Star Formation and Herbig Ae / Be Stars

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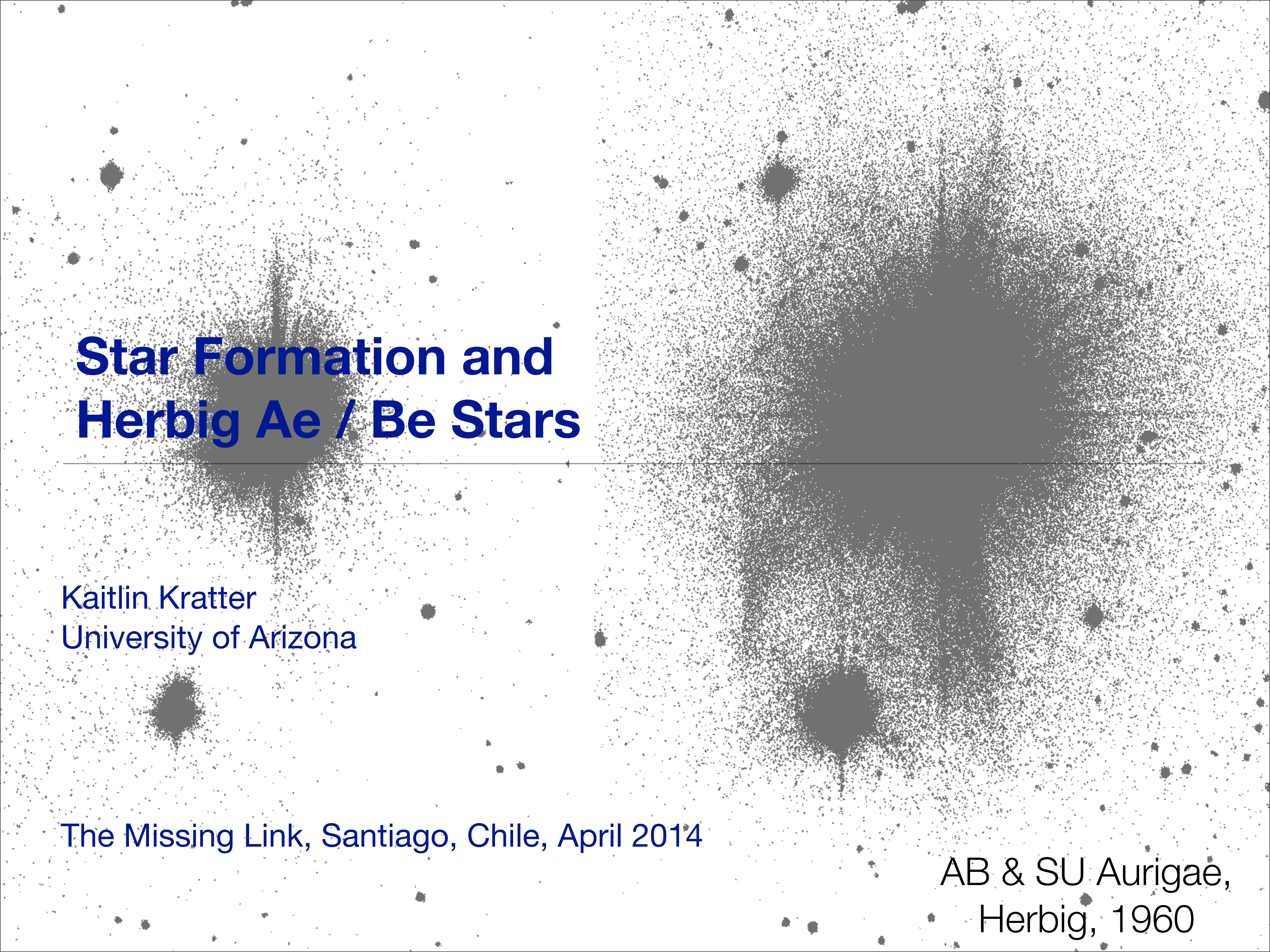
University of Arizona

The Missing Link, Santiago, Chile, April 2014



AB & SU Aurigae,
Herbig, 1960

Defining Herbig Ae/Be Stars

TABLE 1

THEORETICAL NUCLEAR (t_N) AND CONTRACTIVE (t_K) TIME SCALES AS A FUNCTION OF STELLAR MASS ($m/m_\odot$)

$m/m_\odot$	Main-Sequence Spectral-Type Corresponding to $m/m_\odot$	t_N (years)	t_K (years)	$(t_K/t_N)^{-1}$
1.5	F0	1.1×10^9	1.2×10^7	92
2.0	A5	5.2×10^8	5.8×10^6	90
3.5	B9	1.1×10^8	1.4×10^6	79
6.0	B5	3.7×10^7	4.4×10^5	84
11.0	B1	1.3×10^7	1.5×10^5	87
20.0	O9.5:	6.4×10^6	4.5×10^4	140

TABLE 2

PREDICTED NUMBERS OF STILL-CONTRACTING STARS OF LARGE MASS

Spectral-Type Interval	Adopted Value of $(t_K/t_N)^{-1}$	N_{MS}: Number of Main-Sequence Stars pc^{-3}	N'_C: Number of Contracting Stars within 1 kpc	N'_C, but Corrected to Limit of $m_v = 13.0$
B0–B1 V	100	4.6×10^{-7}	2.9	40.
B2–B3 V	85	2.5×10^{-6}	18.	155.
B5–B8 V	80	1.7×10^{-5}	130.	660.
B9–A0 V	80	3.5×10^{-5}	280.	780.

Herbig, 1960

- A or B spectral type
- IR excess
- Emission lines
- Nebulosity

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table for theorists

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Herbig, 1960

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table for theorists

table for observers

Defining an object class, modestly

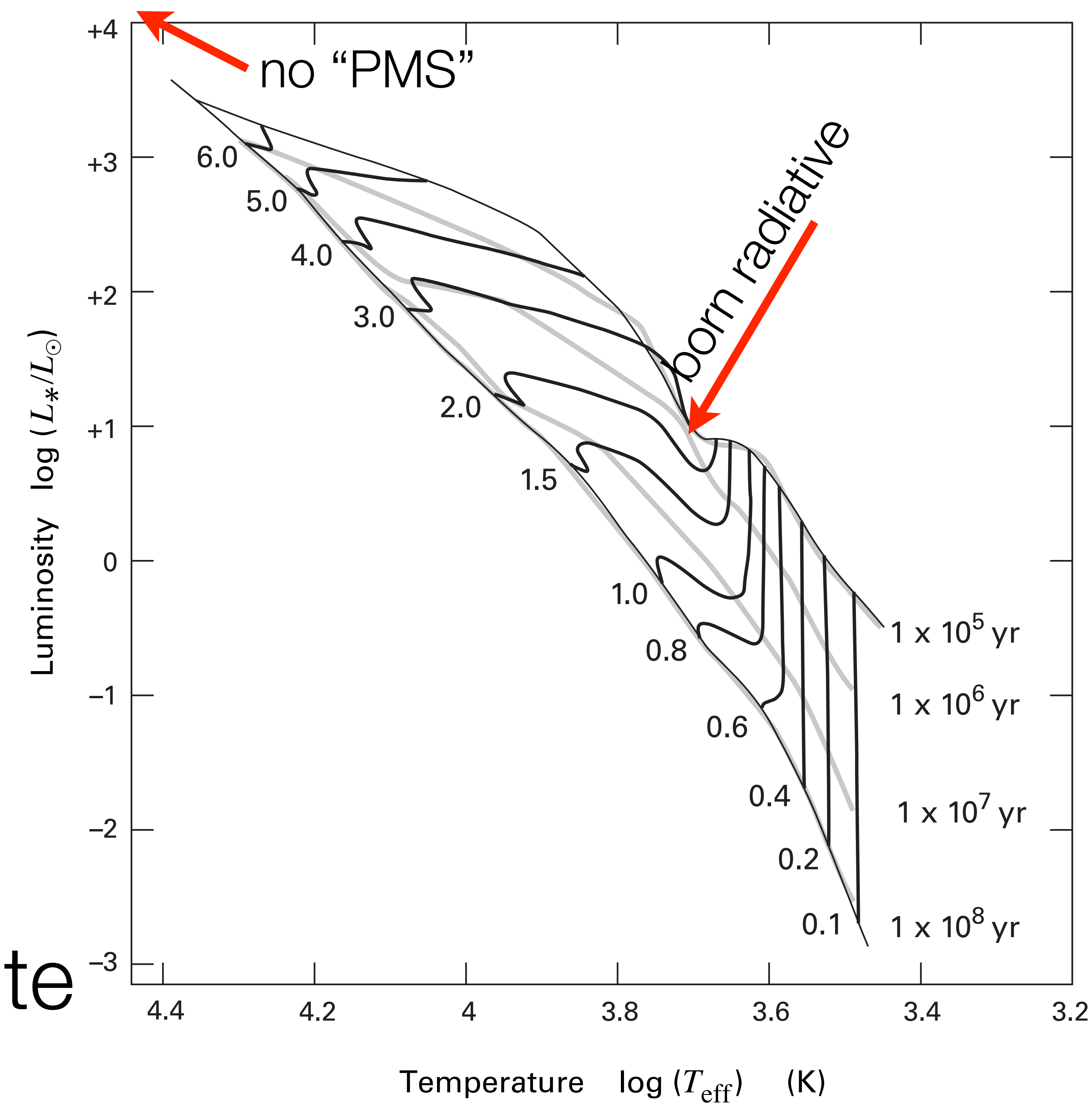
type. Although it is entirely possible that this list of peculiar objects does contain examples of still-contracting stars of large mass, no convincing proof of this supposition could be found. The essential reason was that, although there are some striking spectroscopic peculiarities among the stars examined, at the dispersions employed in this investigation the peculiarities did not appear to be unique to this group: they may be found as well in stars that are not associated with nebulosity.

Herbig 1960

Theoretical definition of “Intermediate” Mass

- Upper limit: 8
  - evolution: SN, winds
  - formation: no PMS, importance of radiation pressure, formation of HII region
- Lower limit: 1.5-3
  - evolution: significant mass loss
  - formation: multiplicity, radiative PMS

Palla & Stahler 2005



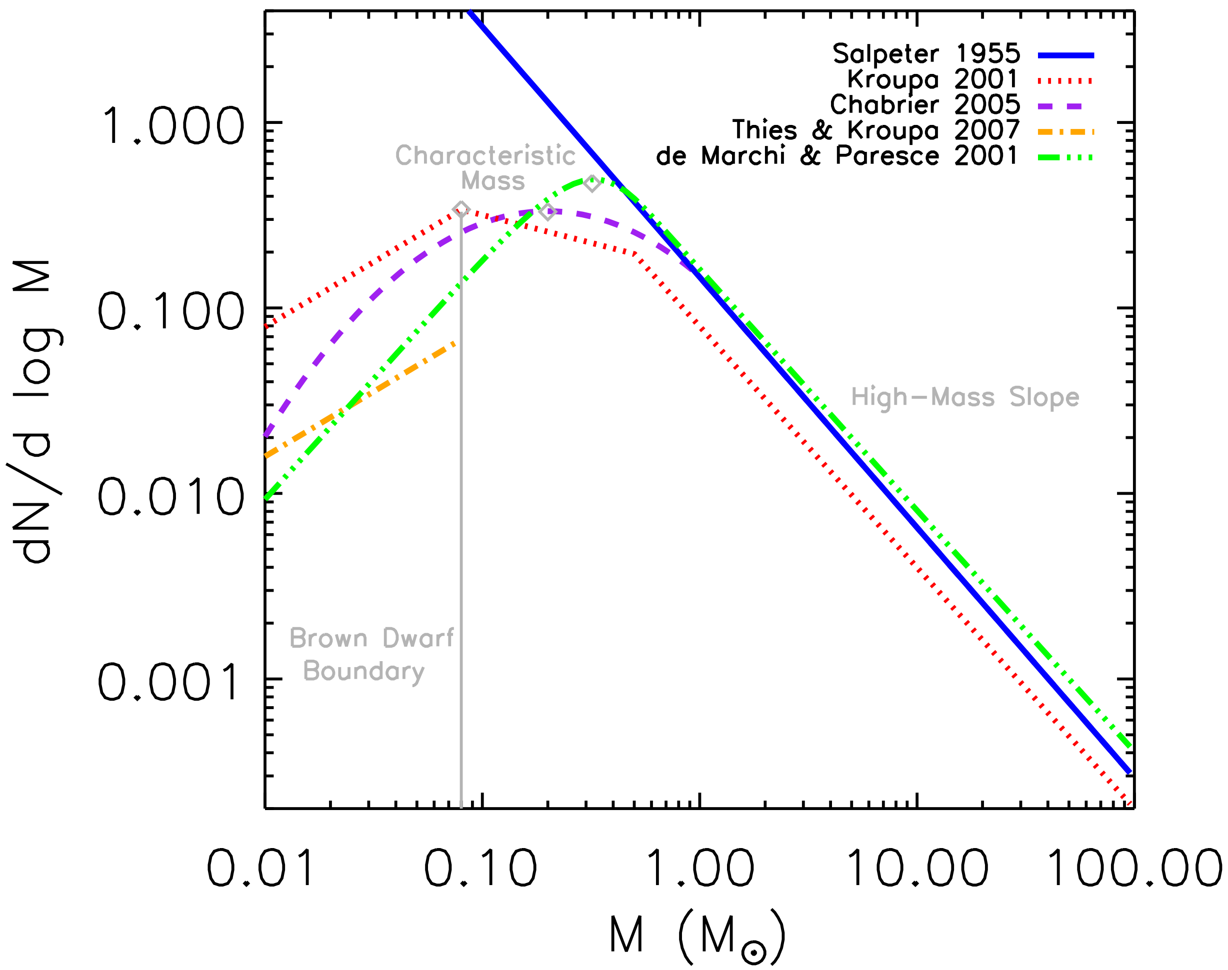
Herbig Ae/Be’s don’t quite match up..

Intermediate Mass Stars are in the Transition Zone

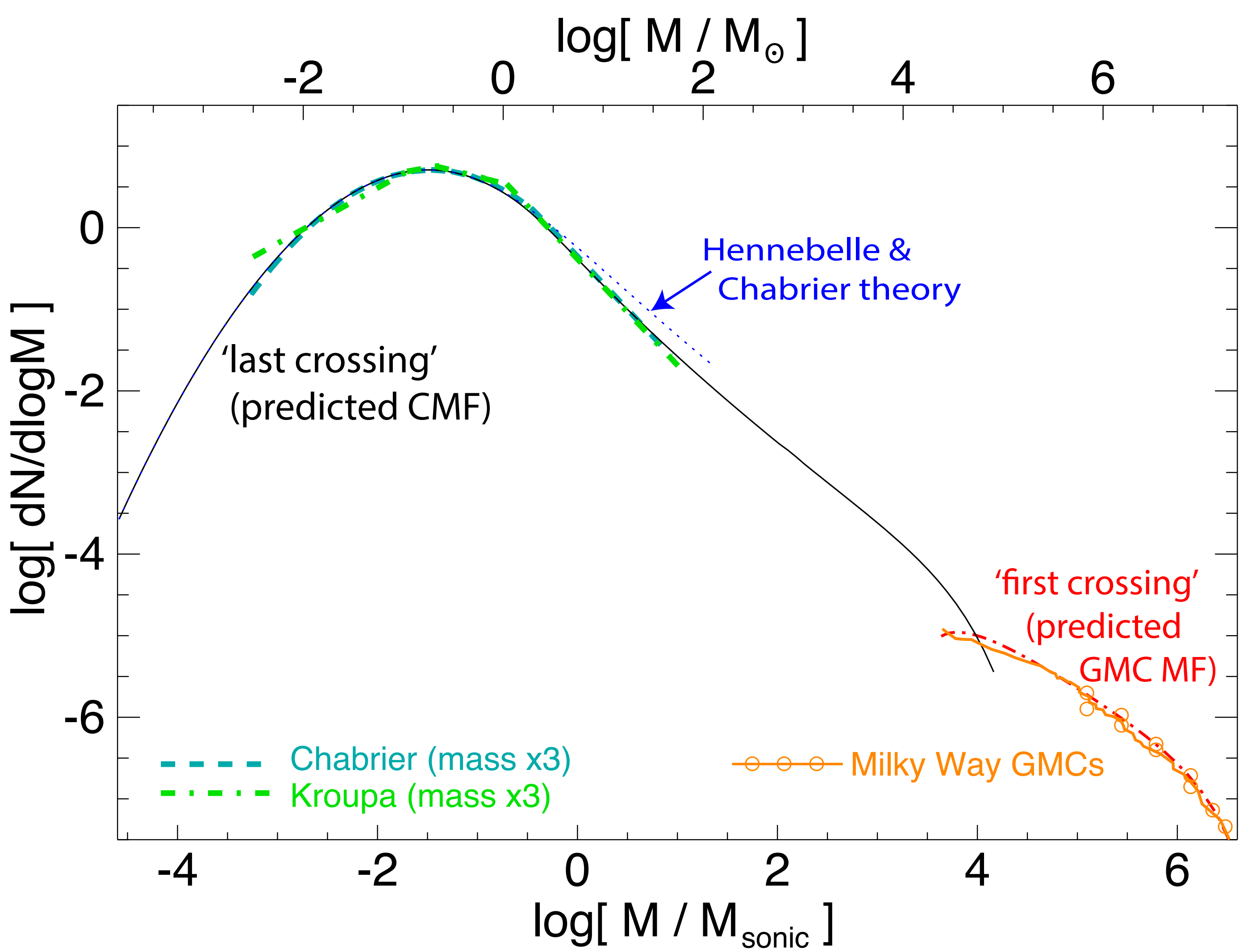
- Luminosities: **transition** zone in stellar structure on the PMS (or the end of the PMS)
- Accretion rates onto cores: **transition** zone between non-turbulent and turbulent initial conditions
- Ionization: **transition** zone between irrelevance and HII region dominated feedback
- Disks and Planets: the last (but easier to image) place for planets?

Does transition imply a break in formation process?

Do we need more than one mode of star formation: CMF vs IMF

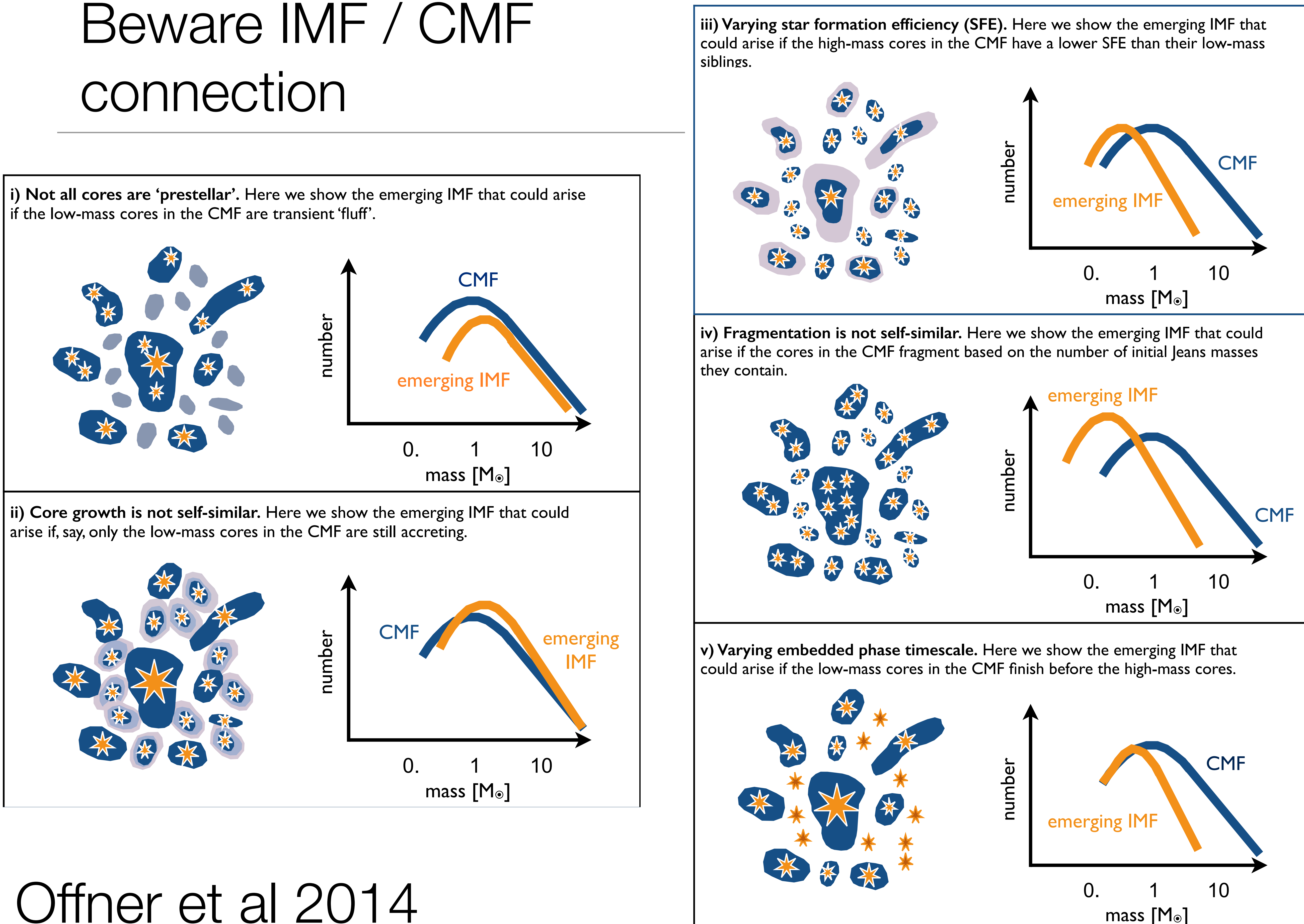


Possible evidence for a single mode?



Offner et al 2014

Beware IMF / CMF connection



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.

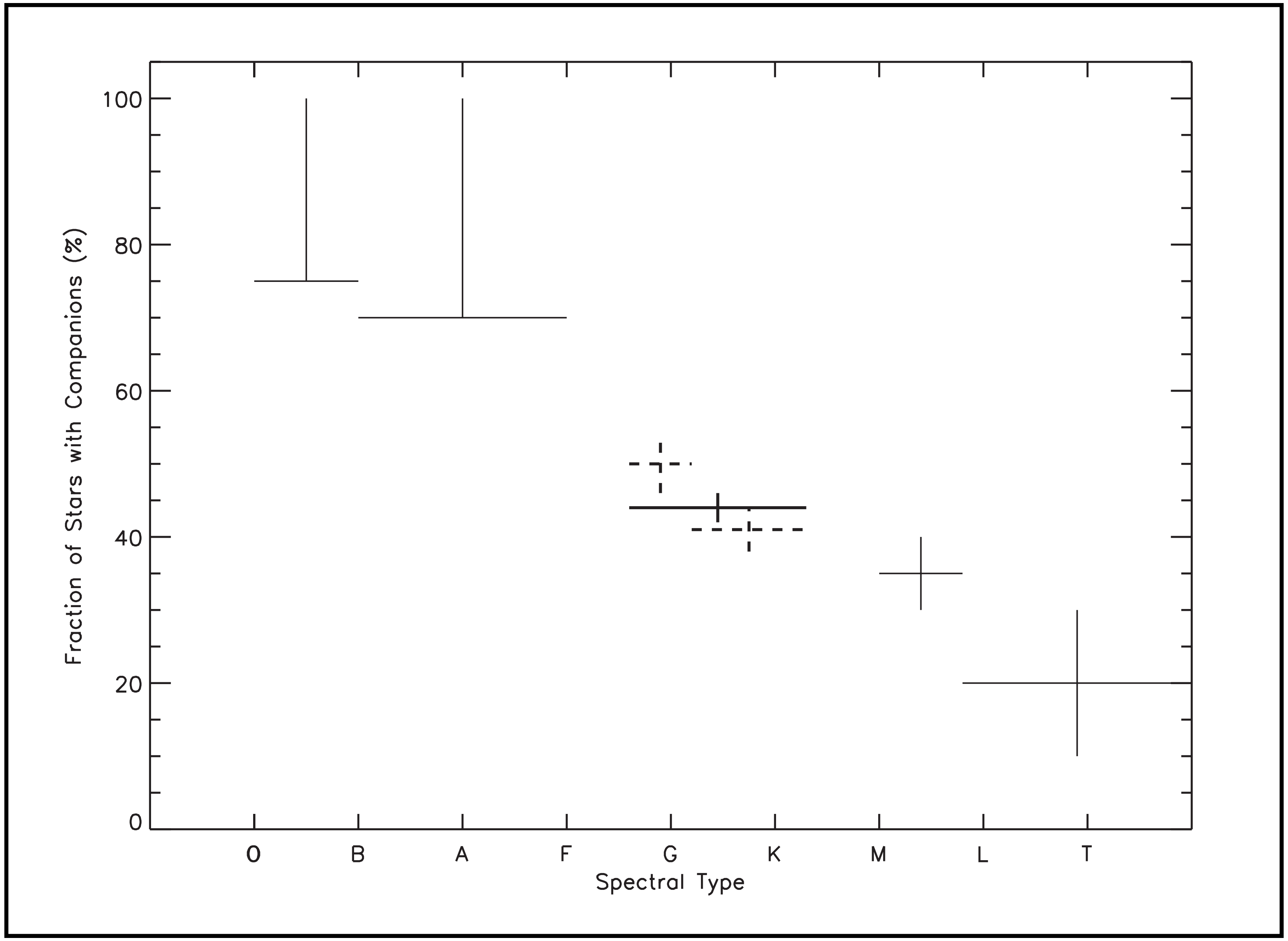
iii) Varying star formation efficiency (SFE). Here we show the emerging IMF that could arise if the high-mass cores in the CMF have a lower SFE than their low-mass siblings.

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.

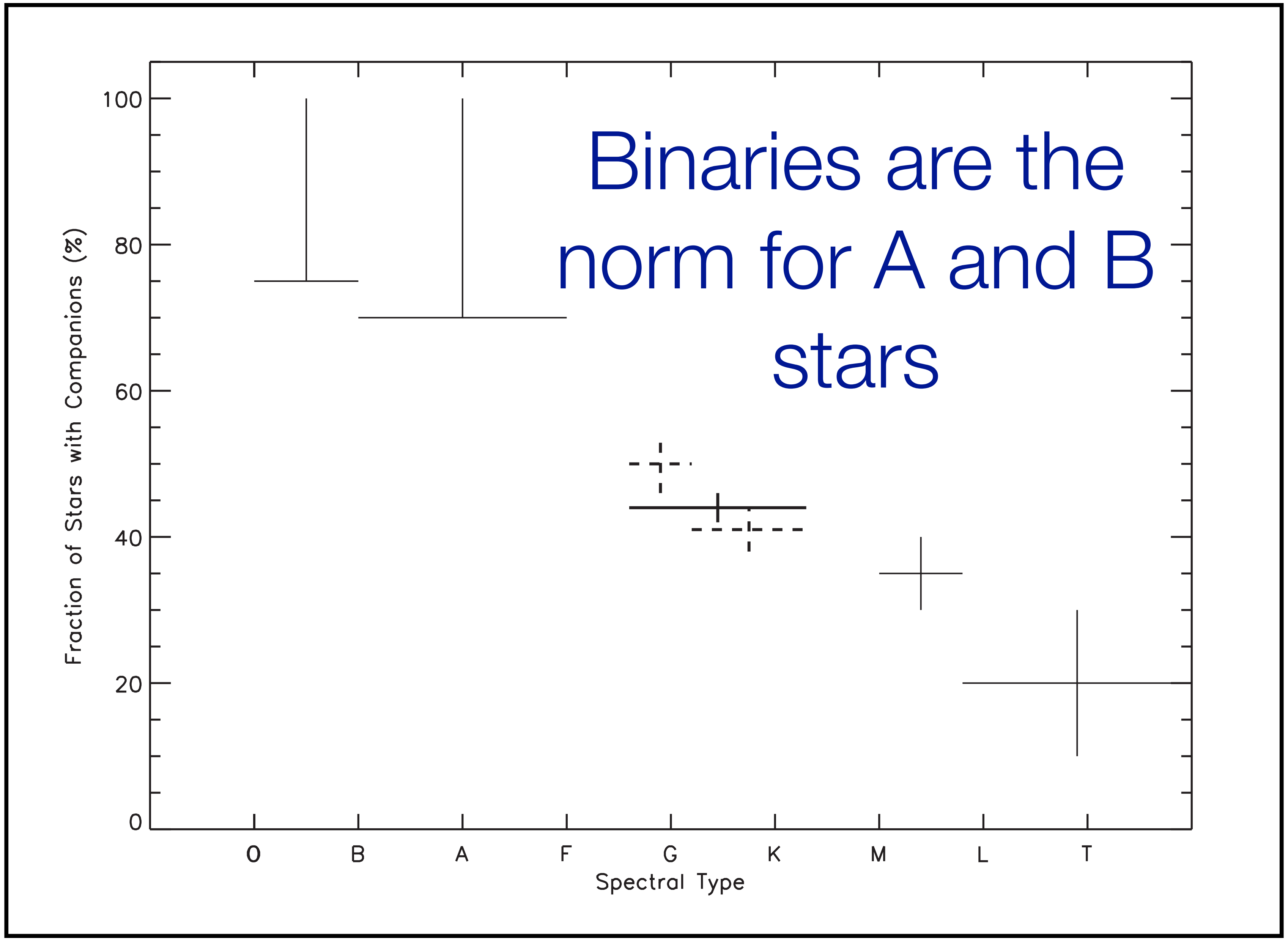
Offner et al 2014

Multiplicity is **Mass** Dependent



Raghavan 2010

Multiplicity is **Mass** Dependent



Raghavan 2010

Two Star Formation Models

- Competitive Accretion
- Turbulent Core Fragmentation

Two Star Formation Models

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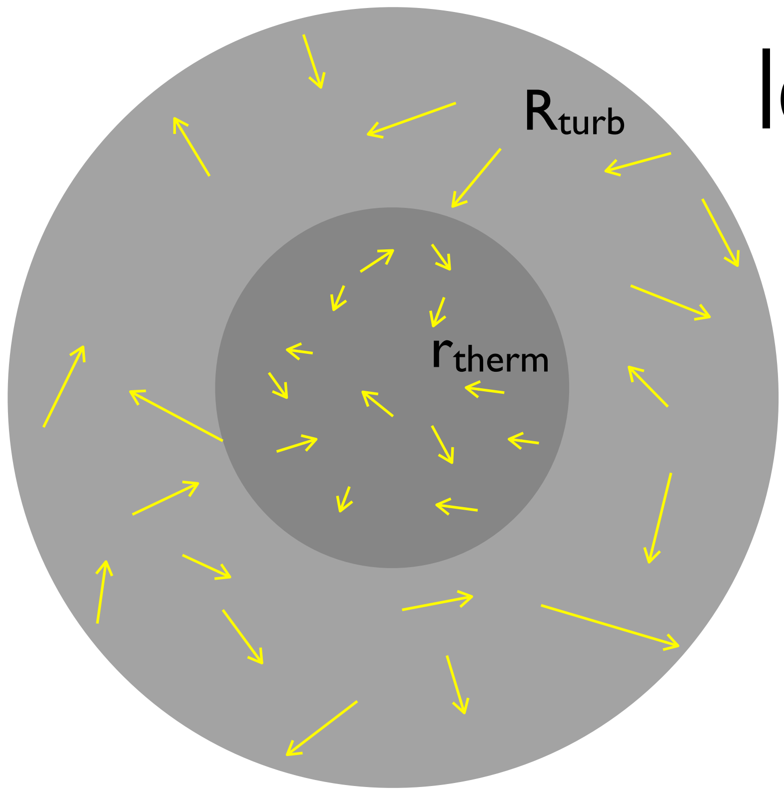
Two "camps" are converging. Elements of both cartoons are likely correct.

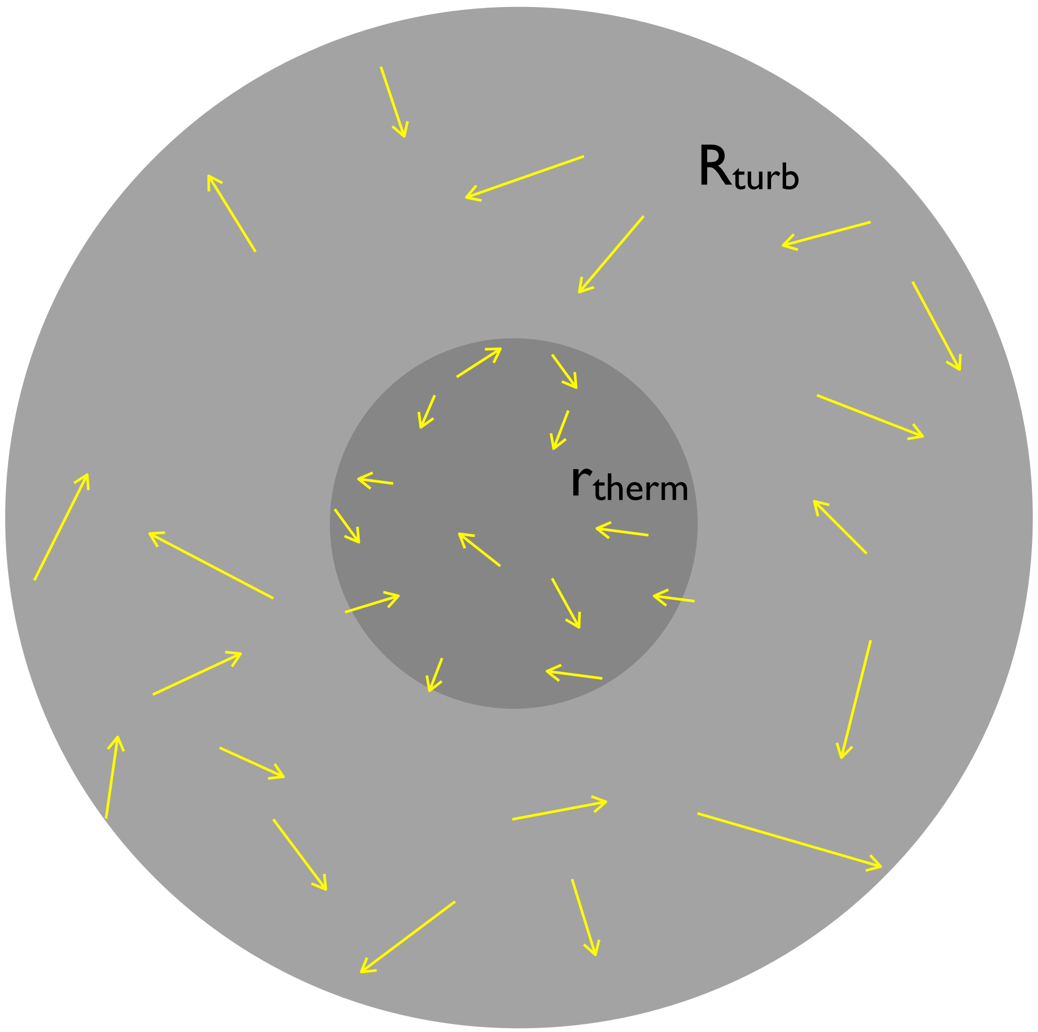
Padoan 1995,
McKee & Tan 2004

Turbulent Core Accretion



lower mass

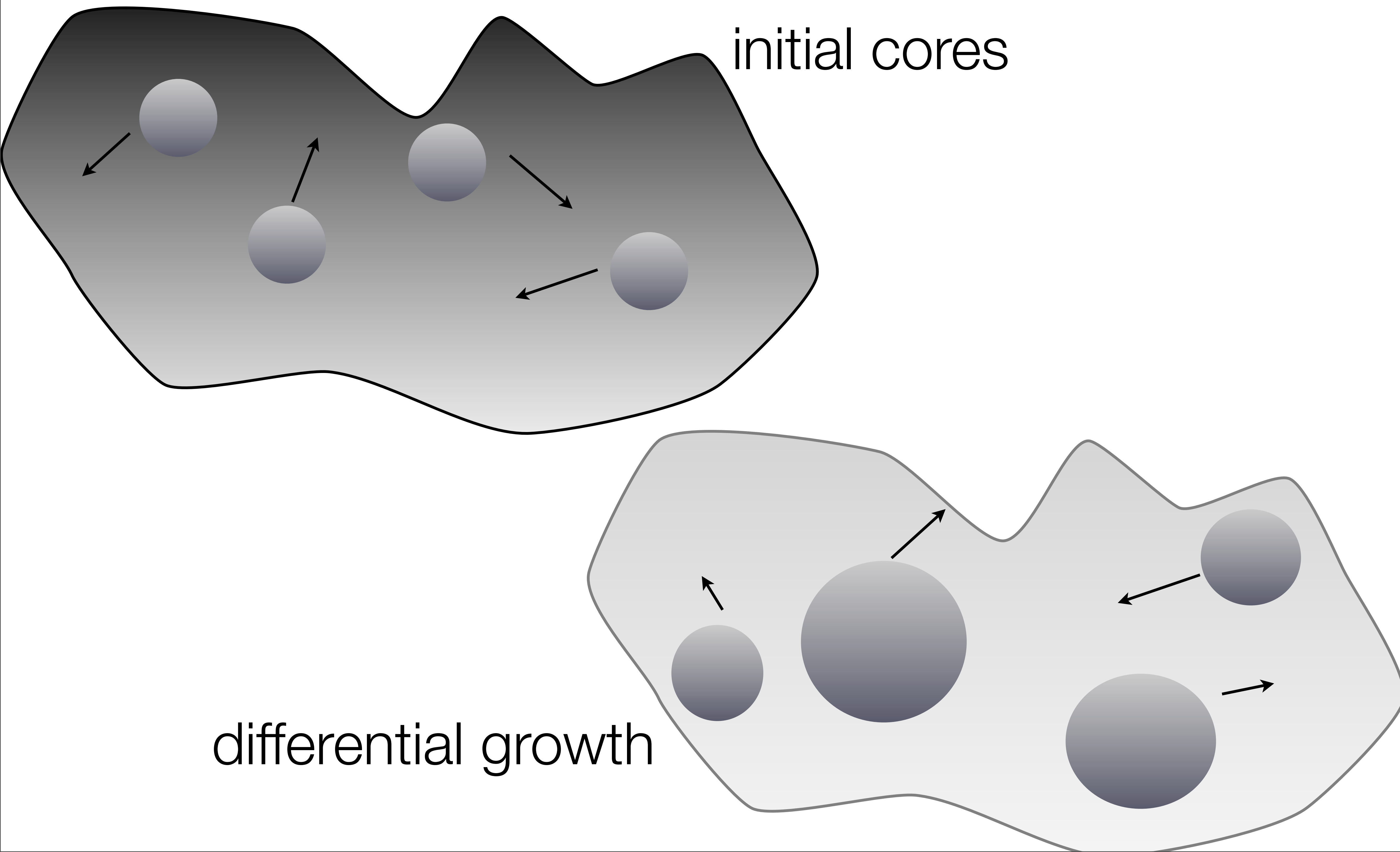
higher mass



- Scaling up from A to O changes contribution of thermal core
- This causes change in accretion rate with core mass

Bonnell et al 1997

Competitive Accretion

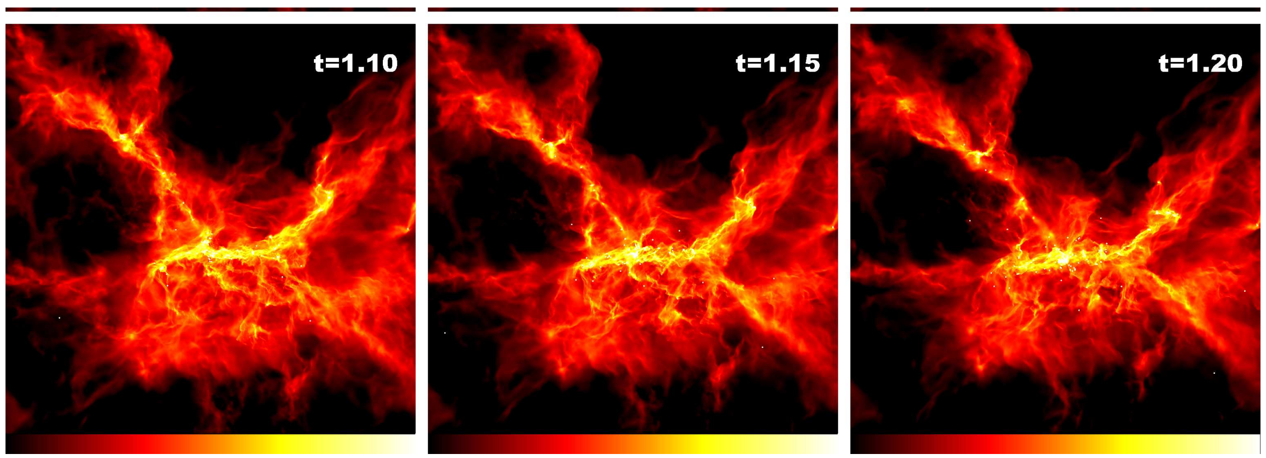


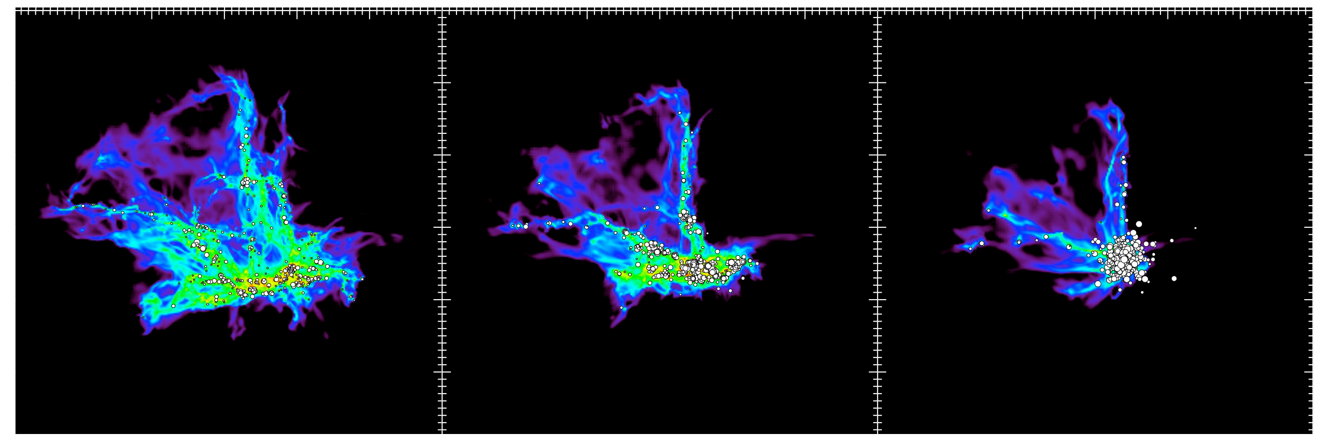
Do we need more than one formation model theoretically?

- Competitive Accretion: No. All stars start the same, and intermediate mass ones grow more, but not as much as massive ones

- Turbulent Core Model: No. There exists a spectrum of density perturbations that seed stars of different masses

Comparing two numerical models that create intermediate mass stars





Bate 2012: CA

Krumholz et al 2012: TC

numerical differences

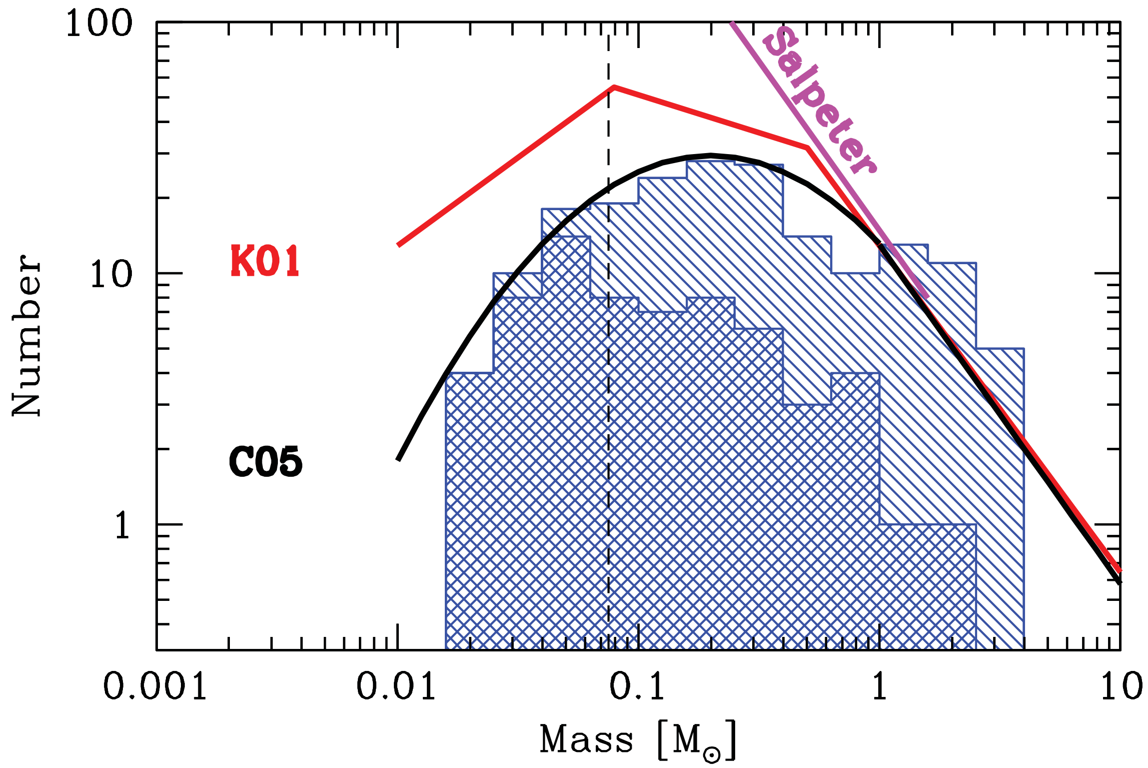
	CA	TC
turbulent spectrum	k^{-4}	k^{-2}
density	$1.2 \times 10^{-19}\ r^0$	$8.6 \times 10^{-18}\ r^{-1.5}$
Feedback	radiation	radiation, winds
$\mathcal{M}$	13	7.5

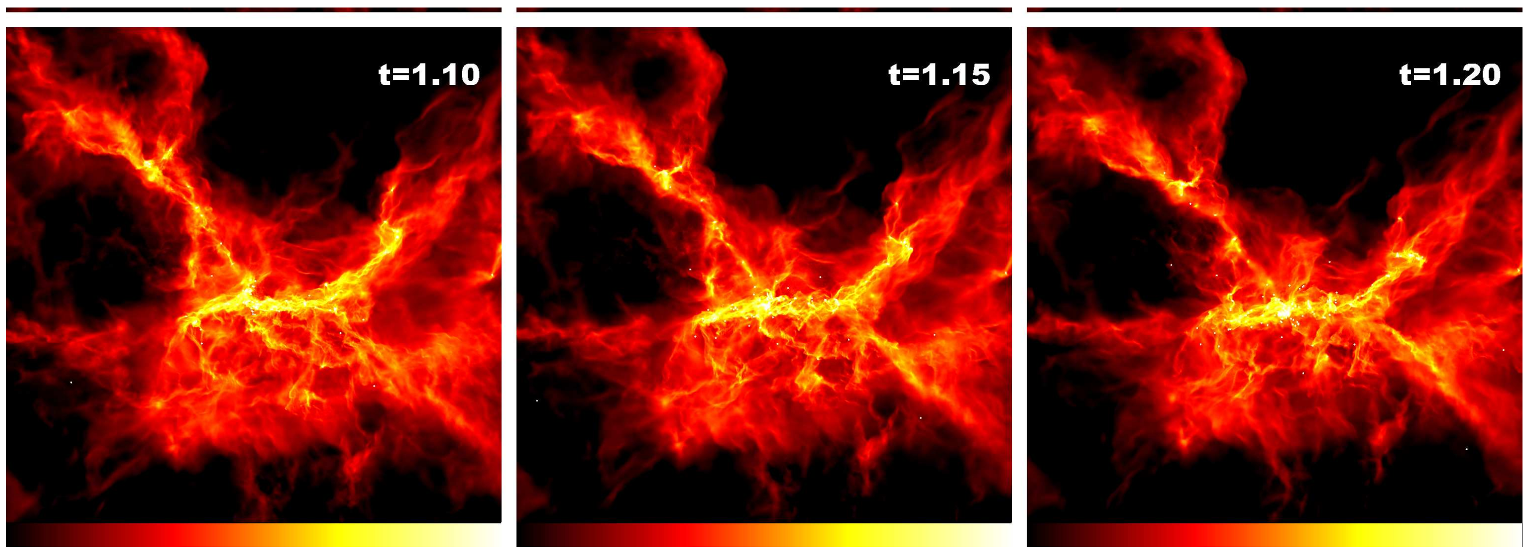
Competitive Accretion: Source for Herbig Ae/Be

Table 2. The numbers of single and multiple systems for different primary mass ranges at the end of the radiation hydrodynamical calculation.

Mass range ($M_\odot$)	Single	Binary	Triple	Quadruple
$M < 0.03$	7	0	0	0
$0.03 \le M < 0.07$	20	0	0	0
$0.07 \le M < 0.10$	8	3	0	0
$0.10 \le M < 0.20$	17	7	1	0
$0.20 \le M < 0.50$	21	9	2	2
$0.50 \le M < 0.80$	5	2	0	1
$0.80 \le M < 1.2$	2	1	1	0
$M > 1.2$	4	6	1	4
All masses	84	28	5	7

- Low mass end only (consistent with cluster mass)
- Tend to be in the center of the potential well
- Good agreement with field multiplicity and IMF

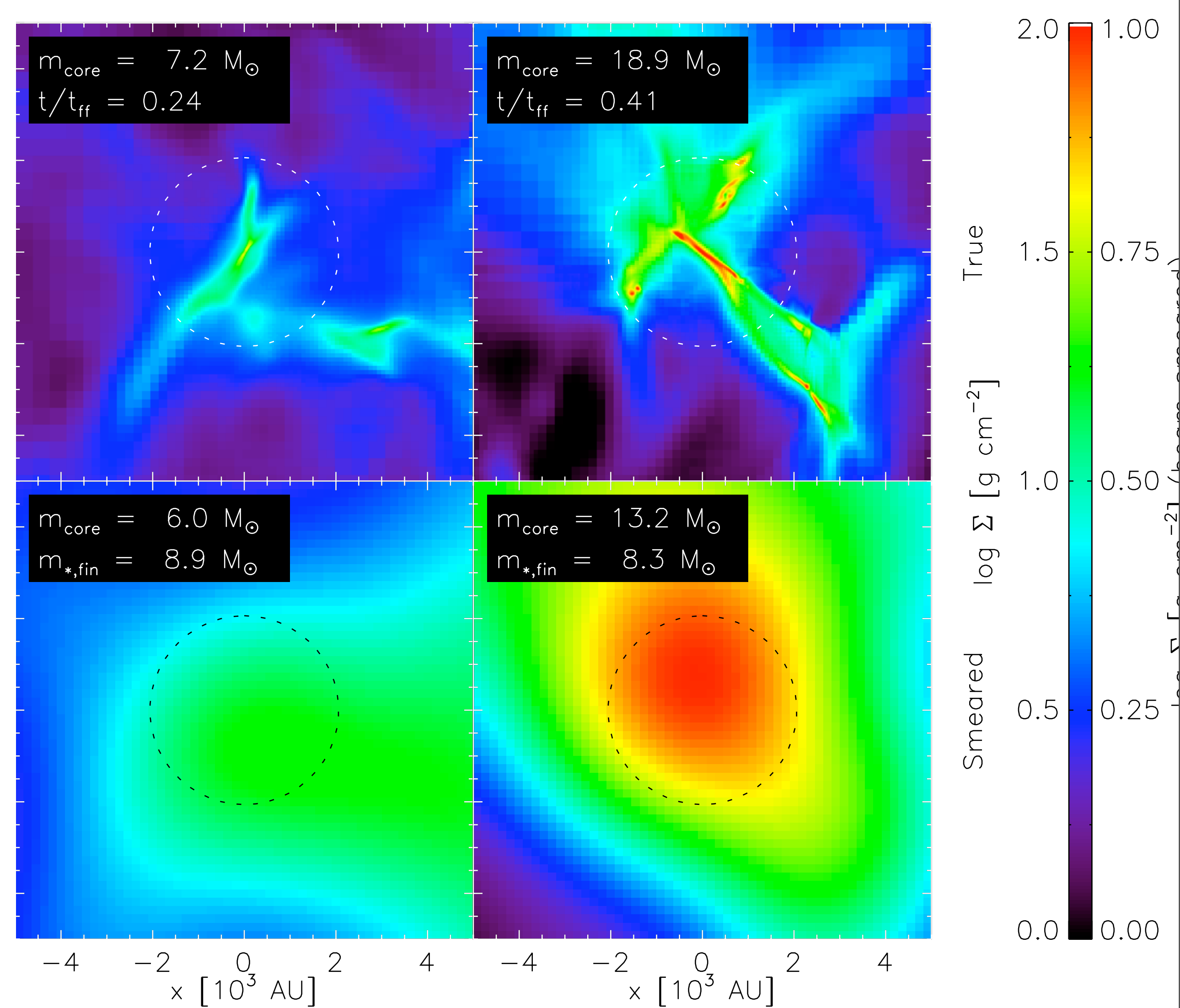


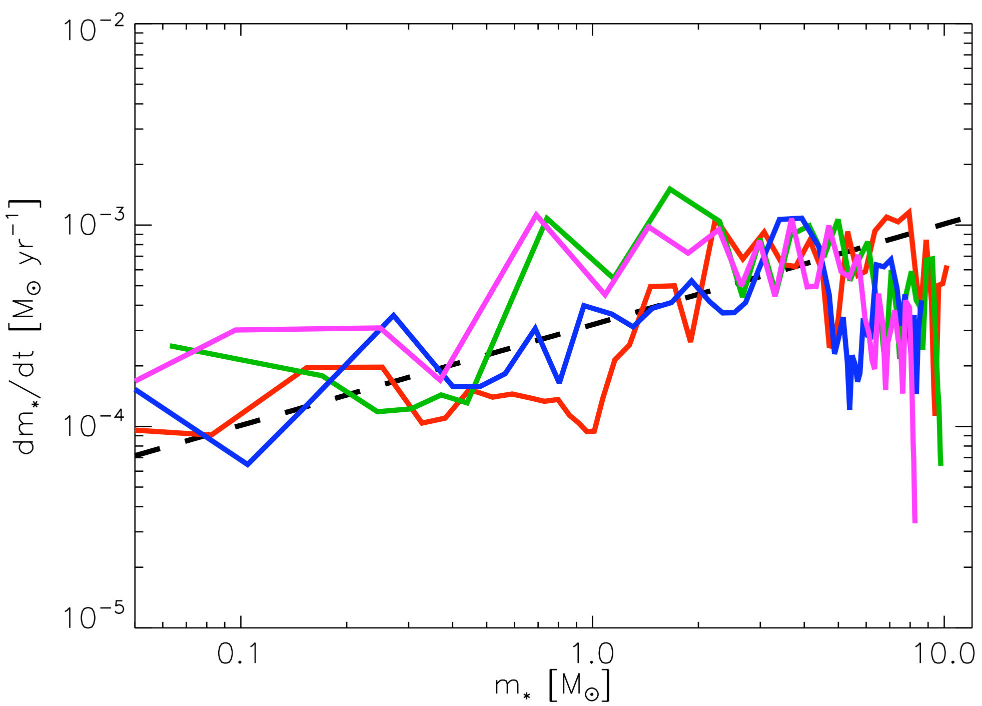


SFE too high

Turbulent Core with winds, radiation

- Feedback reduces SFE (not enough)
- Massive cores don't all fragment
- Sub fragmentation not visible even when occurring (see Schnee et al 2009, Offner et al 2012)



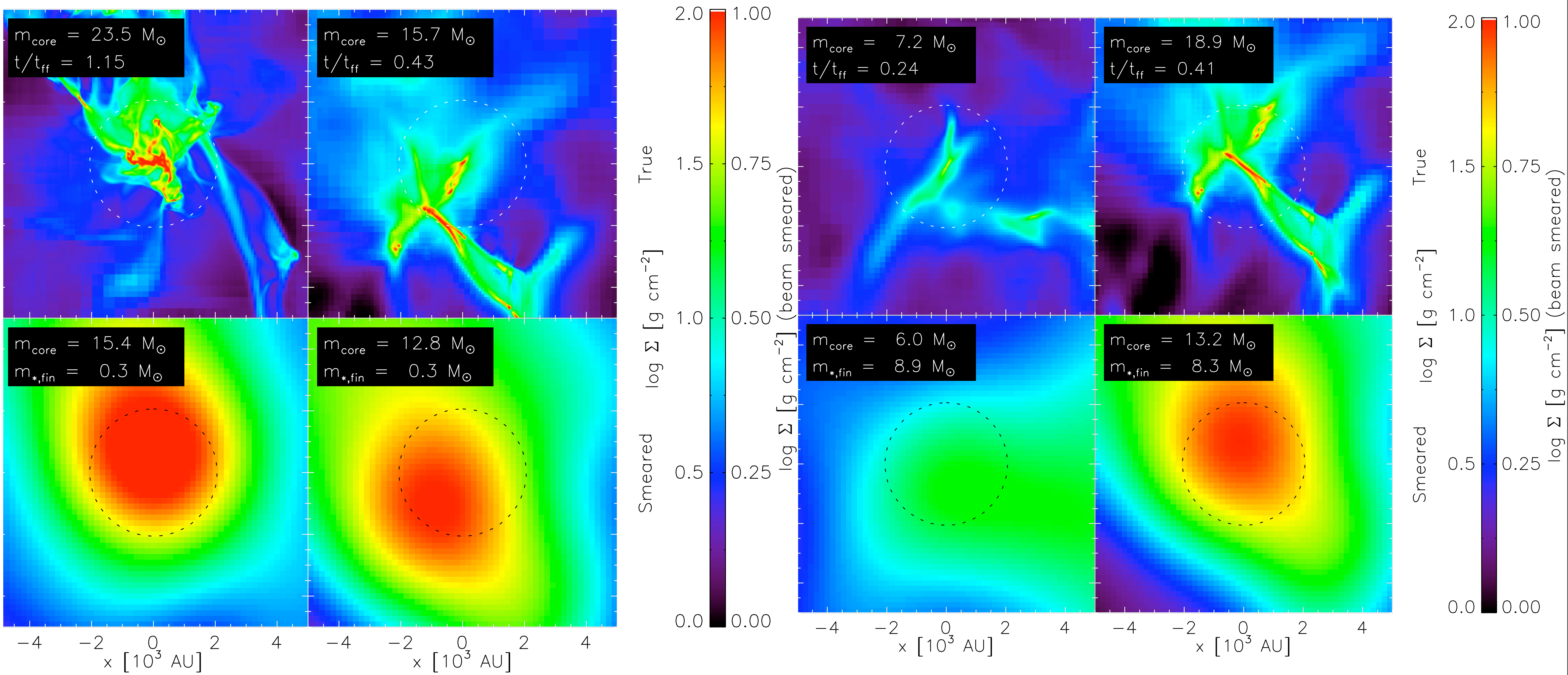


McKee & Tan 2004

$$\dot{m}_* = 1.2\times10^{-3} \left(\frac{m_{*f}}{30\,M_\odot}\right)^{3/4} \Sigma_{\rm cl}^{3/4} \left(\frac{m_*}{m_{*f}}\right)^{1/2} M_\odot\ {\rm yr}^{-1},$$

Krumholz et al 2012

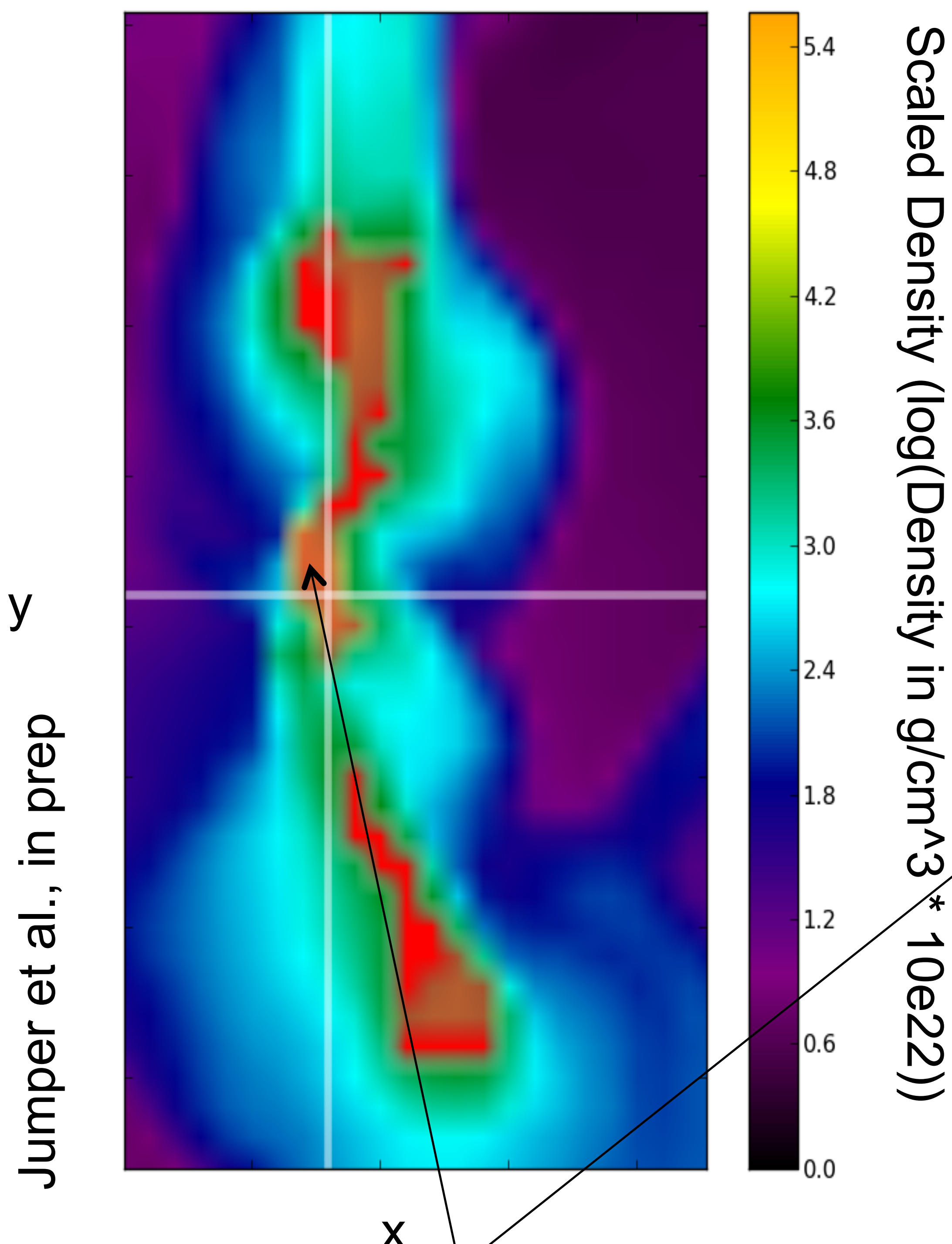
Low vs Intermediate / High Mass Stars

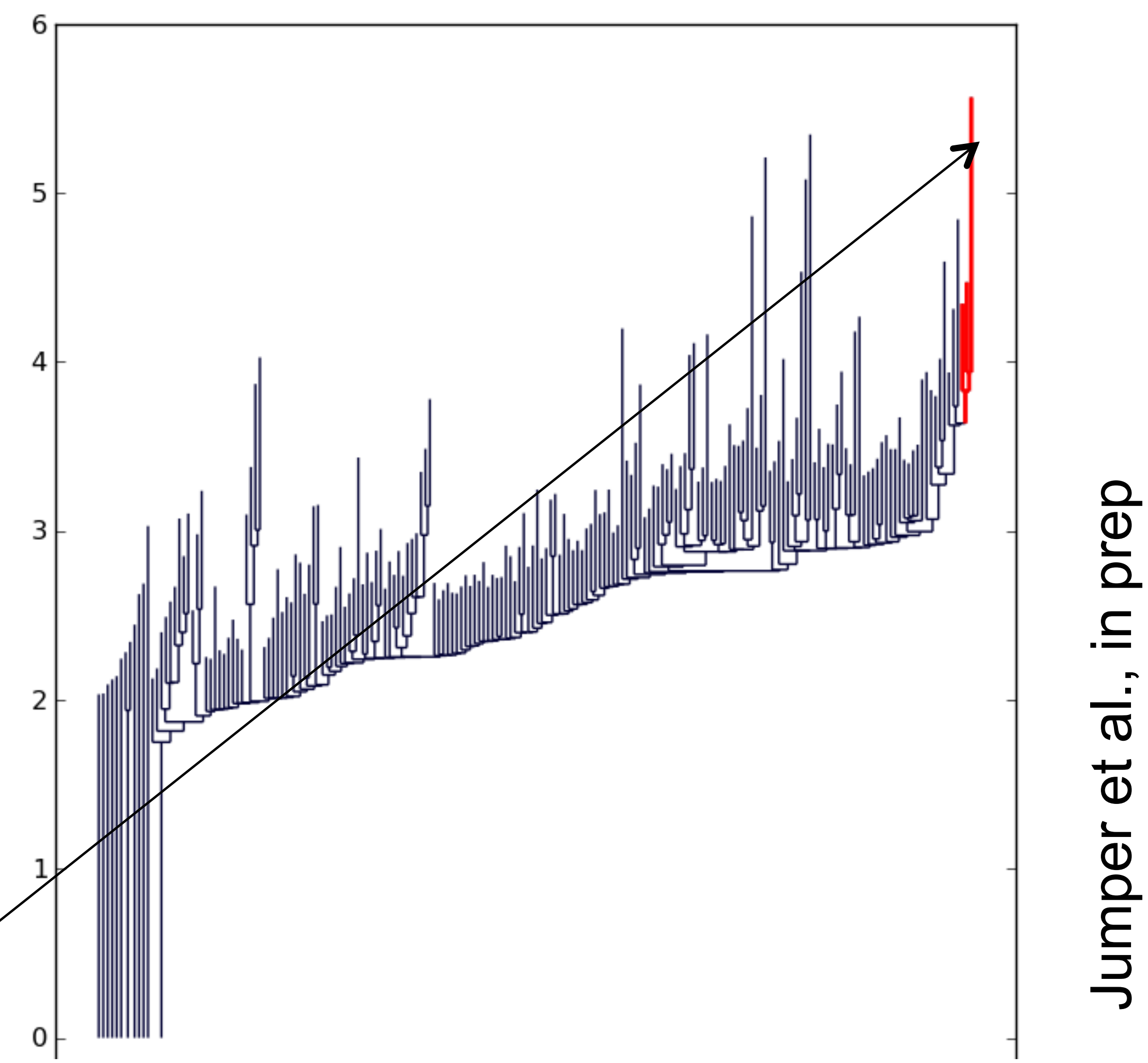


“Cores” are not different in mass, but in fragmentation properties. The distinction is due to stochastic ICs, location in potential.

Like CA: massive stars need potential. Like TC: identifiable, long lasting core.

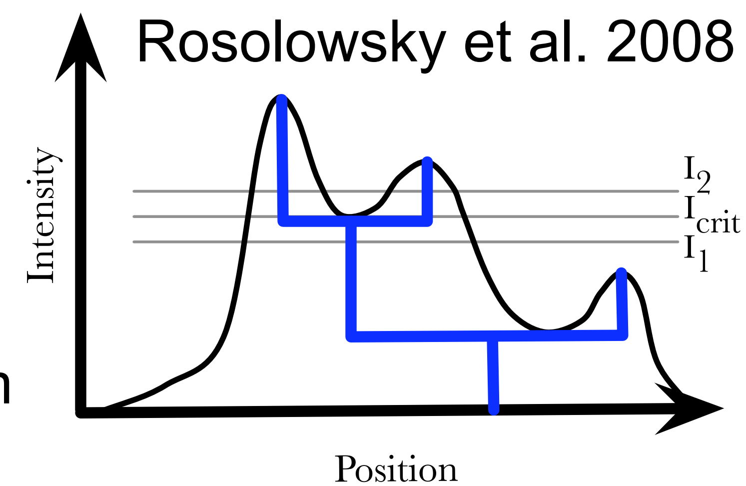
Understanding turbulent fragmentation

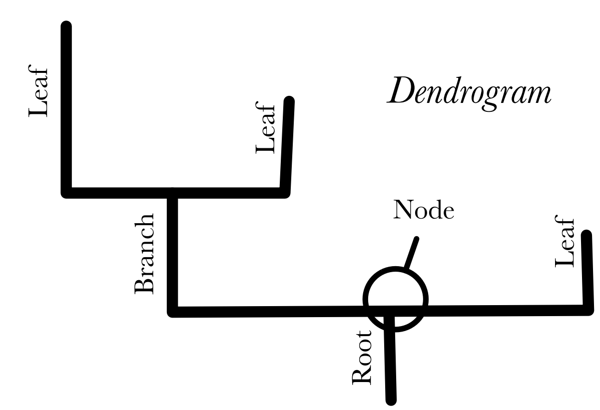




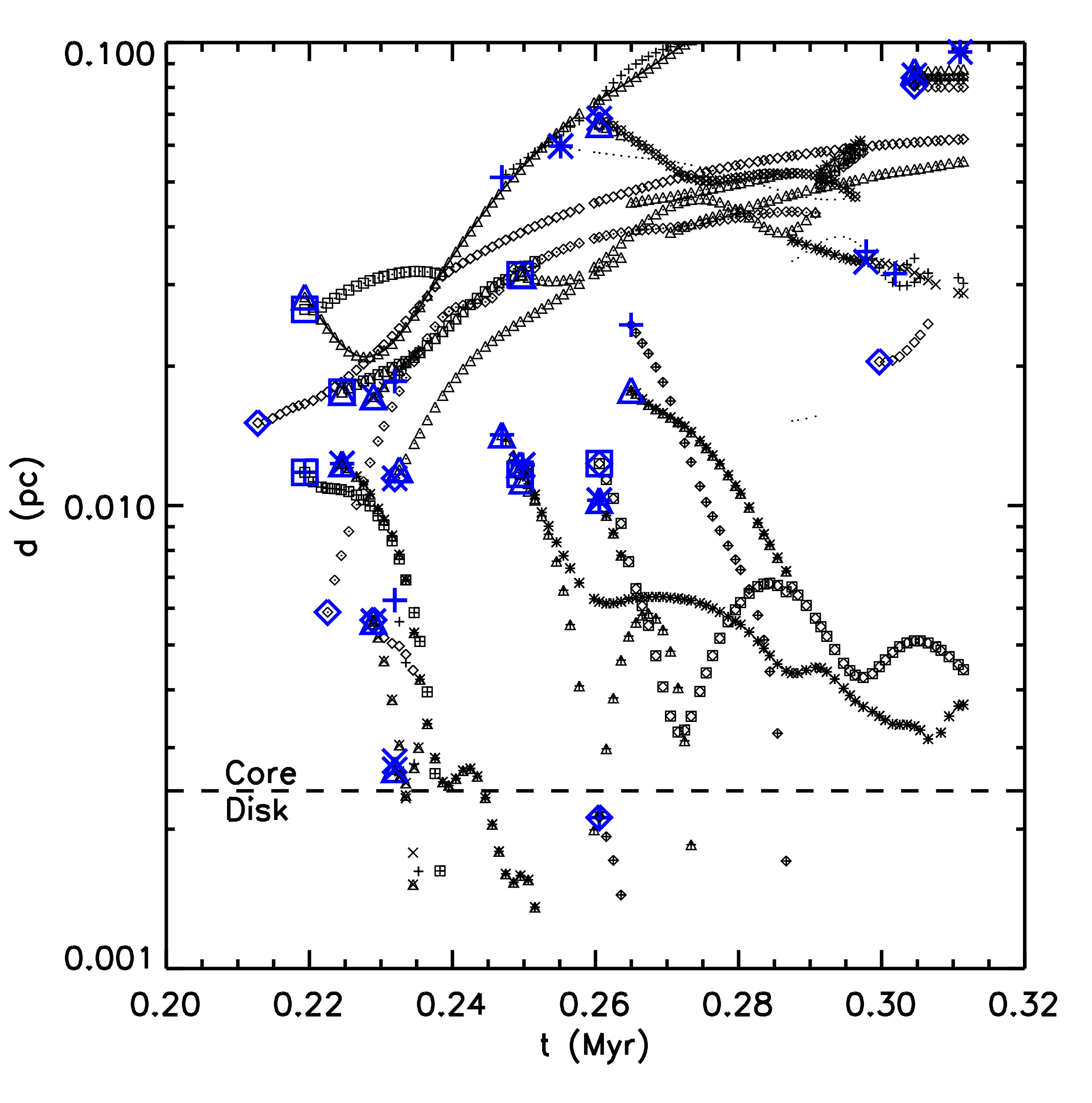
A structure and its corresponding dendrogram representation, both highlighted in red.

Rosolowsky et al. 2008



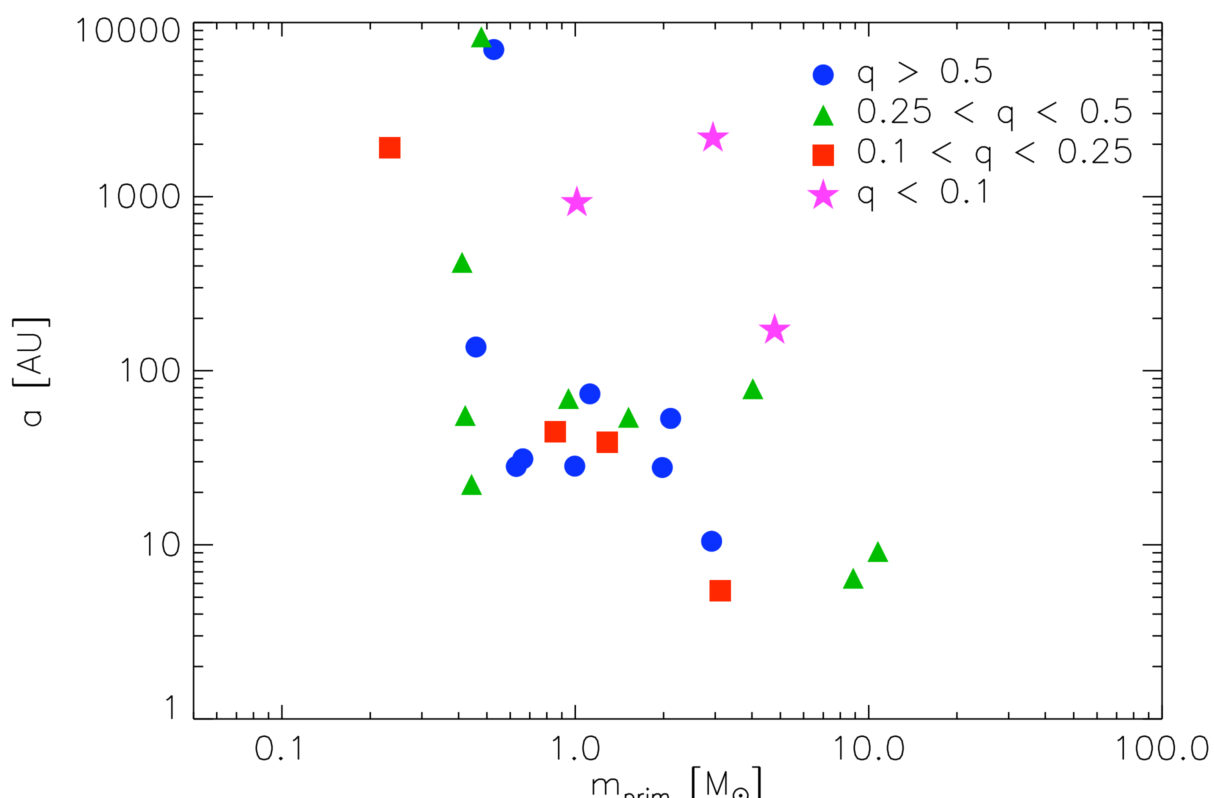


Binaries form from filaments on these scales, then evolve

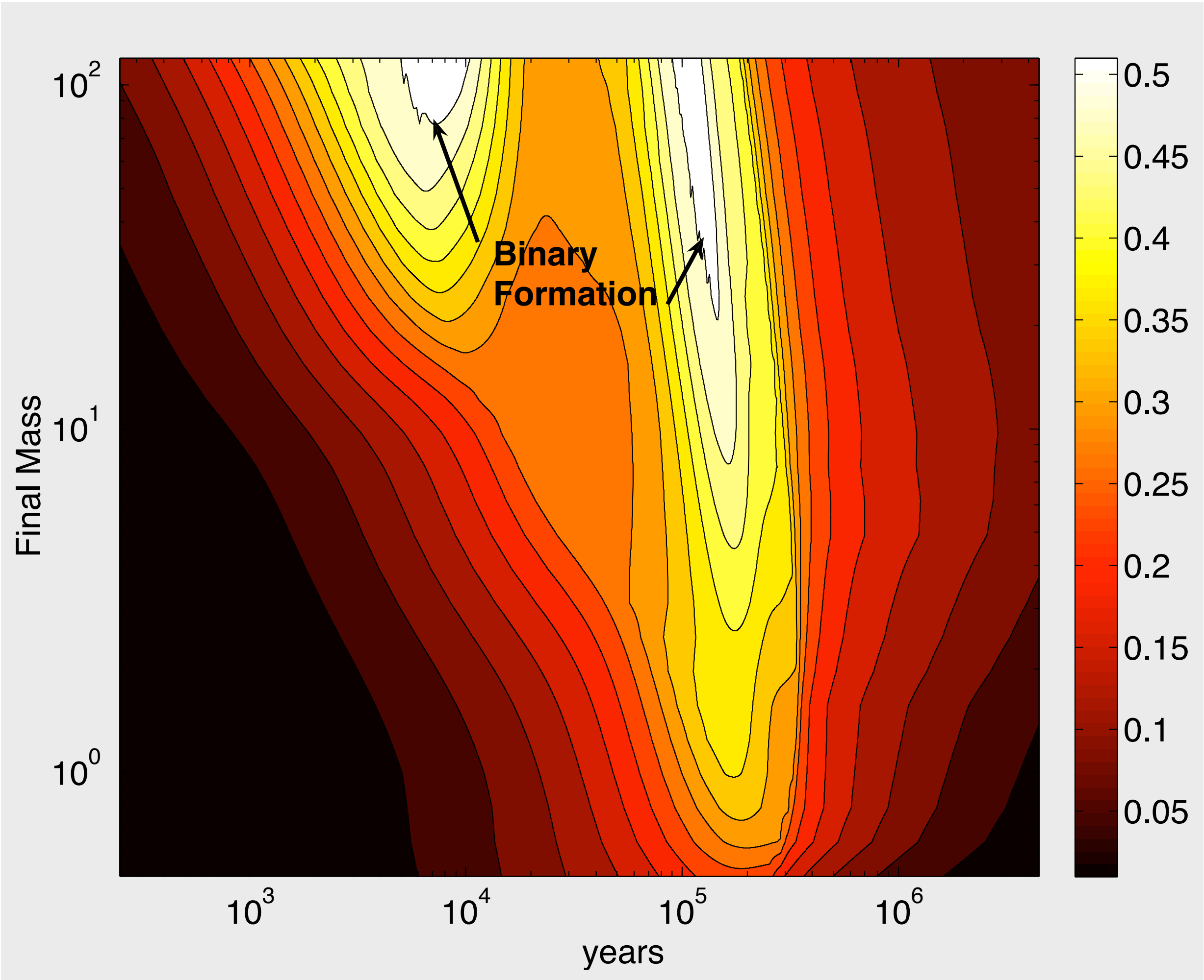


Offner, Kratter et al 2010,
Krumholz et al 2012

- Both low and high mass star form binaries and interact at early times
- Lower mass star form in highly fragmented cores start out in very hierarchical multiples, but likely decay
- Higher mass stars form as multiples in centrally condensed regions, and may keep a higher fraction of bond companions



Disk Fragmentation becomes alternate binary formation mechanism for more massive stars



Intermediate mass stars might harbor massive, self-gravitating disks at early times. Magnetic disk instabilities should also be more efficient

Kratter et al 2008, 2010

How do we know if disks fragment?

Environment → **Derived**

$$\Gamma = \frac{\dot{M}_{\rm in}}{M_{*d}\Omega(R_{\rm circ})}$$

set by core/ turbulence: orbital time / mass doubling time

$$\xi = \frac{\dot{M}G}{c_{\rm s,disk}{}^3}$$

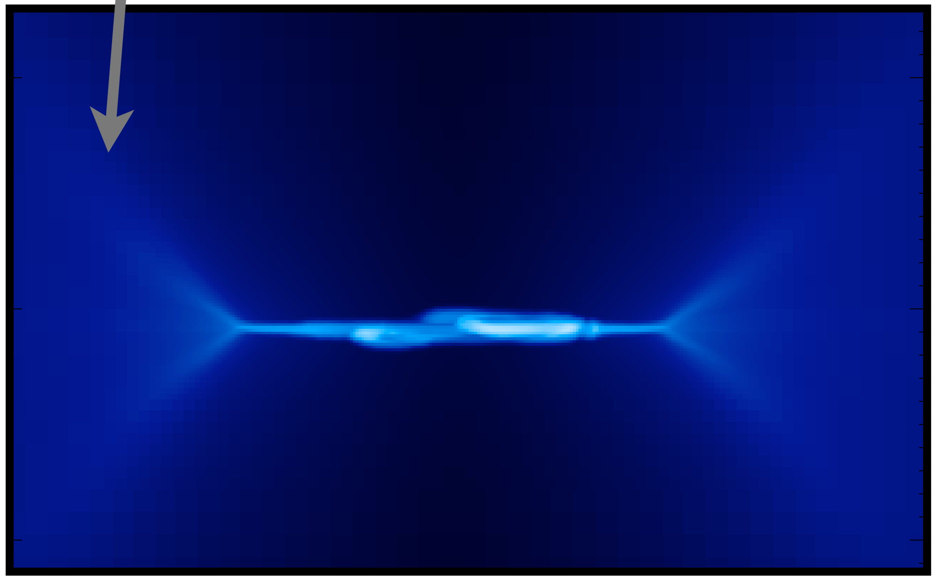
set by core and disk thermodynamics

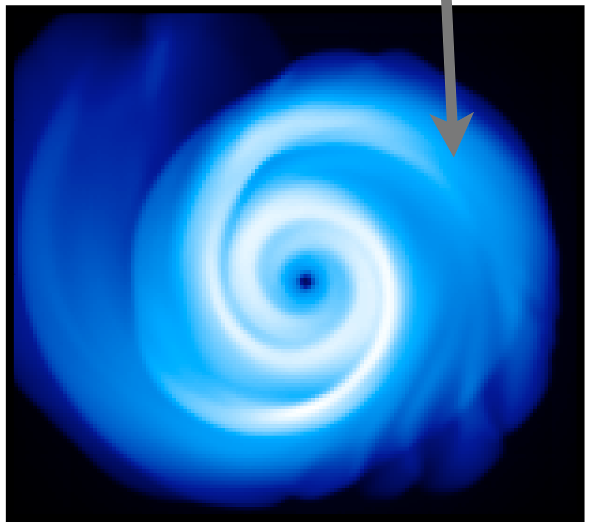
$$\mu = \frac{M_d}{M_d + M_*}$$

set by relative accretion rates

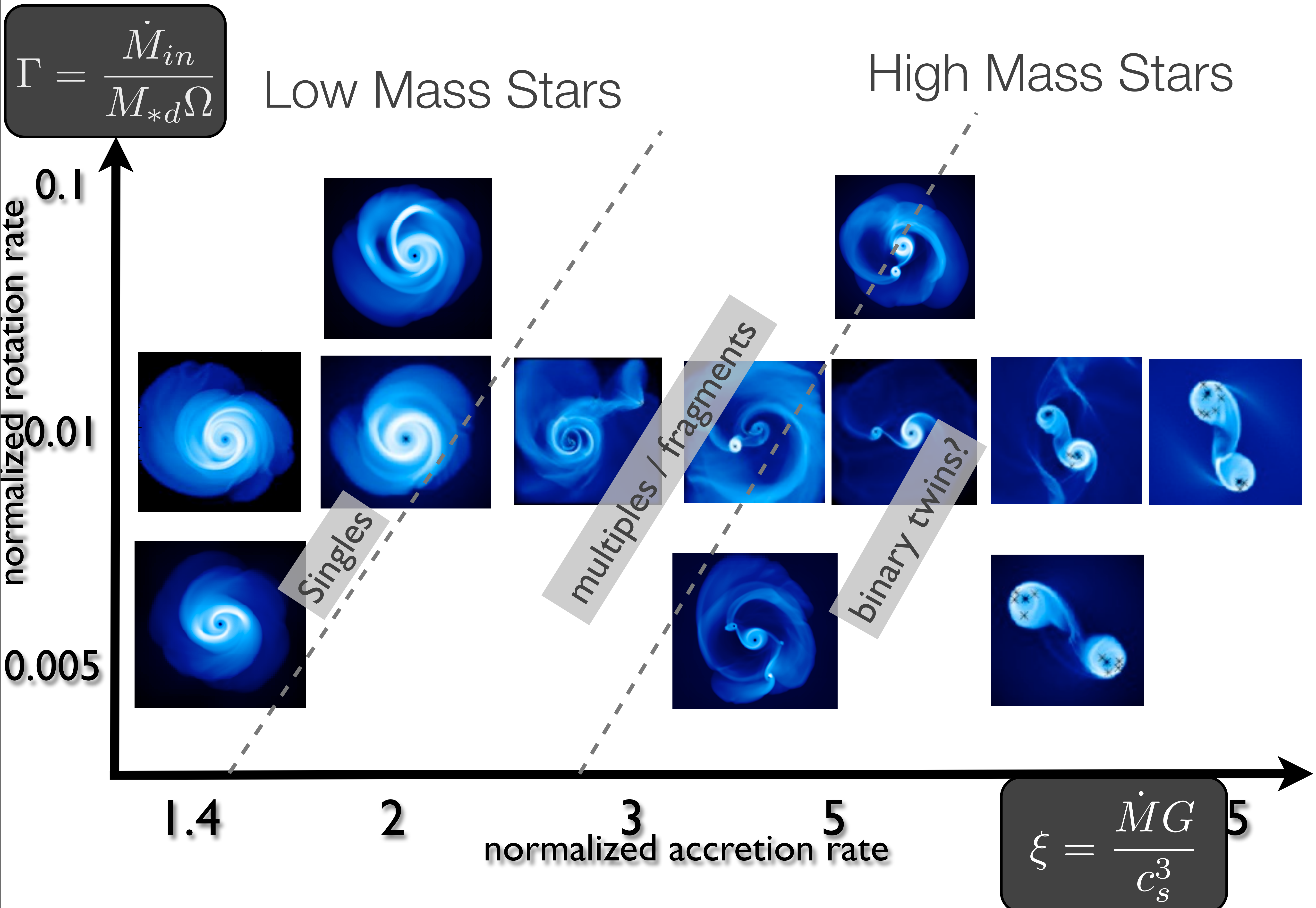
$$Q = \frac{c_s\kappa}{\pi G \Sigma}$$

purely local disk quantity





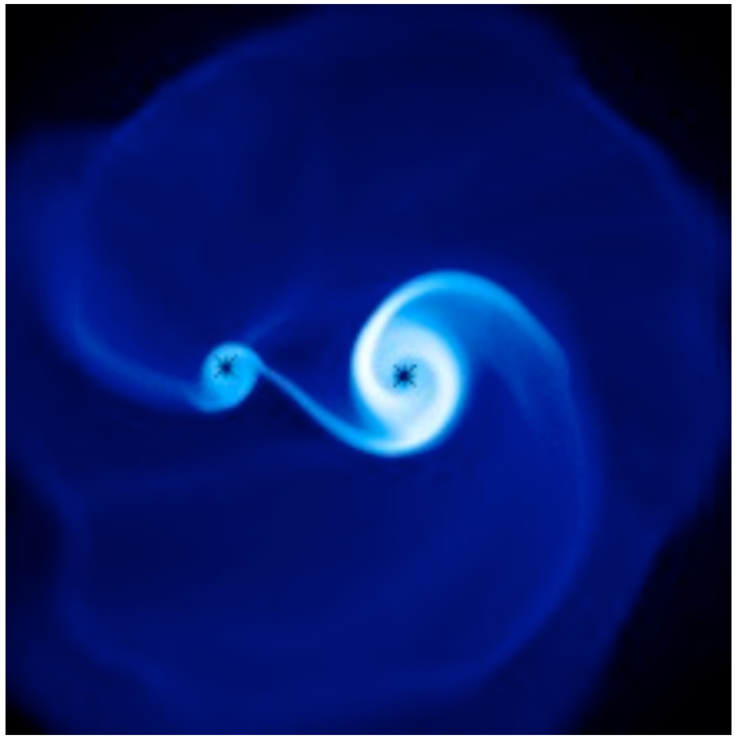
Toomre, 1964, Kratter et al 2008, 2010



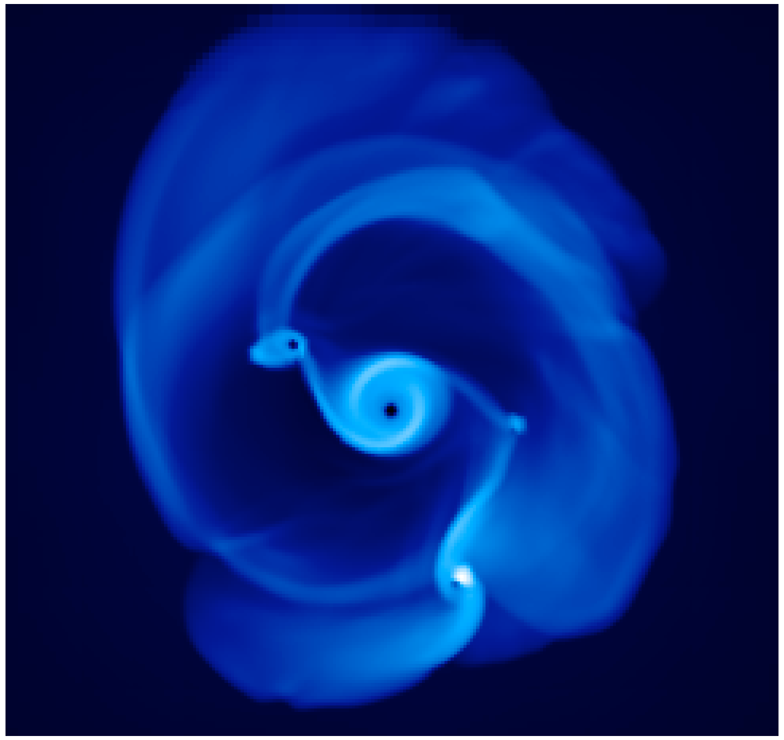
Kratter et al 2010

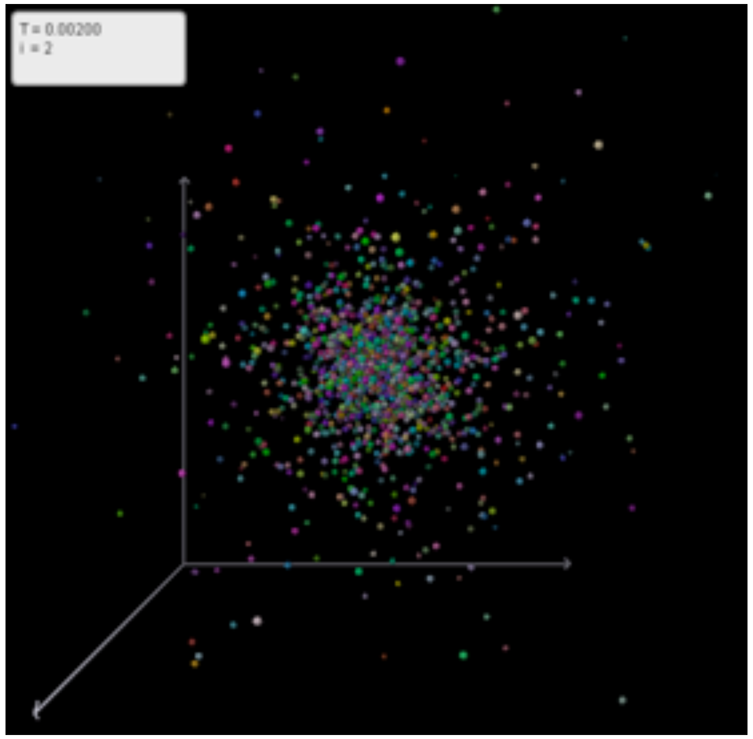
Orbital properties are not fixed at birth

- Cluster Evolution
- Dynamical Interactions
- Disk interactions?



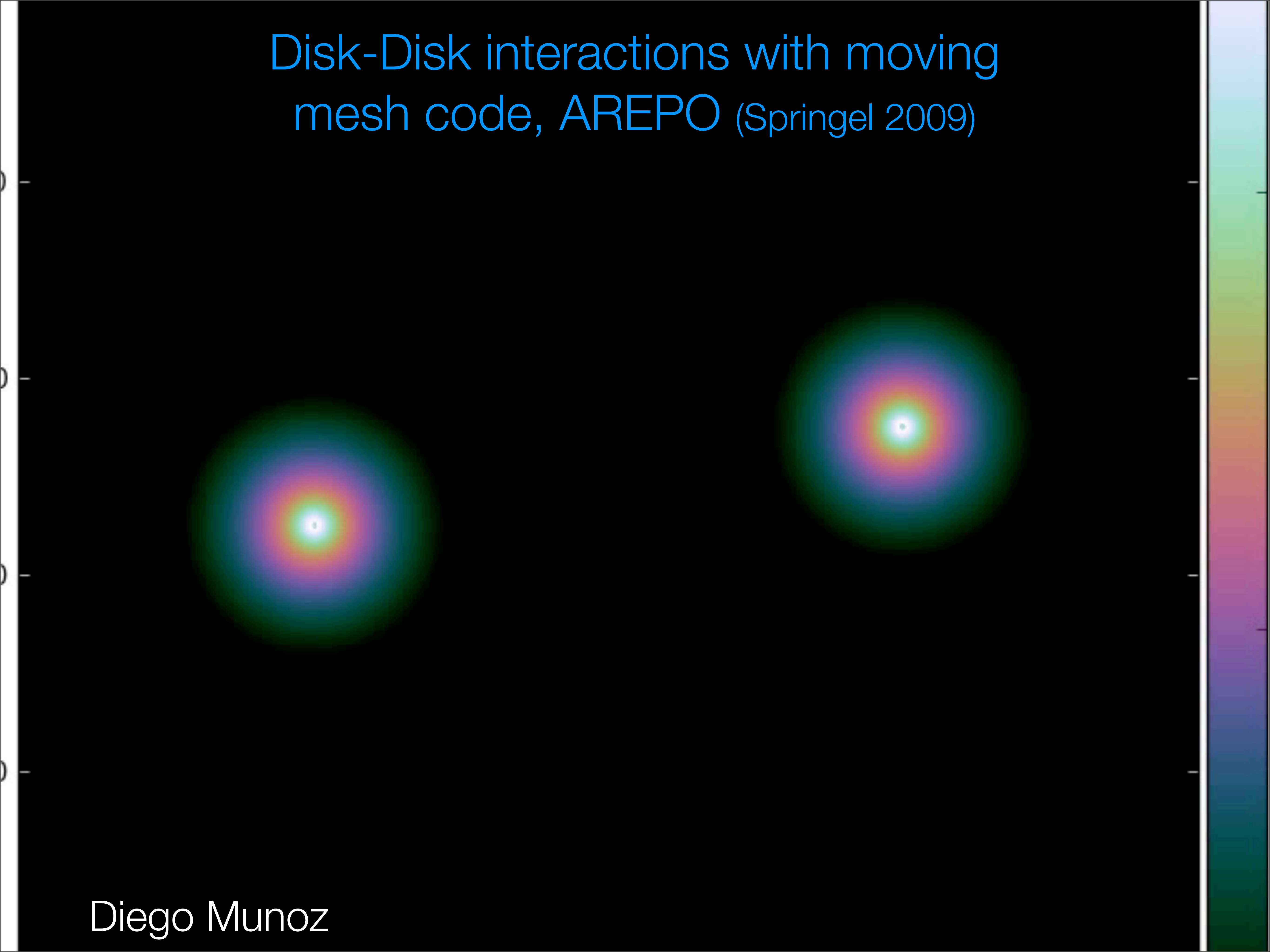
Kratter et al 2010





Kroupa 1995

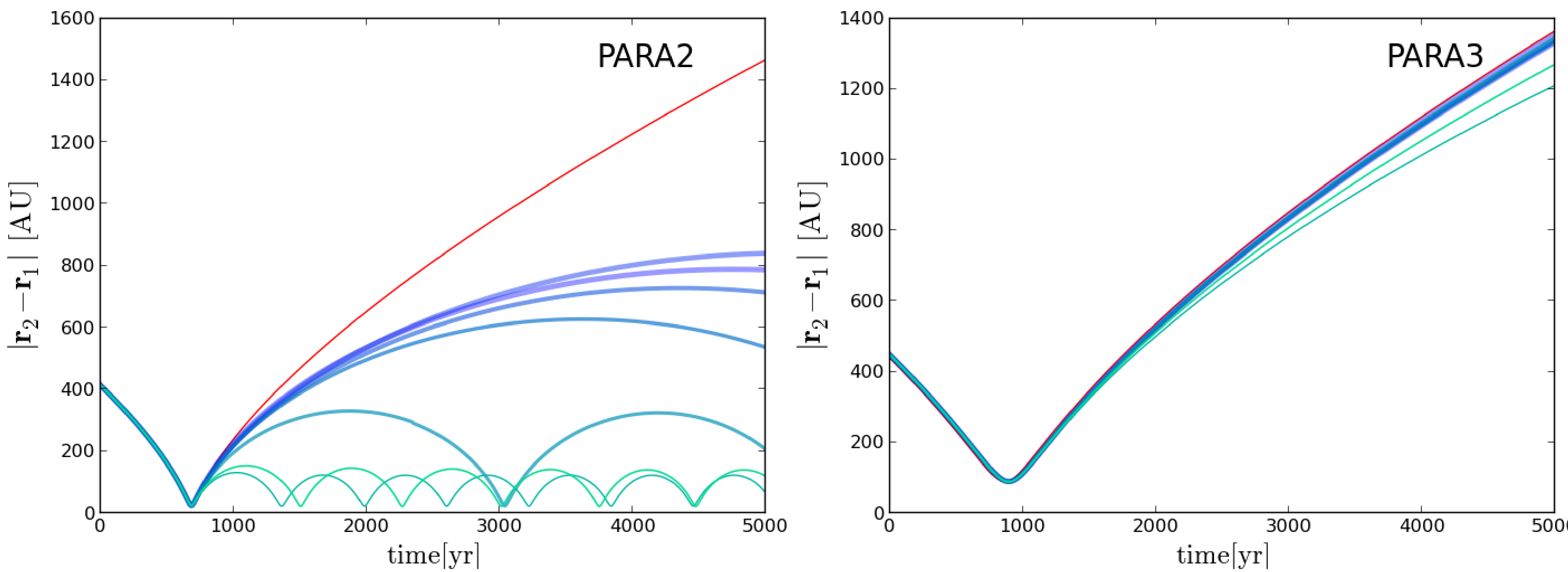
Disk-Disk interactions with moving mesh code, AREPO (Springel 2009)



Diego Munoz

Disk-Disk interactions

- Need high stellar densities for close enough interactions
- Disk-orbit misalignment aids in orbit change, but outcome is not well aligned



Munoz, Kratter et al, in prep

Disk Alignment in Binaries

does this shed light on formation?

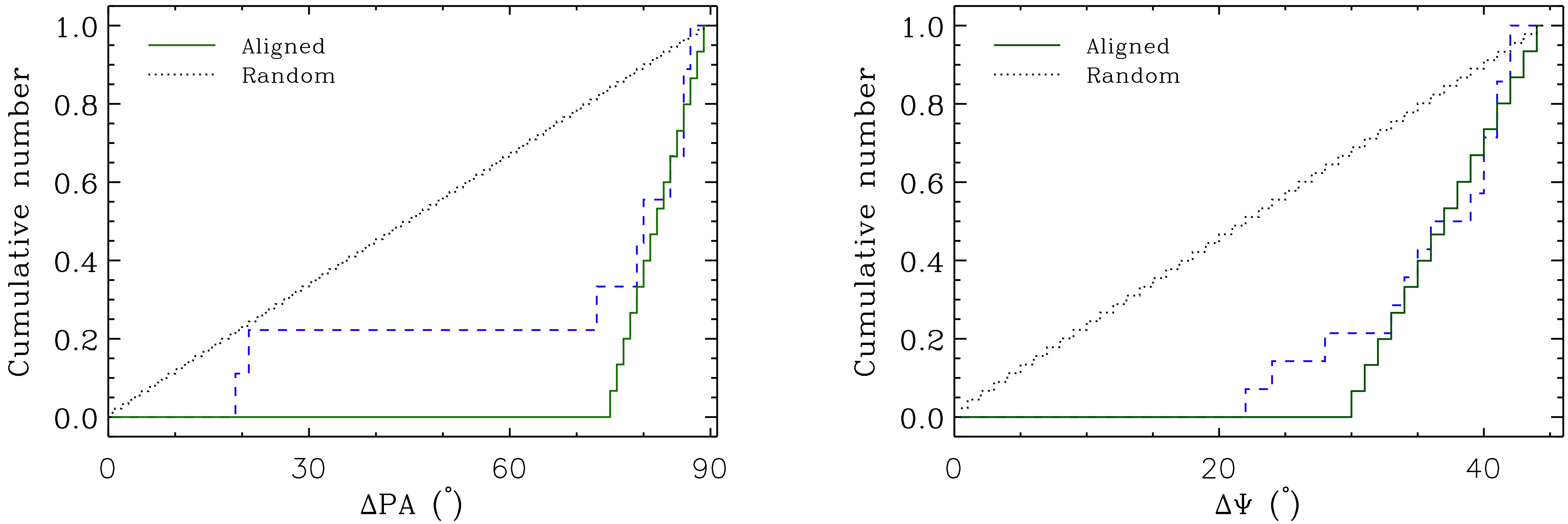


Fig. 4. The distribution in the difference between spectropolarimetrically predicted disk PA and observed disk PA for the sample presented in Table 3 (blue dashed). This is compared to a random distribution (black short dotted). On the *left* we show a distribution where polarisation signatures are always orientated perpendicularly to circumstellar disks and on the *right* we present the distribution for a scenario where the spectropolarimetric signatures can be either perpendicular or parallel to disks (see the text for more detail). Both model distributions have a maximum error of 15°. In both cases, a random orientation of disk and polarisation position angles can be discarded at the 3σ level.

Wheelwright et al 2011

Stellar Structure, Disks

- Early development of radiative zone means that internal luminosity gets more important

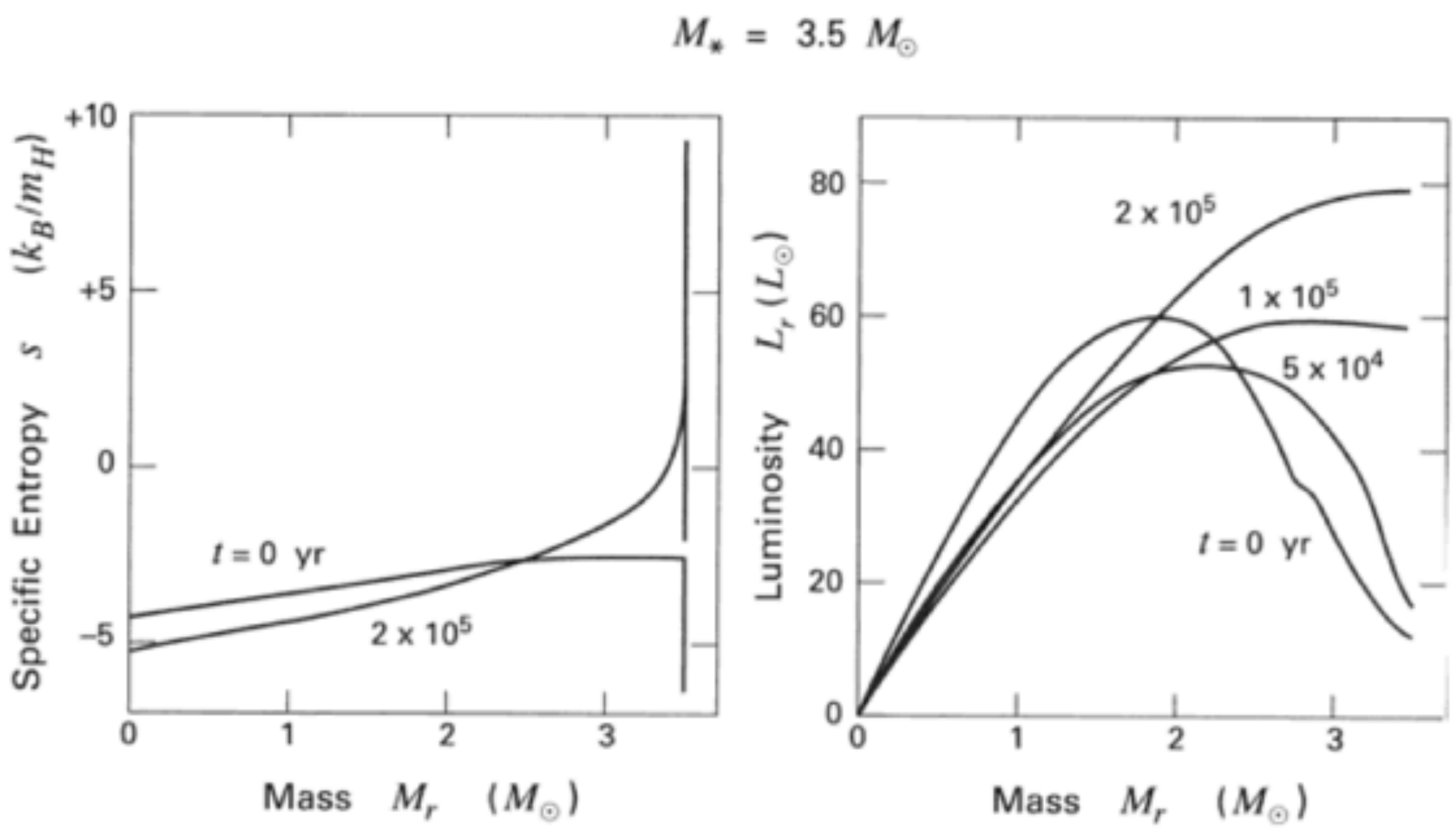


Figure 18.7 Thermal relaxation in a 3.5 $M_\odot$ star. The left panel shows the evolution of the specific entropy, while the right follows the internal luminosity. Both plots cover the first 2×10^5 yr of quasi-static contraction. The zero point of specific entropy is arbitrarily set at $T = 2.05 \times 10^5$ K, $\rho = 5.16 \text{ g cm}^{-3}$.

At accretion midpoint...

$$1.5M_\odot \rightarrow \frac{L_{\rm acc}}{L_{\rm int}} \approx 100$$

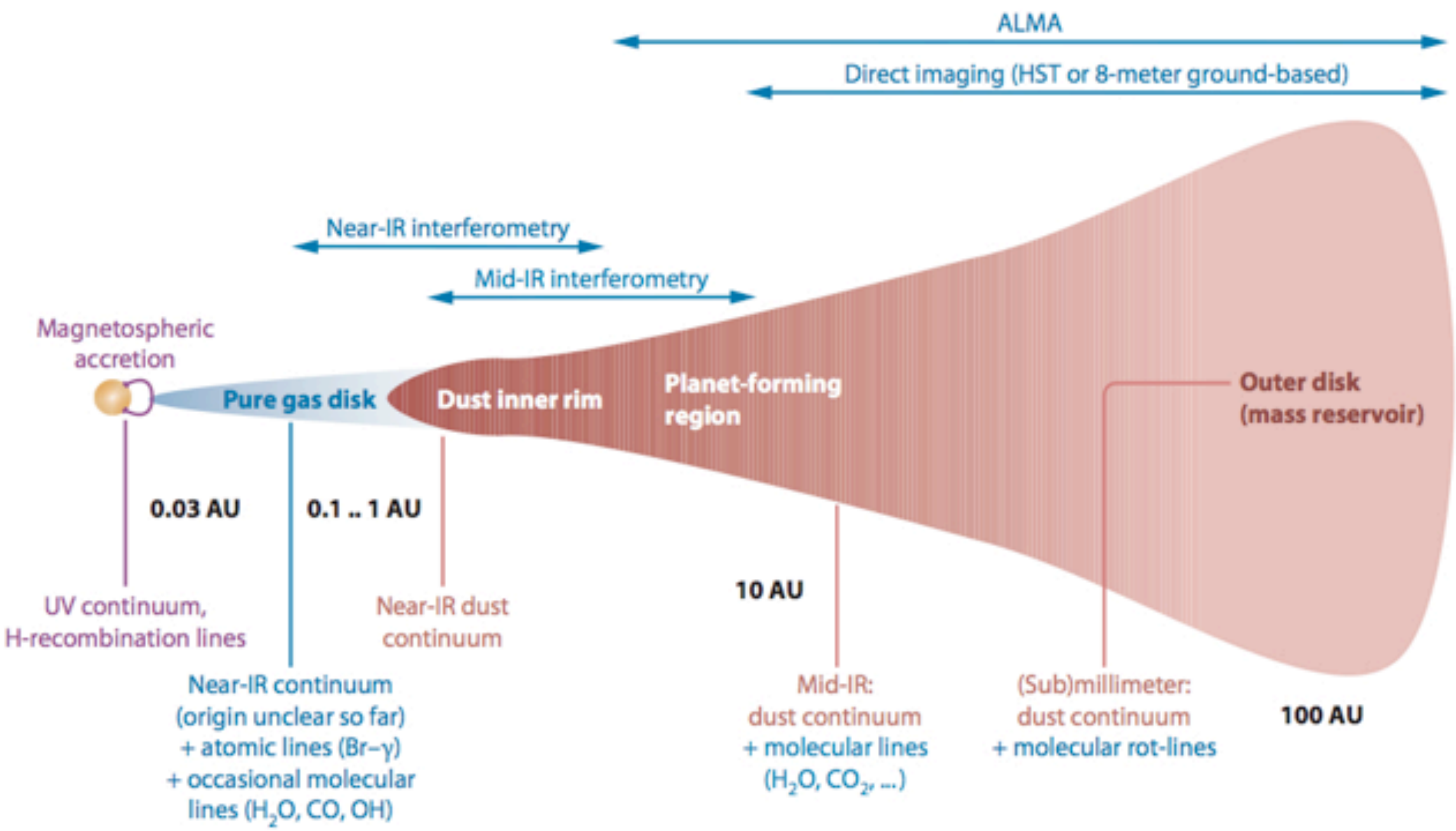
$$5M_\odot \rightarrow \frac{L_{\rm acc}}{L_{\rm int}} \approx 1$$

$$\sigma T_d^4 = f(\tau)\left(\frac{3\dot{M}\Omega}{8\pi} + \epsilon\frac{L_*}{4\pi R_d^2}\right)$$

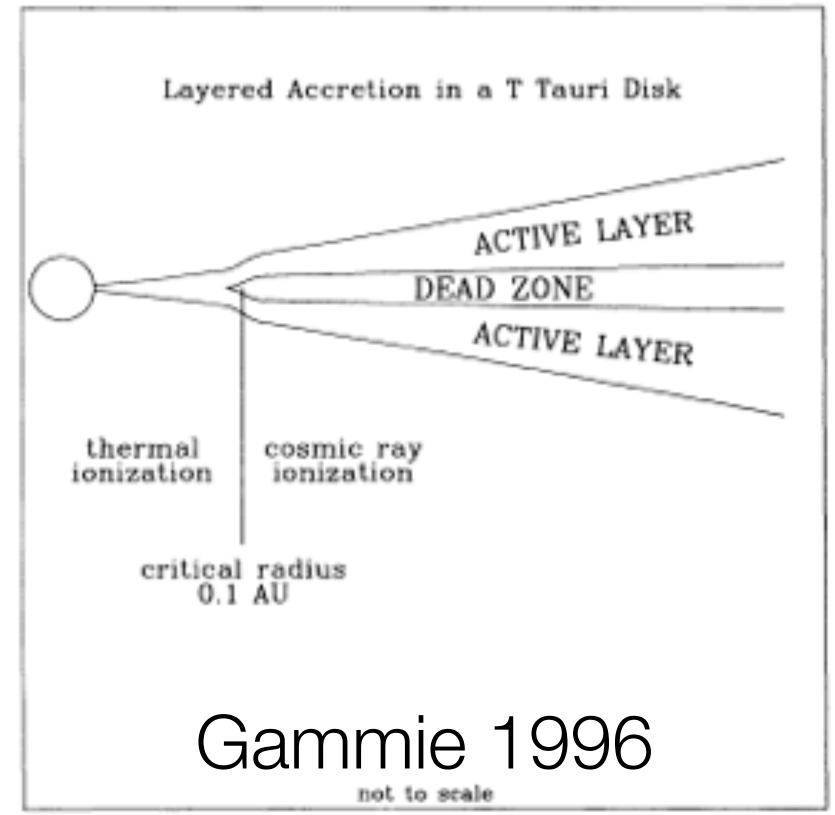
influences planet formation / accretion disk physics for intermediate mass stars

Palla & Stahler 2004, 2005

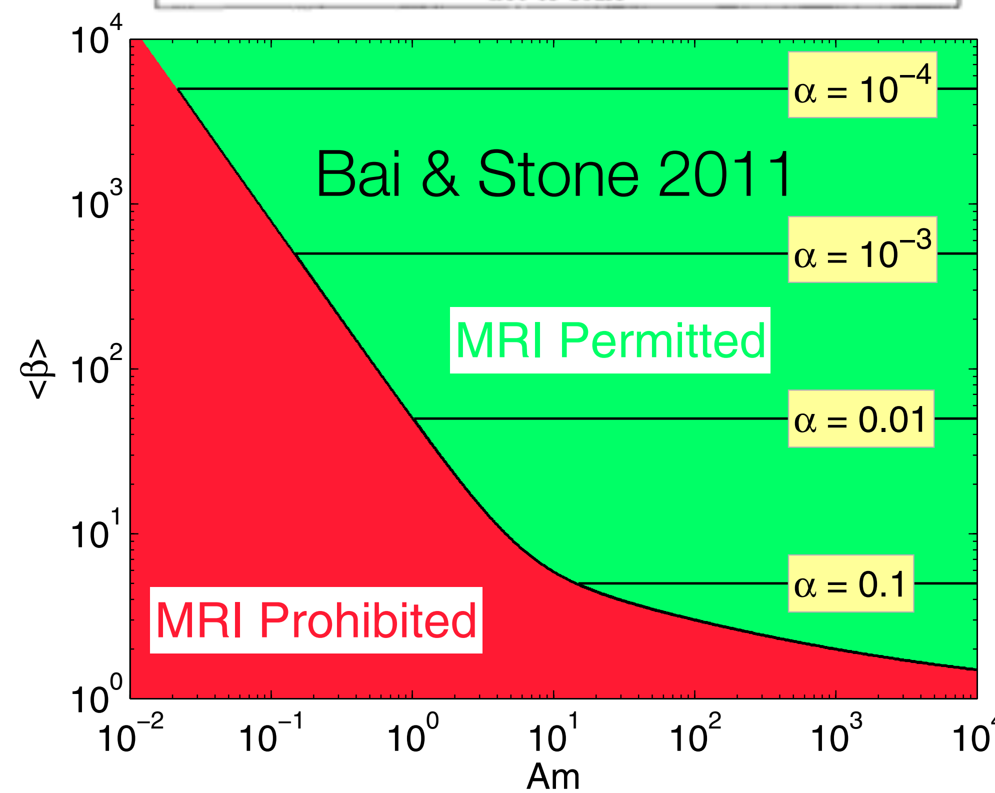
Planet formation and accretion depends on radiation



Dullemond & Monnier 2010



Gammie 1996



What is the maximum mass planet host?

Conclusions

- Even theorists agree that one mechanism can mostly explain low, intermediate, and high mass star formation. **And there aren't even two very different theories.**
- Observations (see next talk) agree with continuity, but very different physical systems look the same observationally
- Starting with Herbig Ae/Be's, conditions are plausible for fragmentation of disks into low or equal mass companions
- Herbig Ae/Be's can be interesting sites to study planet formation and disks, but may not be totally representative of solar analogs due to stellar structure on PMS