Three short stories: youngest protostars, disk accretion, debris disks

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Outline

Studying the youngest protostars

IR spectroscopy of Class 0 sources

How do disks accrete?

Supersonic surface accretion in a Class I disk

Protoplanetary disks --> debris disks

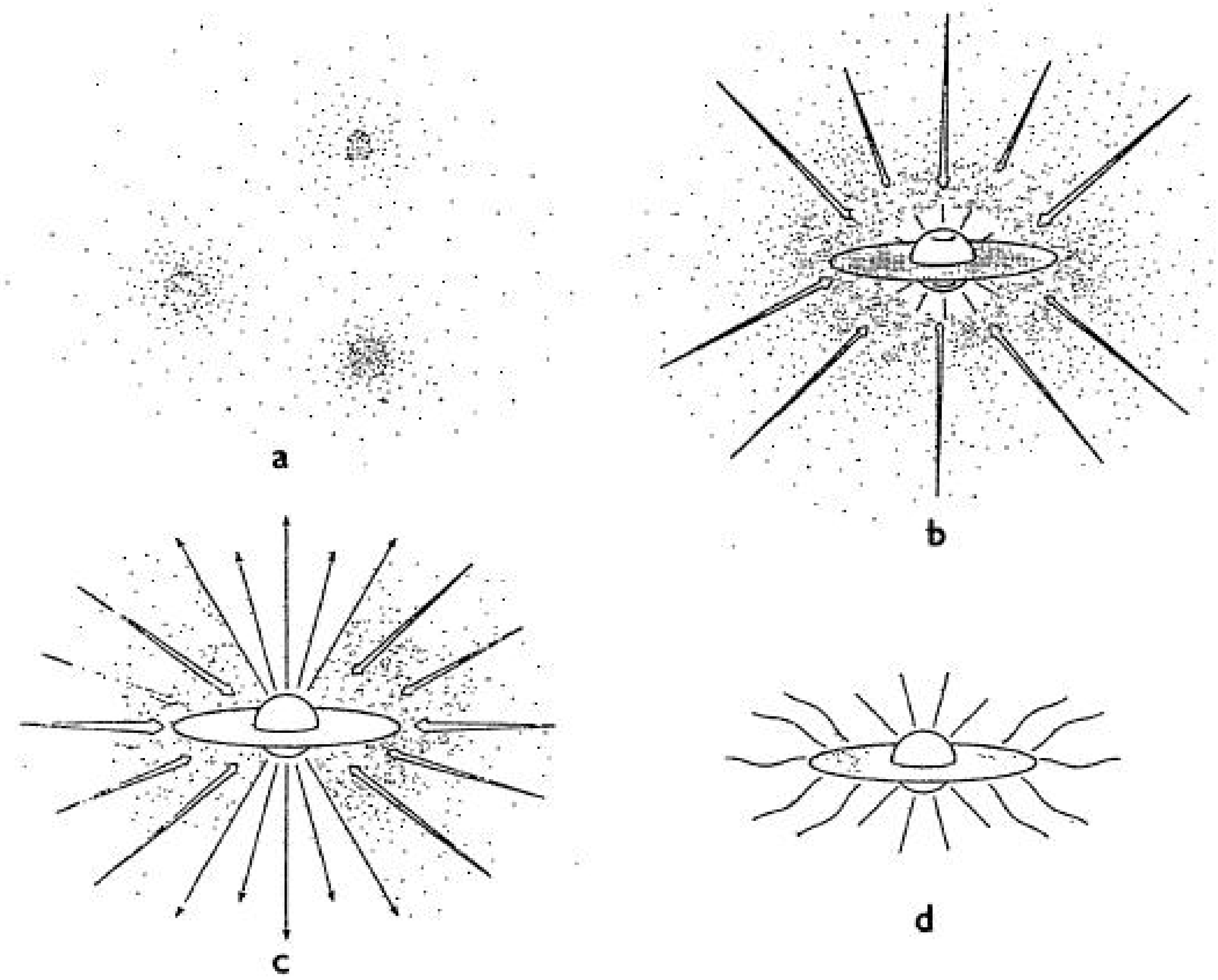
Insights from disk rings

Studying the Youngest Protostars

IR Spectroscopy of Class 0 Sources

How do protostars accrete?

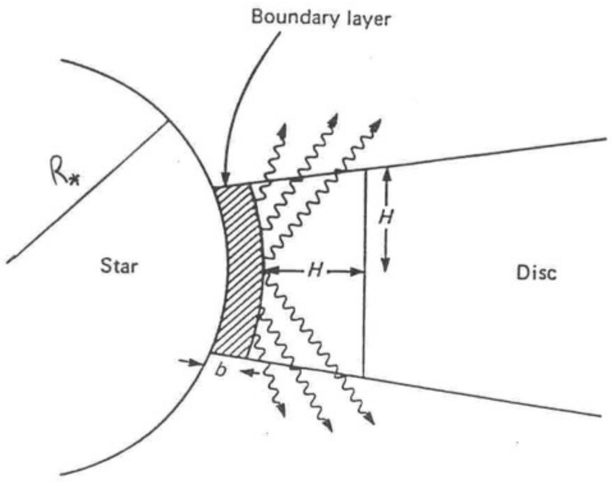
Shu et al. 80's



- Do disks exist?
- How do disks accrete?
- How do stars solve their angular momentum problem?

Accretion onto Star

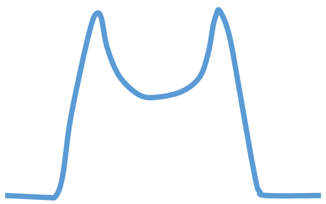
Via a boundary layer?



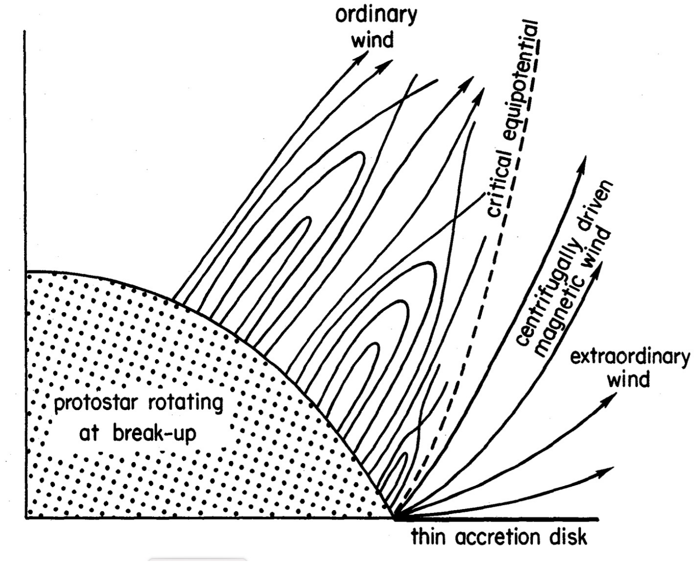
Credit: B. Ryden

$b < H < R_*$

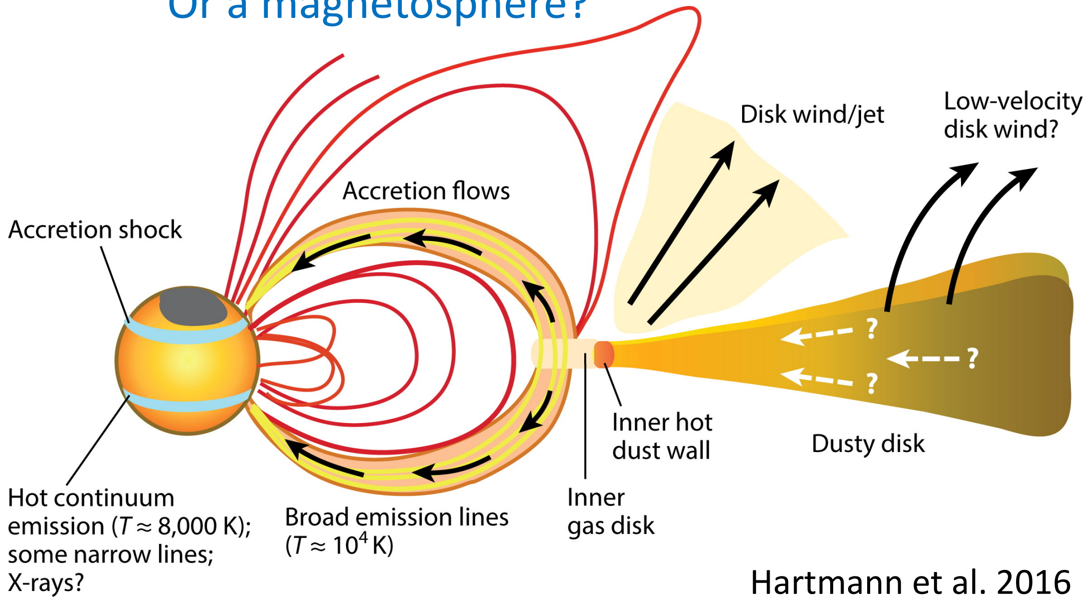
Double-peaked profile from a thin annulus



Spun to break up, equatorial accretion



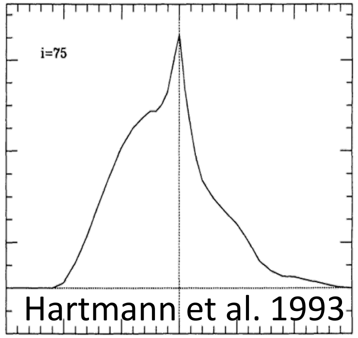
Or a magnetosphere?

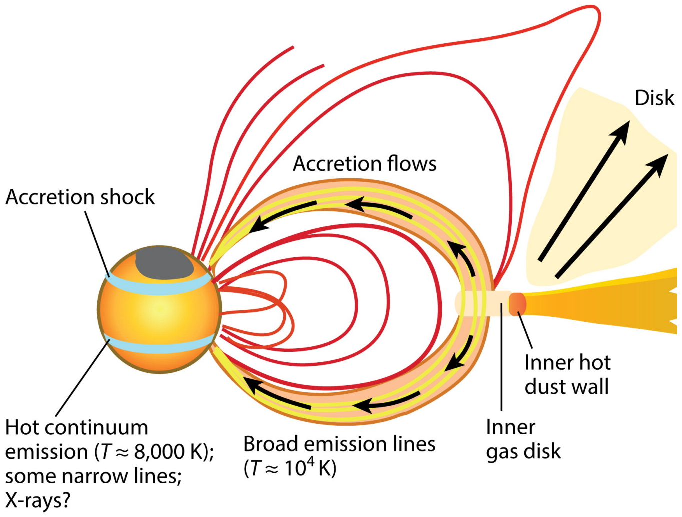


Hartmann et al. 2016

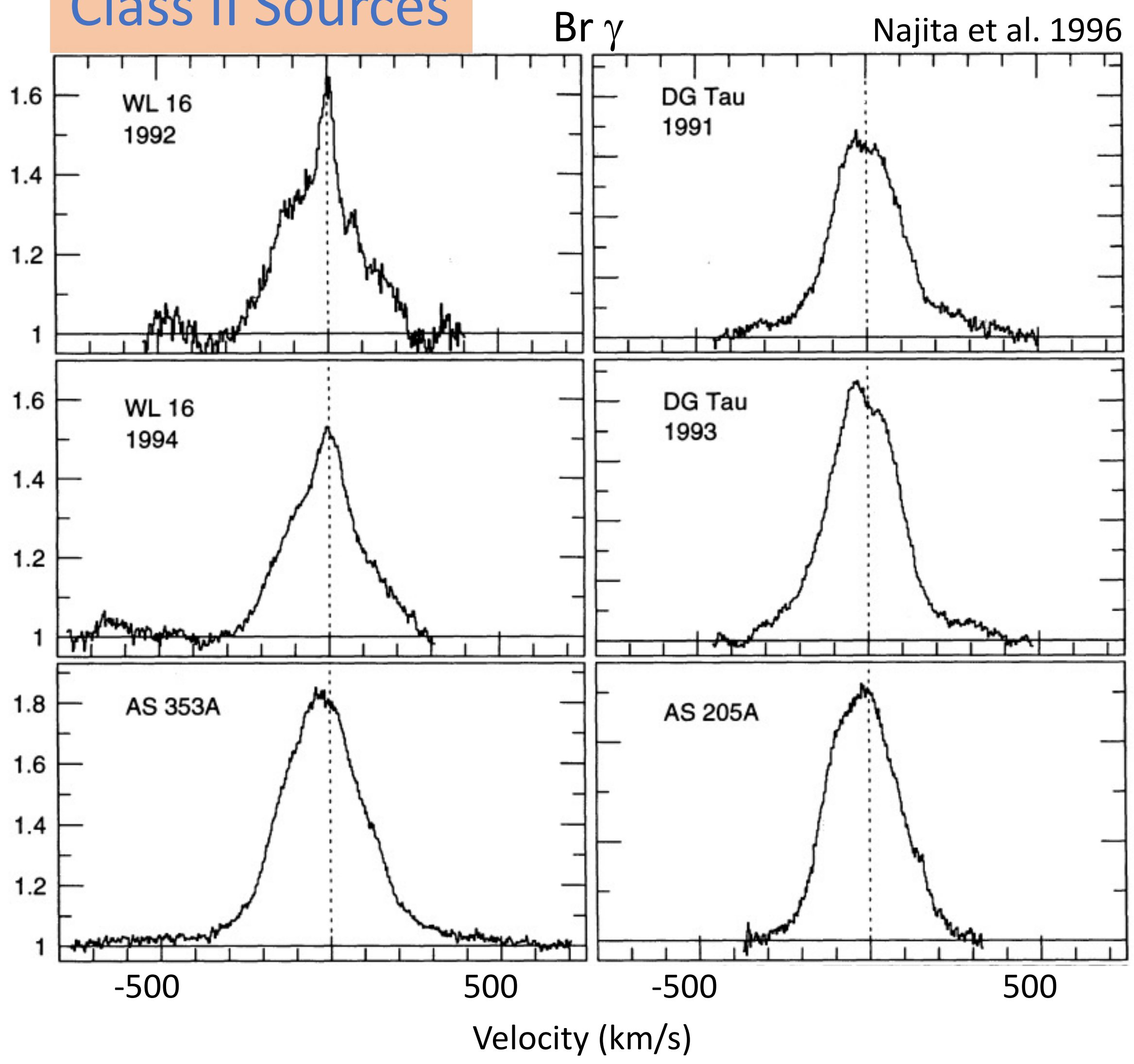
Stellar Accretion via Magnetospheres

Theoretical profiles

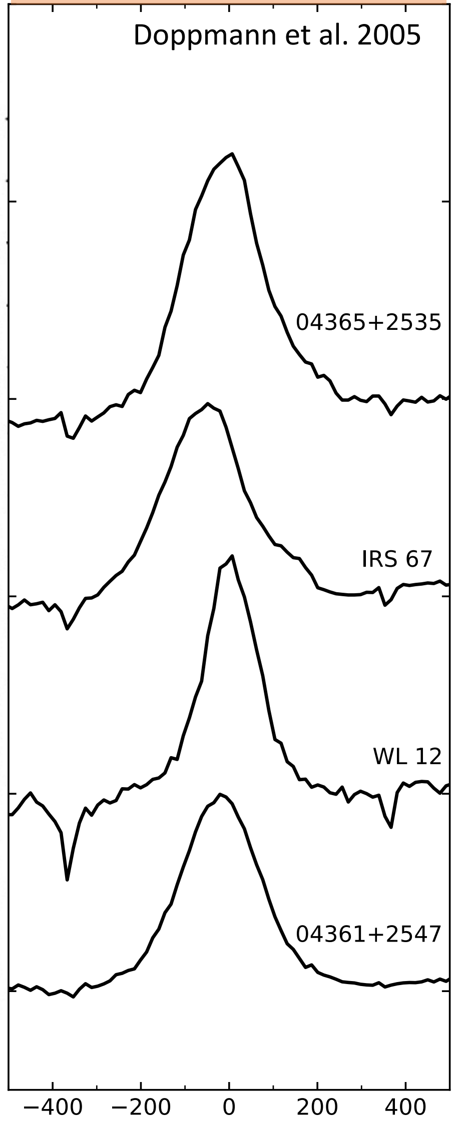




Class II Sources



Class I Sources

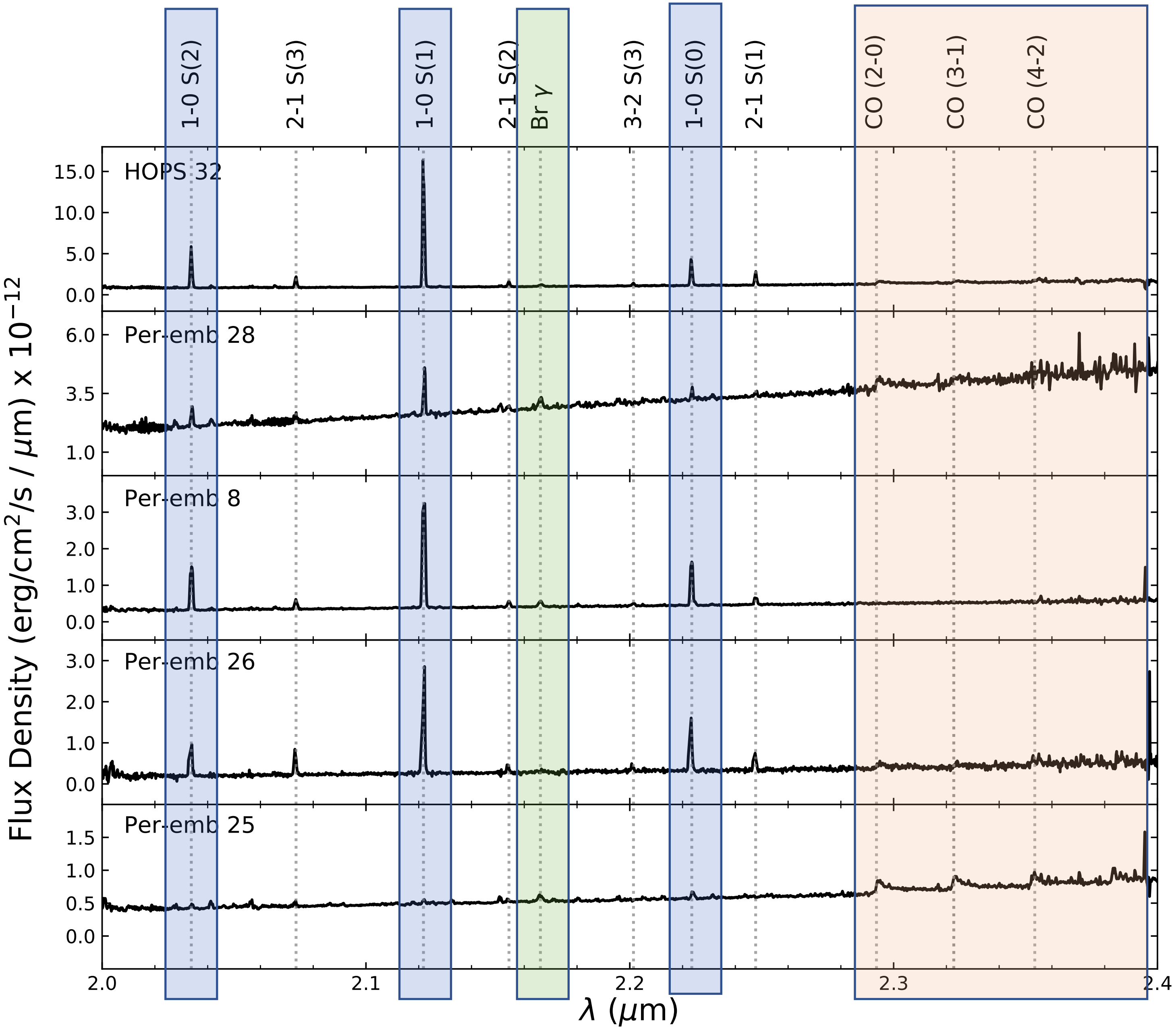


Also Calvet & Hartmann 1992; Hartmann+1994; Muzerolle+1998

NIR Spectroscopy of Class 0 Sources

Stefan Laos + T. Greene, K. Stassun, JN
arXiv:2108.10169

- Keck/MOSFIRE (R=2400)
- Outflow/jets (H_2)
- Disk accretion (CO overtone)
- Stellar accretion (Brγ)



NIR Spectroscopy of Class 0 Sources

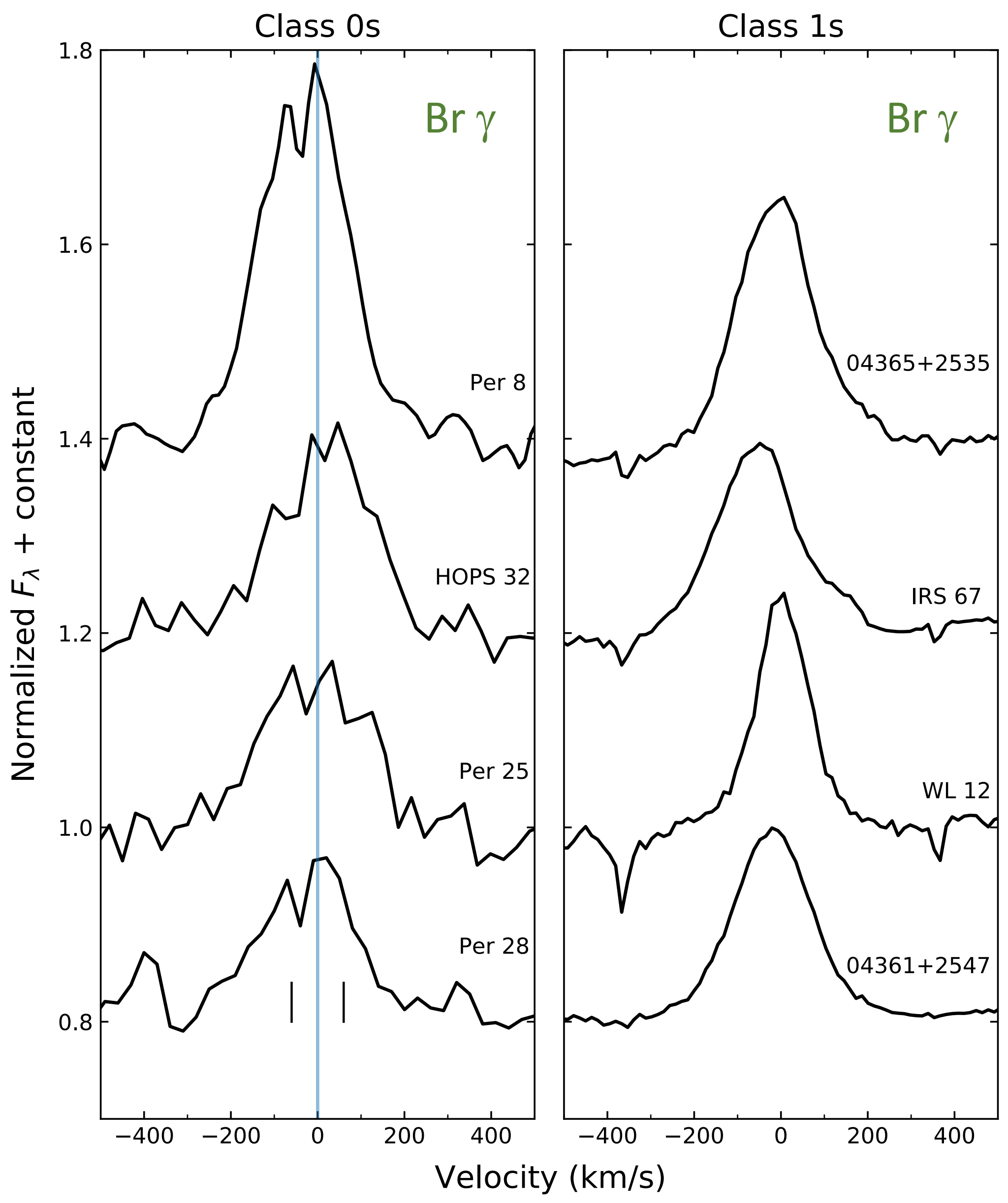
Takeaways:

Can observe Class 0 sources in NIR!

Br γ profiles like Class I/II

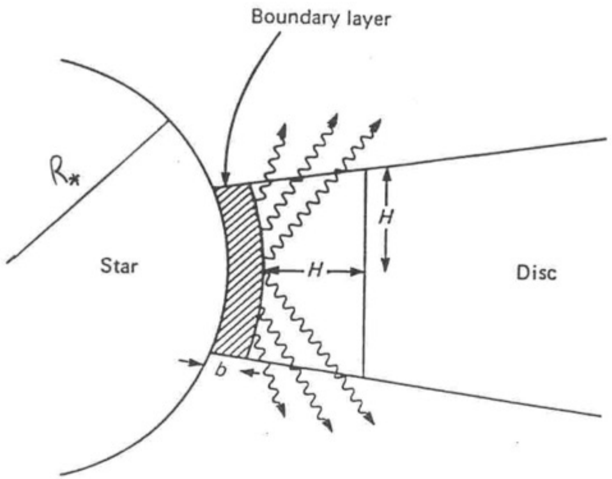
- Organized stellar B forms early
- Star rotates below breakup
- Accretion through magnetosphere

Protostars ”grow up” quickly – feeding behavior established early



Accretion onto Star

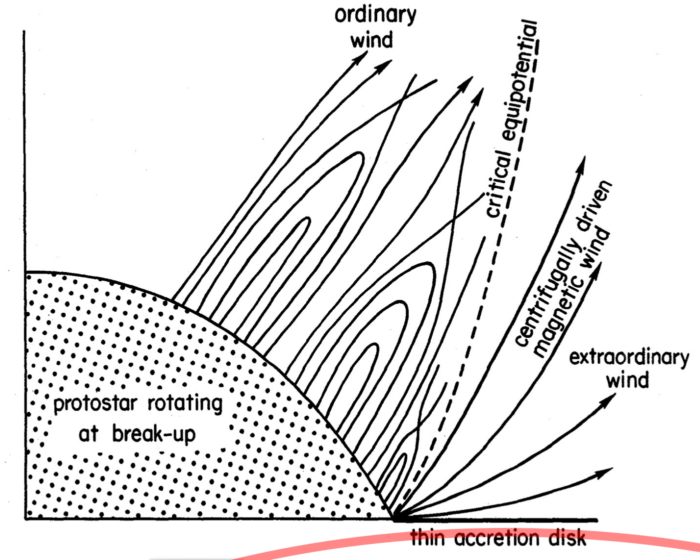
Via a boundary layer?



Credit: B. Ryden

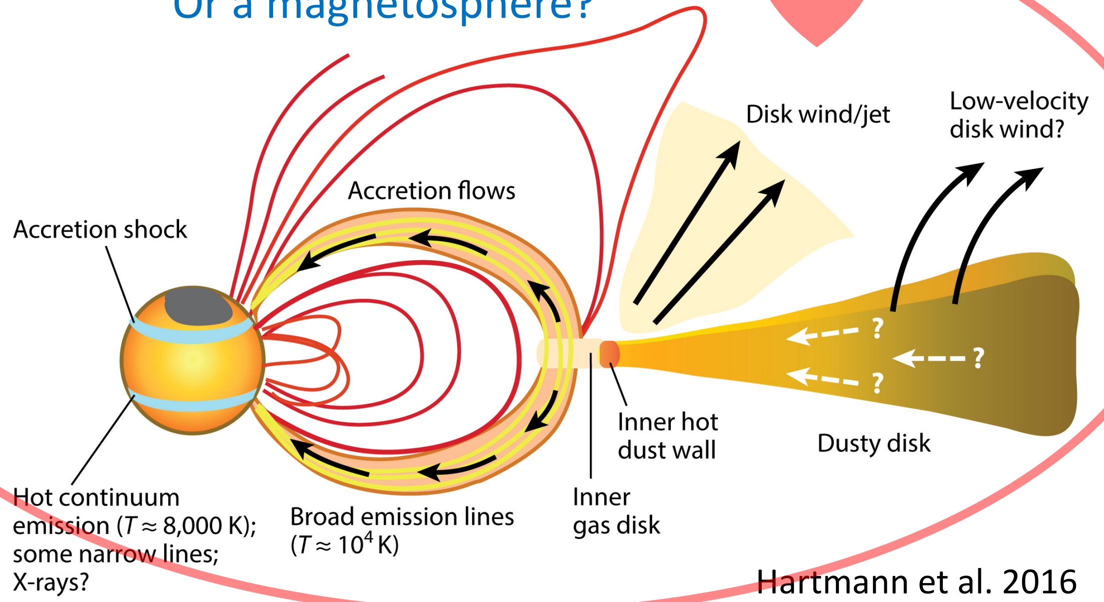
b < H < R*

Spun to break up, equatorial accretion



Are magnetospheres always the answer?

Or a magnetosphere?



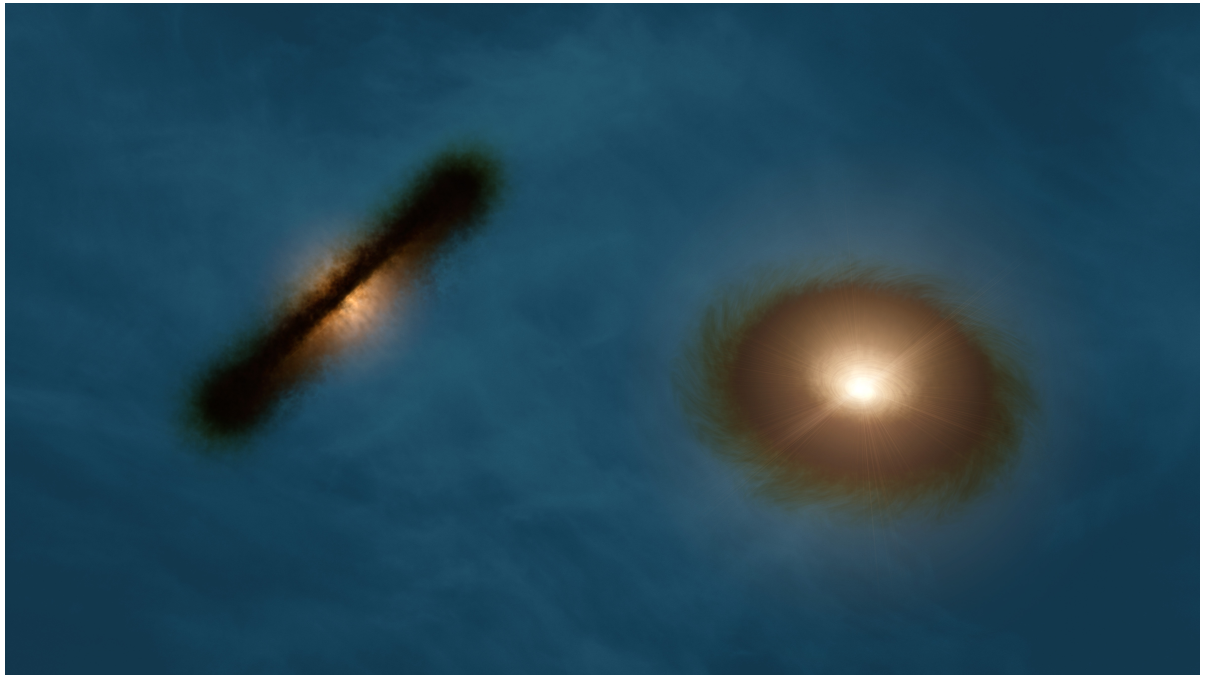
Hartmann et al. 2016

How do disks accrete?

Supersonic surface accretion in a Class I Disk

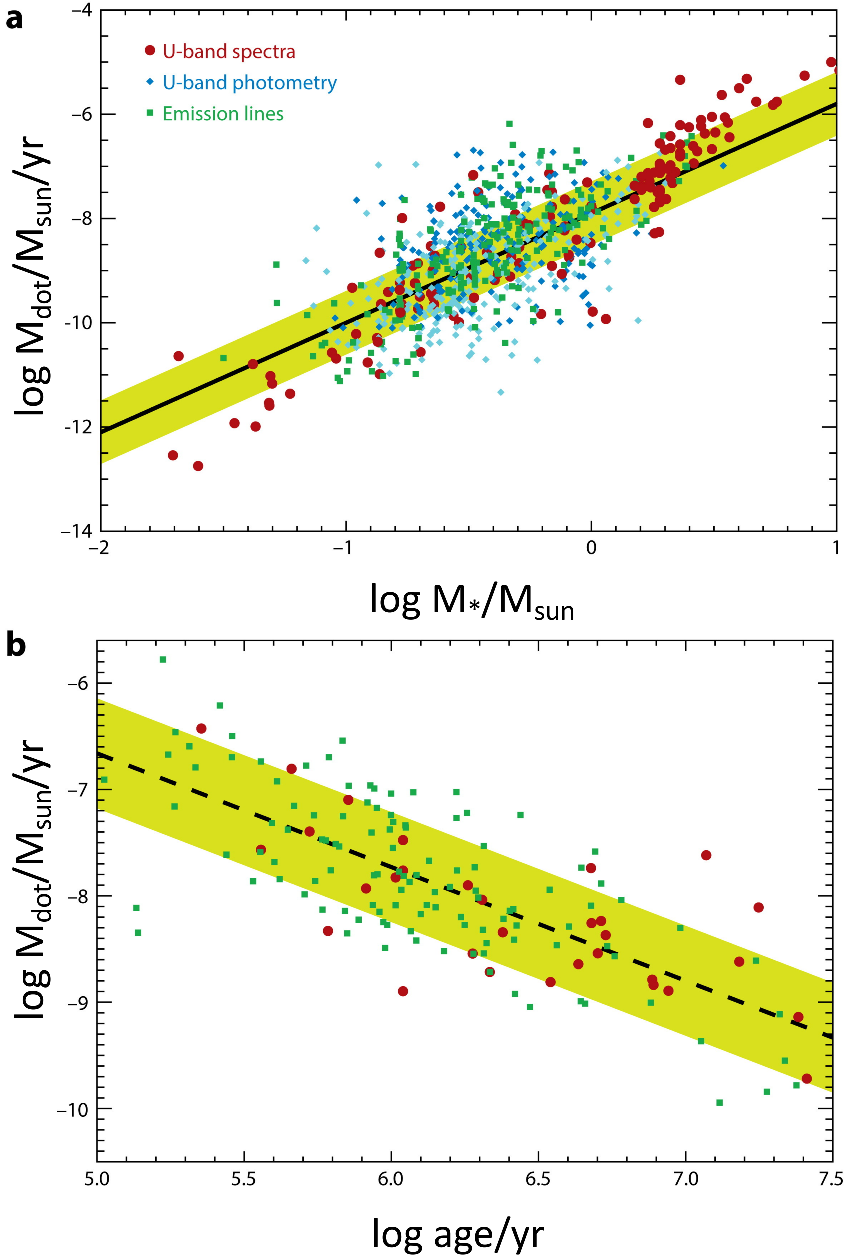
(Najita et al. 2021)

Stars accrete through disks

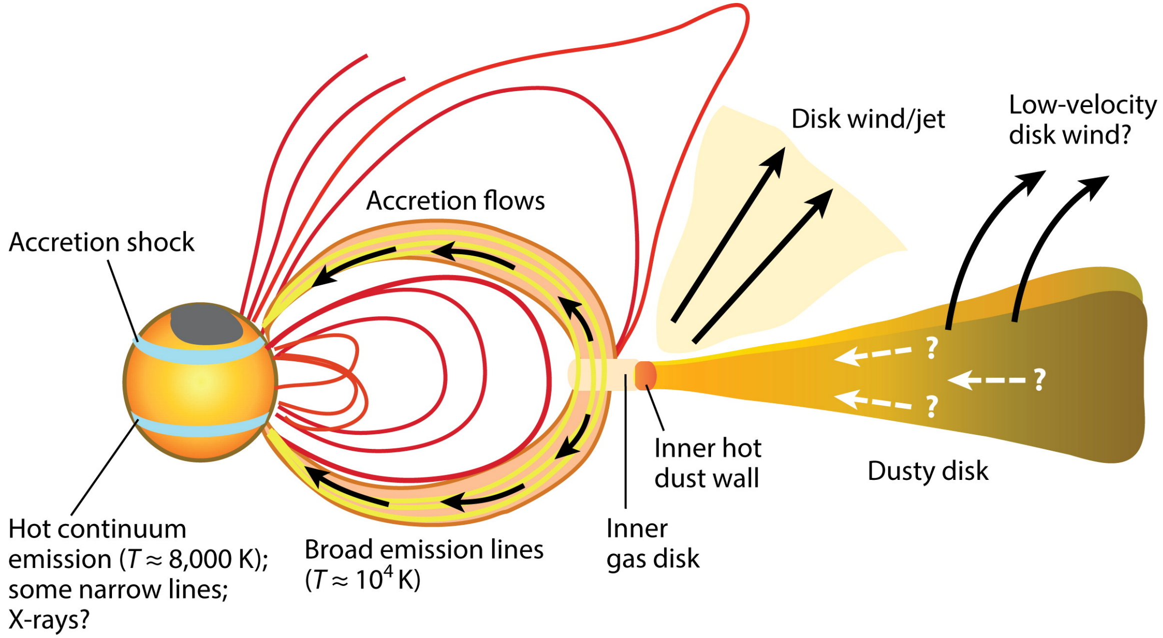


They all do it.
How do they do it?

Hartmann et al. 2016



How does matter reach the magnetosphere?



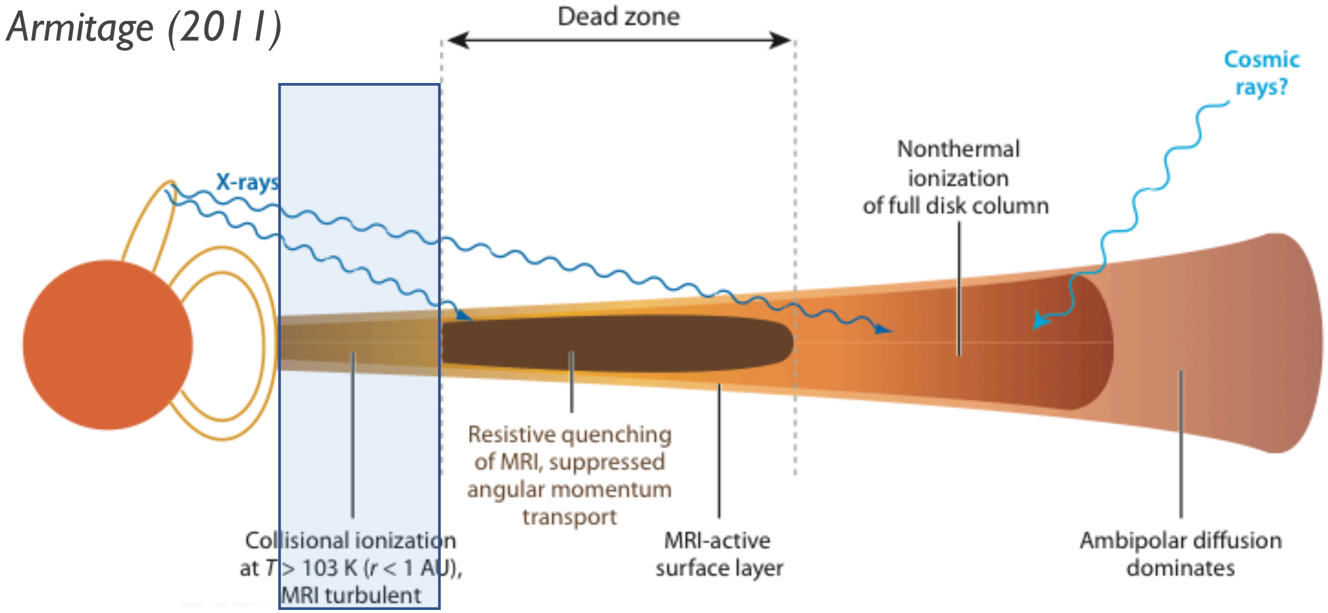
Stars accrete via magnetospheres and transport angular momentum to the inner disk, which is removed in a wind/jet from inner disk.

But how does accreting matter reach the magnetosphere?

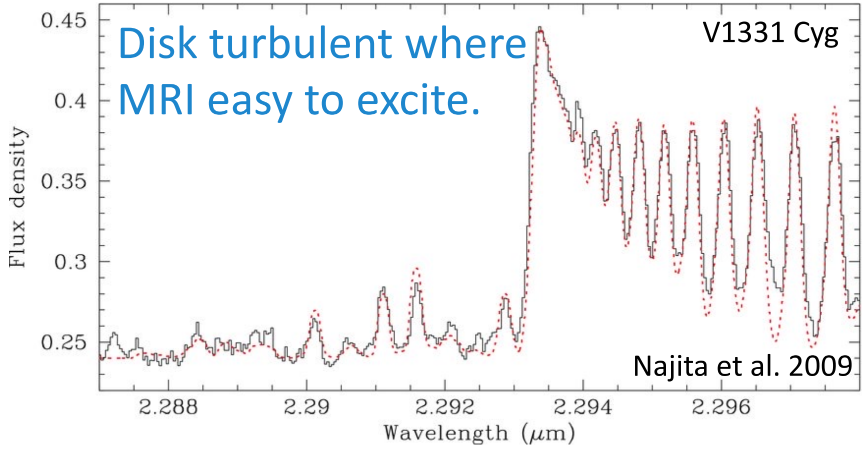
How do disks accrete: via MRI in inner disk

Hot inner disk (> 1000 K)
collisionally ionized

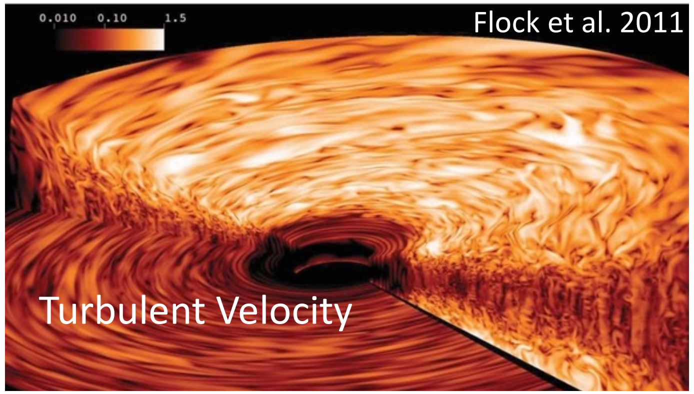
Armitage (2011)



Disk turbulent where MRI easy to excite.



Najita et al. 2009

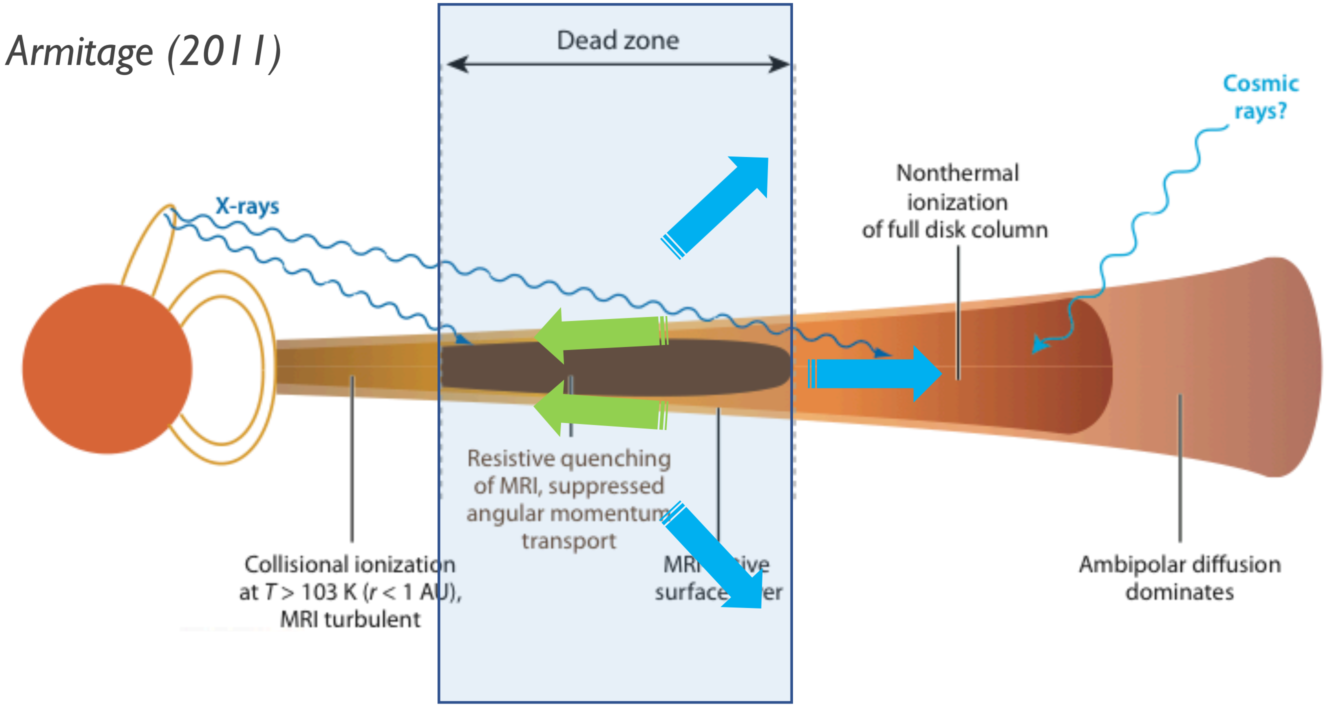


Flock et al. 2011

How do disks accrete: planet formation region

Difficult “middle” region:
- MRI turbulence?
- MHD winds?
- Other?

Armitage (2011)



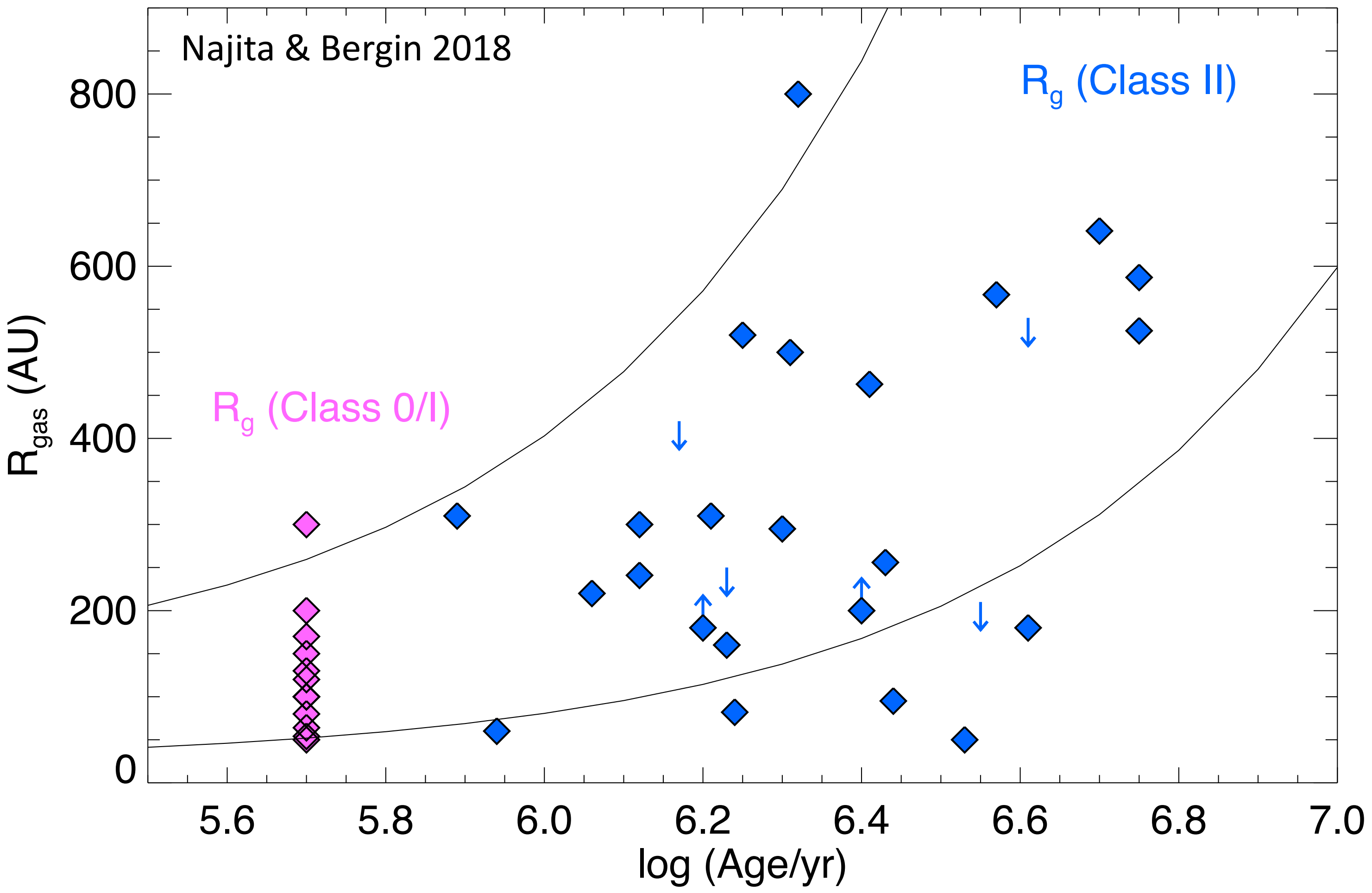
Open questions
- How do disks accrete?
- Where, how much of disk accretes?

Can we look in the disk for clues?

Gas disks grow larger as they age

Some Class II gas disks are bigger than Class I disks.

“in-disk” angular momentum transport is significant enough for this to happen



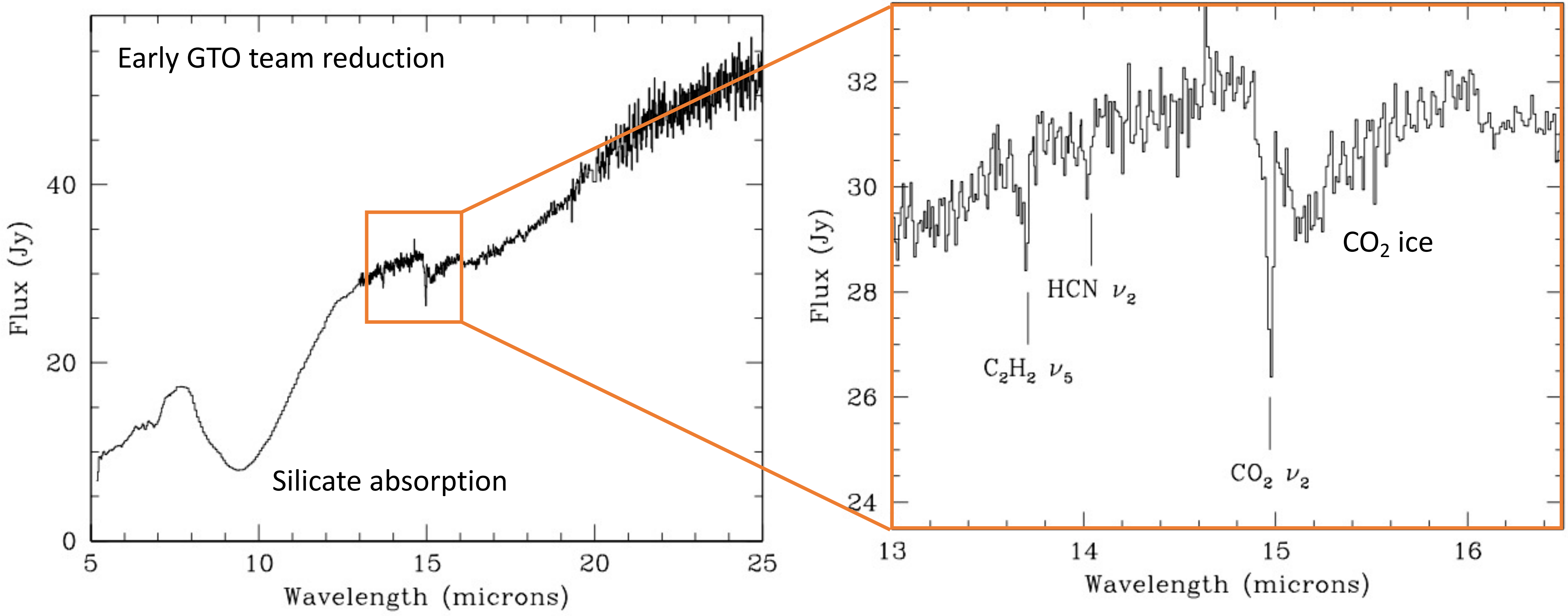
GV Tau N & TEXES

GV Tau: Class I source in Taurus
a.k.a. Haro 6-10, IRAS 04263+2426

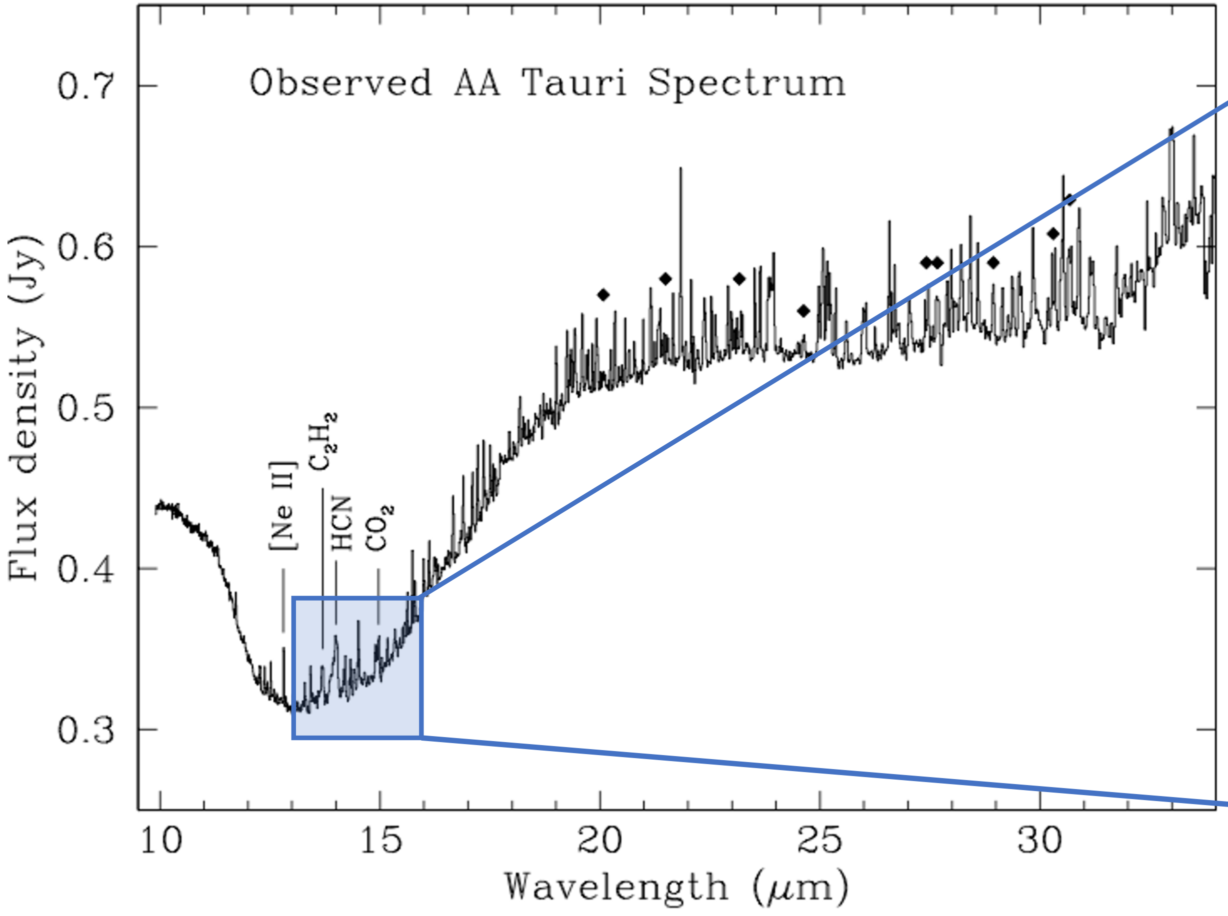
Weak gas and dust emission from envelope, more evolved Class I source (Hogerheijde et al. 1998).

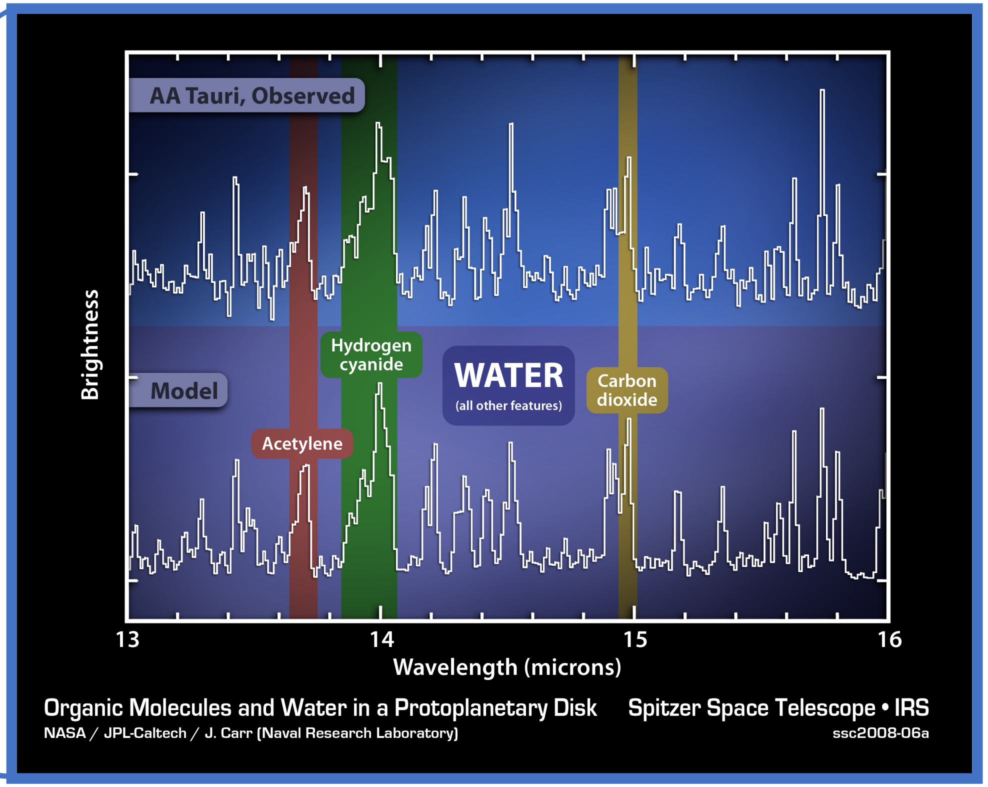
GV Tau N: IR companion of optically visible TTS

GV Tau N: Spitzer/IRS molecular absorption



Inner Disk Molecules in Emission

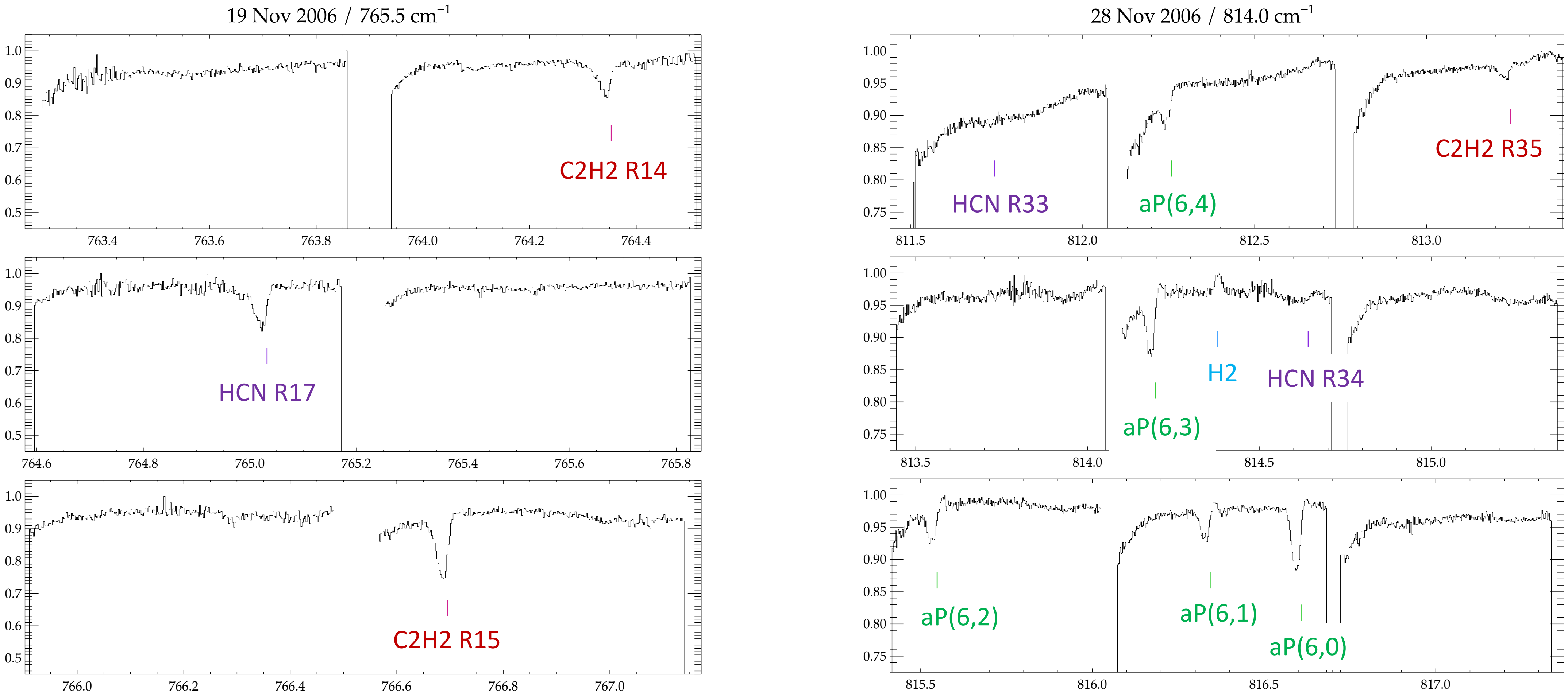




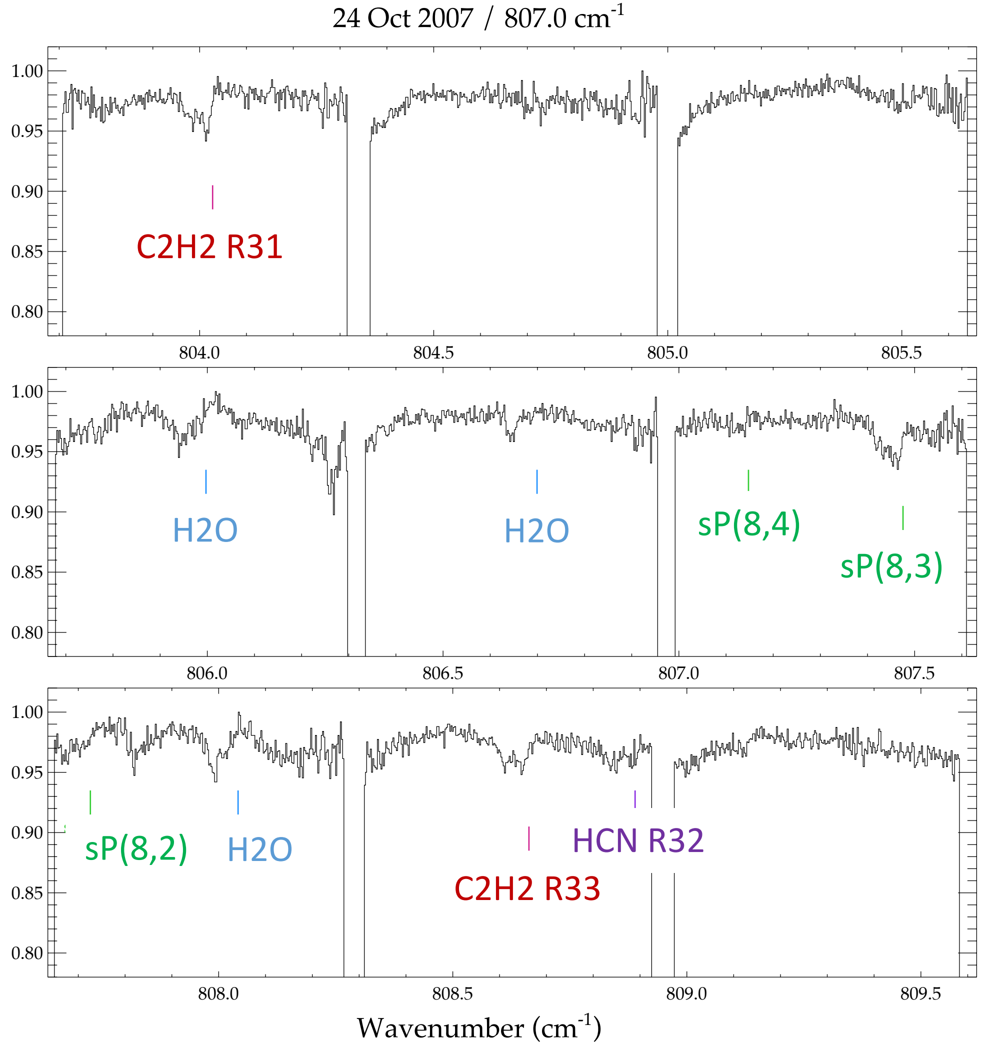
GV Tau N: TEXES/Gemini 2006

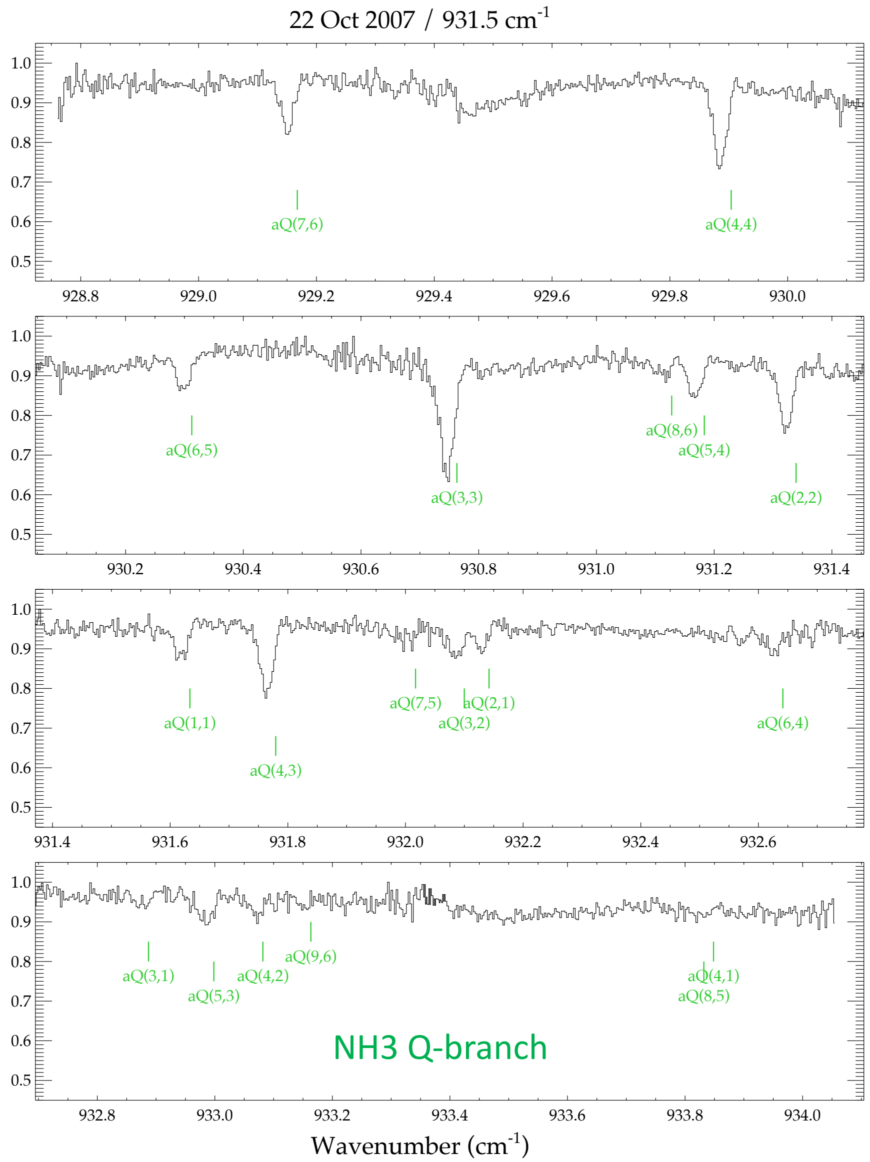
R = 100,000 MIR spectrograph on IR-optimized Gemini-North telescope

First NH_3 detection from disks



GV Tau N: TEXES/Gemini 2007





GV Tau N: high resolution line profiles

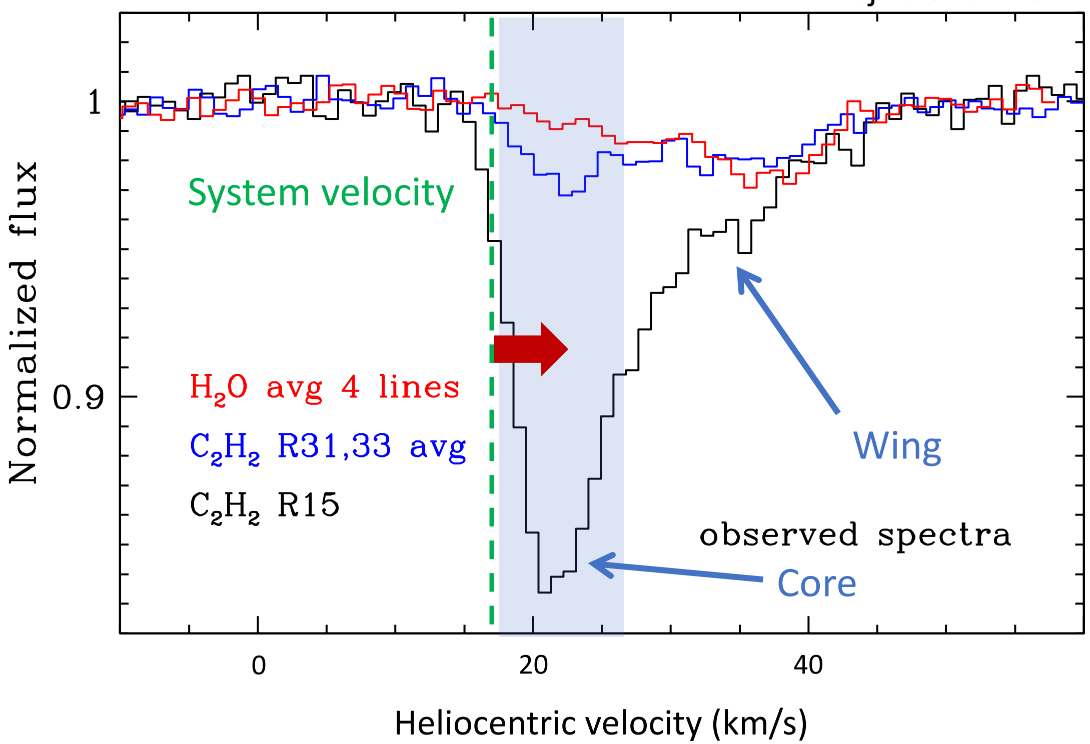
Redshifted line profiles

- 4-20 km/s
- C2H2, HCN, NH3, H2O
- TEXES/Gemini R=100,000

Measure component equivalent widths and infer

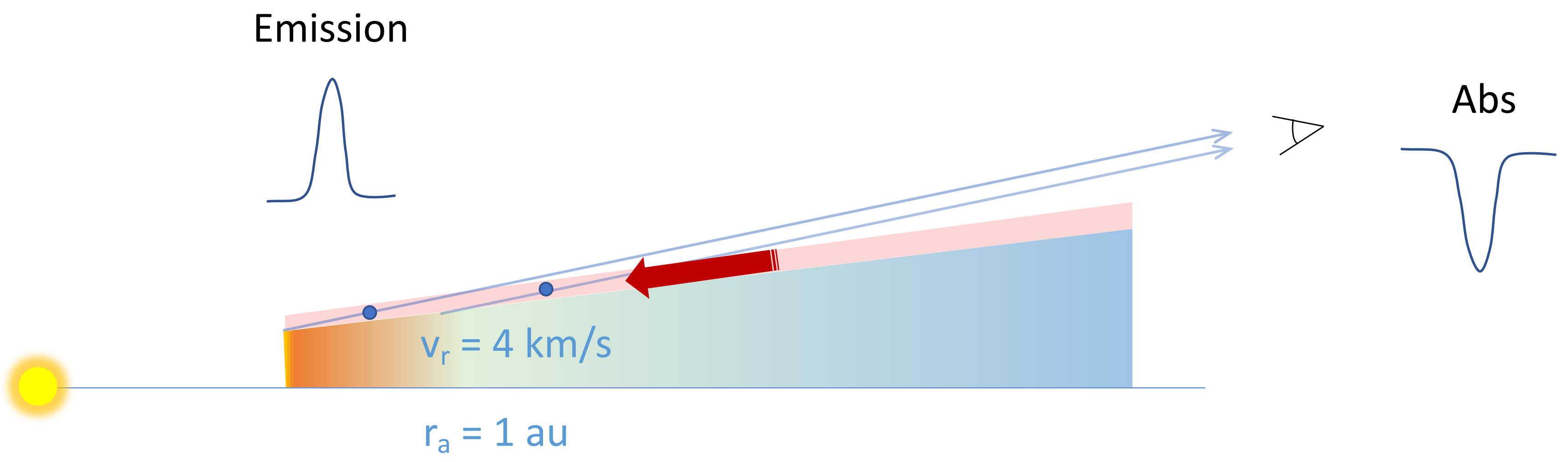
- Temperature T
- Absorption column density N
- Intrinsic line width Δv
- Filling factor f

Najita et al. 2021



- Molecular abundances, temperature of inner disks at ~ 1 au
- High column density → disk atmosphere viewed edge on
- Supersonic inflow velocities

Inner disk atmosphere seen edge on



Disk accretion in action through disk atmosphere?

Accretion rate ~ TTS:

10^{-8} - 10^{-7} M_{sun}/yr

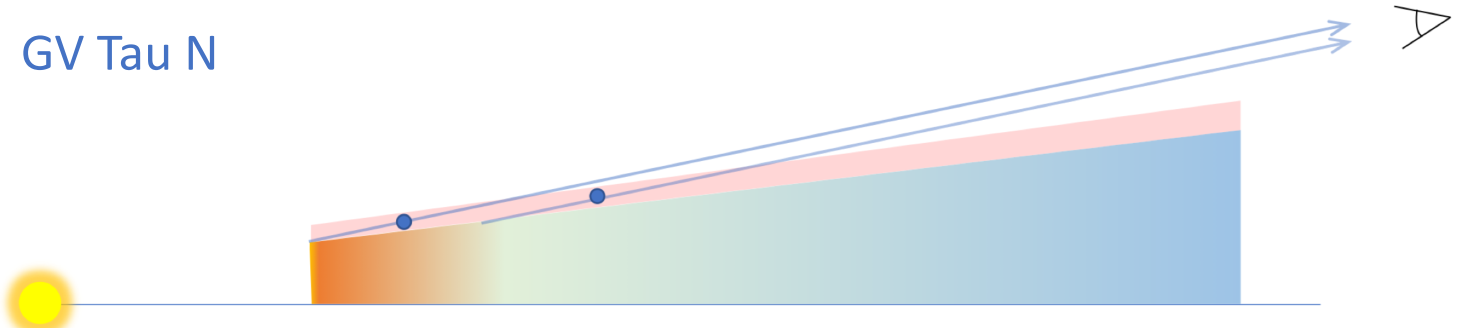
i.e.,

$\dot{M}$dot = $2\pi r_a m_H v_r N_{perp}$

$N_{perp} \sim 0.1\, N_{abs} / x_{mol}$

Familiar But Different

GV Tau N



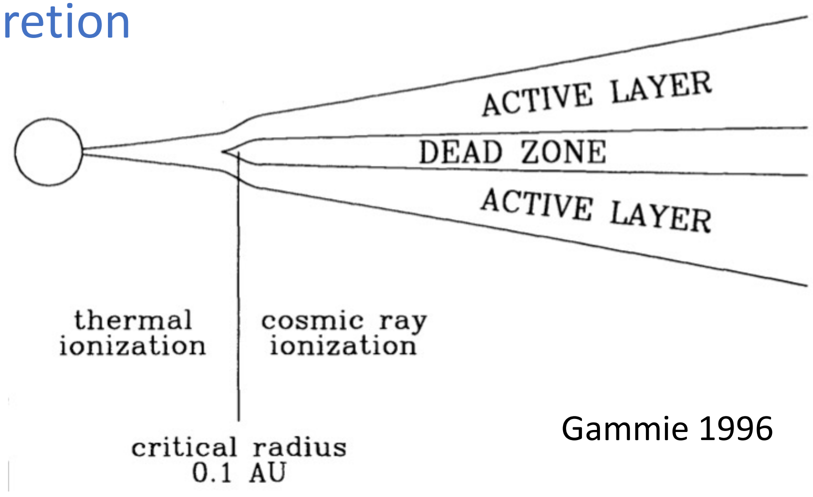
Slim and fast:

$\Sigma_H \sim 0.01$ g cm^{-2}

$v_r \sim 4$ km/s (few c_s)

In plain view

Layered Disk Accretion



Gammie 1996

Thick and slow:

$\Sigma_H \sim 100$ g cm^{-2}

$v_r < 1$ m/s

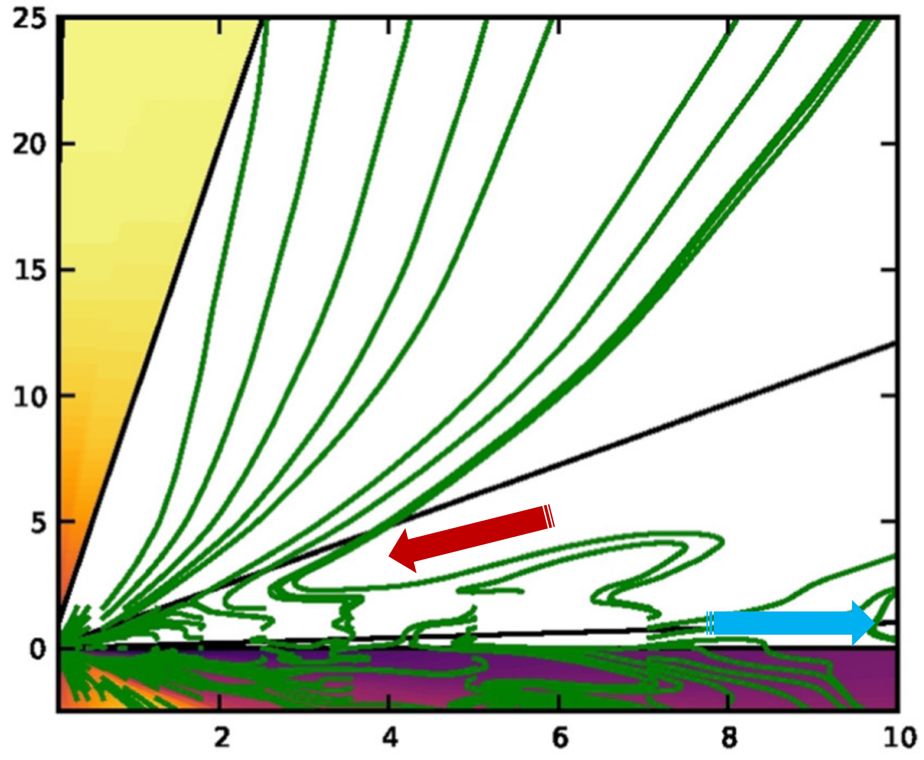
Unobservable

For an alpha-disk:
$v_r = -3/2\ \alpha(c_s^2/v_\phi)$

Why disk inflow?

- **Rapid accretion** at disk surface drags **B** in.
- Surface connects to midplane at larger r, spins down surface to
- Sub-Keplerian rotation (60%)
- **Supersonic inflow** $v_r = 2\text{-}4\ c_s$.
- Inward pinched **B** launches wind, but removes little angular momentum.

Global Evolution of an Accretion Disk with Net Vertical Field: Coronal Accretion, Flux Transport, and Disk Winds
Zhu & Stone 2018



Disk radius (au)

For GV Tau N:

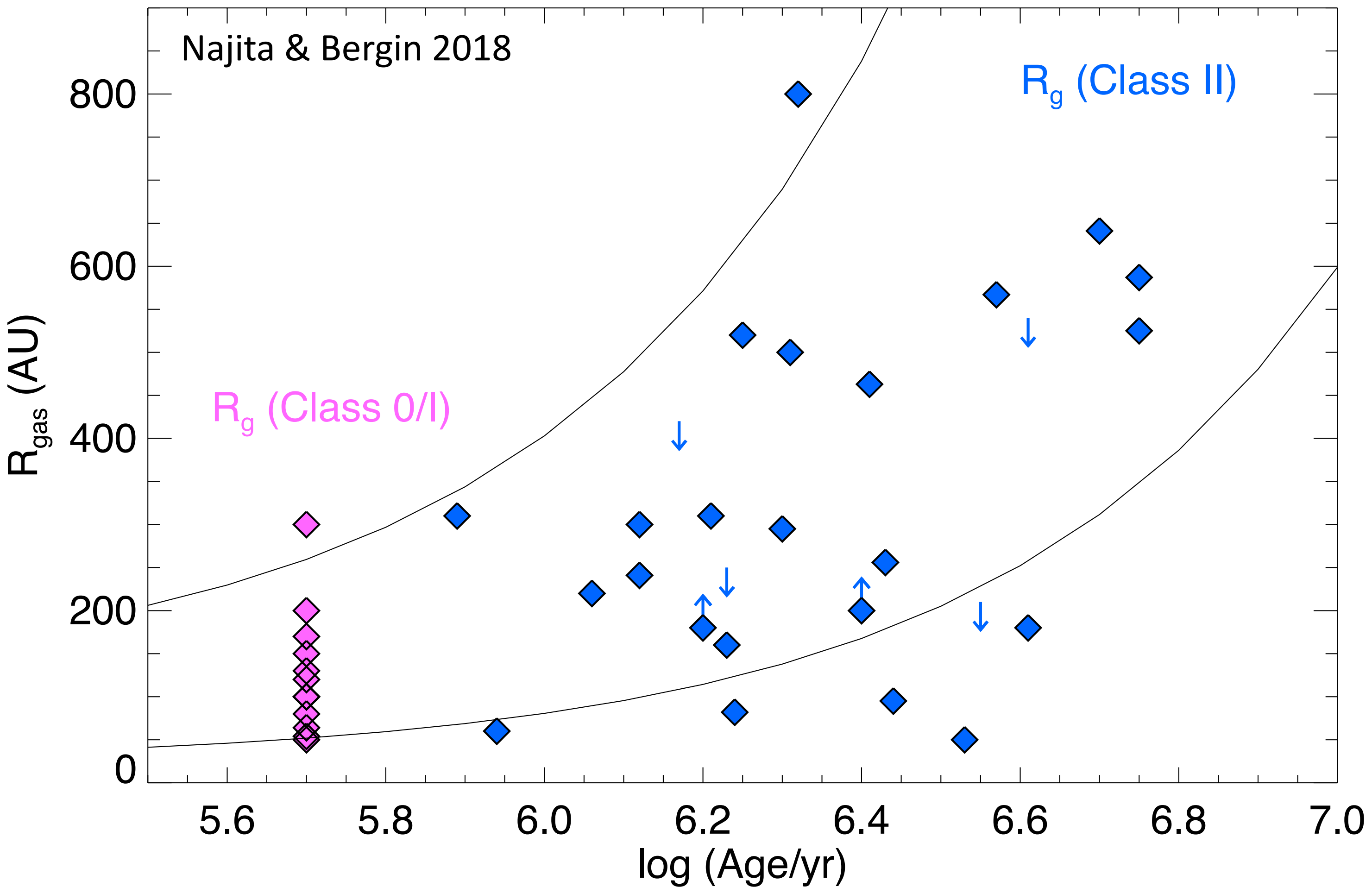
- $v_r = 2\text{-}4\ c_s = \sim 4$ km/s (observed velocity shift)

Wow! are we observing accretion in action?!

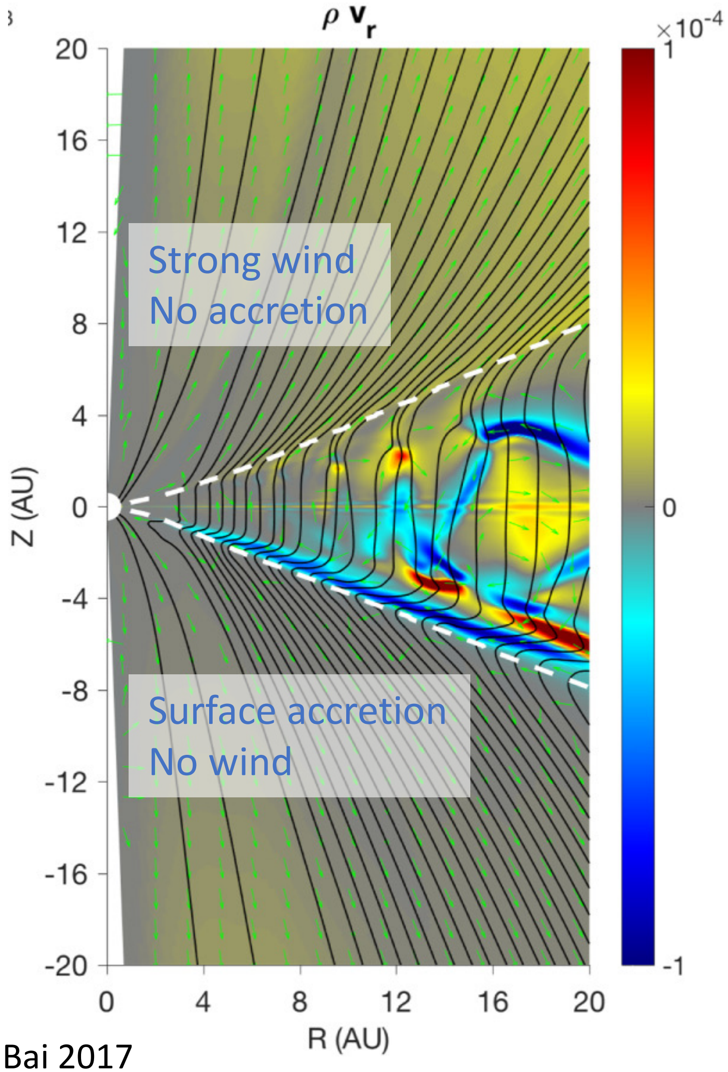
Gas disks grow larger as they age

Some Class II gas disks are bigger than Class I disks.

“in-disk” angular momentum transport is significant enough for this to happen

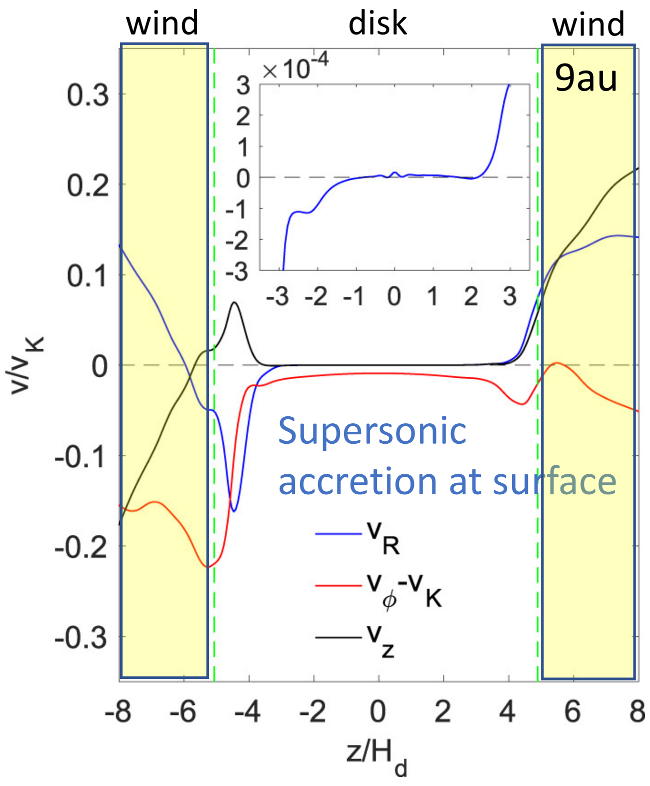


Magnetocentrifugal Wind-driven Accretion



Bai 2017

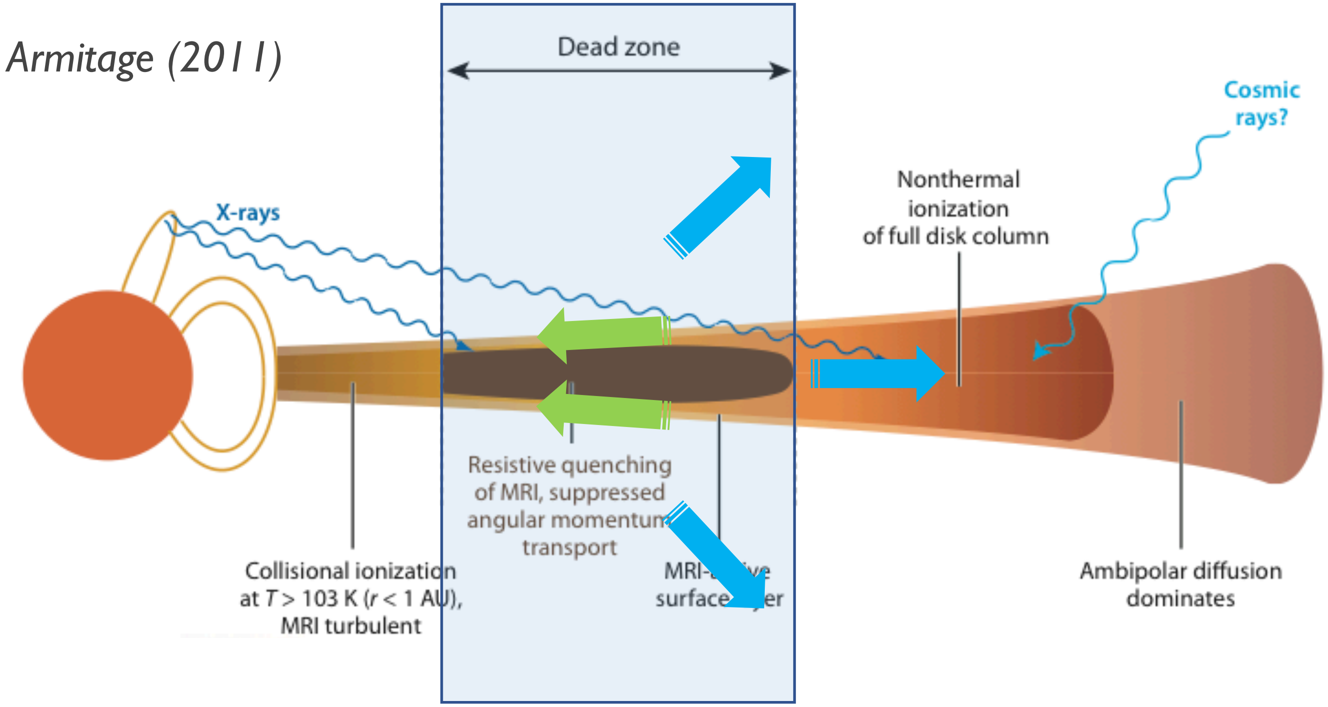
Net vertical magnetic field **anti-aligned** with disk rotation



- Asymmetric, supersonic accretion
- Asymmetric wind

How do disks accrete: planet formation region

Armitage (2011)



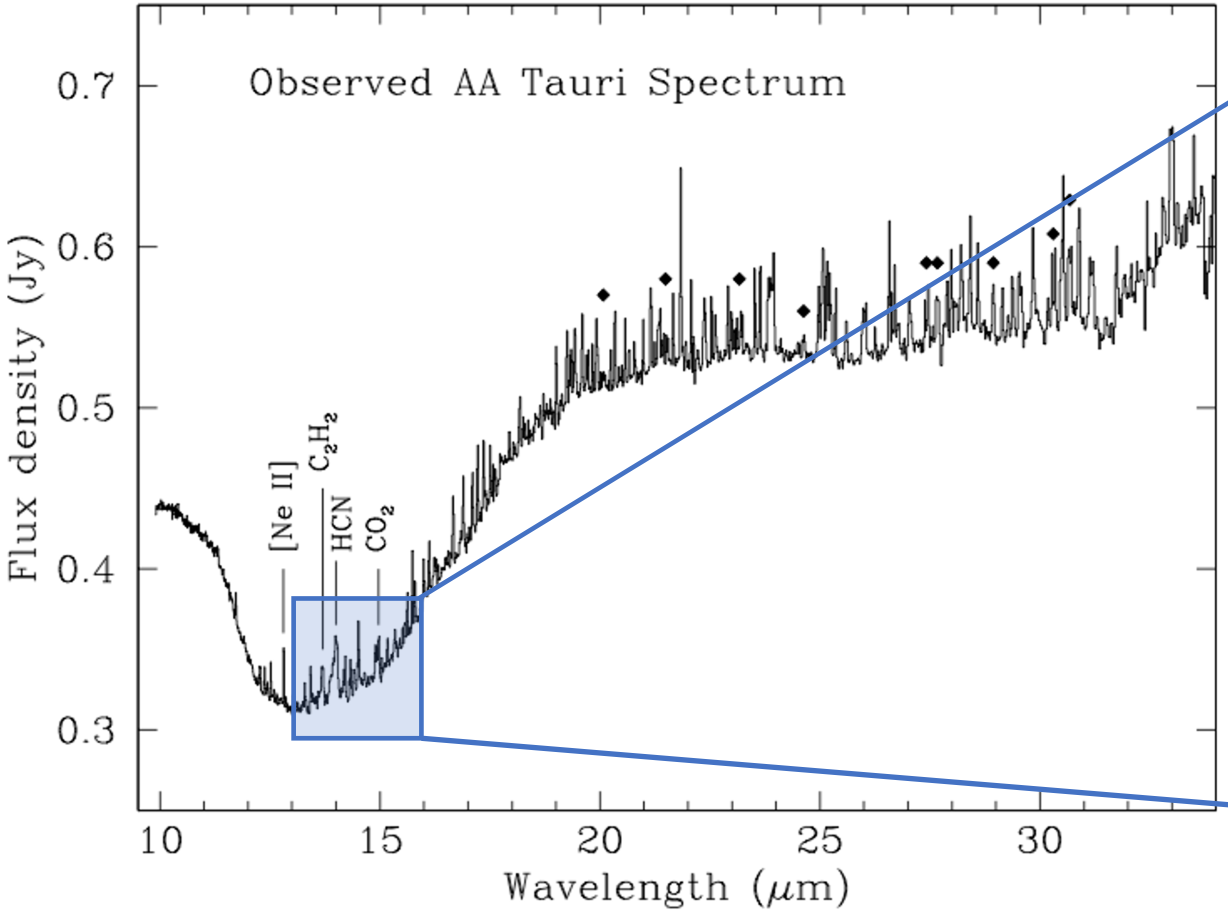
Open questions

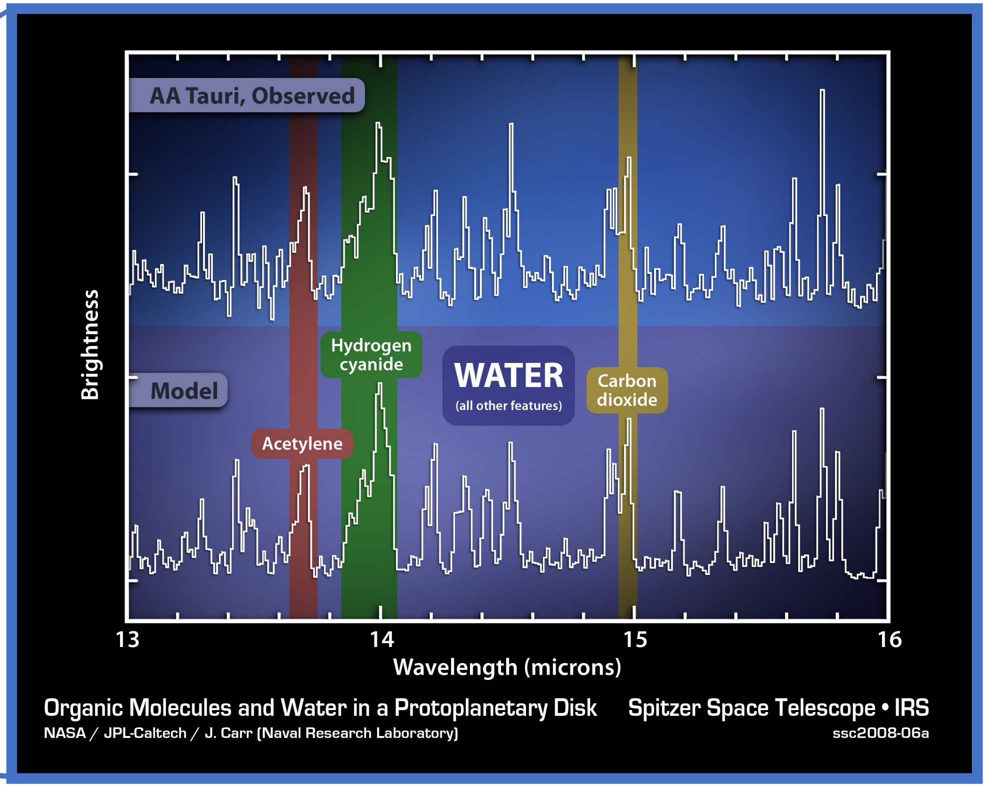
- How do disks accrete?
- Where, how much of disk accretes?

Fortuitous line of sight:
Supersonic surface accretion flows?

Inner Disk Atmospheres in Emission

...may be major accretion zones

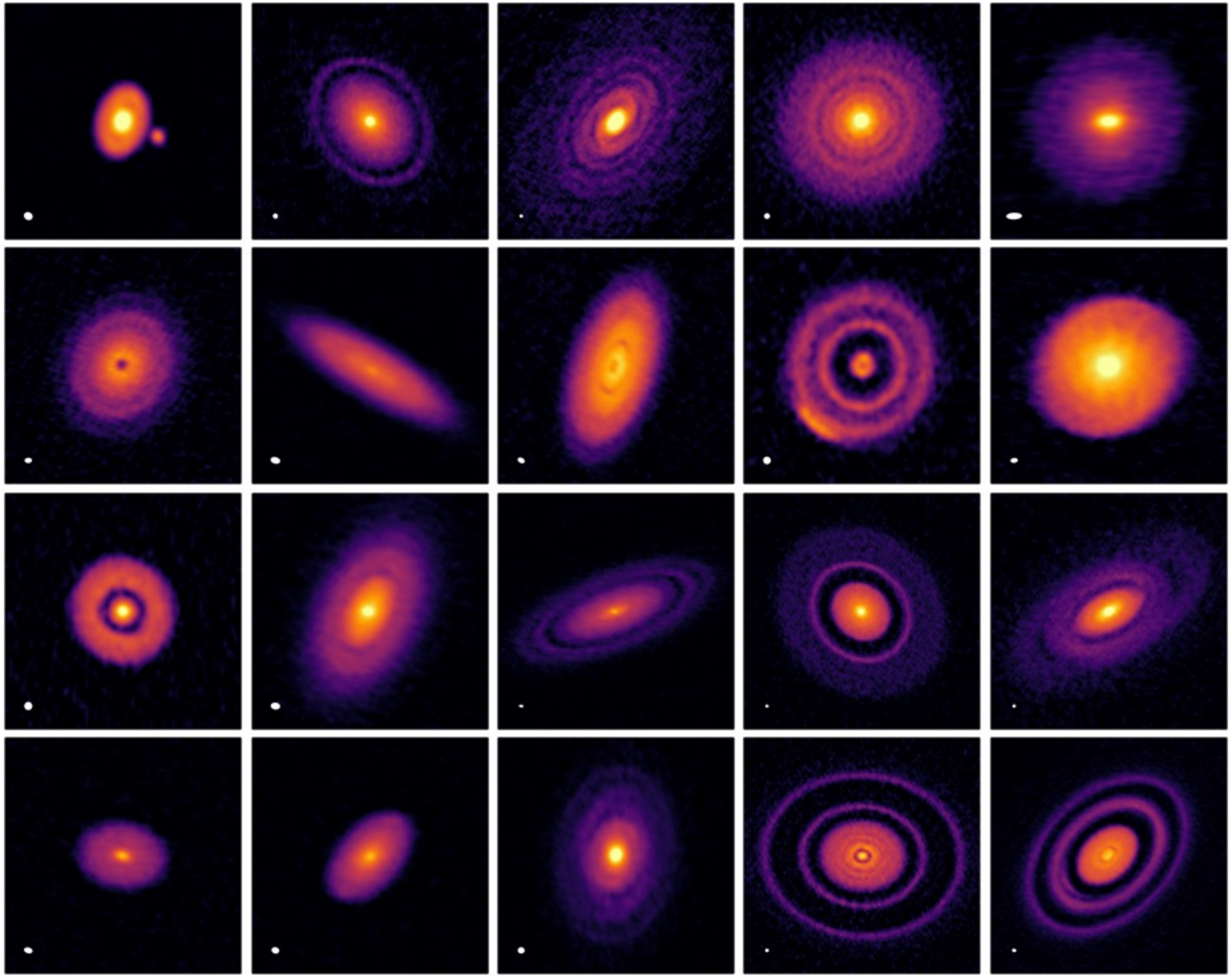




Protoplanetary disks --> Debris disks

Insights from disk rings (Najita, Kenyon, & Bromley, submitted)

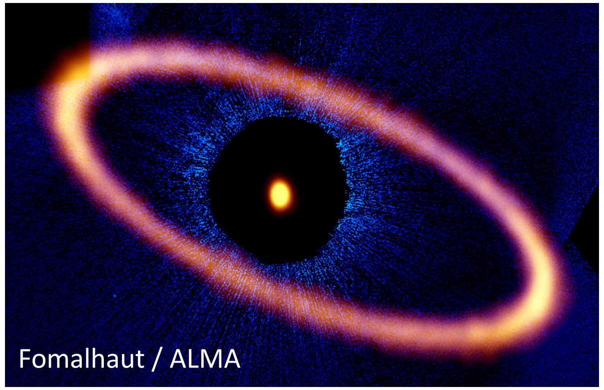
Protoplanetary disks have rings of solids

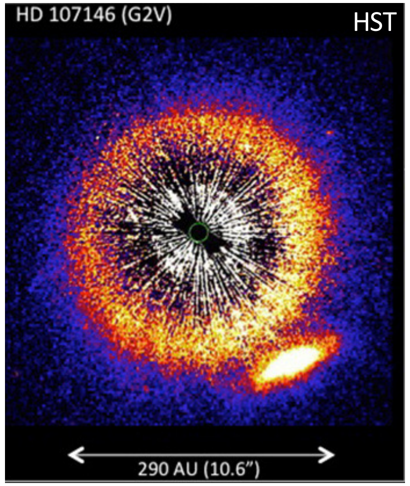


Rings > 30 au

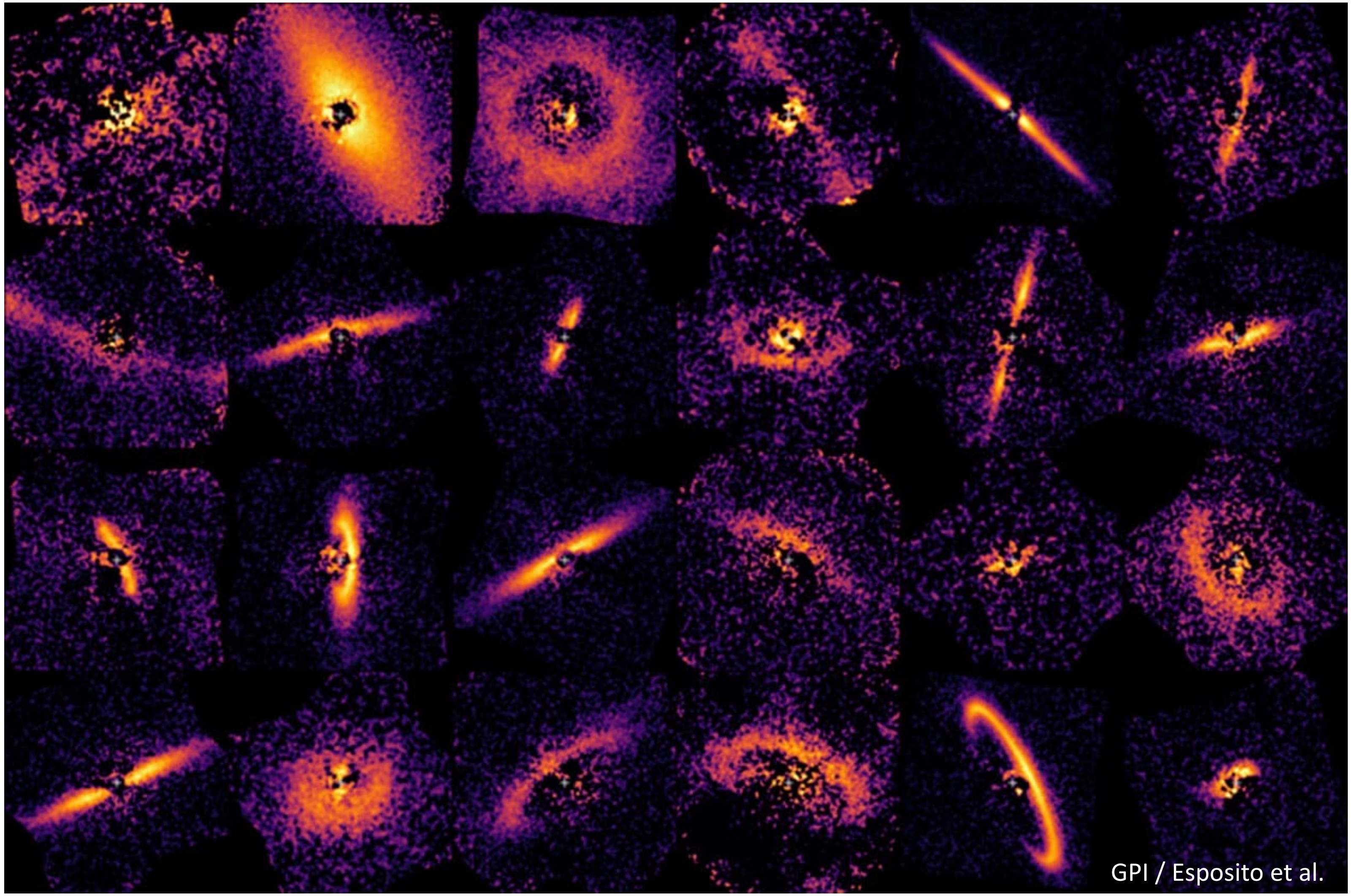
DSHARP

Debris disks also have rings



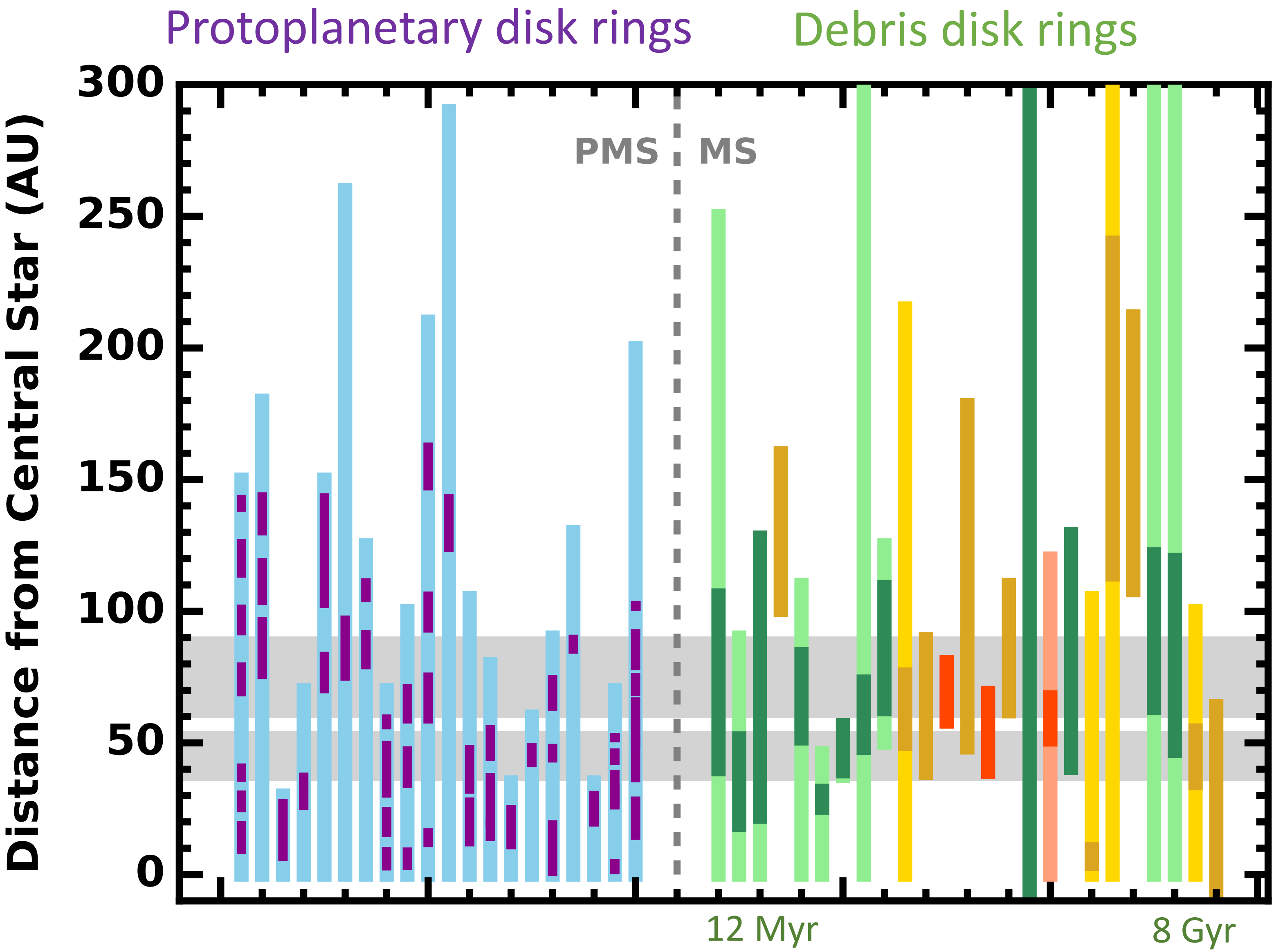


Rings > 30 au



Ring Sizes: evolutionary connection?

- Rings similar in size
- DD ring sizes don't increase with age

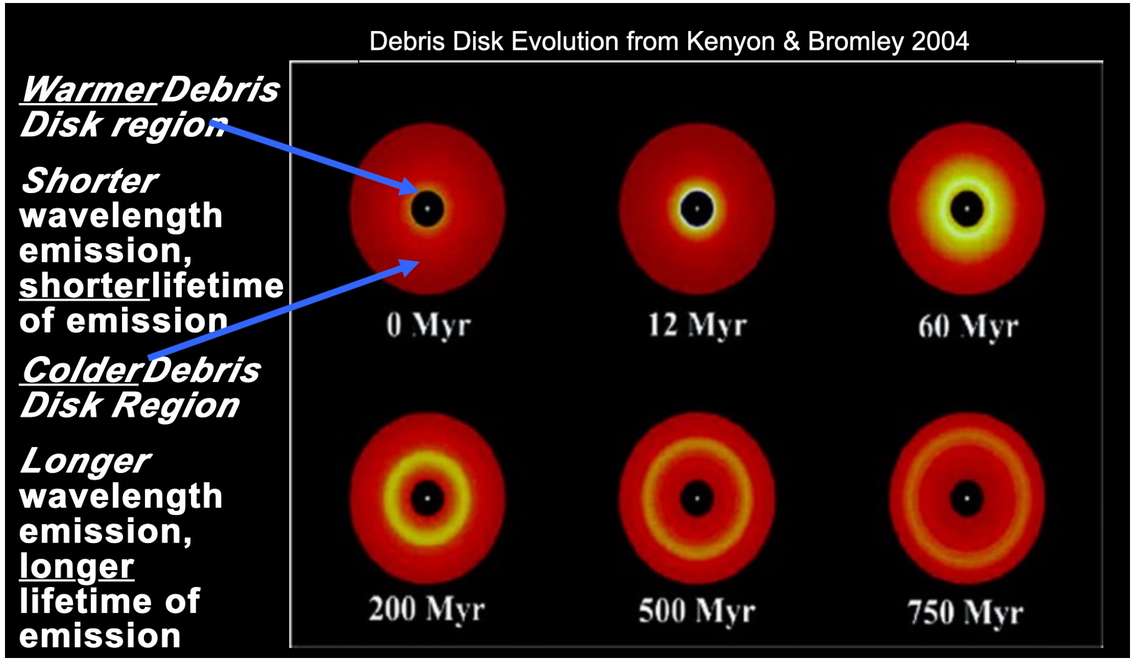


DSHARP

Hughes et al, ARAA

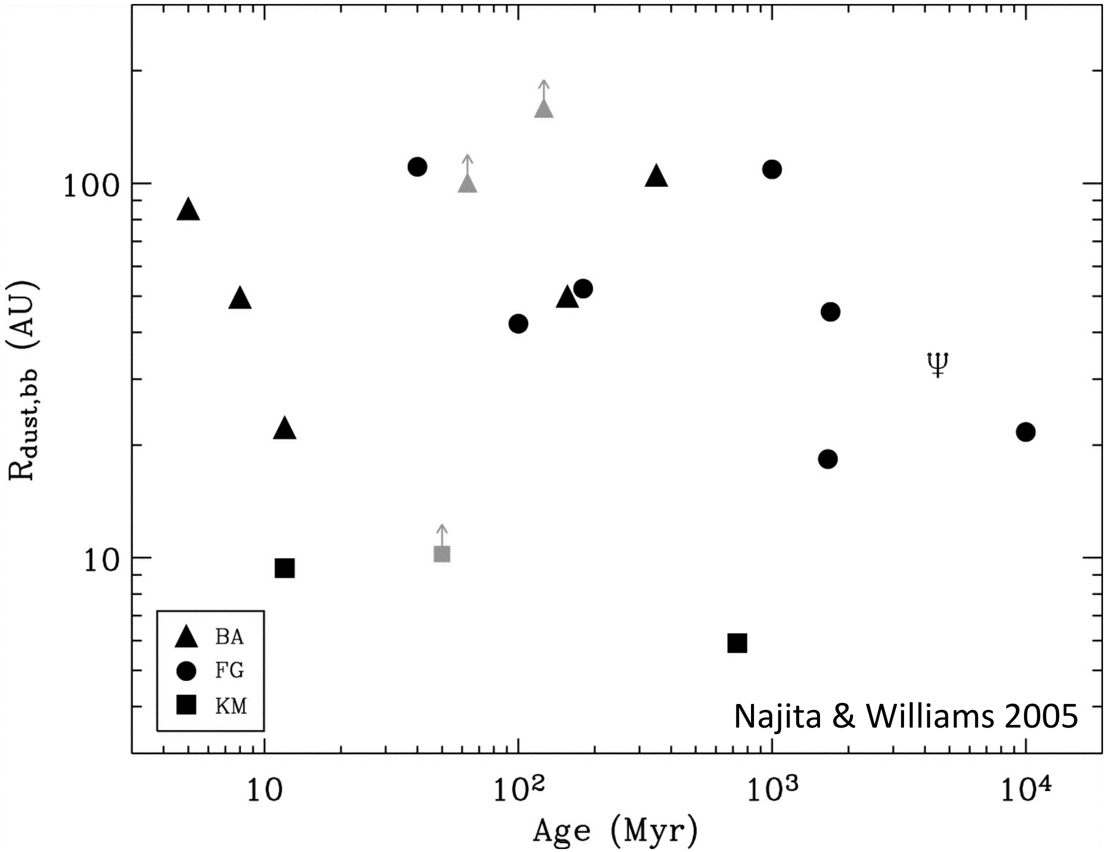
Disk sizes → Planetesimal disks not continuous, extended

Predicted to grow with age in extended disks of planetesimals



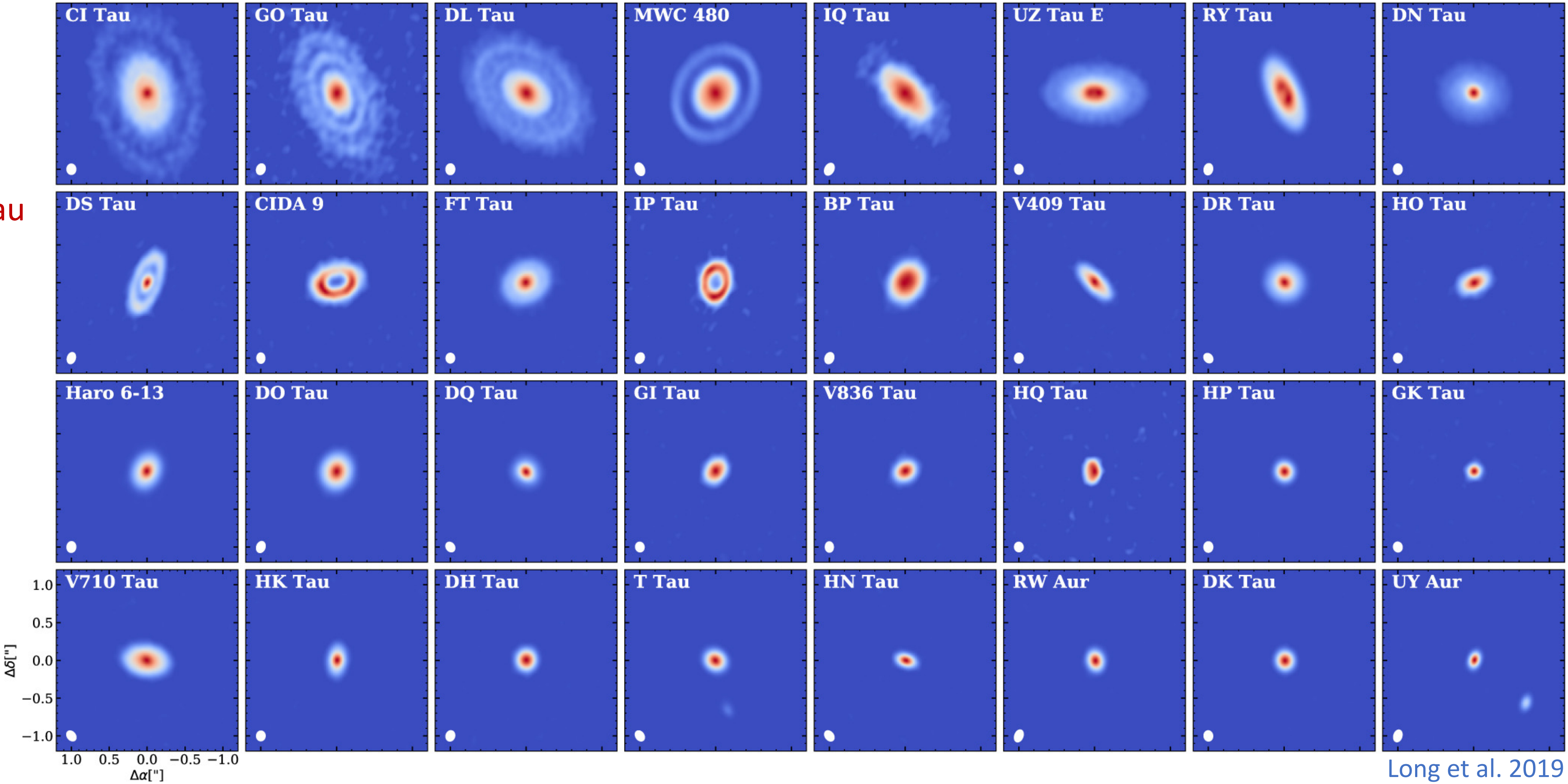
Slide from Thayne Currie

No size-age trend observed



Protoplanetary disks are diverse in size

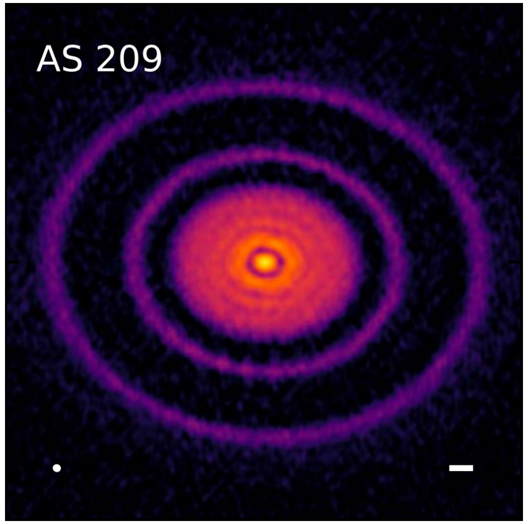
About 20% have large rings > 30 au

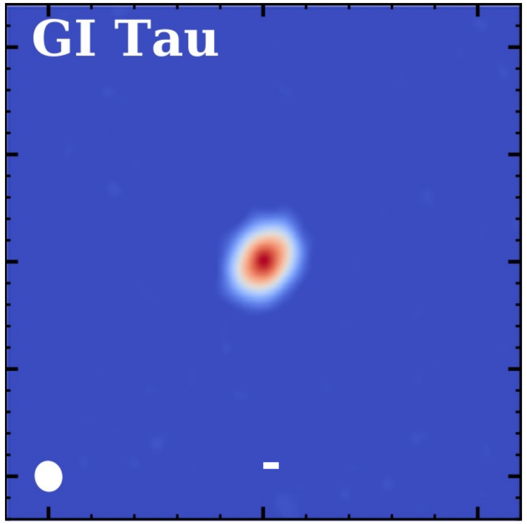


Long et al. 2019

How do

Protoplanetary disks

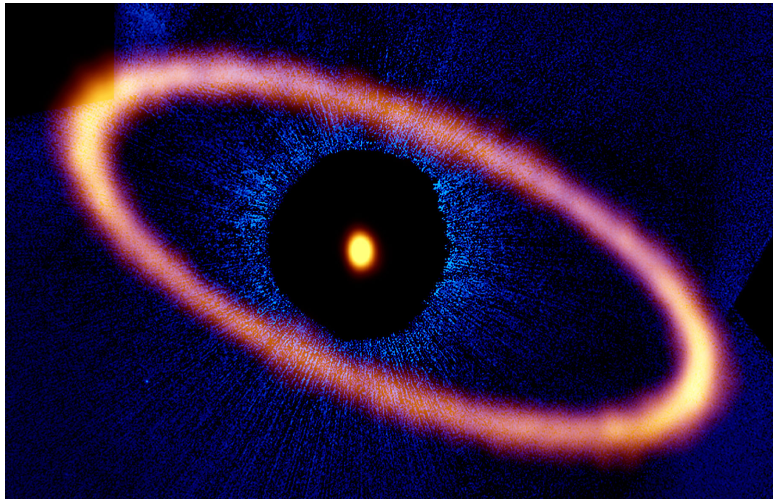




evolve into

?

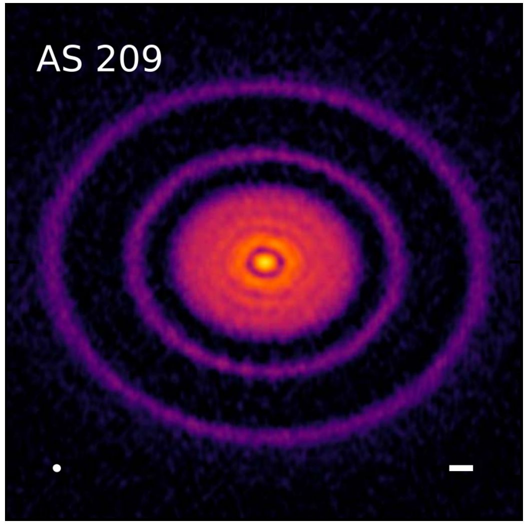
Debris disks

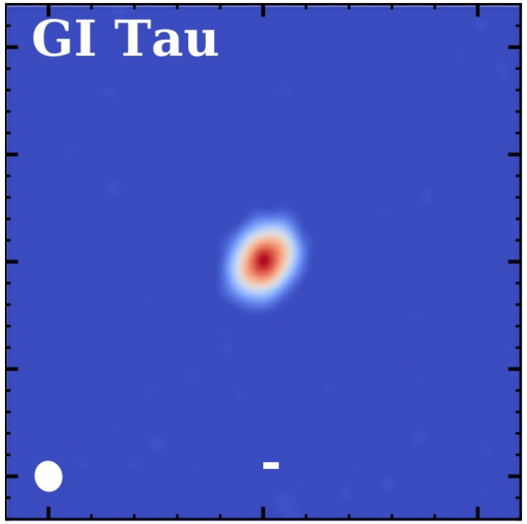


and how does the Solar System fit in?

How do

Protoplanetary disks

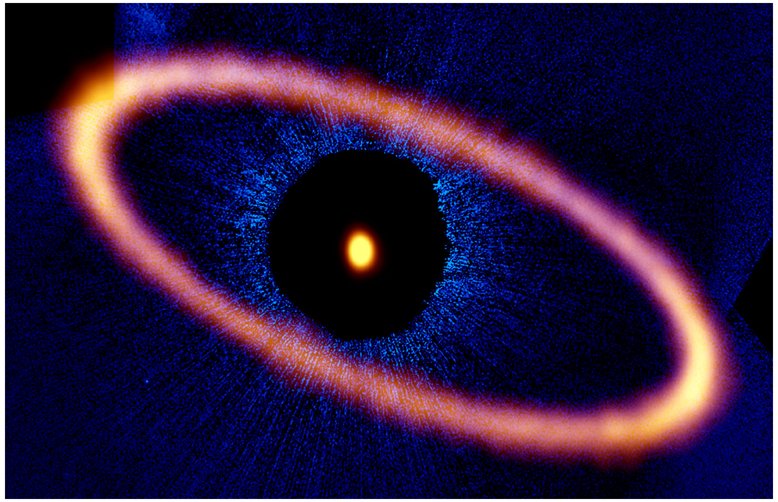




evolve into

?

Debris disks



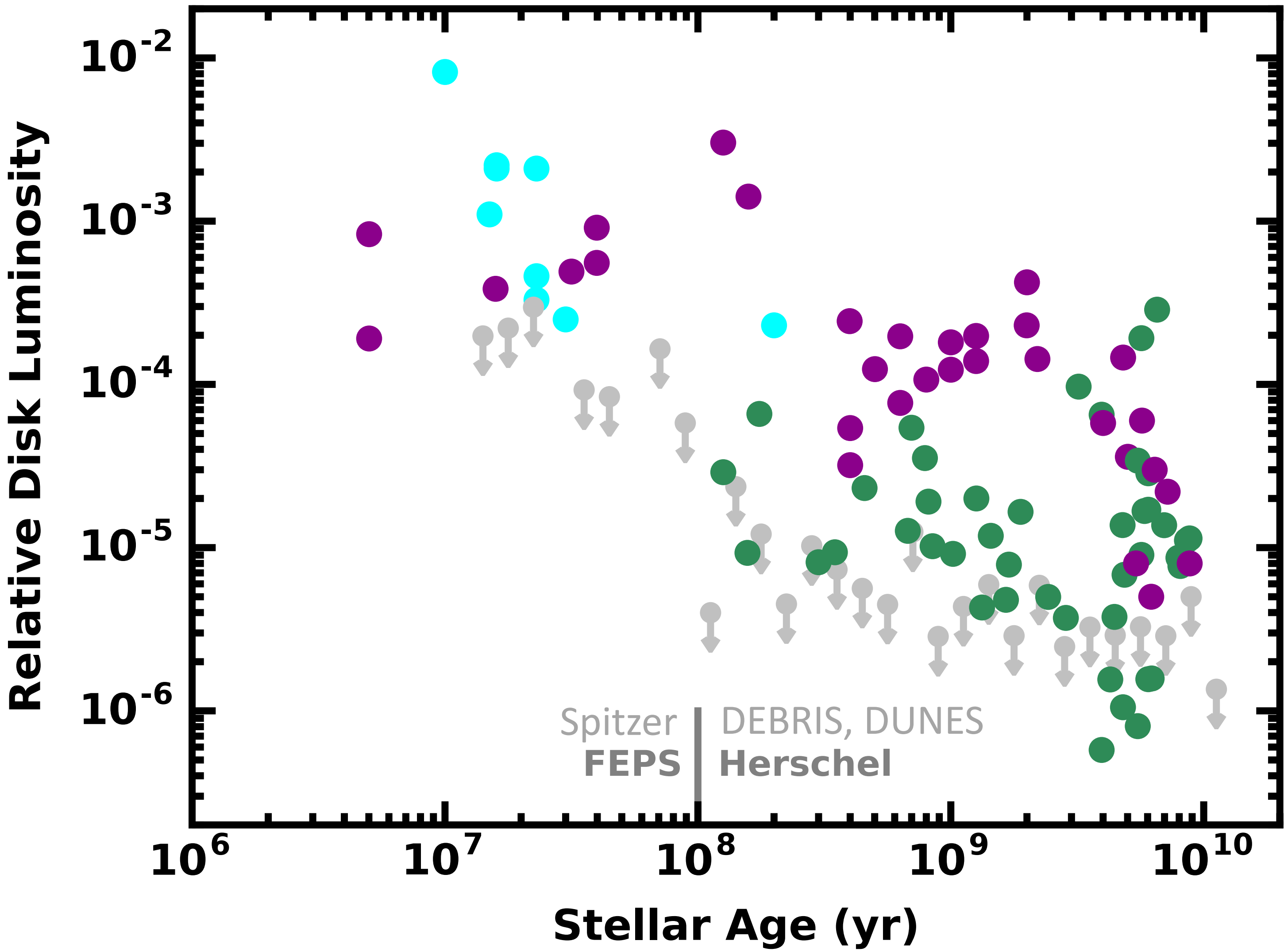
and how does the Solar System fit in?

Using demographics to connect PPDs and DDs

- Sizes
- Debris luminosities
- Incidence rates

Using demographics to connect PPDs and DDs

Debris disk luminosity vs. age



Using demographics to connect PPDs and DDs

Incidence rates

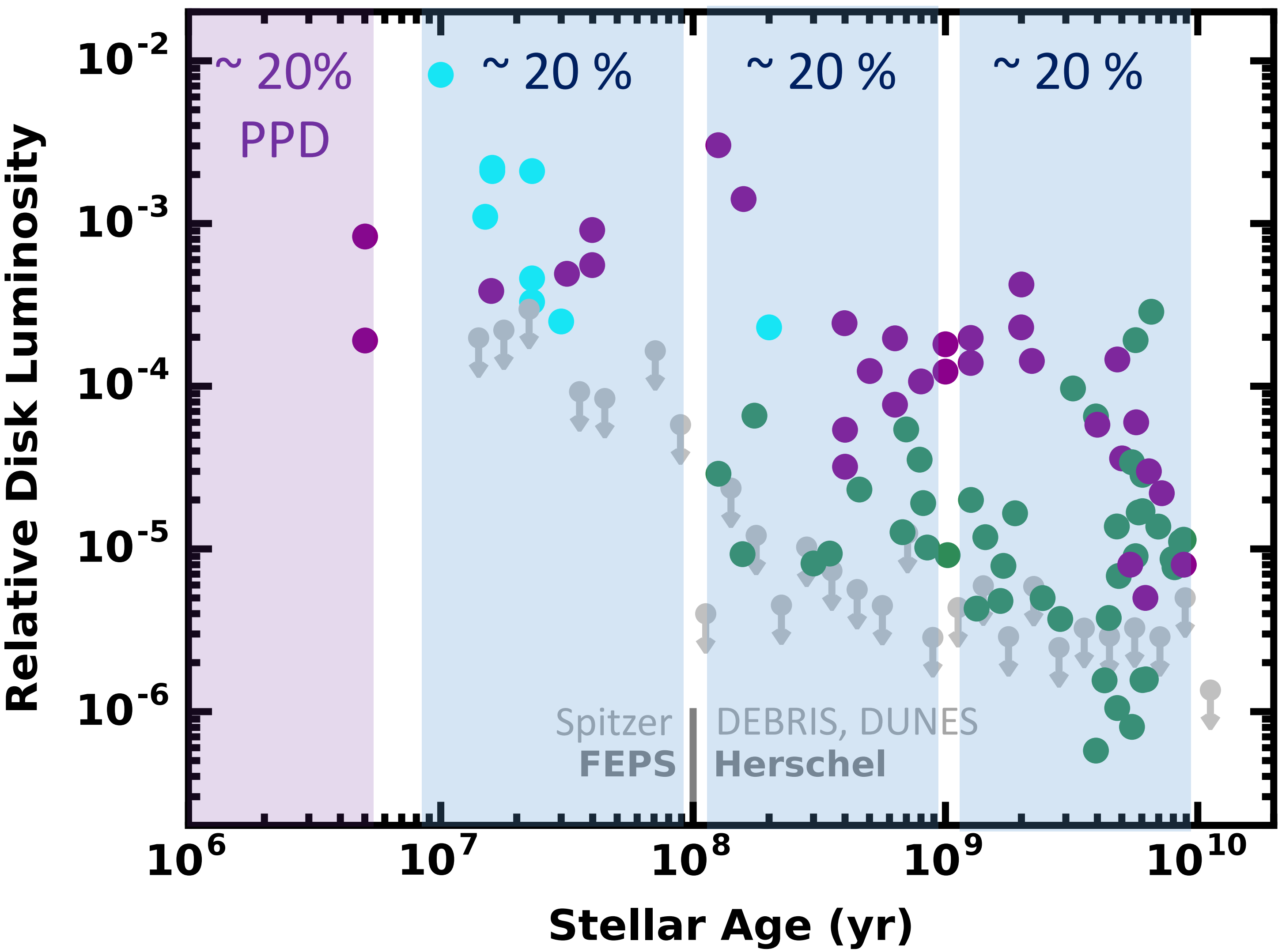
Age	Frequency (> 30 au)
few Myr (PPDs)	~ 20%
10-100 Myr	~ 20%
0.1 – 1 Gyr	~ 20%
1 – 10 Gyr	~ 20%

Taurus

Herschel

Using demographics to connect PPDs and DDs

Debris disk luminosity vs. age

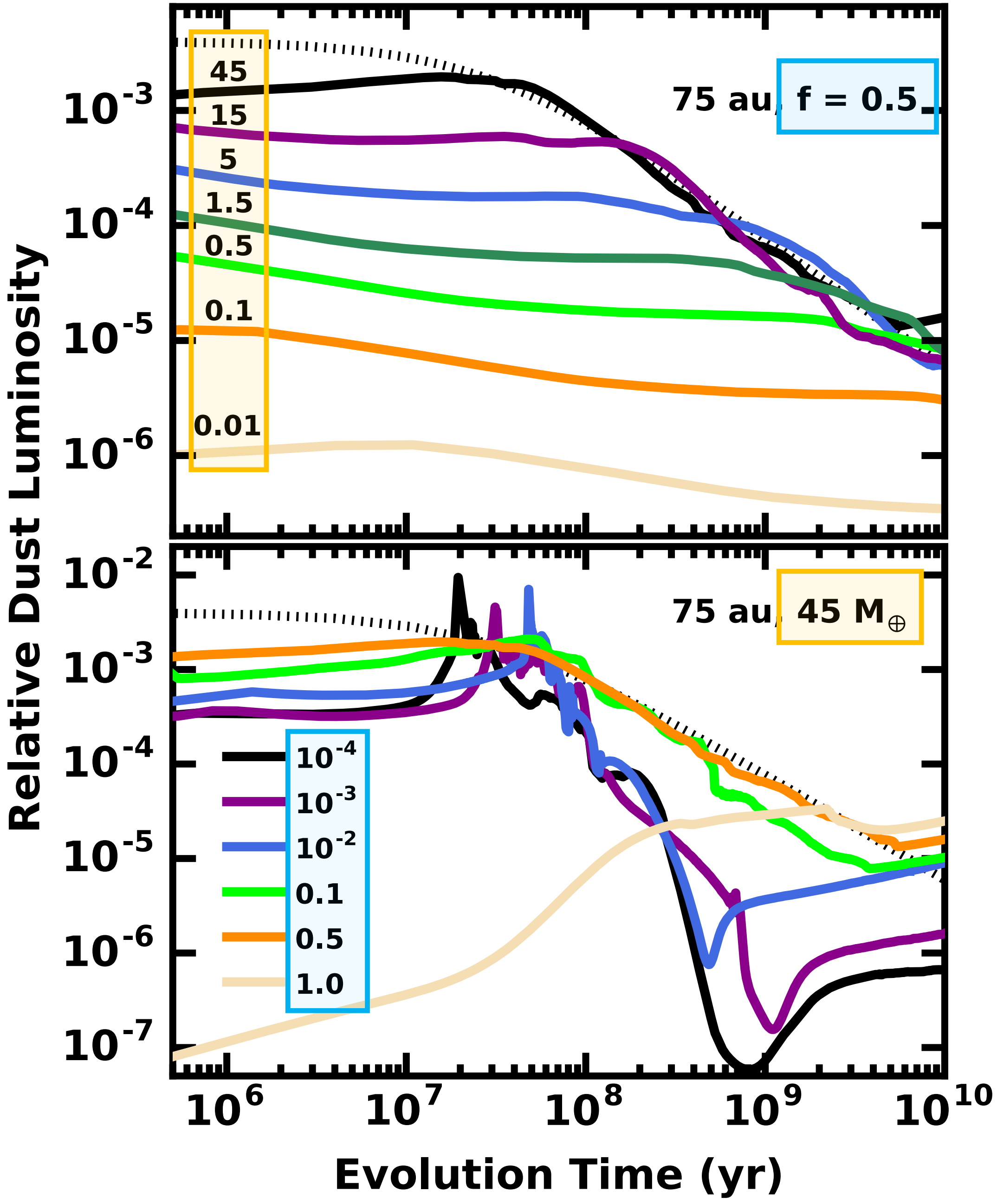


Can evolutionary models connect known PPDs to DDs?

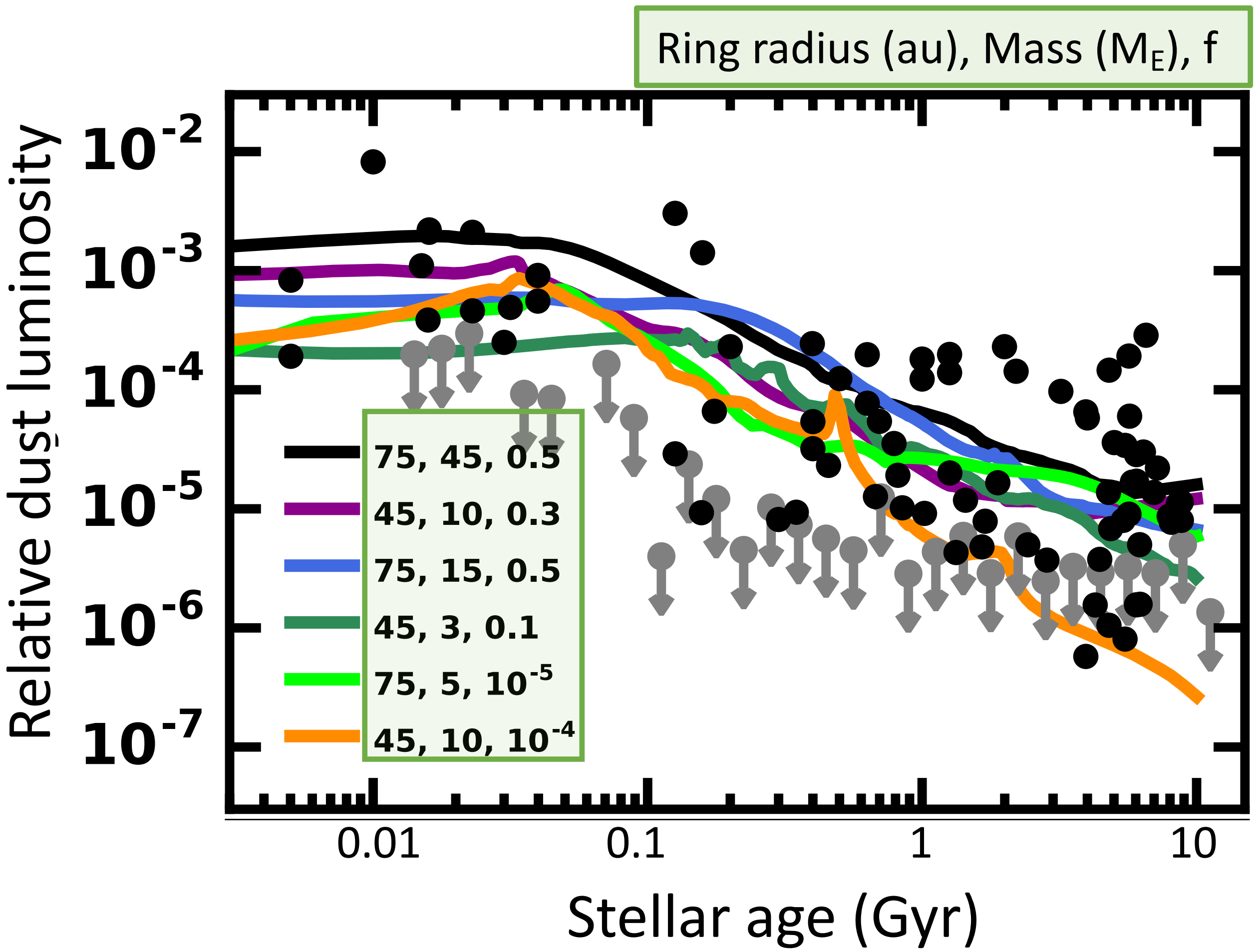
Evolutionary models of rings of solids

Building on work by Kenyon & Bromley…

- Pebbles (1 cm) + planetesimals (100 km)
- Ring radius: 45 au, 75 au
- f = planetesimal mass fraction
- M_0 = initial solid mass (M_{Earth})



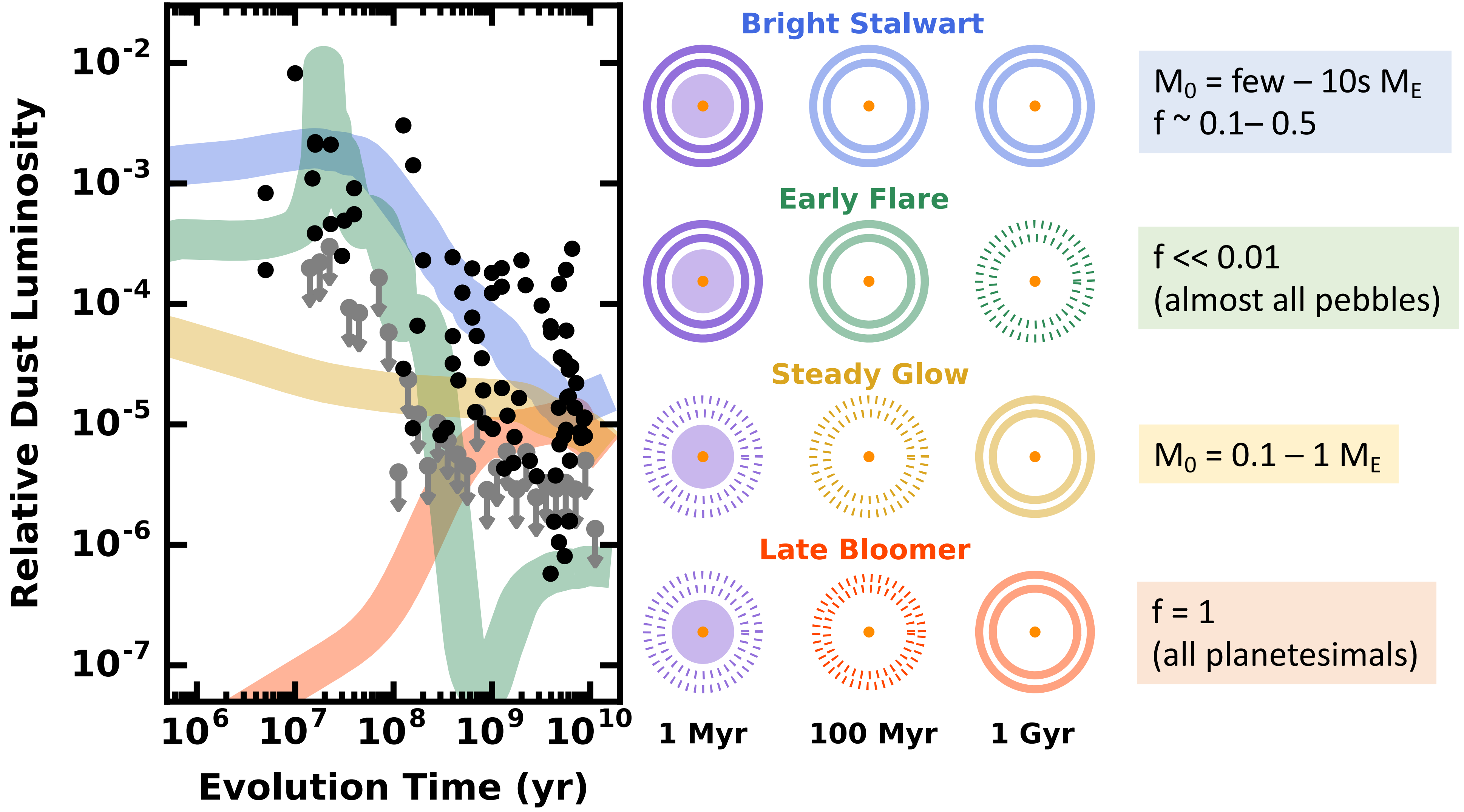
Massive PPD rings match debris demographics



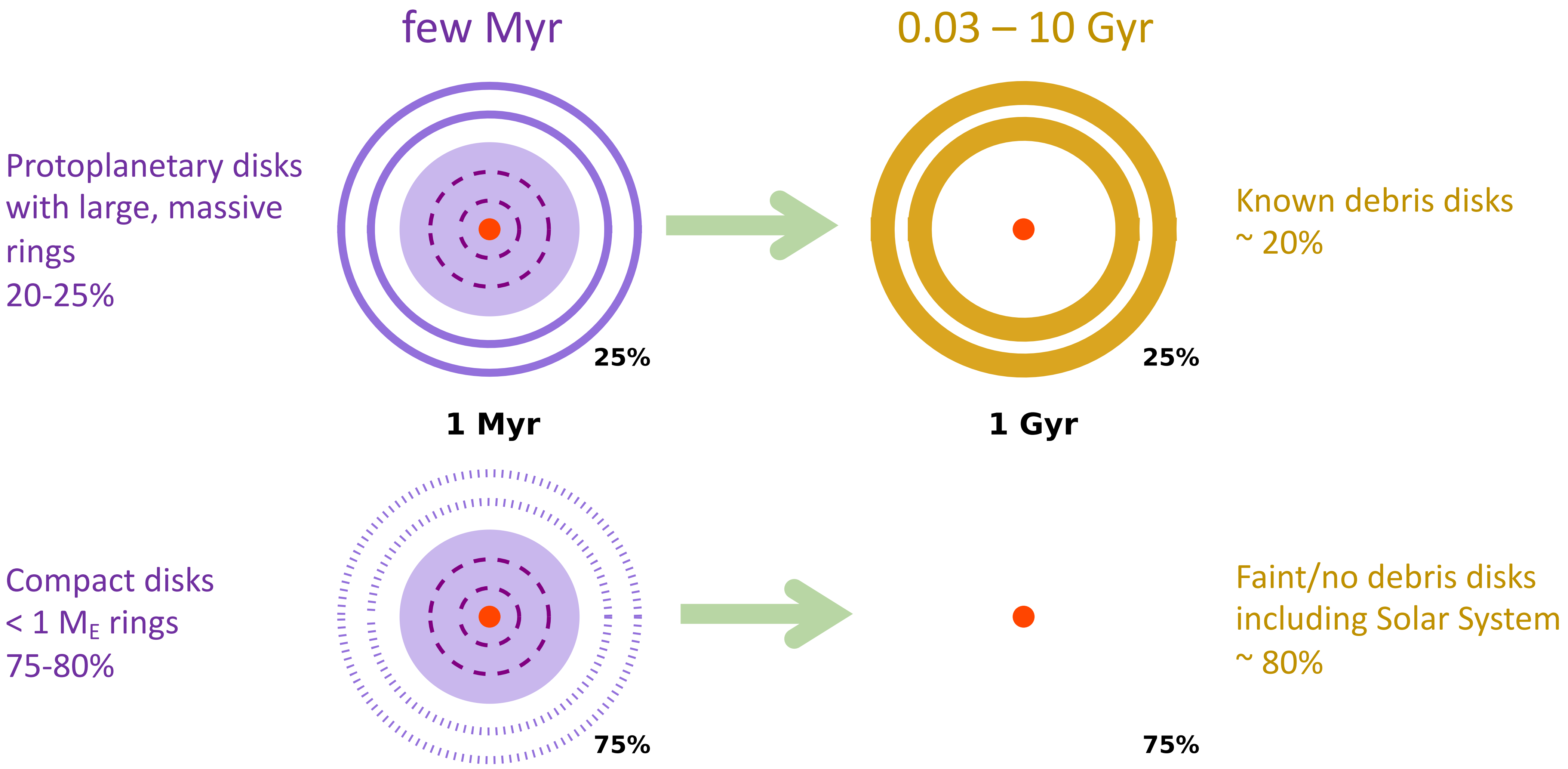
Most DDs evolve from PPD rings with

- High mass M_0 ~ 10 M_E,
- Planetesimal formation efficiency f = 0.1 - 0.5

Evolutionary Pathways for Pebble/Planetesimal Rings



Evolution of Solids in Disks



Summary

Youngest protostars

Early magnetospheric accretion (strong B_*, slow rotation)?

How do disks accrete?

Via supersonic surface accretion flows in disk atmosphere?

Protoplanetary disks --> debris disks

PPDs with large, massive rings → known debris disks

Compact PPDs have little/no planetesimal rings →

Solar System