From dust and molecules to planets
The ALMA revolution

Ewine F. van Dishoeck

Leiden Observatory, The Netherlands / MPE

Thanks to many colleagues and collaborators for input

(i.p. Michiel Hogerheijde, Sean Andrews)

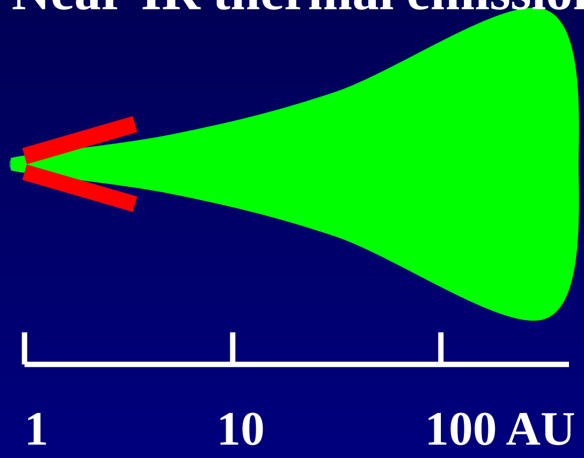
ALMA is producing fantastic results, even at early stage!

-200 astronomers each in Hakone Japan and Puerto Varas Chile late 2012 presenting a wealth of exciting data; quality excellent

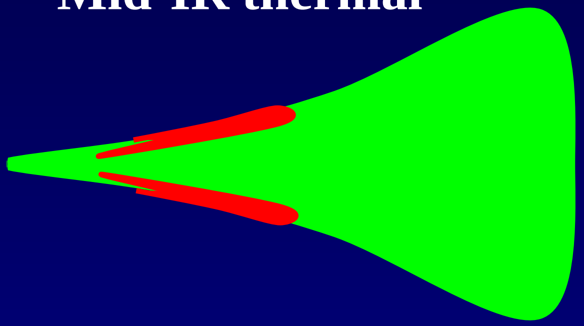
Thanks to the ALMA staff and everyone who made this possible!

Mm vs IR: probing different parts of disks

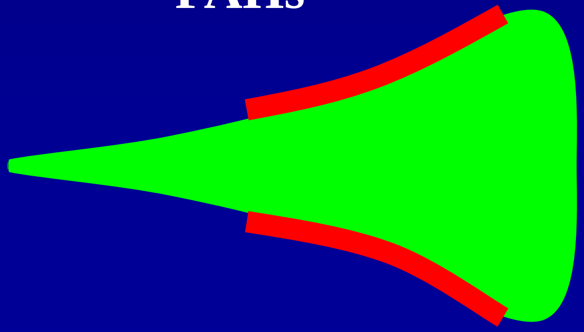
Near-IR thermal emission



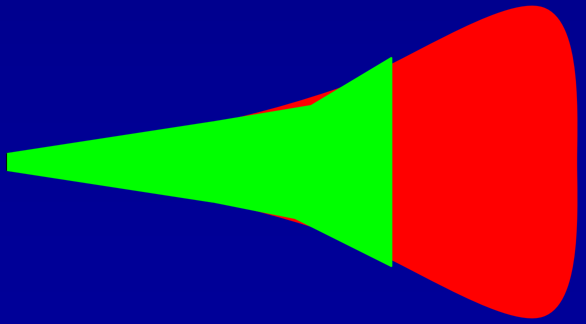
Mid-IR thermal



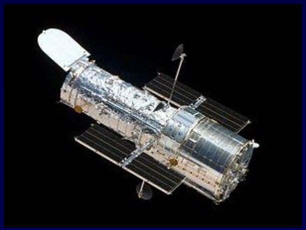
Scattered light
PAHs

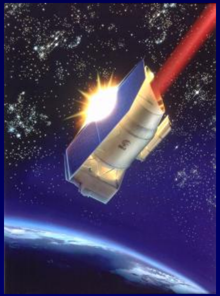


Mm emission

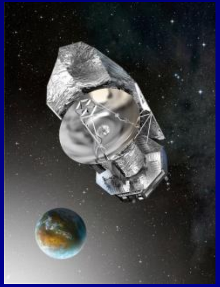


ALMA in concert with other facilities

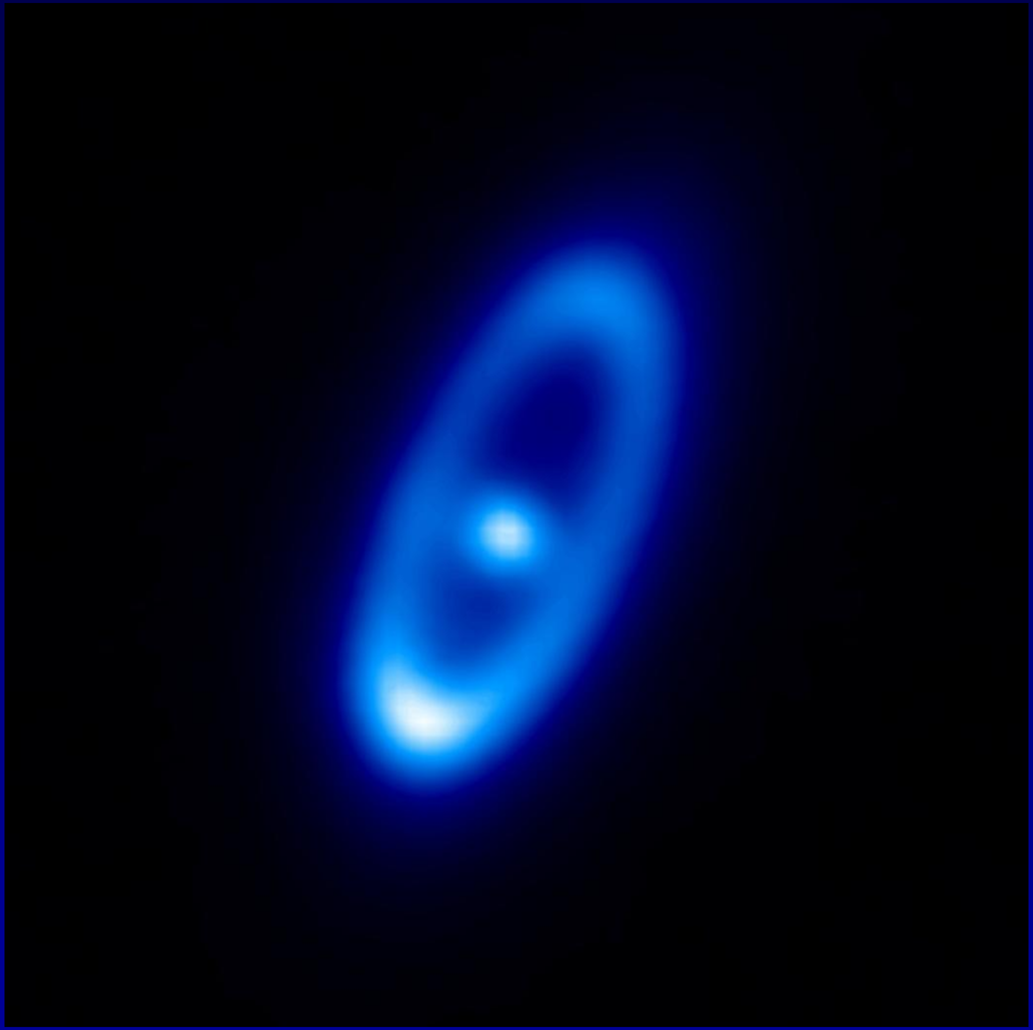







We have come a long way



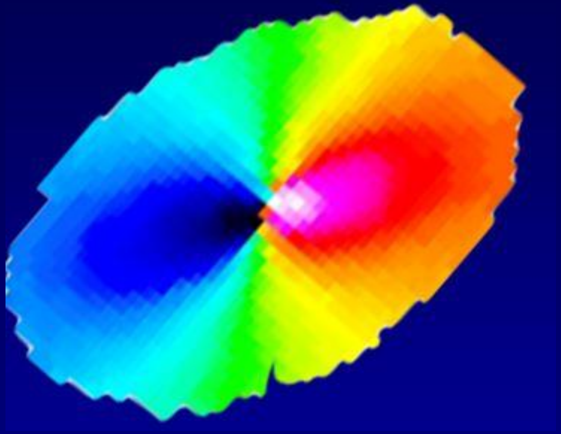
Fomalhaut
Herschel-PACS
70 μm
Debris disk

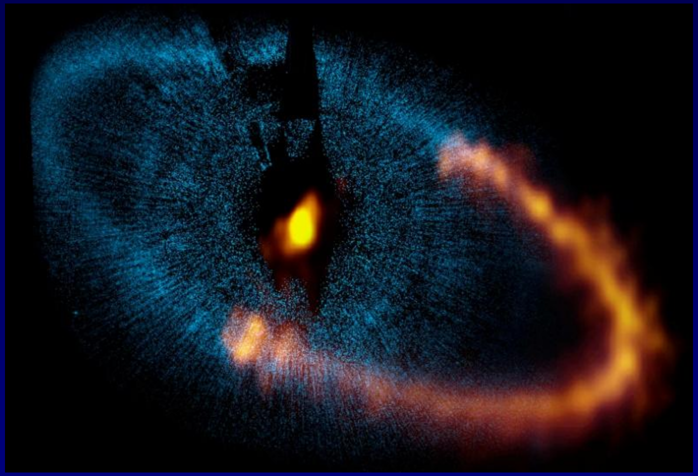
Acke et al. 2012

- **Small dust grains produced by collisions of planetesimals**
- **Two planets sheperding the dust ring**

Disk evolution

Protoplanetary gas-rich disks — ? → **Debris gas-poor disks**



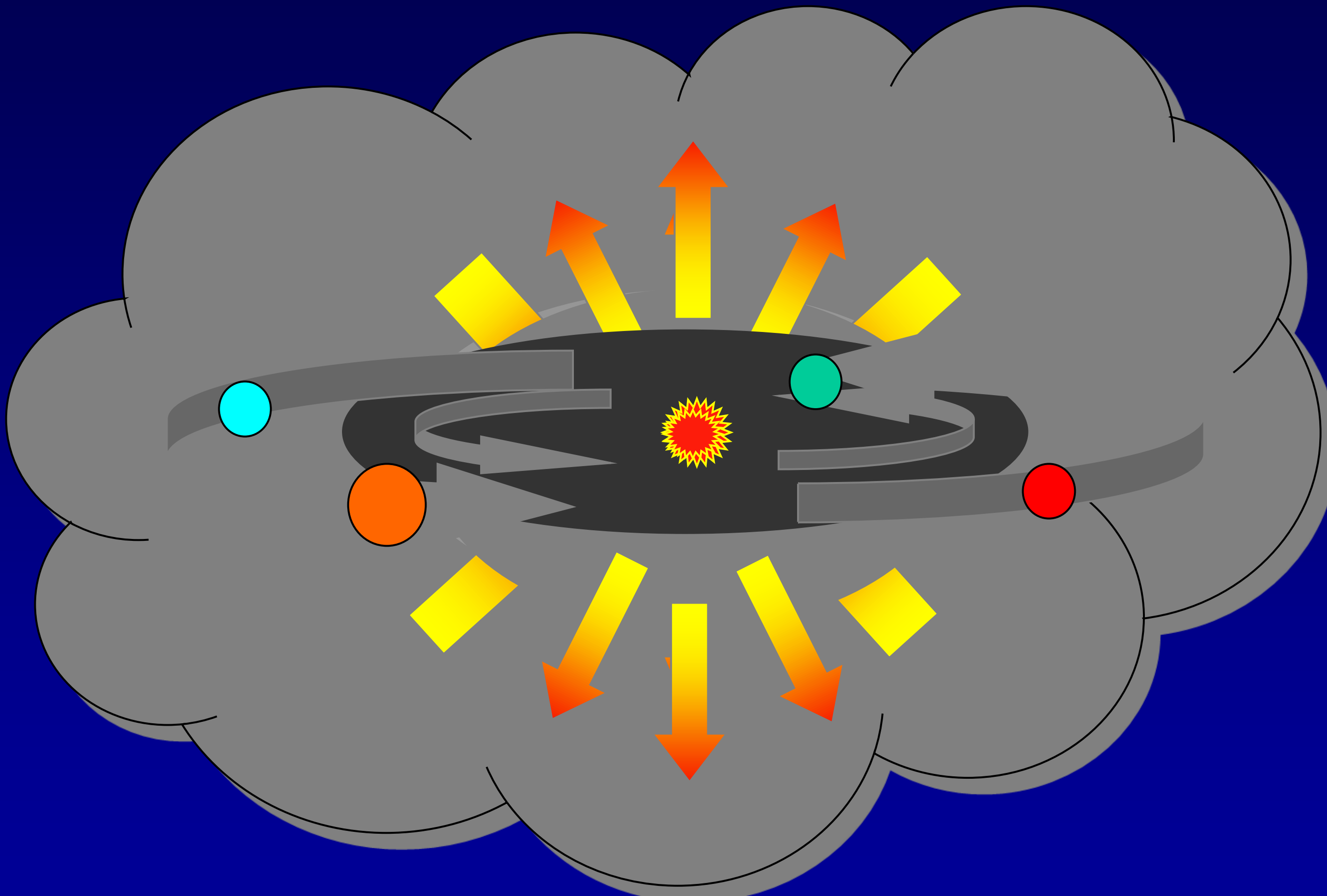


Boley et al. 2012

- Mass 0.001-0.1 M_{Sun} (~10 M_{Jup}) gas + dust
- Typical ages: few Myr
- Smooth distributions
- Gas and dust 'primordial'

- Mass <10^{-6} M_{Sun} (<1 M_{Earth}), dust only
- Ages: ~10 Myr → 1 Gyr
- Irregular distributions, gaps, holes
- Dust produced by collisions of planetesimals
- Original gas disappeared

Follow material during star and planet formation

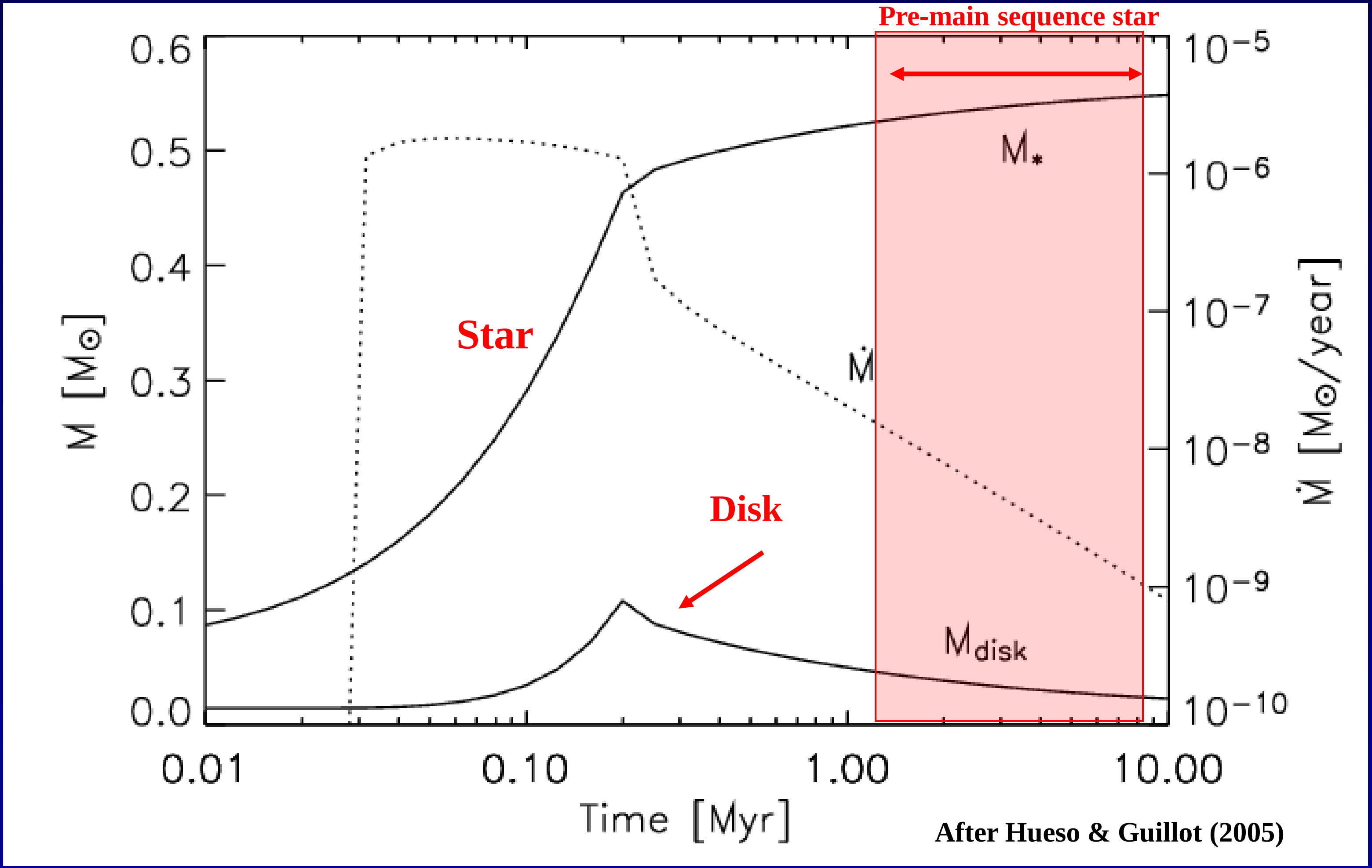


Inventory at each stage? How pristine is material in comets and planets?

When do circumstellar disks first form and how?

Polarimetry and magnetic activities in envelopes and disks

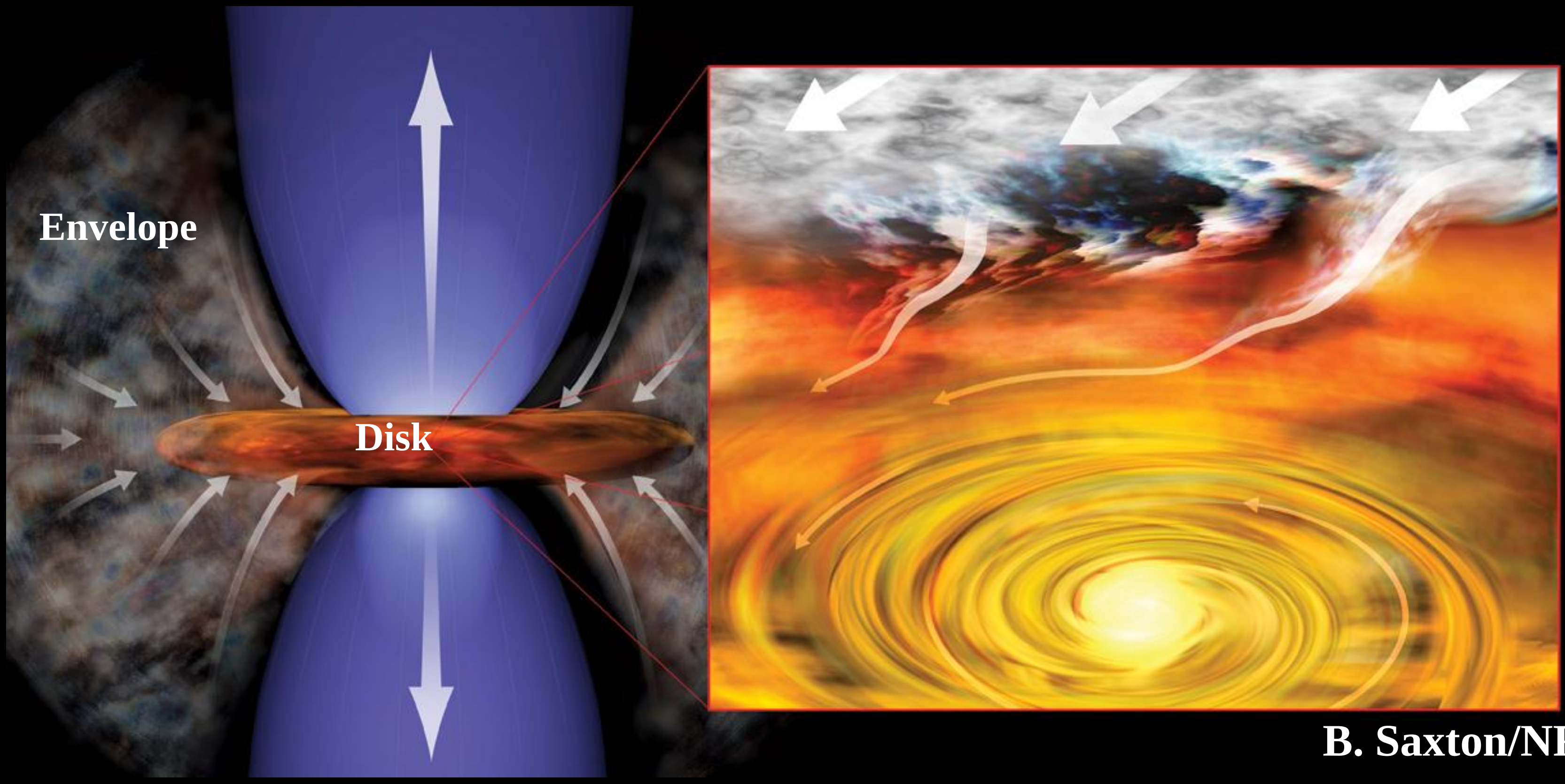
Disk formation and spreading



How early do rotationally supported disks form?

Shu 1977
Cassen & Moosman 1981

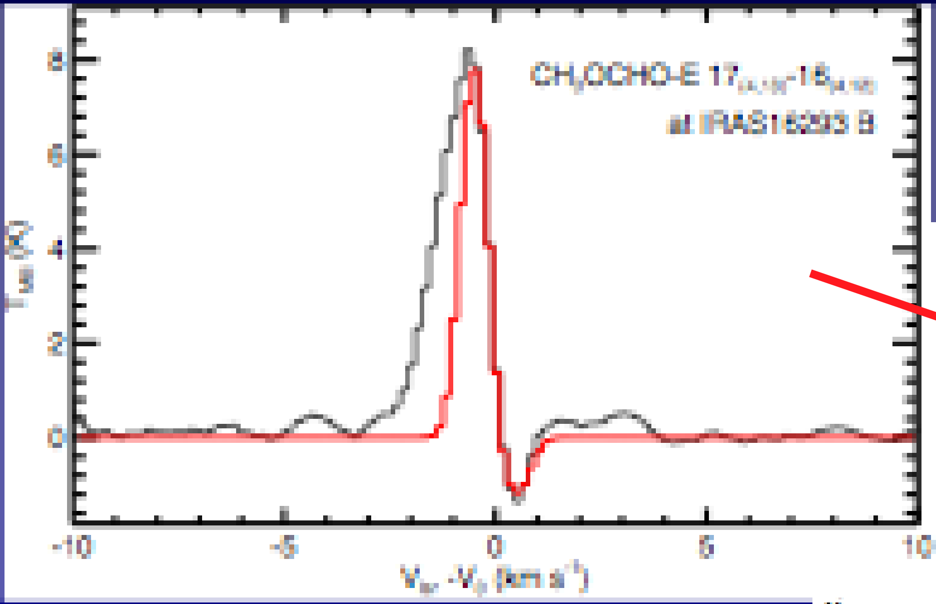
Building up disks and stars



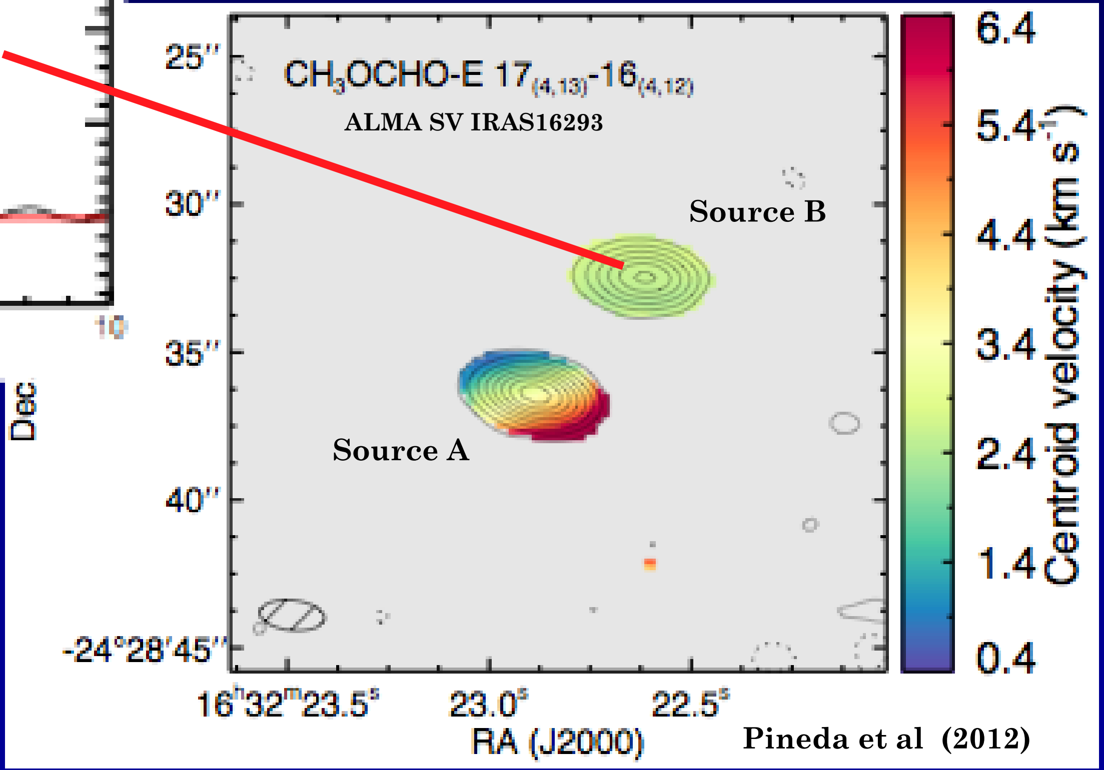
B. Saxton/NRAO

Key diagnostic: kinematics of gas as star is being built

ALMA: Unambiguous detection of infall



Infall profile!
Supersonic infall (~0.3km/s)



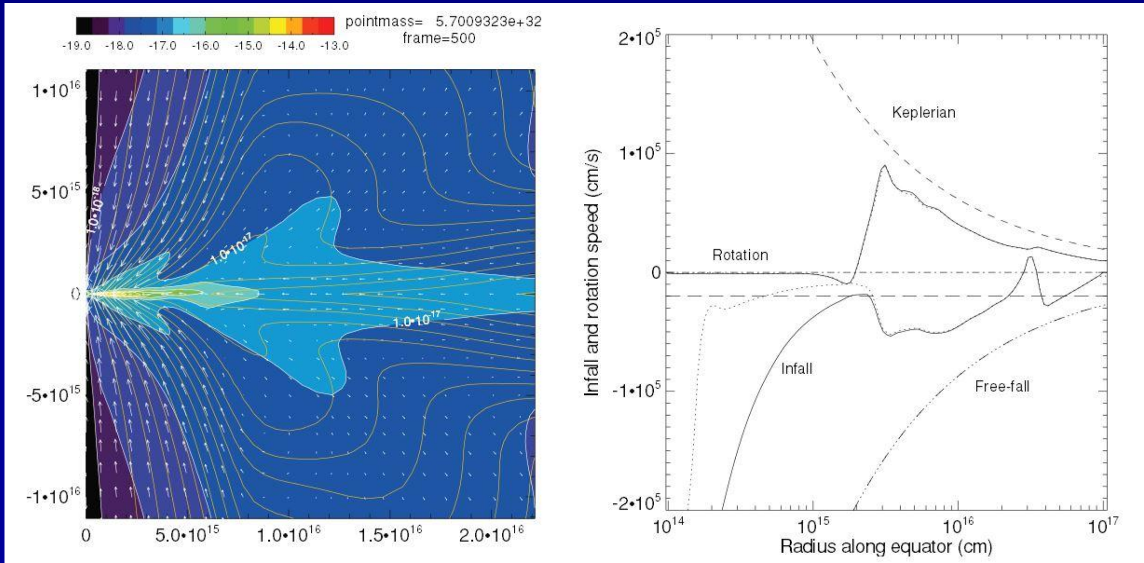
IRAS 16293 -2422
ALMA SV data

Get accretion rate through modeling

Pineda et al. 2012

But is a stable disk formed?

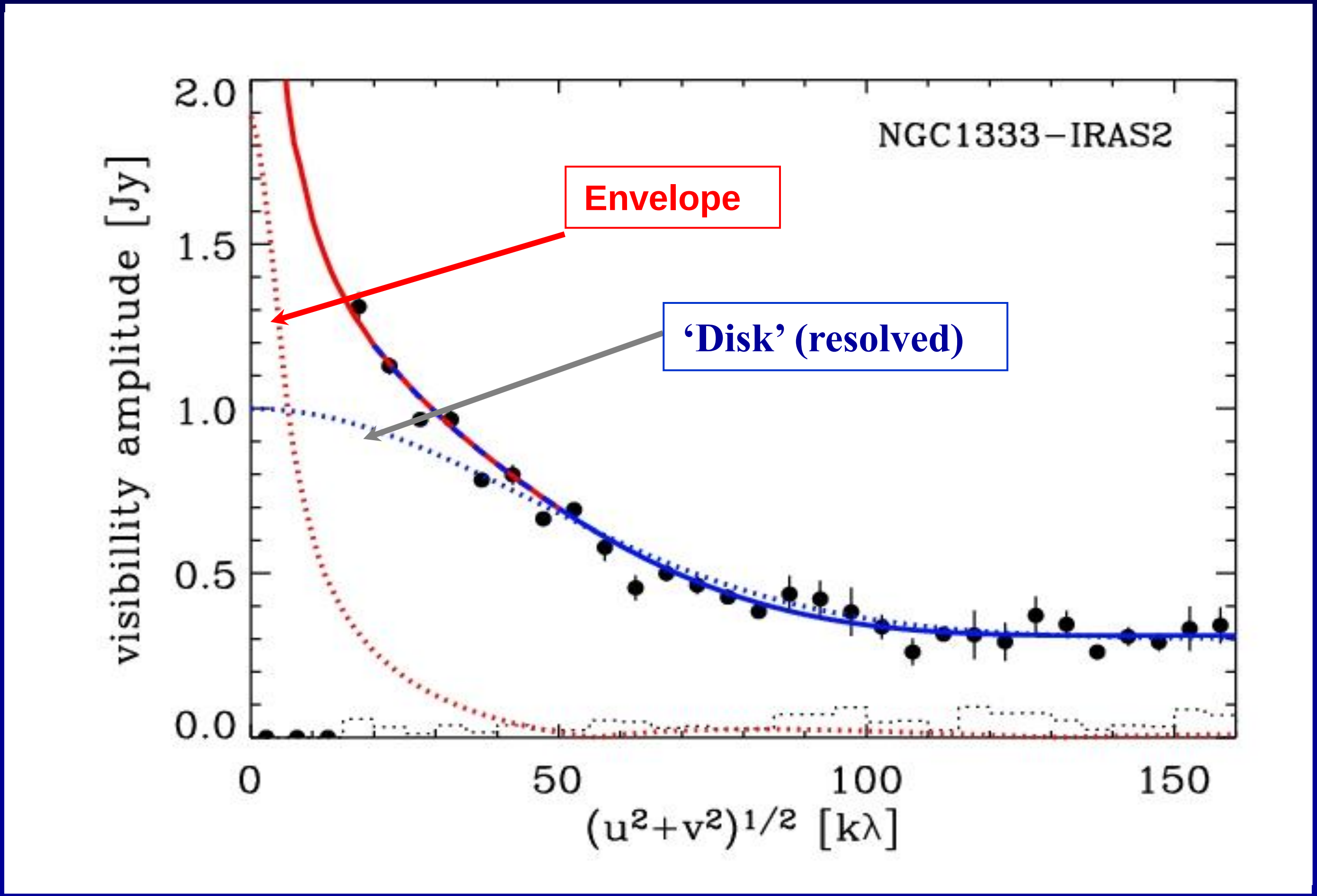
- Efficient magnetic braking
- Episodic accretion→ drain most of disk onto star
  - Note two timescales involved
    - Envelope → disk
    - Disk → star
    - No reason that they should be the same



Li et al. 2011
Inutsuka et al. 2010
Chiang et al. 2008
Vorobyov & Basu 2005
Galli & Shu 1996
Galli et al. 2006, 2012

Young disks in Class 0 protostars

Dust resolved in inner envelope and a compact source = 'disk?'

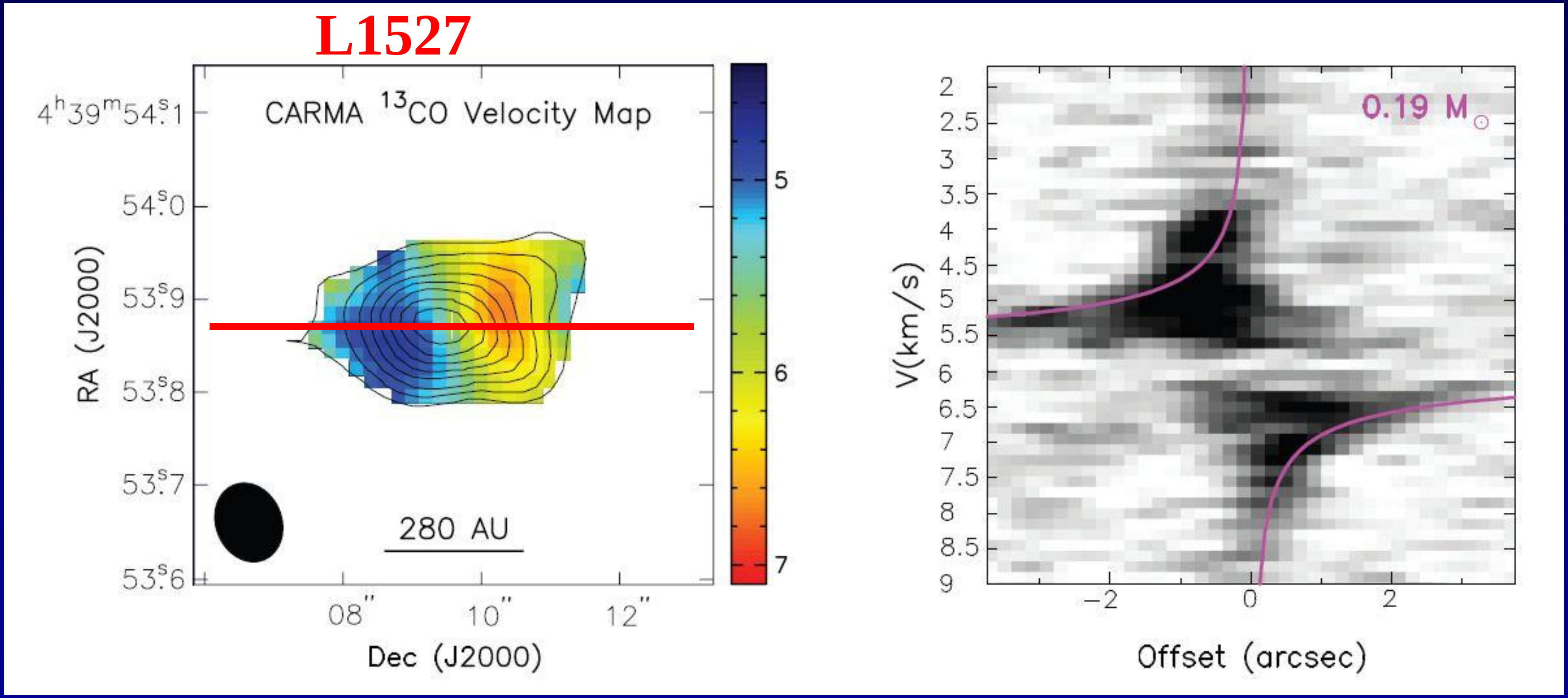


850 µm SMA

But: no Keplerian signature found on arcsec scale!
Dust 'disk' is not true disk→ *ALMA!*

Jørgensen et al. 2005, Brinch et al. 2007
Keene & Masson 1991
Looney et al. 2000, Harvey et al. 2003

Youngest rotating disk?

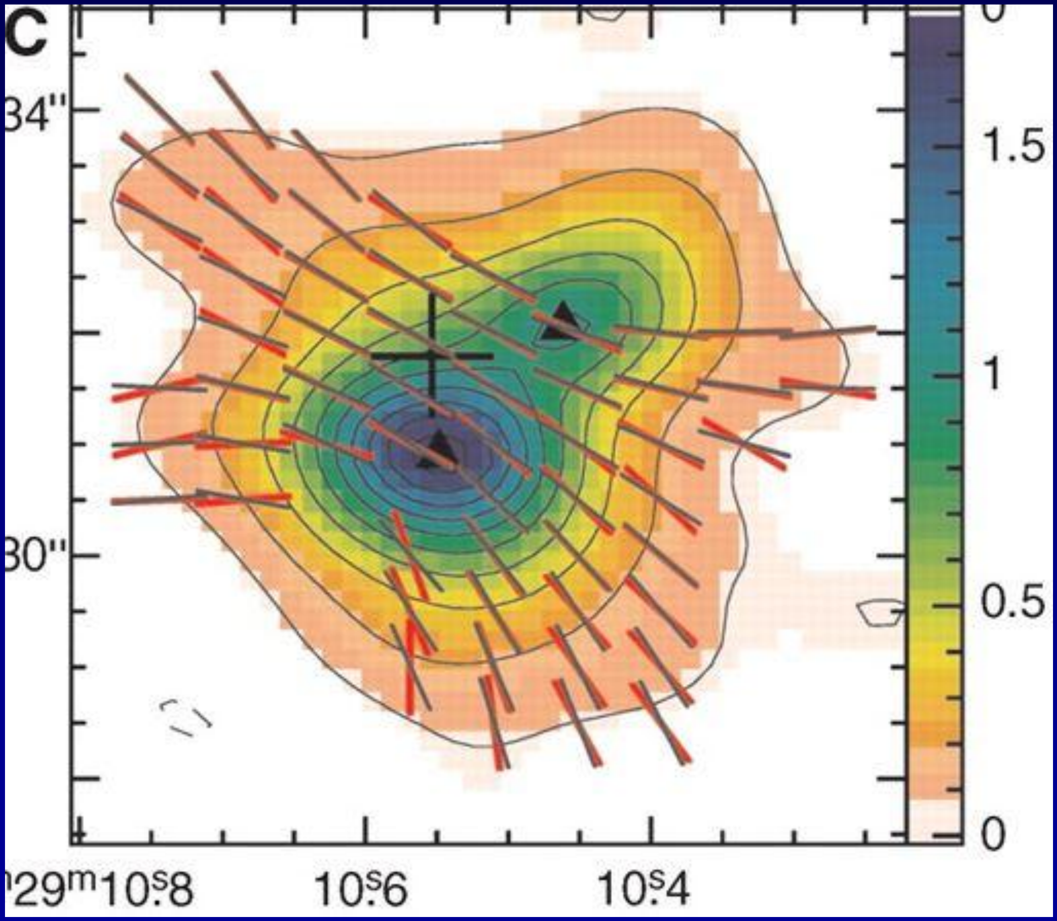


Tobin et al. 2012, Nature

- Data suggest Keplerian rotation with $V \propto R^{-0.5}$ around a 0.2 M_{sun} star

-Is this consistent with Ohashi ALMA data? $V \propto R^{-1}$ on larger scales

Magnetic field measurements



NGC 1333 IRAS4A

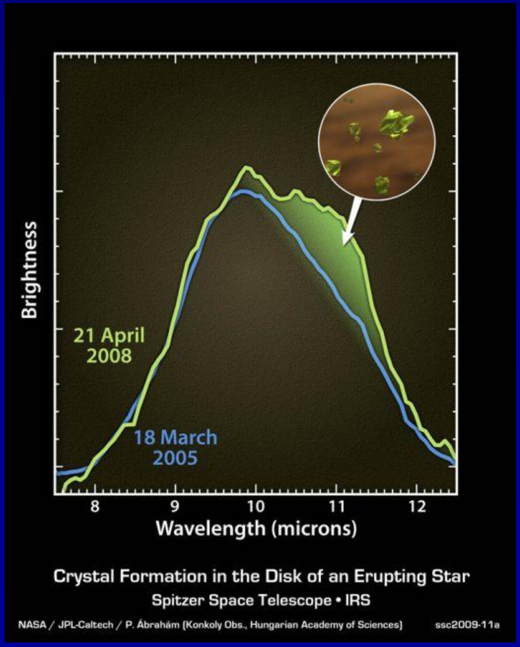
SMA

Girart et al. 2006

ALMA can provide magnetic field direction (cont pol) + strengths (Zeeman)

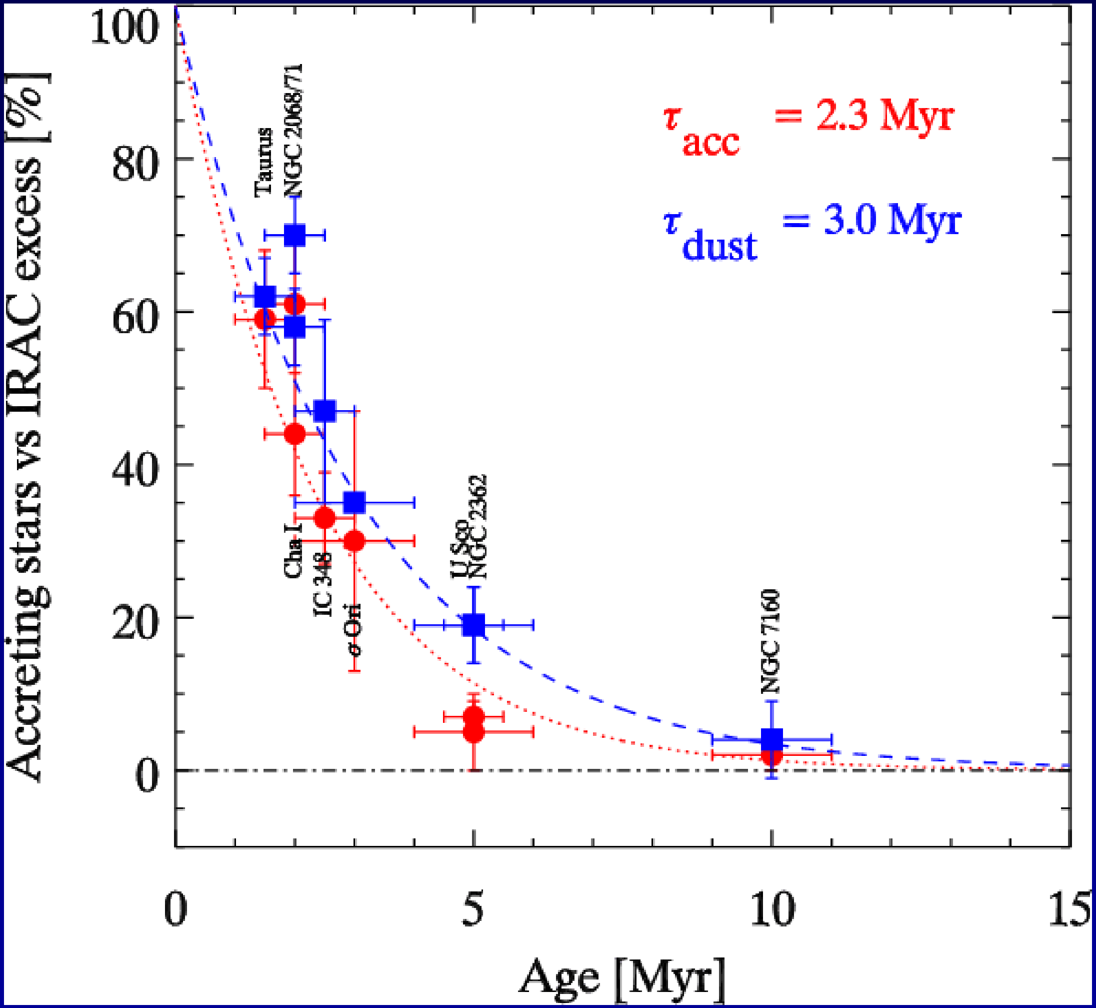
Disk evolution

What is the process of grain growth and evolution?



Global view

Inner disks disappear in a few Myr



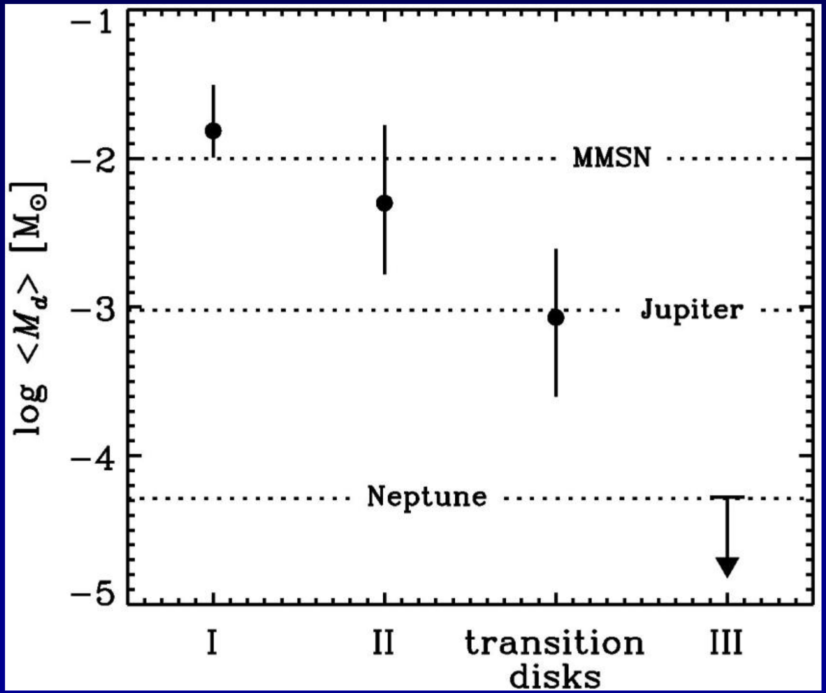
Accretion rate and near-IR excess decrease strongly after a few Myr

Cores of giant planets have to be built within a few Myr

Haisch et al. 2001, Hernandez et al. 2008, Fedele et al. 2010

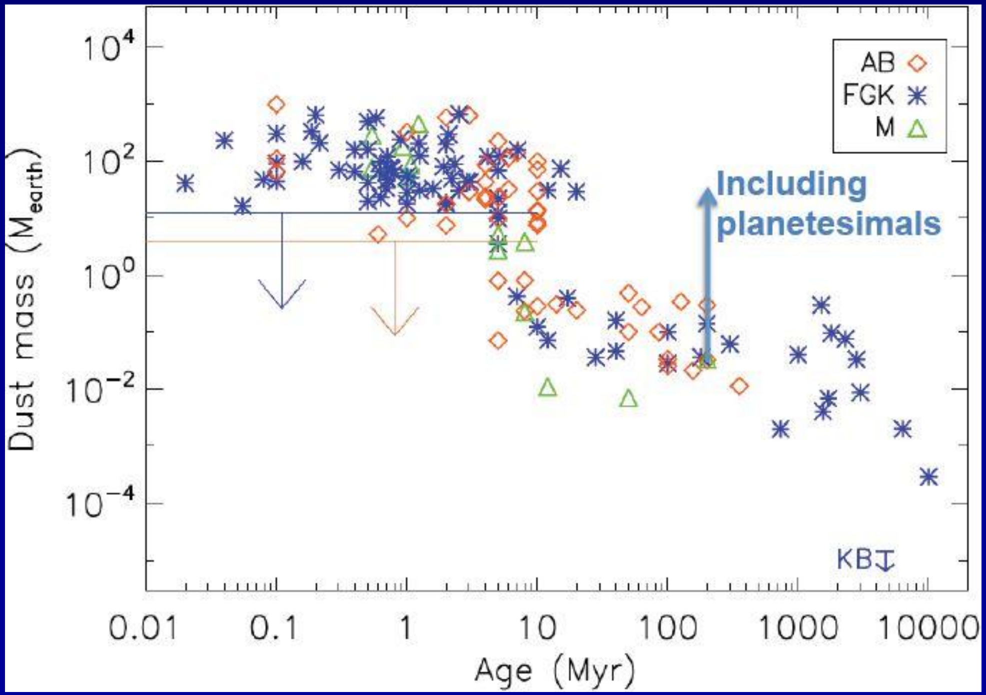
Global view
Outer dust disk evolution

Gas rich disks



Andrews & Williams 2007

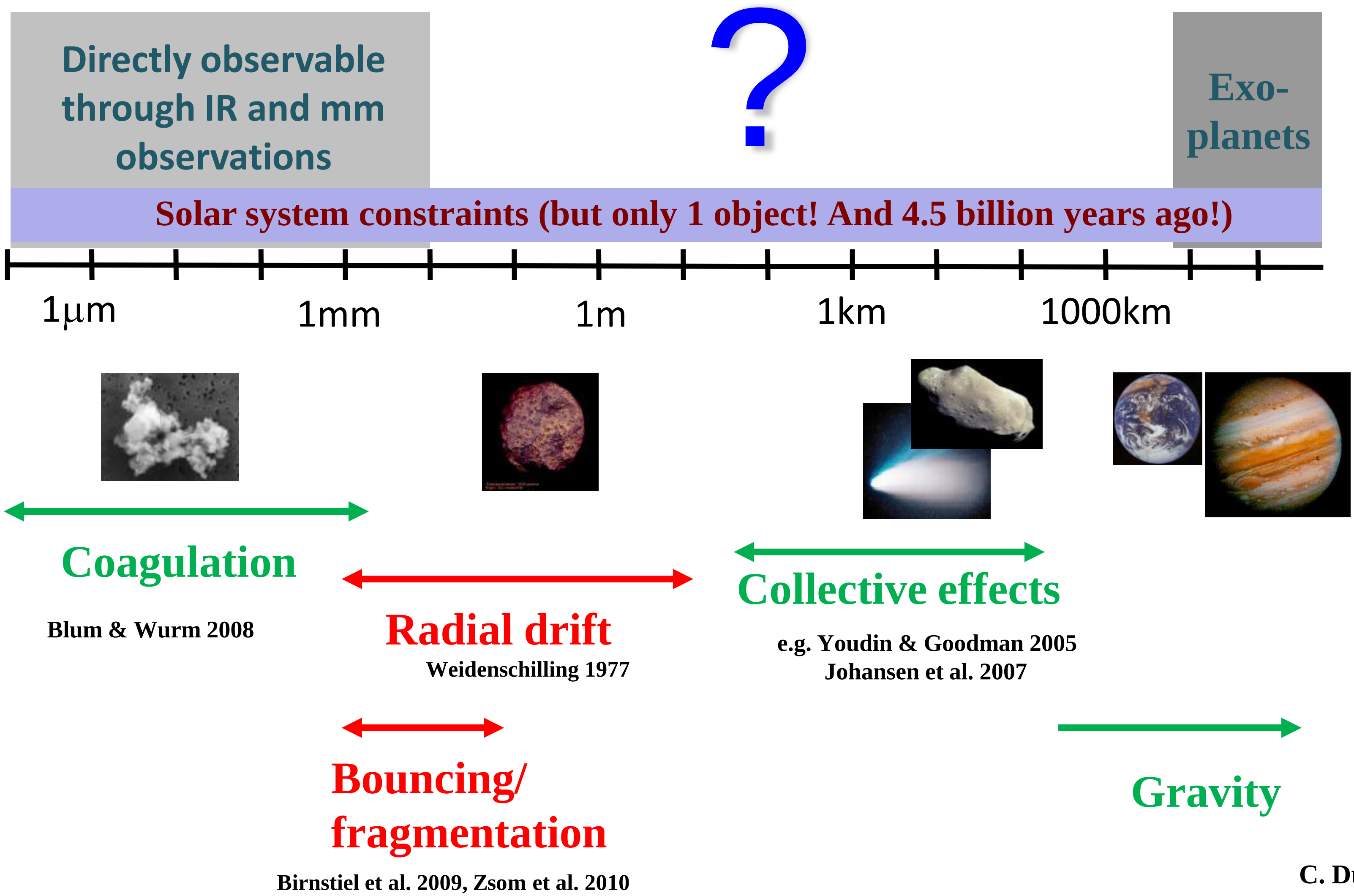
Gas rich → Debris disks



Wyatt 2008

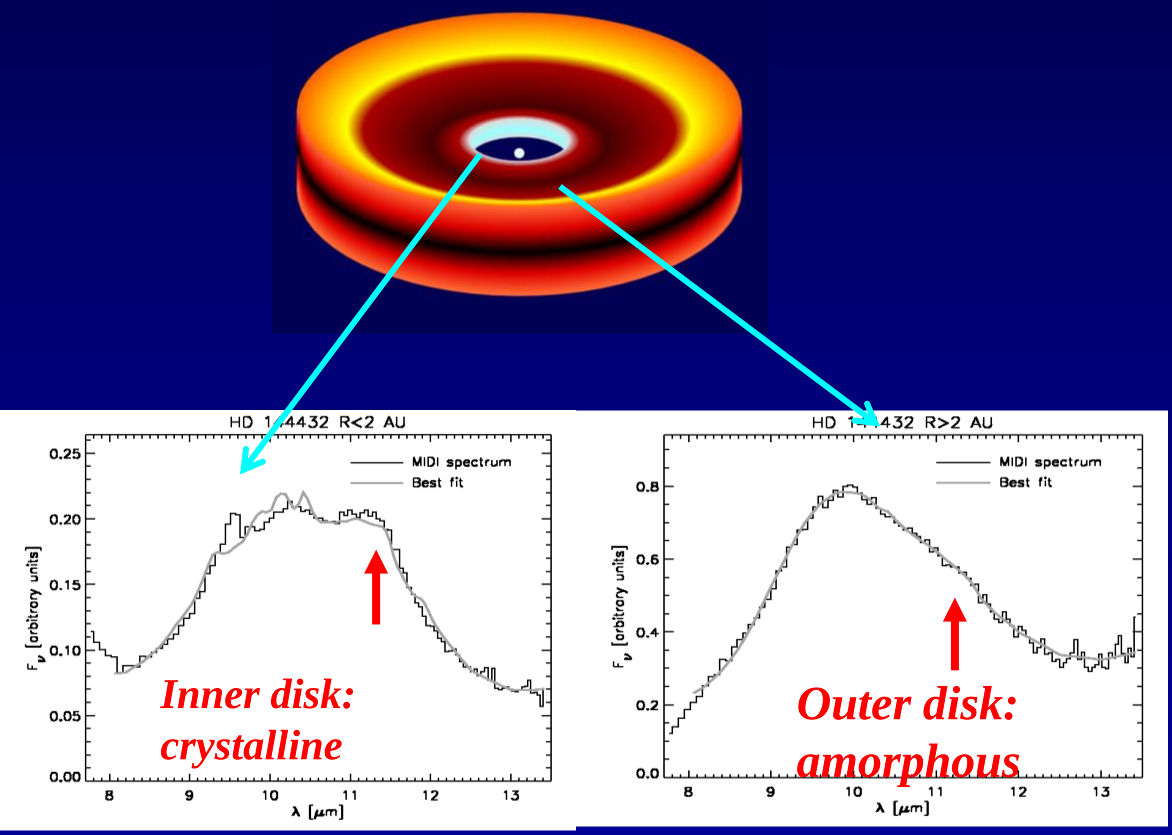
By 10 Myr, significant drop in (small) dust grains; stochastic events at later stages

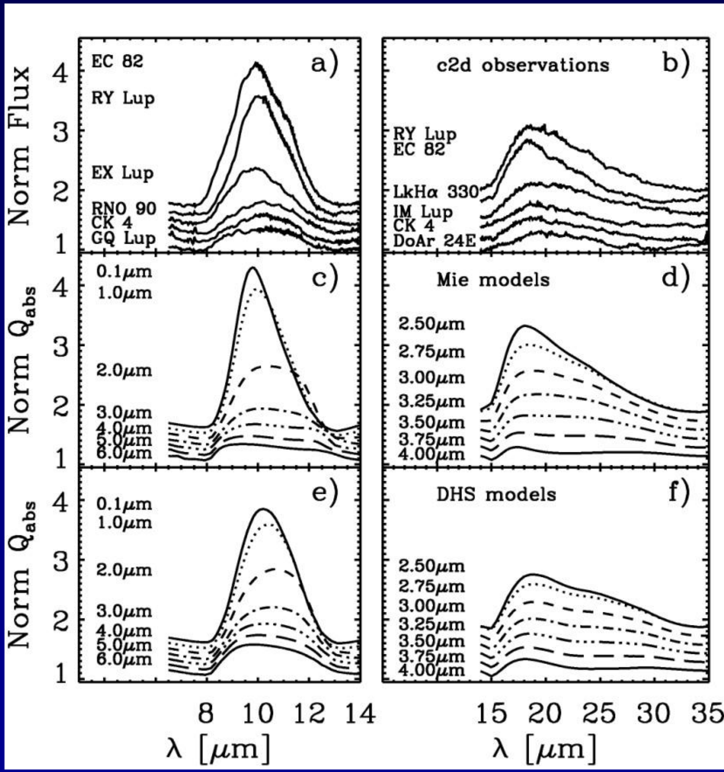
How to grow dust and build planets?



C. Dullemond
S. Andrews

Grain growth and crystallization inner disk
Silicate features





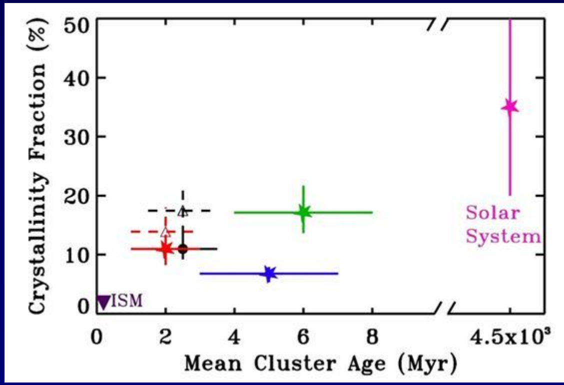
Kessler-Silacci et al. 2006
Olofsson et al. 2009, 2010
Oliveira et al. 2011

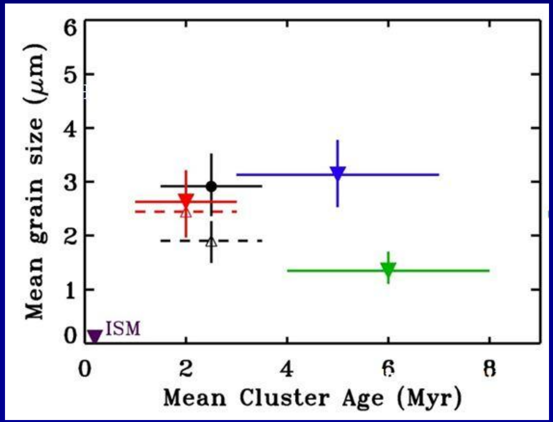
Van Boekel et al. 2004, 2005
Also: Furlan et al. 2006
Bouwman et al. 2008
Watson et al. 2009, Juhasz et al. 2010
Sturm et al. 2010, 2013 Herschel
McClure et al. 2012

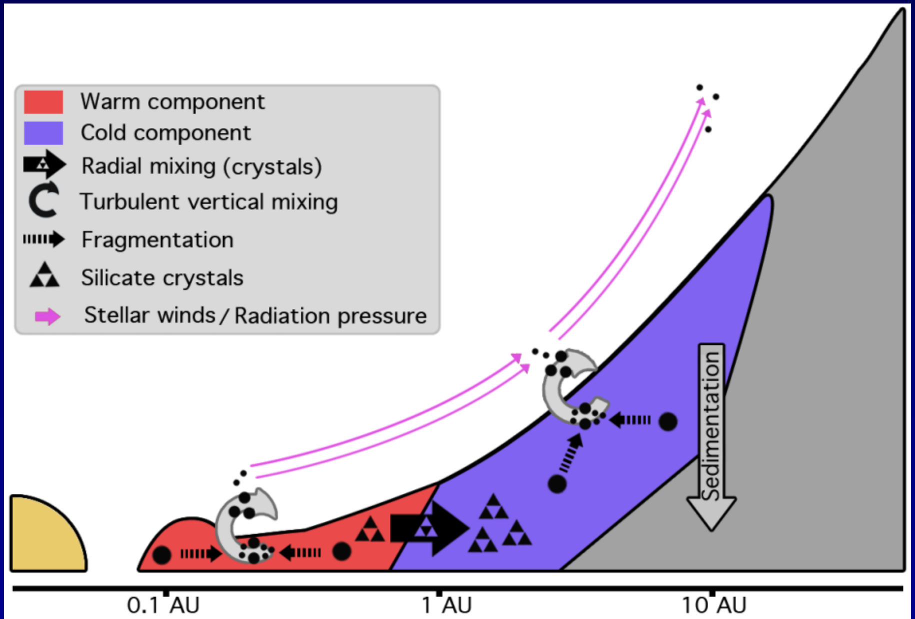
Grains grow to μm size in surface layers

Grain growth occurs early

Hundreds of sources Spitzer



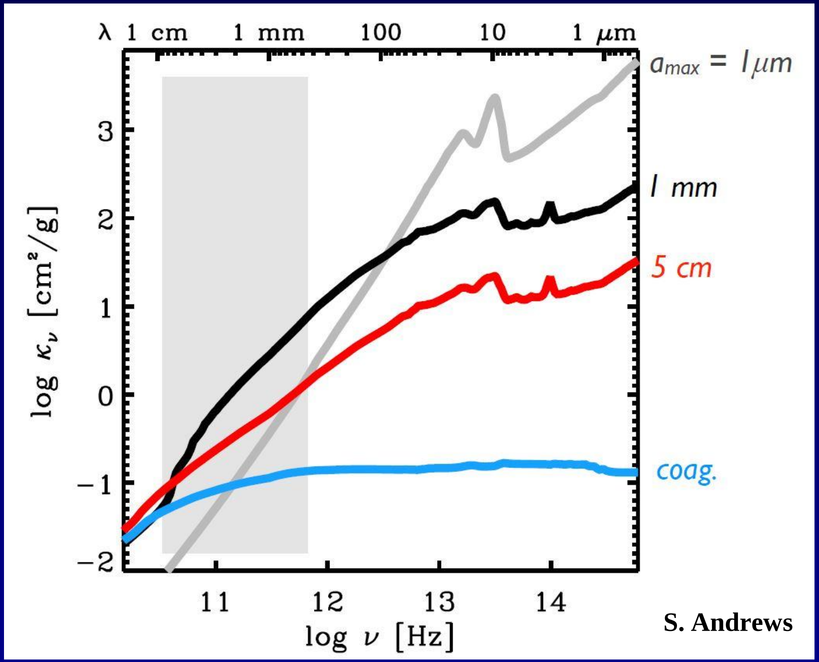




Oliveira et al. 2011, Olofsson et al. 2010

- Grain growth and crystallinity are established early (≤ 1 Myr) and maintained by continuous growth and destruction until disk dissipation

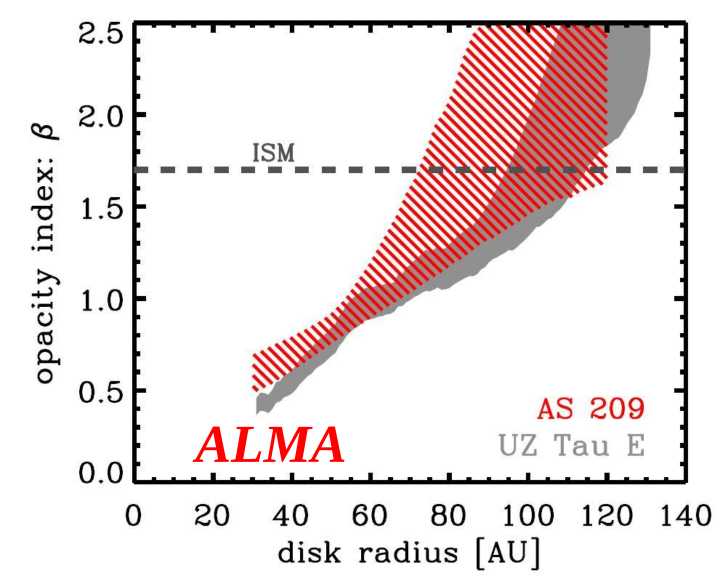
Grain growth outer disk



β<1 found for many disks

Testi et al. 2003, Rodman et al. 2006,
Lommen et al. 2007, 2009,
Ricci et al. 2009-2012 + many

Next step: radial variations in disk

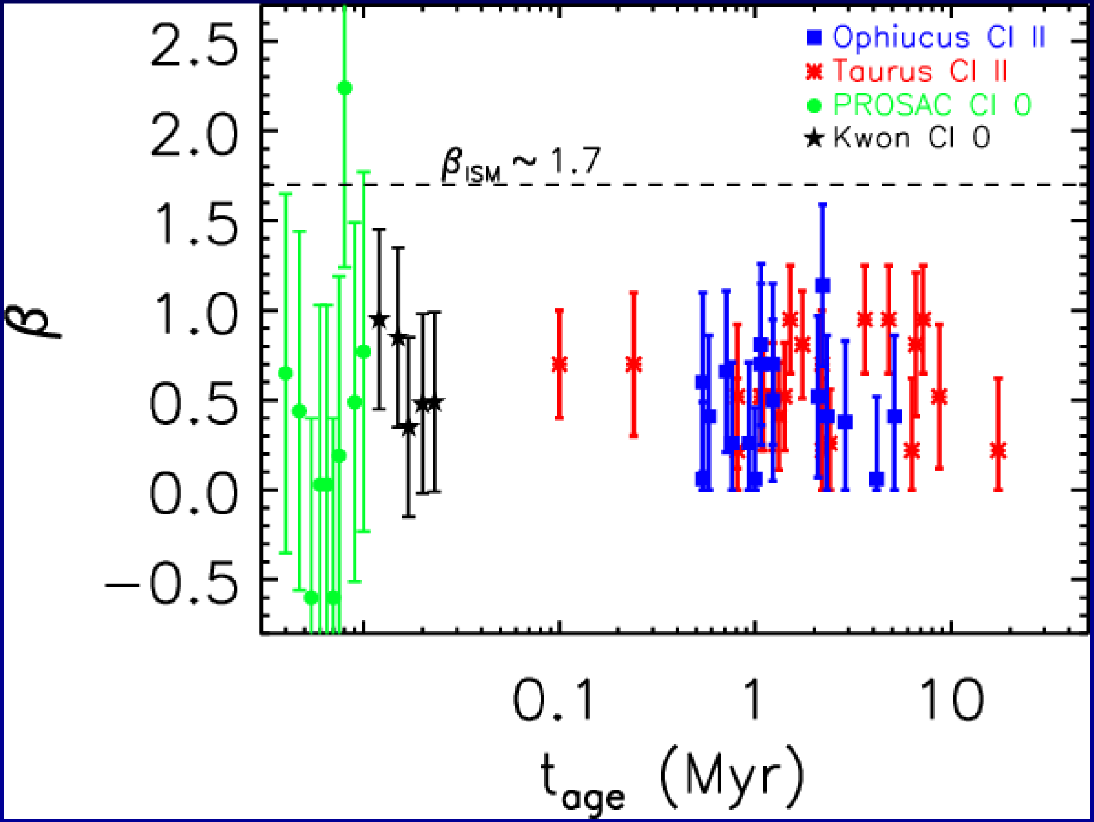


Perez et al. 2012, Guilloteau et al. 2011, Isella et al. 2011

Mm-cm slope is measure of grain growth from <1 mm to dm size

Slope α = 2 + β; β<1→ pebbles

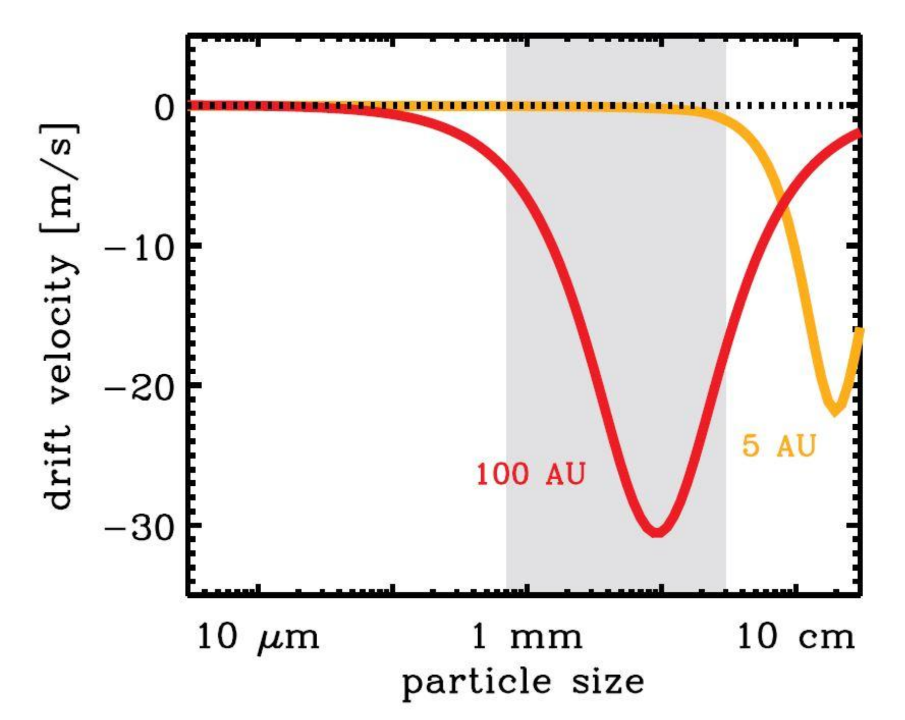
Grain growth occurs early, even in BD disks



Ricci et al. 2010, Ricci, Pinilla et al. 2012

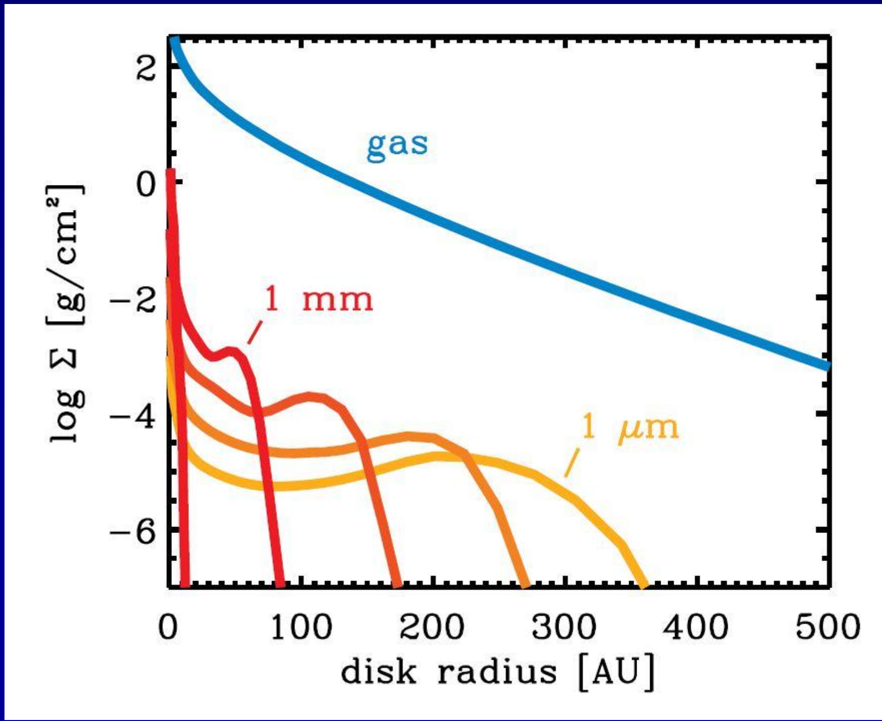
But: radial drift and the m-size barrier

Drift dust w.r.t. gas



ALMA will test this as function of disk radius

Size-sorting with radius

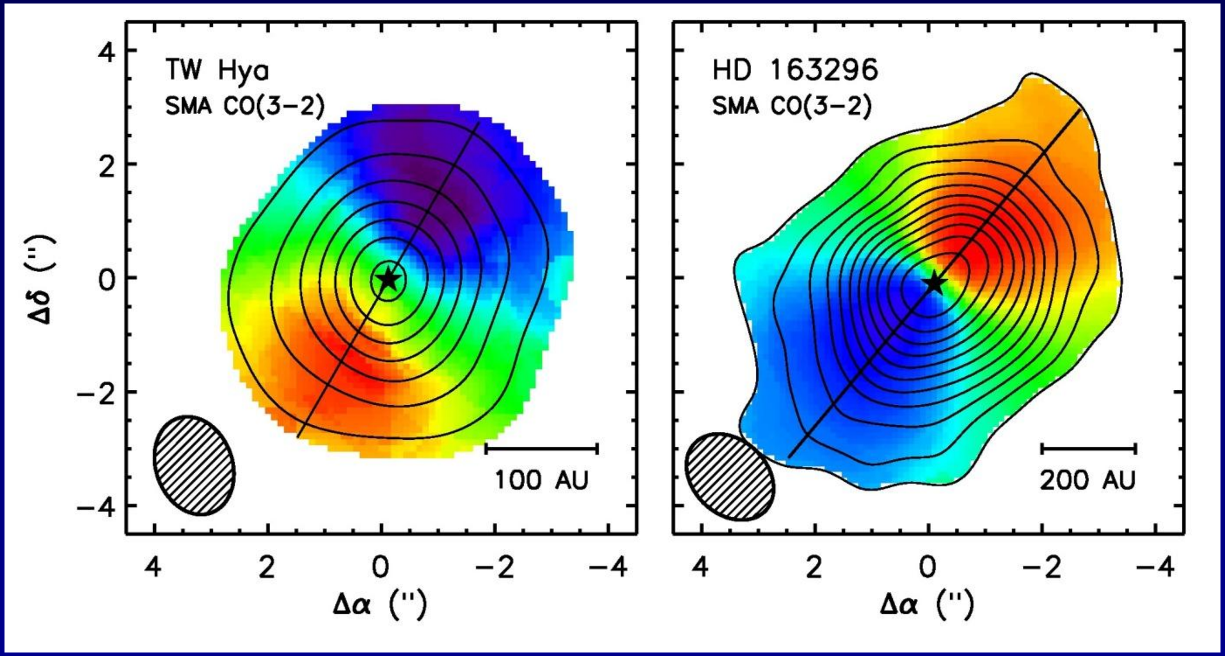


Drift velocities too fast → need dust trapping

Gas kinematics, transport

How does gas evolve in circumstellar disks?

Gas structure



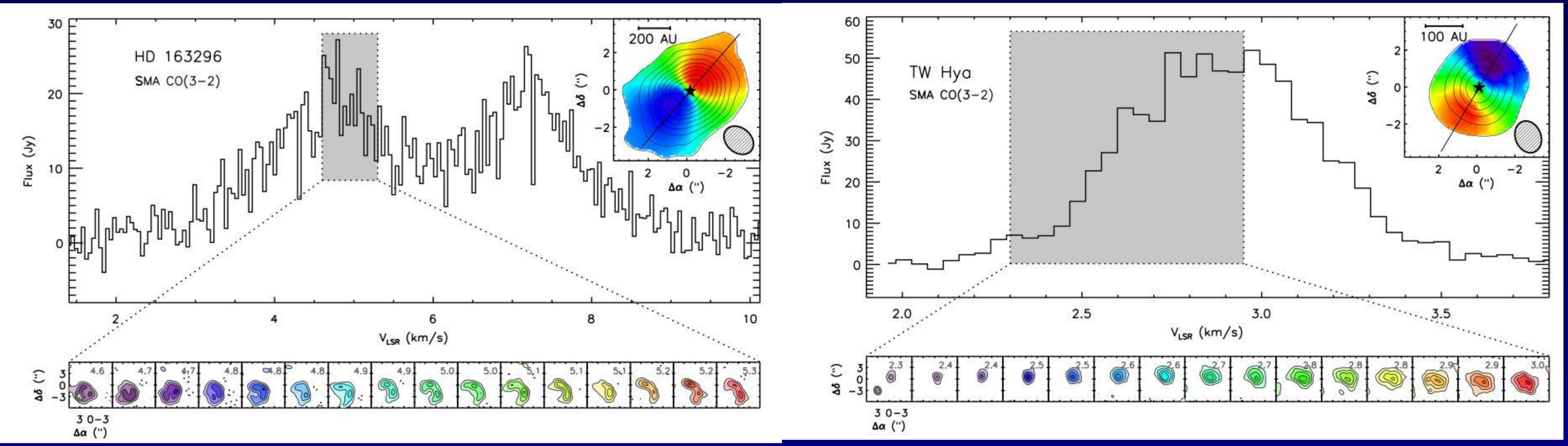
Williams & Cieza 2011

e.g. Koerner et al. 1993
Dutrey et al. 1996
Simon et al. 2000

- **Most disks show Keplerian velocity structure**
- **Gas disk is flared, heated by stellar radiation**
- **ALMA CSV: evidence for warp in TW Hya disk**

Rosenfeld et al. 2012

Turbulence



Hughes et al. 2011

- High S/N spectra limit turbulence to

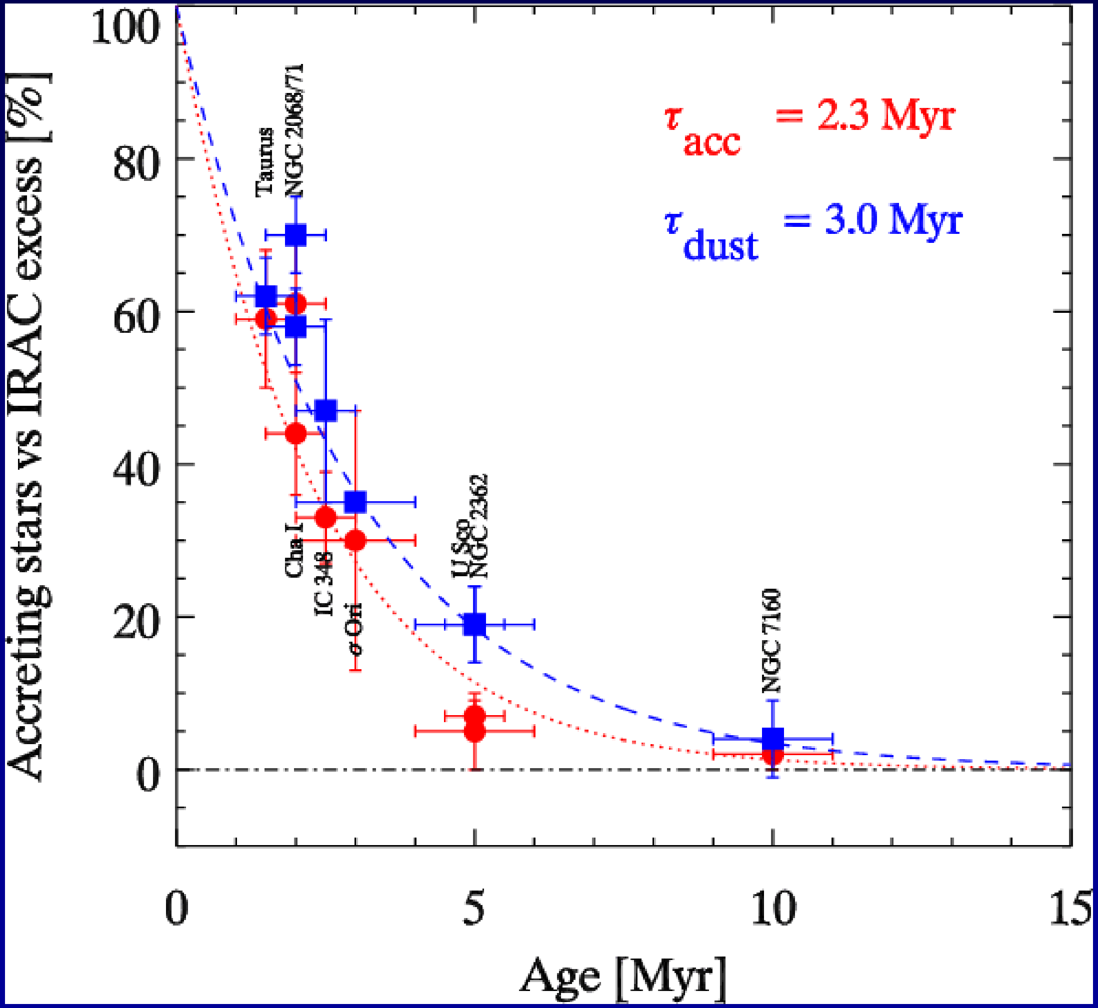
  < 40 m/s for TW Hya

  ~300 m/s for upper layers of HD163296 disk (0.4 Mach)

- DM Tau: 0.4-0.5 Mach at intermediate layers (Guilloteau et al. 2012)

- Important for planet-formation models; mixing of material

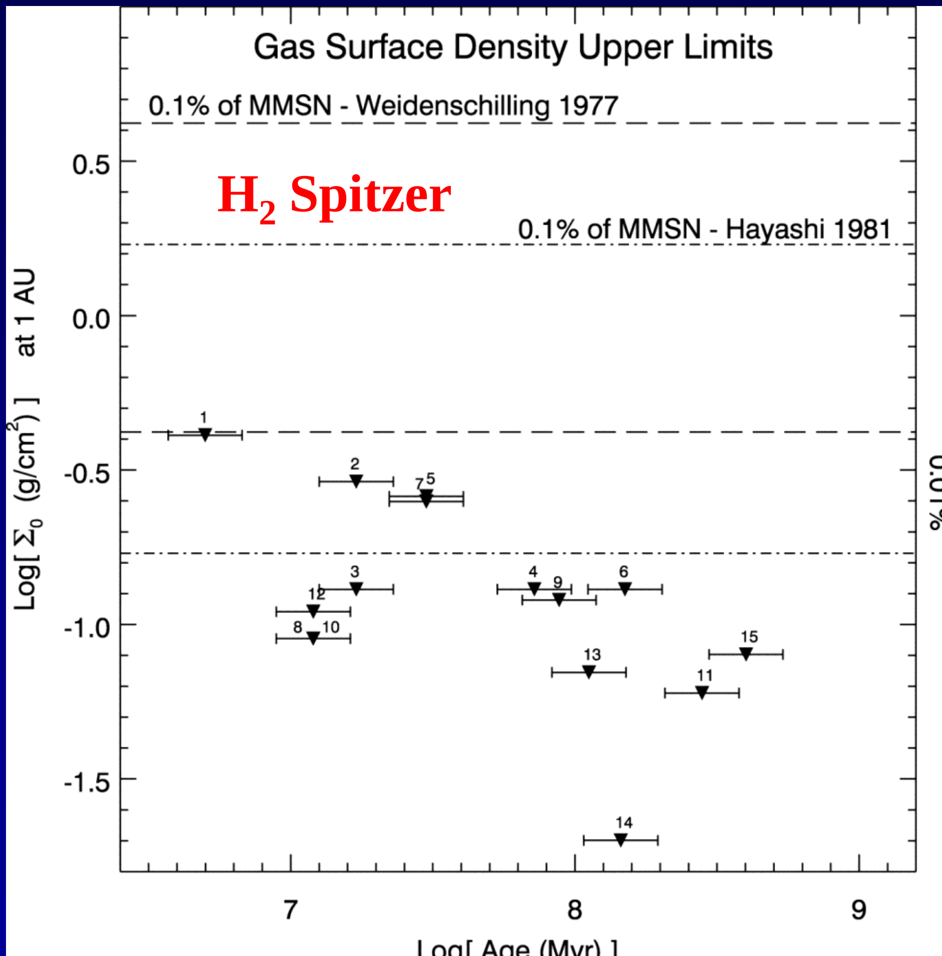
Disk evolution: Inner gas disks disappear in a few Myr



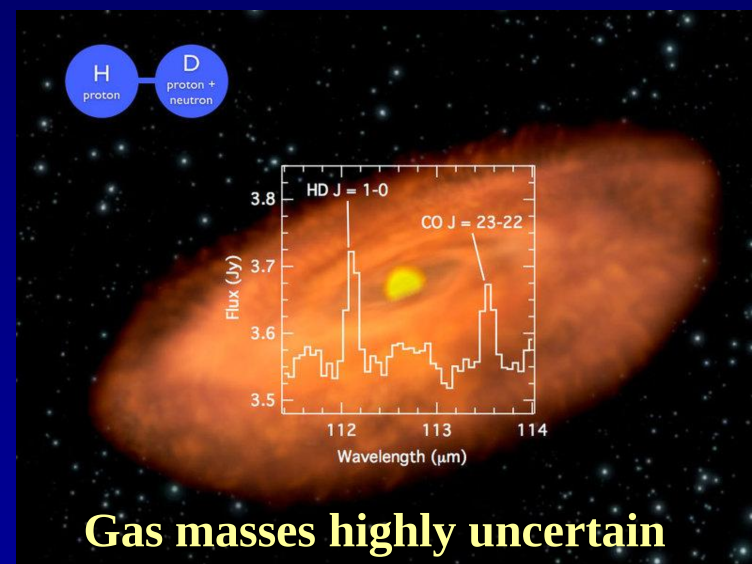
Accretion rate and near-IR excess decrease strongly after a few Myr

Fedele et al. 2010

Outer gas disk evolution?



Only a few gas-rich disks left by 10 Myr



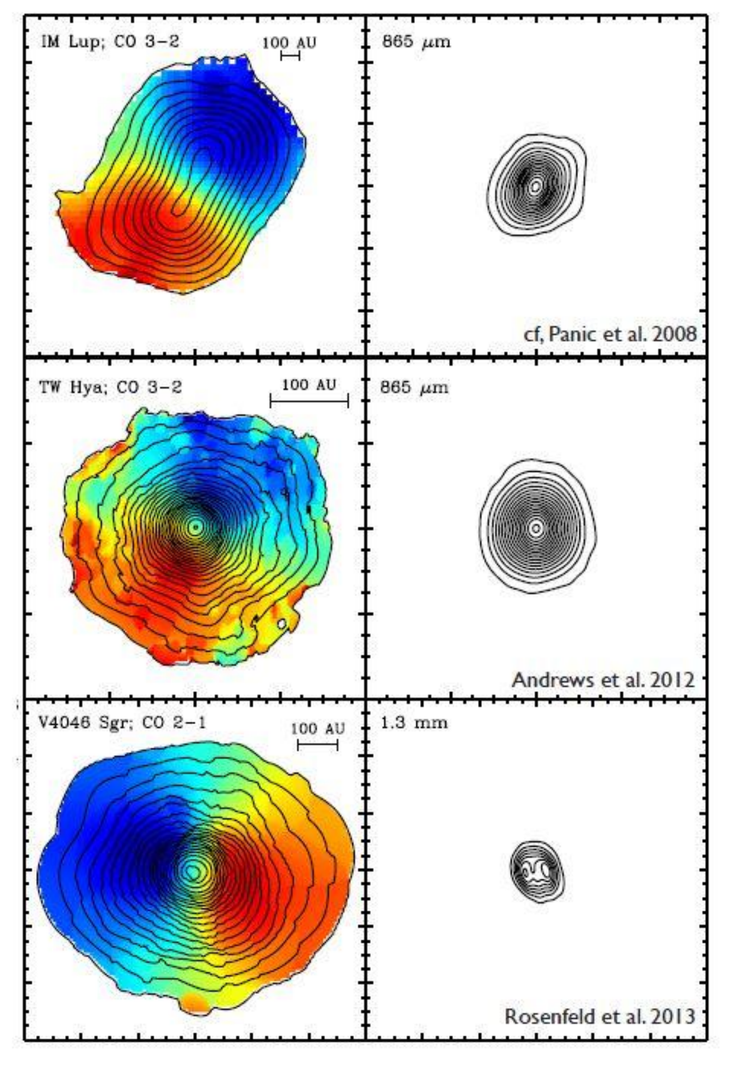
Bergin et al. 2013

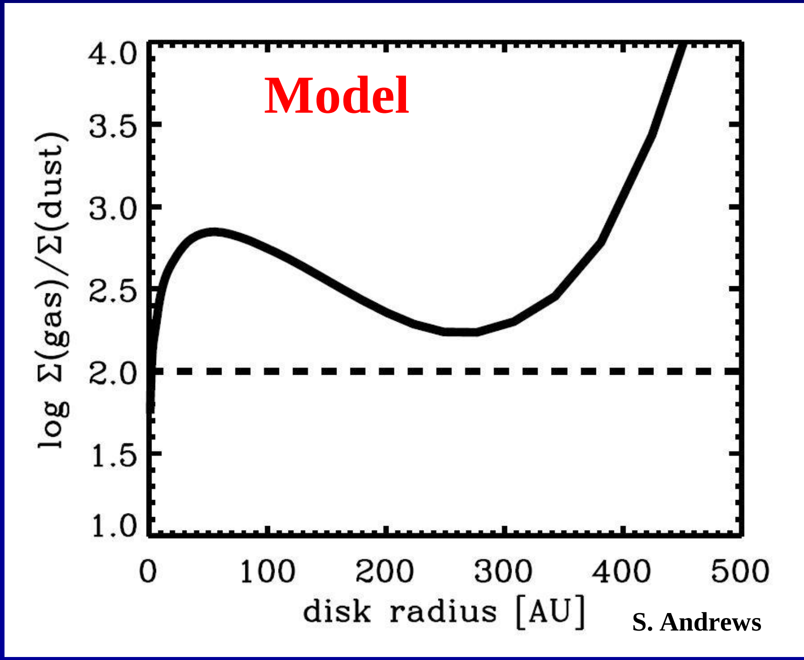
Pascucci et al. 2006, Dent et al. 2005
GASPS et al. in prep.

Need ALMA observations of gas tracers (CO isotopologs, ...)

Gas-dust ratio with radius

Gas **Dust**





Gas disk dispersal mechanisms

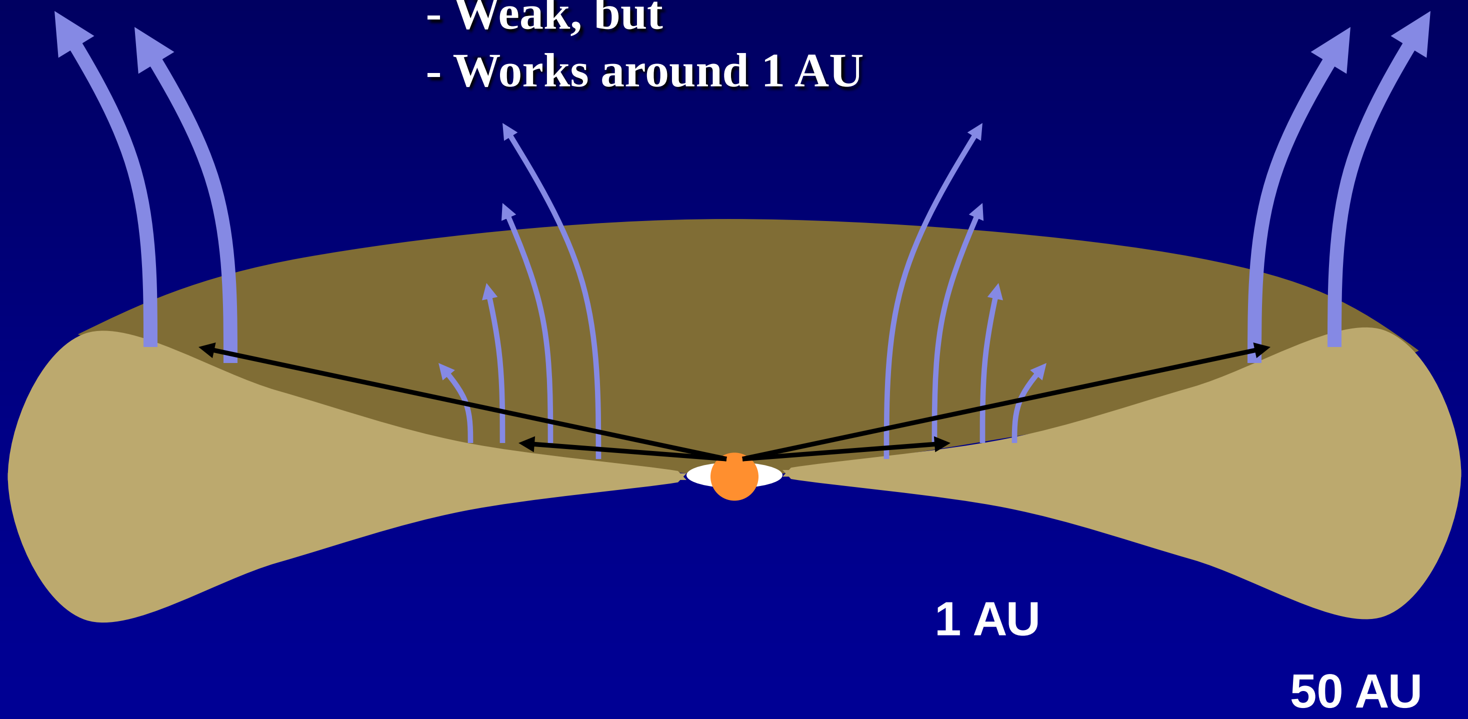
- Accretion onto star
- Giant planet formation
- Photoevaporation
- Stellar winds
- Truncation by stellar encounter

Hollenbach et al. 2000

Photoevaporation

FUV Photoevap:
- Strong, but
- Works > 50 AU

X, EUV Photoevap:
- Weak, but
- Works around 1 AU

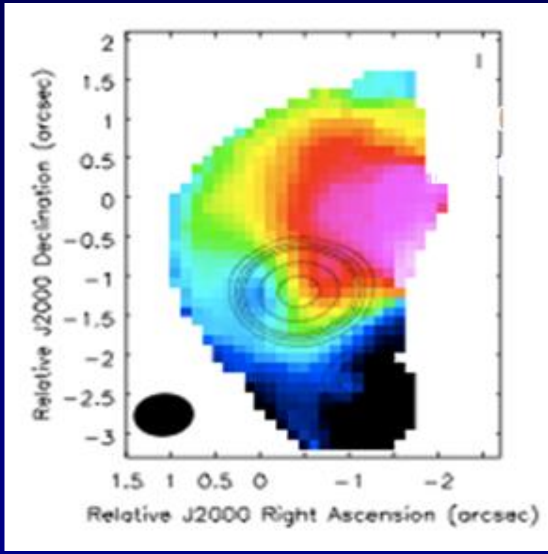


Mechanism requires :
- Low mass disks (<0.002 M_{Sun})
- Low accretion rate (<10^{-10} M_{Sun}/yr)

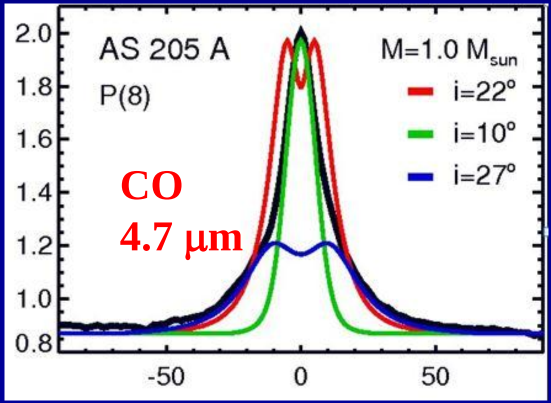
Hollenbach et al. 1994
Clarke et al. 2001
Alexander et al. 2007
Owen et al. 2010

ALMA detection of disk winds?

AS 205 CO ALMA

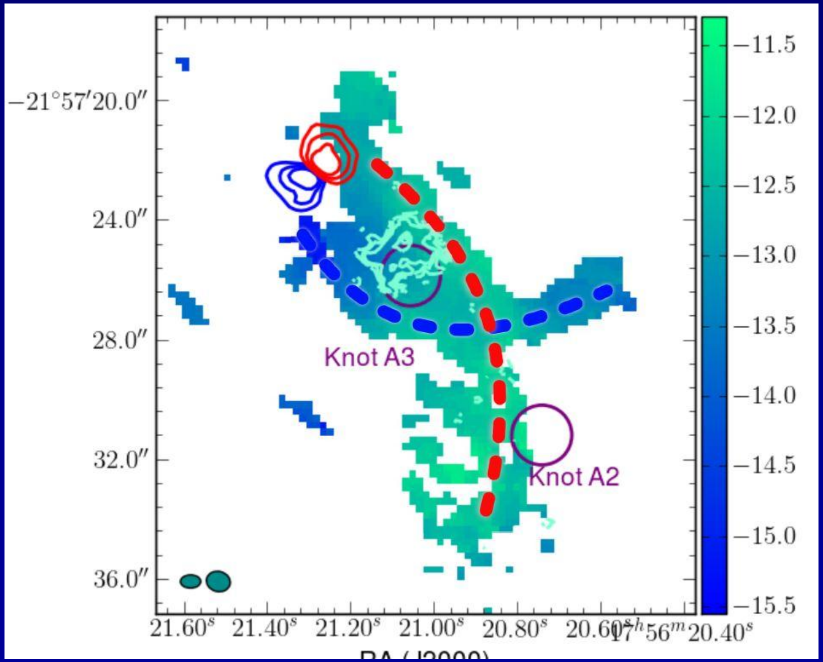


Salyk et al., in prep.



Slow disk winds: **Bast, Pontoppidan et al. 2011**

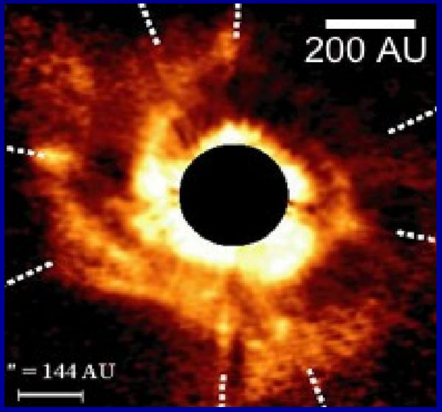
HD 163296 CSV data CO 2-1



Klaassen et al., subm.

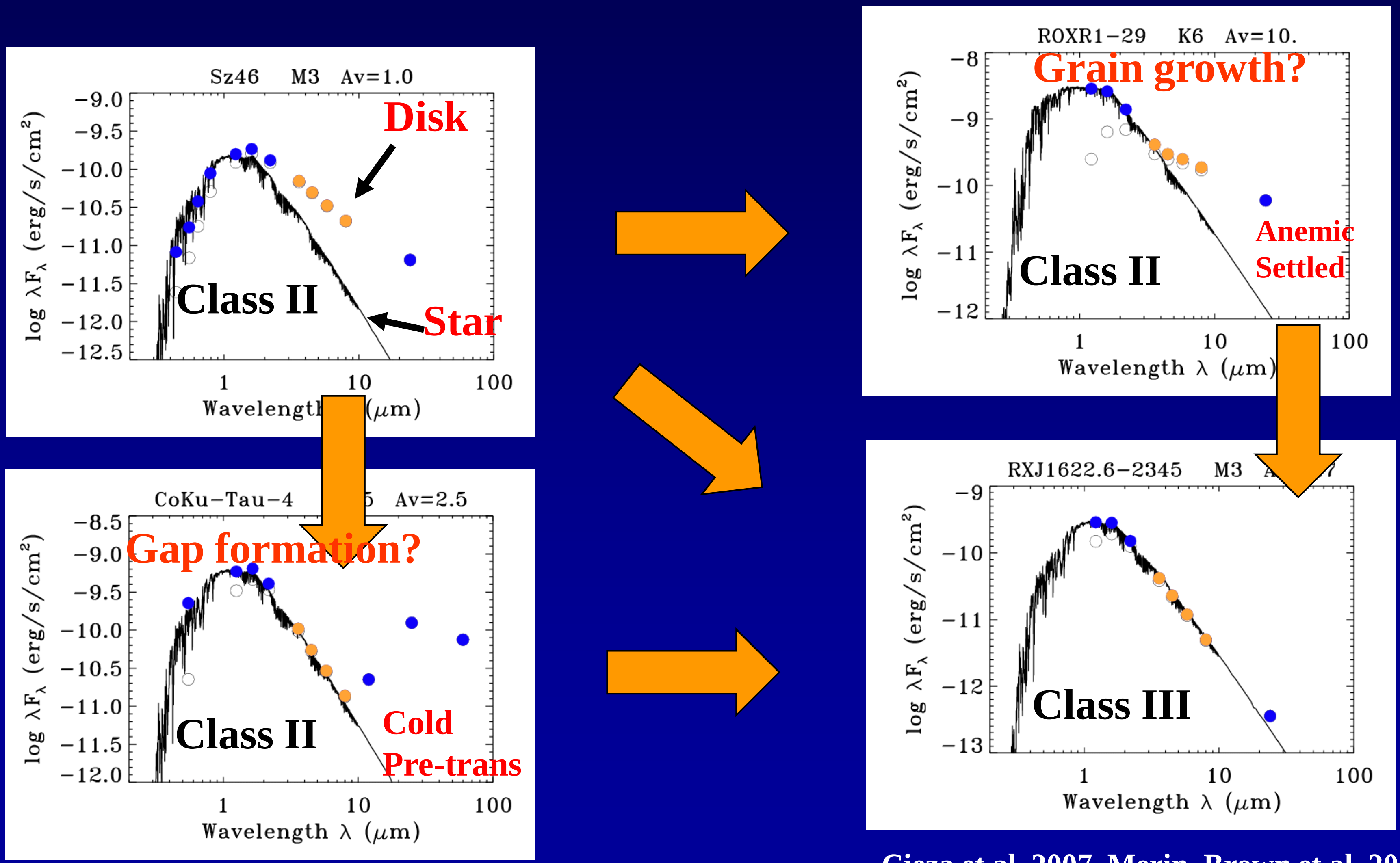
What is the origin of gaps and holes in transition disks?

What are the observational signatures of embedded planets in disks?



Transitional disks

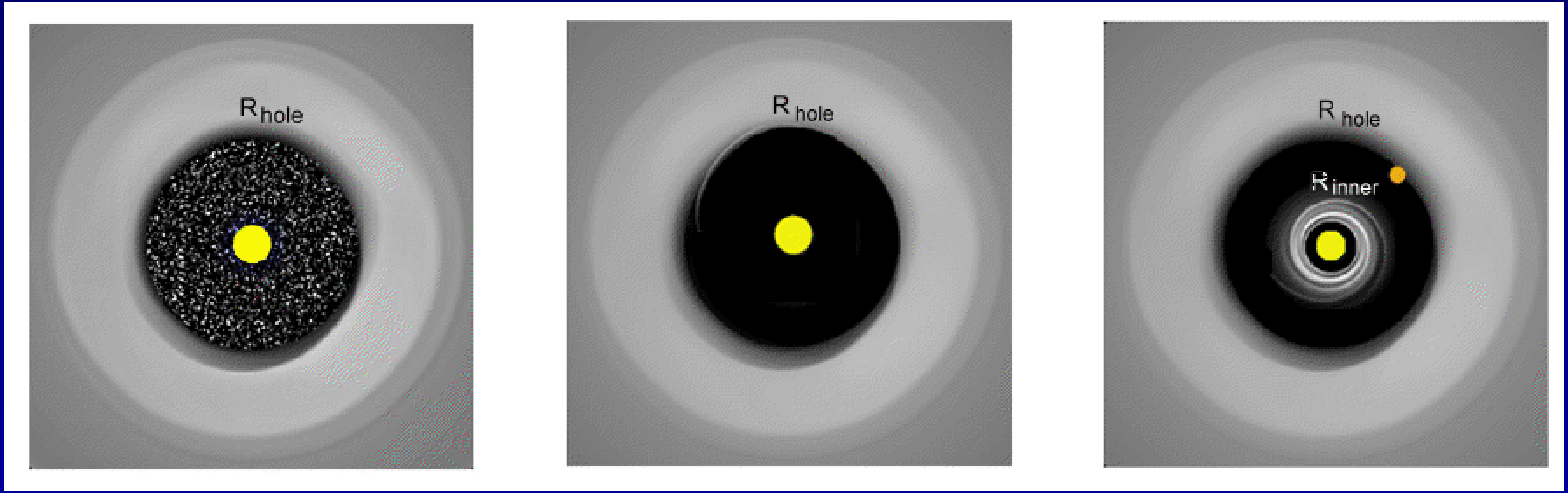
There are multiple paths from protoplanetary to debris disks



Cieza et al. 2007, Merin, Brown et al. 2010

Transitional disks

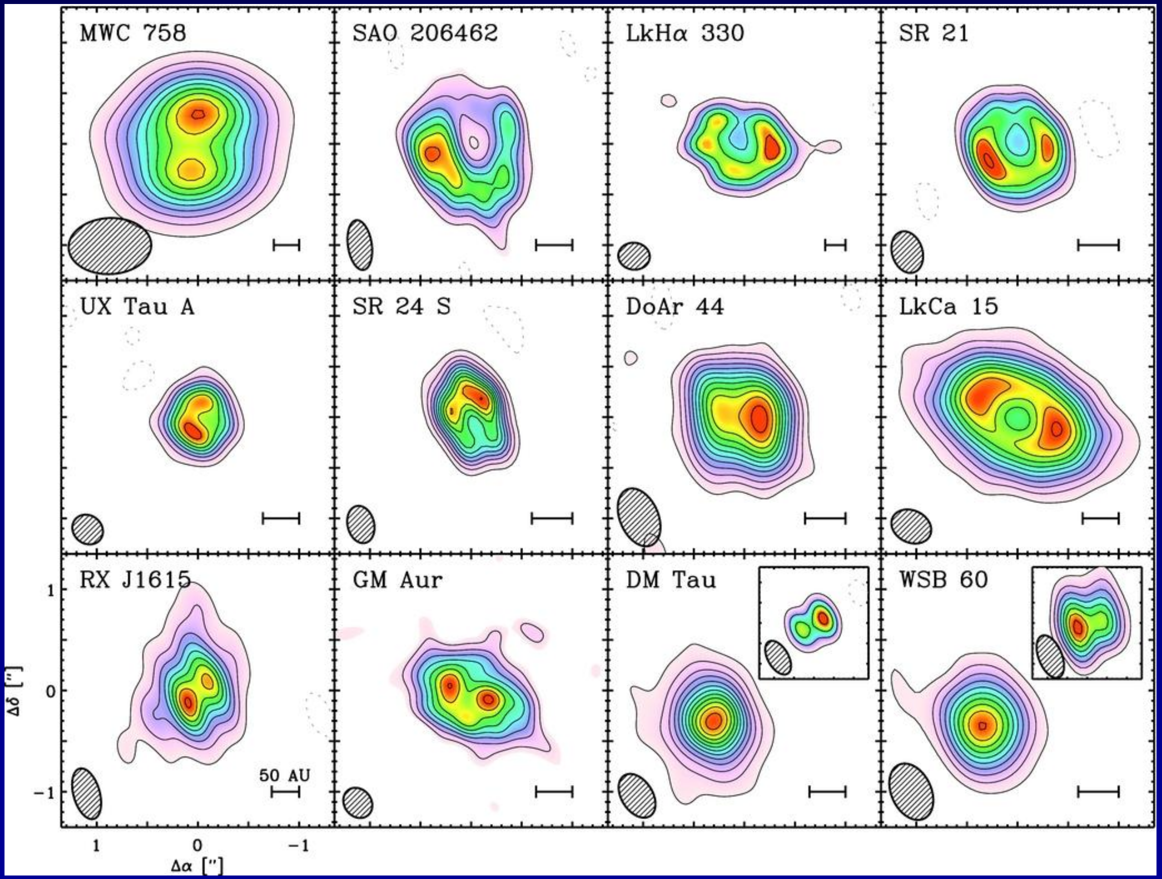
Dust hole mechanisms



Cartoon
Strom & Najita

ALMA resolved images of dust and gas can distinguish them

Transitional disks: pre-ALMA images

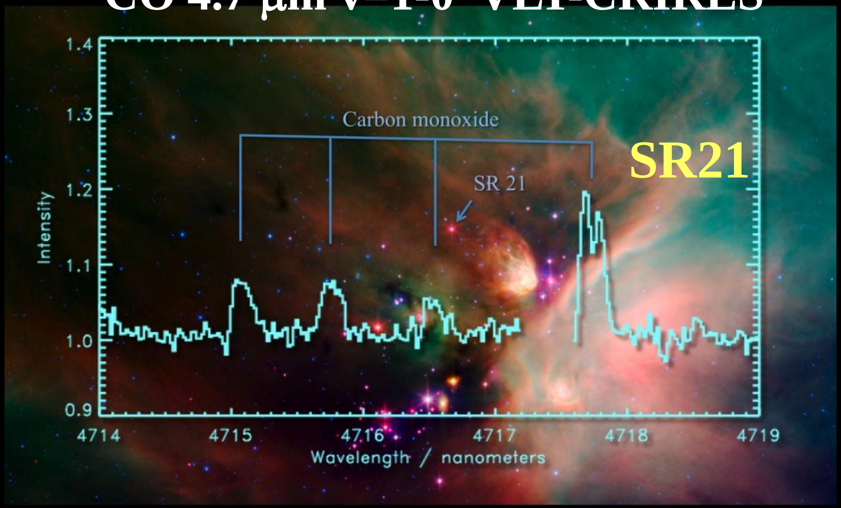


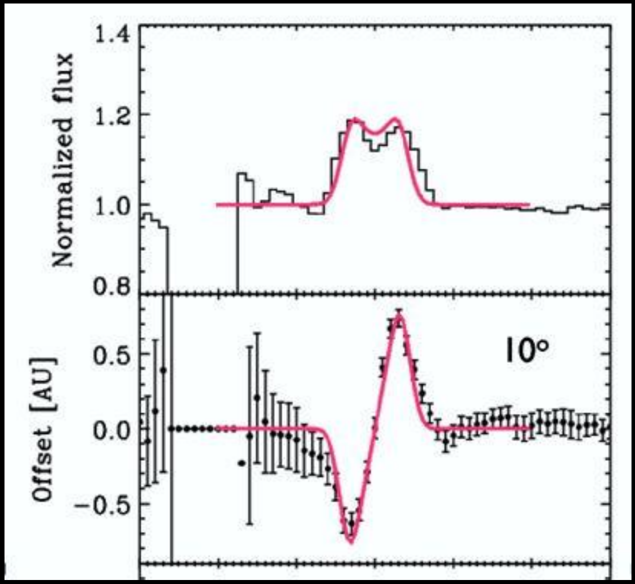
Brown et al. 2008, 2009
Andrews et al. 2011
Lyo et al. 2011
Isella et al. 2012
Hughes et al. 2009
Pietu et al. 2006

- Dust holes found even when not obvious from SED
- Asymmetries hinted at, but too low S/N
- No sensitivity for gas

Gas inside dust holes

CO 4.7 μm v=1-0 VLT-CRIRES





- SR 21 disk has dust gap of ~20 AU

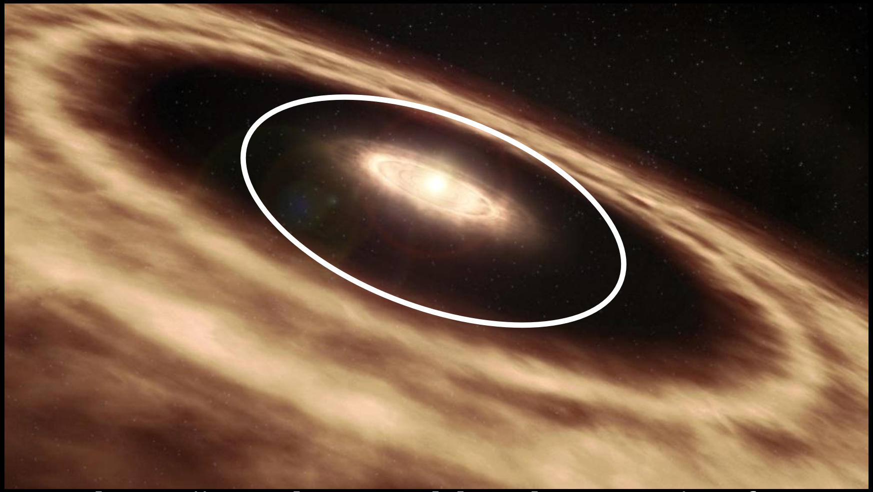
  Brown et al. 2007, 2009

- Spectroastrometry of near-IR lines pinpoints location to 7±1 AU
  ⇒ well inside gap!

  Pontoppidan et al. 2008

- Molecules can survive inside dust holes

  Bruderer et al. 2013



Also: Najita et al. 2003, Salyk et al. 2009, IR interferometry

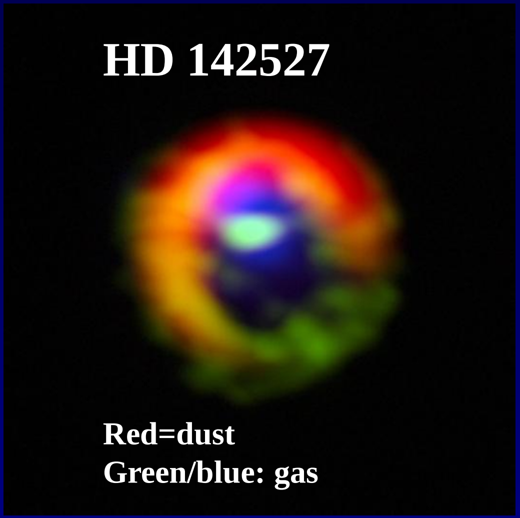
ALMA images of disks with cavities

HD135344B

Figure deleted

Perez et al.

HD 142527



Gas streams across gap

Casassus et al. 2013, Fukugawa et al.

- Asymmetries in dust and gas point to dust traps

- Traps triggered by planets?

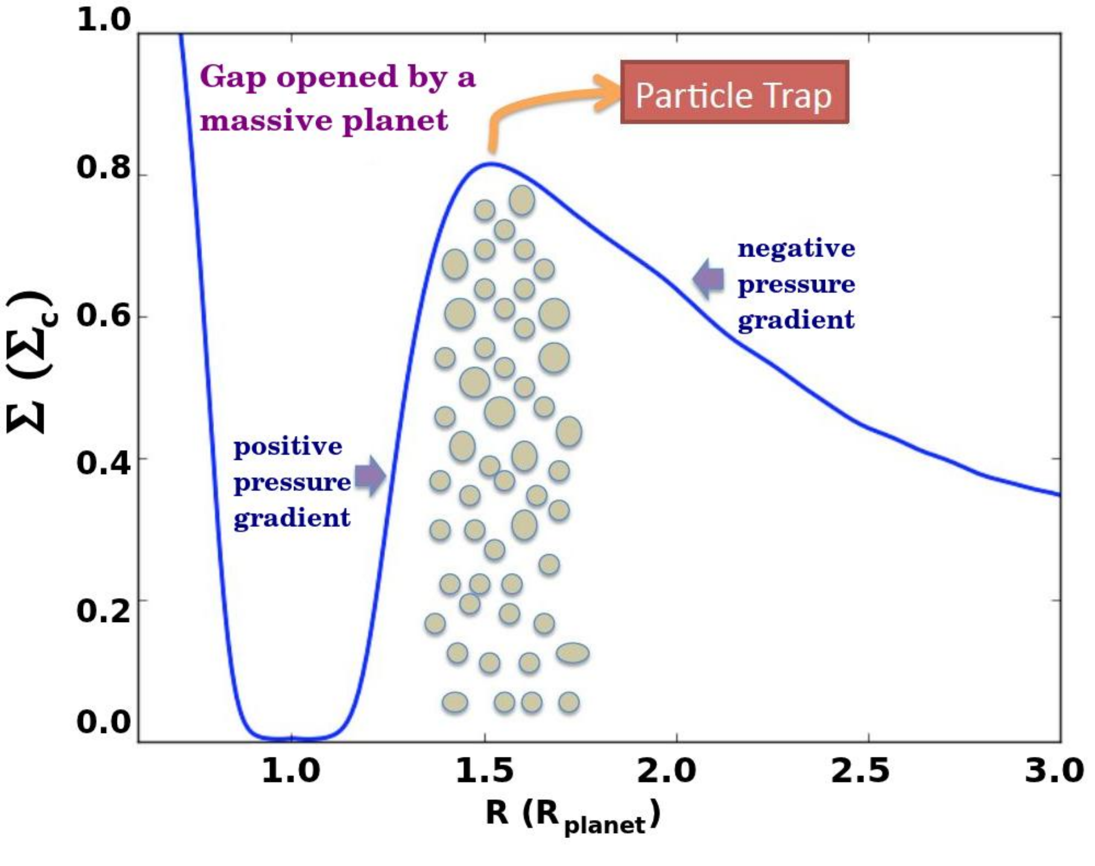
IRS48

Figure deleted

Van der Marel et al. subm.

Dust trapping by pressure bumps

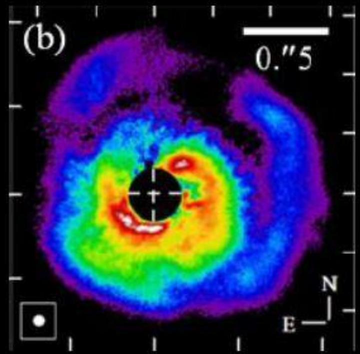
- Planet generates a radial pressure bump in gas, where dust is trapped
- Dust hole much larger than gas hole in IRS48 ⇒ massive planet (10-20 M_{Jup})



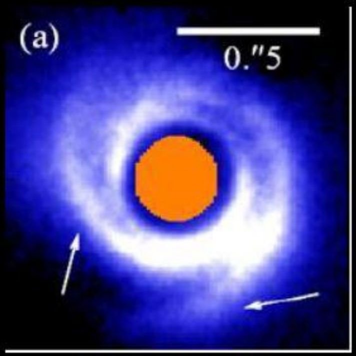
Gas and dust distribution can constrain location and mass of planet(s)→ALMA

Barge & Sommeria 1995
Klahr & Henning 1997
Pinilla et al. 2012
Birnstiel et al. 2013
+ many others

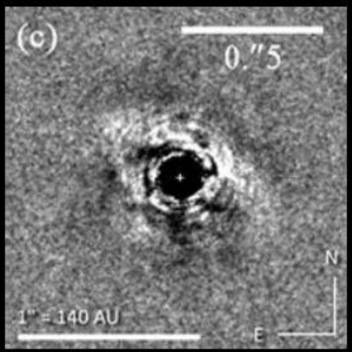
Polarimetric imaging: SEEDS



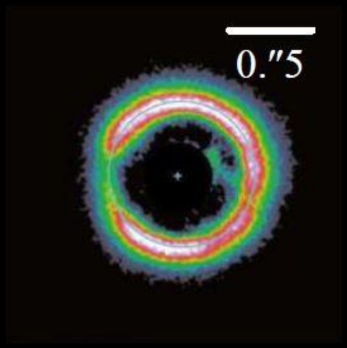
AB Aur
(Hashimoto+ 2011)



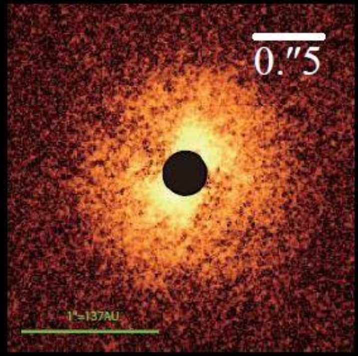
SAO 206462
(Muto+ 2012)



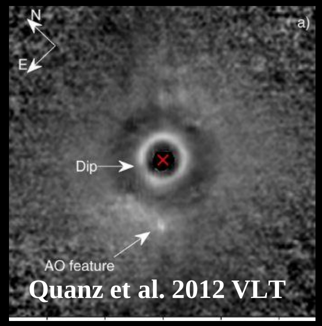
LkCa 15
Thalmann+ (2010)



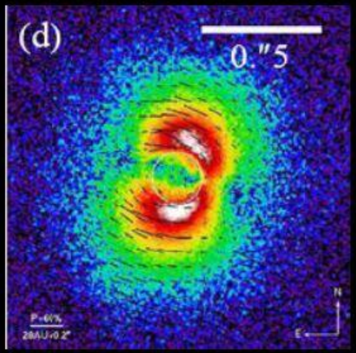
J1604-2130
(Mayama+ 2012)



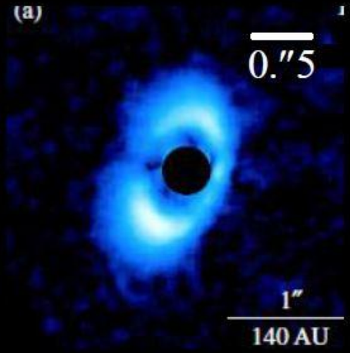
MWC 480
(Kusakabe+ 2012)



HD 169142
(Morita@ASJ2012,
Momose+ in prep.)



UX Tau A
Tanii+ (2012)



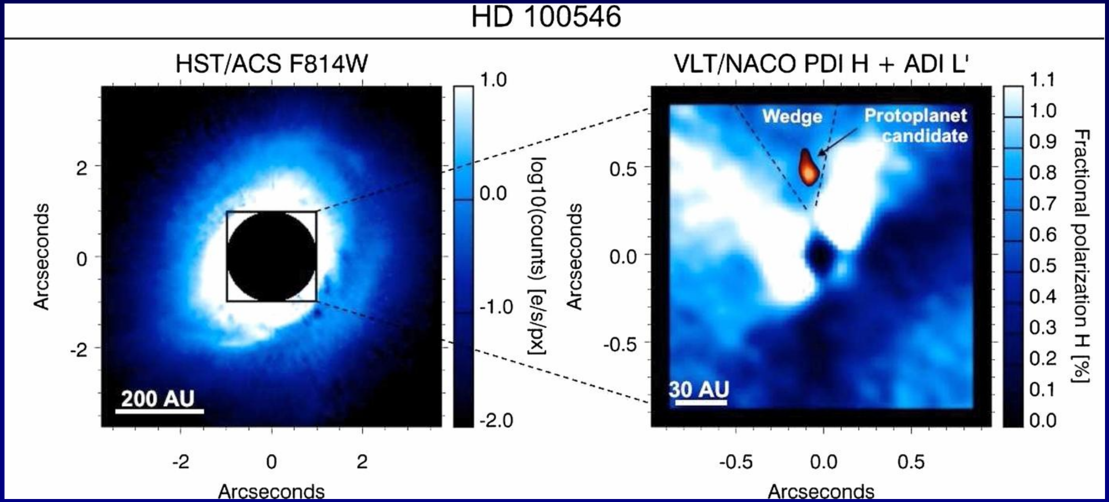
PDS 70
(Hashimoto+ 2012)

Gaps, rings, spirals, ...

Next step: link near-IR images with ALMA data

Imaging embedded protoplanets?

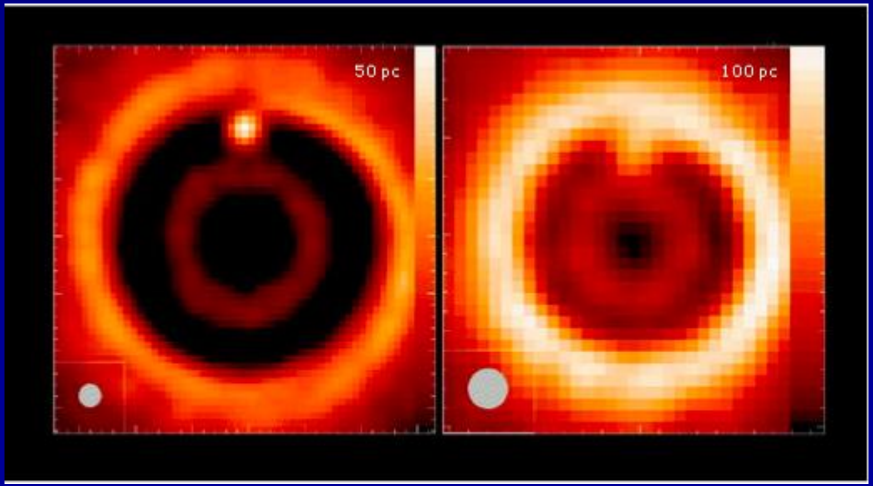
Near – IR PDI imaging



PDI imaging down to ~0.1”

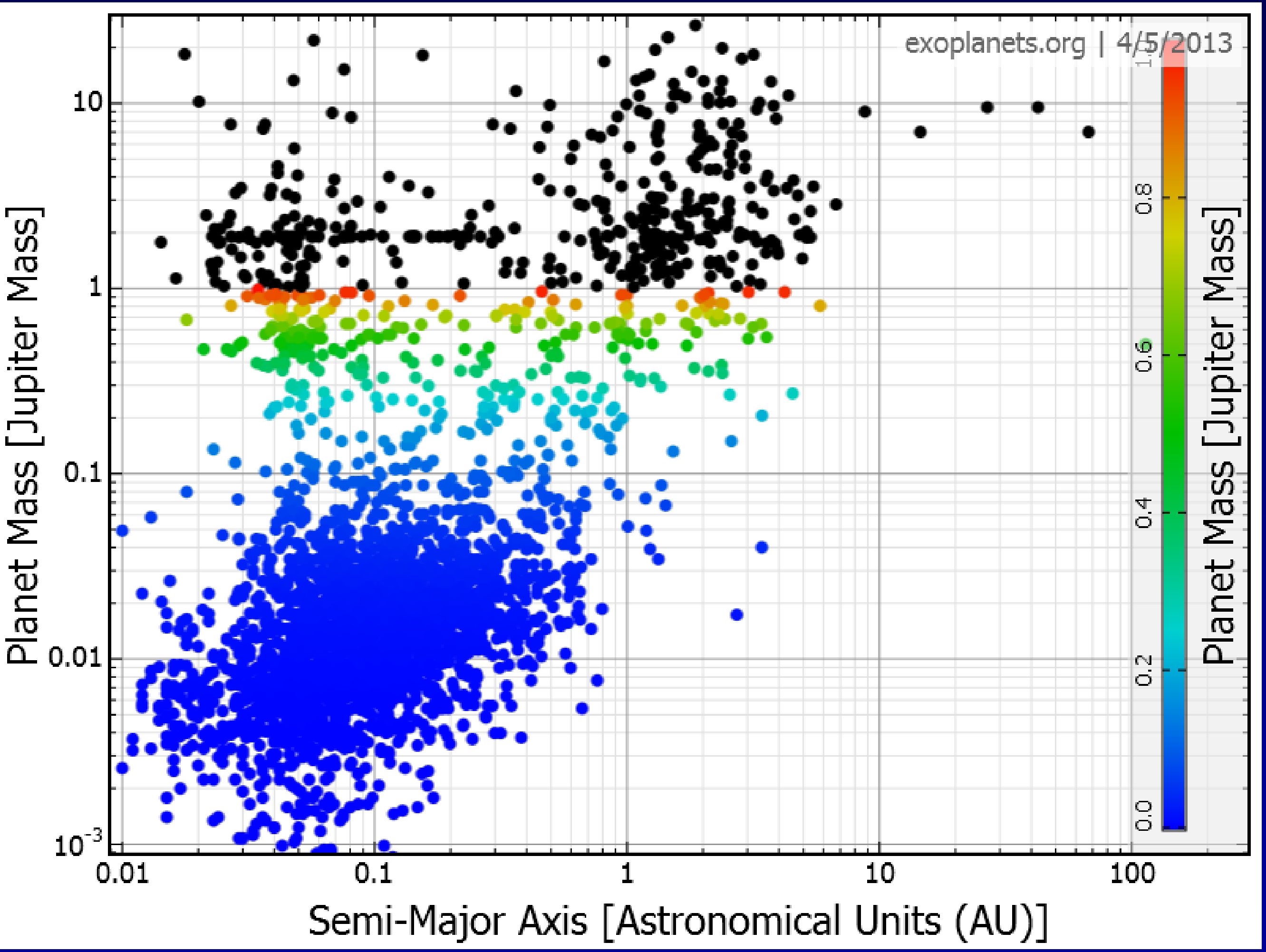
Quanz et al. 2013

ALMA simulation



Wolf & d’Angelo 2005

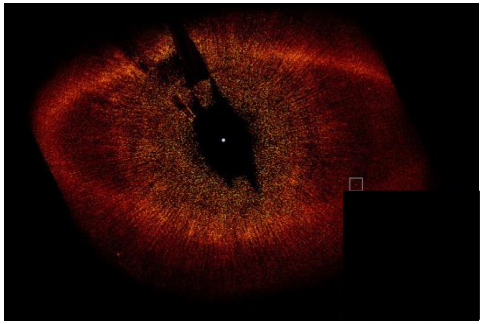
Confirmed exoplanets
(w/wo Kepler candidates)



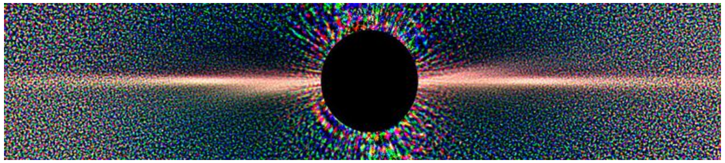
How do these statistics compare with hole sizes?→ Migration
Check with population synthesis models

Debris disks
What do they tell us about planet formation?

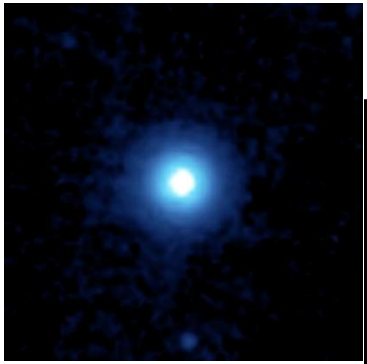
The Fab Four



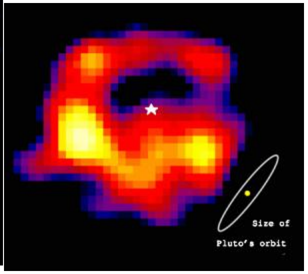
Fomalhaut



β Pic

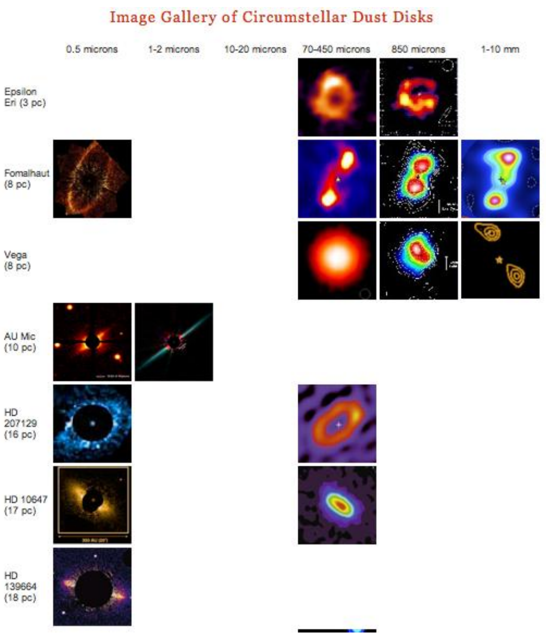


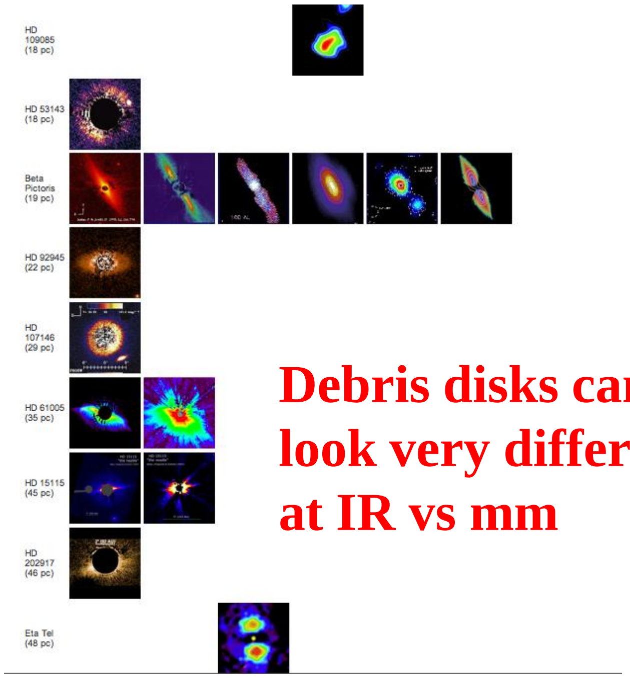
Vega



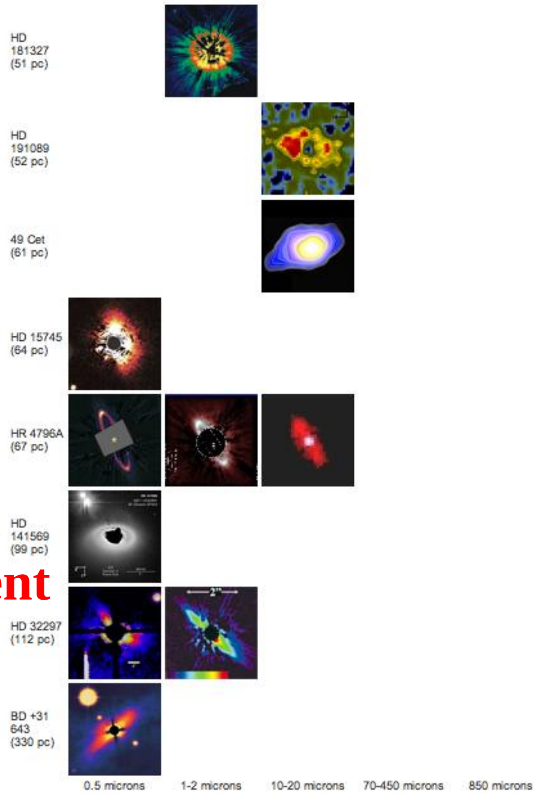
ε Eri

Many more debris disks





Debris disks can look very different at IR vs mm



Courtesy: Paul Kalas, www.disksite.com

Dynamical processes

- **Oligarchic growth**
  - **Scattering**
- **Unseen planet**
  - **Secular perturbations**
  - **Resonant perturbations**

Debris disk does not necessarily imply planet

(but is often the most plausible explanation)

Wyatt 2008

Dust migration structures due to planet

I low mass, low eccentricity

e.g., Dermott et al. (1994),

Ozernoy et al. (2000) ε Eri

II high mass, low eccentricity

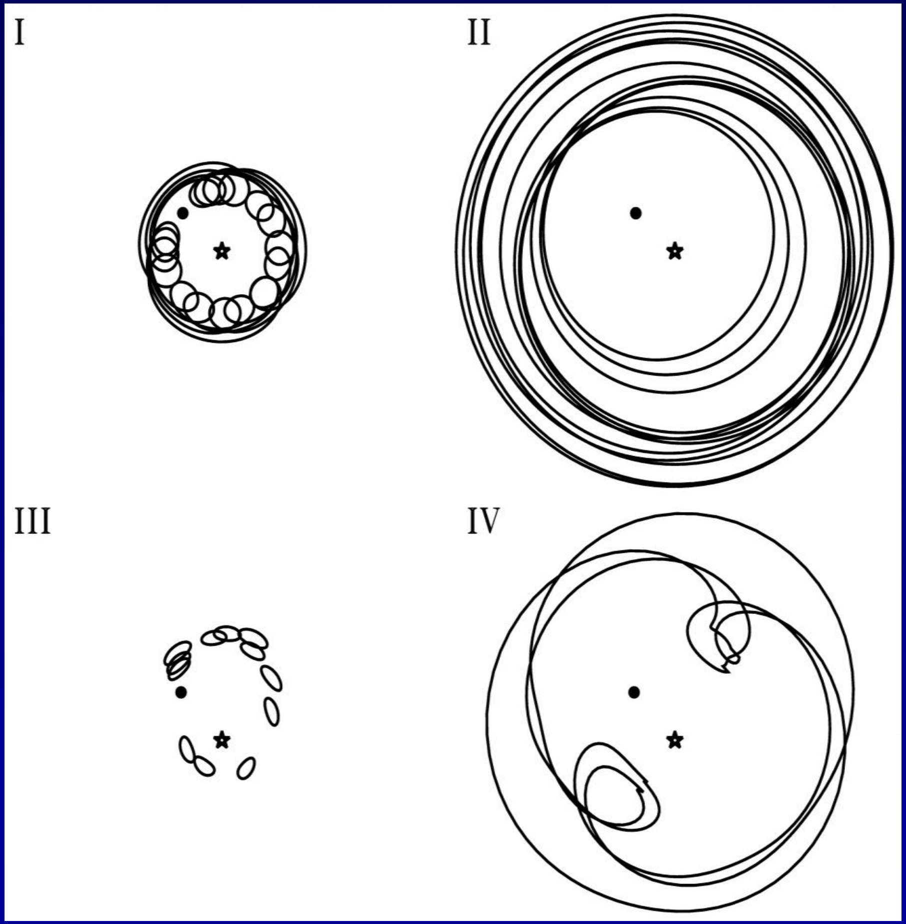
e.g., Ozernoy et al. (2000) Vega

III low mass, high eccentricity

e.g., Quillen & Thorndike (2002)

IV high mass, high eccentricity

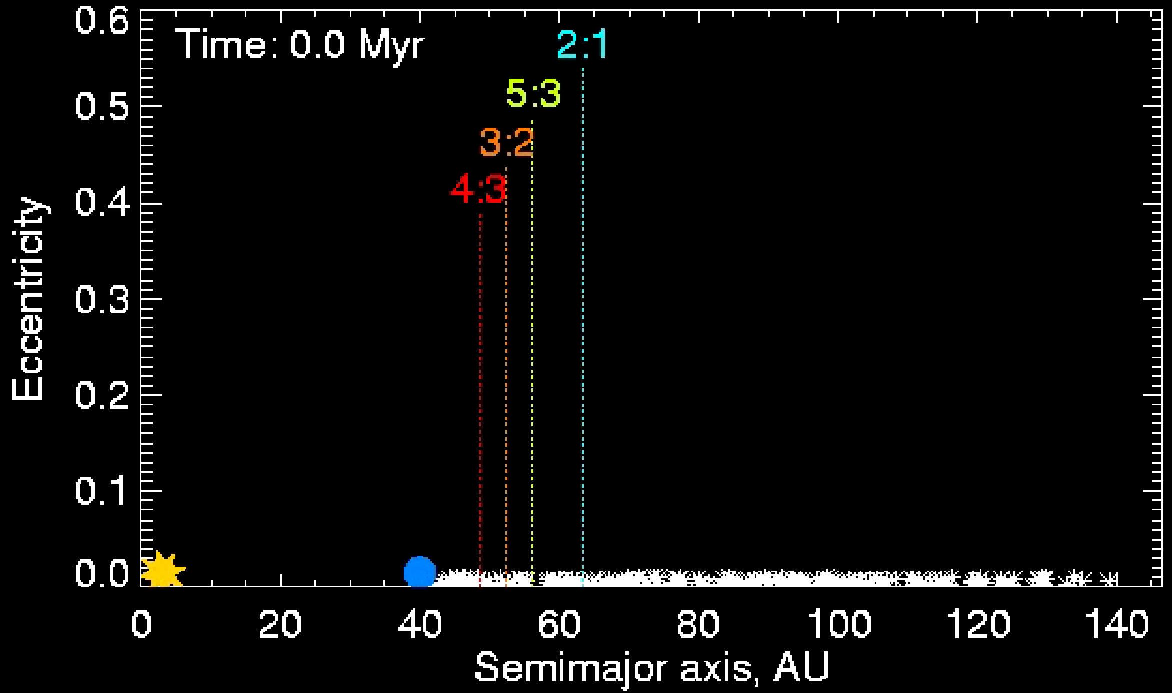
e.g., Wilner et al. (2002), Moran et al. (2004)



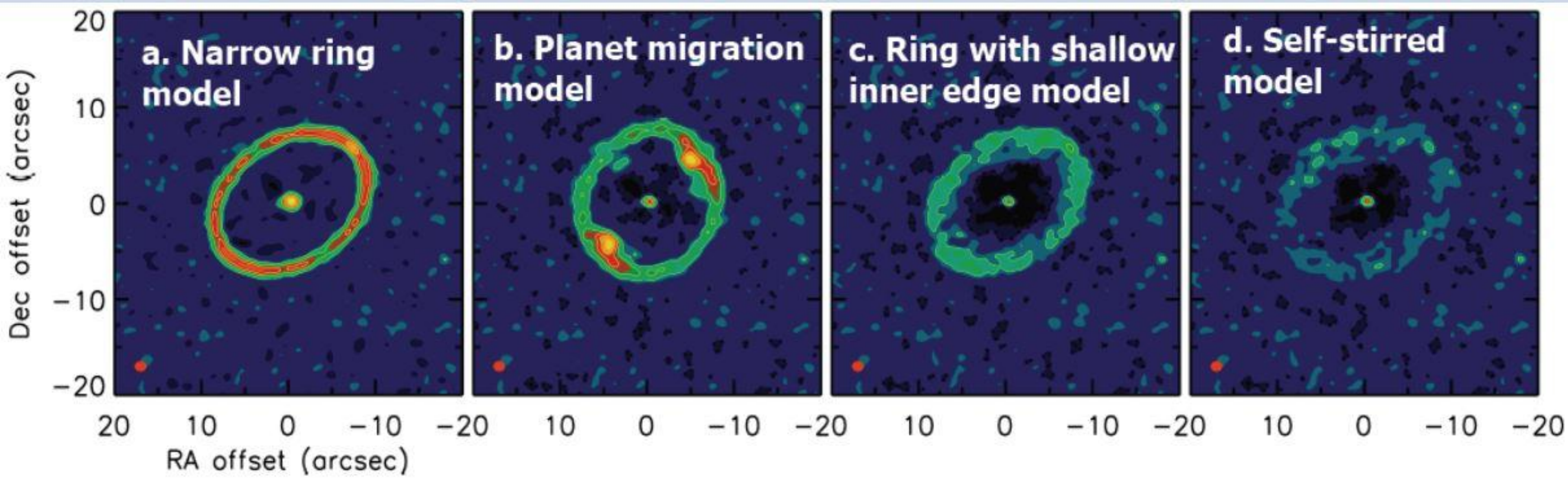
Kuchner & Holman 2003

Populating resonances

The outward migration of a Neptune mass planet (●) around Vega sweeps many comets (∗) into the planet's resonances



Planetary architectures from ALMA data

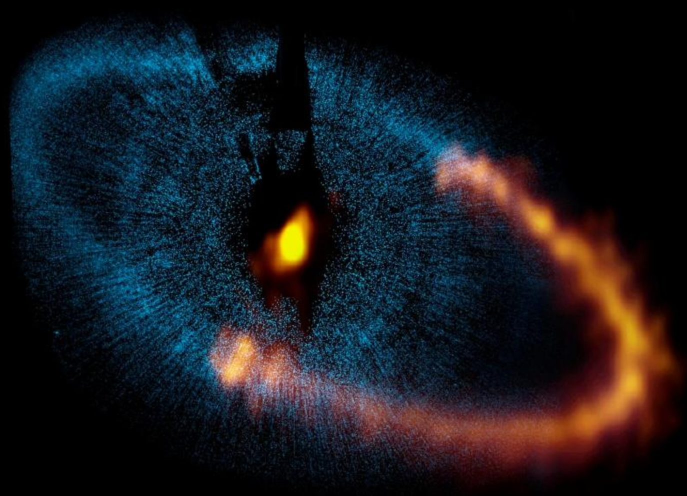


Belt shepherded by planets	Outward migrating planet at inner edge	Late Heavy Bombardment	Planets still growing in outer disk

Wyatt 2012
Hakone meeting

ALMA images of debris disks

Fomalhaut

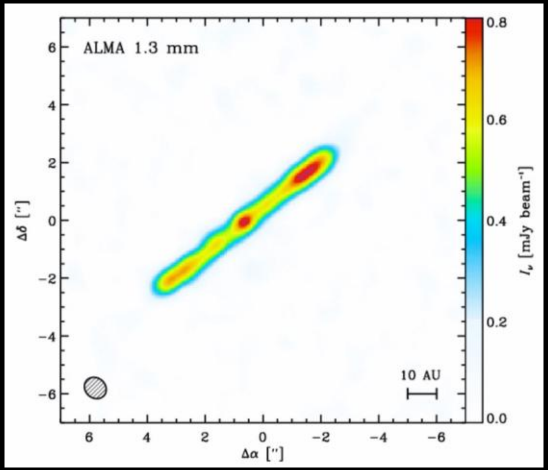


Boley et al. 2012

Distribution of dust consistent with presence of shepherding planets

AU Mic

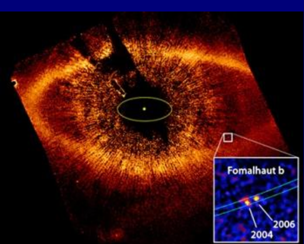
HST



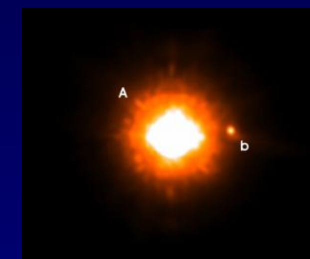
Exo-Kuiper Belt at ~40 AU

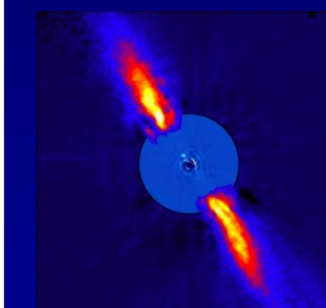
MacGregor et al. 2012

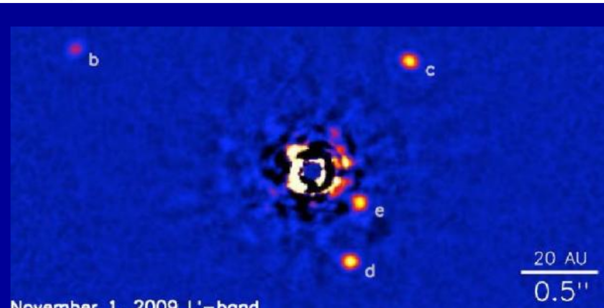
Directly imaged young planets



Host	SpT	Distance (pc)	Separation (AU)	Mass (MJ)	Age (Myr)	Reference
Beta Pic	A5V	19	8	7-12	8-30	Lagrange+10
HR8799	A5V	39	15,24,38,68	5-13	30-160	Marois+08
GJ758	**G9**	**16**	**29**	**10-30**	**0.7-6000**	**HiCIAO/SEEDS**
Kap And	**B9**	**52**	**55**	**13**	**30**	**HiCIAO/SEEDS**
SEEDS-P1	**G0**	**18**	**44**	**~3**	**200**	**HiCIAO/SEEDS**
DH Tau		*140*	*330*	*10*	*~1*	*CIAO/SDPS*
SR21	*K4?*	*125*	*1100*	*12.5*	*~1*	*Kuzuhara+11*
GQ Lup	*K7*	*156*	*100*	*17*	*~1*	*Neuhauser+05*
1RX160929	K7	145	330	6-11	4-6	Lafreniere+08
AB Pic	K2V	46	258	11-16	30-40	Chauvin+05
2M1207	L2	52	54	2-10	2-12	Chauvin+05
CT Cha	K7	160	440	11-23	<2	Schmidt+08







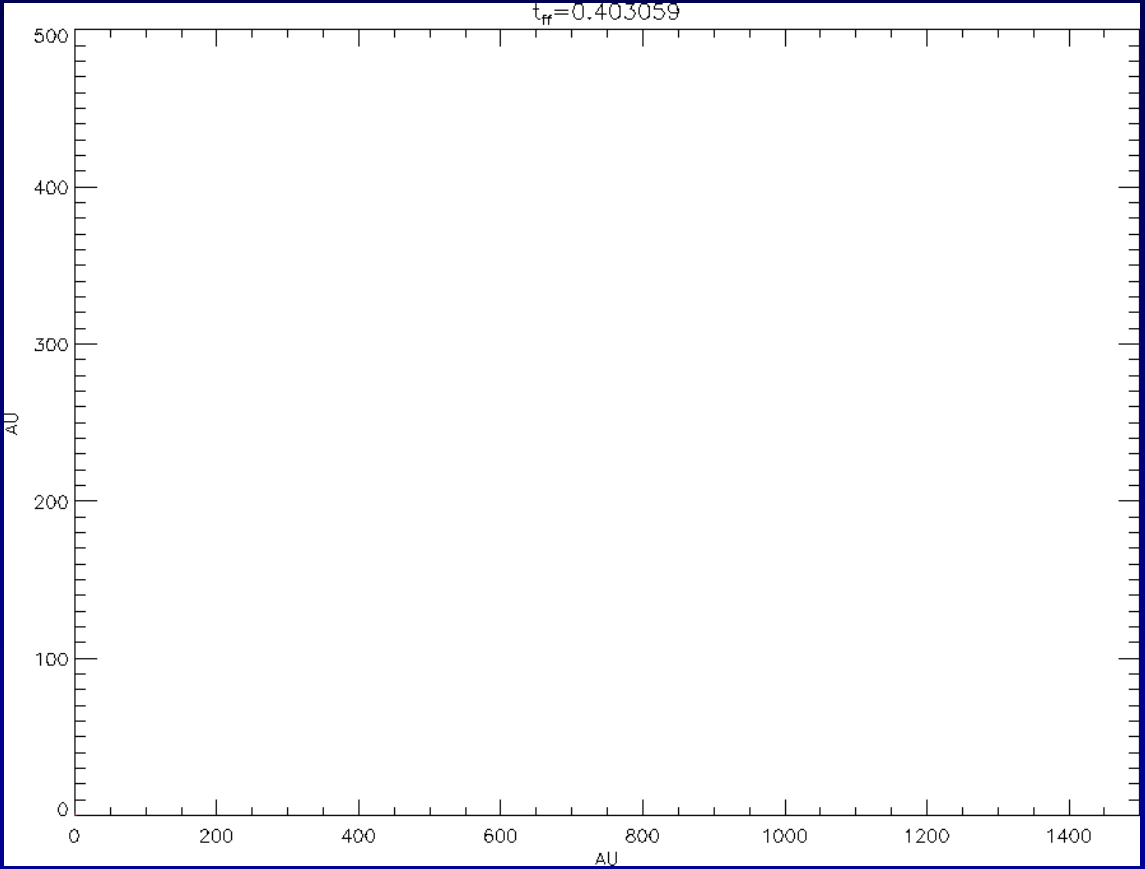
What is the full extent of disk chemistry, and what is the detectable limit of molecular material in disks?

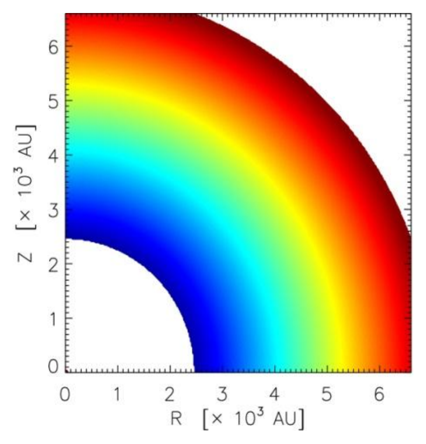
Astrochemistry

Economist March 15 2013

The great test tube in the sky

2D Disk formation



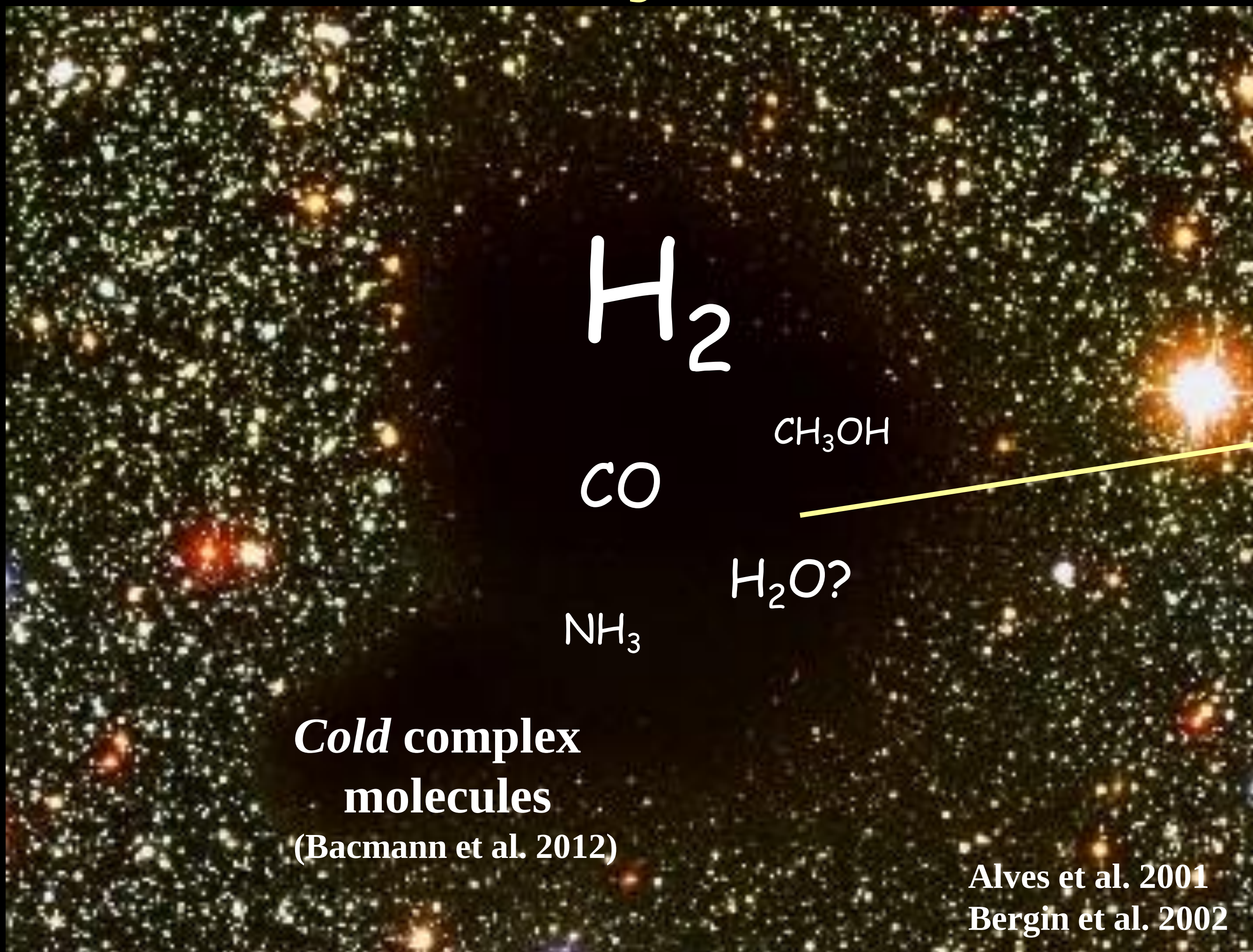


Numerical:
Van Weeren , Brinch & Hogerheijde 2008
Based on Yorke & Bodenheimer

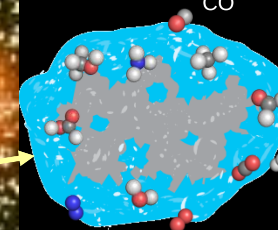
Semi-analytic:
Visser et al. 2009, 2011
Visser & Dullemond 2010

- **Layered accretion: outer envelope parcels end up in surface layer disk**
- **Accretion onto 2D disk fundamentally different from 1D**
- **More material enters disk on back side, far from star**

Cold dense cores: sites of solar systems formation



Grains with icy mantles



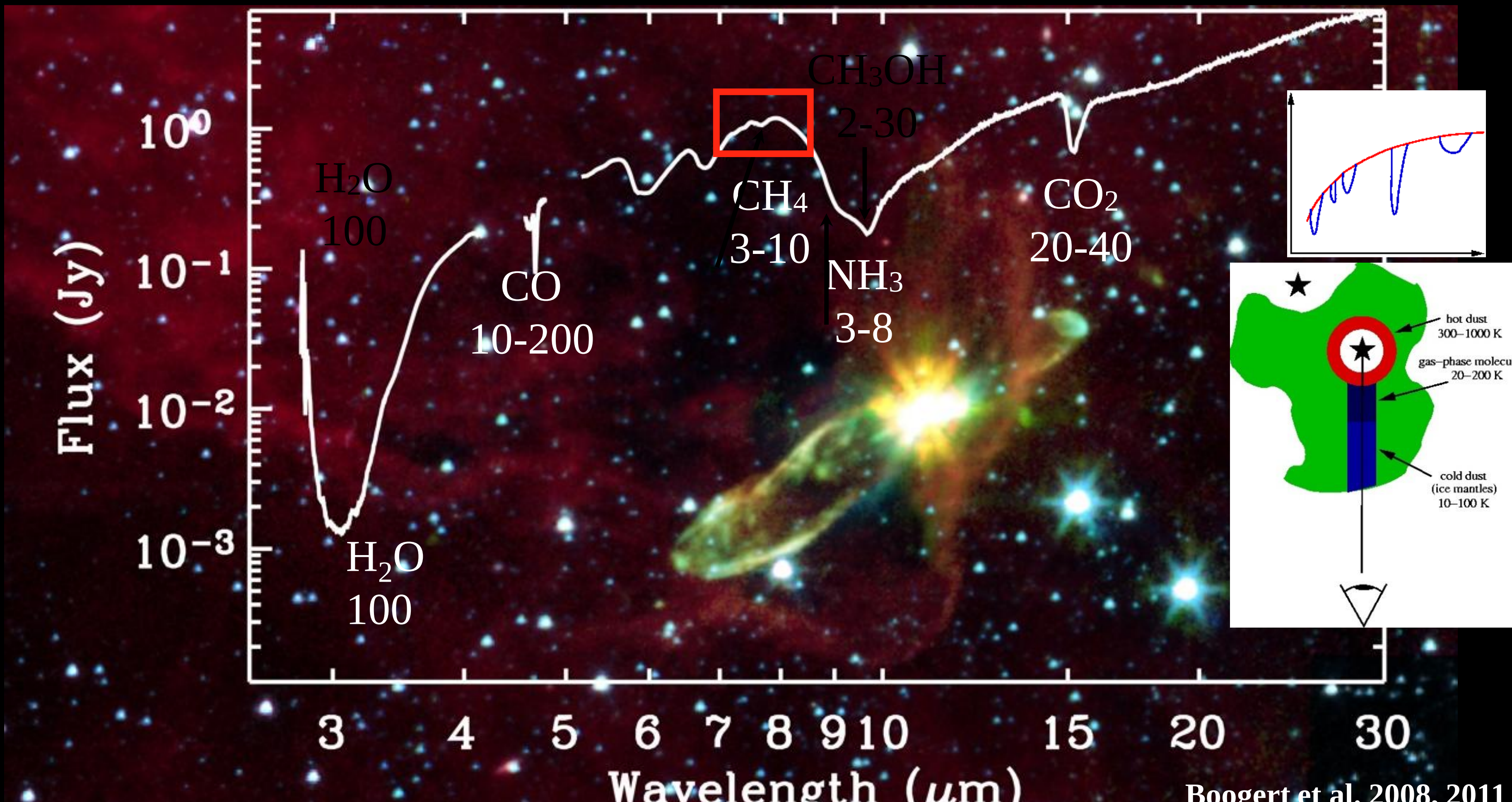
0.3 µm

t_{depl}~2.10^9/n yr

n=2.10^4 – 5.10^5 cm^{-3}, T=10 K

Many molecules frozen out onto grains

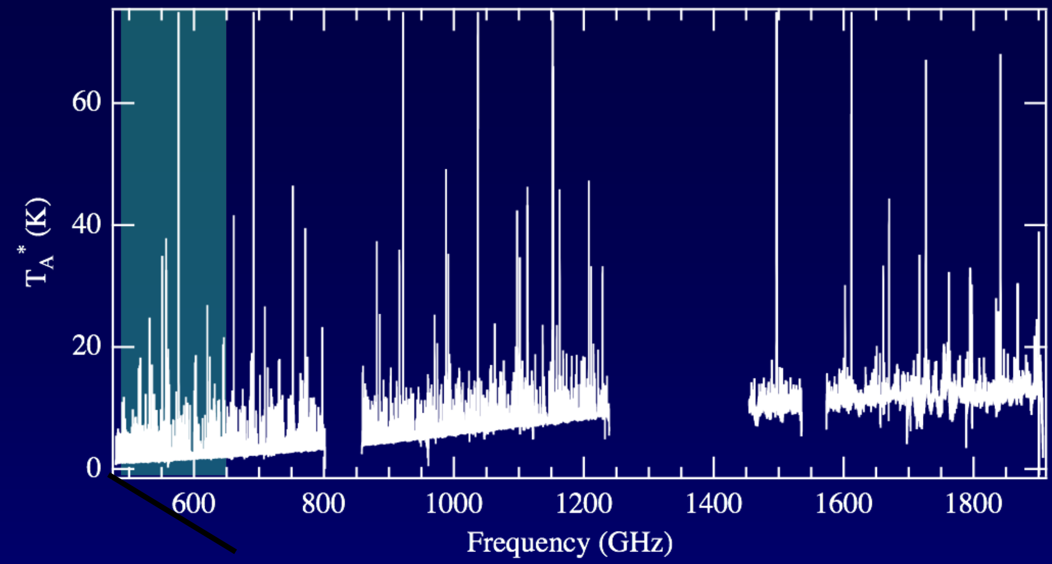
Ice inventory: Spitzer legacy



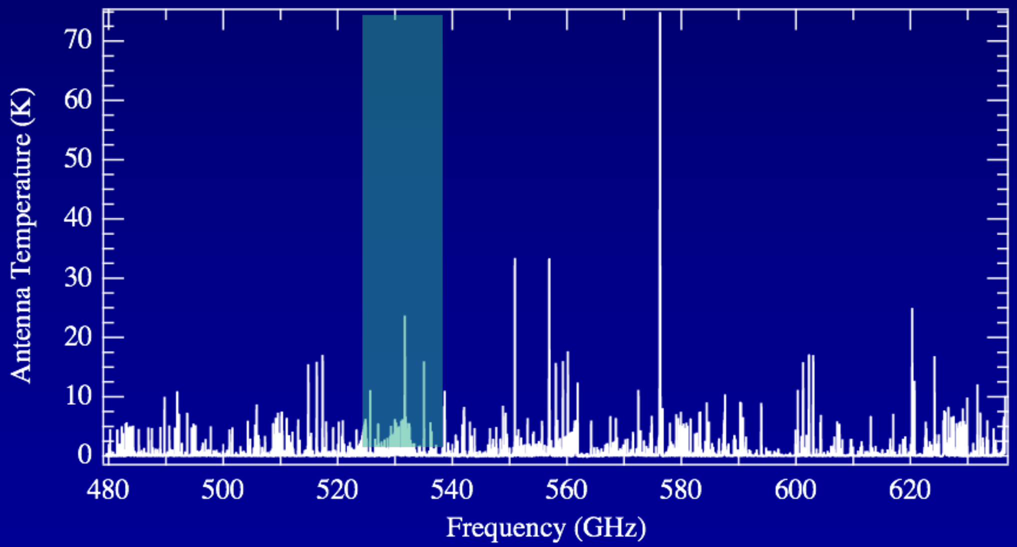
Montage: S. Bottinelli

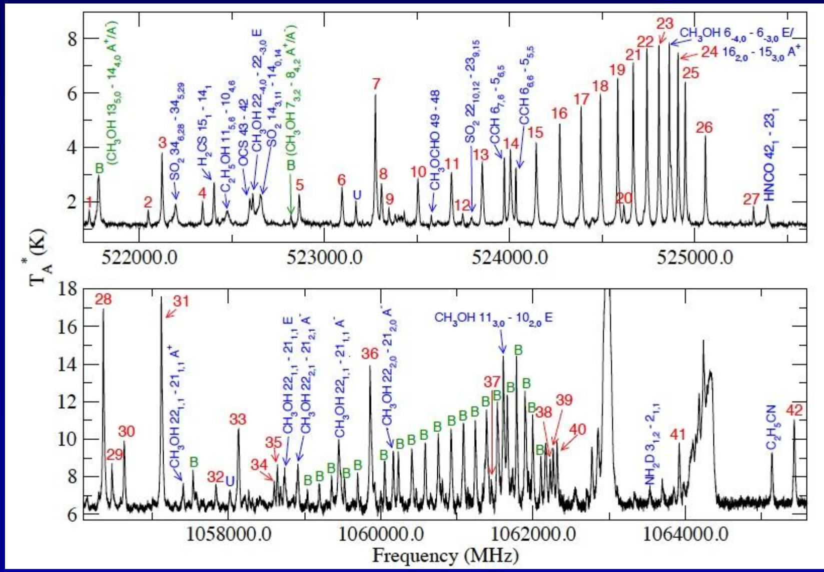
- Ices contain significant fraction of heavy elements (50% or more)
- Overall composition very similar; NH_3, CH_3OH largest variations

Boogert et al. 2008, 2011
Pontoppidan et al. 2008
Öberg et al. 2008, 2011
Bottinelli et al. 2010
Whittet , Cook, Chiar+



Orion-KL
Herschel-HIFI





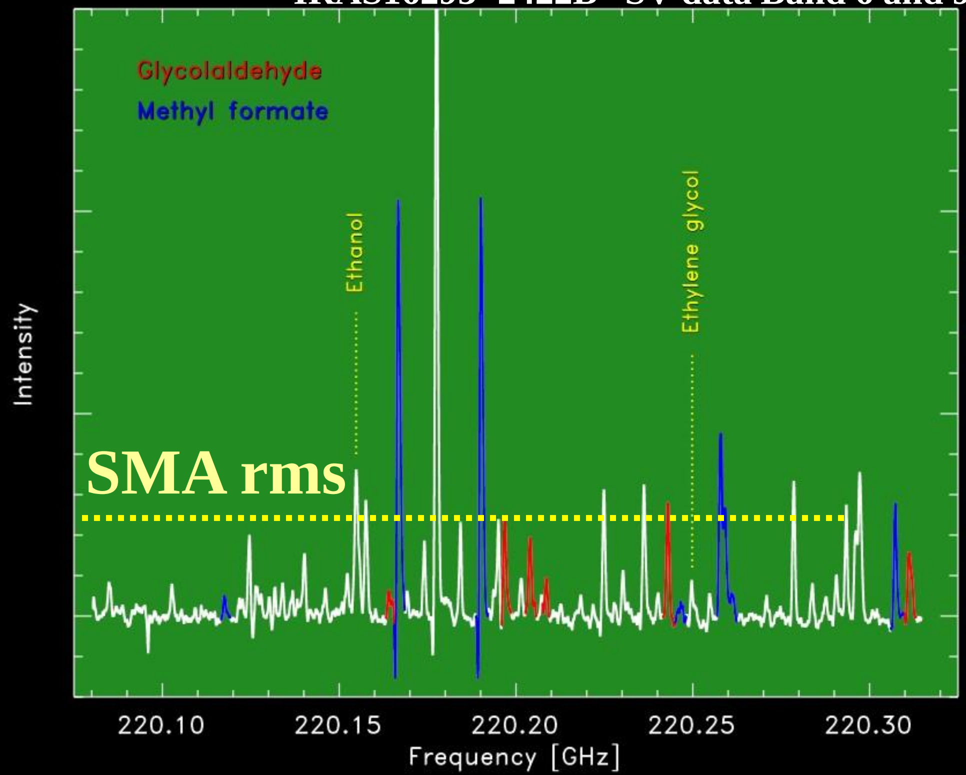
Bergin et al. 2010, Wang et al. 2010

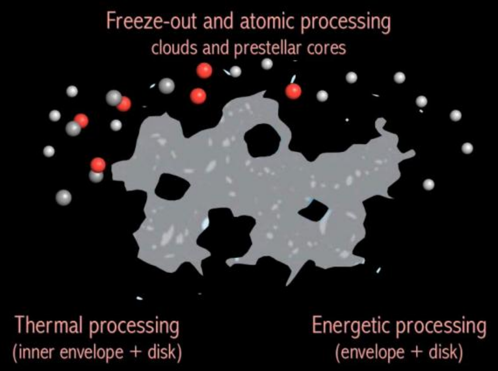
Herschel strength: excitation conditions of known species

ALMA strength: image, extent of chemical complexity

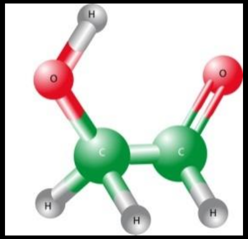
Complex organics around low-mass protostars with ALMA

IRAS16293 -2422B SV data Band 6 and 9





Öberg et al. 2009

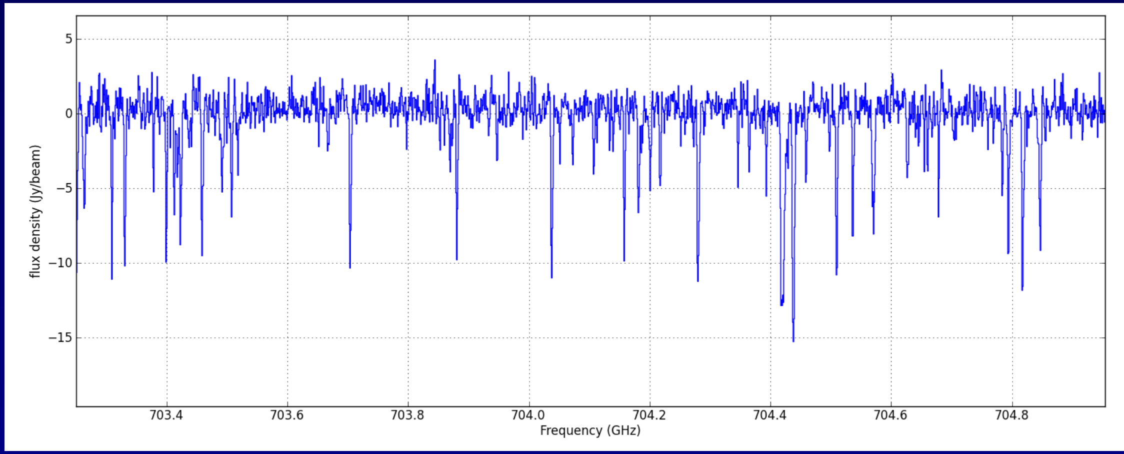


- Factor 10 more lines than previous data at this frequency
- Simplest sugar, glycolaldehyde, detected

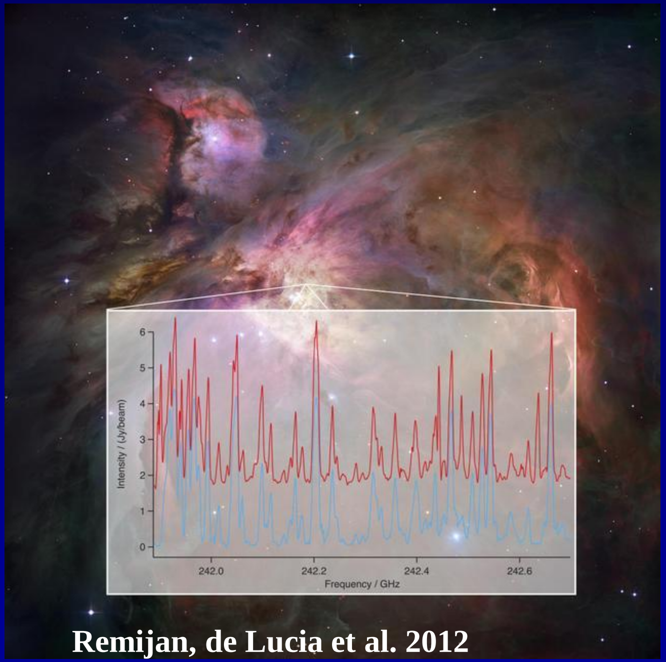
Jørgensen et al. 12

The astrochemistry (r)evolution

IRAS 16293 -2422B ALMA B9 spectrum



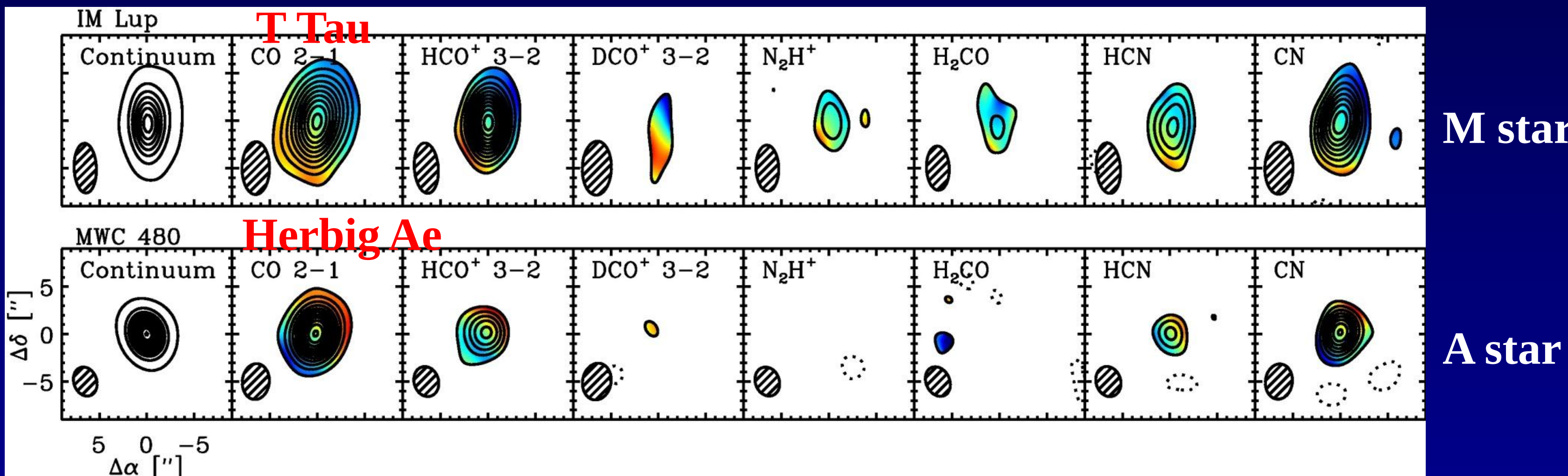
Orion B6 CSV



- Many Unidentified lines, typically 50% of lines!
- Lots of (boring) laboratory work needed to identify them

Pre-ALMA surveys of disks

DISCS SMA survey



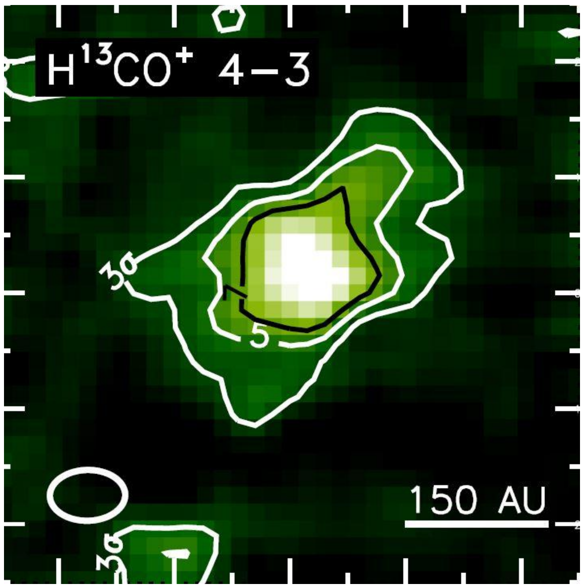
- Absence of most molecules around A stars
- No detection of molecules more complex than H_2CO, not even CH_3OH

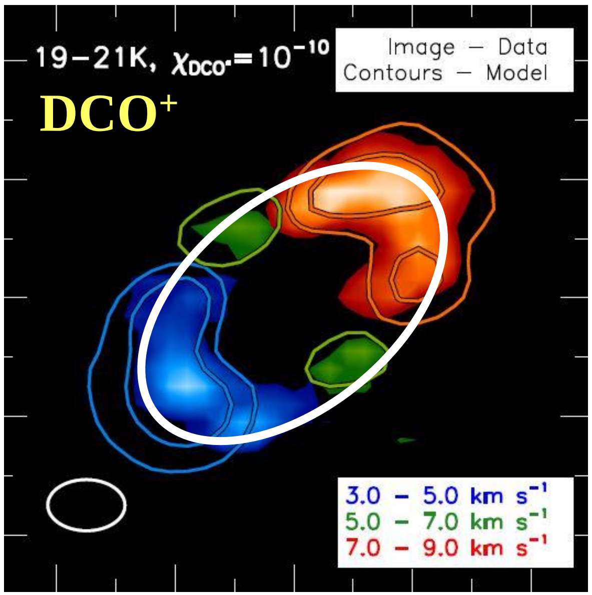
Öberg et al. 2010, 2011

Also: Dutrey et al. 2007, Thi et al. 2004
Henning et al. 2010, Chapillon et al. 2009
and others

Early ALMA results: resolved CO snow line

HD 163296 ALMA Band 7 SV data





20 K radius

G. Mathews et al. subm.
Qi et al. 2011 SMA

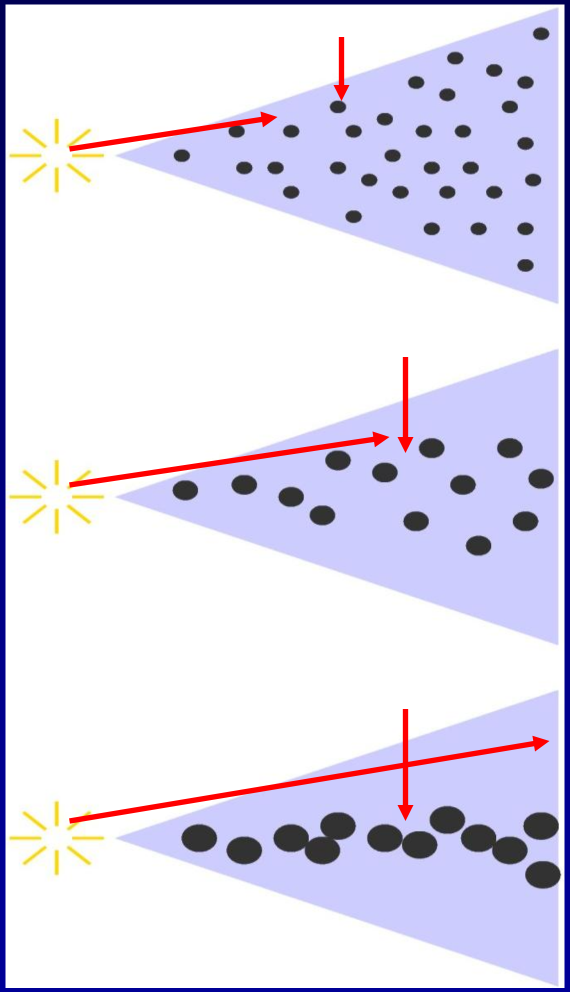
- CO freezes out at ~20 K ⟺ 145±15 AU
- Lack of CO and low o-H_2 enhances H_2D^+ and thus DCO^+

See talk Öberg for case of TW Hya using N_2H^+

Sophisticated thermo-chemical models

Importance of UV, grain growth + settling

- Disk evolution
  - Grain growth + settling
  - Mass loss
- Much deeper penetration of UV
  - Enhances photodissociation and photodesorption
  - Heats gas deeper into disk



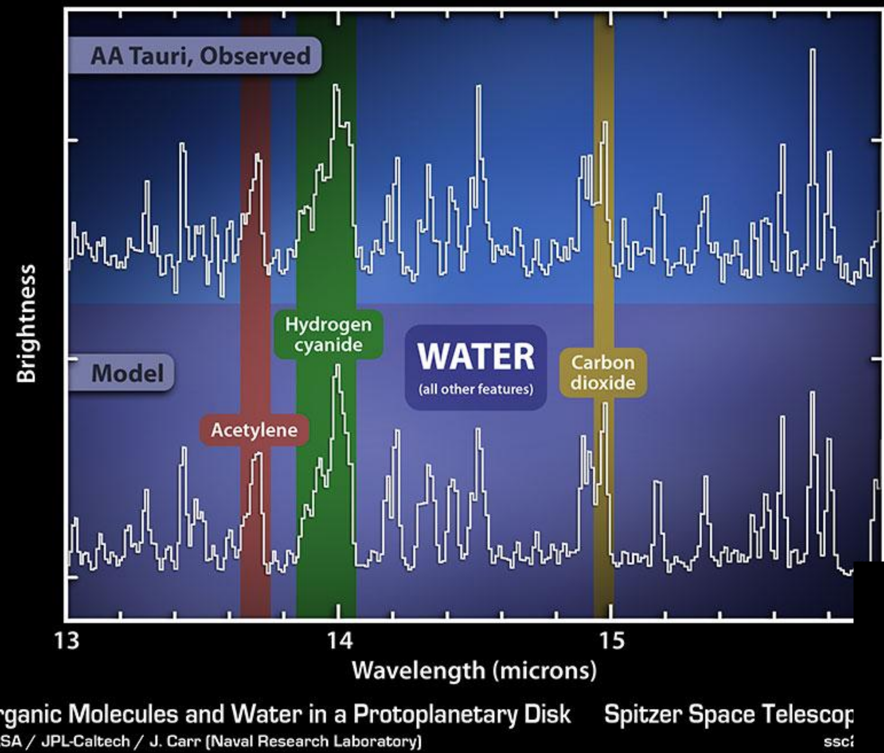
Kamp & Dullemond 2004, Jonkheid et al. 2004, 2007
Aikawa & Nomura 2006, Gorti & Hollenbach 2009
Woitke et al. 2009, 2010, Glassgold et al. 2009
Vasyunin et al. 2011, Najita et al. 2011, Walsh et al. 2012
Bruderer et al. 2012, 2013

Models provide important guideline of trends but do not take them too literally

→ 'Back to basics'

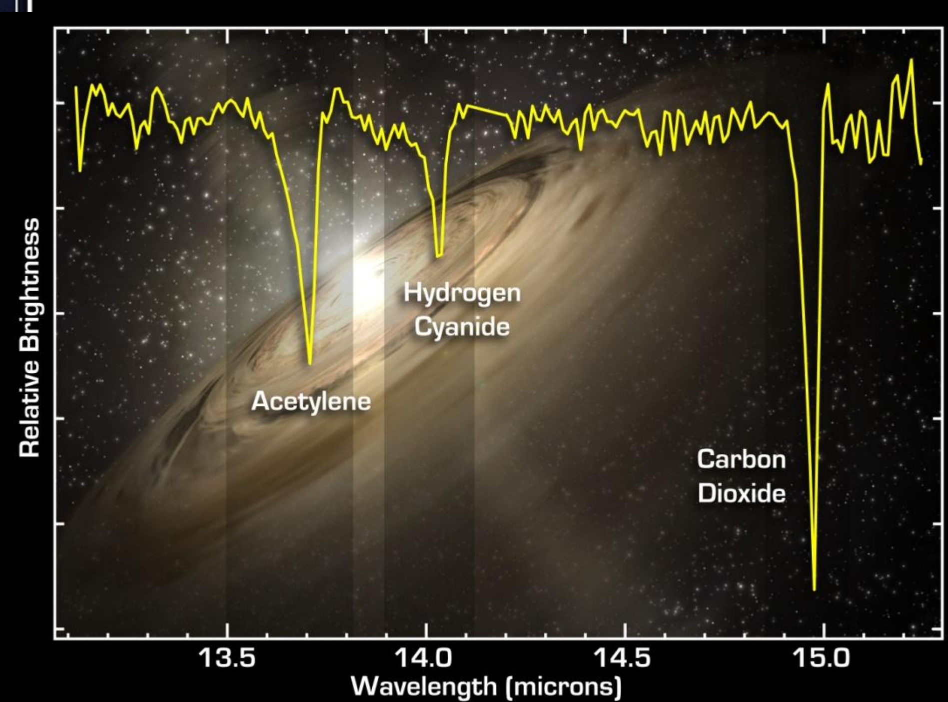
Let ALMA data speak for themselves

Inner few AU of disks: water and organics



Carr & Najita 2008, 2011
Salyk et al. 2008
Pontoppidan et al. 2010
Salyk et al. 2011
Najita et al. 2013

T Tau disks have rich chemistry, but not Herbig Ae (UV pd)

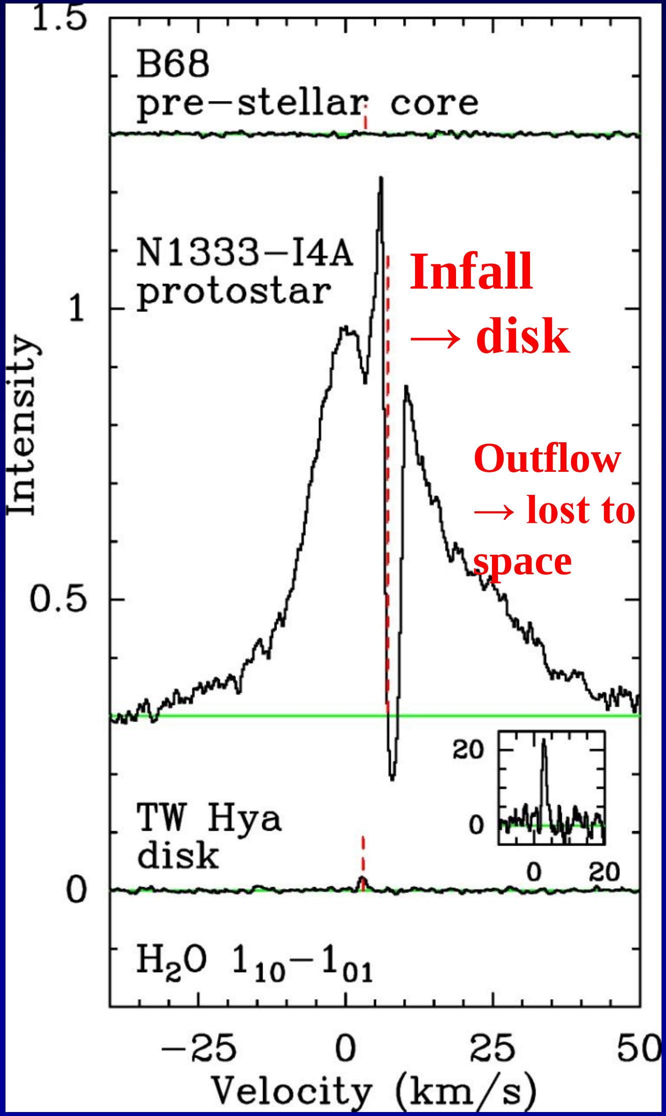


ALMA can (barely) detect the optically thick rotational lines of this hot HCN but not image them

Lahuis et al. 2006

Water: from cores to disks

Herschel –HIFI 557 GHz

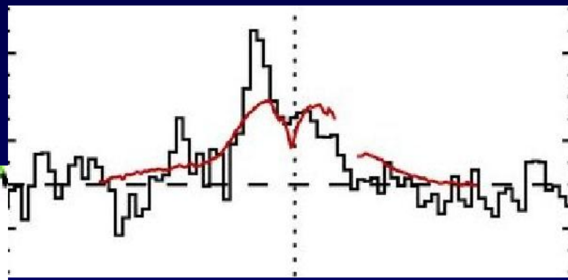


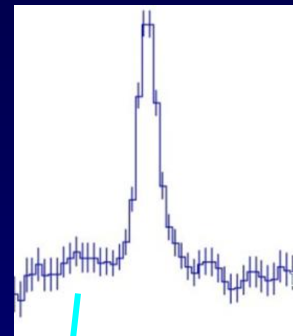
vD et al. 2011

Movie

Based on
Cuppen et al. 2010

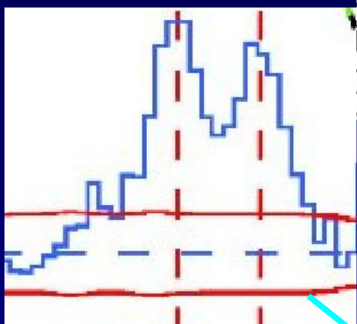
Water across the disk





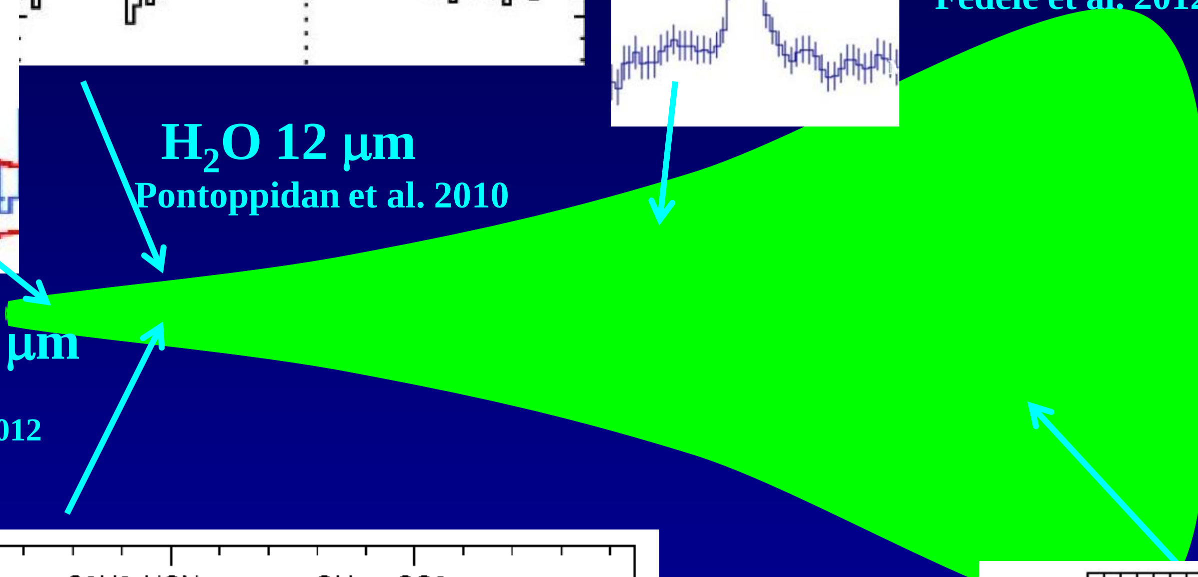
[O I] 63 μm

Mathews et al. 2010
Sturm et al. 2010, Meeus et al. 2012
Fedele et al. 2012, 2013



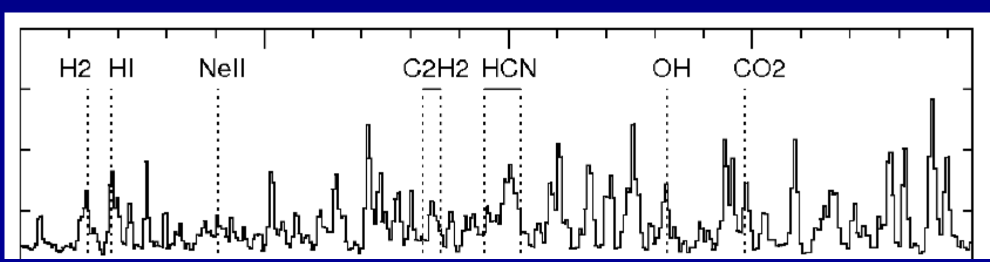
H_2O 12 μm

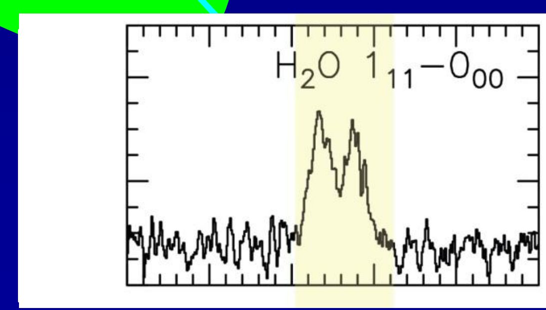
Pontoppidan et al. 2010



H_2O, OH 2.9 μm

Salyk et al. 2008
Mandell et al. 2008, 2012
Fedele et al. 2011





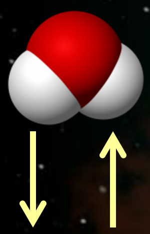
Water, OH 10-17 μm

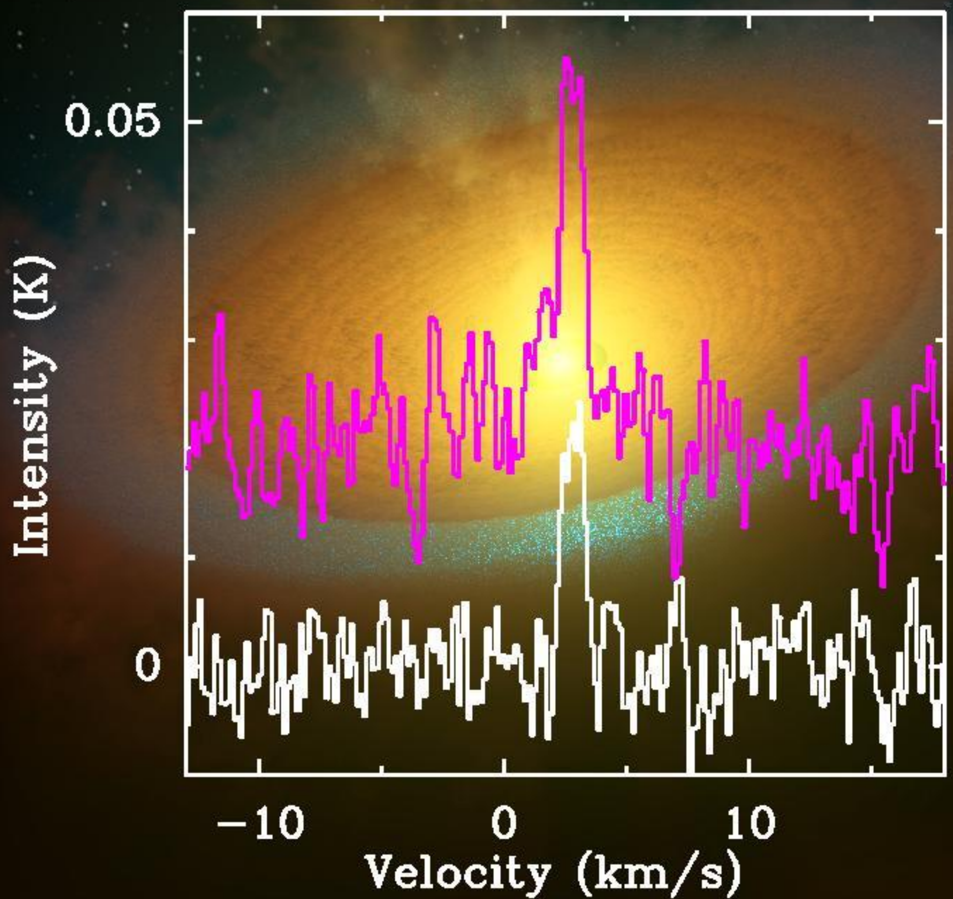
Carr & Najita 2008, 2011,
Pontoppidan, Salyk et al. 2010, 2011

H_2O submm

Hogerheijde et al. 2011, in prep.

Detection of the cold water reservoir in TW Hya disk (~6000 oceans of ice)





p-H_2O 1_{11}-0_{00}
1113 GHz

o-H_2O 1_{10}-1_{01}
557 GHz

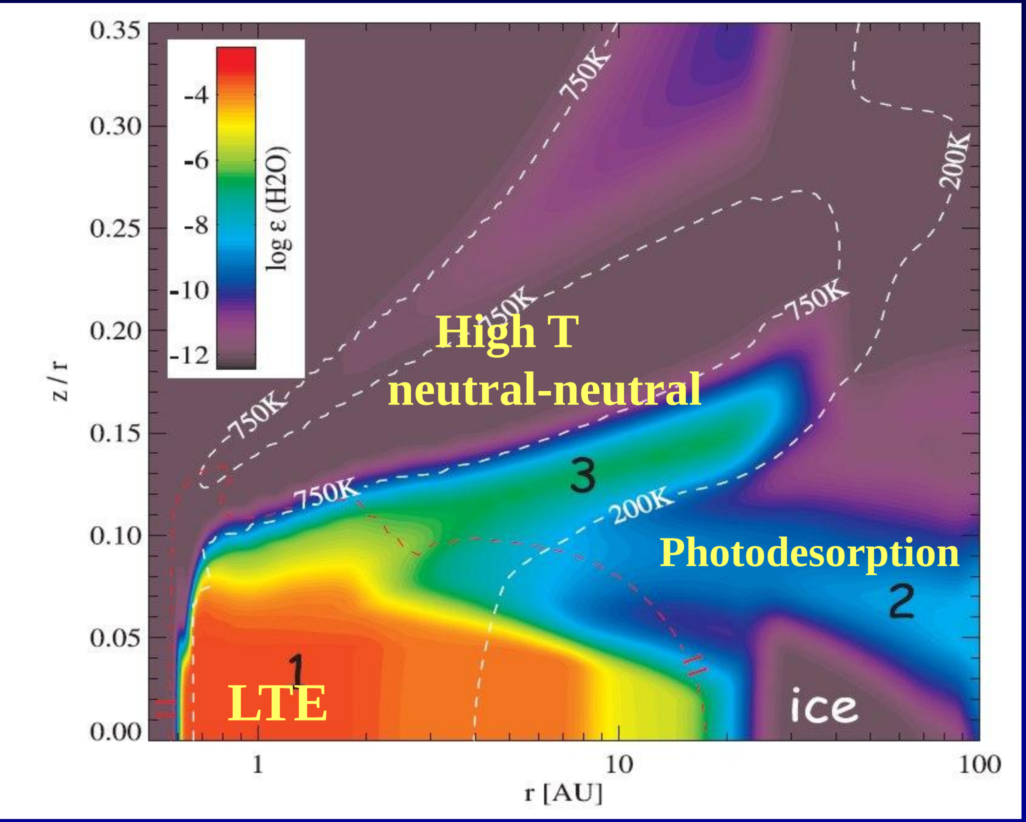
Bergin et al. 2010

Hogerheijde et al. 2011 Science

Also: HD 100546 detection

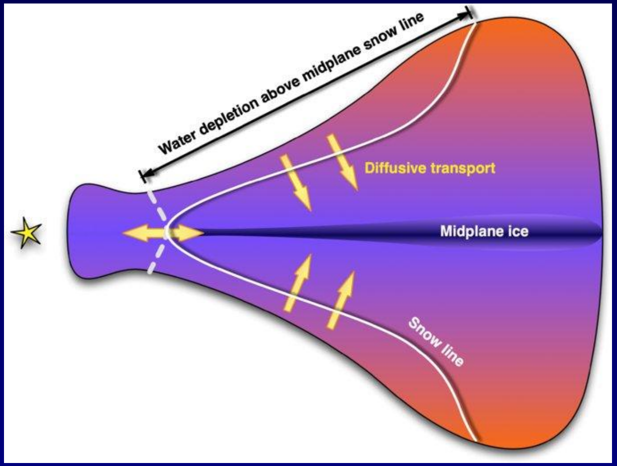
- **Emission originates from ~100 AU radius**
- **Weak signal implies settling of icy grains**

Water reservoirs: models

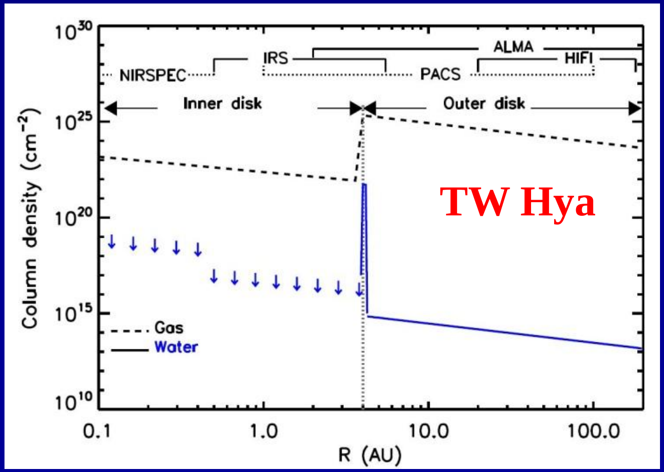


Woitke et al. 2009
Kamp et al. subm.

Probing the snow line

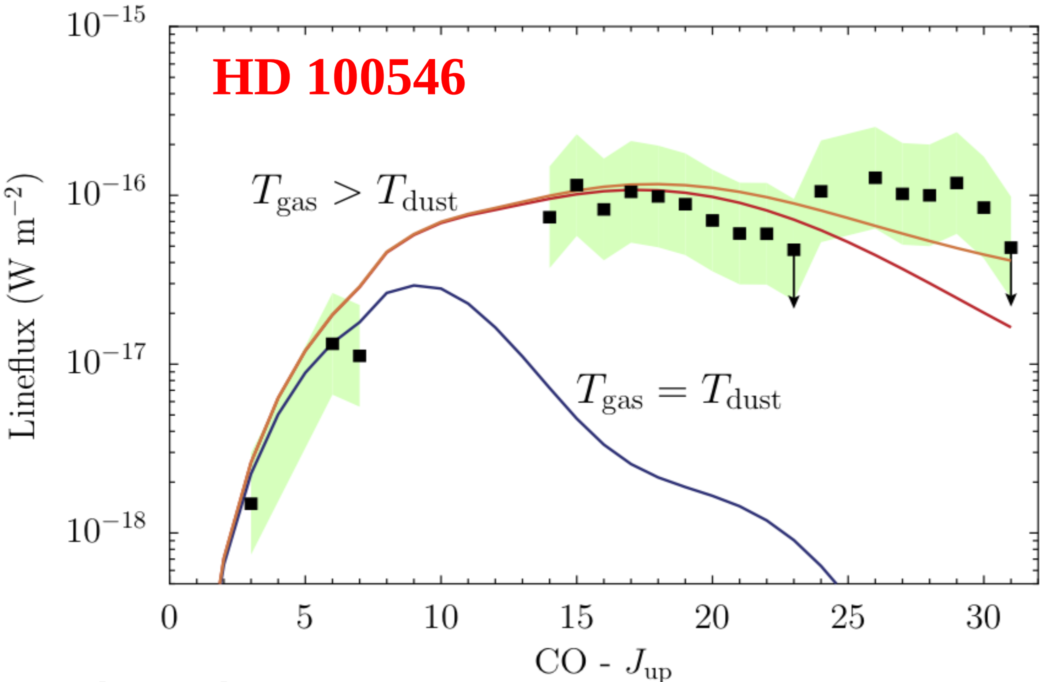


Meijerink et al. 2009

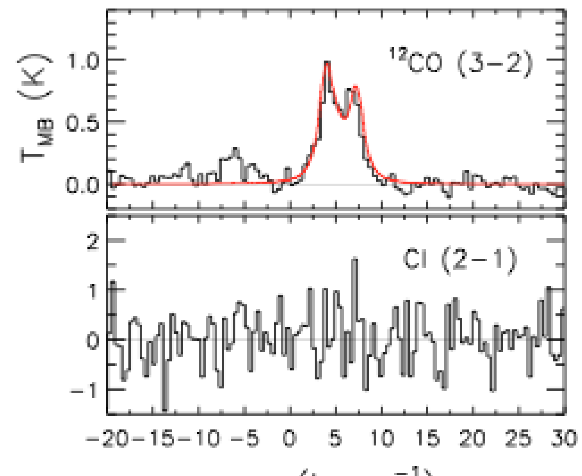


Zhang et al. 2013: dry inner disk

Evidence for carbon poor warm atmosphere?



Bruderer et al. 2012, 2013



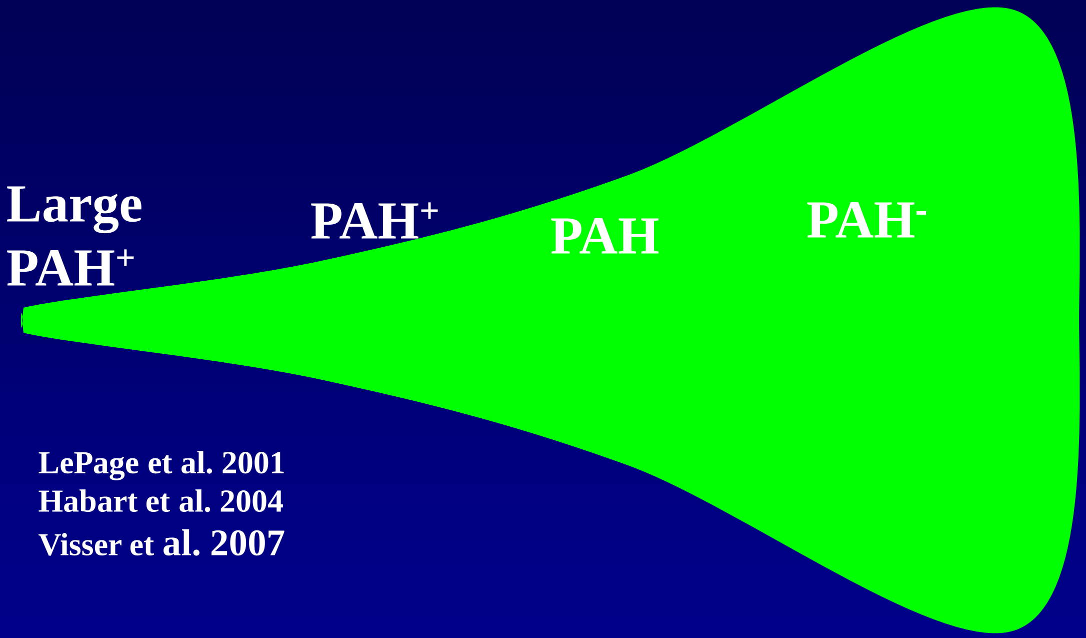
APEX: Panić et al. 2010
Chapillon et al. 2007
Herschel: Fedele et al. in prep

Upper limit of [CI] together with the CO ladder and [OI] indicate high gas-to-dust ratio, but low amount of volatile carbon

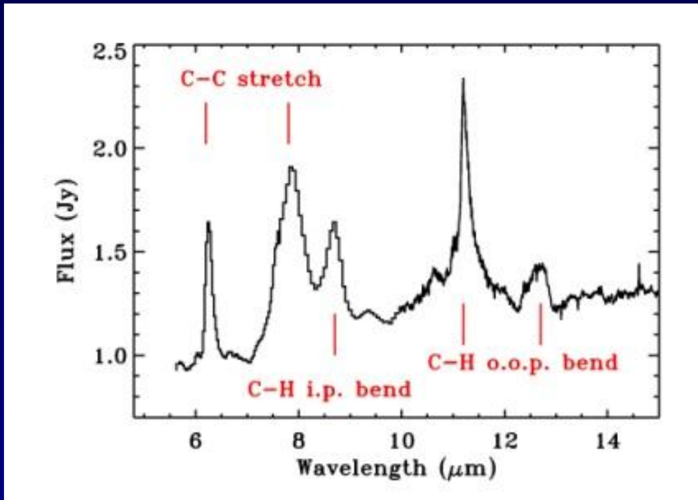
Starting to probe C/O in planet-forming zones?

Need deep ALMA observations [C I]

PAHs and organic matter in disks

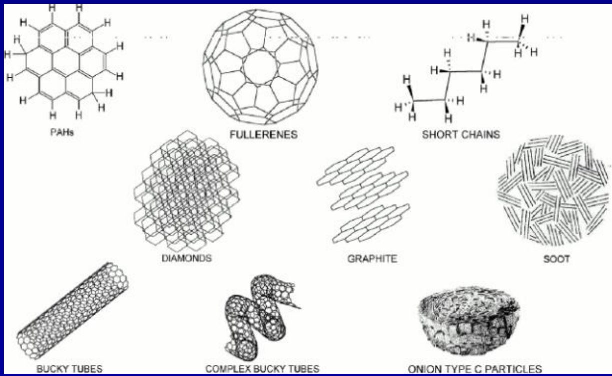


LePage et al. 2001
Habart et al. 2004
Visser et al. 2007



- Abundance PAHs is factor 10-100 lower than in ISM
- Only large PAHs (N_C>80) can survive in inner disk

- Lack of carbon in inner disk? (Lee et al. 2010)



Geers et al. 2006, 2007, 2008; Oliveira et al. 2010, Acke et al. 2010

Can we fully ascertain the processing of planetary materials, and their connections to meteorites, planetesimals, comets and KBOs?

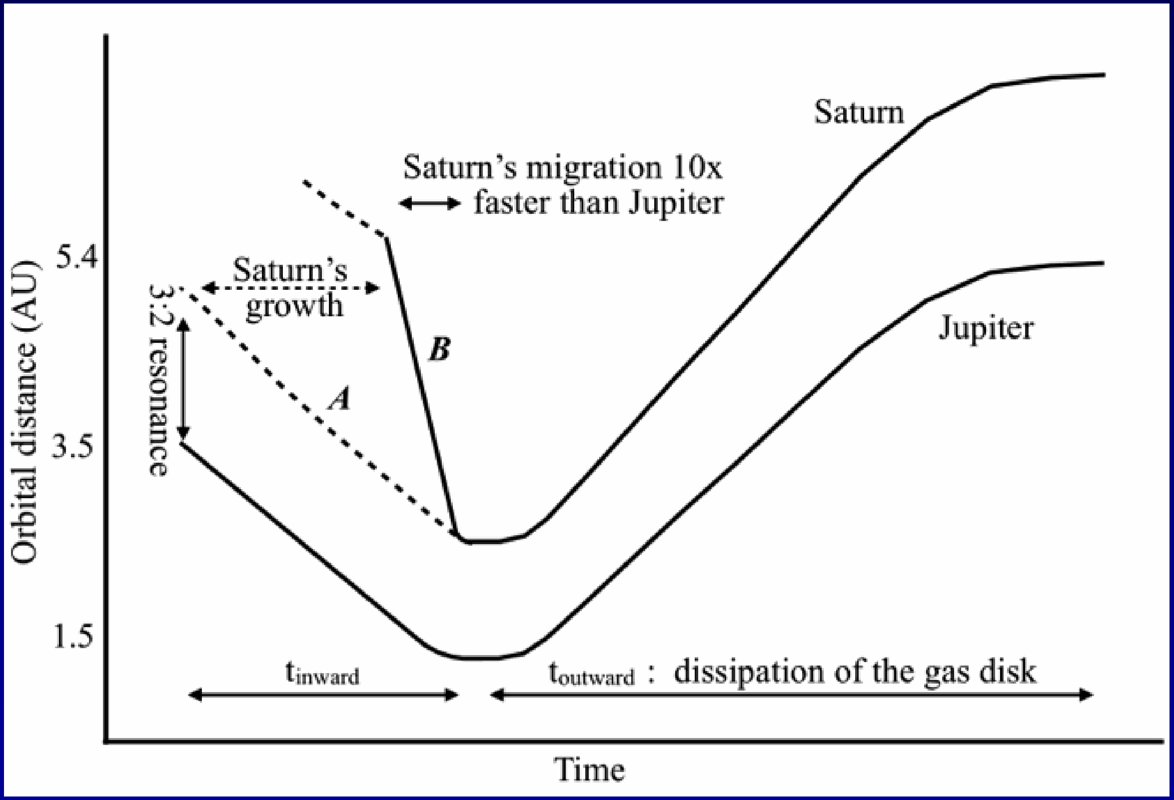
What do mm continuum and line observations tell us about solar system bodies

- **Chondrites and the protoplanetary disk: Krot et al.**
- **Protoplanetary dust: Apai & Lauretta**

History of our solar system

Grand Tack scenario

during gas-rich phase (first few Myr)



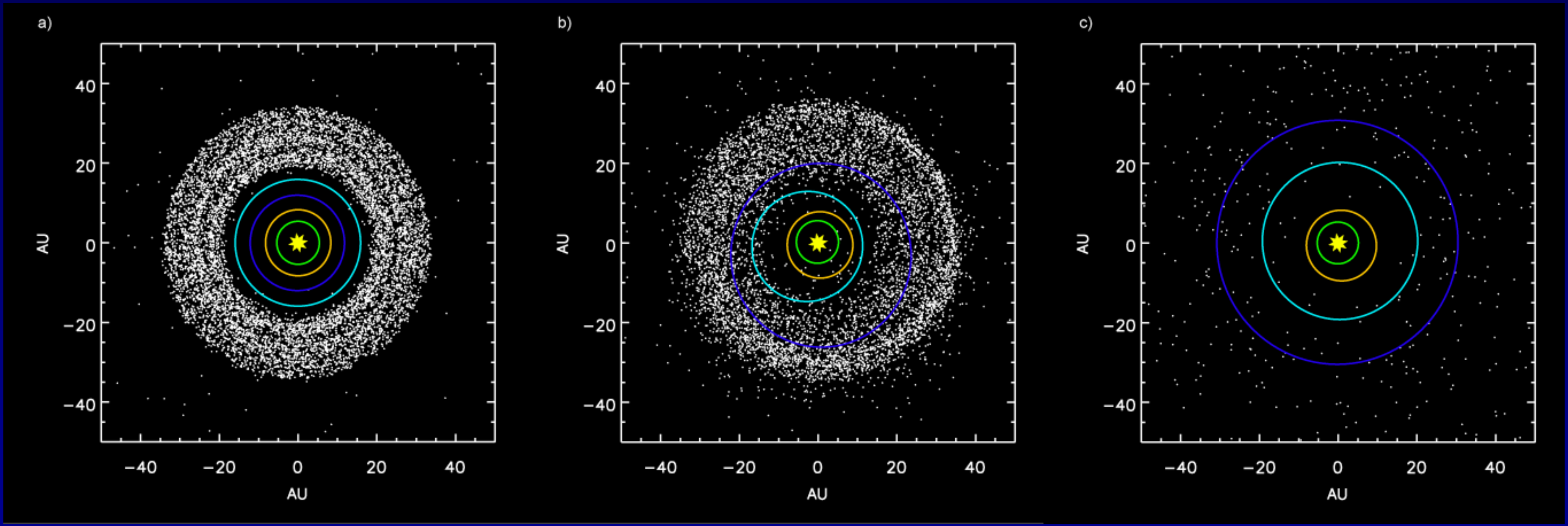
Walsh et al. 2011

- Jupiter and Saturn first migrate inward, then outward
- Explains why Mars is small

Nice model: outward migration Neptune

Gas-poor phase, ~700 Myr

Early **Middle** **Late**

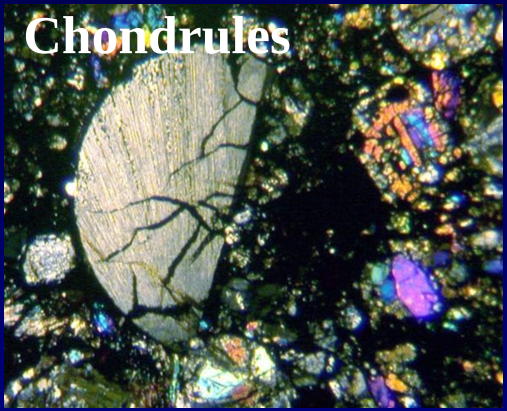


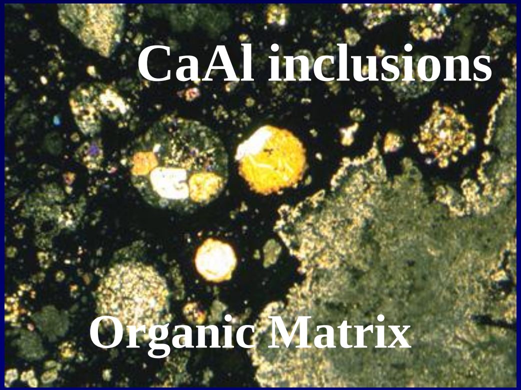
Dark blue: Neptune, light blue Uranus, Orange: Saturn, green: Jupiter

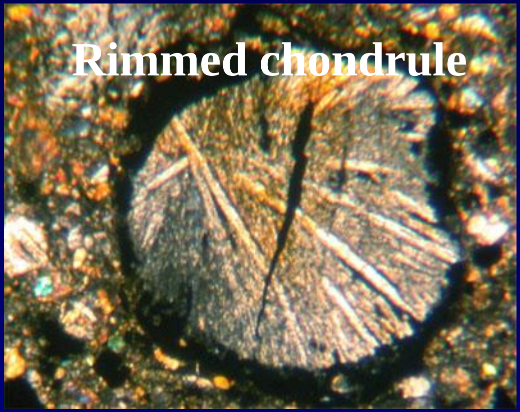
Gomes et al. 2005

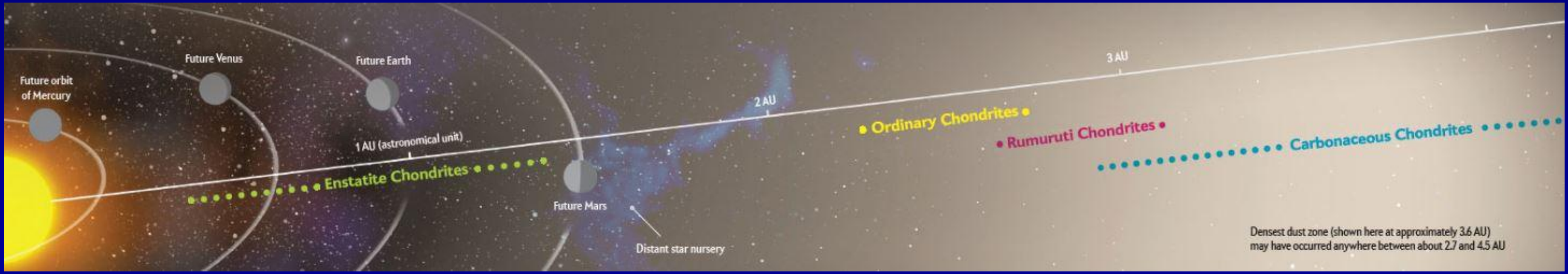
- Jupiter and Saturn reach 2:1 resonance
- After 600-800 Myr, Uranus, Neptune and Saturn move outward, note Neptune-Uranus swapping
- Planetesimals ejected

Meteorites and their origin





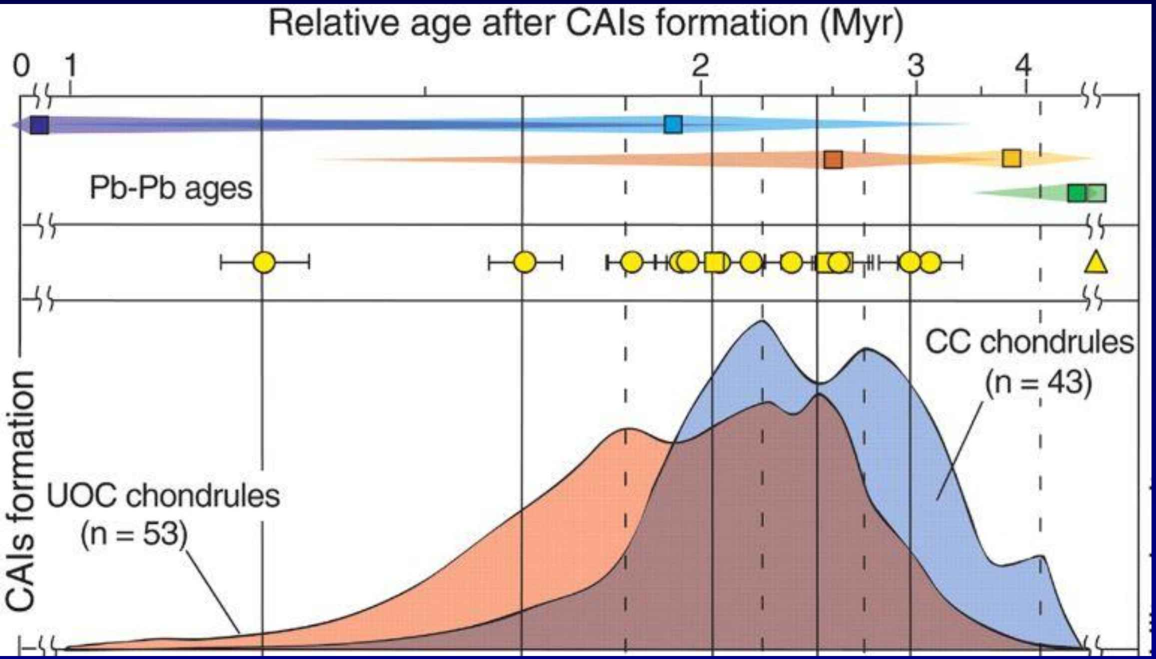




Rubin 2013

Most primitive carbonaceous chondrites come from 2.7-4.5 AU

Timescale formation solids



t=0 for solid formation set by oldest meteorites = Calcium-Aluminum inclusions (CAI)

Chondrules form after 2-3 Myr

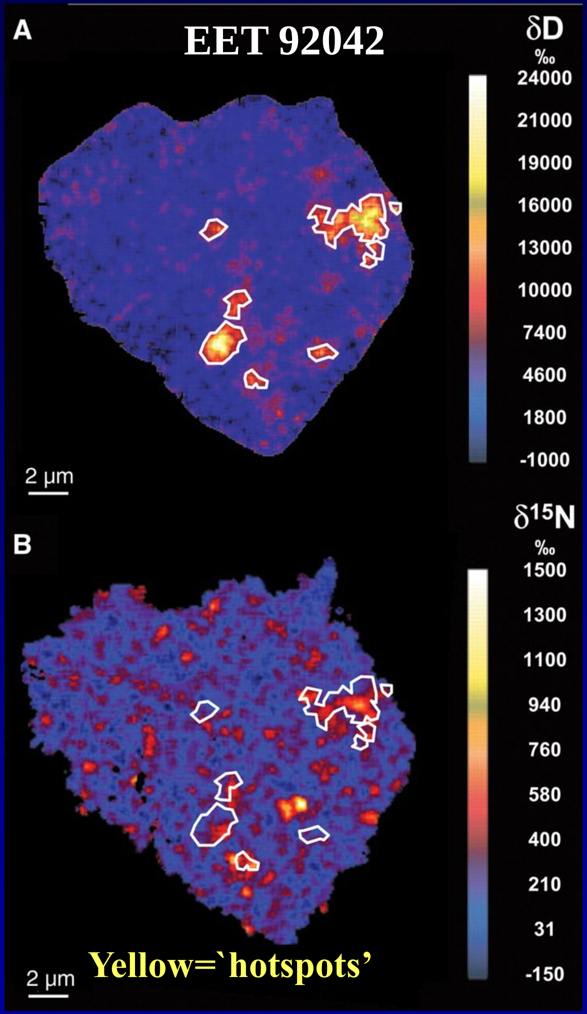
Villeneuve et al. 2009
But see Conelly et al. 2012

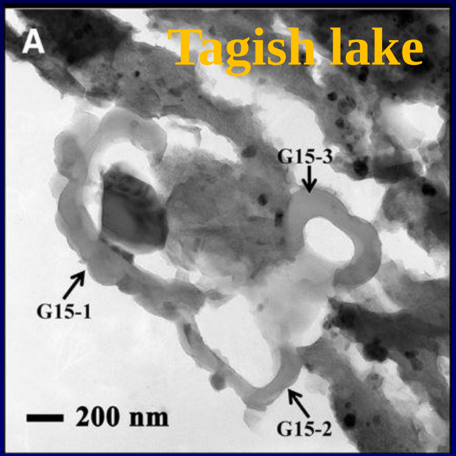
Planetesimal differentiation & igneous activity

Planetary accretion & differentiation

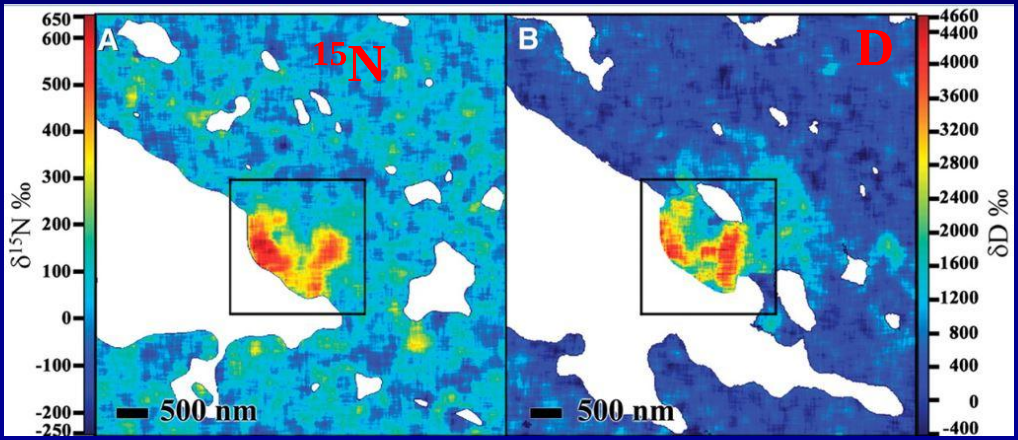
30 Myr

Carbonaceous chondrites: D and ^{15}N





Organic globule (no silicates)

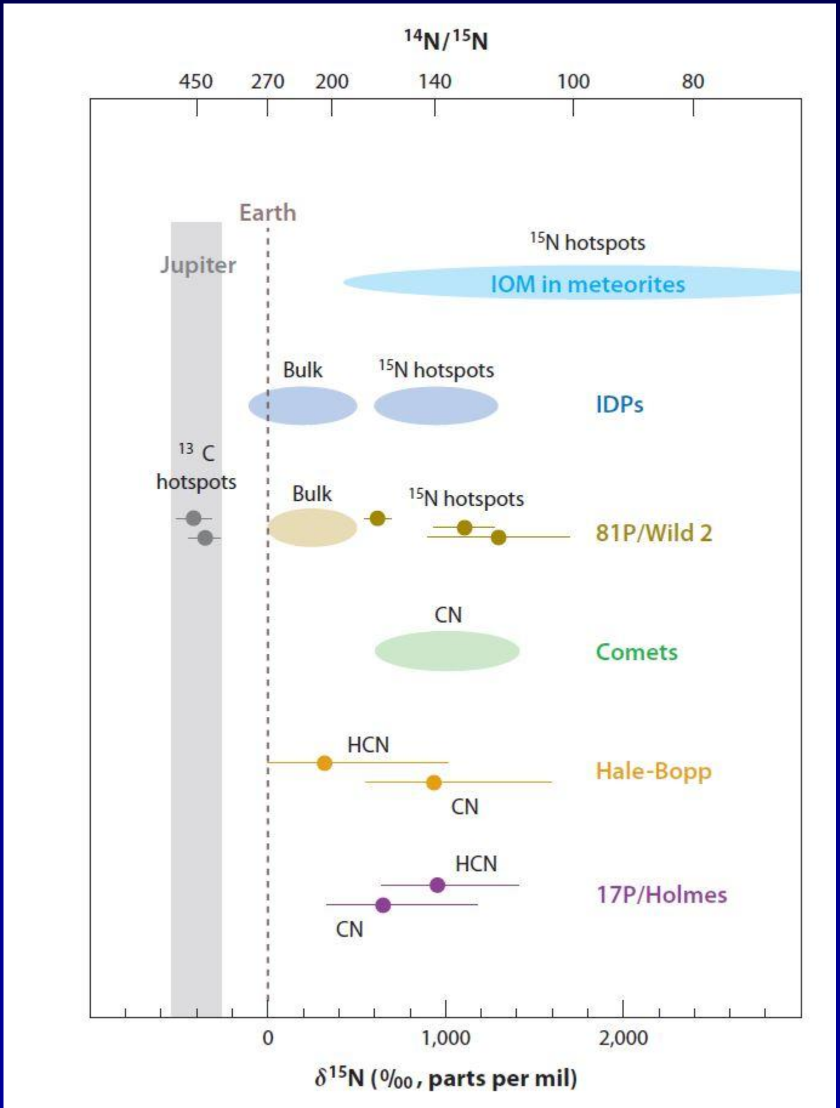


SIMS/NanoSIMS

Nakamura et al. 2006

Busemann et al. 2006

Nitrogen fractionation comets



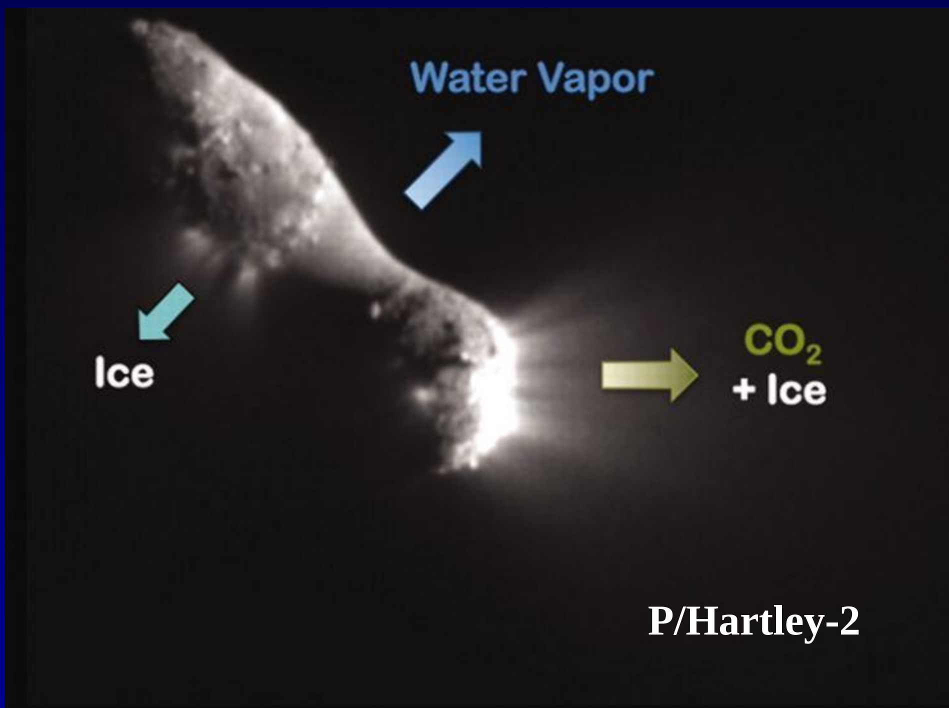
Can we trace this back to interstellar clouds and disks?

→ ALMA!

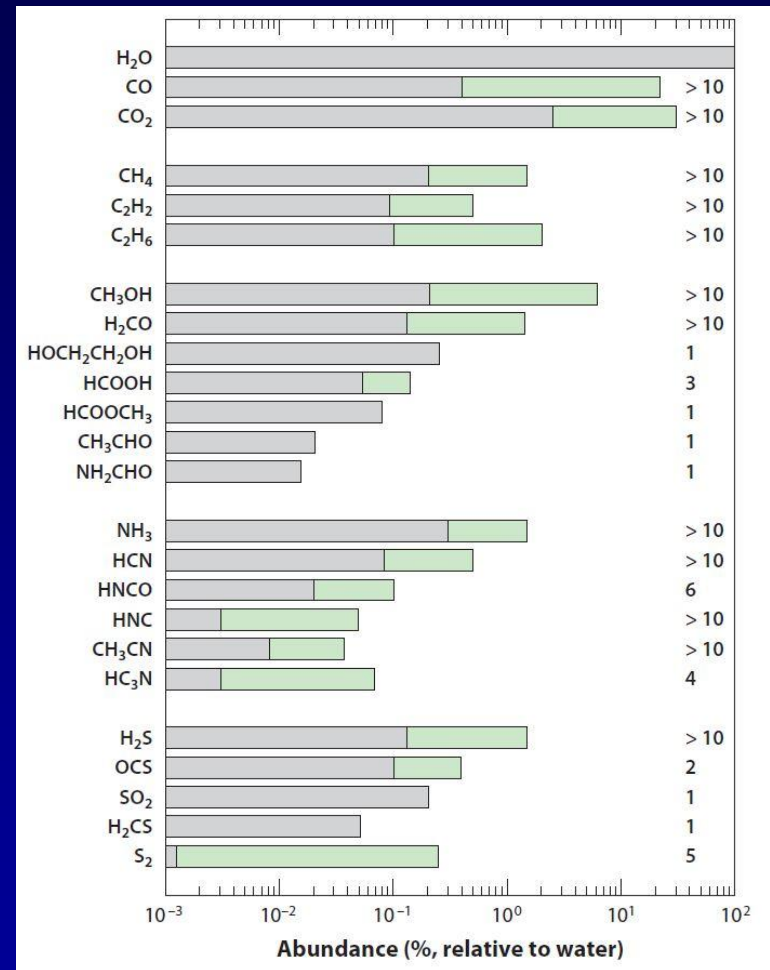
Mumma & Charnley 2011

Also: HDO/H_2O

Comets are heterogeneous



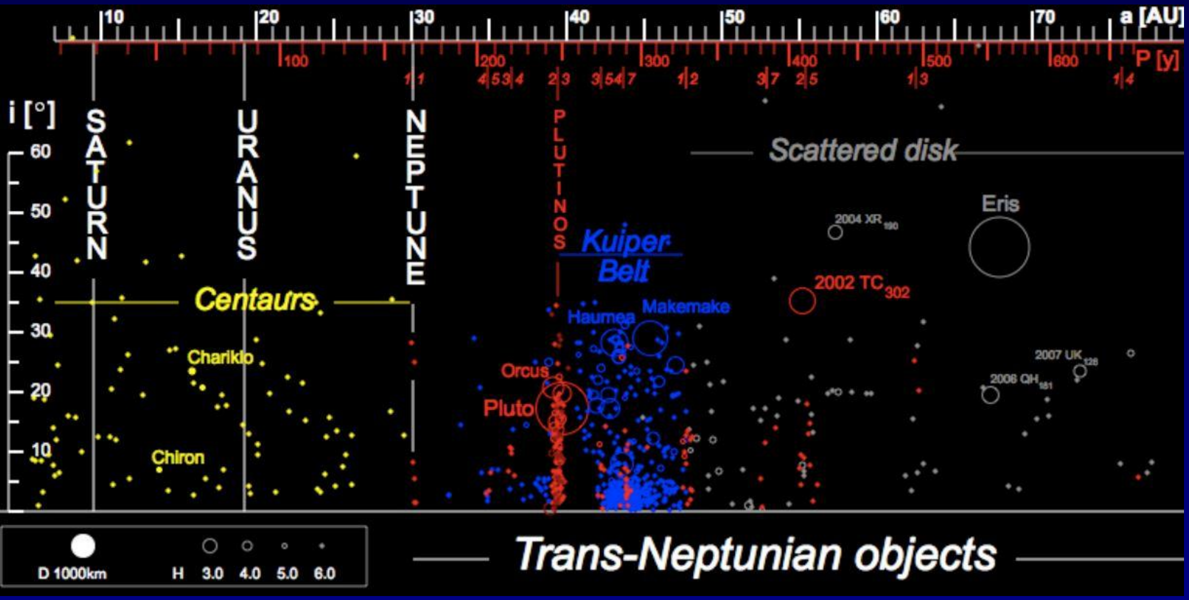
A'Hearn et al. 2011

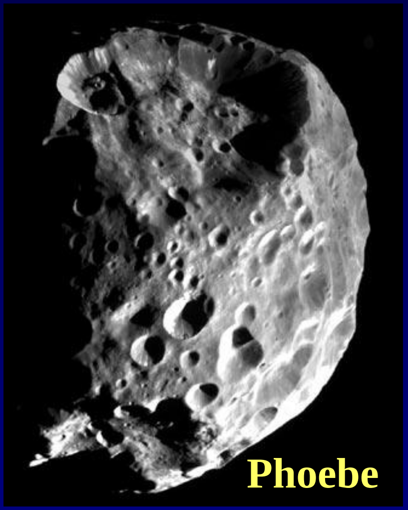


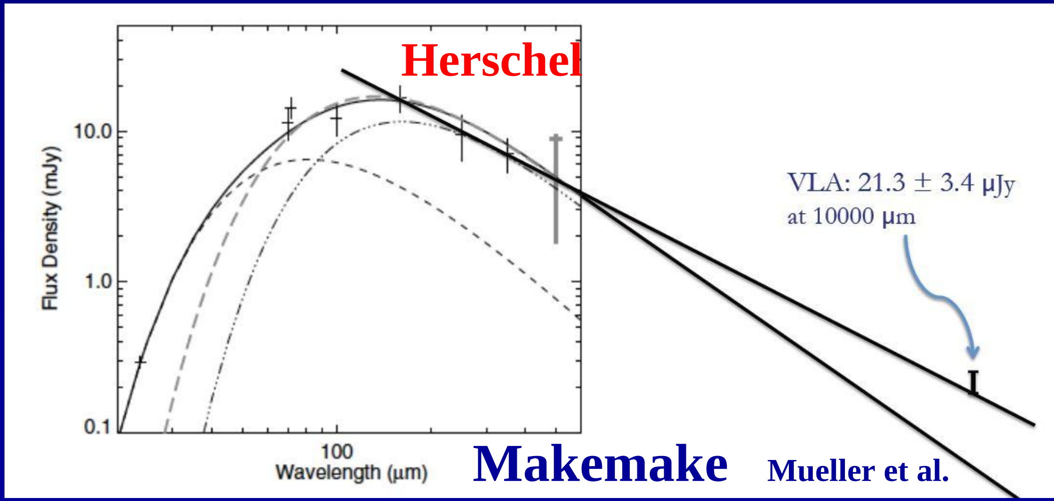
Mumma & Charnley 2011, Bockelée-Morvan et al. 2011

ALMA allows near-simultaneous measurement of species and comparison with protostars and disks

TNOs are cool



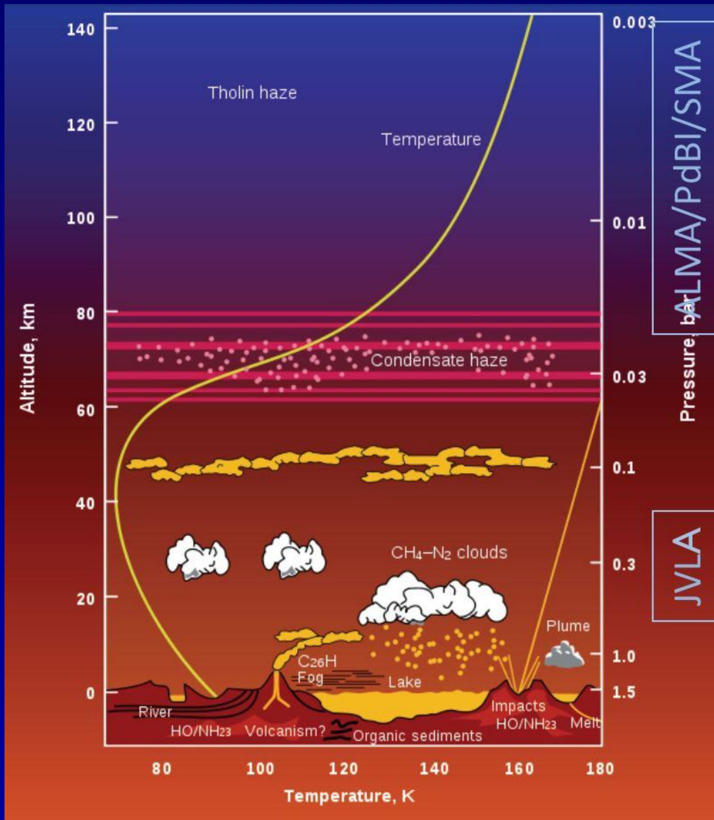




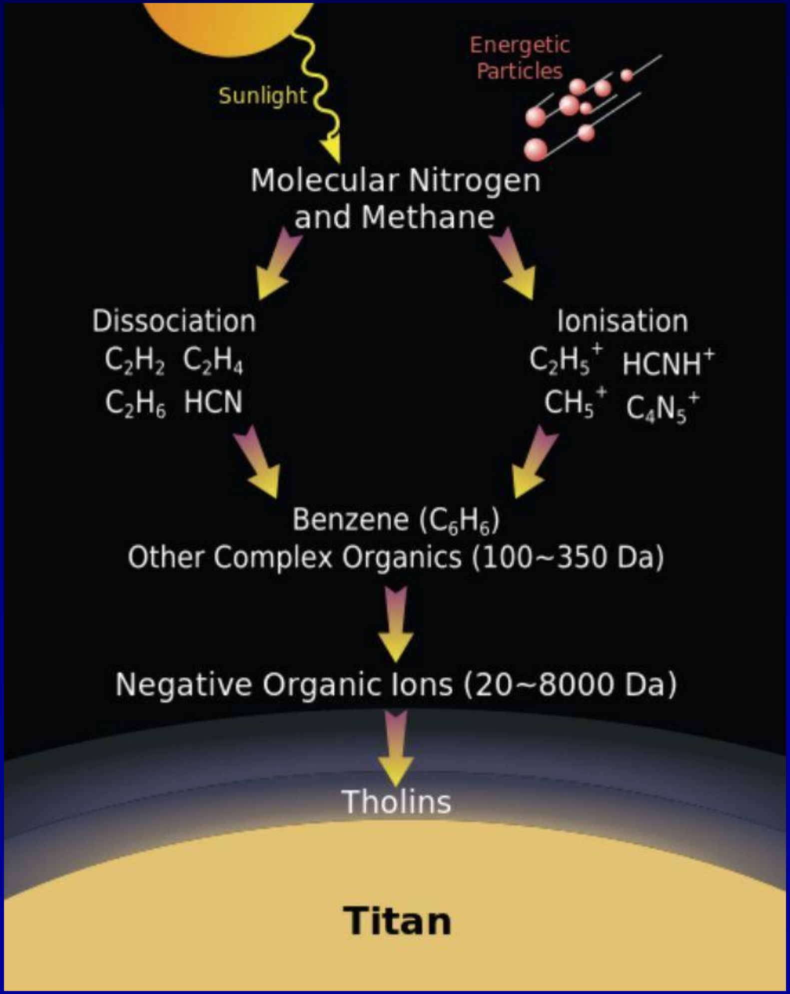
- ALMA can determine sizes, density, surface composition

Planet atmospheres

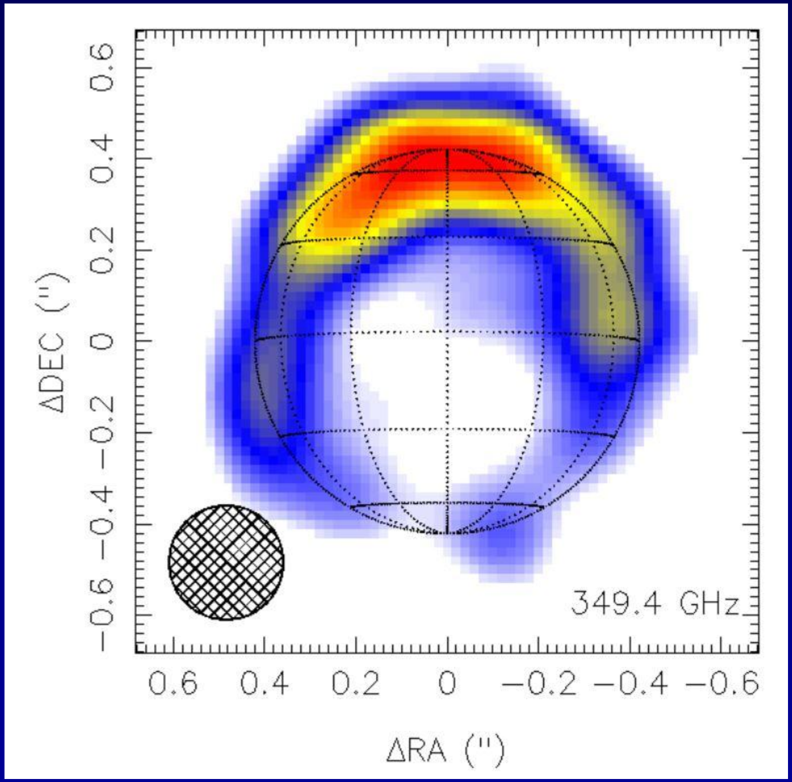
- Origin
- Similarity and differences
- How do they work?
  - Winds, seasons, ...
    - E.g., Great Saturn storm



Titan chemistry



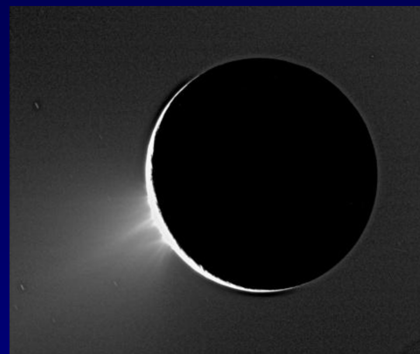
CH_3CN eSMA



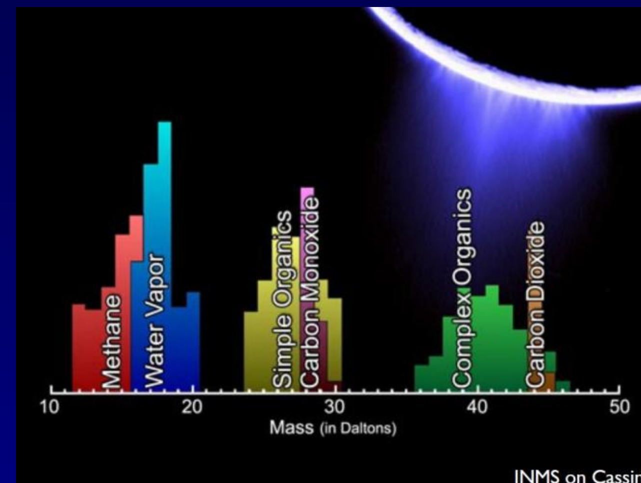
Gurwell et al.

$^{14}N/^{15}N$ ratios

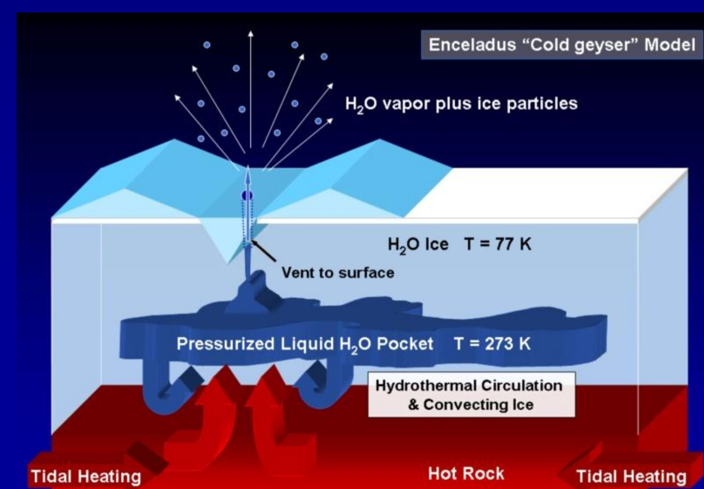
Complex organics Enceladus



Evidence for tectonic activity, geysers, jets
'Super Yellowstone'



Unique object to probe subsurface chemistry



Conclusions

- **ALMA will revolutionize all aspects of disk physics and chemistry**
- **ALMA will make crucial connection with our and exo-solar systems**

Let 's Rock with ALMA!