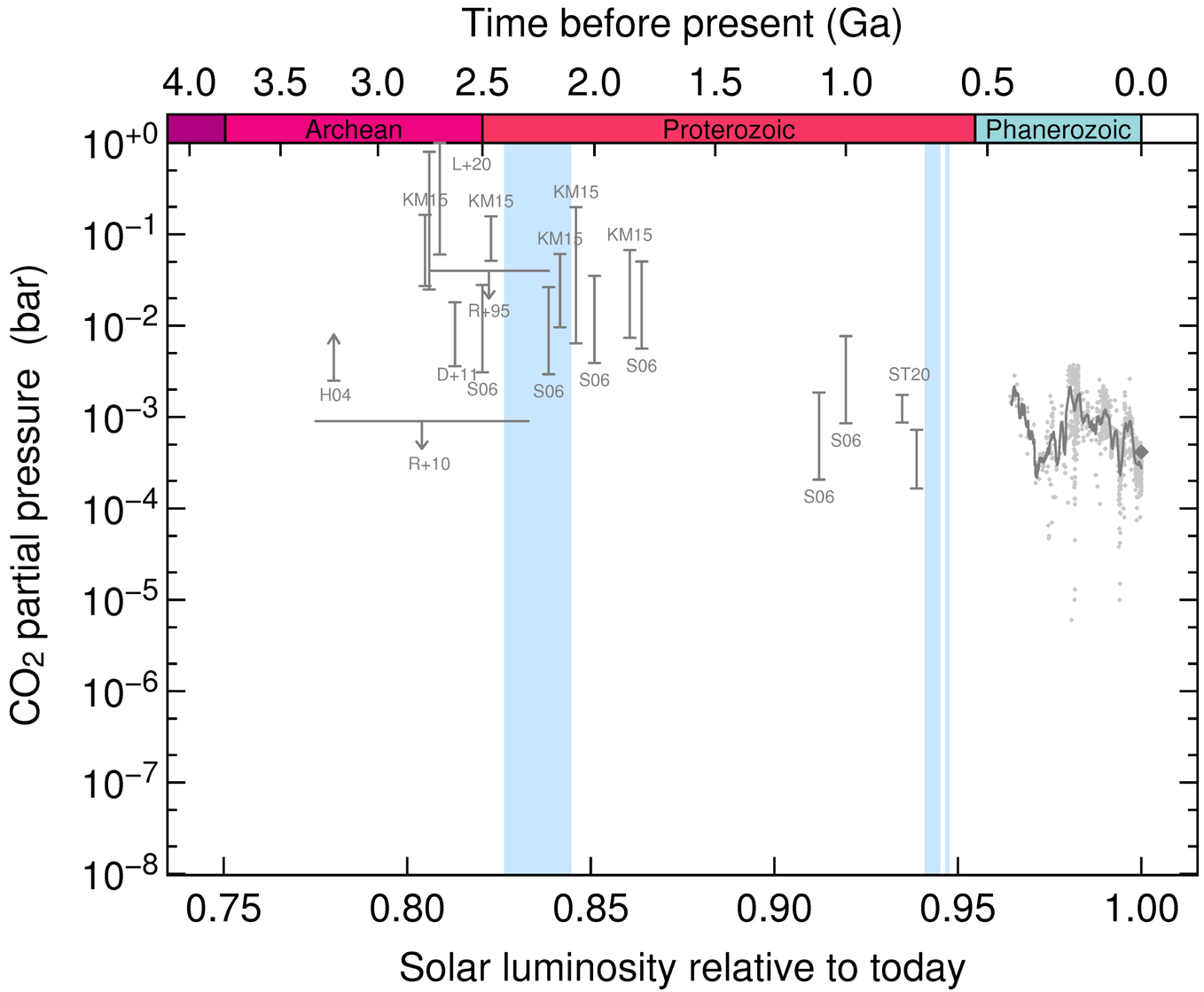

+ past global glaciations
+ empirical CO_2 estimates

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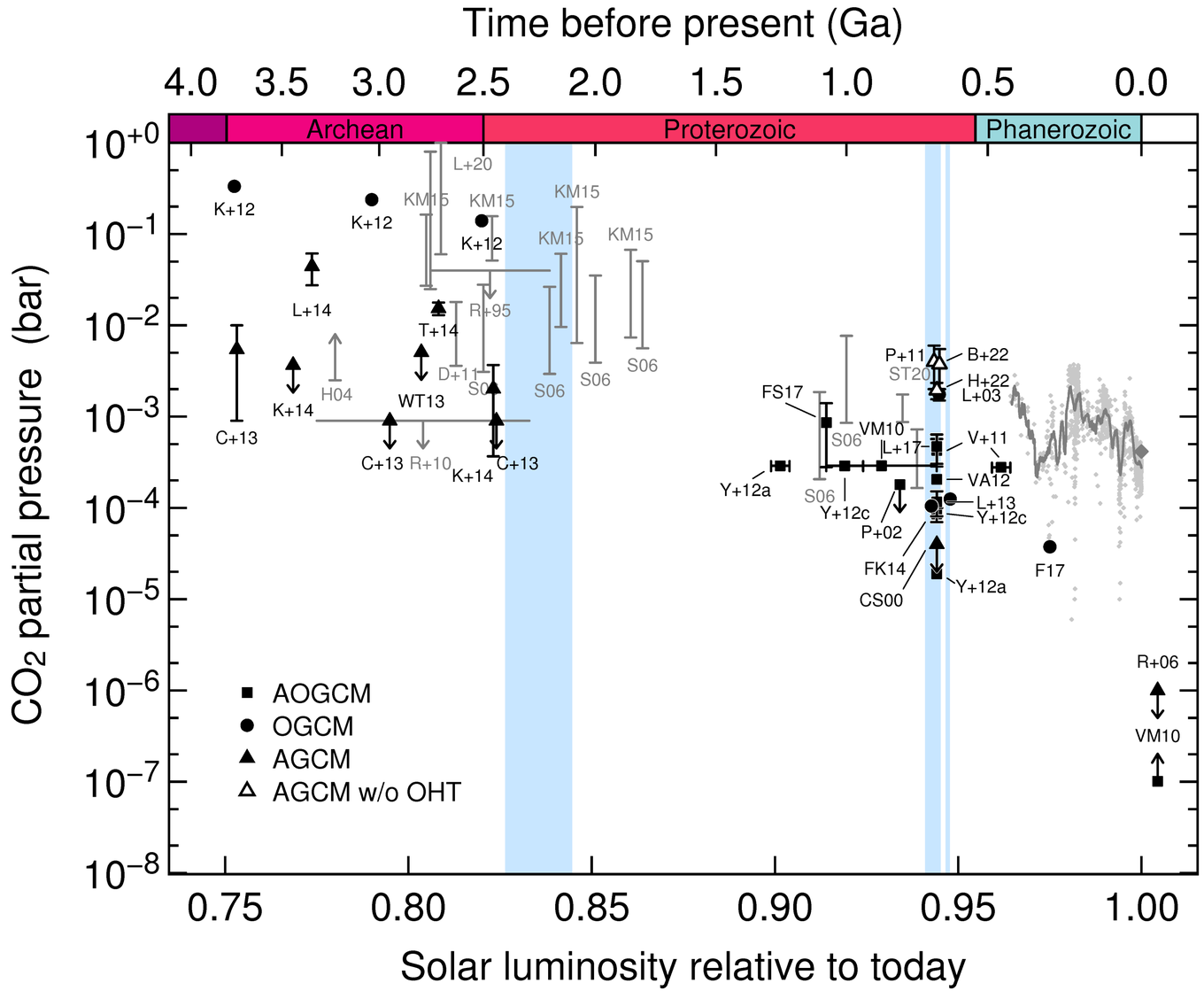
Building a Synthesis Diagram



+ past global glaciations
+ empirical CO_2 estimates
+ 3D model simulations

- Focus on early Earth (Faint Young Sun Paradox) and ~ 700 million years ago (Snowball Earth)
- Atmosphere models with simple ocean/without sea-ice dynamics artificially stable

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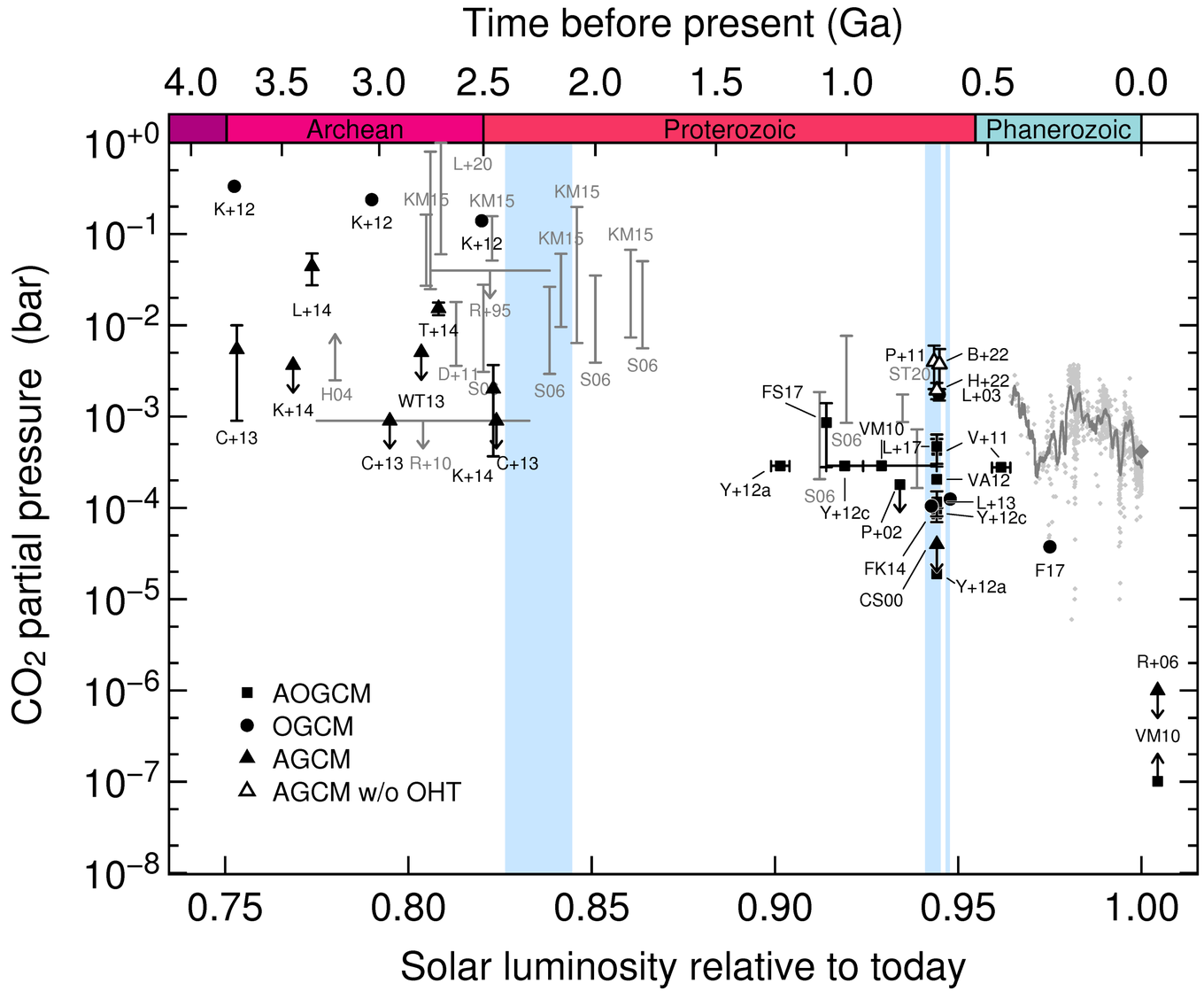
Building a Synthesis Diagram



+ past global glaciations
+ empirical CO_2 estimates
+ 3D model simulations

- Considerable differences even for similar models/boundary conditions due to model physics
- Comparison difficult (different models & model types, vastly different boundary conditions…)

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Model, Boundary Conditions & Simulation Protocol

Idea: Trace the Snowball bifurcation with one model & consistent boundary conditions

- **Model**: CLIMBER-3α (ocean general circulation model at 3.75° resolution, dynamic/thermodynamic sea-ice model, fast atmosphere)
- **Boundary conditions**:
  - Aquaplanet configuration
  - Obliquity 23.5°, circular orbit
  - Time slices every 150-300 million years, characterised by solar constant
  - Simulations with decreasing CO_2 to pinpoint Snowball bifurcation

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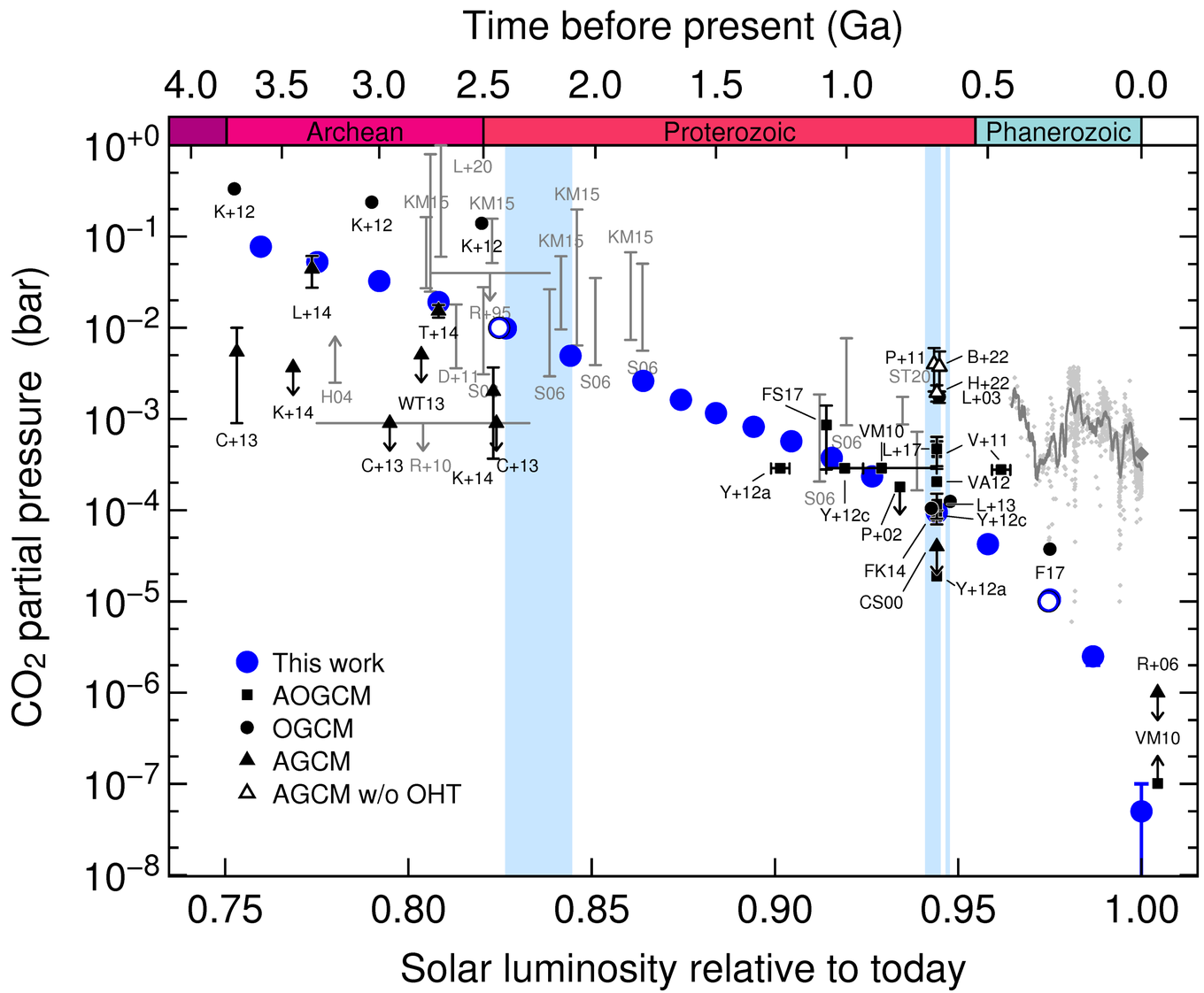
Aquaplanet Simulations in the Synthesis Diagram



- Logarithmic decrease (as expected)
- Very low critical CO_2 values in modern times (due to strong low-latitude insolation, baseline water-vapour greenhouse warming)
- Present-day Earth refuses to freeze over even without CO_2!

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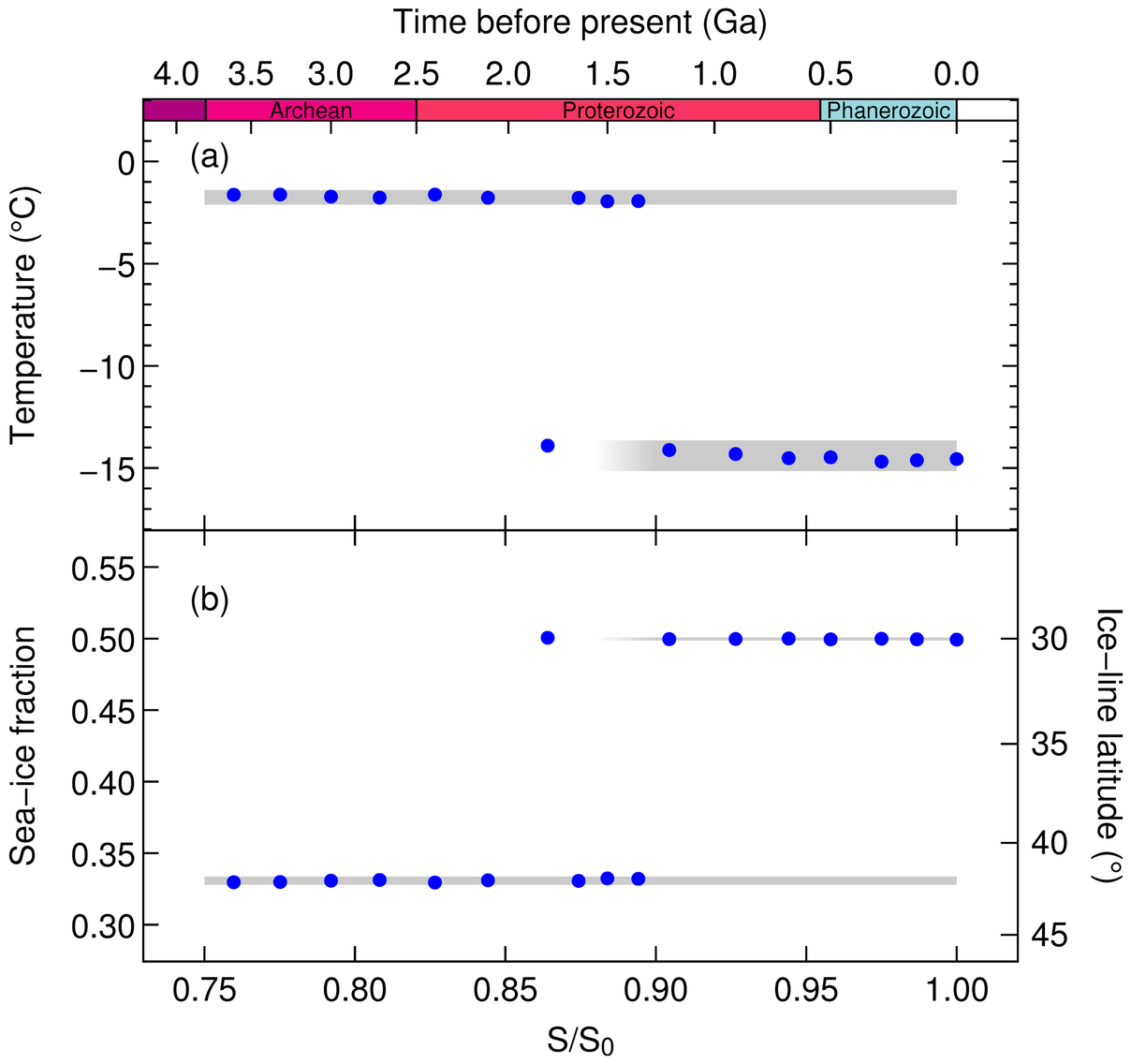
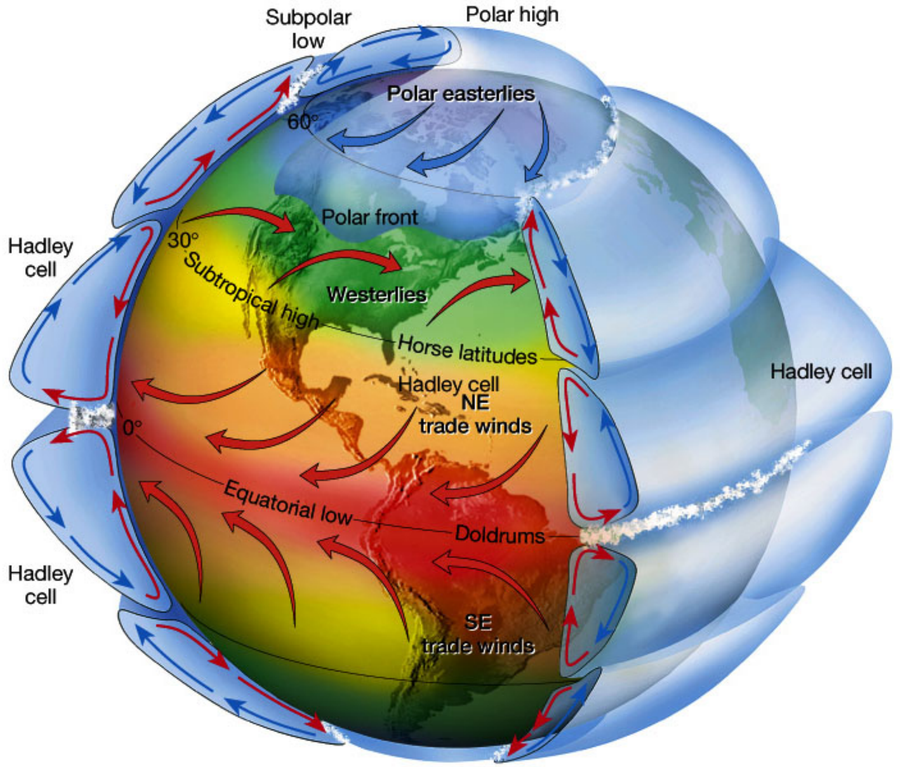
Global Properties of Critical States



Marked shift in critical-state properties!

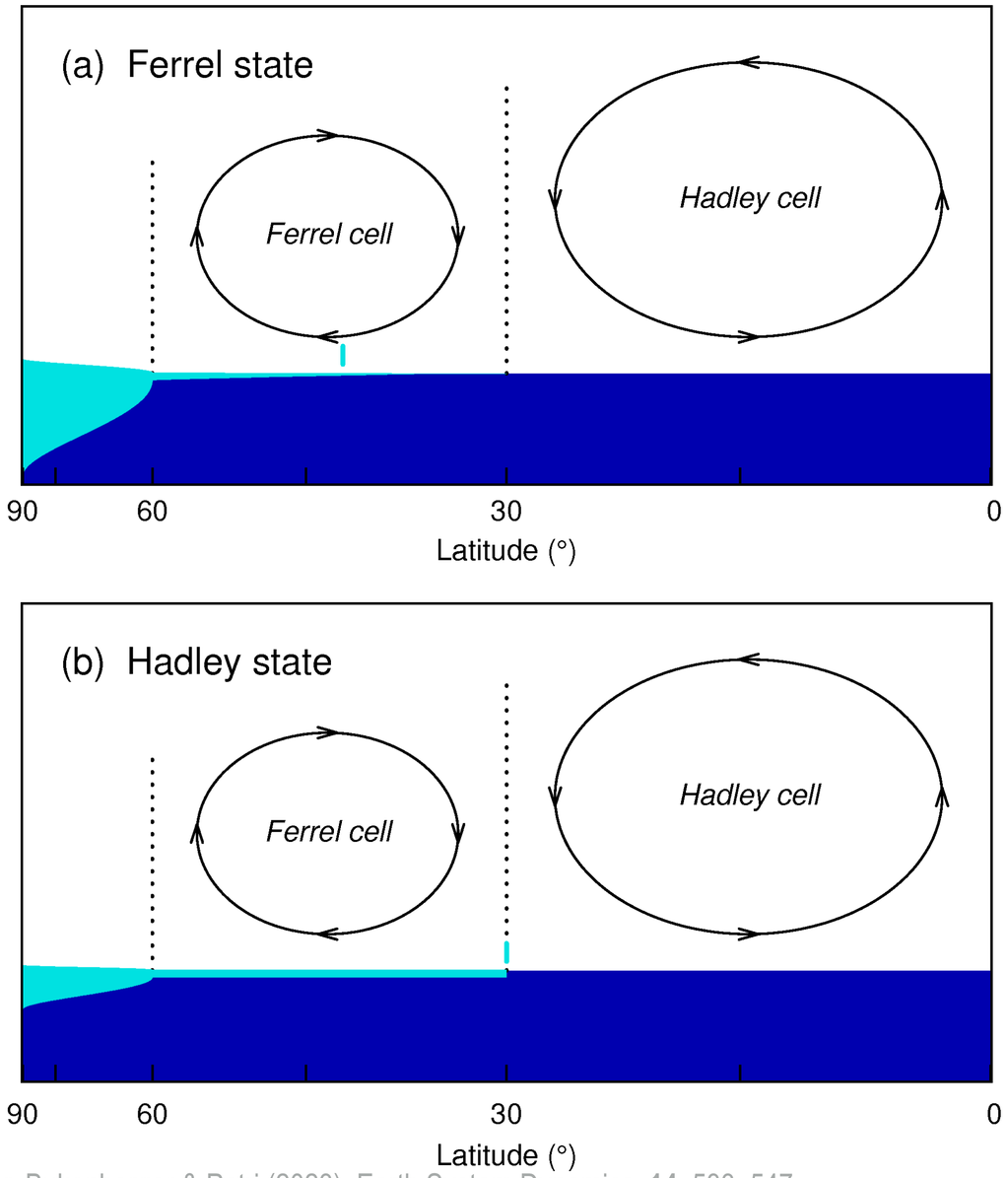
“Hadley states”

“Ferrel states”



Feulner, Bukenberger & Petri (2023), Earth System Dynamics, **14**, 533–547; Lutgens, Tarbuck: The Atmosphere (2001)

Critical-State Dynamics through Earth's History



- Hadley states unstable at lower solar luminosities due to smaller temperature difference across Hadley-cell boundary
- Fundamental cause: different spatial distributions of solar vs. greenhouse forcing (aha!)

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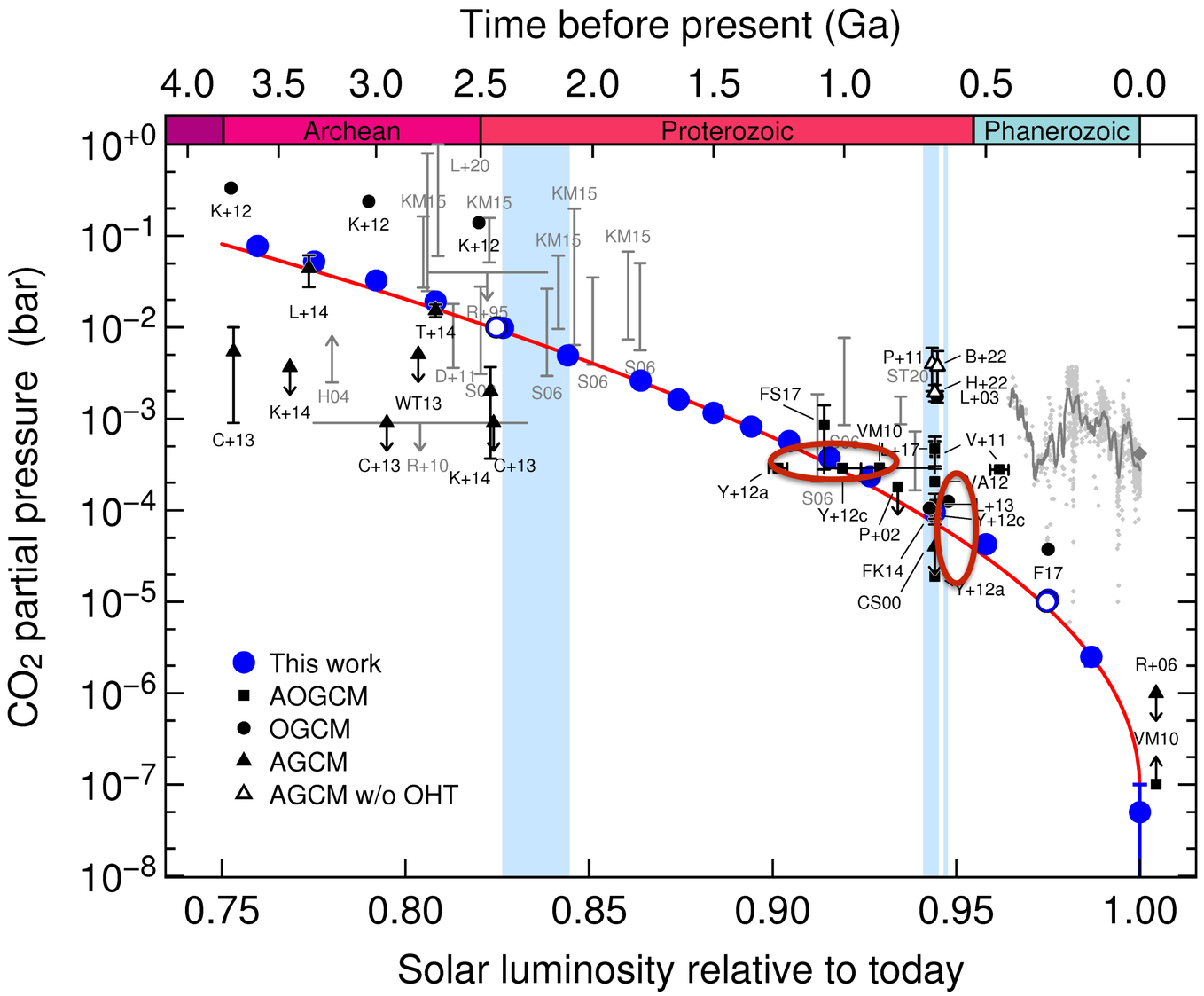
Similar Behaviour in Comprehensive Models



Yang et al. (2012a, c): "Modern" Snowballs with CCSM3/CCSM4:

- Reduction in solar luminosity: critical sea-ice fraction about 40% (33% in our model) – Ferrel state
- 94% of solar constant plus decreasing CO_2: critical sea-ice fraction about 60% (50% in our model) – Hadley state
- Regime shift at similar time

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Summary

- Comprehensive synthesis of earlier modelling results on the Snowball bifurcation in context of empirical CO_2 estimates
- Quantification of Snowball bifurcation in aquaplanet simulations for 18 time slices spanning Earth's history
- Unexpected regime shift in critical-state properties (at about 1200 Ma) from "Ferrel states" at low solar luminosities to "Hadley states" at high solar luminosities
- Interplay between energy balance and large-scale atmospheric dynamics affecting sea-ice dynamics

Key Messages

- Faint Young Sun Paradox not (fully) resolved yet
- Habitability assessments depend on model physics/parametrisations/assumptions, 3D models *with sea-ice dynamics* required for cold limit
- Modern Earth does not freeze over even when all CO_2 is removed
- Internal dynamics of climate system matters for planetary habitability…!

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Many thanks for your attention!

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Model data: https://doi.org/10.5880/PIK.2022.003

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