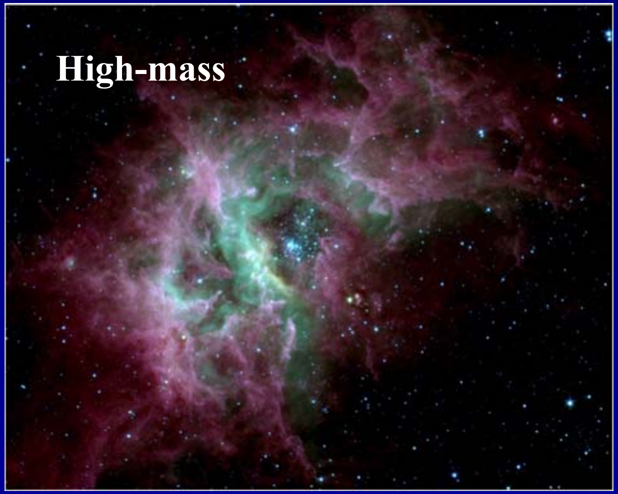
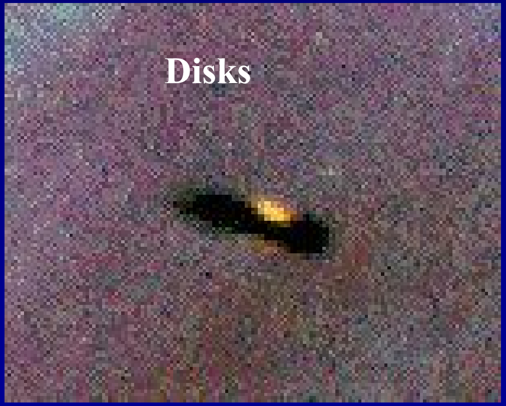
Star and planet formation in our Galaxy: ALMA-ELT synergies

Ewine van Dishoeck

Leiden Observatory/MPE Garching



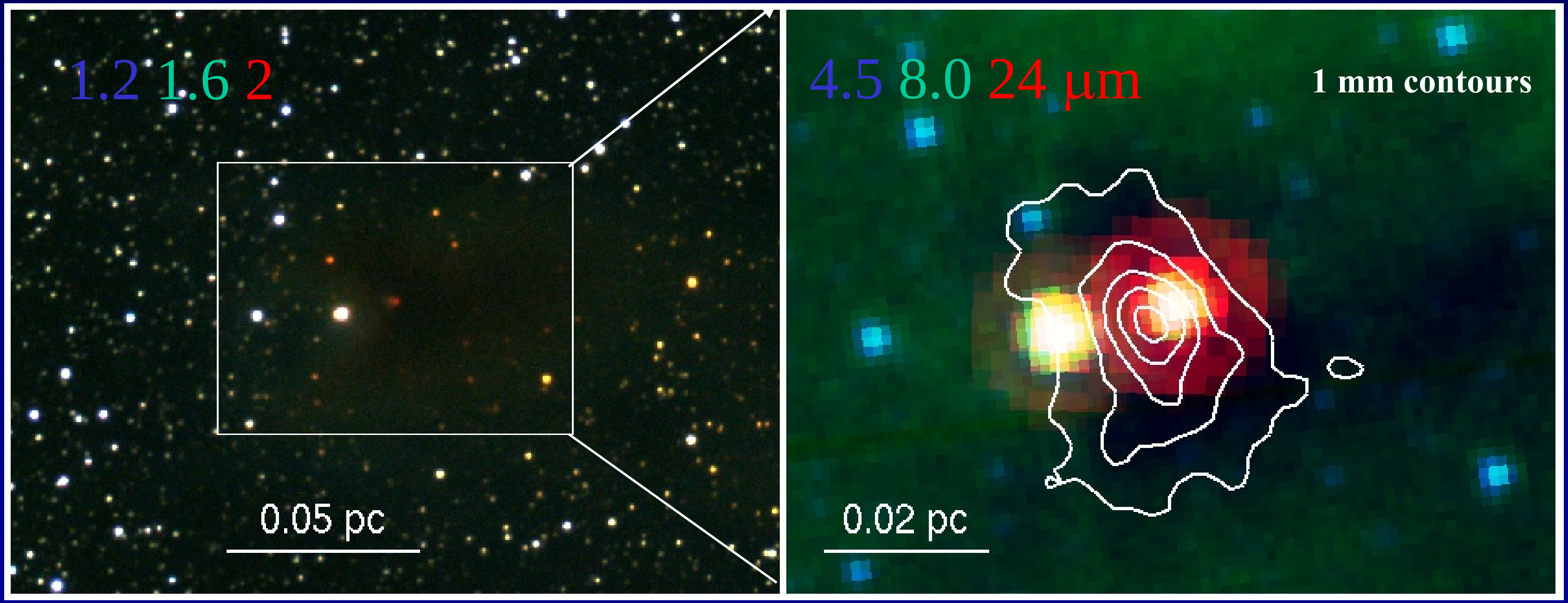


Thanks to many colleagues, i.p. K. Pontoppidan, C. Dullemond, J. Jørgensen

March 26, 2009

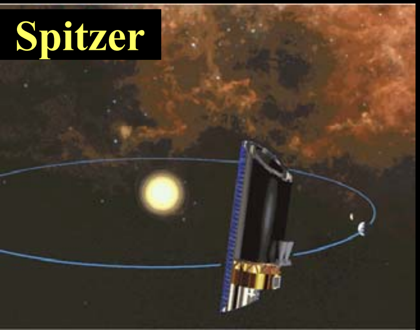
ALMA-ELT conference, ESO

Why ALMA and ELT? Need long wavelengths

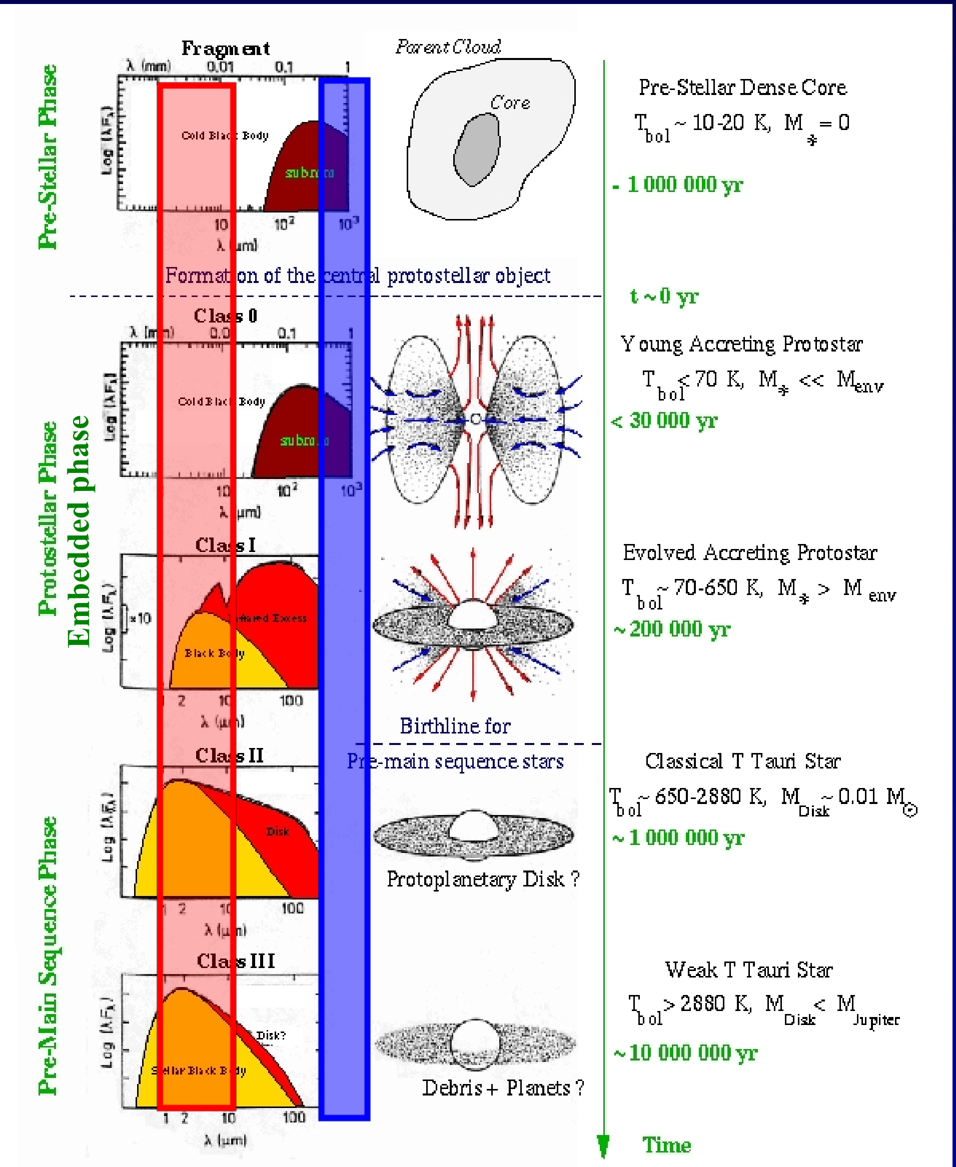


From visible to infrared light

HH 46 star-forming region



Standard cartoon: isolated low-mass SF



- Classification by SED: movement of matter from envelope to disk to star

- Mid-far IR probes bulk of luminosity =>

Source lists for ALMA and ELT
- Large-scale Spitzer + Herschel surveys
- Large-scale submm and near-IR survey

⇒Complete, unbiased catalogs with hundreds to thousands of sources

Strength of ALMA

- High angular resolution, with enough sensitivity to image
  - Down to 0.01” ~1 AU at 150 pc, 30 AU at 3 kpc
- High spectral resolution
  - Down to 0.01 km/s => kinematics and dynamics
  - Multitude of lines => physical diagnostics + chemistry
- Long wavelengths
  - Dust optically thin

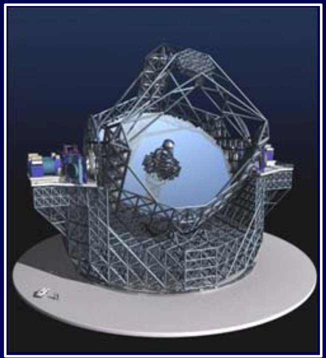
IR + submm surveys: statistics => timescales
ALMA + ELT: physics + chemistry

Why we need broad wavelength coverage

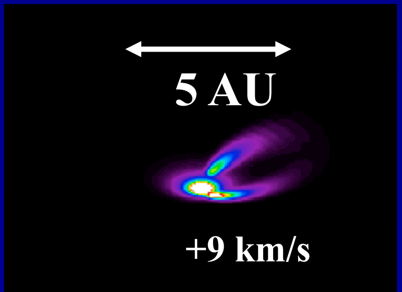
	Optical & near-IR	Mid-IR 3-28 μm	Far-IR 28-350 μm	Submm 0.3-3 mm	Radio cm
Cont	Stars	Warm dust	Cooler dust, SED peak	Cold dust	Large grains, ionized gas
Solid		Silicates, oxides, ices, PAHs, ….	Hydrous silicates, ices, carbonates		
Gas	[O I] 6300Å	Simple (symmetric) molecules C_2H_2, CH_4, HCN…	H_2O, OH, hot CO, [OI], [C II]	Myriad of molecules	Heavy mol, H

JWST-MIRI ⇔ ELT-midIR

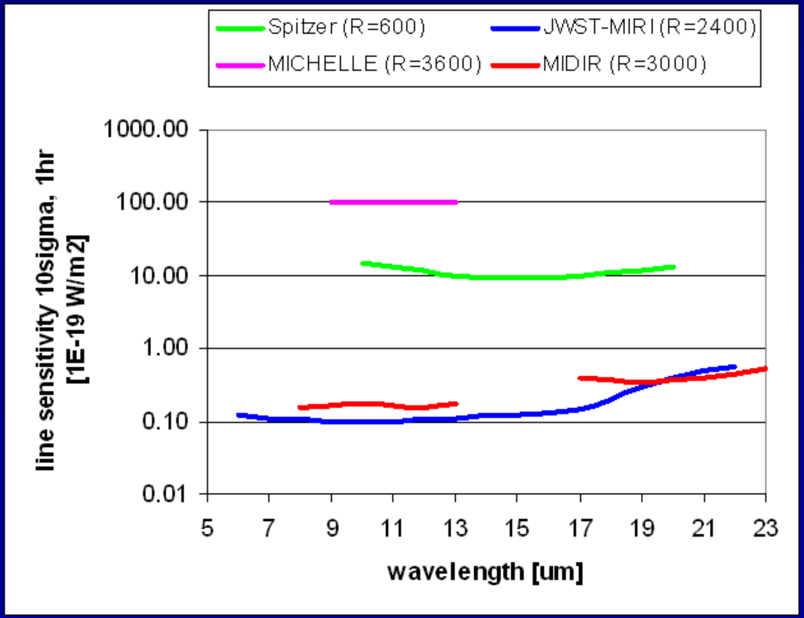
- continuous spectral coverage
- larger FOV with constant PSF
- better imaging sensitivity
- much better LSB sensitivity
- better spectro-photometric stability
- 100% sky coverage, good weather



- 5 – 8 times higher angular resolution
- high spectral resolution (kinematics!)
- comparable PS spectroscopic sensitivity



Disk kinematics
Pontoppidan



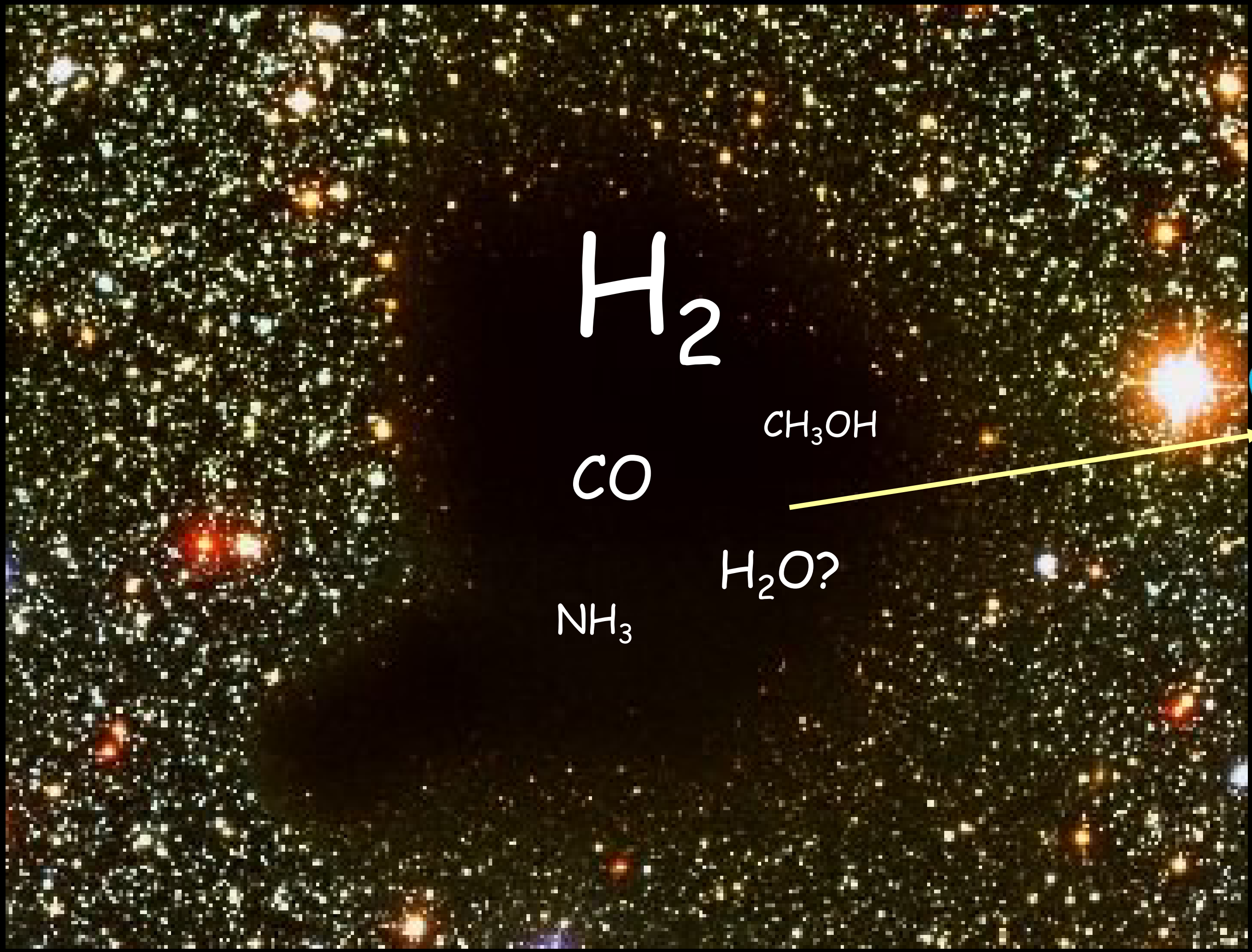
This talk

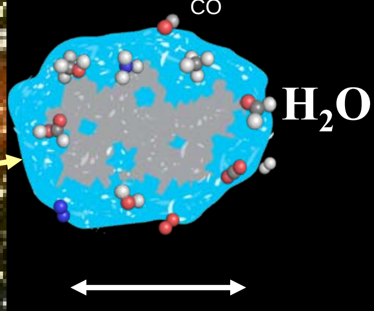
- Illustrate main questions for each stage with a few recent examples
- Focus mostly on low-mass star formation
  - Too little on high mass star formation
  - Too little on chemistry
- Apologies to everyone whose work is not cited

Inspiration from Kandinsky

‘Stars’ (1938)

Pre-stellar cores



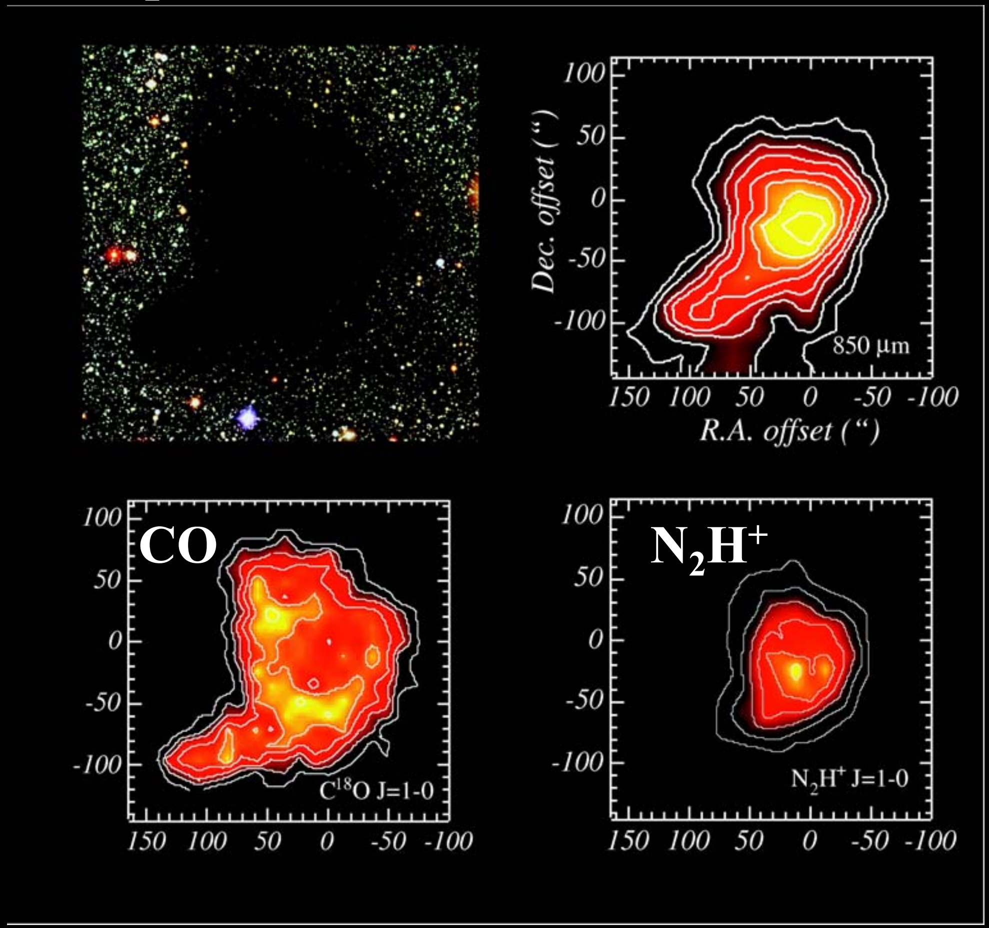


t_{depl}~2.10^9/n yr

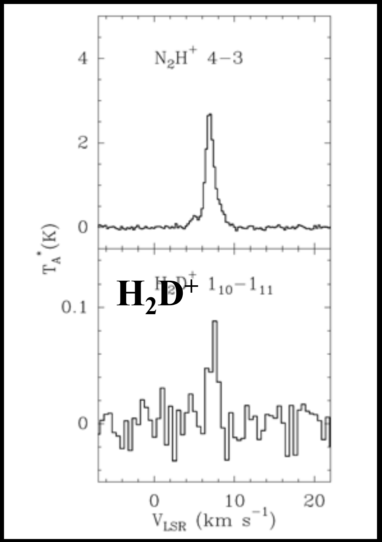
n=2.10^4 – 5.10^5 cm^{-3}, T=10 K

Prestellar cores

Optical **Submm continuum**



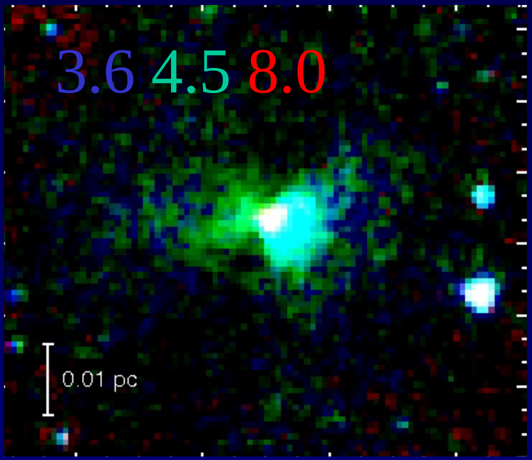
More than 90% of all molecules except most volatile species frozen out on T~10 K grains



Q: What are the initial conditions for star formation?
- physical structure densest part of core
- kinematics?

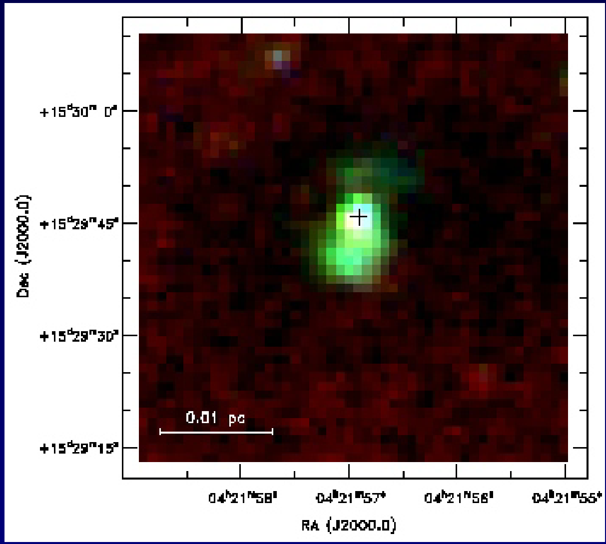
Bergin et al. 2002
Caselli et al. 02, 03,08
Ohashi et al. 1999
Van der Tak et al. 2005

Starless vs star-forming cores



L1521F L~0.05 L_{Sun}

Very Low Luminosity Objects



IRAM 04191 L~0.08 L_{Sun}

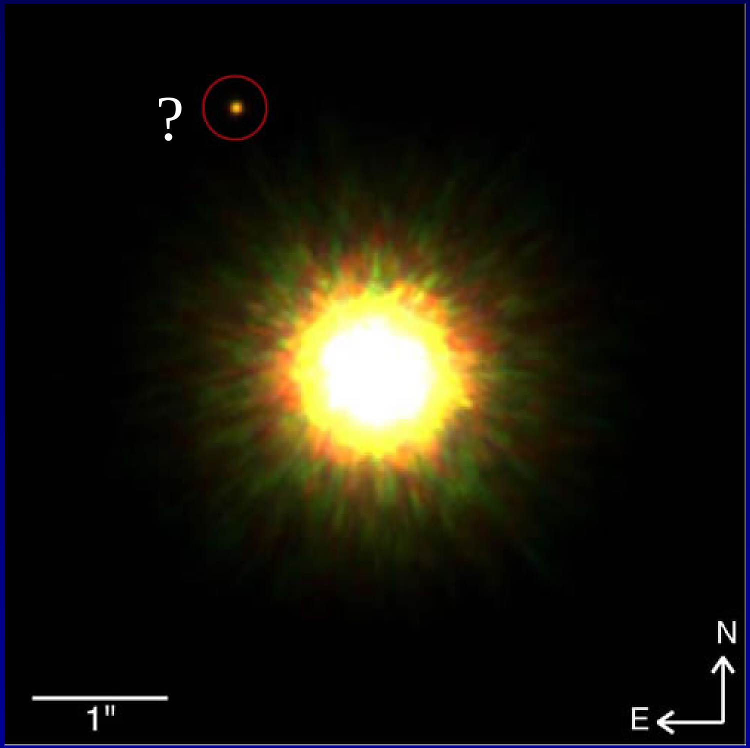
-75% of 'starless' cores based on IRAS have no IR source down to 0.01 L_{sun} after Spitzer

Q: What prevents some clouds from collapsing? Why do some sources have low accretion rate in spite of much larger reservoir?

Q: Formation brown dwarfs?
Like stars or planets?

Bourke et al. 2005, 2006
Crapsi et al. 2005
Dunham et al. 2006

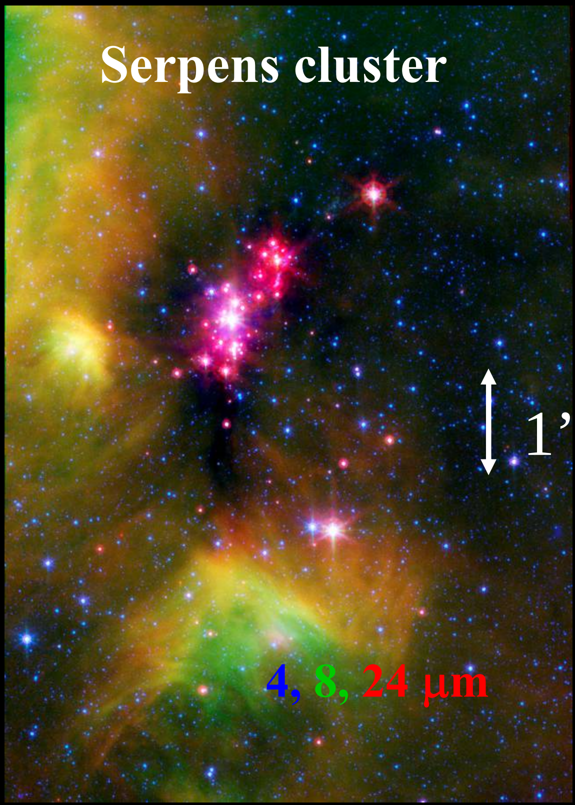
Very low mass objects



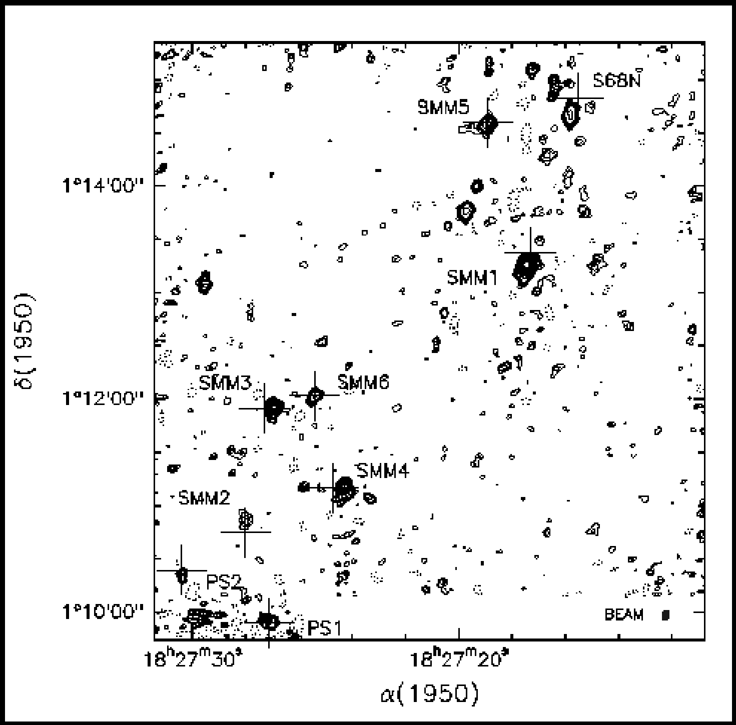
Lafrenière et al. 2008

Q: Multiple paths to planets?
Q: Origin free floating planets/BDs?

Formation of stellar clusters or aggregates



Harvey et al. 2006

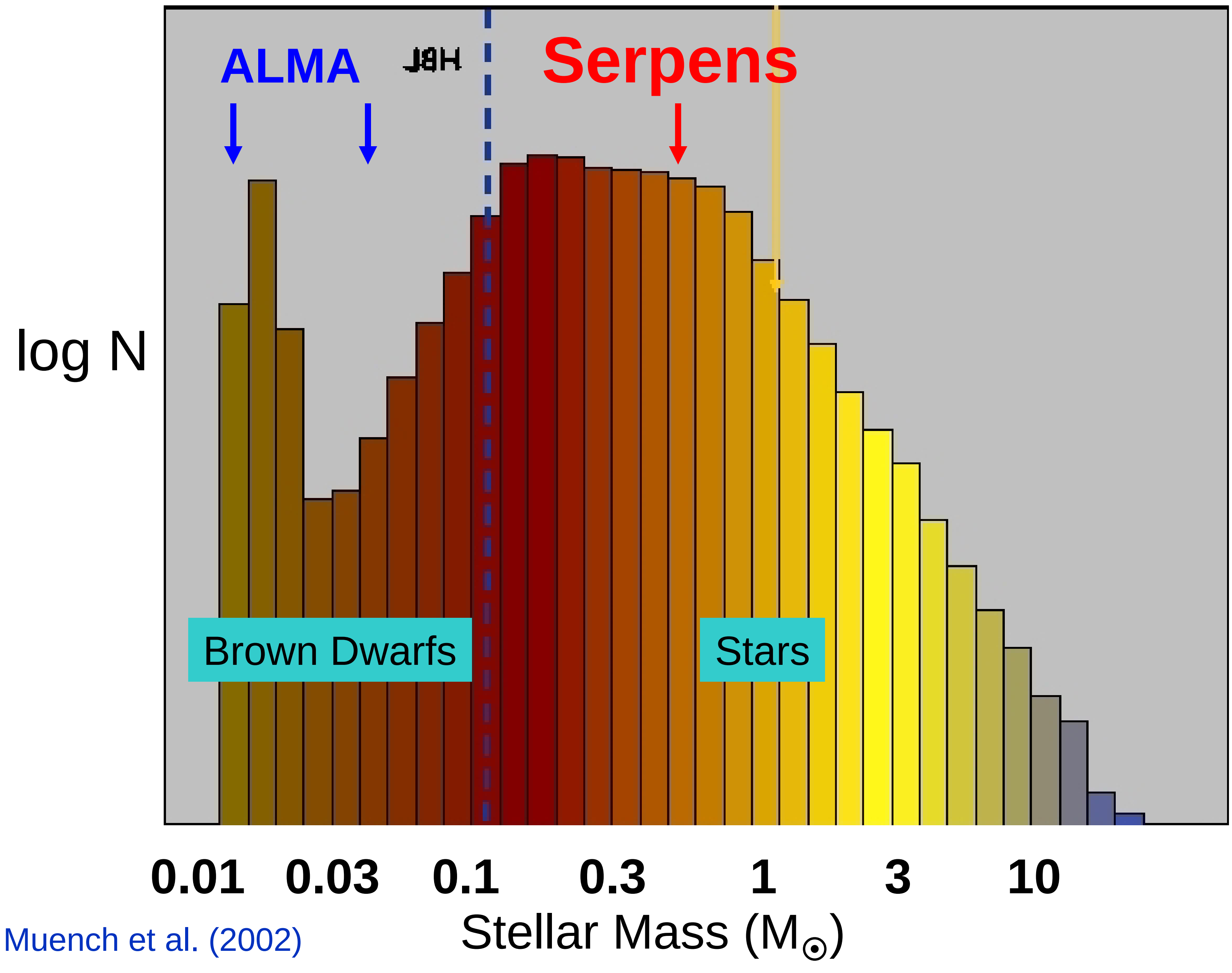


1 mm cont

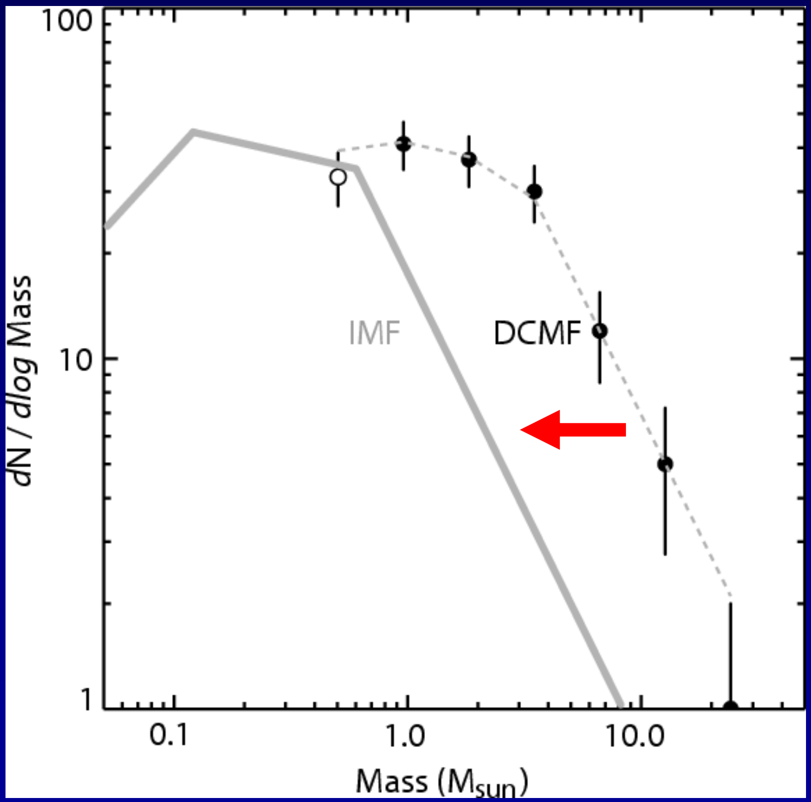
Testi & Sargent 1998

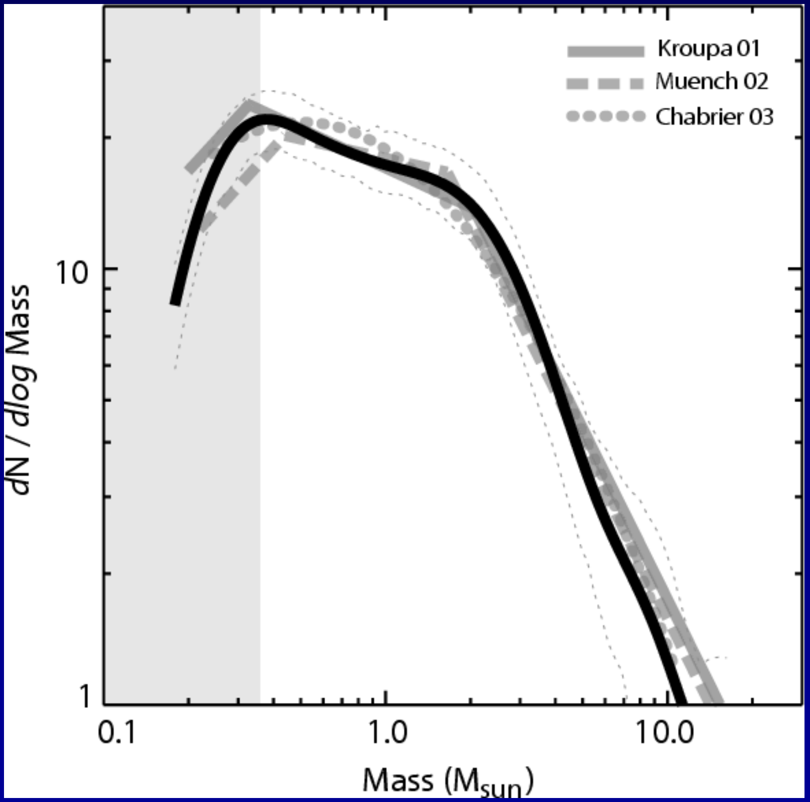
Q: what is relation cloud or clump structure and IMF?
why do most stars form in groups or clusters?

Stellar vs. Clump Mass Function



Dense core mass function



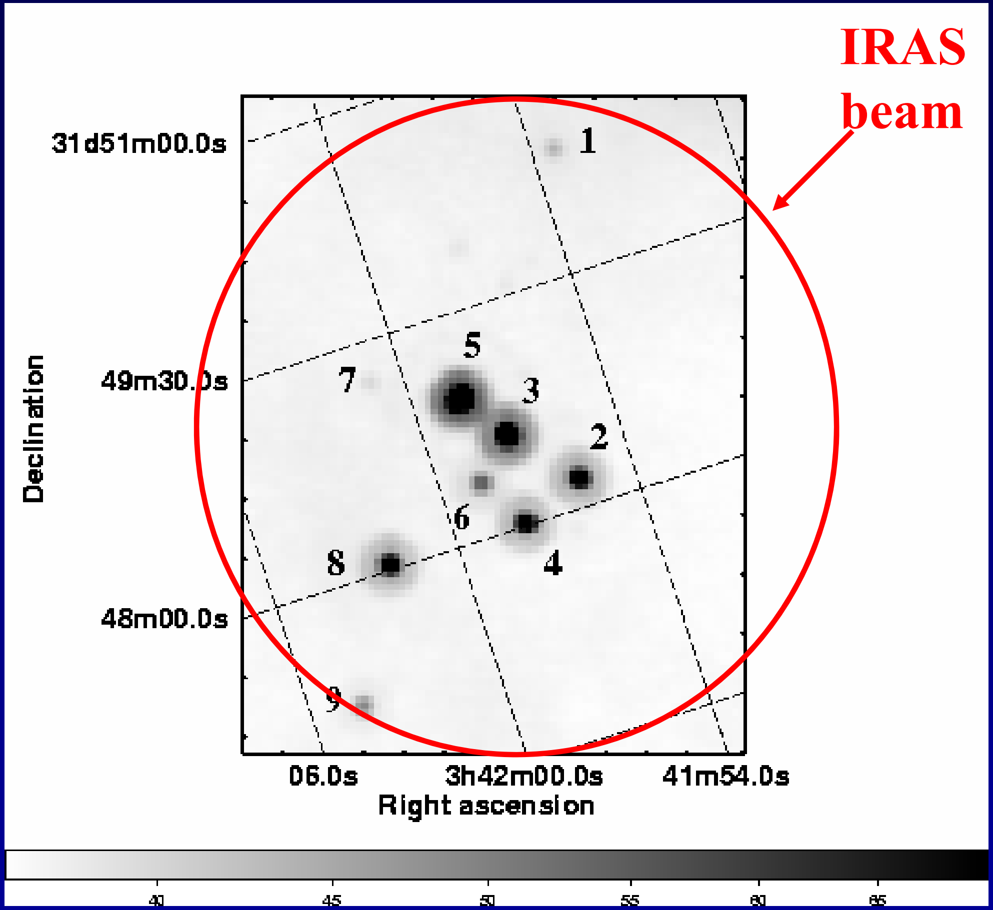


30±10% of dense core mass goes into stars

Alves et al. 2007
Motte et al. 1998
Enoch et al. 2008, …

Aggregate in Perseus: IRAS 03388+3139 d=260 pc

Need for high spatial resolution mid-IR and submm



MIPS-24 image.

9 objects within 90” (0.1 pc).

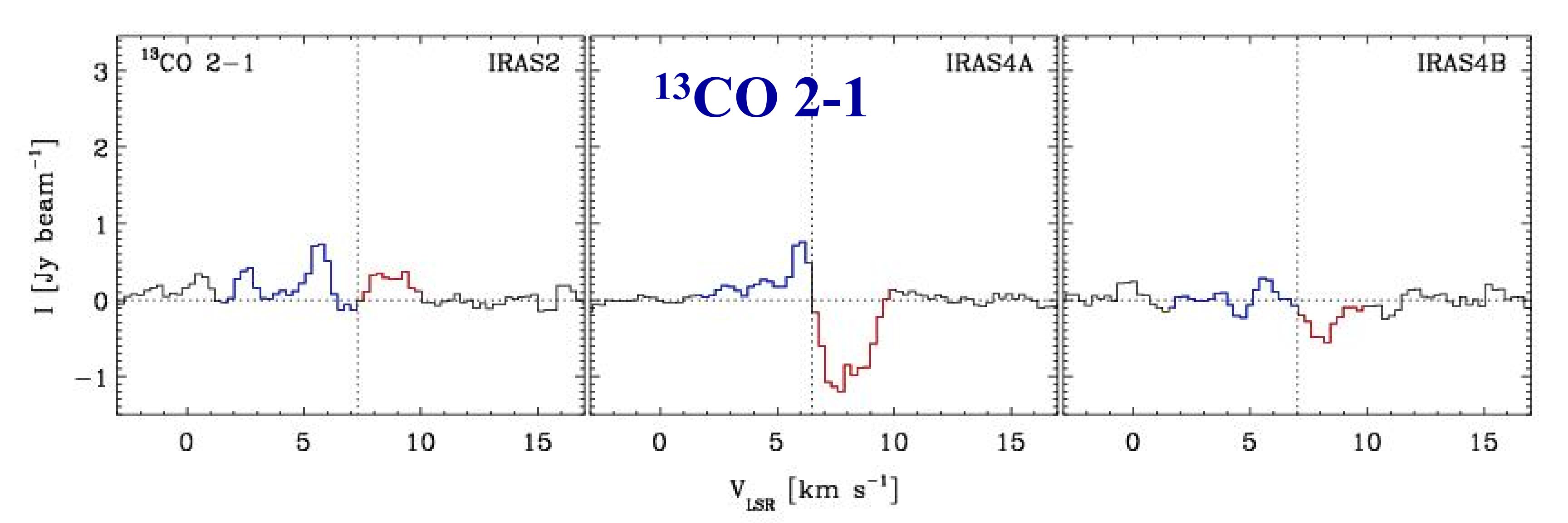
Rebull et al. 2006

Q: what fraction of stars forms as binaries or multiples?
are they all co-eval? What determines rate of evolution?

Looney et al. 2000

Infall: mass accretion onto star

Q: what are the accretion rates in the earliest stages?
how do they vary with time?

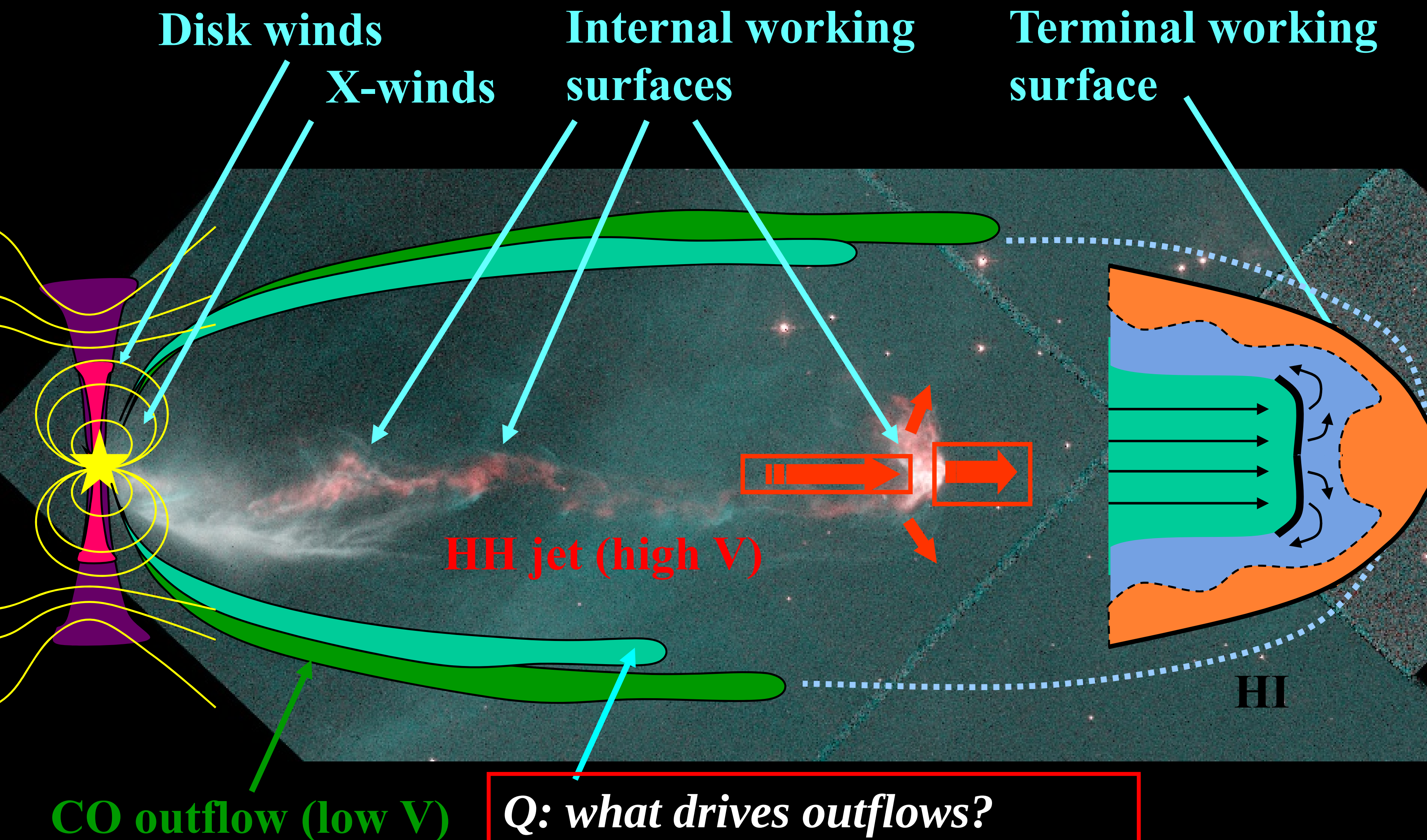


- SMA PROSAC survey of 9 Class 0 sources finds red-shifted absorption against continuum for only 2 sources and only in low-density tracer (=> large scale infall rather than small scale accretion)

Jørgensen et al. 2007
Di Francesco et al. 2001


NGC 1333 outflows
Ha, [SII]
Walawender, Bally,
Reipurth 2006
Spitzer/IRAC
Jørgensen et al. 2006

Physics of outflows:
Jets, winds => wide-angle cavities

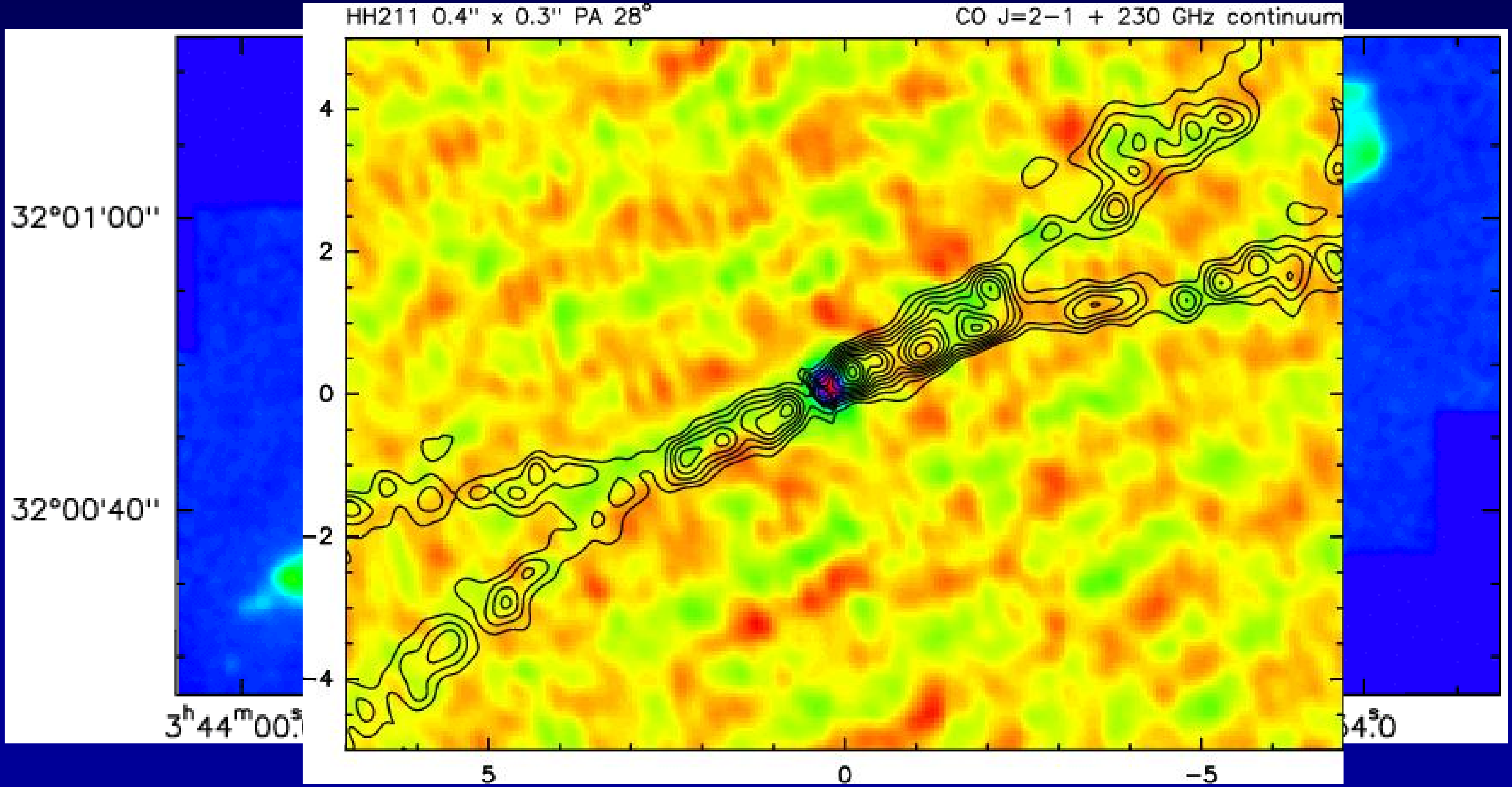


Q: what drives outflows?
outflow structure with time?

J. Bally

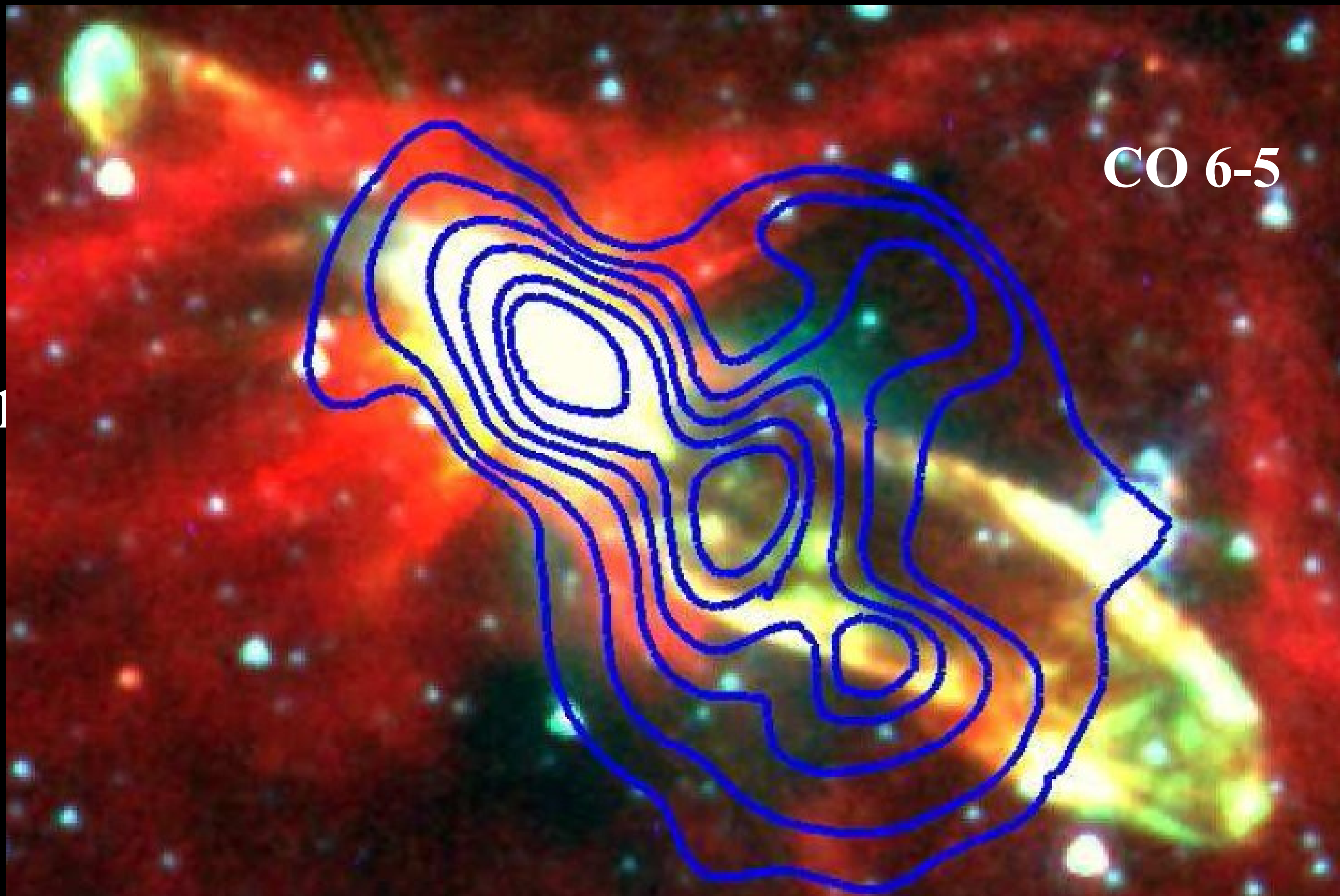
HH 211 Class 0 protostar

1.5”→ 0.3” resolution at PdB
Dynamical age 1000 yr



Gueth et al. (in prep)

Warm quiescent gas around outflows

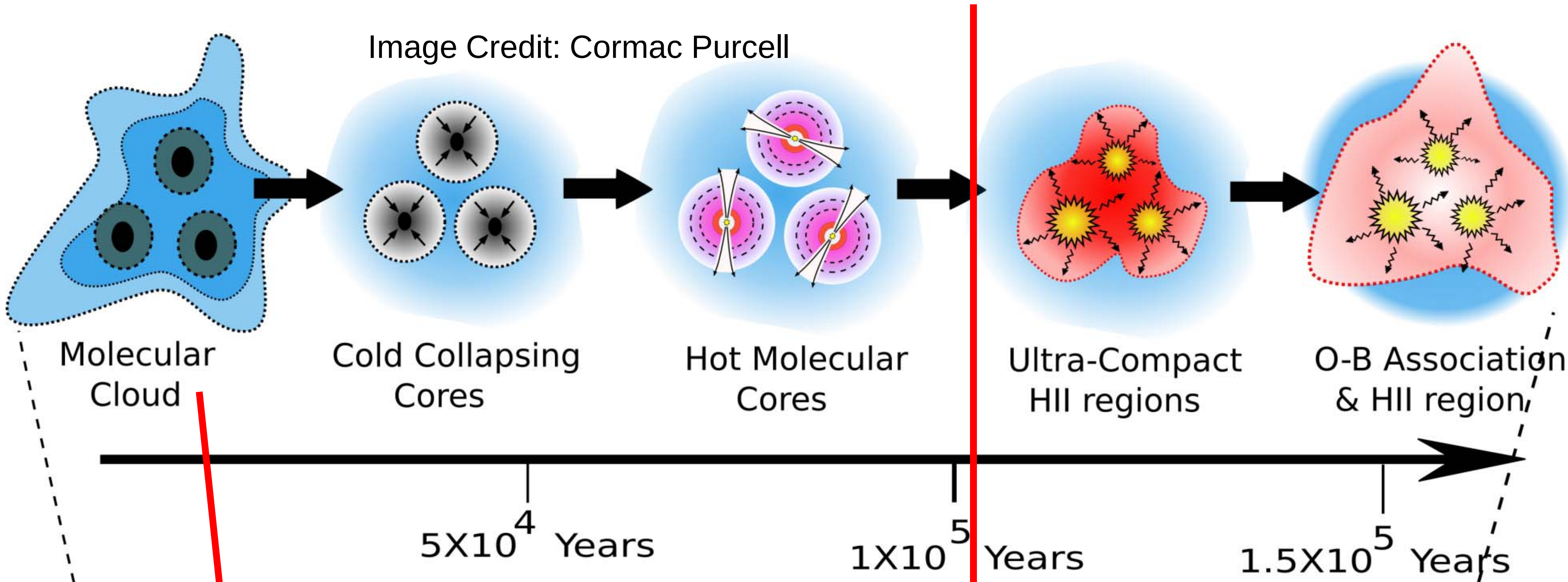


APEX-
CHAMP+

- Peaks around red outflow
- Avoids bow shock
- Narrow CO 6-5 around outflow => photon-heated gas!

Van Kempen et al. 2009

High-mass star formation

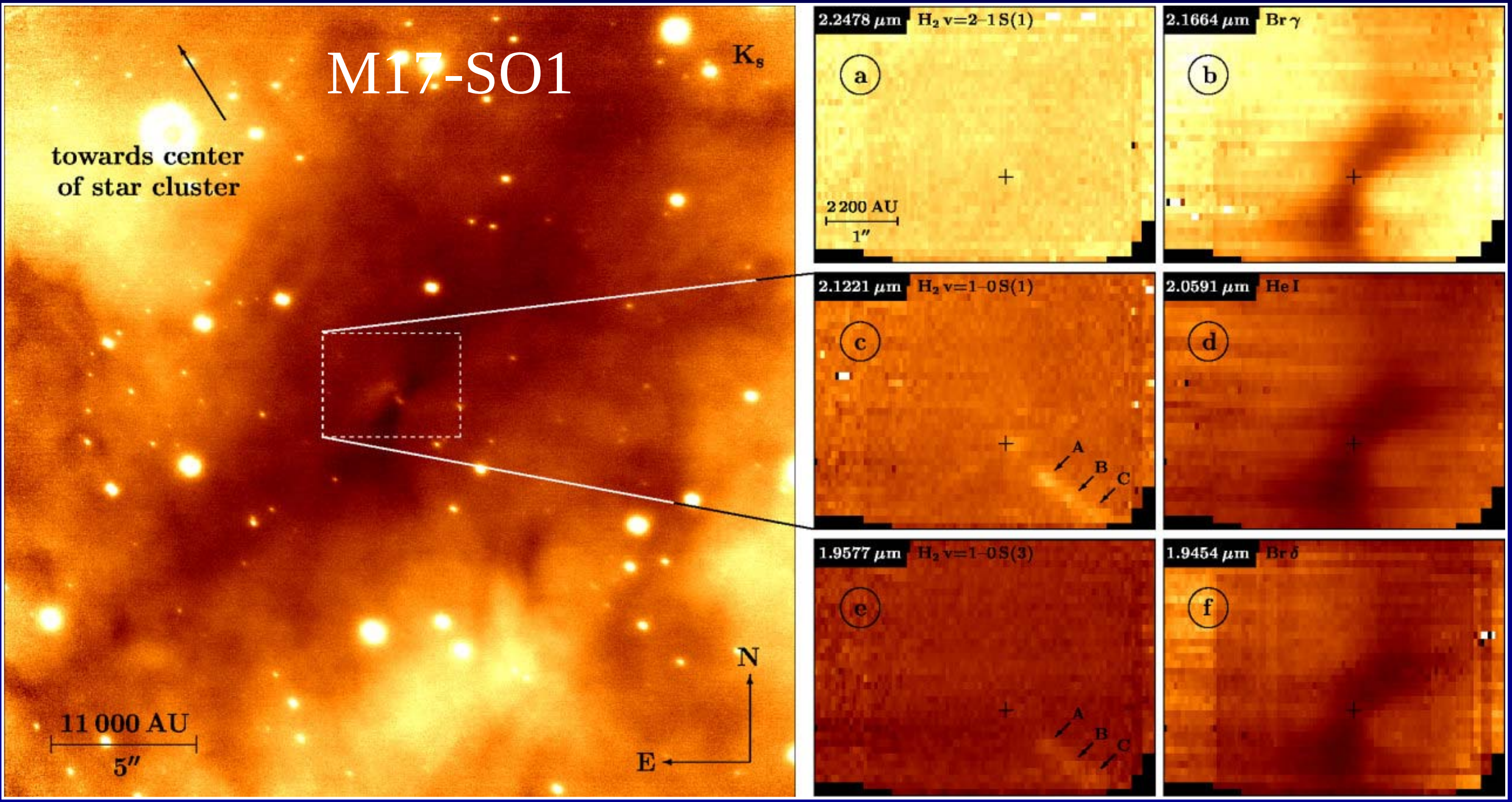


Observed as cold, dense cores
• Infrared-dark clouds
•"mm-only" cores

•Hyper-compact HII regions (eg Kurtz et al. 2005)
•Ultra-compact HII regions - well studied (see Churchwell and co.)

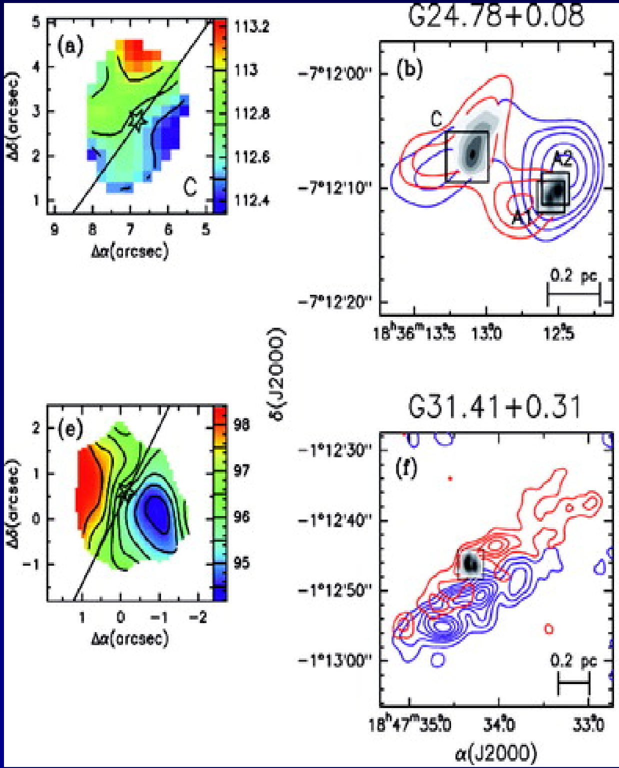
Q: is high-mass star formation scaled-up version of low-mass SF or dominated by competative accretion/mergers of low-mass stars?

Q: Characteristics of disks around massive stars?

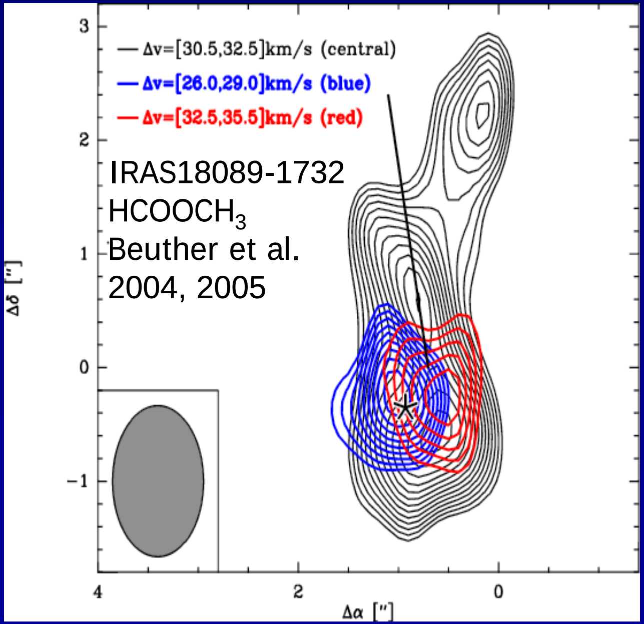


Nürnberger et al. 2007

Potentially disk-tracing molecules



G24.78 & G31.41
CH_3CN
Beltran et al.
2004, 2005



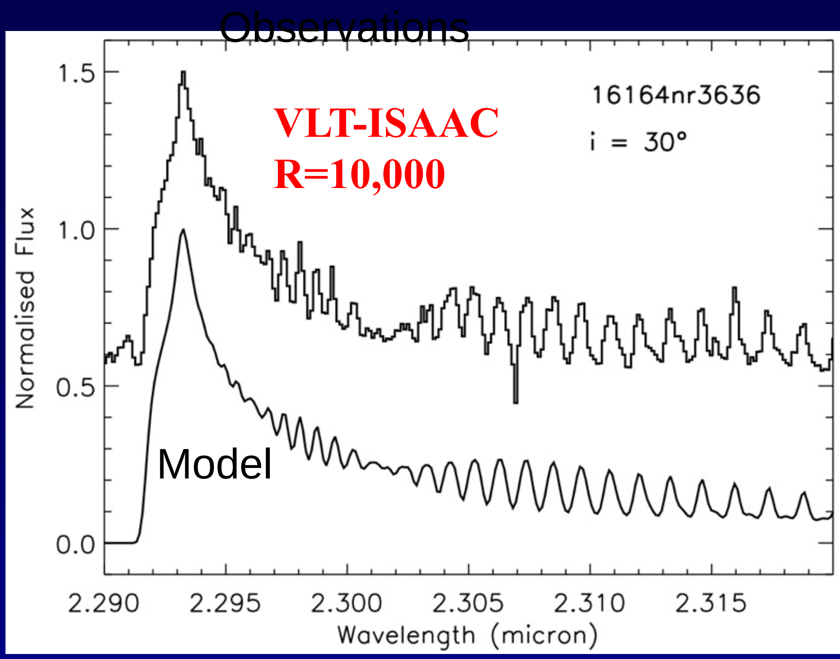
IRAS18089-1732
$HCOOCH_3$
Beuther et al.
2004, 2005

- Disks found around B stars, but disappear fast
- Only large toroids seen around O stars

Cesaroni et al. 2006, 2007

Disks around O stars in mid-IR lines!

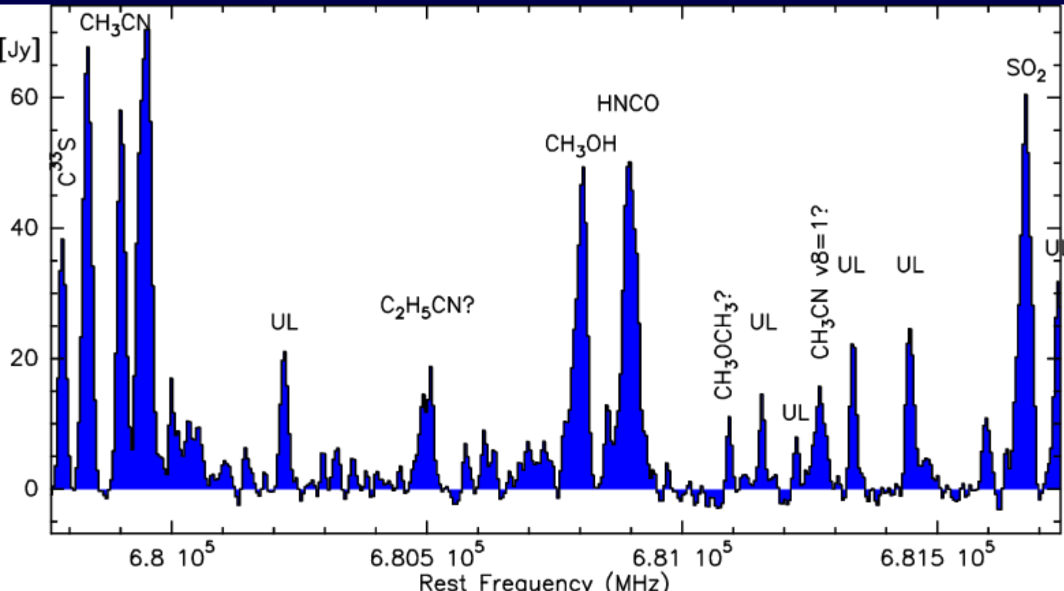
- **CO bandheads: spectral profiles require a Keplerian velocity profile**



- **Distance: 3.6 kpc**
- **Central star: ~30 M_{sun} (O7)**
- **T_{ex}(CO): ~4000 K**
- **R (CO):~ 3AU**

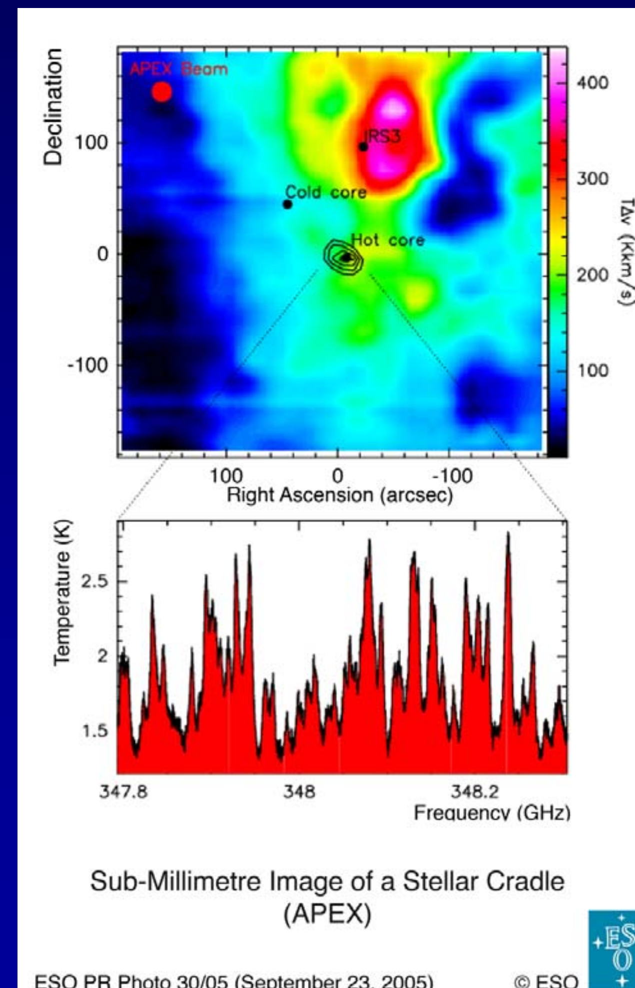
Bik & Thi 2004

Hot cores: complex chemistry



Orion-KL: 690 GHz spectra SMA

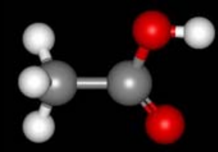
G327 with APEX



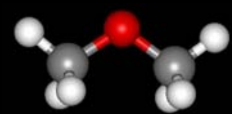
Beuther et al. 2008
Blake et al. 1987, Ohishi et al. 1995, Wright et al. 1996,
Schilke et al. 1997, 2001,
White et al. 2003, Comito et al. 2005, ….

Some complex organic molecules

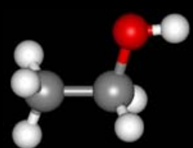
Detected



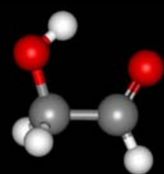
Acetic acid



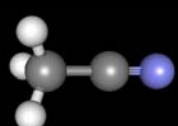
Di-methyl ether



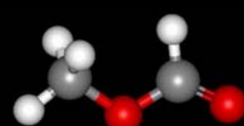
Ethanol



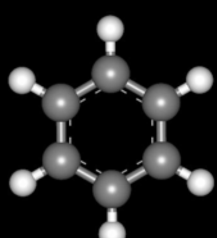
Sugar



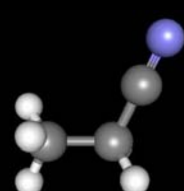
Methyl cyanide



Methyl formate

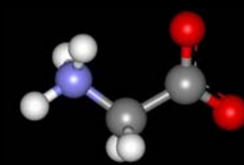


Benzene

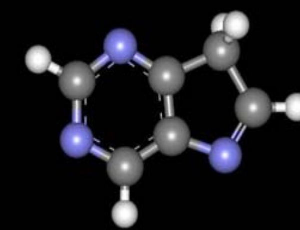


Ethyl cyanide

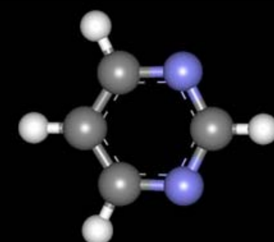
Not (yet) detected



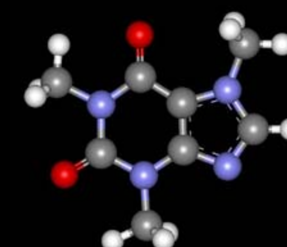
Glycine



Purine



Pyrimidine



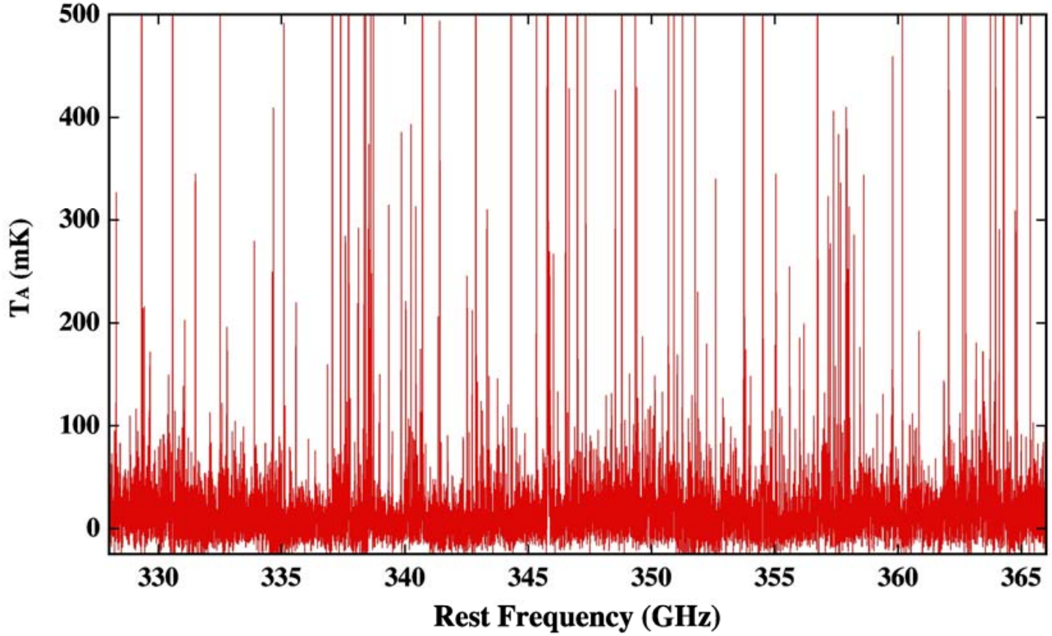
Caffeine

Q: how far does chemical complexity go? Can we find pre-biotic molecules?

Based on Ehrenfreund 2003

Inventory of complex organics toward solar mass protostar

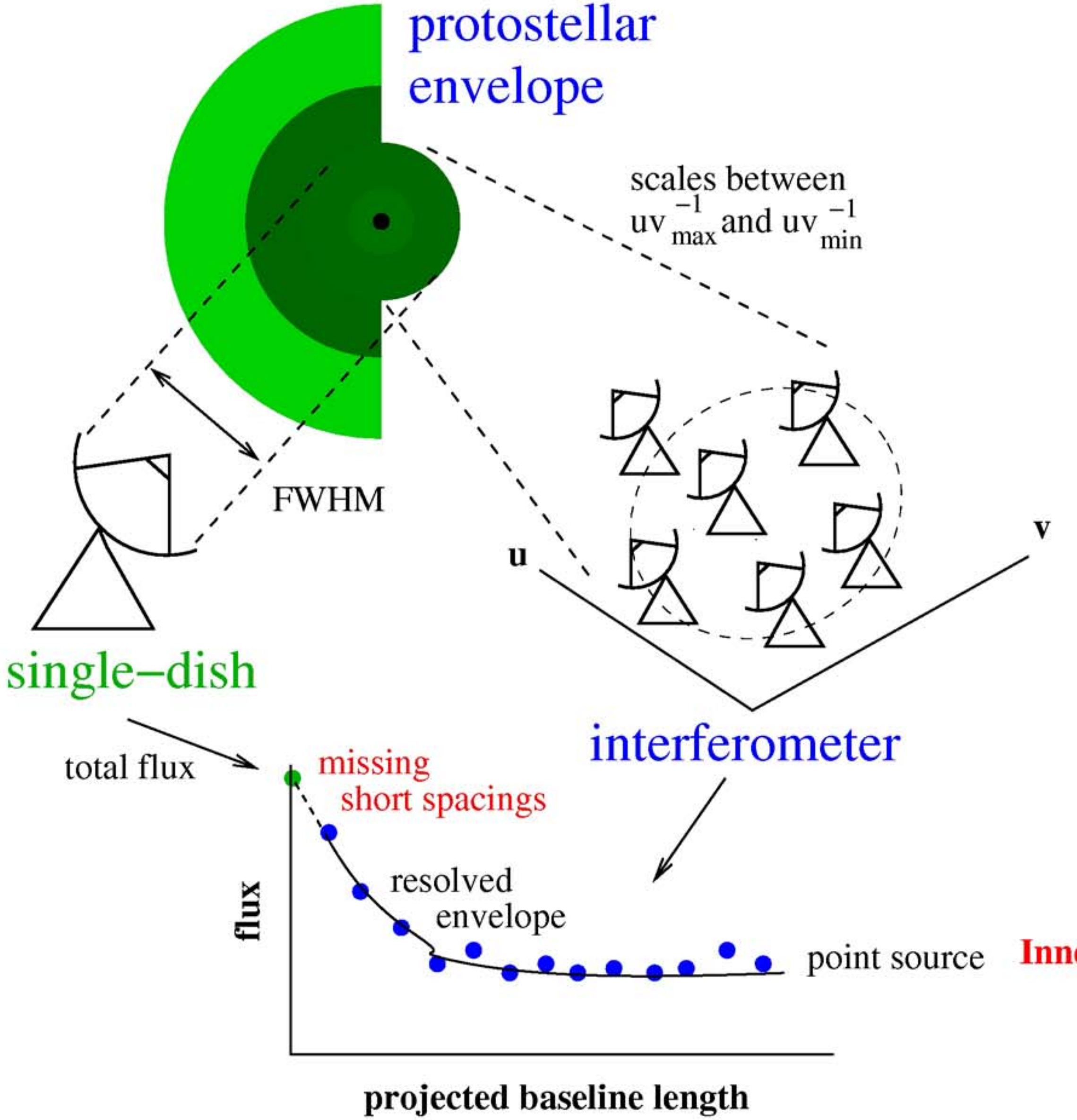
Spectral survey toward IRAS 16293-2422



Caux, Ceccarelli et al., in prep.

Q: which fraction of these complex molecules will end up in disk and how are they modified there?

Young disks: Envelope vs disk



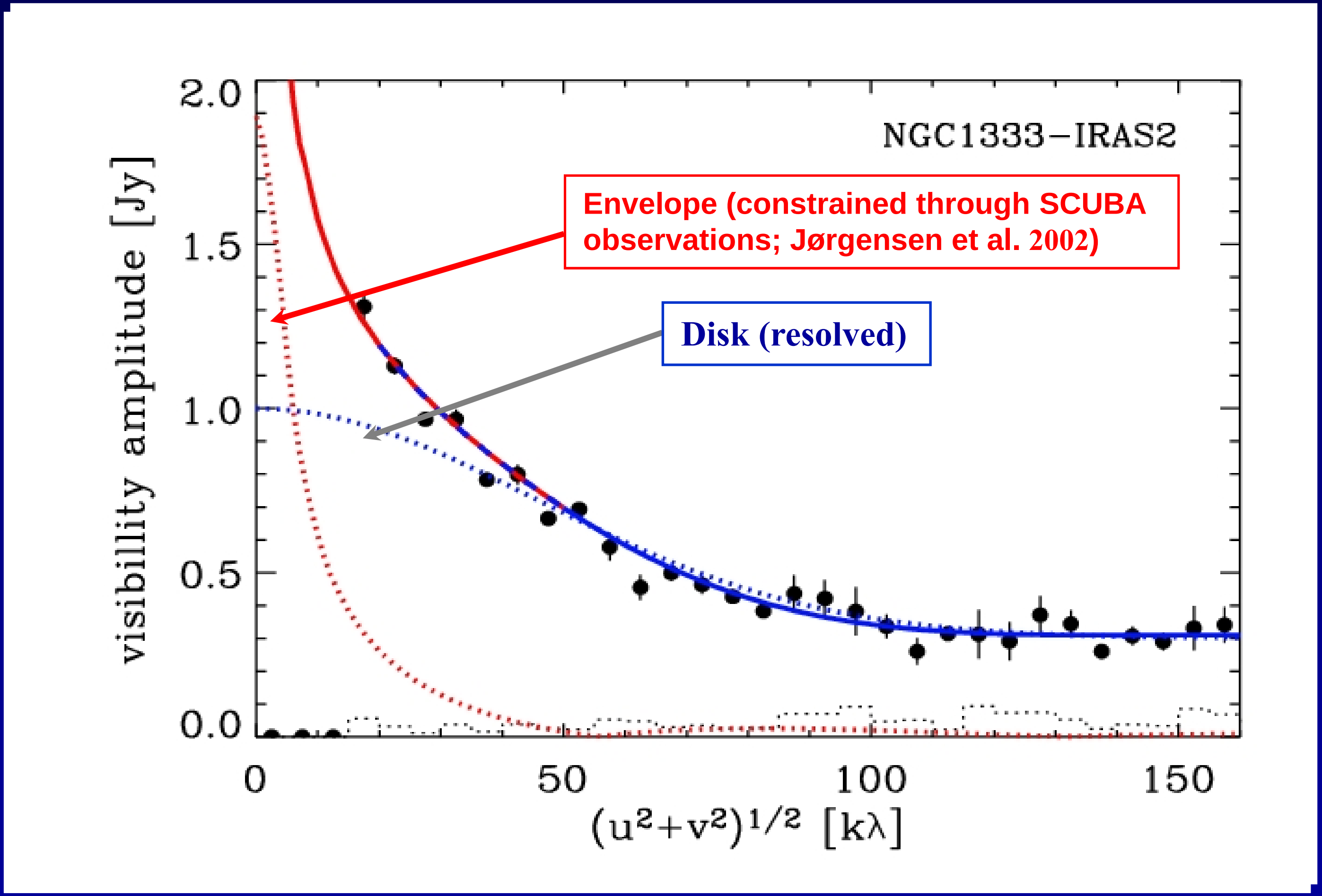
Inner envelope or disk?

Envelope overwhelms disks except on longest baselines

M. Hogerheijde

Young disks: NGC1333-IRAS2A Class 0 protostar

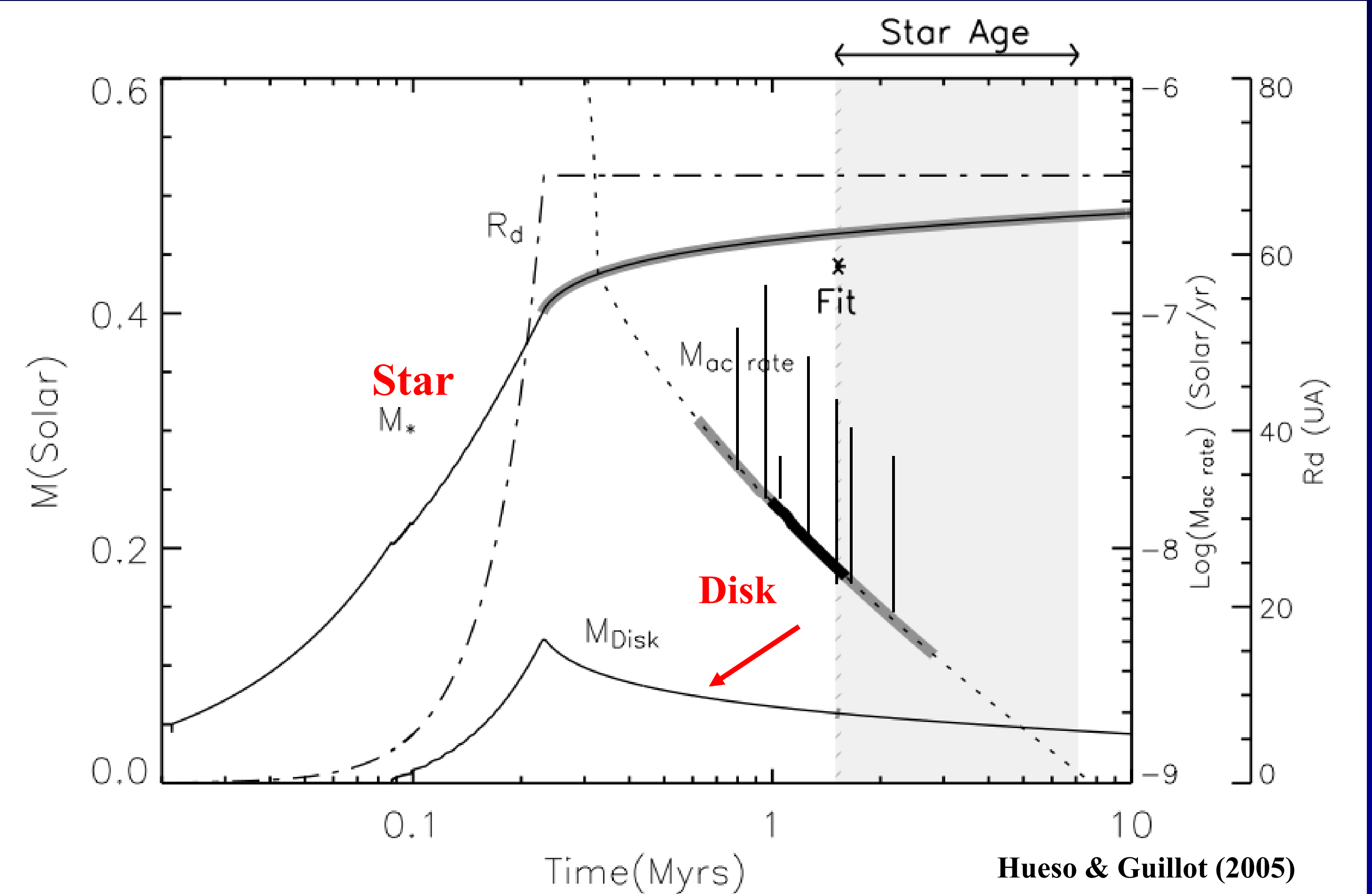
SMA resolves the dust in the inner envelope <u>and the circumstellar disk</u>



850 μm

Jørgensen et al. 2005
Keene & Masson 1991
Hogerheijde et al. 1999
Looney et al. 2000, Harvey et al. 2003

Formation and viscous spreading of disk



Hueso & Guillot (2005)

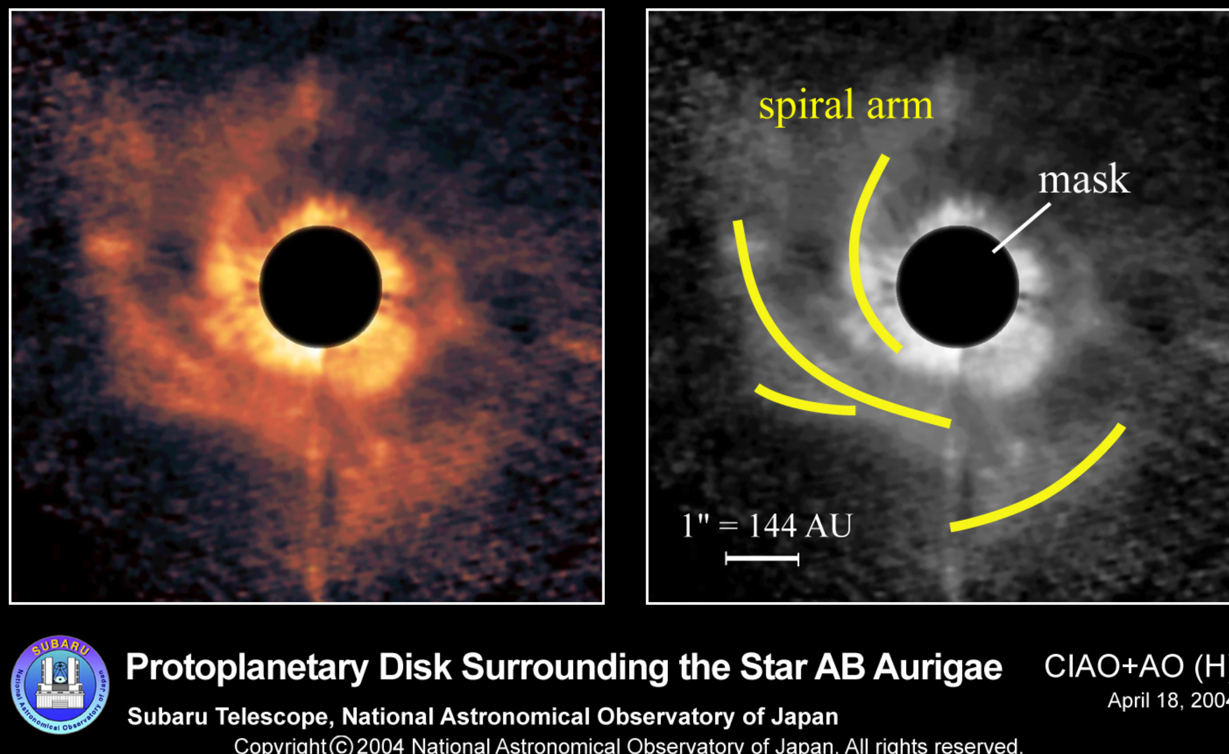
Q : how does disk form and grow with time?

can we see episodic accretion in embedded phase

gravitational instabilities in young disks?

AB Aur spiral arms

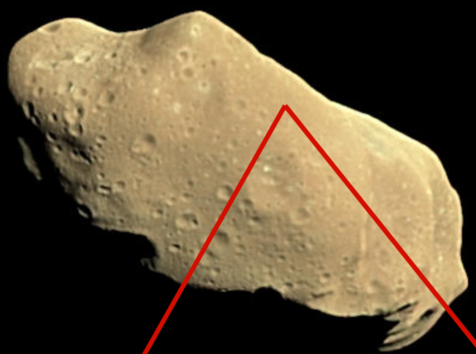
Near-IR scattered light

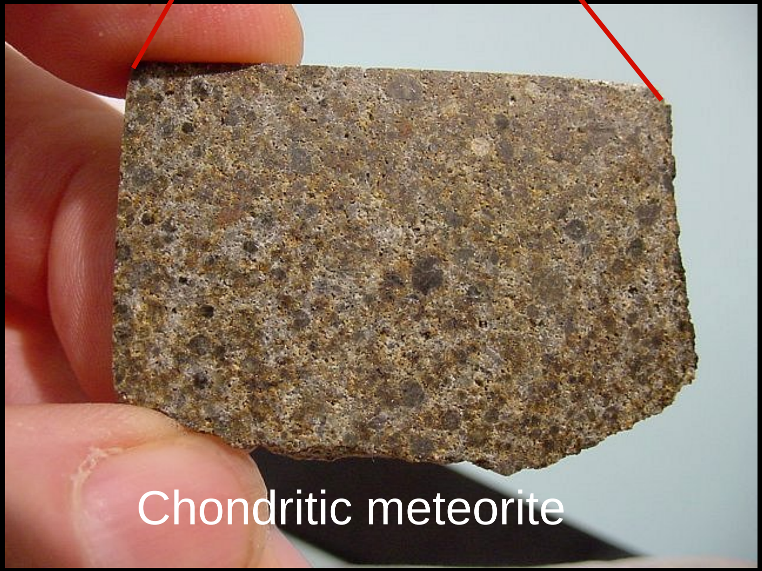


Fukugawa et al. 2004

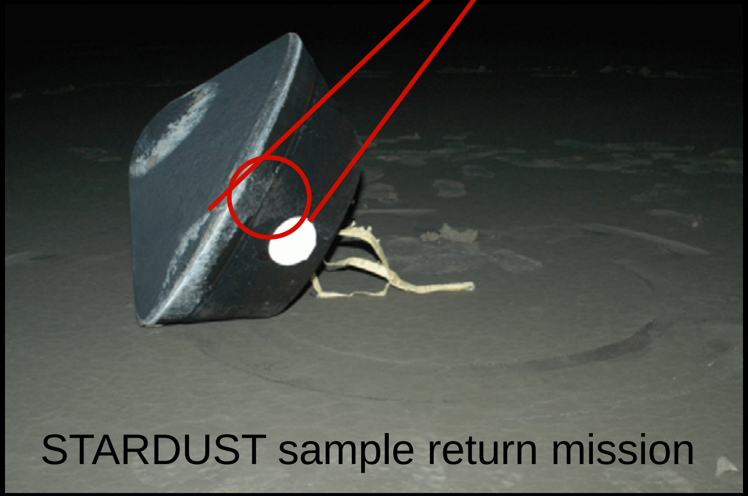
Spiral arms also seen in (sub)mm images by Corder et al. 2005, Piétu et al. 2005, Lin et al. 2006

Billion dollar question: how were ‘we’ formed 4.5 billion yrs ago?



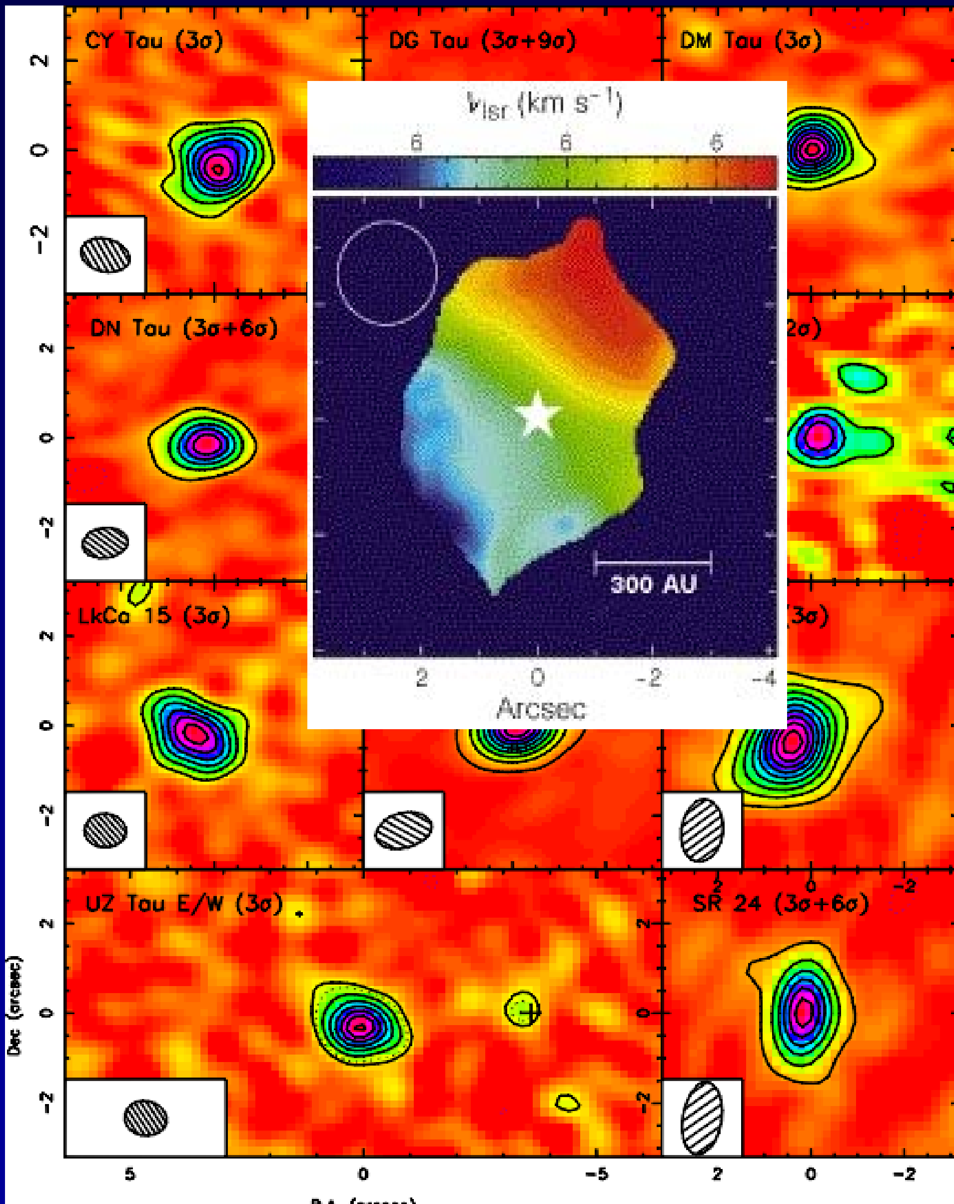


Chondritic meteorite

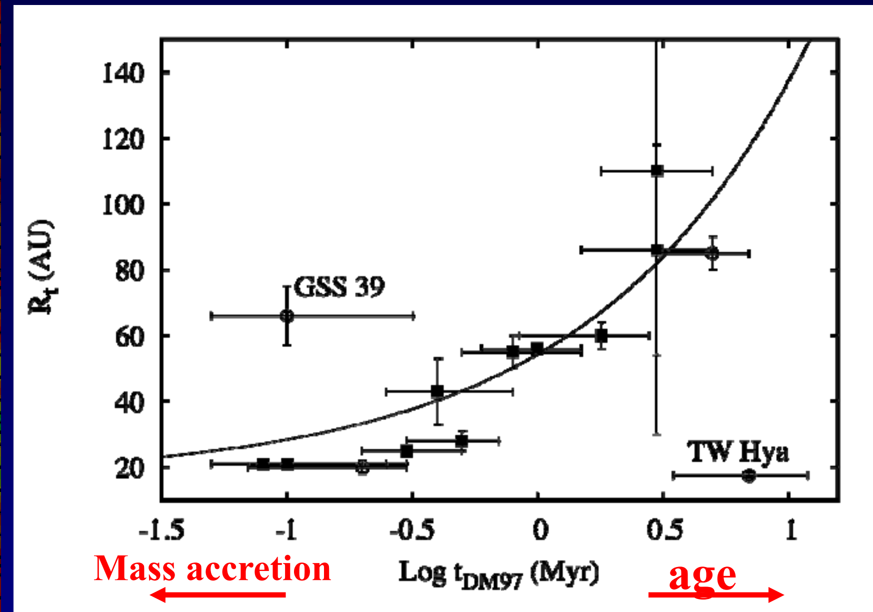


STARDUST sample return mission

Disk around pre-main sequence stars



Isella, Carpenter & Sargent 2009 CARMA



- Constrain masses + sizes of disks, velocity patterns of *outer* disks, level of turbulence, …

Q: how do disks and stars co-evolve?

See also Dutrey, Guilloteau, & Simon, Ohashi et al, Kitamura et al , Qi et al, Andrews & Williams, ….

Circumbinary vs. circumstellar disks

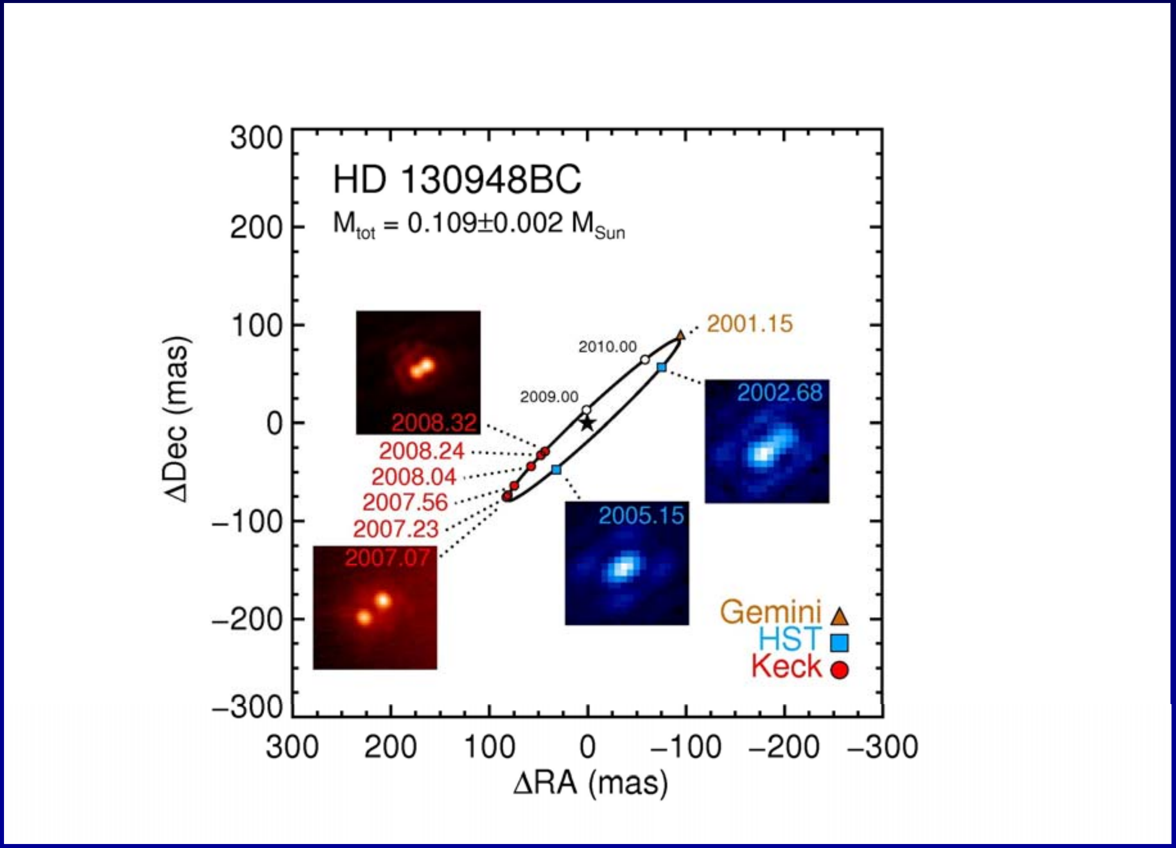
267 GHz continuum

~800 AU

Beam 0.45”x0.25”

Pietu et al. 2009

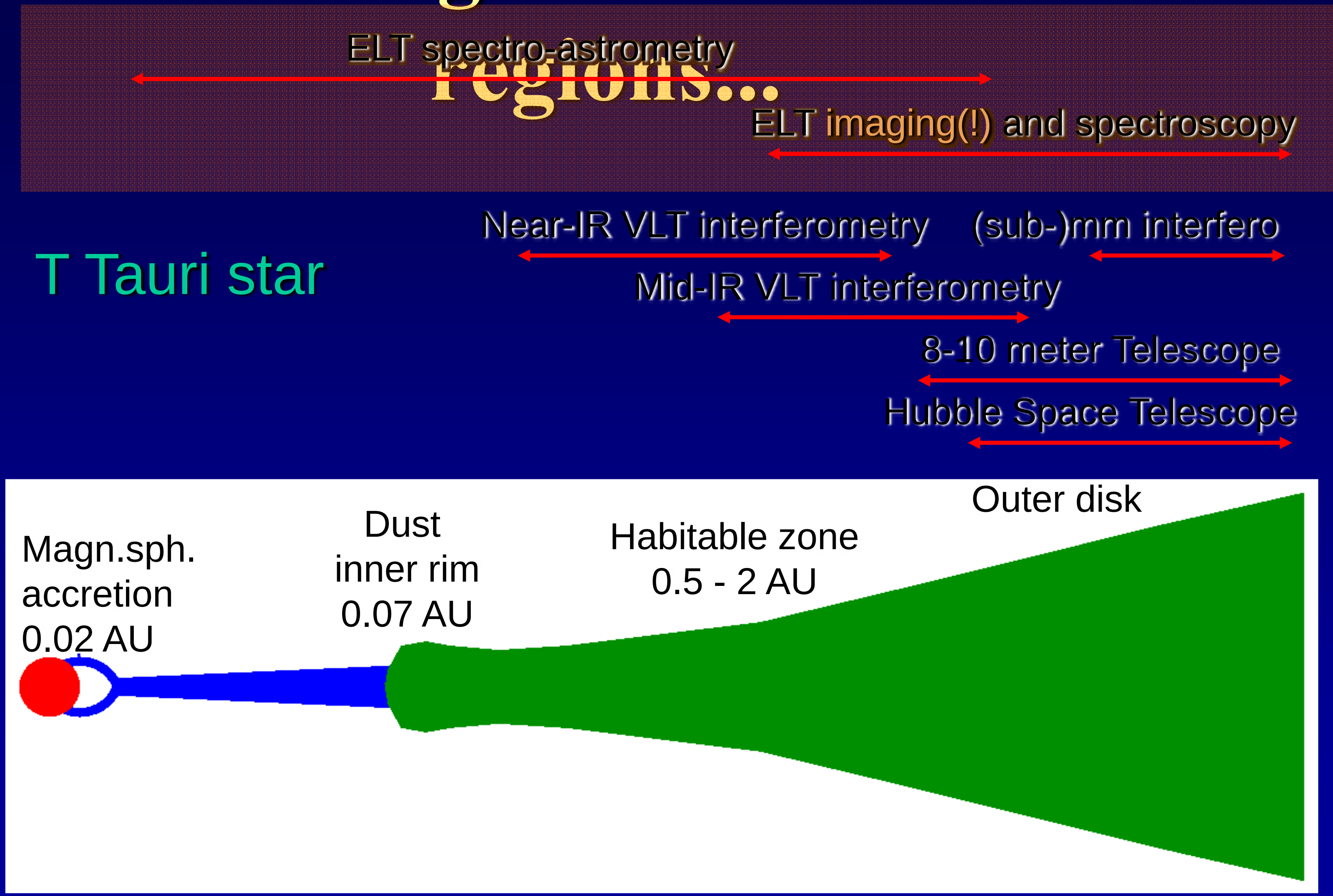
Binaries as testbeds of stellar structure and evolution



Dupuy et al. 2008

Q: What are the ages of young stars?

Probing the inner disk regions...



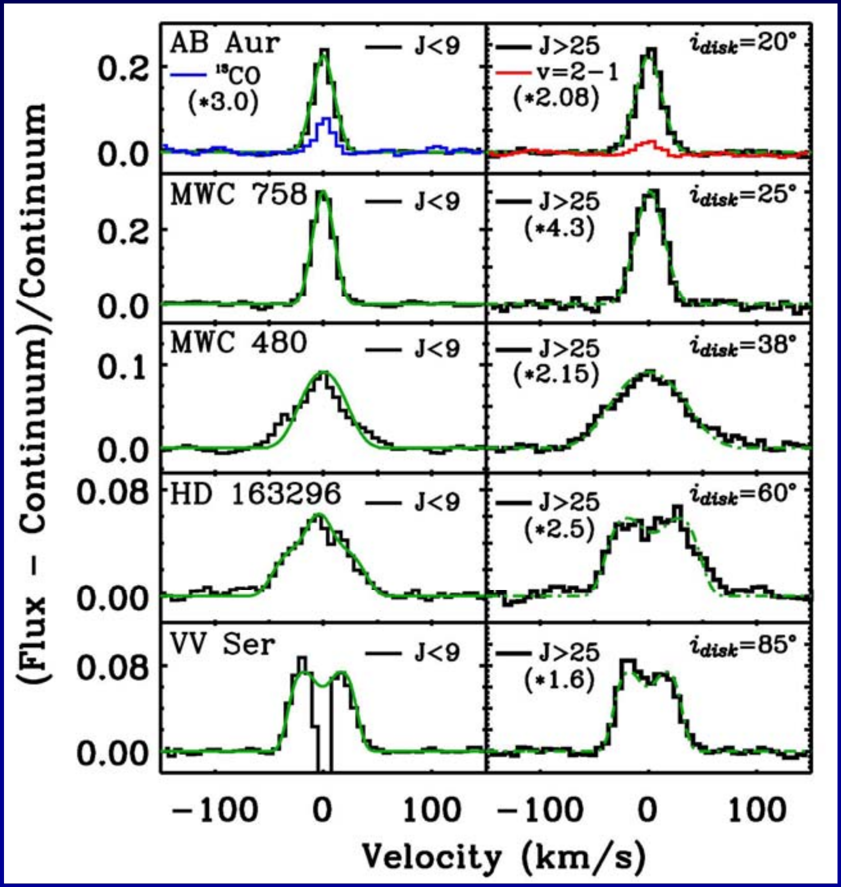
Note: ALMA can only image lines *outside* ~10 AU; ELT *inside* 10 AU

Hot gas in inner disks

CO v=1-0 band at 4.7 μm in disks around Herbig stars

Low-J **High-J**

inclination



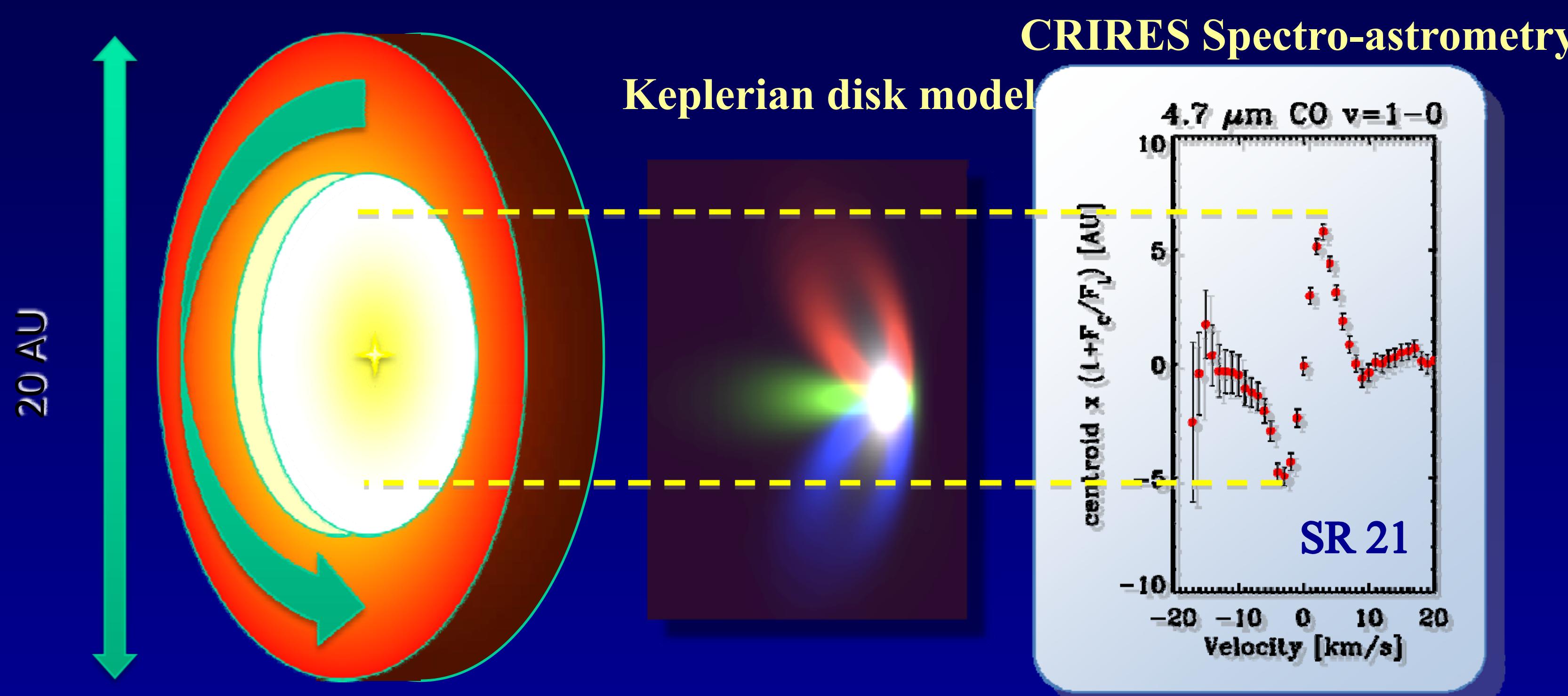
R=25000
Keck-NIRSPEC

T_{ex}~1000 K

Blake & Boogert 2004
Brittain et al. 2003, 2007
Najita et al.2003

Excitation by collisions (inner few AU) and resonant fluorescence (larger R)

Spectro-astrometry at milliarcsec resolution

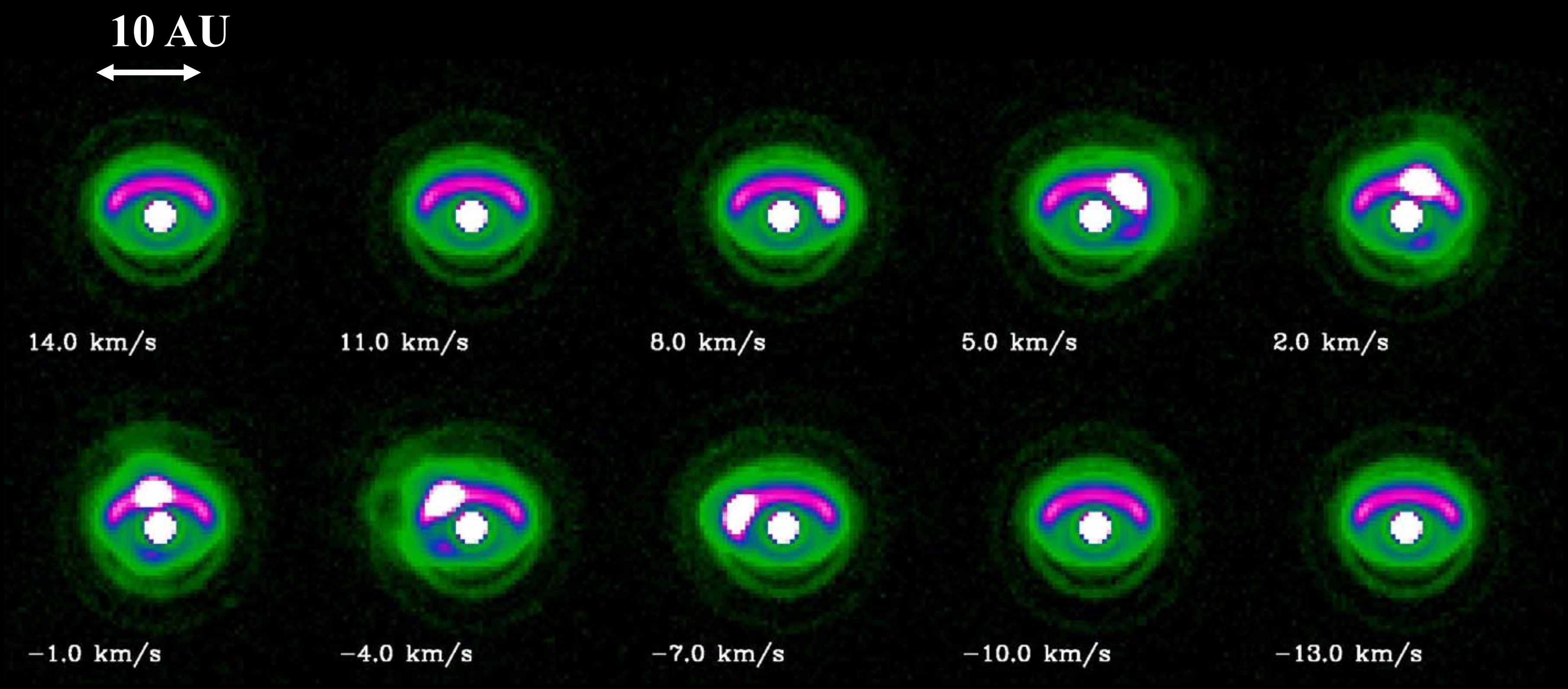


< 1 mas RMS @ λ/Δλ = 100,000

- Can locate gas down to 1 AU scale
- ELT can image kinematics directly down to few AU with IFU

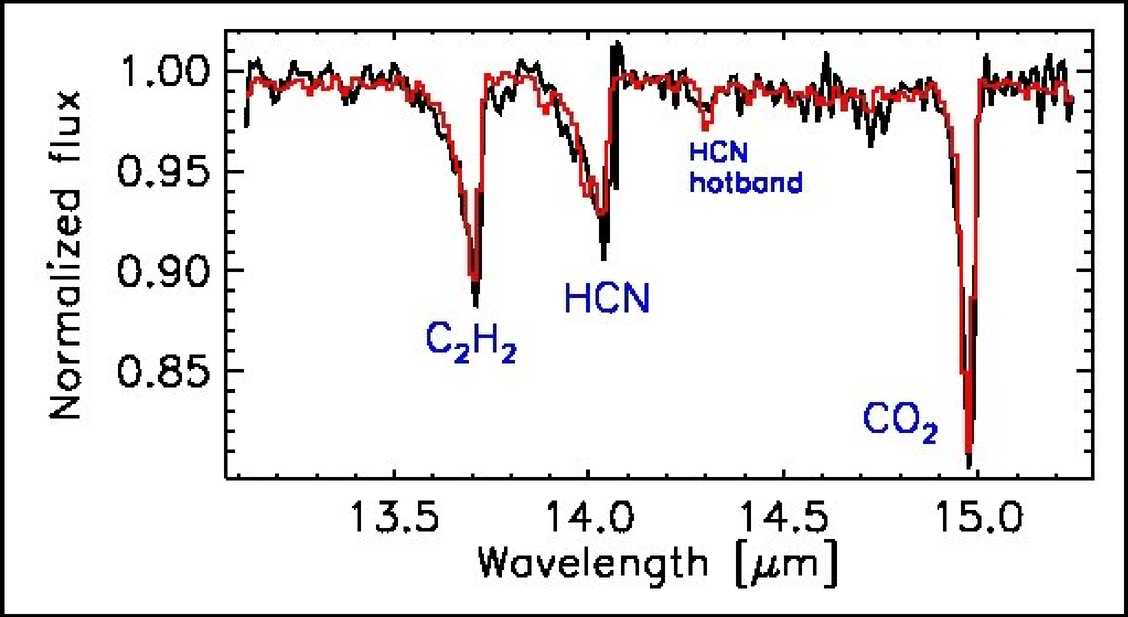
Pontoppidan et al. 2008

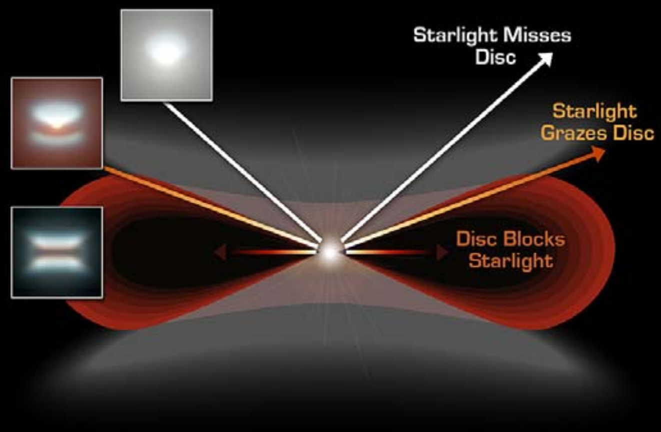
Imaging disk kinematics with ELTs



Pontoppidan et al. 2009

Hot organic molecules in planet-forming zone

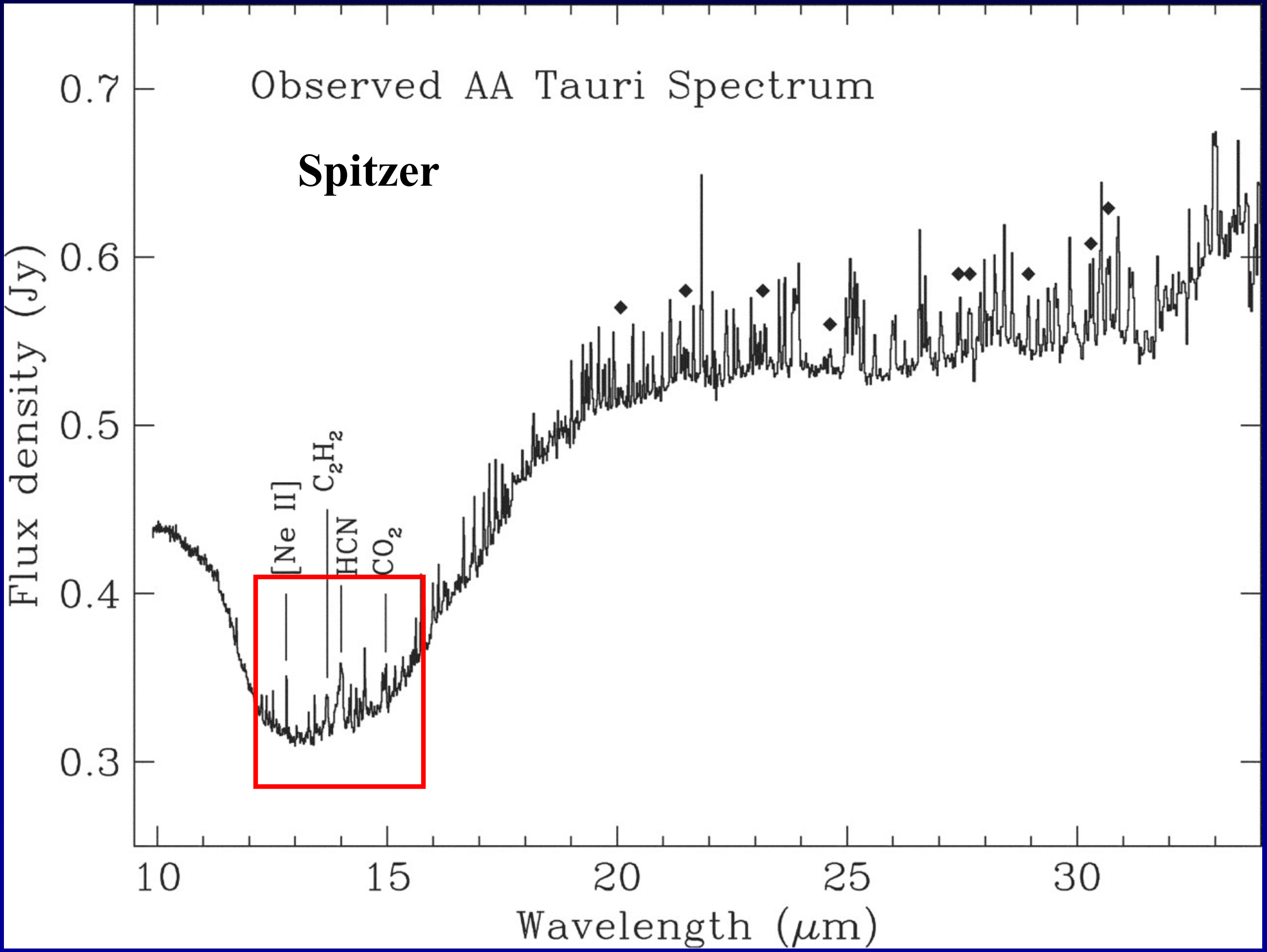




Lahuis et al. 2006

- Large abundances of ~10^{-5} of hot (300-700 K) C_2H_2, HCN, CO_2 found in inner few AU of protoplanetary disk

Water and organics in AA Tau

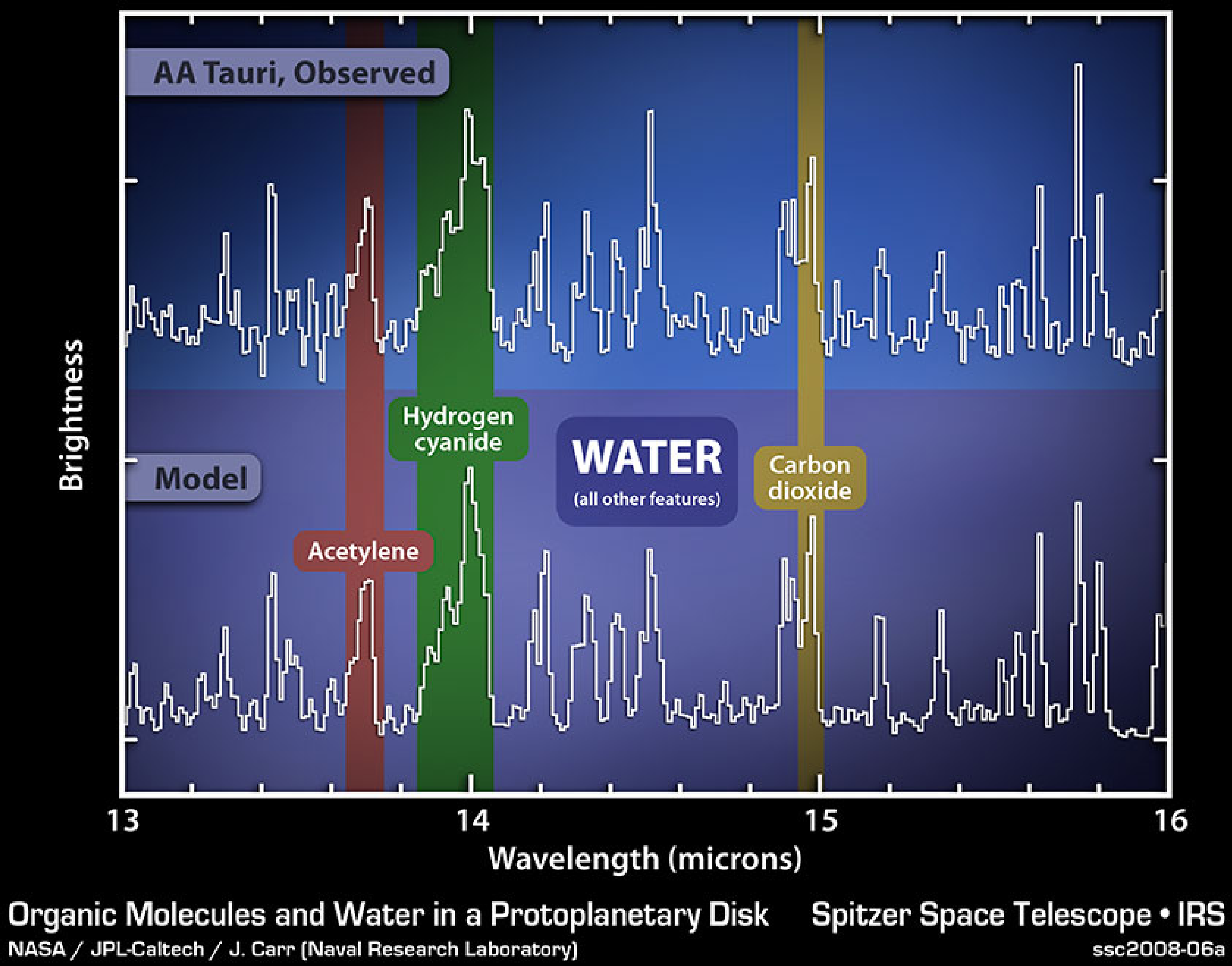


R=600

Carr & Najita 2008

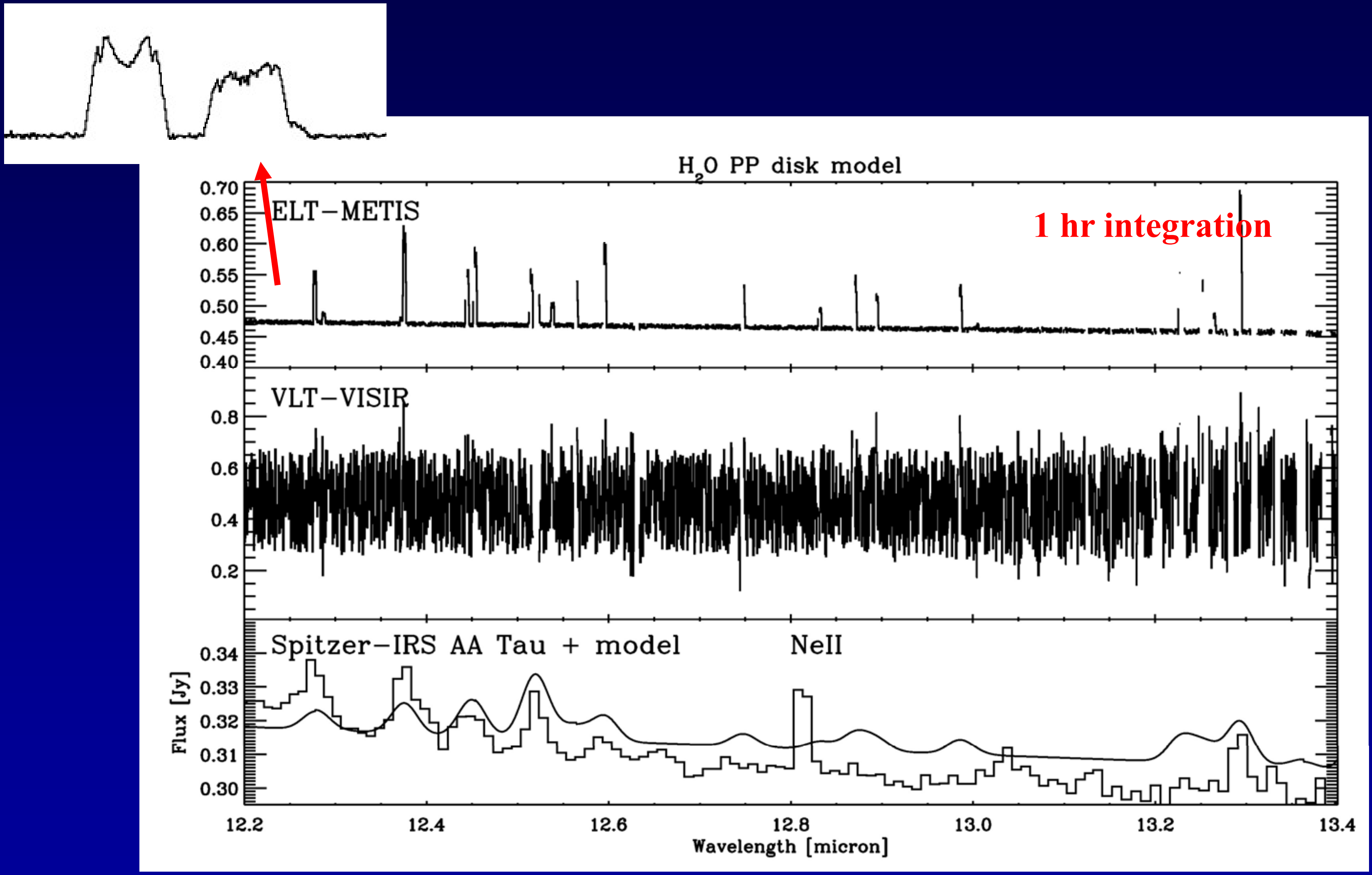
- Note richness of mid-IR spectra!

Hot water and organics in inner disk are common



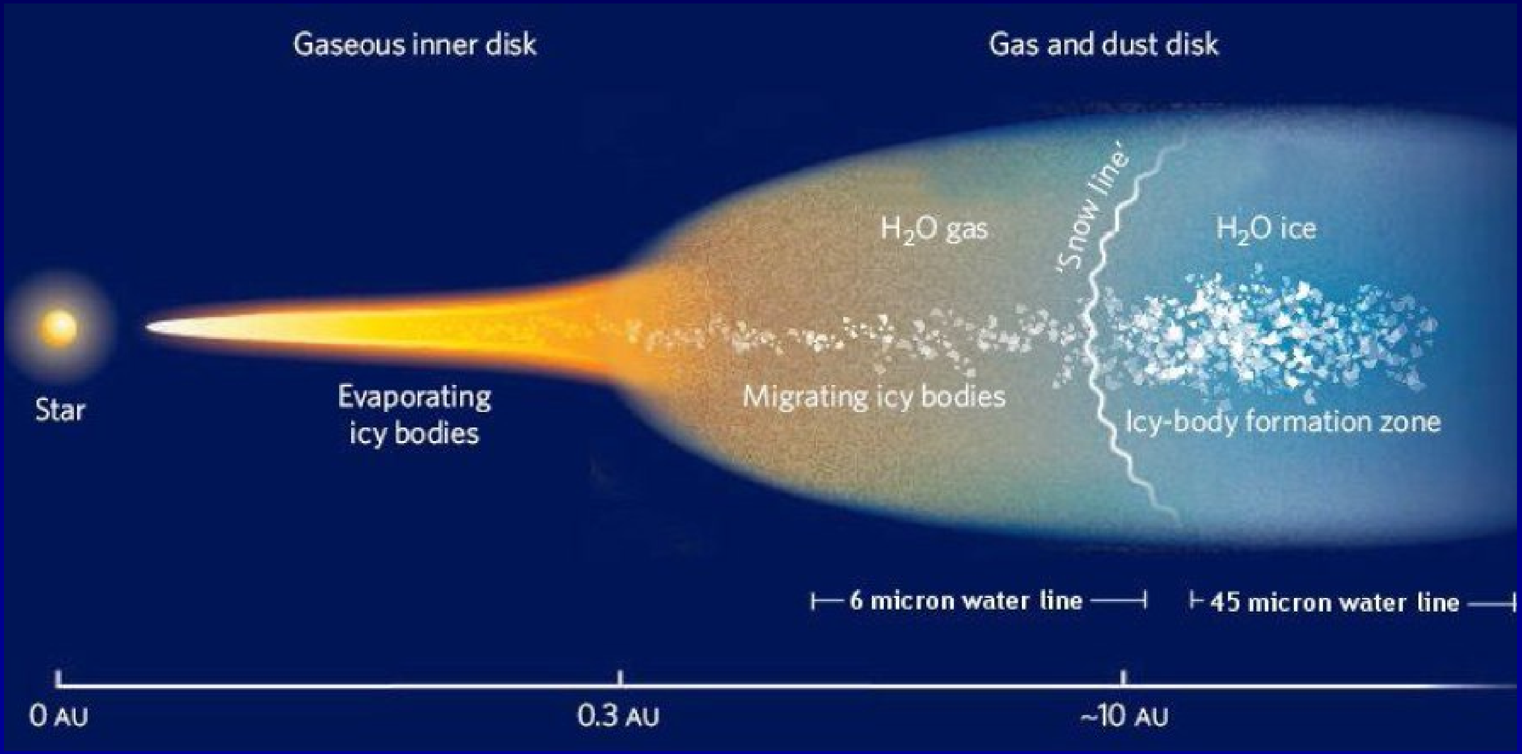
Carr & Najita 2008
Salyk et al. 2008

Need ELT for kinematics



Simulation: Pontoppidan et al. 2009

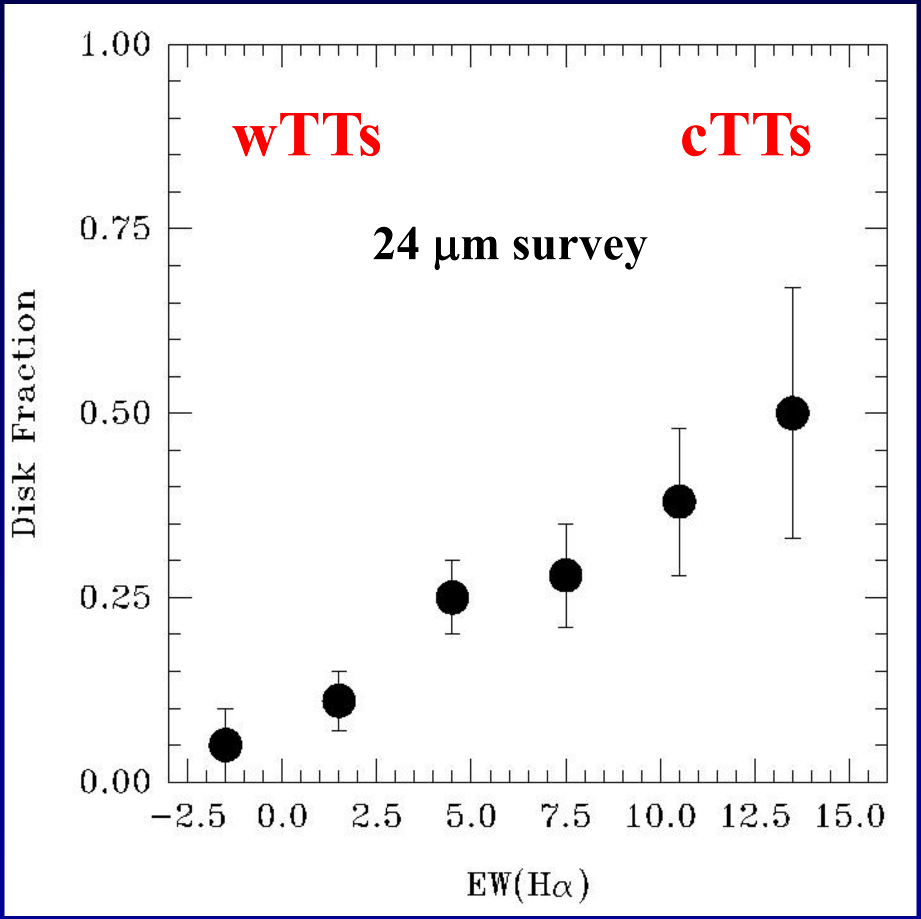
Q: Where is the snow-line in disks? (important for planet formation)



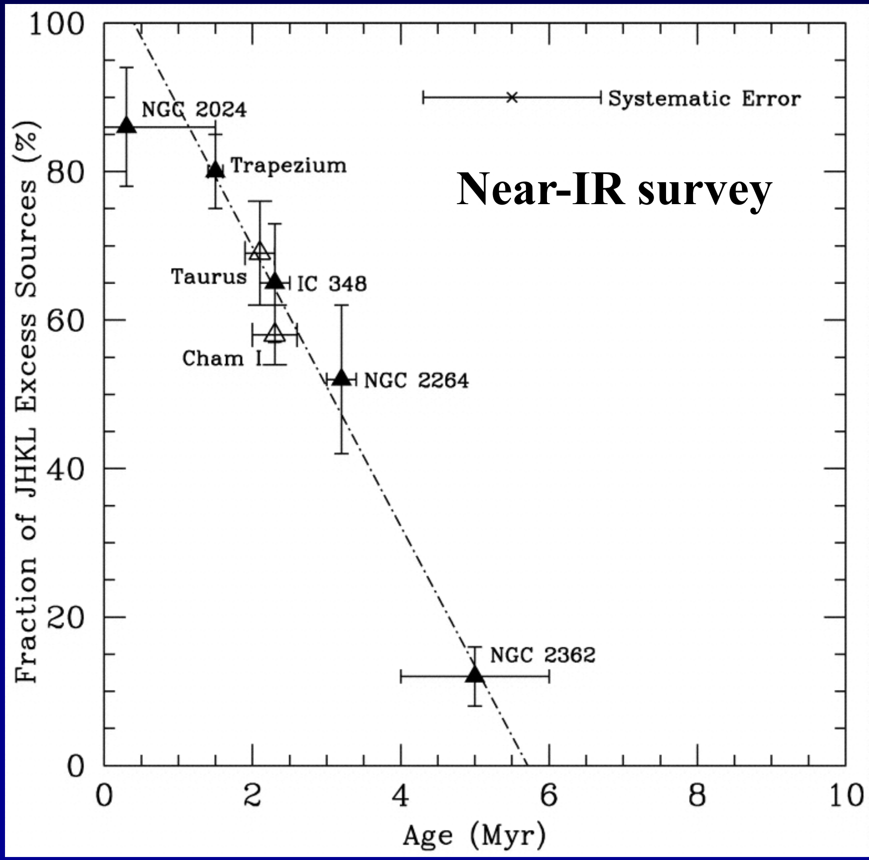
van Boekel 2007

Need ALMA Band 5 to image H_2O, $H_2{}^{18}O$ lines with ALMA

Most (inner) dust disks disappear in few Myr



Cieza et al. 2007

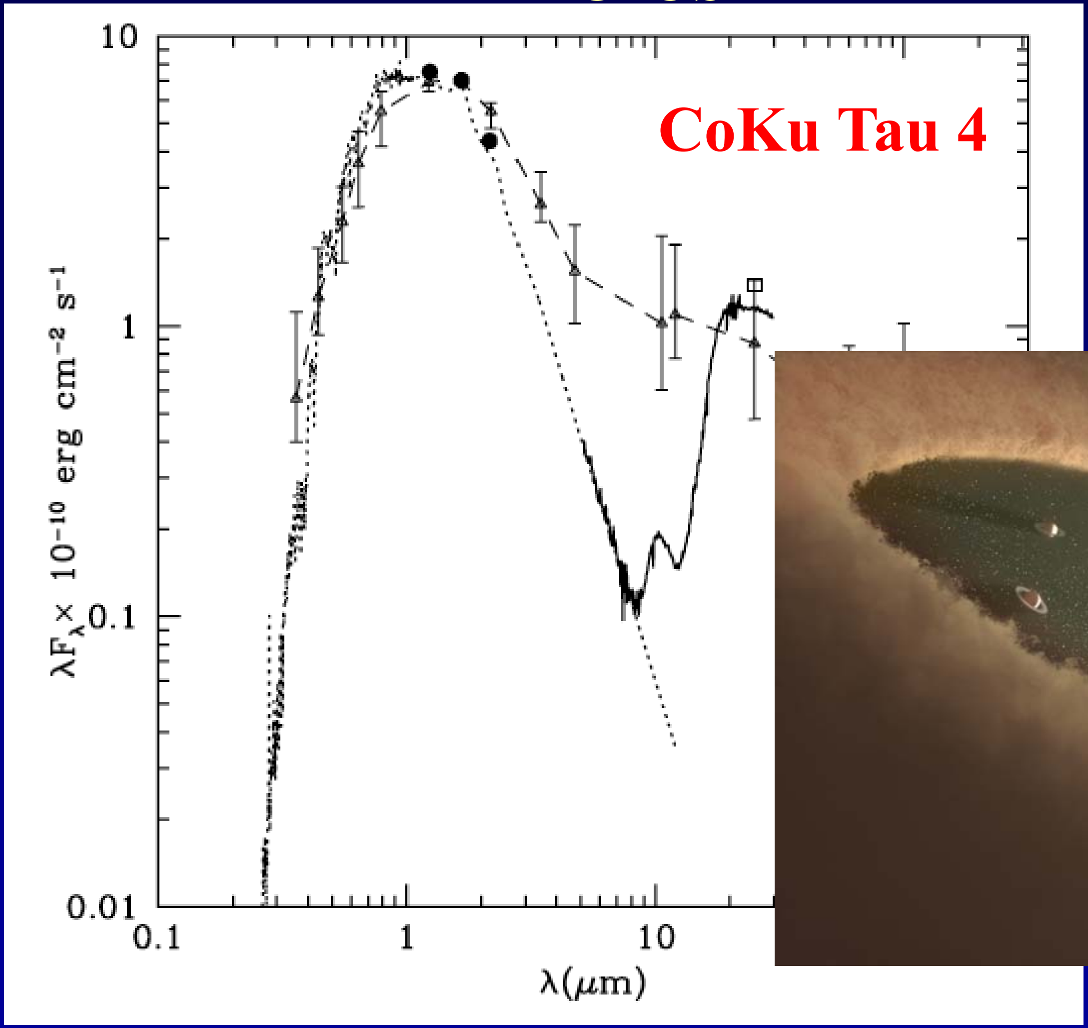


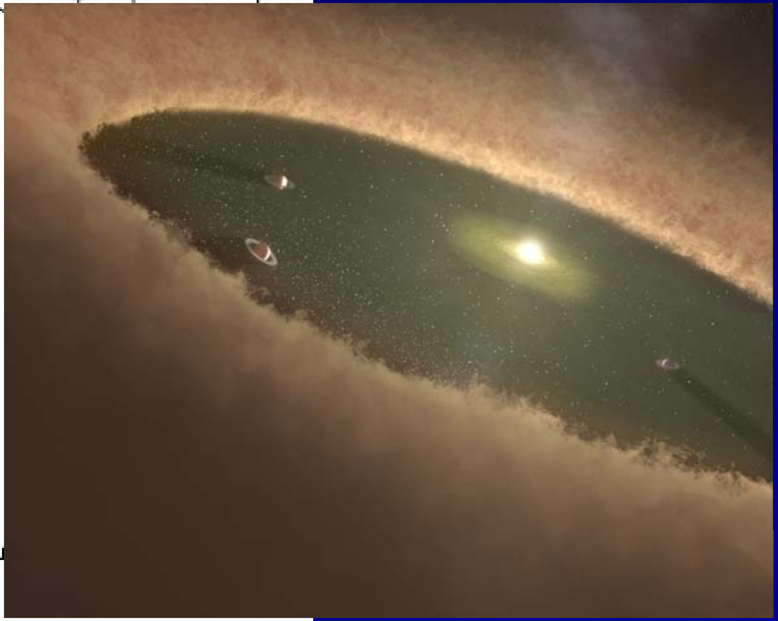
Haisch et al. 2001

Disk fraction is a smooth function of Hα eq. width (=> accretion rate)

Q: Do gas and dust disappear at the Same time?

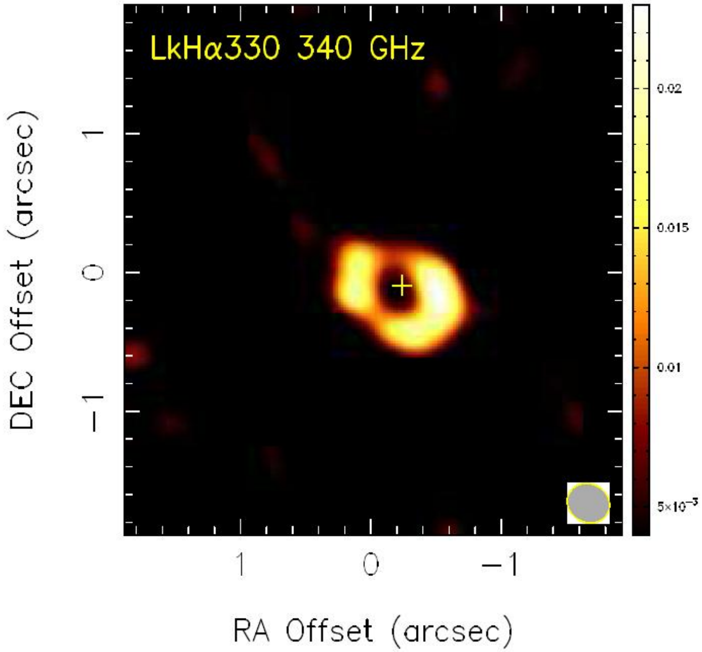
"Transition disks": Huge inner dust holes





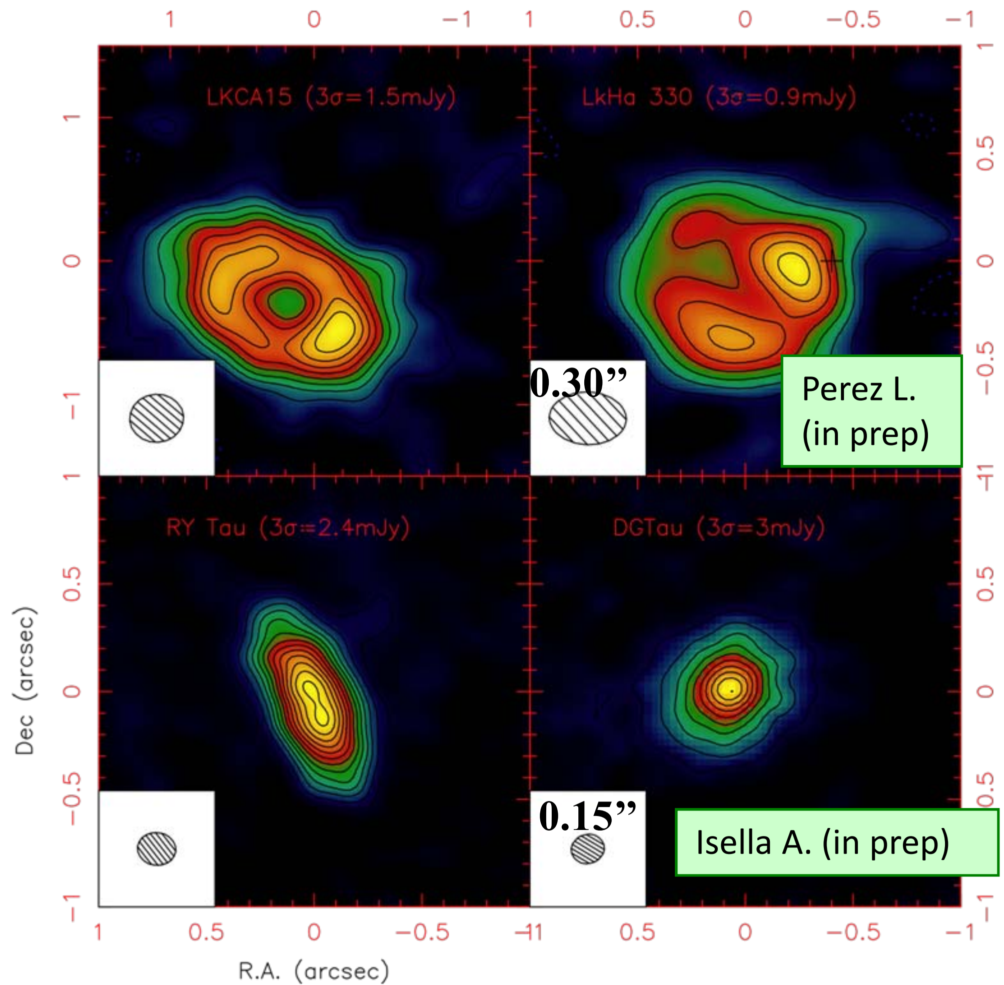
Calvet et al. 2002, D'Alessio et al. 2005, Forrest et al. 2004,
Brown et al. 2007, Espaillat et al. 2007, Merin et al. 2009

Transitional disks



Brown et al. 2008
(e)SMA

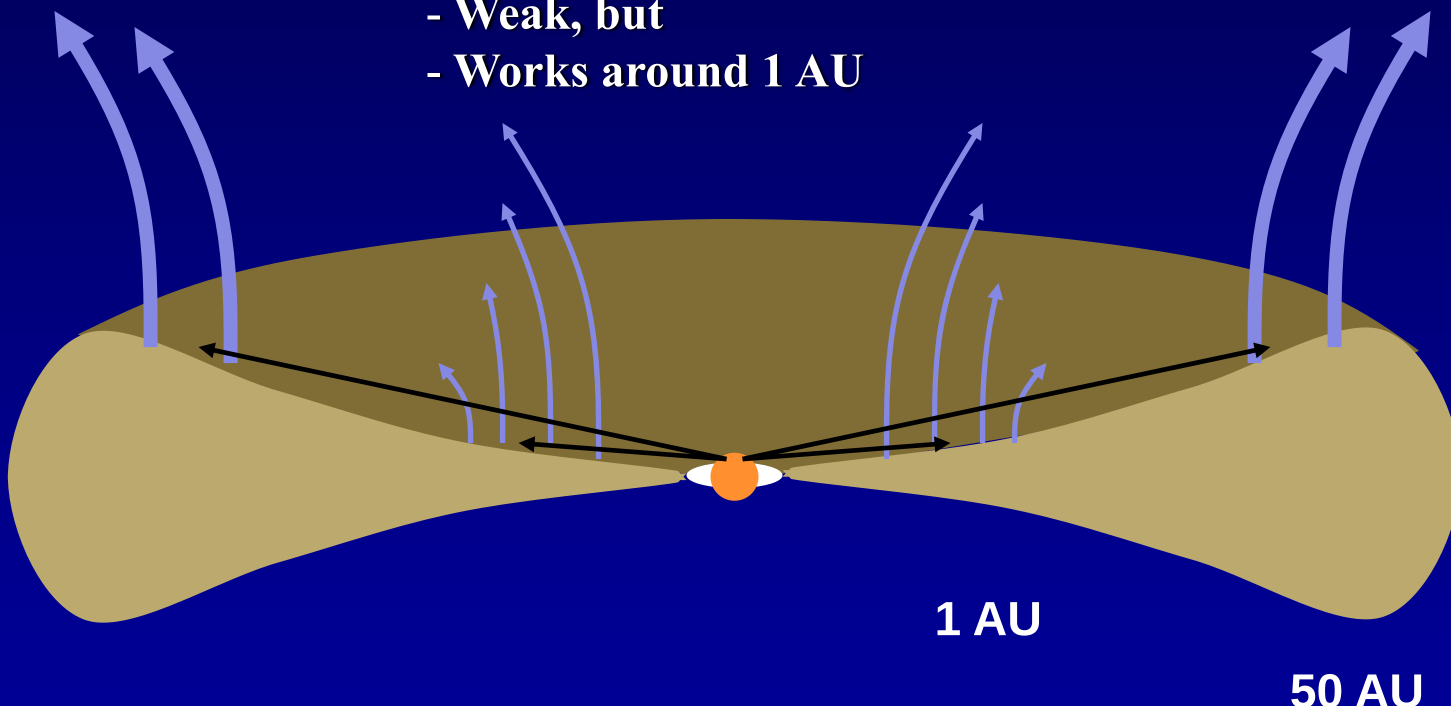
CARMA



Q: How and when is gas lost from disks?
Multiple paths of disk evolution?

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

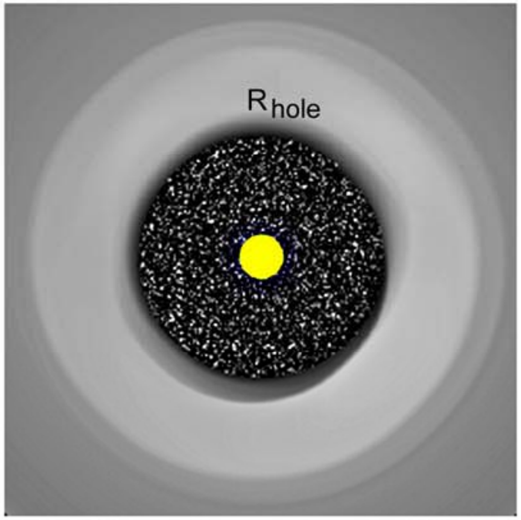
EUV Photoevap:
- Weak, but
- Works around 1 AU



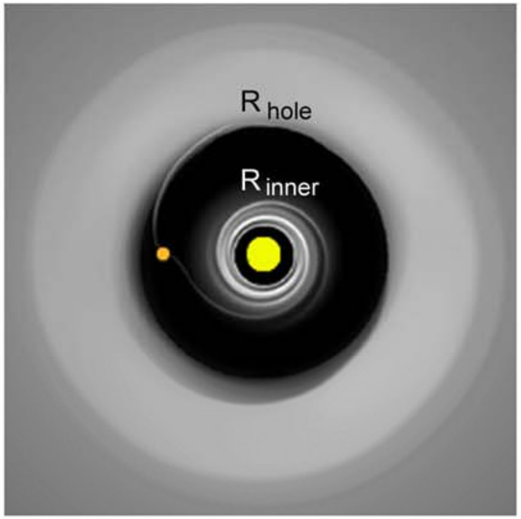
Hollenbach et al. 1994
Gorti & Hollenbach 2007
Alexander et al. 2007

Possible interpretations

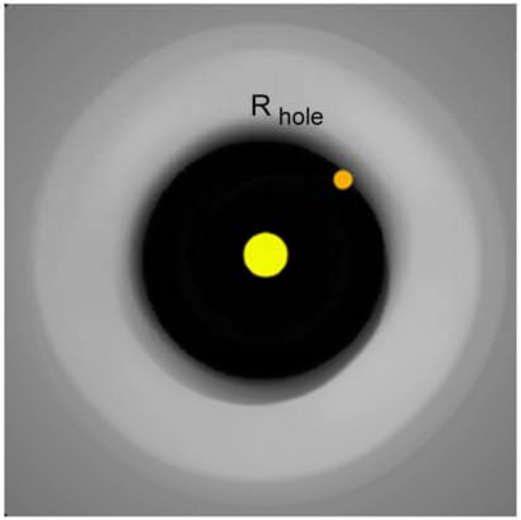
- Photoevaporation
- Grain growth to large particles
- Jupiter-type planets



Grain growth:
Planetesimals

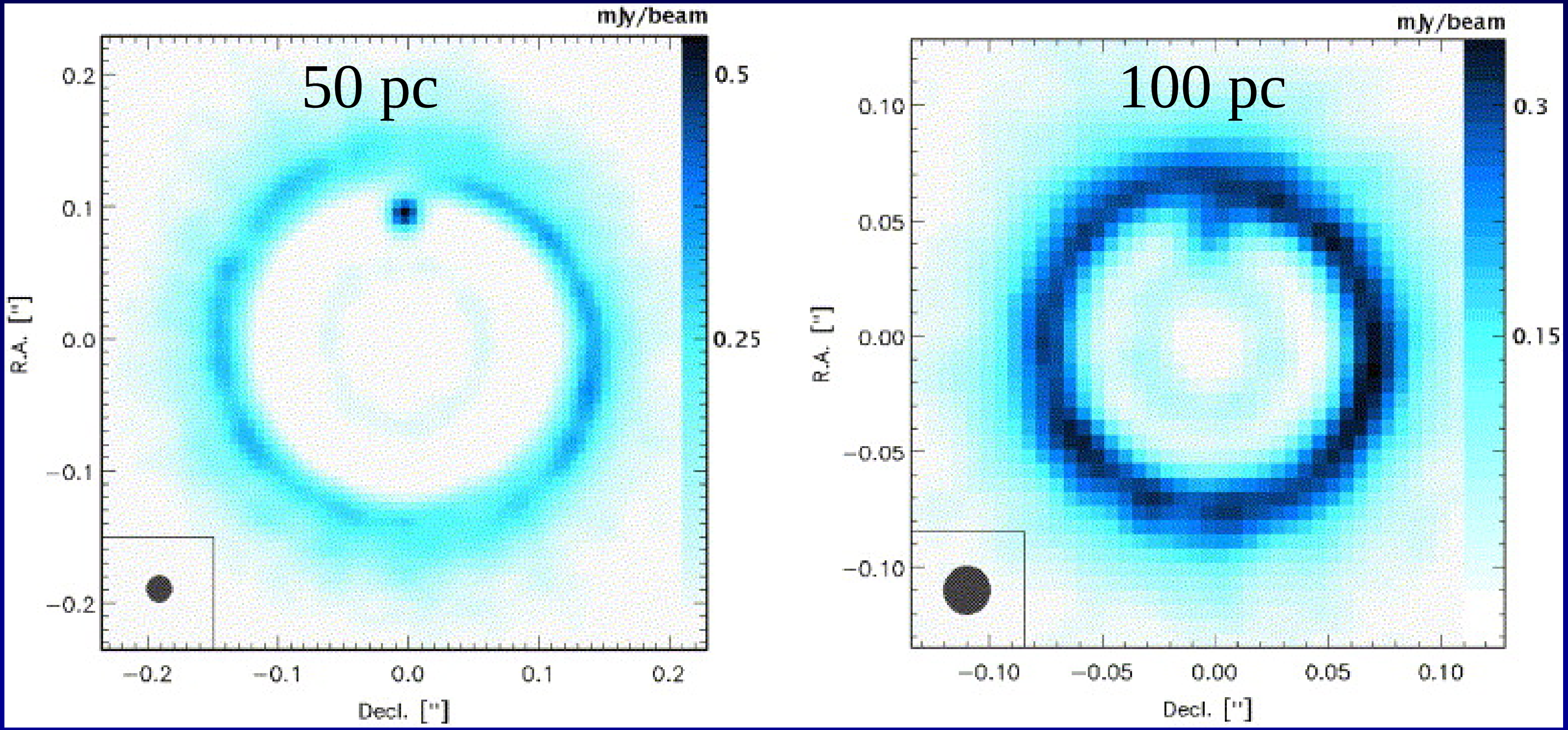


Jupiter-type planets



Supra Jupiter-type planets
(5-10 M_J)

Where are the protoplanets?
When and how formed?
Gravitational instabilities or core accretion?

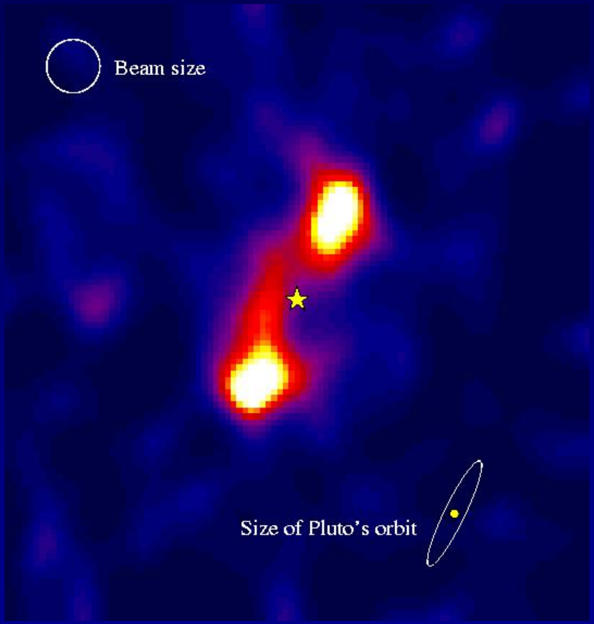


ALMA simulation 850 GHz, 1 M_{Jup} around 0.5 M_{Sun} at 5 AU

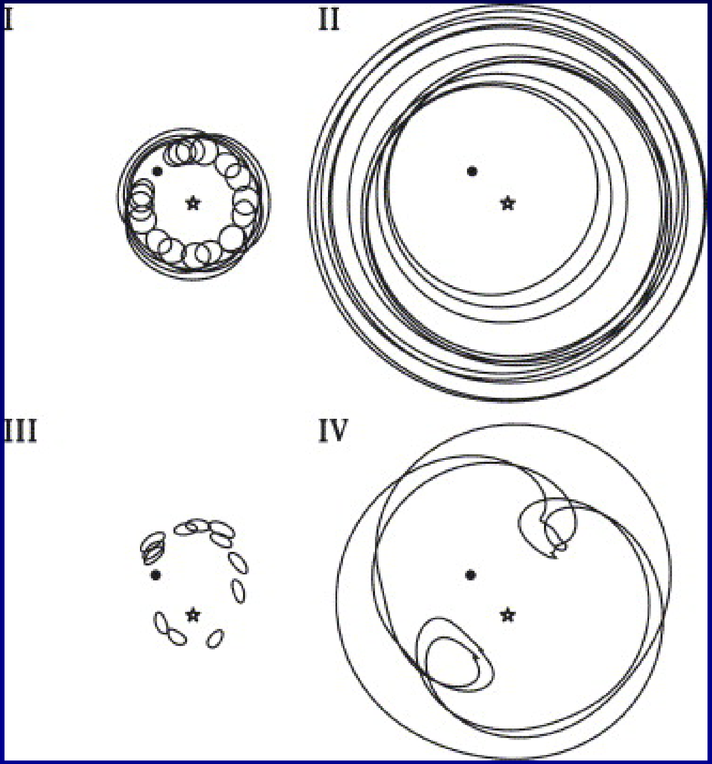
Wolf & d'Angelo 2005

- **ALMA**
- **IR with coronagraphs**

Debris disk structures



Holland et al. 1998



Kuchner & Holman 2003

Q: How do young planetary systems evolve?

Q: What planetary architectures are inferred from debris disk structures? Diversity?

Q: Relation with observed mature planetary systems?

Conclusions

- ALMA and ELT will jointly be essential and unique to answer many key questions in star and planet formation
- Many of the source lists will come from unbiased surveys being carried out now
  - Spitzer, Herschel mid- and far-IR
  - Submm and near-IR wide field
- Sophisticated analysis and modeling tools essential