First Results from ALMA (and some others…) on Proto-Planetary Disks

Anne Dutrey (LAB, France)

Many thanks to my close collaborators: S.Guilloteau, V.Pietu, V.Wakelam, F. Hersant, E. DiFolco, Y-W Tang and E.Chapillon

Circumstellar Disks around low-mass PMS Stars

Precursor of Solar type stars

→ T Tauri & HAe stars from 0.5 to ~ 2-3 Msun

c),d) Proto-planetary Disks

~ 10^4 (class 0) – 10^5(Class I) to 10^6 (Class II) years

→ Dust emission optically thick at λ= 1 μm

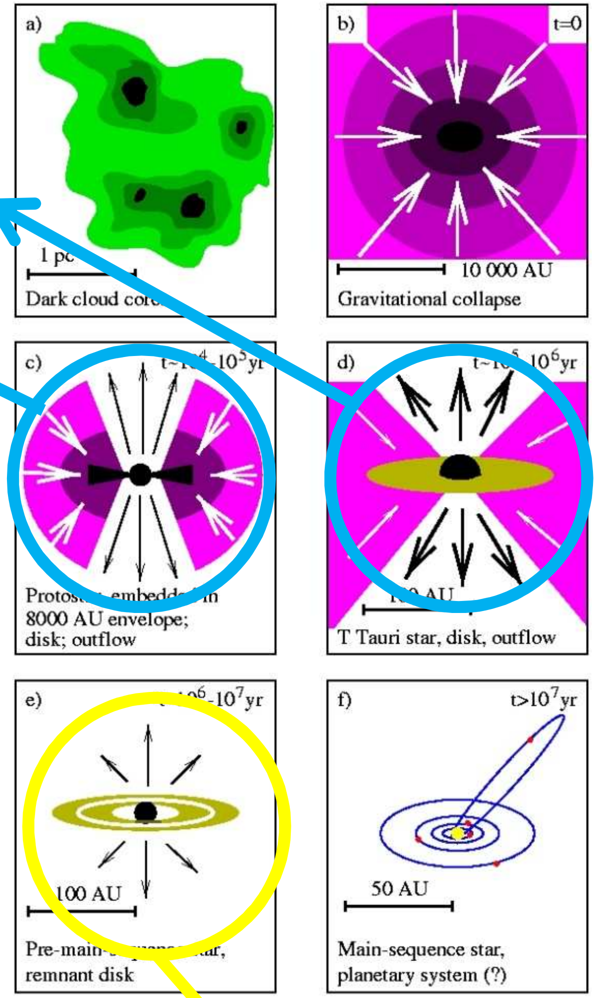
optically thin / moderate opacity at λ= 3mm

→Massive ~ 0.05 → 0.01 Msun (H2+Dust)

enough gas to form a "proto-Jupiter"

→ Gas rich with Gas/Dust ~ 100 (?)

1% of dust –> dynamics governed by gas



Hogerheijde 1998, after Shu et al. 1987

Class II

Class O & I

Class III & Debris disks: Gas Free

Circumstellar Disks around low-mass PMS Stars

Precursor of Solar type stars

→ T Tauri & HAe stars from 0.5 to ~ 2-3 Msun

Outline:

Which instruments for which kind of observations ?

Herschel, IRAM 30-M & PdBI, CARMA, SMA, VLA, ALMA

What are the relevant observables ?

→ Flux density, Brightness

→ Data Analysis (simple models…)

Results: which quantity are we able to measure ?

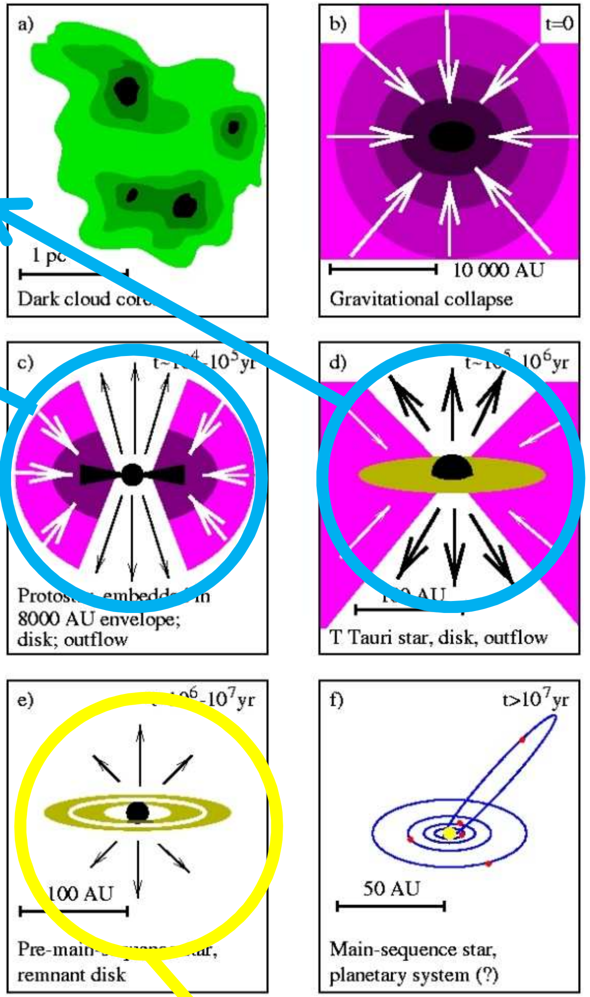
→Geometry (size, cavities, spiral waves …) …

→ Temperature, Density, Turbulence …

→ Velocity Field …

→ Dust properties (composition, size) …

→ Molecular Complexity …



Hogerheijde 1998, after Shu et al. 1987

Class II

Class O & I

Class III & Debris disks: Gas Free

Which Instruments ?

At 150 pc, Uranus ◯ = 0.3”

1990 - CO detection

-Morphology & Kinematics (Keplerian)

2000- Density / Temperature ?

(excitation conditions ?)

2003 - Turbulence ?

- from CO

1997- Molecular Complexity ?

- HC_3N

1990 - Dust Disks ?

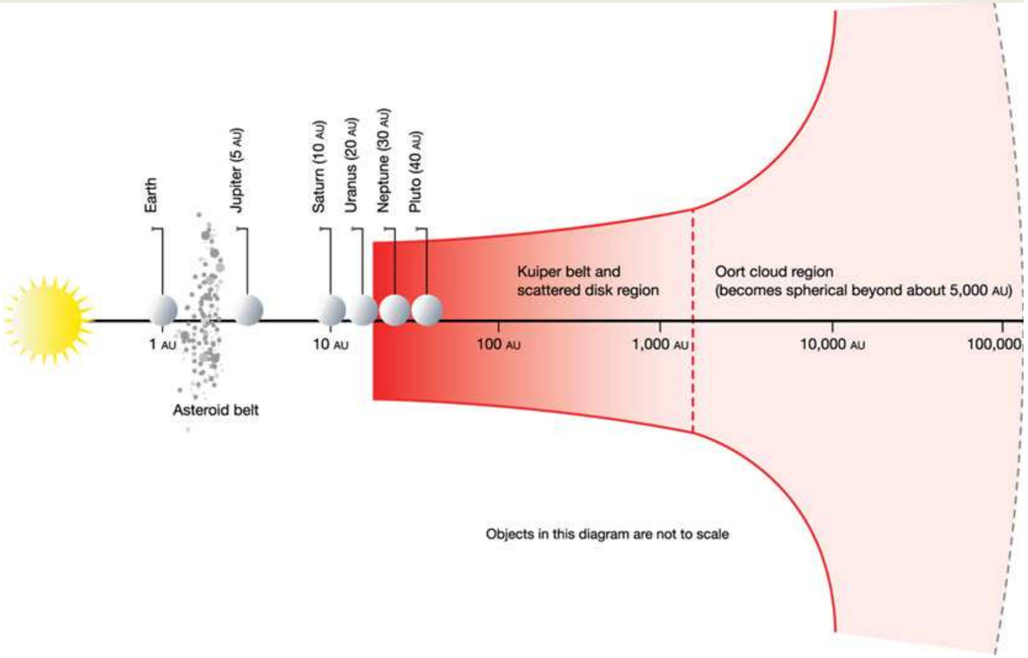
- Surveys: grain growth

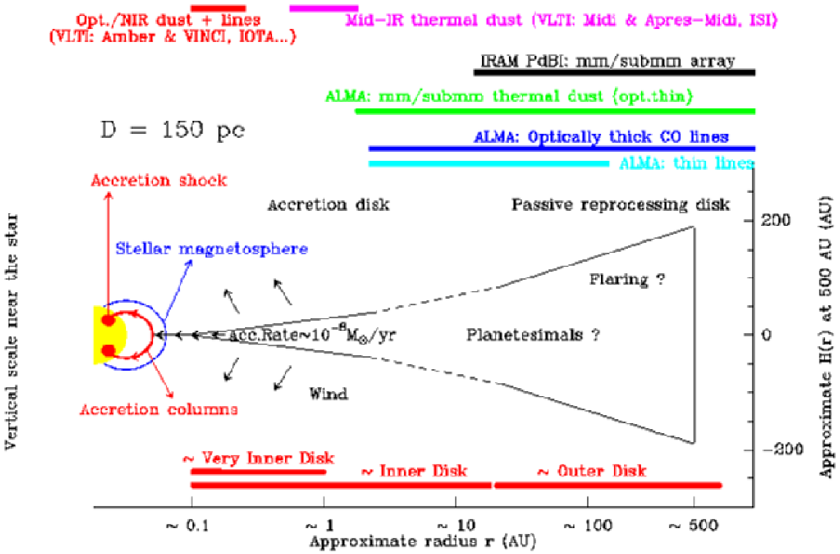
- Radial properties

2006 - Inner Cavities around single stars …

-In dust disks

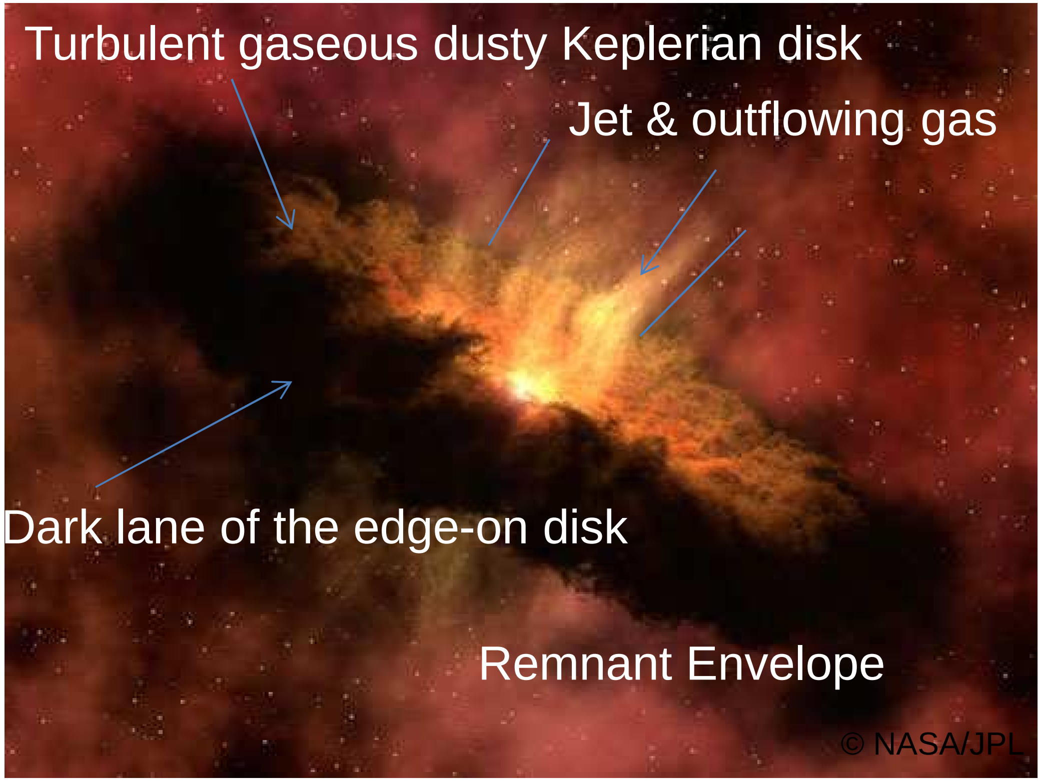
-In Gas disks





Which Instruments ? Tracers …

Turbulent gaseous dusty Keplerian disk:
-Cold (10-100K) outer disk (R> 30 AU): CO, CN – mm/submm
- Warm (very) inner disk and surface (R< 10-30 AU): H_2, H_2O, CO – IR lines



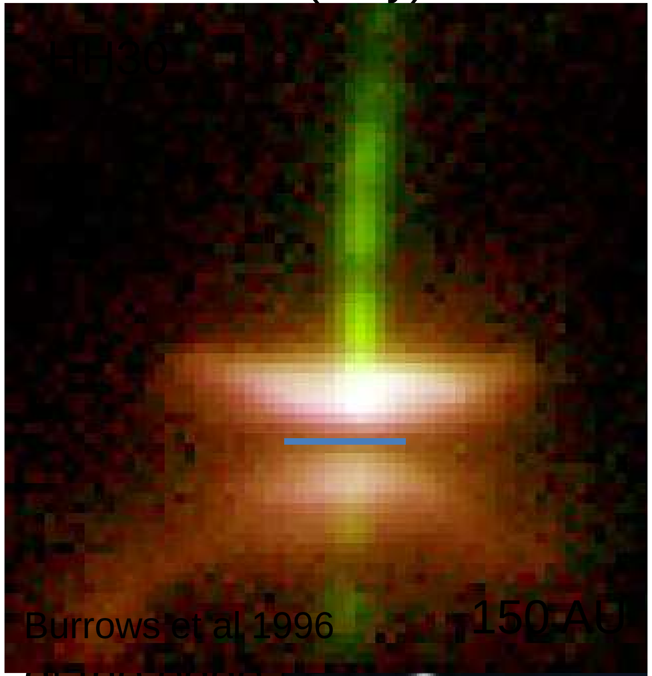
© NASA/JPL

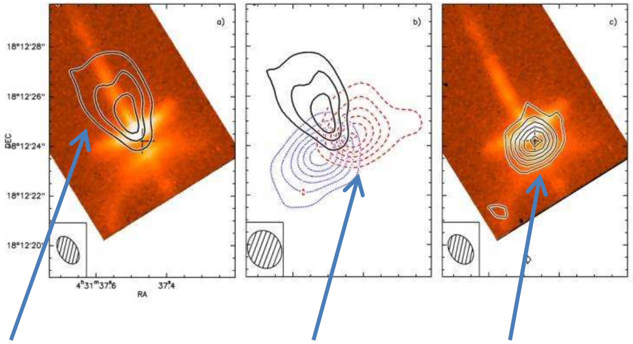
Jet & outflowing gas:
- Jet: OI, SII, … opt./IR lines (shocks)
- Colder outflow (« jet envelope ») »: CO
SiO (as shock tracer close to the jet)
Mm/submm lines

Remnant Envelope:
- Molecular lines – mm/submm
- Reflection nebula in IR

Which Instruments ?   Tracers …

Turbulent gaseous dusty Keplerian disk:
-Cold (10-100K) outer disk (R> 30 AU): CO, CN – mm/submm
- Warm (very) inner disk and surface (R< 10-30 AU): H_2, H_2O, CO – IR lines





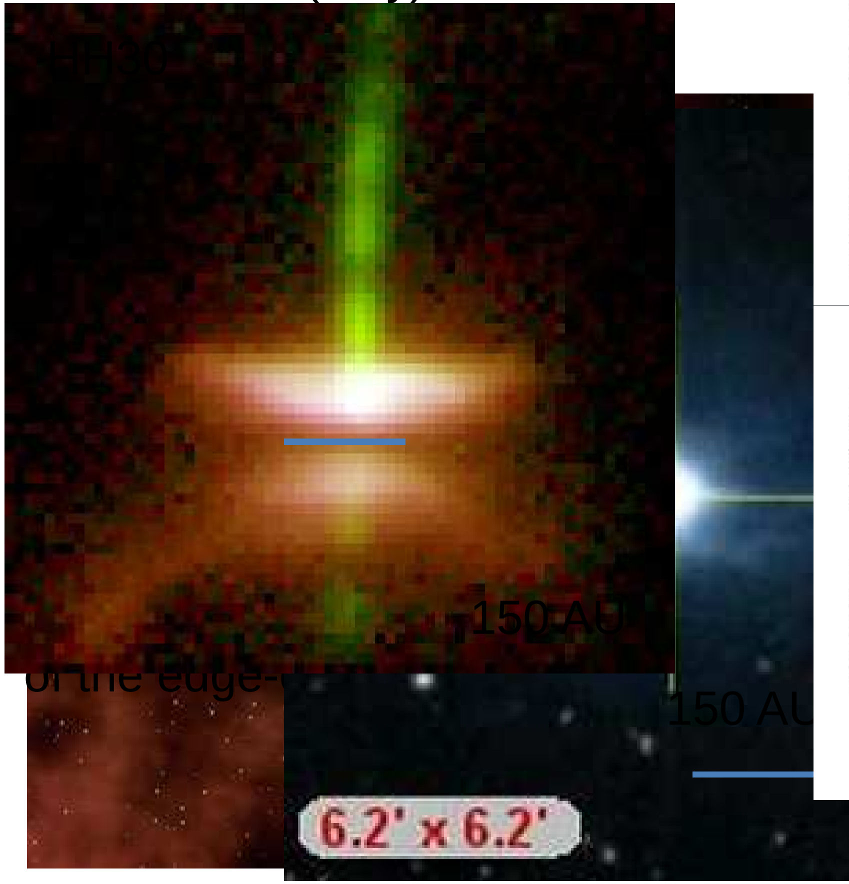
(shocks)
pe ») »: CO
the jet)

bmm
- Reflection nebula in IR

of the edge-

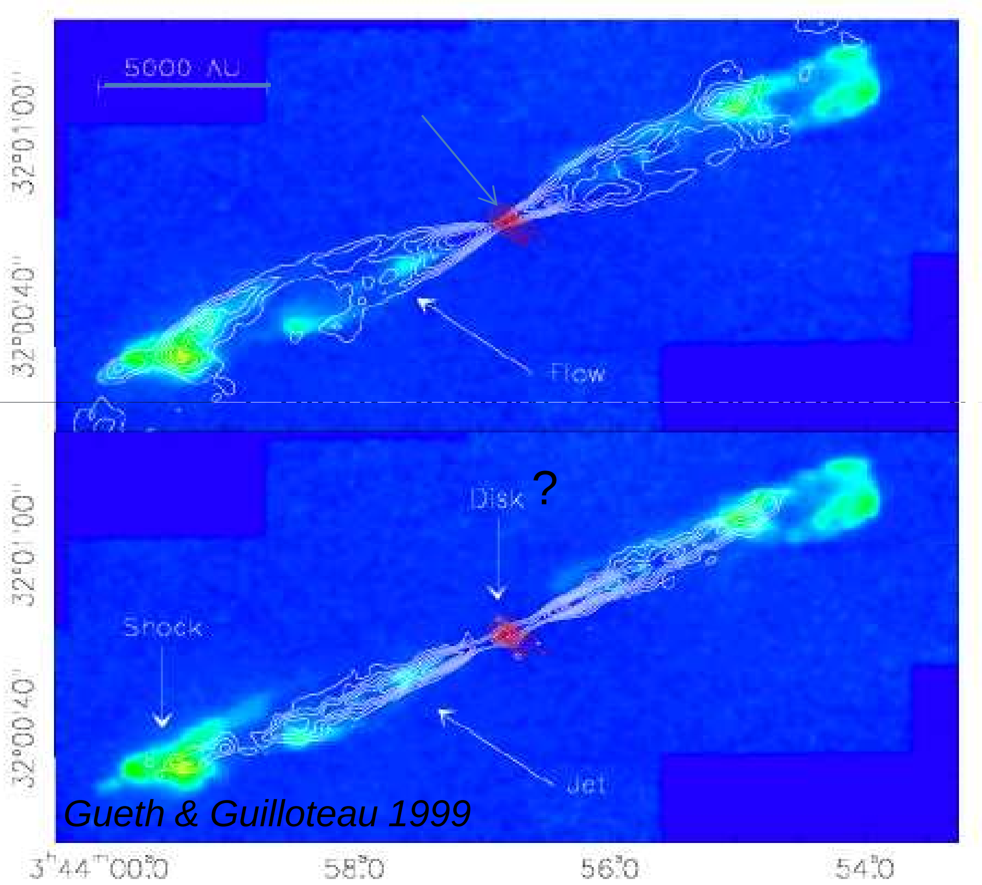
Which Instruments ? Tracers …

Turbulent gaseous dusty Keplerian disk:
-Cold (10-100K) outer disk (R> 3
- Warm (very) inner disk and sur



of the edge-

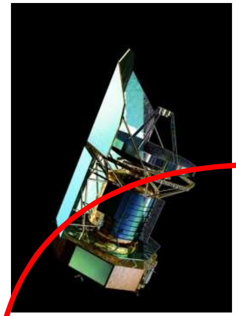
HH211 PdBI CO (~10^4 years, Class 0)



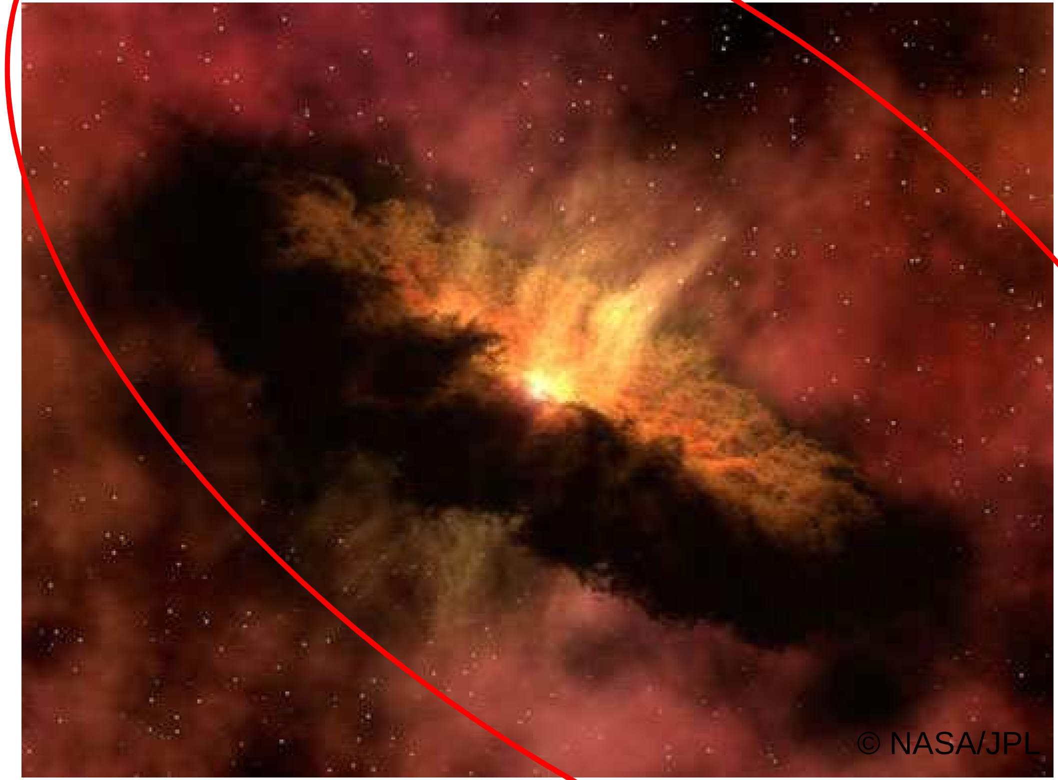
Gueth & Guilloteau 1999

CO

Which Instruments ?



Herschel Far-IR: unresolved data → integrated flux of the whole object
Envelope (young object) + disk + outflow (& jet)
-HIFI (spectrometer):157−212 & 240−625 µm
-PACS (imaging photometer): 60−85 or 85−130, 130−210 µm
-SPIRE (im. photometer):250, 350, 500 µm & (spectro) 194−324 & 316−671 µm


© NASA/JPL

Constrains on the dust properties
Warm molecules at disk surface /jet

DATA analysis
→ Strongly model dependent

→Strong hypothesis on the geometry of the system (can be known from resolved interferometric data)

→ Spectroscopy
= kinematics

IRAM 30m radiotelescope: unresolved data, 10’’ at 1.3mm or 1500 AU– λ= 3 to 0.8mm
Spectroscopy of many ‘cold’ molecular lines, integrated spectrum + dust emission

Which Instruments ?

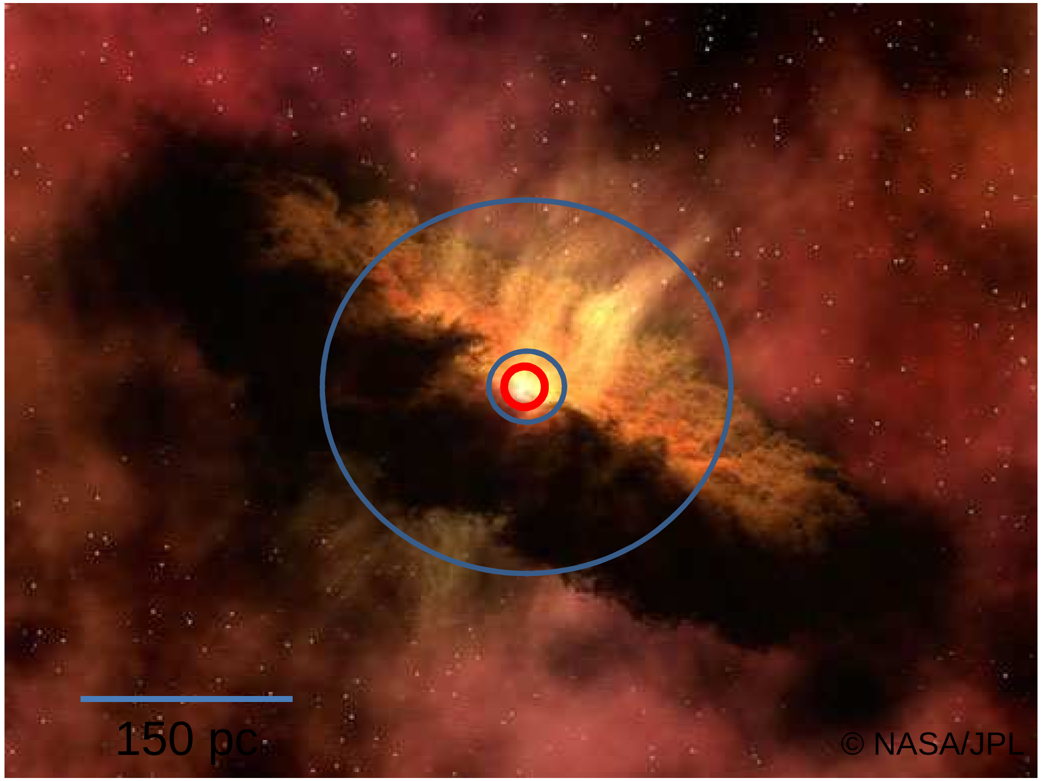
Interferometer: measures the visibility per baseline B
~ fourier transform of the intensity of the source
Angular resolution = Lambda/ Bmax
Data = specific intensity or brightness distribution (Jy/Beam or K)
spectro-imaging → acurate kinematics
in Keplerian motions for 1 Msun:
0.1 km/s ≡ 7 AU at 100 AU

VLA, PdBI, SMA, CARMA, ALMA

Prior to ALMA:
data at R ~ 0.3'' – 2'' ~ 40 – 300 AU
(1.3- 0.8mm, obtained in 10 years)

Which Instruments ?

Interferometer: measures the visibility per baseline B
~ fourier transform of the intensity of the source
Angular resolution = Lambda/ Bmax
Data = specific intensity or brightness distribution (Jy/Beam or K)
spectro-imaging → acurate kinematics
in Keplerian motions for 1 Msun:
0.1 km/s ≡ 7 AU at 100 AU



© NASA/JPL

VLA, PdBI, SMA, CARMA, ALMA

Prior to ALMA:
data at R ~ 0.3'' – 2'' ~ 40 – 300 AU
(1.3- 0.8mm, obtained in 10 years)

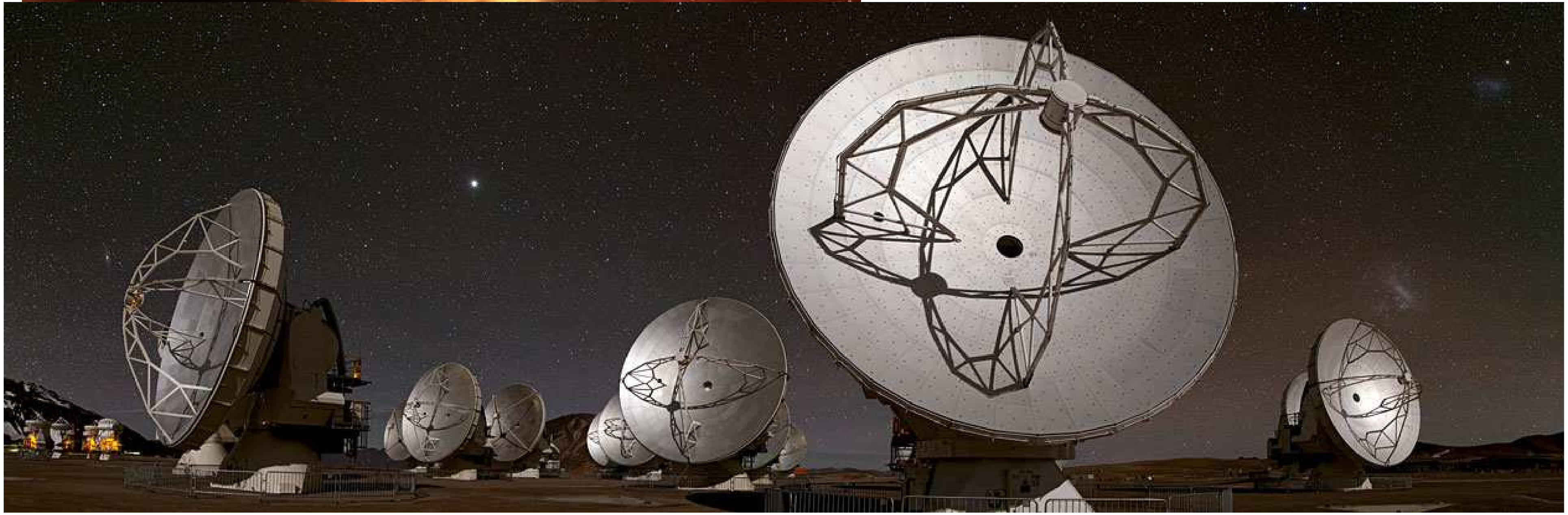
ALMA /cycle I: 0.16 – 0.1 ~ 20-15AU
(0.8mm & 0.5mm)
base ~ 20 km: ~ 0.02'' ~ 2 AU
(~1mm)

Which Instruments ?

Interferometer: measures the visibility per baseline B
~ fourier transform of the intensity of the source
Angular resolution = Lambda/ Bmax
Data = specific intensity or brightness distribution (Jy/Beam or K)
spectro-imaging → acurate kinematics

in Keplerian motions for 1 Msun:
0.1 km/s ≡ 7 AU at 100 AU

ALMA at Chajnantor Plateau
5000 m
Cycle 1: 32 antennas at least



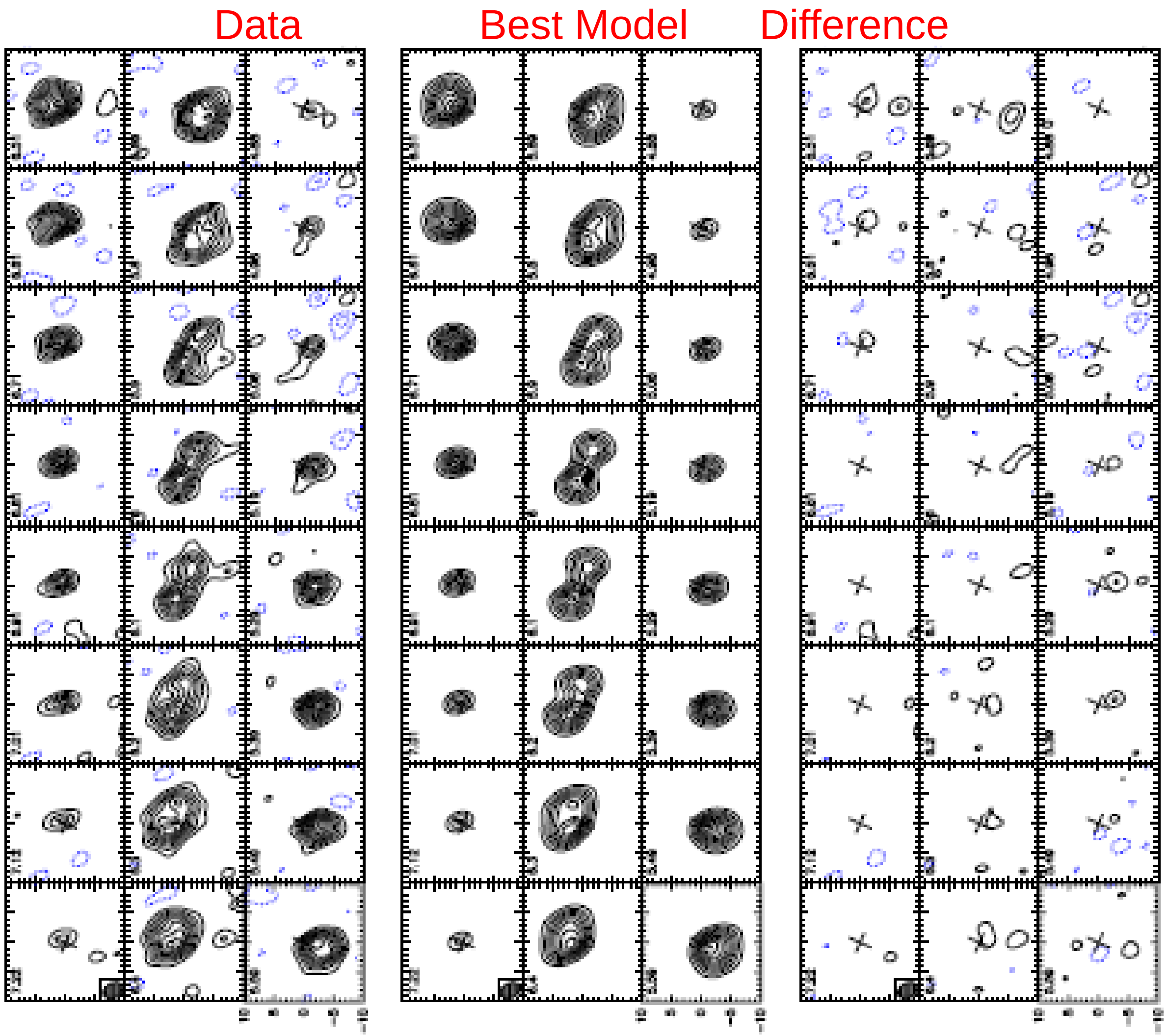
Data Analysis at Submm/mm

Dutrey et al 1994 – Guilloteau et Dutrey 1998 – Dartois et 2003, Piétu et al 2007
Qi et al 2006, 2008 ... – Hughes et al 2007, 2010, 2011 - Andrews et al 2012 ...

- Direct comparison of predicted visibilities to observed visibilities
- χ^2 analysis possible ➔ errorbar

- Rotation : $v(r) = v_0 . (r/r_0)^{-v}$
  - Keplerian : $v = 0.5$ & $v_0 = (G.M/r_0)^{1/2}$ – stellar mass measurement
- Line width : $DV = \sqrt{(v_{th}^2 + v_{turb}^2)}$ - thermal + turbulent
- Parametric Laws for Temperature & Density :
  - $T(r) = T_0 . (r/r_0)^{-q}$ – vertically isothermal
  - $T(r,z) = T(r) + (T_m - T(r)) \cos((\pi z)/(2 z_q))^{2\delta}$ – $T(z>z_q) = T(r)$ & $T_m = T(\text{plane})$
  - $\Sigma(r) = \Sigma_0 . (r/r_0)^{-p}$ - power law
  - $\Sigma(r) = \Sigma_0 . (r/r_0)^{-g} . \exp(-(r/r_c)^{2-g})$ - viscous model
  - $h(r) = h_0 . (R/r_0)^{h}$, or $h(r) = \sqrt{(2kT(r)/(\mu m_H))}\, r/v(r)$ - hydrostatic
  - $n(r,z) = n(r,0) . \exp[-(z/h)^2]$
  -
- Molecular excitation : LTE / non-LTE
- Sometimes associated to the fit of the SEDs

- CO as gas tracer
- Power of spectro-imaging (~ 300 AU)



DM Tau:
0.5 Msol, Age ~ 5 Myrs

CO J=1-0,
pdBI data

Guilloteau & Dutrey 1998

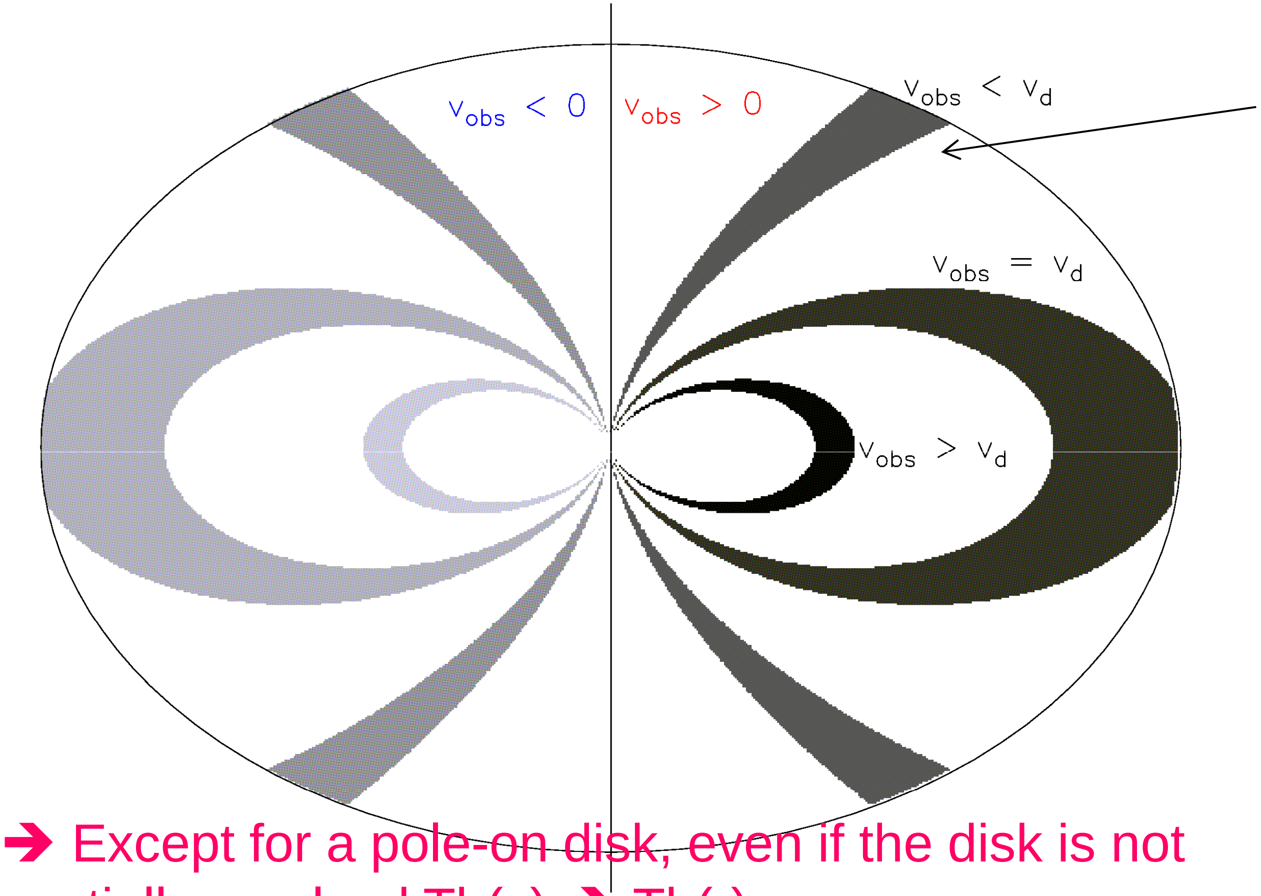
➔ Keplerian Rotation
(stellar mass measurement for free)

➔ Determination of the physical parameters (eg temperature, density, turbulence…) versus r and z.

ERRORBARS

Fourier plane → Image plane

Keplerian Rotation in Disk



$V(r) \approx \sqrt{(G.M_*/r)}$

+ Velocity coherent area at a given velocity
+ Proportional to dV (local line width)

+ Fraction of disk covered at any velocity: $dV / (2V(R_{out}) \sin(i))$

→Need to take this into account to analyse molecular lines

➔ Except for a pole-on disk, even if the disk is not spatially resolved Tb(v) ➔ Tb(r)

In EMISSION, Integrated line flux $S \,\alpha\, R^2\, dV \cos(i) <T_{ex}>$

In ABSORPTION, Equivalent Width $W \,\alpha\, dV$

Radial CO analysis – DM Tau

Increasing opacity

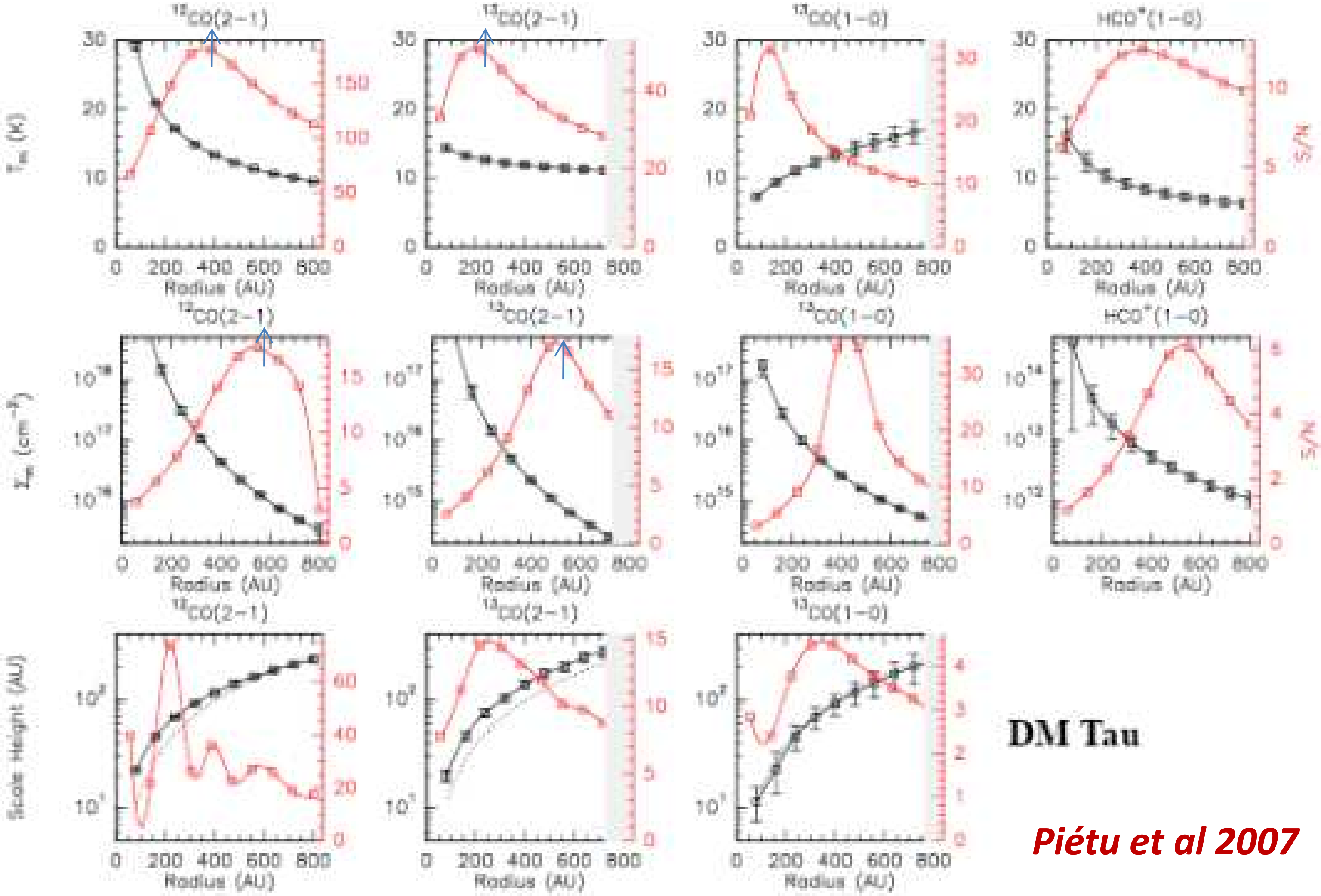
Interferometry: resolved …
T_B (r) measured!

Thermalised lines:

Opt.Thick:
$T_B(r) \alpha T_k(r)$

Opt.Thin:
$T_B(r) \alpha F(\Sigma(r),T_k(r))$

Subthermal:
$T_k(r) \rightarrow T_{ex}(r)$



Piétu et al 2007

➔ **Compromise angular resol./line opacity: still true with ALMA…**

Vertical CO line opacities
Resolved emission → Brightness (r) is measured

If optically thick & thermalized lines → Tb(r) = Tk(r)

CO J=3-2 and higher lines are not thermalized everywhere

If optically thin & thermalized lines → Tb(r) ~ Σ_{mol}(r)/Tk(r) for J=1-0

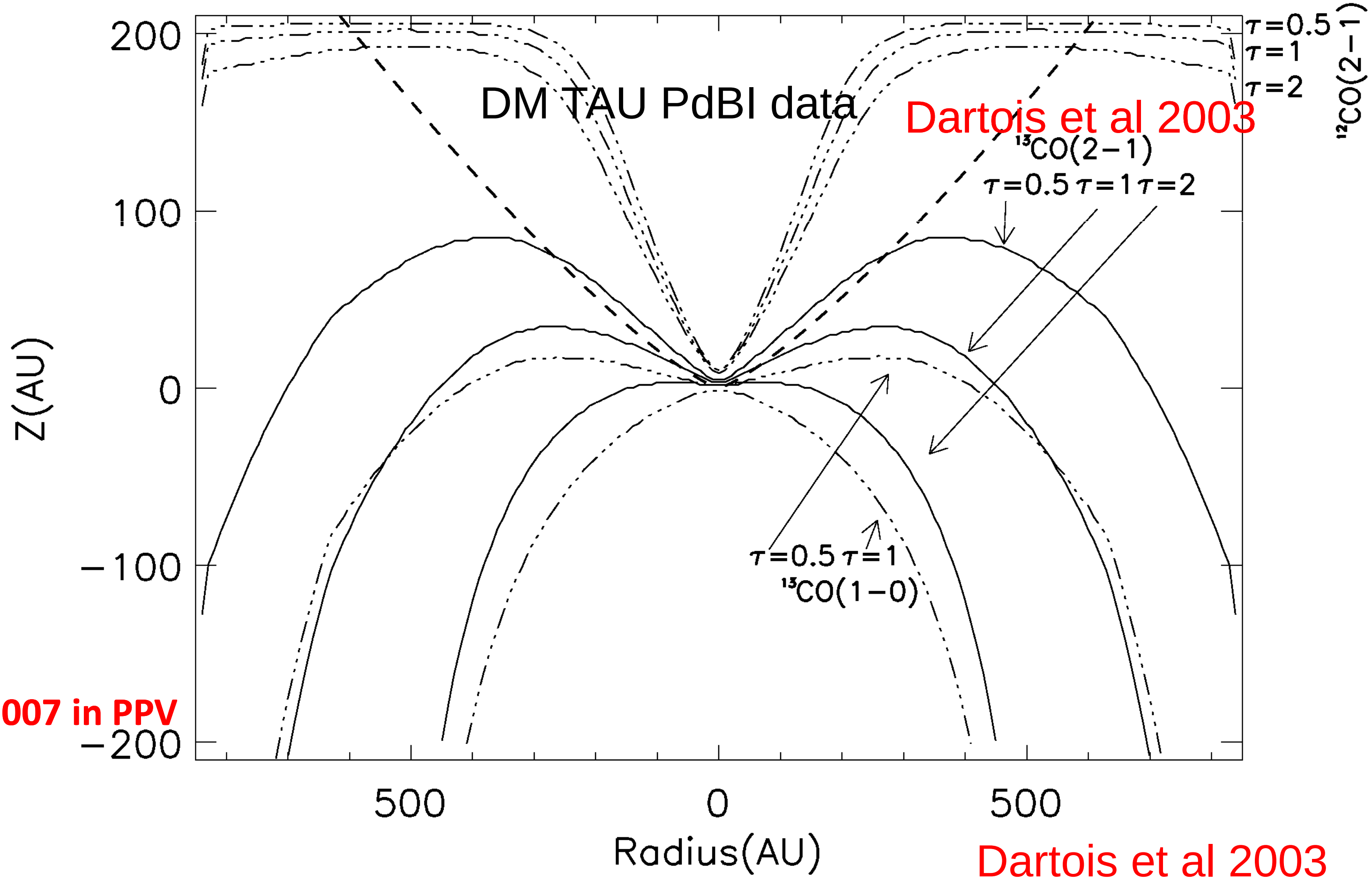
$\Sigma(H_2) = \Sigma_{mol} / X(mol)$

X(mol) difficult to constrain

$\Sigma(H_2) = \Sigma_{dust} \times G/D$

→H_2 mass is not yet well constrained distribution ~ known

Non-LTE → replace Tk by Tex …



See also
Dutrey, Guilloteau, Ho, 2007 in PPV

Dartois et al 2003

Gas Temperature – models & data

Dutrey et al 1994 – Guilloteau et Dutrey 1998 – Dartois et al 2003. Piétu et al 2007
Qi et al 2006, 2008 ... – H
Akiyama et al 2011 ...

Dartois et al 2003

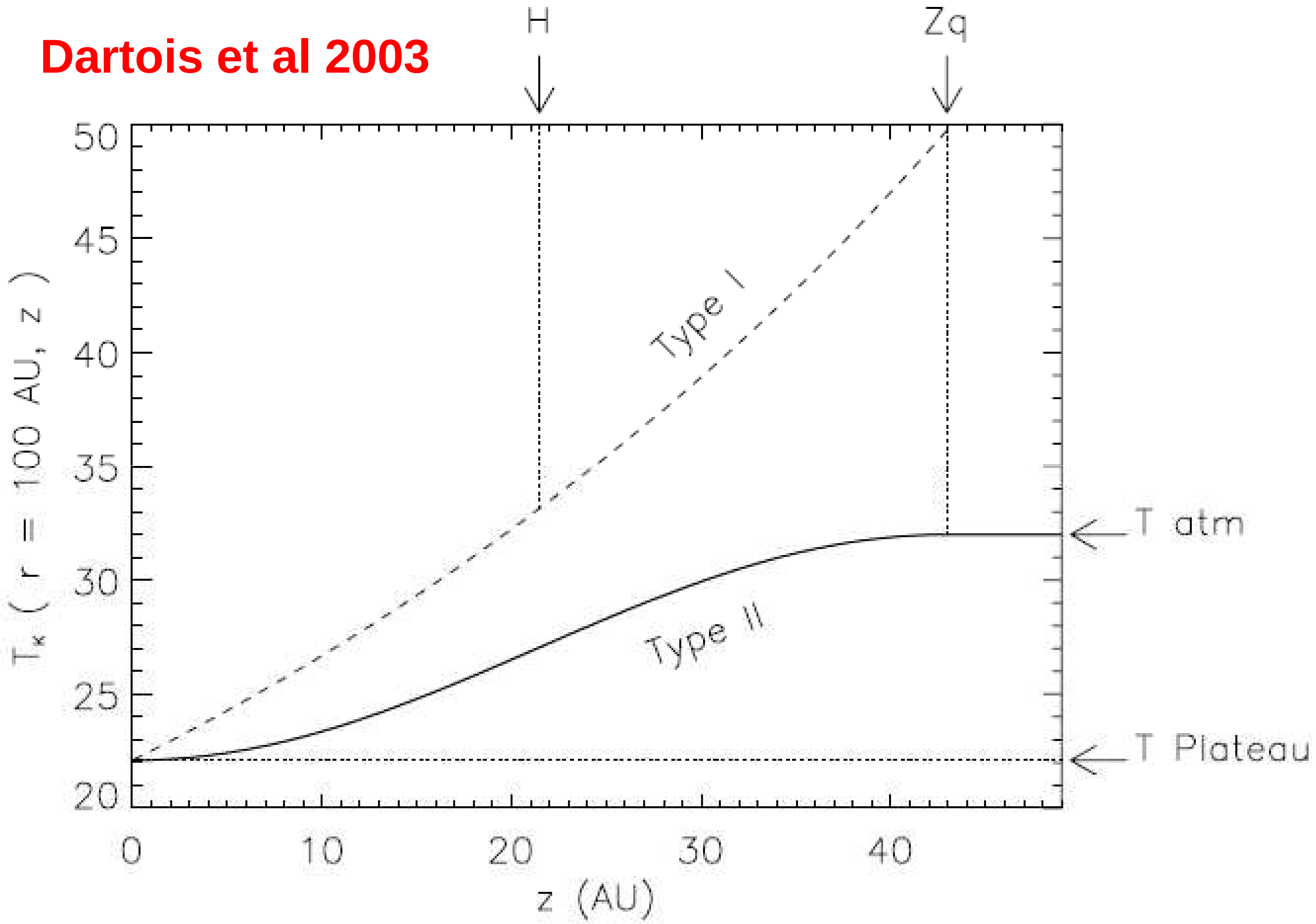
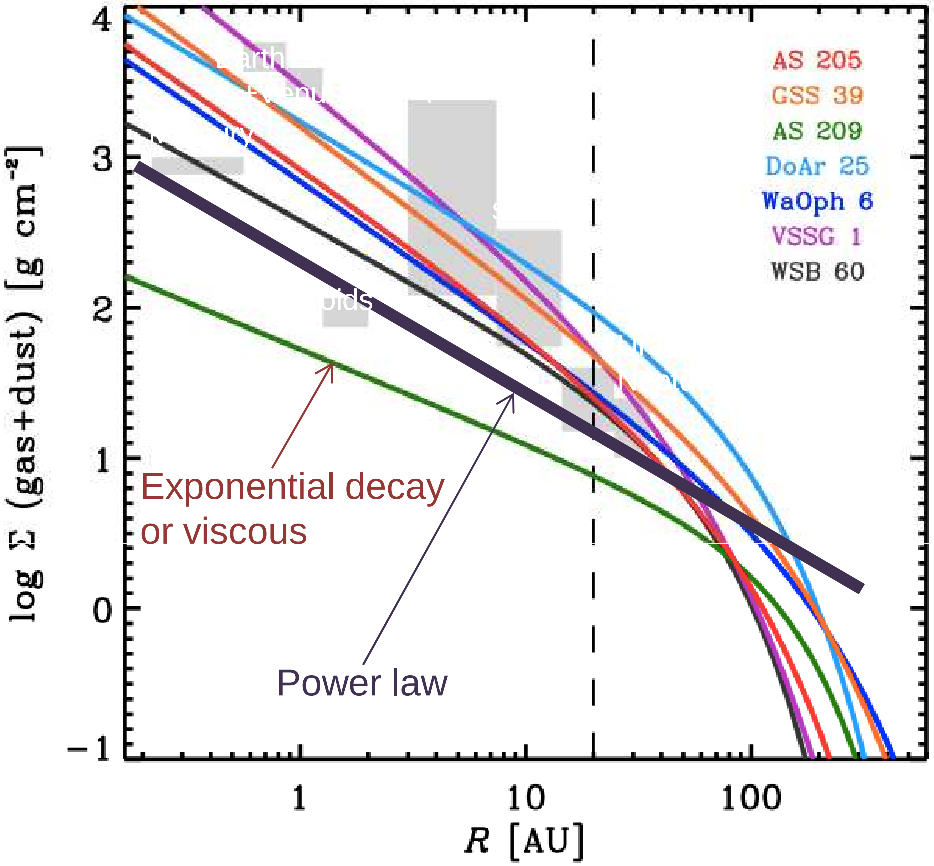


Fig. 6. Comparison of the behavior of the kinetic temperature laws for type I and type II models versus the vertical scale z: $T_k(r = 100\ \mathrm{AU}, z)$. type I: $\gamma = 1.5$ (close to CG97). type II: $\delta = 2$, $r \leq R_q$ with $R_q = 180$ AU (close to dA99).

Surface density of gas & Dust

Dutrey et al 1994 – Guilloteau et Dutrey 19
Qi et al 2006, 2008 ... – Hughes et al 2007,
Akiyama et al 2011 ...



Exponential decay or viscous

Power law

Originally based on α-disk model (Shakura & Sunyaev 1973)

Viscous disk paradigm predicts exponential edge
Mimicks radius dependent slope
which is steeper outside, flatter inside
→Viscosity is a power law of radius (with constant exponent in time)

$$\Sigma(r) = \Sigma_0 \left(\frac{R_0}{r}\right)^{\gamma} \exp\left(-(r/R_c)^{2-\gamma}\right)$$

Kitamura et al 2002, Hughes et al. 2007; **Isella et al. 2009**; Andrews et al. 2009

What the theory tells us …

- Surface chemistry (on grains) (need for a realistic size distribution)
- Neutral-neutral (low and high T)
- Ion-neutral
- 3 body reactions (?)

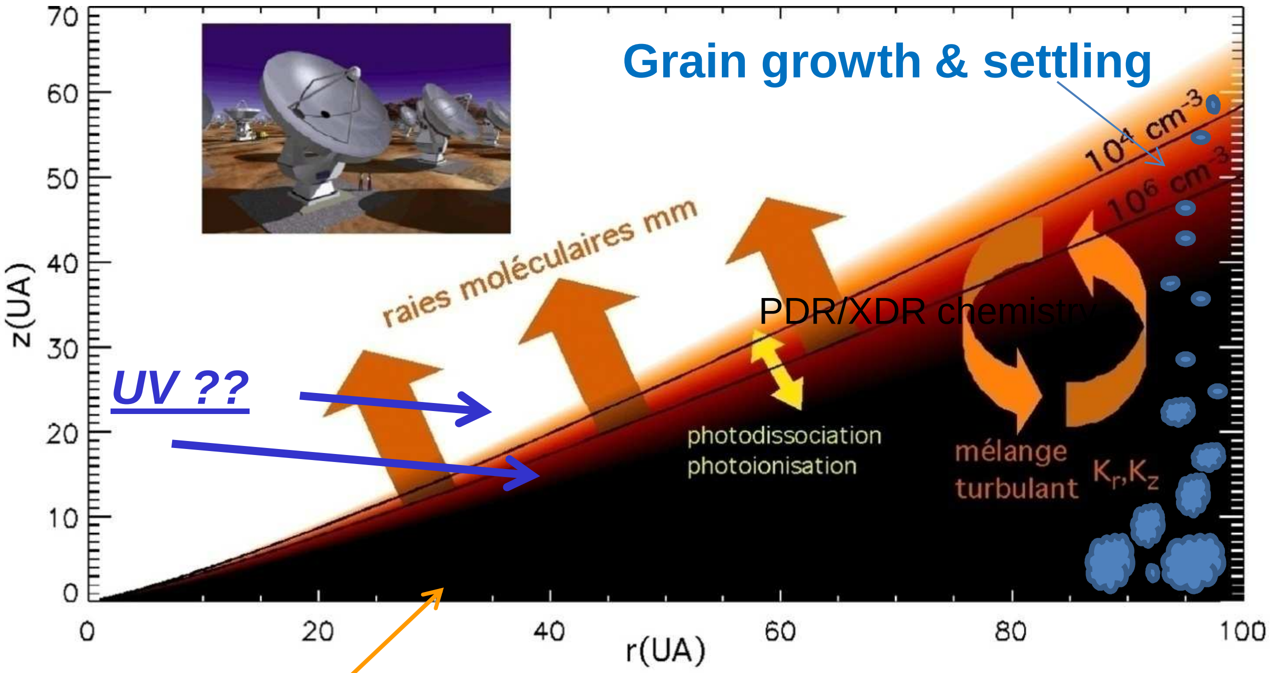
- Photodissociation, photoionization by UV
- Interactions with X rays
- Interactions with cosmic rays

z

-Surface(3-5H): XDR/PDR Chemistry

-Molecular layer (1-3H) ~ 20-30 K

- Mid-plane (0-1H) with a cold dense cloud chemistry ~ 5-8 K



Several molecules observed near the mid-plane or at very cold T~7 K !!!

What the observation tells us …

0, 4) Geometry of gas and dust in Class II objects ?
Disk geometry because resolved data from mm interferometery

1) Gas disks: rotation, density, temperature, turbulence …

2) Dust disks: density, temperature, grain growth, G/D ?

3) Molecular complexity: how far can we go ?

→ Focus on a few promising examples …
AB Auriga
TW Hydra

→ **More and more inner (R < 20 AU) Cavities ….**

Rotation …

Rotation of a gas and dust disk ?

(T = 0 = a long debate …)

10^4 yr ~ Class 0: large (1000 AU or more) flattened envelope

→ Keplerian rotation ?

10^5 yr ~ Class I: disk shape , what about rotation ?
→ Keplerian rotation ? In some cases …

10^6 yr ~ Class II: rotating (Keplerian) disk
- resolved structure
- some large disks R~ 500-800 AU (sensitivity bias)

Temperature in the molecular layer: towards a (partly) cold molecular layer ?

- **CO/^{13}CO PdBI data:** ***Dartois et al 2003***, ***Pietu et al 2007***

→ First evidence for a gas temperature vertical gradient

→ The outer disk is cold @ r ~ 100 AU, Tk~ 10 K

(a priori no excitation problem: J=1-0 & J=2-1)

Similar Results: ~ 8-10K at 100 AU - PdBI images of DM Tau and/or LkCa15

- **CCH J=2-1 (CID):** ***Henning et al 2010***
- **CN/HCN J=1-0 & J=2-1 (CID):** ***Chapillon et al 2011***

- **H2O low Tspin (**13.5 +/- 0.5 K**) in TW hydra (Herschel):** ***Hogerheijde et al 2011***

- **CS J= 3-2 & 5-4 (CID):** ***Guilloteau et al 2012***

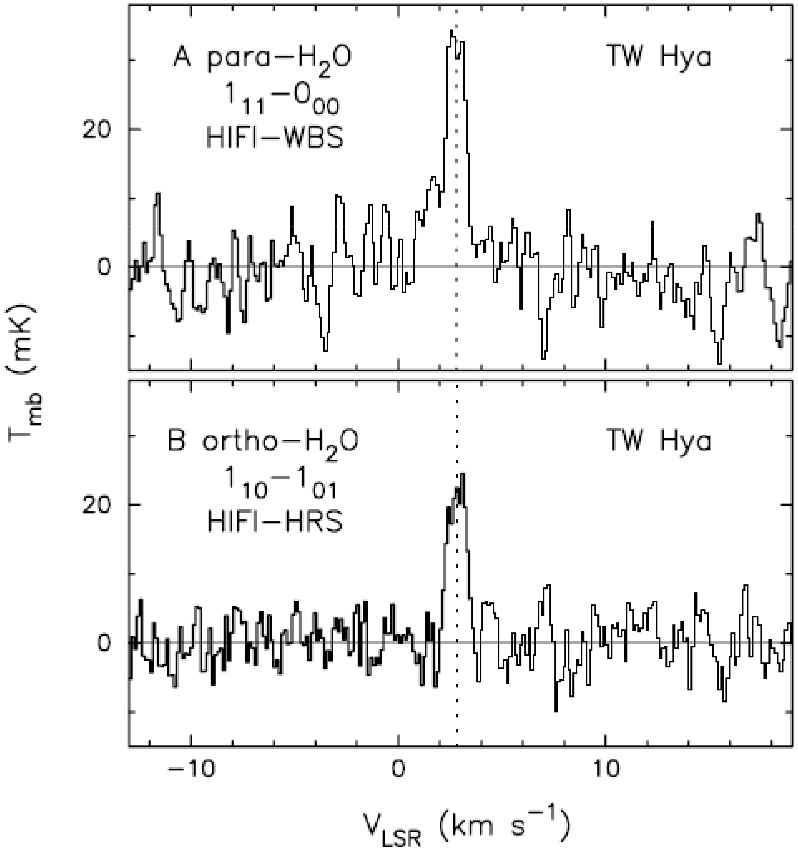
- Role of vertical/Radial mixing ? ***Semenov et al., 2006, Aikawa 2007***
- Accuracy of photo-desorption rates ? ***Oberg et al 2007…***

  → Effect on CO chemistry by ***Hersant et al 2009***

H2O Paradigme – Herschel data on TW Hya

Hogerheijde et al 2011

A cold reservoir of (icy) water with a desorption at low temperature ?



Tspin = icy grain temperature

TW Hydra: Tspin = 13.5 +/- 0.5 K

CS Temperature and Molecular Layer in DM Tau
Guilloteau et al 2012

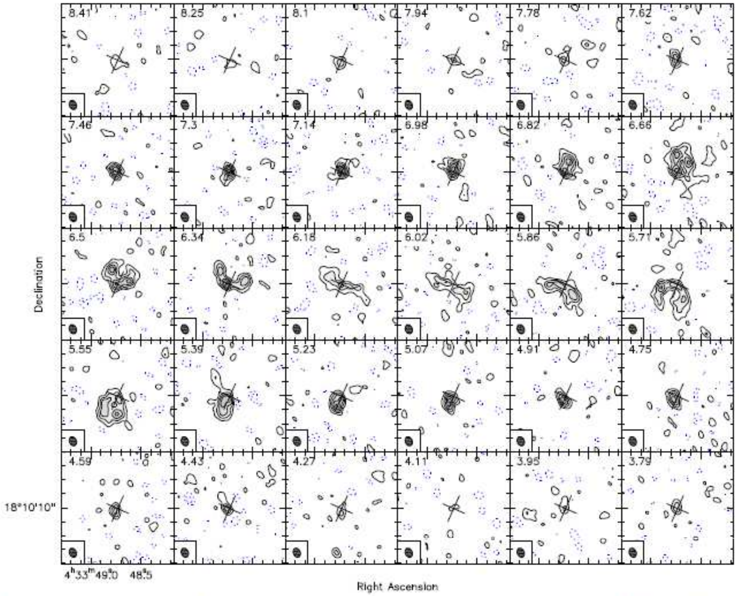


Fig. 1. Channel maps of the CS J=3-2 emission towards DM Tau. The angular resolution is 1.4″ × 1.0″ and the spectral resolution 0.16 km s^{-1}. Contour spacing is 10 mJy/beam, corresponding to 2σ and 0.4 K brightness. The cross indicates the position, orientation, and aspect ratio of the dust disk.

- 1.4 x 1.0'' resolution images PdBI data

-0.126 km/s spectral resolution (with 0.080 km/s channel spacing)

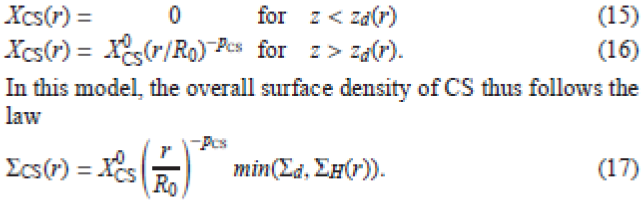
- CS 3-2

Temperature:

- CS J=5-4 line flux confirms low temperature.
- Best fit 11 +/- 2 K (3-2 + 5-4)

Density:

Best model given by a « cold » molecular layer



$$X_{\rm CS}(r) = 0 \quad \text{for} \quad z < z_d(r) \qquad (15)$$

$$X_{\rm CS}(r) = X^0_{\rm CS}(r/R_0)^{-p_{\rm CS}} \quad \text{for} \quad z > z_d(r). \qquad (16)$$

In this model, the overall surface density of CS thus follows the law

$$\Sigma_{\rm CS}(r) = X^0_{\rm CS}\left(\frac{r}{R_0}\right)^{-p_{\rm CS}} min(\Sigma_d, \Sigma_H(r)). \qquad (17)$$

@~1H above midplane

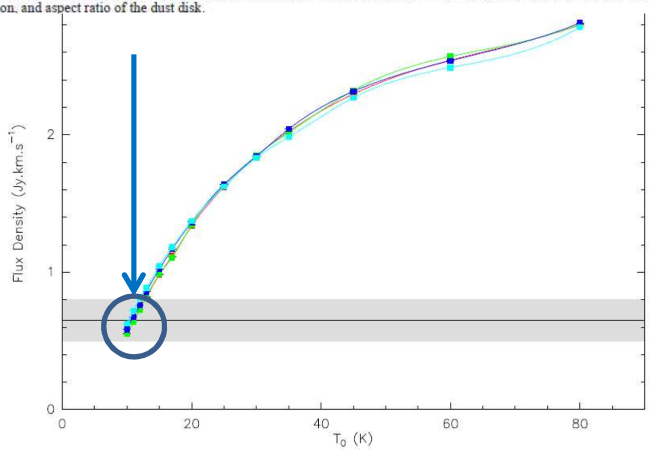
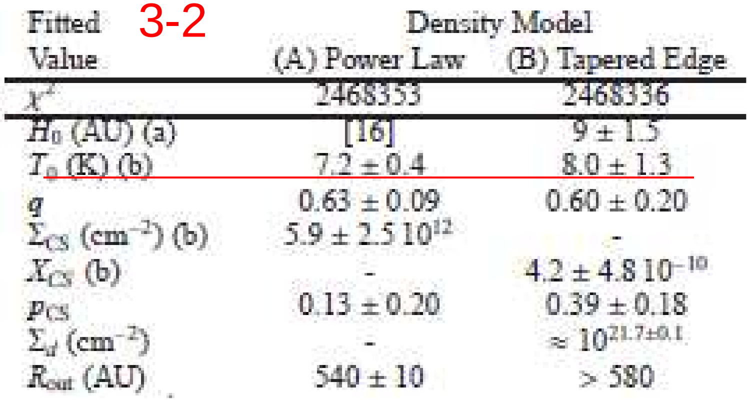


Fig. 5. Predicted CS J=5-4 line flux from the best fit models derived from CS J=3-2 observations, as a function of assumed kinetic temperature profile. The 4 curves corresponding to the different exponents q = 0, 0.2, 0.4, and 0.6 are essentially degenerate. Errorbars are $\pm1\sigma$. The shaded gray area indicates the measured line flux and its $\pm1\sigma$ range. Calibration uncertainty is not included.

ALMA ??



3-2

Fitted Value	Density Model (A) Power Law	Density Model (B) Tapered Edge
χ^2	2468353	2468336
H_0 (AU) (a)	[16]	9 ± 1.5
T_0 (K) (b)	7.2 ± 0.4	8.0 ± 1.3
q	0.63 ± 0.09	0.60 ± 0.20
$\Sigma_{\rm CS}$ (cm^{-2}) (b)	$5.9 \pm 2.5\ 10^{12}$	-
$X_{\rm CS}$ (b)	-	$4.2 \pm 4.8\ 10^{-10}$
$p_{\rm CS}$	0.13 ± 0.20	0.39 ± 0.18
Σ_d (cm^{-2})	-	$\approx 10^{21.7\pm0.1}$
$R_{\rm out}$ (AU)	540 ± 10	> 580

How to trace the disk mid-plane ?

→ Wait for CN 3-2 from ALMA …

- H_2D^+ formed in gas phase only at low temperature, easily destroyed by CO, N_2

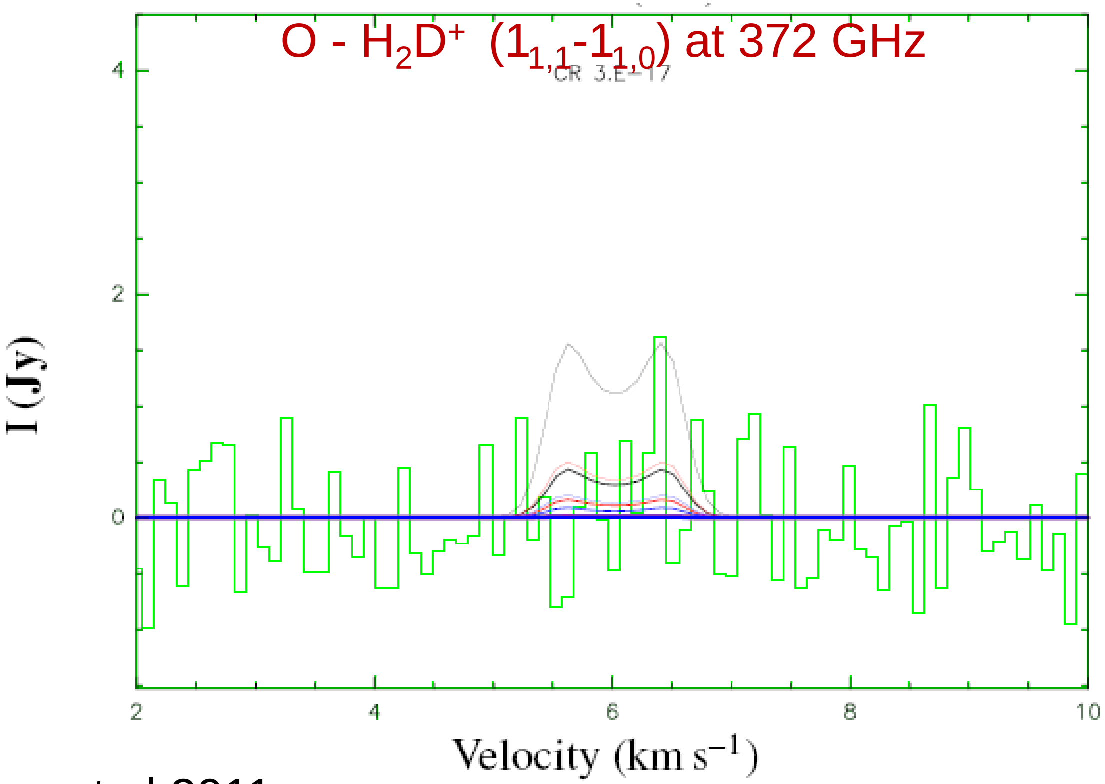
$H_3^+ + HD \rightarrow H_2D^+ + H_2$ // $H_2D^+ + CO \rightarrow DCO^+ + H_2$ - $H_2D^+ + CO \rightarrow HCO^+ + HD$

→should be abundant in the
→ cold depleted mid-plane

- No detection , so far …

Chapillon et al 2011

→JCMT (10hrs) - DM Tau
→ APEX (4hrs) - TW Hya
- 3x more sensitive than previous data → H_2D^+ still not detected !



O - H_2D^+ ($1_{1,1}$-$1_{1,0}$) at 372 GHz

- Analysis: chemical model from Parise et al 2011

Turbulence versus radius in disks
Molecular lines & dust emisssion

Dartois et al 2003, Pietu et al 2007 – PdBI data, DM Tau, MWC480, LKCa15

- **Turbulence →** Amplitude of the local velocity fluctuations

- **Spectrum** local line-width given by DV = $\sqrt{(v_{th}^2 + v_{turb}^2)}$

- **Link to α (viscosity parameter)** depends on the nature of the turbulence of the order of ≈ $\sqrt{\alpha}.c_s$ - $\alpha.c_s$, with sound speed c_s such as $H(r) \approx c_s / \Omega$

→If the molecular disk is spatially,spectrally resolved → DV(r)
→Since lines have different opacities → DV(z)

ALMA: DV(r,z)
Spec.&.Ang. Resol

- So far, CO and isotopologues (^{13}CO, $C^{18}O$)

→Subsonic broadening DV ~ 0.1 – 0.4 km/s < c_s

- Well suited for ALMA sensitivity and angular, spectral resolution

→If the thermal structure is properly constrained, linked to line opacity, density structure … etc

→Will remain the main uncertainty, even with ALMA

See also **Hughes et al 2011: TW Hya, HD163296**

« CS » Turbulence in DM Tau Guilloteau et al 2012

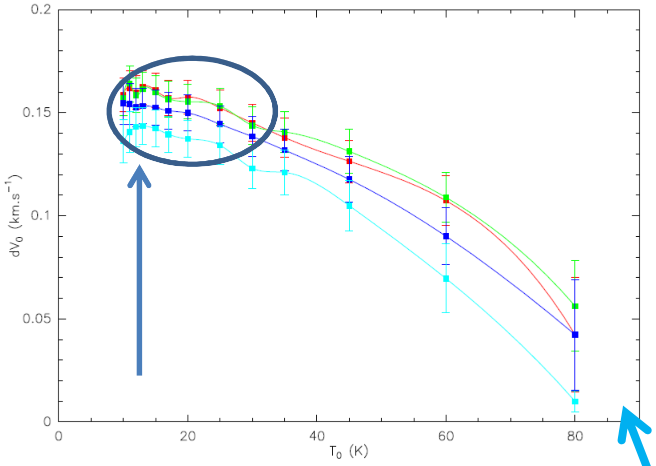


Fig. 4. Derived nonthermal linewidth dV_0 at $R_v = 300$ AU as a function of assumed kinetic temperature profile. T_0 is the temperature at $R_t = 300$ AU. The 4 curves correspond to different exponents $q = 0$ (red), 0.2 (green), 0.4 (blue), and 0.6 (cyan). Errorbars are $\pm 1\sigma$.

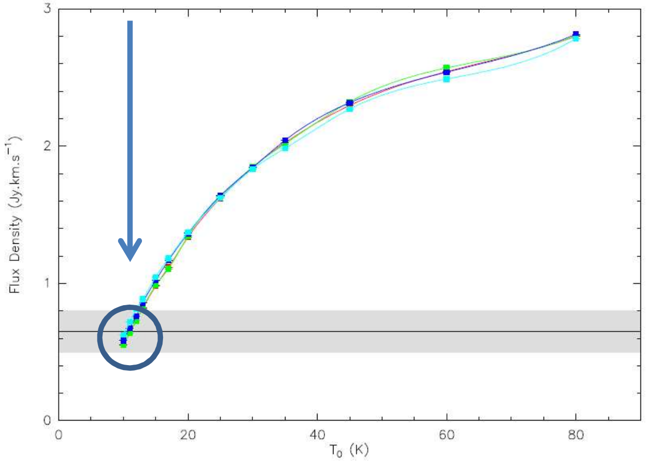


Fig. 5. Predicted CS J=5-4 line flux from the best fit models derived from CS J=3-2 observations, as a function of assumed kinetic temperature profile. The 4 curves corresponding to the different exponents q = 0, 0.2, 0.4, and 0.6 are essentially degenerate. Errorbars are $\pm 1\sigma$. The shaded gray area indicates the measured line flux and its $\pm 1\sigma$ range. Calibration uncertainty is not included.

- To reduce the thermal contribution → better to use a « heavy molecule » such as CS

$$\Delta V(r) = \sqrt{\frac{2kT(r)}{\mu m_H} + \delta V_{\mathrm{tu}}(r)^2}$$

where $\mu = 44$ is the CS molecular weight

- 1.4 x 1.0’’ resolution images
- 0.126 km/s spectral resolution (with 0.080 km/s channel spacing)

- Non-thermal turbulent width as function of assumed temperature

dV = 0.12 km/s
for best fit T = 8 +/- 1 K from CS J=3-2

This corresponds to Mach ~ 0.3 - 0.5

Chemistry & molecular Surveys
CLASS II

- **Detections prior to ALMA:**
  CO, ^{13}CO, $C^{18}O$ (many papers)

  HCO^+, CN, HCN, HNC, CS, H_2CO and C_2H (Dutrey et al 1997: DM Tau & GG Tau, Henning et al 2010, **CID**, Chapillon et al 2012, **CID**: MWC480, DM Tau, LkCa15)

  DCO^+ (van Dishoeck et al 2004: TW Hya, Guilloteau et al 2006, DM Tau)

  N_2H^+ (Dutrey et al 2007, DM Tau, LkCa 15, **CID**)

  DCN (Qi et al 2008: TW Hya)

  $H^{13}CO+$ (Qi et al 2008: TW Hya)

  H_2O (Herschel, Bergin et al 2010, Hogerheijde et al 2011)

  → HC_3N (IRAM 30-m, Chapillon et al 2012, in DM Tau, GO Tau, MWC480 and LkCa15, **CID**)

- **Deep unsuccesful search**
  H_2D^+ (APEX+ JCMT, Chapillon et al 2011 in DM Tau & TW Hya) - no detection
  Sulfur-bearing molecules: CCS, H2S (IRAM 30-m, Dutrey et al 2011, Chapillon et al 2012, **CID**)

Chemistry & molecular Surveys

CLASS II

- **ALMA Era - How far can we go in term of complexity ?**

  → H_2O (Herschel, Bergin et al 2010, Hogerheijde et al 2011)

  → **HC_3N** (IRAM 30-m, Chapillon et al 2012, in DM Tau, GO Tau, MWC480 and LkCa15, **CID**)
  First cyanopolyyne: the more complex molecule detected to far

- **Deep unsuccesful search**
  → H_2D^+ , ALMA cycle 0 proposal by Qi et al – no result yet …

- **New detections …**

  → ALMA verification time 1 & Cycle I: binary proto-star (Class 0) IRAS16293-2422
  – Jorgensen et al 2012 - simplest sugar: Glycolaldehyde ($HCOCH_2OH$)

  → ALMA verification time: HD163296, Herbig Ae (A0) Star of 2.4 Msun
  - Qi et al 2013, submitted – c- C_3H_2
  - surrounded by a large (& warm) CO disk

HOW FAR CAN WE GO ?

ALMA verification time 1 & Cycle I: binary proto-star (Class 0) IRAS16293-2422

Jorgensen et al 2012 - simplest sugar: Glycolaldehyde (HCOCH2OH)

Low-mas proto-star
Located at 120 pc
Binary of separation ~ 5''

Unresolved: 2.5''x 1.''

Several complex molecules

Glycolaldehyde already
detected towards
- Galactic Center – SgrB2
-Hot molecular core: G31.41

-Tentative detection of
ethylene glycol

- Emphasize the importance
of UV photochemistry

CH3OH-CO ice
mildly heated

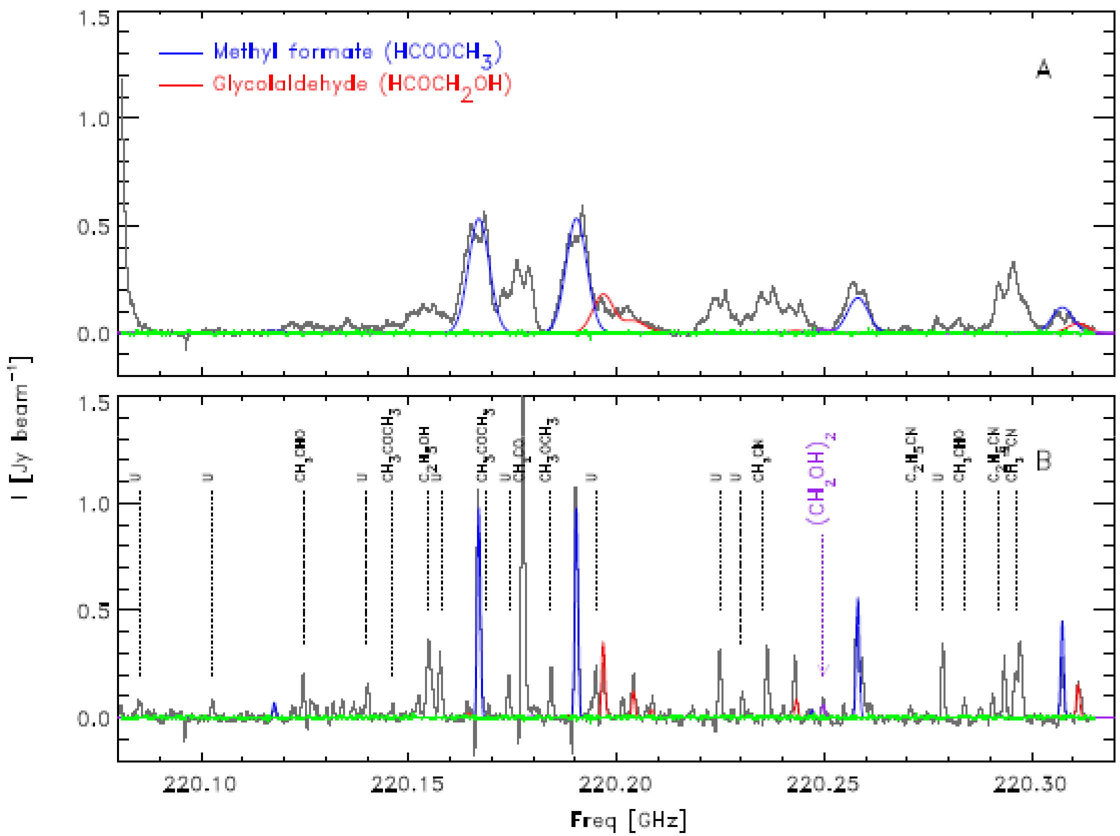


Fig. 1.— Spectra in the central beams toward the continuum peaks of IRAS16293A (upper) and IRAS16293B (lower). Fits from LTE models of the methyl formate (blue) and glycolaldehyde (red) emission are overplotted. The purple line indicates the model fit to the possible ethylene glycol transition. The X-axis represents the frequencies in the rest frame of the system (i.e., corrected for the system $V_{\rm LSR}$ of 3 km s^{-1}). The green line is an indication of the RMS level (13 mJy beam^{-1}) represented by a spectrum extracted from an off source position. Note the much narrower lines toward IRAS16293B which facilitate identification of individual features.

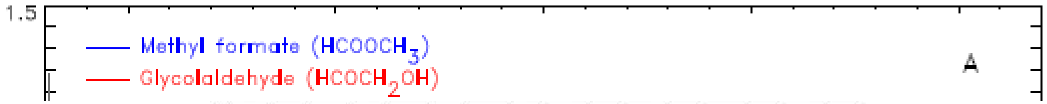
ALMA verification time 1 & Cycle I: binary proto-star (Class 0) IRAS16293-2422

Kristensen et al 2012, CO 6-5 at 0.2’’ or 25 AU at 0.5mm

Low-mas proto-star

Located at 120 pc

Binary of separation ~ 5’’



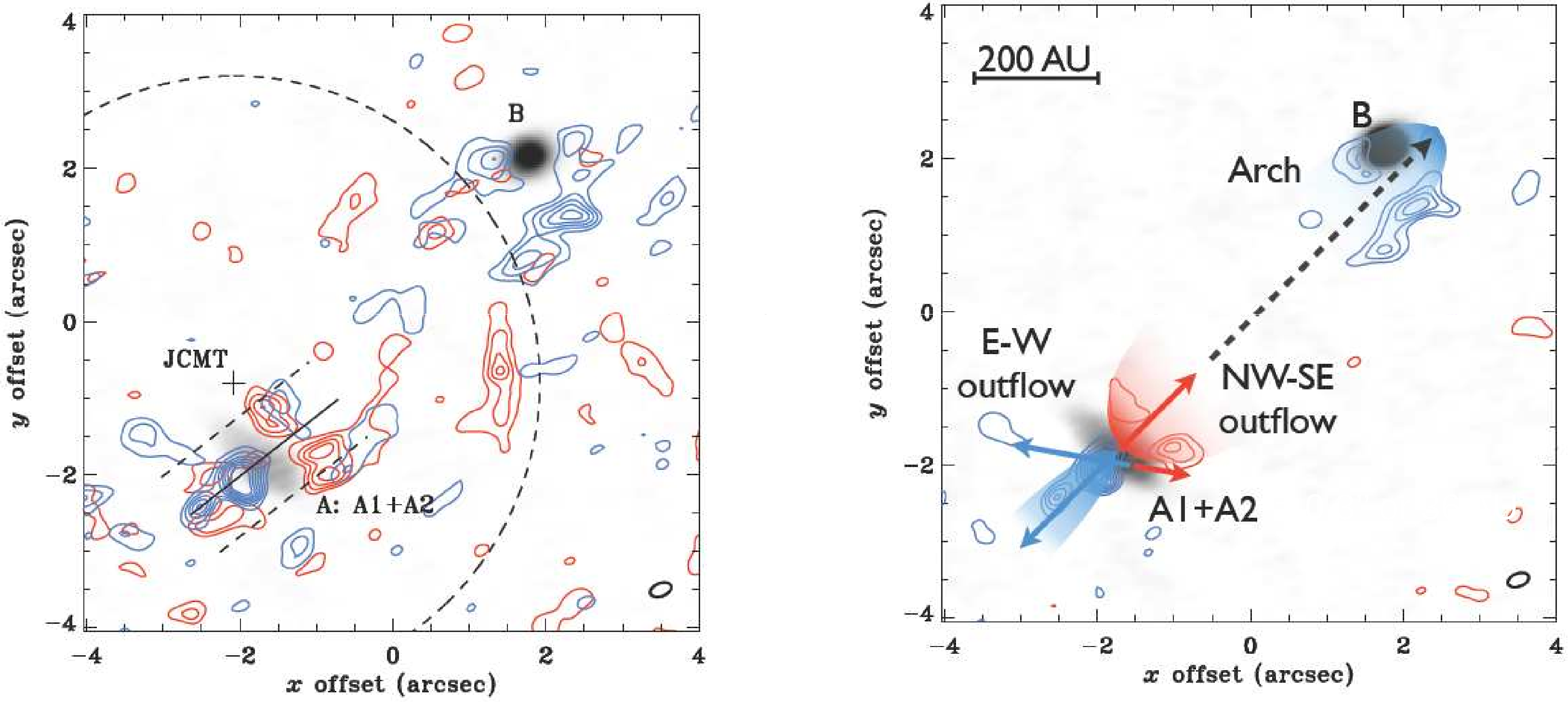


Fig. 1. *Left:* Map of CO J=6–5 emission towards I16293 with contours at 6, 12, 18, ...σ of integrated intensity. Integration limits are −10 to +1 km s^{-1} and +7 to +18 km s^{-1} for the blue- and red-shifted emission, respectively. The underlying gray-scale image shows continuum emission at 690 GHz. The positions of sources A and B are marked; source A consists of the two sources A1 and A2. Offsets are recorded from $16^\mathrm{h}32^\mathrm{m}22\overset{\mathrm{s}}{.}753$; $-24°28'34\overset{''}{.}747$ (J2000). is marked with a cross and the beam is shown as a m (Fig. 4). *Right:* The emission integrated over the highest velocities (from −10 to −4 km s^{-1} and +12 to +18 km s^{-1}) is shown in contours at 5, 10, 15, ...σ. The different features are highlighted by arrows and are labeled. The black dashed arrow is an extrapolation of the red lobe of the NW-SE outflow.

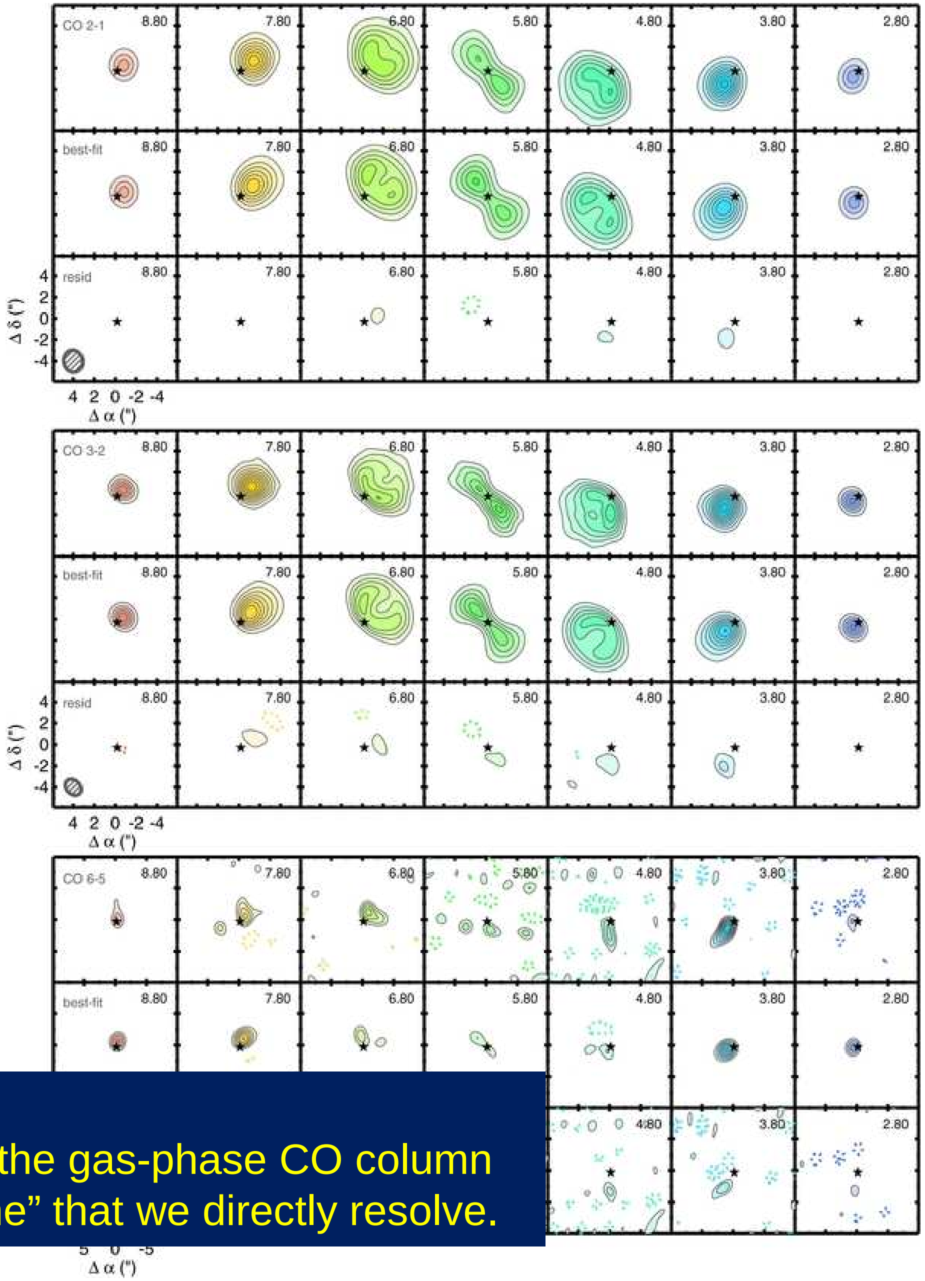
ALMA verification time 1: HD163296, Herbig Ae 2.3 Msun, 4Myr old
Located at 120 pc – Class II

Isella et al 2009,
Tilling et al 2012

Large molecular disk
CO extends up to 500 AU

Several 'mm' molecules …
CO, ^{13}CO, H_2CO …

Several warm gas lines
OI, CII, OH, H2O, H2
CO 36-35, …
→ Inner disk surface or jet



SMA observations - Qi et al 2011 →
The freeze-out at 19 K leads to a significant drop in the gas-phase CO column density beyond a radius of ~155 AU, a "CO snow line" that we directly resolve.

ALMA verification time 1: HD163296, Herbig Ae 2.3 Msun, 4Myr old
Located at 120 pc – Class II

Warm source !

Qi et al 2013 - c-C3H2 J= 6-5 detected (1.3mm, 217.88 GHz) !

Ang.Resol ~ 0.9'' x 0.7''
or ~ 100 AU

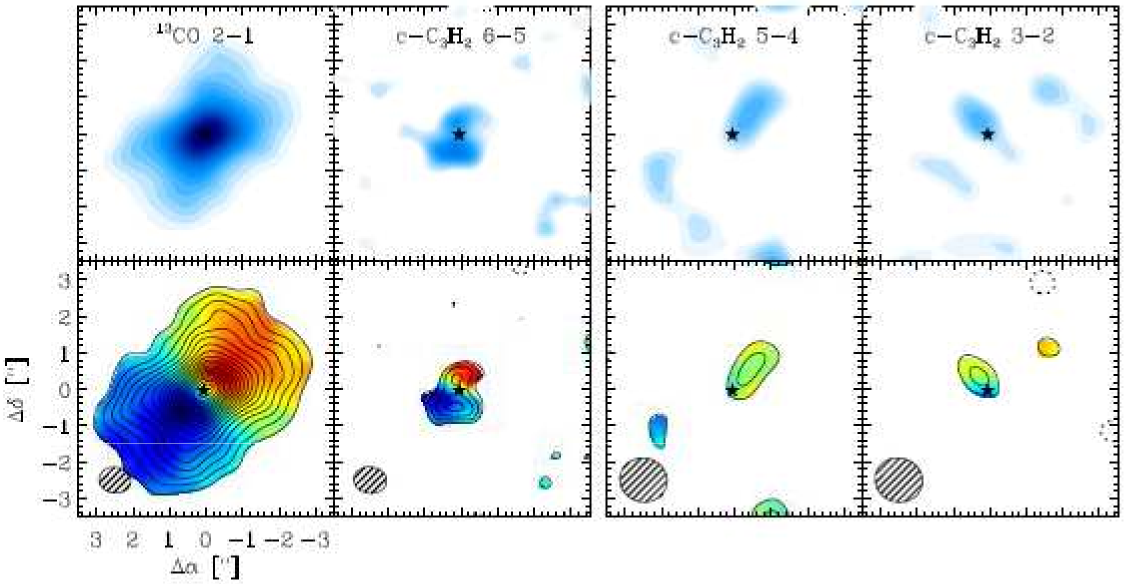


Fig. 1.— The integrated intensity maps summed between 0 and 11 km s^{-1}) and intensity-weighted mean velocity fields of ^{13}CO 2 − 1 and c-C$_3$H$_2$ 6 − 5 lines (left panel), c-C$_3$H$_2$ 5 − 4 and 3 − 2 lines (right panel) toward HD 163296. The resolved velocity field of the c-C$_3$H$_2$ 6 − 5 line agrees with the CO kinematics. In the c-C$_3$H$_2$ maps, the first contour marks 3σ followed by 1σ contour increases. The rms varies between 6 and 9 mJy km s^{-1} per beam. Synthesized beams are presented in the lower left corners. The star symbol indicates the continuum (stellar) position. The axes are offsets from the pointing center in arcseconds.

Large molecular disk
CO extends up to 500 AU

Several molecules …
CO, CS, H2CO …

→ **Disk origin …**
c-C3H2 is a (very) small cyclic Hydrocarbon
One of the most abundant molecules in ISM

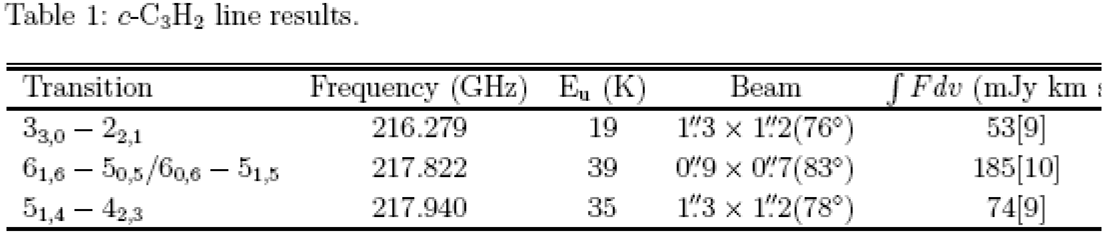


Table 1: c-C$_3$H$_2$ line results.

Transition	Frequency (GHz)	E$_u$ (K)	Beam	$\int F dv$ (mJy km
$3_{3,0} - 2_{2,1}$	216.279	19	1''.3 × 1''.2(76°)	53[9]
$6_{1,6} - 5_{0,5}/6_{0,6} - 5_{1,5}$	217.822	39	0''.9 × 0''.7(83°)	185[10]
$5_{1,4} - 4_{2,3}$	217.940	35	1''.3 × 1''.2(78°)	74[9]

C_3H_2 extends from 35 to 165 AU
Rout coincides with the (CO) snow-line
CO freeze-out limit the formation
of hydrocarbons in gas phase?

Chemistry & molecular Surveys
CLASS II

- **ALMA Era - How far can we go in term of complexity ?**

  → H_2O (Herschel, Bergin et al 2010, Hogerheijde et al 2011)

  → **HC_3N** (IRAM 30-m, Chapillon et al 2012, in DM Tau, GO Tau, MWC480 and LkCa15, **CID**)
  First cyanopolyyne: the more complex molecule detected to far

- **Deep unsuccesful search**
  → H_2D^+ , ALMA cycle 0 proposal by Qi et al – no result yet …

- **New detections …**

  → ALMA verification time 1 & Cycle I: binary proto-star (Class 0) IRAS16293-2422
  – Jorgensen et al 2012 - simplest sugar: Glycolaldehyde ($HCOCH_2OH$)

  → ALMA verification time: HD163296, Herbig Ae (A0) Star of 2 Msun
  - Qi et al 2013, submitted – c- C_3H_2
  - surrounded by a large (& warm) CO disk

SoFar, only the more abundant molecules seen in the ISM have been observed in DISKS

Dust in Proto-planetary Disks

1990 Beckwith et al – 1.2mm survey using IRAM 30-m
1996 Dutrey et al - 3mm survey using IRAM array (PdBI)

Miyake et Nakagawa 1993, 1995

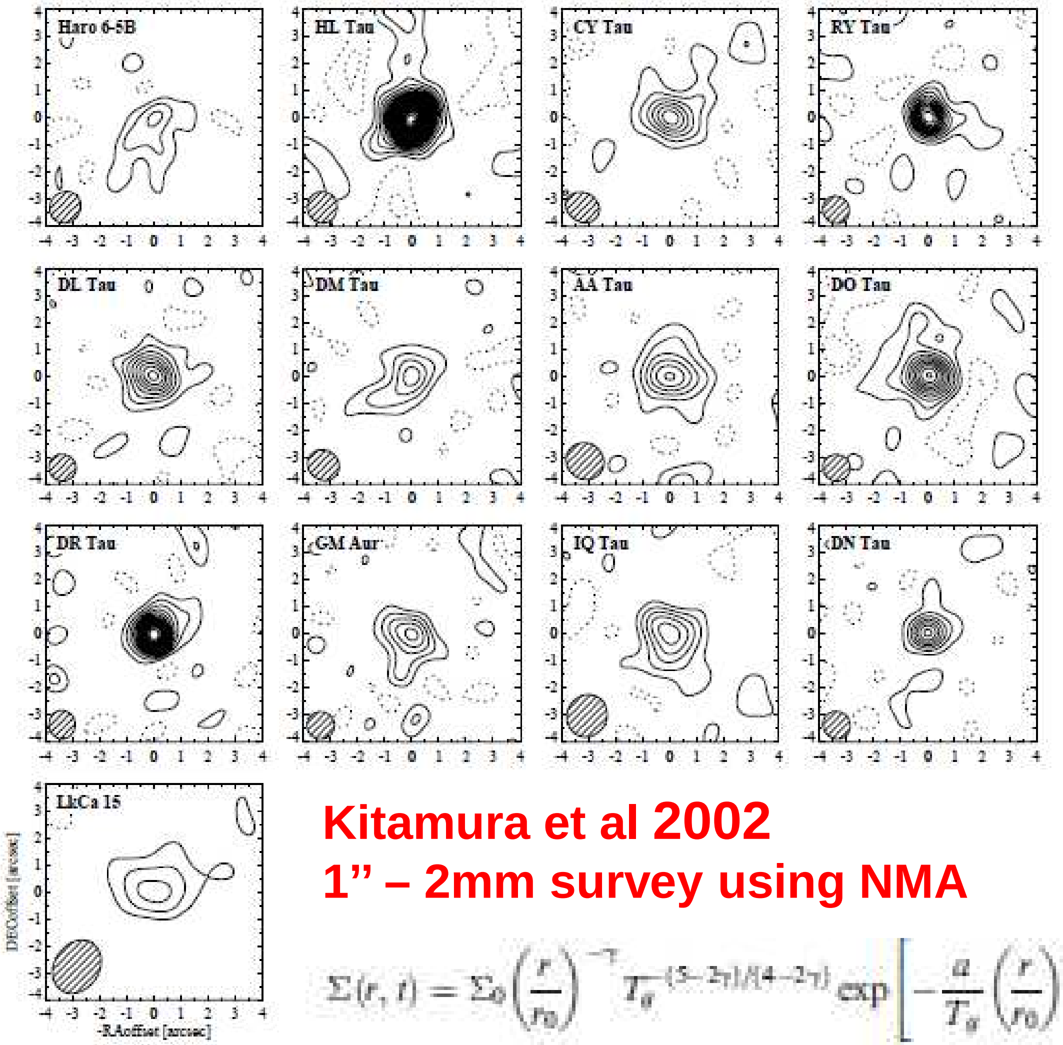
$K_\nu = K_o(\nu / \nu_o)^\beta$ (cm^2/g)

β = 1.7 ≡ ISM-like 'sub-µm' sized
β = 0.5 ≡ 'mm-cm' sized

+ Mm properties of disks:
+ large particles
+ Size of 'mm' disks ~ 1-2 ''
(bulk of 'mm dust' emission)

2002: Kitamura et al
First analysis of mm maps+SEDs
Power law & viscous model
→Best model/source

→T, q, Σ, p …
→Dust β ~ 1, grain growth



Kitamura et al 2002
1'' – 2mm survey using NMA

$$\Sigma(r,t) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-\gamma} T_a^{-(5-2\gamma)/(4-2\gamma)} \exp\left[-\frac{a}{T_a}\left(\frac{r}{r_0}\right)^{2-\gamma}\right]$$

Dust in Proto-planetary Disks
Self similar surface density distributions

Guilloteau, Dutrey, Piétu, Boehler 2011 **PdBI data at 2.7 and 1.3mm ~ 20 sources**
best resolution ~ 0.3" or 40-50 AU

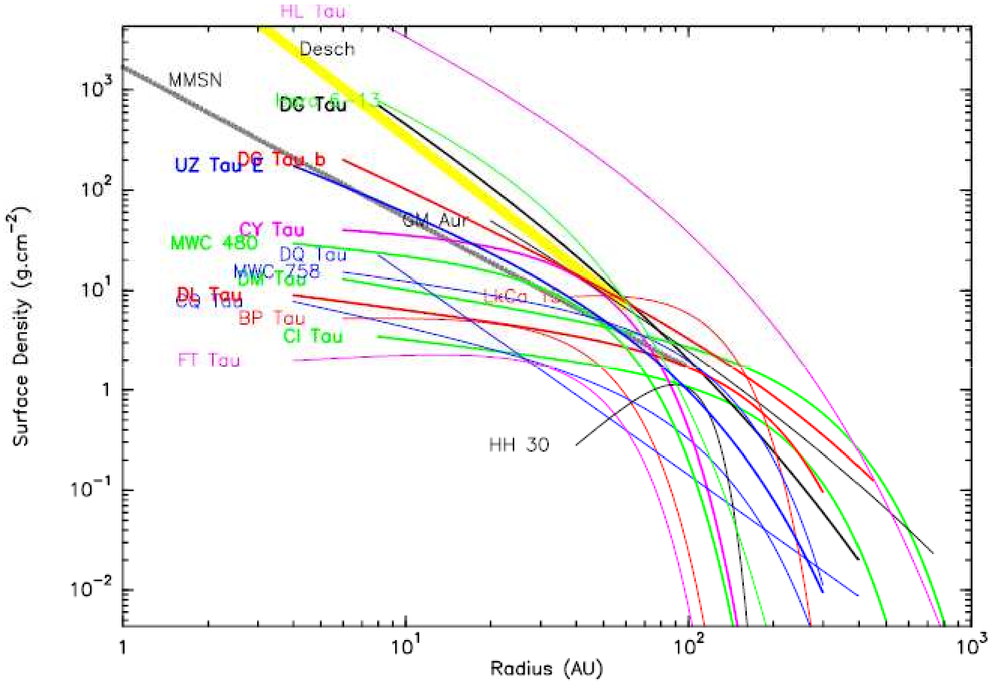


Fig. 12. Surface densities of observed sources. Thick lines are for sources in which a variation of β and thus κ with radius was derived. Thin lines are for sources for which we assumed $\kappa(1.3\,\mathrm{mm} = 2\,\mathrm{cm}^2.\mathrm{g}^{-1}$. The grey line is the MMSN, while the yellow area indicates the Solar Nebula from Desch 2007.

Viscous disk paradigm predicts exponential

$$\Sigma(r) = \Sigma_0 \left(\frac{R_0}{r}\right)^{\gamma} \exp\left(-(r/R_c)^{2-\gamma}\right)$$

Mimicks radius dependent slope
Steeper outside, flatter inside

(See also Hughes et al. 2007; Isella et al. 2009; Andrews et al. 2009)

ALMA: 0.1" = 15 AU ~ H(r) at 100 AU
→ LARGE CONTINUUM SURVEY
→precise β (spectral dependence)
→measurements (several bands)
→Σ(dust) RESOLVED

Viscosity is a power law of radius - with constant viscosity and γ in time

Dust in Proto-planetary Disks
grain radial distribution

PdBI data at 2.7 and 1.3mm (best resolution ~ 0.3'') - Survey of ~ 20 sources

Guilloteau, Dutrey, Piétu, Boehler 2011

- **Analysis:** Compare « power laws » and « viscous » models for surface density

$$\Sigma(r) = \Sigma_0 \left(\frac{R_0}{r}\right)^{\gamma} \exp\left(-(r/R_c)^{2-\gamma}\right)$$

- Results:

-In most cases no significant differences between both models BUT

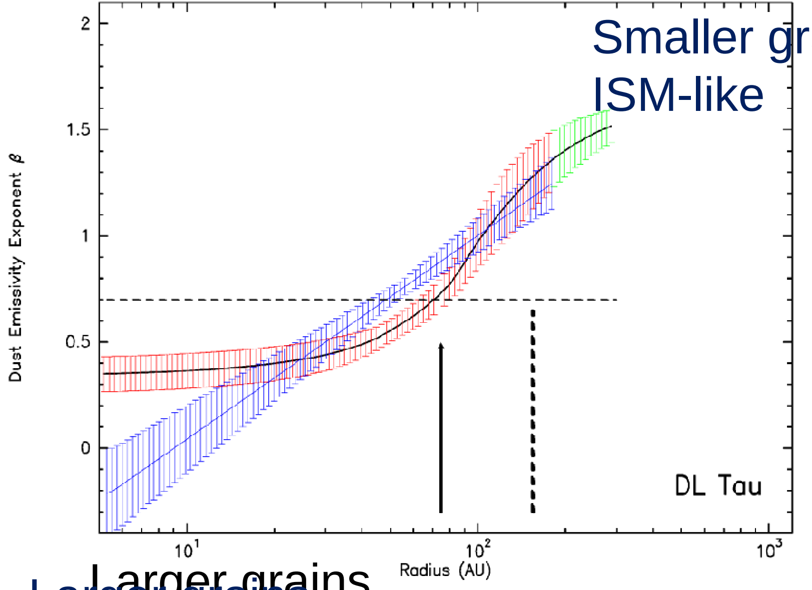
- β, the dust spectral index, varies with radius ! $K_\nu = K_o\ (\nu / 230\ \mathrm{GHz})^{\beta(r)}$

Impacts on

- **the local gas/dust ratio, varies in (z,r)**
- **the extinction curve in the UV (z,r)**
- **disk UV field and chemistry**

Red: $0 \leq \beta(r) \leq 1.7$ (ISM)

Blue: simple power law for β(r)



Smaller grains
ISM-like

Larger grains

Larger grains

→This result is confirmed by new VLA/CARMA surveys !

Dust in Proto-planetary Disks
grain radial distribution in AS209

Perez et al 2012

VLA, CARMA, SMA data at ~ 0.3’’-0.7’’ Data at 9.8 & 8.0 mm, 1.3mm, 0.8mm

Multi-wavelength modelling
(viscous model)

Best model
→ Larger grains in the
the inner disk

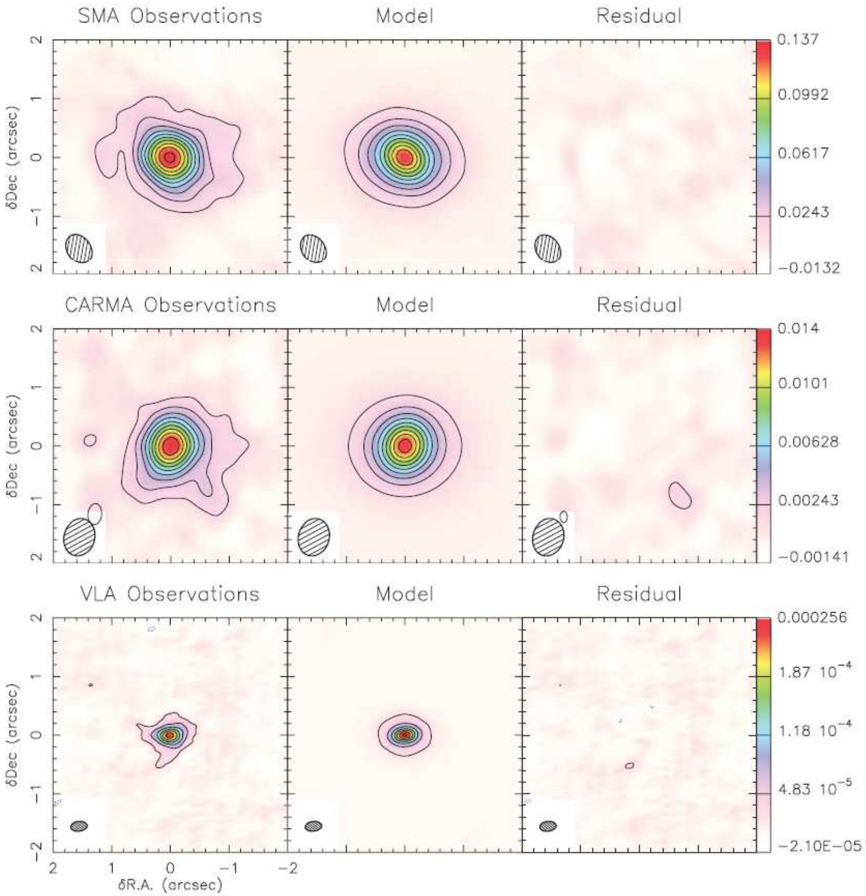


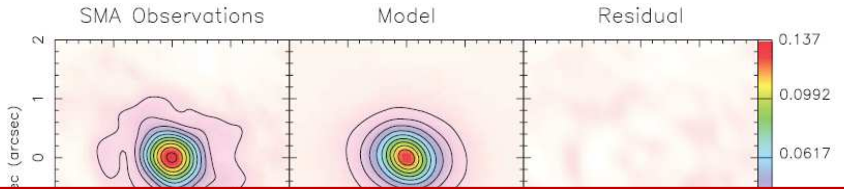
Figure 3. Continuum emission toward AS 209, observed at 0.88 mm (top panels), 2.8 mm (middle panels), and 8.0 and 9.8 mm (combined through multi-frequency synthesis, bottom panels). Each observation, accompanied by the best-fit disk emission and a residual map obtained by subtracting the best-fit model from the observations, used Briggs weighting with robust = 0.7 (SMA, CARMA), while VLA data used natural weighting. Contours start at -3σ, stepping by 3σ (CARMA, SMA) and 6σ (VLA), where σ is the rms noise on each map: $\sigma_{SMA} = 4.4$ mJy beam^{-1}, $\sigma_{CARMA} = 0.47$ mJy beam^{-1}, $\sigma_{VLA} = 0.01$ mJy beam^{-1}

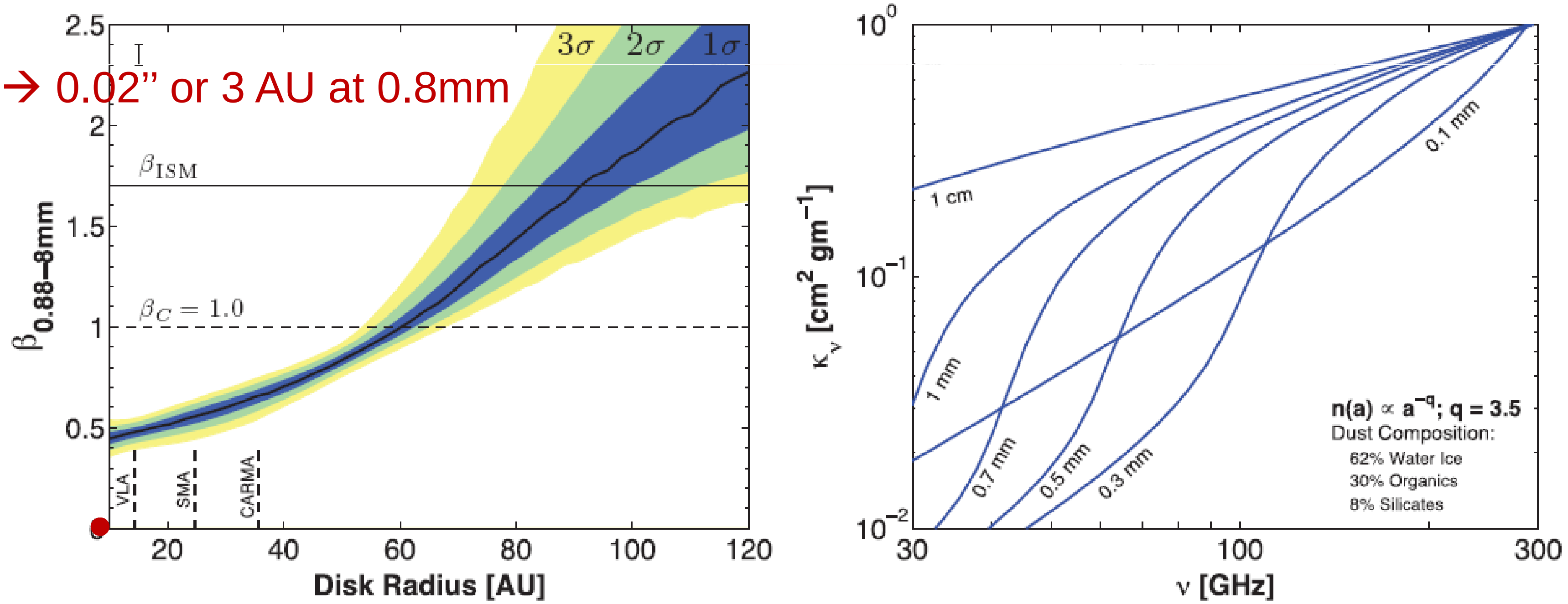
Dust in Proto-planetary Disks
grain radial distribution in AS209

Perez et al 2012

VLA, CARMA, SMA data at ~ 0.3''   Data at 7mm, 1.3mm, 0.8mm

Multi-wavelength modelling
(viscous model)





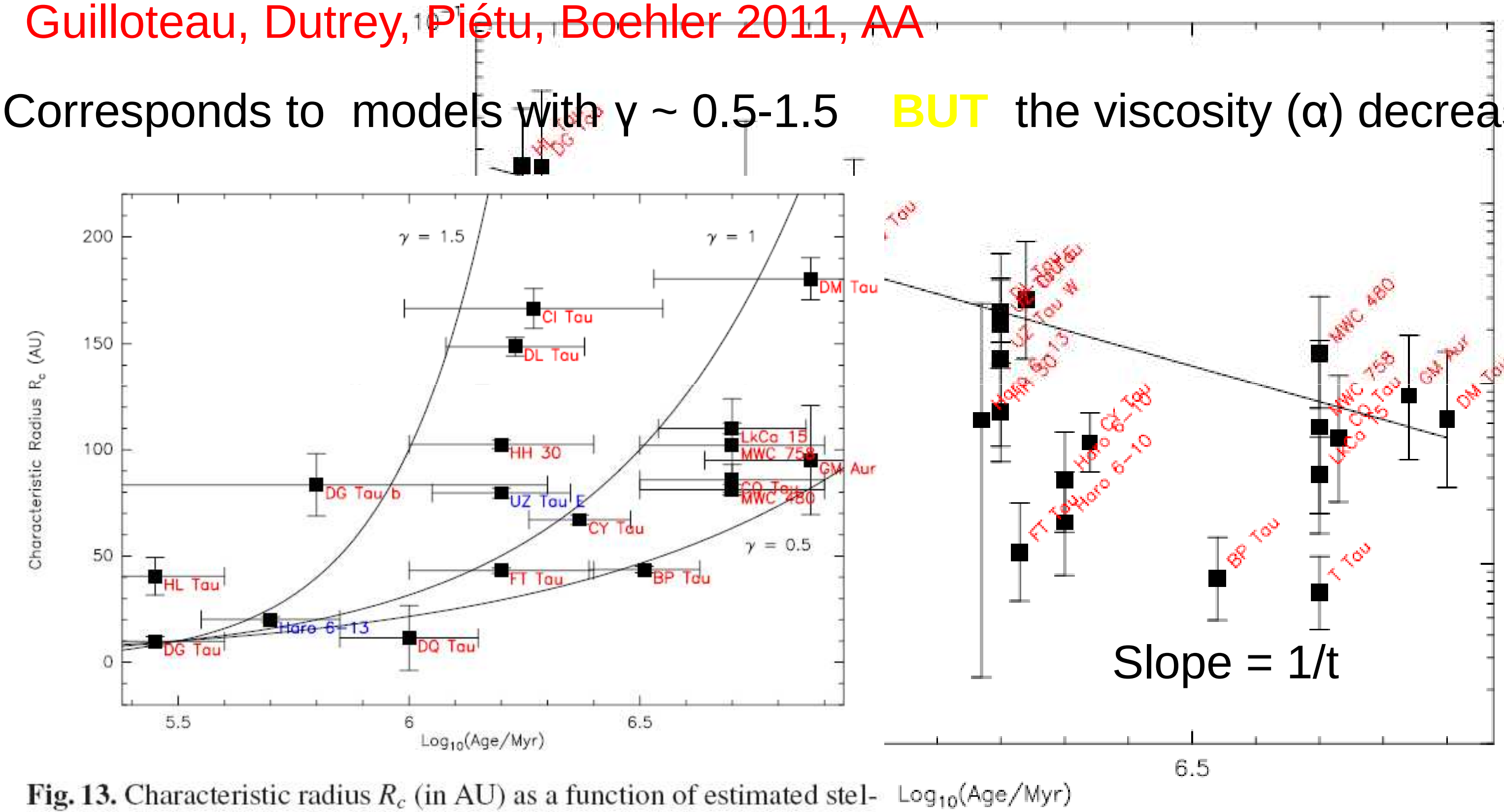
20 km → 0.02'' or 3 AU at 0.8mm

igure 4. Left: dust opacity spectral slope, β, vs. radius, inferred from multi-wavelength observations of the AS 209 disk. Black line: best-fit $\beta(R)$, co
onfidence interval constrained by our observations. Vertical dashed lines indicate the spatial resolution of our observations, error bar in top-left corn
dditional systematic uncertainty on $\beta(R)$ arising from amplitude calibration uncertainty. Right: dust opacity (normalized at 300 GHz) for $a_{\rm max}$ between 0.1

Self-similar viscous model
… turbulence behaviour - not so simple…

Guilloteau, Dutrey, Piétu, Boehler 2011, AA

Corresponds to models with γ ~ 0.5-1.5 **BUT** the viscosity (α) decreases with time



Slope = 1/t

Fig. 13. Characteristic radius R_c (in AU) as a function of estimated stellar ages (in Log_{10} of 10^6 years).

Self similar viscous model: viscosity is a time independent power law of radius

→ **ALMA …**

$$\alpha(R_{100}) = \frac{R_c^{(2-\gamma)} R_{100}^{\gamma}}{3(2-\gamma)^2 c_s(R_{100}) H(R_{100}) t_*}$$

ALMA: dust and gas disk around the BD ρ -oph 102– Ricci et al 2012

- TTauri-like phase (disk & outflow)
- ρ -oph 102: 60 Mjup (or 0.06 Msun) and spectral type M6
- D = 130 pc → Resolution of 0.89mm data: 0.6 = 70 AU

→ Grain growth should be less efficient than in TTauri disks

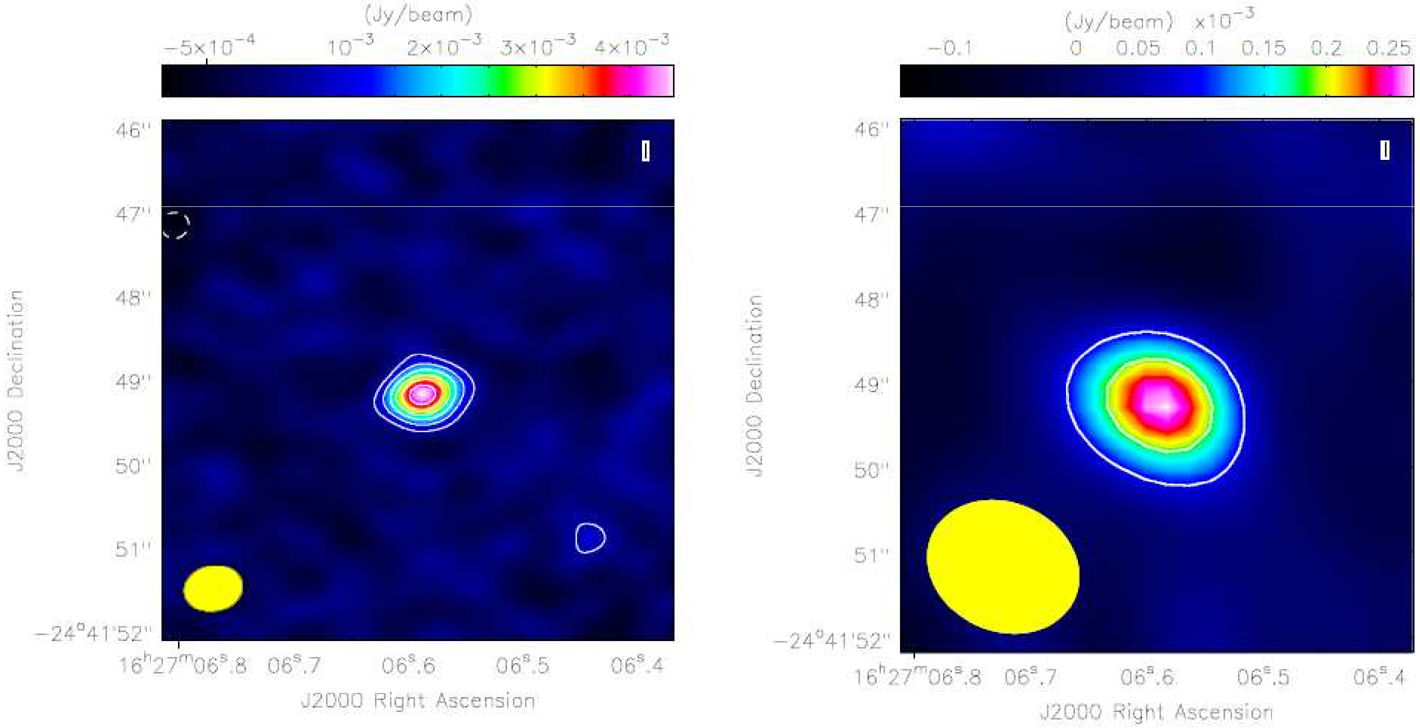


Figure 1. Continuum maps of ρ-Oph 102. Left panel) Continuum map at 0.89 mm. White contour lines are drawn at $-3, 3, 6, 9, ..., 18\sigma$, where $\sigma = 0.22$ mJy/beam is the rms noise measured on the map. Right) Continuum map at 3.2 mm. White contour lines are drawn at 3 and 6σ, where $\sigma = 0.031$ mJy/beam. In each panel, the yellow filled ellipse in the lower left corner indicates the size of the synthesized beam, i.e. FWHM = 0.71″ × 0.54″, PA = 100 deg at 0.89 mm, and FWHM = 1.82″ × 1.50″, PA = 66 deg at 3.2 mm. For both maps, a Briggs weighting with robust parameter = 2 (natural weighting) was used to maximize the signal-to-noise ratio.

Dust disk:

Rout < 40 AU

Grain growth

2-6. 10^{-6} Msun

Or if G/D = 100

2-6. 10^{-4} Msun

ALMA: dust and gas disk around the BD ρ -oph 102– Ricci et al 2012

- TTauri-like phase (disk & outflow)
- ρ -oph 102: 60 Mjup (or 0.06 Msun) and spectral type M6
- D = 130 pc → Resolution of 0.89mm data: 0.6 = 70 AU

GAS DISK: CO J=3-2 is detected

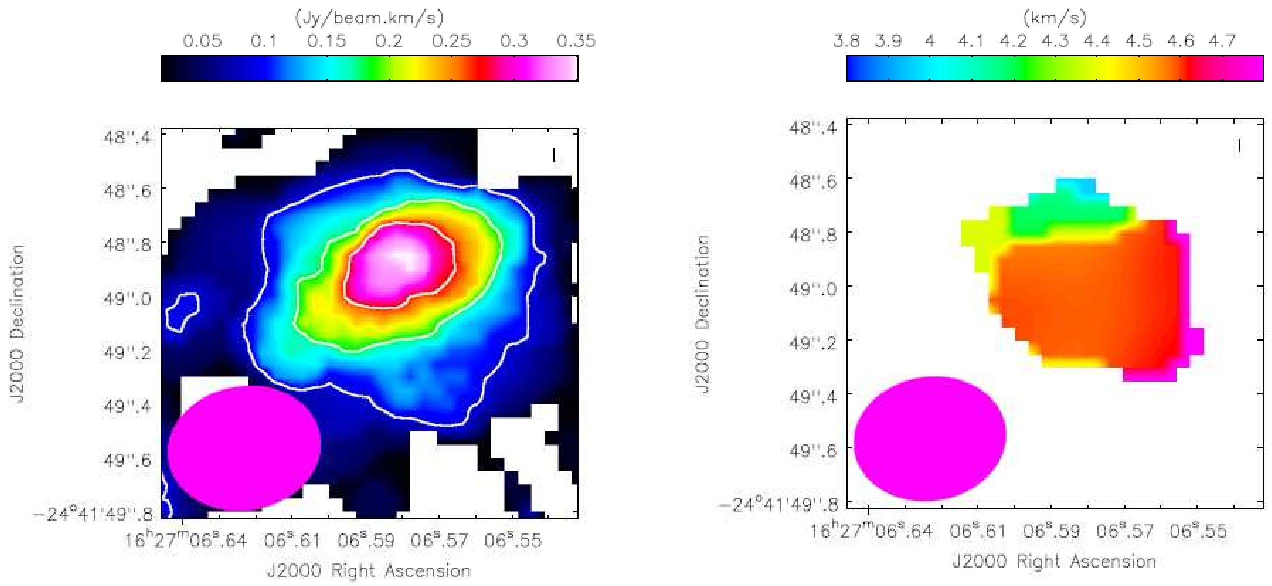


Figure 2. CO($J = 3 - 2$) maps of ρ-Oph 102. Left panel) Moment 0 CO($J = 3 - 2$) map. White contour lines are drawn at $2, 4, 6\sigma$, where $\sigma = 45$ mJy/beam·km/s is the measured rms-noise. Right) Moment 1 CO($J = 3 - 2$) map. In each panel, the magenta filled ellipse in the lower left corner indicates the size of the synthesized beam, i.e. FWHM = $0.57'' \times 0.46''$, PA = 99 deg. For the imaging, we adopted a Briggs weighting with robust parameter = 0 and considered only projected baselines longer than 70 kλ to highlight the emission from structures with angular scales $\lesssim 3''$. White pixels have been masked out for the computation of the moment maps.

GAS disk:

Consistent with gas in Keplerian rotation in an inclined disk orbiting at distances R > 10 AU from a 0.06 Msun BD

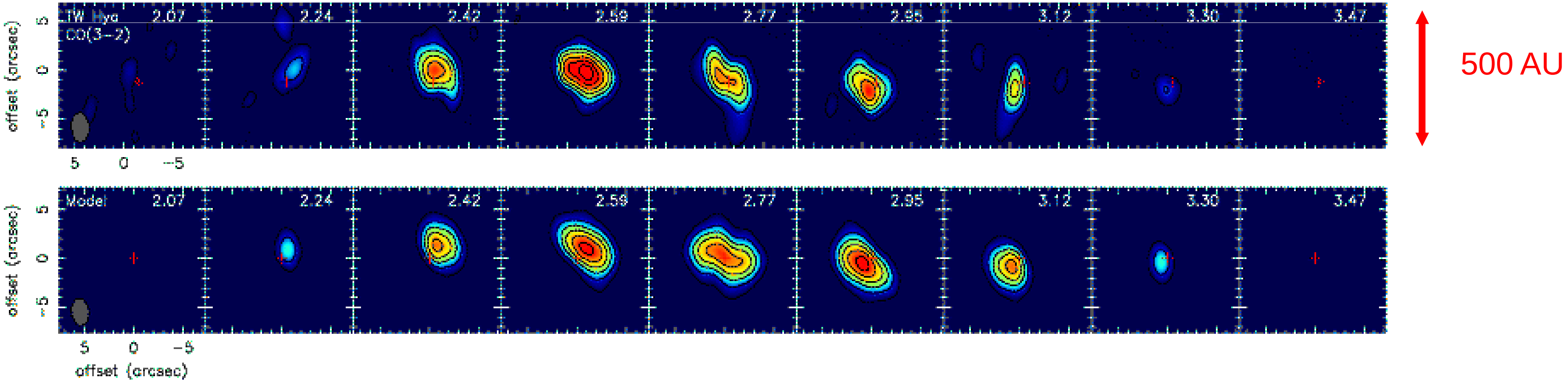
Limited data but

Gas Rich disk with large grains !

TW Hya the closest disk (~ 55 pc)

- TW Hydra , 0.8 Msun, age ~ 10^7 yr
- a CO disk of about Rout = 150 AU
- most nearby protoplanetary disk at 55 pc (dec. -34)
- nearly face on (7º)
- Dust depleted cavity R < 4 AU (Hughes et al 2009)

- Dust, CO J=3-2: disk structure, kinematics, M_*, chemistry



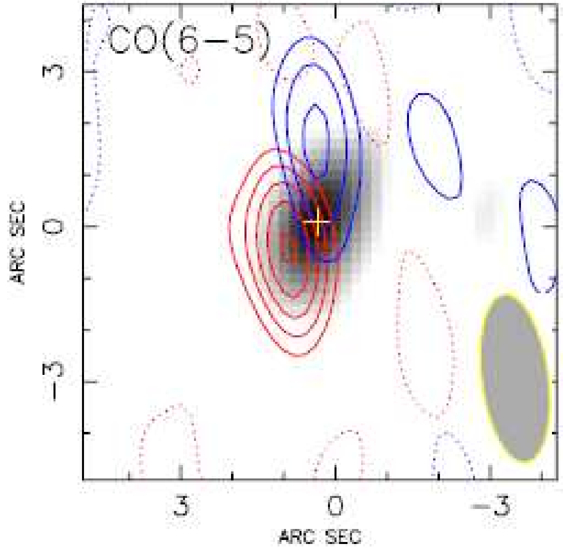
SMA data, Resolution ~ 3''

Qi et al. 2004, 2006

Recent estimates: M2.5V, 0.4 Msun, and 3 Myr (Vacca & Sandell 2011)

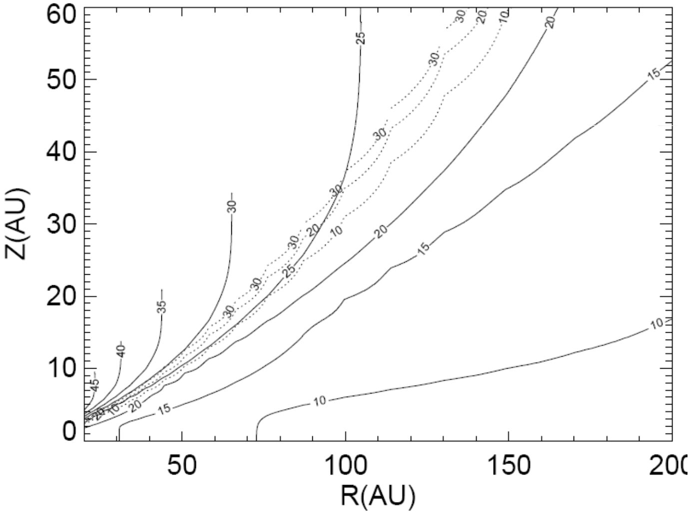
TW Hya SMA

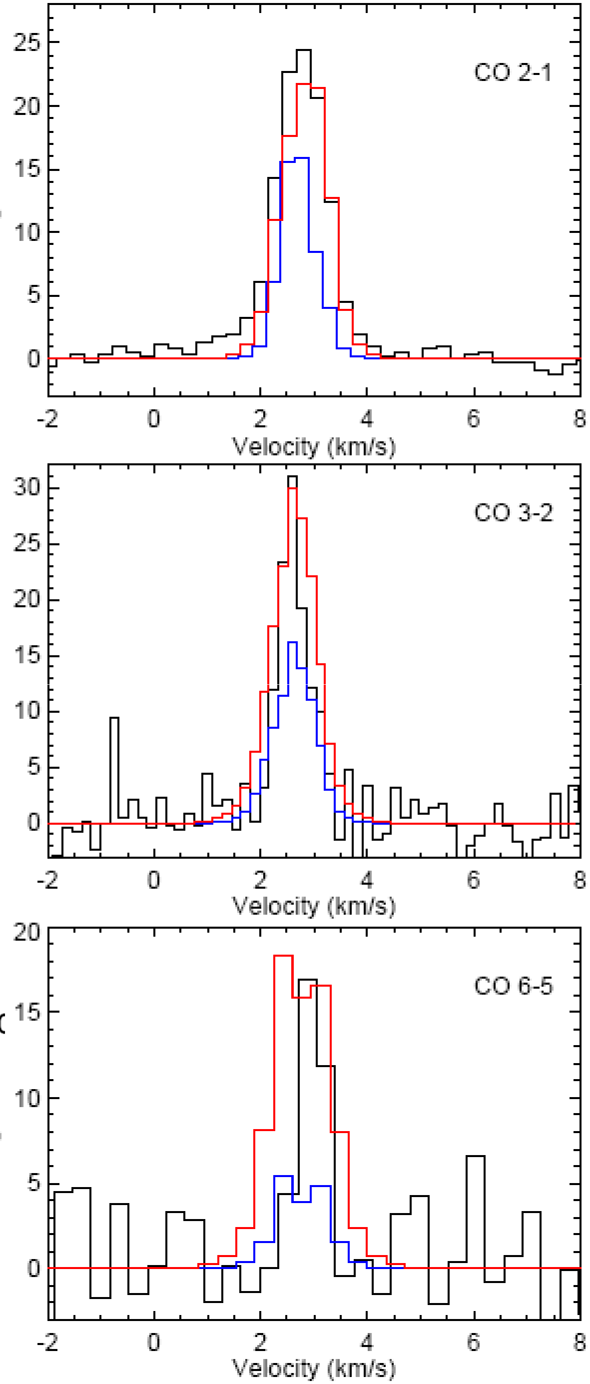
- CO (6-5)
- Hot, dense, gas
- X ray heating



C. Qi et al 2006

X-ray Heating is needed
to explain the strength
of the CO 6-5 line





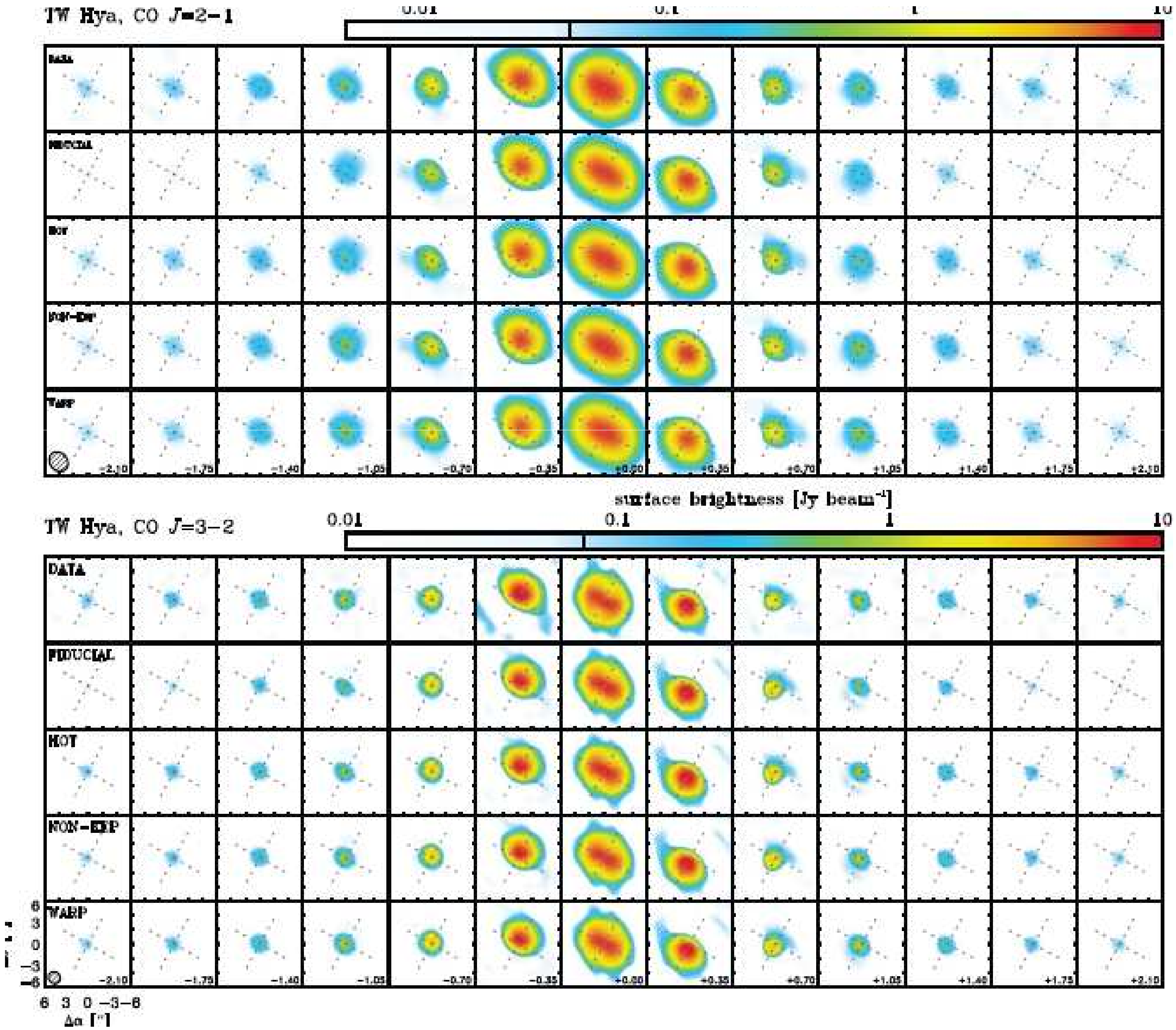
Blue: Canonical Model

(Calvet et al. 2002, Qi et al. 2004)

Red: Model with X ray heating

ALMA DATA CO J=2-1 & J=3-2

Rosenfeld et al 2012



ALMA data:
CO 2-1 & 3-2

S/N ~ 10

Resolution is about a factor 1.5-2 better
(2.5'' in CO 2-1
1.6'' in CO 3-2)

Velocities ~20 km/s
→
Gas as close as 2 AU

ALMA DATA CO J=2-1 & J=3-2

Rosenfeld et al 2012

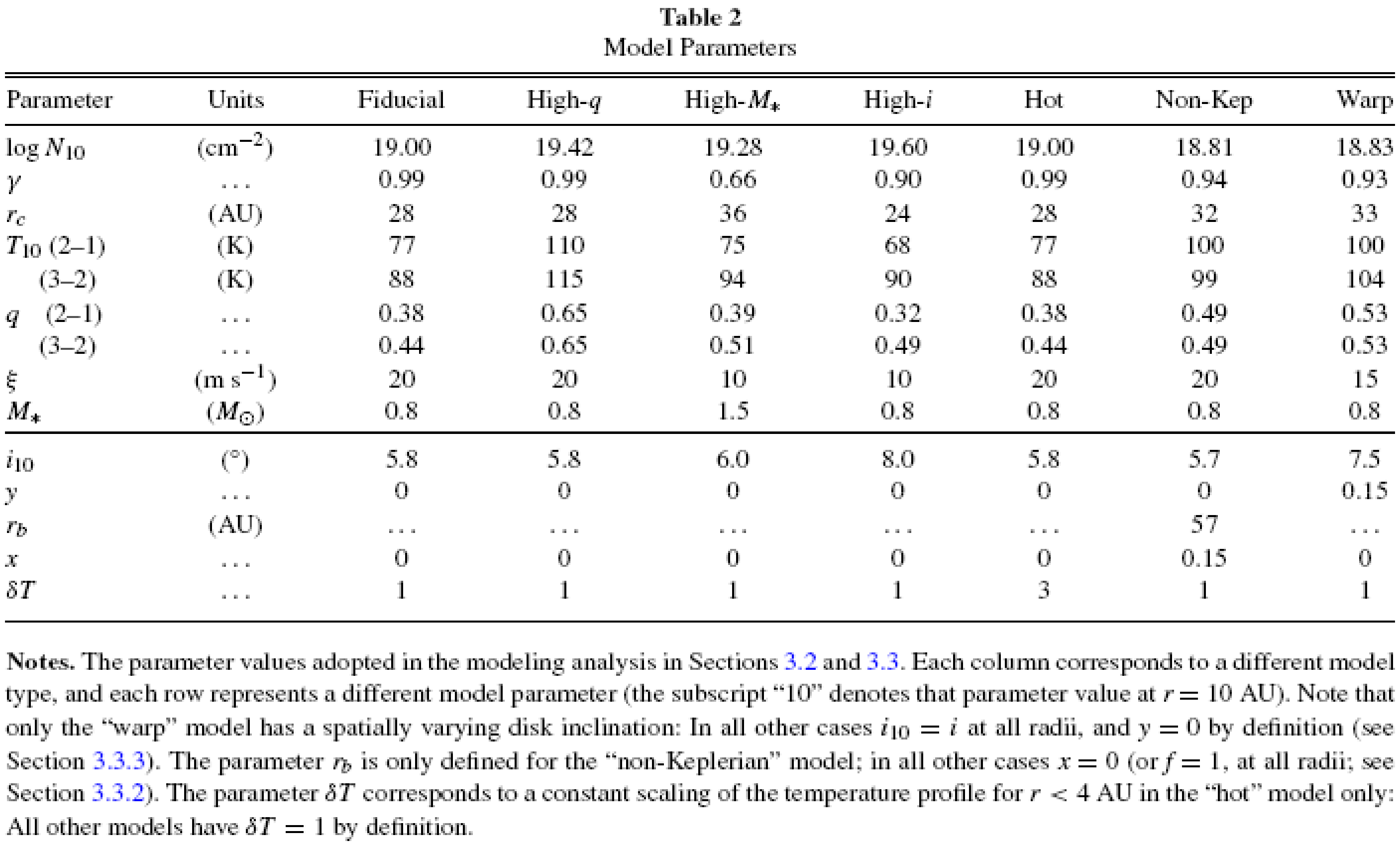


Table 2
Model Parameters

Parameter	Units	Fiducial	High-q	High-M_*	High-i	Hot	Non-Kep	Warp
$\log N_{10}$	(cm^{-2})	19.00	19.42	19.28	19.60	19.00	18.81	18.83
γ	...	0.99	0.99	0.66	0.90	0.99	0.94	0.93
r_c	(AU)	28	28	36	24	28	32	33
T_{10} (2–1)	(K)	77	110	75	68	77	100	100
(3–2)	(K)	88	115	94	90	88	99	104
q (2–1)	...	0.38	0.65	0.39	0.32	0.38	0.49	0.53
(3–2)	...	0.44	0.65	0.51	0.49	0.44	0.49	0.53
ξ	(m s^{-1})	20	20	10	10	20	20	15
M_*	($M_\odot$)	0.8	0.8	1.5	0.8	0.8	0.8	0.8
i_{10}	(°)	5.8	5.8	6.0	8.0	5.8	5.7	7.5
y	...	0	0	0	0	0	0	0.15
r_b	(AU)	...	...	...	...	...	57	...
x	...	0	0	0	0	0	0.15	0
δT	...	1	1	1	1	3	1	1

Notes. The parameter values adopted in the modeling analysis in Sections 3.2 and 3.3. Each column corresponds to a different model type, and each row represents a different model parameter (the subscript "10" denotes that parameter value at $r = 10$ AU). Note that only the "warp" model has a spatially varying disk inclination: In all other cases $i_{10} = i$ at all radii, and $y = 0$ by definition (see Section 3.3.3). The parameter r_b is only defined for the "non-Keplerian" model; in all other cases $x = 0$ (or $f = 1$, at all radii; see Section 3.3.2). The parameter δT corresponds to a constant scaling of the temperature profile for $r < 4$ AU in the "hot" model only: All other models have $\delta T = 1$ by definition.

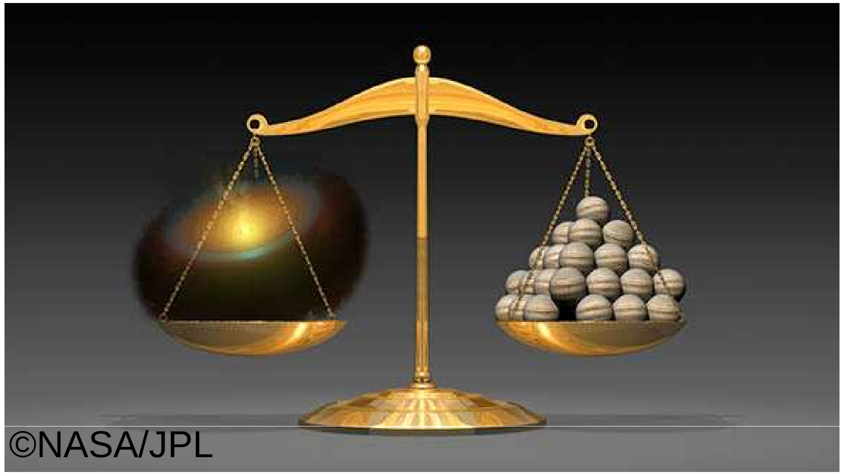
A central warp ?

(scattered light image
Roberge et al 2005)

TW Hydra: Herschel detection of HD J=1-0 & 2-1

By Bergin et al 2013, Nature

→ Almost a direct measurement of the GAS Mass !



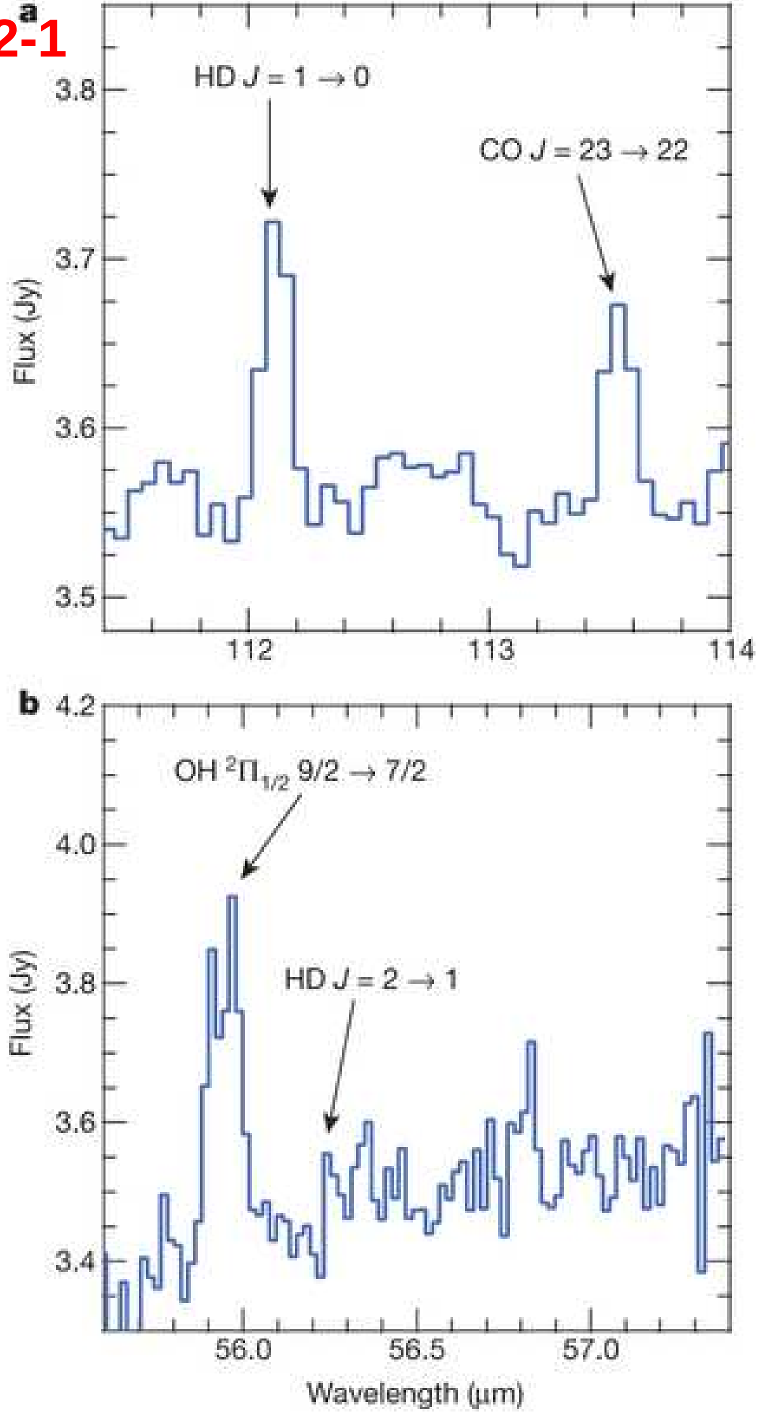
©NASA/JPL

Based on the new data, the mass of TW Hydrae's disc is equivalent to ~50 Mjup, towards the high-mass end of the previous range of estimates (0.0005-0.06 MSun*).*

→ Mdisk(total) > 0.05 Msun

This disc has the potential to build a planetary system like our own, or possibly even more complex and exotic than the Solar System

IS THIS A UNIQUE CASE ?



Inner Disks & Cavities
What the observation tells us …

Geometry of inner gas and dust disks ?
→Inner ~ R <= 20 AU (snowline ~ 1-3 AU for Ttauri star…)

(T = 0)

10^4 yr ~ Class 0: large (1000 AU or more) flattened envelope
→ WAIT for ALMA results

10^5 yr ~ Class I: disk shape , what about rotation ?
→Some holes in binary systems … CB26 ?

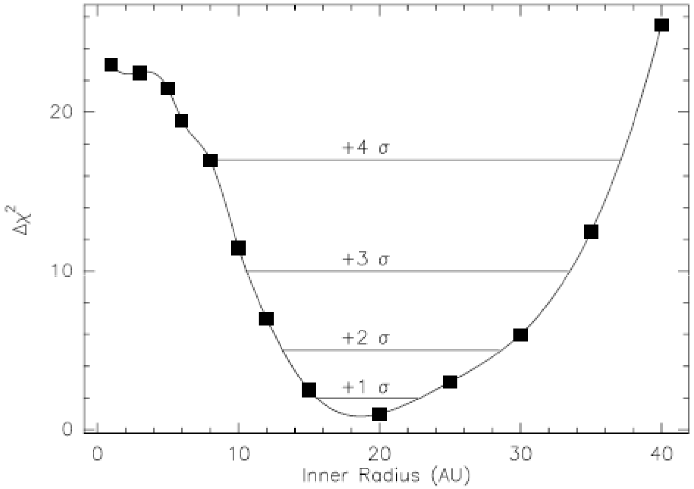
10^6 yr ~ Class II: rotating (Keplerian) disk
- **resolved structure**
- **some large disks R~ 500-800 AU (likely biaised)**

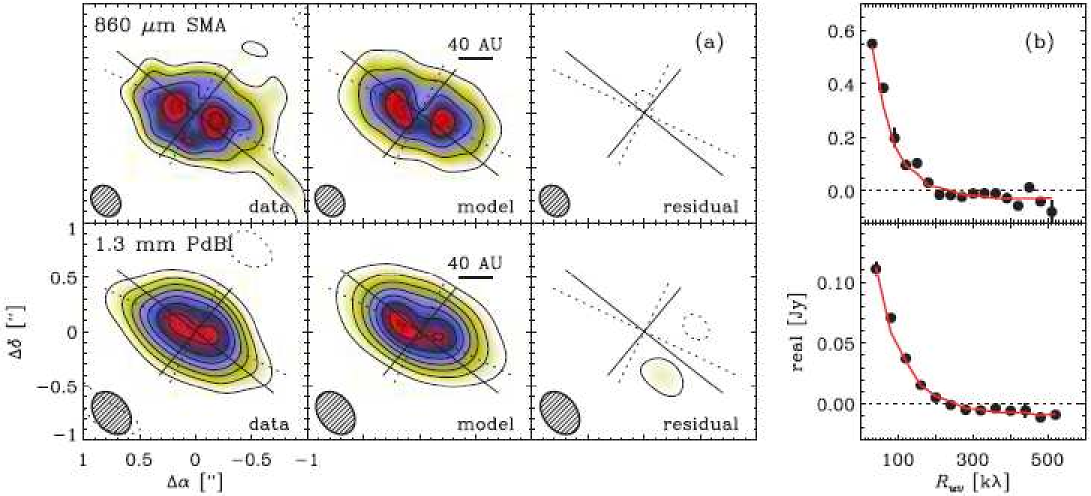
→More and more inner cavities and spiral features …
→ Transition disks / planet formation (G/D ~ 100)

Geometry from CO … The GM Aur case

Dutrey et al., 2008 (CID) → **Rin = 20 AU**
Spectroscopic detection

Hughes et al., 2009 **– same dust inner radius**





Analysis 12CO, 13CO, C18O 1-0, 2-1
PdBI data

The cavity is «devoid » of dust and gas

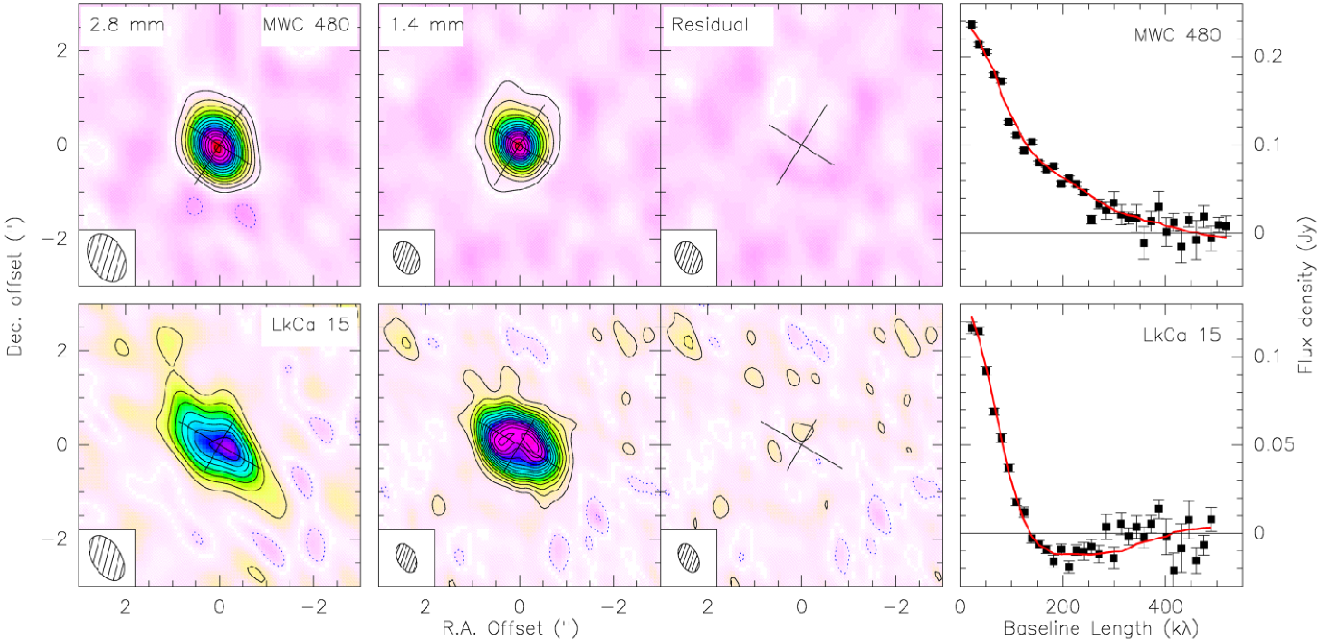
CO line wings are tidally truncated « super resolution »
→companion: is this a planet ? (mass ~ 5 – 10 Mjup)

Cavity Radius < Pluto's Orbit

Geometry thermal dust emission LkCa15

PdBI: The A+ configuration provides baselines up to 750m (0.3'' or 30 AU).
The observations were done in track-sharing mode.

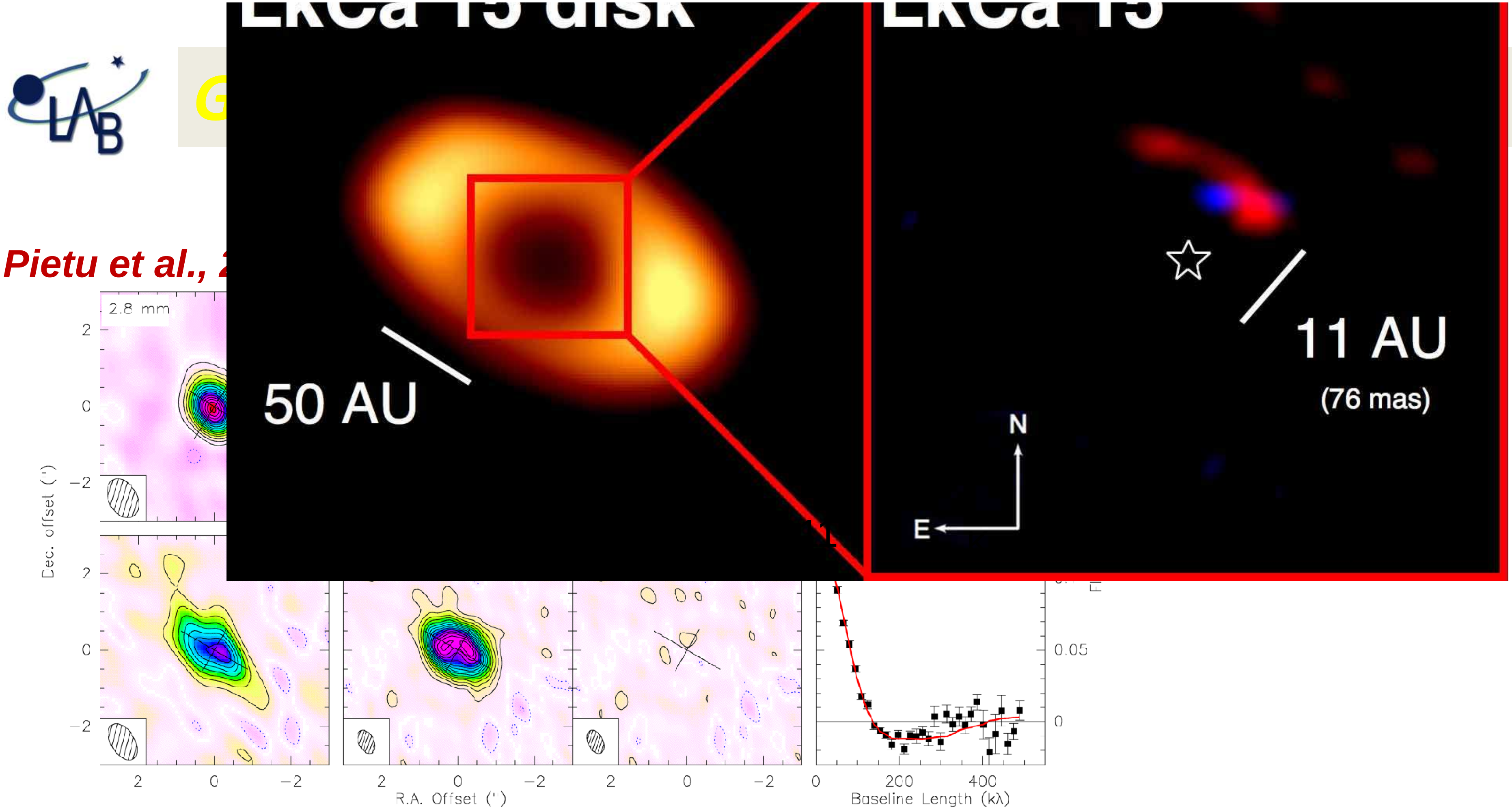
Pietu et al., 2006



When does planet formation start ?

G

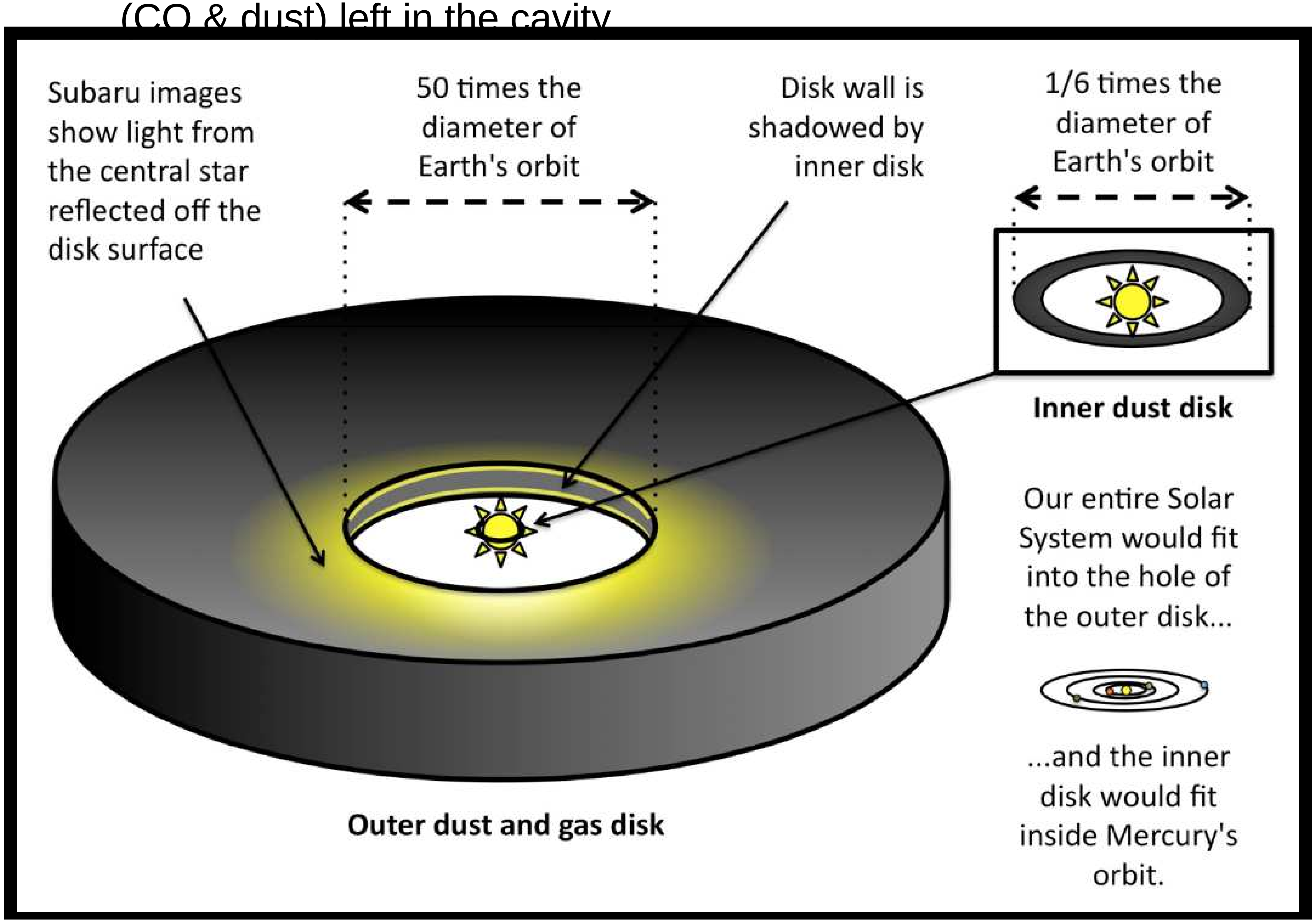
Pietu et al., 2



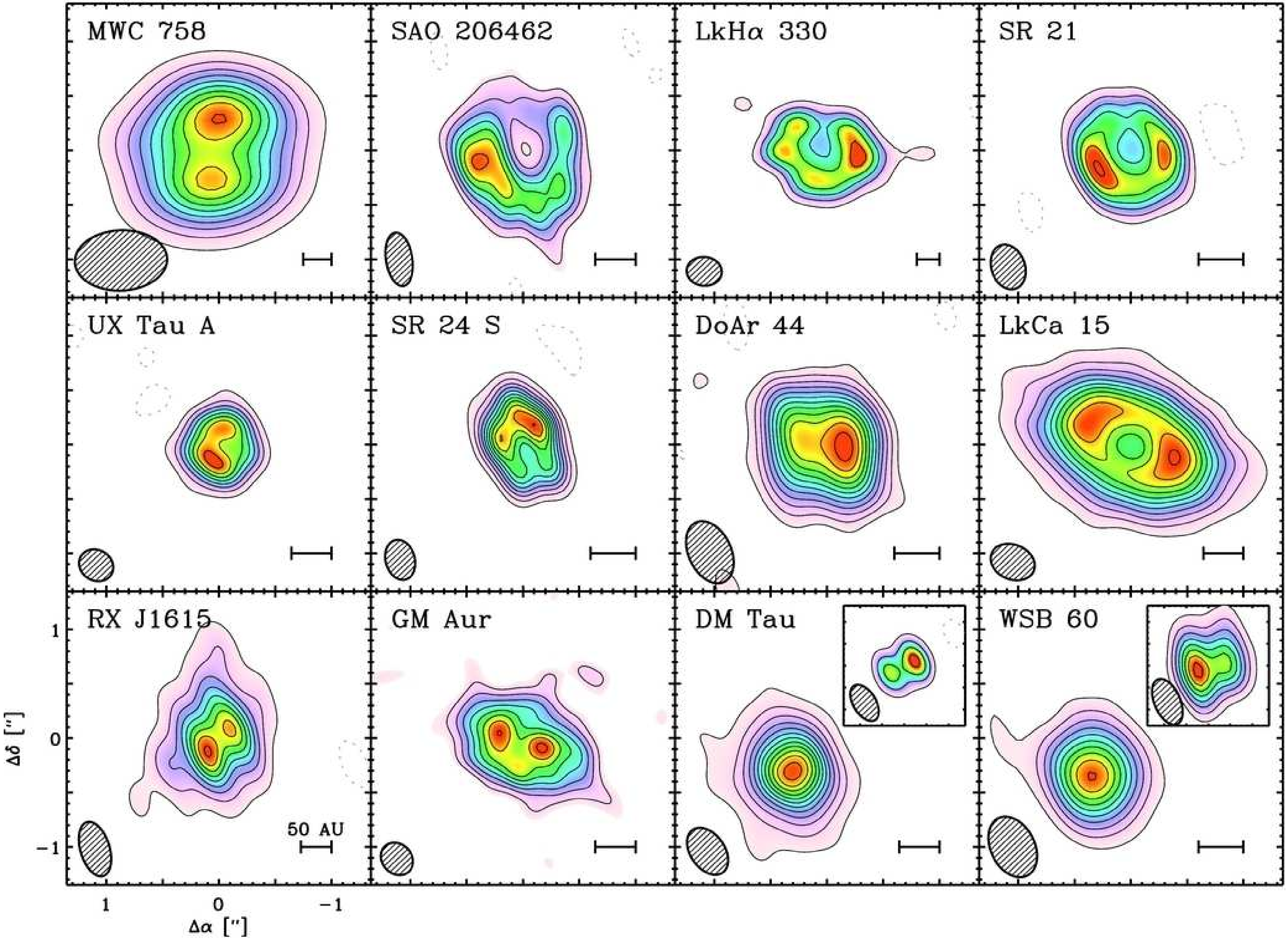
When does planet formation start ?

Geometry from thermal dust emission

LkCa15 inner disk and gap …
ALMA will allow observers to trace the amount of material
(CO & dust) left in the cavity

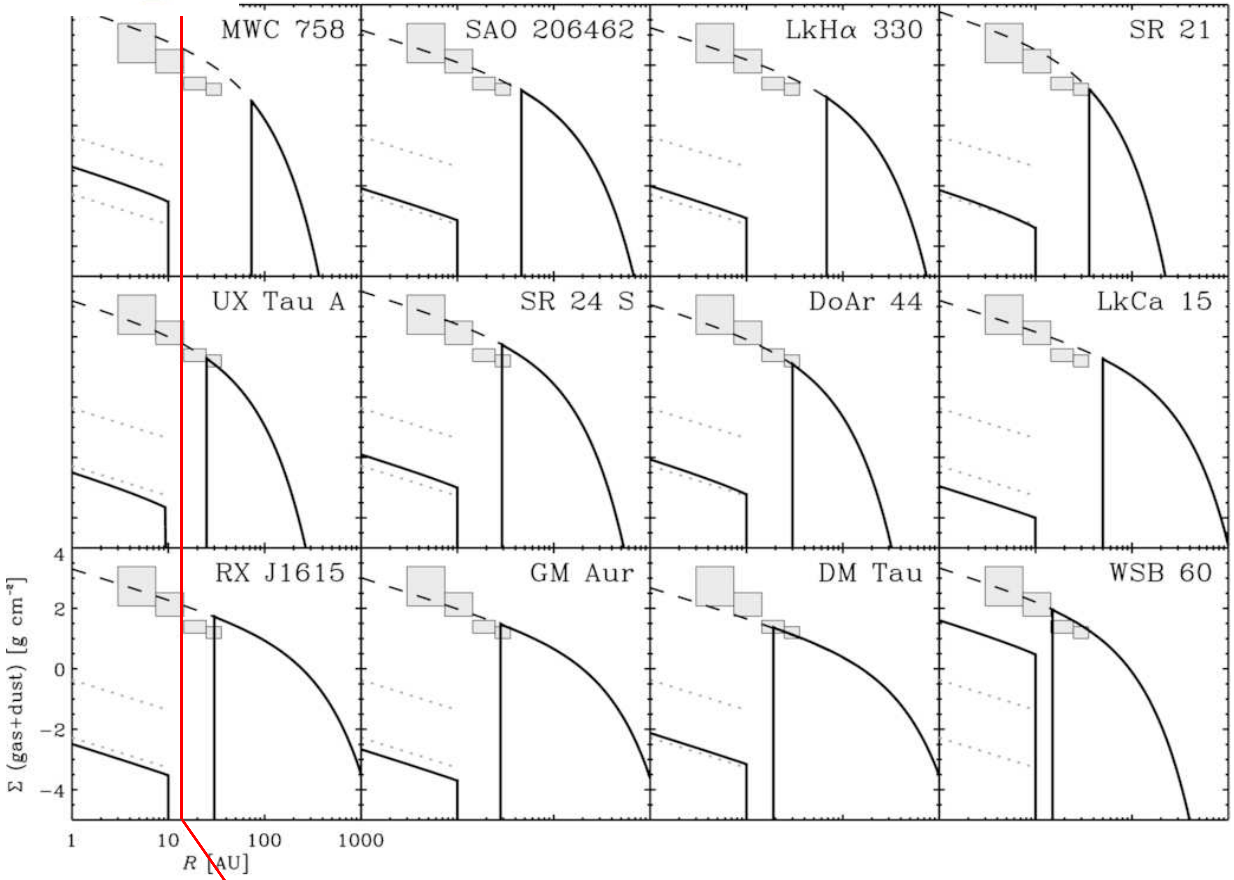


Des p'tit's trous, des p'tits trous, toujours des p'tits trous …



SMA 0.88 mm thermal dust emission. Contours at 3σ intervals, and synthesized beams in the lower left corner.

Geometry from thermal dust emission



Model surface density profiles (solid curves with G/D = 100. The underlying global density profiles, Σ_g are overlaid as dashed curves. The Σ gradient parameter was fixed in the modeling to $\gamma = 1$, meaning that $\Sigma \propto 1/R$ at small radii ($R < R_c$) and $\Sigma \propto 1/e^R$ at large radii ($R > R_c$). The gray squares correspond to the estimated surface densities in the Minimum Mass Solar Nebula (MMSN), Weidenschilling 1977).

Dotted lines in the inner disk mark the expected surface densities for one earth mass and one lunar mass of material (gas + dust), assuming $\Sigma \propto 1/R$ from 0.1 to 10 AU.

Unresolved ↘ Resolved - The material inside the disk cavities is *not* resolved by SMA

ALMA with 0.03'' or 2-3 AU resolution at 0.8mm should resolve it …

From Resolved Images of Large Cavities in Protoplanetary Transition Disks by Andrews et al. 2011 ApJ

ALMA Casassus et al 2012

First glance inside a planet forming cavity in a large gas-rich disk ?

The star HD142527
D=140 pc (D=198 pc)
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr

The gas and dust disk
Radius ~ 980 AU

- IR imaging at 1.65 and 2.2 µm by Fukagawa et al 2006
- Thermal IR imaging

→ Spiral features & cavity

- mm/submm dust disk maps
- Large CO disk

- Far-IR & IR: warm molecules

→ Very inner disk

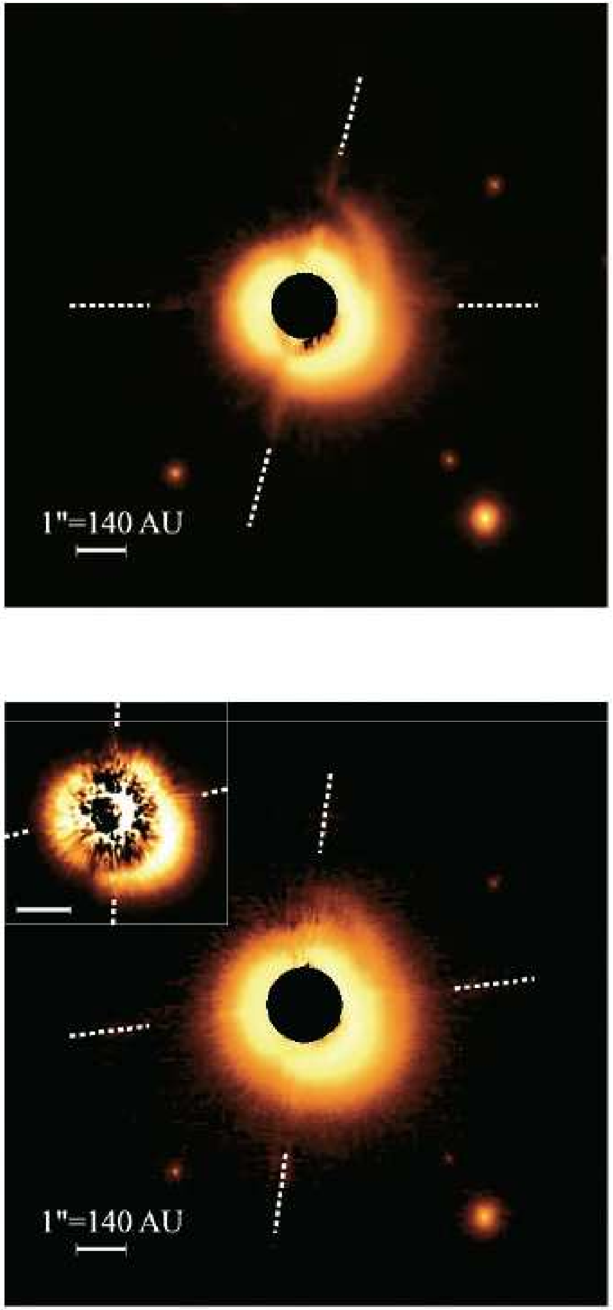


FIG. 1.—*H*- (*top*) and *K*-band (*bottom*) images of the disk around HD 142527. The central software mask has a radius of $r = 0''.66$ (*top*) and $r = 0''.75$ (*bottom*). The images are displayed in logarithmic scale. In the upper left-hand corner of the bottom panel, the image taken with the smaller occulting mask ($0''.6$ in diameter)

ALMA Casassus et al 2012

First glance inside a planet forming cavity in a large gas-rich disk ?

The star HD142527
D=140 pc (D=198 pc)
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr

The gas and dust disk
Radius ~ 980 AU

- IR imaging at 1.65 µm by Fukagawa et al 2006
- **Thermal IR imaging**

→ Spiral features & cavity

- mm/submm dust disk maps
- Large CO disk

- Far-IR & IR: warm molecules

→ Very inner disk

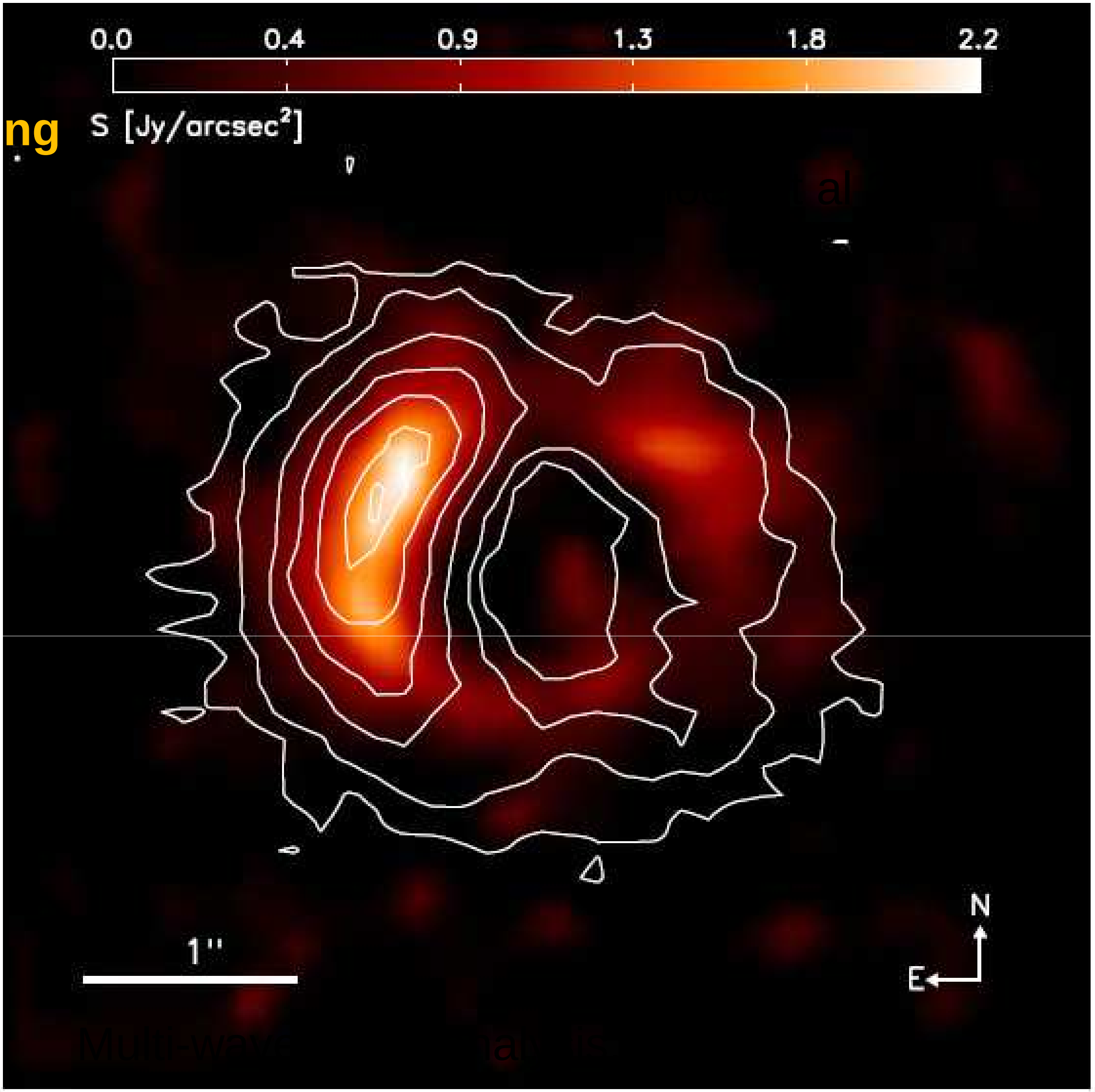
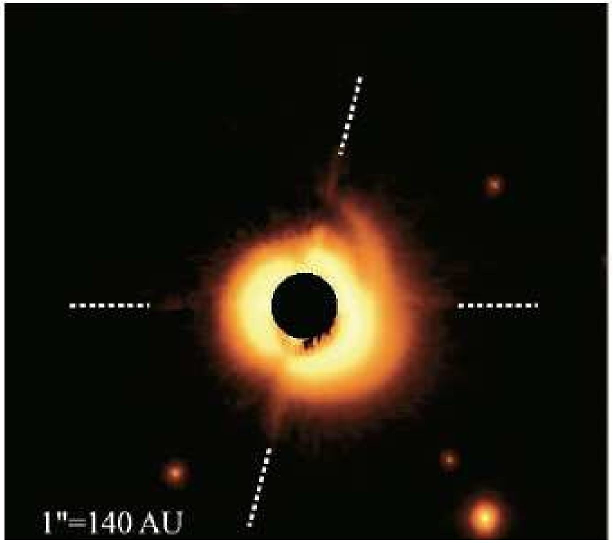


Fig. 4. Central component-subtracted VISIR 18.72 μm image of HD 142527. The color bar shows the surface brightness with a cut-off at 3.1 Jy/arcsec^2. The overplotted contours from the 24.5 μm Subaru image are at 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 5.3 Jy/arcsec^2.

ALMA Casassus et al 2012

First glance inside a planet forming cavity in a large gas-rich disk ?



The star HD142527
D=140 pc (D=198 pc)
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr

The gas and dust disk
Radius ~ 980 AU

- **IR imaging at 1.65 µ**
Fukagawa et al 2006
- Thermal IR imaging
→ Spiral features & c

- mm/submm dust disk
- Large CO disk

- Far-IR & IR: warm m
→ Very inner disk

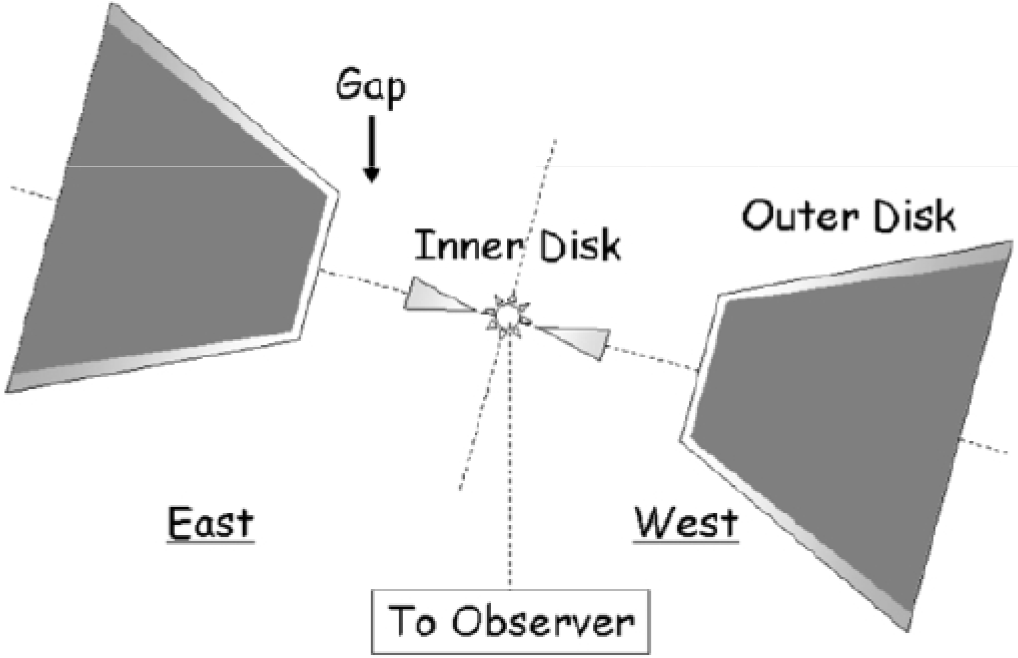


Fig. 5.—Schematic view of the model of the HD 142527 system. The gap between the inner and outer disks exists at r = 80–170 AU.

2527.
ttom).
The images are displayed in logarithmic scale. In the upper left-hand corner of the
bottom panel, the image taken with the smaller occulting mask (0″6 in diameter)

ALMA Casassus et al 2012

First glance inside a planet forming cavity in a large gas-rich disk ?

The star HD142527
D=140 pc (D=198 pc)
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr

The gas and dust disk
Radius ~ 980 AU

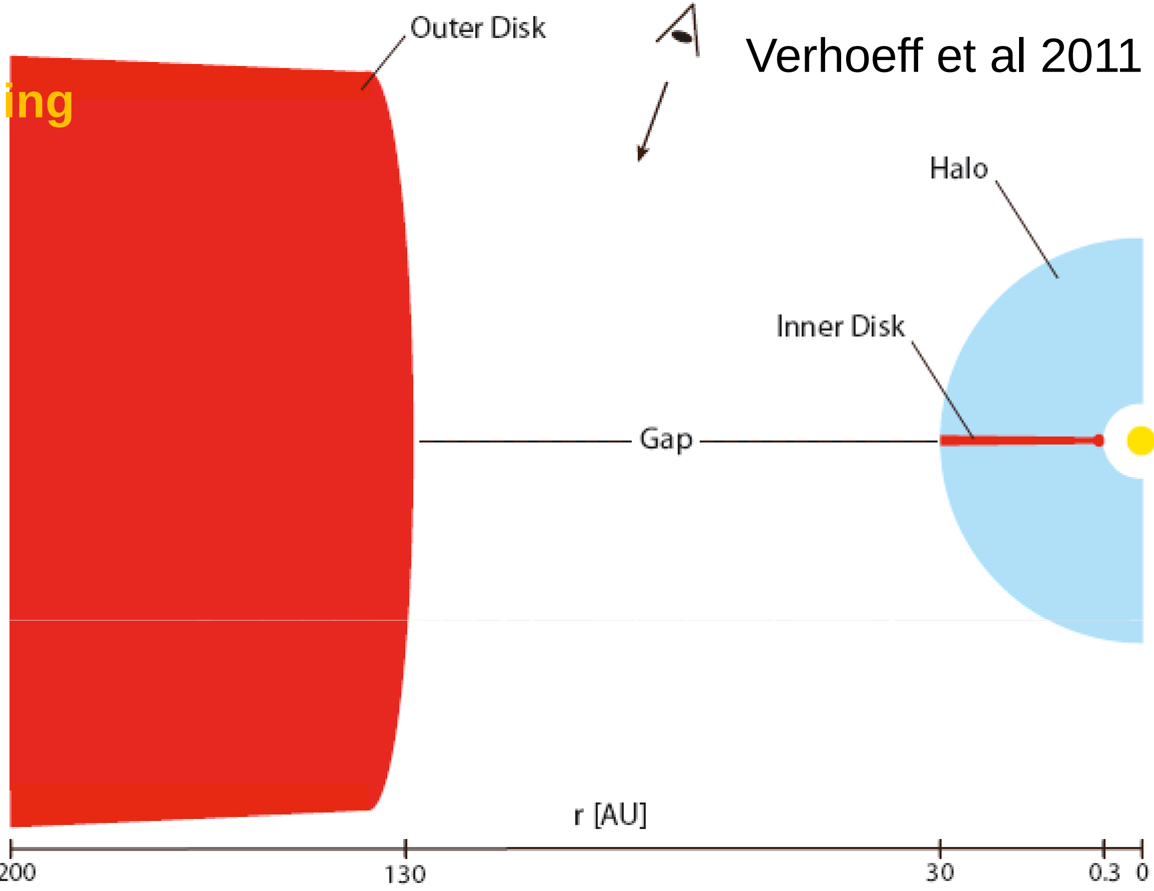
- IR imaging at 1.65 μm by Fukagawa et al 2006
- **Thermal IR imaging**

→ Spiral features & cavity

- mm/submm dust disk maps
- Large CO disk

- Far-IR & IR: warm molecules

→ Very inner disk



Verhoeff et al 2011

Fig. 17. Pictographic display of our model of the disk around HD 142527.

Fig. 4. Central component-subtracted VISIR 18.72 μm image of HD 142527. The color bar shows the surface brightness with a cut-off at 3.1 Jy/arcsec^2. The overplotted contours from the 24.5 μm Subaru image are at 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 5.3 Jy/arcsec^2.

ALMA Casassus et al 2012

First glance inside a planet forming cavity in a large gas-rich disk ?

The star HD142527
D=140 pc (D=198 pc)
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr

The gas and dust disk
Radius ~ 980 AU

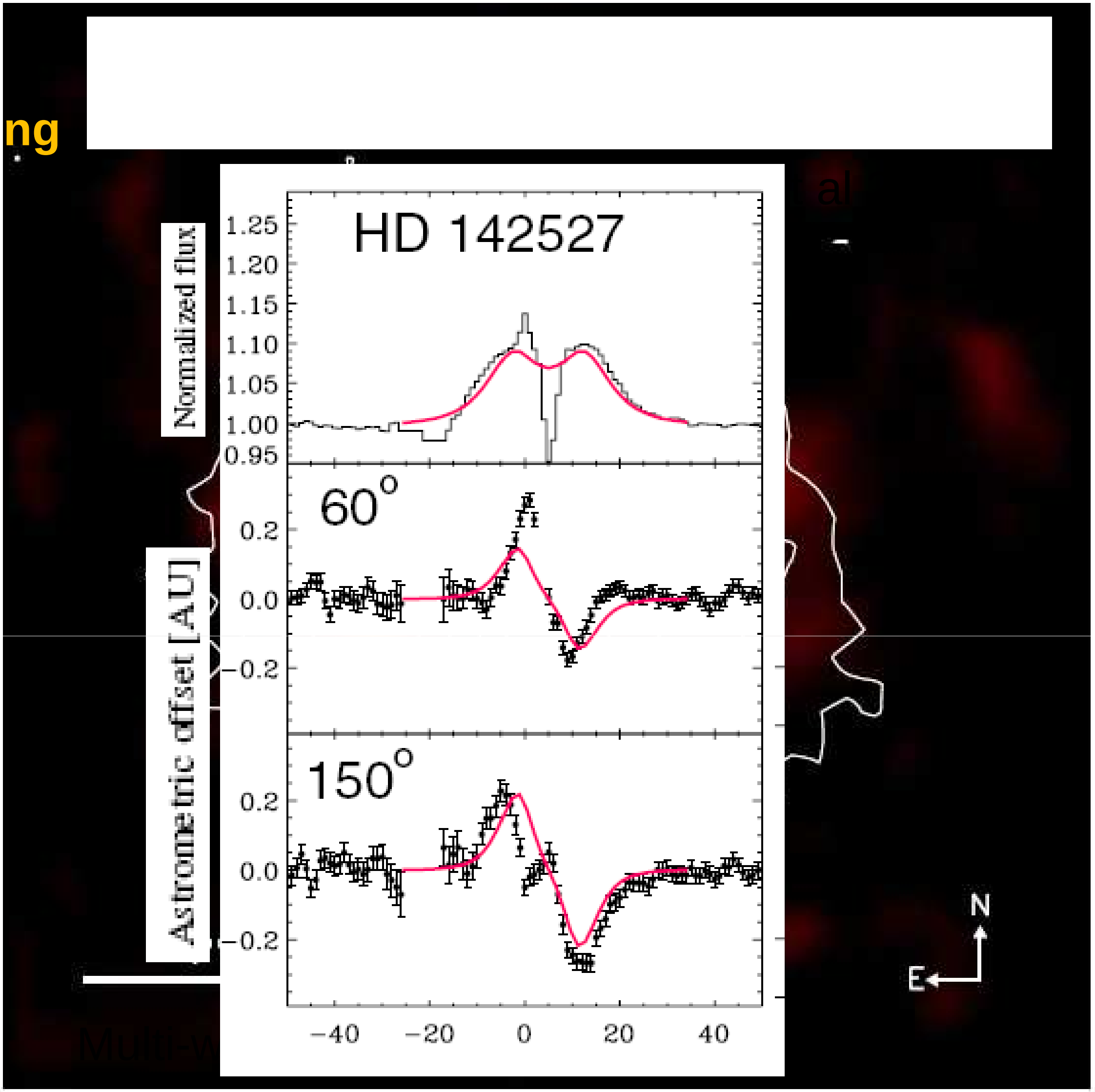
- IR imaging at 1.65 μm by Fukagawa et al 2006

→ Spiral features & cavity

- mm/submm dust disk maps
- Large CO disk

- Far-IR & IR: warm molecules

→ Very inner disk



From Pontoppidan et al 2011, CRIRES spectro-astrometry
Line shape is double peaked as in Keplerian rotation
Emission arises as clase as R ~ 0.2 AU

ALMA Casassus et al 2012

First glance inside a planet forming cavity in a large gas-rich disk ?

The star HD142527
D=140 pc (D=198 pc)
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr

The gas and dust disk
Radius ~ 980 AU

- •IR imaging at 1.65 µm by Fukagawa et al 2006
- •Thermal IR imaging
- → Spiral features & cavity

- •mm/submm dust disk maps
- •Large CO disk
- →Inner hole and gas

- •Herschel: warm molecules
- → Very inner disk the star

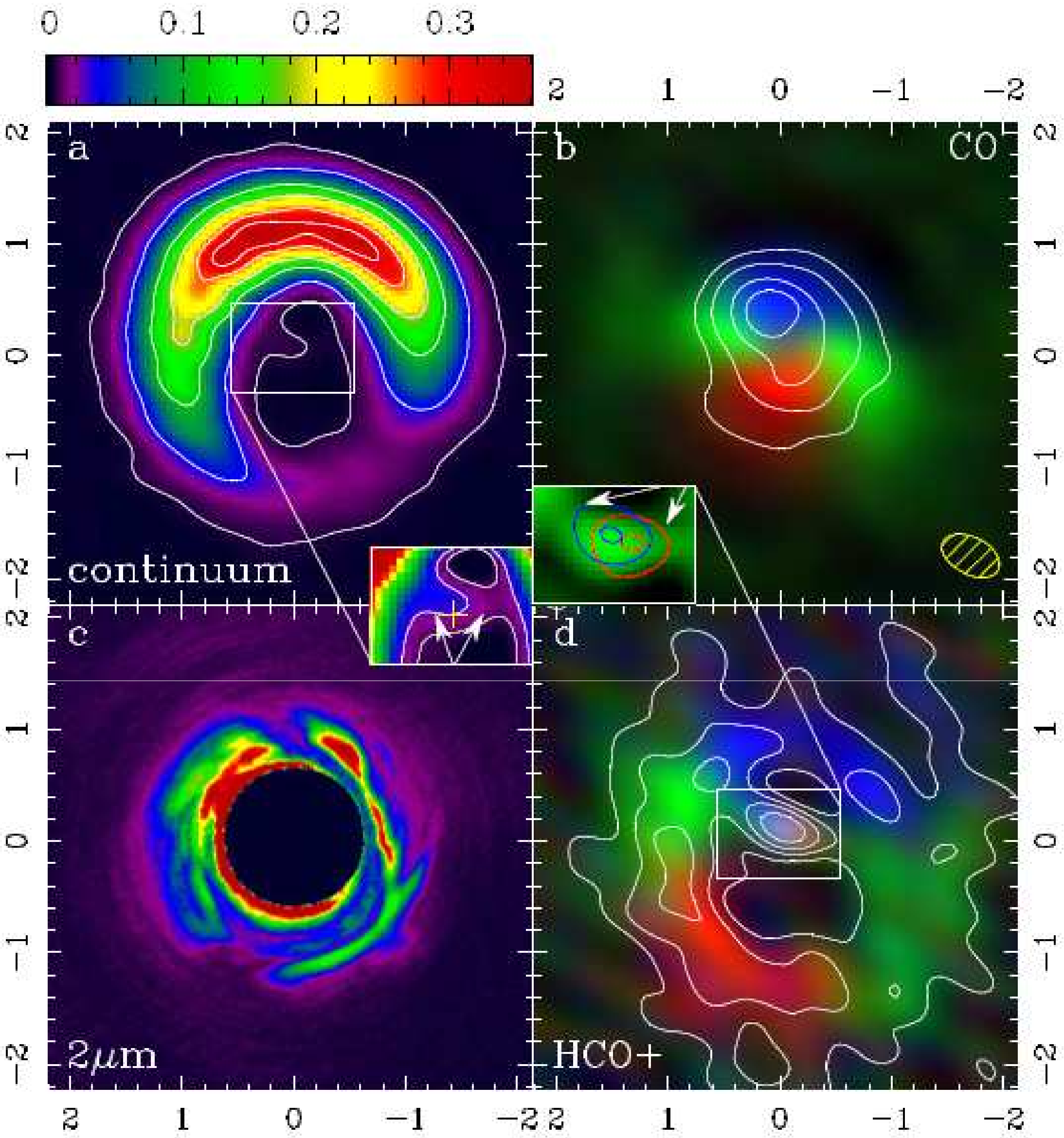


Figure 1 **ALMA observations of HD 142527, with a horseshoe dust continuum surrounding a cavity that still contains gas.** We see diffuse CO gas in Keplerian rotation (coded in doppler-shifted colours), and filamentary emission in HCO⁺, with non-Keplerian flows near the star (comparison models illustrative of Keplerian rotation are shown in SI). The near-IR emission abuts onto the inner rim of the horseshoe-

ALMA Casassus et al 2012

First glance inside a planet formi cavity in a large gas-rich disk ?

The star HD142527
D=140 pc
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr

The gas and dust disk
Radius ~ 980 AU

- IR imaging at 1.65 µm by Fukagawa et al 2006
- **Thermal IR imaging**

→ Spiral features & cavity

- mm/submm dust disk maps
- Large CO disk

- Far-IR & IR: warm molecules

→ Very inner disk

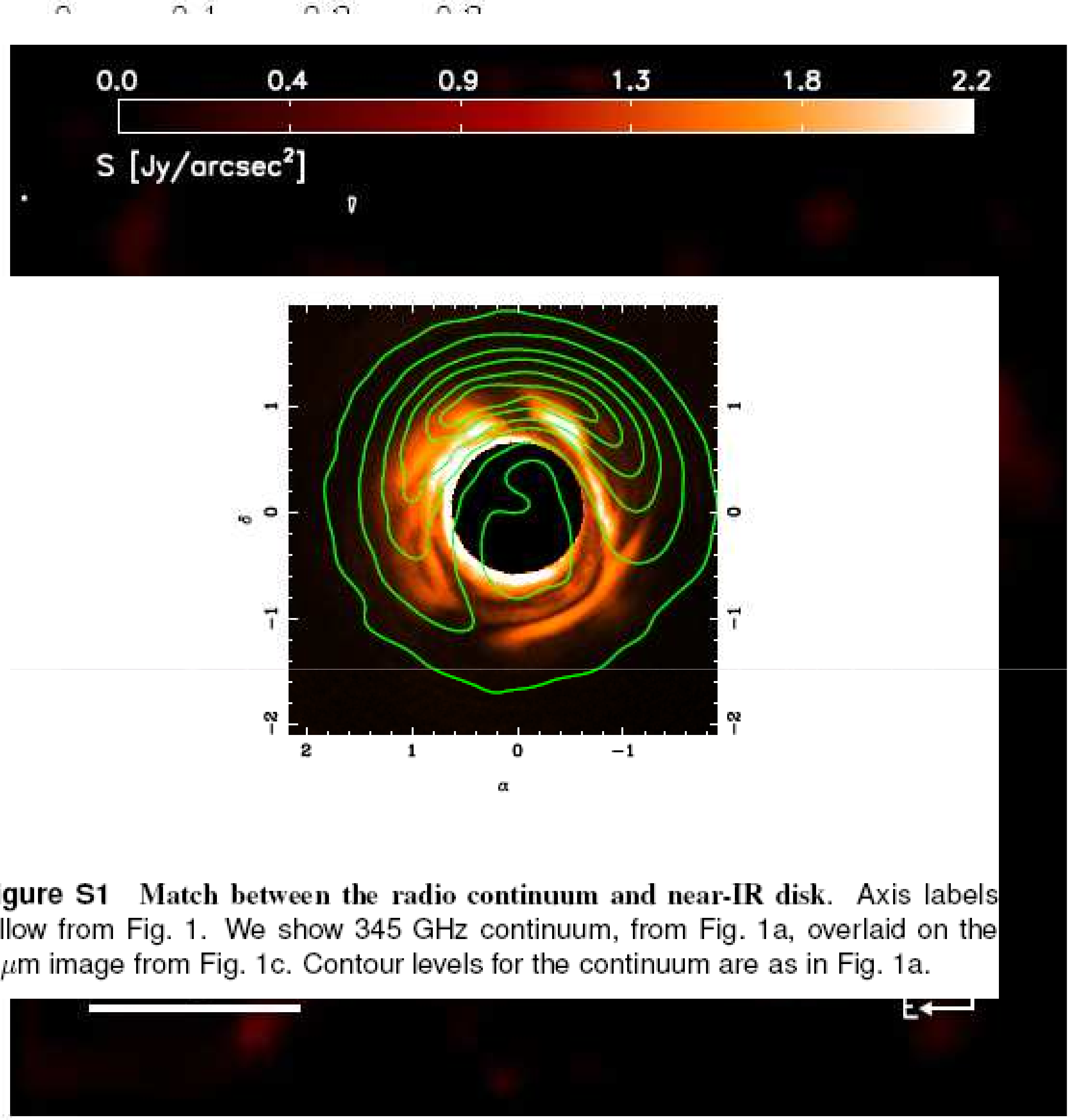


Figure S1 **Match between the radio continuum and near-IR disk.** Axis labels follow from Fig. 1. We show 345 GHz continuum, from Fig. 1a, overlaid on the 2 μm image from Fig. 1c. Contour levels for the continuum are as in Fig. 1a.

Fig. 4. Central component-subtracted VISIR 18.72 μm image HD 142527. The color bar shows the surface brightness with a cut-off 3.1 Jy/arcsec^2. The overplotted contours from the 24.5 μm Subaru i age are at 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, and 5.3 Jy/arcsec^2.

are shown in SI). The near-IR emission abuts onto the inner rim of the horseshoe-

AB Aurigae

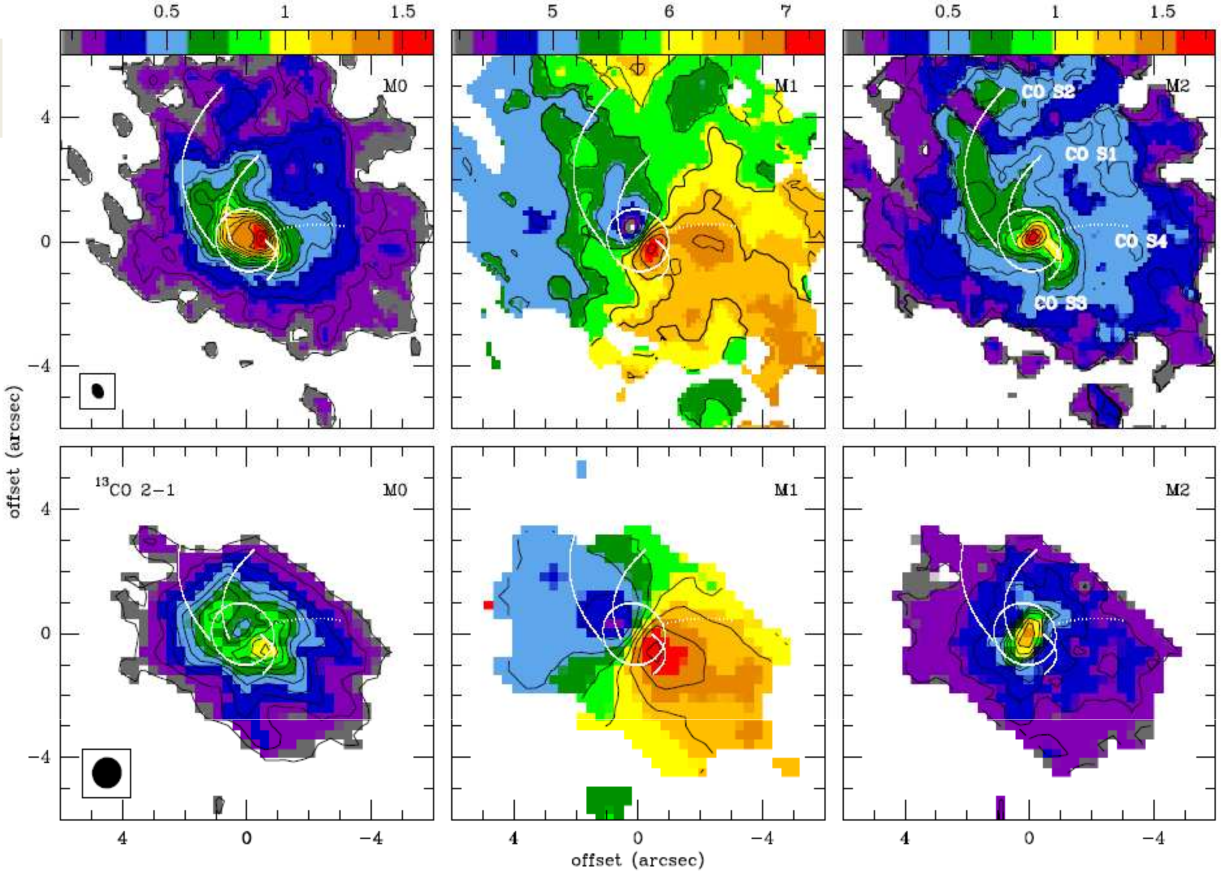
- Pietu et al 2005: PdBI:
- ^{13}CO & ^{12}CO + dust
- Ring + envelope
- Inner hole: R_{in} = 70 -100 AU
- Low inclination ~ 25-35 °
- Rotation is not Keplerian!
- $V(r) = V_o (r/r_o)^{-0.41+/-0.01}$

➔ Not self-gravitating ...
➔ Youth ?

- Tang et al 2012: SMA+PdBI+30m
- ^{13} CO & ^{12}CO + dust
- Still not Keplerian ...
- Spirals in the envelope ....
- Counter rotation /disk rotation

→ Accretion above/below mid-plane:
→ Projection effects

How to reconcile everything ?



Tang et al 2012: SMA+PdBI mosaic+30m

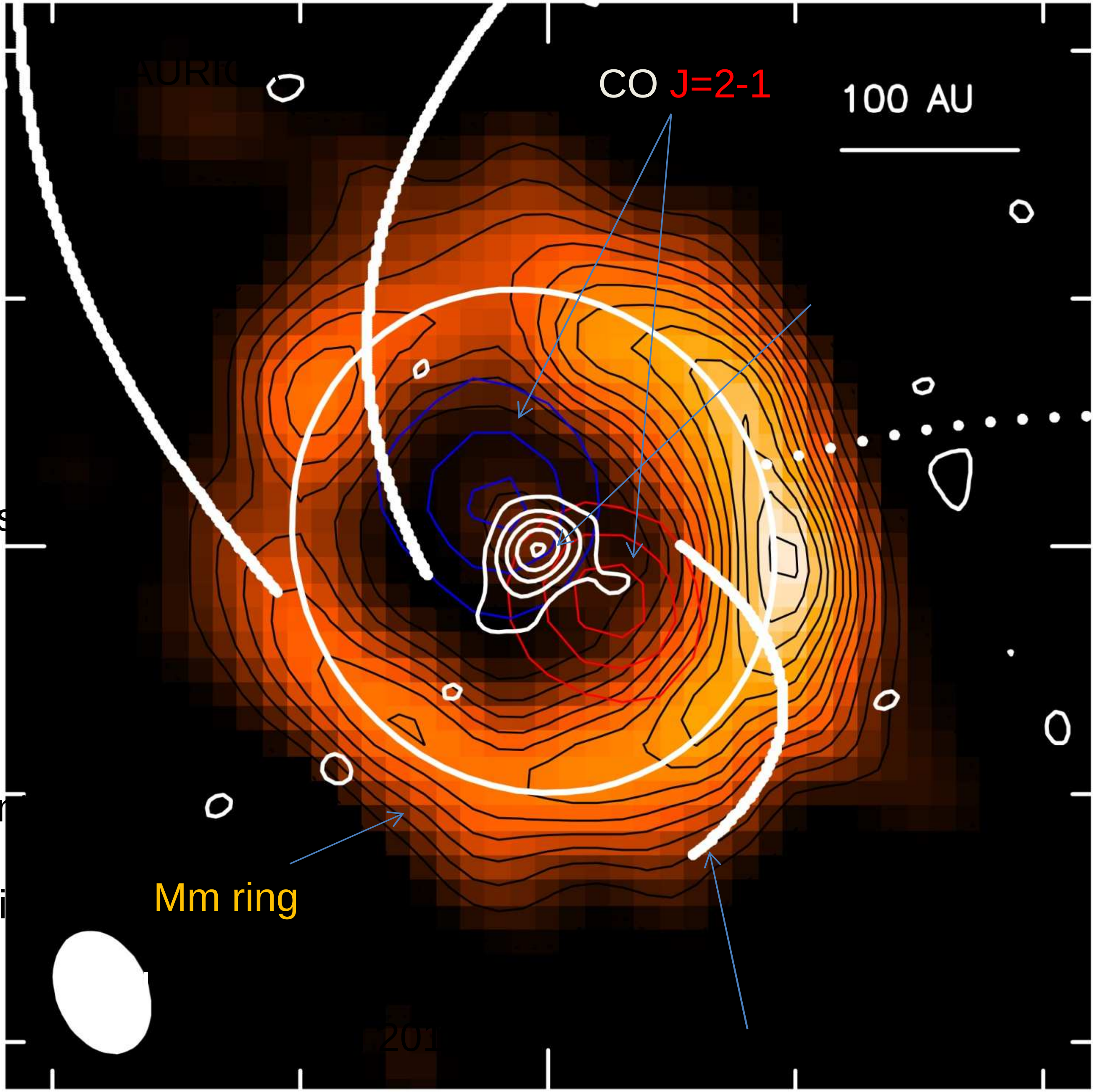
→ ALMA Cycle I B7 & B9

Wide dust gap
Warped disk
Asymmetric dust ring

→ at least, one undetected Companion of 0.03 Msun at a radius of 45 AU.

→BUT cannot explain the apparent counter-rotation of the gas in the outer spirals

→ A projection effect ?
→accreting gas infalling preferentially well above/or below the main disc plane from the surrounding remnan envelope along quasi parabolic/spiral like trajectori

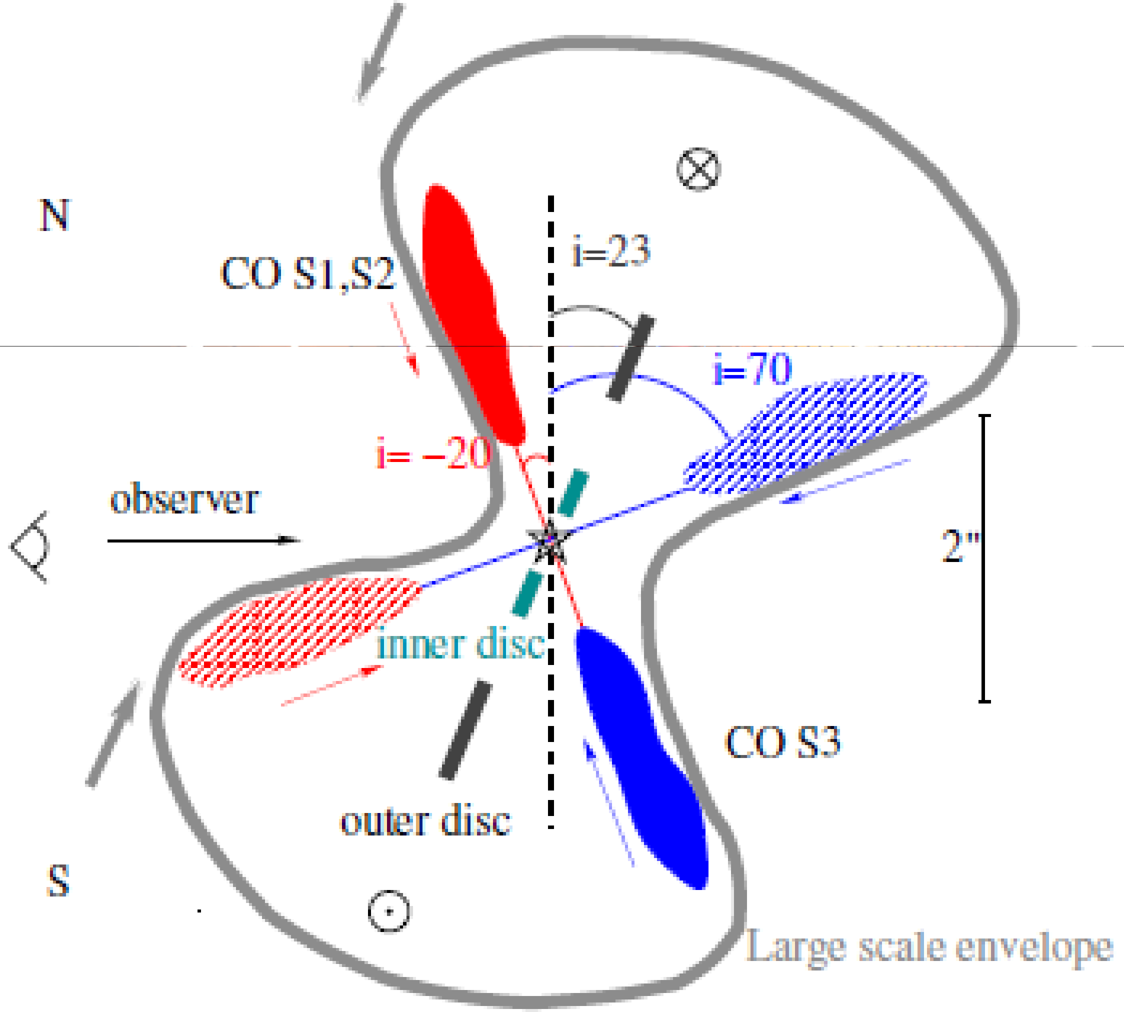


Wide dust gap
 Warped disk
Asymmetric dust ring

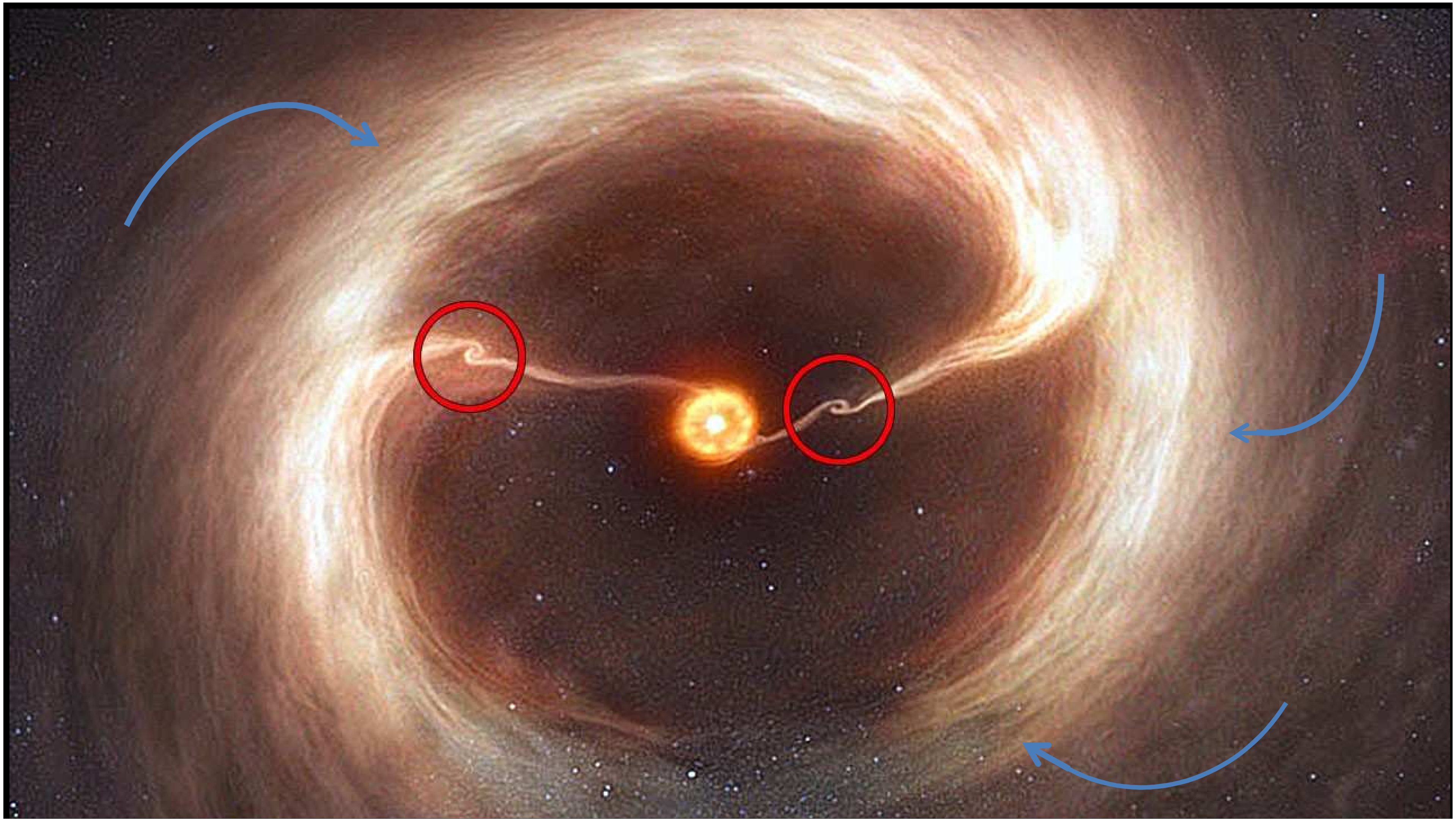
→ at least, one undetec
Companion of 0.03 Msu
at a radius of 45 AU.

→BUT cannot explain th
apparent counter-rotatio
of the gas in the outer s

→ A projection effect ?
→accreting gas infalling
preferentially well above
below the main disc pla
from the surrounding re
envelope along quasi
parabolic/spiral like traje



An artist view (or astronomer dream) of the HD 142527 system …
Likely also valid for AB Aur which should be still accreting
above/below the disk mid-plane…



Inner Disks & Cavities
What the observation tells us …

Geometry of inner gas and dust disks ?
→Inner ~ R <= 20 AU (snowline ~ 1-3 AU for Ttauri star…)

(T = 0)

10^4 yr ~ Class 0: large (1000 AU or more) flattened envelope
→ WAIT for ALMA results

10^5 yr ~ Class I: disk shape , what about rotation ?
→Some holes in binary systems … CB26 ?

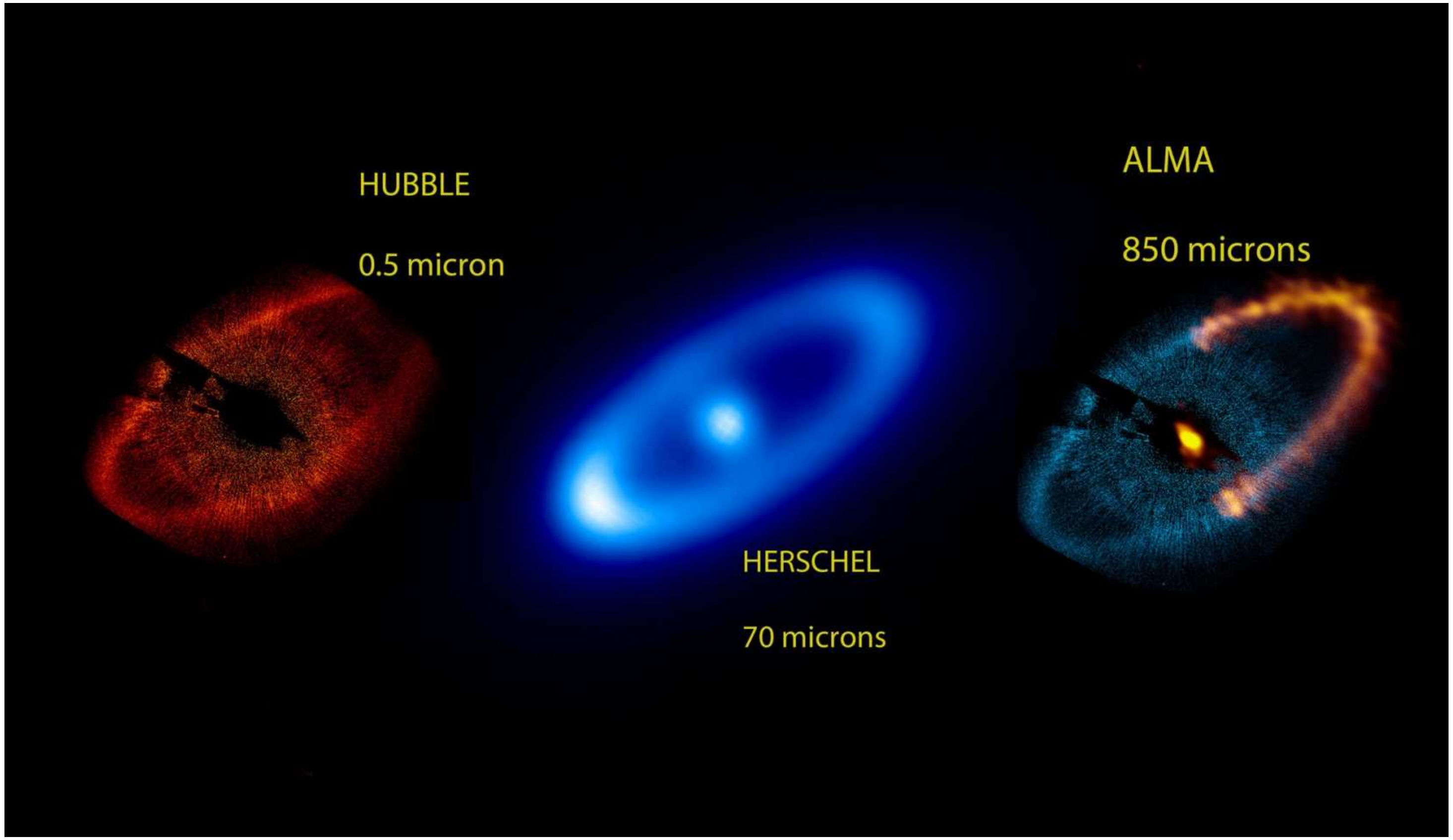
10^6 yr ~ Class II: rotating (Keplerian) disk
- resolved structure
- some large disks R~ 500-800 AU (likely biaised)
→More and more inner cavities and spiral features …
→ Transition disks / planet formation (G/D ~ 100)

→WHAT ABOUT OLDER (gas-free) Disks ?

Imaging Gas-free Disks with ALMA Fomalhaut

Boley et al 2012 - half ring (mosacing needed)

These submm observations demonstrate that the parent body population is 13-19 AU wide with a sharp inner and outer boundary



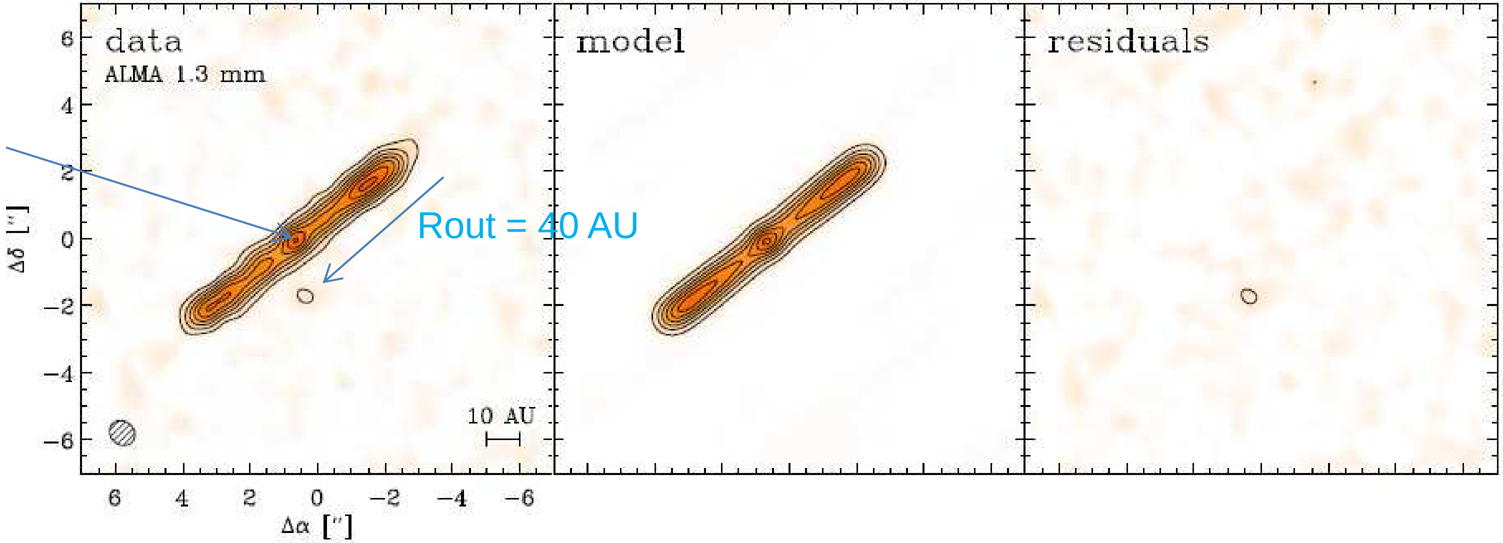
Imaging Gas-free Disks with ALMA

AU Mic 10Myr-old, M-type star

MacGregor et al 2012 - 1.3mm data, obtained at 0.″6 resolution (6AU)

The cold dust belt of mass ~1 Mmoon is resolved in the radial direction with a rising emission profile that peaks sharply at the location of the outer edge of the "birth ring" of planetesimals hypothesized to explain the midplane scattered light gradients.

A new centrally peaked component
-stellar corona or activity ?
(no variation as in radio flares)
- dust origin ?



Rout = 40 AU

Fig. 2.— *(left)* The observed 1.3 mm emission from AU Mic, *(center)* the best-fit model (see §3.3), and *(right)* the imaged residuals. Contours are drawn at 4 σ (120 μJy beam^{-1}) intervals.

ALMA ≡ Planet Forming Region

ALMA = high angular and spectral resolutions

1) Inner disks ~30 AU → up to ~ 2-3 AU (150 pc) resolution at 1.3mm
2) Departure from 2D geometry
3) Dynamics & Gravitation

CO lines → robust tracers (excitation cond.)
of kinetics and physics (density, temperature)

Gas Disk Structure: Large temperature/density changes within a few AU

1) Temperature & Density determination:

Vertical stratification, molecular layer location - warm versus colder ?
Absolute disk mass, mass(r,z) , best fit ?

2) **Turbulence:** map of DV(r,z) → ALMA will open a new domain (dynamics)

Dust Disk Structure:

1) Temperature & Density determination:

2) **Grains properties**

Grain size varies with (r,z) – settling, radial and vertical variations, evolution with time?
UV extinction & G/D variable in (r,z) -Interactions with gas disks ? surface chemistry needed

Molecular complexity ? How far can we go ? **(**depends on ALMA characteristics)