Fragmentation modes
&
the morphology of
Star Forming Regions

~~(& Massive cluster formation (maybe ;))~~

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Bad Honnef / 'Aggregates' meeting / 5 December 2016

The Growth of Fragmentation modes & the morphology of Star Forming Regions

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(s)he's not a perfect 10 anymore !

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Morphology:
- matters
- can be quantified
- varies over time

(s)he's not a perfect 10 anymore !

Morphology Zoom-in : Spitzer IR data
Example: the ONC star-forming region

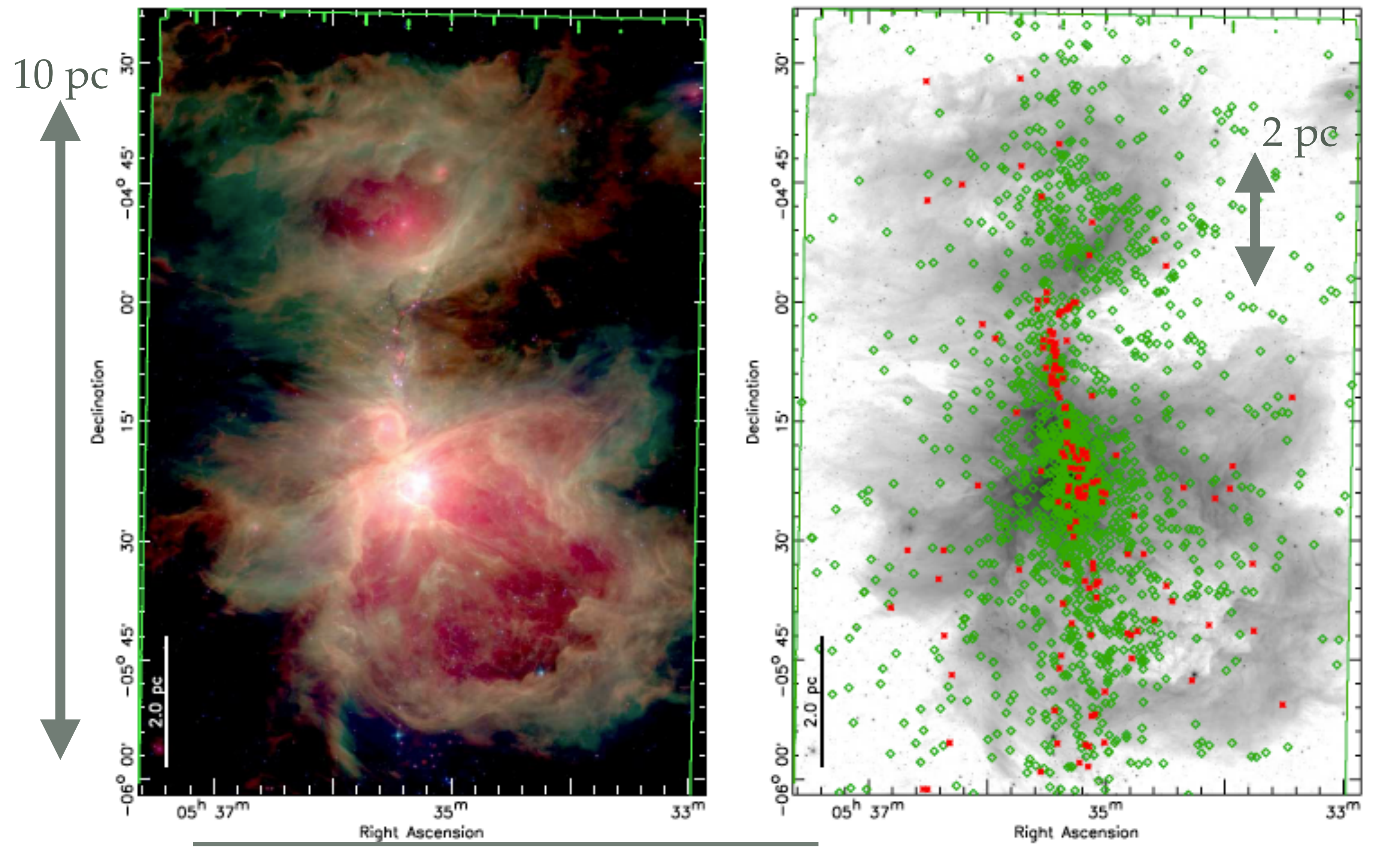
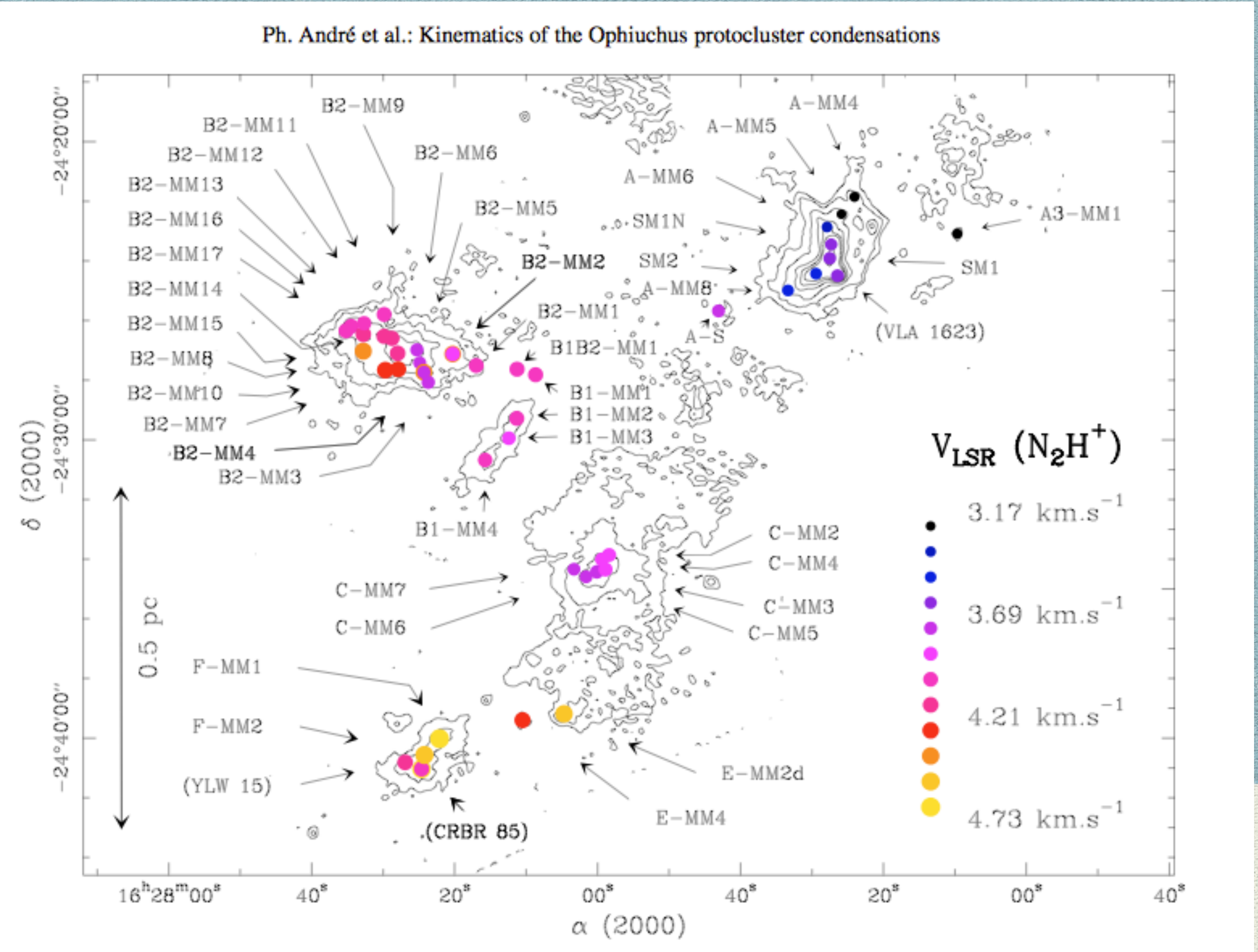


Figure 14. Left: mosaic of the ONC field. Blue is 4.5 μm, green is 5.8 μm, and red is 24 μm. Right: 4.5 μm image with the positions of dusty YSOs superimposed. Green diamonds are young stars with disks, red asterisks are protostars (including the faint candidate protostars and the 10 red candidate protostars detected at 24 μm but not at 4.5, 5.8, and 8 μm). In both panels, the green line outlines the surveyed field. The Orion Nebula is the extremely bright region just south of the center of the mosaic. The central region of this nebula is saturated in the 24 μm band. The extended reflection nebula to the north of the Orion Nebula is NGC 1977. Between the Orion Nebula and NGC 1977 is a filament rich in protostars known as the OMC-2/3 region. The large bubble to the southwest of the Orion Nebula is the extended Orion Nebula (Güdel et al. 2008).

Green : young stars (TTauri, ..)

Red dots : proto-stars

Credits : S. Megeath et al. 2012, 2015

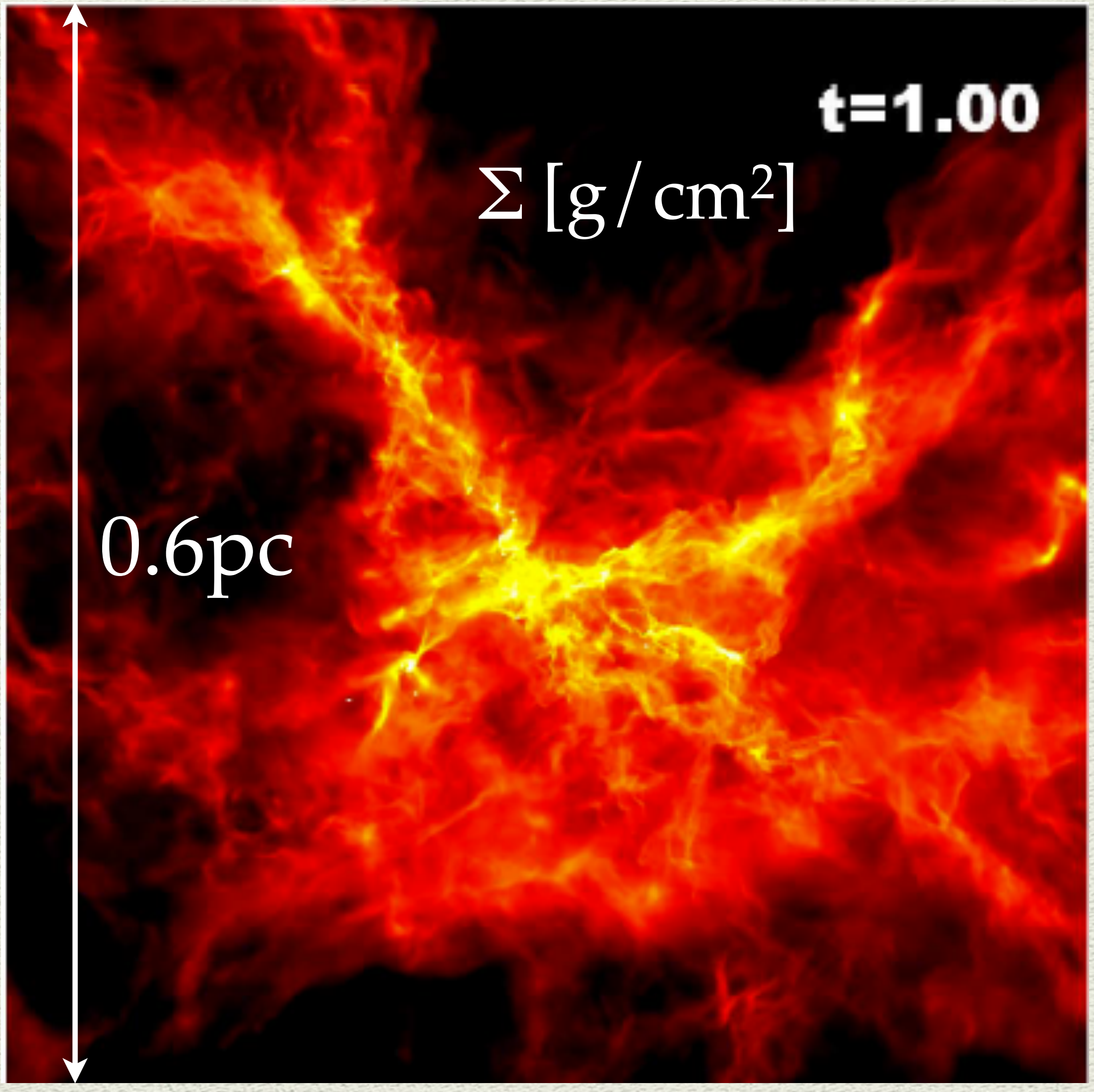


Kinematics in the ϱOphiuchus region (IRAM 30 m data)

credits : Ph. André et al. 2007, AA

Fragmentation in star-formation calculations

- SPH *re*simulation of isothermal collapse but *with* opacity
- Time in units of the free-fall time ~ 2 x 10^5 yrs
- From 250 ▷ 180 cores formed
- $M = 500\ M_{Sun}$, $R_o \approx 1/2$ pc $T \approx 10$ K
  ($\varrho \approx 1.8 \times 10^3\ M_{Sun}$ / pc^3 initially)
- Linear resolution ~ 0.5 AU

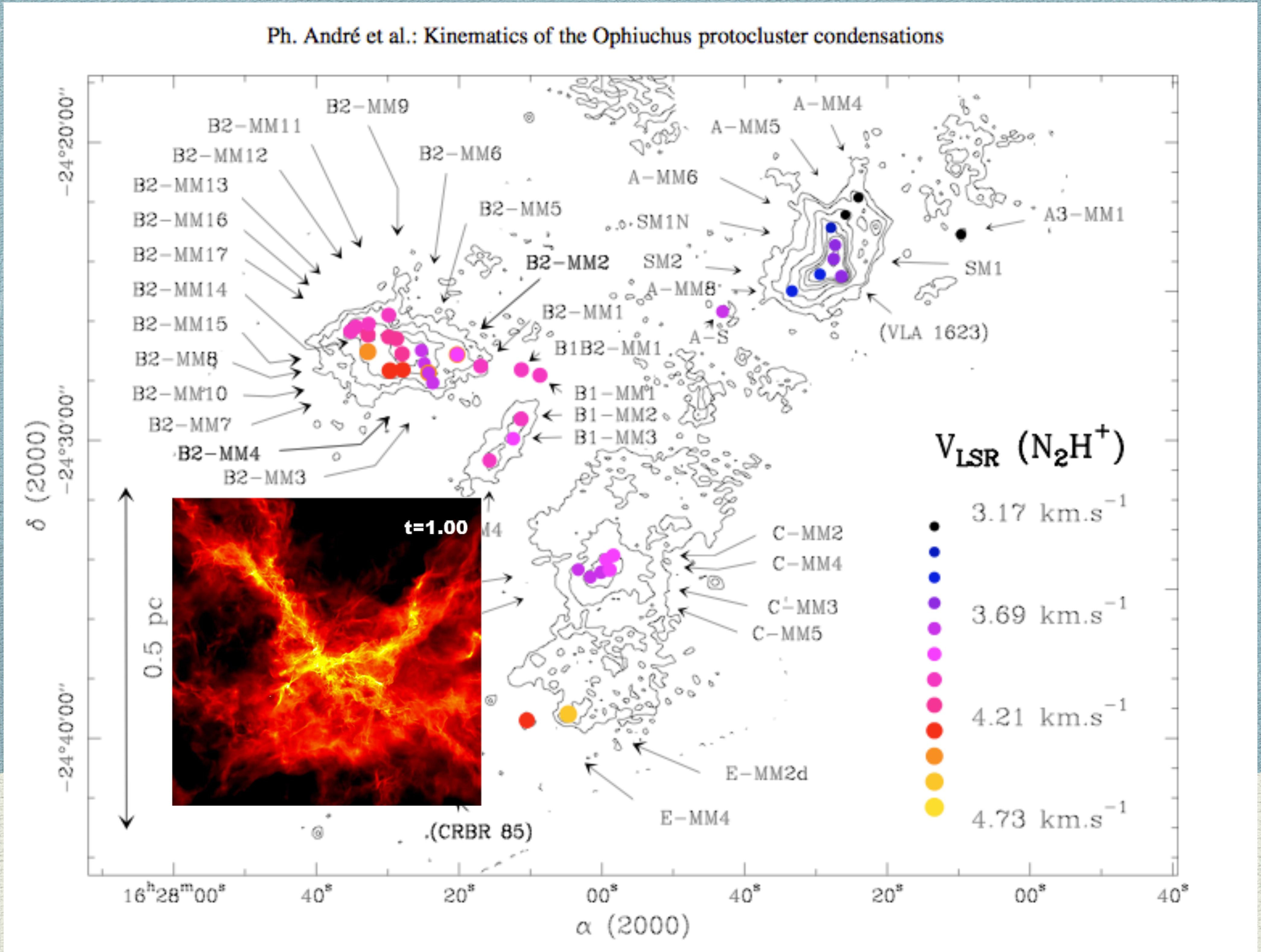


M. Bate 2011, MN

Still ~ 3 orders of magnitude from rich clusters

Transition : embedded ▷ gas-free. Yes, but how .. ?

- embedded cores / associations m.f. ~ cluster m.f.
- details of mass-loss unclear, slower than energy argument would suggests (winds, SN, .. *e.g.* J. Dale 10/2015 webcast STScI) ▷ boost survival rate
- active star-forming regions with gas have stellar kinematics compatible with *in-situ* star formation (*e.g.* ρ Ophiucus [André et al. 2007] or NGC1333 where σ ~ 0.8 km/s [Foster et al. 2015, In-Sync survey])
- Phase-mixing and relaxation on a time-scale well exceeding the star-formation time-scale



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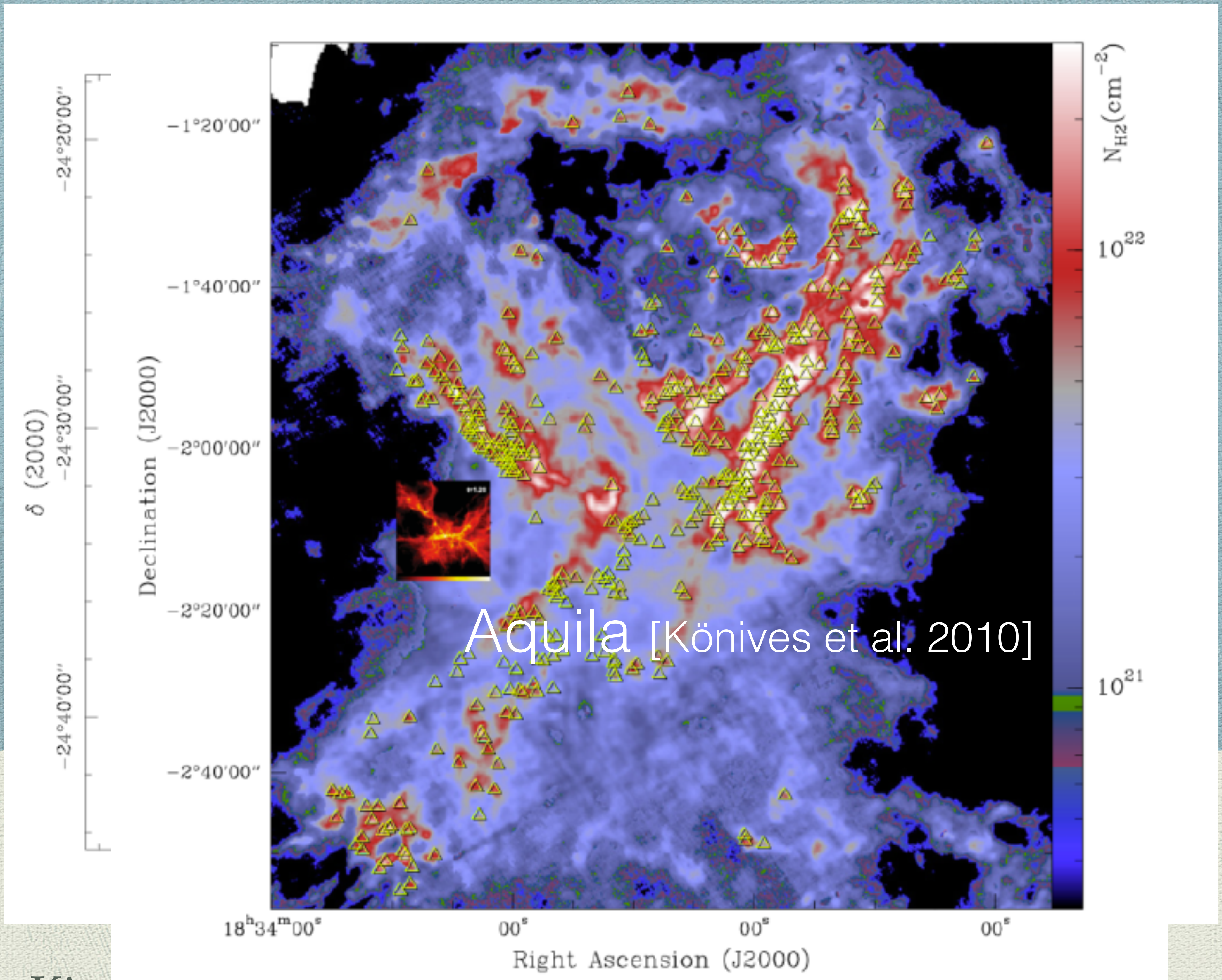

Kinematics in the ρOphiuchus region (IRAM 30 m data)

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Initial conditions for stellar dynamics: different approaches

$\sigma^2 \approx k_\beta T$

- Classic argument: stars are *as cool/cold as* gas is
- All mixed up, no mass- or length scale: monolithic collap-se, no structure in density or velocity
- Some spatial profile (King, Plummer, ..) with velocities drawn from «equilibrium» d.f. (*e.g.* Caputo et al. 2014, ..)
- Turbulence imprints young stellar spatial distributions (W43 - Nguyen et al. 2013; G0.253+0.016 / ALMA, Rathborne et al. 2015)
- 'Fractal' distribution : looks like star-forming region, but velocities odd, ad hoc (Goodwin & Withworth 2004, R. Allison et al. 2009++, B. Elmegreen 1997, ..)

Study the fragmentation of self-gravitating fluids

- Cold fluid perturbed by density fluctuations : linear analysis
- Work on a spherical mesh (boundaries) but with randomly seeded perturbations (in density)
- Write Lagrangian operators
- Integrate .. but stay coherent

$$\frac{d^2}{dt^2}r' = -\nabla_{r'}(\Phi + \delta\Phi)$$

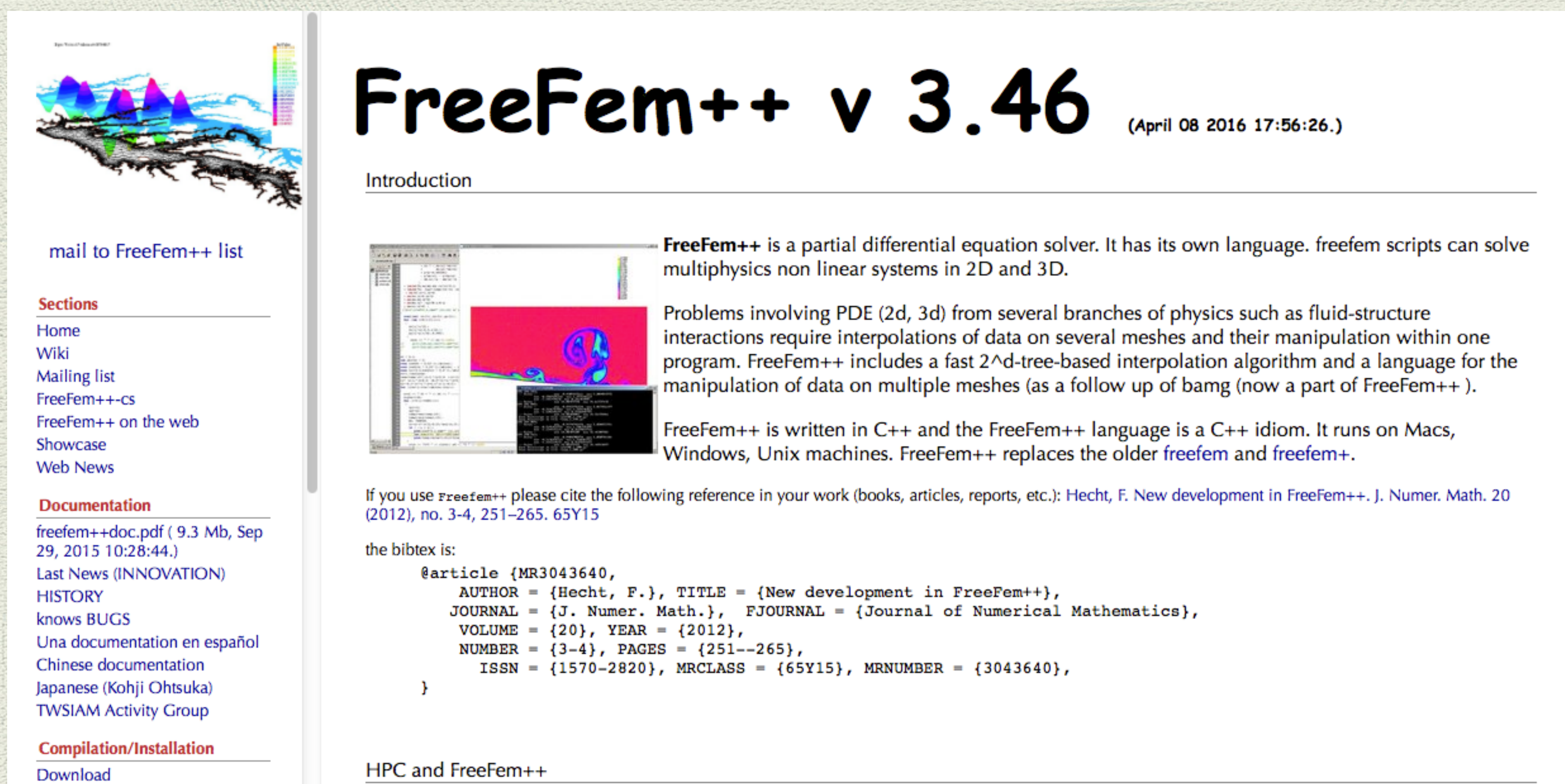
$$\nabla_{r'} = \nabla_r + \xi \cdot \nabla_r(\nabla)$$

$$r' = r + \xi$$

Results begin to "look like" star forming regions but something is missing : time + resolution ($\triangleright$stellar cores)

Fragmentation of self-gravitating fluids

- http://www.freefem.org (le FEM fatal .. ;)



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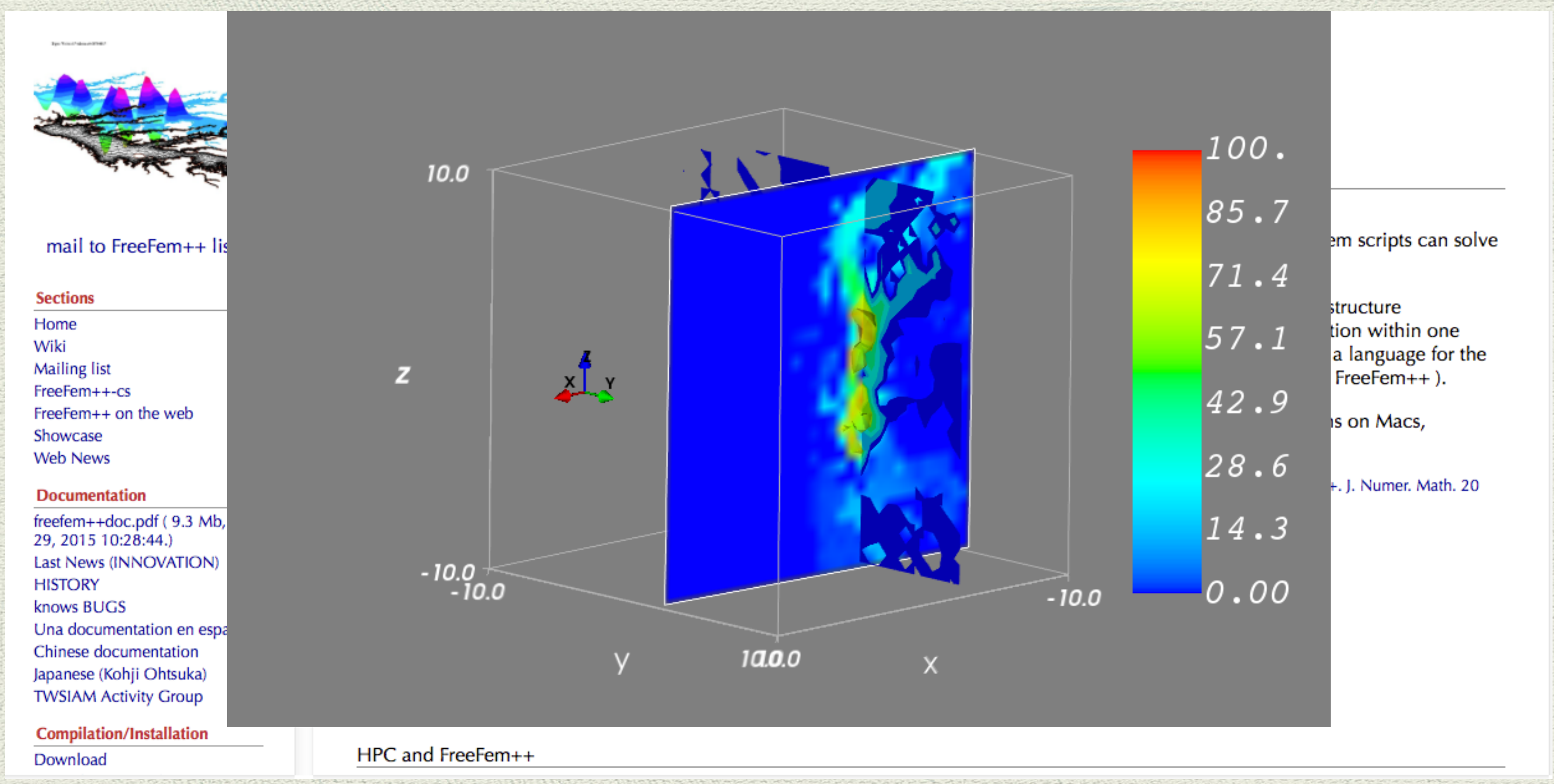
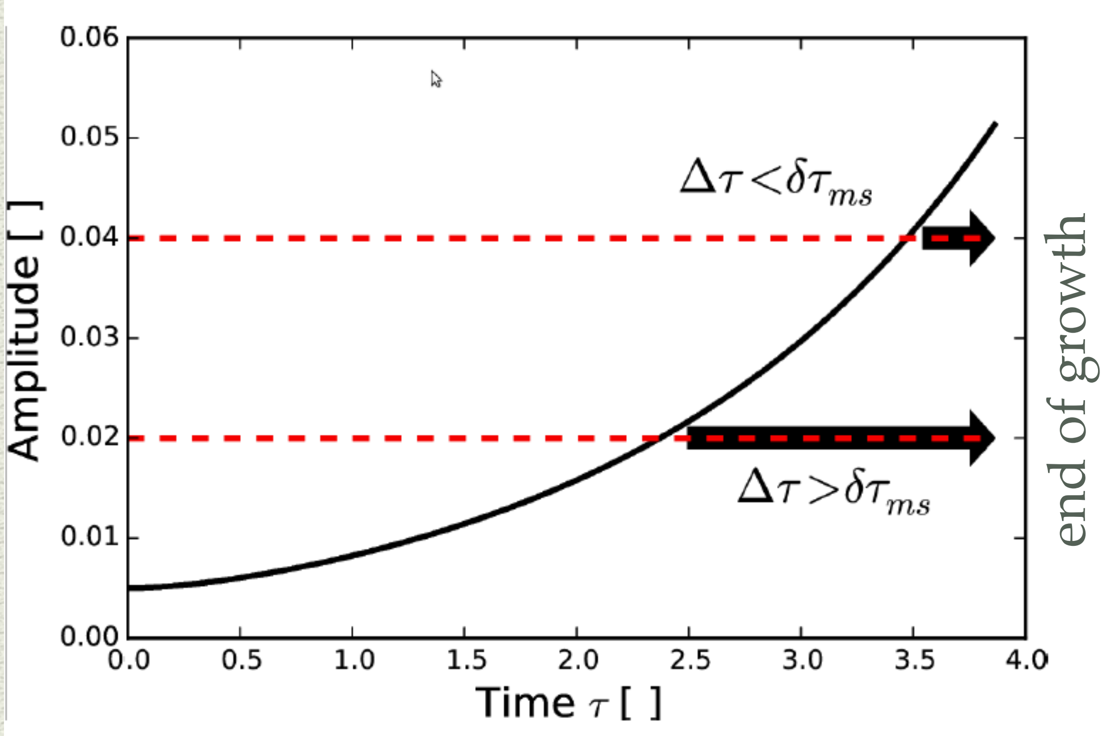


Fragmentation of self-gravitating fluids

- Problem : all stars are not born equal (mass)
- star - star interactions should come to dominate the internal structure of fragments / relaxation takes us quickly into the non-linear regime

strong function of the content in stars

$$t_{ms} = \frac{0.138}{6}\pi\left(\frac{3}{4\pi}\right)^{1/2}\frac{\langle m_\star\rangle}{\max\{m_\star\}}\frac{N_\lambda}{\ln 0.4N_\lambda}(G\rho_g)^{-\frac{1}{2}}$$



- Take two : restart the computation but with a collisional N-body code (Nbody6/7++, kira, ..)

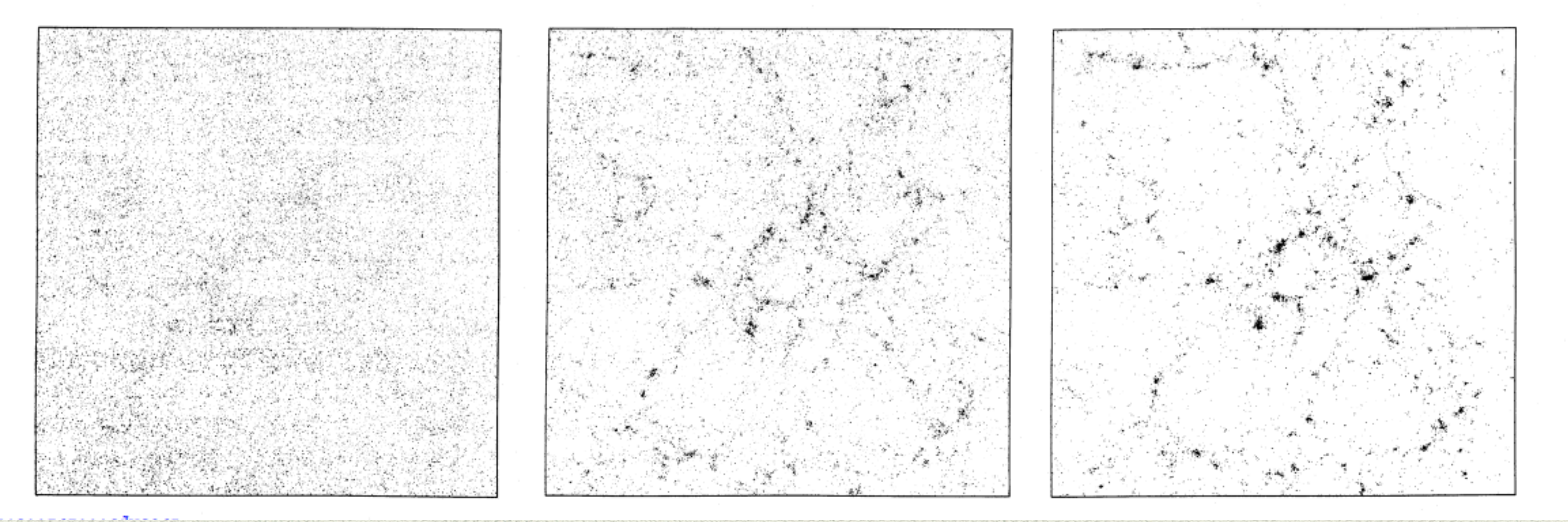
Building up by cooling & accreting:

fragmentation modes but with

unconstrained growth

:: Fragmentation in cosmology : some familiar faces from *la Cosa Nera*

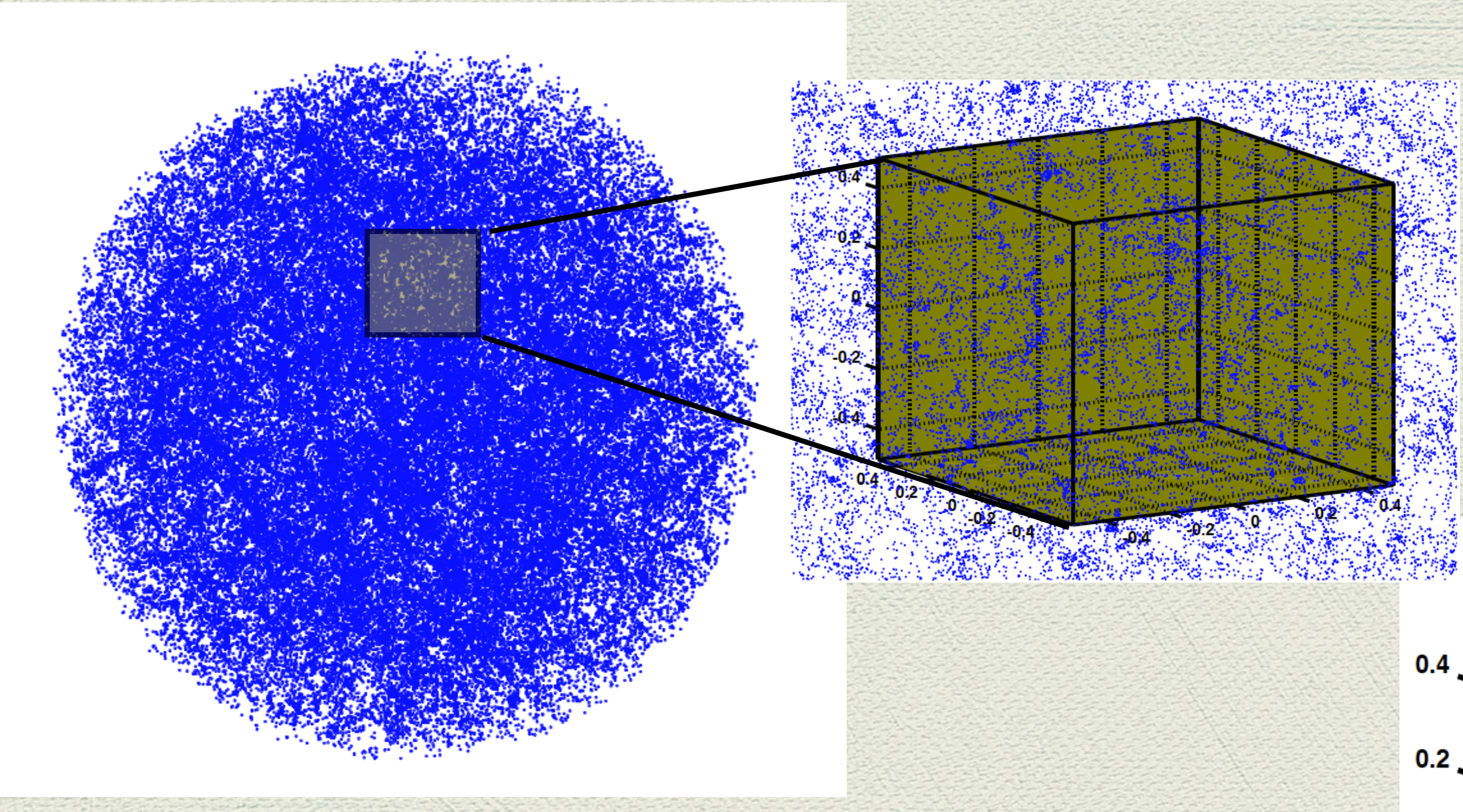
Davis et al. (1985) CDM 'Bottom-up' picture …



time

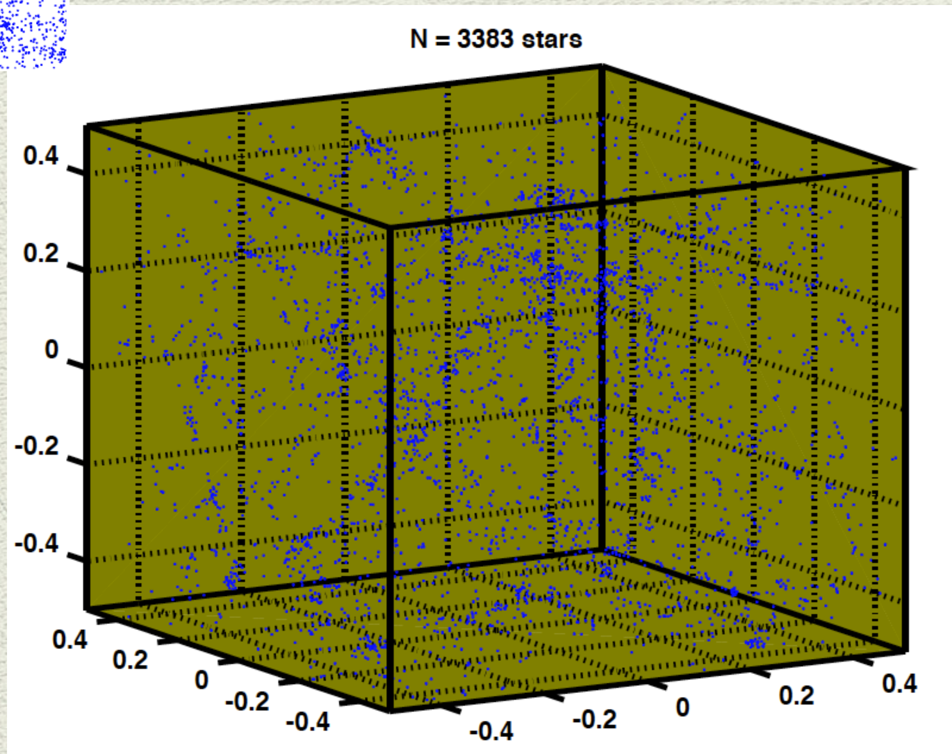
Procedure - avoid boundaries

Dorval et al. 2016, in the press ..



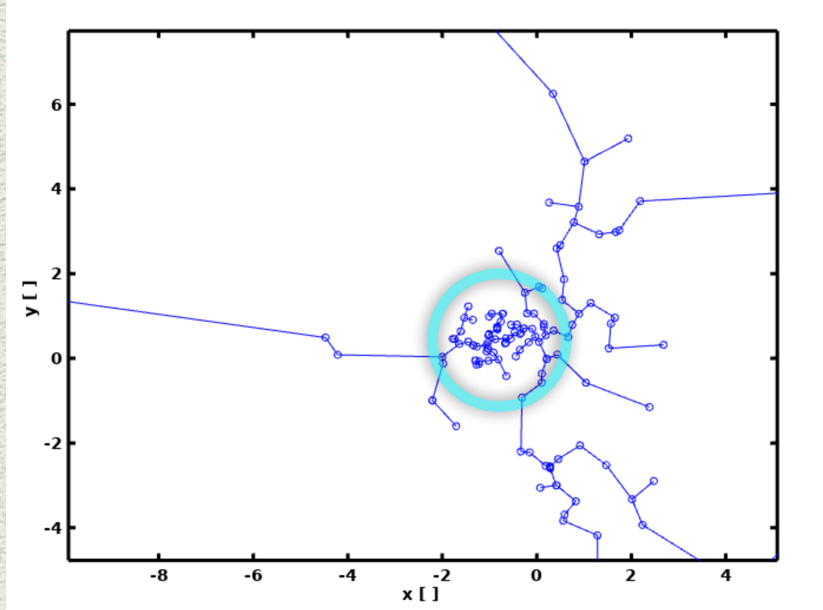
N ~ 100k stars

Extract subset of stars



The Minimum Spanning Tree

- Delaunay Triangulation + Kruskal's algorithm
- Implementation from NRv3 (C++)



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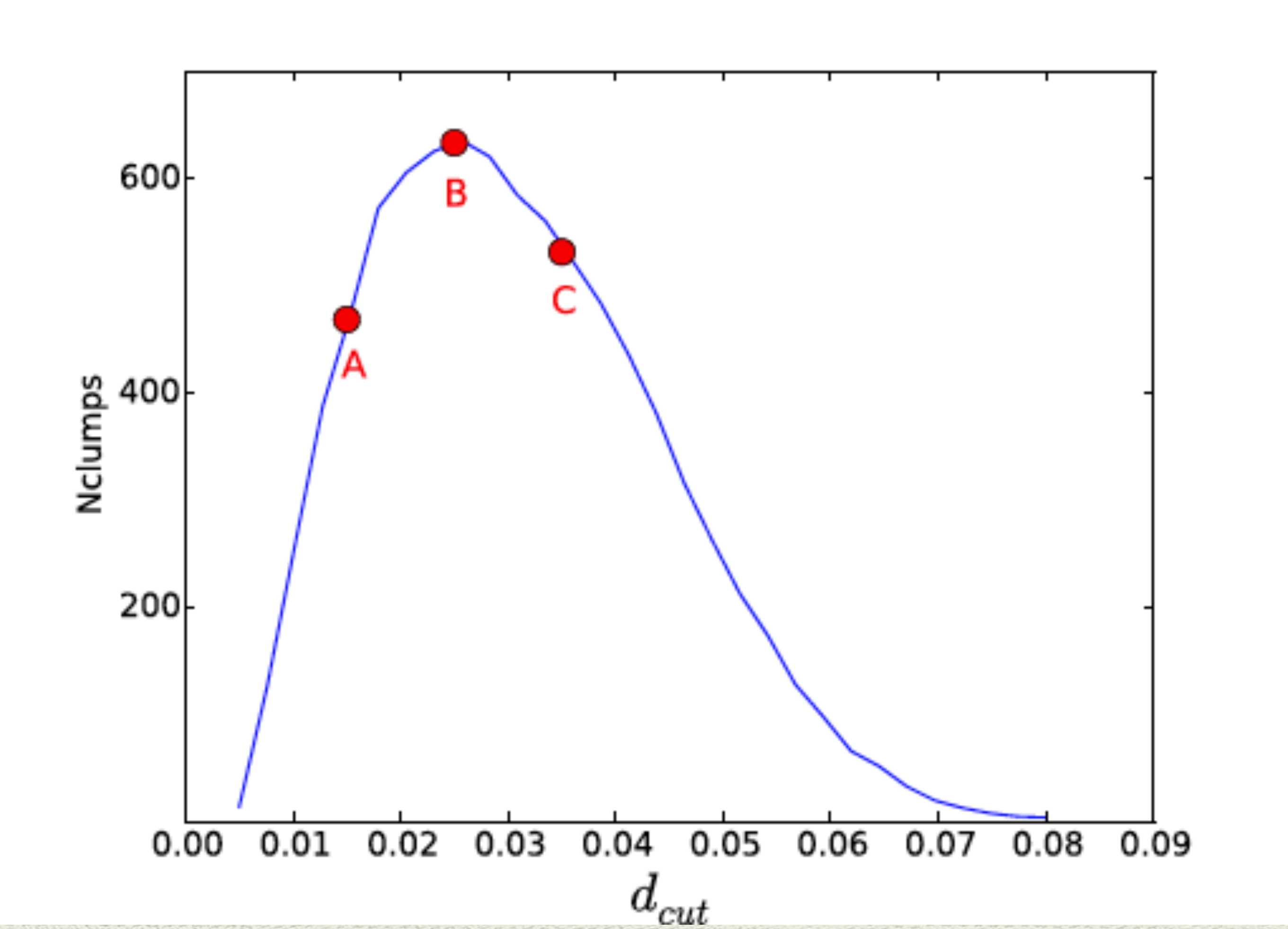

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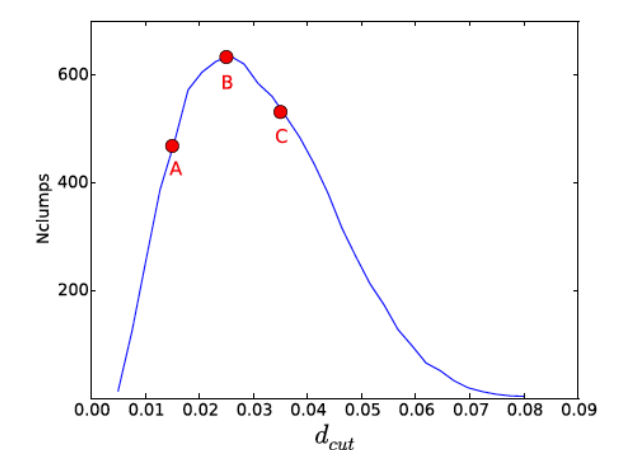
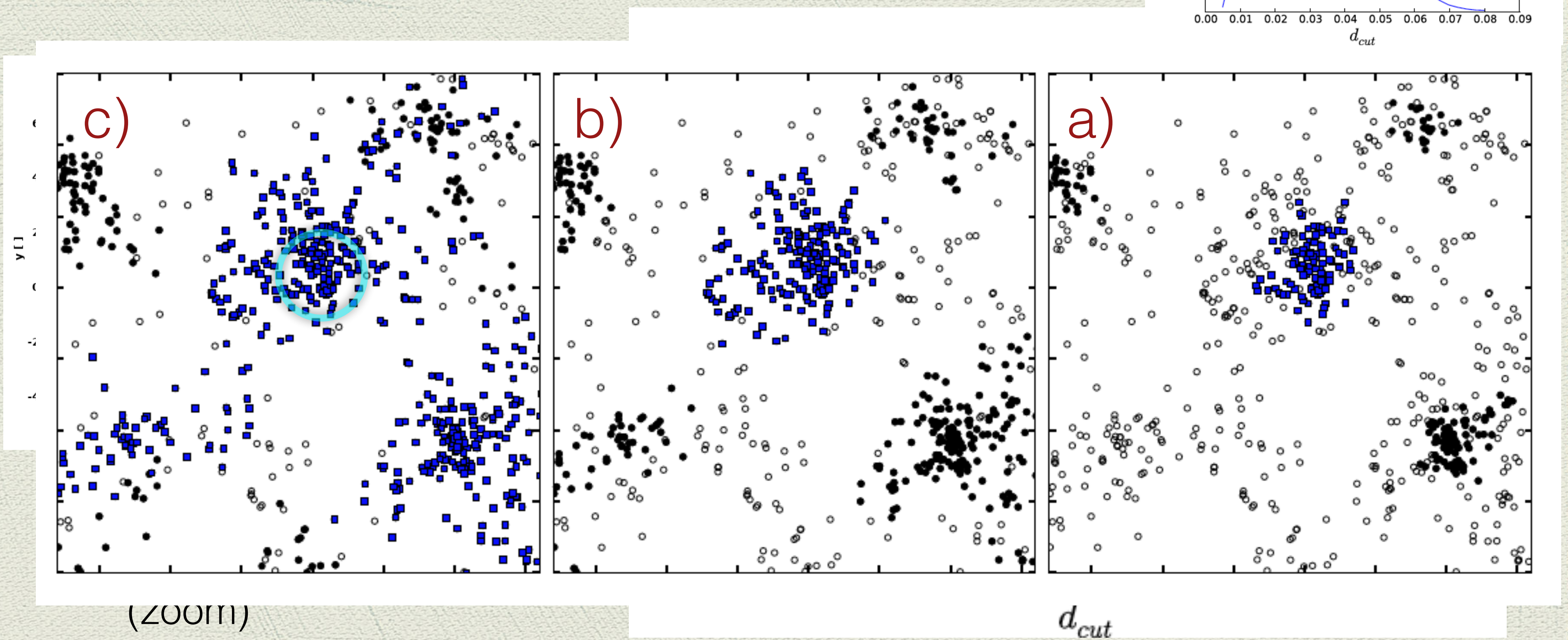
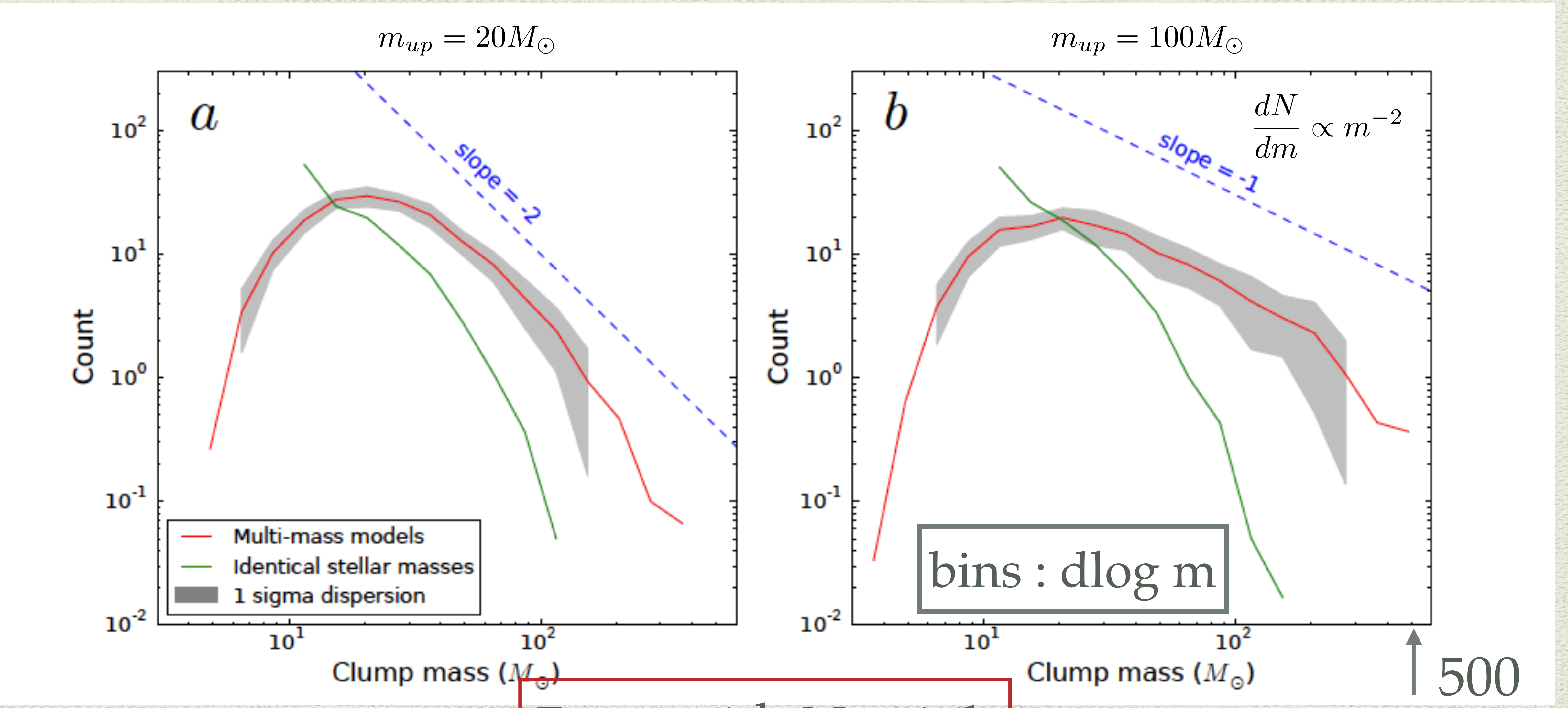




Stellar clumps:
mass function, and stellar m.f.

Equal-mass models vs Salpeter IMF (two upper truncation values)



Runs with N = 15k

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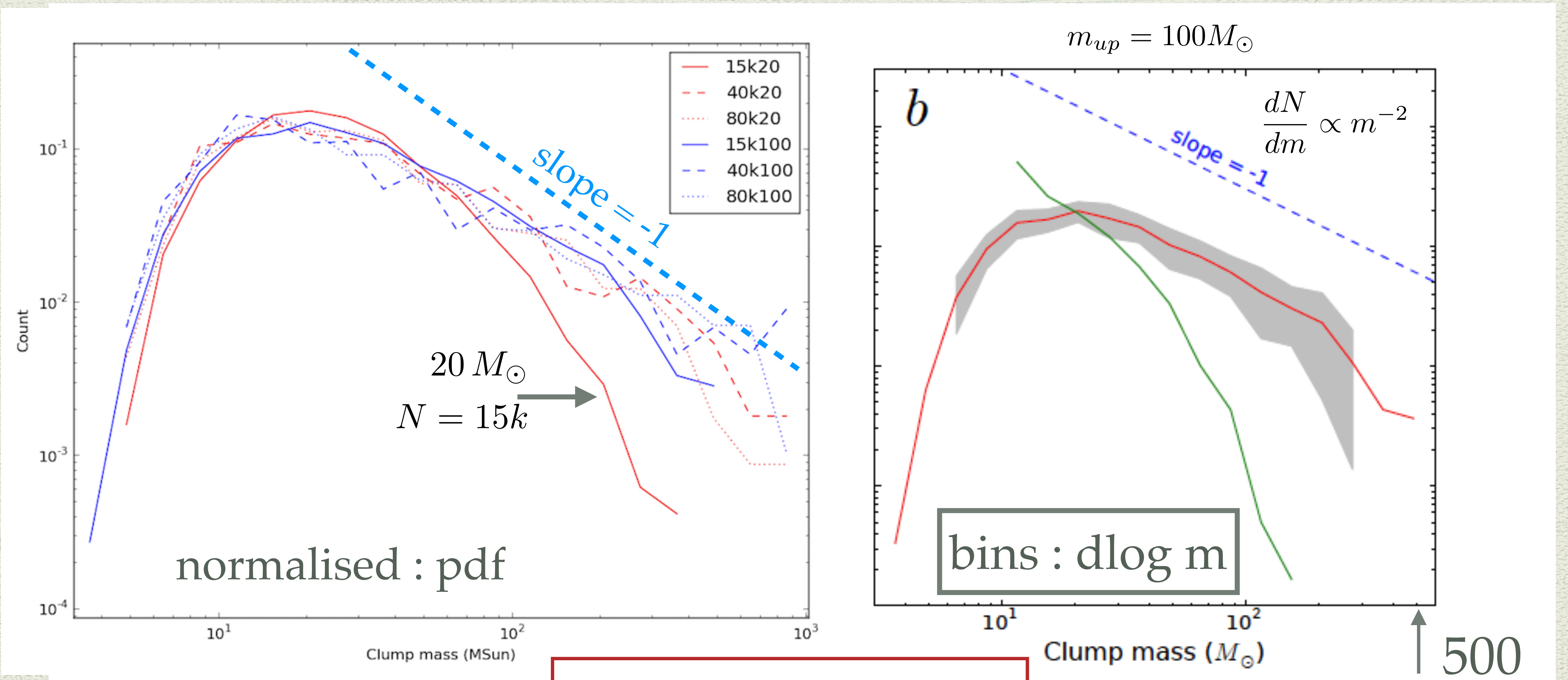
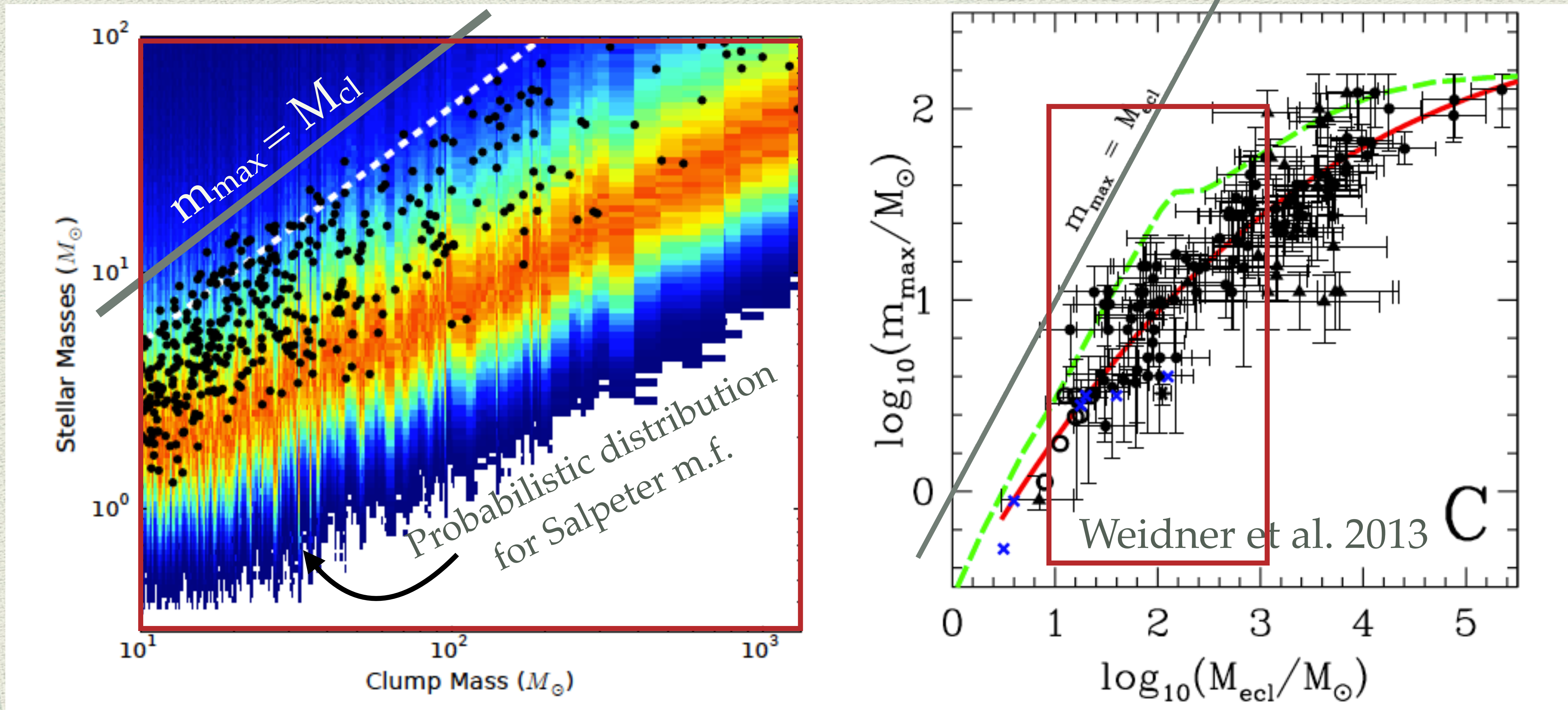


Runs with N = 15k

Stellar clumps:

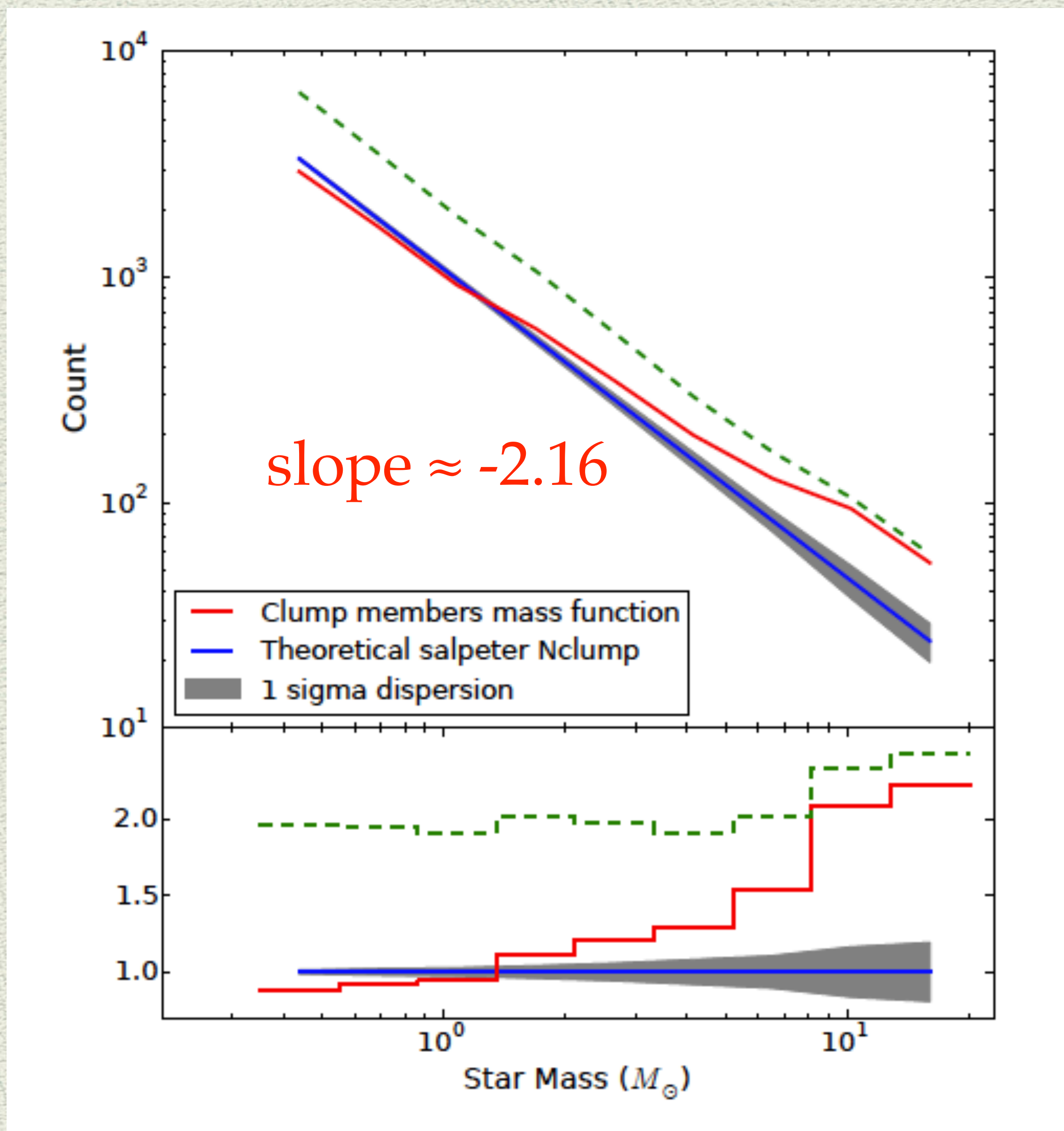
correlation with max{$m_\star$}



:: white dash: prediction from «radius of influence» of most massive star in clump

Stellar clumps:

top-heavy, segregated ..



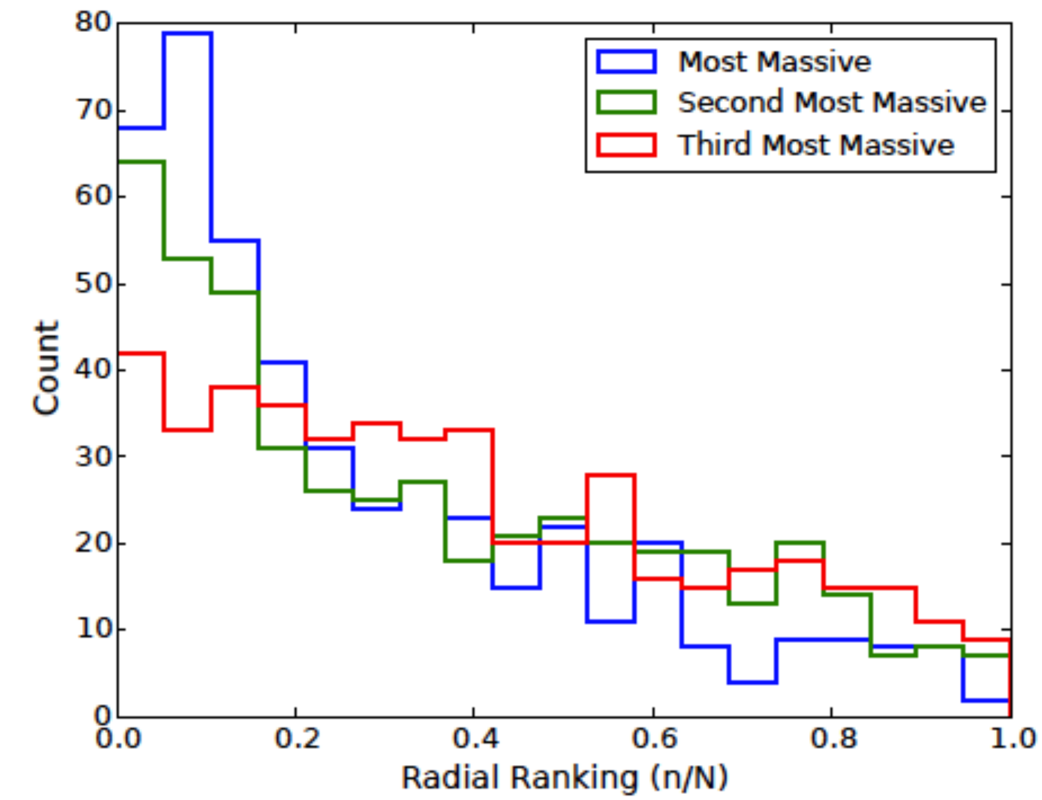


Figure 10. Radial ranking of first, second and third most massive star in each clump for a model with N = 40 000 stars (R40h100).

Ranking diagnostics of Maschberger et al. (2010) for hydro simulation

:: blue / grey : Salpeter (ensemble averaging)

cf. Vesperini, McMillan 2007, -12, -15

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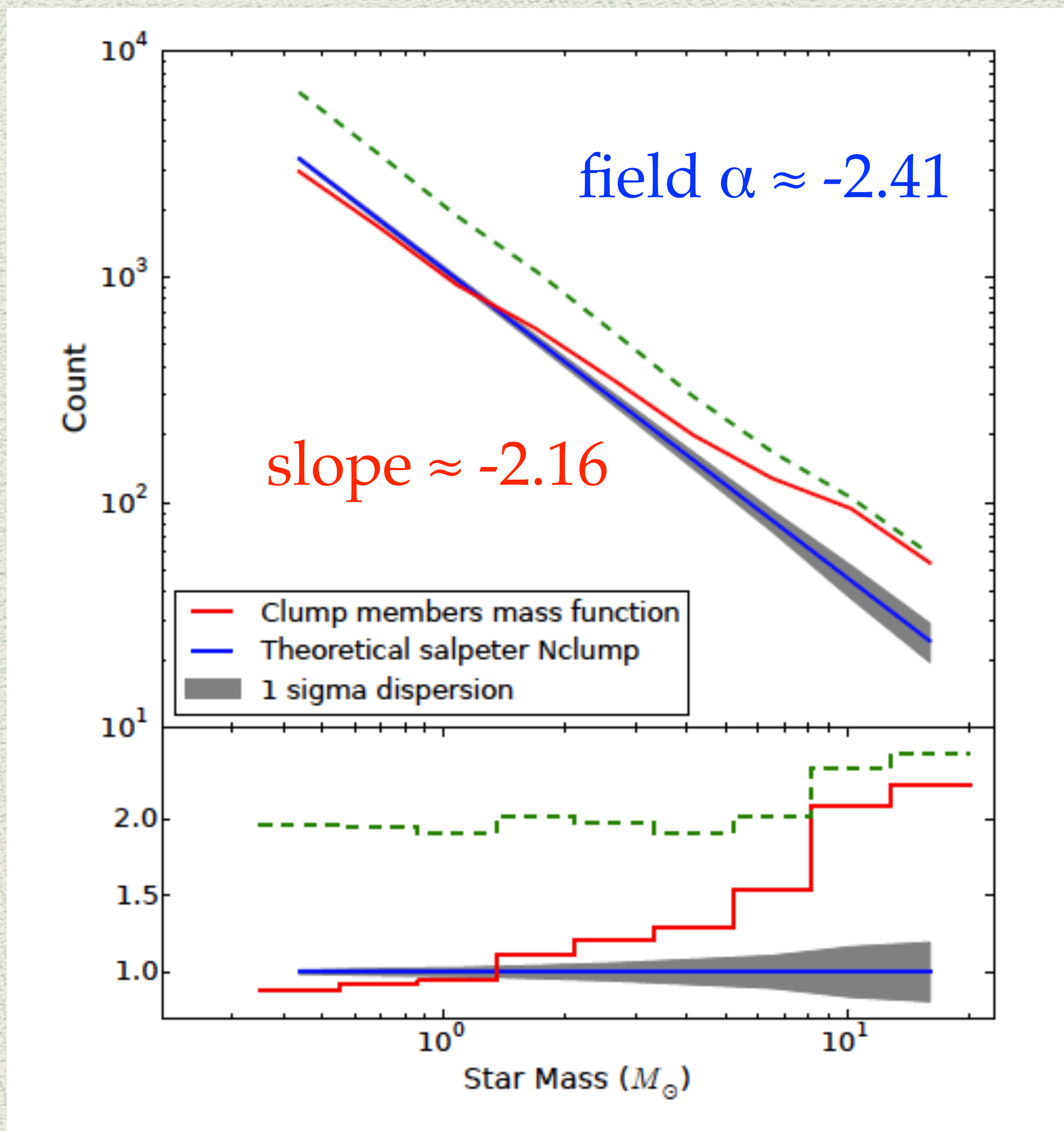

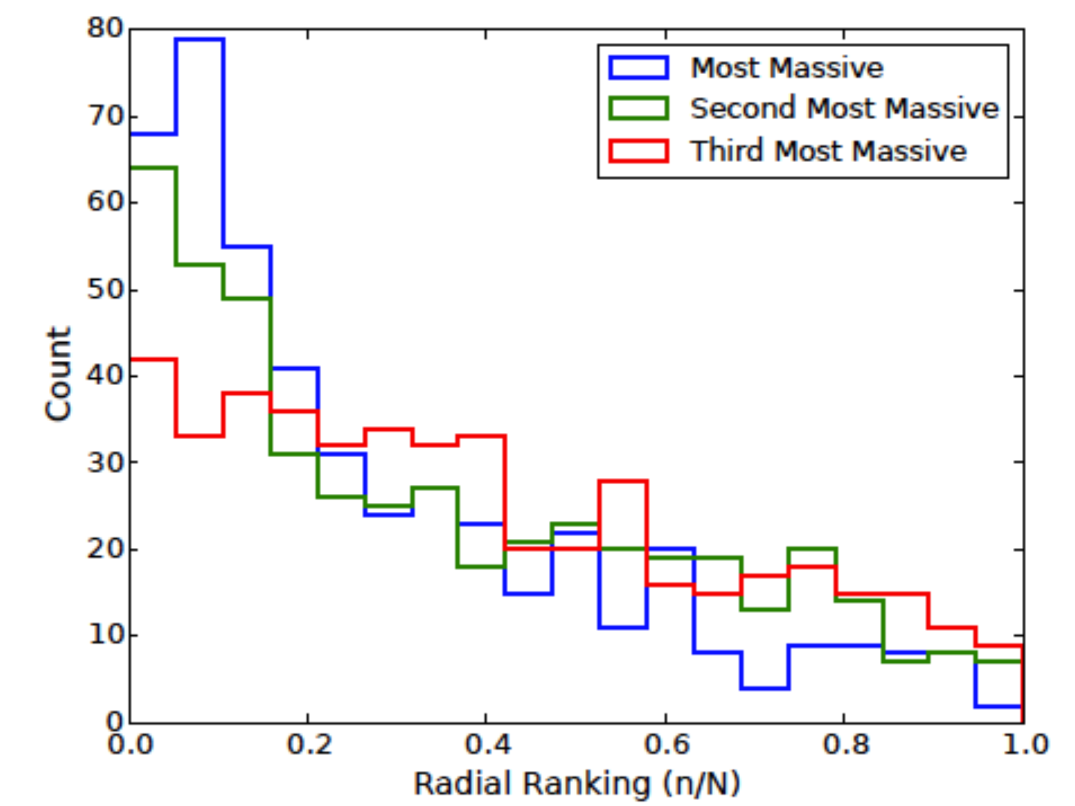

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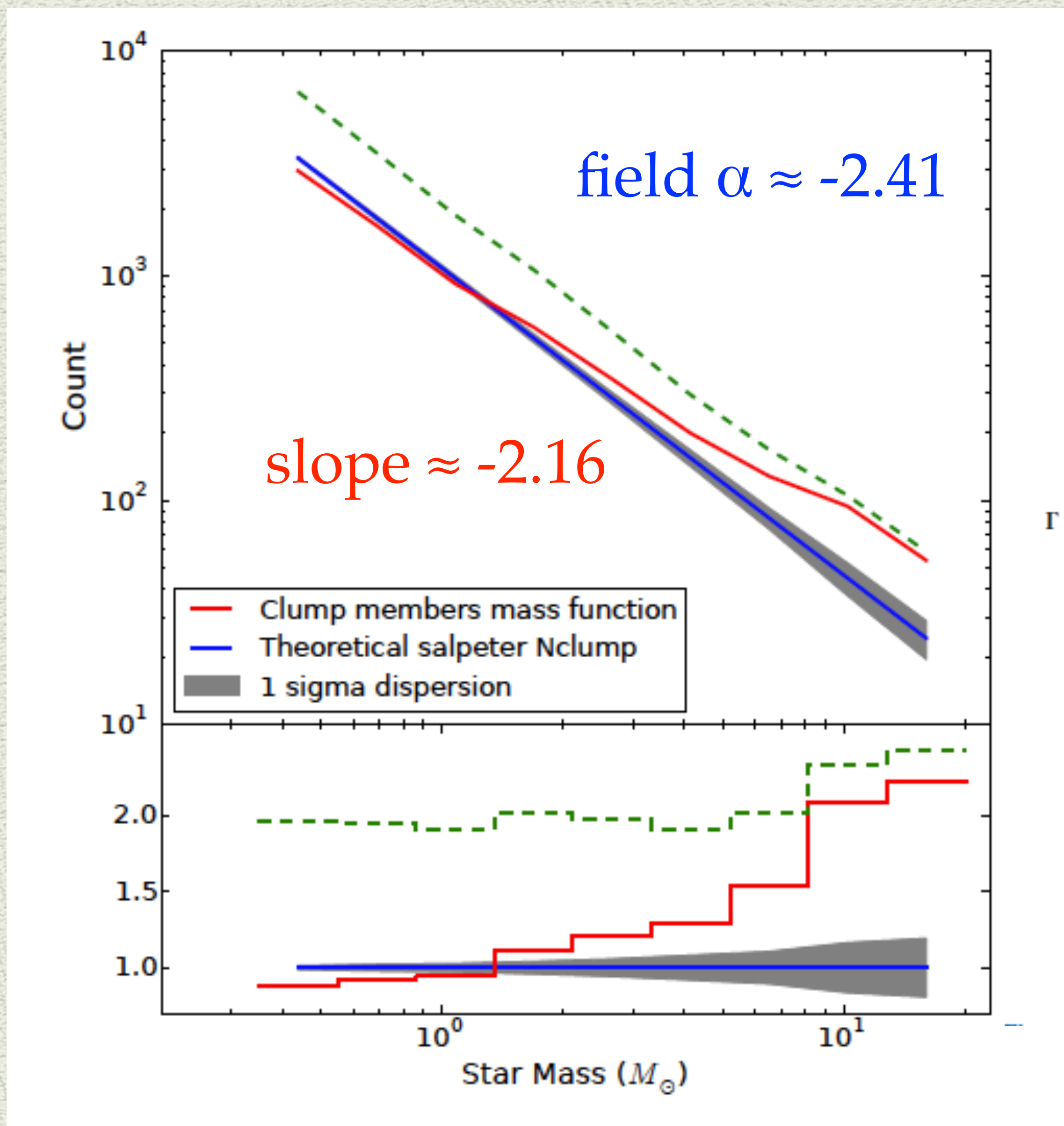

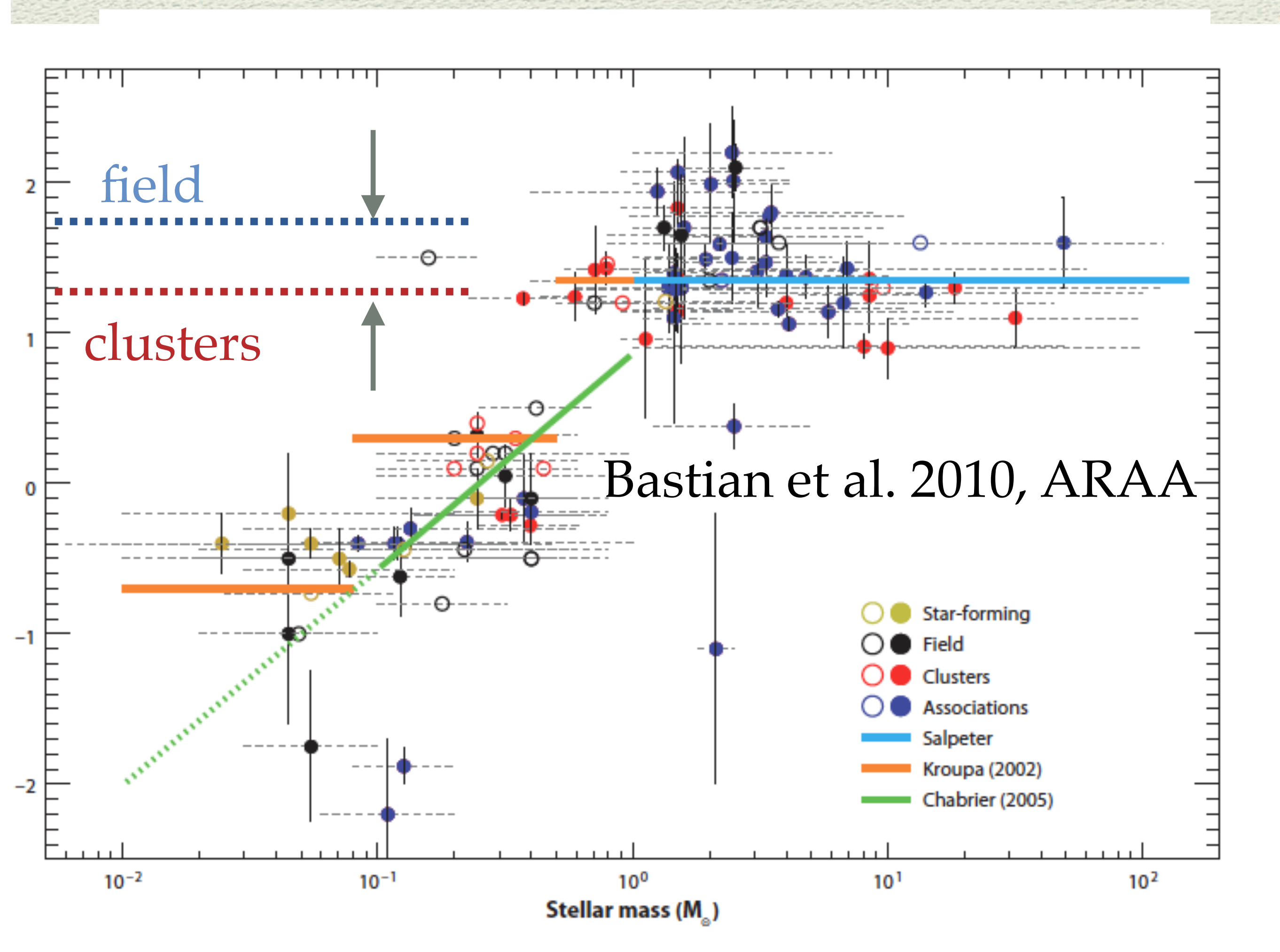

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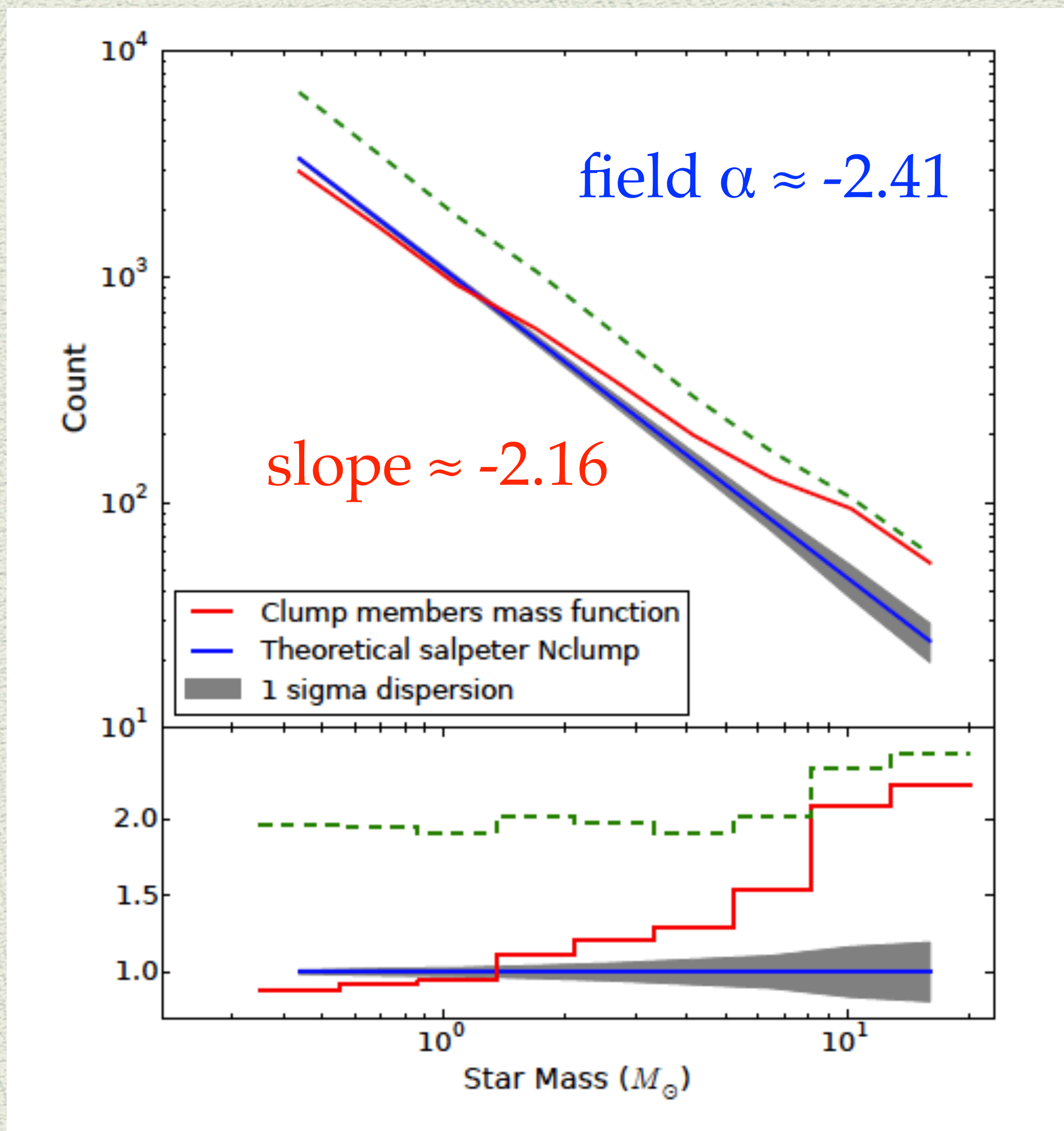

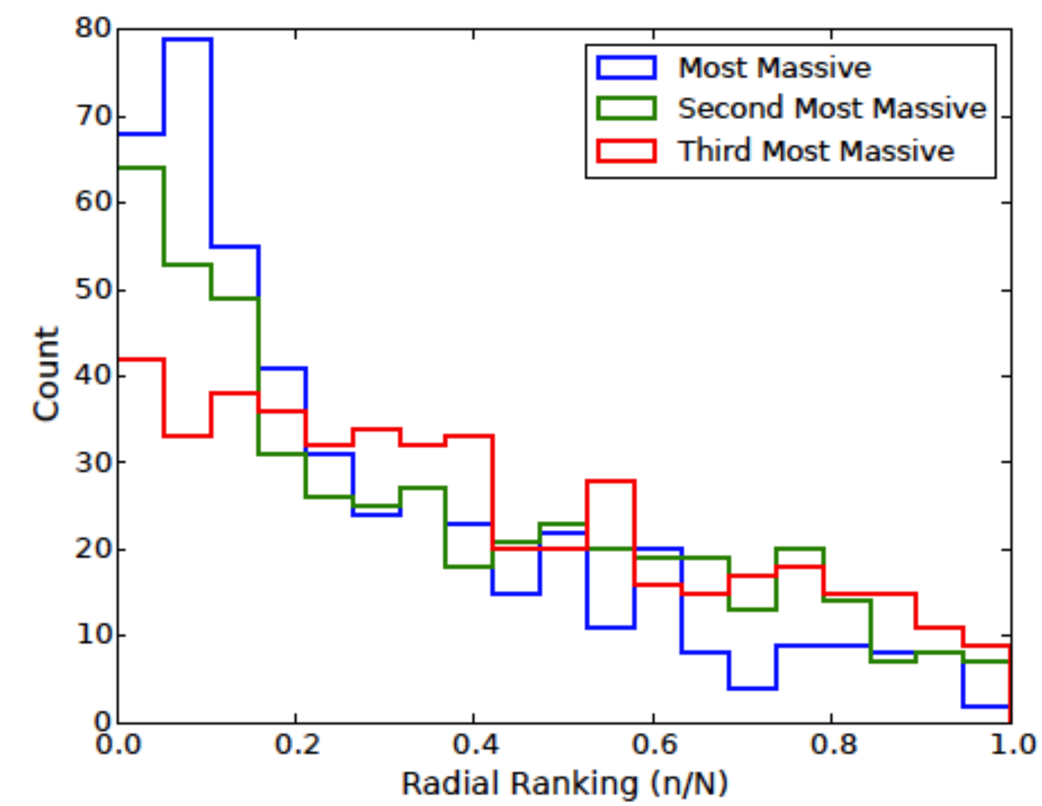

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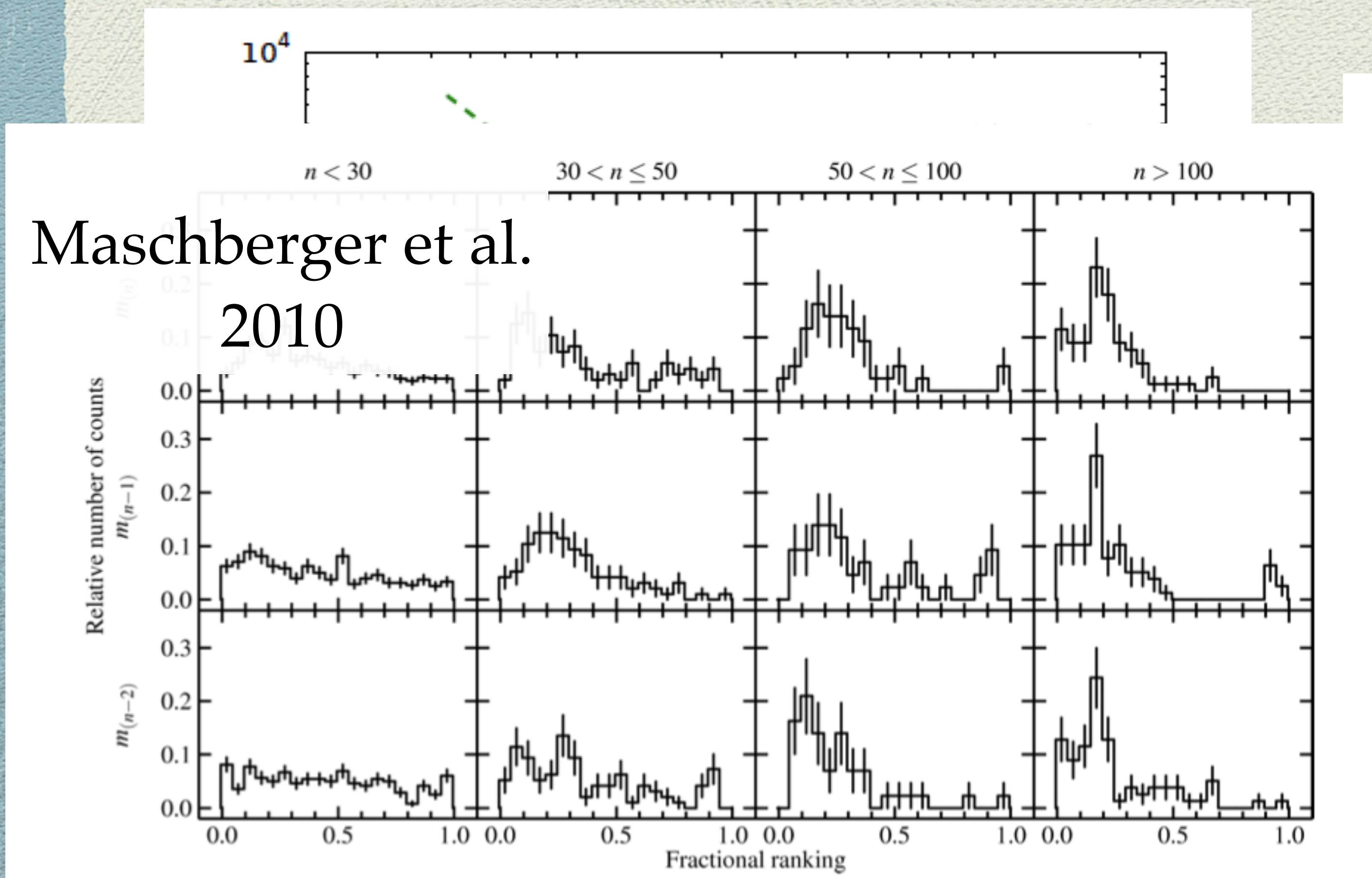
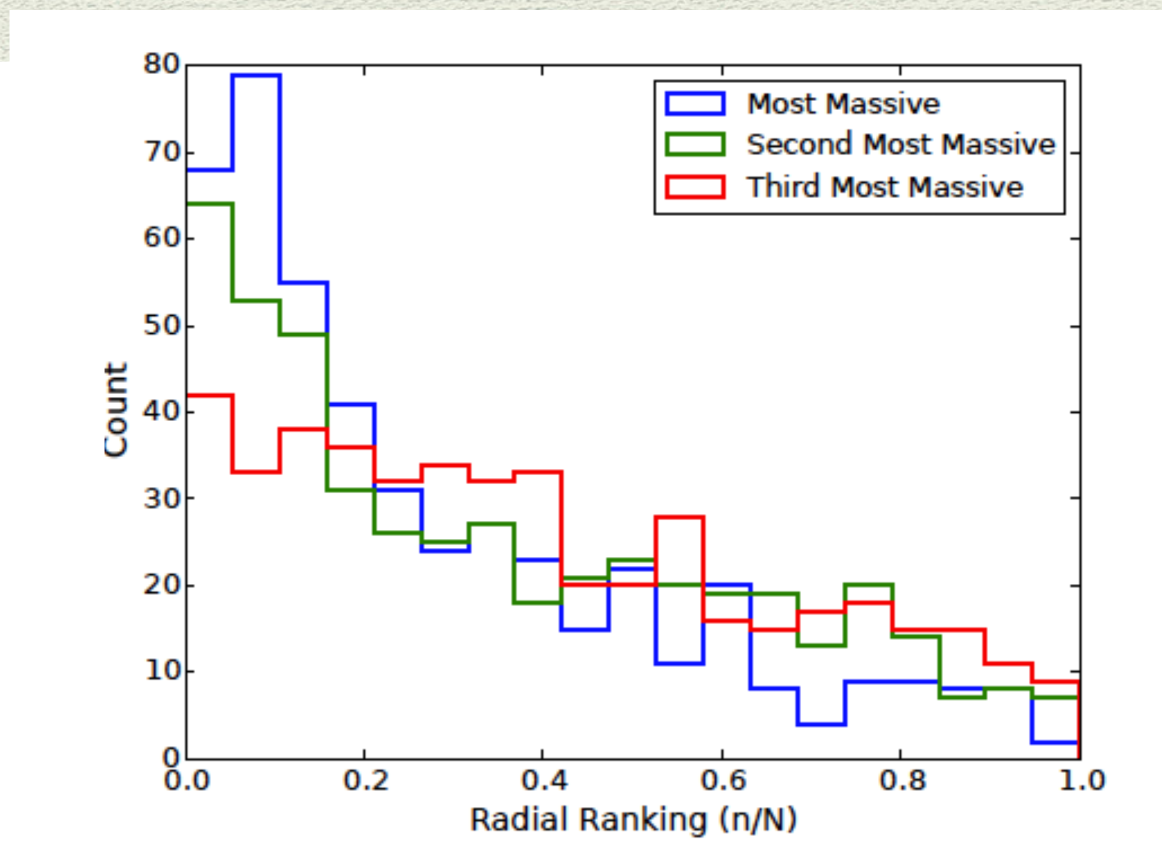


Figure 13. Histogram of the fractional radial ranking of the most massive (top), second most massive (middle) and third most massive (bottom) sink particle in its associated subcluster, split up by the number of sinks in the subcluster. The composite population of the 10^4 $M_\odot$ calculation is used to make the histograms. In the absence of mass segregation, the histogram would be flat: the peak at small values shows that the massive sinks are preferentially found near the cluster centre. The second peak with a ranking of ≈1, especially for the second and third most massive sink, is due to mergers, where two centres are still present.



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Initial conditions : the MVP approach

Most Valuable Paper .. 😊

A DYNAMICAL ORIGIN FOR EARLY MASS SEGREGATION IN YOUNG STAR CLUSTERS

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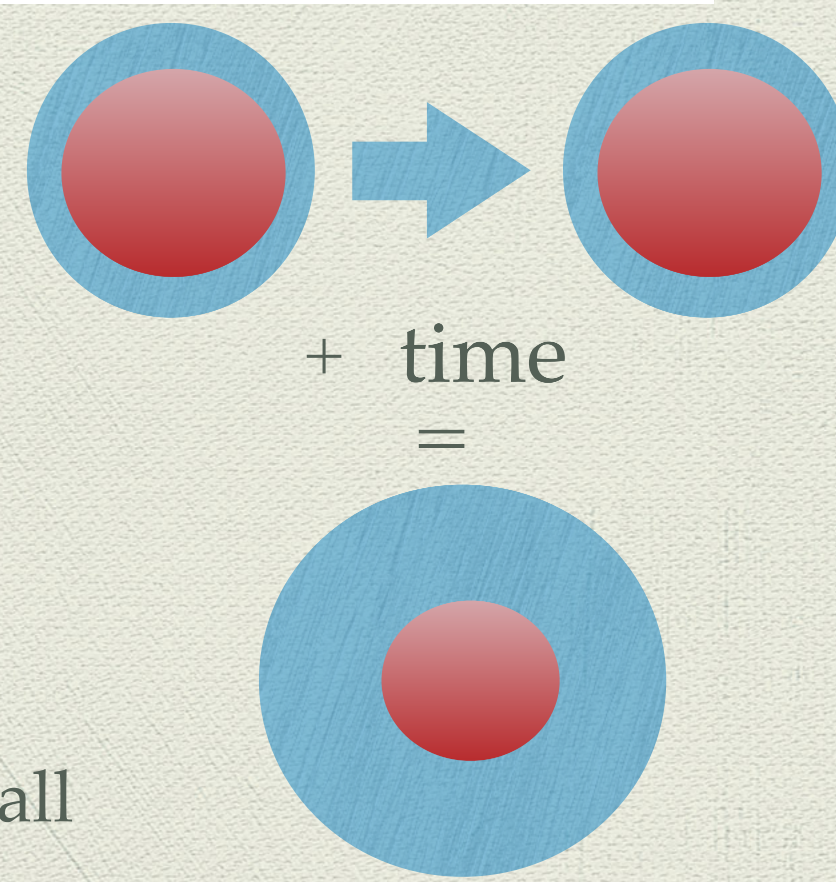
Astronomical Institute "Anton Pannekoek" and Section Computational Science, University of Amsterdam, Kruislaan 403, Amsterdam, Netherlands; spz@science.uva.nl
Received 2006 September 18; accepted 2006 December 12; published 2007 January 11

- *le* Mc + EV + SPZ (2007, 2014) : Mass segregation amplified by repeated mergers (▷ inheritance, memory)
- Segregation continues during the relaxation phase + beyond (in the classic fashion, then)



:: Consequently sub-units would segregate if small enough, *before* the global relaxation phase

Also : Allison et al. 2009, R. Parker, ..

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AND
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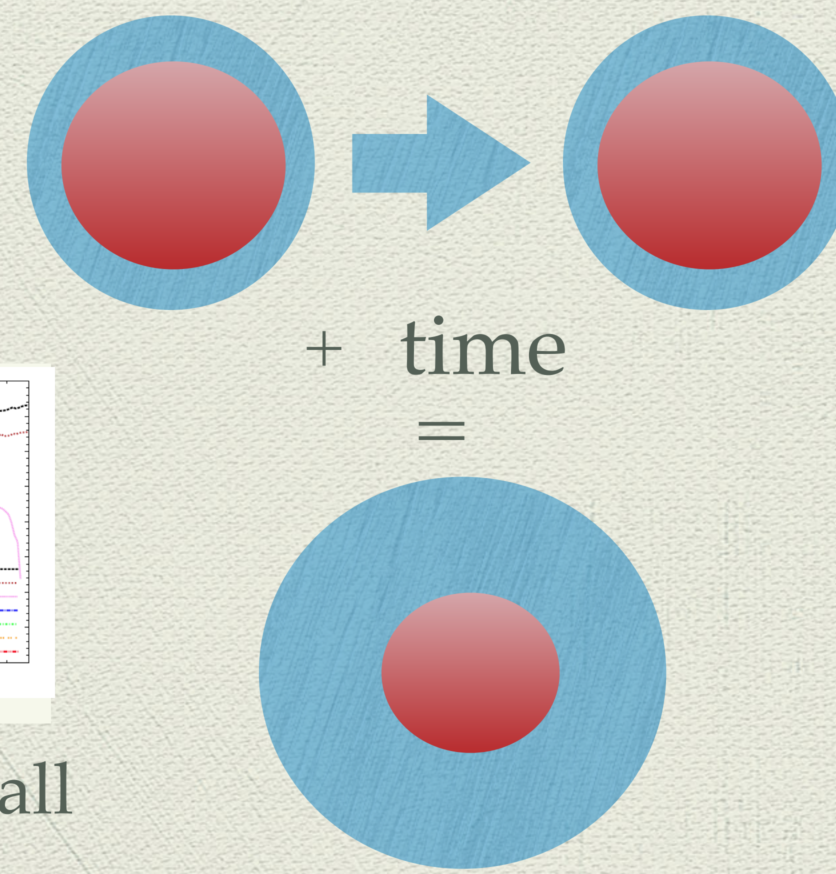
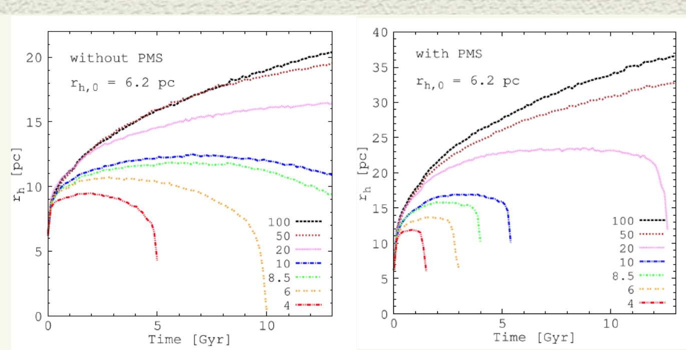


:: see e.g. Haghi et al. 2014



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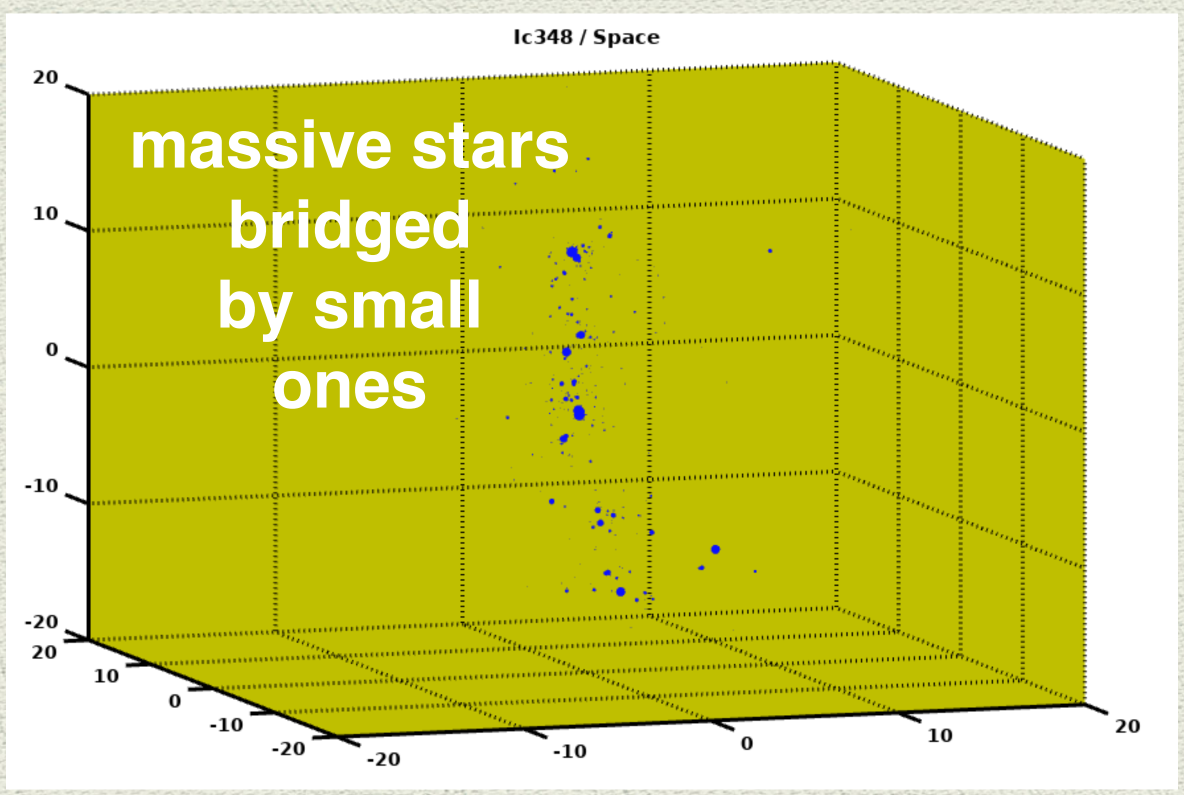
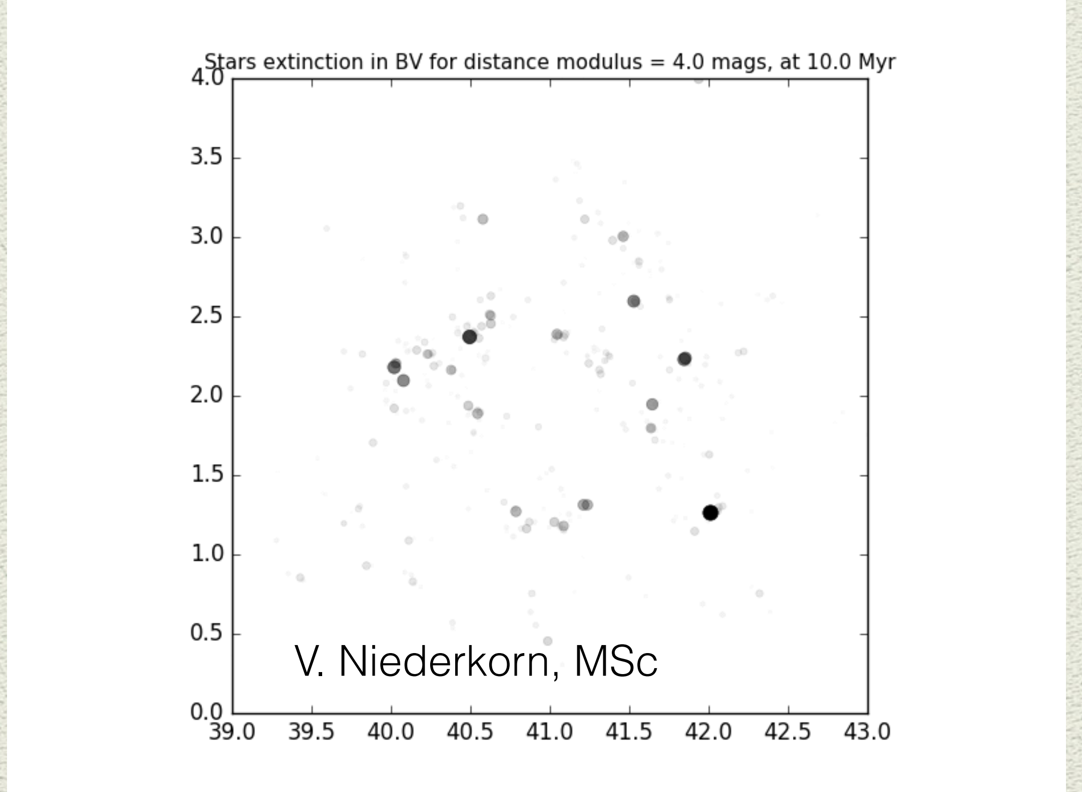
Morphology - The Minimum Spanning Tree approach

- Delaunay Triangulation + Kruskal's algorithm
- Implementation from NRv3 (C++)
- Morphology : apparent vs real .. selection, extinction
- Use the Pann-Starrs1 extinction map (Green et al. 2015, ..)





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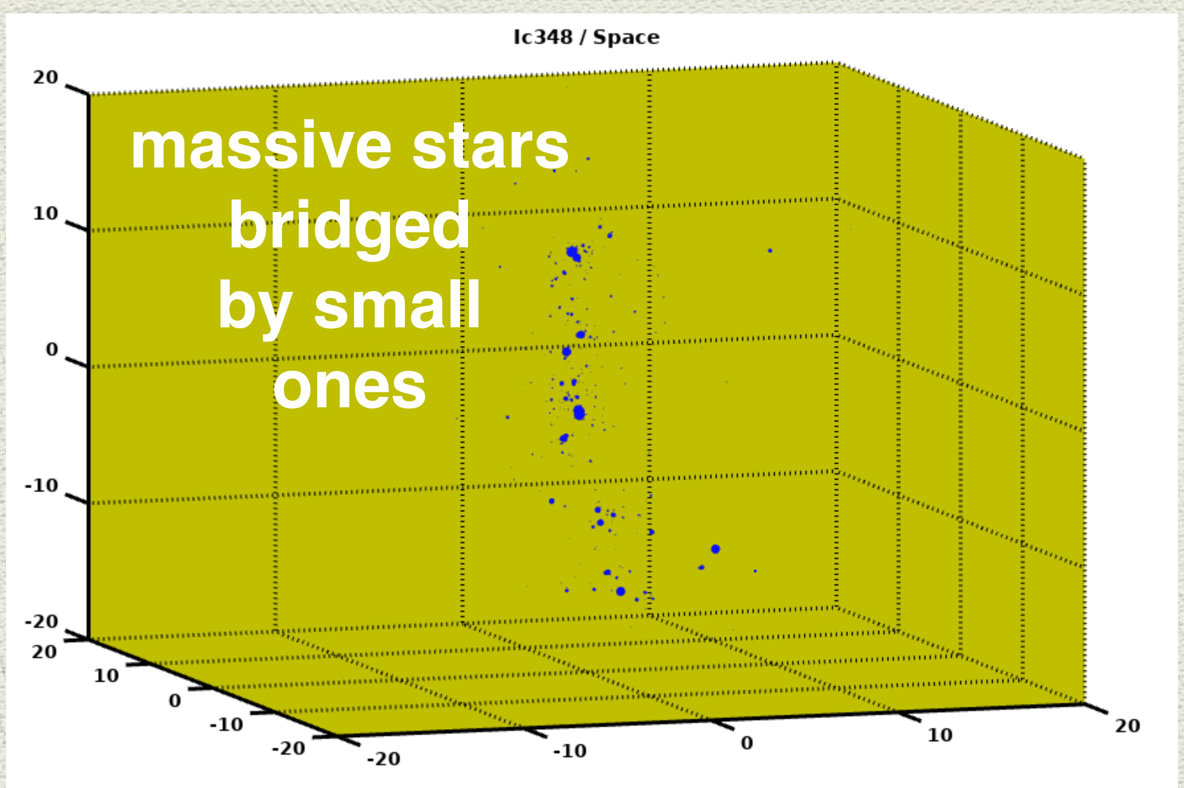
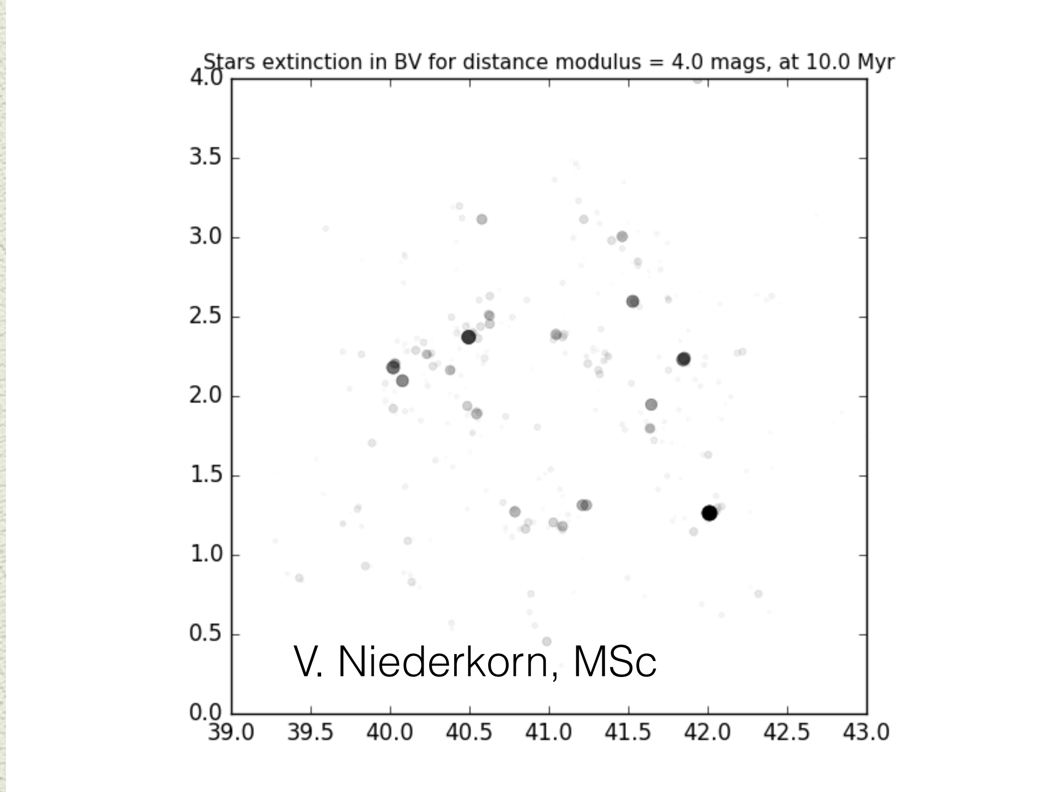
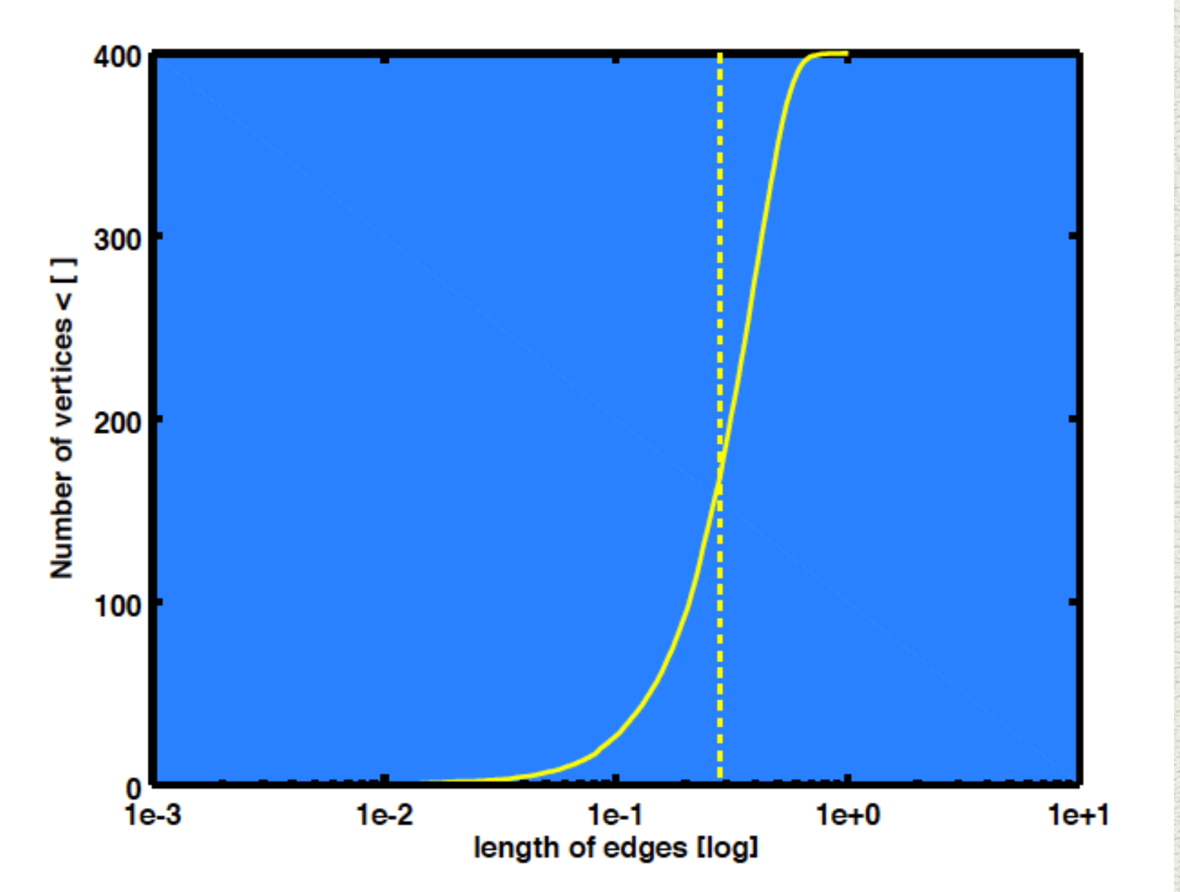




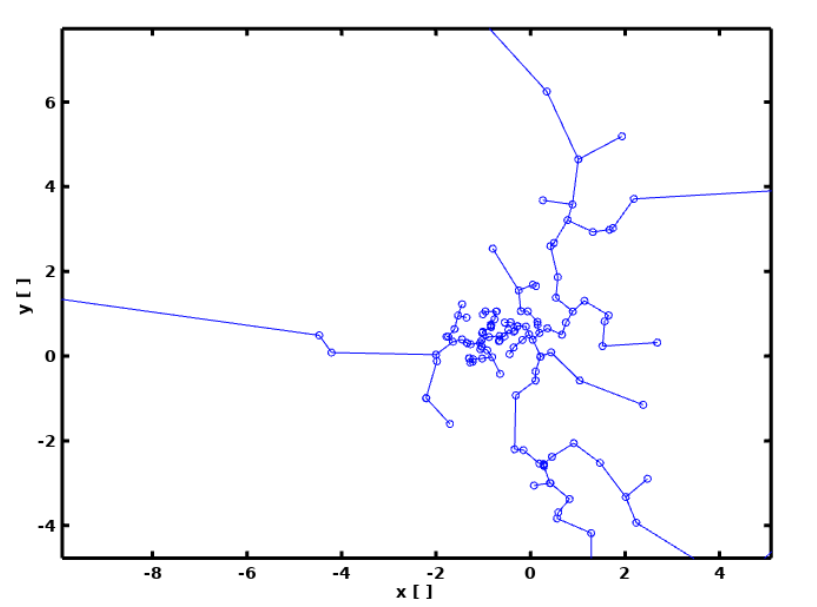
MST: distribution of edges

- Distribution differs if selected stars are "packed" together
- Useful to determined relative mass segregation (Alison, Parker ..)
- Cumulative distribution

Uniformly sampled surface / normalized



MST reconstruction (zoom)



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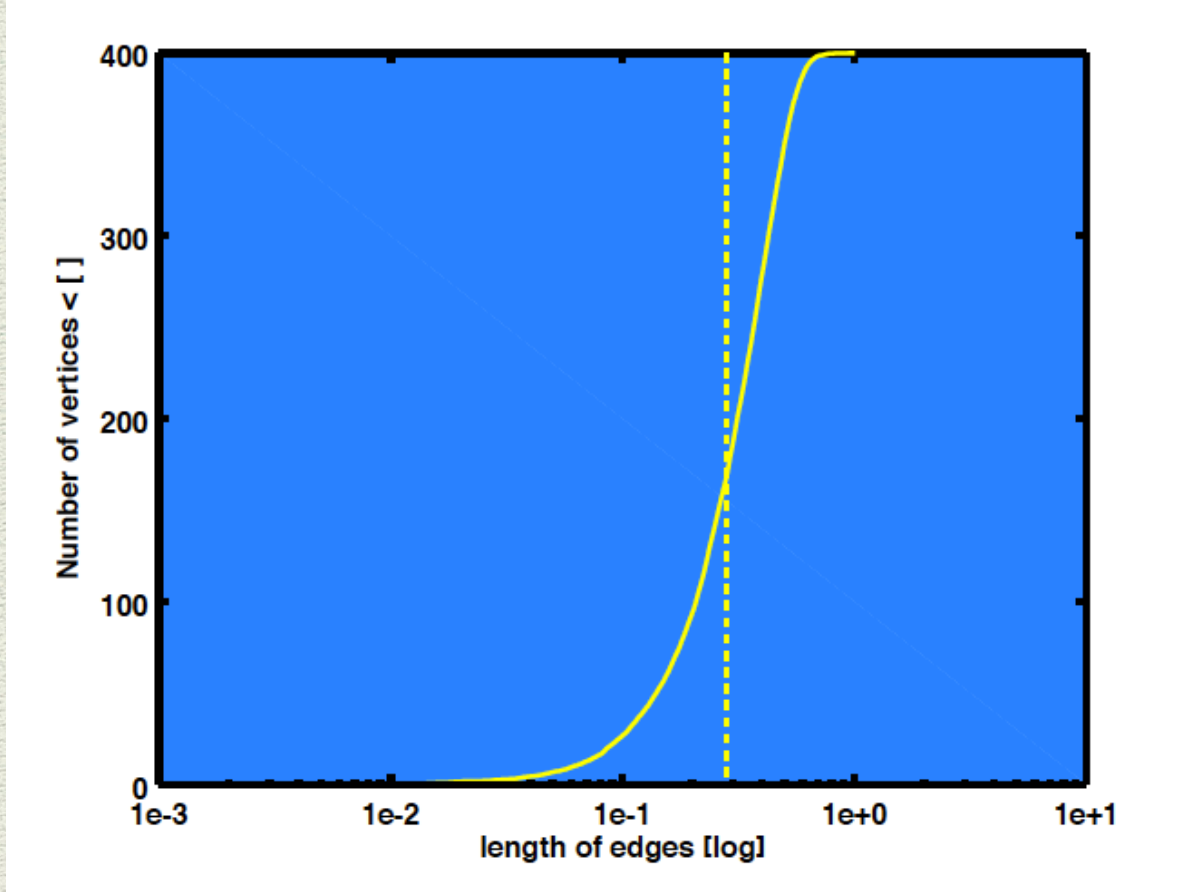
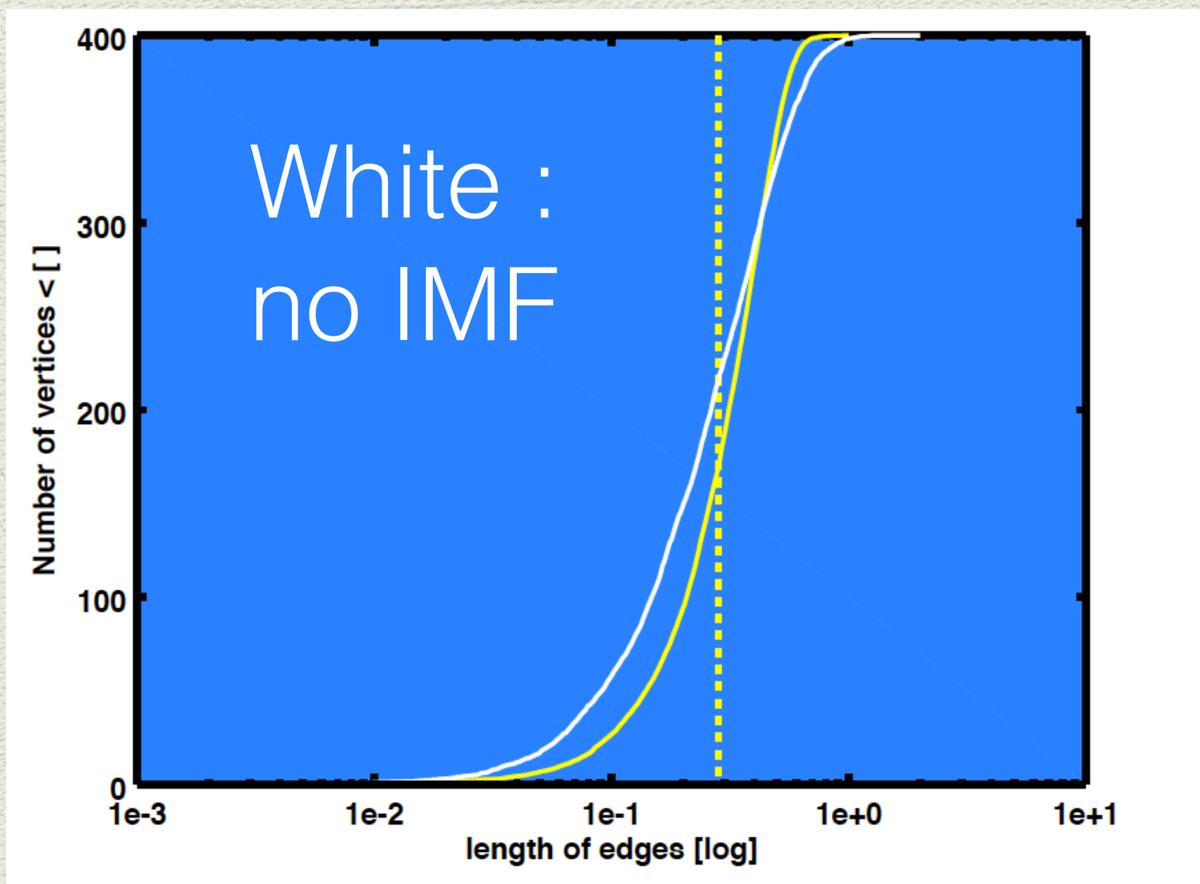


Uniformly sampled
+ fragmented model



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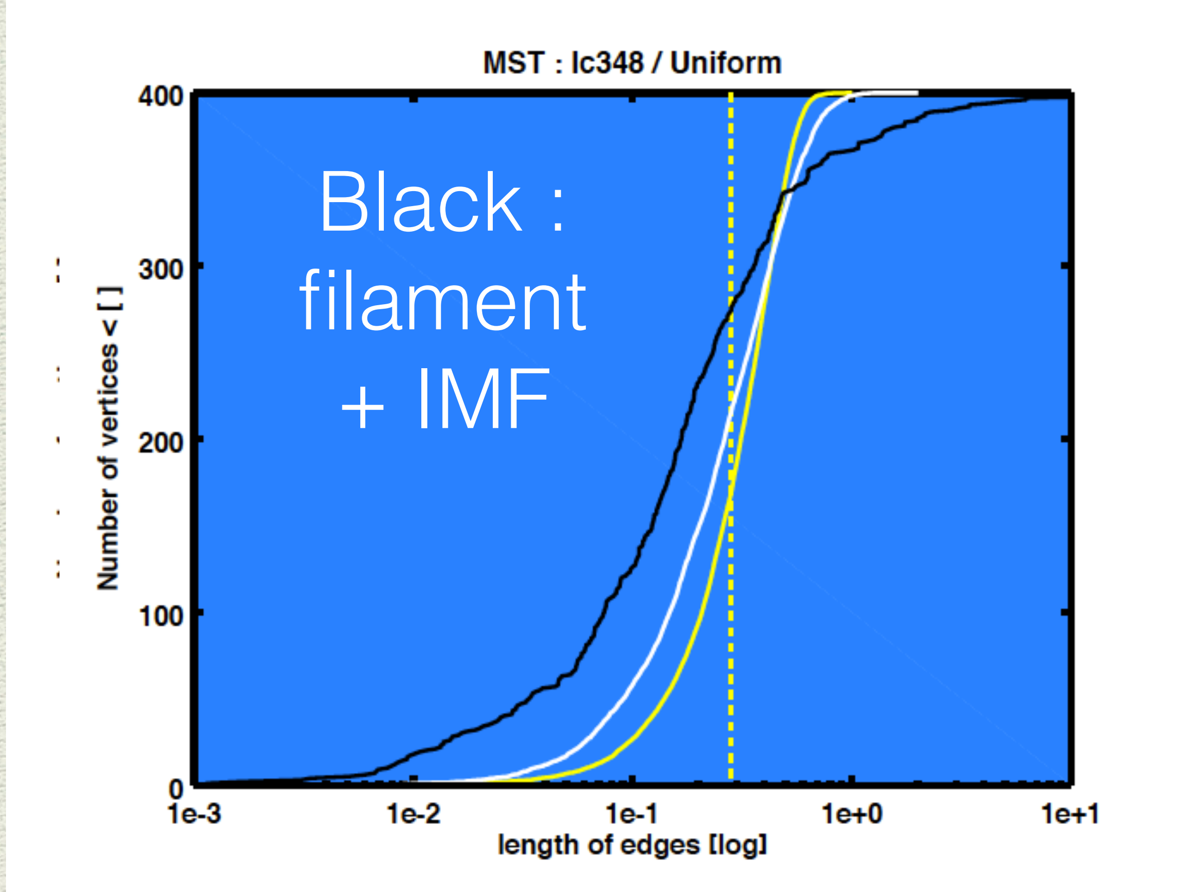

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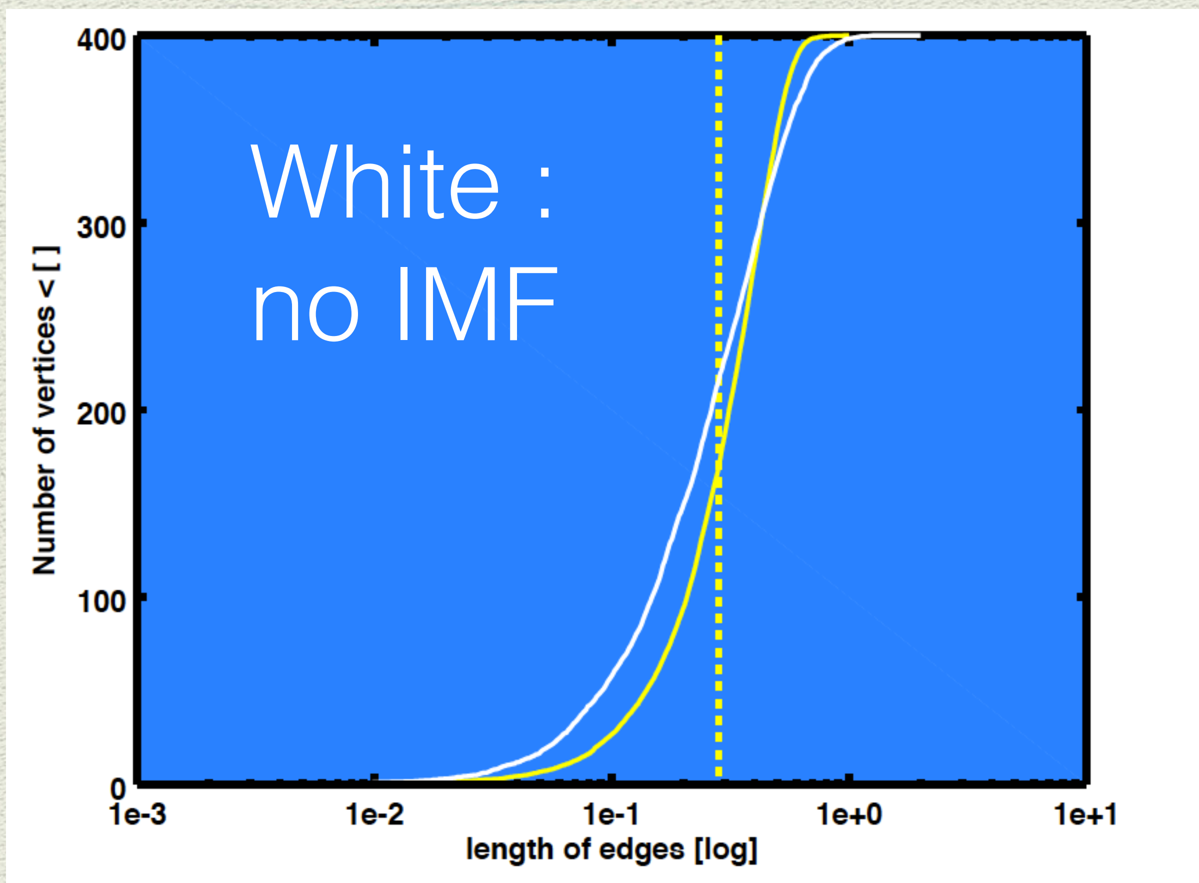

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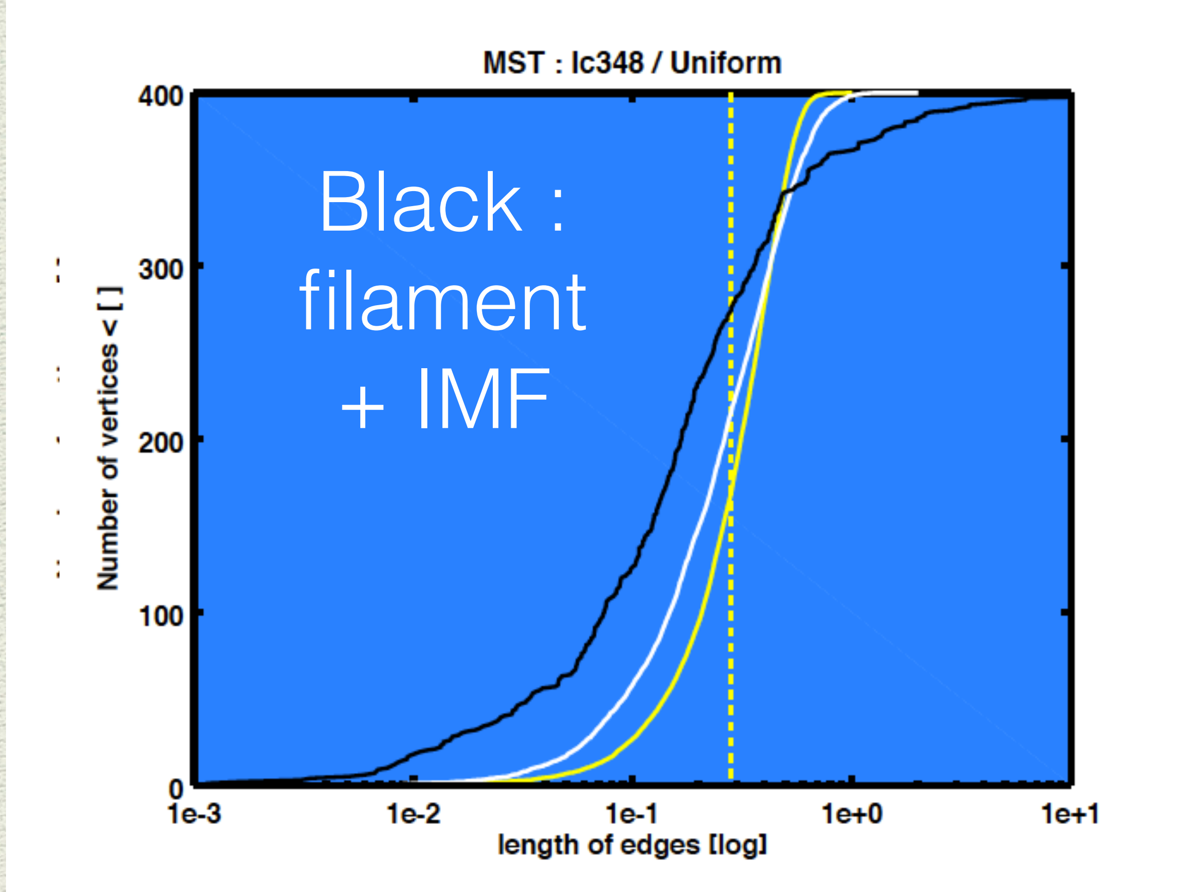

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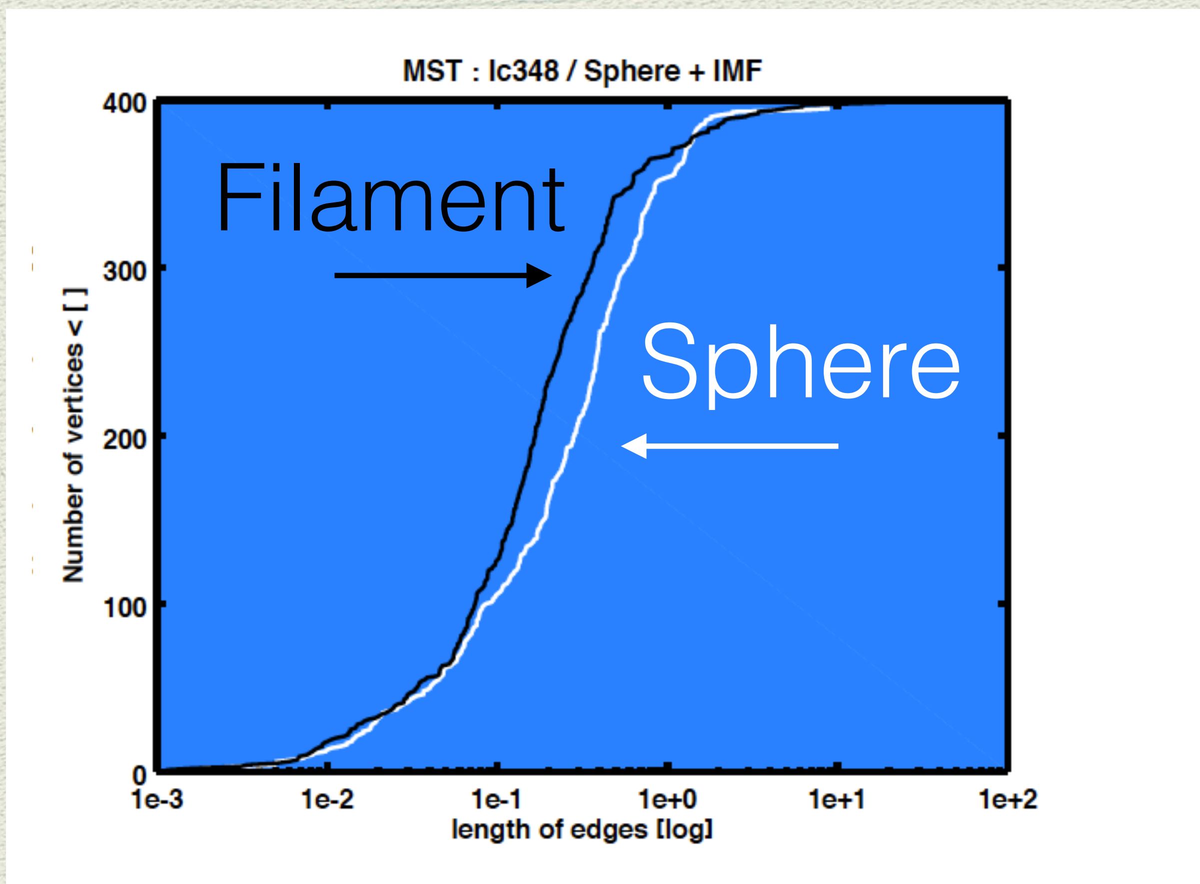
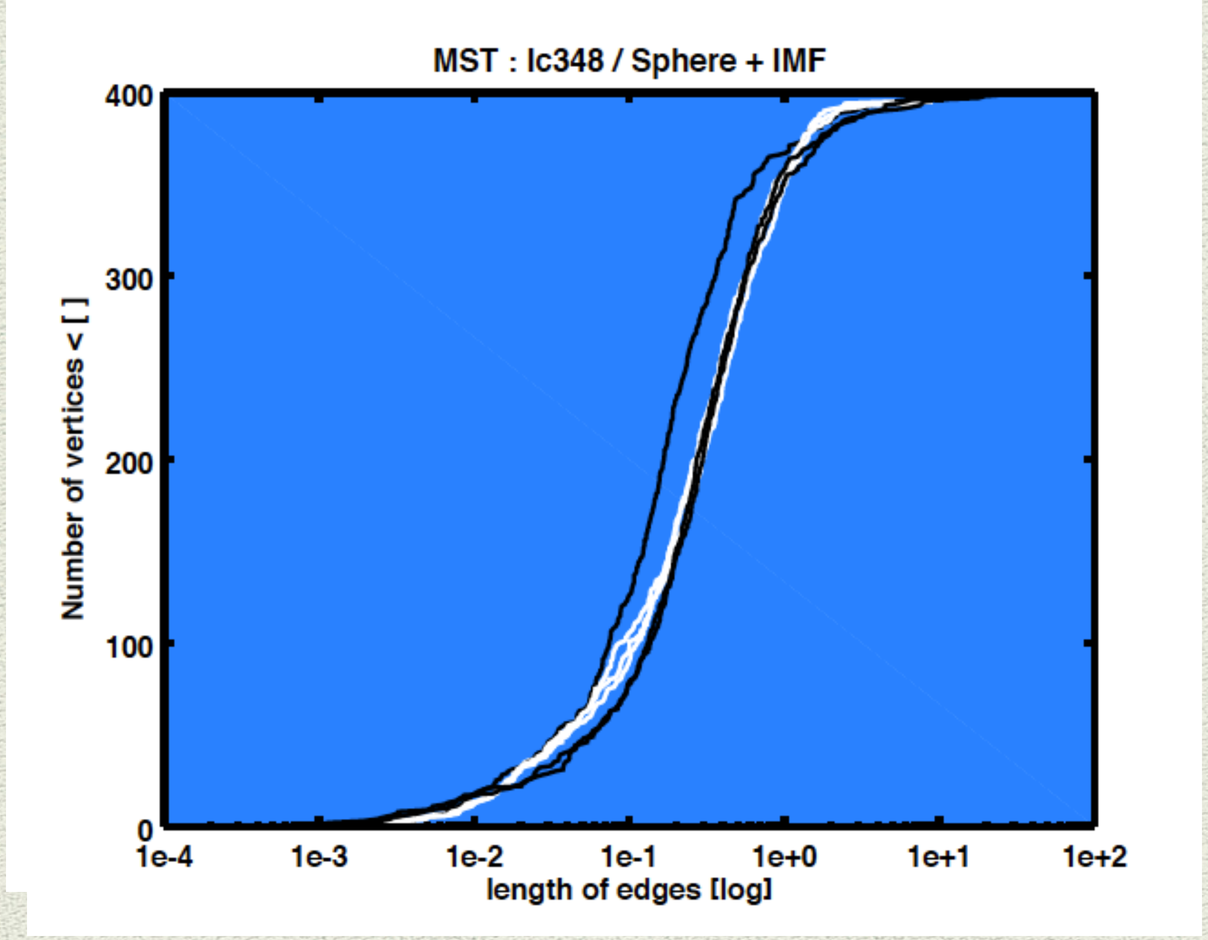


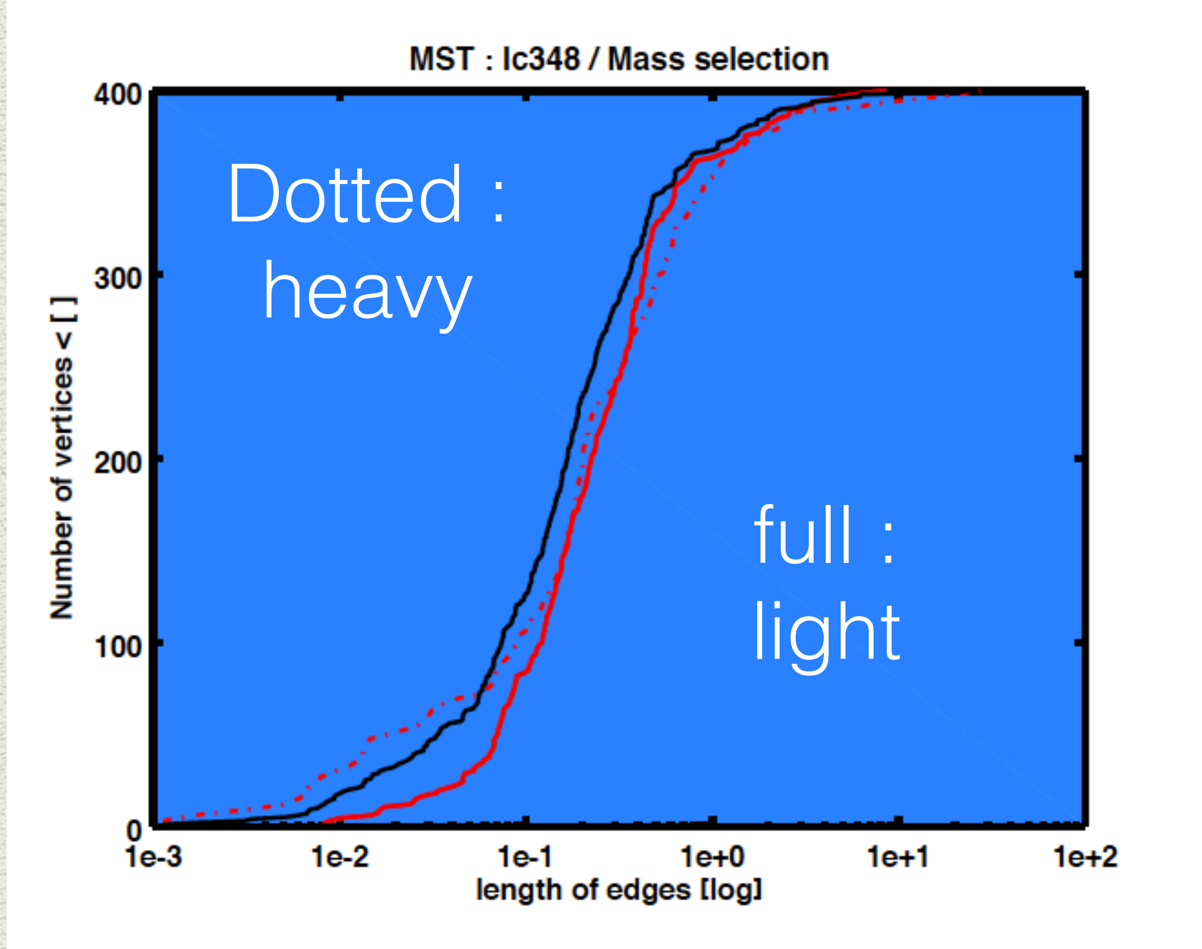
Effect of global geometry

MST: distribution of edges

Different projection angles



Selection by mass / renormalized



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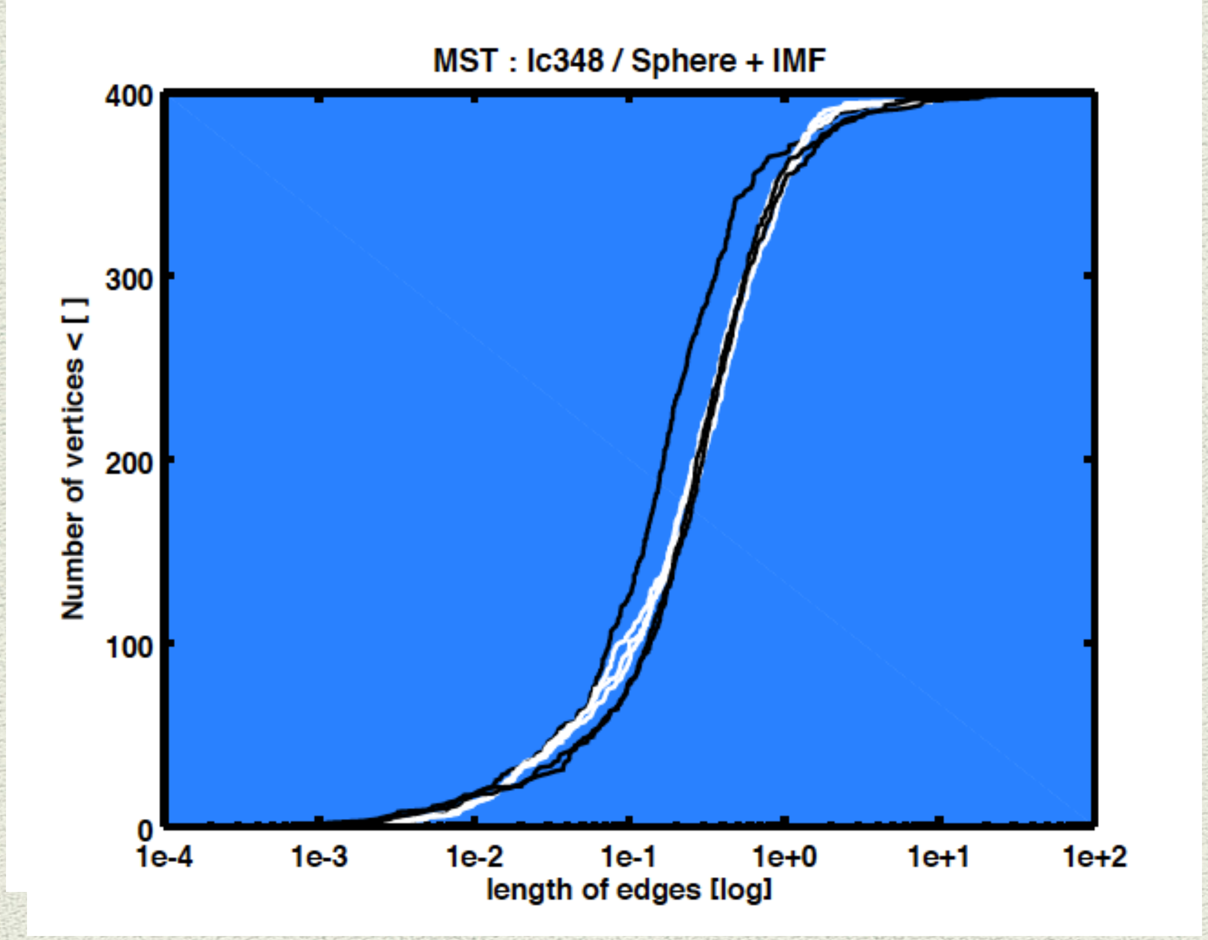
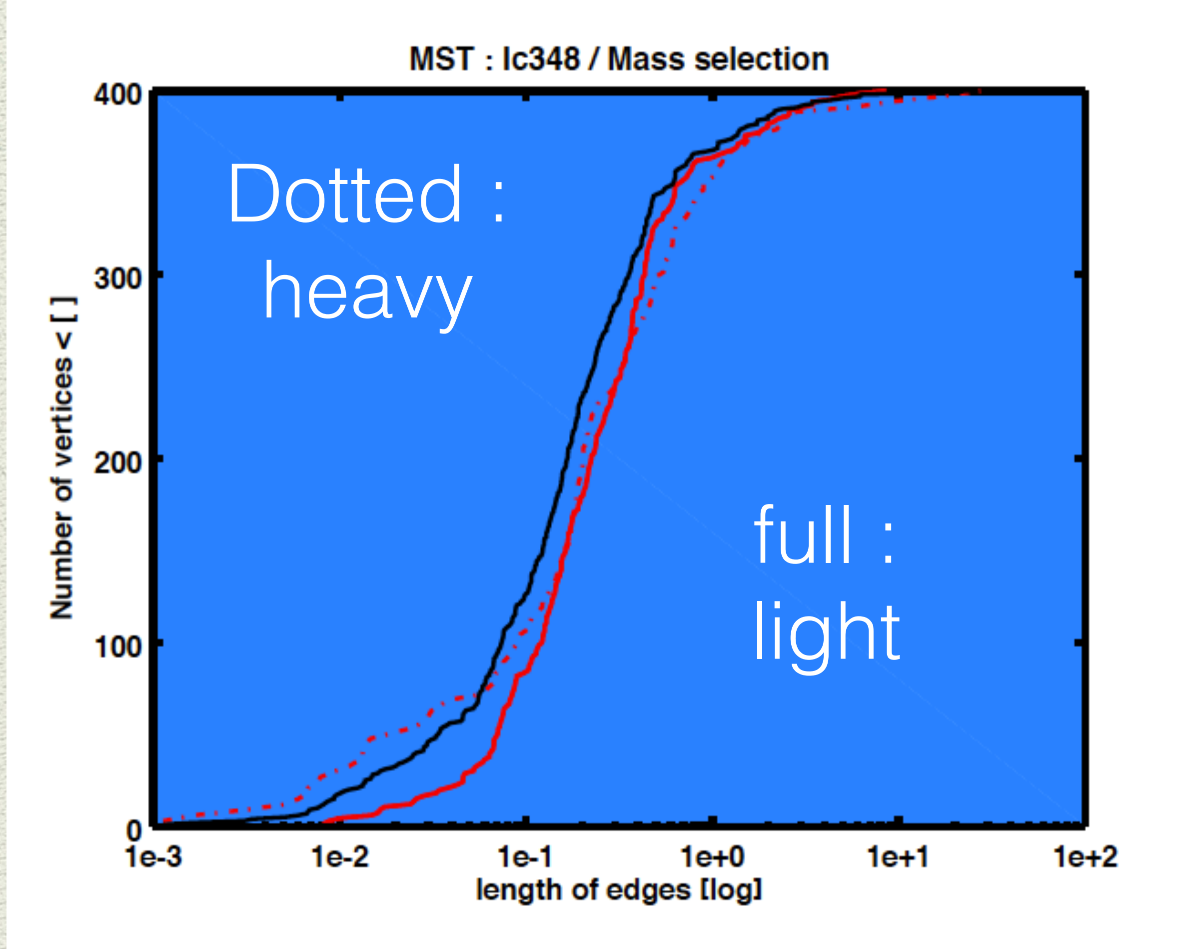
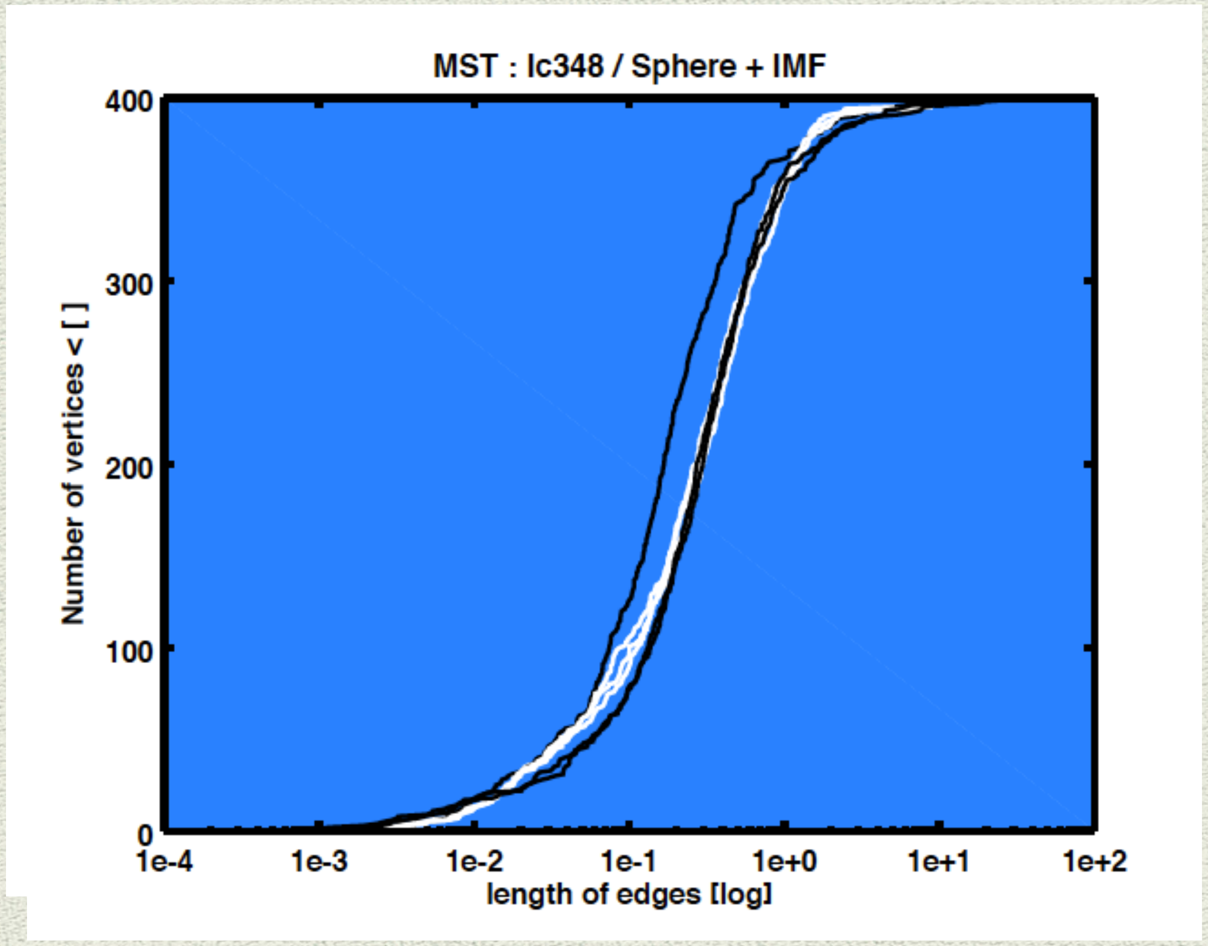


Selection by mass / renormalized

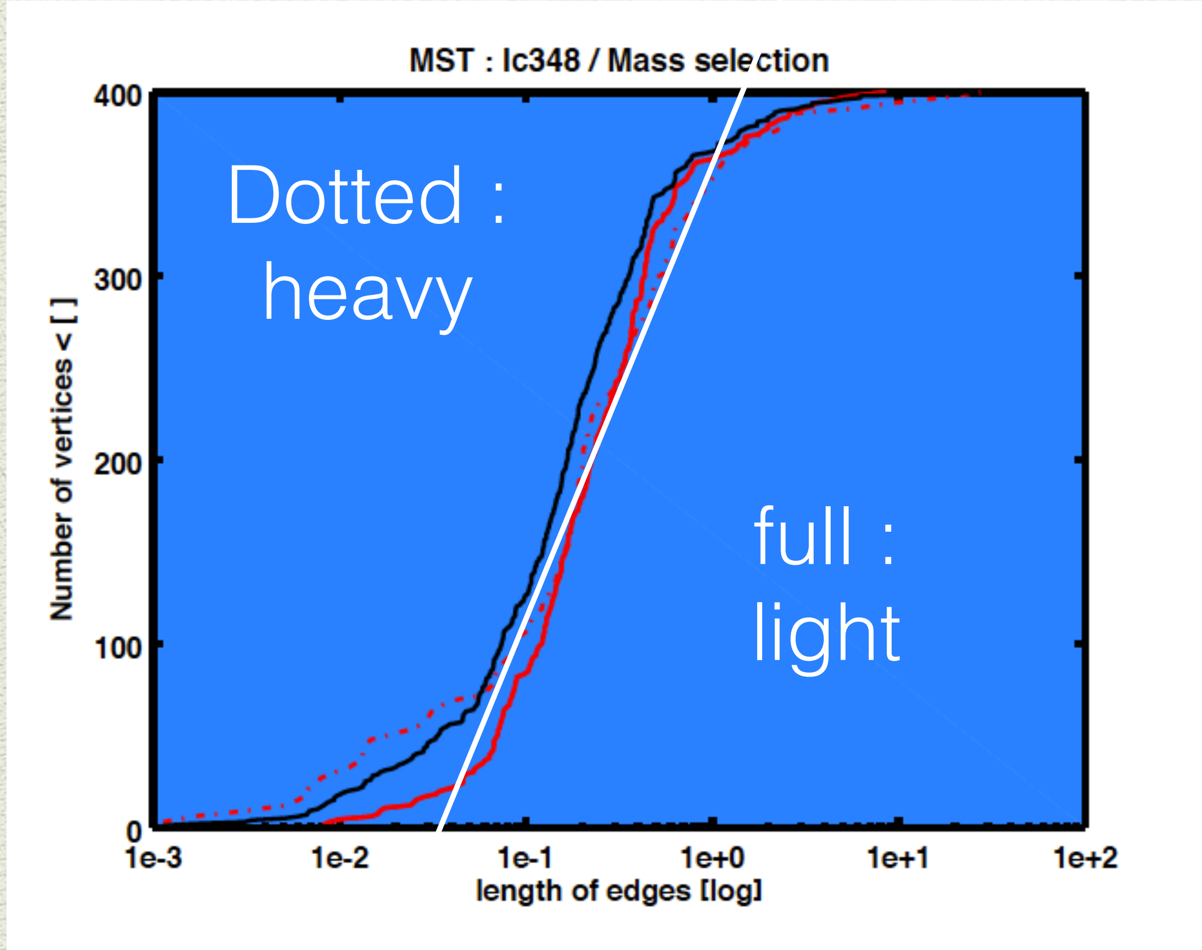


MST: distribution of edges

Different projection angles



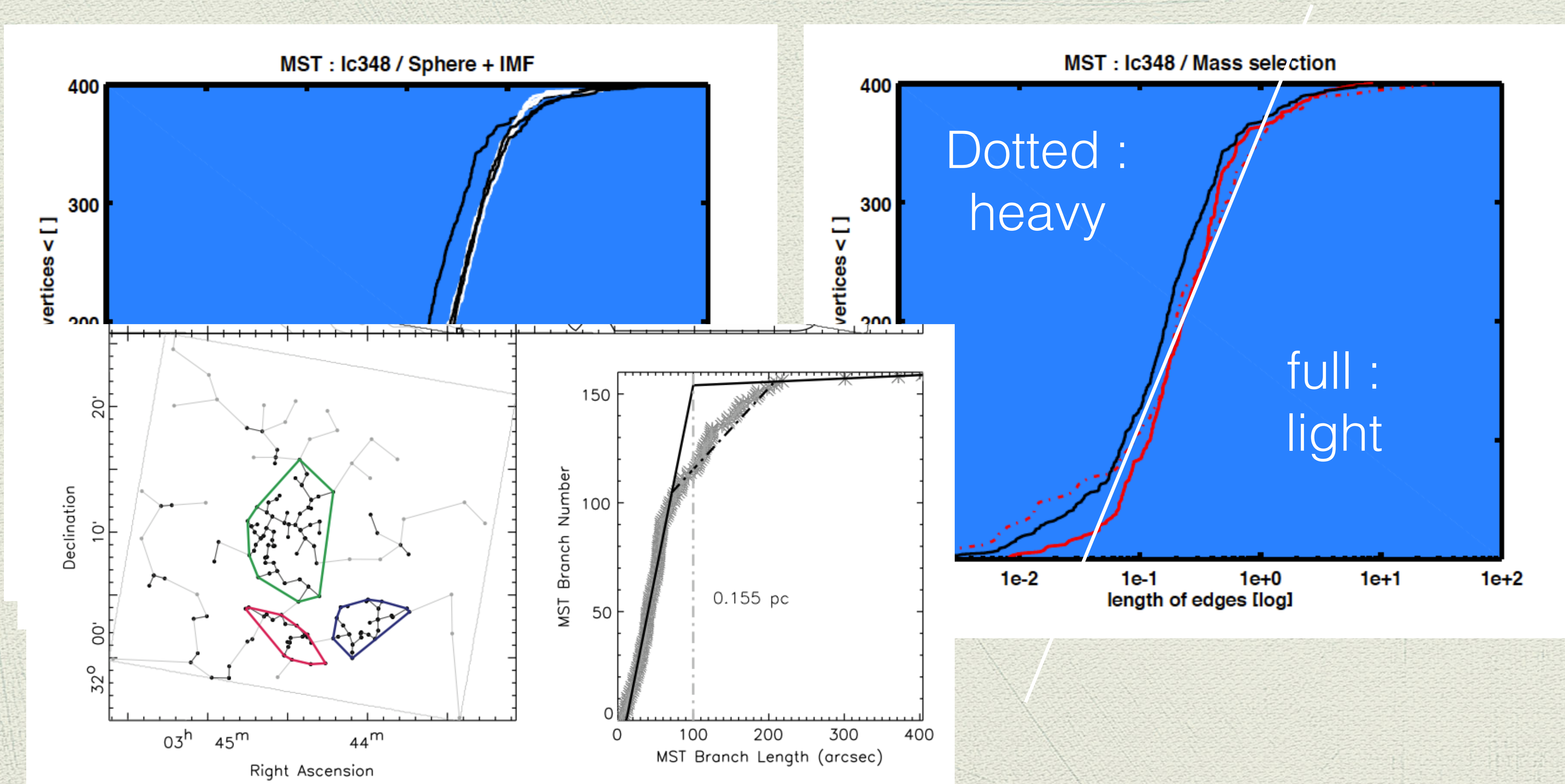
Selection by mass / renormalized



MST: distribution of edges

Different projection angles

Selection by mass / renormalized



Guthermut et al. 2009, ApJS

Summary

- Young clusters (open, rich, even globulars) start out with odd geometry and sub-virial global velocities
- They should mix quickly yet have time to form stars first
- A calculation based on adiabatic («cosmological») expansion allows to setup fragmented stellar systems with self-consistent velocities + cover large area (>> 1 pc^2)
- The stellar clumps are top-heavy with respect to field stars ;
- The dynamics along filaments enhances breaks in the MST statistics.