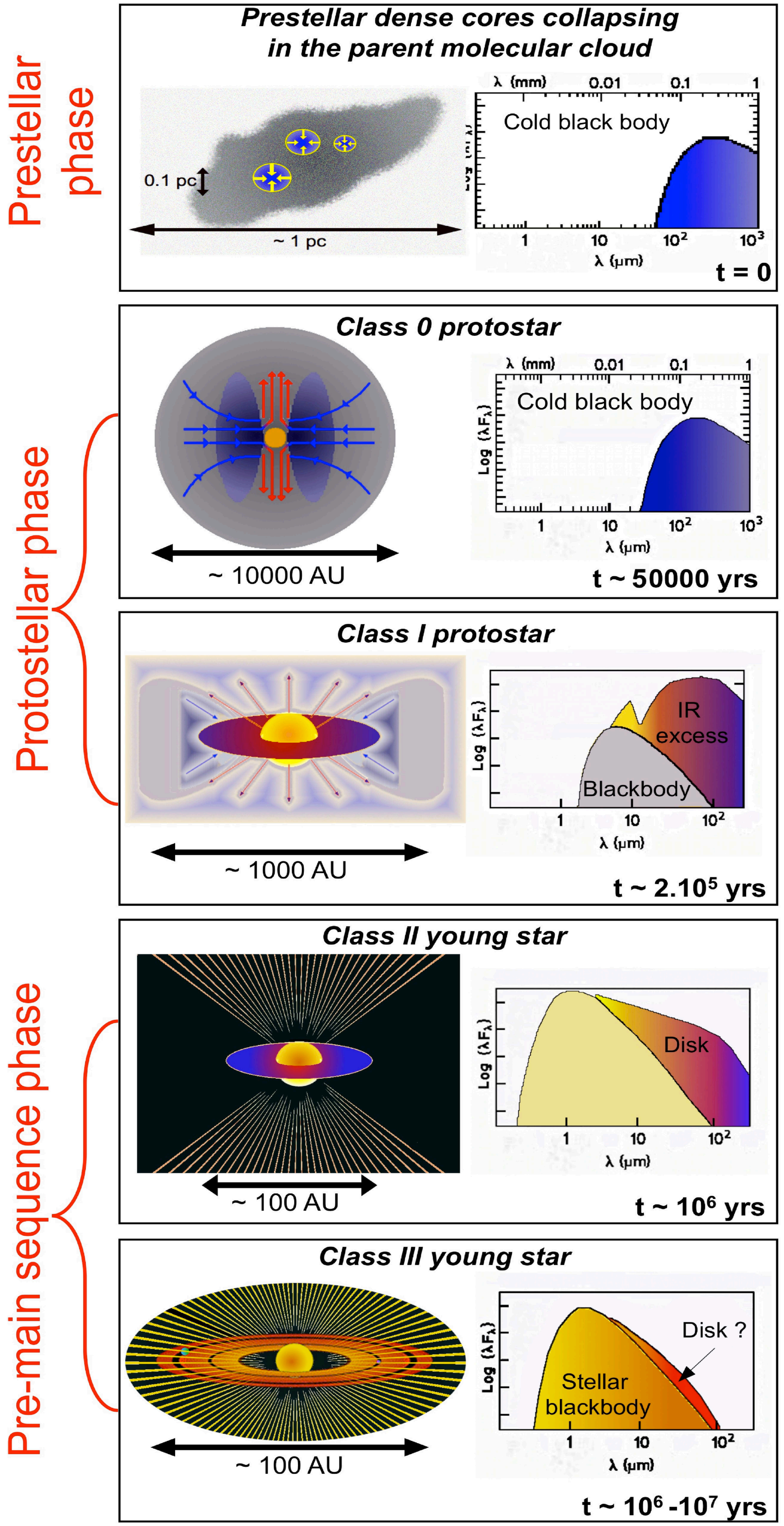
PROTOPLANETARY DISKS

Anaëlle Maury
CEA/AIM (France) & Harvard/Smithsonian CfA (USA)

My boundaries in time ....



T_{bol} = 10 - 20K
M_* = 0

T_{bol} < 70K
$M_* << M_{env}$

T_{bol} ~ 100 - 700K
$M_* > M_{env}$

T_{bol} ~ 700 - 3000K
M_{disk} ~ 0.01 M_o

T_{bol} > 3000K
$M_{disk} < M_{Jup}$

Time

Shu et al. 1987

Lada 1987

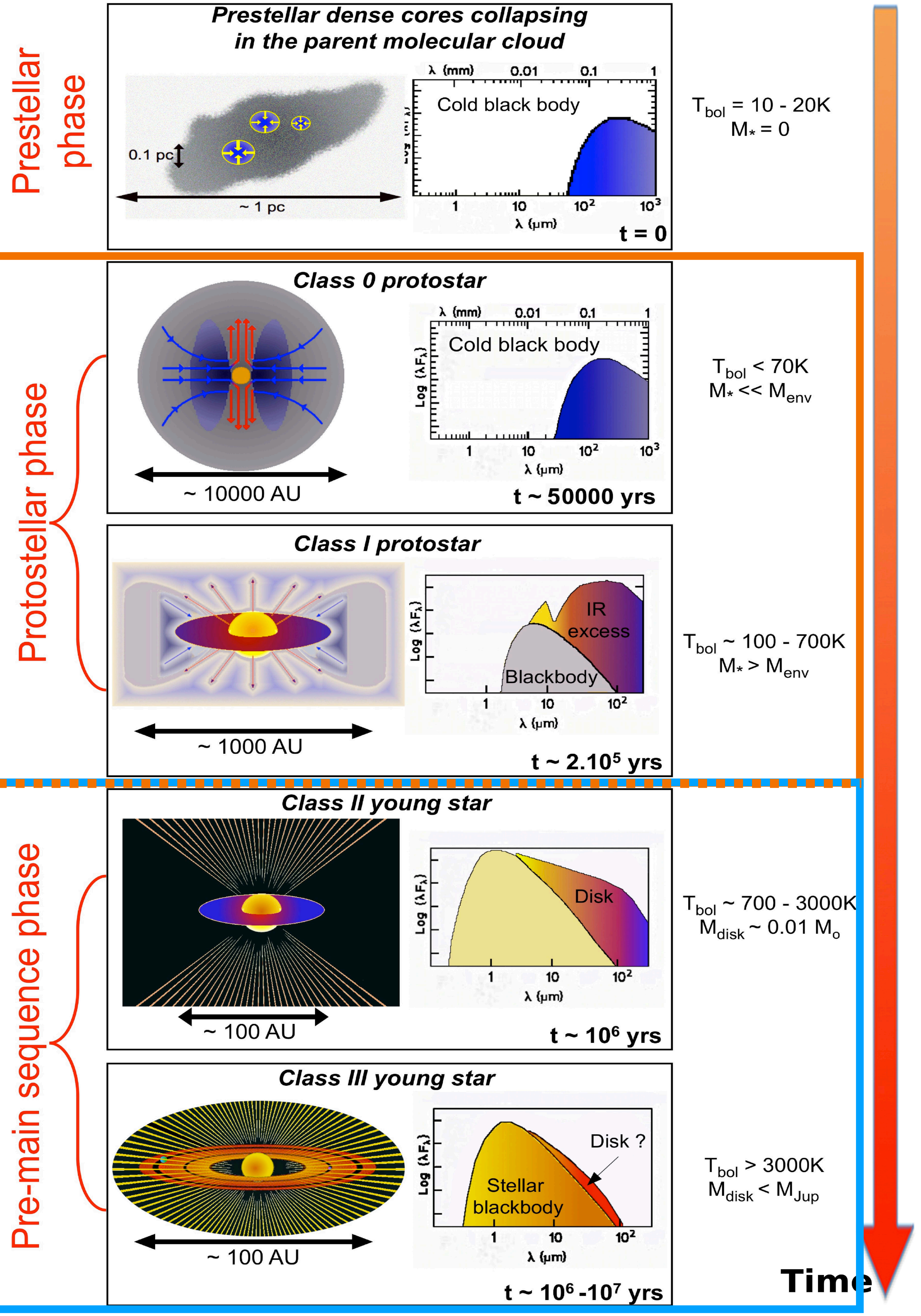
André et al. 1993

André et al. 2001

My boundaries in time ….

THIS LECTURE

LEONARDO TESTI'S LECTURE



Shu et al. 1987

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~~PROTOPLANETARY DISKS~~

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My boundaries in scales ….

My boundaries in scales ….

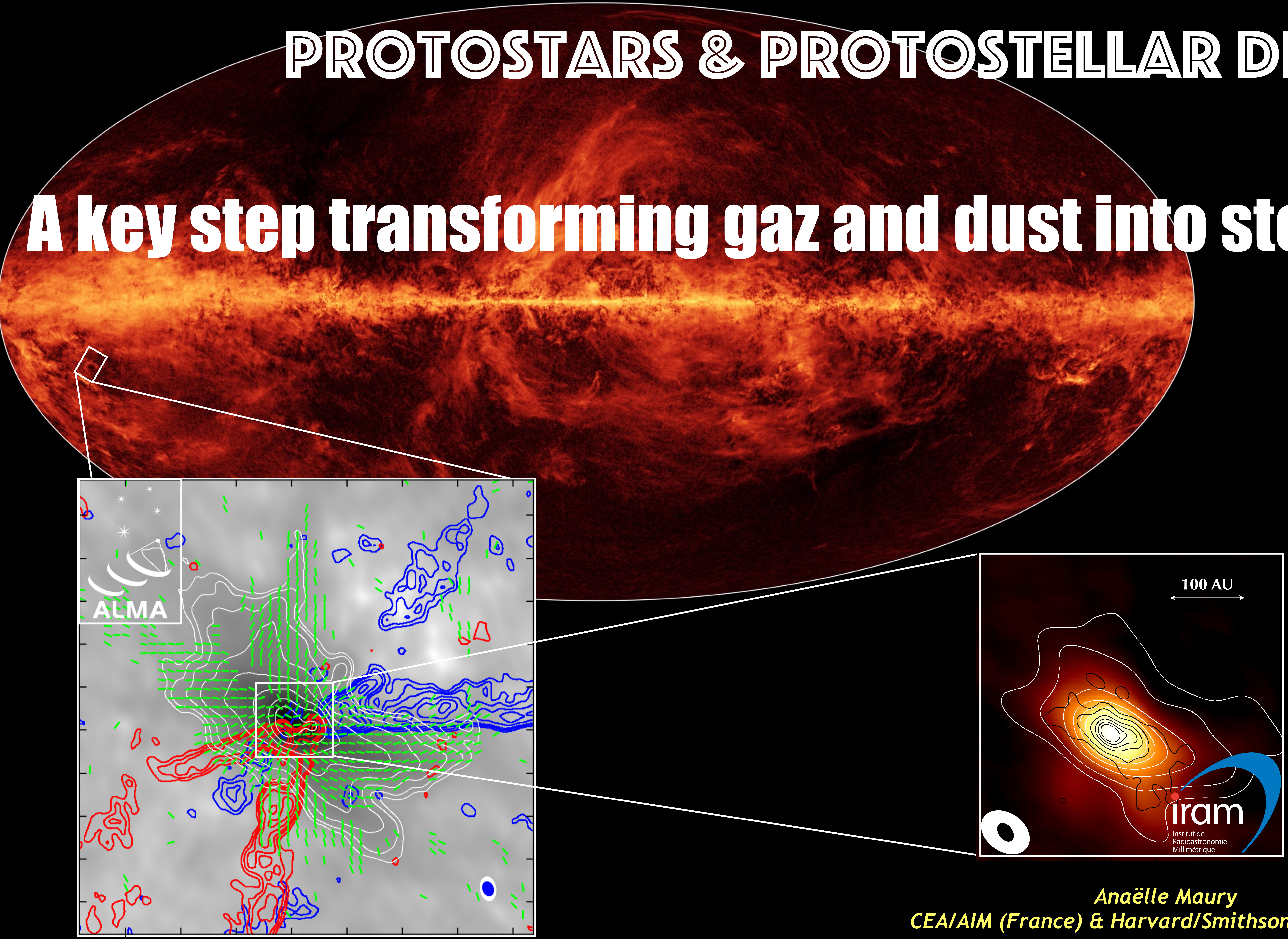
ALESSANDRO TRAFICANTE'S LECTURE

FREDERIQUE MOTTE'S LECTURE

THIS LECTURE

PROTOSTARS & PROTOSTELLAR DISKS

A key step transforming gaz and dust into stellar systems



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I. Protostars

TODAY

From starless cores to protostars: triggering of gravitational instability

Population studies & typical timescales

Transporting material from large to small scales: infall, accretion & the luminosity problem

« *And yet, it rotates* » …. angular momentum problem & the physics of the formation of disks

Observations: statistical properties of protostellar disks: sizes (& masses)

II. Disks and dust

TOMORROW

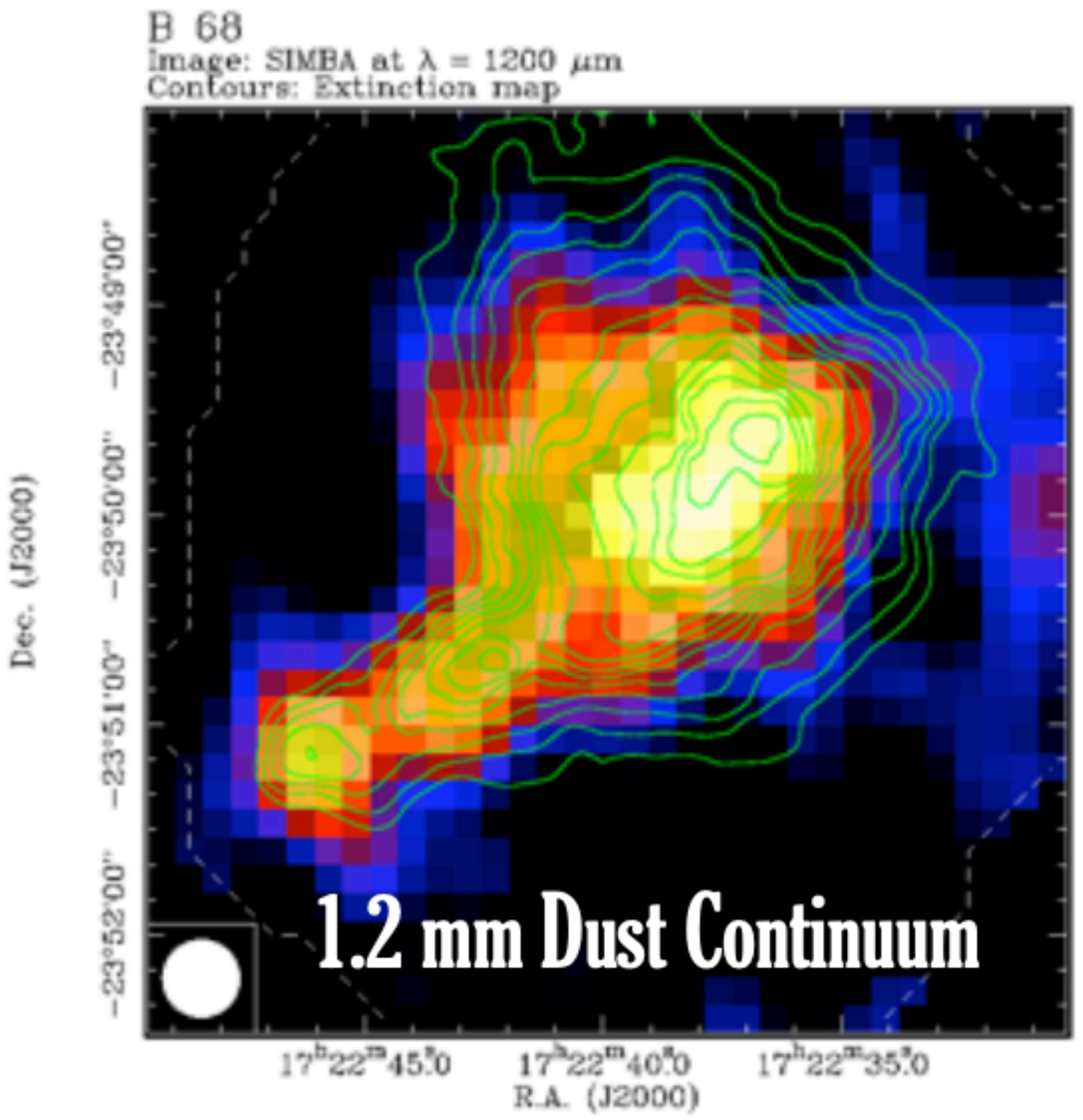
What sets the properties of the most pristine disks ?

Cabinet de curiosités: structures and sneak peaks at individual objects

What do we know of dust evolution while the star-disk system is built ?

Which instruments for the future (if time allows …) ?

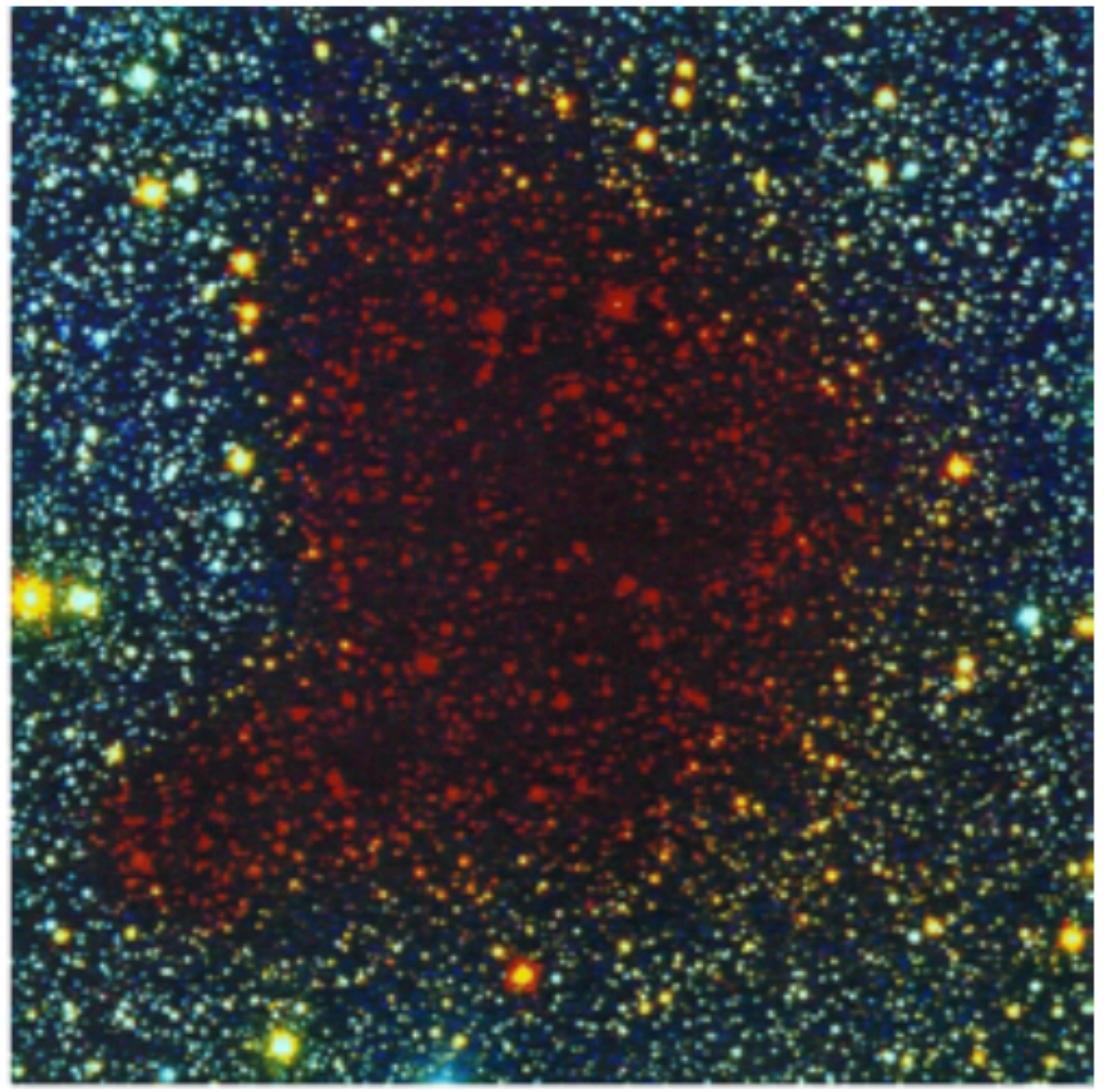
An isolated core: the Bok globule B68



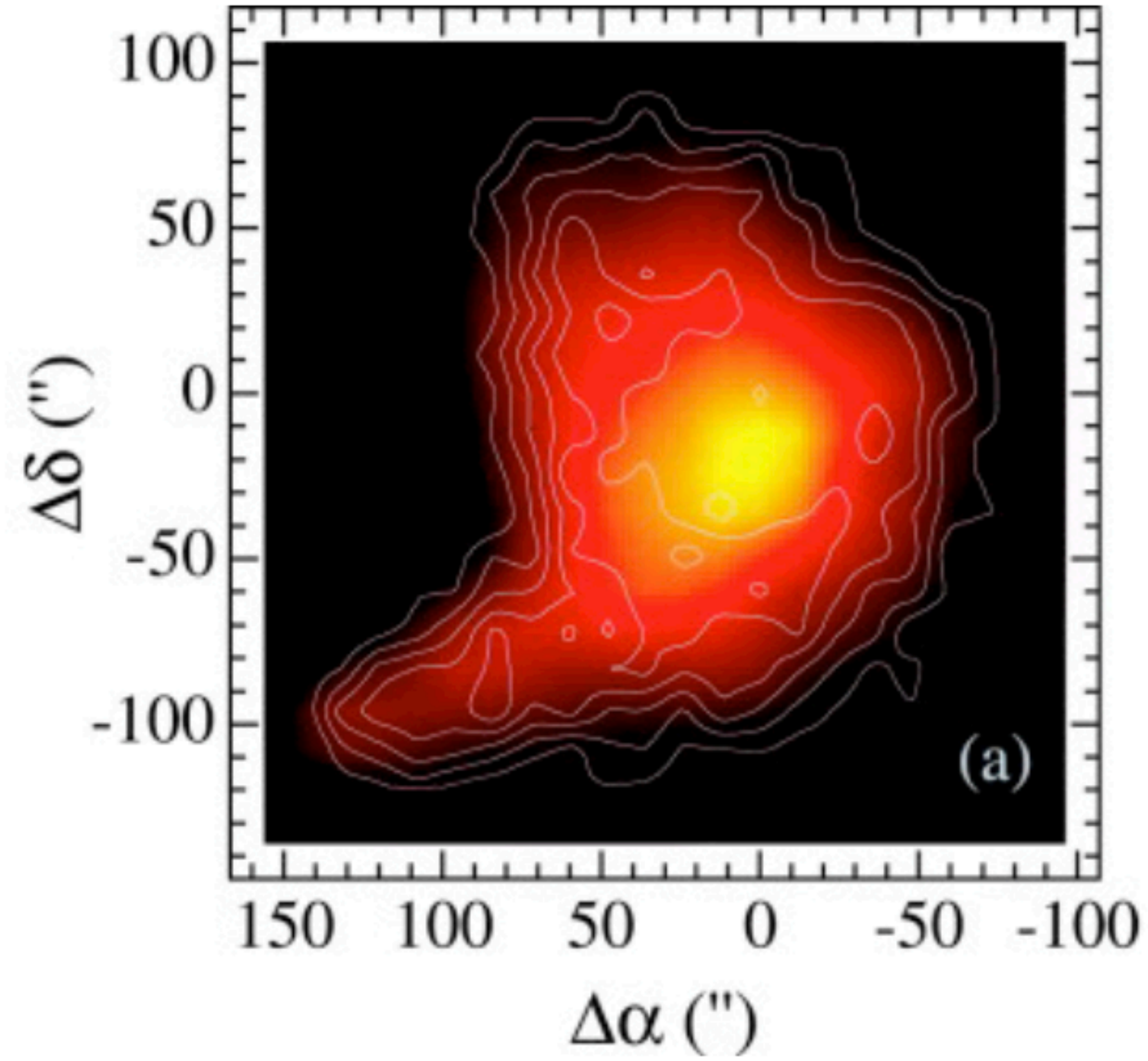
1.2 mm Dust Continuum

Optical

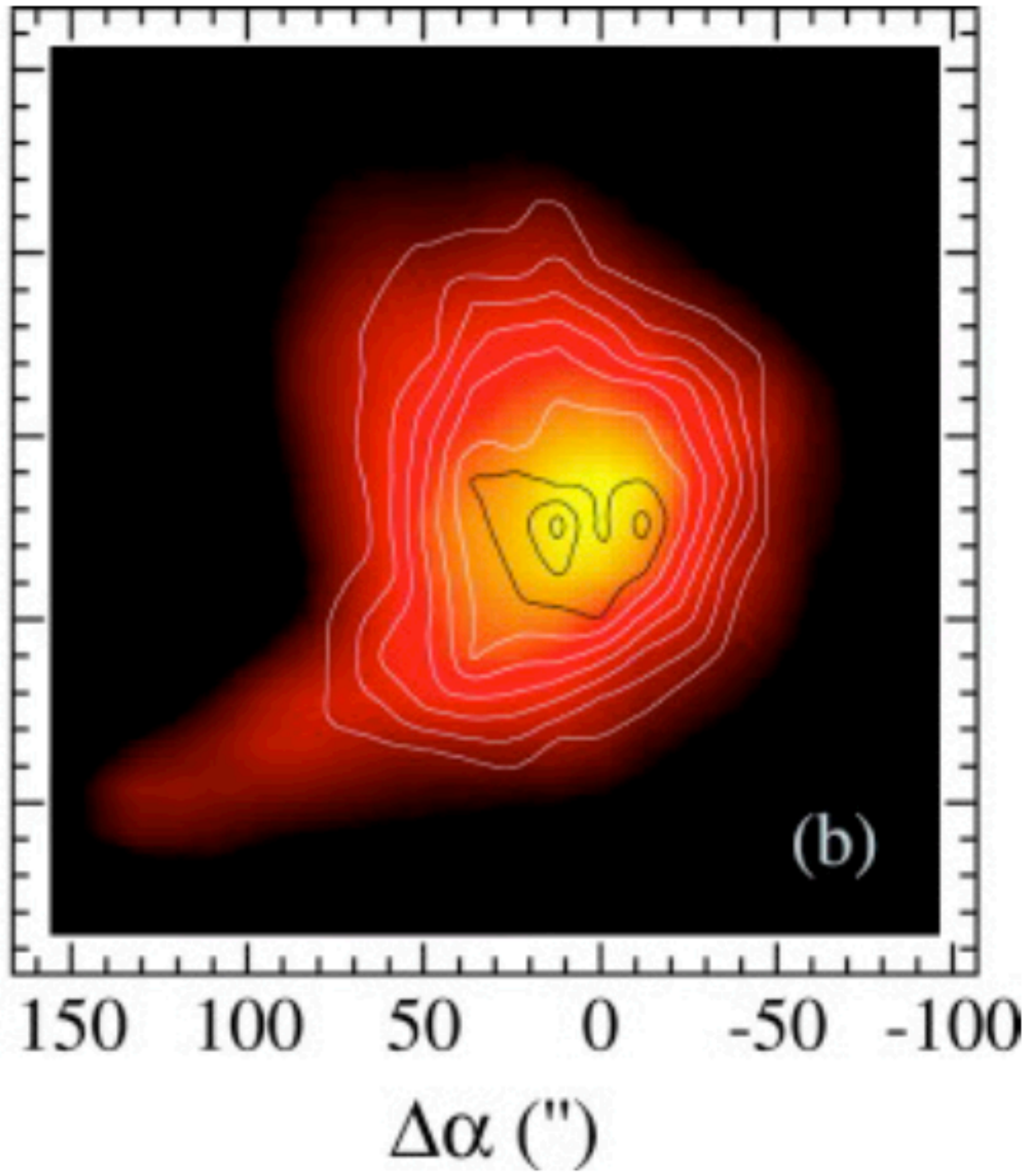
Near Infrared



$C^{18}O$



N_2H^+



Isothermal cloud in pressure equilibrium

$$\frac{dP}{dr} = -\frac{GM_r}{r^2}\rho \qquad \& \qquad \frac{dM_r}{dr} = 4\pi r^2 \rho$$

which can be combined into the Emden equation $\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2}{\rho}\frac{dP}{dr}\right) = -4\pi G\rho$

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Solved with boundary conditions: $\rho(0) = \rho_c$ and $\left.\frac{d\rho}{dr}\right|_{r=0} = 0$

and taking into account the equation of state (Bernoulli): $P = nkT = \frac{kT}{m}\rho = v_s^2\rho$

with the isothermal sound speed

$$v_s = \sqrt{\frac{\partial P}{\partial \rho}} = \sqrt{\frac{kT}{m}} \approx 0.06\sqrt{T[K]}[kms\, s^{-1}]$$

m is the mass of a gas particle

Isothermal cloud in pressure equilibrium

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with the isothermal sound speed

$$v_s=\sqrt{\frac{\partial P}{\partial\rho}}=\sqrt{\frac{kT}{m}}\approx 0.06\sqrt{T[K]}[kms\,s^{-1}]$$

m is the mass of a gas particle

At the outer edge (r=R) the cloud is bound by the outer pressure P_0
which is equal to the inner pressure at this point:

$$P_0=v_s^2\rho(R)$$

Isothermal cloud in pressure equilibrium

Using variable subsitutions: $\begin{cases} y = \dfrac{\rho}{\rho_c} \\ x = r\sqrt{\dfrac{4\pi G m \rho_c}{kT}} \end{cases}$ leads to the following form of the Emden equation:

$$y'' - \frac{y'^2}{y} + \frac{2y'}{x} + y^2 = 0$$

With boundary conditions :

$$y(0) = 1 \text{ and } y'(0) = 0$$

the family of solutions are Bonnor-Ebert spheres

Stability

One can calculate P0(R), and derivate the criterium for stability : $\frac{\partial P_0}{\partial R} < 0$

$$P_0(x) = v_s^2 \rho_c y(x) = \left(\frac{kT}{m} \right)^4 \frac{1}{G^3 M^2} \frac{I^2(x) y(x)}{4\pi}$$

with $I(x) = \int_0^x y(x') x'^2 dx'$

$$R = \left(\frac{kT}{4\pi G m \rho_c} \right)^{1/2} = \frac{Gm}{kT} M \frac{x}{I(x)}$$

Stability

One can calculate P₀(R), and derivate the criterium for stability : $\frac{\partial P_0}{\partial R} < 0$

$$P_0(x) = v_s^2 \rho_c y(x) = \left(\frac{kT}{m}\right)^4 \frac{1}{G^3 M^2} \frac{I^2(x)\, y(x)}{4\pi}$$

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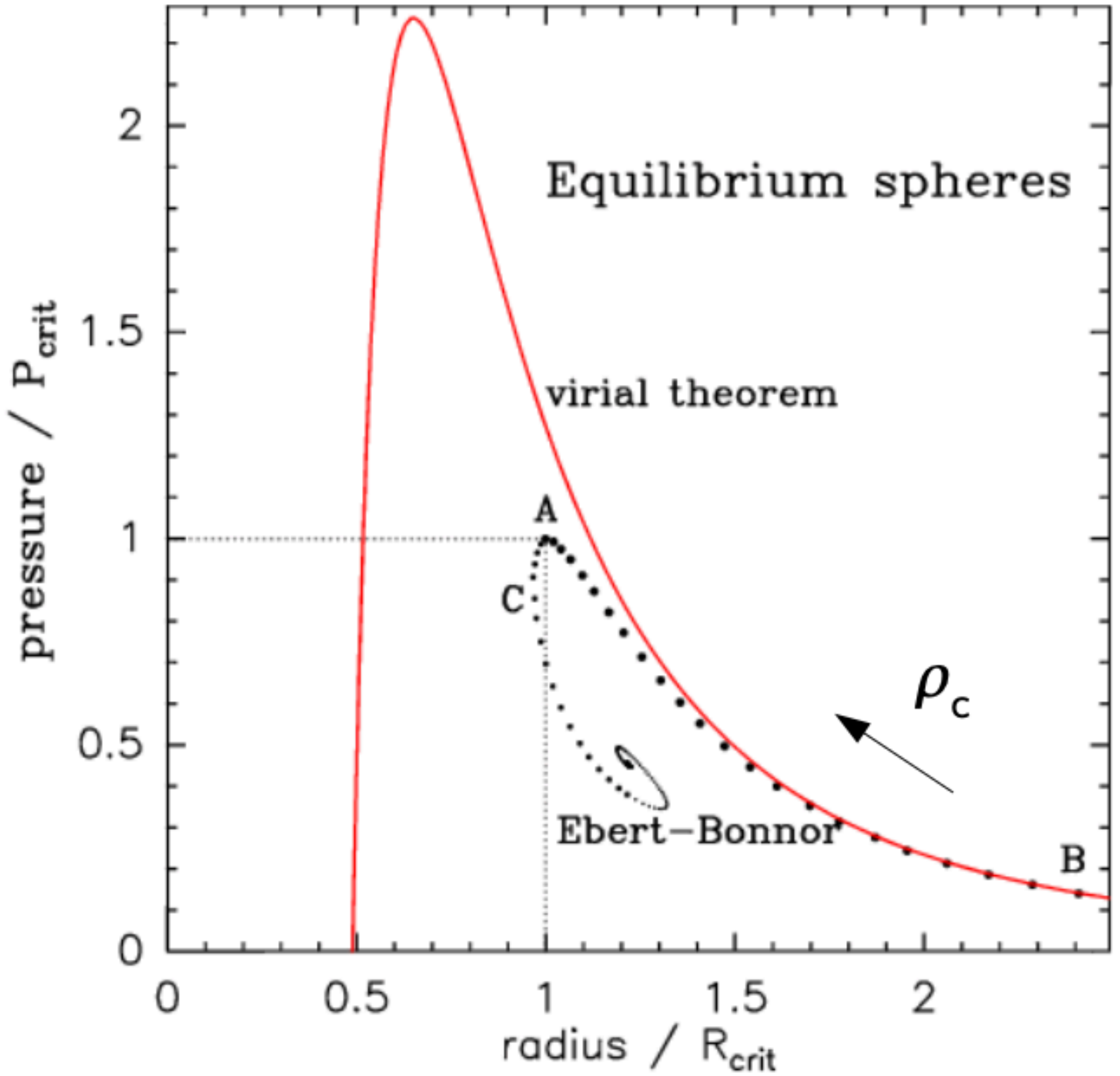
$$R = \left(\frac{kT}{4\pi G m \rho_c}\right)^{1/2} = \frac{Gm}{kT} M \frac{x}{I(x)}$$

Leads to the following expressions of the critical values for stability:

$P_{crit} = 1.40 \frac{k^4}{G^3 m^4} \frac{T^4}{M^2}$ maximum outer pressure

$R_{crit} = 0.411 \frac{Gm}{kT} M$ minimum radius for stability



Critical mass: singular isothermal sphere

$$M = 4\pi \int_0^R r^2 \rho \, dr = \frac{1}{\sqrt{4\pi\rho_c}} \left[\frac{kT}{Gm}\right]^{3/2} \int_0^{x_u} y \, x^2 \, dx$$

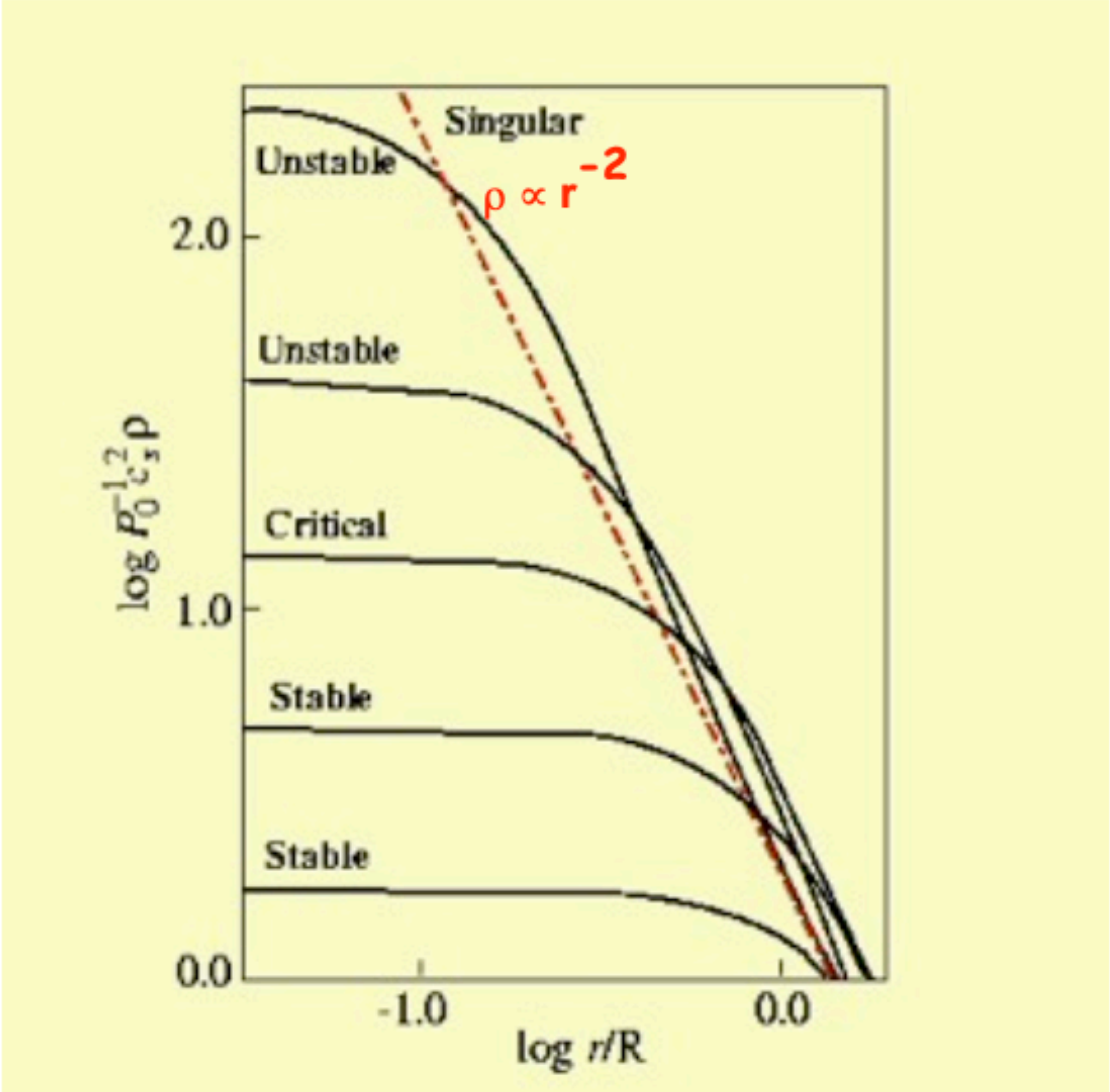
with $x_u = R\sqrt{4\pi G \rho_c / v_s^2}$

Critical mass derived from critical pression and radius expressions:

$$M_{crit} = 1.18 \frac{v_s^4}{G^{3/2}} P_{ext}^{-1/2}$$

or depending on density and the ambient temperature:

$$M_{crit} = 1.18\,(c_s^4/G^{3/2})\,\rho_0^{-1/2} \propto T^{3/2}\,\rho_0^{-1/2}$$



For the dense regions of molecular clouds: $n_H = 10^4$ cm^{-3} T= 10 K, we find:

- $M_c \sim 1.0\ M_\odot$
- $R_c \sim 0.05$ pc

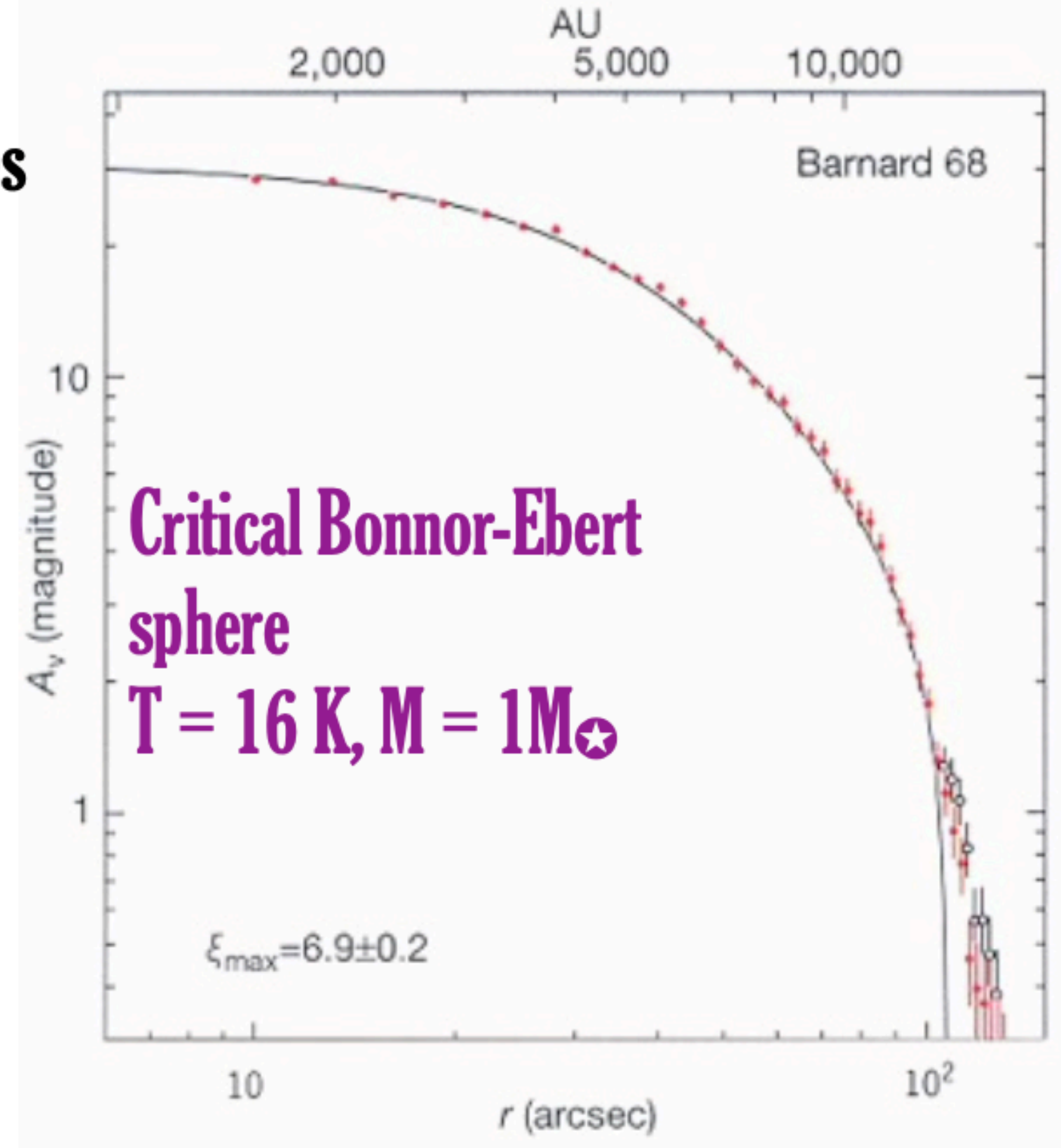
Warning: the picture is probably much more dynamical ! This is a textbook example

See F. Motte's lecture this week

An isolated core: the Bok globule B68

Relatively isolated, hence not many external disturbances

Though not main mode of star formation, their isolation makes them good test-laboratories for theories!



Critical Bonnor-Ebert sphere
T = 16 K, M = $1M_\odot$

Alves et al. 2001, Nature

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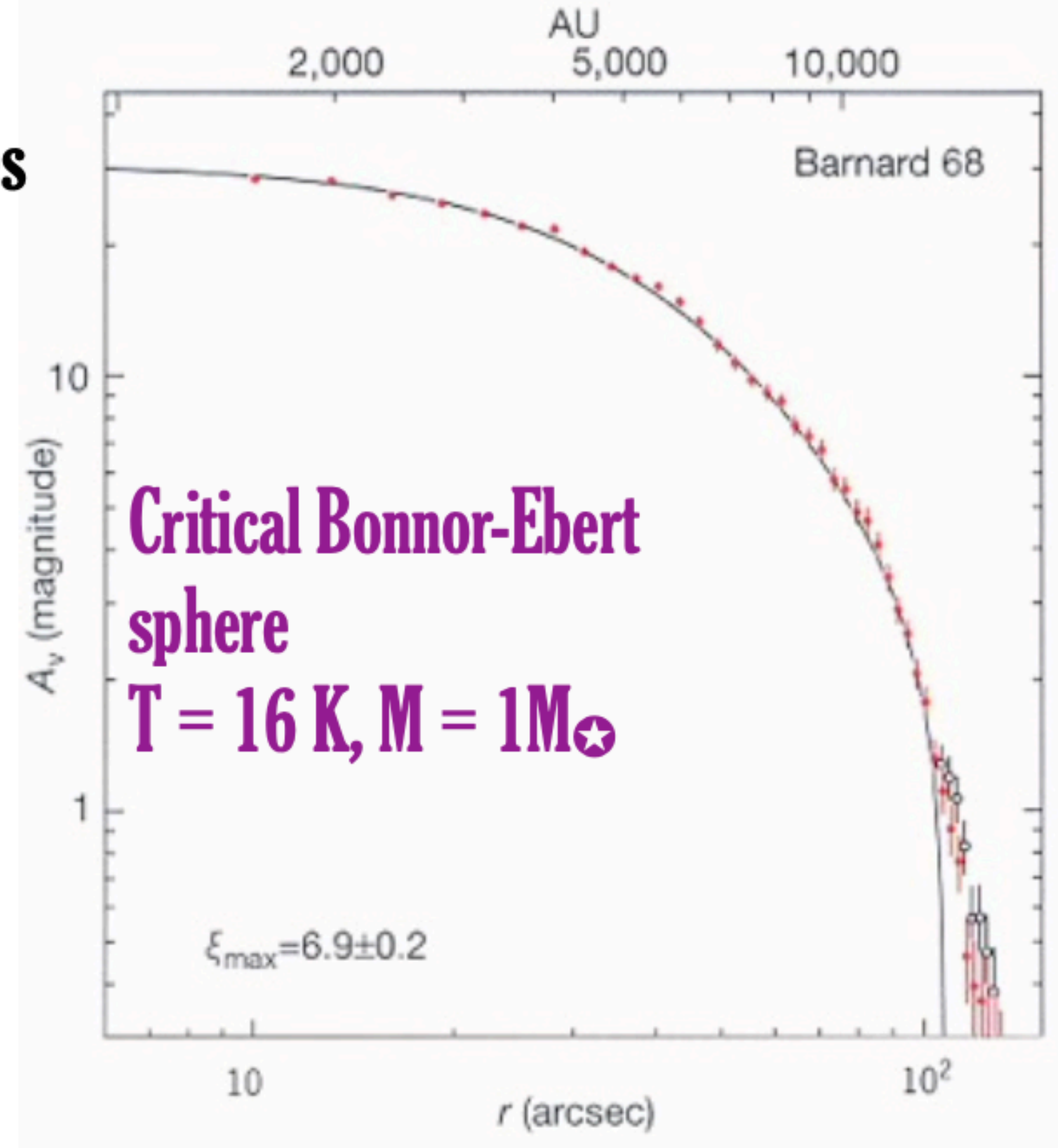


Critical Bonnor-Ebert sphere
$T = 16$ K, $M = 1 M_\odot$

Alves et al. 2001, Nature

In astrophysics, the Bonnor–Ebert mass is the largest mass that an isothermal gas sphere embedded in a pressurized medium can have while still remaining in hydrostatic equilibrium. Clouds of gas with masses greater than the Bonnor–Ebert mass must inevitably undergo gravitational collapse to form much smaller and denser objects.

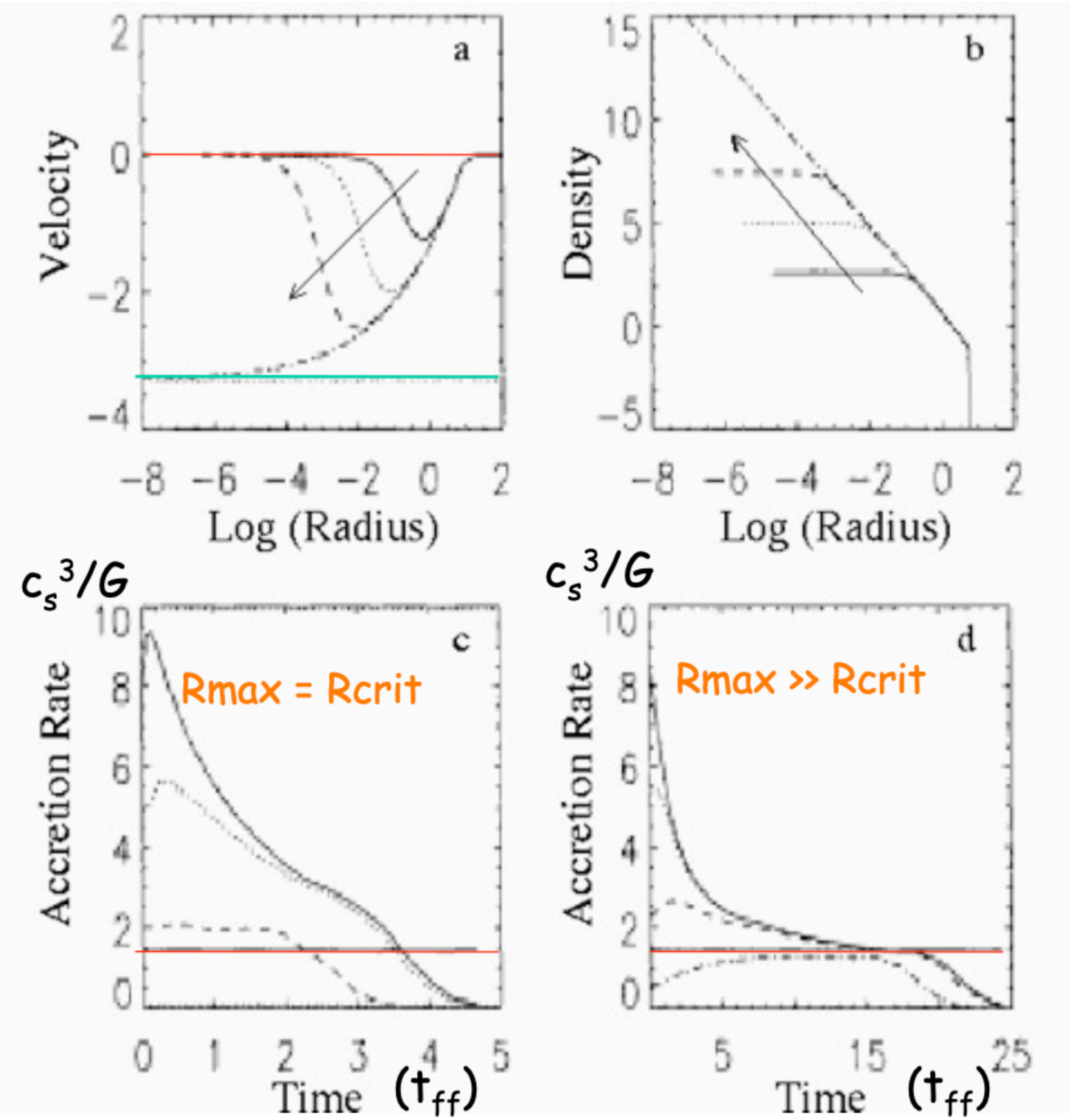
Collapse of Bonnor-Ebert spheres

Ways to cause BE sphere to collapse:

- Increase external pressure until $M_{critical}<M$
- Load matter onto BE sphere until $M>M_{critical}$

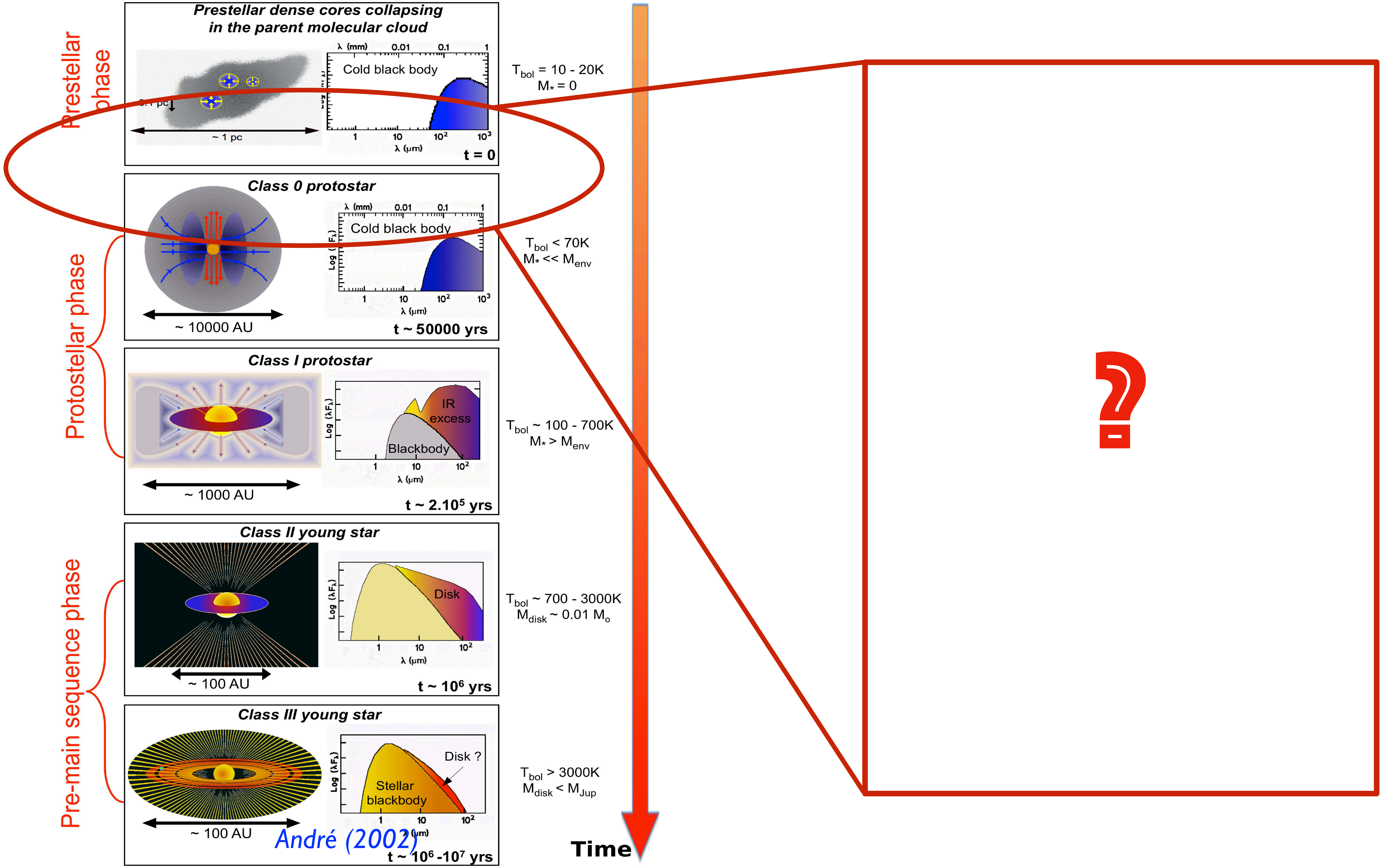
The accretion rate has an initial peak at
$10\ c_s^3/G \sim 2\ 10^5\ M_\odot$ /year,
then decreases with time.

If $R_{max} >> R_{critical}$:
late phase with $dM/dt \sim c_s^3/G$
(cf.Shu)



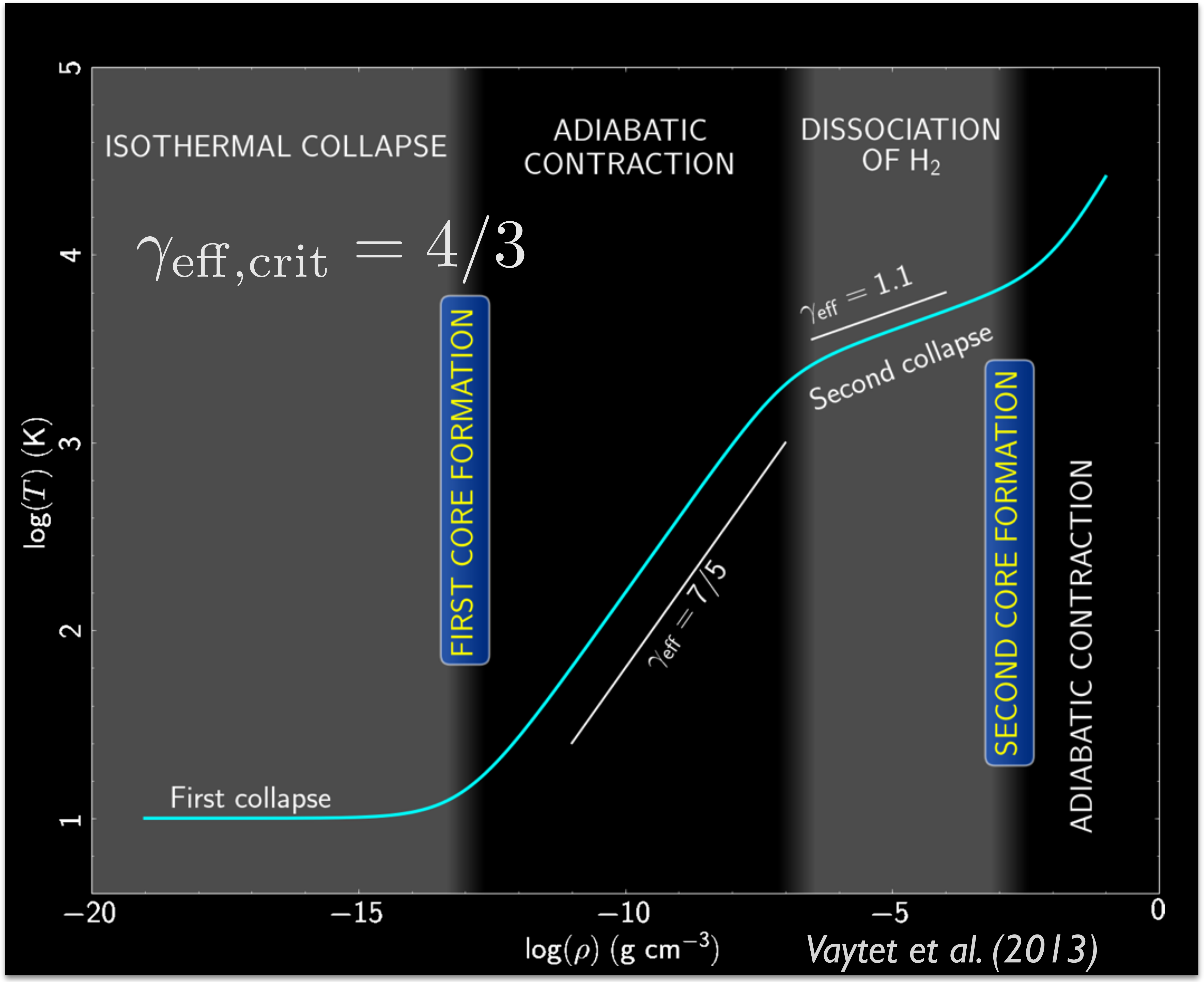
Foster & Chevalier (1993)

We have triggered the collapse, what happens next ?



André (2002)

We have triggered the collapse, what happens next ?



Vaytet et al. (2013)

$$M_{\mathrm{Jeans}} \propto \rho^{\frac{3\gamma_{\mathrm{eff}}}{2}-2} \quad \text{if} \quad P \propto \rho^{\gamma_{\mathrm{eff}}}$$

SEE HENNEBELLE'S LECTURE

Prestellar dense core collapse
(R=0.01 pc, T=10 K, n=10^6 cm^{-3})

First collapse

Isothermal ***$10^{4,5}$ yr***

Adiabatic **First Larson core**
(R=10 AU, T=100 K, n=10^{12} cm^{-3})

a few 10^3 yr

H_2 dissociation

Second collapse

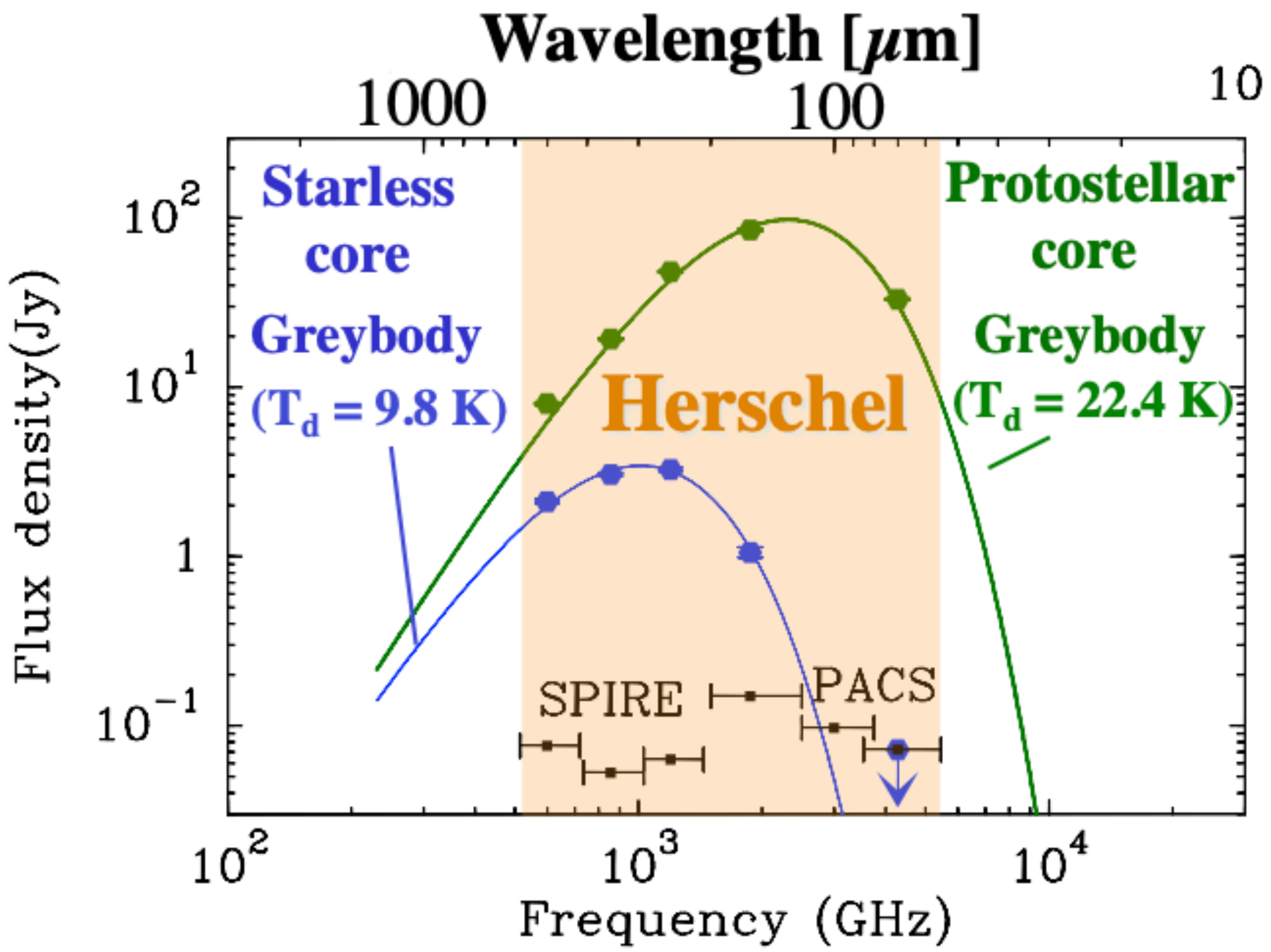
Quasi - isothermal ***10^2 yr***

Second Larson core
(R=0.01 AU, T=$10^{4\text{-}5}$ K, n=0.01cm^{-3})

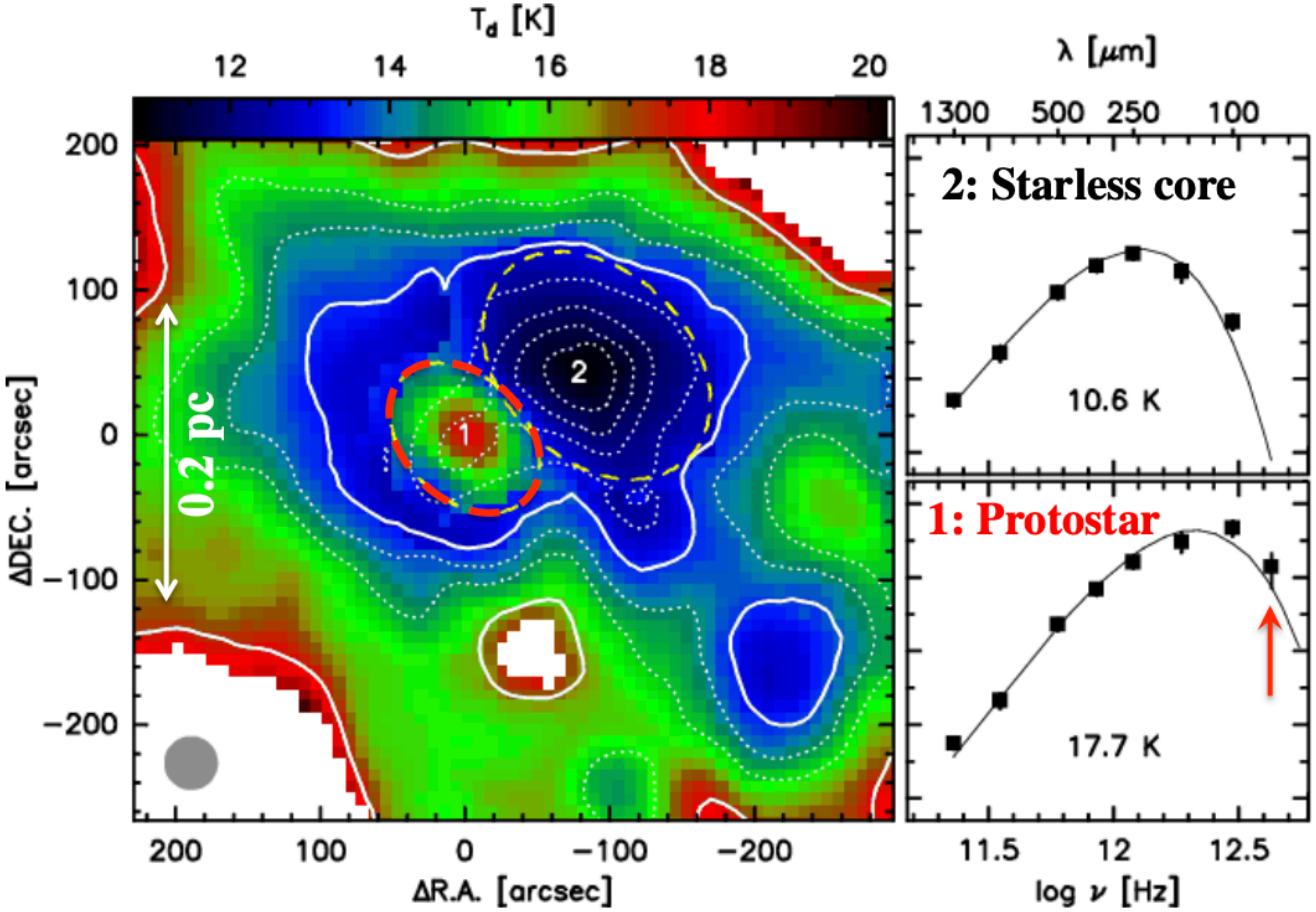
Larson (1969)

Main accretion phase: ***10^4-10^5 years …***

How to recognize protostars from prestellar cores ?



CB 244: T_{dust} map & N_H contours



Protostar

=

emission at wavelengths < 70 microns

($F_{70\mu}$ <–> L_{proto}
cf. Dunham,
Crapsi, Evans e.a.
2008 *Spitzer* c2d)

A. Stutz, R. Launhardt et al. 2010
***Herschel* EPoS Project (PI: O. Krause)**

Counting protostars: typical timescales for the main accretion phase

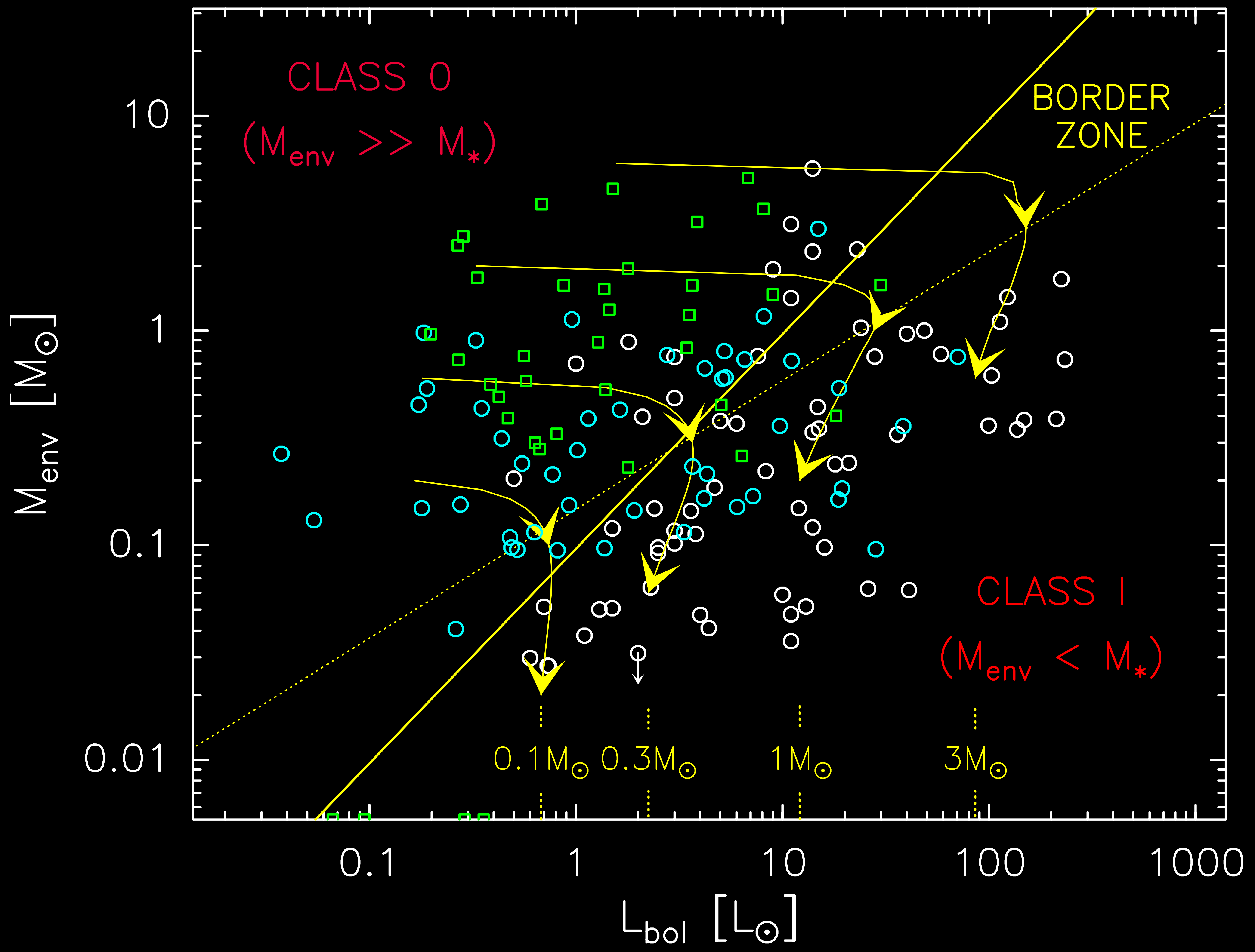
Spitzer surveys gave average Class 0 lifetime 1-5 x 10^5 years
(Enoch+ 2009, Evans+ 2009)
See Dunham+2015 for (small) updates on c2d & Taurus numbers

Complete surveys including sub-mm wavelengths:

Class 0 lifetime 5x10^4 years

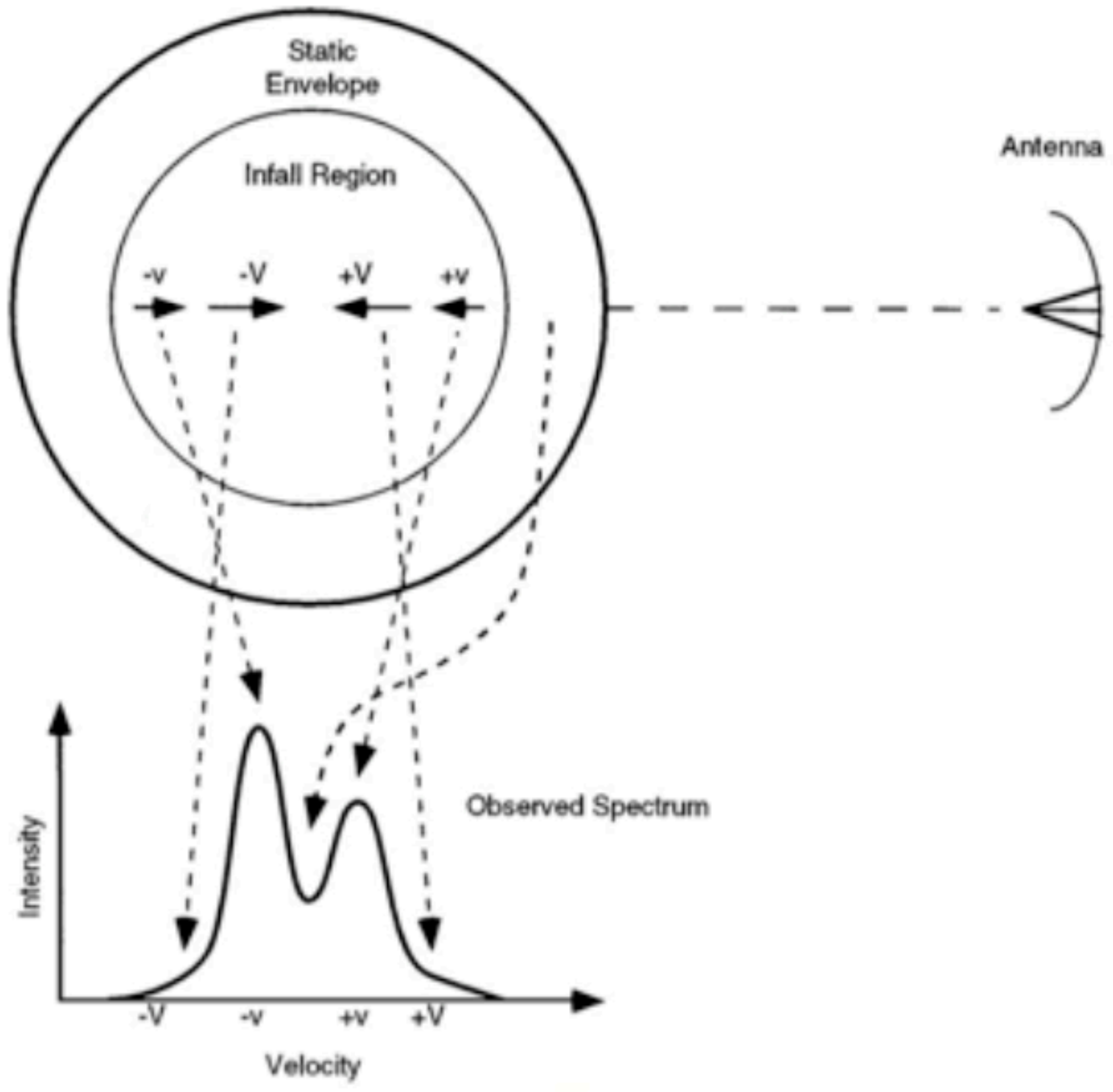
+ over-abundance of low-luminosity Class I protostars

Maury+ (2011)
Aquila protostars
Sadavoy+ (2014)
Perseus protostars



The accretion has to be efficient to get such a short phase
Corollary: there are not many young protostars …

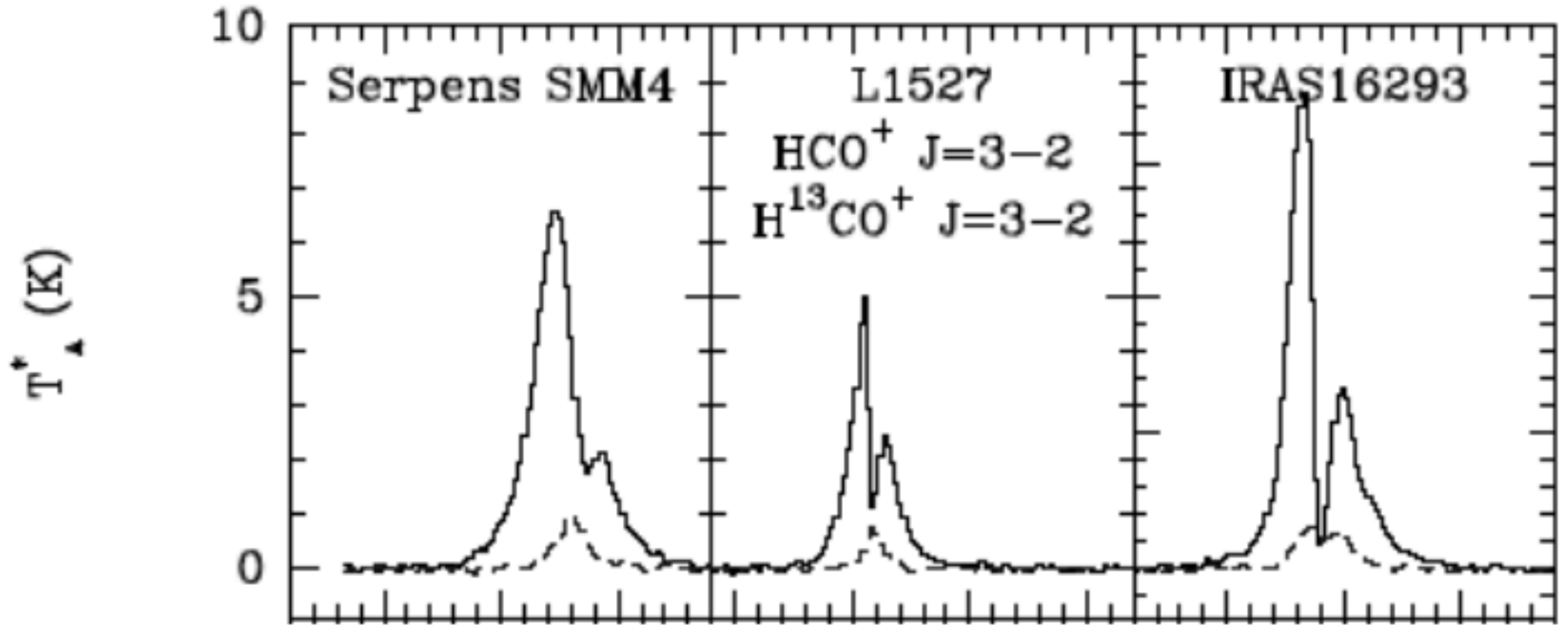
Observing the infall

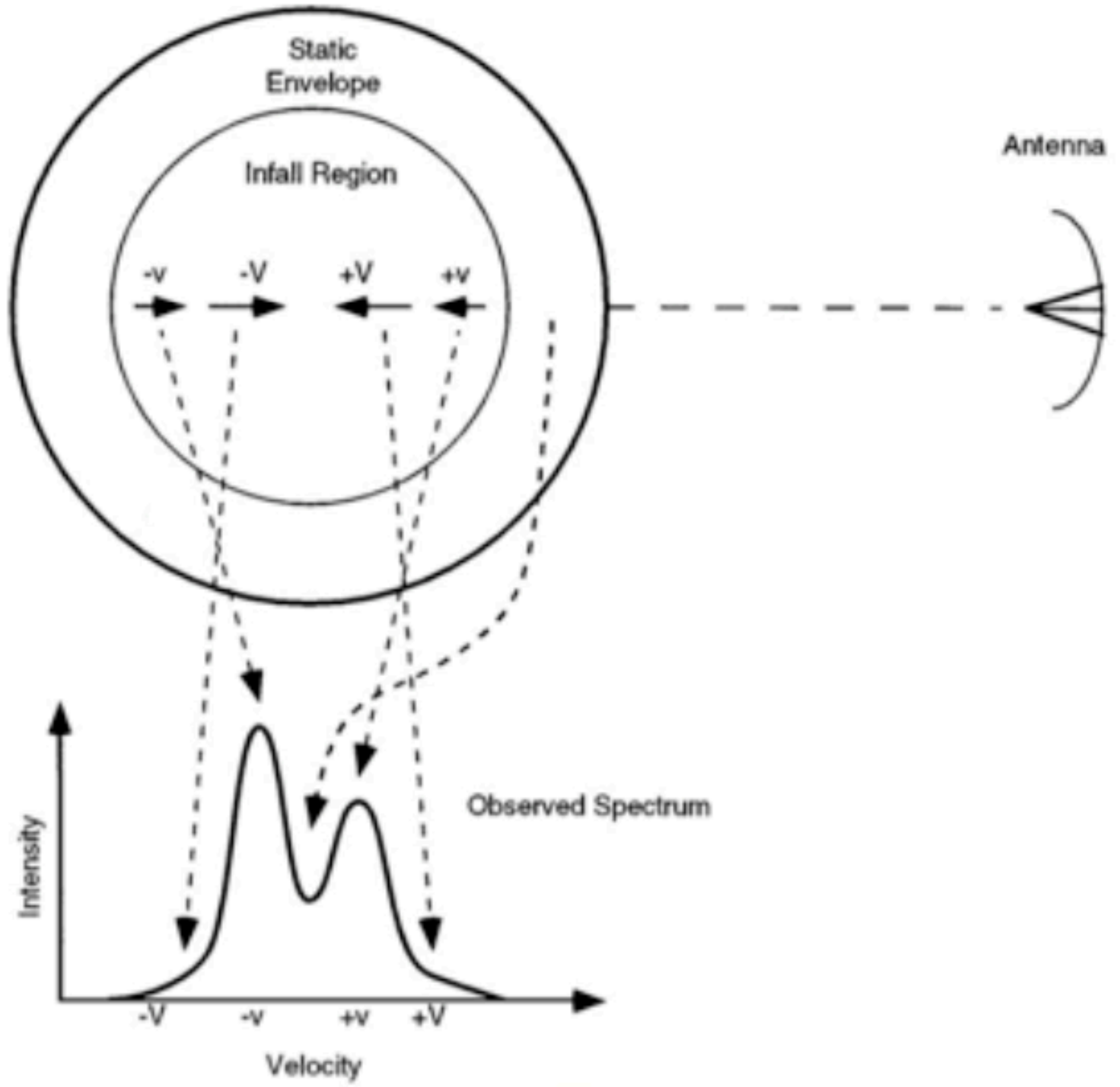


Observing the infall

- Identified through asymmetric line profiles

  Commonly used: HCO+, CS, H2CO, N2H+

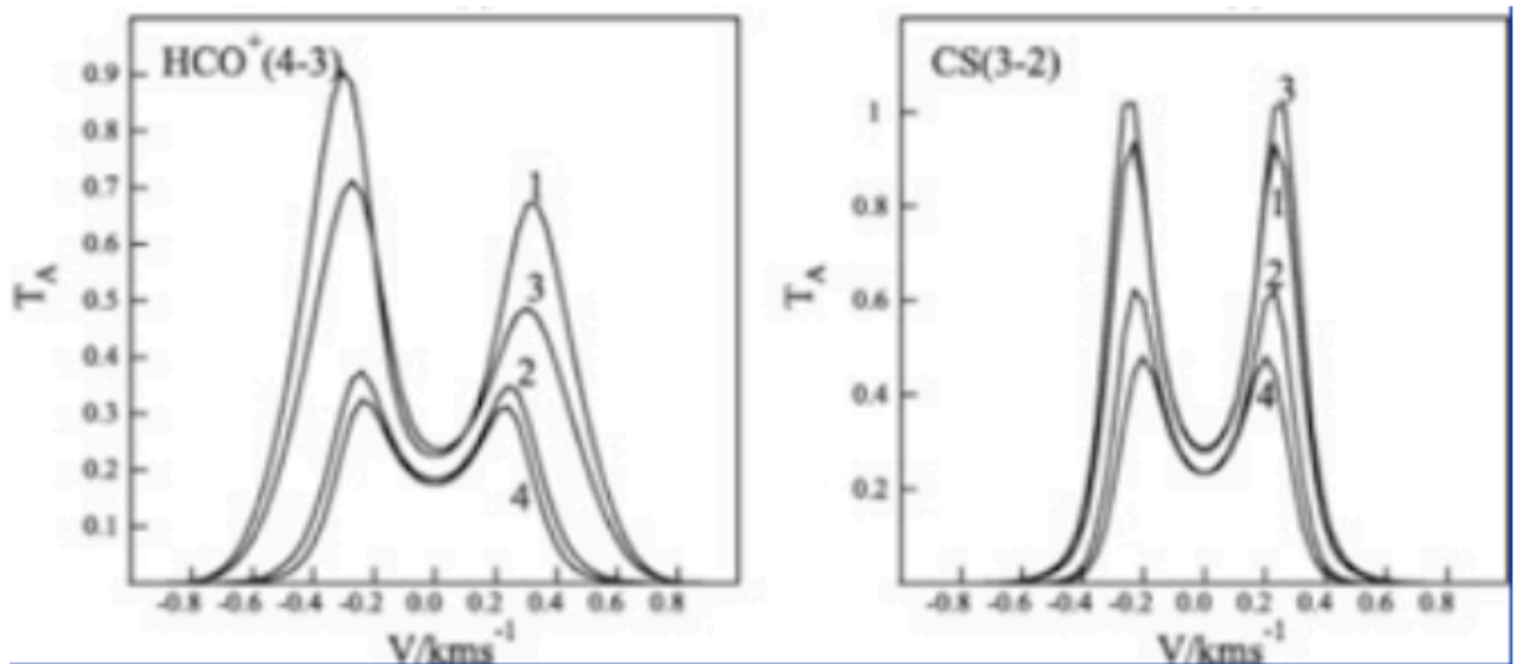


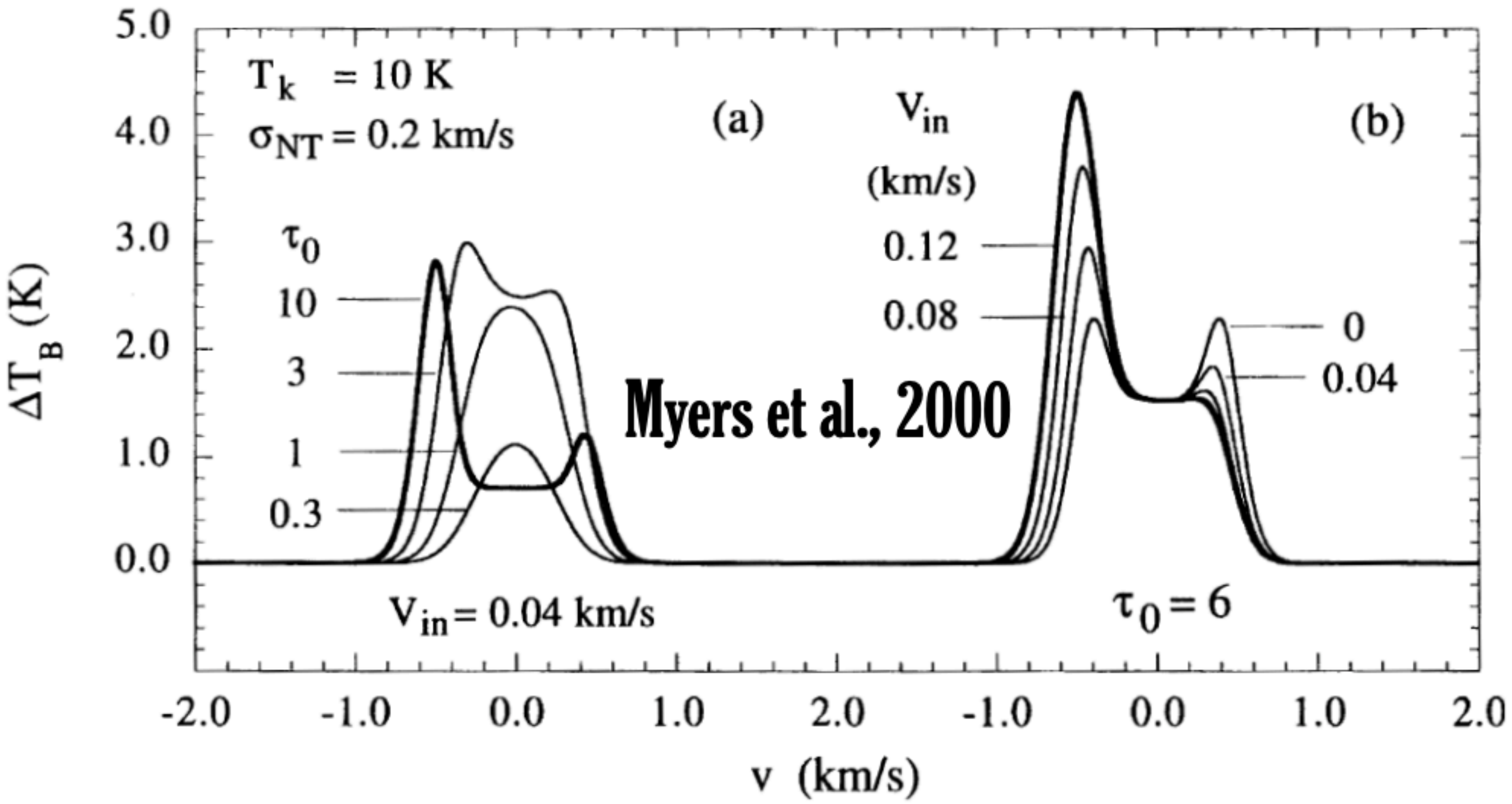


- Caution!

  Depletion can affect line profiles

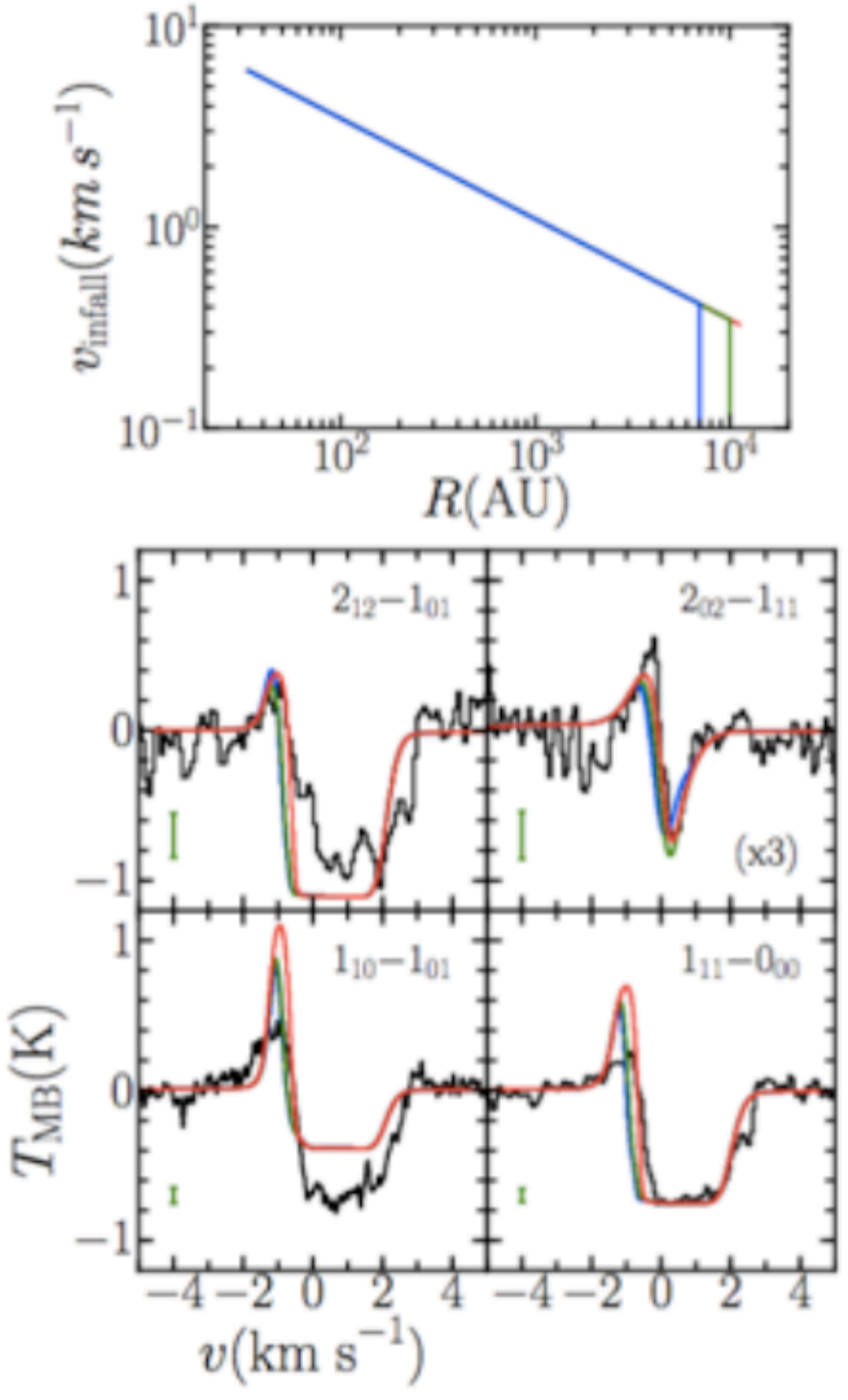
  and infall signature !





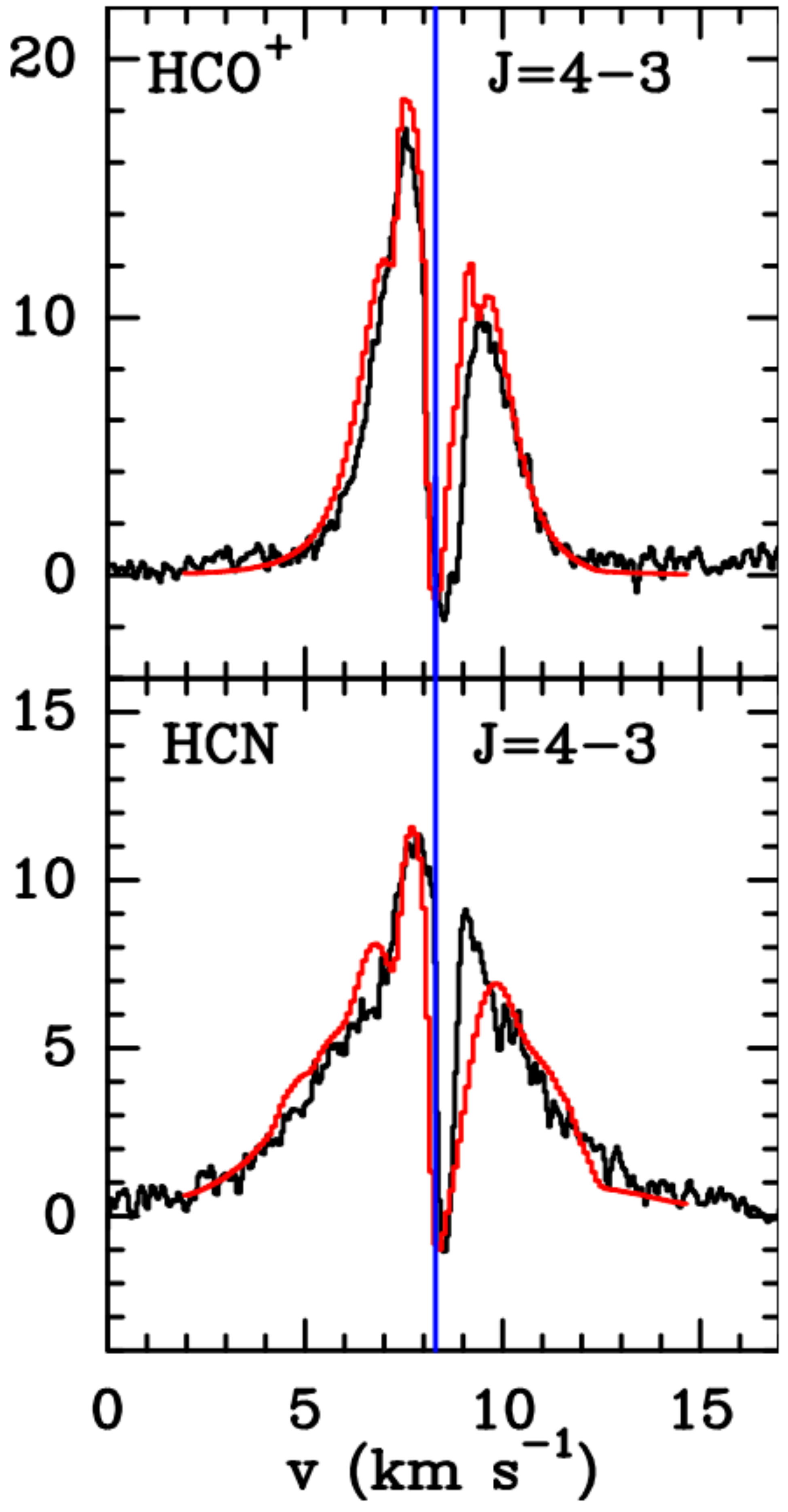
Myers et al., 2000

Measuring the infall



IRAS4A (Mottram+ 2013): water lines
Herschel WISH

B335 (Evans+ 2015):
ALMA 50 AU resolution



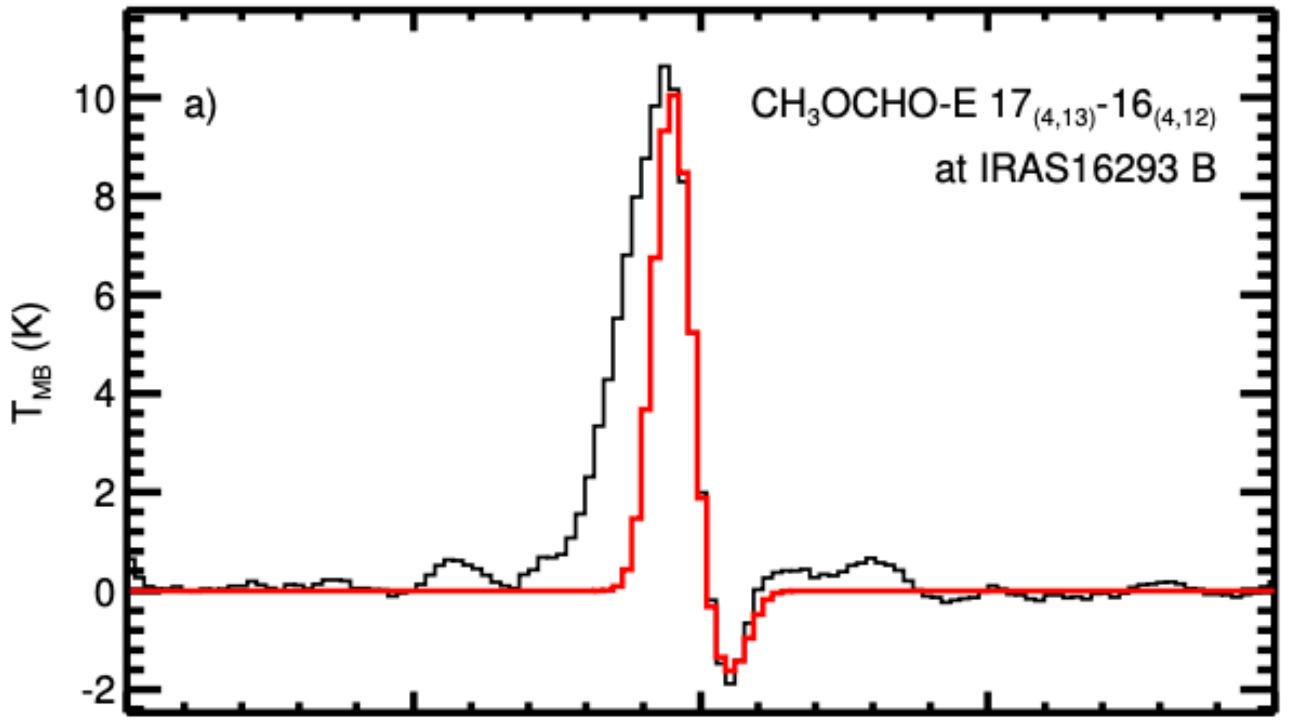
mass infall rate 3x10^{-6} M$_o$/yr

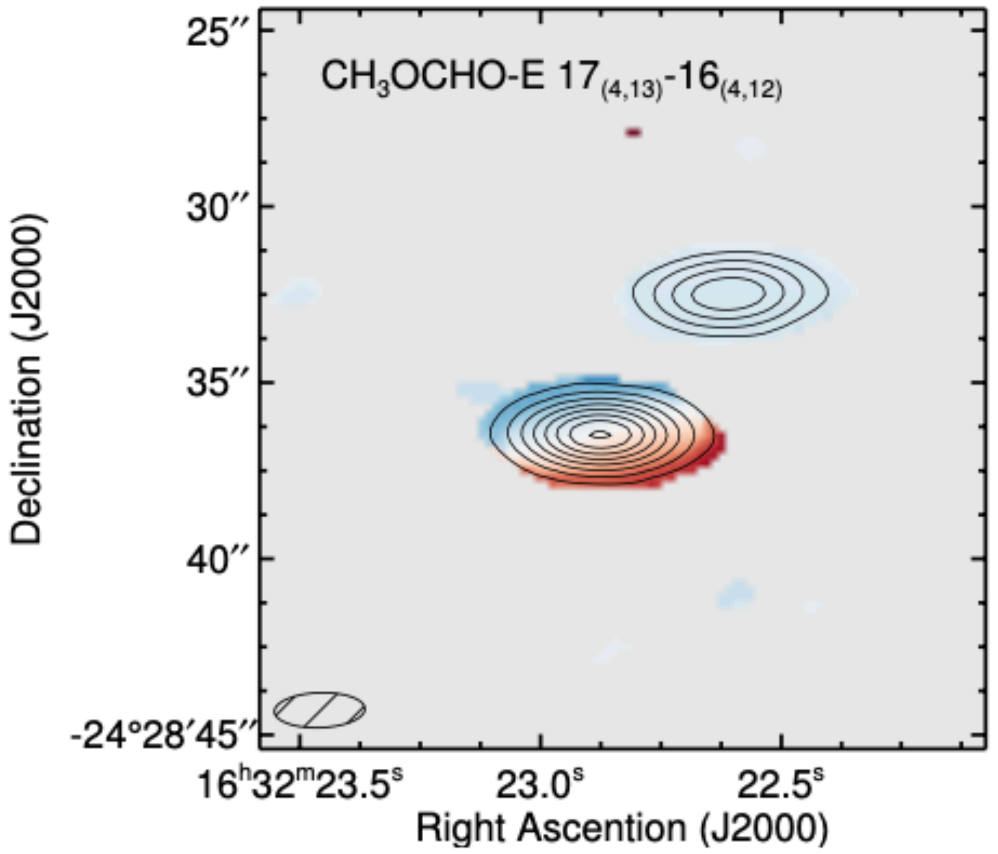
accretion rate 9.6x10^{-7} M$_o$/yr

age 5x10^4 yrs

$$\dot{M}_{\rm acc} = \frac{L_\star R_\star}{G M_\star f_{\rm acc}},$$

IRAS 16293B (Pineda+ 2012): ALMA 120 AU resolution



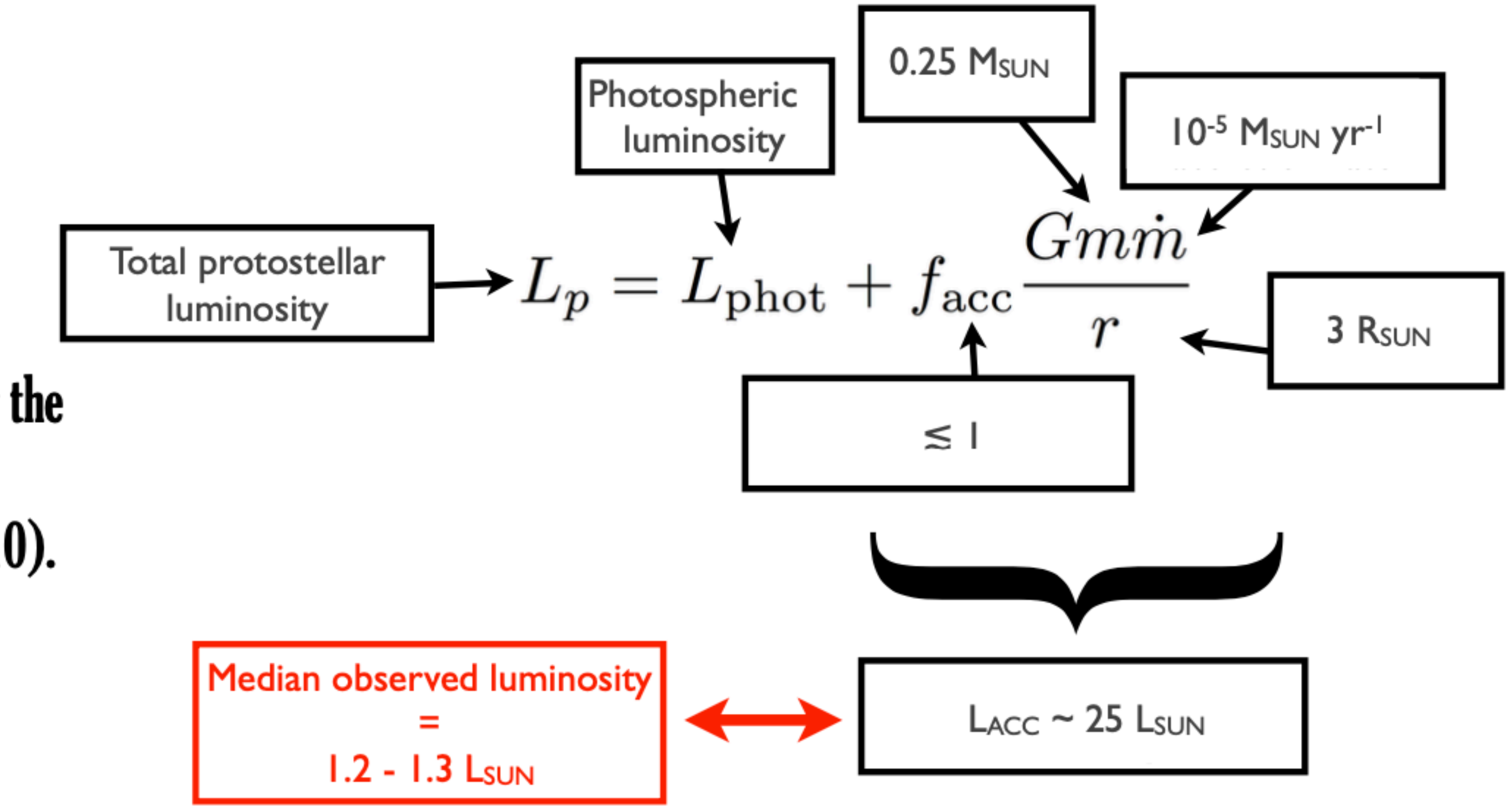


infall speed 0.5-0.7 km/s

mass infall rate 4x10^{-5} M$_o$/yr

Luminosity problem:

Protostars have luminosities < than would be expected for the accretion rate determined from the IMF + observed star formation rate (Kenyon & Hartmann 1990, Dunham+ 2010).



$$L_p = L_{\rm phot} + f_{\rm acc}\frac{Gm\dot{m}}{r}$$

Total protostellar luminosity

Photospheric luminosity

0.25 M_{SUN}

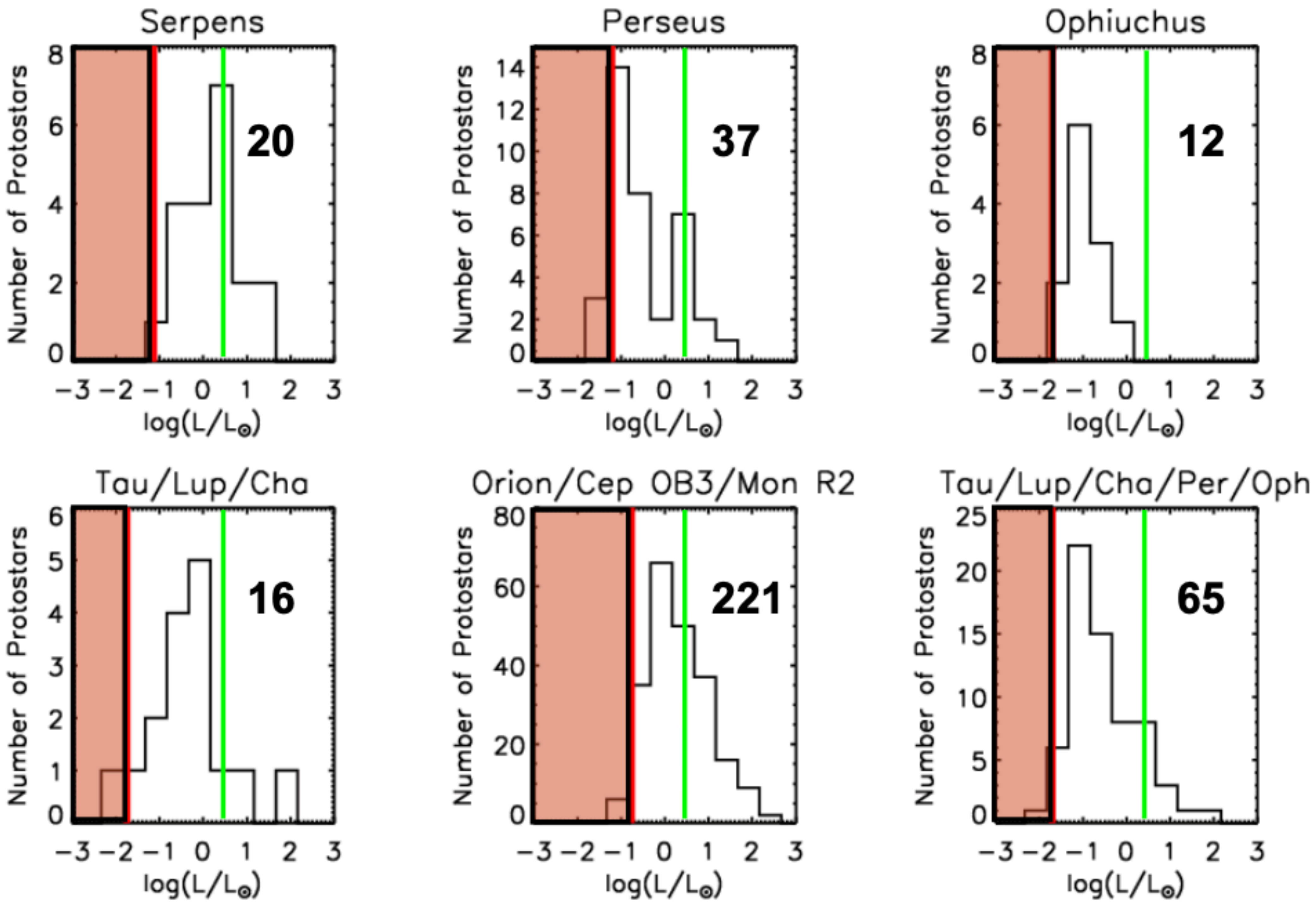
10^{-5} M_{SUN} yr^{-1}

3 R_{SUN}

≲ 1

L_{ACC} ~ 25 L_{SUN}

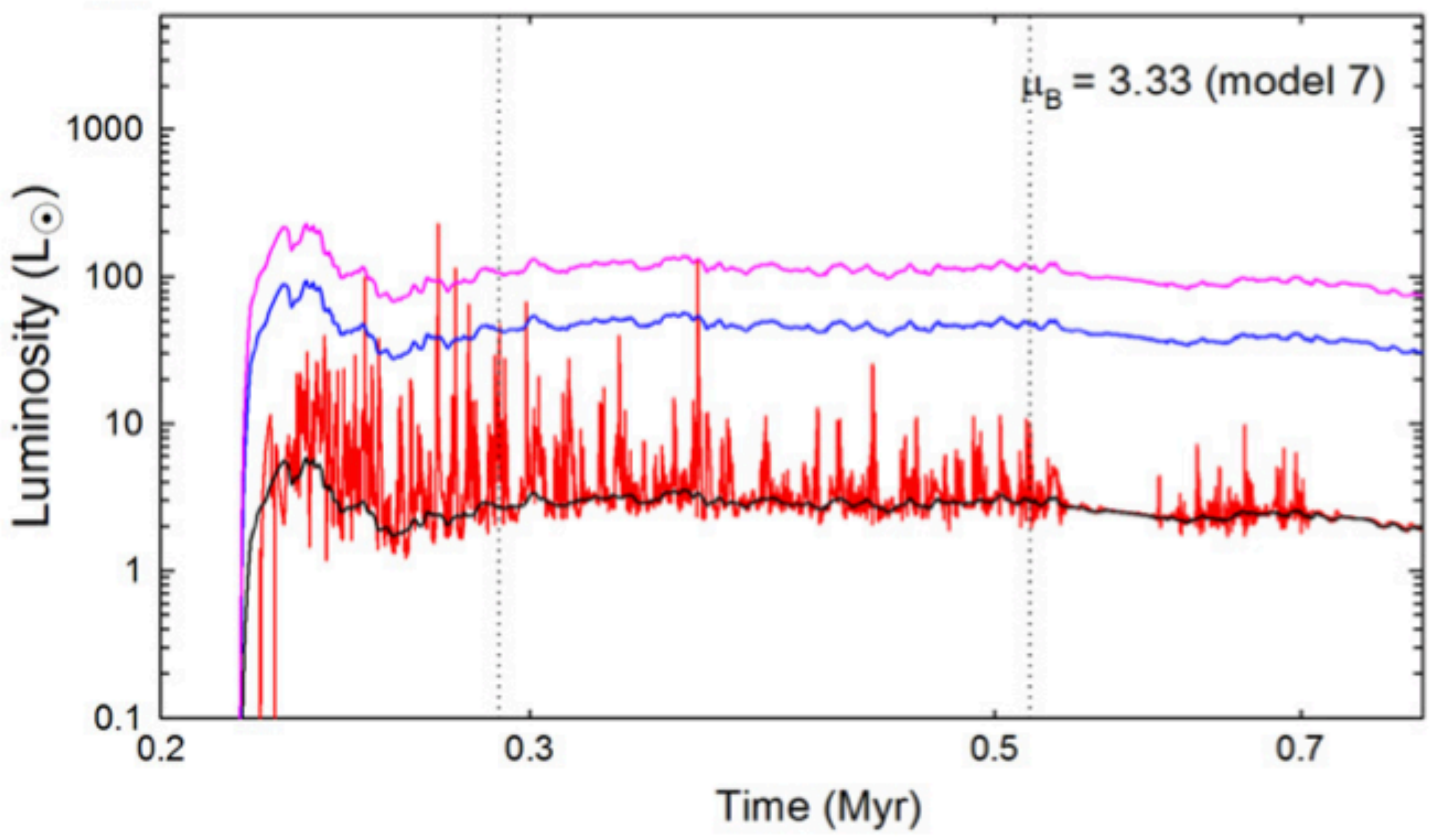
Median observed luminosity = 1.2 - 1.3 L_{SUN}



Spitzer surveys: luminosities < than expected for continuous accretion over 5 x 10^5 years (L_{acc} ~ 5 L_{sun}), particularly for low mass regions (Kryukova+ 2012)

Caution: improved the coverage of the low luminosity tail by extrapolating bolometric luminosity from a well sampled SED in the MIR but lacks FIR data points

Episodic Accretion ?



Offner+ 2011, Dunham+ 2014, Vorobyov+ 2015

Embedded protostars: difficult to observe the accretion bursts directly

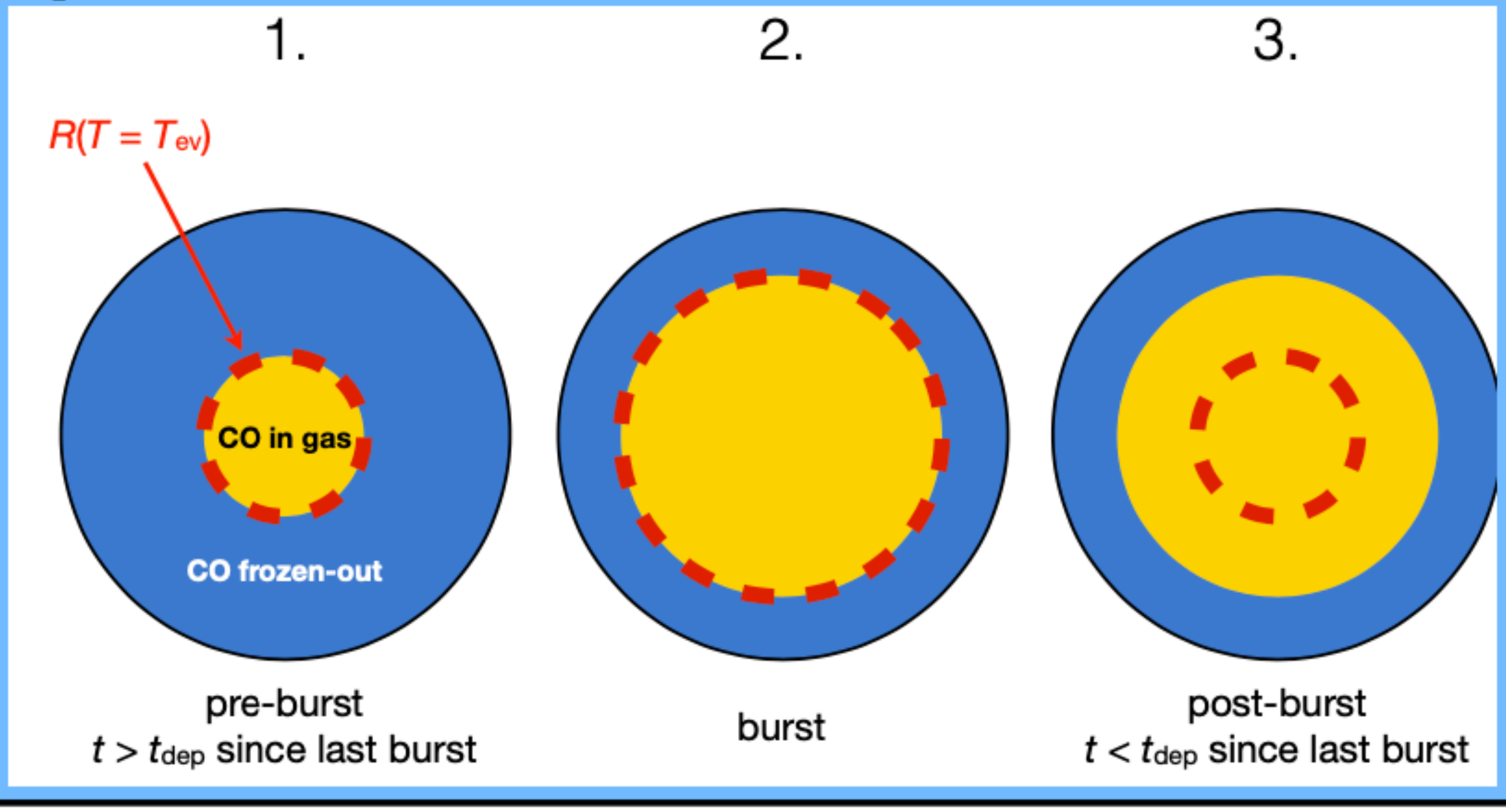
Some indirect clues:
- periodic shocks observed in protostellar jets
- chemical probes of temperature variations

Jorgensen+ (2015), Anderl+ (2015): extent of C18O emission in protostellar envelopes does not follow the expectations from the temperature profile

=> suggests a recent increase in temperature that allowed CO in the gaz phase at larger radii in the recent past

chemistry timescale > cooling down timescale of the gaz would explain why CO is observed where the current temperature is <30K

=> interpreted as a clue for accretion burst

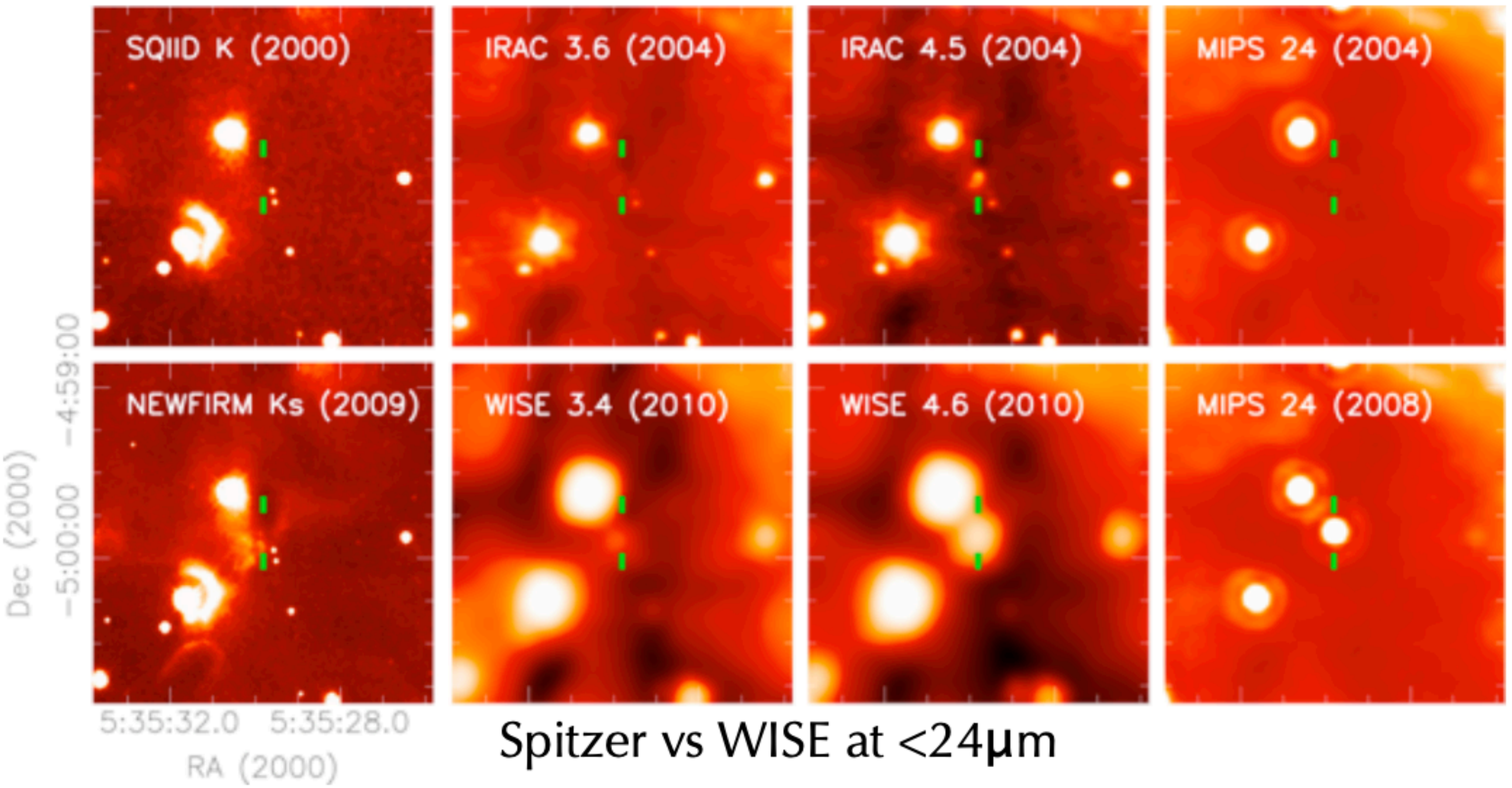


pre-burst
$t > t_{dep}$ since last burst

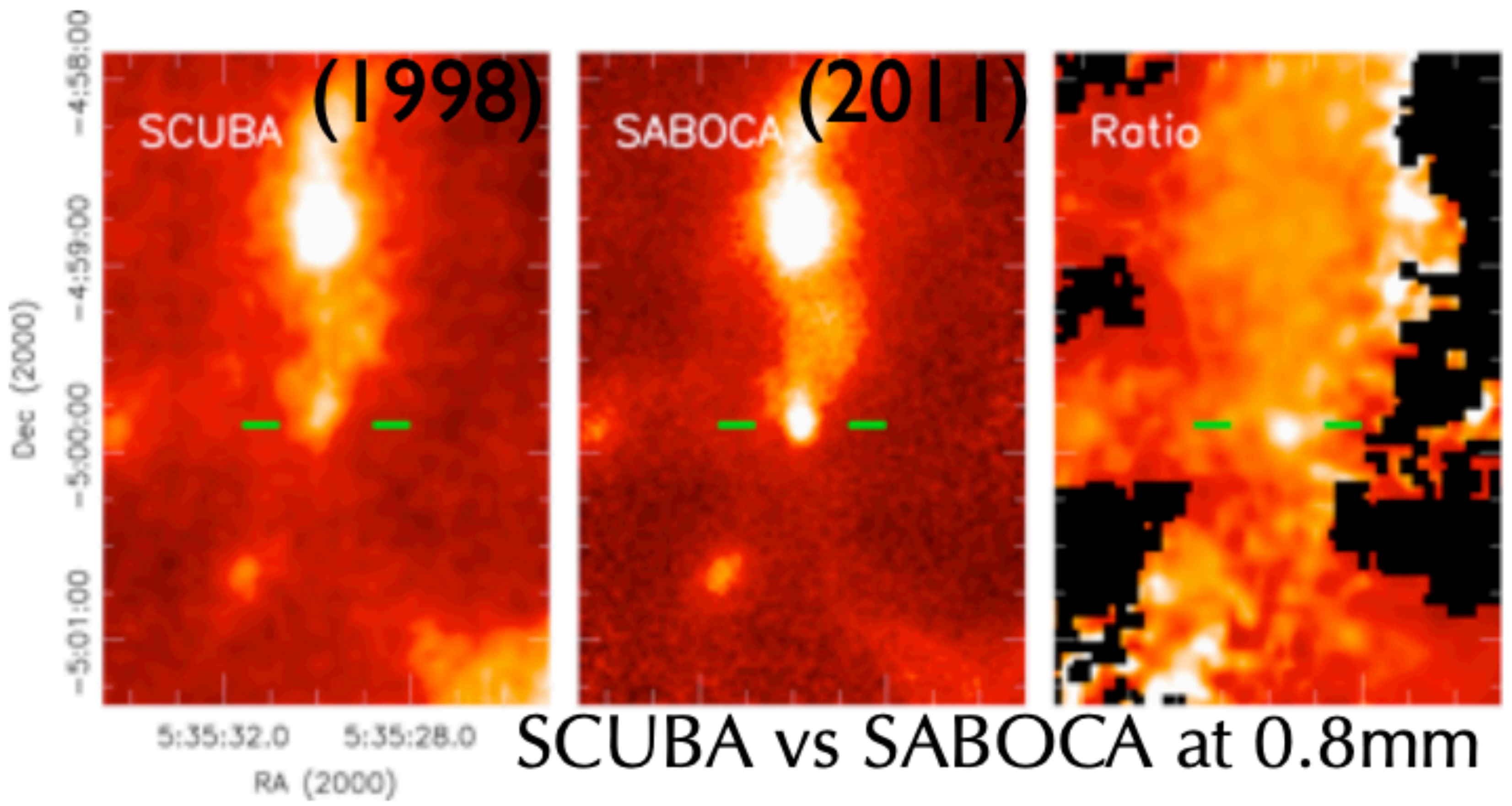
burst

post-burst
$t < t_{dep}$ since last burst

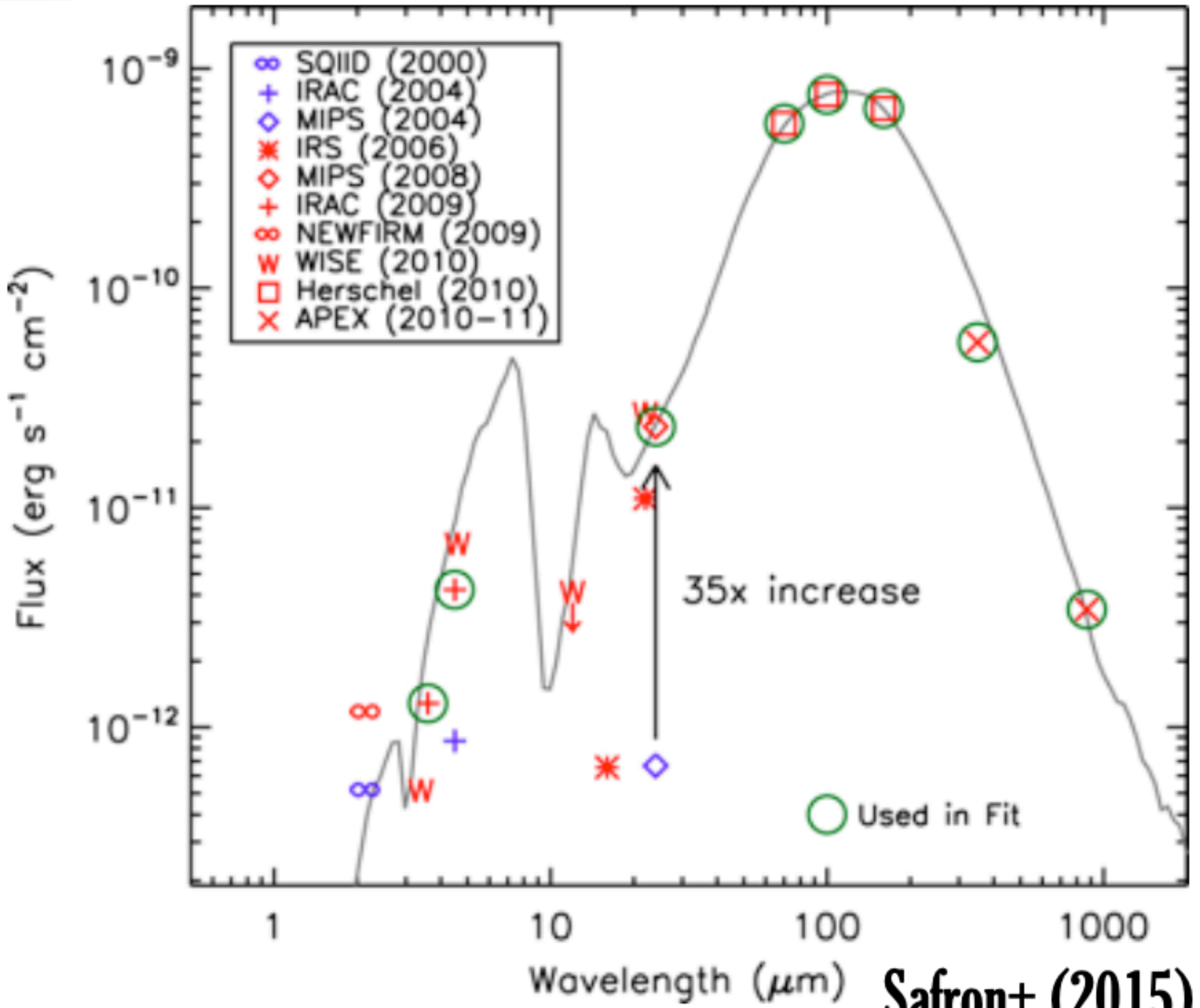
HOPS 383



Spitzer vs WISE at <24μm



SCUBA vs SABOCA at 0.8mm



Safron+ (2015)

x35 in bolometric luminosity ?

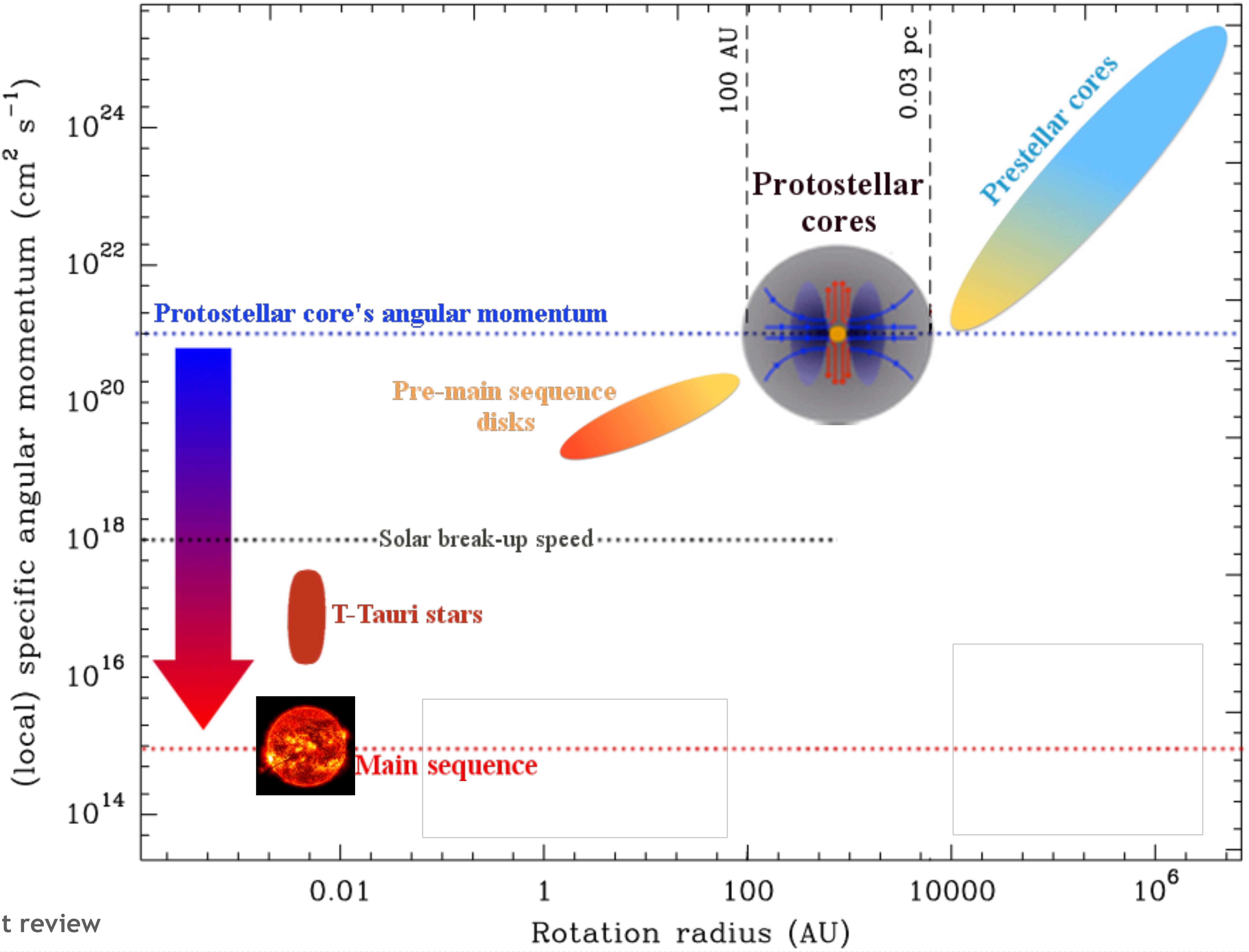
The infamous angular momentum problem

From observations of j at the 0.1 pc core's diameter

to the Sun's size :

factor of 10^6 in angular momentum

Observations of angular momentum content in star-forming structures



Based on Belloche (2013)

See also Maury, Hennebelle, Girart 2022 for a recent review

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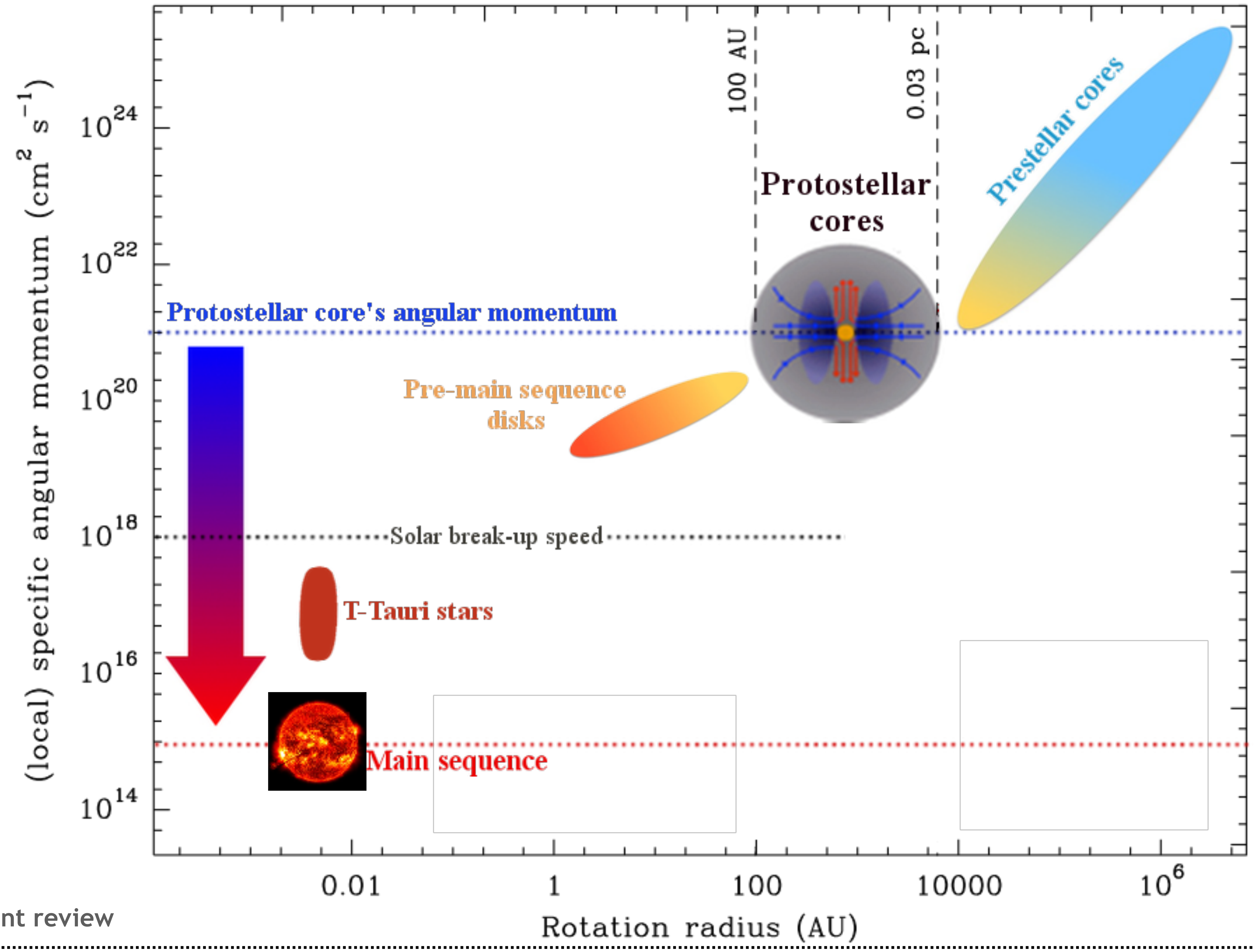

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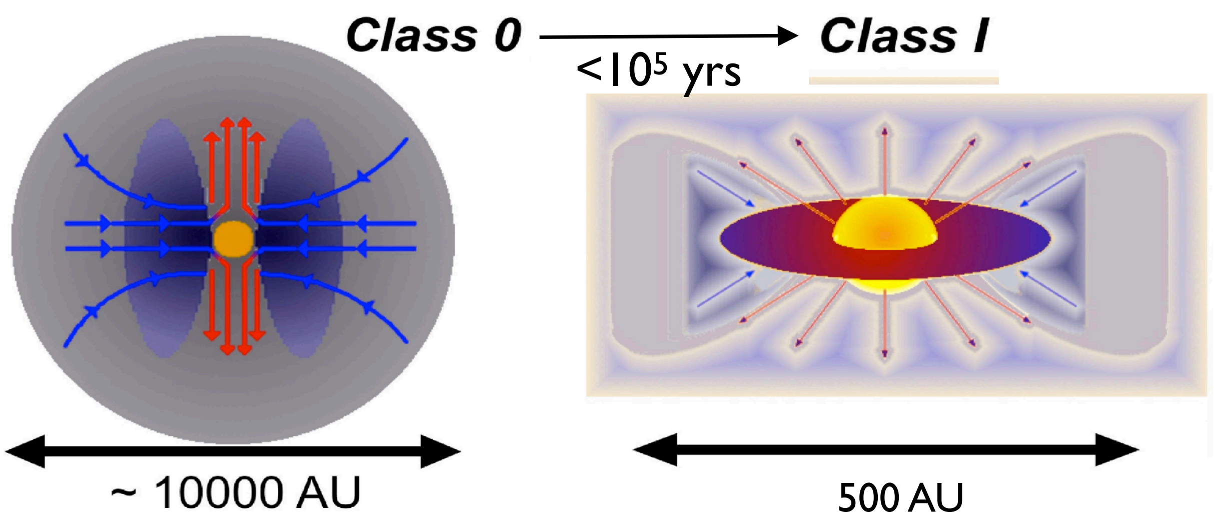


Class 0 phase = main accretion phase

>50% of the final stellar mass is assembled:
need to get rid of the 10.000 AU envelope's angular momentum
during its accretion on 0.1 AU protostellar embryo

… by the formation of a protostellar disk ?

Are disks the solution to the angular momentum problem ?

$$L = I\omega \sim MR^2\omega$$

initial size $R \sim 1\text{pc}$, initial spin ω

$L = Mr^2\Omega$ final size r, final spin Ω

$\Omega = \sqrt{\frac{GM}{r^3}}$ for a Keplerian rotation

$\sqrt{GMr} = R^2\omega$ Where the gravitational acceleration is balanced by the centrifugal acceleration.

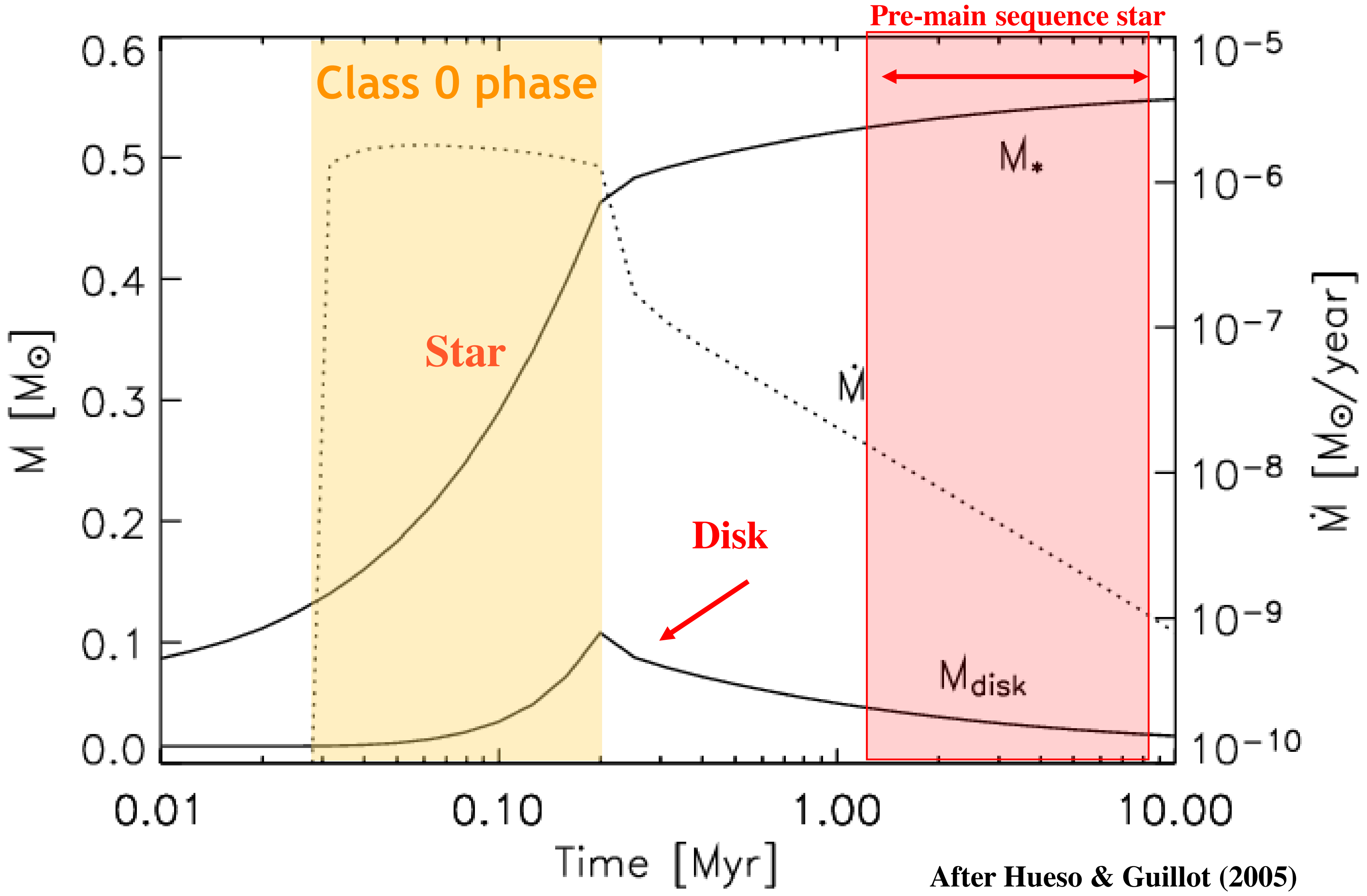
$\boxed{r_c = \frac{R^4\omega^2}{GM}}$ is known as the centrifugal radius.

Initial core angular momentum + angular momentum conservation in protostellar collapse

→ centrifugal radius R_c → material piles up in disk

- $R_c \sim c_s\Omega_0^2t^3/16$ in traditionally inside-out collapsing core with solid body rotation (Terebey, Shu & Cassen, 1984): increasing with time because in inside-out collapse rarefaction wave moves out.

Class 0 protostars: the craddle for the first circumstellar disks



After Hueso & Guillot (2005)

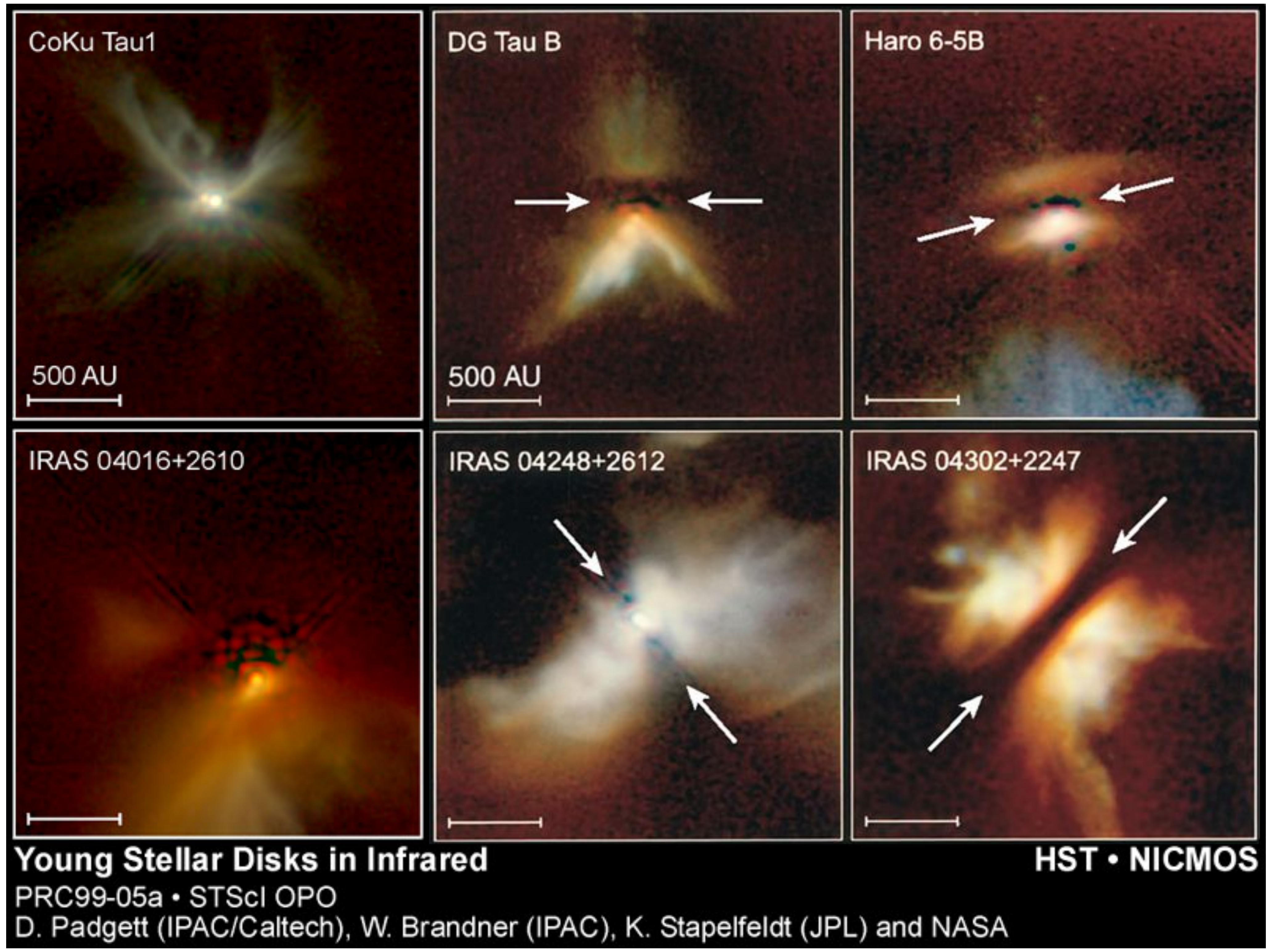
Simple hydrodynamics from $j_{core} = 10^{21}$ cm^2 s^{-1} ==> ≥200 au disks in <10^4 yrs

Back in 2010 …

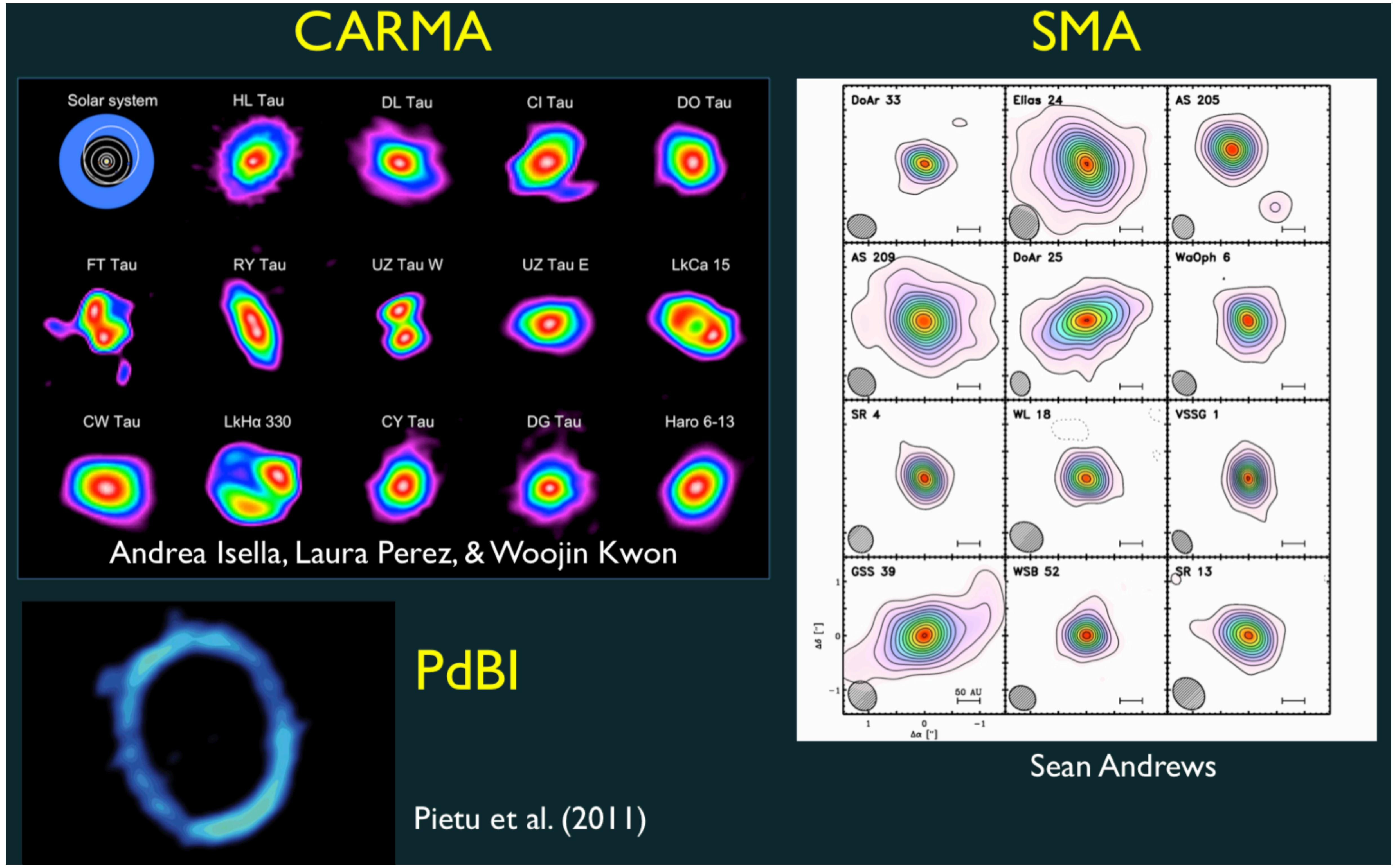
Disks are ubiquitous around T-Tauri young stars

Seen in infrared absorption

Seen in mm dust emission



Young Stellar Disks in Infrared **HST • NICMOS**
PRC99-05a • STScI OPO
D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA



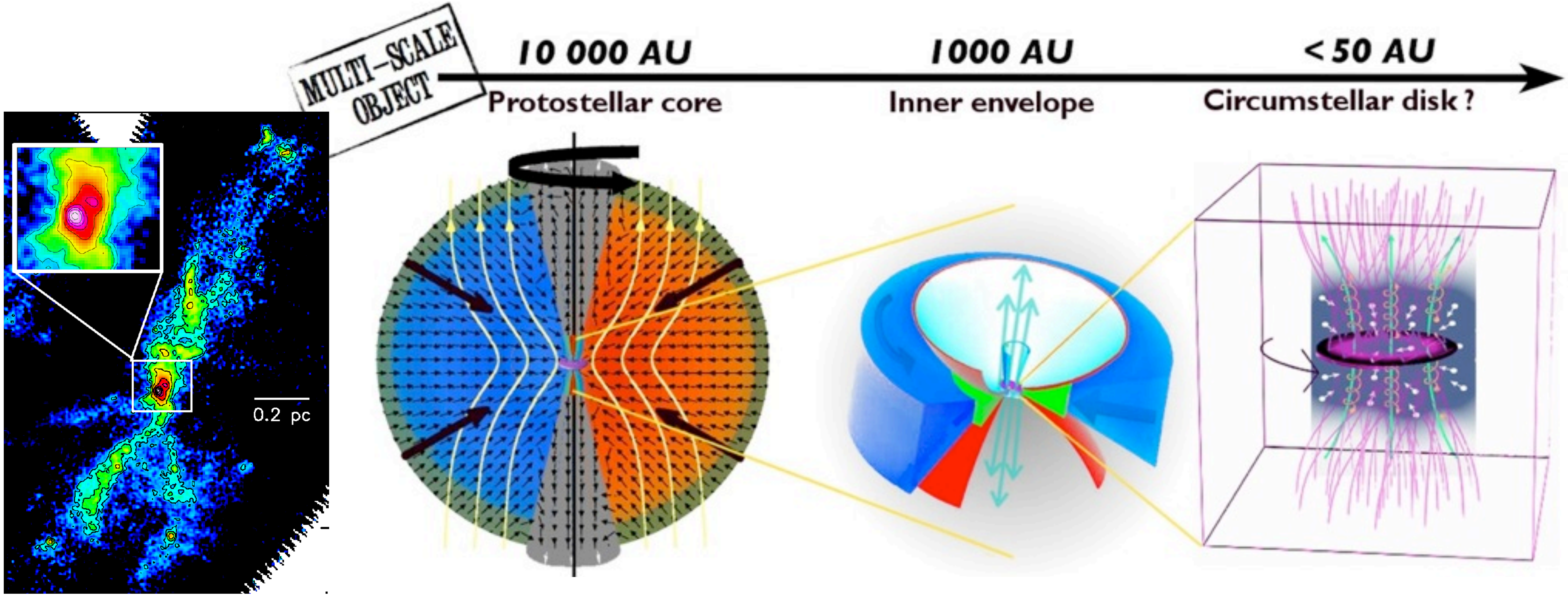
Andrea Isella, Laura Perez, & Woojin Kwon

Sean Andrews

Pietu et al. (2011)

But almost no constraints on disks around young embedded protostars …

Anatomy of a typical protostar



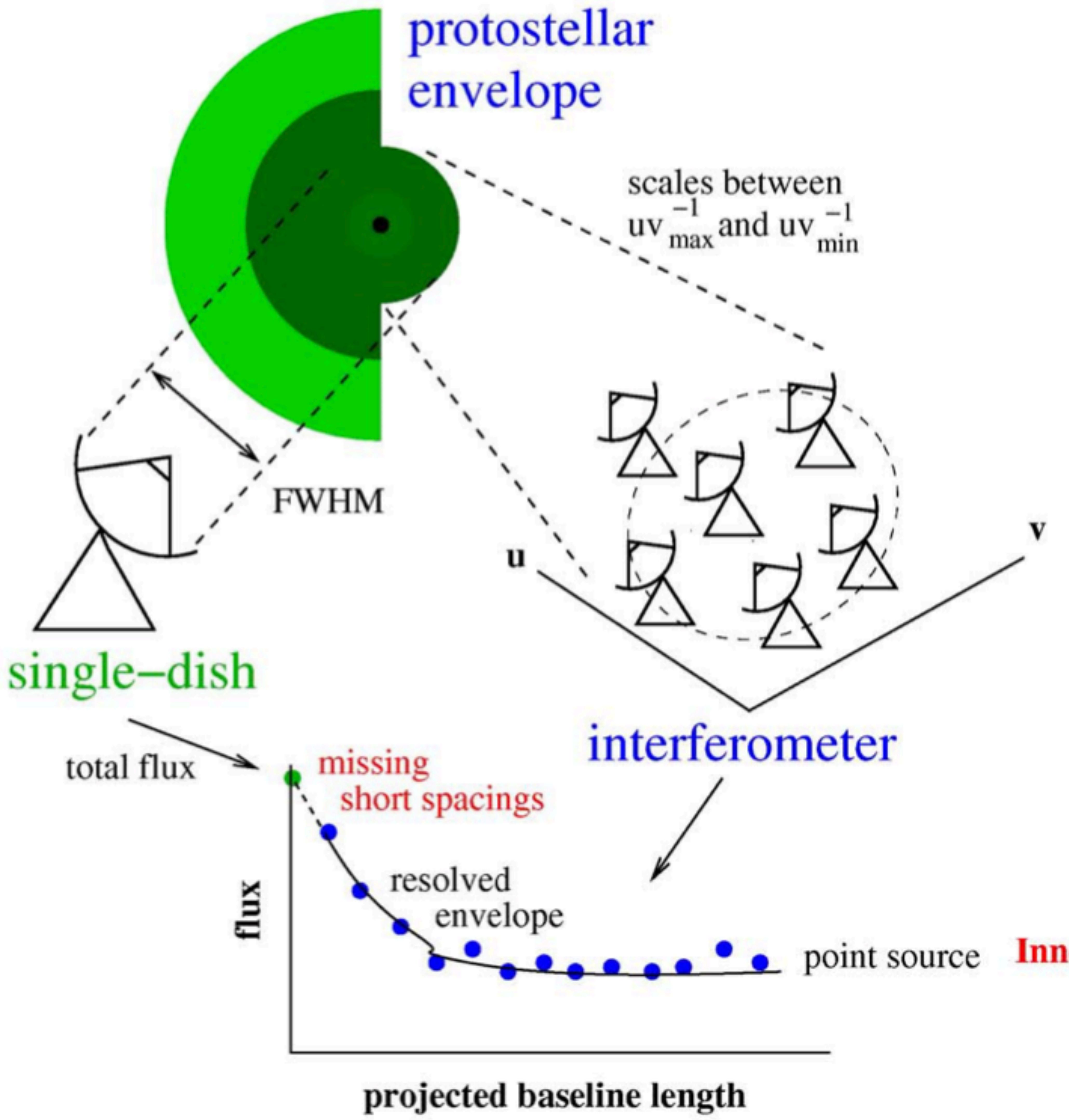
MULTI-SCALE OBJECT

10 000 AU Protostellar core

1000 AU Inner envelope

< 50 AU Circumstellar disk ?

Column density:	10^{21} N_{H2}/cm^2	--	10^{23} N_{H2}/cm^2
Temperature:	5K	--	500 K
Gas mass:	1-5 M_o	--	< 0.01 M_o

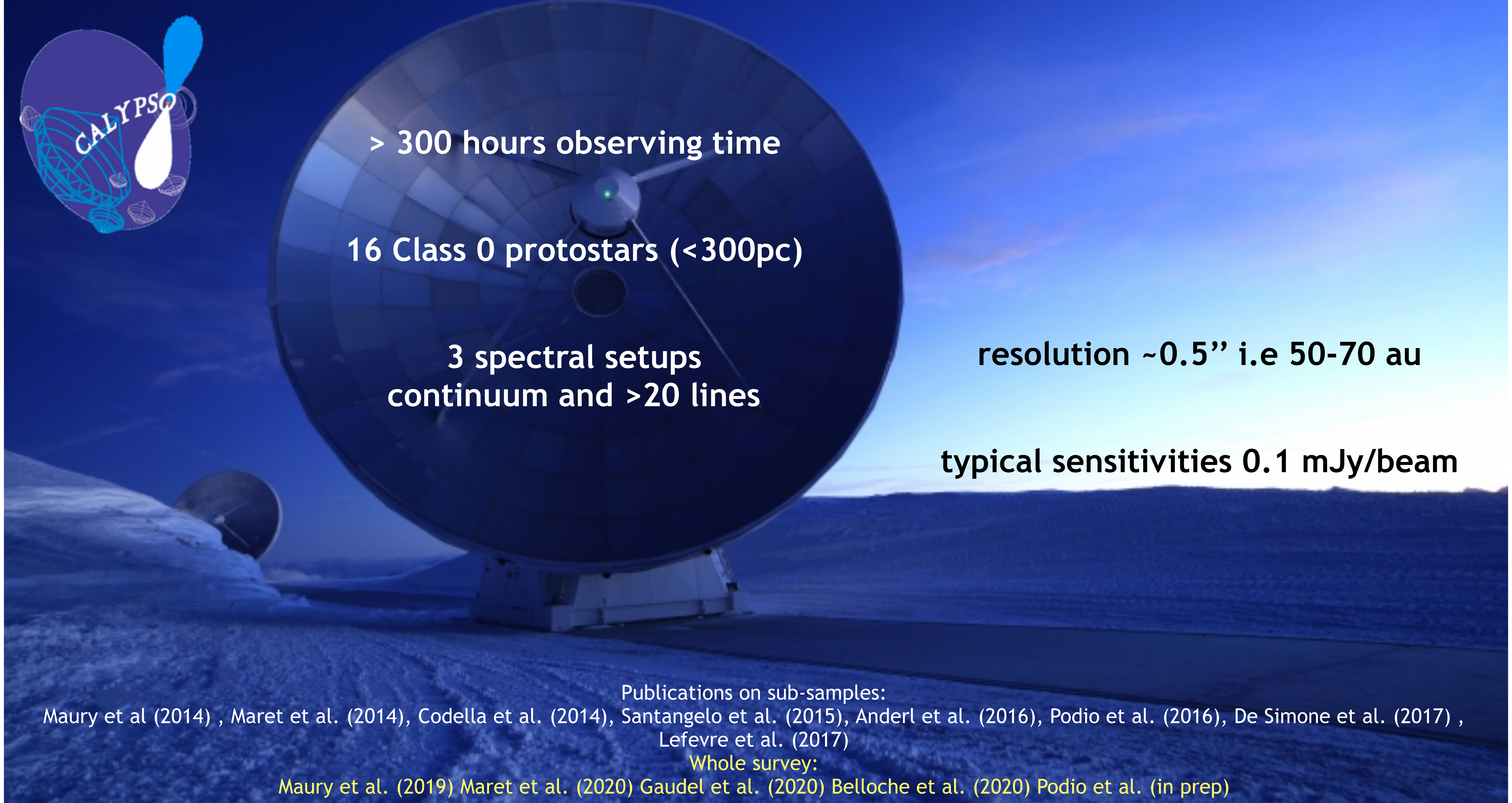


Inner envelope or disk?

CALYPSO:
the IRAM Plateau de Bure Large Program
to solve the angular momentum problem in Class 0 protostars

A dive into the small-scale physics of the youngest envelopes, disks and outflows.

Core team: Ph. André (AIM) - A. Maury (AIM) - C. Codella (INAF) - S. Maret (IPAG) - S. Cabrit (LERMA) - F. Gueth (IRAM) - A. Belloche (MPIfR) - L. Testi (ESO / INAF) - B. Lefloch (IPAG) - S. Bontemps (LAB) - P. Hennebelle (AIM) - A. Bacmann (IPAG) - B. Commercon (MPIA) - L. Podio (Arcetri) - S. Anderl (IPAG) - M. Gaudel (AIM)



> 300 hours observing time

16 Class 0 protostars (<300pc)

3 spectral setups
continuum and >20 lines

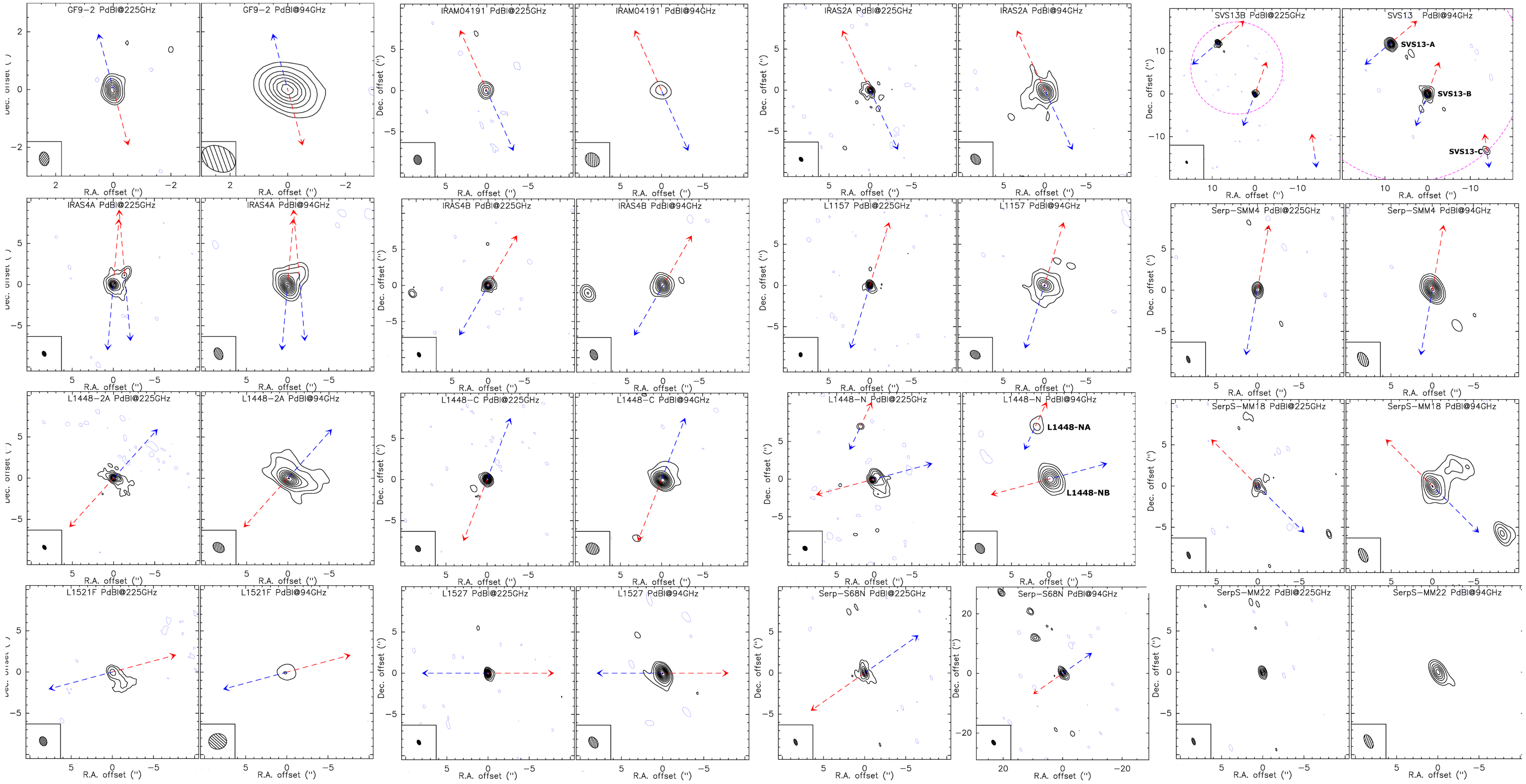
resolution ~0.5'' i.e 50-70 au

typical sensitivities 0.1 mJy/beam

Publications on sub-samples:
Maury et al (2014) , Maret et al. (2014), Codella et al. (2014), Santangelo et al. (2015), Anderl et al. (2016), Podio et al. (2016), De Simone et al. (2017) , Lefevre et al. (2017)

Whole survey:
Maury et al. (2019) Maret et al. (2020) Gaudel et al. (2020) Belloche et al. (2020) Podio et al. (in prep)

The survey



Maury et al (2010, 2014, 2019) Maret et al. (2014, 2020) Codella et al. (2014)
Santangelo et al. (2015) Anderl et al. (2016) Podio et al. (2016) De Simone et al. (2017), Gaudel et al. (2020) Belloche et al. (2020)

Envelope description in the spatial domain

$$\rho(r) = \rho_{\rm flat} \left[\frac{R_{\rm flat}}{\left(R_{\rm flat}^2 + r^2\right)^{1/2}} \right]^p \equiv \frac{\rho_{\rm flat}}{\left(1 + (r/R_{\rm flat})^2\right)^{p/2}} \qquad T(r) = 60 \left(\frac{r}{2 \times 10^{15}\ {\rm m}} \right)^{-q} \left(\frac{L_{\rm bol}}{10^5\ {\rm L}_\odot} \right)^{q/2} \ {\rm K}$$

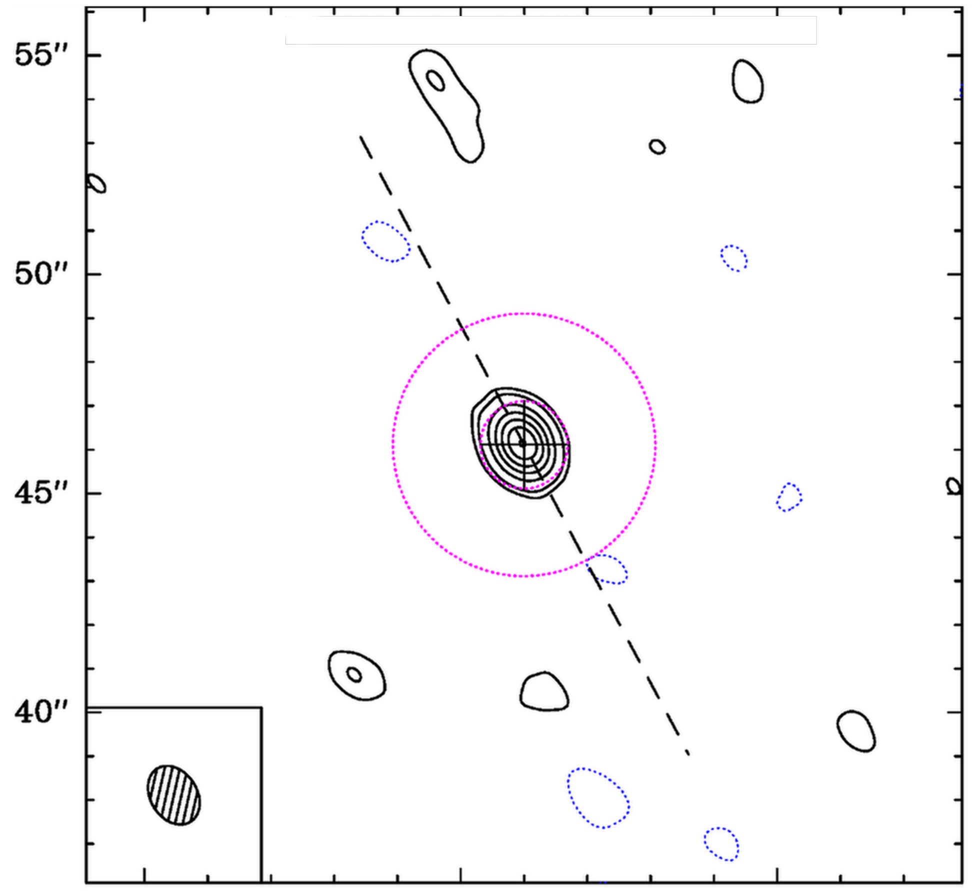
$$\longrightarrow I(r) \propto r^{-(p+q-1)}$$

Envelope description in the Fourier domain with interferometric baseline $b = \sqrt{u^2 + v^2}$,

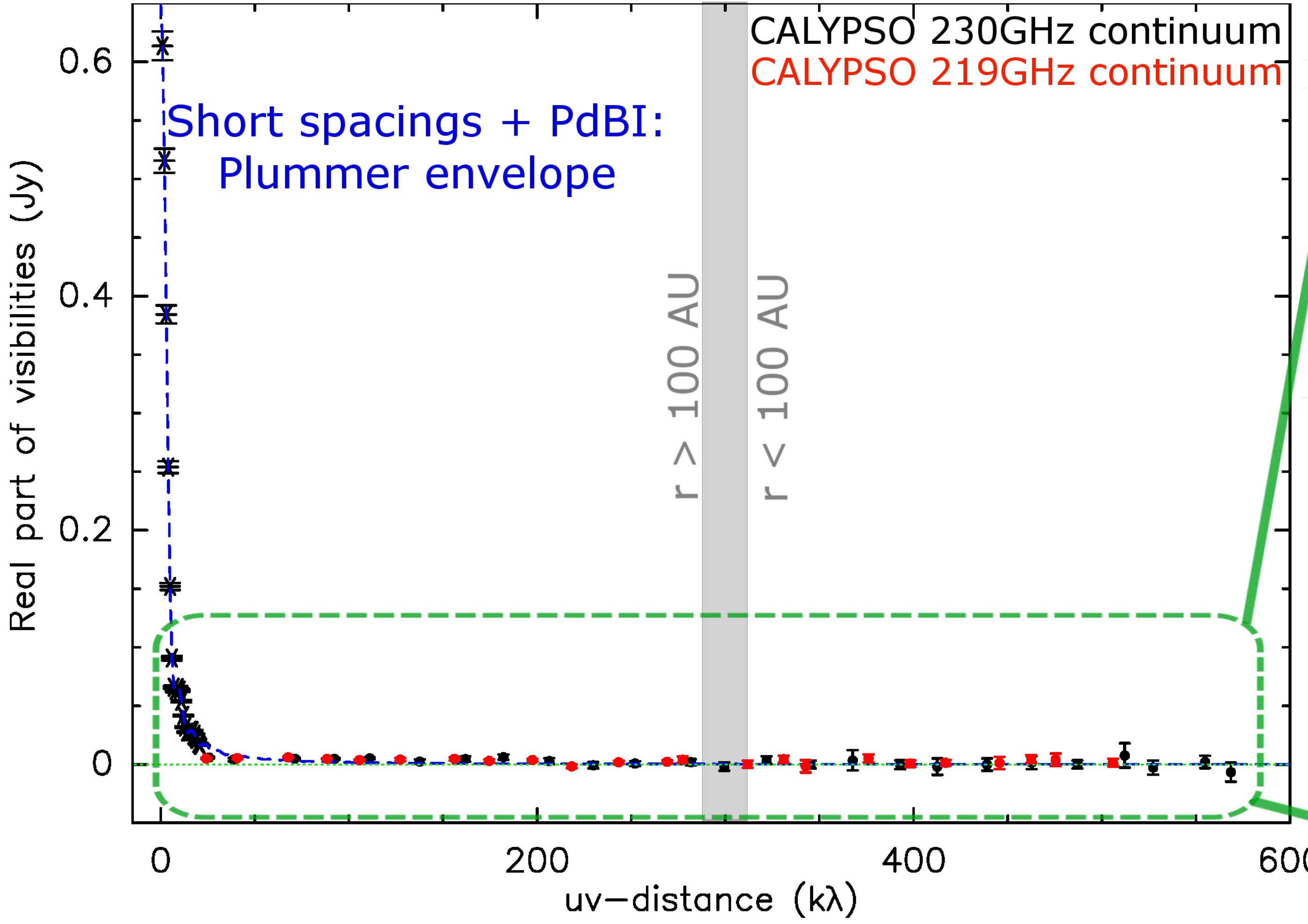
$$V(b) = 2\pi \int_0^\infty I_\nu(r_{\rm b}) J_0\left(2\pi r_{\rm b} b\right) r_{\rm b} dr_{\rm b} \qquad \text{with} \qquad J_0(z) = \frac{1}{2\pi} \int_0^\infty \exp\left(-iz\cos\theta\right)$$

$$\longrightarrow V(b) \propto b^{p+q-3}$$

IRAM04191: continuum @ 231Ghz

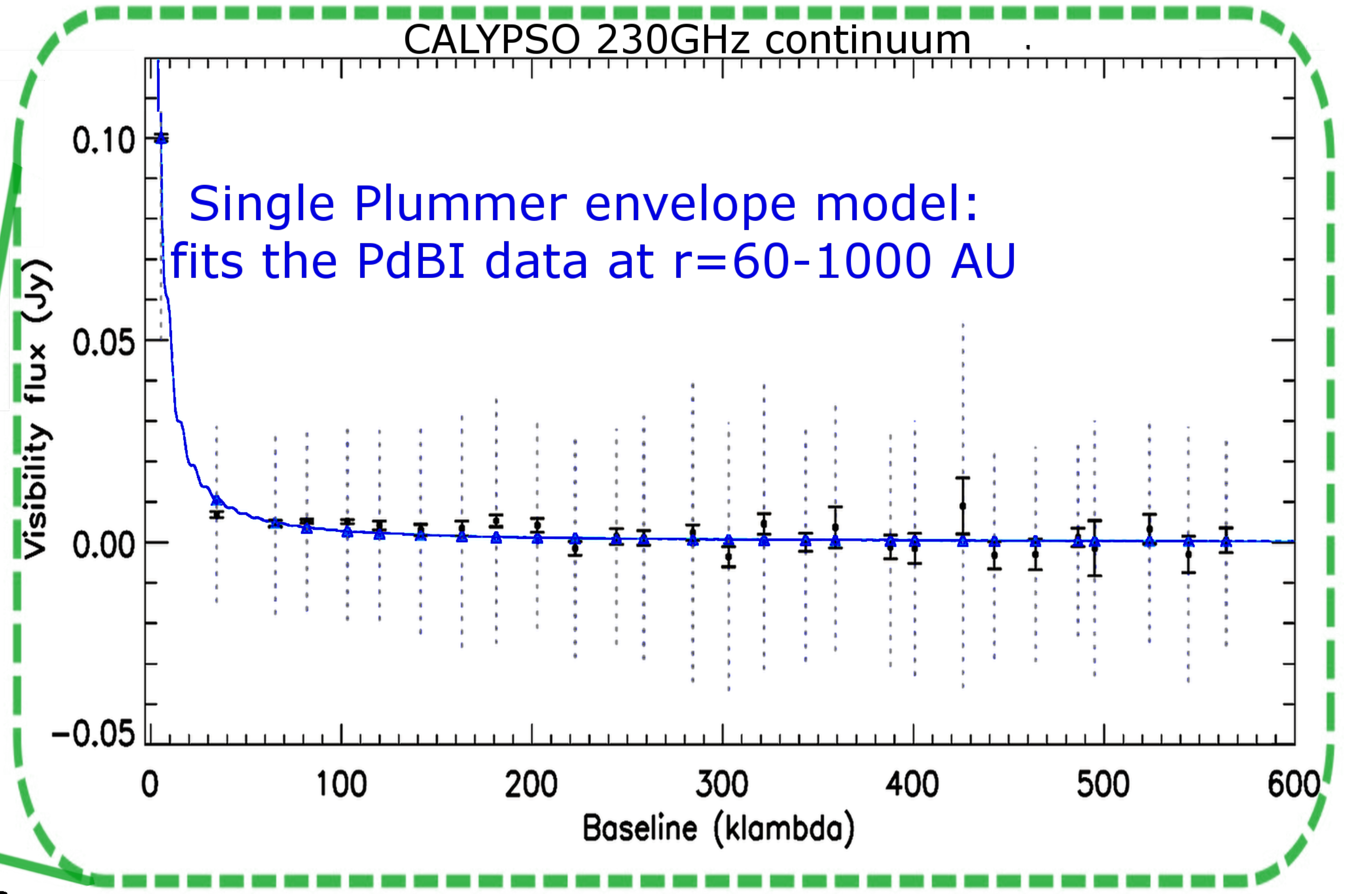


IRAM04191 envelope visibility profile



Short spacings + PdBI: Plummer envelope

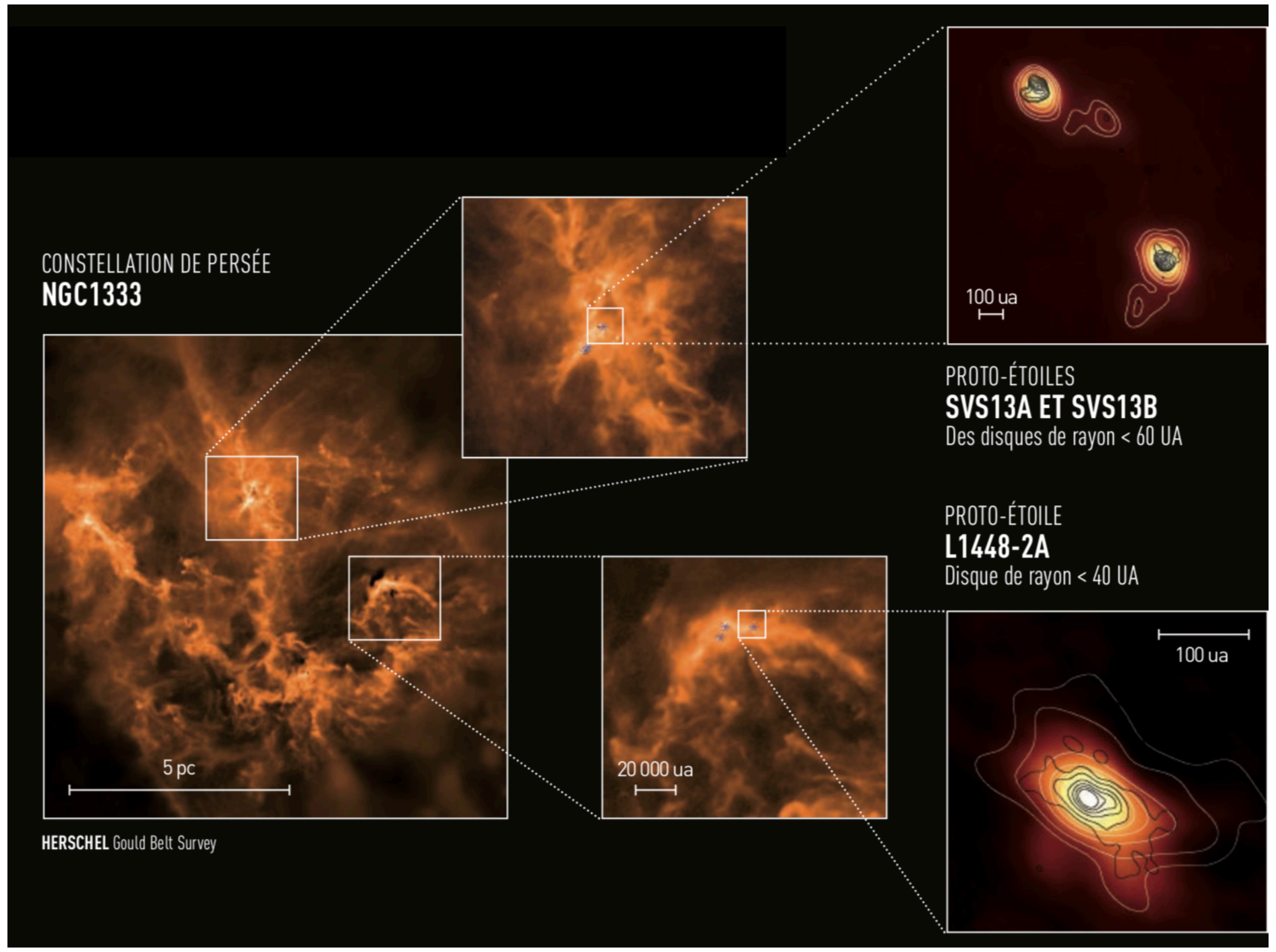
Zoom on the PdBI data



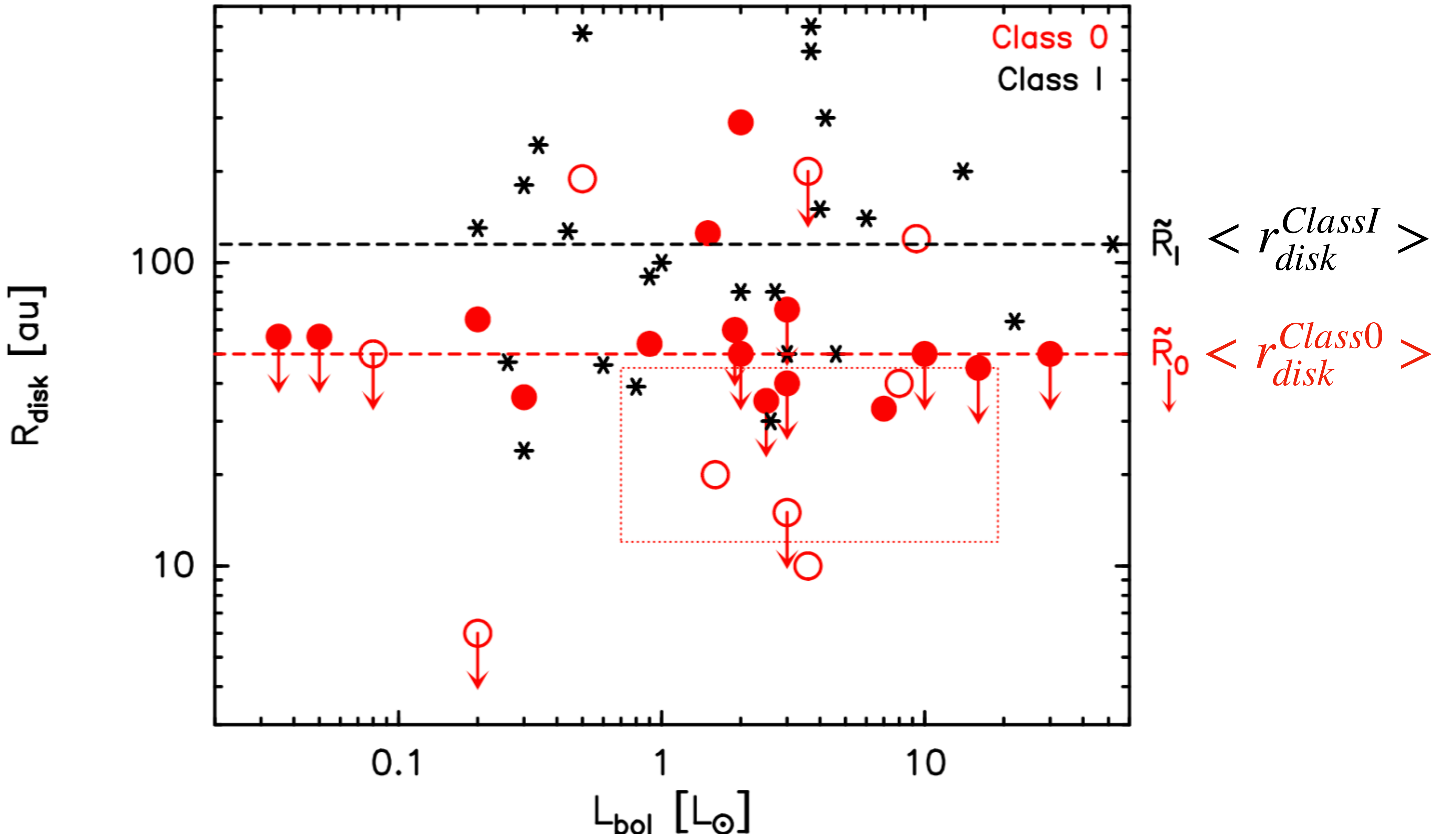
Single Plummer envelope model: fits the PdBI data at r=60-1000 AU

CALYPSO survey of 1.3+2.7 mm dust continuum emission

>70% Class 0 show disk components but >72% have r_{disk} < 60 au



Class 0 median disk radius < 50 au

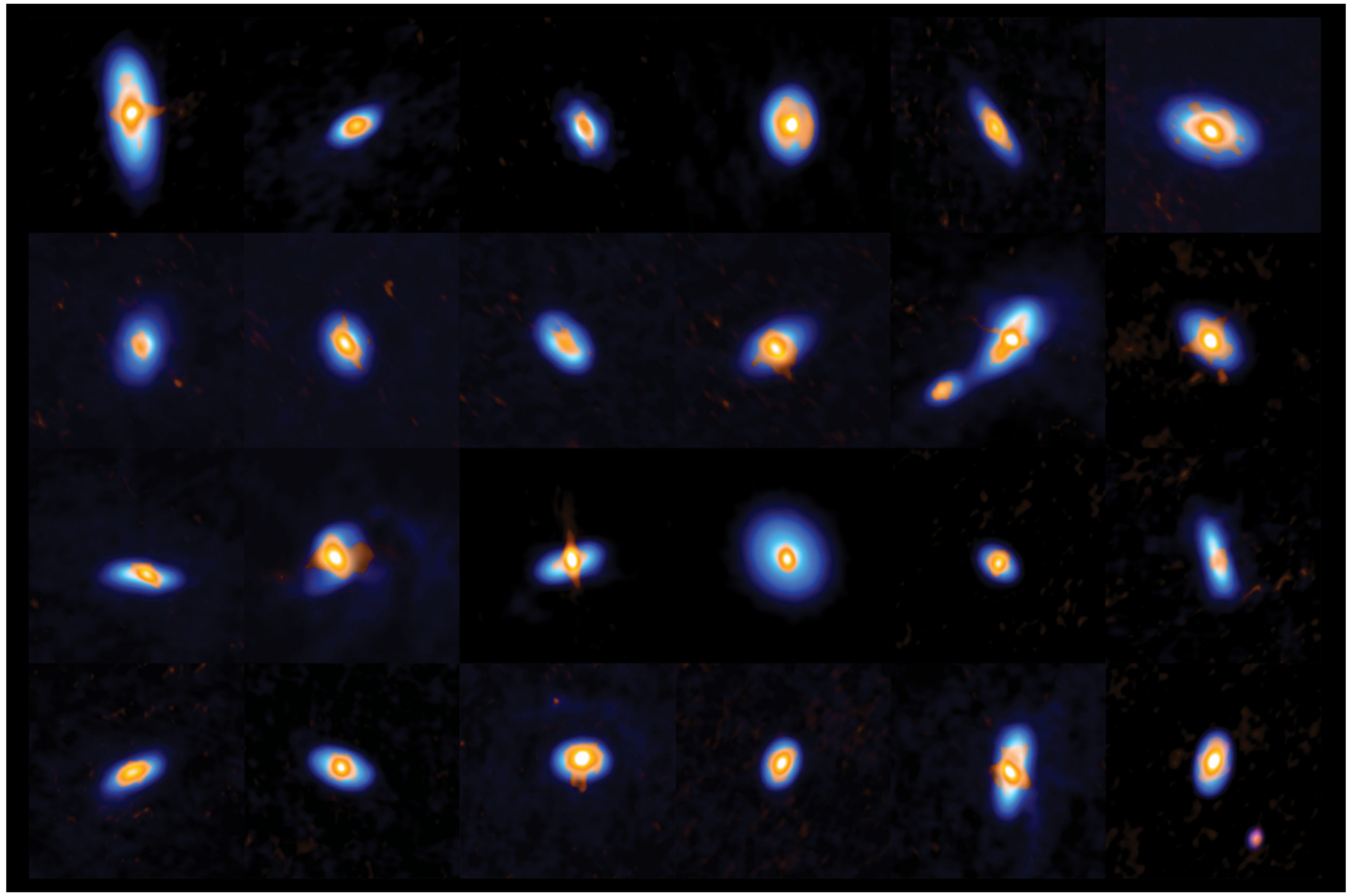


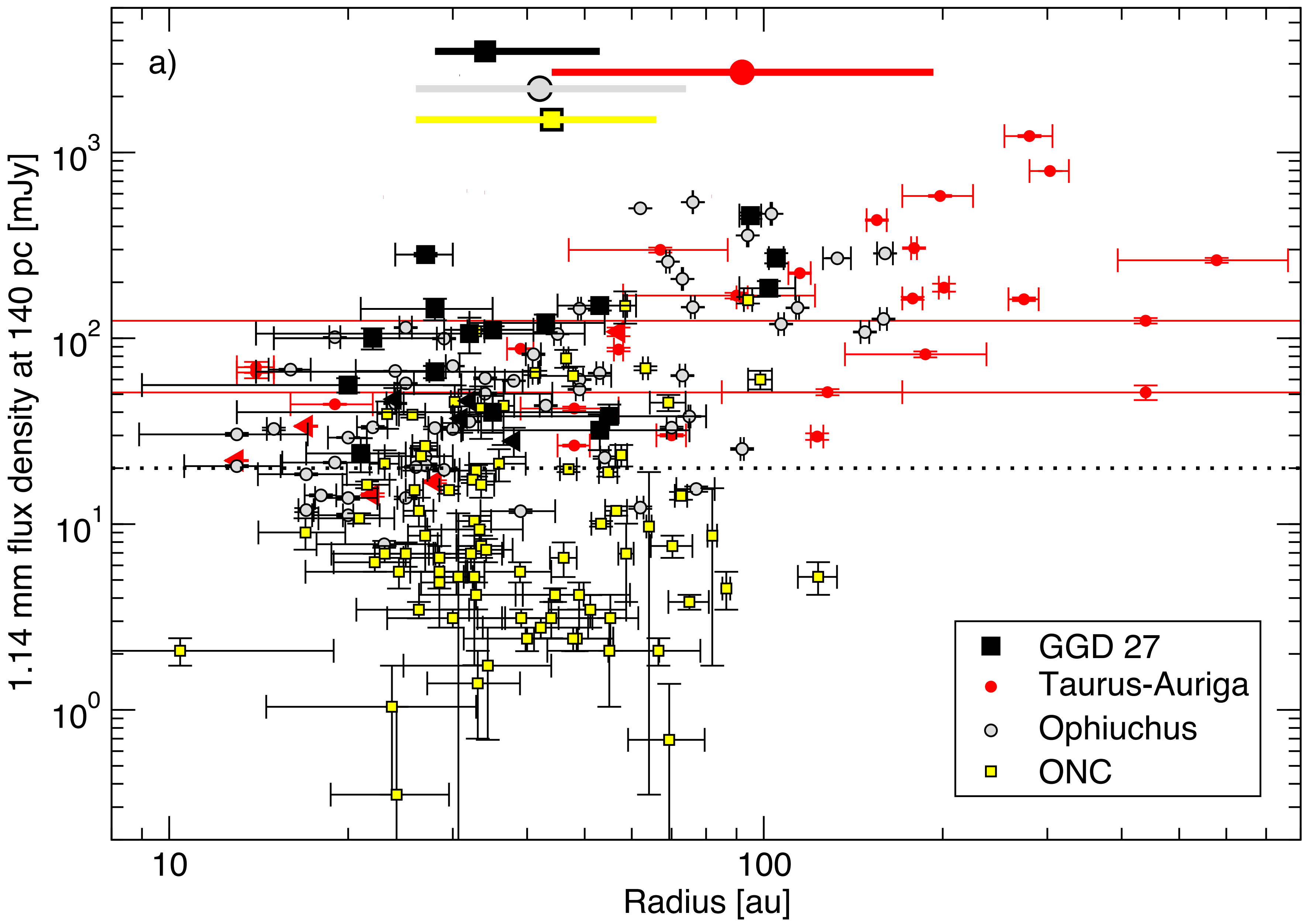
Including the literature (CARMA/Vandam, ALMA & SMA results, 26 Class 0 protostars):
>75% Class 0 disks have r_{disk} < 60 au

Protostars: disks are present but SMALL

Maury, André, Testi et al. 2019

More recent ALMA surveys have confirmed the CALYPSO results, finding Rdisks <50 au





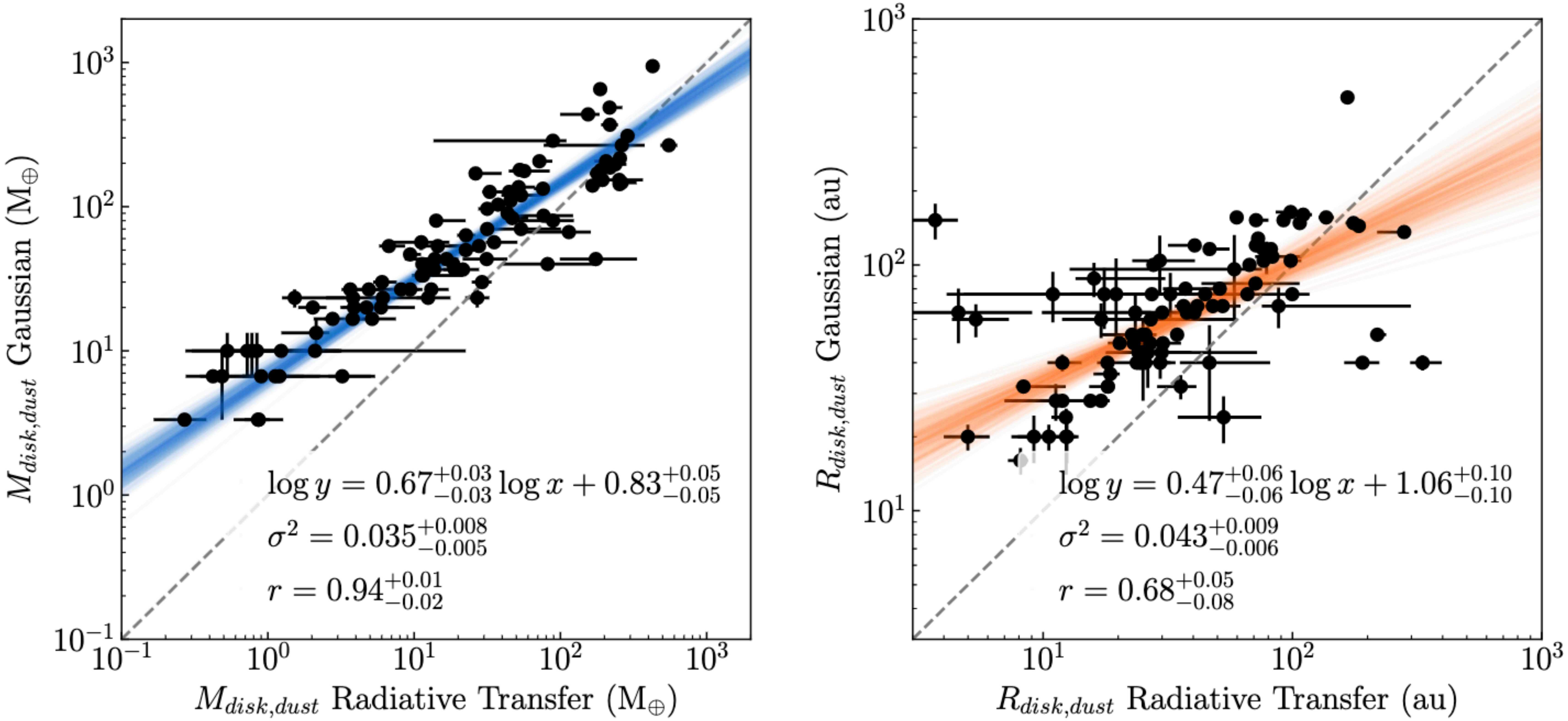
Tobin et al. 2020 in Orion:

Median disk dust radius 29 au - 11% of R_{disk} > 100 au

Busquet et al. 2019 in GGD 27:
paucity of disks with R_{disk} > 100 au

For a review, see Tsukamoto, Maury, Commerçon et al. (PPVII, 2023)

For sizes of Class II disks, see lecture by L. Testi tomorrow



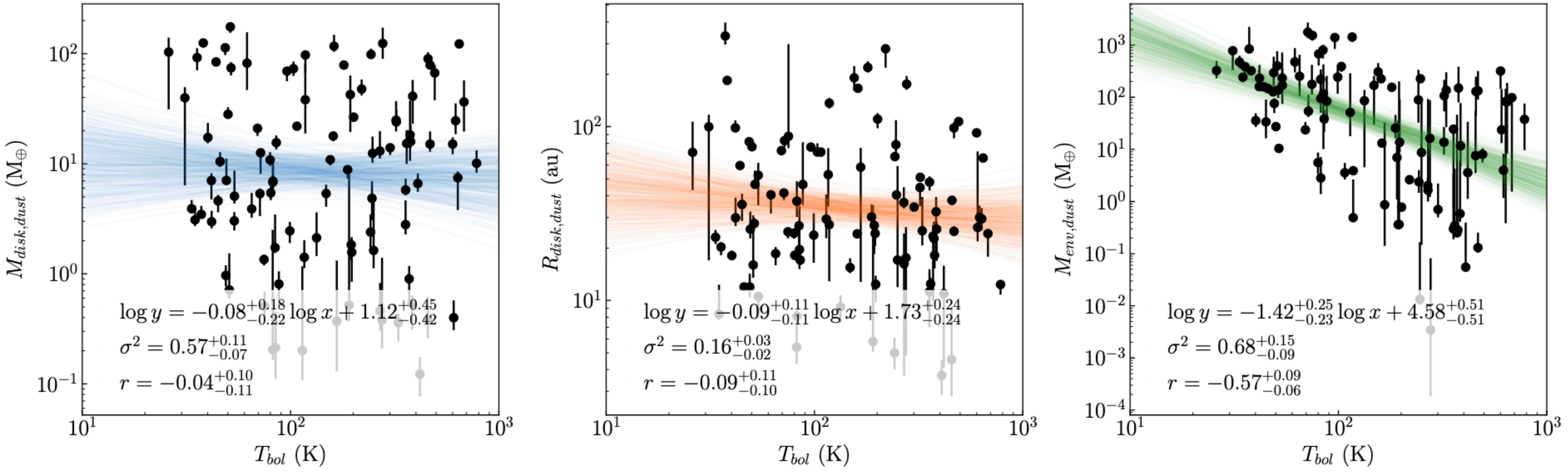
Sheehan+ (2022) from VANDAM survey

Full radiative transfer allows to estimate better disk sizes from the dust emission:

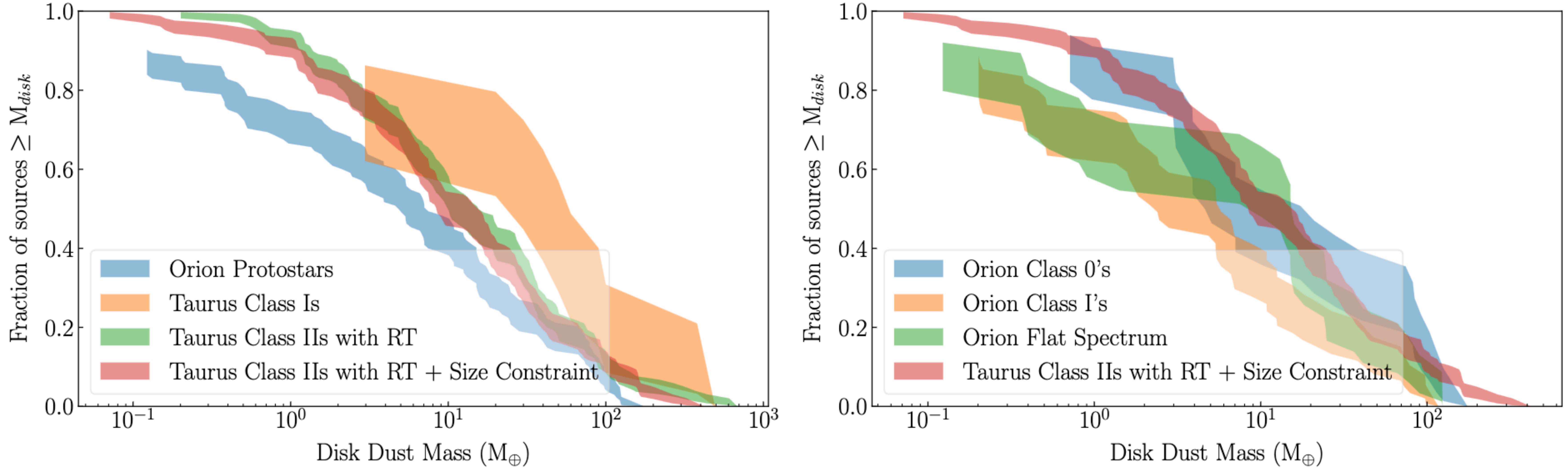
=> disks significantly smaller and less massive than estimates from simple Gaussian fitting

See also talk by Tung Ngo this week

Sheehan+ (2022) from VANDAM survey

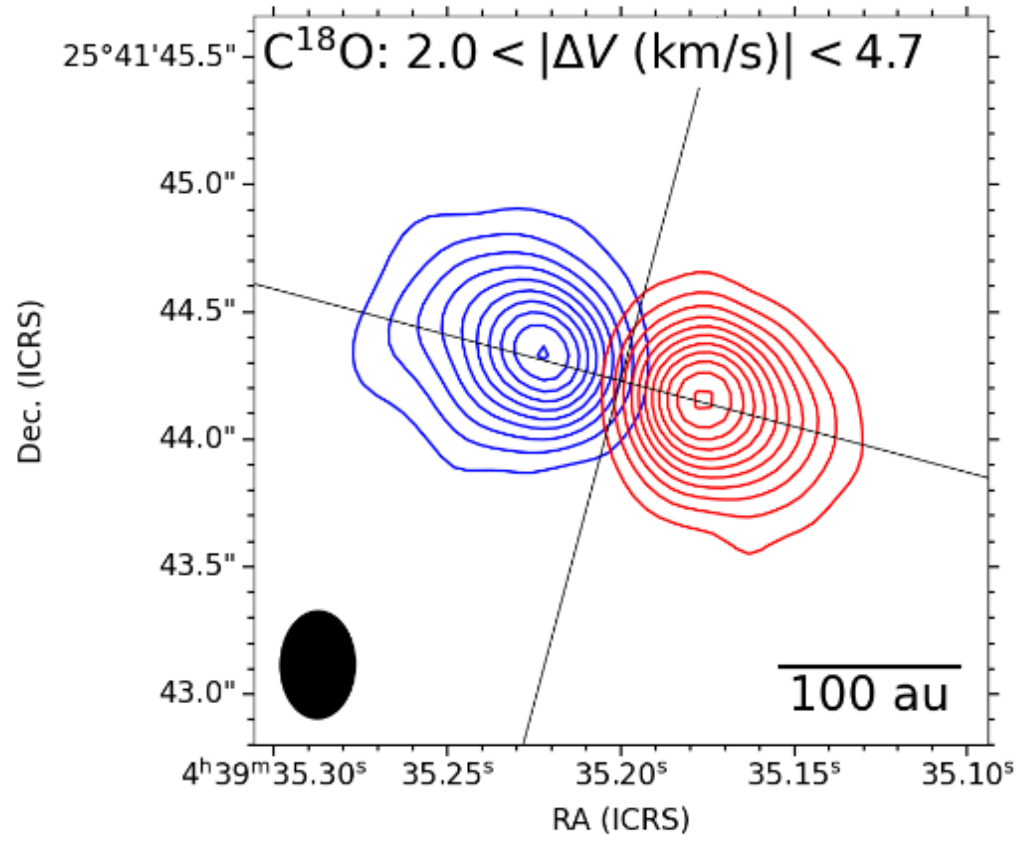


No clear evolution trend of the disk properties if using T_{bol} as evolutionary tracer



The disks are a few Earth masses, but loosely constrained
(issues with dust properties and temperature)
=> kinematics needed

Beware of the dust properties!
See my 2d lecture and L. Testi's lecture + K. Demyk lecture this week



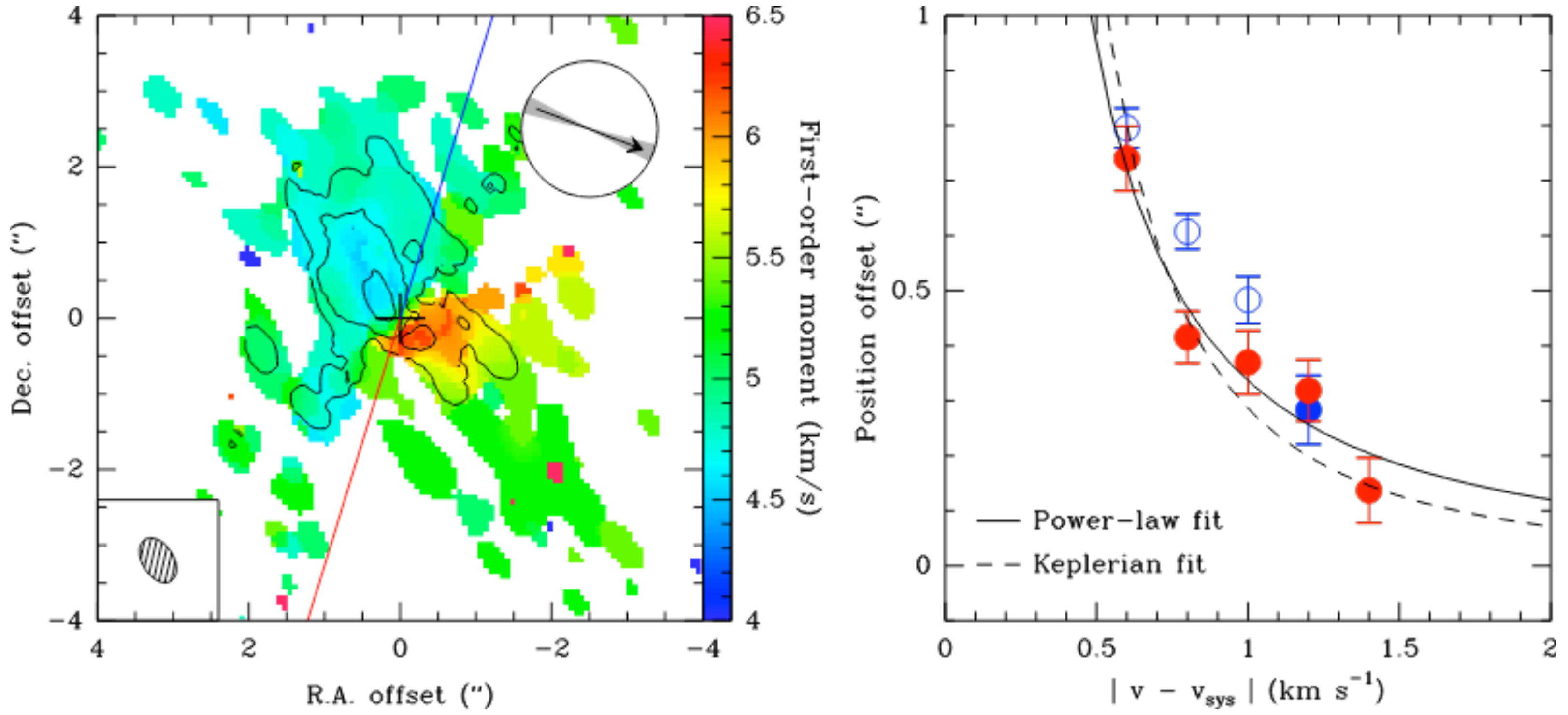
Aso et al. (2021)

Mix of infall and Keplerian motions

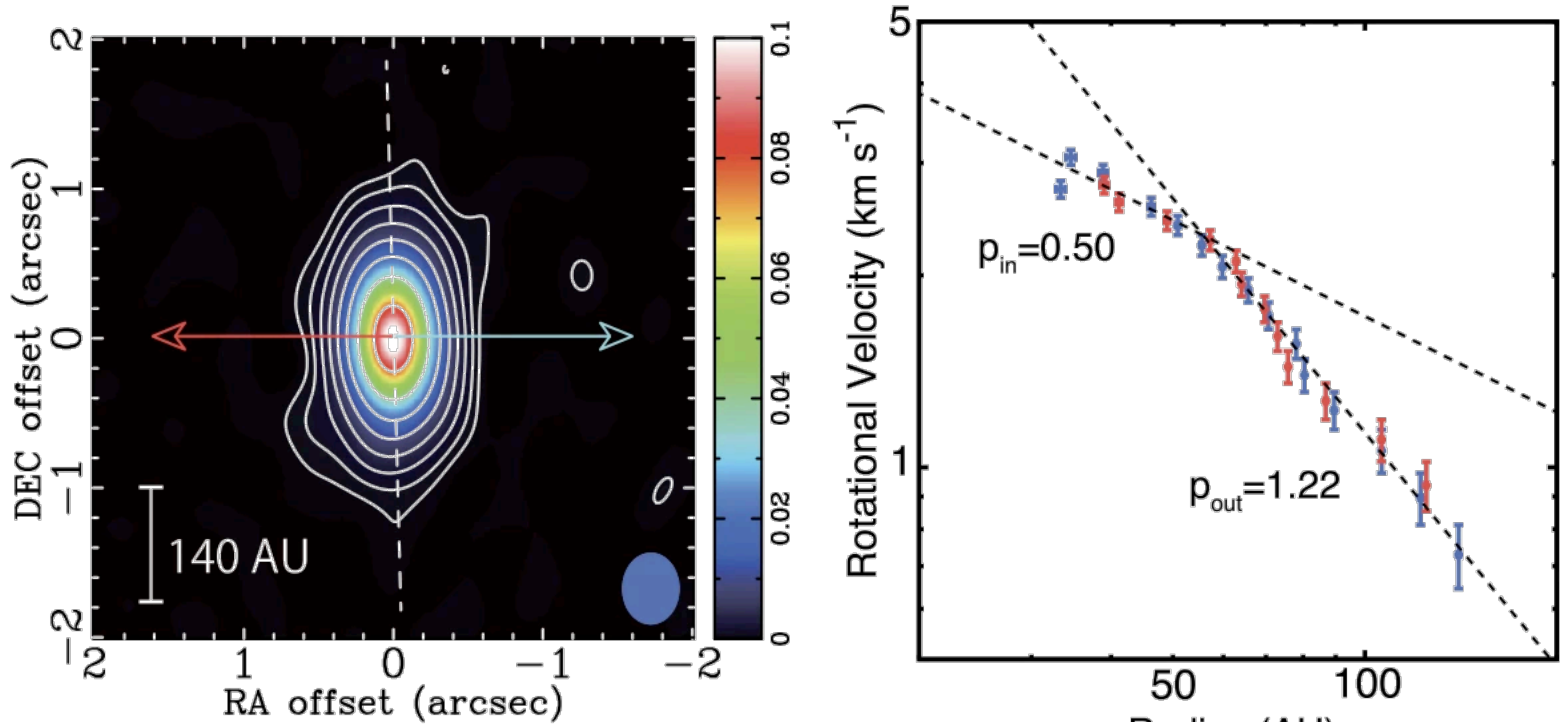
-

150 au disk in Class I TMC1-A

Maret & CALYPSO collab. 2020: 1/15 Class 0 Keplerian disk spatially resolved at scales ~50 au (L1448-C)



Aso et al. (2017)



Class 0/I L1527 disk resolved from gas kinematics obtained with ALMA

- Keplerian radius 74 au

Gas in Keplerian motions observed in the largest disks (spatially resolved) - few of them
=> disk radii mostly consistent with dusty radii in the current small samples

You want to know how come disks are

AN ORDER OF MAGNITUDE SMALLER THAN WHAT HYDRO MODELS PREDICT

FROM CONSERVATION OF ANGULAR MOMENTUM ?

Come back tomorrow …