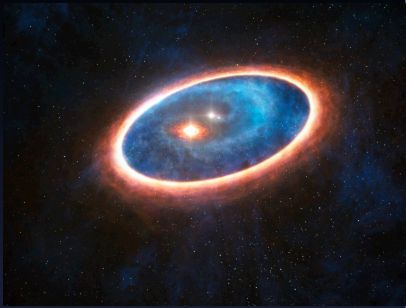
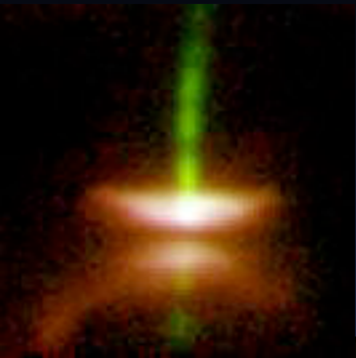


Observations of Disks (coming from ALMA and some others ...)

Anne Dutrey (LAB, France)

Many thanks to:
E.Chapillon,
E.Difolco,
F. Hersant,
S.Guilloteau,
V.Pietu,
Y-W Tang
V.Wakelam &
KIDA



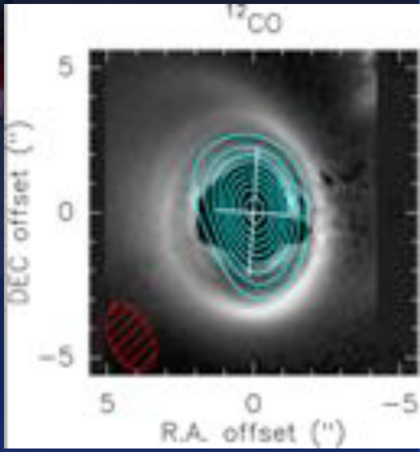
HH30 (© HST)

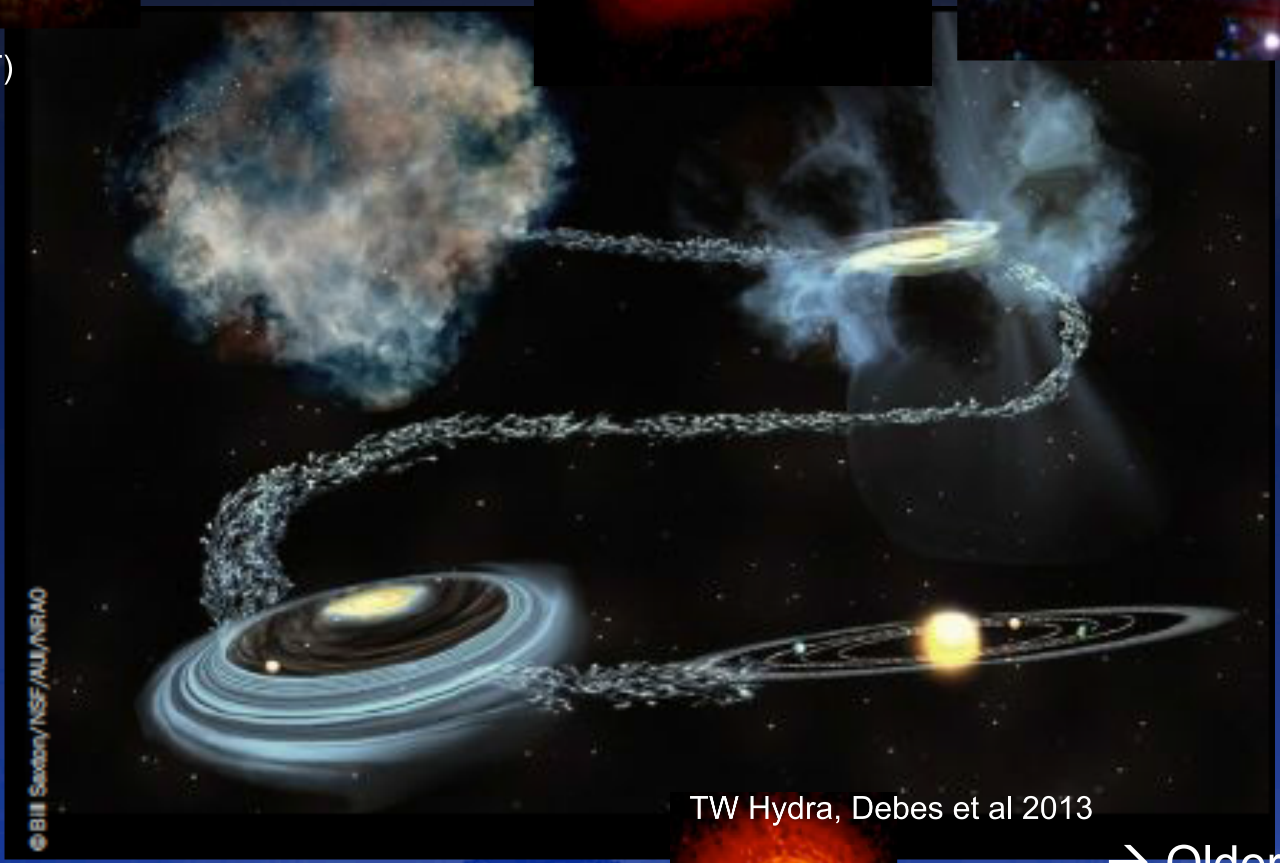
HL Tau (ALMA Partnership 2015)

L1527 (©Nature)

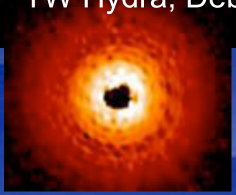
HD141569

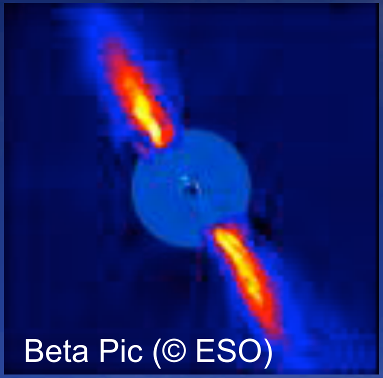
Perrot et al 2015





TW Hydra, Debes et al 2013



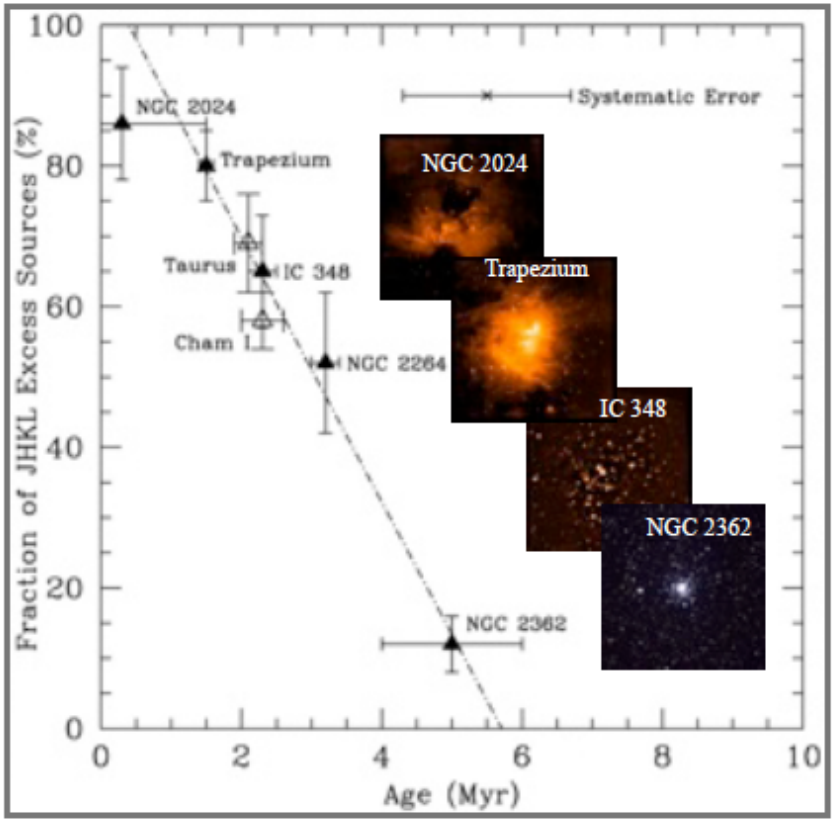


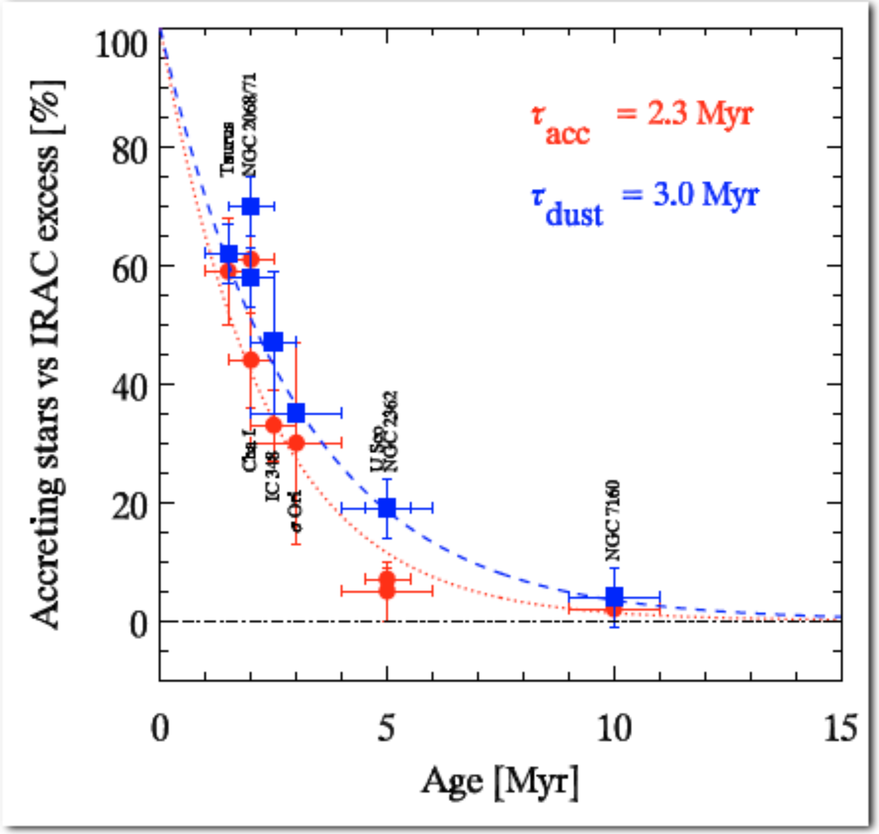
Beta Pic (© ESO)

→ Class II Disks (TTauri & Herbig Ae)
- Protoplanetary disks
- Transition disks: central hole with proto-planets ?

→ Older Disks
- Class III (TTauri)
- Hybrid disks (Herbig Ae)
- Debris disks (A stars)

Disk disappearance & timescale





Haisch et al. 2001, Fedele et al. 2010

- Mean lifetime ~ 3-5 Myr (about the same for gas and dust)
- Older disks ~20-30 Myr: are they protoplanetary or more evolded ?
- A Jupiter forms in about < 10Myr

Outline

Protoplanetary disks:

→ Observed Gas and Dust properties
- Keplerian rotation
- Temperature and Density
- Turbulence

→ **Transition Disks**

→ Dynamics: symetry departure, spirals ….

→All along illustration through famous examples
- HL Tau
- TW Hydra
- HD163296
- LkCa15

Hybrid and debris disks:

→ Observed gas and dust properties

→ More and more cases …
- Hybrid disks: HD141569 & HD21997
- Debris disks: Beta Pictoris ….

Perspectives and pending questions ...

Circumstellar Disks around low-mass PMS Stars

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

CLASS II ~ 10^6 years → TTauri & Herbig Ae stars or

precussors of solar type stars ~ 0.5 to 2-3 Msun

→**Massive disks** ~ 0.05 → 0.01 Msun (H_2+Dust) i.e. enough gas to form a "proto-Jupiter"(up to 5-10 % of stellar mass)

→ Gas rich with Gas/Dust ~ 100 (?)
→ 1% of dust

→ **Gas:** mostly H_2 which is not easy to detect (no dipole moment) except in the IR (quadrupole moment): warm gas at disk surface

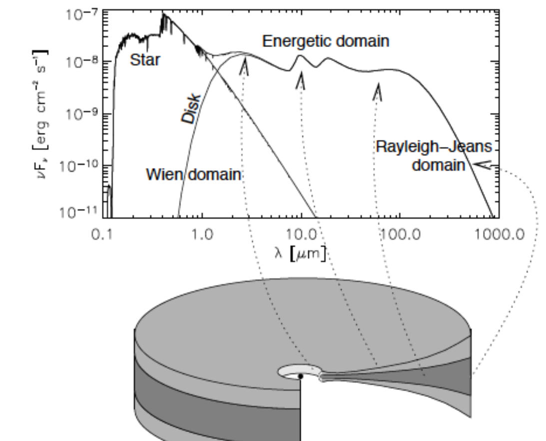
Gas properties rely on trace molecules: CO (more abundant after H_2 with H_2/CO ~10^4 -10^5), CS, CN, HCO^+ …

→ **Dust** emission is optically thick at λ= 1 µm (IR and optical reflection nebulae)

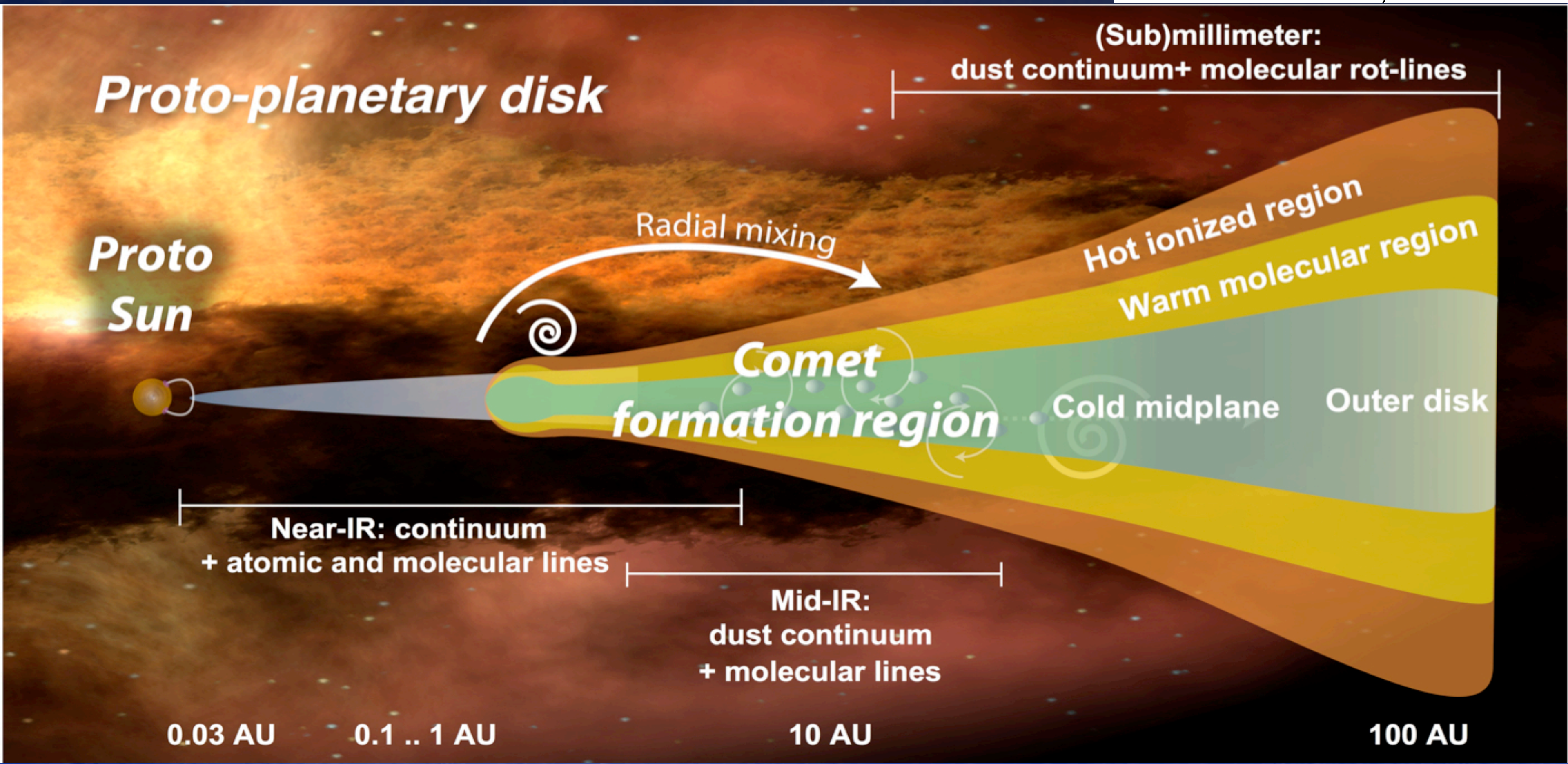
optically thin / moderate opacity at λ= 3mm (mass tracer)

First observations based on unresolved emission
→ Modelling of the Spectral Energy Distribution

Protoplanetary Disks basic properties



Dullemond et al 2007, PPV



What observations tell us …

- **Opt. to NIR – Dust**

- Scattered light emission: optically thick emission of the small dust at disk surface
- High angular resolution images revealing substrucures, departure from symetry and spirals
- Several molecular, ion lines in IR → warm gas at PDR surface
- Opt./NIR interferometry: very hot (thermal) very closed to the star (inner dust radius)
- Dust modelling of images and SED → **Tdust(r,z)**

→ **Due to the optical dust thickness in NIR, the interior of the disk (bulk of gas) cannot be studied**

- **Mm/submm Arrays - Gas and Dust resolved observations**
- → The disk is resolved →the brightness distribution is measured : Tb(r)

Optically thick dust or thermalized lines → Tb(r) = **Tk(r)** → eg ^{12}CO rotational lines

Optically thin dust or thermalized lines → Tb(r) ~ f(Σ_{mol}(r),Tk(r)) – IF Tk(r) known → **Σ_{mol}(r)**

Mass determination is complex: distribution ok, absolute value difficult even for ALMA

$\Sigma(H_2) = \Sigma_{mol}$ / X(mol) → X(mol) difficult to constrain → chemistry needed !

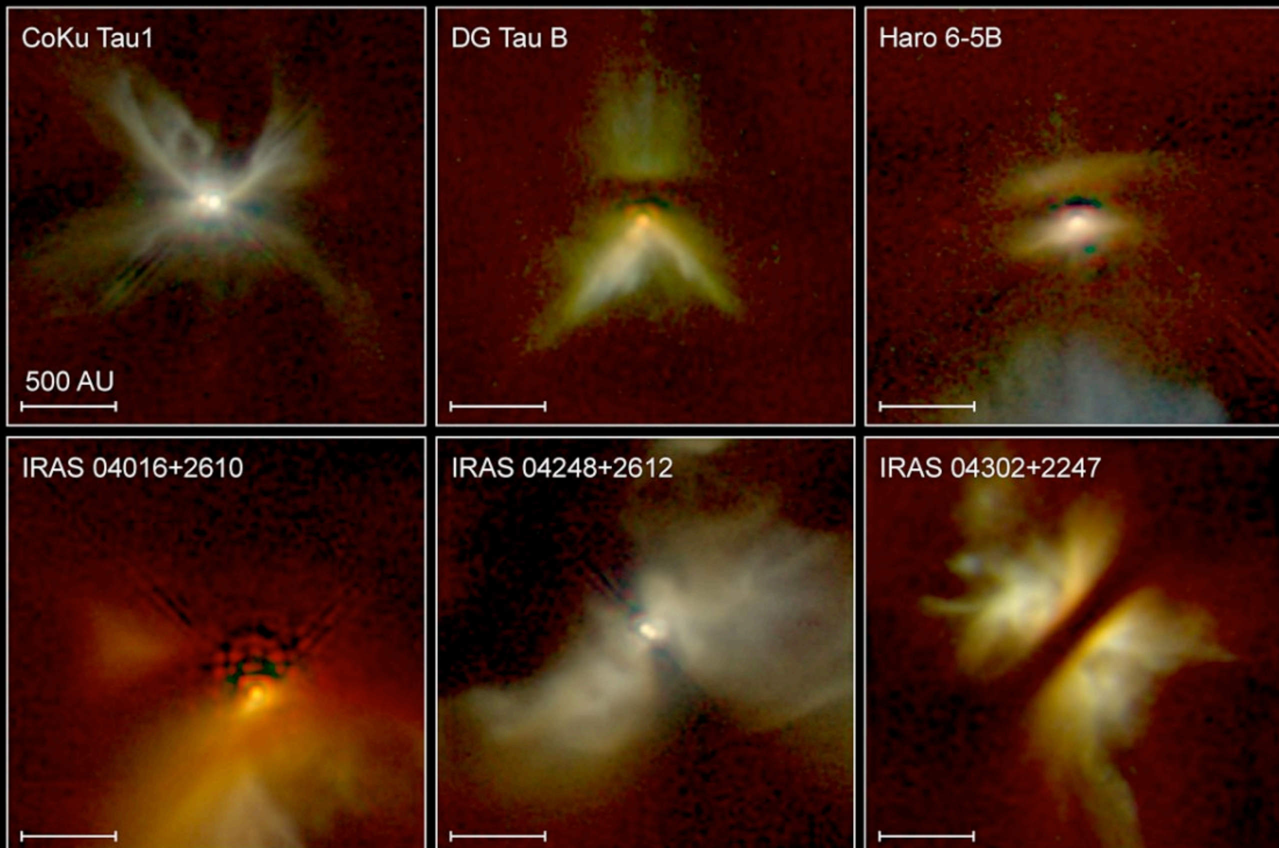
$\Sigma(H_2) = \Sigma_{dust}$ x G/D → **G/D ???**

H_2 mass is not well constrained even if distribution ~ known
→ **fundamental for planet formation**

Non-LTE → replace Tk by Tex … CO J=3-2 and higher lines are not thermalized everywhere

TTauri stars in Taurus

~1995 – Young edge-on disks around low-mass PMS stars (Class I & II) observed by HST - scattered light



Young Stellar Disks in Infrared

Hubble Space Telescope • NICMOS

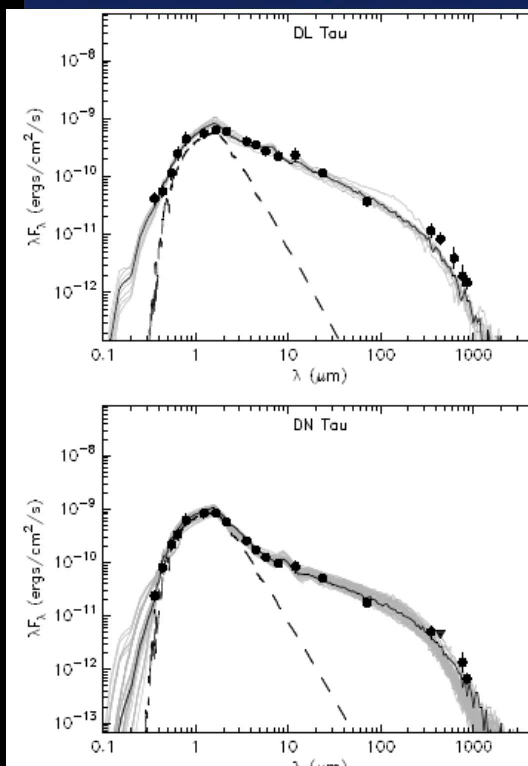
PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

Optical / NIR

Taurus-Auriga
A cold molecular cloud

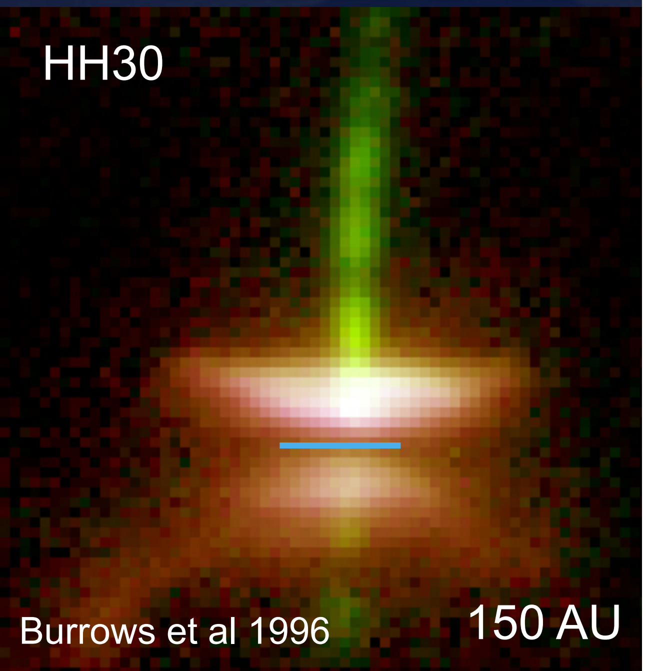
At 150 pc

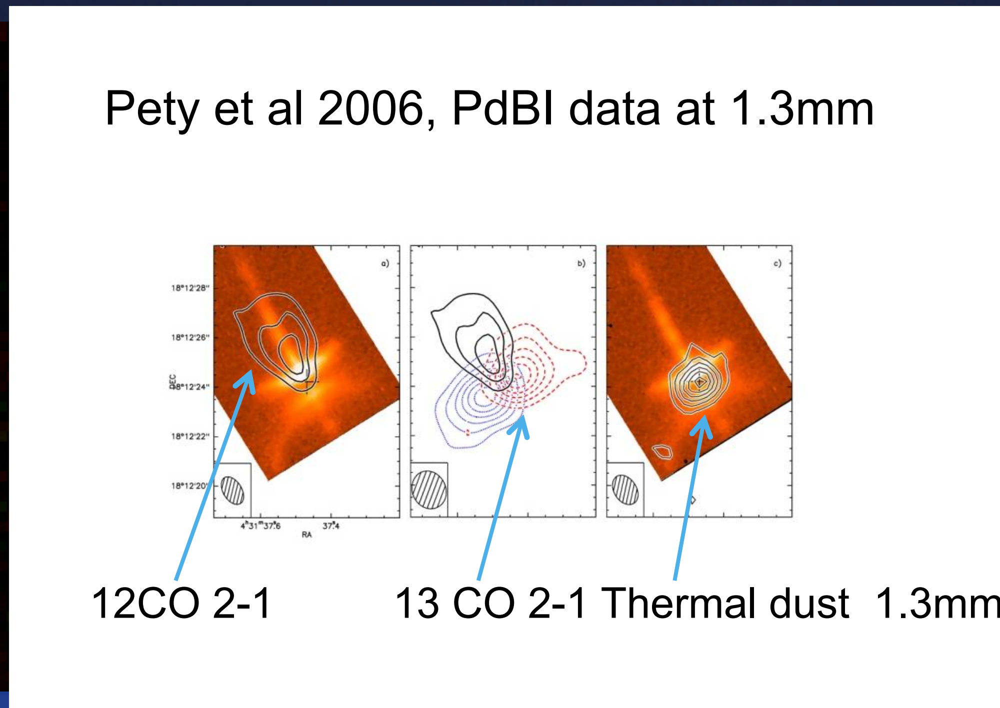
Robitaille et al 2006



The young disk around HH 30 (class II)

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): H2, H2O, CO – IR lines





Scattered light

Disk Physics

→ Temperature governed by the dust:

- Imposed by the central energy source (star + accretion shocks/columns).

Local energy generation due to accretion is negligible at distances > 10 AU.

- Nearly independent of the gas: dust will impose the gas kinetic temperature whenever the density is high enough (not true at the disk surface, PDR)

- Dust temperature depends on the opacity as a function of wavelength
  - Absorption in the UV and Visible domain
  - Emission in the mid-IR and mm domains
  - Grains of different size will have different temperatures…
- Dust properties are essential to understand the SED of disks

→ Gas dominates the dynamics

- small grains ($a < 1\,\mu m$) are dynamically coupled to the gas

→ Strong density and temperature gradient

eg at R ~ 100 AU: 10 K at 50 K in 60 AU – 10^8 at 10^5 cm^{-3}

Gas and Dust disk Structure

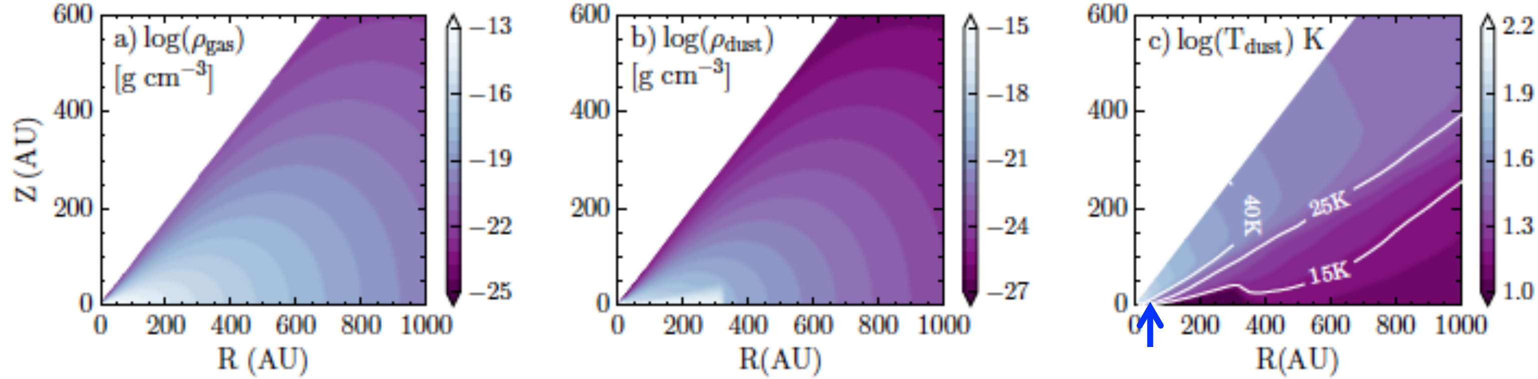
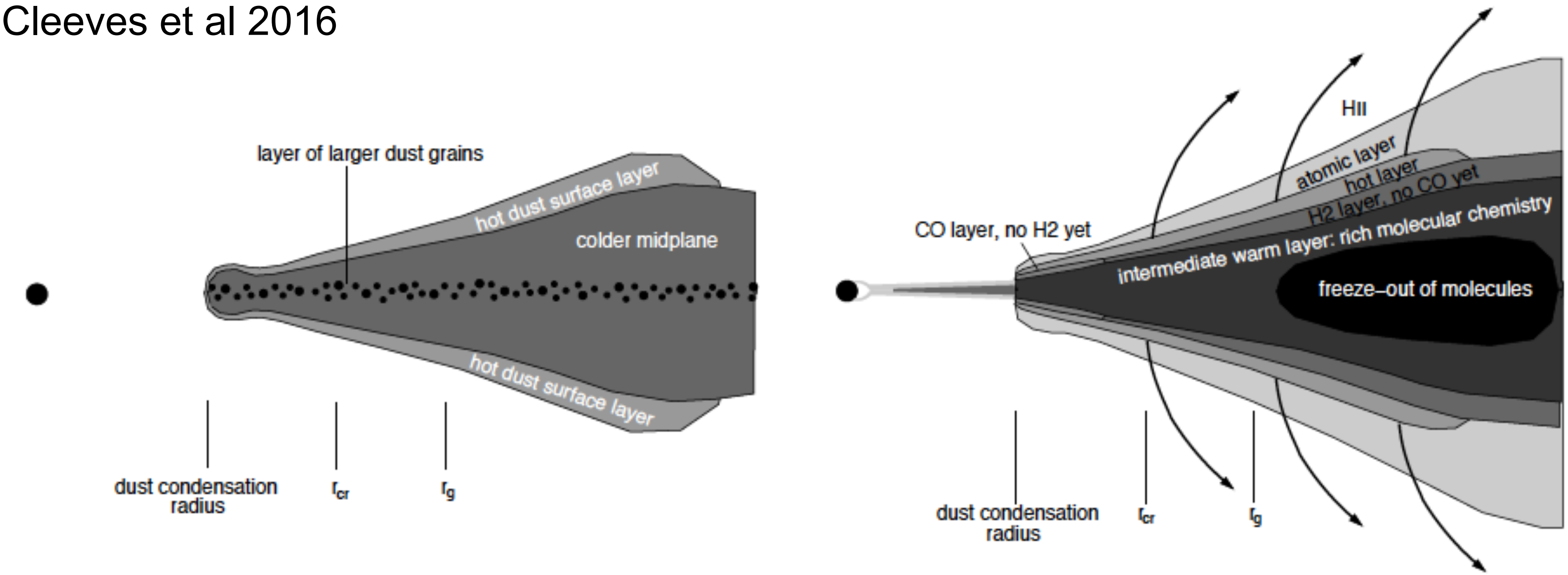


Figure 6. IM Lup model disk structure: a) gas density; b) total dust density from small and large grains; and c) dust temperature.

Cleeves et al 2016



Dullemond et al 2007, PPV

Analysis of Images and SED of a circumstellar Disk

How complex it can be ….

Cleeves et al 2016 – Study of the gas and dust disk surrounding the Ttauri star IM Lupi

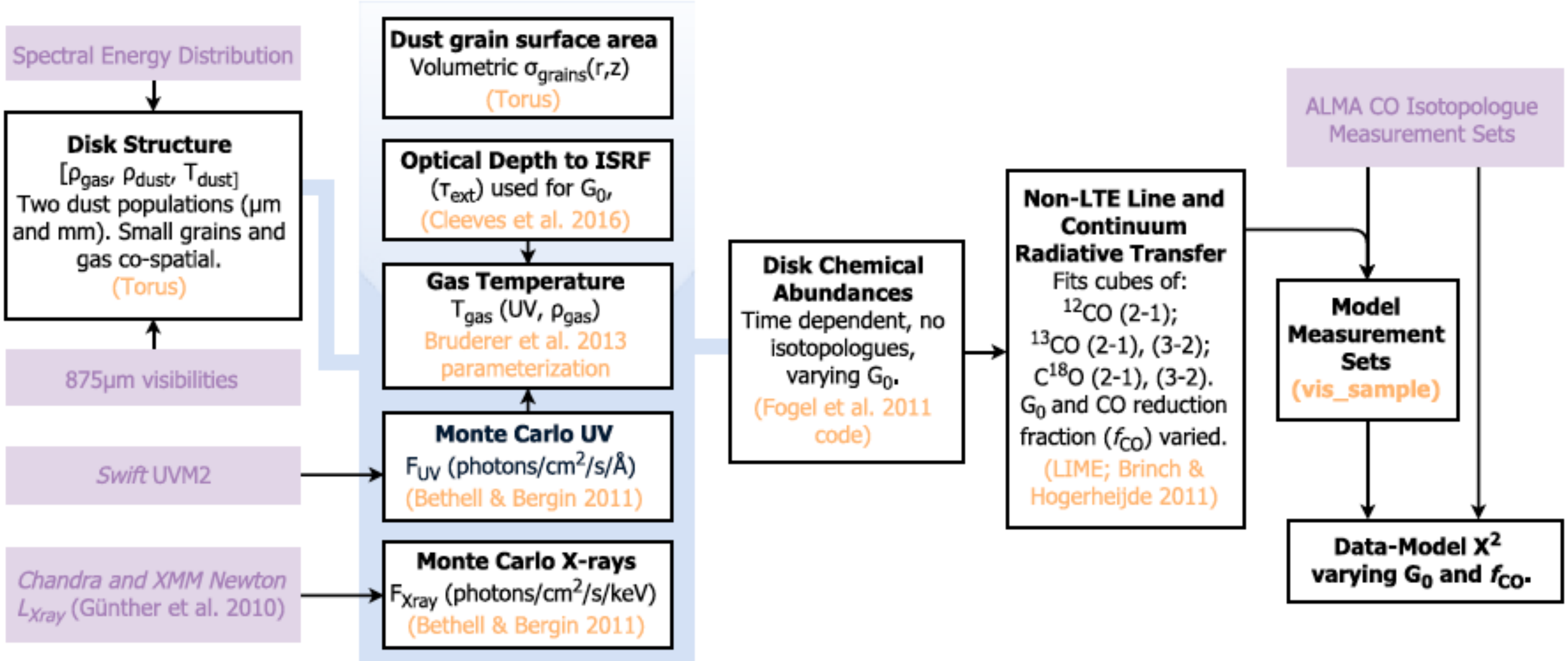
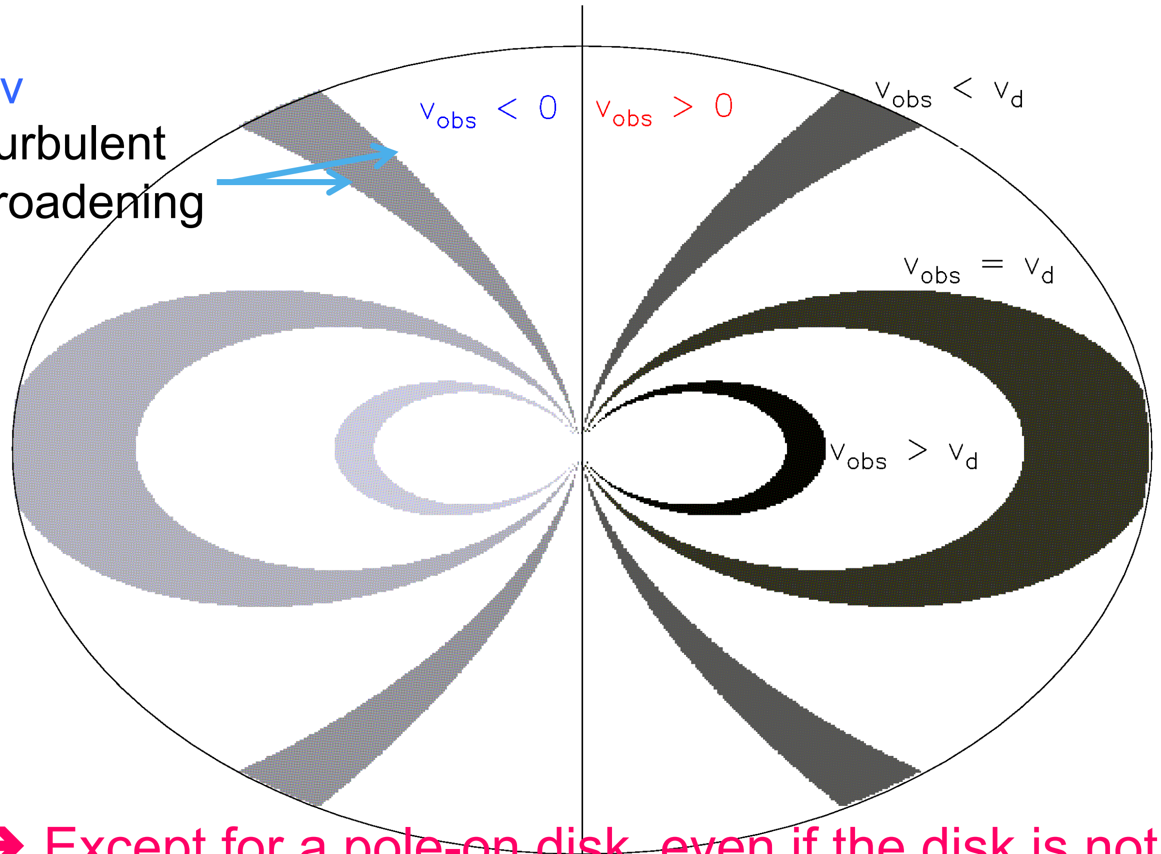


Figure 4. Schematic of our disk chemical modeling procedure. Observations are highlighted in purple while methods are shown in orange.

Global structure - How to handle the « hidden » degeneracies ???

Keplerian Rotation in Disk
Only a fraction of the disk emits at a given velocity

Dv
Turbulent broadening



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

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

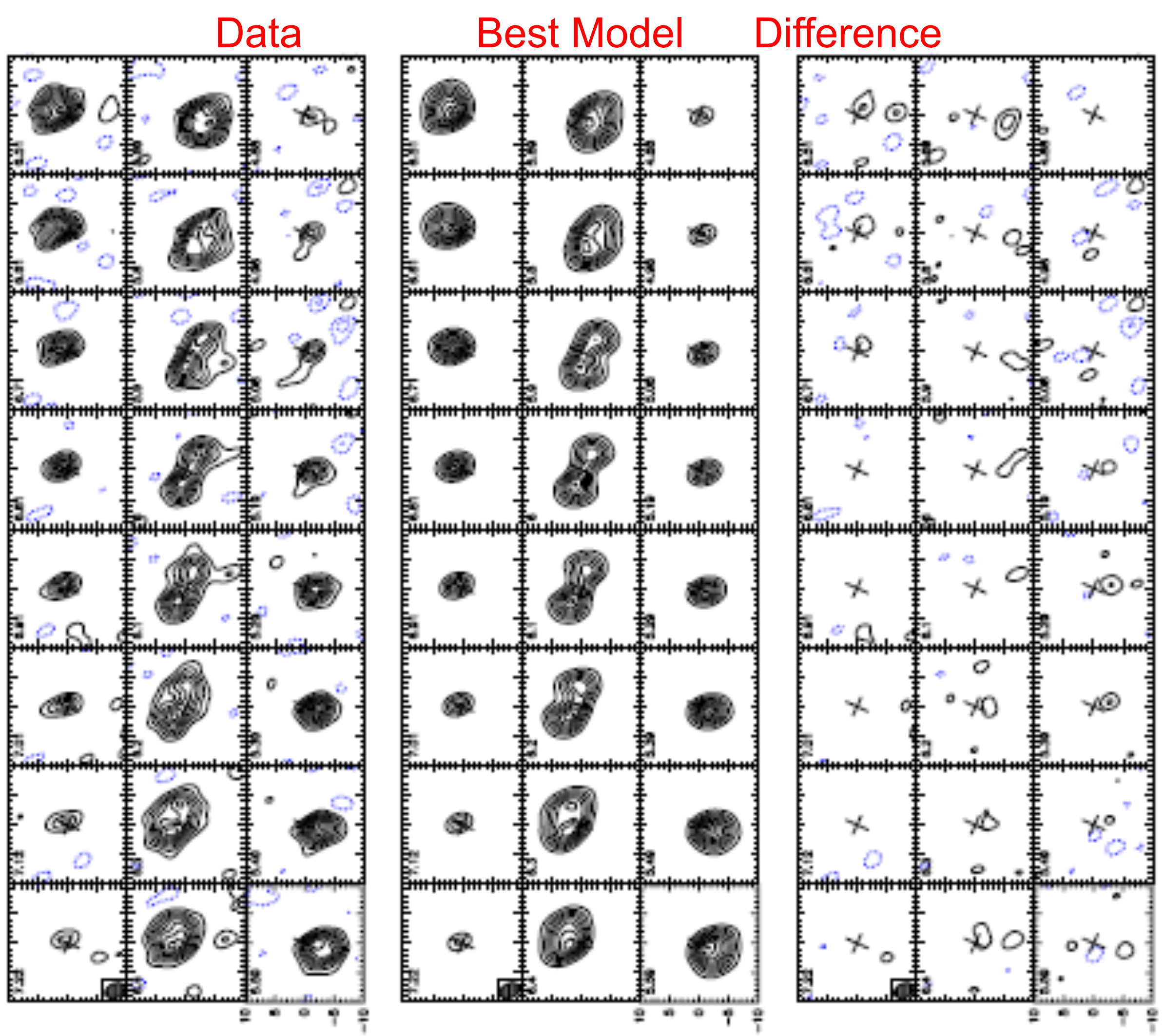
+ Fraction of disk covered at any velocity: $dV / (2V(R_{out}) \sin(i))$

→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 $W \; \alpha \; dV$

Early 1990: mm array 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)

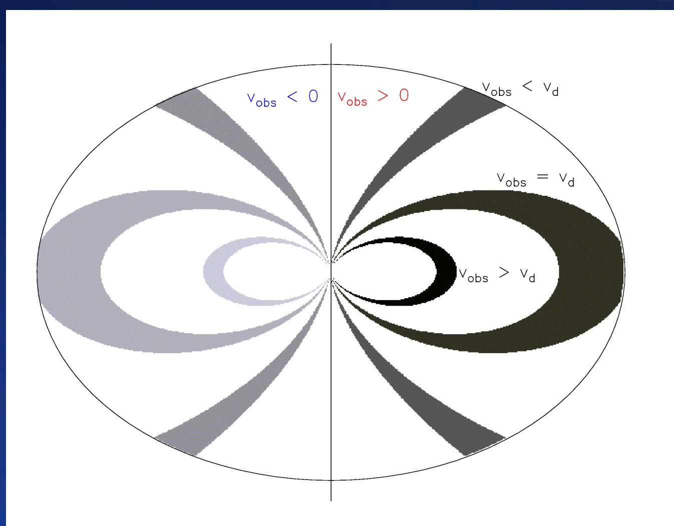
→ Comparison to a 3D disk model of the emitting CO distribution

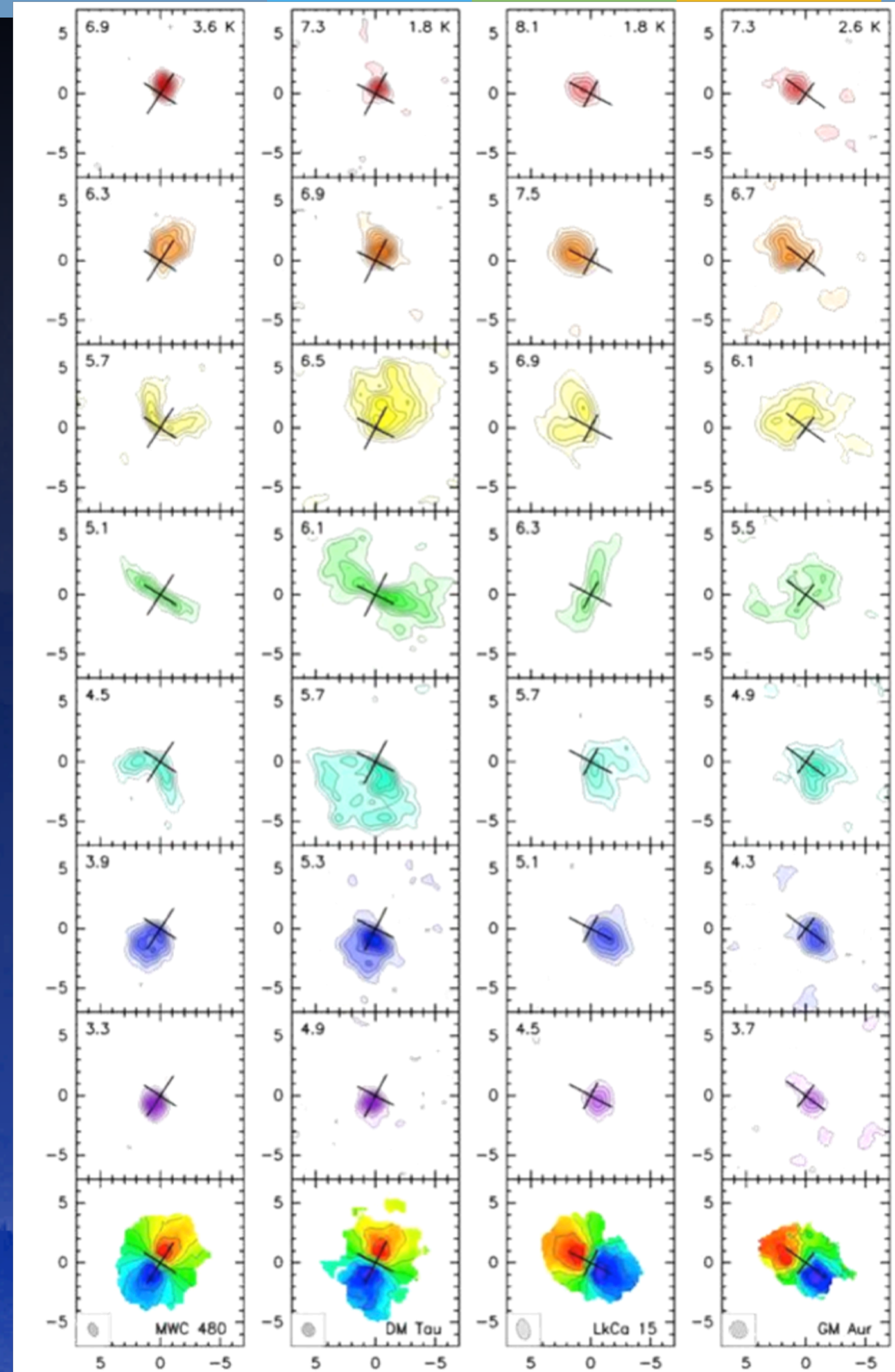
→ Determination of the gas structure (eg temperature, density, turbulence…) versus r and z.

ERRORBARS

Fourier plane → Image plane

CO 2-1 channel maps at high angular resolution of ~ 100 au From IRAM array





Simon et al 2000

ALMA verification time 1

- HD163296 Herbig Ae 2.3 Msun

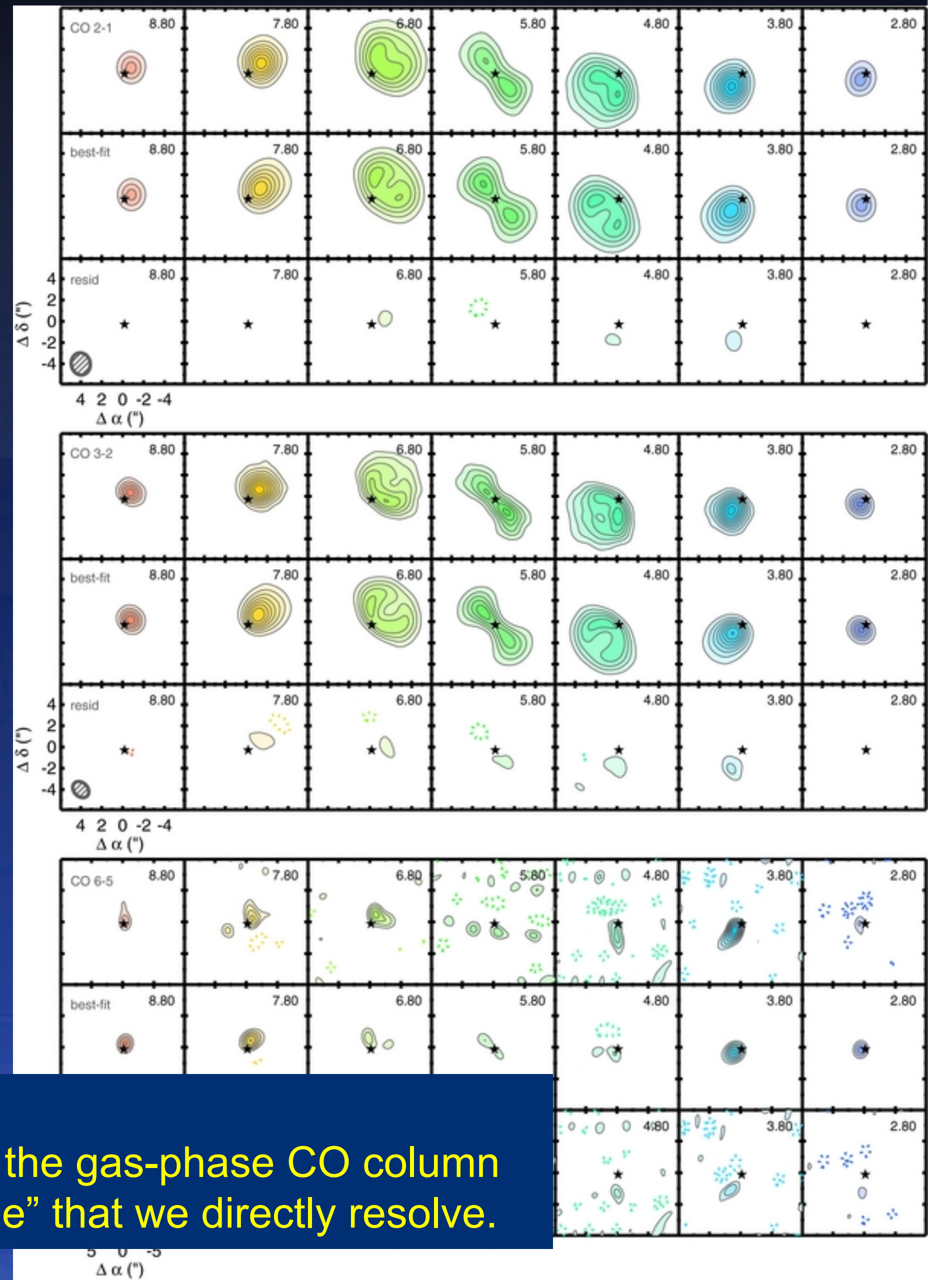
4Myr old, at 120 pc - Class II

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 …

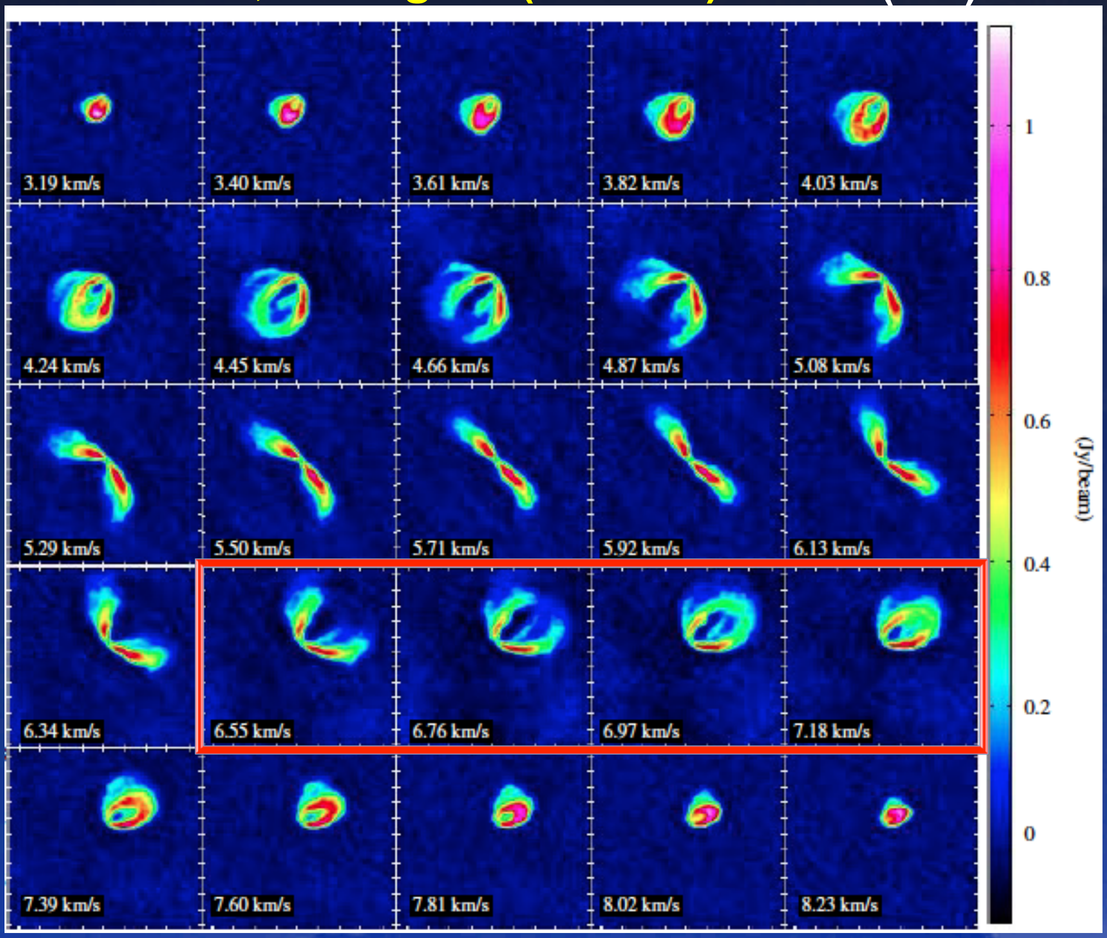
Several warm gas lines
OI, CII, OH, H_2O, H_2
CO 36-35, …
→ Inner disk surface or jet



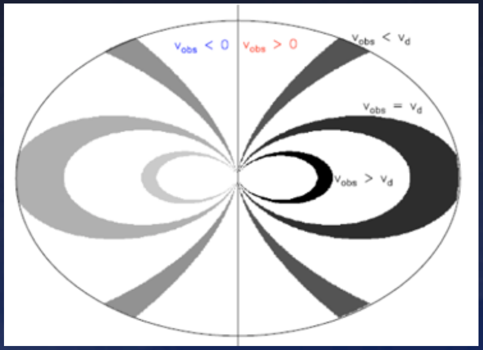
SMA observations - Qi et al 2011 ⟶
The freeze-out at 19 K leads to a significant drop in the gas-phase CO column density beyond a radius of ~155 AU, a "CO snow line" that we directly resolve.

CO molecular layer @ 1-3H
Temperature gradient

HD163296, Herbig Ae (warmer) ^{12}CO (3-2)

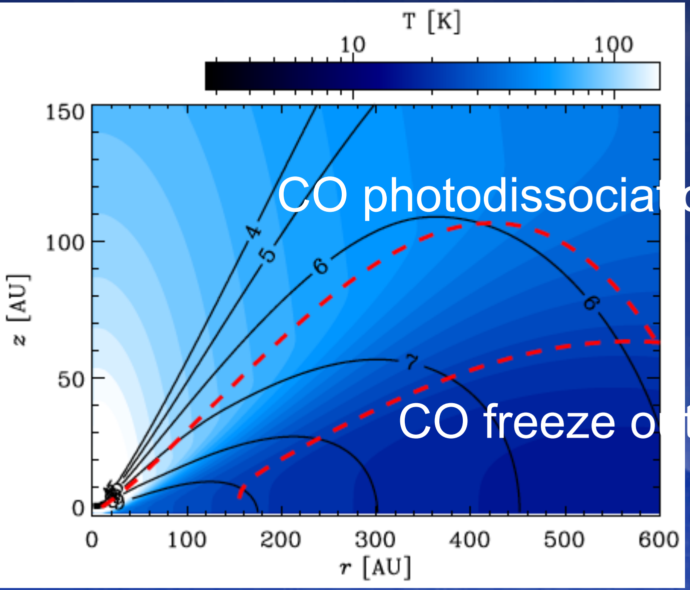


Velocity pattern for Keplerian rotation



iso-velocity lines

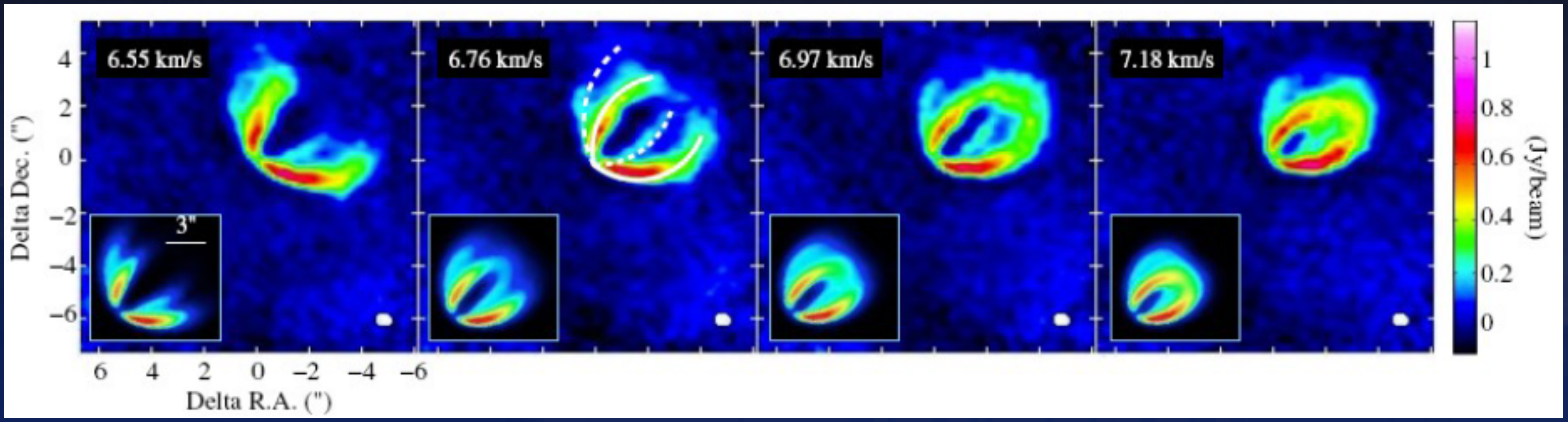
Optically thick & thermalised ^{12}CO => vertical Temperature gradient

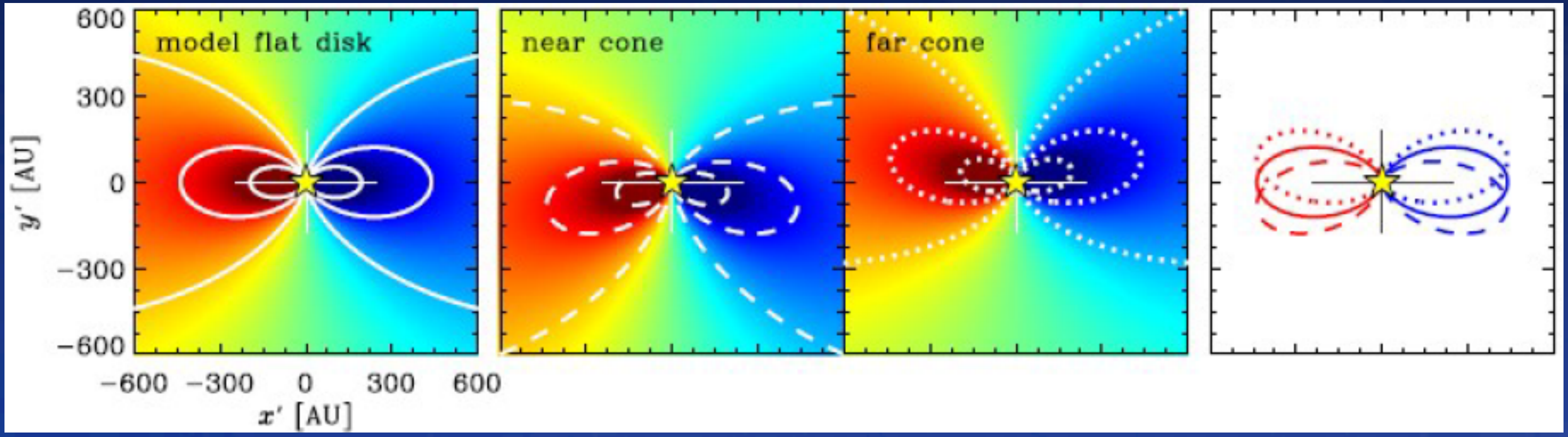


De Gregorio-Monsalvo2013, Rosenfeld2013

The location of the CO vertical layer

Disk inclination 42º





ALMA resolved two ^{12}CO layers *above and below* the mid-plane (+/- 15º)
(high spatial + <u>spectral</u> resolutions dv~0.2km/s)

Measuring the turbulence with ALMA

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 $\approx \sqrt{\alpha}.c_s$ - $\alpha.c_s$, with sound speed c_s such as $H(r) \approx c_s/\Omega$ (Cuzzi et al 2001)

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

• So far, CO and isotopologues (^{13}CO, $C^{18}O$)
→Subsonic broadening DV ~ 0.1 – 0.4 km/s < c_s

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

where μ = 44 is the CS molecular weight

Better to use an 'heavy' molecule : CS
(Guilloteau et al 2012, DM Tau, CS J=3-2)

dV = 0.12 km/s for best fit T = 8 +/- 1 K
This corresponds to Mach ~ 0.3 - 0.5

Can be done with ALMA (sensitivity and angular & spectral resolution needed)
→**If the thermal structure is properly constrained**, linked to line opacity, density structure … etc

Turbulence in TW Hya

CID collaboration: Teague et al 2016

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

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

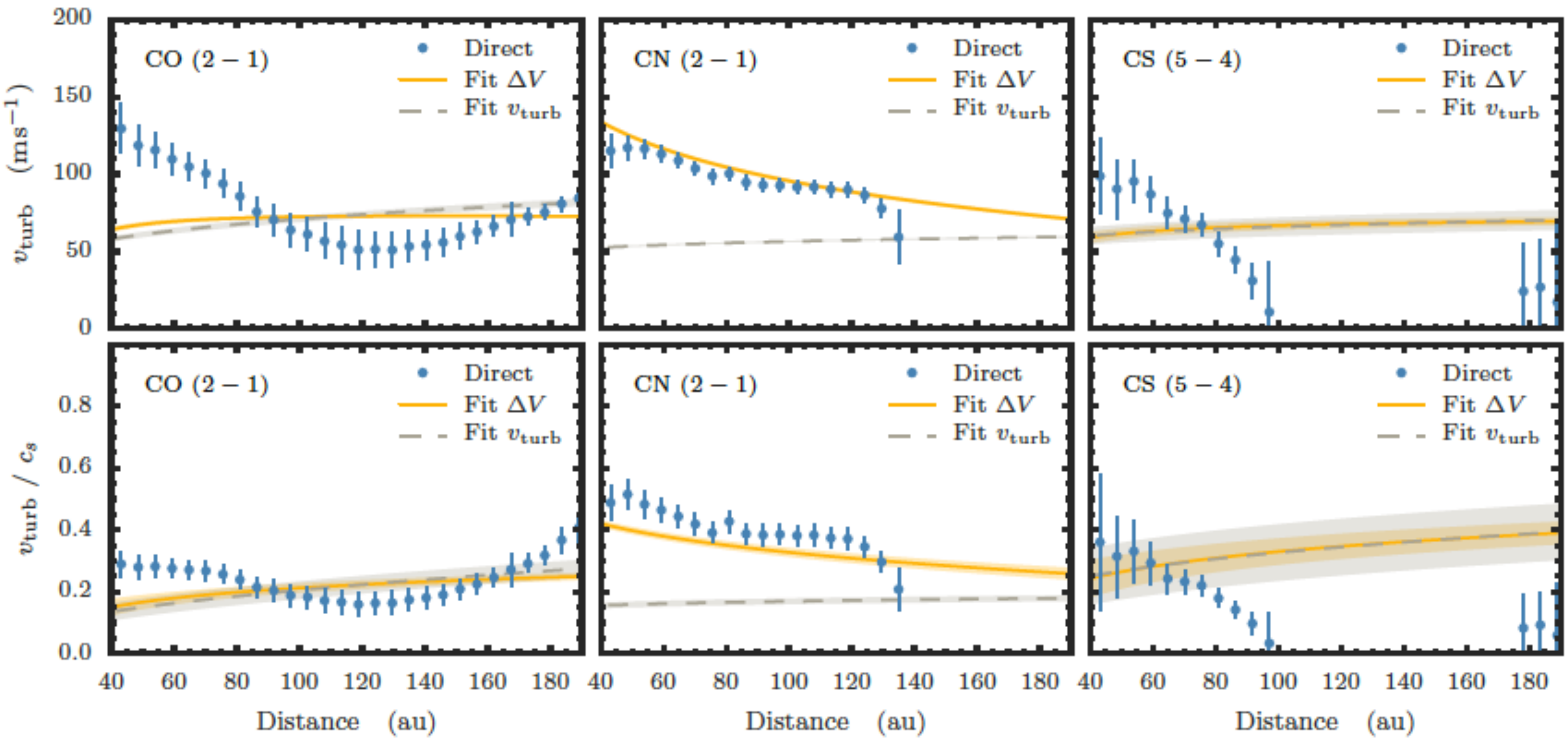


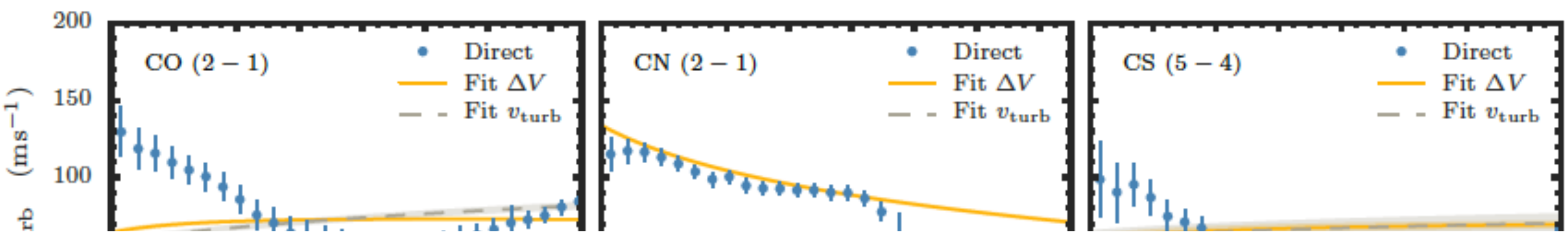
Fig. 4. Radial profiles of the turbulent width in m s^{-1}, top row, and as a function of local sound speed, bottom row. The blue dots show the results of the direct method, where the CO and CN lines were assumed to be fully thermalised, and CS to be co-spatial with CN in order to derive a $T_{\rm kin}$ value. Yellow solid lines show the results from the global fit where the total linewidth was fit for, while dashed gray dashed lines show the global fit where $v_{\rm turb}$ was fit for individually. The 1 σ uncertainties are shown as bars on the direct method and shaded regions on the lines.

Turbulence in TW Hya

CID collaboration: Teague et al 2016, accepted

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

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



→ **In TW Hya: turbulence < 0.2 Cs (sound speed)**

→ **A few other objects: turbulence < 0.3-0.4 Cs**

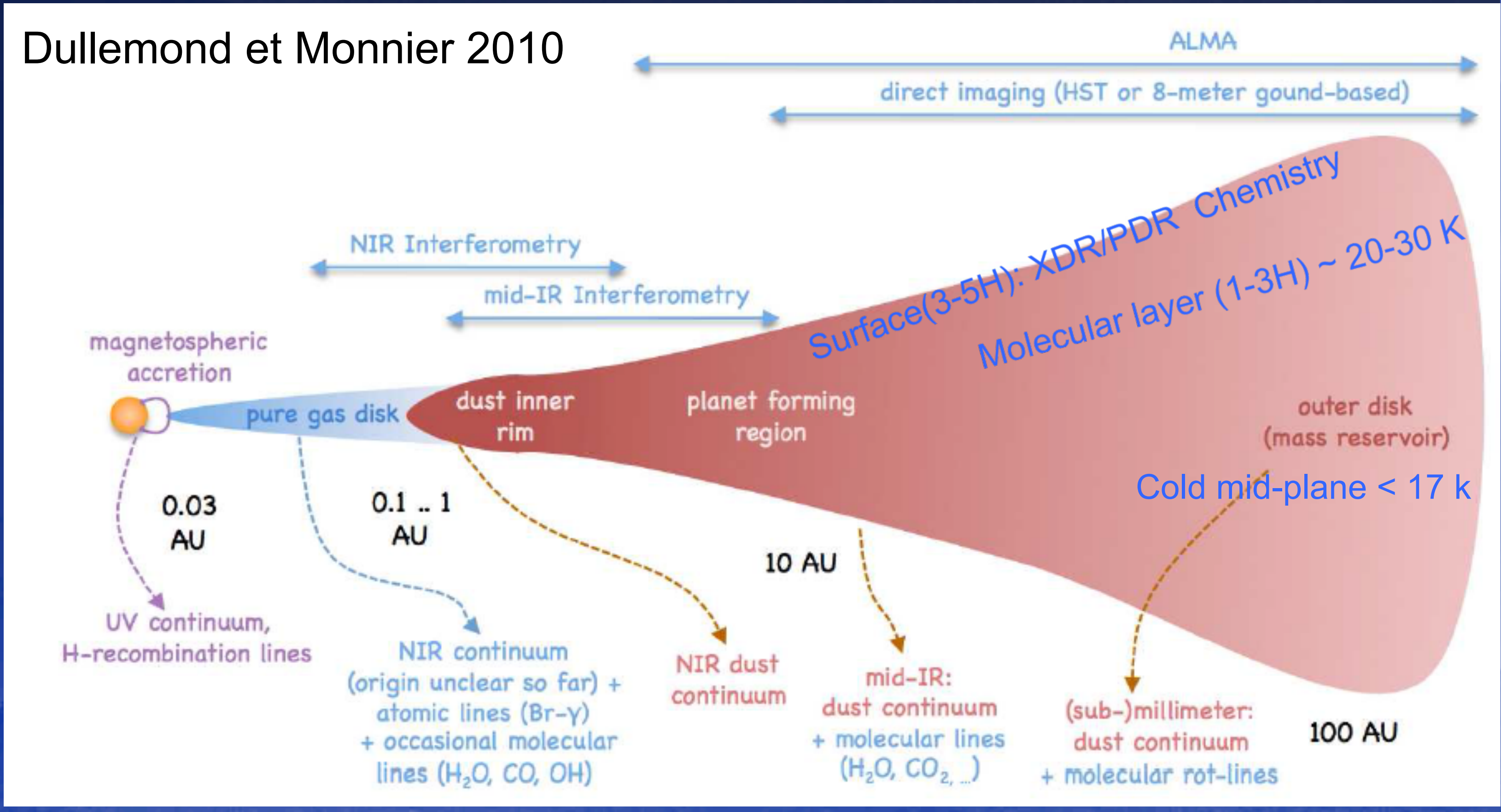
→ **Limited by the accuracy of the absolute flux calibration of ALMA (knowledge on Tk ?) - 3% accuracy needed**

→ **Specific ALMA observations needed !**

fit where v_{turb} was fit for individually. The 1 σ uncertainties are shown as bars on the direct method and shaded regions on the lines.

Molecules in Disks

- 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



Gas phase: Molecular Complexity is limited by sensitivity even with ALMA

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)
- DCO^+ (van Dishoeck et al 2004: TW Hya)
- N_2H^+ (Dutrey et al 2007, DM Tau, LkCa 15)
- 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 GO Tau, MWC480 and LkCa15)
- HD (Herschel, Bergin et al 2013, TW Hydra)

Unsuccessful so far …

- H_2D^+ APEX, JCMT, ALMA cycle 0 proposal by Qi et al
- CCS, H_2S (IRAM 30-m, Dutrey et al 2011)

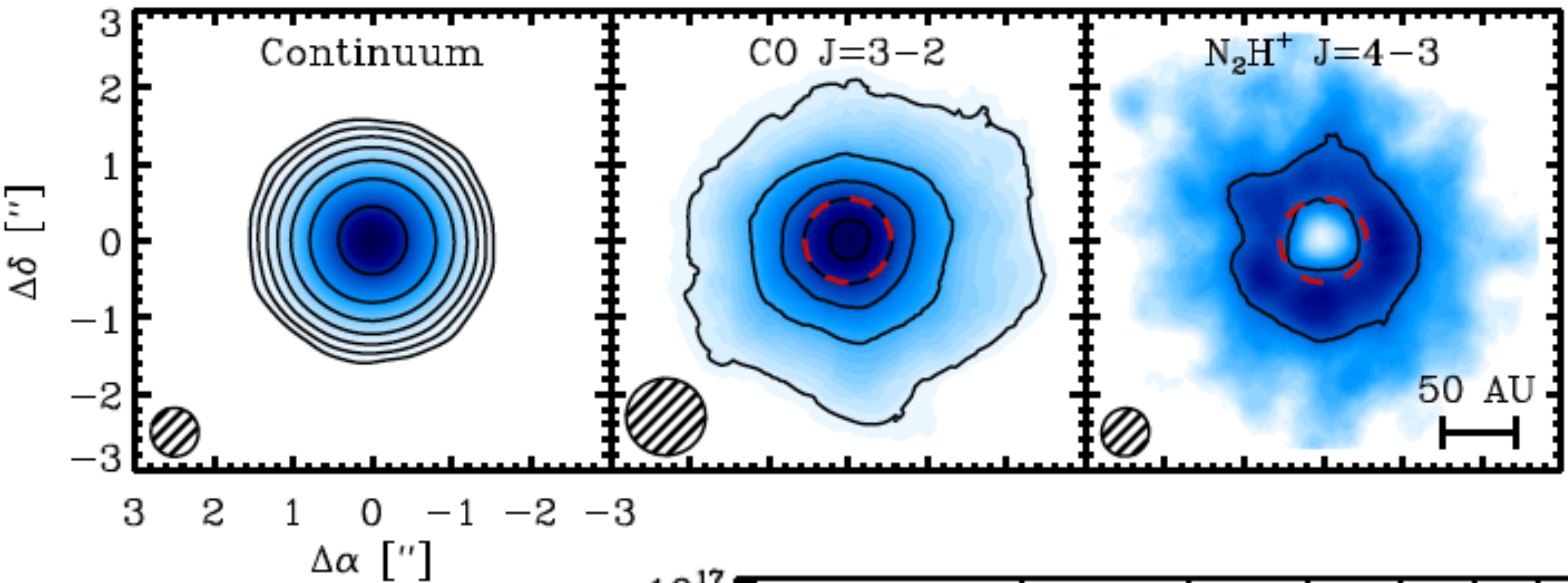
Submm molecular rotation lines

New detections …

- $c\text{-}C_3H2$ in HD163296, (A0, 2 Msun) warm disk (ALMA, Qi et al 2014)
- SO in the HAe disk around AB Aur (IRAM, Fuente et al 2014)
- N_2D+ in AS209 (ALMA, Huante et al 2015)
- CH_3CN in HAe (warm) disk of MWC 480 (ALMA, Oberg et al 2015)
- CH_3OH in TW Hydra (ALMA Walsh et al 2016)
- $H^{13}CN$, $HC^{15}N$ (Guzman et al 2017)

But

Observations of chemical « structures »: molecular rings, chemical differences…



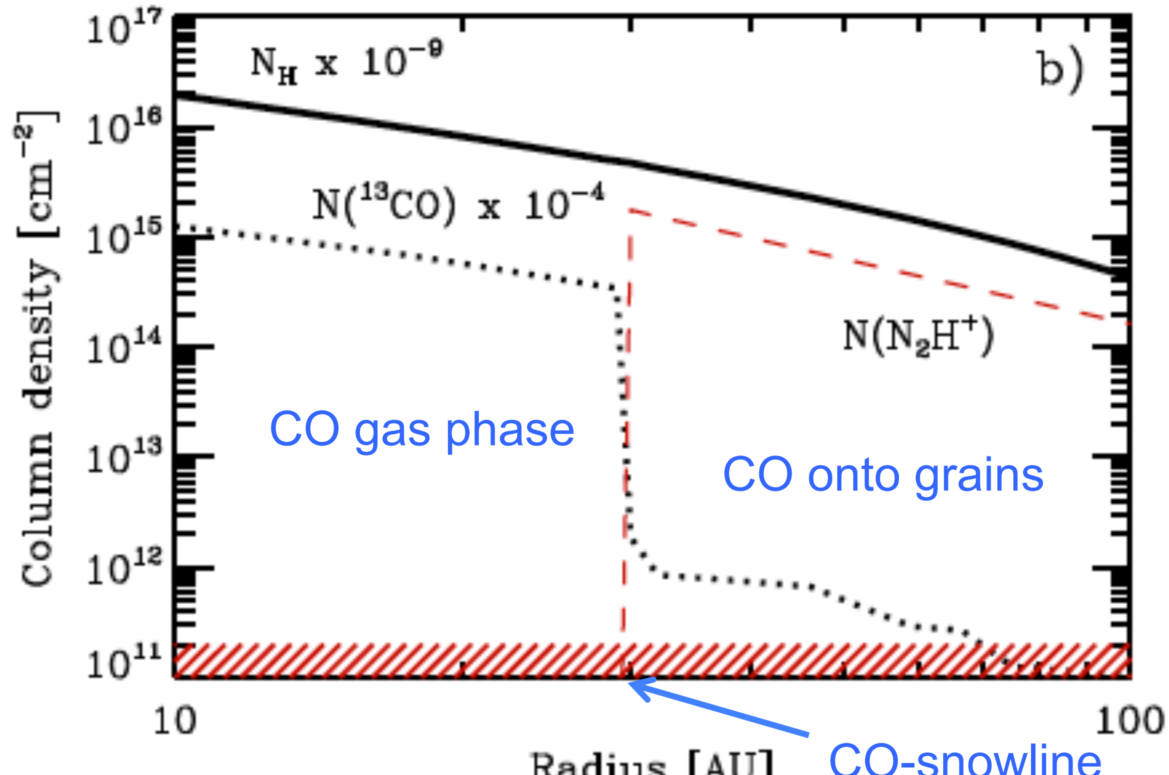
TW Hydra : ALMA (N_2H^+)
Qi et al 2013

CO snowline at 30 au

N_2H^+ ring because in inner disk:

$N_2H^+ + CO \rightarrow N_2 + HCO^+$

→ ***Chemical difference***



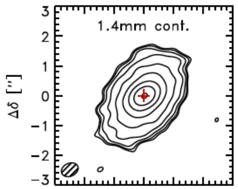
Molecular Rings seen with ALMA

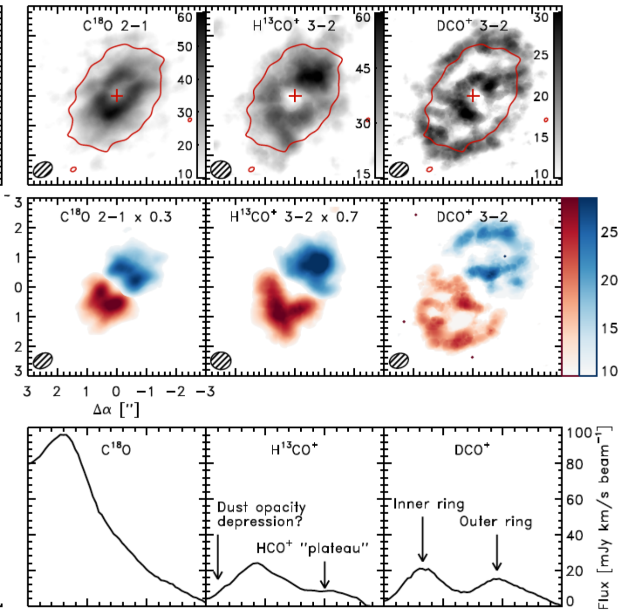
1. $H_2D^+ + CO \rightarrow H_2 + DCO^+$
2. $HCO^+ + D \rightarrow DCO^+ + H$
3. $CH_2D^+ + O \rightarrow DCO^+ + H_2$

$C^{18}O$ → CO abundance enhanced at large radii

- **Possible origin of CO desorption** near the dust disk edge:
→ may occur via non thermal processes involving CRs
or high energy photons
or a radial thermal inversion arising from dust migration

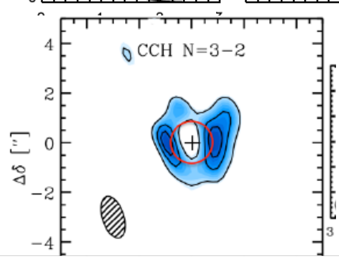
IM Lupi Oberg et al 2015





Inner ring:
→ Balance of CO freeze-out and thermal desorption due to radial decrease of T

Outer ring:
→ Non thermal desorption of CO ice in low column density outer disk

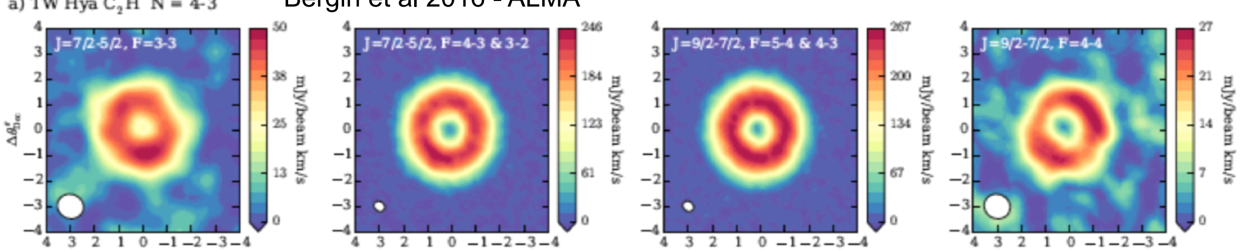


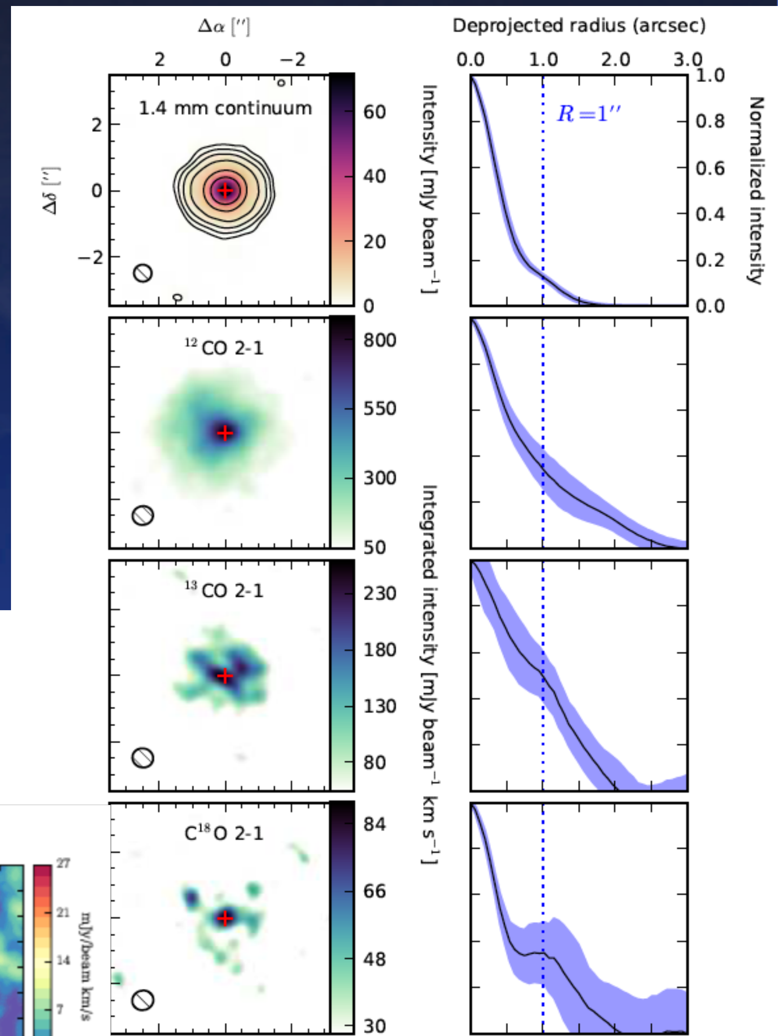
TW Hya Kastner et al 2015 – SMA

Possible origin of the rings:

- Efficient photo-destruction of small grains
- Photodesorption and photodissociation of hydrocarbons such as C_2H_2.

Bergin et al 2016 - ALMA



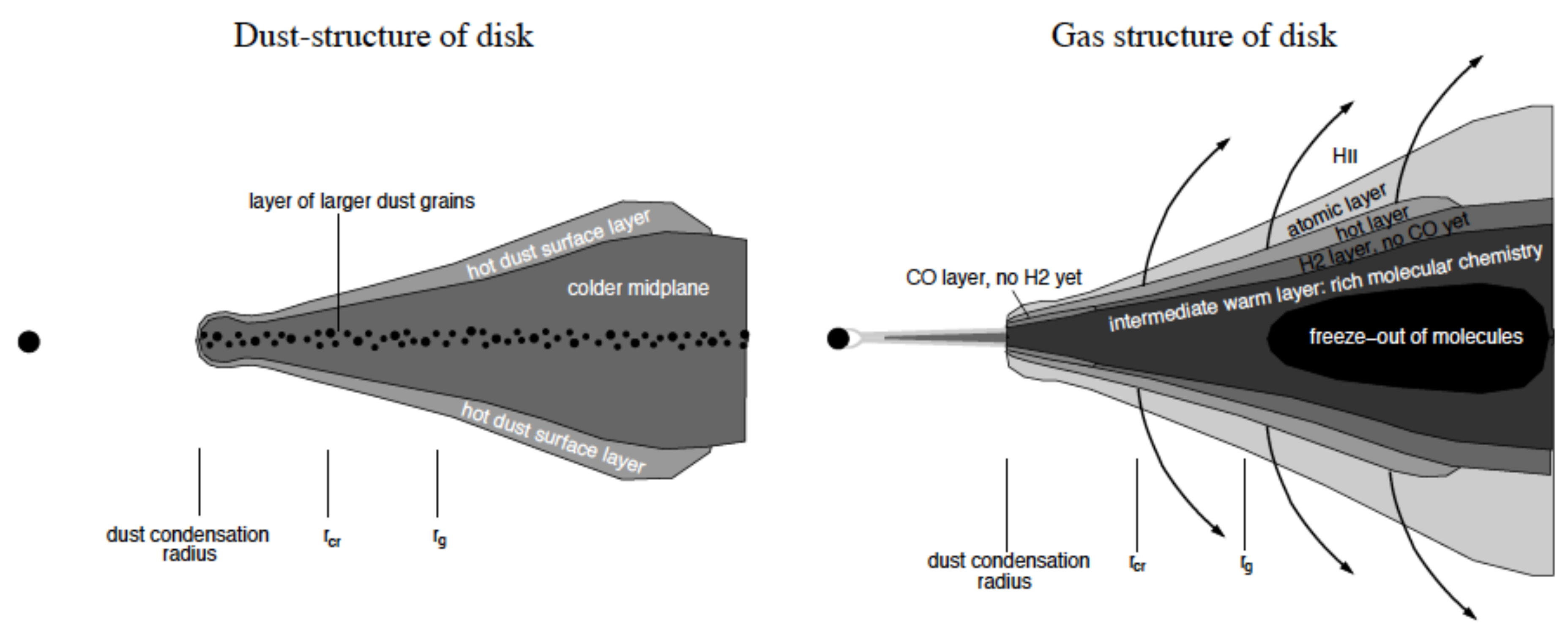


AS 209 Huang et al 2016 - ALMA

Gas and **Dust** disk Structure

Dust is only 1% of the mass but
In most of the disk, this is the dust temperature which governs the gas temperature
- Dust particles heated by the stellar UV heats the gas by collisions
- Not true onto the disk surface (PDR)

Gas dominates the dynamics
- small grains (a < 1μm) are dynamically coupled to the gas



Dullemond et al 2007, PPV

Impact of Dust on Gas Disk & Molecules

Formation of complex molecules at grain surface
→ Molecular complexity ?

Dust evolution - Impact:
- Grain growth:

→ deeper UV penetration, extinction curve changes
- Dust settling

→the local gas/dust ratio varies in (z,r)

Larger grains have a colder temperature
→ possible impact on gas-grain chemistry !

Cold mid-plane (< 17 K):
→ Molecules stick on grain surfaces
→ Deuteration ?

→ Observational characterization of grain properties (size, comp., temperature…)

Dust in Proto-planetary Disks
grain radial distribution

$K_\nu = K_o(\nu/\nu_o)^\beta$ (cm²/g)

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

+ Mm properties of disks:
Beckwith et al 1990
→ larger particles than in ISM

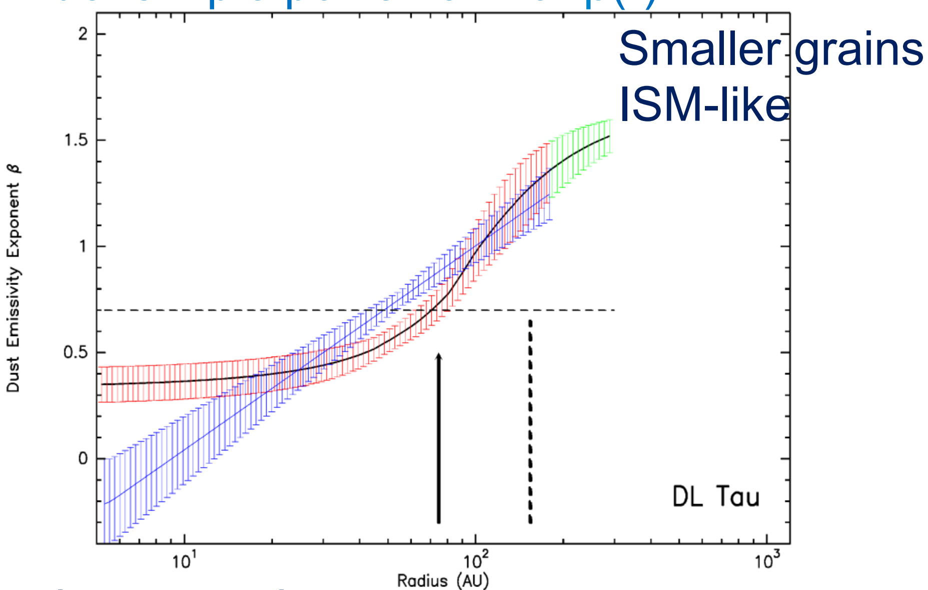
+ PdBI data at 2.7 and 1.3mm
Survey of ~ 20 sources (resol ~50- 70 au)
Guilloteau, Dutrey, Piétu, Boehler 2011

- $K_\nu = K_o\ (\nu/230\ \text{GHz})^{\beta(r)}$

- Larger grains inside !

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 $\beta(r)$



→Several similar results (VLA/CARMA surveys)

Dust in Proto-planetary Disks
grain radial distribution in AS209

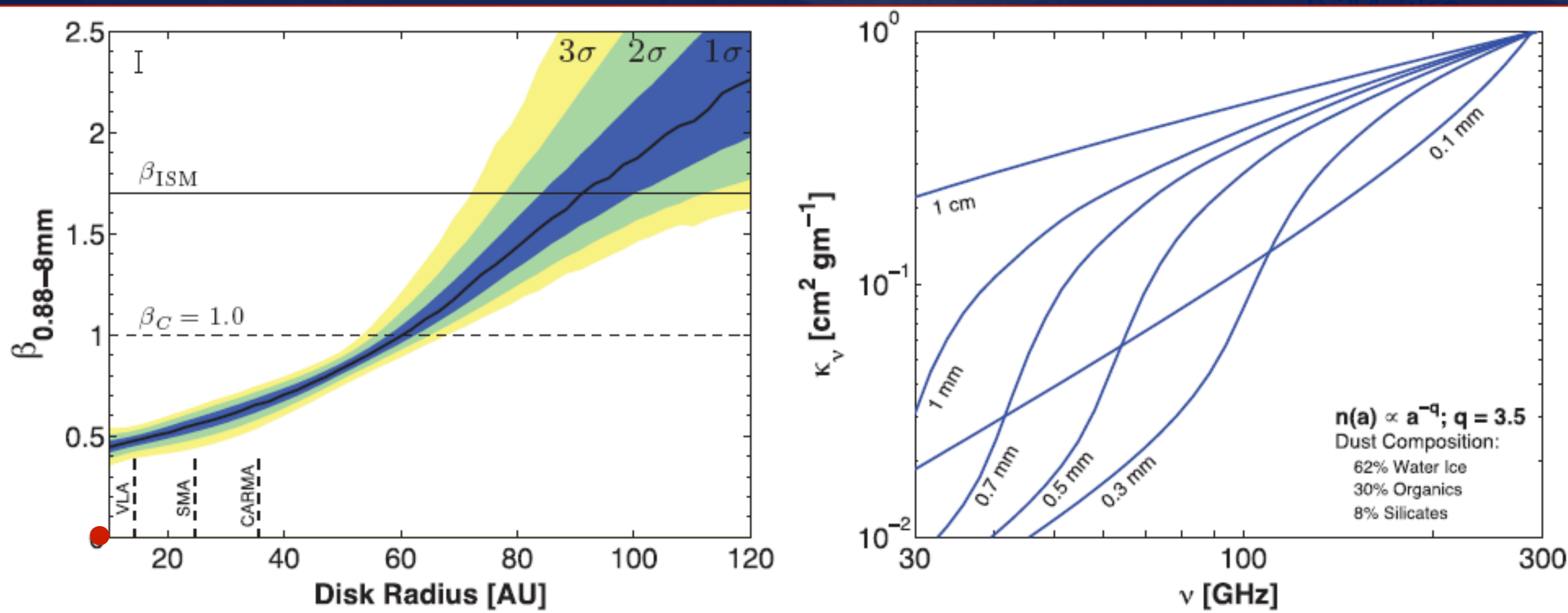
Perez et al 2012

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

Multi-wavelength modelling
→ Larger grains in the inner disk

With ALMA: 20 km → 0.02'' or 3 AU at 0.8mm

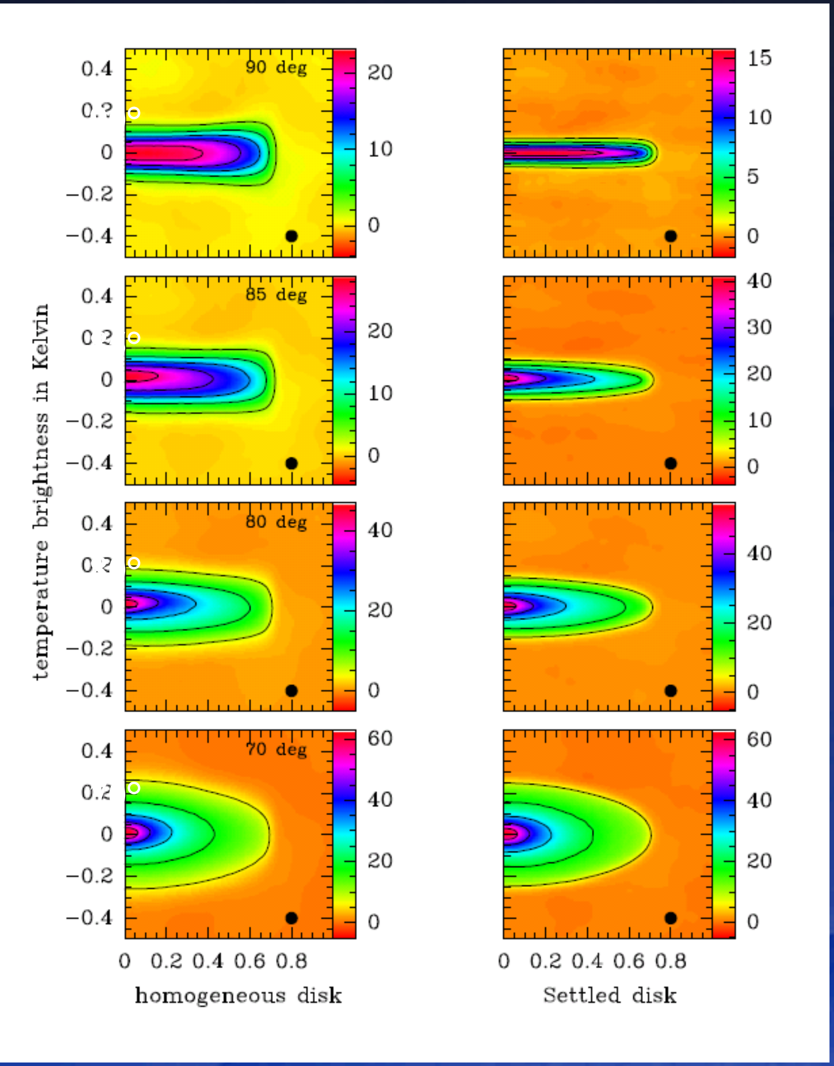
Smaller grains



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_{max} between 0.1

Dust settling - ALMA simulations

Not settled **Settled**



Simulated ALMA images ALMA @0.5mm, configuration 2.5 km

Scale height (grains) ~3-5AU @100UA

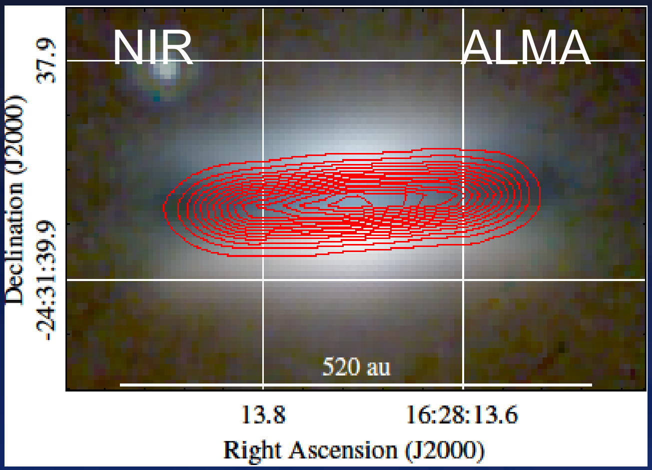
Settling observable for incli > 70°

Optimum Obs. Strategy:

2 frequencies - 0,45 mm + 1,3mm
moderate base - 2,5km
Int. Time T_{int} ~ 30min

Y. Boehler PhD, Boehler et al 2013

Flying Saucer: an edge-on disk



Located at 120 pc (Rho Oph) – Grosso et al 2003

Stellar Mass (from CO): $M_* = 0.578 \pm 0.002\ M_\odot$

$i = 90.8 \pm 0.4°$ $PA = 2.98 \pm 0.02°$

$R_{out} = 187.0 \pm 0.1$ au (at 120 pc)

$H(r) = 12.7 \pm 0.3\ (r/100\ \text{au})^{0.34 \pm 0.04}$ au

$\Sigma(r) = \Sigma_{100}\ (r/100\ \text{au})^{+0.49 \pm 0.02}$ au

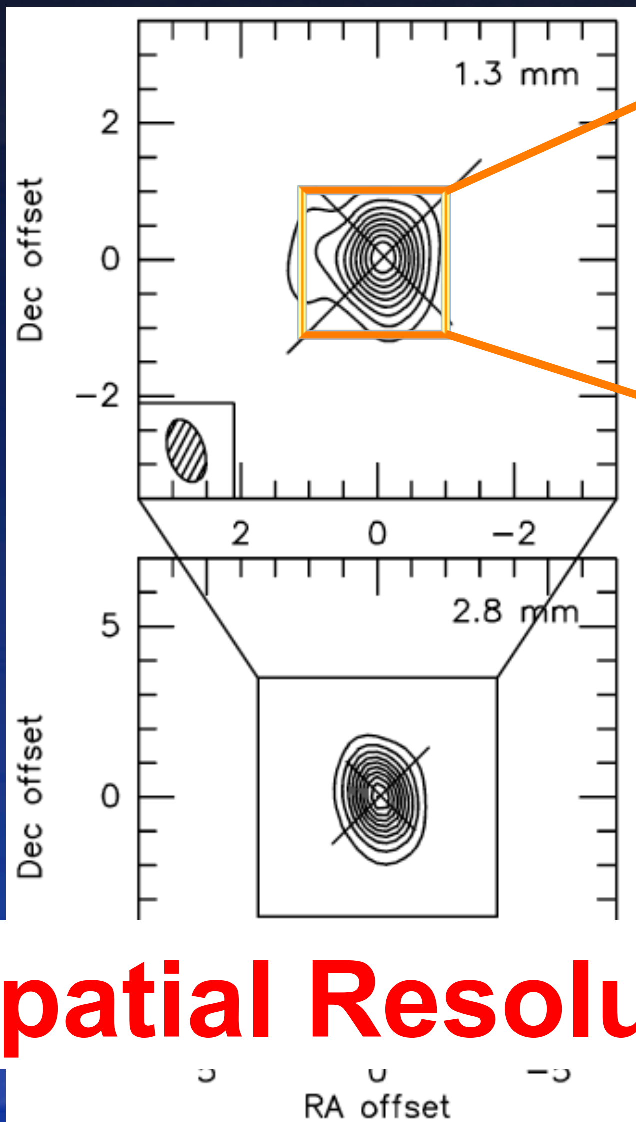
- In the mid-plane of the NIR dark lane (after correction for proper motions)
- Best fit parameters by « simple » dust disk model
  - Perfectly edge-on
  - Smaller outer radius than reflection nebula
- Apparent ***small flaring*** exponent and apparent ***positive surface density index*** (increasi ng outwards) are the ***signature of a settled dust disk***, as demonstrated by Boehler et al 2013

Guilloteau etal 2016 see also https://www.eso.org/public/news/eso1604/

HL Tau multiple rings

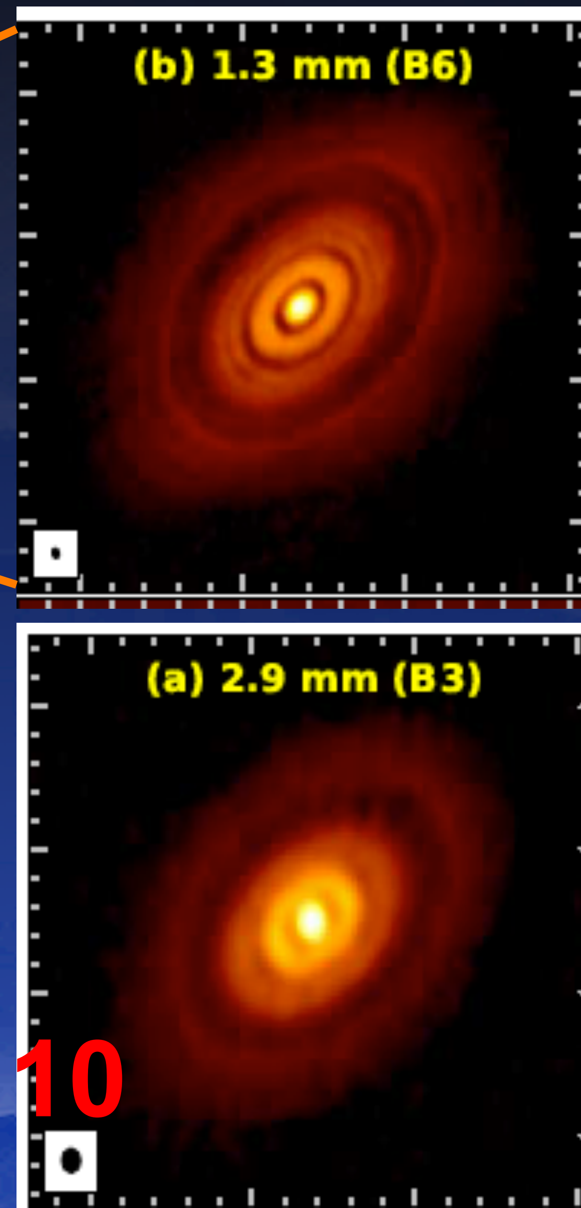
ALMA partnership 2015

Plateau de Bure Intereferometer (IRAM)
Guilloteau+2011



Class I

Young disk

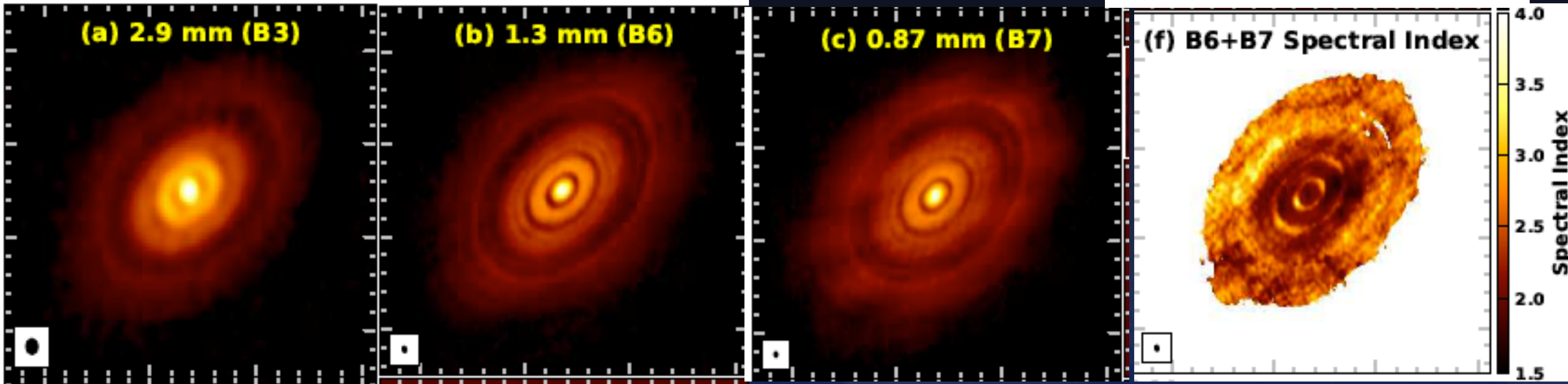


2"≈ 300ua

Spatial Resolution x 10

HL Tau multiple rings

15



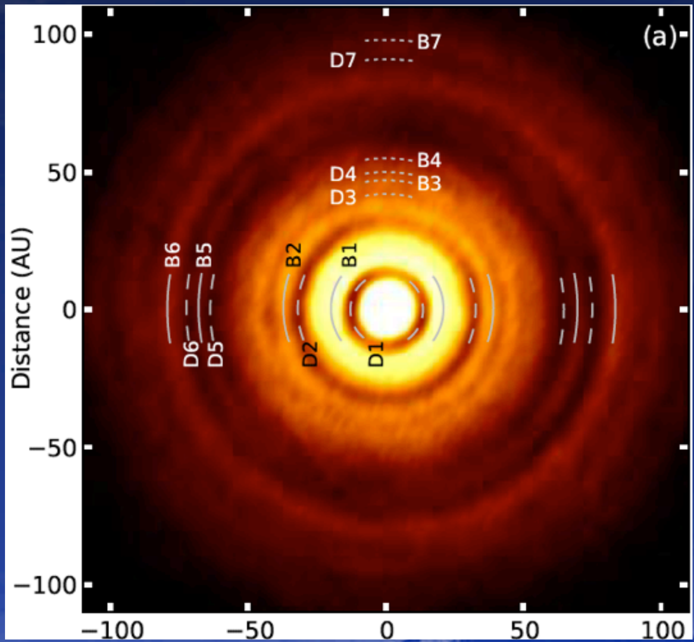
15 km-baselines campaign: 0.025" ~ 3.5ua
HL Tau: 0.7M$_\odot$, envelope, <1Myr, 140pc

- ✓ Many rings in a massive (~0.05-0.14 M$_\odot$) disk
- ✓ Resonances (?) and ring center offsets
- ✓ Variations of dust emission properties

  (linked with various snowline locations ?)

On-going planet formation ?

- ➢ Rings forming planets or planet-induced rings?



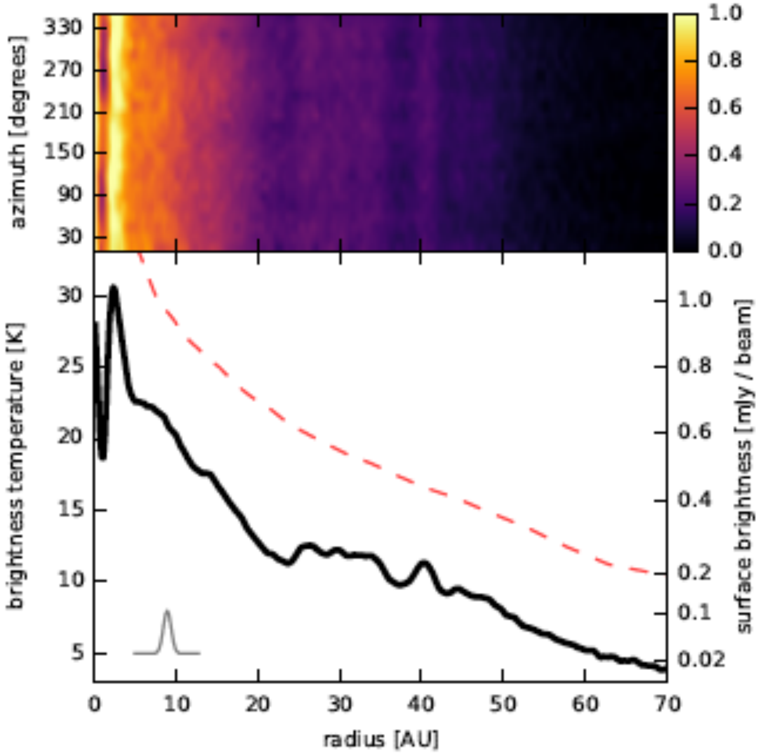
Class I - Young disk

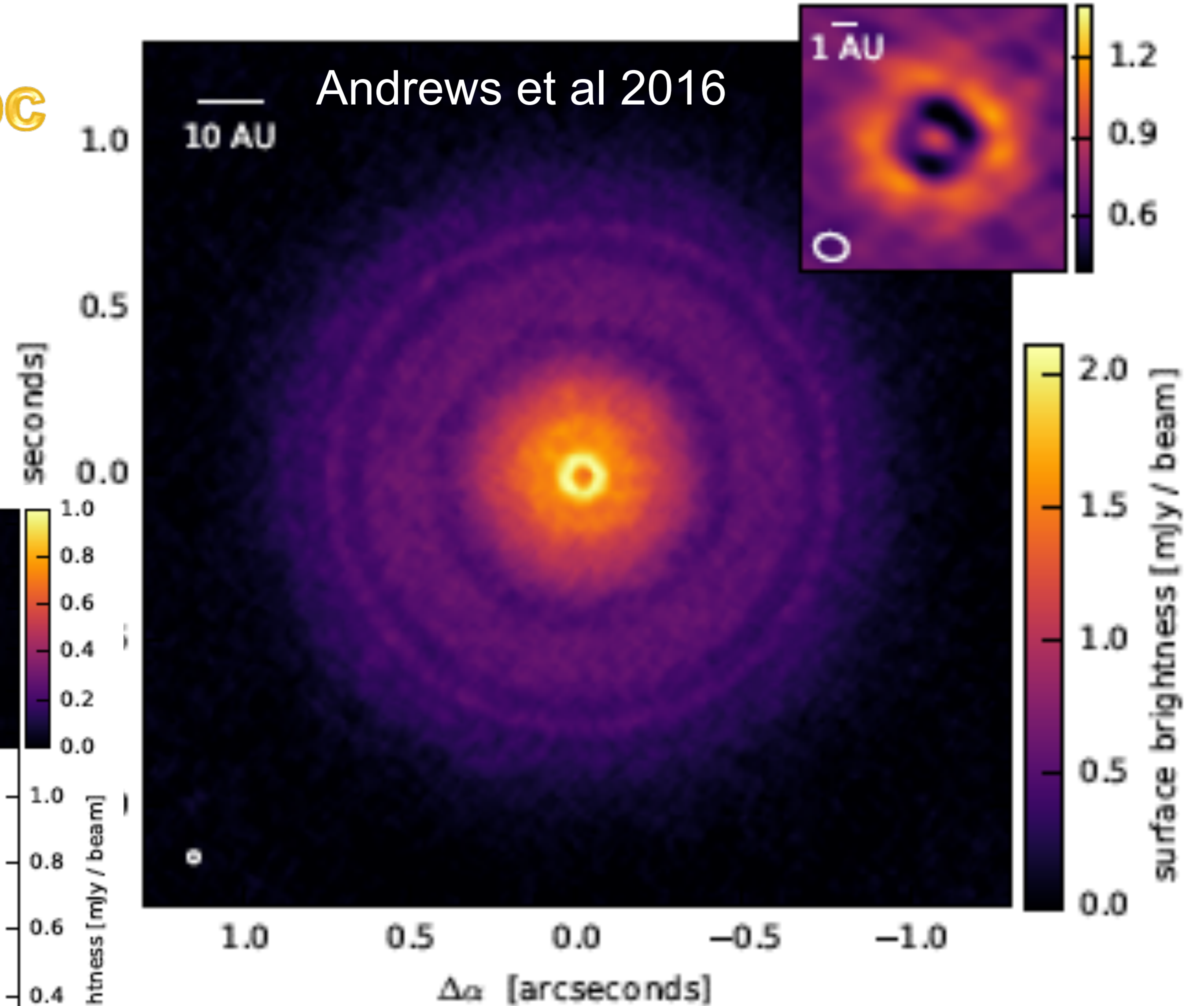
Do all disks show rings at high resolution?

Rings again !
In TW Hydra at 56 pc

0.8 Msun - 8 Myr

ALMA observations
0.87 mm , 30Mas or 1.6 au





e 1. A synthesized image of the 870 μm continuum emission he TW Hya disk with a 30 mas FWHM (1.6 AU) circular The RMS noise level is $\sim$35 μJy beam^{-1}. The inset shows -wide (10.8 AU) zoom using an image with finer resolution 8 mas, or 1.3 × 1.0 AU, FWHM beam).

HD 163296

ALMA

~ 0.2" or 30 au

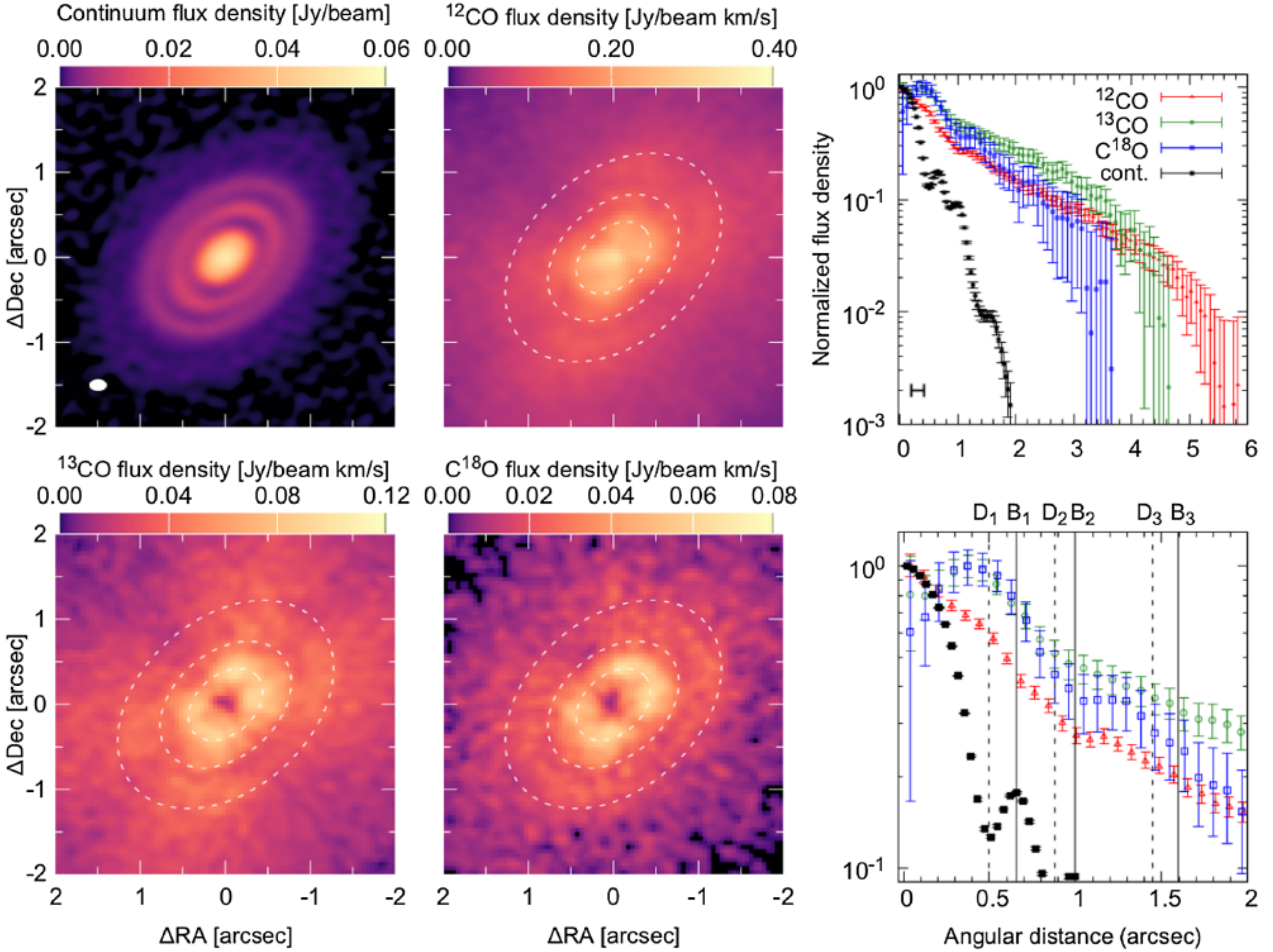


FIG. 1. ALMA images of the HD 163296 disk emission recorded in 1.3 mm dust continuum (top left), ^{12}CO (top middle), ^{13}CO (bottom left), and C^{18}O (bottom middle) $J = 2 - 1$ line emission. The angular resolution of the observations, $0.22'' \times 0.14''$, is indicated by the filled white ellipse in the continuum image. The dashed ellipses in the CO maps indicate the locations of the dark rings seeing in the continuum map. Azimuthally averaged profiles, normalized to the peak intensities, are shown in the right panels. They are calculated by averaging on elliptical annuli with a position angle of 132°, an eccentricity of 0.7, and a width equal to 1/4 of the angular resolution of the observations. The error bars are calculated by dividing the root mean square noise of the observations (see Table I in the Supplemental Material [26]) by the square root of the number of independent beams in each annulus. The vertical lines indicate the position of the dark (*D*) and bright (*B*) rings observed in the continuum map. The horizontal bar in the top right panel indicates the angular resolution of the observations.

Isella et al 2016

HD163296 – Some rings are also seen in the CO Gas

Interpreted as created by 3 proto-planets with masses 0.1, 0.3 and 0.3 Mjup orbiting at 62, 105 and 160 au from the star

Isella et al 2016

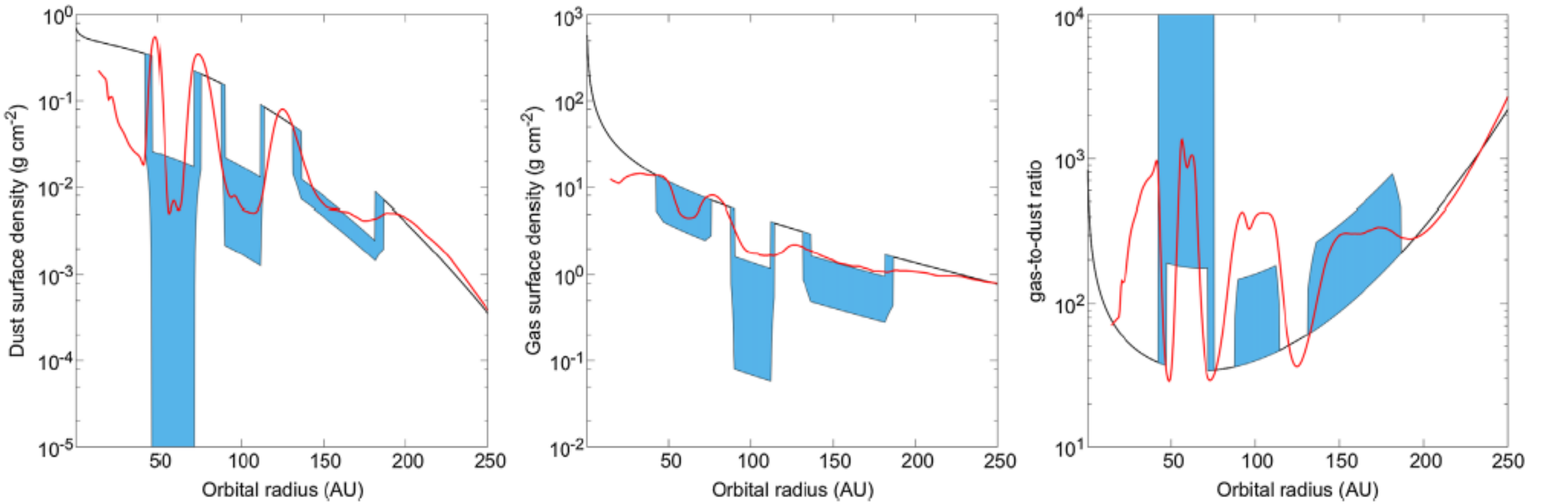


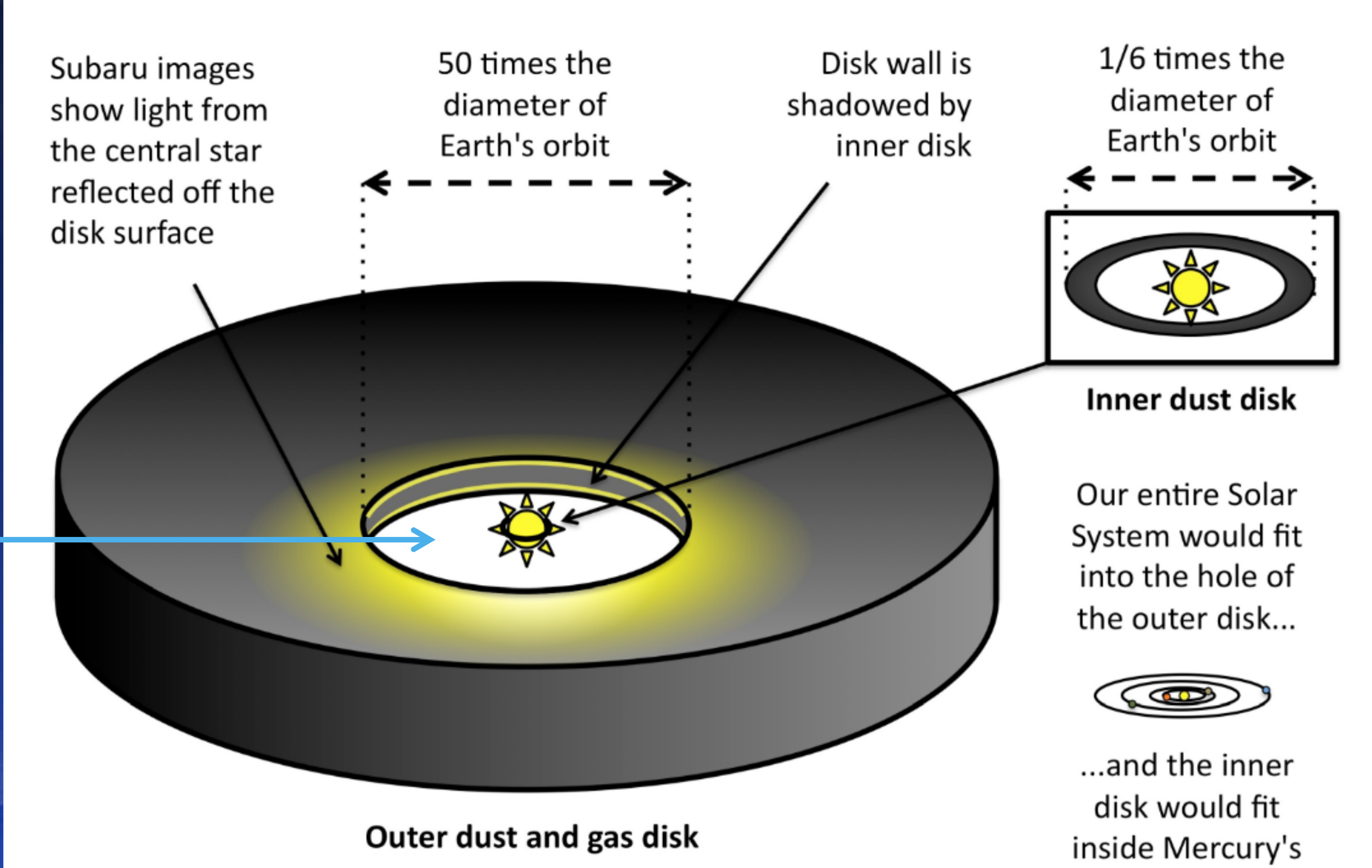
FIG. 2. Constraints on the dust and gas surface density (left and middle panels, respectively), and on the gas-to-dust ratio (right panel), derived by comparing ALMA observations of the HD163296's disk with synthetic models for the disk emission. The red solid curve indicates the prediction for a disk model perturbed by three planets with masses of 0.1, 0.3, and 0.3M_J orbiting at 62, 105, and 160 A.U. from the central star.

Transition disks - Structure

→ A disk with a central inner hole partially or totally devoid of gas and dust
May be due to planet formation …. gravitational truncation
Possible role of photo-evaporation

Holes can be as large as radius ~ 30-40 au

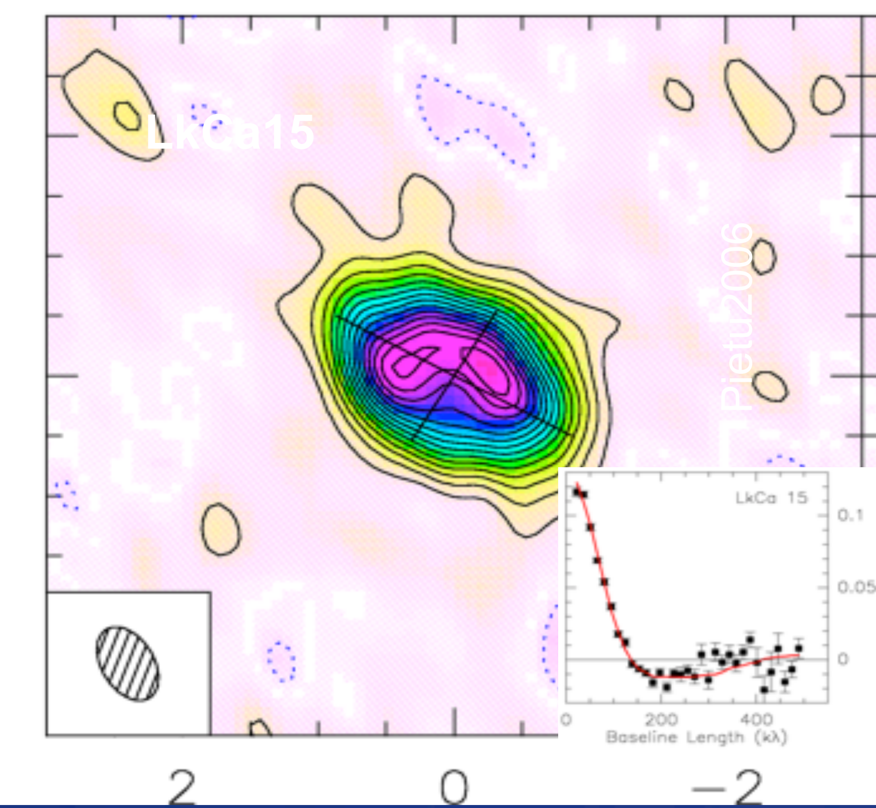
Possibly residual gas (CO) and dust



A scheme of LkCa15 inner disk …

Transition disks - LkCa15

Sub-mm cavity 50 au (PdBI, IRAM)



20% of sources w/ sub-mm cavities

R~40 au (resolution)

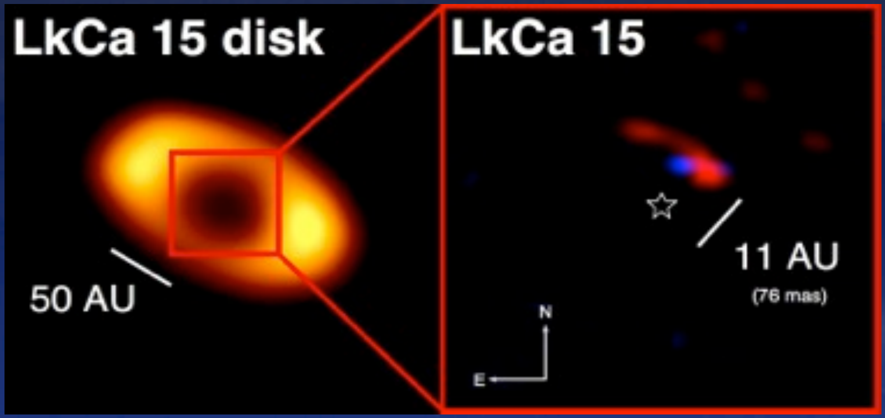
But observational limits…

Interpretation:

- Gap or
- Change of grain emission properties

Origin of the cavity ?

IR imaging:
Planetary candidate



Andrews11, Kraus12

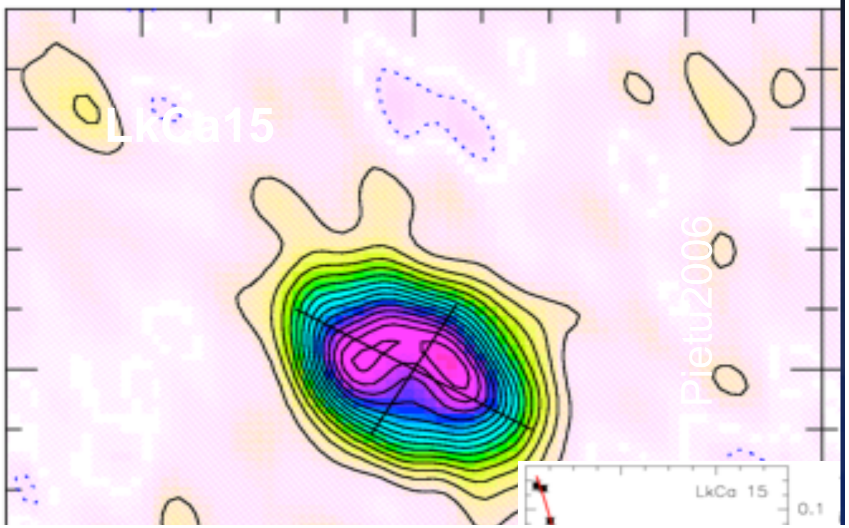
LkCa15 – Pietu et al 2006

Radius = 45 au

A 5-10 Mjup planet a 30 au would create a hole of such a radius (46 au).

LkCa15: a transition disk

Sub-mm cavity 50 au (PdBI, IRAM)



At least 1 planet of M > 5-10 Mjup

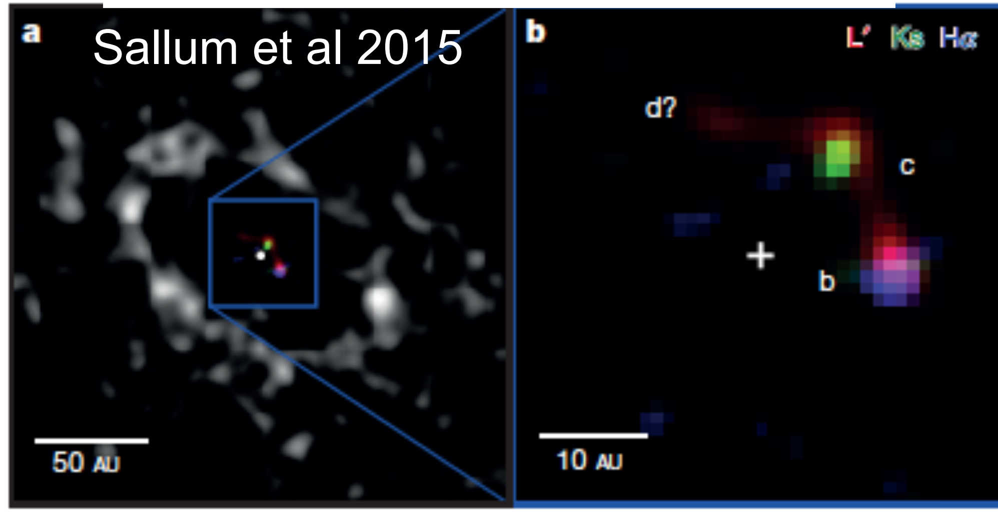


Figure 1 | Composite Hα, Ks, and L′ image. a, The coloured image shows Hα (blue), Ks (green), and L′ (red) detections at the same scale as VLA millimetre observations[29] (greyscale). **b,** Zoomed in composite image of LBT and Magellan observations, with b, c, and d marked.

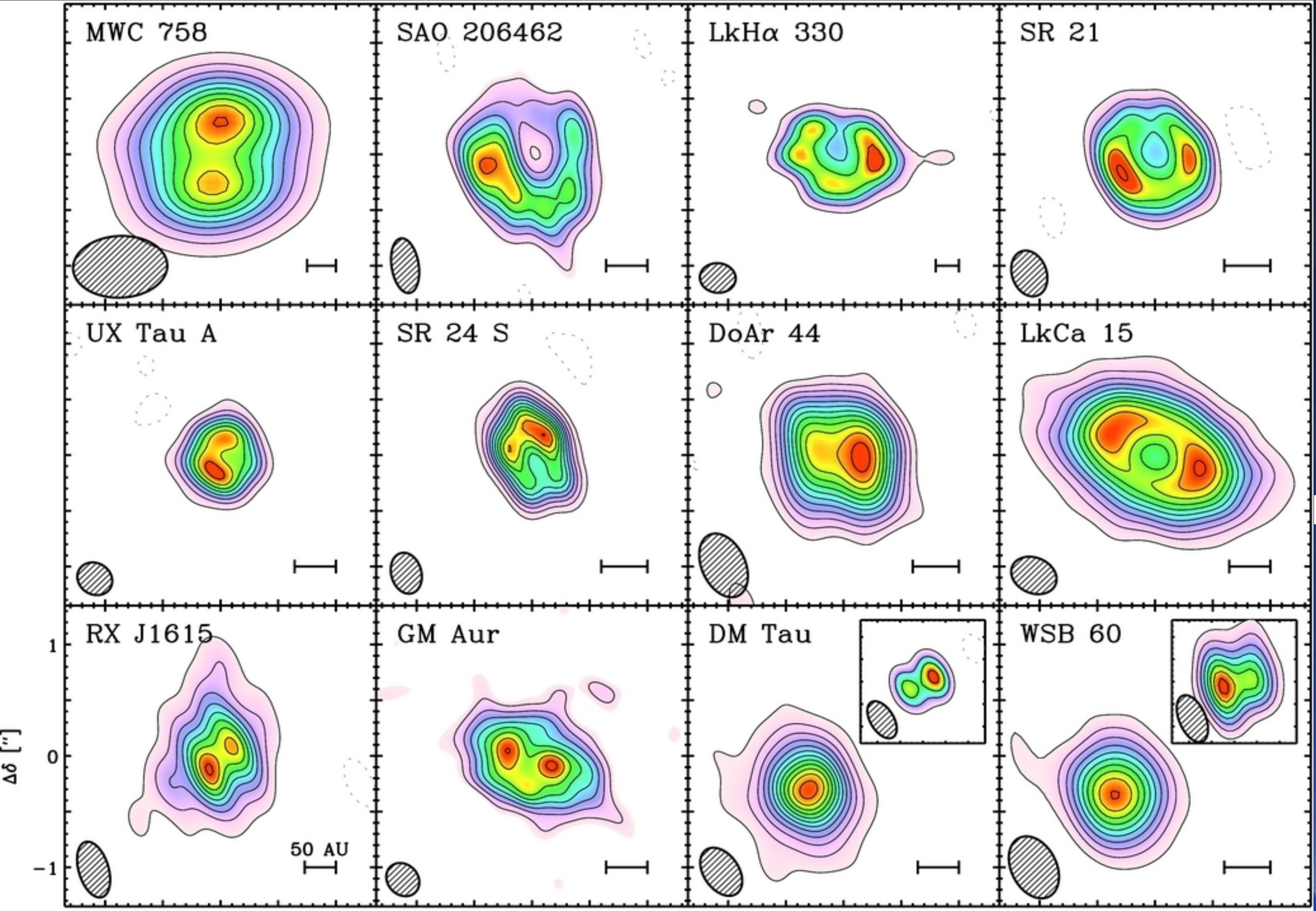
Table 1 | Model and experimental results

Component	Date	Instrument	λ	PA* (°)	s† (mas)	Δ‡ (mag)	M§ (mag)	$M_p\dot{M}$ ǁ (M_J^2 yr^{-1})	a¶ (AU)
Model fit results									
LkCa 15 b	15 Nov 2014	MagAO	Hα=656.3 nm	-104 ± 3	93 ± 8	5.2 ± 0.3	15.8 ± 0.3	3×10^{-6}	$14.7\pm^{2.1}_{2.1}$
LkCa 15 b	5–7 Feb 2015	LBT	Ks=2.18 μm	$-86\pm^{26}_{16}$	$125\pm^{25}_{40}$	$6.0\pm^{2.0}_{0.5}$	$14.2\pm^{2.0}_{0.5}$	10^{-5}	$14.7\pm^{2.1}_{2.1}$
LkCa 15 b	15 Dec [illegible]	LBT	L′=3.8 μm	[illegible]	$106\pm^{81}_{19}$	$5.4\pm^{0.1}_{4.9}$	$13.6\pm^{0.1}_{4.9}$	10^{-5}	$14.7\pm^{2.1}_{2.1}$
LkCa 15 c	5–7 Feb 2015	LBT	Ks=2.18 μm	$-48\pm^{22}_{10}$	$85\pm^{15}_{15}$	$5.5\pm^{0.5}_{0.5}$	$13.7\pm^{0.5}_{0.5}$	10^{-5}	$18.6\pm^{2.5}_{2.7}$
LkCa 15 c	15 Dec 2014	LBT	L′=3.8 μm	$-44\pm^{16}_{21}$	$68\pm^{37}_{43}$	$4.8\pm^{0.7}_{4.3}$	$12.9\pm^{0.7}_{4.3}$	10^{-5}	$18.6\pm^{2.5}_{2.7}$
LkCa 15 d	15 Dec 2014	LBT	L′=3.8 μm	$14\pm^{32}_{24}$	$87\pm^{72}_{70}$	$5.9\pm^{2.1}_{5.4}$	$14.1\pm^{2.1}_{5.4}$	5×10^{-6}	$18.0\pm^{6.7}_{5.4}$
LBT joint fit results									
LkCa 15 b	Dec 2014–Feb 2015	LBT	Ks+L′	$-98\pm$[illegible]	$95\pm$[illegible]	$\Delta Ks=6.0\pm0.5$	14.2 ± 0.5	10^{-5}	$14.7\pm^{2.1}_{2.1}$
						$\Delta L'=5.0\pm0.5$	13.2 ± 0.5		
LkCa 15 c	Dec 2014–Feb 2015	LBT	Ks+L′	$-42\pm^{12}_{10}$	$80\pm^{15}_{10}$	$\Delta Ks=5.5\pm0.5$	13.7 ± 0.5	10^{-5}	$18.6\pm^{2.5}_{2.7}$
						$\Delta L'=5.0\pm0.5$	13.2 ± 0.5		

→ Still controversial ….

Image deconvolution artifacts ???

Transition disks: with inner holes …



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

Radius 20-40 au

Rout =

200- 300 au

Pietu2006, Guilloteau2008, Hughes2009, Brown2009, Isella2009, Andrews2010,11

From Sean M. Andrews et al. 2011 ApJ 732

CO gas in inner (dust) cavities

Some generic cavity properties:

- ✓ Gas depletion $\times 10^{-1}$-10^{-2}
- ✓ Dust depletion larger $\times 10^{-3}$-10^{-5}
- ✓ $R_{gas} < R_{dust(mm)}$ (down to R_{gas}~20au)
- ✓

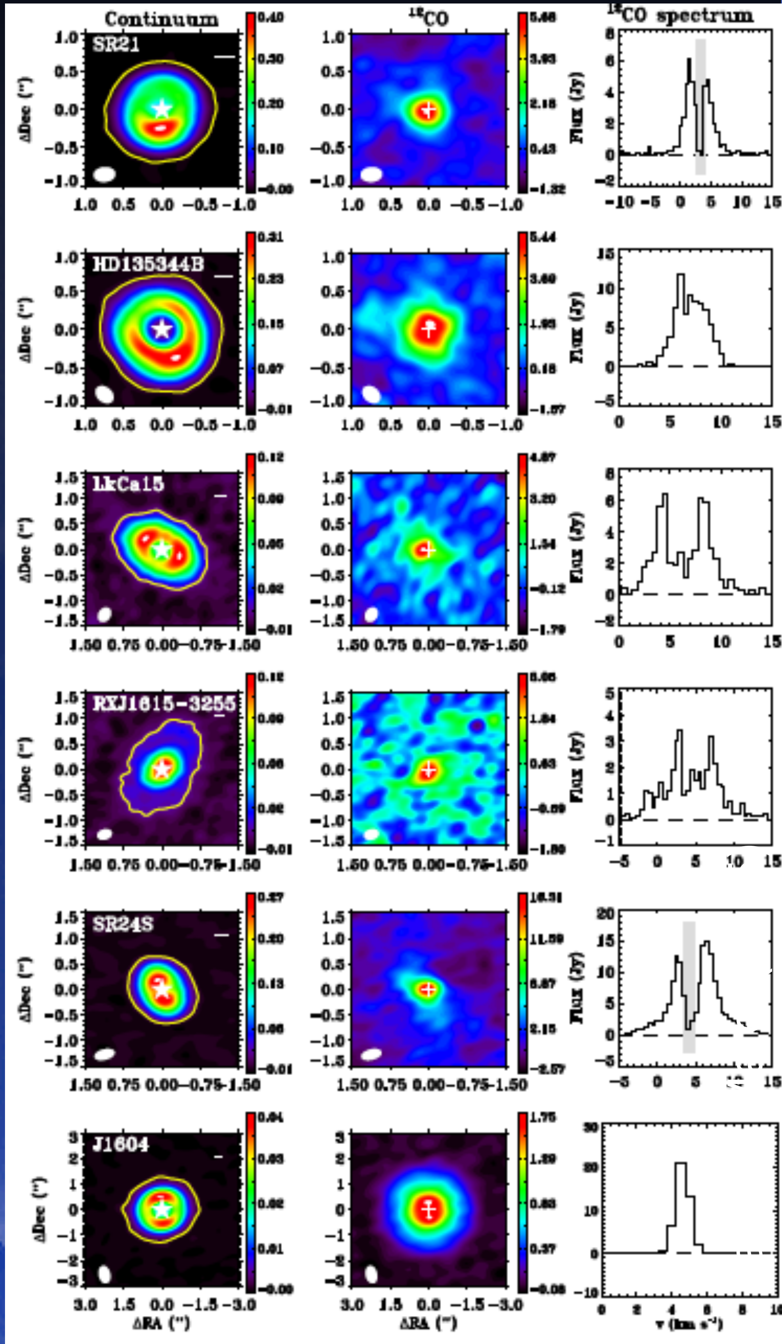
Possible clearing mechanisms:

- o Photoevaporation by EUV (but still accretion)
- o Grain growth lowers dust opacity
- o Trapping/Clearing by proto-planet(s)

$$R_H = a_p \left(\frac{M_p}{3M_\star} \right)^{1/3}$$

Further observational tests:

- ➢ sharpness of the cavity wall (dust vs. gas)
- ➢ IR emission from grains R<50 au



Van der Marel et al 2015

The star HD142527

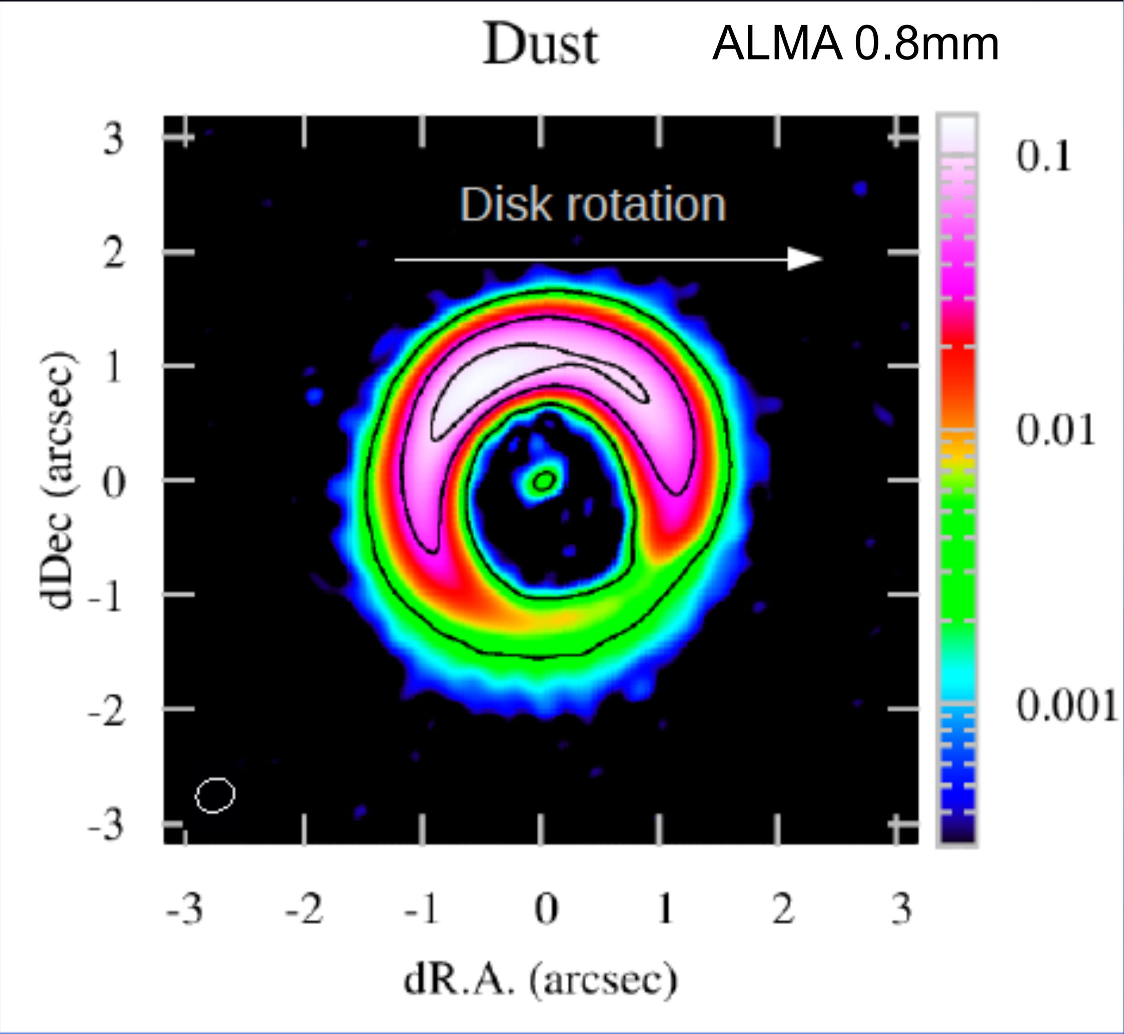
D=140 pc (D=198 pc)
Herbig Ae - F6 ~ 2.2 Msun
Age ~ 5 Myr
Binary Star (separation ~15 au)

Large outer gas and dust disk
Inner radius ~ 165 au
Outer 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



Boehler et al 2017, submitted

Large Elliptical cavity

Contrast of ~ 25 between north and south side

Inner disk not resolved
- < 10 AU

The star HD142527

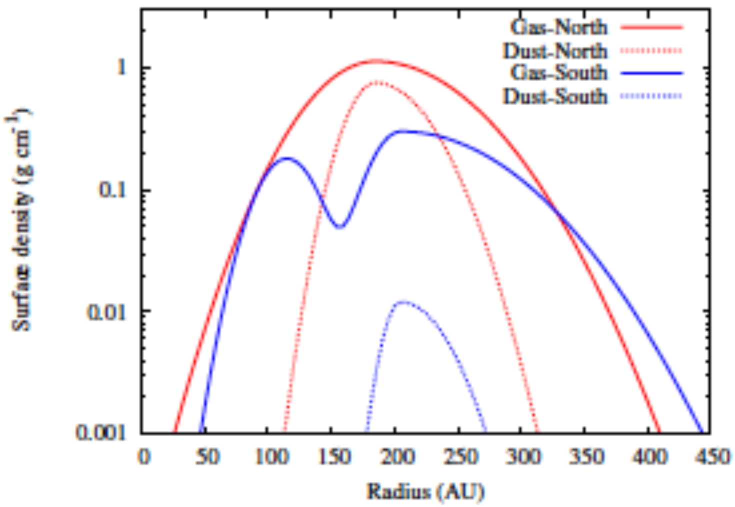
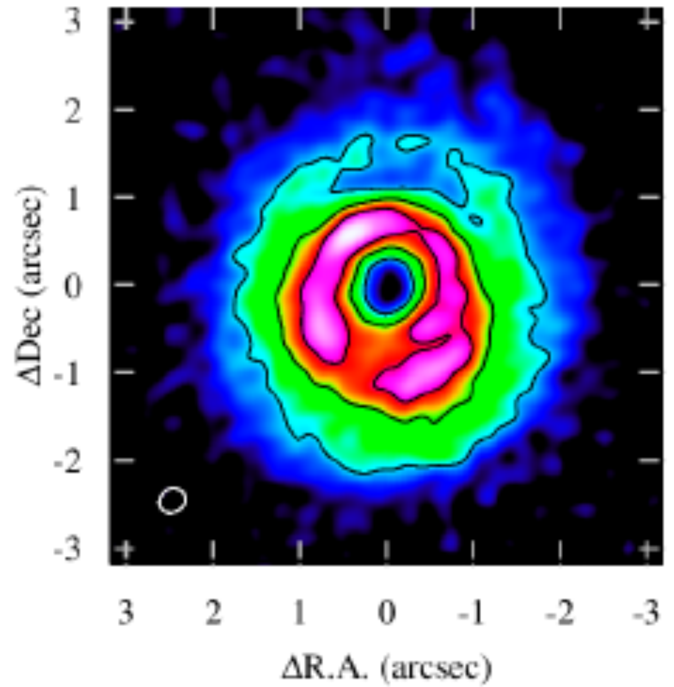
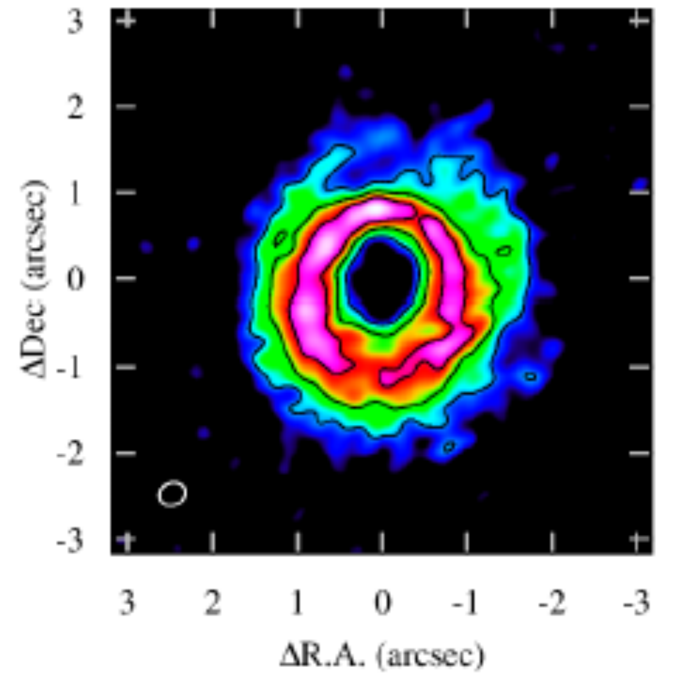


Figure 13. Gas and dust surface densities for the north and south profile.

12CO 3-2



13CO 3-2



<u>Contrast between the north and south profiles:</u>

- 65 for the dust
- 4.5 for the gas

Boehler et al 2017, submitted

<u>Gas to dust ratio:</u>

- North: 1.5
- South: 20

Assuming classical CO/H2 Abundances

Far away from a smooth distribution

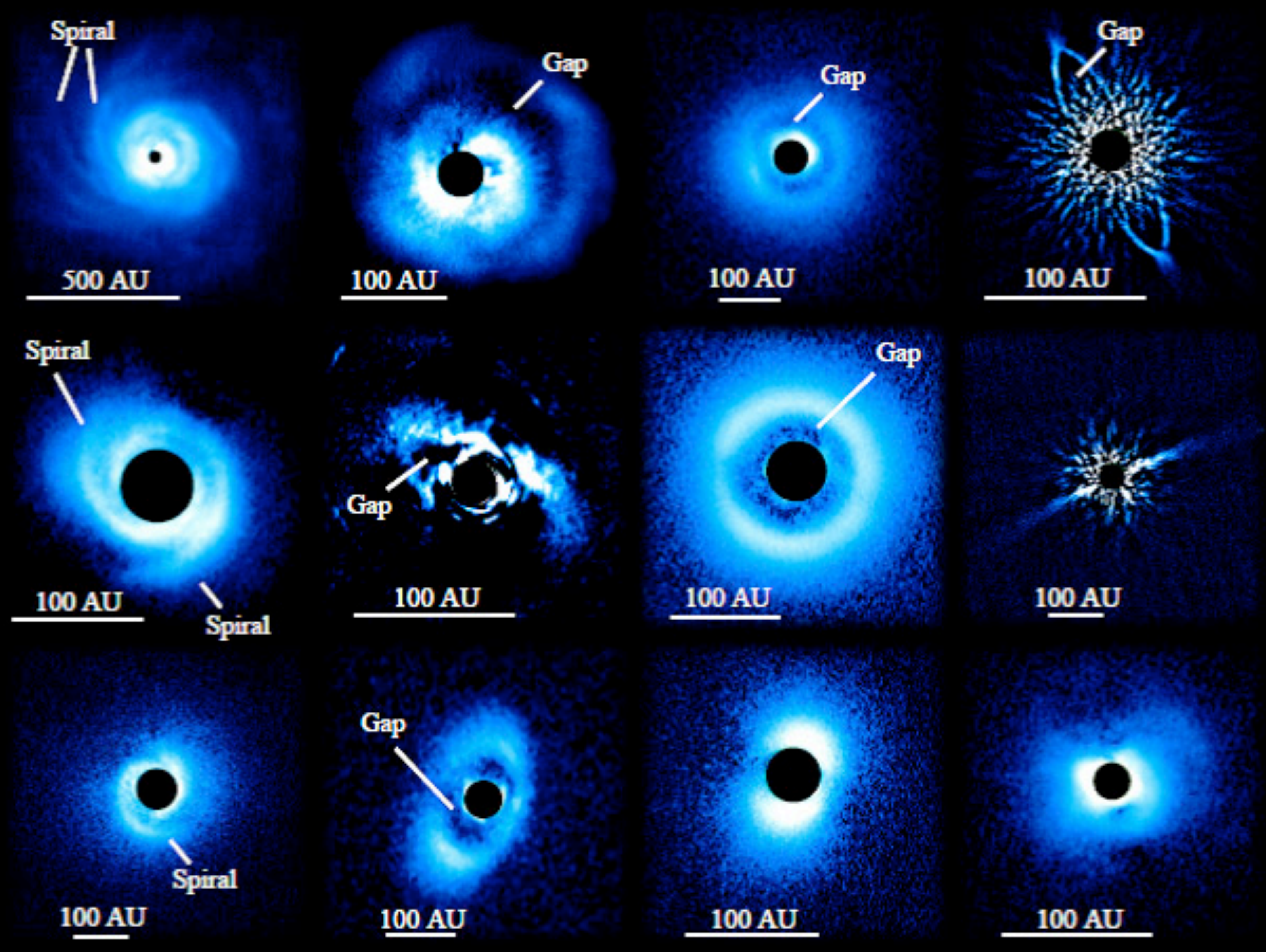
→ **Gravitational disturbances …**

→Gravitational instability (massive disks)
→Binary or planet formation
→Accretion creating spirals (Hennebelle et al 2017)

- Inner cavities in circumbinary disks… GG Tau
- Inner cavities in transition Disks … LkCa15
- Gaps in disks ... origin still debated
- Rings … origin still debated

- Direct imaging of spirals …
  - In NIR dust ... eg SPHERE or SUBARU observations
  - Also in CO gas (thanks to ALMA 0.” data)

SEED Survey copyright SUBARU, NAOJ



~2014: SPIRALS EVERYWHERE ! MWC 758

Marino et al 2015, ALMA + VLA

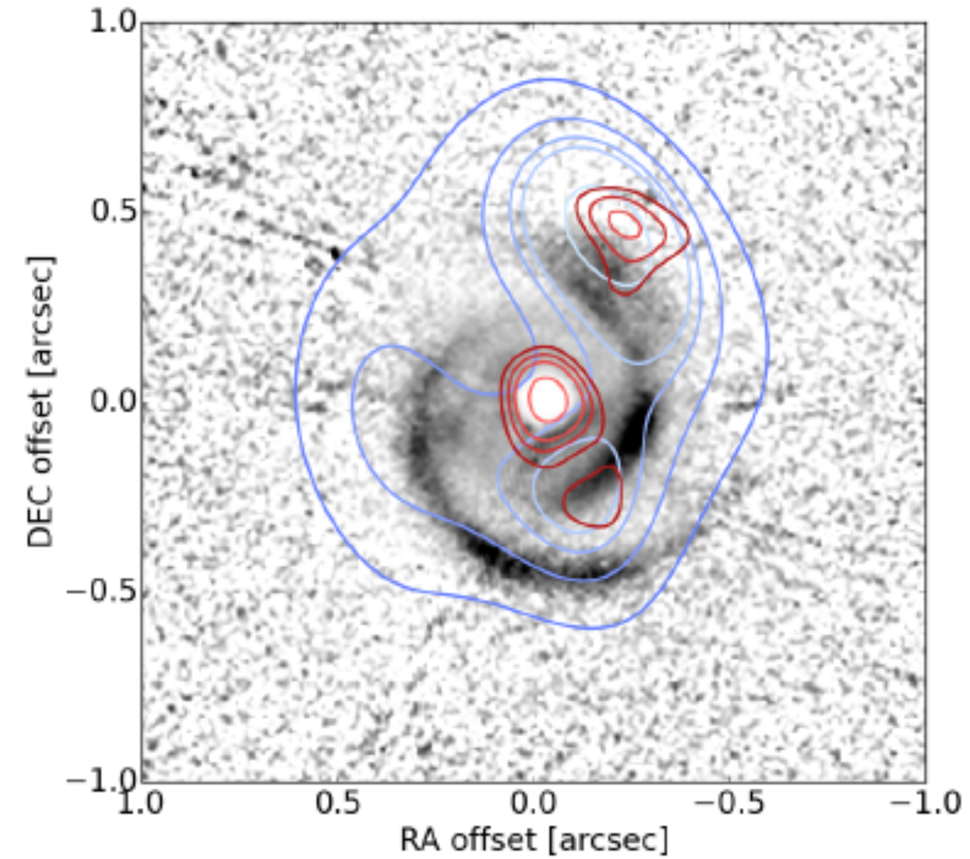
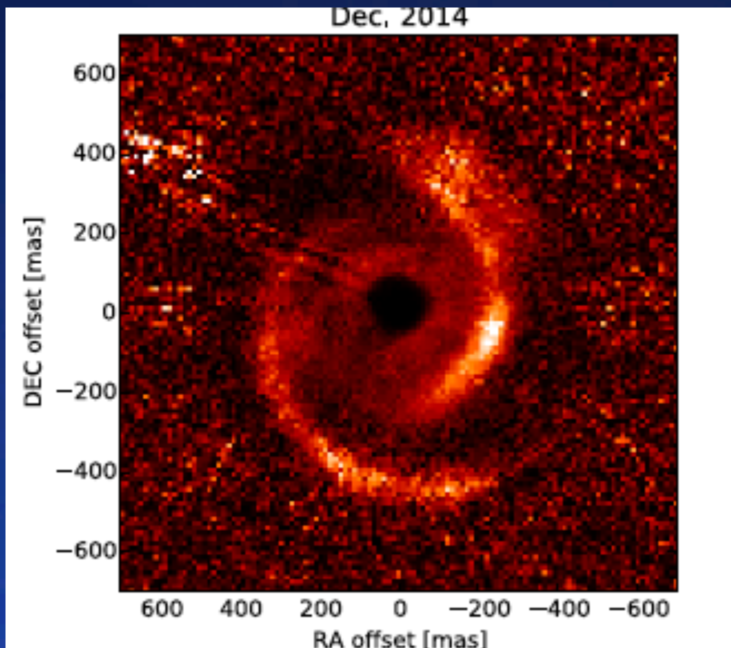


FIG. 7.— SPHERE/IRDIS-ALMA-VLA overlay. In grey scale, the polarised intensity scaled by r^2 to highlight the surface density of the disk, obtained with SPHERE/IRDIS PDI. The decrement in the center correspond to the position of the coronagraph. The ALMA band 7 MEM map is represented in blue contours, while the restored VLA Ka map is presented in red contours. The contour levels are arbitrary to emphasise the disk morphology. The x & y axes indicate the offset from the stellar position in the RA and DEC in arcsec, i.e. north is up and west is right.

Benisty et al 2015 – SPHERE/VLT



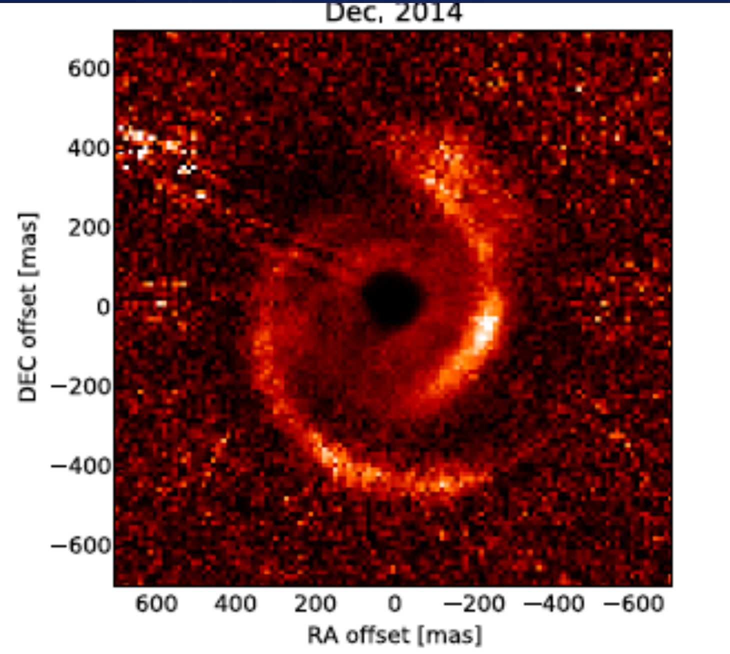
~2014: SPIRALS EVERYWHERE ! MWC 758

+ Optically thick dust emission → disk surface

Fit of spiral waves due to gravitational disturbances created by two young planets

Location of the two young planets as diamonds

Benisty et al 2015 – SPHERE/VLT



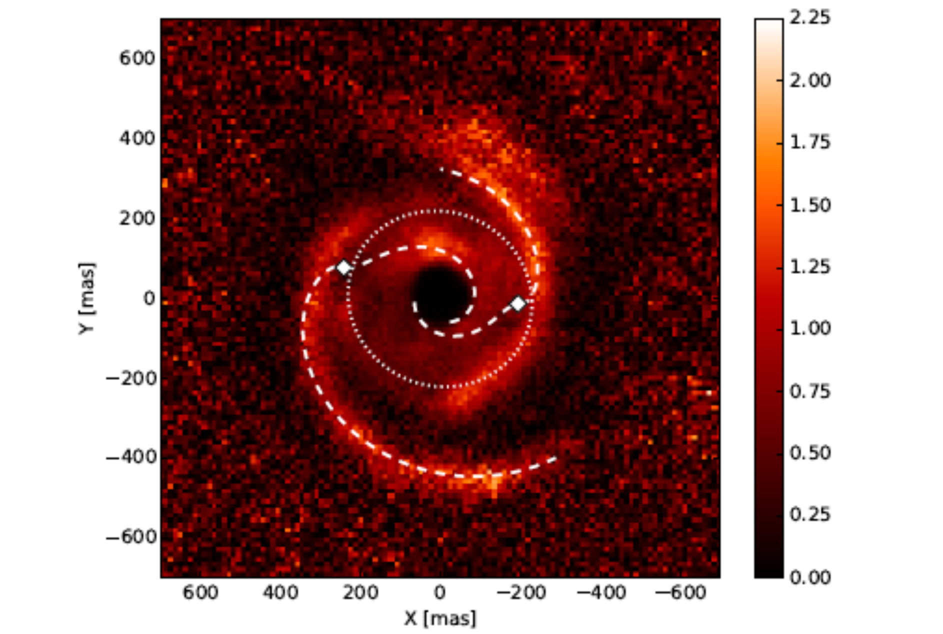


Figure 2. Best-fit model in dashed lines. The locations of the planets are indicated by white diamonds. The dotted ellipse is a projected circle with radius 0.25″. The color scale is arbitrary.

Thermal dust emission (ALMA) in the disk around Elias 2-27

1.3mm Mm dust emission → disk mid-plane

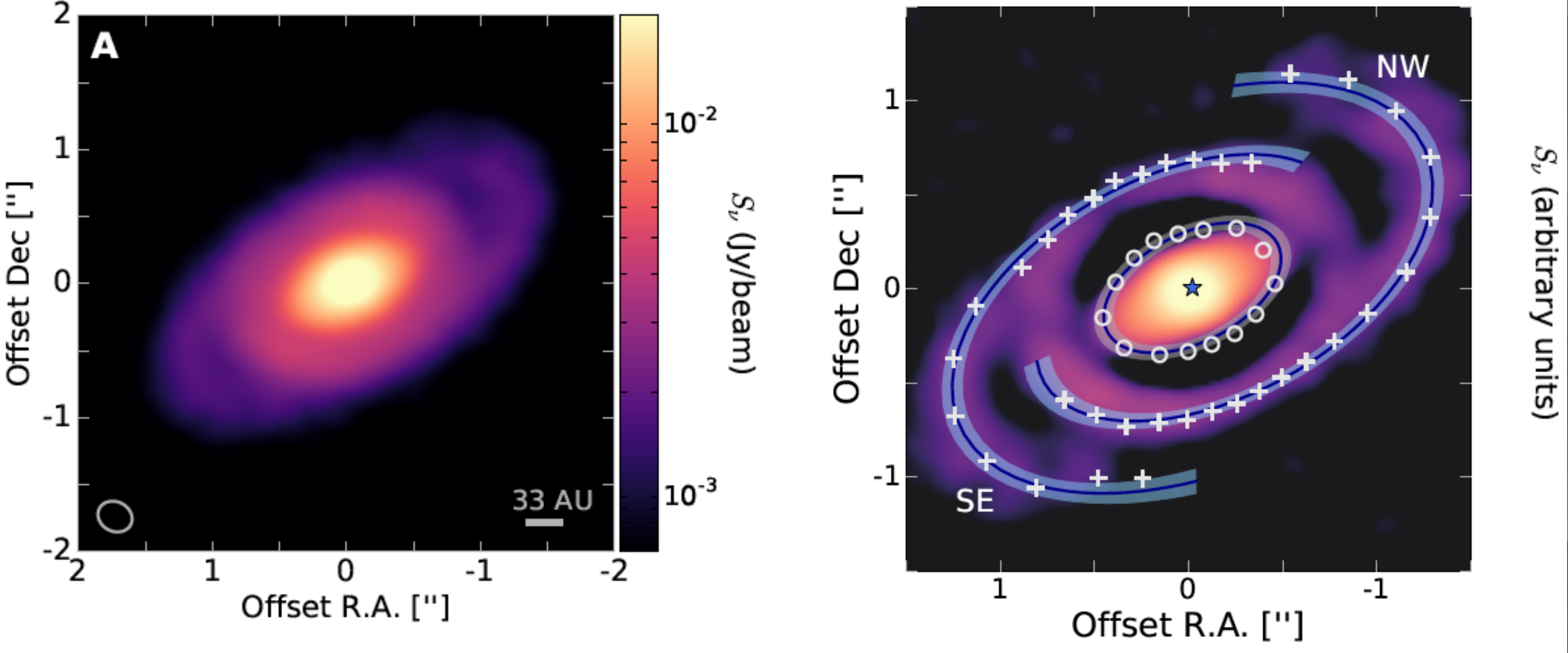
→ The observed spirals trace shocks of spiral density waves in the mid-plane of the disk.

→ Gravitational unstability unlikely (disk should fragment at large scale, Md/M* too low)

→ **Planet formation**

Perez et al 2016

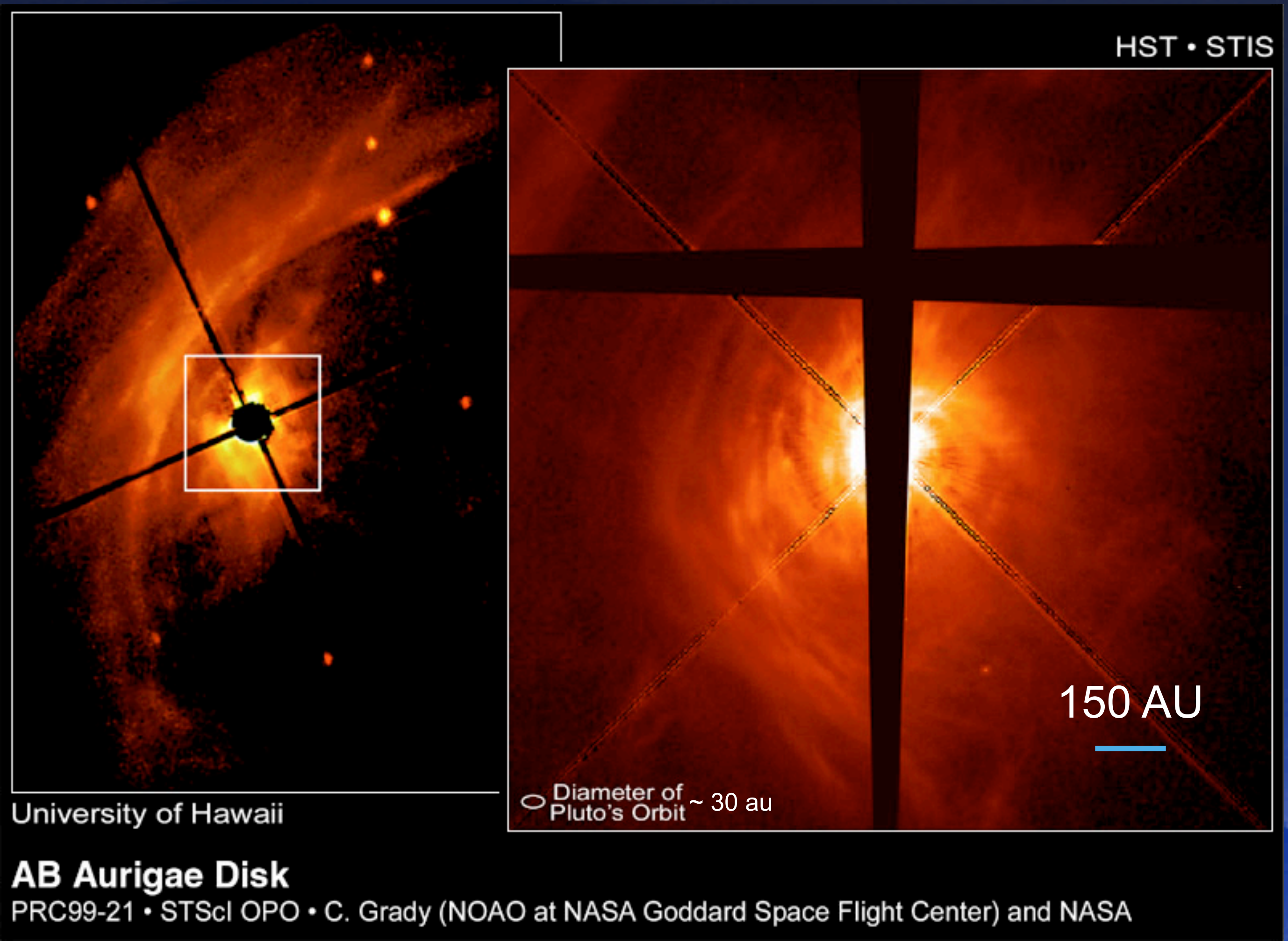
Best fit of the spirals
Superimposed to the
unmasked imaged
Where the large scale
dust emisssion
has been removed



AB Aurigae

Herbig Ae star (A0 – 2 Msun) ~1Myr

+ a very large scale reflection nebula
+ a gas and dust disk with central hole

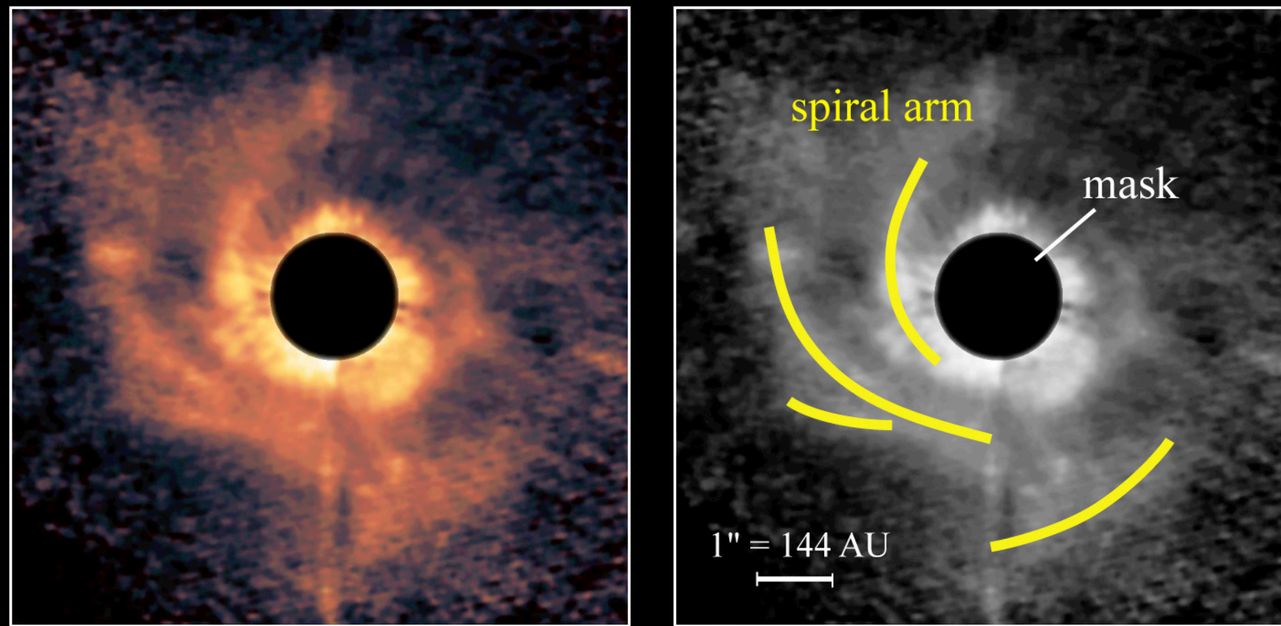


AB

Herbig Ae star (A0

+ a very large scale re

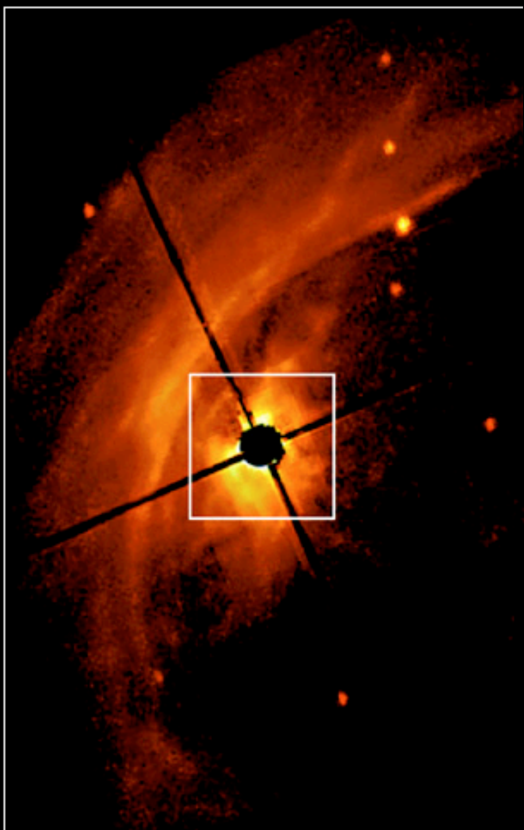
+ a gas and dust disk



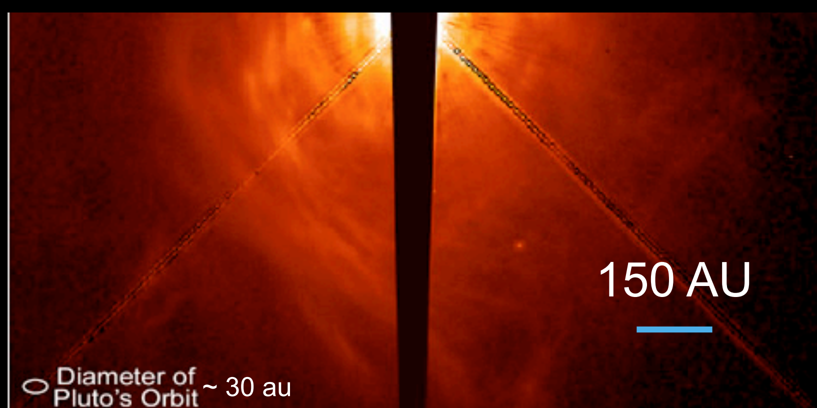
Protoplanetary Disk Surrounding the Star AB Aurigae CIAO+AO (H)

April 18, 2004

Subaru Telescope, National Astronomical Observatory of Japan



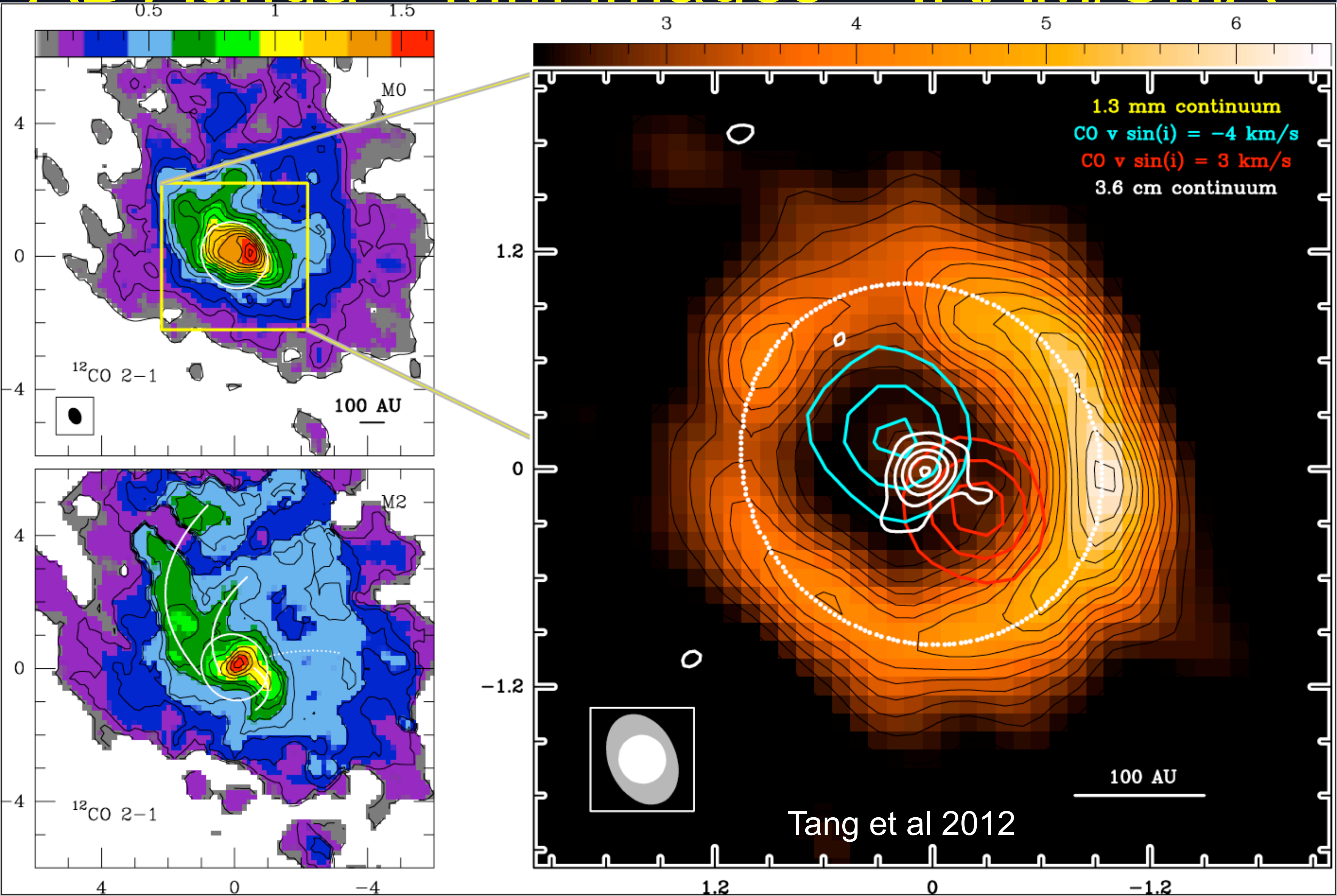
University of Hawaii



AB Aurigae Disk

PRC99-21 • STScI OPO • C. Grady (NOAO at NASA Goddard Space Flight Center) and NASA

AB Auriga – Mm images – IRAM/SMA



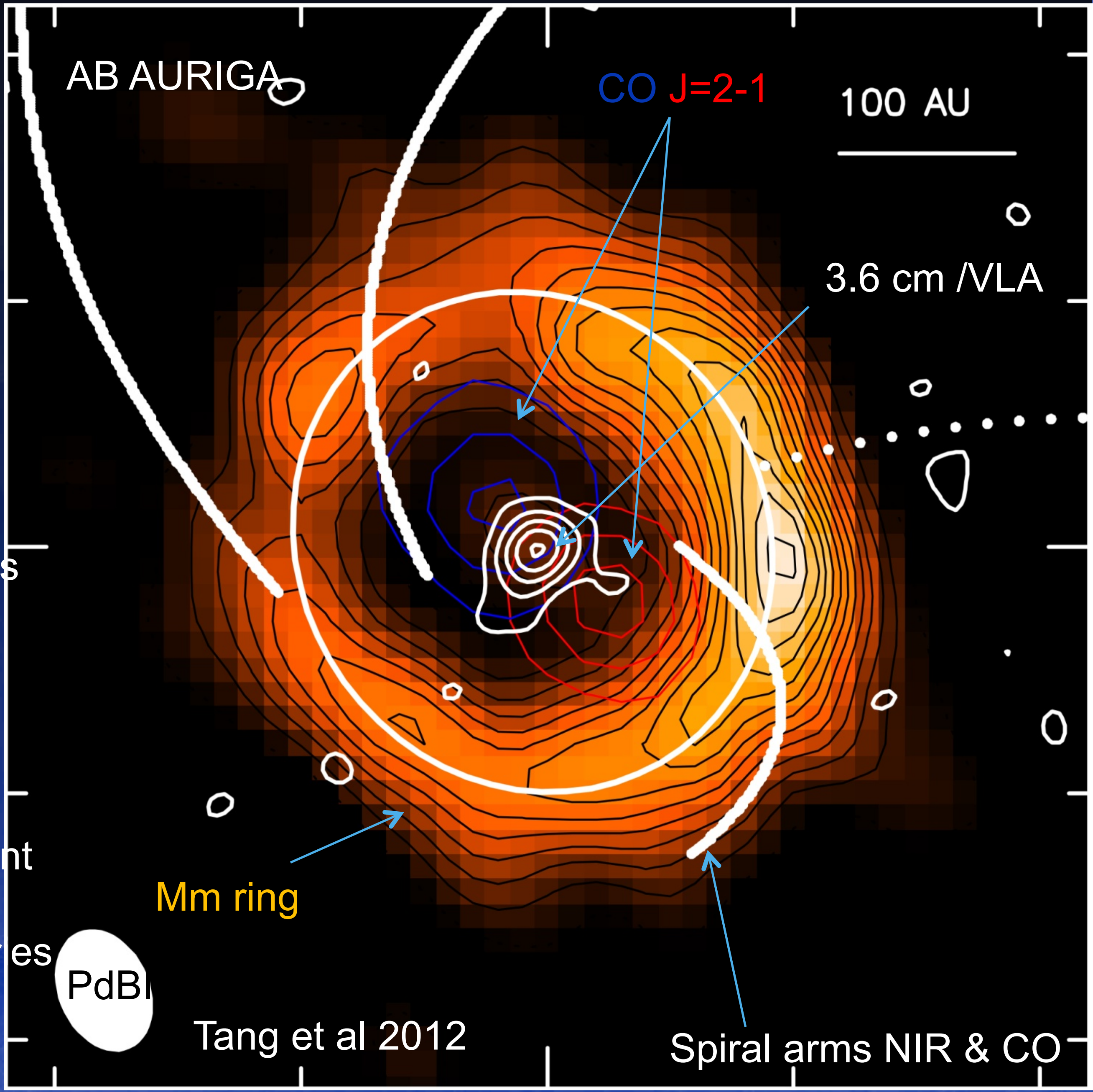
Tang et al 2012

Wide dust gap
Warped disk
Asymmetric dust ring
(intensity contrast

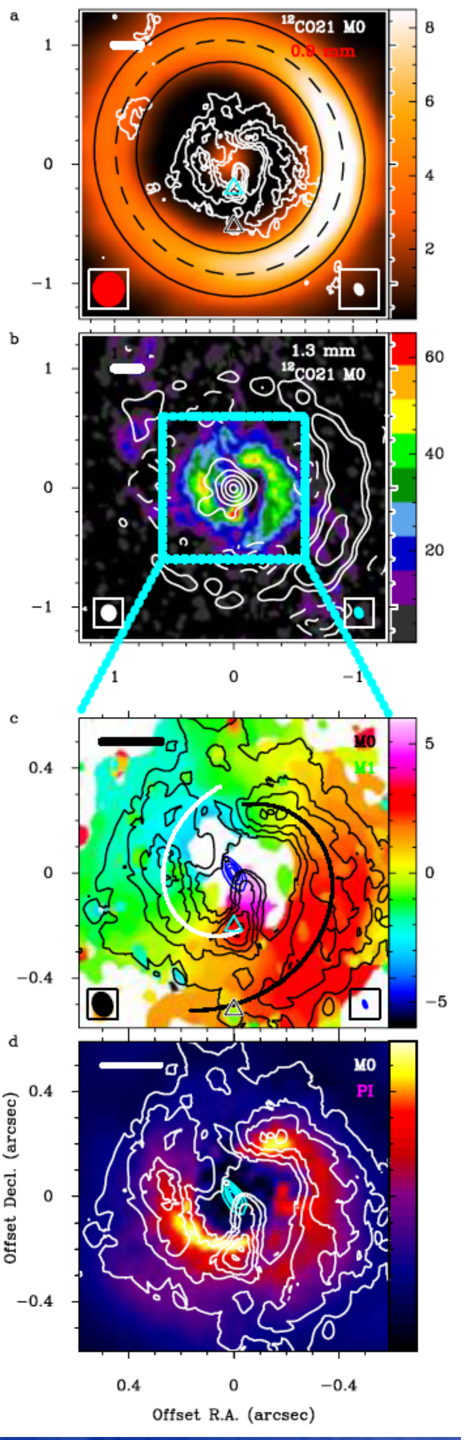
→ at least, one undetected Companion of 0.03 Msun at a radius of 45 AU.

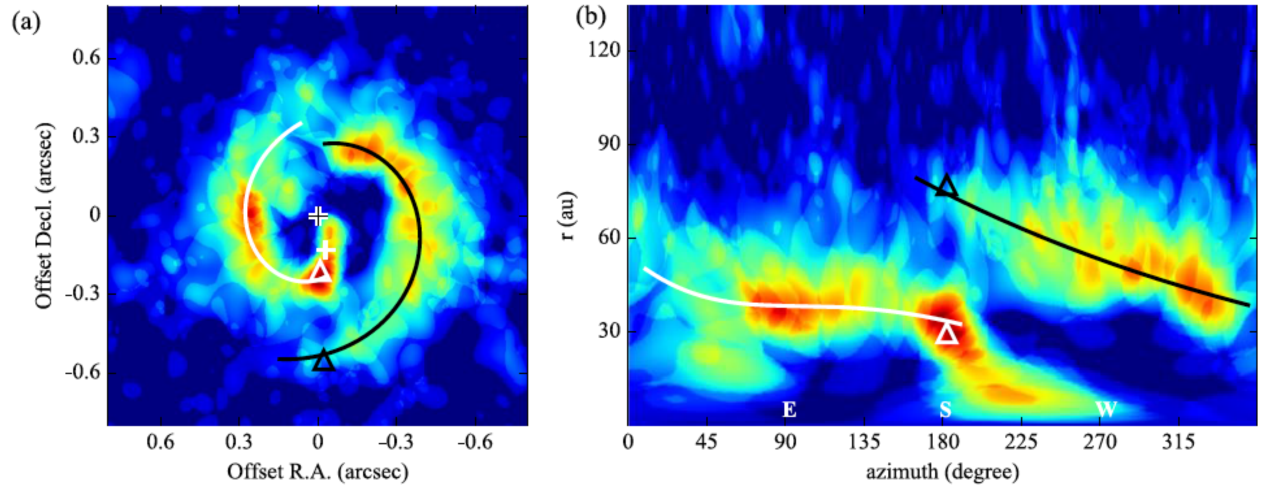
→BUT cannot explain the apparent counter-rotation of the gas in the outer spirals

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



ALMA – CO 2-1 & dust continuum – Tang et al 2017
resolution is 0.07'' or 10 au





(Location of possible planets: Dong et al 2015)

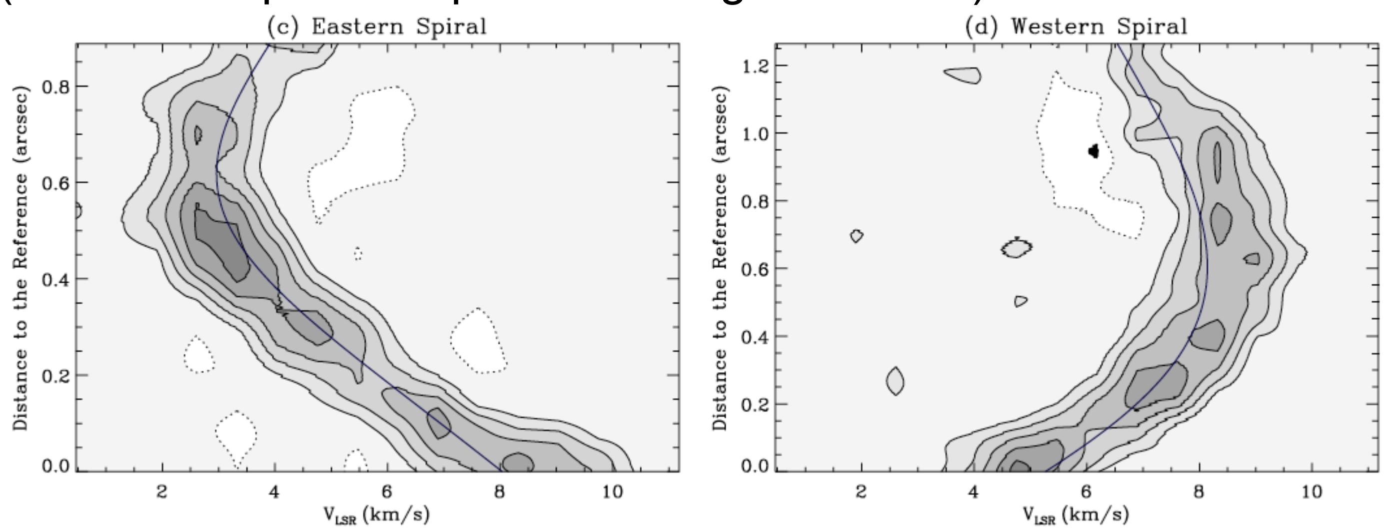
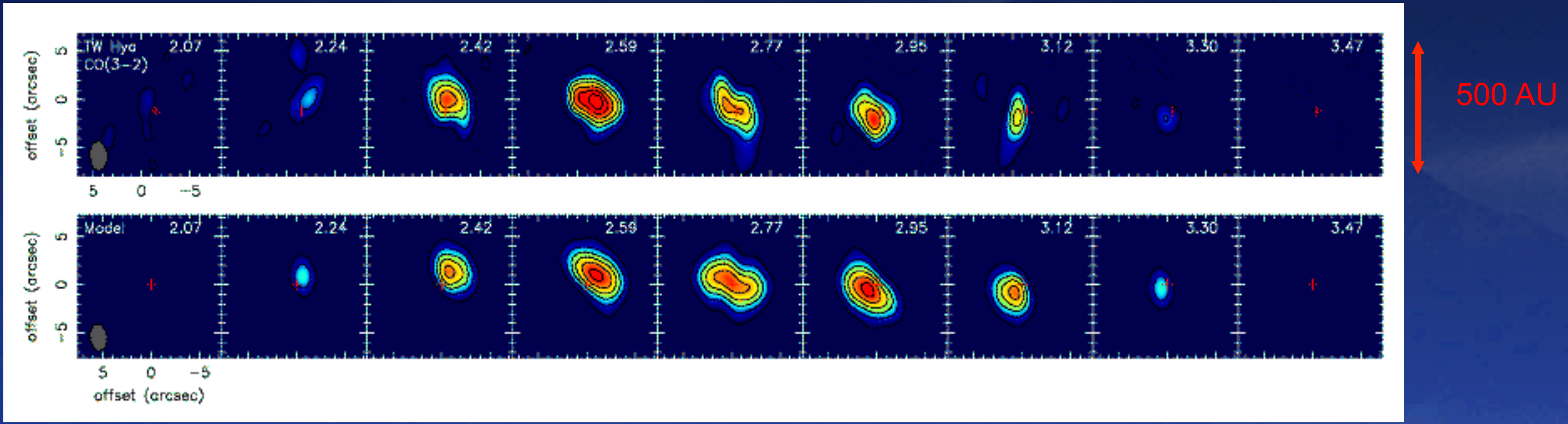


FIG. 3.— (a): De-projected moment 0 map of ^{12}CO 2-1 emission. The arcs and pluses mark the best fit spiral and the origins of the best-fit in corresponding colors. The triangles mark the possible locations of the planets. (b): De-projected moment 0 map of ^{12}CO in polar coordinate. The rest of the symbols are the same as in panel a. (c) and (d): Position-velocity plots of ^{12}CO 2-1 along the eastern and western spirals marked in panel a. The x-axis is v_{LSR} in units of km/s, and the y-axis is the distance to the starting point of the arm, which is the near end toward the star of the arm, in units of arcsecond. The contours are -3, 3, 6, 9, 12 and 15σ, where 1 σ is 0.16 mJy per $0.''11$ beam. The curves mark the expected Keplerian velocity with stellar mass of 2.4 $M_\odot$ and an inclination angle of 23.2° (solid line)

TW Hya the closest T Tauri 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 (7°)
- Dust depleted cavity R < 4 AU (Hughes et al 2009)

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



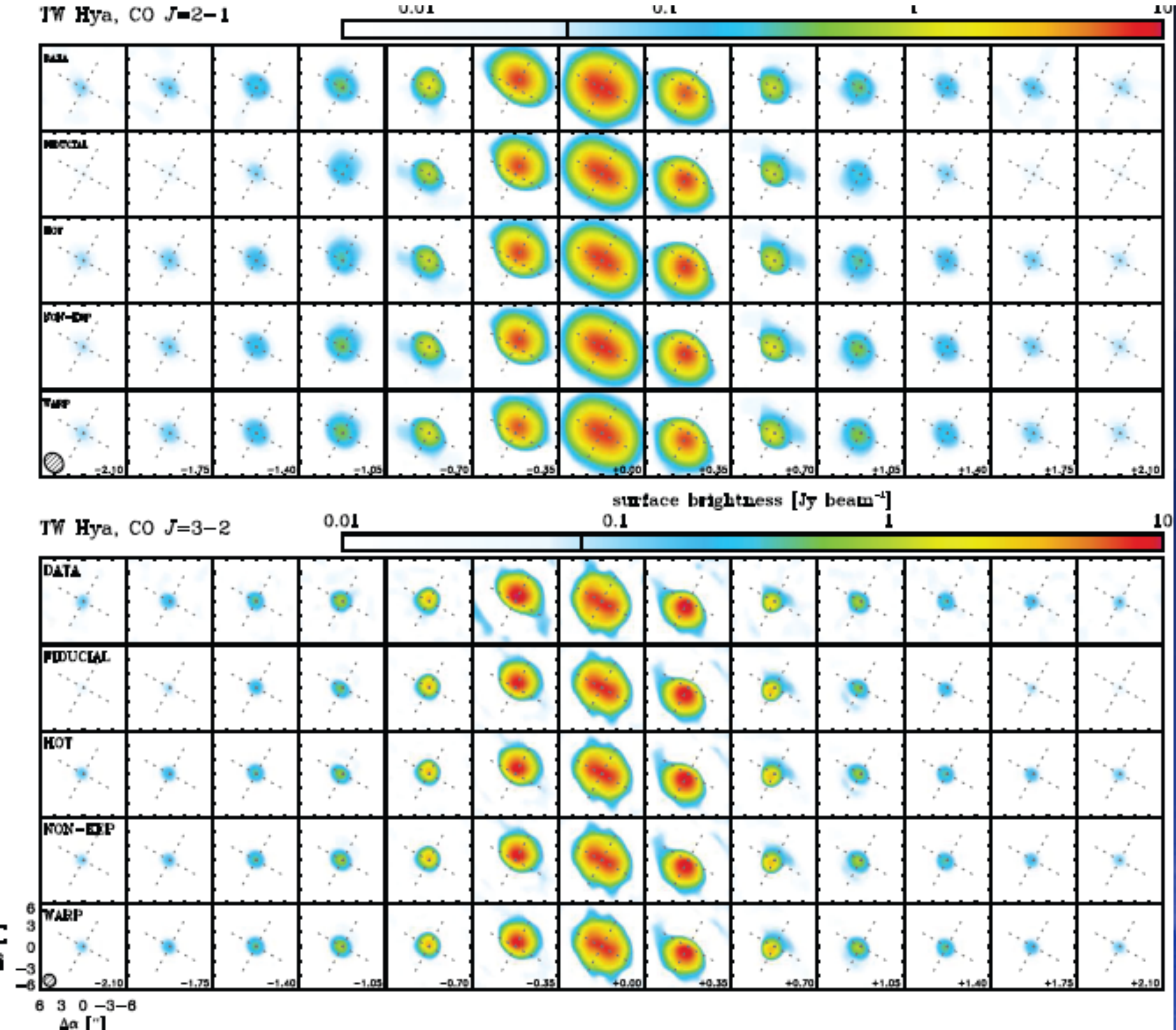
SMA data, Resolution ~ 3’’

Qi et al. 2004, 2006

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

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

Rosenfeld et al 2012, ALMA Science verification time:



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, ALMA Science verification time:

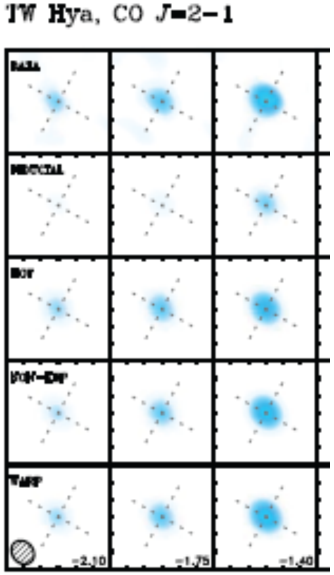
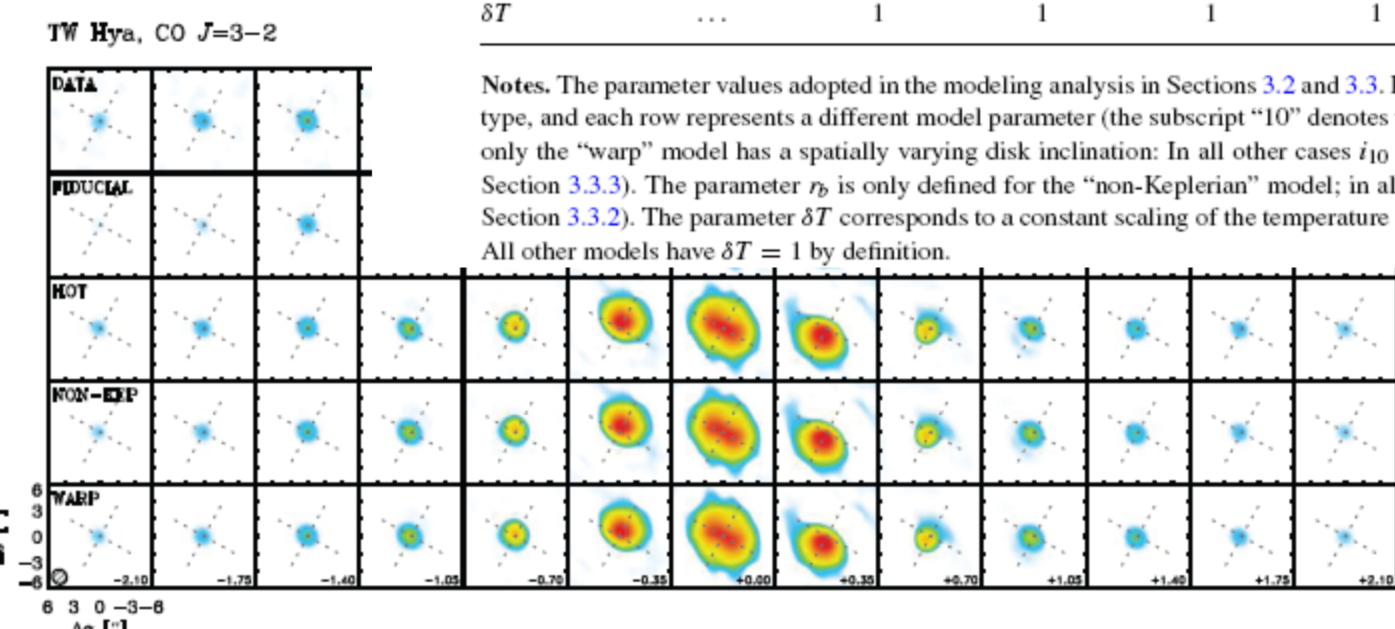


Table 2
Model Parameters

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 – Gas Disk Properties

- A CO disk from ~2 au to 120 au (several studies)
  - inclination ~ 7° - almost face-on
  - maybe an inner warp
  - A CO snowline at about 20 au from star, beyond CO freezes out onto grains
  - In overall, CO abundance (H_2) is less than 10^{-4} (e.g. Favre et al 2013)

- Other « classical molecules:
  - CS, CN, HCO^+, H_2CO, HCO^+ ...

- Thanks to a closer distance: several molecules detected

  - DCN (ALMA), DCO^+ (SMA) (Oberg et al 2012)
  - H_2O (Herschel, Hogerheijde et al 2011)
  - N_2H^+ (ALMA, Qi et al 2013)
  - HD (Herschel, Bergin et al 2013)
  - NH_3 (Herschel, Salinas et 2016)
  - CH_3OH (ALMA, Walsh et 2016)

  - HD → reanalysed by Schwartz et al 2016 based on a better study of the gas temperature using several lines of ^{12}CO, ^{13}CO and $C^{18}O$ to better constrain the vertical temperature gradient

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

By Bergin et al 2013, Nature

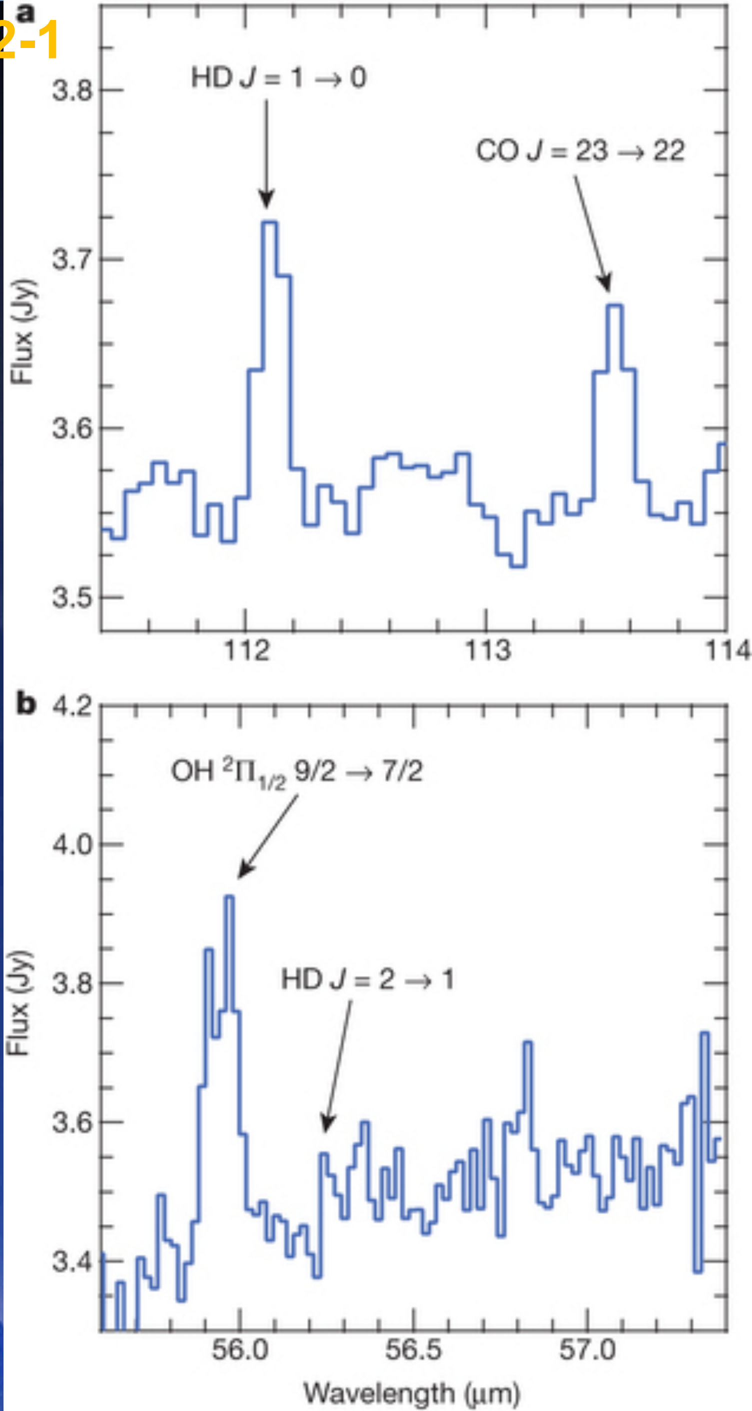
→ Almost a direct measurement of the GAS Mass !

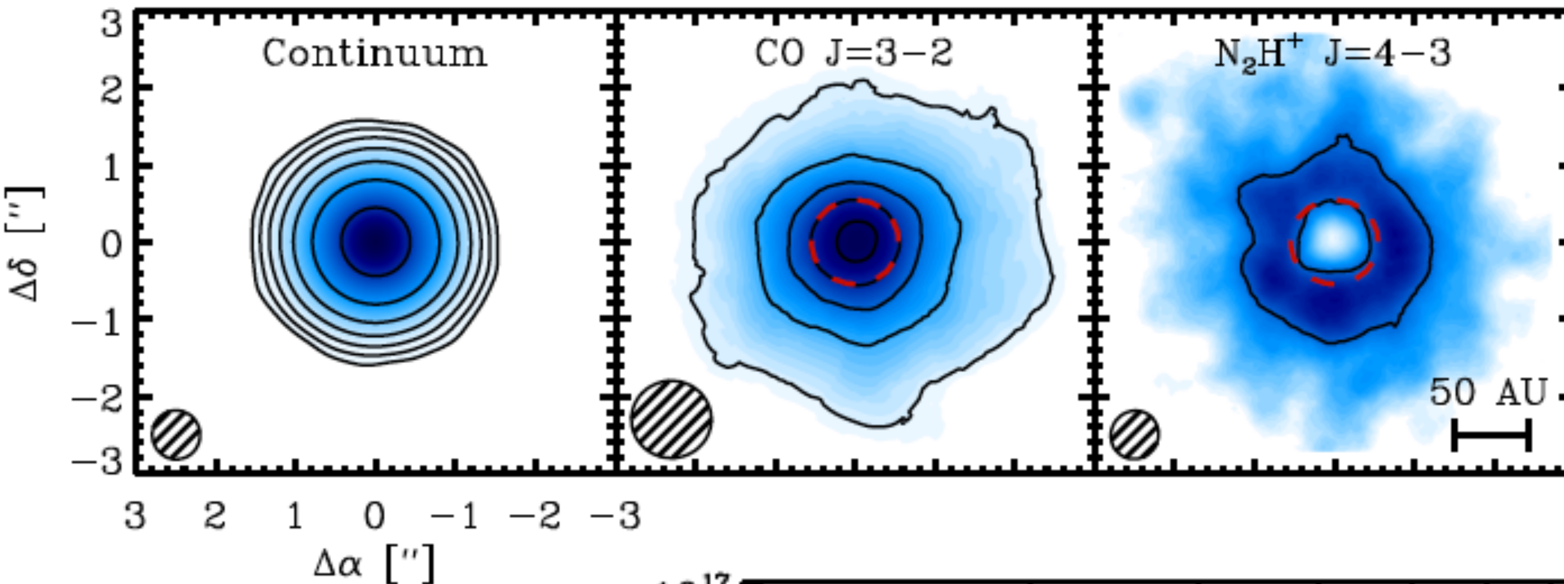

©NASA/JPL

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 *: massive enough to form a planetary system*

→ *Main uncertainty – Gas temperature* ***Tgas(r,z)***
(Schwartz et al 2016)
→ *Seen face-on: no access to the altitude z !*





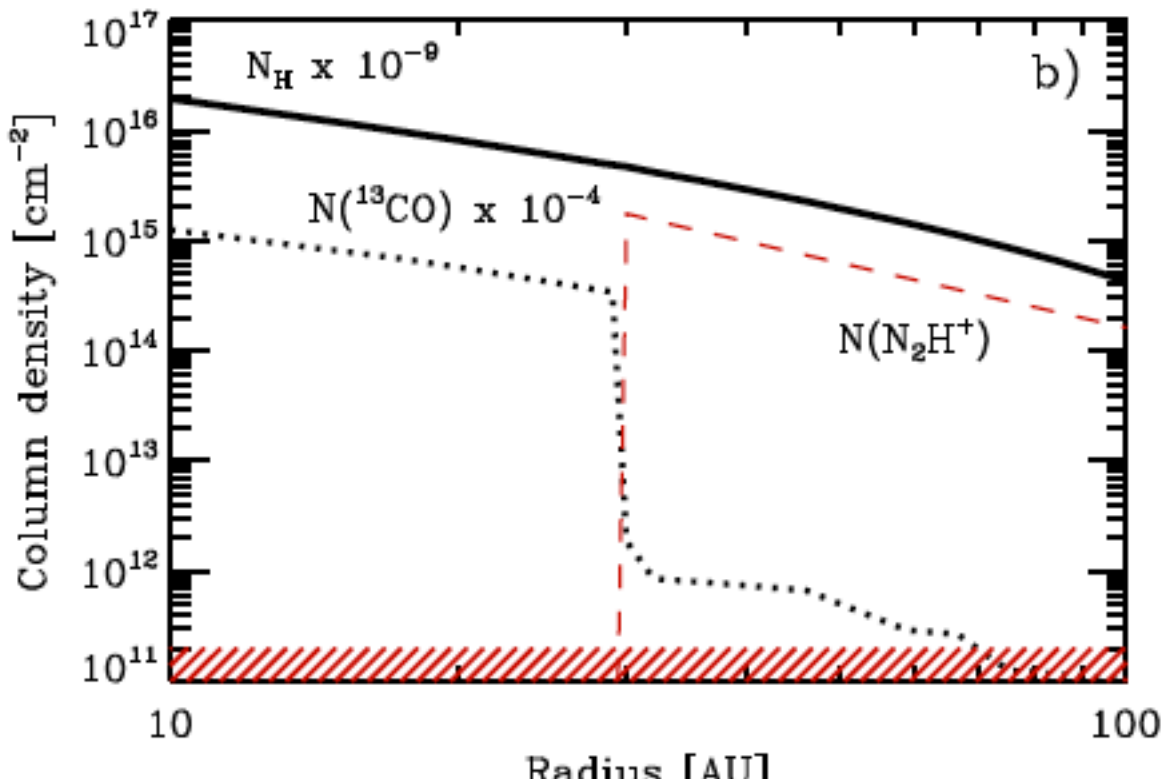
TW Hydra : ALMA (N_2H^+)
Qi et al 2013

CO snowline at 30 au

N_2H^+ ring because in inner disk:

$N_2H^+ + CO \rightarrow N_2 + HCO^+$

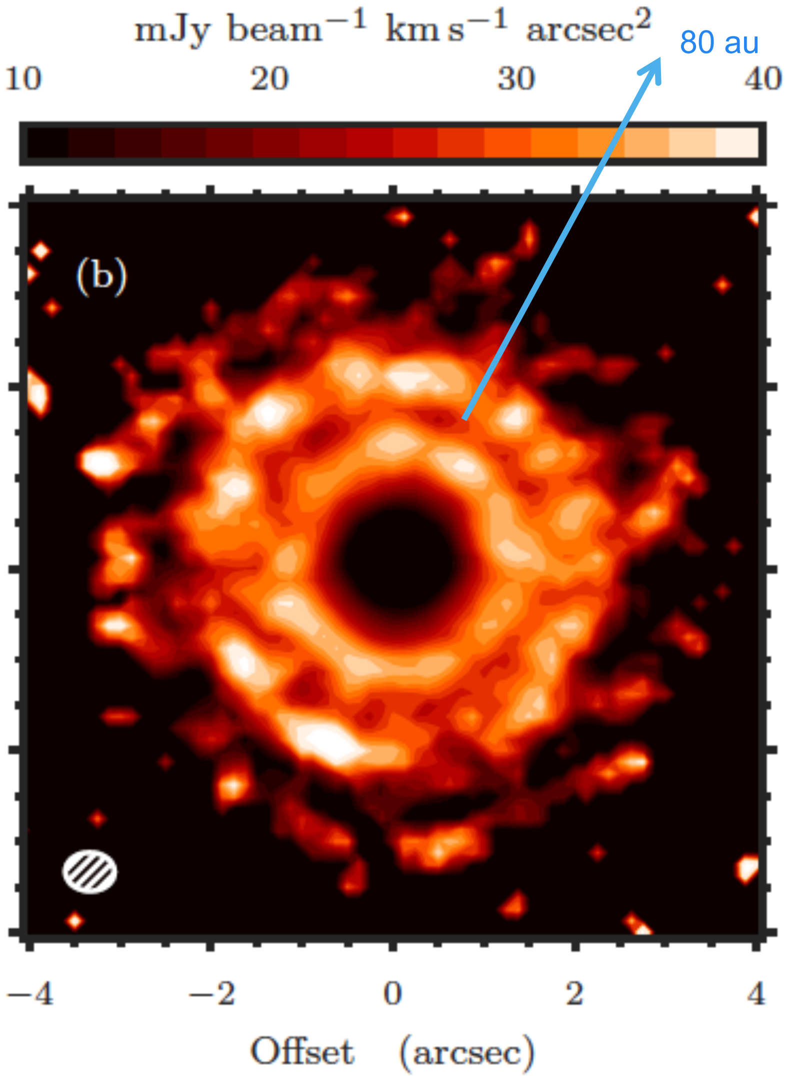
→ ***Chemical difference***

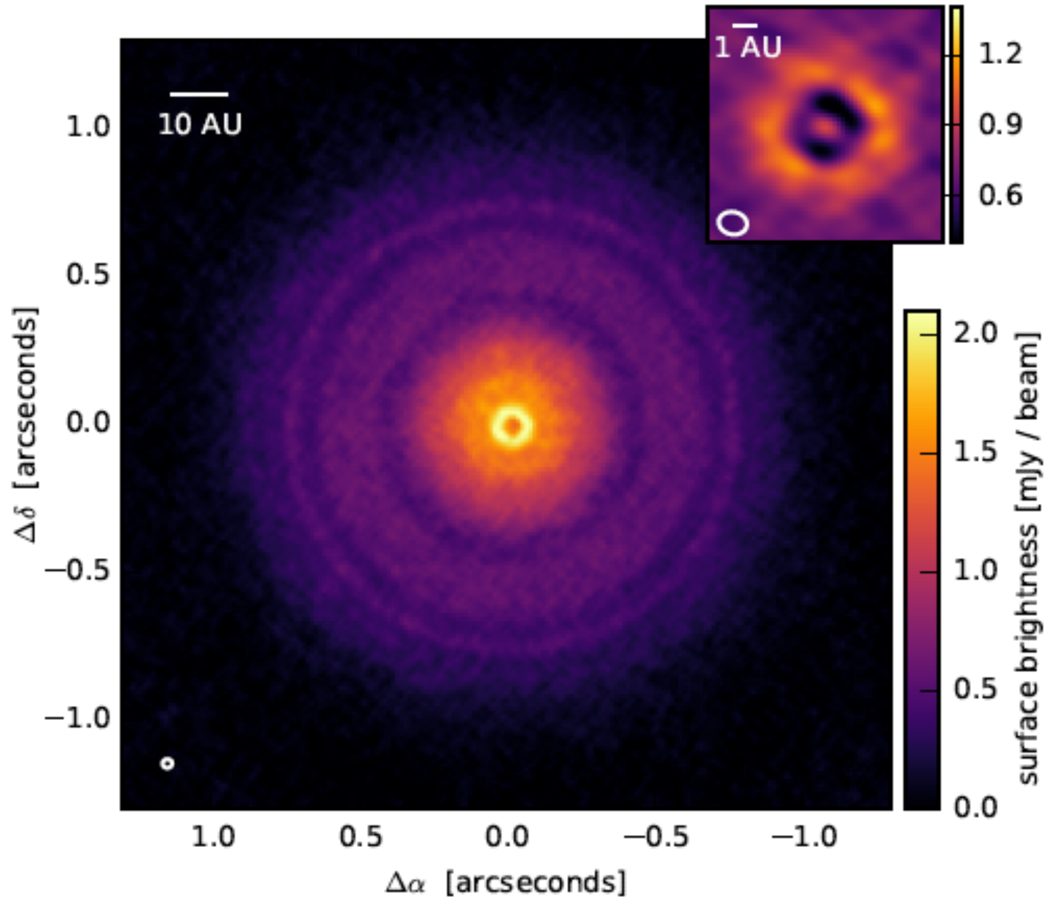


TW Hya the closest disk (~ 55 pc) - DUST DISK

NIR Debes et al 2013

Mm ALMA Andrews et al 2016

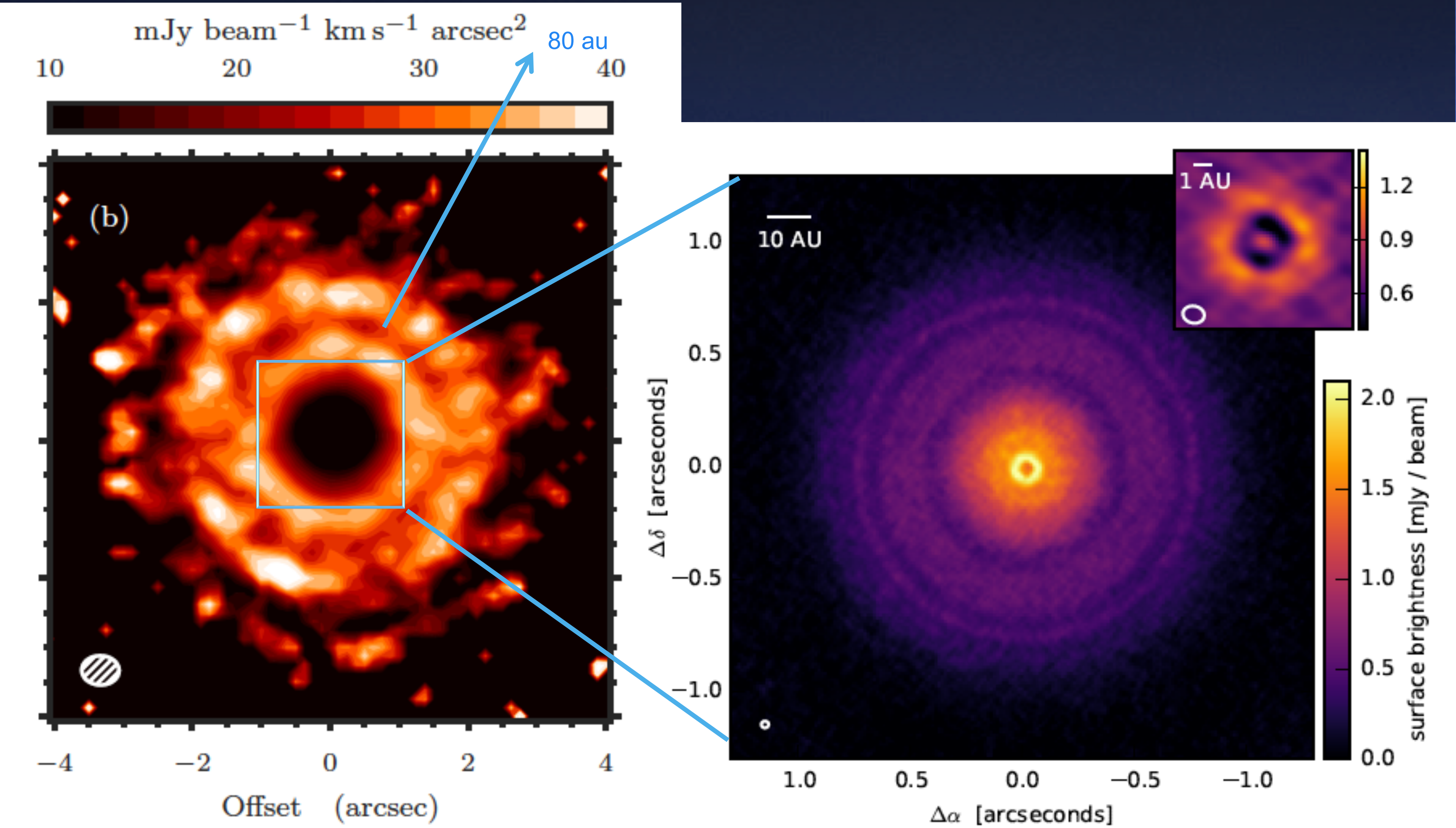




TW Hya the closest disk (~ 55 pc) - DUST DISK

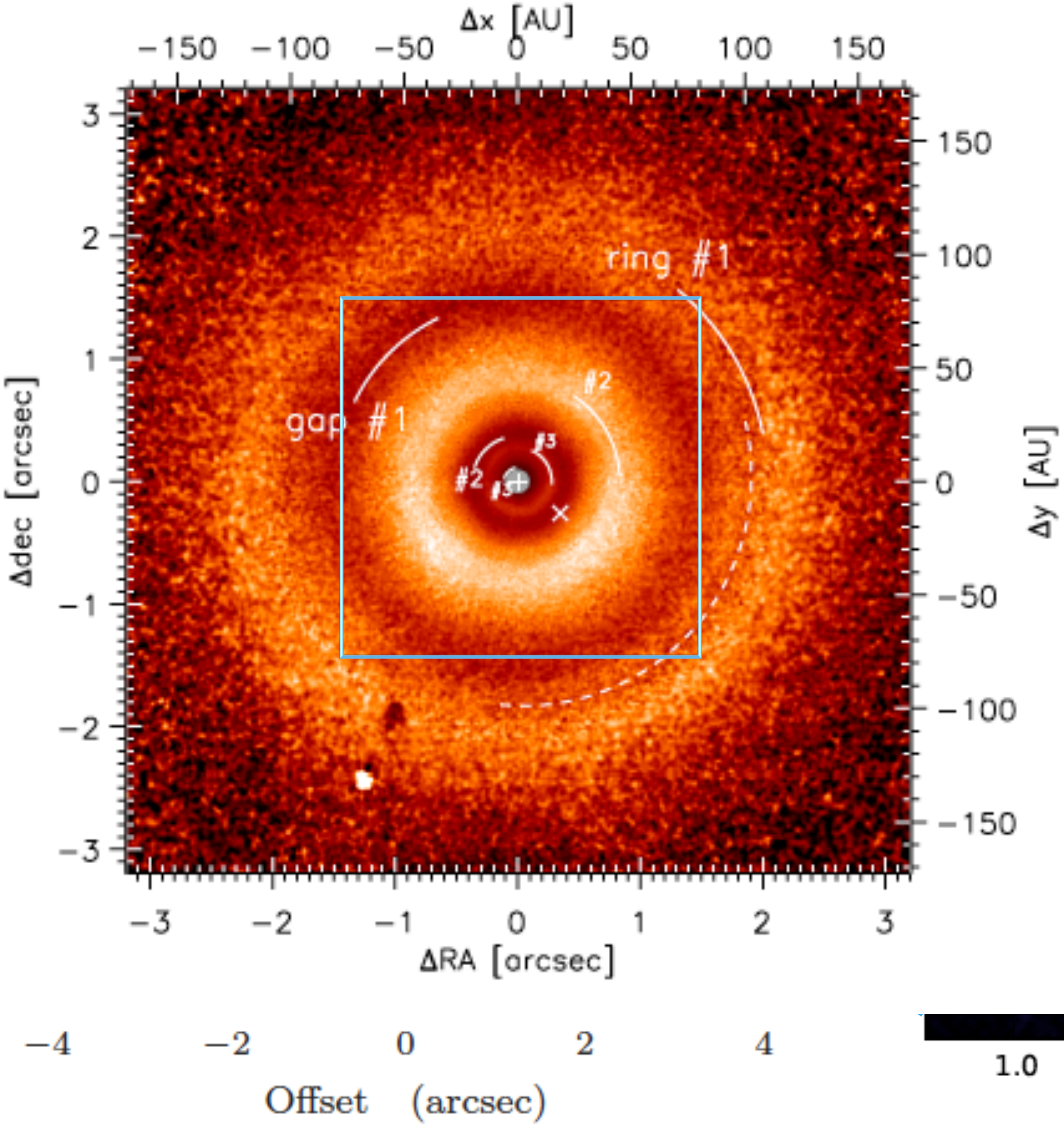
NIR Debes et al 2013

Mm ALMA Andrews et al 2016

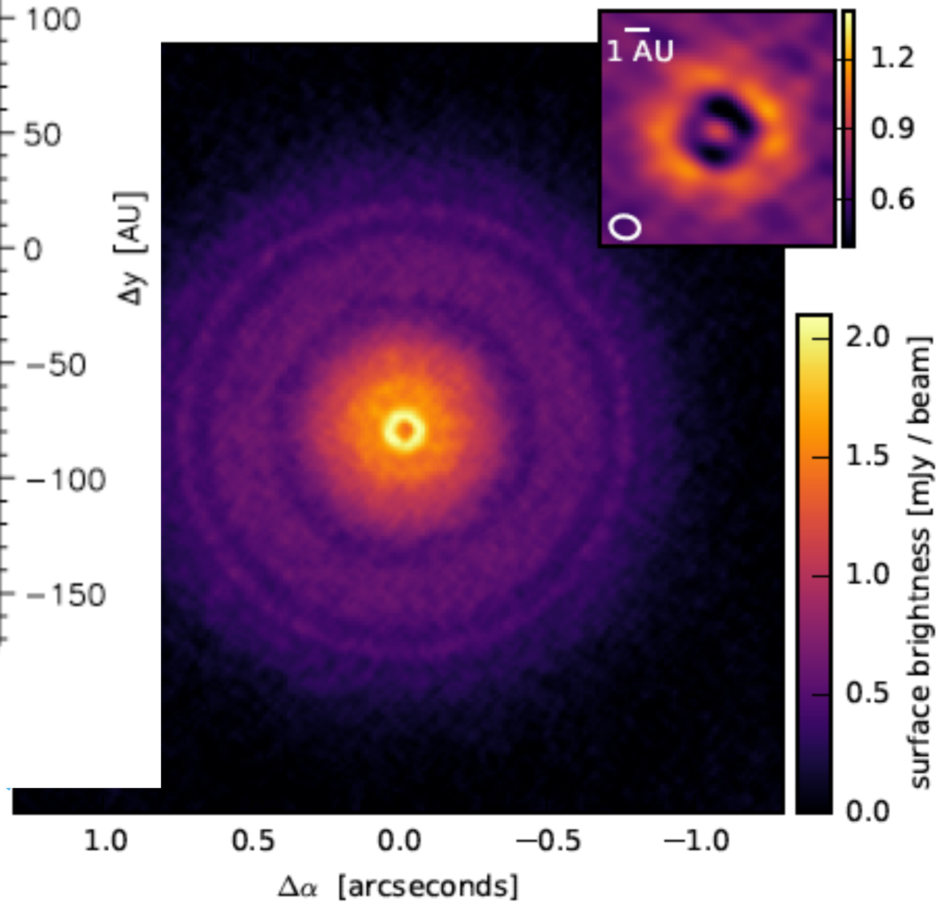


TW Hya the closest disk (~ 55 pc) - DUST DISK

Van Boeckel et al. 2017 – SPHERE – J band

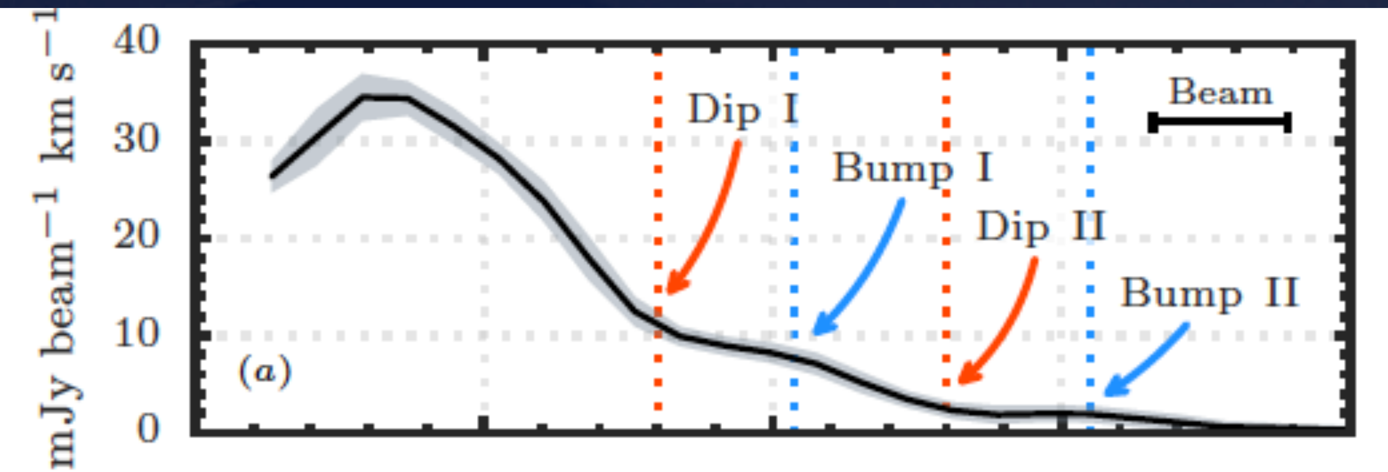


Mm ALMA Andrews et al 2016



Teague et al 2017 ALMA - CS 5-4 at 0.5 '' or 27 au

+ 1.6'' dip is coincident in location, depth and width with features observed in dust scattered light at near-infrared wavelengths.
+ 3.1'' bump: a region of intensified desorption due to enhanced penetration of UV Radiation at edge of disk surface density (photochemical processing of gas and ices)

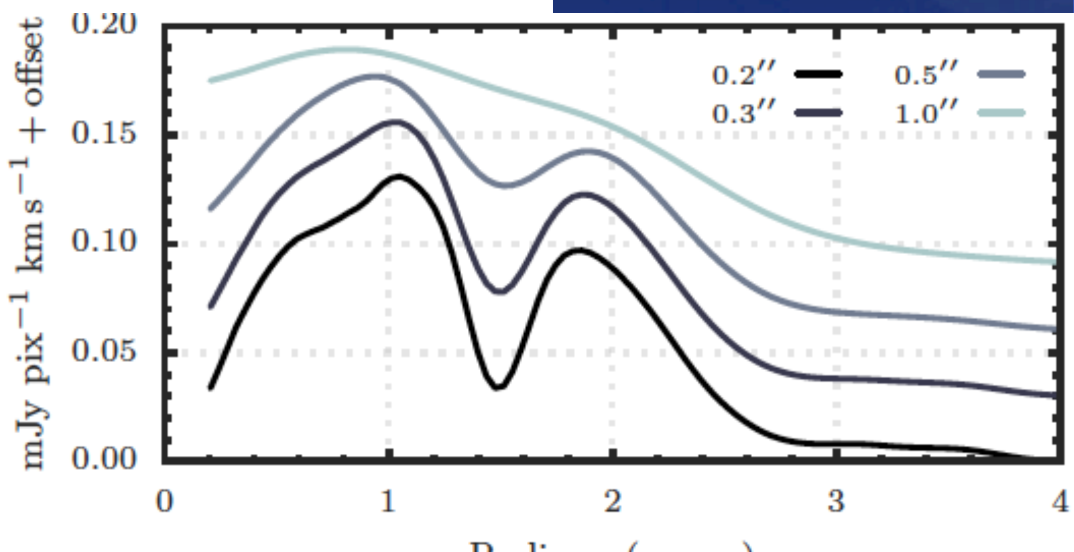


- Dip at 90 au 30-55 %
- Enhancement at 120 au

Impact of UV field onto the CS distribution

Thermo-chemical model

+ Non-LTE calculations (LIME)

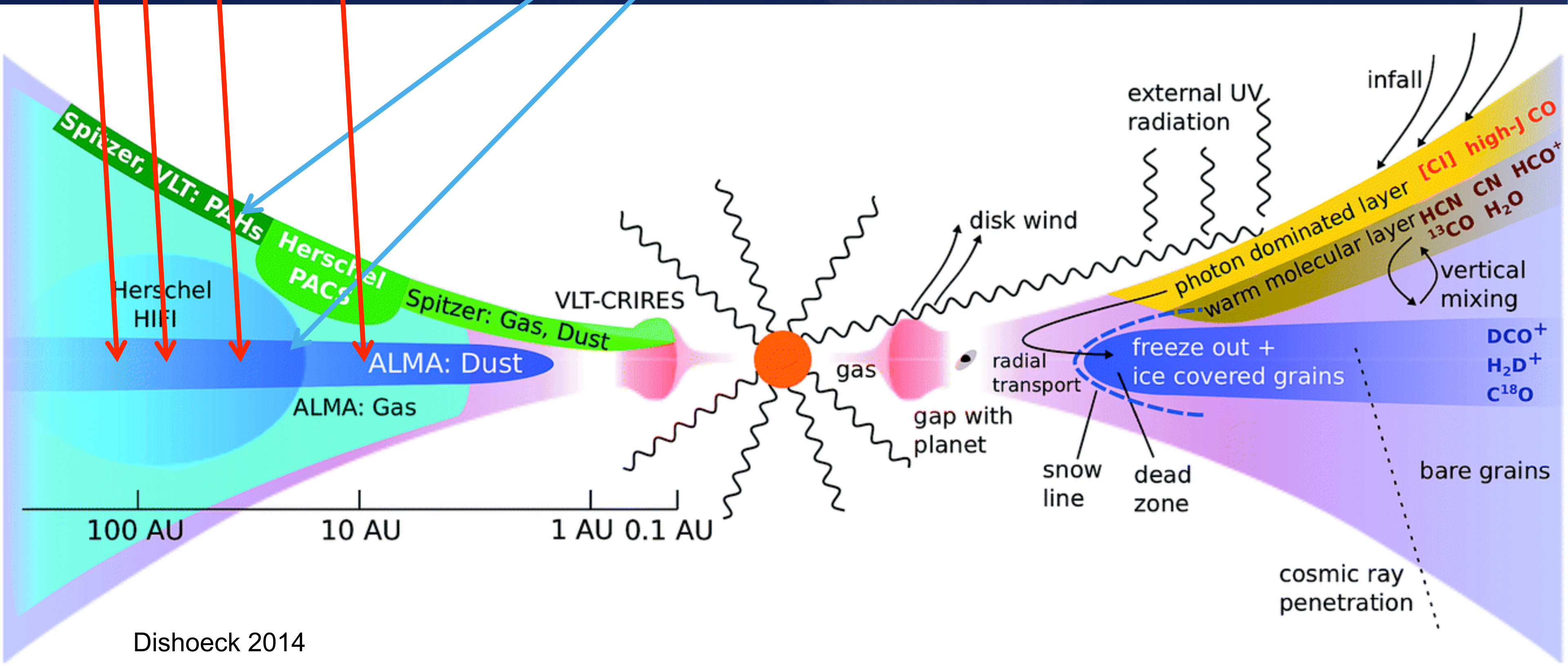


Protoplanetary disks - Summary

Spirals detected at disk surface and mid-plane in dust and CO emissions in one case, at least, inside a large cavity

Gaps and multiple rings, several cases

(large) cavities in CO gas and dust are common



Dishoeck 2014

Protoplanetary disks - Summary

Spirals detected at disk surface and mid-plane in dust and CO emissions in one case, at least, inside a large cavity

Gaps and multiple rings, several cases

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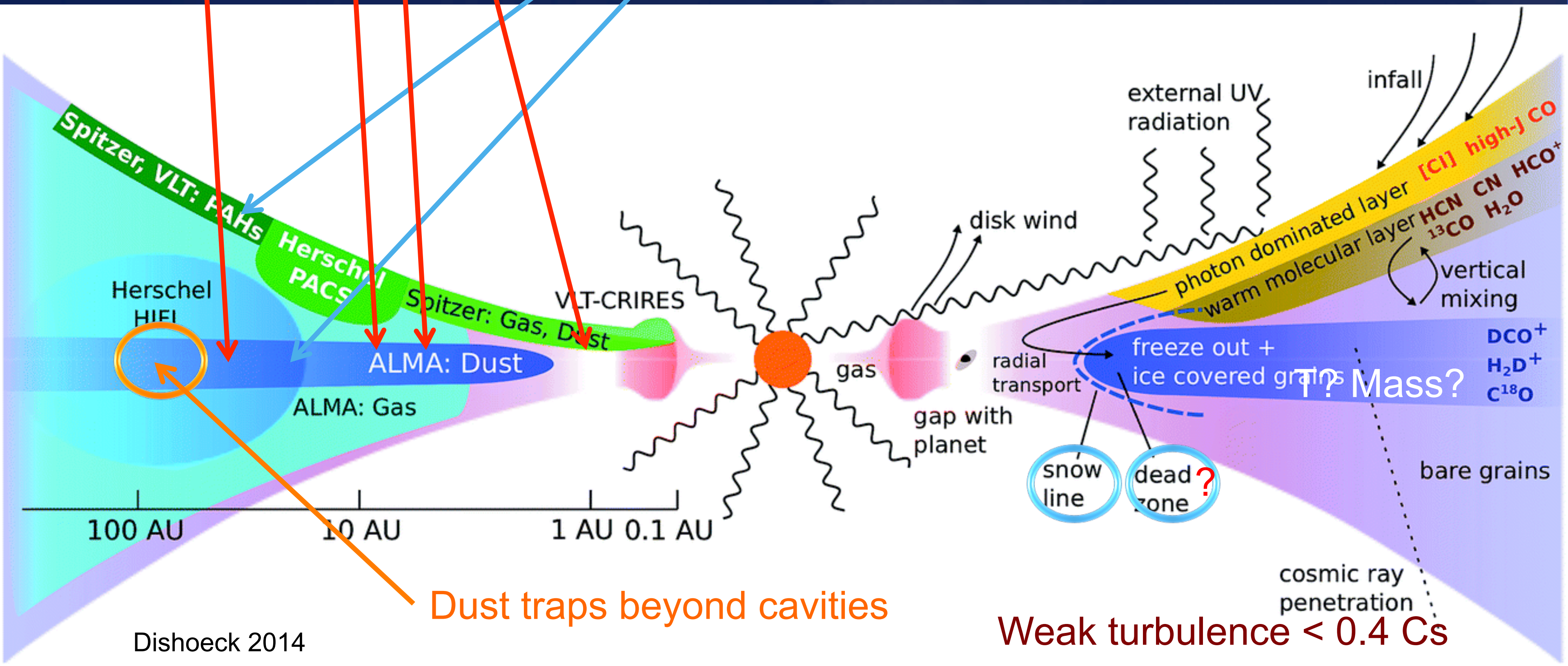
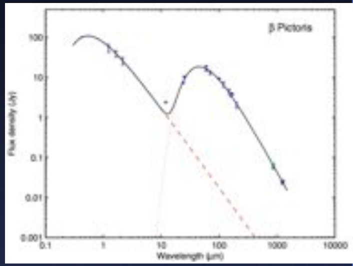


Dust traps beyond cavities

Weak turbulence < 0.4 Cs

Dishoeck 2014

Circumstellar Disks around > 10-100 Myr stars
→ Different kinds of objects …



- PMS stars: WTTS (weak acc.lines), NNTS (no IR excess)
- MS stars: debris disks, Exo-zodii disks, kuiper-belt disks…

→ Many new dectetions of warm dust thanks to Herschel:

DUNES (FJK*): Eiroa et al 2013, DEBRIS (A to M *): Matthews et al 2010...

Class II → Class III gas and dust have dissipated

Disk Masses: 0.01 Msun →

→ dust is of second generation:

- small dust particles are resulting from collisions of planetesimals (regular replenishment needed because small dust particles are pushed by radiation pression)

+ Debris disks (maybe associated to a young planetary system)

$F = L_{ir}/L_{*} << 1$

Gas and dust are secondary - low mass disk << M_*

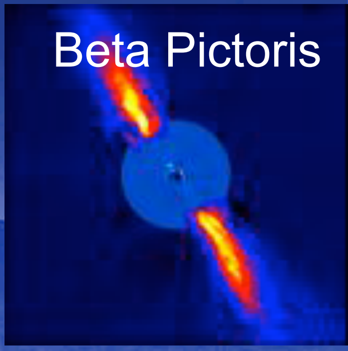
- Gas poor with low Gas/Dust < 0.1 - Mgas << Mdust

→ some ionized species (Fe II , Al III , C IV and Mg II) :
the " Falling Evaporating Bodies" Scenario (FEB, Beust et al 1990, …)

some mm (cold) CO: destruction of planetesimals ?

→ Dust emission is optically thin from optical to mm range

- very low mm dust emission



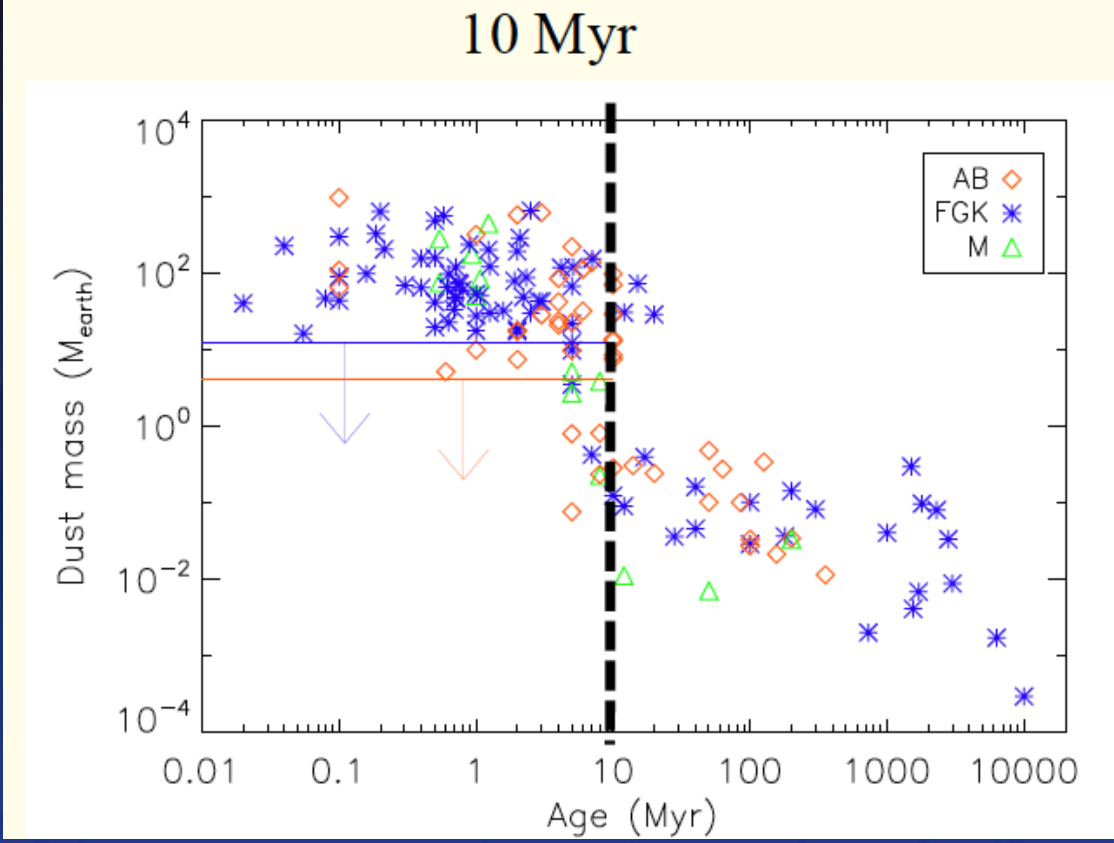
Comparison Protoplanetary/Evolved Disks

Protoplanetary Disks:

- Dust from 0.1 – 100 AU
- Massive gas disk
- Molecular Gas (H_2, CO …)
- Accretion onto star
- Optically thick dust emission

Debris Disks:

- Dust observed in belts
- No (extended) gas emission
- FEB
- No accretion
- Optically thin dust emission



Panic et al 2013, MNRAS

Masses of DUST disks: pp ~3.10^{-4} Msun → 3.10^{-7} MSun

Planet Formation in evolved Disks

Many gaps and rings observed, interpretated as due planet/disk interactions

Some planets have been detected around stars where debris disks (IR) are observed e.g.

- HD106096 b :

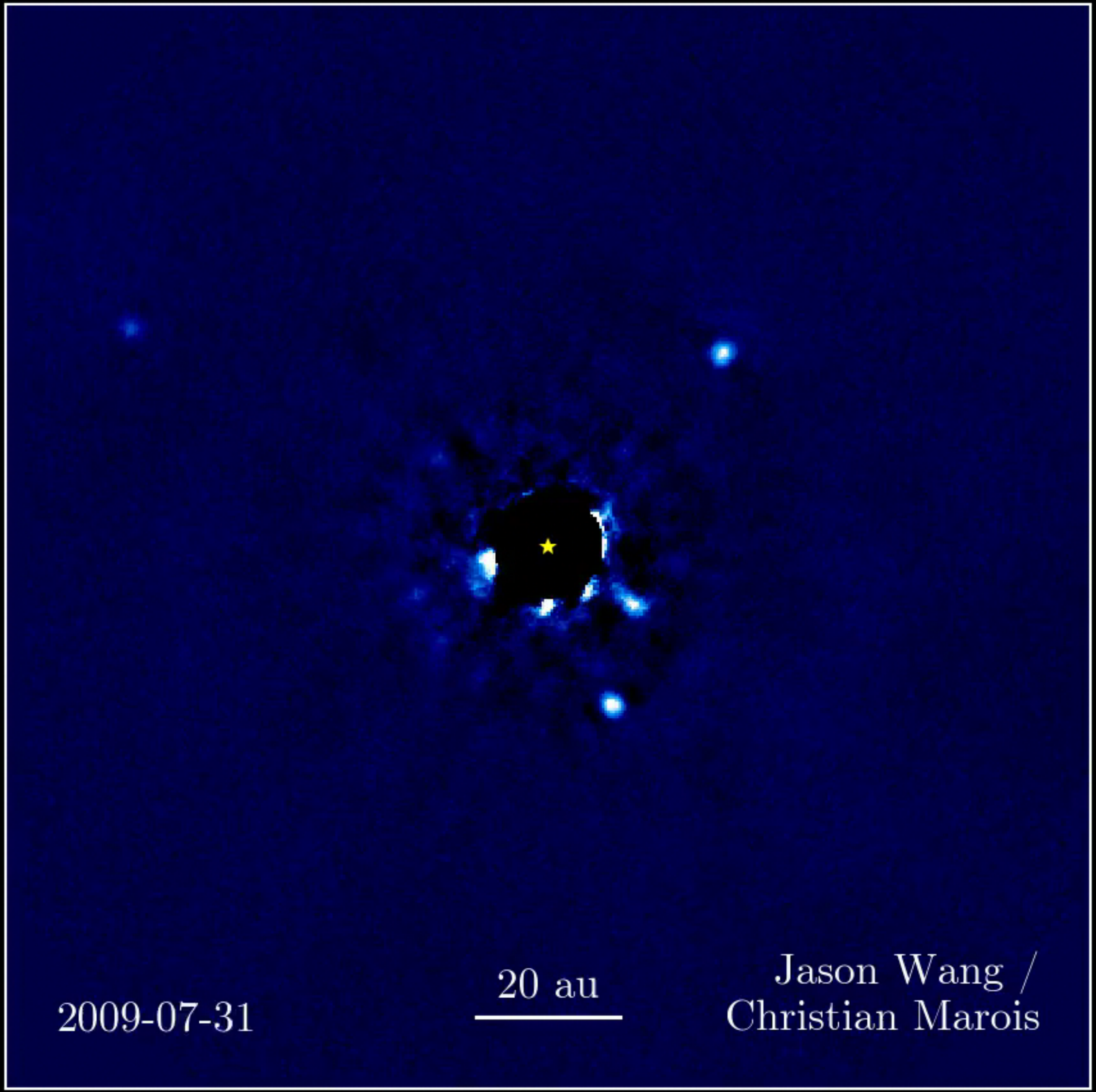
  - planet is at 7arcsec (or 650 au in projection), Bailey et al. 2014
  - disk resolved by SPHERE and GPI with radius of 65 au
  Lagrange et al. 2016, Kalas et al. 2016
  → Planet should be at 2000/3000 au if in the disk plane

- HR8799 :
  - 4 planets from 16 to 68 au, Marois et al. 2009, 2010
  - disk resolved by Herschel and ALMA (150-400 au)
  Booth et al. 2016, Matthews et al. 2014.

- HD95086 b :
  - 1 planet at 56 au, Rameau et al. 2013

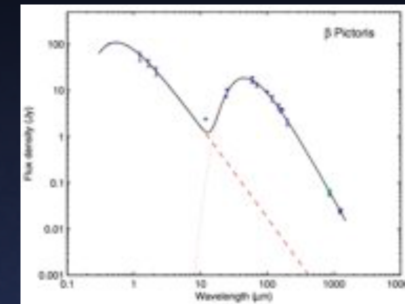
- Beta Pictoris b

HR8799 : A movie composed of 7 years of observations using the Keck telescope



Circumstellar Disks around > 10 – 100 Myrs stars

Hybrid Disks



A few disks where classified as “debris disks” based on their NIR dust

Properties

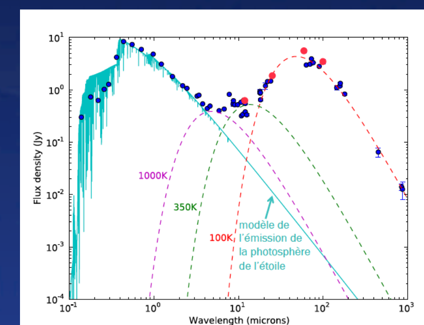
Recent (~>2000) observations reveal that they still harbor a large amount of CO gas

- 49 Ceti (40 Myr, Moor et al. 2001, ApJ 740)
- HD21997 (30 Myr, Kospal et al. 2013, astroph 1310.5068)
- HD141569 (5 Myr, Dent et al. 2005, MNRAS 359).

- more and more CO detections

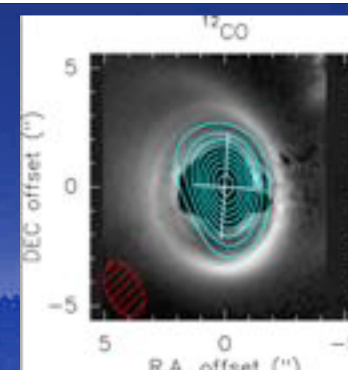
→ A new class of disks: Hybrid disks

HD141569



- gas is mostly/partly primordial
- dust emission is very weak from NIR (opt. thin) to mm range

-→ attempt to derive a GasDust ratio in some cases



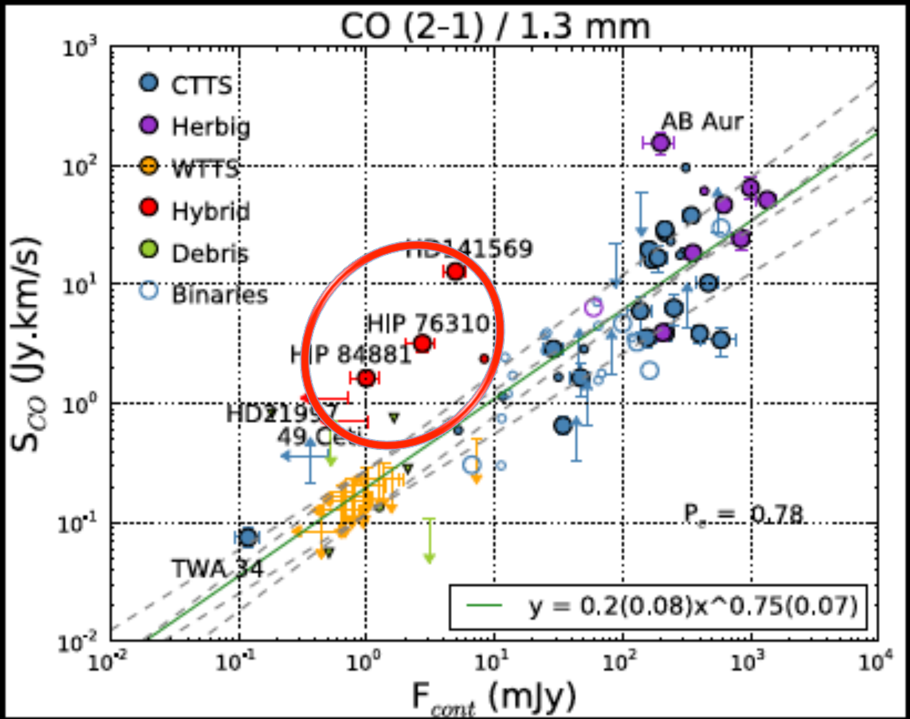
dust is of second generation:

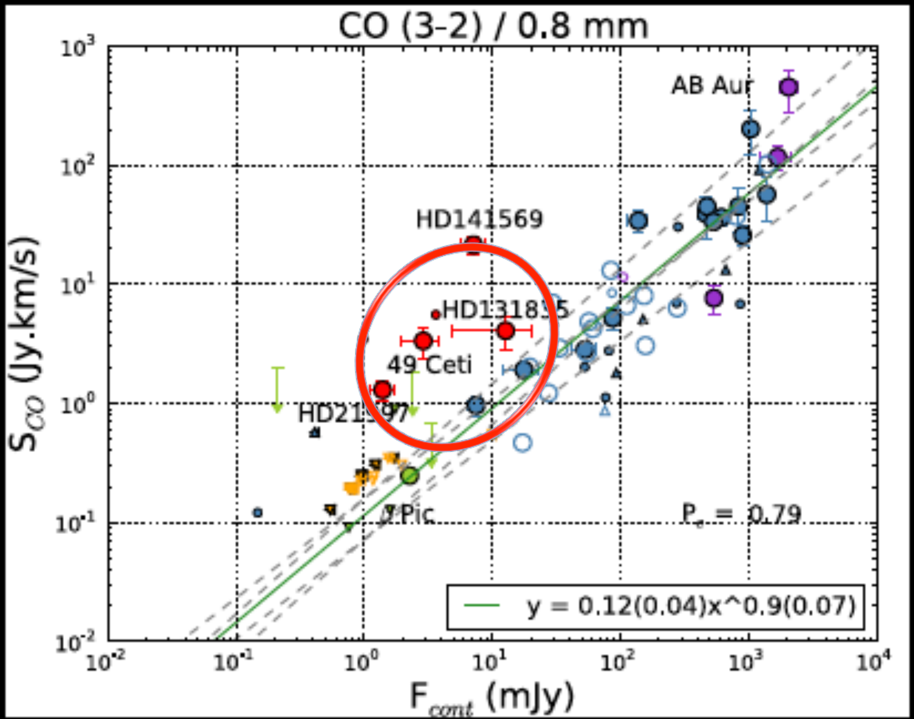
- small dust particles are resulting from collisions of planetesimals (regular replenishment needed because small dust particles are pushed by radiation pression)

Gas and Dust evolution: a very interesting correlation

116 measurements
103 disks
60 articles (1994-2016)

Hybrid disks are above the correlation
→ 1/ intrinsic …
→ 2/ evolution of Gas and Dust different (dust dissipates first)
-





Pericaud et al 2017 – survey of Herbig Ae, CTTS, WTTS, hybrid and debris disks at 1.3 and 0.8mm and CO 2-1 and 3-2.

Gas and Dust evolution: a very interesting correlation

+ HD141569 or HD21997:
- dust may evolve faster than the gas in a first step
- Then the gas is dissipated

+ Debris disks are expected to lie in the optically thin part

+ Beta Pic position could be higher because of the recent CO gas enhancement

More Observations needed !
Gas/Dust ratio measurements

Sco/Fcont ~1000 → Hybrid disks

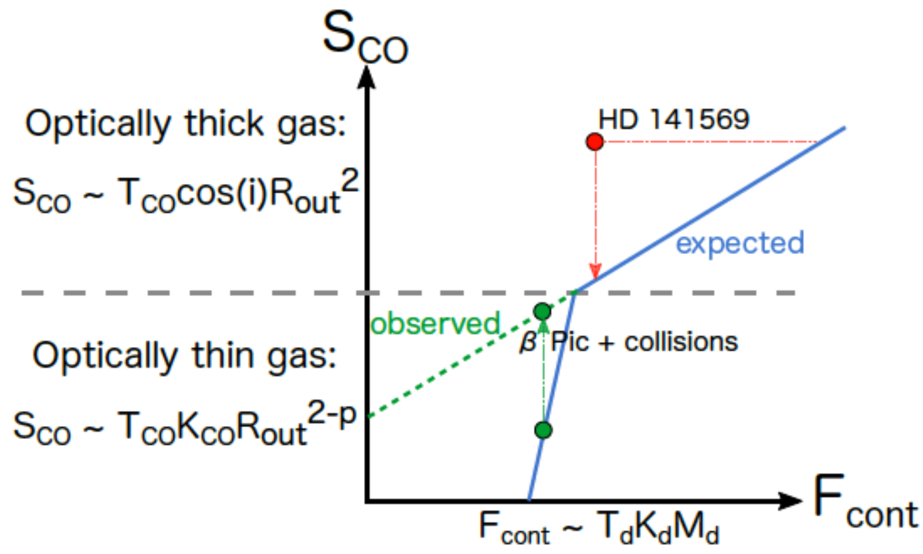


Fig. 13: Diagram showing the physical parameters which dominate the emission of the CO gas and dust (see Section 4.2 for details). The higher part of the plot represents the optically thick regime of the gas, and the lower part represents the optically thin regime. In a hybrid disk such as HD 141569, the dust may evolve faster than the gas in a first step, moving the disk out of the correlation. In a second step, the natural gas dissipation moves downwards in position. On the contrary, debris disks are expected to lie in the optically thin region. For β Pic, the position of the disk in the diagram could be higher than expected because of the gas enhancement produced by collisional events. For both sources, the arrows show the expected path in the diagram resulting from their possible evolutions.

HD21997 – A 30 Myr disk around a A type star at 72 pc

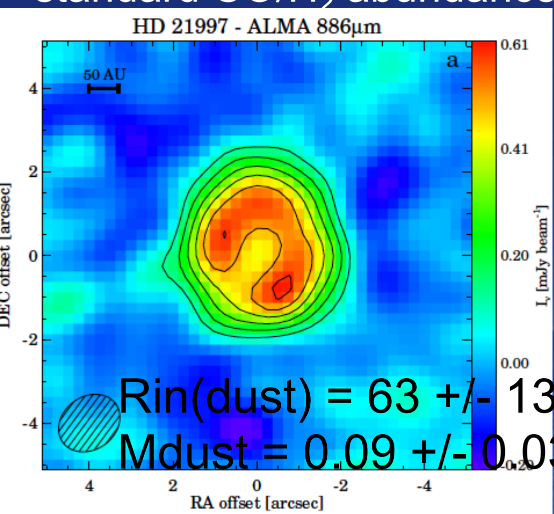
Moor et al 2013, Kospal et al 2014

Best Modelling:

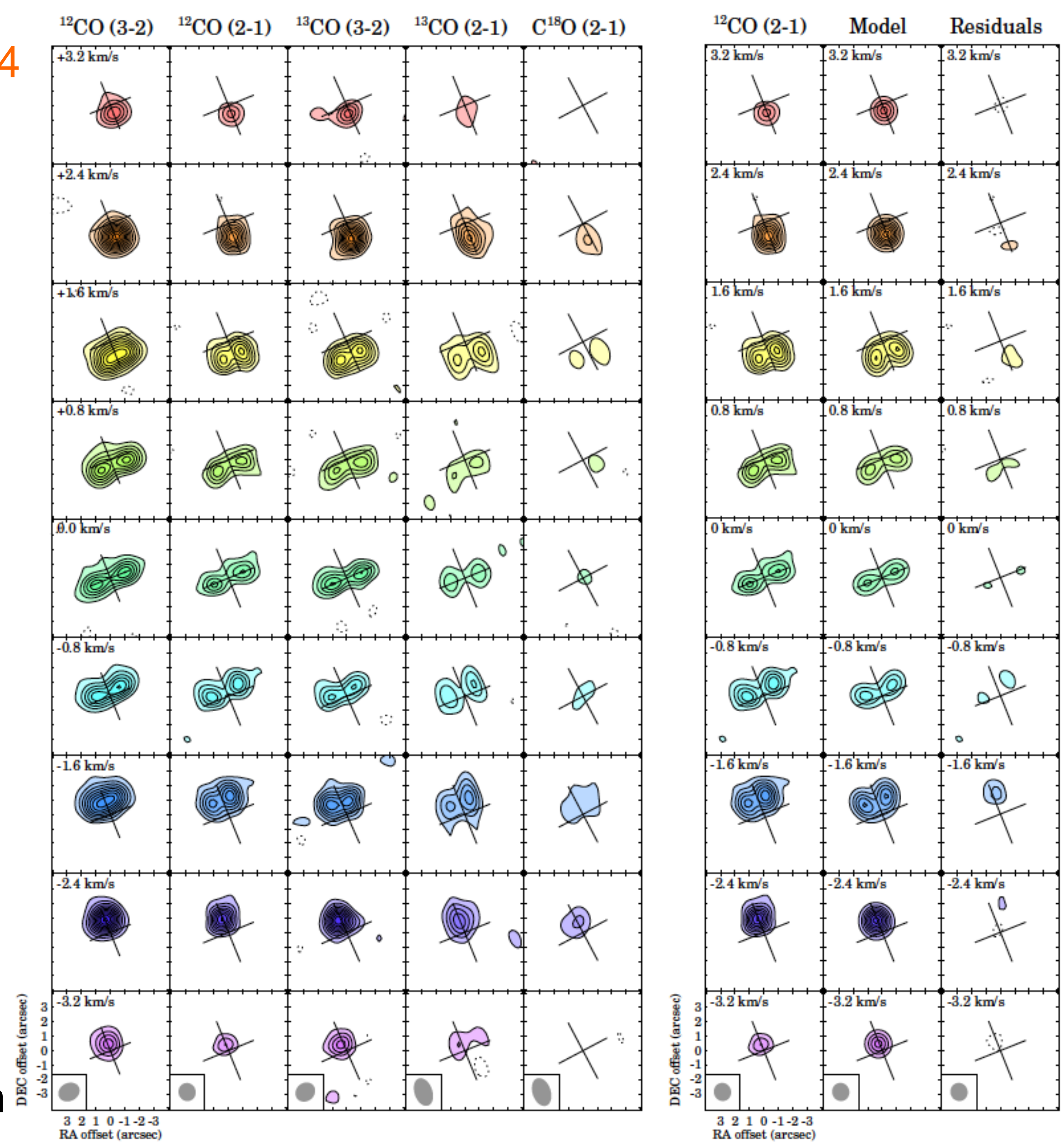
Rin < 26 au, Rout = 138 au
Inclination = 32degrees
Mstar = 1.8 Msun
Gas temperature is very low ~6-9 K

Total CO gas is (4-8) 10^{-2} Mearth
Gas not colocated with mm dust
(gas at 26-55 au where dust free)

Gas/Dust ~ 300 - 700 ? (assuming standard CO/H_2 abundance of 10^{-4})



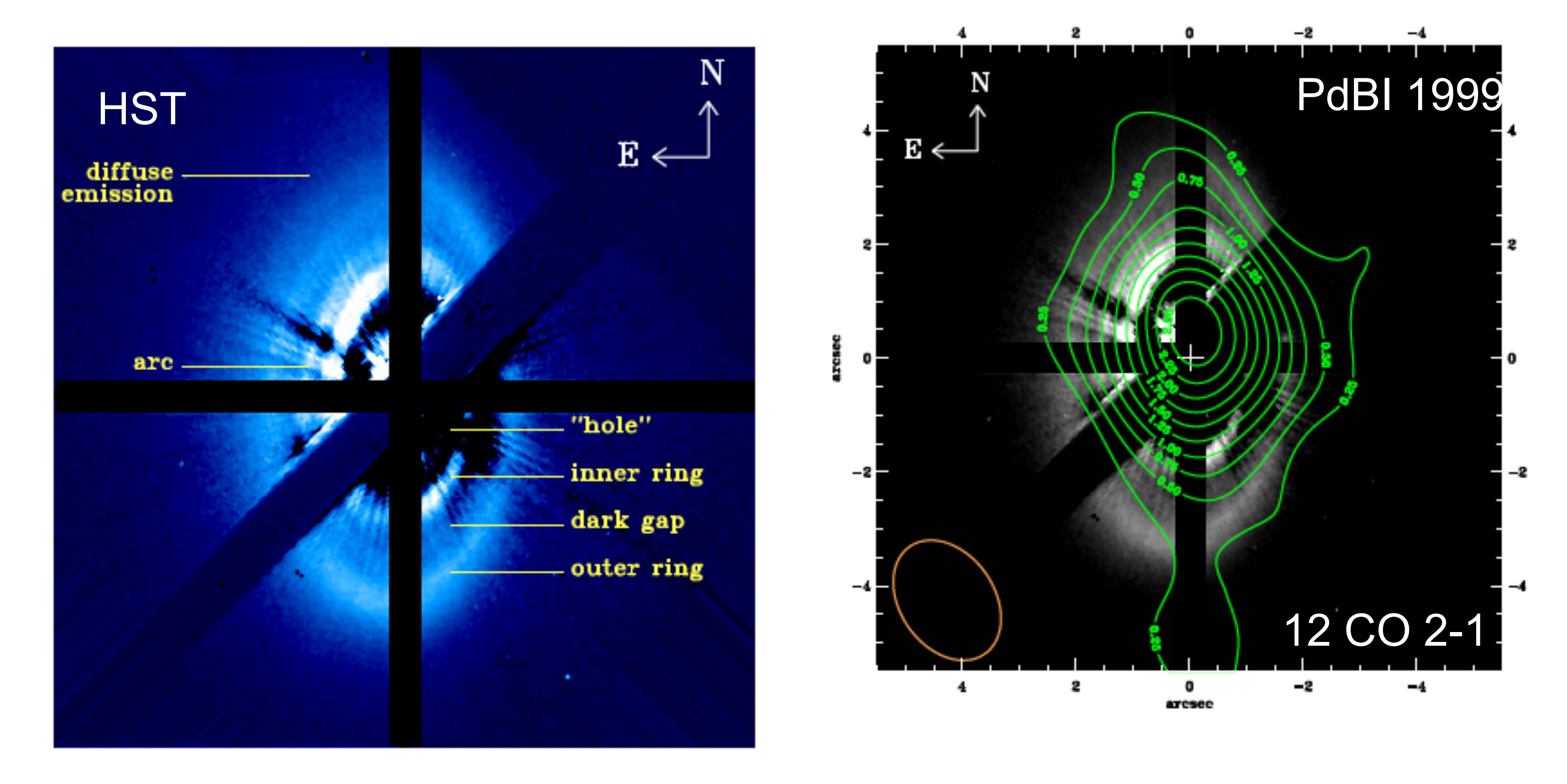
Rin(dust) = 63 +/- 13 au
Mdust = 0.09 +/- 0.03 Mearth



HD 141569, a B9.5/A0Ve star + 2 M-dwarf (M2 & M4) but likely unbound (Weinberger 2000, ApJ, 544, 937)

A NIR disk of radius 450 au, peak at 325 au (Augereau et al 1999, 2004)

A warm gaseous inner: double-peaked Hα, Brγ and OI lines (Dunkin1997,Brittain2007), [OI] and [CII] lines (Sturm et al. 2013).

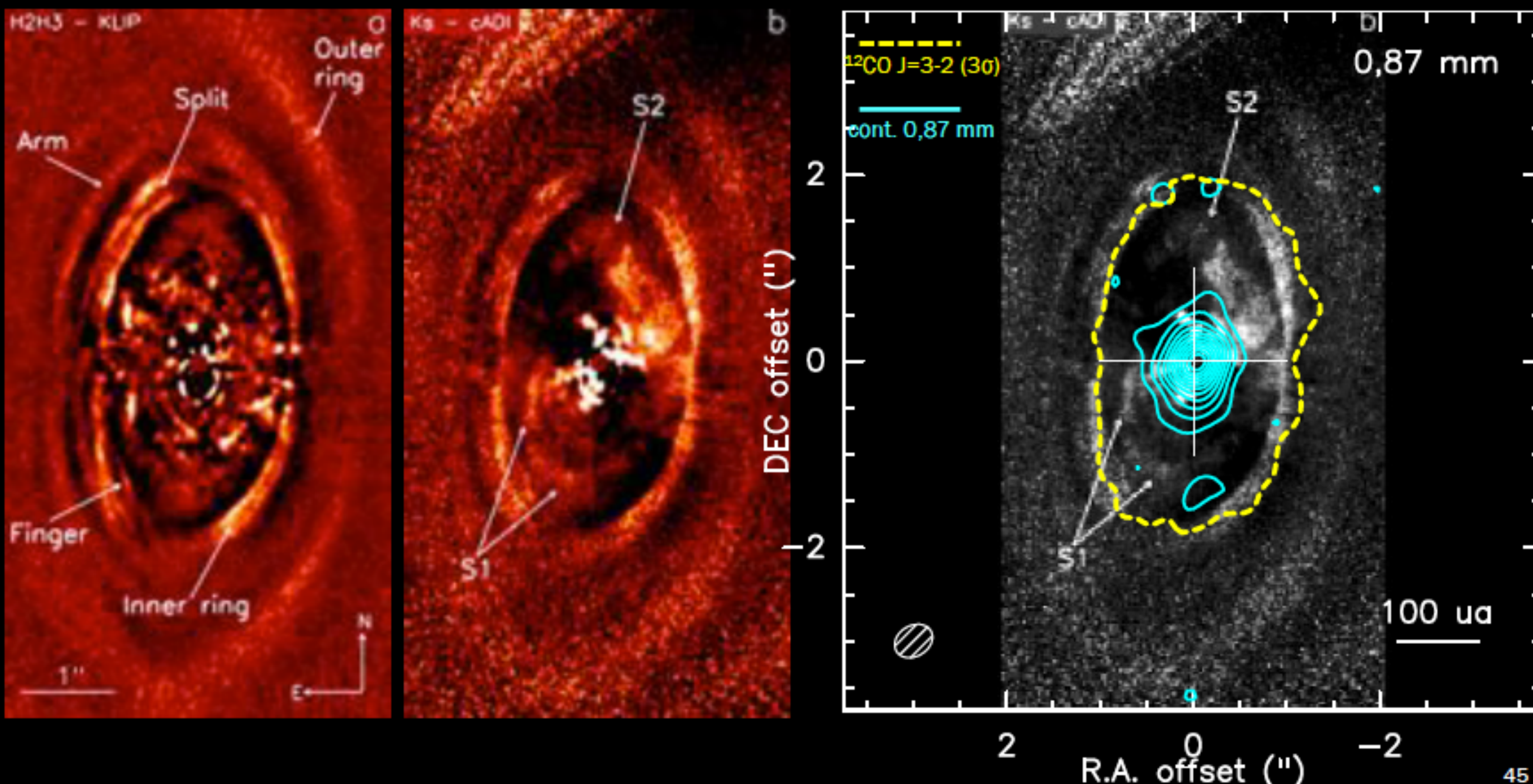


HD 141569

Augereau et al 1999 → A NIR disk of 450 au with gap

Perrot et al 2015
SPHERE image: many substructures

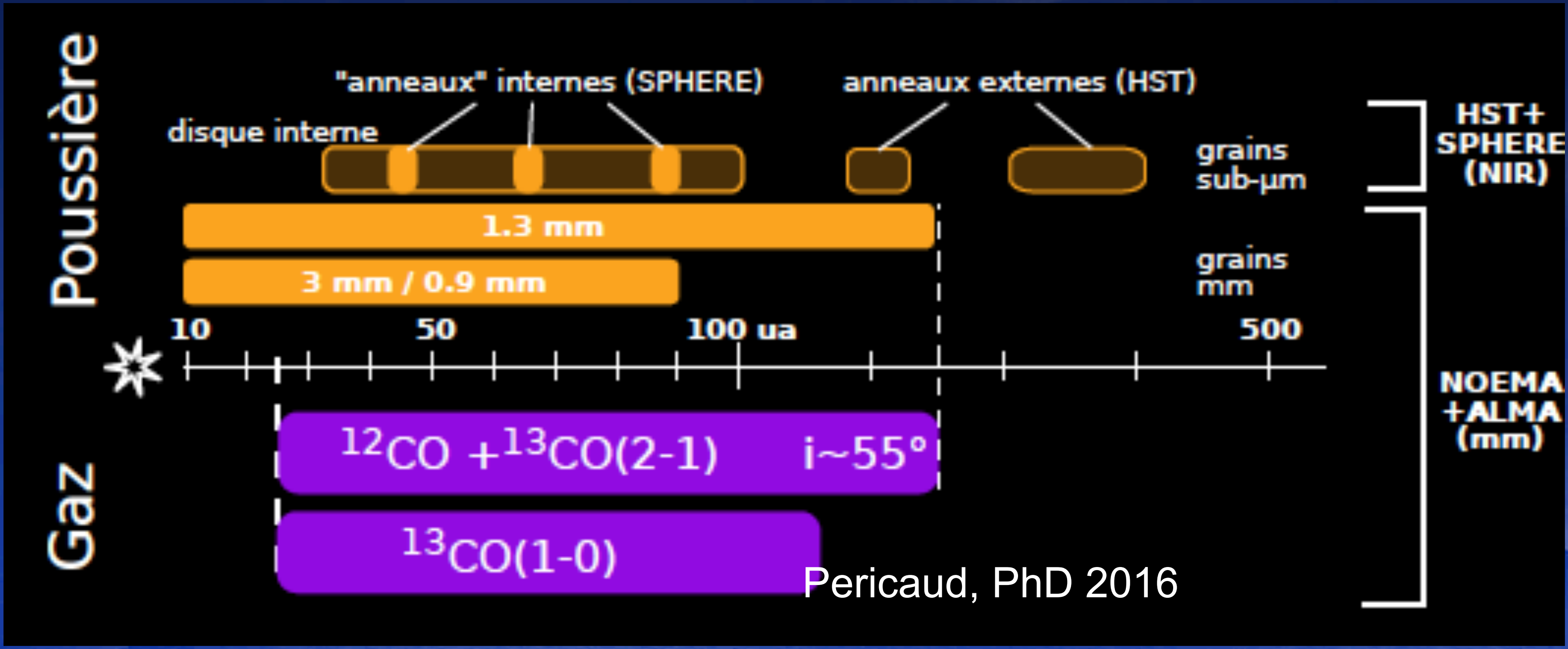
ALMA data superimposed



HD 141569 A summary of the disk properties (Pericaud 2016, PhD)

Preliminary analysis of ALMA data (DI Folco et al 2017, in prep.)
→ CO gas partly primordial
→ CO/dust → Gas/Dust > 100 (under « classical » assumptions)

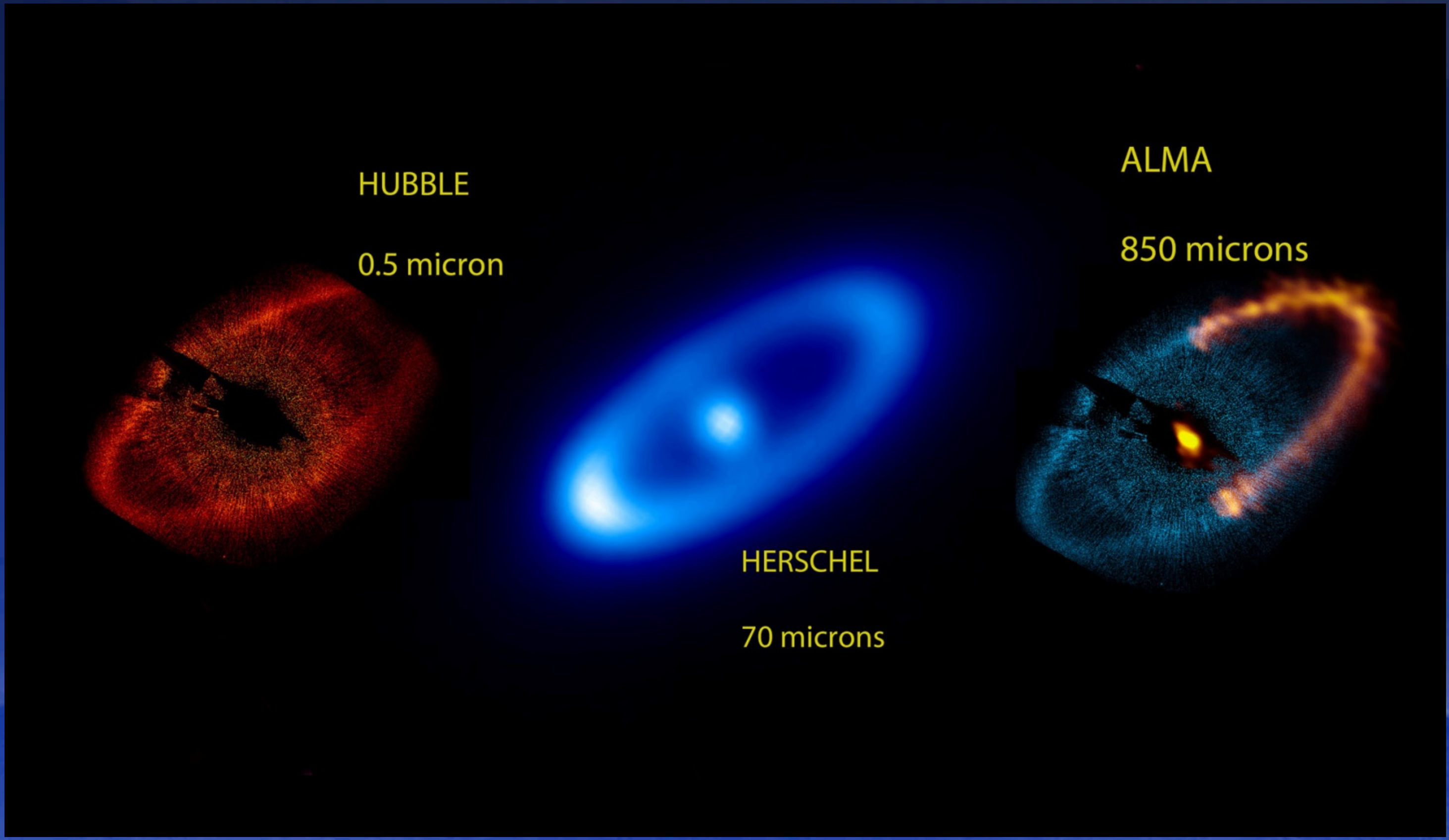
→ Also derived in HD21997 by Moors et al 2014



Imaging Gas-free Disks with ALMA Fomalhaut

Boley et al 2012 - half ring (mosaicing needed)

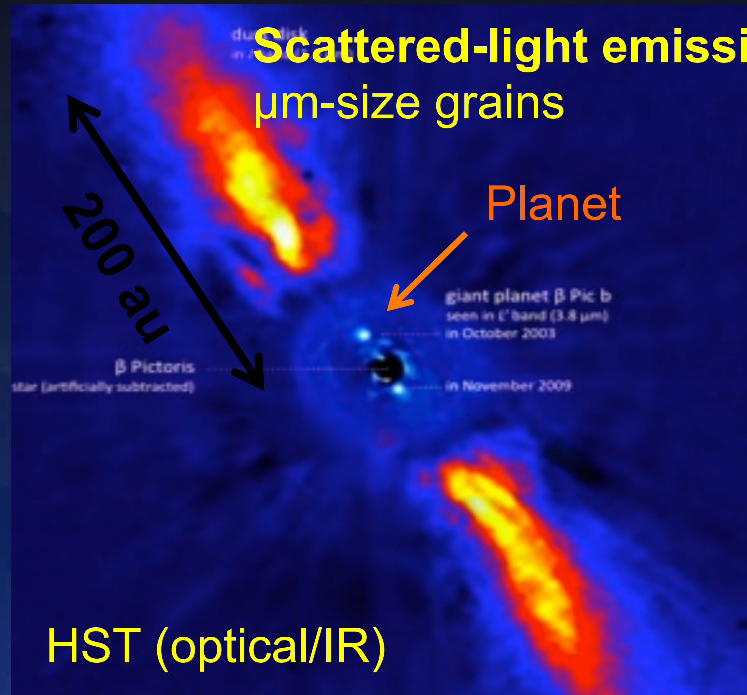
These submm observations demonstrate that the parent body population is 13-19 AU wide with a sharp inner and outer boundary



Planetesimal collision at late stages of planet formation - Beta Pictoris

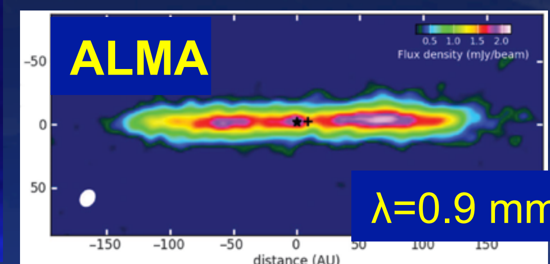
Debris disk

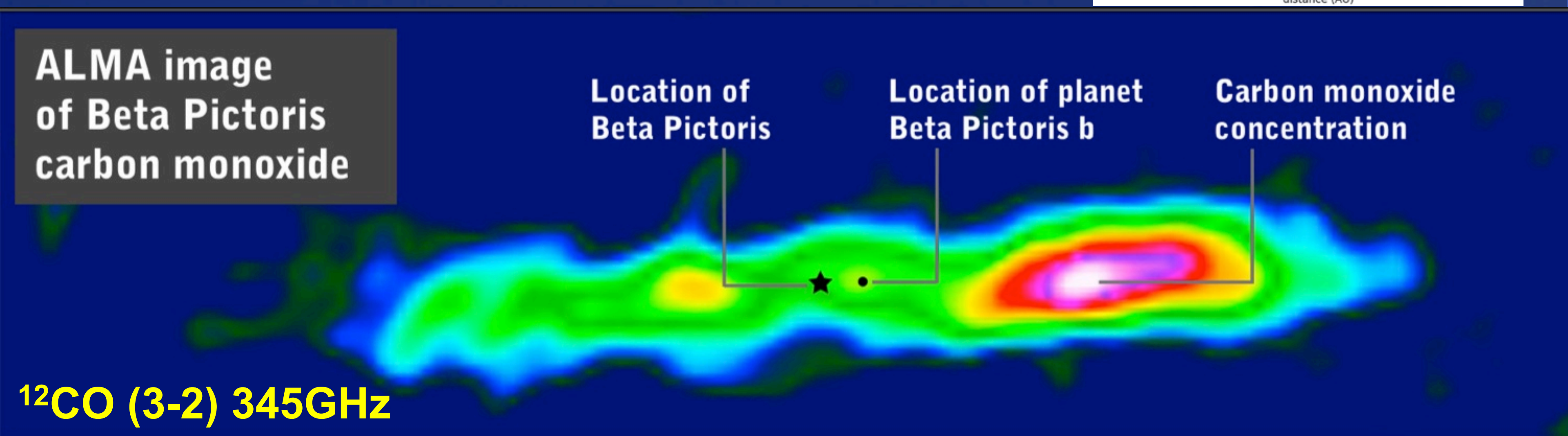
Distance 65 l-yr
Age 20 Myr
Star 2 M_{sun}
Planet 8 $M_{jupiter}$
Edge-on disk



Dent et al 2015

Dust thermal emission
mm-size grains





Beta Pictoris

Deprojected map of CO
0.3% Moon mass of CO

Clump of gas @80au = 30% of all CO

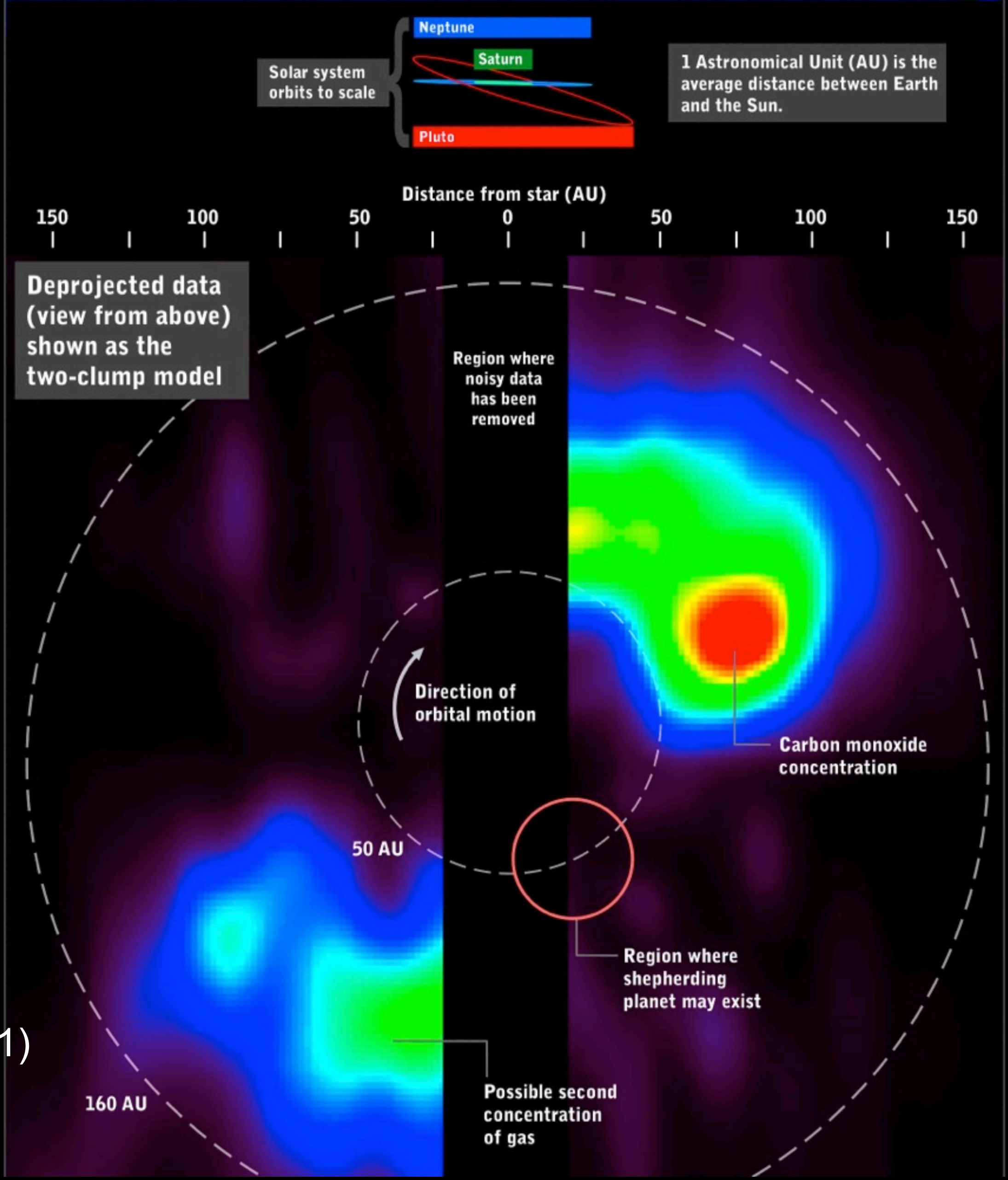
Gas is not primordial
(-> needs replenishment)

Possible scenarios:

1/ Collision of Mars-mass icy bodies

2/ Enhanced collision of planetesimals or comets in mean-motion resonance with an unseen planet (M_{Saturn})

→ Matra 2016 in prep.
A resolved CO 2-1 clump
migration is favoured (radially wide CO 2-1)
=> resonance on inclined orbit



Dynamical event in the era of terrestrial planet formation !

Beta Pictoris

Matra 2016: new CO data (CO 2-1)

→ A CO clump at radius 85 au spanning radially over 100 au

→ More likely due to comets (CO must be produced on a broad range of radii).

CO disk vertically tilted, coherent with what Is seen in scattered light

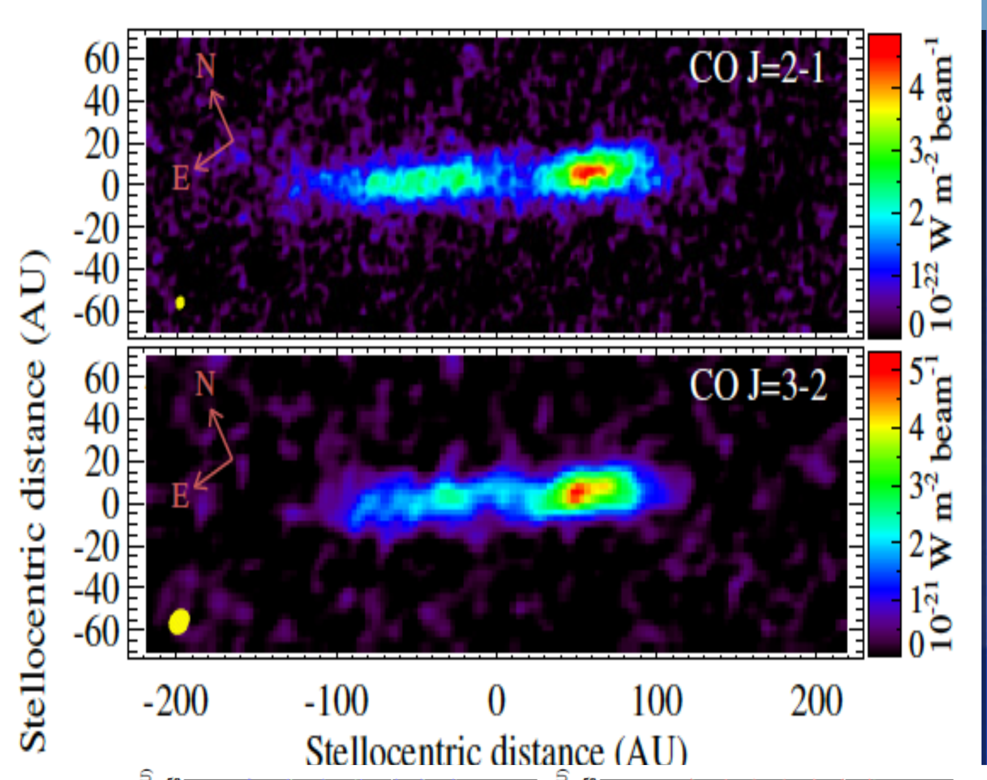
Scale height H ~ $R^{0:75}$

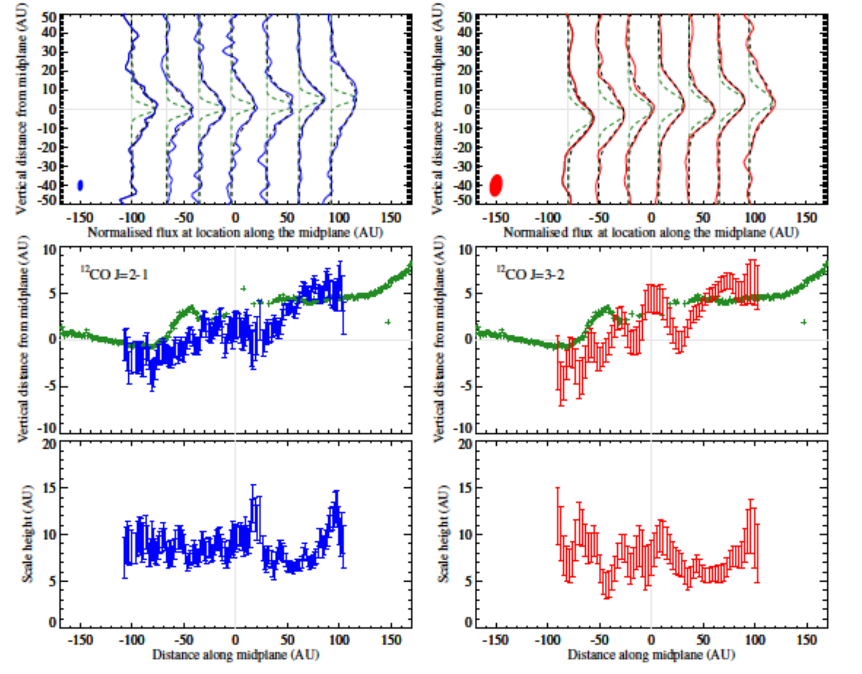
Mass of CO 3.4 +0.5/-0.4 Mearth

NLTE study of CO excitation conditions

Shows that CO cannot be primordial

→ Cometary origin …





Altitude of CO gas above the mid-plane

Evolved Disks or young « solar sytems »

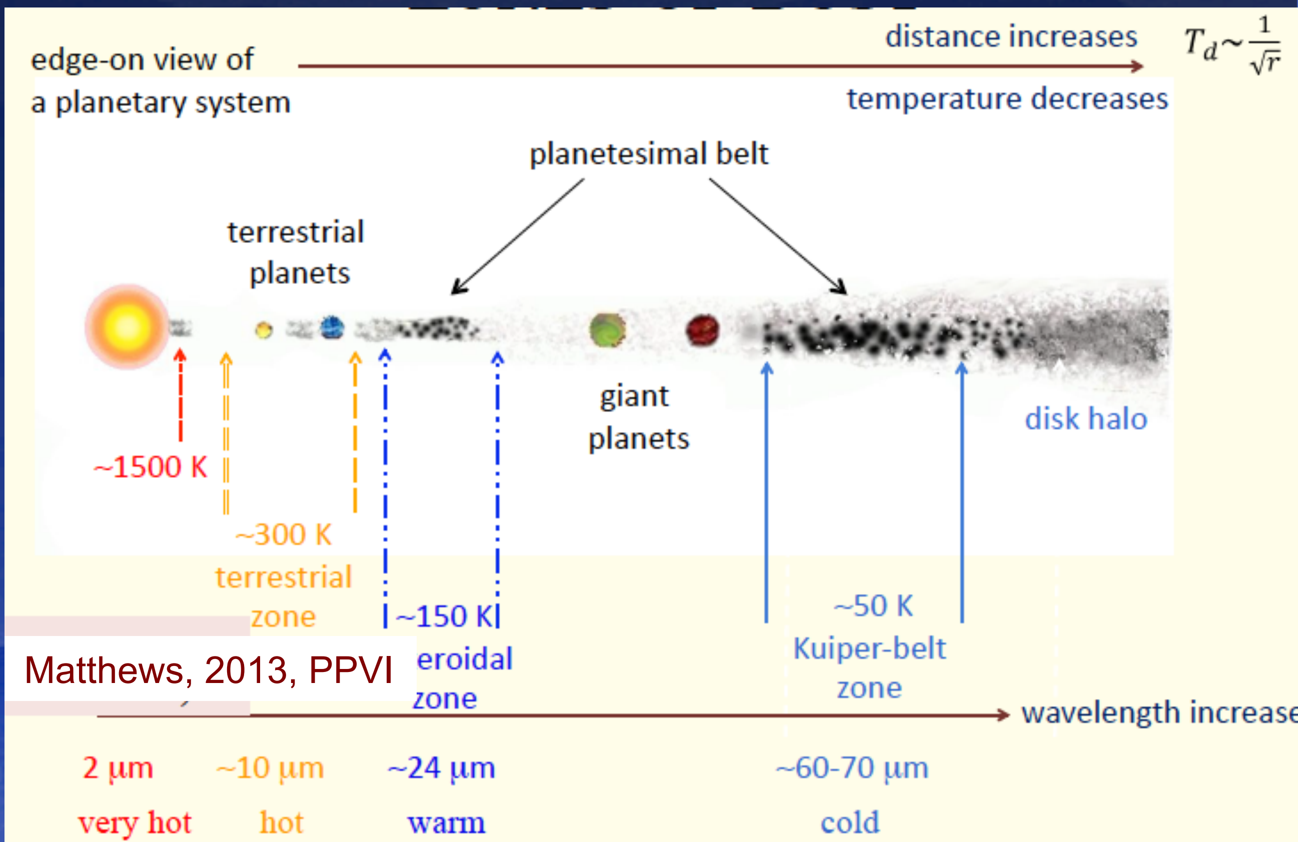
→ Importance of resonances to shape the dust disk together with embedded (usually unseen) planet(s).
→ Some cases where planets are directly observed (DD)

→ Some cold CO emission observed, secondary origins for DD, at least partly primordial For HD

NIR imaging:
→ Observations of Arcs, ellipses, rings, spirals

ALMA imaging:
→ CO images
→ mm dust images

→ More needed to characterize the dust and gas distribution, Gas/Dust ratio, etc…



Matthews, 2013, PPVI

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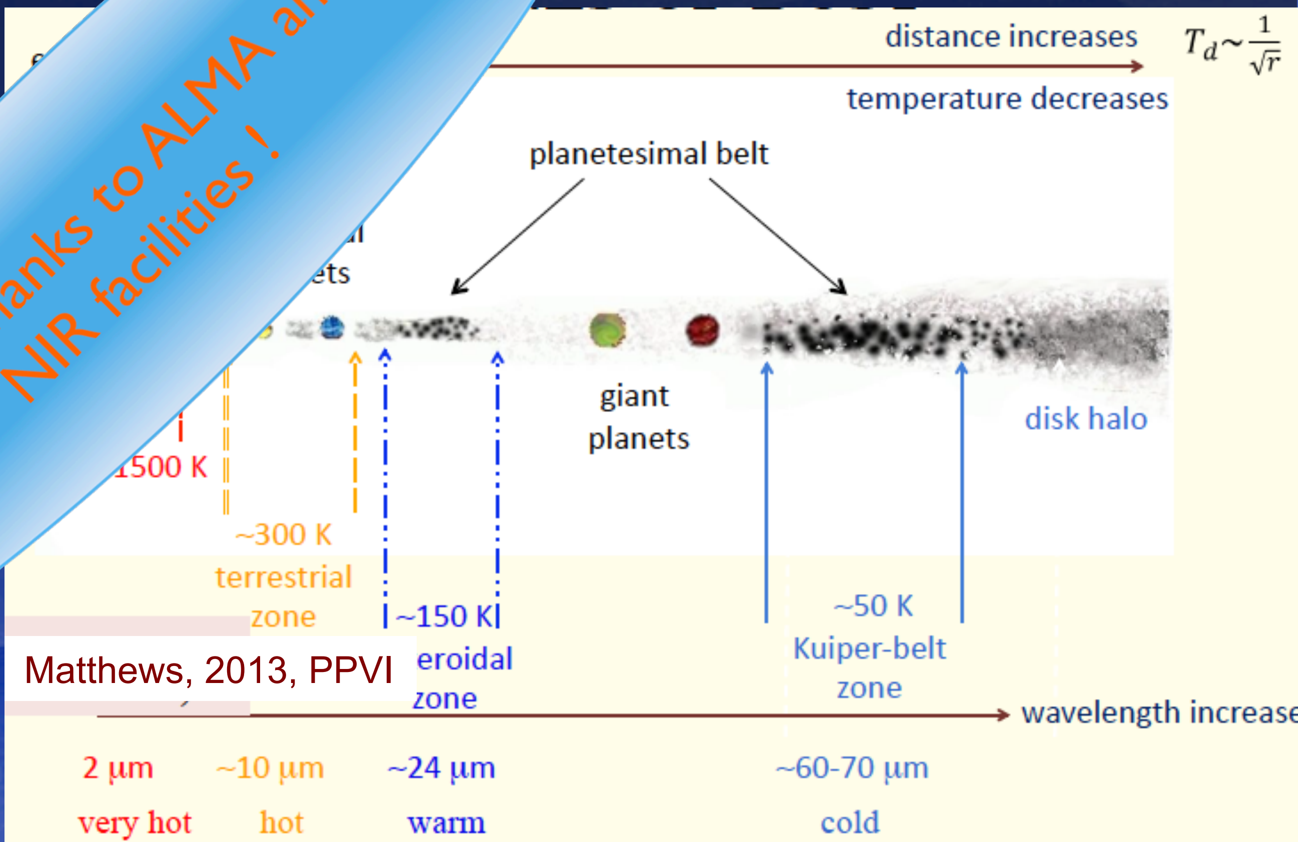
In Progress thanks to ALMA and new NIR facilities !



Matthews, 2013, PPVI

Circumstellar Disks - perspective

Protoplanetary Disks:

- Many resolved images (ALMA, SPHERE, SUBARU …)
  → Asymetries: dust trap, cavities, rings, spirals
- Density & temperature of gas and dust:
  → Large temperature/density changes within a few AU

→ still a lot to do

- Physics of the mid-plane ? (planets formation ?)
  → Molecular complexity is so far lilmited

Evolved Disks:

- Many resolved images of dust ringsbut also CO gas clumps (ALMA)
- Some of these disks also harbor planets (observed)
  → Asymetries & origin of gas (secondary, exocomets versus collisions)

- More and more disks with hybrid properties around 10-30 Myr stars
  → Dust is secondary, part of gas is primary
  → ~ late stage of giant planet formation (gas accretion) ?

→ New domains of investigations !

WARNING !

→ About 50 % of stars are binaries or multiple systems such as GG Tau …
→ a large fraction of faint small (R < 30-50 au) but dense disk (eg Pietu et al 2014) …

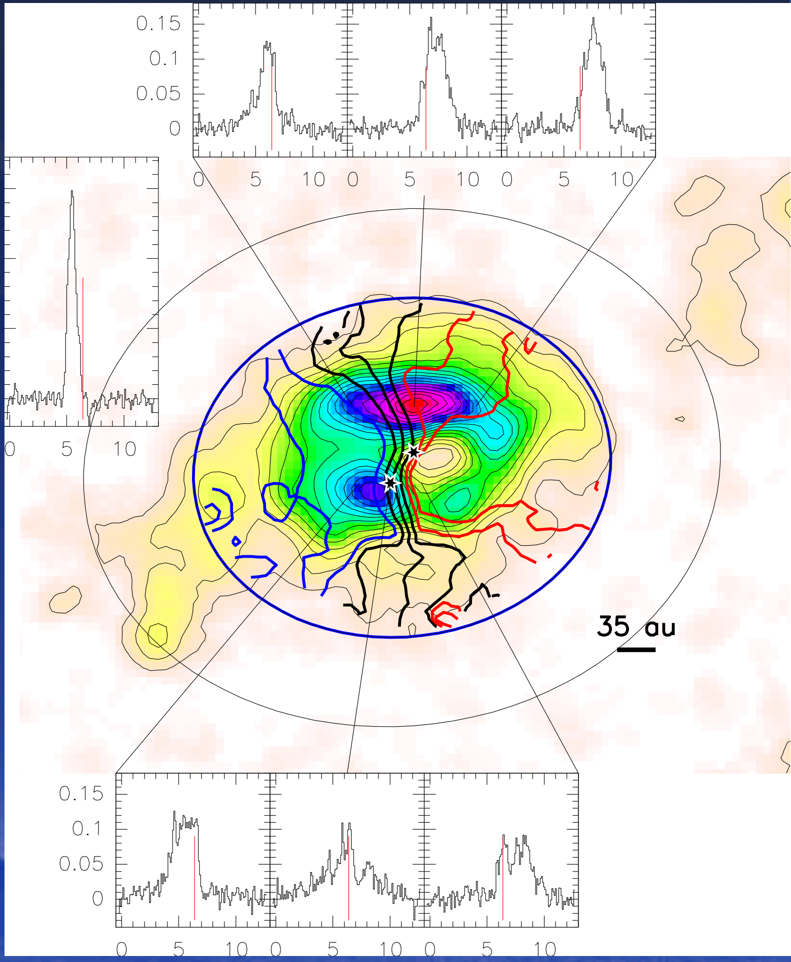
→ What about disk evolution and planet formation in these objects ?

→ So far, we still focus on large (R > 300 au) disks

They may be not representative

With ALMA, we are just starting to resolve (large) disks to understand their basic properties..

What about the smaller ones ?



GG TAU triple
ALMA CO 6-5

Dutrey et al 2014