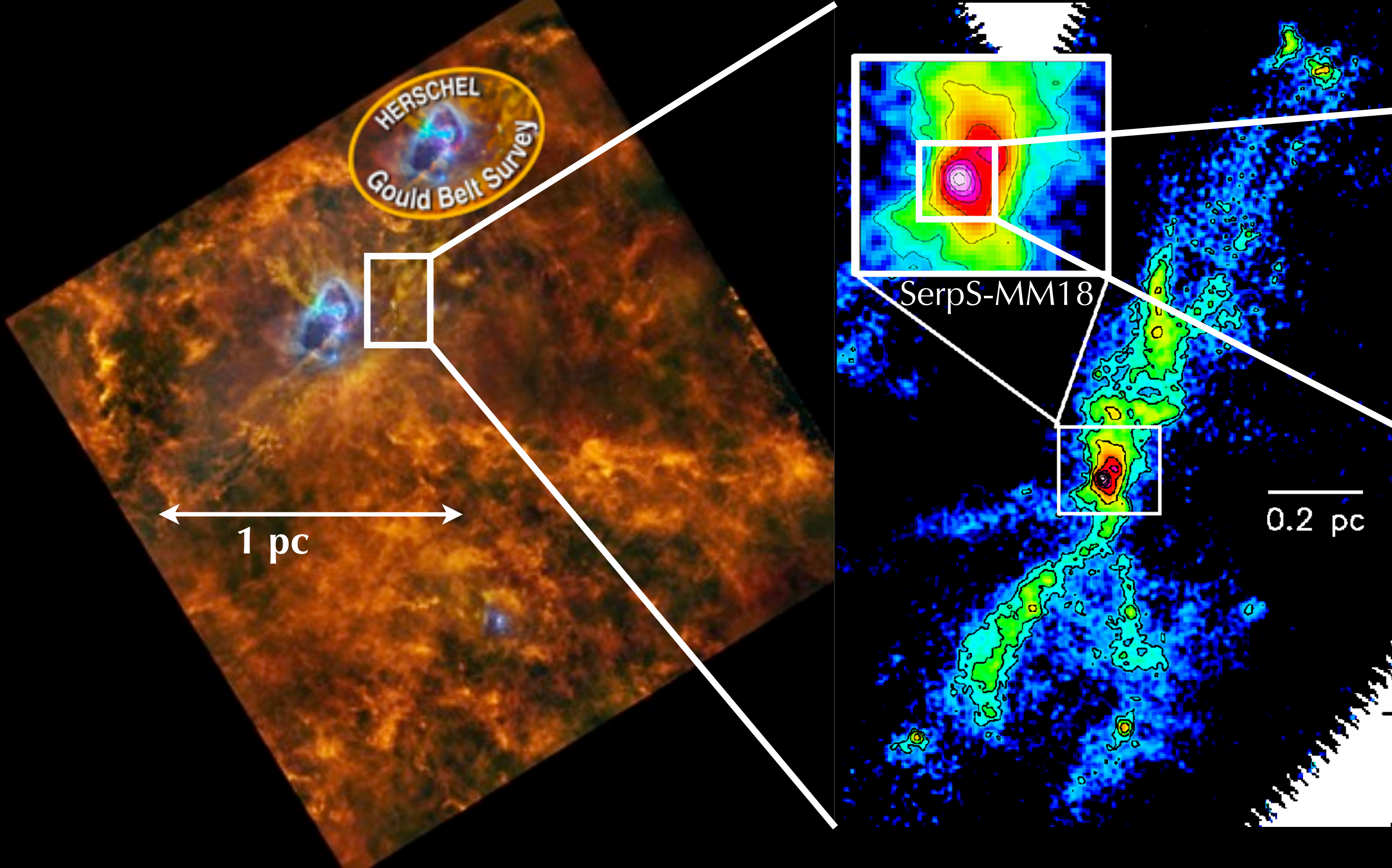
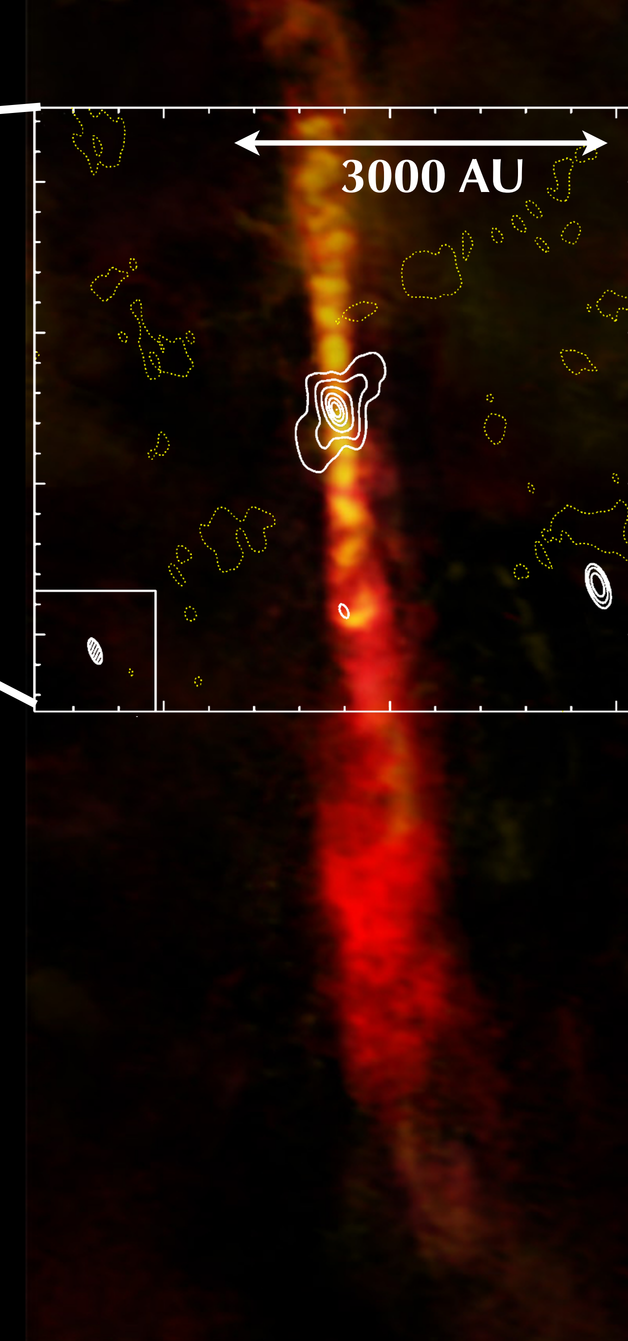




The Chronology of the Formation of the Solar System

Chapter I: From molecular clouds to protostellar cores

Chapter II: Formation of the protoplanetary discs

A. Maury & B. Commercon - Les Houches 2017

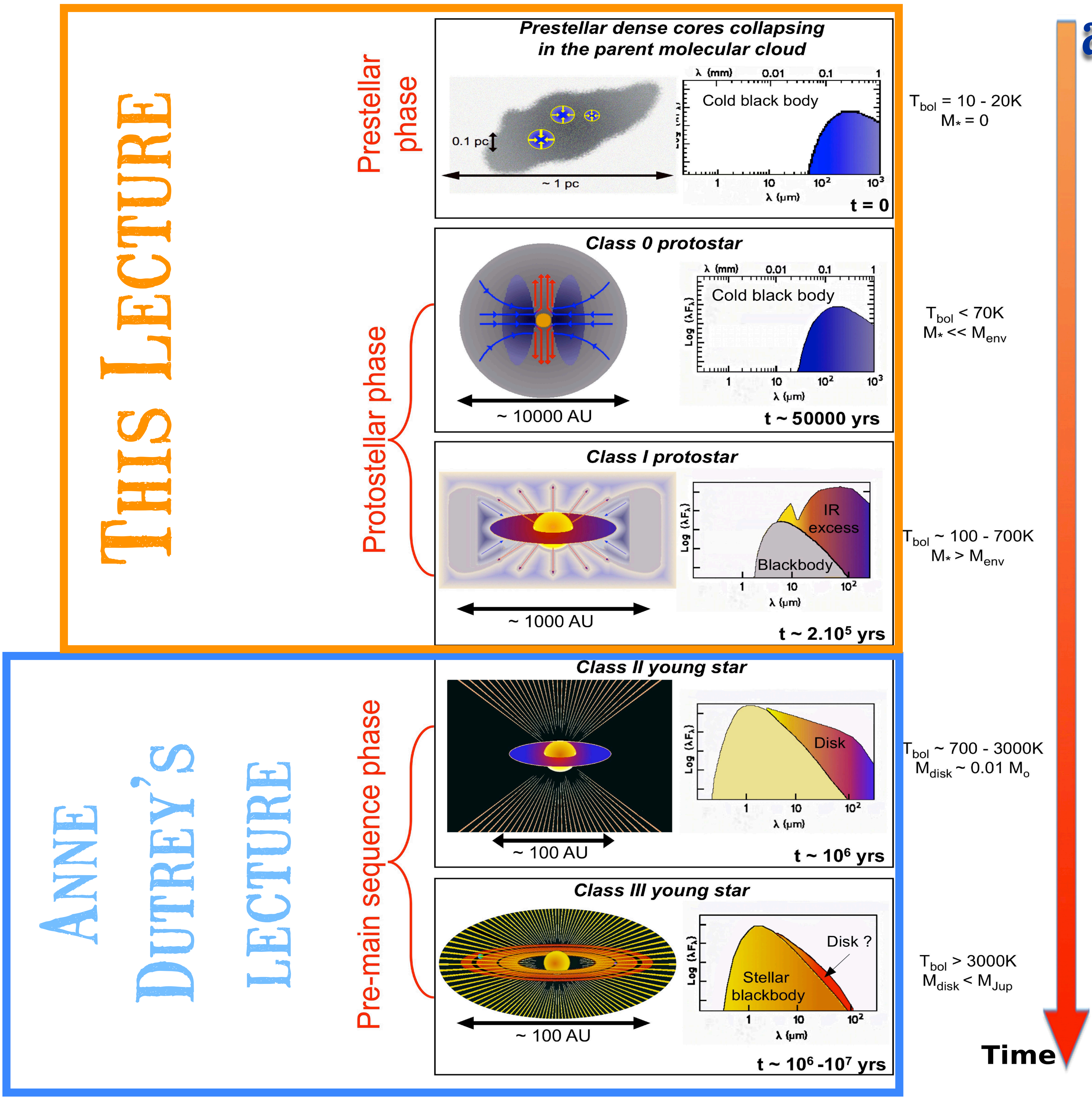
Today:
Chapter I

From molecular clouds to protostellar cores : filaments, stability of cores and formation of protostars

Questions addressed in this lecture

What controls the efficiency of core/star formation in GMCs ?
How to measure the stability of prestellar cores ?
Protostars: when and where do we form them ?

The formation of solar-type stars: an observational scenario



Shu et al. 1987

Lada 1987

André et al. 1993

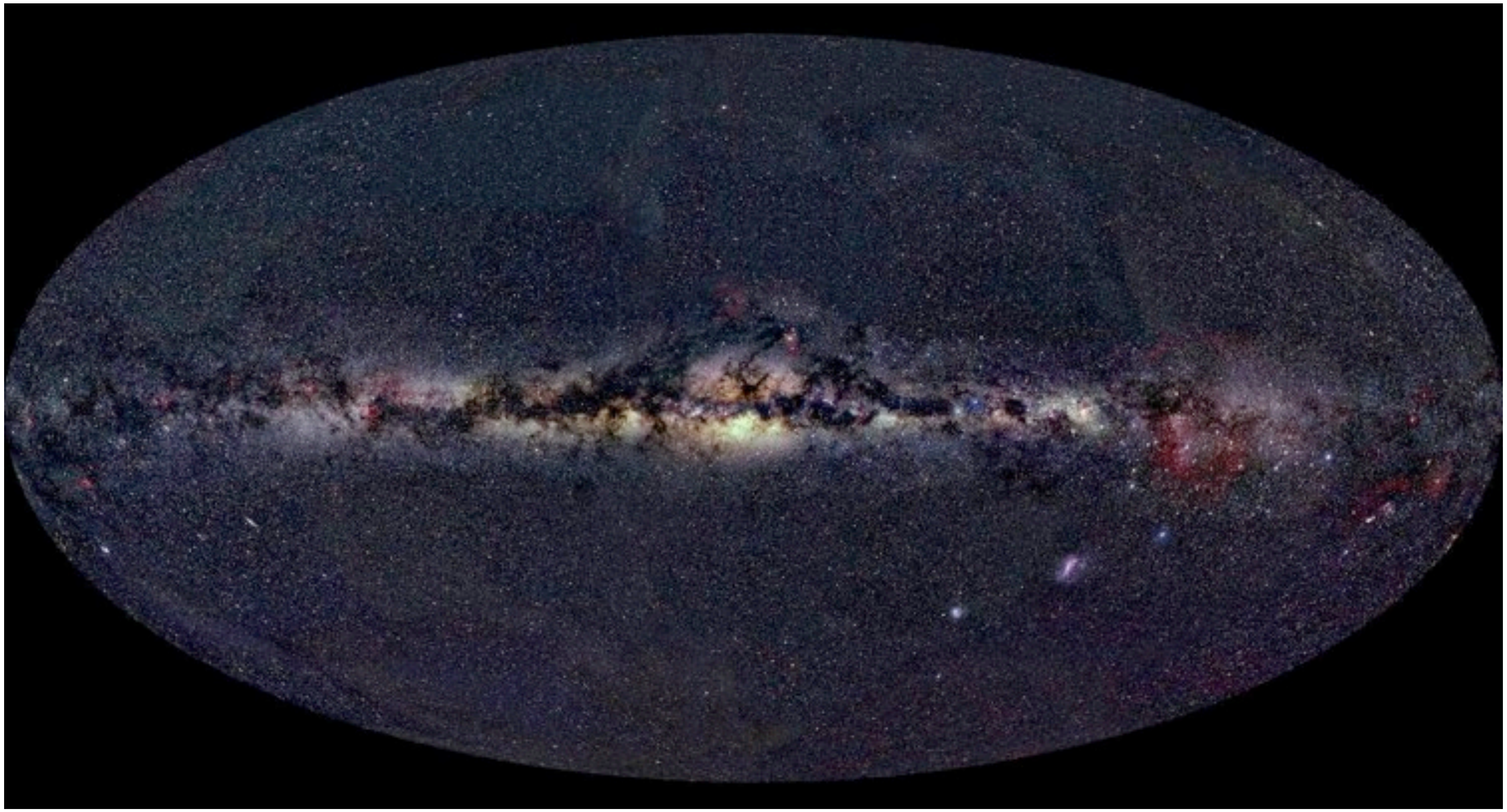
André et al. 2001

I. Molecular clouds: properties of stellar nurseries

II. Dense cores in filamentary structures

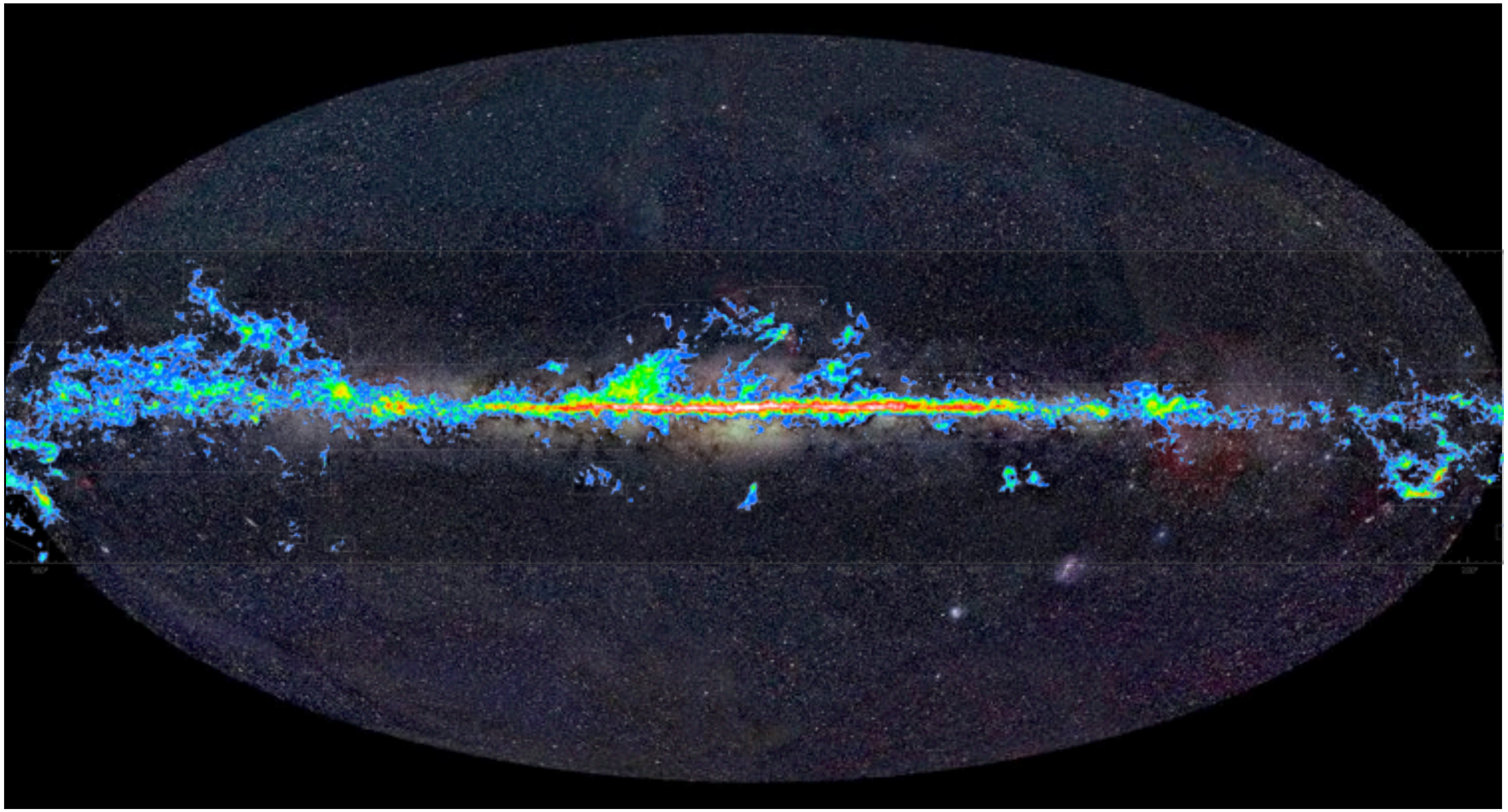
III. Formation of protostars

I. Molecular clouds: properties of stellar nurseries



Optical image of the Milky Way (A. Mellinger)

I. Molecular clouds: properties of stellar nurseries



Optical image of the Milky Way (A. Mellinger)

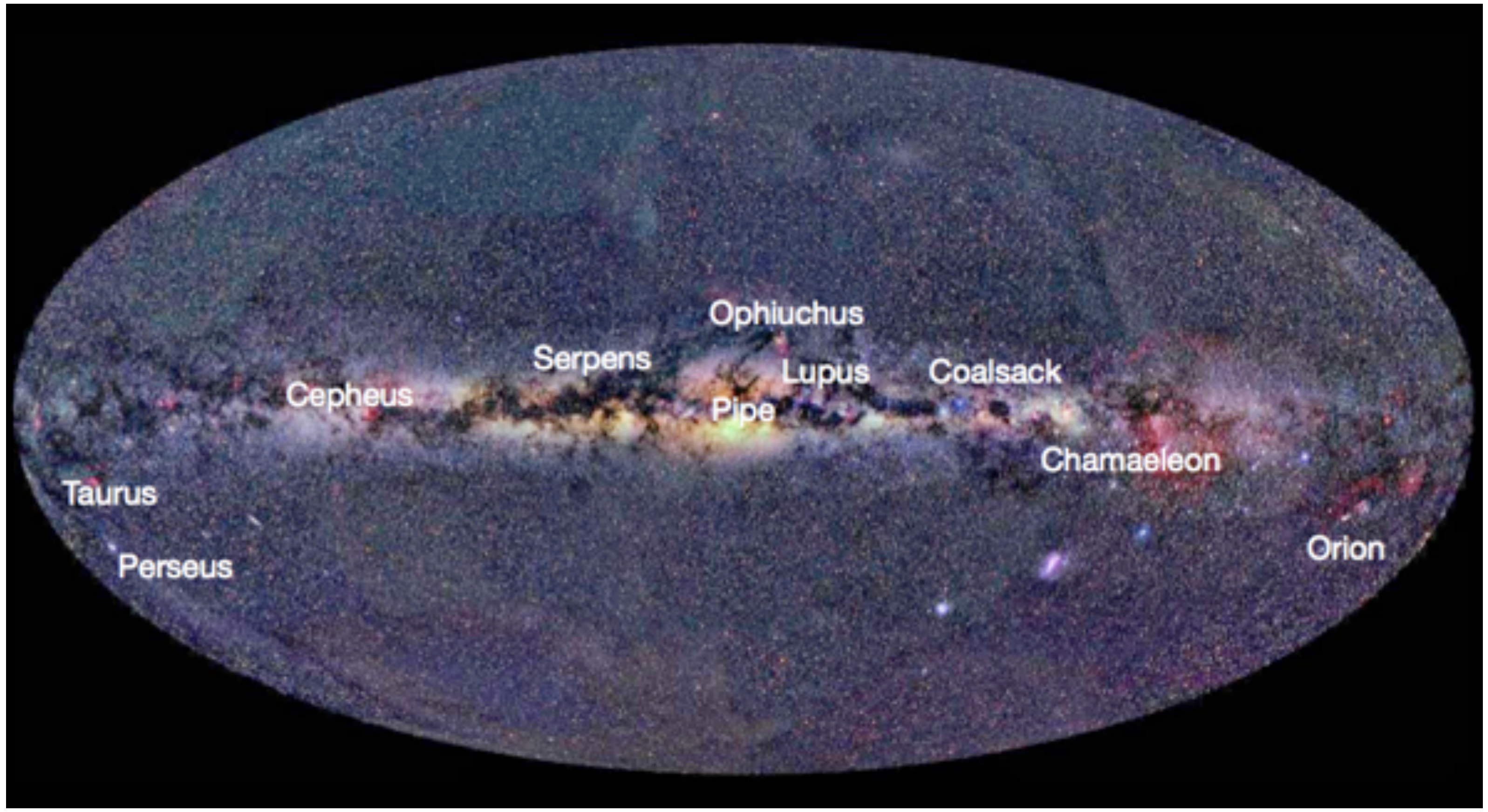
+

CO emission

(Dame T., Hartmann D., Thaddeus P. 2001)

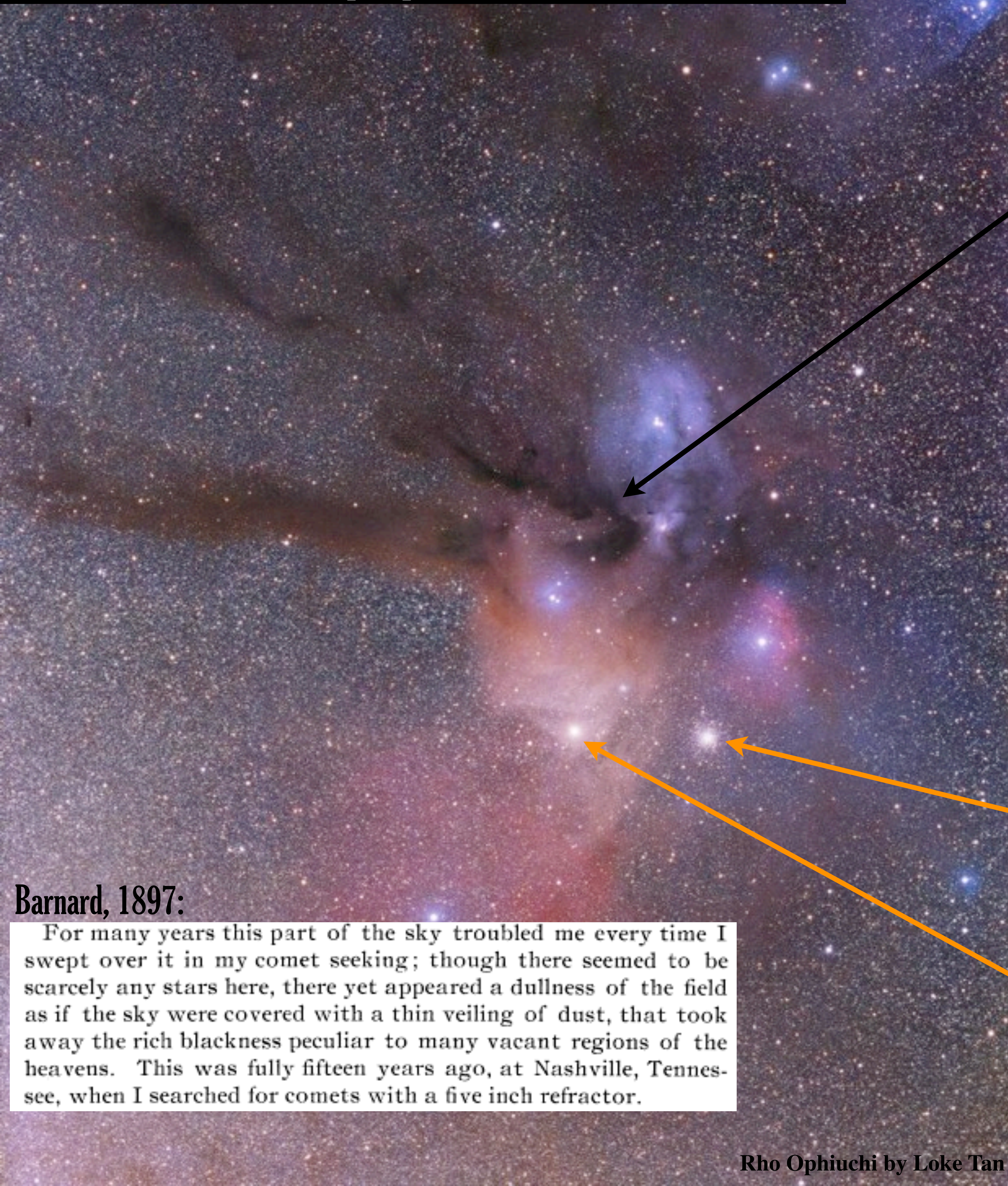
I. Molecular clouds: properties of stellar nurseries

Optical image of the Milky Way (A. Mellinger)



	Size (pc)	Mass (M_0)	ϱ (cm^{-3})	T (K)	A_V (mag)
Giant Molecular Clouds	10 - 60	10^4 - 10^6	100 - 10^3	20 - 50	~ 2
Molecular Clouds	2 - 20	10^2 - 10^4	10^2 - 10^4	10 - 30	~ 5
Bok Globules	0.1 - 10	1 - 10^2	10^3 - 10^5	10 - 30	~ 10
Cores	<0.1 - 1	0.1 - 100	> 10^5	7 - 15	~ 20

I. Molecular clouds: properties of stellar nurseries


Rho Ophiuchi by Loke Tan

ϱ-Ophiuchus Molecular Cloud

D ~ 120 pc

M ~ $15 \times 10^3\ M_0$

One of the closest Star forming clouds

M4 (globular cluster)

Antares

Barnard, 1897:

For many years this part of the sky troubled me every time I swept over it in my comet seeking; though there seemed to be scarcely any stars here, there yet appeared a dullness of the field as if the sky were covered with a thin veiling of dust, that took away the rich blackness peculiar to many vacant regions of the heavens. This was fully fifteen years ago, at Nashville, Tennessee, when I searched for comets with a five inch refractor.

Jeans analysis: stability of star-forming structures

$$M_J = \frac{\pi^{3/2}}{8} \frac{c_s^3}{\sqrt{G^3 \rho}}$$

	Size (pc)	Mass ($M_\odot$)	ρ (cm^{-3})	T (K)	A_V (mag)	M_J ($M_\odot$)
Giant Molecular Clouds	10 - 60	10^4 - 10^6	100 - 10^3	20 - 50	~ 2	15 - 100
Molecular Clouds	2 - 20	10^2 - 10^4	10^2 - 10^4	10 - 30	~ 5	6 - 300
Bok Globules	0.1 - 10	1 - 10^2	10^3 - 10^5	10 - 30	~ 10	2 - 90
Cores	<0.1 - 1	0.1 - 100	> 10^5	7 - 15	~ 20	1 - 3

With typical densities, temperatures and sizes of MC:

all gaz of density > 10^3 cm^{-3} should collapse within 2.10^6 years ...

Time-scale for collapse

- The collapse time-scale t_{ff} when $M > M_J$ is given by the time a mass element at the cloud surface needs to reach the centre.

- In free-fall, an mass element is subject to acceleration $g = \frac{GM}{R^2}$
- The time to cover a distance R can therefore be estimated from:

$$R = 1/2\, g t_{ff}^2 = 1/2 \frac{GM}{R^2} t_{ff}^2$$

- i.e for a pressure-free 3D homogeneous sphere:

$$t_{ff} = (3\pi/32G\varrho)^{1/2}$$

- For a giant molecular cloud, this would correspond to:

$$t_{ff} \sim 7{*}10^6\,\mathrm{yr}\,(m/10^5M_{sun})^{-1/2}\,(R/25\mathrm{pc})^{3/2} \sim \text{a few } 10^6 \text{ years}$$

- + if higher density at cloud center = > faster collapse.

With typical densities, temperatures and sizes of MC:

all gaz of density > 10^3 cm^{-3} should collapse within 2.10^6 years ...

Time-scale for collapse vs lifetimes of MCs

Simple Jeans analysis :
with typical densities, temperatures and sizes of MC,
all gas of density > 10^3 cm^{-3} should collapse and form stars within 2.10^6 years ...

BUT

- Cloud lifetimes estimated by Blitz & Shu (1980) to be around 30 Myr in Milky Way
  - Locations downstream from spiral arms
  - Stellar ages associated with GMCs
- Shorter lifetimes of 5-10 Myr proposed by Ballesteros-Paredes et al. (1999), Fukui et al. (1998).
  - Lack of 10 Myr old T Tauri stars
  - Cluster ages vs. associated molecular gas

I. Molecular clouds: properties of stellar nurseries

What about the star formation rate ?

- **Optically thin dust emission at (sub)mm wavelengths**

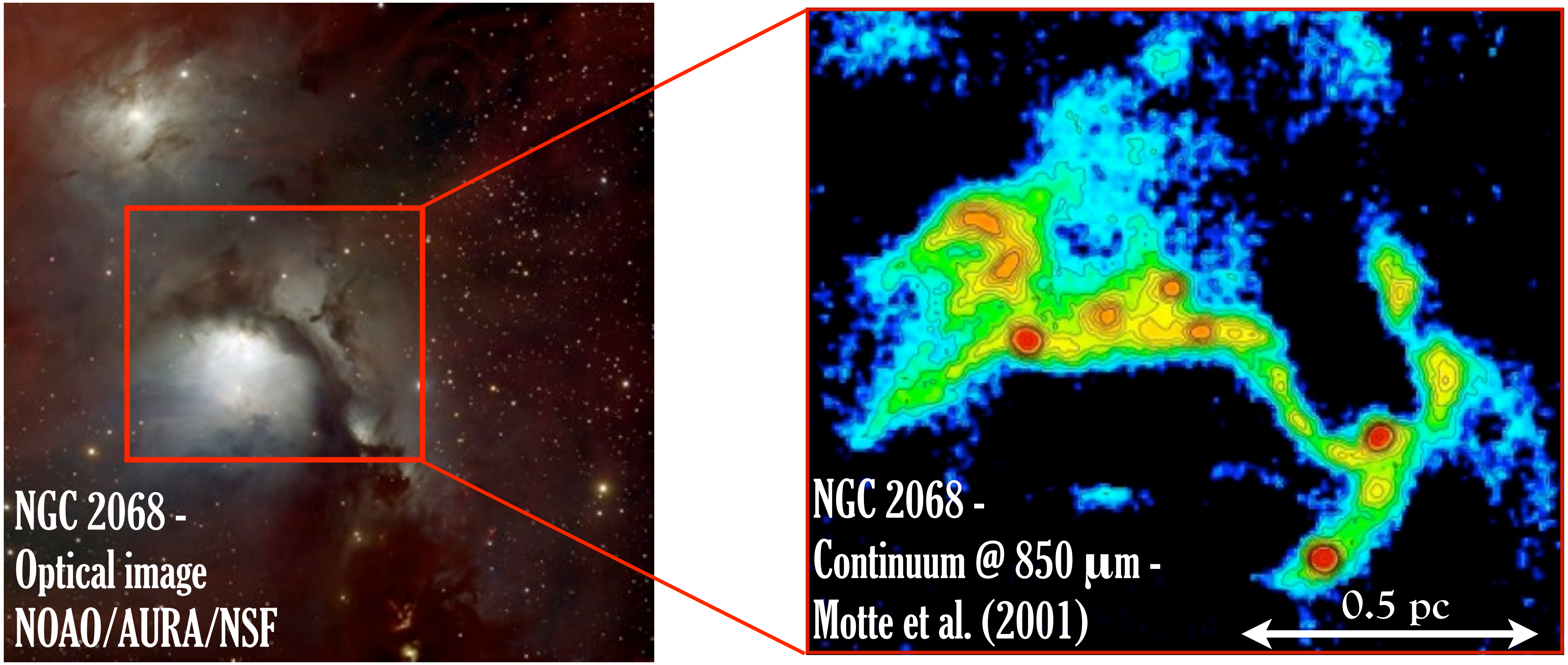
→ Direct mass/column density estimates :

$$M = \frac{S_\nu \, d^2}{B_\nu (T_d) \, \kappa_\nu} \qquad \Sigma = \frac{I_\nu}{B_\nu (T_d) \, \kappa_\nu}$$

S_ν : Integrated flux density

I_ν : Surface brightness

Σ : Column density (g cm^{-2})



I. Molecular clouds: properties of stellar nurseries

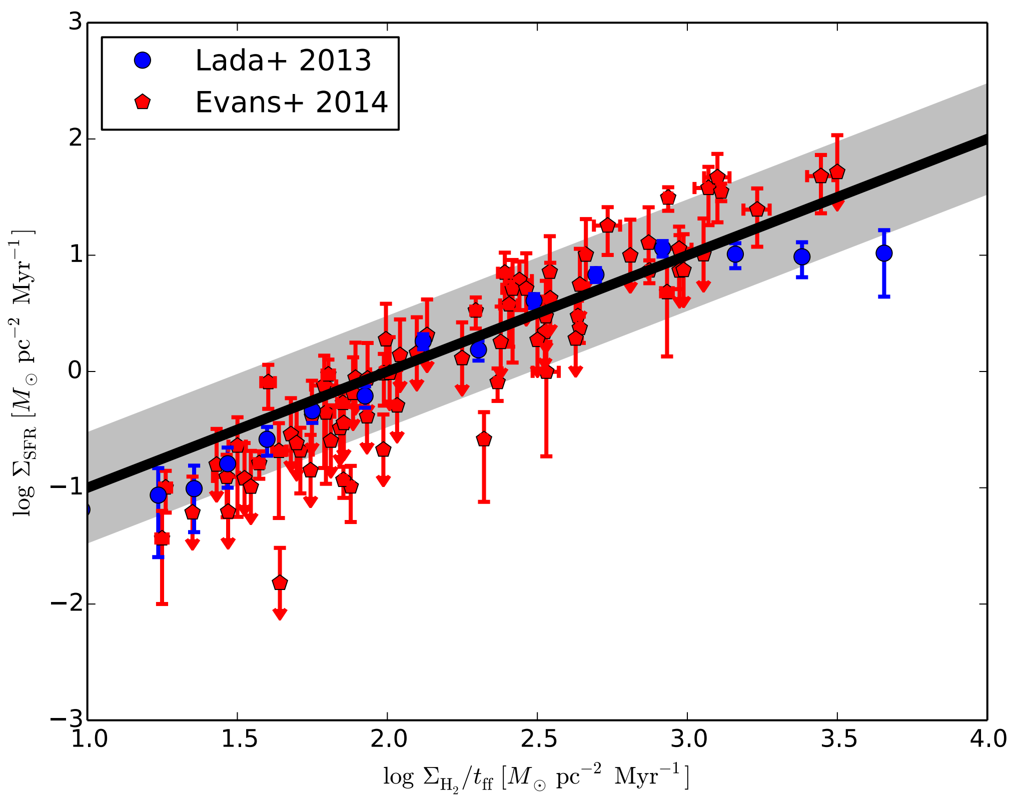
What about the star formation rate / efficiency ?

- In our Galaxy: mass of gaz with $\rho > 10^3$ cm^{-3} is ~ 10^9 $M_\odot$.
- Without support against gravity: expected galactic SFR ~ 300-500 $M_\odot$ / year
- But observations: SFR ~ 3 $M_\odot$ / year (e.g. McKee & Williams 1997)

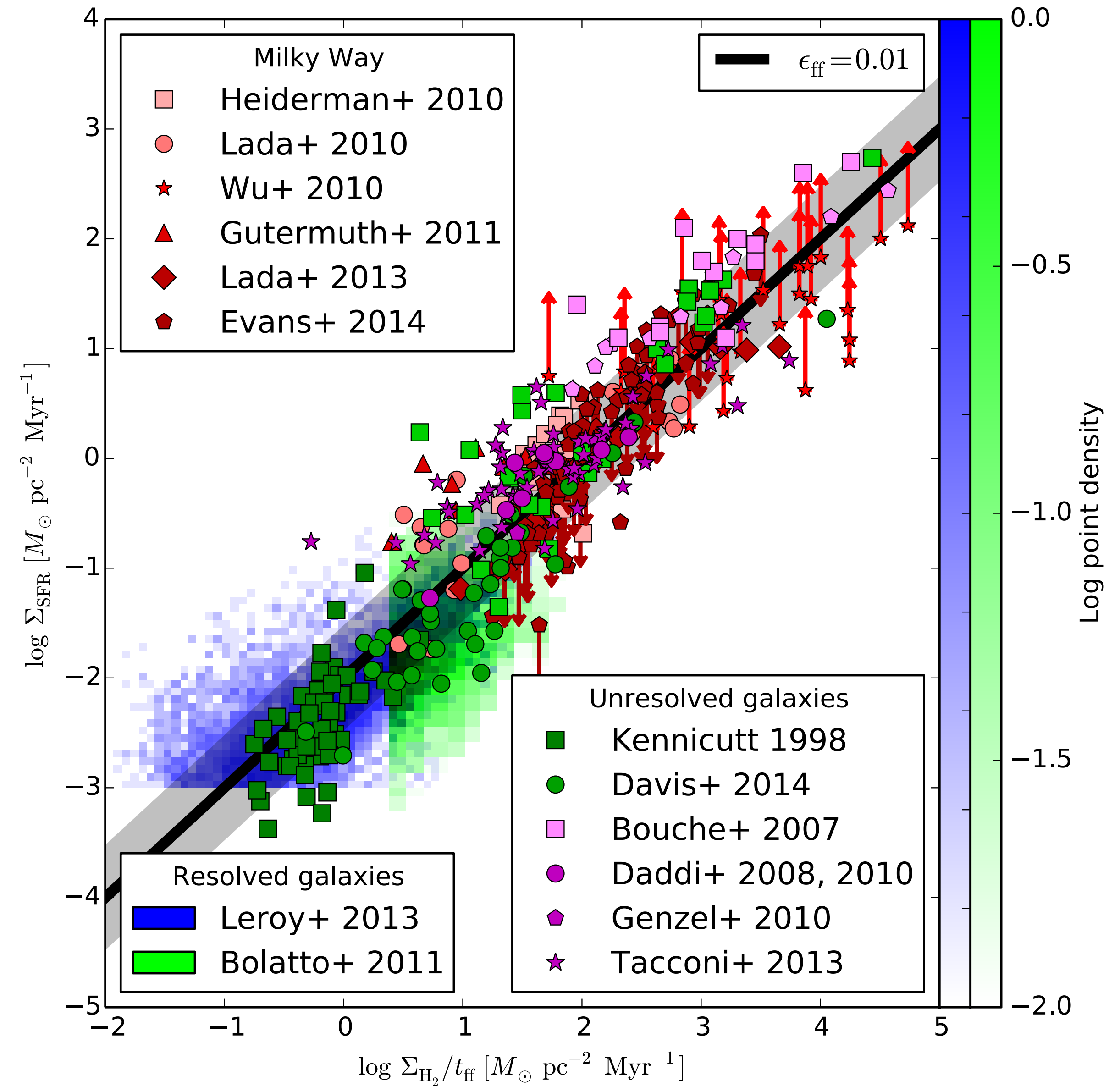
Spitzer C2D in low-mass star-forming clouds (Evans et al. 2009, 2014)

εff ~ 0.01 – 0.1 for clouds with mean densities $n_{H_2} \sim 10^3$ cm^{-3}

+ the data are best fit by $\varepsilon ff \propto (\Sigma / tff)^{0.3-0.5}$



Kennicutt & Evans (2012), Krumholz (2014): on average εff 1%

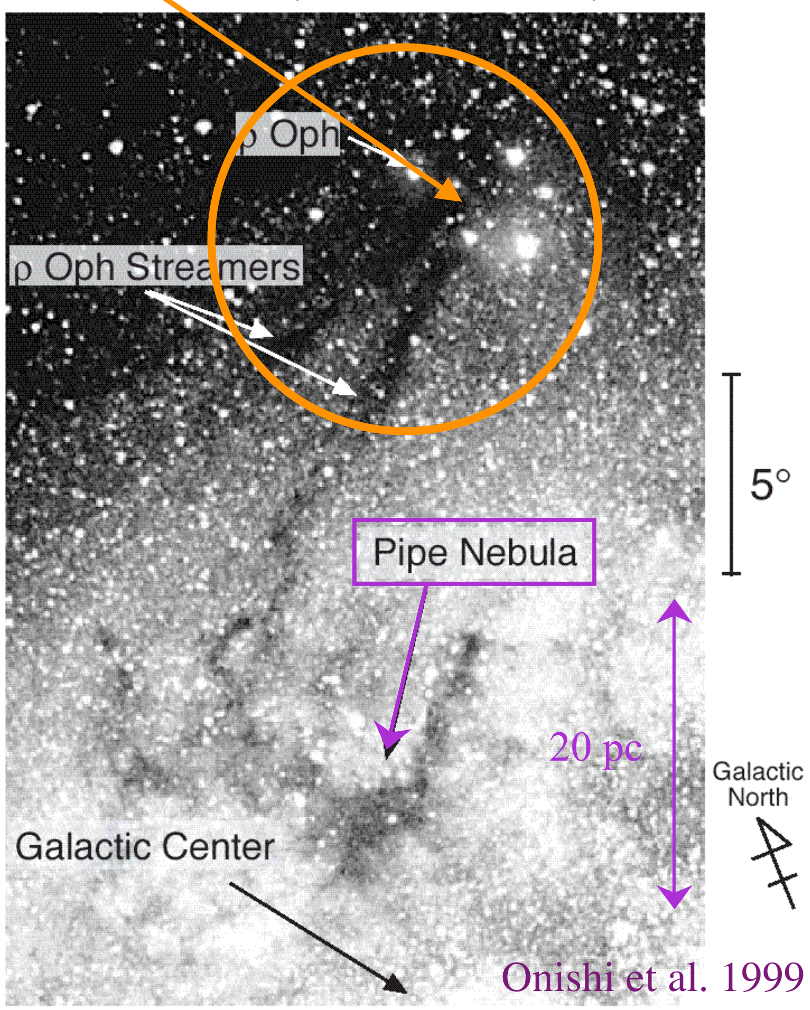


All the dense gas does NOT undergo free-fall collapse

What about the star formation efficiency at local scales ?

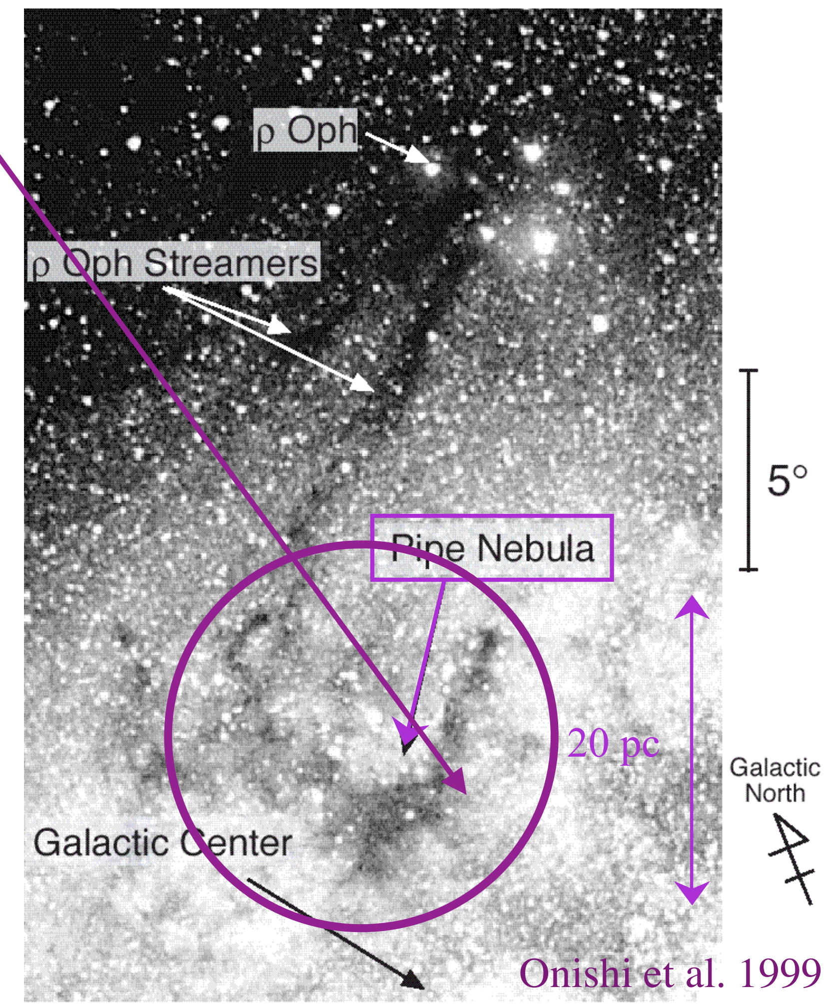
Rho Ophiuchi : very active star formation: SFE ~ 5%

(Lada et al. 2010)



Pipe nebula : very little star formation: SFE < 0.1% except in B59

(Onishi et al. 1999, Tachihara et al. 2002)



What about the observed star formation efficiency ?

Molecular clouds (10-100 pc ; 10^3 cm^{-3})
1-3% / 10^7 yrs (Silk et al. 1997)

Prestellar dense cores (0.1 pc ; 10^5 cm^{-3})
10-30% / 10^6 yrs (Silk et al. 1997; Bontemps et al. 2001)

Prestellar condensations (0.01 pc ; 10^6 cm^{-3})
20-60% / 10^5 yrs (Motte, André & Neri 1998)

At large scales, star formation is an inefficient process: some physical ingredients play important roles in supporting the cold gas from collapsing and form stars.

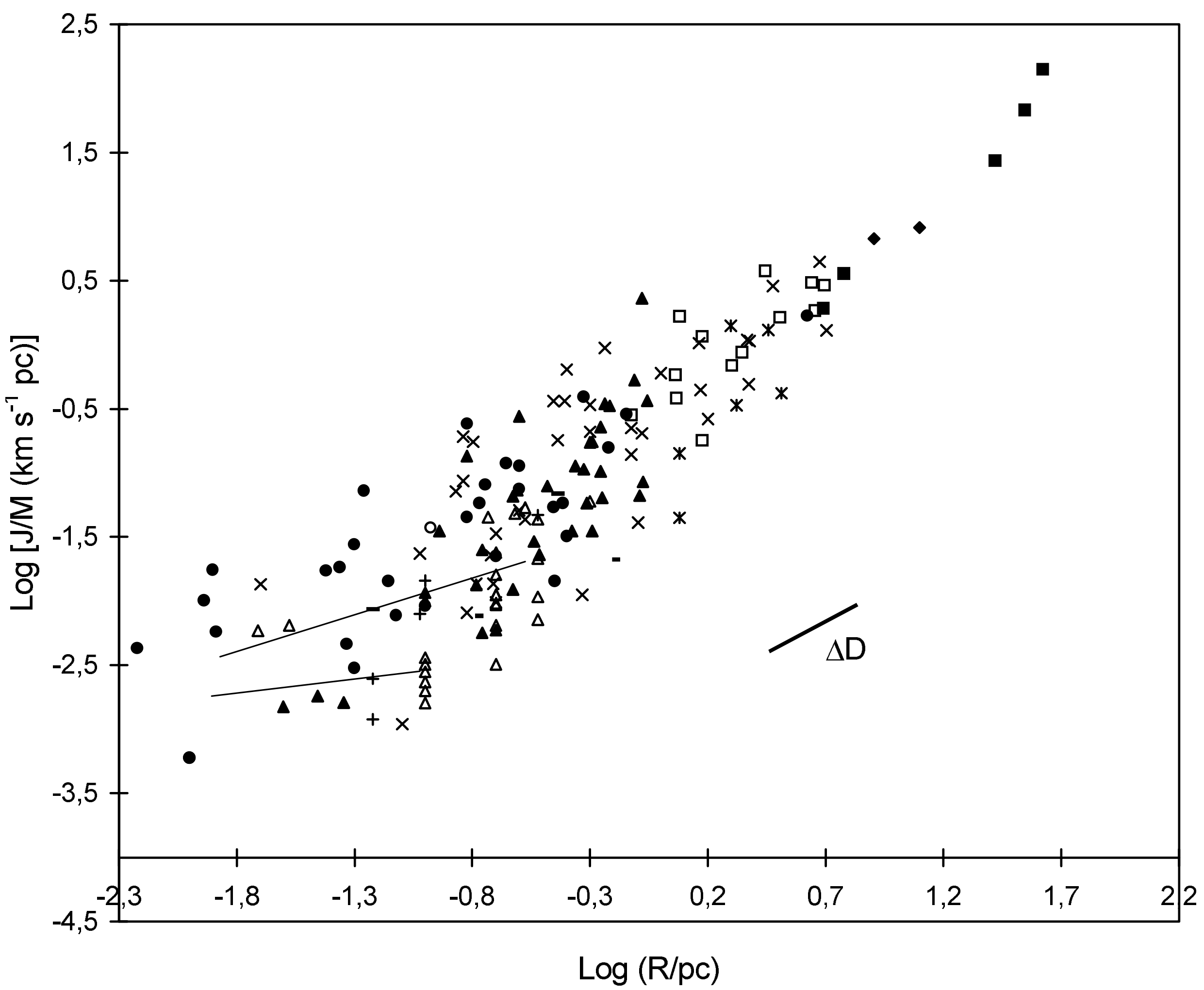
Need sources of additional support for GMC and MC, to lower the global star formation efficiency !

Magnetic fields ?
Turbulence ?
Rotation ?
Feedback processes ?

Rotational support in MC ?

$$\frac{E_{rot}}{E_{grav}} \propto \frac{MV^2}{M^2/R} = \frac{L^2}{M}\frac{1}{R}$$

- Difficult to measure rotation at large scales: velocity gradients are everywhere due to flows, infall, outflows etc ...
- Arquilla & Goldsmith (1986)+ Phillips (1999): study of dark clouds implies rotational support rare at cloud scales



Typically:

velocity gradients 0.4 - 3 km s^{-1} pc^{-1}
angular speeds ~ 10^{-14} - 10^{-13} rad s^{-1}

==> $E_{rot}/E_{grav} < 0.02$

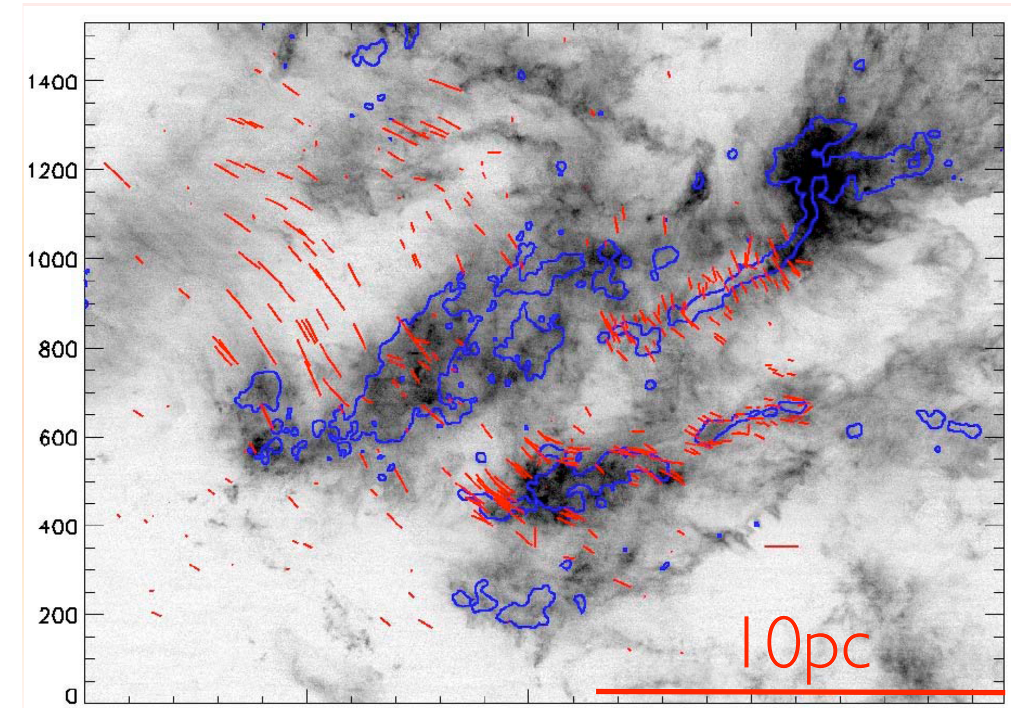
(considering all gradient comes from rotation)

- Note that rotational support becomes important on small scales: conservation of angular momentum during collapse => formation of discs at centrifugal radius

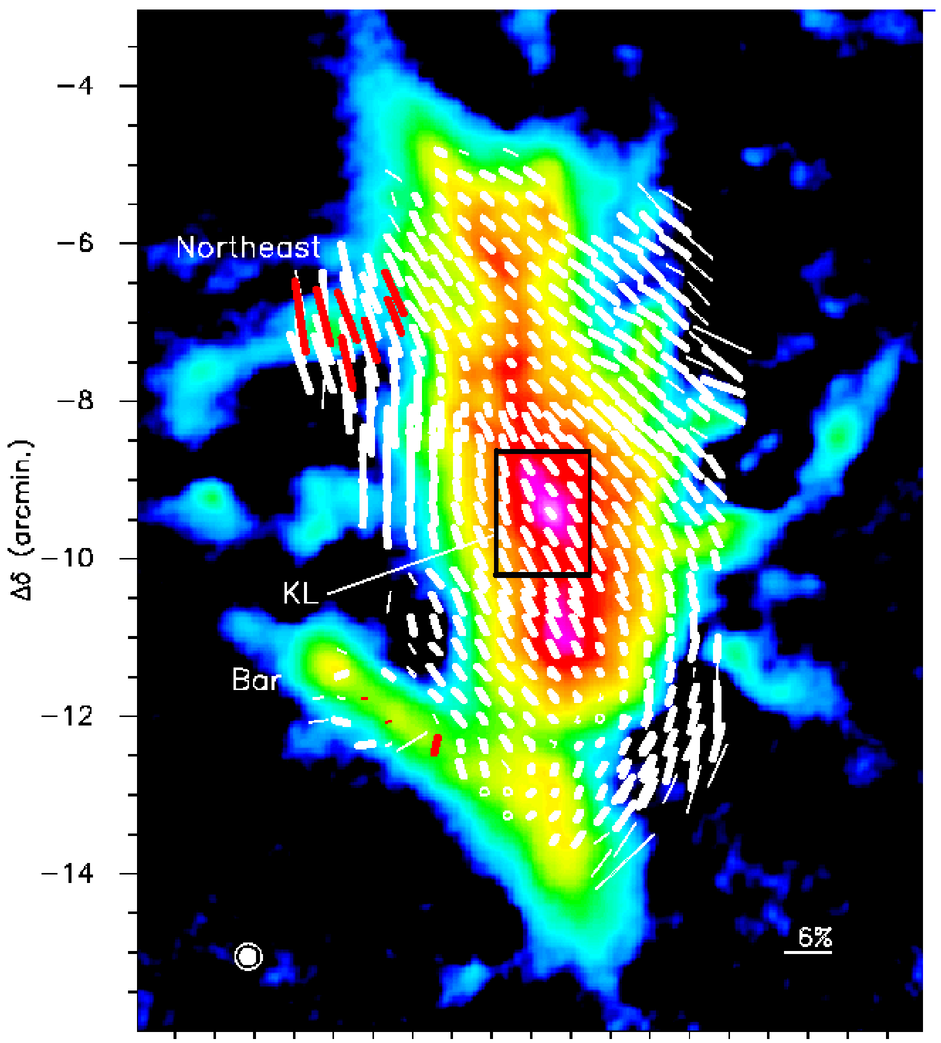
$$R_c = \frac{G^3 M^3 \Omega^2}{16a^8}$$

(cf Chapter 2 ...)

Magnetic fields in MC



Measurements of polarized dust emission toward the low-mass star-forming region Taurus. Goldsmith et al. (2008)



Measurements of polarized dust emission toward the high-mass star-forming region Orion. Houde et al. (2004)

ISM Component	B_{total} (μG)
diffuse ionized medium (synchrotron equipartition, RMs)	7 ± 3
H I clouds (H I Zeeman)	6.0±1.8 ($\lambda \sim 0.1$)
molecular clouds (OH, CN Zeeman)	10 – 3,000+ ($\lambda_C \sim 1$)

See also Falgarone et al. (2008) for Zeeman measurements in star-forming dense cores.

Magnetic support in MC ?

$$M_{cr} = 0.13 G^{-1/2} \int B \, dA = 10^3 \; M_{sun} \left(B / 30 \mu G\right)\left(R / 2 pc\right)^2$$

- **Set magnetic energy ≈ gravitational energy**

$$\pi R^3 \left(\frac{B^2}{8\pi}\right) \approx \frac{GM^2}{R}$$

(to within factors ≈ 1)

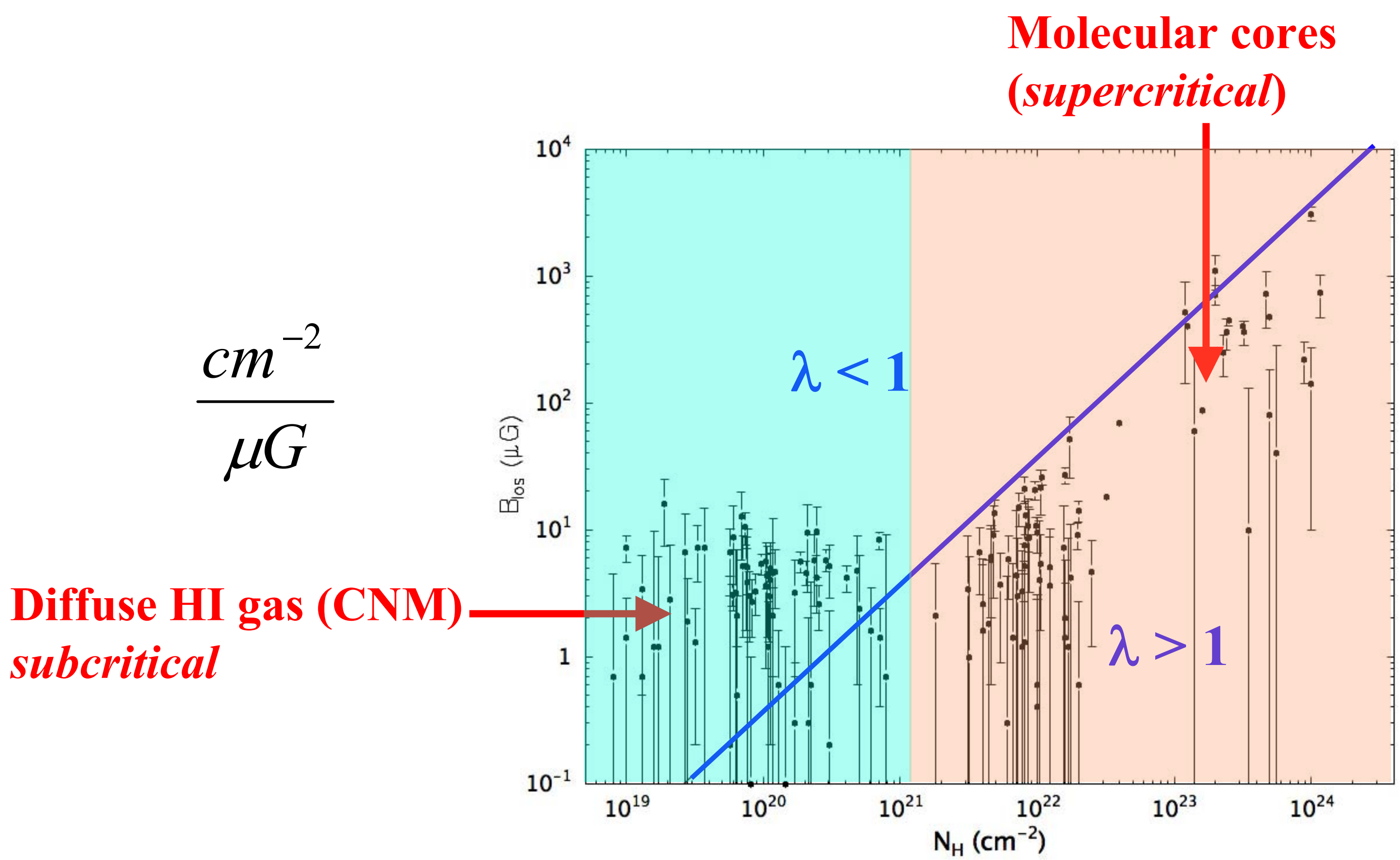
- **Since magnetic flux Φ ≈ $\pi R^2 B$, this relation reduces by simple algebra to**

$$\left(\frac{M}{\Phi}\right)_{crit} \approx \left(\frac{1}{8\pi G}\right)^{1/2}$$

$$\lambda \equiv \frac{(M/\Phi)}{(M/\Phi)_{critical}} \approx 5.0 \times 10^{-21} \frac{N(H)}{B} \qquad \frac{cm^{-2}}{\mu G}$$

- **λ > 1 (*magnetically supercritical*)**
  – Gravitational energy > magnetic energy
  – Self-gravitating cloud *cannot* be supported by *B*

- **λ < 1 (*magnetically subcritical*)**
  – Magnetic energy > gravitational energy
  – *B* supports the cloud *regardless of external pressure*.



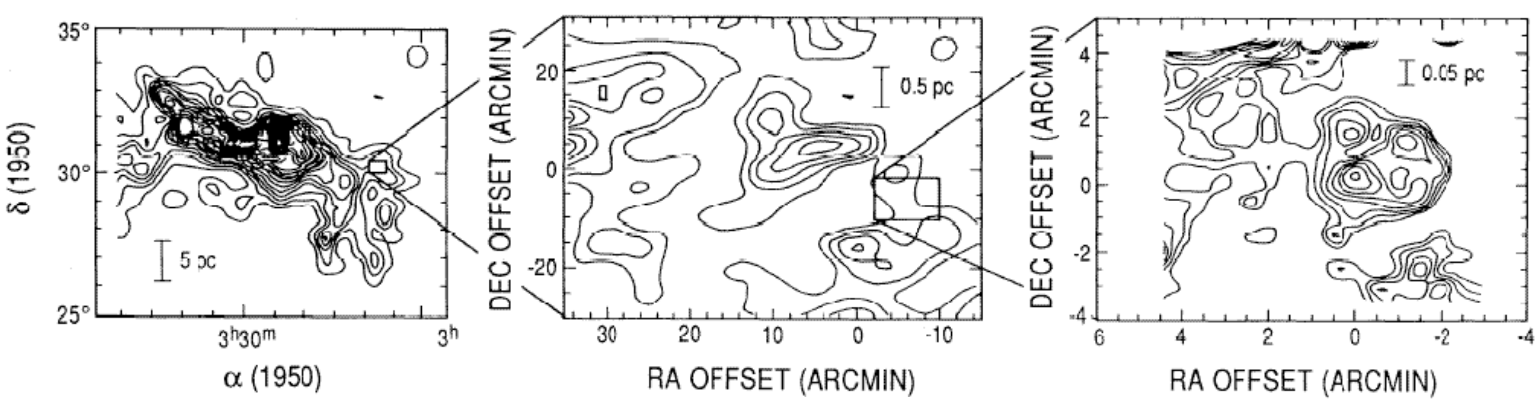
Mass to flux ratios measured with Zeeman measurements.
Crutcher (2007)

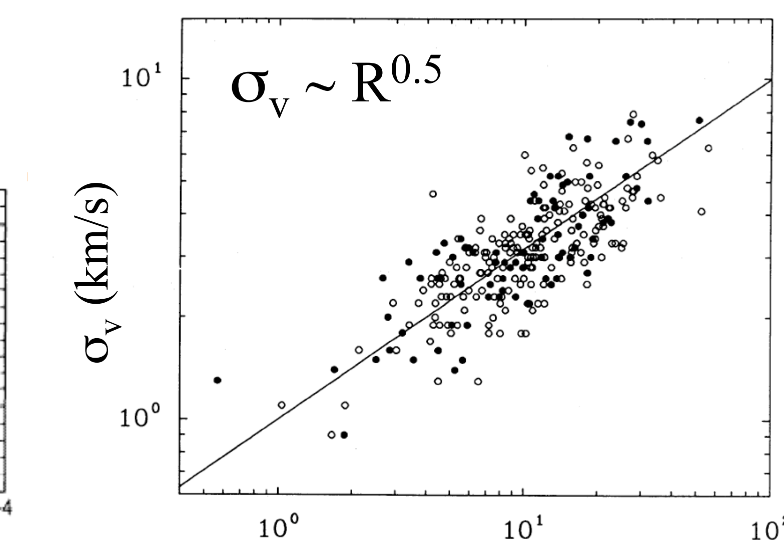
Turbulent support in MC ?

$$M_J^{eff} = \left(\frac{\pi}{G}\right)^{3/2} \times \rho^{-1/2} \times c^3_{s,eff} \quad \text{with} \quad c^2_{s,\,eff} = c_s^2 + \frac{\langle v^2 \rangle}{3}$$

- Doppler linewidth is very narrow: $\Delta v = 2\sqrt{\frac{2\ln 2kT}{m}} = 0.22 km/s \sqrt{\frac{T}{m_{amu}}}$
  CO at 10K Δv = 0.13 km/s

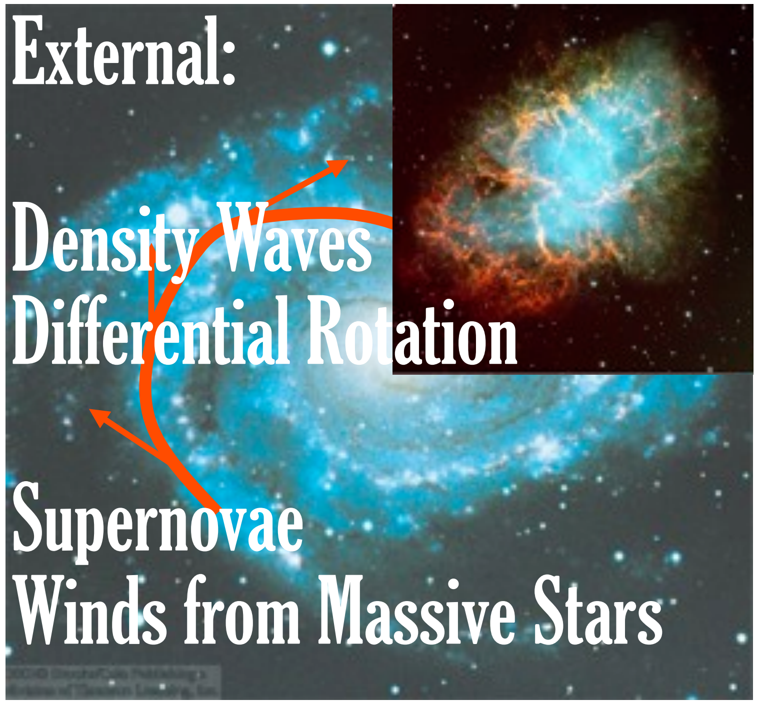
Scaling laws (Larson 1981 and subsequent studies)
+ the fractal structure of the ISM reflect the turbulent nature of the ISM





- Observations in SFR :
  Low-mass regions typically show narrow linewidths
  small velocity dispersion => trans-sonic medium
  => ISM turbulence decays before SF proceeds in $t \sim L / v_{rms}$
  to delay significantly the collapse: need for new progenitors for turbulence ...

Possible progenitors of turbulent support



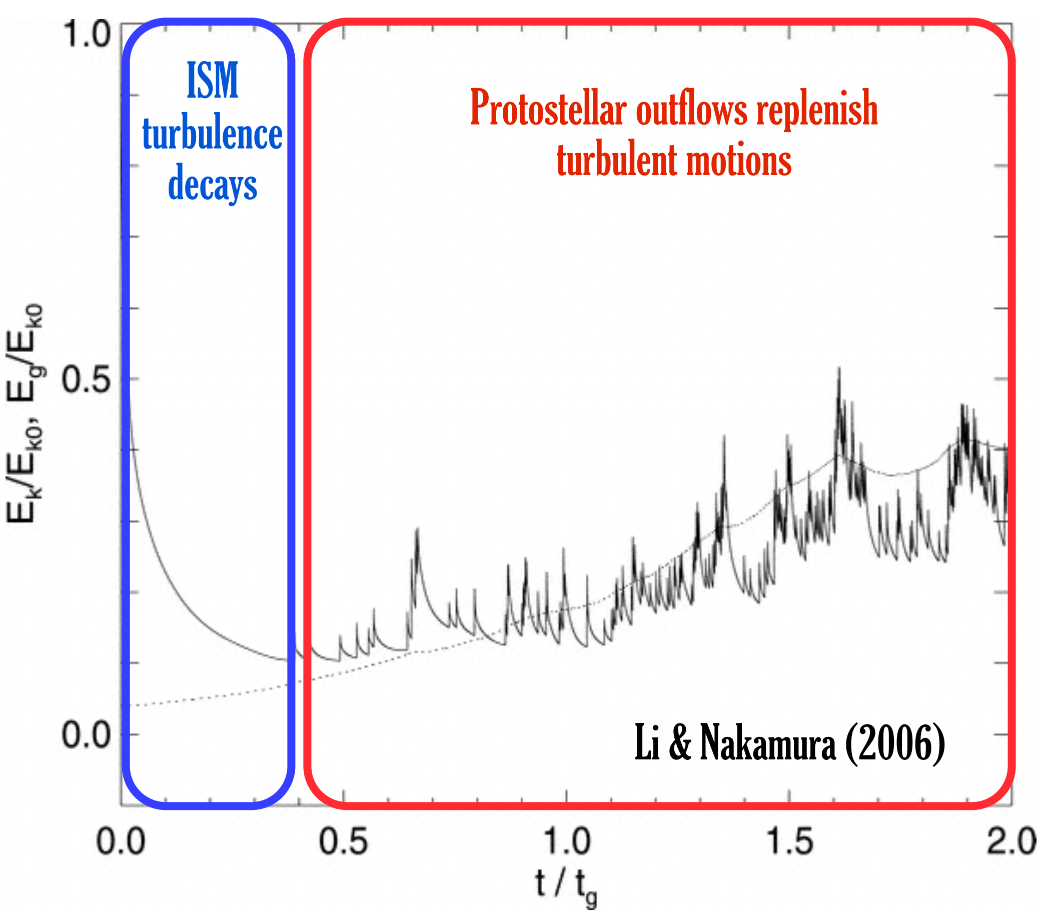
Internal :

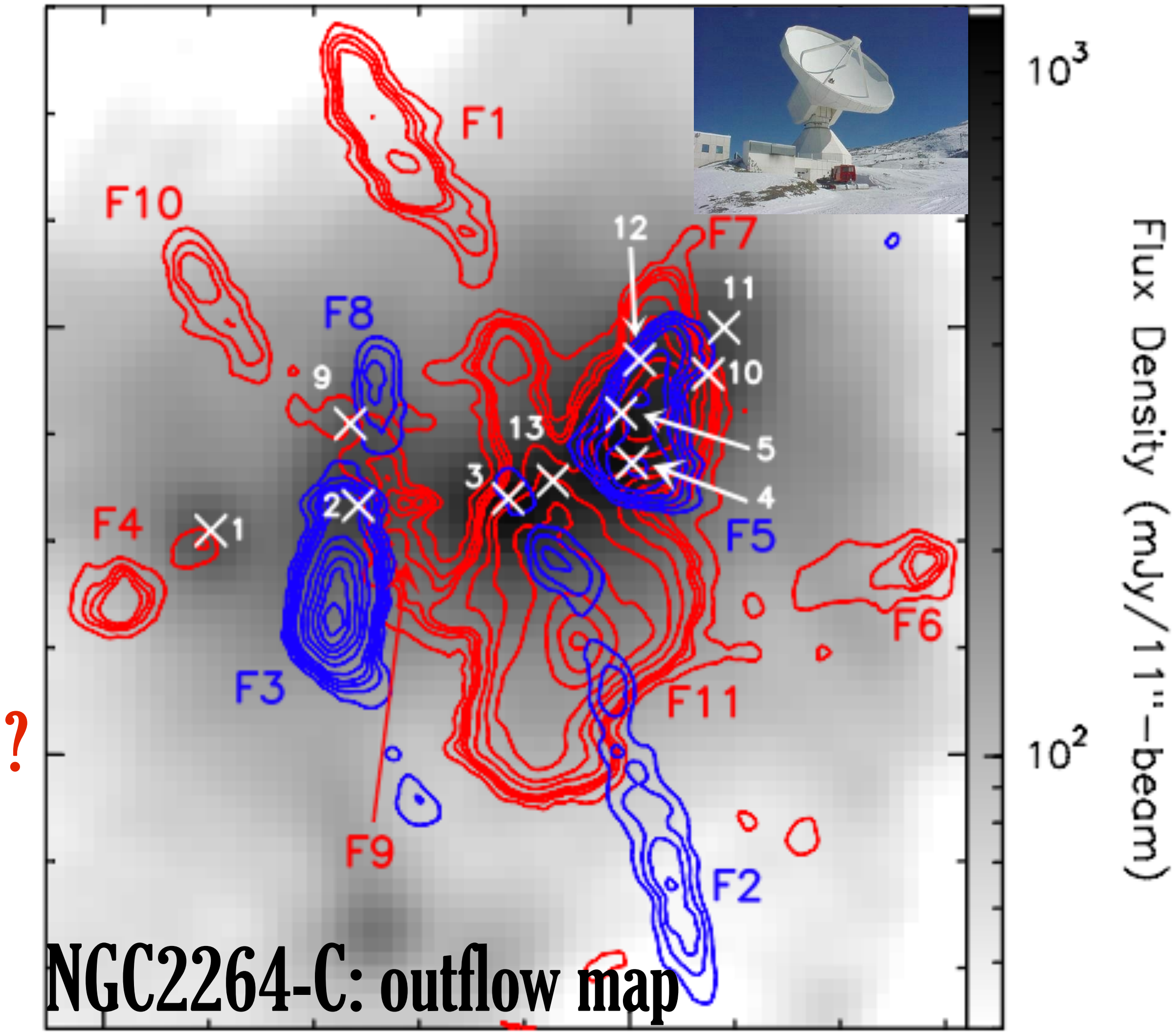
Stellar Winds

Bipolar Outflows

HII

=> only works in cluster-forming clumps ?





^{13}CO mapping :

1D velocity dispersion of the clump : $\sigma_v = \sqrt{\frac{\sum\left[\langle T(v)\rangle \times (v - v_0)^2\right]}{\sum \langle T(v)\rangle}}$

$\sigma_v \sim 1.8$ km/s

NGC 2264-C shows a turbulence enhancement / Larson's classical law.

Rate of turbulent energy dissipation in the clump (MacLow 1999) : $L_{turb} \sim 1.2\ L_o$

$$L_{turb} \approx \frac{1/2 \times M_{cloud} \times \sigma_v^2}{R_{cloud} / \sigma_v}$$

Outflow mechanical luminosity $L_{flow} \sim 0.7 \pm 0.5\ L_o$

Outflows can regenerate the turbulence in NGC 2264-C. Maury+ (2009)

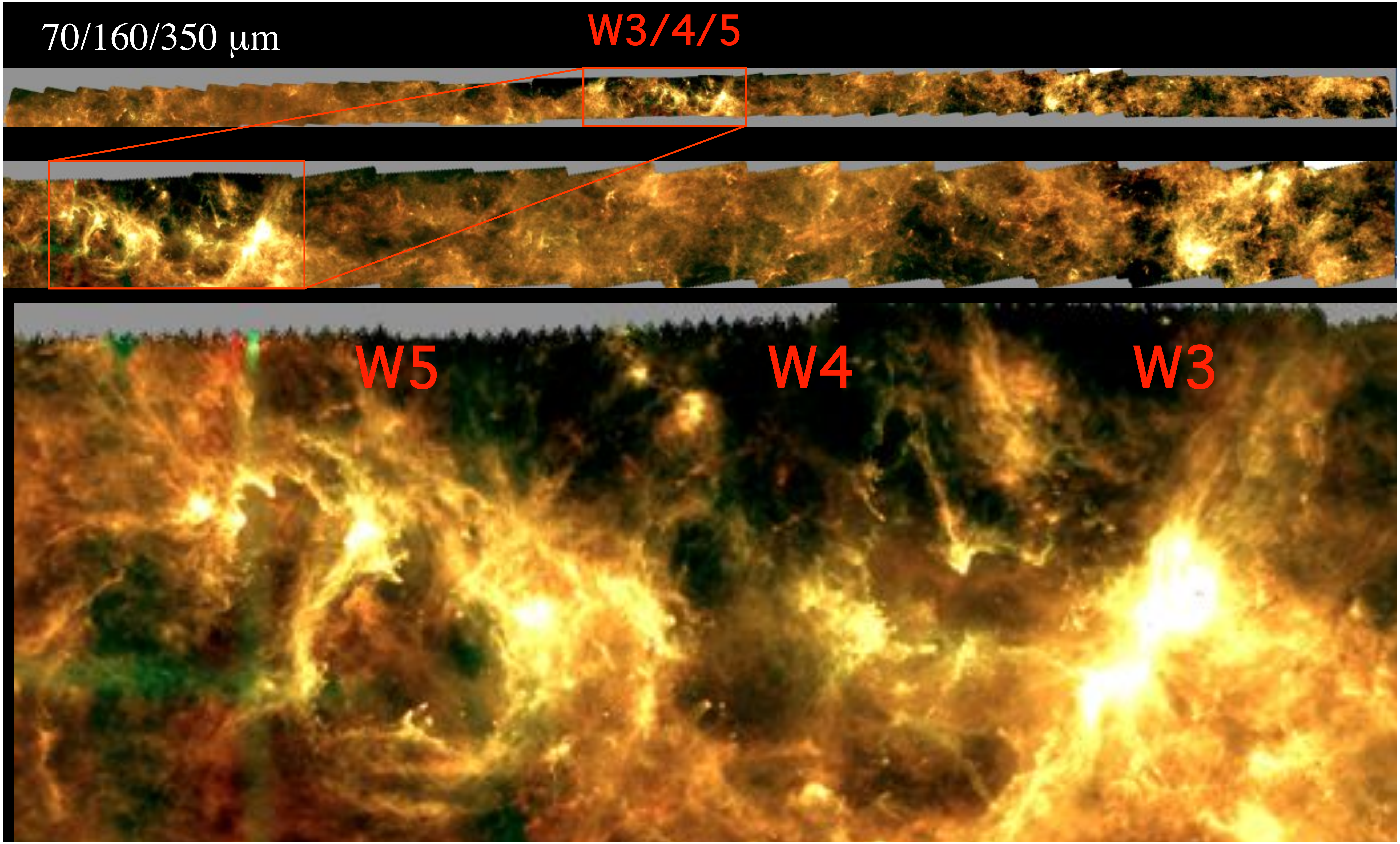
I. Molecular clouds: properties of stellar nurseries

II. Dense cores in filamentary structures

III. Formation of protostars

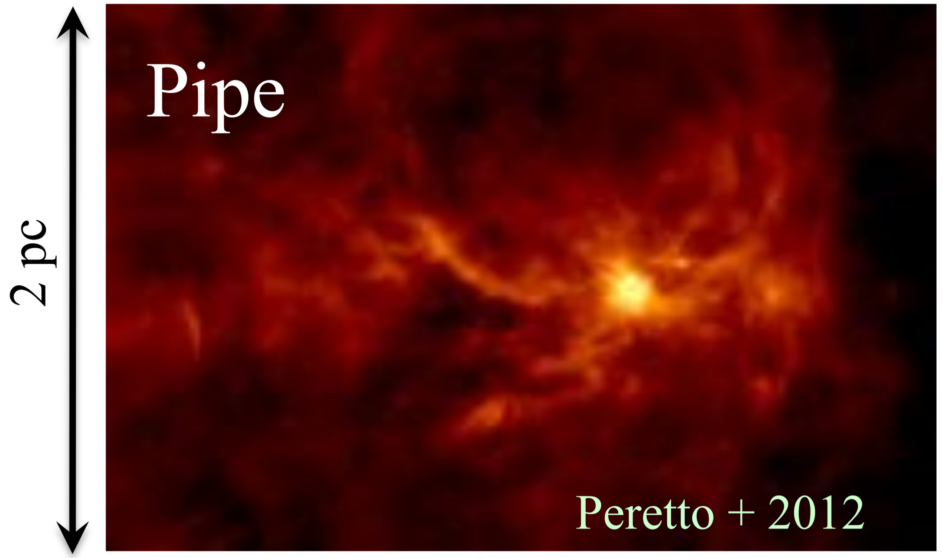
II. Dense cores in filamentary structures

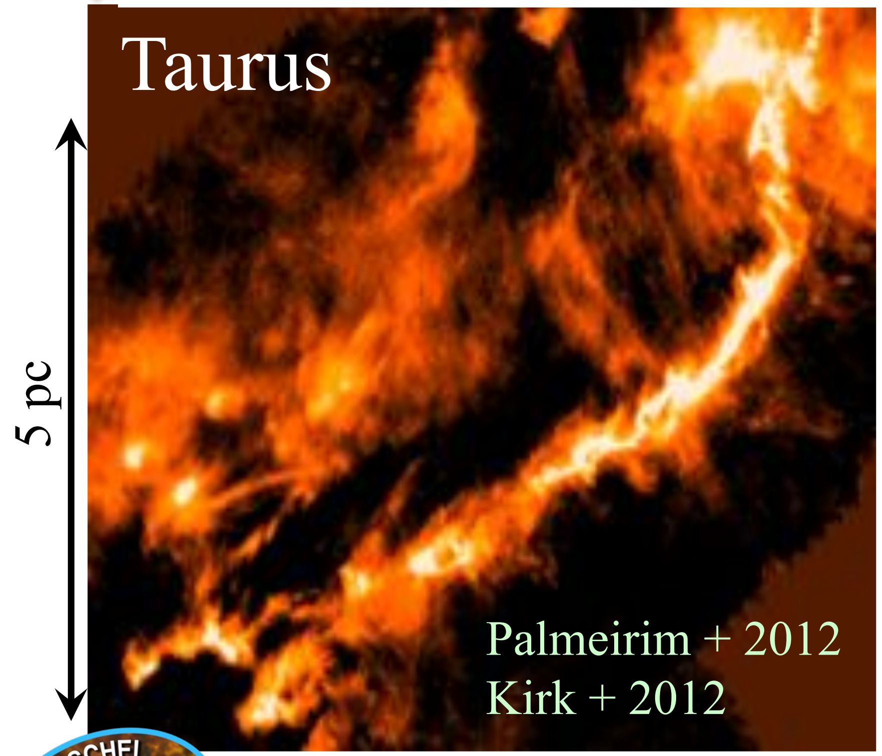
Herschel/HI-GAL image of part of the Milky Way (e.g. Molinari+2010, Schisano+2014)

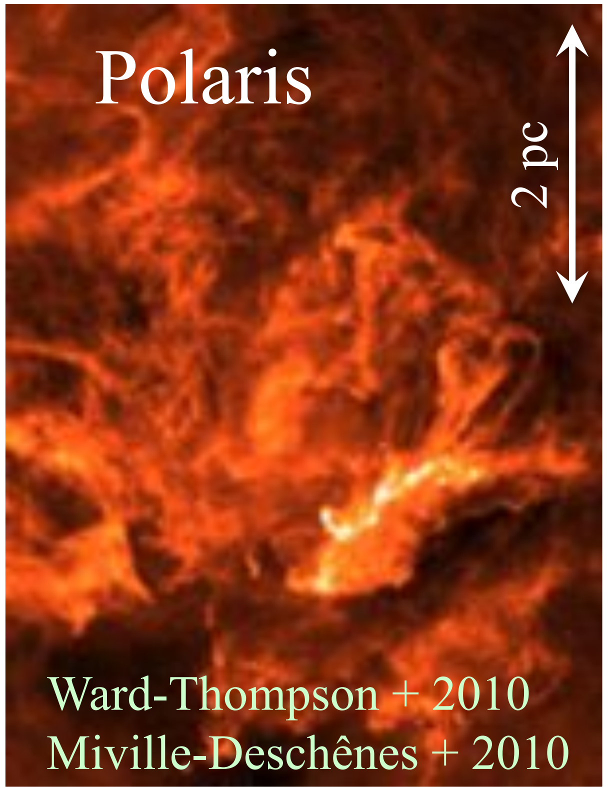


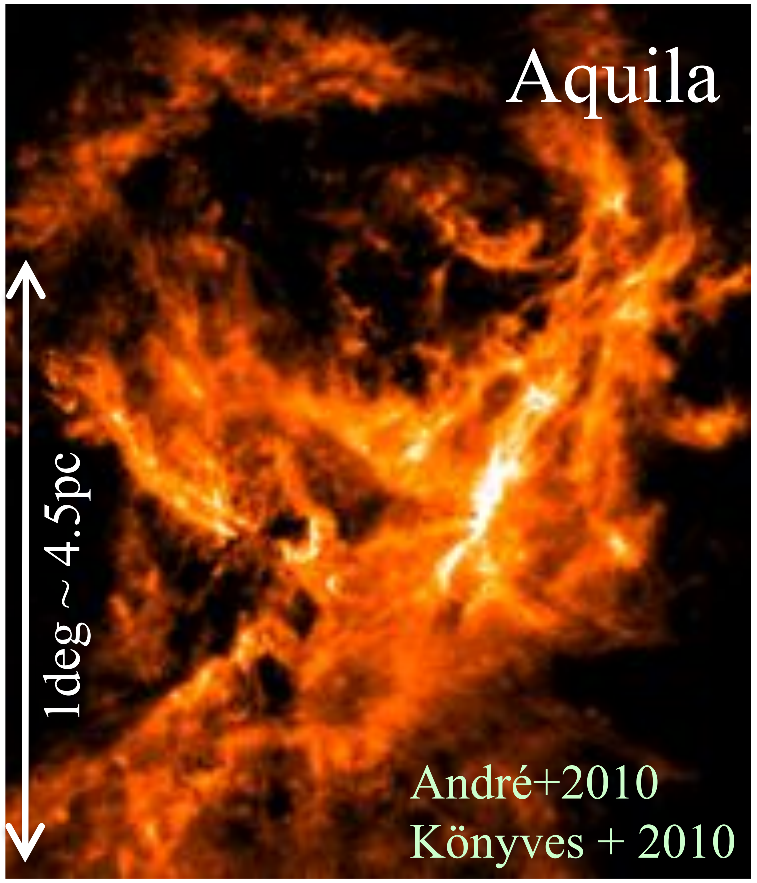
II. Dense cores in filamentary structures

Herschel has revealed a “universal” filamentary structure in the cold ISM



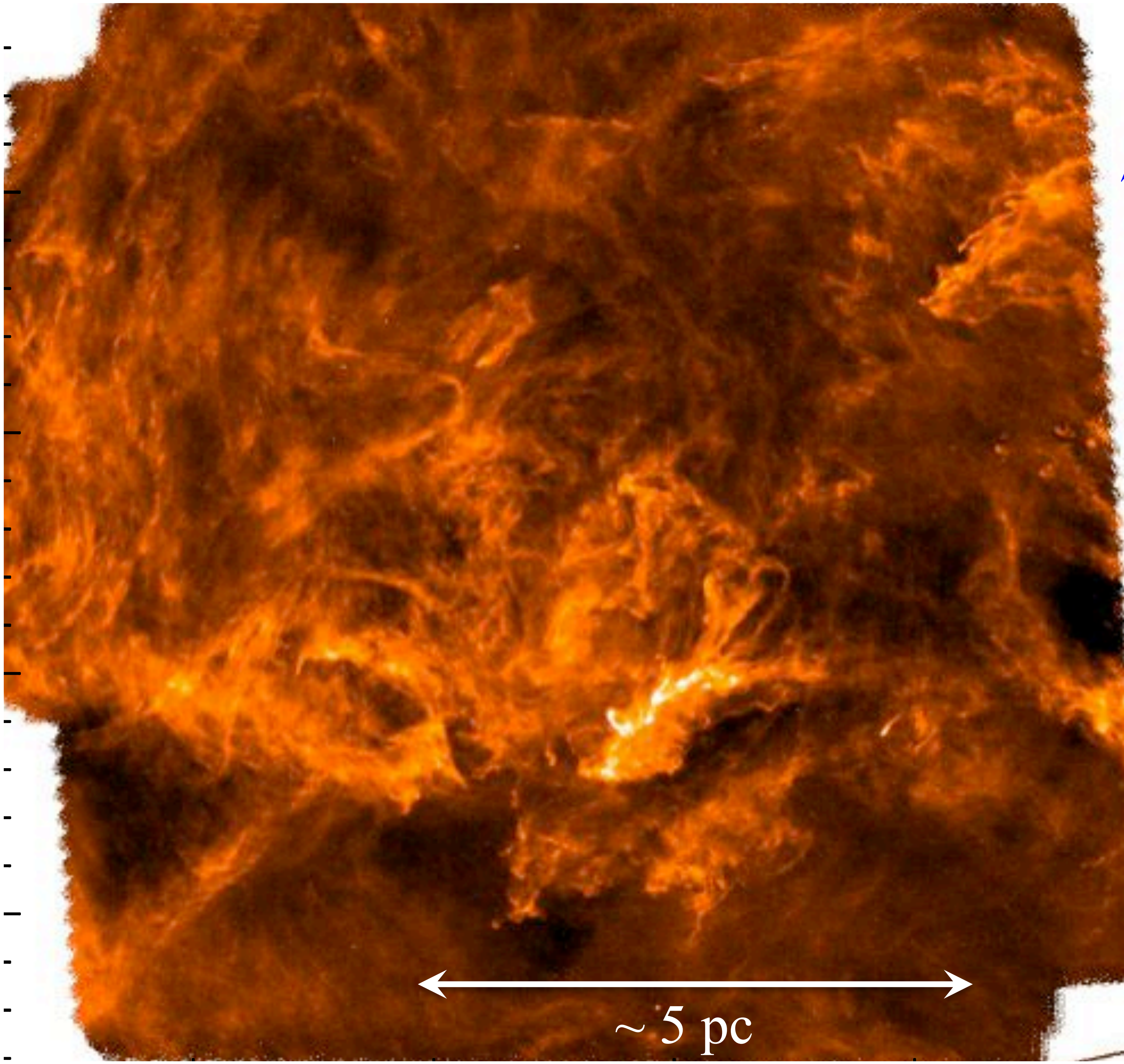






HERSCHEL Gould Belt Survey

Polaris (d ~ 150 pc): Structure of the cold ISM prior to any star formation



Herschel/SPIRE 250 μm image

Gould Belt Survey
PACS/SPIRE // mode
70/160/250/350/500 μm

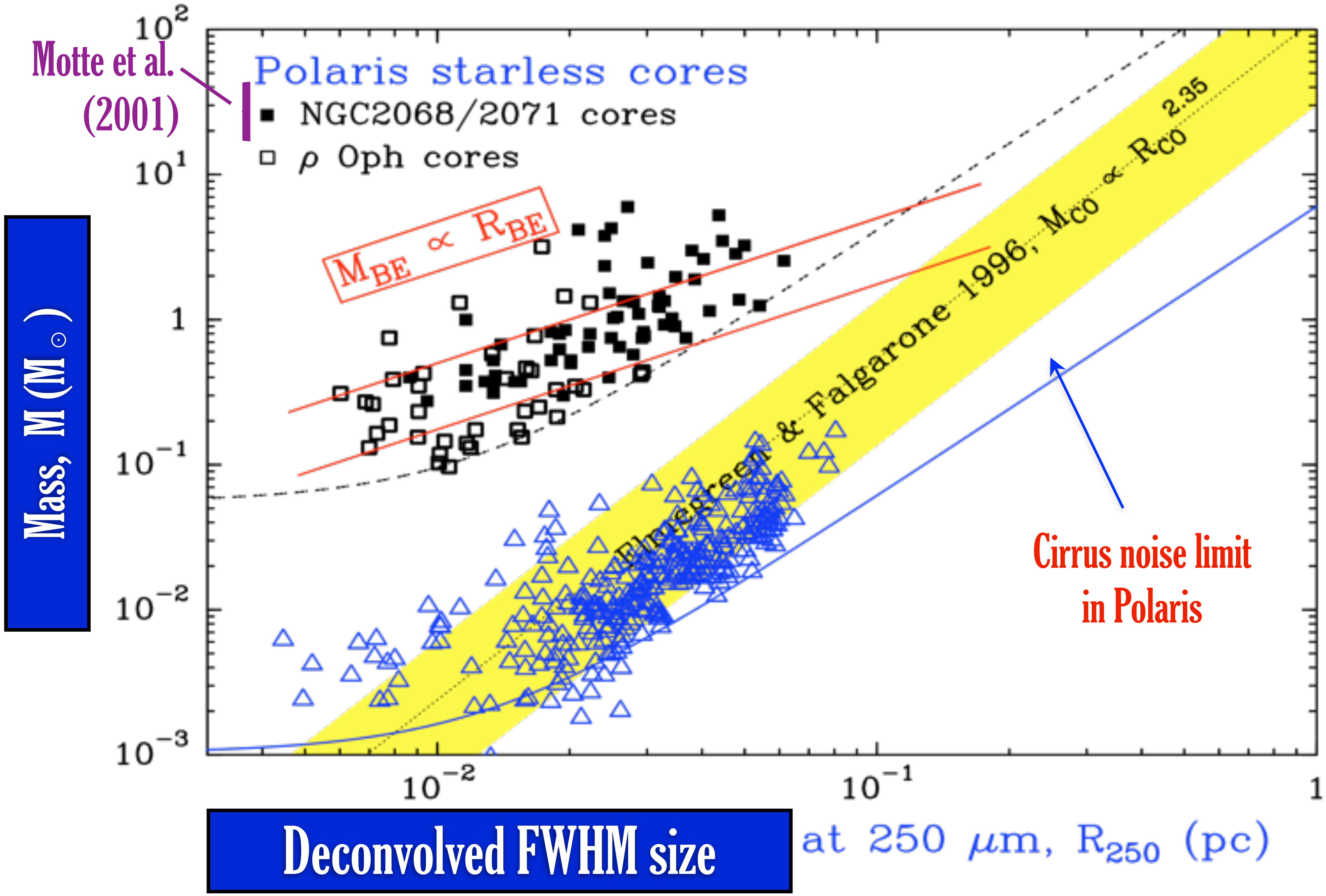
Polaris flare translucent cloud: non star forming

~ 5500 $M_\odot$ (CO+HI)
Heithausen & Thaddeus '90

~ 13 deg^2 field

Miville-Deschênes et al. 2010
Ward-Thompson et al. 2010
Men'shchikov et al. 2010
André et al. 2010

Most of the Polaris starless cores are unbound



~ 350 starless cores

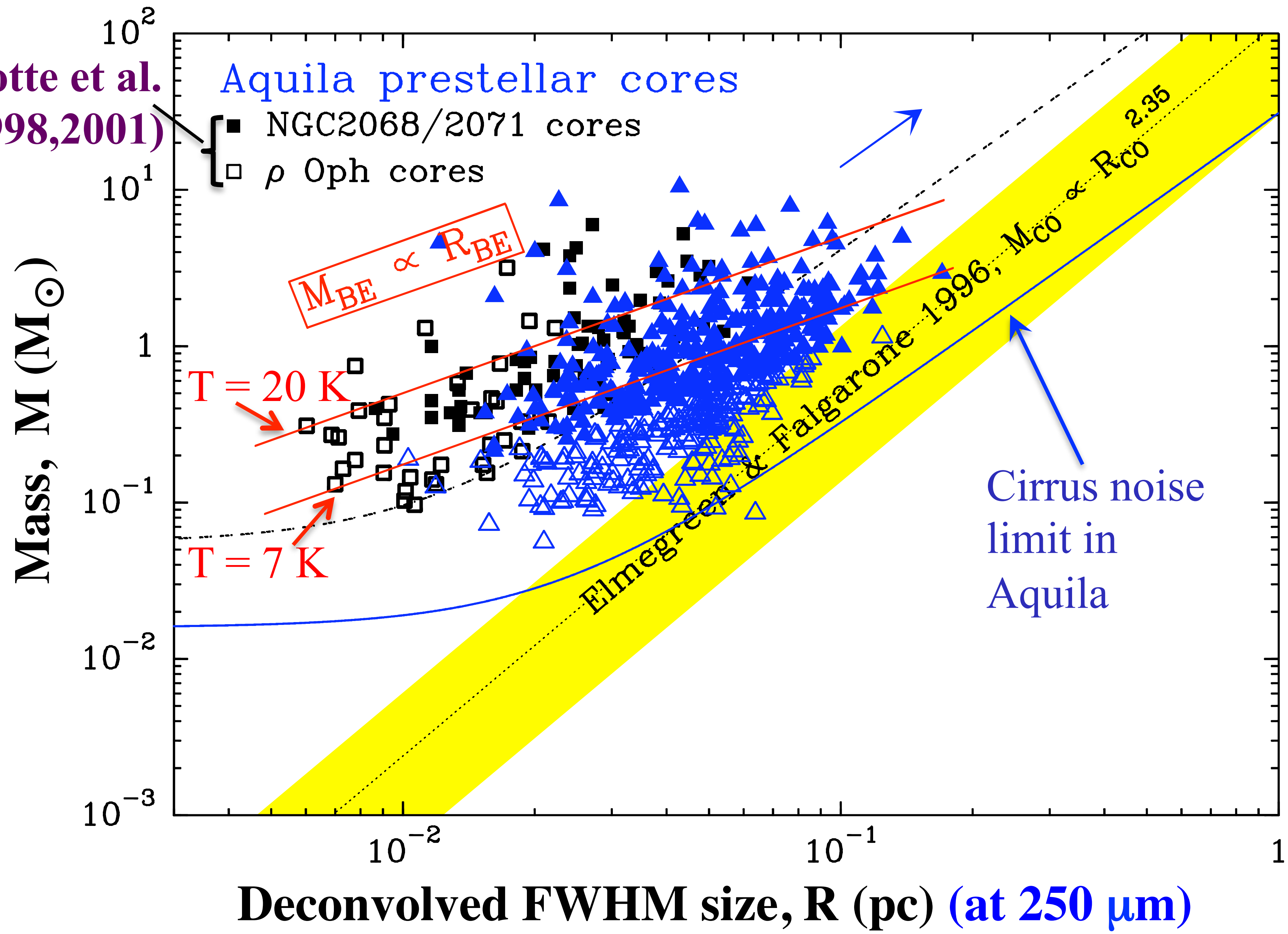
no Class 0 protostars

André et al. 2010
Ward-Thompson et al. 2010

Location in mass vs. size diagram:

2 orders of magnitude below the density of self-gravitating Bonnor-Ebert isothermal spheres

Most of the Aquila starless cores are bound



In Aquila:
>60% of starless cores are bound
=> prestellar

~50 Class 0/I protostars

Könyves et al. 2010, 2016

Location in mass vs. size diagram, consistent with BE spheroids

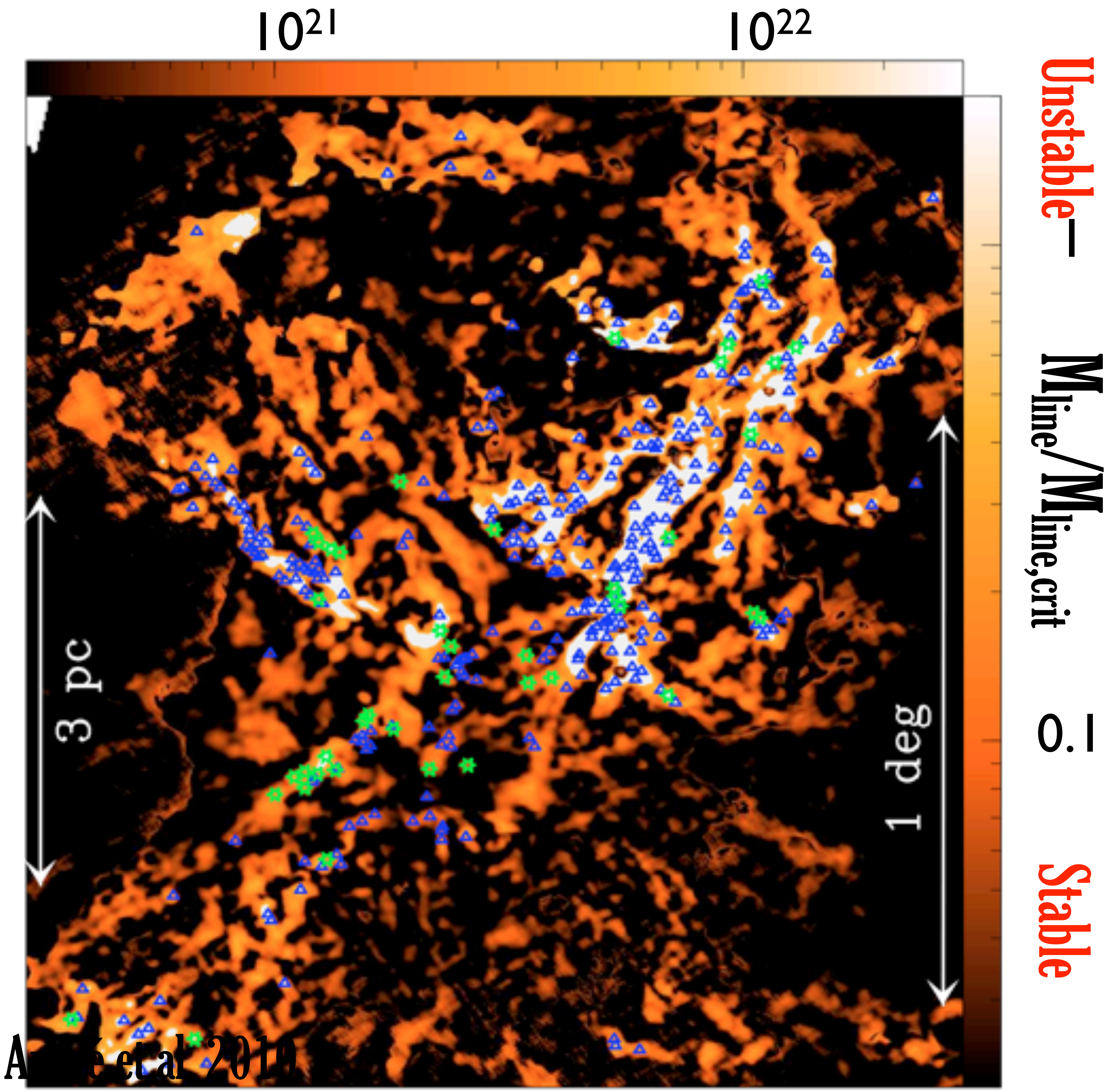
High degree of concentration: N_{H2} / <N_{H2}> ~ 4 on average

Median column density contrast over the background ~ 1.5

II. Dense cores in filamentary structures

~Only the densest filaments are gravitationally unstable and contain prestellar cores (△)

Aquila curvelet N_{H_2} map (cm^{-2})



- ✳ The gravitational instability of filaments is controlled by the value of their mass per unit length M_{line} (cf. Ostriker 1964, Inutsuka & Miyama 1997):
  - unstable if $M_{line} > M_{line,\,crit}$
  - stable if $M_{line} < M_{line,\,crit}$

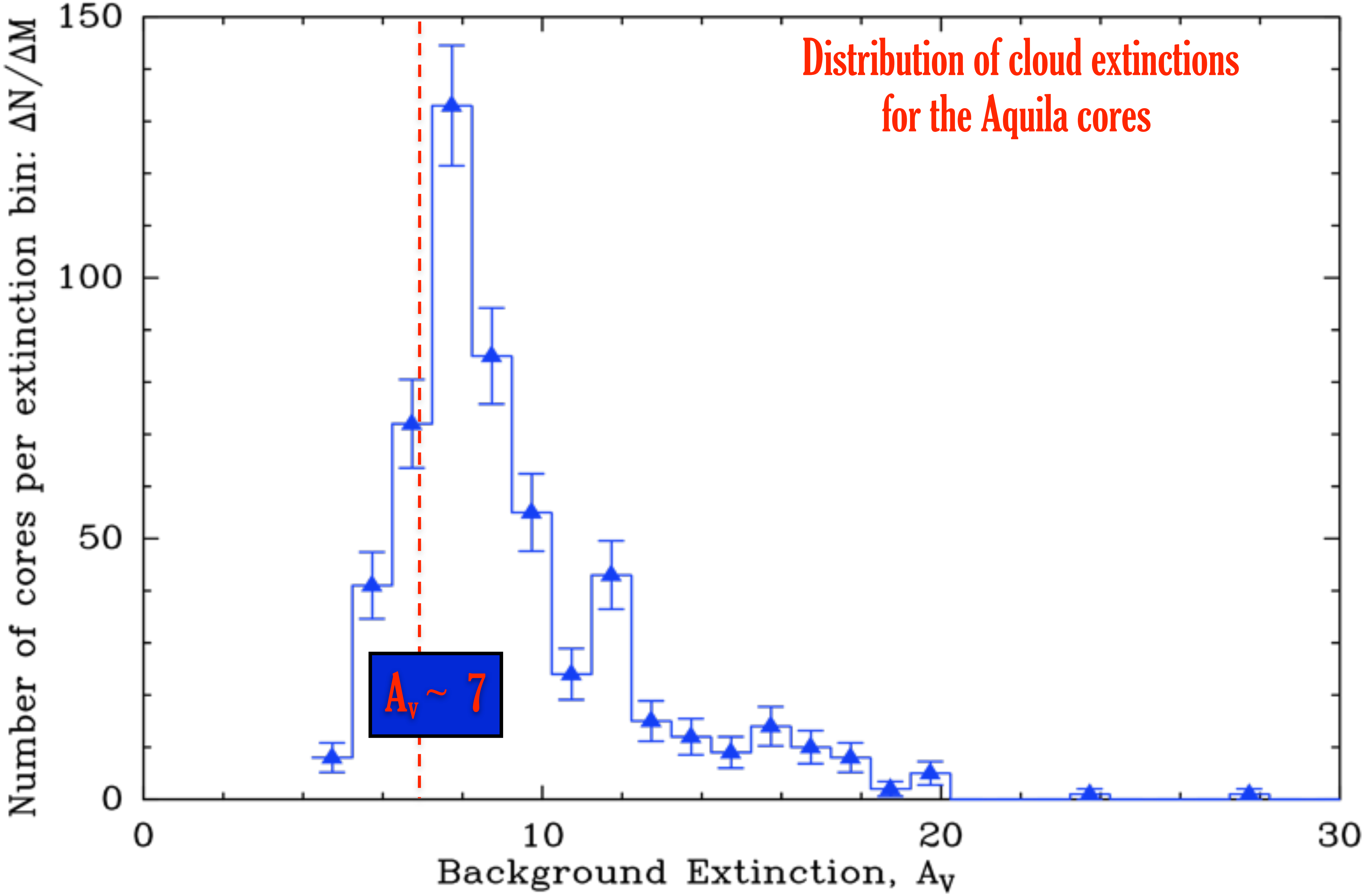
  $M_{line,\,crit} = 2c_s^2/G \sim 15\ M_\odot/\mathrm{pc}$ for T = 10K
- ✳ Simple estimate:

  $M_{line} \propto N_{H2}$ x width

  Unstable filaments highlighted in white in the N_{H2} map

Complex network of filaments form in molecular clouds and the densest ones fragment into prestellar cores via gravitational instability

An extinction “threshold” for the formation of prestellar cores ?



In Aquila,
~ 80% of the prestellar cores
are found above $A_v \sim 7$

cf. Onishi et al. 1998 (Taurus)
Johnstone et al. 2004 (Ophiuchus)
Lada et al. 2010 (8 MCs)

André et al. 2010, IAU Symp. 270

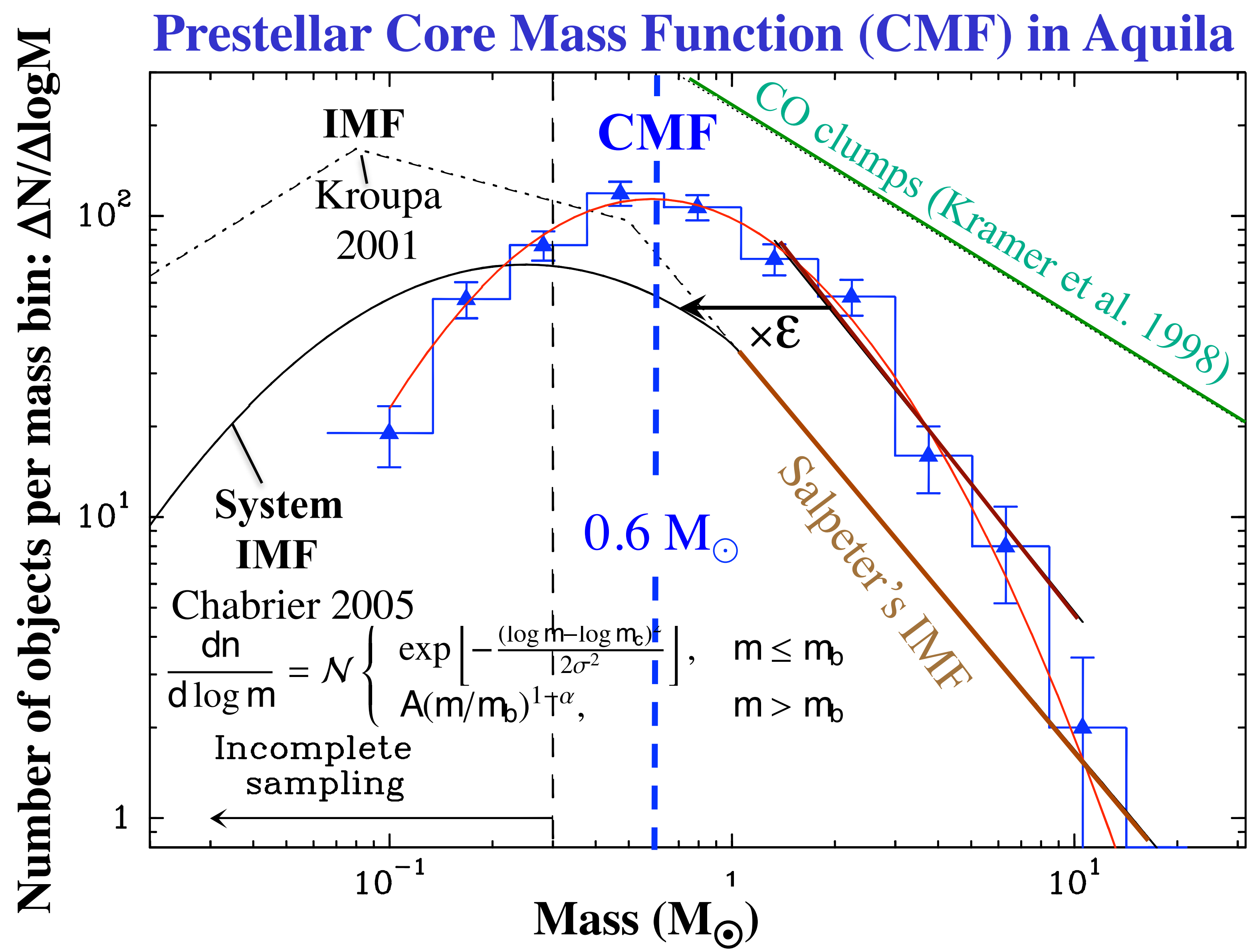
Confirming the link between the prestellar CMF & the IMF

Könyves et al. 2010, 2016

341-541 prestellar cores in Aquila

Factor ~ 2-9 better statistics than earlier studies:

e.g. Motte, André, Neri 1998; Johnstone et al. 2000; Beuther & Schilke 2004; Stanke et al. 2006; Enoch et al. 2006; Alves et al. 2007; Nutter & Ward-Thompson 07



Good correspondence between core mass and system mass:

$M_* = \varepsilon \, M_{core}$ with $\varepsilon \sim 0.3$ in Aquila

The IMF is at least partly determined by pre-collapse cloud fragmentation

(cf. model by Hennebelle & Chabrier 2008)

Estimate of the lifetime of prestellar cores in Aquila

In steady state, the relative numbers of objects in each evolutionary stage reflect the relative lifetimes of the stages

~ 450 *Herschel* prestellar cores:

t_{pre}= 1.1+-0.3 Myr ~ 3-4 t_{ff}

~ 200 *Herschel* Class 0-I protostars:

t_{proto} ~ 0.5 Myr

~ 800 *Spitzer* ClassII YSOs:

$t_{ClassII}$ ~ 2 Myr

Konyves+ (2016)

I. Molecular clouds: properties of stellar nurseries

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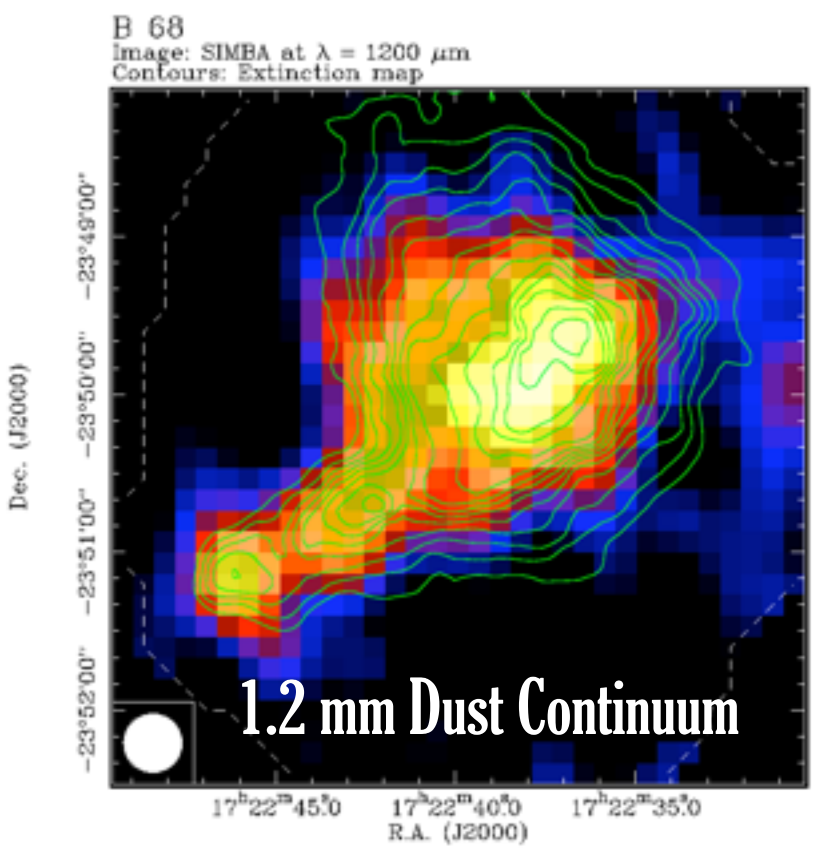
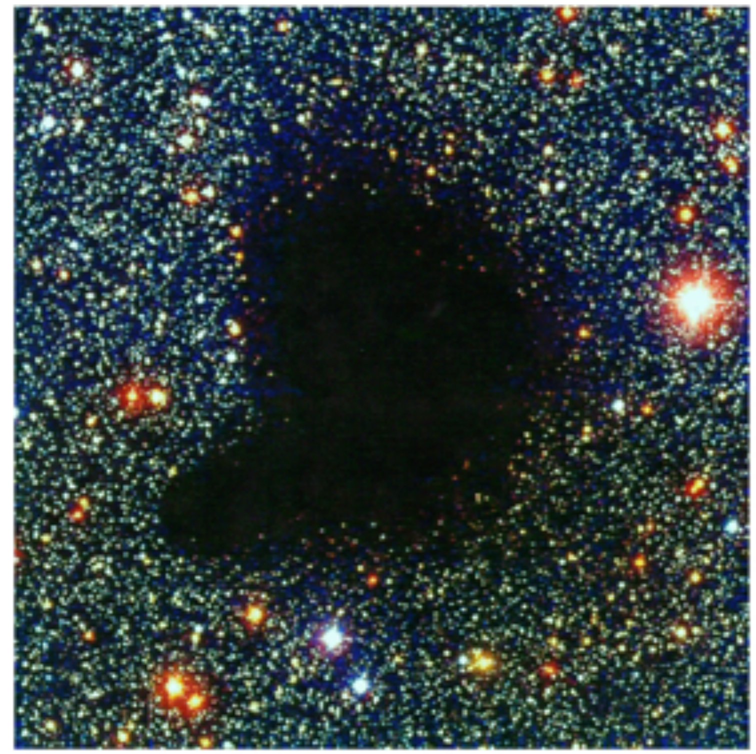
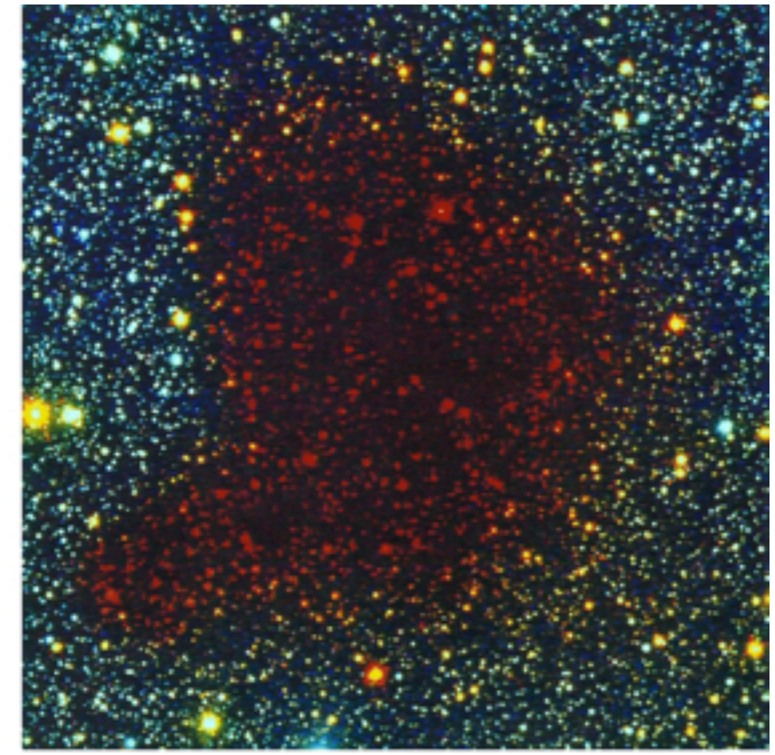
An isolated core: the Bok globule B68



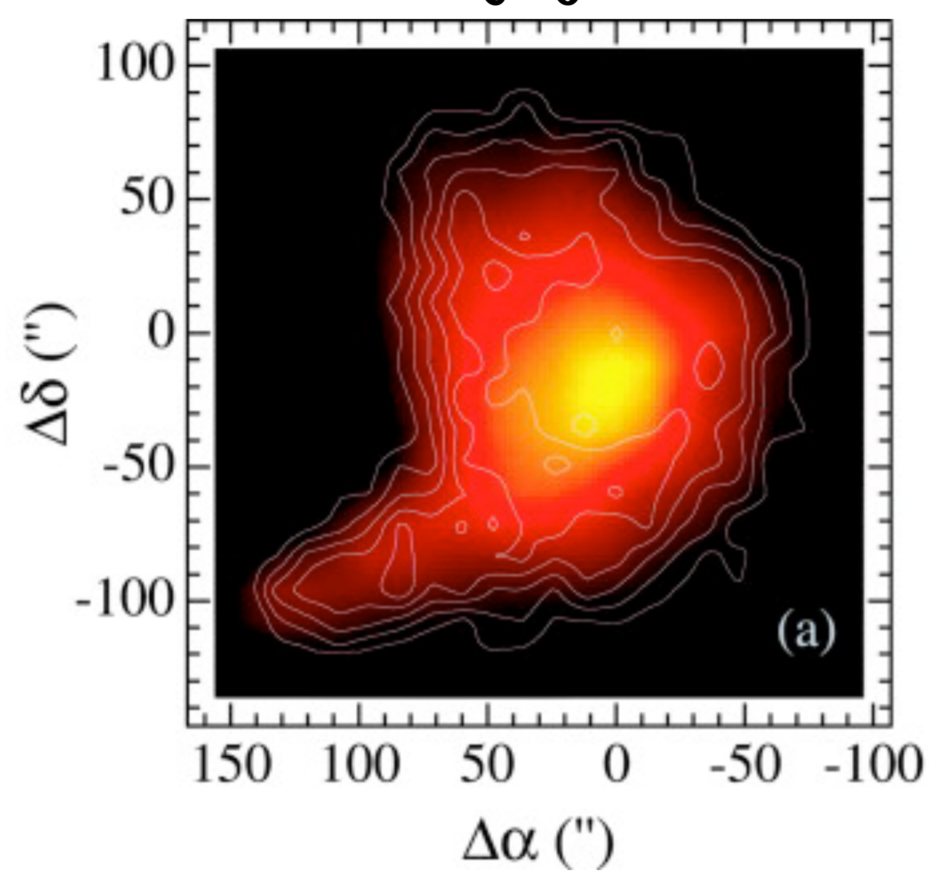
Optical



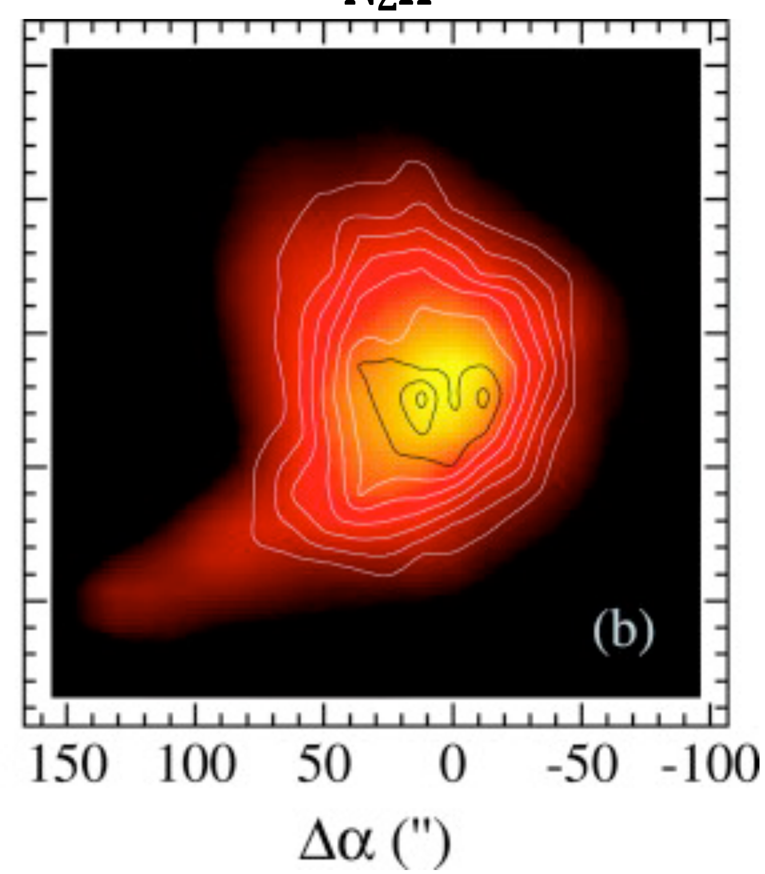
Near Infrared



$C^{18}O$



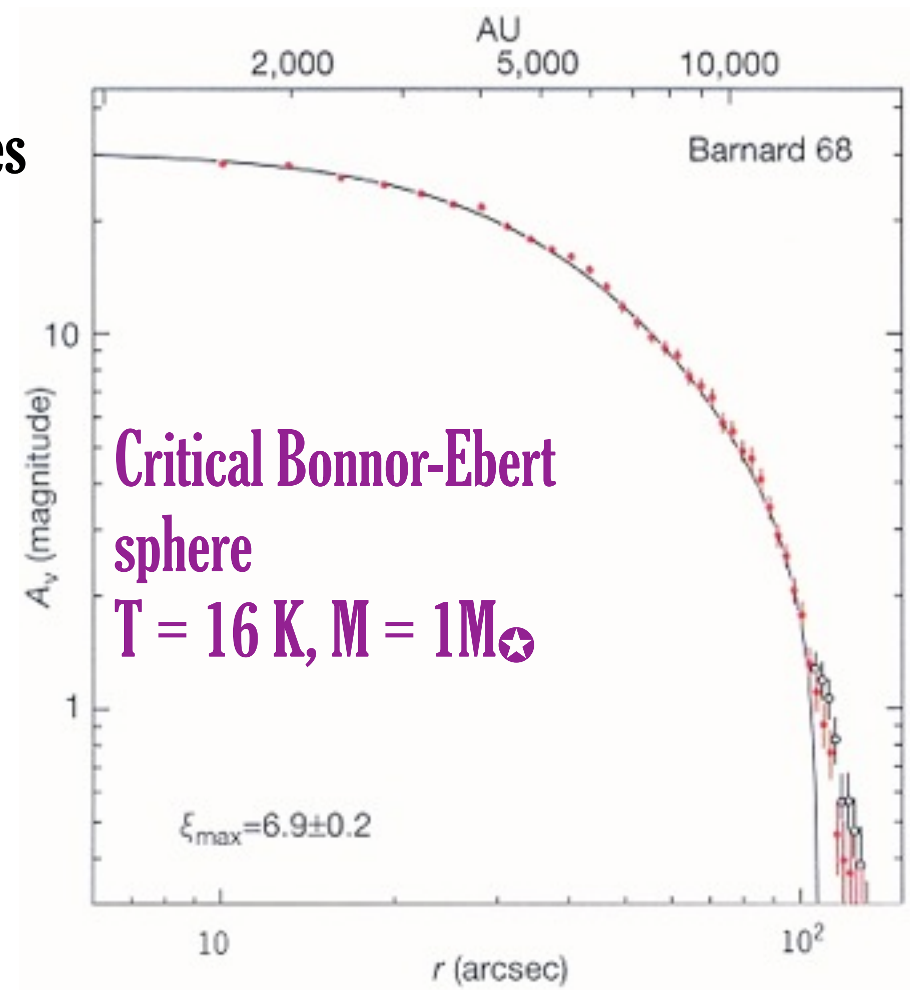
N_2H^+



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!



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.

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 $\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2}{\rho}\frac{dP}{dr}\right) = -4\pi G\rho$

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

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

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

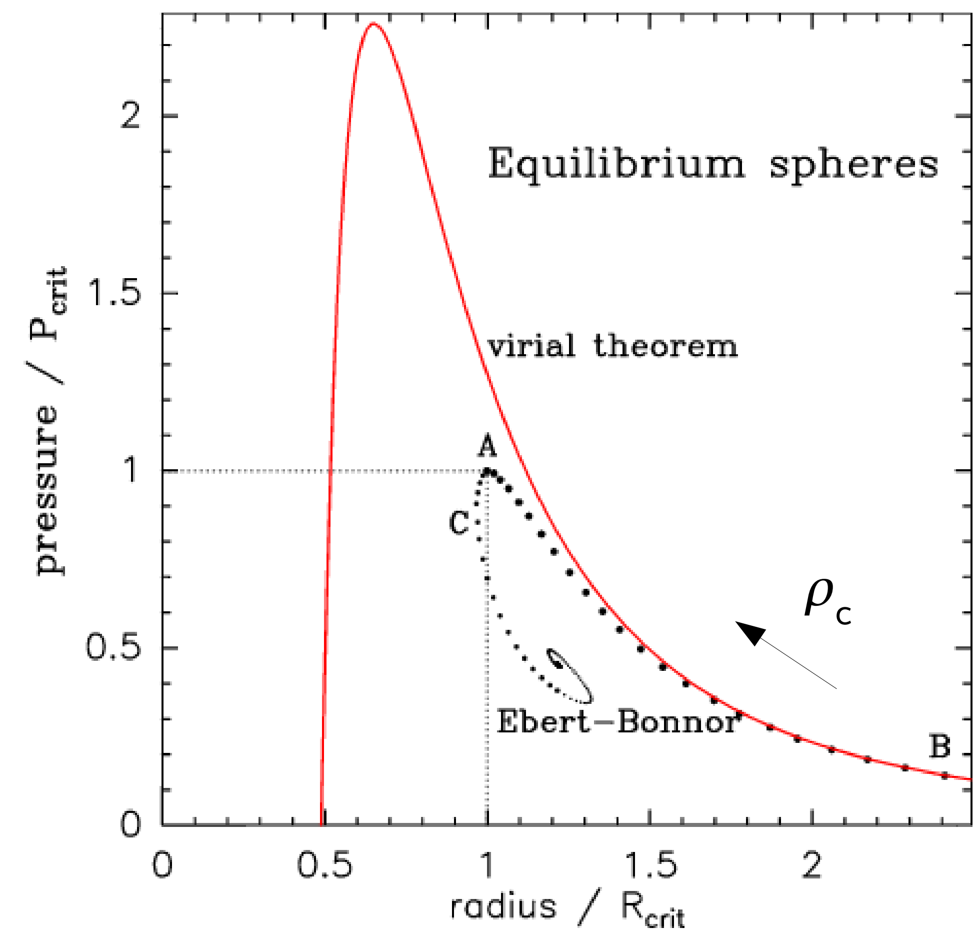
with $I(x) = \int_0^x y(x') x'^2 dx'$

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

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

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

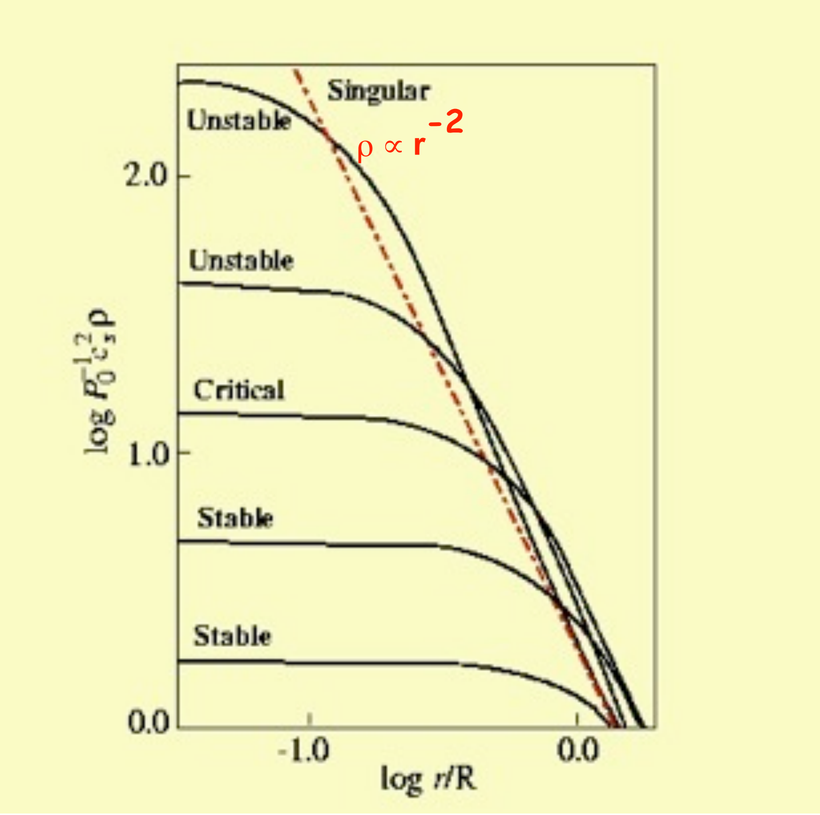
with $x_u = R\sqrt{4\pi G \rho_c / v_s^2}$

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:

$$M_{crit} = 1.18\,(c_s^4/G^{3/2})\,\varrho_0^{-1/2} \propto T^{3/2}\,\varrho_0^{-1/2}$$



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

- $M_c \sim 1.0\, M_\odot$: typical stellar mass
- $R_c \sim 0.05$ pc

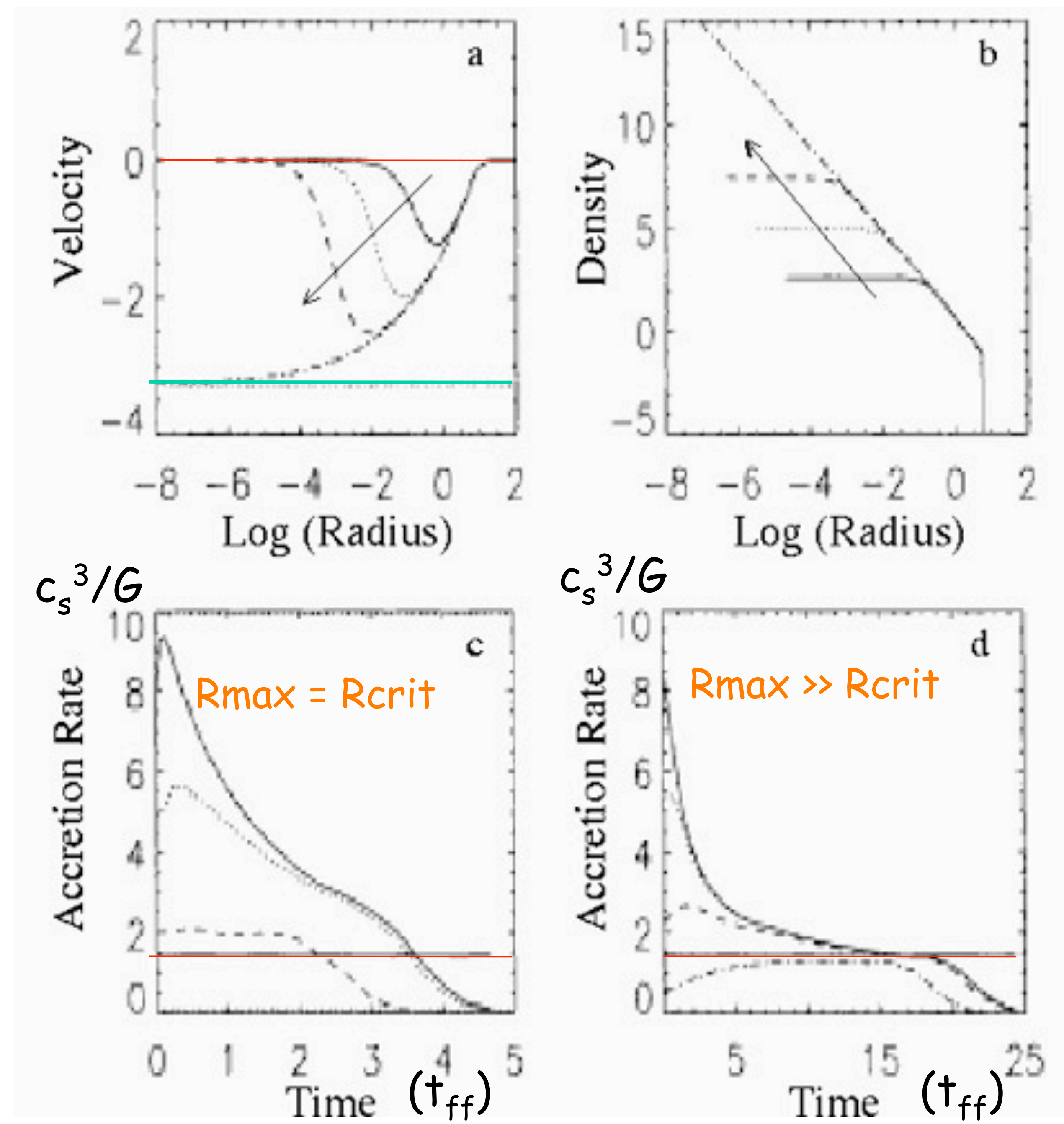
Collapse of Bonnor-Ebert spheres

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)

The different phases of the collapse

Timescale for 1 $M_\odot$

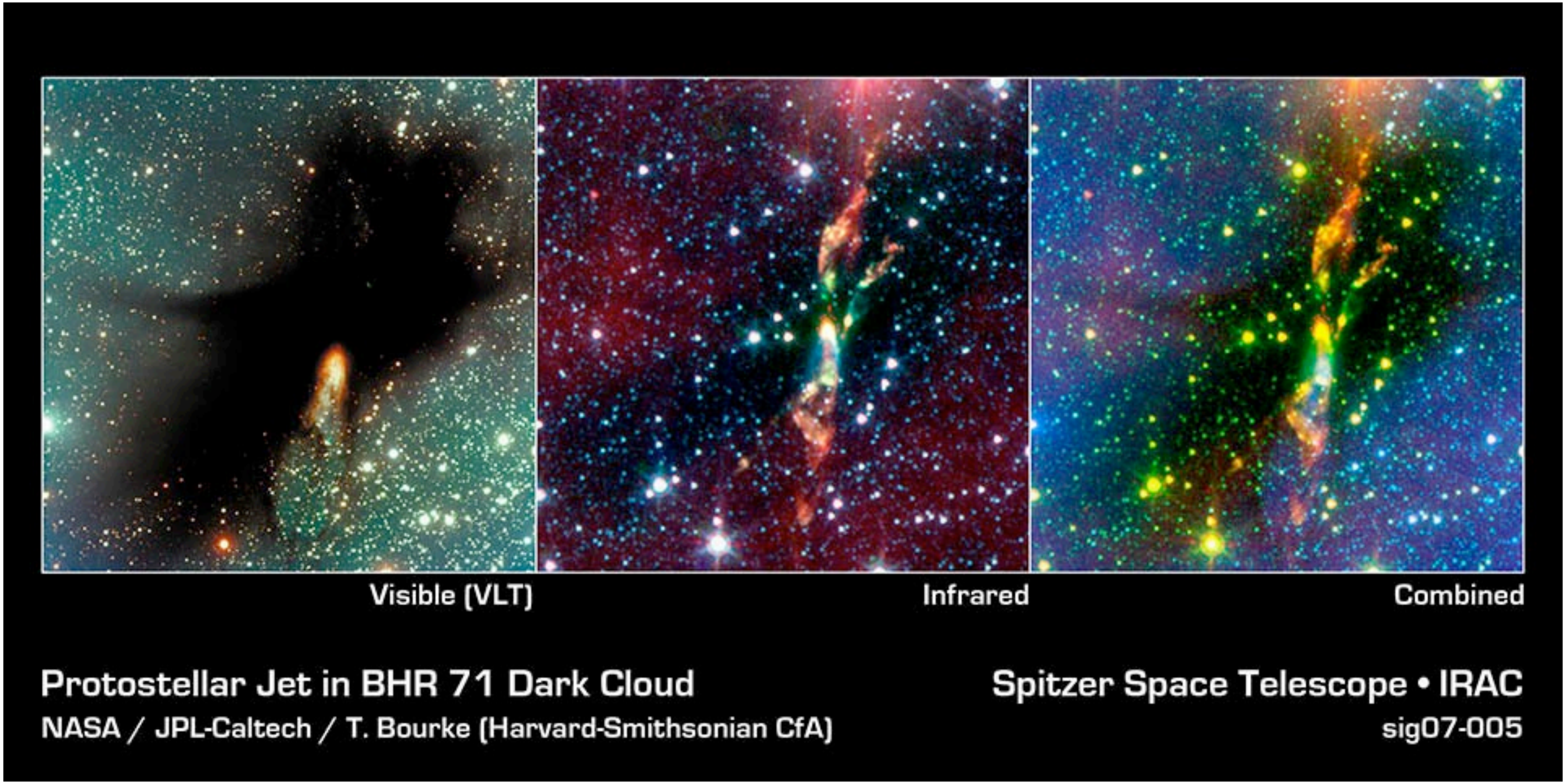
- Step 1:
  400,000 years — Isothermal collapse: cooling via the grain emission maintains T~10K until $n_H \sim 10^{11}$ cm^{-3} ($\rho \sim 10^{-13}$ g cm^{-3})
- Step 2:
  ~1-100 years — Formation of the first hydrostatic core $\rho \sim 2 \times 10^{-10}$ g cm^{-3}
- Step 3:
  ~1-100 years — Formation of the second core (stellar embryo) $\rho \sim 2 \times 10^{-2}$ g cm^{-3}
- Step 4:
  100,000 – 10^6 years — Main accretion phase

See Benoit's lecture for more details !

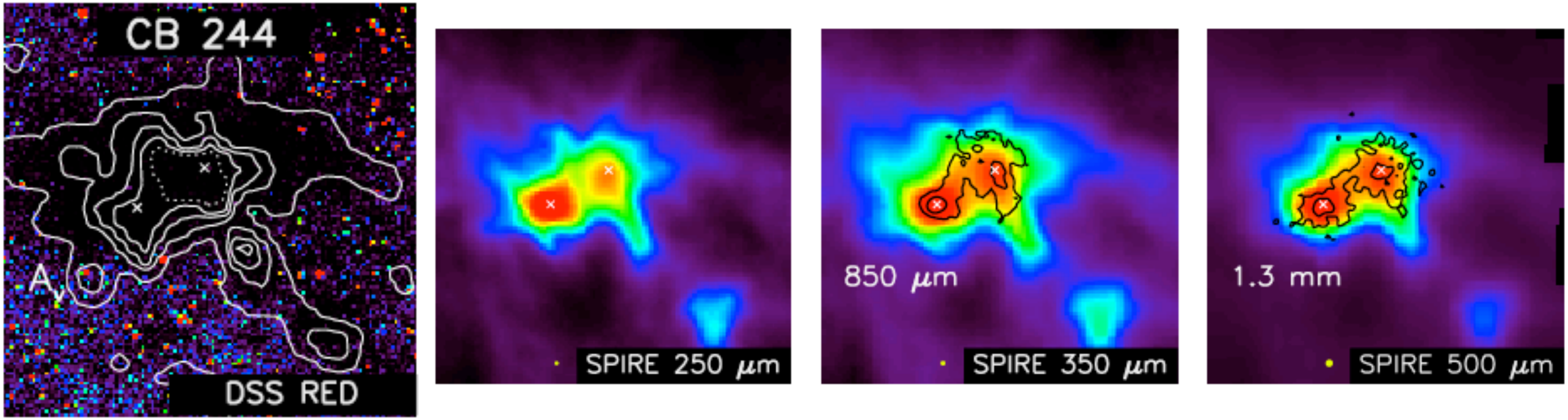
Main accretion phase

- The embryo grows by accreting the envelope in free-fall:
  100.000 years are needed to reach $0.6M_{\odot}$, 10^5 years for $1M_{\odot}$
- Accretion shock at the surface of the protostar:
  the kinetic energy is converted into heat, then radiated:
  $L_{acc} = ½ (dM/dt) V_{ff}^2 = GM/R(dM/dt)$ L_{acc} dominates L_*: it is a protostar
- The dusty envelope totally masks the stellar embryo in the making
  → impossible to see its surface until the envelope becomes transparent (beginning of the T-Tauri phase)

How to recognize protostars from prestellar cores ?

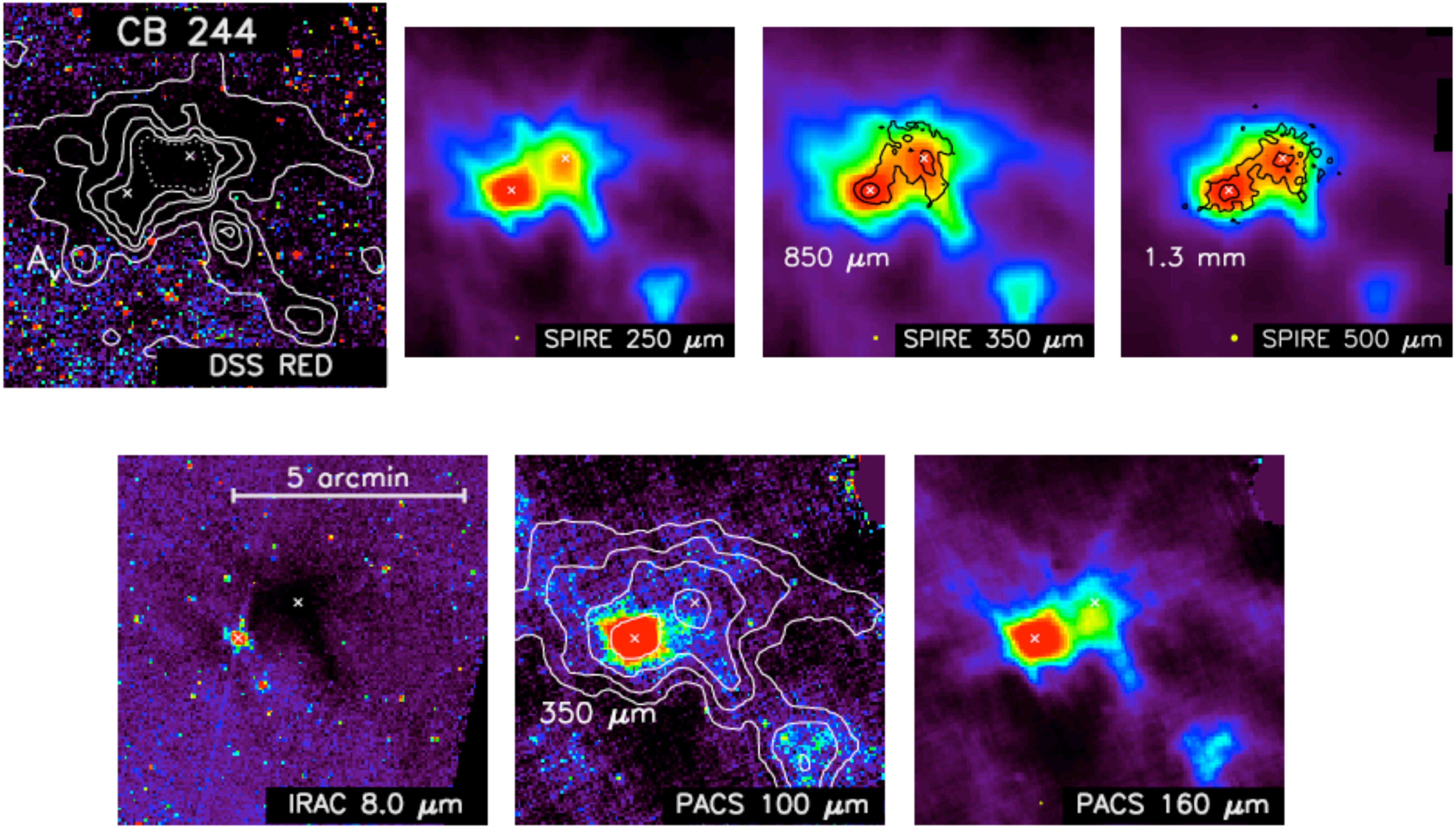


How to recognize protostars from prestellar cores ?



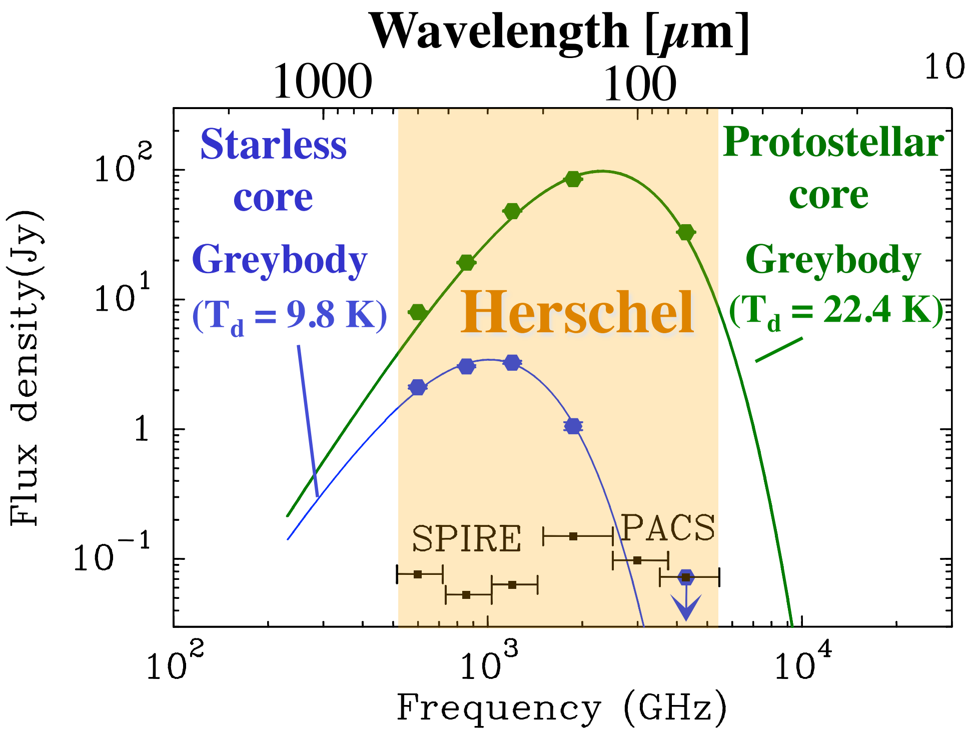
Stutz et al. (2010)

How to recognize protostars from prestellar cores ?



Stutz et al. (2010)

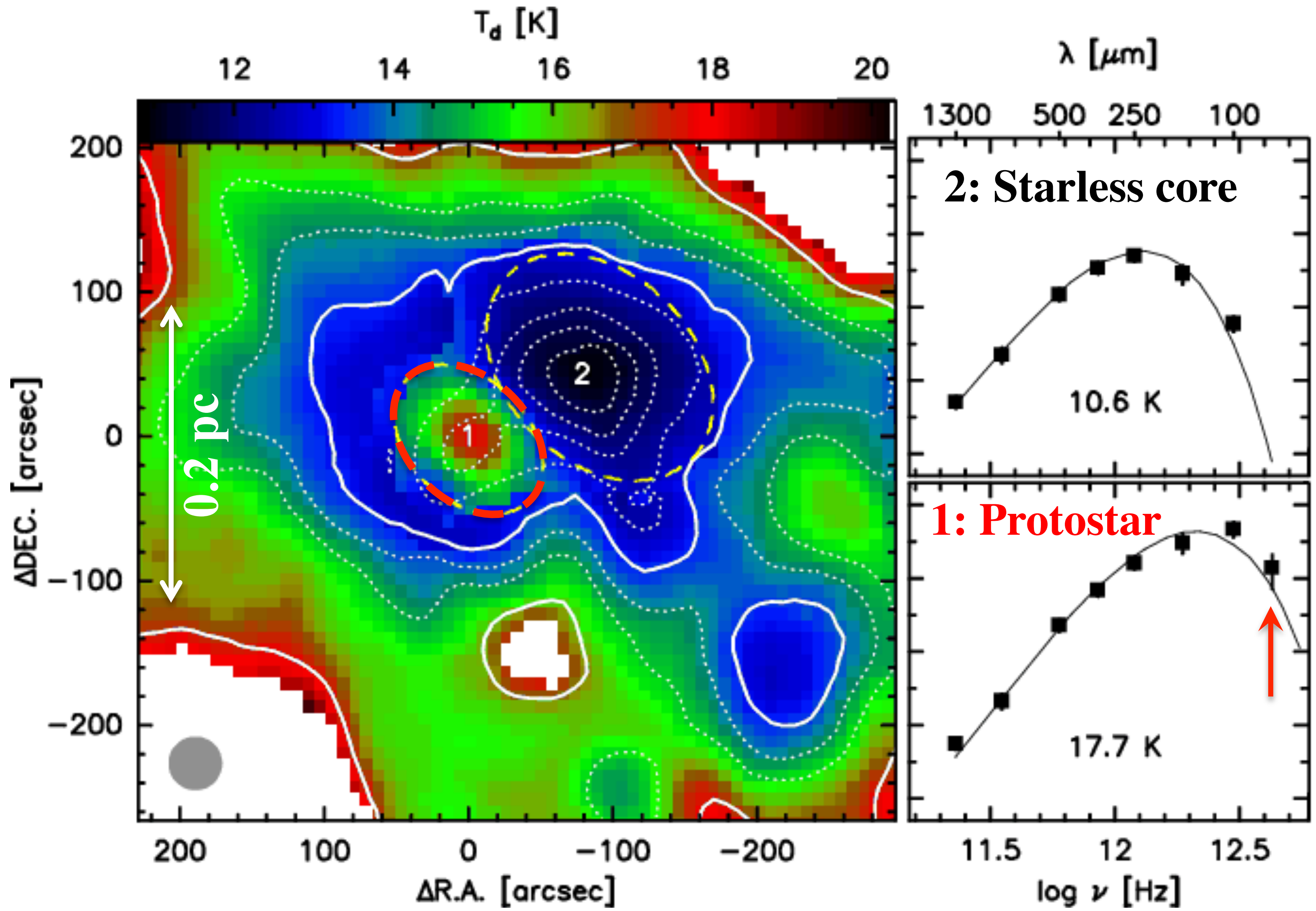
How to recognize protostars from prestellar cores ?



Protostar
=
emission at wavelengths < 70 microns

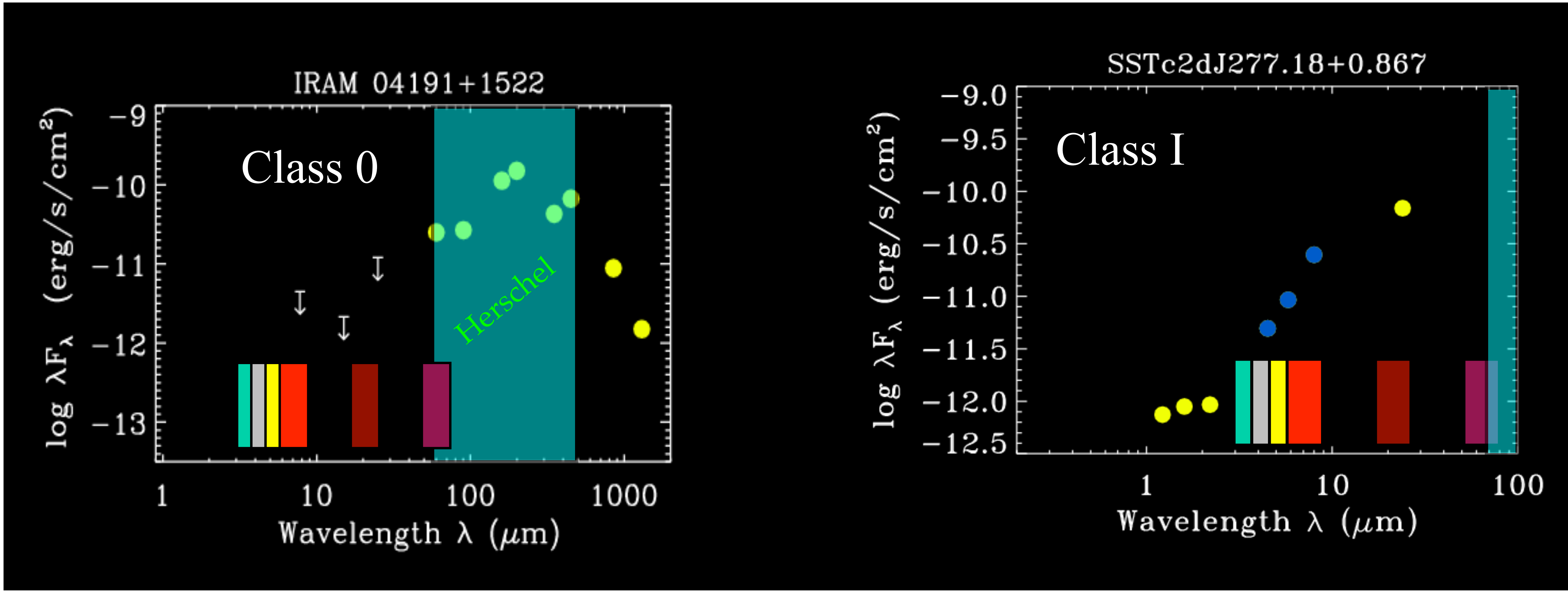
($F_{70\mu}$ <--> L_{proto}
cf. Dunham,
Crapsi, Evans e.a.
2008 *Spitzer* c2d)

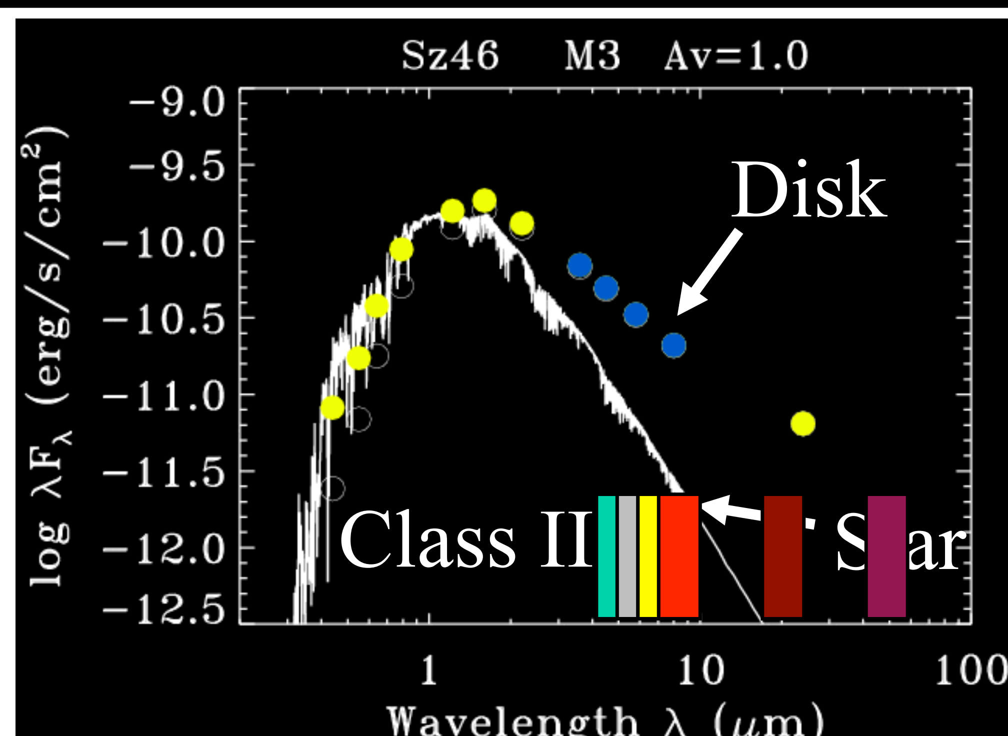
CB 244: T_{dust} map & N_H contours



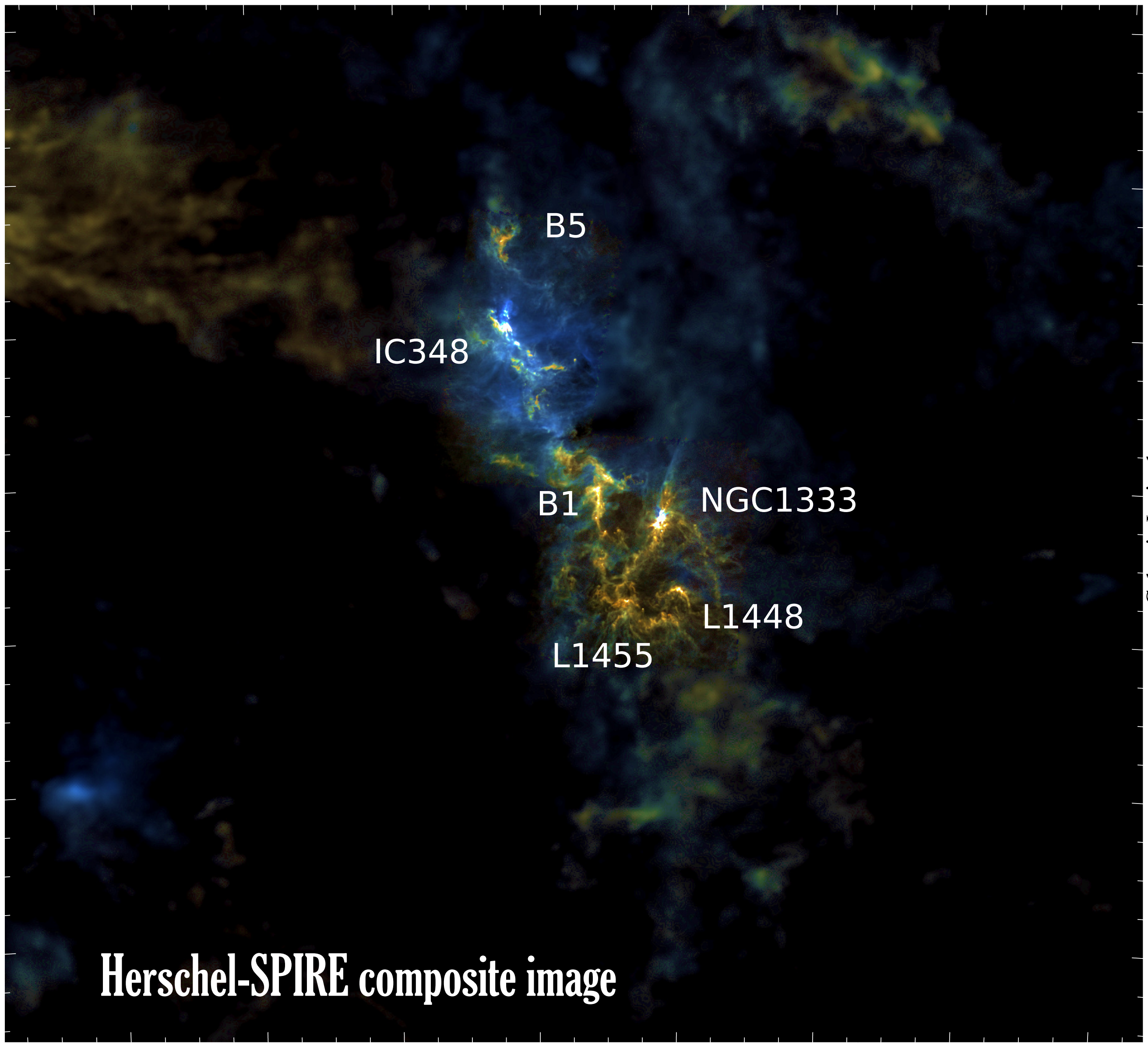
A. Stutz, R. Launhardt et al. 2010
***Herschel* EPoS Project (PI: O. Krause)**

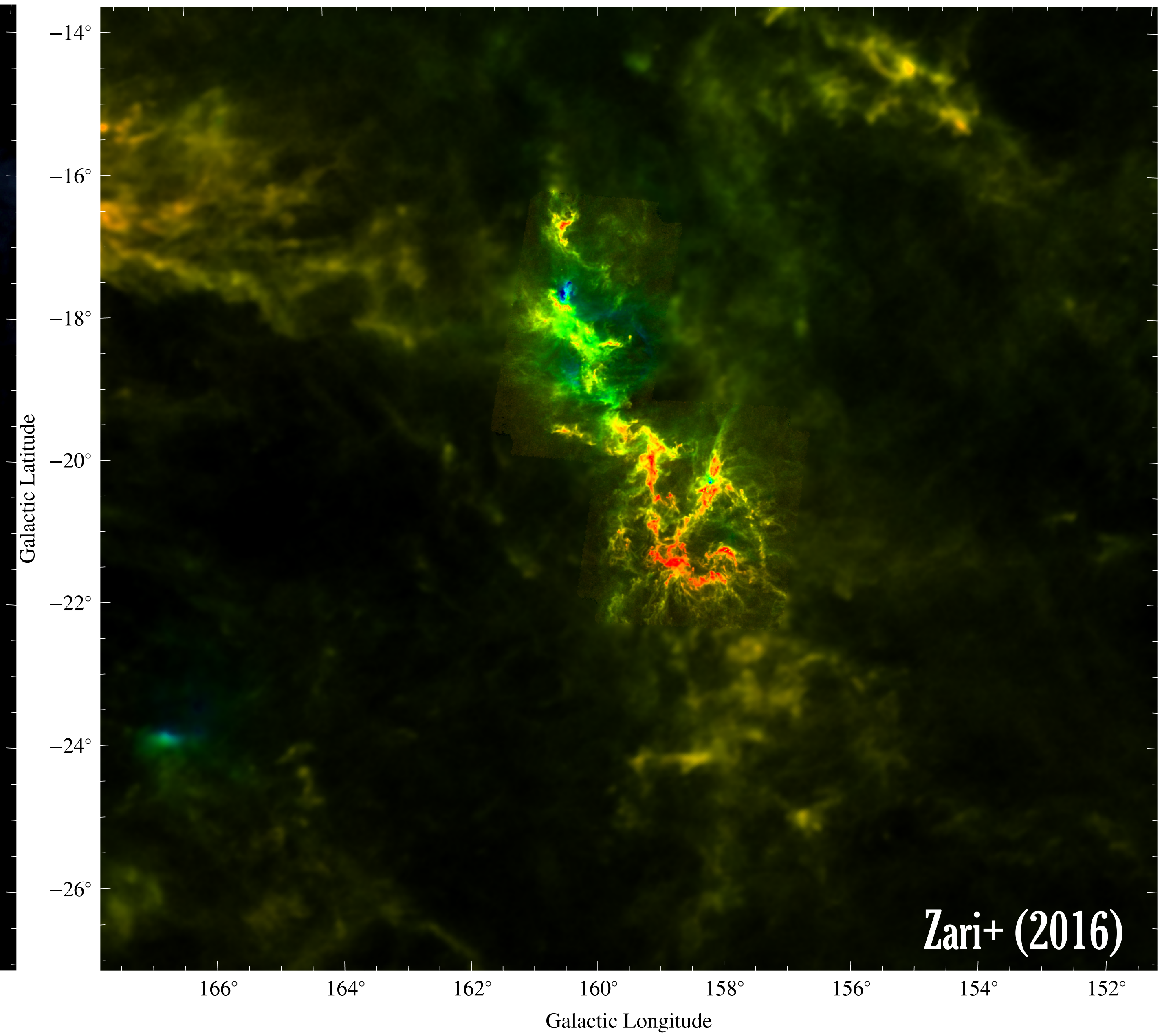
How to recognize protostars from pre-main sequence stars ?





Perseus

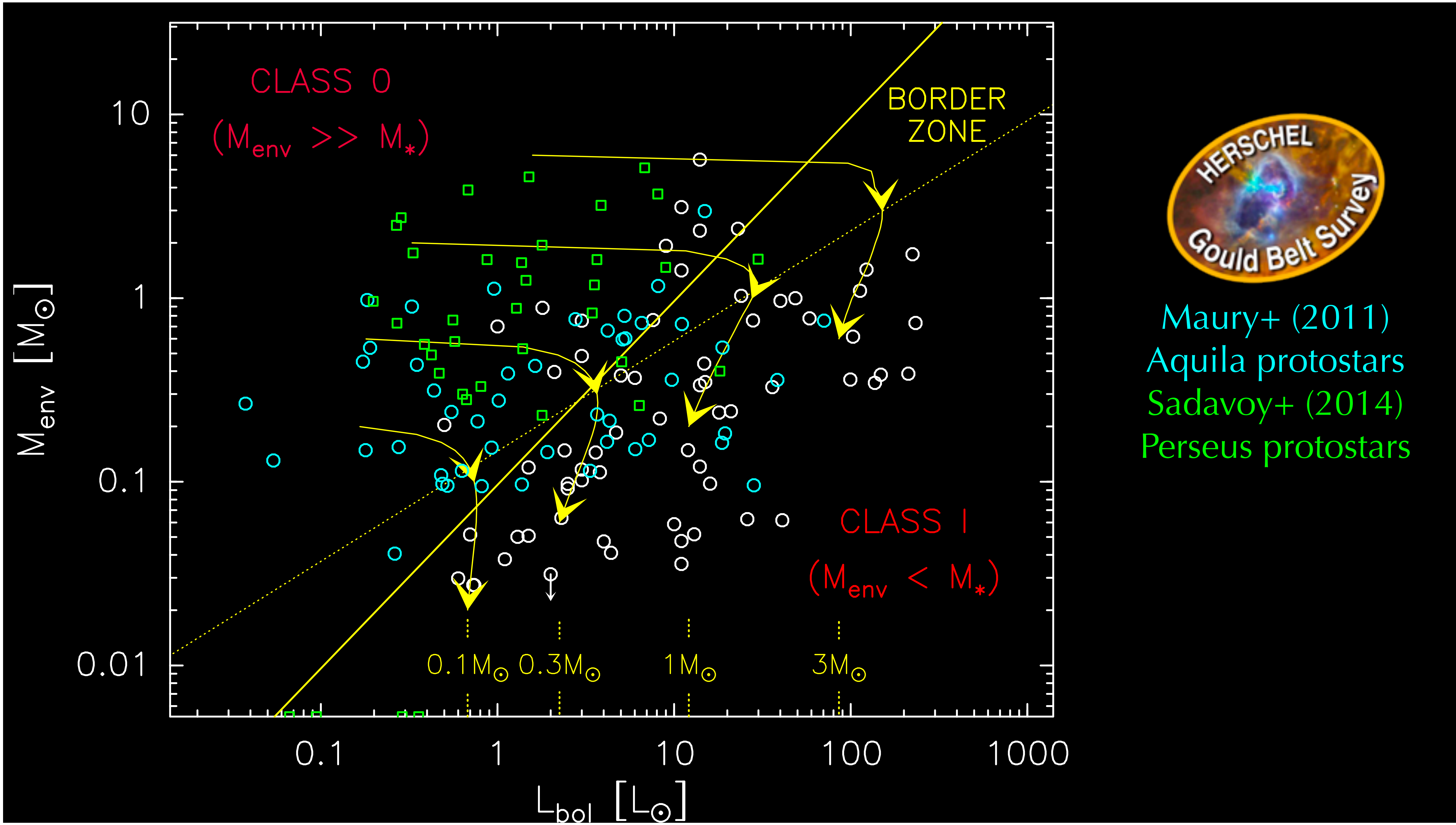

B5
IC348
B1
NGC1333
L1448
L1455
Herschel-SPIRE composite image


−14°
−16°
−18°
−20°
−22°
−24°
−26°
Galactic Latitude
166°
164°
162°
160°
158°
156°
154°
152°
Galactic Longitude
Zari+ (2016)

III. Formation of protostars

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

Also Heiderman & Evans (2015): HCO+ envelope test: age(Stage I) ~ age(Class I)



Herschel + ground-based mm -> discriminate better protostellar stages
Maury+ 2011: **Class 0 lifetime 5x10^4 years** + over-abundance of low-luminosity Class I protostars