Cores, fragmentation, and the earliest observable stages of protostellar disks

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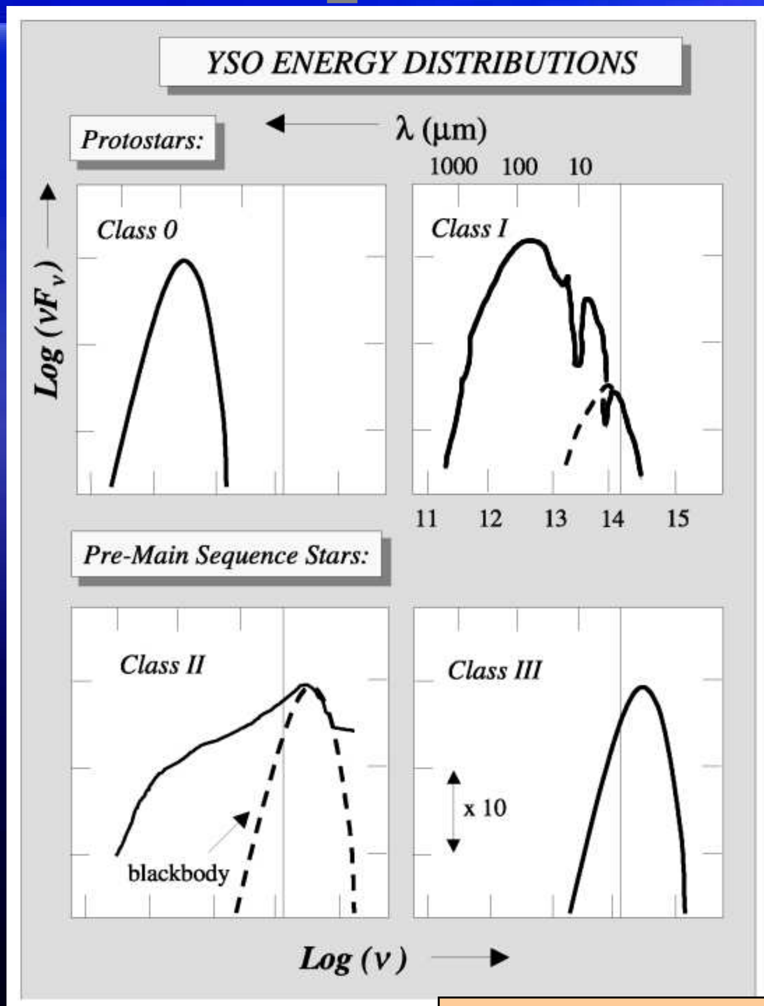
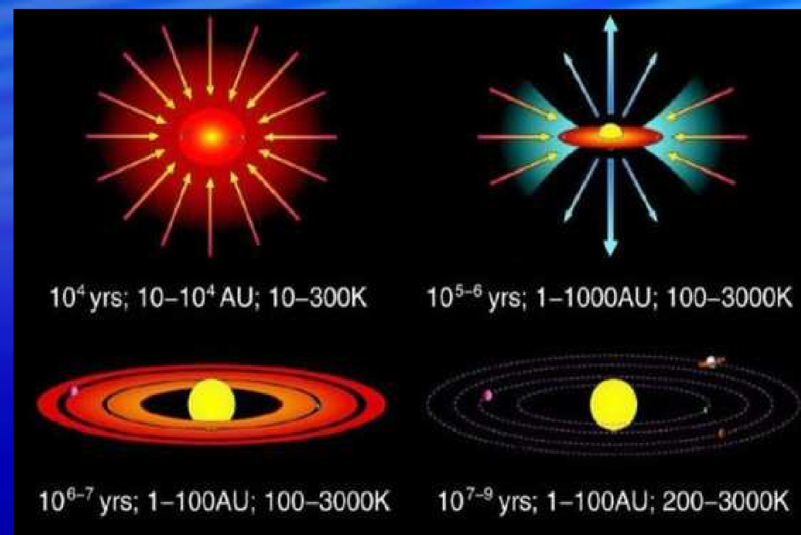
Tyler Bourke, Phil Myers, Doug Johnstone, Fredrik Schöier, Christian Brinch, Ewine van Dishoeck, David Wilner, Dave Lommen, Fred Lahuis, Neal Evans
...and the rest of the *PROSAC* and *c2d* teams

Class 0 protostars…



C. Lada, CreteII



Shu et al. 1987; from *JWST science case*

The quest for Class 0 disks

- a non-exhaustive list

Keene & Masson (1990): Dete
baselines in the embedded

Looney et al. (2000, 2003): BIM
multiplicity, and analytic fits
fast processing of material (

Hogerheijde+ (2000, 2001): Ra
envelopes, inferring the pre

Brown et al. (2000): JCMT+CS
protostars on baselines at 7
radius) disks.

Havey et al. (2003*): IRAM Pd
B335.

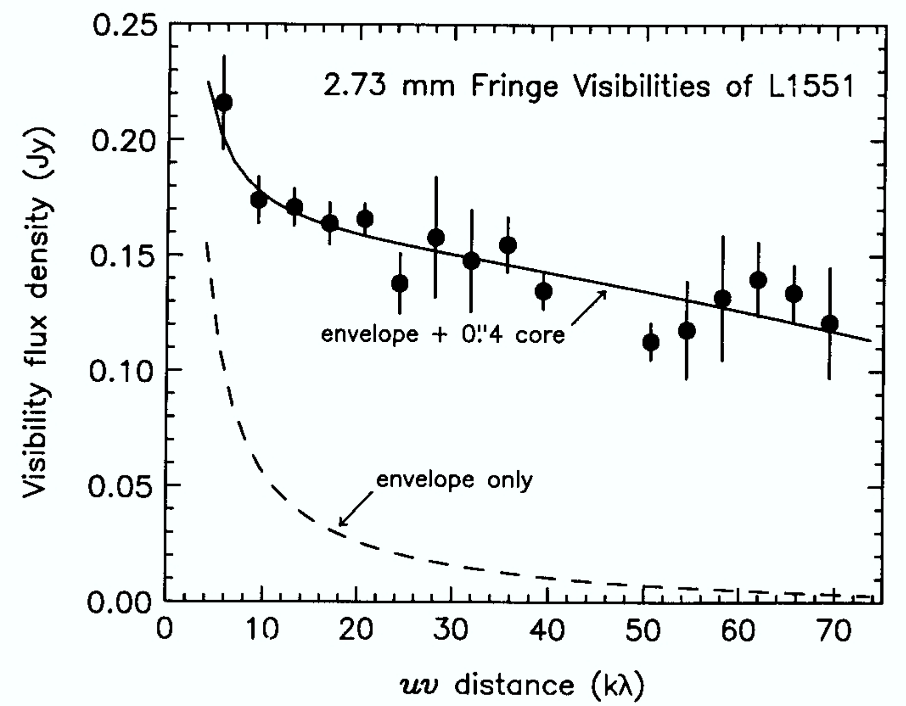


FIG. 3.—The observed 2.73 mm visibilities. The dashed line shows the visibilities resulting from an envelope with 0.29 Jy total flux and with a volume emissivity $\propto r^{-2}$. The solid line shows the visibilities resulting from a similar envelope with a flux of 0.14 Jy plus a compact Gaussian source with a flux of 0.15 Jy (for a total flux of 0.29 Jy) and a half-power radius of 0.''4. It is obvious that the two-component model fits the data much better than a simple power-law source.

Outline

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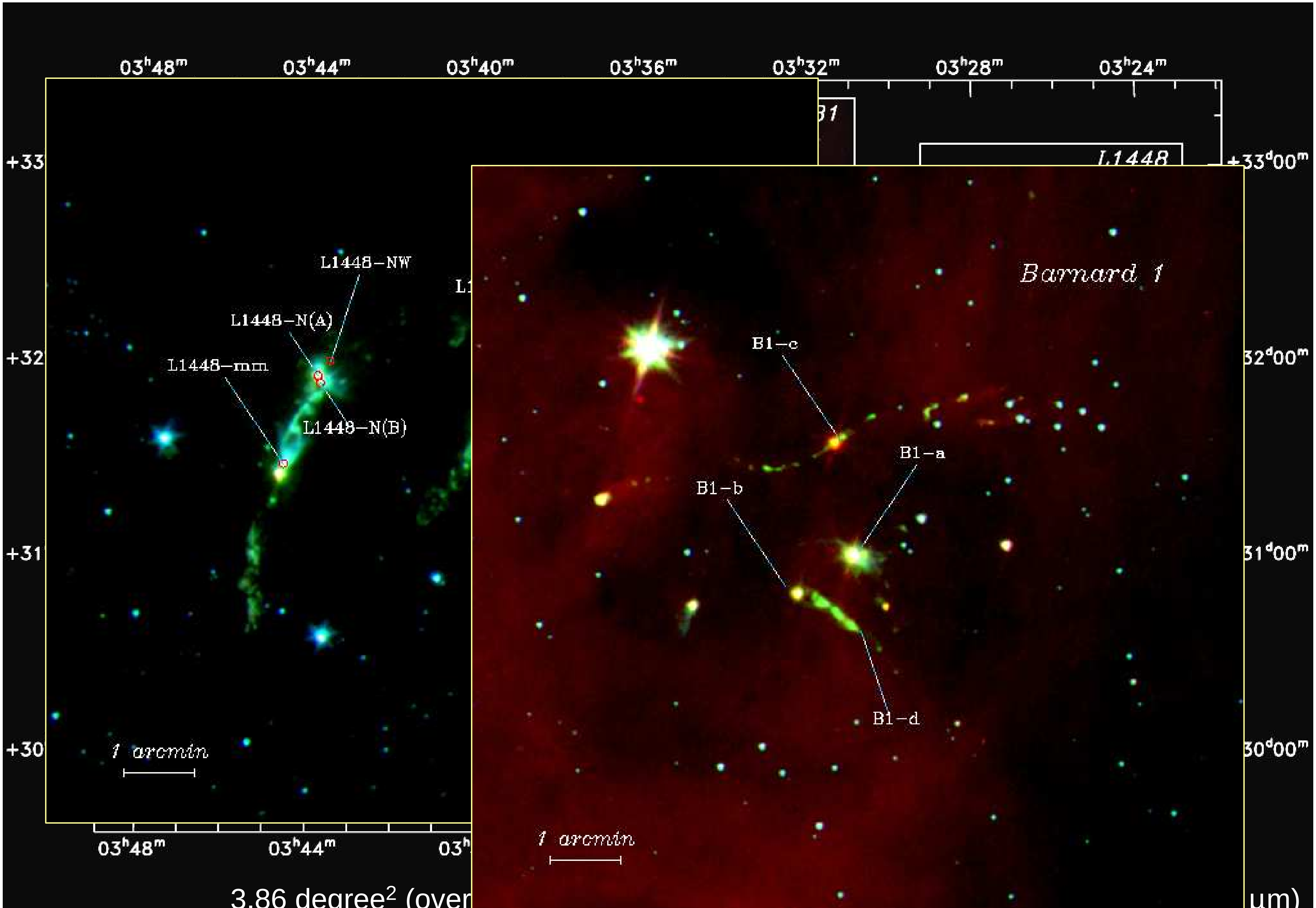
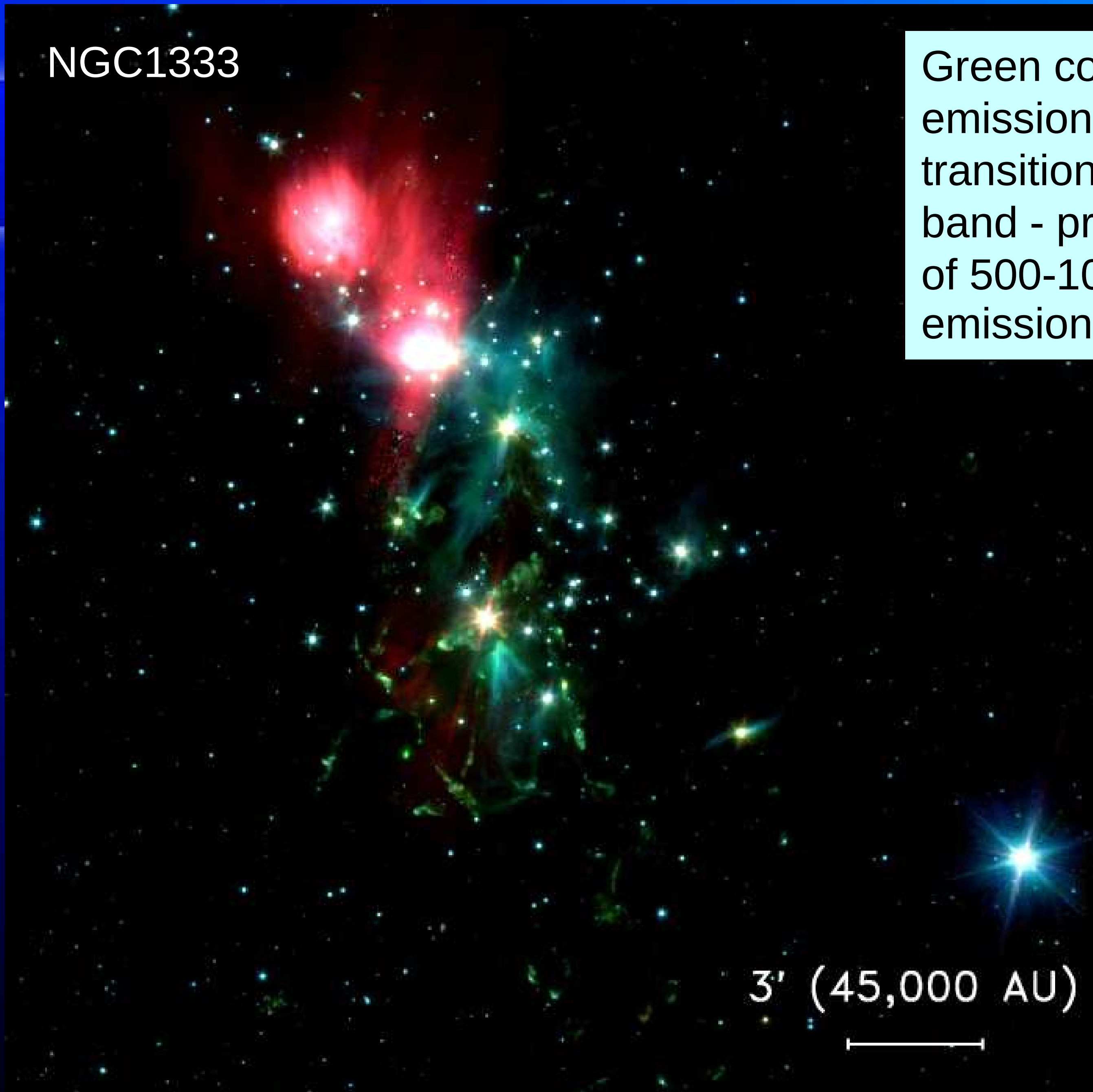
4. Toward less embedded Class I objects



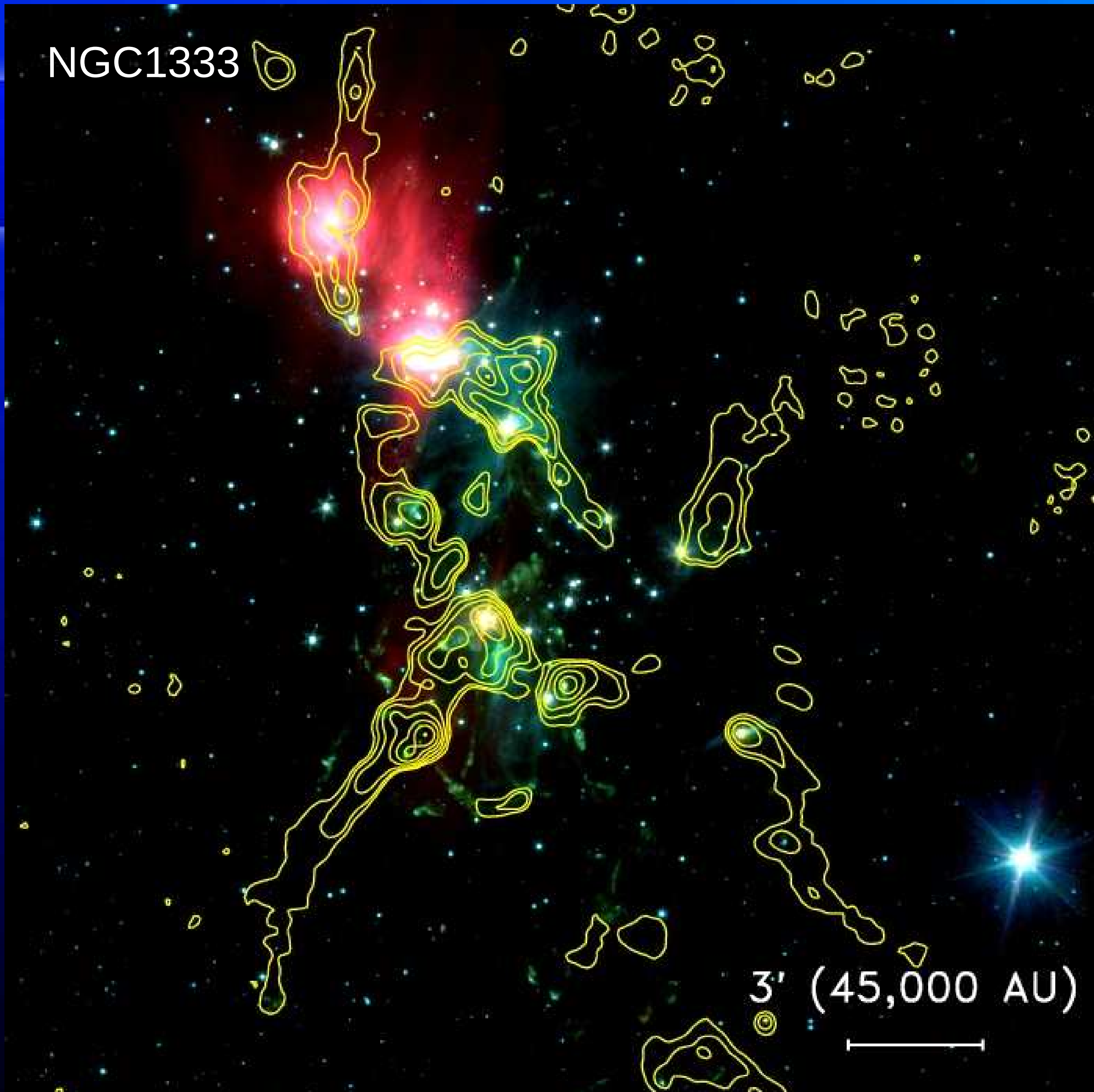
3.86 degree^2 (over ... µm)

Jørgensen et al. 2006, ApJ, 645, 1246



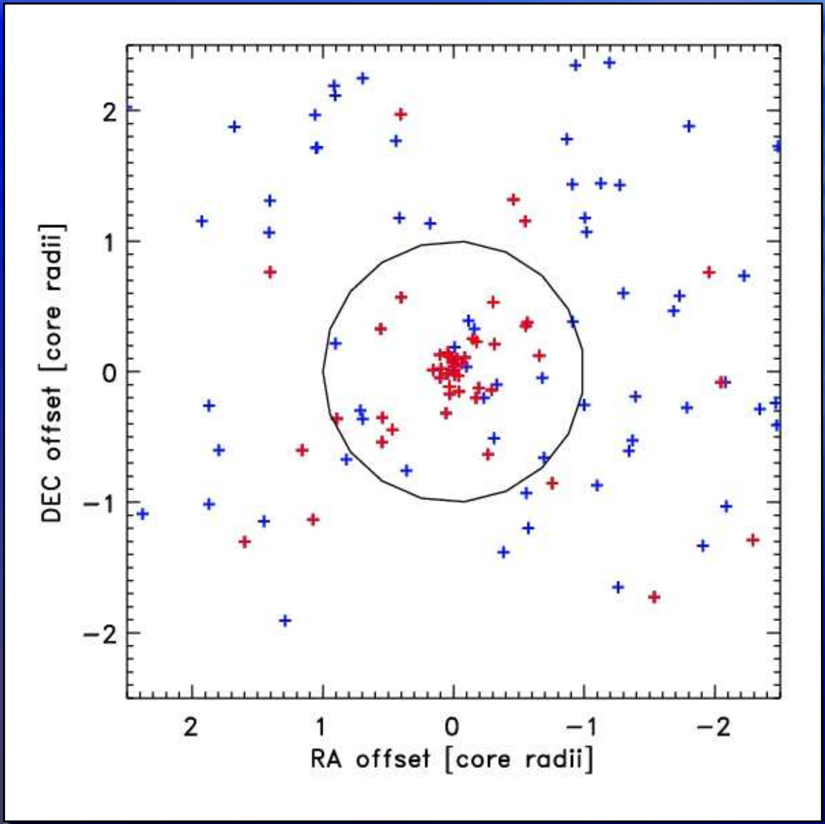
Green colors reflect emission from H_2 rotational transitions in the 4.5 µm band - probing shocked gas of 500-1000 K. Red is PAH emission in the 8 µm band.

Spitzer/IRAC from c2d (*Jørgensen et al. 2006)* and GTO *(Gutermuth et al. 2007)*



Spitzer/IRAC from c2d (*Jørgensen et al. 2006) with SCUBA map (yellow contours; Kirk et al. 2006)*

Comparison: SCUBA+Spitzer maps



Distribution of MIPS sources around centers of SCUBA cores *- with [3.6]-[4.5] > 1.0.*

MIPS-24 micron sources are concentrated toward center of SCUBA cores...

...with most of those within 10-15” of the peaks having red [3.6]-[4.5] colors.

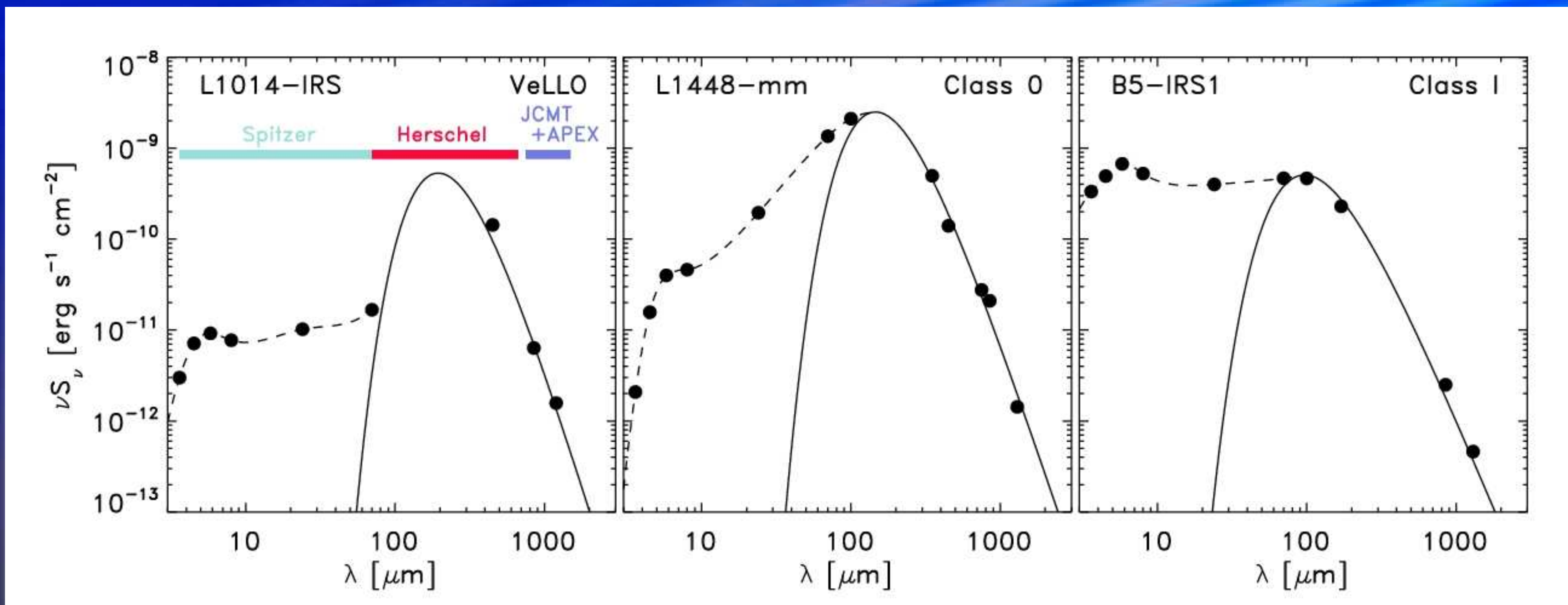
Jørgensen et al. 2007, ApJ, 656, 293

Comparison: SCUBA+Spitzer maps

- Of 72 SCUBA cores, 40 have embedded protostars within 15” (3750 AU). Pre- and protostellar time scales similar.
- Little dispersal of protostars (v ~ 0.1 km/s ≤ c_s). Bondi-Hoyle accretion not applicable
- “Current” star formation efficiency of 10-15%. No significant differences between NGC1333 and other parts of Perseus.
- *Comparison between SCUBA and Spitzer data allow us to build unbiased samples of embedded protostars and most Class 0 sources (including those previously known) are detected at wavelengths as short as 3.6 μm.*

SEDs of low-mass protostars

VeLLO Class 0 Class I



We can now start characterizing even the very deeply embedded protostars at mid-IR wavelengths.

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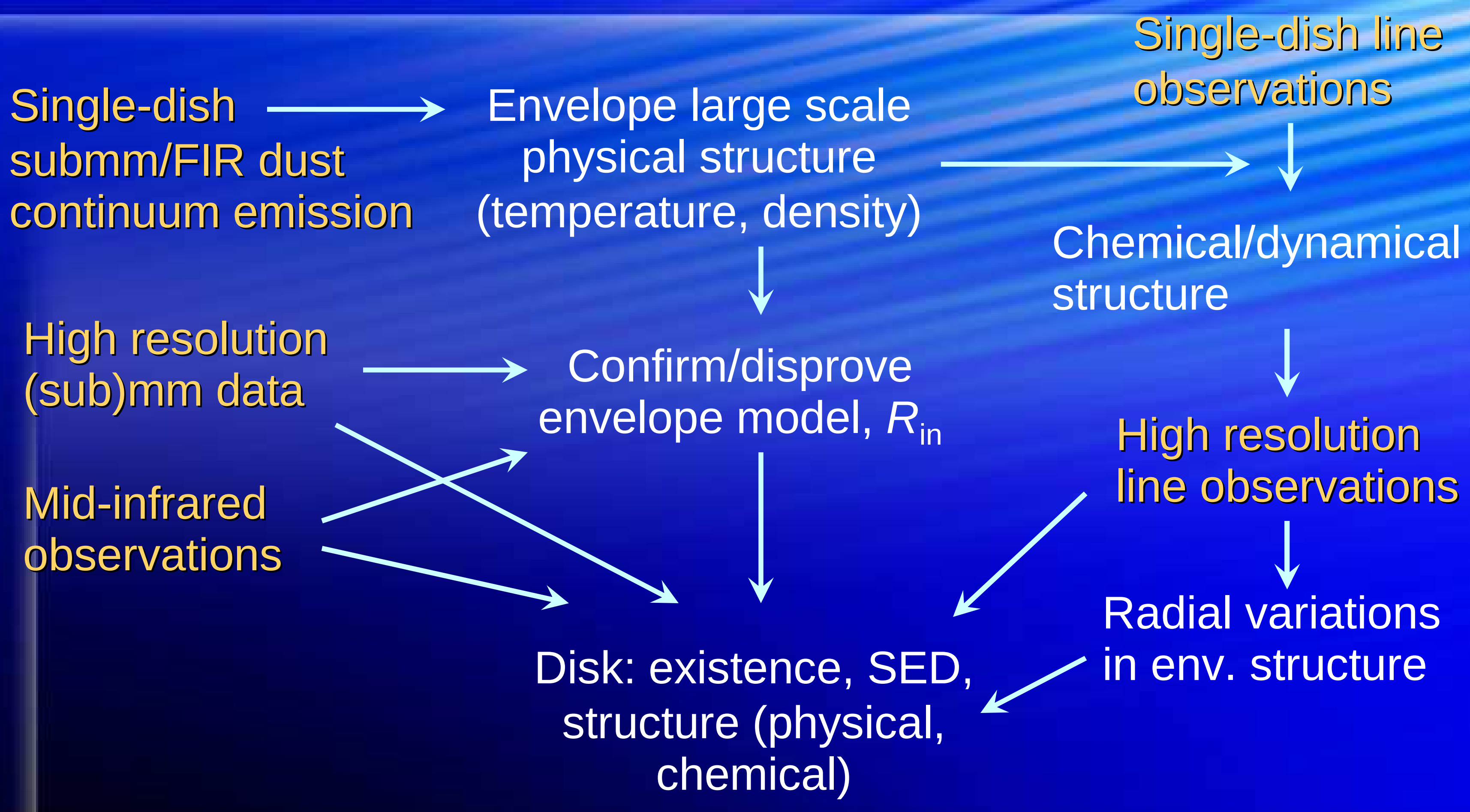
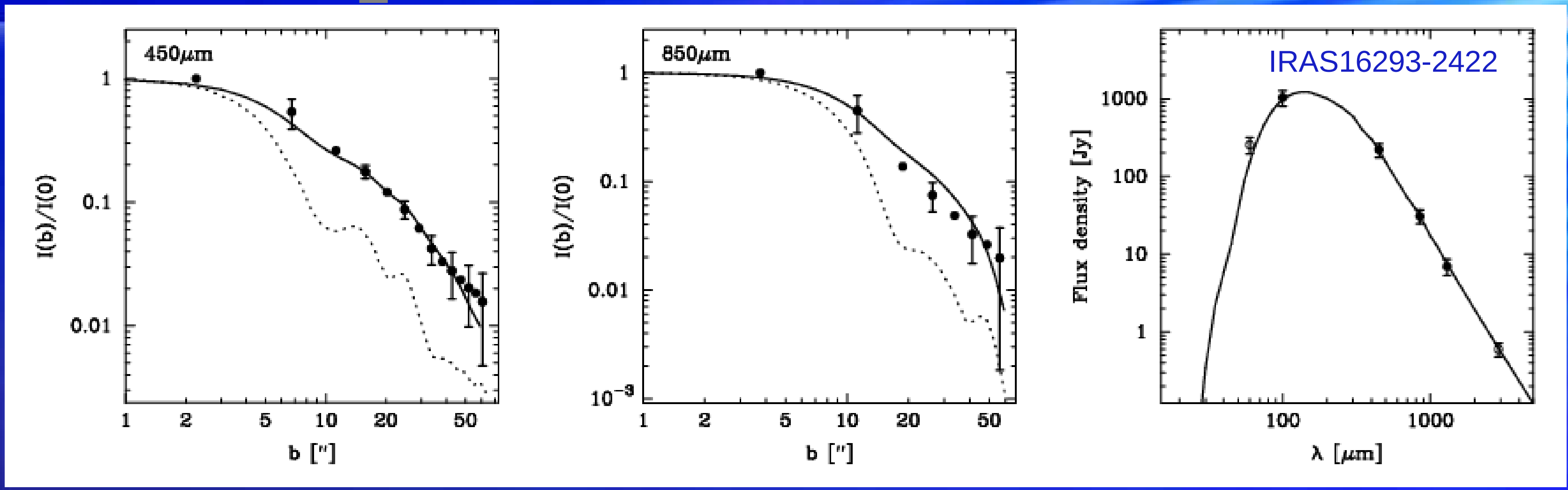
Framework


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

Envelope structure



Data:

- SED, images
- Distance

Constrain:

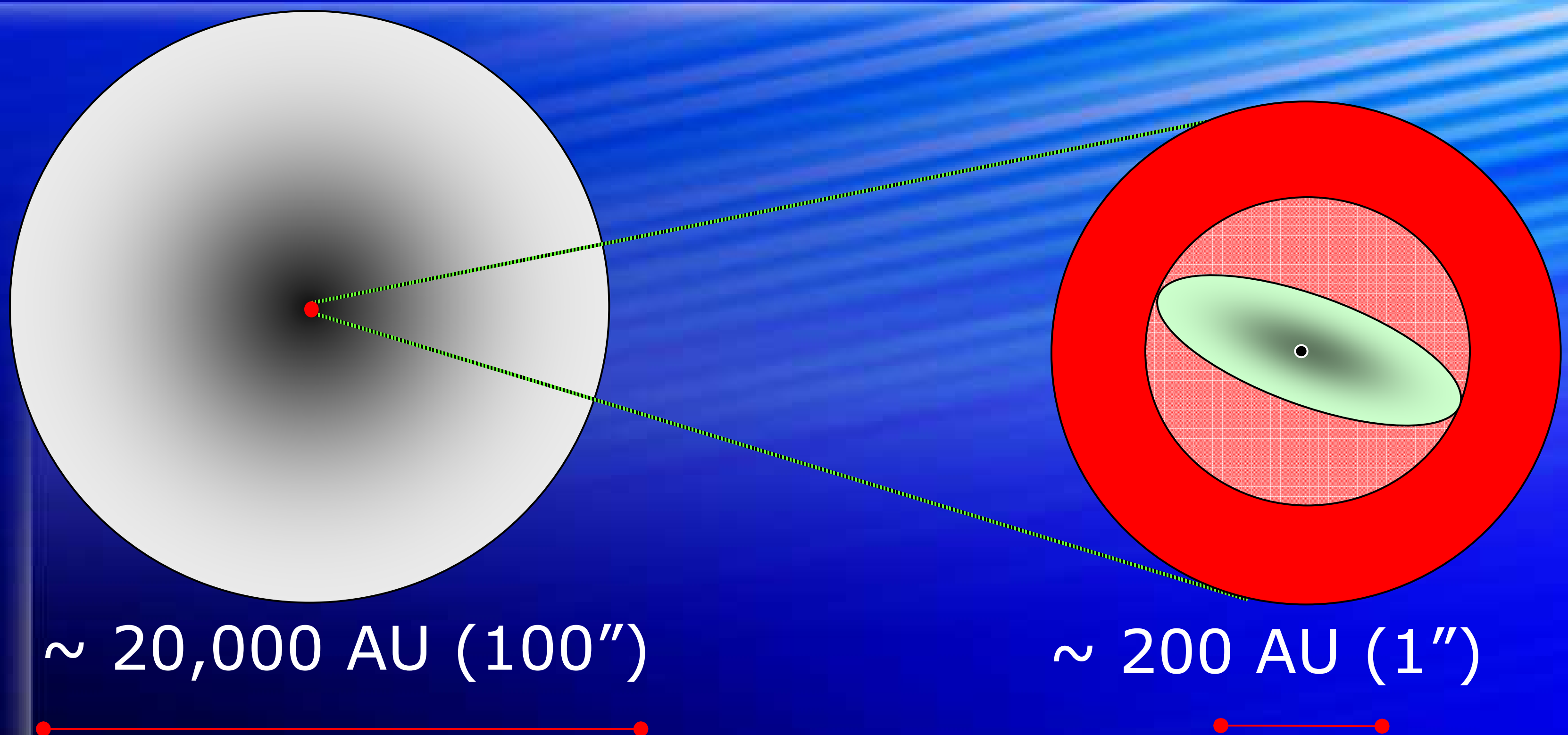
- p, n_0 (or τ_{100}), R_{out}

Radiative transfer, calculate:

- Temperature profile
- Model images, SED

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

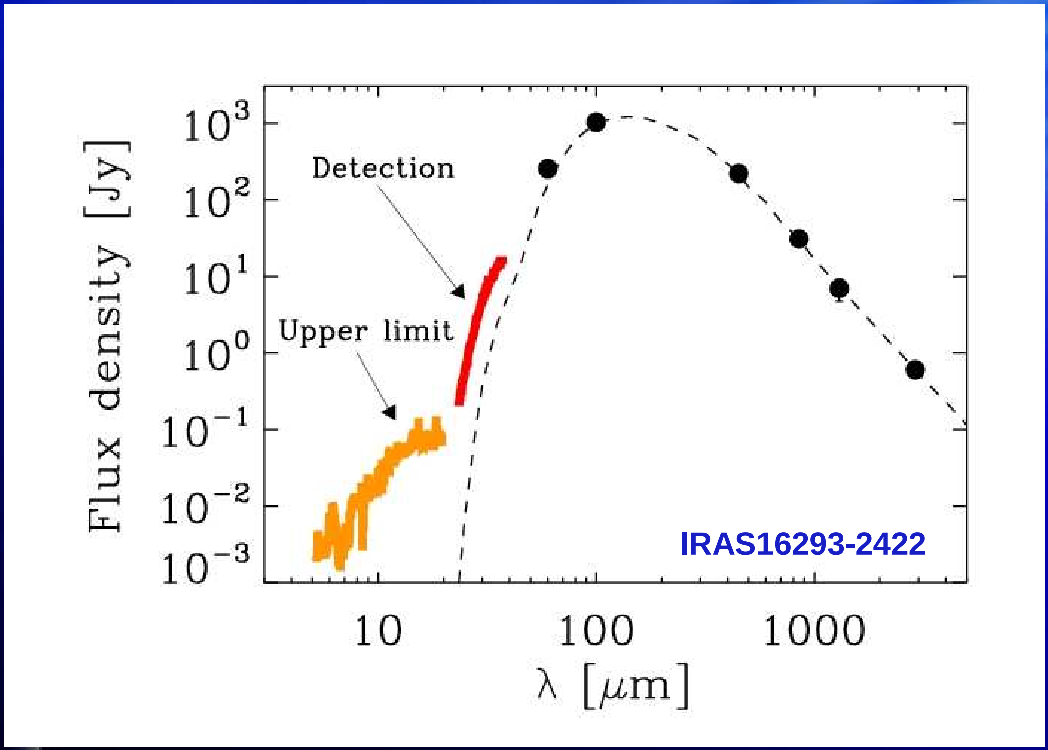
Low-mass protostars



- 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.

Envelope structure

- Trying to fit Spitzer/IRS data for IRAS 16293-2422



IRAS16293-2422 mid-IR is not well-reproduced with standard envelope model extending to 25 AU scales... *but we know it is a binary with a separation of about 800 AU.*

Dashed line: Best fit model of Schöier et al. (2002). Inner radius assumed to be radius where T_{dust} = 300 K.

Blue line: model with r_i = 600 AU ($T_{dust} \approx$ 65 K)

Spitzer: c2d/IRS

Jørgensen et al. 2005, ApJ , 631, L77

Envelope structure

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}

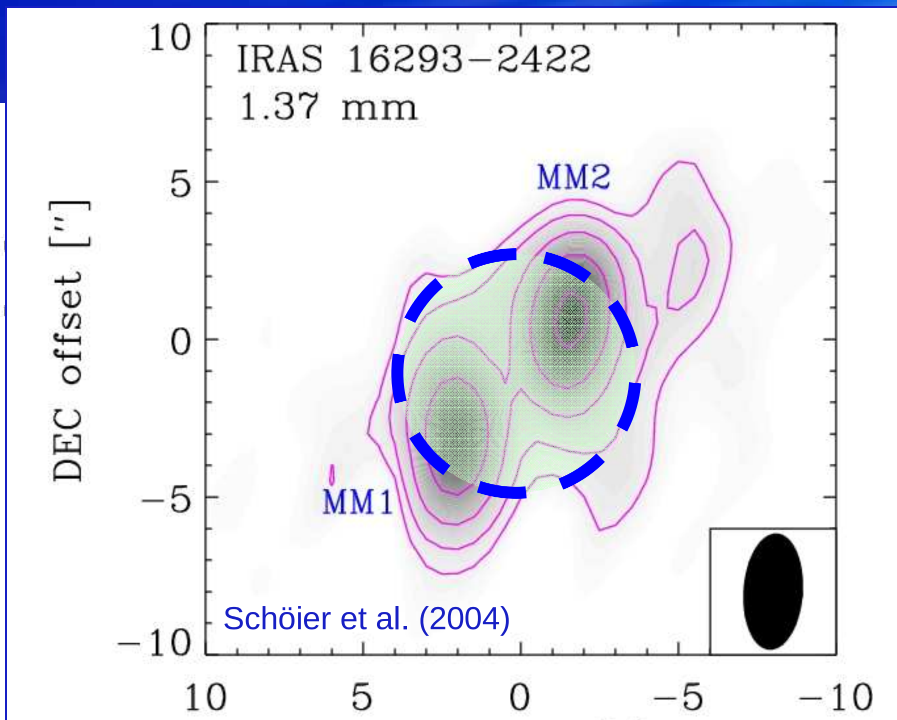
Radiative transfer, calculate:

- Temperature profile
- Model images, SED

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

Envelope structure

- 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").

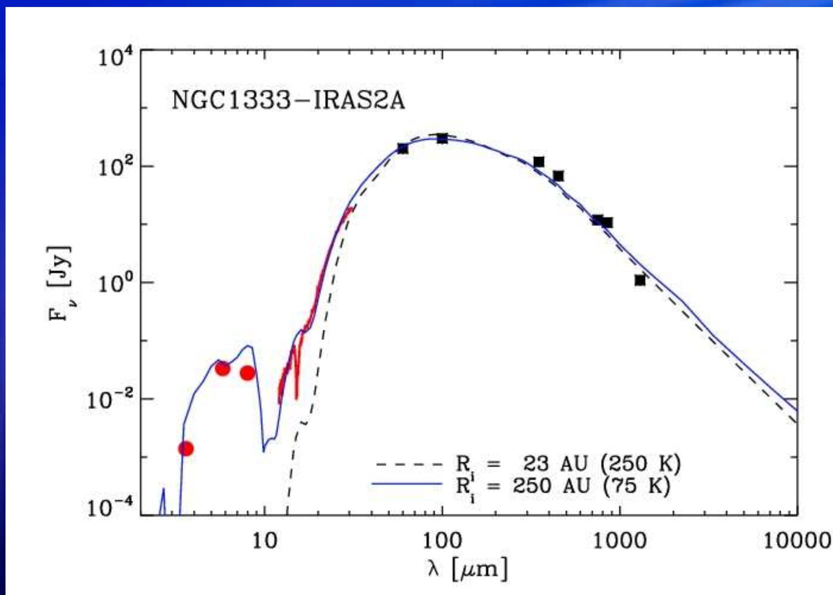
Dashed line: Best fit model of Schöier et al.

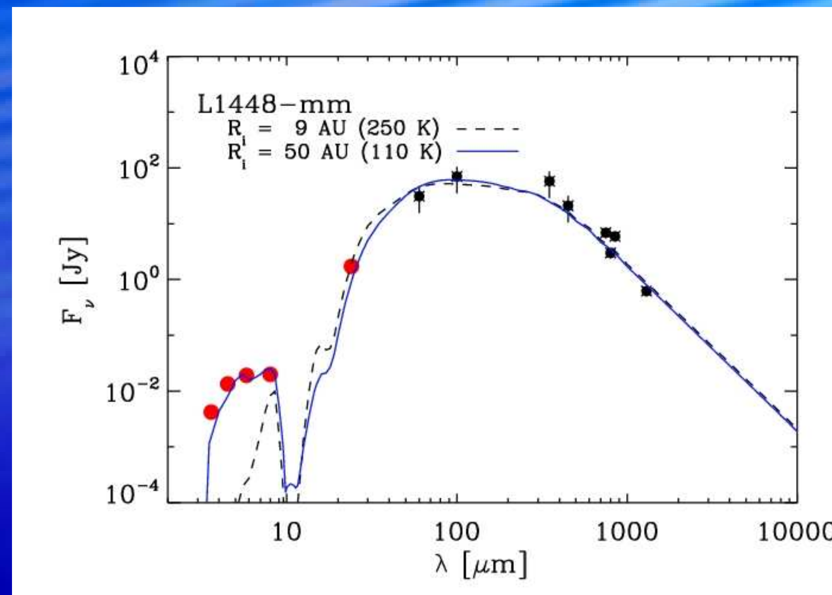
We need data from not just (sub)mm obs. but additional constraints from, e.g., mid-IR (Spitzer) observations are important...

Spitzer: c2d/IRS

Jørgensen et al. 2005, ApJ, 631, L77

Two other low-mass protostars...





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)*

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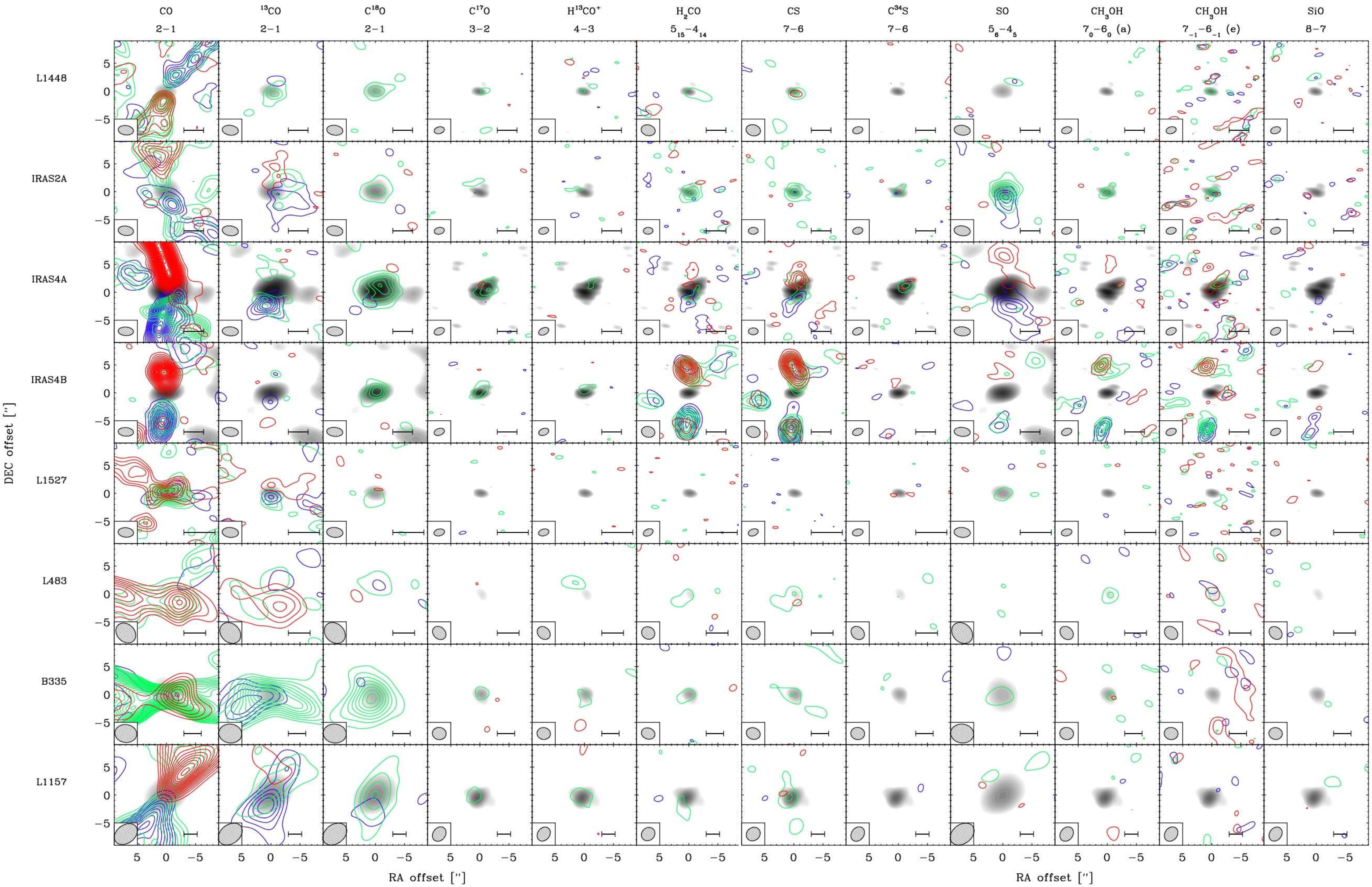
Protostellar Submillimeter Array Campaign “PROSAC”

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 deeply embedded (Class 0) protostars. Half from Perseus and half more isolated cores (including one from Taurus).
- 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 of each source from detailed line and continuum rad. transf. models (Jørgensen et al. 2002; 2004)
- Follow-up program(s) aiming to build comparable sample of Class I sources currently ongoing at the SMA.

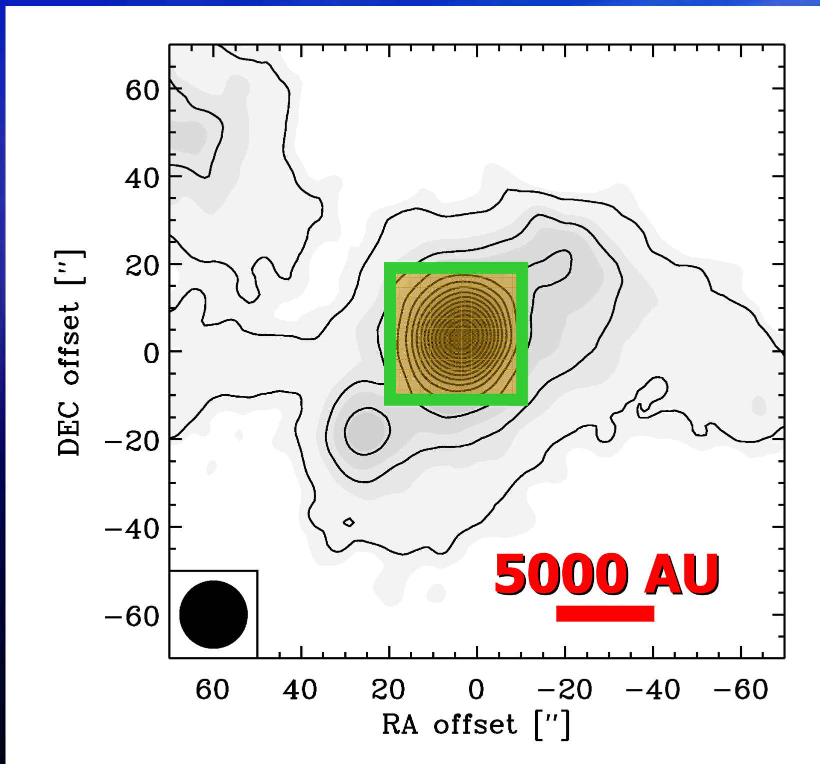
Jørgensen et al. 2007, ApJ, 659, 974



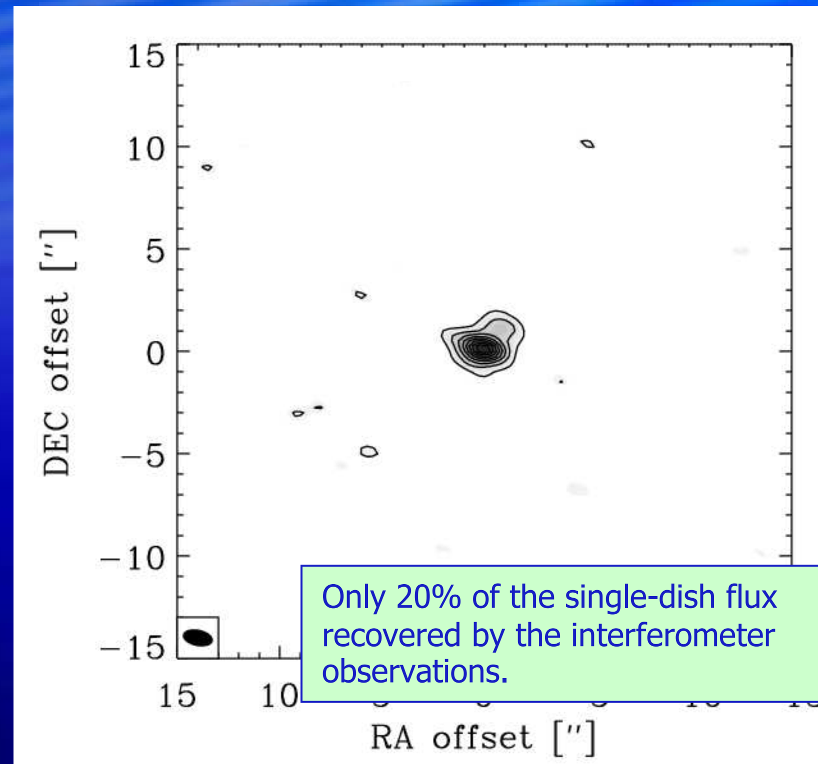
Jørgensen et al. 2007, ApJ, 659, 974

NGC1333-IRAS2A: 850 µm dust continuum

SCUBA 850 µm



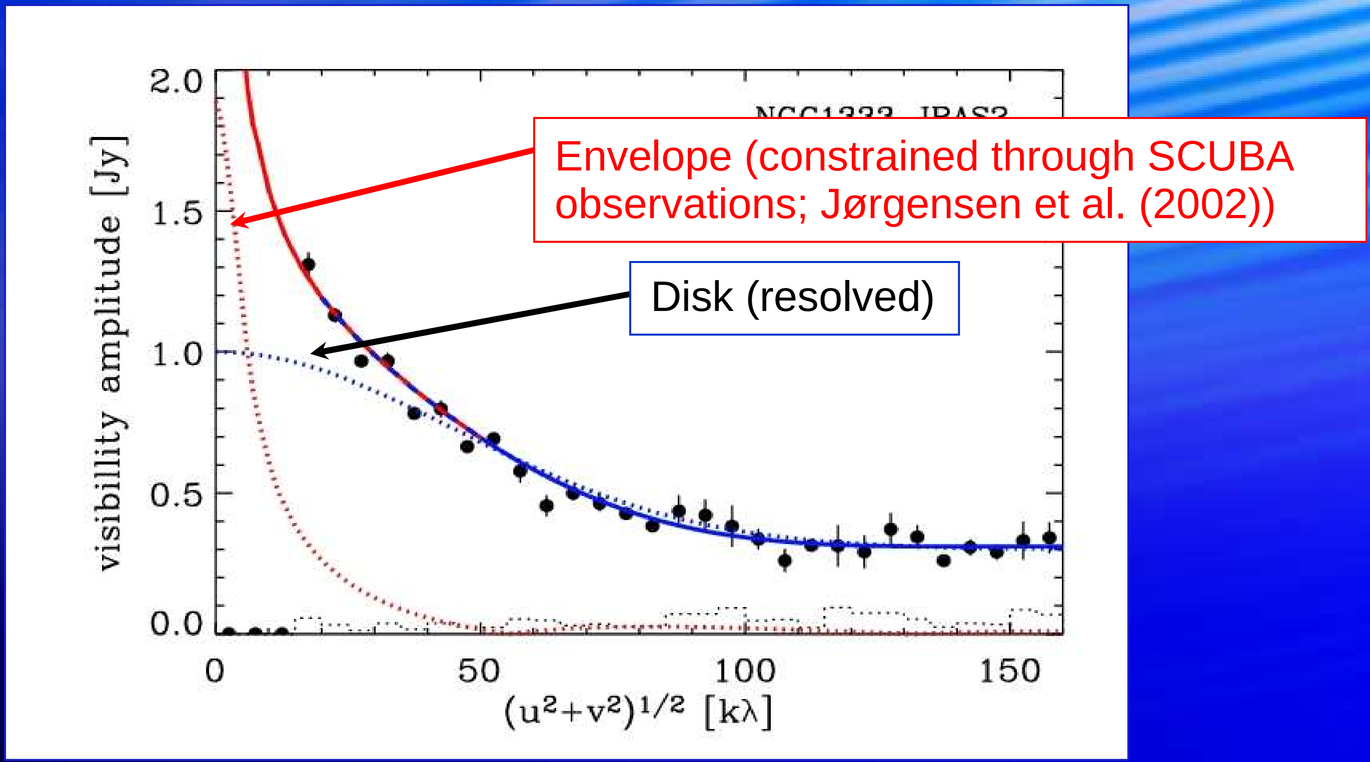
SMA 850 µm



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



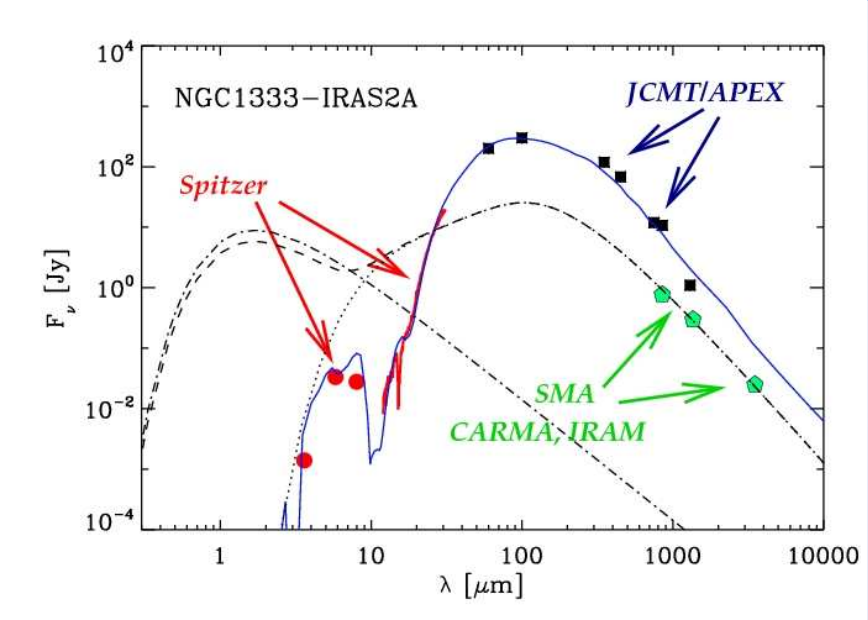
…the SMA resolves the warm dust in the inner envelope *and the (300 AU diameter) circumstellar disk.*

Jørgensen et al. 2005, ApJ, 632, 973

Dust continuum fits for 8 Class 0 protostars

- Disk sizes of < 50 AU - 300 AU (radius)
- Masses of 0.01-0.5 $M_\odot$ (modulo uncertain dust properties etc.) - compared to envelope masses of 0.9 - 4 $M_\odot$
  - Note that objects with lower $M_{disk}/M_{envelope}$ ratios are those with the least collimated outflows
- Comparison between 230 and 345 GHz data suggest dust opacity law, $\kappa_\nu \sim \nu^\beta$ with $\beta \approx 1.0$. Grain growth such as in more evolved disks around Class II protostars? Or just reflecting that we don't understand dust?

Adding it all together



Simple "0D" disk model (Butner et al. 1994).

Inner radius appears most important for shape of short (IRAC) wavelength SED.

$\beta \sim 1$ and disk mass ~ 0.1 $M_\odot$ (size constr. by SMA obs.)

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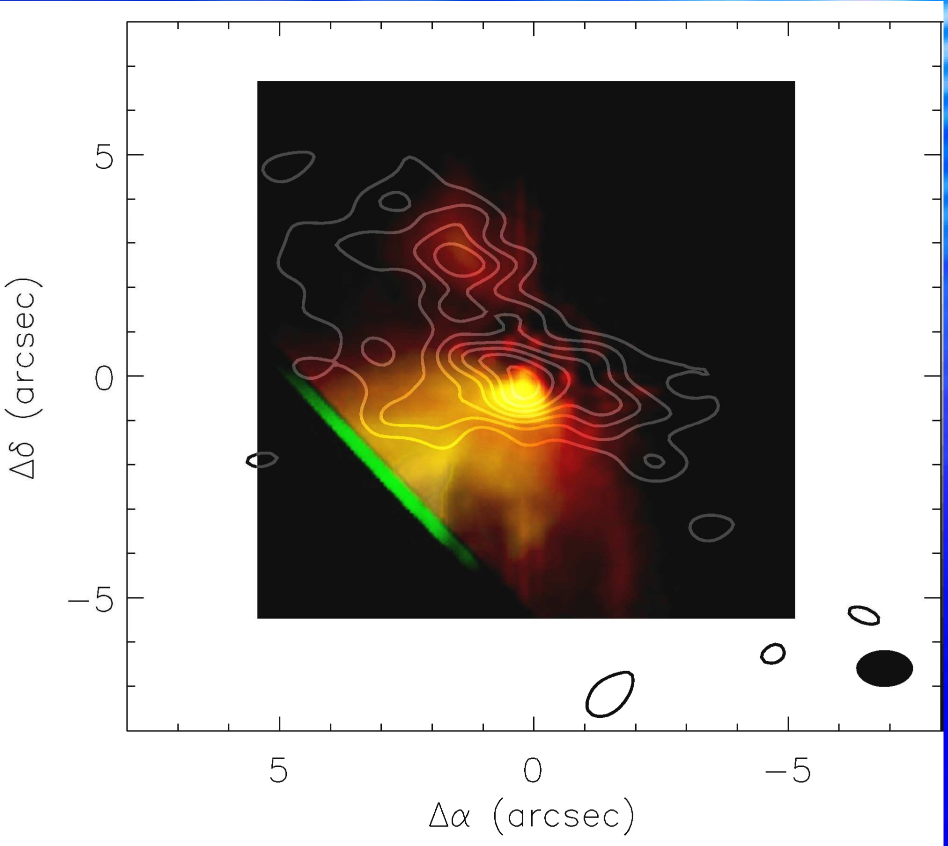
Example: L1489-IRS

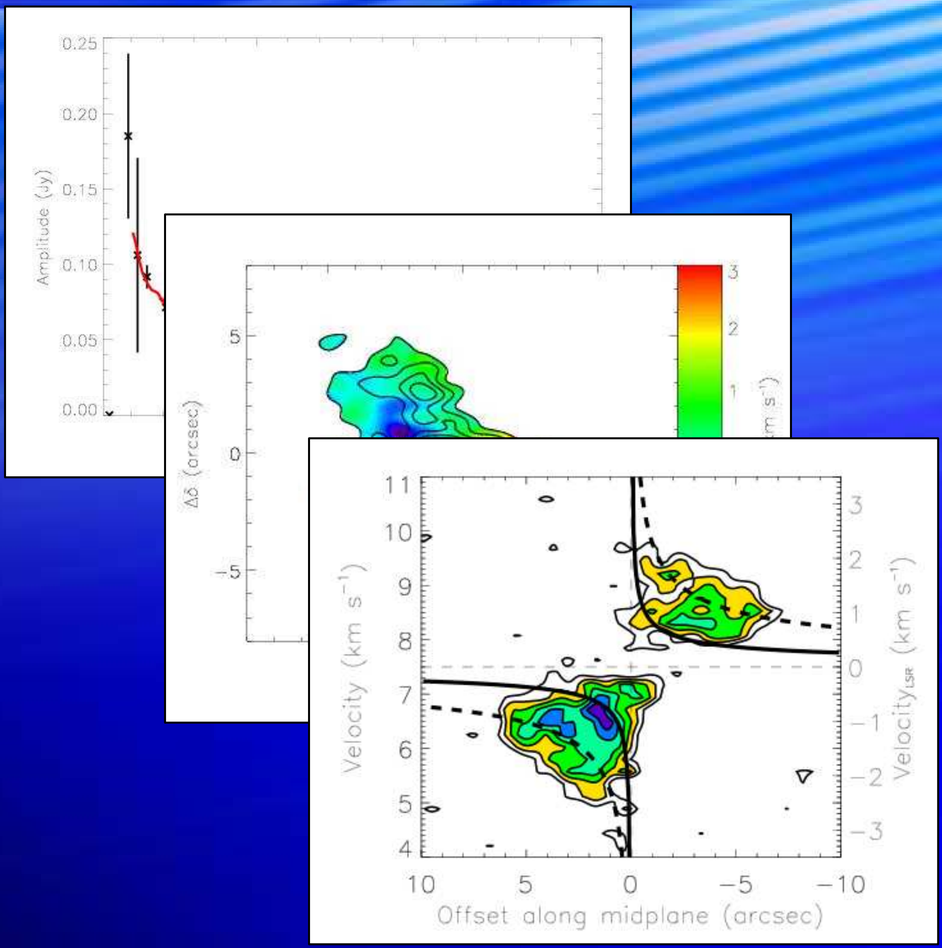
- Class I YSO (3.7 $L_\odot$; T_{bol} = 240 K) in Taurus.
- Large scale infalling and rotating envelope constrained by single-dish observations and 2D radiative transfer *(Brinch et al. 2007).*
- Mapped in HCO$^+$ J = 3-2 and continuum at subarcsecond resolution with the SMA.
- Central disk added to envelope model and modeled self-consistently *(Brinch et al., submitted).*



HST image of L1489 (Padgett et al. 1999) with SMA HCO+ 3-2 emission (contours; Brinch et al. submitted).

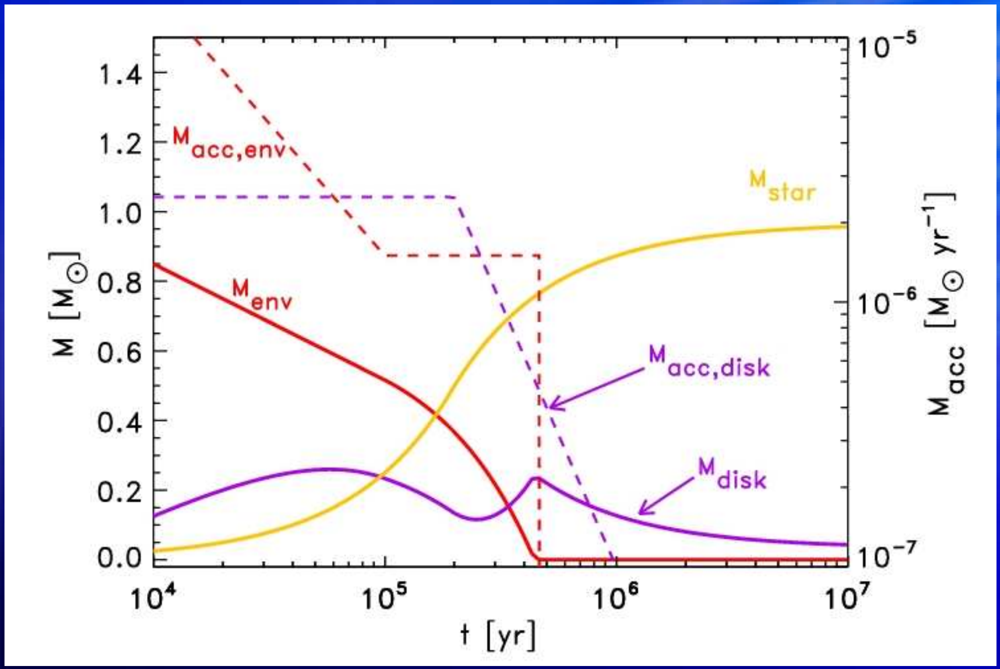
Example: L1489-IRS

- Continuum reveal central disk source - and test envelope structure on small scales.
- HCO^+ 3-2 reveal velocity field including infall + rotation in central Keplerian disk.
- Best fit L1489 IRS model:
  M_{env} = 9e-2 $M_{\odot}$
  M_{disk} = 4e-3 $M_{\odot}$
  M_{star} = 1.4 $M_{\odot}$
- Similar observations for an additional 8 Class I objects in progress...



Brinch et al., A&A, submitted

A legacy for ALMA...?



Systematic survey of *large* sample of embedded YSOs in differing regions, evolutionary stages, etc. could constrain theoretical models for protostellar evolution.

Toy-model[1] for the evolution of 1 $M_\odot$ core inspired by the work of Hueso & Guillot (2005) with simple parameterizations of envelope and disk accretion rates.

[1] any resemblance to actual YSOs is purely coincidental.

Where do we (need to) go next?

Interferometric Studies:

- Dynamics of protostellar envelopes/outflows, envelope dissipation
- Chemistry (radial variations in abundances, shocks)
- More evolved YSOs (direct evidence for Keplerian rotation in disks)

Large-scale mapping suveys:

- Comparison across clouds/cloud samples; relation to environment
- Gould Belt surveys (Spitzer, JCMT, Herschel)

Underlying physics, tools:

- We need to understand dust (better) to relate the emission across wavelengths.
- Also issues for identification of lines, molecular data etc.

Conclusions

- Large scale submillimeter and mid-infrared surveys are building large sample of embedded protostars and characterizing their distribution and physical properties from hundred AU to parsec scales.
- Deeply embedded protostars posses circumstellar disks with significant masses (~0.1 $M_{\odot}$) and sizes (~100 AU). The physical structure of the inner envelope reflects the formation of these disks.
- 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. Still, there are things that we need to understand better - e.g., the properties of dust.