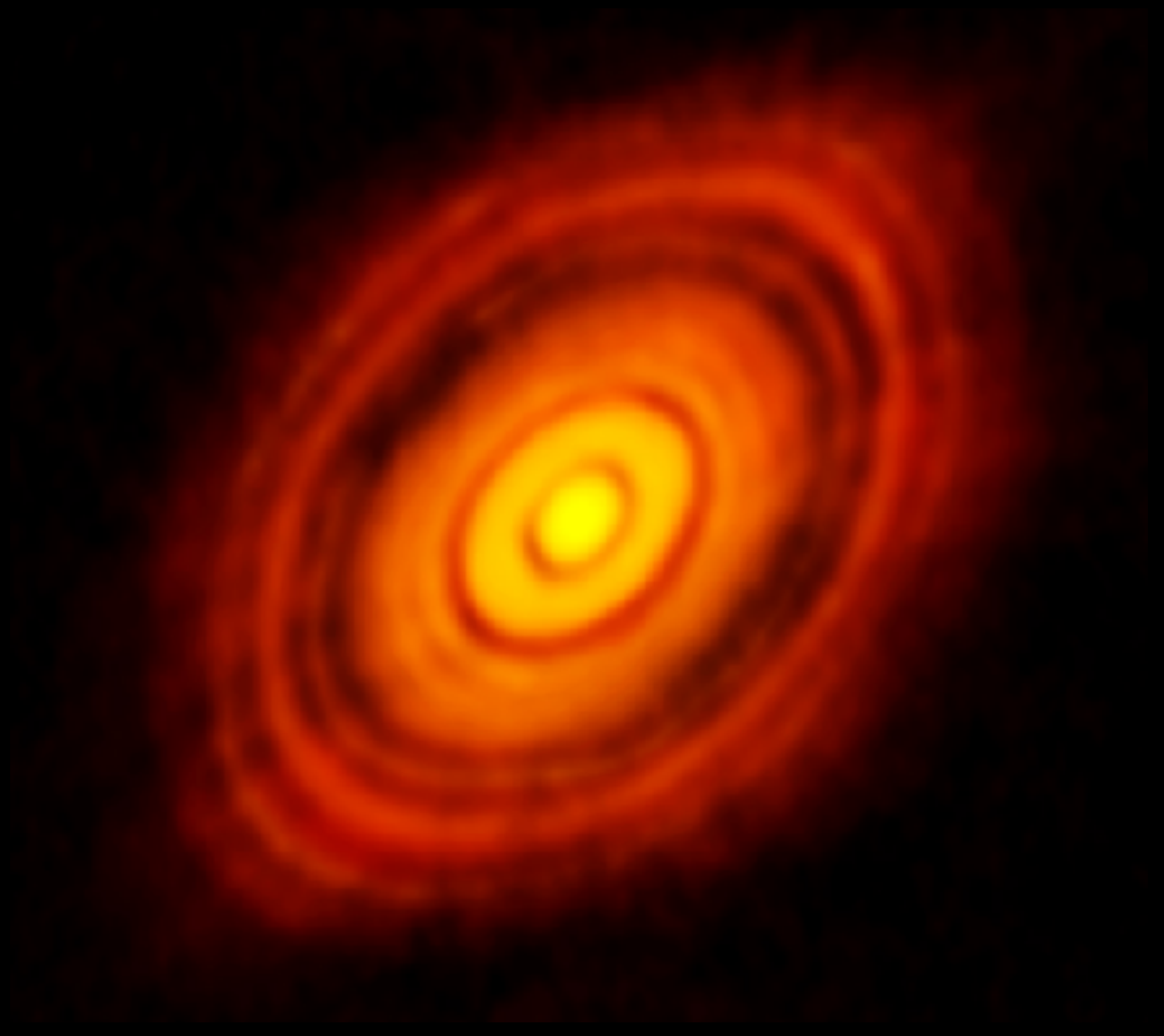
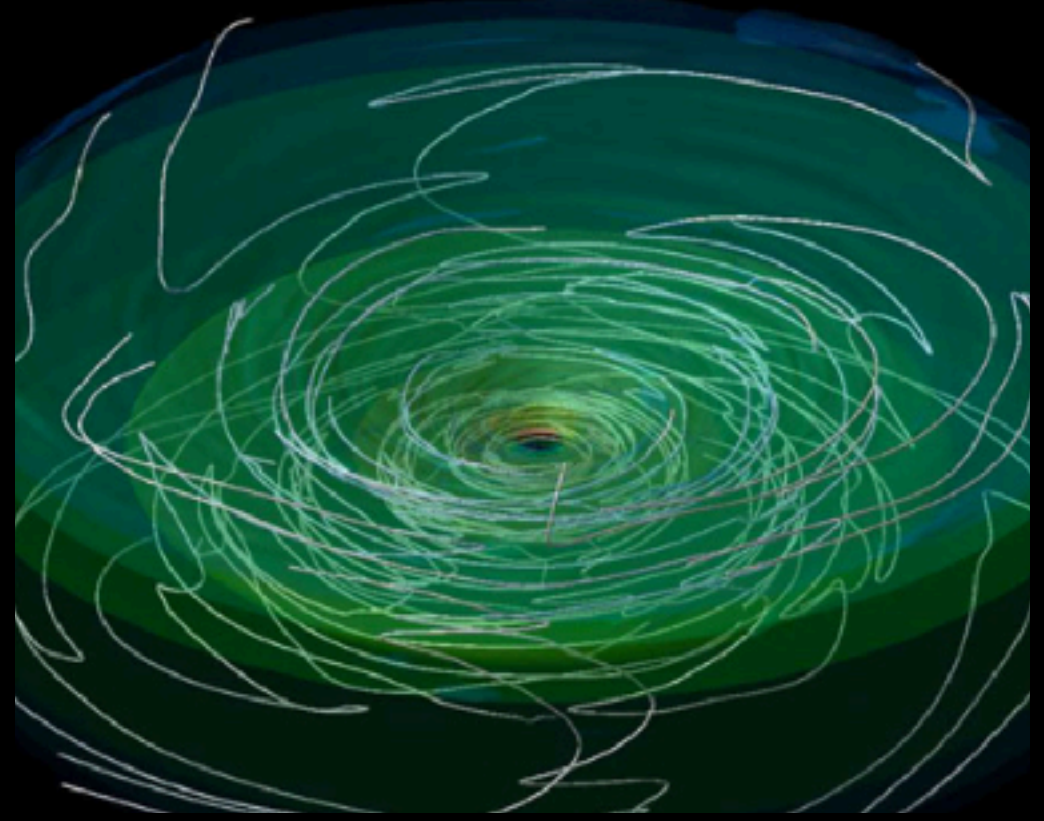
Protoplanetary Disk Evolution and Planet Formation:
A Latest View from Disk Magnetohydrodynamics





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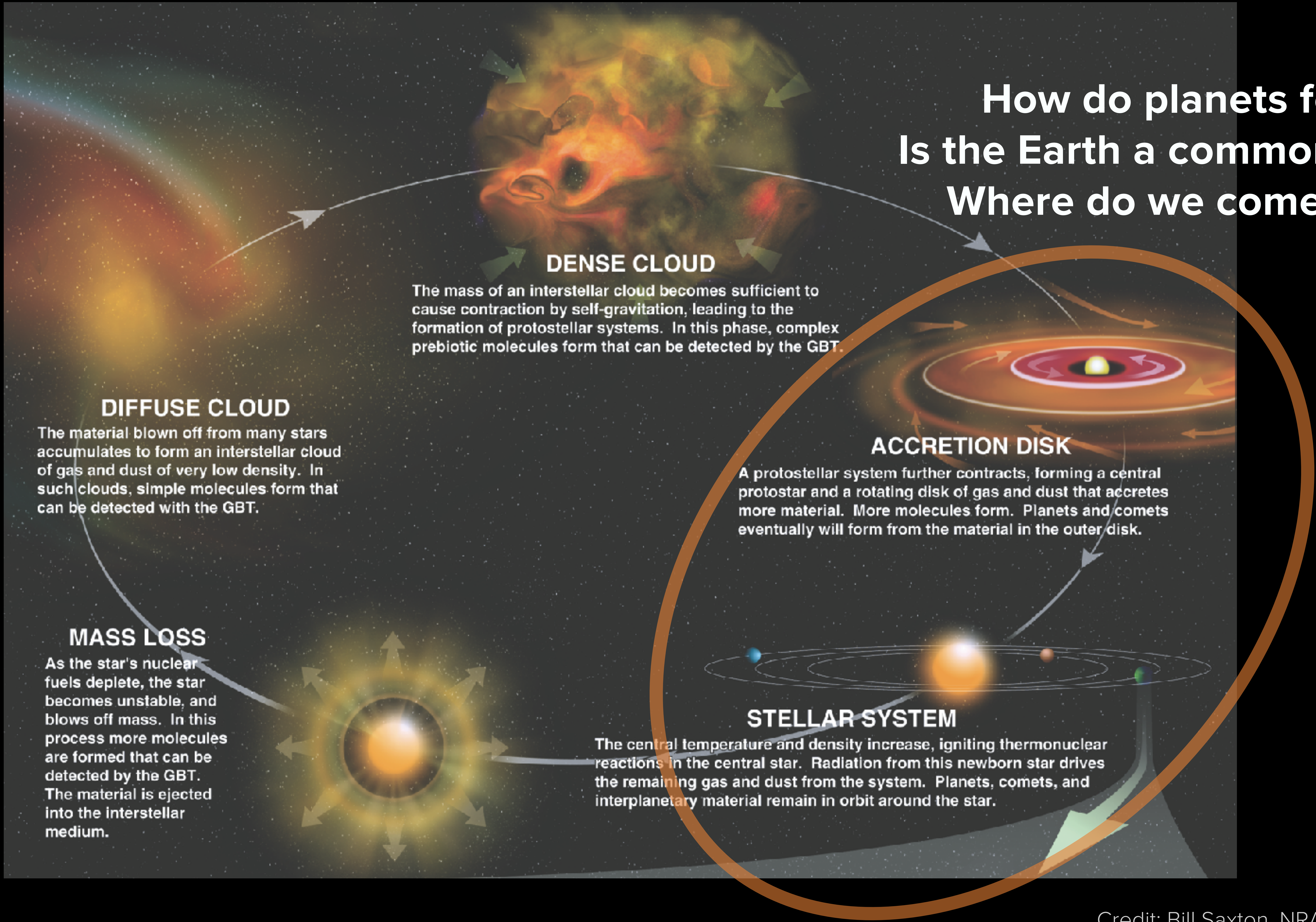
Tokyo Tech

Image credits (from left to right): ALMA Partnership et al. (2015); Suzuki & Inutsuka (2014); A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO); ISAS/JAXA

How do planets form?
Is the Earth a common planet?
Where do we come from?



Credit: Bill Saxton, NRAO/AUI/NSF

Planet Formation: From Dust to Planets

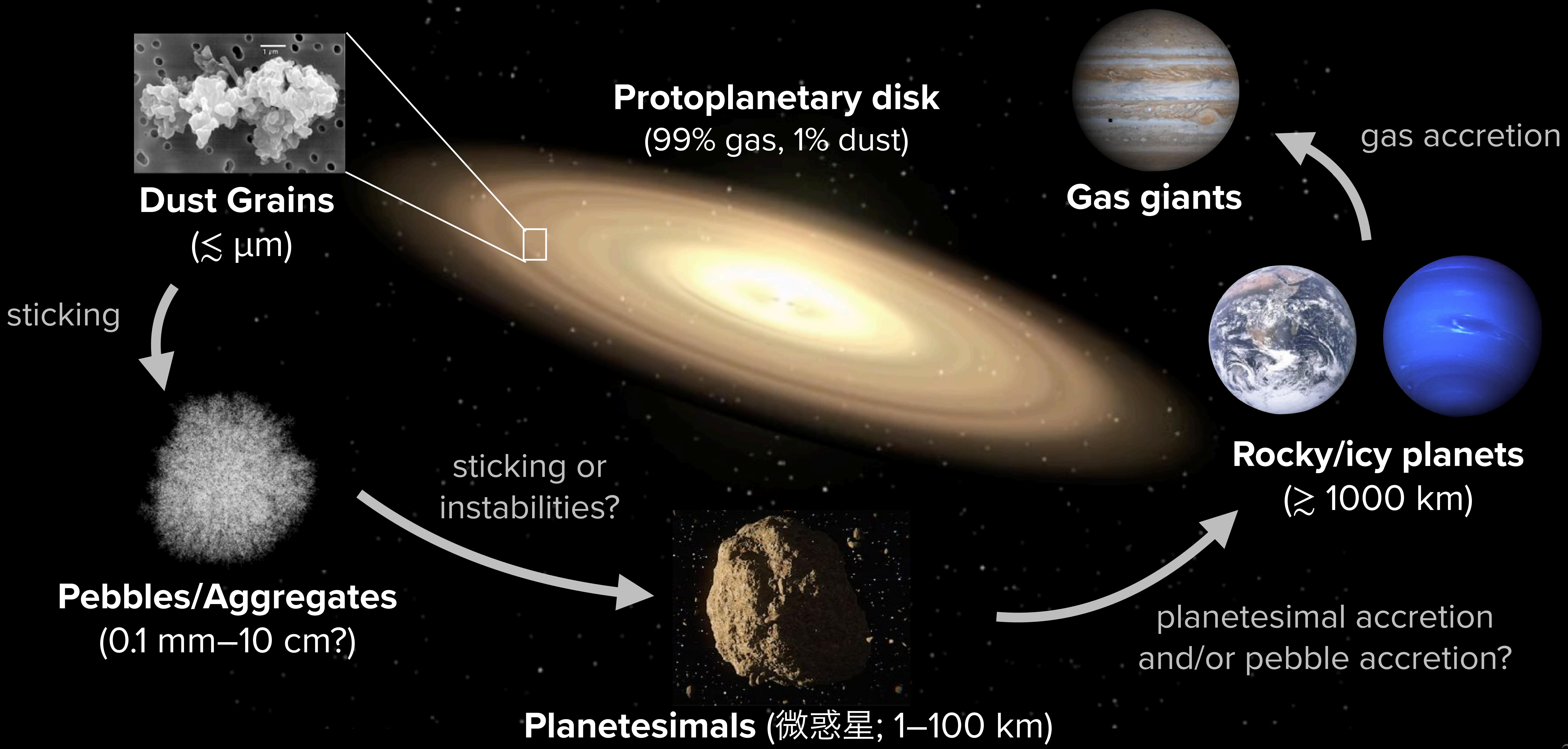
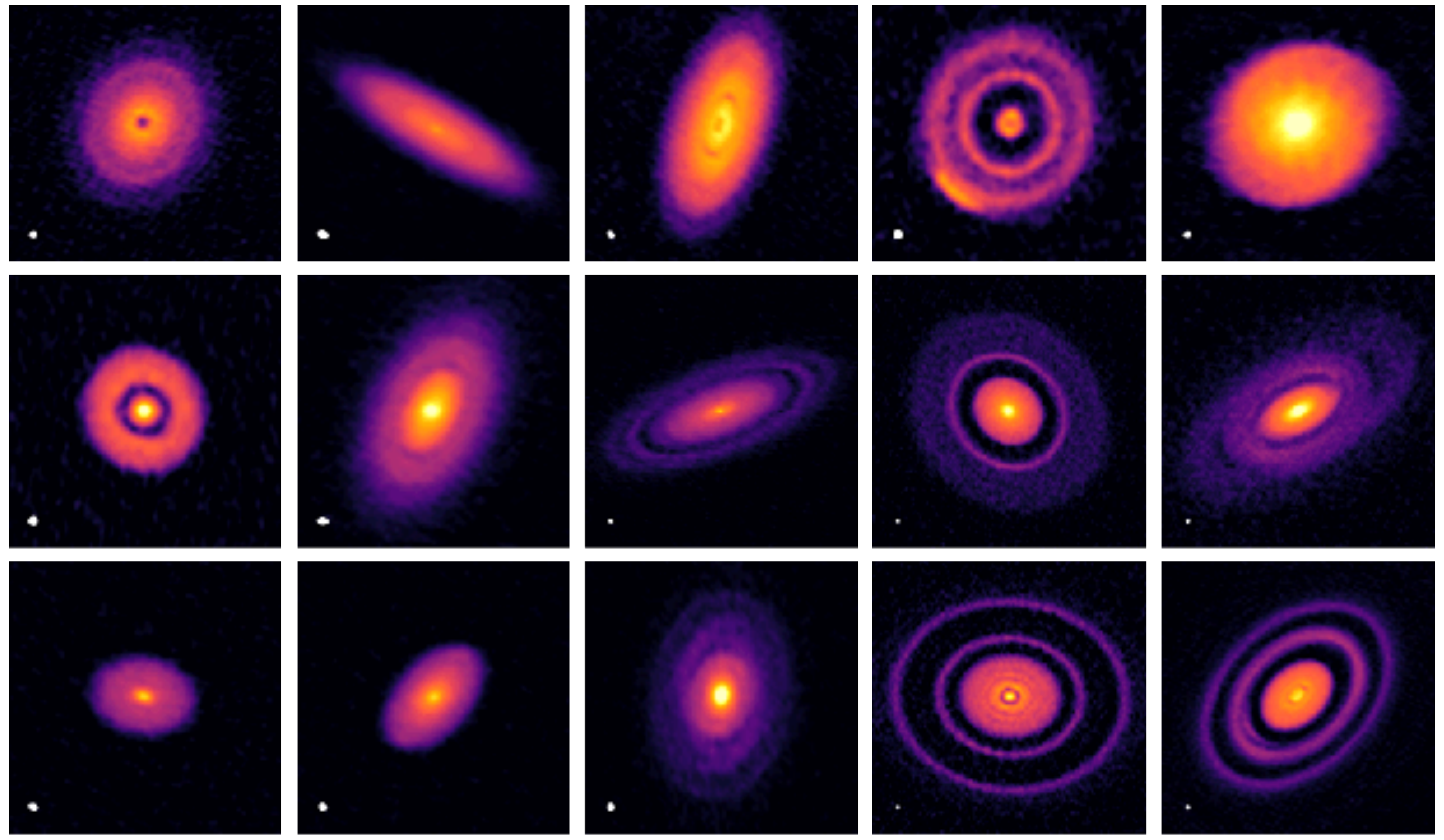


Image credit: NASA/JPL-Caltech

Hot Topics in Planet Formation

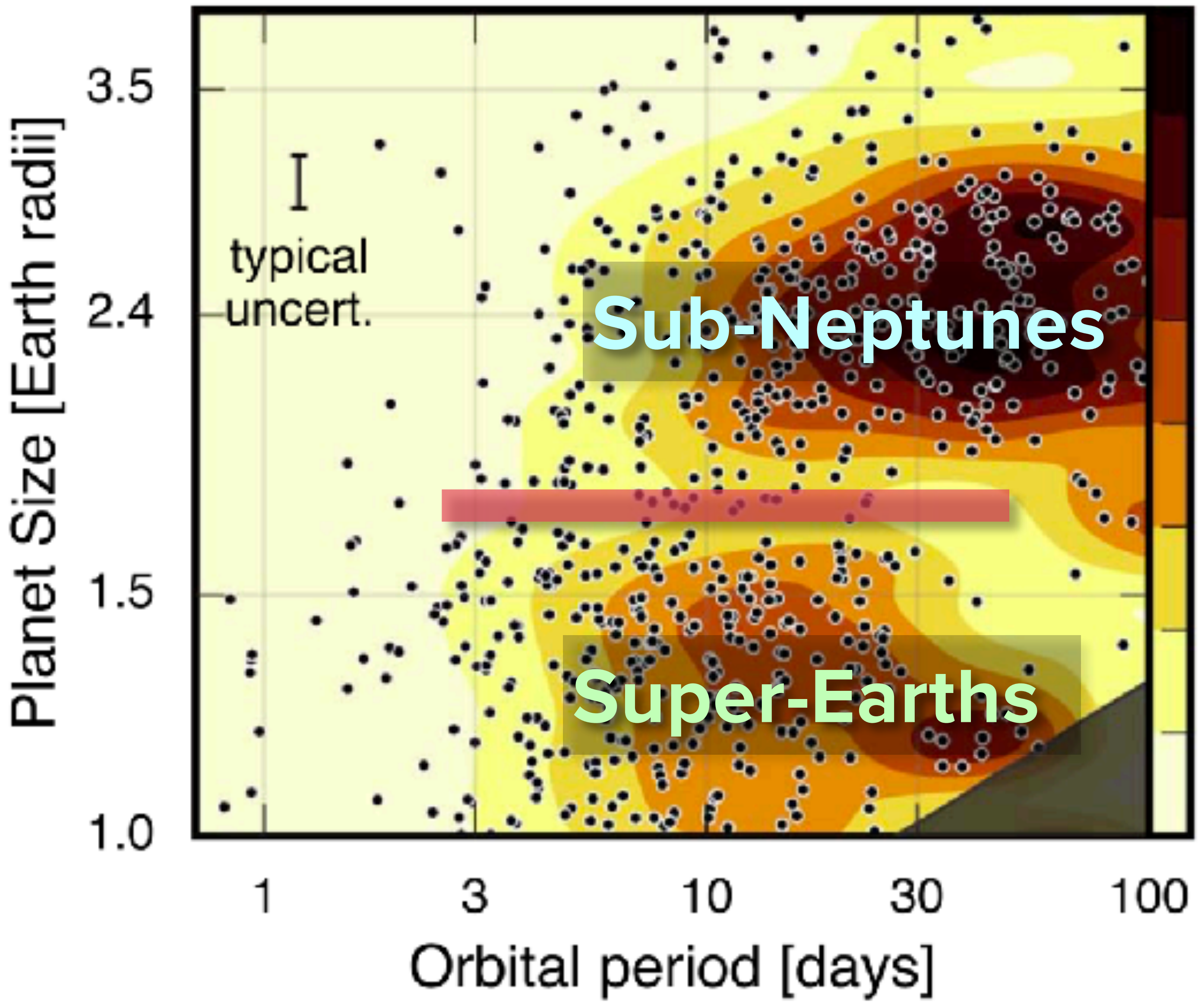
参考：日本惑星科学会誌「遊星人」
特集「新・惑星形成論」
リンク集: satoshiokuzumi.net/yuseijin

Disk Substructures



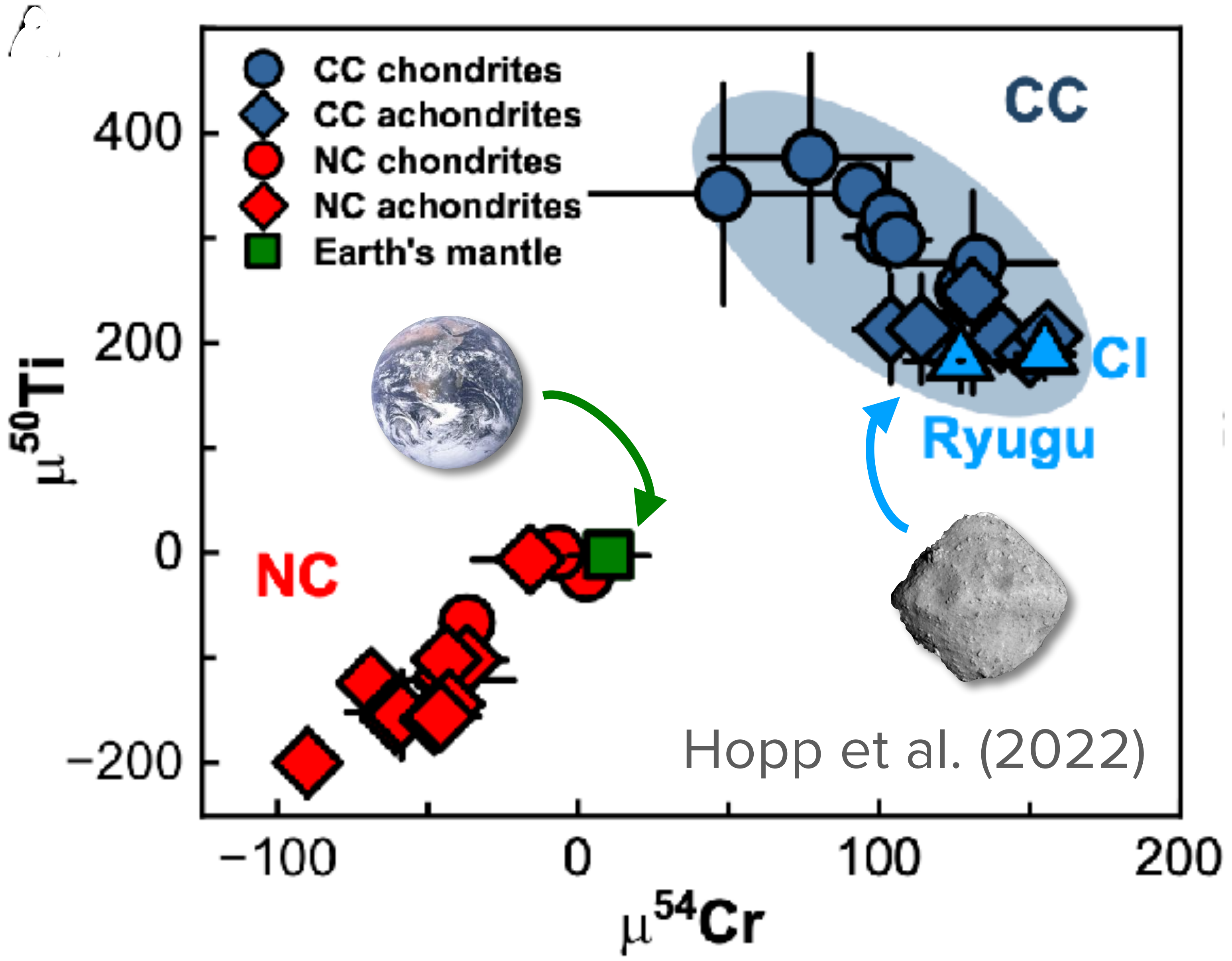
Andrews et al. (2018)

The Planet Radius Gap



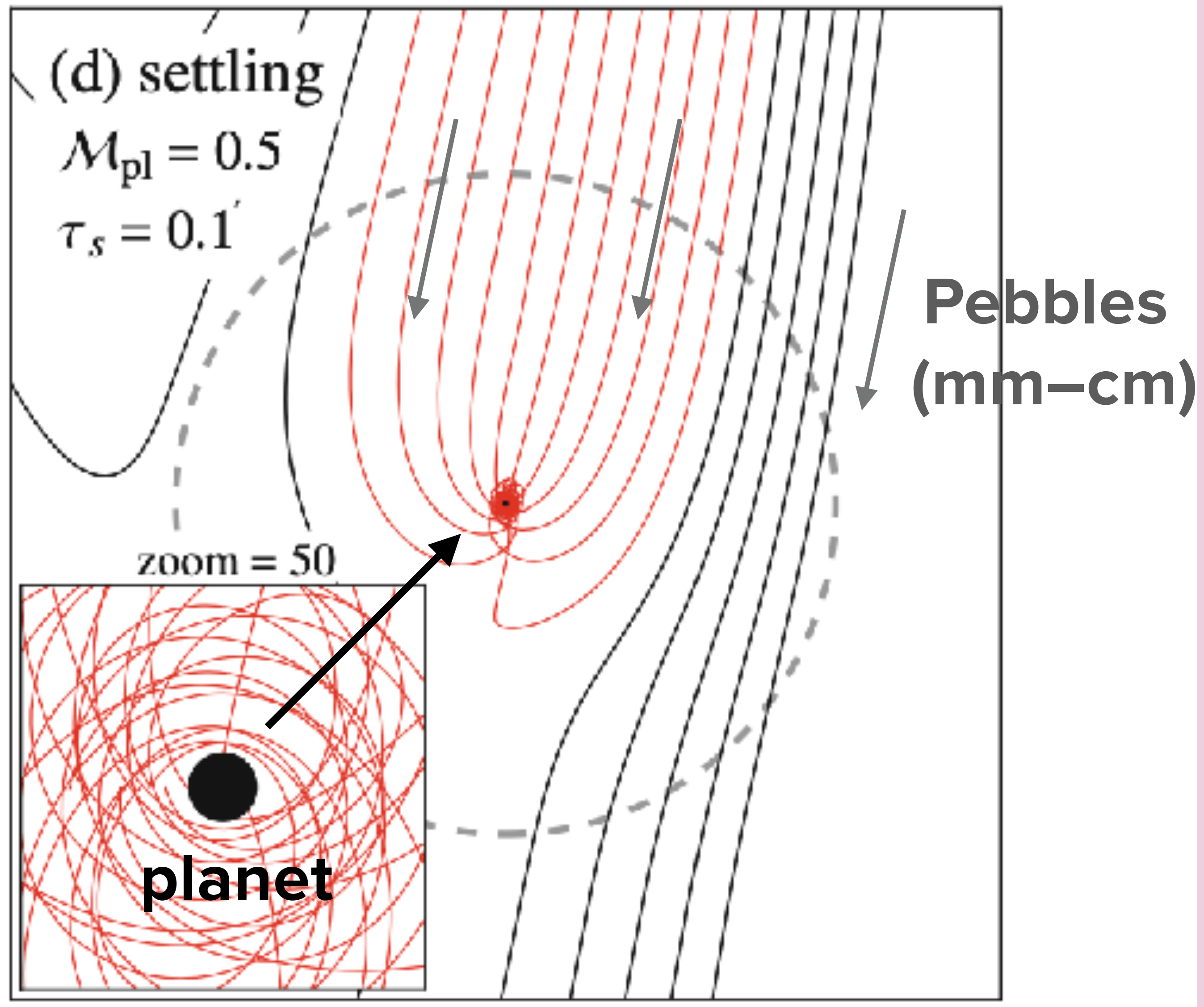
Fulton & Petigura (2018)

Isotopic Dichotomy (同位体二分性) of the Solar System



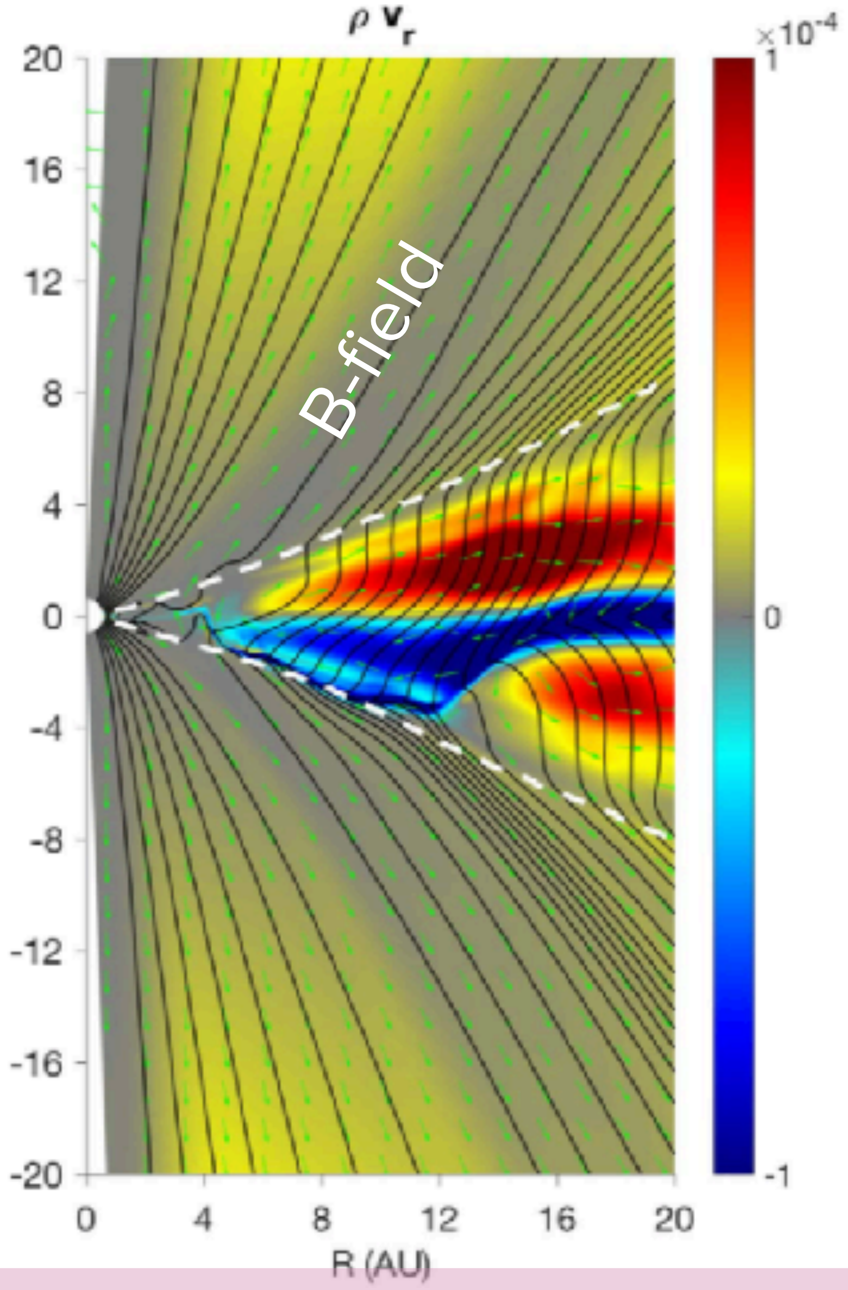
Hopp et al. (2022)

Pebble Accretion



Ormel (2017)

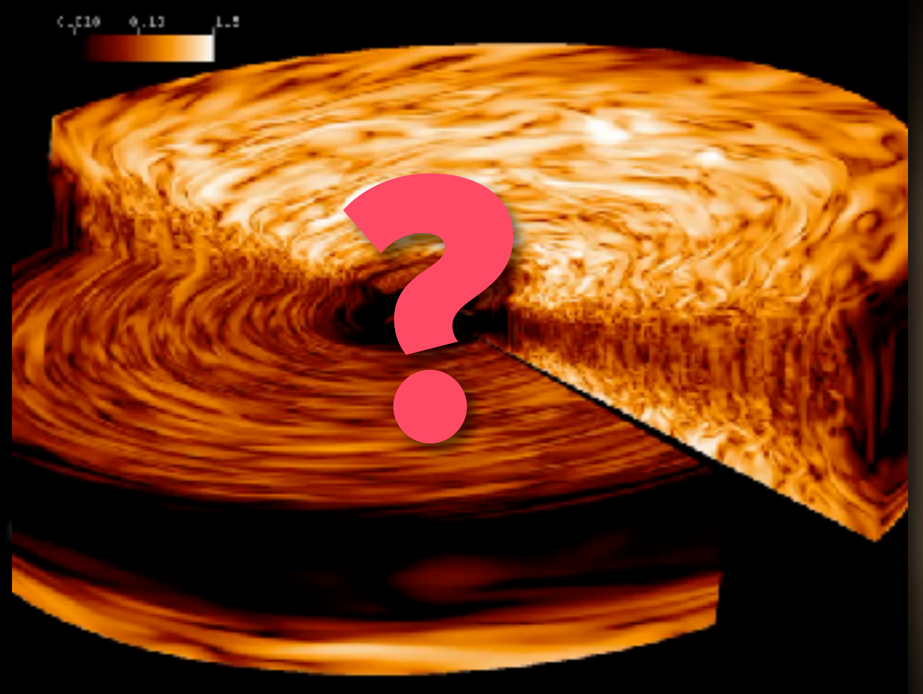
Laminar (Wind-driven) Disk Accretion



Bai (2017)

Protoplanetary Disk Dynamics: Why Does it Matter?

Disk turbulence



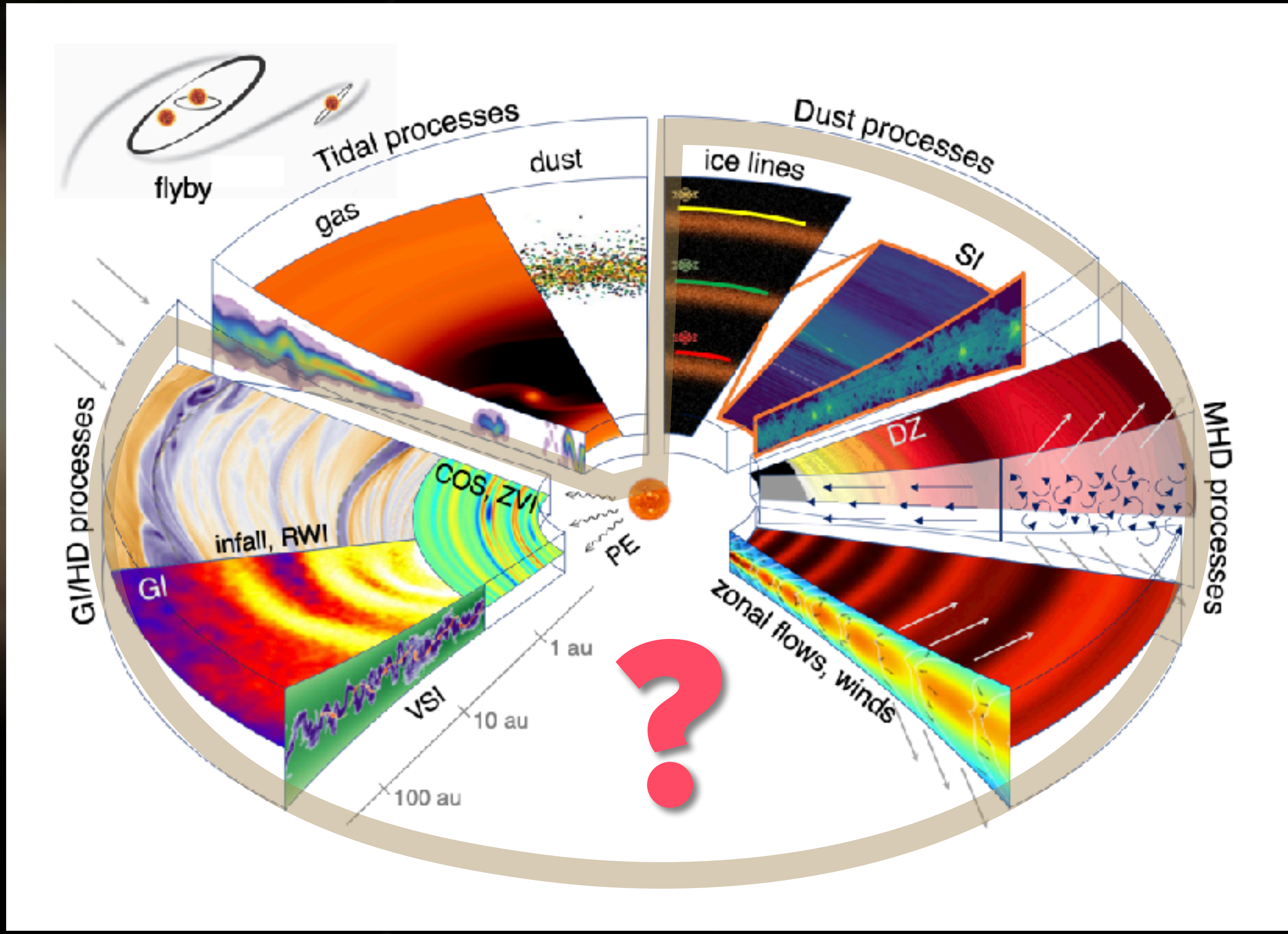
Flock et al. (2011)

Courtesy: 4D2U Project, NAOJ

Disk heating

Credit: A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)

Possible origins of gas/dust substructures



Bae et al. (2023) PPVII Review Chapter 12
(arXiv:2210.13314)

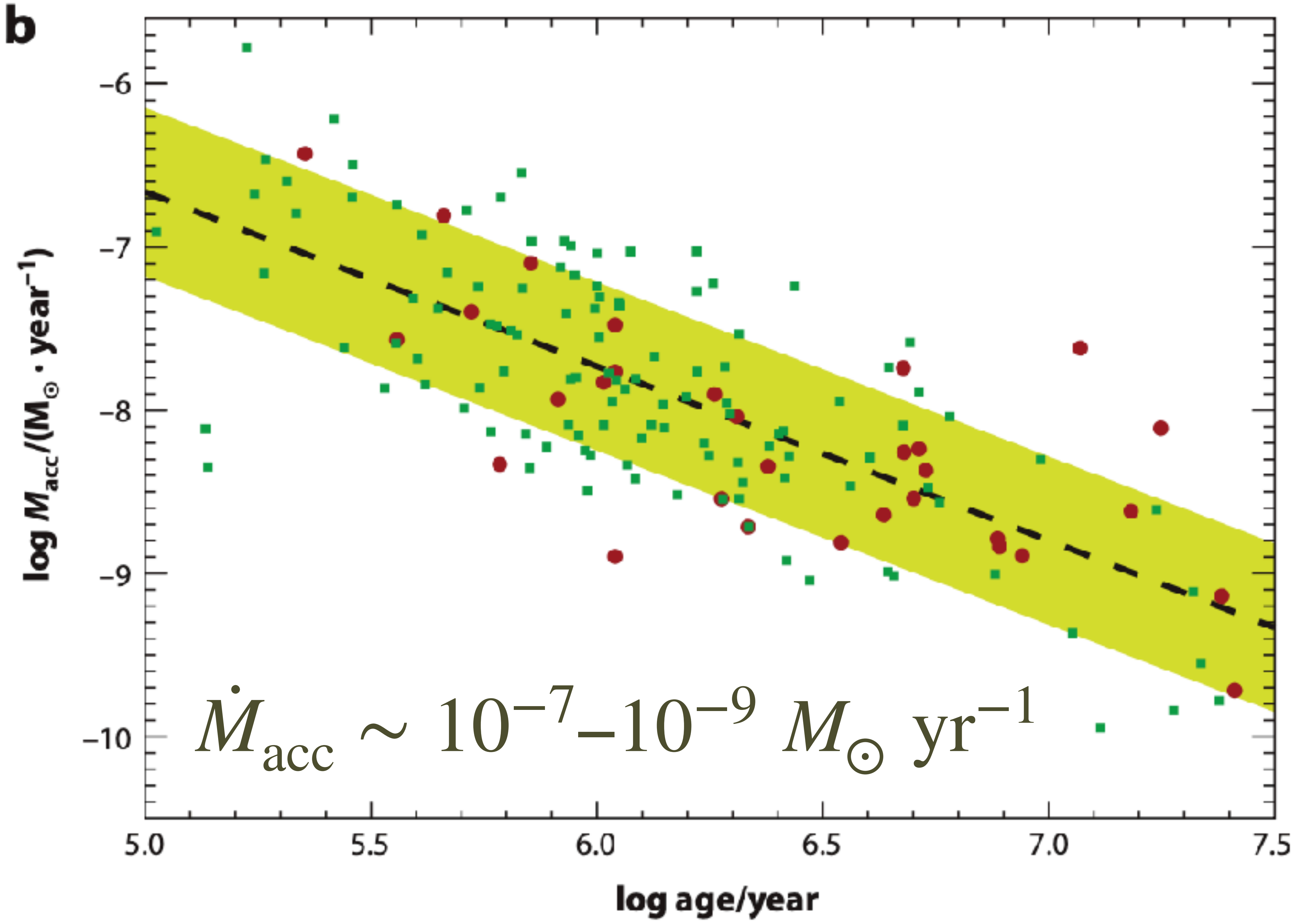
Protoplanetary Disk Dynamics: Why Does it Matter?

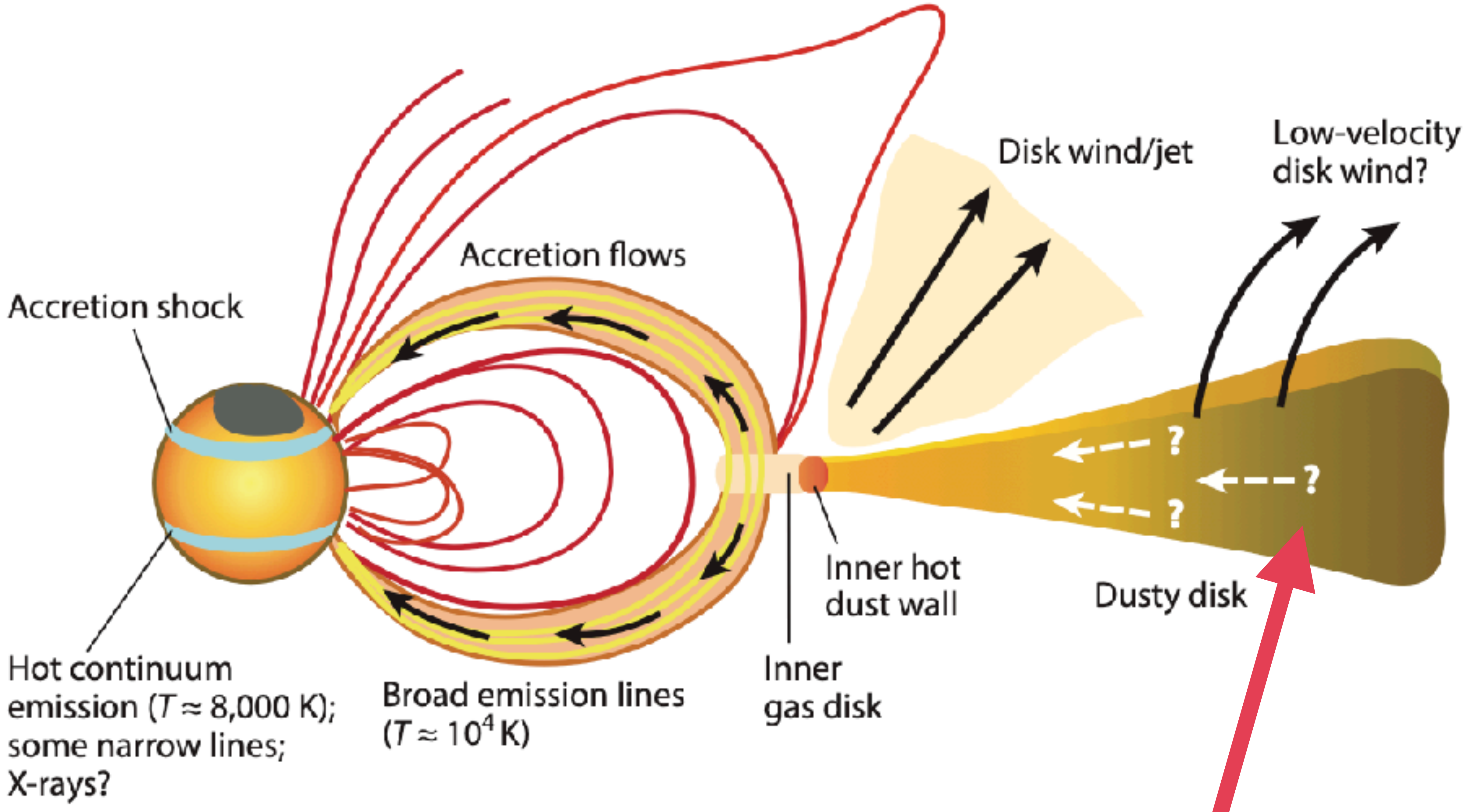
Topics covered in this talk:

- 🌬️ What drives the accretion of protoplanetary disks? Turbulence or magnetic fields?
- ☃️ How does the snow line migrate in the disks?
- 🧭 How strong is the magnetic field in the disks?

Accretion onto Young Stars from their Disks

Accretion rates vs. ages of young stars



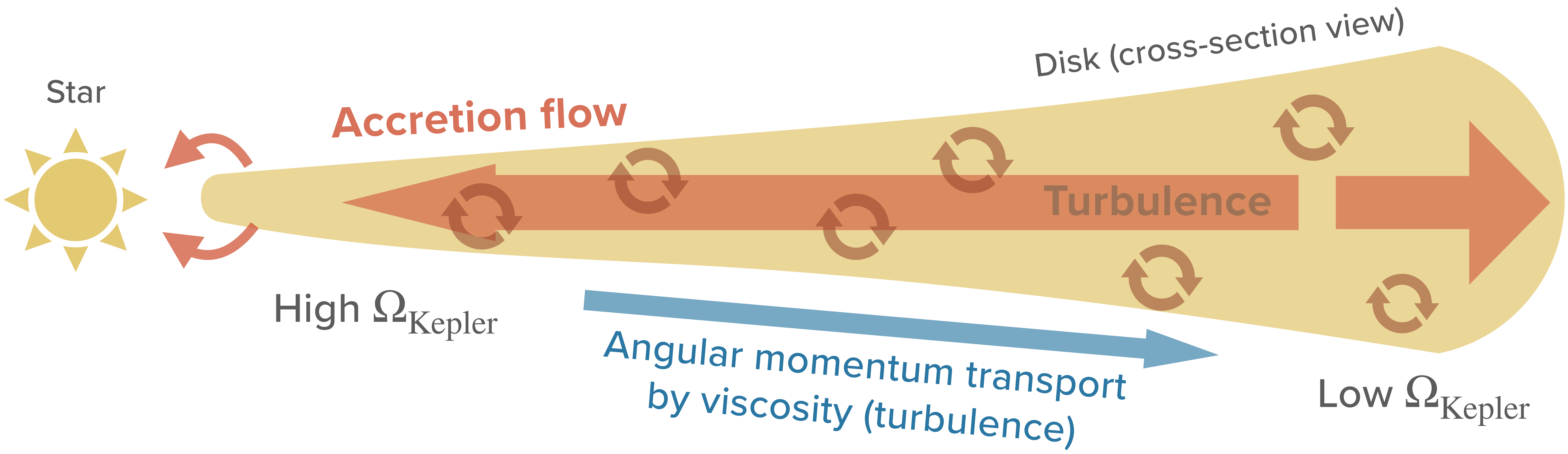


What is the origin of disk accretion?
What happens in the disks?

Hartmann et al. (2016)

Classic Model: “Viscous” Accretion Disks

Lynden-Bell & Pringle (1974)



Problem

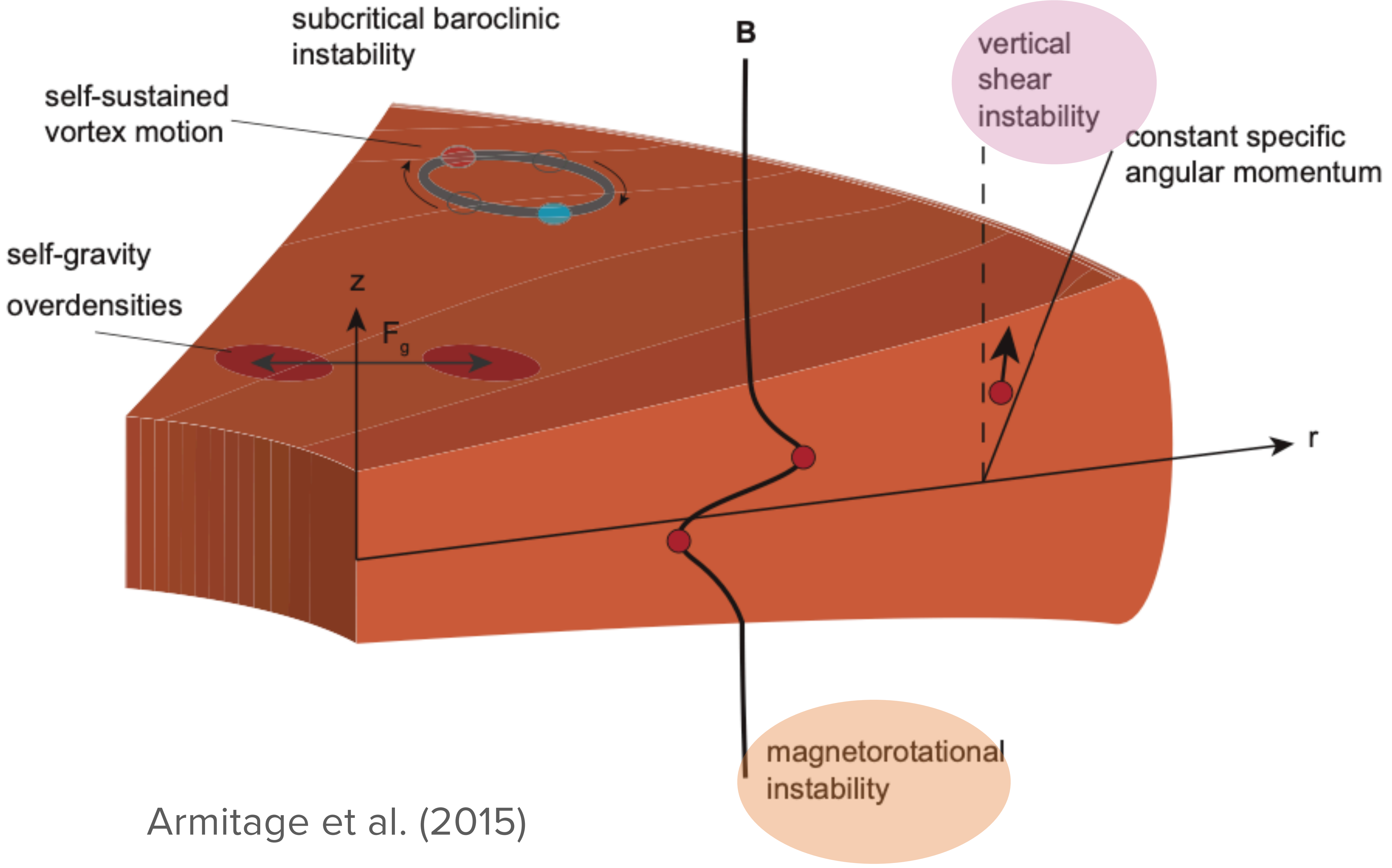
The origin and nature of disk turbulence are unknown!

➜ Assume turbulent viscosity = α × sound speed × disk thickness

In many cases, α is assumed to be constant both in space and in time.

Possible Drivers of Protoplanetary Disk Turbulence

Magnetic field



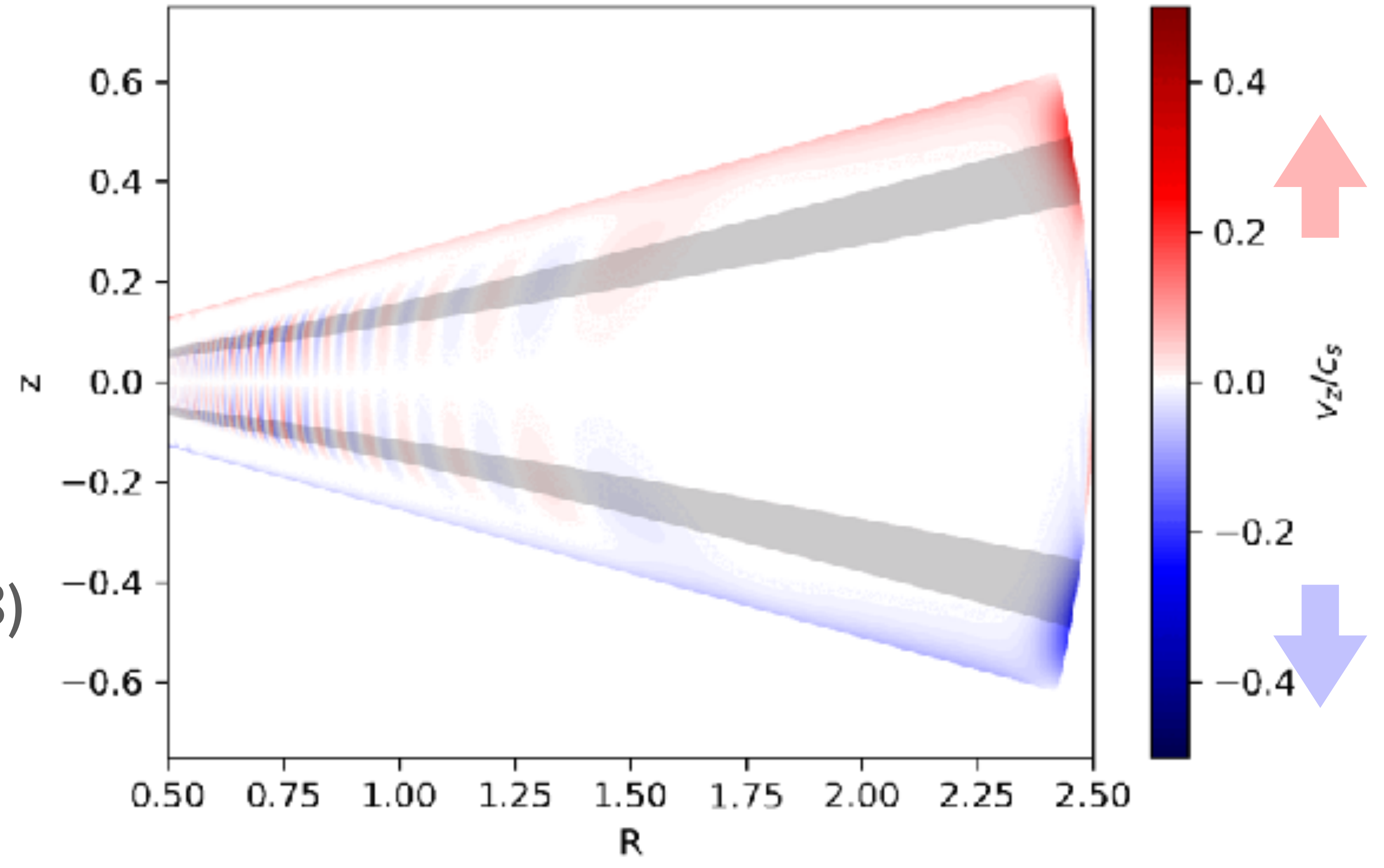
Armitage et al. (2015)

VSI

Requires
fast cooling

e.g.,
Urpin & Brandenburg (1998)
Nelson et al. (2013)

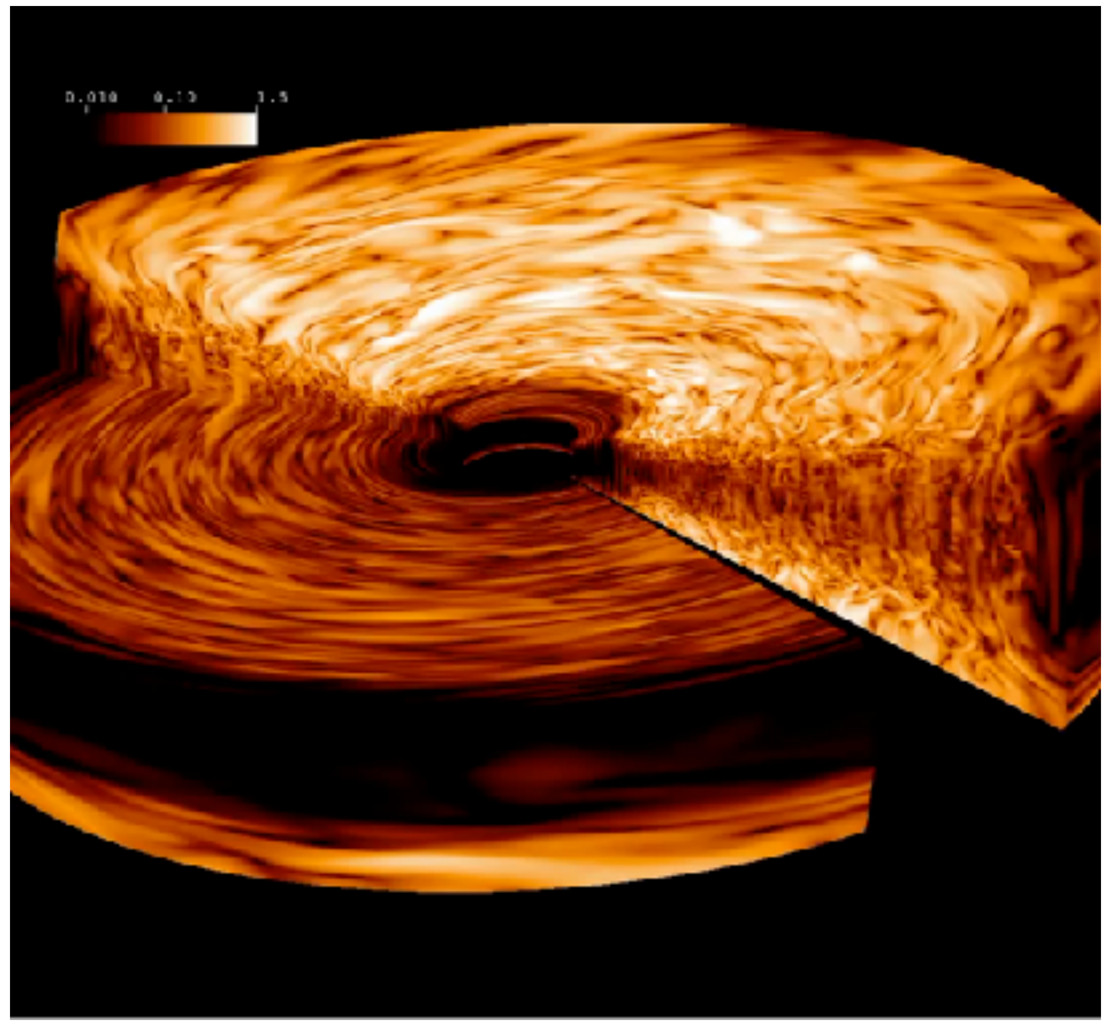
Credit: Y. Fukuhara (Tokyo Tech)



MRI

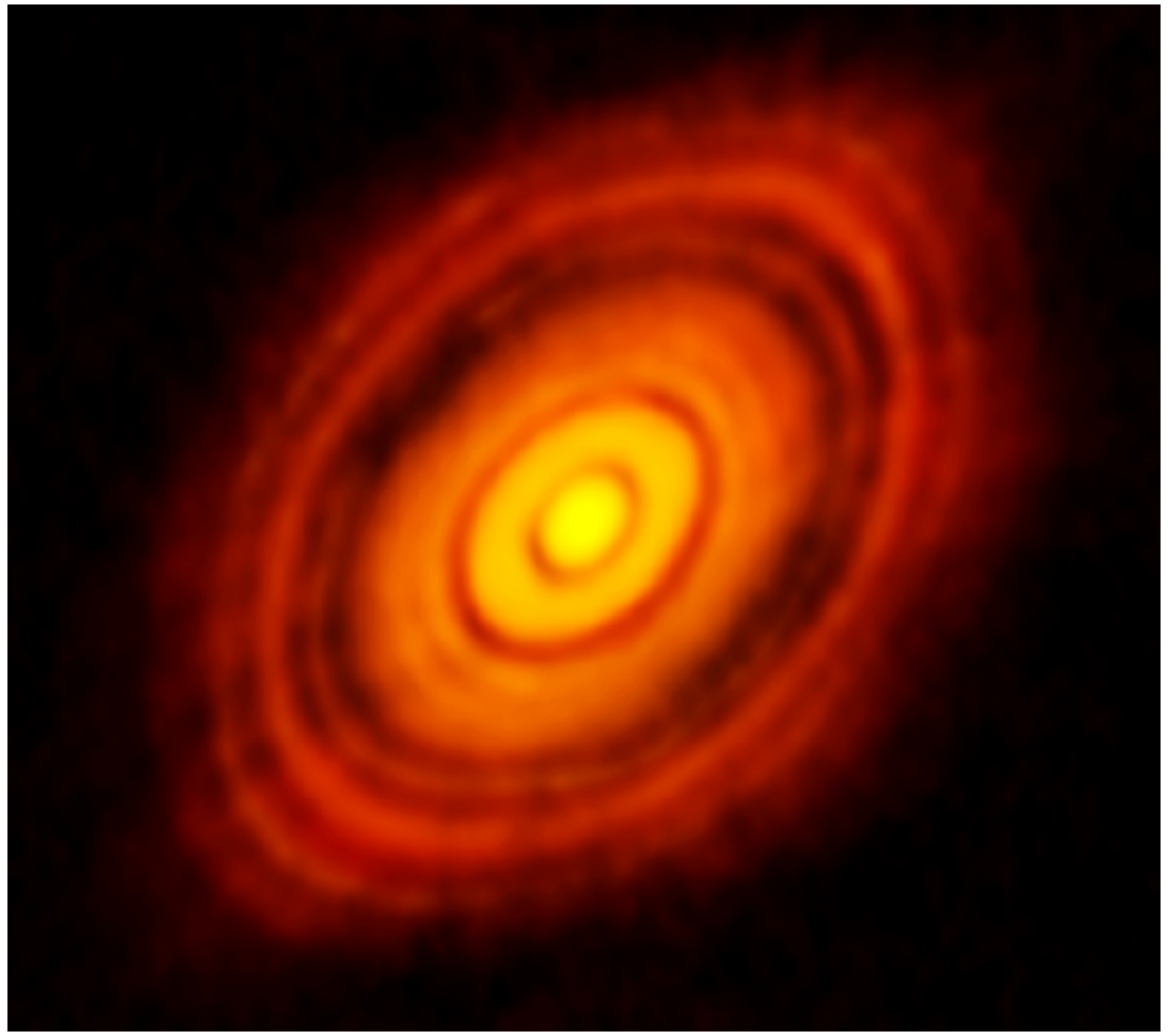
Requires
suficient ionization
(e.g., T $\gtrsim$ 1000 K)

e.g.,
Balbus & Hawley (1991)
Bai (2011)



Flock et al. (2011)

Are Protoplanetary Disks Really Turbulent??

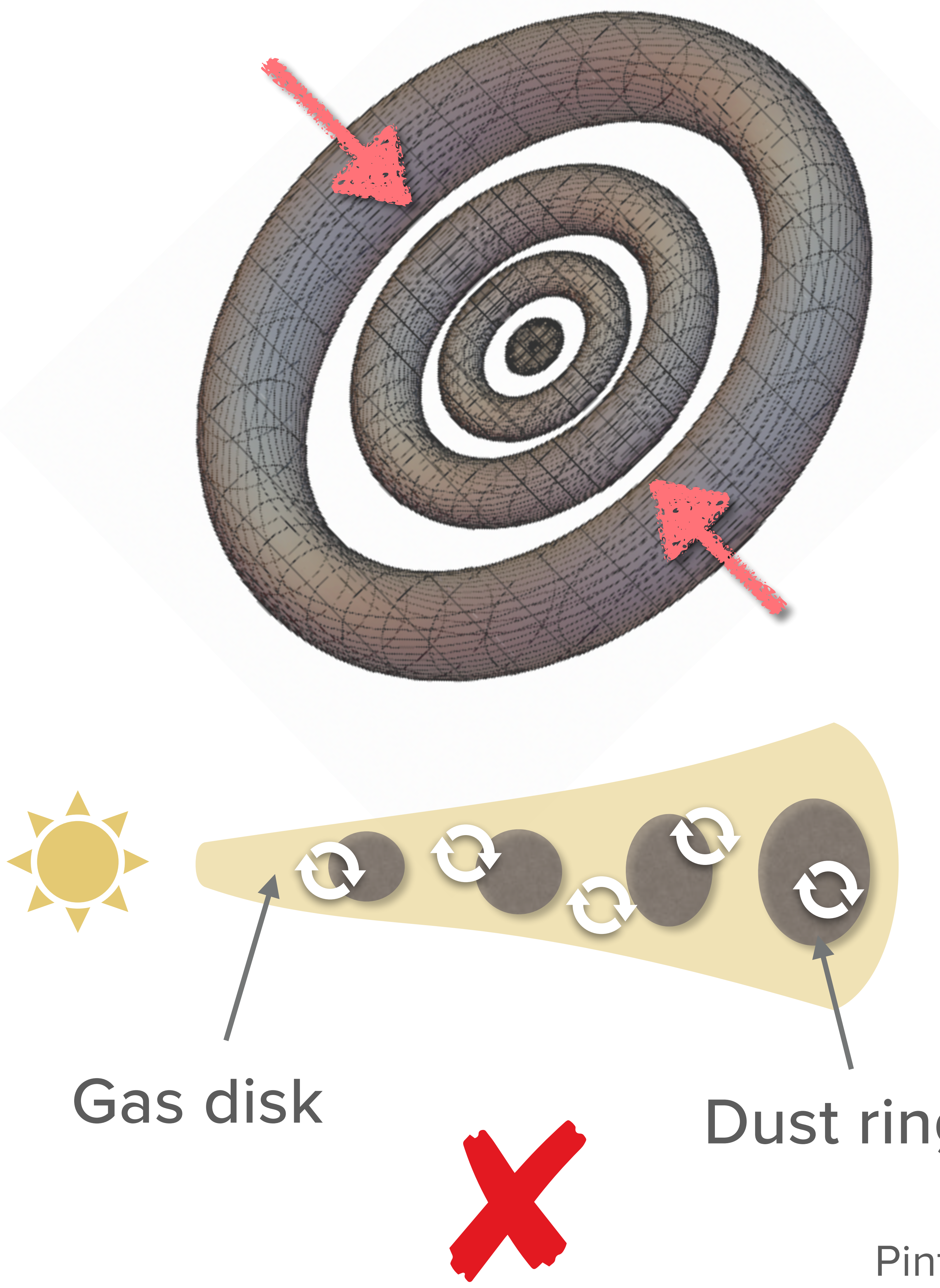


<u>Dust</u> distribution in HL Tau disk

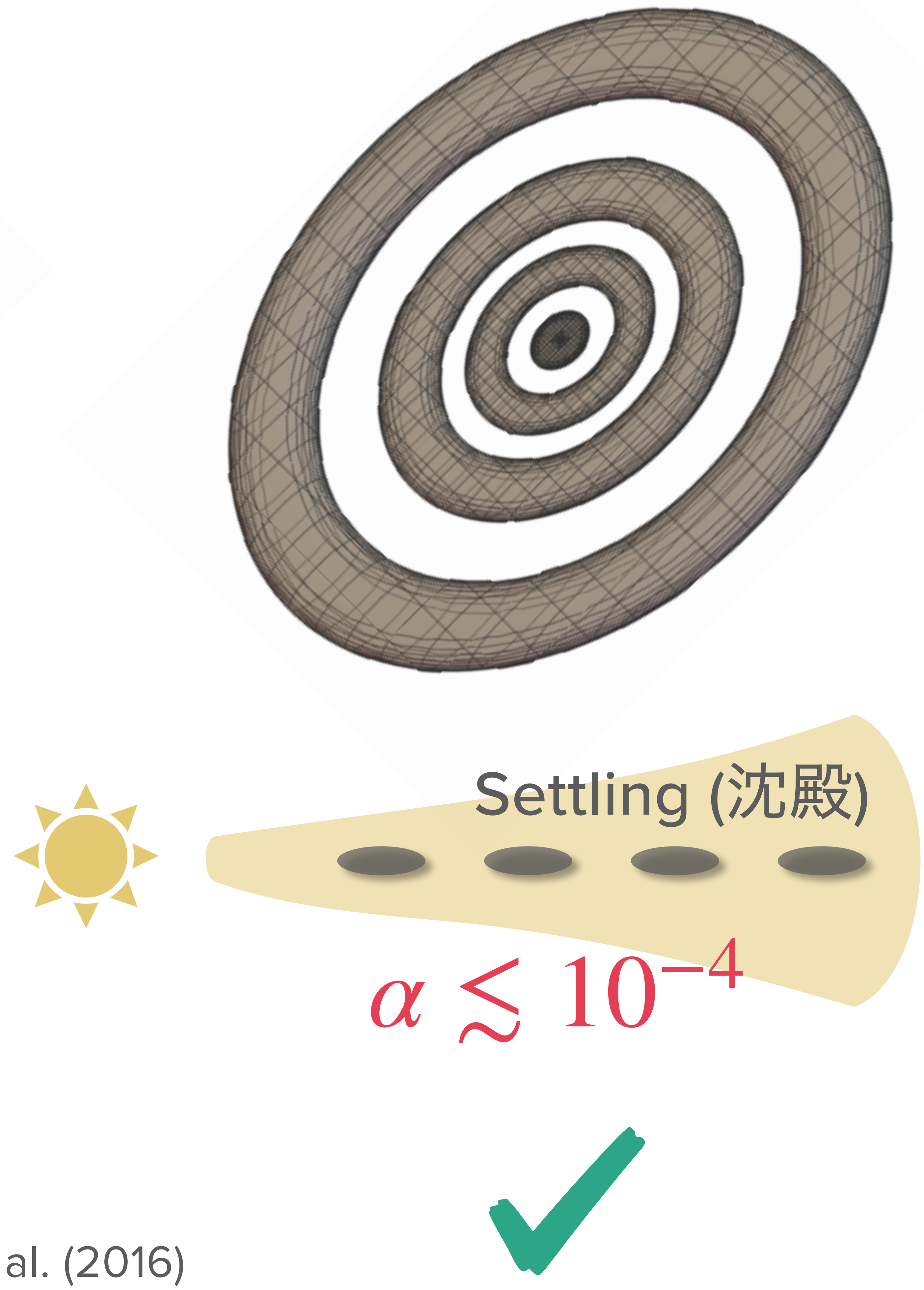
(ALMA Partnership et al. 2016)

$\alpha \sim 10^{-2}$ from observed accretion rate

Vertically thick rings



Vertically thin rings



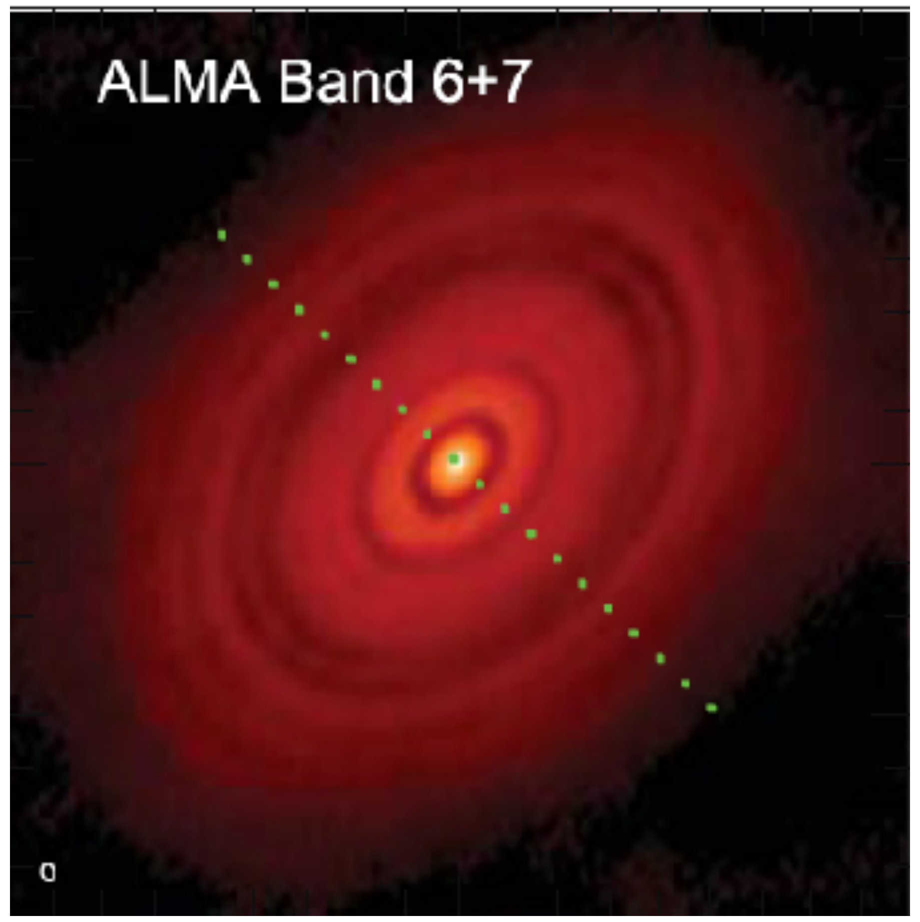
$\alpha \lesssim 10^{-4}$

Pinte et al. (2016)

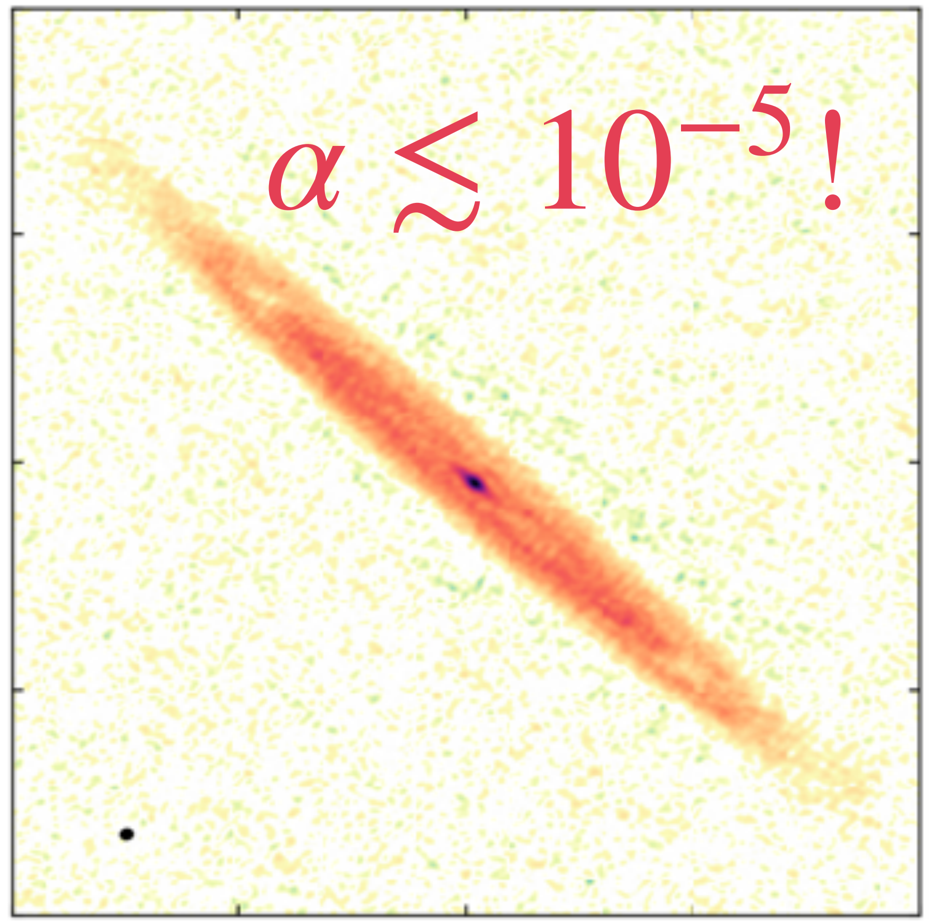
In Many Disks, Turbulence Is Weak or Absent !

- **High level of dust settling**

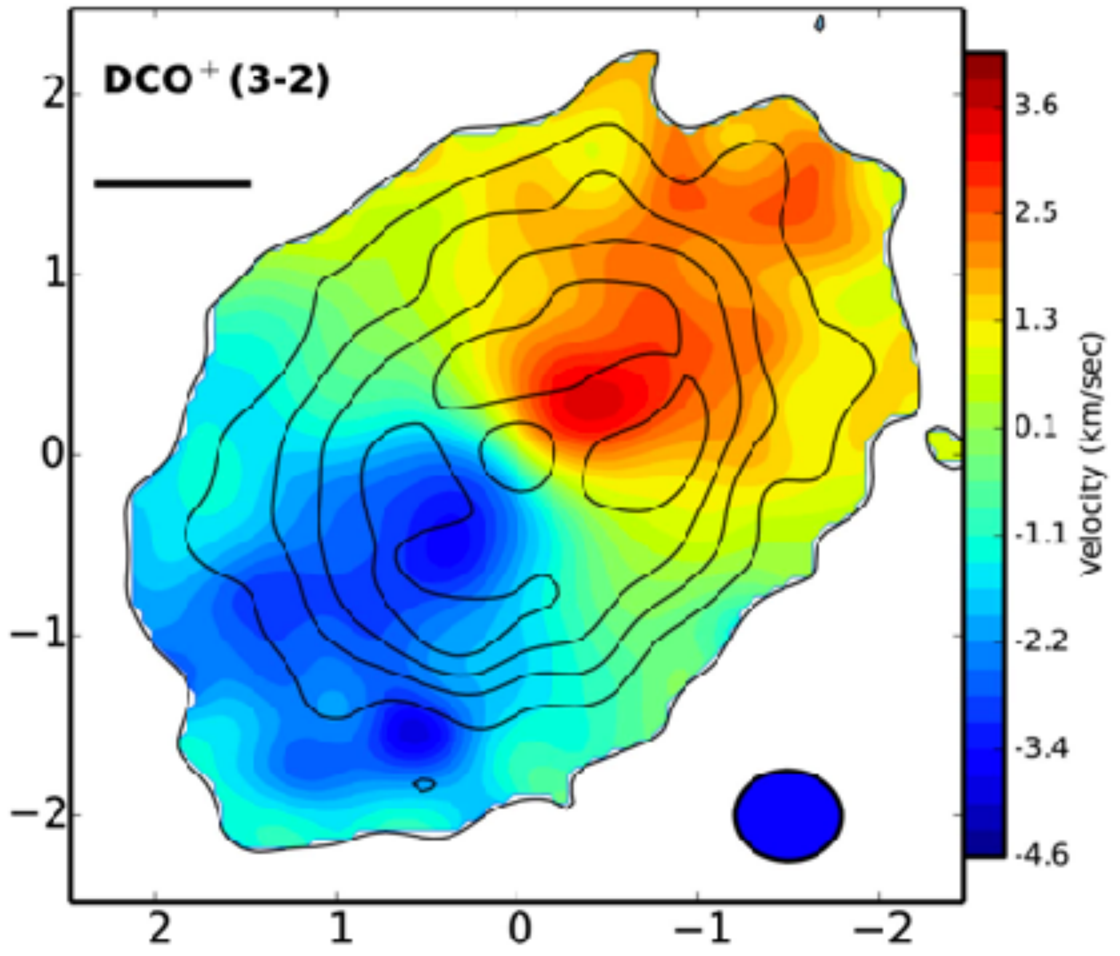
HL Tau (Pinte et al. 2016)

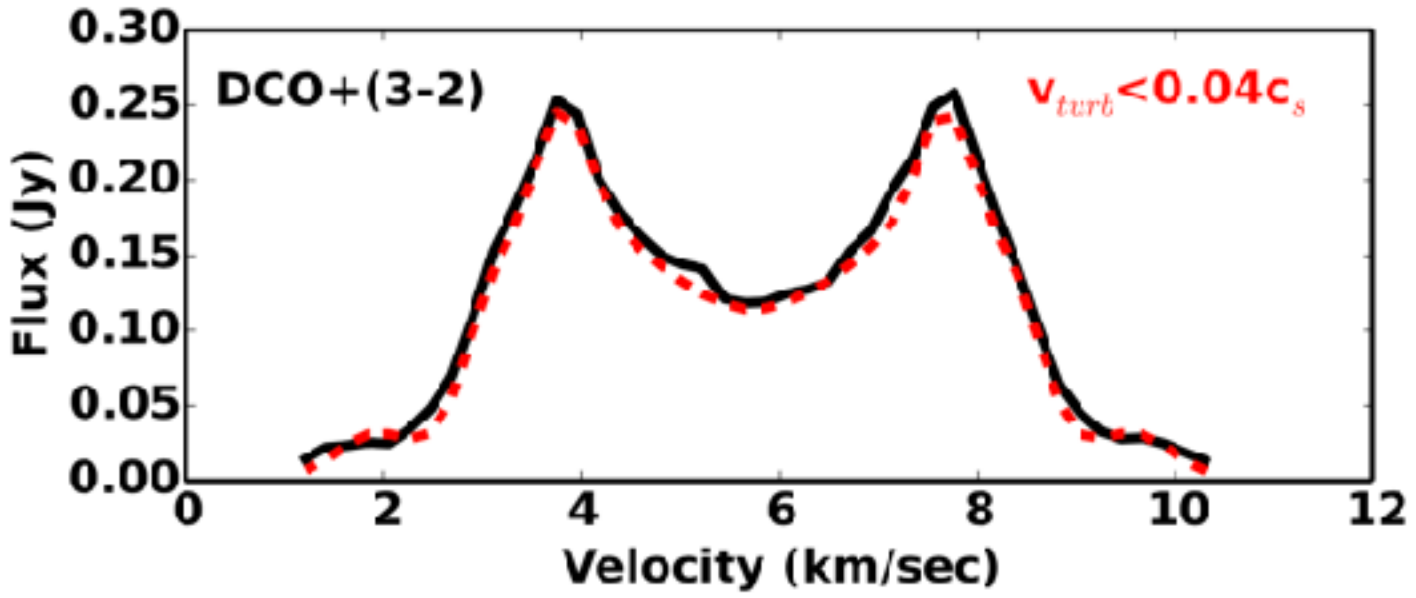


Oph 163131 (Villenave et al. 2022)



- **Weak/absent line broadening**





HD 163296 (Flaherty et al. 2017)

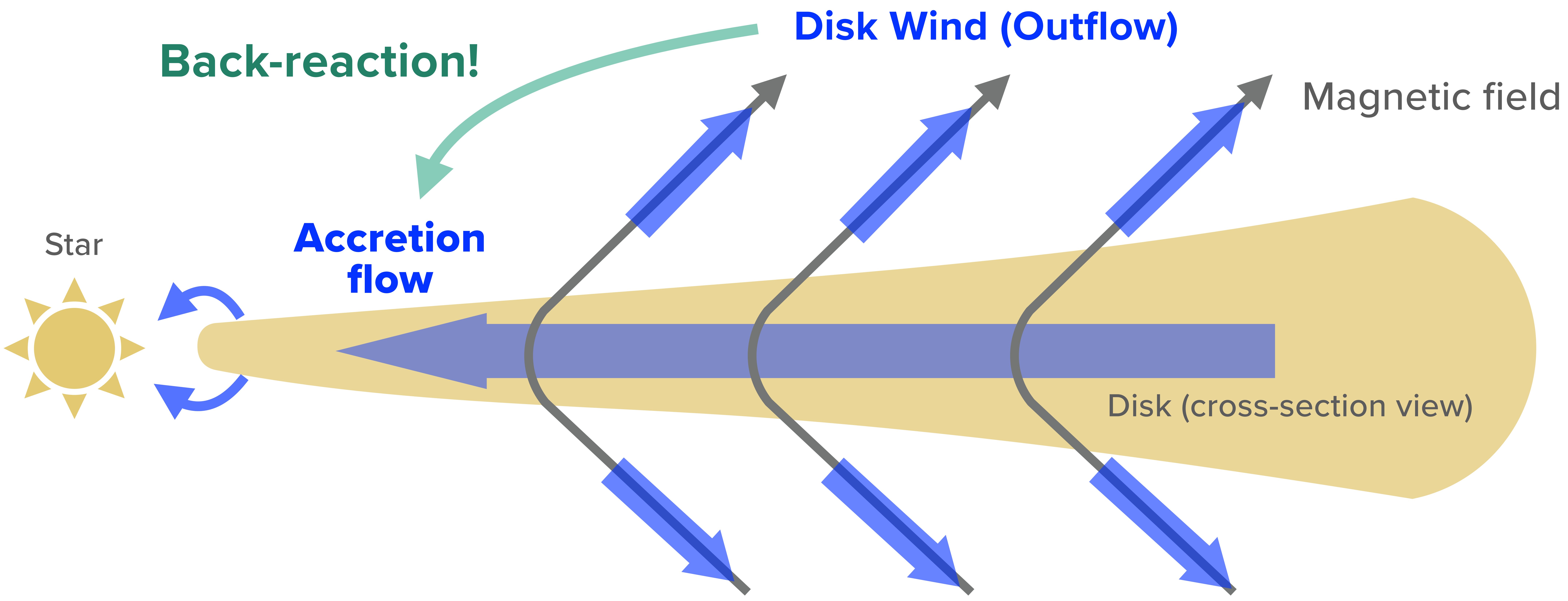
For a review, see Rosotti et al. (2023)

However, among the examples shown here,
HL Tau and HD 163296 have high accretion rates.

Then What Drives Disk Accretion??

Disk Accretion without Turbulence: Driven by MHD Winds

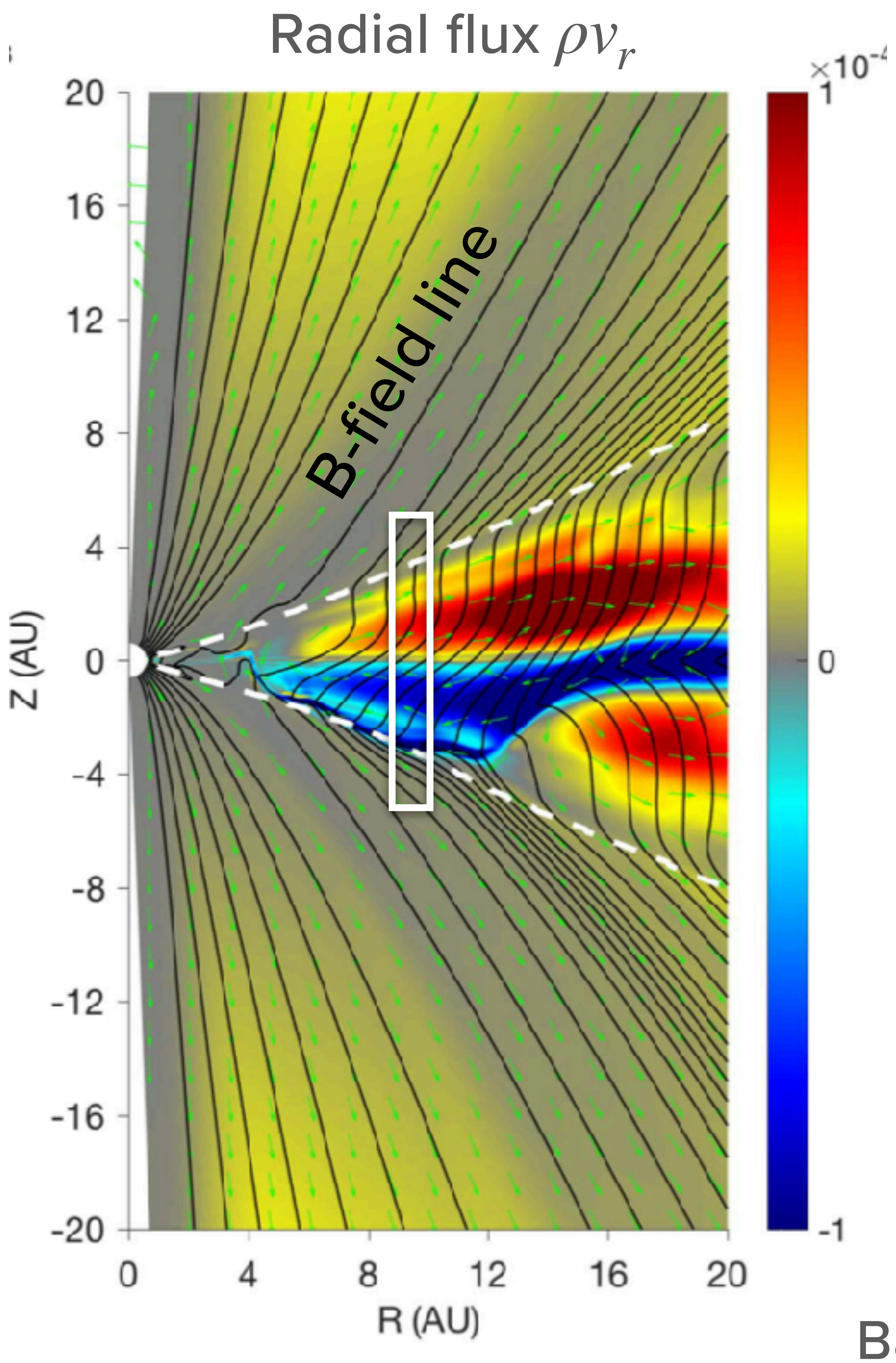
Blandford & Payne (1982); Shibata & Uchida (1986)



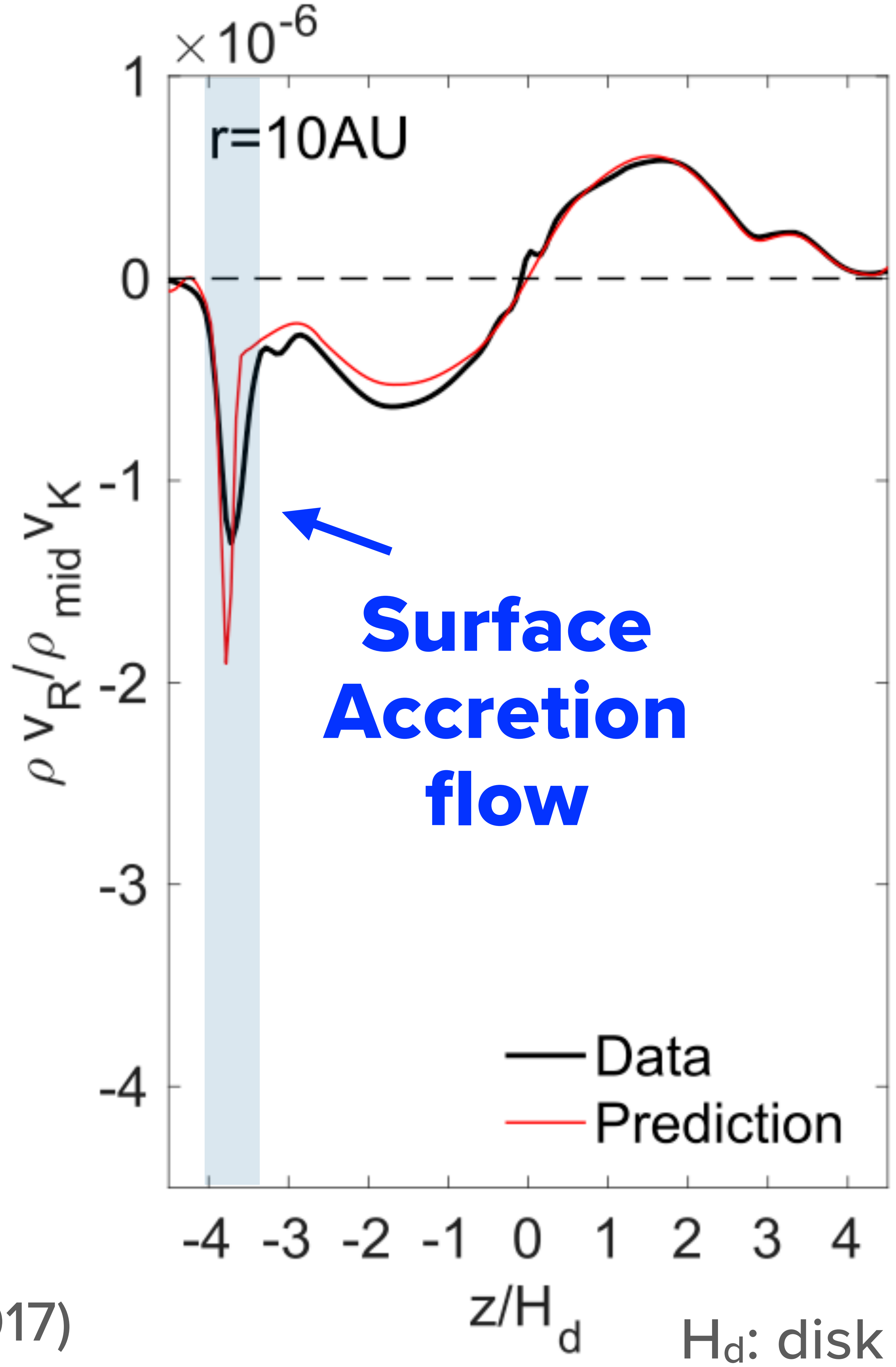
For more introduction, see 森 (2021) 遊星人

Accretion Flow Driven by MHD Disk Winds

2D Global MHD simulation with all non-ideal effects (Ohmic/Hall/ambipolar resistivities)

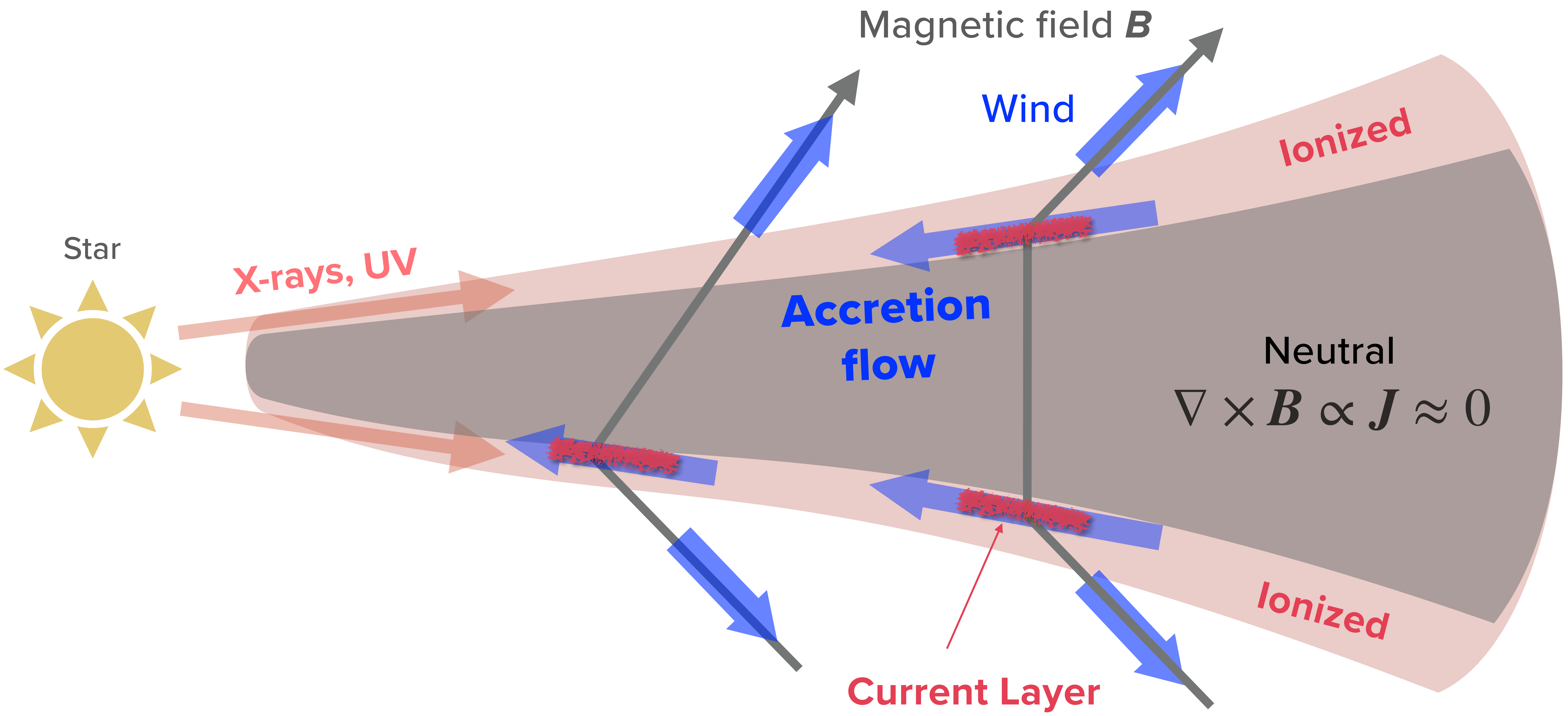


Bai (2017)

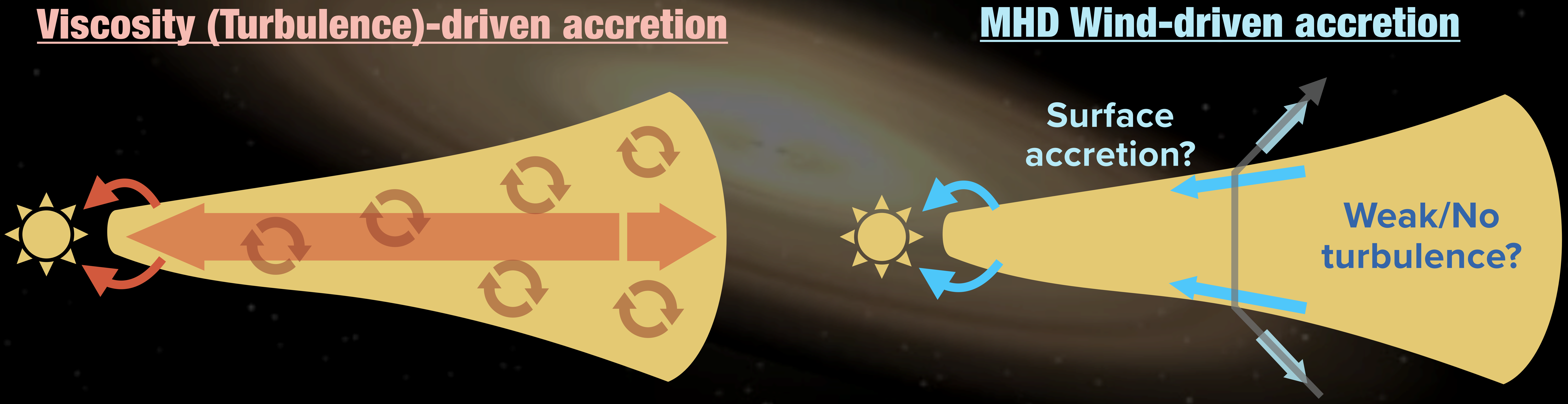


H_d: disk scale height

Why Surface Accretion?

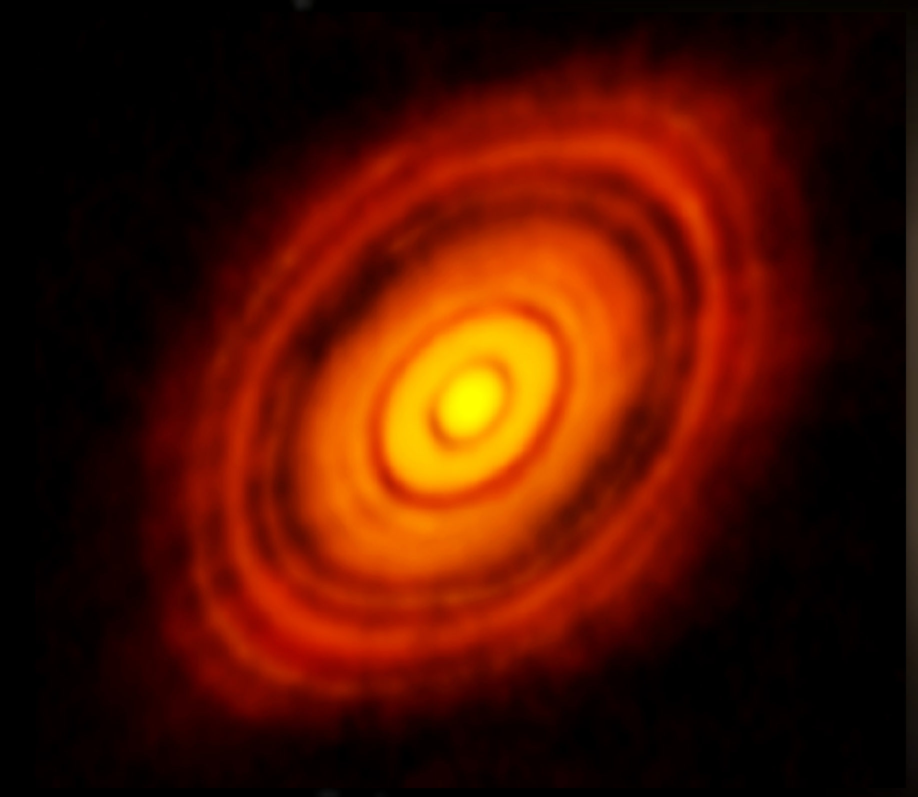


What Drives Protoplanetary Disk Accretion: Summary

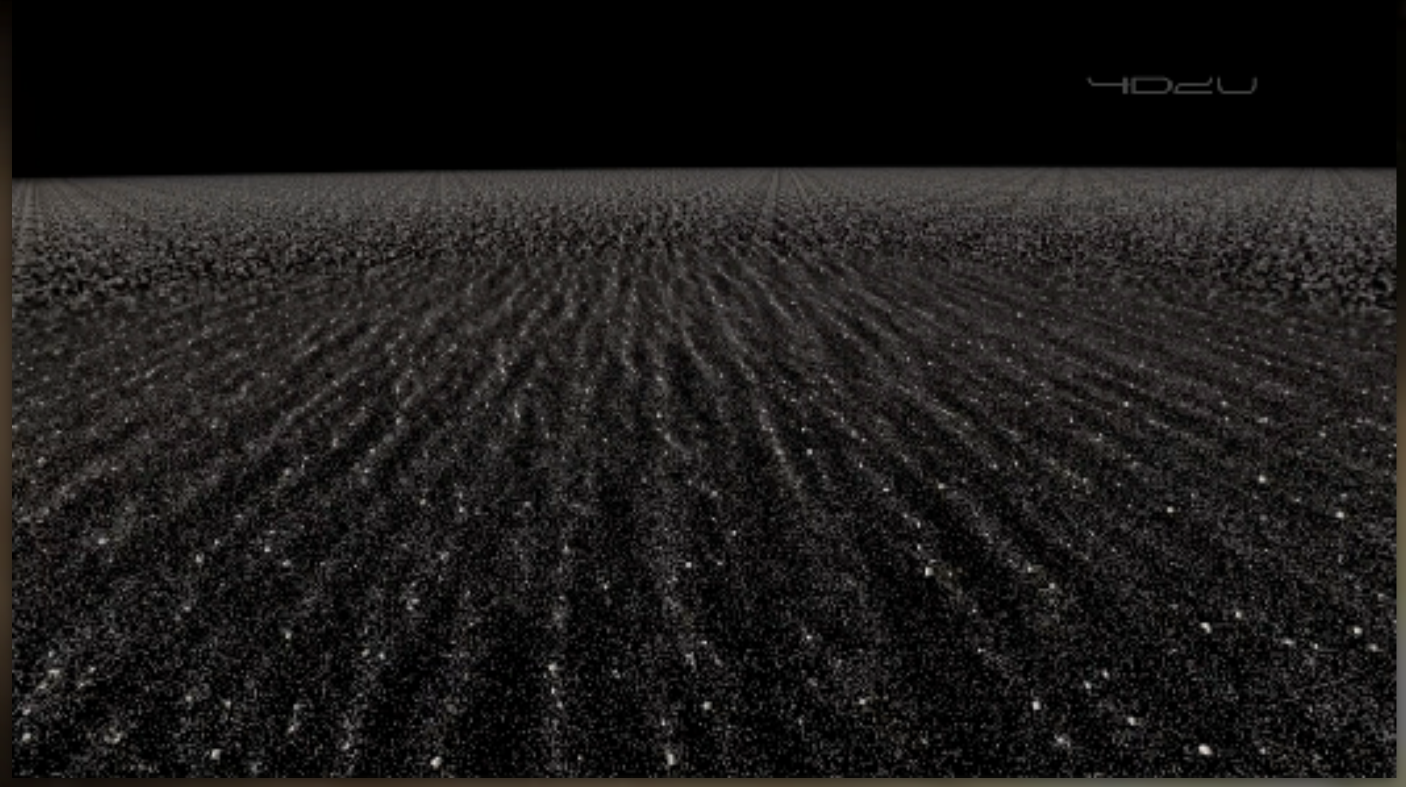


Is Wind-Driven Accretion Favorable for Planet Formation?

Dust settling

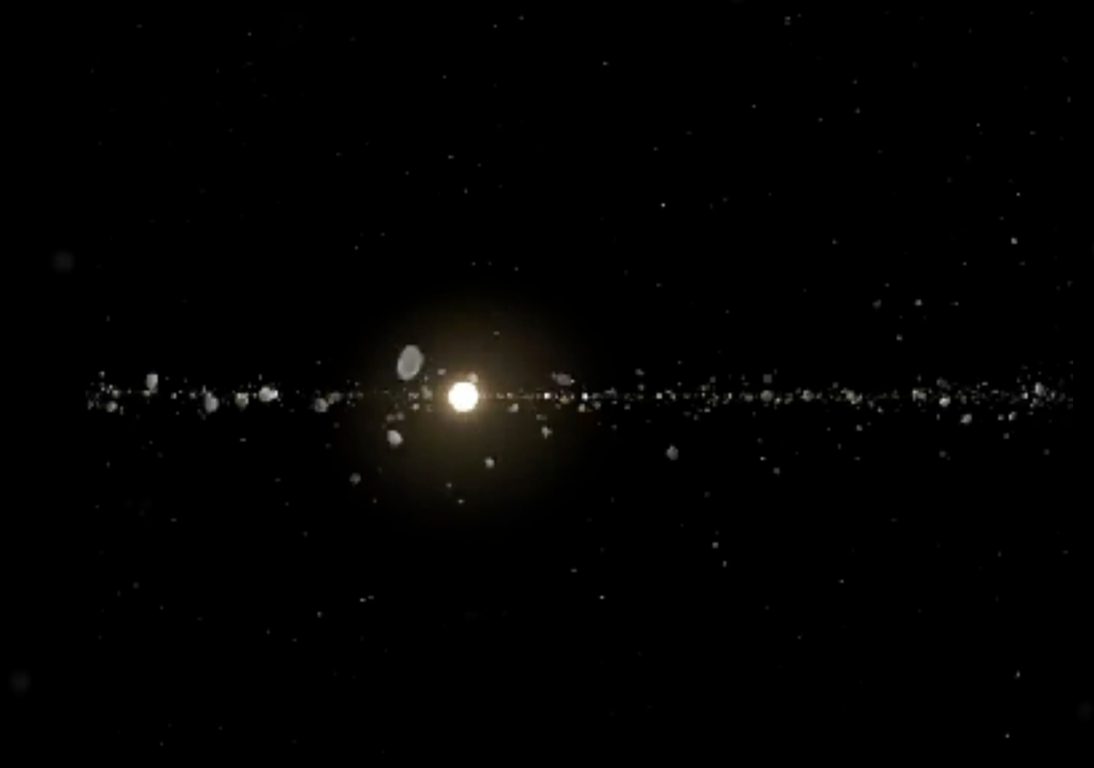


Planetesimal formation

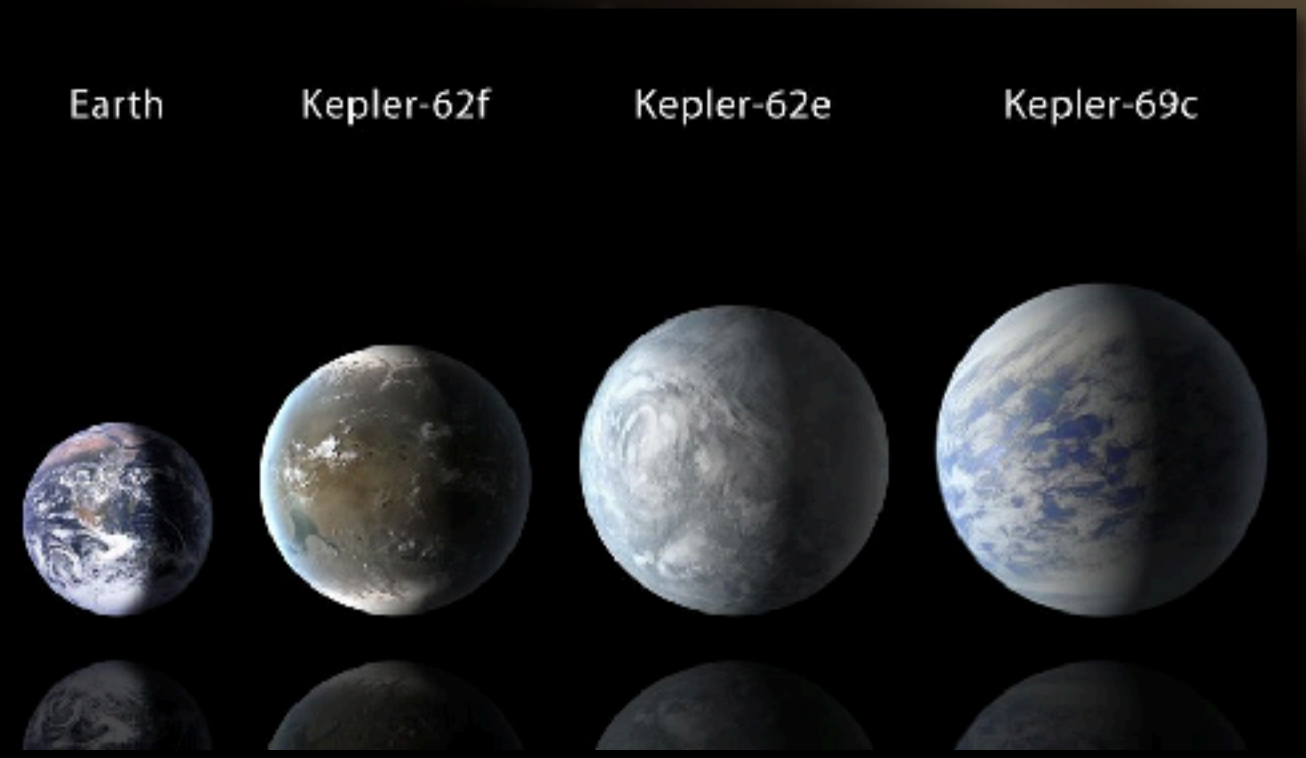


Courtesy: 4D2U Project, NAOJ

Planetesimal growth

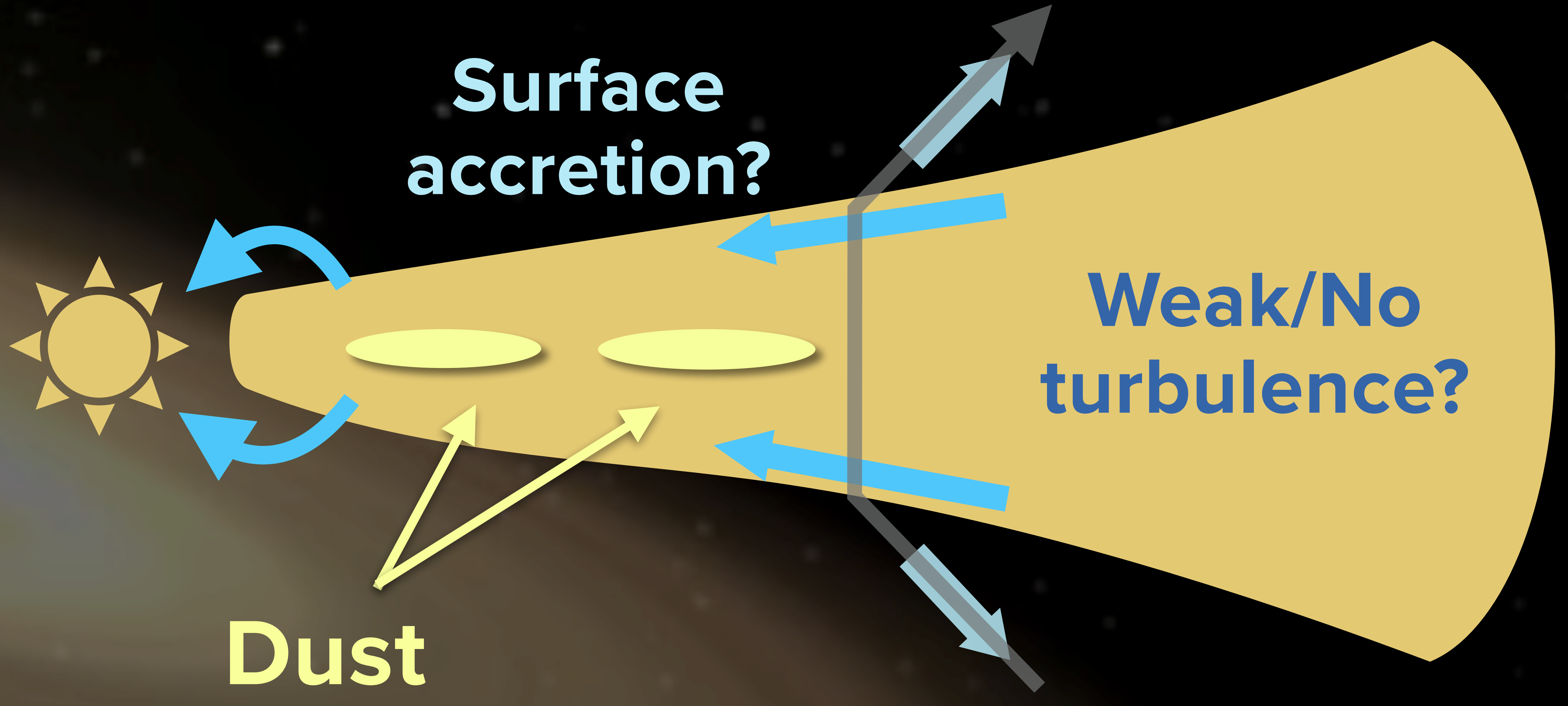


Super-Earth formation



Courtesy: 4D2U Project, NAOJ

MHD Wind-driven accretion

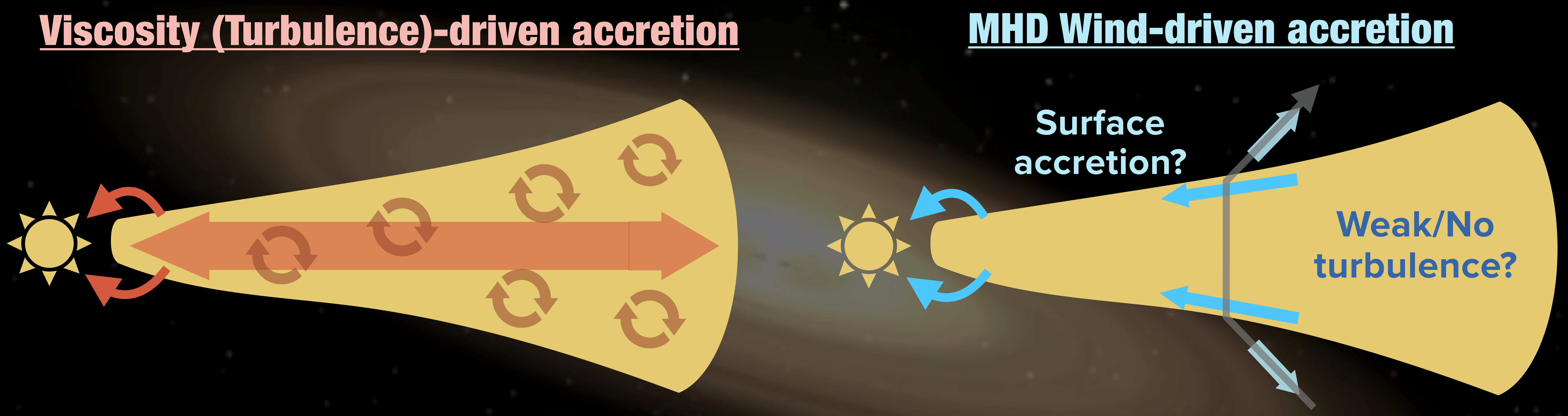


- Effects on planet formation yet to be fully investigated!
- Needs further understanding of the accretion flow structure

Pinte et al. (2016); Okuzumi, in prep; Gressel et al. (2012); Ogihara & Hori (2018)

Thermal Structure of Protoplanetary Disks

Internal Heating of Magnetically Accreting Protoplanetary Disks

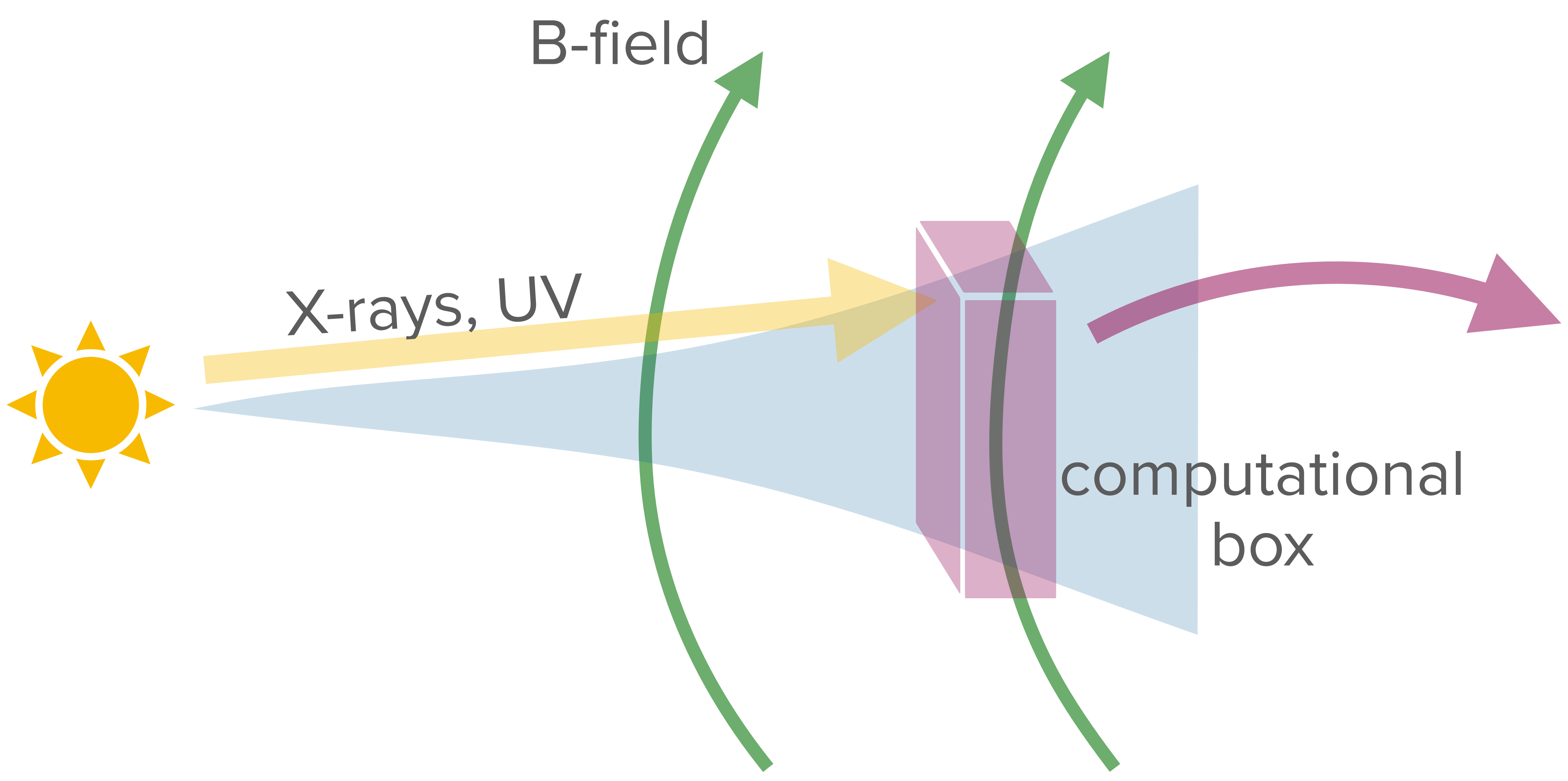


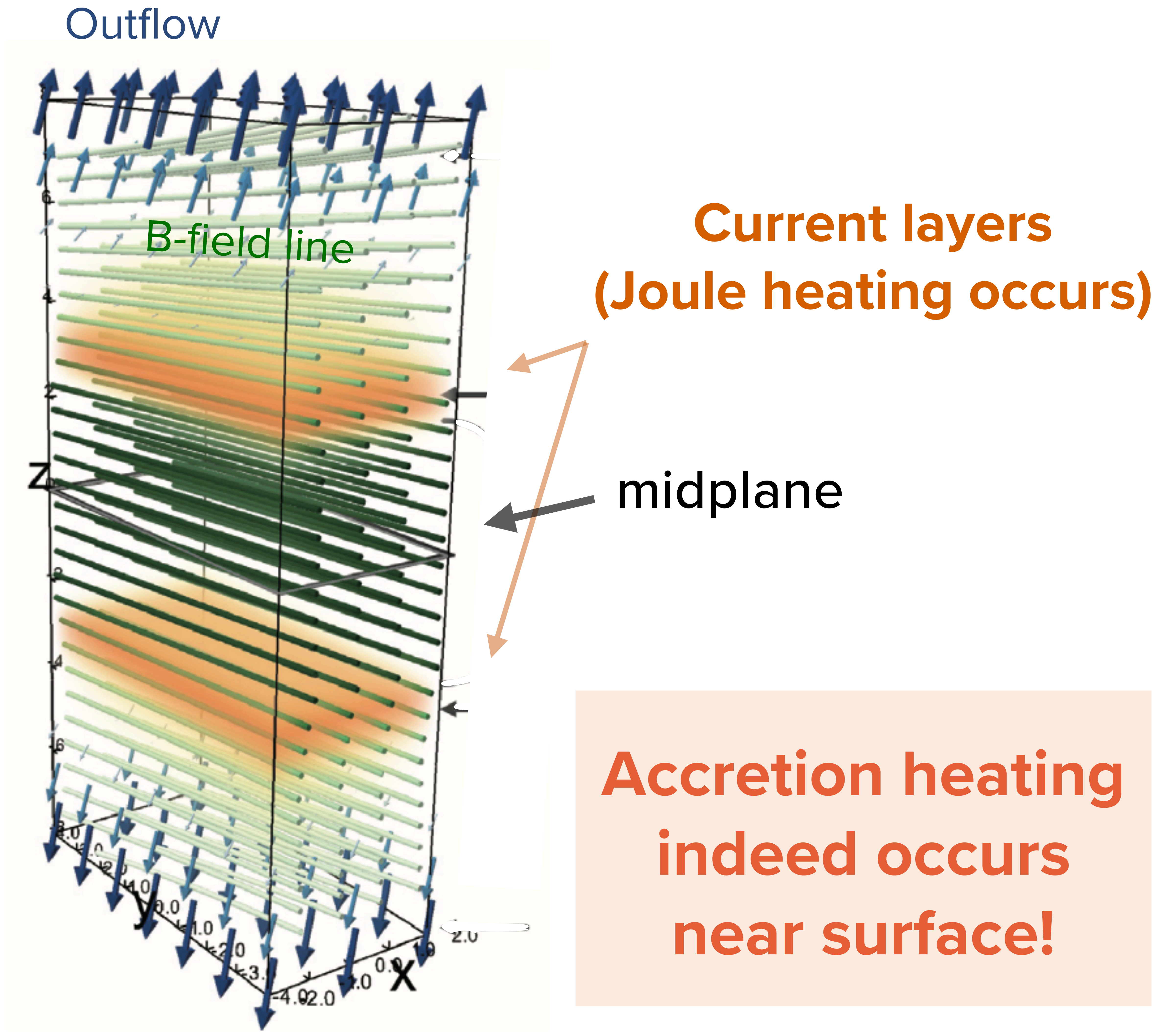
Assuming spatially uniform turbulence, most of the accretion energy is released around the midplane.

Most of the accretion energy is released near the surface or is carried away by winds.

Mori, Bai, & Okuzumi (2019)

Internal Heating of Magnetically Accreting Protoplanetary Disks



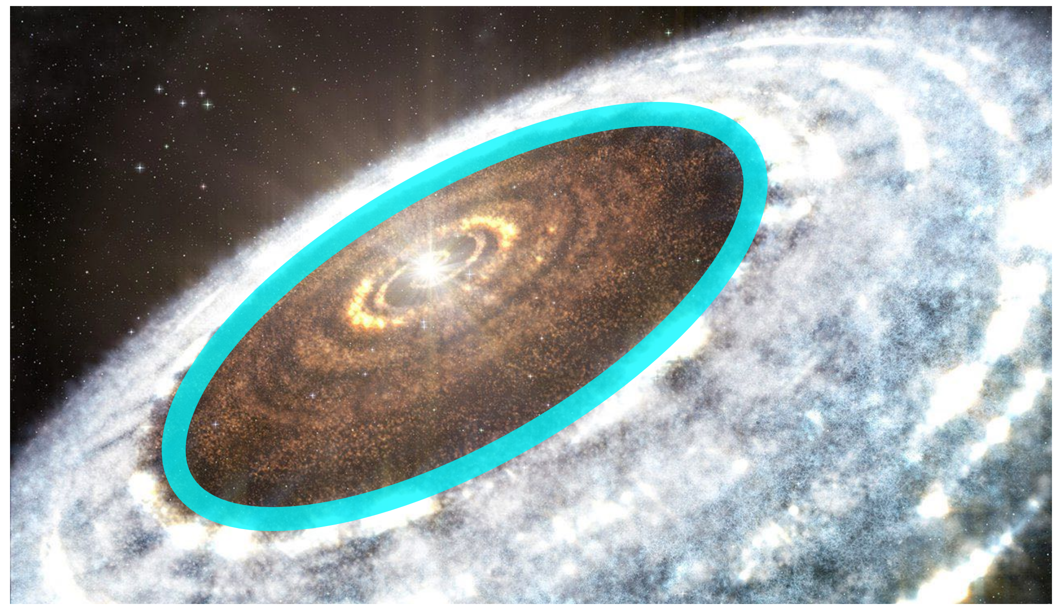


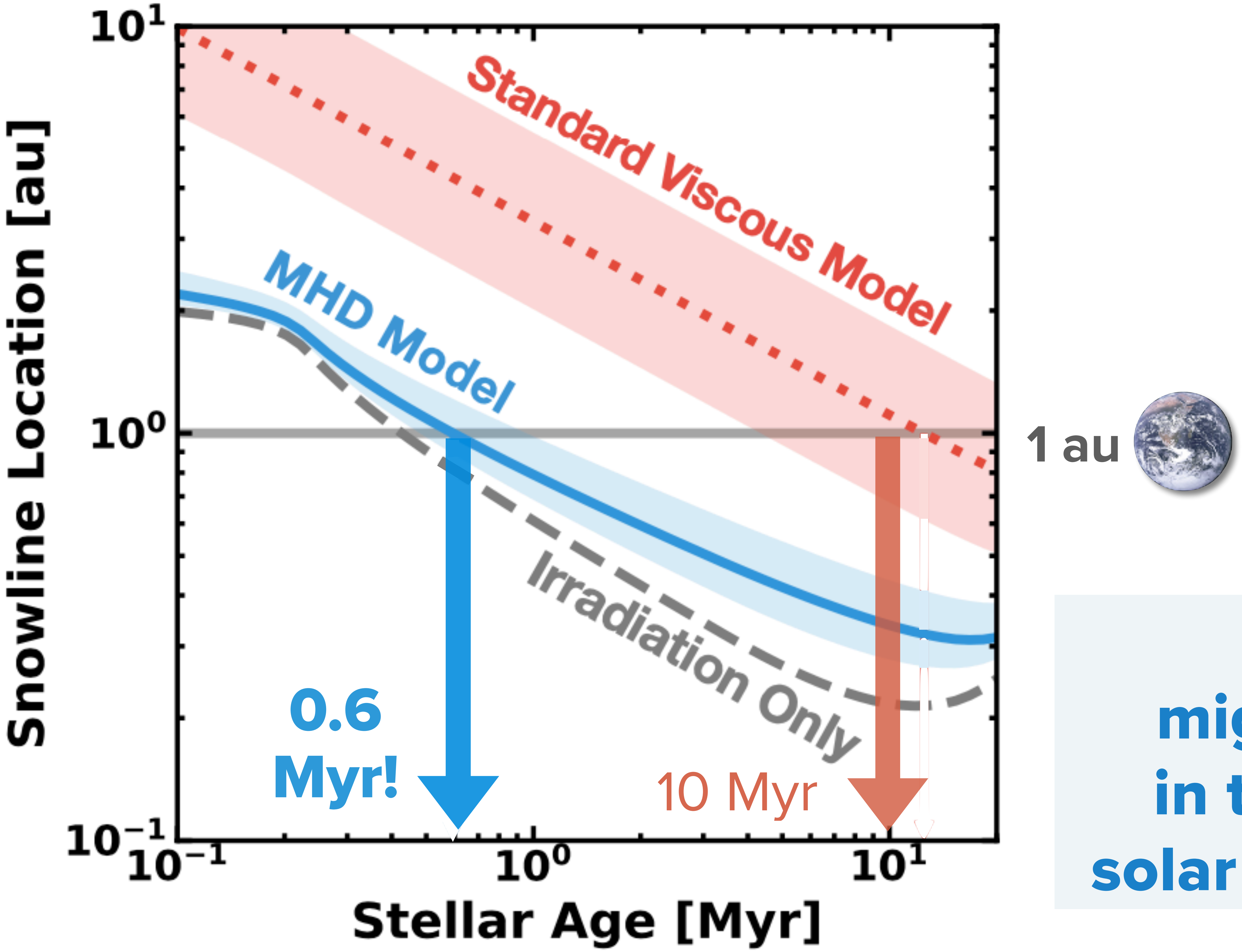
- Radially local MHD simulations with Athena (Stone et al. 2008)
- Includes all non-ideal MHD effects (Ohmic resistivity, ambipolar diffusion, Hall effect)
- Ionization fraction from an ionization model including grains

Accretion heating indeed occurs near surface!

Mori, Bai, & Okuzumi (2019)

Snow Line Migration in Magnetically Accreting Protoplanetary Disks



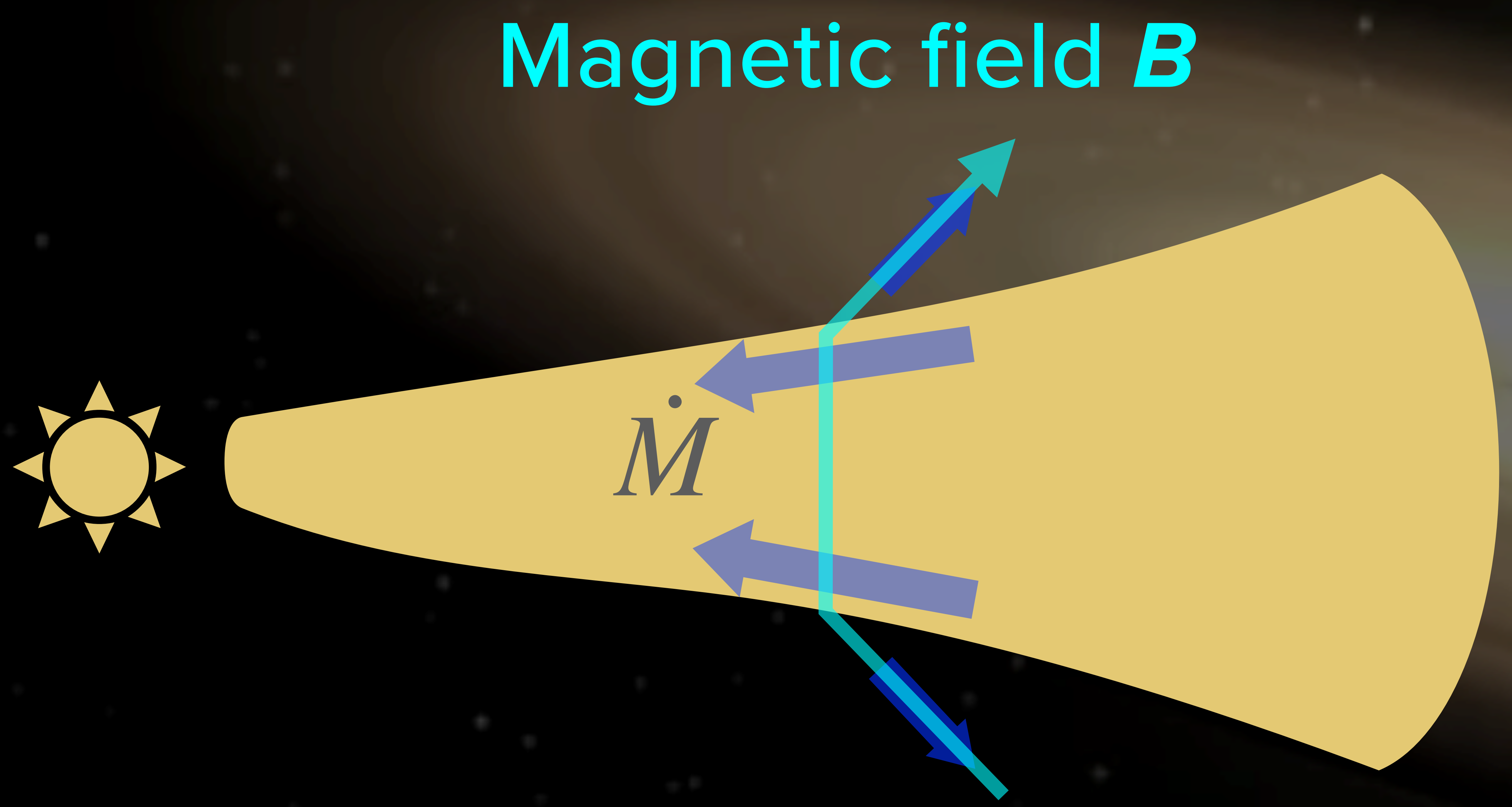


Mori, Okuzumi, et al. (2021)

The snow line migrated inside 1 au in the early phase of solar system formation!?

(But see also Kondo, Okuzumi, et al. 2023)

Open Issue: How Strong is the B-field in Protoplanetary Disks?



- MHD Wind-driven accretion rate is a function of **magnetic field strength:**

$$\dot{M} = -\frac{2r}{\Omega_{\mathrm{Kepler}}(r)}(B_z B_\phi)_{\mathrm{surface}}$$

e.g. Wardle (2007)

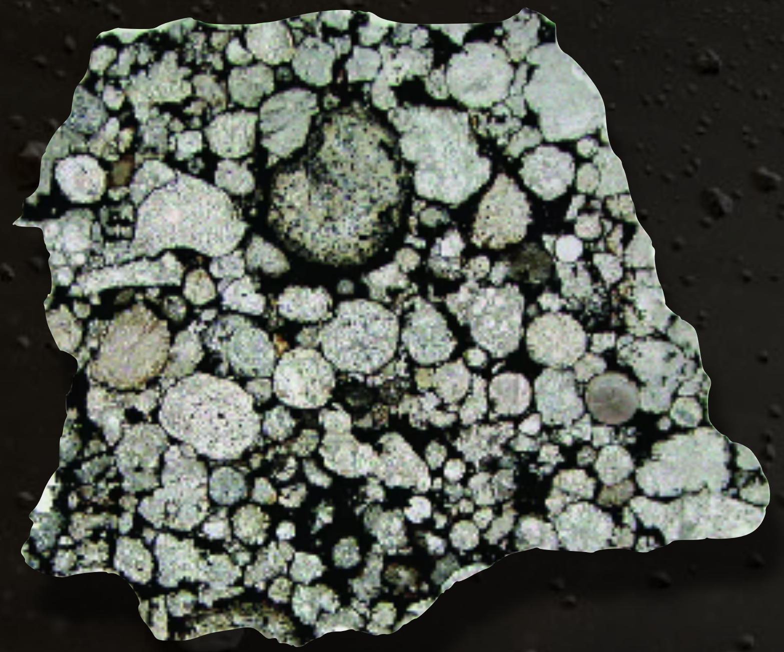
- Simulations predict

  $|B| \sim$ 0.01–1 G at midplane

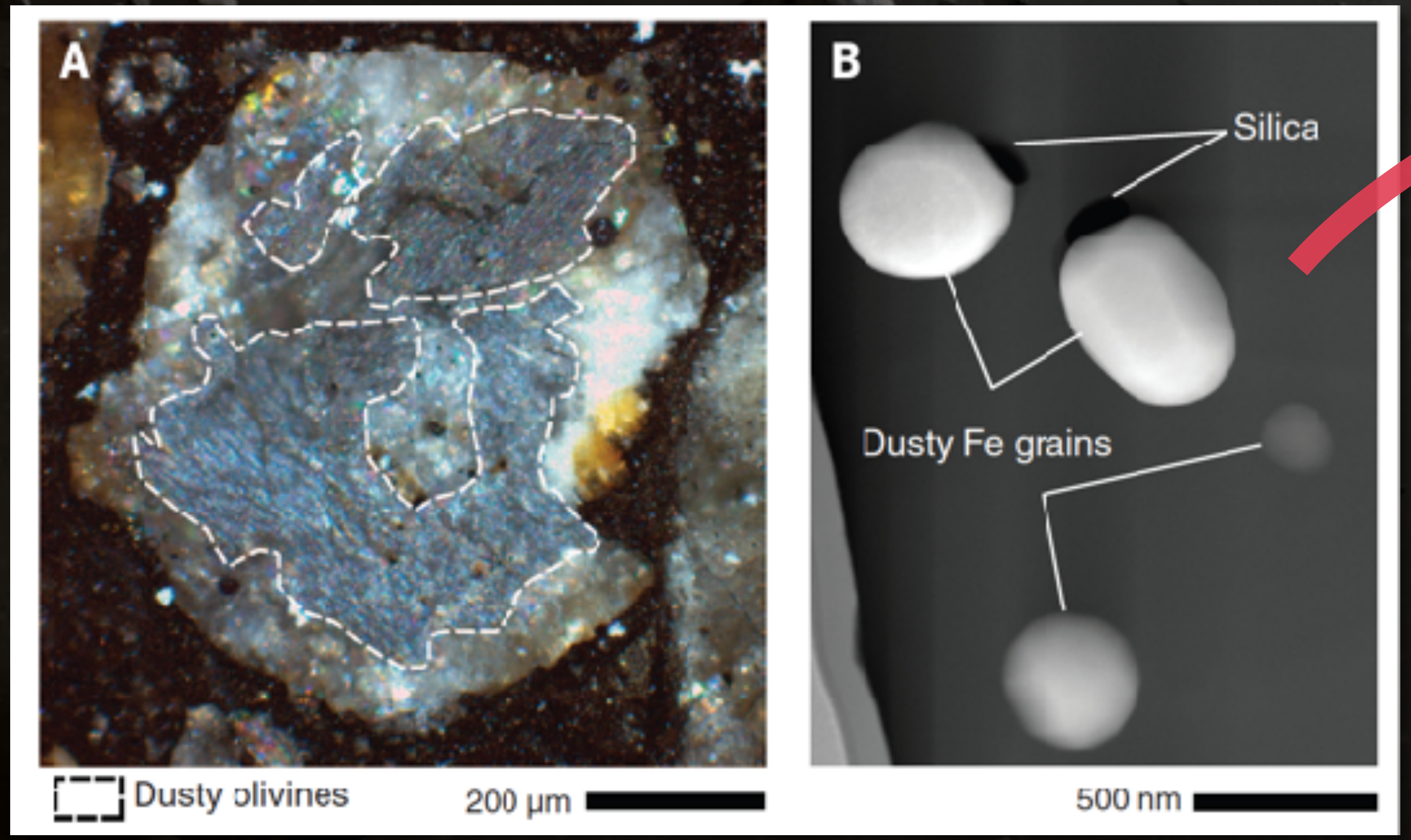
  for disks with observed accretion rates ($10^{-9...-7}$ M_{sun}/yr)

For a review, see Weiss et al. (2021)

Constraining the Disk B-field Strength from Solar System Solids



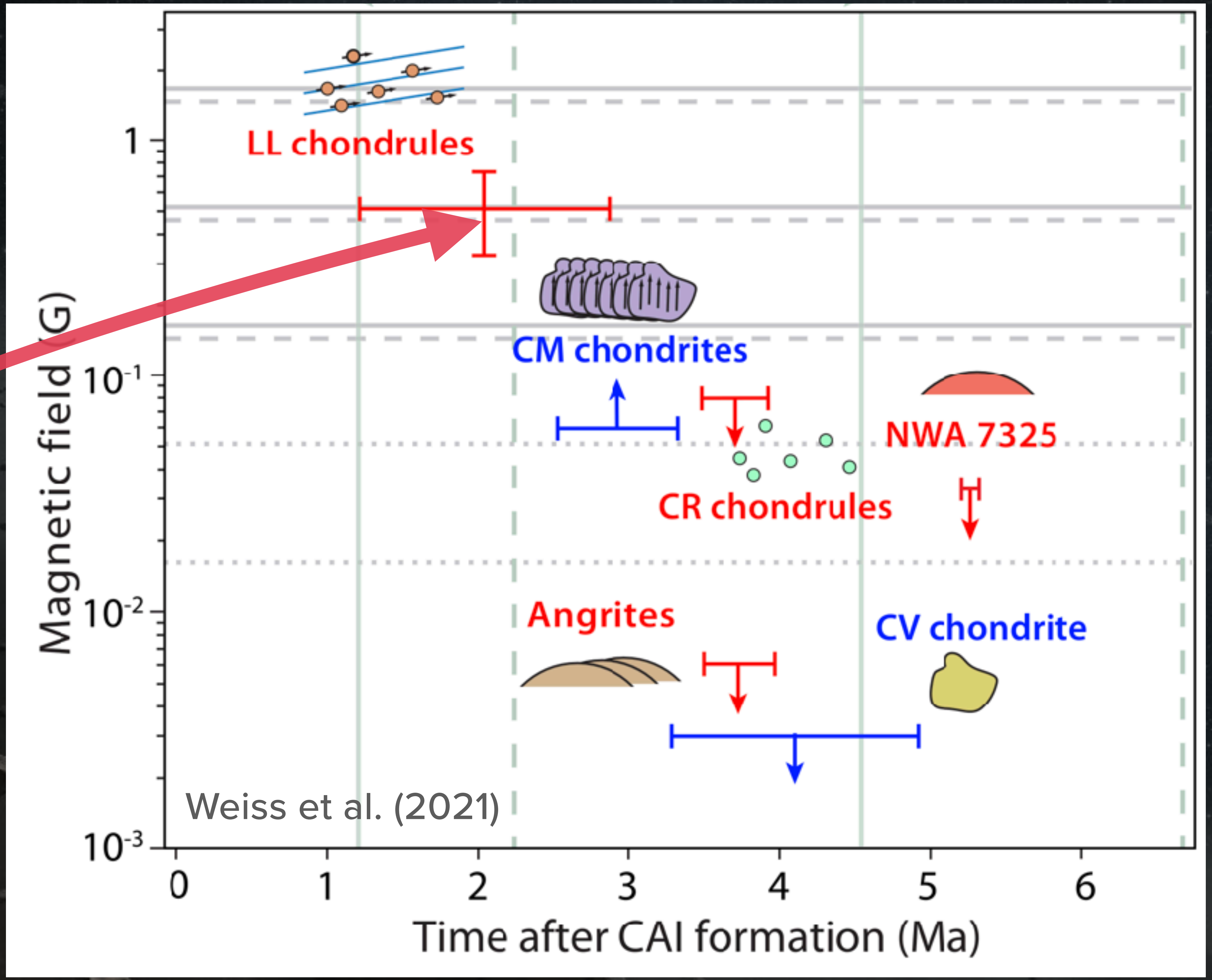
Meteorites (隕石):
Fragments of asteroids



Magnetized (磁化した) particles!

Fu et al. (2014) Science

Estimated B-field in the Sun's protoplanetary disk

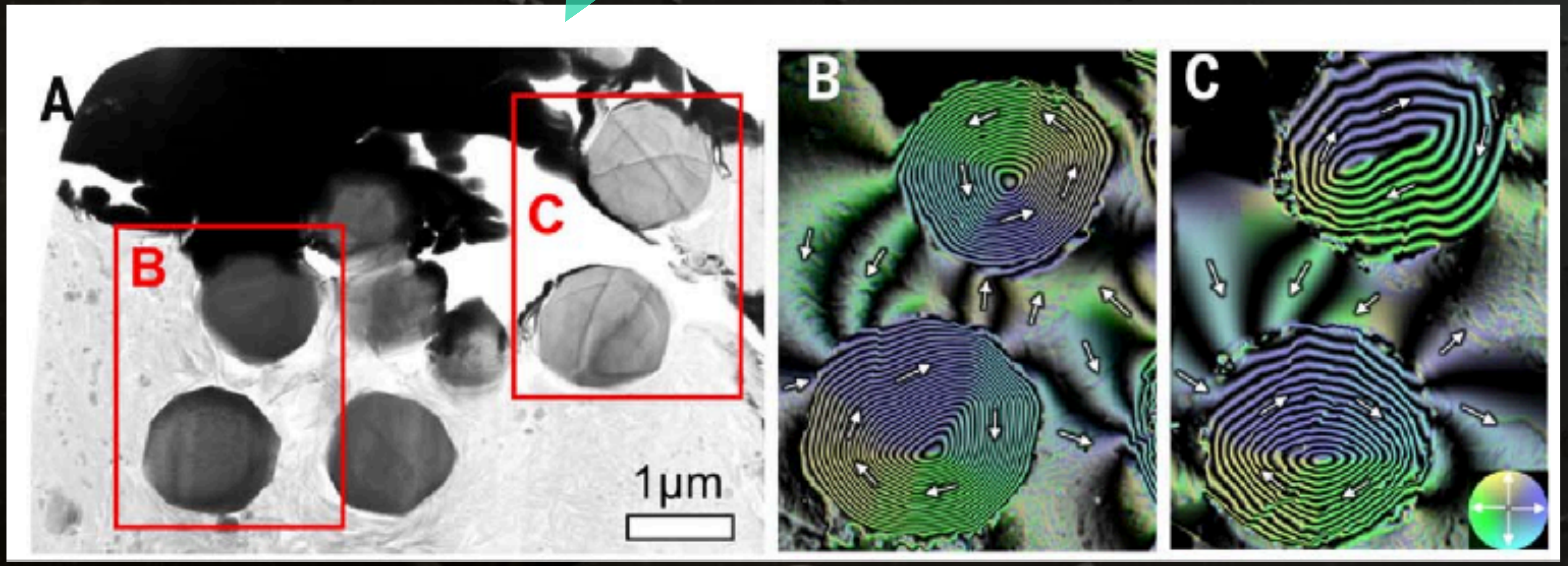


CAI: the oldest solids in the solar nebula

Constraining the Disk B-field Strength from Solar System Solids

Asteroid Ryugu

Returned samples

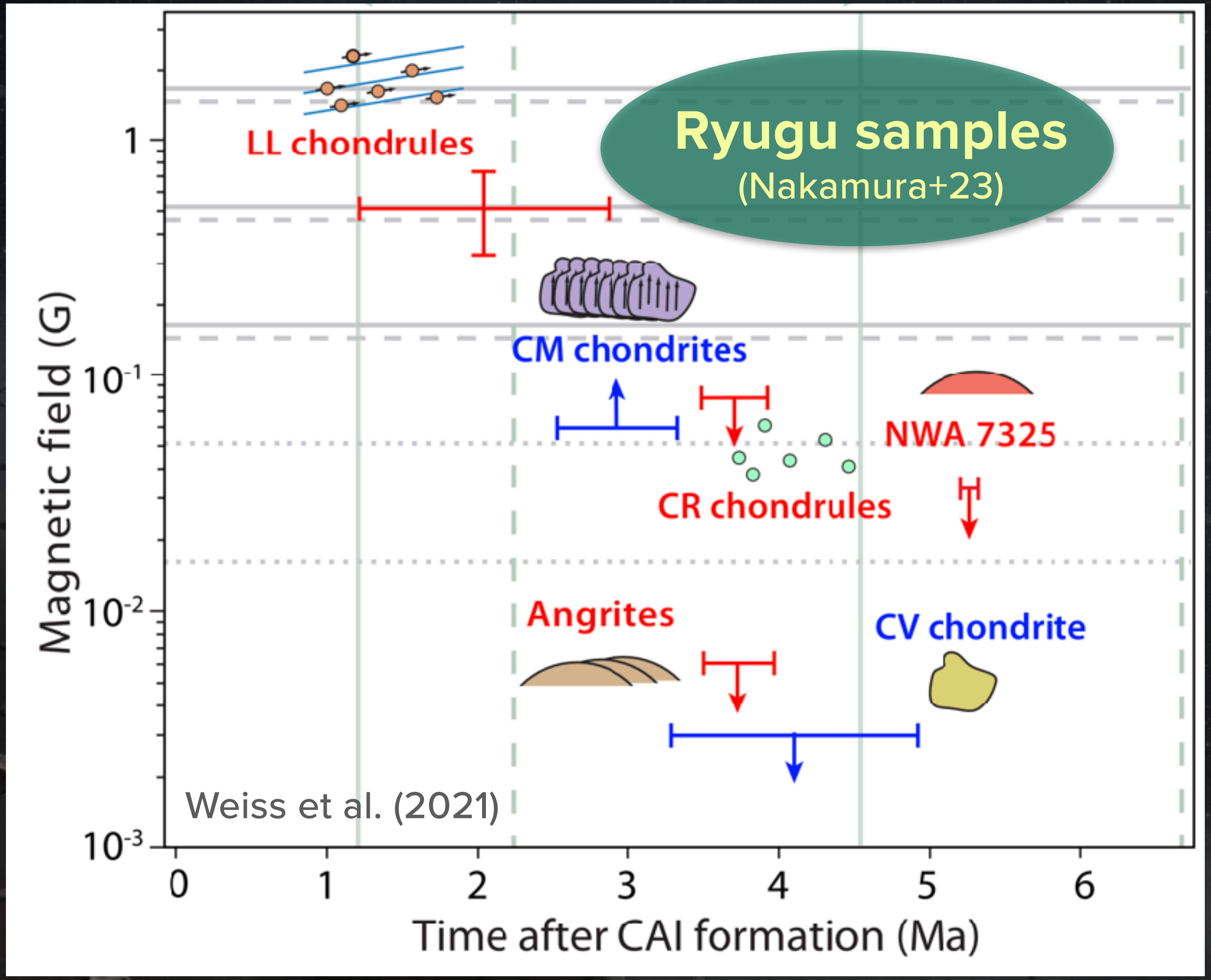


Magnetized magnetite (磁鉄鉱)！

(Formed in liquid water in Ryugu)

Nakamura et al. (2023) Science

Estimated B-field in the Sun's protoplanetary disk

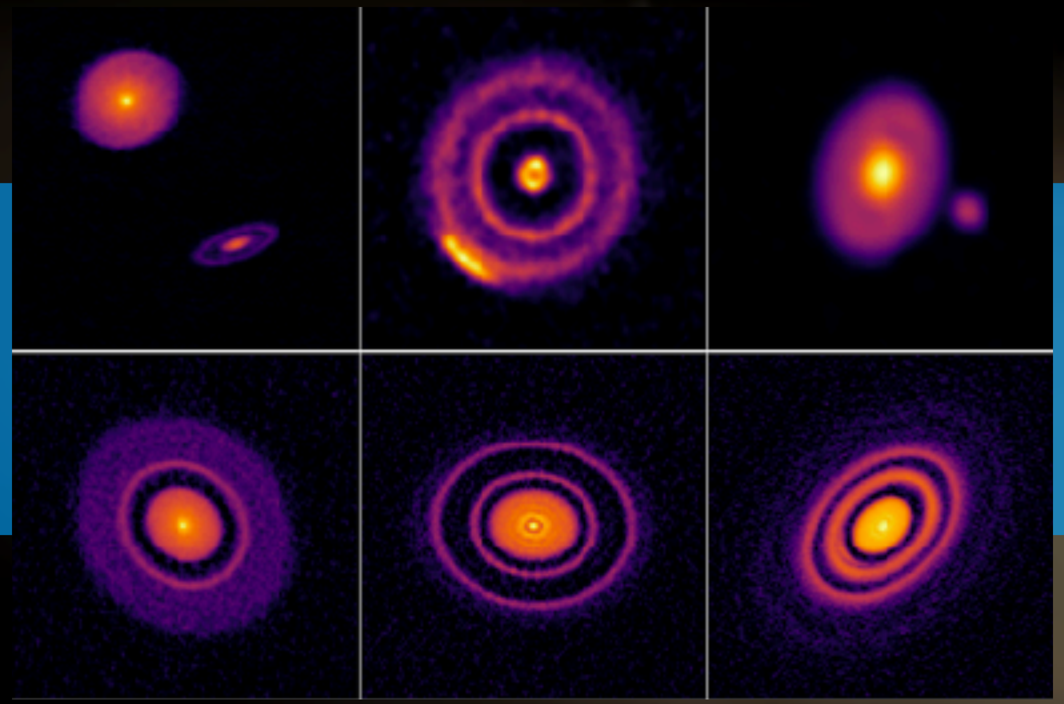


CAI: the oldest solids in the solar nebula

Summary

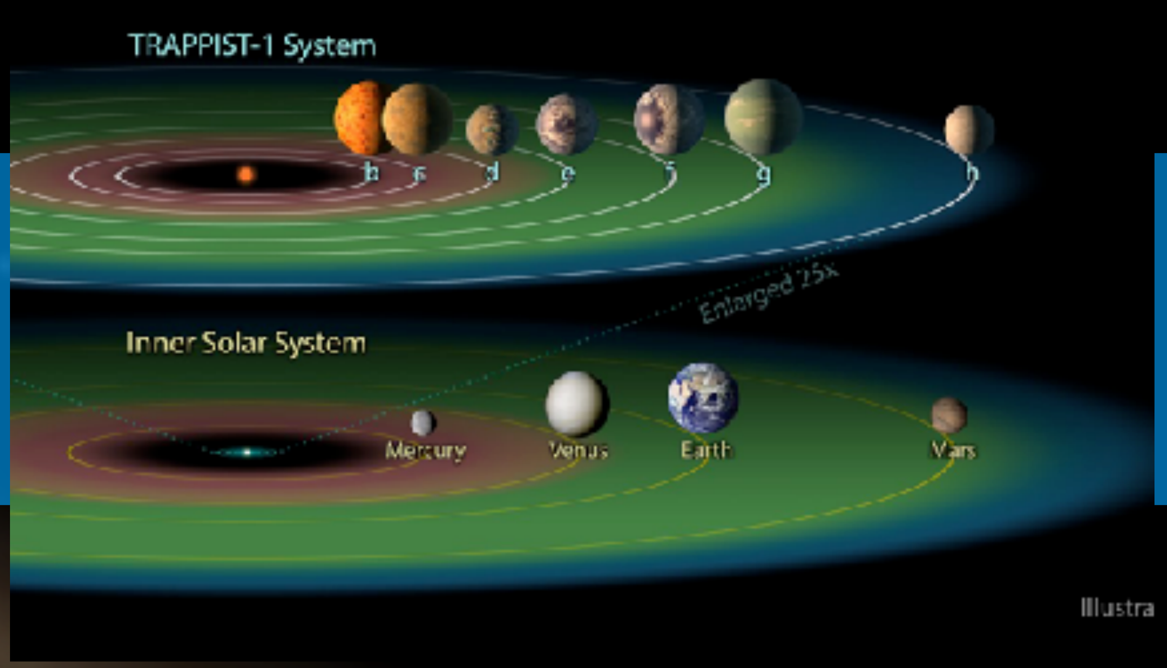
Star formation

Protoplanetary disks



Small bodies

Planets



Origin of Life?

Disk observations

Solar system Exploration

Exoplanet observations

多様な観測からヒントを得ながら惑星形成の謎を解明できる時代へ