How to identify the youngest protostars

Dimitris Stamatellos
School of Physics & Astronomy
Cardiff University

Starless/Prestellar Cores

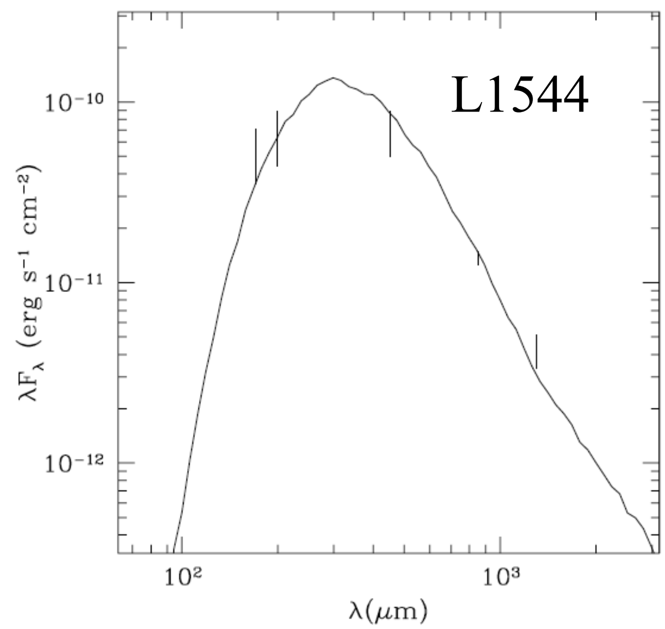
Presence of a central luminosity source:
-Compact cm radio source
-Bipolar molecular outflow
-Internal heating

Class 0

-Centrally peaked but extended submm continuum emission
-High ratio of submm to bolometric Luminosity (>0.05%)

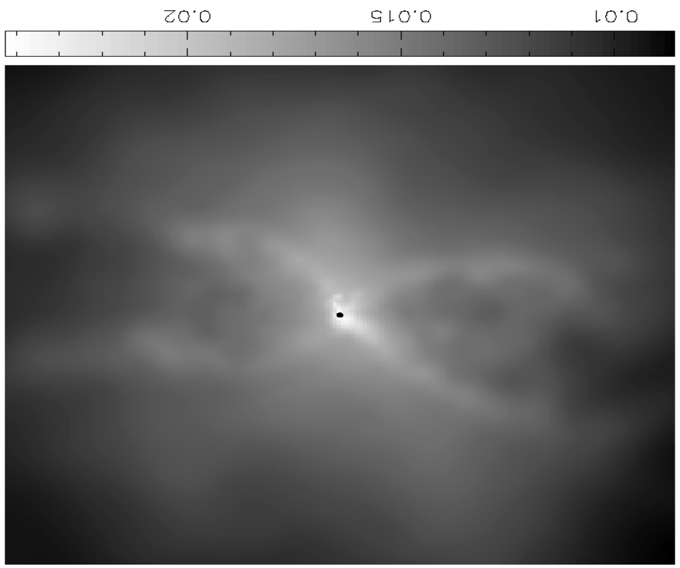
Class I

- Typical extents: 2000 AU to > 15000 AU
- Typical masses: 0.05 -10 $M_\odot$
- Typical temperatures: 7-20 K
- Density profiles: Flat in the centre; fall off as r^{-n} (n=2-4) in the envelope
- Various shapes



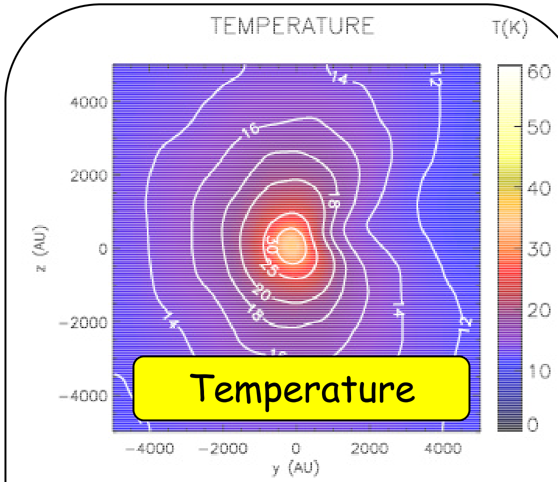
SPH simulations of the collapse of a turbulent molecular cloud

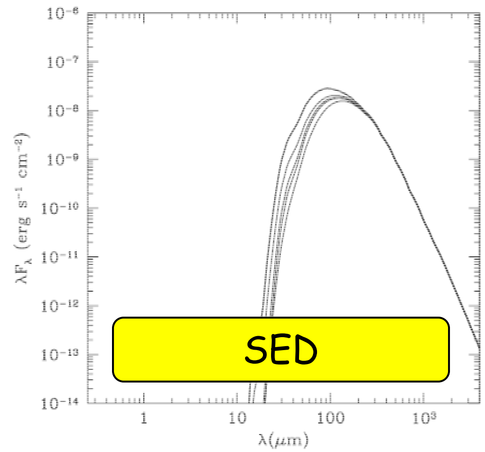
-SPH code DRAGON -
(Goodwin et al. 2004,2005)

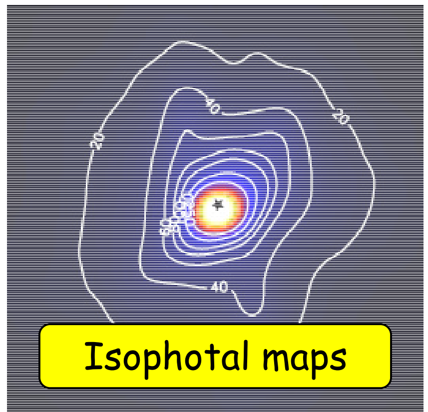


Column density profile

3D Monte Carlo continuum
radiative transfer code
PHAETHON
(Stamatellos & Whitworth 2003)





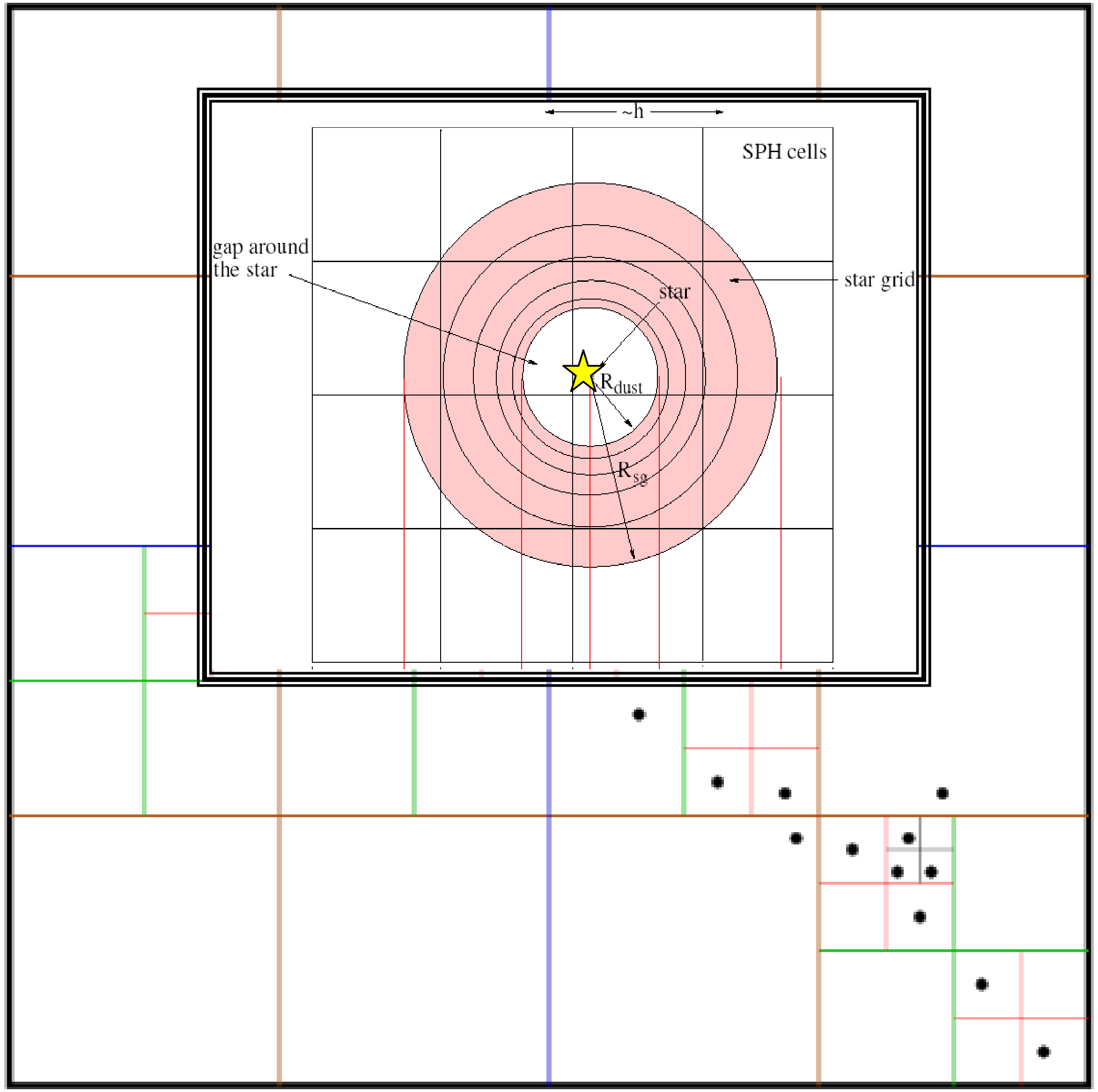


Monte Carlo radiative transfer in SPH

Smoothed particle hydrodynamics (SPH) (Lucy 1977)

- Uses a large number of particles to represent the fluid
- Physical quantities are known at the particles and can be calculated at every point in the fluid by interpolation.
- Particles interact with each other with gravity and hydrodynamic forces (pressure, viscosity)
- An octal *tree* (Barnes & Hut 1986) is used to calculate gravity forces and find neighbours

Construction of radiative transfer cells using the SPH tree



Stamatellos & Whitworth, A&A, in press

Turbulent cloud initial conditions

$$\rho = \frac{\rho_c}{(1 + (r/R_0)^2)^2}$$

Plummer 1915, MNRAS, 76, 107

$\rho_c = 3 \times 10^{-18}$ g cm^{-3}

$R_0 = 5000$ AU

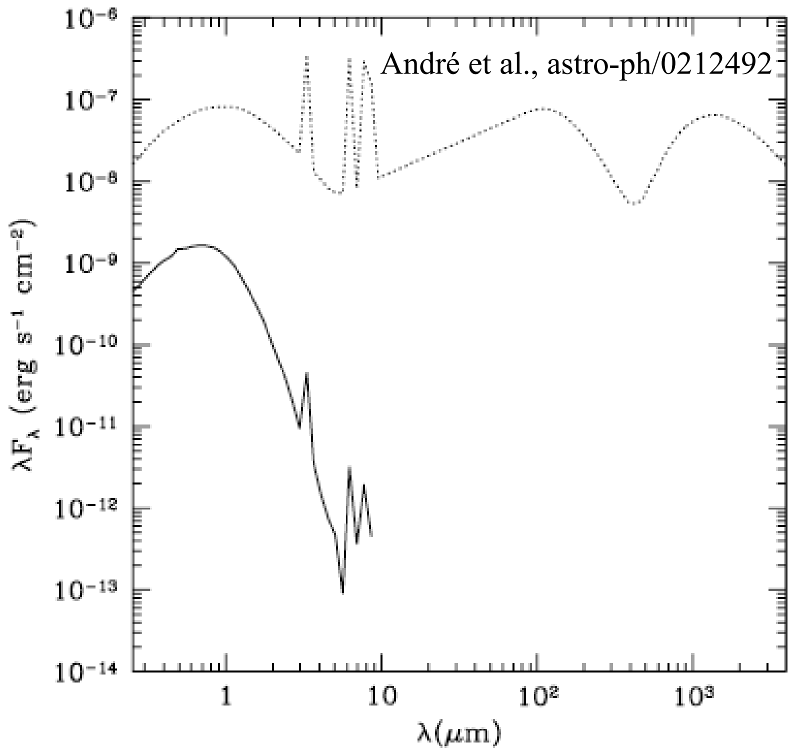
size 5×10^4 AU

mass 5.4 $M_\odot$

Interstellar radiation field

Young protostar

Luminosity sources



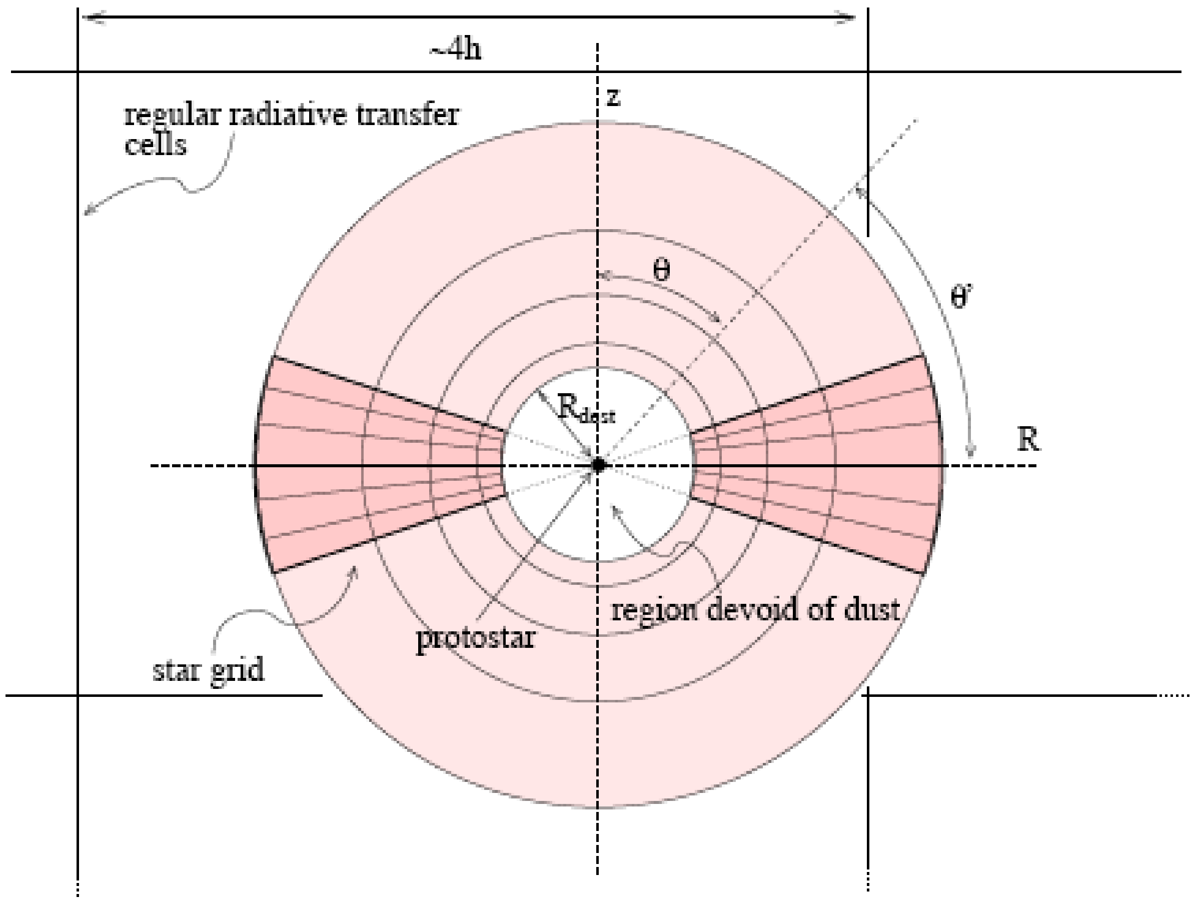
$$L_\star = \left(\frac{M}{M_\odot}\right)^3 L_\odot$$

$$L_{acc} = G\frac{M_\star\,(dM_\star/dt)}{R_\star}$$

The region around the protostar

$$\rho(z,R) = \rho_0 \left(\frac{R_0}{R}\right)^2 e^{-\frac{1}{2}\left(\frac{z}{H}\right)^2}$$

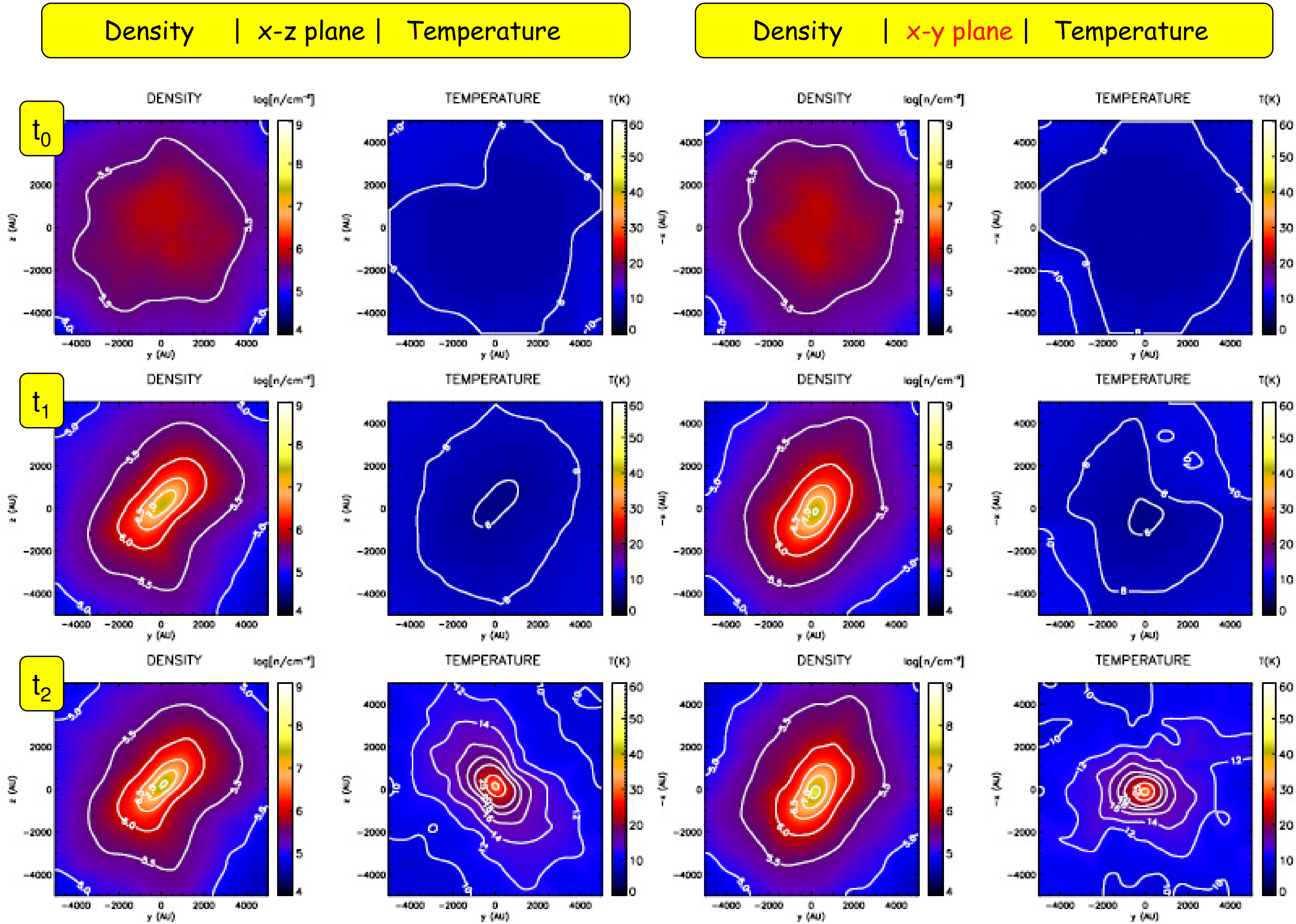
Wood et al. 2004, ApJ 59, 1049
Wood et al. 2004, ApJ, 564, 887

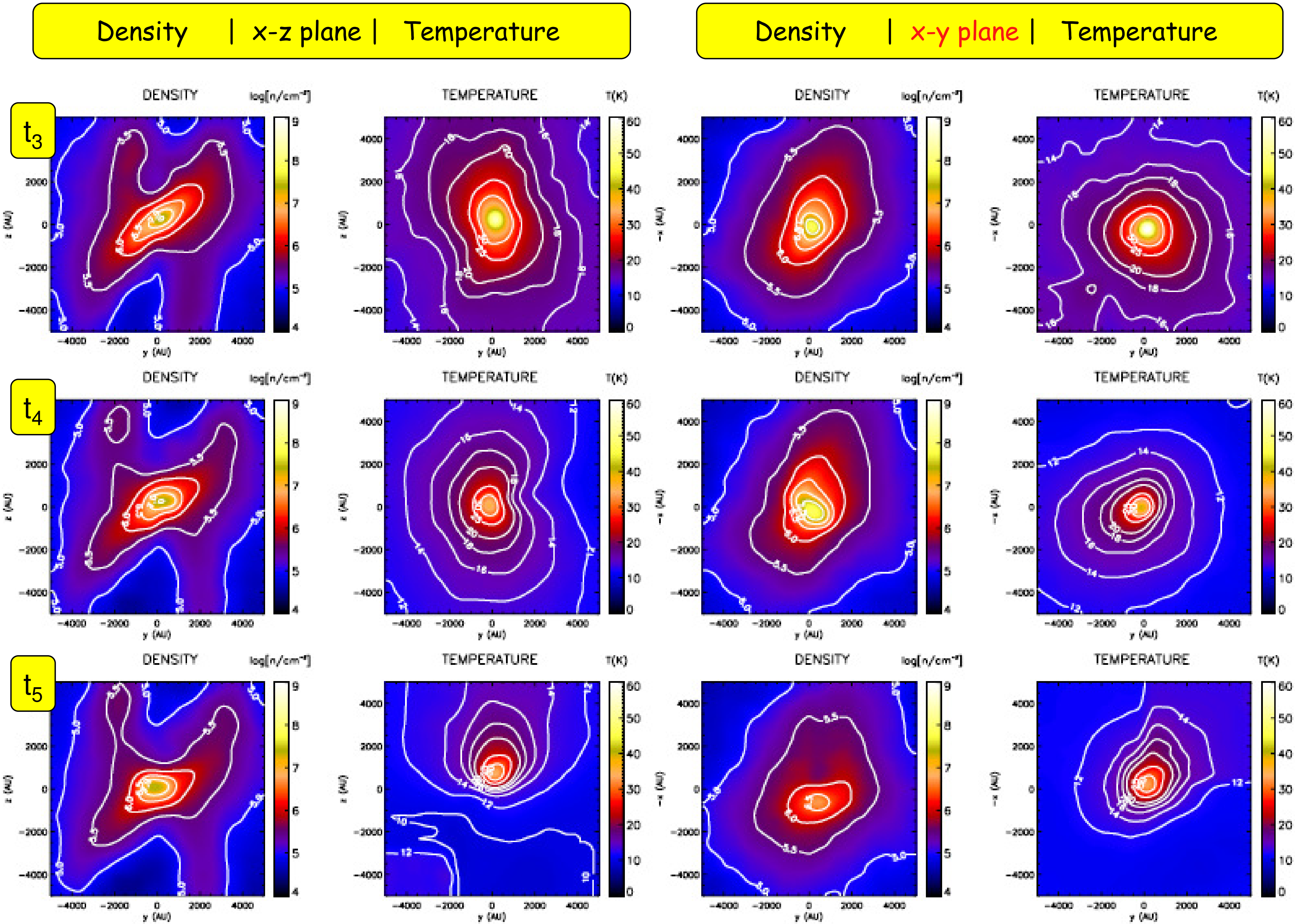


Time-frames during the collapse of the molecular cloud

id	time (yr)	$M_\star (M_\odot)$	R_S (AU)	Z_S (AU)	$M_S (M_\odot)$	$\dot{M}_\star (M_\odot/yr)$	$L_{TOT} (L_\odot)$	$T_\star$ (K)
t0	0	-	-	-	-	-	-	-
t1	5.3×10^4	-	-	-	-	-	-	-
t2	5.3×10^4	0.01	4.0	3.4	0.04	5×10^{-5}	5.7	5150
t3	6.0×10^4	0.20	4.0	0.4	0.09	1×10^{-5}	27.2	7650
t4	6.8×10^4	0.49	4.0	0.4	0.05	2×10^{-6}	12.3	6250
t5	6.9×10^4	0.53	4.0	0.4	0.01	4×10^{-7}	2.5	4200

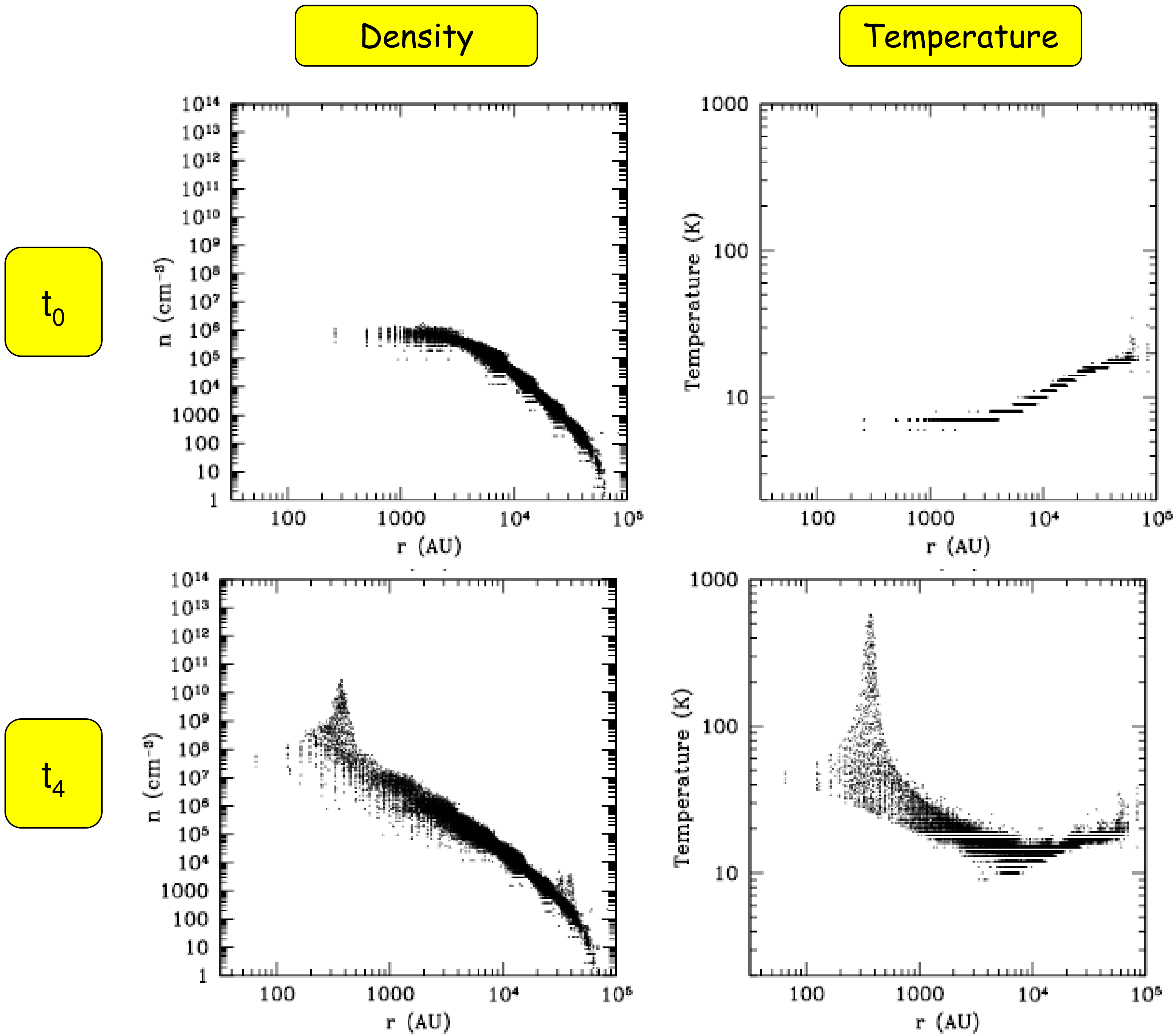
Stamatellos et al., A&A, in press


Density | x-z plane | Temperature
Density | x-y plane | Temperature
t_0
t_1
t_2
DENSITY
TEMPERATURE
log[n/cm⁻³]
T(K)
y (AU)
z (AU)
−x (AU)

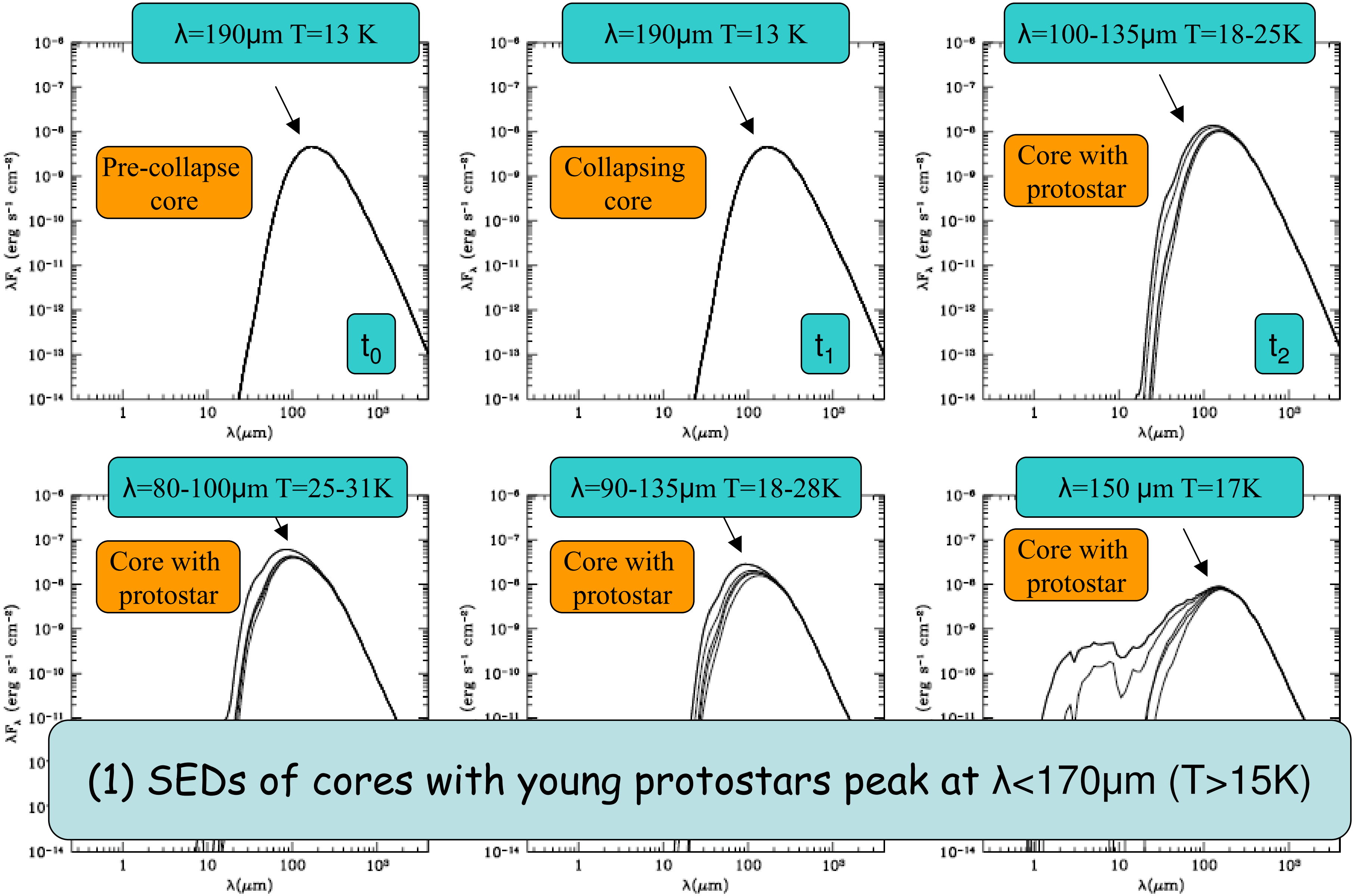


Density | x-z plane | Temperature
Density | x-y plane | Temperature
t3
t4
t5
DENSITY
TEMPERATURE
log[n/cm^-3]
T(K)
y (AU)
z (AU)
-x (AU)

Stamatellos et al., A&A, in press



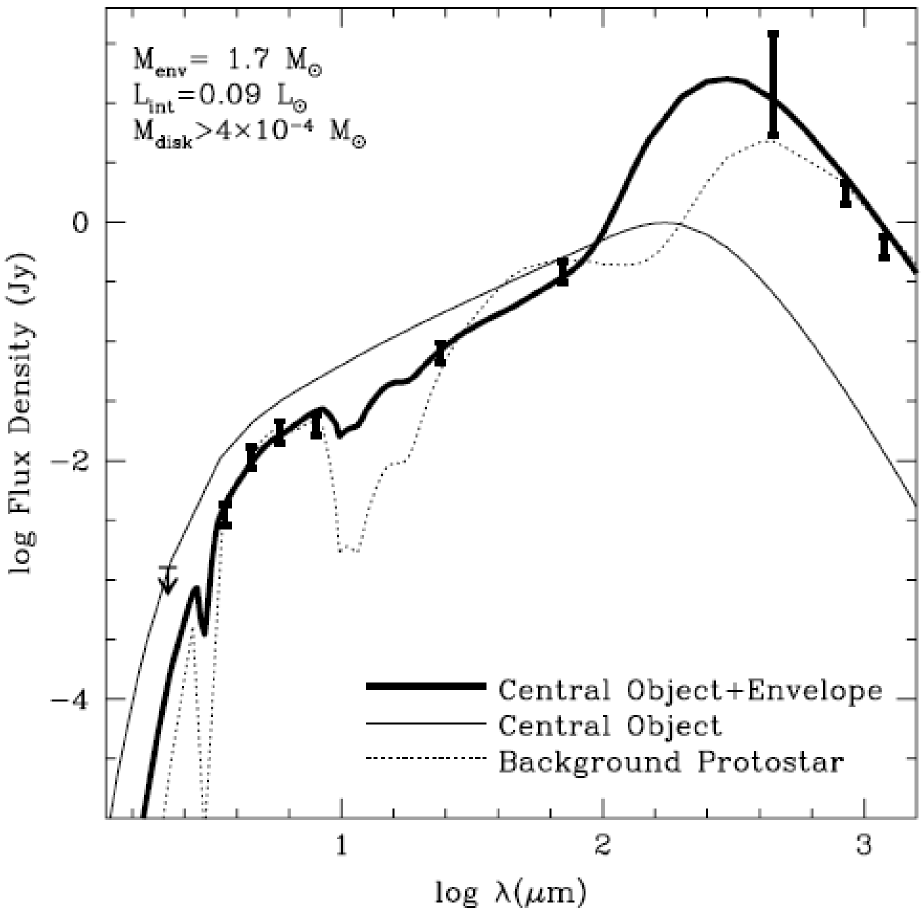
Spectral Energy Distributions (SEDs)

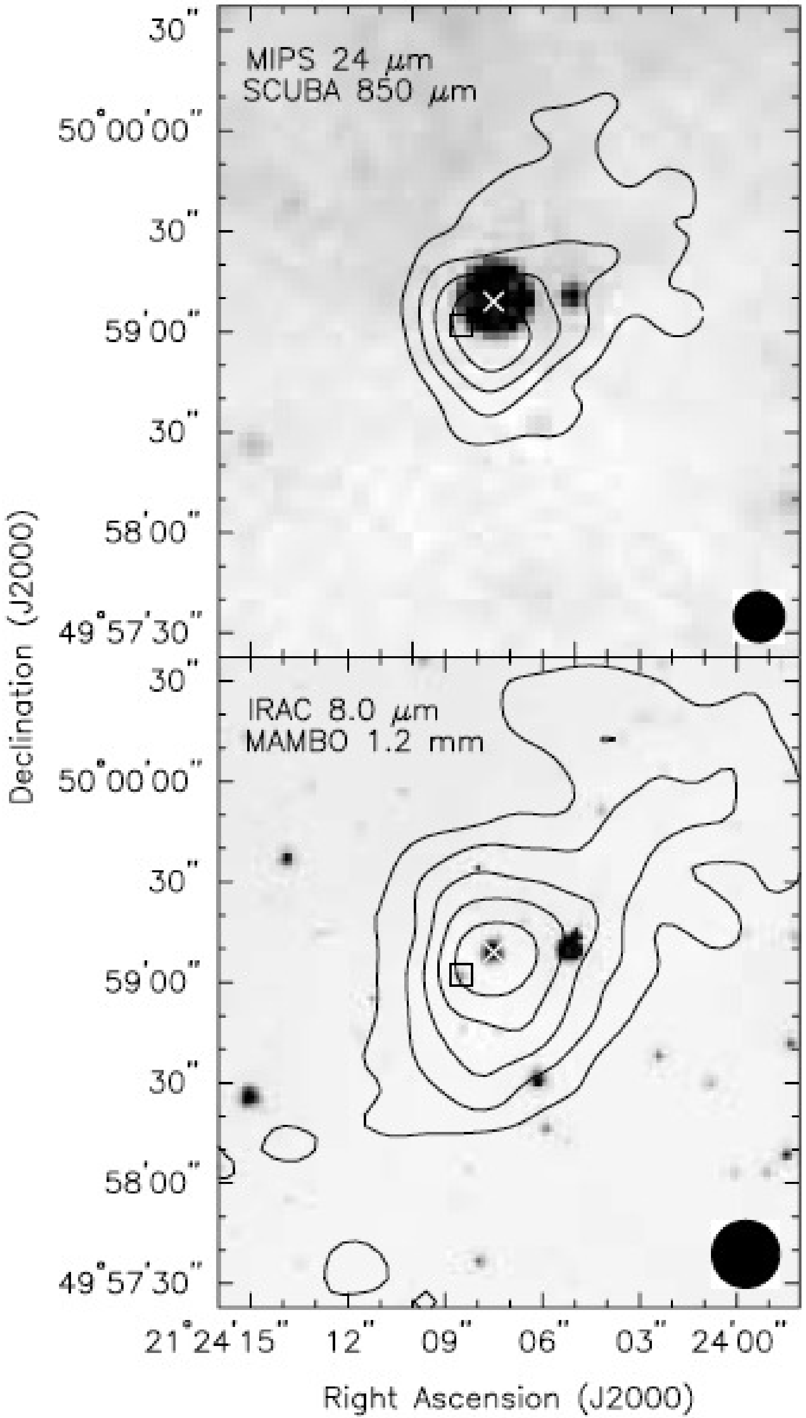


(1) SEDs of cores with young protostars peak at λ<170μm (T>15K)

L1014

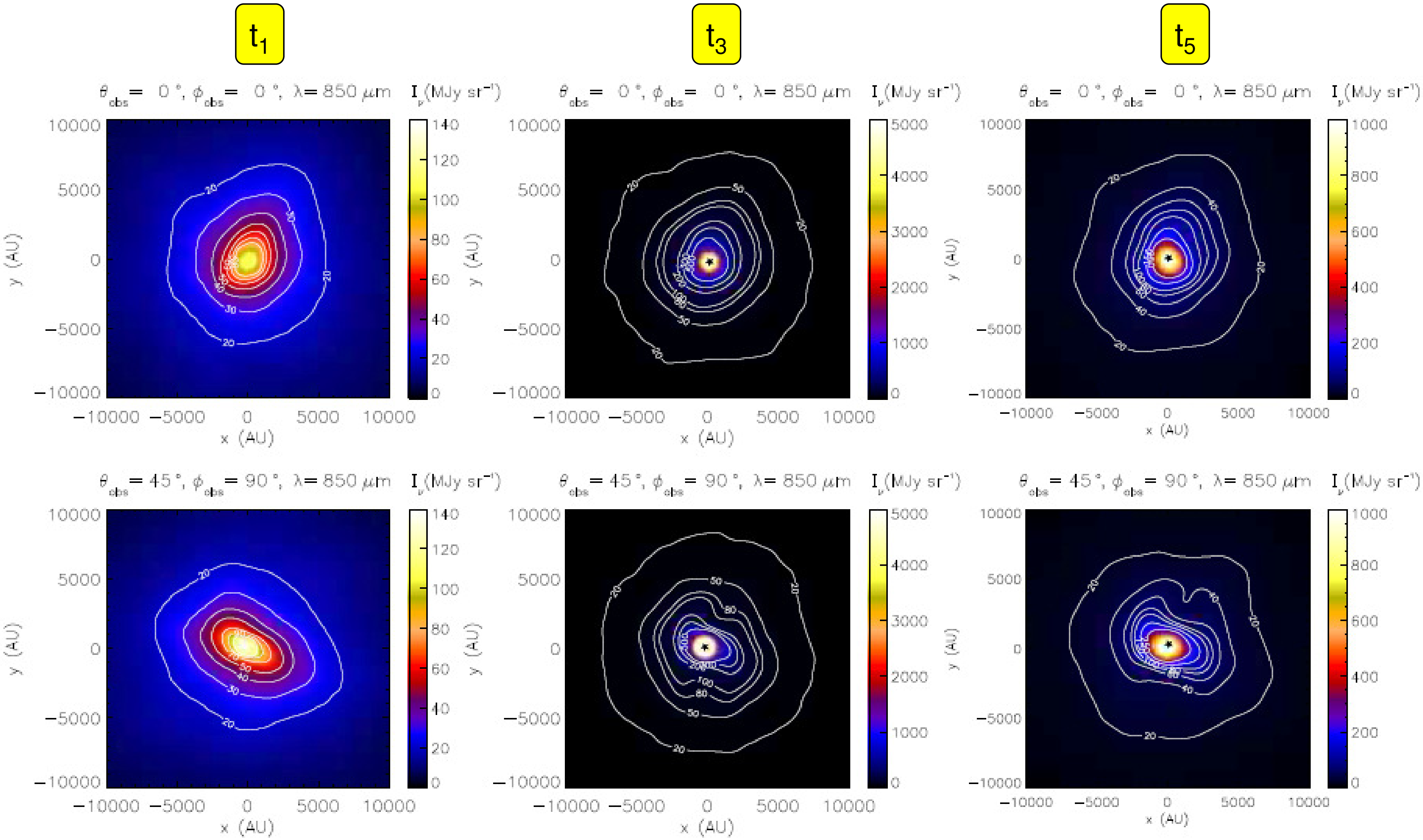
- Young protostar ?
- Protostar off center ?
- Ejected brown dwarf ?





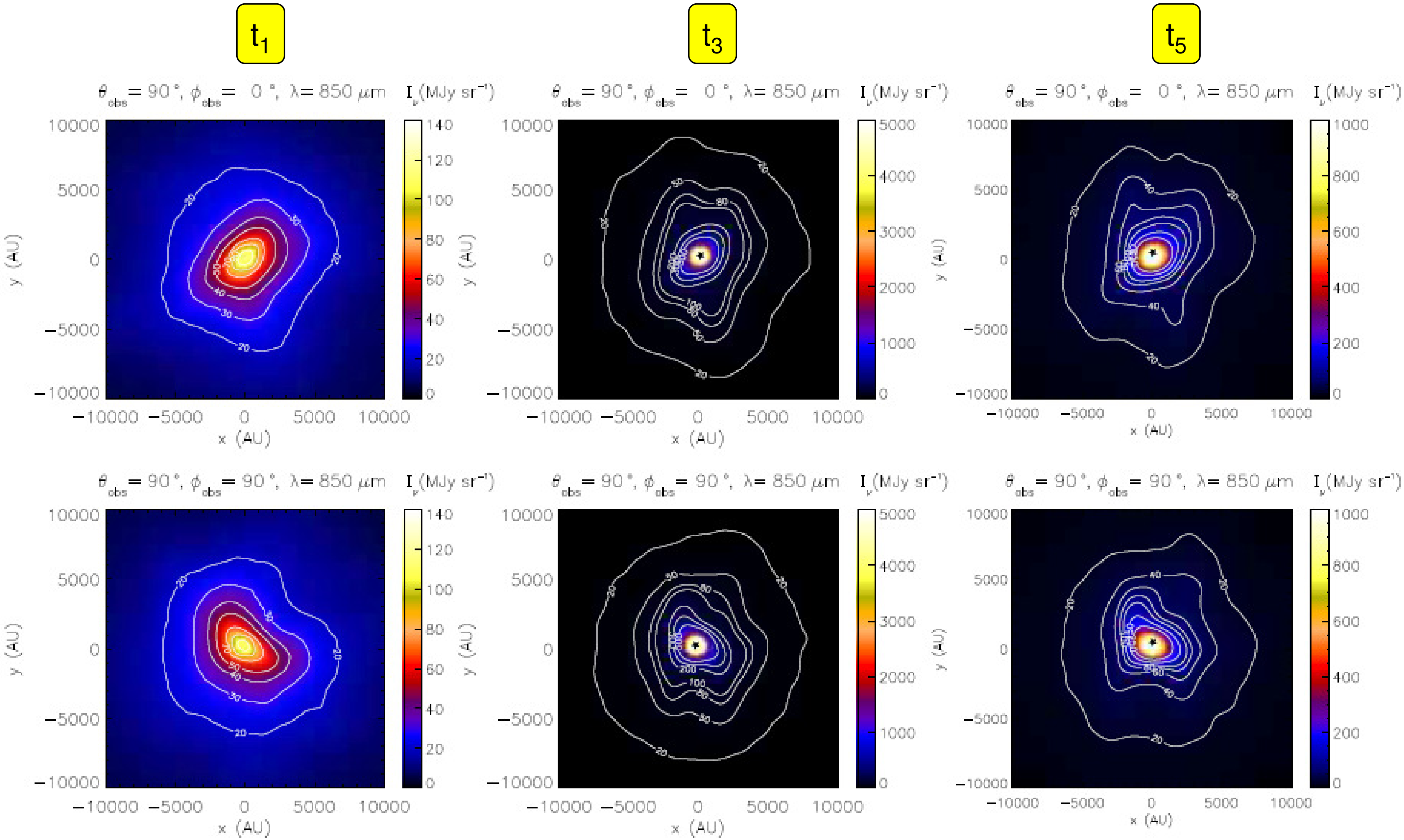
Young et al., 2004, ApJS, 154, 396

850 micron maps (different viewing angles)



Stamatellos et al., A&A, in press

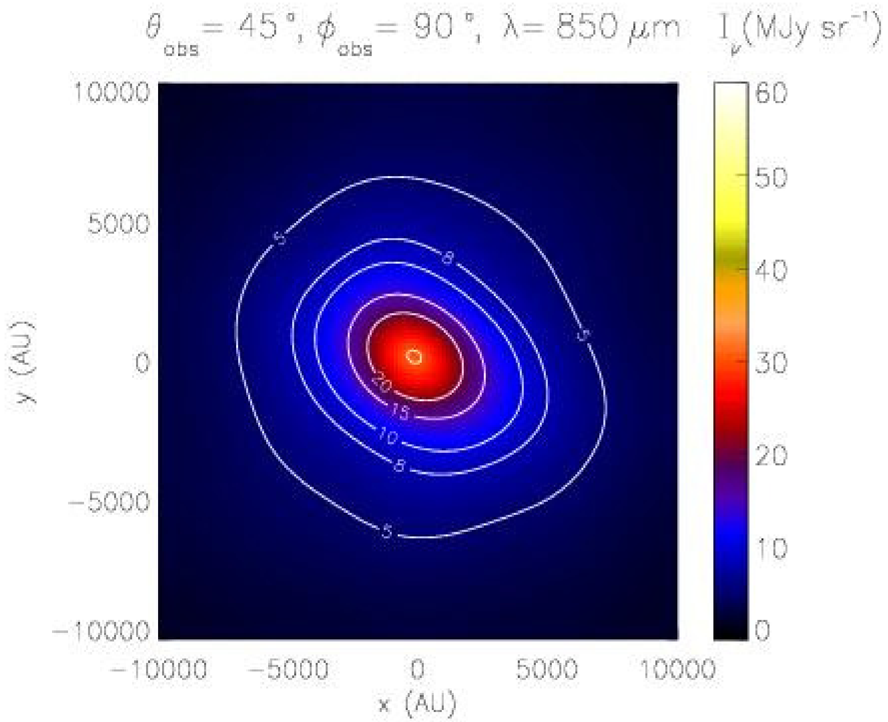
850 micron maps (different viewing angles)



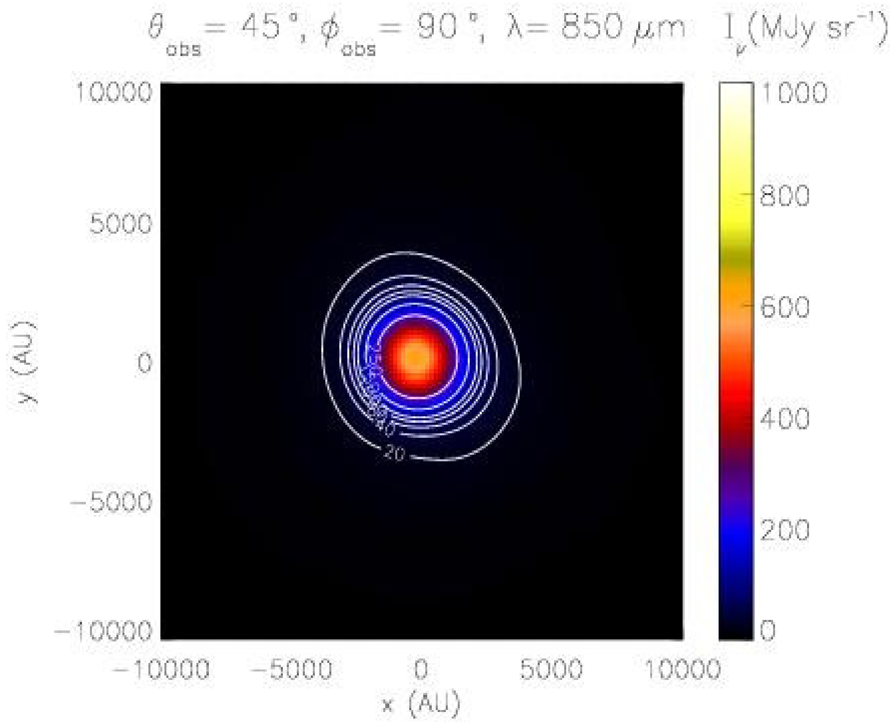
Stamatellos et al., A&A, in press

Shapes of prestellar cores and protostars

prestellar core



Core with young protostar



(2) Cores with protostars appear more circular than prestellar cores

Goodwin et al., MNRAS, 423, 169

Conclusions

➔Cores about to form a star are colder than pre-collapse cores

➔As the protostellar system evolves the peak of the SED initially moves to shorter wavelengths but then back to longer wavelengths

➔The peak of the SED of a newly formed protostar depends only weakly on viewing angle

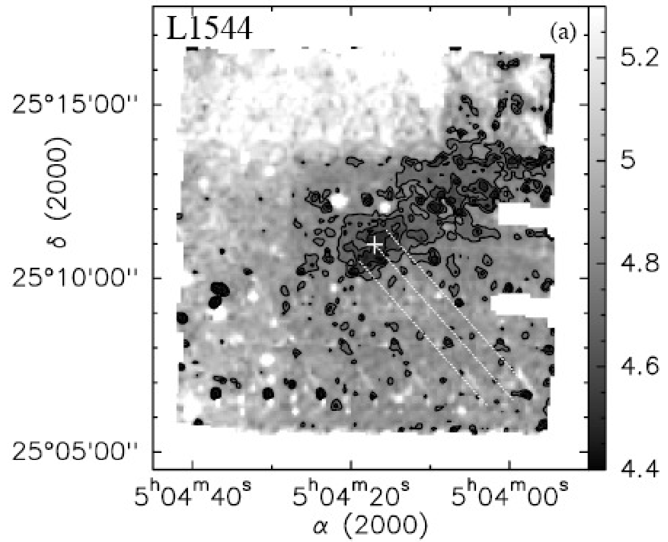
➔A newly formed protostar cannot be observed in the IR because it is too deeply embedded

➔**Criteria for identifying cores thay may harbour protostars:**

- SED peaks at wavelengths shorter than ~170 μm, i.e. relatively "hot" cores (T>15K) (for a common ISRF)
- Spherical within $(2\text{-}4)\times10^3$ AU

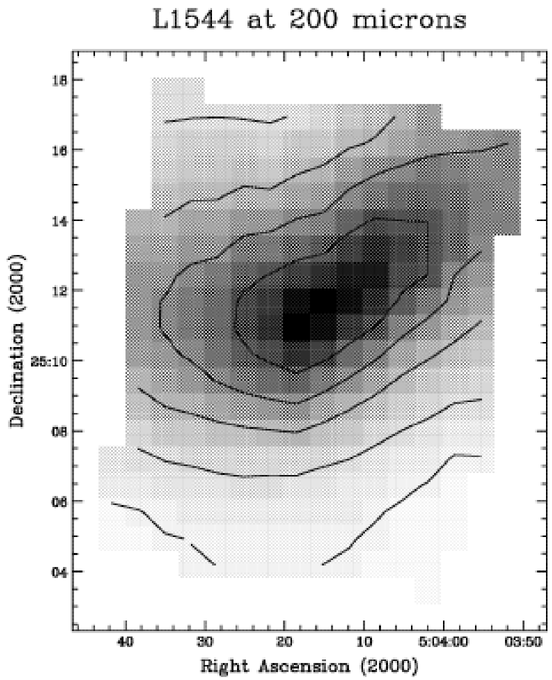
Prestellar core L1544

7 μm (ISOCAM)



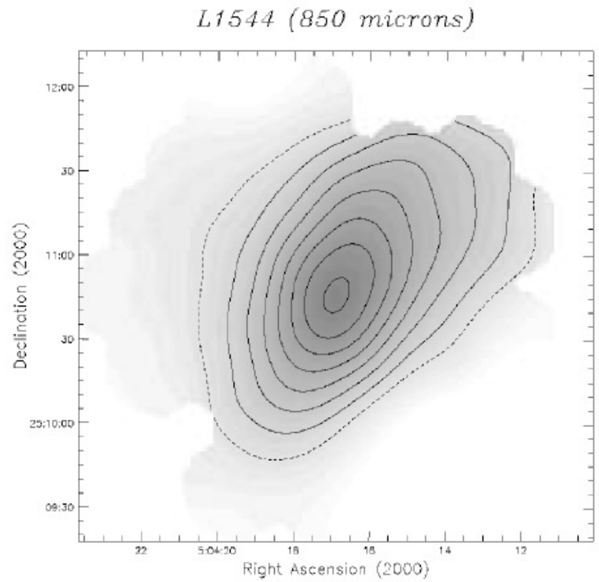
Bacmann et al. 2000

200 μm (ISOPHOT)



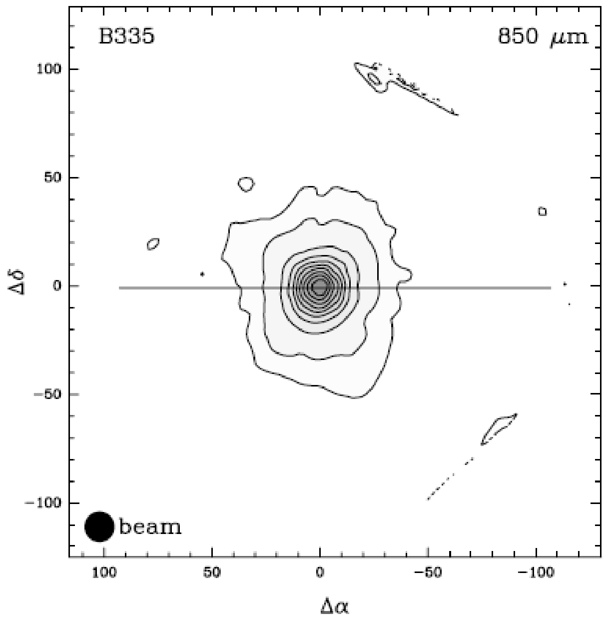
Ward-Thompson et al. 2002

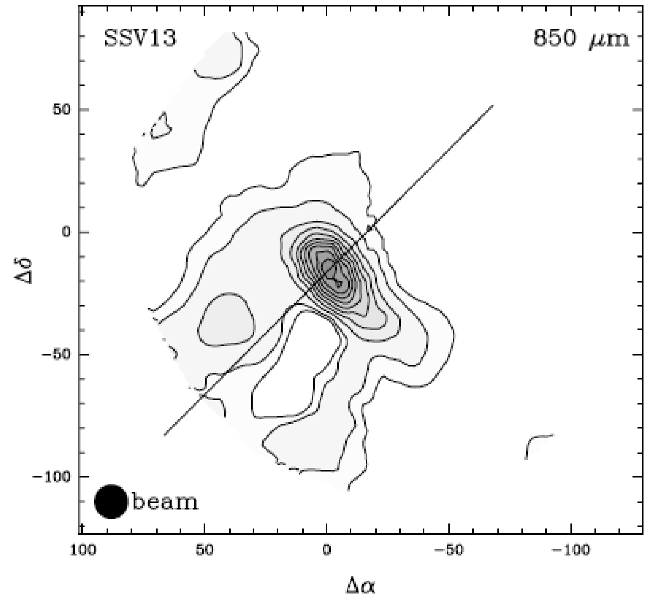
850 μm (SCUBA)



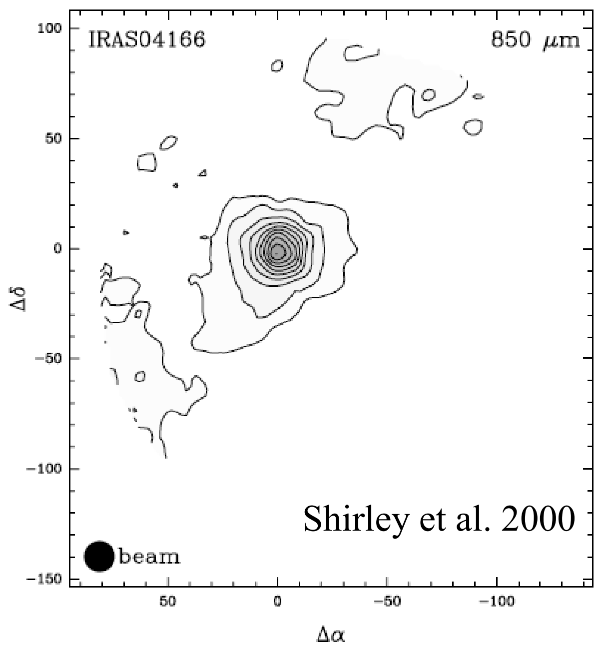
Kirk et al. 2005

Class 0





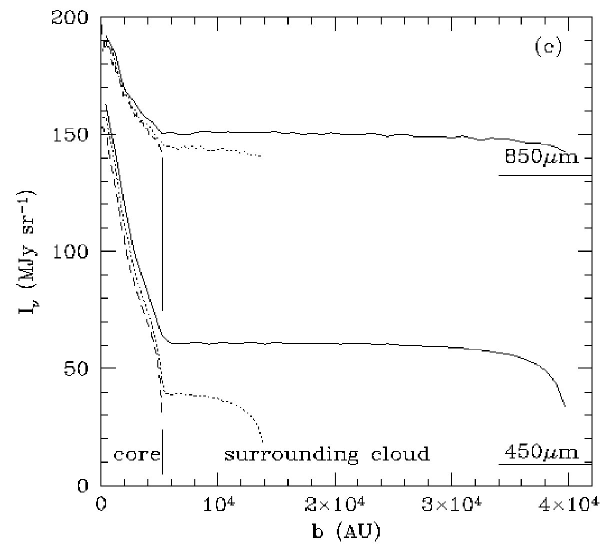
Class I



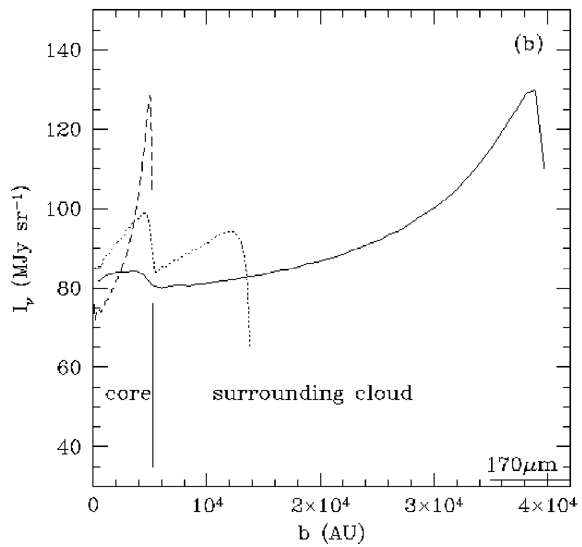
Shirley et al. 2000

Radiative transfer modelling of prestellar cores

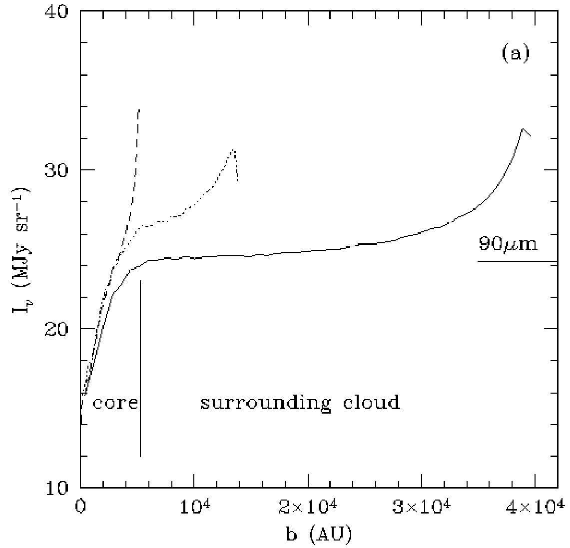
850 μm



170 μm



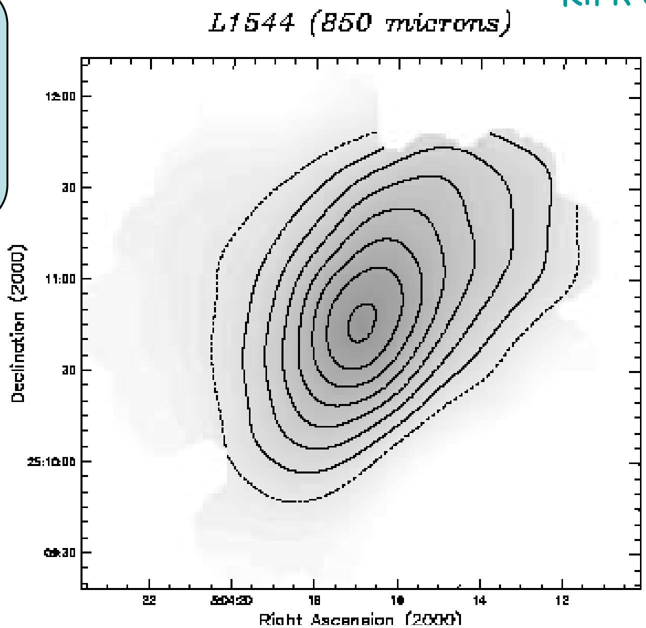
90 μm

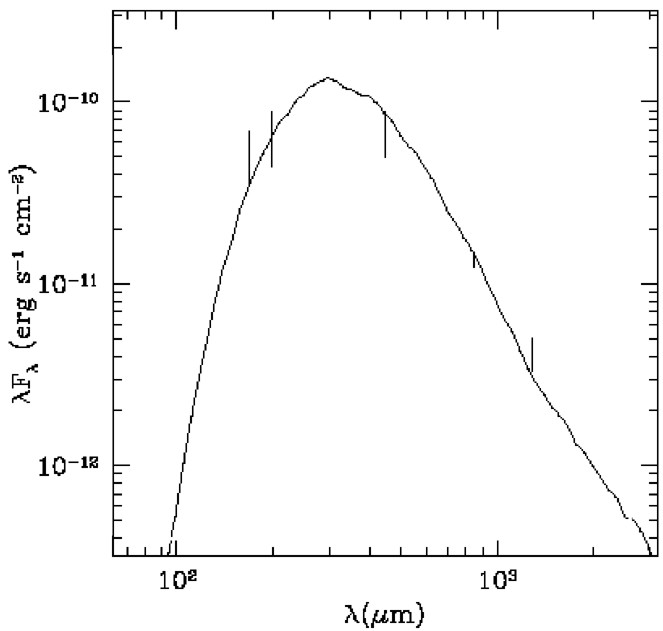


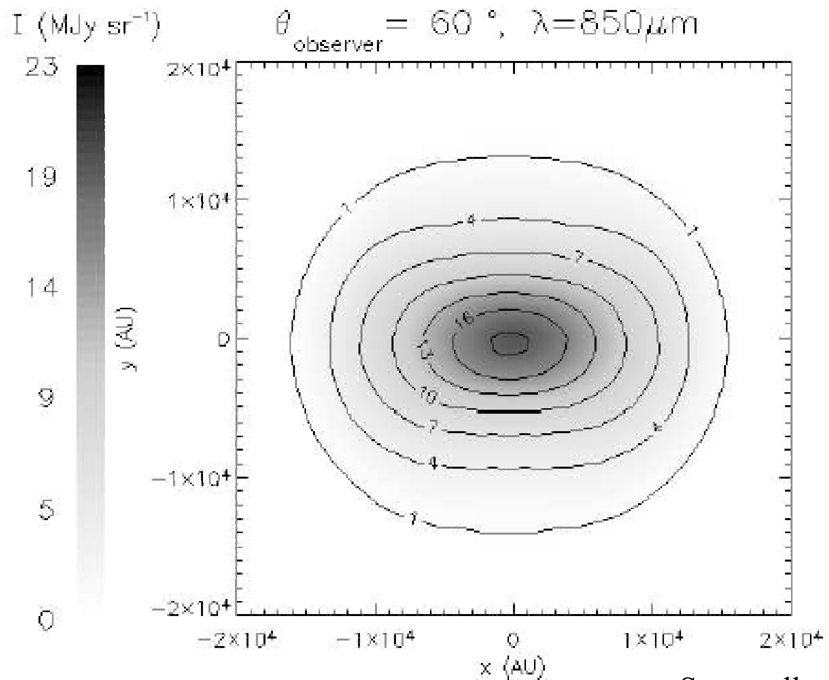
Radiative transfer modelling of prestellar cores

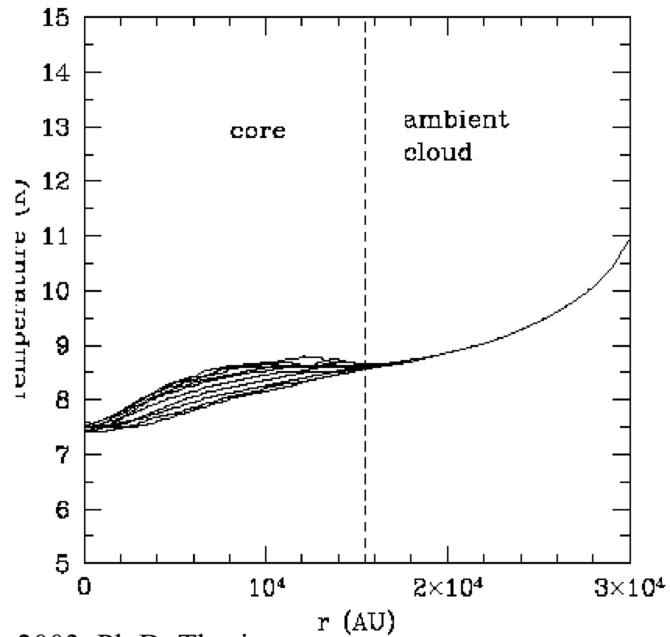
L1544

Kirk et al. 2005









Stamatellos, 2003, Ph.D. Thesis