Evolution of Circumstellar Disks & Planet Formation: From Spitzer to Herschel

"Recent" Reviews:

Meyer et al. (2007) PPV
Meyer (2009; 2010)
Williams & Cieza (2011) ARAA

Michael R. Meyer
Institute for Astronomy, ETH-Zurich
Chronology of the Solar system
14 February 2013, Les Houches

From the ISM to Planets: concept Map #1

ISM: Gas & Dust

Star Forming Environment

Circumstellar Disks: Gas & Dust

Central Stars

Planetary Systems

From the Disks to Planets: concept Map #2

Circumstellar Gas

Circumstellar Dust

mm/meter-sized bodies

Isolation Mass

Ices

Oligarchs

Lunar Mass Solids

Km-sized planetesimals

Gas Giants

Super Earths/Ice Giants

Terrestrial Planets

During the Lectures…

I. What are the most important results?

II. How do we know what we claim?

III. What are the largest sources of uncertainties?

IV. What are the big open questions?

Key Concepts for Tonight: Part A

1. ***Different wavelengths trace different radii.***

2. ***Planet forming disks start at 10-20 % the mass of the star.***

3. ***We can constrain distributions of initial conditions in disks.***

4. ***Disk evolution paths are diverse and thus hard to detect.***

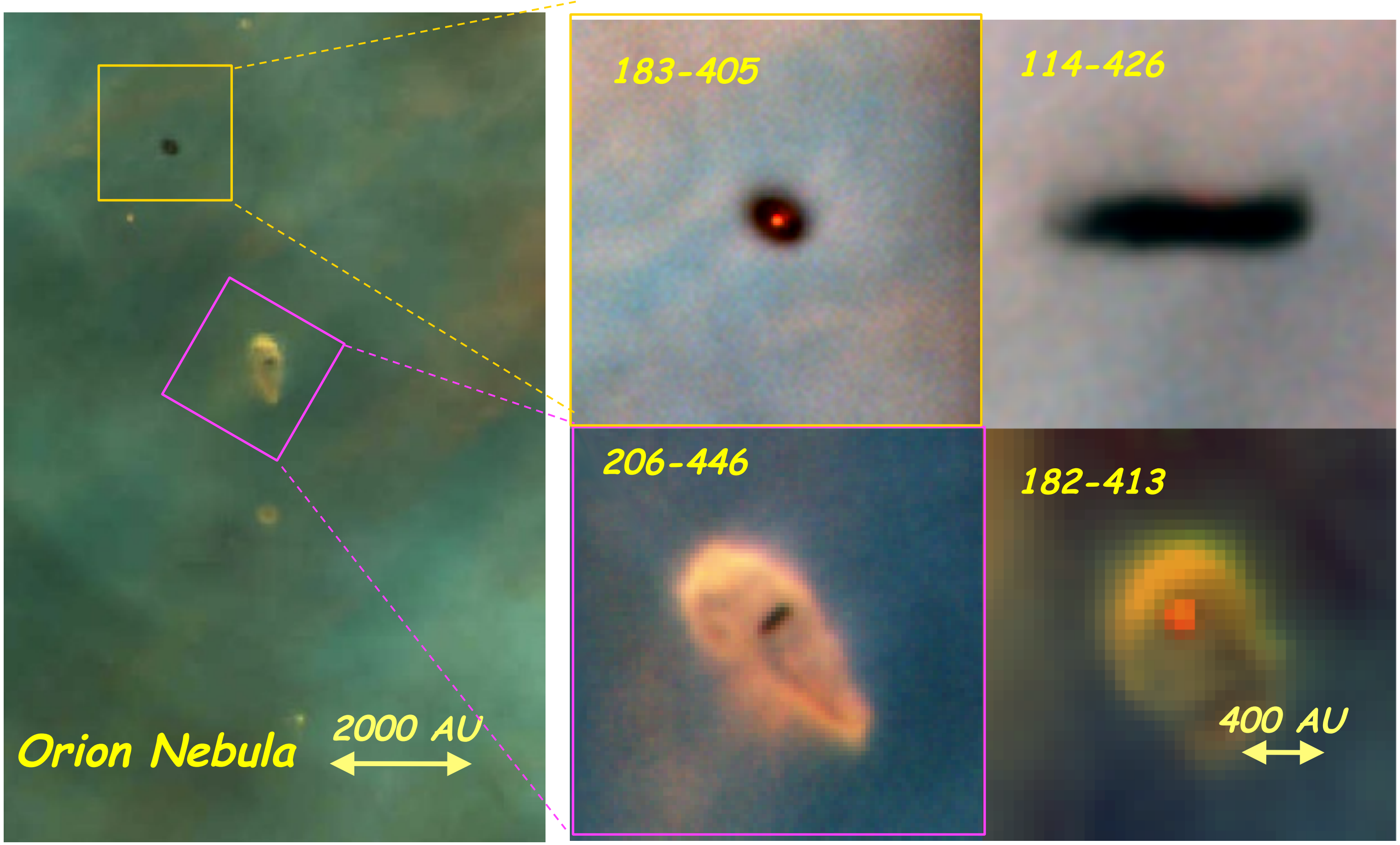
5. ***Carbon, delivered to the nebula in solid form, was processed.***

6. ***Disk chemistry is stellar mass and time dependent.***

Evidence for Disks Around Young Stars

- Optical & near-IR polarization:
  - Elsaesser & Staude (1978).
- mm and IR excess emission:
  - Rucinski (1985) & Myers et al. (1987).
- blue-shifted mass-loss:
  - Appenzeller et al. (1984) & Edwards et al. (1987).
- kinematic signatures of rotation:
  - disk-dominated systems (Welty et al., 1989).
- direct images from HST:
  - O'Dell & Wen (1992) ; McCaughrean & O'Dell (1996).

Direct Images of Circumstellar Disks



O’Dell & Wen 1992, Ap.J., 387, 229. McCaughrean & O’Dell 1996, AJ, 108, 1382.

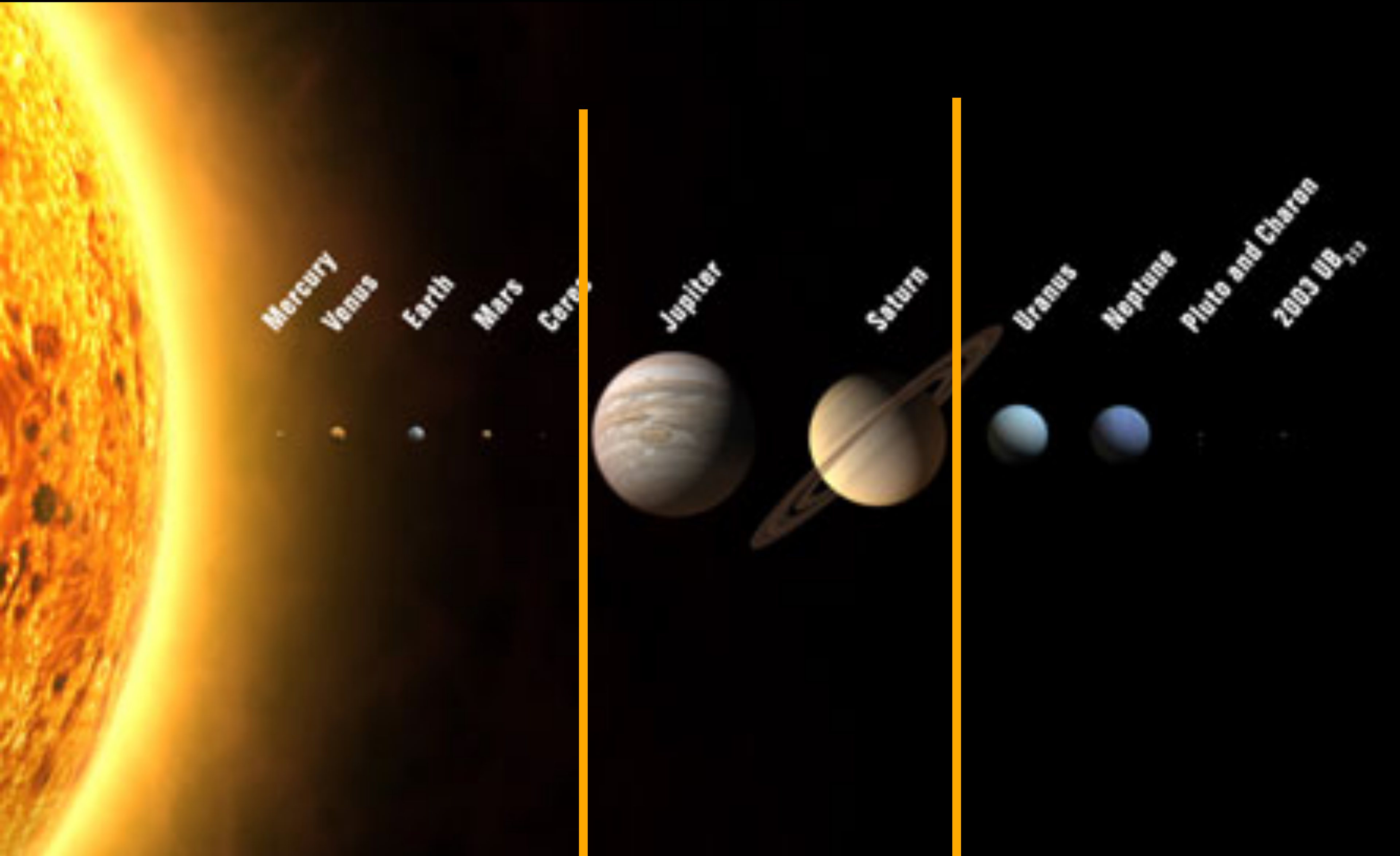
Random History of "Some" IR Facilities…

Ground-based photometry and spectroscopy (1969-today).
IRAS 1982-1983
MM-wave disk studies (1985-today)
ESO-VLT (6-10 meter) 2001-today.
Spitzer 2003-2008 (main cryogenic phase)
Herschel 2009-2013
ALMA 2011-???
SOFIA 2011-???

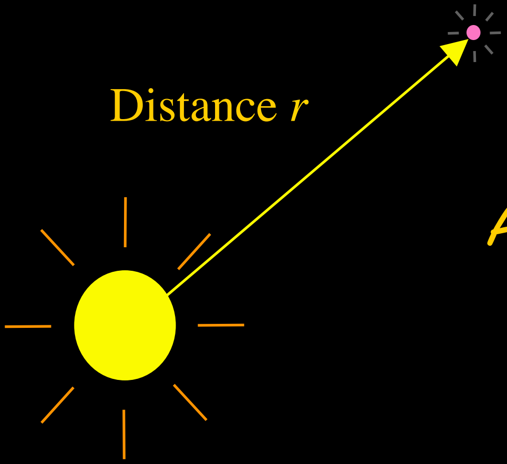
JWST 2018-???
ESO/E-ELT 2020-???

And many more:
C-CAT, NOEMA, JAXA/ESA SPICA/SAFARI 2020-???

Planet Formation = Saving the Solids



Radiative heating: isolated particle



Particle radius *a* (spherical; rapidly spinning)
Temperature *T*

Distance *r*

Luminosity *L*

Absorbed radiative power: $\pi a^2 \times \frac{L}{4\pi r^2}$

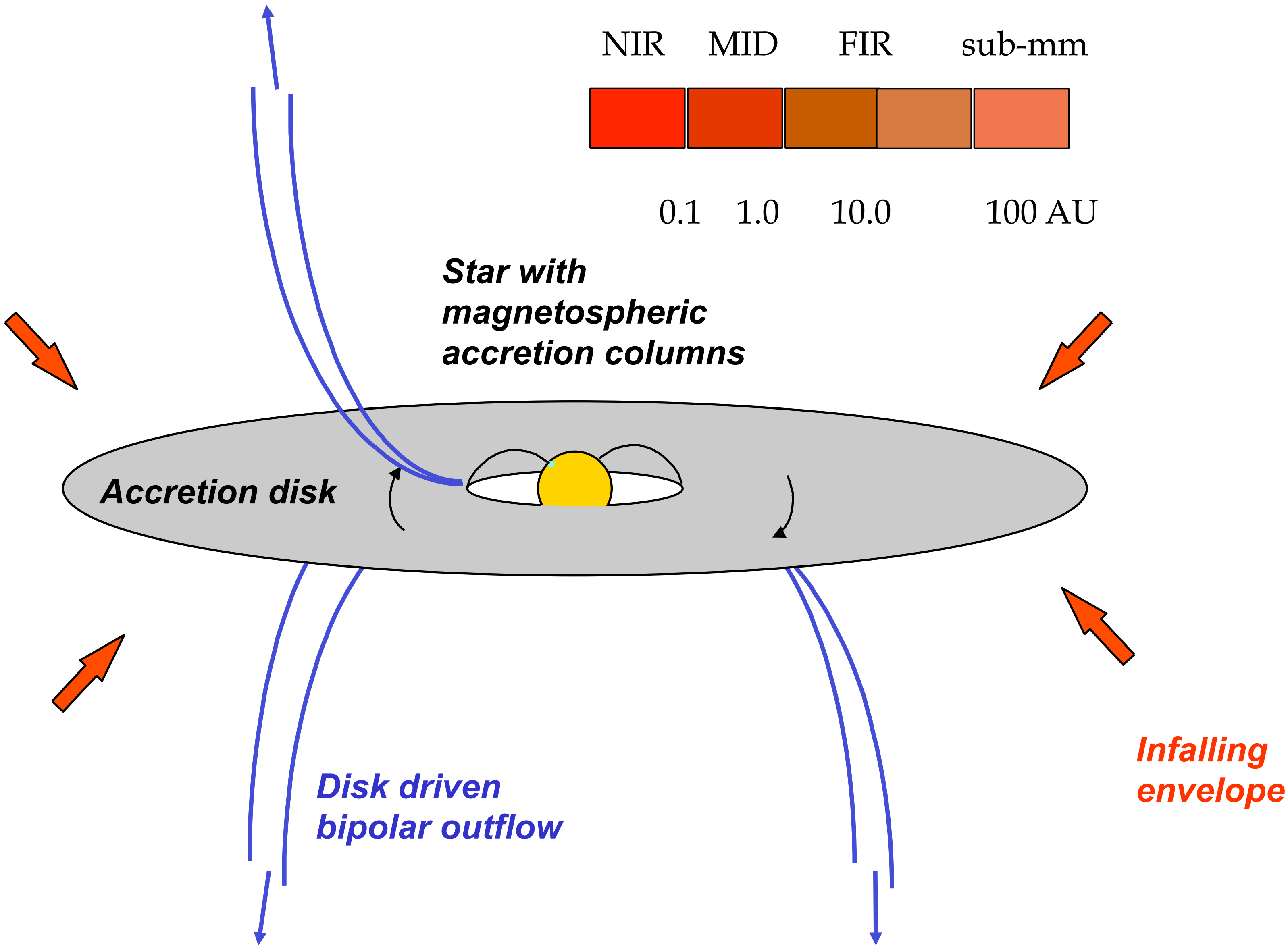
Emitted radiative power: $4\pi a^2 \times \sigma T^4$

$$T = \left(\frac{L}{16\pi\sigma} \right)^{1/4} r^{-1/2}$$

Using ε_ν for small particles: $T \sim r^{-2/5}$

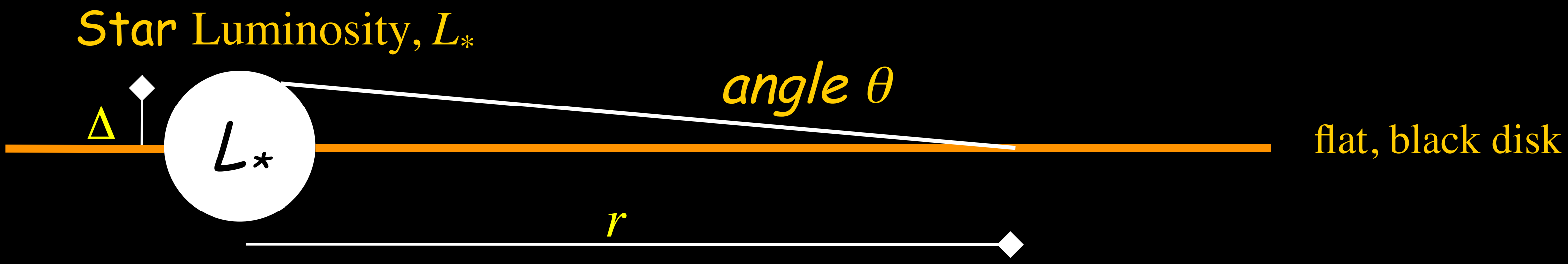
cf L. Spitzer, Jr., *Physical Processes in the Interstellar Medium*, ch. 9.1

Different Wavelengths Trace Different Radii!



Optically-thick/geometrically thin

Lynden-Bell & Pringle 1974, *MNRAS*, **168**, 603.
Adams, Lada, & Shu 1988, *Ap. J.*, **326**, 865.



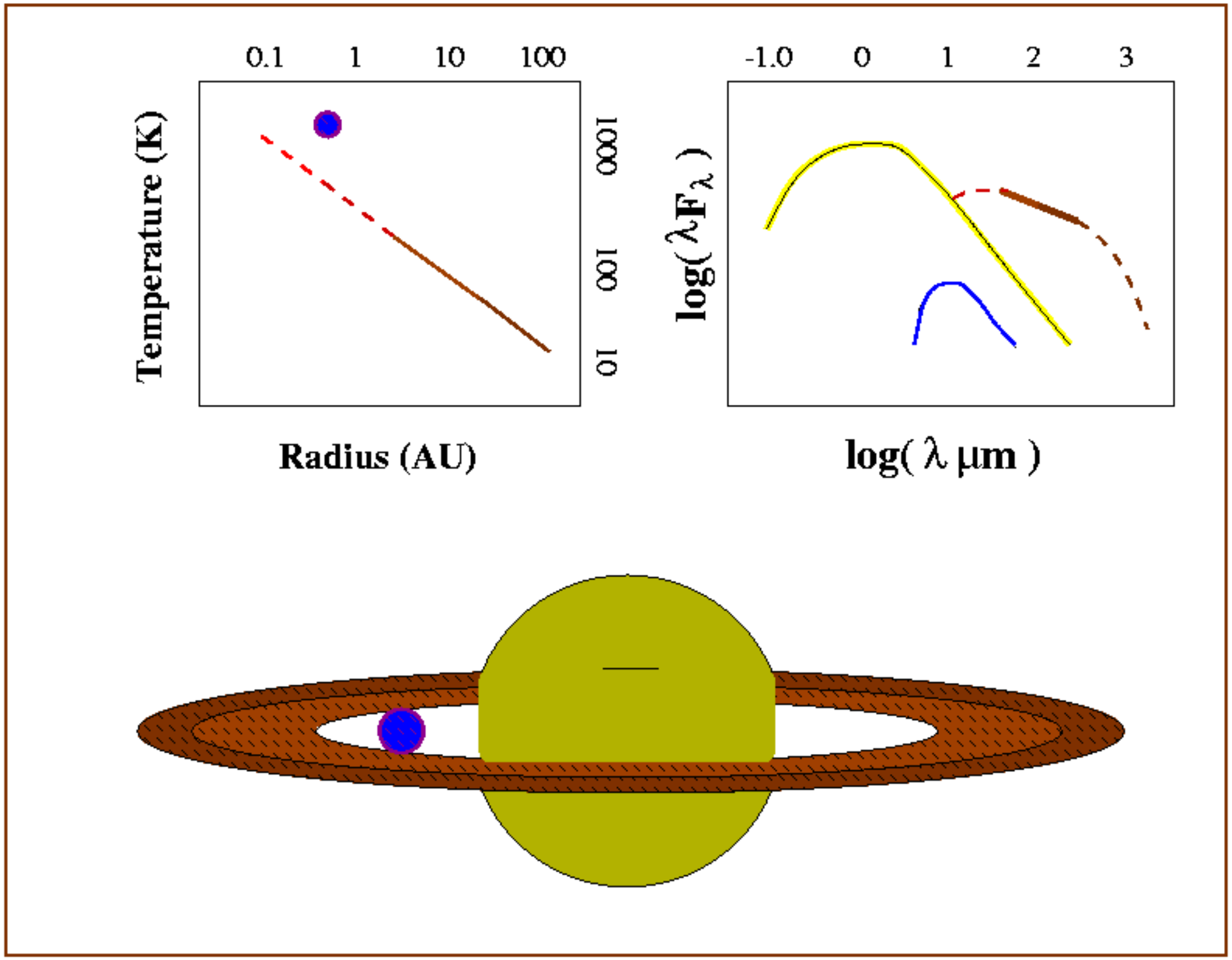
Power/area absorbed ~ $\frac{L_*}{4\pi r^2} \sin\theta$

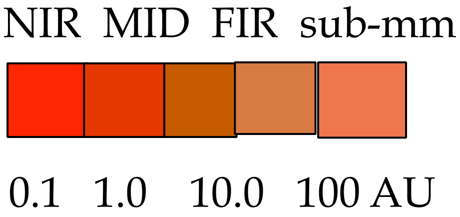
$$\sim \frac{L_*}{4\pi r^2}\frac{\Delta}{r} \sim \frac{L_*}{r^3} \qquad (r \gg \Delta)$$

Power/area emitted = $\sigma T^4 \sim \frac{L_*}{r^3}$ $\qquad T(r) \sim r^{-3/4}$

Also true for accretion energy.

Blackbody Disk with Dynamically Cleared Gap





NIR MID FIR sub-mm

0.1 1.0 10.0 100 AU

1. How much gas is required for $\tau = 1$?

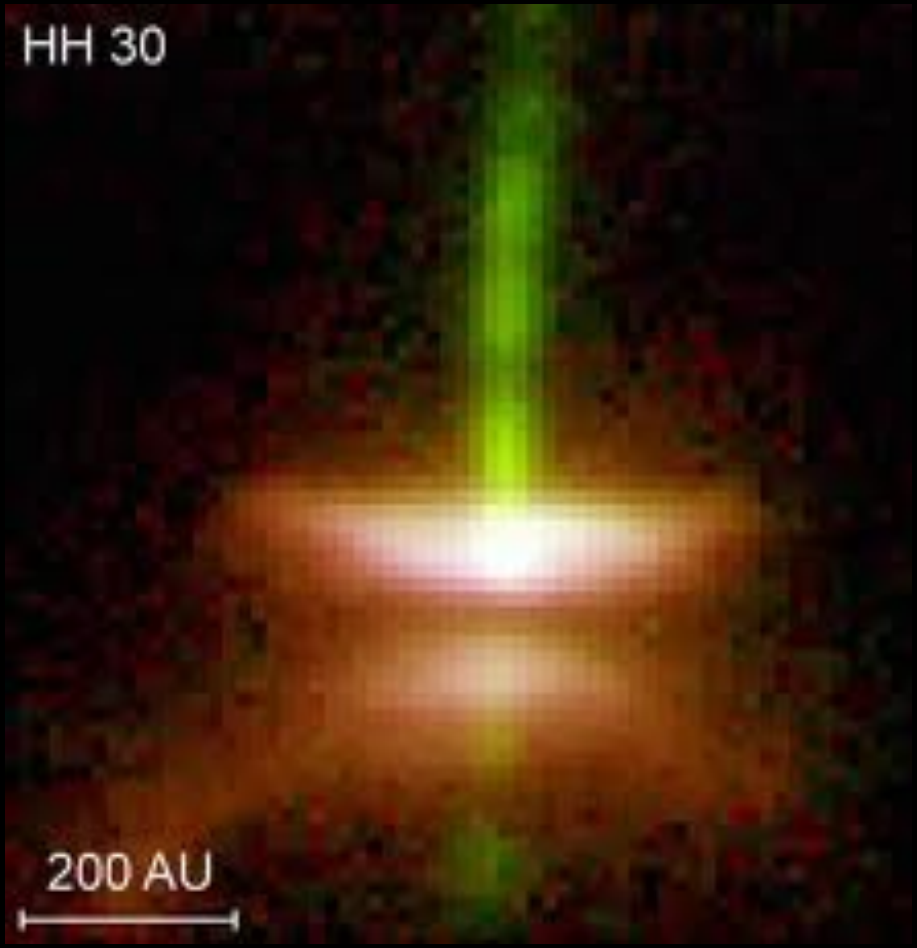
- ***M(accretion) > 10^{-7} M_{sun}/year?***

2. How much *dust* is required for $\tau = 1$?

- Near-IR r < 0.1 AU: ~ 2-10 M(Ceres).
- Mid-IR 0.1-1.0 AU: ~ 0.1-2 M(Earth).
- FIR 1.0-10.0 AU: 0.1-10 M(Jupiter).

It is often assumed that optically-thin implies a "debris" disk rather than primordial disk, though this need not be the case.

Protostellar Collapse:
The First Stages of Planet Formation



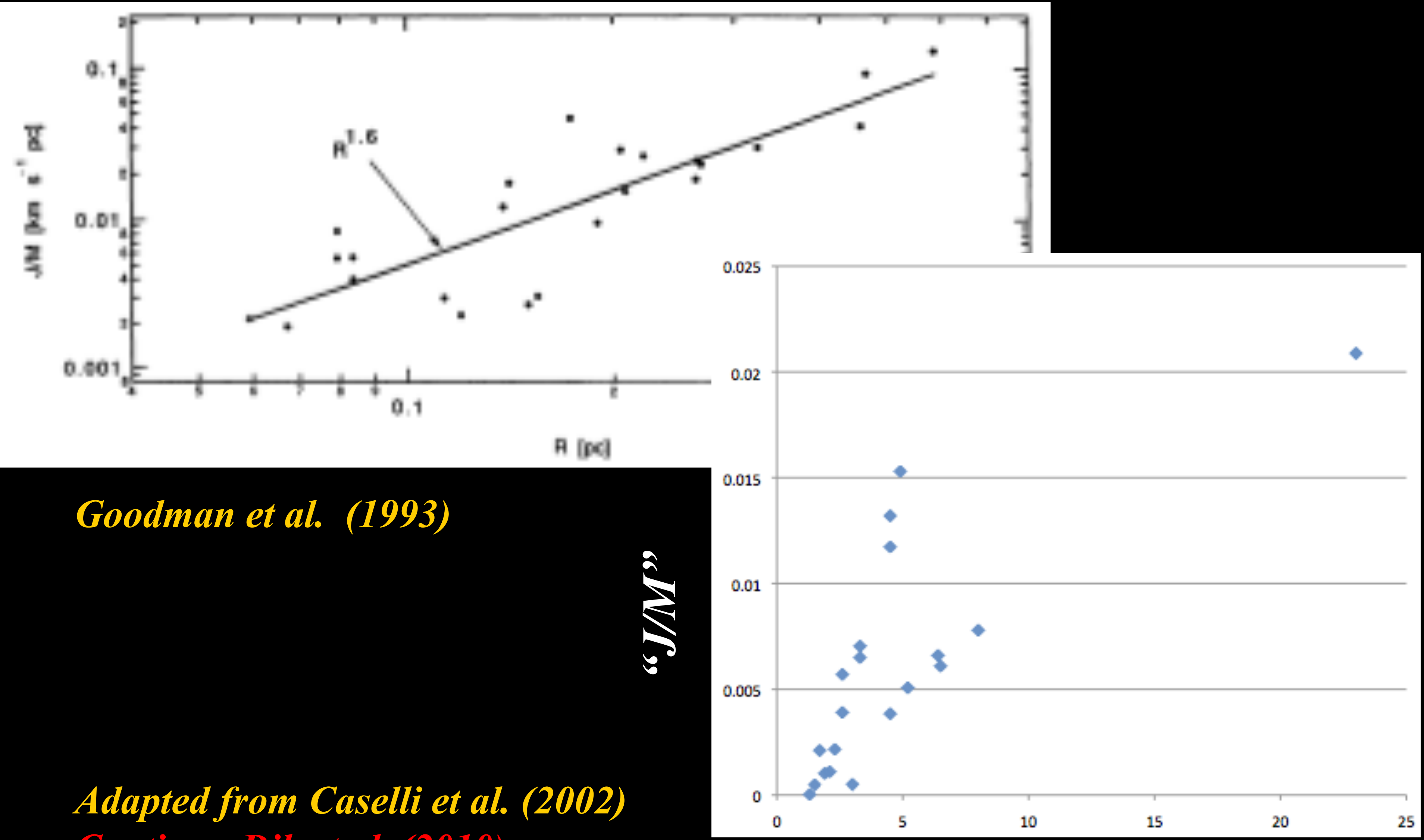
Disks begin as massive
As gravity will permit.

Almost all the mass a star
Will have passes through
Its disk.

It is the last stable disk that
We take as initial conditions
Of planet formation.

HH 30: HST/NASA

Outcome #4: Binary Fraction depends on Mass. Does Specific Angular Momentum of Cloud Cores?



Goodman et al. (1993)

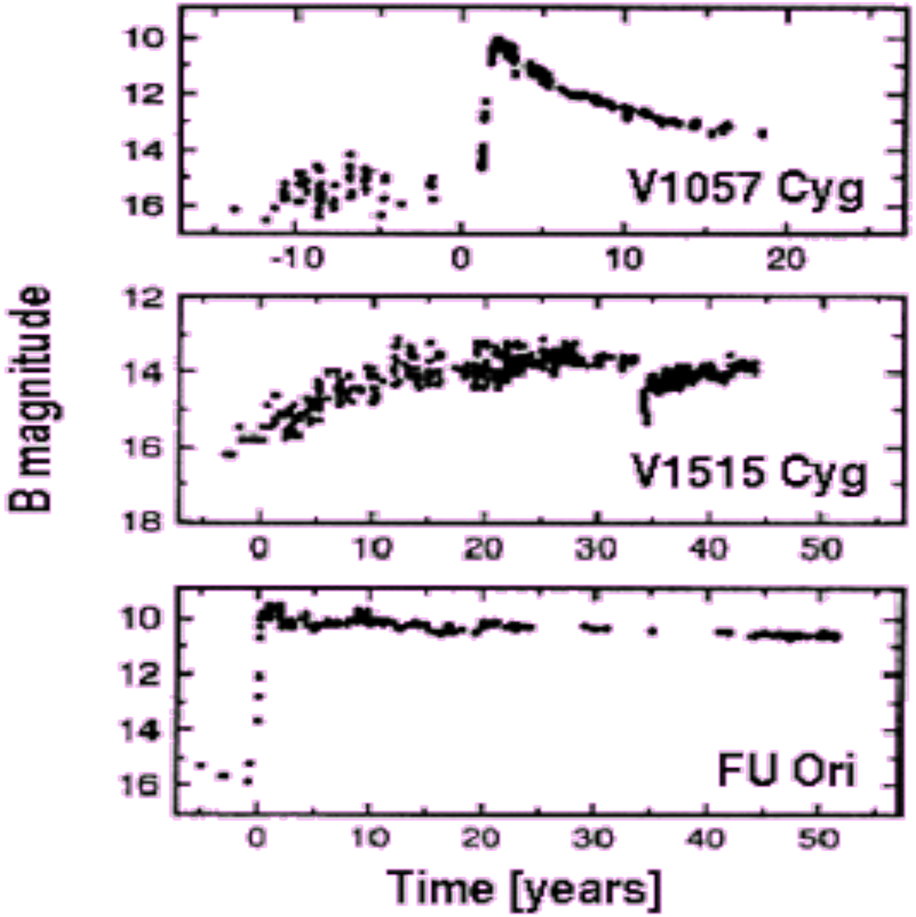
"J/M"

Adapted from Caselli et al. (2002)

Caution: Dib et al. (2010)

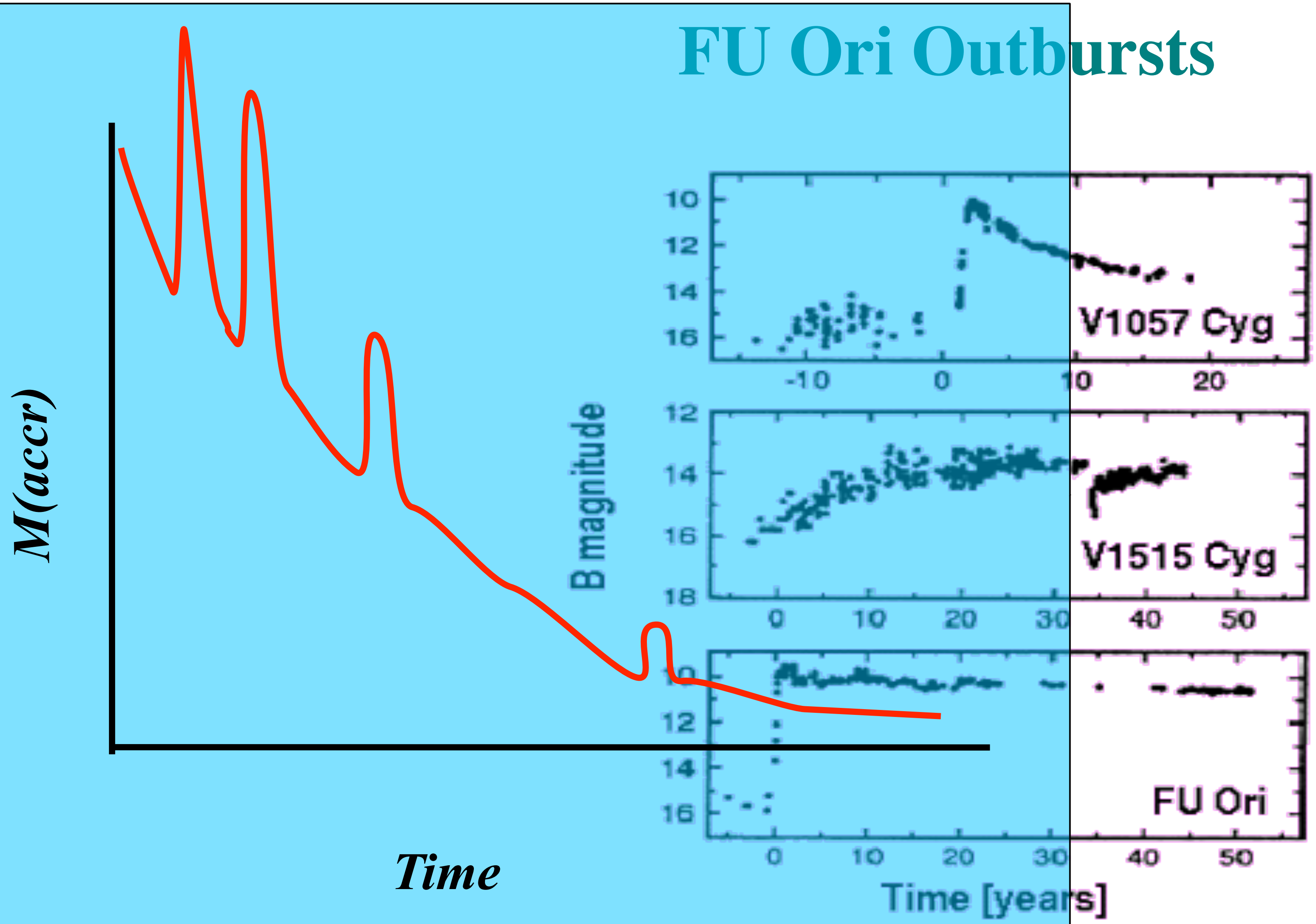
Core Mass (Msun)

FU Ori outbursts on timescales of 10-30,000 years



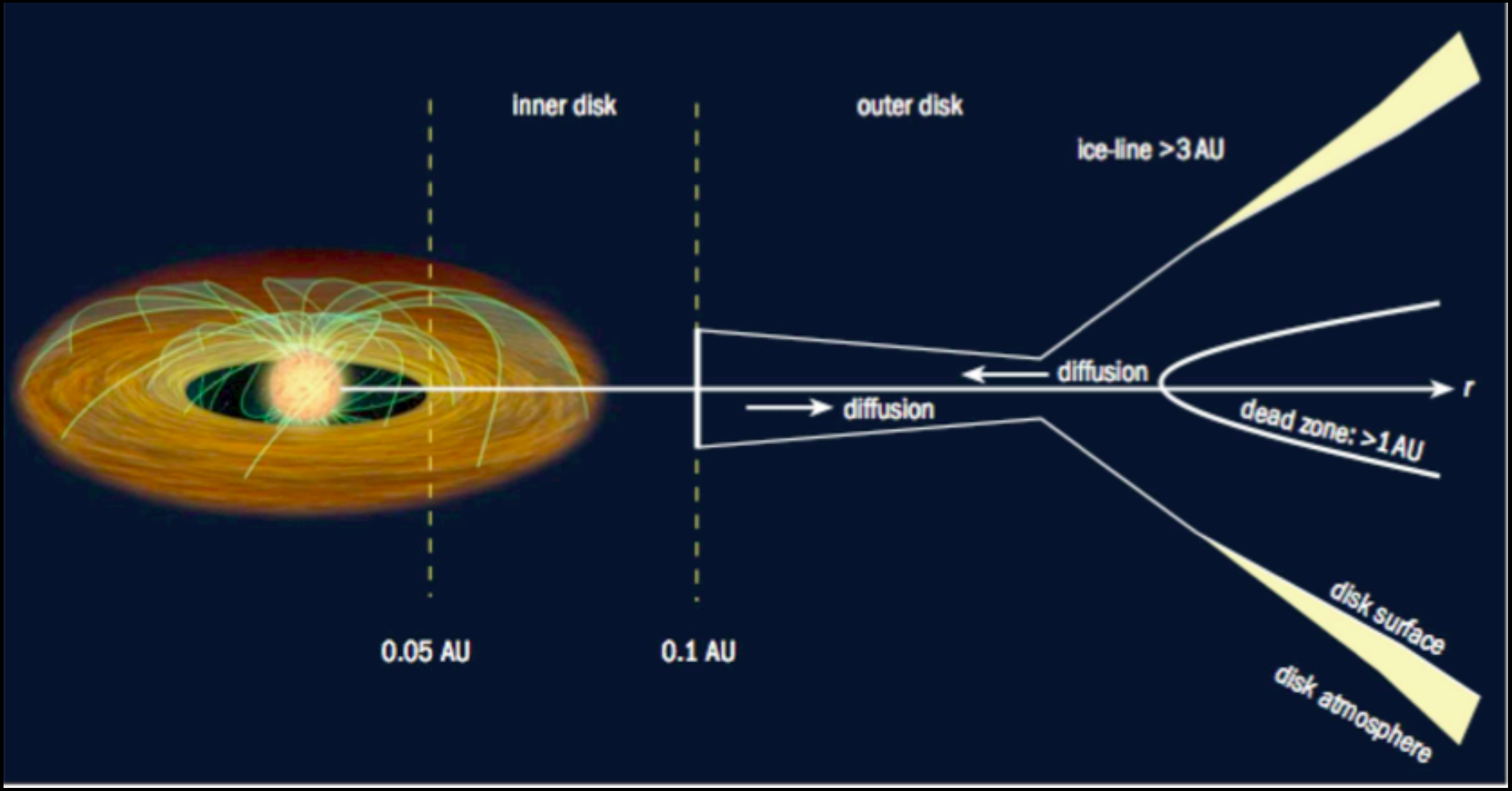
Kenyon & Hartmann (1995) Ann Rev Ast Astrophys.

FU Ori Outbursts



Kenyon & Hartmann (1995) Ann Rev Ast Astrophys.

Initial Conditions in Protostellar Disks.



From M. Meyer, Physics World, November, 2009
Based on Dullemond et al. (2001) with artwork from R. Hurt (NASA)

Typical Disk Parameters

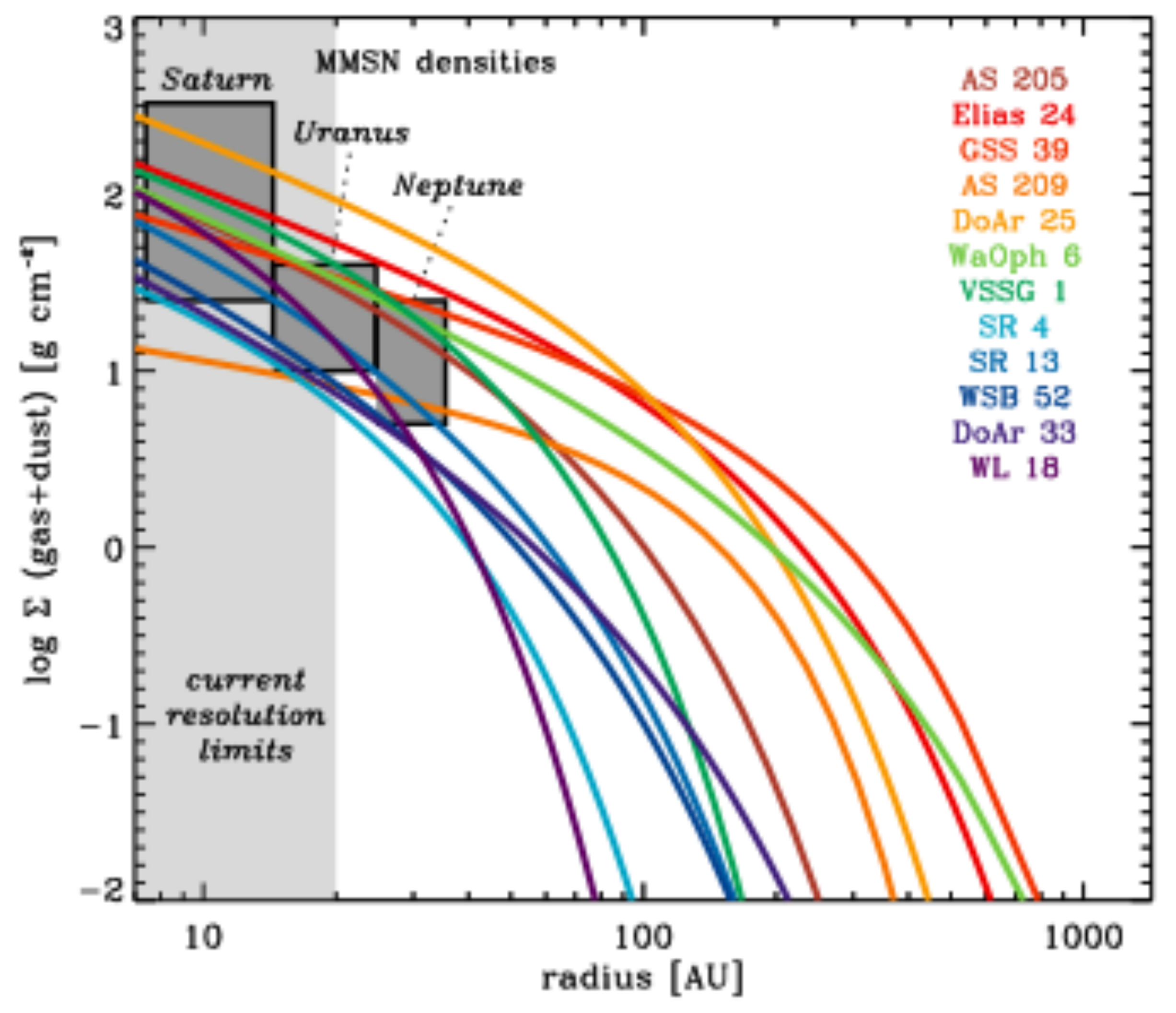
Parameter	**Median**	**~1σ Range**
Log(M(disk)/M(star))**[all ~1 Myr]** **[detected disks only]**	-3.0 dex -2.3 dex	±1.3 dex ±0.5 dex
Disk lifetime	*2-3 Myr*	*1-6 Myr*
Temperature power law [$T(r) \sim r^{-q}$]	0.6	0.4-0.7

Parameter	**Median**	**~1σ Range**
R(inner)	0.1 AU	~0.08-0.4 AU
R(outer)	200 AU	~90-480 AU
Surface density power [$\Sigma(r) \sim r^{-p}$] **[Hayashi min. mass nebula]** **[steady state viscous α disk]**	0.6 **1.5** **1.0**	0.2-1.0 (predicted) (predicted)
Surface density norm. Σ_o (5AU)	14 g cm^{-2}	±1 dex

Taken from (or interpolated/extrapolated from):

Muzerolle et al. (2003), Andrews & Williams (2007), Hernandez et al. (2008), Isella et al. (2009)

Gas Mass Surface Density: Observed Conditions

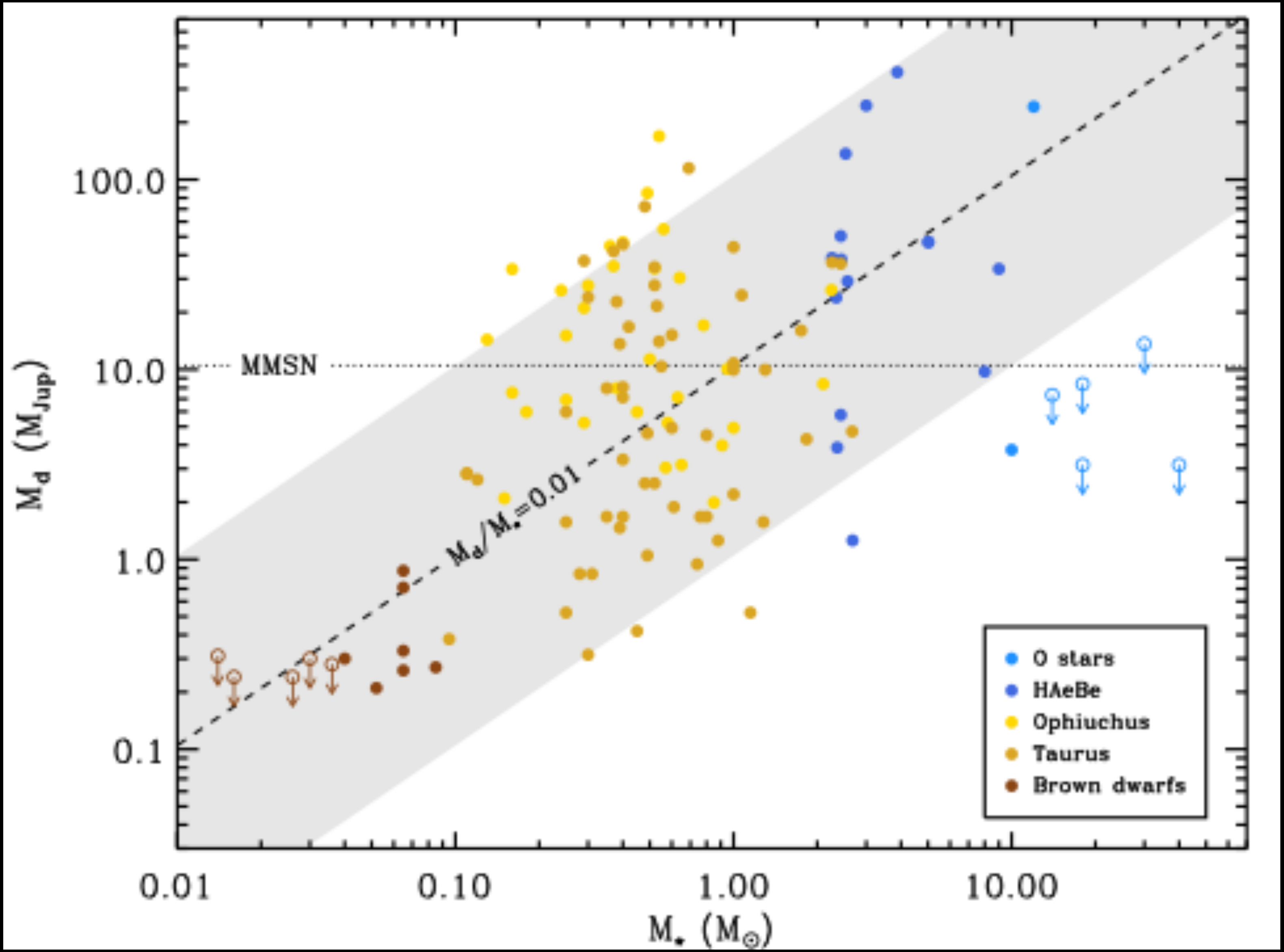


From Williams & Cieza ARAA (2011)

Properties Influencing Disk Evolution

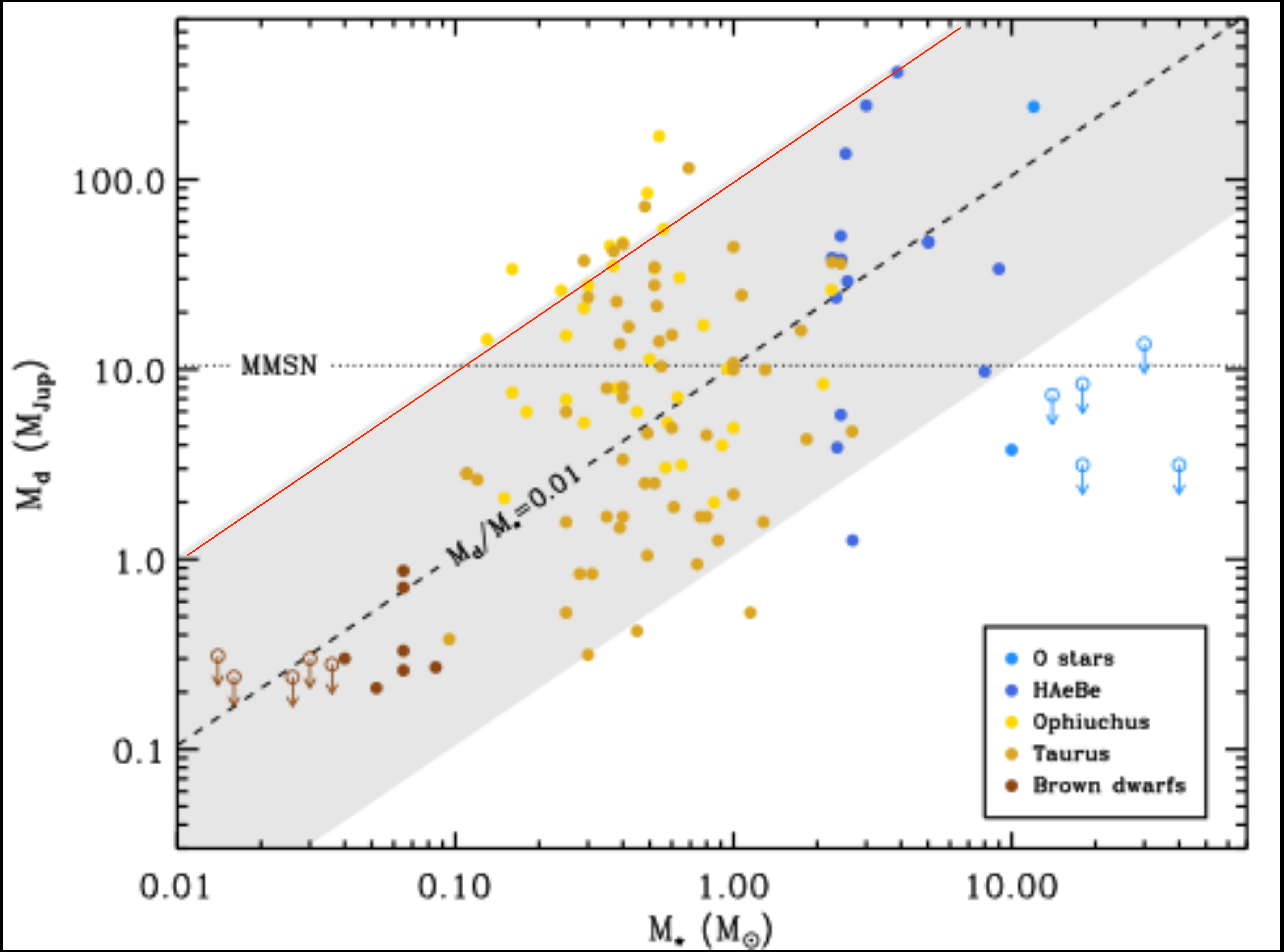
- **Stellar Mass:**
- **Luminosity & Incident Spectra:**
- **Initial cloud core angular momentum:**
- **Composition:**
- **Companions versus Mass and Orbital Radius:**
- **Formation environment:**

Disk mass depends on star mass (as expected)



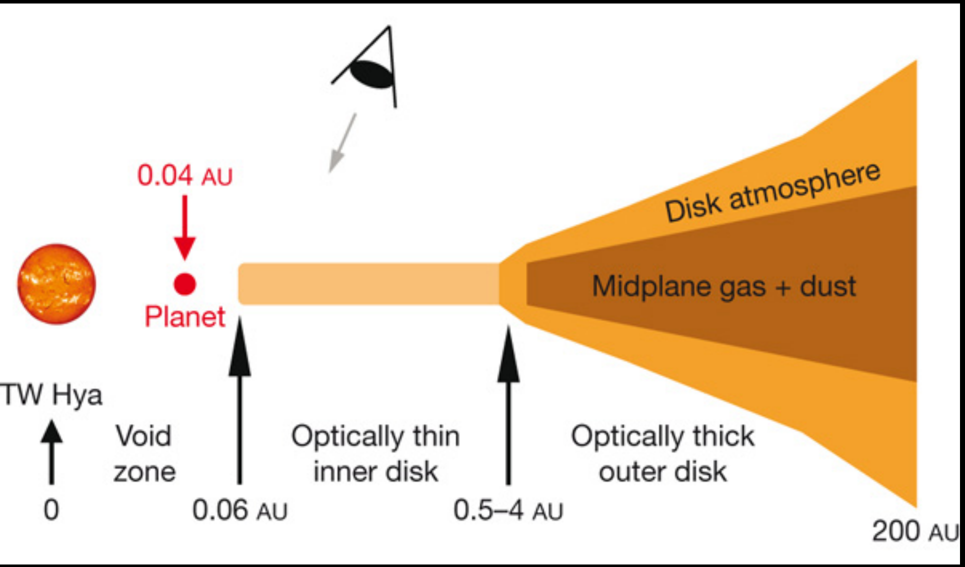
From Williams & Cieza ARAA (2011)

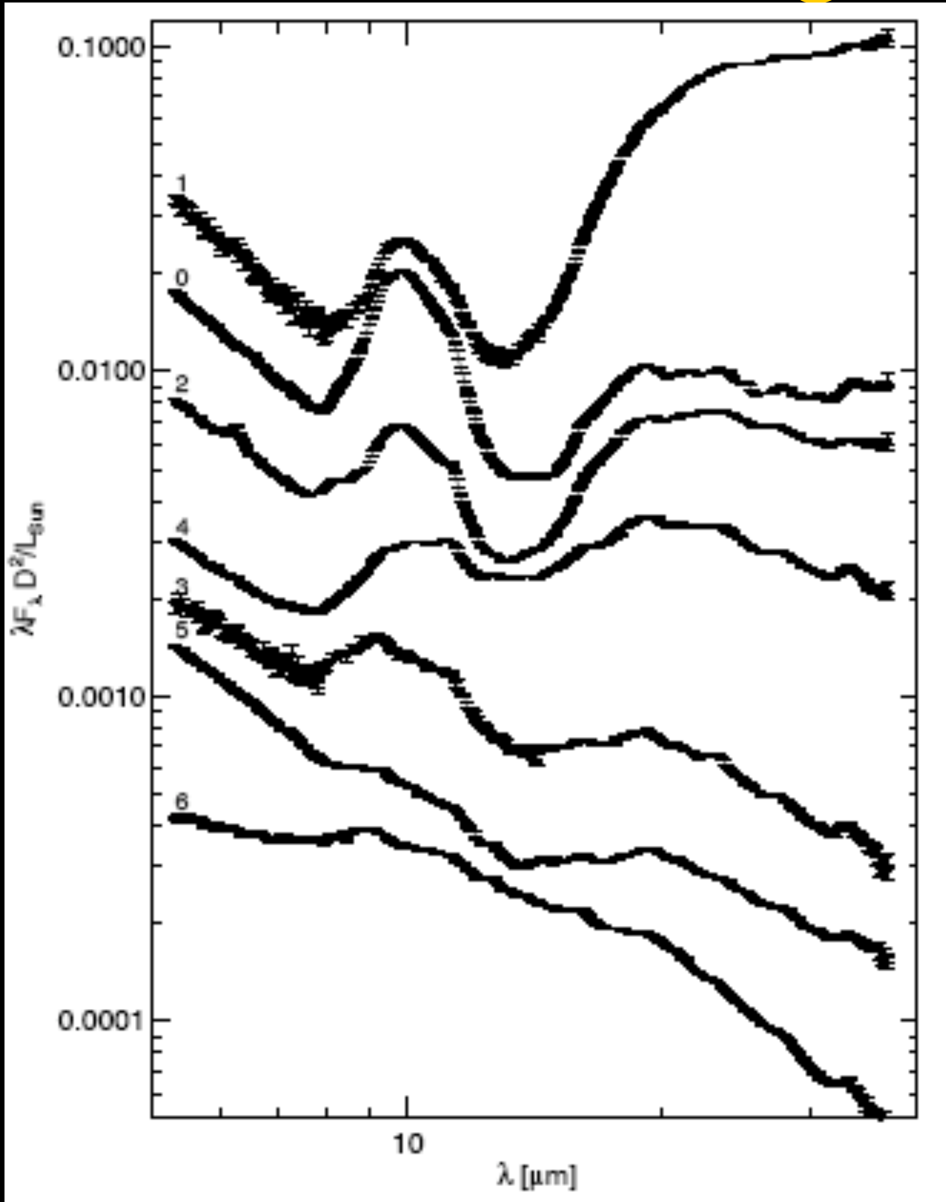
Disk mass depends on star mass: initial condition



From Williams & Cieza ARAA (2011)

Confounding Variables:
T Tauri Disk Evolution and Errors in Age





Transition Disks:

Espaillat et al. (2007);

Brown et al. (2007)

Few disk parameters correlate:

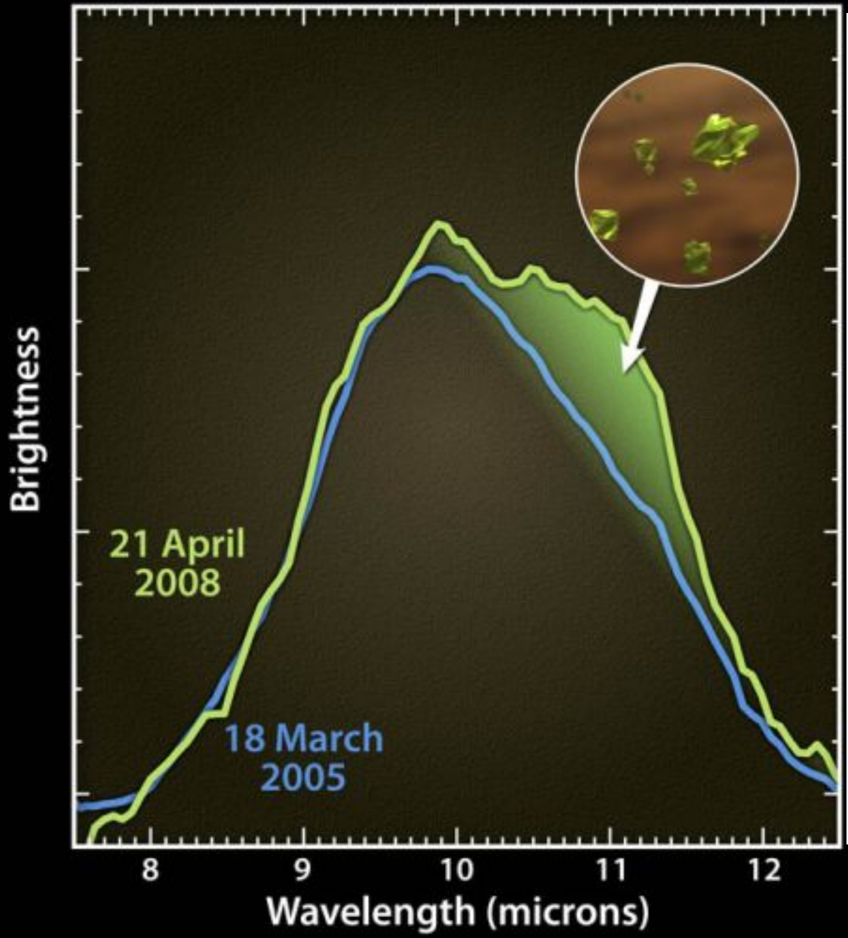
Bouwman et al. (2008)

Pascucci et al. (2008)

Cortes et al. (2009)

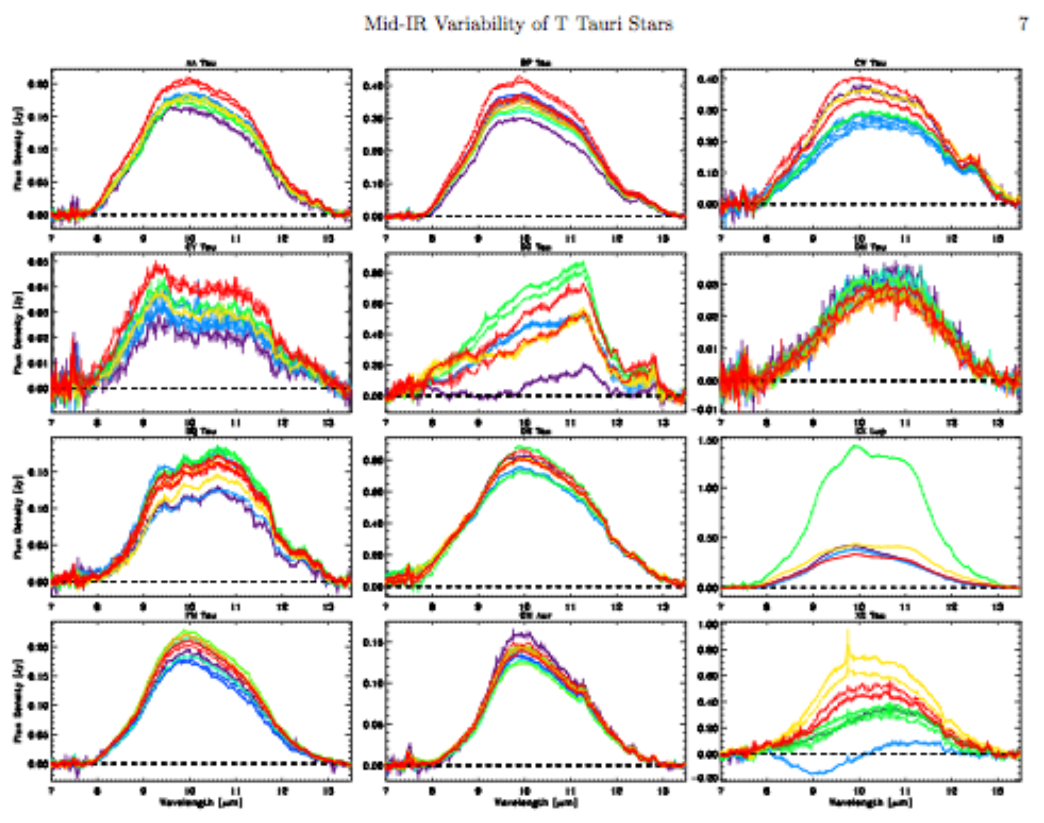
Watson et al. (2007)

Accretion Variability can drive compositional change in disks!.



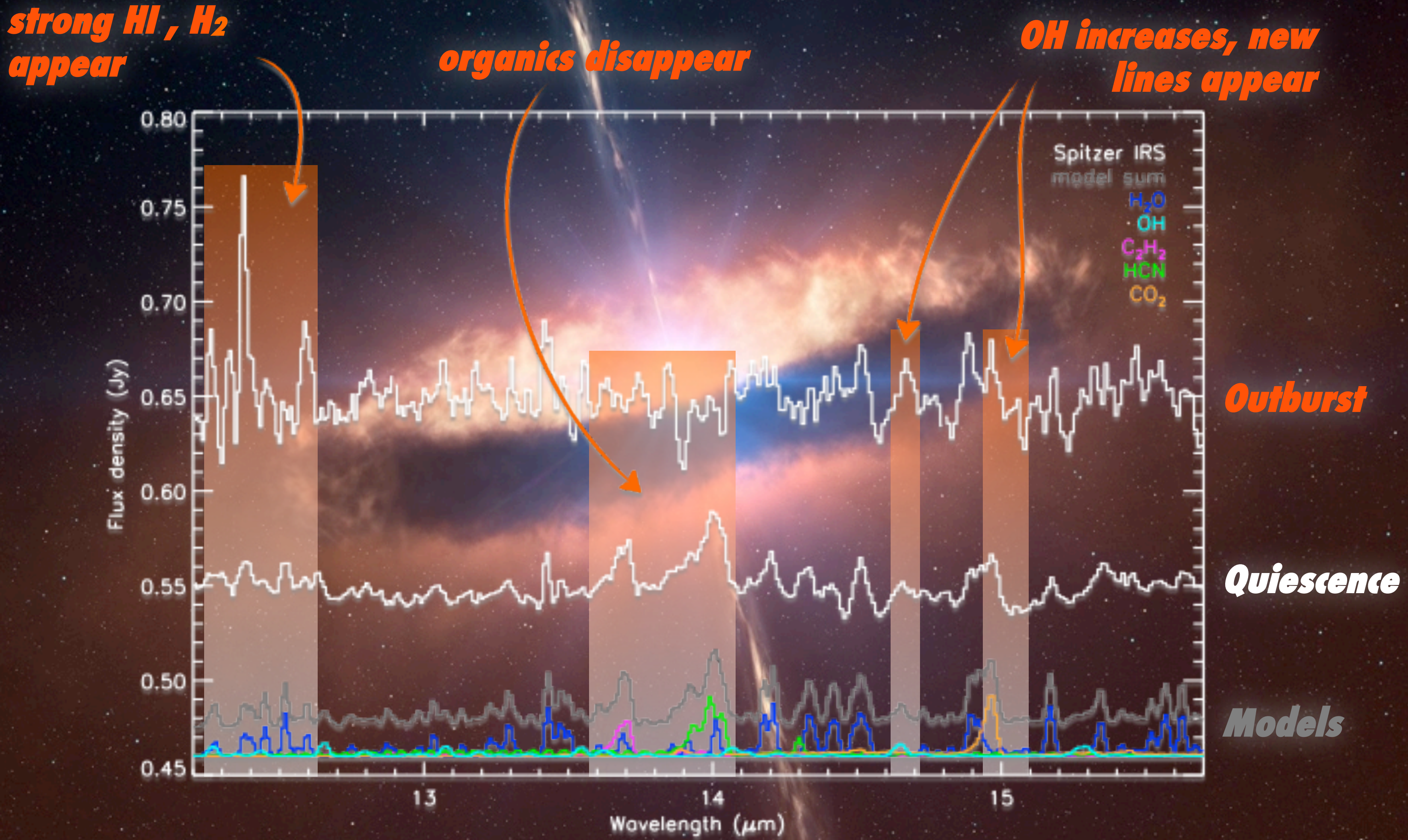
Crystal Formation in the Disk of an Erupting Star
Spitzer Space Telescope • IRS

NASA / JPL-Caltech / P. Ábrahám (Konkoly Obs., Hungarian Academy of Sciences) ssc2009-11a


Mid-IR Variability of T Tauri Stars 7

Leisenring et al. (in prep)

EX Lupi: episodic accretion does affect the molecular gas at planet-forming radii in the disk



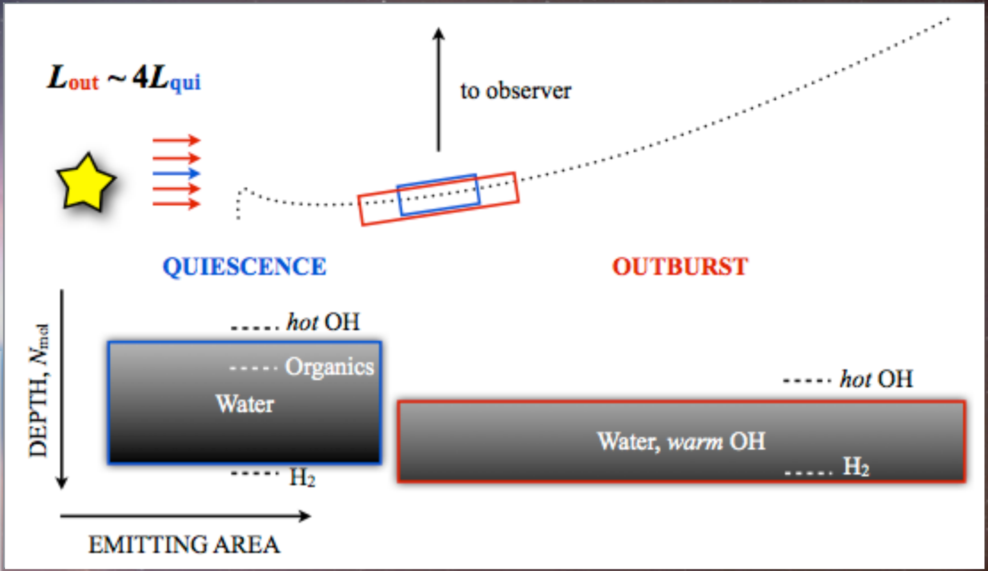
(Banzatti et al. 2012)

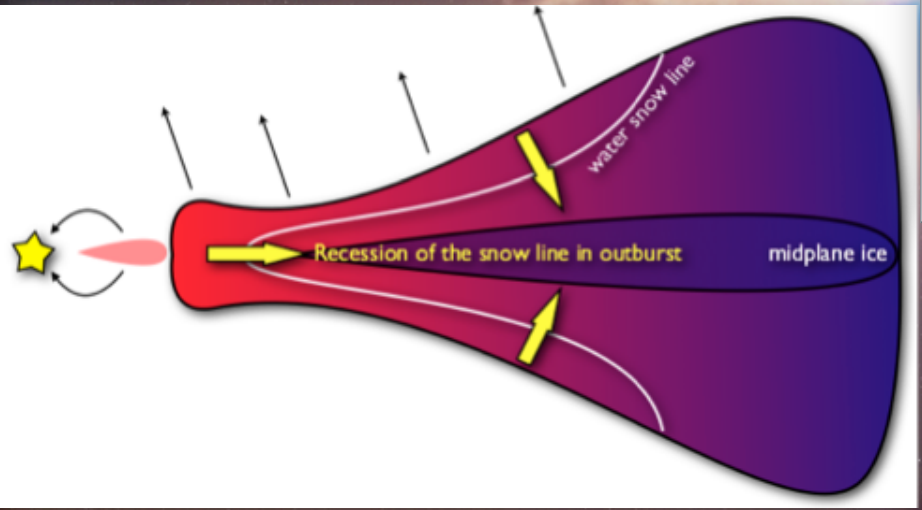
UV radiation drives chemistry !

OUTBURST (single slab LTE model):

- water from a larger area (x4)
--> larger extent of the warm emitting layer? New water?

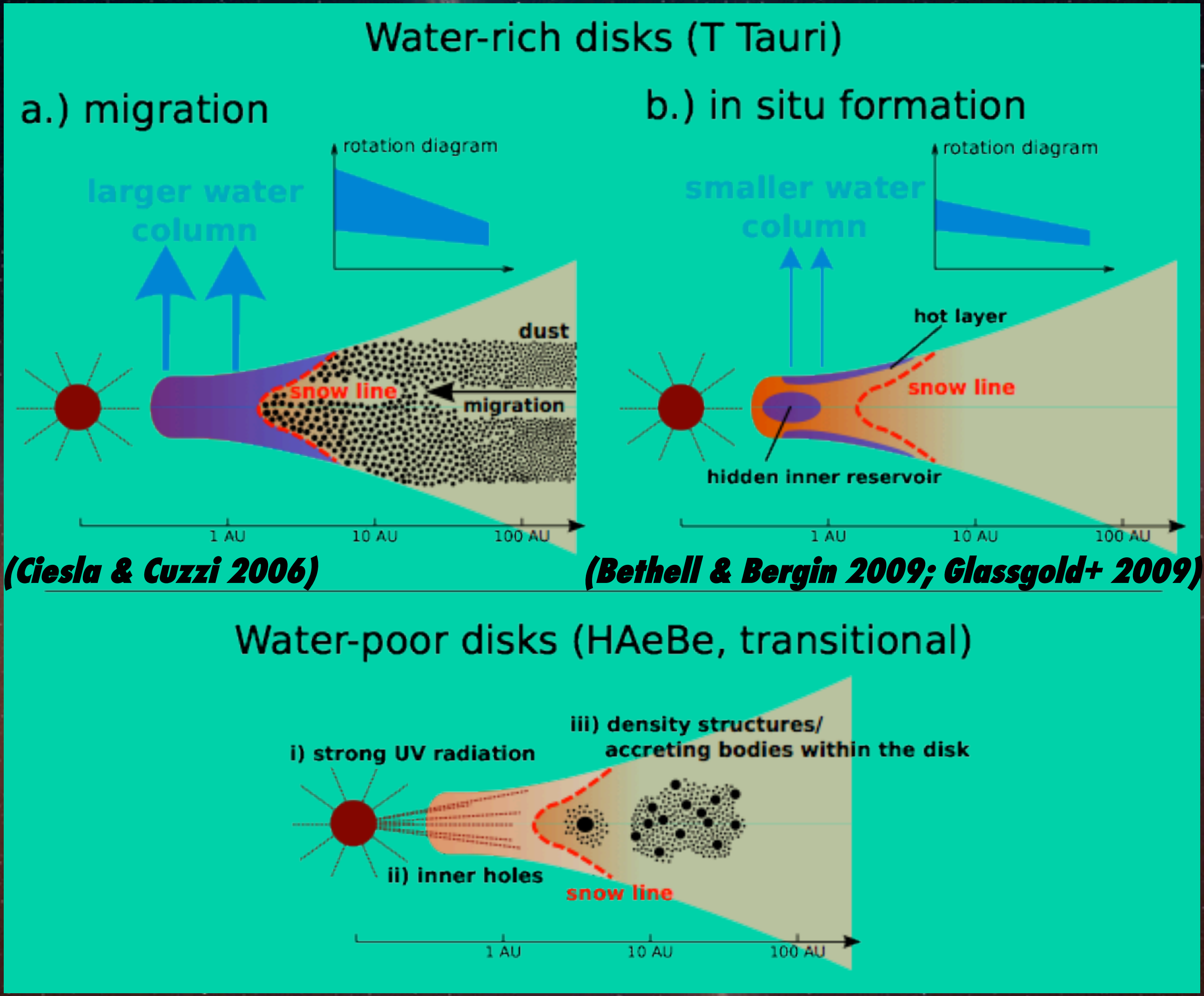
- OH produced
--> UV photodissociation of water?
(Tappe+ 2008, Najita+ 2010)





UV-driven chemistry:
in favor or against these important molecules (e.g. organics)?

Lifting the veil on planet formation processes (?)...



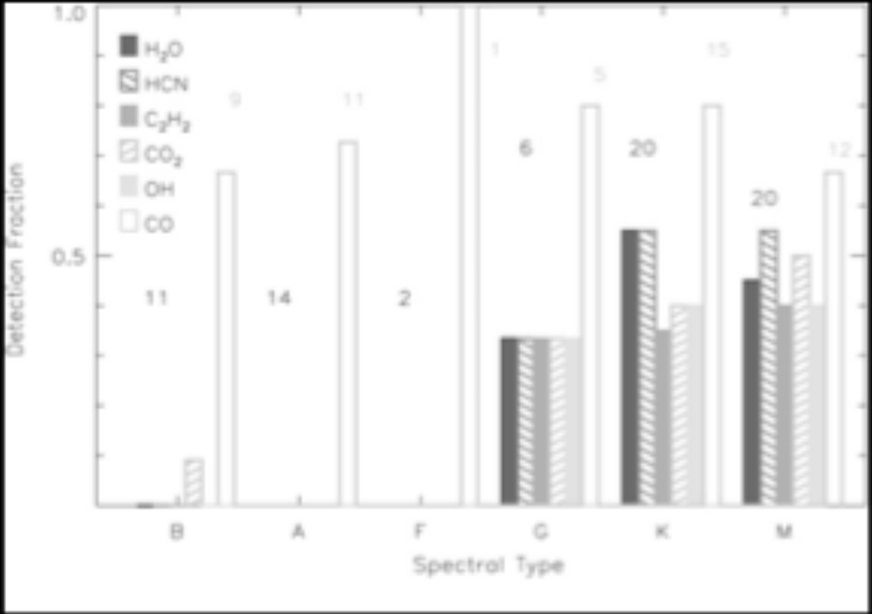
(Ciesla & Cuzzi 2006)

(Bethell & Bergin 2009; Glassgold+ 2009)

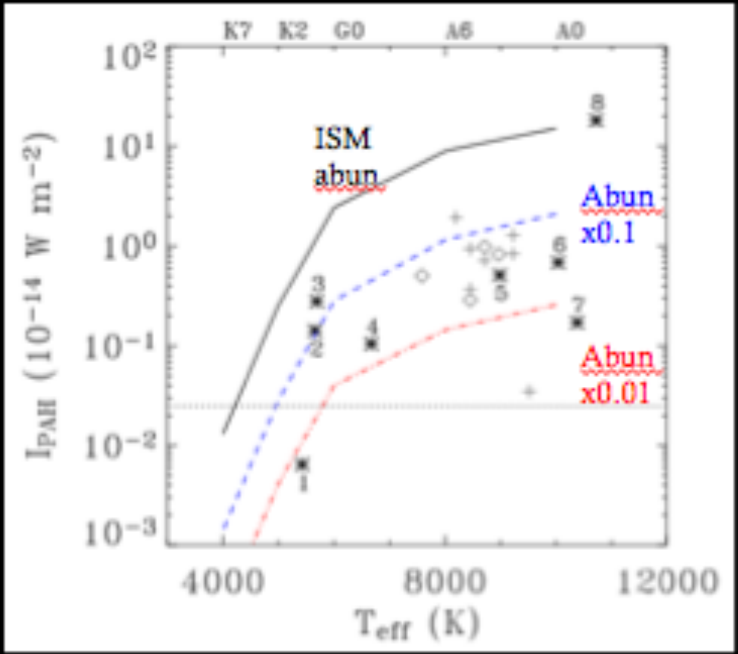
Banzatti, Pontoppidan, Meyer, Bruderer (submitted)

Disk Chemistry Studied with Spitzer

Wide variety of molecules now detected in planet-forming zone (0.1-10 AU) :
H_2O, HCN, C_2H_2, OH, CO



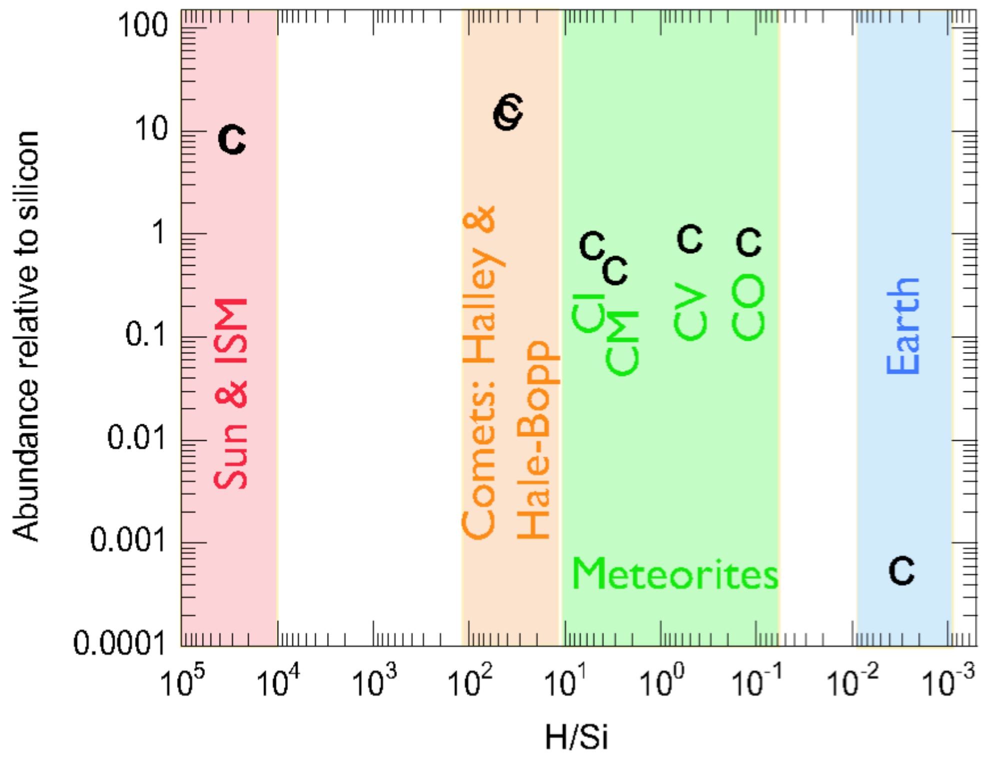
Pontoppidan et al. (2010)



Geers et al. (2006)

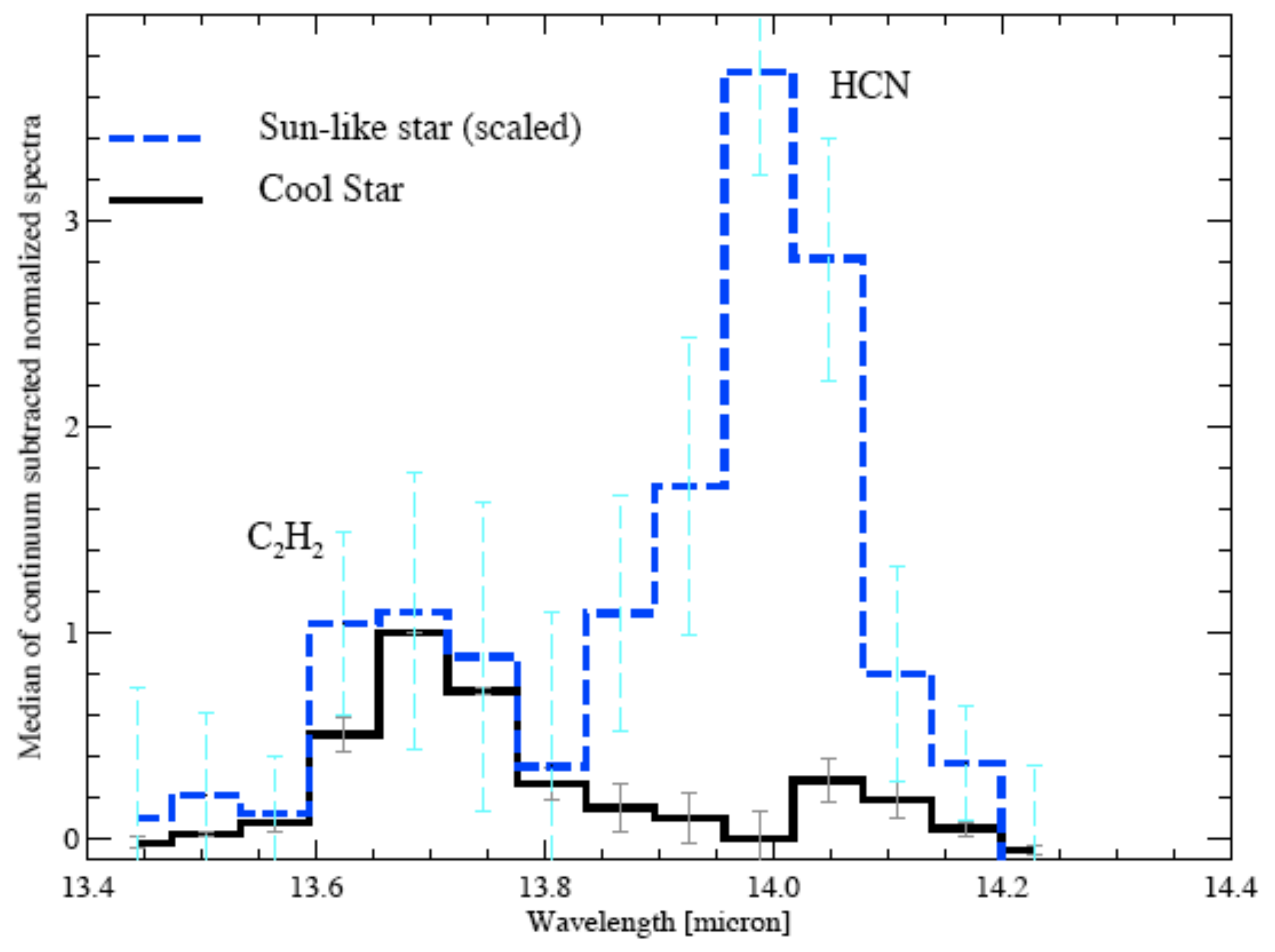
PAHs around T Tauri disks, though less frequent than in HAeBe disks (11 vs. 54%), and at reduced abundance w.r.t. ISM.

The carbon problem



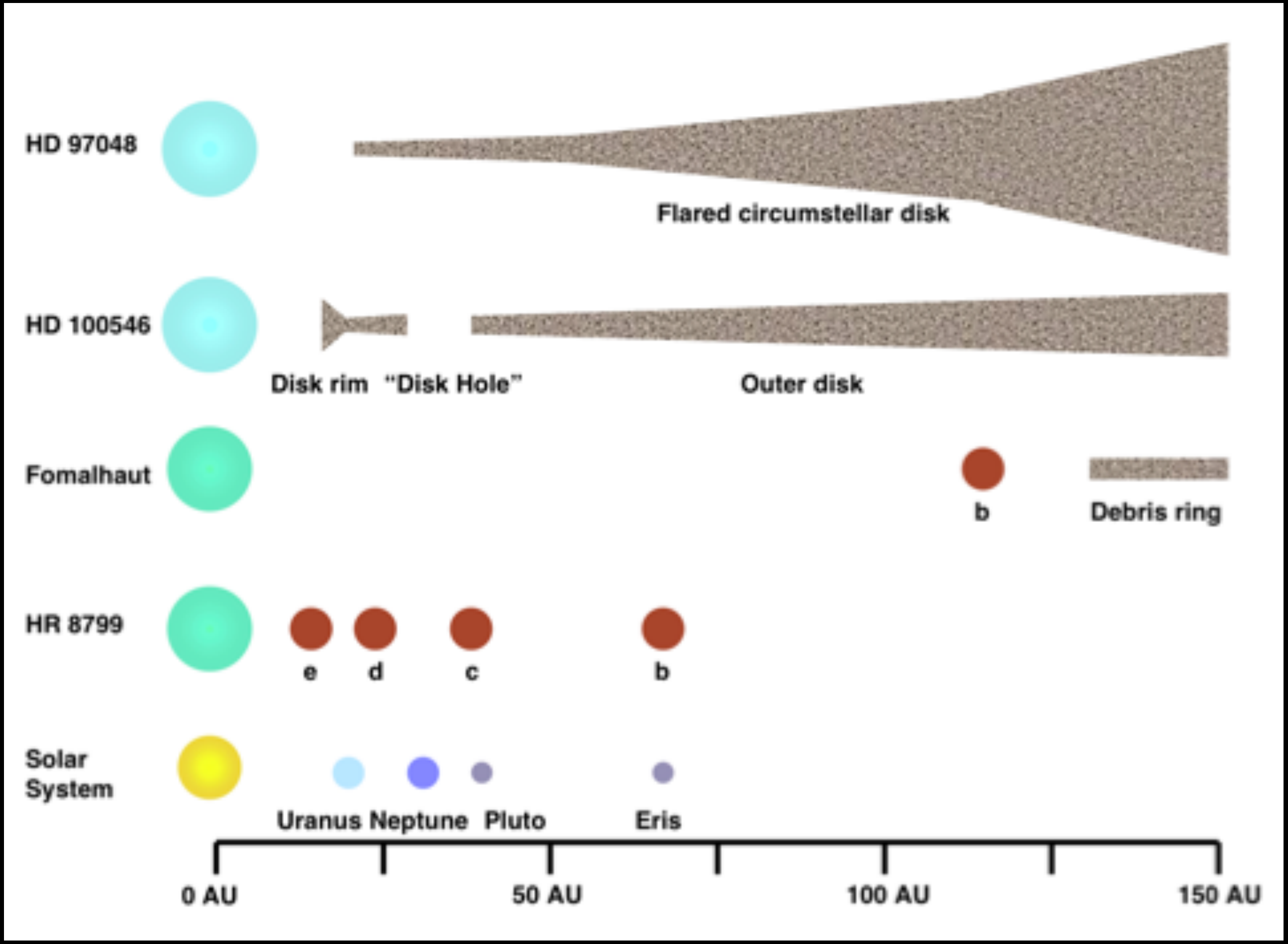
Most of the carbon in the ISM is in solid form…
Are primordial carbon grains being combusted in inner disk during planet formation?
(Gail et al. 2002; Jeong-Eun et al. 2010)

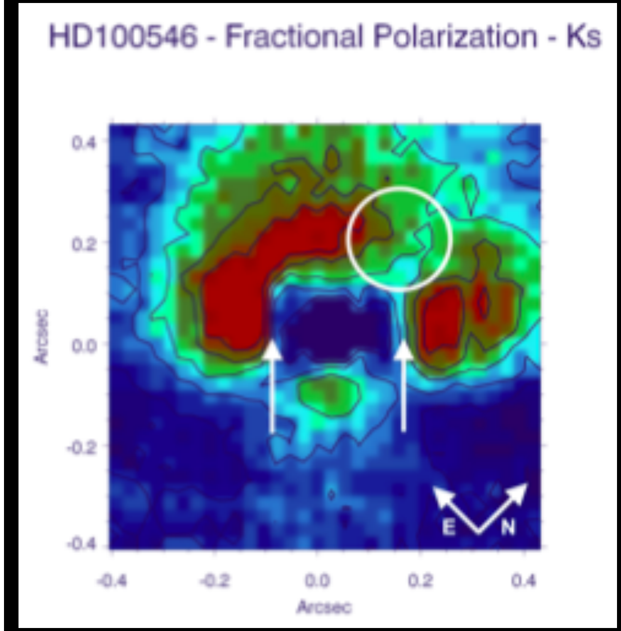
Disk chemistry may vary with stellar mass (and time).



Pascucci et al. (2009); cf. Carr & Najita (2008); Pontoppidan et al. (2010)

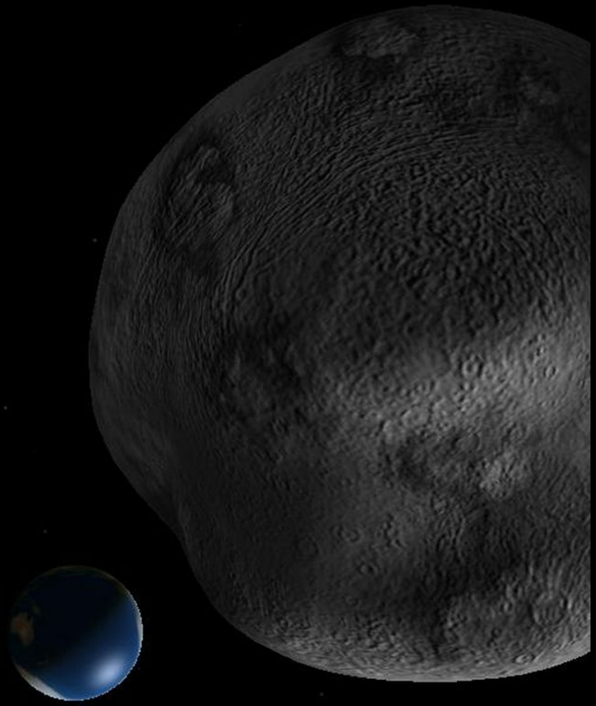
Observations: Dust in Scattered Light





(Quanz et al. 2011); See also 69 um Foresterite ring at 10-20 AU (Mulders et al.)!

Evolution of Circumstellar Disks & Planet Formation: From Spitzer to Herschel Part "B"



2012 da 14

All explained in a future Nice Model elaboration…

Michael R. Meyer
Institute for Astronomy, ETH-Zurich
Chronology of the Solar system
14 February 2013, Les Houches

Key Concepts from Tonight: Part A

1. *Different wavelengths trace different radii.*

2. *Planet forming disks start at 10-20 % the mass of the star.*

3. *We can constrain distributions of initial conditions in disks.*

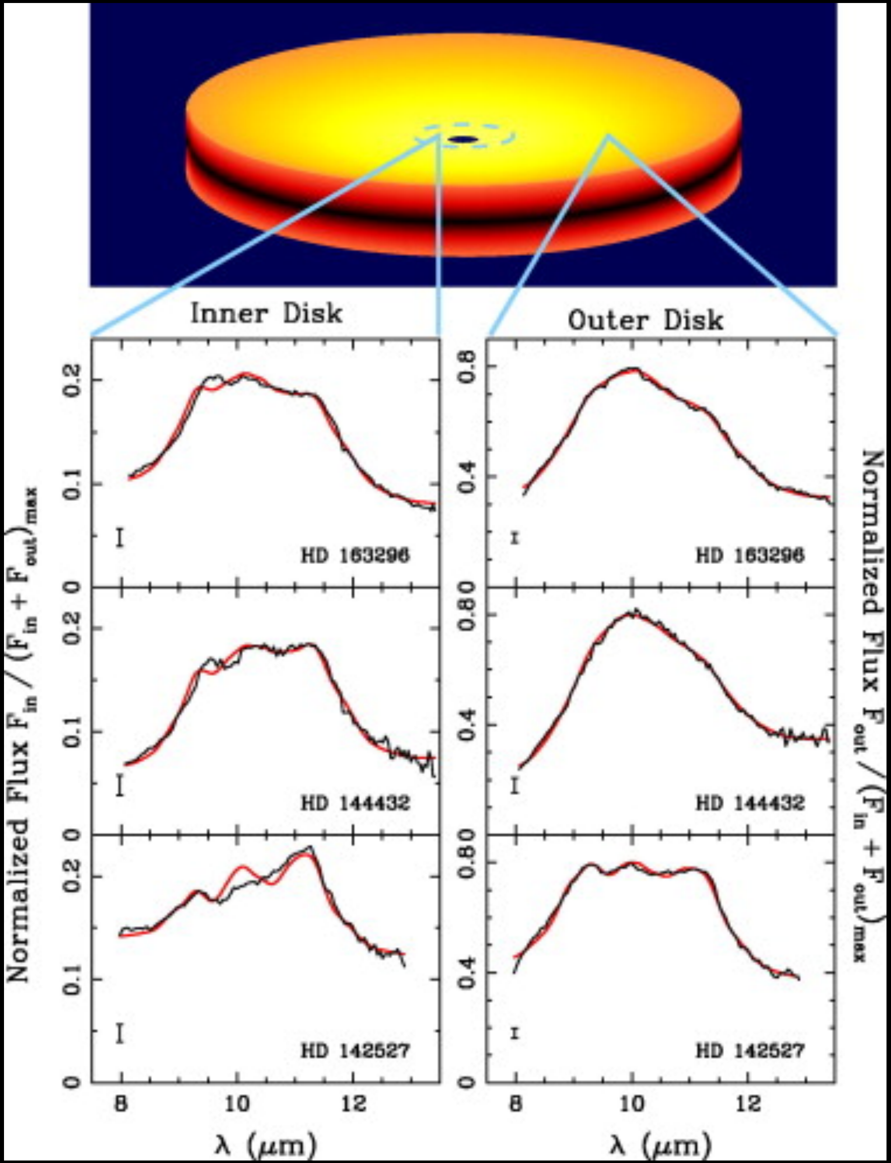
4. *Disk evolution paths are diverse and thus hard to detect.*

5. *Carbon, delivered to the nebula in solid form, was processed.*

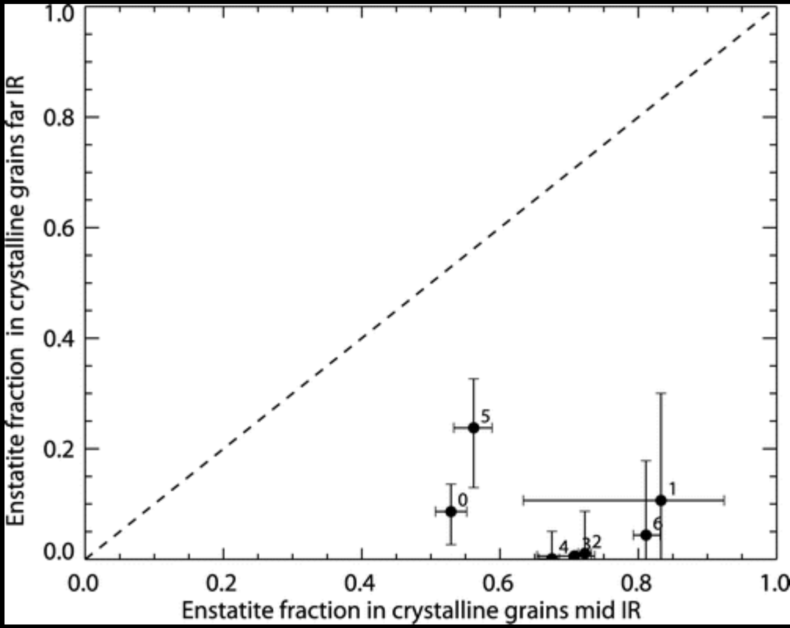
6. *(Inner) Disk chemistry is stellar mass and time dependent.*

7. *We may be witnessing planets in formation.*

Silicates throughout the disk….

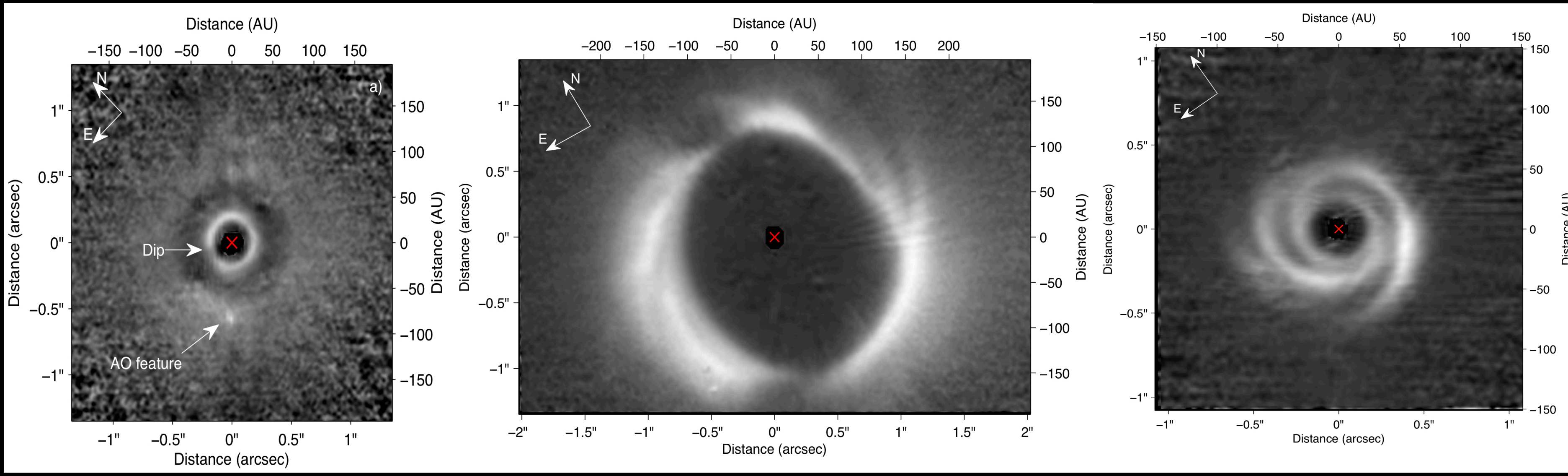


van Boekel et al. (2004)



Bouwmann et al. (2008)

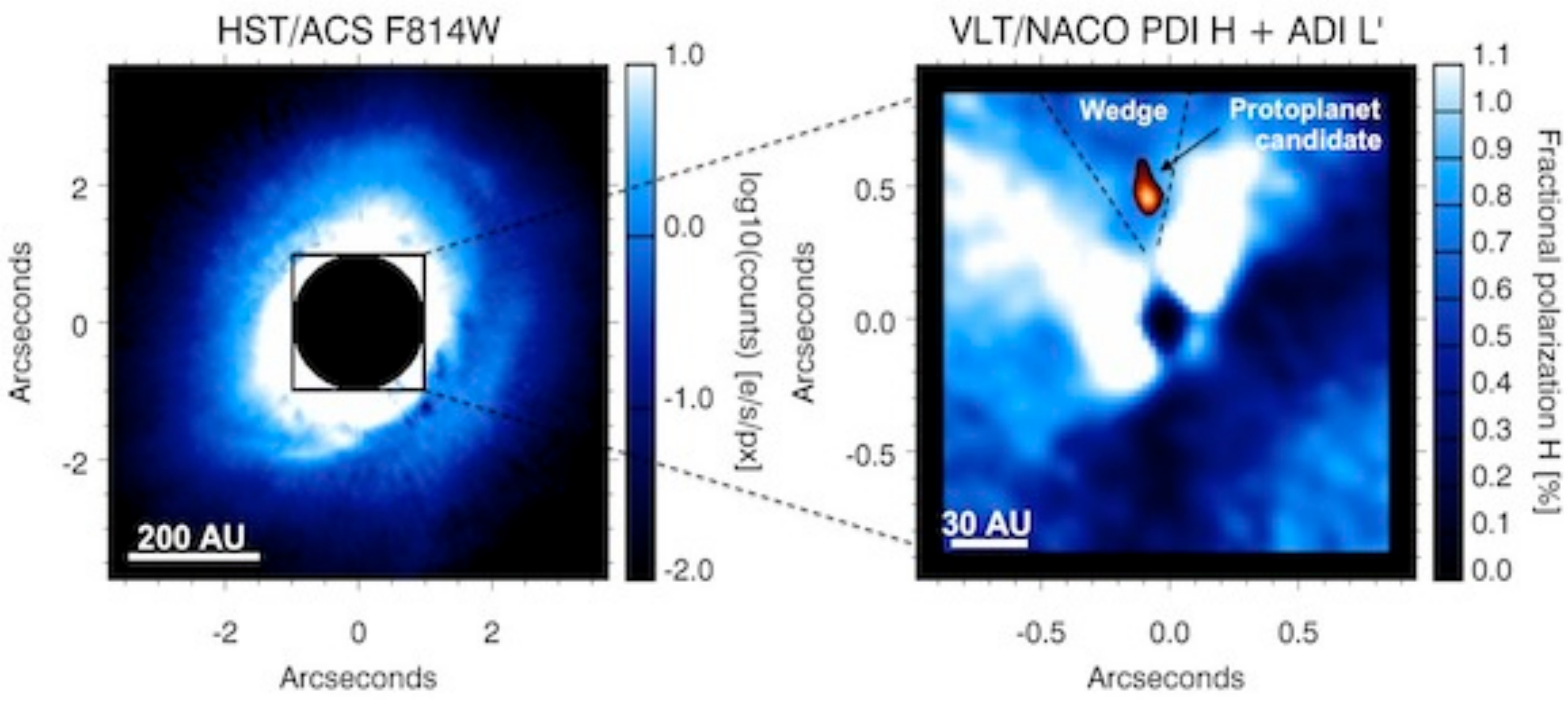
The Power of Resolved Images…



Obtained with NACO on the VLT, but only precursor for SPHERE!

From Quanz et al.; Avenhaus et al.; Garufo et al. (2013)

Watching planets in formation…



HD 100546b: Source at 40-50 AU. Did it form there or was it ejected?

From Quanz et al. (2013); see also Kraus & Ireland (2011)

Key Concepts for tomorrow: Part B

1. ***Global disk evolution derived from diverse stellar ensembles.***

2. ***We can constrain evolution in gas to dust from primordial to debris.***

3. ***Inner disks (< 10 AU) clear efficiently, very fast!***

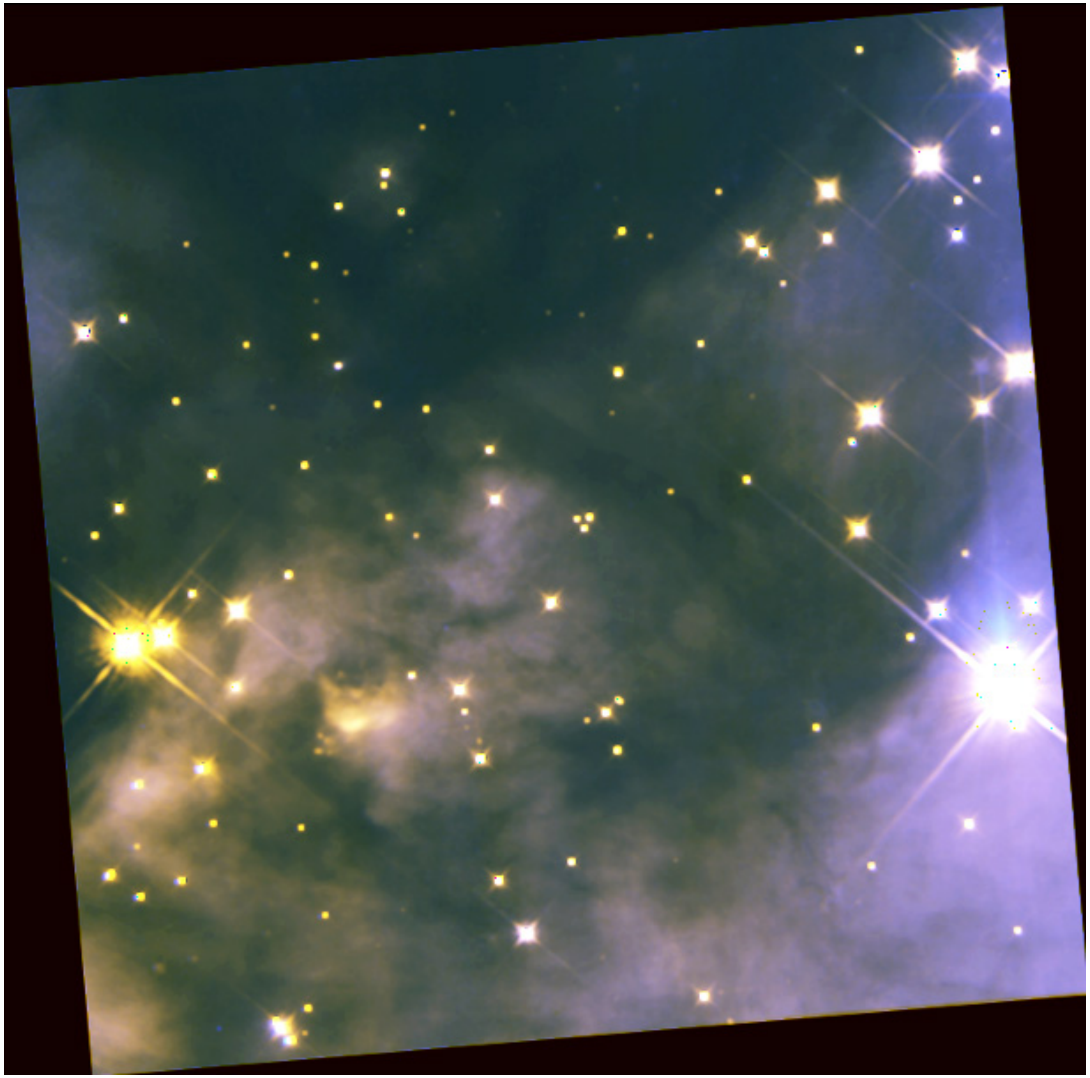
4. ***Debris (and small planets) could be extremely common.***

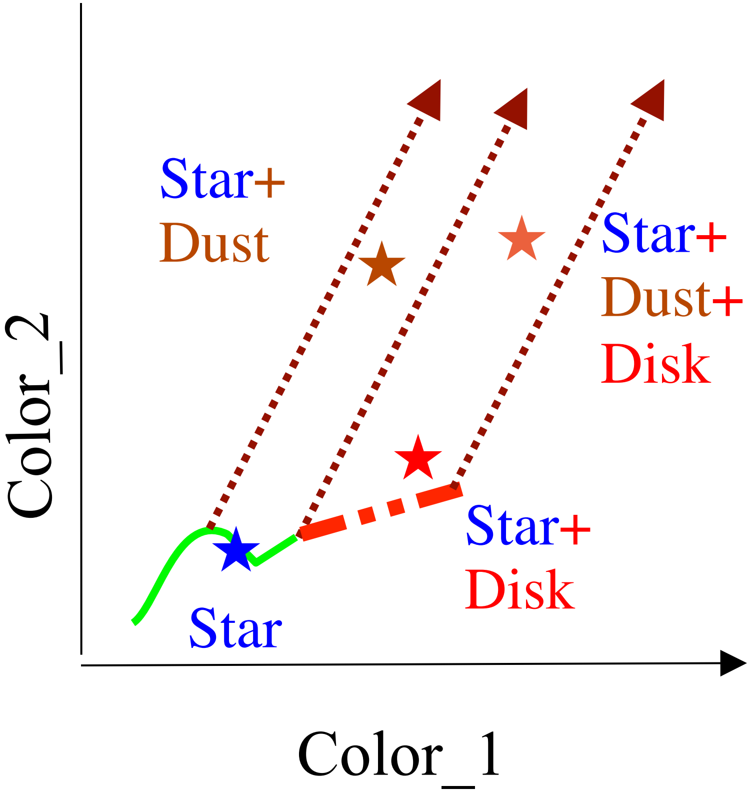
5. ***Warm debris and transient debris are rare.***

6. ***Disk chemistry + dynamics = planet composition.***

7. ***We may be able to trace specific giant impacts in other systems.***

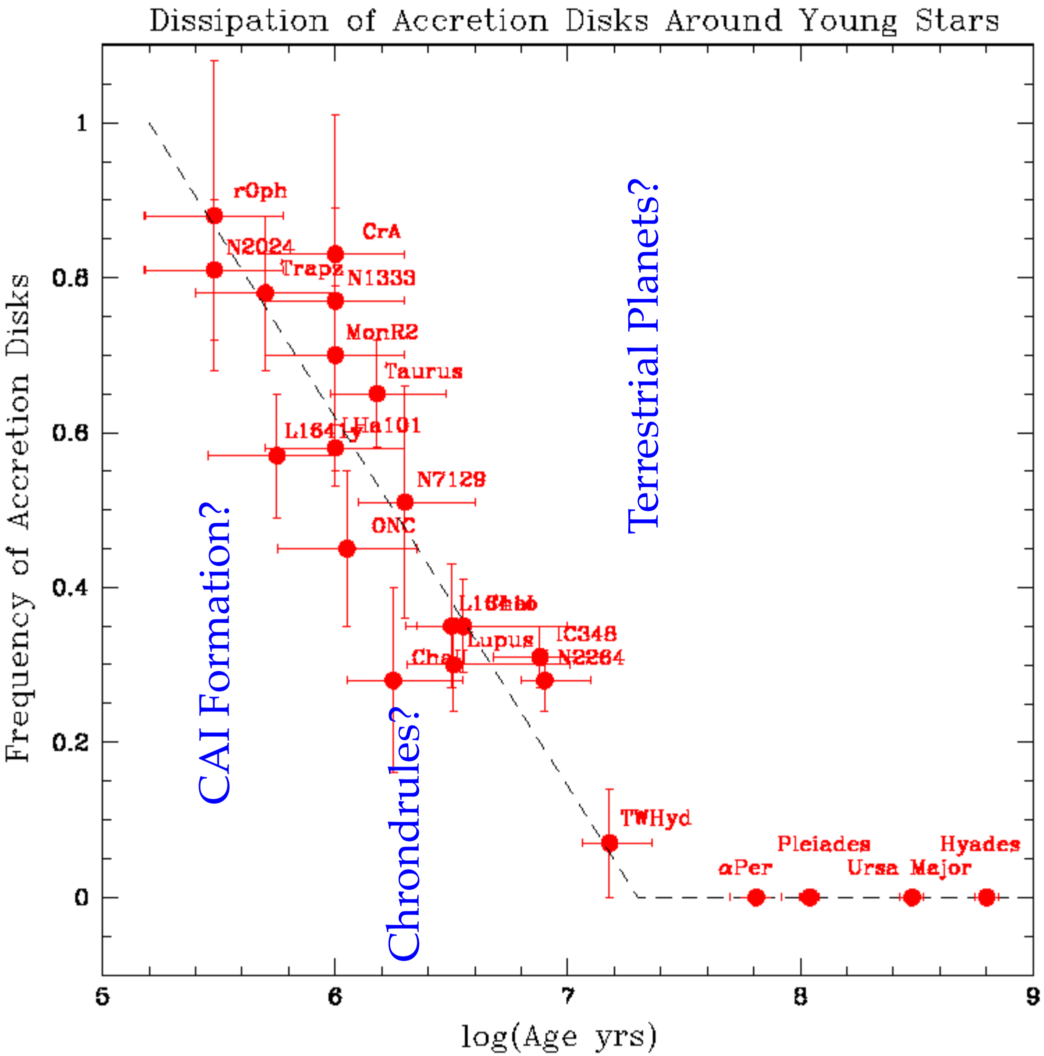
8. ***At least 2 aspects of our solar system appear to be uncommon.***





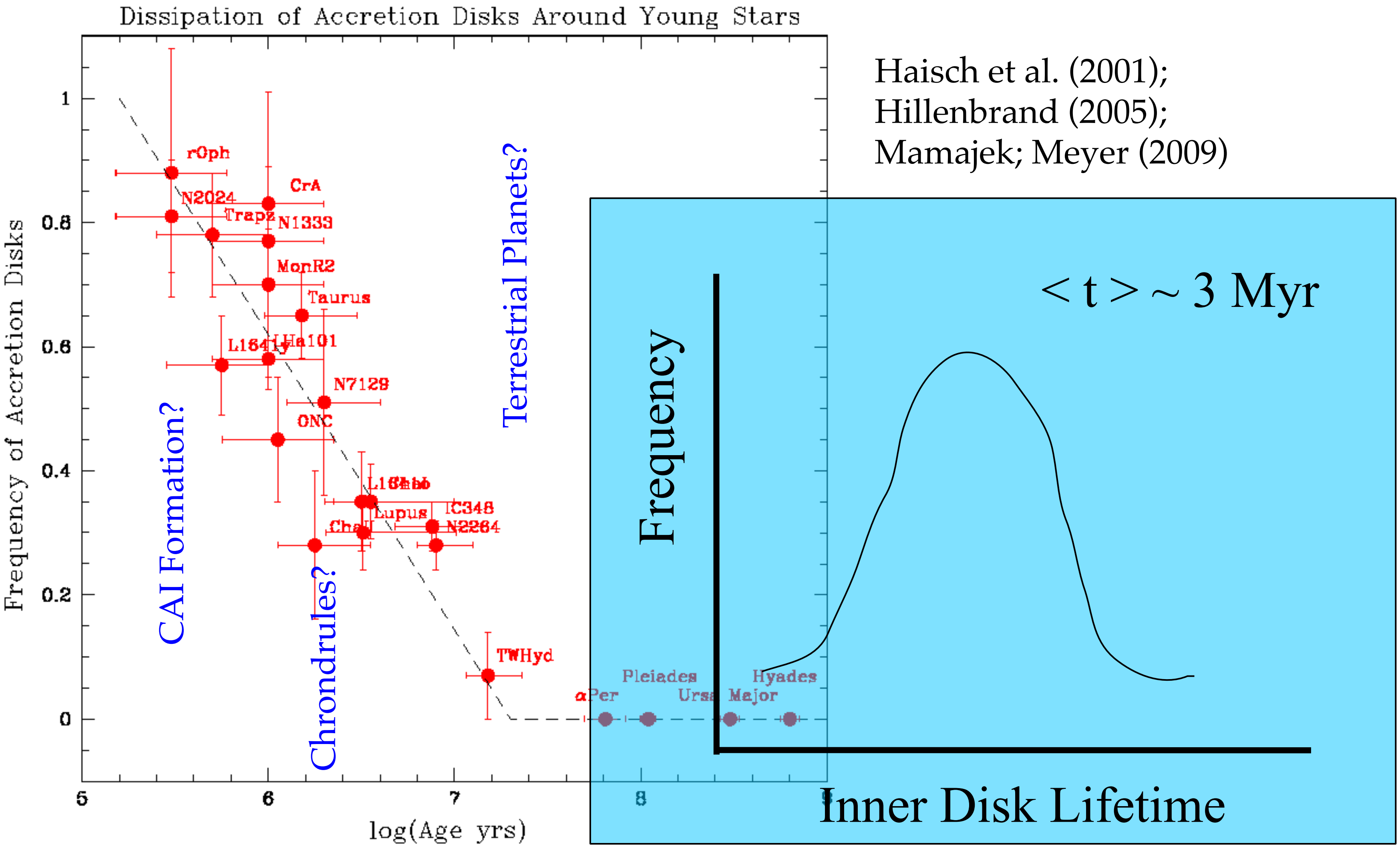
NICMOS/HST Mosaic F810W/F110W/F150W of NGC 2024 (Liu, Meyer, Cotera, and Young 2003, AJ)

Inner (< 0.1 AU) Accretion Disk Evolution 0.1-10 Myr



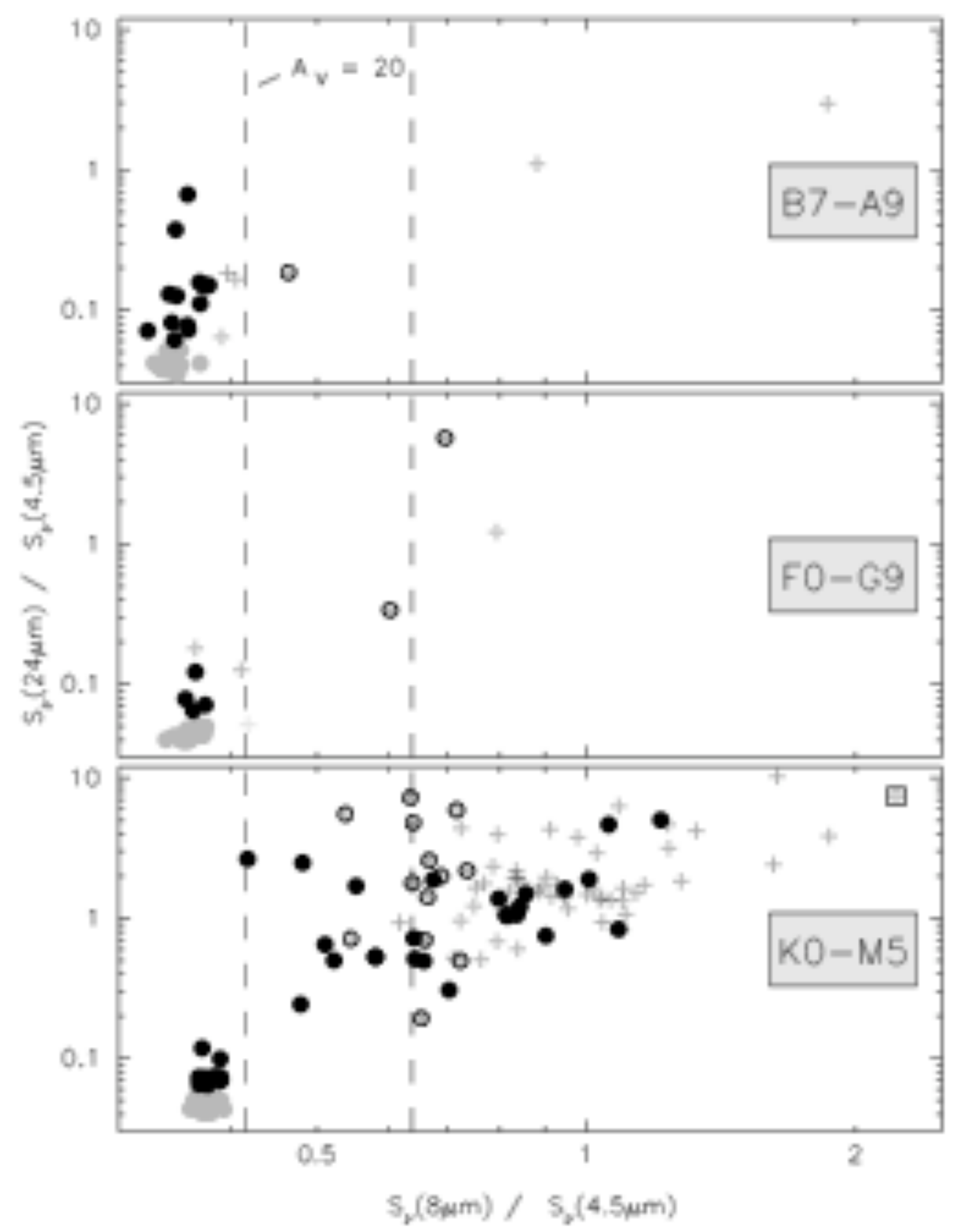
Haisch et al. (2001);
Hillenbrand (2005);
Mamajek; Meyer (2009)

Inner (< 0.1 AU) Accretion Disk Evolution 0.1-10 Myr



Haisch et al. (2001);
Hillenbrand (2005);
Mamajek; Meyer (2009)

Disk Evolution in Upper Sco at 5 Myr: 220 Stars



=> Primordial disks last longer around lower mass stars.

=> Duration of the "transition" ~10^5 yrs.

Carpenter et al. (2010);
Muzerolle et al.; Luhman;
And many others…

Herschel Results #1: Photometry

Harvey et al (2012) – Survey of lowest mass young stars.

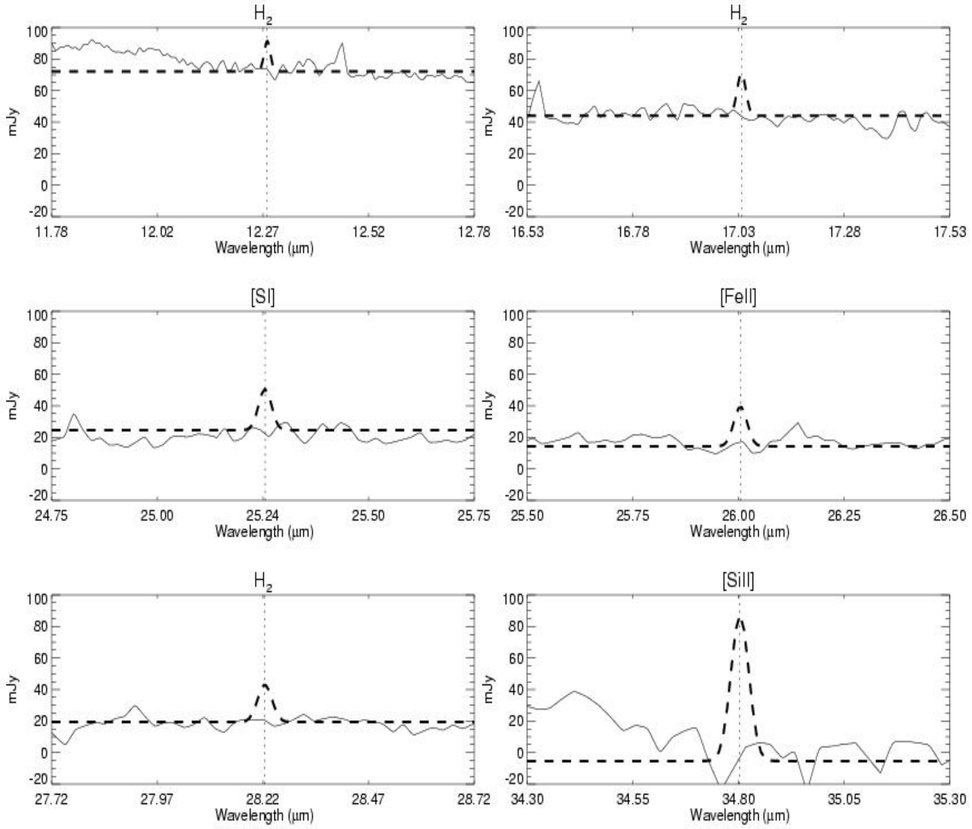
- disk masses somewhat smaller than expected.
- no clear differences in geometry compared to T Tauri.

Cieza et al. (2013) – Survey of "Weak" T Tauri stars.

- A few examples of large inner holes.
- Two "cold" disks (out of 16 surveyed).
- Not yet surveyed for gas…

Expect more results on radii of outer disk (cf. Donaldson et al. 2012)

(Massive) Gas disk lifetimes appear to be < 10 Myr.

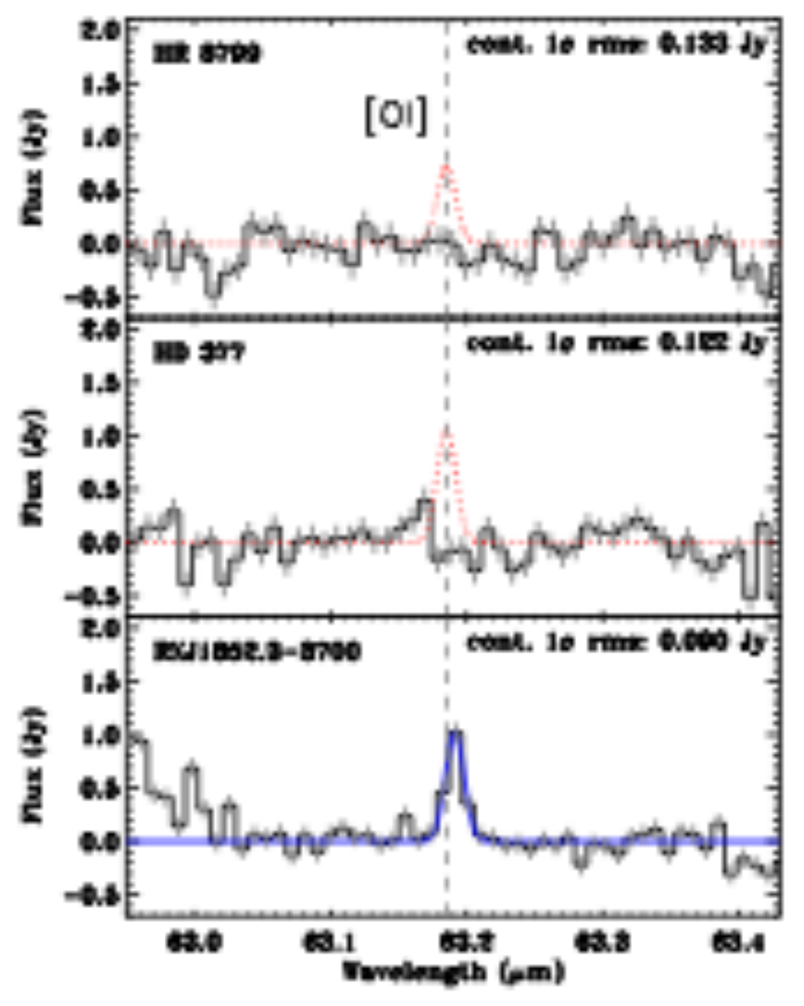


=> No gas rich disk (> 0.1 Mjup) detected.

=> 20 stars with ages 3-100 Myr

Hollenbach et al. (ApJ, 2005); Pascucci et al. (2006).

Herschel Results #2: PACS Spectra



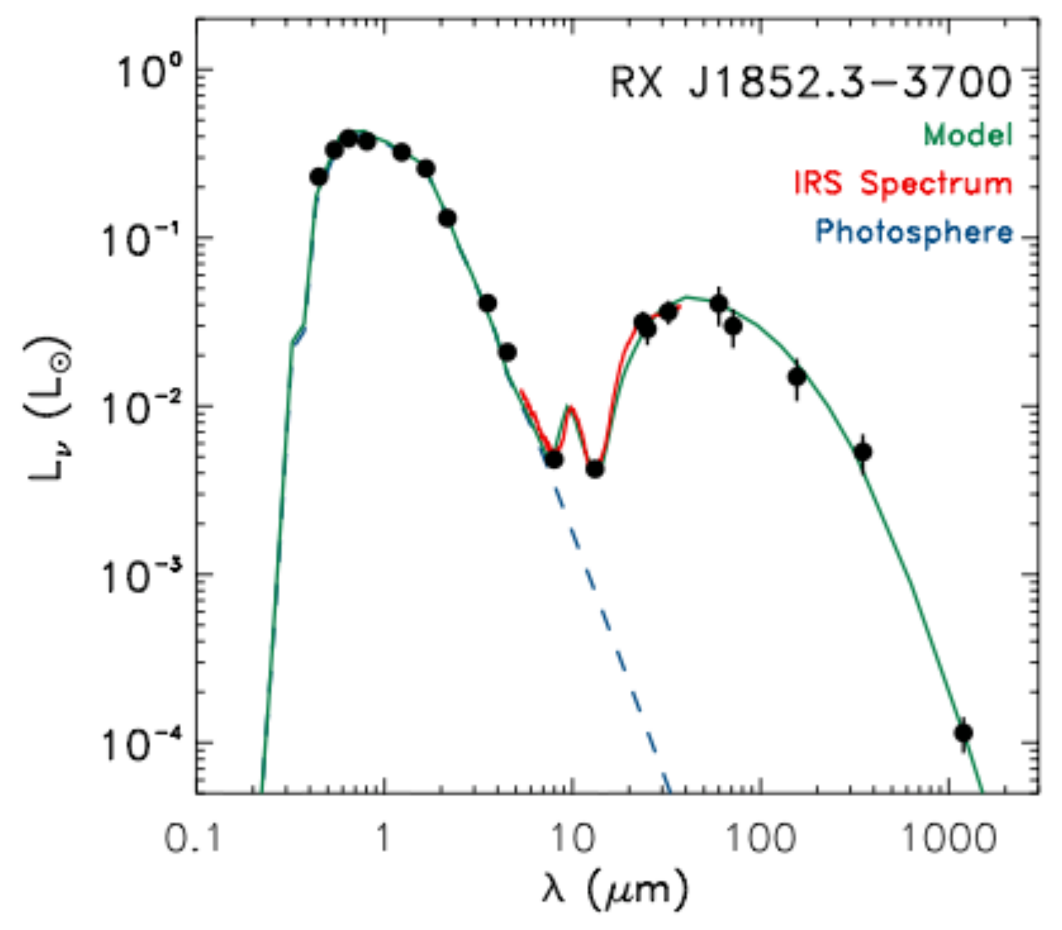
Stars 10-100 Myr.
HR 8799 – planetary system.
HD 337 – debris disk.
RX J1852 – transitional disk.
Geers et al. (2012

[OI] emission correlates
With far-IR disk continuum.

Survey paper on Herbig Ae/Be
Stars (Meus et al. 2012).

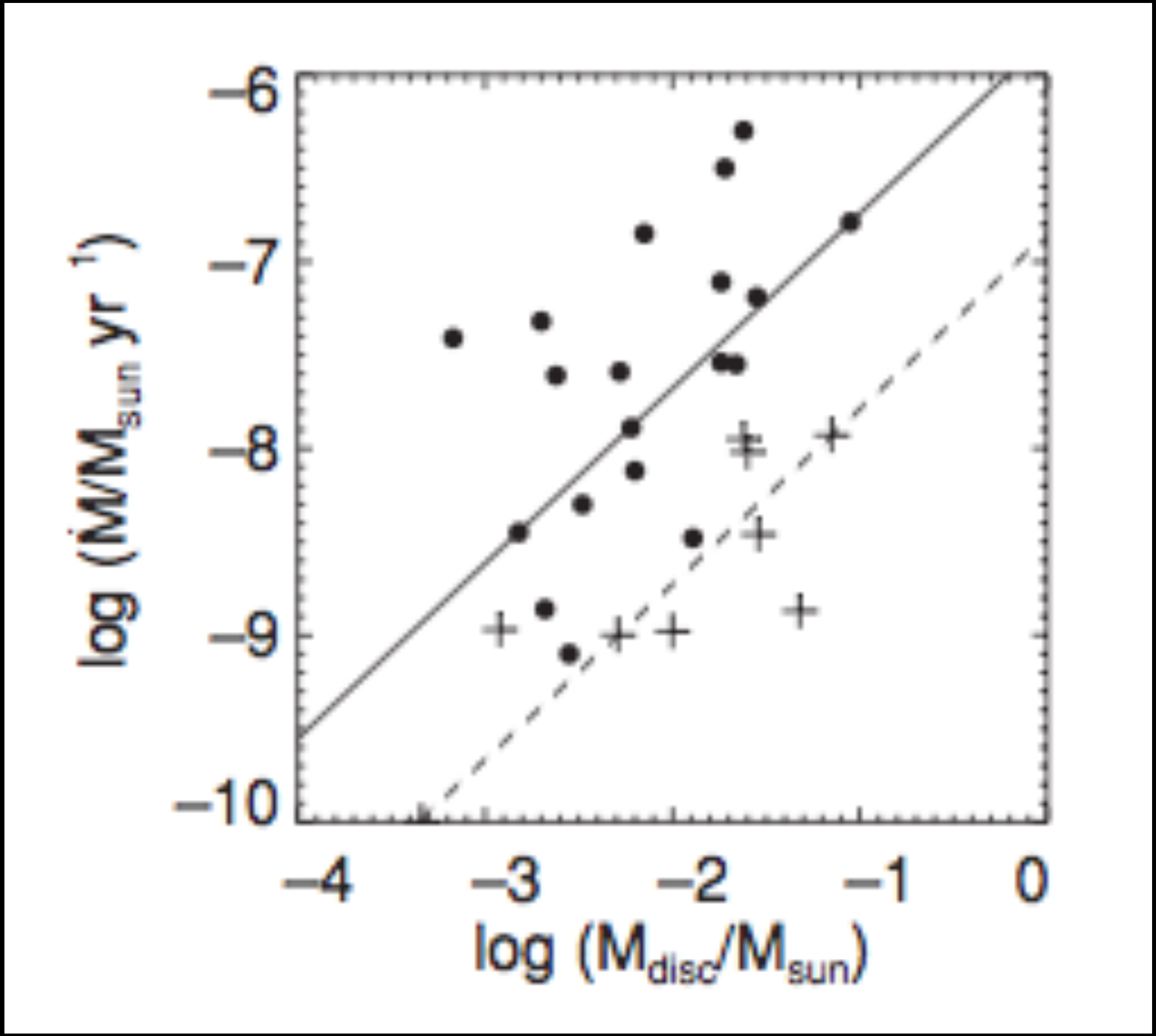
Dent, Kamp, Woitke, Thi et al. – GASPS Herschel Key Program

Transitional RX J1852: (photo-evaporation not gas giant) but could still form an ice giant beyond 10 AU!



Geers et al. (2012); See also Hughes et al. (2010)

Transition Disks with Low Mdot?



Several ways to get transition disks:

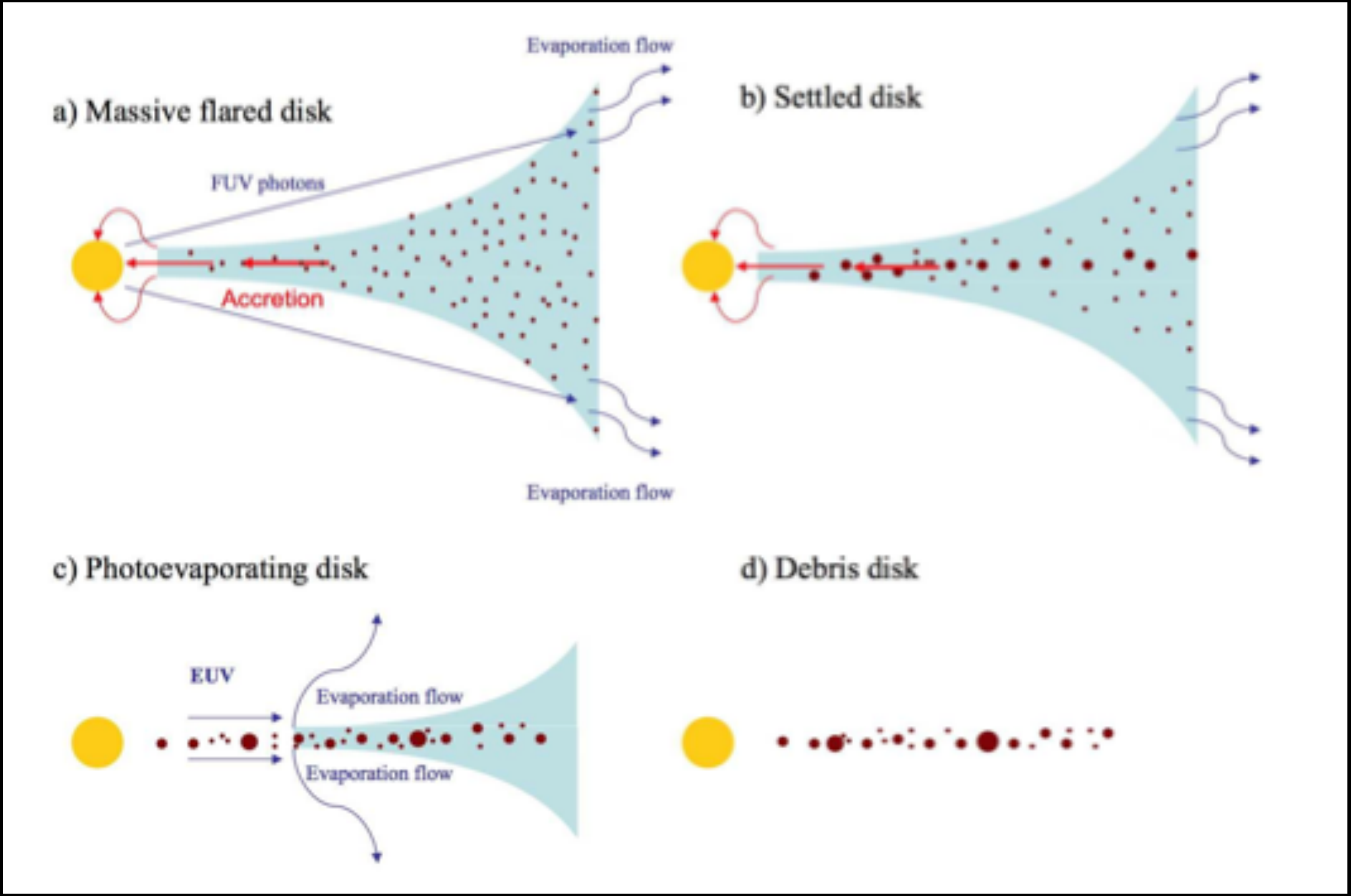
- Planet formation.
- photoevaporation.
- Opacity effects?

Najita et al. (2007)
See also Williams & Cieza (2011)

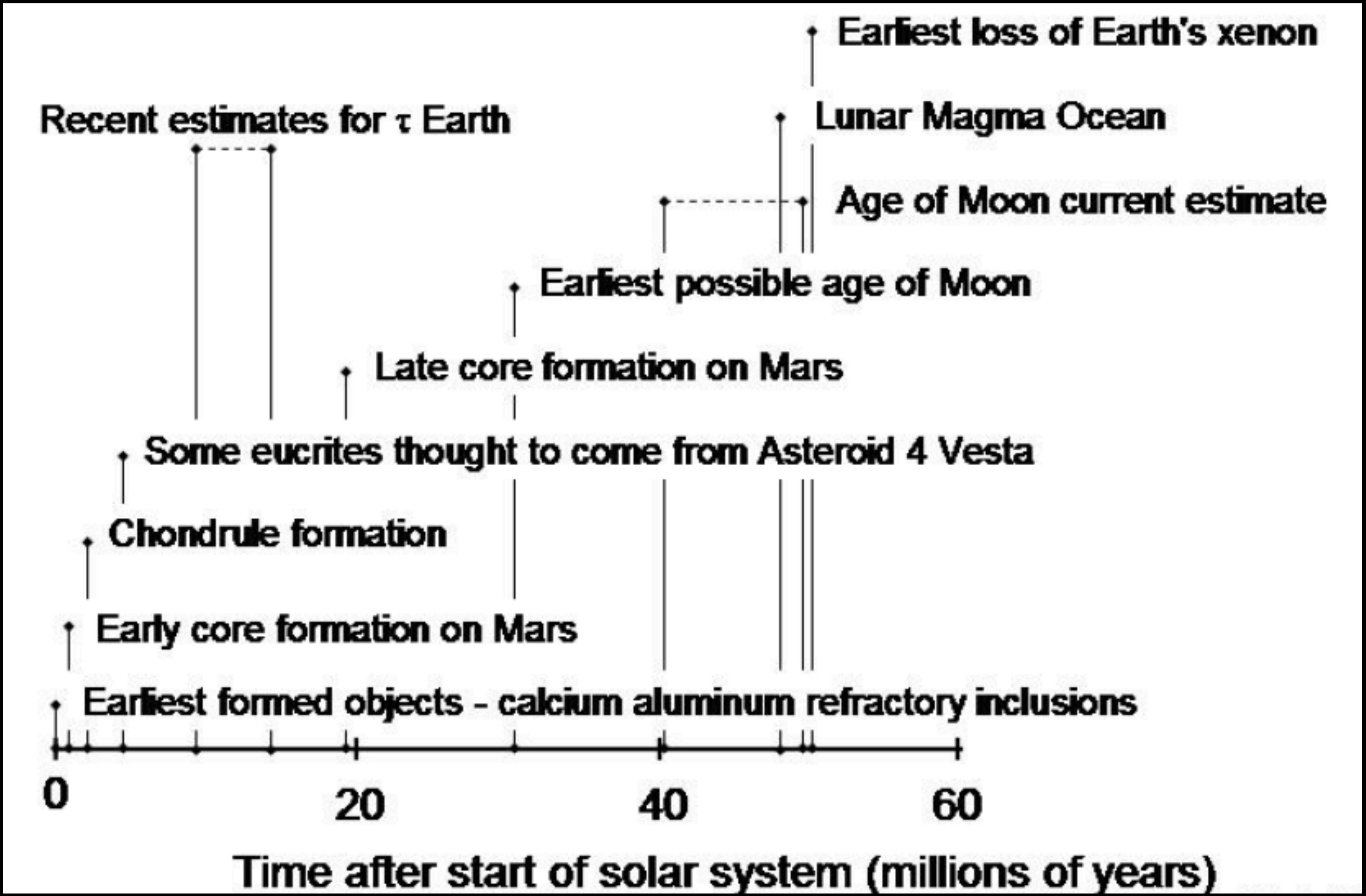
- Primordial (Gas Rich) Disks:
  - Required for gas giant planet formation.
- Debris (Dusty) Disks:
  - Trace evolution of planetesimal swarms: collisions of parent bodies then dust removal.
- How can you tell the difference?
  - Absence of gas (Gas/Dust < 0.1).
  - Dust processing through mineralogy (silica?).

Debris dust may be generated early on in gas rich disks and could dominate opacity before gas dissipates!

Primordial Disk Evolution: A Scenario…



From Williams & Cieza ARAA (2011)


Earliest loss of Earth's xenon
Recent estimates for τ Earth
Lunar Magma Ocean
Age of Moon current estimate
Earliest possible age of Moon
Late core formation on Mars
Some eucrites thought to come from Asteroid 4 Vesta
Chondrule formation
Early core formation on Mars
Earliest formed objects - calcium aluminum refractory inclusions
0
20
40
60
Time after start of solar system (millions of years)

Planet Formation Timescale as a Function of Stellar Mass and Orbital Radius:

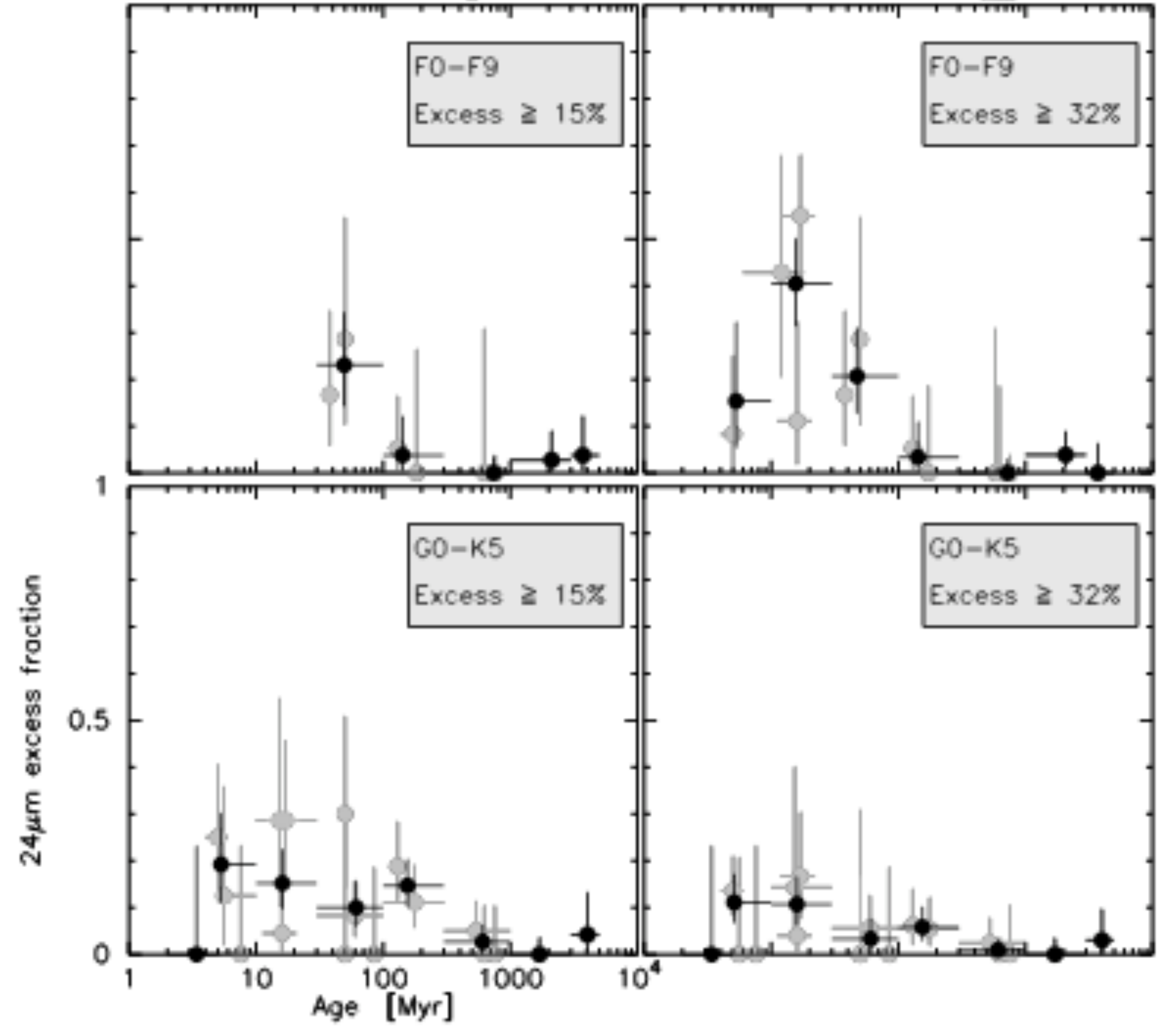
$$t_p \sim \rho_p \times R_p / [\, \sigma_d \times \Omega_d]$$

with $\sigma_d \sim M_* / a$ and $\Omega_d \sim \mathrm{sqrt}(M_* / a^3)$

$$t_p \sim [\rho_p \times R_p \times a^{5/2}] / [M_*^{3/2}].$$

Massive planets farther out around stars of higher mass.

Yet disks last longer around stars of lower mass!



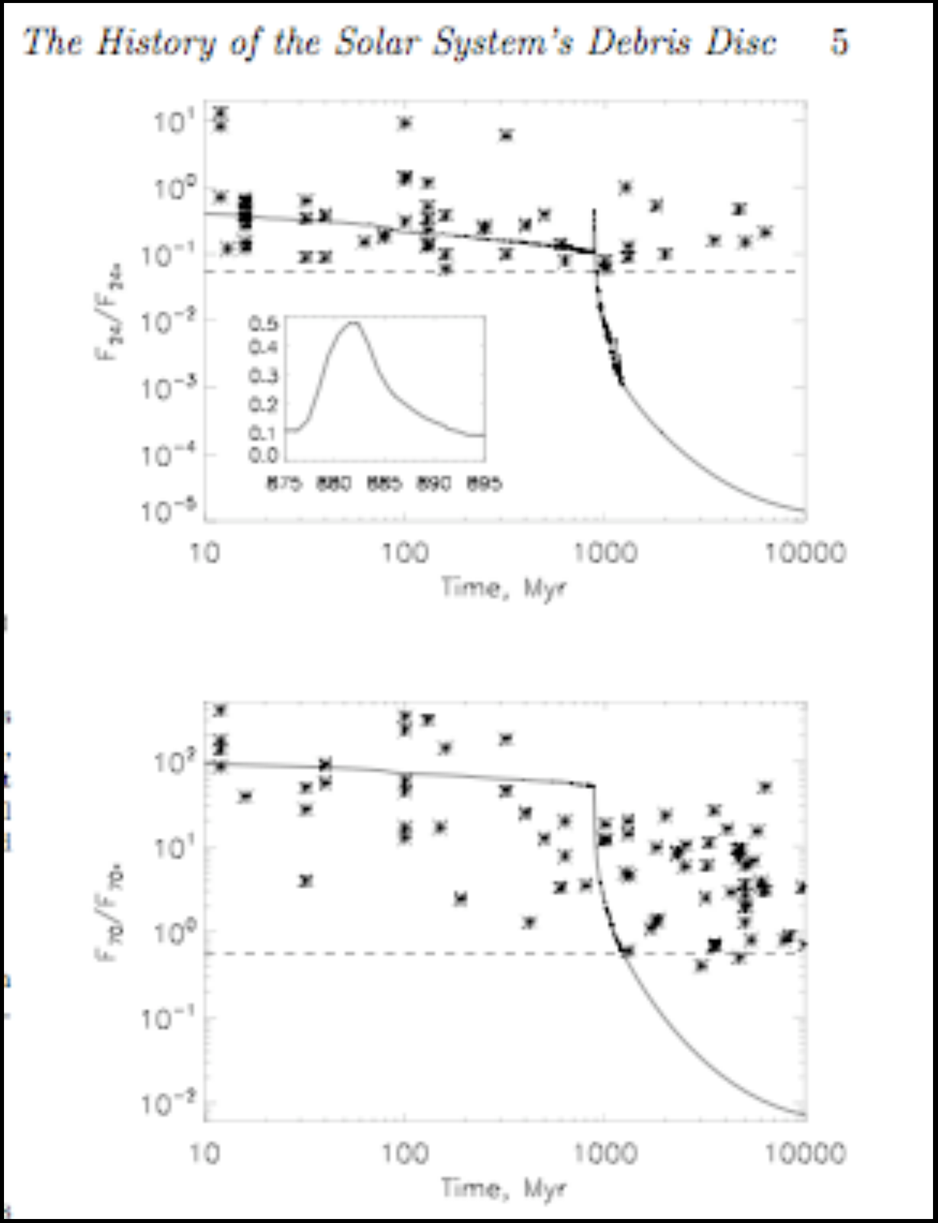
Carpenter et al. (2010)

Late Heave Bombardments Around Sun-like stars…

are rather special events!

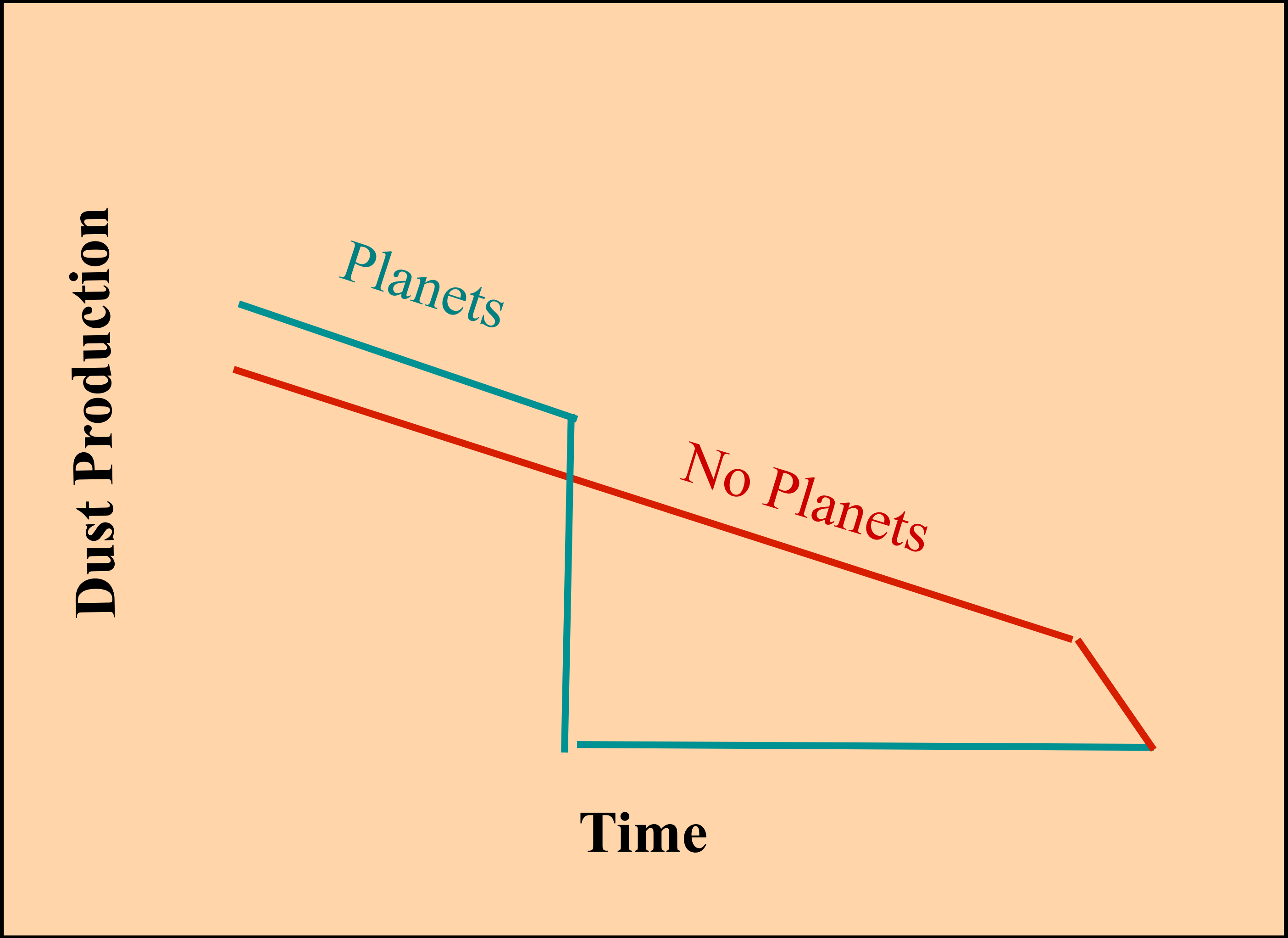
Was our system unusually bright from 8 to 24 microns at early times?

Booth et al. (2009)
Cf. Greaves et al. (2009)
& Meyer et al. (2007)

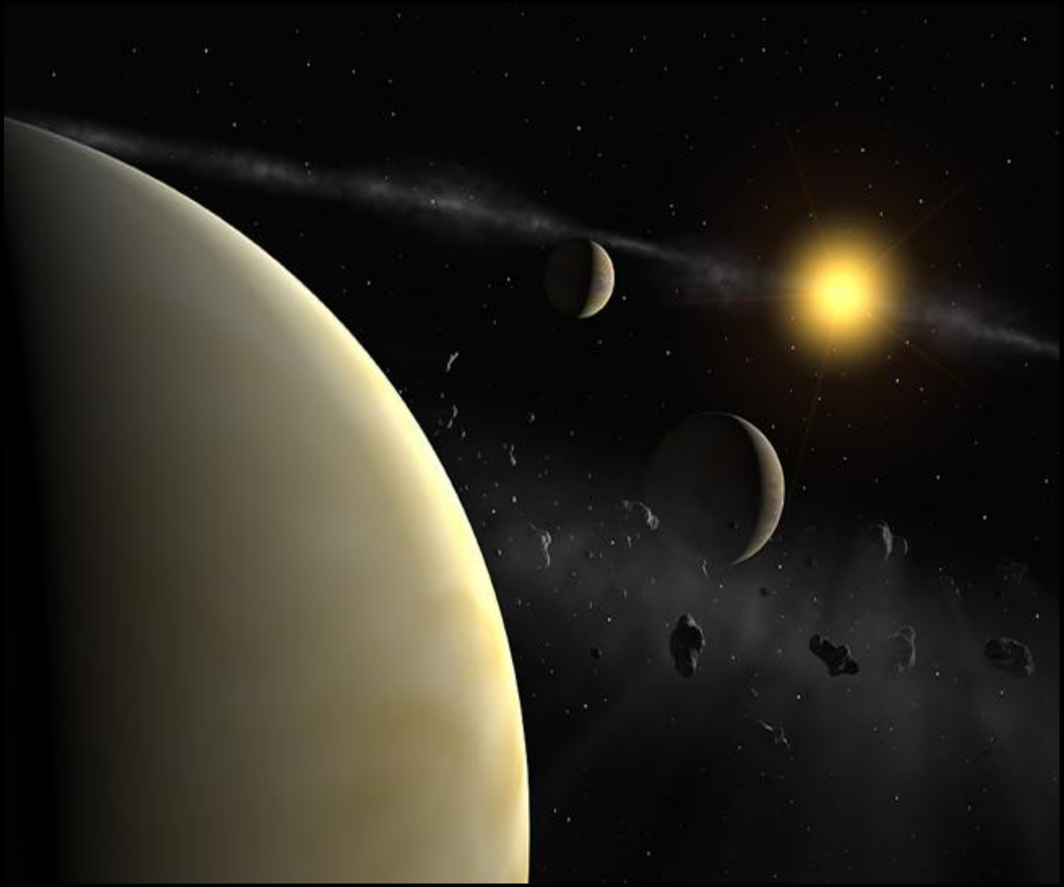


The History of the Solar System's Debris Disc 5

The connection between planetesimal belts and presence/absence of giant planets is not clear.

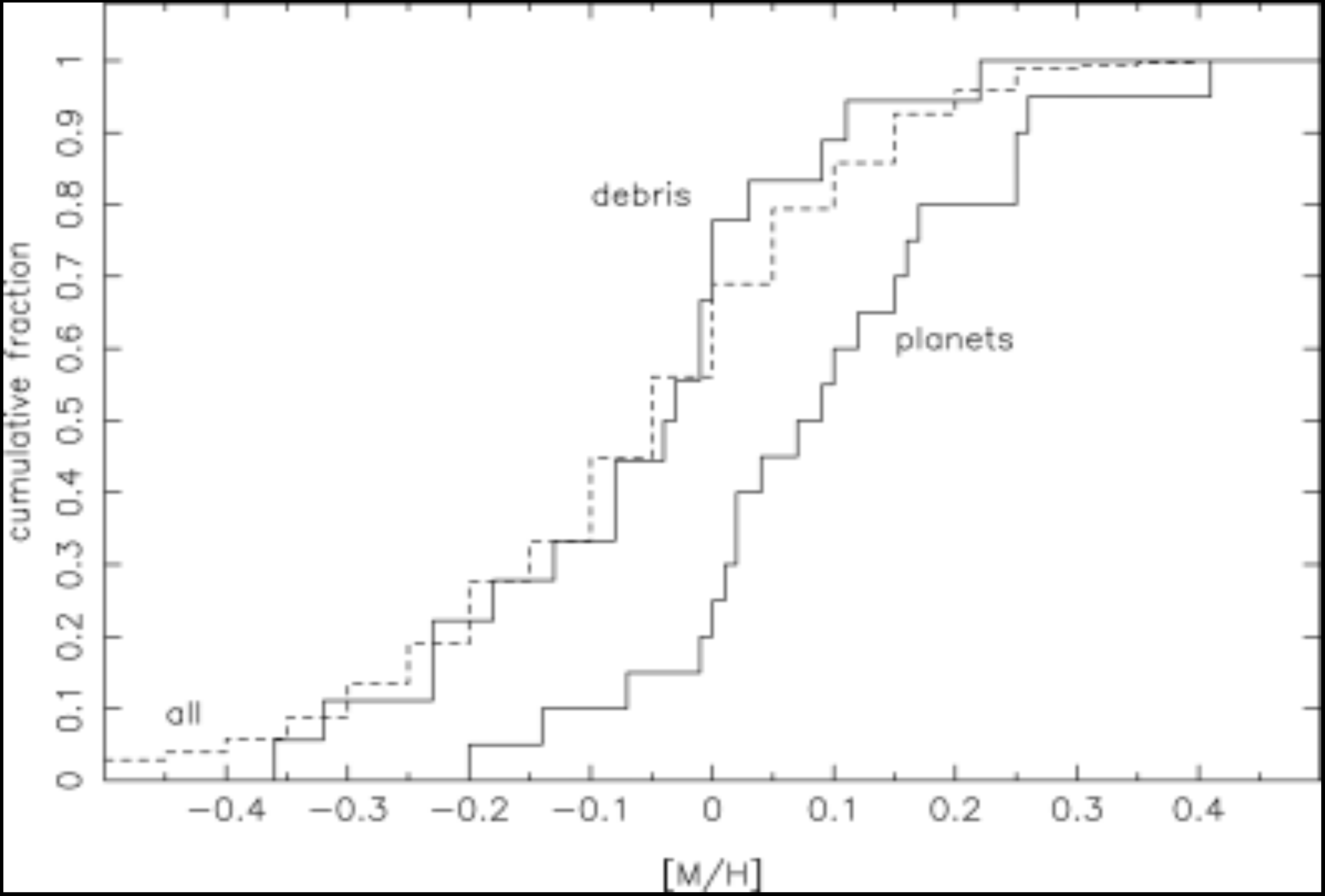


No link between debris and RV planets found! Could debris disks be more common than Gas Giants?



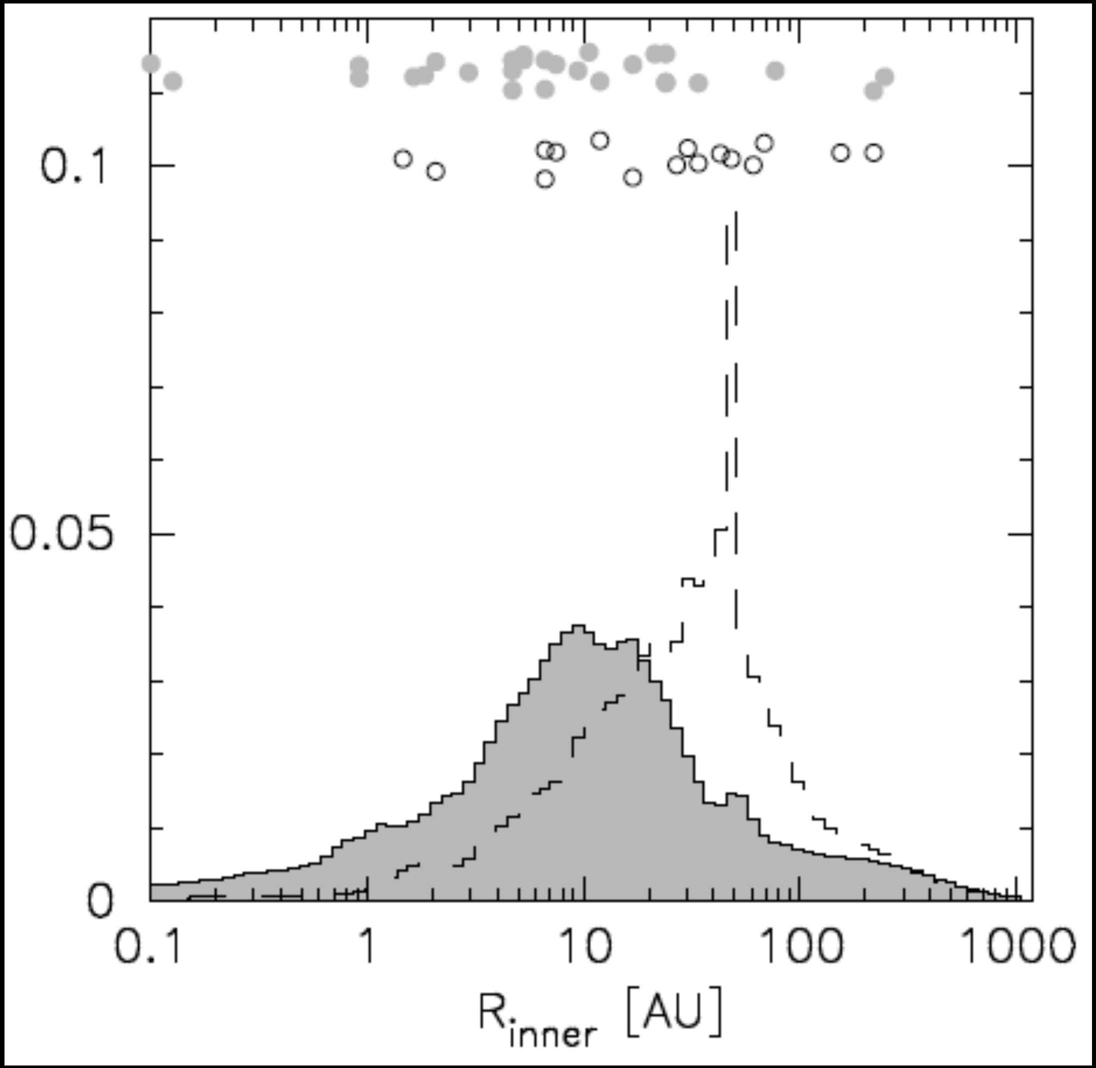
Moro-Martin et al. (2007a; 2007b), Kospal et al. (2009), Bryden et al. (2006)
Notable Exceptions: HD 69830, HR 8799, Fomalhaut, Beta Pic, eps Eri…

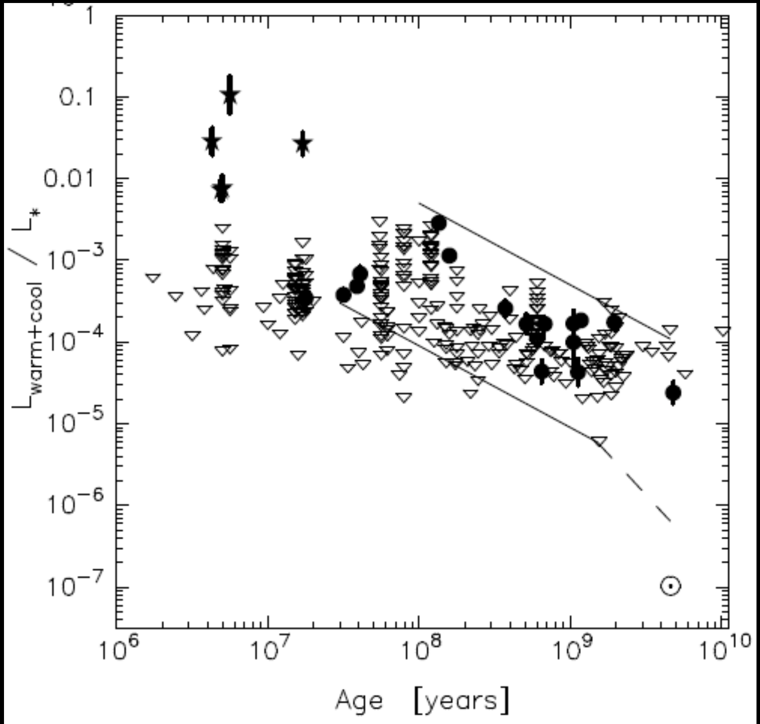
Debris Disks vs. Metallicity: More "diverse" than RV planet systems?



Greaves et al. '06; Bryden et al. '06; Najita et al. (in preparation).

Spitzer/FEPS (Meyer et al. 2006)
The Last Word:
Carpenter et al. (2009)

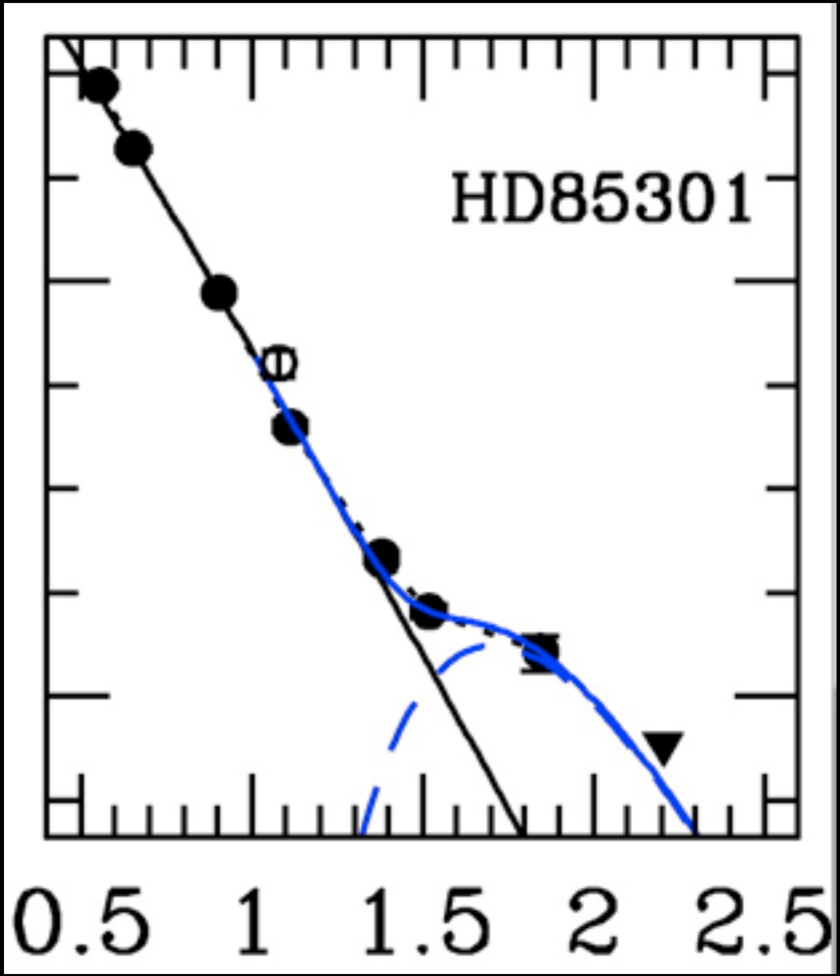


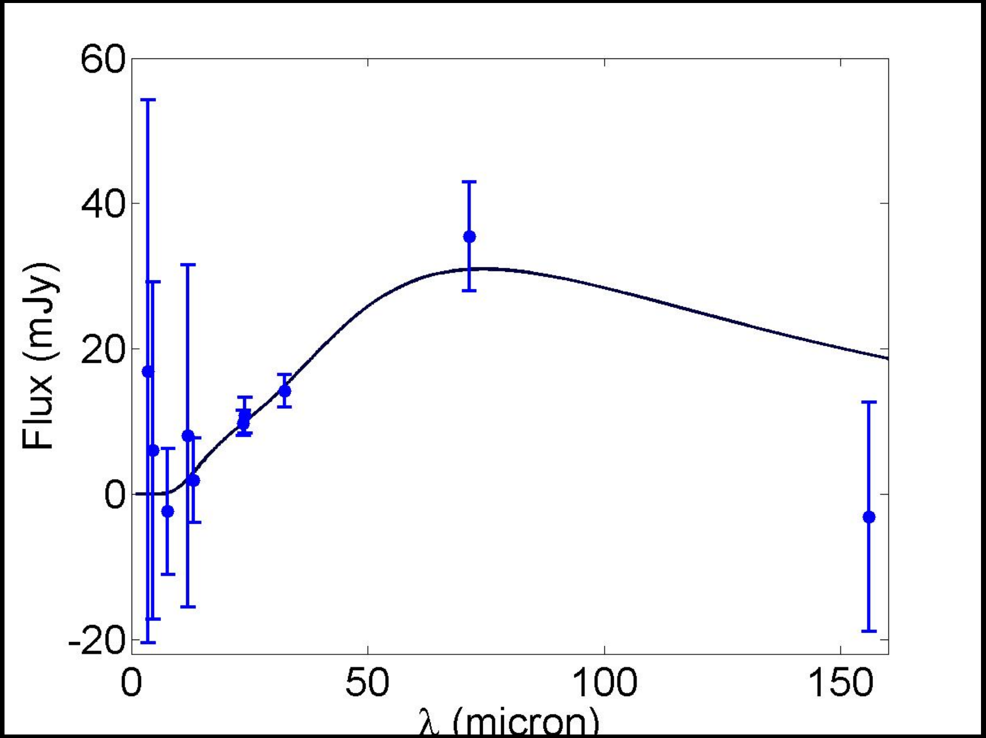


Evolution in Disk Luminosity:
A stars: Su et al. (2006)
G stars: Bryden et al. (2006)
M stars: Gautier et al. (2007)

Distribution of Inner Hole Sizes: cf. Morales et al. (2009)

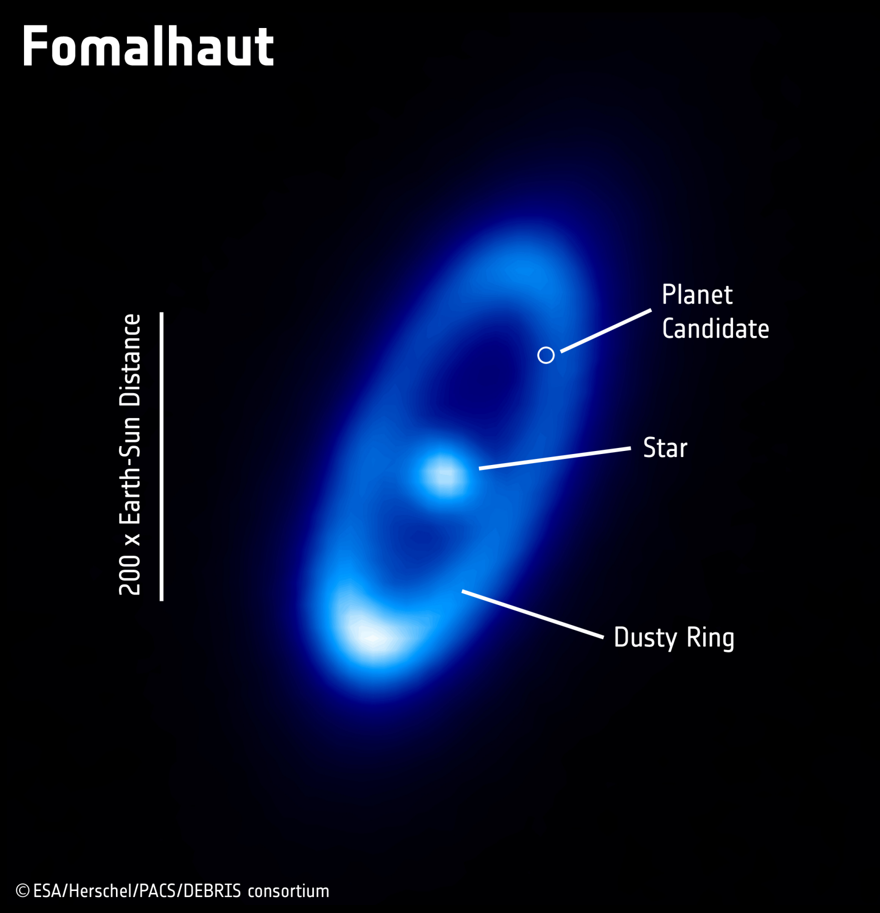
About 30 % of debris systems are Multi-Temperature Debris Disks: Bands or Rings?



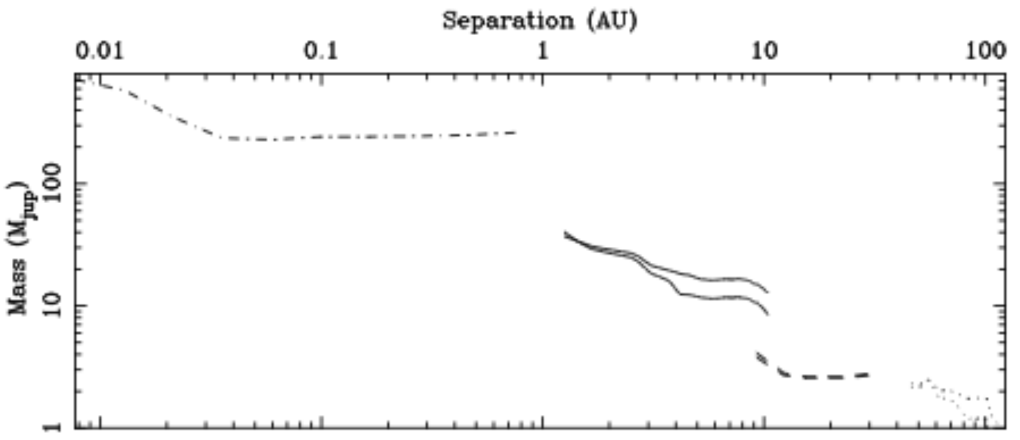


Beta Leo, HR 8799, Fomalhaut, Eps Eri

Herschel Results #3: Debris Disk Imaging



© ESA/Herschel/PACS/DEBRIS consortium



Acke et al. (2012)

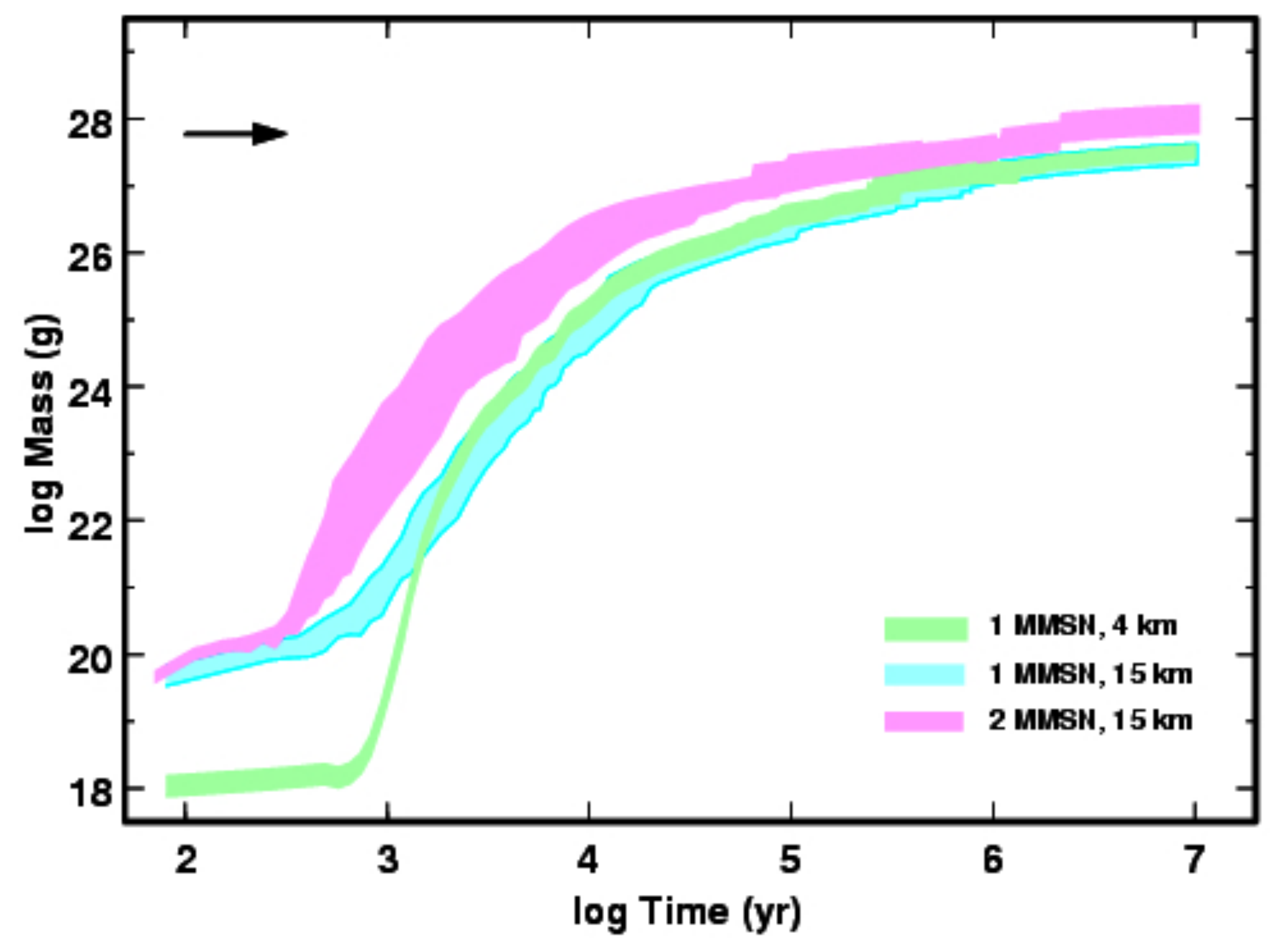
Kenworthy et al. (2013)

Herschel Results #4: Surveys…

Stay tuned for results from

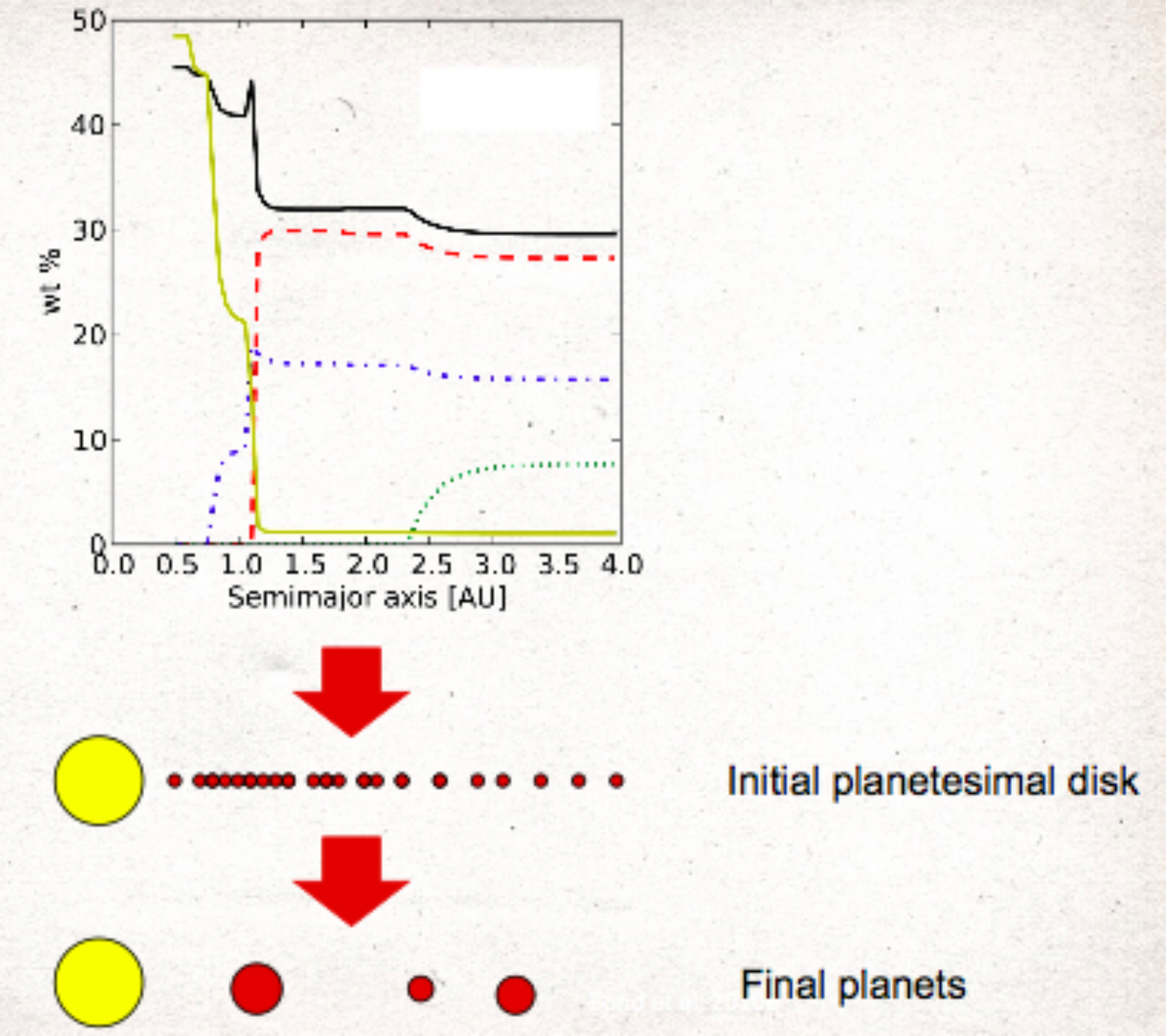
GASPS (Dent et al.) – Gas from Post-T Tauri stars
DIGIT (Evans et al.) – Gas and Dust from Protostars
DUNES (Eroa et al.) – FGK stars.
DEBRIS (Matthews et al.) – Volume limited sample.

After Gas is Gone:
Terrestrial Planet Growth: > 10^7 yr



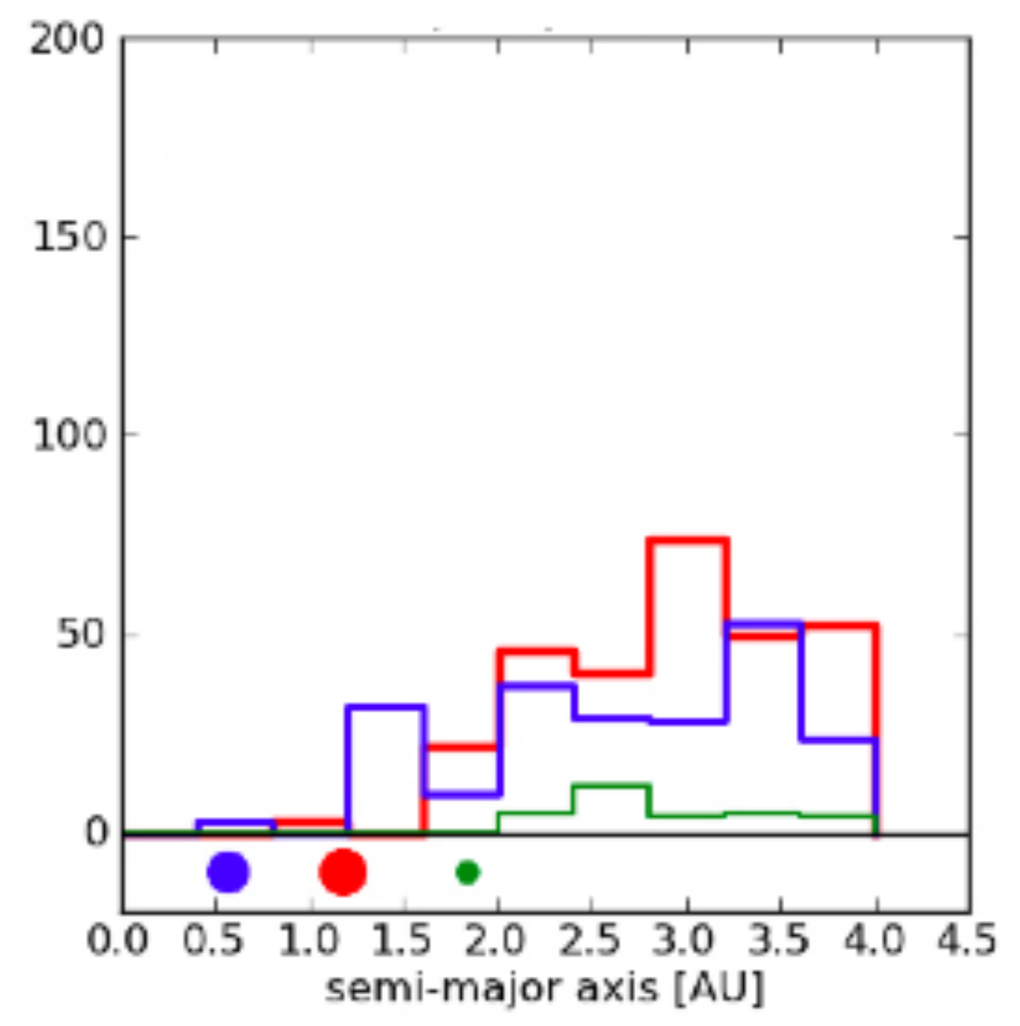
S. Kenyon (Harvard-Smithsonian CfA) & B. Bromley (Utah); cf. J. Stadel & B. Moore (UniZ)

Planetesimal Dynamics = Compositional Differences



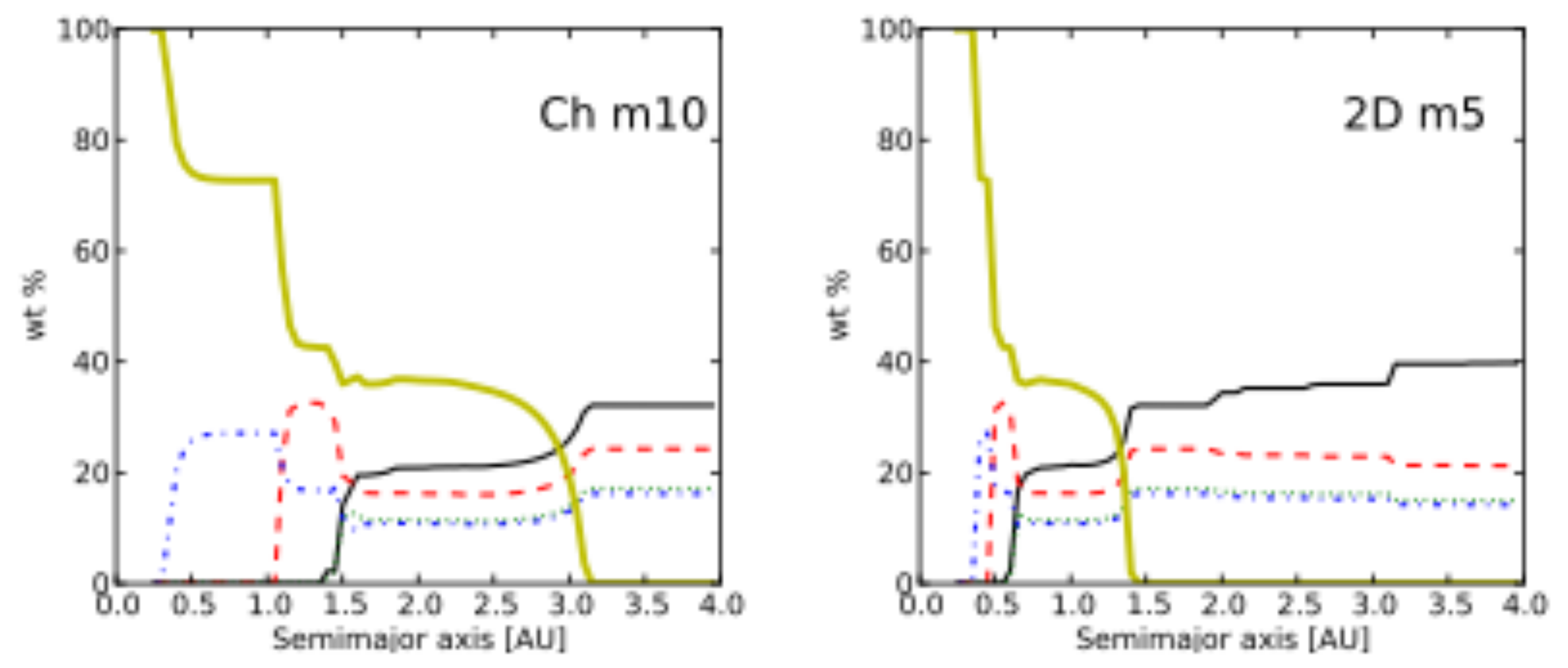
Raymond et al. (2004); Morishima et al. (2008); Bond et al. (2009); Elser et al (2012)

Planetesimal Dynamics = Compositional Differences



Raymond et al. (2004); Morishima et al. (2008); Bond et al. (2009); Elser et al (2012)

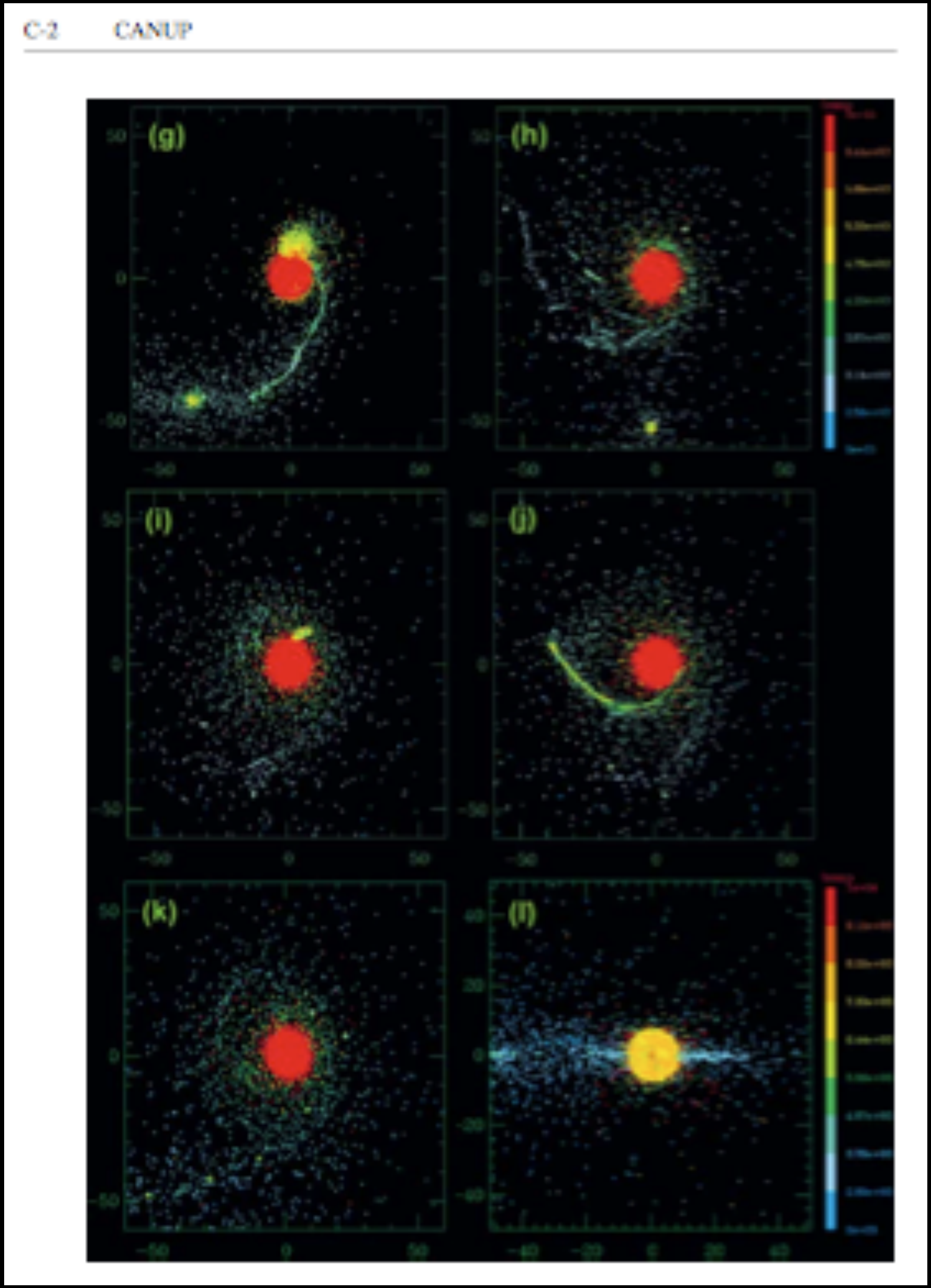
Chemistry + Dynamics = Planet Composition!



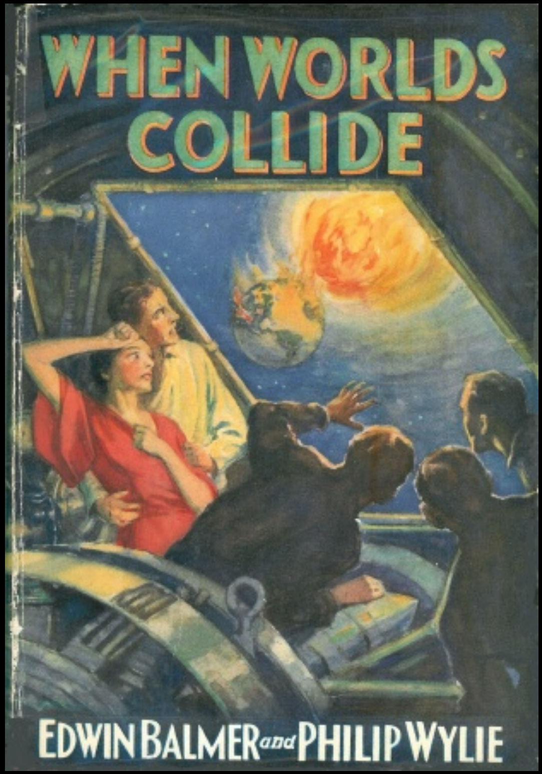
O
Fe
Si
Mg
C

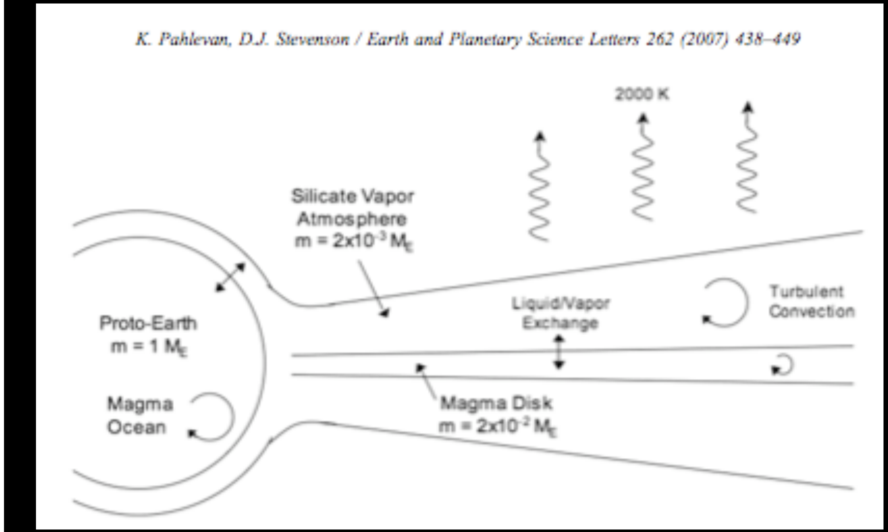
Hot Disk ***Cool Disk***

Extreme abundances from know Exoplanet hosts for two disk models. Elser et al (2012); See also Bond et al. (2010; 2009).



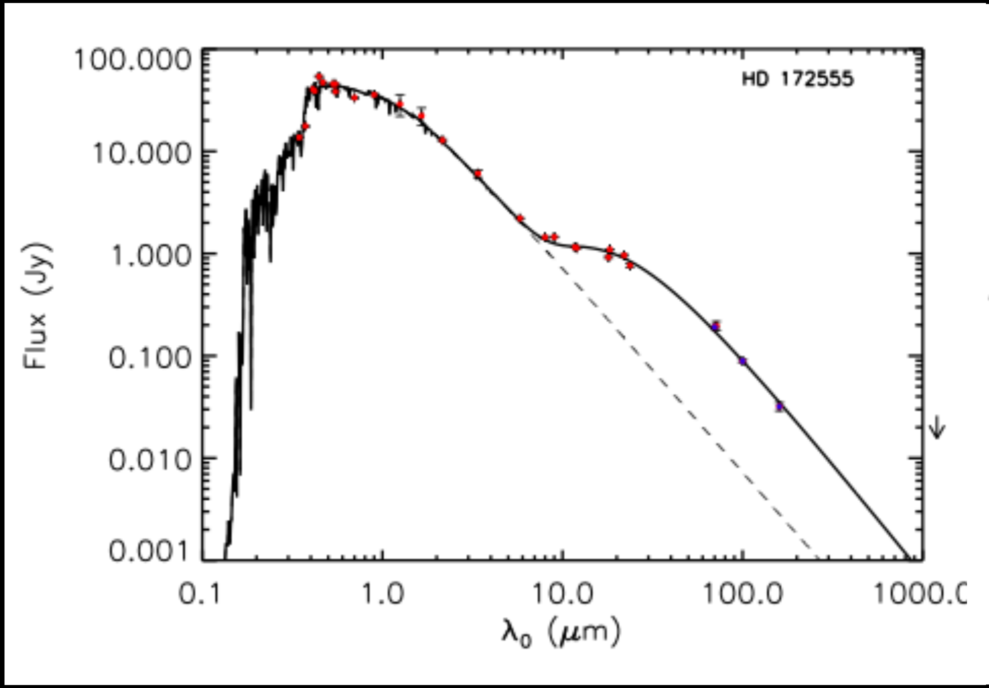
C-2 CANUP

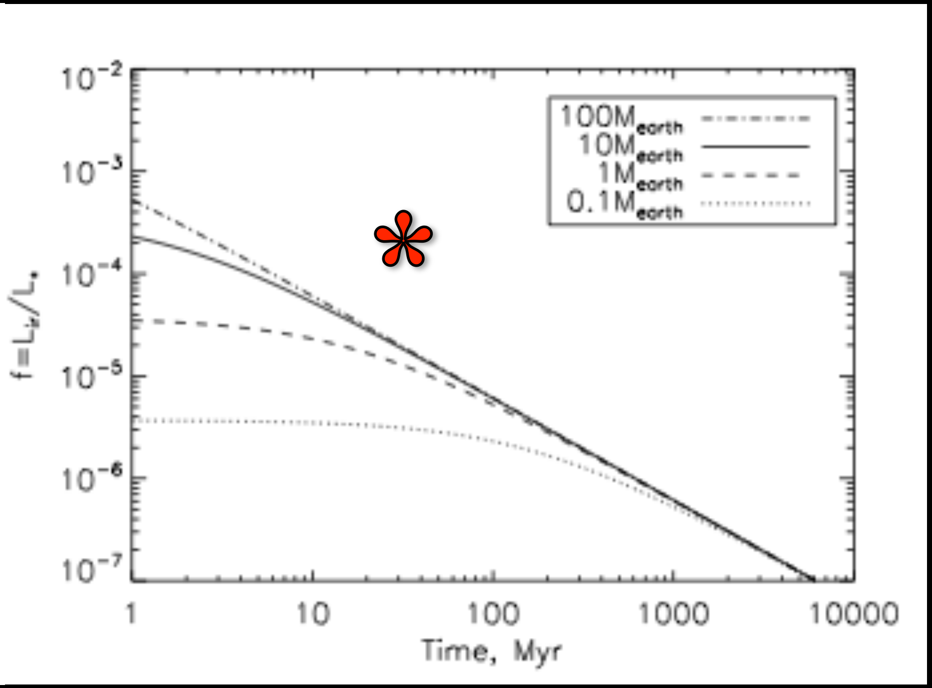




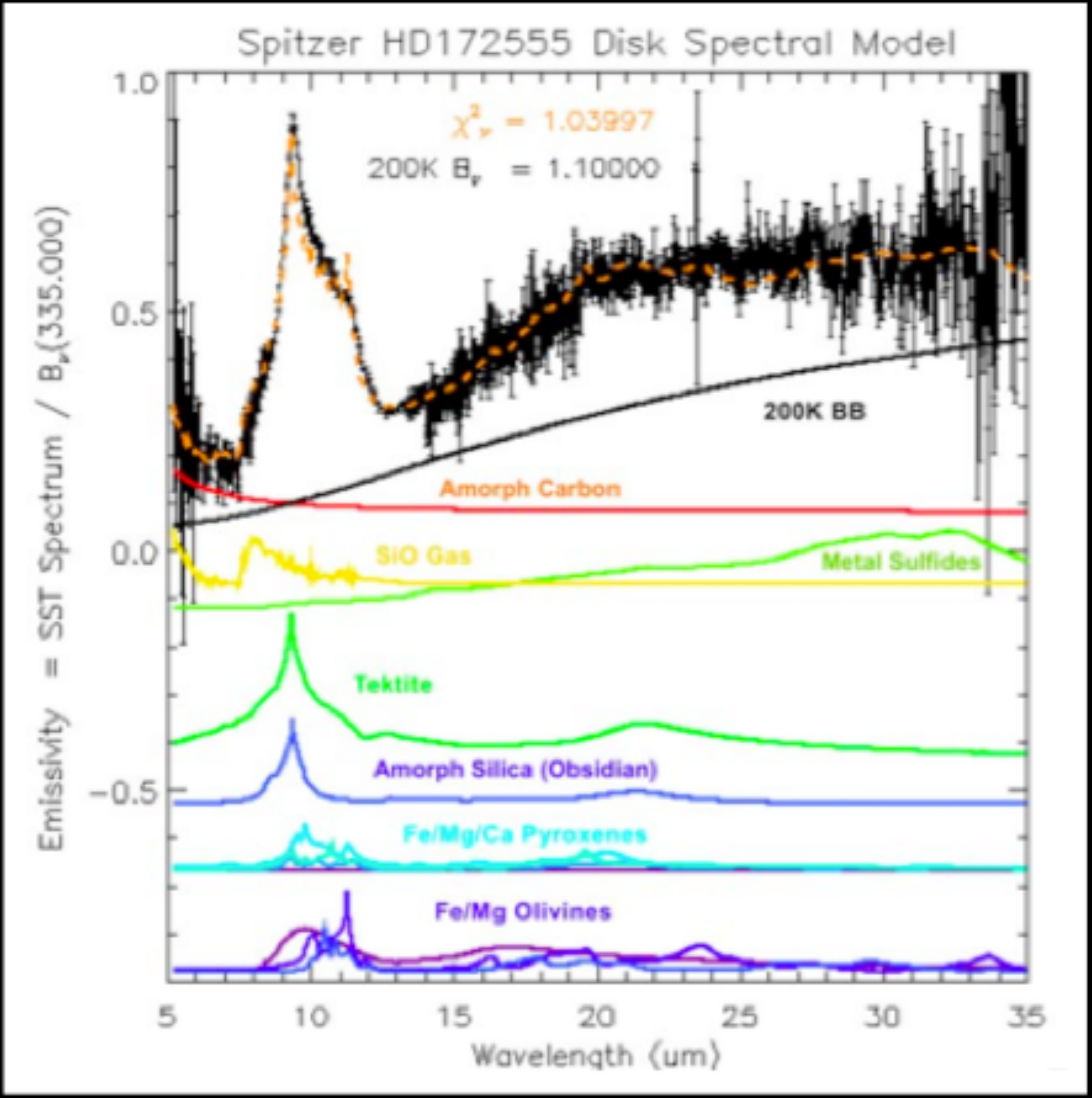
K. Pahlevan, D.J. Stevenson / Earth and Planetary Science Letters 262 (2007) 438–449

The Transient Debris of HD 172555





Wyatt et al. (2007); Lisse et al. (2009); Riviere-Marichalar et al. (2012);



We can observe recent collisions:

Non-equilibrium dust signature (too much)

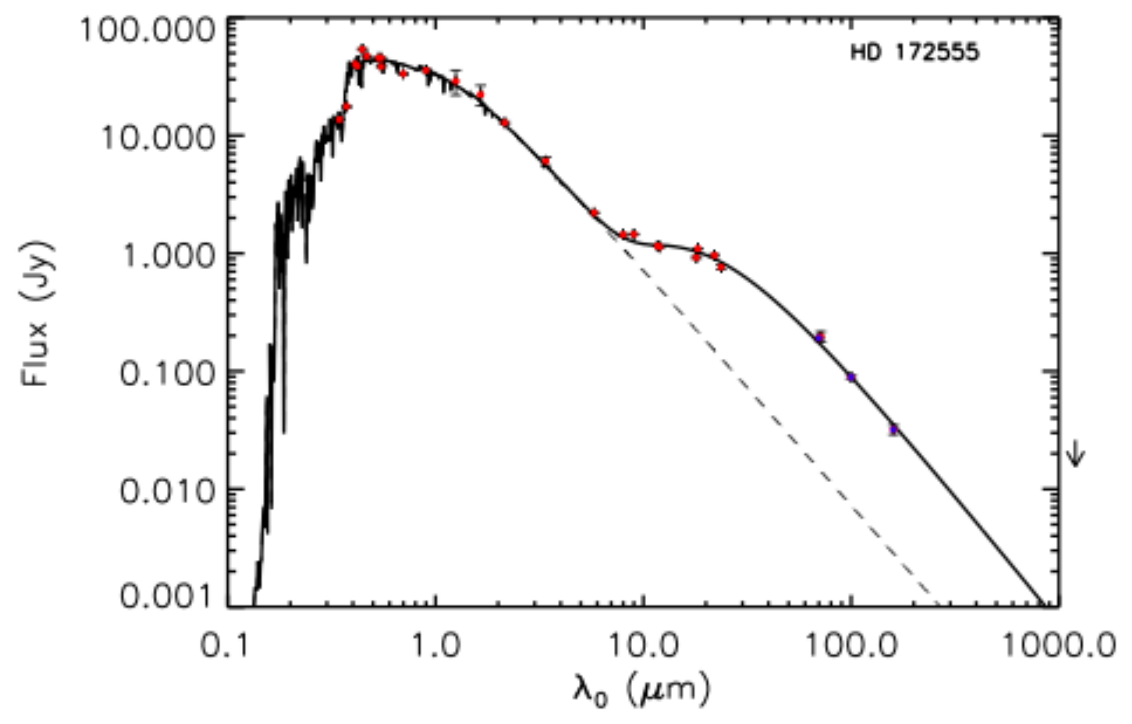
Unusual mineralogy.

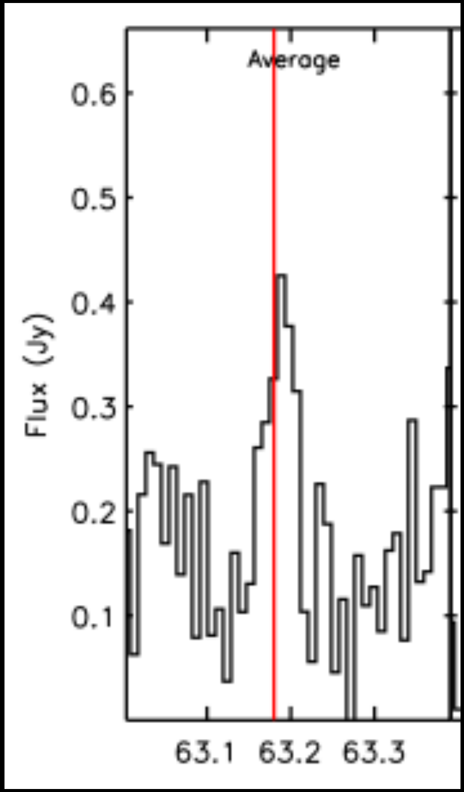
Transients are *rare* in Spitzer samples (< 1%?).

Collisions < 10 AU likely to melt embryos and < 50 AU embryos reach 500 K!

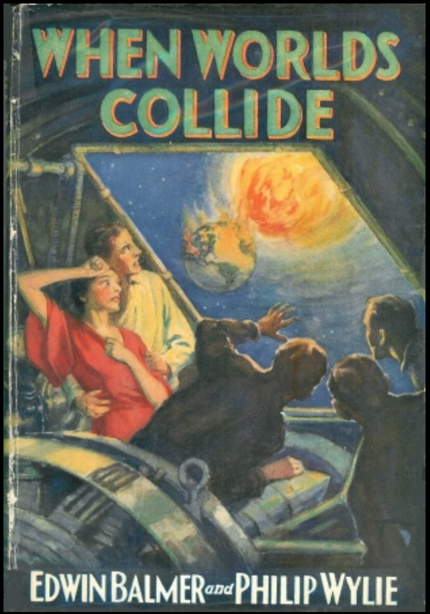
Wyatt et al. (2007); Lisse et al. (2009); Meyer et al. (in prep)

PACS on Herschel:
[OI] detection in Transient Debris Disk



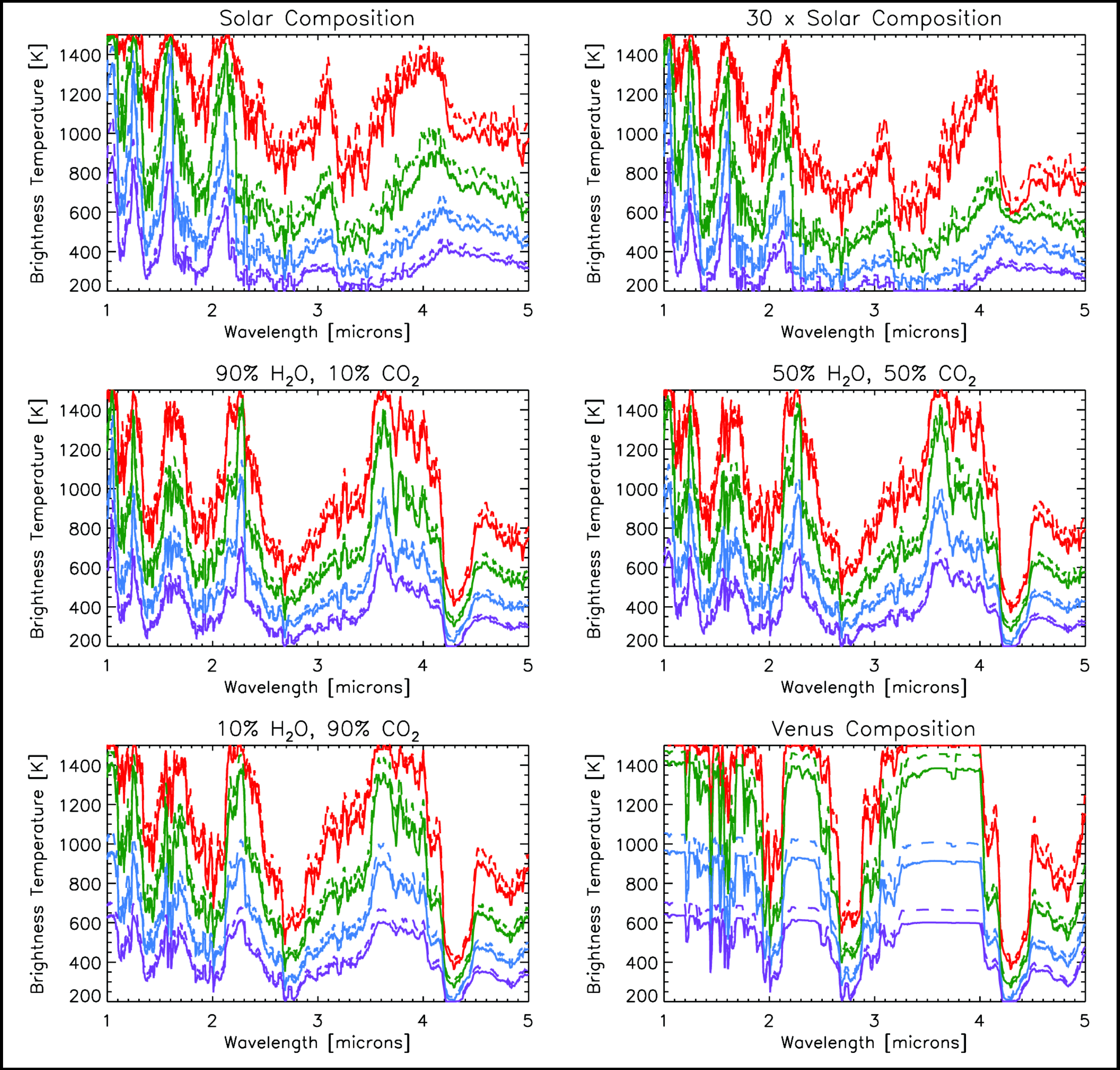


Riviere-Marichalar et al. (2012); cf. Pahlevan et al. (2011); Takasawa et al. (2011)

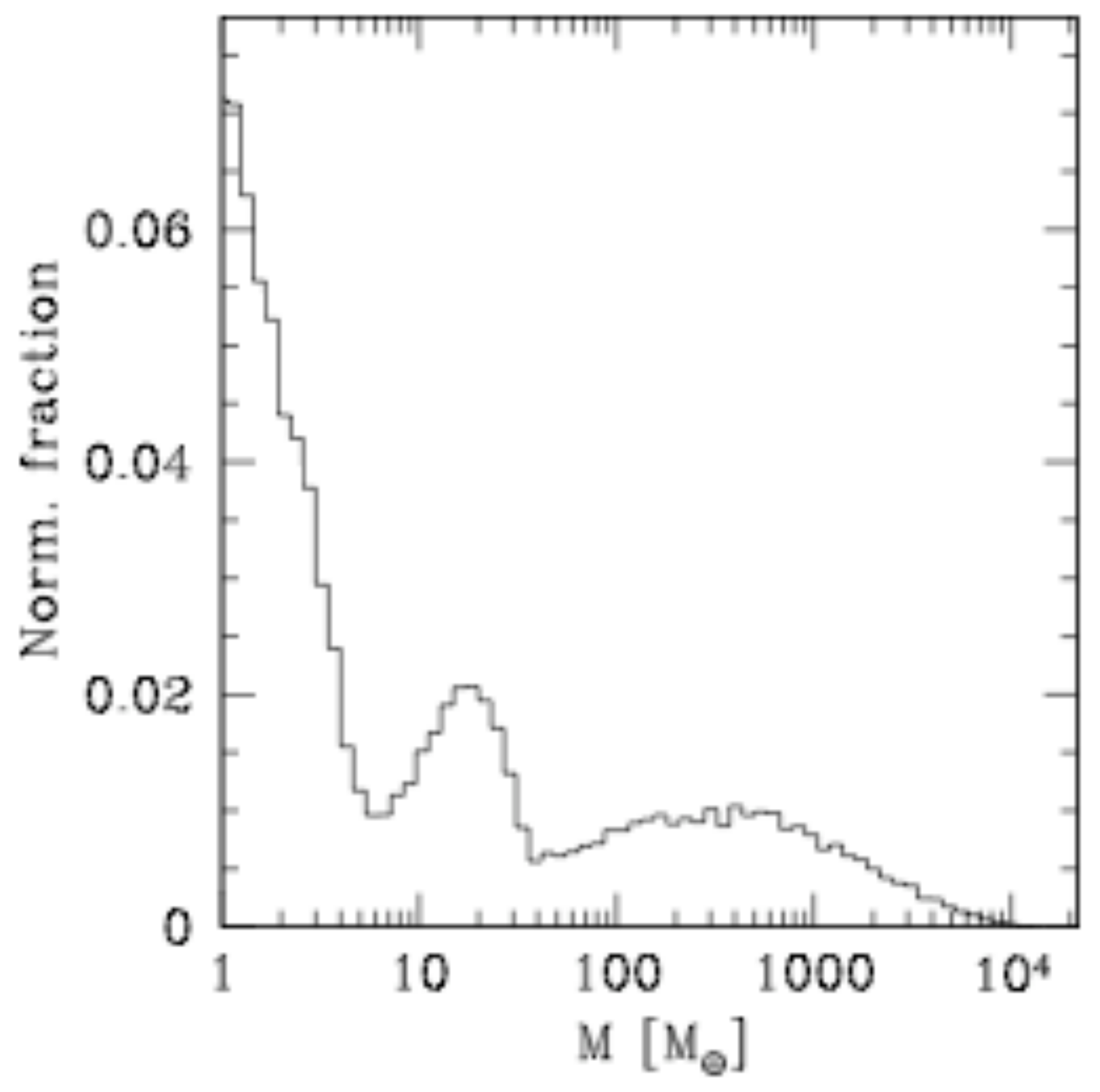


... you can see them with next generation instruments!

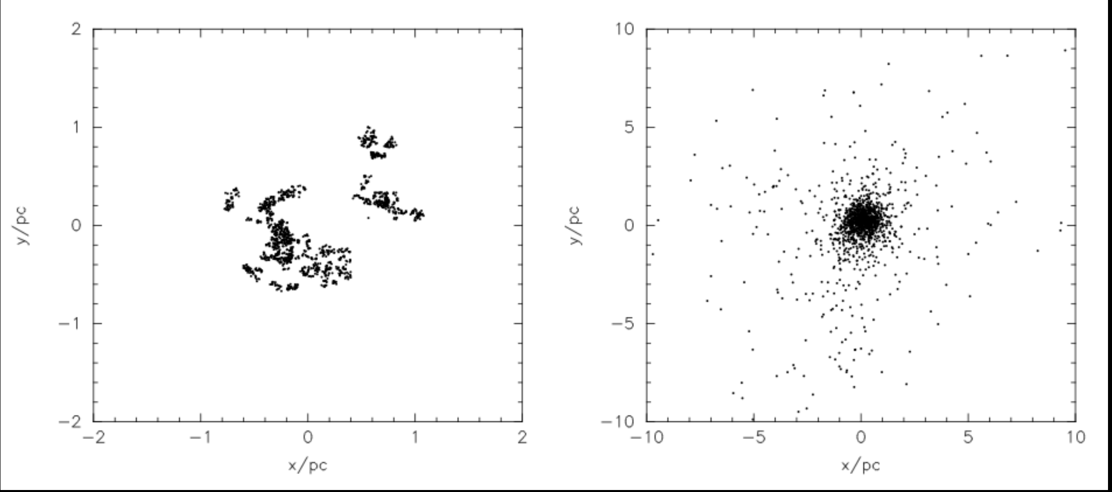
Mamajek & Meyer (2007); Miller-Ricci, Meyer, Seager, Elkins-Tanton (2009)



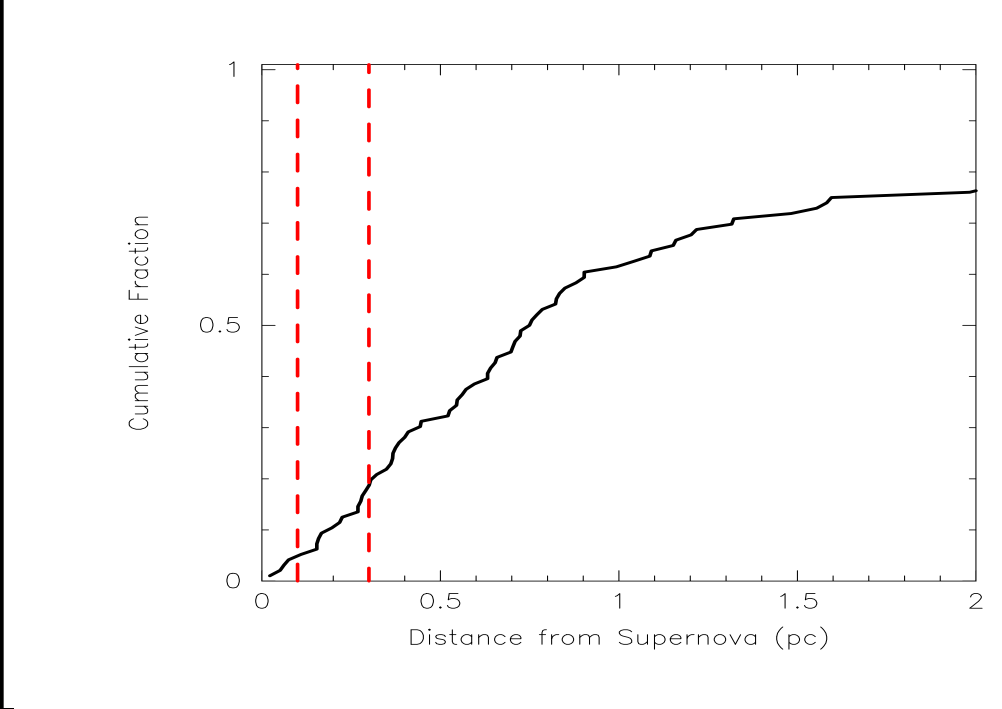
Population Synthesis Models:
Terrestrial planets may be very common!



Ida & Lin (2004)
Mordasini et al. (2009)
Howard et al. (2011)
Mayor et al. (2012)
Bonfils et al. (2012)



But our level of initial 26Al may be not…



Parker et al. (in prep)

Key Concepts for tomorrow: Part B

1. ***Global disk evolution derived from diverse stellar ensembles.***

2. ***We can constrain evolution in gas to dust from primordial to debris.***

3. ***Inner disks (< 10 AU) clear efficiently, very fast!***

4. ***Debris (and small planets) could be extremely common.***

5. ***Warm debris and transient debris are rare.***

6. ***Disk chemistry + dynamics = planet composition.***

7. ***We may be able to trace specific giant impacts in other systems.***

8. ***At least some aspects of our solar system appear to be uncommon.***

Searching for Planets with Direct Imaging Requires Novel Instrumentation and Good Targets!

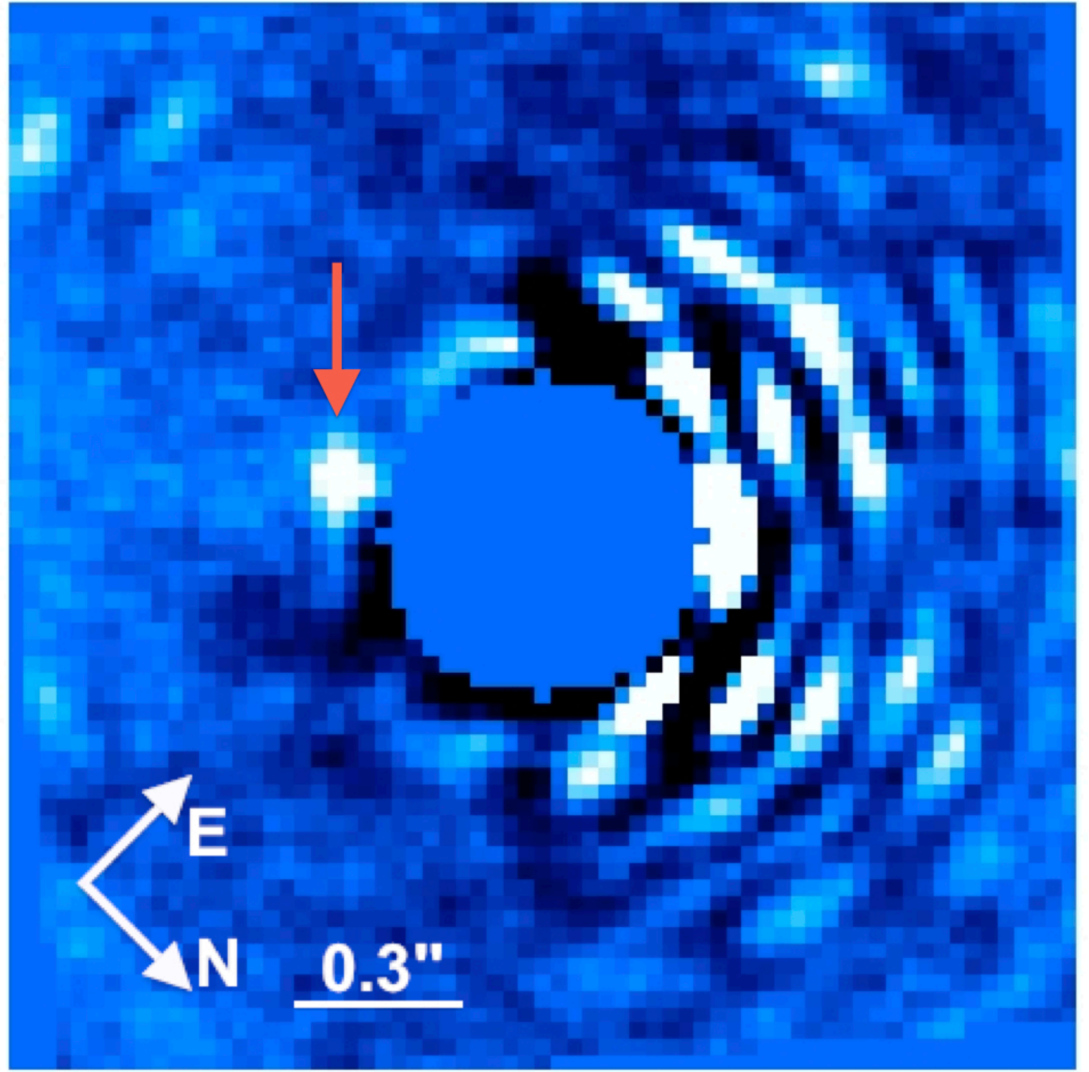
- Beta Pic b
  (Lagrange et al. 2010)
- ~ 8 Mjupiter @ 8-15 AU
- Narrow-band 4.05 um
- T ~ 1400-1700 K
  (Quanz et al. 2010)

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

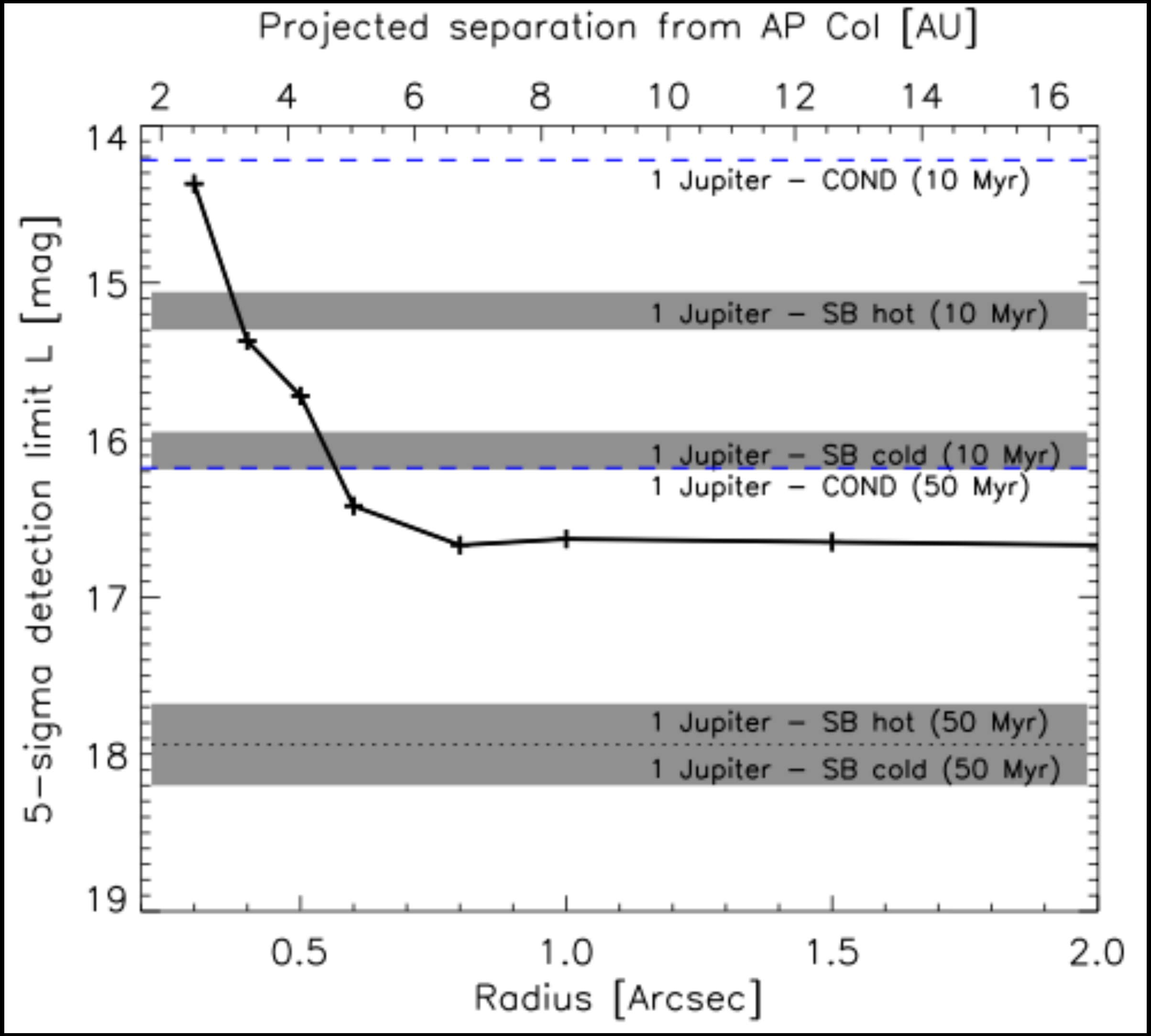
Universiteit Leiden

ESO

Max-Planck-Institut für Astronomie Heidelberg
Centro Astronomico Hispano Aleman Almeria

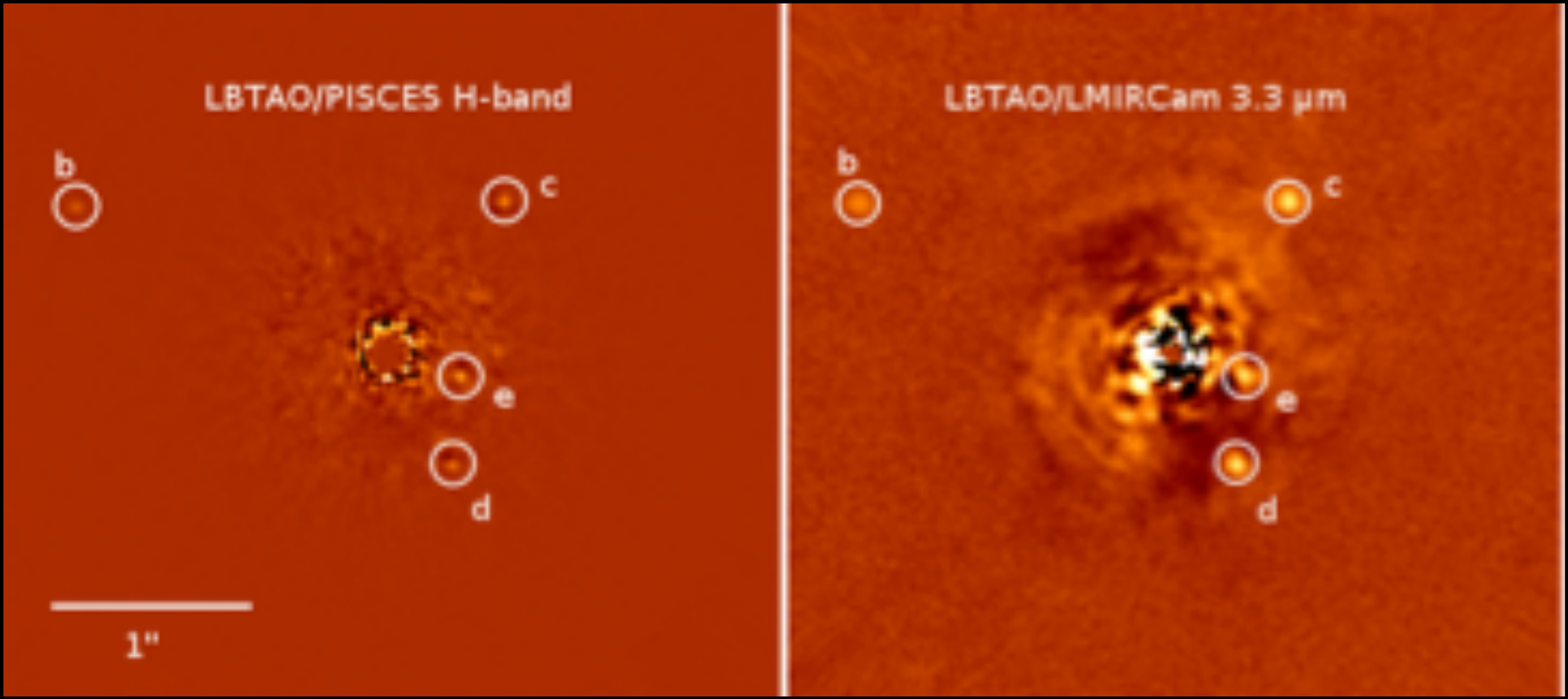


Searching for Planets with Direct Imaging Requires Novel Instrumentation and Good Targets!



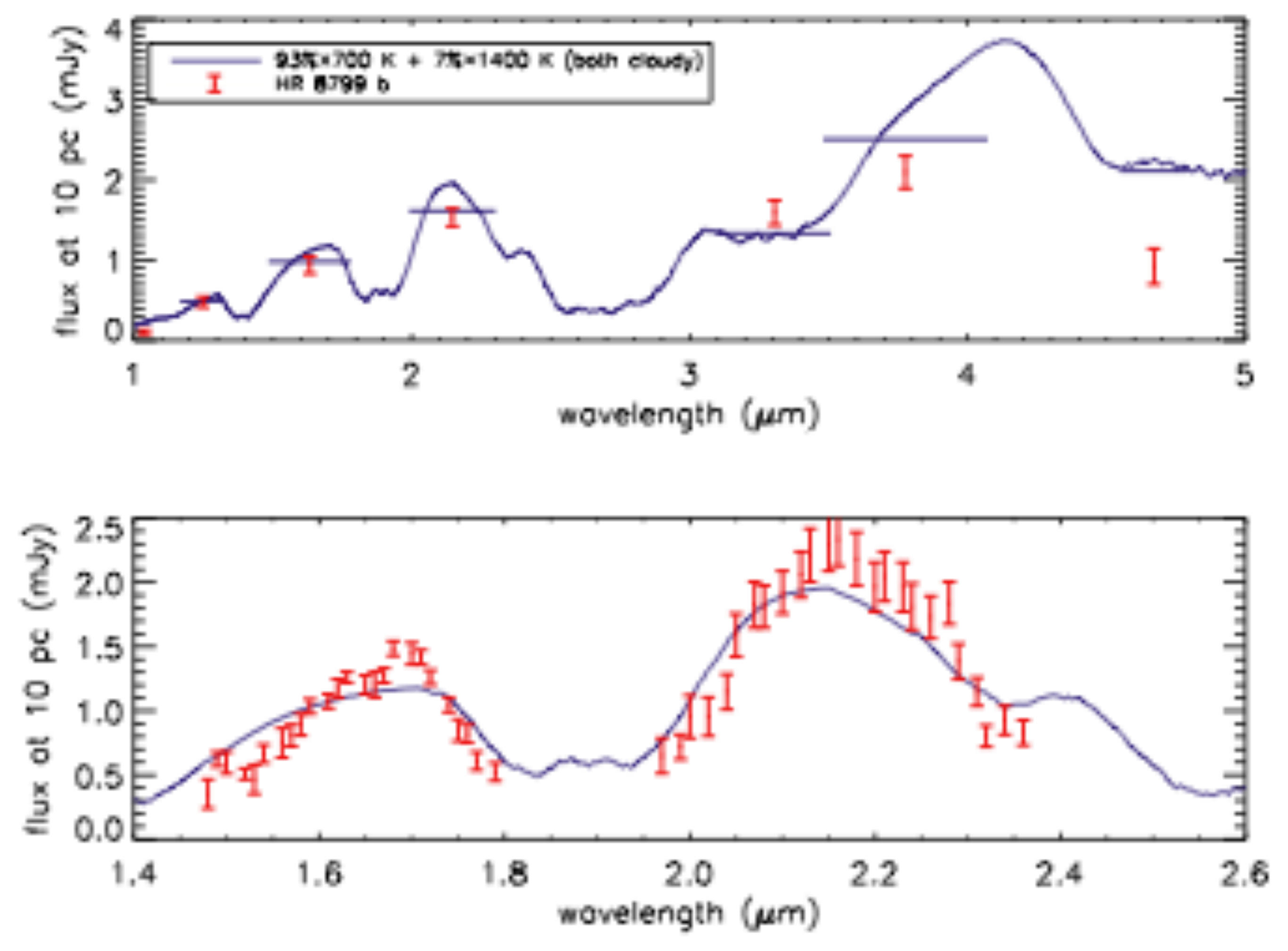
AP Col – recently recognized 40 Myr M Dwarf @ 8.2 pc (Quanz et al. 2012)

HR 8799 *may* have formed through Gravitational Instability.



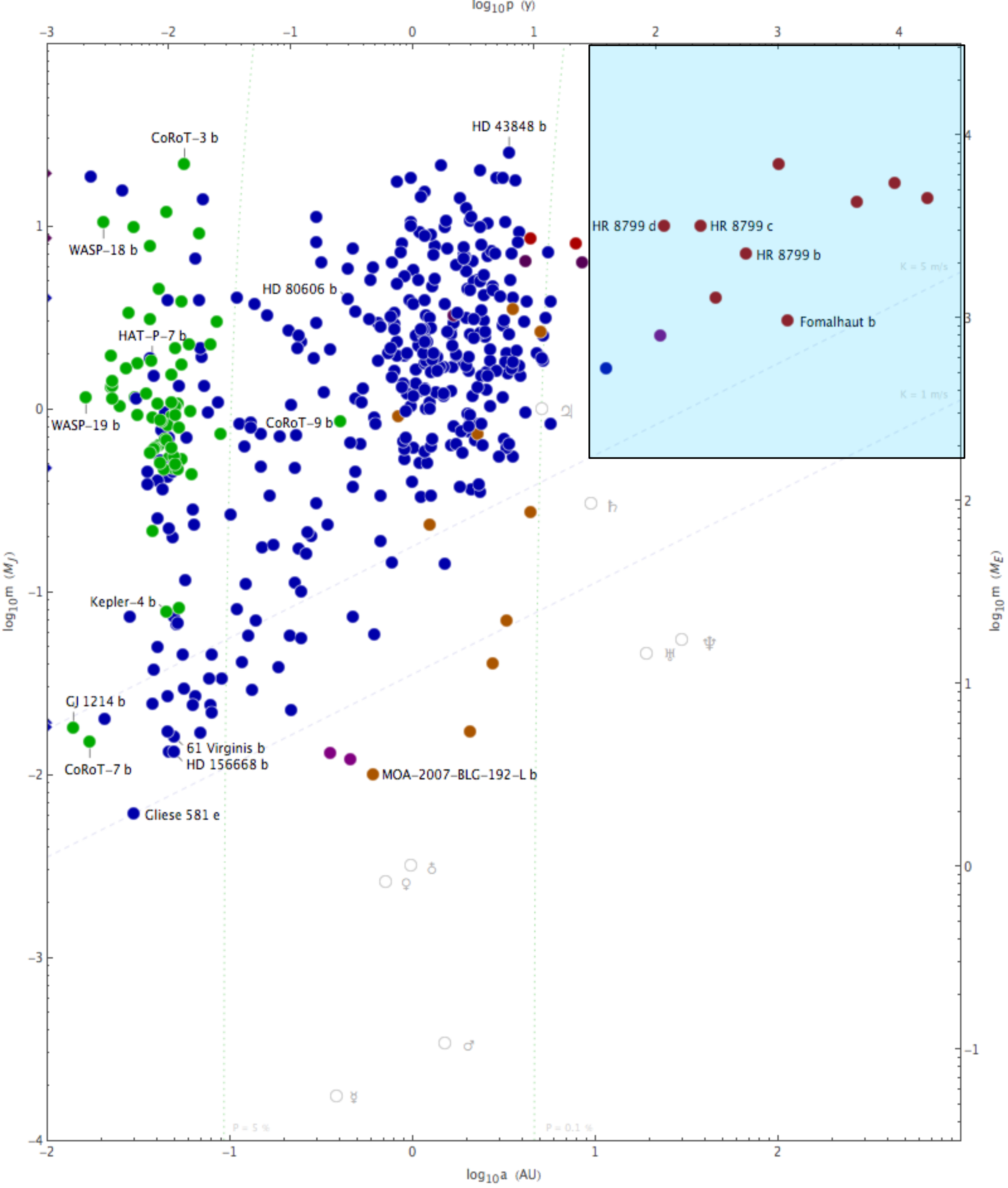
Marois et al. (2008); New LBT data from Skemer et al. (2012)

HR 8799: New spectral models are required.



Skemer et al. (2012); Barman et al. (2011); Madhusudhan et al. (2011)

Future Surveys: (2012)



J-L. Beuzit et al.

NIRCam
NIRISS
MIRI
(2018)

Detect very low mass planets at large radii about the nearest stars. (cf. Beichman et al.)