Tracing high energy radiation with molecular lines by the deeply embedded protostar L1634

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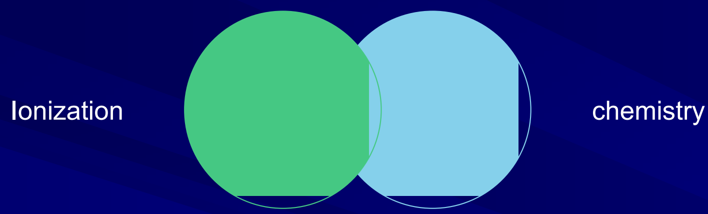
Introduction

Ionization fraction: a key parameter

ISM



	Agents of ionization	Ionization regulates
Difuse clouds	UV radiation field	Rich chemistry
Dense cores	▪Through low energy cosmic rays ▪X-rays	▪Ion-neutral reactions ▪Time scale for SF

Probing the cosmic-ray ionization rate

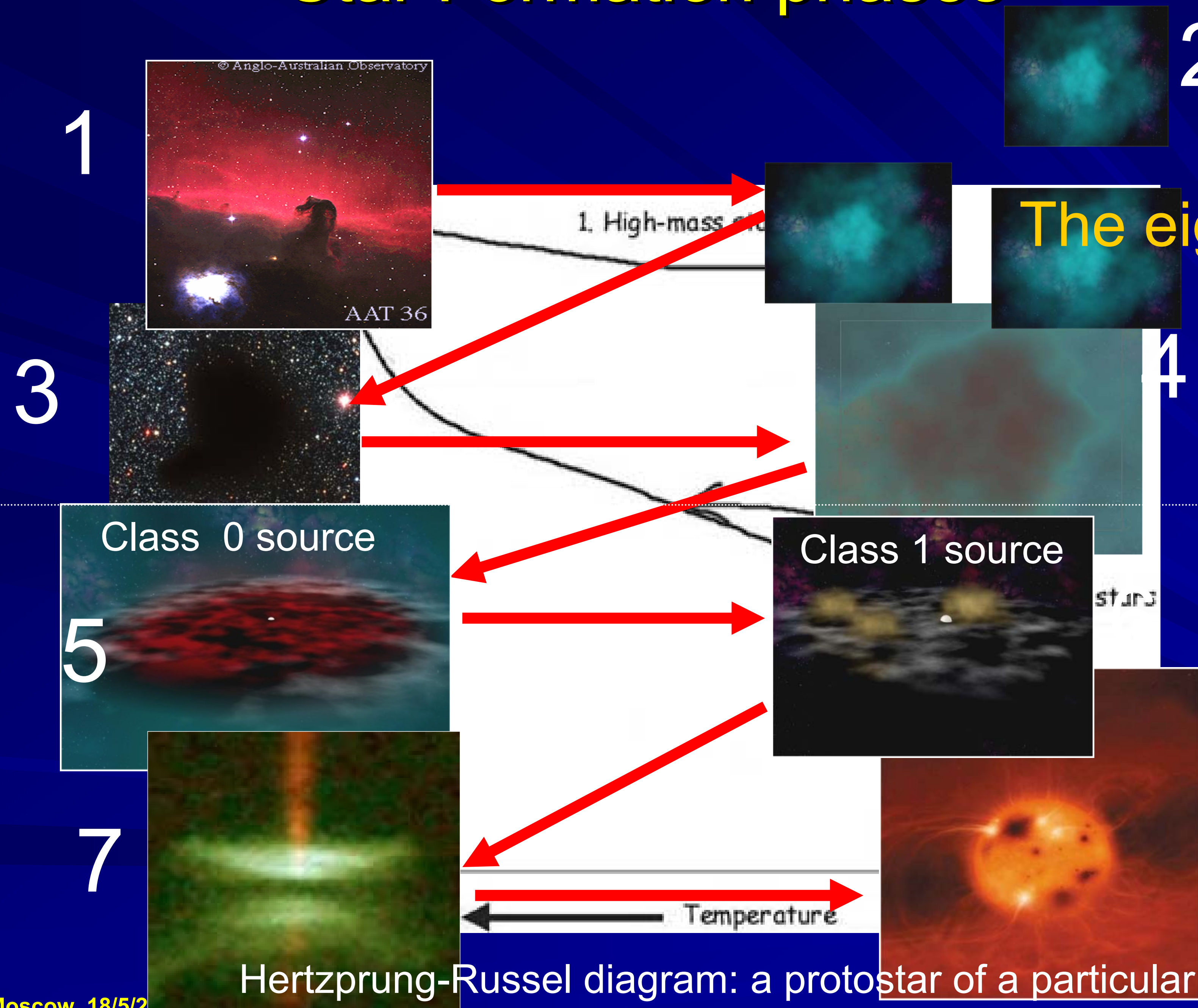
By observations of abundance ratios
By modeling

ζ_{CR} = [10^{-16} -- 10^{-17}] s^{-1} per H atom

ζ_{CR} varies with location in the Galaxy

Molecular studies of SF regions are useful to measure the ionization rate across the Galaxy

Star Formation phases



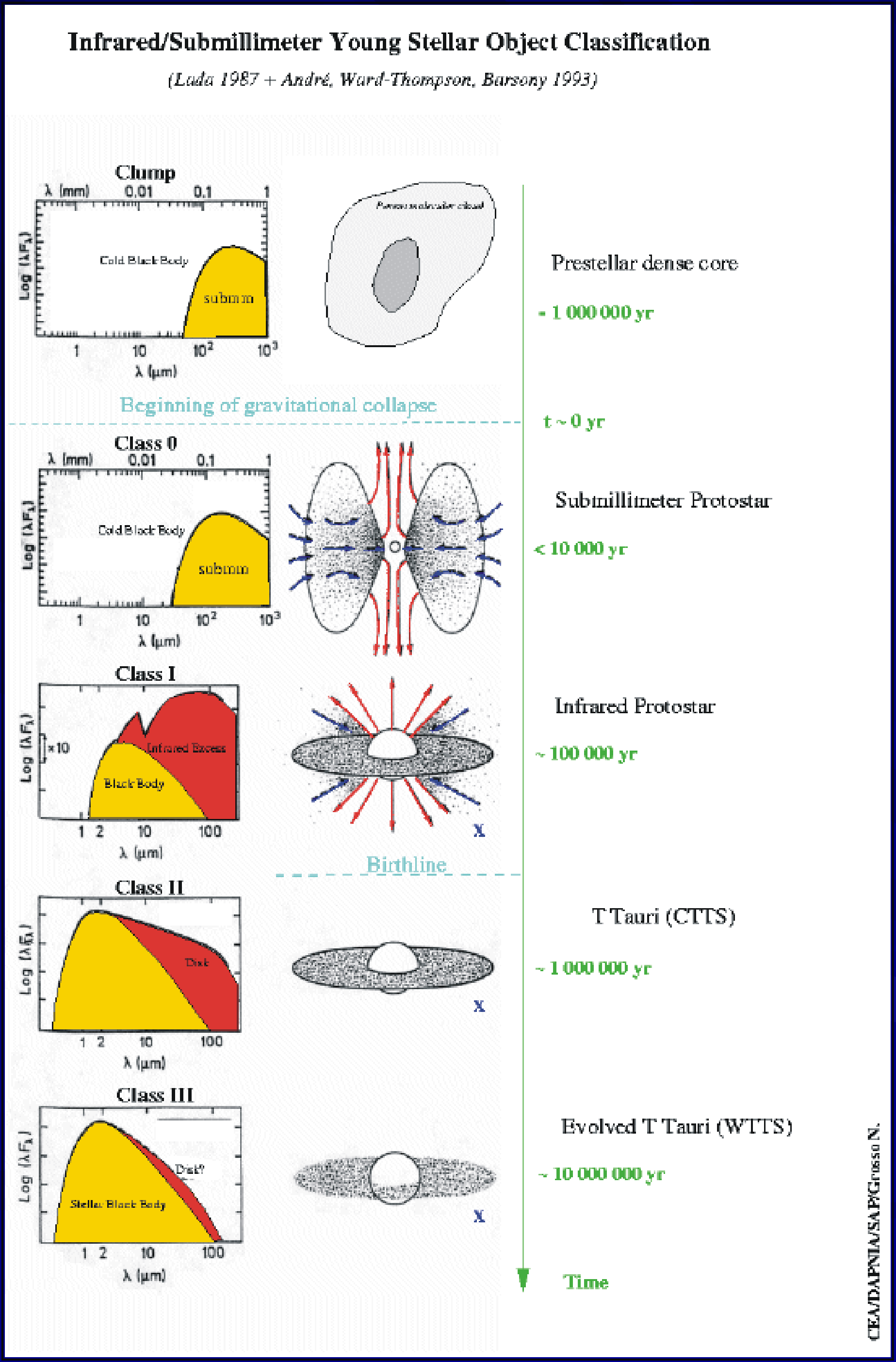
Gravitational collapse

10^7 yr

Hertzprung-Russel diagram: a protostar of a particular mass will follow a path

MS
main sequence

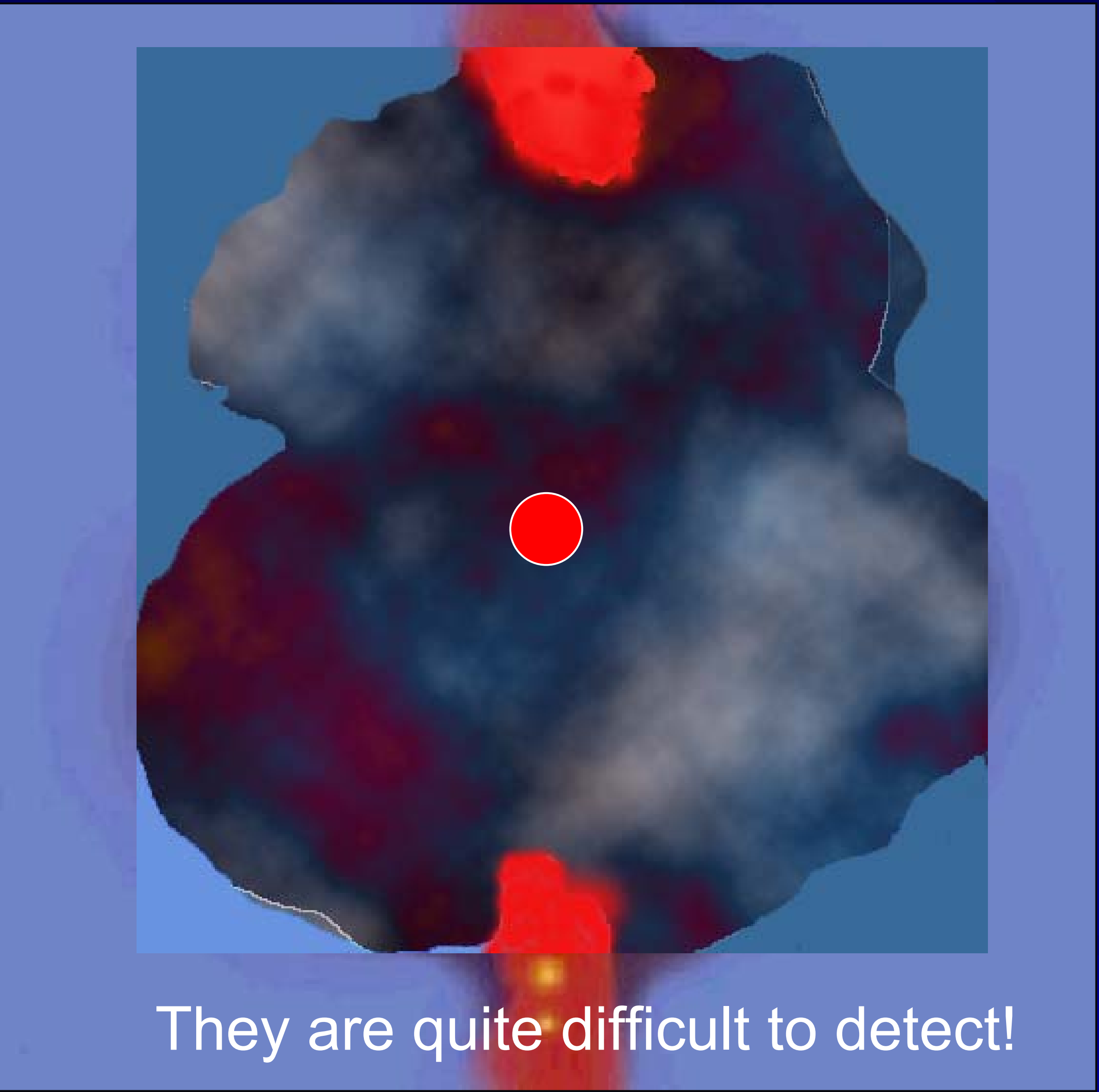
Stages of evolution of a protostar



Moscow, 18/5/2009

André & Montmerle, 1994, ApJ 420, 837

Class 0 Sources



They are quite difficult to detect!

protostar

dusty envelope

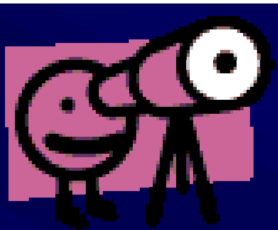
flattened disk

bipolar outflow

André, Ward-Thompson & Barsony, 1993, ApJ 406, 122

- Class 0 sources are highly obscured
- They are extremely rare (because they spend only a short time in their evolutionary phase ~ 10^4 yr)

The observational identification of the earliest evolutionary stage is very difficult!



Methods applied to find Class 0 sources and deeply embedded source candidates

Searching for their powerful molecular outflows (Davis & Eislöffel, 1995, A&A 300, 851)

Large-scale mapping of potentially interesting star formation regions with bolometer arrays (Stanke et al., 2000, A&A 355, 639)

Comparing large-scale, high angular resolution sub-millimeter continuum maps of a star formation region with near-infrared surveys of the same region (Hurt et al., 2001, AAS 198)

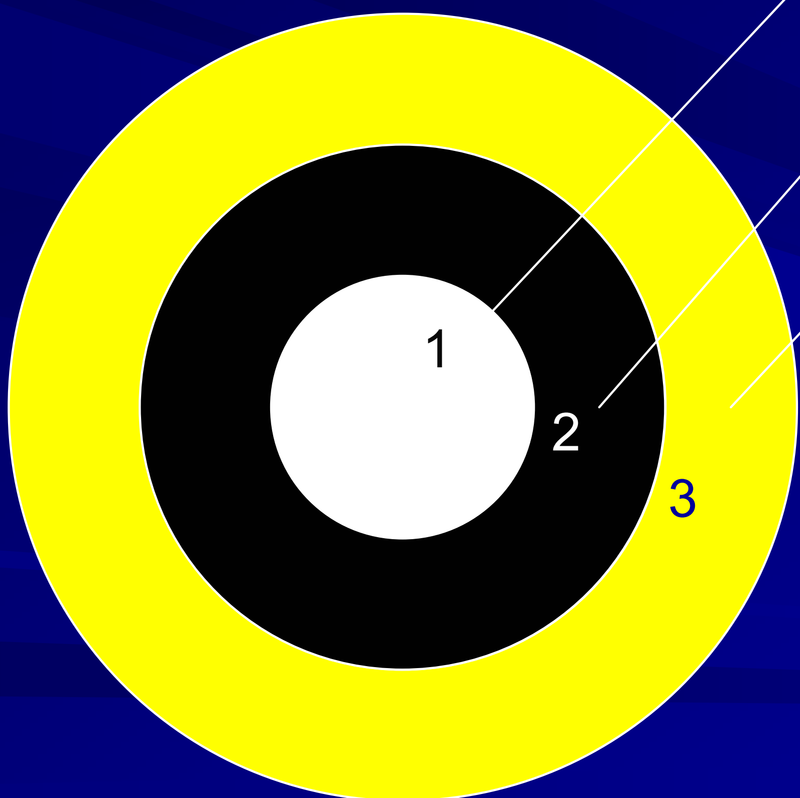
Goal of the Project

To contribute to the understanding of the physical structure (dust density and temperature profiles) and processes in Class 0 sources

- **To examine closely the structure of Class 0 sources**
  - Geometry
  - density and temperature distributions as function of the radius of the envelope

- **To derive physically refined properties of Class 0 sources**
  - Masses
  - Sizes
  - temperatures and luminosities
  - Ages
  - Constraint ζ_{CR}

How?



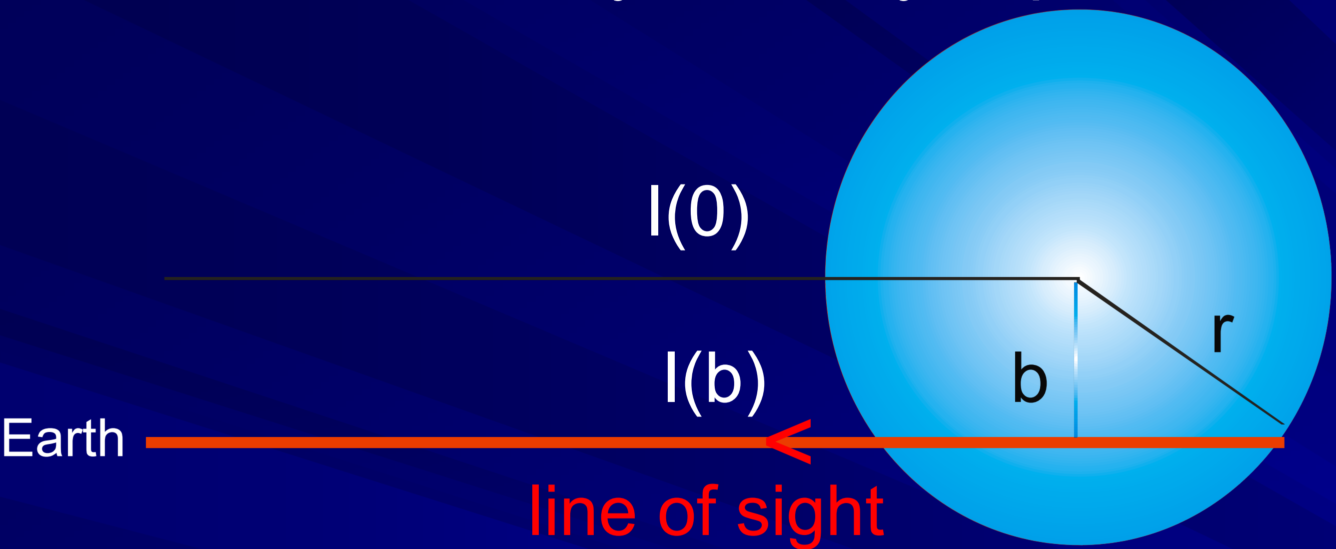
Theory
By using an analytic theory of emission from protostars

Observations
Deriving information of the thermal emission of the dust

Modeling
Applying an envelope model, techiques (Blackbody fitting and Radiative Transfer), and an evolutionary scheme for protostars

I. The Standard Envelope Model:

an analytic theory of protostellar emission



optically thin emission
Rayleigh-Jeans approximation

$$I_\nu(b) = 2\kappa_\nu \int_b^{r_0} B_\nu[T_d(r)]\,\rho(r)\,\frac{r}{\sqrt{r^2-b^2}}\,dr$$

Observed intensity for a spherically symmetric envelope

I_ν observed intensity at a frequency ν
b impact parameter
κ_ν mass opacity
B_ν Planck function as a function of frequency ν
$T_d(r)$ dust temperature distribution
$\rho(r)$ density distribution
r_0 outer radius

Adams, 1991, ApJ 382, 544

Observed intensity for a spherical symmetric envelope

$$I_\nu(b) = 2\kappa_\nu \int_b^{r_0} B_\nu[T_d(r)]\,\rho(r)\,\frac{r}{\sqrt{r^2-b^2}}\,dr$$

if the emission is in the Rayleigh-Jeans limit, and if $r_o >> b$,

$I_\nu \propto b^{-m}$ $\kappa \propto \nu^\beta$ $T_d(r) \propto r^{-q}$ $\rho(r) \propto r^{-p}$

observations   Radiative transfer

$$m = p + q - 1$$

$$q = 2/(4+\beta)$$

The standard envelope model suggests single power-law indices for the density, temperature and dust opacity distributions

Adams, 1991, ApJ 382, 544

II.Thermal emission from the dust

A.- Imaging of Class 0 sources

Instrumentation

-SCUBA camera

-James Clerk Maxwell Telescope (Hawaii)

RESULTS:

6 regions observed at 450 and 850 μm in Orion and Perseus

HH 211	L 1448
L1455	L 1634
NGC 1333	L 1641

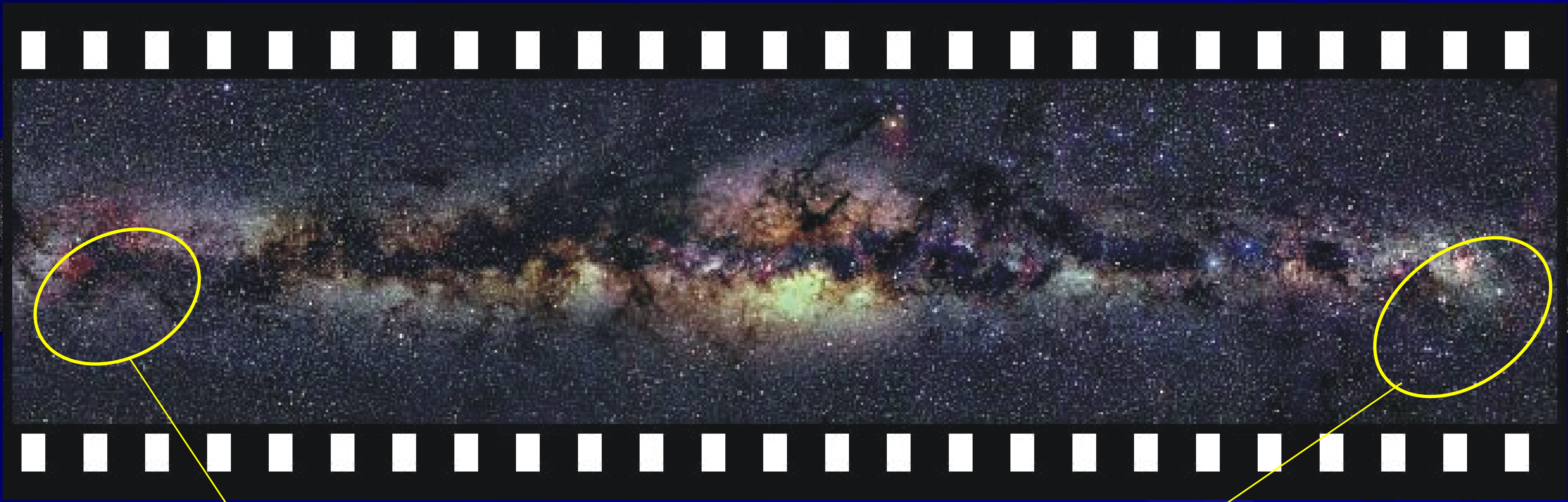
(>3σ) 36 sources found

12 sources detected for the first time

9 Class 0 sources investigated in detail

Rengel M., Eislöffel J., Hodapp K, 2003, ANS 324, 10

360-degree Milky Way Panorama

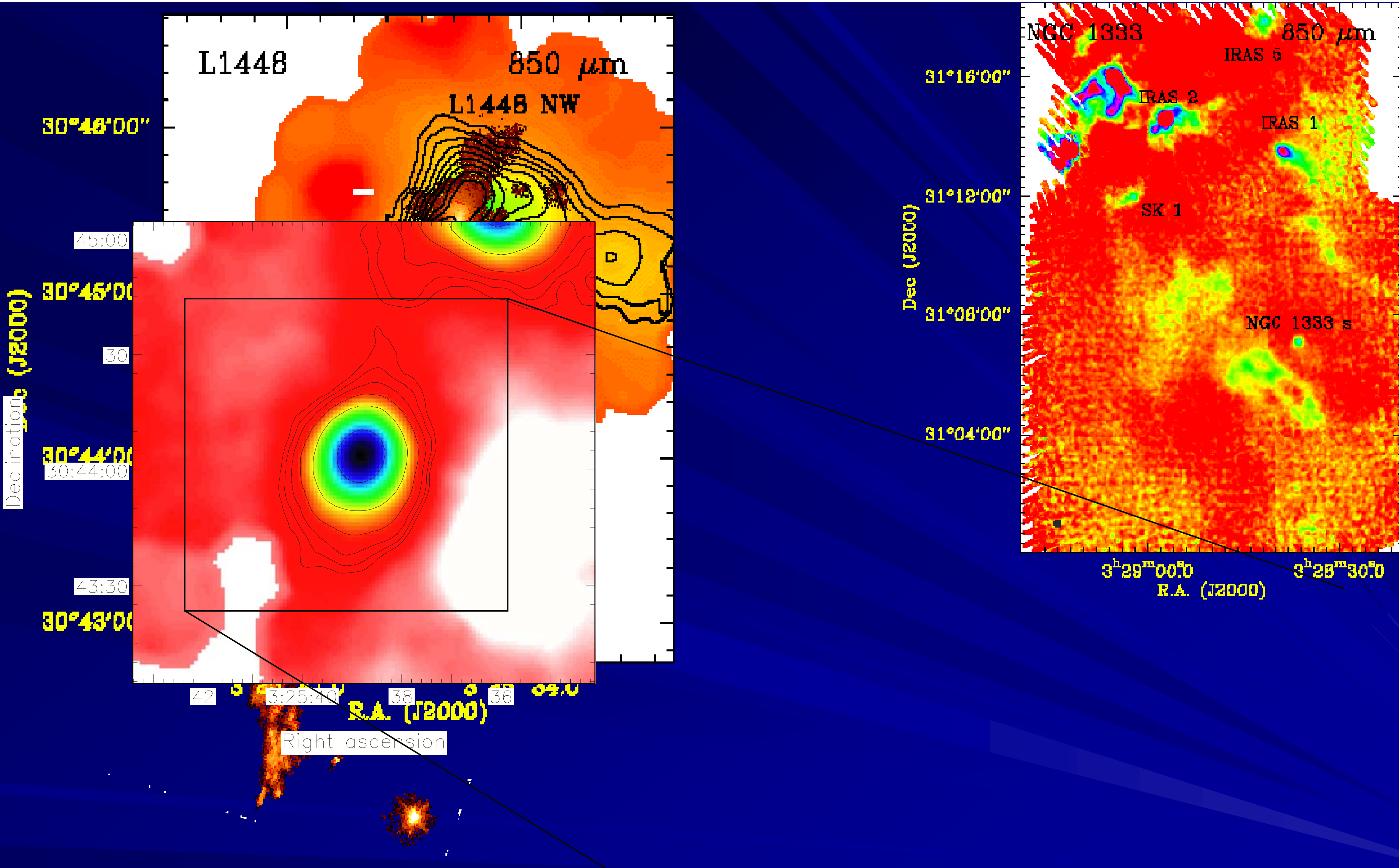


Picture: courtesy of Axel Mellinger

300 pc L1448
350 pc L1455, NGC 1333, HH211

460 pc L1634
390 pc L1641

1 pc = 30.85678 x 10^{15} m

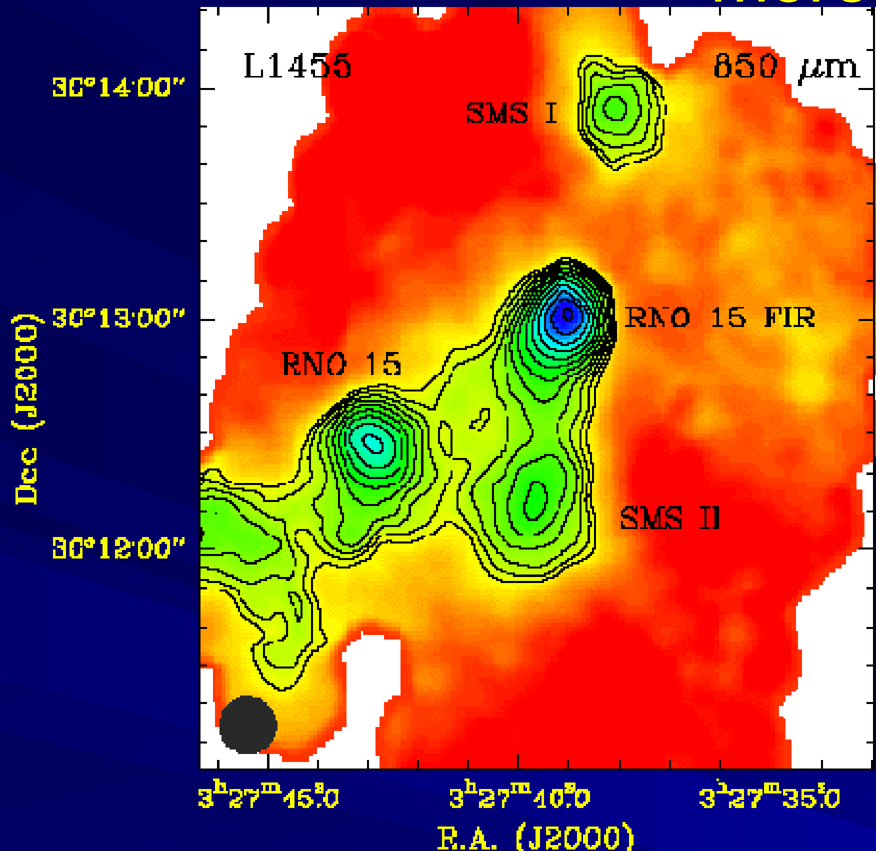


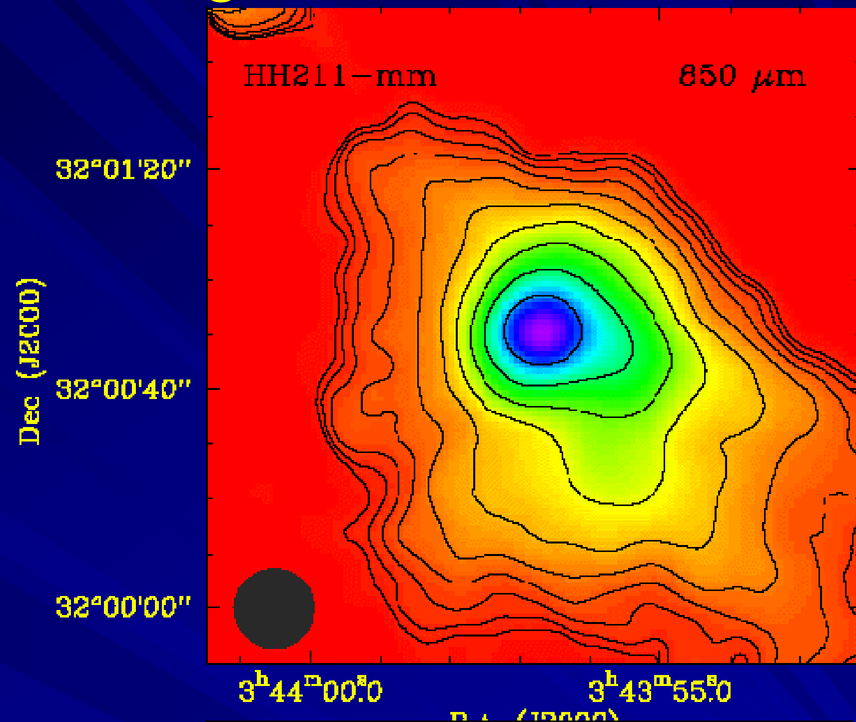
Example of the contour map of L 1448 at 850 μm

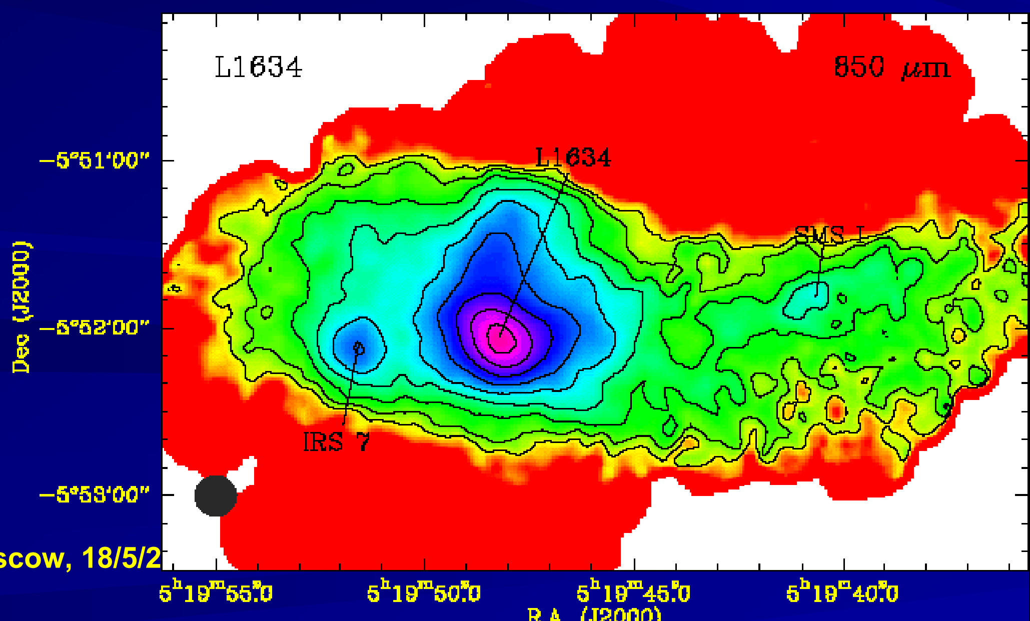
Moscow, 18/5/2009

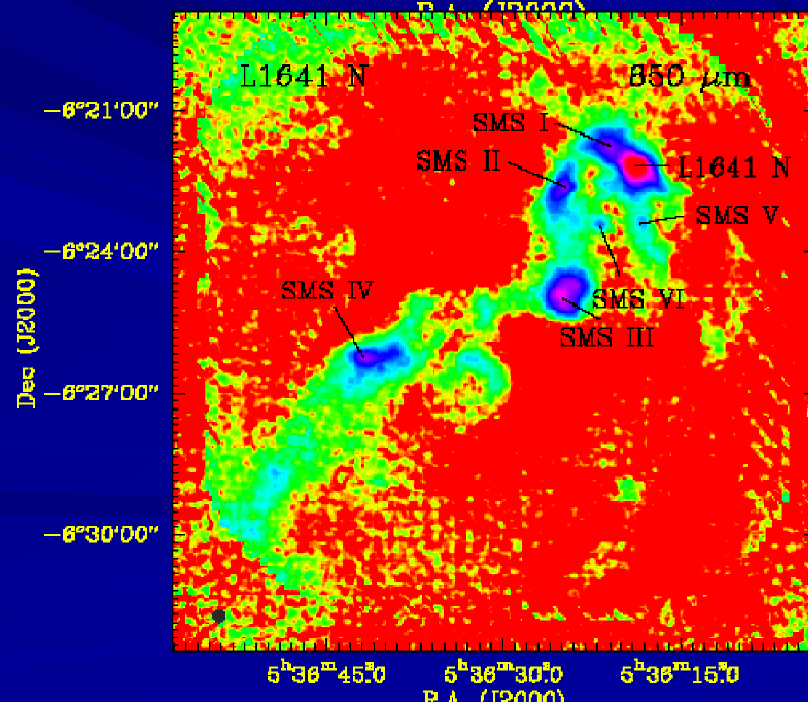
Rengel M., Eislöffel J., Hodapp K, 2003, ANS 324, 10

more observed regions









Rengel 2004, PhD Thesis

B.- Deriving physical properties

From observations

R E S U L T S

α=(2.8 +/- 0.4)

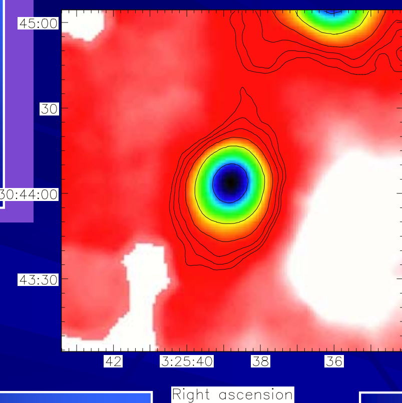
$$\alpha_{450\,\mu m/850\,\mu m} = \frac{\log\left(S_{450\,\mu m} / S_{850\,\mu m}\right)}{\log\left(850\,\mu m / 450\,\mu m\right)}$$

Spectral indices

$$M_D = \frac{S_\nu D^2}{B_\nu (T_d) \kappa_\nu}$$

a/*b*=1.3 +/- 0.2

Aspect ratio a/b



Gas and dust masses

S_ν fllux at 850 μm
D cloud distance
B_ν Planck function
T_d dust temperatur
κ_ν opaciity at 850 μ

Objects can be roughly described as spherically symmetric

M_D=(2.5 +/- 0.6) $M_\odot$

Source sizes

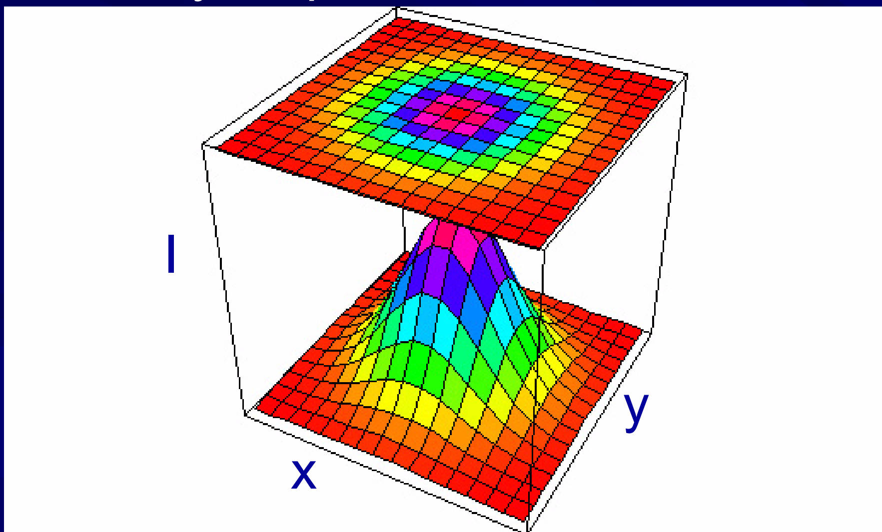
Radial profiles *m*

Moscow, 18/5/2009

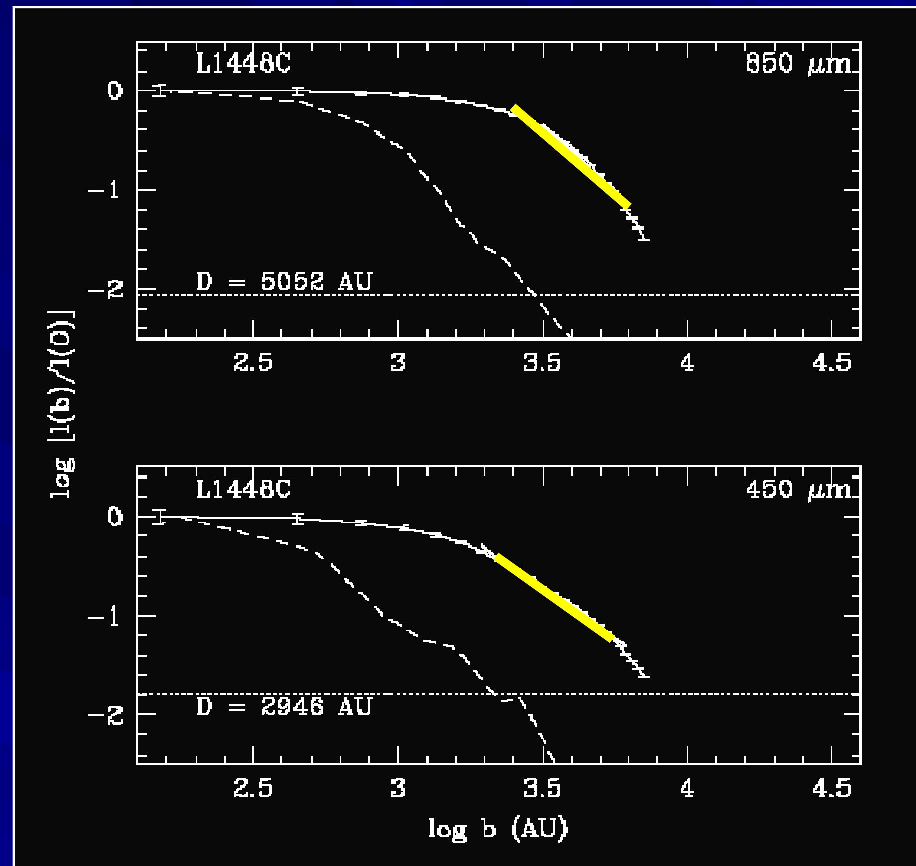
Rengel 2004, PhD Thesis

Radial profiles

Intensity map

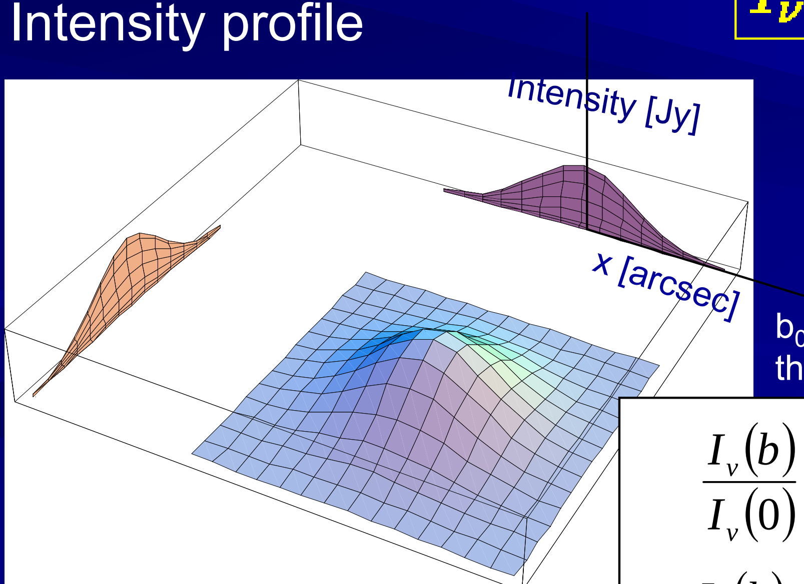


Normalized radial profiles



$$I_\nu \propto b^{-m}$$

Intensity profile



b_0 normalization factor to the peak emission

$$\frac{I_\nu(b)}{I_\nu(0)} = \left(\frac{b}{b_0}\right)^{-m}$$

$$\log\frac{I_\nu(b)}{I_\nu(0)} = -m\log\left(\frac{b}{b_0}\right)$$

m=1.74 ± 0.02

➔

***q*=0.42 ± 0.04**

Result consistent with other works

$$q = \frac{2}{4+\beta}$$

1 AU = 1.496 x 10^{11} m

B.- Deriving physical properties

From observations

R

E

S

U

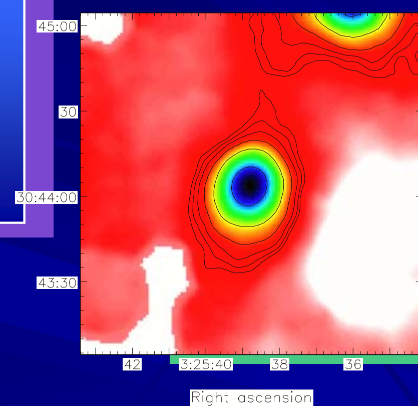
L

T

S

Spectral indices

Aspect ratio a/b



Gass and dust masses

Source sizes

4000-9000 AU (850 μm)

Radial profiles
m

1 AU = 1.496 x 10^{11} m

Moscow, 18/5/2009

Rengel 2004, PhD Thesis

B.- Deriving physical properties

By the blackbody fitting

R $S[Jy] = \Sigma\Omega \cdot (1 - e^{-\tau}) \cdot B(\lambda, T)$

E $\Sigma\Omega$ effective solid angle

β sub-mm slope of the spectral energy distribution

S $\tau = \tau_{100} \cdot \left(\frac{\lambda}{100\mu m}\right)^{-\beta}$

U dust optical depth

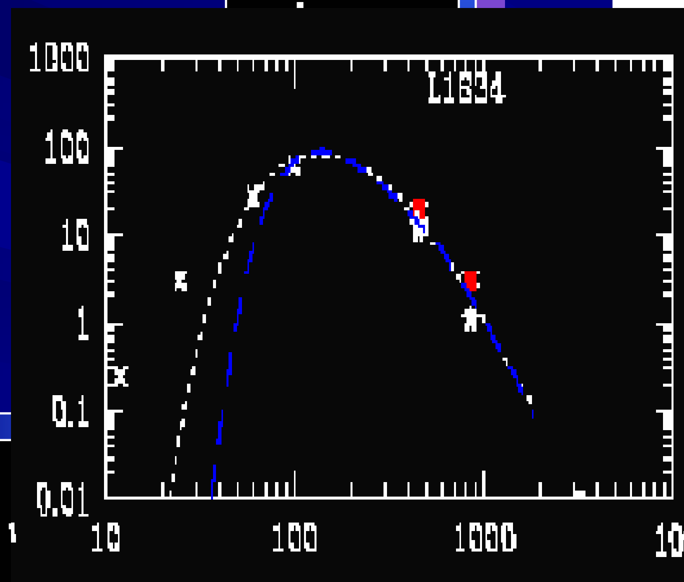
L

T

S

19 $L_{\odot}$ [18.8-19.2] $L_{\odot}$

Best obtained fit to the Spectral Energy Distribution for L 1634



$= 4\pi D^2 \int_0^\infty$ *Spectral Energy Distribution* (ν) $d\nu$

D distance to the object

ν frequency

42.1 K

Cool object!

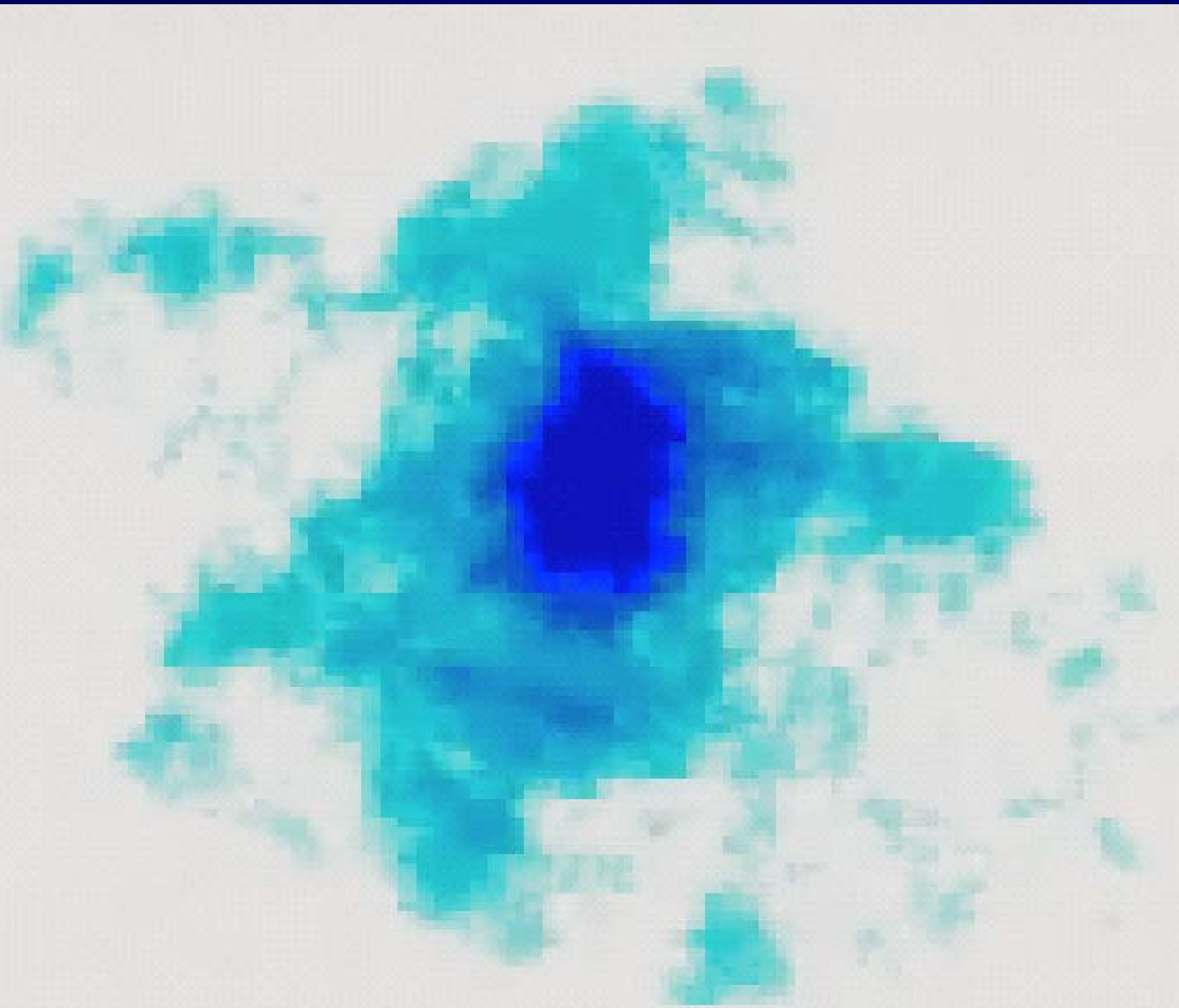
2.0 ± 0.1

Evolutionary indicator $L_{sub\text{-}mm}/L_{bol} > 0.005$ **Class 0 source**

1 Jy = 10^{-26} W m^{-2} Hz^{-1}

A more detailed physical interpretation on the internal structure of these objects requires radiative transfer modeling …

III.- The Envelope Fitting Procedure



Temperature profile

Spectral Energy Distribution

Intensity map

stellar luminosity
effective temperature
ut outer radius
density distribution
density power-law index
ub sublimation radius
nv mass of the envelope

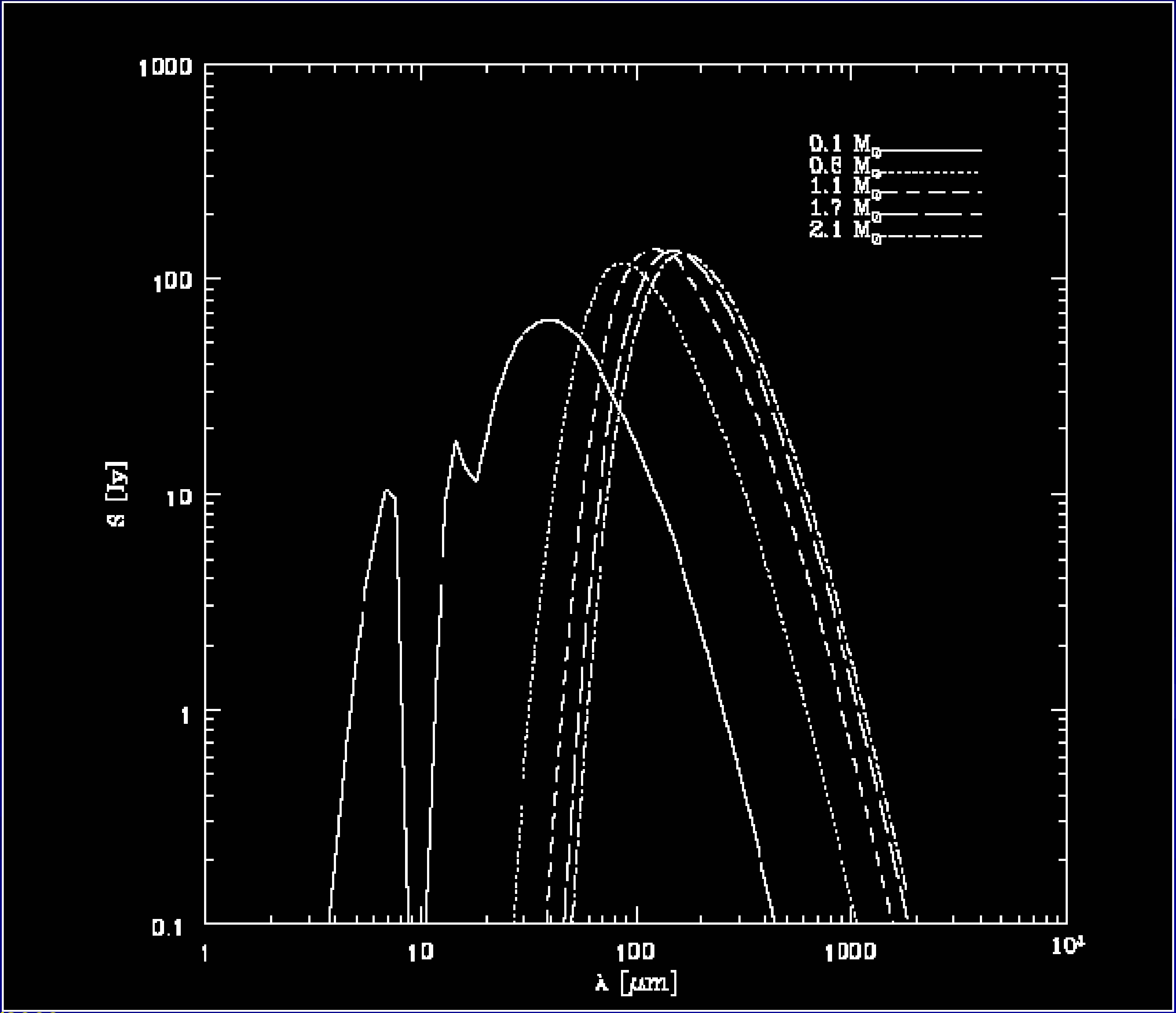
istribution: silicate (62.5%), graphite (37.5%)
zes: 0.005-0.25 μm
Optical constants: Draine & Lee, 1984

Basic assumed model

Wolf, S., Henning, T., Stecklum, B., 1999, A&A, 349, 839

Changes in envelope mass

Variations in the spectral energy distribution due to changes in the envelope mass



L_*=11 $L_\odot$
p=1.6
R_{out}=3000 AU
R_{sub}=5 $R_\odot$

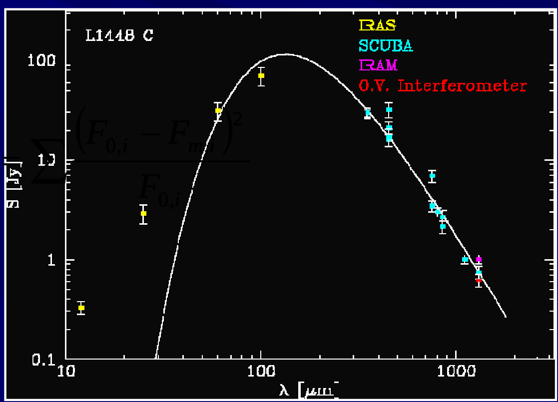
1 $M_\odot$ = 1.9891 x 10^{30} kg

1 Jy=10^{-27} W m^{-2} Hz^{-1}

$$S^2 = \sum \frac{(F_{0,i} - F_{m,i})^2}{F_{0,i}}$$

Comparation of models with observations

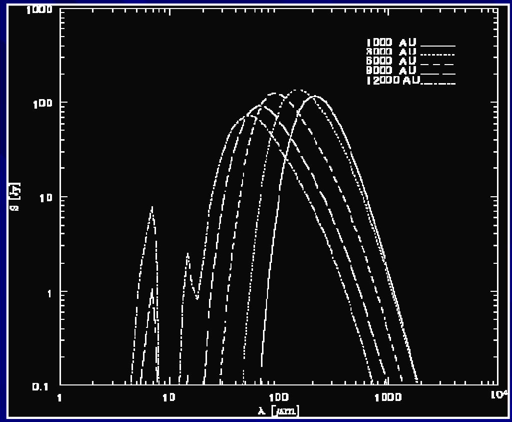
Observed spectral energy distribution



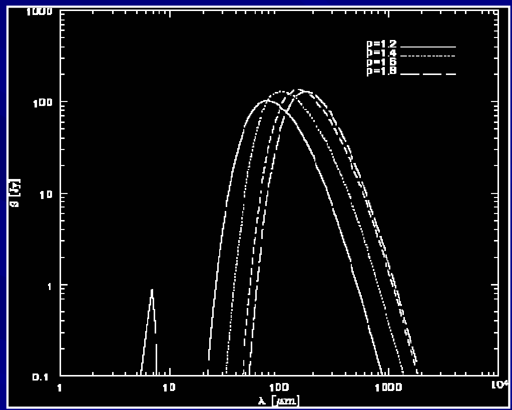
$$S^2 = \sum \frac{(F_{0,i} - F_{m,i})^2}{F_{0,i}}$$

$F_{o,i}$ observed flux at wavelength *i*
$F_{m,i}$ modeled flux at wavelength *i*

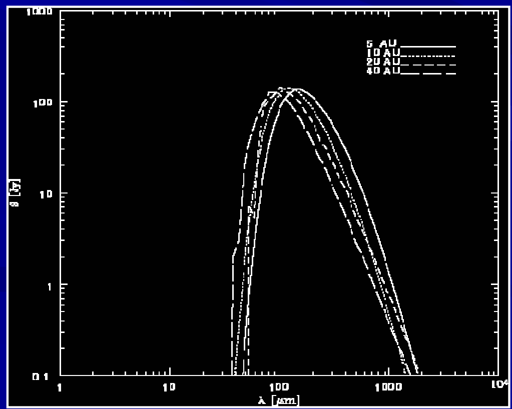
Modelled spectral energy distributions



Outer radius



p



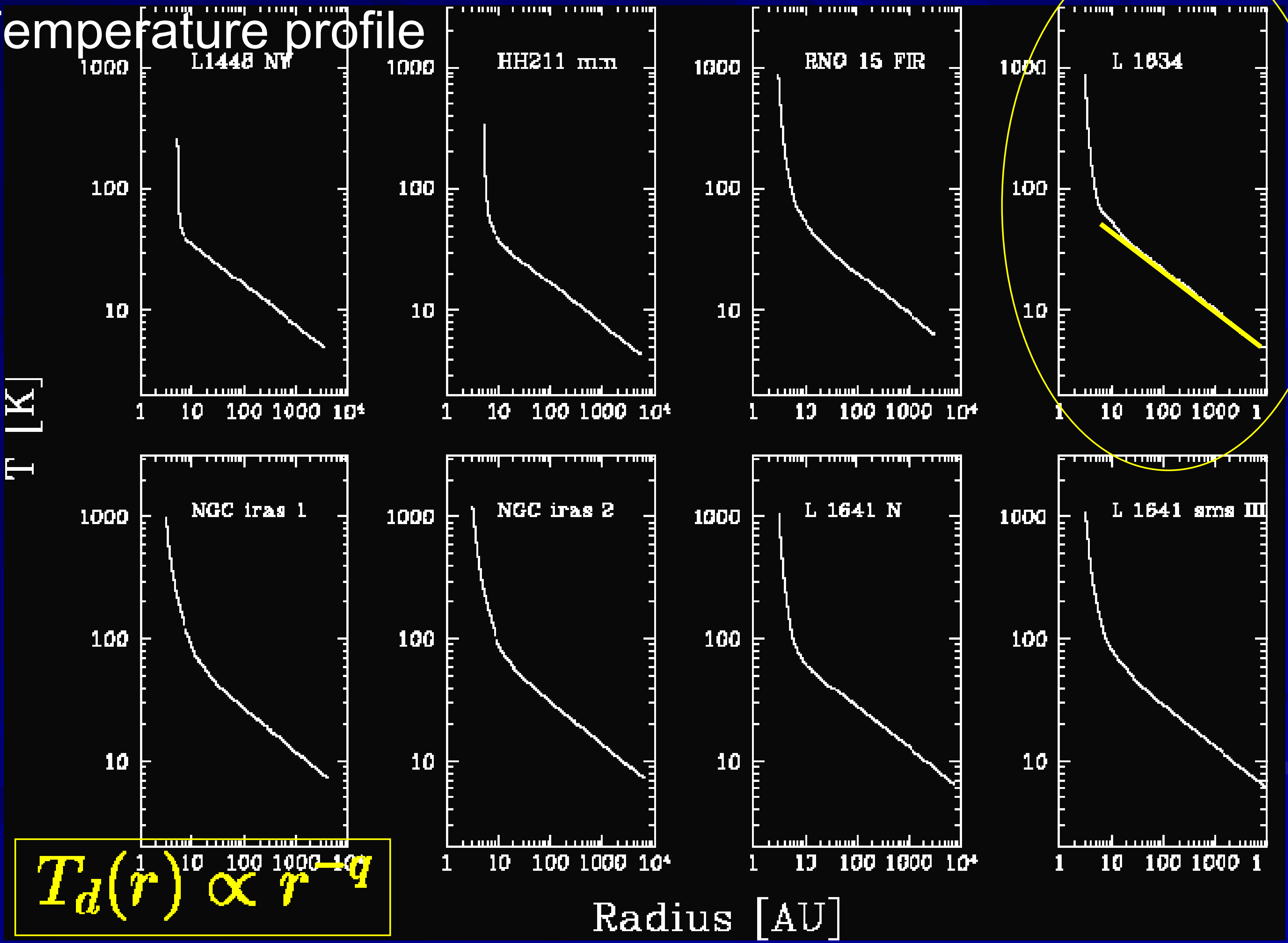
Inner radius

Rengel 2004, PhD Thesis

Modelling observations: Radiative Transfer

Temperature profile

R E S U L T S



$$T_d(r) \propto r^{-q}$$

Moscow, 18/5/2009

1 AU = 1.496 x 10^{11} m

Rengel, Froebrich, Wolf, Eislöffel, 2004, Baltic Astronomy, 13, 449

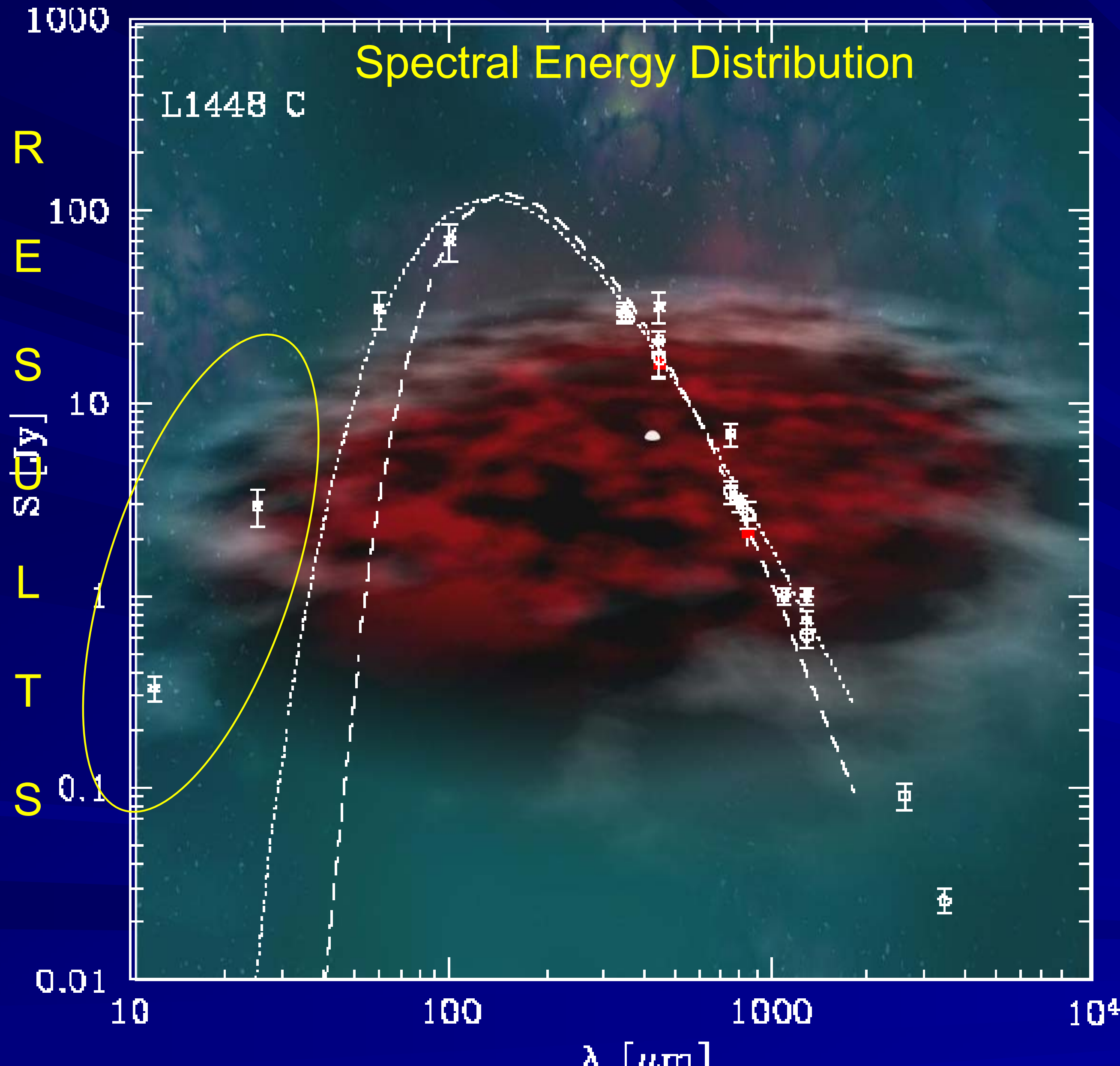
$$\rho(r) \propto r^{-p}$$

L 1448 C

Output Parameters:

L_{bol}	=	11 $L_{\odot}$
R_{sub}	=	5 AU
R_{out}	=	3000 AU
p	=	1.6
M_{env}	=	1.7 $M_{\odot}$

R
E
S
L
T
S



Blackbody - observations

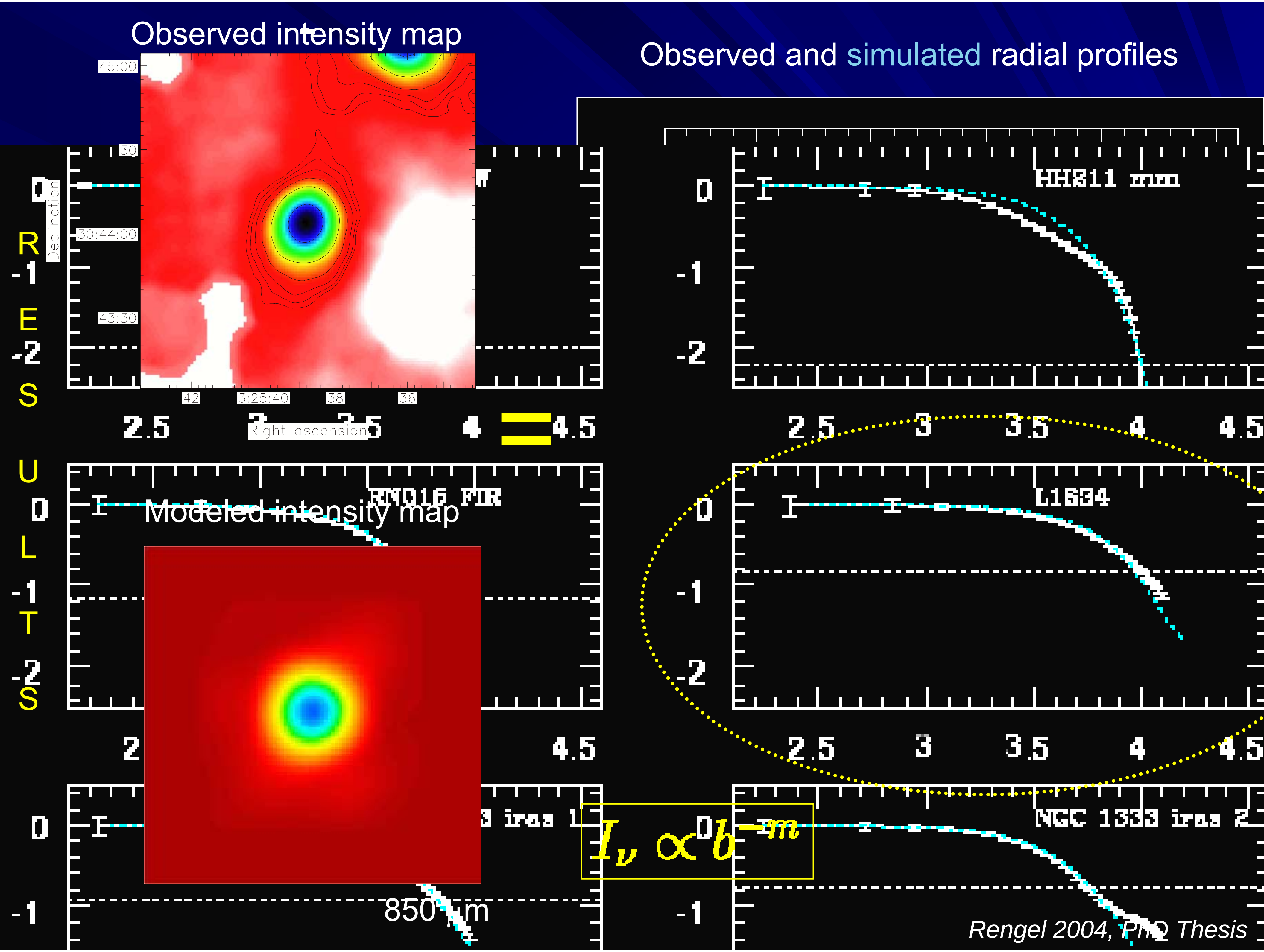
------- Radiative transfer modeling

1 Jy=10^{-27} W m^{-2} Hz^{-1}

1 $M_{\odot}$ = 1.989 x 10^{30} kg
1 $L_{\odot}$ = 3.90 x 10^{26} W

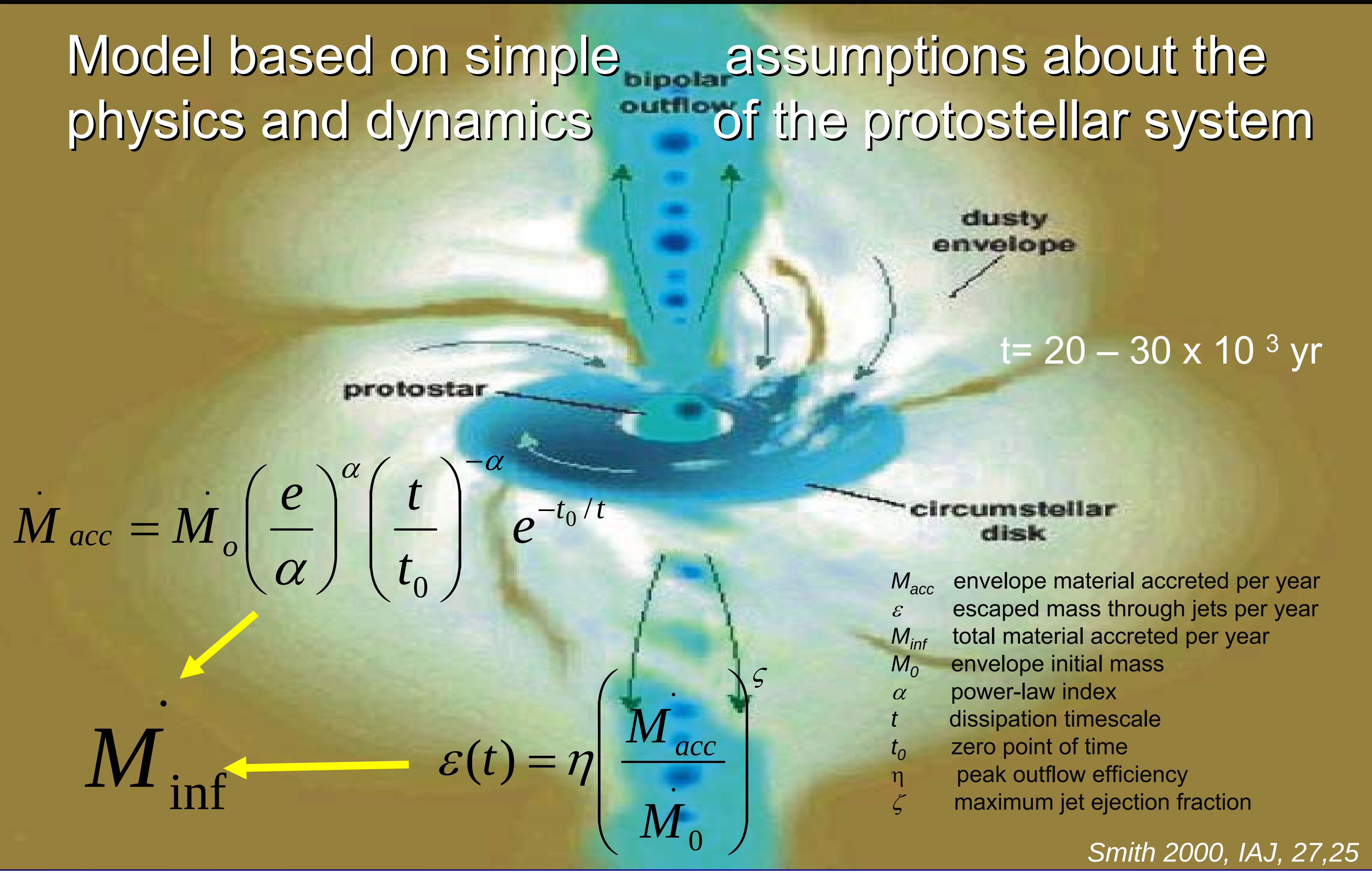
1 AU = 1.496 x 10^{11} m

Rengel, Froebrich, Wolf, Eislöffel, 2004, Baltic Astronomy, 13, 449


Observed intensity map
Observed and simulated radial profiles
RESULTS
Modeled intensity map
HH211 mm
RNO15 FIR
L1634
NGC 1333 iras 2
Declination
Right ascension
$I_\nu \propto b^{-m}$
850 μm
Rengel 2004, PhD Thesis

III. An evolutionary scheme for Class 0 Sources

Model based on simple assumptions about the physics and dynamics of the protostellar system



t= 20 – 30 x 10 ^{3} yr

$$\dot{M}_{acc} = \dot{M}_o \left(\frac{e}{\alpha}\right)^{\alpha} \left(\frac{t}{t_0}\right)^{-\alpha} e^{-t_0/t}$$

$$\dot{M}_{\inf}$$

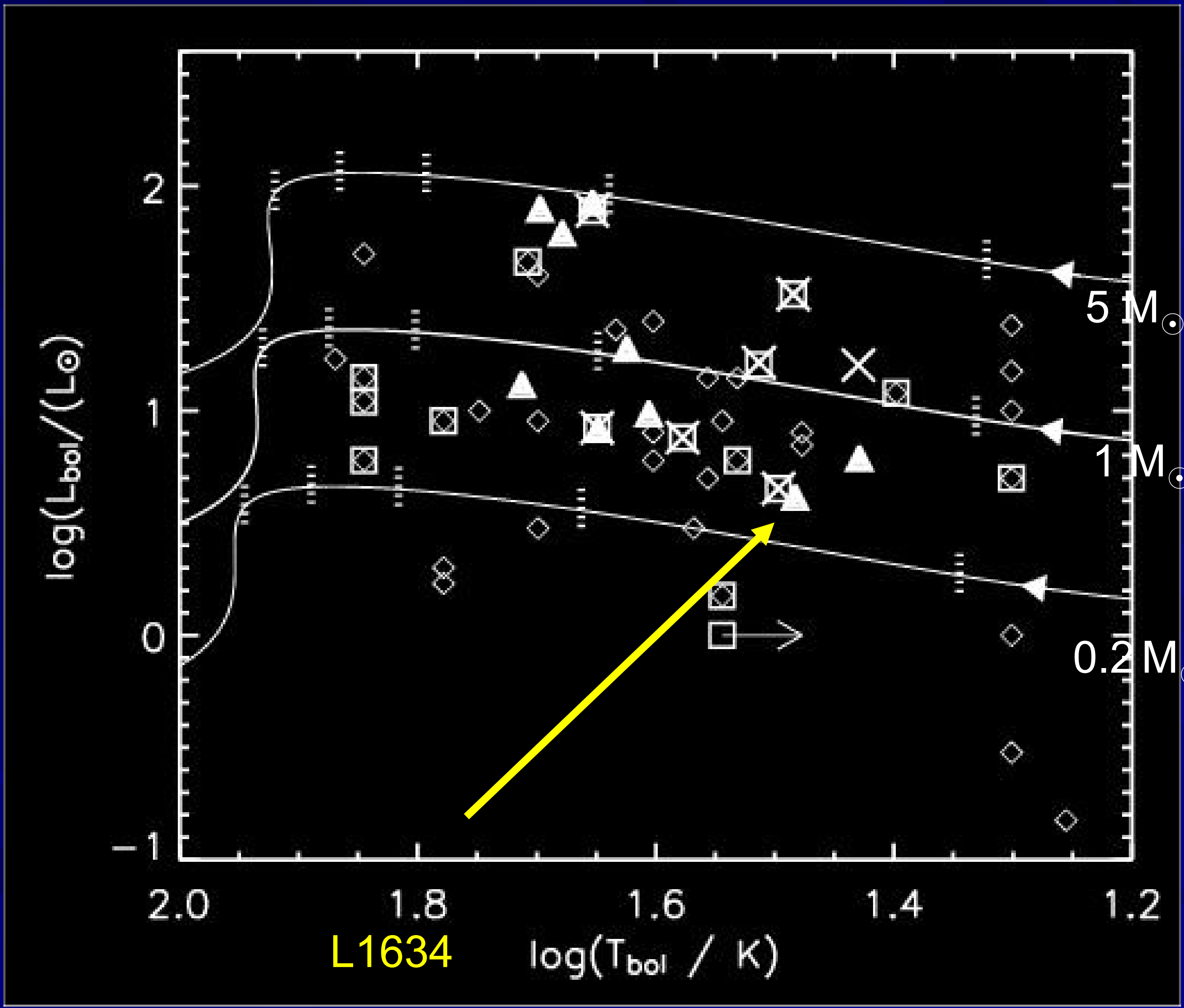
$$\varepsilon(t) = \eta \left(\frac{\dot{M}_{acc}}{\dot{M}_0}\right)^{\varsigma}$$

- M_{acc} envelope material accreted per year
- ε escaped mass through jets per year
- M_{inf} total material accreted per year
- M_0 envelope initial mass
- α power-law index
- t dissipation timescale
- t_0 zero point of time
- η peak outflow efficiency
- ζ maximum jet ejection fraction

Smith 2000, IAJ, 27,25

Mass and age determination

R
E
S
U
L
T
S



50.000 yr 40.000 yr 30.000 yr 20.000 yr

Direct analog to the Hertzprung-Russel Diagram = Bolometric Luminosity-Temperature Diagram

Evolutionary tracks for protostars
(Smith 2002, Myers 1998)

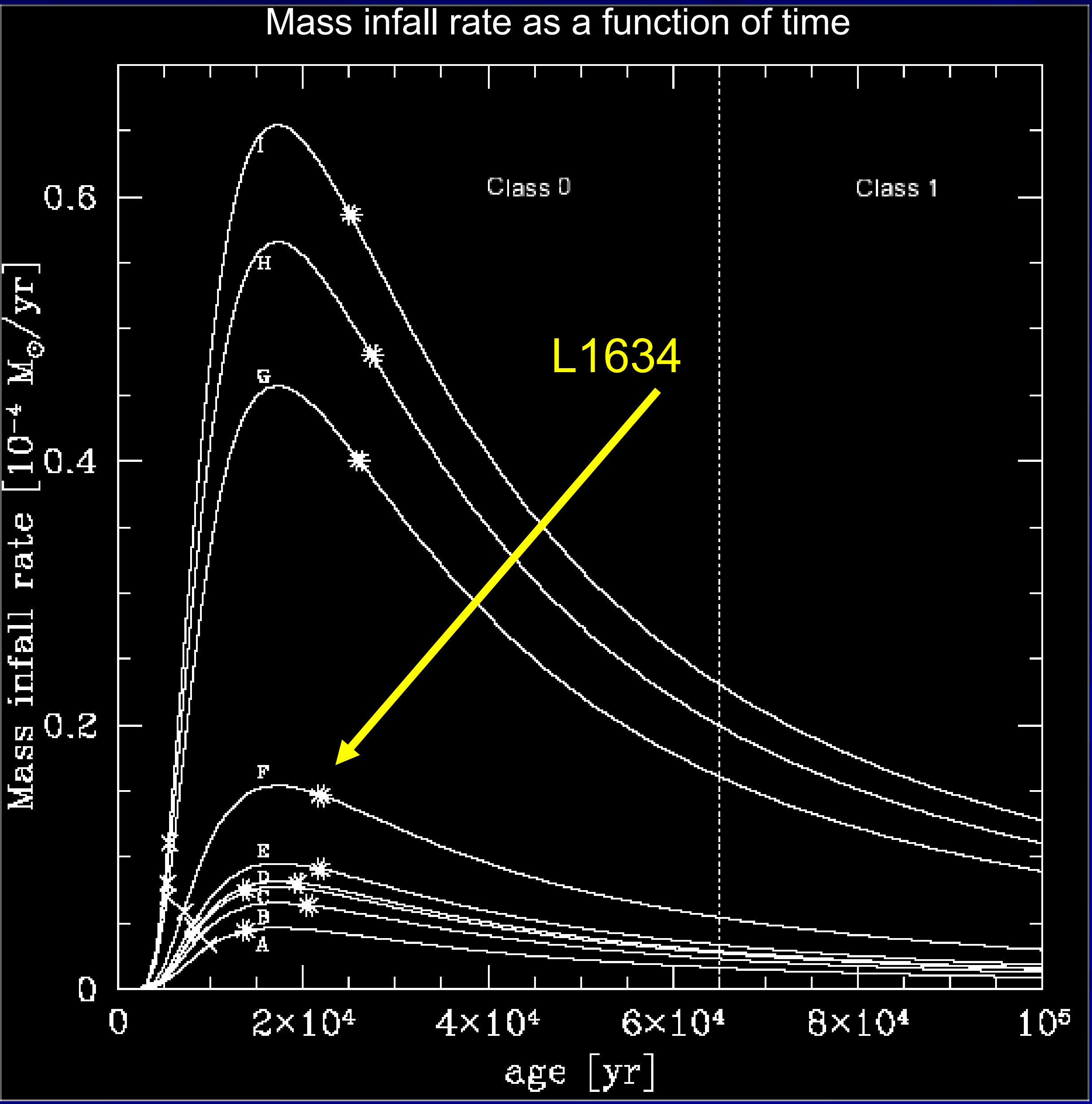
1 $M_\odot$ = 1.989 x 10^{30} kg
1 $L_\odot$ = 3.90 x 10^{26} W

▲ Rengel 2004
□ André et al. 2000
✕ Froebrich et al. 2003
◇ Stanke 2000

Moscow, 18/5/2009

Rengel M., Hodapp K., Froebrich D., Wolf S., Eislöffel J. In "Proc. 13th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun", Hamburg (Germany), 5-9 July 2004, F.Favata et al., eds.

Infall Evolution



- Class 0 sources grow by accretion at rate that is initially high, but declines with time

- Mass infall rate strongly time-dependent
- Peaking at t ~ 17000 yr

- Mass infall dominated by Class 0 phase, thus determining protostellar evolution

1 $M_{\odot}$ = 1.9891 x 10^{30} kg

$M_{env}=M_{core}$

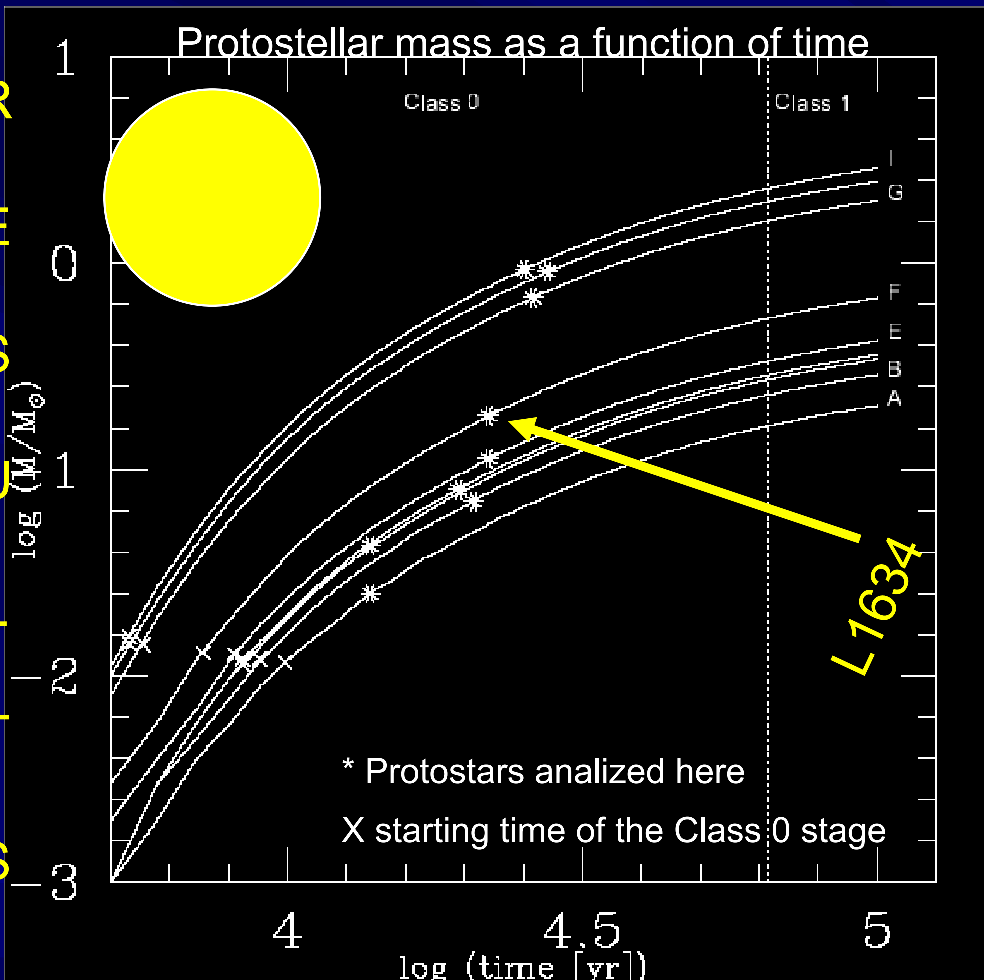
* Protostars analized here

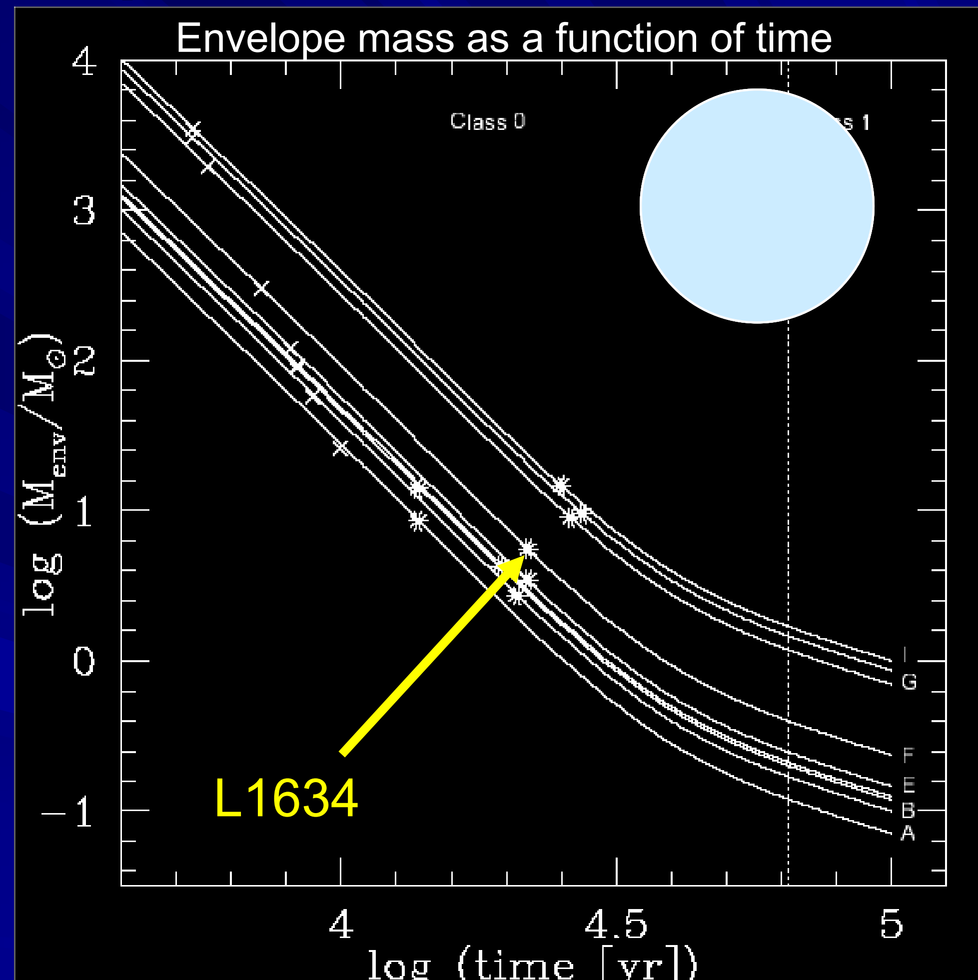
X starting time of the Class 0 stage

Rengel 2004, PhD Thesis

Evolution of the protostellar core and envelope masses

R E S U L T S





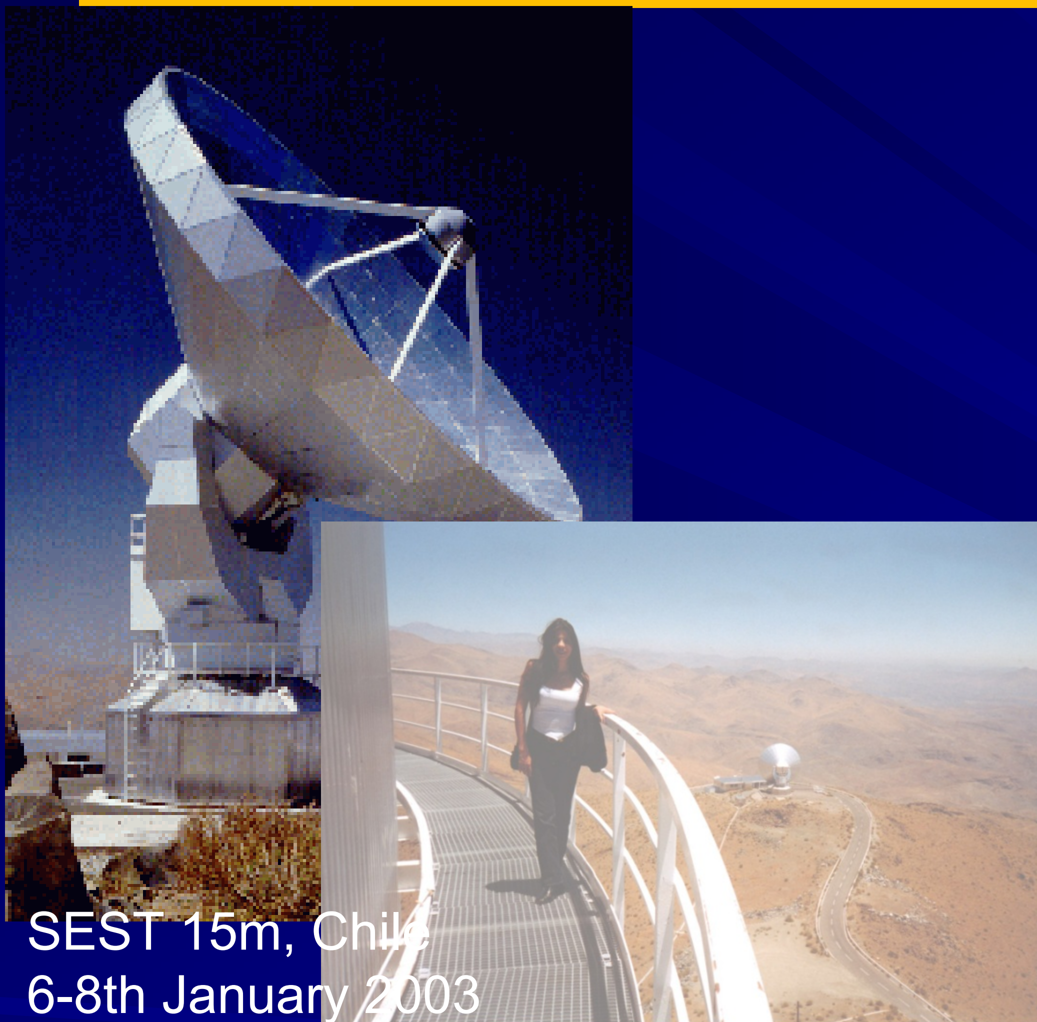
Core still growing in mass in Class 0 phase by accretion of envelope material, gradually reaching final size and mass. Envelope is lossing its material.

Moscow, 18/5/2009

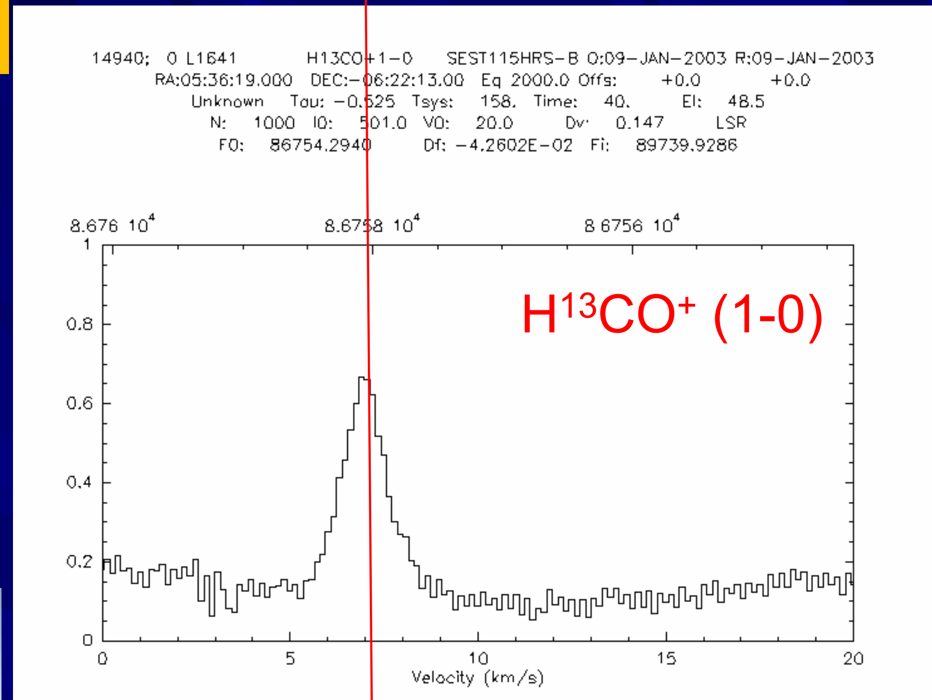
1 M$_\odot$ = 1.9891 x 10^{30} kg

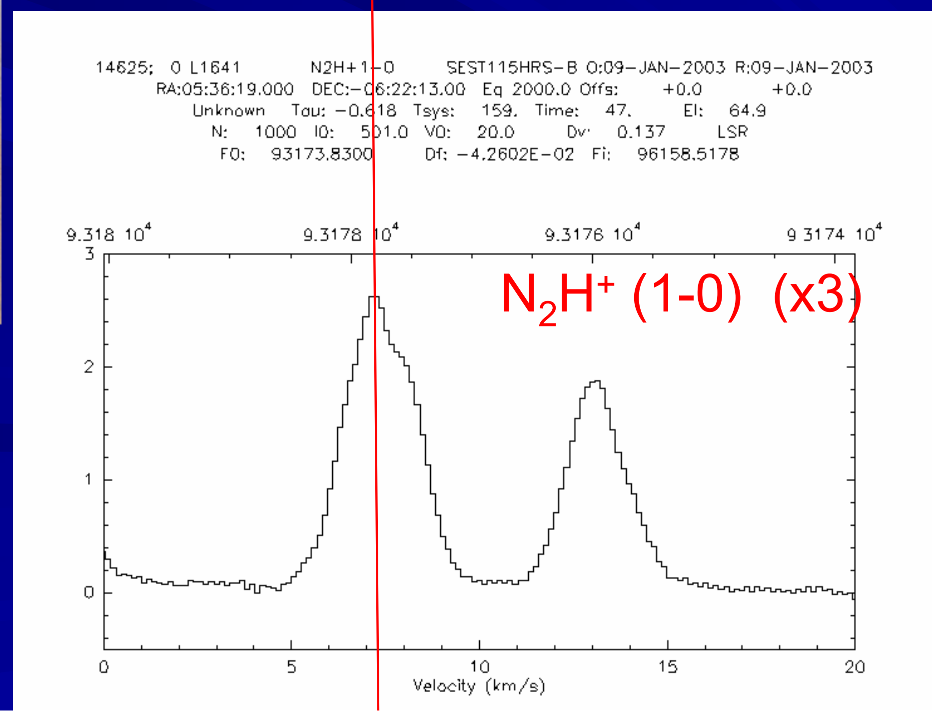
Rengel 2004, PhD Thesis

Line profiles of molecular transitions



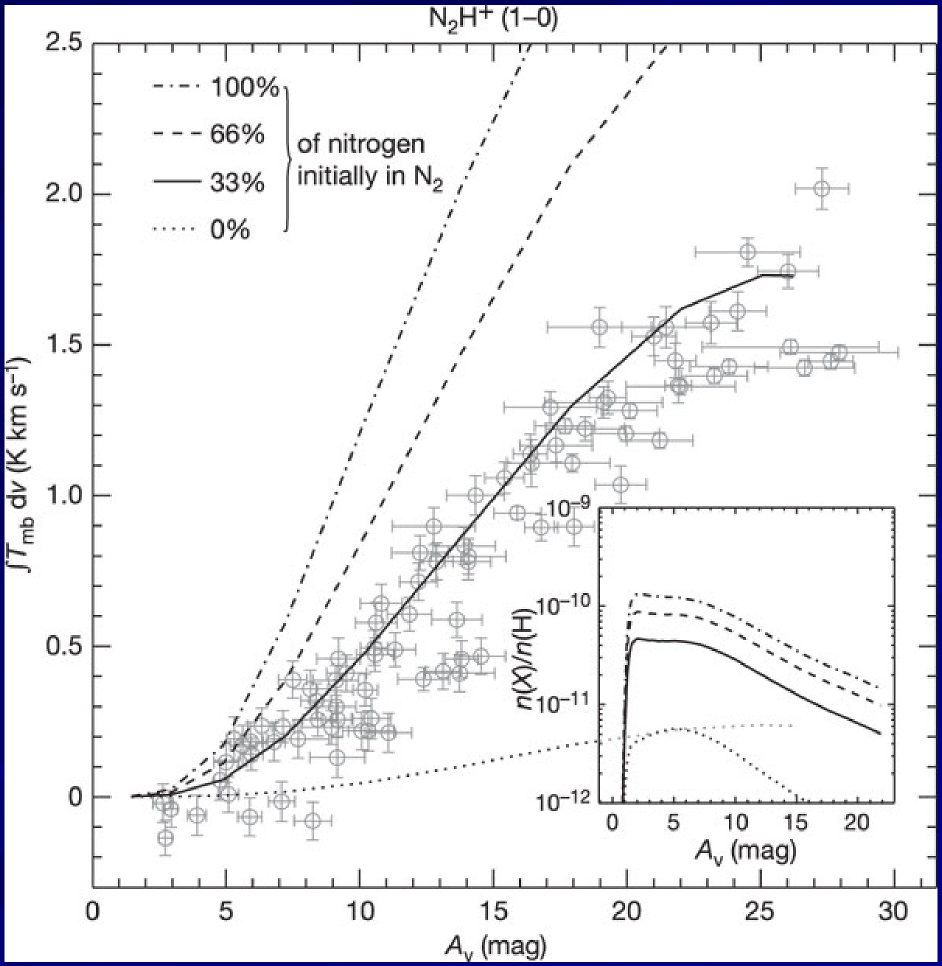
SEST 15m, Chile
6-8th January 2003





Instruments: heterodyne receivers
SESIS 100 [78 – 116 GHz]
IRAM 115 [80-116 GHz]
SESIS 150 [128-170 GHz]
IRAM 230 [210 – 238 GHz]

N_2H^+ **abundance** depends solely on the N_2 abundance



Maret et al. 2006, Nature 442

N_2H+ **abundance ~ 1 x 10** $^{-10}$

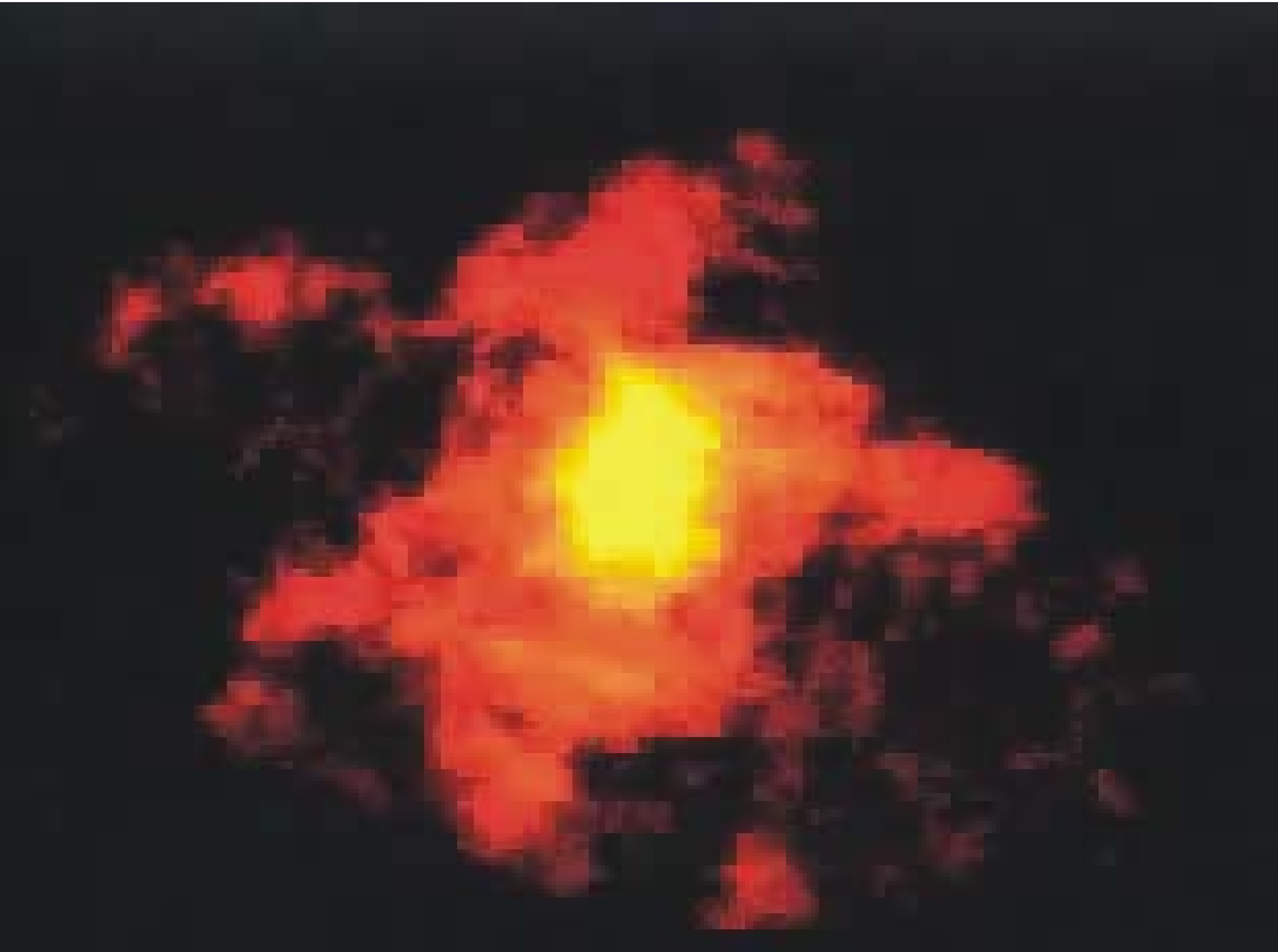
$H^{13}CO+$ **abundance ~ 2 x 10** $^{-7}$

As a first aproximation:

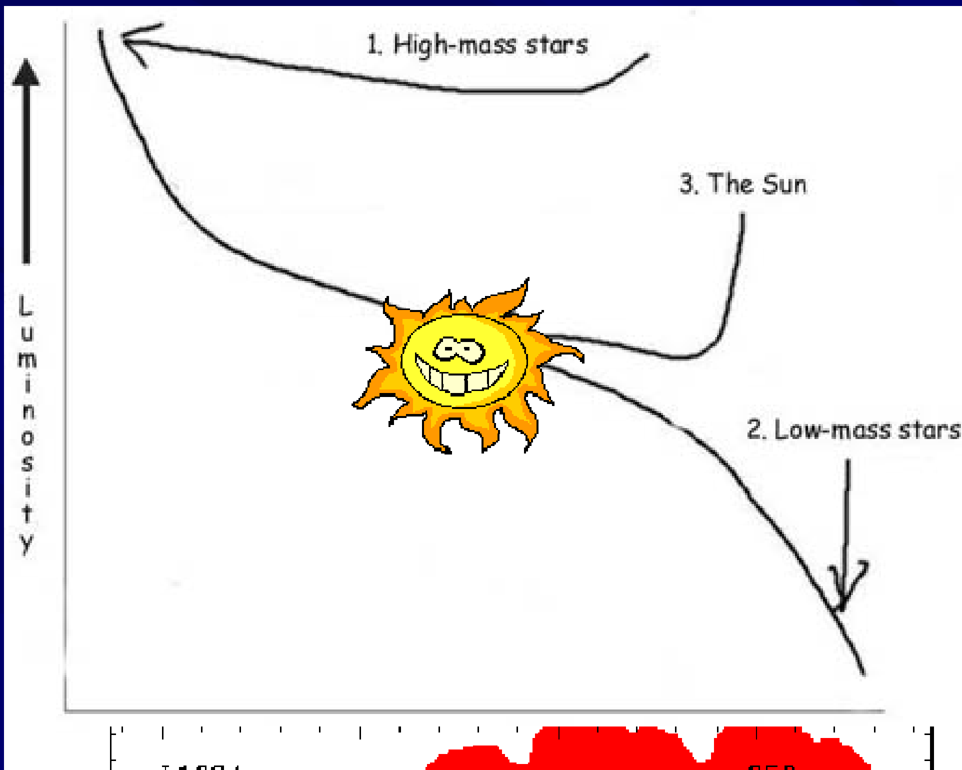
$$\zeta_{CR} \; \alpha \; \sum abundances$$

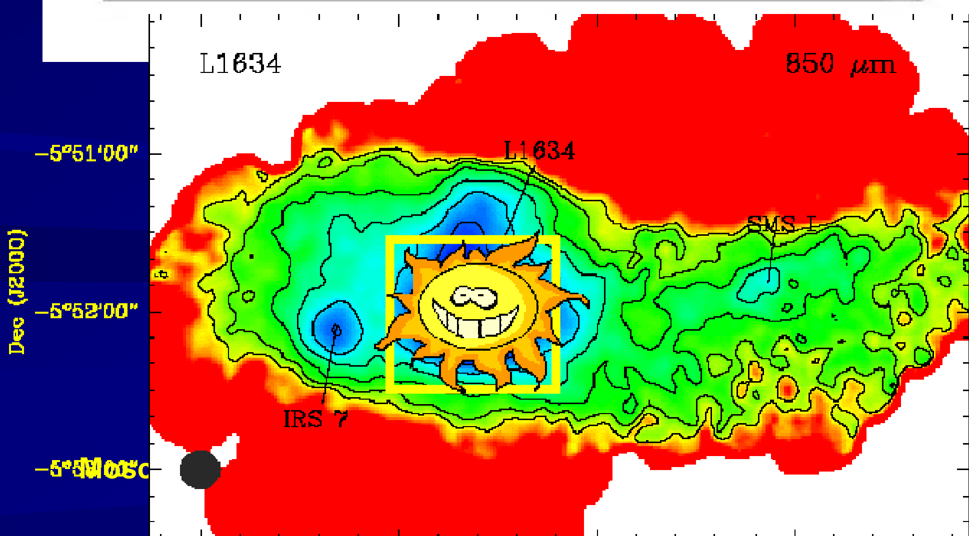
$\sim 2 \times 10^{-17}\ s^{-1}$

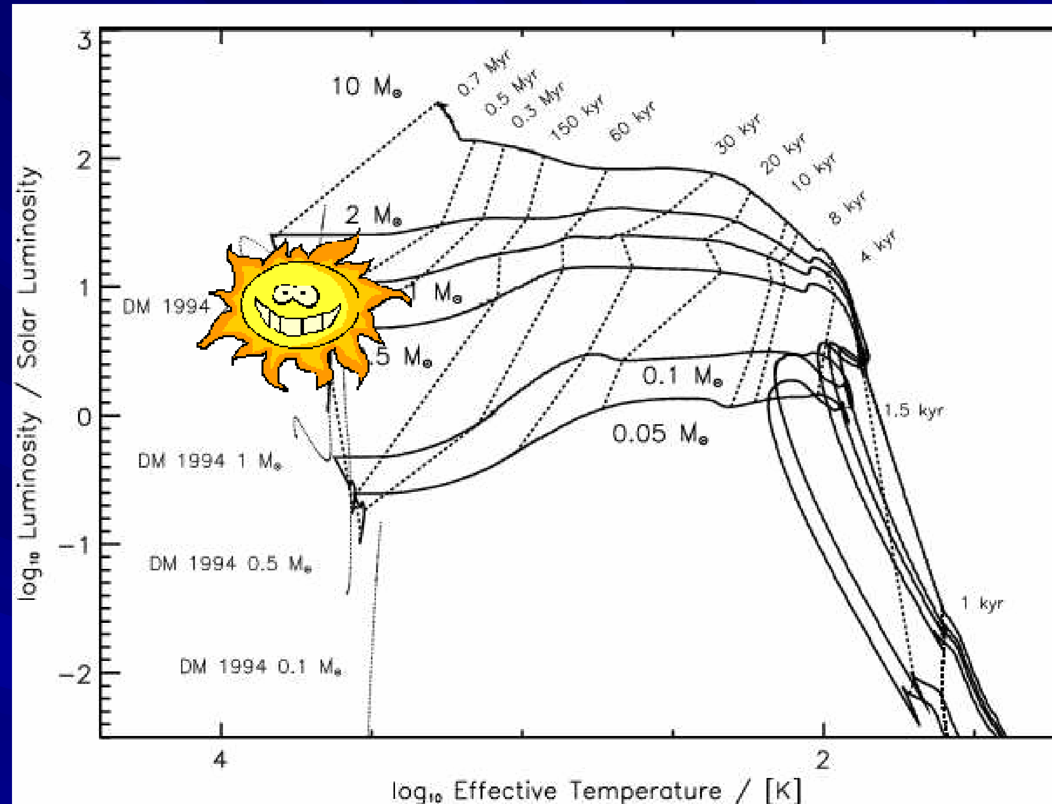
Standard , caused by CR since there is not known to be a potent X-ray in the vecinity



A version of today's Sun







Wuchterl & Tscharnurter 2003, A&A 398, 1081

L_{bol} =19 $L_{\odot}$

T_{bol}=42 K

Age= 22 kyr

R_{out}=6000 AU

M_{env}=2.5 $M_{\odot}$

M_{final}=1.09 $M_{\odot}$ *Rengel 2004, PhD Thesis*

Summary and Conclusions

- With the SCUBA camera, thermal dust emission of 36 embedded sources (nine Class 0 sources and 12 new sub-mm objects) in Orion and Perseus were detected.

- The fundamental physical structure of a Class 0 envelope is characterized by two radial distributions: $\boldsymbol{T(r) \propto r^{-q}}$, and $\boldsymbol{\rho(r) \propto r^{-p}}$. From Interpretation of observations, q=0.42 ± 0.04 and p=2.1 ± 0.1 (450 μm) and 2.3 ± 0.1 (850 μm). These values are expected for all theoretical models and numerical studies of collapse.

- I have modelled nine Class 0 envelopes using single power-law density and temperature distributions → embedded systems can be modelled with the standard **envelope** model.

- I have shown that a 1D spherically symmetric model reproduces well the observed properties of Class 0 sources. → It fits the **SEDs** and the **radial profiles** for the sample.

- Deviations can be due to **non-spherical geometry** of sources and outflows, between others.

- From molecular studies of young protostars it is possible to constraint abundance of metals and fraction of ionization.

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