Habitability in Alpha Centauri AB: an astrodynamics perspective

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Outline

- What is a habitable planet?
- Habitable zones
  - Basic definition
  - Application to binary stars
- Astrodynamics
  - Orbital variations and stability
  - Spin evolution and tides
- Insights from basic climate models
- Prospects from the ground & JWST
- Summary

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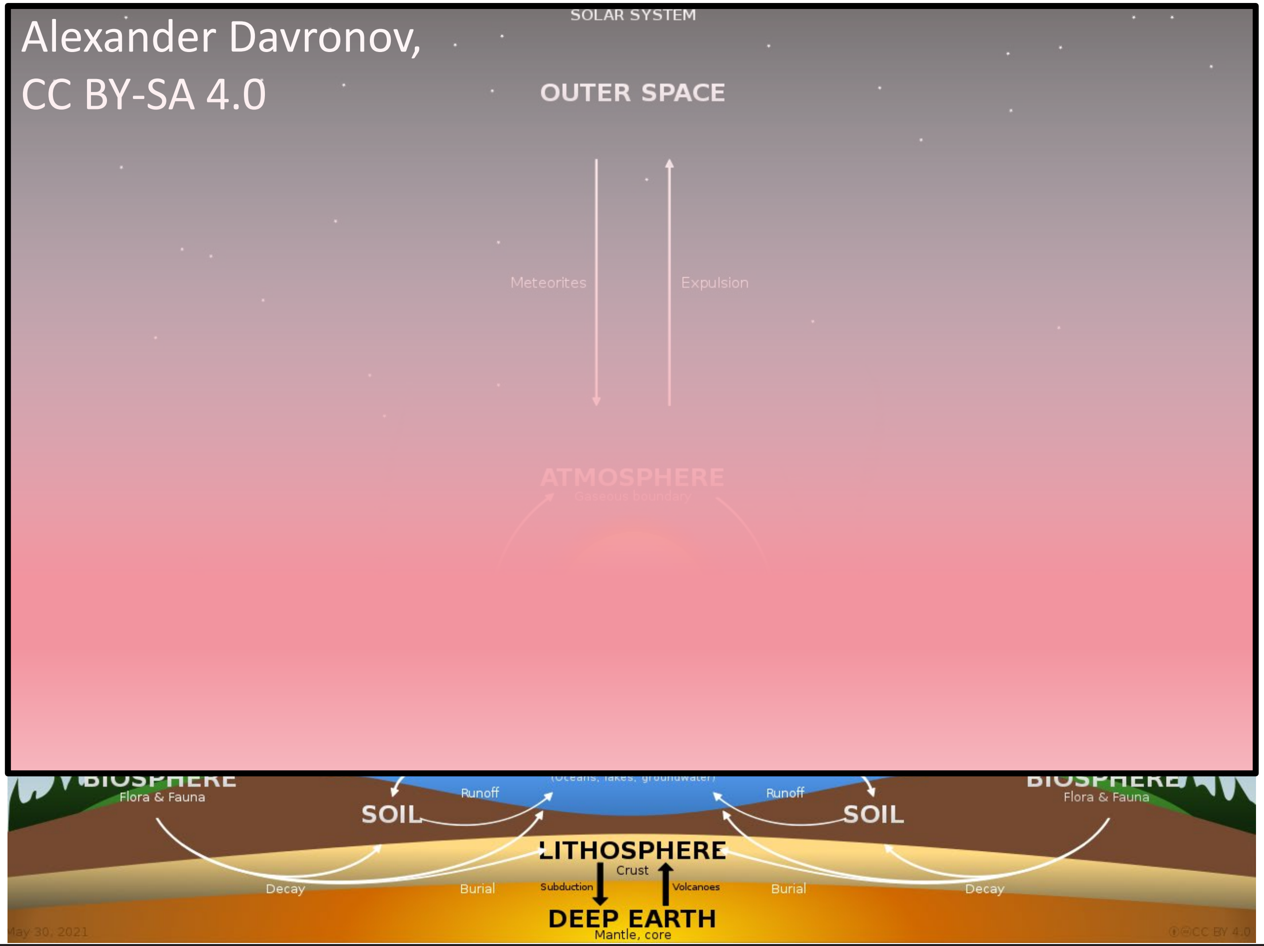
What is a habitable planet?

- *A world that has the <u>capacity</u> of hosting and sustaining life.*
  - Capacity ≠ realization
- What conditions allow for this capacity?
  - External energy source (i.e., radiation from nearby star(s))
  - Sufficiently massive planet (i.e., very little atmospheric loss)
  - Sources of chemicals for metabolic processes
    - Sulfur, methane, water
  - Appropriate surface temperature for metabolic processes
    - Liquid water?



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What is a habitable planet?

- "If a tree falls in a forest with nobody around, does it make a sound?"
  - Subsurface life could be independent of the external energy source/atmospheric properties (e.g., subterranean or subglacial)

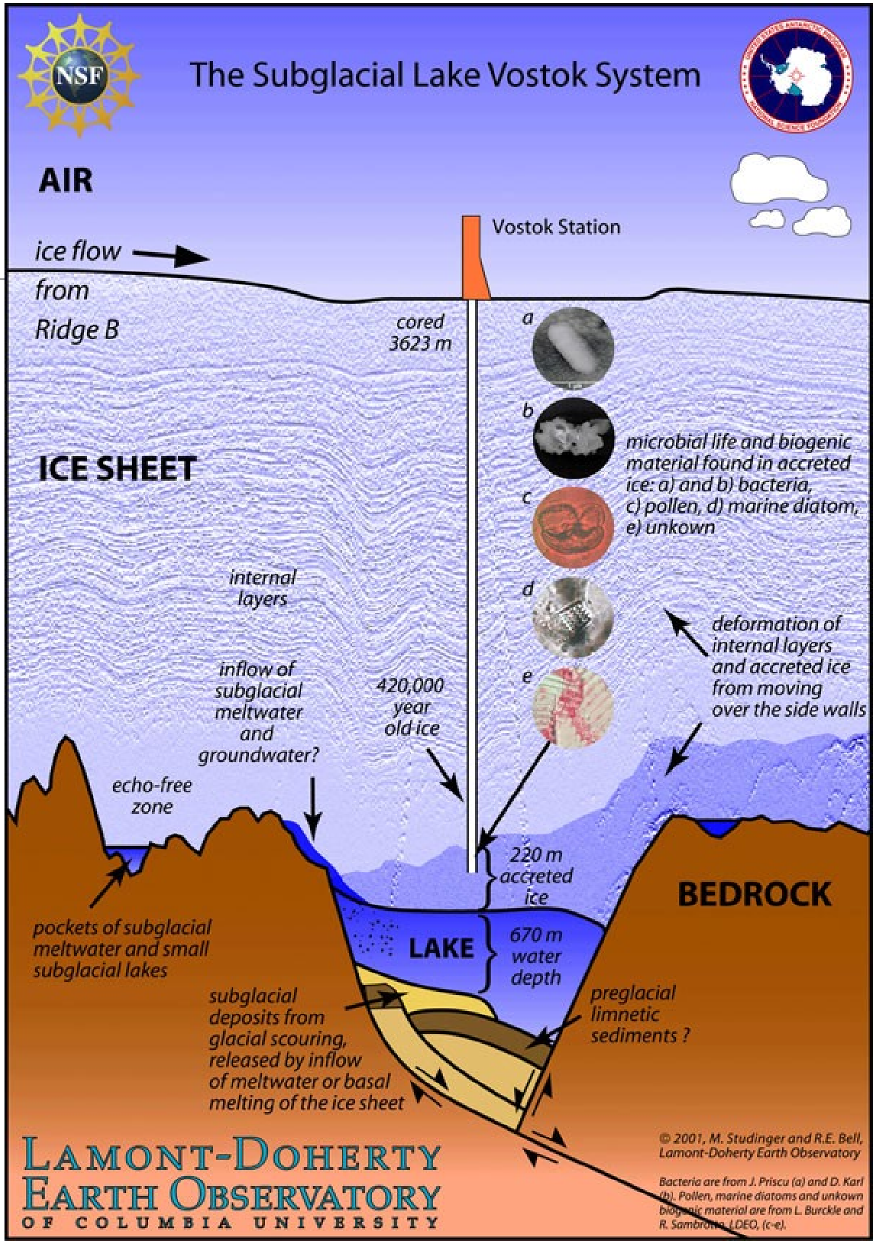
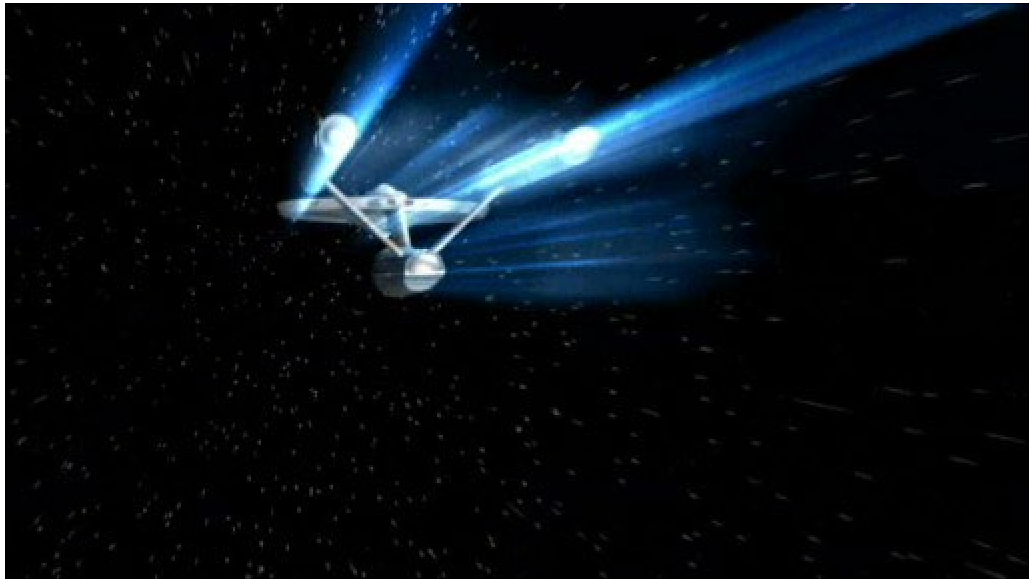


Image credit: Lamont-Doherty Earth Observatory of Columbia University/NASA

What is a habitable planet?

- Practical limitations
  - Remote observations (no FTL travel)
  - Transit spectroscopy samples atmosphere



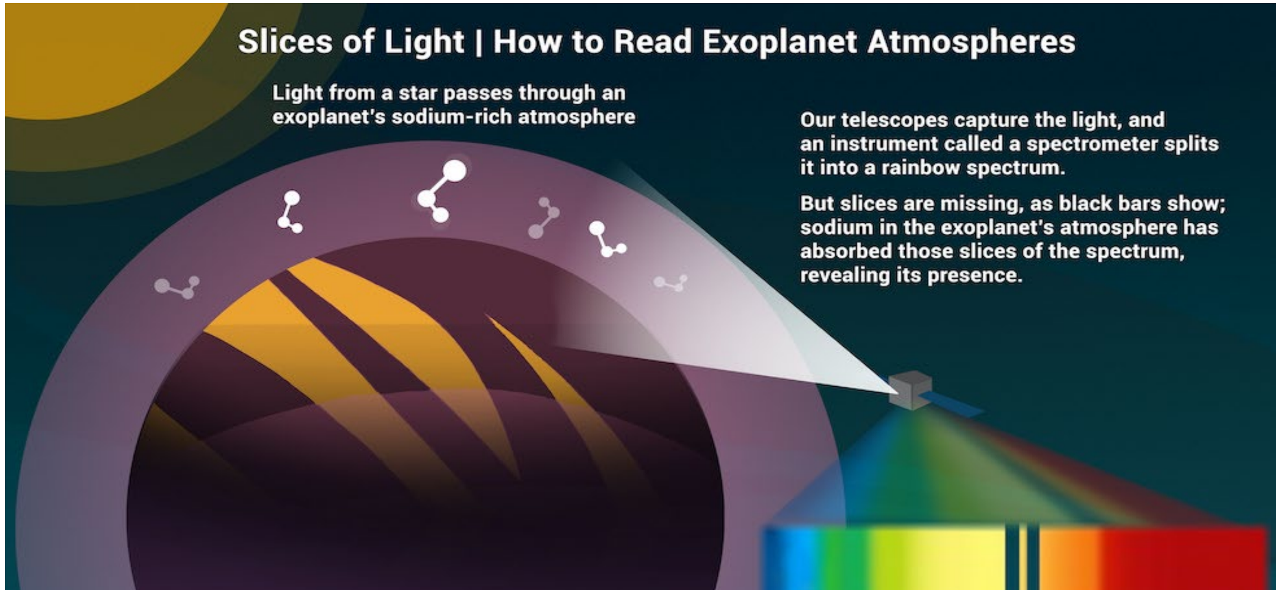
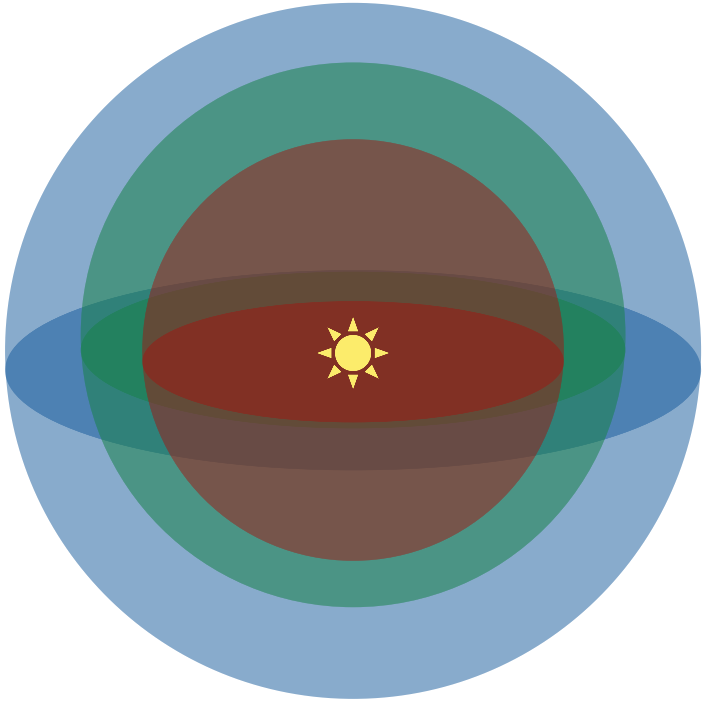


Image Credit: NASA

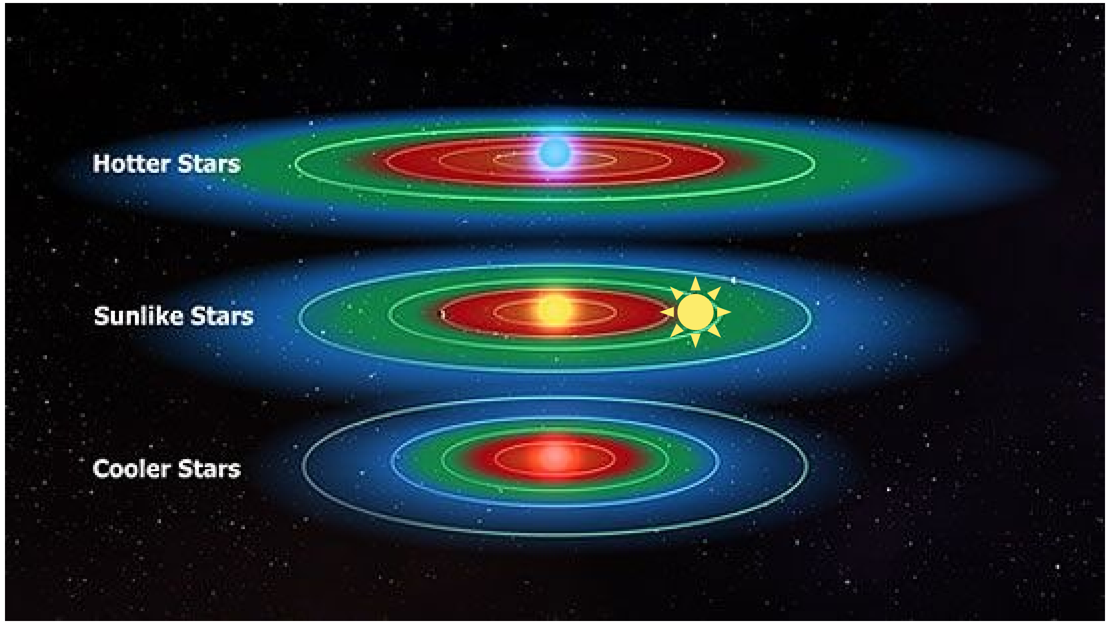
Habitable Zones: basic definition

- *“The region around a star in which life-supporting planets can exist.”* (e.g., Huang 1960, Dole 1964, Shklovskii & Sagan 1966)
- Questions
  - Shape/extent of the region?
  - Conditions for life-supporting planets?
  - Duration of the potential for life supporting planets?



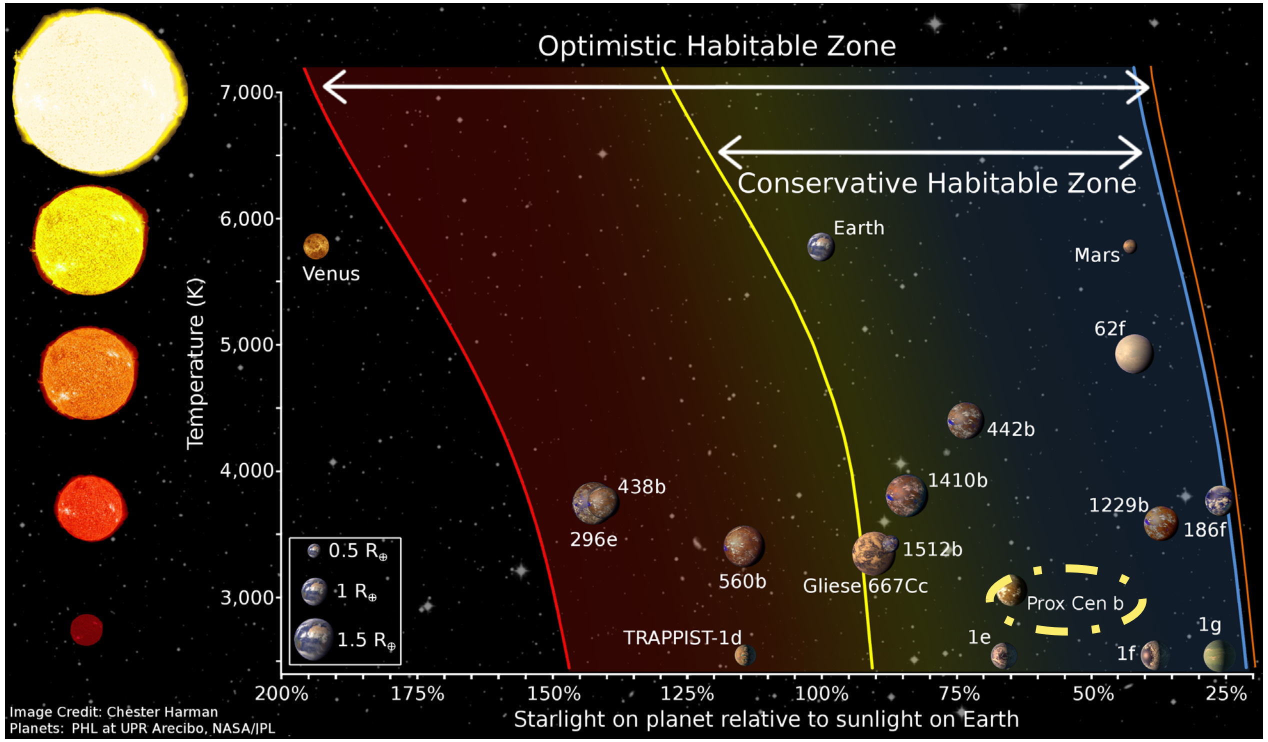
Habitable Zones: basic definition

- Habitable zones around main sequence stars (Kasting+ 1993)
  - Assume Earth-like planet and atmosphere ($CO_2/H_20/N_2$) and apply a 1D climate model (energy balance) with altitude
  - Spherical shell of habitability, where liquid water can exist on the surface of the planet
  - Stellar evolution is slow, habitability is only temporary for inner edge



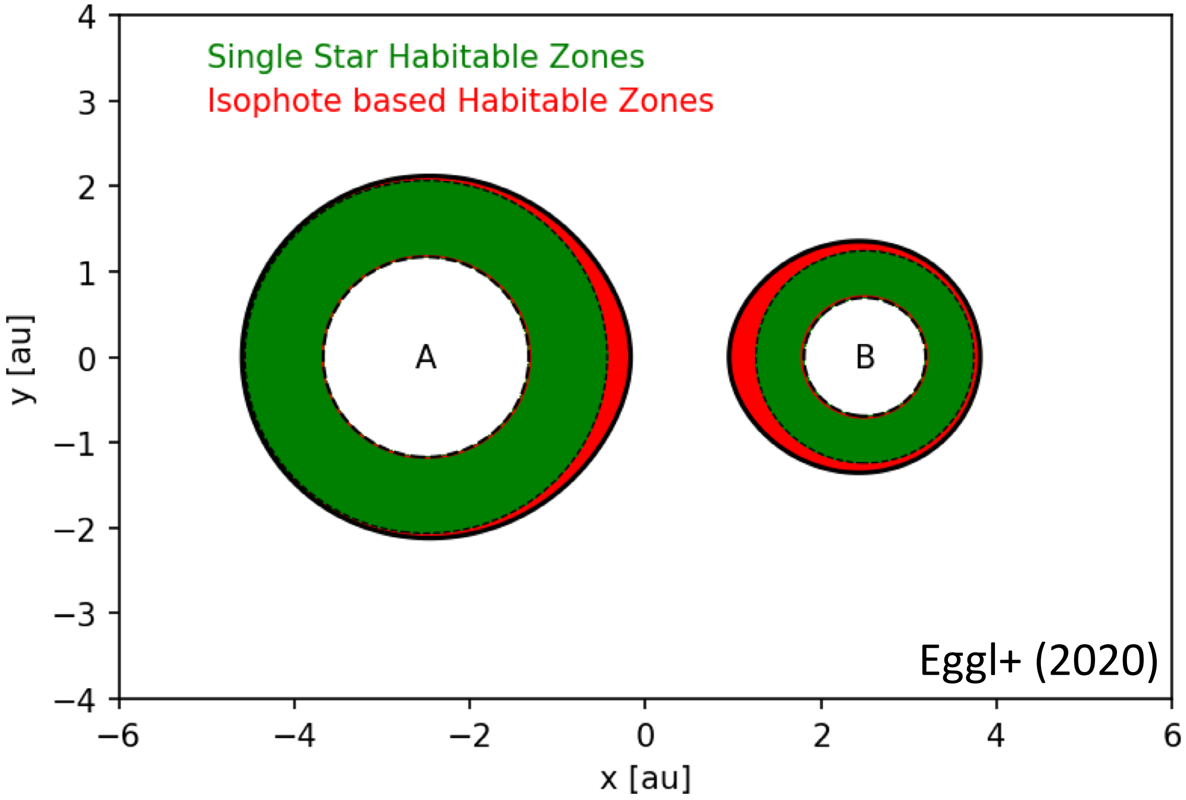
Habitable Zones: basic definition

- Spherical symmetry from the inverse square law of light
  - $d_{HZ} = 1\ AU \sqrt{\frac{L/L_\odot}{S_{eff}}}$; (scaled radius)
  - S_{eff} is determined by the assumed planetary atmosphere
  - $L/L_\odot$ depends on the star (External energy source)
- Atmospheres
  - Runaway Greenhouse (water loss) -> Maximum Greenhouse (e.g., Kasting+ 1993, Underwood+ 2003)
- New estimates use updated spectral databases for atmospheric heat transfer (e.g., Kopparapu+ 2013a, 2013b)



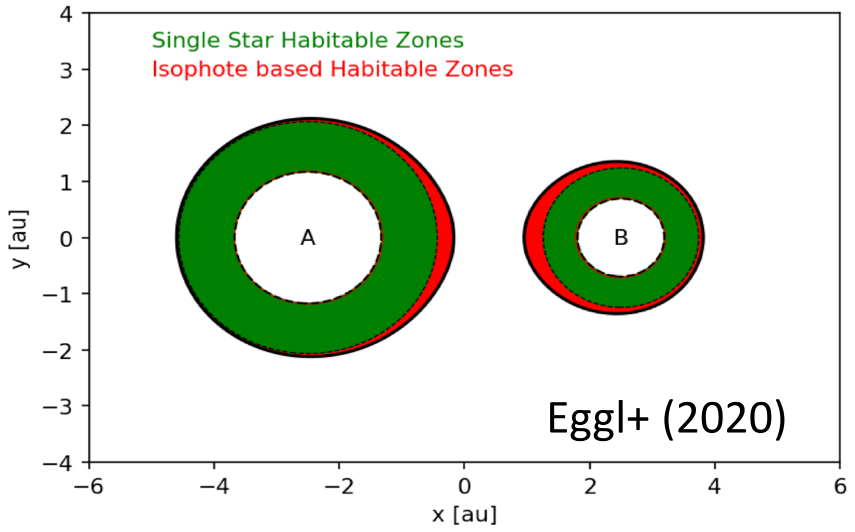
Habitable Zones: application to binary stars

- Kasting, Whitmire & Reynolds (1993)
  - Considered (qualitatively) the potential for binary stars
  - No planets yet confirmed in binary systems
- Two stars introduces multiple sources of external energy
  - Ignore the stellar companion -> companion is too dim or far away (e.g., Quarles+ 2012)



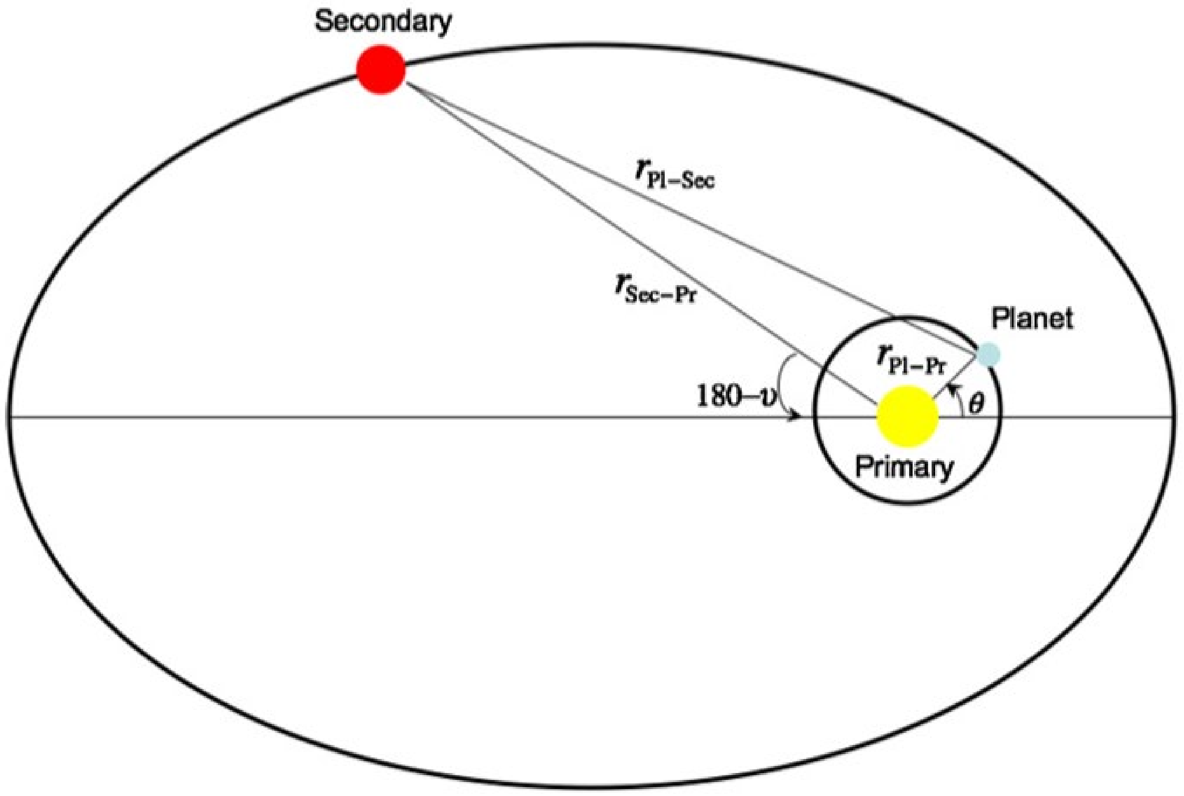
Habitable Zones: application to binary stars

- Two stars introduces multiple sources of external energy
  - Include a time varying Flux -> $S(t) = L_A/R_A^2(t) + L_B/R_B^2(t)$ (e.g., Eggl+ 2012, Kane & Hinkel 2013, Forgan 2012, Forgan 2016)
  - Include spectral (SED) weights -> $S(t) = w(T_A)L_A/R_A^2(t) + w(T_B)L_B/R_B^2(t)$; (e.g., Kaltenegger & Haghighipour 2013) atmospheres are not equally transparent/opaque to all wavelengths



Habitable Zones: application to binary stars

- Planets in binary systems
  - S-Type (alpha Cen AB)
  - P-Type (Kepler-16b)



Kaltenegger & Haghighipour (2013)

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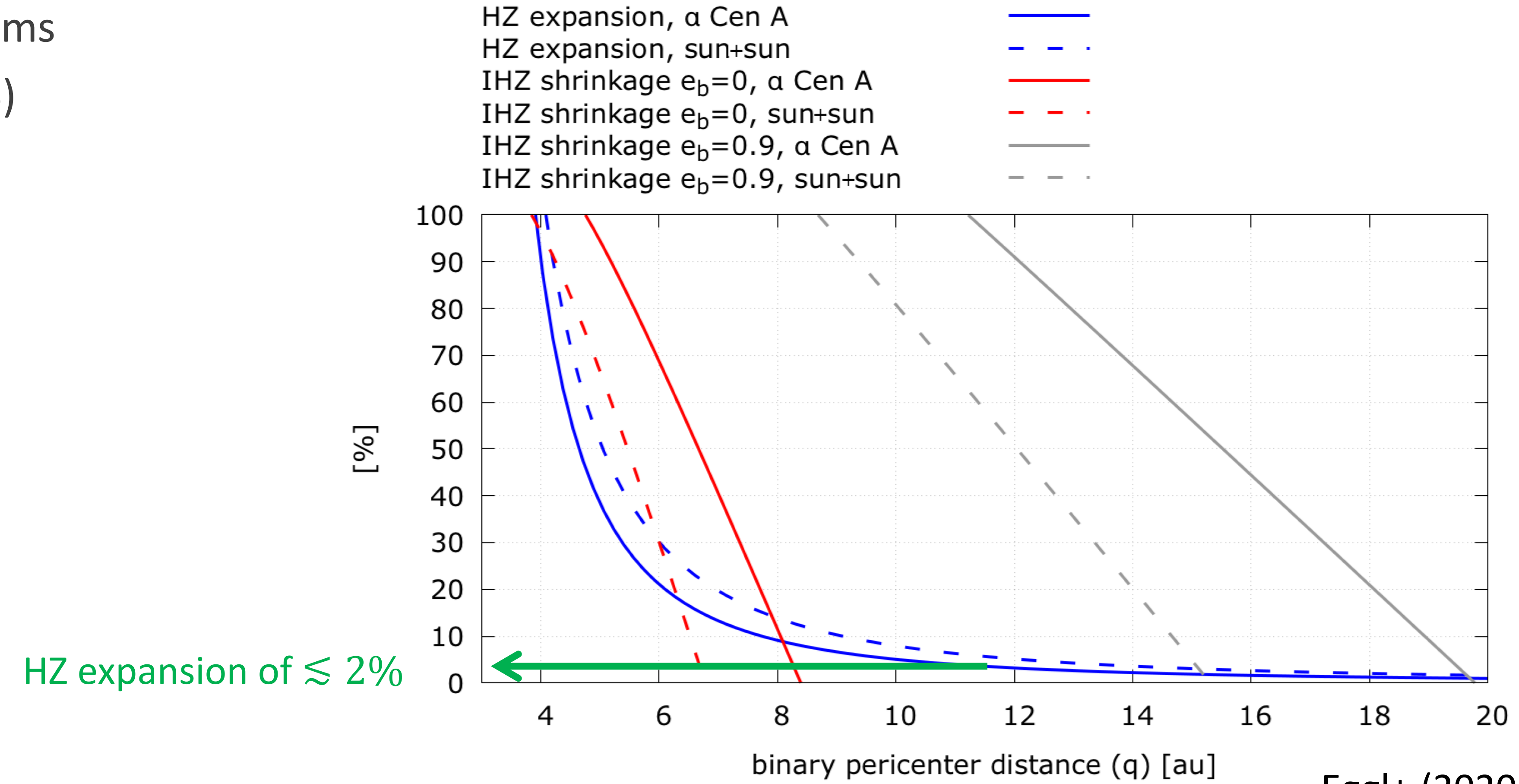


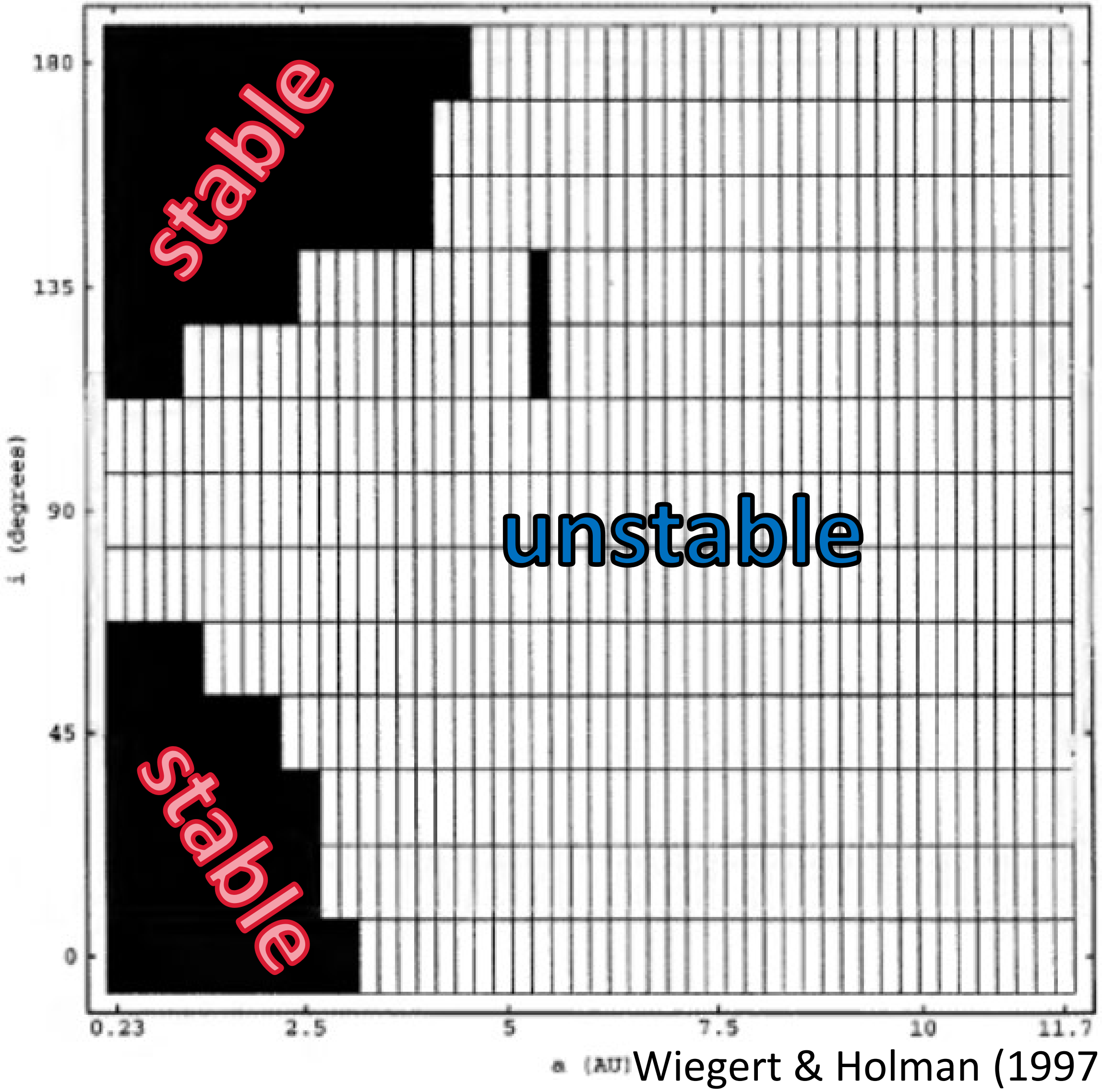
Eggl+ (2020)

Astrodynamics: orbital variations

- Companion stars perturb planetary orbits
  - Energy exchange --> $a_p' = a_p + \Delta a$ (tends to scatter or escape)
  - Angular momentum exchange --> $e_p' = e_p + \Delta \mathrm{e}$
  - Angular momentum exchange --> $i_p' = i_p + \Delta \mathrm{i}$
- Channels to perturb orbits
  - Mean motion resonances (e_p increases; Mudryk & Wu 2006)
  - Evection resonance (e_p increases; Touma & Wisdom 1998)
  - Forced eccentricity (e_p oscillates; Heppenheimer 1978, Andrade-Ines+ 2016)
  - vZKL mechanism (e_p and i_p oscillate; von Zeipel 1910, Kozai 1962, Lidov 1962)
- Instantaneous flux from stars oscillates with a fast (planetary period) and slow (binary period) timescale

Astrodynamics: stabili

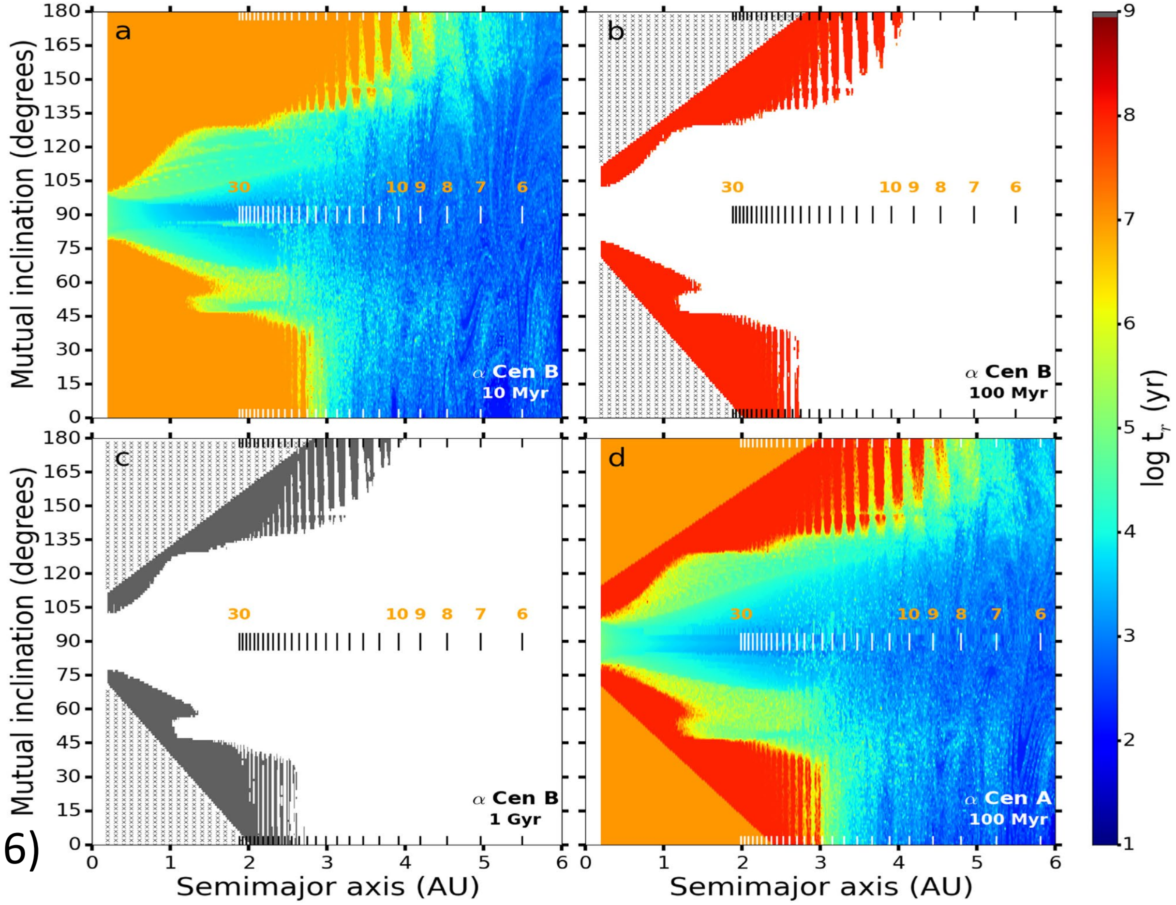
- Free-floating planets may harbor life, but hard to investigate
  - **Habitability condition: planet must orbit a star on an astrobiological timescale (~1 Gyr)**
- Extent of energy exchanges (e.g., Wiegert & Holman 1997)
  - Survey initial orbits (a vs. i) using numerical simulations over ~2.5 Myr
  - Unstable -> $\frac{\Delta a}{a_p} \geq 0.05$; else stable



Wiegert & Holman (1997)

Astrodynamics: stability (Alpha Cen AB)

- Extent of energy and angular momentum exchanges (e.g., Quarles & Lissauer 2016)
  - Survey initial orbits (a vs. e; a vs. i) up to 1 Gyr
  - Unstable -> ejection ($d_p \geq 100\ AU$)



Quarles & Lissauer (2016)

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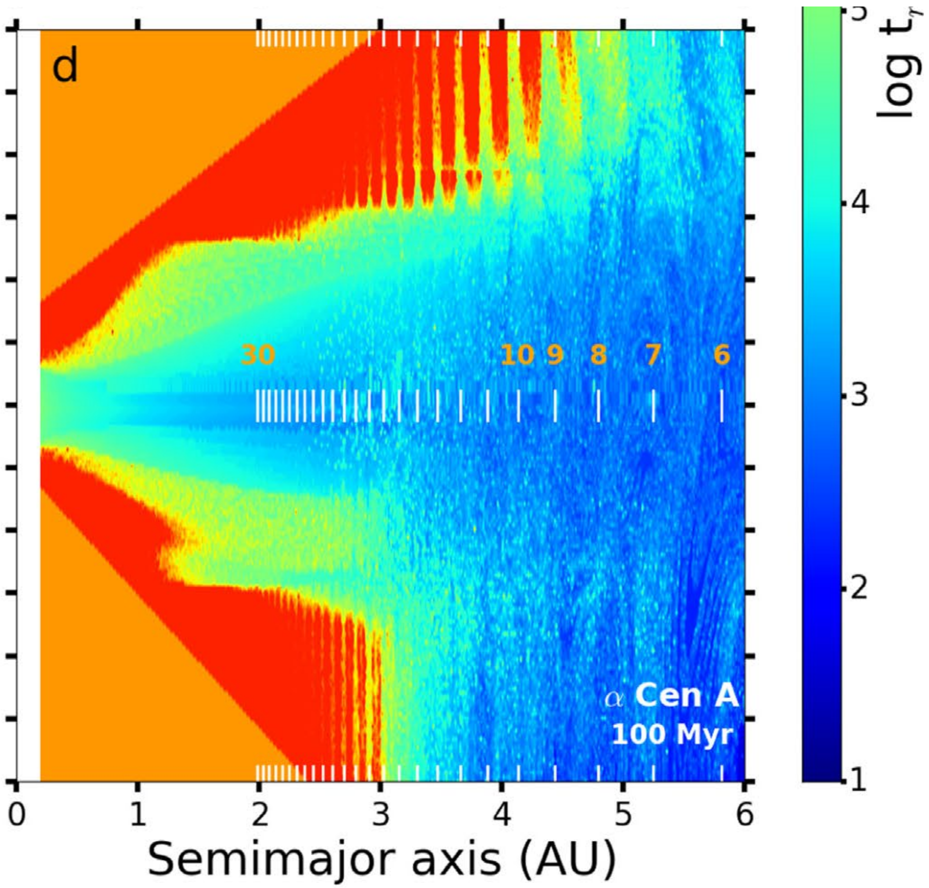
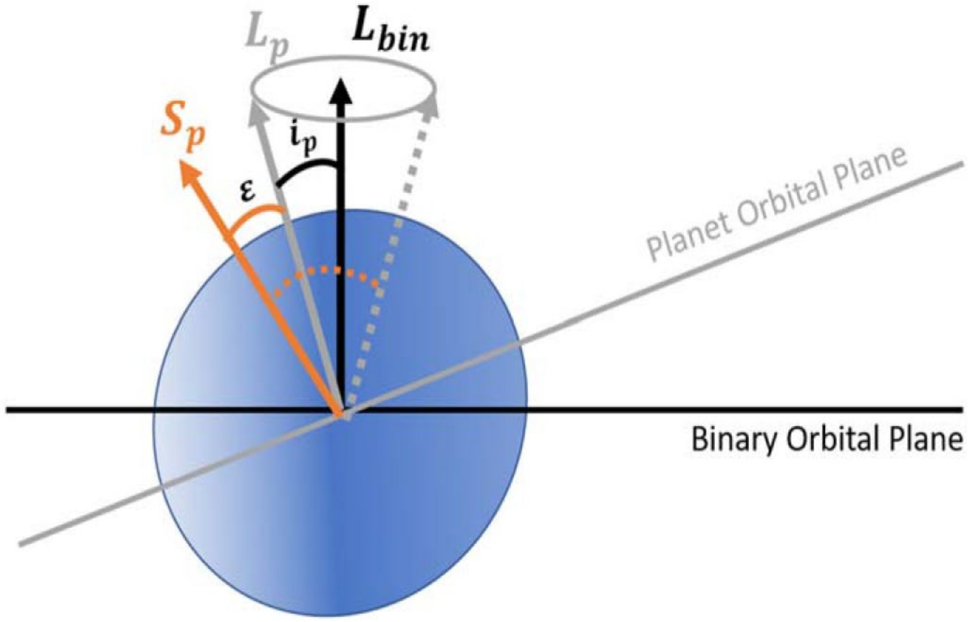


Astrodynamics: spin evolution

- Stably orbiting a star is not the only condition for habitability
  - Earth-based habitability changes due to the Moon's influence on spin
  - **Habitability condition: planet must have a moderately changing obliquity**
- Extent of obliquity variation from a stellar companion (e.g., Quarles+ 2019)
  - Survey initial spin states for planetary obliquity ϵ and spin precession α



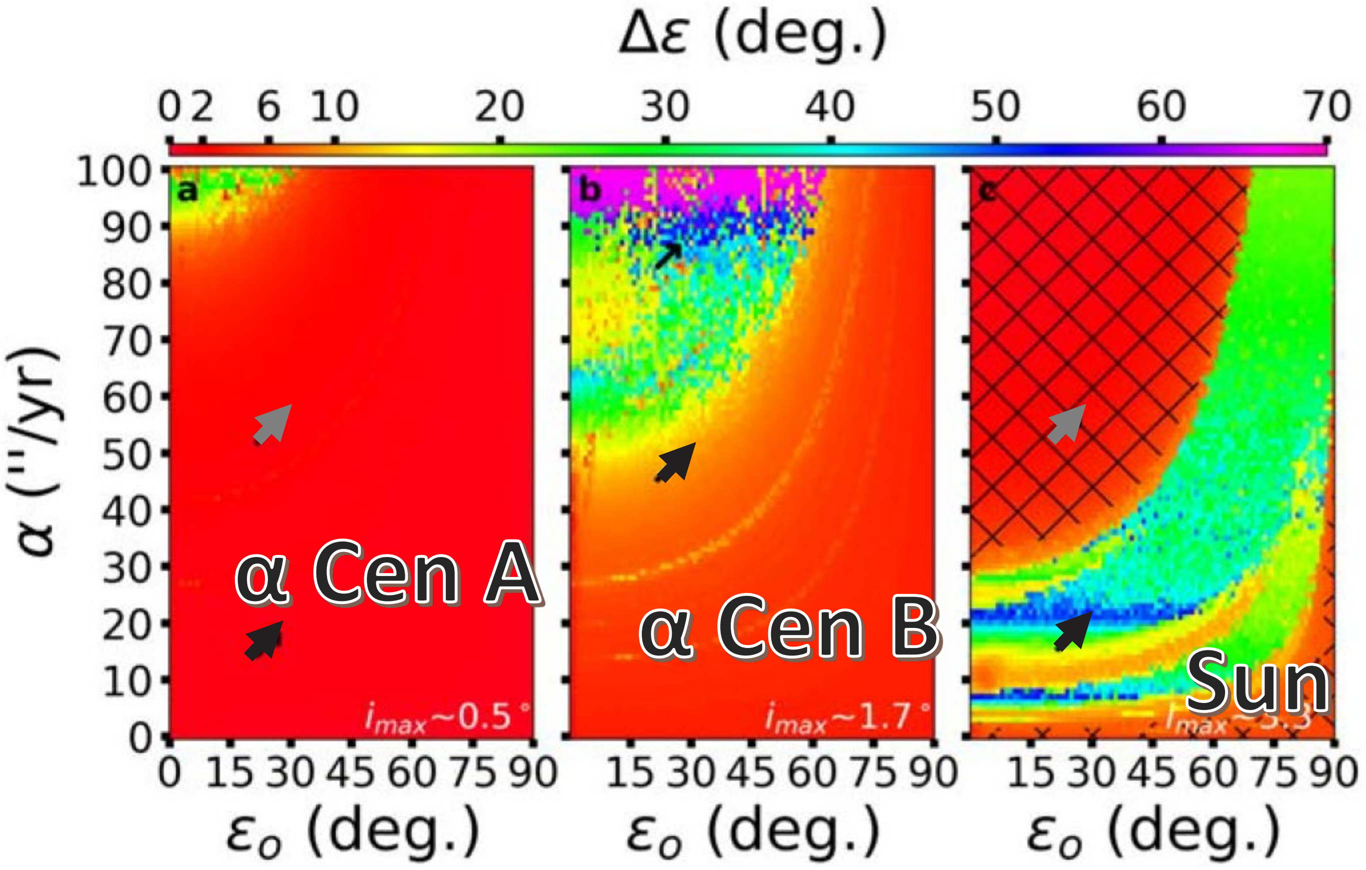
Quarles+ (2019)

w/ moon

moonless

Astrodynamics: spin evolution

- Large obliquity variations through spin-orbit resonance (SOR)
  - Depends on the coupling of spin and angular momentum vectors
- Overlapping frequencies leads to chaotic obliquity evolution (e.g., Laskar+ 1993, Lissauer+ 2012) for a Moonless Earth
  - precession due to Jupiter (i.e., Moon = good)
  - precession due to stellar companion (i.e., Moon ≠ good)



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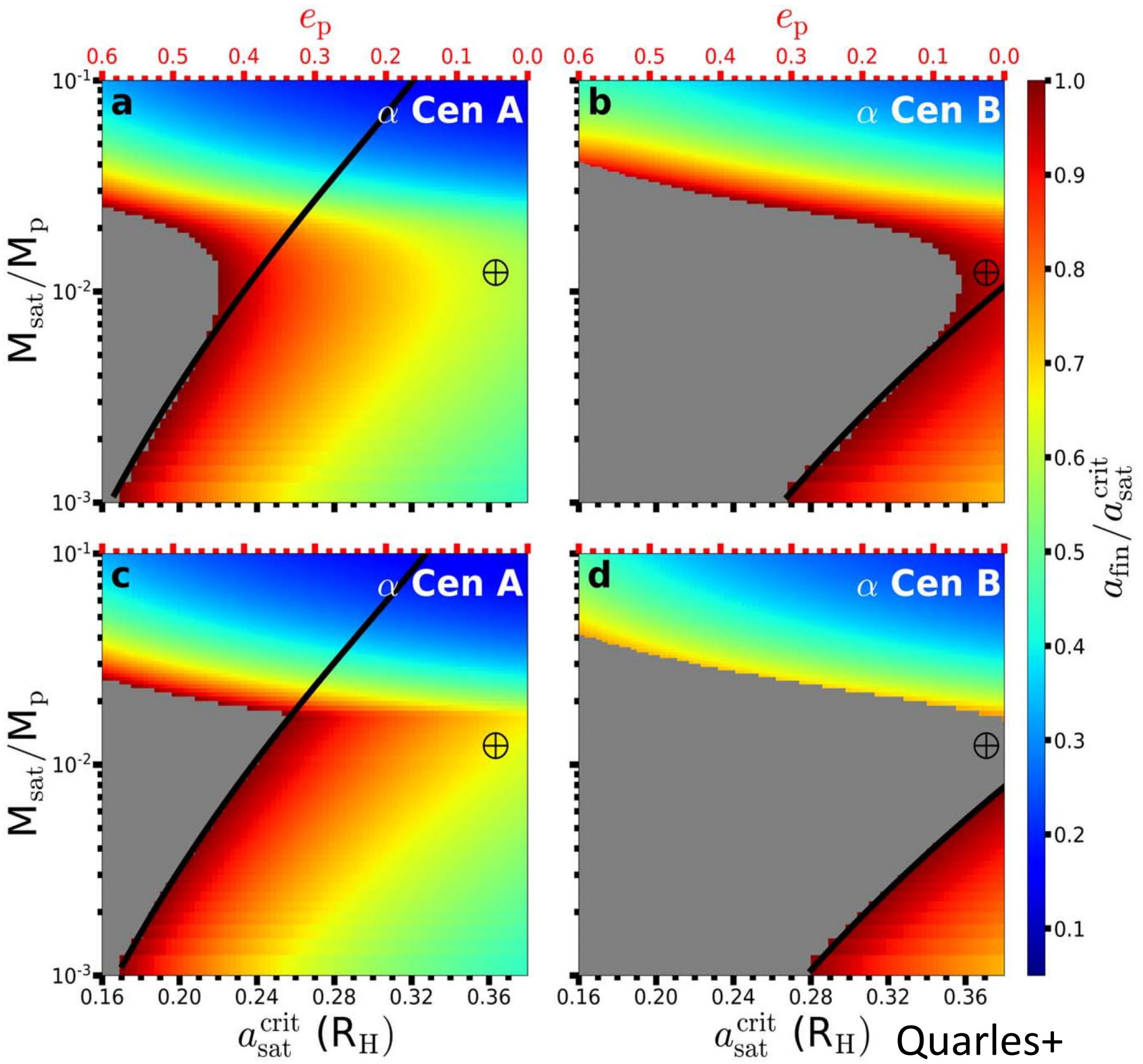
Astrodynamics: tides

- Astrobiological timescales are long (~1 Gyr)
  - Effects due to a moon may be limited by host planet and stellar companion
  - **Habitability condition: planetary orbit must be near circular or moon is massive**
- Outward tidal migration limits the moon lifetime (Quarles 2021)
  - crossing SOR -> increase obliquity variation
  - Keeping a close-in, massive moon increase spin precession to avoid SOR
  - Low-mass moon takes too long to migrate, unless planetary eccentricity is high
  - High planetary eccentricity widens the HZ, but reduces the number of habitable planets (e.g., Kane & Torres 2017)



Quarles+ (2021)

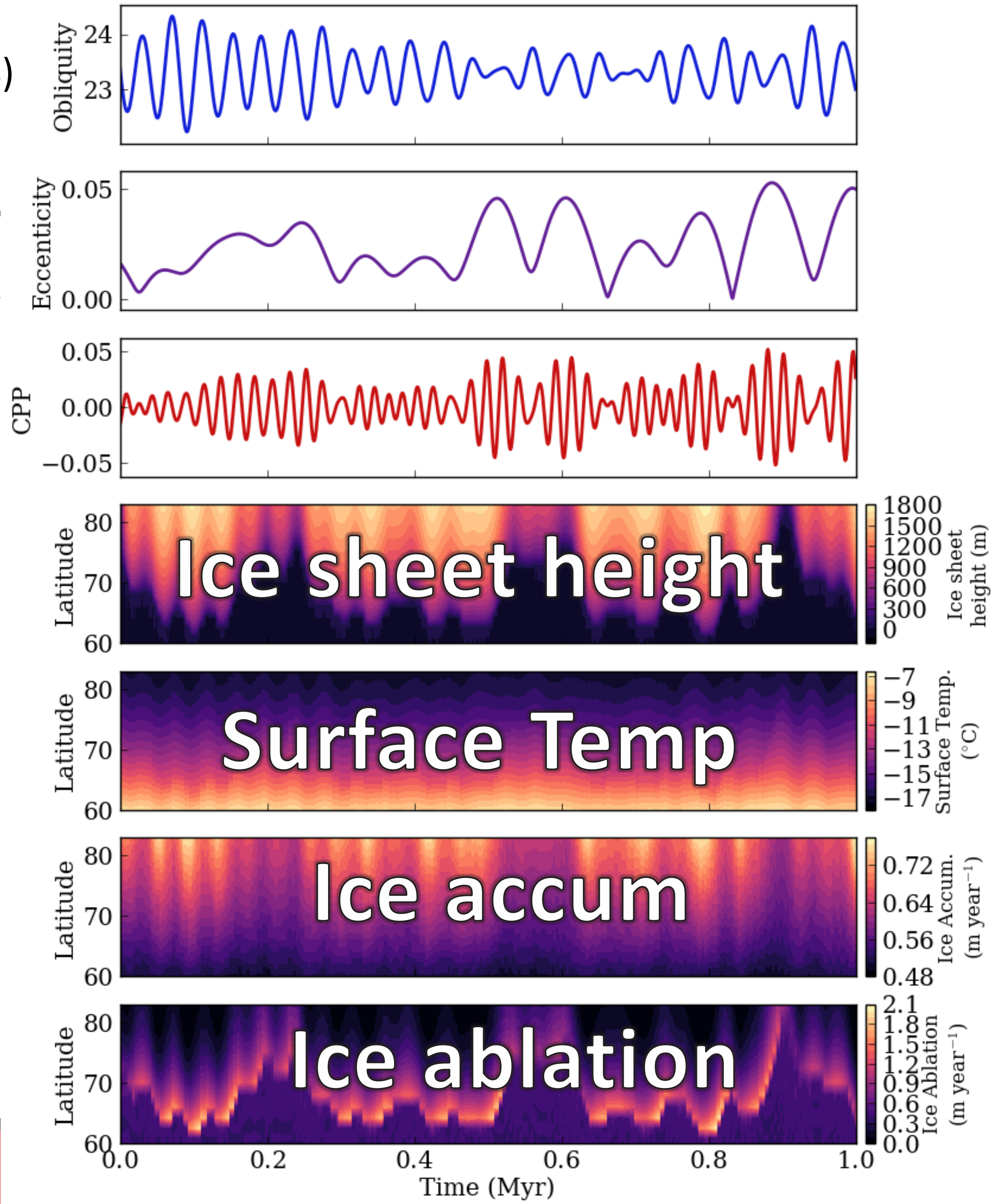
Insights from basic climate models

- Latitudinal Energy Balance Models (LEBMs) solve a heat equation distributed across latitudinal cells
  - Obliquity modifies the **distribution** of the input energy across latitudes
  - Stellar companion modifies the planetary eccentricity (**magnitude** of the input energy)
    - Host star modifies the obliquity; distribution is time-dependent
  - "Realistic" LEBM needs to account for these *time-dependent* variations

- **VPLanet** (Barnes+ 2020) has an LEBM (with land/water) but for a single star
  - Modify VPLanet to accept sampled parameters
  - Sample the radiative flux (N-body integration) and obliquity (secular integration)
  - Periodically solve for the equilibrium state for climate

Insights from basic clim

Deitrick+ (2018)



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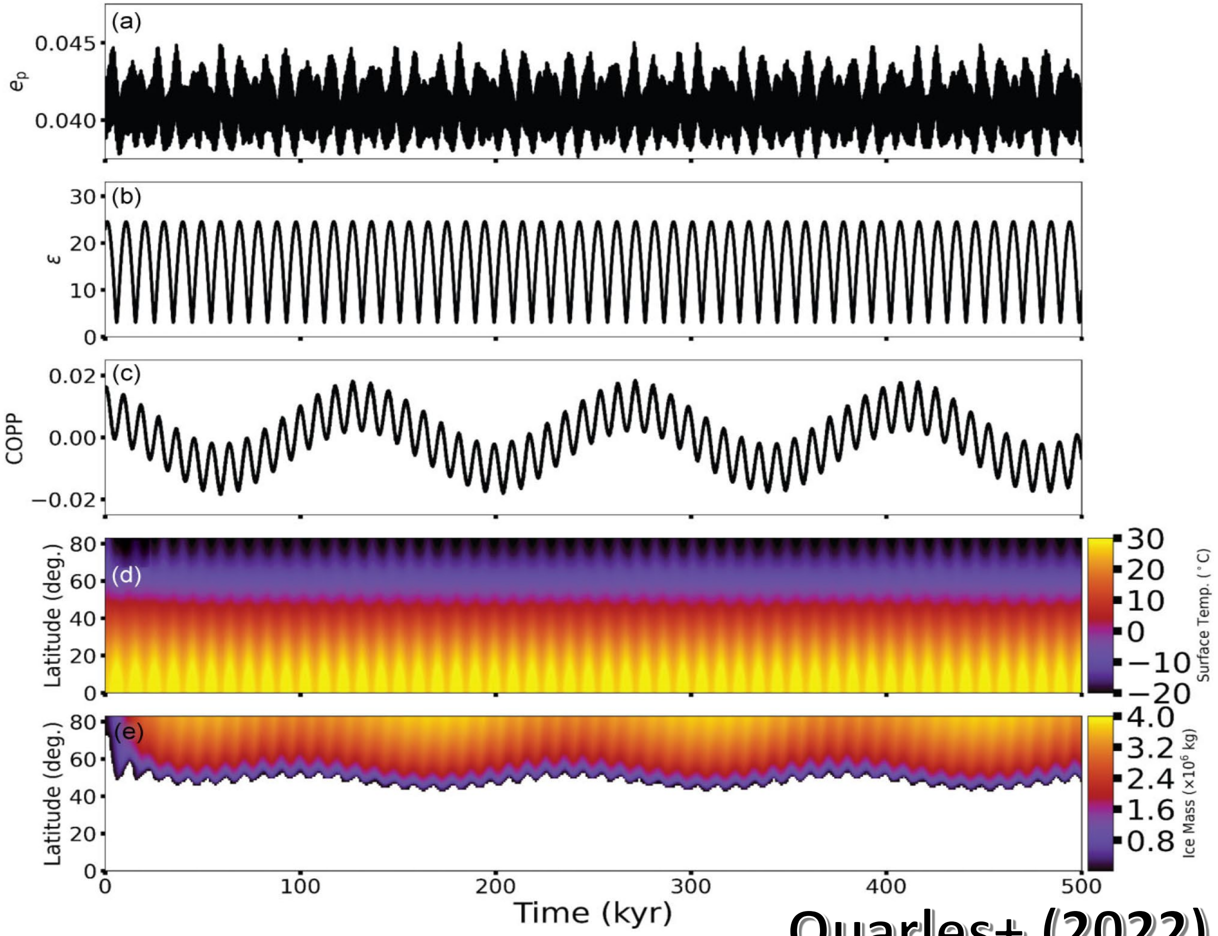
Conditions around Alpha Cen A

- Alpha Cen A is 1.5x brighter than the Sun
  - a_p is 1.23 AU; e_p is 0.045
- Spin-orbit coupling is strong
  - Obliquity variations follow axial precession
  - Regular variations (sinusoidal)
- Spin precession α and obliquity ε_o
  - High ε_o --> ice free states
  - Low ε_o --> ice caps that vary in extent
    - No ice belt or snowball (due to model simplicity)



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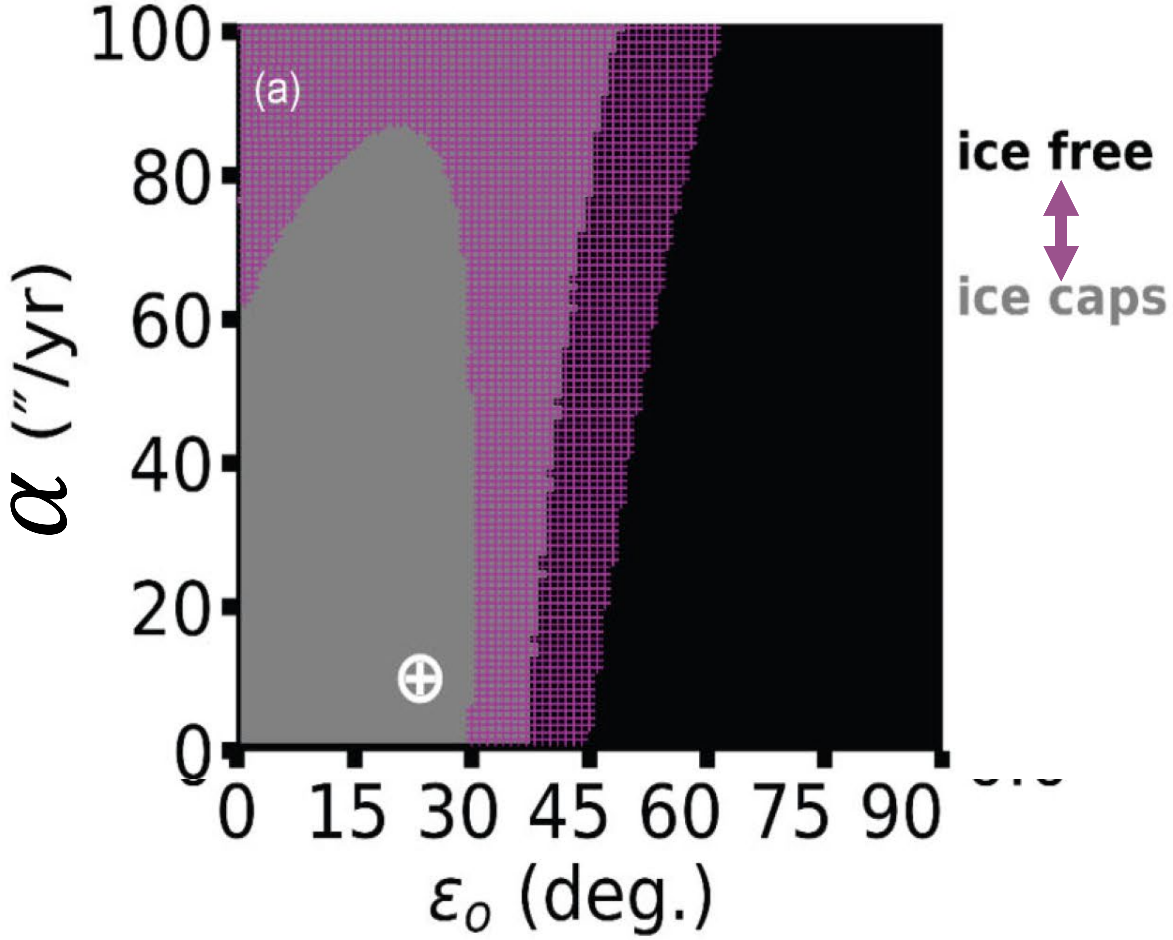
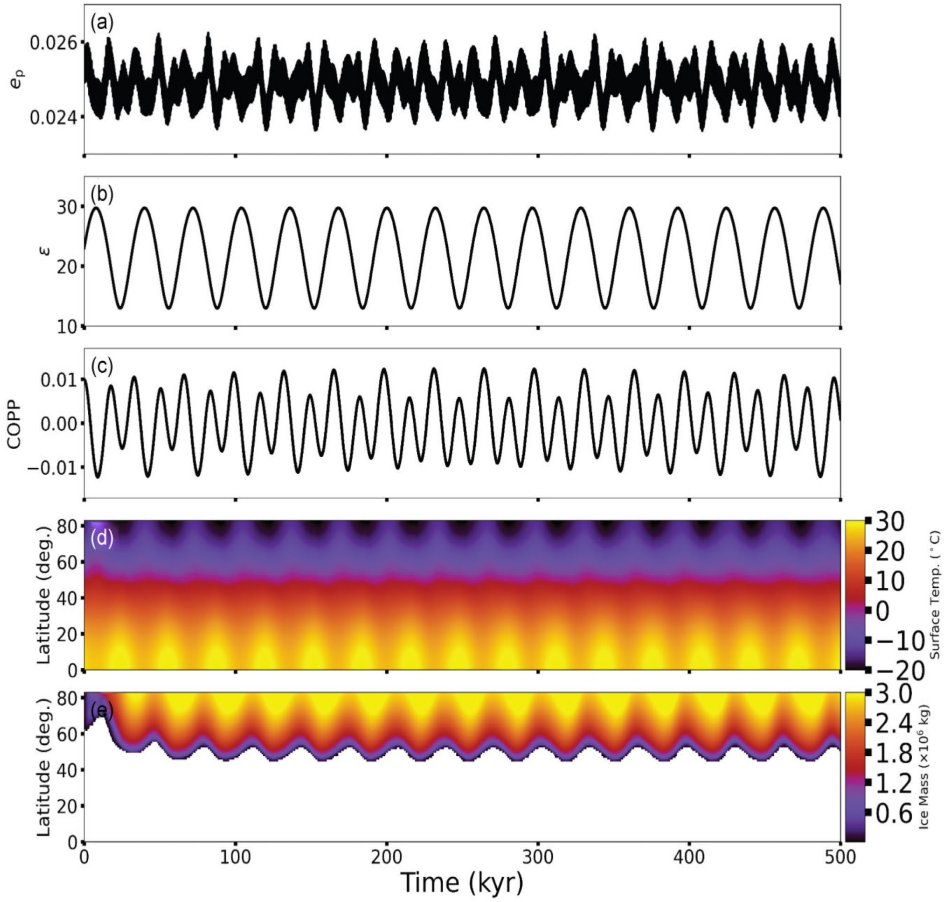


Conditions around Alpha Cen B

- Alpha Cen B is 0.5x as bright as the Sun
  - a_p is 0.707 AU; e_p is 0.025
- Spin-orbit coupling can be weak
  - Leads to large obliquity variations
- Spin precession α and obliquity ε_o
  - High ε_o --> ice belt or snowball
  - Low ε_o --> ice caps that vary in extent
- Increasing i_p --> increases types of states
  - Mixture of states, ice belts (e.g., Rose 2017, Kilic+ 2018) at lower ε_o



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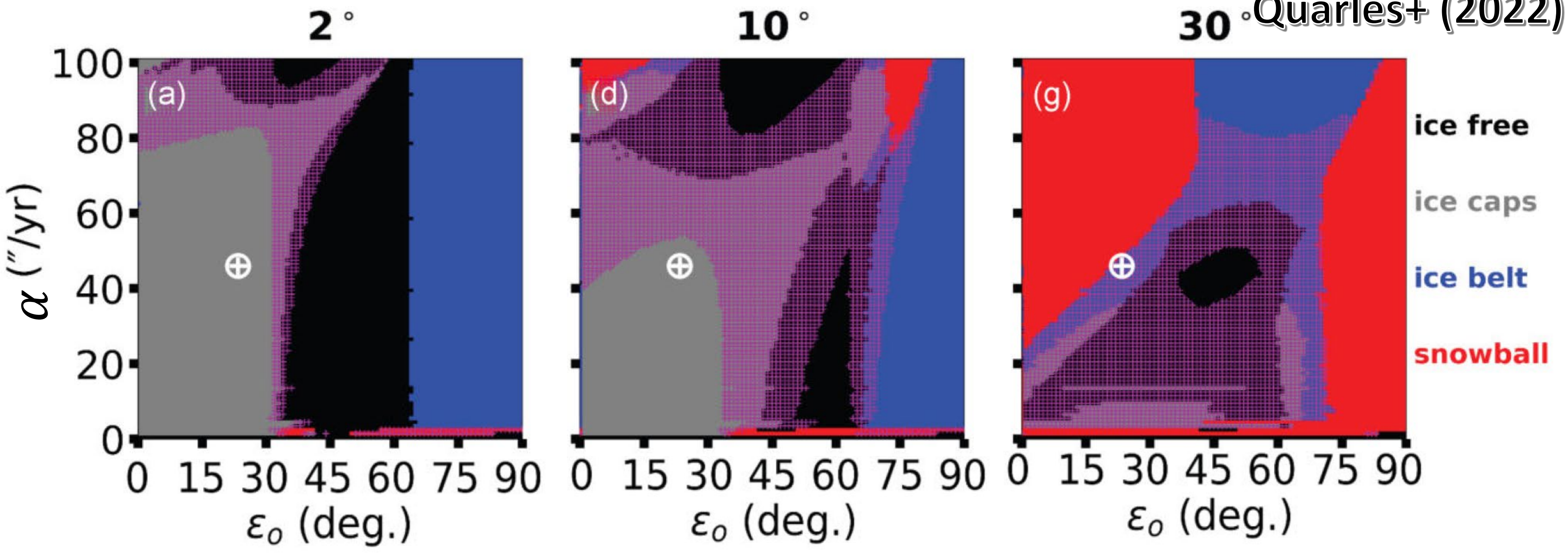
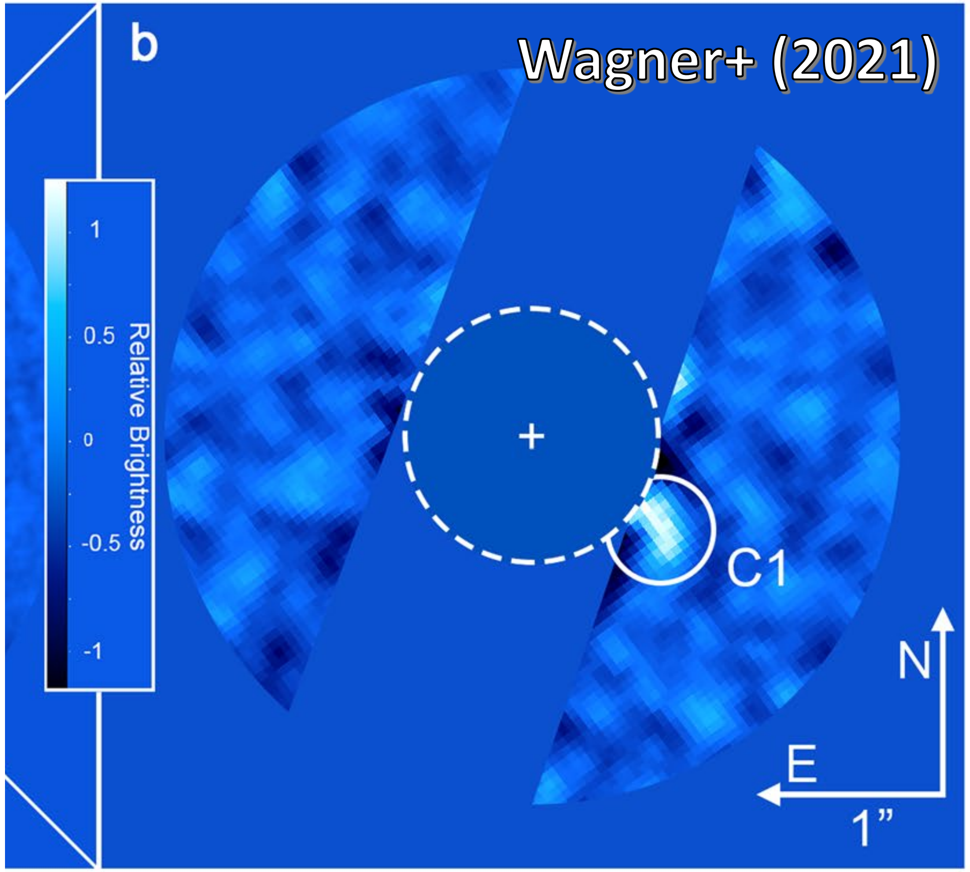
Quarles+ (2022)



Prospects from the ground & JWST

- NEAR campaign using VLT discovers a planet candidate near α Cen A (Wagner+ 2021)
  - Neptune-Saturn sized planet @ $\sim$1.5 AU
  - Implications for habitability -> astrodynamics will be critical
  - Outer planet excludes a range of orbits inward -> only Venus-analogs?
- JWST observations of α Cen A (Beichman+ 2020)
  - Push to smaller planet sizes ($\sim 5\ M_{\oplus}$)
  - Stack potentially stable orbits, bin on overlap region
  - (dis)confirmation of Wagner+ candidate
- Discovery or not: gain information for potential habitablity



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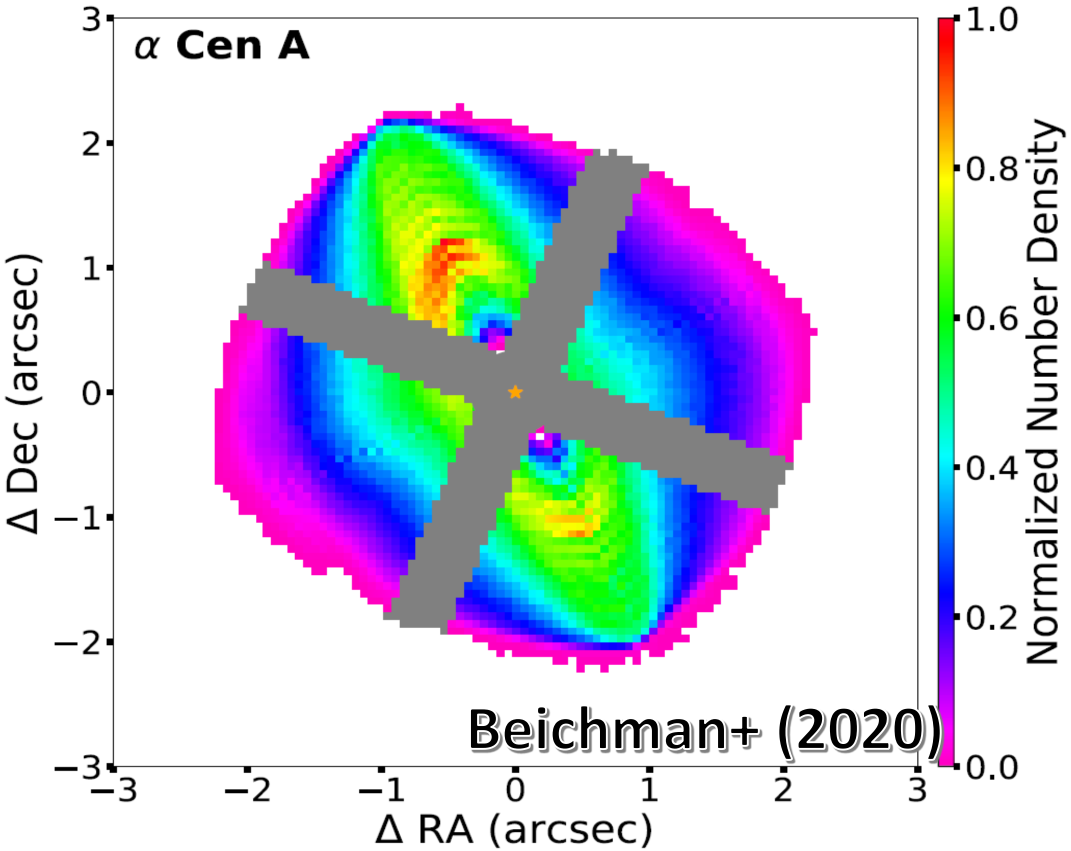

Summary

- Defining a habitable planet carries some **assumptions**
  - Practical definition--> Earth-like planet in a low eccentricity orbit around a star with a moderately varying obliquity
  - Dynamical constraints in a binary like α Cen AB
    - **Forced eccentricity** leads to a widening of the habitable zone
    - Many channels to exchange energy and/or angular momentum to affect **orbital stability**
    - **Spin-orbit interactions** important for a planet orbiting α Cen B
  - Climate model affected by dynamical constraints; especially for inclined orbits
  - Future (non)detections focusing on α Cen A help us better define *habitability as capacity using astrodynamics*

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