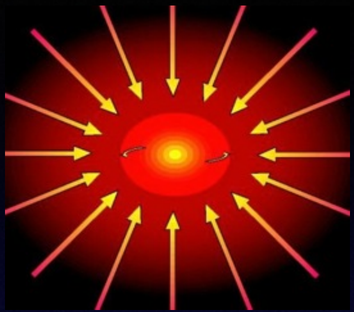
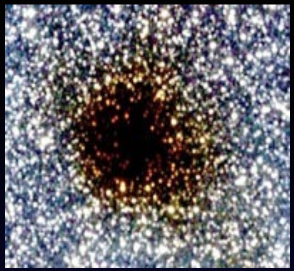
Protoplanetary Disks

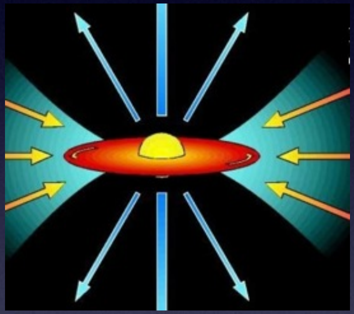
Leonardo Testi (ESO/INAF-Arcetri)

From Cores to Planetary Systems

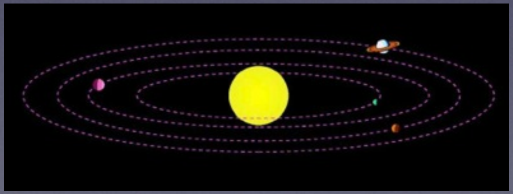


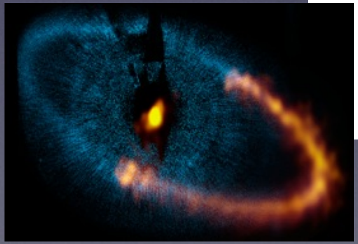


Core

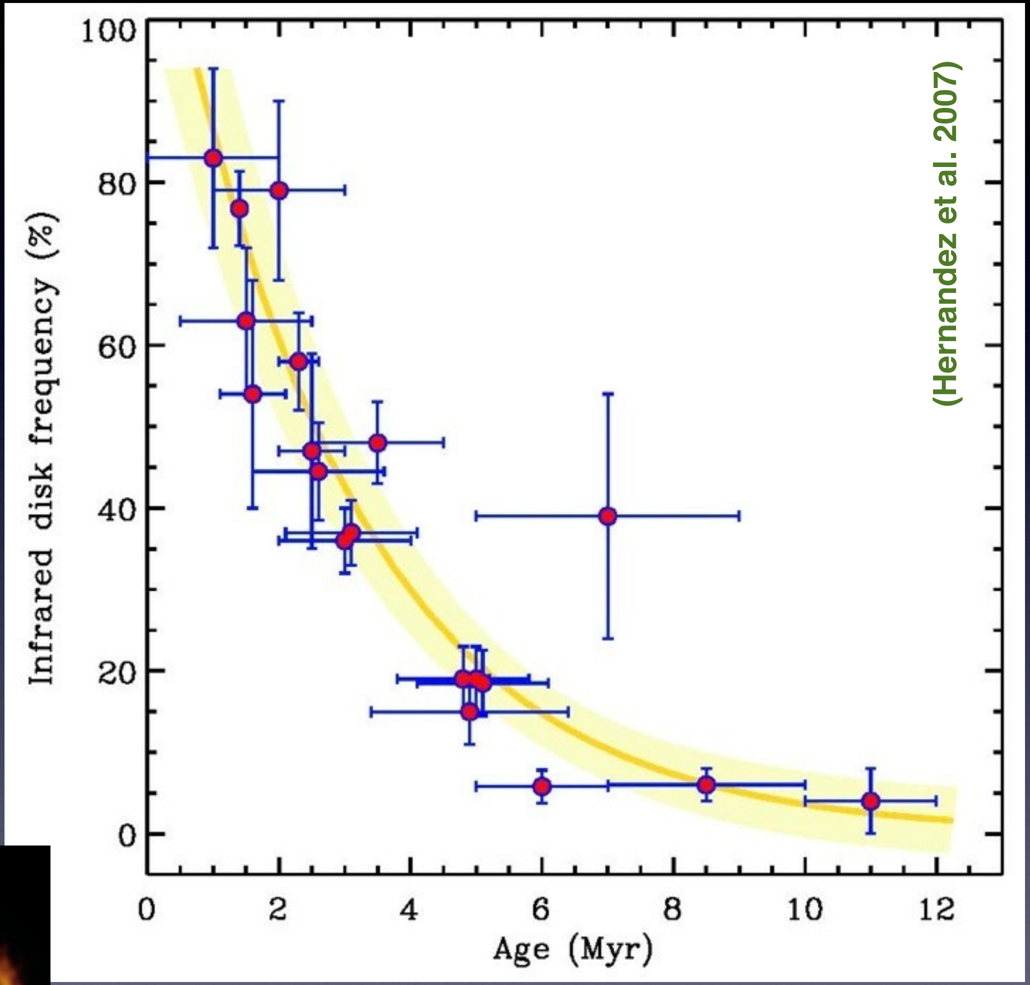


Disk





Debris Disk



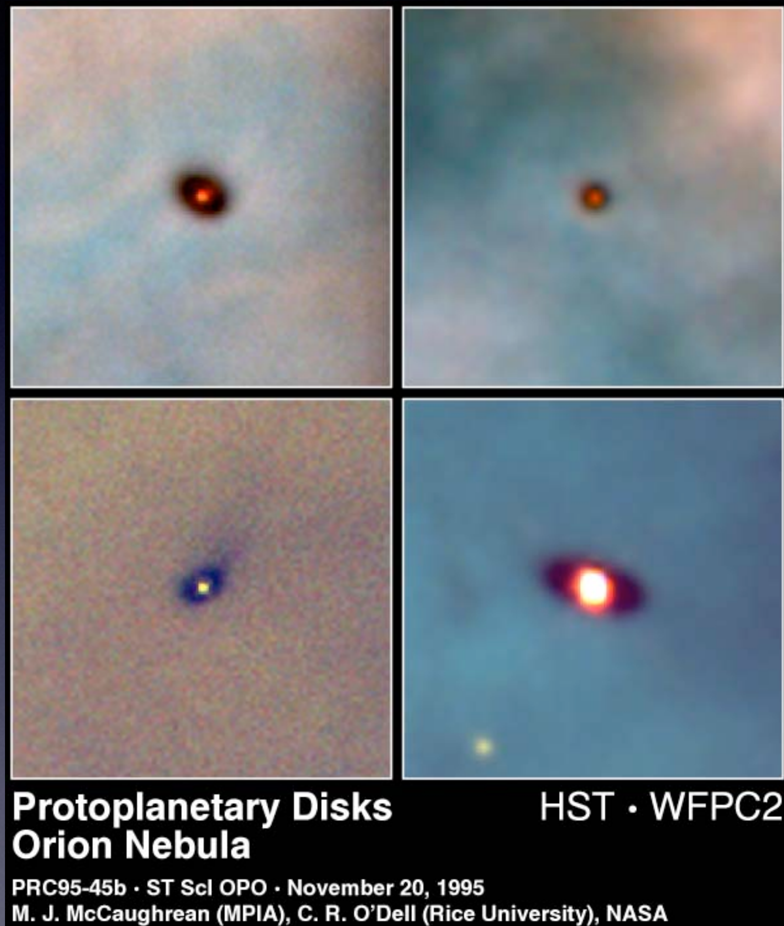
Inner disk clearing:

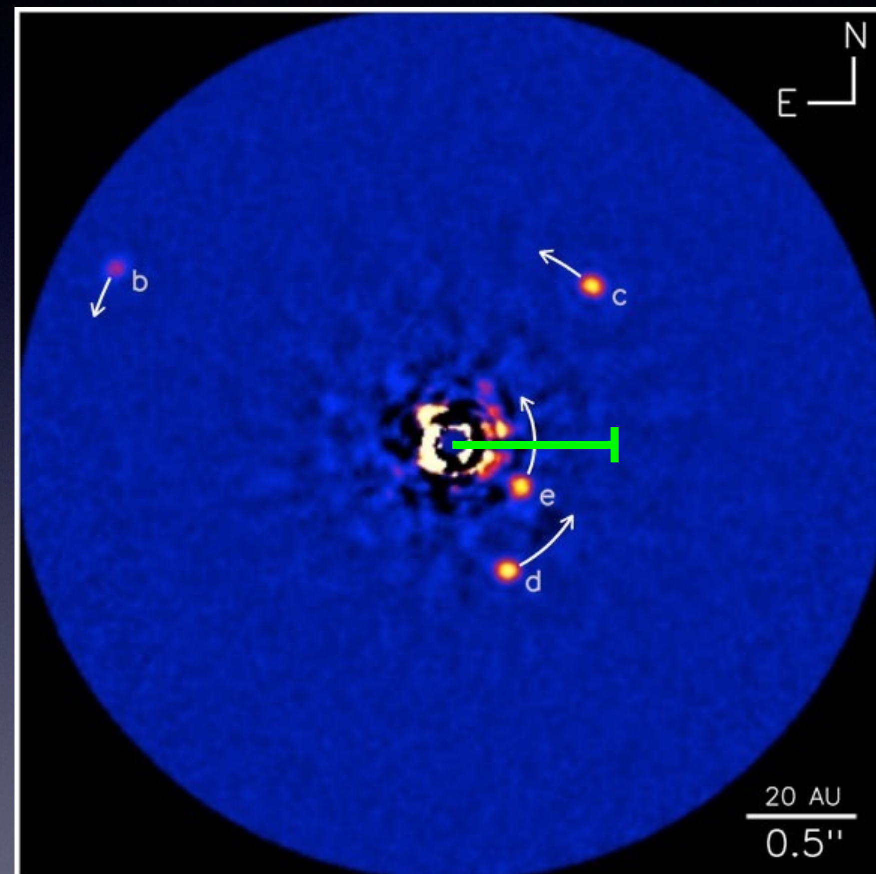
e-folding time t~2-3 Myr

(but see Bell et al. 2013 for a possible revision)

Origins of Planetary Systems

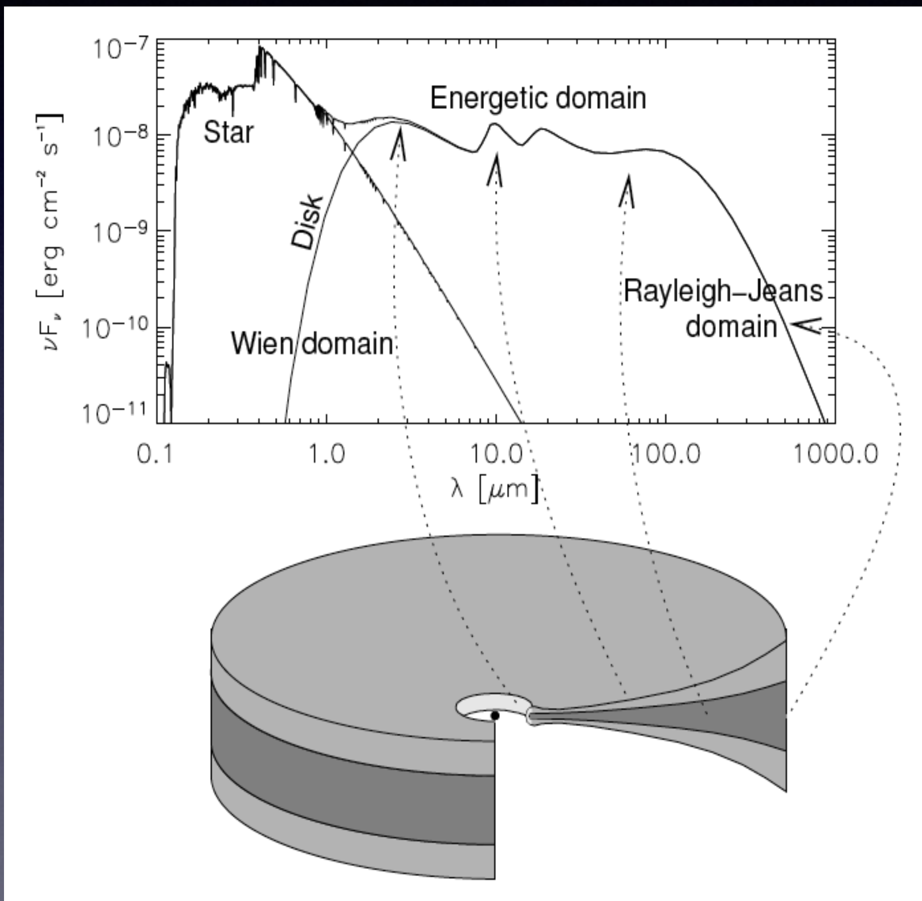
(McCaughrean & O'Dell 1995)

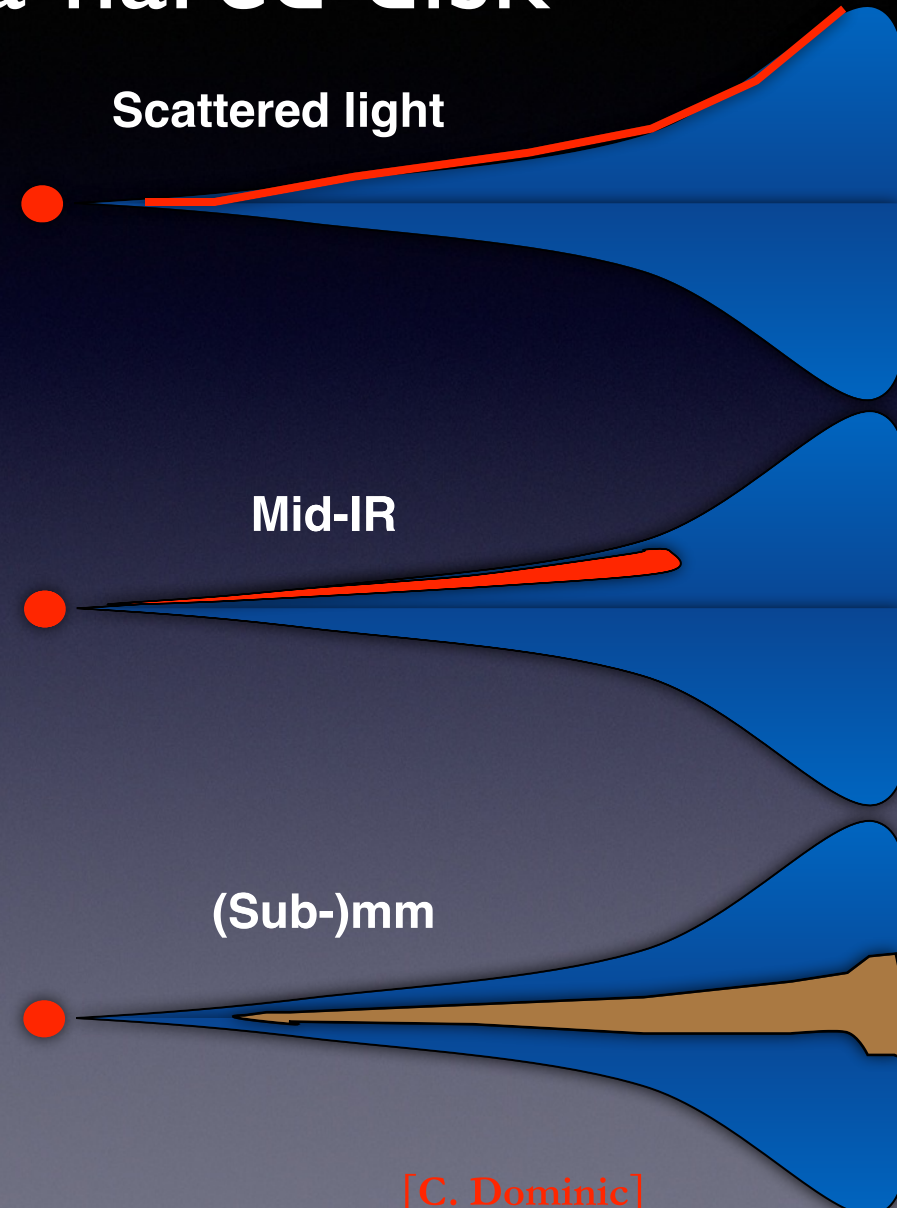




(Marois et al. 2010)

Emission of a flared disk

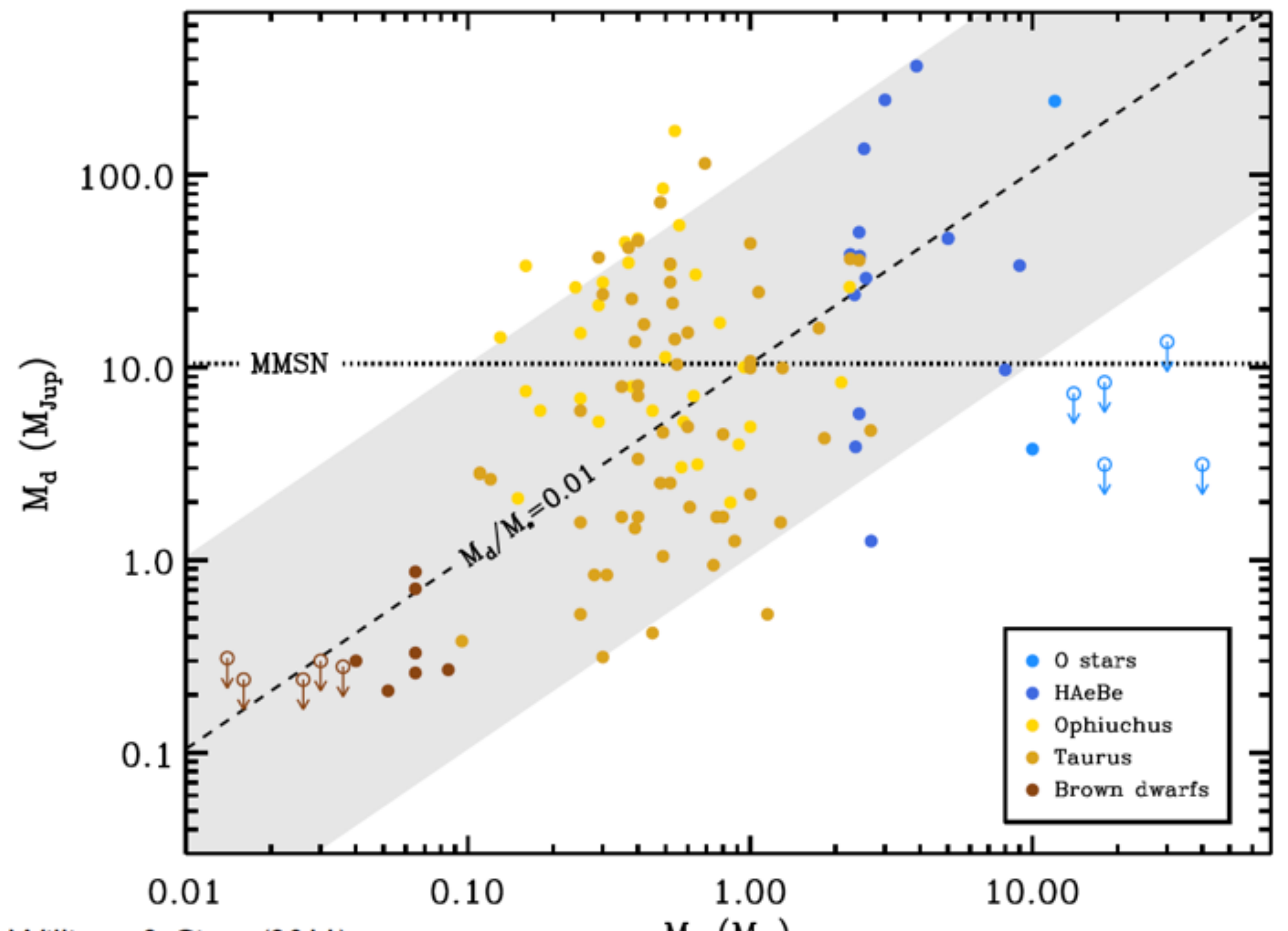




[C. Dullemond]

[C. Dominic]

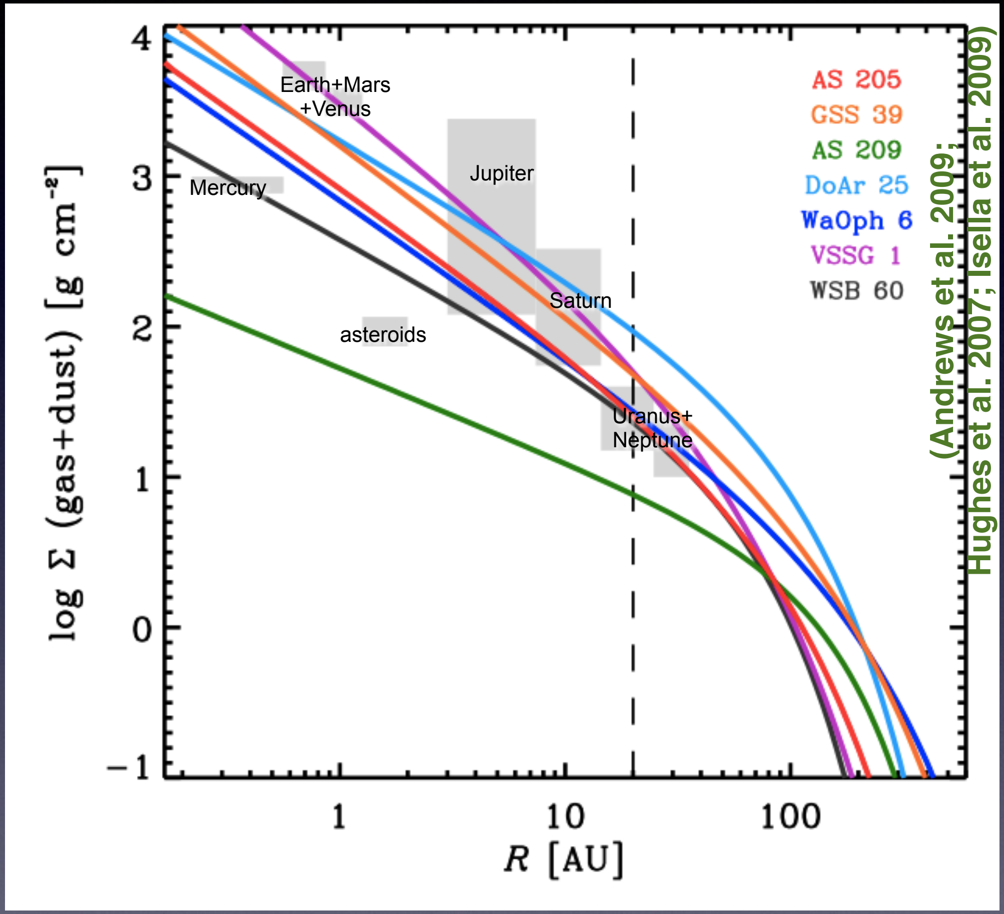
Disk masses



Williams & Cieza (2011)

Radial structure

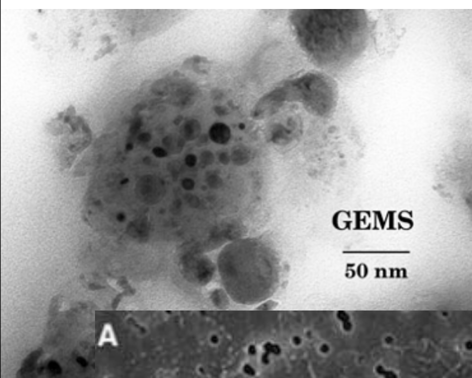
- N.B. assumption: $S_g/S_d=100$
- Observations are consistent with the structure derived from viscous evolution models
- Radial distribution of mass is consistent with the expectations from MMSN
- g~1
- 10AU@140pc=0.14"

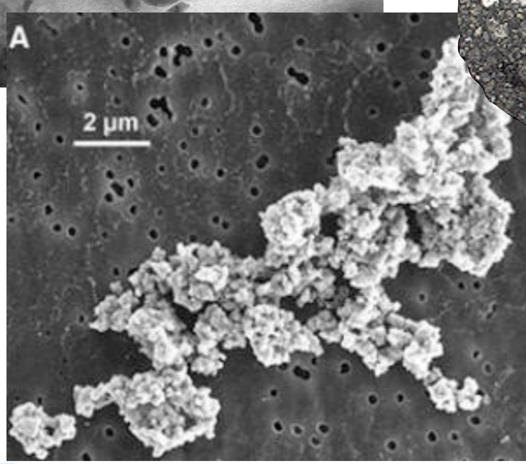


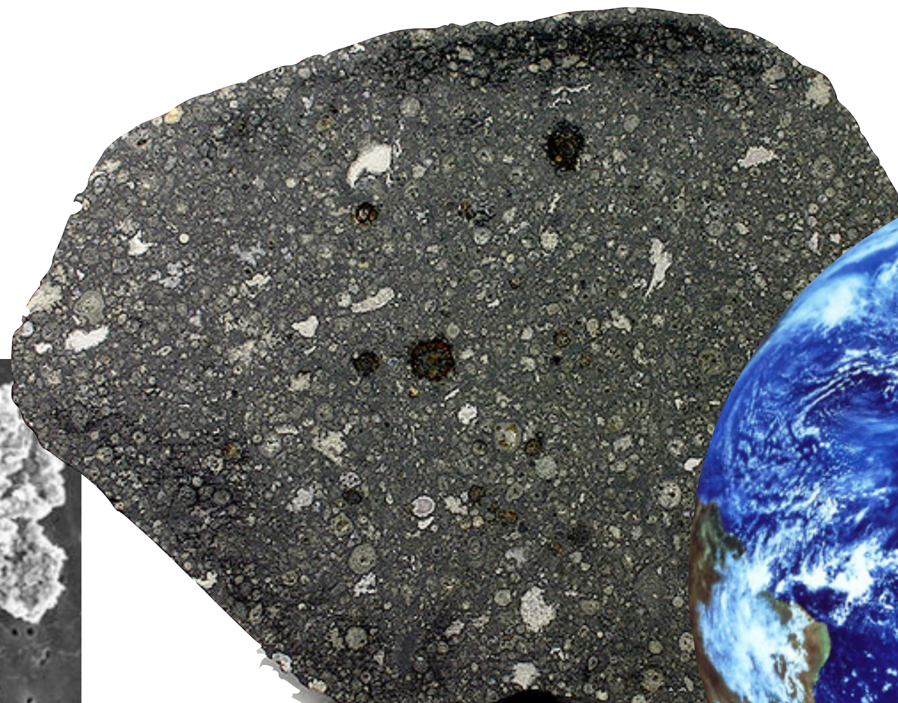
Some key questions related

- Grain growth process to form rocky cores
  - Overcoming barriers
  - Timescales and location
- Gas/dust co-evolution and chemistry
- Disk evolution and dissipation
- Planet-disk interaction (migration, gaps, debris disks)
- Environmental effects

Grain growth and the dawn of planets

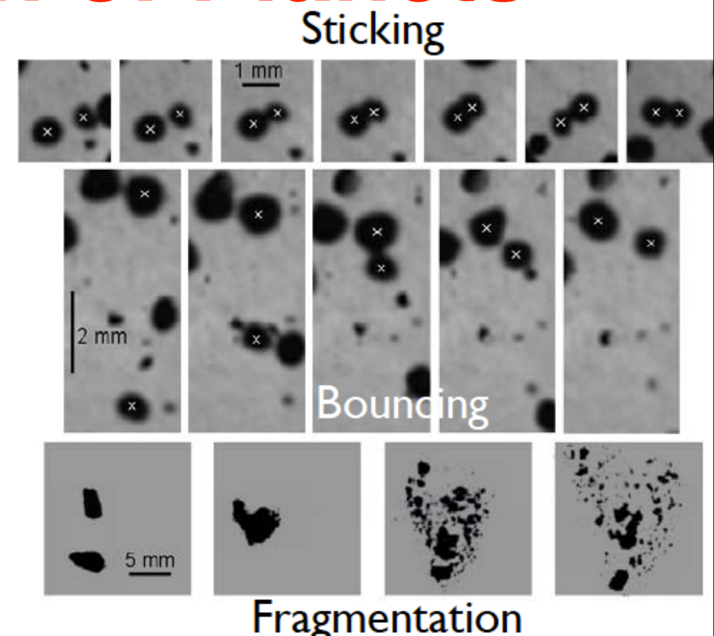


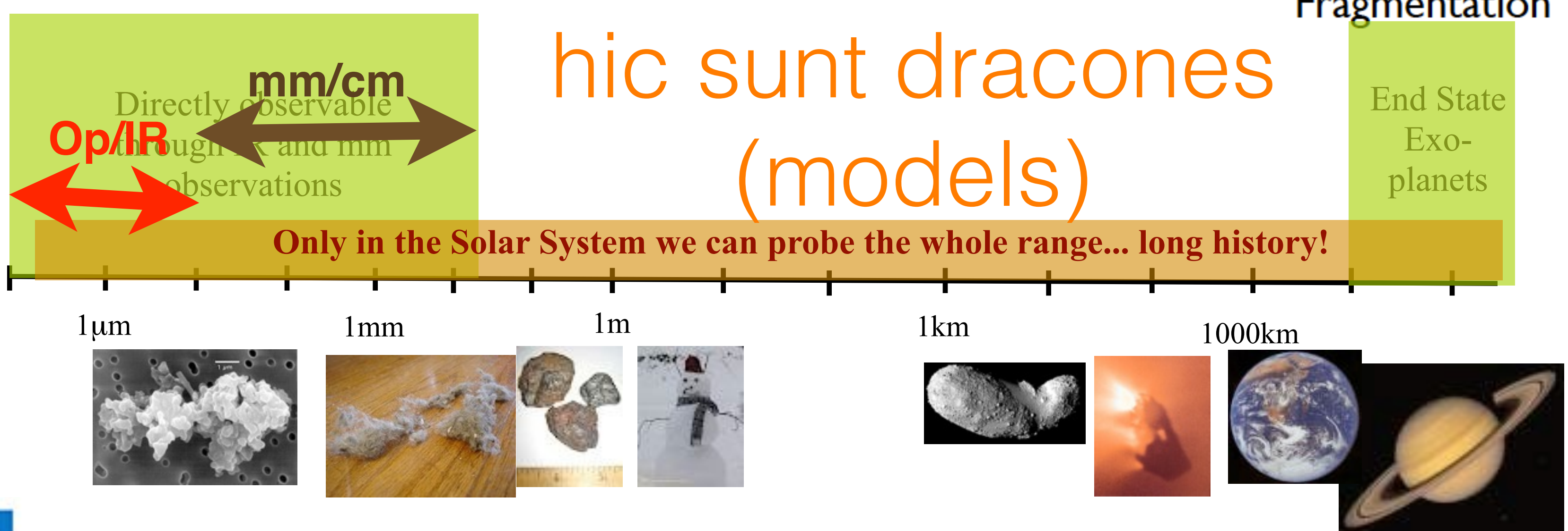




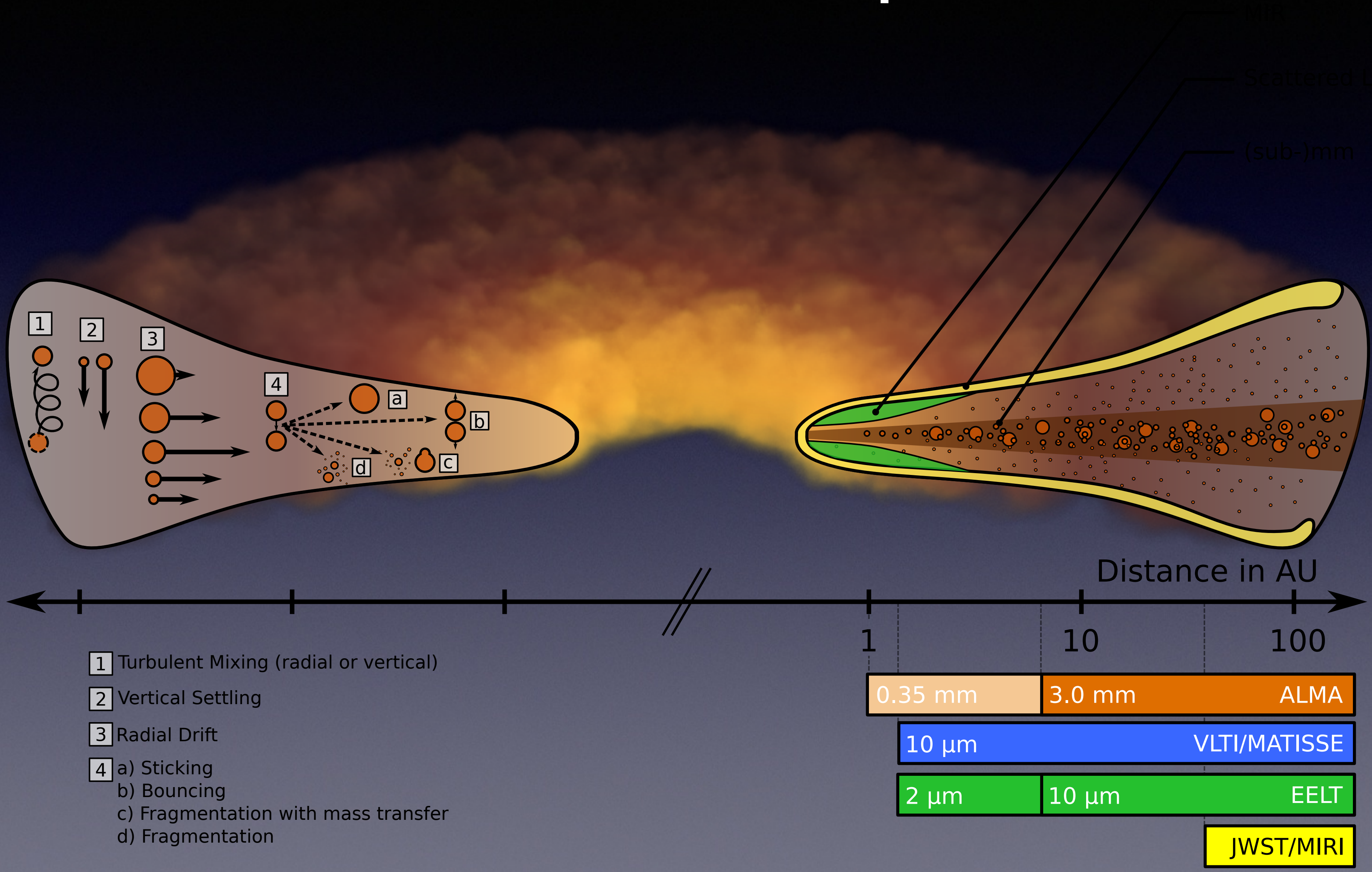
Grain Growth the Dawn of Planets

- The core-accretion scenario
  - Dust growth and planetesimals formation
  - Formation of rocky cores
  - Gas accretion from disk



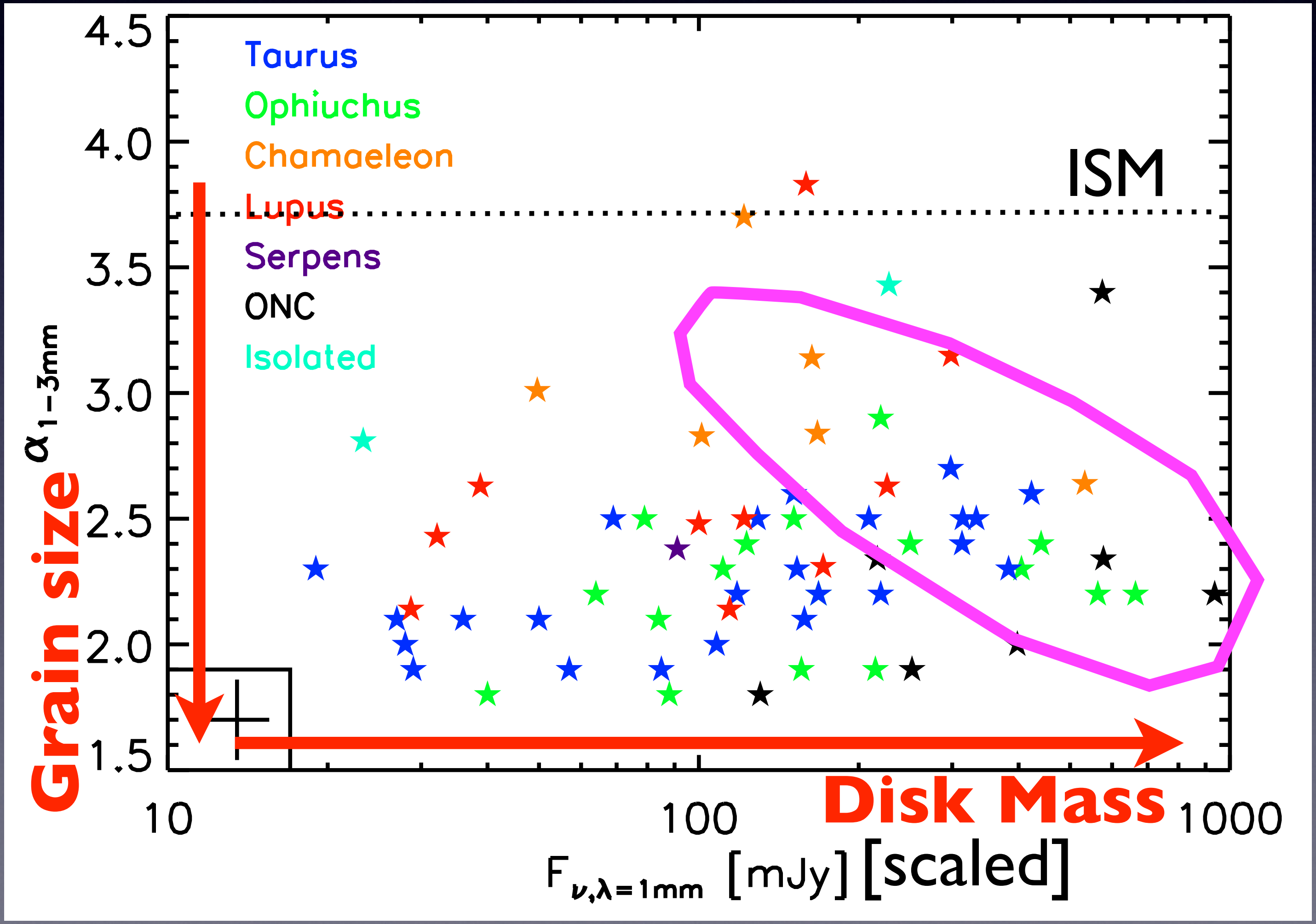


Processes and how to probe them



Grain growth in disks

- Widespread evidence for grain growth
- K-M stars (no BDs), “single” class II YSOs



Models from:
Birnstiel et al. 2010

Data from:
Ricci et al. 2010a,b,c,
Lommen et al. 2007, 2009, 2010,
Ubach et al. 2012

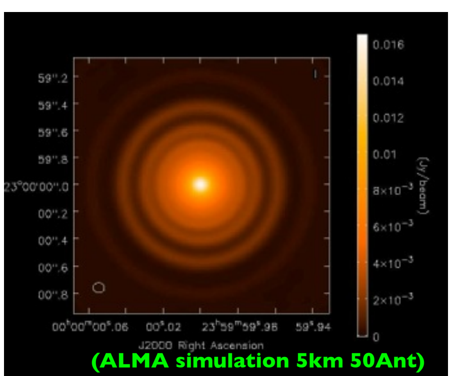
Gas-dust interactions

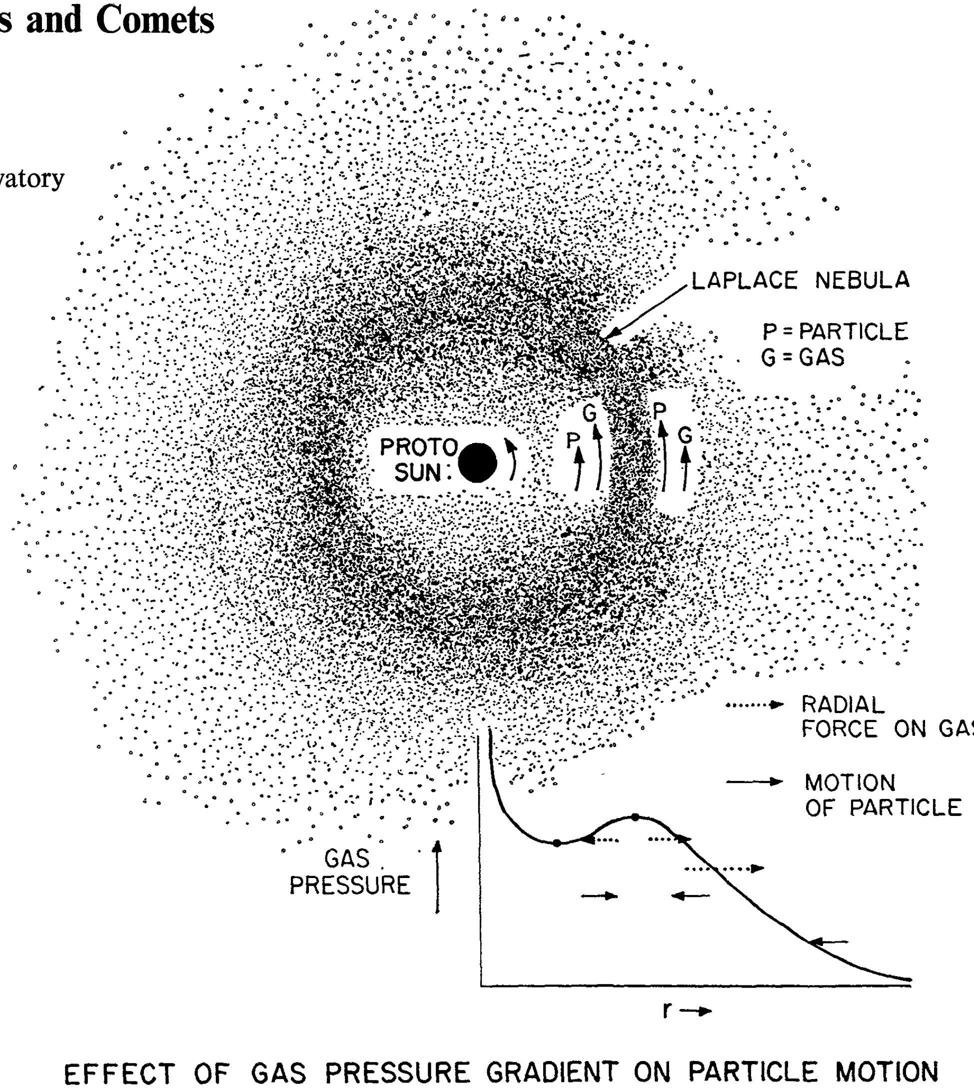
On Certain Aerodynamic Processes for Asteroids and Comets

By Fred L. Whipple

Smithsonian Astrophysical Observatory and Harvard College Observatory

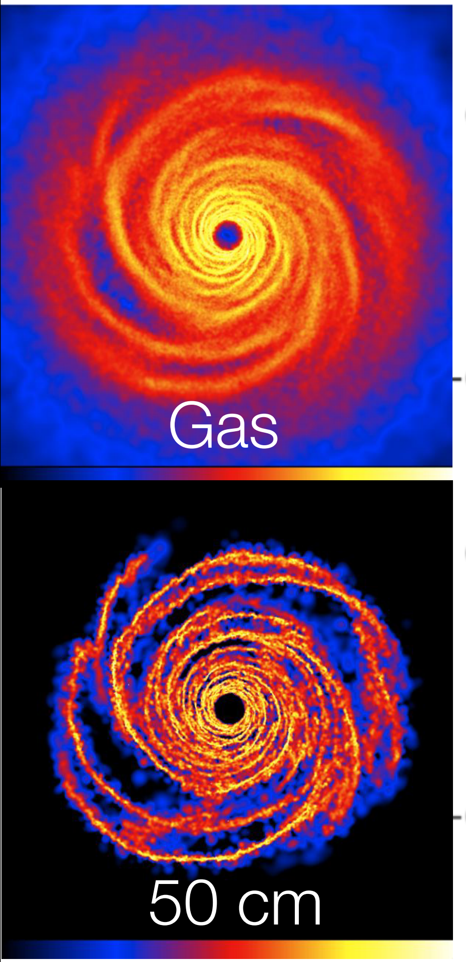
(Pinilla, Birnstiel, Ricci et al. 11)

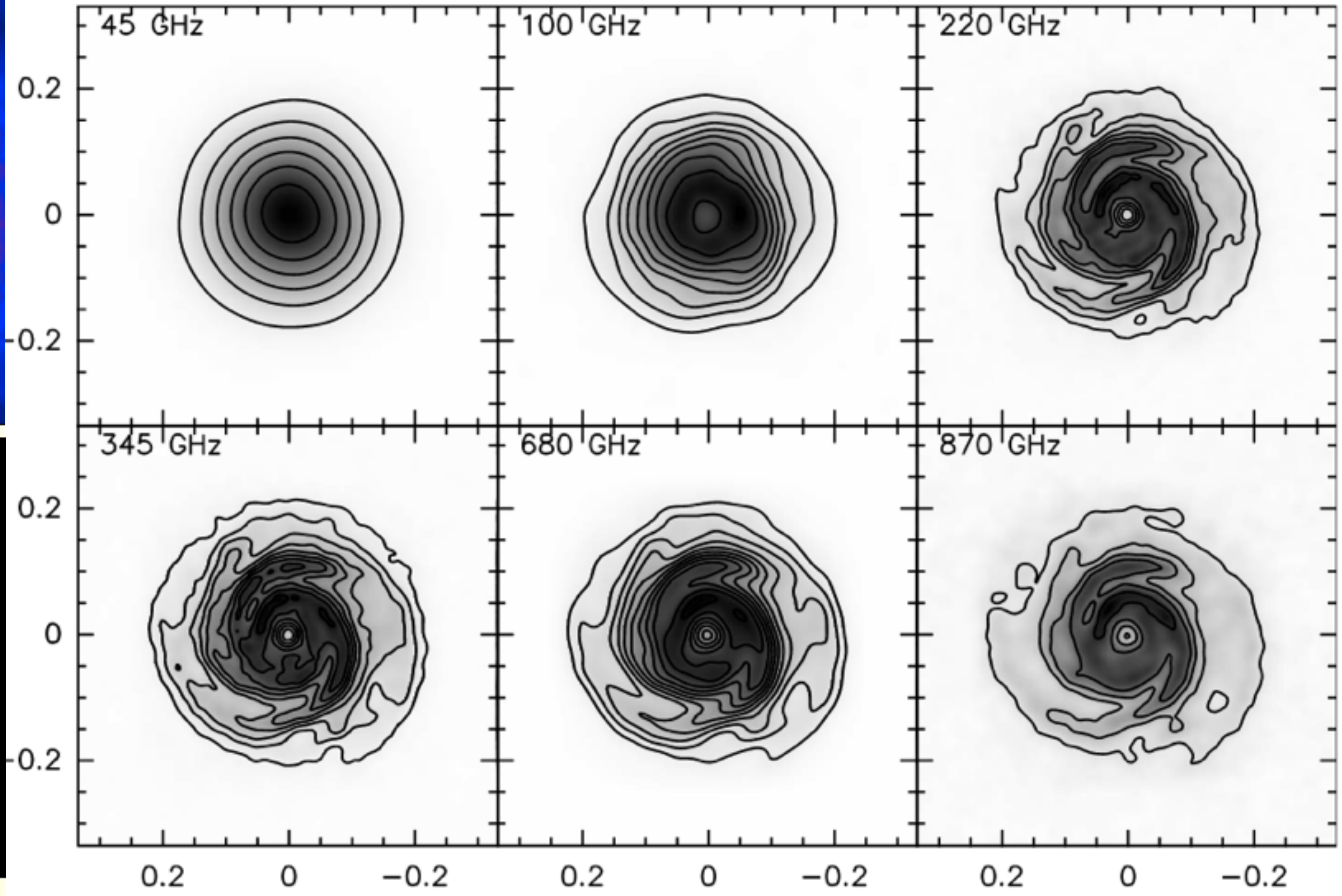




(Whipple 1972)

Slowing down radial drift: grain trapping



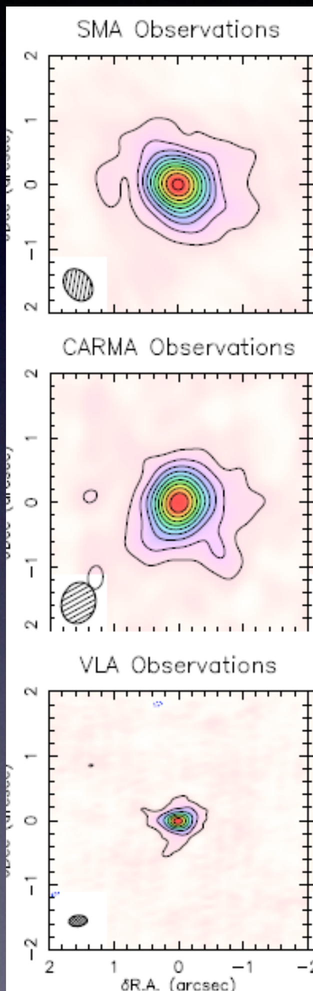


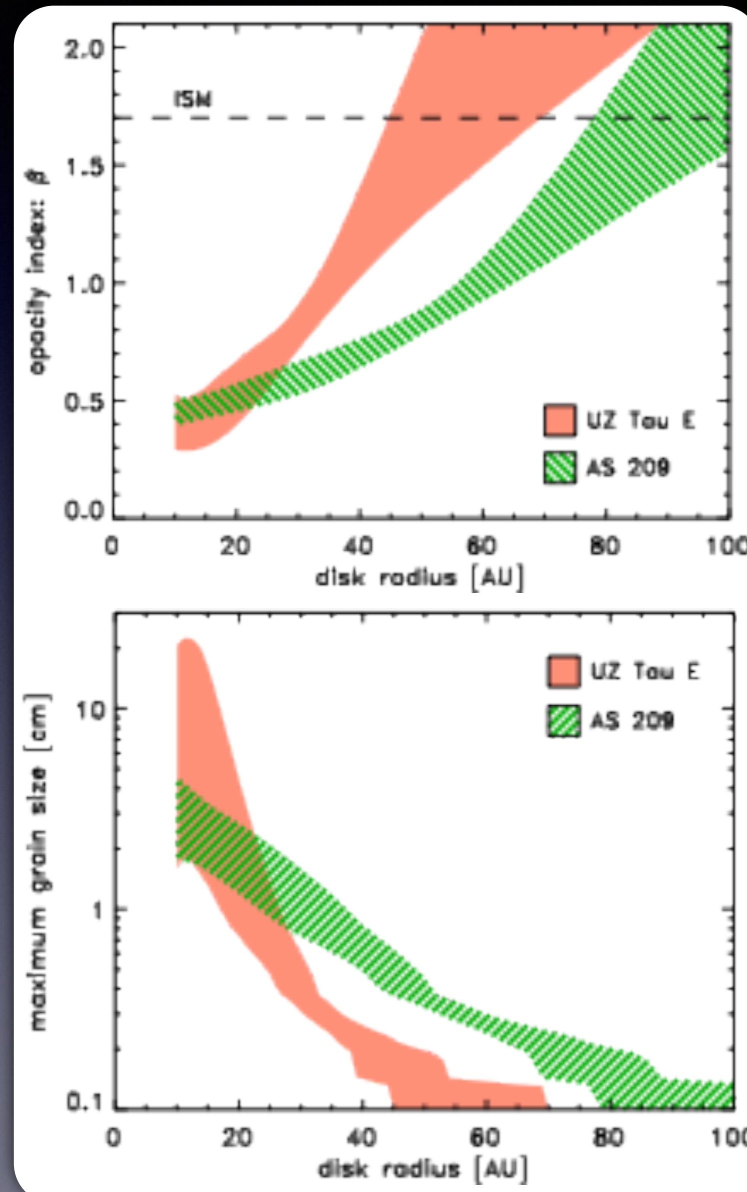
(Cossins, Lodato, Testi 2010; Dipierro et al. 2013)

- Grain Trapping: e.g. spiral arms, vortices, density enhancements
- Predictions will be tested observationally

Grain properties gradient

(Perez et al. 2012, ApJ 760, L17)



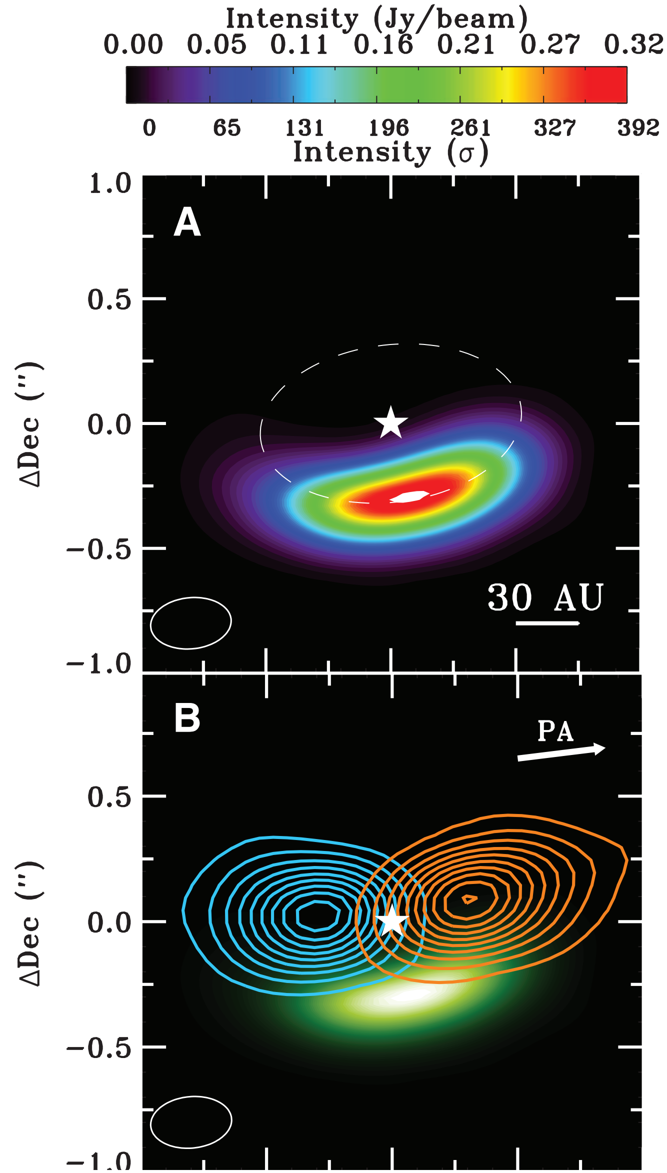


Data from: Perez et al. 2012; Harris et al. 2013
Models: Birnstiel et al. 2012

Disks@EVLA

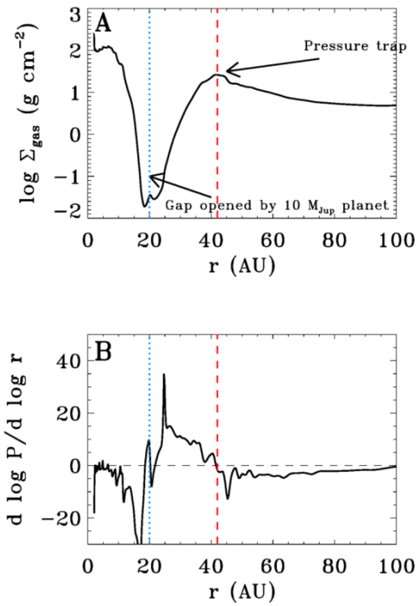
ALMA data on IRS48

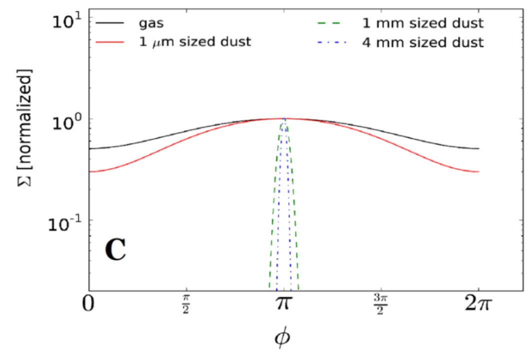
- Known Transitional Disk (disk with inner hole, supposedly carved by planets or photoevaporation)
- A0 central star
- ALMA Cycle 0 Band 9 observations at ~0.23” resolution
- CO(6-5) and dust continuum

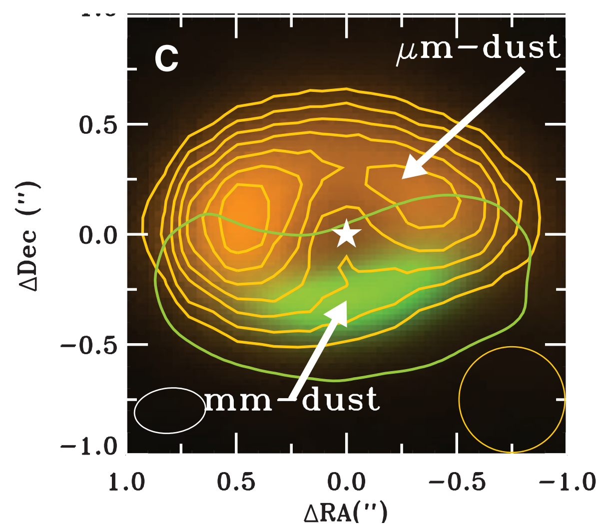


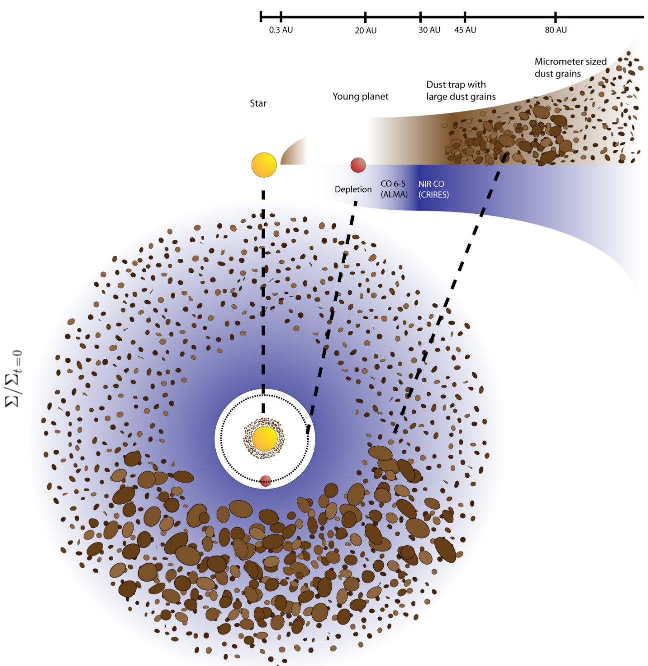
(van der Marel et al. 2013, Science)

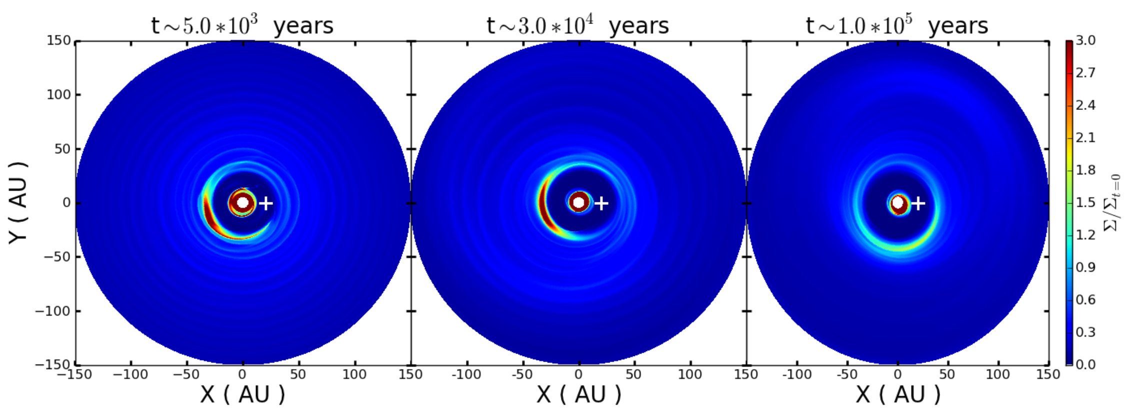
Dust size segregation





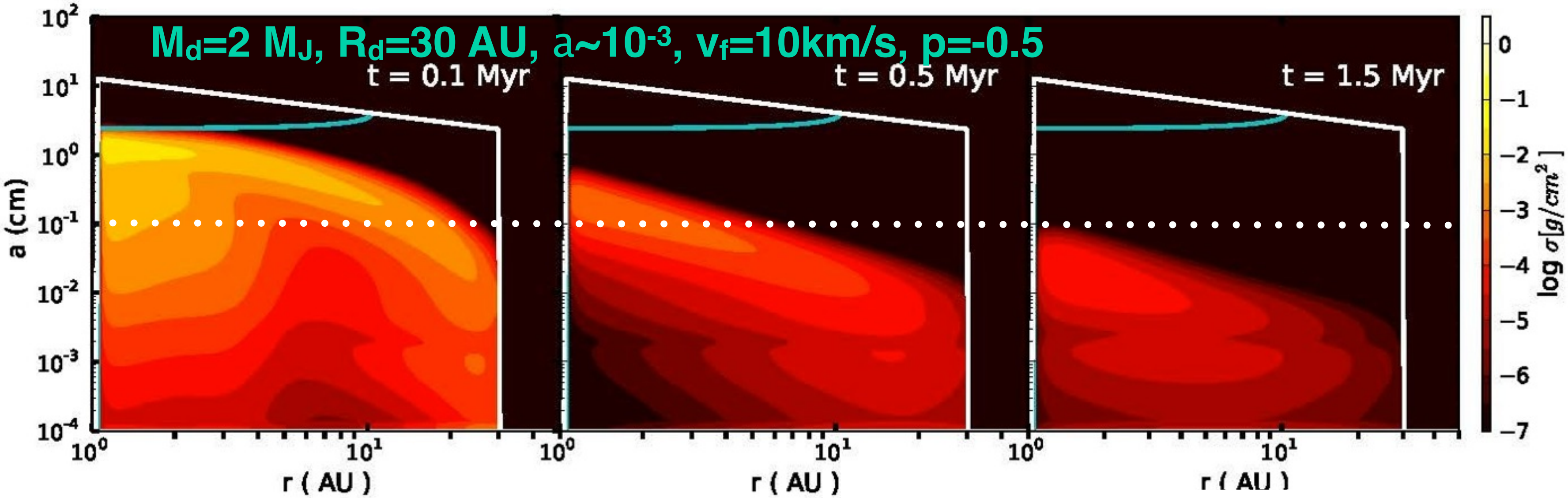






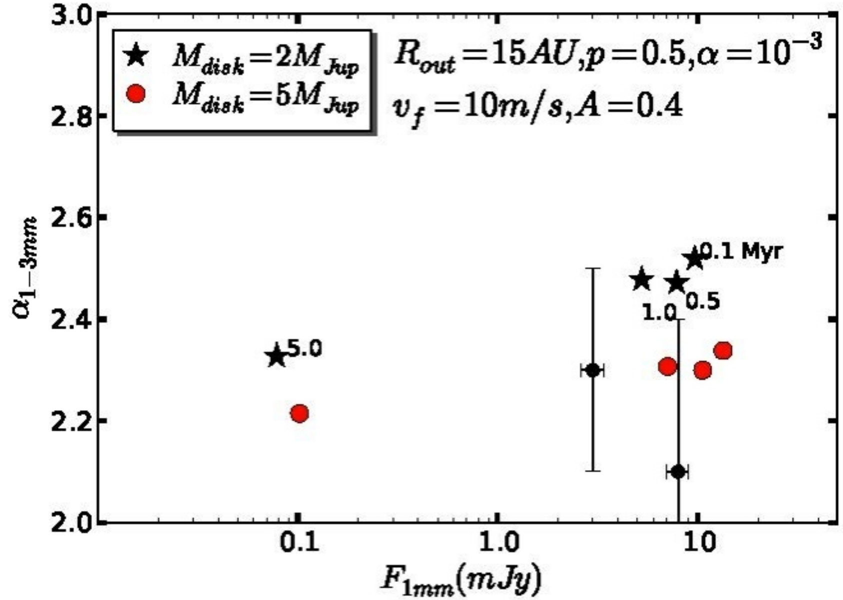
(van der Marel et al. 2013, Science)

Dust evolution in BD disks: initial models

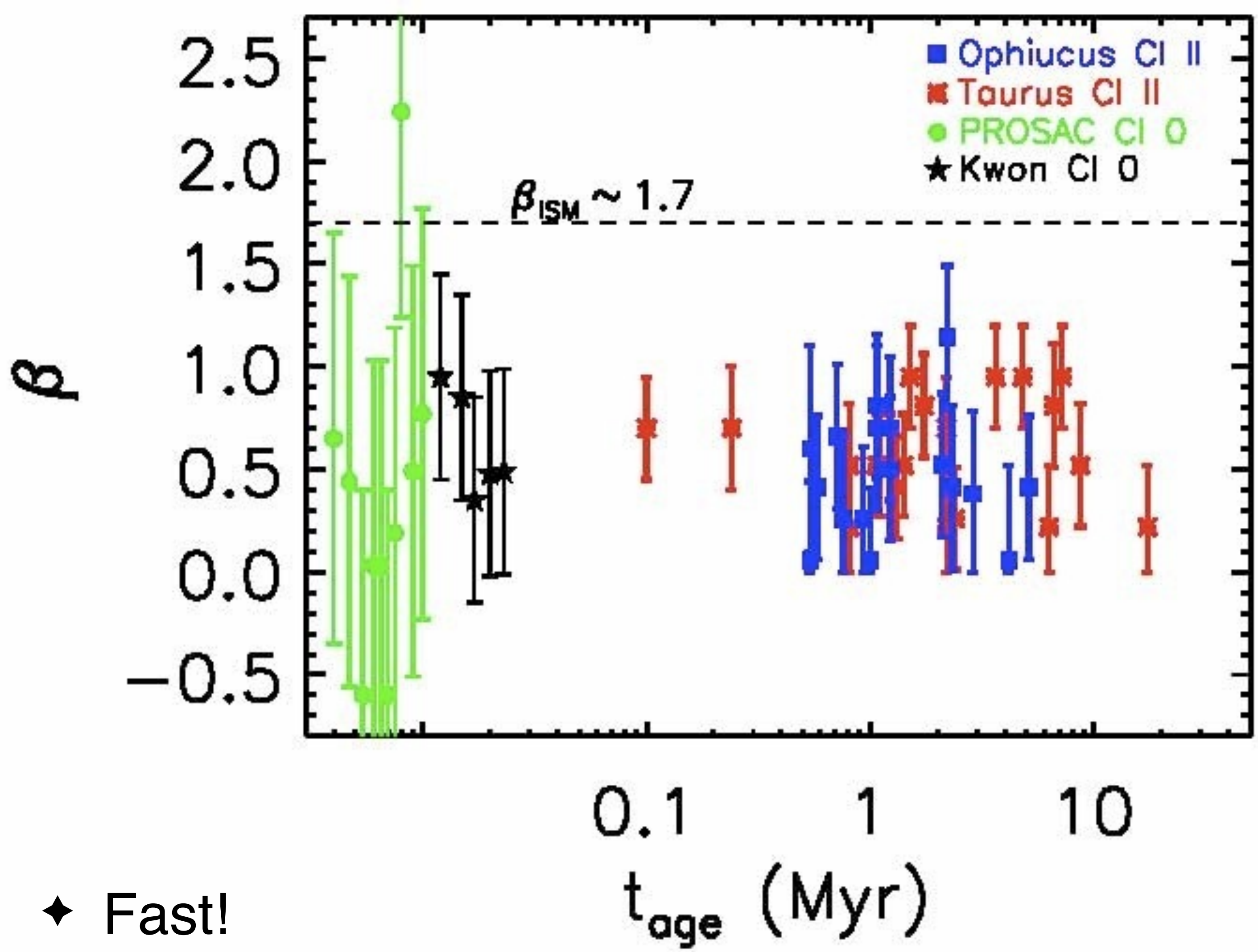


(Pinilla et al. 2013)

- To reproduce the observations, it is necessary to use extreme parameters
- Very fast radial drift is the main problem
- Especially for the disk radius and amplitudes of the overdensities necessary to stop radial drift



Growth timescale

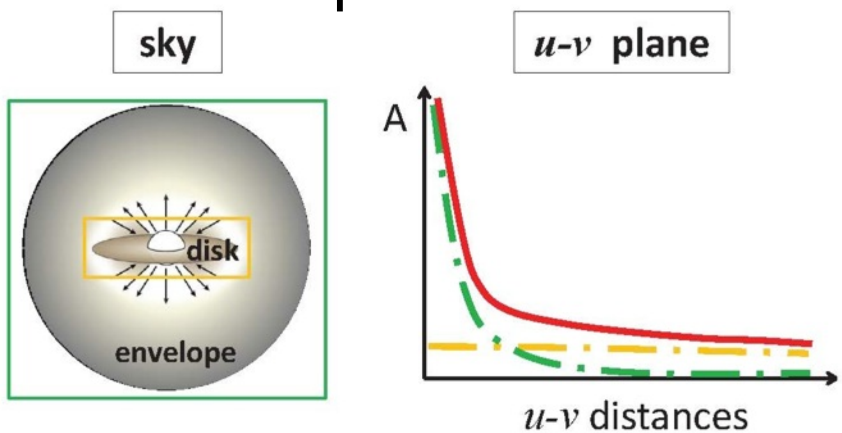


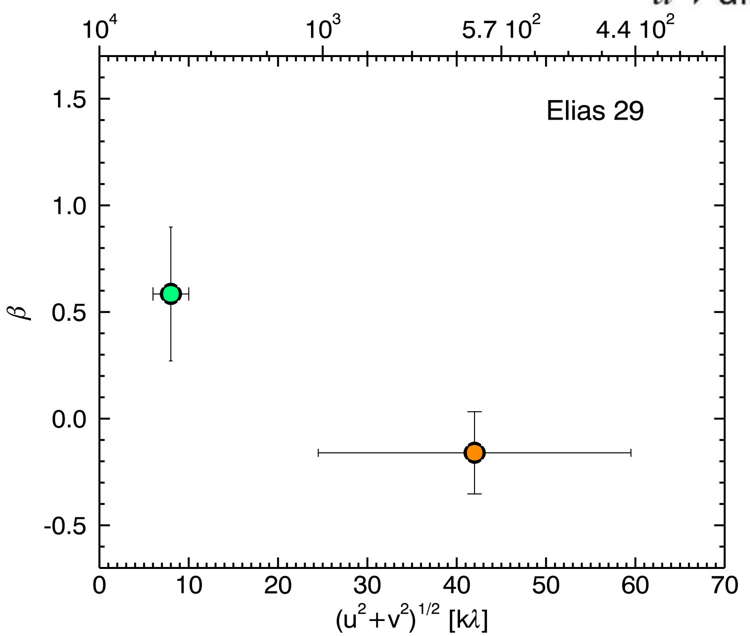
(Ricci et al. 2010, A&A 538, 114)

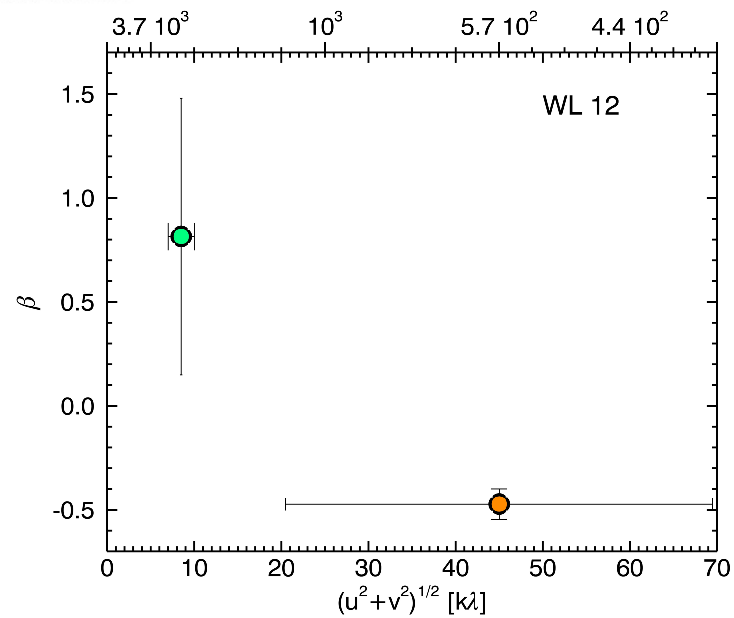
- Fast!
- Early growth in protostars?

Dust evolution in Class I

- Easier to separate disk/envelope







(Miotello et al. 2013)

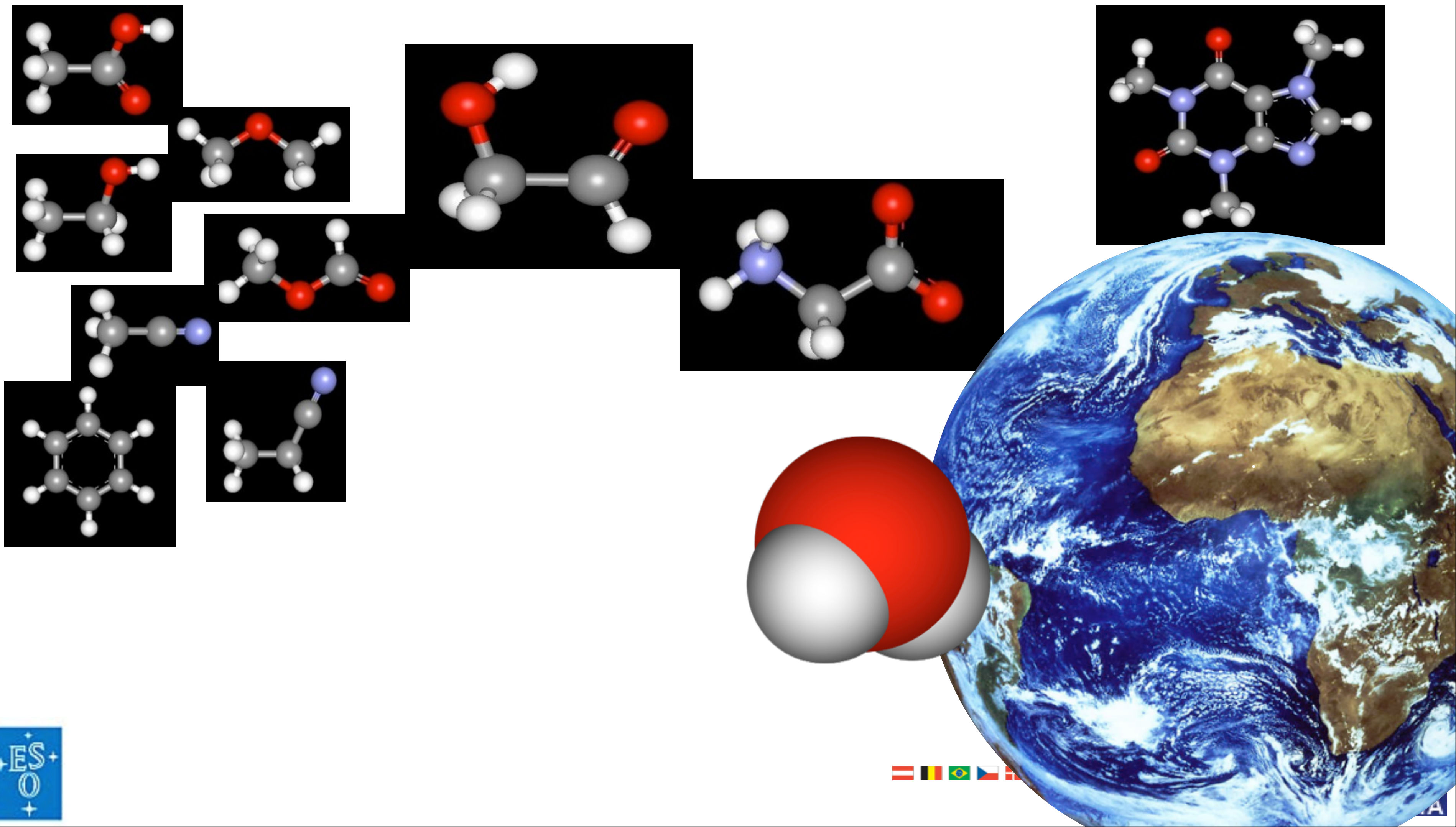
State of the Art & Future Directions

- Grains grow and settle in disks around all type of PMS objects
- Grain evolution can be very fast as we see highly processed grains around objects of all ages between 1 and 10 Myr
- Plausible physical structures in the disk can stop migration

- **Key predictions and tests:**
  - Grain growth in Class 0 and I (Chiang et al. 2012; Miotello et al. 2013)
  - Radial gradient of dust properties (Guilloteau et al. 2011; Perez et al. 2012; Trotta et al. 2013,...)
  - Small-scale segregation of large grains (full ALMA resolution needed, but first results coming out: Casassus et al. 2013, van der Marel et al. 2013)
  - Disks need high gas densities for grains to grow: faint disks should be a late evolutionary stage disks around BDs should not grow grains

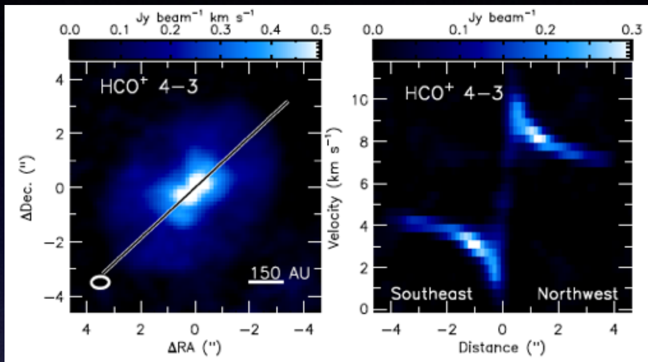
- **Need high angular resolution/spectral resolution MIR to link mid plane grain growth with surface properties and global disk evolution models**
- **Early growth may imply modifications of the overall picture**

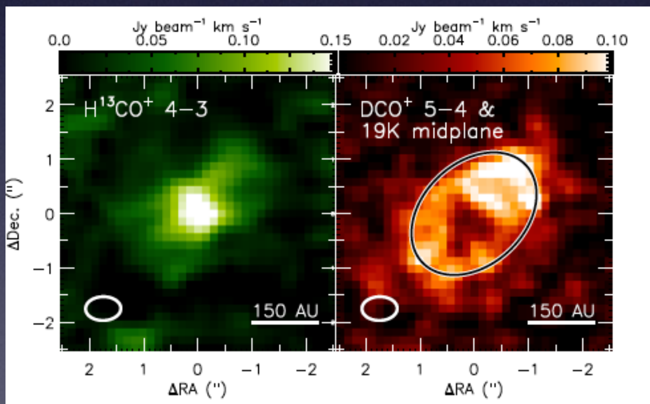
Molecular gas: water and complex organics

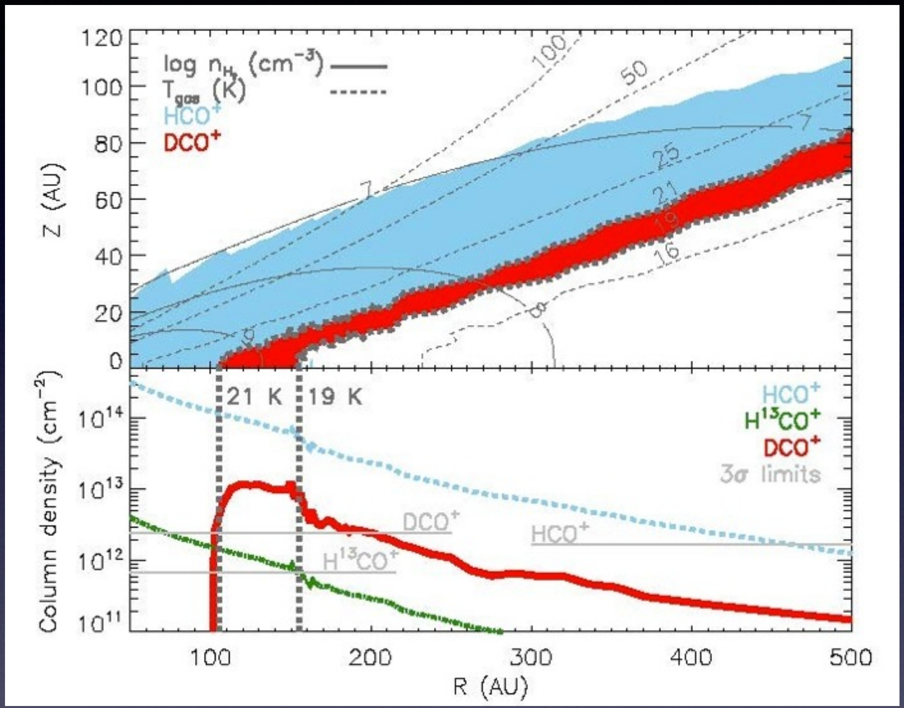


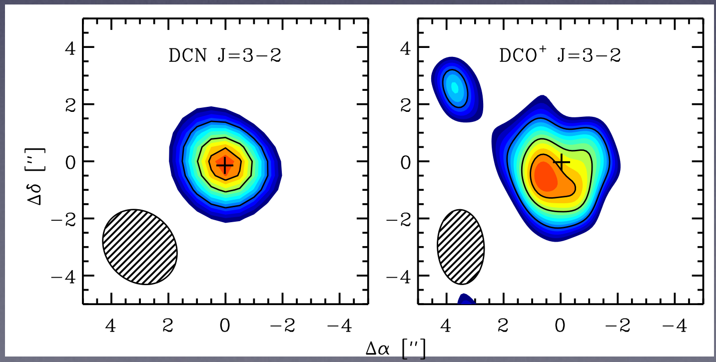
HD163296 as seen by ALMA

(Mathews et al. 2013)





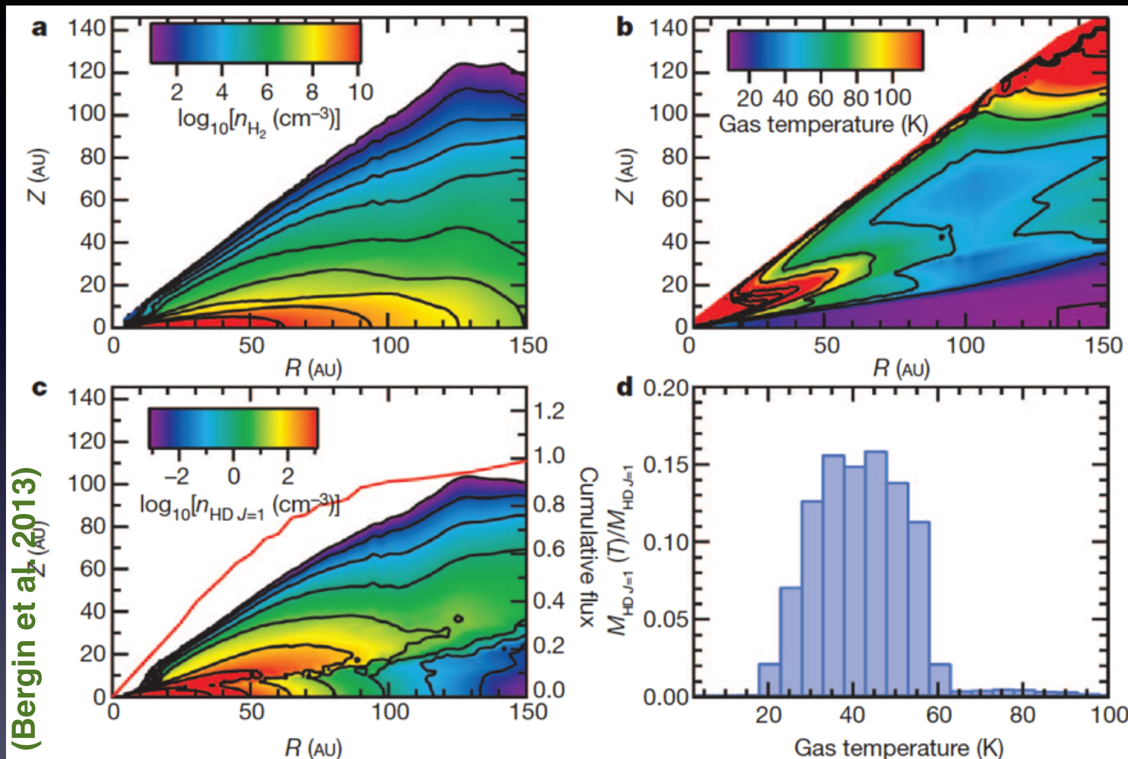


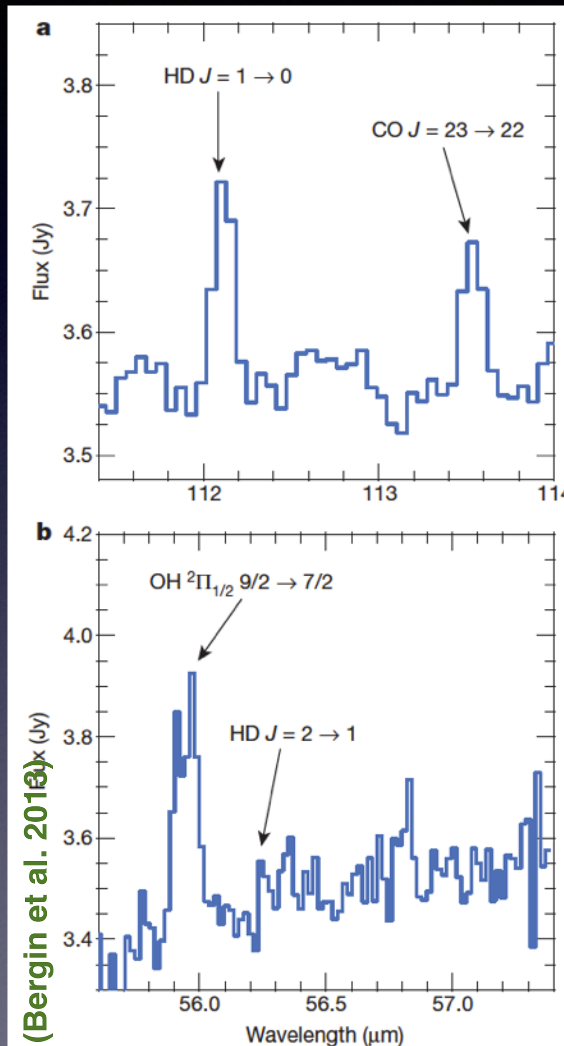


(Oeberg et al. 2012)

- CO snowline and disk tomography

Disk masses: (sub)mm continuum

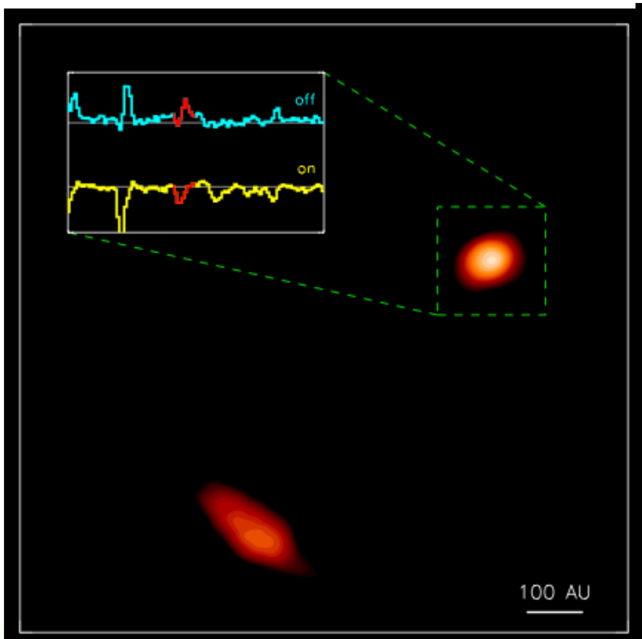


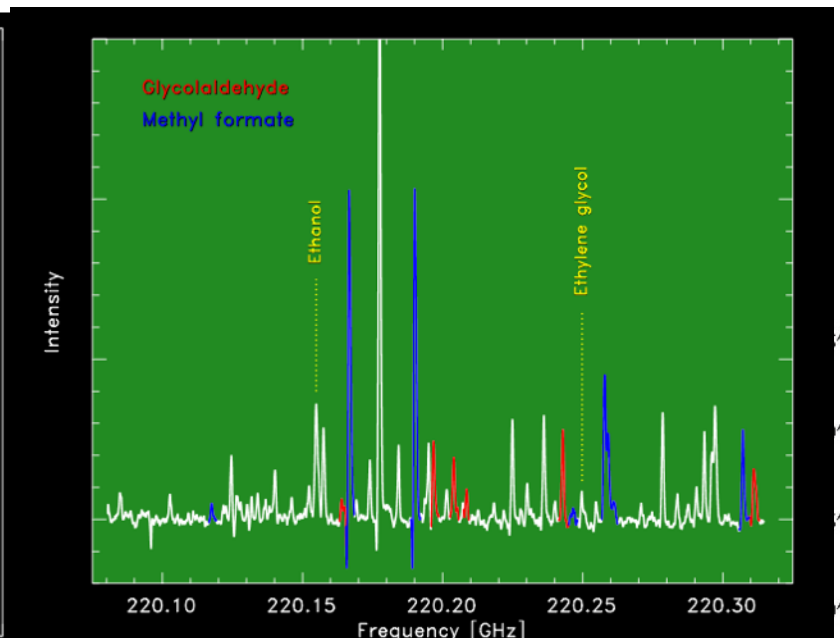


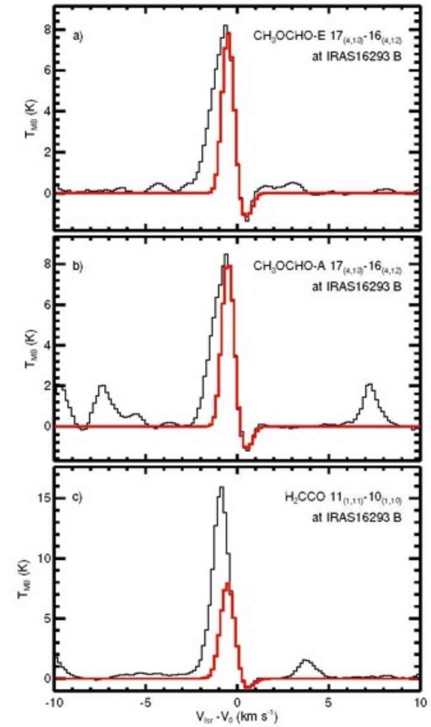
- HD has been detected with Herschel in the nearest disk. This is the best constraint on the gas mass in disks

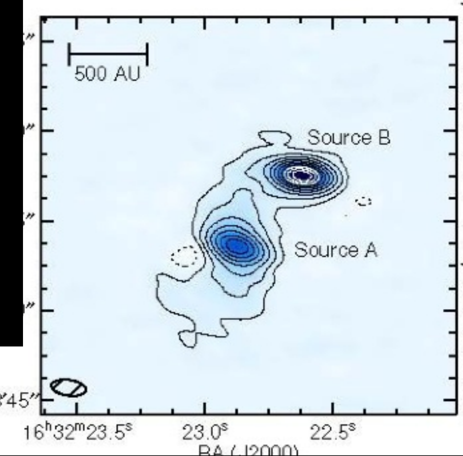
ALMA SV Science Results

- Infall and pre-biotic molecules in IRAS16293
  - Jorgensen et al. 2012, ApJ 757, L4; Pineda et al. 2012, A&A 544, L7, Persson et al. 2012, in press
- First glycoaldeheyde detection in solar mass protostar
  - From B9 first released dataset. This simple sugar is found within ~25~AU from the central protostar and infalling into the inner regions of the disk.



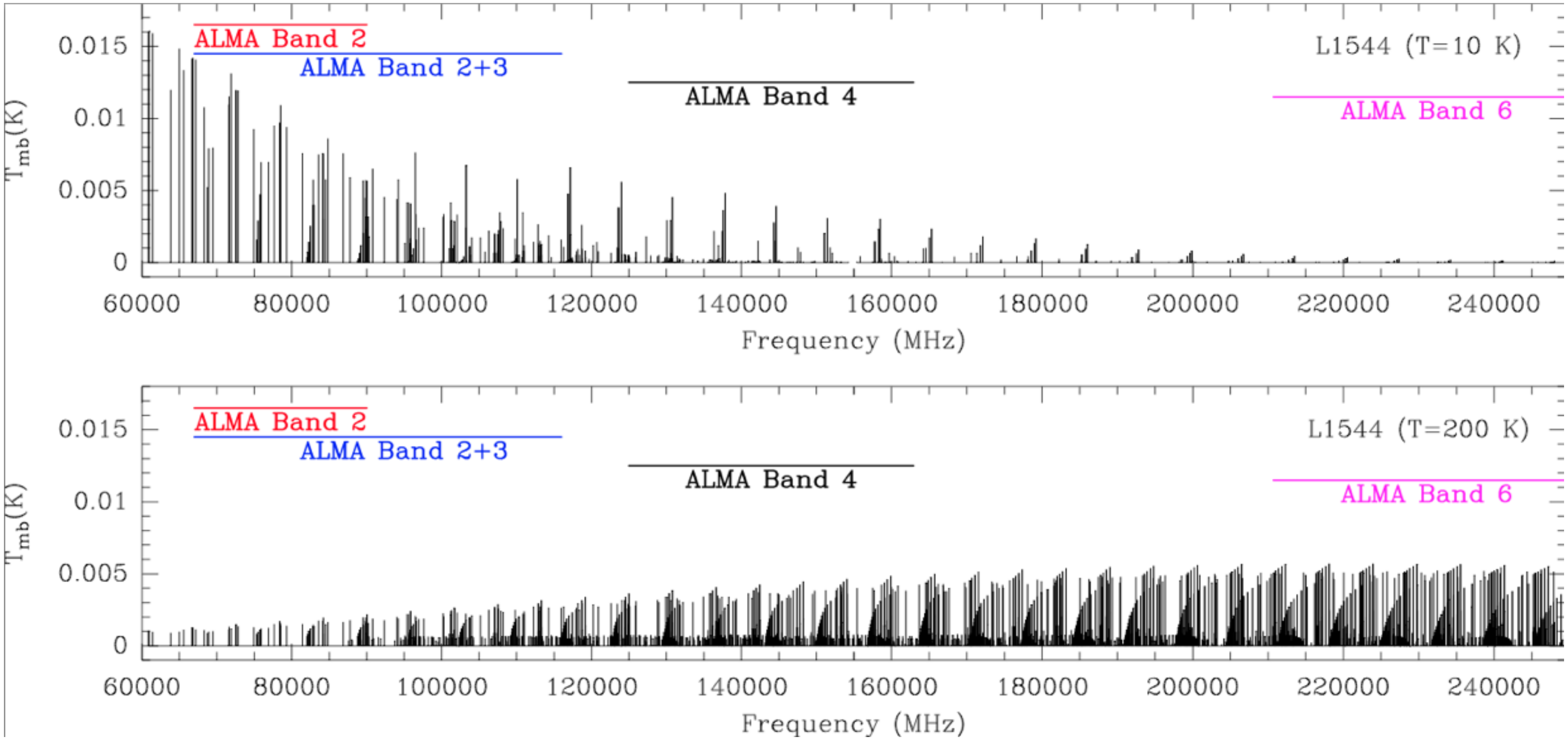






The path to pre-biotic molecules

- The holy grail of pre-biotic molecules in the ISM: glycine
- Predicted intensities of glycine in the ALMA bands
  - Keys: sensitivity, spectral coverage and get the molecules out of the ices...

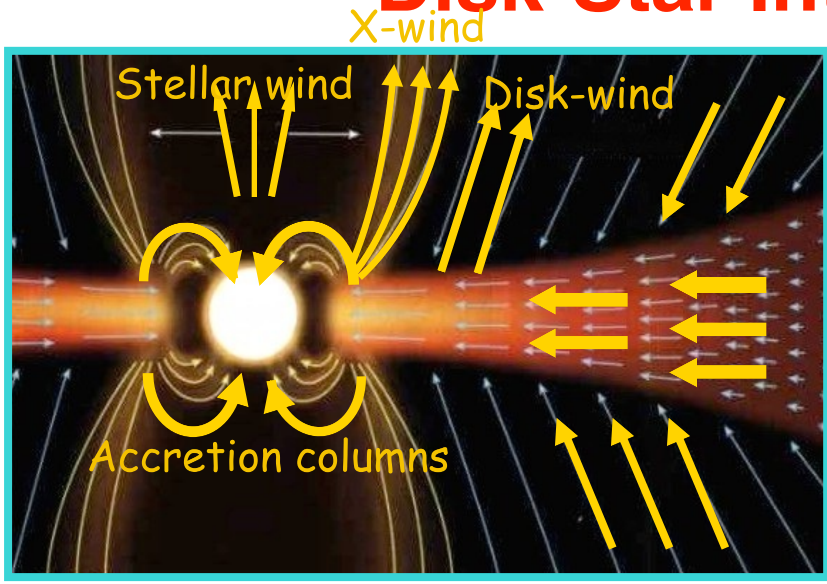


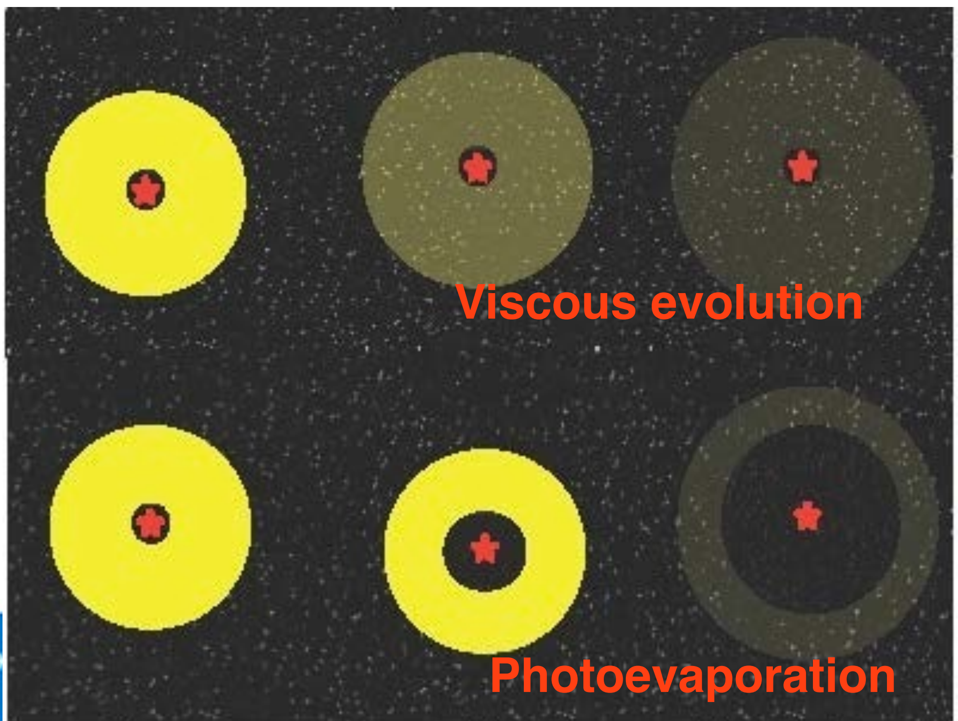
(Jimenez-Serra et al. 2014)

Disk-star interactions

- Accretion onto the central star
- Disk-star-wind connection
- Disk dissipation
- Effects on chemical evolution of disks

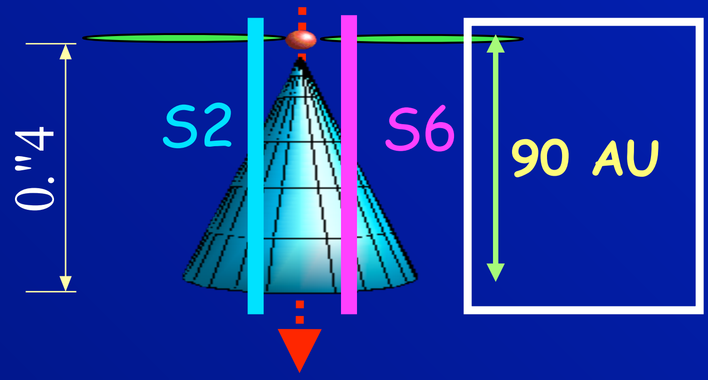
Disk-Star Interaction Region



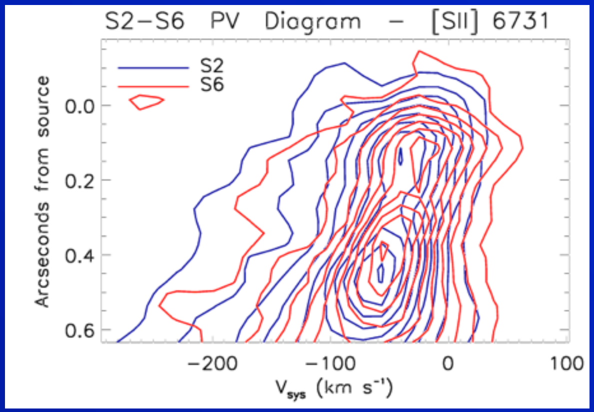


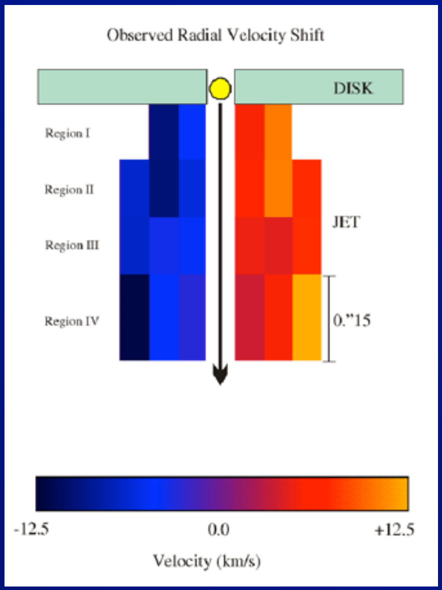
- Accretion is driven by viscosity
  - Accretion is linked to the inner stelalr and/or “X-”wind.
- What we know:
  - Photoevaporation removes the disk inside-out
- Planet formation “competes” for resources with these two processes and interacts with them

First detections of jet base rotation : DG TAU, RW AUR



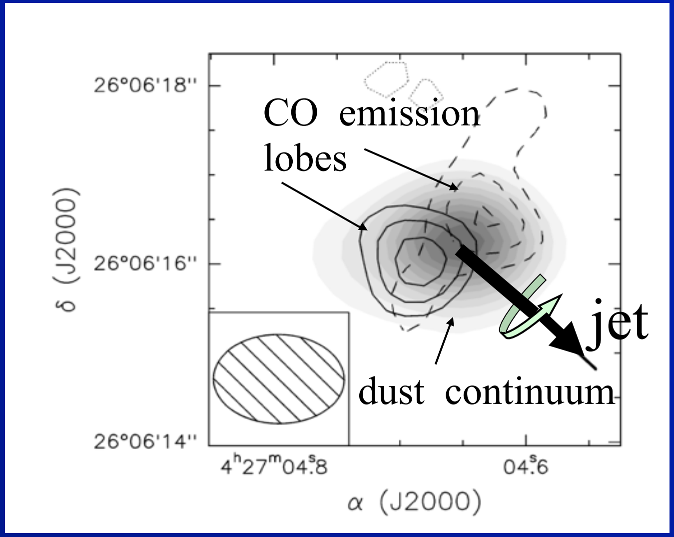
Small VELOCITY SHIFT
in symmetrically opposed slits (in all lines, corrected for uneven slit illumination)





30 AU

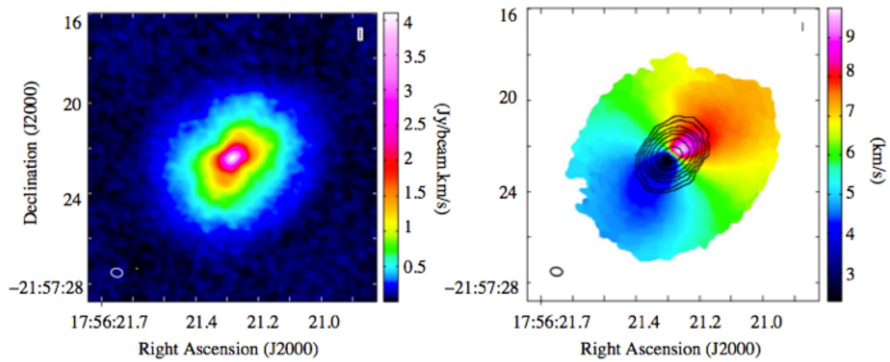
Bacciotti et al, 2002 ApJ

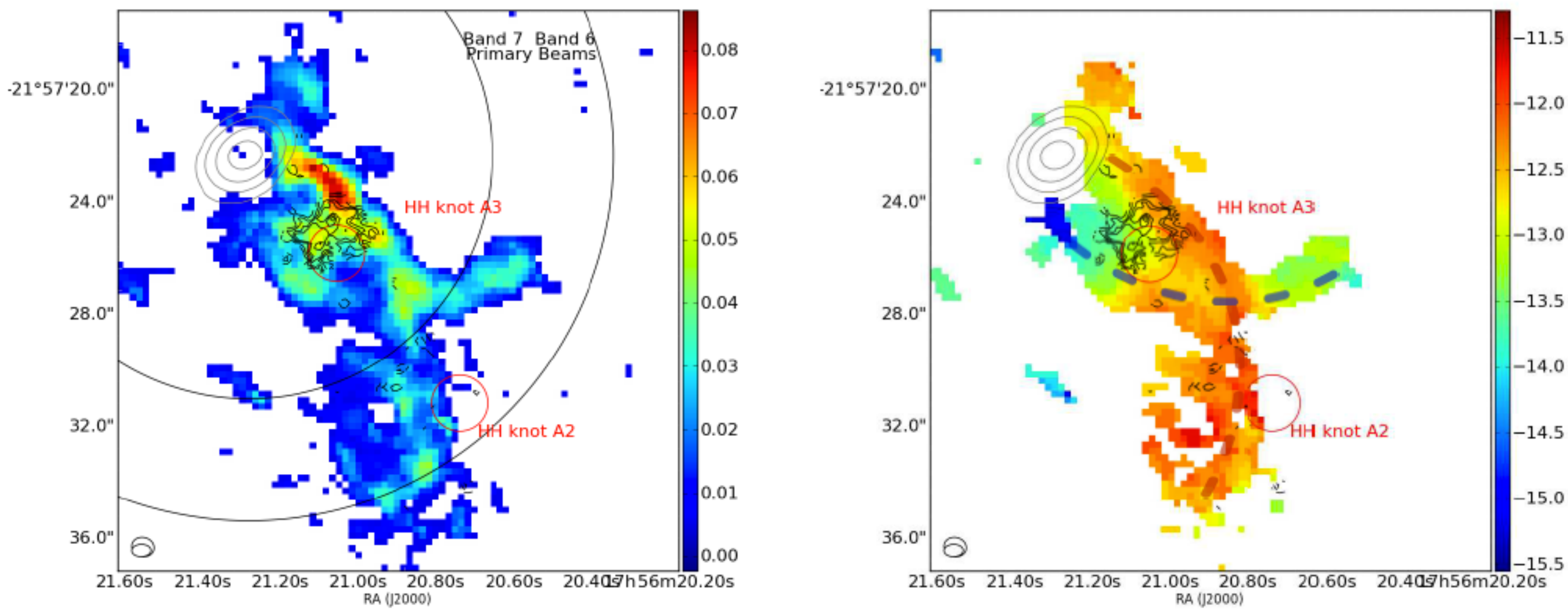


DG Tau disk rotates in the same sense and along the same rotation axis

Testi, Bacciotti et al. 2002, A&A

HD163296 as seen by ALMA



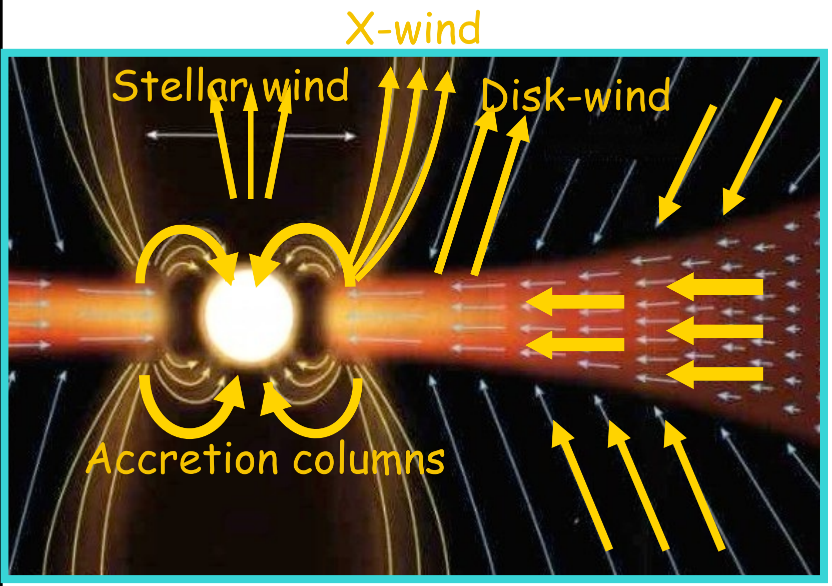


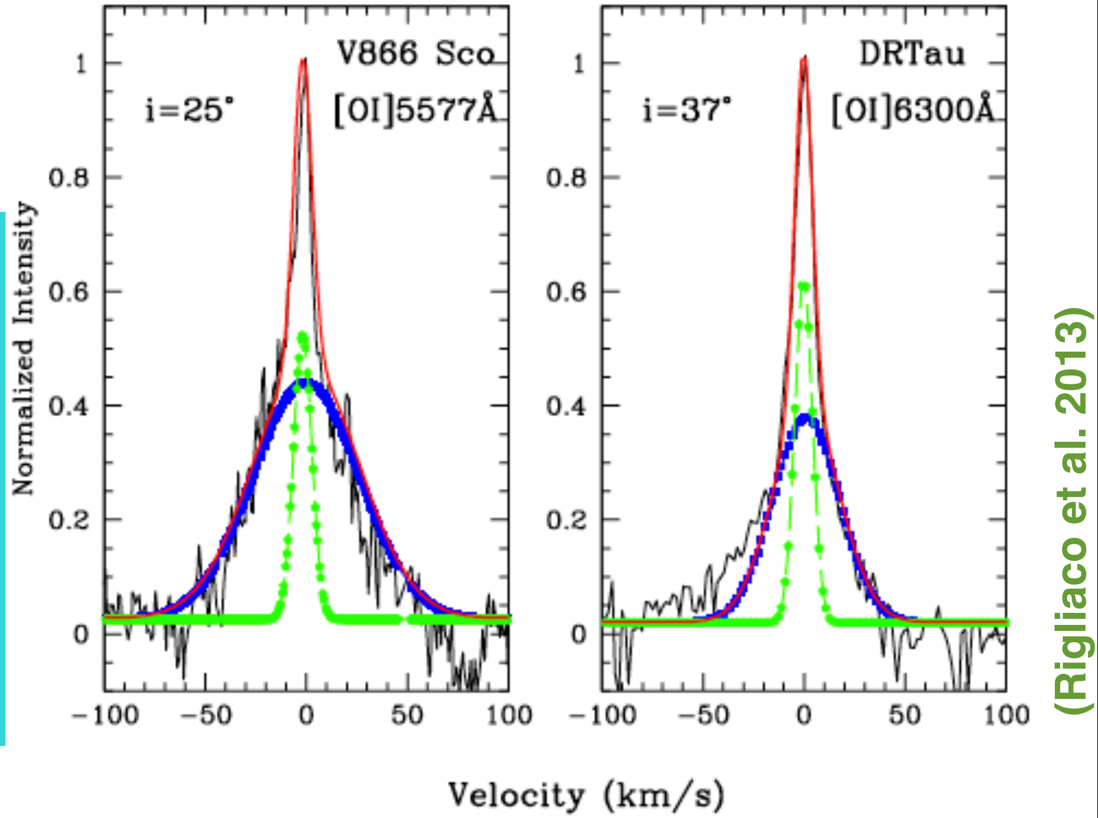
(Klaassen et al. 2013)

- CO disk wind

Winds in optical forbidden lines

Low Velocity Component



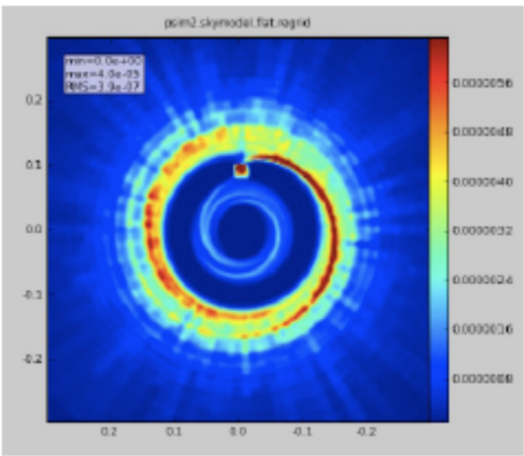


- Working hypothesis:
  - Narrow component is the real wind from outer disk
  - broad component is photodissociated upper layer of the inner disk

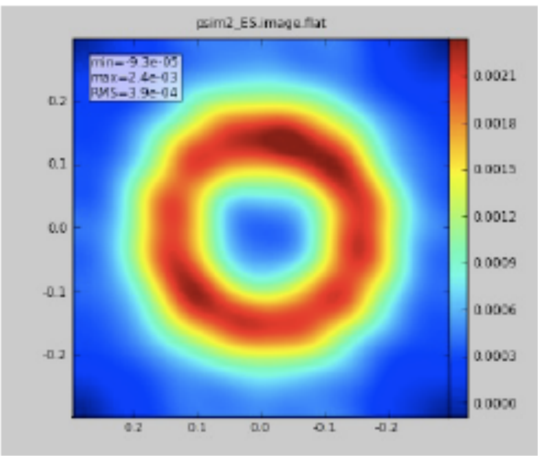
Observing gaps with ALMA

Proto-planetary disk (ALMA band 9)

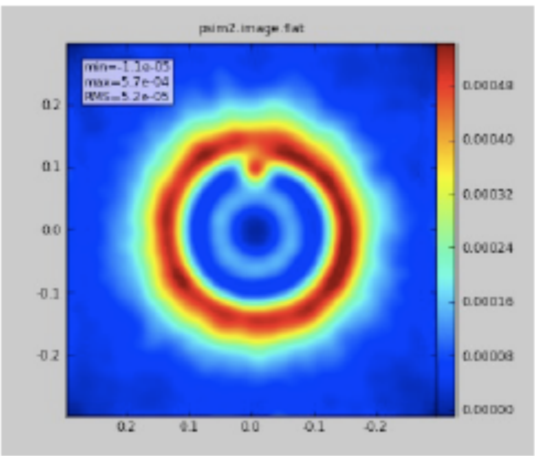
A simulation by Sebastian Wolf (Wolf and D'Angelo 2005)



Skymodel

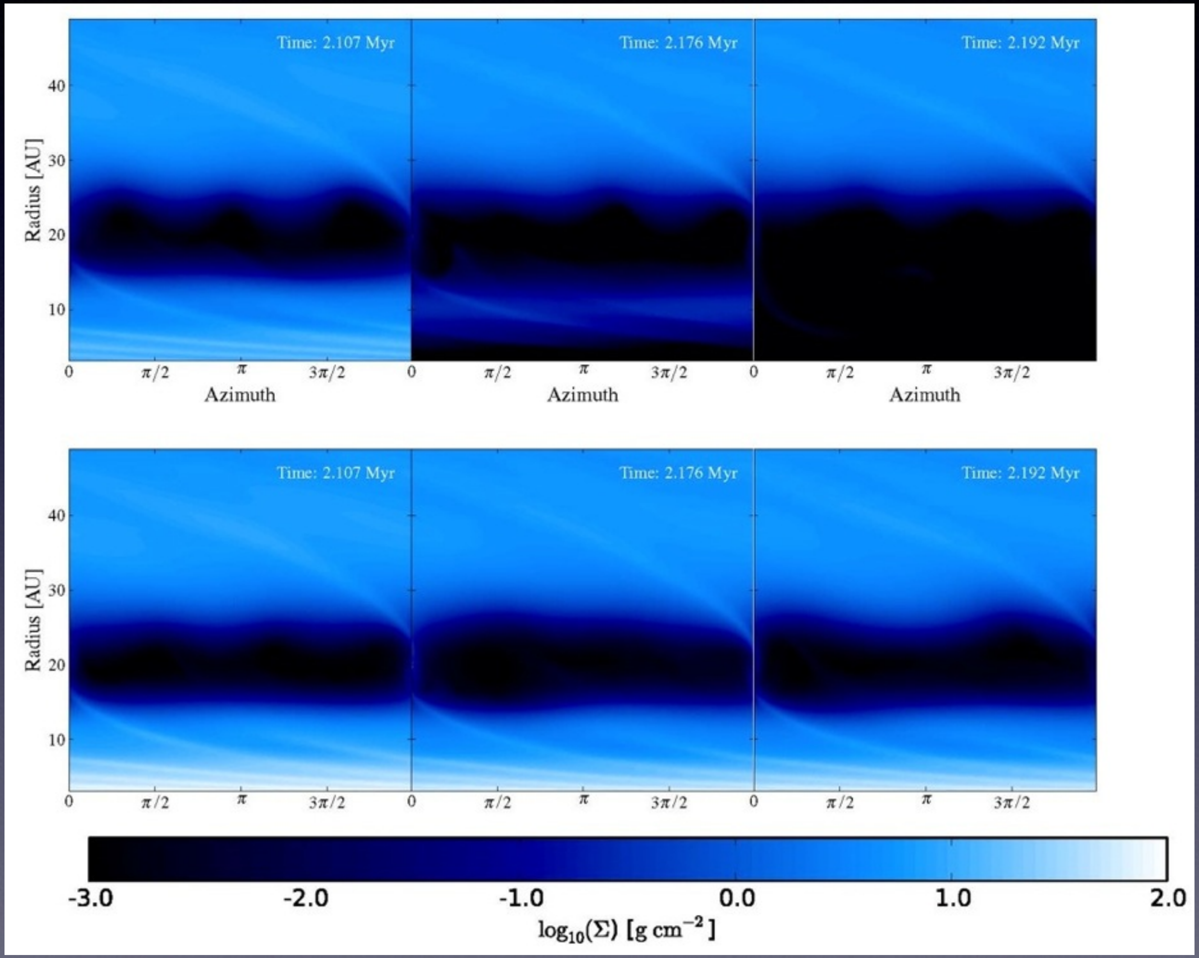


Early Science
(30 mins)



Full Array
(10 mins)

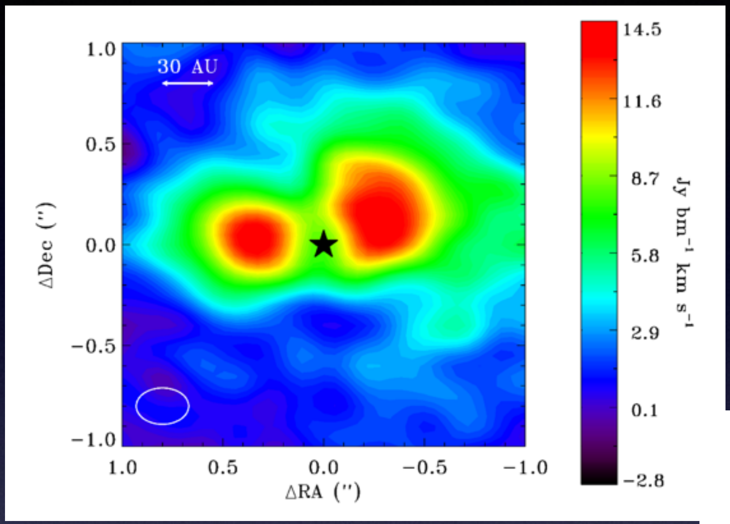
Are gaps long-lived?



(Rosotti et al. 2013)

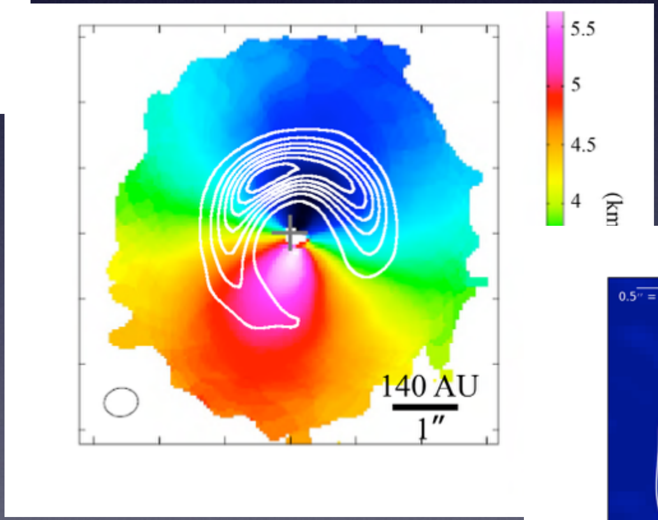
- Disk-Planets-Photoevaporation: initial simulations

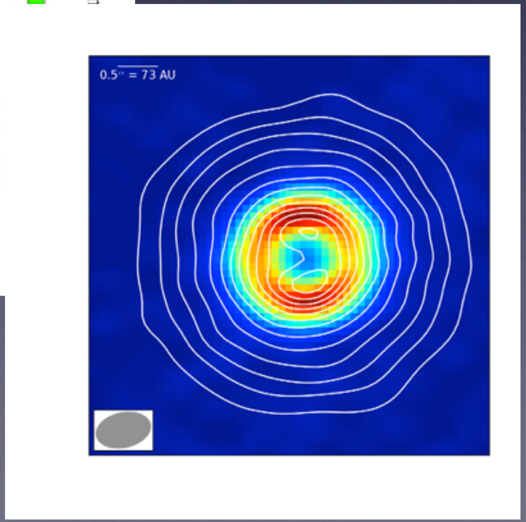
Transitional disks



IRS48: dust and gas

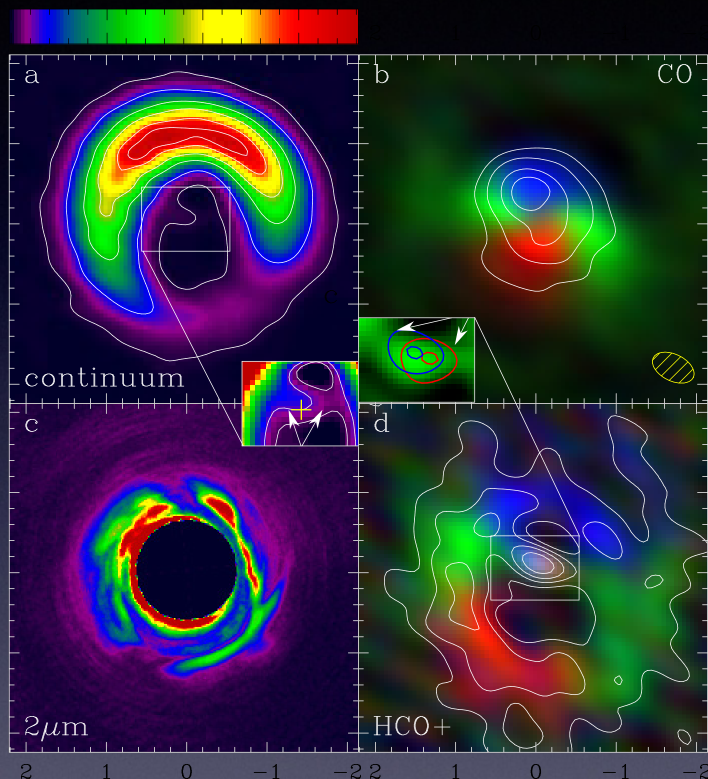
HD142527: dust and gas

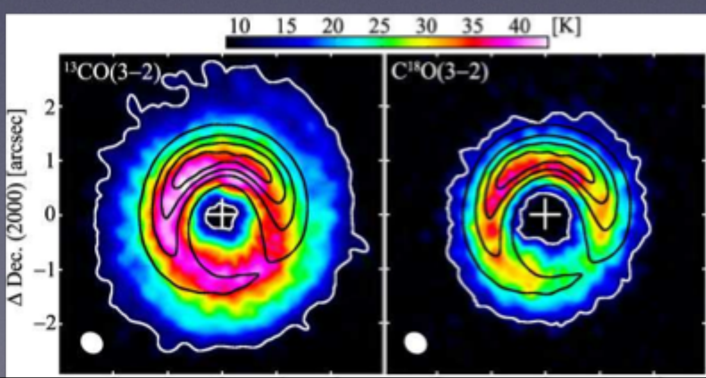




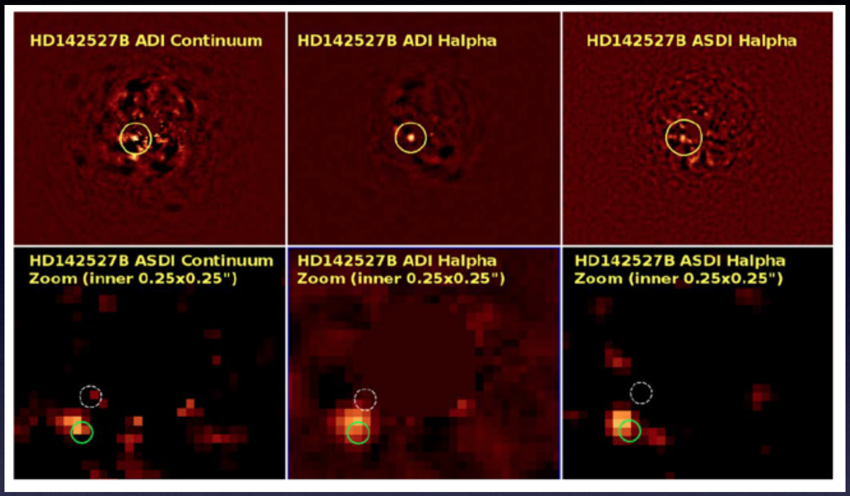
J160421.7 (Carpenter; see also Mathews et al. 2012)

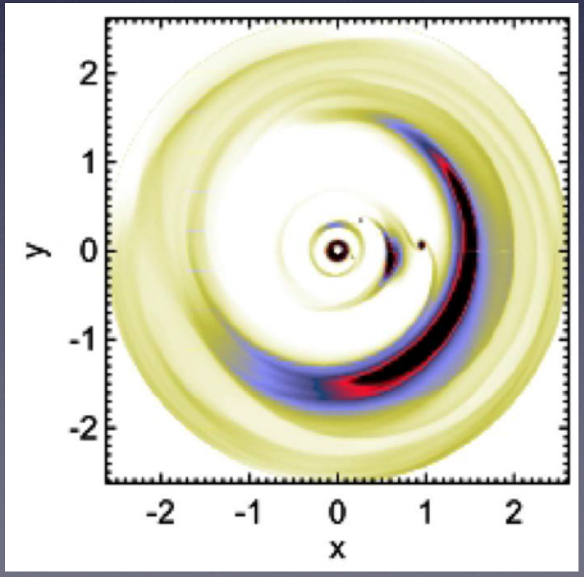
Example: HD142527





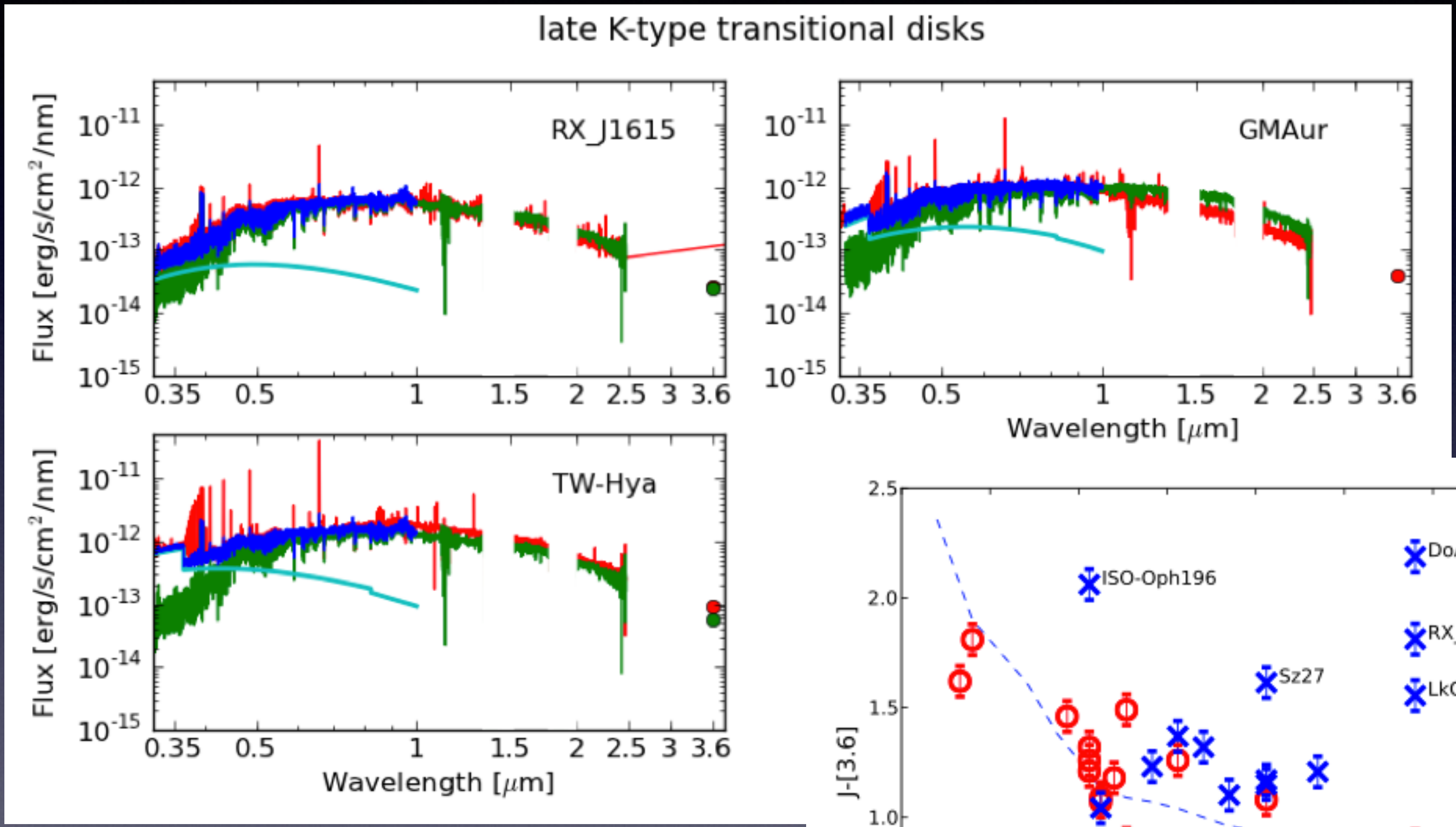
(Casassus et al. 2013; Fukagawa et al. 2013)

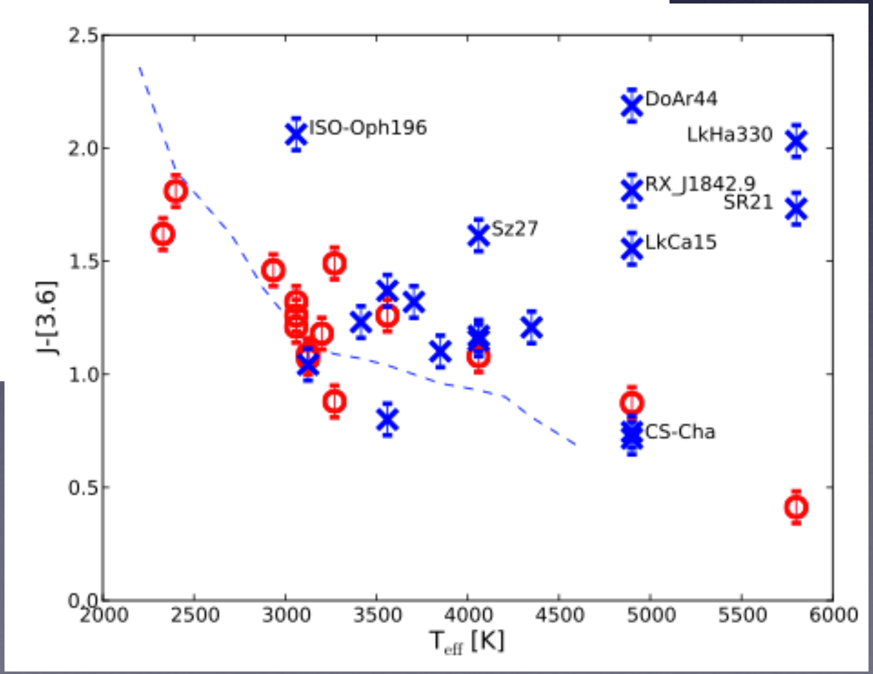




(Close et al. 2014)

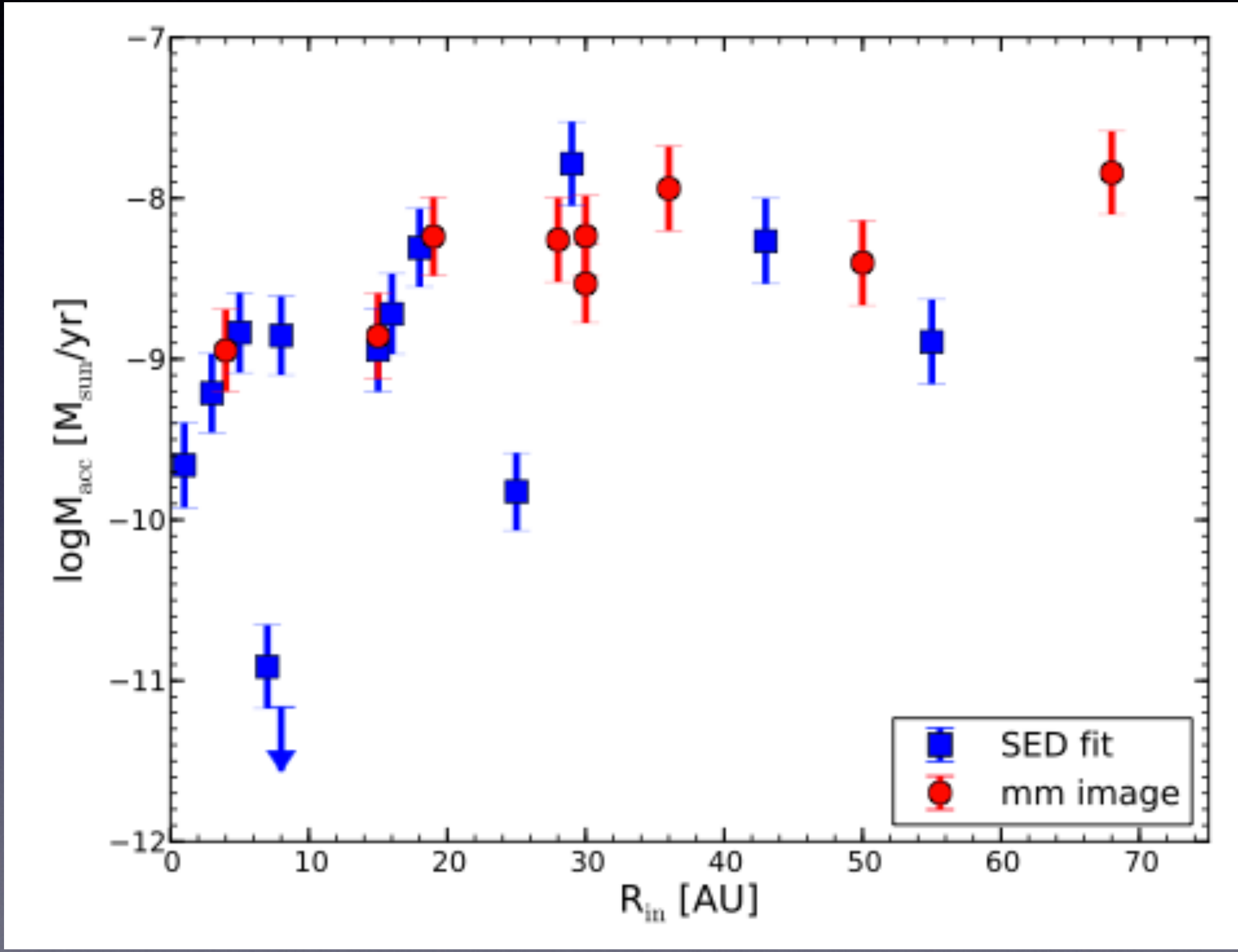
Inner regions of TDs





(Manara et al. 2014)

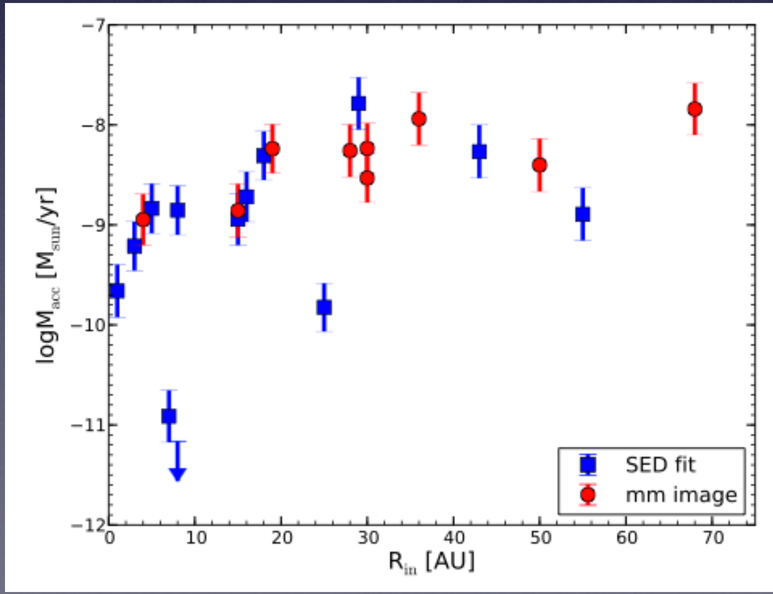
Inner regions of TDs



(Manara et al. 2014)

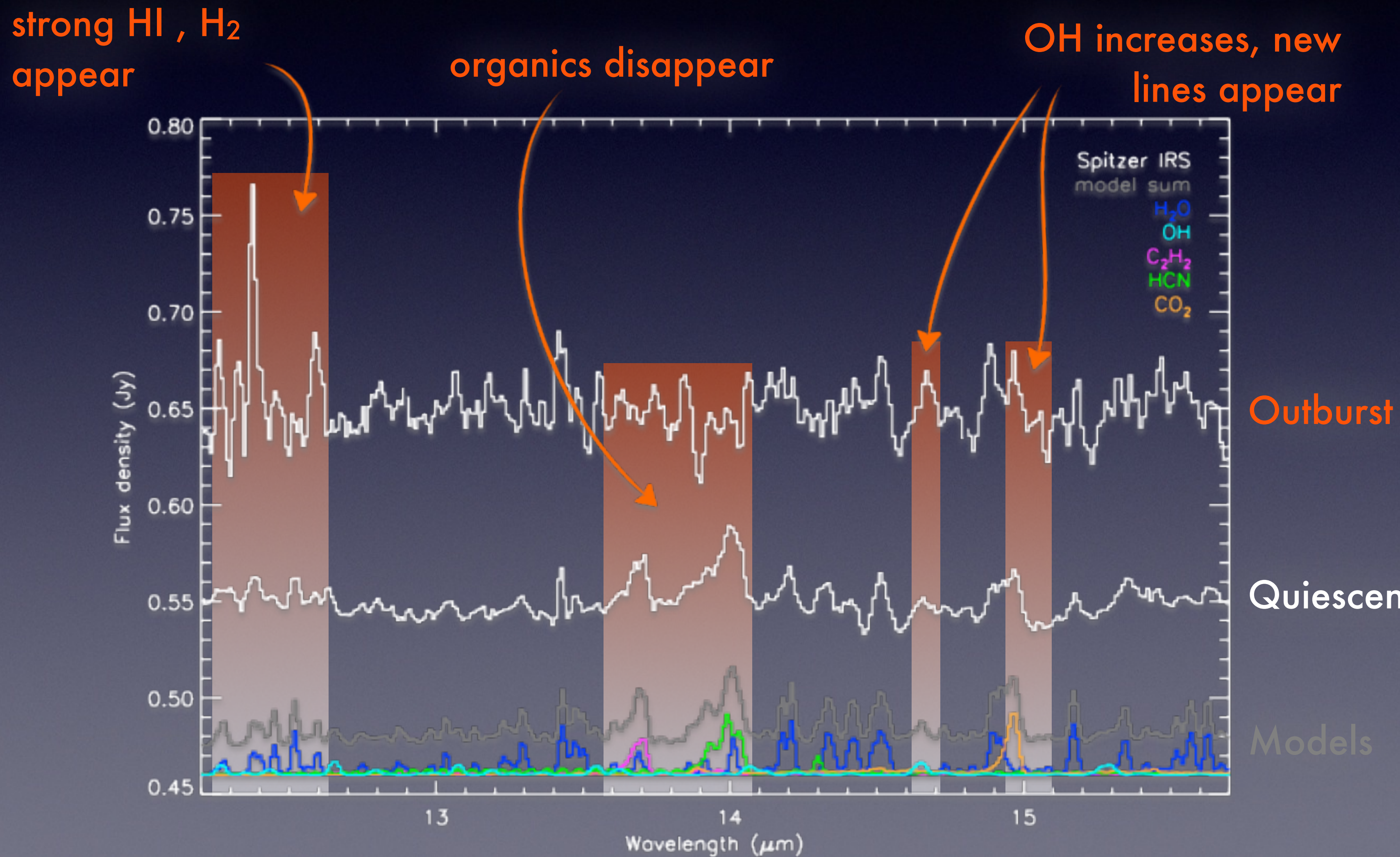
Inner regions of TDs

- Gas rich inner disk?
  - Fast filtration of material through planets?
  - Accumulation in an “inner” disk?



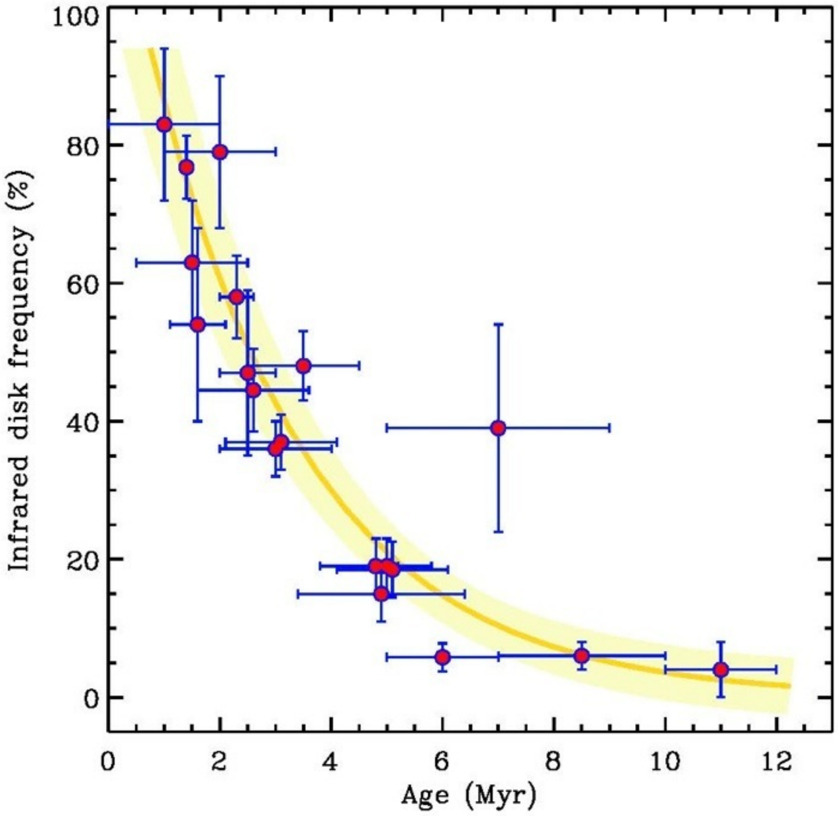
(Manara et al. 2014)

Effects of variable accretion on inner disk chemistry

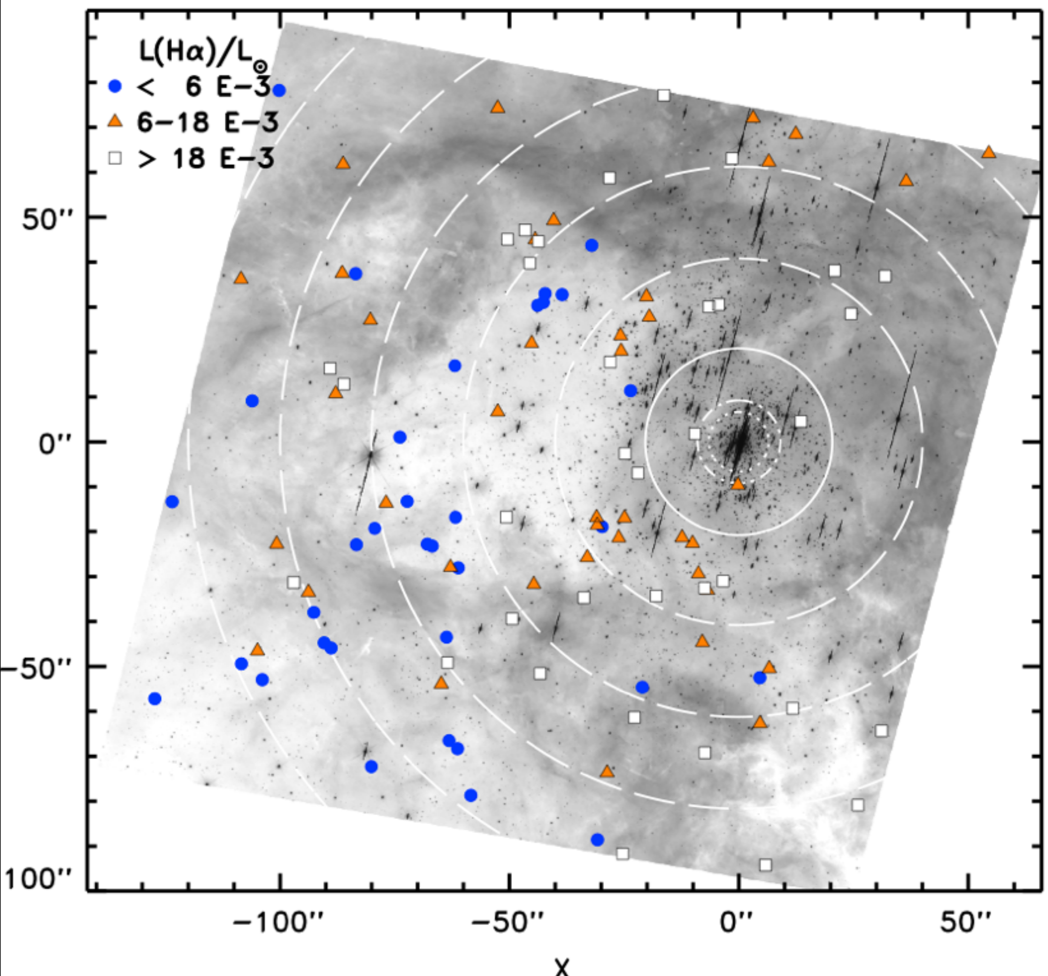


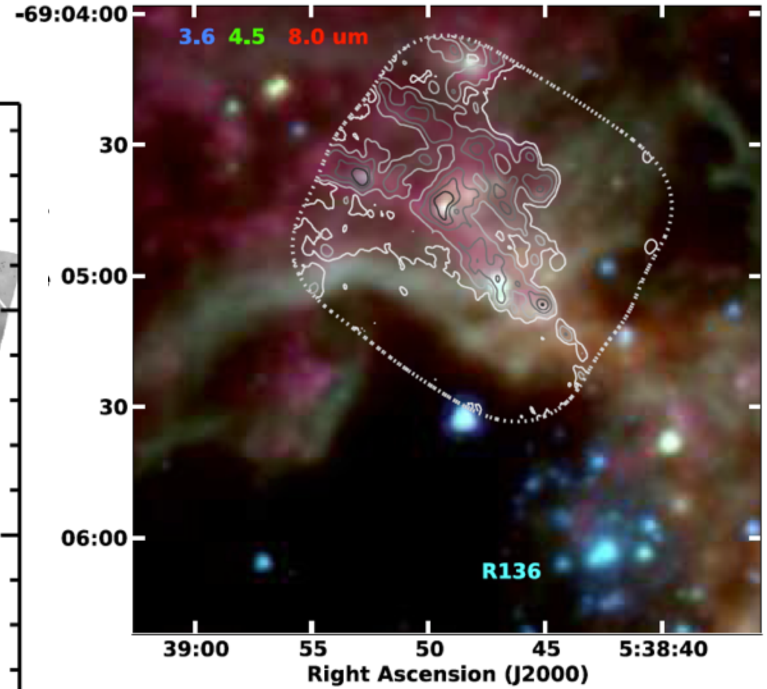
(Banzatti et al. 2012)

A second chance for forming planets?



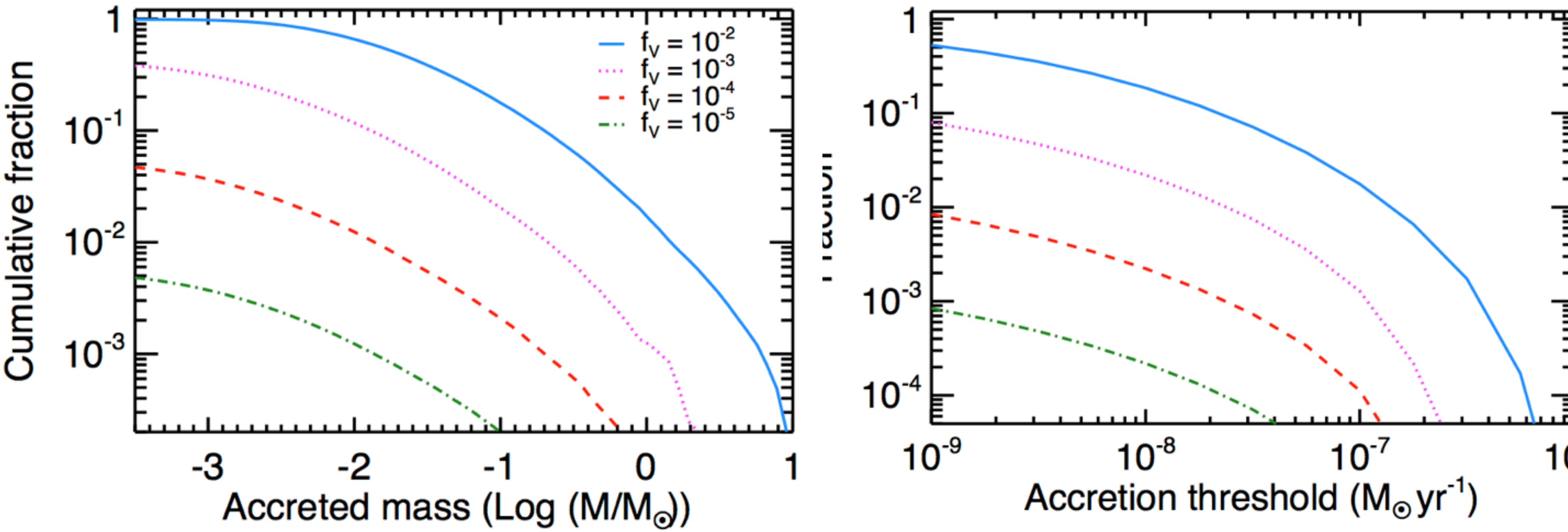
The case of 30Dor





(de Marchi et al. 2011; Indebetouw et al. 2013)

Reforming the disk



(Scicluna et al. 2014)

- Key parameters: <Dv>~1km/s, clumps filling factor
- A significant fraction of stars could go through this process
- At any given time we expect at most few %

Summary

- Grain growth in protoplanetary disks
  - We are starting to assemble a consistent picture for solids evolution
  - ALMA+MIR observations will provide unique tests
  - Look at the "freaks": they will provide key tests and insights
- Is Solar System unique?
  - Very common from Exoplanets surveys, but how many like our own?
  - Is SS itself a "freak"? Difficult to believe: need to explain origin!
- Water and prebiotic molecules in disks (and planets)
  - $H_2O/H_2{}^{18}O/HDO$: cold $H_2{}^{18}O$ will be though even for ALMA! HDO ok
  - Possibility of detecting pre-biotic molecules (but watch for weeds in your garden!)
  - Chemical evolution under the effect of the central star!