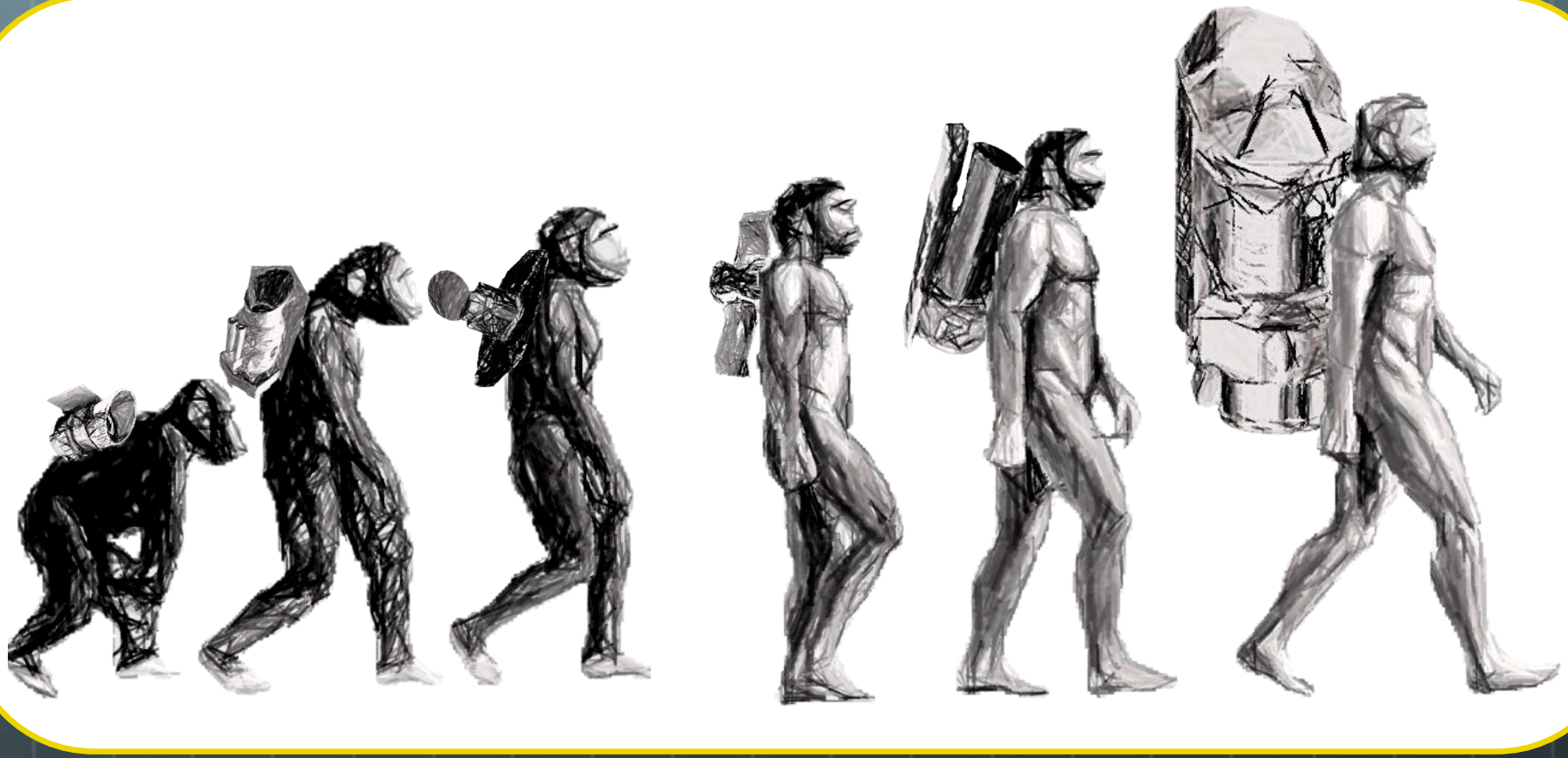
Protoplanetary disks
...before Herschel



Klaus Pontoppidan, Space Telescope Science Institute

A reminder of history

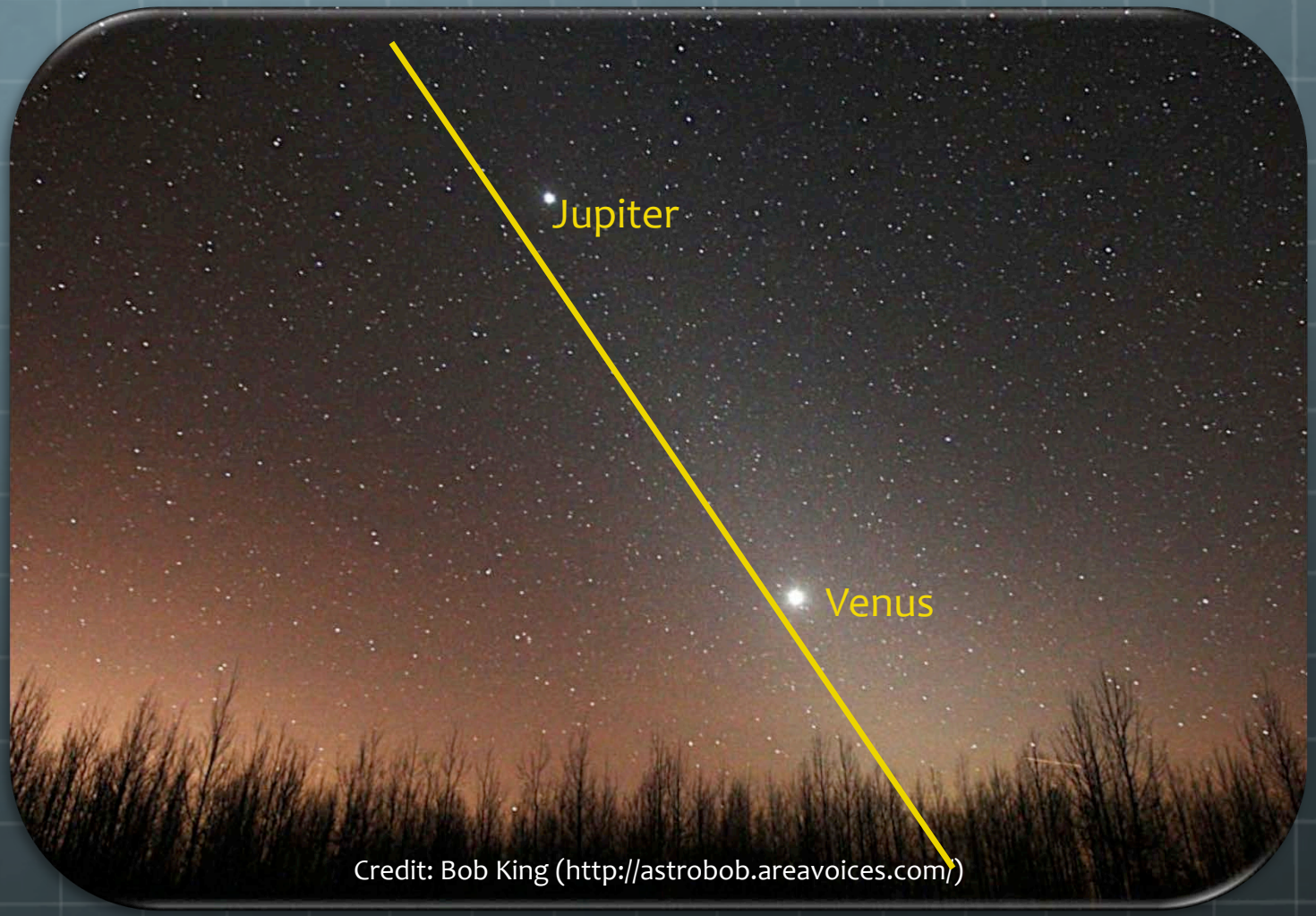
- What were the observational state of planet formation in 1980?
  - Planet formation == formation of the Solar System.
  - Circumstellar disks were thought of as a byproduct of star formation: 1) a requirement for shedding excess angular momentum and 2) a mechanism for accreting material onto the star.
  - A disk was a flat, rotating and gaseous structure of 0.01 Msol, 100 AU, orbiting a single solar-mass star.
  - It was active – i.e., viscously accreting and expanding.
  - There were no direct observations of disks.

"Because the circumstellar material is in the form of a highly flattened disk[,] rather than a spherical shell, it is presumed to be associated with planet formation."

Smith & Terrile 1984

What are we looking for?

Flattened disk-like structures in near Keplerian rotation



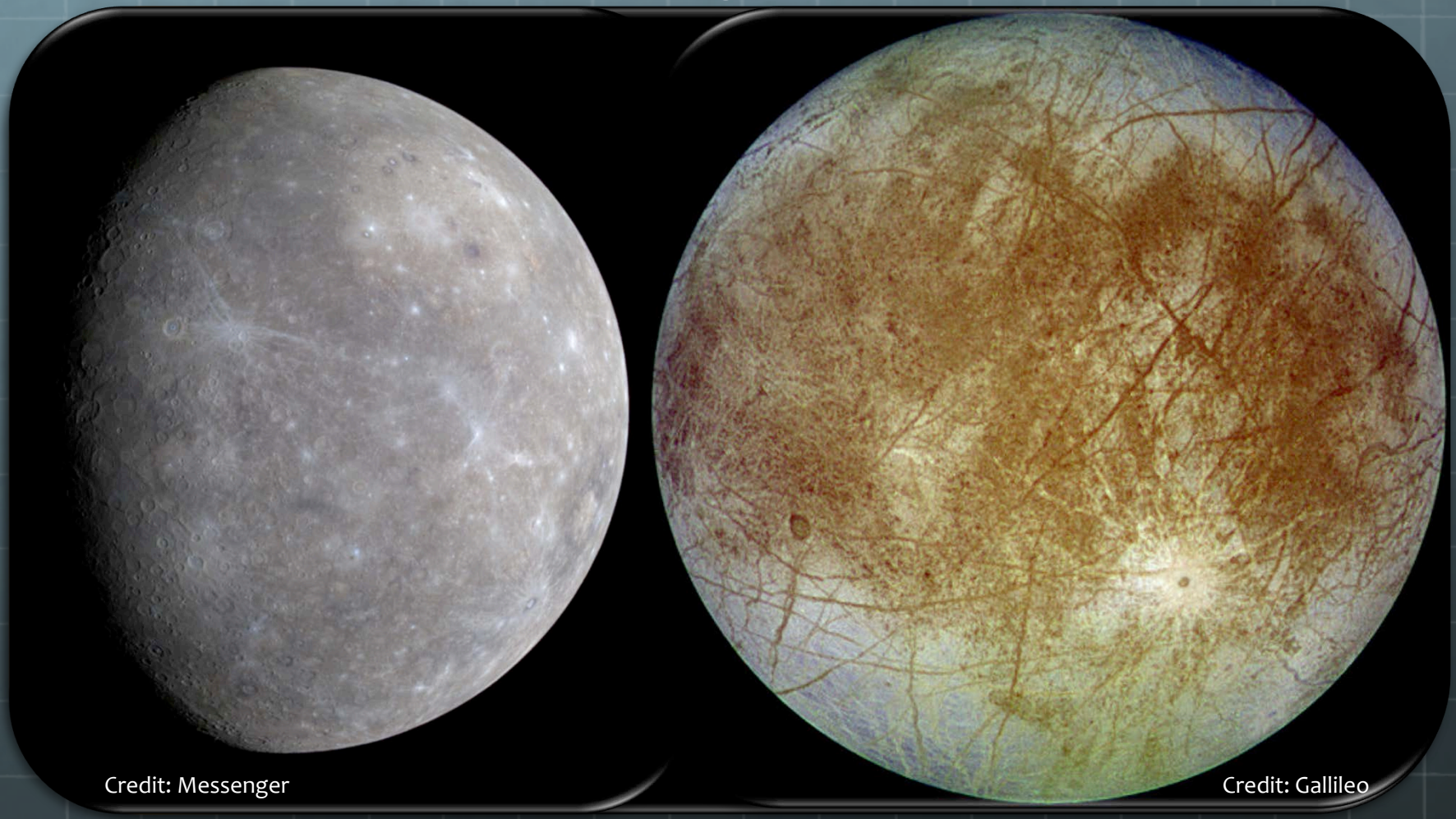
What are we looking for?

Planets forming as part of a parent "protoplanetary disk"

Credit: Michael Stegina/Adam Block/NOAO/AURA/NSF

What are we looking for?

Radial chemical gradients

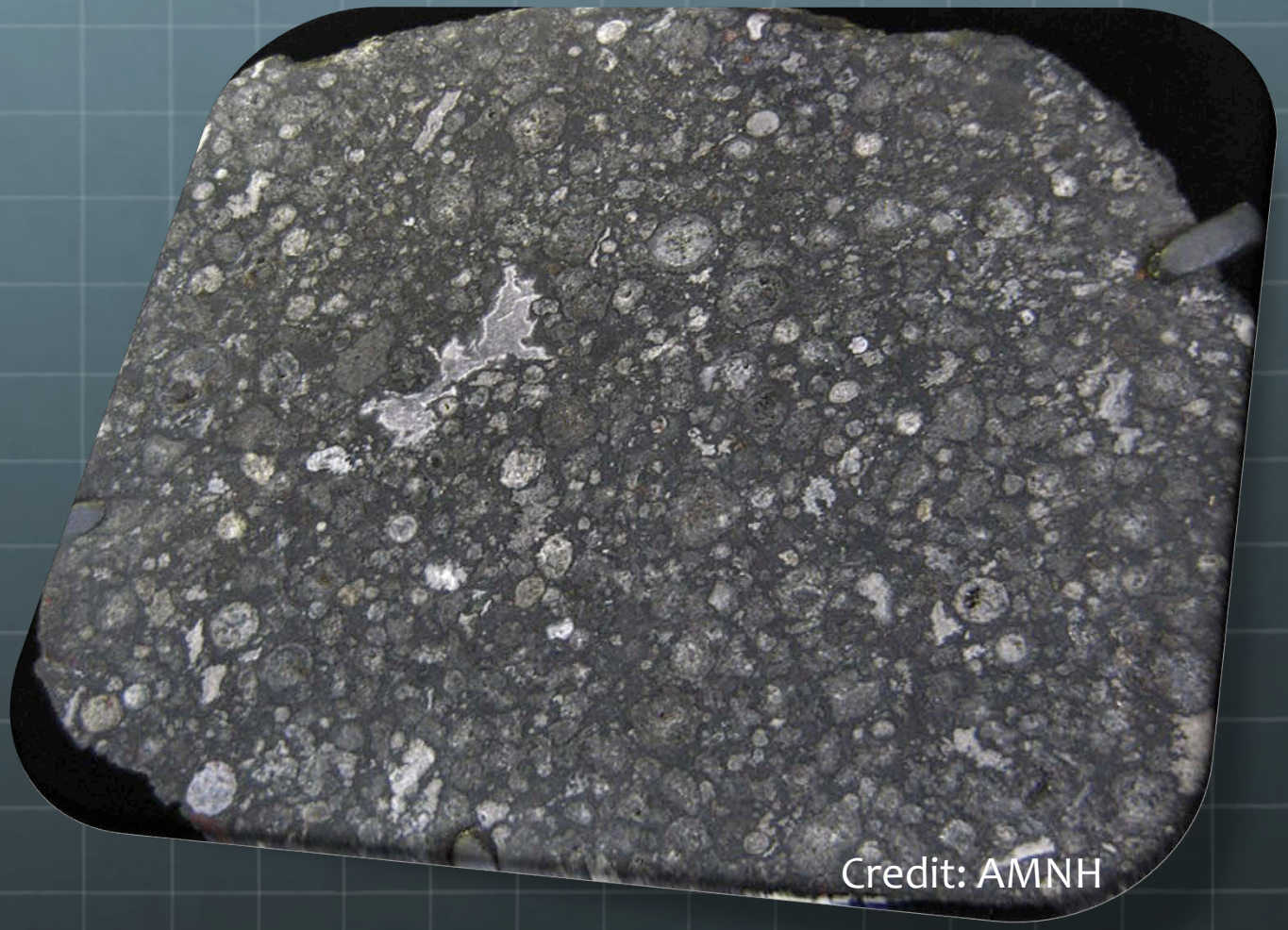


Credit: Messenger

Credit: Gallileo

What are we looking for?

An energetic environment in the inner few AU



Credit: AMNH

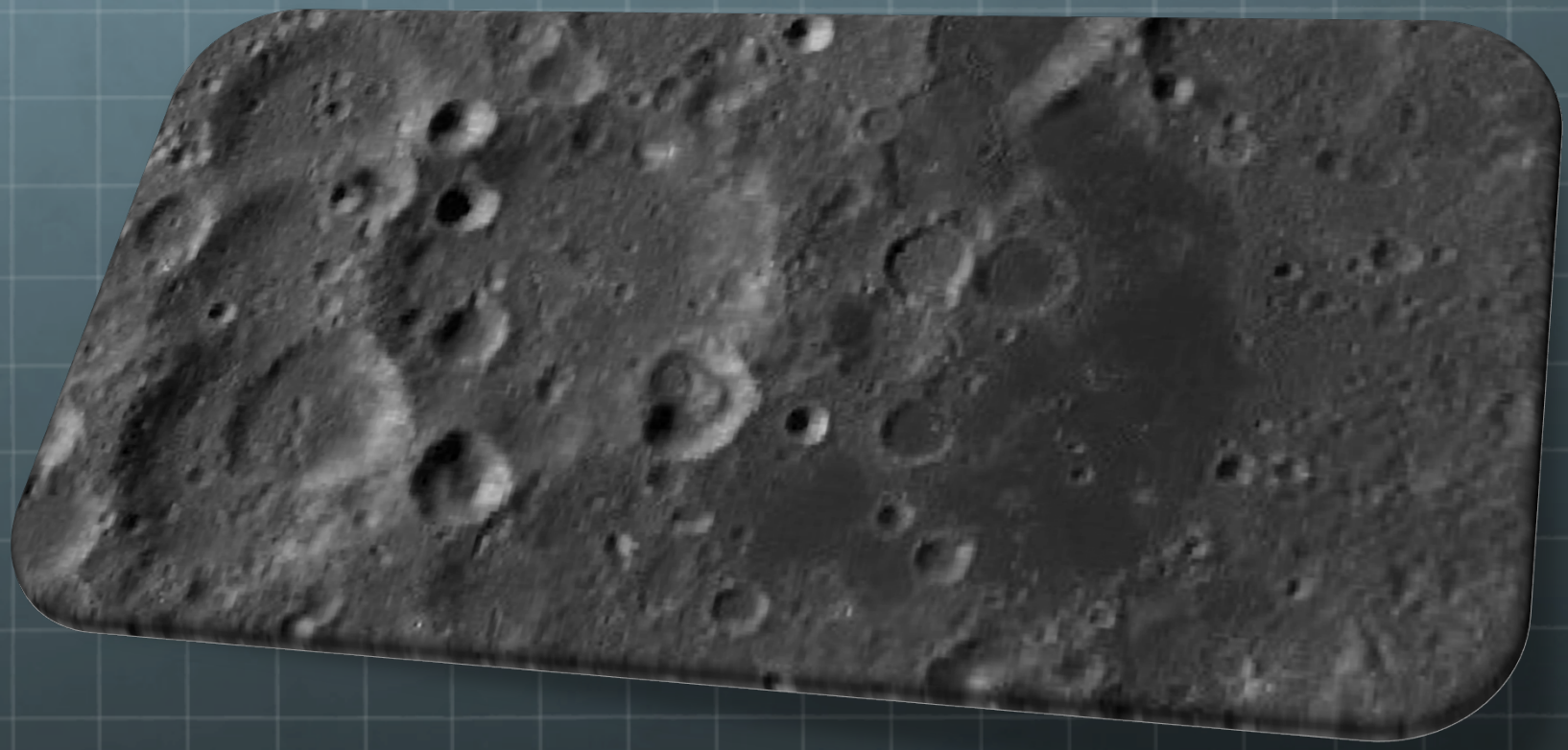
What are we looking for?

A gas-rich environment (at least initially)

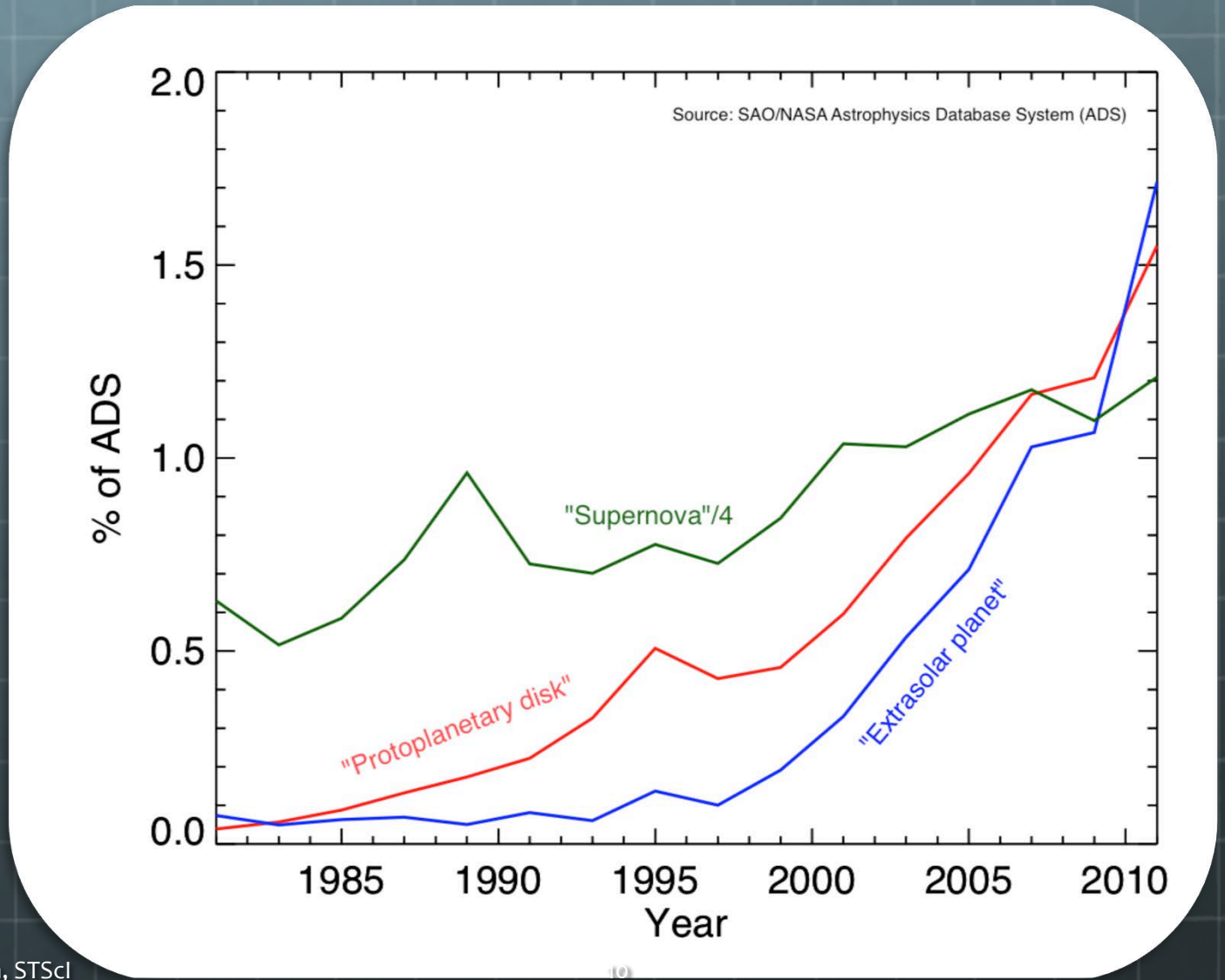
Credit: Cassini

What are we looking for?

Hierarchical growth



Two decades of protoplanetary disks



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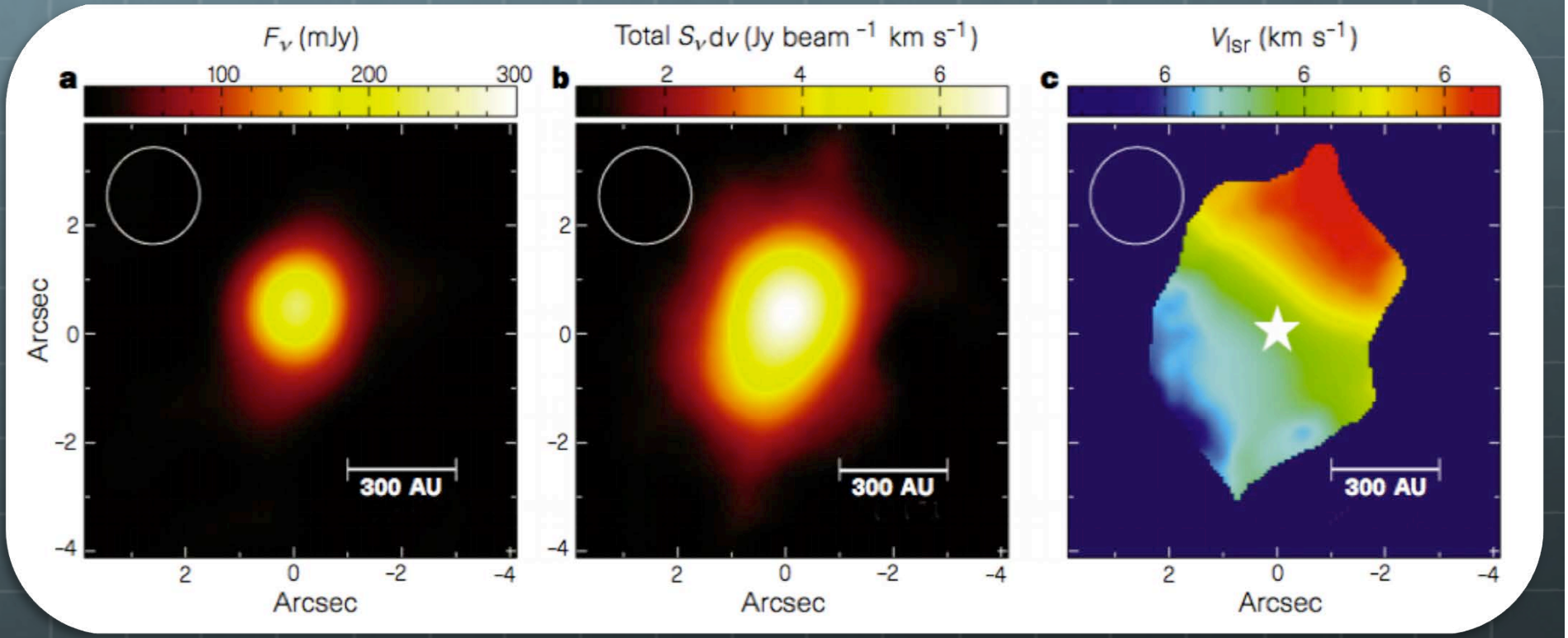
Key questions – before Herschel

	Solar System	Exoplanetary Systems	Protoplanetary disks
Time scale for giant planet formation/disk dispersal	~5 Myr	Long enough	~5 Myr
Frequency of planet formation	1/1	>2/10	>1/100?
Mechanism for planet formation	Core accretion + oligarchic growth	Both core accretion and grav. instability.	Growth tracked up to ~1 cm.
Evolution of orbital structure	Planet-planetesimal interactions?	Planet-gas disk interactions?	Planet-gas disk interactions?
Availability of water and organics	Abundant beyond 3 AU	water is present in some atmospheres	Abundant inside 1 AU
Chemical history: complete reprocessing or modifying the ISM?	Complete reprocessing at 3 AU, ISM inheritance in comets?	Constraints from white dwarf contamination (carbon deficit).	Some reprocessing.
Magnitude of disk turbulence	Planets exist	Planets exist	Indirect evidence using accretion rates of 10^{-7}-10^{-10} Msol/yr

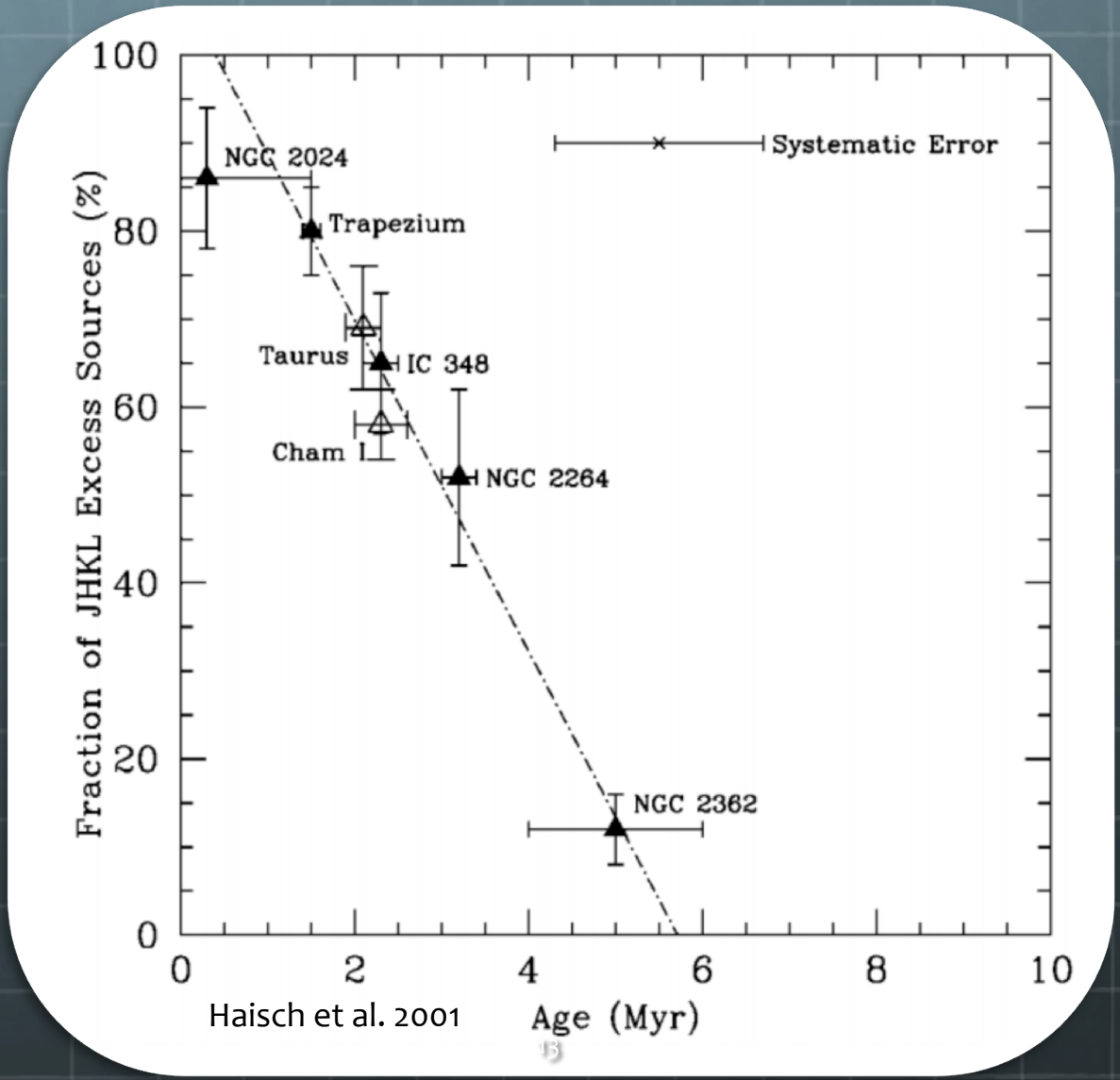
Existence of protoplanetary disks



Mannings et al. 1997

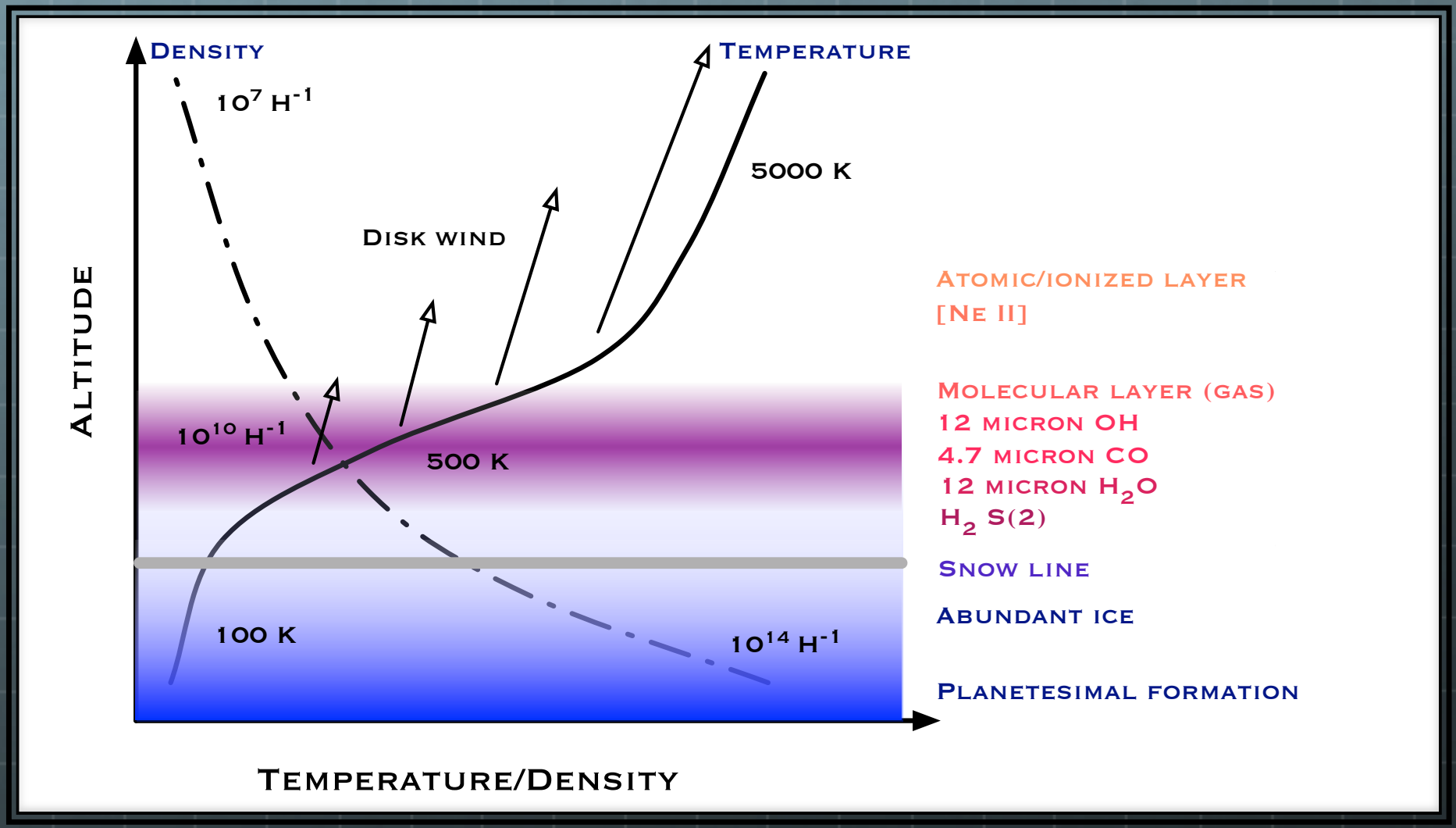
Disk lifetime

The lifetime of a protoplanetary disk is a few million years



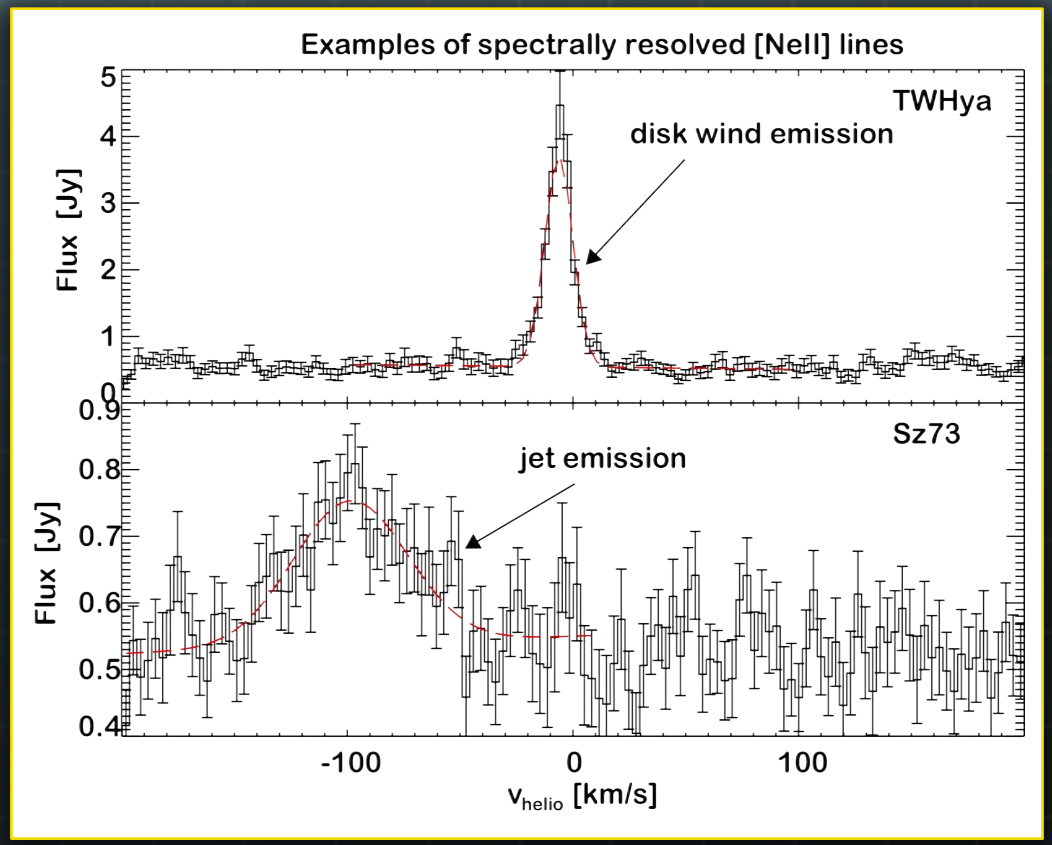
Haisch et al. 2001

Dispersal mechanism

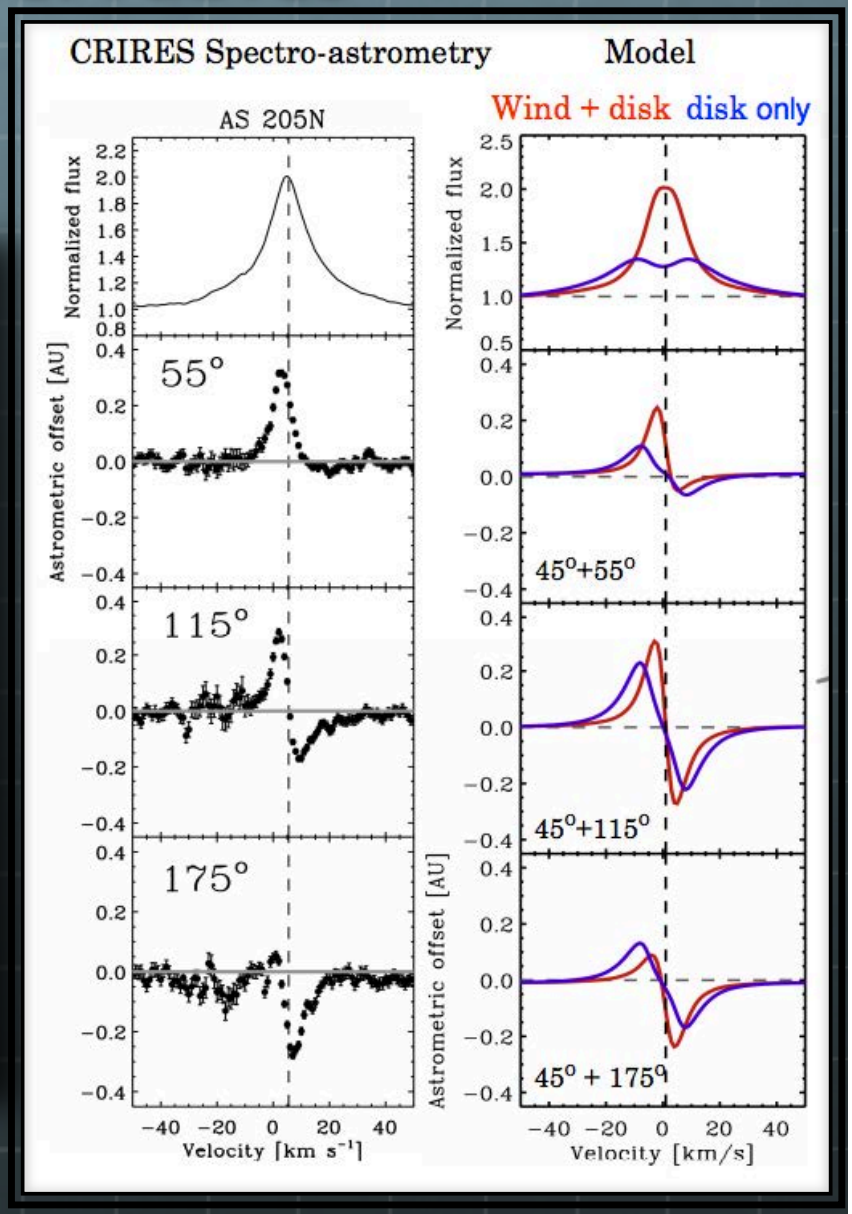


e.g., Hollenbach et al. 2000, Alexander et al. 2006

Disk wind observables

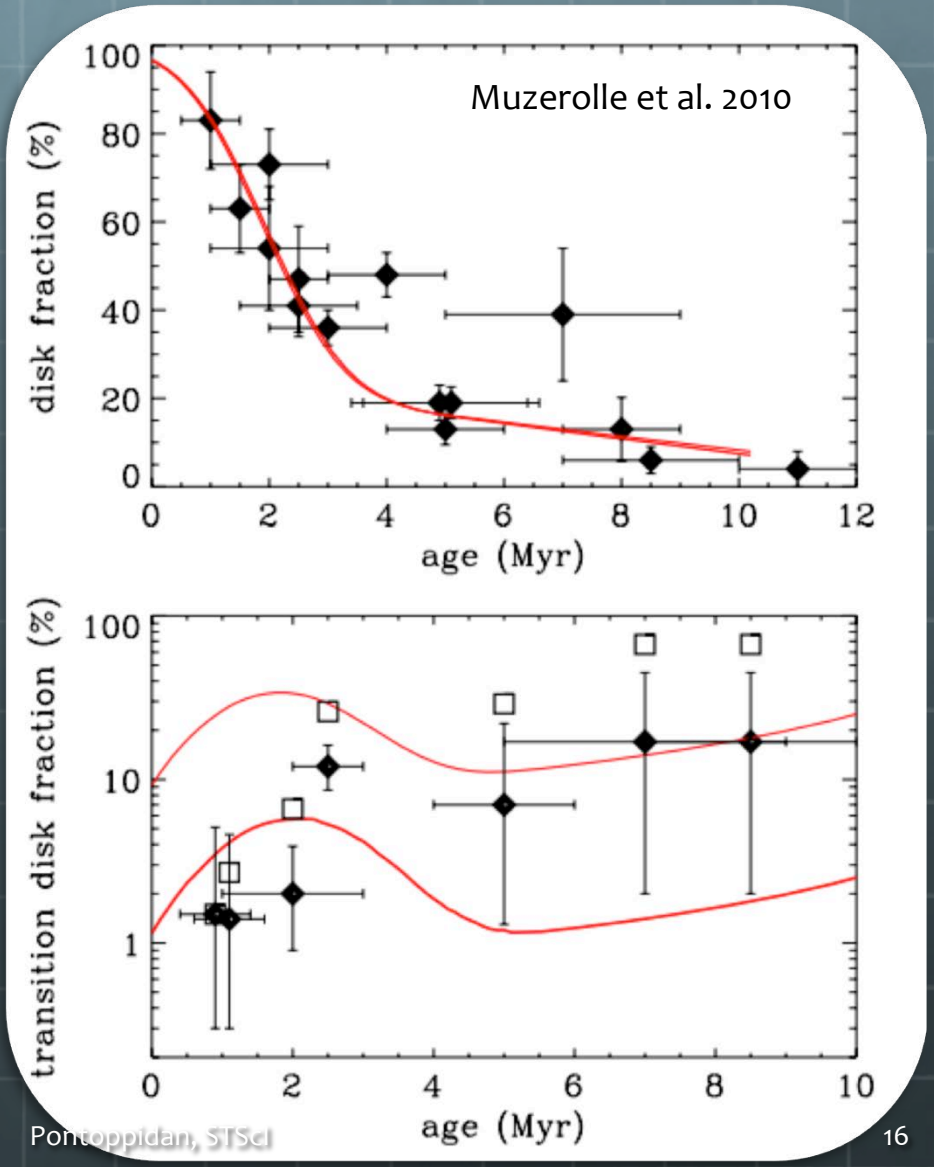


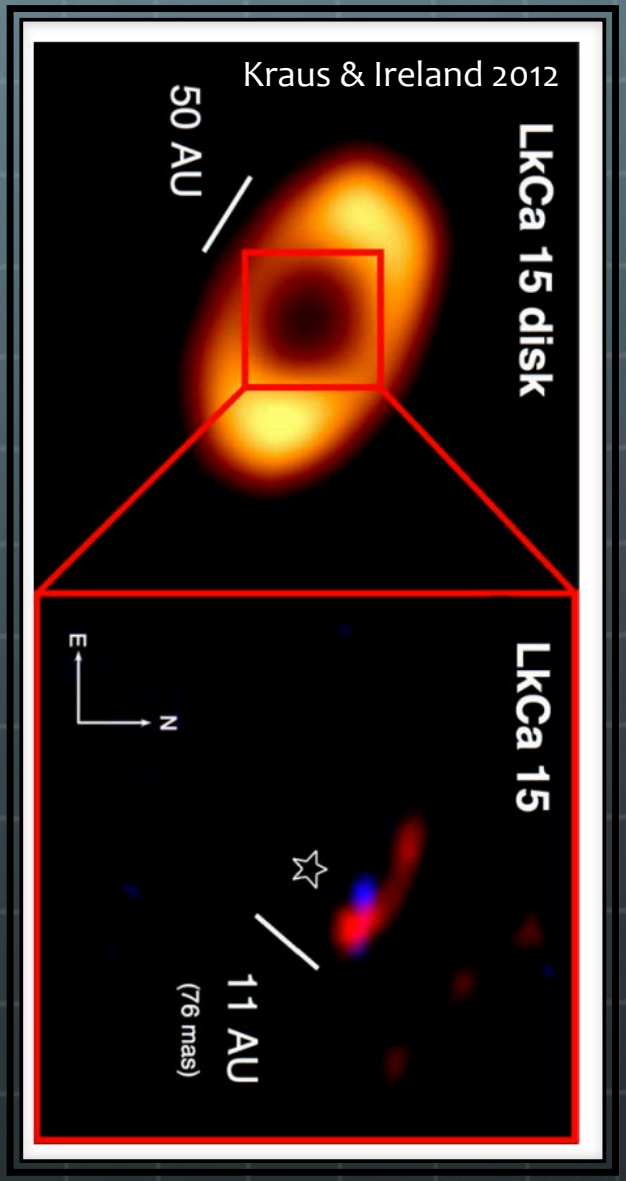
Pascucci & Sterzik 2009



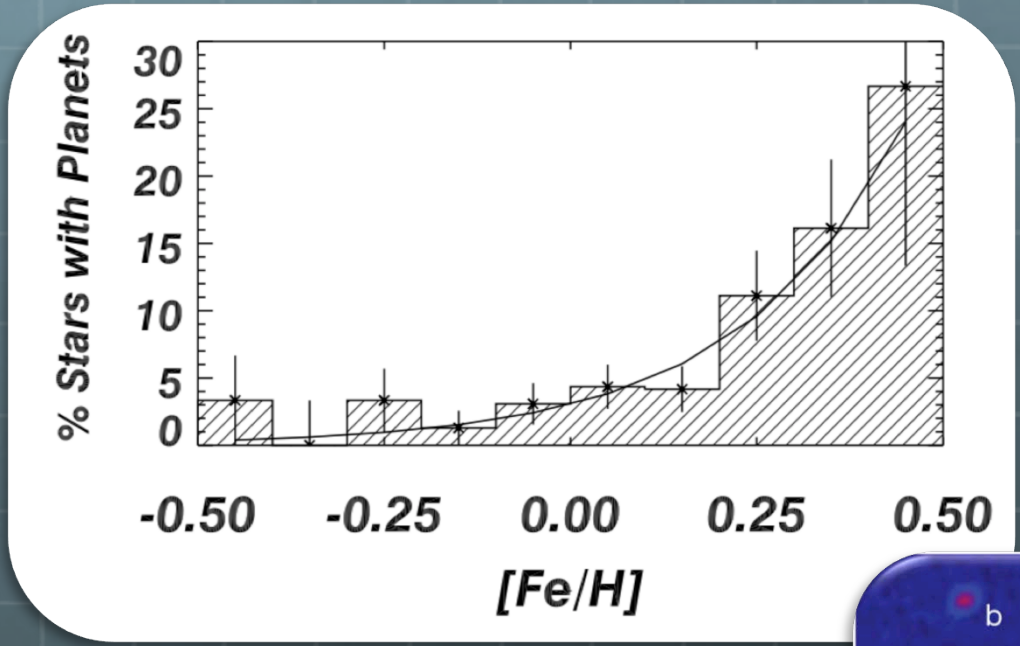
Pontoppidan et al. 2011

Frequency of planet formation





Planet formation mechanisms

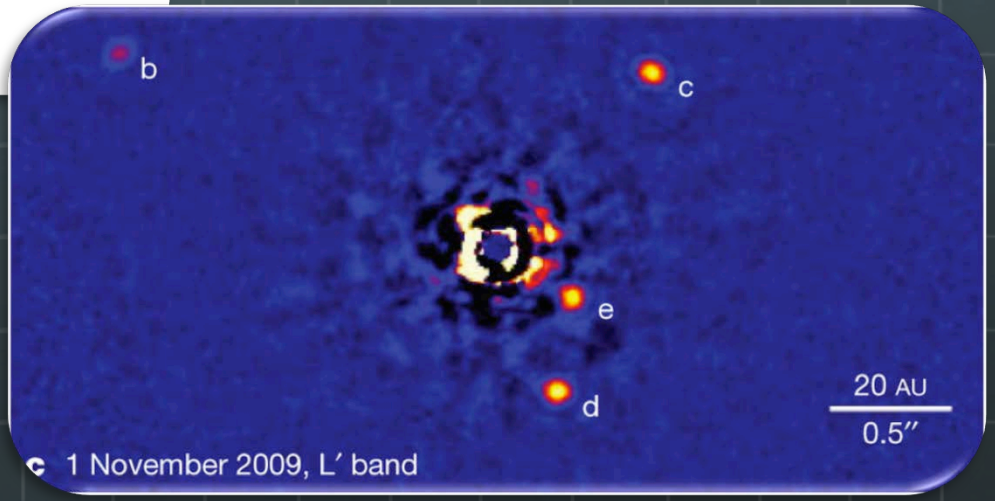


Fischer & Valenti 2005

Gravitational instability?

Boss 1997

Marois et al. 2010



Core accretion?

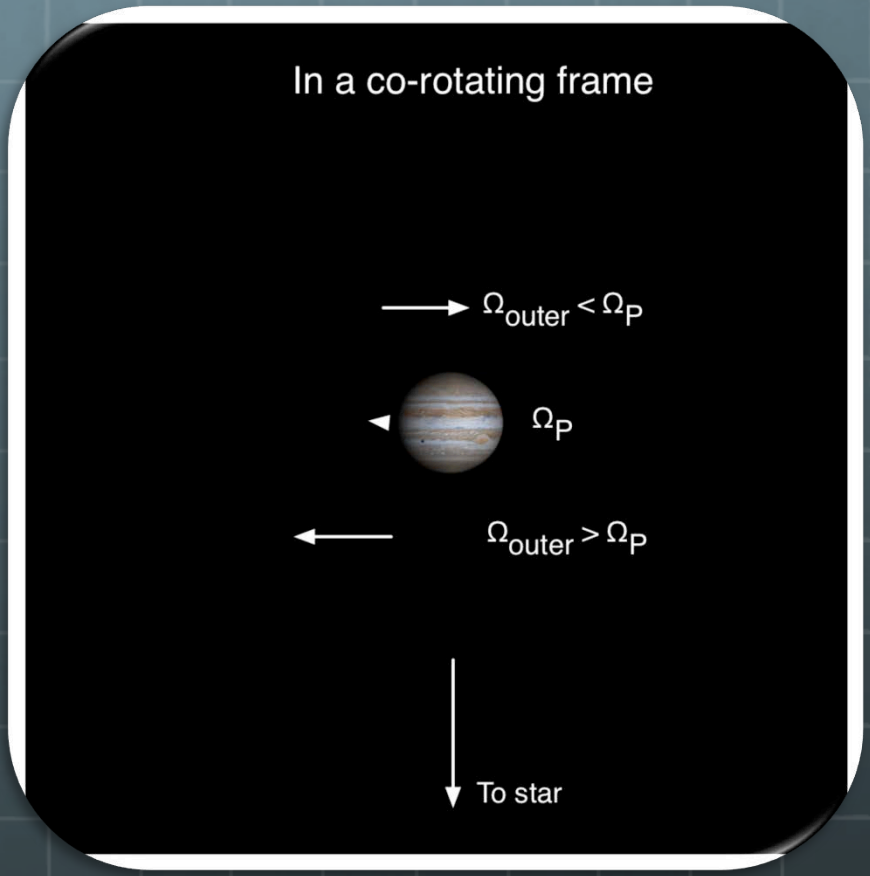
Pollack et al. 1996

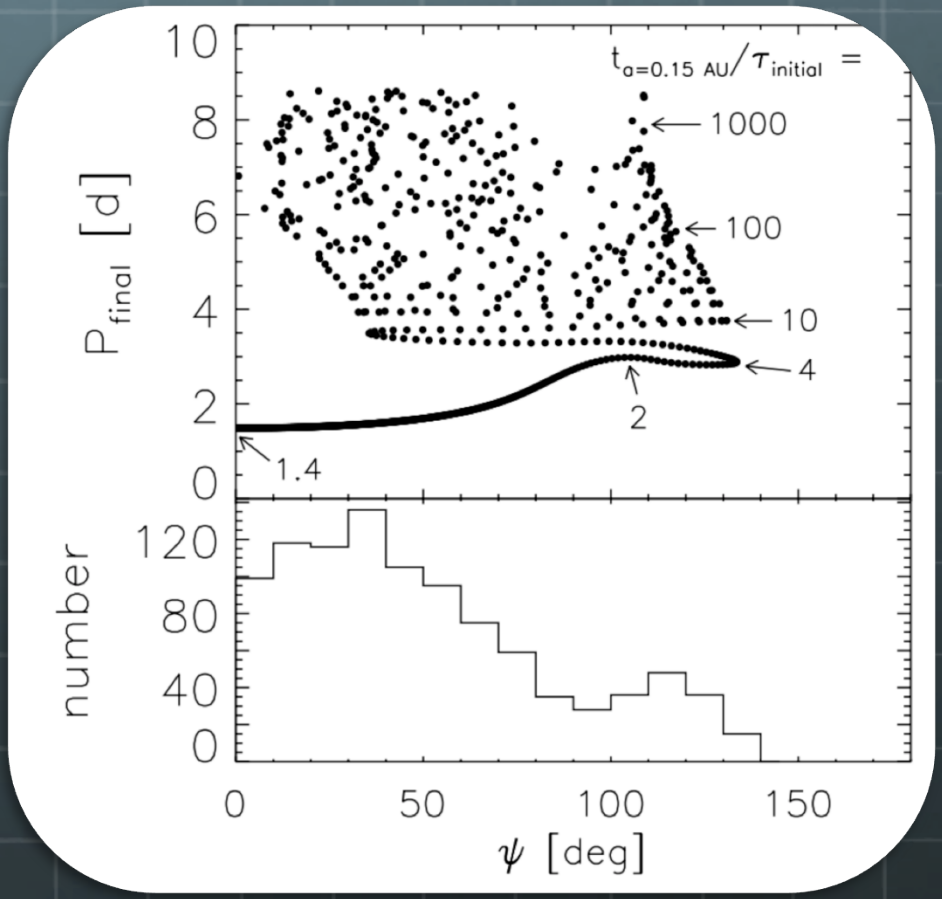
Evolution of planetary orbits

Planet-disk angular momentum exchange (migration)

OR

Kozai cycles with tidal friction

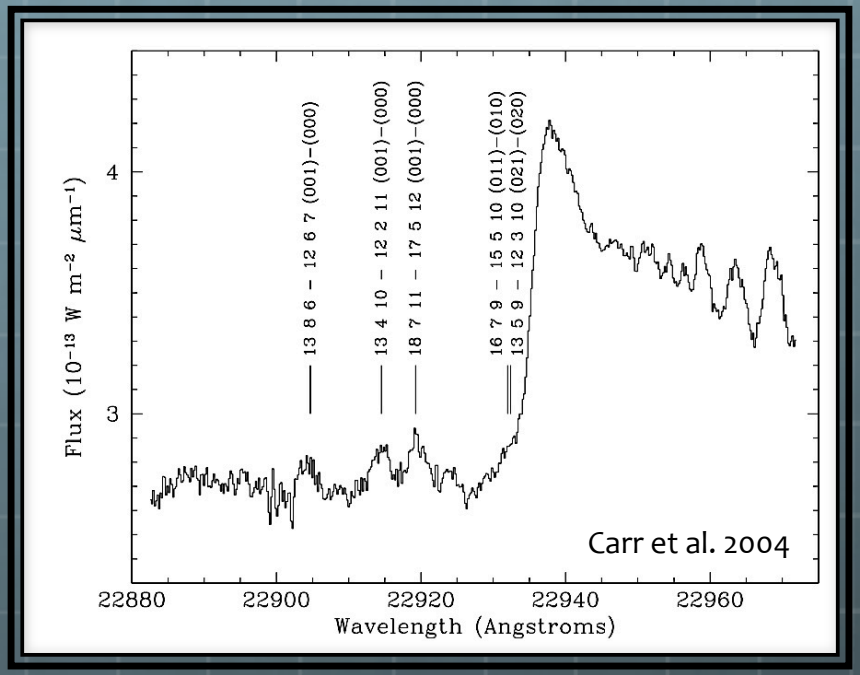




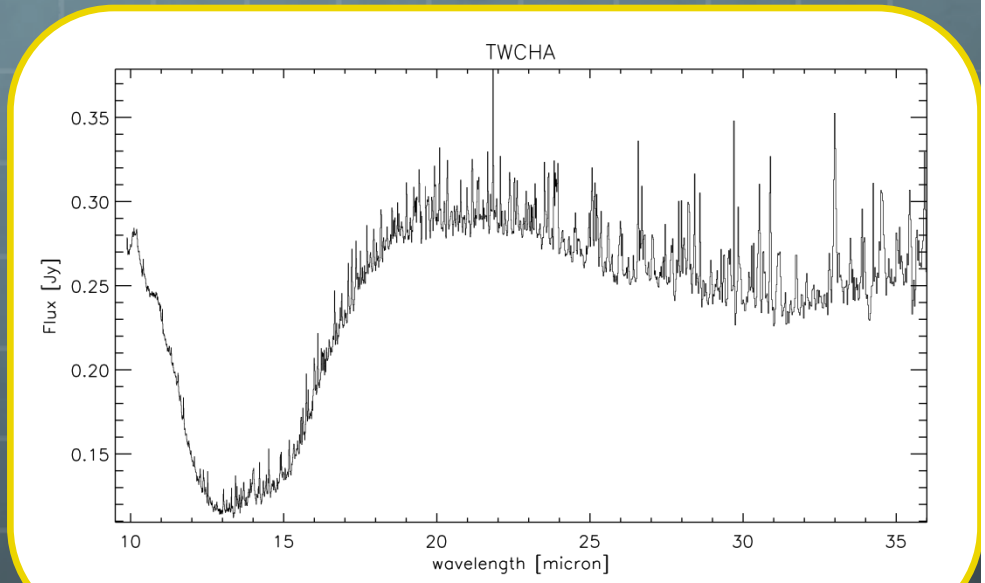
e.g., Goldreich & Tremaine 1980

Fabrycky & Tremaine 2007

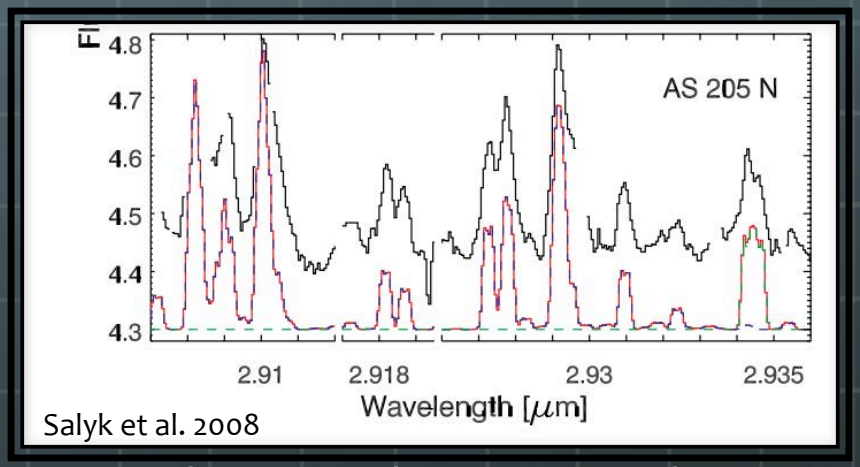
Availability of water and organics



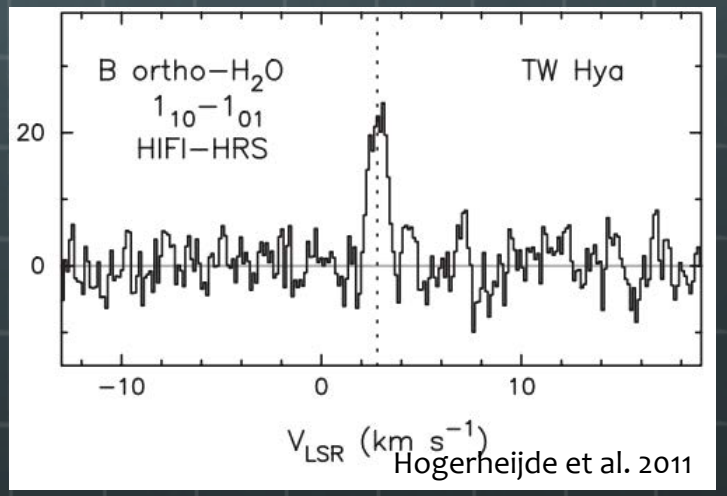
Carr et al. 2004



Pontoppidan et al. 2010



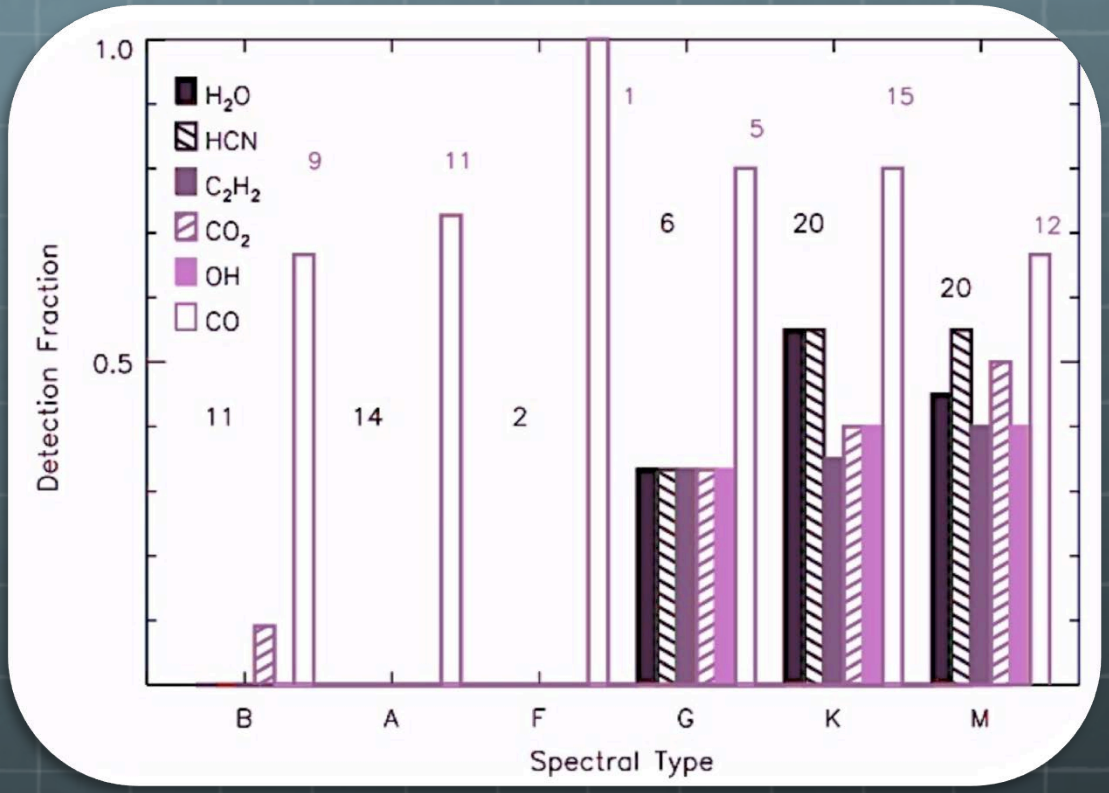
Salyk et al. 2008



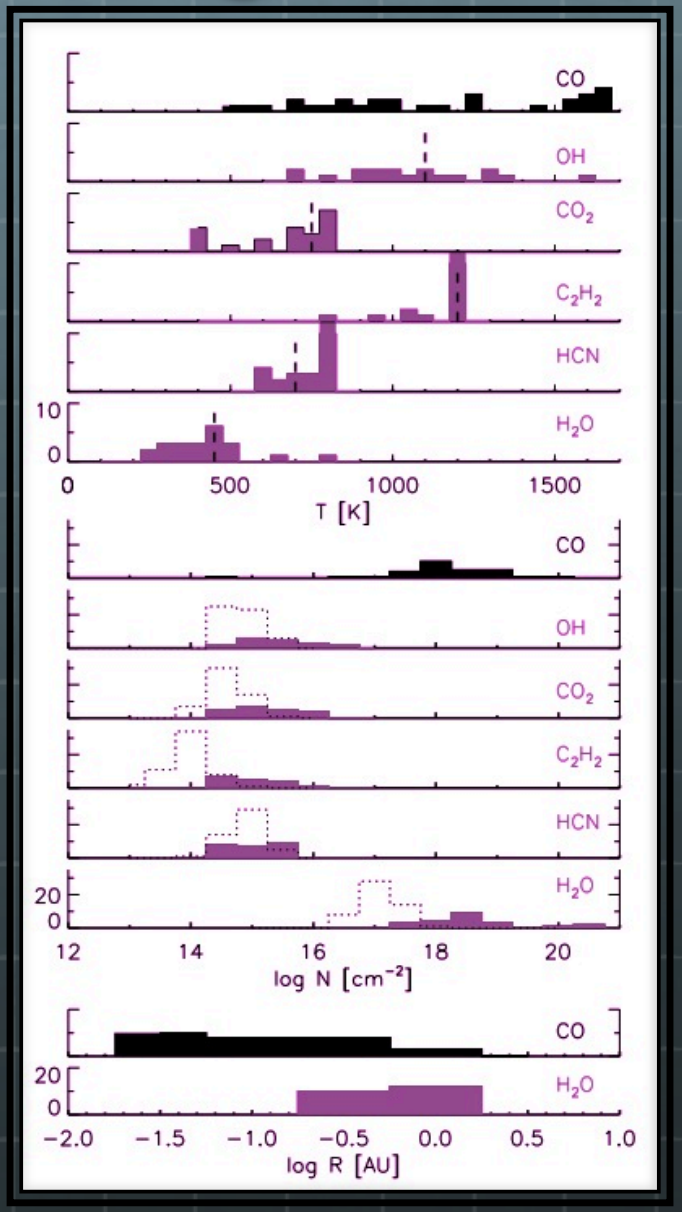
Hogerheijde et al. 2011

See also posters by Banzatti et al. , Kamp et al., Meeus et al., Riviere-Marichalar

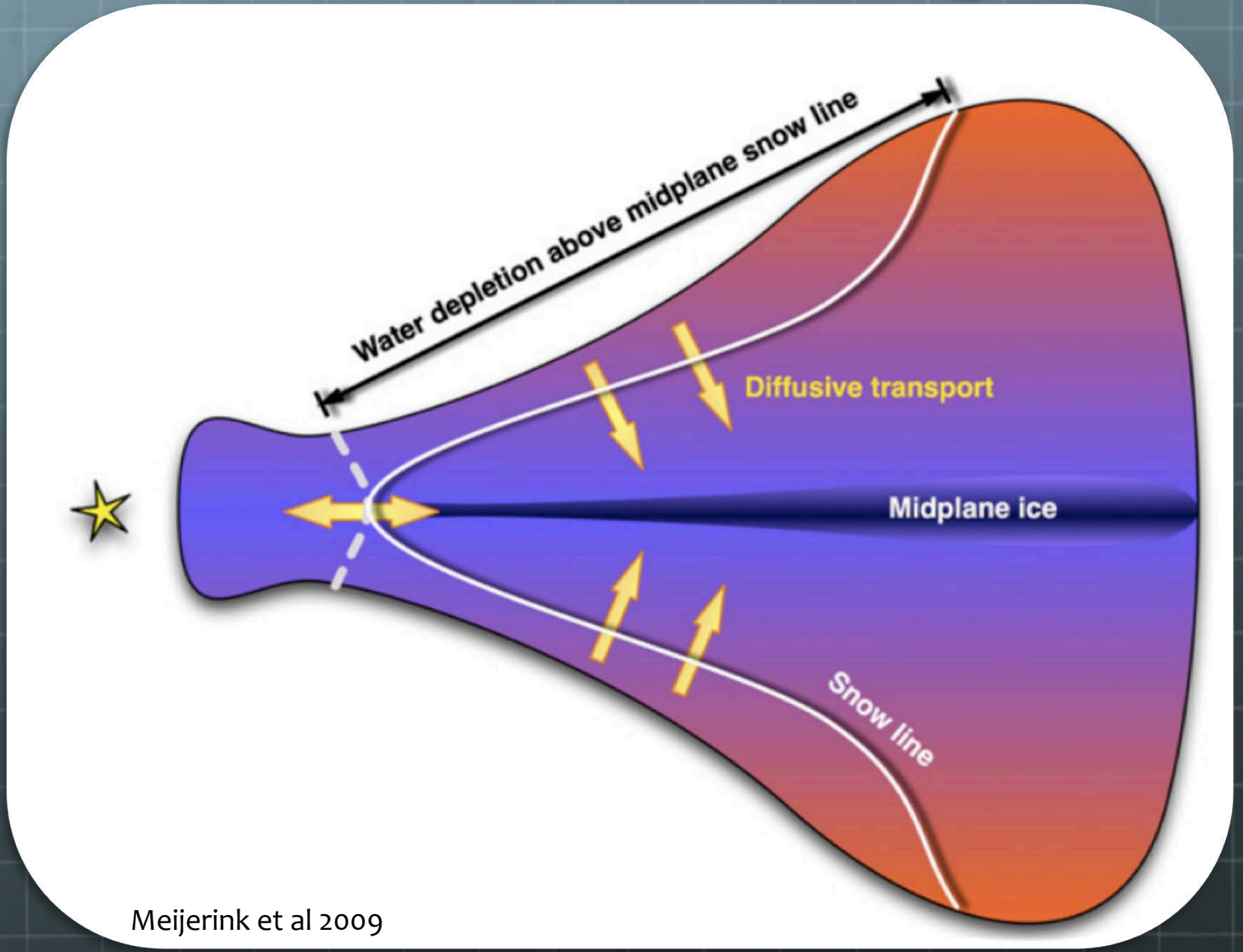
Availability of water and organics



Pontoppidan et al 2010, Salyk et al 2011

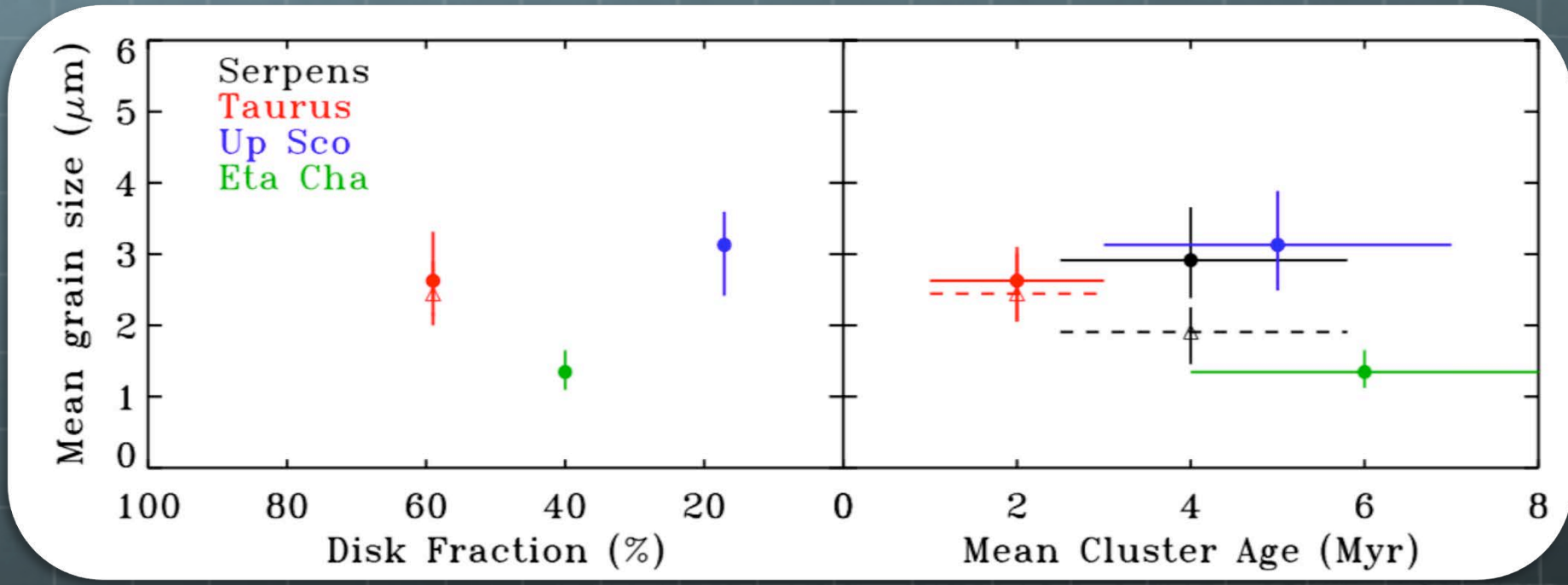


Availability of water and organics



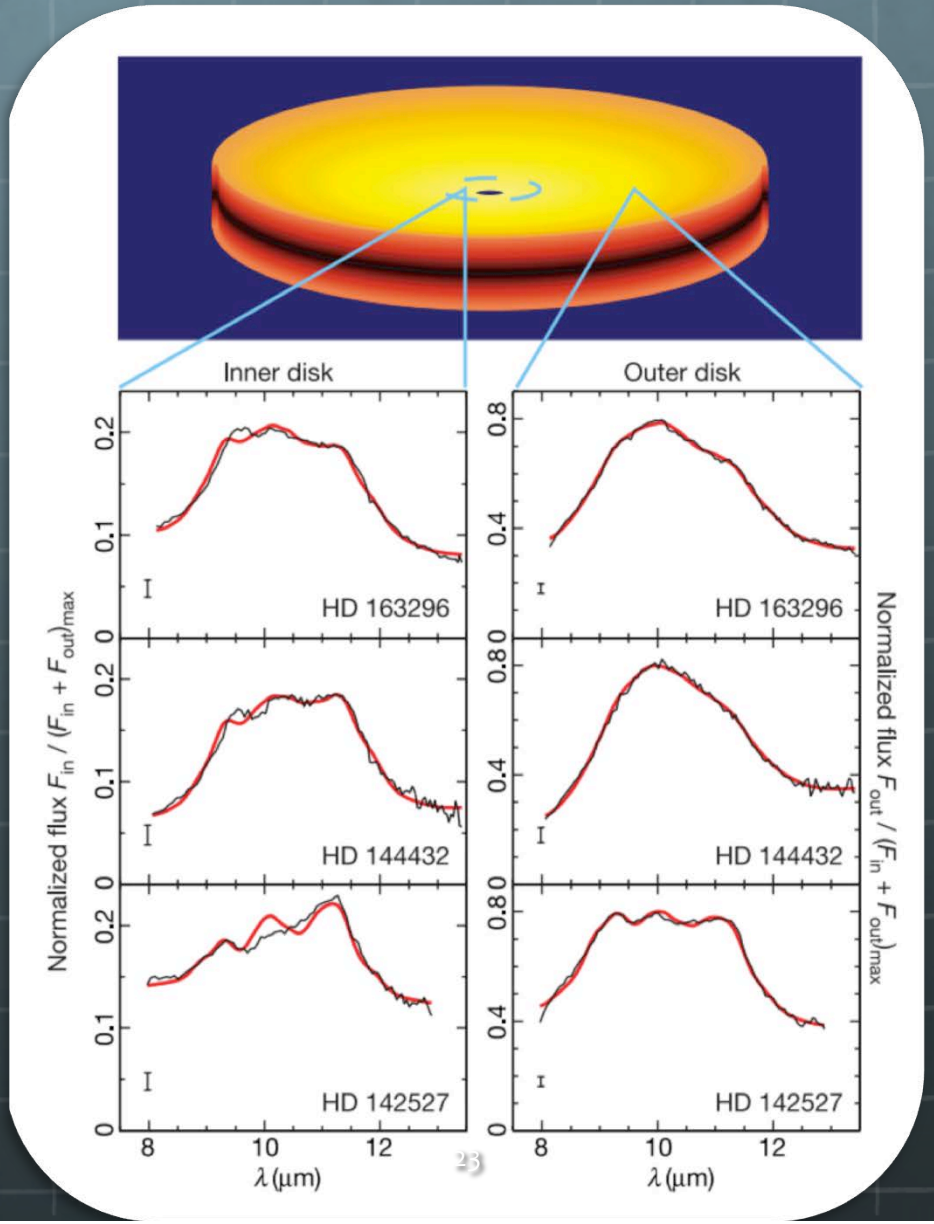
Meijerink et al 2009

Dust history



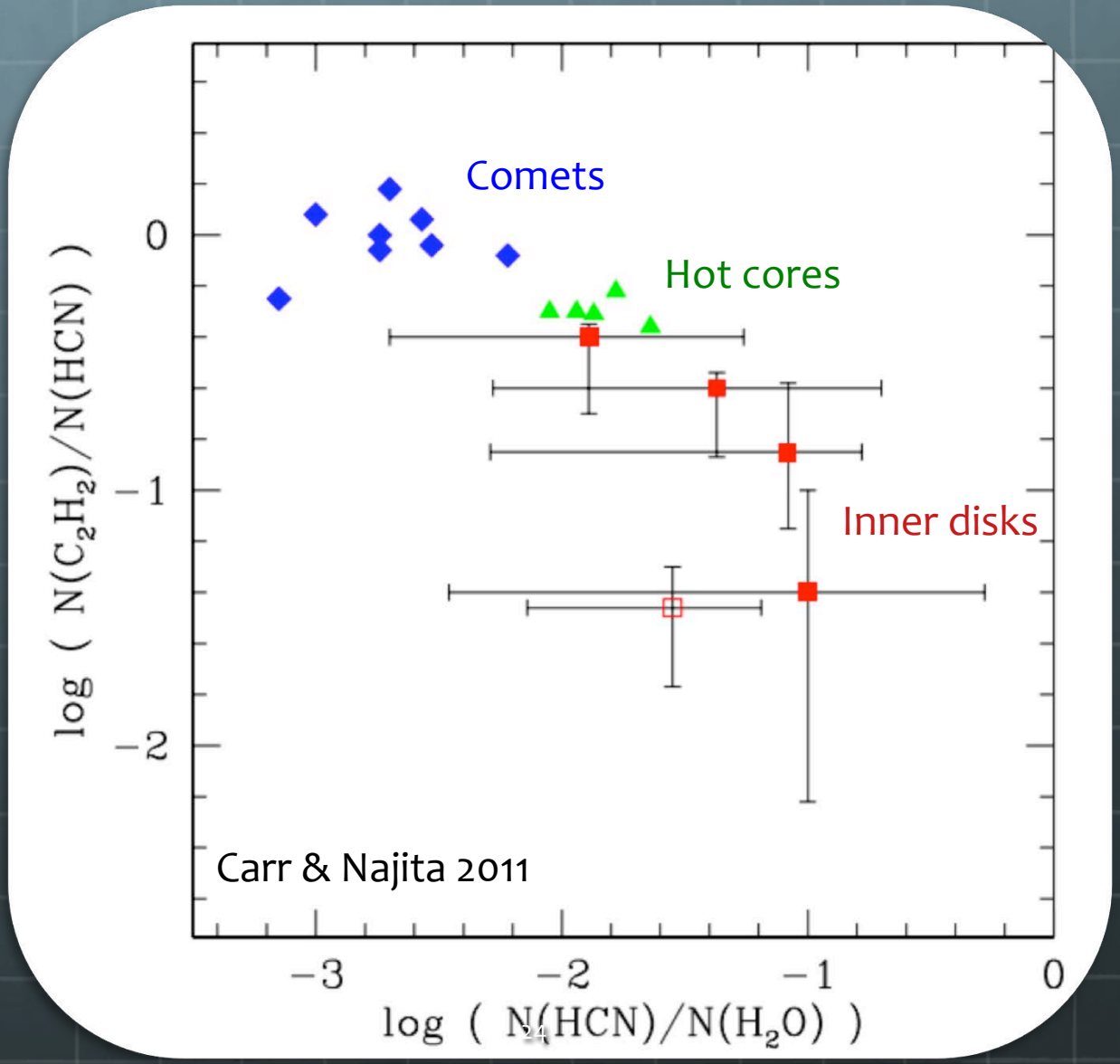
Oliveira et al. 2011

Dust history

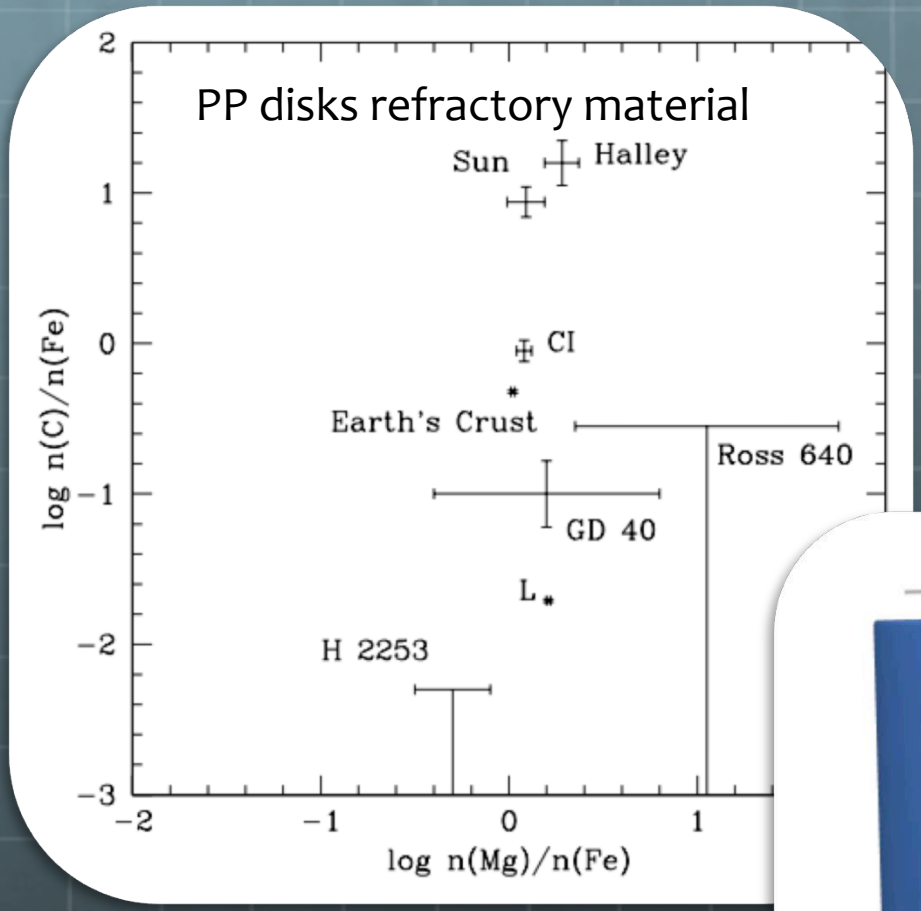


van Boekel et al. 2004

Chemical history

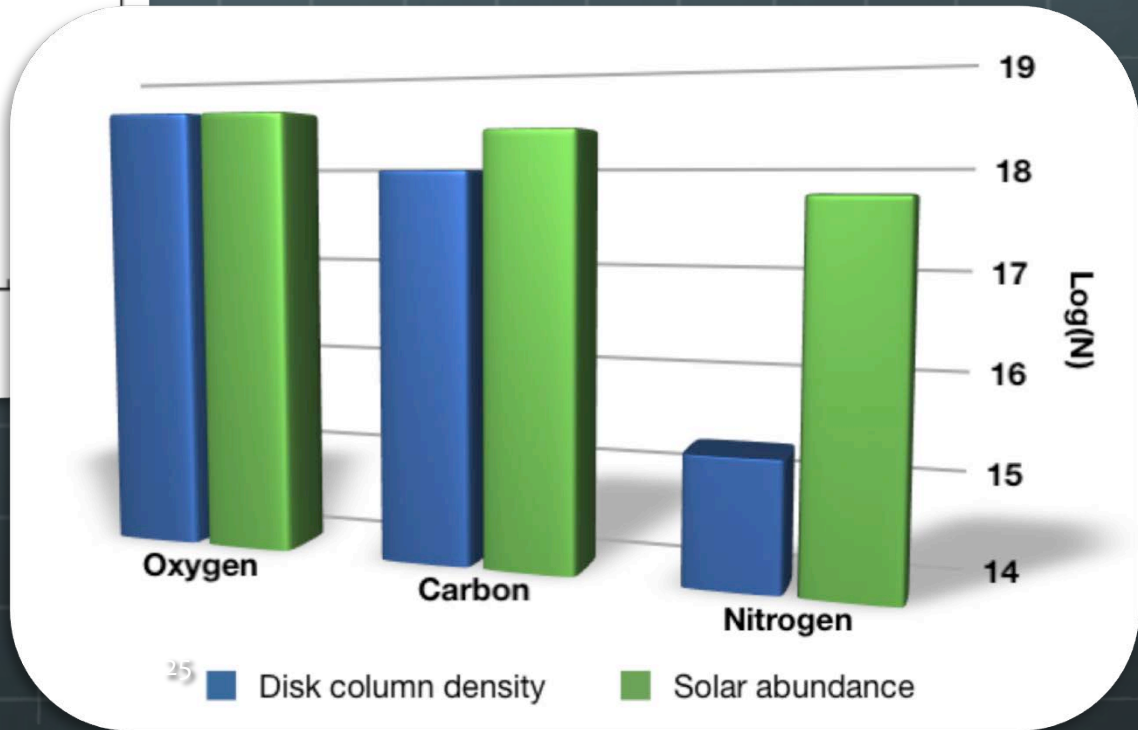


Chemical history



Jura 2006

PP disk gas



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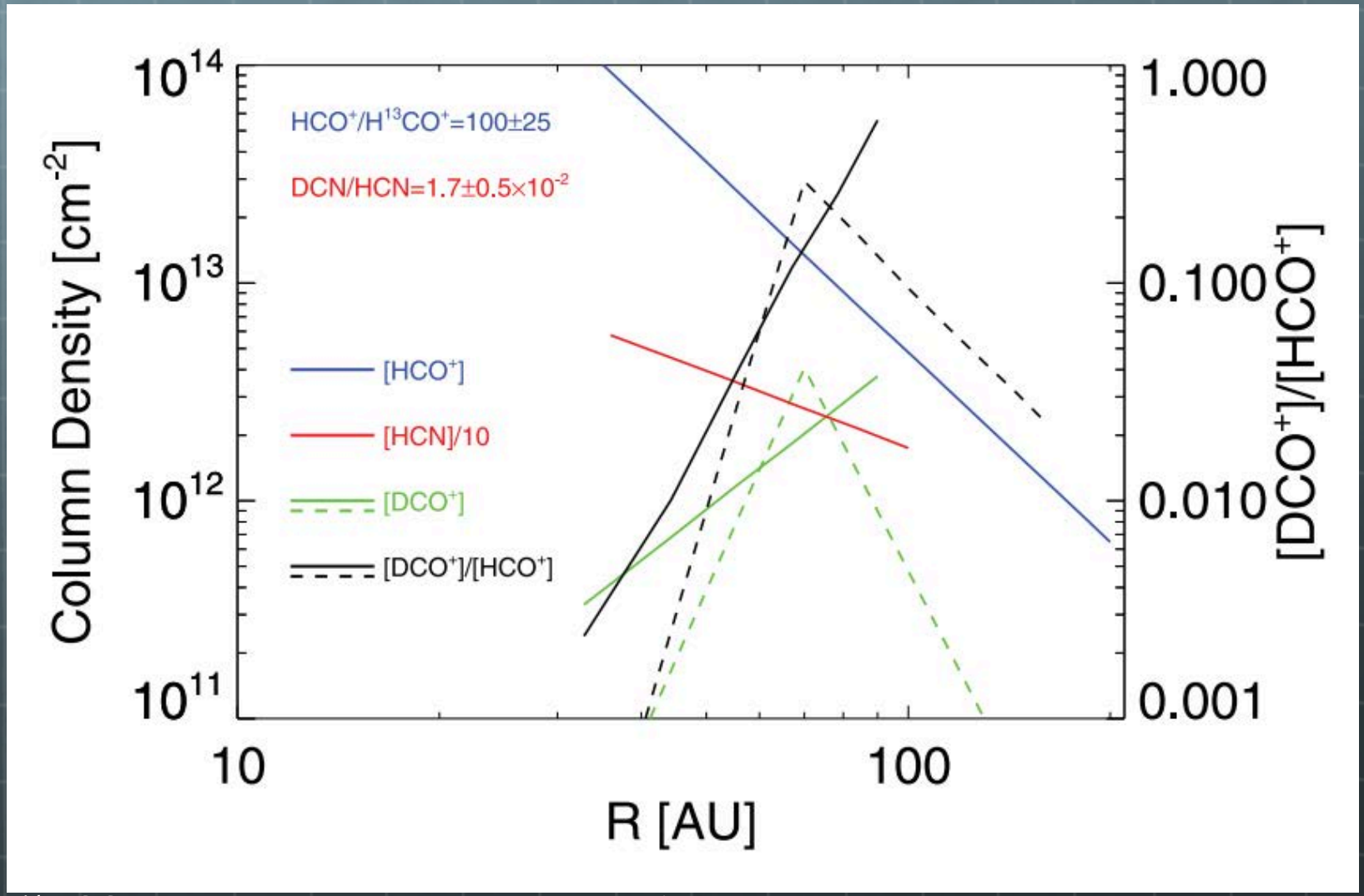
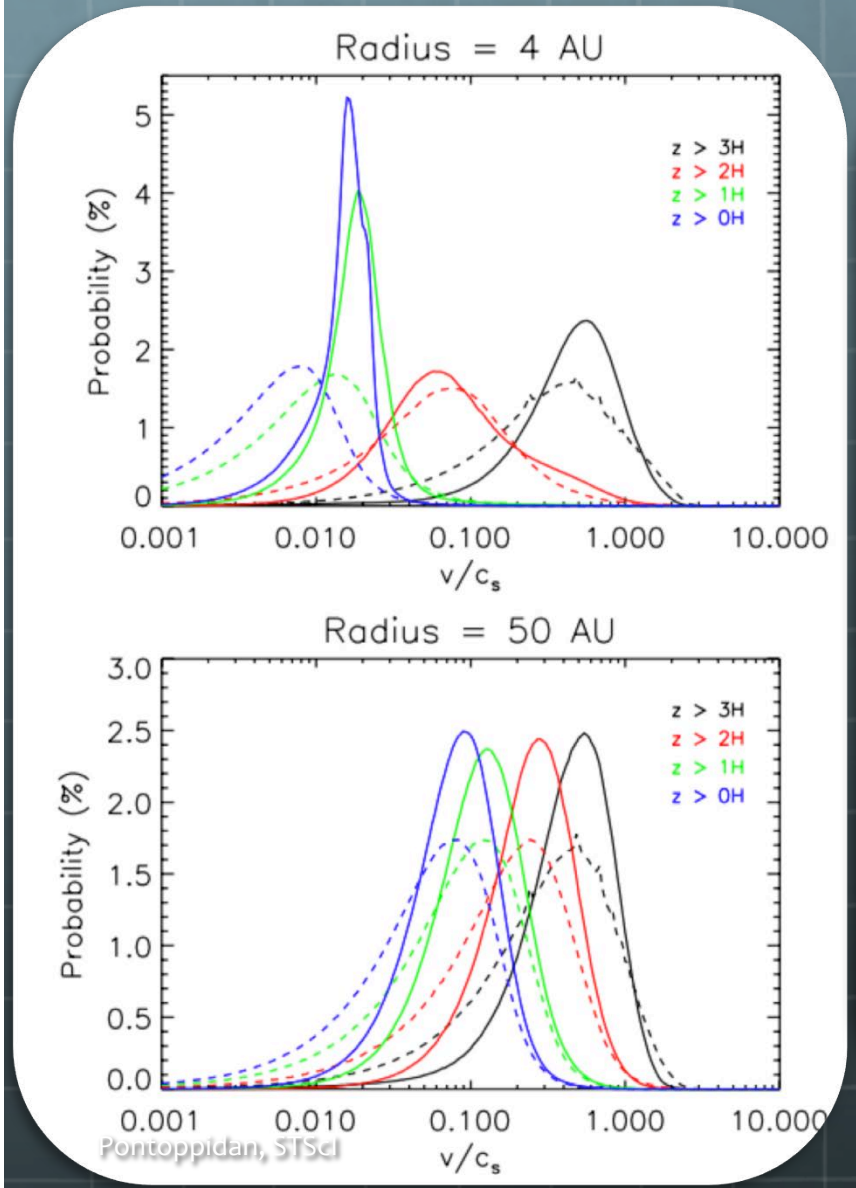
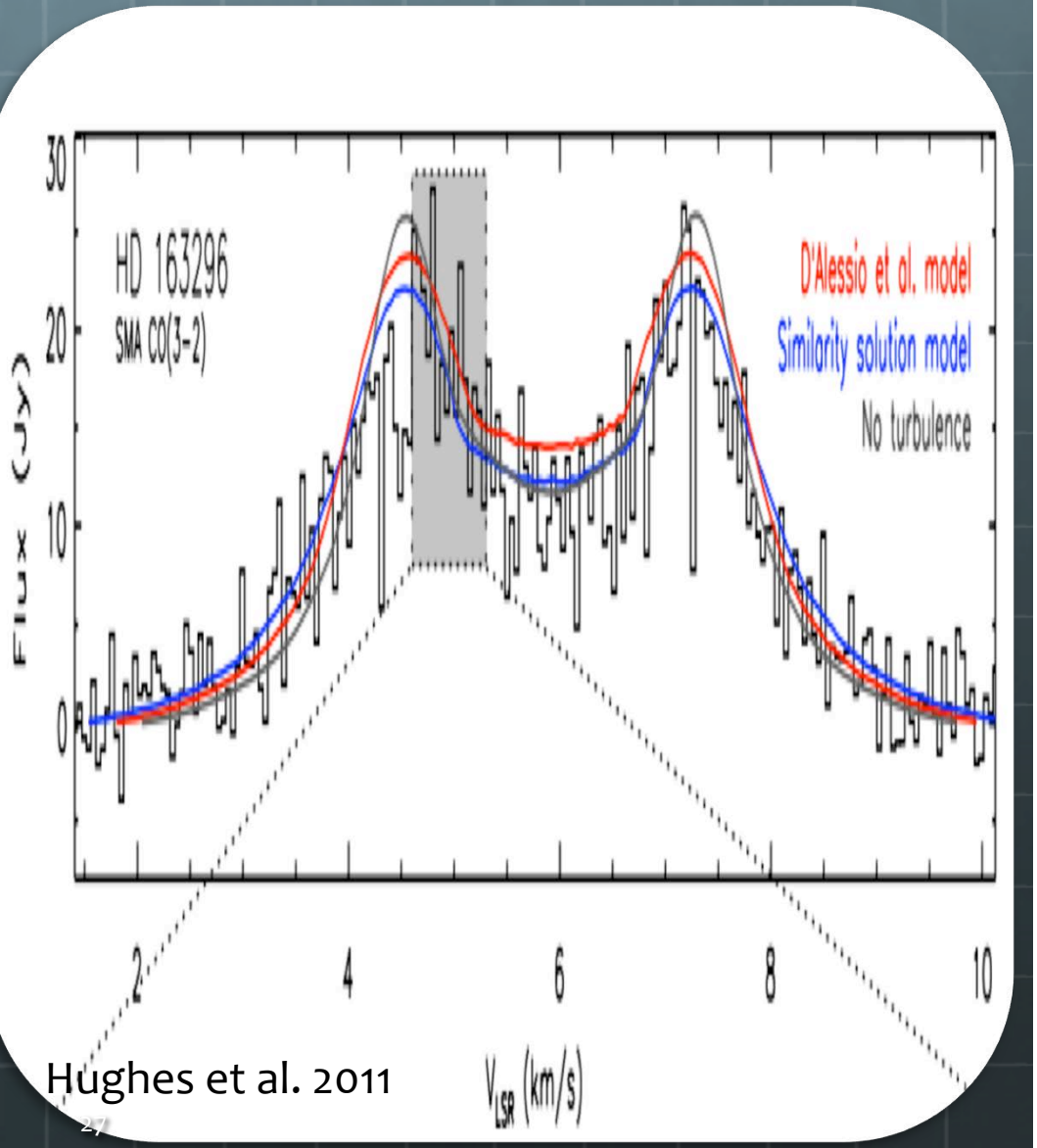
Chemical history



Disk turbulence

Armitage et al. 2011





Hughes et al. 2011

Recap

- The observational study of protoplanetary disks is in rapid growth.
- The key questions have become clear:
  - Timescale and existence of different types of planet formation.
  - Chemical structure on 0.1-100 AU scales (and its relevance for astrobiology).
  - Dynamic evolution.
- Herschel is likely to make fundamental contributions to all of these subjects.