“Star-forming regions, clumps, and cores”

Star formation process at intermediate scales: from clumps to cores

Frédérique Motte (IPAG Grenoble)

Completed by lectures of Alessio Traficante:
from star-forming regions to clumps

See also talks by Simon Chevalier, Yann Bernard, Alice Nucara, Carlotta Sanna…

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Star formation process at intermediate scales: from clumps to cores

IPAG

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Lecture 1 (FM): Cores
Lecture 2 (FM): Cores within protoclusters/clumps
Lecture 3 (AT): Star-forming regions
Lecture 4 (AT): Clumps

Observational Projects:

HOBYS

W43 HERO

ALMA IMF

Outline / Part I

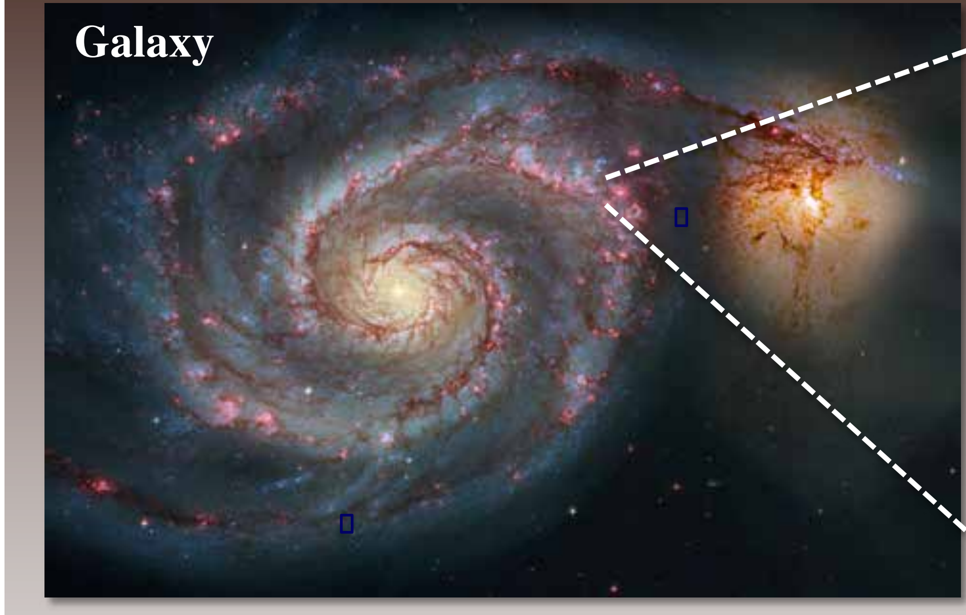
1. Why are intermediate scales (pc to 0.01 pc) crucial for star formation?
    - Origin of the stellar masses and IMF
    - Star formation scenario for low-mass stars
    - Observational tracers

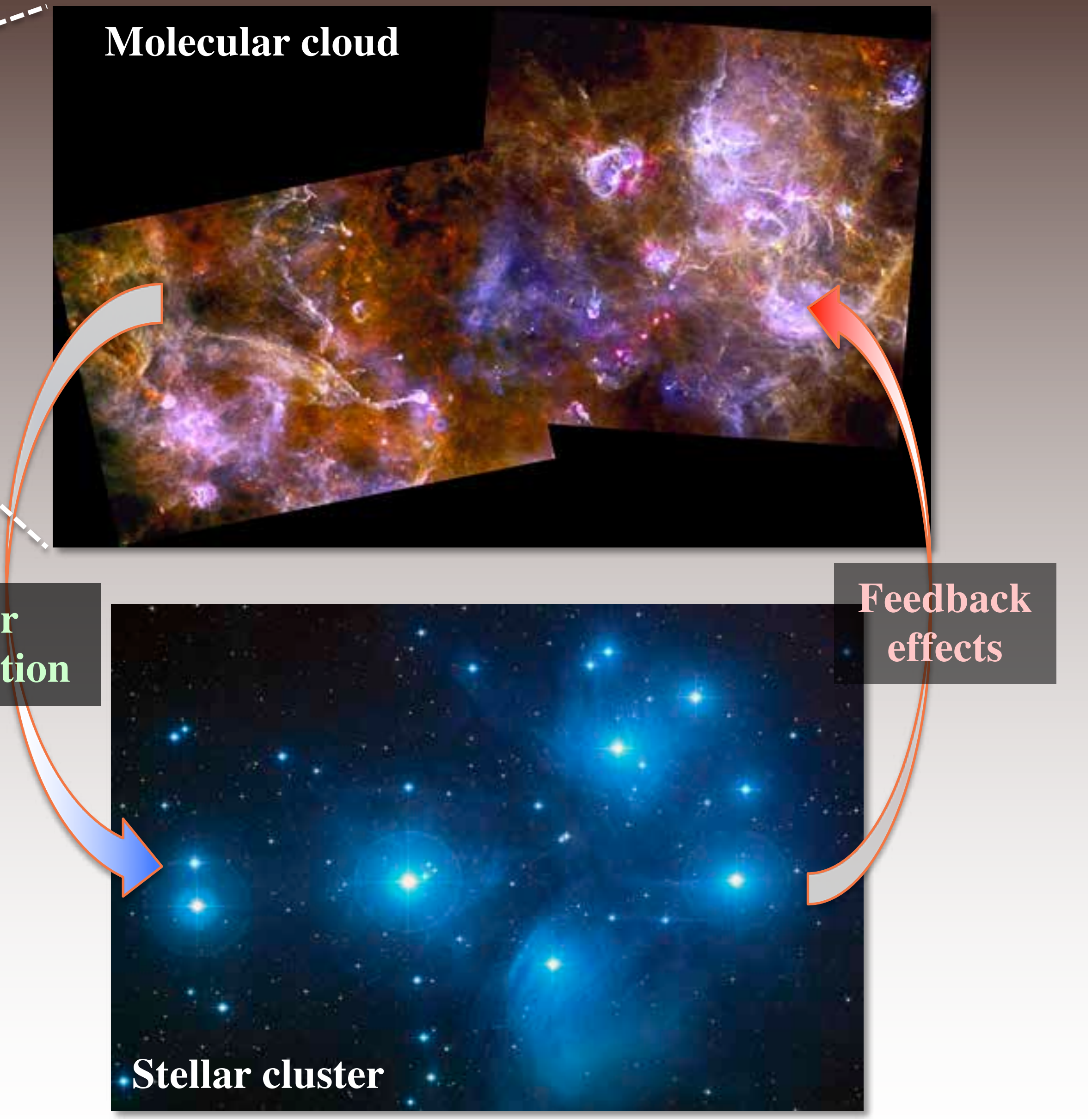
2. What is a core?

3. Detailed characteristics of (isolated) cores

4. Caveats of our present definition of cores

Tight link between stars and the ISM





Main open question:
What is the effect of galactic environment on the star formation process (IMF, SFR)?

The Initial Mass Function (IMF)

Initial mass function of stars (IMF)
= mass distribution of stars at birth

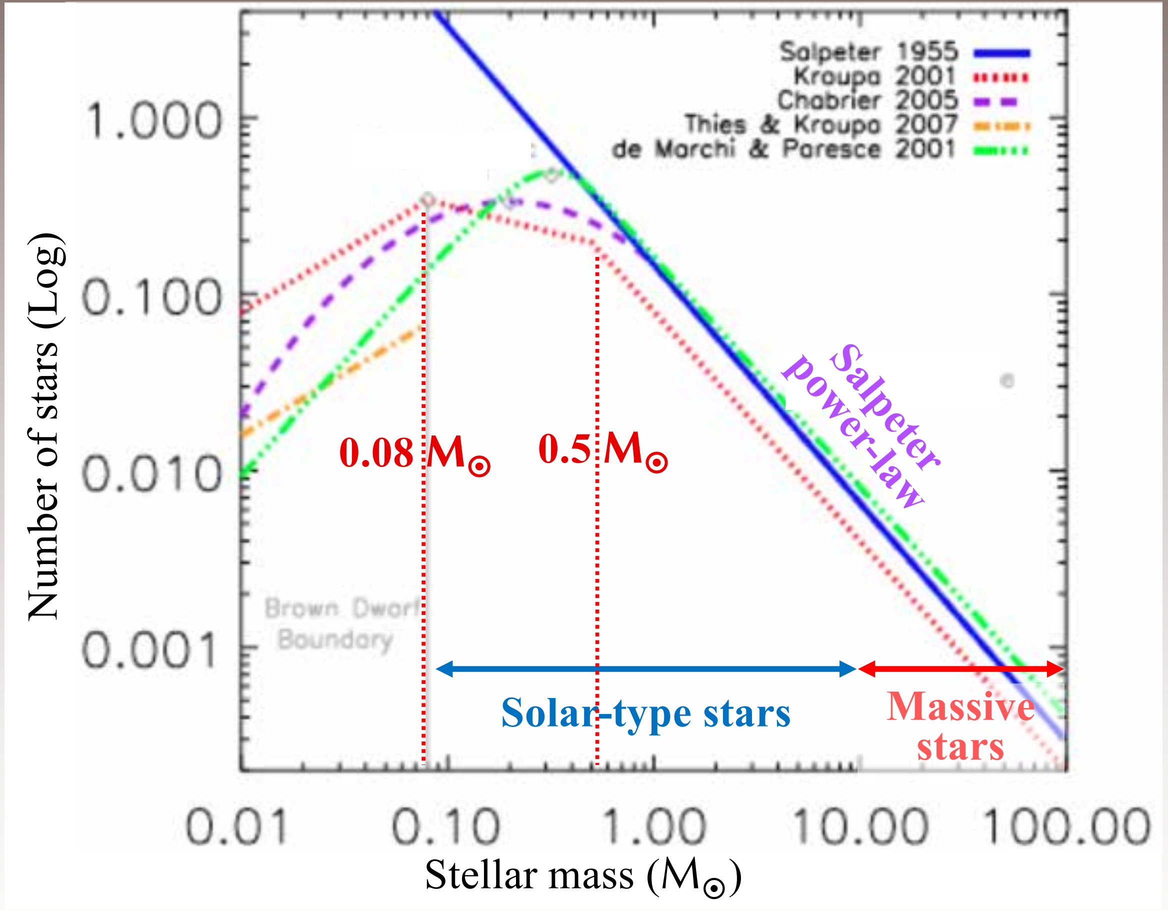


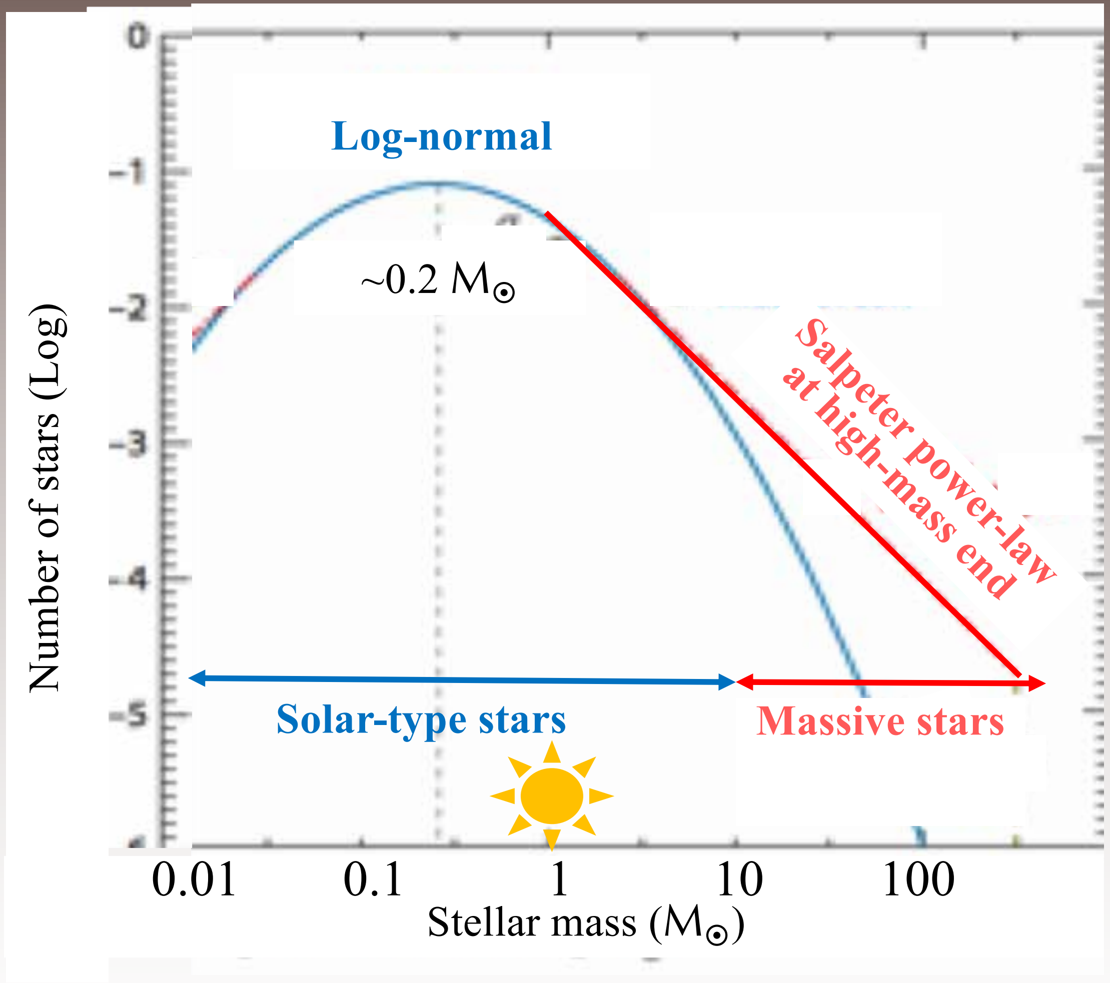
Figure adapted from Offner+ 2014

The shape of the IMF has long been considered universal (Bastian +2010; Kroupa +2013, see however Hopkins 2018; Hennebelle ARAA 2024).

- Measured in our solar neighborhood and nearby clusters (Salpeter 1955; Scalo 1986; Moraux+ 2003; Offner+ 2014).
- Modeled by broken power-laws or a log-normal function plus a power-law (Kroupa+ 2001; Chabrier+2005).

Is the IMF really universal?

Canonical IMF of stars



Top-heavy IMF are measured:

- in the 30Dor *starburst* cluster (Schneider+ 2018)
- in young massive clusters near the Galactic Center (Lu+ 2013; Hosek+ 2019; Hußmann+ 2012)
- in young clusters of Cygnus X (Maia+ 2016).

Bottom-light IMF are measured in low-metallicity environments (e.g., Li+ 2023).

→ JWST and ELT studies

Evolutionary sequence of low-mass star formation, the gravo-turbulent quasi-static view

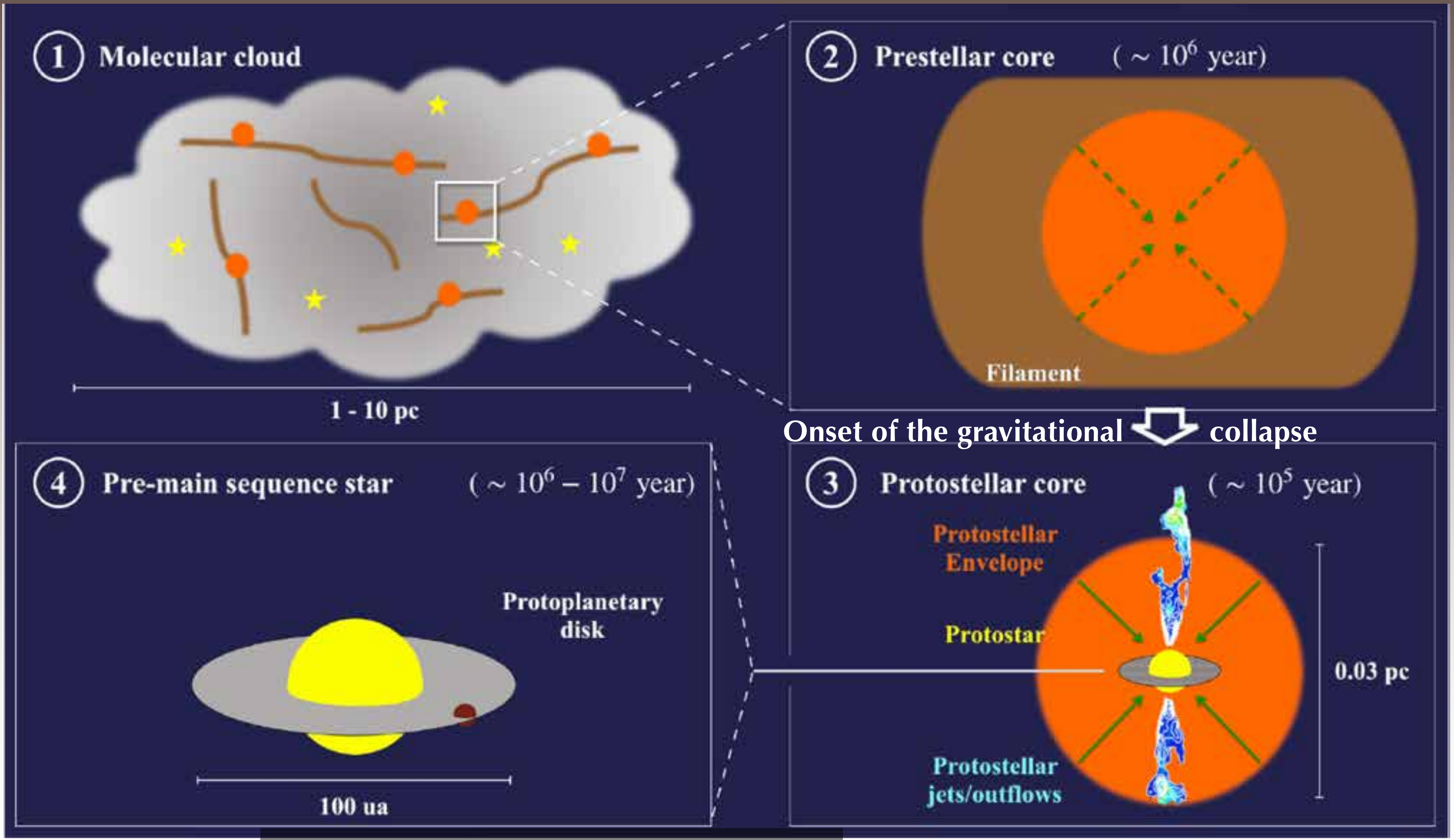
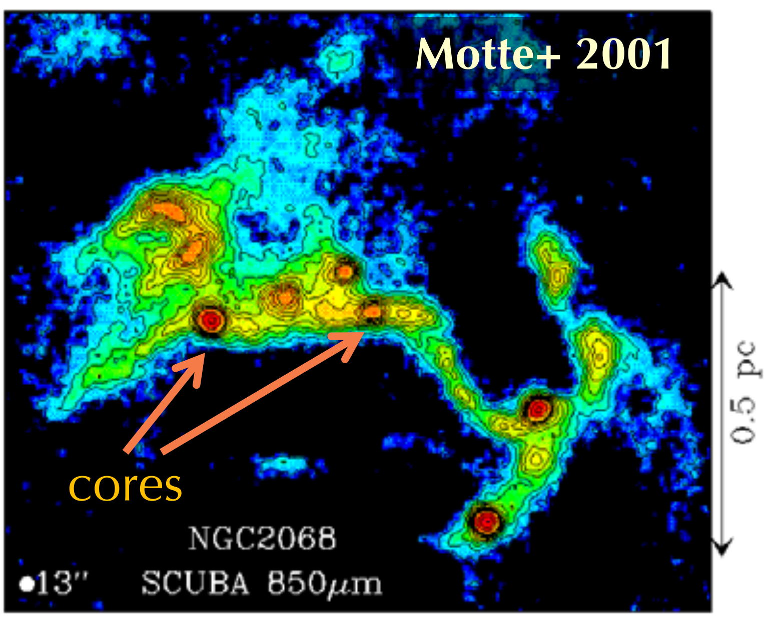


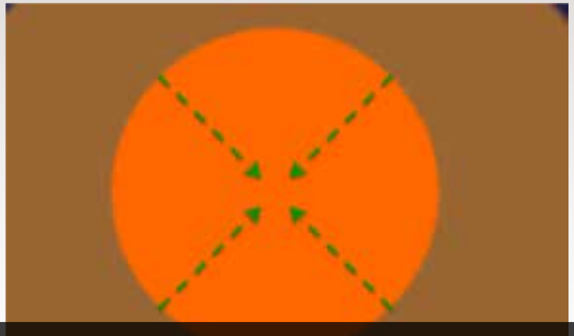
Figure adapted from Pouteau+ 2022

Origin of stellar masses

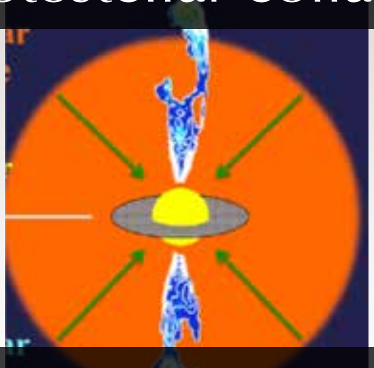
- In the gravo-turbulent quasi-static view, cores are the gas reservoir used to form one star, or a small system.
- Observationally, they are gravitationally bound small-scale (0.05 pc) fragments.



→ Studying cores should give constraints on the origin of stellar masses.
Physics at play at prestellar stage and during the protostellar collapse:

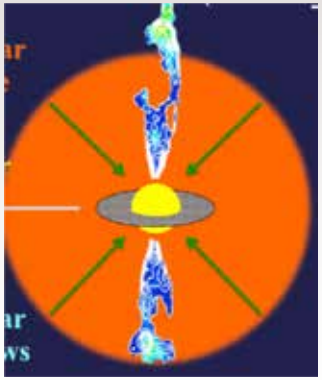


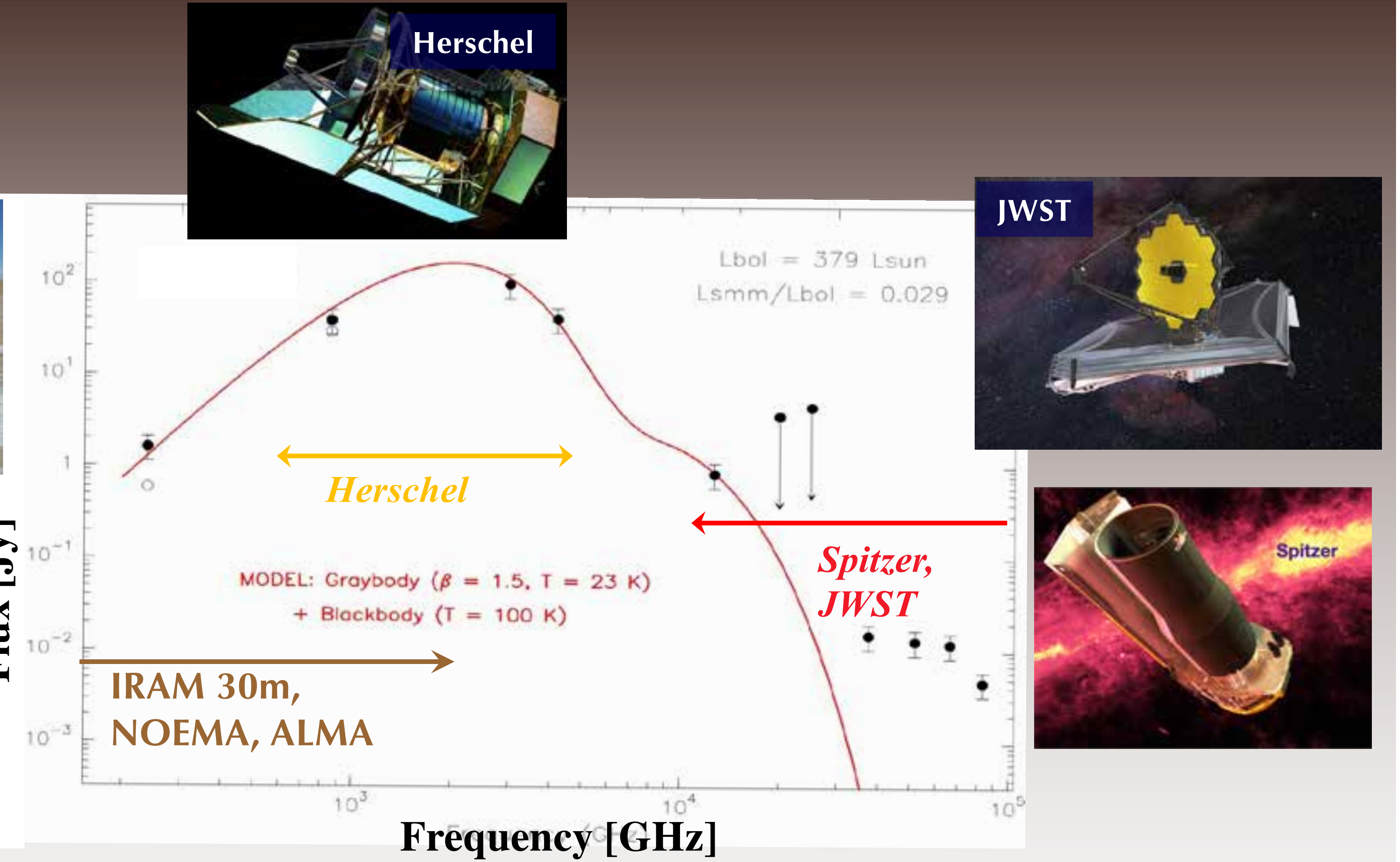
concentration/fragmentation



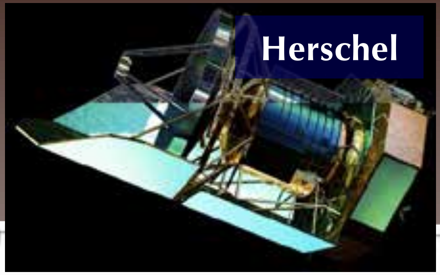
accretion/ejection

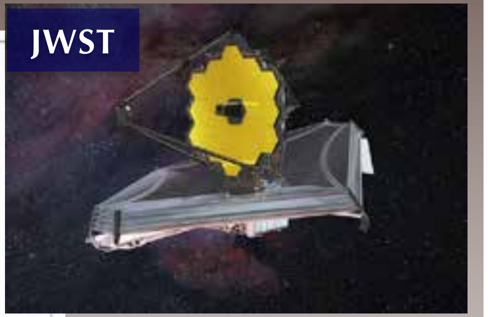
Spectral energy distribution of protostars

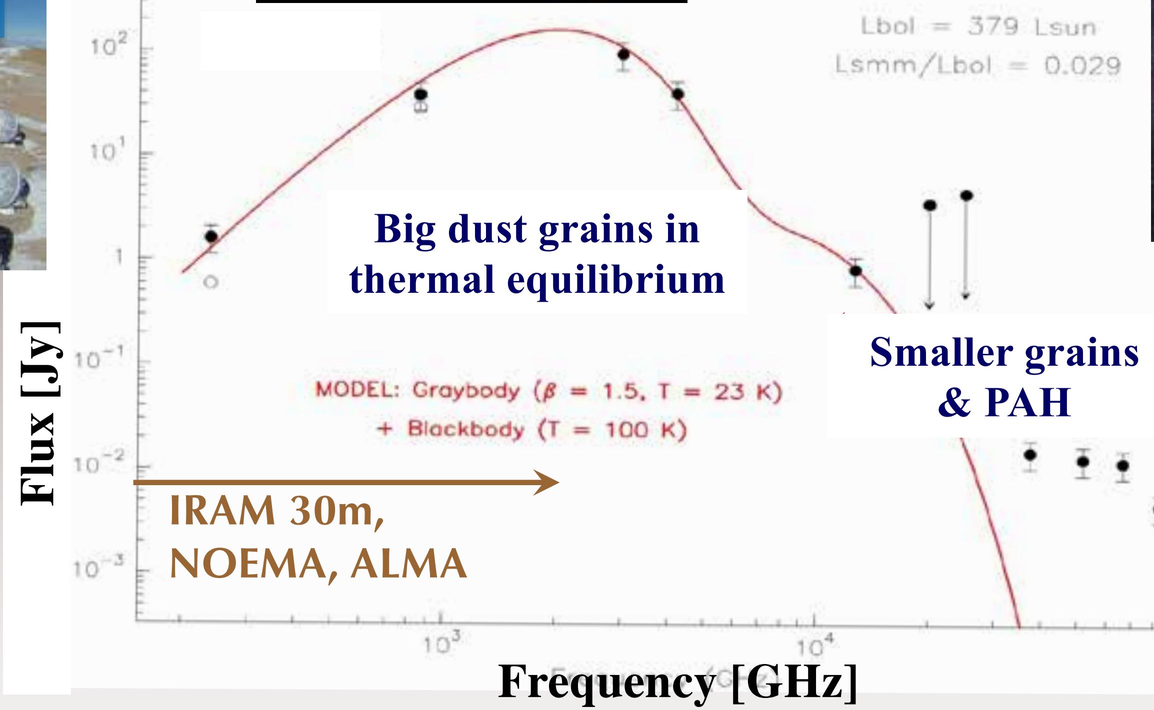




Spectral energy distribution of protostars



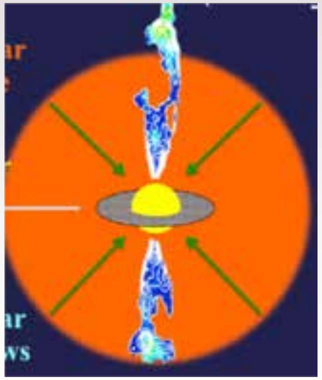




Big dust grains in thermal equilibrium

Smaller grains & PAH

IRAM 30m, NOEMA, ALMA



Modified black body → bulk of the protostellar envelope @ ~20 K

+ NIR-MIR spectrum → closer to the protostellar embryo @ 100 K

Mass and column density calculation

Thermal dust emission of clouds and cores is mostly optically thin at $\lambda > 100\ \mu\text{m}$

⇒ **Column density images and mass measurements** of the gas reservoir for star formation, using modified black body fits and a dust opacity law like

$$\kappa_\nu = 0.1\ \text{cm}^2\ \text{g}^{-1} \times (\nu/1000\ \text{GHz})^2$$

(*Hildebrand 1983; Ossenkopf & Henning 1994*) → **lecture by Karine Demyk**

Core mass (gas + dust) calculated from thermal dust continuum emission in the optically thin assumption:

Integrated flux

Distance to the Sun

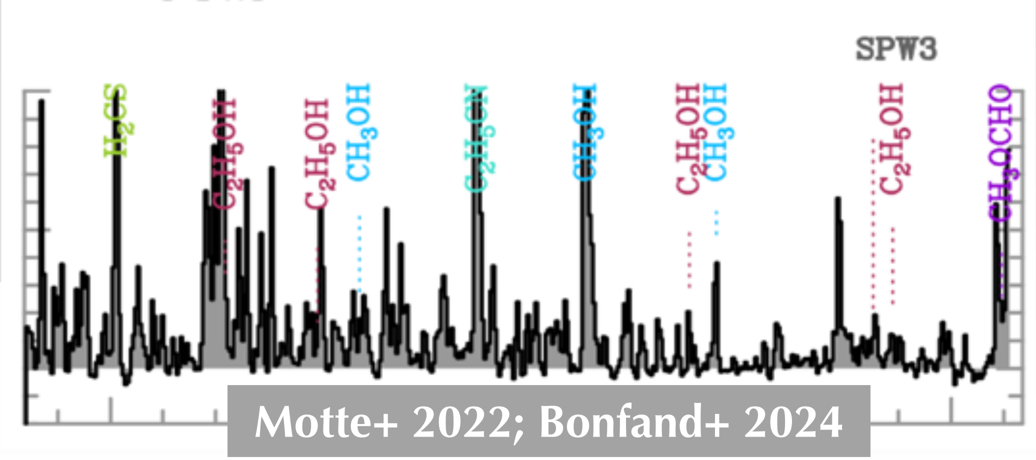
$$M_{core}^{\text{opt thin}} = \frac{S^{\text{int}}.\,d^2}{\kappa_{1.3\text{mm}}.\,B_{1.3\text{mm}}(T_\text{d})}$$

Dust opacity per unit mass N_{H2}

Planck function at dust temperature T_d

Molecular lines, tracers of…

- Gas with increasing density (n_{H2}=10^2 to 10^7 cm^{-3} @10-50 K)
  - → CO, CS, HCN, HCO^+, N_2H^+, … and isotopologues
- Turbulence (and magnetic) support against gravity
  - → line width of optically thin lines, Zeeman effect, ion-versus-neutral molecules
- Heating (up to several 100 K)
  - → several transitions (e.g., H_2CO, CH_3CN, complex organic molecules - COMs)
- Kinematics:
  - → optically thin lines: inflow, rotation, outflows (CO), shocks (SiO),
  - → optically thick lines: infall
- Chemical evolution
  - → deuteration
  - → chemical complexity



Motte+ 2022; Bonfand+ 2024

Part I
Introduction on star-forming cores

Cores are assumed to be the direct progenitors of stars → crucial for the origin of the IMF

Observationally, they are gravitationally bound small-scale (0.02-0.1 pc) fragments.

Their SED peaks in the FIR wavelength domain and they are extensively studied with radio-telescopes and interferometers.

QUESTIONS!

Outline / Part II

1. Why are intermediate scales (pc to 0.01 pc) crucial for star formation?

2. What is a core?
   - A bit of history
   - Prestellar versus protostellar cores
   - Their density structure compared to analytical theories

3. Detailed characteristics of (isolated) cores

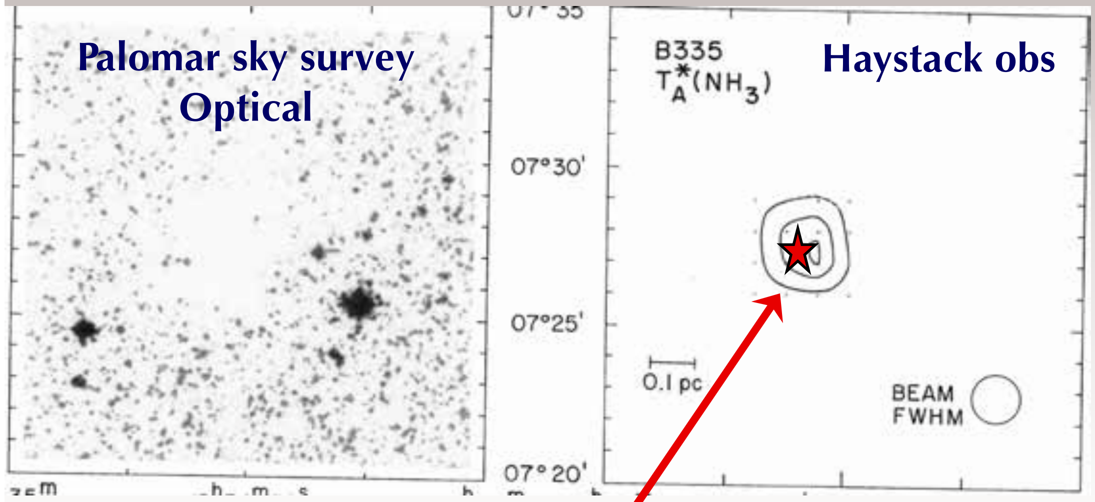
4. Caveats of our present definition of cores

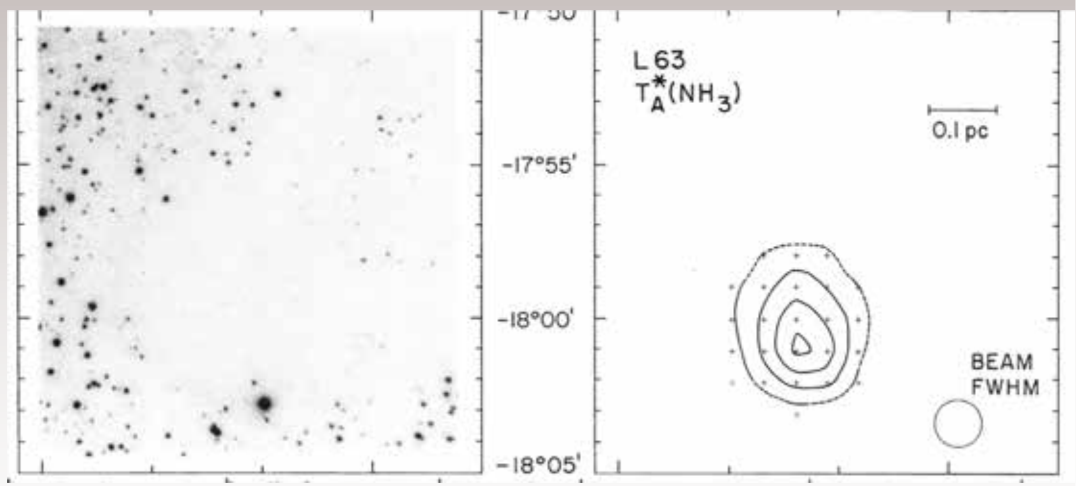
A bit of history about cores

1985-1995: Dense cores in dark clouds (<500 pc)
= Star progenitors traced by dense gas tracers like $C^{18}O$, NH_3, HCN
→ 0.1 pc, 1 $M_\odot$, $n_{H2} > 10^4\ cm^{-3}$

Protostellar cores = associated with an *IRAS* source (12-100 µm) → 15K

Prestellar cores = without any IR emission → 10 K, prolate





IRAS point source

Benson & Myers 1989; Myers 1991

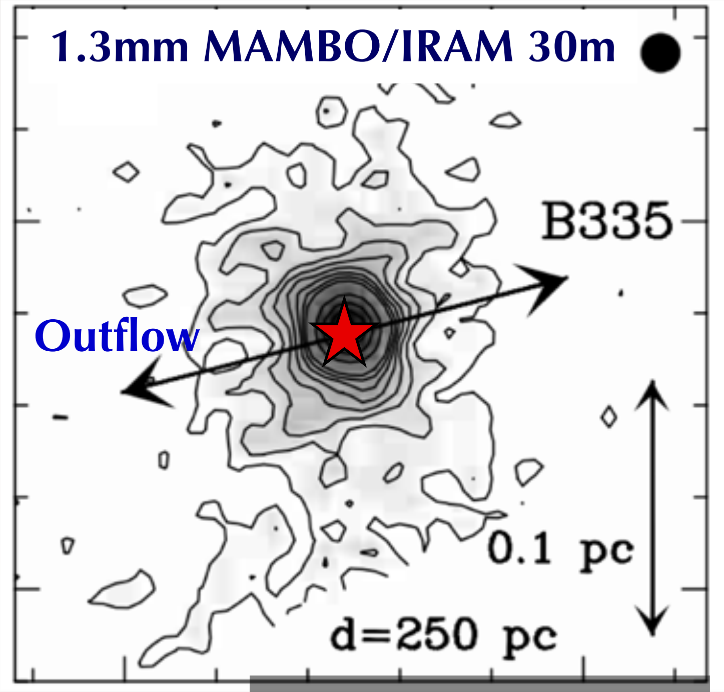
Starting to characterize cores

1995-2010: Prestellar and protostellar cores at higher resol (<500 pc)

Structure traced by dust continuum emission (e.g., @ 1 mm)

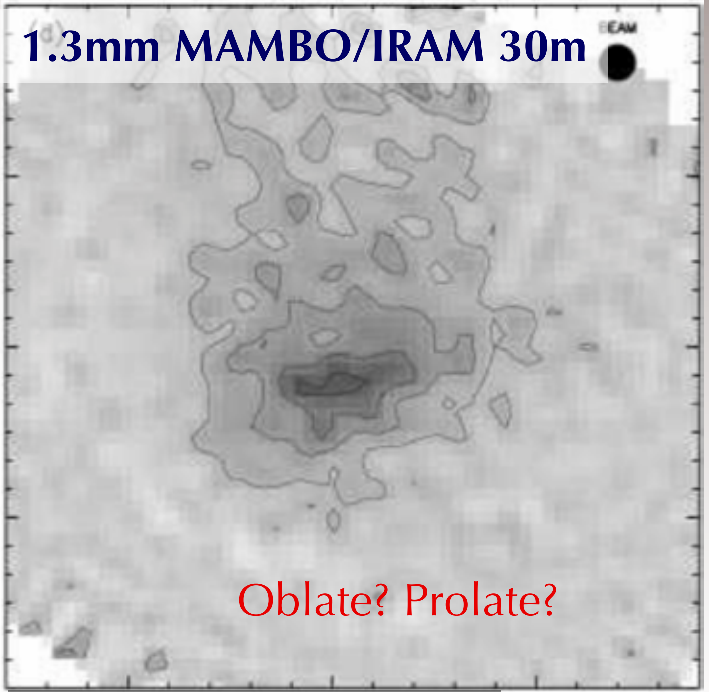
Nature traced by outflow (e.g., CO 2-1) surveys

Protostellar core



Motte & André 2001

Prestellar core



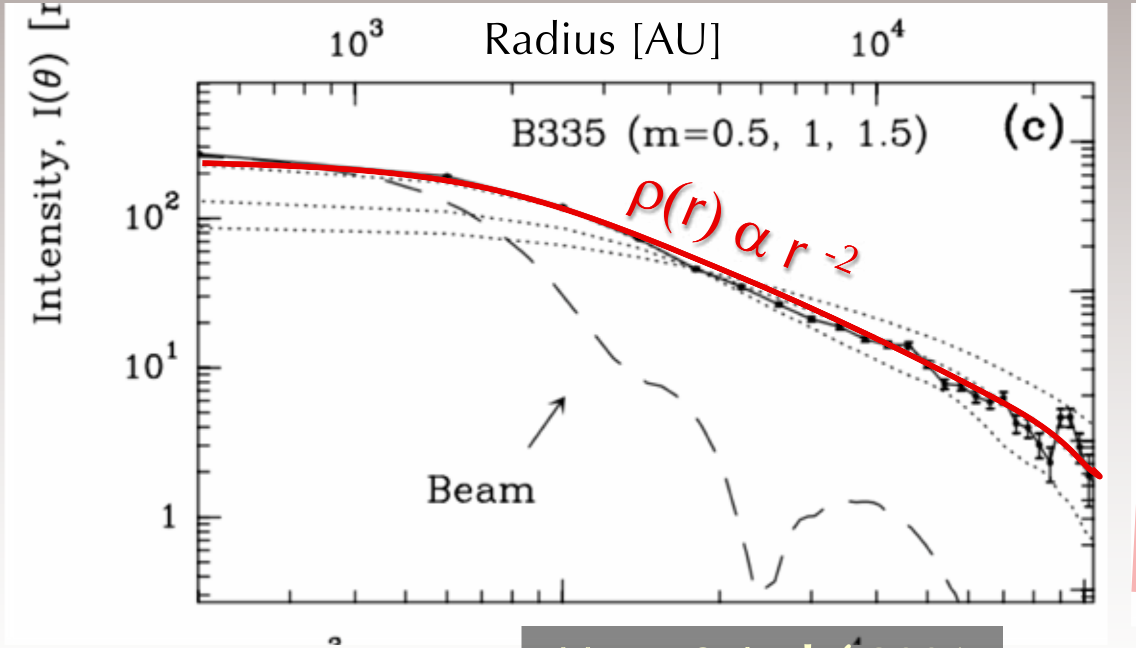
Ward-Thomson+1999

Density profiles of cores (1)

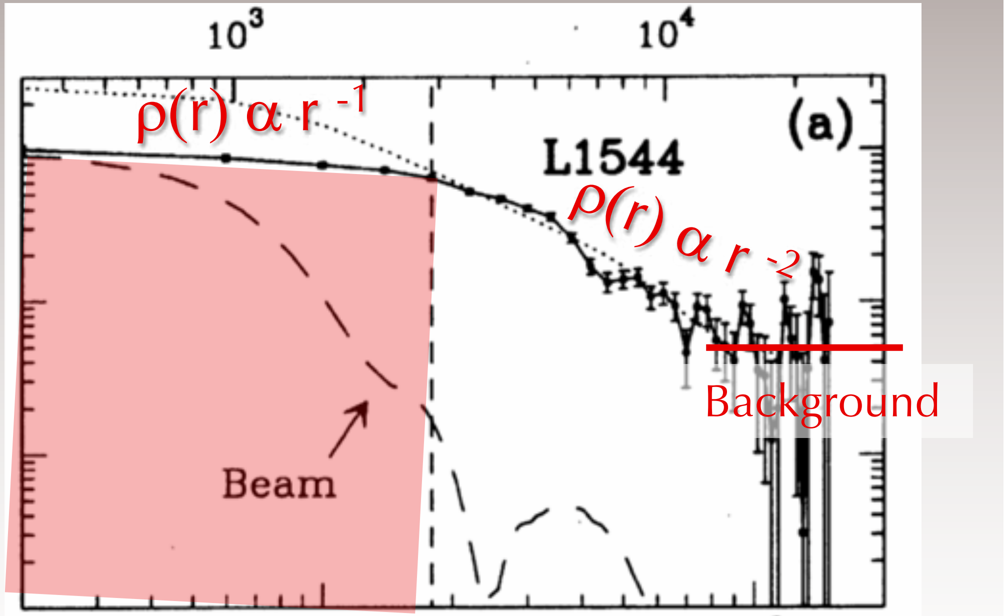
1995-2010: Structure of prestellar and protostellar cores
(Column) density profiles of known cores @ 120 to 500 pc
→ ~singular isothermal spheres versus ~Bonnor-Ebert spheres

Protostellar cores = r $^{-2}$ density profile

Prestellar cores = flat inner part



Motte & André 2001



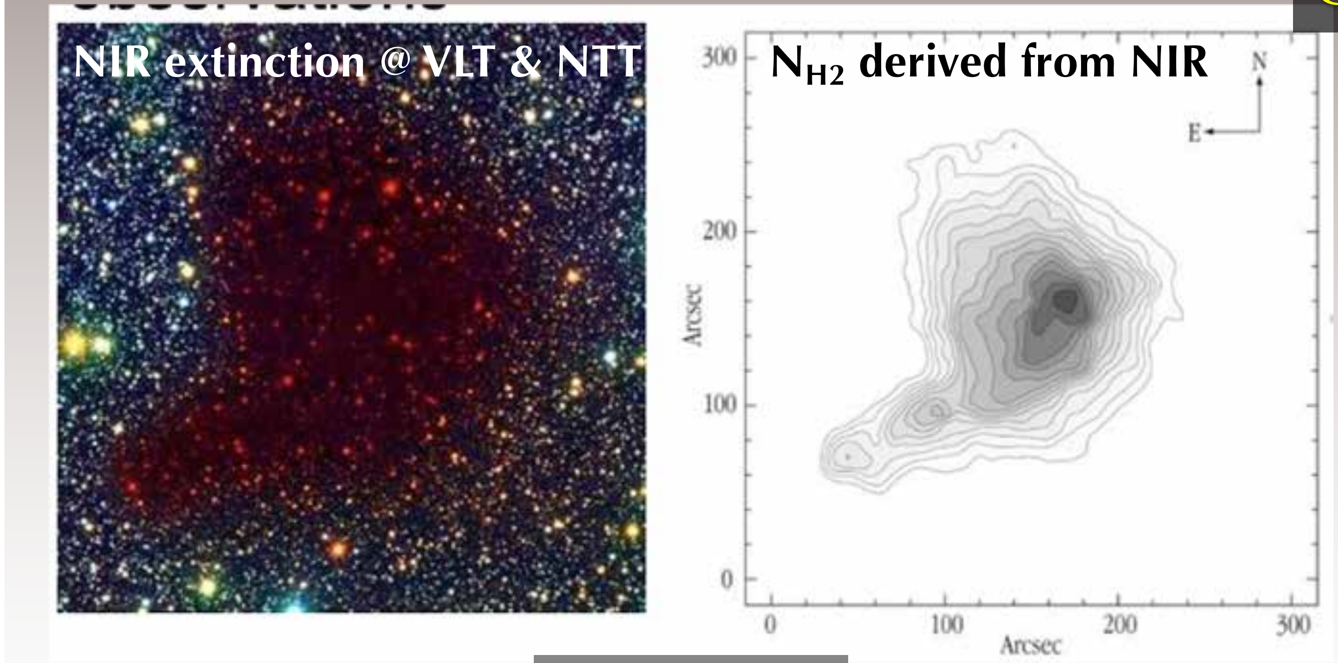
Ward-Thomson+1999

Density profiles of cores (2)

Caveat of submm dust emission = unknown temperature profile

1995-2010: The NIR extinction view of the B68 prestellar core

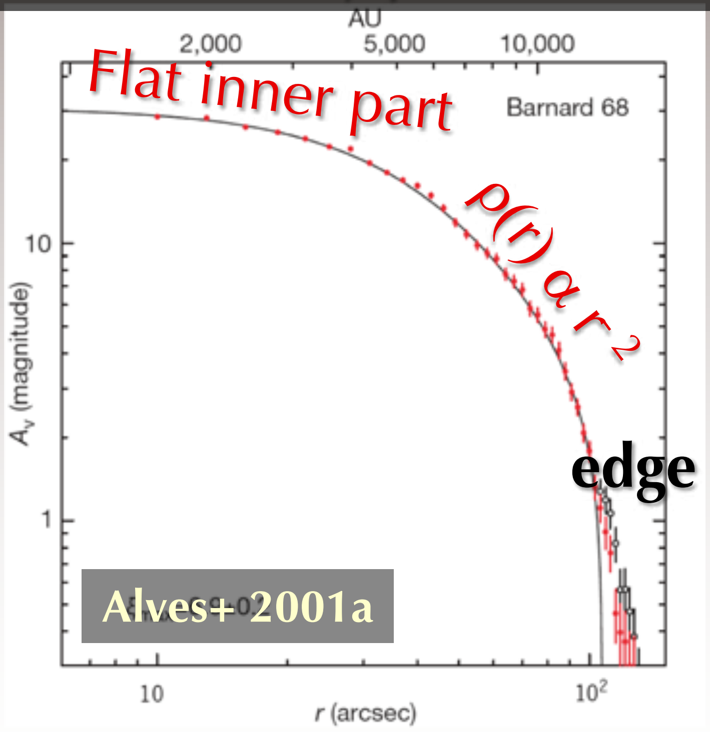
→ A critical Bonnor-Ebert sphere (16K, 1 $M_\odot$) with an **edge(?)**


NIR extinction @ VLT & NTT

N_{H2} derived from NIR

Alves+ 2001b

Column density profile of B68



Flat inner part

$\rho(r)\ \alpha\ r^{-2}$

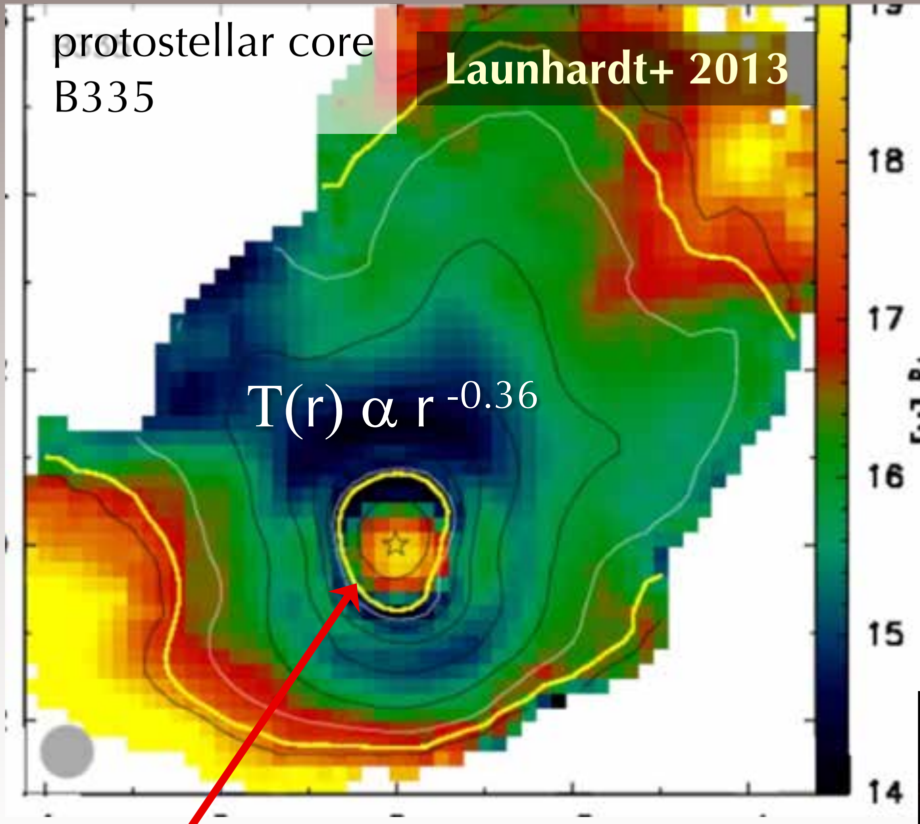
edge

Alves+ 2001a

Temperature profile of cores (1)

>2010: Herschel (70-500 μm) temperature profiles improve density structure analyses

→ self-screening for all cores + central heating for protostars

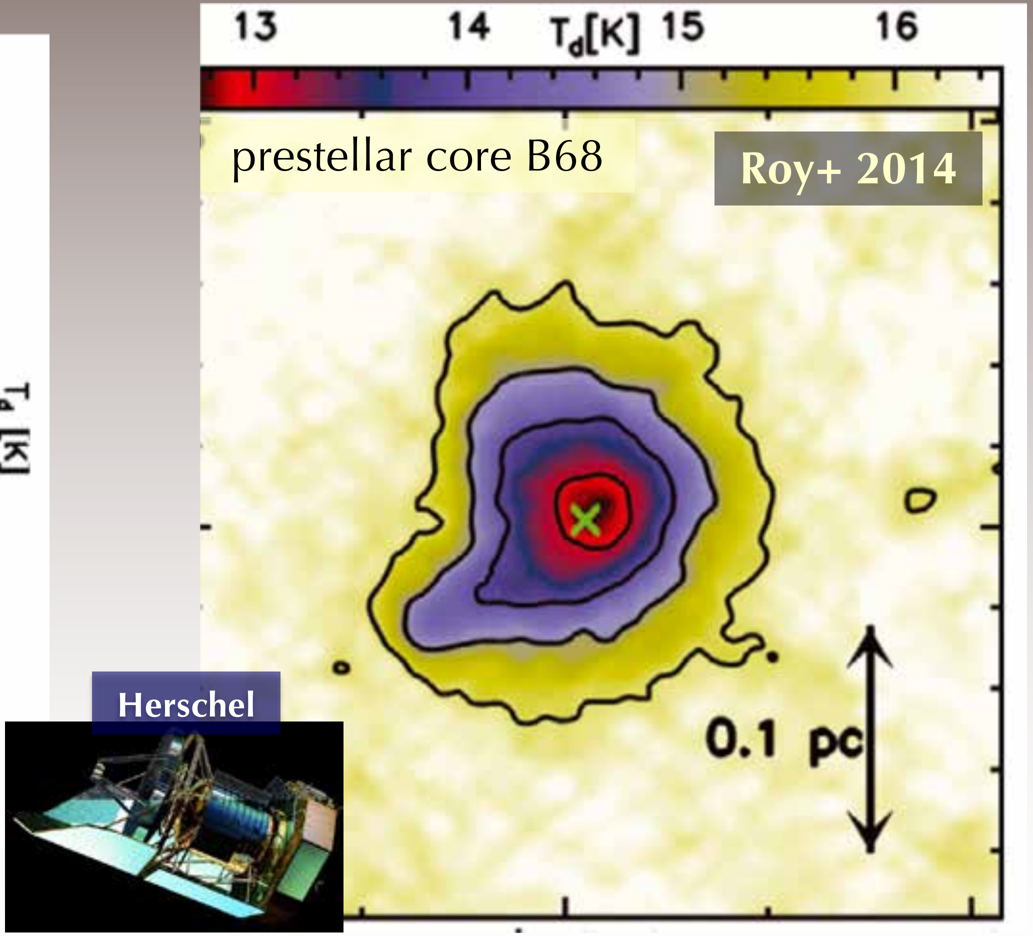


protostellar core B335

Launhardt+ 2013

$T(r) \propto r^{-0.36}$

Protostellar heating



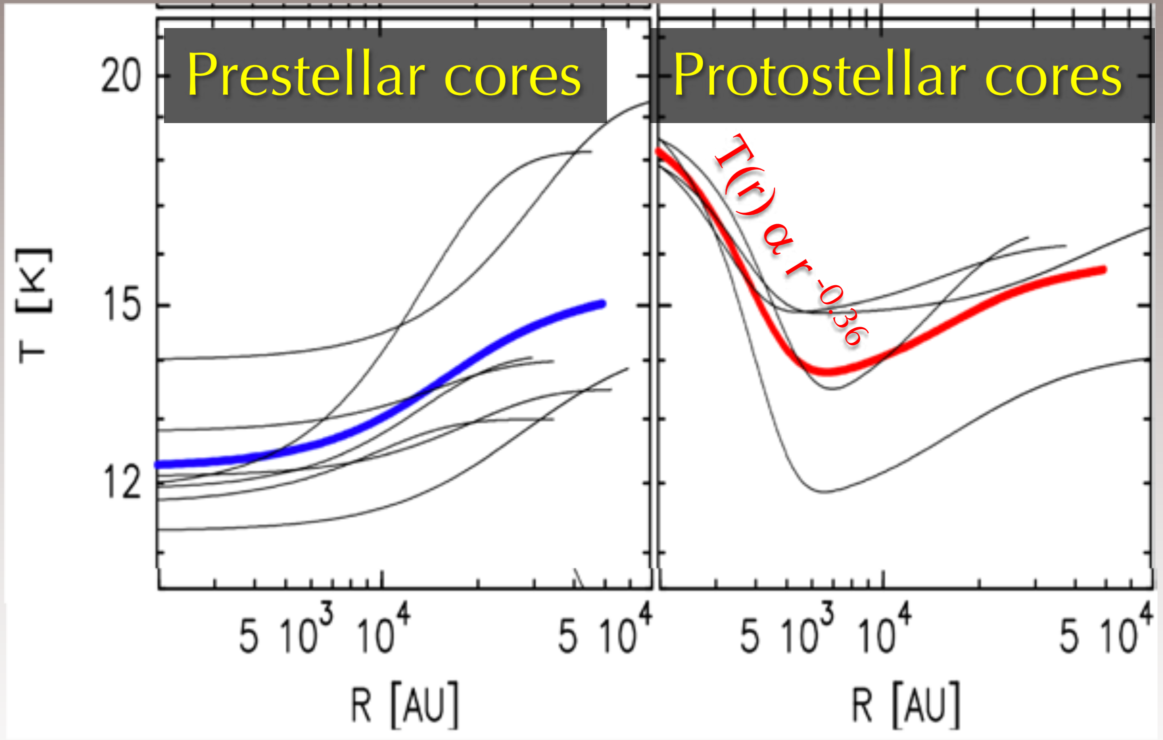
prestellar core B68

Roy+ 2014

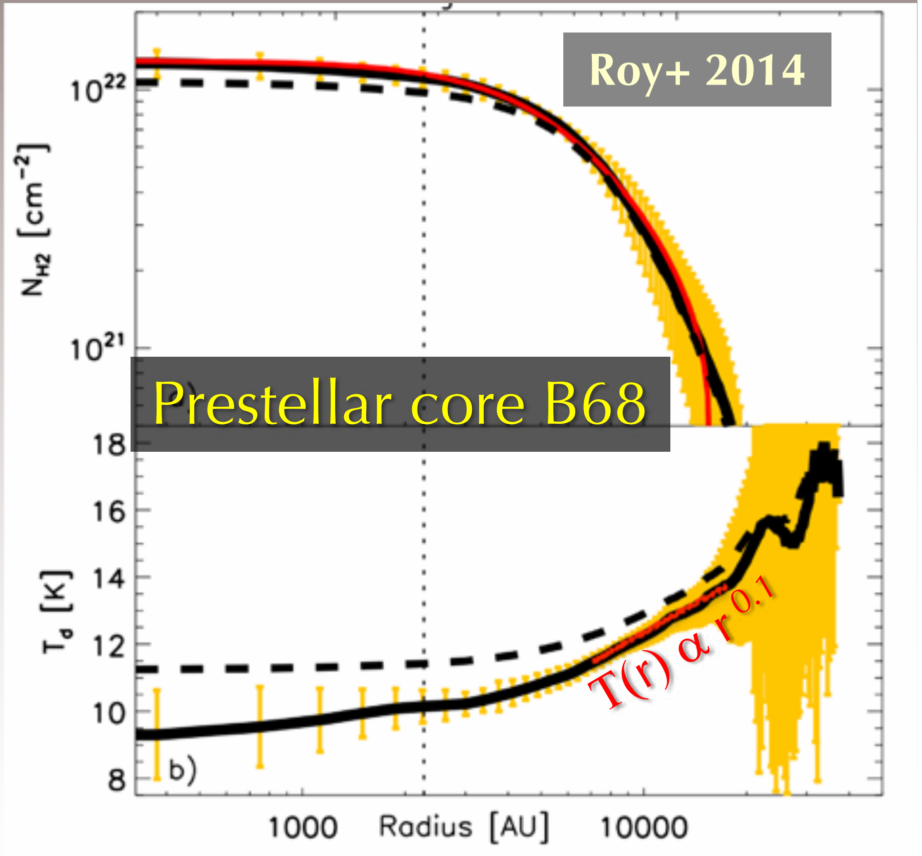
Herschel

Temperature profile of cores (2)

- Central heating for protostars in agreement with $T_{dust}(r) \alpha\ r^{-0.36}$ (Terebey+ 1993; Peretto+ 2020).
- Self-screening for all cores



Launhardt+ 2013



Roy+ 2014

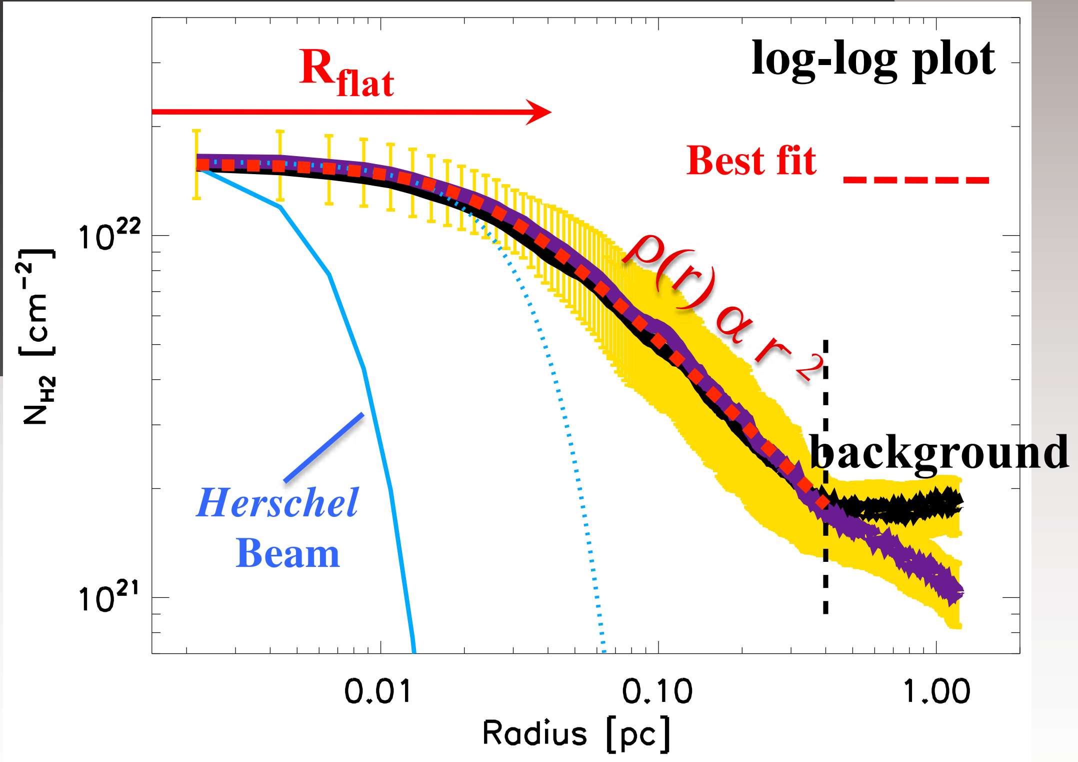
Density structure of other cloud structures…

Ubiquitous density structure: $\rho(r) \propto r^{-p}$ with p= 1.5 to 2

- of the inner part of protostellar cores (Maury+ 2019)
- of massive protostellar clumps (e.g., Beuther+ 2002)
- the hub gas surrounding HII regions (Didelon+ 2015)
- of the "Plummer-like" transverse profile (2D) of filaments:

$$\rho(r) = \rho_c / [1 + (r/R_{flat})^2]$$

(Palmeirim+ 2013; Arzoumanian+ 2019)



Transverse profile of the Taurus B213 filament

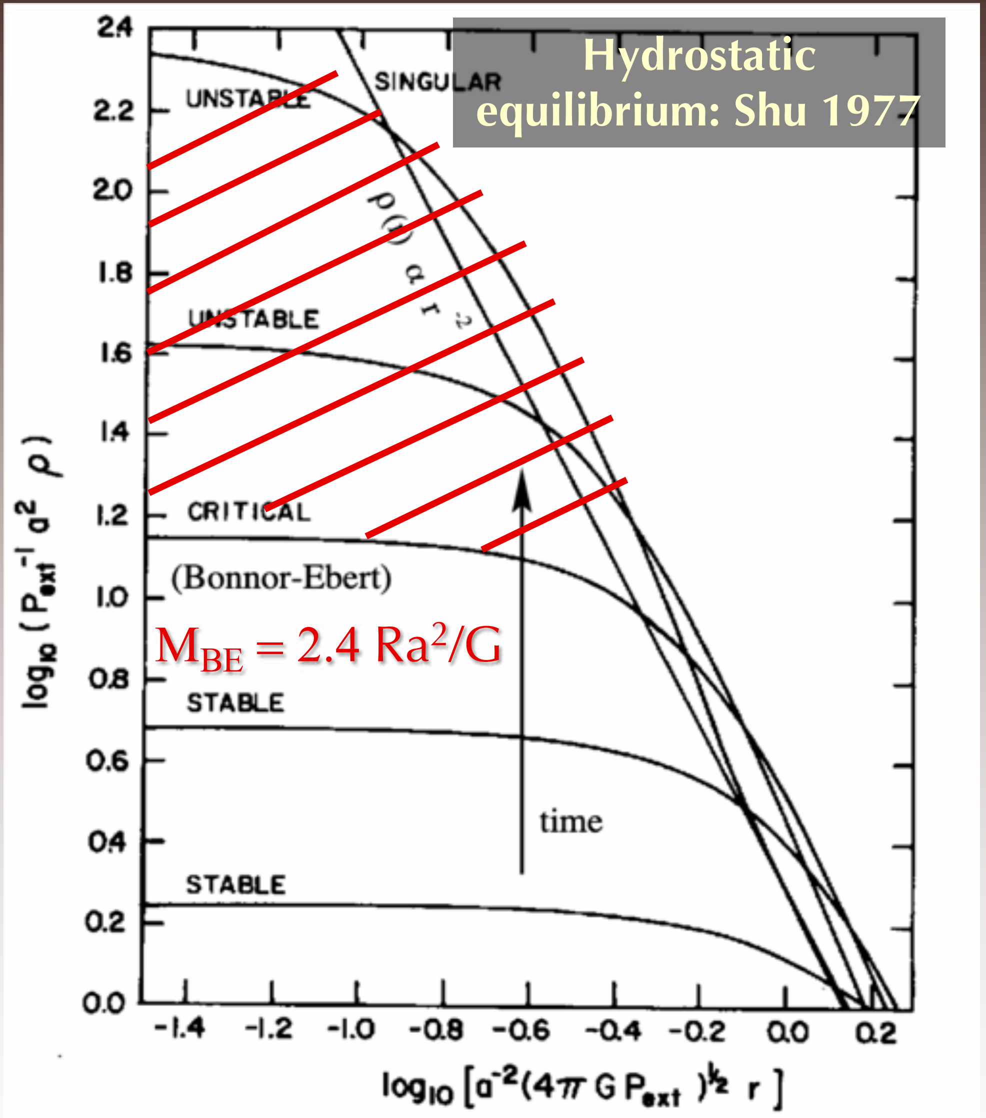
Palmeirim+ 2013

Analytical theories of core formation & collapse

Observations in relative agreement with analytical theories describing the formation and collapse of a self-gravitating isothermal sphere.

1. Formation
Cloud fragments concentrate up to become prestellar cores with shape close to that of a critical BE sphere (Bonnor 1956; Ebert 1956).

Unstable prestellar cores should collapse before reaching a Singular Isothermal Sphere (initial condition of Shu's model of Shu 1977) → decreasing M_{acc}



Hydrostatic equilibrium: Shu 1977

Dynamical evolution: Larson 1969; Penston 1969; Whitworth & Summers 1985…

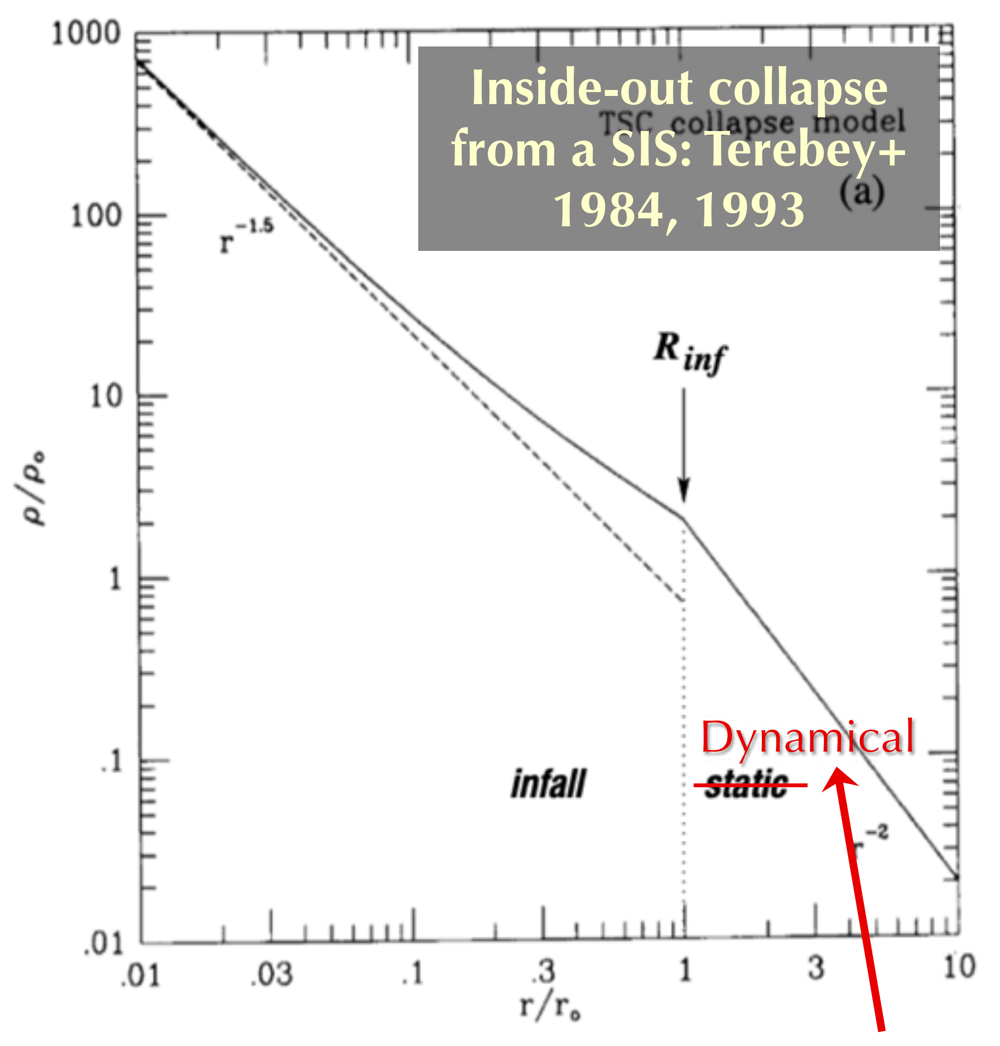
Analytical theories of core formation & evolution

2. Collapse

The protostar undergoes a free-fall collapse in its inner part, while keeping

- a static outer envelope ('standard model', e.g., Terebey+ 1984)
- a dynamical outer envelope (e.g., Foster & Chevalier 1993).

In dynamical models, envelopes are denser as observed by Motte & André (2001)



Inside-out collapse from a SIS: Terebey+ 1984, 1993

Collapse of a BE-like sphere: Henriksen+1997; Basu 1997…

Part II
What is an (isolated) core?

Cores are identified using dust emission, extinction and molecular lines.

Their density and temperature profiles evolve from their prestellar to their protostellar stages.

Analytical theories of the formation and collapse of a self-gravitating isothermal sphere correctly describe **isolated** cores.

QUESTIONS!

Outline / Part III

1. Why are intermediate scales (pc to 0.01 pc) crucial for star formation?

2. What is a core?

3. Detailed characteristics of (isolated) cores
    - Stability of prestellar cores
    - Gravitational infall
    - Lifetimes
    - Bolometric luminosity

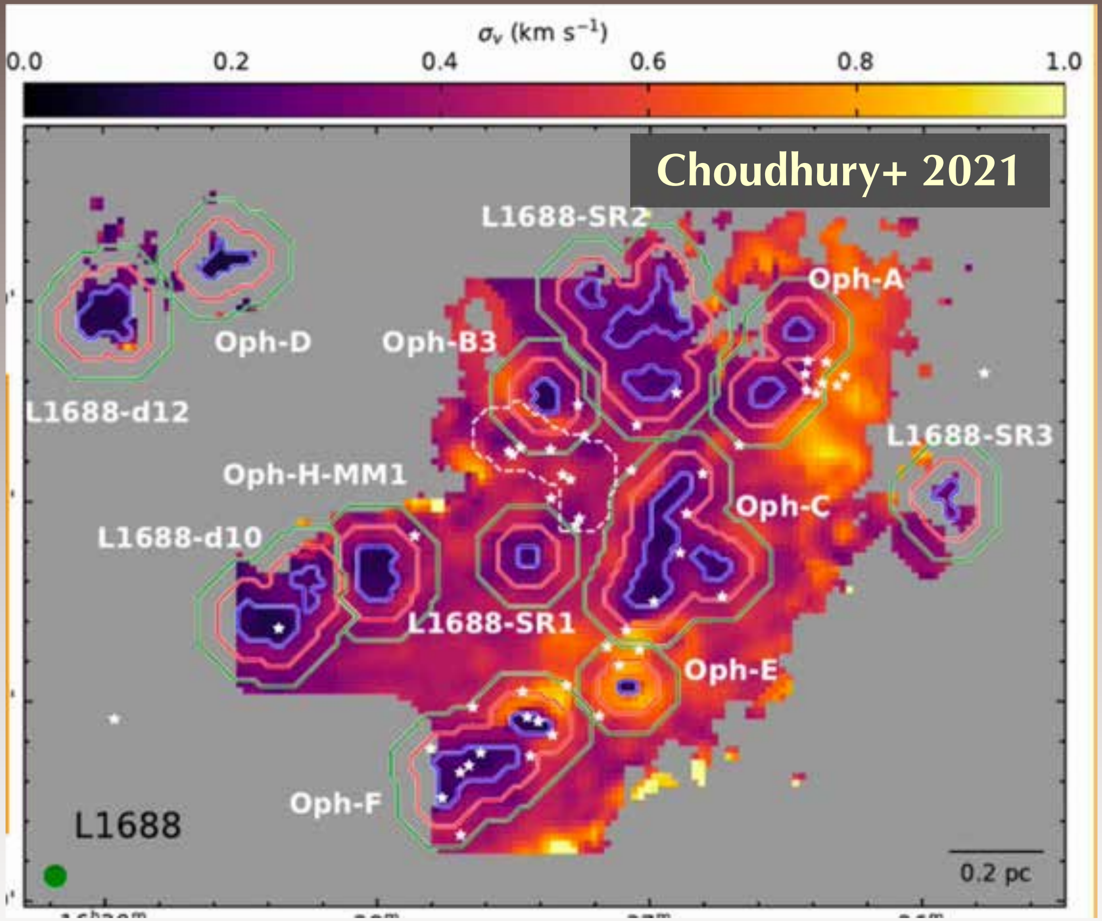
4. Caveats of our present definition of cores

Stability of prestellar cores (1)

Turbulence level measured from line width

- Transition to coherence @0.1 pc
  Subsonic line width:
  $\sigma_{NT} < \sigma_{Th}$ (e.g., Pineda+ 2010; Chen + 2019; Choudhury+ 2021).

- Orion A cores have supersonic line width
  → bound by gravity **and** outer pressure (Kirk+ 2017; Cheng+ 2021).



Stability of cores (2) and B field topology

B field strength @ 0.1 pc

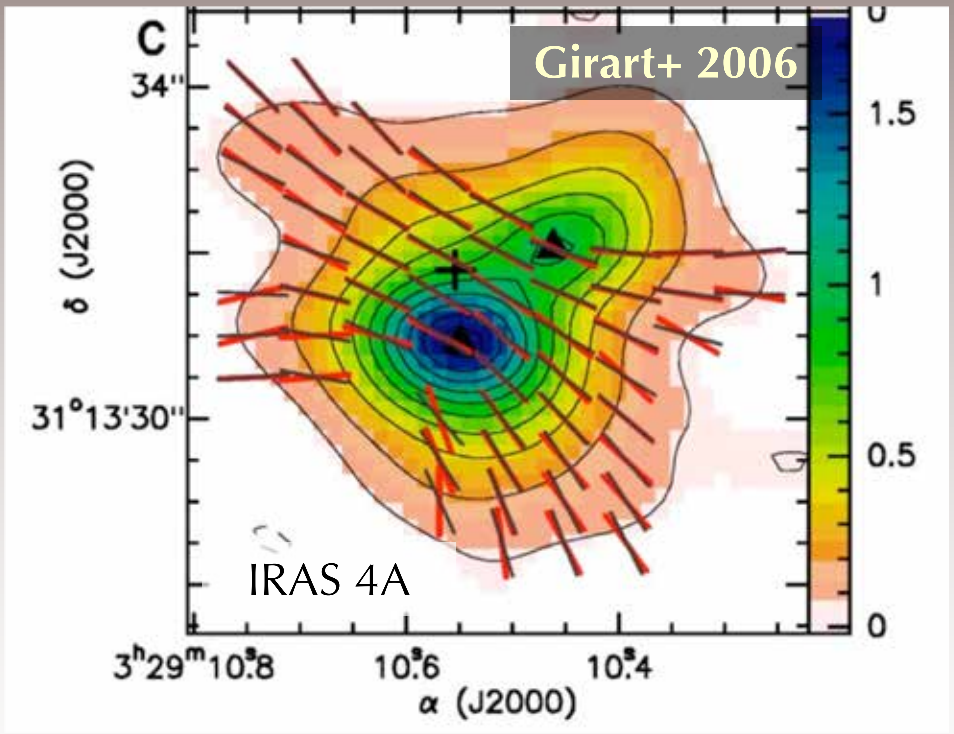
- Difficult to measure
- Prestellar cores: supercritical by a factor 2

B field topology @ 0.1 pc

(Koch+ 2014; Zhang+ 2014)

- Either perpendicular or parallel to the core elongation (Li+ 2013; Koch+ 2013; Pillai+ 2016; Alina+ 2019)
- Sometimes displaying an hour glass morphology (Girart+ 2006)
- Uncorrelated with outflows

→ **Lecture by Anaëlle Maury**



Girart+ 2006

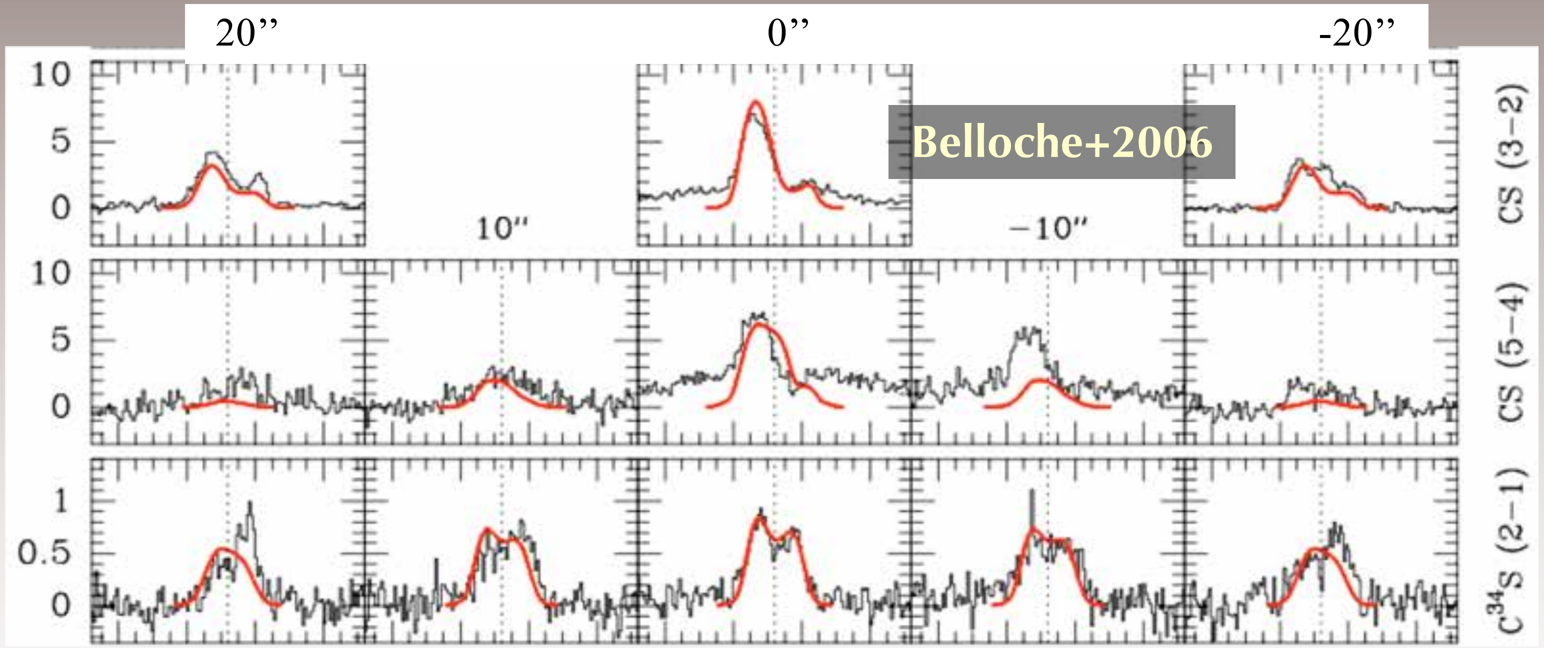
Cores infalling or on the verge of collapse

1. Gravitational infall of protostellar cores @ 0.1 pc

Imaging of optically thick molecular lines tracers (HCO$^+$, CS,…)

→ 10^{-5}-10^{-2} $M_\odot$/yr accretion rate (e.g., Mardones+ 1997; Evans+ 2015)

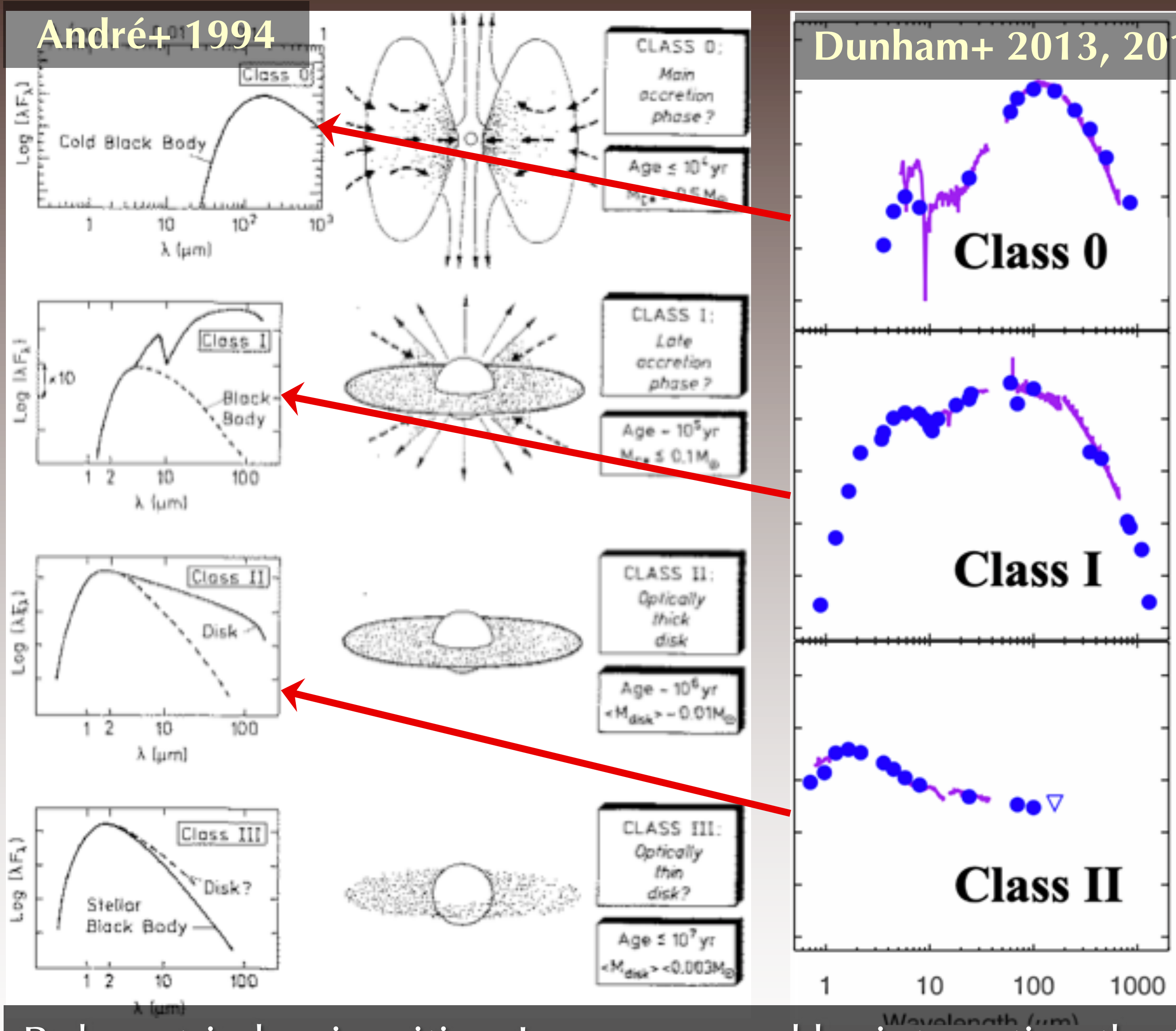
+ rotation → Lecture by Anaëlle Maury



Belloche+2006

2. Prestellar cores display oscillations/pulsations (Lada+ 2003)

Evolutionary sequence of protostellar cores



Low-mass protostars

Class 0
$L_{SMM}/L_{BOL} > 0.5\%$
$T_{BOL} \leq 70$ K

Class I
$\alpha \geq 0.3$
$70 \text{ K} < T_{BOL} \leq 670$ K

~0.1-100 $L_\odot$

Class II
$-1.6 \leq \alpha < -0.3$
$670 \text{ K} < T_{BOL} \leq 2800$K

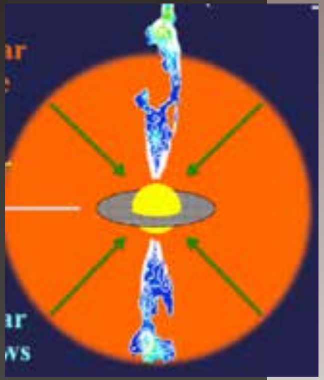
High-mass protostars (König+ 2017; Motte+ in prep.)

10^2-10^5 $L_\odot$

Bolometric luminosities, L_{bol}, measured by integrating the SED of protostellar cores from 2 μm to 1 mm. Angular resolution and luminosity leaking issues!

Lifetimes of cores

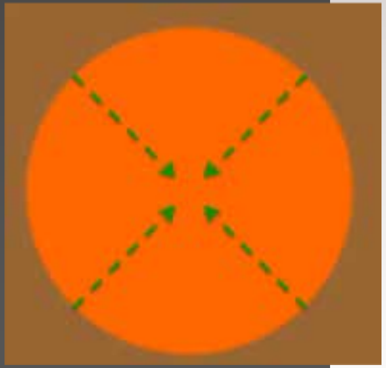
Statistically estimated from the number of Class II or UCHII regions



Protostellar cores live for a few free-fall times

initial $n_{H2} \sim 10^5\ \mathrm{cm}^{-3} \rightarrow \tau_{ff} \sim 10^5$ yr

- Class 0s: 0.1-0.2 Myr (Dunham+ 2015)
  Revised to 0.05 Myr using submm surveys
- Class Is: 0.3-0.5 Myr (Dunham+ 2015)
- High-mass protostars: 0.1-0.2 Myr (Motte+ 2018).



The lifetime of prestellar cores forming

- low-mass stars live for 10 free-fall time: 1.2 Myr
  (Jessop & Ward-Thompson+ 2000; Könyves+ 2015)
- high-mass stars are short lived **if they exist**
  - (Motte+2007, 2018; Duarte-Cabral+ 2013)

The quest of high-mass prestellar cores

What could be the high-mass analog of low-mass prestellar cores?

- High-mass prestellar cores with additional support against collapse

  ⇒ @Small scale : massive prestellar cores

  0.01-0.1 pc, >10-100 $M_\odot$

  'Core-fed' accretion (e.g., McKee & Tan 2003).

- Low-mass prestellar cores within a massive clump

  ⇒ @Large scale: massive starless clumps

  0.1-1 pc, >100 $M_\odot$

  @Small scale within the clump: prestellar cores

  'Clump-fed' accretion through gas flows (e.g., Smith+ 2009).

→ Unbiased census of clumps + high-resolution follow-ups

@Herschel, IRAM 30m, APEX, CSO @ALMA

Unbiased census of clumps and follow-ups for cores

Massive starless clumps are fewer in number than protostellar ones (Motte+ 2007; Csengeri+ 2014; Traficante+ 2015; Svoboda+ 2016, …).

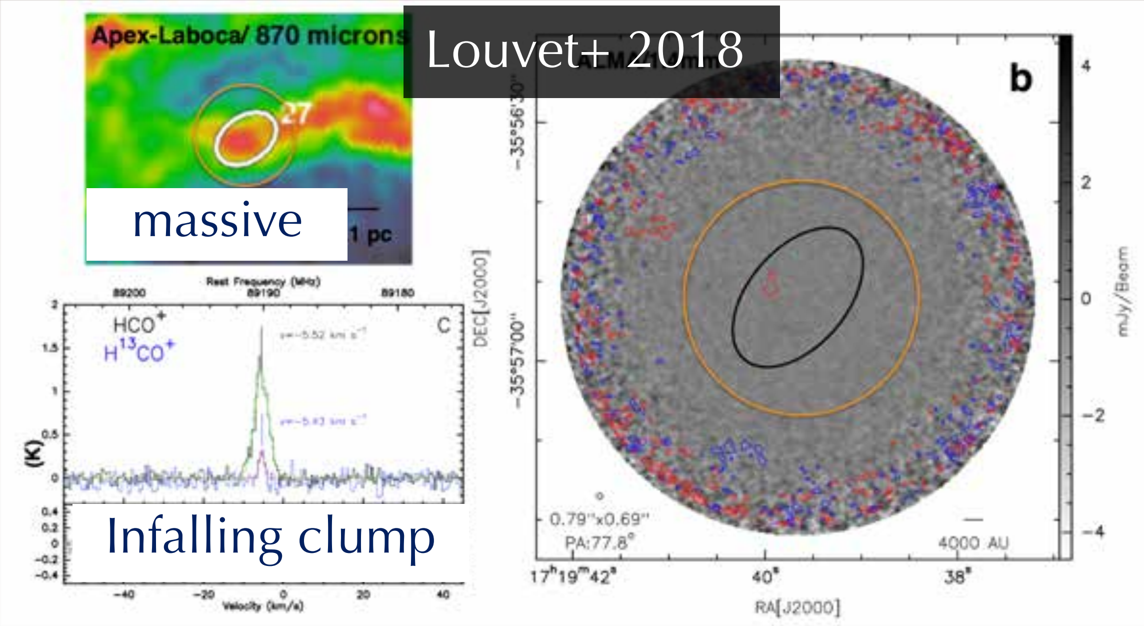
Within them, no high-mass prestellar cores, sometimes low-mass protostars (Louvet+ 2018; Bontemps+ 2010).

$\Rightarrow$ Prestellar lifetime

$<$ protostellar lifetime

$< 2 \times \tau_{\text{free-fall}}$

(Russeil+ 2010; Tigé+ 2017; Motte+ 2018)



Louvet+ 2018

massive

Infalling clump

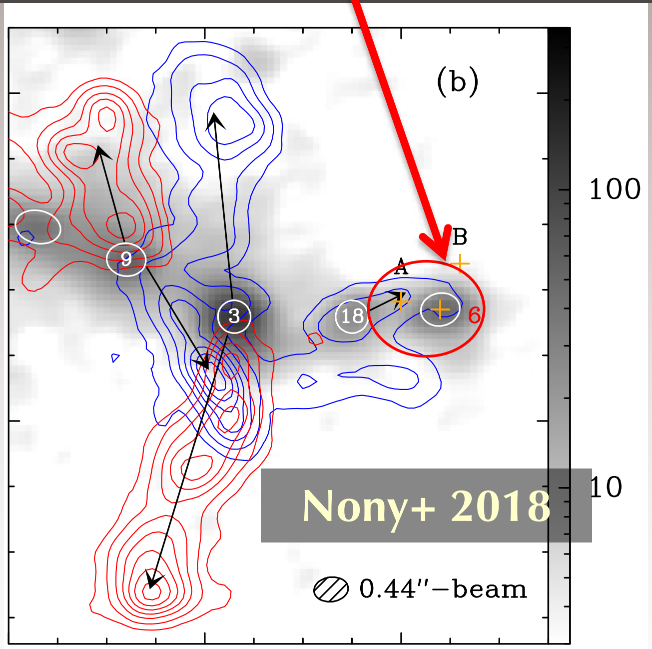
ALMA

One good high-mass prestellar core candidate!

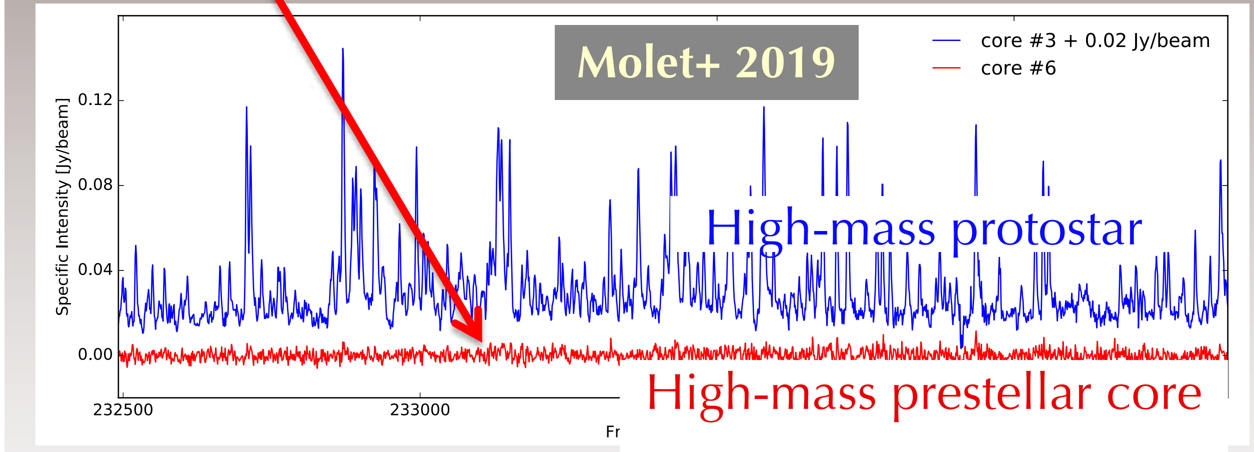
In the W43-MM1 ridge, a core

Nony+ 2018

- with 56 $M_\odot$ within 2000 AU
- gravitationally bound α_{vir} =0.2-0.3 using ^{13}CS(5-4) lines (ΔV ~ 3.3 km/s)
- No outflow
- No line forest typical of hot cores



CO(3-2) and SiO(5-4)



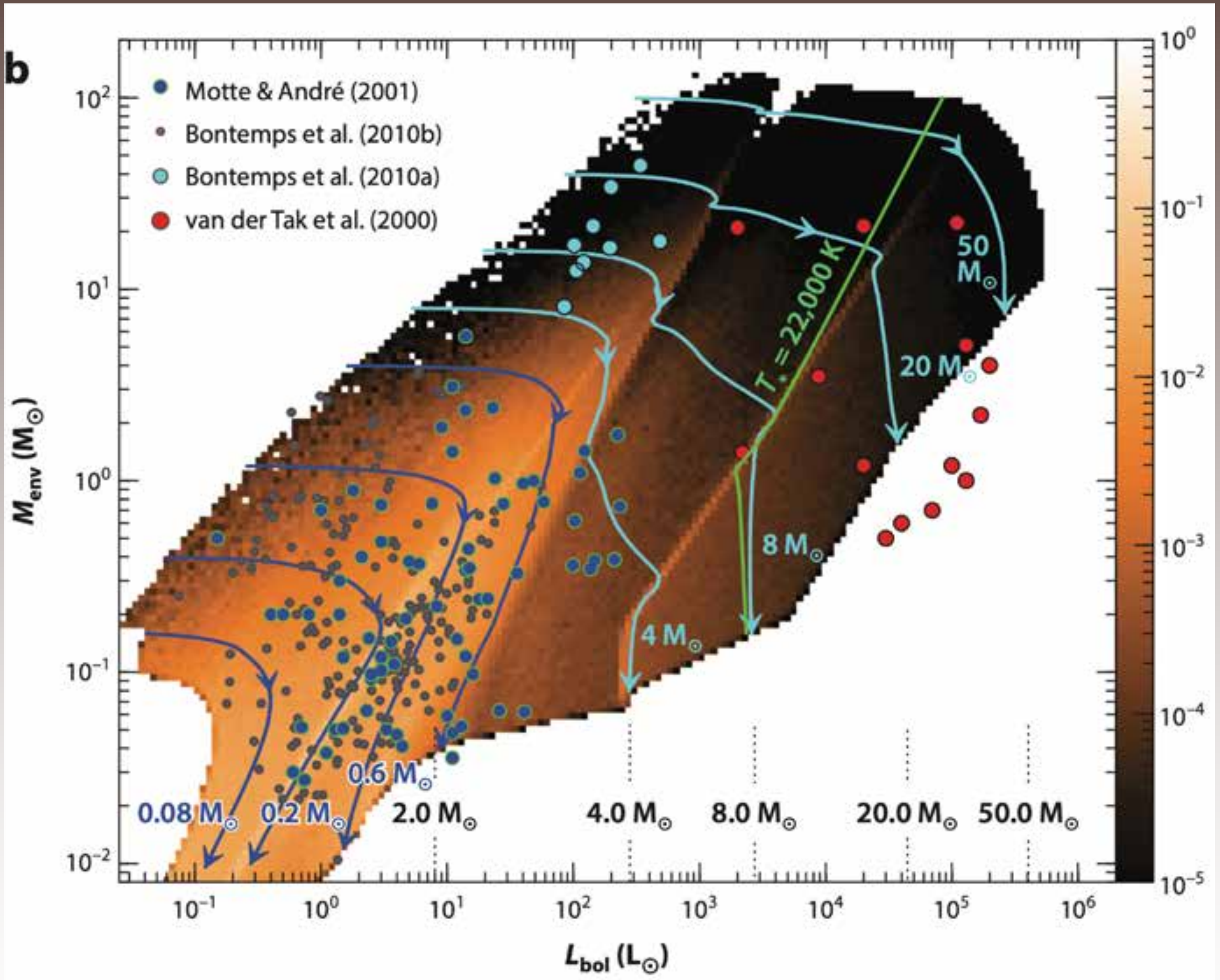
Core-mass growth is needed to explain ALMA-IMF census of intermediate-mass & larger-scale prestellar core (Valeille-Manet+).

Evolutionary diagram of protostellar cores

Mass versus luminosity diagram compared to models of protostellar evolution (Bontemps+ 1996; Molinari 2008; Peretto+ 2020)

→ constrain

- mass accretion rate, $M_{acc}(t)$
- core mass growth, $M_{growth}(t)$
- Burst, x factor and % time



Duarte+ 2013; Motte+ 2018

Part IV

Detailed characteristics of (isolated) cores

Prestellar cores are gravitationally bound, long-lived cloud structures, on the verge of collapse.

Protostars are gravitationally collapsing (short timescale) and rotating. Their luminosity increases with time.

QUESTIONS!

Outline / Part IV

1. Why are intermediate scales (pc to 0.01 pc) crucial for star formation?

2. What is a core?

3. Detailed characteristics of (isolated) cores

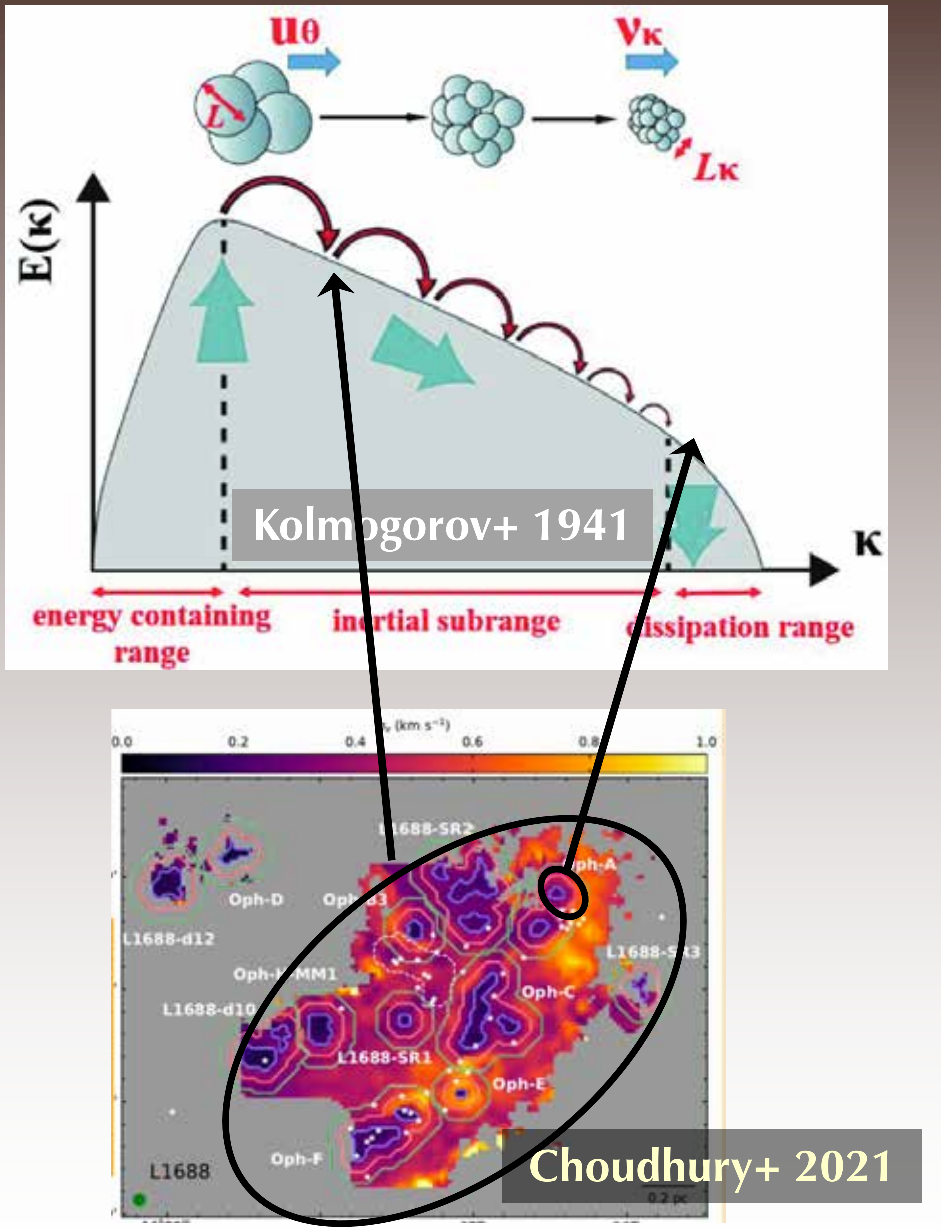
4. Caveats of our present definition of cores
    - Cores in a scale-free environment
    - Inflowing gas in dynamical scenarios for cloud and core formation
    - Various Galactic environments to be investigated

Cores in fractal molecular clouds

Both gravity and turbulence are scale-free processes.

1. Clouds are shaped by a turbulent cascade and display a multi-fractal structure (Frisch 1995; Miville-Déchênes+ 2010; Robitaille+ 2020)
2. Cores could be the coherent cloud structures at the dissipation scale (Pineda+ 2010; Robitaille+ 2019).

BUT ARE THEY REALLY?

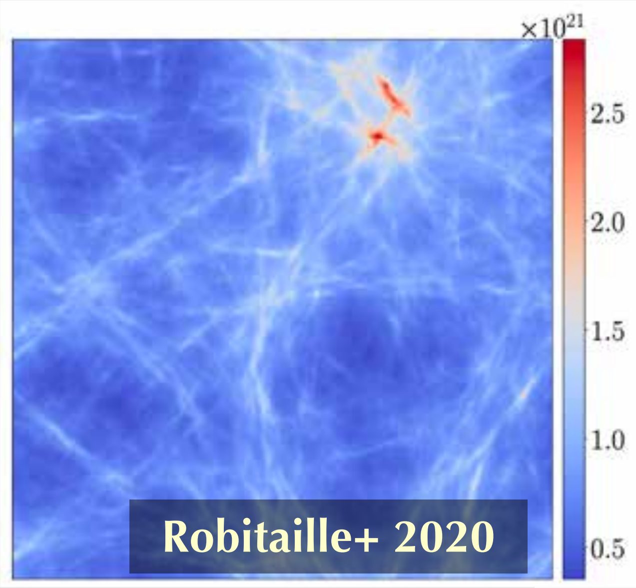


Kolmogorov+ 1941

Choudhury+ 2021

Multi-fractal nature of molecular clouds

- Fractional Brownian motion (fBm) models: reproduce the scale-free spatial density structure of clouds (Elmegreen 2001).
- Multiplicative cascade model: reproduces the hierarchical nature of filaments in molecular clouds (Robitaille+ 2020).



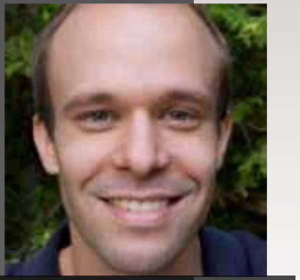
Robitaille+ 2020

Multiscale non-Gaussian Segmentation (MnGSeg, Robitaille+2019)

Based on complex wavelets, it combines

- PDFs as a function of spatial scales and orientation
- Power spectrum analysis of reconstructed maps

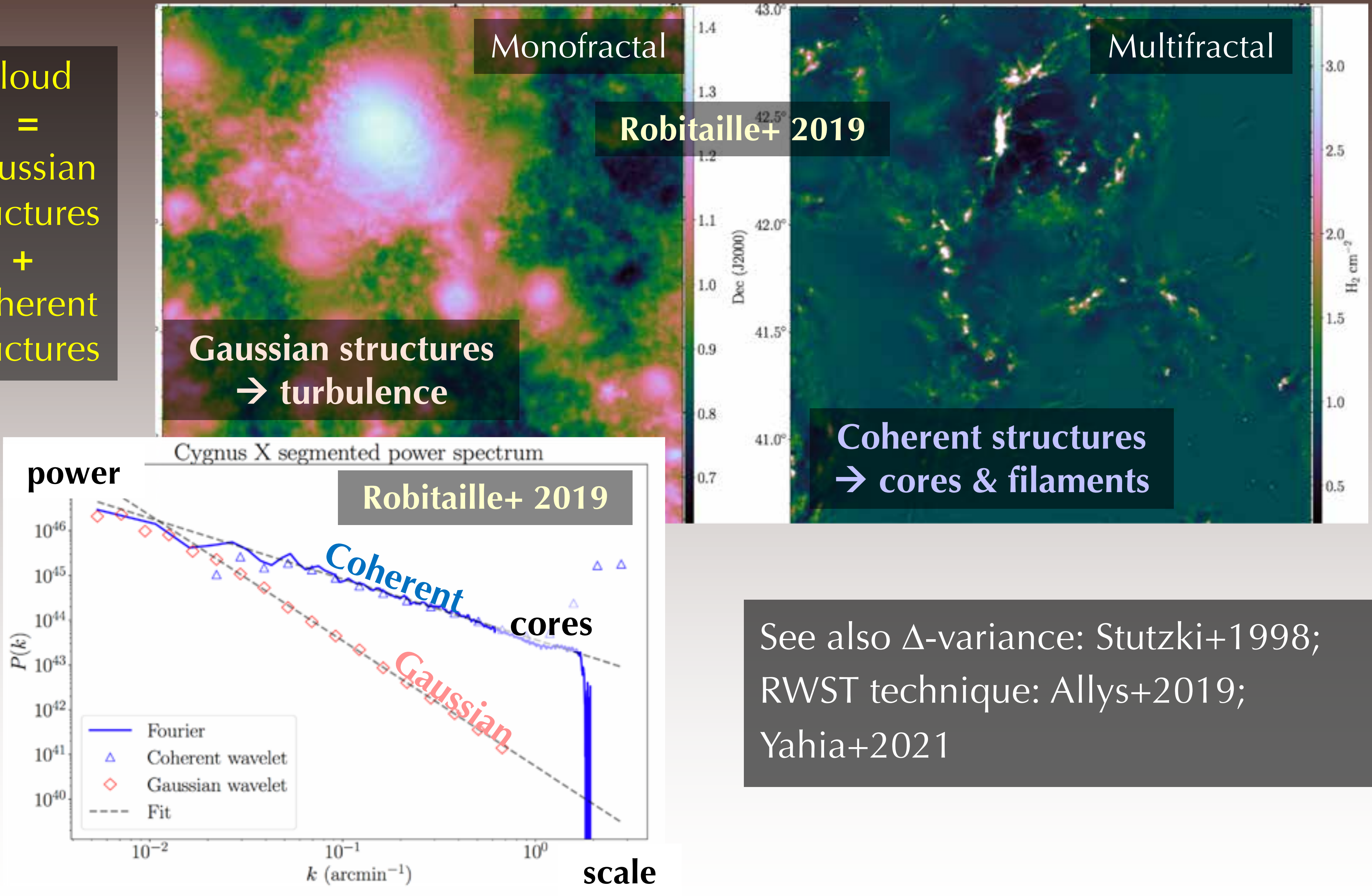
→ Separation of Gaussian turbulent structures and non-Gaussian coherent structures associated with star formation



J.-F. Robitaille

SF structures of clouds are coherent in spatial scales

Cloud
=
Gaussian structures
+
Coherent structures



Robitaille+ 2019

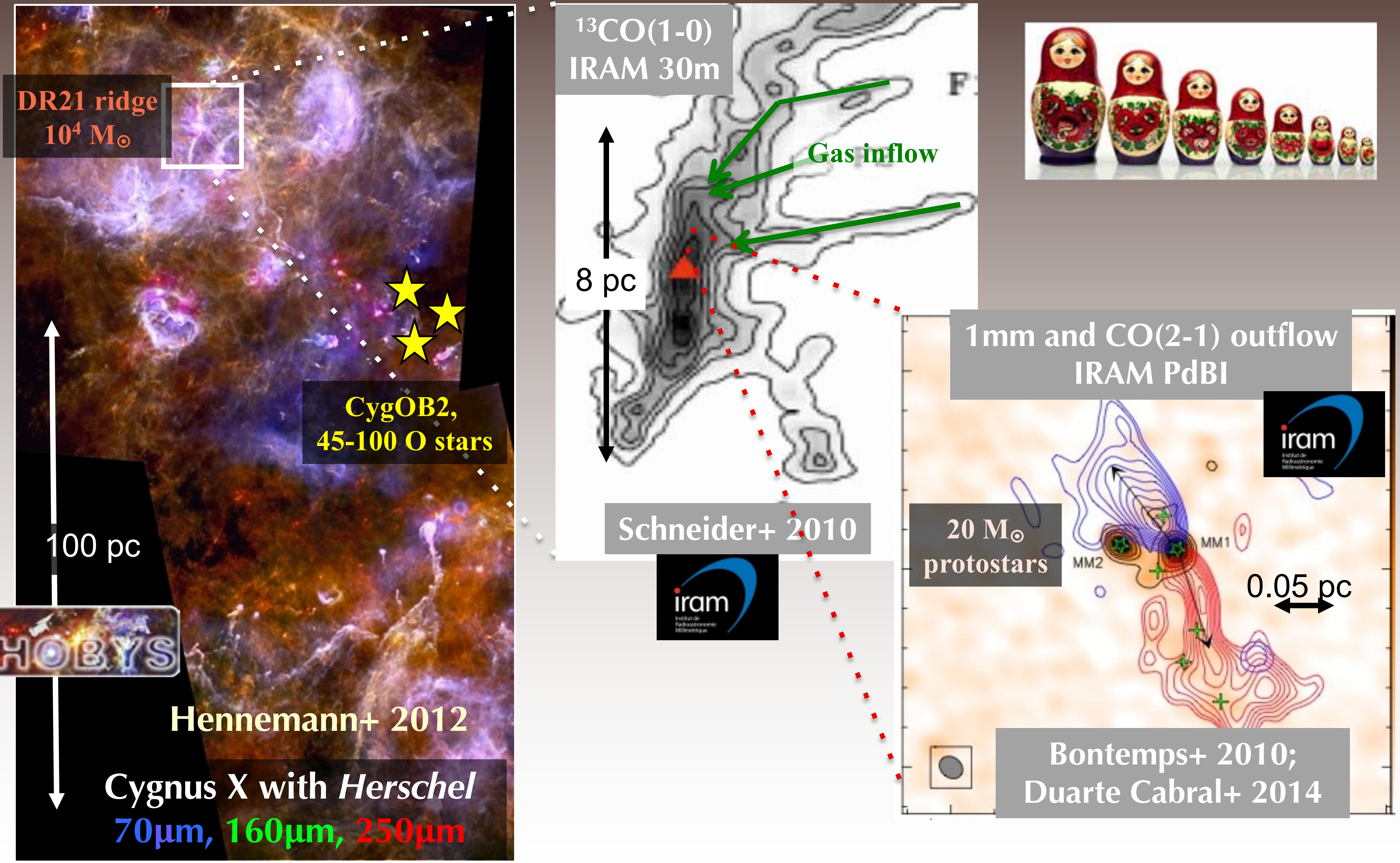
Gaussian structures → turbulence

Coherent structures → cores & filaments

Robitaille+ 2019

See also Δ-variance: Stutzki+1998; RWST technique: Allys+2019; Yahia+2021

From cloud complexes to individual protostars: Is there a dynamical link?



DR21 ridge
10^4 M$_\odot$

CygOB2,
45-100 O stars

Hennemann+ 2012

Cygnus X with *Herschel*
70µm, 160µm, 250µm

^{13}CO(1-0)
IRAM 30m

Gas inflow

Schneider+ 2010

1mm and CO(2-1) outflow
IRAM PdBI

20 M$_\odot$
protostars

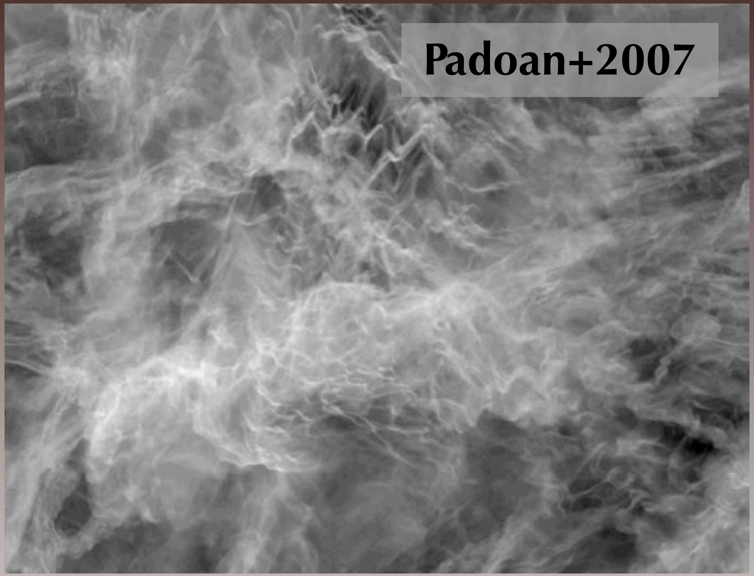
Bontemps+ 2010;
Duarte Cabral+ 2014

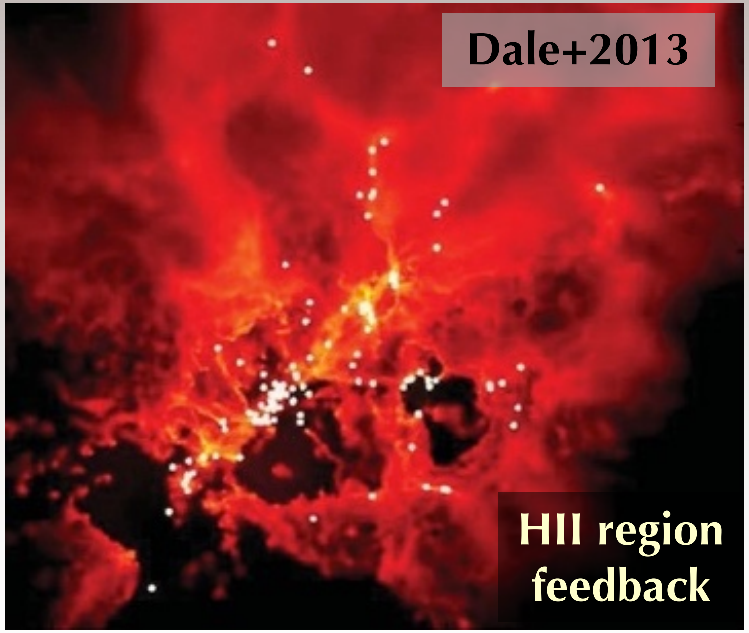
Quasi-static gravo-magneto-turbulent picture

1. Filaments form through supersonic shocks (e.g., Padoan+2007)

2. Stars form within gravitationally supercritical filaments (André+2010)

Turbulence is driven by protostellar outflows, HII regions, supernovae…





Quasistatic formation of interstellar filaments and stars

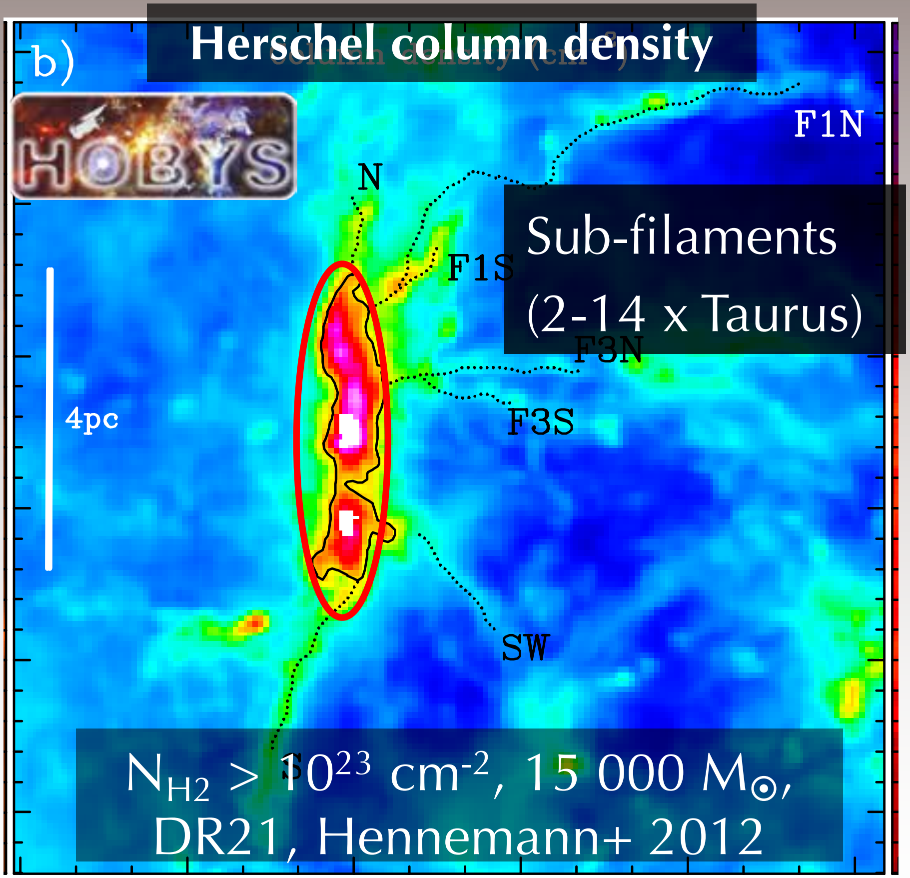
Ridges/Hubs definition

From the *Herschel*/HOBYS survey, high-mass stars form in clusters within high-density elongated ridges or in spherical hubs

⇒ 5-10 pc^3 /1 pc^3 clumps with mean densities above 10^4-10^5 cm^{-3}

See also

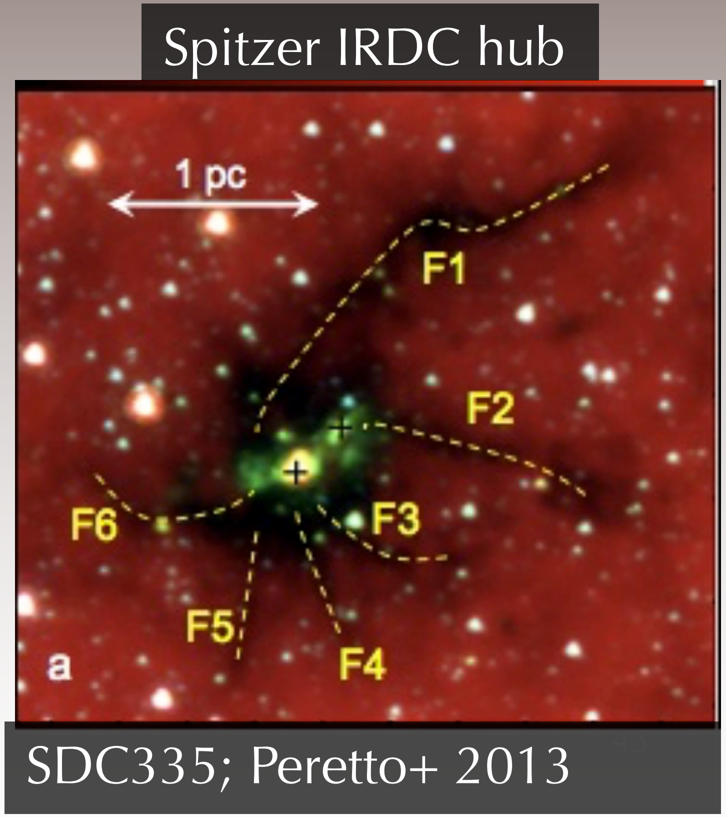
Hill+ 2011;
Nguyen Luong+ 2011, 2013;
Didelon+ 2014,
…



Herschel column density

Sub-filaments
(2-14 x Taurus)

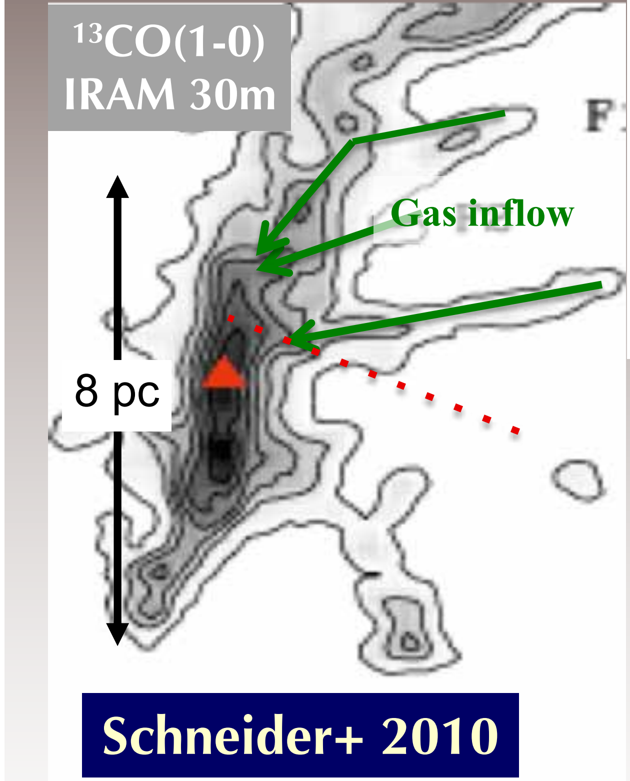
$N_{H2} > 10^{23}$ cm^{-2}, 15 000 $M_{\odot}$,
DR21, Hennemann+ 2012



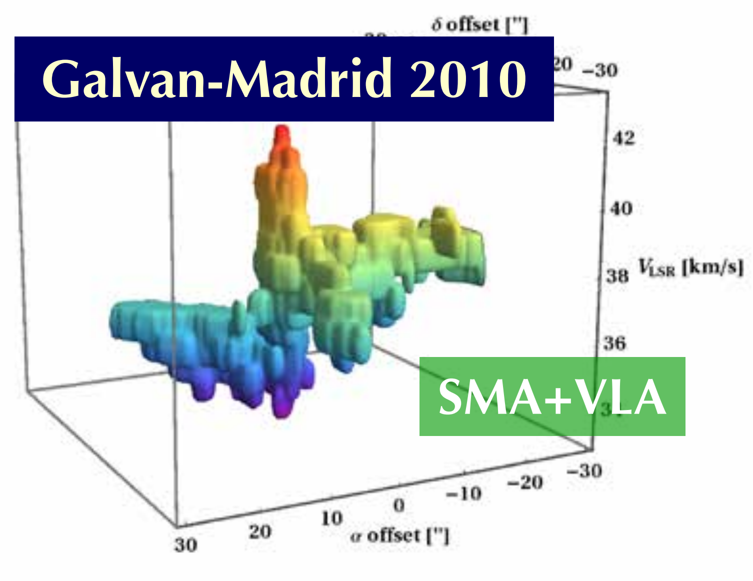
Spitzer IRDC hub

SDC335; Peretto+ 2013

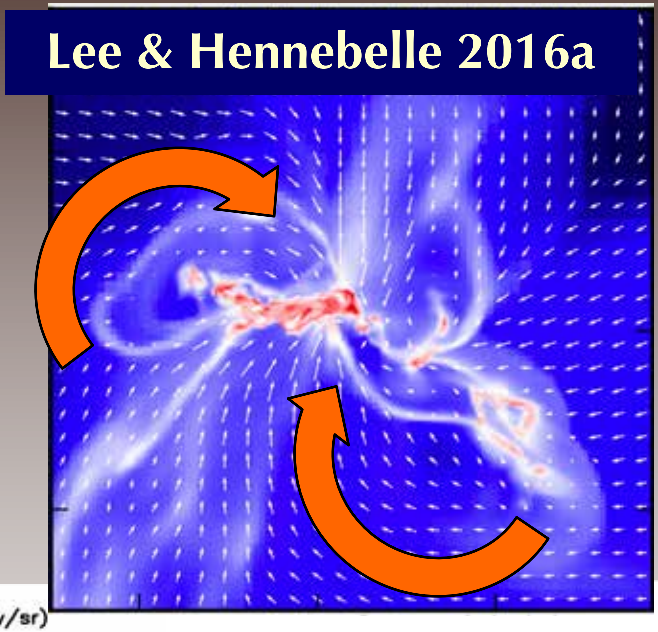
Hubs and ridges observations and simulations suggest a more dynamical picture

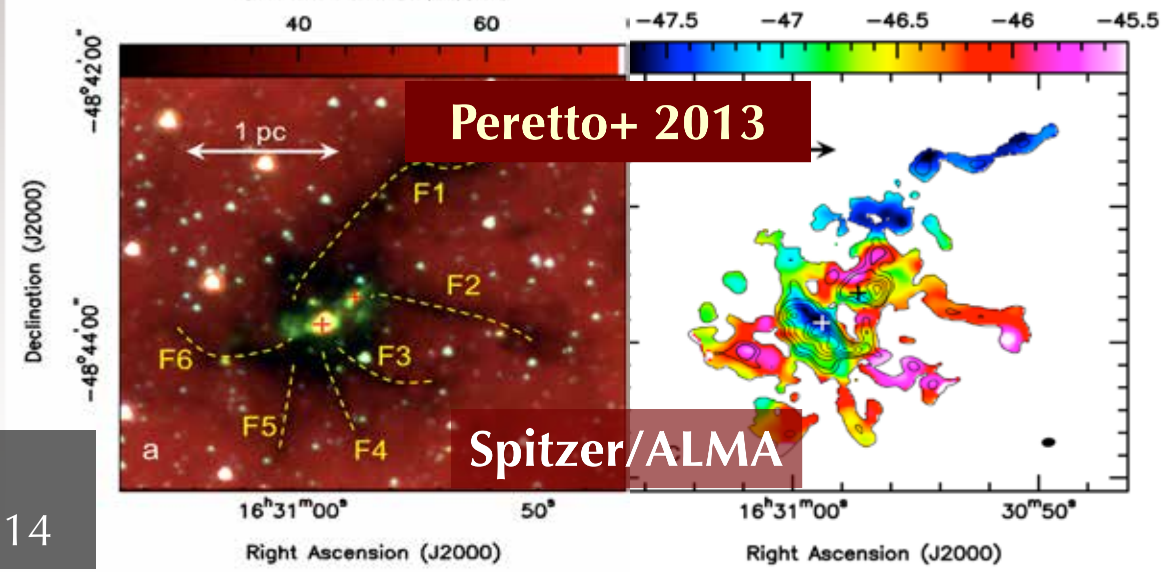

^{13}CO(1-0)
IRAM 30m

Schneider+ 2010


Galvan-Madrid 2010

SMA+VLA

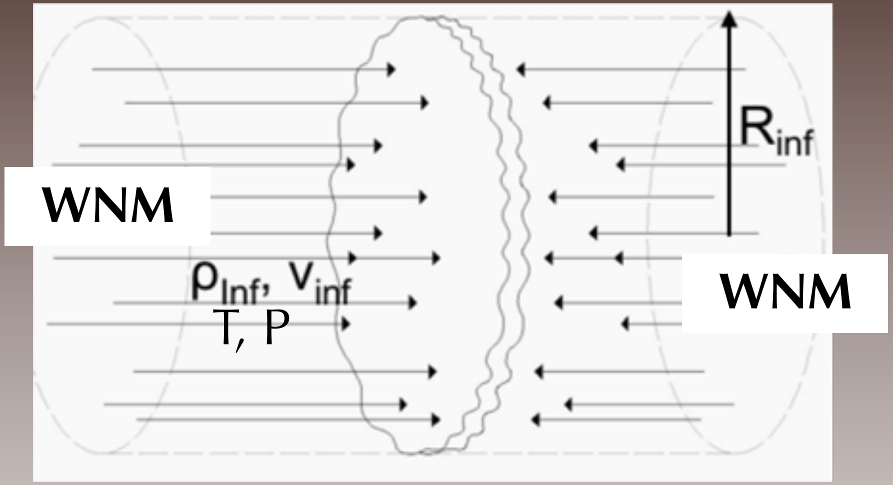

Lee & Hennebelle 2016a


Peretto+ 2013

Spitzer/ALMA

And many other references…
Smith2009; Gomez & Vazquez-Semadeni 2014

Dynamical picture 1:
Converging flow theories



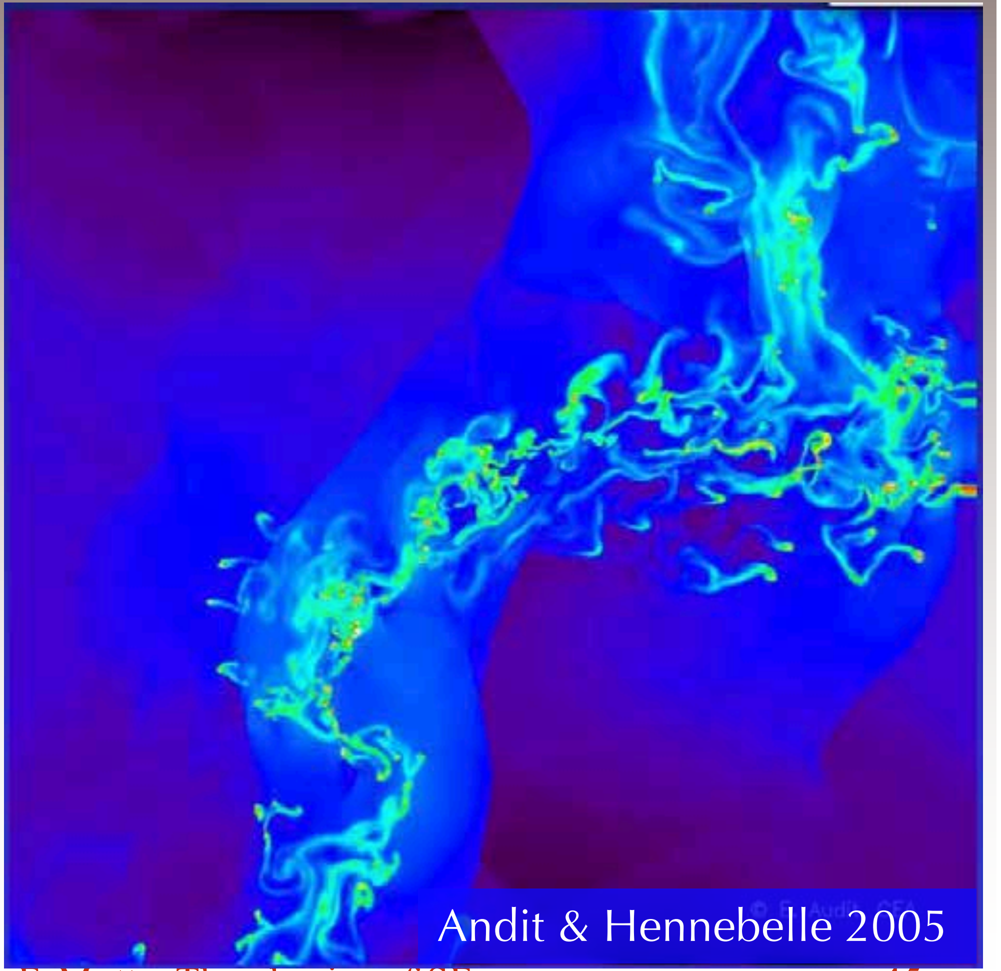
Converging flow theories:

Ballesteros-Paredes+1999; Heitsch & Hartmann +2008; Smith+2009; Vazquez-Semadeni+1999; …

Compression driven by large-scale instabilities (Galactic arms, bar…)

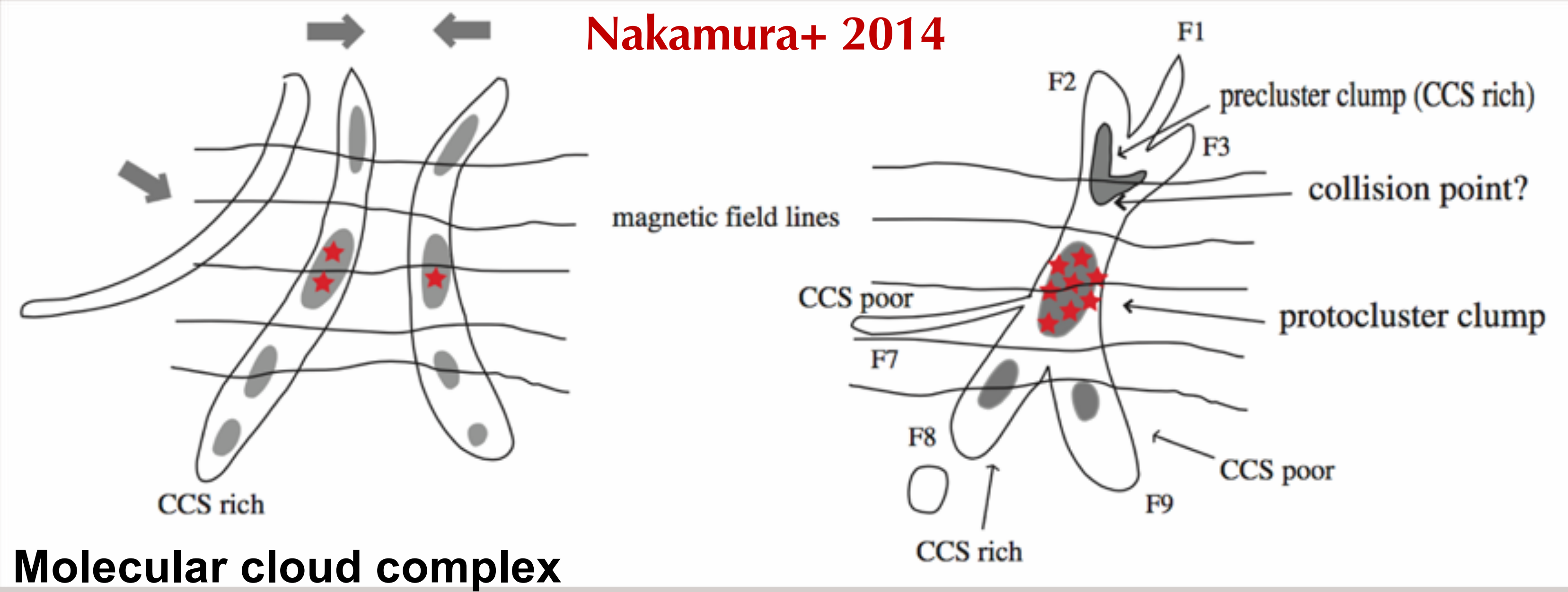
Parts of the cloud undergo global collapse, other parts disperse.

Turbulence is driven by compression and gravitational contraction.

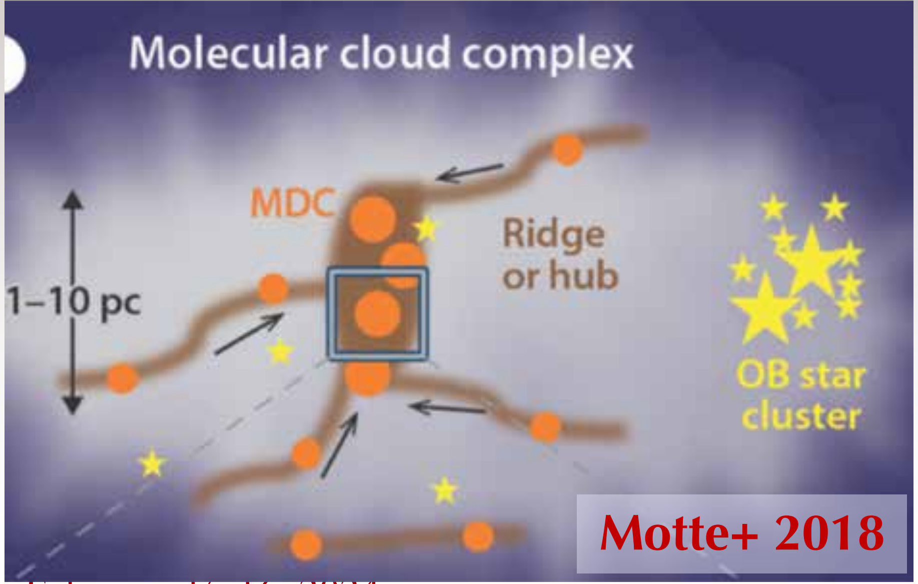


Andit & Hennebelle 2005

Dynamical picture 2: Clump-clump collision (could be associated to converging flows)



Nakamura+ 2014



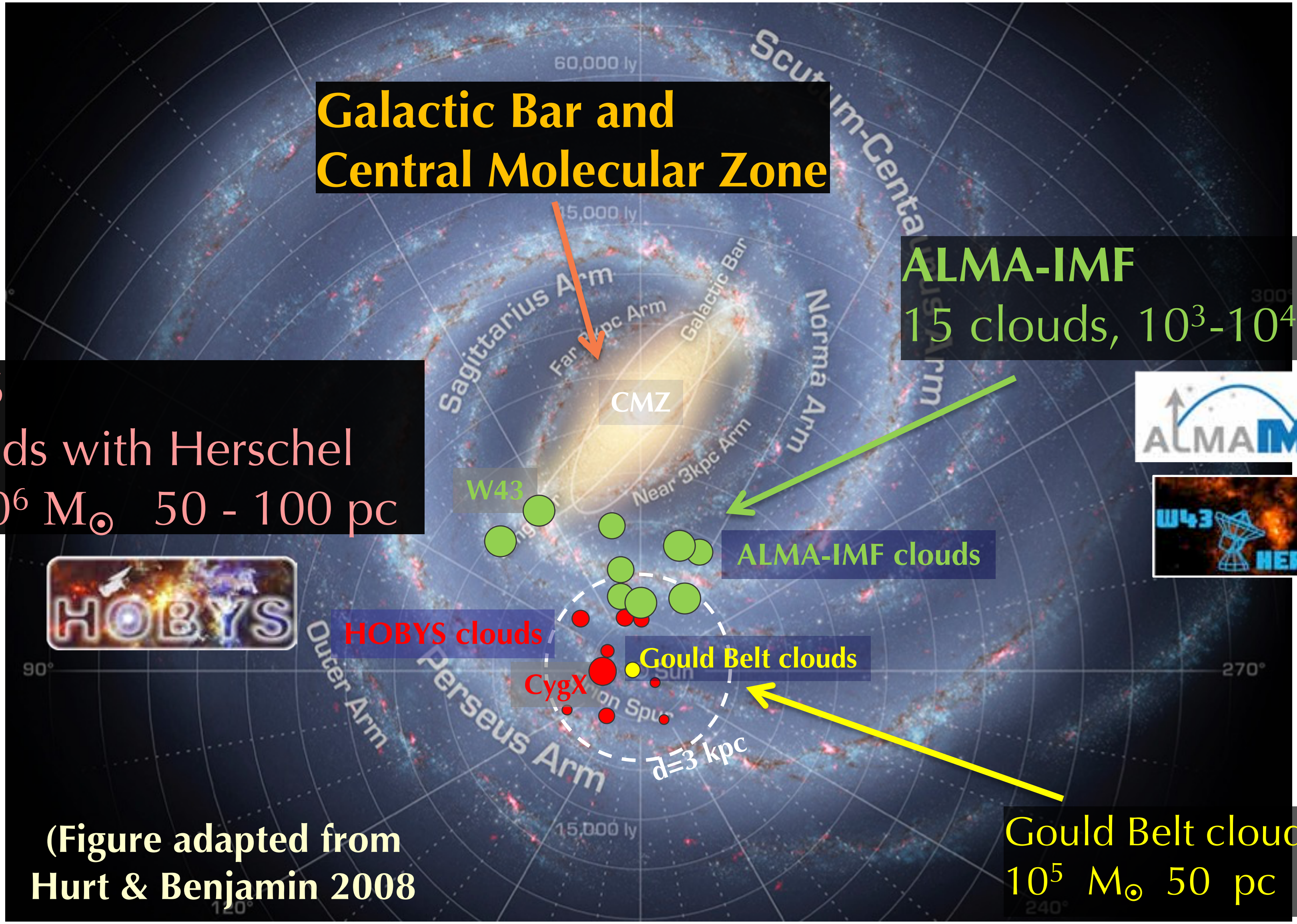
Motte+ 2018

Some clumps merge into ridges/hubs, filaments continuously feed them.

Ridges undergo global collapse.

They form mini-starburst clusters (high SFE over a few 10^5 yrs)

Cloud diversity: local clouds, clouds in the closest MW arms, at the tip of the Galactic bar and in the CMZ



Galactic Bar and Central Molecular Zone

ALMA-IMF
15 clouds, 10^3-10^4 $M_\odot$ 1 pc

HOBYS
10 clouds with Herschel
10^5 - 10^6 $M_\odot$ 50 - 100 pc

Gould Belt clouds:
10^5 $M_\odot$ 50 pc

(Figure adapted from Hurt & Benjamin 2008

Summary of Lecture 1

Cores are assumed to be the direct progenitors of stars

Observationally, they are gravitationally bound small-scale (0.02-0.1 pc) fragments.

Their SED peaks in the FIR wavelength domain.

Prestellar cores, on the verge of collapse, evolve into protostars.

Caveats: Cores form in multi-fractal clouds, which may be traversed by hierarchical inflowing gas.

QUESTIONS!

Two opposing scenarios for cloud and star formation

Quasi-static versus dynamical formation of clouds and stars: a good example of a paradigm change!

YOUR OPINION!

Who thinks the quasi-static view is more probable in our MW?
Who thinks the dynamic view is more probable in our MW?

Two opposing scenarios for cloud and star formation

Quasi-static versus dynamical formation of clouds and stars: a good example of a paradigm change!

YOUR OPINION!

Who thinks the quasi-static view is more probable in our MW?
Who thinks the dynamic view is more probable in our MW?

Many arguments (HI merging, global collapse, hierarchical infows, high-density ridge) are in favor of the dynamical view.

But local clouds and more isolated clouds could be correctly described by a quasi-static model.