ALMA Science:
a review of (sub)mm band science and instruments in the ALMA era

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Italian node of European ALMA Regional Centre

SISSA – February 2014

Enter the ALMA world through the ALMA Science Portal

http://almascience.eso.org/

All PI and CoI must be registered

Current call Tools and info

All the documents and tools
Cycle 2 primer, Proposer Guide, OT Guide

Access to Helpdesk for any request (FAQ, problems, F2F...)

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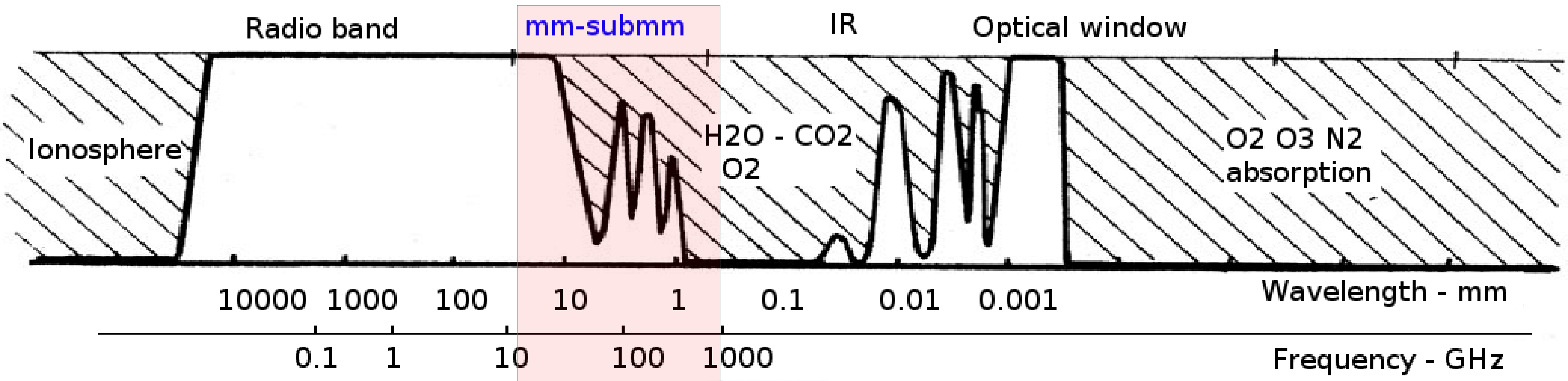
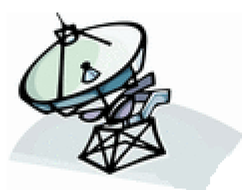
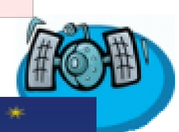
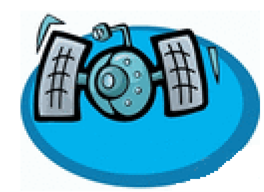
Outline









Signals in (sub)mm band — What can we get out of them?

The reasons for ALMA — Pills of interferometry; ALMA properties; Writing a proposal

Galactic Science — **From planets to our Galaxy**

Extragalactic Science — AGNs; Submm galaxies; Galaxy clusters

(sub)mm band science

General words & ALMA pros

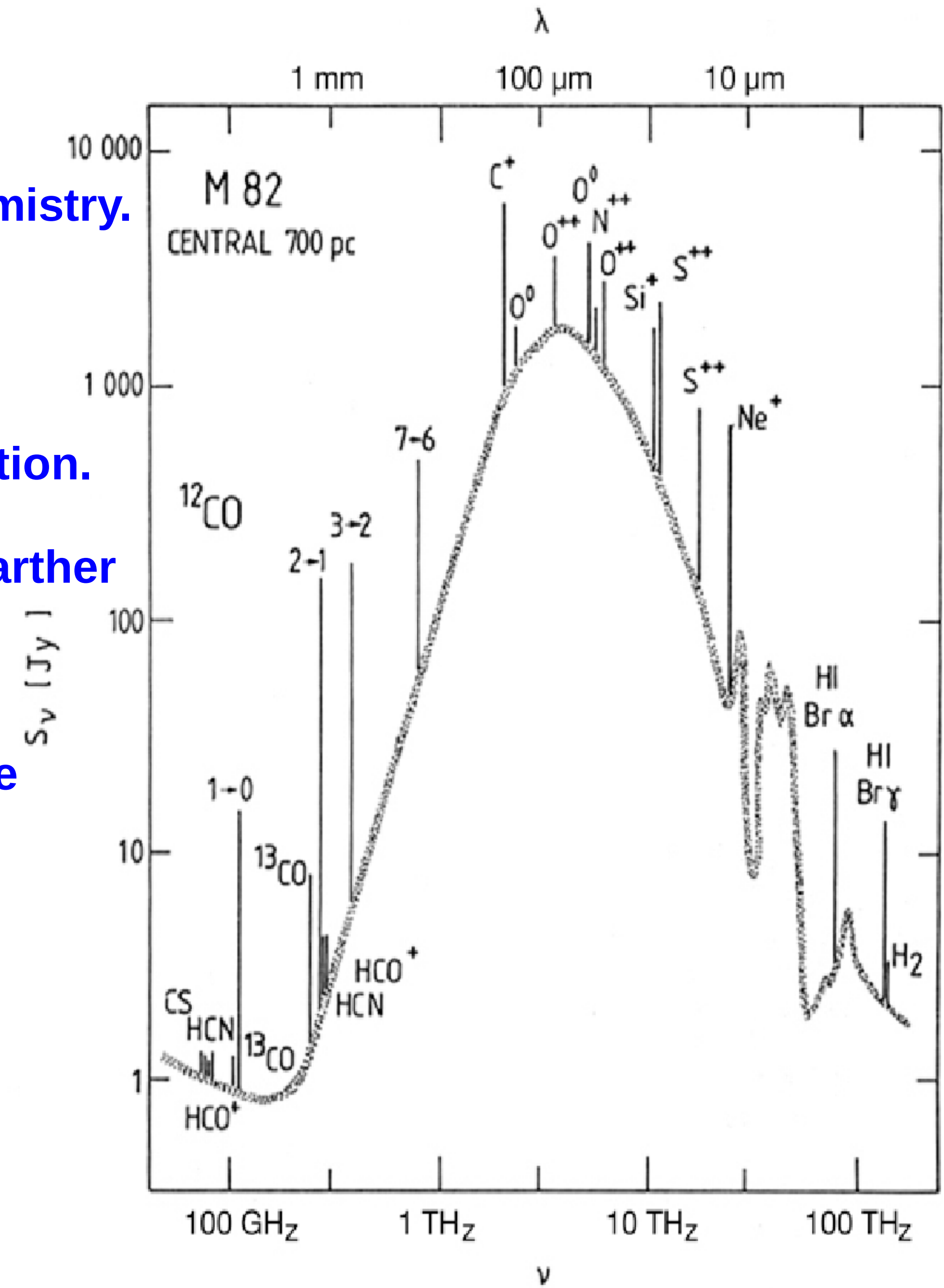
Sub(mm) is characterized by dust and rich chemistry.

Dust and moleculae are mostly (but not only) associated with forming structures.

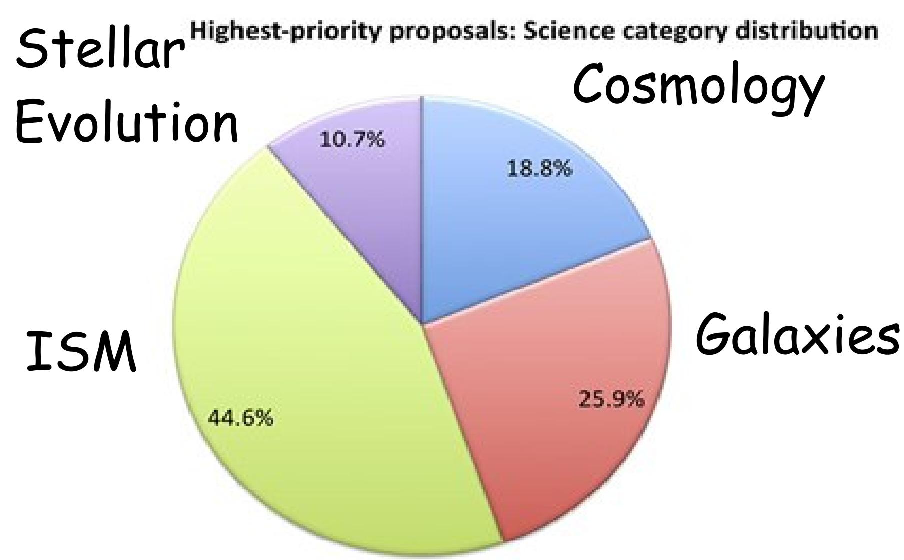
Hence **sub(mm) helps studying structure formation.**

Higher resolution and sensitivity allows to go farther so to investigate a deeper sky region, getting more sources and more statistics on populations.

Higher spectral resolution allows to detect more narrow lines and more details from broad lines, and hence investigate chemical compositions, source dynamics and pressure and temperature structures.



	Full array	Cycle 0
Frequency range:	**10 bands 30-900 GHz**	**4 bands (3, 6, 7, 9)**
Antennas:	**50x12m** + ACA	**16x12m** (no ACA)
Sensitivity	**0.15 mJy in 1 min @ 230 GHz**	**0.5 mJy in 1 min @ 230 GHz**
Max baseline:	**150m-16km**	**2 configs: 18-125m, 36-400m**
Angular Resolution:	**20 mas @ 230 GHz**	**1000 mas @ 230 GHz**
	70 correlator modes	**14 correlator modes**
	Mosaic capability	**Limited mosaic** capabilities
	Pipeline reduction in Chile	**Reduction @ ARCs**



Cycle 0:

- 111 Highest-priority + 51 filler proposals (out of 919 submissions)
- 108 (98%) Highest-priority PIs received some data

Galactic & Solar System science

Planets & small bodies

Surface studies

- Mapping regions that may contain ice at mm wavelength can help determining the surface temperatures and hence **if the ice is stable** (e.g. Mars polar caps).

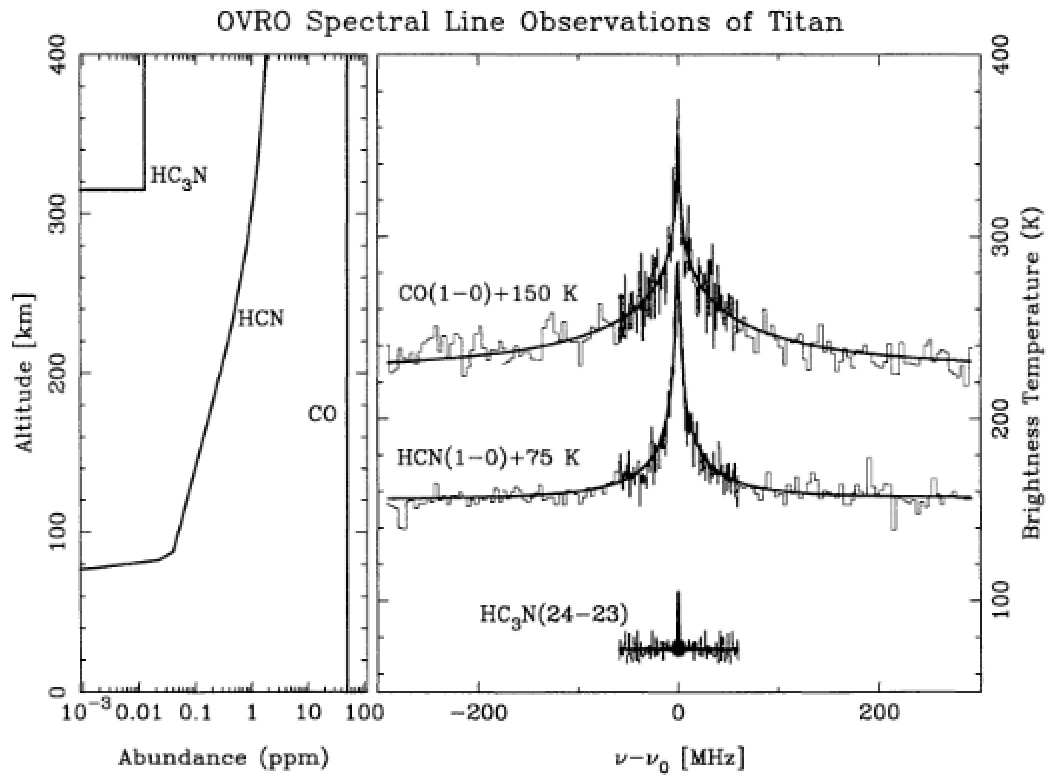
- Mapping the surface temperature as a function of wavelength constrains the properties of the planet heat from the interior, useful to study **the planetary magnetic fields.** (e.g. to determine if Mercury has a molten core)

Atmospheric studies

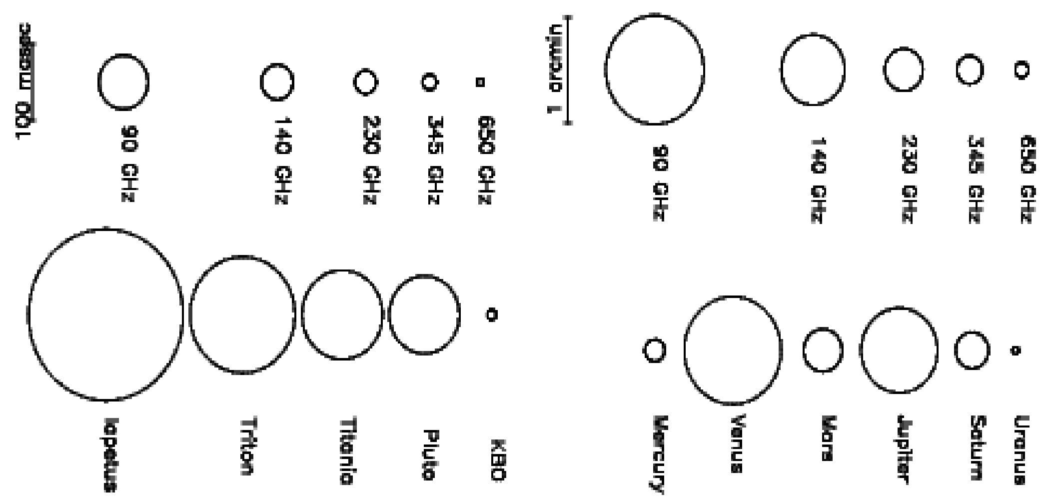
- Since spectral line shape (i.e. Doppler and pressure broaden lines) depends on molecular abundances and temperature profiles they can be used to reconstruct **vertical structures and dynamics of planetary Atmospheres, (seasonal variations and climate models)**

Calibrations

- Planets & satellites are "relatively" stables, so are often used as **flux calibrators at sub(mm)** Proper models of flux density distribution (they are typically extended wrt to telescope beams) including time variability (e.g. seasonal variations) are crucial also for other science observations.



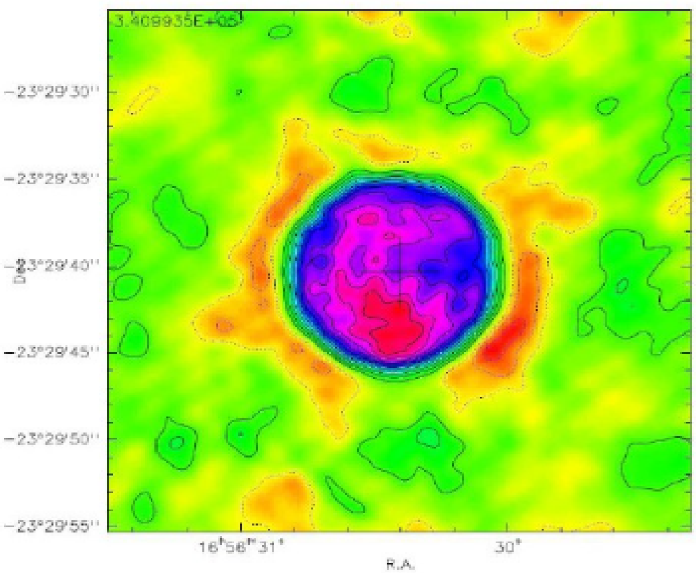
ALMA beam sizes



Solar System bodies sizes

PI: T. Encrenaz

Sulfur and water mapping in the mesosphere of Venus



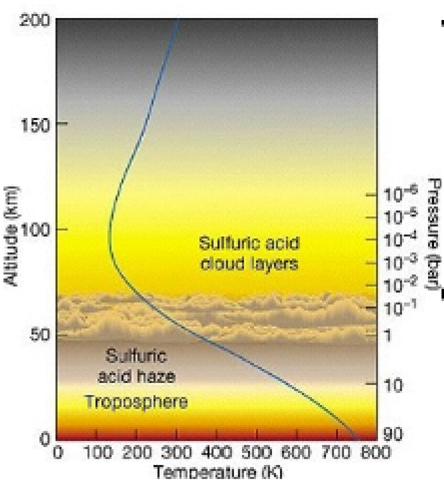
Venus ~10" - 16 antenna – beam ~1"

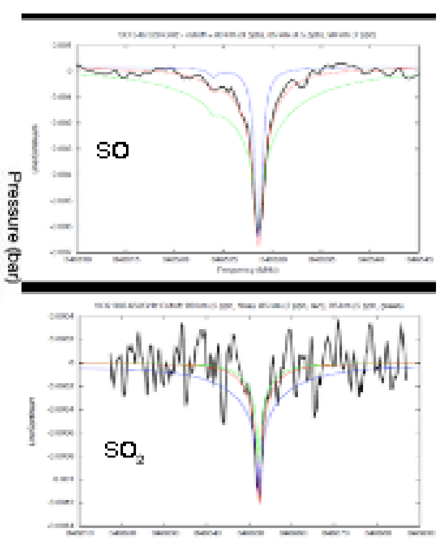
OBSERVATIONS

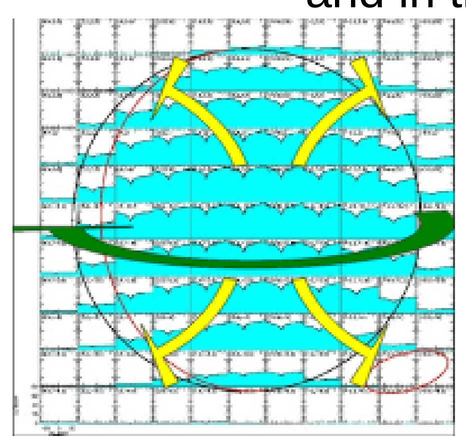
- Cycle 0
- 1.2 hr on-source
- Band 7 (0.85 mm): SO2, SO, HDO and CO
- **spatial resolution 1.2-2.4"" (for a disk of 11")**
- 16 antennas

At 80-110 km of altitude sulfur species SO2 and SO, that may be indicative of Venus' volcanic activity, and showed an abundance increase with altitude

Variation estimated horizontally, vertically and in time (24hr and 11d).



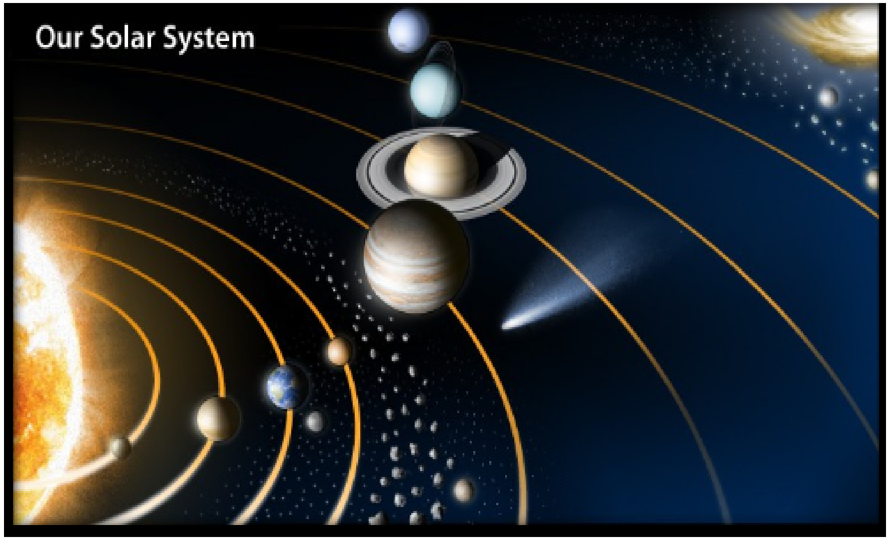




By mapping the CO(3-2) line's Doppler-shifts, they derived the wind field near the upper boundary of the mesosphere

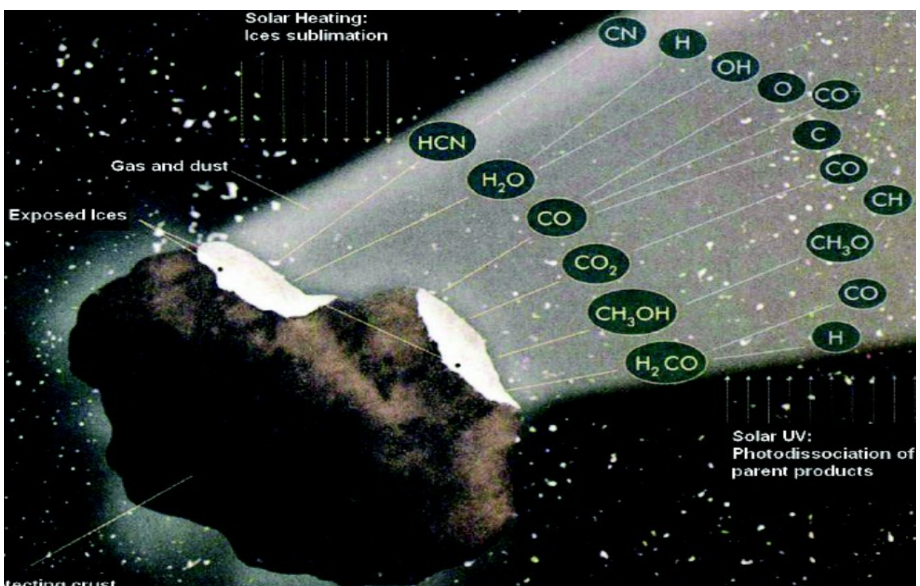
Moullet et al. 2013

Comets & small bodies



Observing **small bodies** will allow to **image their surfaces**, determine their sizes and orbits.
At 3AU a 10km asteroid has flux $1/\lambda^2$ mJy

Comets come back as remnants of the Planet formation era. Comets preserve the material left from the protoplanetary Solar nebula.
Cometary ices aggregated at the time the Solar System formed (c. 4.5 Gyr ago), and have remained in a frozen, relatively quiescent state ever since
Their composition and structure may provide information about the physical and chemical conditions in the Early Solar System.

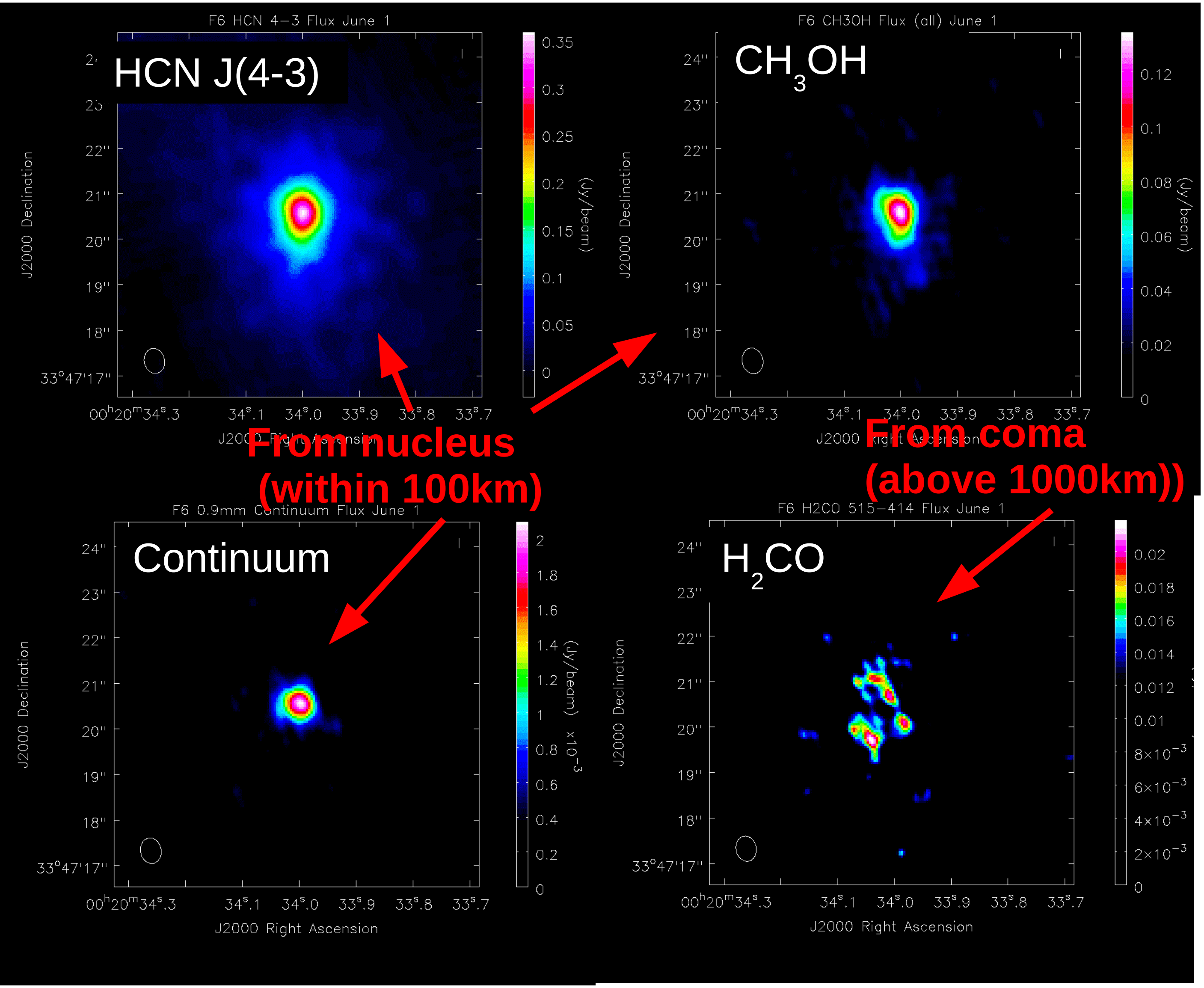


The nuclei can be detected in far away comets without obscuration.
1Km nucleus at 1AU has 1mm flux of 0.1mJy.

Getting closer to the Sun, dust and ice grains are released. mm observations can unveil the nuclear mechanisms, composition and evolution as function of distance from Sun.
Spectroscopy reveals the composition of comae, and the dynamics of the emission.
Typical lines are molecules of H, C, N, O, including prebiotic moleculae

PI: M. Cordiner

Comet C/2012 F6 Lemmon with ALMA



OBSERVATIONS

- Cycle 1 Director's Discretionary Time proposal
- 1.2 hr on-source
- Band 7 (0.8-0.9 mm): HCN, CH_3OH, H_2CO
- 30 antennas
- Spatial resolution 0.4 arcsec
- Spectral resolution 0.4km/s

First ALMA observations of a comet

H_2CO (Formaldehyde): not peaked, so not from the nucleus

CH3OH (Methanol) time variation, maybe rotating

Chemical origin of HCN, HNC and H2CO in nucleus

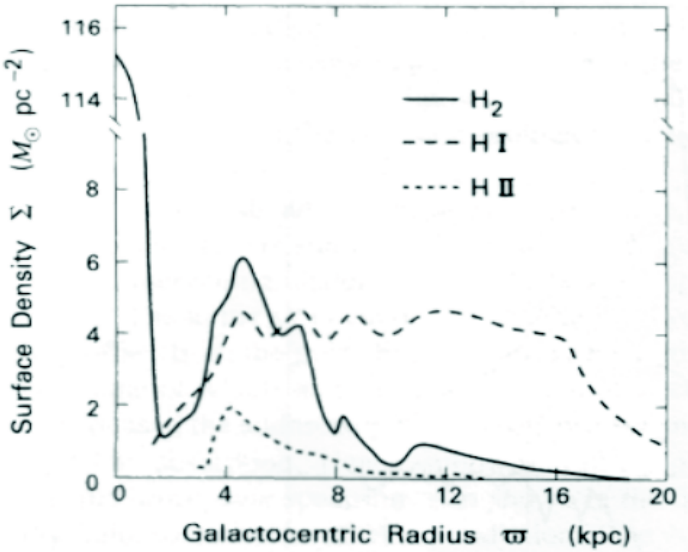
Organic molecules (CH3OH): impact on Astrobiology

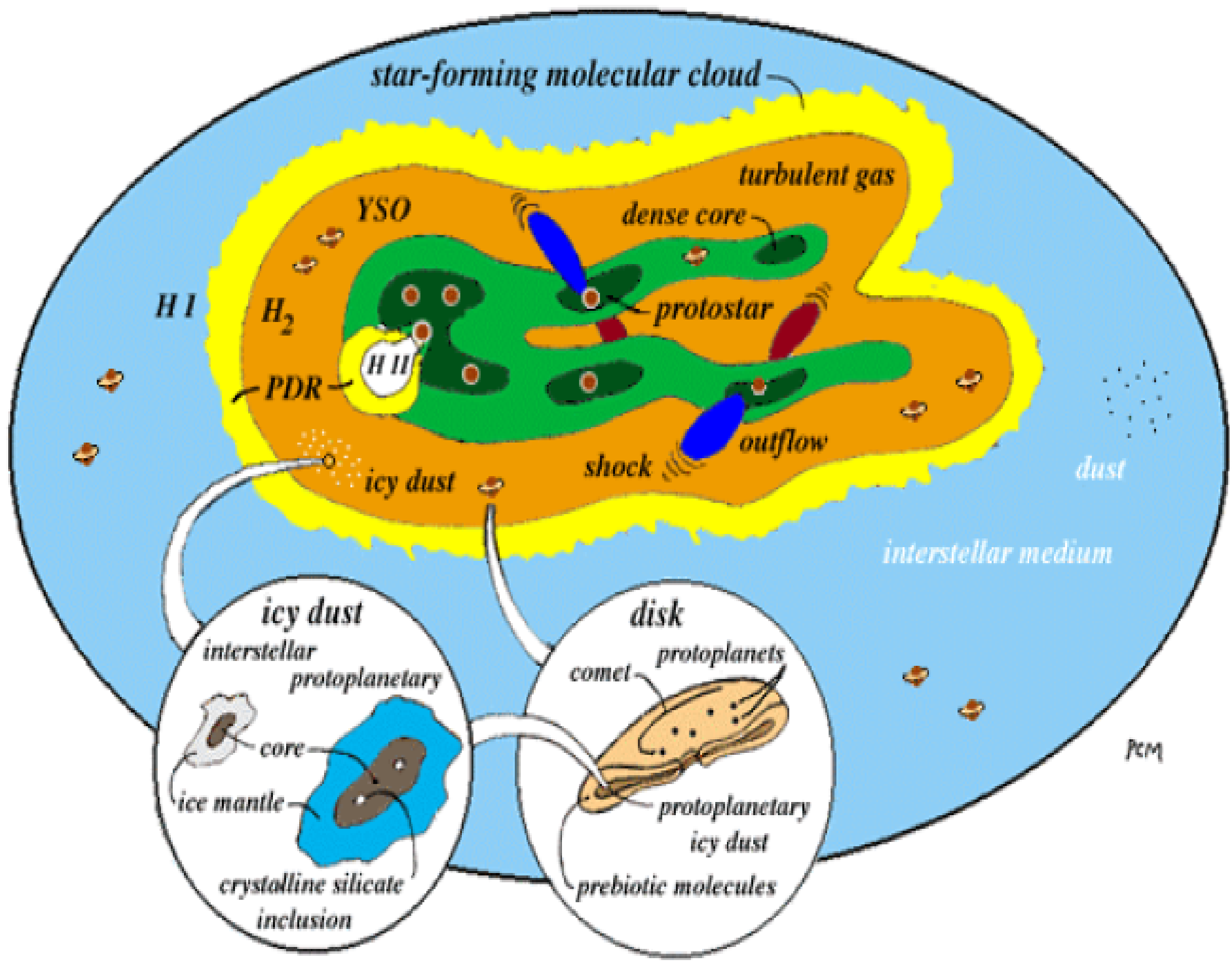
Cordiner et al. 2014

Interstellar medium

The ISM is constituted by 90% of H, 9% of He and traces of other components
H appears in H2, HI and HII.
80% of H2 is in giant molecular clouds, peaking in the Galactic center.

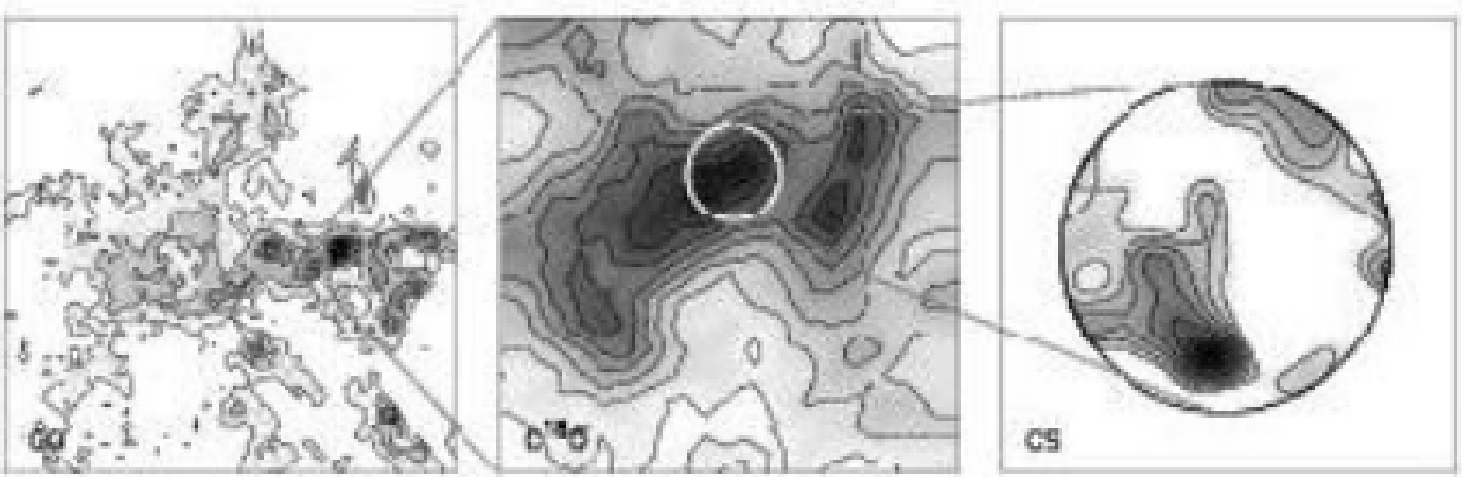
(Stahler & Palla)





Clumps & Cores

Molecular clouds are highly structured complexes made of clumps (where clusters can form) and cores (where a single or binary star form). Objects are typically located along filaments.



Clouds	clumps	cores
$D \geq 10$ pc	$D \approx 1$ pc	$D \approx 0.1$ pc
$n(H_2) \approx 10^2\text{-}10^3$ cm^{-3}	$n(H_2) \approx 10^5$ cm^{-3}	$n(H_2) \approx 10^7$ cm^{-3}
$M \geq 10^4\ M_\odot$	$M \approx 10^3\ M_\odot$	$M \approx 10\text{-}10^3\ M_\odot$
$T \approx 10$ K	$T \approx 50$ K	$T \approx 100$ K
CO, ^{13}CO	CS, C^{34}S	NH_3, CH_3CN
$N(CO)/N(H_2) \approx 10^{-4}$	$N(CS)/N(H_2) \approx 10^{-8}$	$N(CH_3CN)/N(H_2) \approx 10^{-10}$

NOTES on SCALES

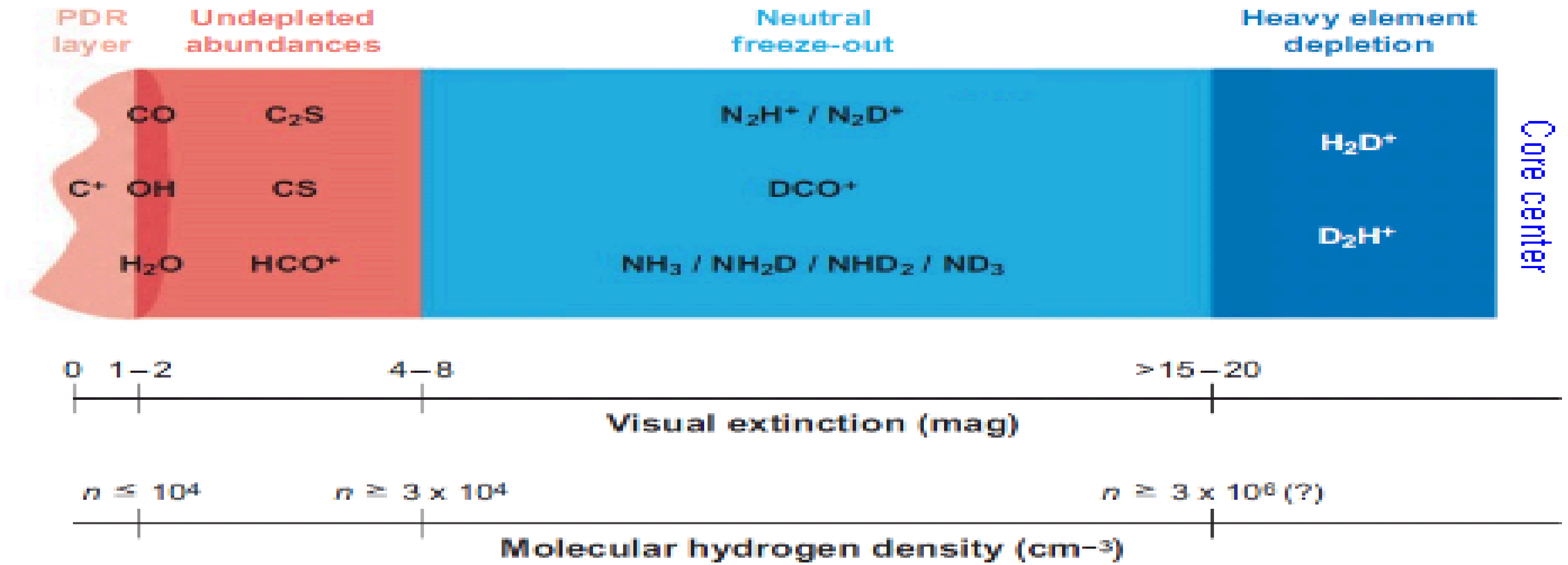
SF sites 150-500 pc

0.1 pc @ 200 pc -> 1.7arcmin

Larger than ALMA beams

Hot Cores

Hot molecular cores represent an early evolutionary stage in massive star formation prior to the formation of an ultracompact H II region (UCH II).
Single-dish line surveys toward hot cores have revealed high abundances of many molecular species and temperatures usually exceeding 100 K.
Hot Molecular Cores are usually associated with masers of H2O, CH3OH.

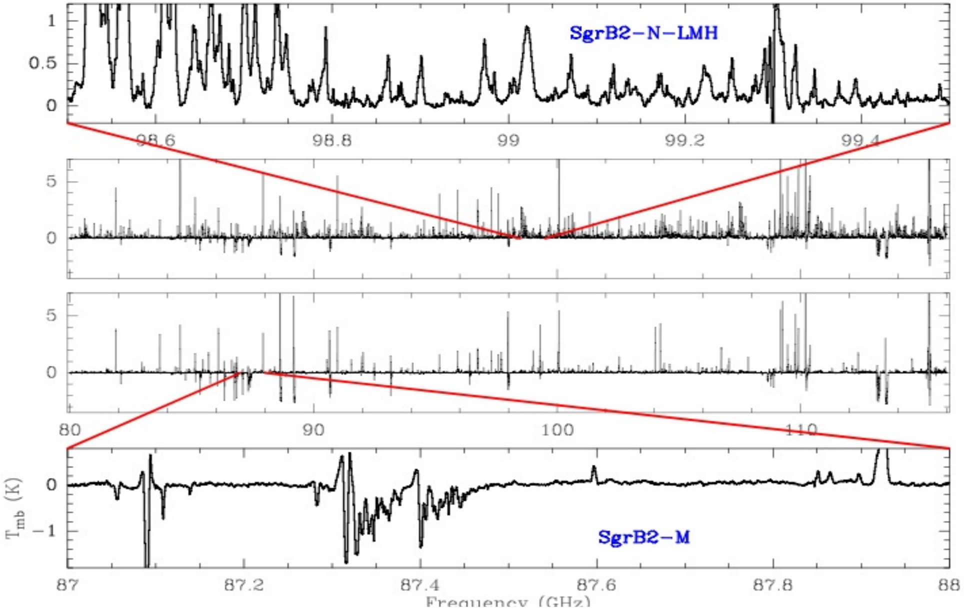


Different chemical species provide information on the different core layers.

Abundances and velocity patterns provide details on composition (including IMF, fragmentation, outflows …) on-going chemical processes.

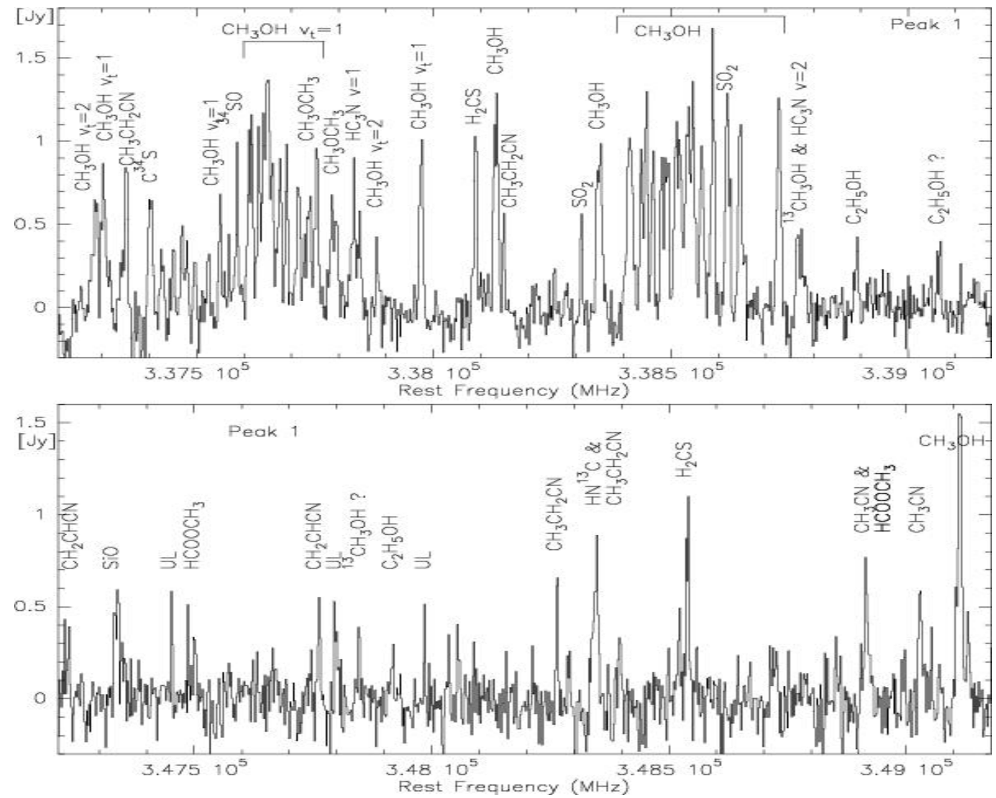
Hot cores

Belloche et al. (2007) 80-116GHz scan SgrB2(N, M)



These are two hot, dense cores in one of the most complex and massive sites of SF in the Galaxy.
SgrB2(N): **ca. 100 features/GHz >3sigma** of emitted/absorbed by 51 molecular species.
lines from 60 rare isotopologues.
40% of the features are yet unidentified (15% of which are at >=10sigma) 1 sigma (TA*) = 15-30mK
SgrB2(M): **25 features/GHz above 3sigma**,
41 molec. species, 50 isotopologues.
Unidentified ca. 50% of the features (of which 7% are >=10sigma).
The number of features per GHz translates, for the whole 80-116GHz range, into 3700 and 950 lines.

Beuther et al. (2007) spectral scan

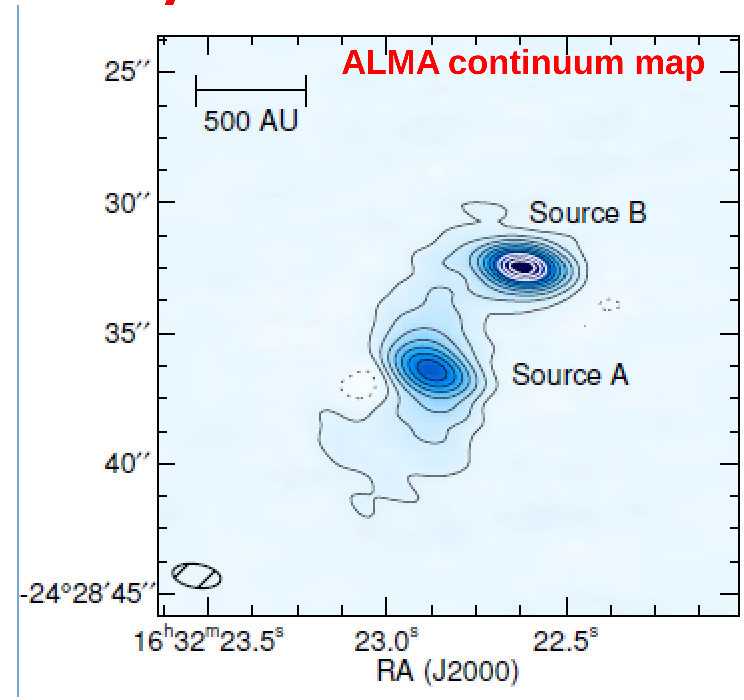


LSB and USB spectra at 862 μm towards one of the submm peaks in G29.96-0.02 (galactic massive SFR). Spatial resolution 0".64 x 0".47 (SMA).

The First ALMA view of the proto-binary IRAS 16293-2422

OBSERVATIONS: Science Verification

- Band 6: ~220 GHz
- ~16 antennas; angular resolution 2.5'' x 1.0''
- Spectral resolution ~0.08 km/s
- 5.4 hrs on source

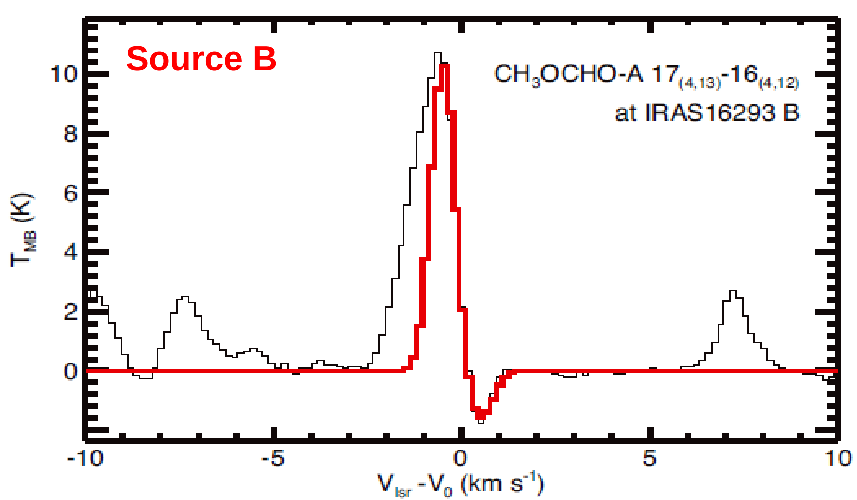


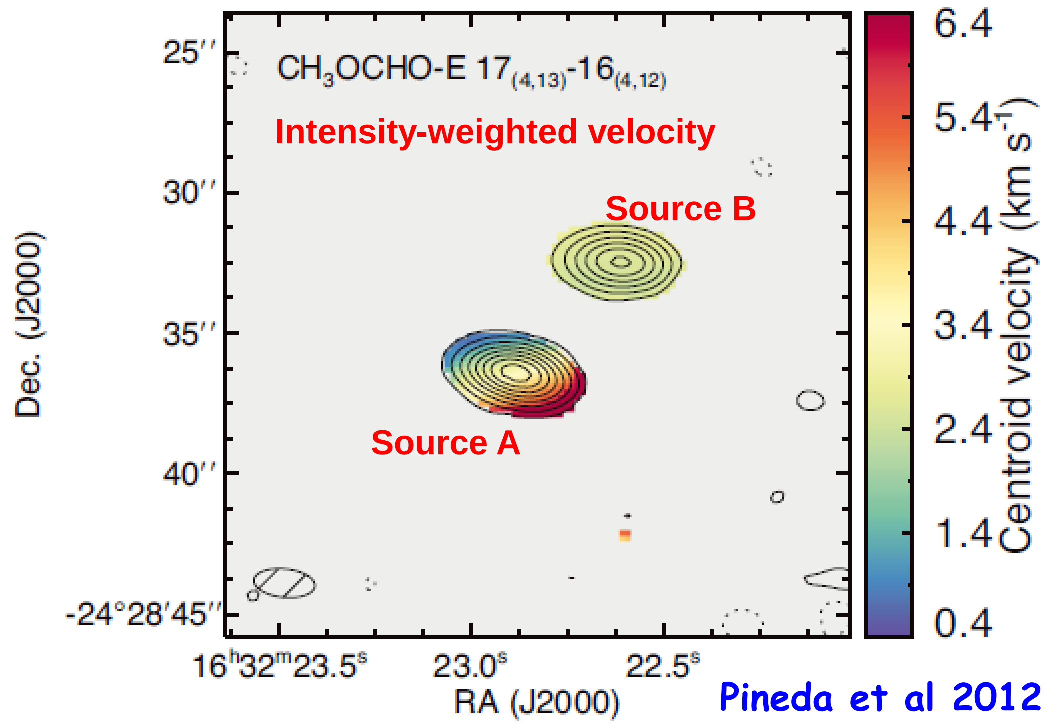
Hot-core 100AU at 120pc

Source B: First detection of an inverse P-Cygni profile in 3 emission lines → Infall → at the beginning of pre-main sequence

Infall rate of 4.5×10^{-5} $M_\odot$/yr

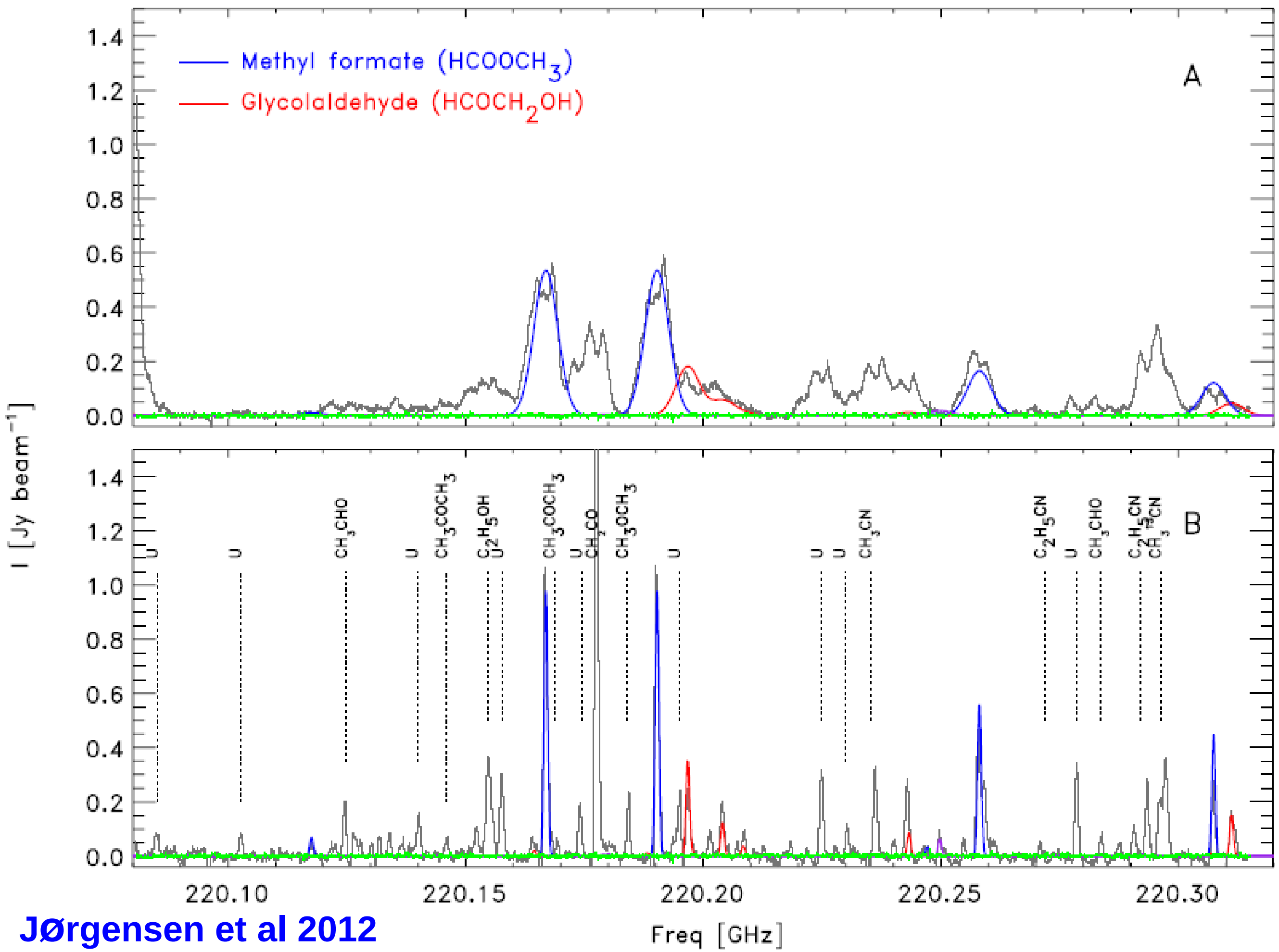
Source A: evidence of rotation with an axis close to the line-of-sight





Pineda et al 2012

Detection of glycolaldehyde in IRAS 16293-2422



Jørgensen et al 2012

In hot corinos Formaldehyde and Methanol form on grain surfaces and are injected in gas phase by sublimation were may form Complex organic molecules Reactions generate organic Molecules in 10^4 yr.

Glycolaldehyde, propenal and propanal are the most complex molecules so far detected (Ceccarelli et al. 2005)

The glycolaldehyde lines have their origin in warm (200–300 K) gas

Rich spectrum: ~30% of lines remains unassigned

13 lines of glycolaldehyde: $HCOCH_2OH$ -- > **a simple sugar-like molecule.** Under Earth-condition it is the first step in the reaction leading to the formation of ribose (part of RNA).
First detection of a pre-biotic molecule in a solar-type protostar with ALMA

First determination of acetone abundance, CH_3COCH_3: tracer of hot gas and enhanced UV radiation (Dall'Olio, Thesis @ IT-ARC)

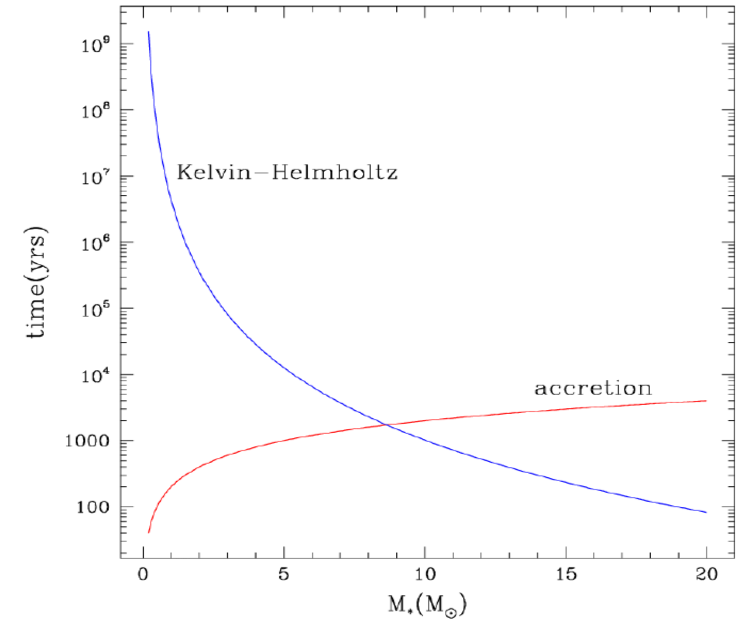
Low mass star formation

Accretion on the protostar
Contraction of the protostar

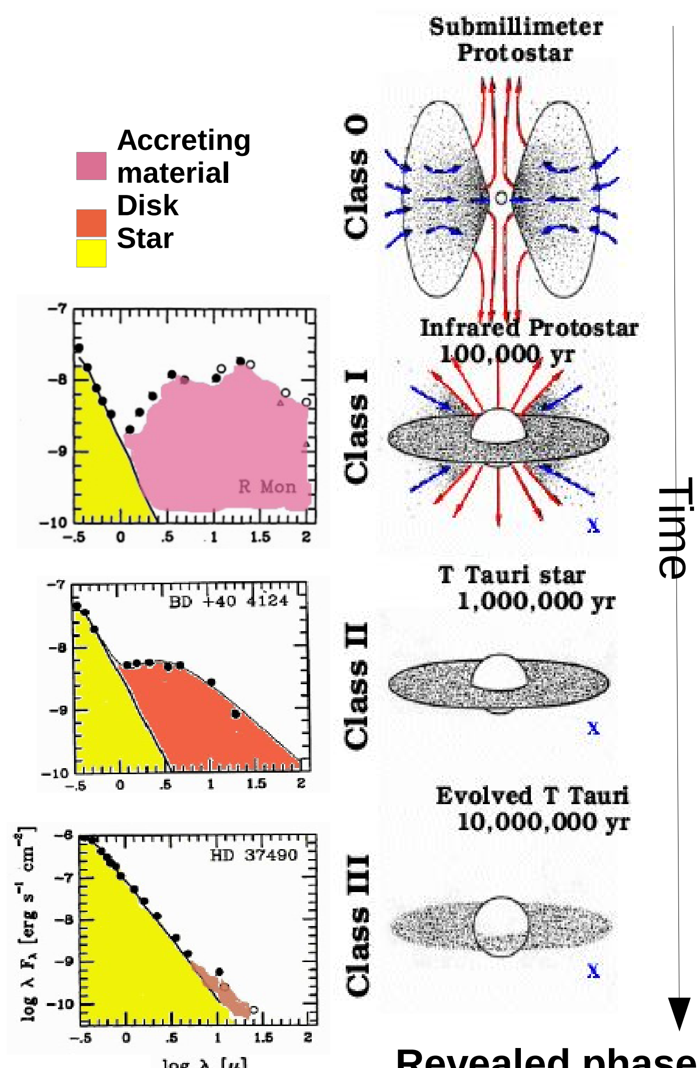
$t_{acc} = M_* / (dM_{acc}/dt)$

$t_{KH} = GM^2 / R_* L_*$

For $M_* < 8M_{sun}$ $t_{acc} < t_{KH}$



Embedded phase **Observables**



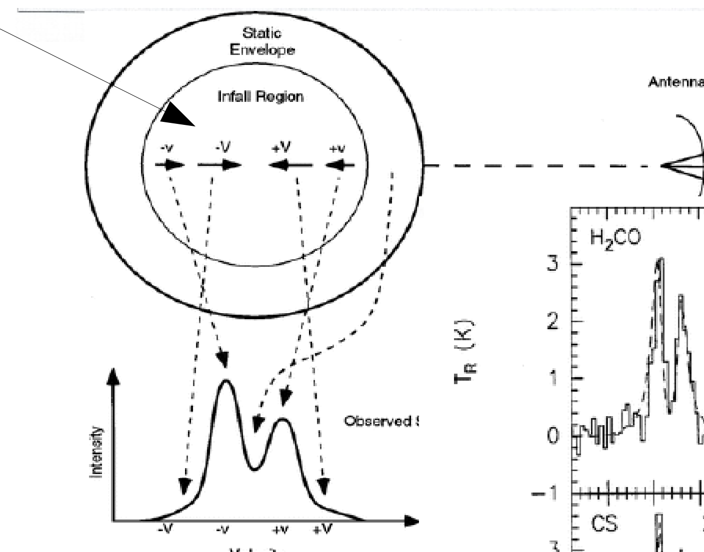
Dusty environment
Infall
Outflows

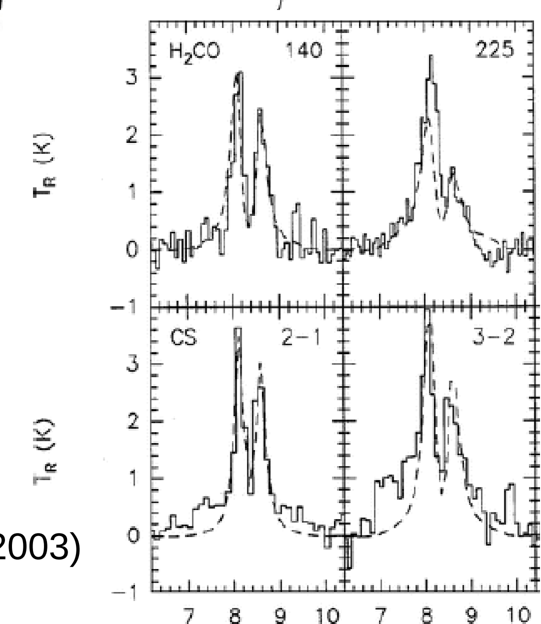
Disk
Outflows
Infall

Disk without accretion

Protoplanetary disk

Revealed phase



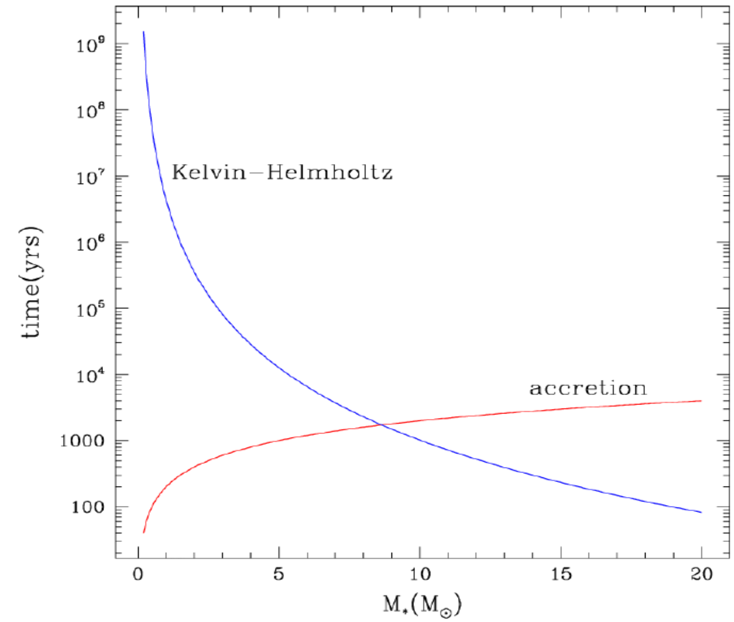


(Zhou et al. 2003)

Low mass star formation

Accretion on the protostar $t_{acc} = M_* / (dM_{acc}/dt)$
Contraction of the protostar $t_{KH} = GM^2/R_* L_*$

For $M_* < 8 M_{sun}$ $t_{acc} < t_{KH}$



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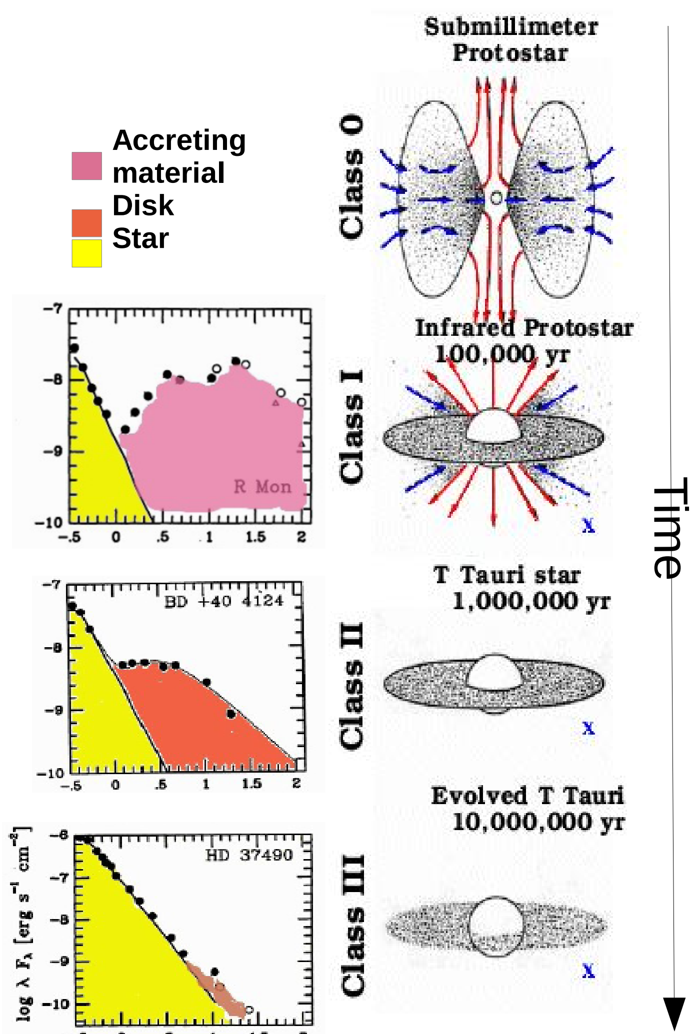

Dusty environment
Infall
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Disk
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Disk without accretion

Protoplanetary disk

Revealed phase

NOTES on SCALES

Jeans scale 10000 AU
Planet formation 1-10 AU
Outflows < 10AU
Protostellar disk = 100 AU
PDR (HII regions) 1000 AU
Nearest Ttauri star 50 pc
Lowmass SF sites 150 pc
High mass SF sites 500 pc

10 AU @ 100 pc -> 0.1arcsec

ALMA reaches 20-100 mas
@ 200kpc (LMC) -> Jeans scale

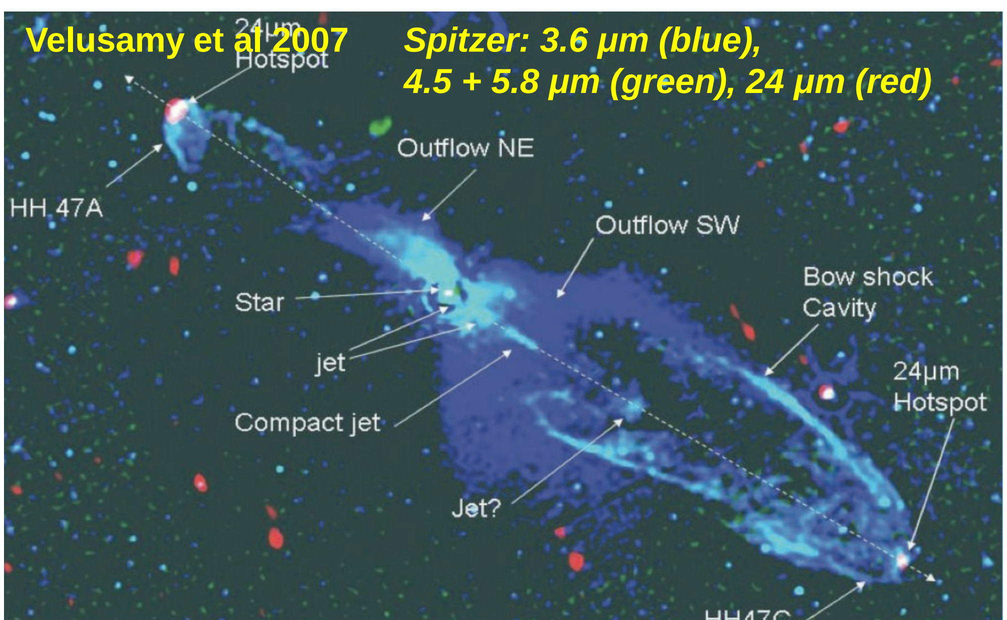
ALMA observations of the HH 46/47 molecular outflow

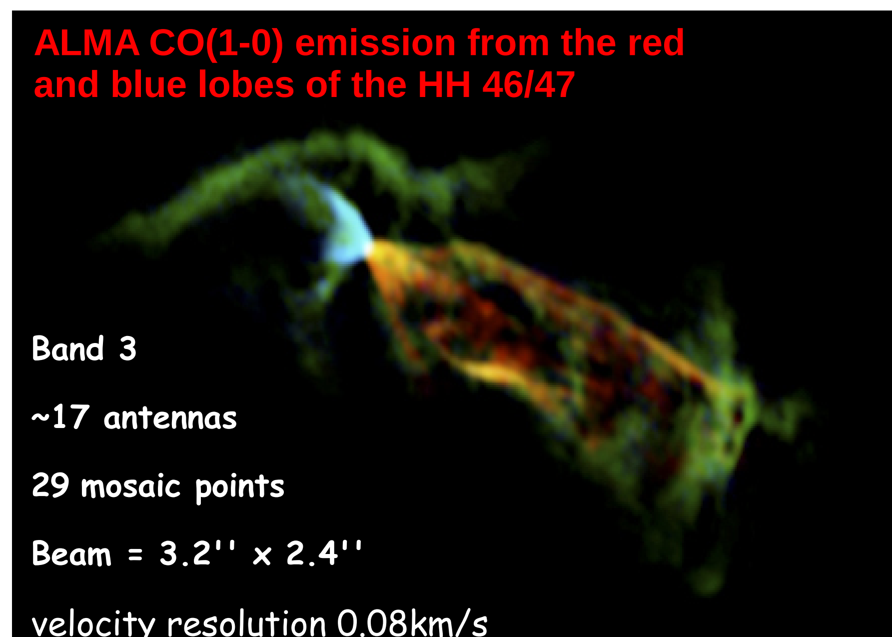
PI: D. Mardones

As stars form inside molecular clouds, they eject mass in energetic bipolar outflows. The resulting bipolar wind from a young stellar object (YSO) may reveal itself through **Herbig-Haro (HH) objects**, obscured in optic by the molecular cloud

CO traces highly collimated jets and their (internal or leading) bow shocks and map the ambient gas that has been swept-up well after it has been entrained by the protostellar wind and has cooled.

Outflows may be responsible for the clearing of material from the core, a process that could result in the termination of the infall phase, affect the star formation efficiency in the cloud, and determine the mass of stars. Outflows can affect the kinematics, density and chemistry of a substantial volume of their parent clouds, and thus can be important to the turbulent dynamics and energetics of their host cores.





Arce et al. 2013

ALMA observations of the HH 46/47 molecular outflow

PI: D. Mardones

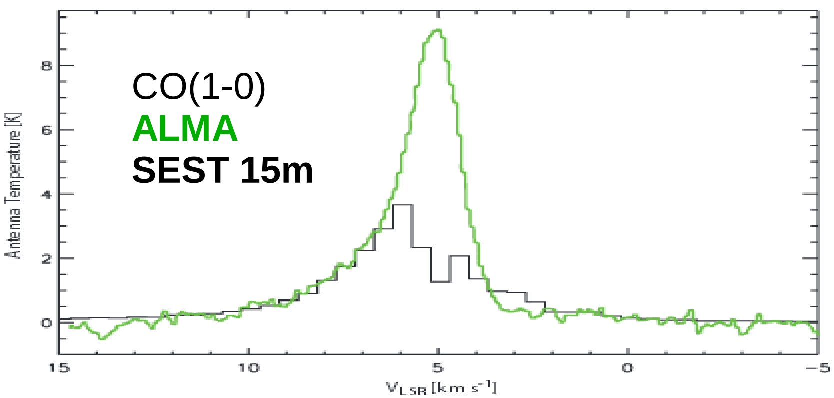
First interferometric map of the CO outflow associated with HH 46/47

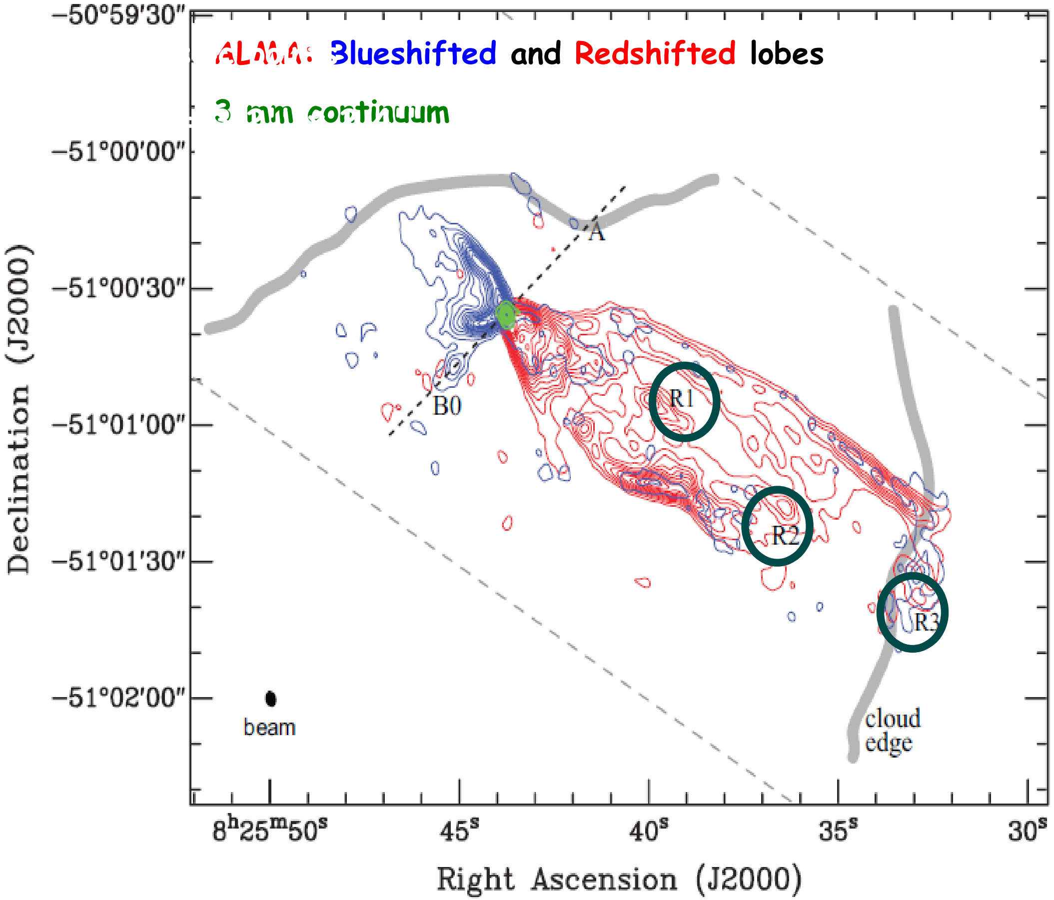
Different outflows morphology traces different environment densities

Red lobe: 3 clumps indicate multiple ejection episodes

Outflow emission at much higher (x6) velocities than expected from previous observations
(-30 km/s blue, 40 km/s red)

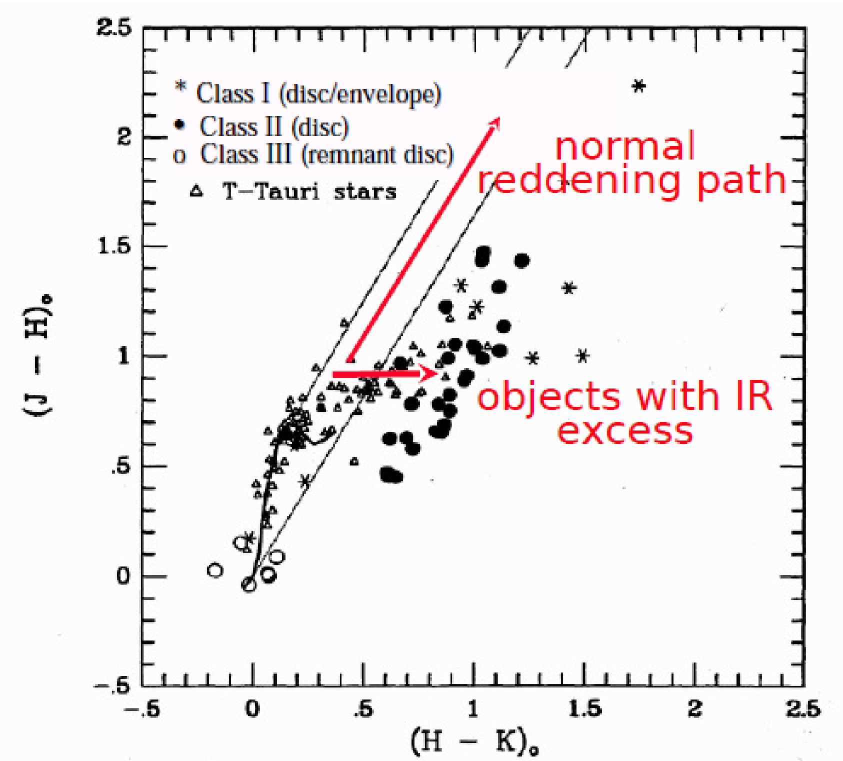
If HH 46/47 is representative: **similar molecular outflows may be much more energetic than previously thought**

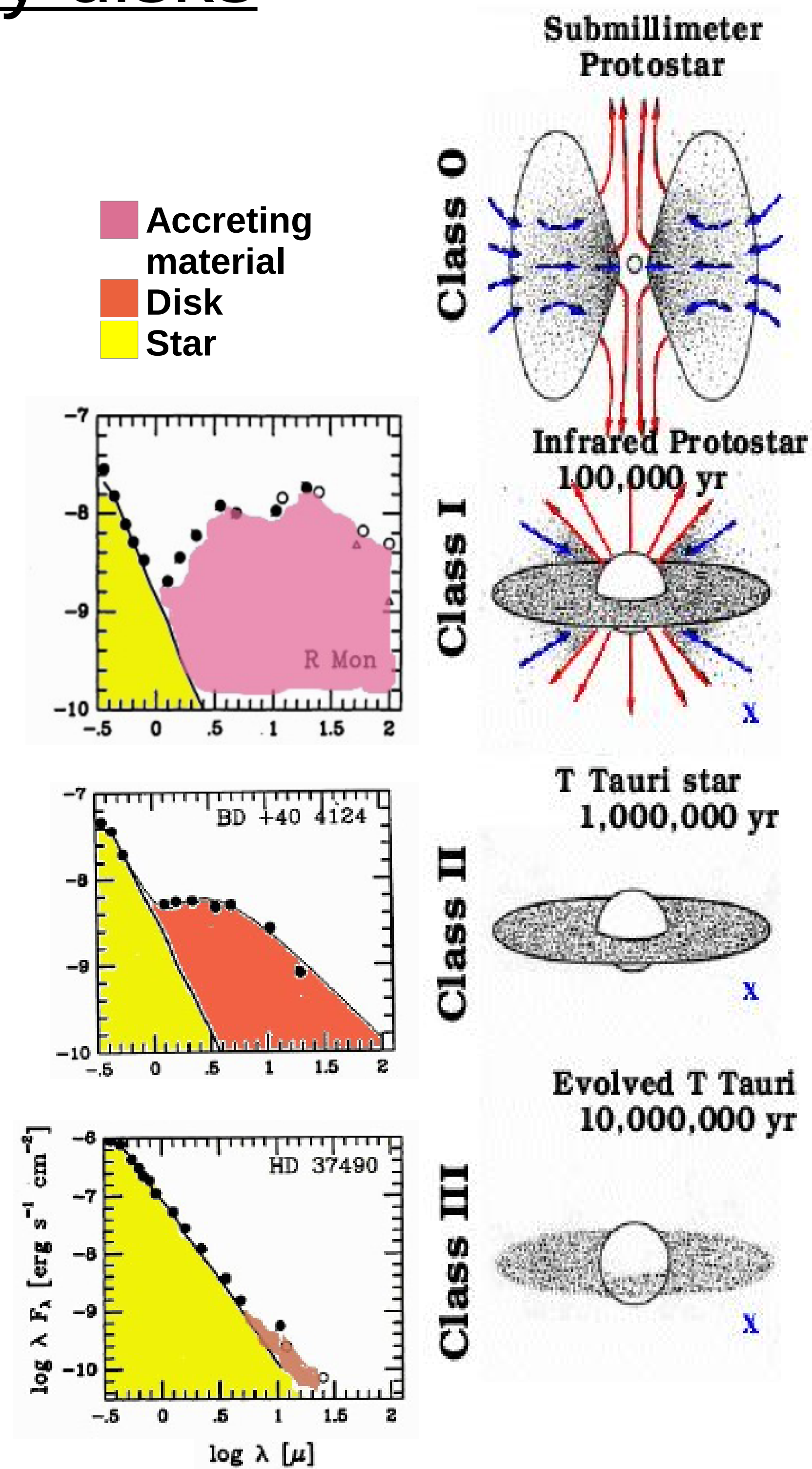




Arce et al. 2013

Protoplanetary disks





Presence of discs in stars were identified by IR excess and SEDs. Different star-disc classes show different SEDs. In sub(mm) optically thin envelopes of protostars are observable

Ttauri: young star <10-20Myr 0.5<M<2Msun (class 2)

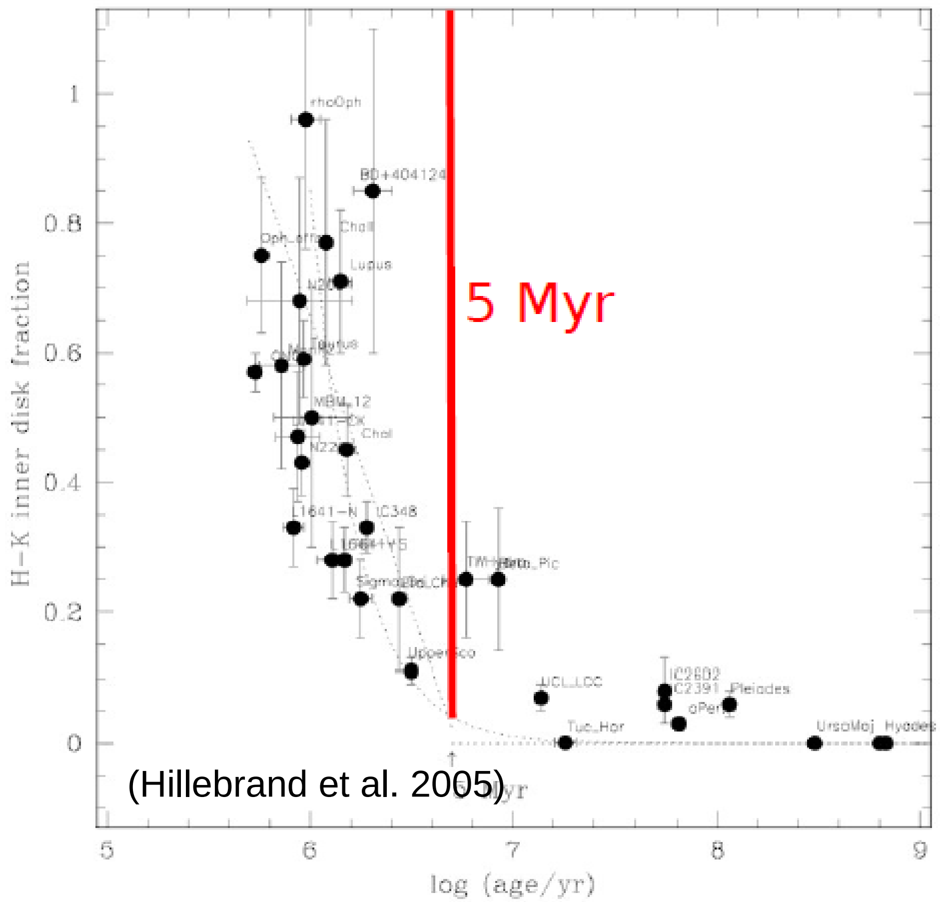
Herbig Ae/Be: <10Myr 2<M<8 MSun (class 3)

Protoplanetary disks

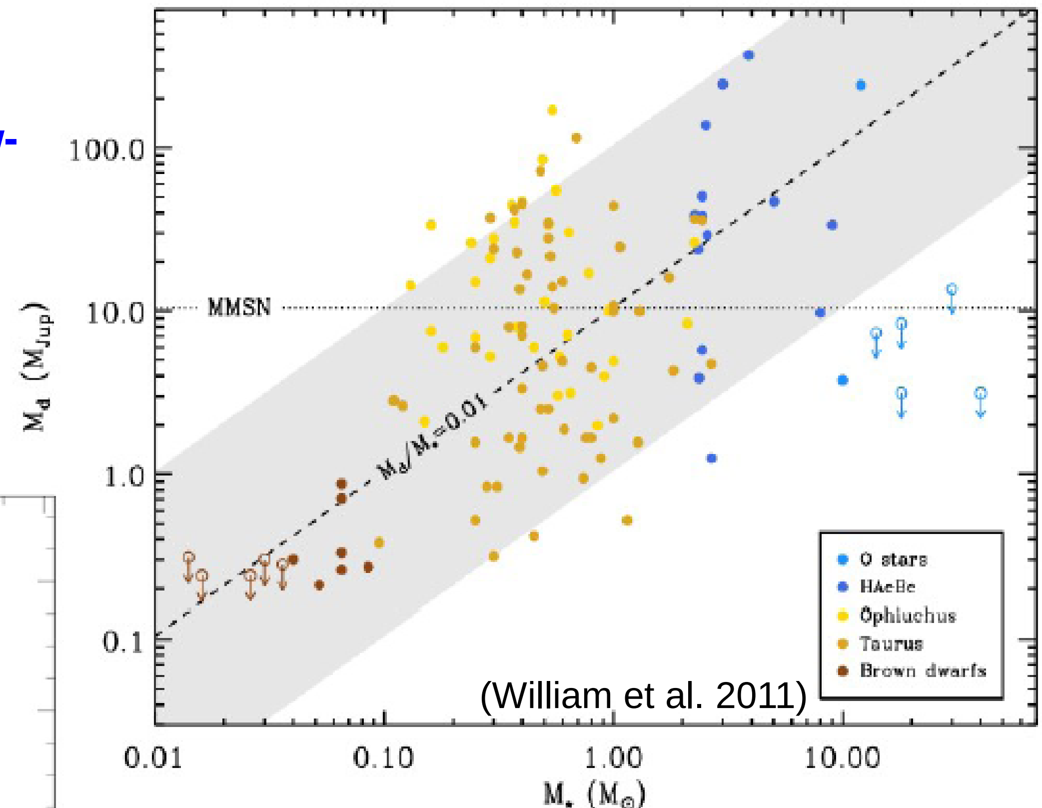
Since discs are optically thin in mm regime, fluxes traces the mass of the disc.

Massive star loose disc more rapidly than low-mass star of same age.
For star masses 0.04<M<10Msun the disk is typically 1% of the star mass.

For O-type star no disk were detected (before ALMA) in submm indicating very short disk life or a different formation scenario.



(Hillebrand et al. 2005)



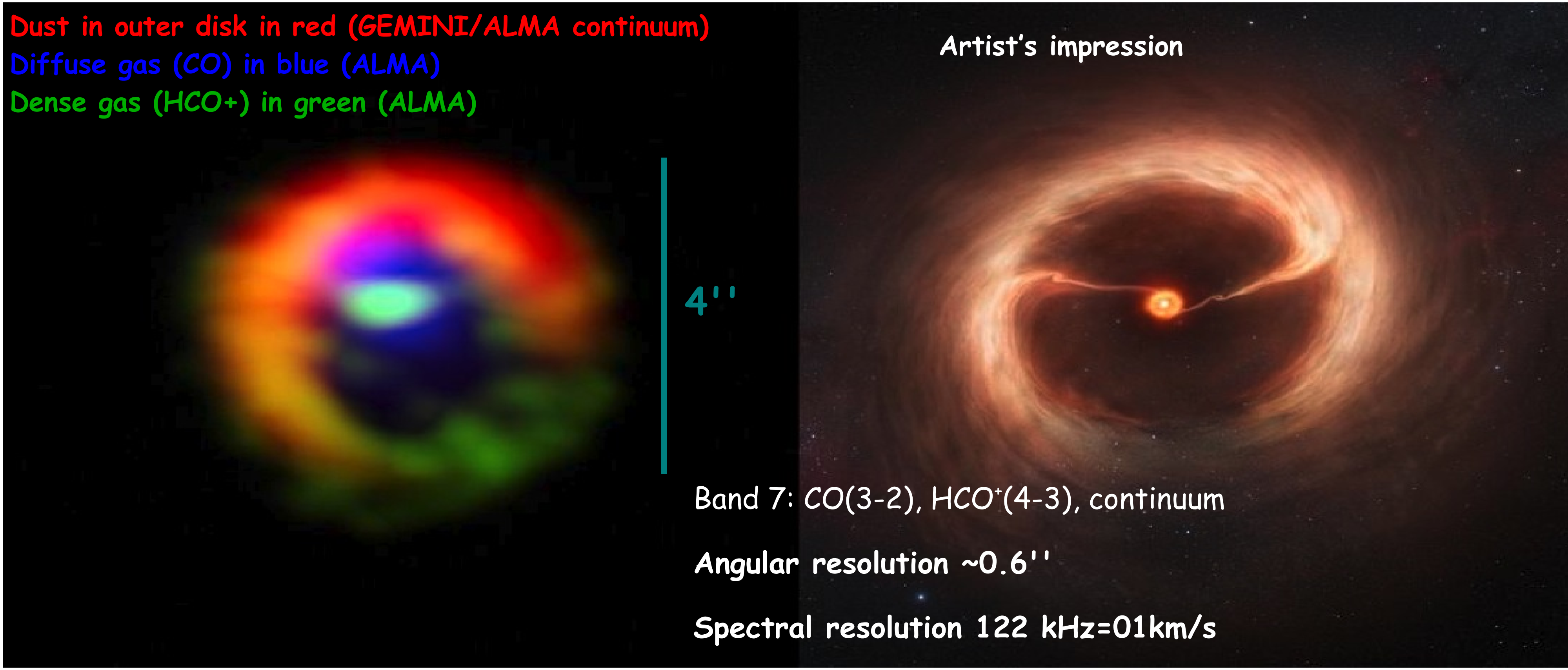
(William et al. 2011)

High mass stars harbour high mass disk (i.e. can form more massive planets)

After 5Myr no disk remain except around low-mass Ttauri stars.
Discs are depleted by UV radiation (stronger in more massive stars), by the presence of a star companion (about 30% of Ttauri are in binary systems), and by grain/planet growth and inner tidal forces.

Flow of gas through a protoplanetary gap: HD 142527

PI:S. Casassus



Herbig Ae star, at 140 pc , 2 Myr, 1.9 $M_\odot$ Inner disk 10 AU, outer disk 140 AU, planetary body 90 AU

First detection of diffuse CO inside the dust gap

HCO$^+$ in dense outer disk and cross-gap filaments with resolution. comparable with optic
HCO$^+$ mass flow rate ~10^{-8} $M_\odot$/yr, sufficient to maintain accretion at the present rate

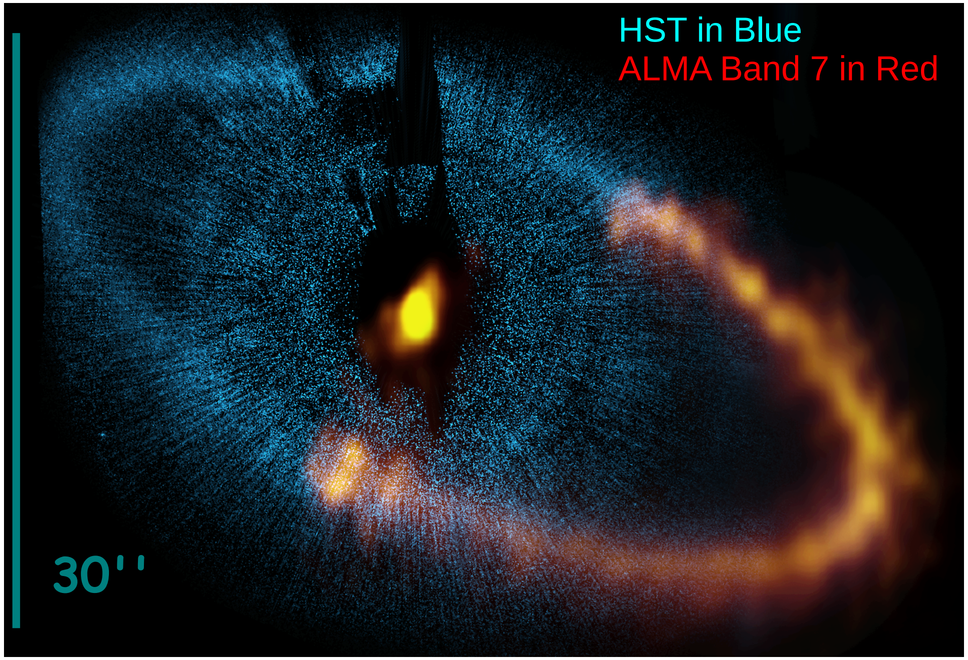
Filaments and residual gas in gap suggest gas inflow towards the star and maybe depletion from planet formation

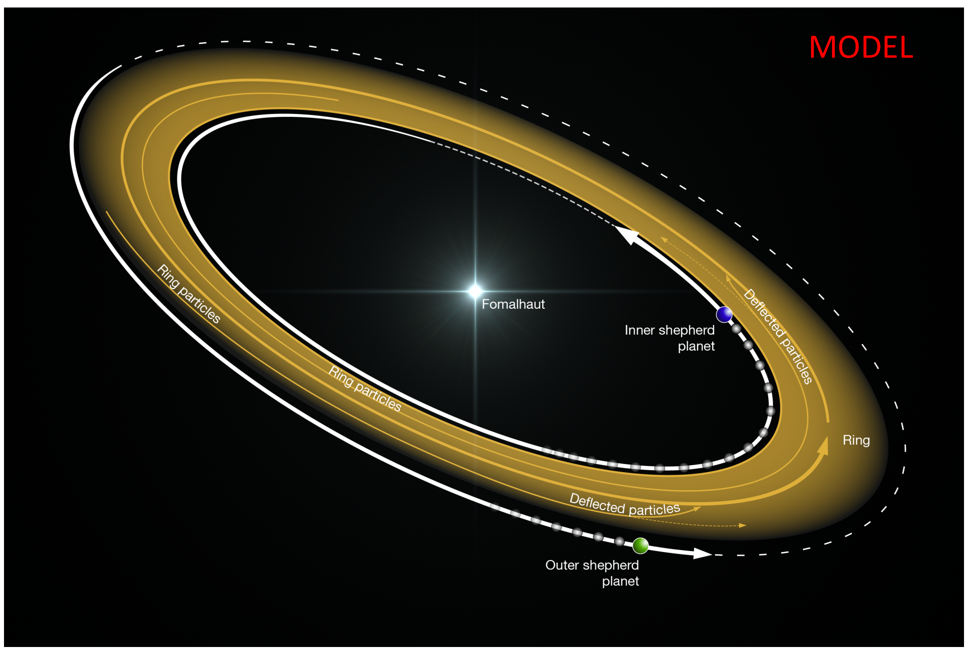
Casassus et al 2013

Constraint the planetary system: Fomalhaut

PI: S. Boley

The dynamical evolution of planetary systems leaves observable signatures in debris disks





OBSERVATIONS

- Band 7 – continuum
- 140 min on source
- rms~0.06 mJy/beam
- **Angular resolution ~1.5''**

A3V star with a debris ring at 7.69 pc

ALMA traces **large grains (1mm), not moved by star radiation**: disk's sharp edges and ring-like structure

Models: **2 planets** in the sharp inner (13AU) and outer (19 AU) boundary

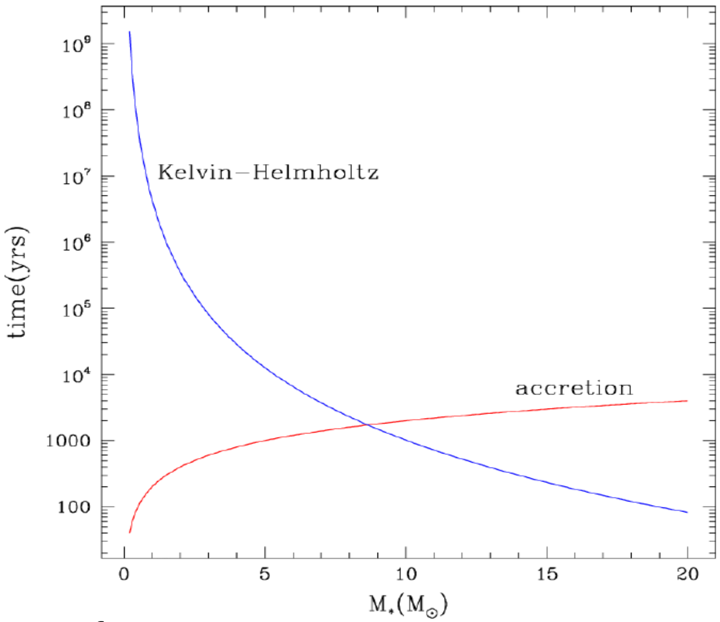
Properties of the profiles allow to estimate masses <3M_Earth

Boley et al 2012

High mass star formation

Accretion on the protostar $t_{acc} = M_* / (dM_{acc}/dt)$

Contraction of the protostar $t_{KH} = GM^2/R_* L_*$



For $M_* < 8M_{sun}$ $t_{acc} < t_{KH}$

For $M_* > 8M_{sun}$ $t_{acc} > t_{KH}$

Hence massive stars enter MS while still accreting.

However they are crucial for ISM enrichment
(via winds and supernovae explosions)
and UV radiation.

High-mass stars are **rare**

- For each 1000 stars of 1 Msun, only a single 10 Msun star forms
- The nearest star with M > 10 Msun is at d ~ 400 pc

High-mass stars **evolve fast**

- The most massive stars go supernova in 3 Myr
- Fast evolution means there are only very few objects in each phase!

=> Observing each stage of evolution is difficult (resolution, distance, time...)

High-mass stars are frequently **obscured** or in dense clusters

- Need high-resolution observations to disentangle dense cluster cores
- Need deep infrared observations to penetrate the dust

High mass star formation

Proposed models:

- **Monolithic collapse (non-spherical collapse through disks)**
    * A protostellar core forms by core collapse
    * Accretion occurs through a disc
    * A massive outflow develops very early during the accretion phase

    Evidences:
    - **presence of disk and outflows**
    - **possible isolated star formation** (no need of dense clusters)
    - formation at cluster center together with the other cluster members

- **Competitive accretion (many low-mass star merge to form one massive)**
    * Densest area of the cloud: gravitational collapse leads to a protocluster
    * Fragments/protostars/cores in the center have
        - higher accretion rates
        - more material available to accrete from

    Evidences:
    - **unlikely presence of disk and outflows**
    - possible stellar collision
    - **unlikely isolated star formation**
    - formation at cluster center after the other cluster members

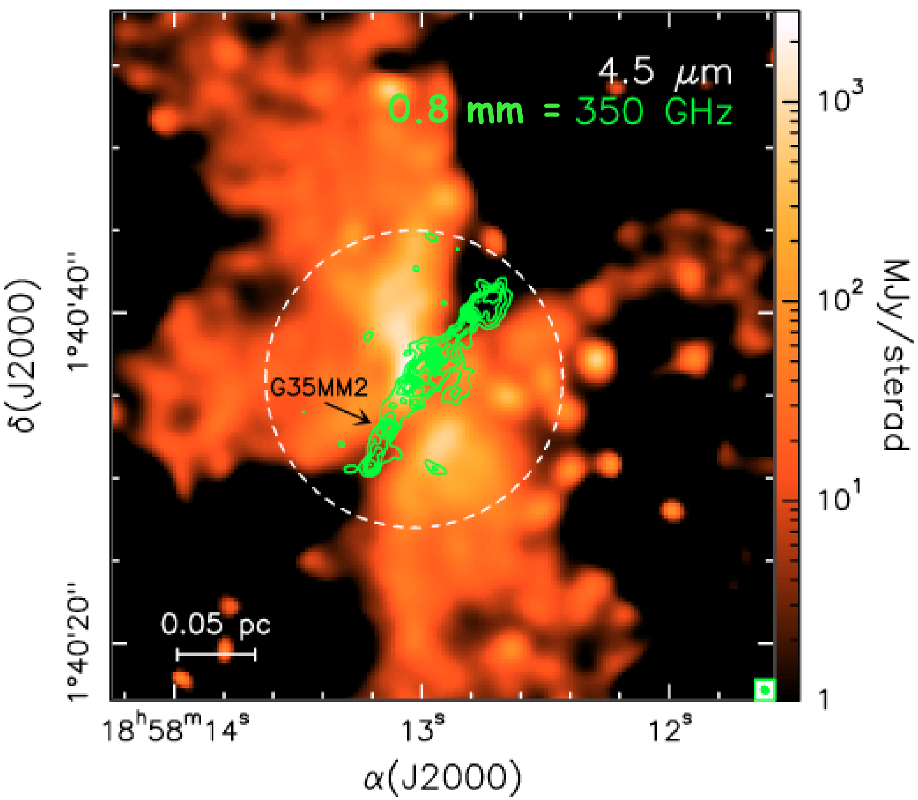
- **Stellar mergers scenario (massive stars are formed in the collision of lower-mass sources).**
    * Stellar mergers are rare, and mostly in the densest regions
    of tightly-packed clusters

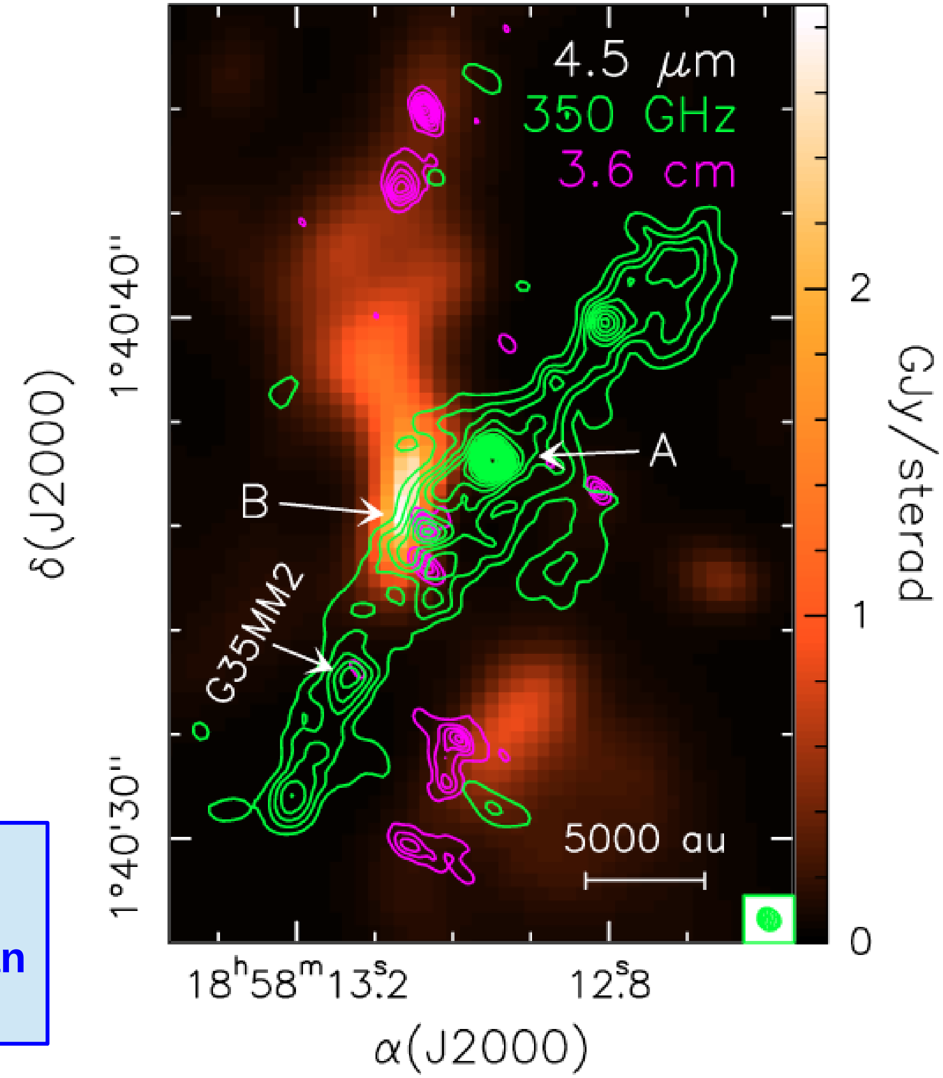
    Evidences:
    - **unlikely presence of disk and outflows**
    - stellar collision
    - **unlikely isolated star formation**

A candidate circumbinary Keplerian disk in G35.20-0.74 N

A detailed investigation of the disk properties around high-mass star (OB-type) was missing to limited previous angular resolution in (sub)mm

PI: R. Cesaroni





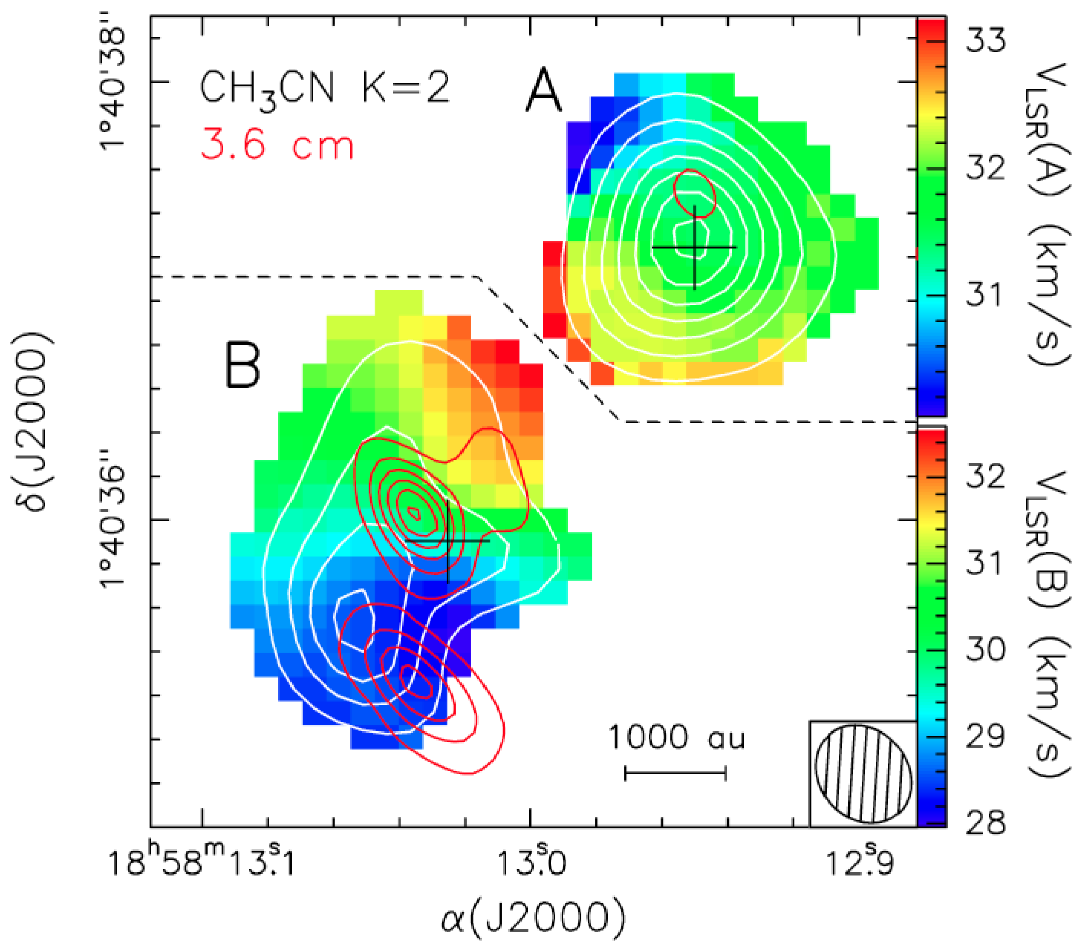
- Band 7 (350 GHz): continuum + CH_3CN
- **Angular resolution ~0.4'', 7 times better than previous mm observations**

Star forming region at 2.19 kpc. YSOs are powering outflows in A and B cores

Sanchez-Monge et al 2013

A candidate circumbinary Keplerian disk in G35.20-0.74 N

PI: R. Cesaroni



The 2 dense cores are detected also in CH_3CN (hot-core tracer) with velocity gradient

Core B: edge-on Keplerian disk rotating about a central mass of ~18 $M_\odot$

Disk radius ≥2500 AU, disk mass ~3 $M_\odot$

Evidence of binary system of stars comparing bolometric luminosity and estimated stellar mass

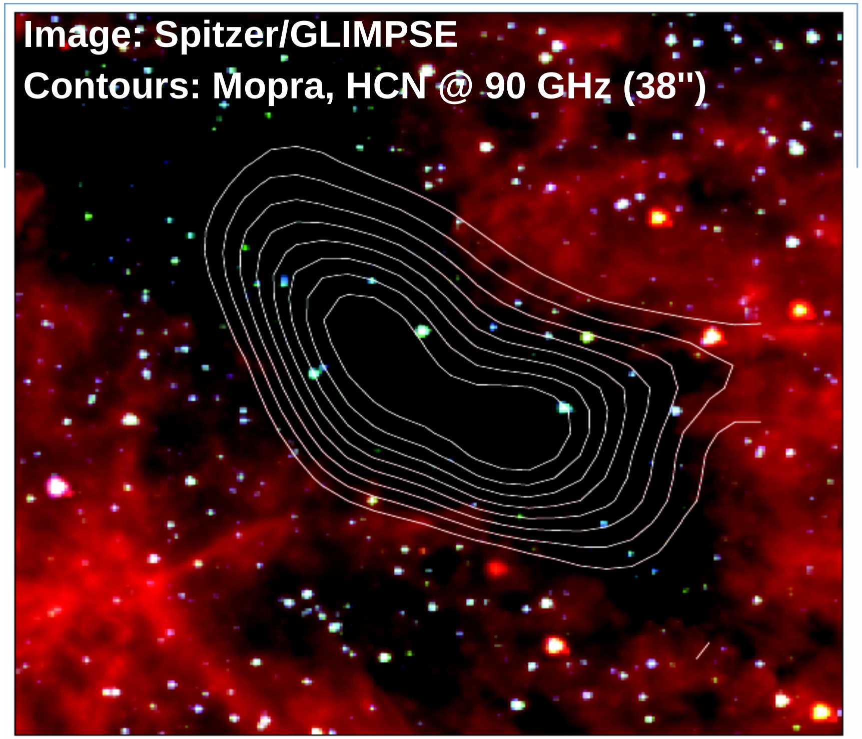
Sanchez-Monge et al 2013

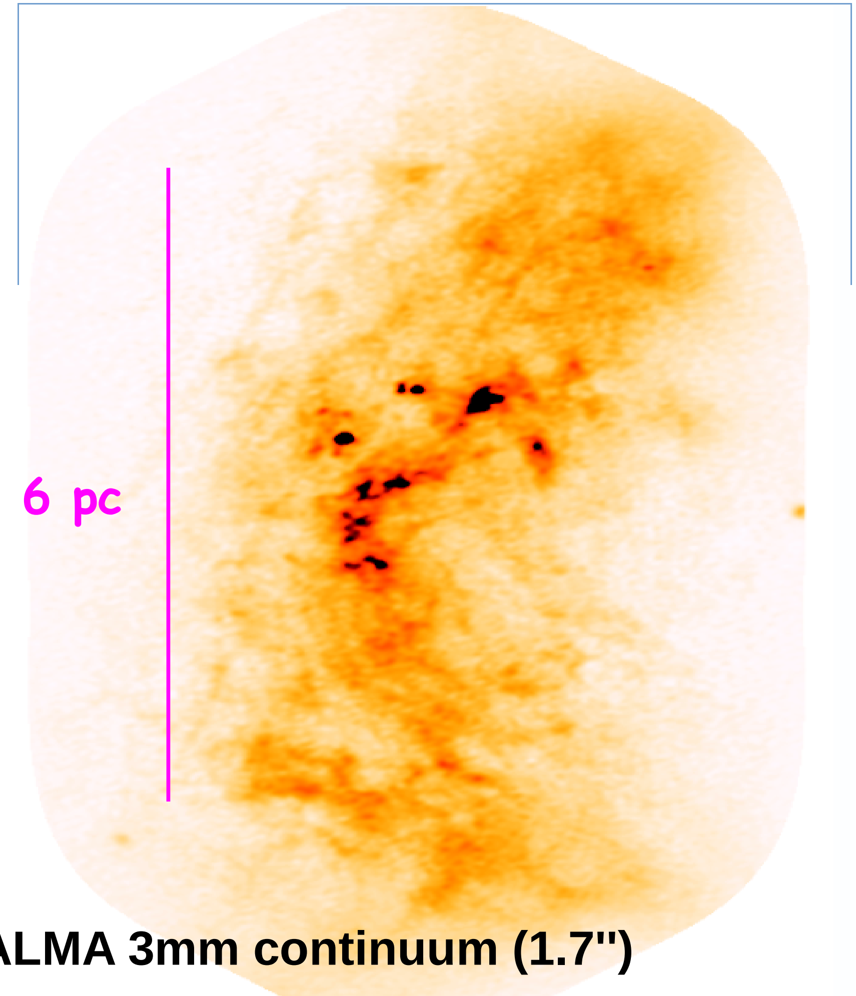
Massive proto-cluster formation: caught in the act

PI: J. Rathborne

G0.25+0.16 is a cold, dense, massive clump that is maybe the progenitor of young massive clusters (YMCs)

No previous evidence of ongoing star formation.





ALMA 3mm continuum (1.7")

OBSERVATIONS

- 90 GHz (Band 3) **continuum and HCO^+, HNCO, SiO**
- 13 point mosaic
- 25 antennas
- synthesized beam **1.7" = 0.07pc**
- Continuum rms 0.20 mJy/beam
- Line rms 0.70 mJy/beam per channel

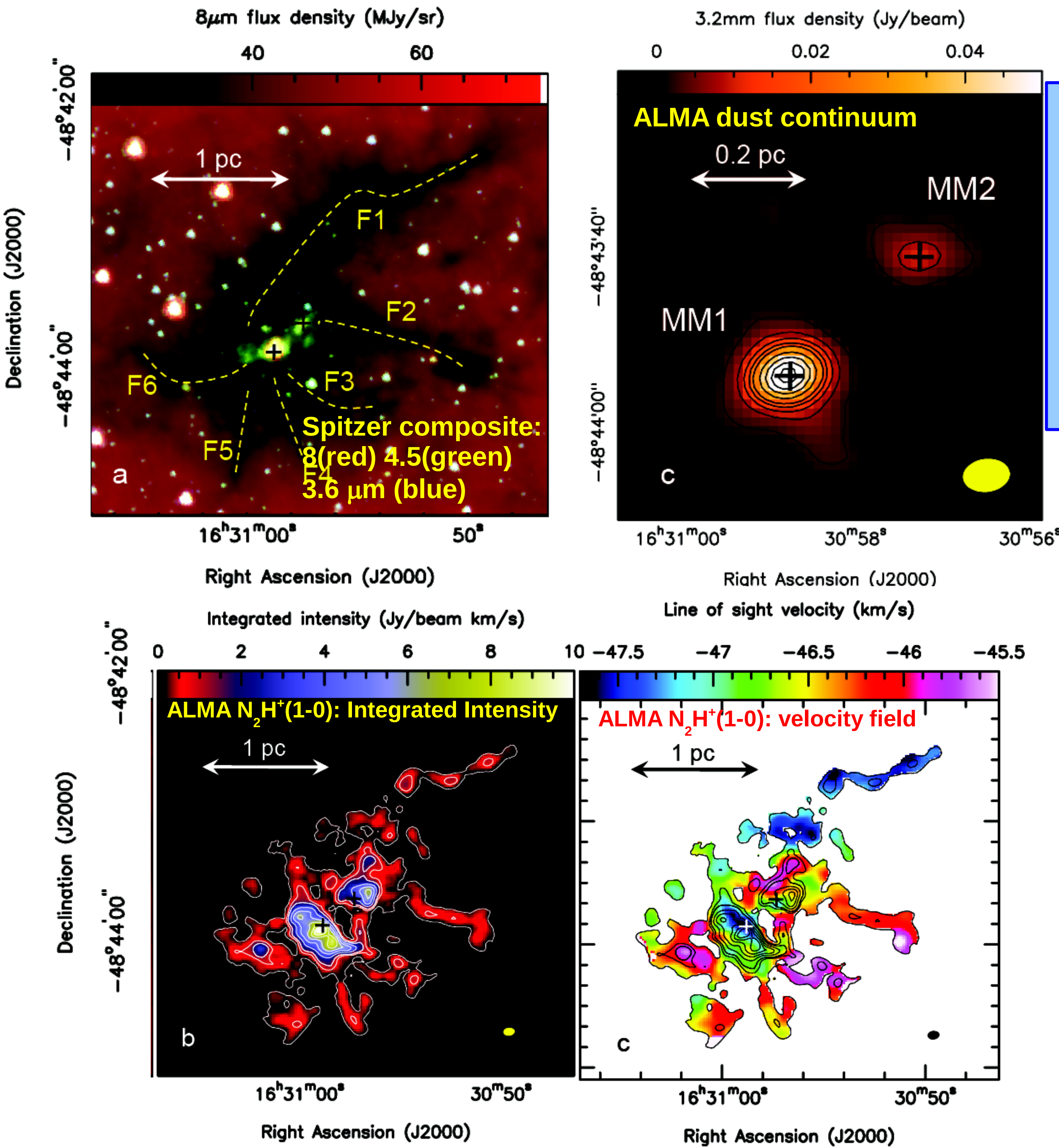
Location, mass, and kinematics of its **small-scale fragments**

Filaments with a very complicated **velocity structure and chemical pattern**

Large-scale shock fronts, small scale outflows

Where do massive stars get their mass from?

PI: N. Peretto



OBSERVATIONS

- 3mm (Band 3) dust continuum and CH_3OH(13-12) and N_2H^+(1-0)
- 16 antennas, 11 mosaic points
- Beam = 5.6" x 4.0"
- Vel. Resolution = 0.1 km/s
- Continuum rms 0.40 mJy/beam
- Line rms 14 mJy/beam

SDC335: massive IR dark cloud at 3.25 kpc

ALMA dust continuum: resolved the two IR protostars

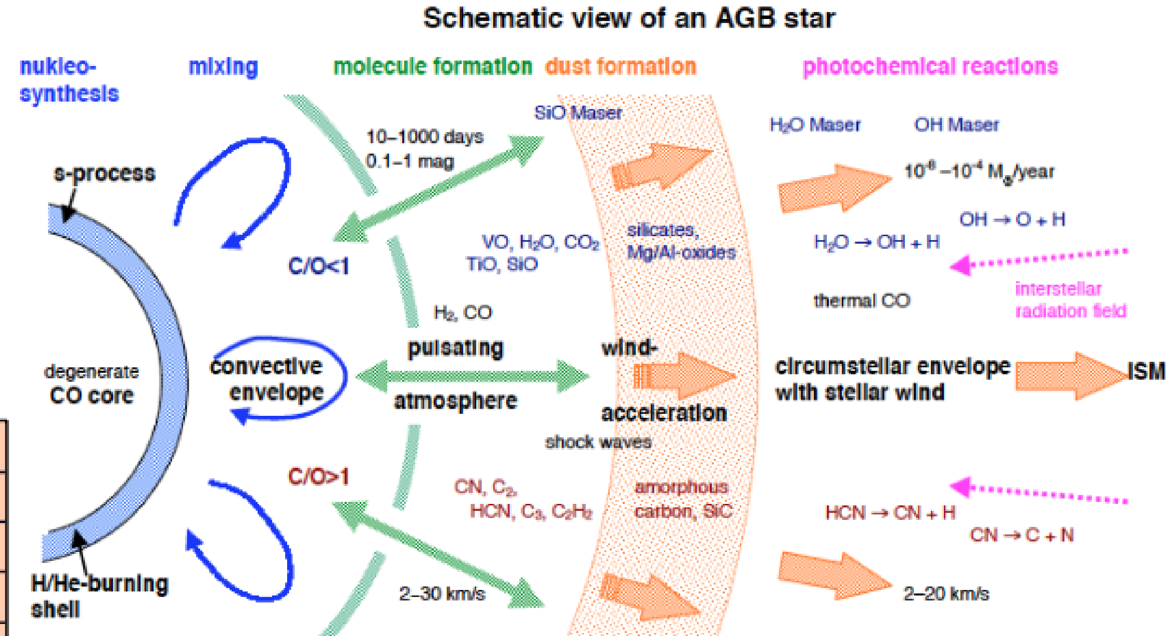
MM1: **one of the most massive protostellar cores** ever observed in the Galaxy, 545 $M_\odot$

First obs of network of cold, dense, pc-long filaments: velocity field suggests that SDC335 is globally collapsing along converging filaments

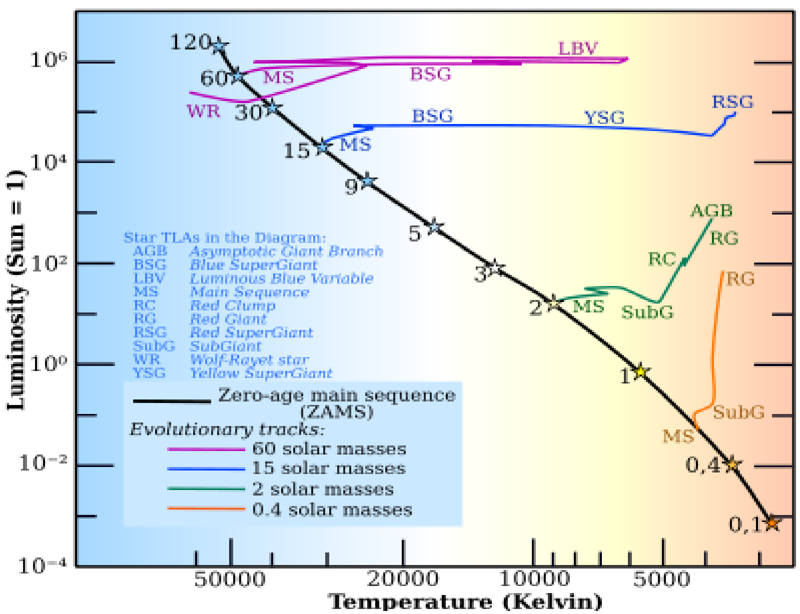
Constrain to massive sf models

Peretto et al 2013

AGB stars

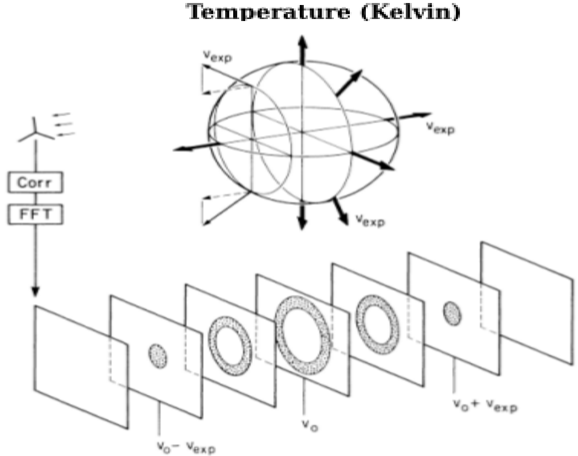


The asymptotic giant branch is the region of the Hertzsprung–Russell diagram populated by evolving low- to medium-mass stars. This is a period of stellar evolution undertaken by all low- to intermediate-mass stars (0.6–10 solar masses) late in their lives



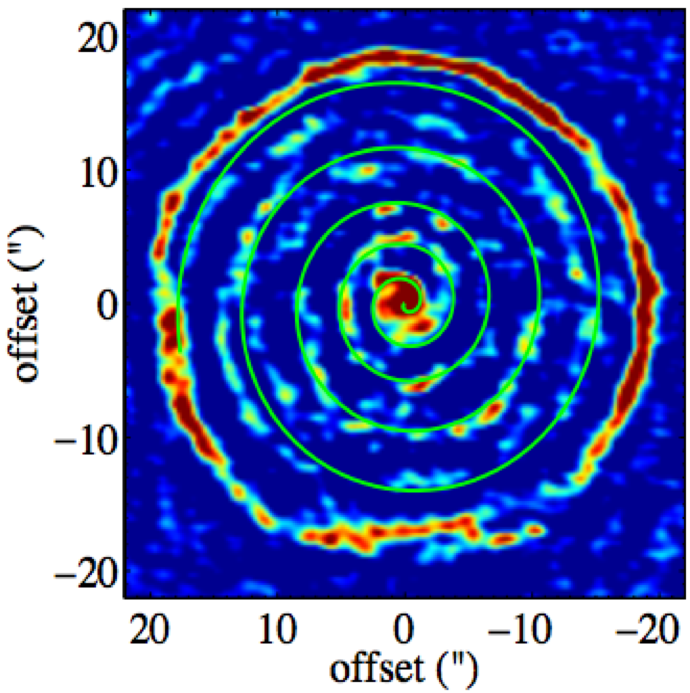
AGB stars are typically long-period variables, and suffer mass loss in the form of a stellar wind. **Thermal pulses produce periods of even higher mass loss and may result in detached shells of circumstellar material.**
During the thermal pulses, short periods of increased mass loss, which last only a few hundred years, material from the core region may be mixed into the outer layers.

After these stars have lost nearly all of their envelopes, and only the core regions remain, they evolve further into short-lived preplanetary nebulae.



For an envelope expanding with constant velocity the iso-velocity curves are circles

ALMA Observations of AGB Stars – R Sculptoris



CO(3-2) Velocity Channel Movie

PI: M. Maercker

OBSERVATIONS

- ~15 antennas, ~4 hrs
- Band 7: CO(3-2),
- **resolution = 1.3"**
- 45 pointed mosaics
  (50" x 50" field)

Maercker et al. 2012;
Vlemmings et al. 2013

Spiral structure in shell: an unseen shepard companion that modulates the loss of mass from the star?

Observations + hydrodynamic simulations: a binary system, a thermal pulse about 1800 yr ago lasting ~200 yr

~3×10^{-3} $M_\odot$ of material ejected at v = 14.3km/s, a **mass-loss rate 30 times higher than pre-pulse**

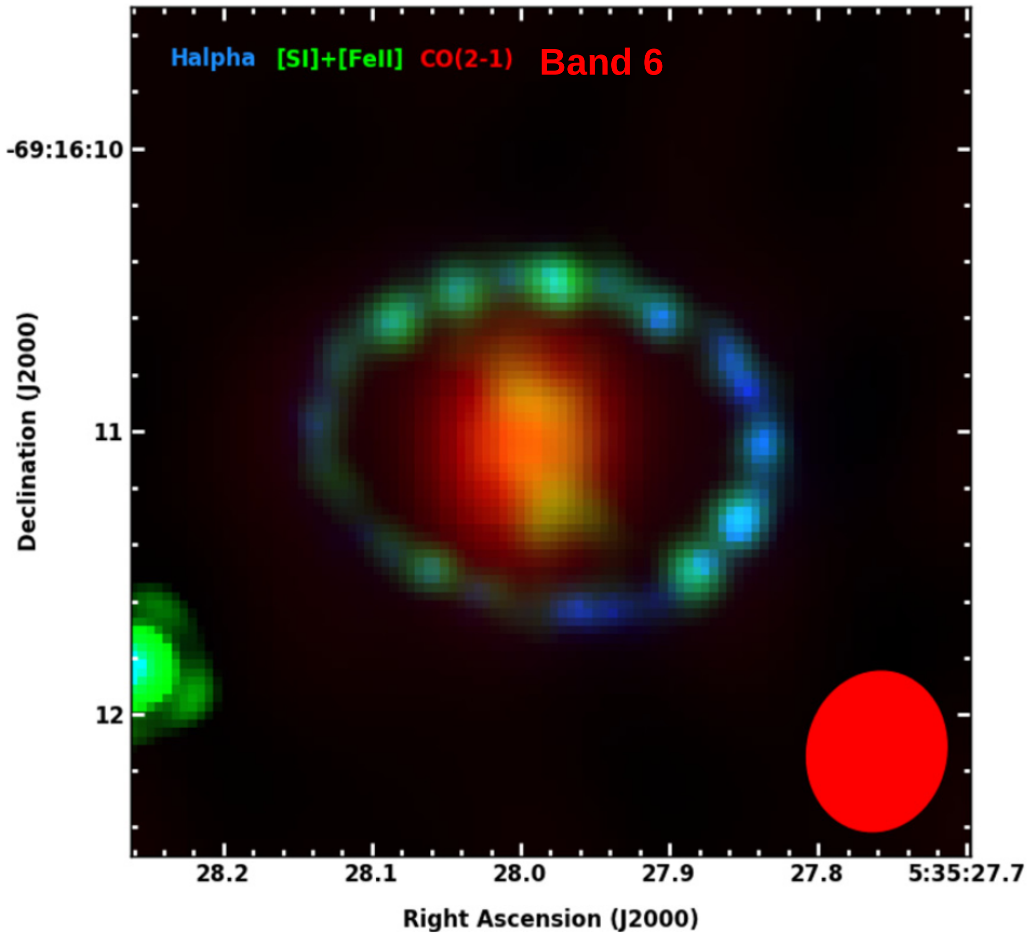
~3 times more mass into ISM than previously thought

CO IN THE COLD DEBRIS OF SUPERNOVA 1987A

PI: R. Indebetouw

In submm supernovae appear more promptly and further away than at longer wavelengths. Very bright SNII could easily be detected and monitored with ALMA up to a distance of 350 Mpc, i.e. z ~ 0.1. As the ejecta expand and cool, dust is formed.

SN1987A: unique laboratory to study shock physics and particle acceleration, cosmic dust and element production



Kamenetzky et al 2013

OBSERVATIONS

- CO and SiO in the ejecta of SN1987A
- Band 3 (2.6 mm), ~1.5"
- Band 6 (1.3 mm), ~ 0.5"

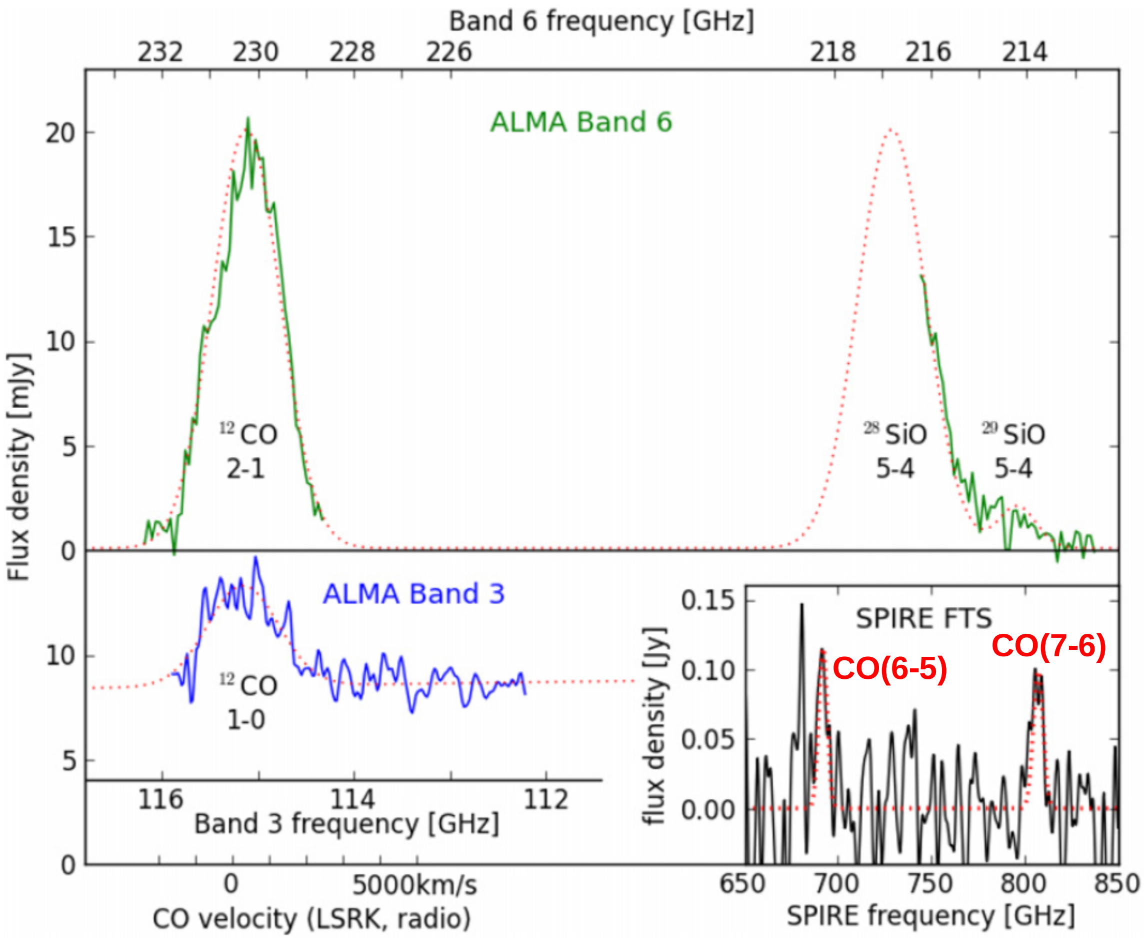
Detection from CO(1-0), CO(2-1) and the red wing of SiO(5-4)

Rotational CO(2-1) emission: <1", located at the center of the debris (vibrational CO was observed soon after explosion, no other CO observed since then)

ALMA + *Herschel*: SN environment filled with cool molecules 25 yrs after the explosion. Hence dust continues to form.
First such emission detected in a SN remnant!

CO IN THE COLD DEBRIS OF SUPERNOVA 1987A

PI: R. Indebetouw



FWHM ~ 2200 km/s (broad) consistent with NIR lines and CO models: origin from the expanding ejecta

Narrower than lines of the ejecta metal lines observed in visible: CO originates from a more centrally condensed source

Models: lines emitted from 0.01 $M_\odot$ of CO, T > 14 K, confined within at 35% of a spherical volume expanding at ~2000 km/s

Kamenetzky et al 2013

Galactic Center Sgr A*

The Galactic center provides a unique opportunity to study at very high spatial resolution the physical processes occurring in a galactic nucleus, in particular the nature of the molecular cloud population and the physical phenomena occuring in the vicinity of a massive black hole.

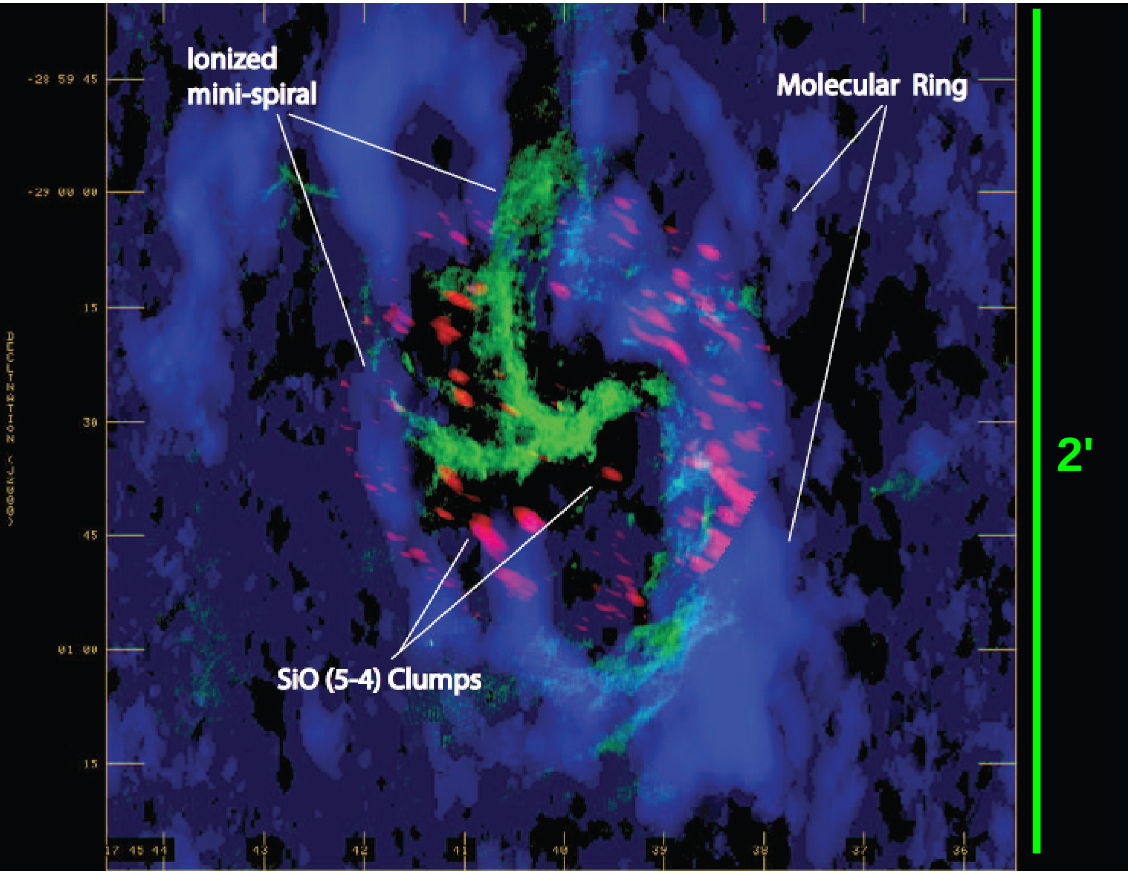
Roughly one tenth of the Galaxy's ISM resides within a region 400 pc in extent, in a crowded environment with strong shear, magnetic fields and frequent cloud-cloud collisions.

At the dynamical center lies Sgr A*, a strong radio continuum source and the best black hole candidate in the known Universe - proper motion studies indicate it has a mass of approximately 2.5 million solar masses.

ALMA's southern hemisphere location makes the Galactic center a key science target.

Galactic Center Sgr A*

ALMA Science Verification



Green: VLA 3.6 cm image
Red: ALMA SiO emission
Blue: OVRO HCN(1-0) emission

OBSERVATIONS

- 12 x 12m antennas
- 7 point-mosaic at the position of Sgr A*
- SiO(5-4), Band 6
- Spatial resolution ~2''
- Spectral resolution ~3 km/s

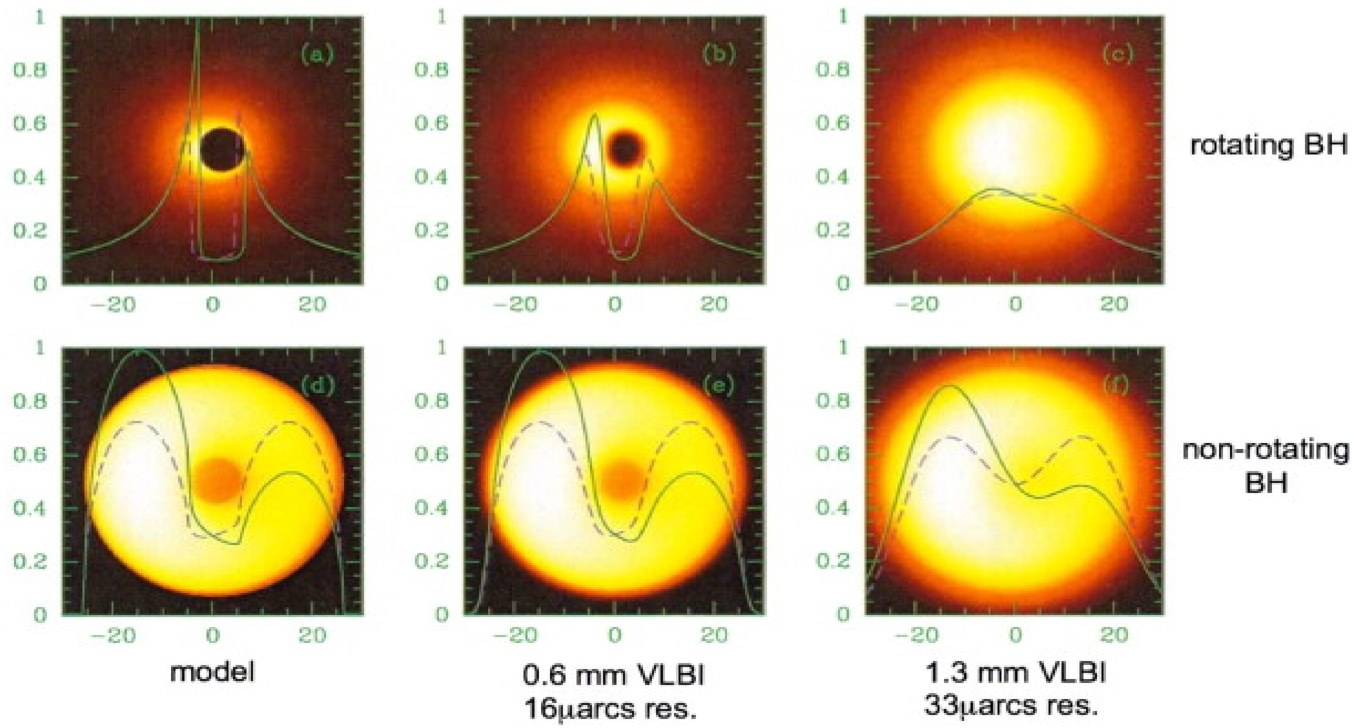
Detection of 11 SiO clumps within 0.6 pc (15") of Sgr A*

SiO clumps --> embedded protostellar outflows --> an early stage of massive star formation near Sgr A* in the last 10^4-10^5 yr

This is the first observation of star formation so close to the galactic center

Yusef-Zadeh et al. 2013

Galactic Center Sgr A* and the mm-VLBI

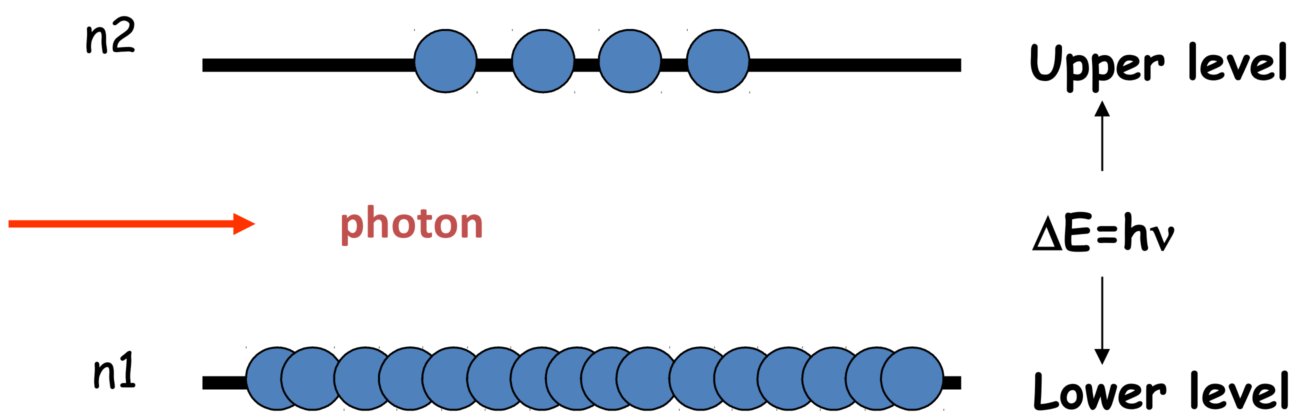


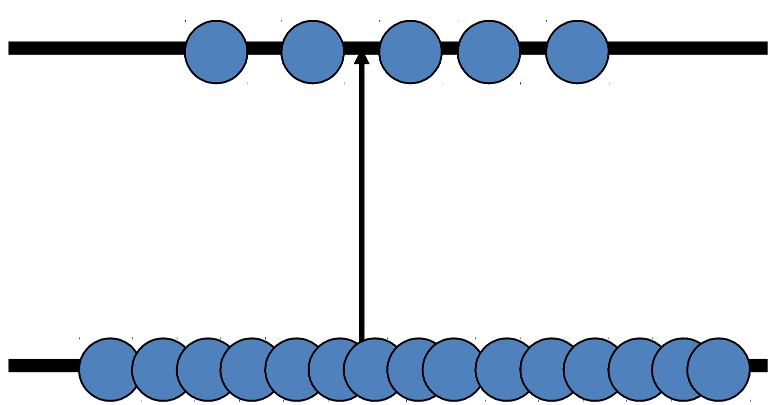
If the emitting region is uniformly distributed around the supermassive black hole, then Falcke et al. (2000) showed that photons are expected to be deviated by the strong gravitational field within a few Schwarzschild radii, therefore creating **a "shadow" in a putative mm/submm high resolution image.**

The (sub)mm VLBI network, will reach an angular resolution of a few 10 μarcsec, which would allow us to resolve the black hole "shadow". This would really be a major result, essentially the first "picture" of a black hole. The shape and the contrast of the "shadow" would also allow us to determine whether the black hole is rotating or not.

Two levels transitions

n2 < n1



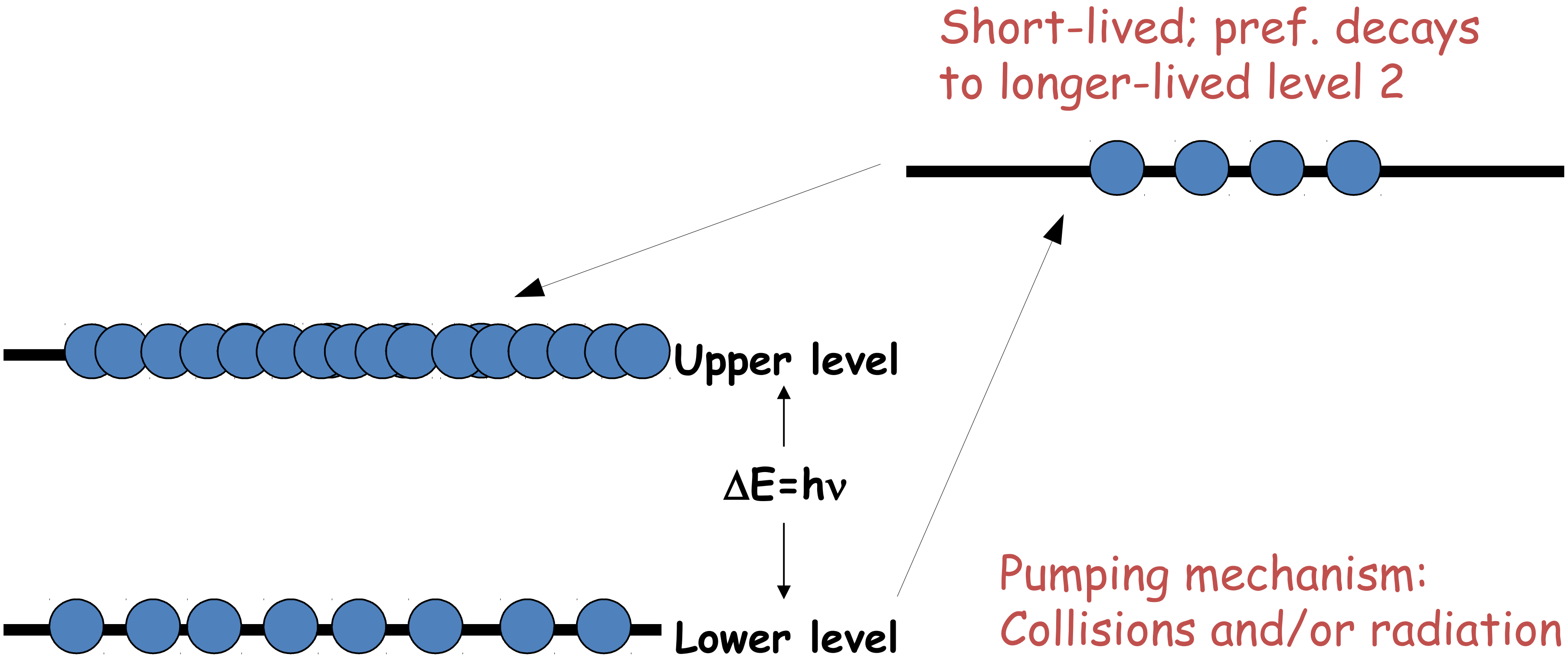


Commonly a photon
is absorbed and particles
Move from a lower to a
Upper energy level

In terrestrial pressure and temperature
conditions collision induce a Boltzmann
distribution of the particles in the energy
levels, so that the
upper level is more crowded and
its population decreases exponentially

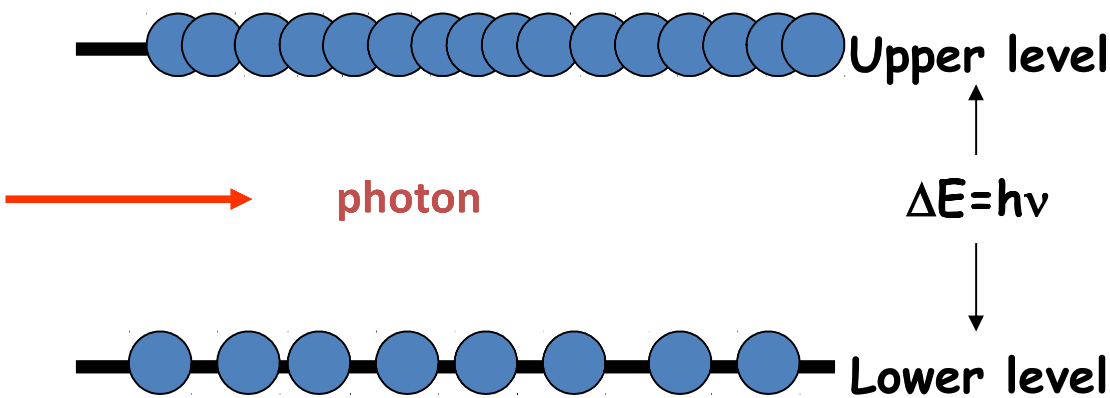
Maser mechanism

n2 > n1 : population inversion

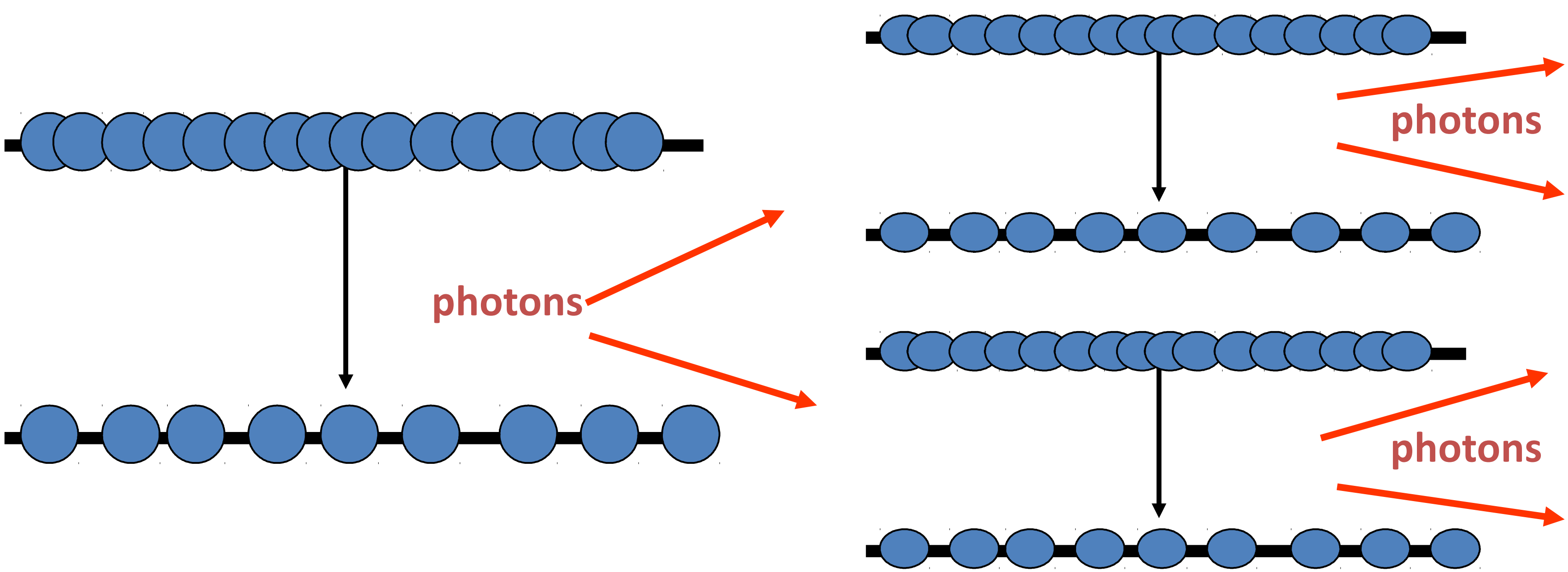


Maser mechanism

n2 > n1 : population inversion



Photon production
inject other mechanisms in
other molecules,
so that the emission is enforced
if molecules have the same velocity
and density is high enough



Masers

Molecula		Frequency	First detection
Hydroxyl	OH	1.6-1.7 GHz	1965: Weaver et al.
Water vapour	H2O	22 GHz	1969: Cheung et al.
Methanol	CH3OH	6.7, 12 GHz	1971: Barrett et al.
Formaldehyde	H2CO	4.8 GHz	1974: Downes & Wilson
Methylidyne radical	CH	3.3 GHz	1973: Turner & Zuckerman
Silicon oxide	SiO	43, 86 GHz	1974: Snyder & Buhl
Ammonia	NH3	18.5 GHz	1982: Wilson et al.
Hydrogen cyanide	HCN	89 GHz	1987: Guilloteau et al.

If $\rho < \rho_{crit}$ (ca. $10^{9\text{-}11}$ cm^{-3} per H2O)
we have a population inversion (the lower level became more crowded).

To allow for low collision levels but allowing for inversion the region must be extended,
To allow for similar velocity of the particles the region shouldn't be too extended
(typical size of 1AU).

These conditions are common in the initial and final stages of stellar evolution:
Masers are commonly in the stellar formation regions and in the circumstellar environment of giant stars

Masers

Table 1. Astronomical Maser Transitions Observable with the EVLA

Species	Transition	Frequency (MHz)	Number/Type
OH $^2\Pi_{3/2}$	$J=\frac{3}{2}, F=1\rightarrow 2$	1612.2310(2)	*T* SFR/*H* O-CSE
	$F=1\rightarrow 1$	1665.4018(1)	*H* SFR/*T* O-CSE
	$F=2\rightarrow 2$	1667.3590(1)	*H* SFR/*T* O-CSE
	$F=2\rightarrow 1$	1720.5300(1)	*H* SFR
	$J=\frac{5}{2}, F=2\rightarrow 2$	6030.747(5)	*T* SFR
	$F=3\rightarrow 3$	6035.092(5)	*T* SFR
	$J=\frac{7}{2}, F=4\rightarrow 4$	13441.4173(2)	*S* SFR/ *T* SNR
OH $^2\Pi_{1/2}$	$J=\frac{1}{2}, F=0\rightarrow 1$	4660.242(3)	*T* SFR
	$F=1\rightarrow 1$	4750.656(3)	*T* SFR
	$F=1\rightarrow 0$	4765.562(3)	*T* SFR
H_2O	$J_{K_-,K_+}=6_{16}\rightarrow 5_{23}$	22235.08(2)	*H* SFR/*H* O-CSE
CH_3OH[a]	$J_k=5_1\rightarrow 6_0 A^+$	6668.5192(8)	*H* SFR/Cl II
	$9_{-1}\rightarrow 8_{-2}E$	9936.202(4)	*1* SFR/Cl I (W33-Met)
	$2_0\rightarrow 3_{-1}E$	12178.597(4)	*H* SFR/Cl II
	$2_1\rightarrow 3_0 E$	19967.3961(2)	*S* SFR/Cl II
	$9_2\rightarrow 10_1 A^+$	23121.0242(5)	*S* SFR/Cl II
	$6_2\rightarrow 6_1 E$[b]	25018.1225(4)	*T* SFR/Cl I
	$7_2\rightarrow 7_1 E$	25124.8719(4)	*T* SFR/Cl I
	$8_2\rightarrow 9_1 A^-$	28969.942(50)	*S* SFR/Cl I
	$4_{-1}\rightarrow 3_0 E$	36169.265(30)	*T* SFR/Cl I
	$7_{-2}\rightarrow 8_{-1}E$	37703.700(30)	*S* SFR/Cl II
	$6_2\rightarrow 5_3 A^+$	38293.268(50)	*S* SFR/Cl II
	$6_2\rightarrow 5_3 A^-$	38452.677(50)	*S* SFR/Cl II
	$7_0\rightarrow 6_1 A^+$	44069.410(10)	*T* SFR/Cl I
NH_3[c]	$(J,K)=$ (9,6)	18499.390(5)	*S* SFR
	(6,3)	19757.538(5)	*S* SFR
	(3,3)	23870.1296(1)	*S* SFR
HC_3N	$J=1\rightarrow 0$	9098.1152 (2)	*1* SFR
H_2CO	$J_{K_-,K_+}=1_{10}\rightarrow 1_{11}$	4829.6600	*S* SFR
CH $^2\Pi_{1/2}$	$J=\frac{1}{2}, F=0\rightarrow 1$	3263.795(3)	*T* SFR
	$F=1\rightarrow 1$	3335.481(2)	*T* SFR
	$F=1\rightarrow 0$	3349.194(3)	*T* SFR
SiO $v=0$	$J=1\rightarrow 0$	43423.858(10)	*1 SFR* (Orion-KL)/*S* O-CSE
SiO $v=1$	$J=1\rightarrow 0$	43122.079(21)	*3 SFR*/*H* O-CSE
SiO $v=2$	$J=1\rightarrow 0$	42820.582(23)	*3 SFR*/*H* O-CSE
SiO $v=3$	$J=1\rightarrow 0$	42519.373(27)	*S* O-CSE
^{29}SiO $v=0$	$J=1\rightarrow 0$	42879.916(10)	*1* SFR (Orion-KL)/*S* O-CSE
^{30}SiO $v=0$	$J=1\rightarrow 0$	42373.359(10)	*1* SFR (Orion-KL)/*S* O-CSE
SiS	$J=1\rightarrow 0$	18154.880(2)	*1* C-CSE (IRC+10216)

Menten 2007, IAU242

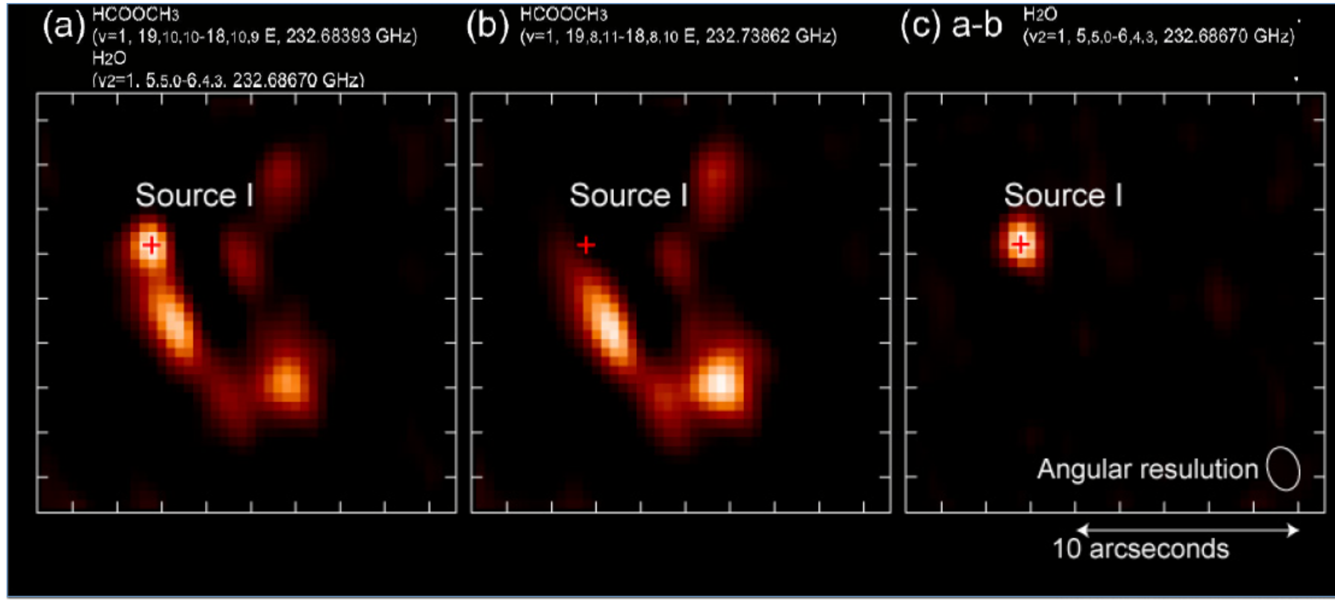
Bursting Water Maser Feature at 232 GHz in Orion KL

PI: T. Hirota

SV data

OBSERVATIONS

- **Orion KL nebula**
- SV data: spectral line survey 215-245 GHz (Band 6)
- Spectral resolution ~ 0.60 km/s
- 20 min on source per spectral setting
- 16 antennas
- synthesized beam 1.7"x 1.4"
- rms ~ 10 mJy/beam per channel



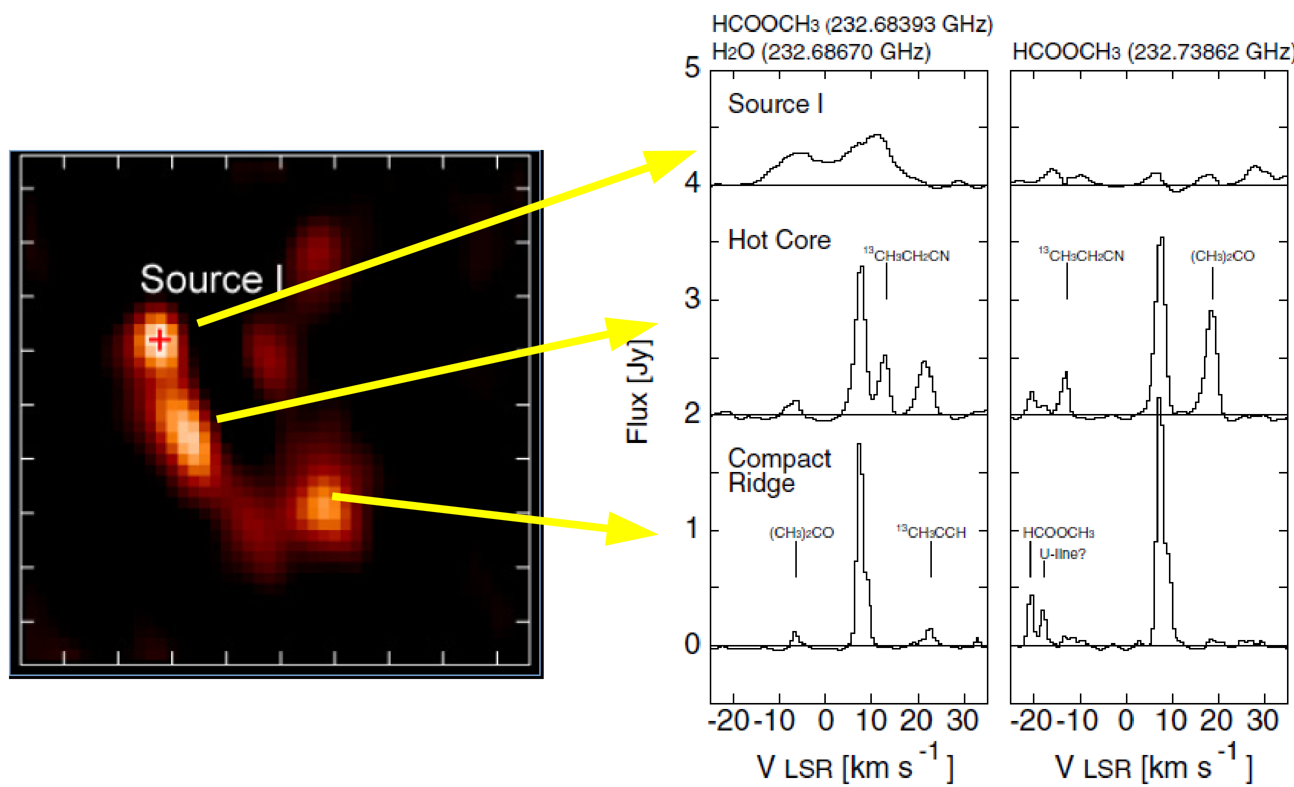
First detection of vibrationally excited H_2O in a star formation region

Blended with $HCOOCH_3$ lines

But distingushable by imaging

Higher excitation energy of 3500 K possibly tracing hotter gas

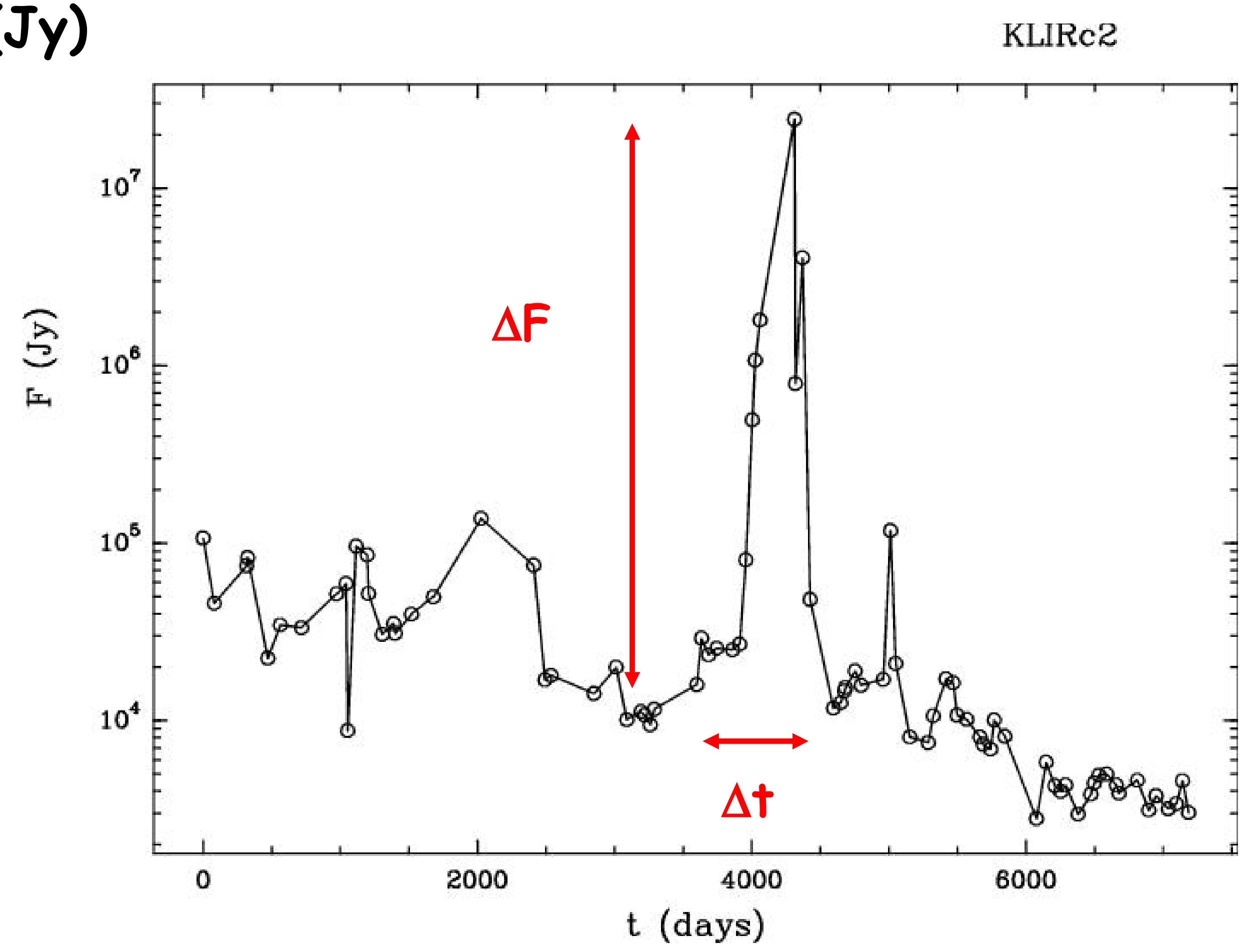
To be checked by higher spatial resolution observations



Hirota et al 2012

Monster-burst in KLIRc2 1997-99 (with Medicina radiotelescope)

F (Jy)



time (days)

Start: 14 Dec. 97
Peak: 18 Jan. 99
End: 29 Oct. 99

ΔF = 2.44 107 Jy
× 1262

Δt = 684 days

Up: 400 d.
Down: 284 d.

Brand et al. 2007, IAU242

Summary

Sub(mm) is characterized by dust and rich chemistry.

Dust allows the investigation of earlier and later stages of stellar formation.

Higher resolution and sensitivity allows to go farther reaching the sites of massive star formation to unveil the underlying mechanism.

Higher spectral resolution allows to detect more narrow lines and more details from broad lines, allowing for dynamical and chemical details in Solar System objects, in protoplanetary disks, in star forming regions.

Missing topic: Solar science