Probing the Inner 200 AU of Low-Mass Protostars

...waiting for ALMA

Jes Jørgensen

Harvard-Smithsonian Center for Astrophysics

Fredrik Schöier, Tyler Bourke, Philip Myers, Ewine van Dishoeck, David Wilner, Fred Lahuis, Neal Evans

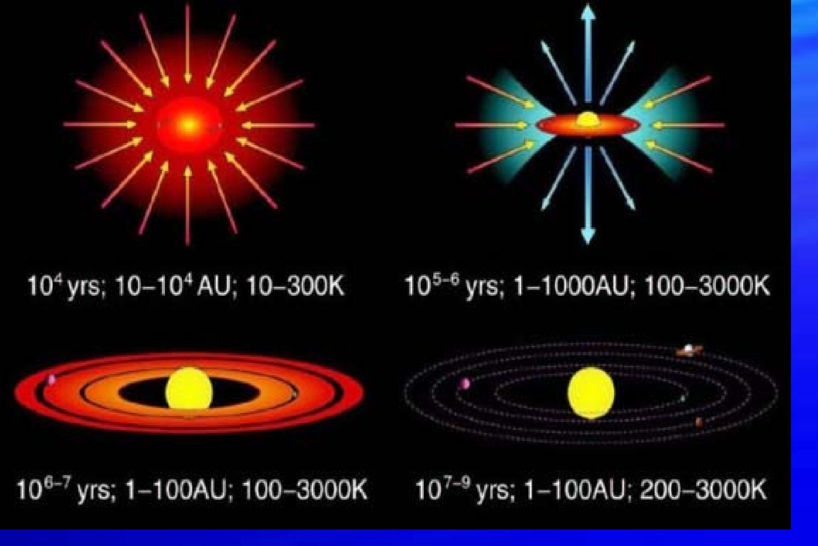
...and the rest of the *PROSAC* and *c2d* teams

This talk

- What are the physical and chemical structure of low-mass protostars on few hundred AU scales?
- Constraints from high-angular resolution submm (SMA) and mid-IR (Spitzer) observations.
- Establishing a framework for interpreting ALMA observations of low-mass protostars.

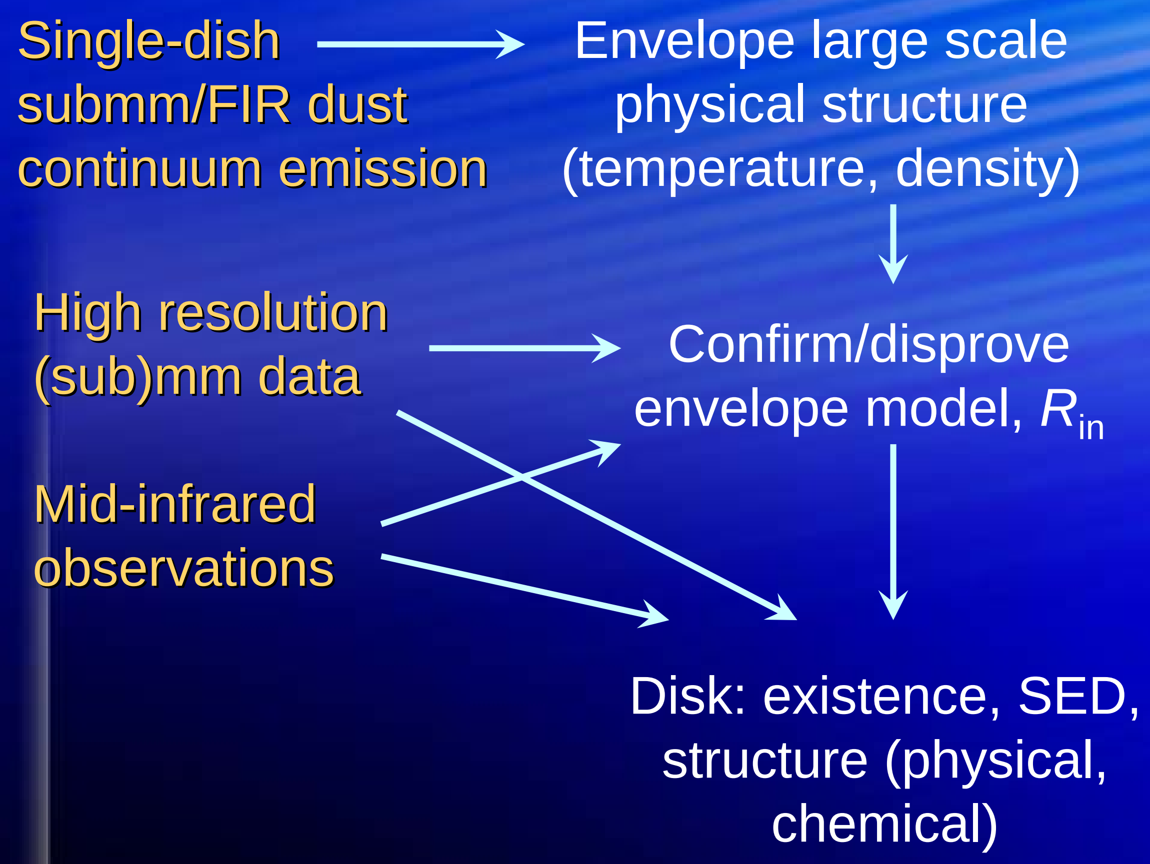
Class 0 protostars…

- Thought to represent the first ~10^4 yrs after collapse
- Emit more than 0.5% of their luminosity at submm wavelengths
- Initial core angular momentum → centrifugal radius, R_c, material piles up in disk: $R_c \sim t^3$ in traditionally inside-out collapsing core with solid body rotation *(Terebey, Shu & Cassen, 1984)* - or $R_c \sim t$ in magnetized cores *(Basu 1997)*
- Heating from central protostar; possibly increases temperature to 100+ K in inner (r < 20-100 AU) envelope → distinct chemistry...?

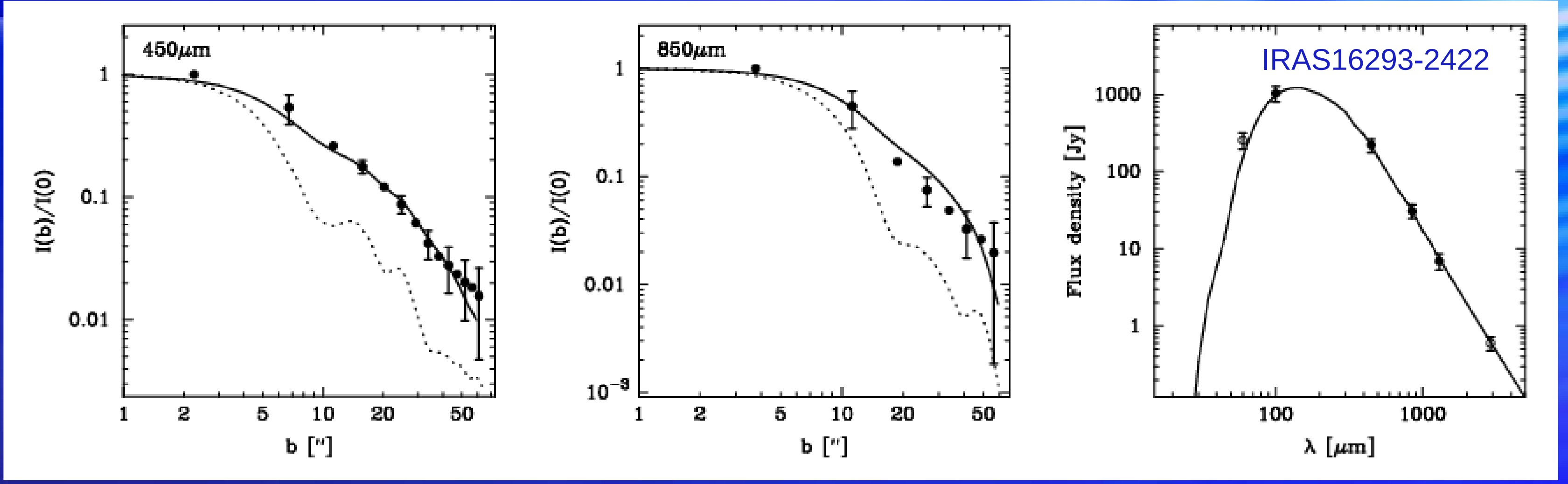


from *JWST science case*

Framework


Single-dish submm/FIR dust continuum emission
Envelope large scale physical structure (temperature, density)
High resolution (sub)mm data
Confirm/disprove envelope model, R_{in}
Mid-infrared observations
Disk: existence, SED, structure (physical, chemical)

Envelope structure...1



Data:

- SED, images
- Distance

Constrain:

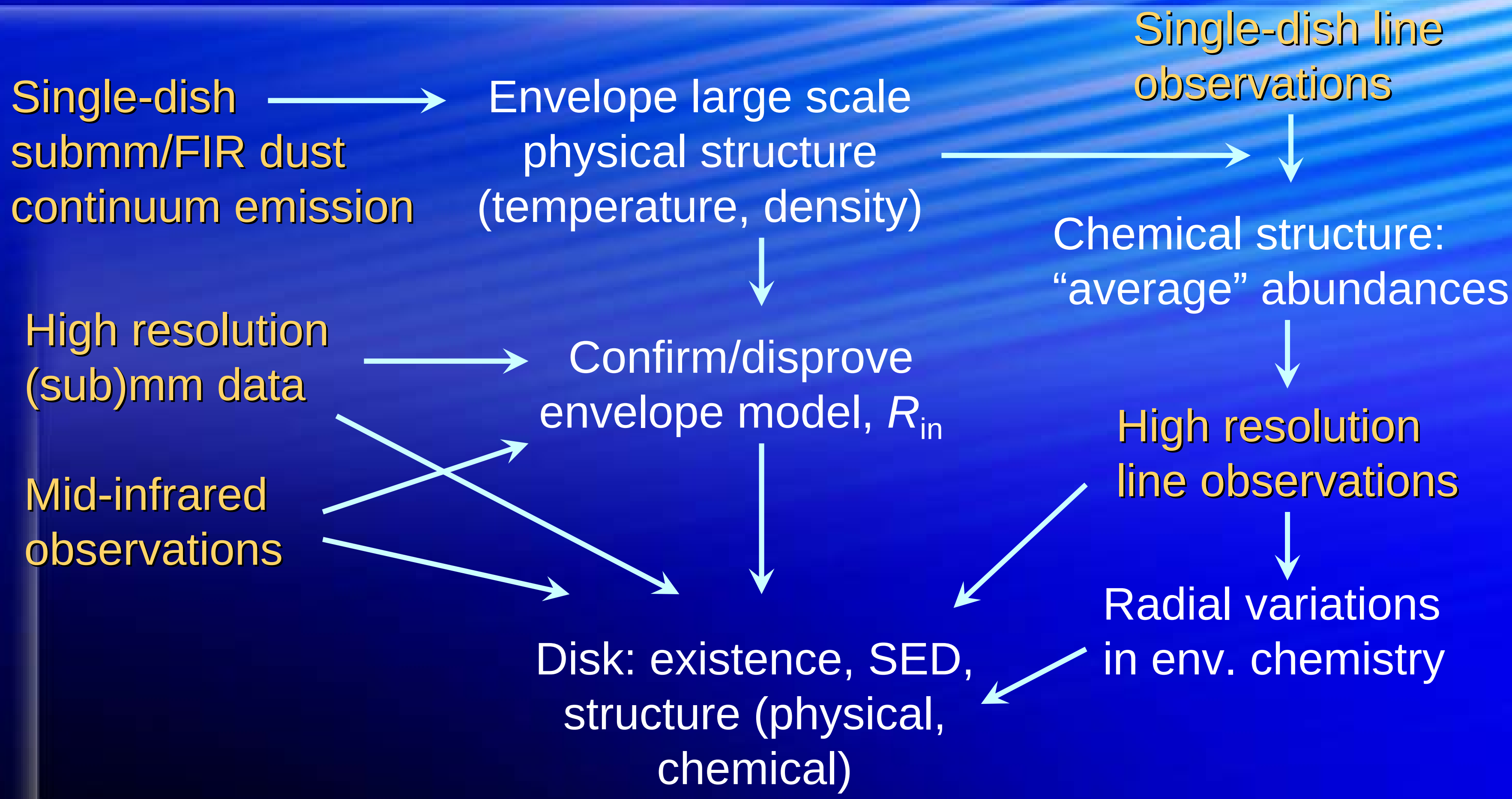
- p, n_0 (or τ_{100}), R_{out}

Radiative transfer, calculate:

- Temperature profile
- Model images, SED

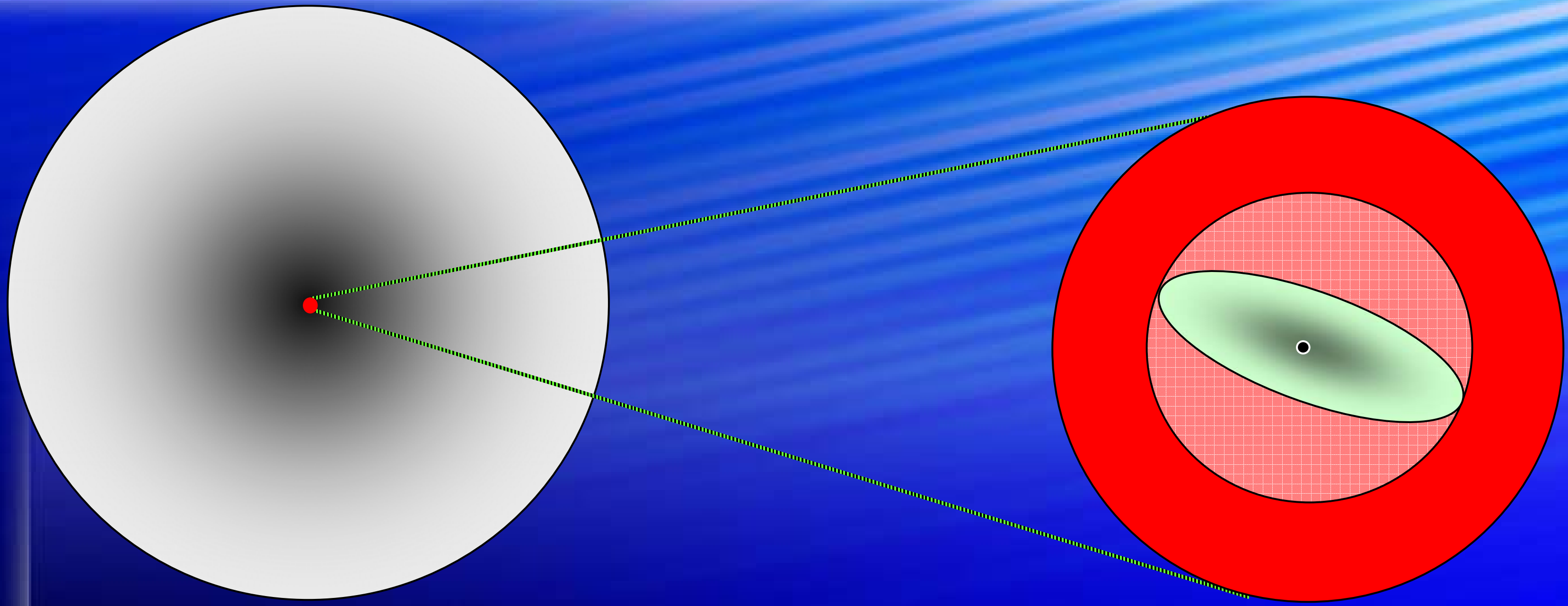
See Jørgensen et al. (2002), Schöier et al. (2002), Shirley et al. (2002)

Framework



Single-dish submm/FIR dust continuum emission
Envelope large scale physical structure (temperature, density)
Single-dish line observations
Chemical structure: "average" abundances
High resolution (sub)mm data
Confirm/disprove envelope model, R_{in}
Mid-infrared observations
High resolution line observations
Radial variations in env. chemistry
Disk: existence, SED, structure (physical, chemical)

Low-mass protostars



~ 20,000 AU (100”)

~ 200 AU (1”)

- Densities ranging from 10^4 cm^{-3} to 10^7-10^8 cm^{-3} (H_2)
- Temperatures ranging from ~10 K to a few hundred K.

Hot cores

Need:

- High excitation lines (probing high densities and temperatures).

- Molecules that are not too sensitive to the chemistry of the outer envelope.

- High angular resolution (beam dilution/mass weighting of lines/contribution from outflows).

The Submillimeter Array on Mauna Kea

- Eight 6 meter antennae.
- Receivers at 230 GHz, 345 GHz and 690 GHz.
- 2 GHz bandwidth with 10 GHz sideband separation.
- Located on the top of Mauna Kea (~ 50% of nights good for 345 GHz science; ~ 10% for 690 GHz).
- Angular resolution of 1.5-3” in compact configurations (best sensitivity to extended structures) to 0.5-1” in extended configurations.

Protostellar Submillimeter Array Campaign "PROSAC"

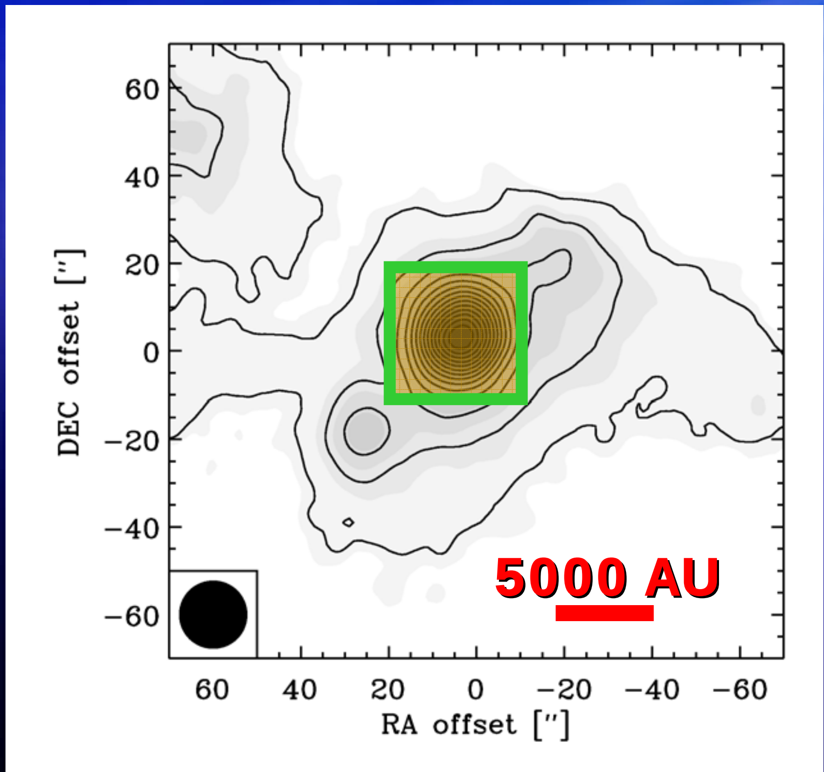
Jørgensen (PI)
Bourke, Di Francesco, Lee, Myers, Ohashi,
Schöier, Takakuwa, van Dishoeck, Wilner, Zhang

- Line + continuum survey (230/345 GHz) of a sample of 8 (+1) deeply embedded (Class 0) protostars
- 3 spectral setups per source: CO, CS, SO, HCO^+, H_2CO, CH_3OH, SiO, ... transitions (and isotopes)
- 20 tracks allocated (and observed) Nov. 2004 - Jan. 2006.

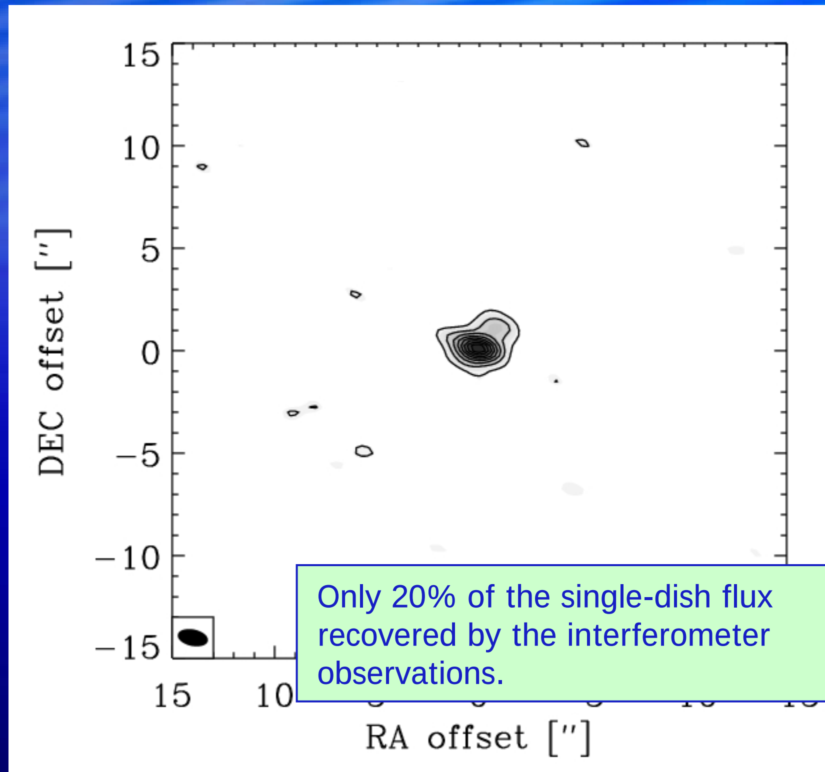
- *"Large scale" envelope structure from detailed line and continuum radiative transfer models (Jørgensen et al. 2002; 2004)*
- Additional short spacing data from the JCMT

NGC1333-IRAS2A: 850 μm dust continuum

SCUBA 850 μm



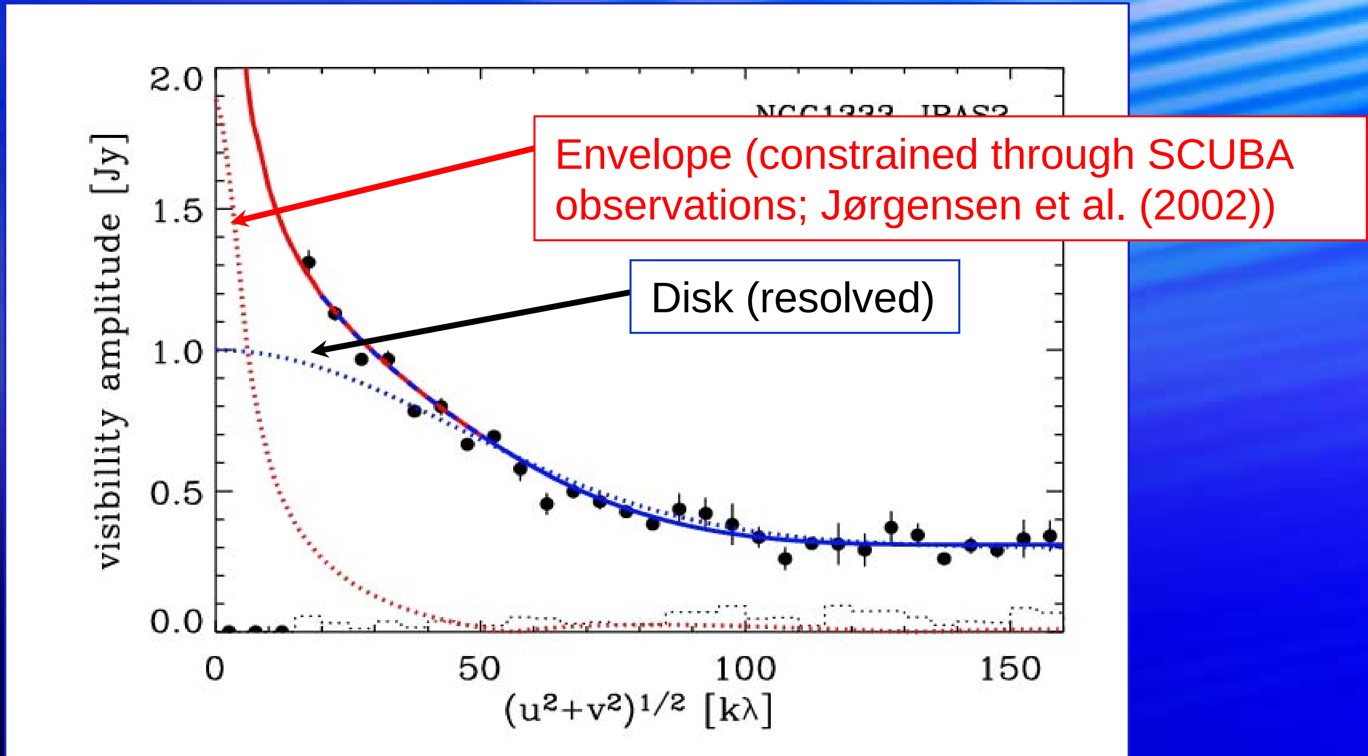
SMA 850 μm



Only 20% of the single-dish flux recovered by the interferometer observations.

Jørgensen et al. 2005, ApJ, 632, 973

NGC1333-IRAS2A: 850 µm dust continuum



…the SMA resolves the warm dust in the inner envelope *and the circumstellar disk.* The disk is a substantial mass reservoir - dominating the column density of the inner (T > 100 K) envelope.

Jørgensen et al. 2005, ApJ, 632, 973

Envelope structure…1

Assume:

- Central source of heating
- Inner radius
- Density profile "type" (e.g., $n = n_0(r/r_0)^{-p}$)
- Dust properties

Data:

- SED, images
- Distance

Constrain:

- p, n_0 (or τ_{100}), R_{out}

Radiative transfer, calculate:

- Temperature profile
- Model images, SED

See Jørgensen et al. (2002), Schöier et al. (2002), Shirley et al. (2002)

The Spitzer Space Telescope

- Imaging at 3.6, 4.5, 5.6, 8.0 µm (IRAC); 24, 70, 160 µm (MIPS)
- Spectroscopy (IRS) at 5-37 µm with $\Delta\lambda/\lambda$ ~ 60-600

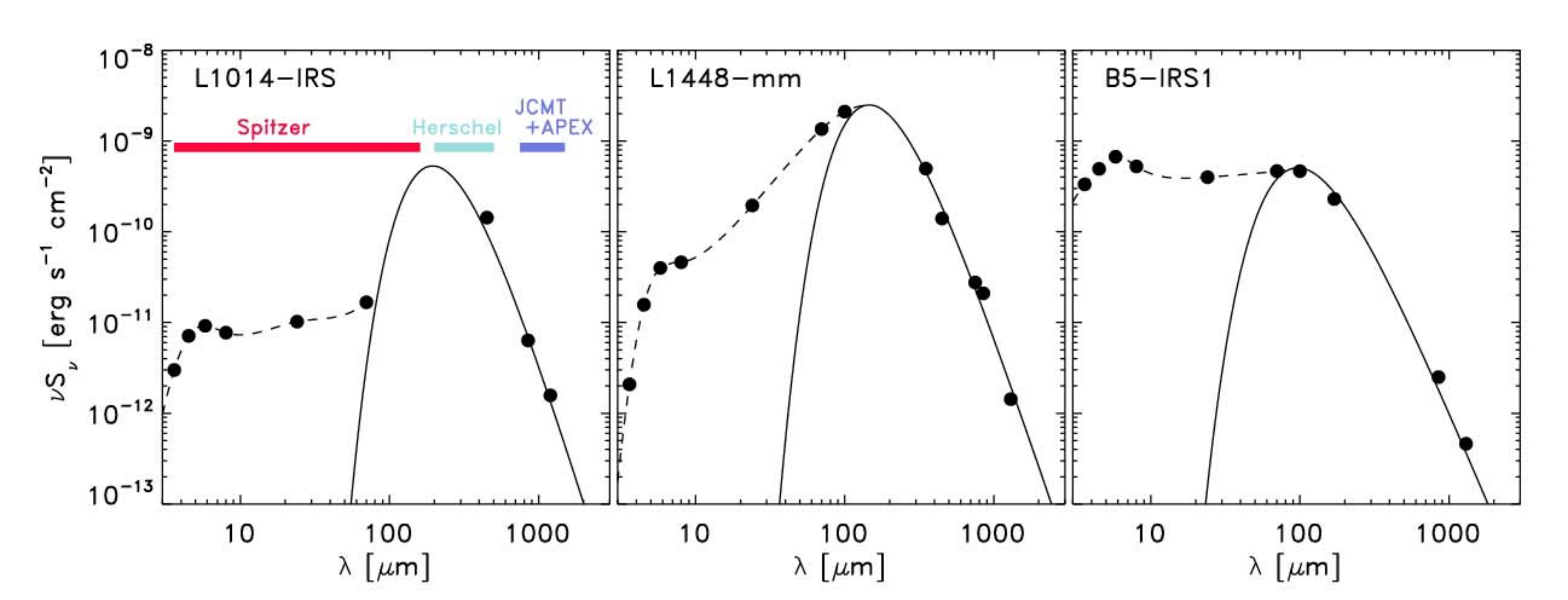
c2d legacy project

(Evans et al.)

...400 hours to image nearby star forming clouds and cores and perform spectroscopy of embedded objects and stars with disks...

mid-IR obs. of low-mass protostars

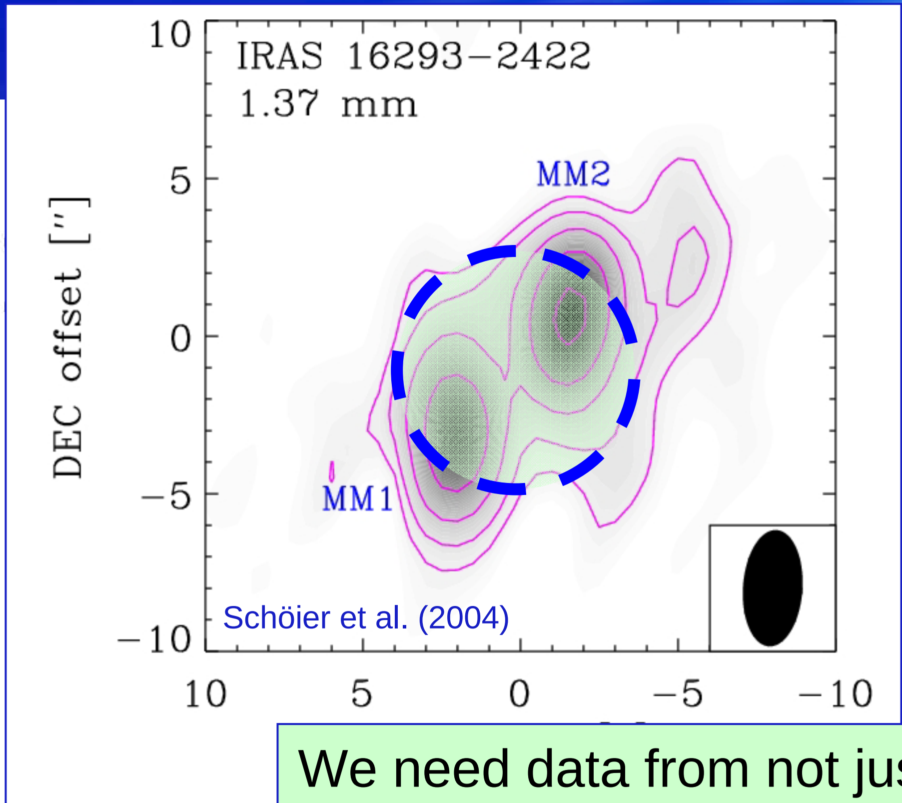
VeLLO Class 0 Class I



For a very deeply embedded protostar, no mid-IR emission should be detected - even with the sensitivity of Spitzer

Envelope structure...2

- Do the envelopes extend all the way to the smallest scales?



Inside 600 AU the envelope has to be "cleared" of material: otherwise envelope severely optically thick at mid-IR wavelengths; no emission escapes from the central source(s).

For comparison the binary sep. (radius) is 400 AU (2.5").

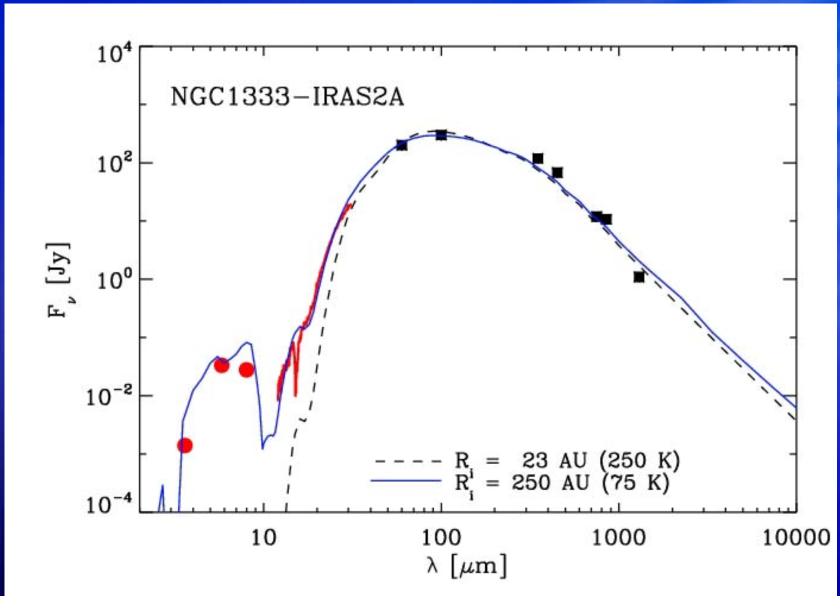
Dashed line: Best fit model of Schöier et al.

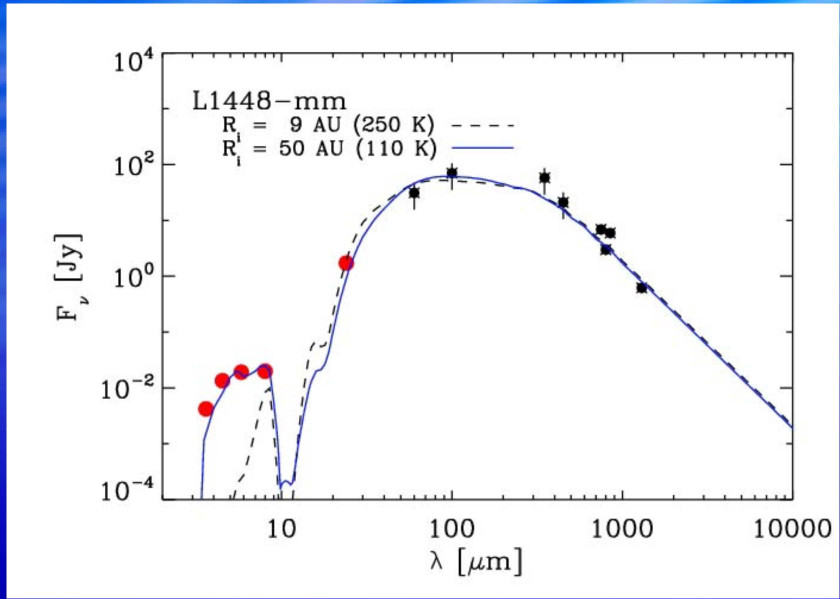
We need data from not just (sub)mm obs. but additional constraints from, e.g., mid-IR (Spitzer) observations are important...

Spitzer: c2d/IRS

Jørgensen et al. 2005, ApJ, 631, L77

Two other low-mass hot core candidates...





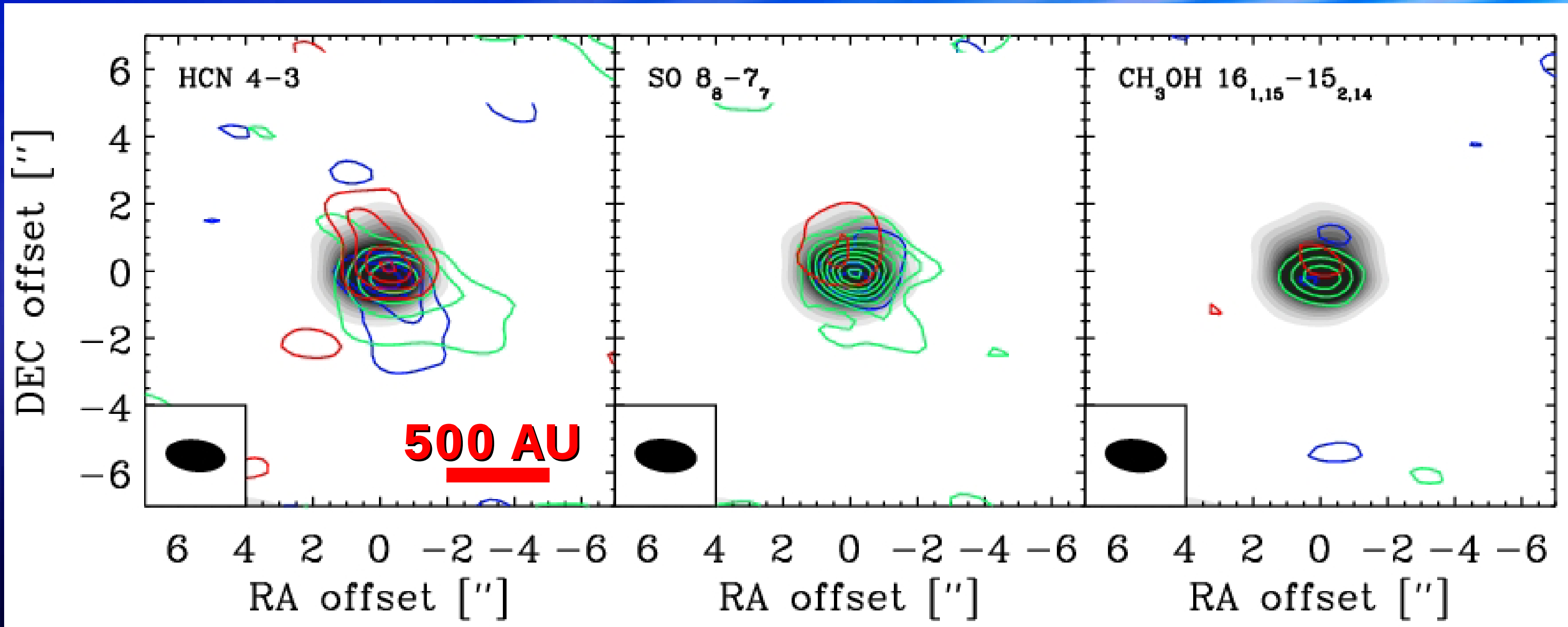
Inner cavities of ~100 AU sizes present to let of “enough” mid-IR emission escape. This is not new: Known already to be a problem for less embedded Class I objects when explaining IRAS measurements *(e.g., Adams et al. 1987, Myers et al. 1987)*

A small summary...

	r_i	Small-scale structure (radius)	$T(r_i)$
IRAS16293-2422	600 AU	400 AU (binary sep.)	65-80 K
L1448-C	50-100 AU	< 100 AU (unresolved SMA disk)	110-85 K
NGC1333-IRAS2A	250 AU	150 AU (resolved SMA disk)	75 K

Nature is cruel: $r_{\mathrm{cent.}} \sim M_{\mathrm{star}} \sim L_{\mathrm{acc.}}$ while $r_{100\ \mathrm{K}} \sim L^{0.5}$

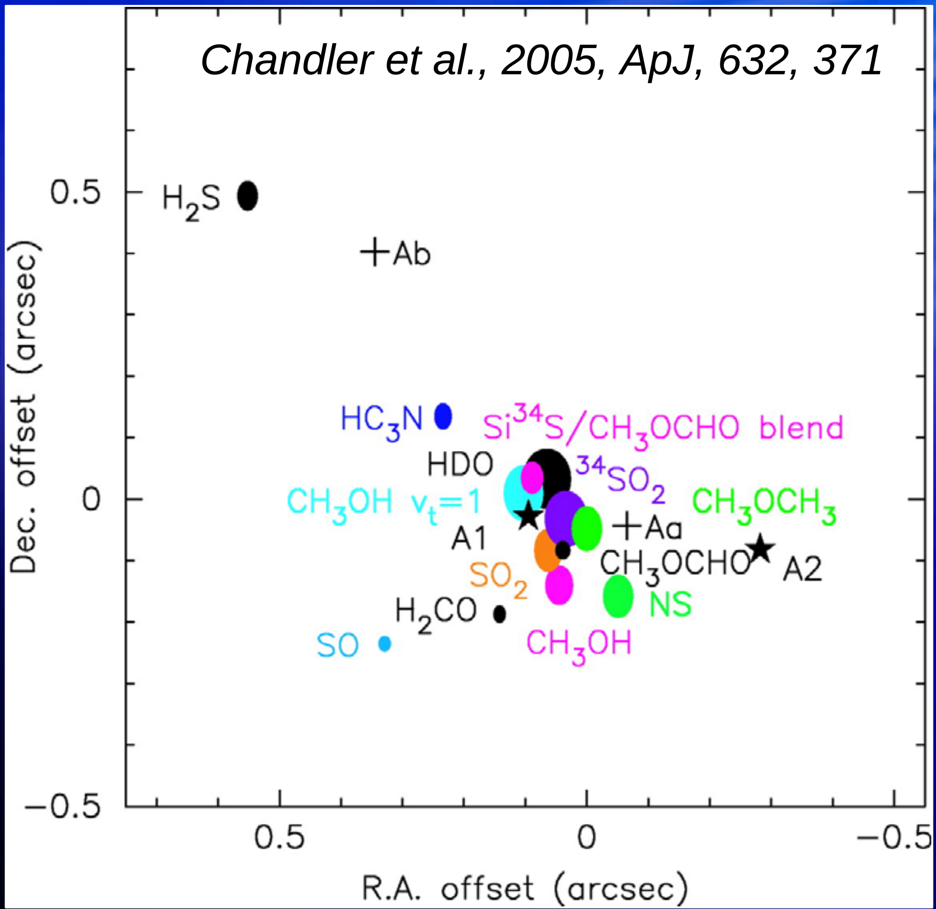
Organic molecules toward IRAS2A



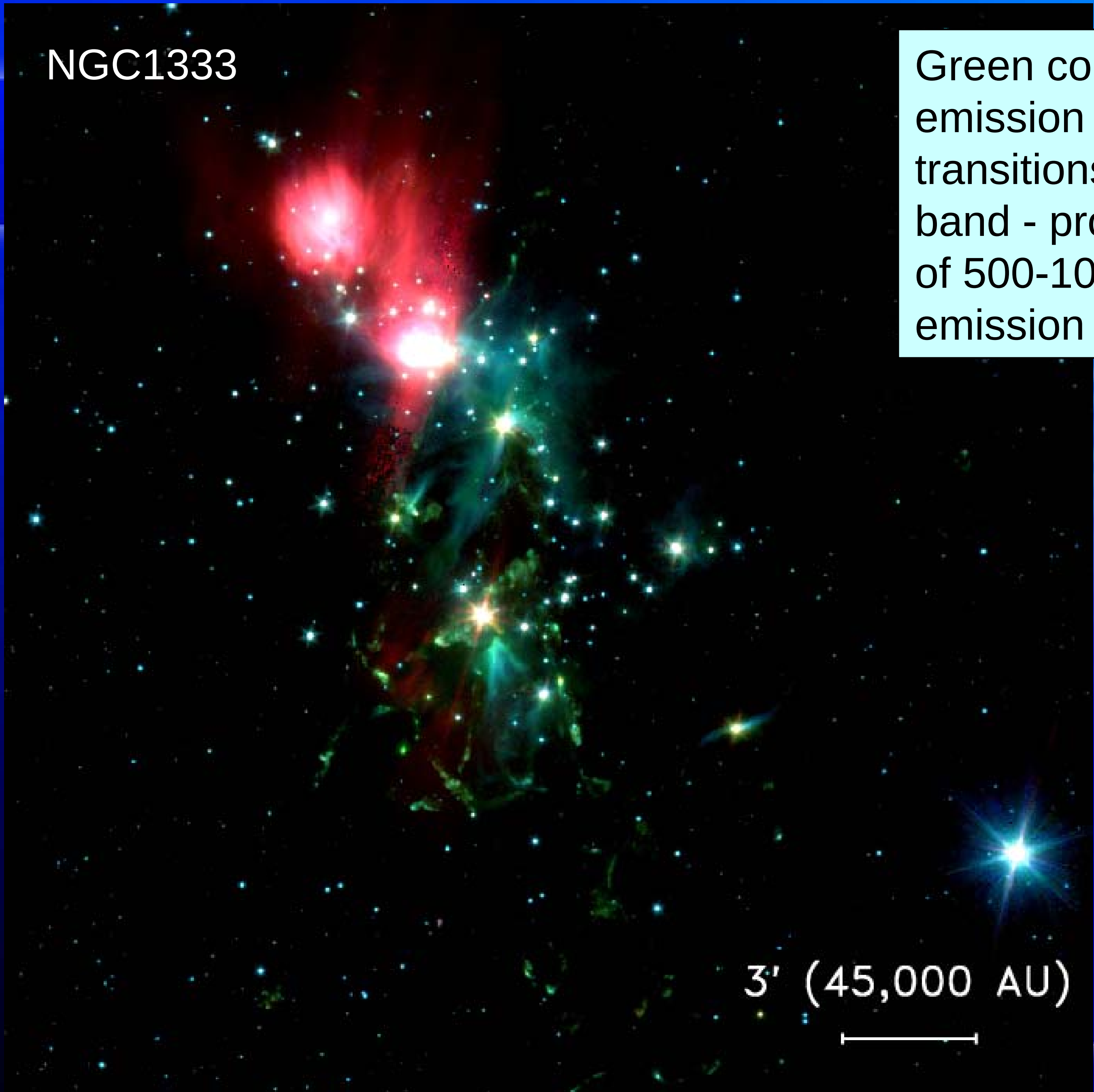
Well, but we do know there is hot gas on small scales...!

Jørgensen et al. 2005, ApJ, 632, 973

Shocks are likely important

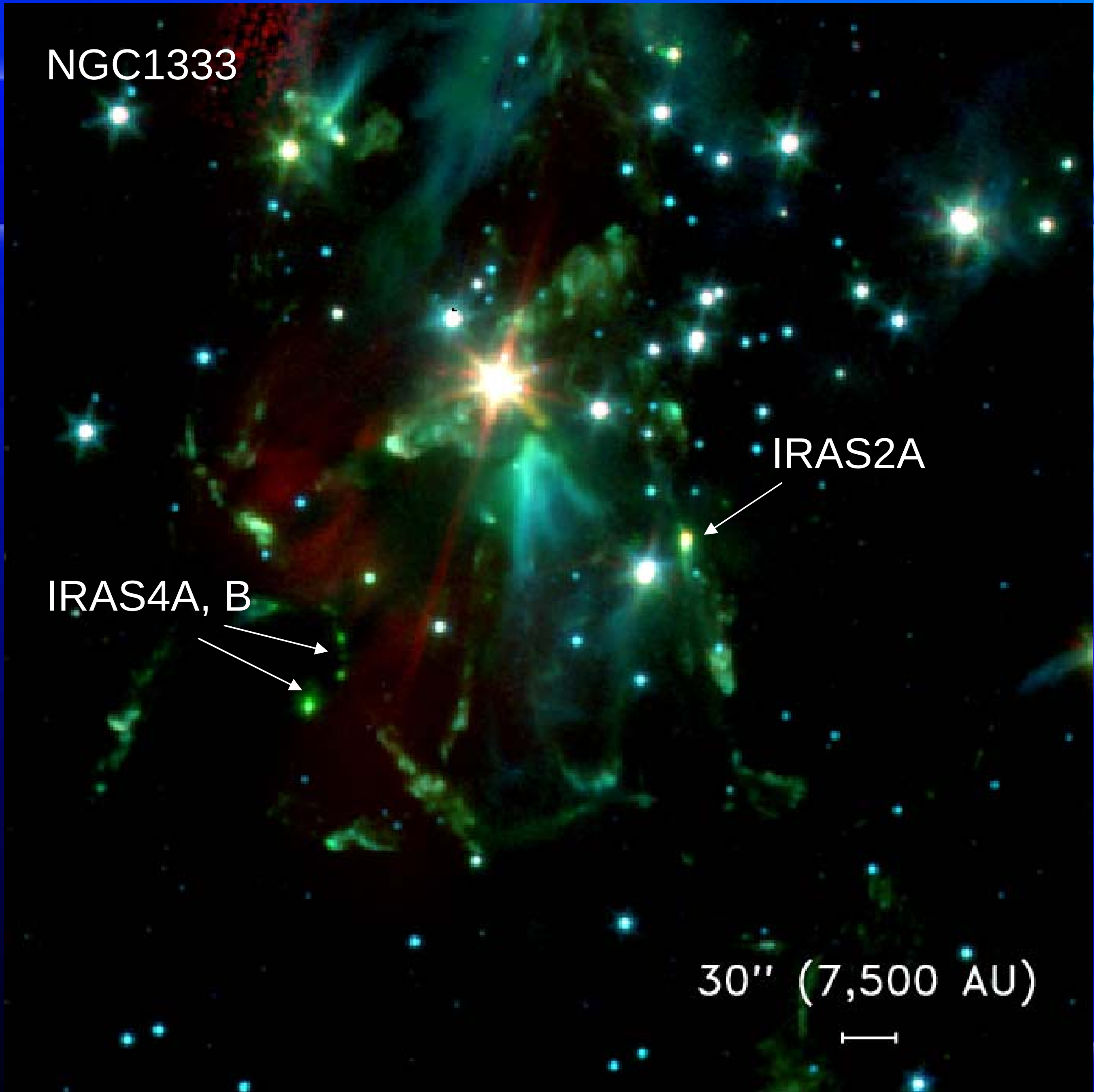


IRAS16293-2422A: high excitation transitions have their origin close to a shock (**A1**) rather than the low-mass protostar (**Aa**) *(Chandler et al. 2005)*.

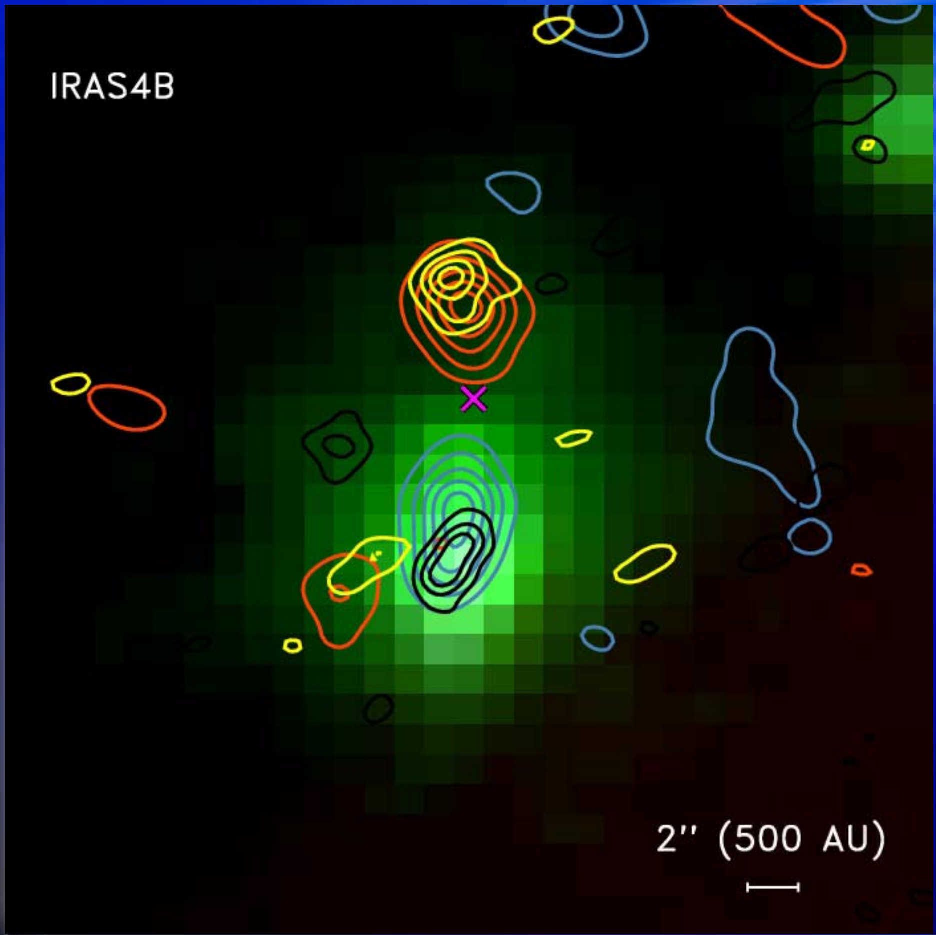


Green colors reflect emission from H_2 rotational transitions in the 4.5 µm band - probing shocked gas of 500-1000 K. Red is PAH emission in the 8 µm band.

Spitzer/IRAC from c2d (*Jørgensen et al. 2006, in press.) and GTO team (Gutermuth et al. in prep.)*


NGC1333
IRAS2A
IRAS4A, B
30" (7,500 AU)

NGC1333-IRAS4B



Green (image): H_2 emission from Spitzer
Red/blue: CO 2-1; yellow/black: CH_3OH 7-6 from SMA obs.

NGC1333-IRAS4B:

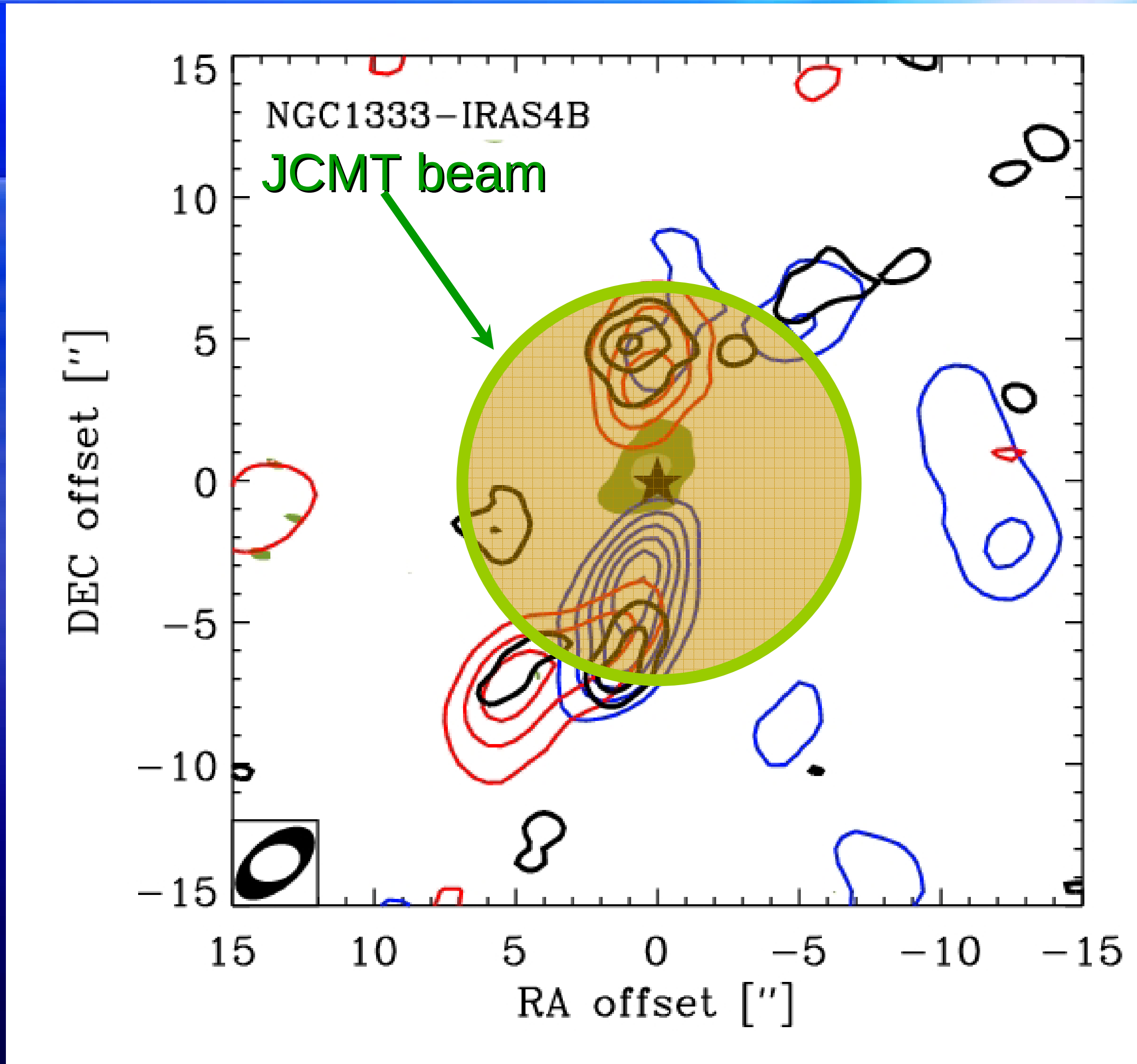
Contours:

CO 2-1 red- and blue shifted outflow emission

CH_3OH 7_{-1}-6_{-1}

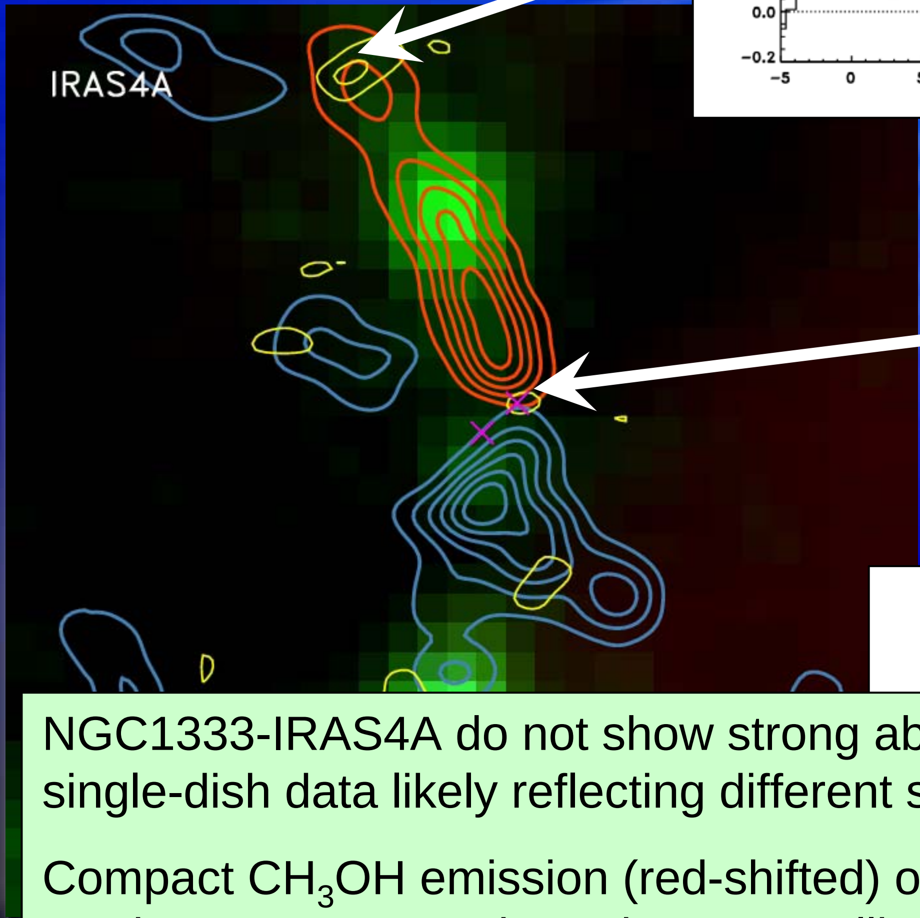
$C^{17}O$ 3-2 (colored)

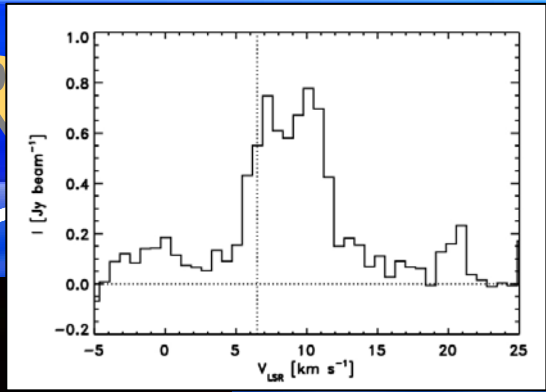
CH_3OH enhanced in shock at scales comparable to the single-dish beam.
(see also Jørgensen et al. 2005, A&A, 437, 501)

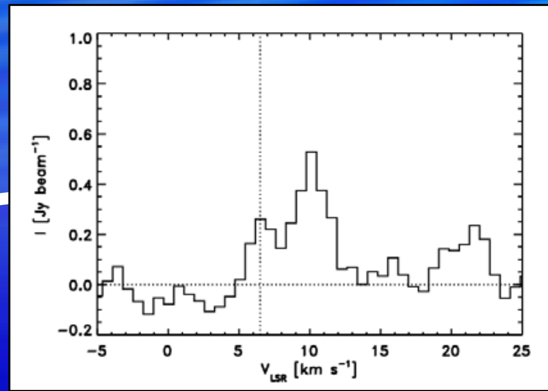


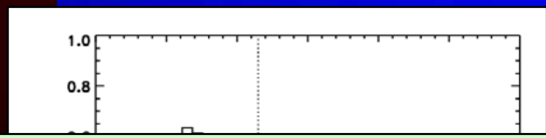
Jørgensen et al./PROSAC team

NGC1333-IR







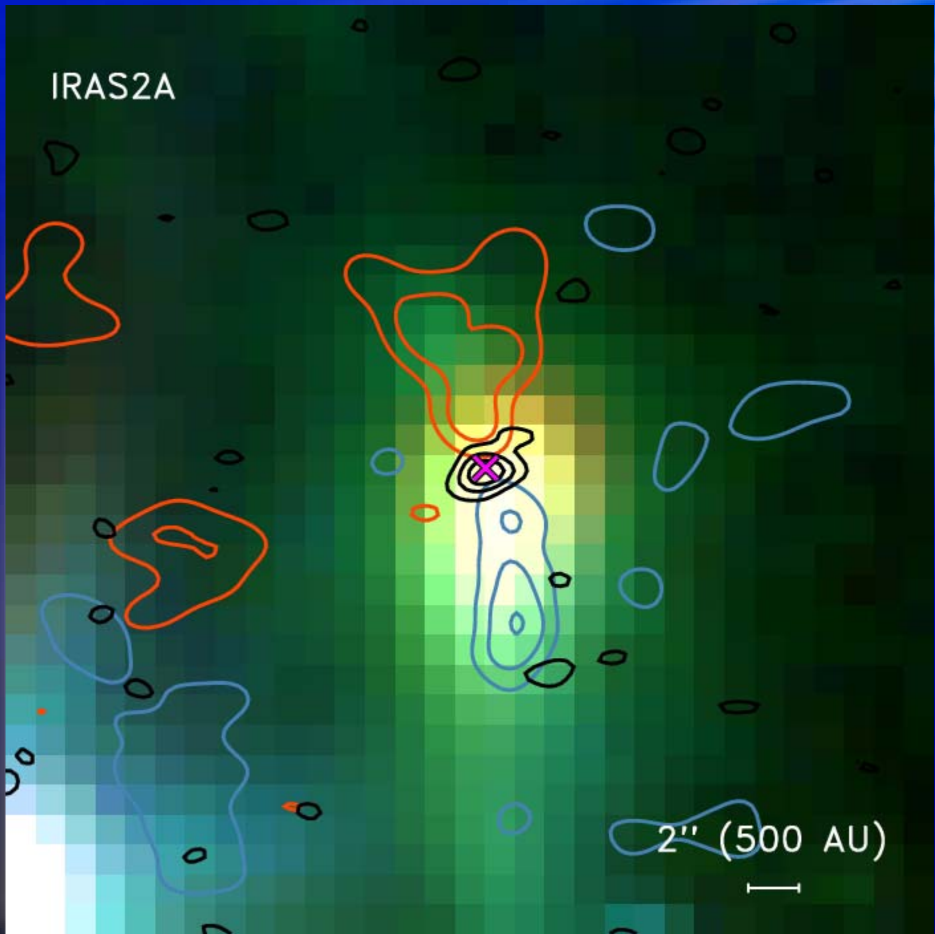


NGC1333-IRAS4A do not show strong abundance enhancements in single-dish data likely reflecting different scales of outflow/shocks.

Compact CH_3OH emission (red-shifted) only seen toward fainter continuum source - where the most collimated outflow has its origin.

Red/blue: CO 2-1; yellow/black: CH_3OH 7-6 from SMA obs.

NGC1333-IRAS2A



The best candidate hot core from single-dish studies *(Maret et al. 2005; Jørgensen et al. 2005)* - but SED + high-res. submm data suggest cavity with max. temperature of 75 K.

Shows compact CH_3OH emission - but also that shocked H_2 is prominent close to the central protostar itself. Similar to IRAS16293-2422A... or related to accretion shock in the disk? (aka. L1157; *Velusamy et al. 2002*)

Green (image): H_2 emission from Spitzer
Red/blue: CO 2-1; yellow/black: CH_3OH 7-6 from SMA obs.

So what are we learning...
...while we are waiting for ALMA?

- Single-dish studies of low-mass hot cores are inconclusive as regards the nature of the gas where complex organics reside (although... complex organic molecules and hot gas *are* present!)
- High angular resolution submm and mid-IR continuum observations penetrate the dusty envelopes of low-mass protostars: disks present on small scales - implying the breakdown of spherical models based on single-dish observations. Cavities are observed on those scales - why envelope material is unlikely to be (radiatively) heated above 80-100 K.
- Shocks are clearly important on all scales in protostellar environments. CH_3OH observations from the SMA - and broad band observations from Spitzer (sensitive to the H_2 emission at temperatures of 500-1000 K) are for example found to be correlated.
- A detailed framework is in place/being continuously developed to perform the full dust and line radiative transfer necessary to interpret coming observations of low-mass protostars, e.g., from ALMA.

Single-dish studies (H_2CO/CH_3OH)

Need:

- High excitation lines (probing high densities and temperatures).
- Molecules that are not too sensitive to the chemistry of the outer envelope.
- High angular resolution (beam dilution/mass weighting of lines/contribution from outflows).

A small back of the PowerPoint slide calculation...

Envelope density profile $n \propto r^{-p}$ with $p \sim 1.5 - 2.0$

$$N = \int_{r_i}^{r_o} n(r)dr \propto \int_{r_i}^{r_o} r^{-p} dr$$ [line of sight column density]

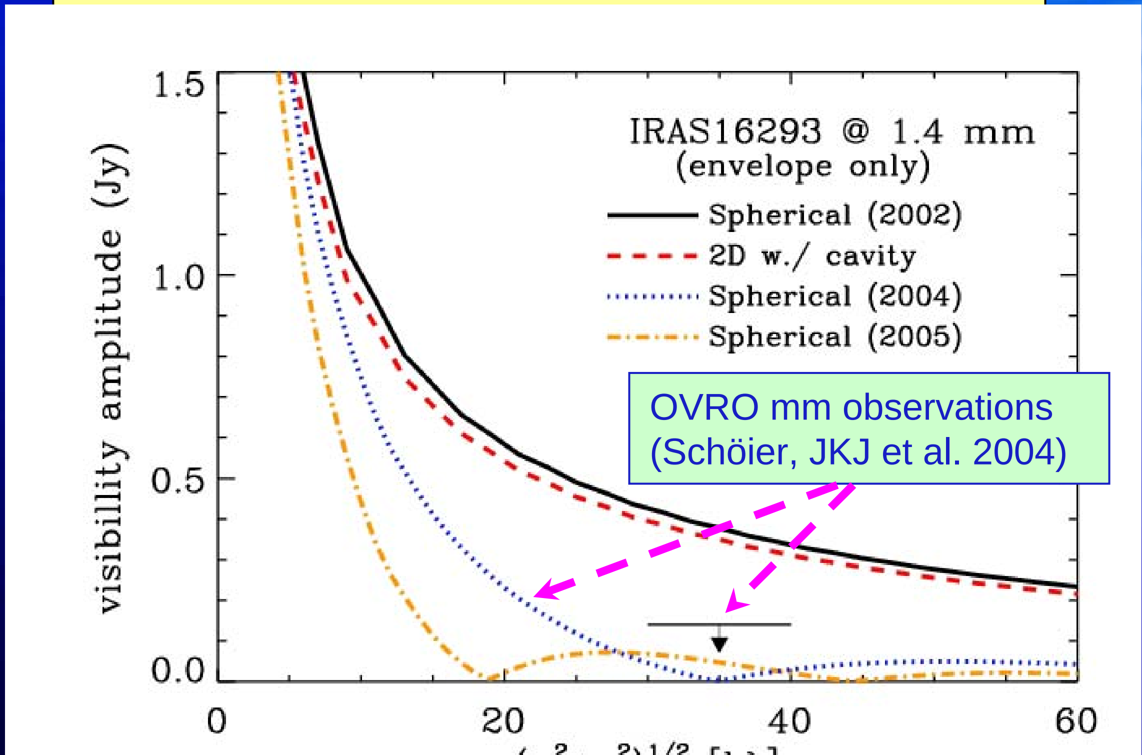
$$= \frac{1}{1-p}(r_o^{1-p} - r_i^{1-p}) \sim r_i^{1-p} \quad r_o \gg r_i$$

$$M = \int_{r_i}^{r_o} 4\pi r^2 n(r) \mu m_{\mathrm{H}} dr \propto \int_{r_i}^{r_o} r^{2-p} dr$$ [mass]

$$= \frac{1}{3-p}(r_o^{3-p} - r_i^{3-p}) \sim r_o^{3-p} \quad r_o \gg r_i$$

The line-of-sight column density (or related extinction) is "determined" by the envelope inner radius, whereas the mass (or beam avg. column) is "determined" by the outer radius.

2D?



Outflow cavity model can explain (mid-IR) SED for specific opening angles,…

…but high angular resolution millimeter interferometer data resolves inner cavity and proves its existence.

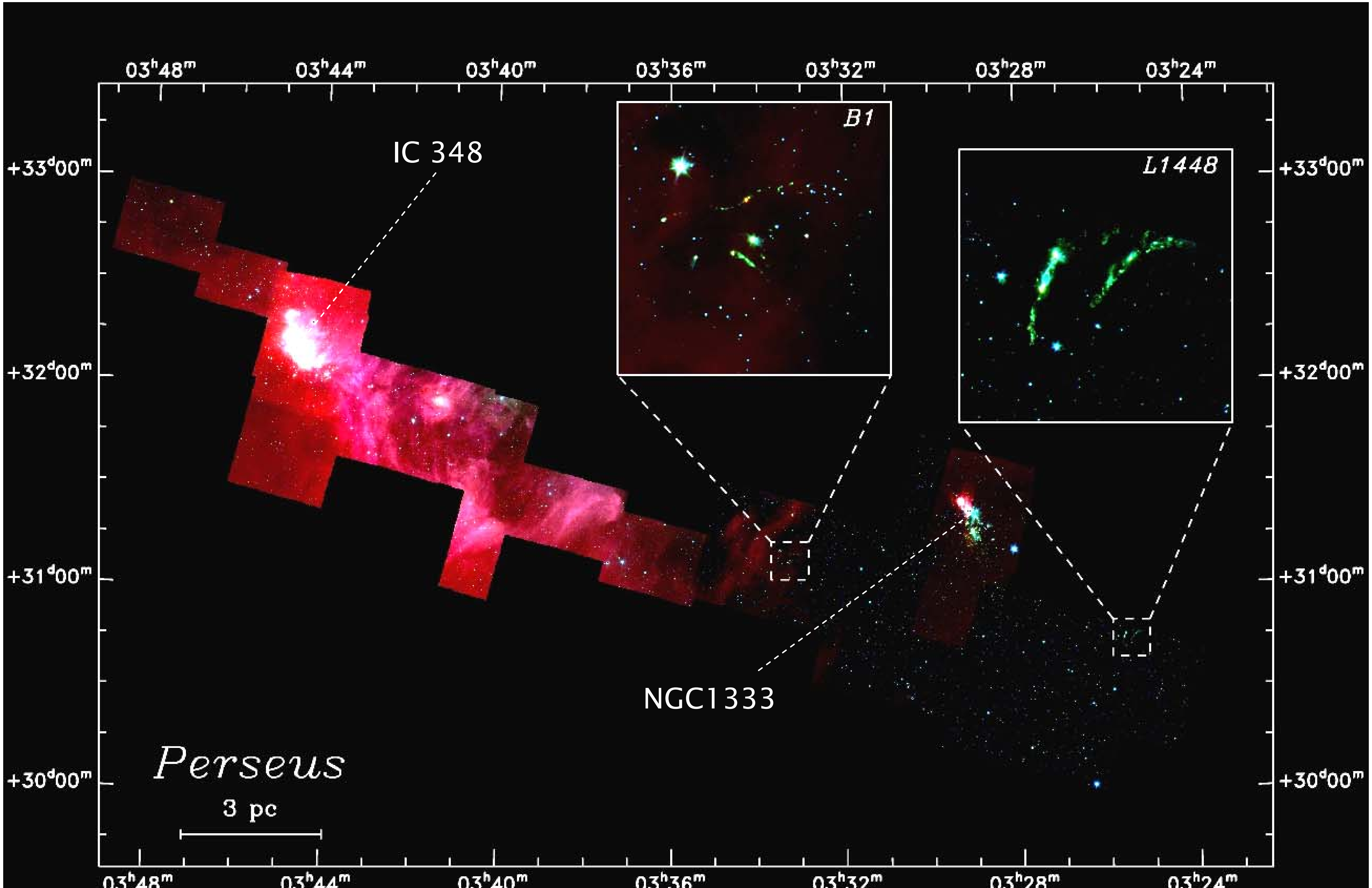
We need data from not just mid-IR obs. but additional constraints from, e.g., the high angular (sub)mm observations (SMA/CARMA) are important...

Jørgensen et al. 2005, ApJ , 631, L77

PROSAC

***PRO**tostellar **S**ubmillimeter **A**rray **C**ampaign*

Jørgensen (PI)
Bourke, Di Francesco, Lee, Myers, Ohashi,
Schöier, Takakuwa, van Dishoeck, Wilner, Zhang



3.86 degree^2 (overlap) mapped by c2d with Spitzer/IRAC (3.6, 4.5, 5.8 and 8.0 μm))

Jørgensen et al. 2006, in press.