Science with ALMA

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ESO Chili
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Main reference: “ALMA Science Case”- January 2001 http://iram.fr/ guillote
Other references are given

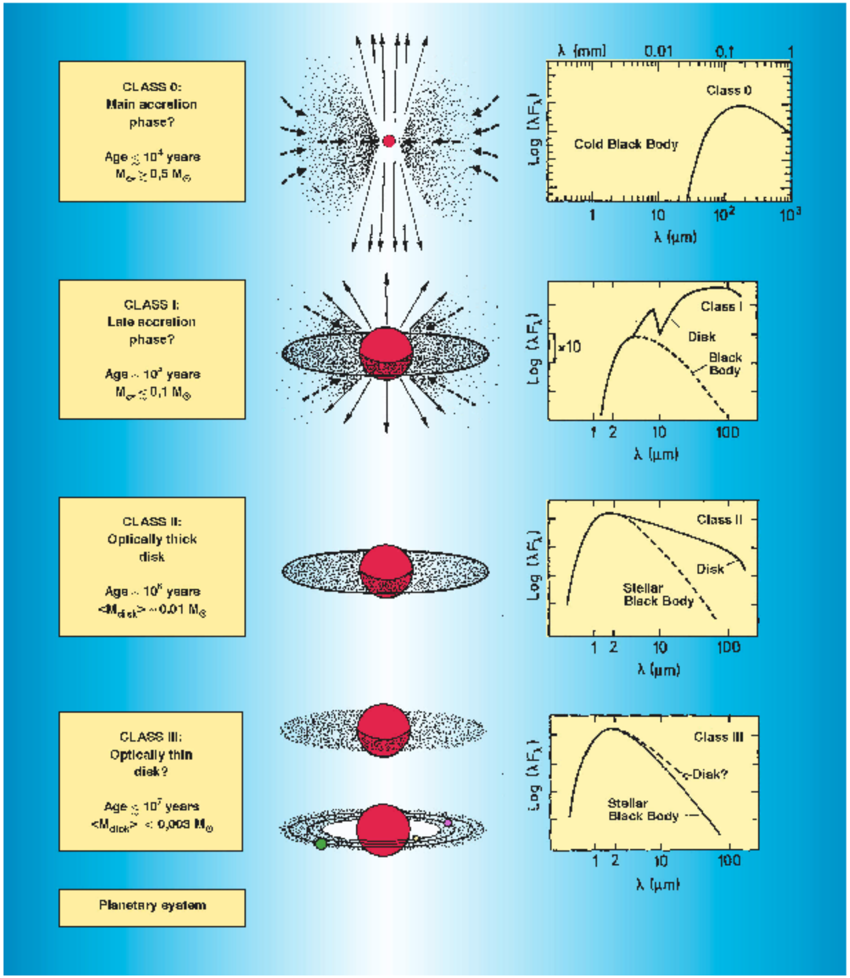
ALMA: scientific goals

- **ALMA is not a specialized telescope,**
- **but very well suited to some domains**
  - **A** High-Z universe
  - **B** Structure and evolution of galaxies
  - **C** Stellar formation and evolution
  - **D** Planetary system formation
  - **E** Solar system
  - **F** Interstellar chemistry (from galaxies to protoplanetary disks and planetology)
  - Dual Polarisation
- **One should even observe the Sun...**(if antenna surface allows...)

C - Star formation & stellar evolution

- First phase of star formation - embedded (class 0/I), PMS (class II)
  - Initial mass function from large scale studies (gas + dust maps)
  - Complete samples in several type of star-forming-regions
  - Velocity field (accretion) in envelopes of Class 0 objects (protostars)
  - Bipolar Jets: proper motions, shocks, physics (models)
  - Keplerien Disks around YSOs: star masses derived from the disk kinematics, evolutionary tracks of proto/PMS stars.
  - Binarity (70 %): gas+ dust distribution, tidal truncation of inner/outer disks
- AGB and Planetary Nebulae
  - AGB phase
  - Planetary Nebulae: dynamics (jets / disks ?)
  - Chemistry of envelope / nucleo-synthesis
- Polarization
- Chemistry

(low-mass) Young Stellar Objects Evolution



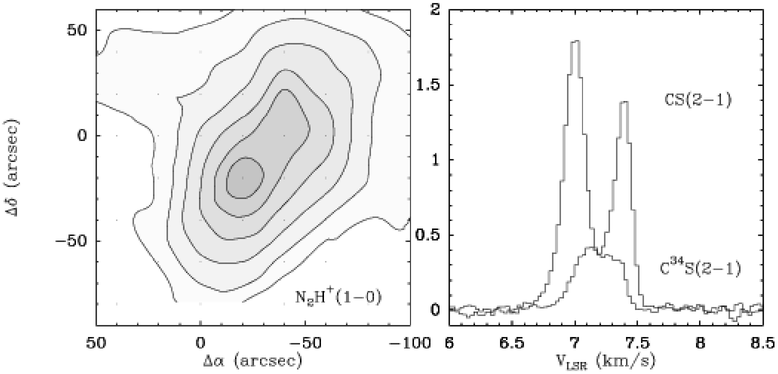
Based on SED: Spectral Energy Distribution

Adams et al. , 1987,
André et al. , 1994

Star Formation - Scales

Component	Size (AU)	Taurus ($''$)	Orion ($''$)	GMC 3kpc ($''$)	Chemical **Characteristics**
Pre-stellar core	$>$10,000	> 70	> 20	> 3	Ions, Long-chains (HC_5N, DCO^+, ...)
Cold envelope	5000	35	10	1.7	Simple species, Heavy depletions (CS, N_2H^+, ...)
Warm inner envelope	500	3	1	0.17	Evaporated species, High-T products (CH_3OH, HCN, ...)
Hot core (high-mass only?)	500	. . .	2	0.17	Complex organics (CH_3OCH_3, CH_3CN,... vib. excited mol.)
Outflow: direct impact	$<$100–500	$<$0.7–4	$<$0.2–1	$<$0.03–0.2	Si- and S-species (SiO, SO_2, ...)
Outflow: walls, entrainment	100–1000	0.7–7	0.2–2	0.03–0.3	Evaporated ices (CH_3OH, ...)
Disk	100	0.7	0.2	0.03	Ions, D-rich species, Photoproducts (HCO^+, DCN, CN, ...)
PDR, compact H II regions (high-mass only)	100–3000	. . .	0.2–7	0.03–1	Ions, Radicals (CN/HCN, CO^+)

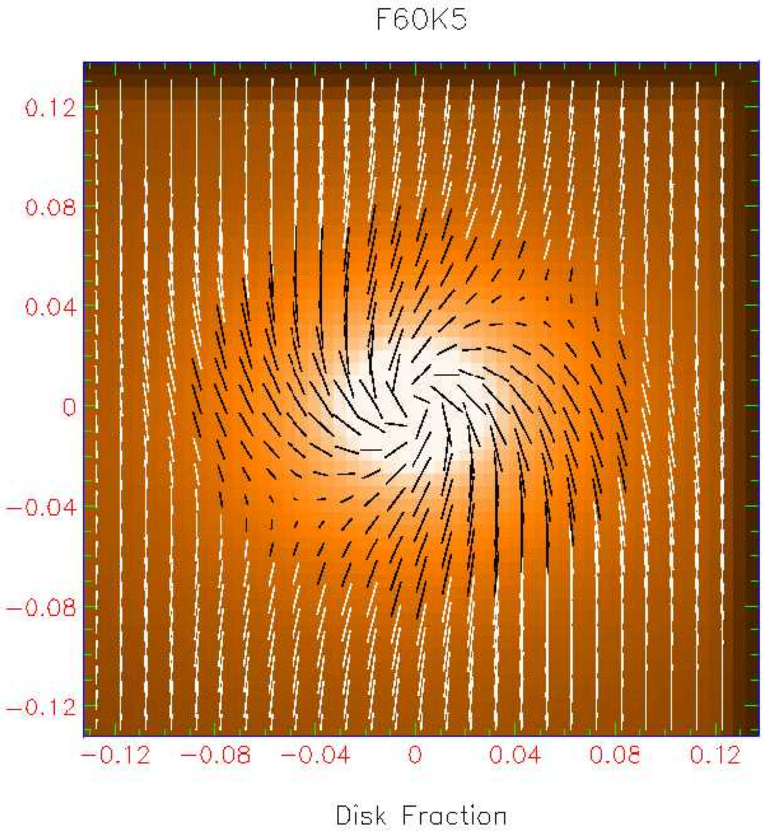
Pre-stellar molecular cores



A very small number of pre-stellar cores have been studied in details so far.
+ L1544 (30-M IRAM data, Tafalla et al.,)
+ Left: N_2H^+ emission showing a flattened dense core of ~ 10000 AU
+ Right: CS and $C^{34}S$ spectra showing redshifted self-absorption & blueshifted asymmetry thought to be characteristic of infall motion (infall velocity $\sim$ 0.01 km/s)

ALMA will allow to studies the first phase of the collapse, the role of the turbulence and the intermittency in pre-stellar cores.

Polarisation in star-forming region

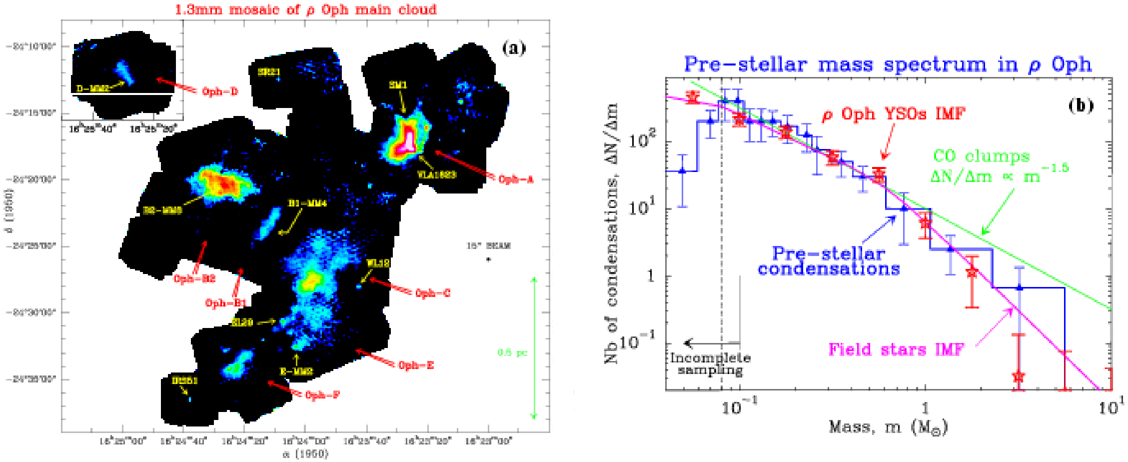


+ Simulation of 0.85 mm continuum (thermal dust emission) image made by ALMA (courtesy A.Chrysostomou)

+ Model of a high-mass star at 1 kpc containing mainly poloidal magnetic field, twisted and pinched by protostellar accretion disk. Lines show the B field traced by the continuum polarization

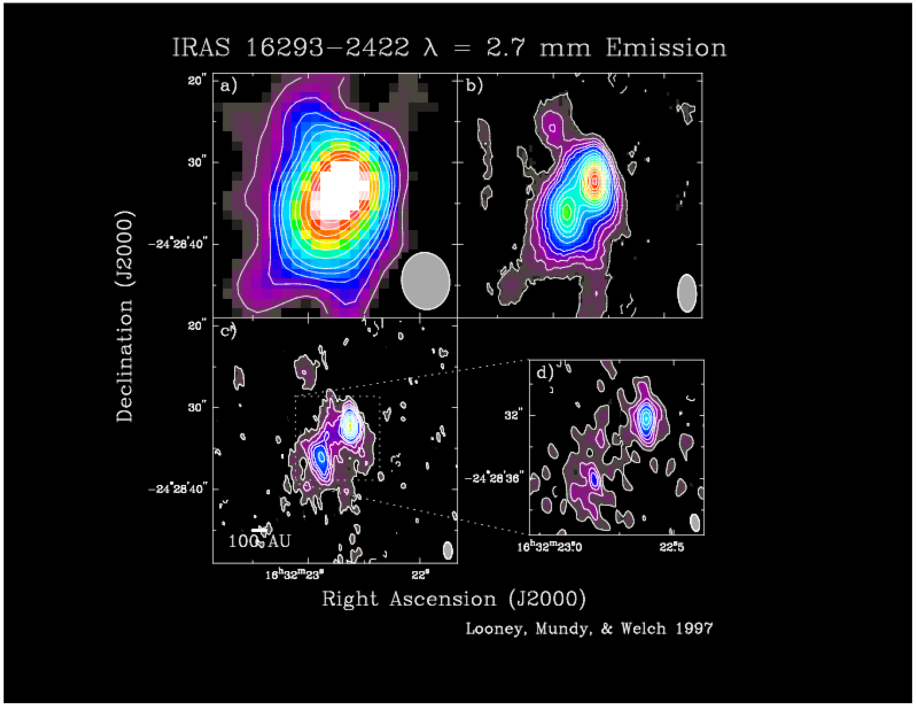
+ ALMA is the only telescope able to provide such detailed images of B field in star-forming regions. It is fundamental to understand the role of B in cloud collapse

Initial mass function



Left: Mm continuum mosaic of the ρ Oph main cloud obtained with the 30-m telescope (MAMBO). Right: Mass spectrum (blue histogram), Motte et al., 1998). It suggests that the stellar IMF is determined at pre-stellar stages by the fragmentation.

Proto-stars: fragmentation & multiplicity (Class 0)



Looney, Mundy, & Welch 1997

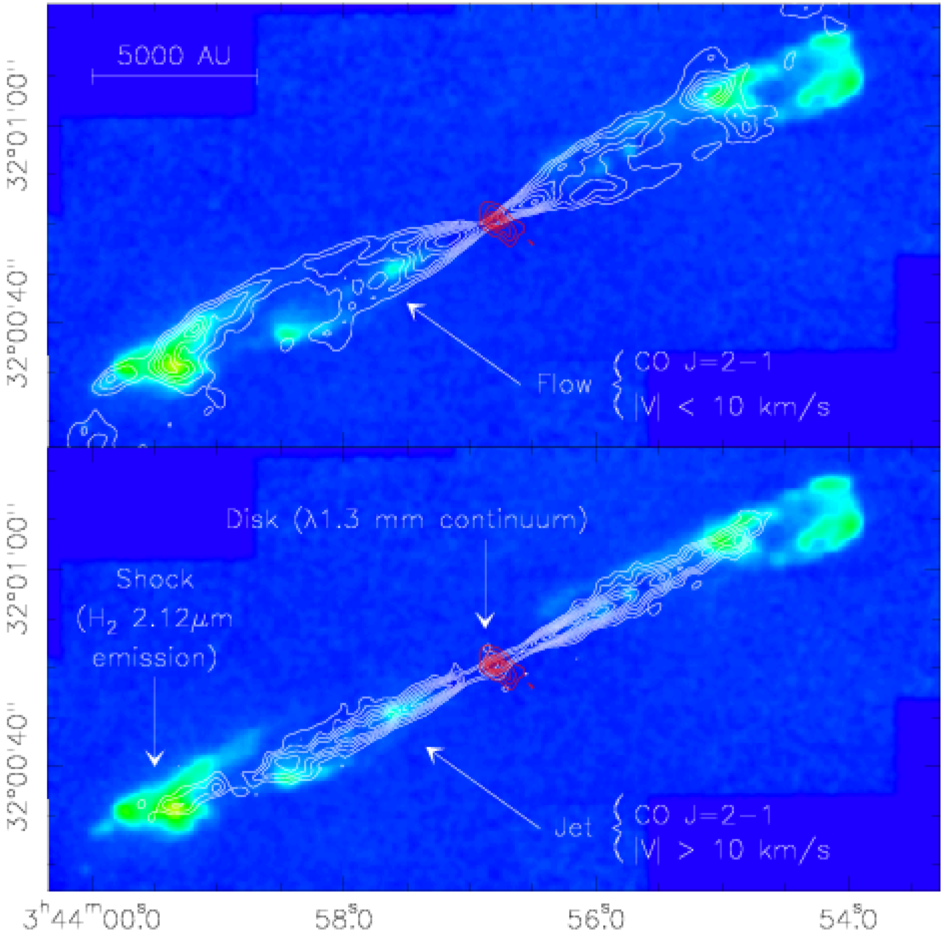
A very small number of protostellar binary systems are detected so far IRAS 16293-2422 (BIMA, ang.resol. from 6 to $0.5''$, Looney et al., 2000)

Observations with ALMA (resol $\leq 0.1''$), will reveal the incidence of binarity in protostellar systems, and the details of the envelope and/or disk fragmentation processes.

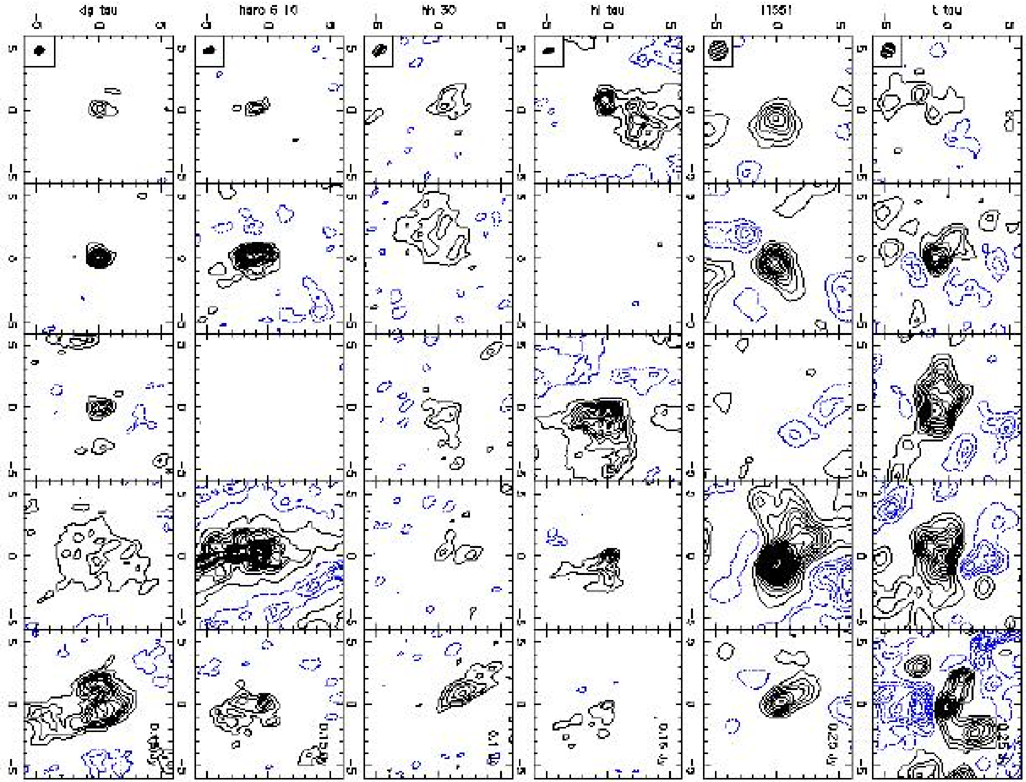
Comparison of the binary population in protostellar and main sequence systems will yield important constraints on theories of the formation and evolution of multiple systems.

Bipolar jets (Classes 0,I)

Overlay of the H_2 2.12 μm emission in the HH 211 molecular outflow and PdBI data (Gueth et al. , 1999)
+ Class 0 protostars have extraordinary jet-like molecular outflows which drive the excess of angular momentum from the initial core.
ALMA will permit studies of protostars environment at different evolutionary stages revealing the detailed causes for the outflow power decline with age.



^{12}CO lines around Embedded Objects (Classes 0,I)



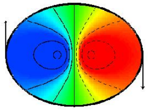
Cloud + Flow + Envelope(?) + Disk(?) = CONFUSION

ALMA = Disentangle in between components by using adapted molecular tracers...

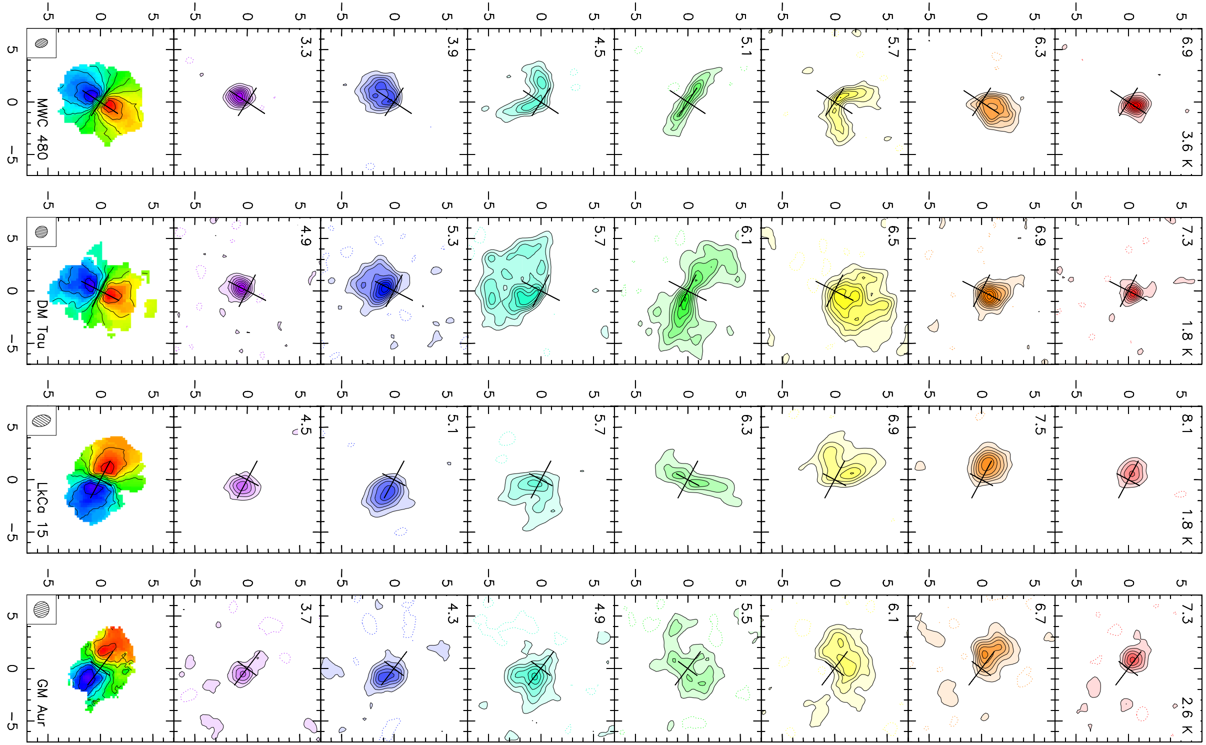
Example of CO disks around PMS stars (Class II)

^{12}CO PdBI data: Simon et al. , 2000

Stars isolated from cloud, similar kinematics

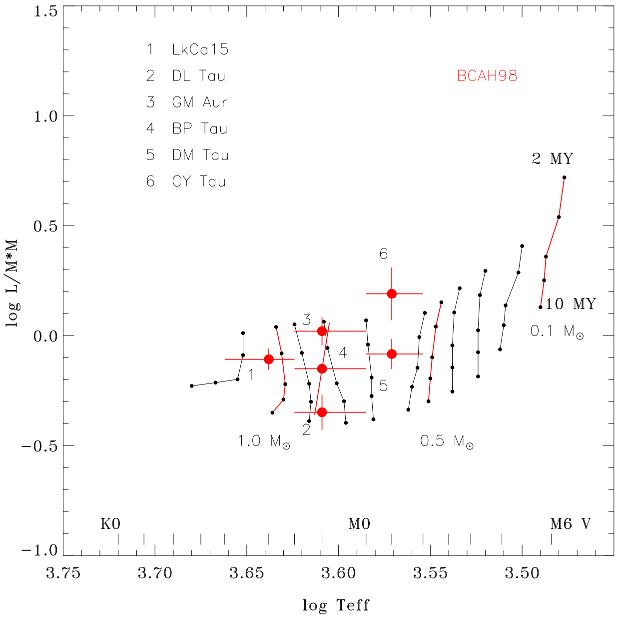


Velocity gradients along the major axis. Keplerian model for inclined disk



Calibrate PMS star evolutionary tracks

Measuring CO dynamical mass in Keplerian disks
High spectroscopic resolution + high sensitivity maps



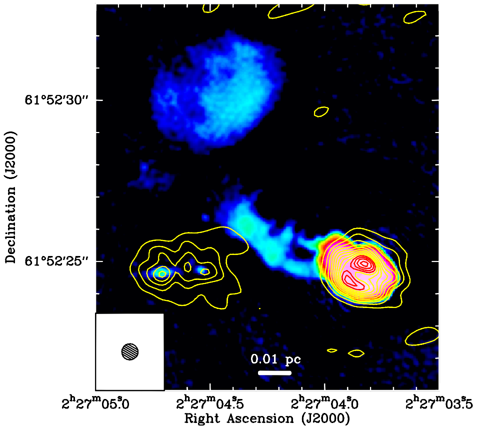
+ Sample of ~ 10 TTauri stars (Simon et al. , 2000, tracks: Baraffe et al. ,

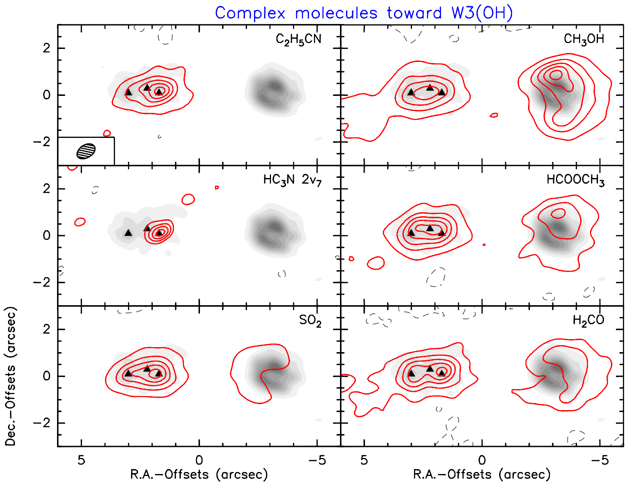
$$+\ v(r/D) = \sqrt{\frac{GM_*}{r}} \times \sin i$$

+ $L_* \propto D^2$ & $M_* \propto D$
+ $L_*/{M_*}^2$ independent on D

ALMA = Significant samples ... Orion A, very-low mass stars...
→ Even on Proto-stars such as Classes I, if disks...

Investigating the high-mass star formation



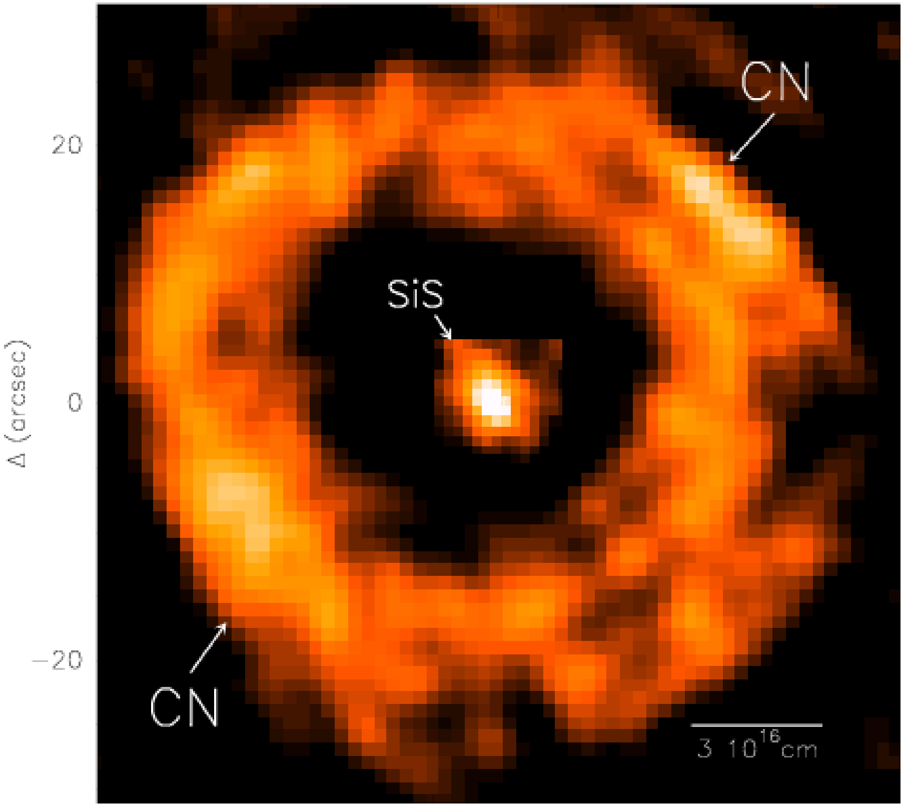


LEFT:VLA 3.6cm emission tracing the free-free radiation (Wilner et al., 2000) + 1.3mm continuum emission (PdBI)

RIGHT:Different molecules observed with PdBI (Schilke et al.,)

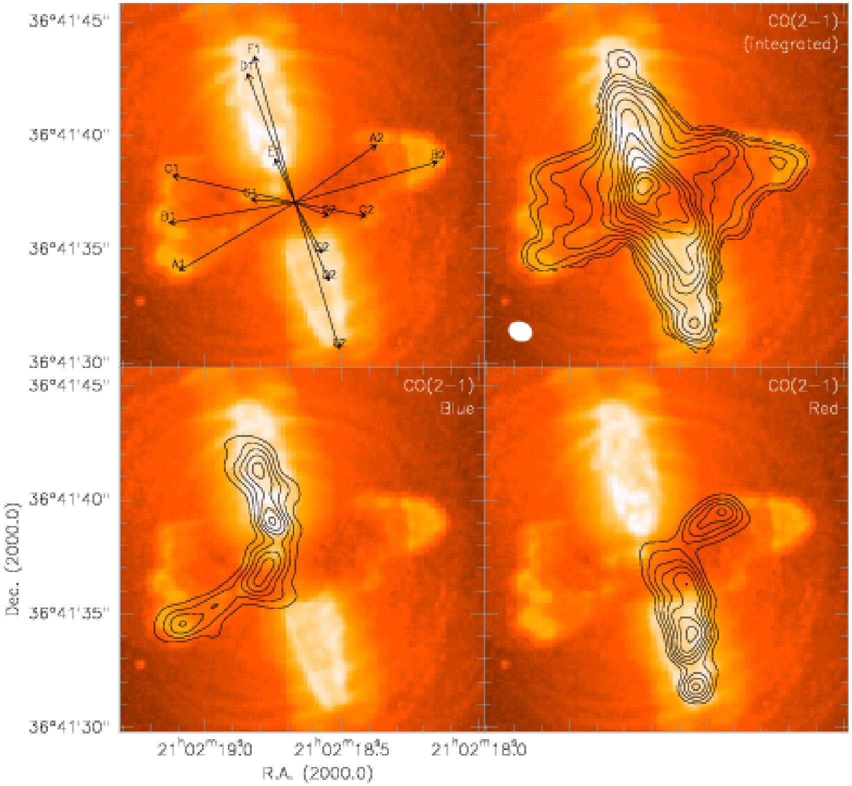
W3OH at 2 pc ($1'' = 2000$ AU) - Two centers of star formation
+ A compact HII region of ~ 1000 AU ionized by a O8 star.
+ At 0.05 pc, a dense clump associated to water masers

IRC+10216



Distribution of SiS and CN 3-mm emission in the envelope of IRC+10216 (Guélin et al.,)
Formation of grains & gas acceleration not fully understood. They control the mass-loss process of the final stellar stage evolution
ALMA will allow to extend this type of observations to stars a few kpc away

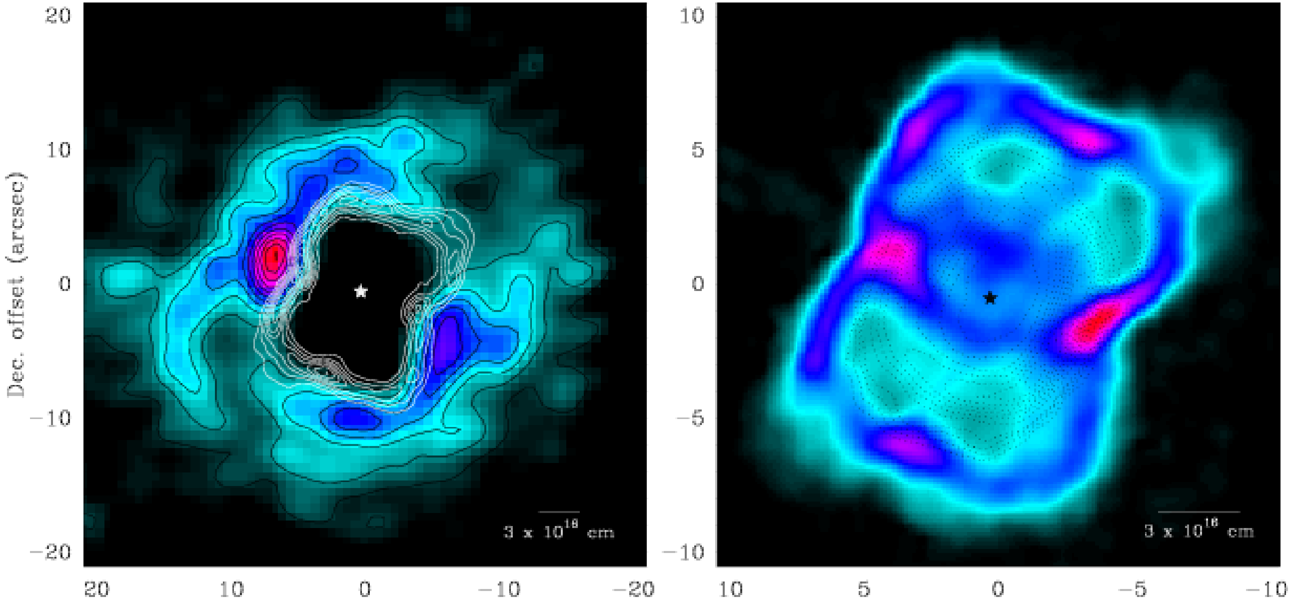
Proto-Planetary Nebula: CRL2688 (post-AGB)



HST image (background): reflected light from the remnant AGB envelope and shocked H_2 gas. Upper right: integrated CO(2–1) emission of the envelope inner regions. Lower panels: blue-shifted and red-shifted CO emission. The cold neutral gas outlines series of collimated high-velocity outflows (left upper panel) that end in the shocked regions.

ALMA will allow to study in detail the physics and chemistry occurring in this still poorly understood phase of stellar evolution.

NGC7027 (planetary nebula)

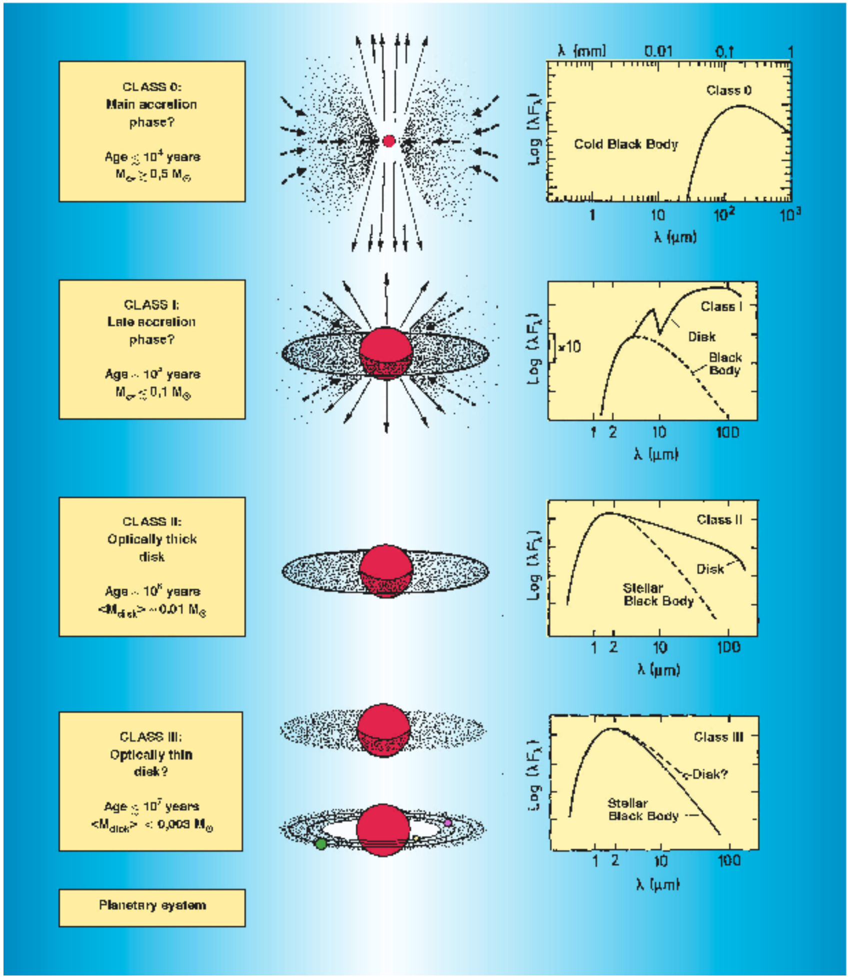


Cold and warm molecular gas, ionized gas in young planetary nebula NGC 7027.
Left panel: CO(1–0) emission (MAP) tracing the cold molecular AGB envelope and near-infrared H_2 emission (contours) tracing the warm and dense gas in the PDR between the ionization front and the expanding molecular envelope.
Right panel: zoom on the H_2 distribution and the ionized cavity (contours).
ALMA will be able to study the different components associated with planetary nebulae, in particular the warm dense gas via high level molecular transitions in the submm.

D - Planetary System Formation

- Protoplanetary disks: physics and chemistry of inner disks (~ 30 AU)
  - Gas/Dust ratio, sedimentation along the mid-plane
  - Proto-planets should be invisible
  - Gaps due to planetary formation can be imaged and analyzed
- Processes leading to disk dissipation...transition disks
- Debris disks
  - Dust properties in debris disks
  - Cold gas (CO) in β Pictoris disk (and Kinematics...)
- Exo-planets should be invisible but detectable by astrometry in some cases

(low-mass) Young Stellar Objects Evolution



Based on SED: Spectral Energy Distribution
Adams et al. , 1987, André et al. , 1994

A few numbers to keep in mind

- **Nearest Protoplanetary Disks $\sim 10^6$ yr:** Class II
  Distance $\sim$140 pc or $1'' = 140$ AU / $\sim$300 pc
- **Debris Disks around old PMS & ZAMS stars $\sim 10^7 - 10^8$ yr:** Class III
  Distance $\sim$ 10-60 pc or $1'' = 10 - 60$ AU → disk of size ~ 100 AU $= 10 - 1.7''$
- **Class II:** Sensitivity & resolution → 0.03''
- **Class III:** Sensitivity → resolved / mosaicing

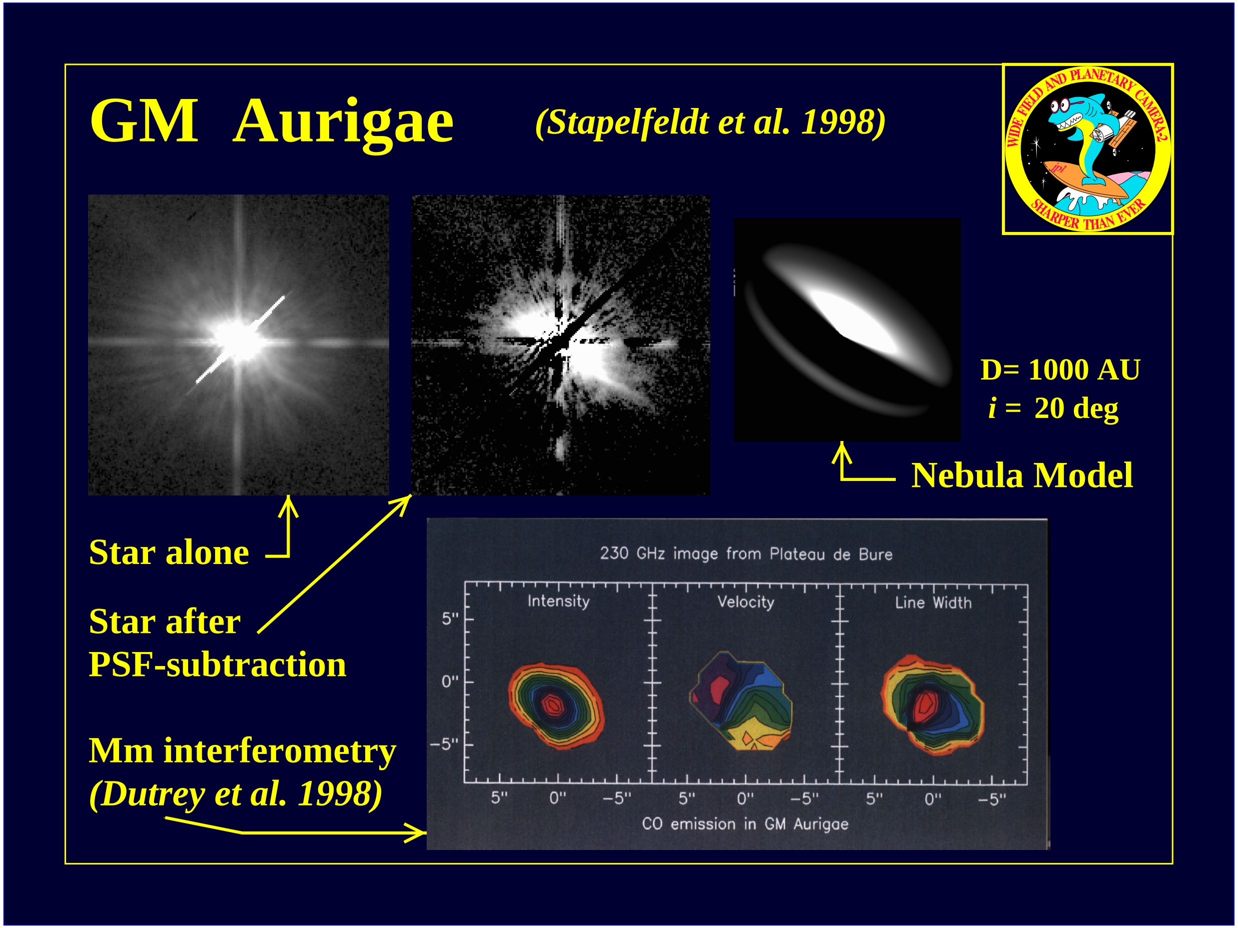
- **Solar System** (up to Kuiper Belt):
  -1) $R \sim 30$ AU or $\sim 0.2 - 0.4''$ at 140-300 pc
  -2) $R \sim 30$ AU or $\sim 3 - 0.5''$ at 10-60 pc

- **Planet migration:** at 140 pc
  $\sim 0.1 \leq \Delta R \leq 15$ AU or $\sim 0.007 \leq \Delta R \leq 0.1''$
- **Gaps by giant planets:** at 140 pc
  $\Delta R \sim 2 - 5$ AU or $\Delta R \sim 0.015 - 0.036''$

- **IRAM-PdBI:** $\sim 0.5 - 3''$ **& NIR-Optical telescopes:** $\sim 0.2 - 0.5''$

- **ALMA:** $\sim 0.03'' + 25\times$ **more sensitive than PdBI in line**

GM Aur: example of a disk around a single star



GM Aurigae *(Stapelfeldt et al. 1998)*

D= 1000 AU
i = 20 deg

Nebula Model

Star alone

Star after PSF-subtraction

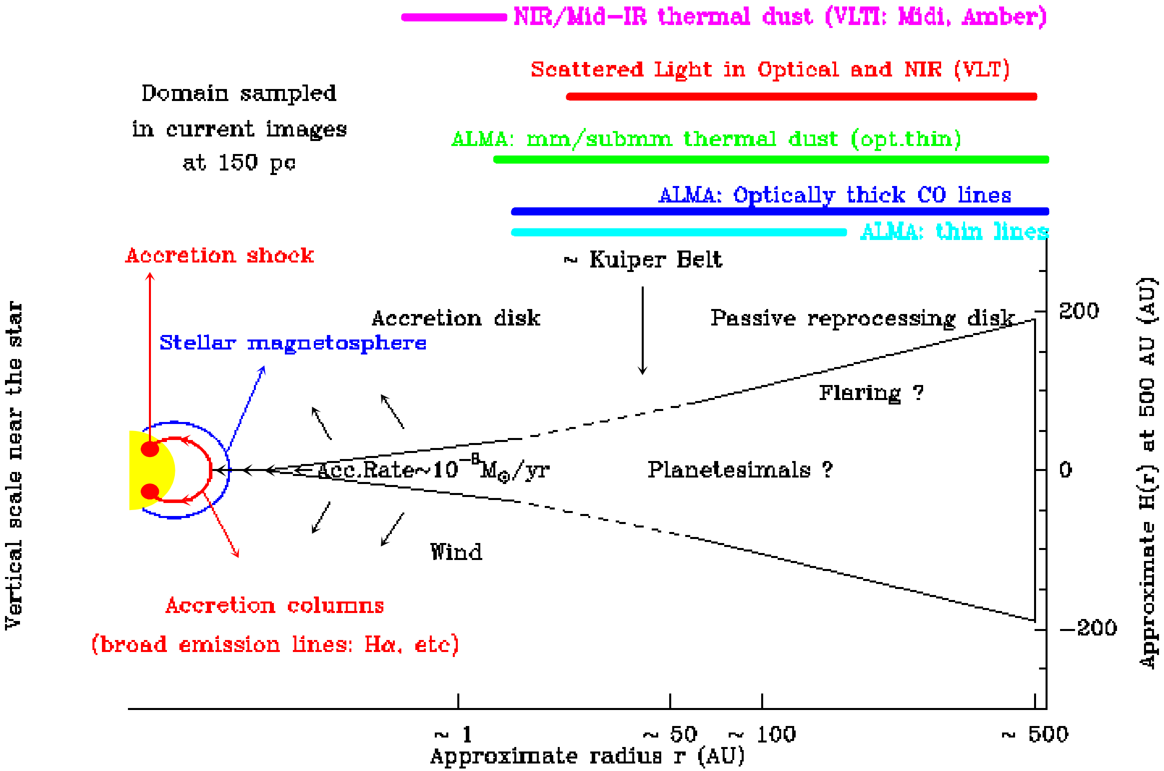
Mm interferometry ***(Dutrey et al. 1998)***

230 GHz image from Plateau de Bure

CO emission in GM Aurigae

Dust (scattered light) + CO emission: same PA, same i, same size = SAME DISK

A protoplanetary disk at 150 pc



(vintage 2000) ALMA → Planet Forming Regions

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^{12}CO PdBI data: Simon et al. , 2000

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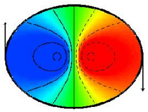
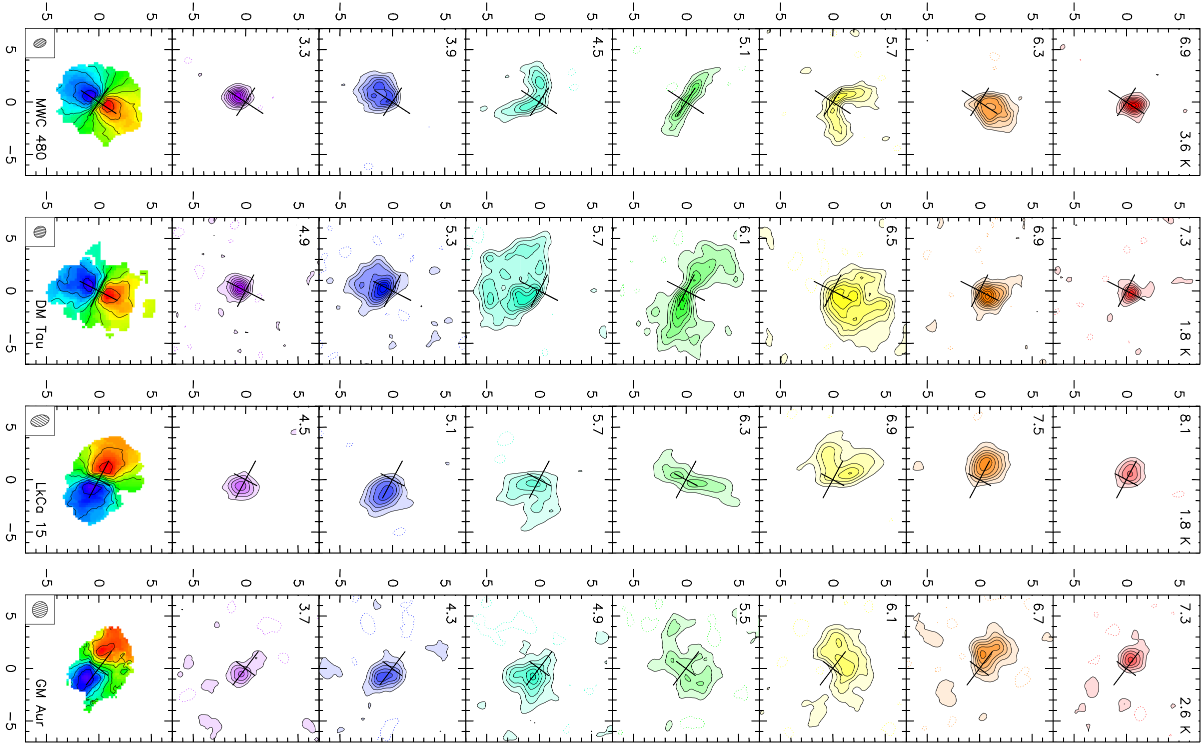
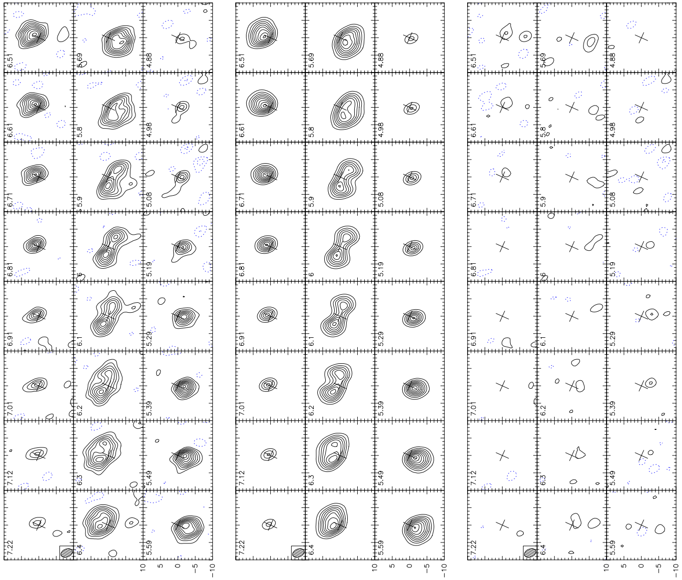


Velocity gradients along the major axis. Keplerian model for inclined disk



DM Tau: PdBI ^{12} CO J=1-0 Analysis

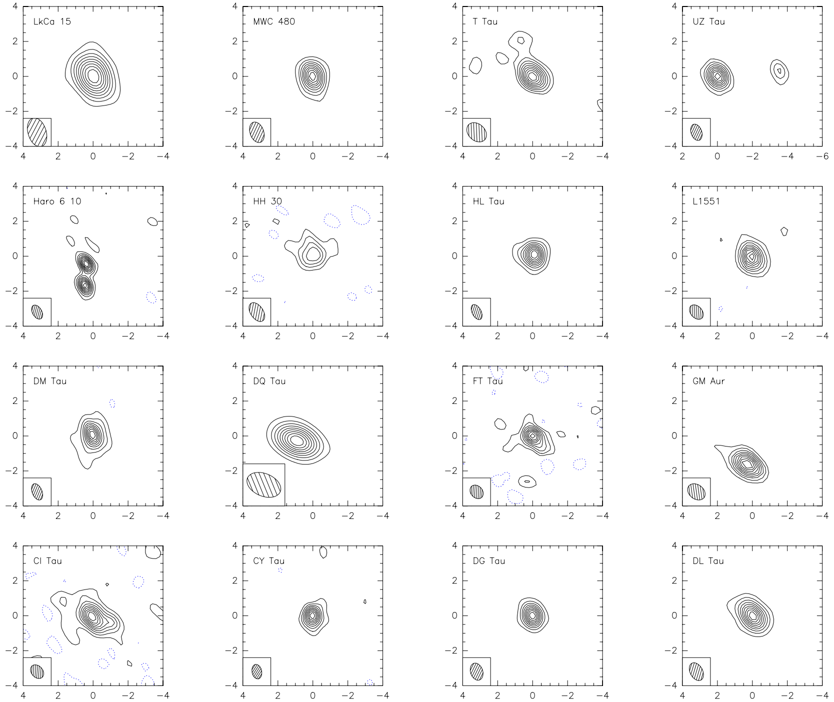
Sensitivity limited: CO outer disk properties ($R \geq 50$ AU)



+ Comparison of CO data with a model of passive disk in hydrostatic equilibrium
+ Interferometric effects are taken into account

Guilloteau & Dutrey 1998 Data - best model - difference: contours are at 2 σ levels

Dust disks around PMS stars



1.3mm PdBI data: Dutrey 2000 (proc.IAU 200), single & multiple stars in Taurus

- Thermal dust emission mostly optically thin betweem 0.8-3mm $\longrightarrow$ disk mass!
- Lot of unknowns... κ_ν, β, gas/dust ratio ... dust distribution ...

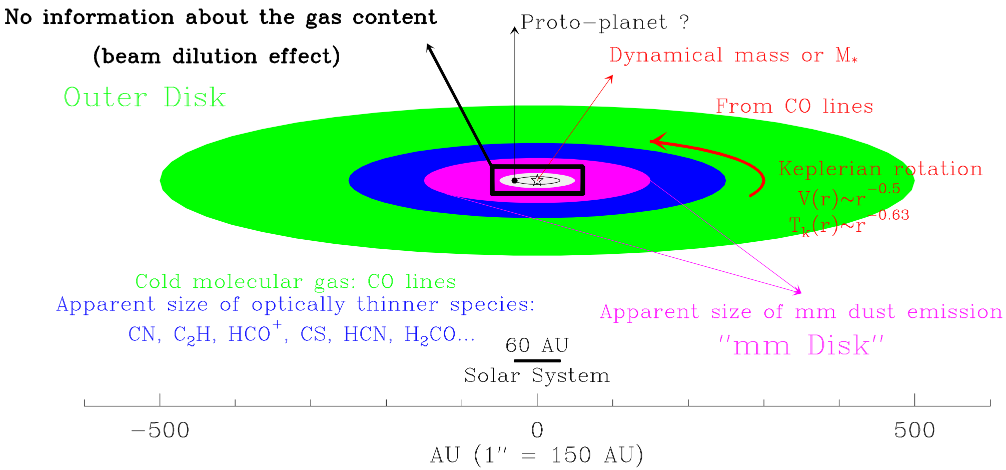
ALMA = Planetary Forming Regions in disks

A “standard” disk as seen today by mm arrays

Approximate scale of a cTTs disk having a few Myr and located at 150 pc

Outer Disk (= "CO disk") ~ "Outer Solar System" > R_{Kuiper}

mm Disk ~ "Solar System" ~ R_{Kuiper}



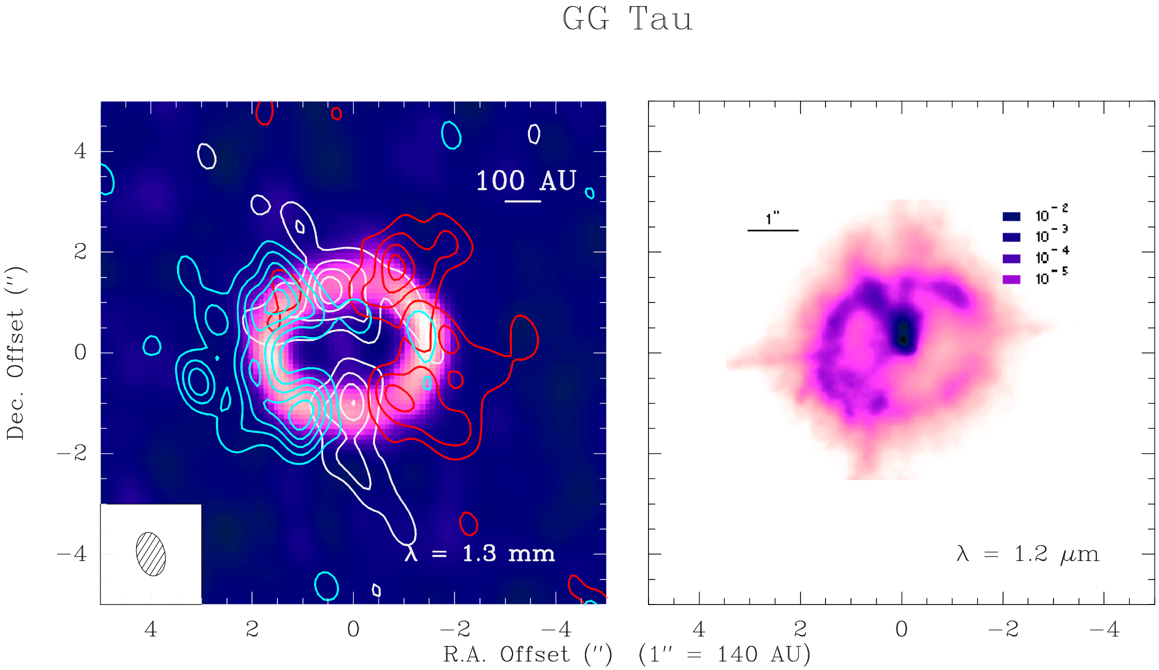
Dutrey et al. 2000, IAU symp.197

Dust and Gas around binaries

- **More than 70 % of stars are binary or multiple systems...**
- **The massive ($0.15\,\mathrm{M}_\odot$) GG Tau ring**
  $\longrightarrow$ Unique ... Why ? Younger ? $\sim 5 \cdot 10^5$ yr
- **The UY Auriga CO ring** ($M_{ring} \sim 3 - 7 \cdot 10^{-3}\,\mathrm{M}_\odot$)
  $\longrightarrow$ Not seen at 1.3mm, why ?
  - Today, inner disks are unresolved but detectable at 1.3mm
  - Today, outer ring is resolved and detectable only in optically thick CO lines
- **The quadruple system UZ Tau**
  - Main binary: E-W sep.$\simeq 3.78''$
  - A ($\sim$ 300 AU) CO and dust disk around the spectroscopic binary UZ Tau East
  - Unresolved inner disk(s) around UZ Tau West of sep.$\simeq 0.34''$
- **ALMA = circumbinary disk frequency ...and properties**

GG TAU: ^{13}CO J=2-1 / 1.3mm & NIR data

From Guilloteau et al. 1999 (mm-left)& Roddier et al. 1996 (NIR-right)

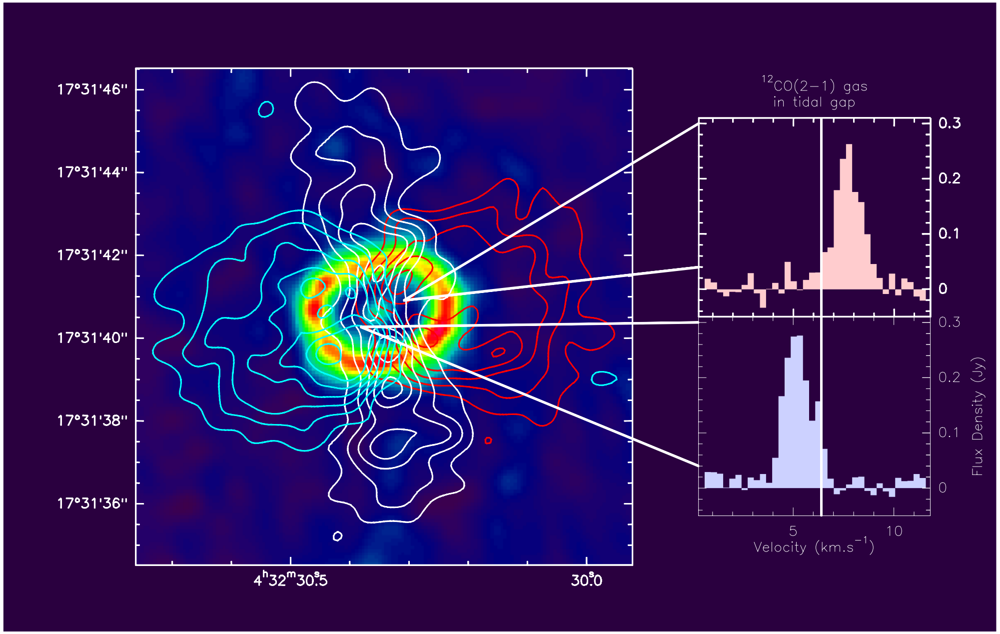


Mm data: massive $(0.15\,\mathrm{M}_\odot)$ and narrow ring:$\Delta r = 80$ AU, edges ~ 10 AU

NIR/mm:same R$_{in}$, PA and i - comparison mm/NIR = Disk scale height

GG TAU: ^{12}CO J=2-1 data from PdBI

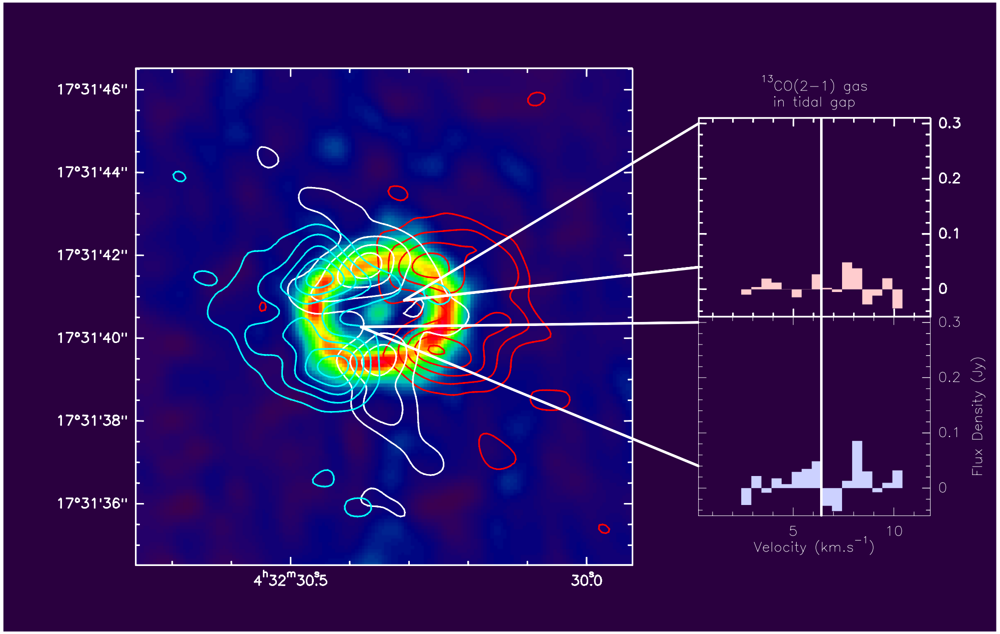
- From Guilloteau & Dutrey 2000 (proceedings IAU 200)



^{12}CO is in Keplerian rotation, fills a significant fraction of the gap → Streamers...
^{13}CO/^{12}CO comparison gives $\sim 6 \cdot 10^{-4}\,\mathrm{M}_\odot$ inside the gap → Accretion rate of $\sim 10^{-6}\,\mathrm{M}_\odot$/yr

GG TAU: ^{13}CO J=2-1 data from PdBI

- From Guilloteau & Dutrey 2000 (proceedings IAU 200)



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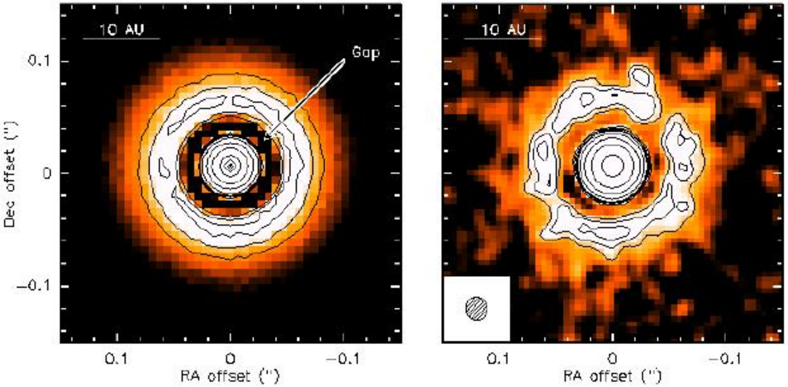
Gaps inside a protoplanetary disk at D=150 pc

- **From Wolf et al. 2002, submitted**



Thermal dust emission (left) at 230Ghz.
Simulation of 3 hours of int.time on long baselines (right). Resolution 0.02".
Gap created by a proto-planet of 1 M_J.

From Protoplanetary disks to debris disks

Evolution of (large) gas and dust disks ? Timescale for disk dissipation ?

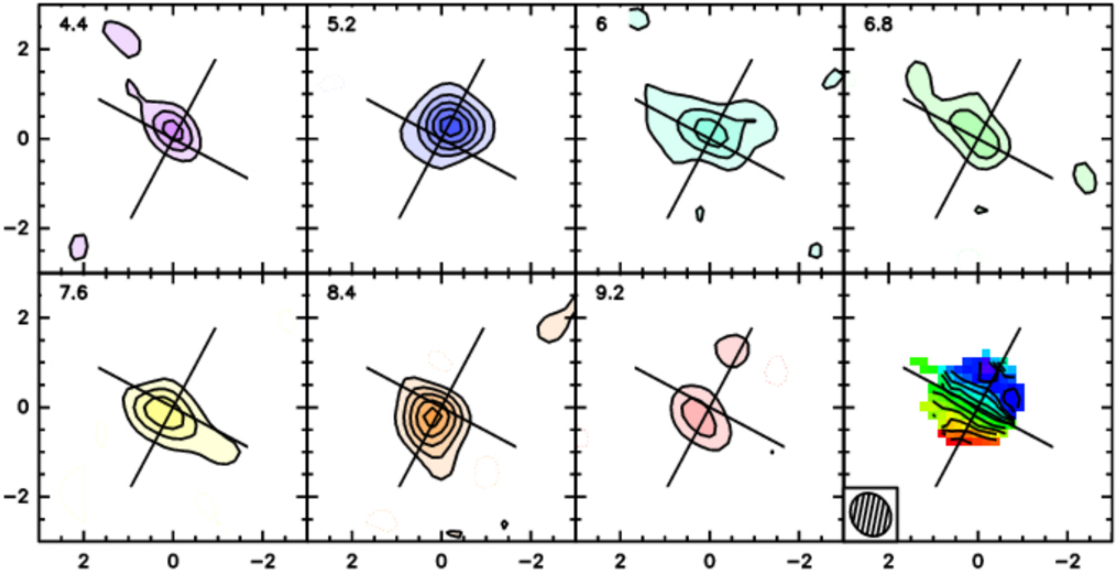
- **The BP Tau Disk:** CTTs of $\sim 5 \cdot 10^6$ years Dutrey et al. 2002
  - Small CO disk (R$_{out} \simeq 100$ AU)
  - ^{12}CO J=2-1 marginally opt.thin (depleted by a few 100/dust)

  → **A transition disk ?**
- **Are current mm arrays missing such disks ?**(BP Tau: 25 hours)

- **The ϵ Eridani Disk:**
  - A debris disk surrounding a young Main-Sequence star
  - Planetary formation within the disk
  - Gas (CO) content ?

- **ALMA = disk evolution towards debris disks (β Pic)**

Opt. thin ^{12}CO J=2-1 emission around BP Tau



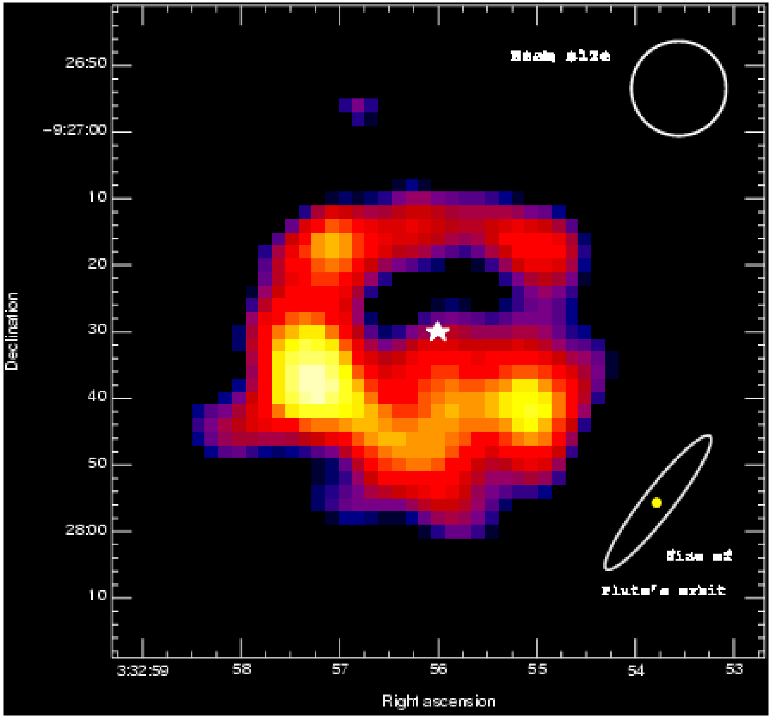
^{12}CO PdBI data: Dutrey et al. 2002, in prep.

A small ($R_{out} \simeq 100$ AU) and optically thin CO disk around a CTTs.

ALMA: ^{13}CO J=2-1 map at same resolution if disk uniform

→ 60-90 hours of integration time for same quality of data

Debris disks



Dusty ring observed around the cool star ϵ Eridani ($d \sim 3$ pc, K2V). SCUBA image at λ 850 μm (Greaves et al., 1998).

+ Pluto orbit at $d = 3$ pc in bottom right corner.

+ Radius of the clearing gap $\sim$ 30 AU.

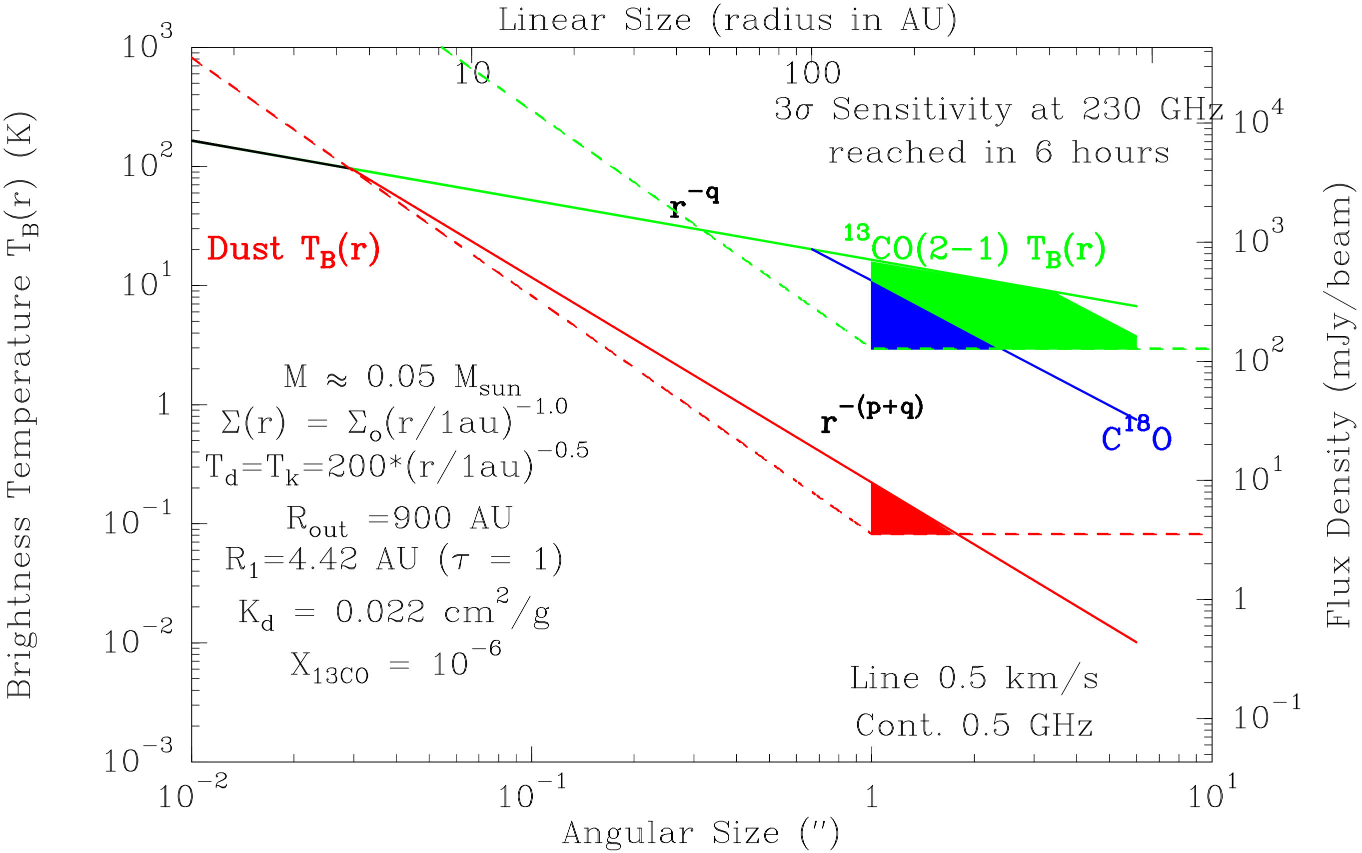
ALMA will be able to study this kind of dusty ring with much more detail, and in a large number of more distant stars.

+ Dust masses down to 10^{-2} M$_{\rm Earth}$ detectable out to $d \approx 100$ pc in $\sim$1 hr.

+ CO column density of order 10^{12} cm^{-2} in 1 hr at resol $\sim 2.5''$ for CO line of ~ 3 km/s (β Pic)

Sensitivity curves for protoplanetary disks

- **Current situation at PdBI for disks at D=150 pc**



Sensitivity curves for protoplanetary disks

- **Expected situation with ALMA for disks at D=150 pc**