Sternentstehung - Star Formation

Winter term 2022/2023

Henrik Beuther, Thomas Henning, & Jonathan Henshaw

18.10 - Introduction & overview (Beuther)
25.10 - Physical processes I (Beuther)
08.11 - Physical processes II (Beuther)
15.11 - Molecular clouds I: the birth places of stars (Henshaw)
22.11 - Molecular clouds II: Jeans analysis (Henshaw)
29.11 - Collapse models I (Beuther)
06.12 - Collapse models II (Henning)
13.12 - Protostellar evolution (Beuther)
20.12 - Pre-main sequence evolution & outflows/jets (Beuther)
10.01 - Accretion disks I (Henning)
17.01 - Accretion disks II (Henning)
24.01 - High-mass star formation, clusters & the IMF (Henshaw)
31.01 - Extragalactic star formation (Henning)
07.02 - Planetarium @ HdA, outlook, questions
13.02 - Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

More information and the current lecture files: https://www2.mpia-hd.mpg.de/homes/beuther/lecture_ws2223.html
beuther@mpia.de, henning@mpia.de, henshaw@mpia.de

Announcement

- Whoever wants to get credit points and by that an examination at the end of the coarse should please send us an email telling us that. (beuther@mpia.de)

- The examinations should then be at the end of the term, some time in March, so that everything is done by the end of March.

Today's lecture

Learning outcomes:

- Why are high-mass stars important?
- Why is high-mass star formation a difficult problem to solve?
- Different theories of high-mass star formation
- Observational evidence
- The IMF

Useful resources:

- Stahler & Palla 2004 - Chapters 11.4, 12, 12.5, 15
- Beuther et al., 2007 (PPV chapter on the Formation of Massive Stars)
- Tan et al., 2014 (PPVI chapter on Massive Star Formation)
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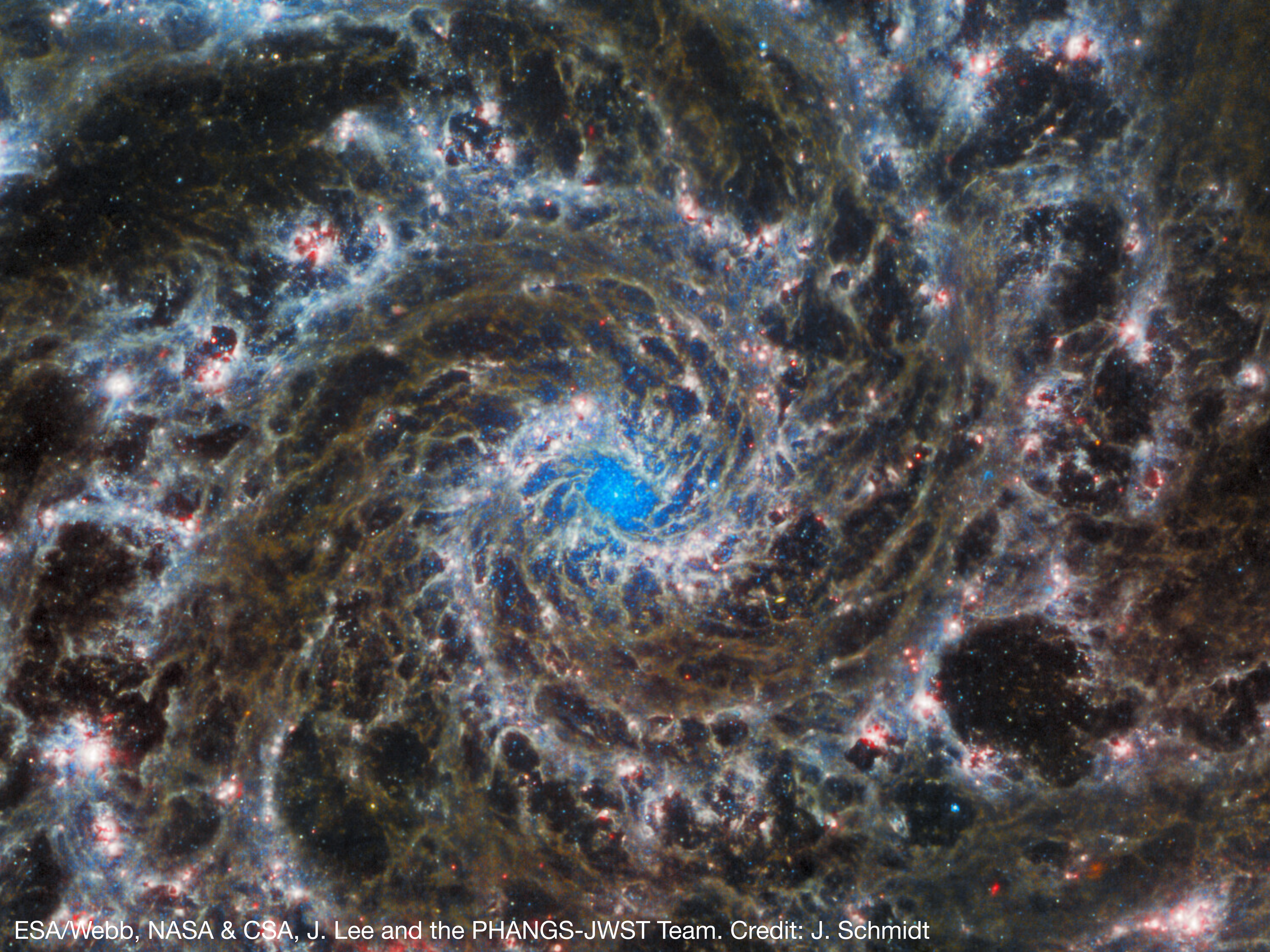
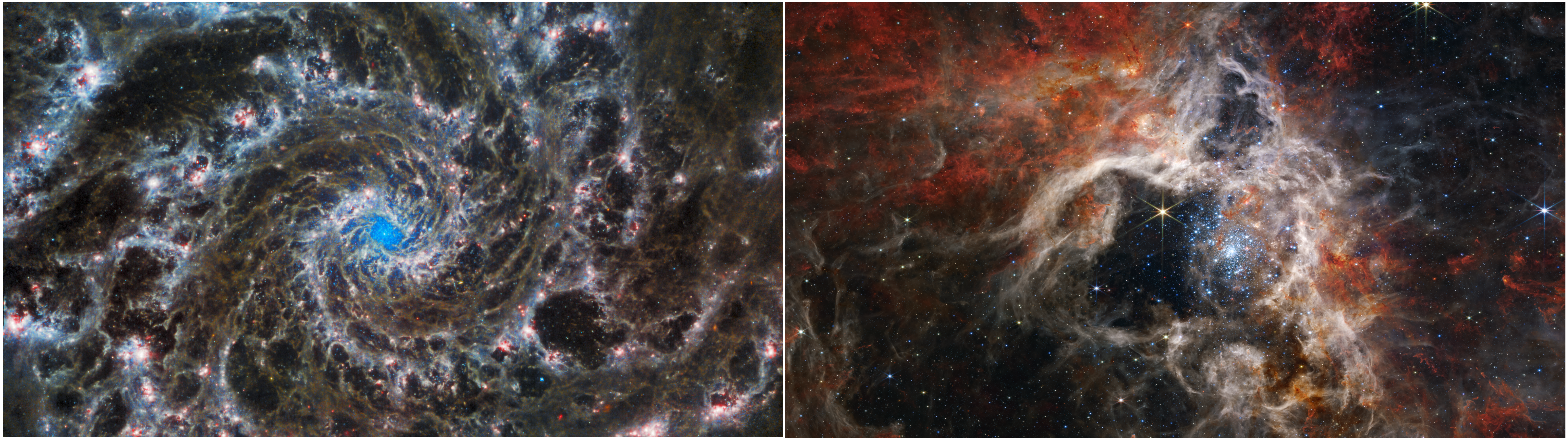


ESA/Webb, NASA & CSA, J. Lee and the PHANGS-JWST Team. Credit: J. Schmidt


IMAGE: NASA, ESA, CSA, STScI, Webb ERO Production Team

SCIENCE: NASA, ESA, CSA, STScI; IMAGE: J. DePasquale (STScI), A. Pagan (STScI), A. M. Koekemoer (STScI)

Why are high-mass stars important?



- Few in number but incredibly luminous —> $L \propto M^3$
- They inject vast amounts of energy into ISM (radiation, outflows, winds, supernovae)
- They tend to form in groups, clusters and associations — strengthens their influence on the surrounding interstellar medium
- Their "feedback" helps to sculpt the interstellar medium
- Drive galaxy evolution: produce all of the heavy elements, coordinated star bursts
- Directly influence the formation of low-mass stars

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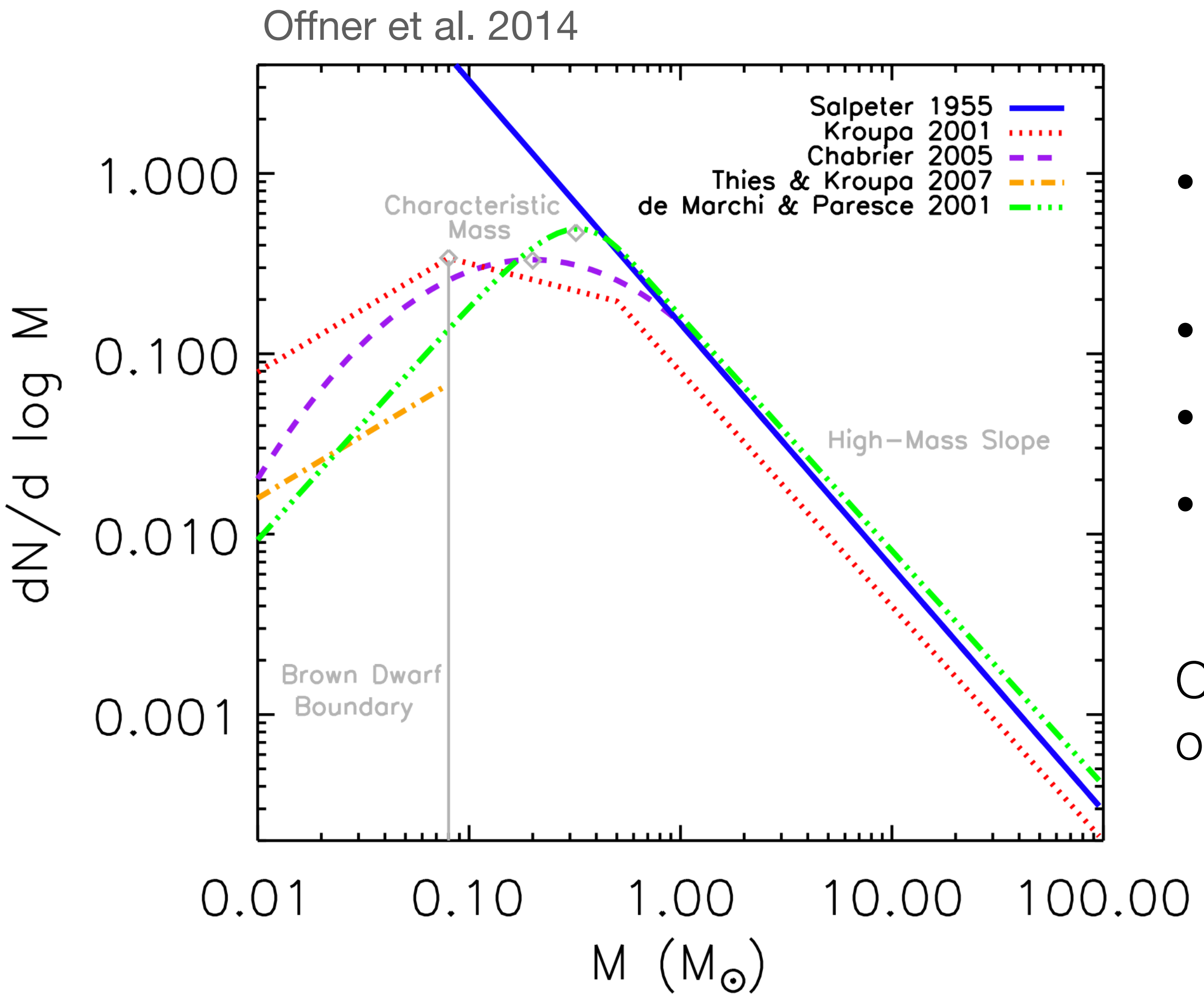
Offner et al. 2014

- High-mass stars are rare (100x 1Msun star for each 30Msun star, plus 1Msun stars live ~1000x longer)
- No observable pre-main sequence phase
- Short lives
- They tend to form in clusters

Combined these factors make it extremely challenging to observe the formation of high-mass stars

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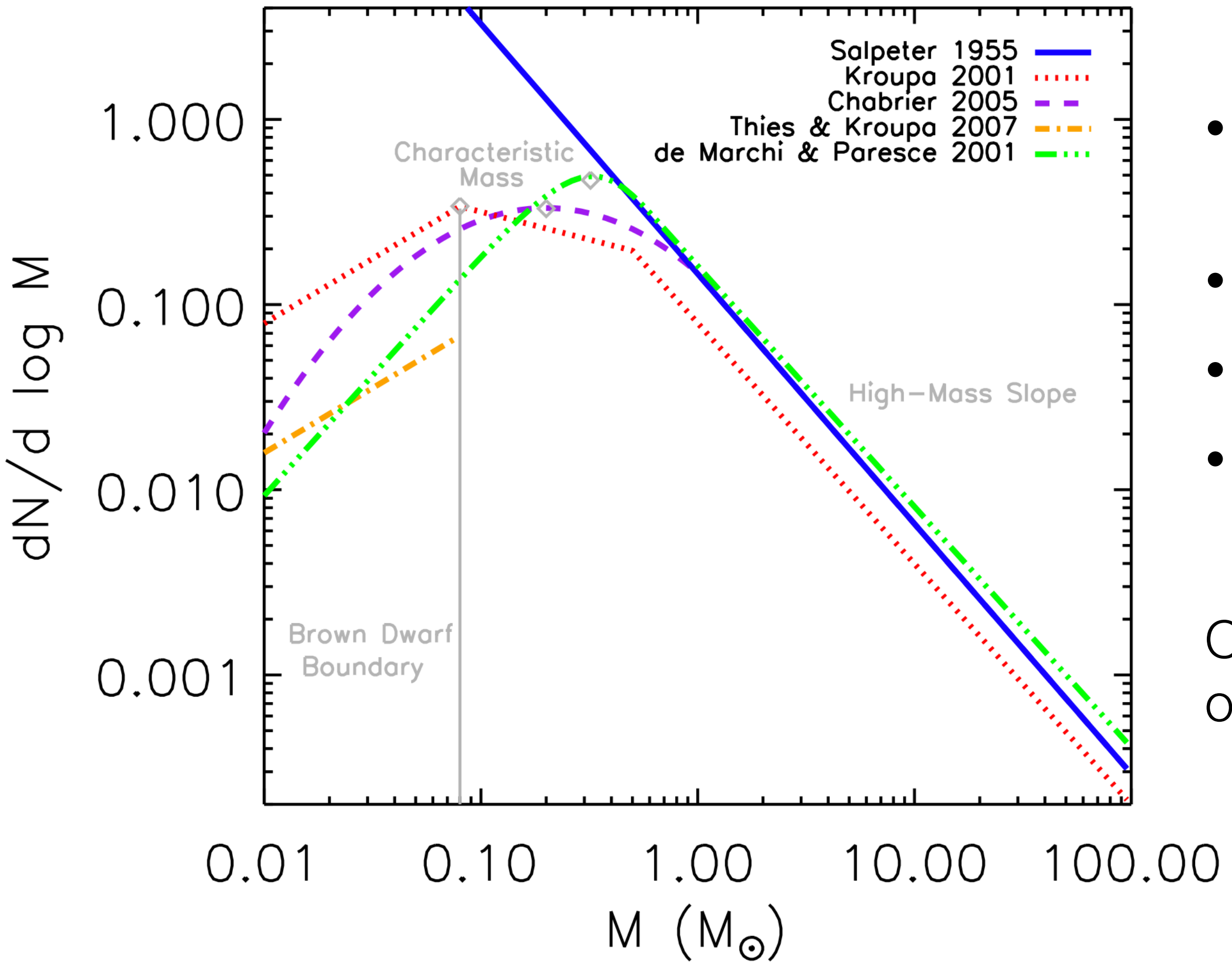

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Consider the Kelvin-Helmholz timescale (S&P04; pg. 21): The time taken to radiate away thermal energy at a given luminosity (also the total time taken to reach a stars main-sequence values of M, R, L).

$$t_{\mathrm{KH}} = \frac{GM_*^2}{R_* L_*} \sim 3 \times 10^7\,\mathrm{yrs} \left(\frac{M_*}{M_\odot}\right)^2 \left(\frac{R_*}{R_\odot}\right)^{-1} \left(\frac{L_*}{L_\odot}\right)^{-1}$$

For a star 60x Msun, this can be as short as 10000 yrs —> high-mass stars ignite before the collapse/accretion has finished —> **Live fast. Die young.**

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Radiation exerts a force on free-electrons via Thomson scattering.

$$\sigma_{\rm T} = (q^2/mc^2)^2$$

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Equating the two…

$$L_{\rm edd} = 4\pi GMc(m_p/\sigma_{\rm T}) = 4\pi GMc/\kappa \longrightarrow$$

Opacity = extinction cross section/mass

Stars with $L > L_{\rm edd} = 1.3 \times 10^{38}\,(M/M_\odot)\,{\rm erg\,s^{-1}} = 3.2 \times 10^4\,(M/M_\odot)\,L_\odot$ are not stable!

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If $L > L_{\rm edd}$ outer gas layers pushed out and star unstable if L provided by nuclear fusion

Why is high-mass star formation a difficult problem?

The accretion dilemma: What about radiation pressure on the dust cocoon surrounding a high-mass star? Again, net force can only be directed inward if:

$$\frac{L}{M} < \frac{4\pi G c}{\kappa} = 2500 \left(\frac{\kappa}{5\,\mathrm{cm}^2\,\mathrm{g}^{-1}} \right)^{-1} \frac{L_\odot}{M_\odot}$$

Dust opacity grows with radiation temperature (no single value can be used in equation above). Flow of material onto star is only maintained if accretion exceeds radiation pressure pressure at dust sublimation radius (T~1500K; kappa~10 $\mathrm{cm}^2\mathrm{g}^{-1}$).

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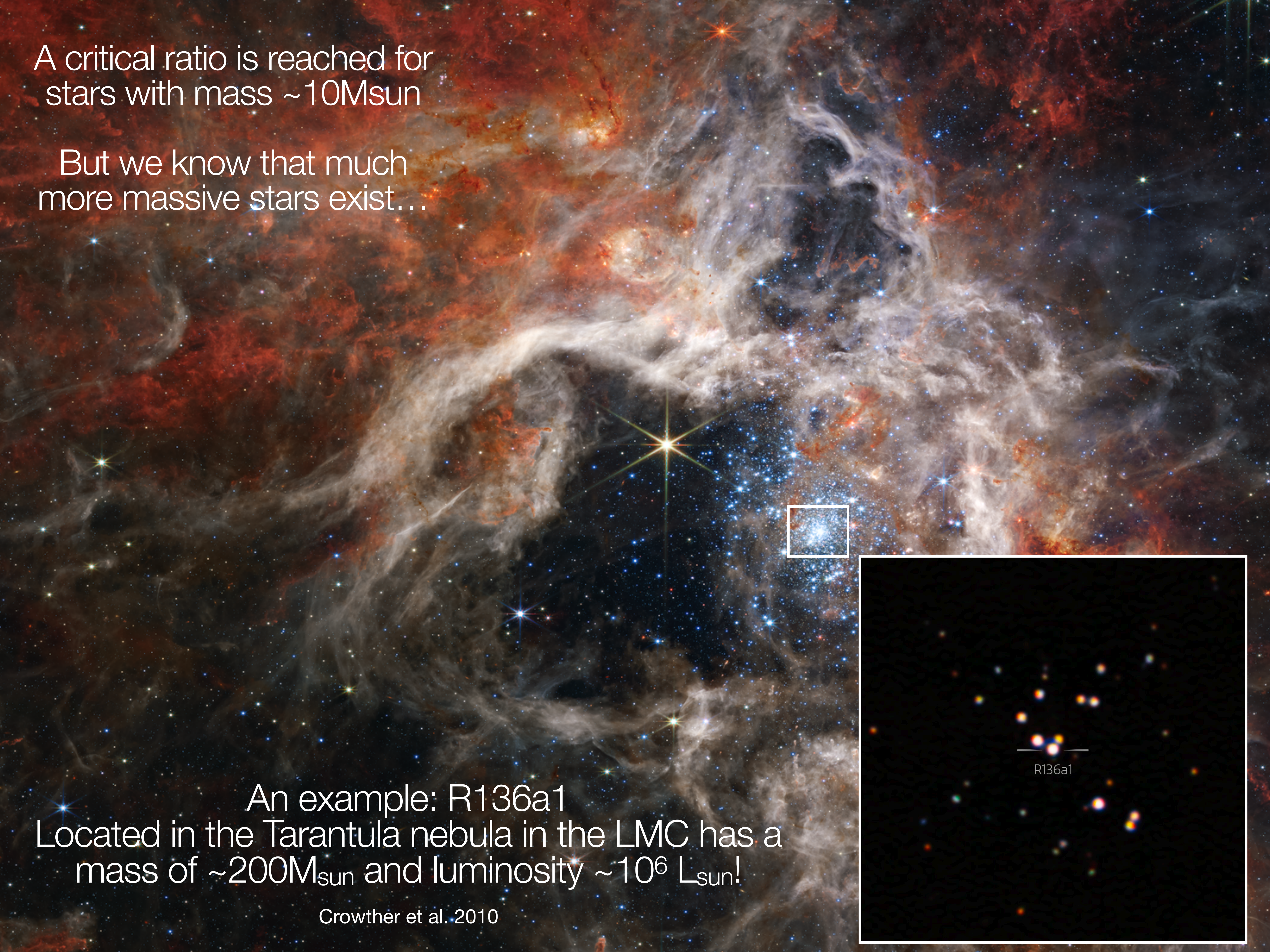
But we know that much more massive stars exist…



An example: R136a1

Located in the Tarantula nebula in the LMC has a mass of $\sim 200 M_{sun}$ and luminosity $\sim 10^{6} L_{sun}$!

Crowther et al. 2010

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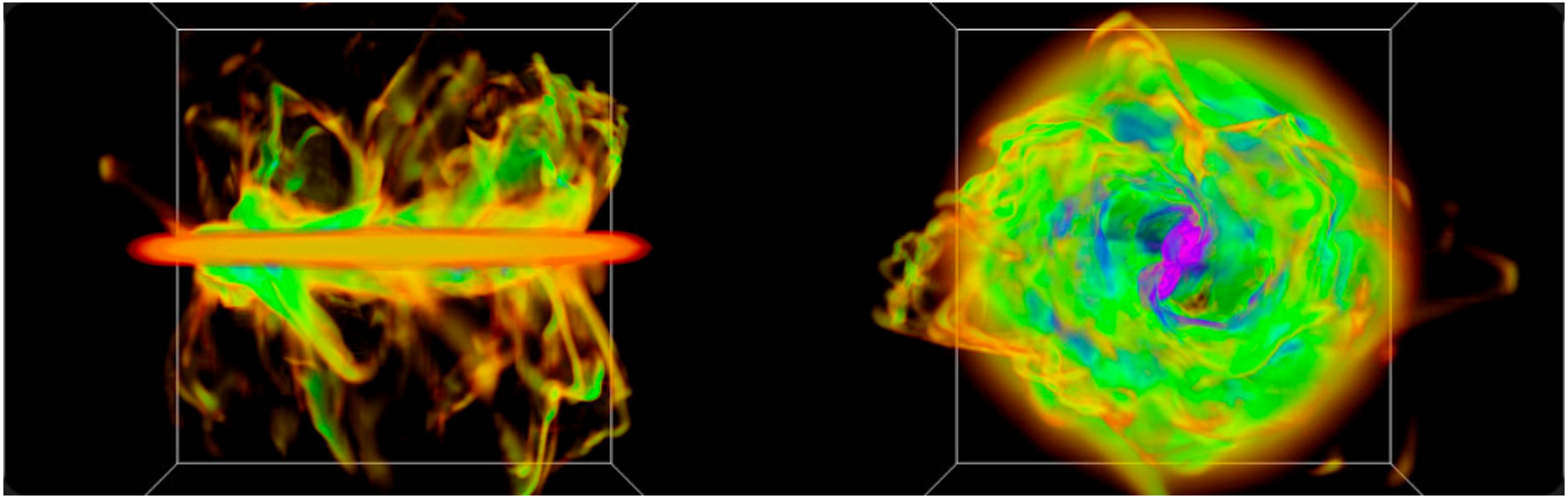
Very high-mass stars <u>do not</u> grow via spherical accretion.

Why is high-mass star formation a difficult problem?

The accretion dilemma: A solution — spherical symmetry is likely a poor approximation, and relaxing it may reduce or eliminate the accretion dilemma



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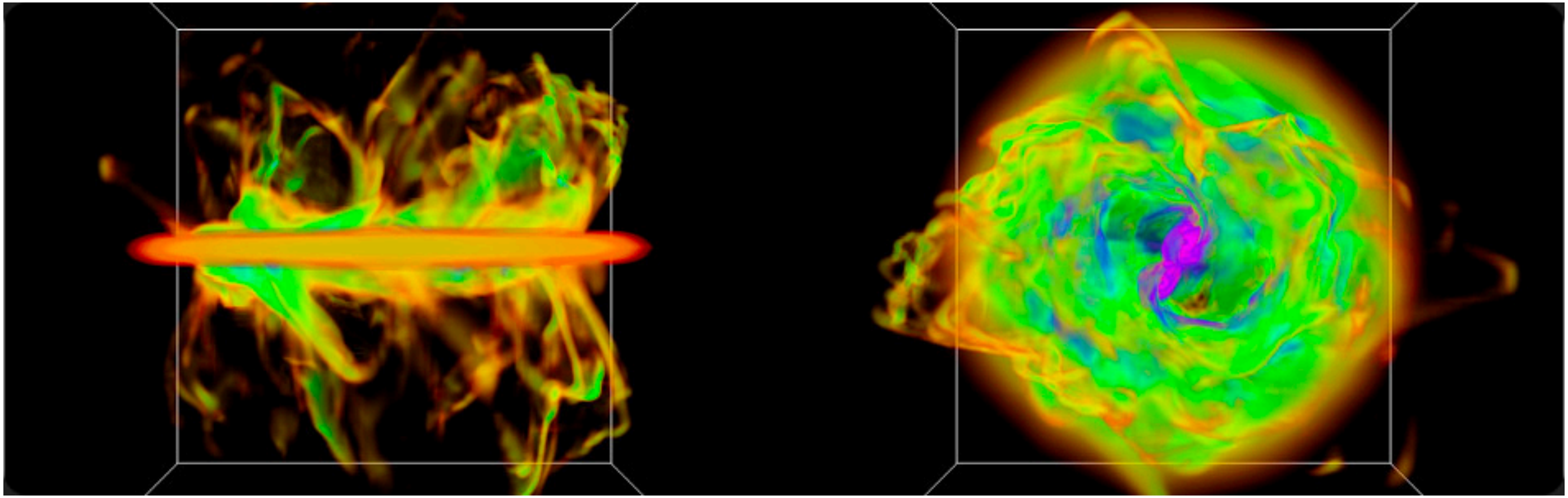

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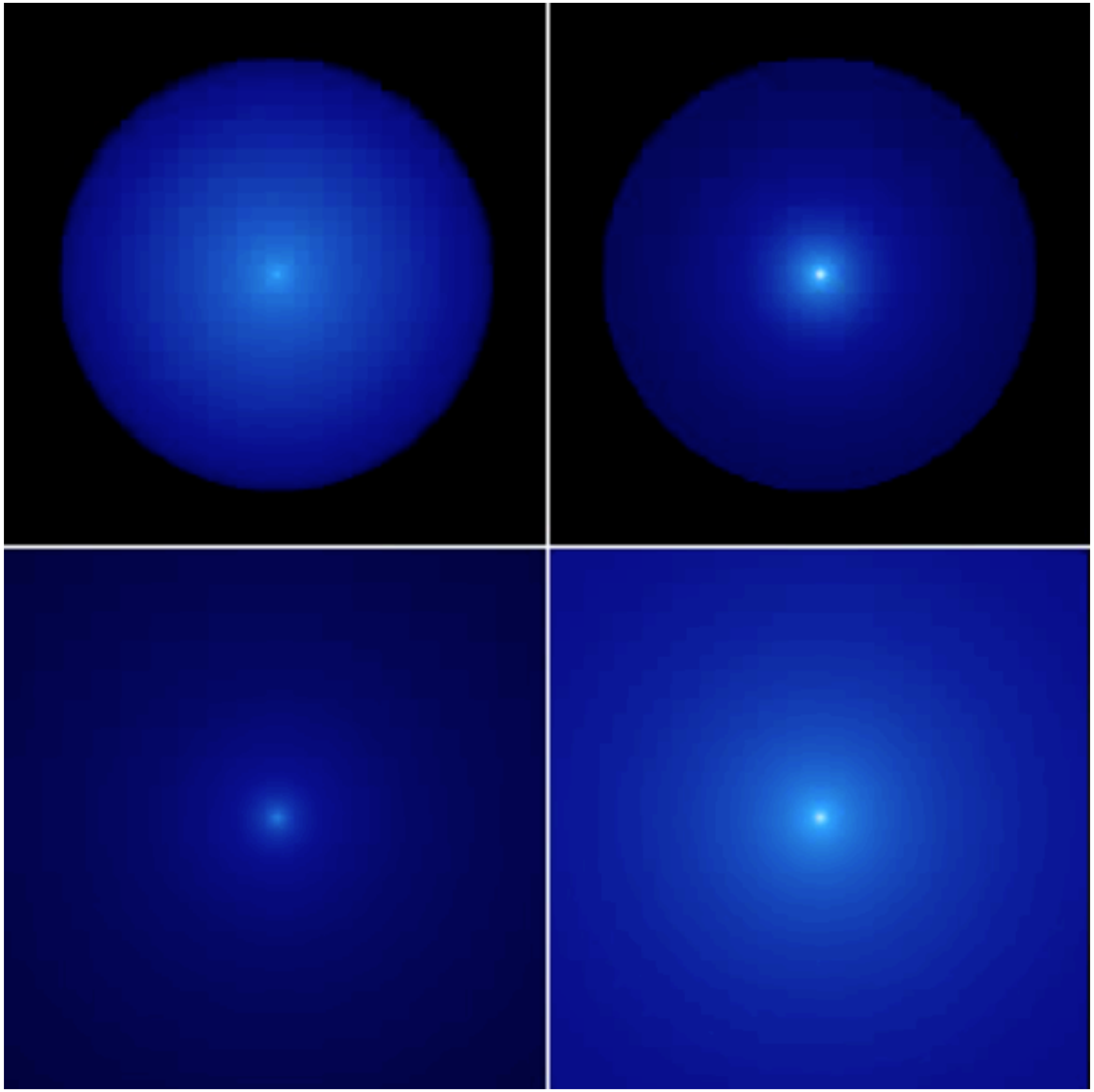
If the radiation can be beamed, then the radiation force can be weaker than gravity over a significant solid angle —> disks, outflow cavity, or any other non-spherical feature can help (more on this later)

Why is high-mass star formation a difficult problem?



Krumholz et al. 2009

- Starting with 100 to 200Msun cores.
- Until ~17Msun smooth accretion flow.
- Low angular momentum gas accretes directly on protostar, high angular momentum gas forms Keplerian accretion disk.
- From 17Msun upwards, radiation pressure starts driving out gas, bubbles form. Further infalling gas moves along the bubble walls and falls onto disk.
- Disk gravitationally unstable forming more stars.
- Stars produced are 41.5Msun and 29.2Msun

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Why is high-mass star formation a difficult problem?

The fragmentation dilemma: Recall that when gravitationally unstable media collapse, they tend to produce objects with a characteristic mass comparable to the Jeans mass

$$M_J = \frac{\pi^{5/2}}{6}\frac{c_s^3}{\rho_0^{1/2}G^{3/2}} = 1.0\left(\frac{T}{10\,\mathrm{K}}\right)^{3/2}\left(\frac{n_{\mathrm{H}_2}}{10^4\,\mathrm{cm}^{-3}}\right)^{-1/2}\mathrm{M}_\odot$$

A high-mass star is an object whose mass is far larger than the Jeans mass of the interstellar gas from which it is forming. **Why, then does this gas not fragment into multiple small stars rather than forming a single large one?**

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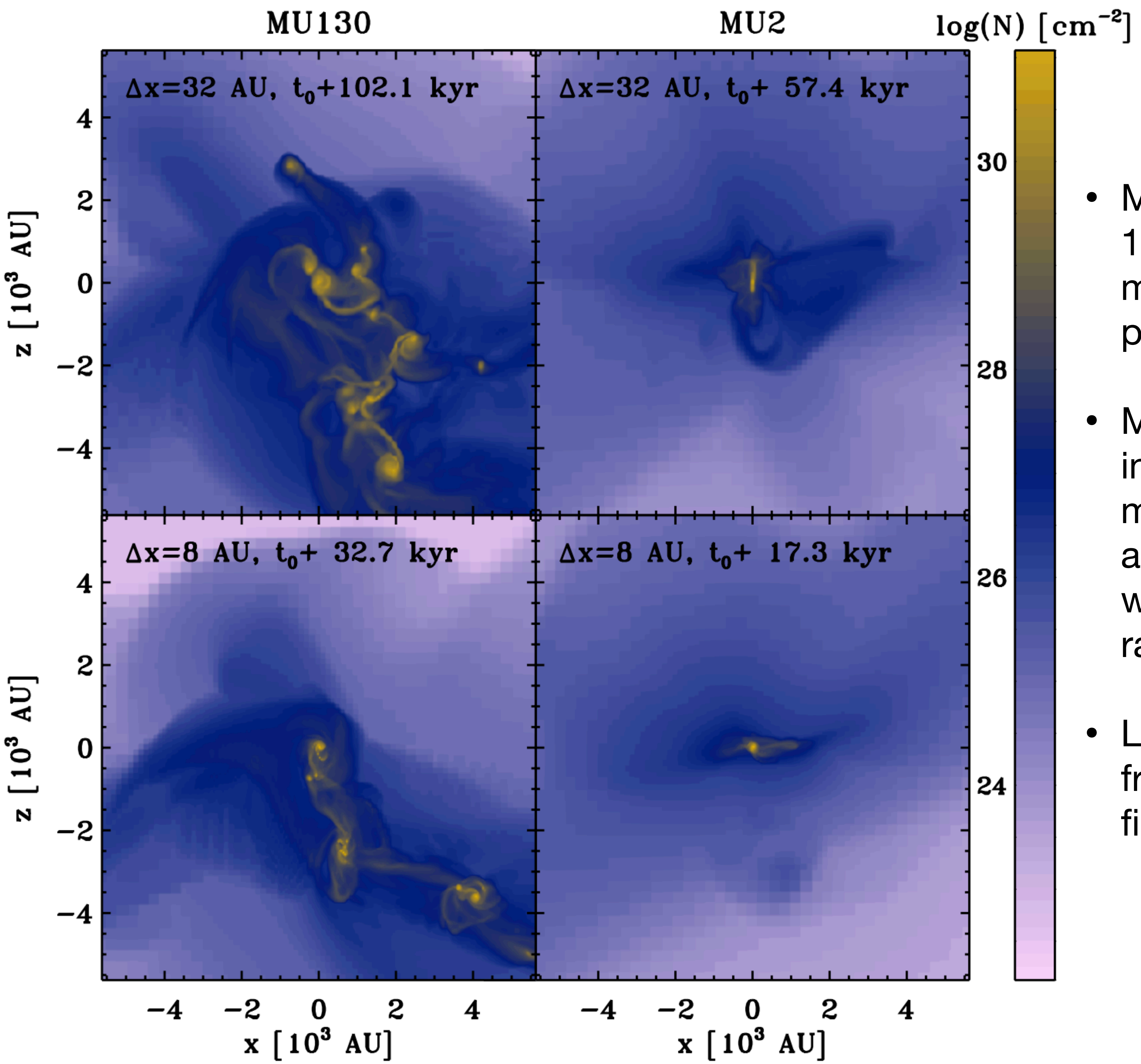
Possible solutions:

1. Radiation feedback
2. Magnetic fields

Why is high-mass star formation a difficult problem?



Commercon et al. 2011

- Magnetic fields reduce fragmentation by: 1) removing angular momentum due to magnetic braking; 2) providing extra pressure support
- Magnetic braking channels material inwards towards star (angular momentum outwards), this raises the accretion rate and hence luminosity which increases the importance of radiation feedback
- Left: weak magnetic field favouring fragmentation; right: strong magnetic field suppressing fragmentation

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Different theories of HMSF

See Tan et al. 2014, Krumholz et al. 2014, Bonnell et al. 2007, Beuther et al. 2007, Motte et al. 2018, Vazquez-Semadeni et al. 2019, Padoan et al. 2020

How do we build the high-mass end of the stellar initial mass function?

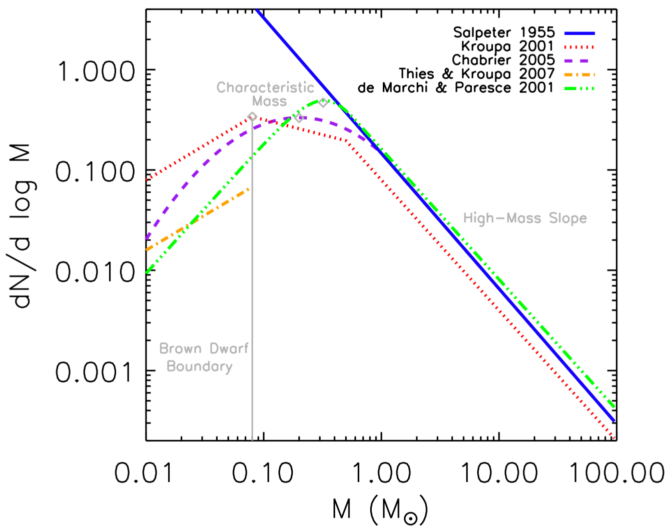
Accretion models

Modified low-mass SF:
Core Accretion

Competitive Accretion

Global Hierarchical Collapse

Inertial flow



Merger or collision models

Gas accretion-driven

Gas free-collision models

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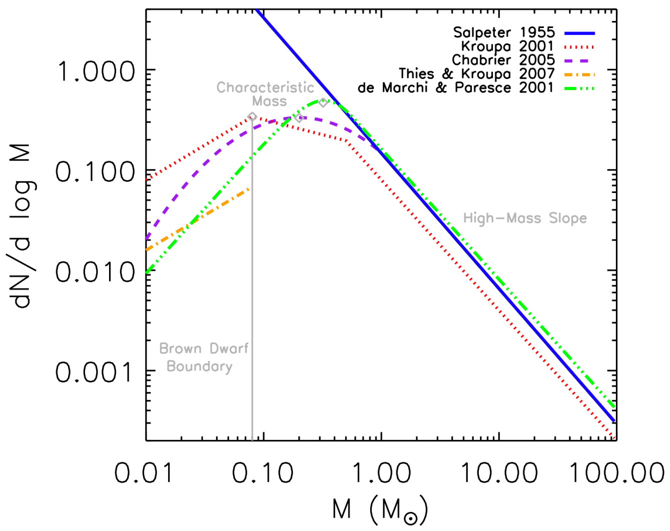

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Each of these models makes different predictions about how high-mass stars are assembled from interstellar gas, some of which are mutually exclusive and lead to differences in the assembly of the IMF.

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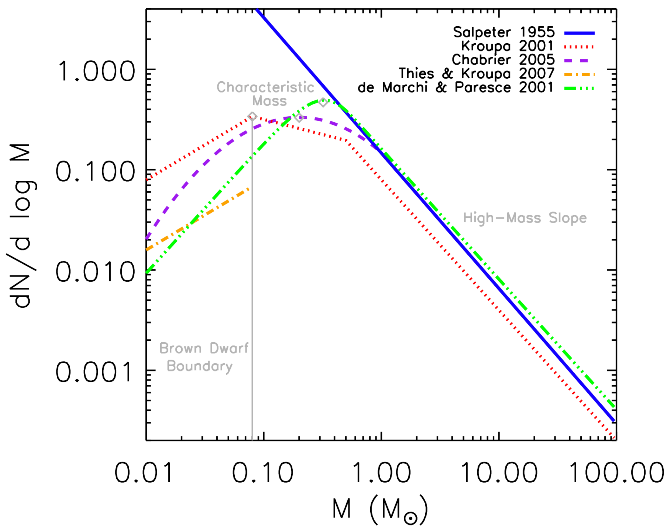

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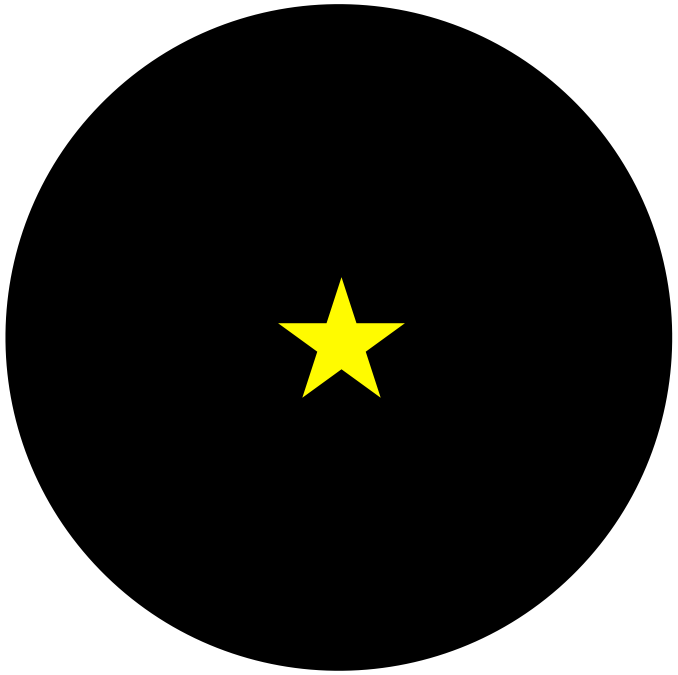
Core Accretion (monolithic collapse)

McKee & Tan 2002, 2003



Different theories of HMSF

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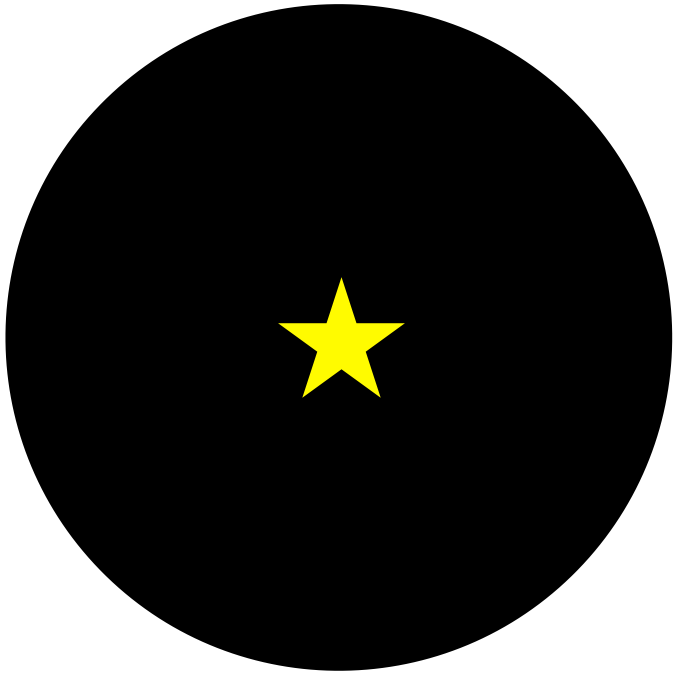
Initial Conditions:

- Self-gravitating, centrally condensed starless cores of gas that condense with a range of masses from a fragmenting clump.
- Internal pressure is mostly non-thermal, in the form of turbulence or magnetic fields.
- The core is reasonably close to virial equilibrium.
- The mass that will eventually end up in the star comes directly from the core



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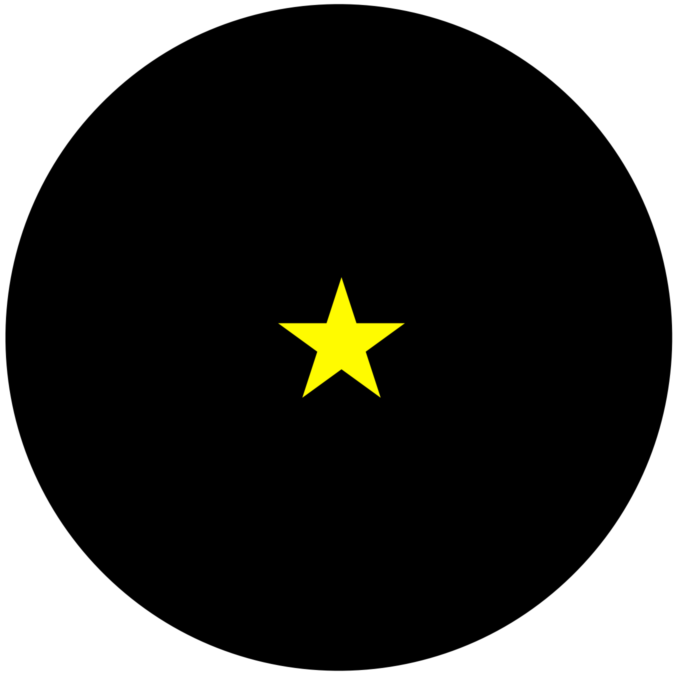

Details

- Core embedded in high-pressure environment. Acc. rate increases
- Accretion rate (through a disc):

$$\dot{m}_* \approx 0.5 \times 10^{-3}\,\mathrm{M_\odot\,yr^{-1}} \left(\frac{m_{*f}}{30\,\mathrm{M_\odot}}\right)^{3/4} \Sigma_{\mathrm{cl}}^{3/4} \left(\frac{m_*}{m_{*f}}\right)^{1/2}$$

- Time for formation:

$$t \sim 1.3 \times 10^{5}\,\mathrm{yr} \left(\frac{m_{*f}}{30\,\mathrm{M_\odot}}\right)^{1/4} \Sigma_{\mathrm{cl}}^{-3/4}$$

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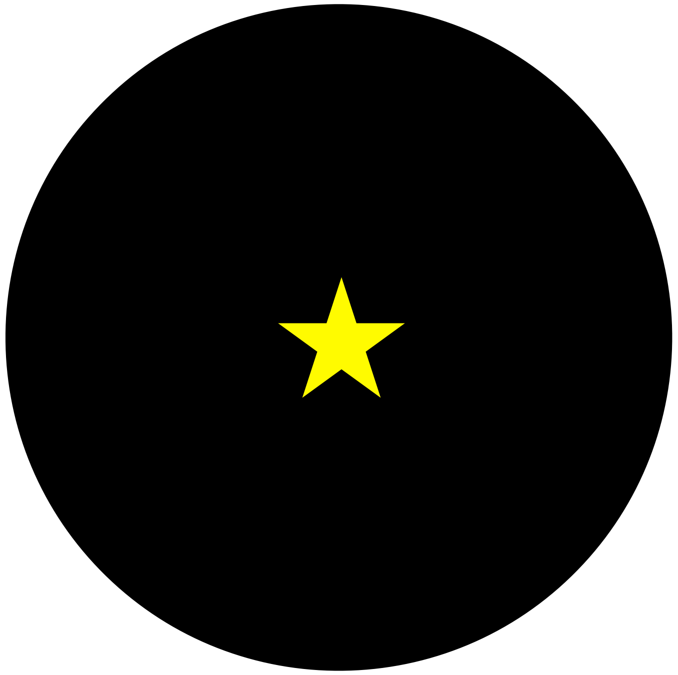

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Potential problems/caveats and predictions

- Predicts the existence of massive starless cores - candidates exist but very few. Rapid evolution? Rare?
- A direct mapping of the CMF to the IMF (more on this later)
- Direct mapping has significant implications: e.g. requires that all cores have the same star formation efficiency
- Fragmentation must be suppressed - earlier discussion on fragmentation - magnetic fields important?
- Suggests relatively massive discs

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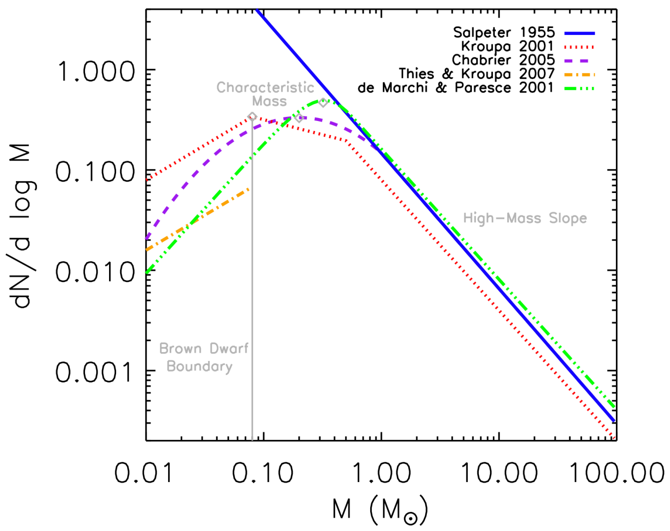

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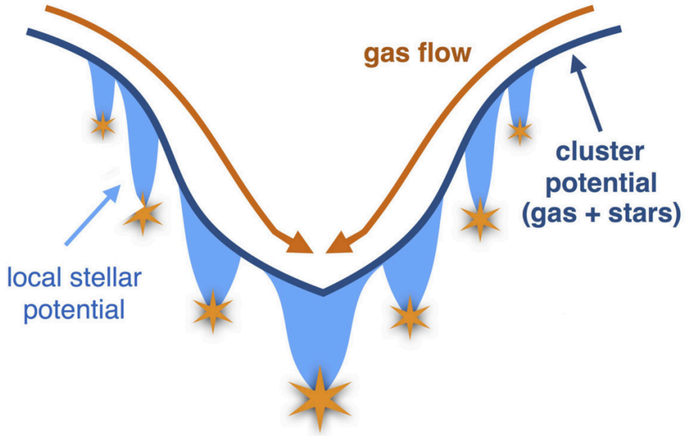
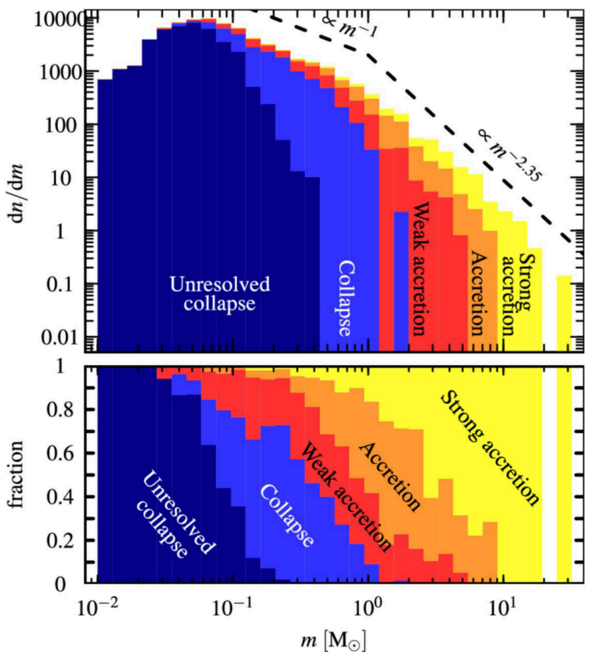
Competitive Accretion

Bonnell et al., 1998, 2004, 2007, Image courtesy of Paul Clark





Different theories of HMSF

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Initial Conditions:

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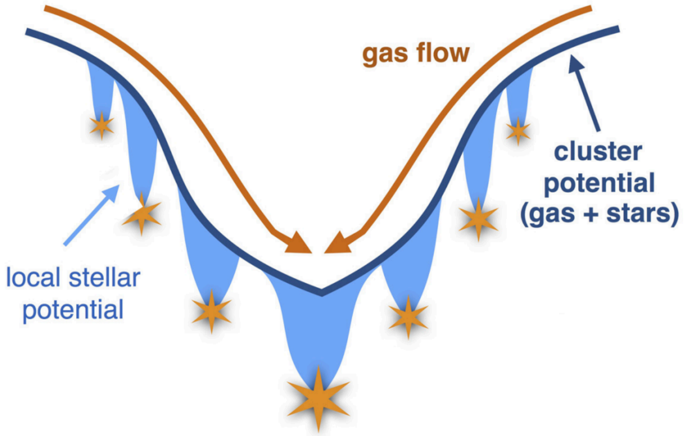

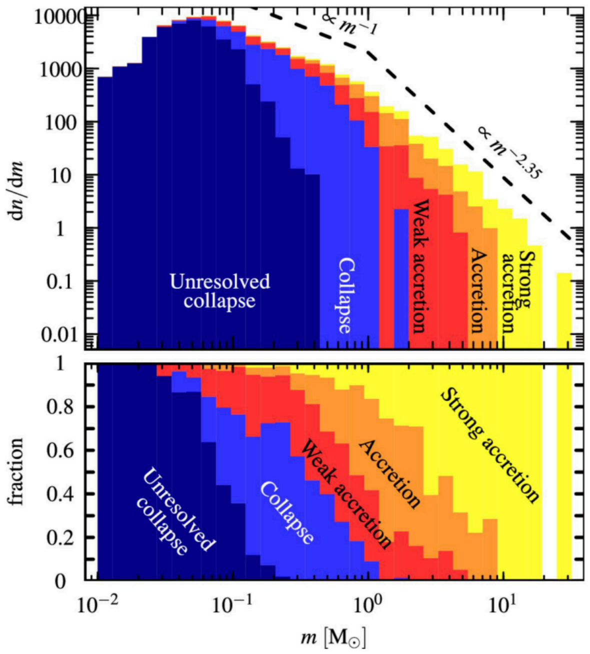

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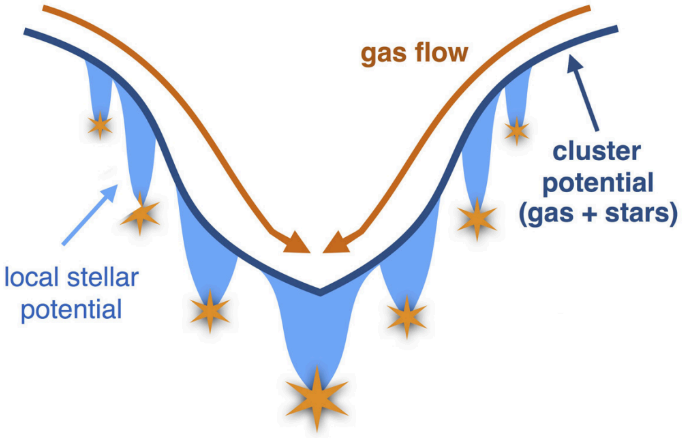

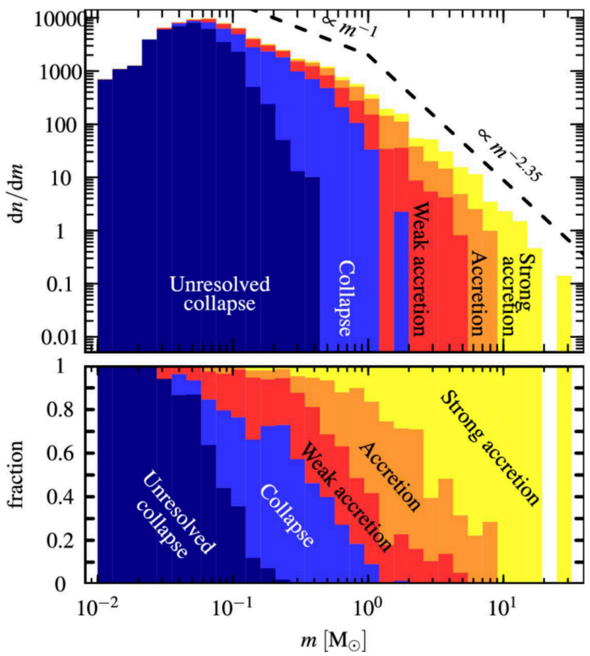

Details

- Stars forming deepest in the potential well accrete more - the rich get richer.
- Accretion rate depends local gas density, the mass of the star and the relative velocity between the gas and the star:

$$\dot{m}_* = \pi \rho_{\rm cl} v_{\rm rel} r_{\rm acc}^2$$

- Average accretion rate of a star

$$\langle \dot{m}_* \rangle \approx 1.5 \times 10^{-5}\,{\rm M_\odot\,yr^{-1}} \left(\frac{\epsilon_{\rm ff}}{0.1}\right)\left(\frac{\epsilon_{\rm cl}}{0.5}\right)^{-1}\left(\frac{m_{*f}}{50\,{\rm M_\odot}}\right)\Sigma_{\rm cl}^{3/4} M_{\rm cl}^{-1/4}$$

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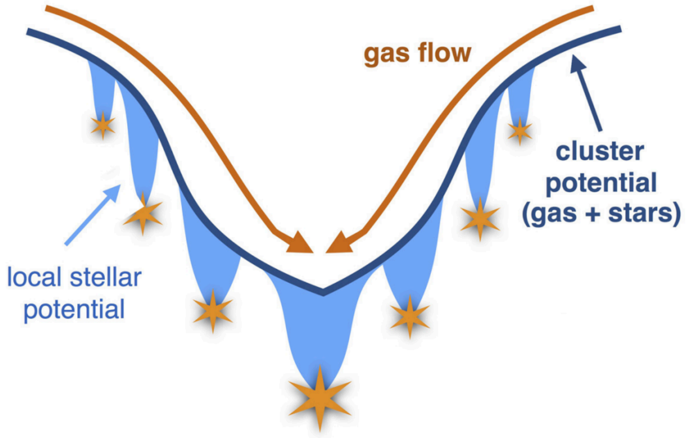

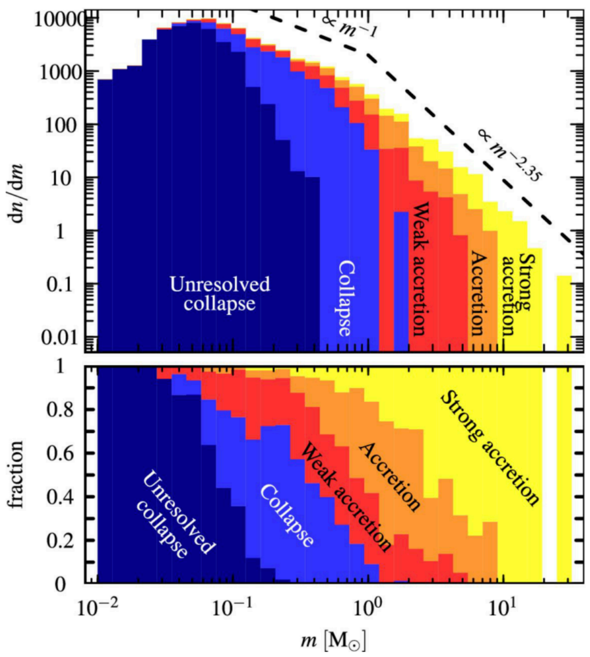

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Potential problems/caveats and predictions

- No high-mass prestellar core phase
- Requires bound collapsing clouds to reproduce the IMF
- Because there is no relation between initial core mass and final star mass, no mapping between CMF and IMF
- Massive stars always form at the centres of clusters
- Relatively small accretion discs, with chaotically varying orientations, reflected in outflow direction

Different theories of HMSF

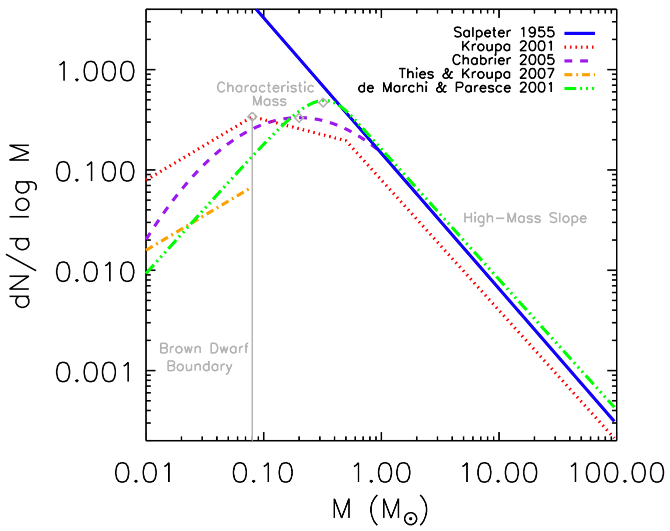
Accretion models

Modified low-mass SF:
Core Accretion

Competitive Accretion

Global Hierarchical Collapse

Inertial flow



Merger or collision models

Gas accretion-driven

Gas free-collision models

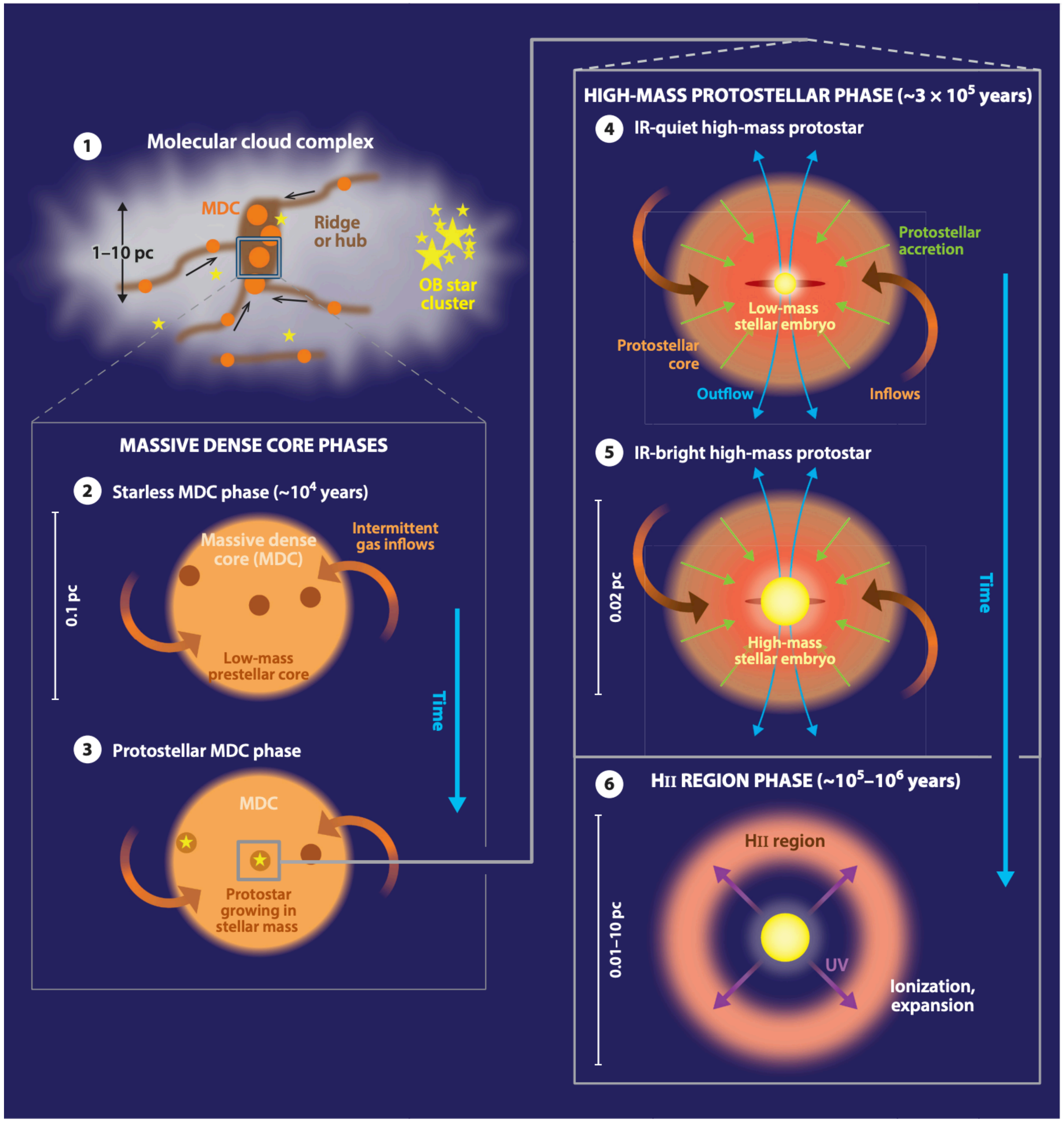
Different theories of HMSF

Global Hierarchical Collapse & Intertial Flow models

Vazquez-Semadeni et al. 2019, Padoan et al. 2020

Important note here: These are NOT the same thing and have important quantitative differences. However, they are qualitatively similar.

Motte et al. 2018



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- Both models seek to describe the hierarchical evolution of molecular clouds: mol. cloud —> filament —> clump —> core —> star.
- Neither model predicts the existence of starless high-mass, gravitationally bound cores in virial equilibrium. Instead, both models favour the view that the mass that ends up in the star can originate far away from the star.
- Key difference is in what drives the formation and evolution of structure:

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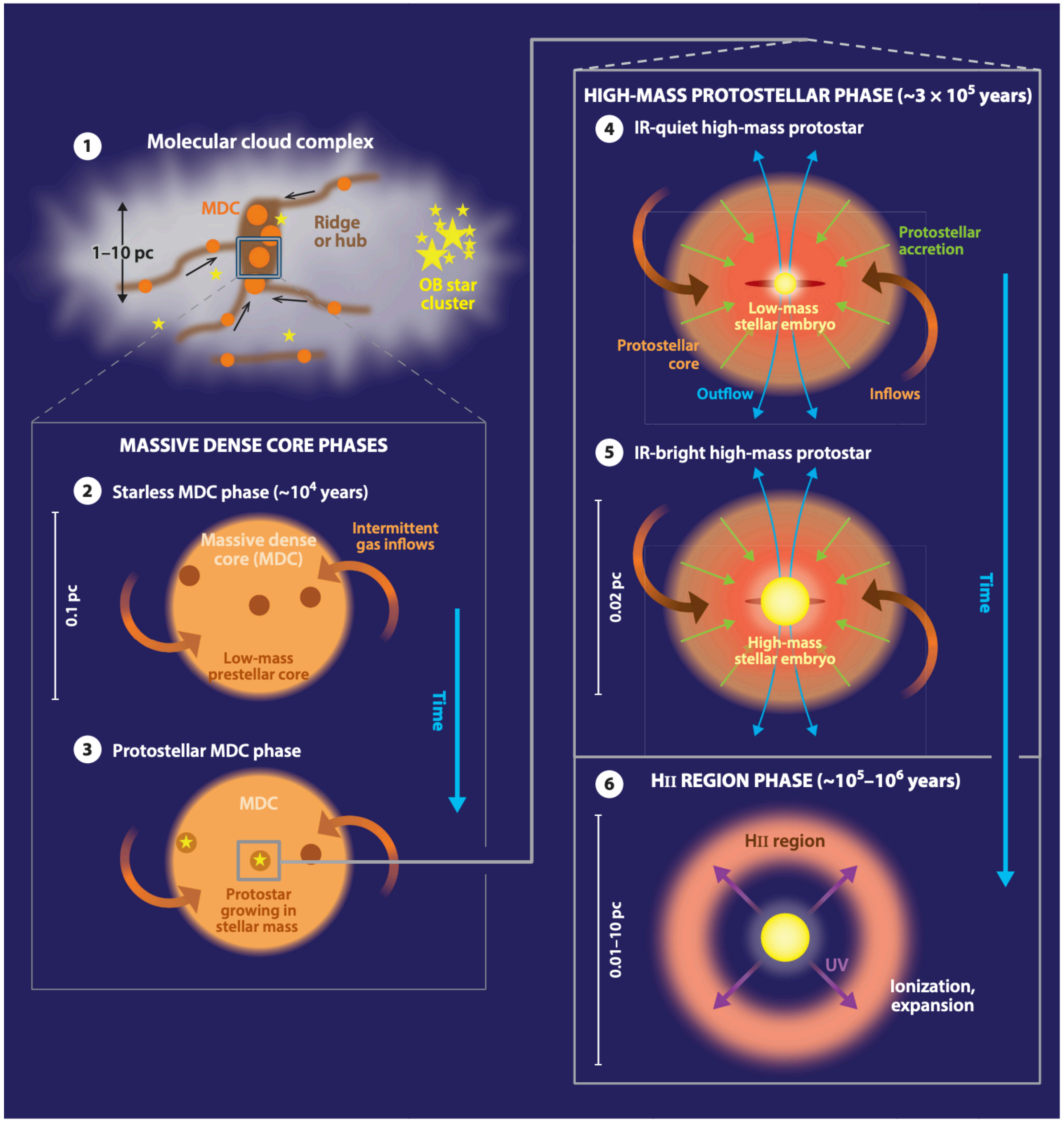

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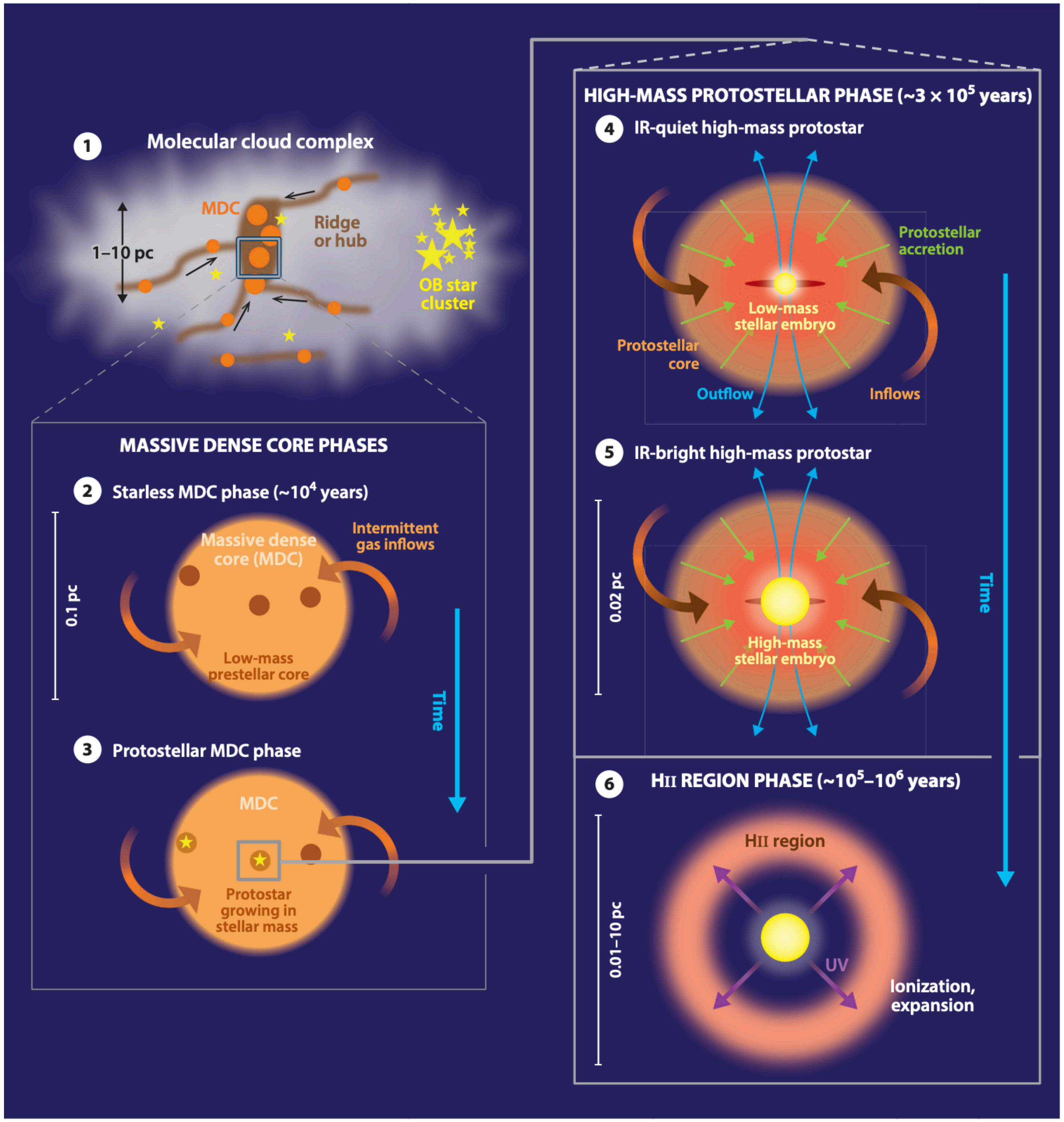

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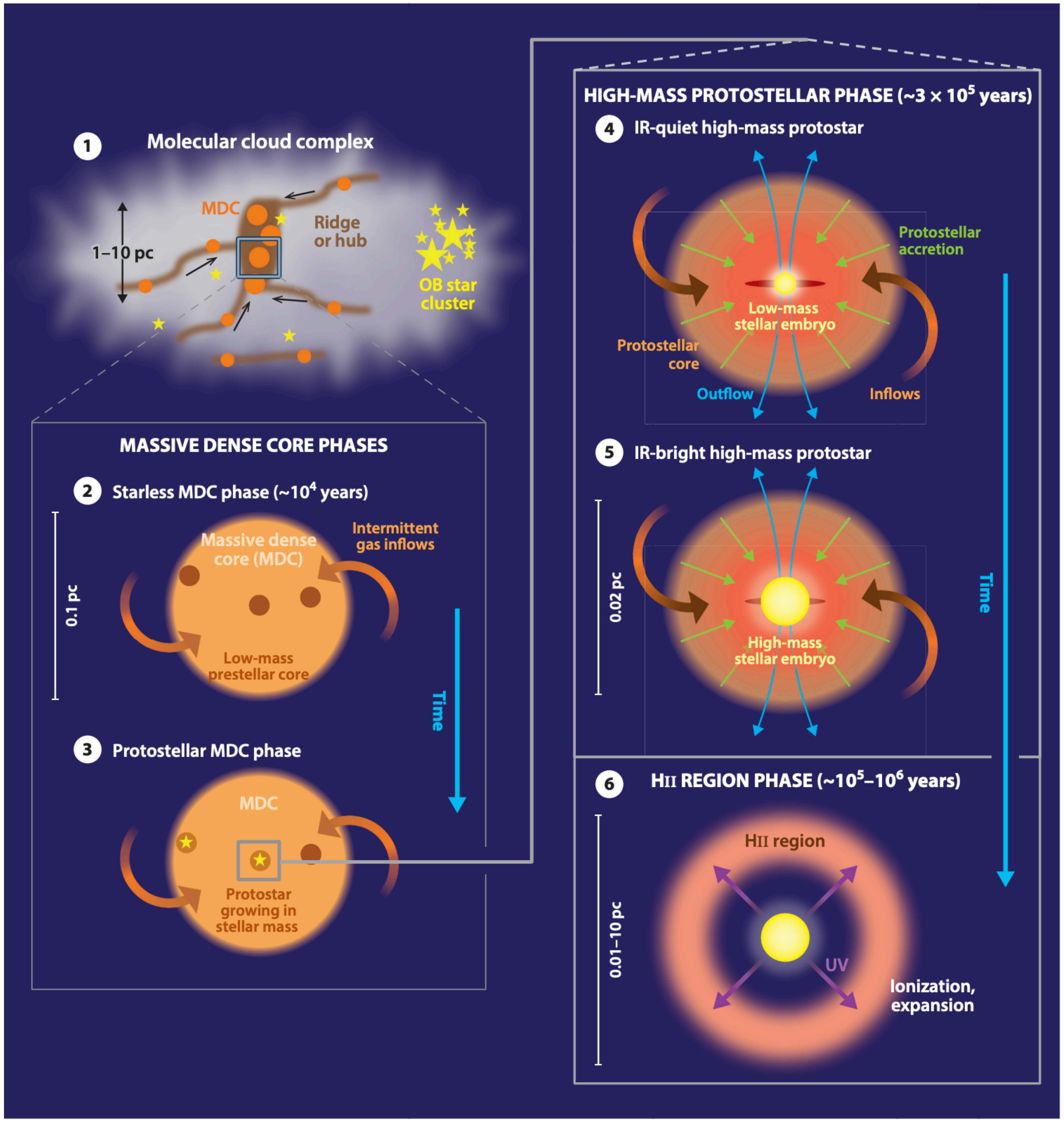
- Key difference is in what drives the formation and evolution of structure:
- In GHC, gravity dominates all scales, filaments are like rivers flowing towards collapsing cores. GHC locally consistent with competitive accretion.
- IF is distinct from core accretion and competitive accretion. Here turbulence is king. Forming filaments, stars form where multiple filaments intersect, but the flow towards smaller scales is driven by (convergent) turbulent flows - gravity only dominates on the smallest scales

Motte et al. 2018



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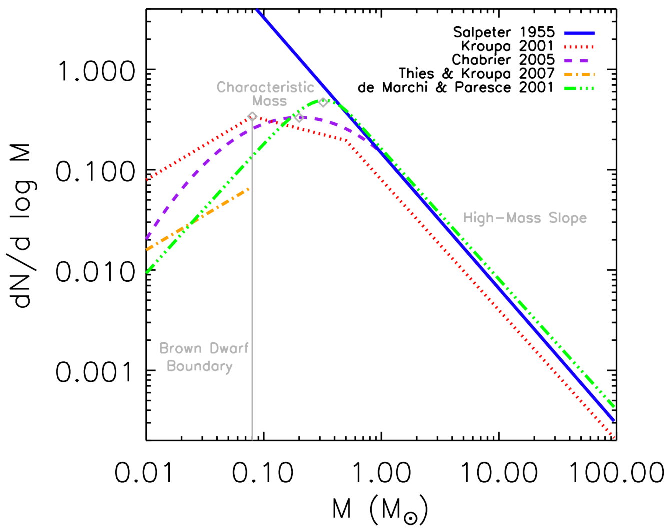

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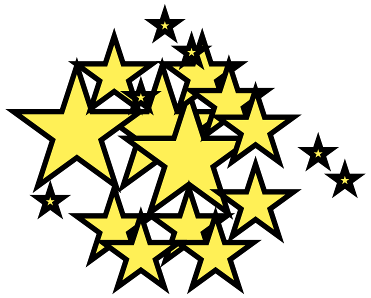
Different theories of HMSF

Coalescence

Bonnell et al. 1998, Portegies Zwart et al. 1999, Bally & Zinnecker 2005



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Initial Conditions:

- In gas-rich clusters - stars accrete gas, reduces total gas plus stellar kinetic energy - system contracts increasing density
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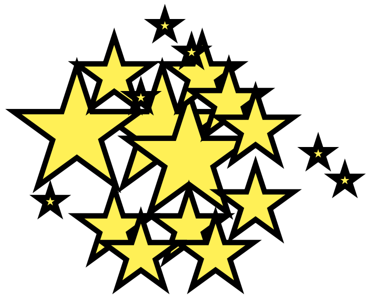
- Stellar densities of 10^6-10^8 stars pc^{-3}



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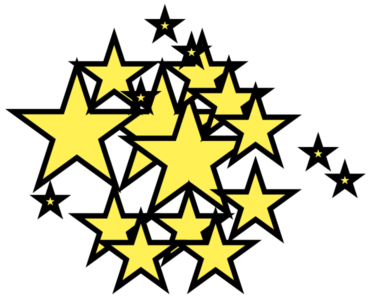

Details

- Cluster cores can puff up (two-body relaxation) faster than they can shrink (energy dissipation) - this depends on the cluster mass - puts a limit on the density that can be reached - rendering collisions unimportant in low-mass clusters
- Collision time needs to be shorter than the lifetime of high-mass stars to be effective - primordial mass segregation
- Depends on the physics of stellar collisions - models generally assume that mass loss during the collision is negligible

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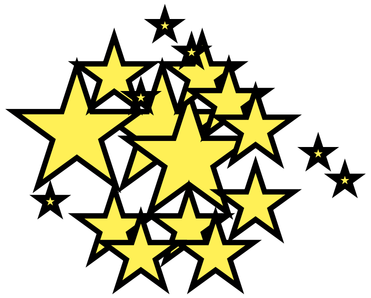

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Potential problems/caveats and predictions

- Requires very high stellar densities
- Orion Nebula Cluster contains a star of ~38 Msun - stars of at least this mass can form without collisions
- General tension with observations - known massive clusters in the Galaxy are insufficiently dense for the effect to be important
- Impacts the IMF - can produce an IMF that is under-populated between 10-100Msun and an over-population at very high masses due to collisions
- Problematic for outflows, jets, discs?

Different theories of HMSF

See Tan et al. 2014, Krumholz et al. 2014, Bonnell et al. 2007, Beuther et al. 2007, Motte et al. 2018, Vazquez-Semadeni et al. 2019, Padoan et al. 2020

How do we build the high-mass end of the stellar initial mass function?

Accretion models

Modified low-mass SF:
Core Accretion

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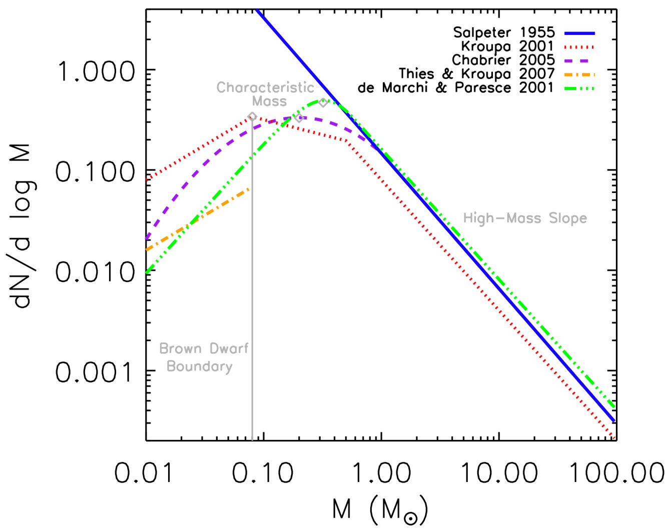

Merger or collision models

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This remains an open question.

Today’s lecture

Learning outcomes:

- Why are high-mass stars important?
- Why is high-mass star formation a difficult problem to solve?
- Different theories of high-mass star formation
- **Observational evidence**
- The IMF

Useful resources:

- Stahler & Palla 2004 - Chapters 11.4, 12, 12.5, 15
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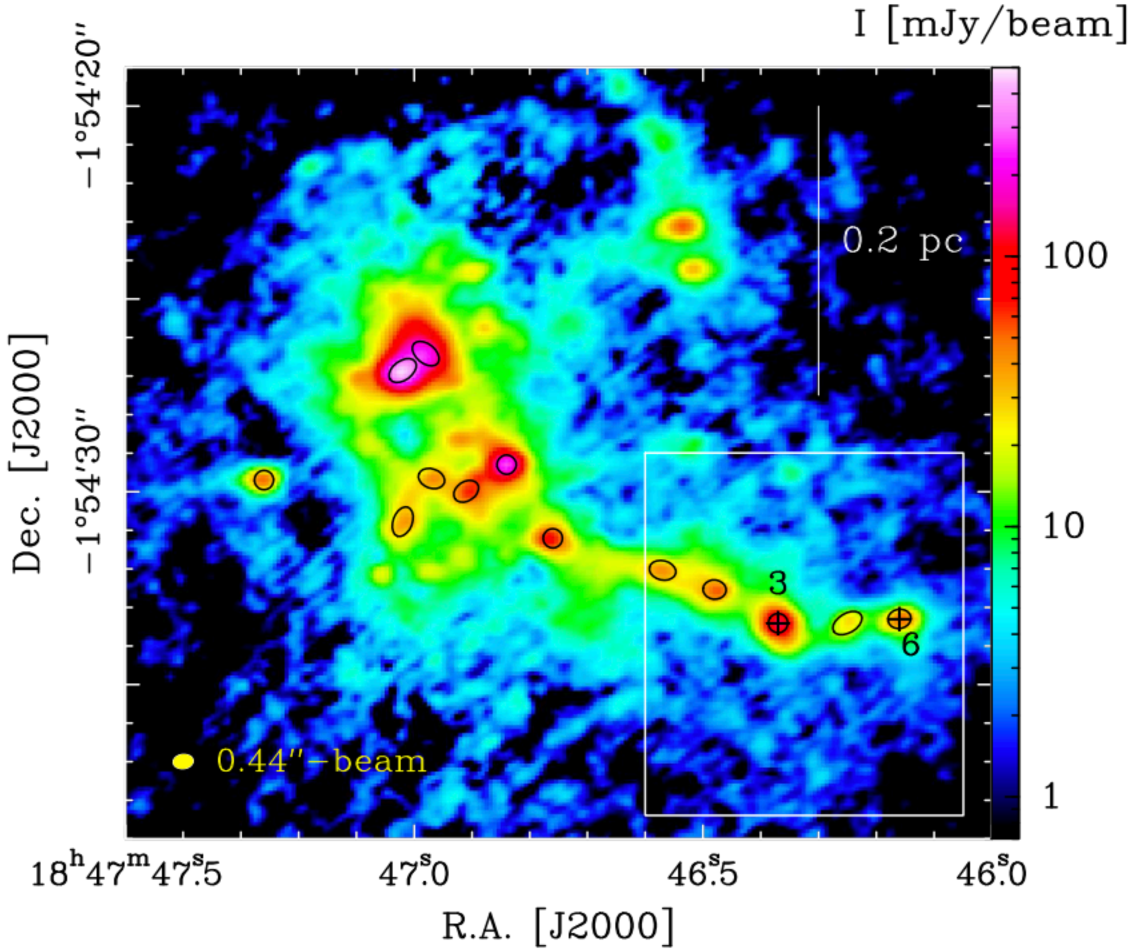
Observational evidence: high-mass prestellar cores?

Nony et al. 2018



In general, such objects are extremely rare. And promising candidates often either fragment or exhibit signatures of SF when examined more closely.

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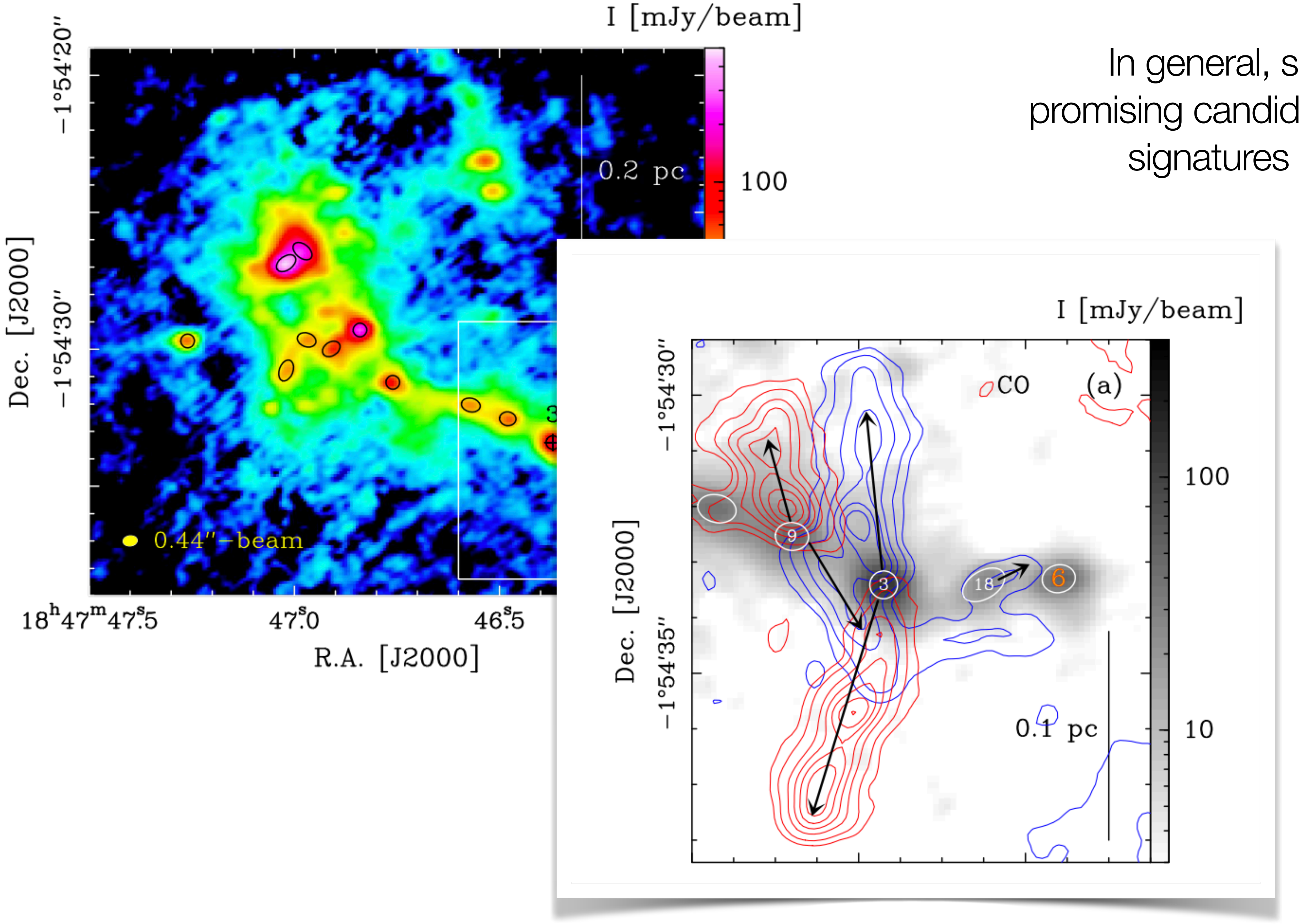

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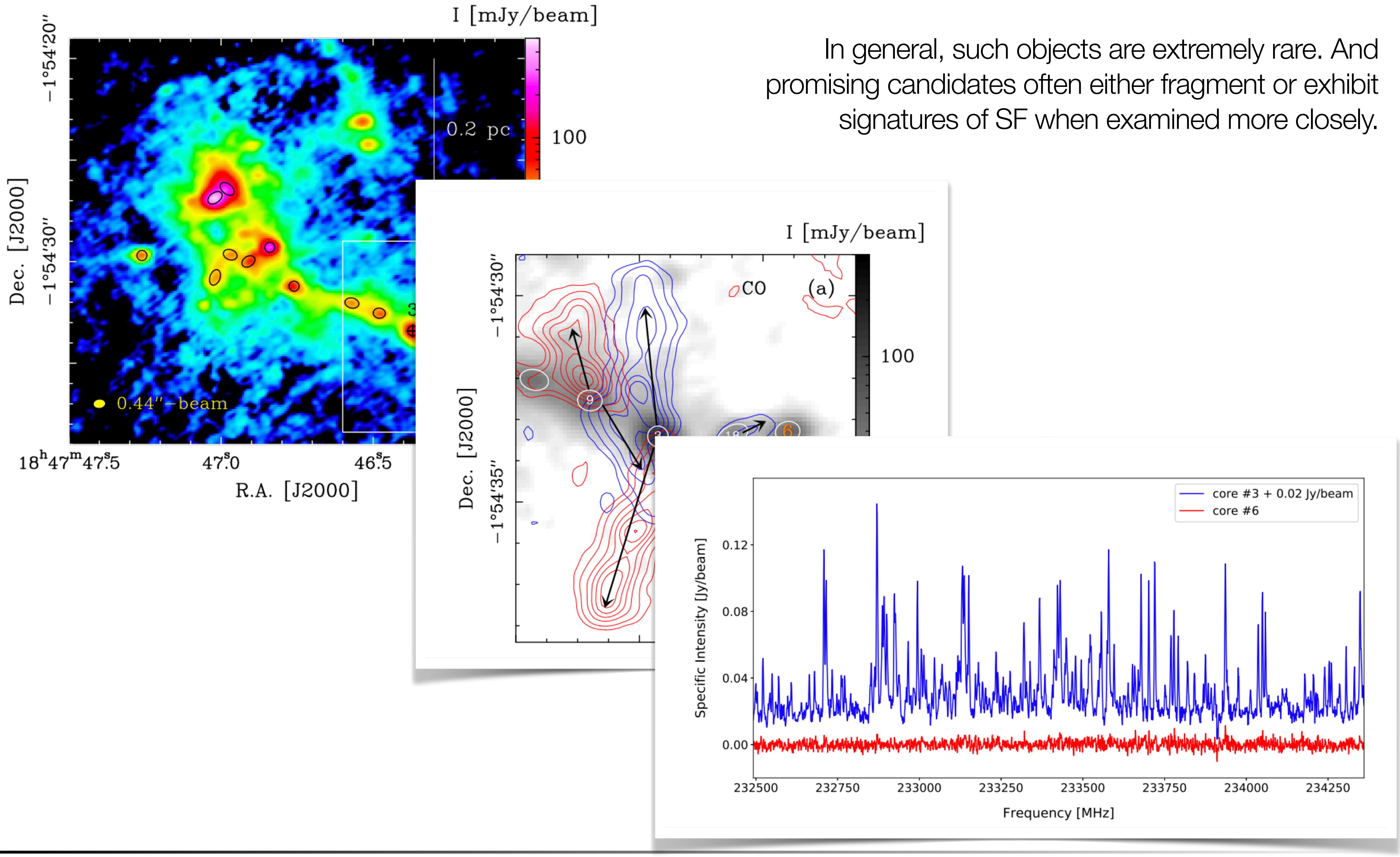

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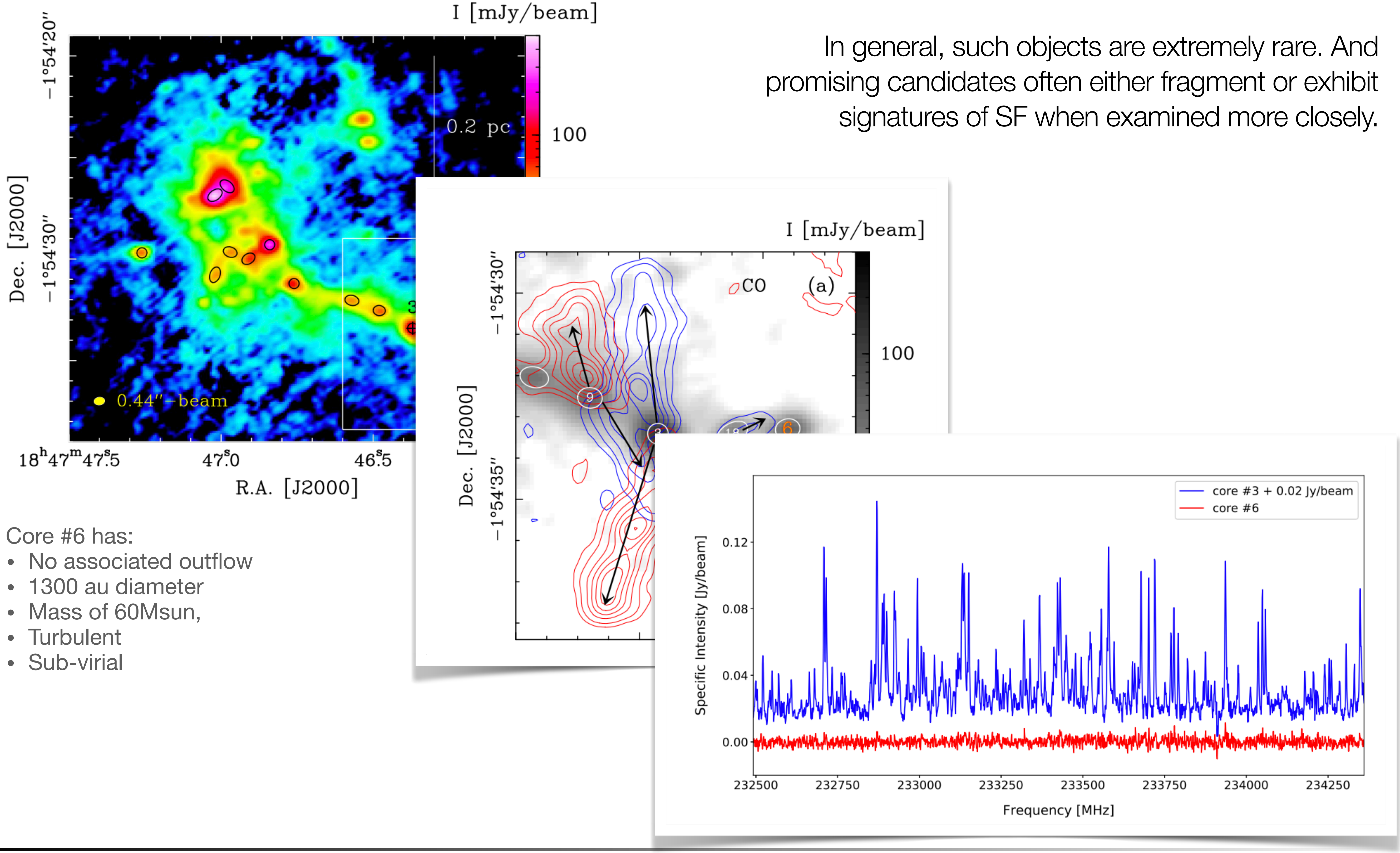

Core #6 has:

- No associated outflow
- 1300 au diameter
- Mass of 60Msun,
- Turbulent
- Sub-virial

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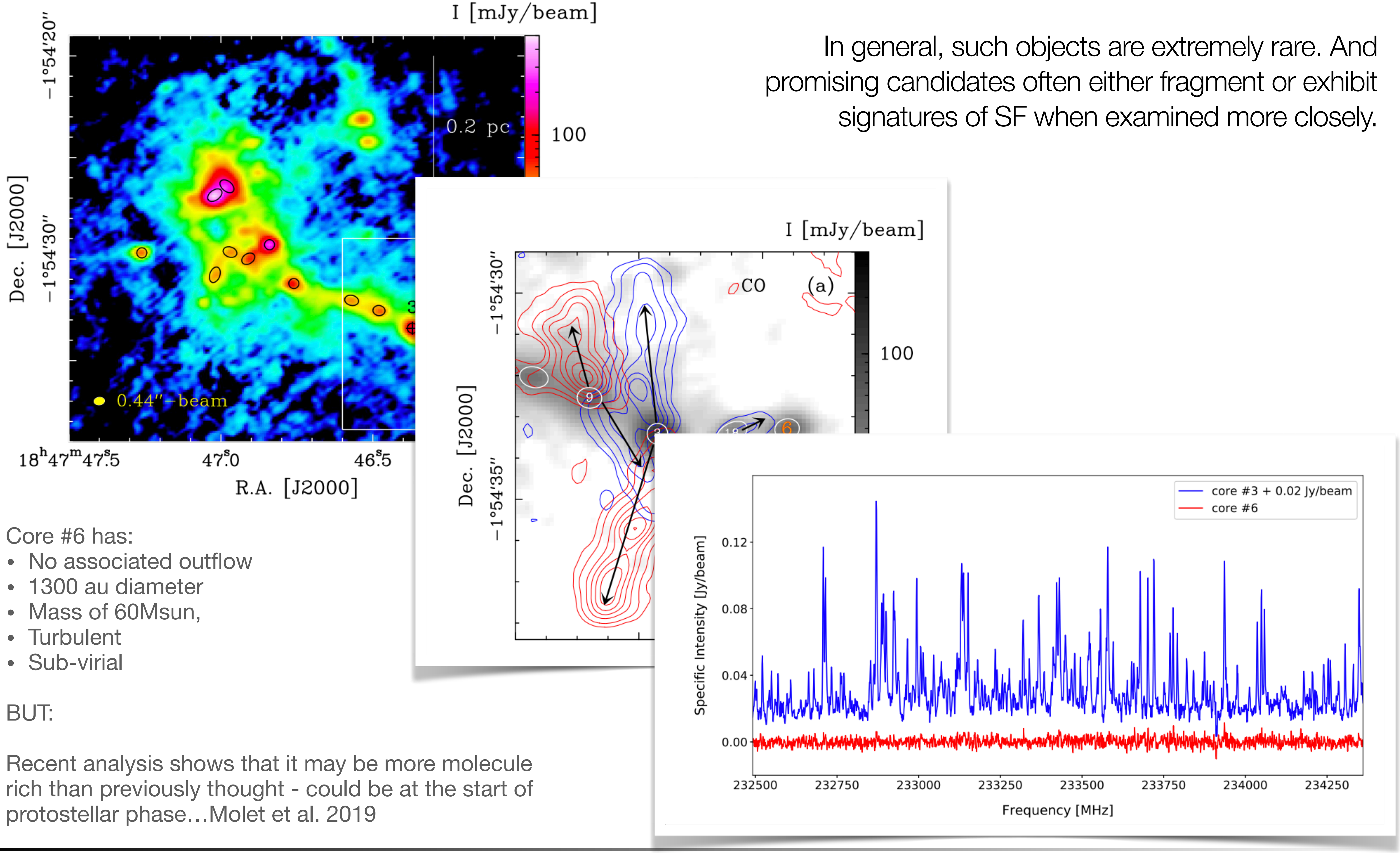

Core #6 has:

- No associated outflow
- 1300 au diameter
- Mass of 60Msun,
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- Sub-virial

BUT:

Recent analysis shows that it may be more molecule rich than previously thought - could be at the start of protostellar phase…Molet et al. 2019

Observational evidence: Outflows (single-dish)

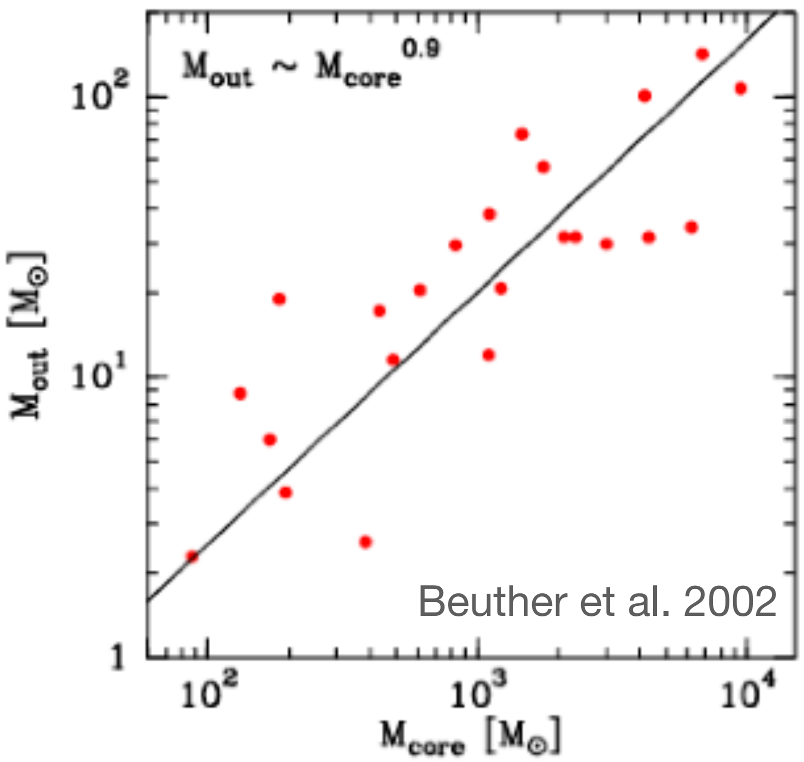
- Early observations claimed different collimation degrees for massive outflows. different formation? See high resolution image on next slide

- Outflow-mass scales with core mass.

- Outflow force implies non-radiative outflow driving.

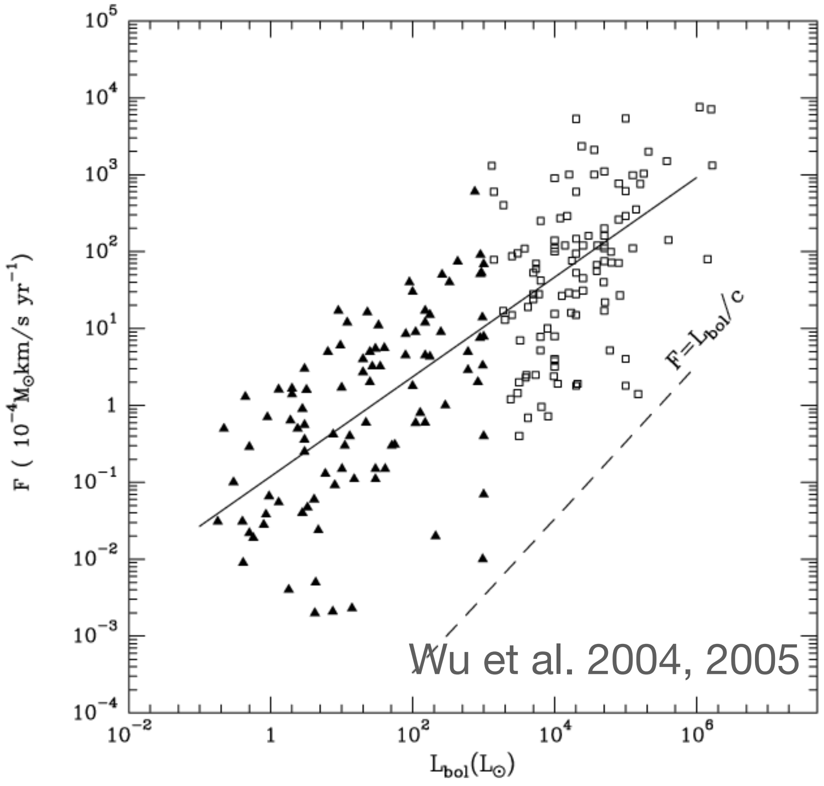
- High outflow rates imply high accretion rates.

Outflow mass vs core mass



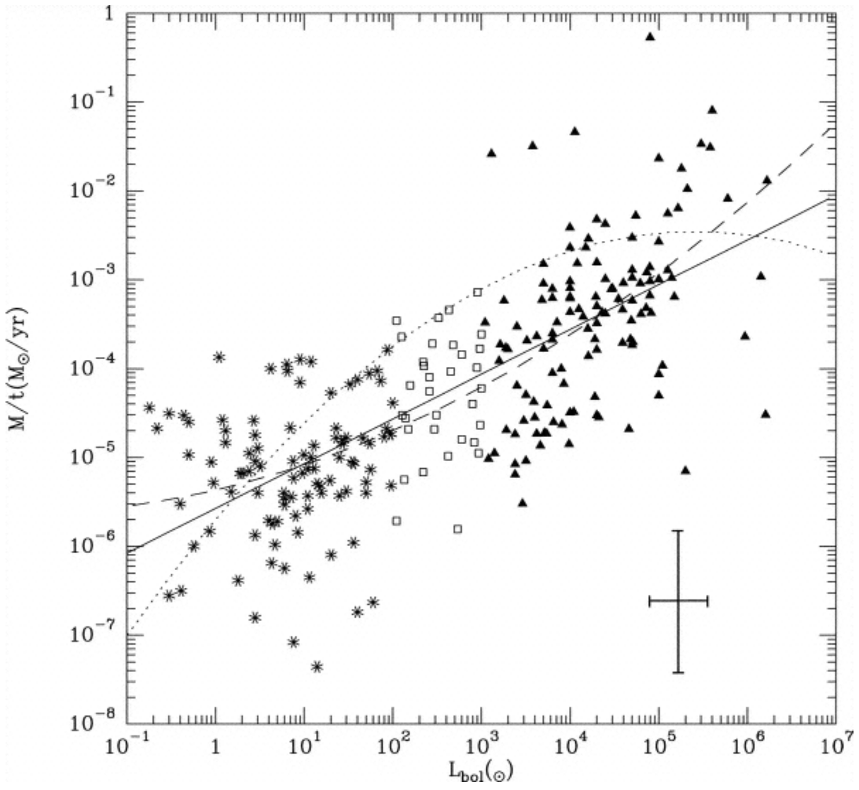
Beuther et al. 2002

Outflow force vs source luminosity

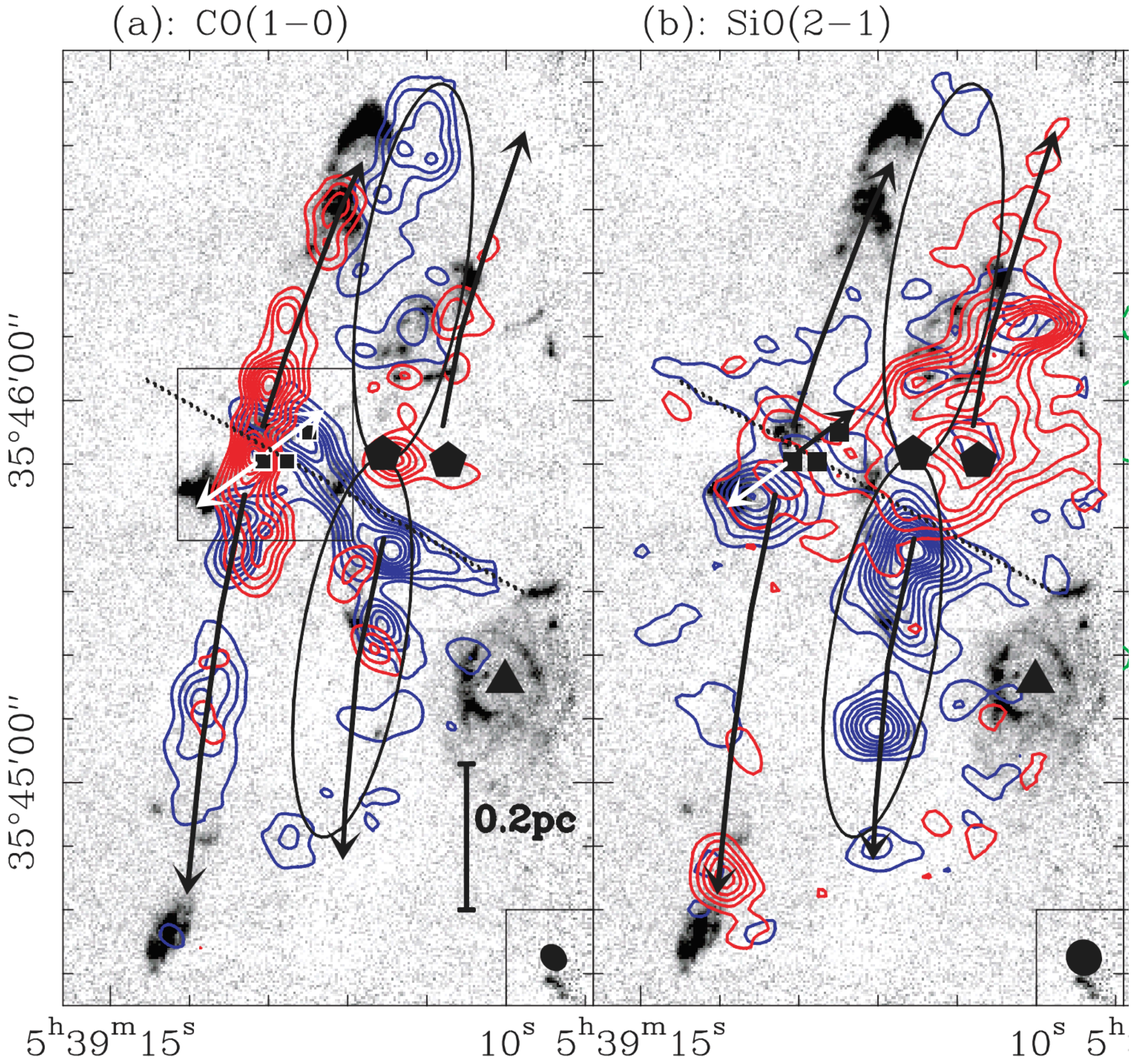


Wu et al. 2004, 2005

Outflow rate vs source luminosity

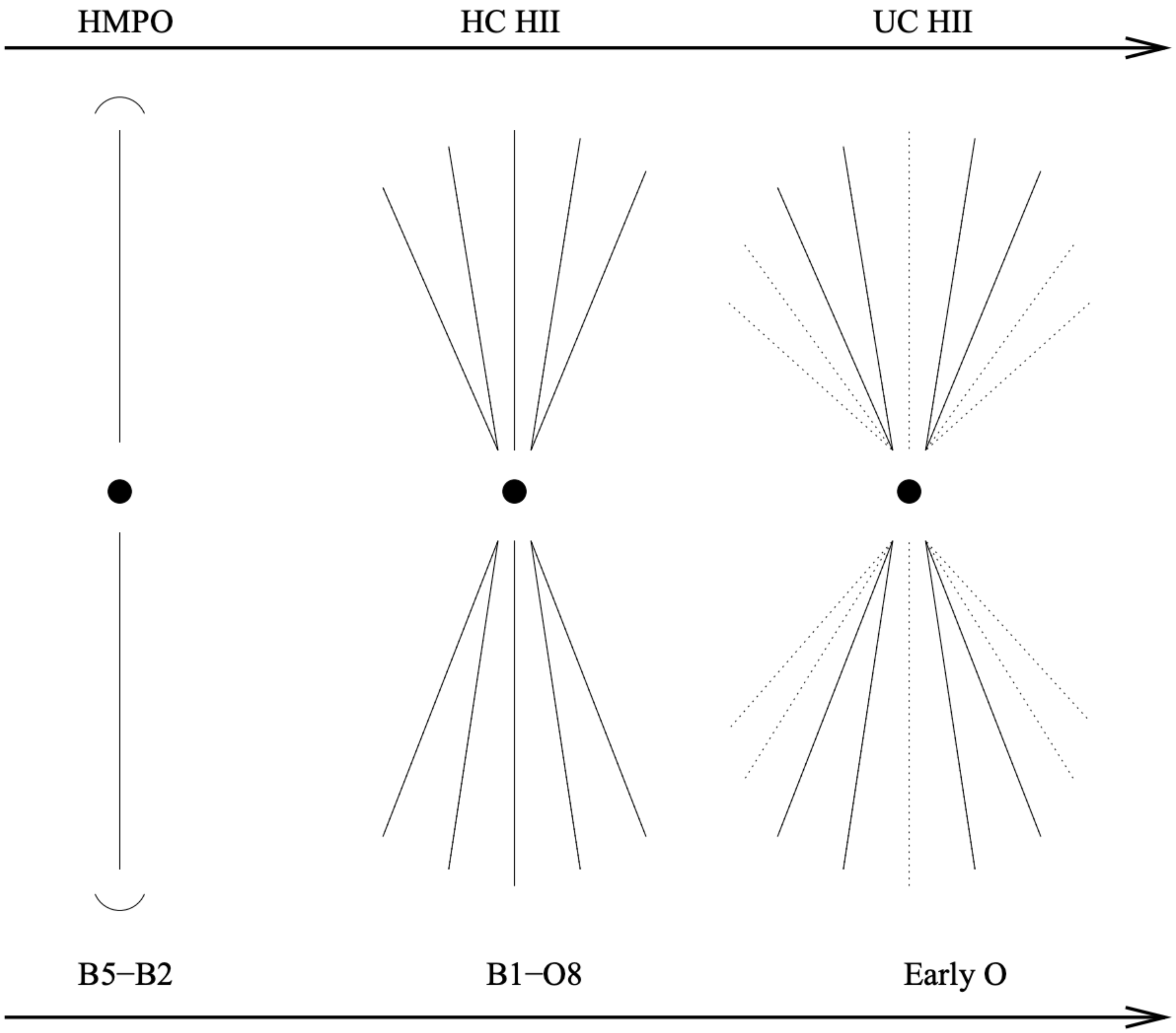


Observational evidence: Outflows (interferometric)



Beuther et al. 2002

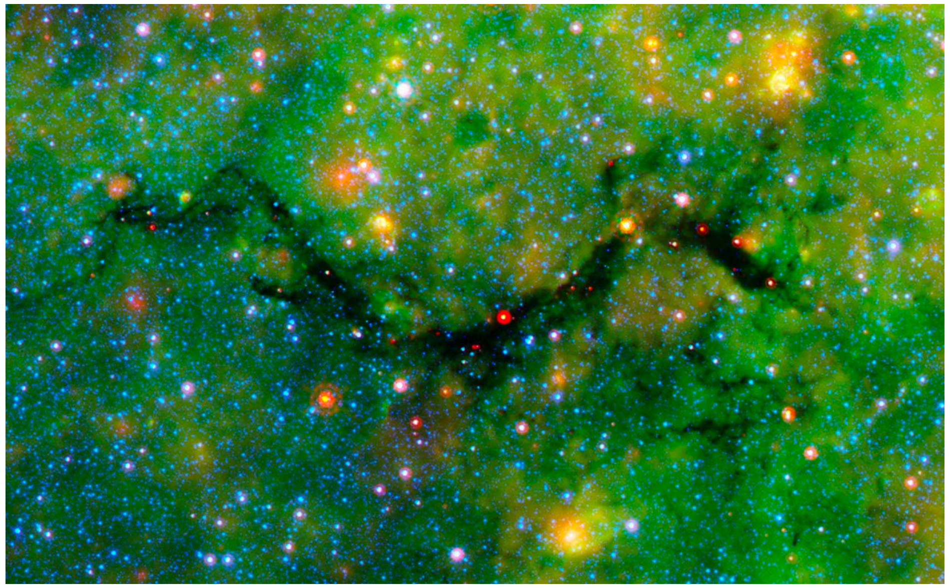
Observational evidence: Outflows (evolution)

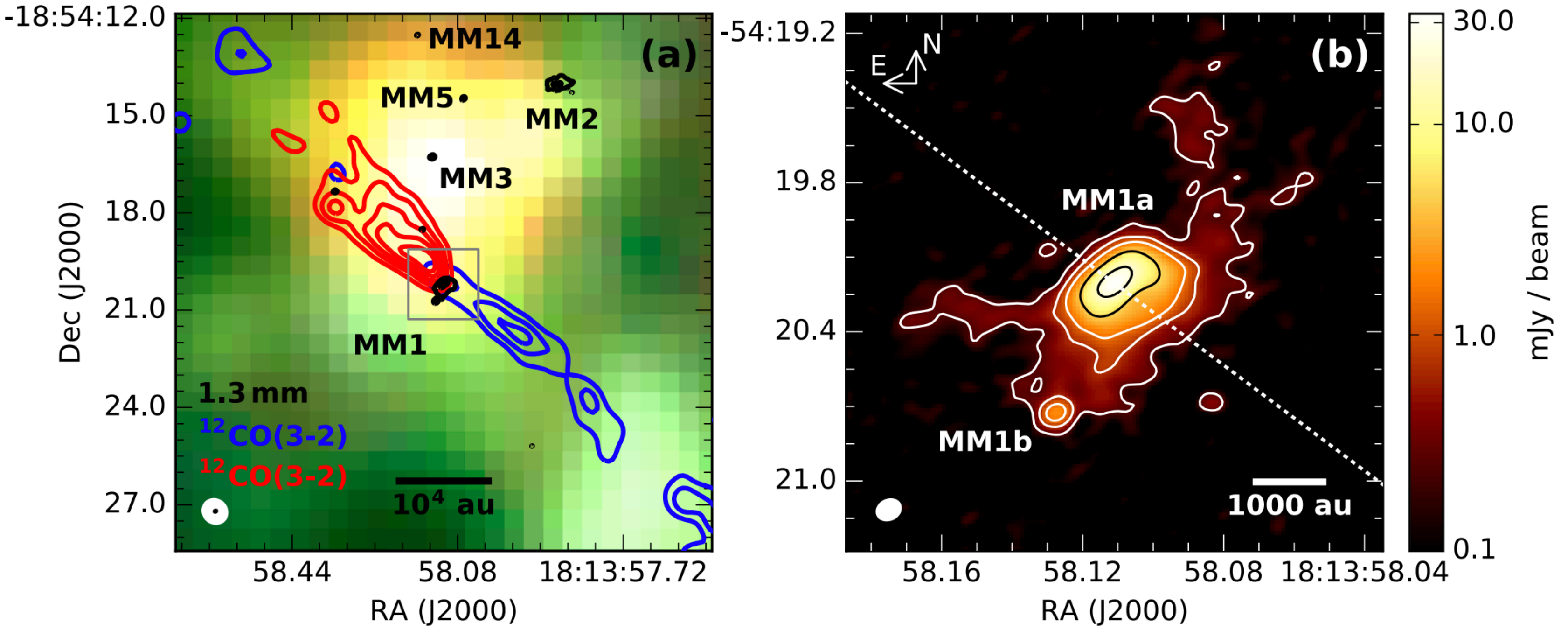


- Outflows are ubiquitous phenomena in star formation
- Jet-like (highly collimated) outflows exist at least up to early B and late O-type stars
- Outflow collimation may decrease with increasing protostellar mass - evolution?

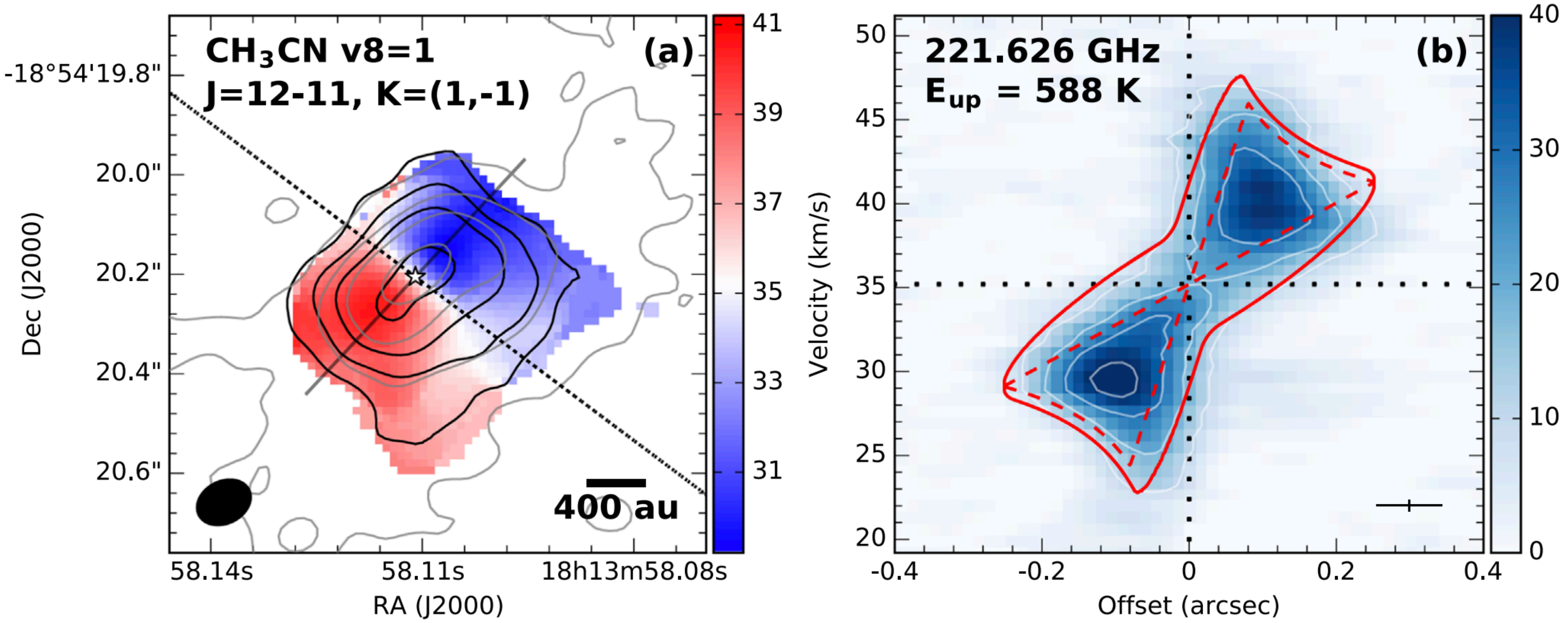
Beuther & Shepard 2005

Observational evidence: Disks: G11.92–0.61 MM1a





- ALMA observations of a young high-mass protostar in an Infrared Dark Cloud
- Outflow clearly detected in CO
- Higher-angular resolution observations show that the source has fragmented
- Examination of the gas kinematics show signatures of rotation perpendicular to the outflow axis
- Rotation consistent with a Keplerian disk - enclosed mass ~40Msun - disk mass ~2-5Msun



Ilee et al. 2018

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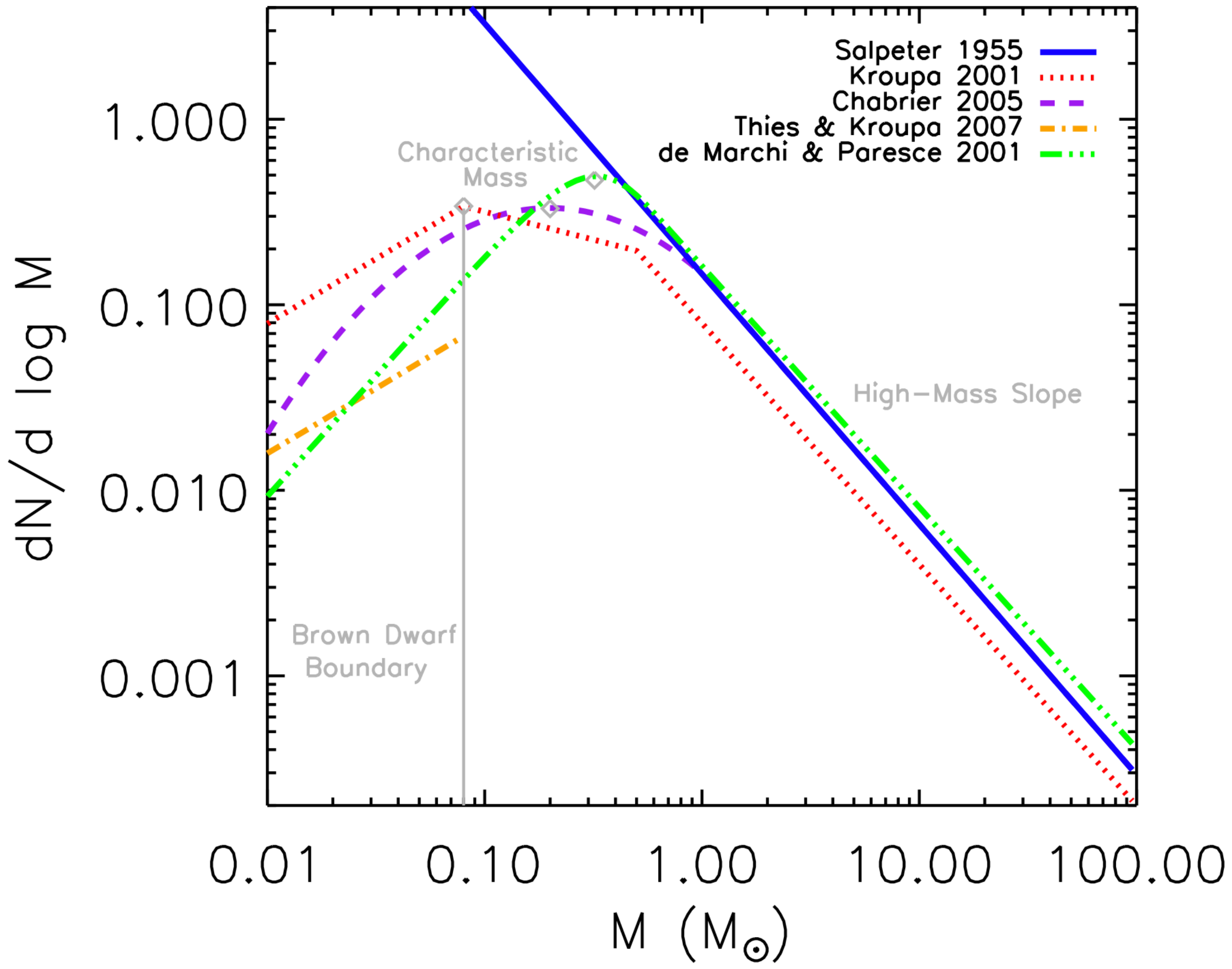
The IMF

Measuring the Stellar Initial Mass Function (IMF) and understanding its genesis, is one of the most important topics in contemporary astrophysics.



Galaxy Structure and Evolution

Tracking build-up of heavy elements

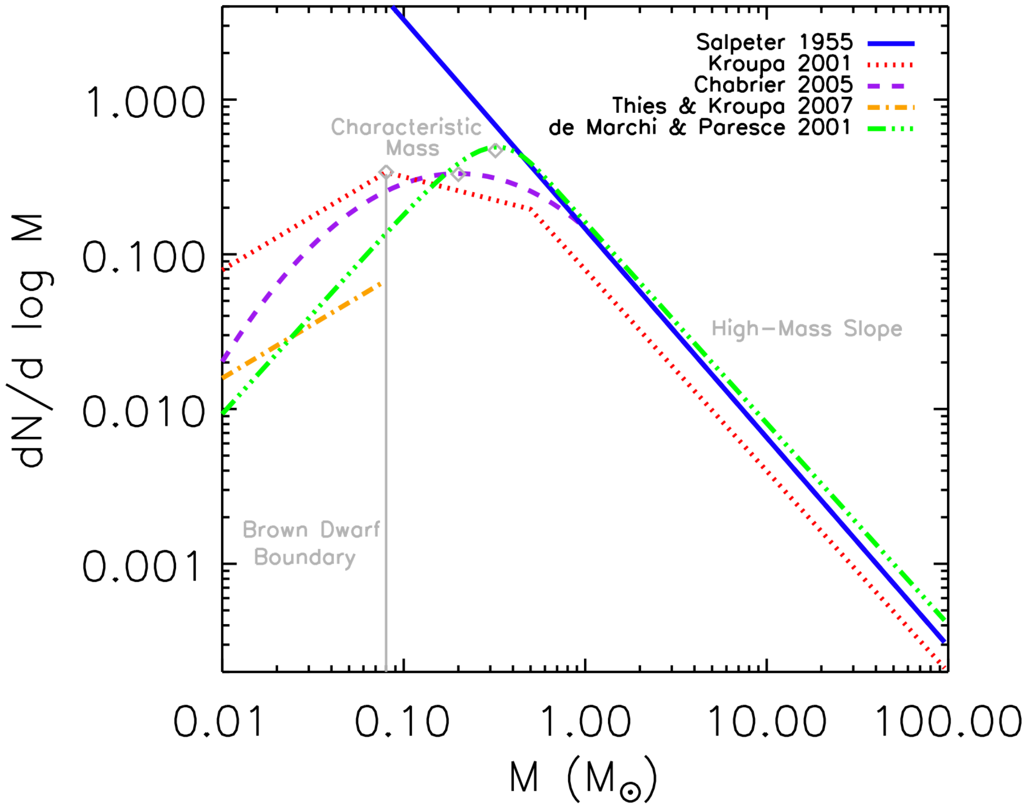
Formation of planets & life

The IMF

The IMF in a nutshell:

A star's mass determines its evolution. The IMF is simply a convenient way of parameterising the relative numbers of stars as a function of their mass.

Offner et al. 2014



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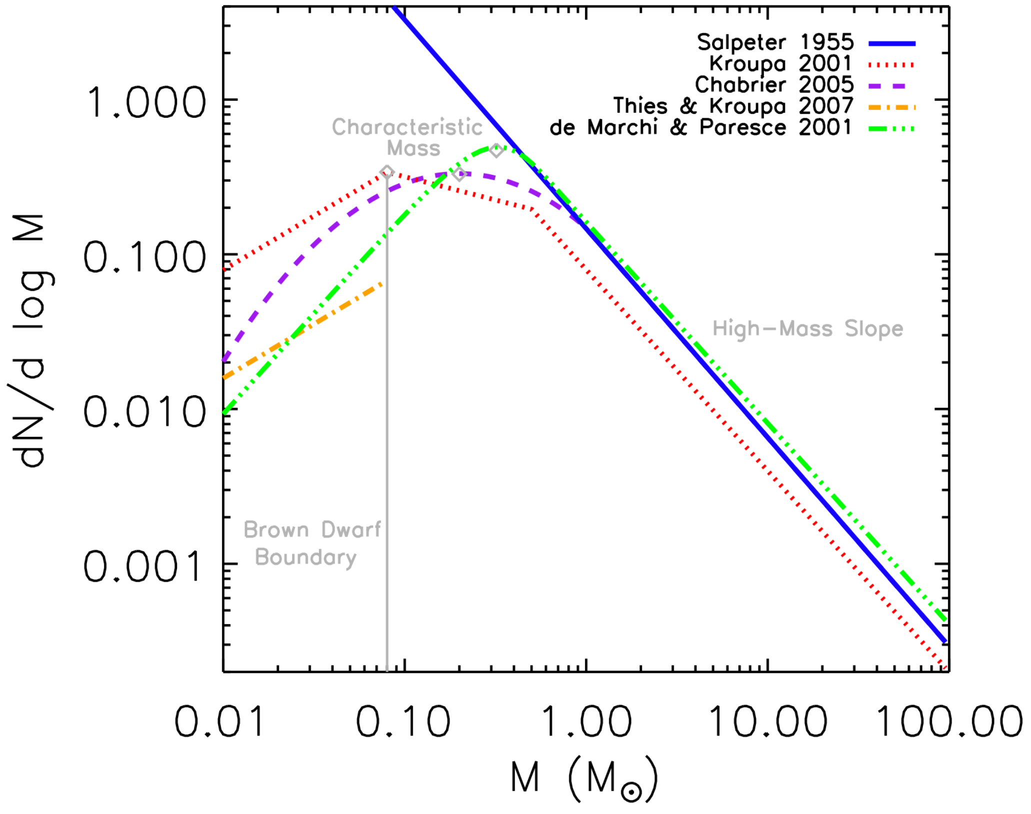
Parameterisation:

- >1Msun: $dn/d\ln m \propto m^{\gamma}$ with $\gamma = -1.35$; Salpeter 1955
- Peak/turnover in the range 0.1-1Msun
- Often described with a series of power-laws (Kroupa 2001), or a log-normal at low-mass and a power-law tail above 1Msun (Chabrier 2003, 2005)

Offner et al. 2014



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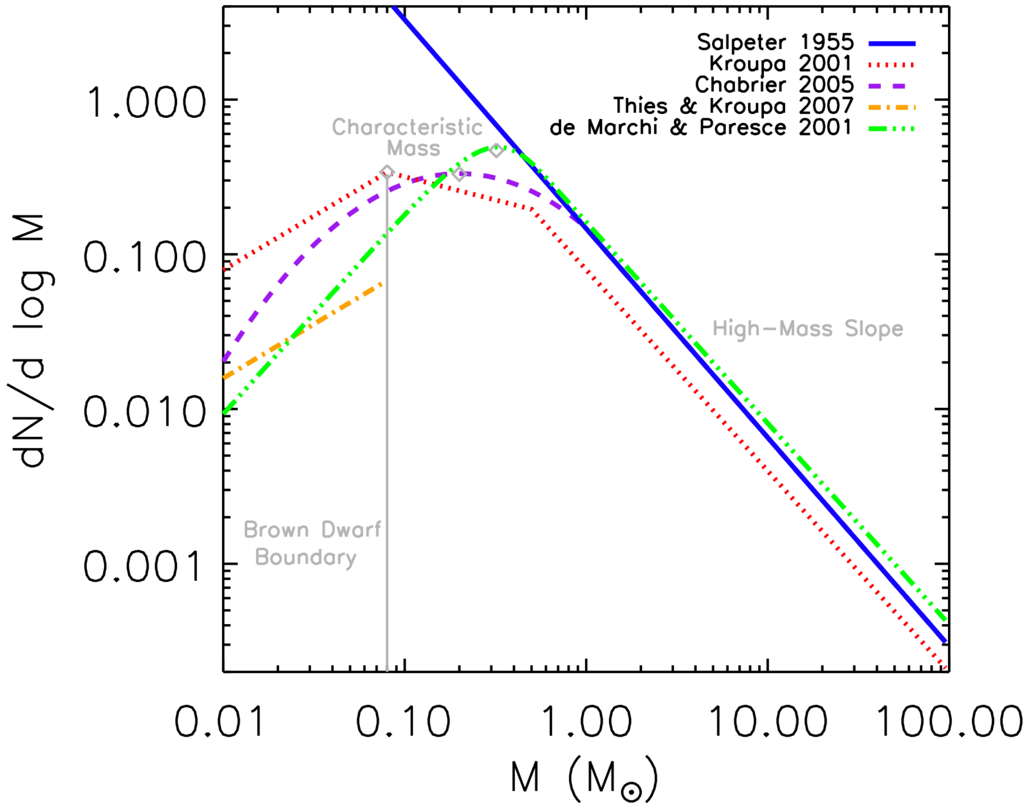
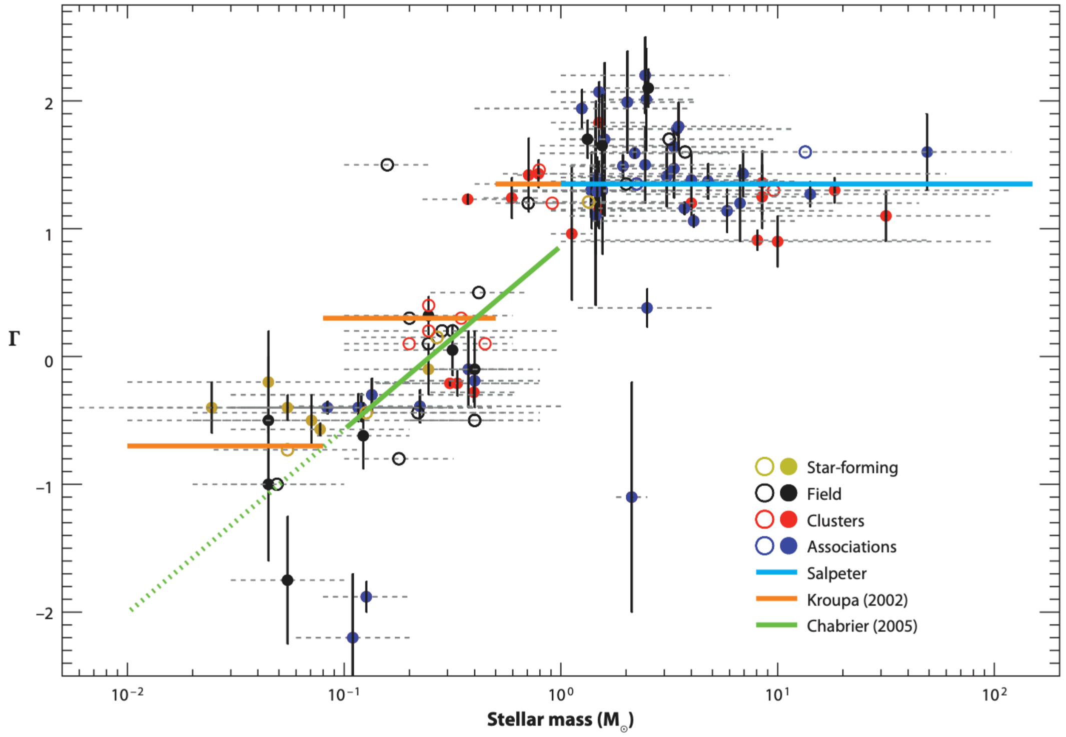
Universality:

- The shape and universality of the IMF are active areas of research
- Within measurement uncertainties however, there appears to be very little variation
- No clear evidence that the IMF varies strongly and systematically as a function of initial conditions after the first few generations of stars

Offner et al. 2014



Bastian et al. 2010



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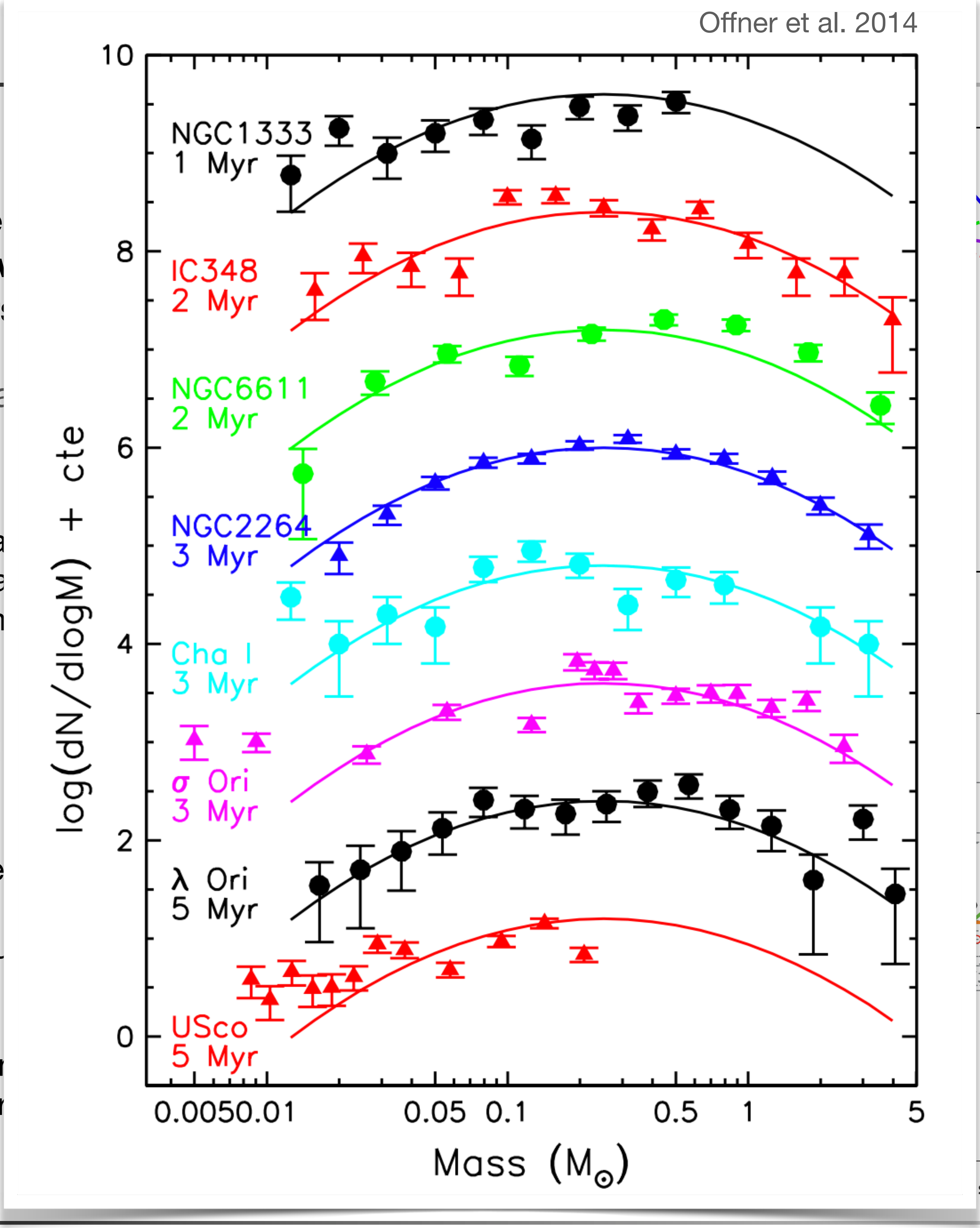
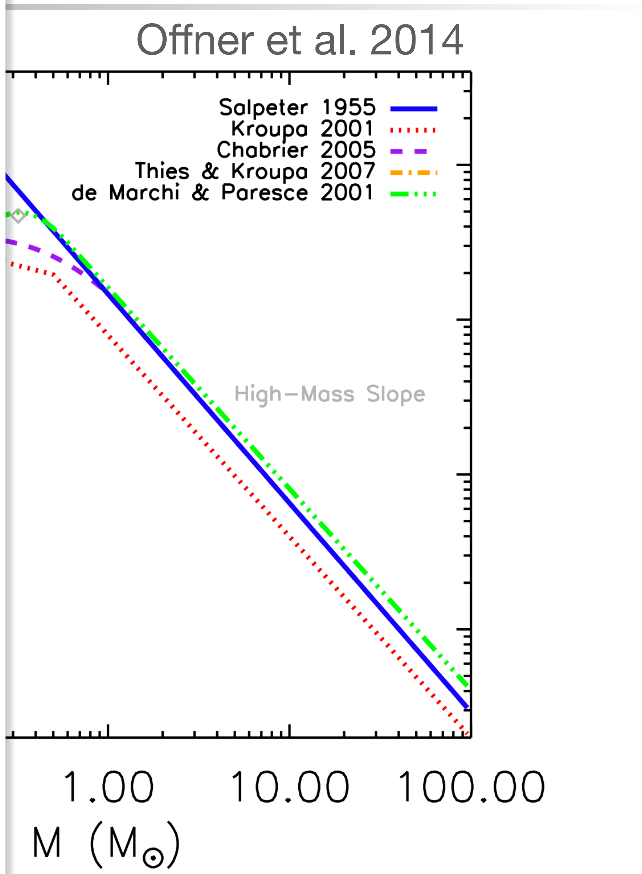
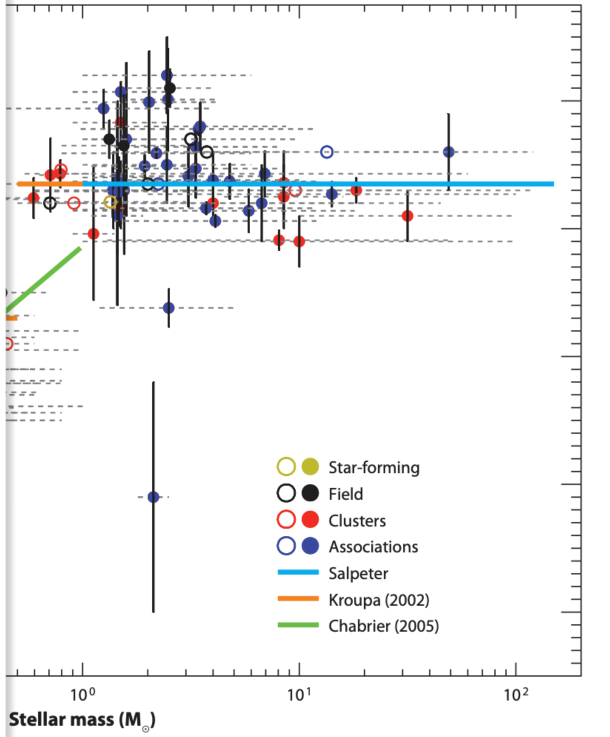
Offner et al. 2014



Offner et al. 2014

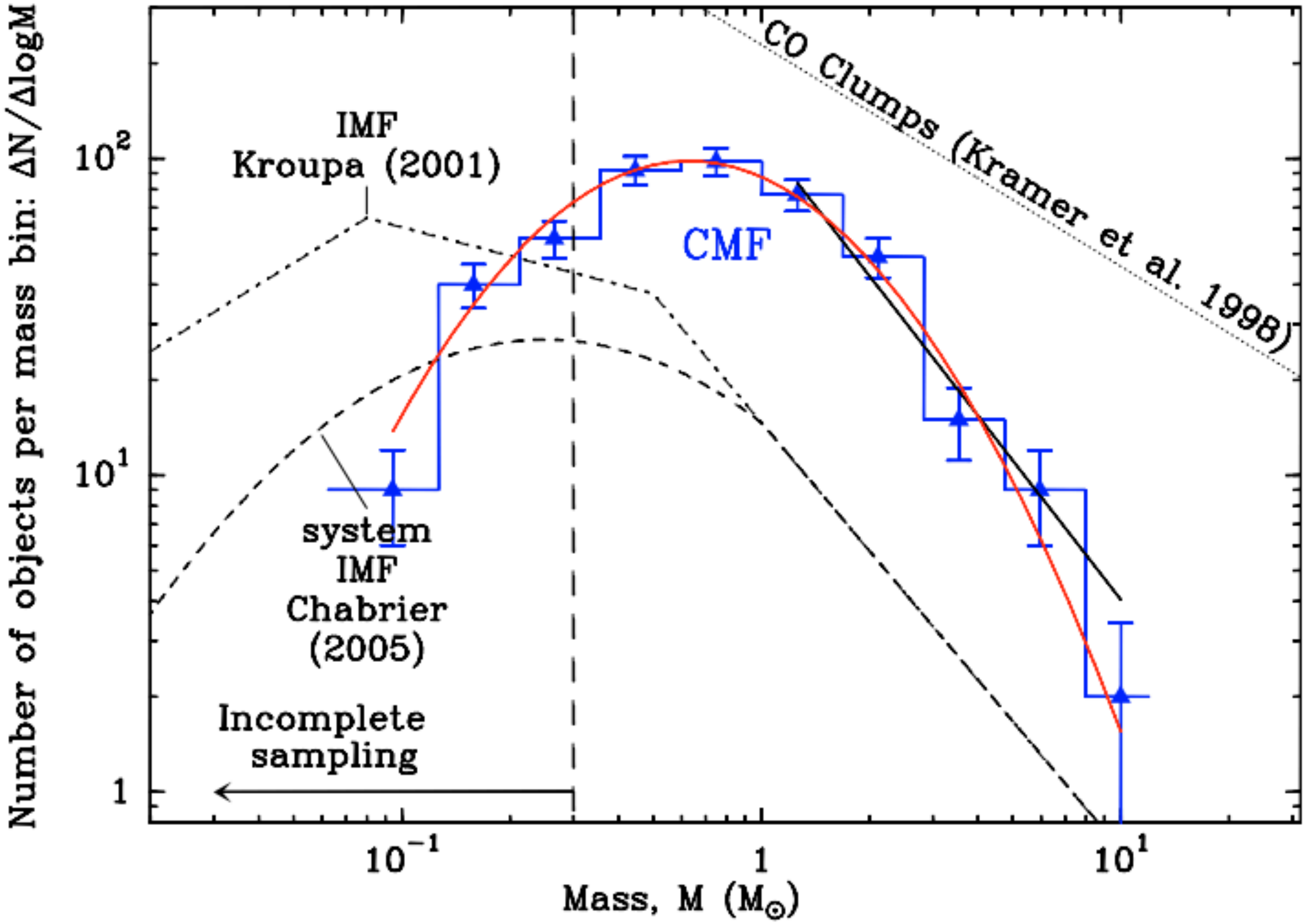


Bastian et al. 2010



The CMF (core mass function)

Könyves et al. 2015



Solid black line = power-law fit with slope = -1.5 +/- 0.2; cf. Salpeter IMF slope with -1.35

The profile of the prestellar Core Mass Function is reminiscent of the IMF but shifted to higher masses

The CMF (core mass function)

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IF the IMF derives directly from the CMF then:

1. All observed cores in CMF derivation must be prestellar
2. Cores must not alter their mass by either accretion or mergers, if they do they must do so self-similarly
3. All cores must have the same star formation efficiency
4. If cores fragment they must do so self-similarly
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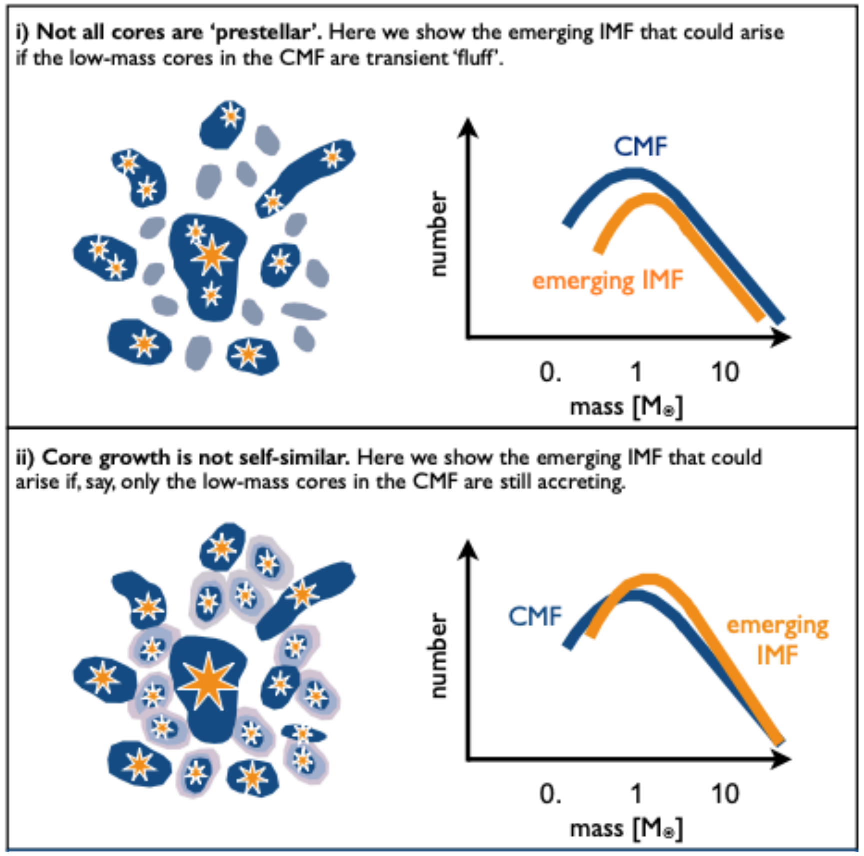
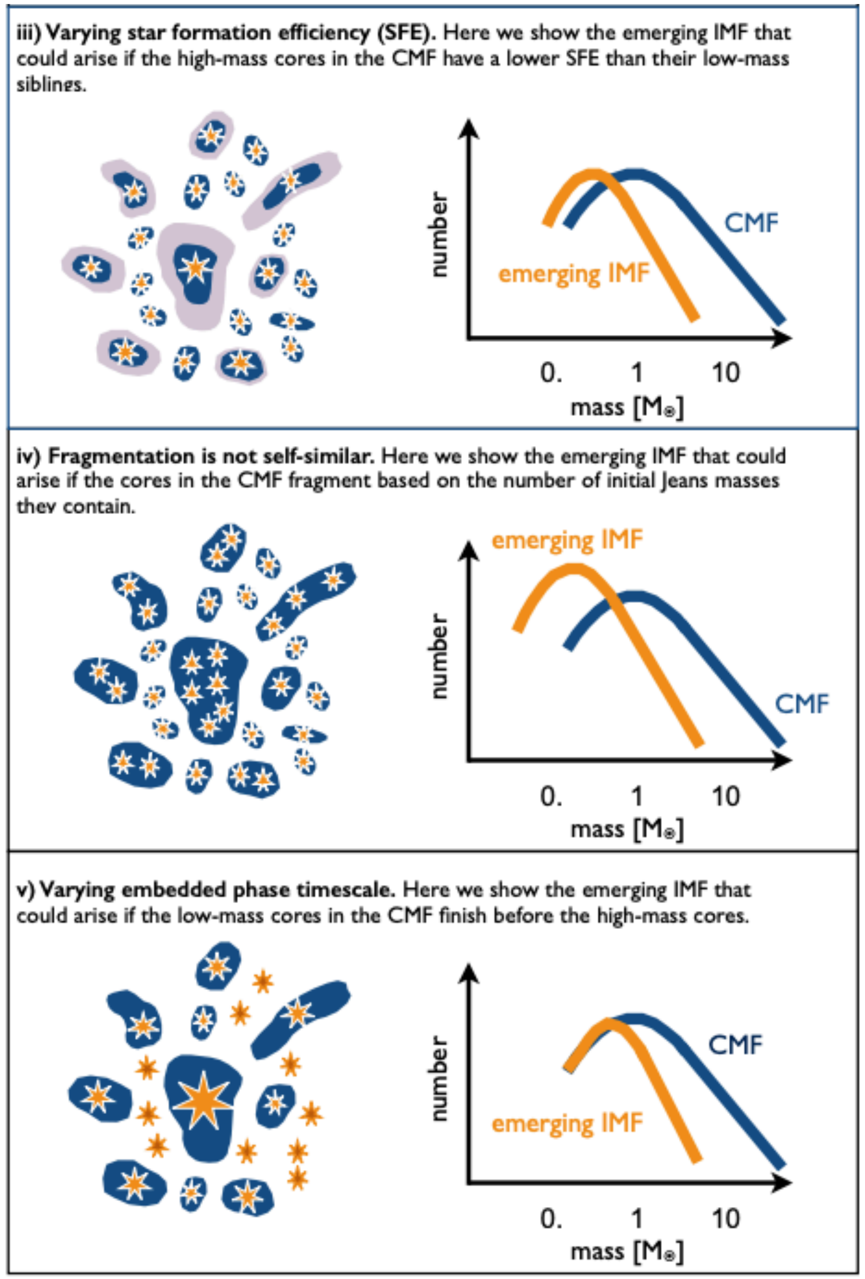


i) Not all cores are ‘prestellar’. Here we show the emerging IMF that could arise if the low-mass cores in the CMF are transient ‘fluff’.

ii) Core growth is not self-similar. Here we show the emerging IMF that could arise if, say, only the low-mass cores in the CMF are still accreting.

Graphic shows what happens if any of the conditions required for direct mapping from CMF to IMF fail?



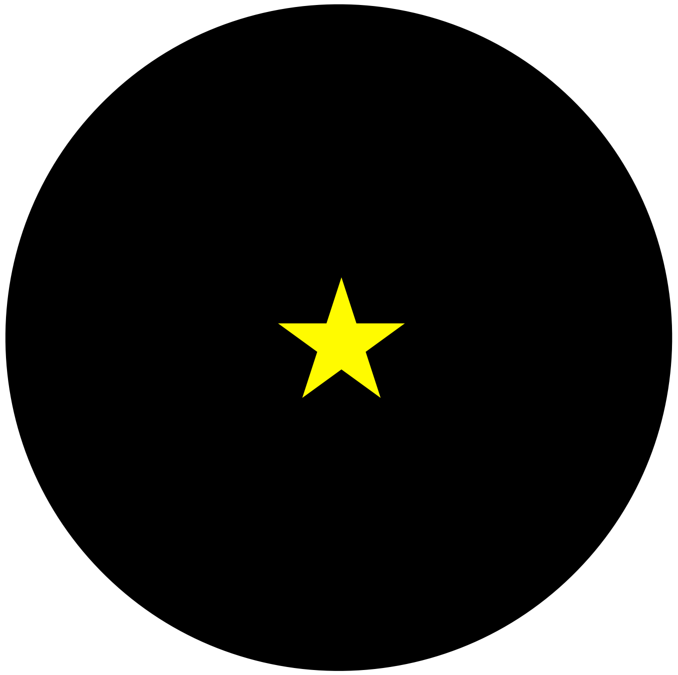
iii) Varying star formation efficiency (SFE). Here we show the emerging IMF that could arise if the high-mass cores in the CMF have a lower SFE than their low-mass siblings.

iv) Fragmentation is not self-similar. Here we show the emerging IMF that could arise if the cores in the CMF fragment based on the number of initial Jeans masses they contain.

v) Varying embedded phase timescale. Here we show the emerging IMF that could arise if the low-mass cores in the CMF finish before the high-mass cores.

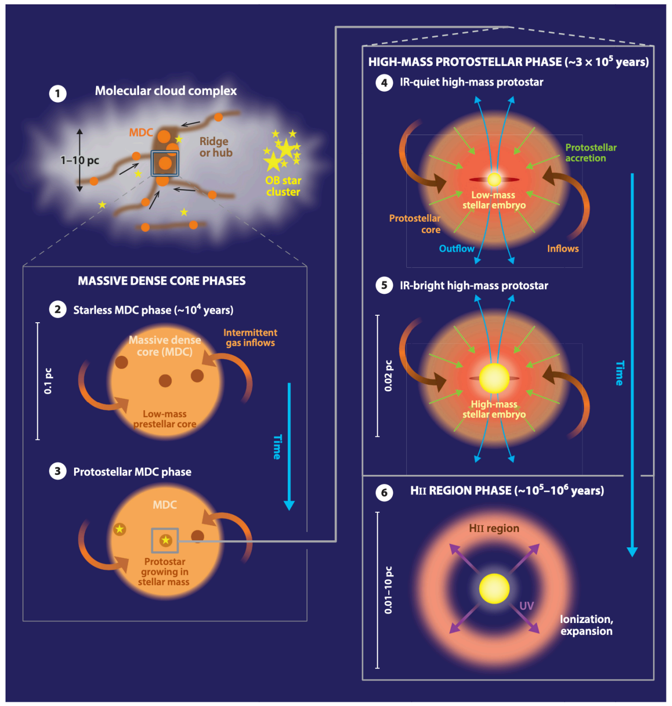
Returning to our theories of HMSF

Core Accretion (monolithic collapse)



“Nature”

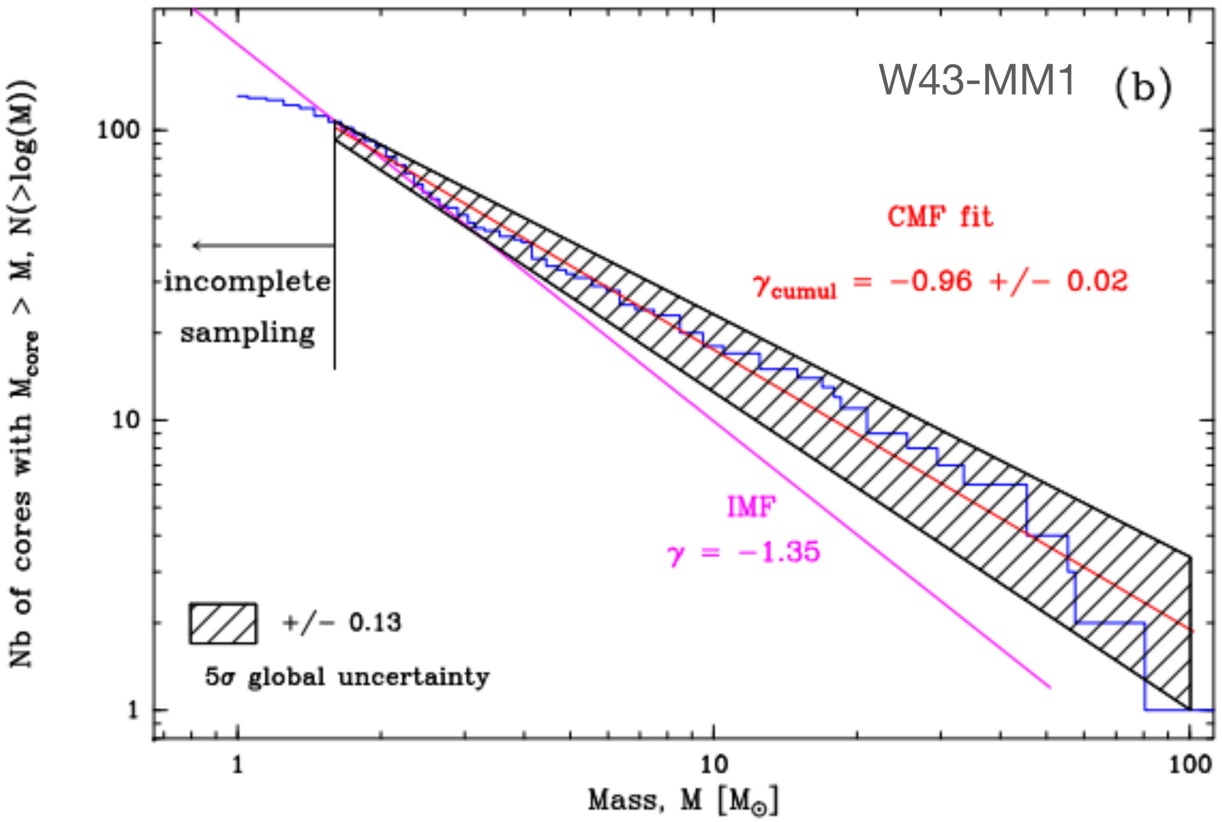
“Others” (competitive accretion, GHC, IF)



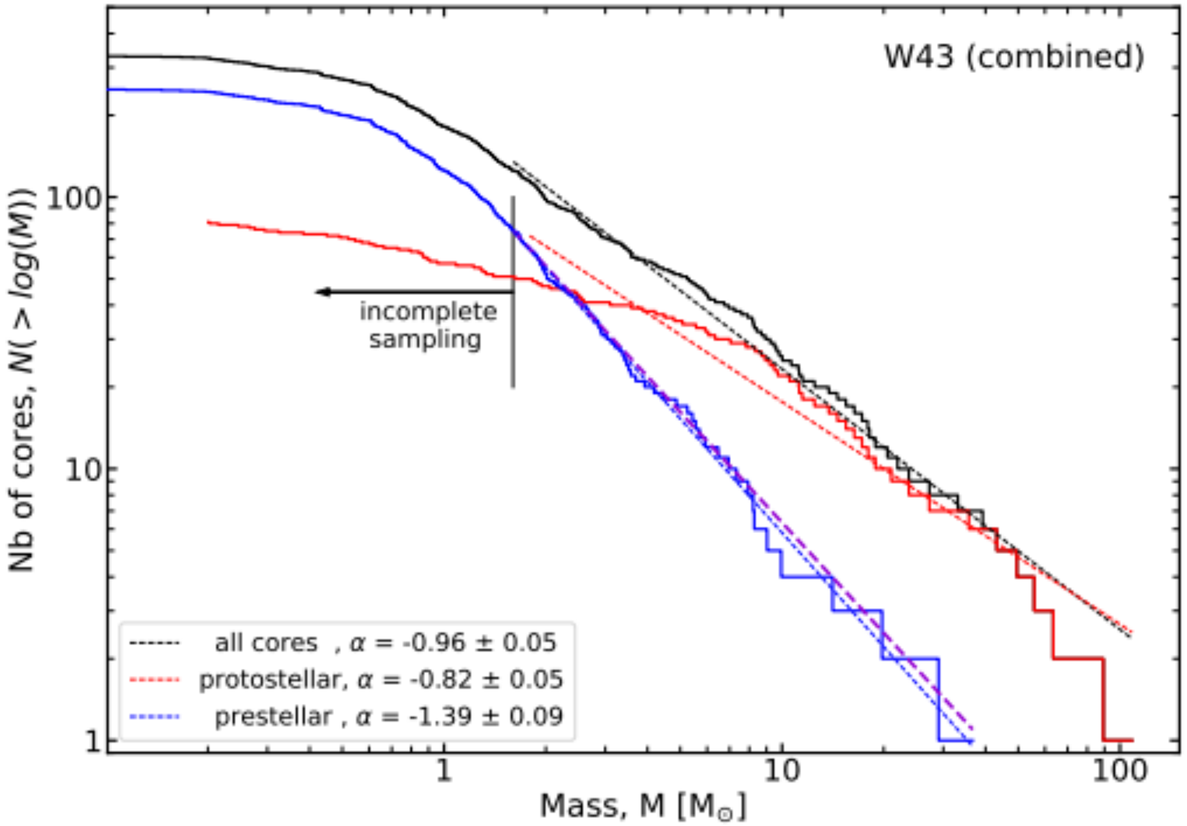
“Nurture”

Something new…

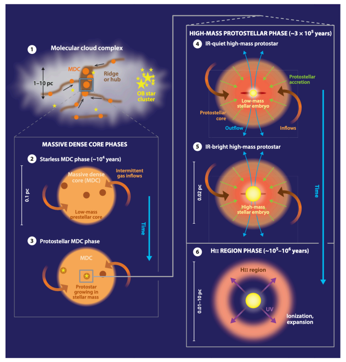
Motte et al. 2018



Nony et al. 2022



Conclusion: Core growth during protostellar phase?



Summary

Learning outcomes:

- Why are high-mass stars important?
  - The energy input and heavy metals produced by high-mass stars influence everything from the evolution of galaxies to the emergence of life
- Why is high-mass star formation a difficult problem to solve?
  - Rare, rapid, reclusive
- Different theories of high-mass star formation
  - Accretion models of various flavours vs. Coalescence of lower-mass stars. The latter appears to be important under very specific circumstances (i.e. very dense high-mass star clusters), and therefore probably not generally applicable. More recent models are attempting to fold in the evolution of the parent cloud.
- Observational evidence
  - High-mass prestellar cores are incredibly elusive. It may be that they are rare and/or evolve rapidly. Alternatively, it may be that the progenitors of high-mass stars are not high-mass, starless cores. Outflows are ubiquitous in star formation. Evidence for disks around high-mass stars is in its infancy but the number of examples is increasing.
- The IMF
  - A parameterised description of the relative numbers of stars of different masses. Its genesis remains one of the big open questions in SF research. Its relationship to the CMF is unclear, direct mapping is the most simple idea, but comes with some pretty strong assumptions.

Connecting Exoplanet Properties to Planet Formation: a New Paradigm Emerges

Prof. Ralph E. Pudritz, McMaster University

One of the great challenges of exoplanetary astrophysics is to understand how the observed properties of exoplanets – their masses, orbital characteristics, bulk properties and atmospheric composition – arise as a consequence of how planets are formed in protoplanetary disks. Where and what materials planets accrete from the disk depends in part upon how they migrate and how the gas and dust in the disks evolve both chemically and dynamically. The vast majority of papers over the last decades have assumed that disk turbulence is the fundamental driver of most of these processes. Recent theoretical and observational advances however point to the importance of the ubiquitous protostellar outflows, now shown observationally to be magnetohydrodynamical disk winds, as the key player. In this talk I will discuss the recent advances in observations, theory, and simulations of planet formation and explore the relative importance of disk winds versus turbulence in controlling planet formation and the observed properties and compositions of exoplanetary populations. Those unable to attend the colloquium in person are invited to participate online through Zoom (Meeting ID: 942 0262 2849, passcode 792771) using the link: https://zoom.us/j/94202622849?pwd=dGlPQXBiUytzY1M2UE5oUDRhbzNOZz09 Prof. Pudritz is visiting the Institut fuer Theoretisches Astrophysik and is available for meetings by arrangement with his host, Ralf Klessen (klessen@uni-heidelberg.de).

Heidelberg Joint Astronomical Colloquium
24 Jan 2023, 16:00
Physikalisches Institut, Philosophenweg 12, Main lecture theatre