

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

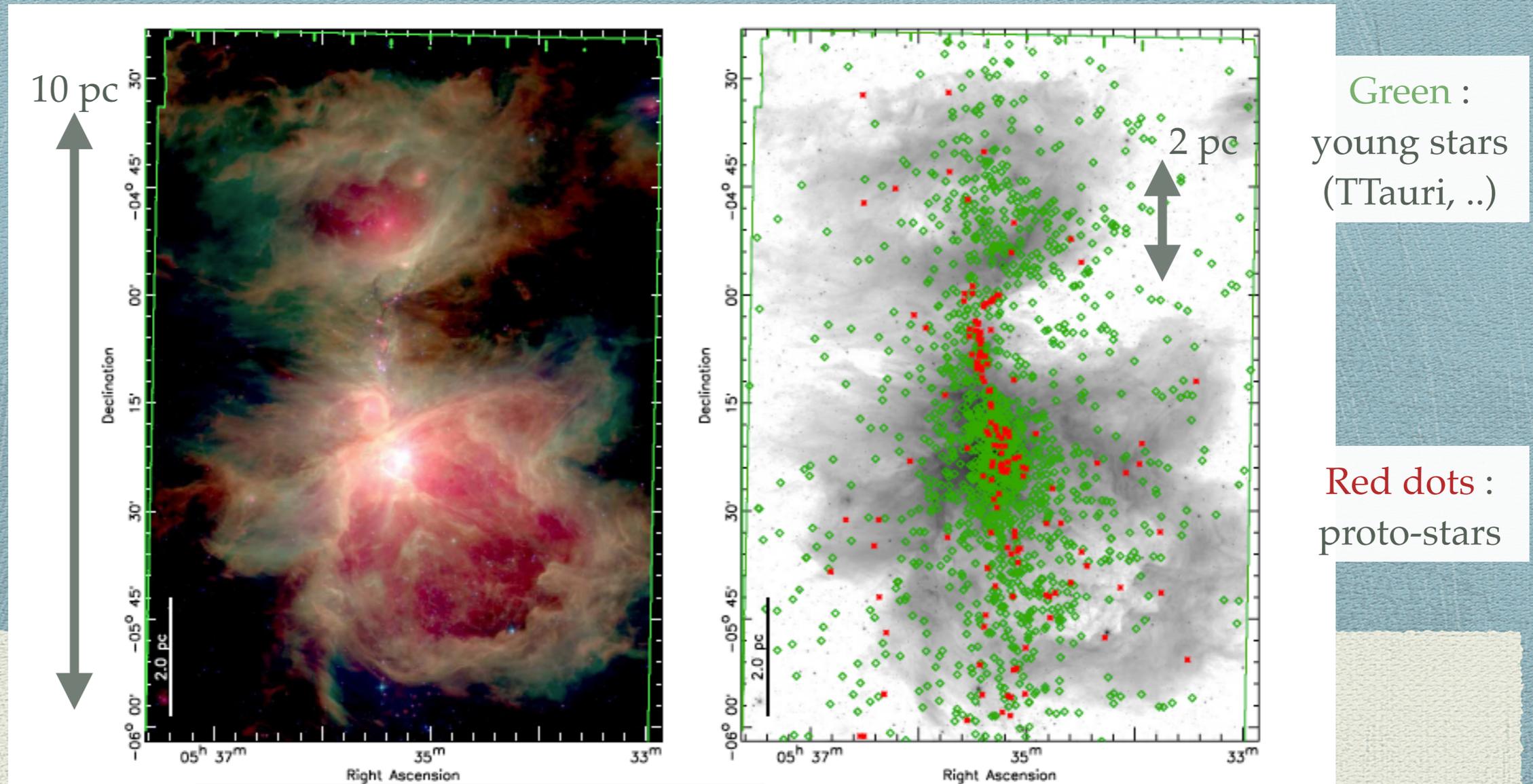
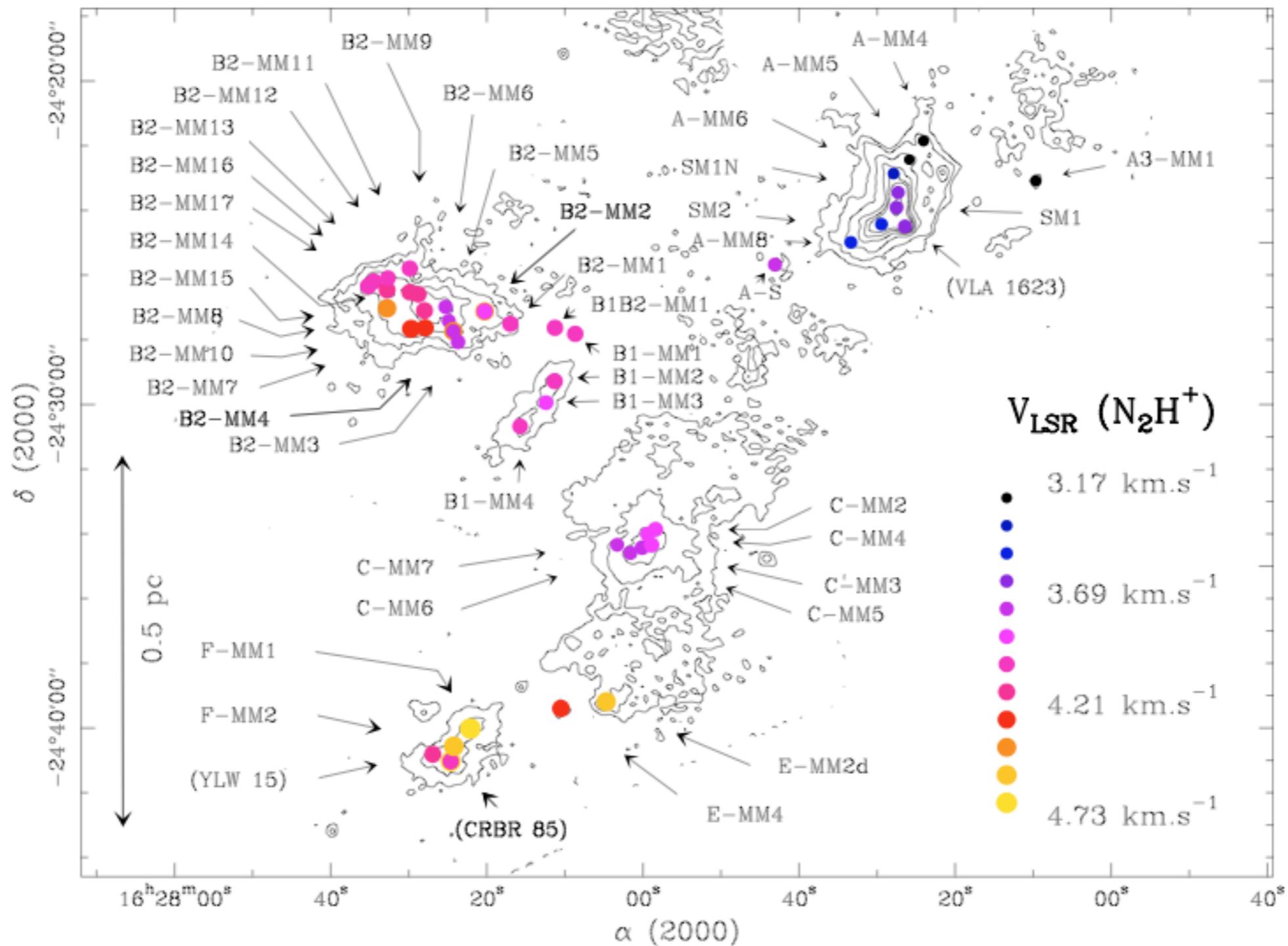


Figure 14. Left: mosaic of the ONC field. Blue is $4.5 \mu\text{m}$, green is $5.8 \mu\text{m}$, and red is $24 \mu\text{m}$. Right: $4.5 \mu\text{m}$ image with the positions of dusty YSOs superimposed. Green diamonds are young stars with disks, red asterisks are protostars (including the faint candidate protostars and the 10 red candidate protostars detected at $24 \mu\text{m}$ but not at 4.5 , 5.8 , and $8 \mu\text{m}$). 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 $24 \mu\text{m}$ 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).

Credits : S. Megeath et al. 2012, 2015

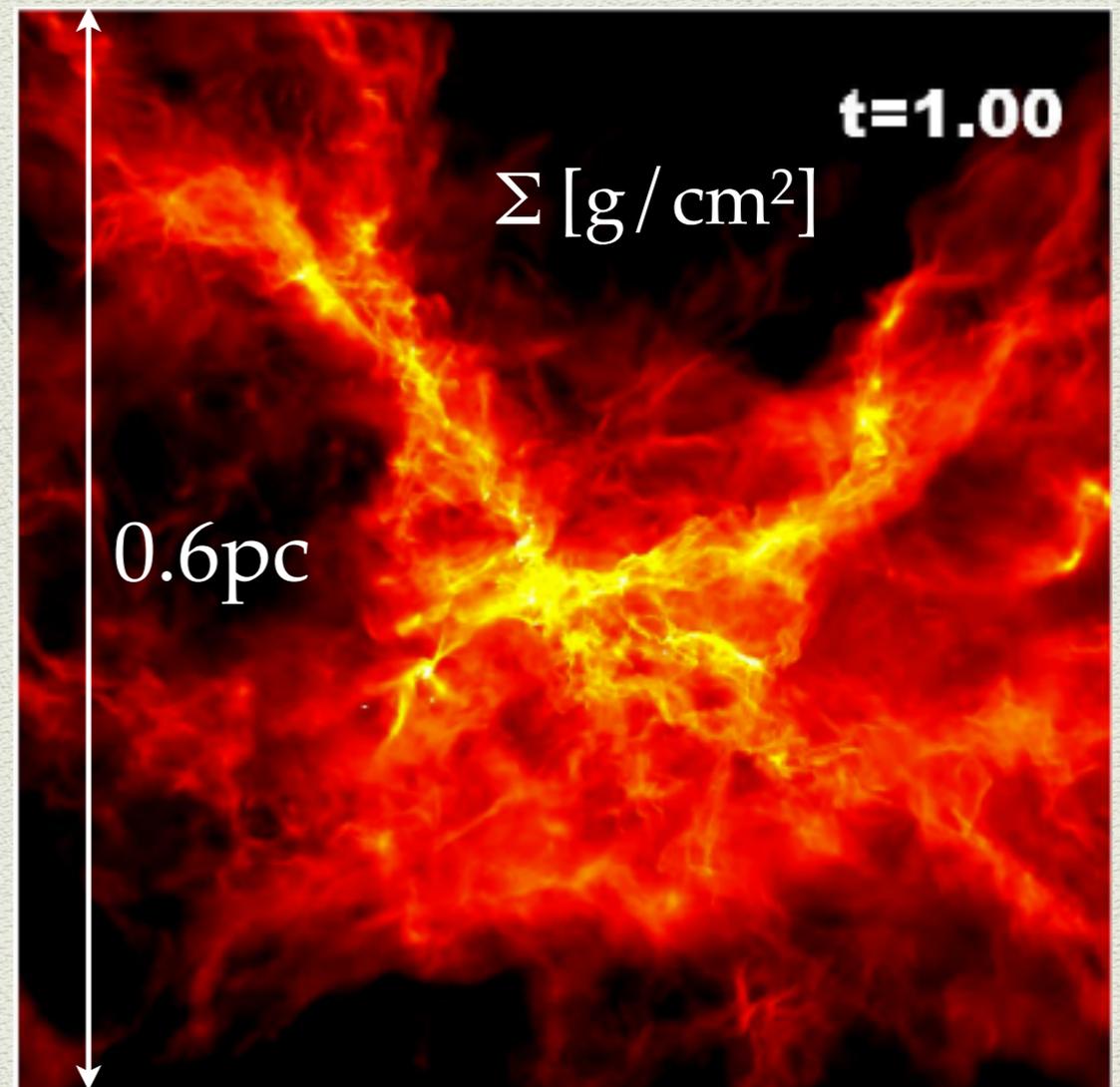


Kinematics in the ρ Ophiuchus region (IRAM 30 m data)

credits : Ph. André et al. 2007, AA

Fragmentation in star-formation calculations

- ◆ SPH resimulation of isothermal collapse but *with* opacity
- ◆ Time in units of the free-fall time
 $\sim 2 \times 10^5$ yrs
- ◆ From 250 \triangleright 180 cores formed
- ◆ $M = 500 M_{\text{Sun}}$, $R_0 \approx 1/2$ pc $T \approx 10$ K
($\rho \approx 1.8 \times 10^3 M_{\text{Sun}} / \text{pc}^3$ initially)
- ◆ Linear resolution ~ 0.5 AU



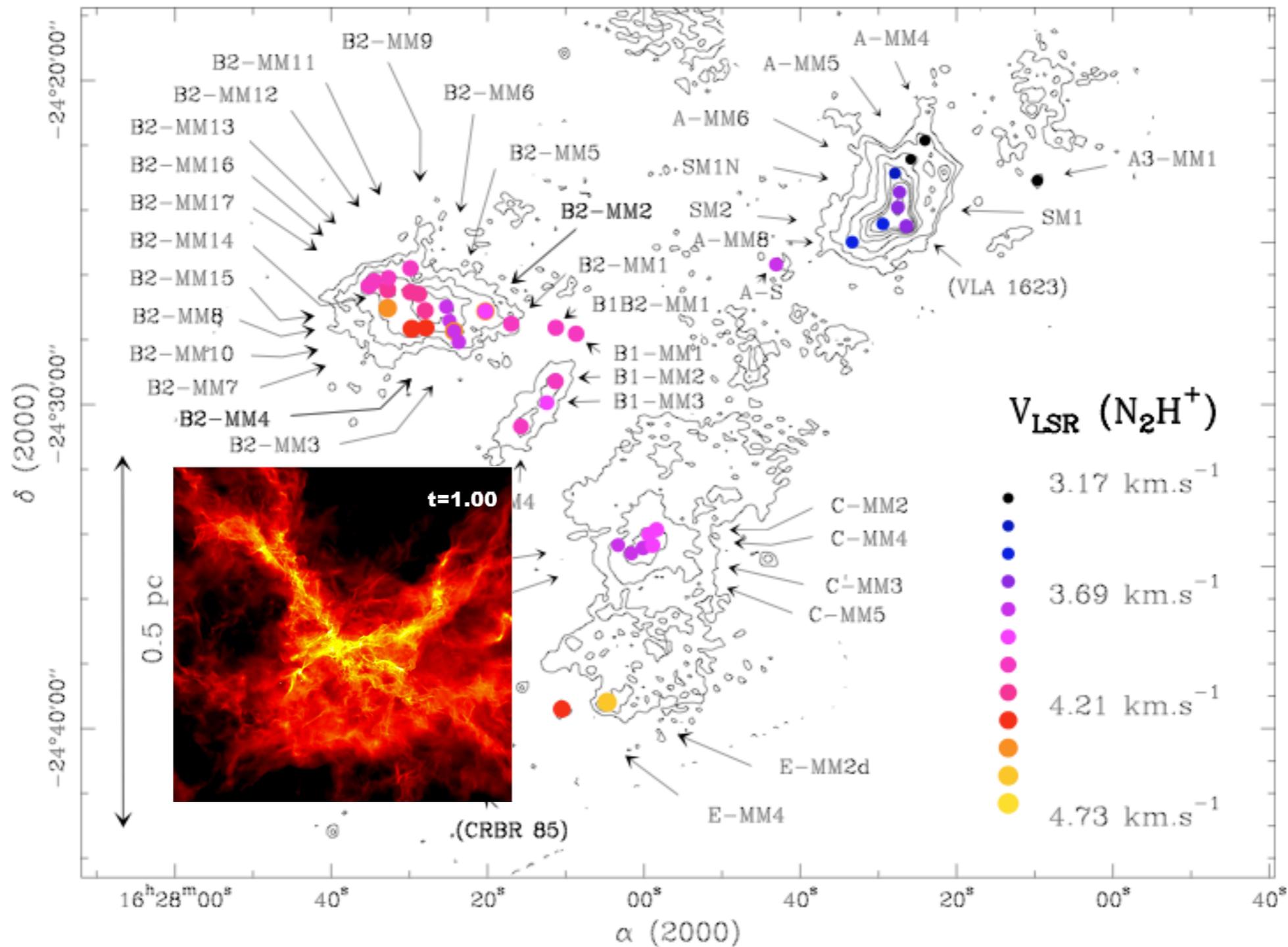
Still ~ 3 orders of magnitude from rich clusters

M. Bate 2011, MN

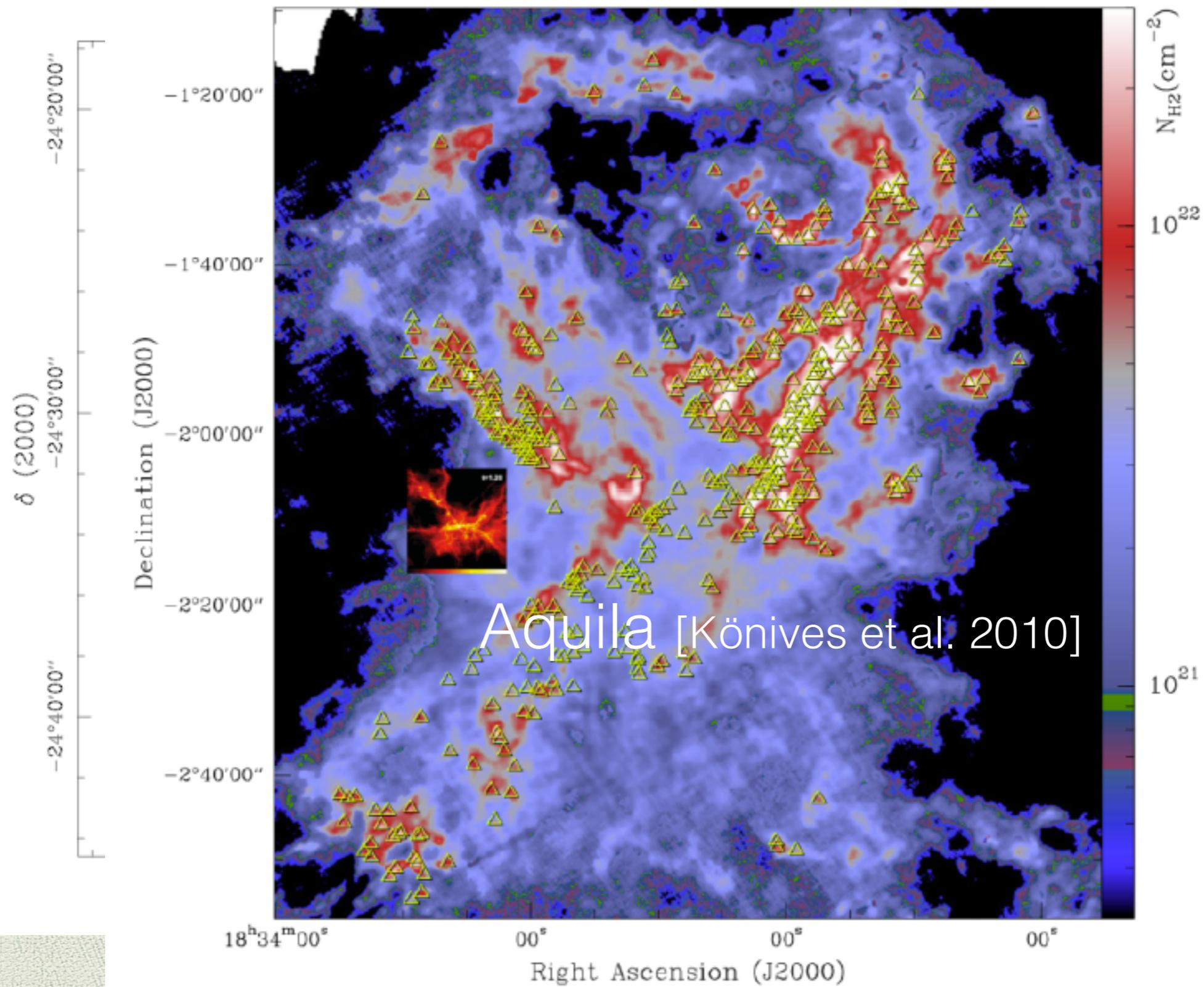
Transition : embedded \triangleright gas-free. Yes, but how .. ?

- embedded cores / associations m.f. \sim cluster m.f.
-  details of mass-loss unclear, slower than energy argument would suggest (winds, SN, .. e.g. J. Dale 10/2015 webcast STScI) \triangleright 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 $\sigma \sim 0.8$ km/s [Foster et al. 2015, In-Sync survey])
-  Phase-mixing and relaxation on a time-scale well exceeding the star-formation time-scale

Ph. André et al.: Kinematics of the Ophiuchus protocluster condensations



Kinematics in the ρ Ophiuchus region (IRAM 30 m data)
credits : Ph. André et al. 2007, AA



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Initial conditions for stellar dynamics: different approaches

- Classic argument: stars are *as cool/cold as gas is* $\sigma^2 \approx k_B T$
- All mixed up, no mass- or length scale: monolithic collapse, 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

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

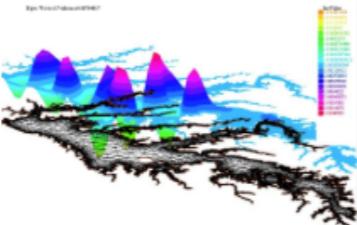
◆ Integrate .. but stay coherent

$$\begin{aligned} \nabla_{r'} &= \nabla_r + \xi \cdot \nabla_r (\nabla) \\ r' &= r + \xi \end{aligned}$$

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 .. ;)



mail to [FreeFem++ list](mailto:FreeFem++@freefem.org)

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- Home
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- FreeFem++-cs
- FreeFem++ on the web
- Showcase
- Web News

Documentation

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- Last News (INNOVATION)
- HISTORY
- knows BUGS
- Una documentación en español
- Chinese documentation
- Japanese (Kohji Ohtsuka)
- TWSIAM Activity Group

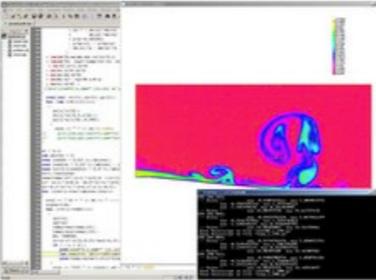
Compilation/Installation

- Download

FreeFem++ v 3.46

(April 08 2016 17:56:26.)

Introduction



FreeFem++ is a partial differential equation solver. It has its own language. freefem scripts can solve multiphysics non linear systems in 2D and 3D.

Problems involving PDE (2d, 3d) from several branches of physics such as fluid-structure interactions require interpolations of data on several meshes and their manipulation within one program. FreeFem++ includes a fast 2^d-tree-based interpolation algorithm and a language for the manipulation of data on multiple meshes (as a follow up of bamg (now a part of FreeFem++)).

FreeFem++ is written in C++ and the FreeFem++ language is a C++ idiom. It runs on Macs, Windows, Unix machines. FreeFem++ replaces the older *freefem* and *freefem+*.

If you use *FreeFem++* please cite the following reference in your work (books, articles, reports, etc.): Hecht, F. New development in FreeFem++. J. Numer. Math. 20 (2012), no. 3-4, 251–265. 65Y15

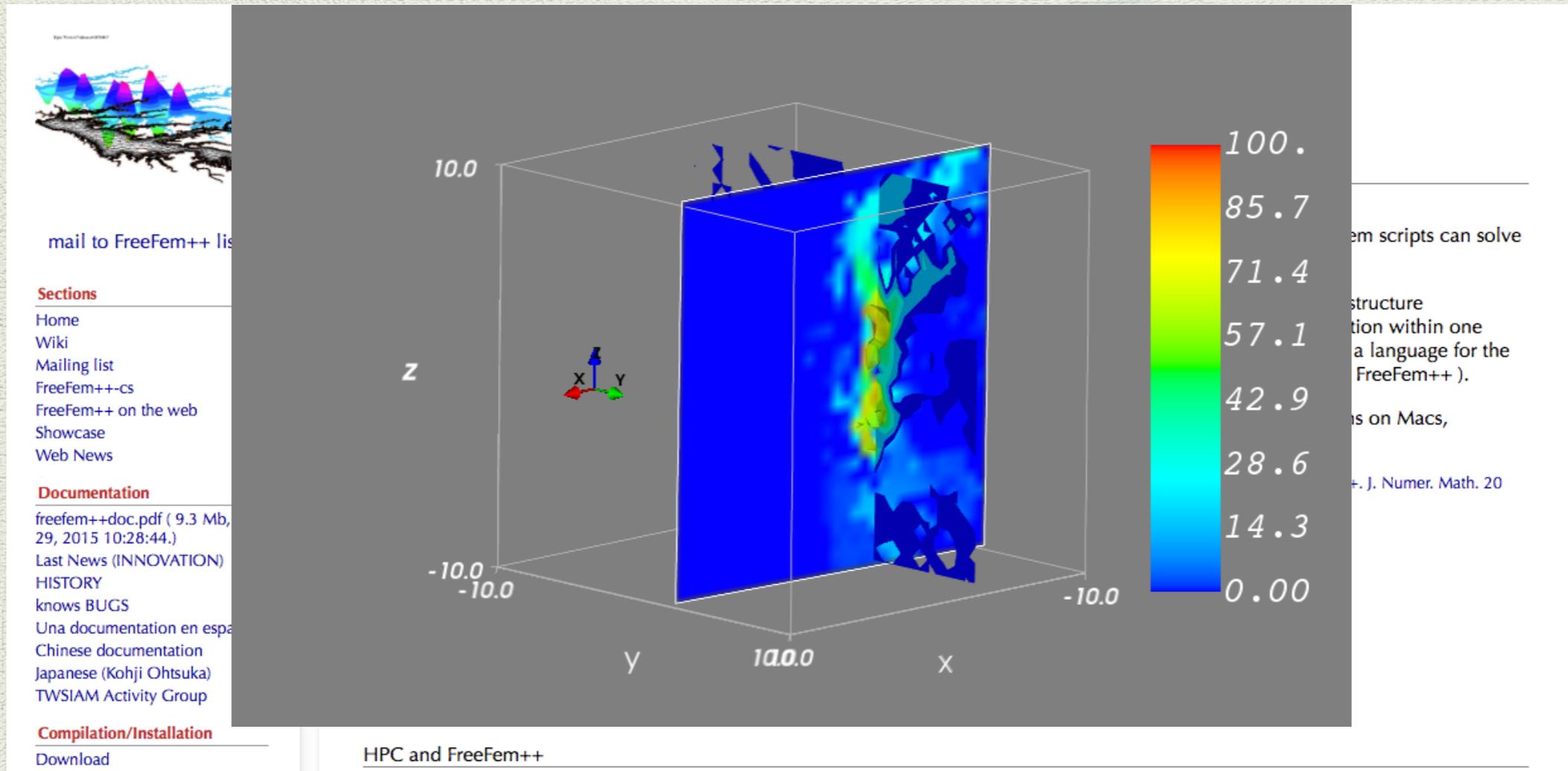
the bibtex is:

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  JOURNAL = {J. Numer. Math.}, FJOURNAL = {Journal of Numerical Mathematics},
  VOLUME = {20}, YEAR = {2012},
  NUMBER = {3-4}, PAGES = {251--265},
  ISSN = {1570-2820}, MRCLASS = {65Y15}, MRNUMBER = {3043640},
}
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HPC and FreeFem++

Fragmentation of self-gravitating fluids

◆ <http://www.freefem.org> (le FEM fatal .. ;)



The screenshot displays the FreeFem++ website interface. On the left, there is a navigation menu with sections: "Sections" (Home, Wiki, Mailing list, FreeFem++-cs, FreeFem++ on the web, Showcase, Web News) and "Documentation" (freefem++doc.pdf (9.3 Mb, 29, 2015 10:28:44.), Last News (INNOVATION), HISTORY, knows BUGS, Una documentation en espa, Chinese documentation, Japanese (Kohji Ohtsuka), TWSIAM Activity Group). Below the menu is a "Compilation/Installation" section with a "Download" link. The main content area features a 3D visualization of a fluid fragmentation simulation. The simulation is shown in a 3D coordinate system with axes labeled X, Y, and Z. The Z-axis ranges from -10.0 to 10.0, and the X and Y axes range from -10.0 to 10.0. The simulation shows a central vertical column of fluid that is breaking apart into smaller, irregular fragments. A color scale on the right indicates the magnitude of the simulation, ranging from 0.00 (blue) to 100.0 (red). The simulation is set within a 3D box with axes labeled X, Y, and Z. The Z-axis ranges from -10.0 to 10.0, and the X and Y axes range from -10.0 to 10.0. The simulation shows a central vertical column of fluid that is breaking apart into smaller, irregular fragments. A color scale on the right indicates the magnitude of the simulation, ranging from 0.00 (blue) to 100.0 (red). The simulation is set within a 3D box with axes labeled X, Y, and Z. The Z-axis ranges from -10.0 to 10.0, and the X and Y axes range from -10.0 to 10.0. The simulation shows a central vertical column of fluid that is breaking apart into smaller, irregular fragments. A color scale on the right indicates the magnitude of the simulation, ranging from 0.00 (blue) to 100.0 (red).

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HPC and FreeFem++

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is on Macs,

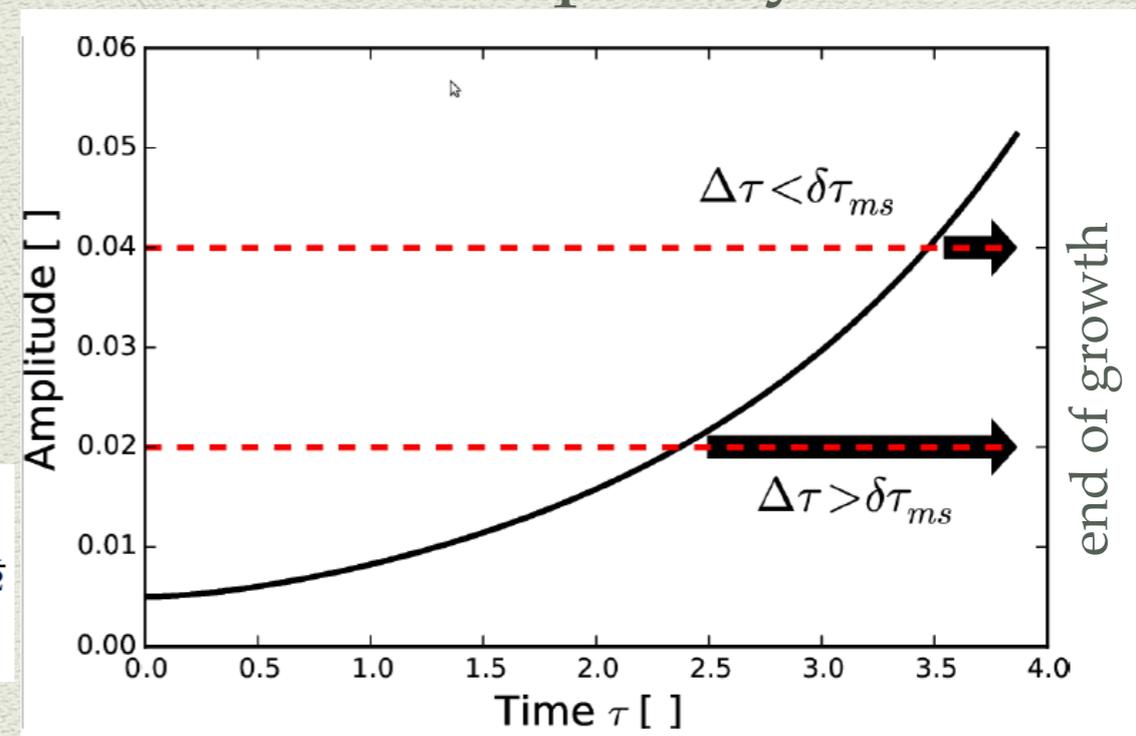
+ J. Numer. Math. 20

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

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

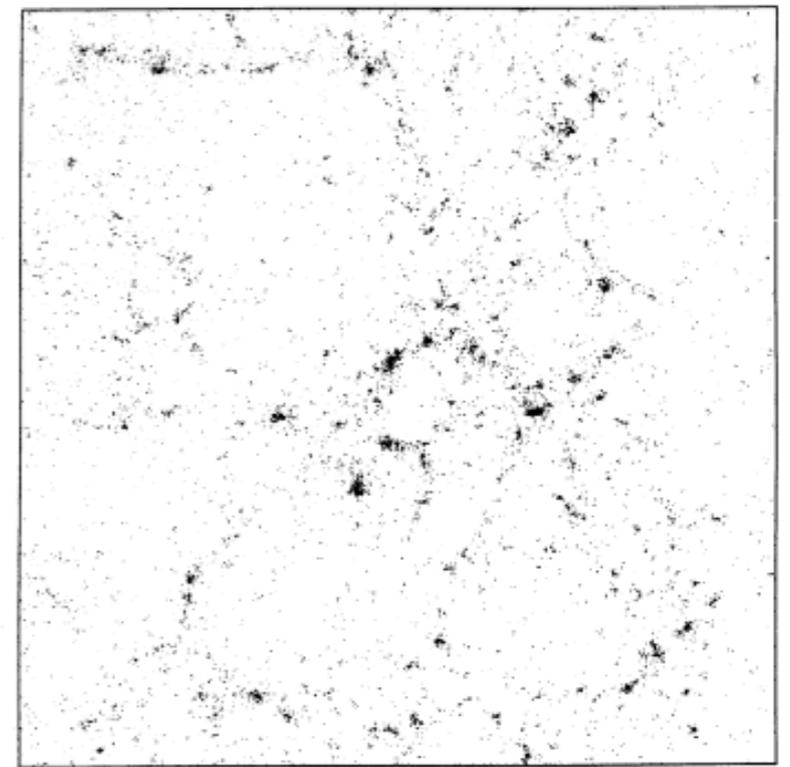
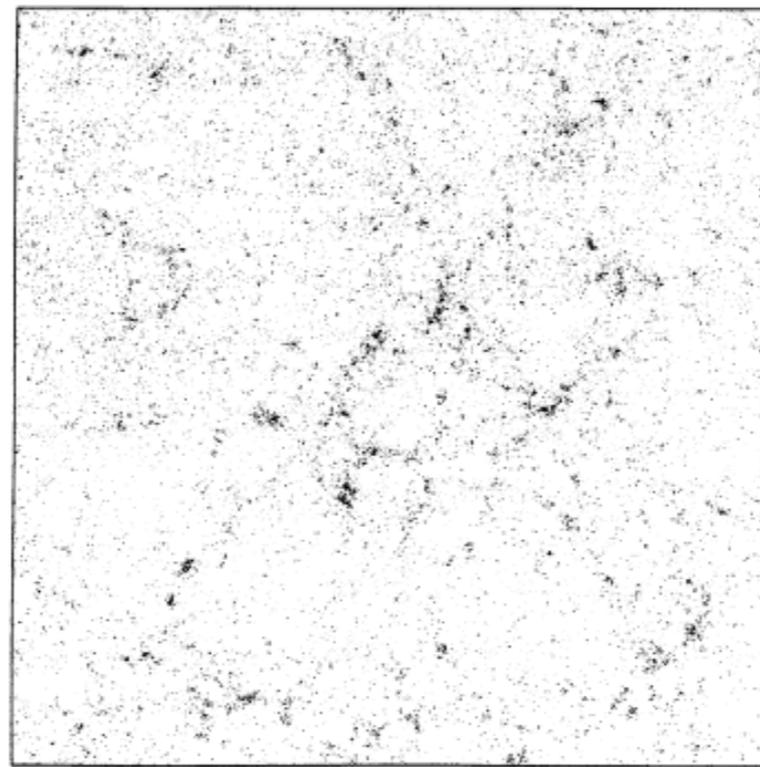
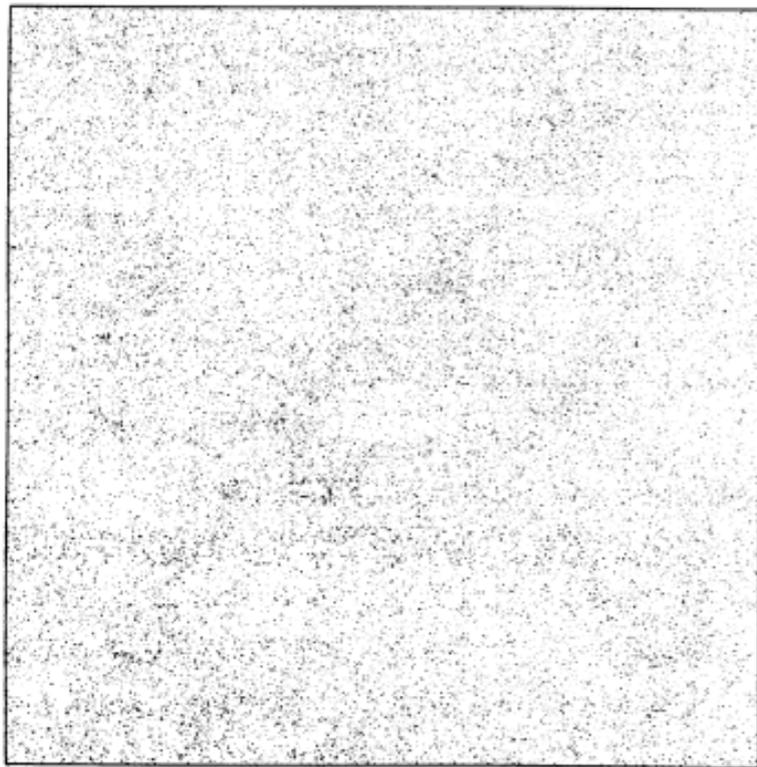


- ◆ Take two : restart the computation but with a collisional N-body code (Nbody6/7++, kira, ..)

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 ...

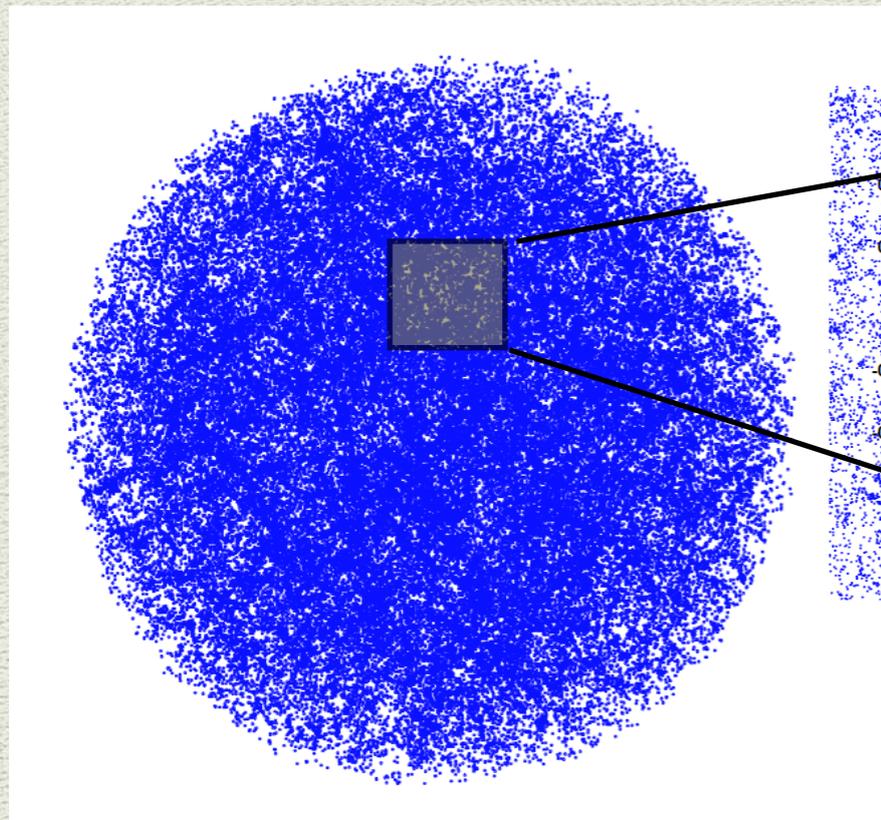


time

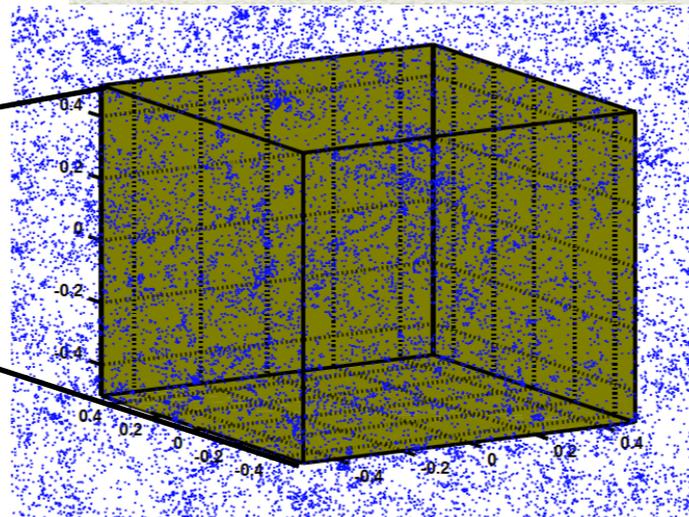


Procedure - avoid boundaries

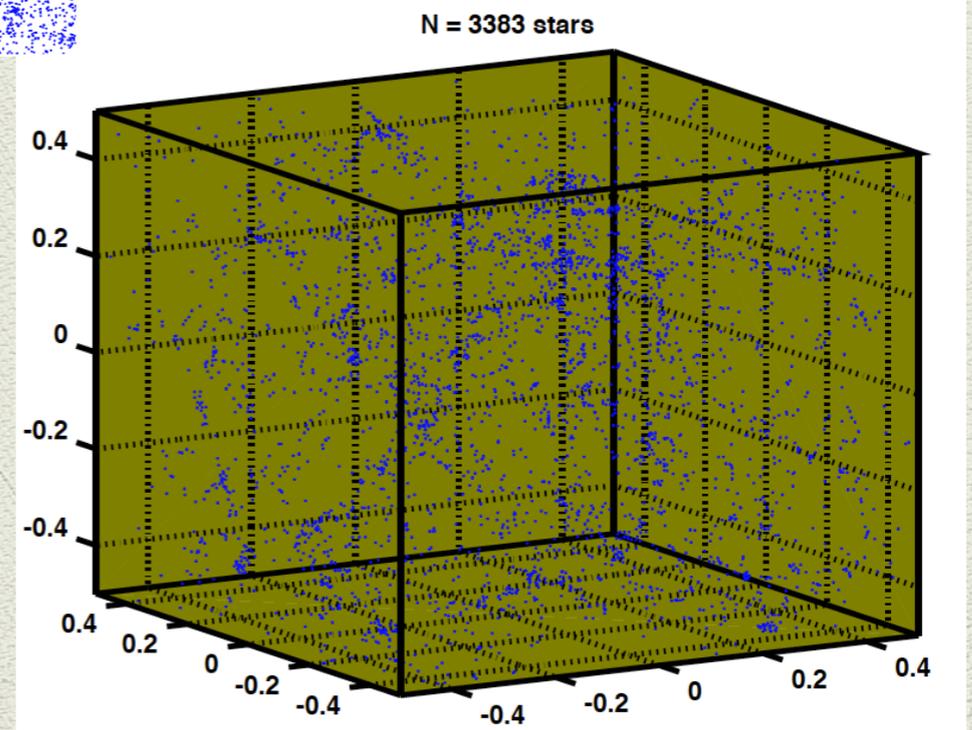
Dorval et al. 2016, in the press ..



$N \sim 100\text{k}$ stars

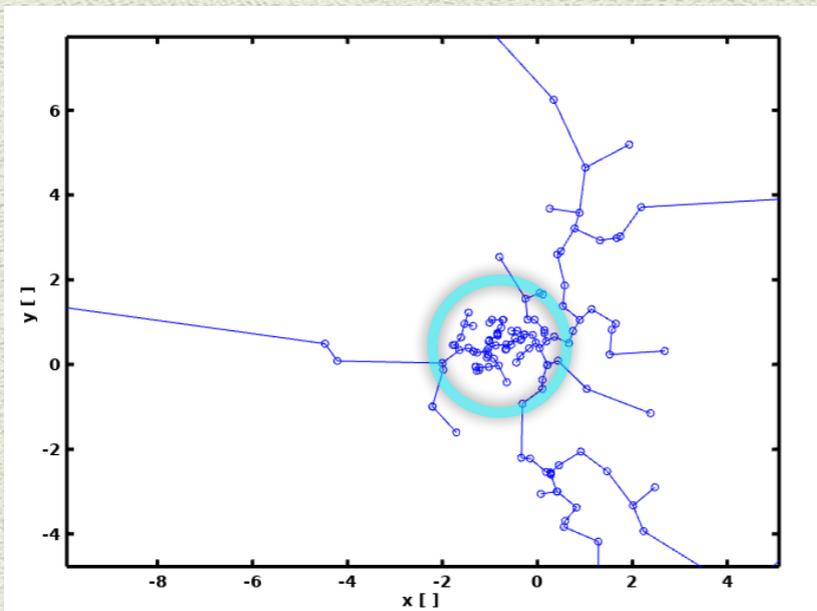


Extract
subset of
stars

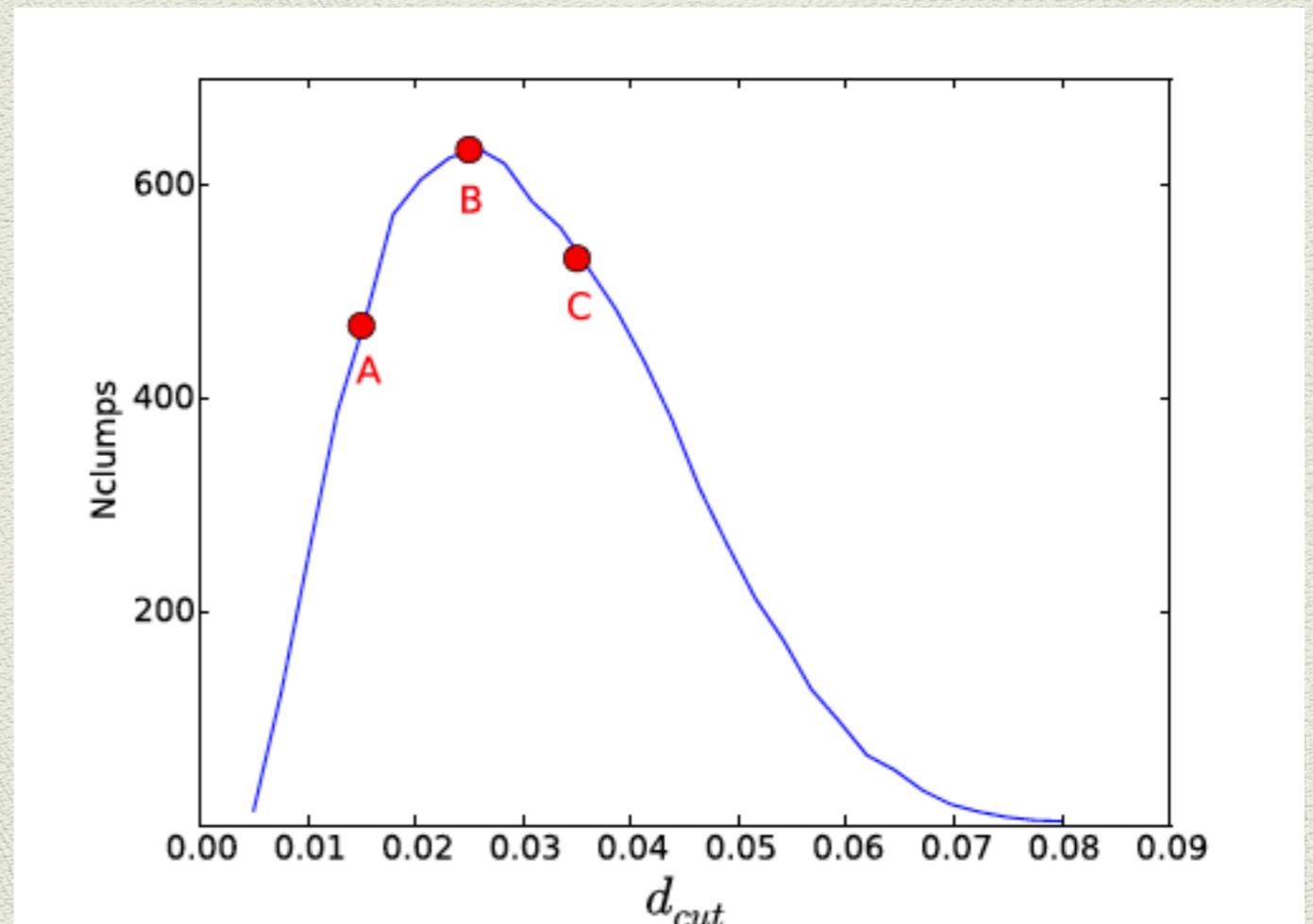


The Minimum Spanning Tree

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

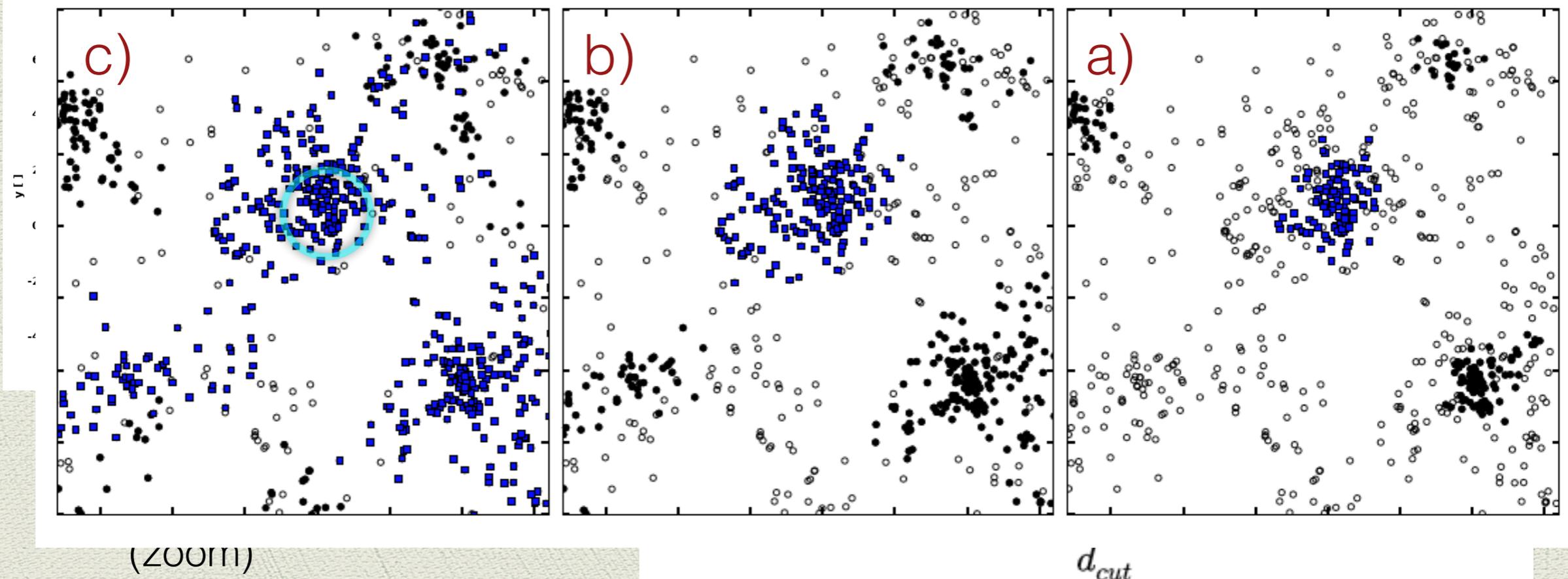
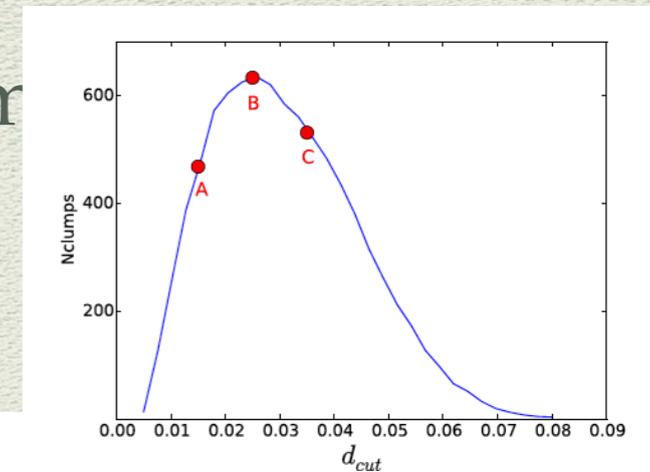


MST
reconstruction
(zoom)



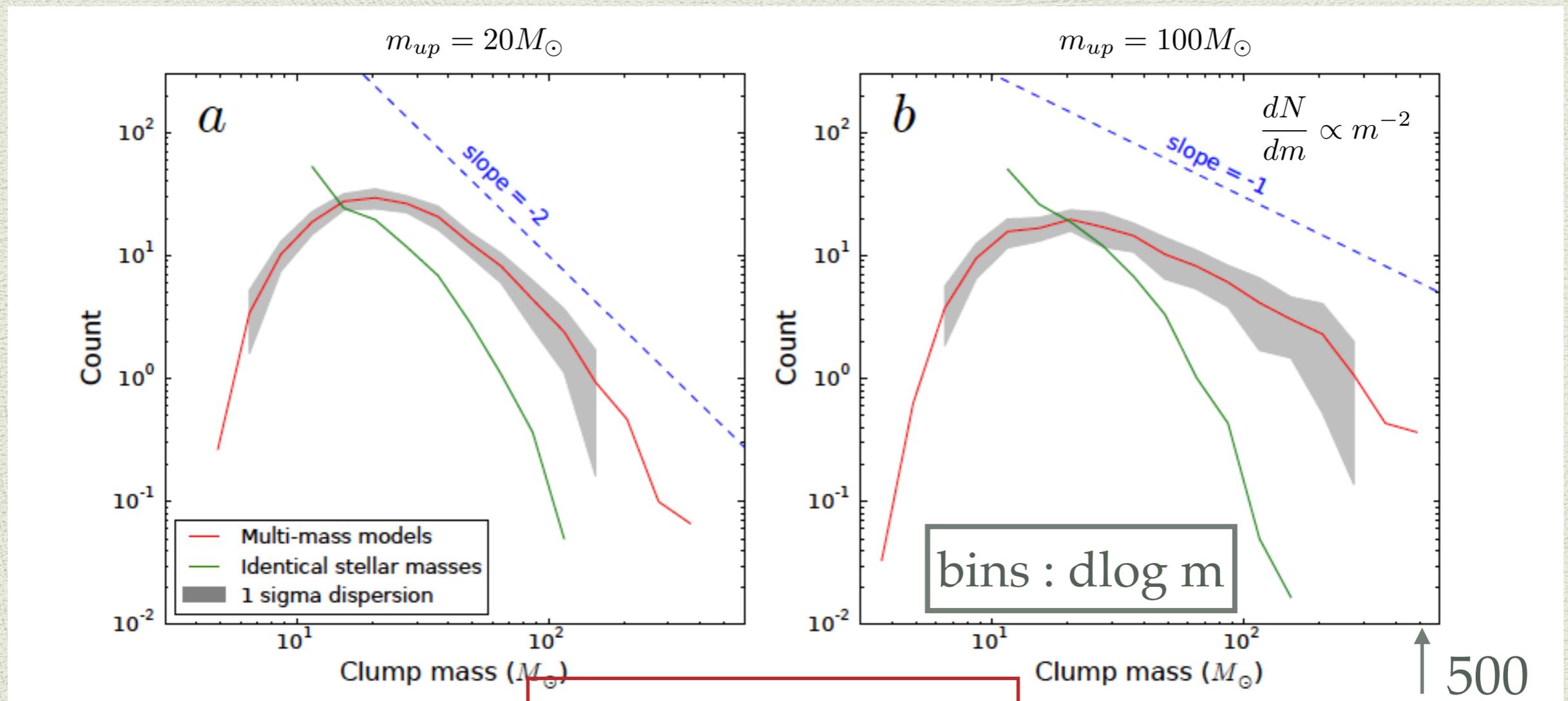
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Stellar clumps: mass function, and stellar m.f.

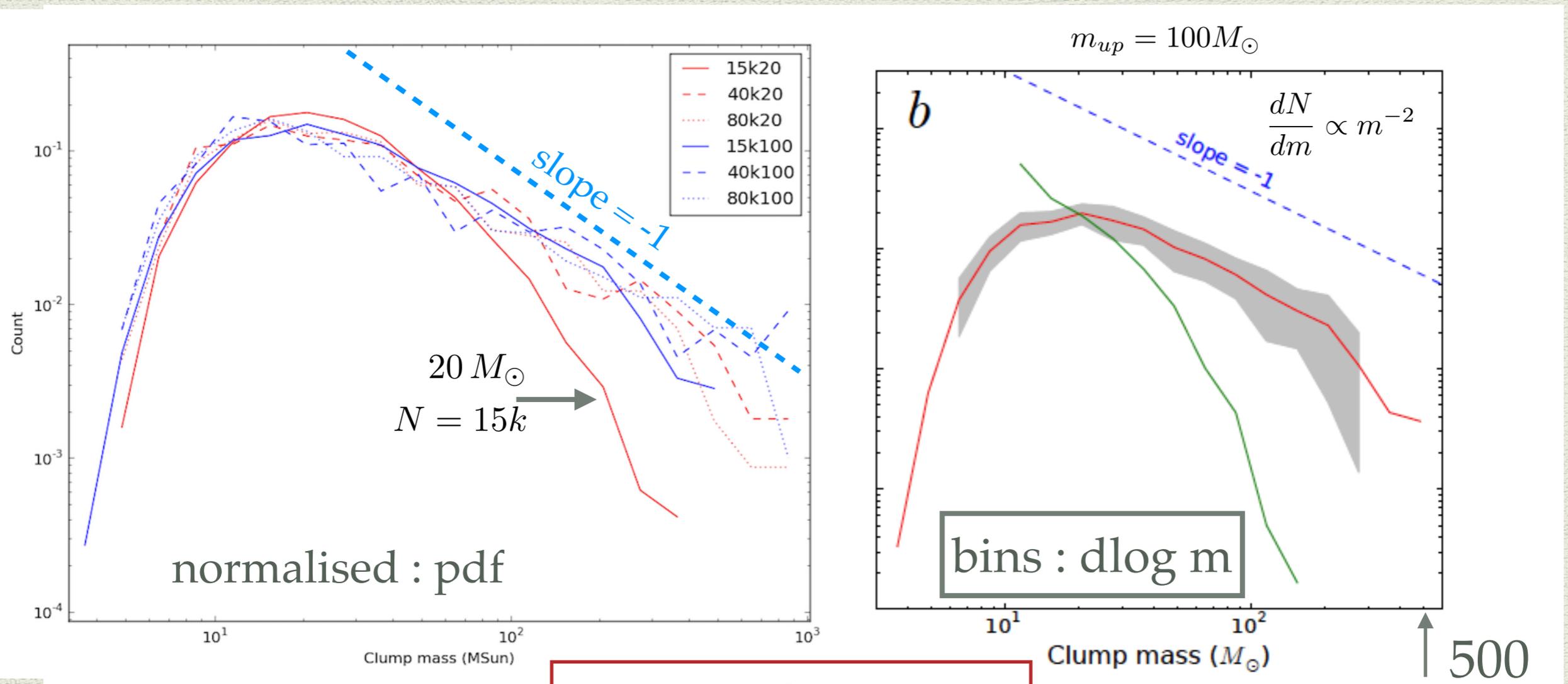
Equal-mass models vs Salpeter IMF (two upper truncation values)



Runs with $N = 15k$

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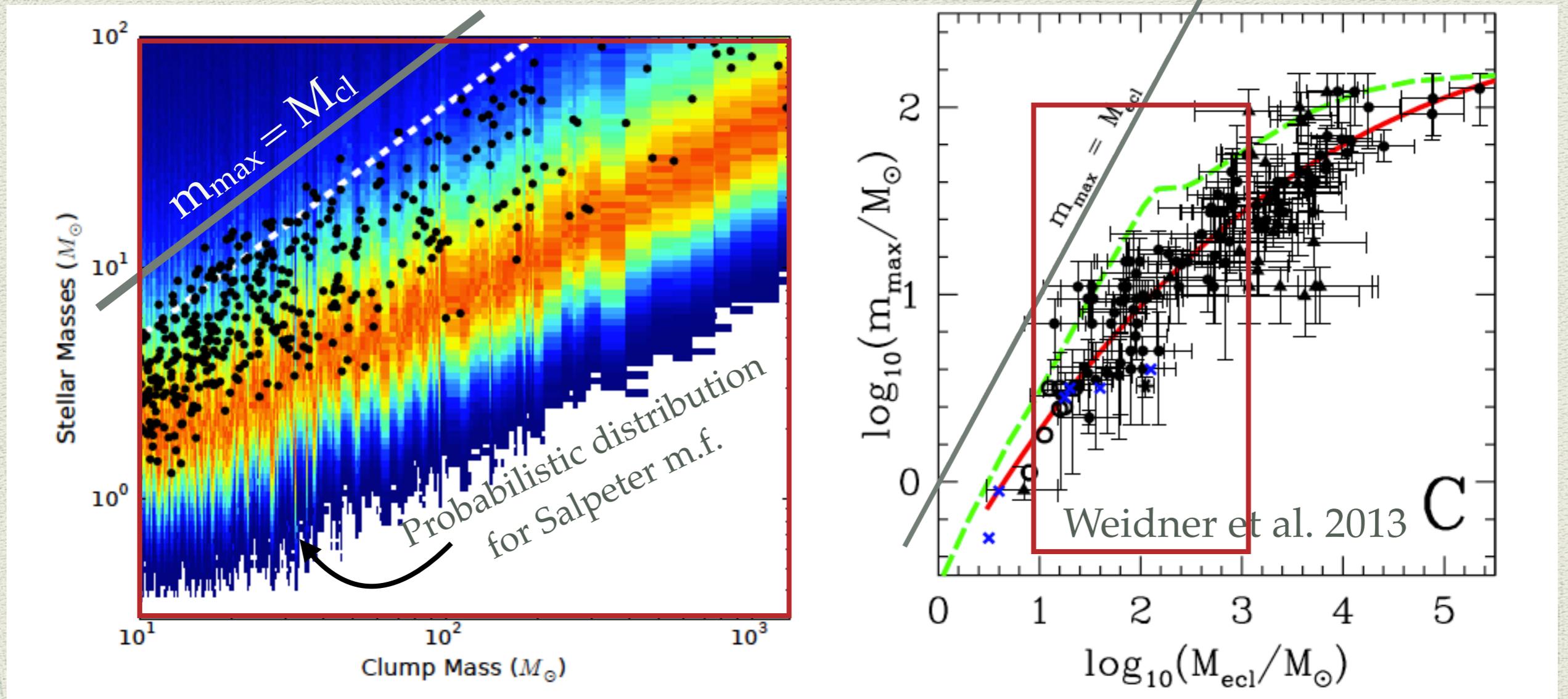
Equal-mass models vs Salpeter IMF (two upper truncation values)



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 ..

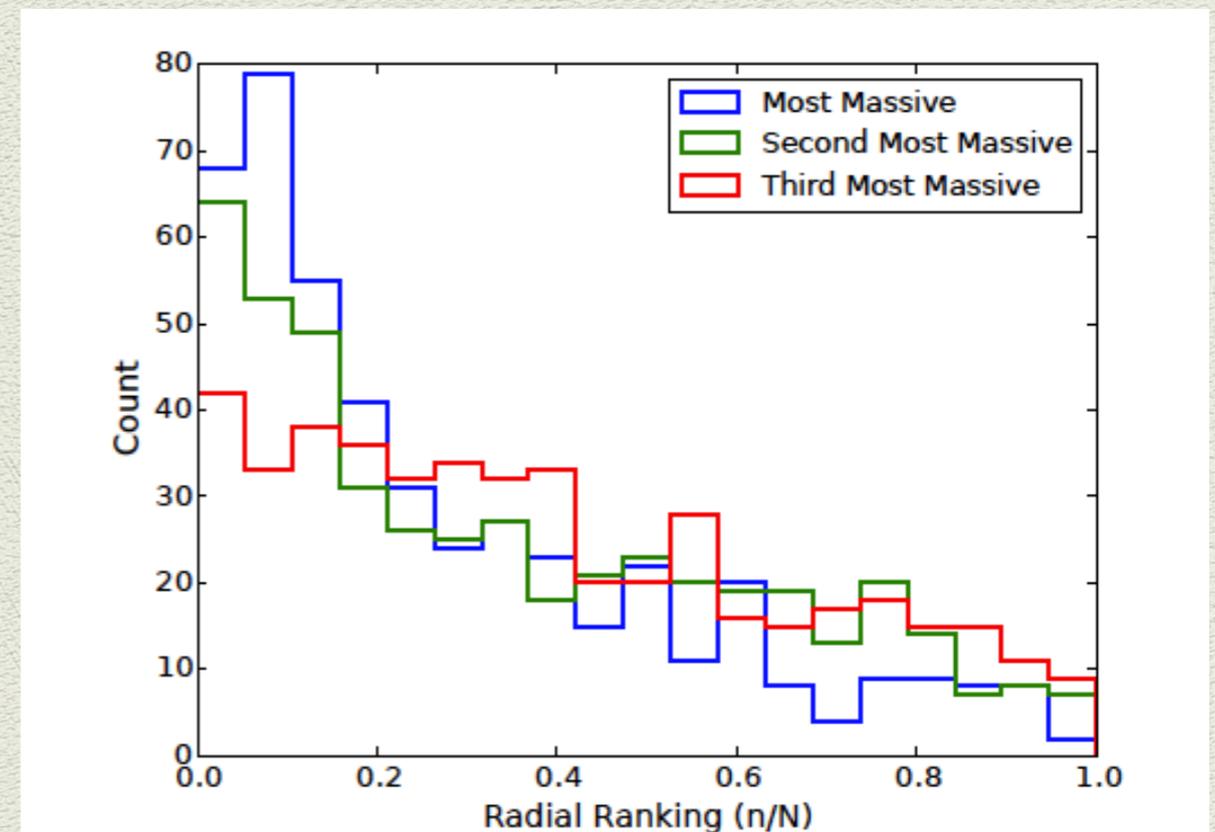
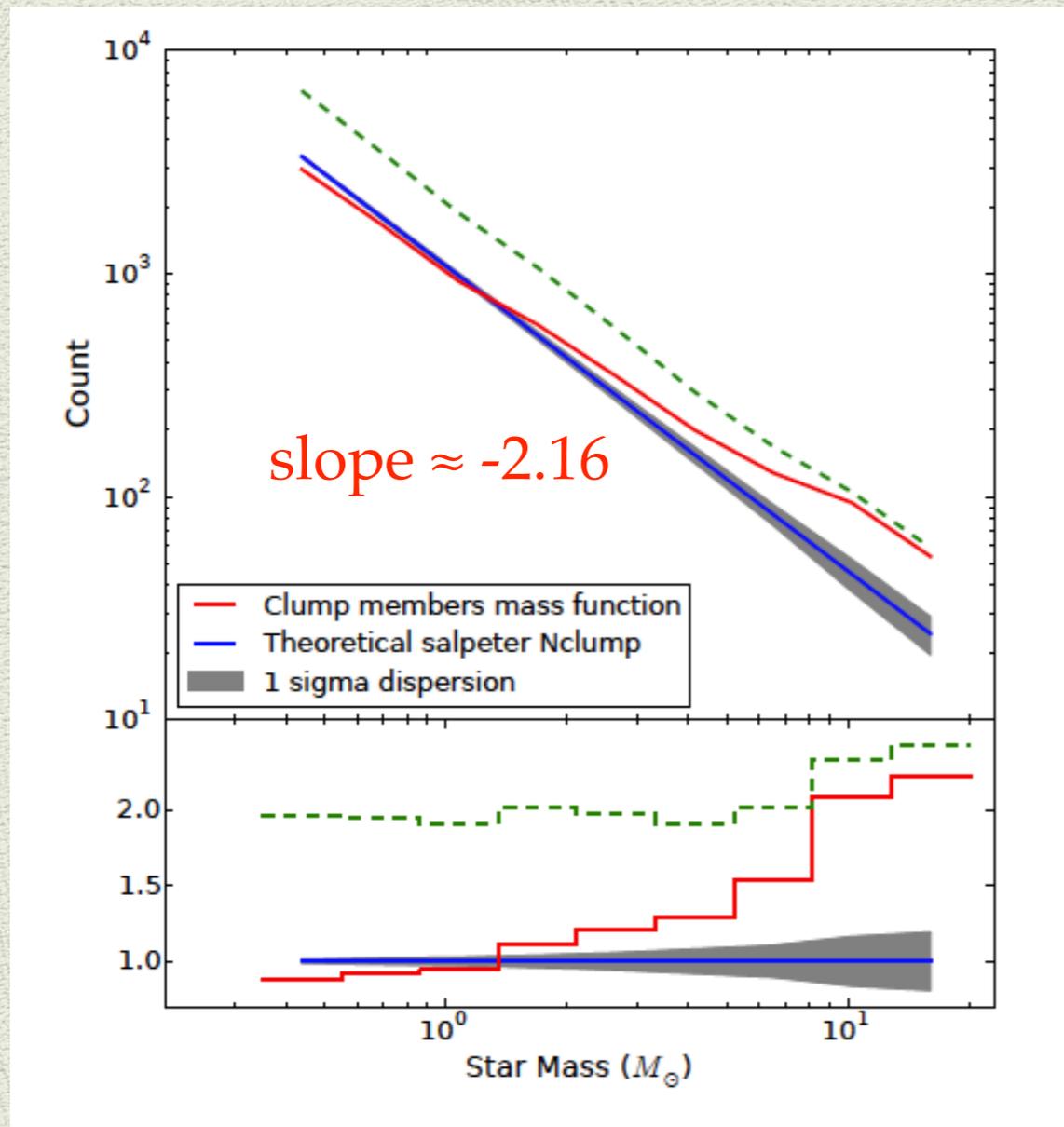


Figure 10. Radial ranking of first, second and third most massive star in each clump for a model with $N = 40\,000$ stars (R40h100).

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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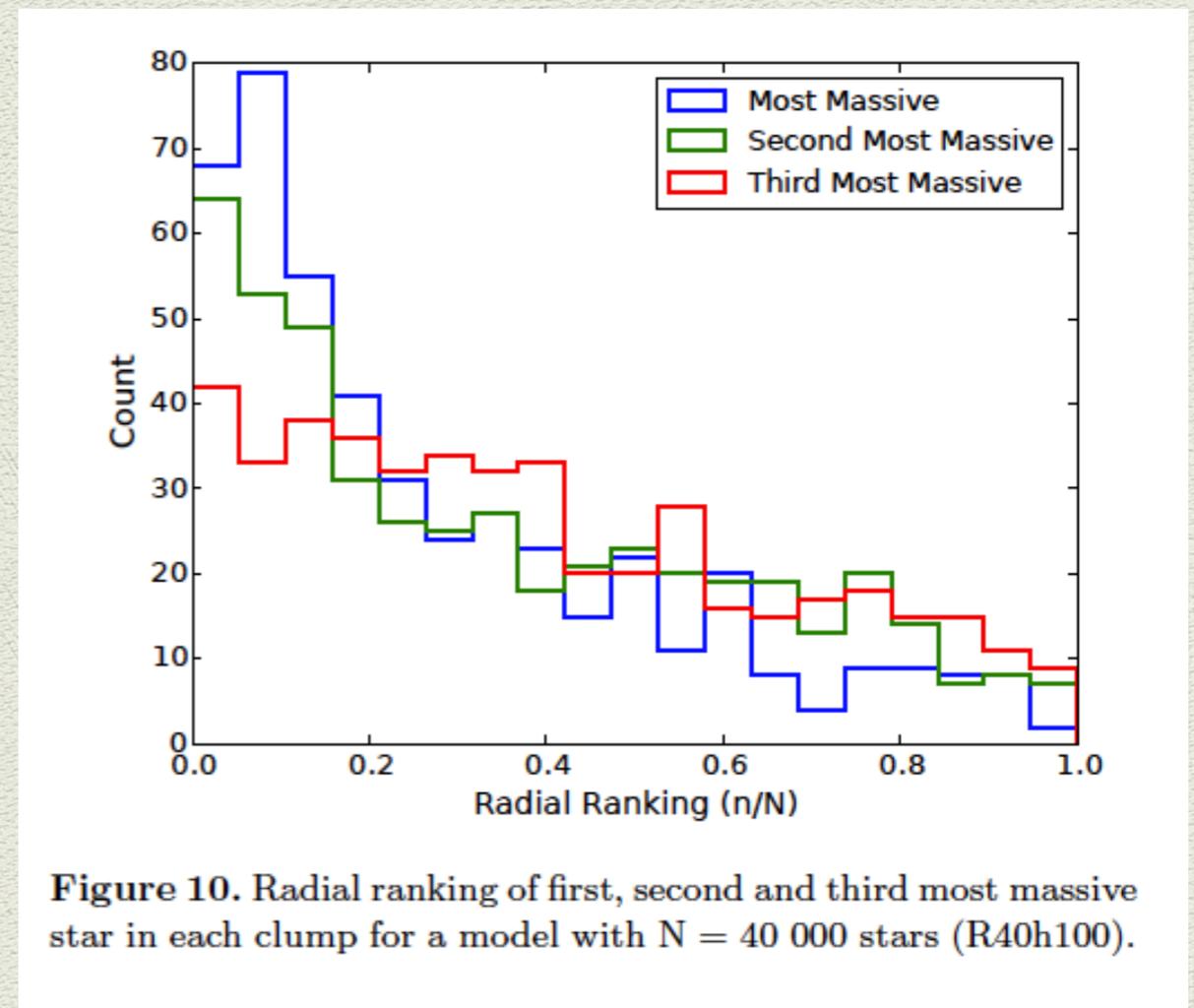
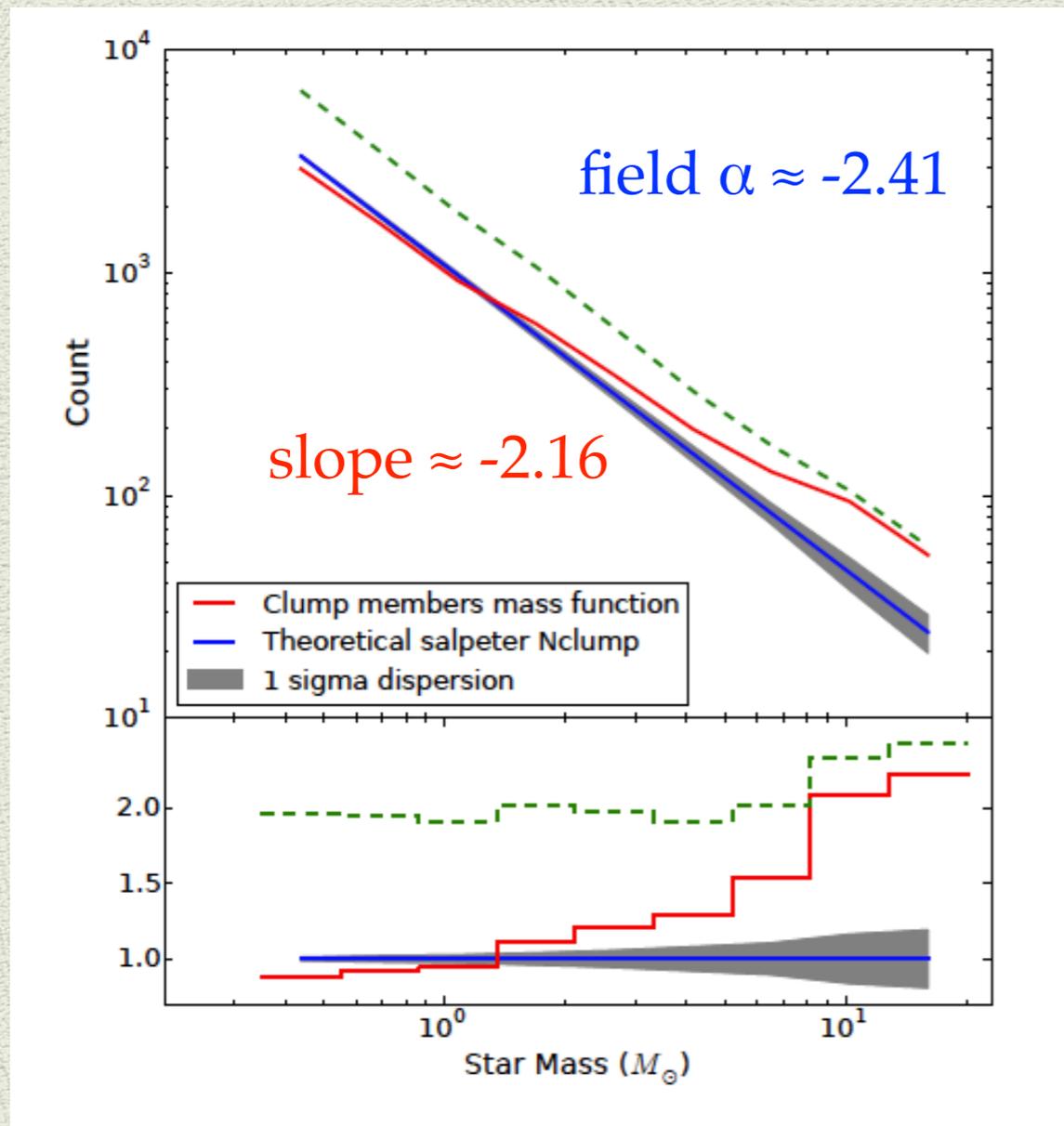


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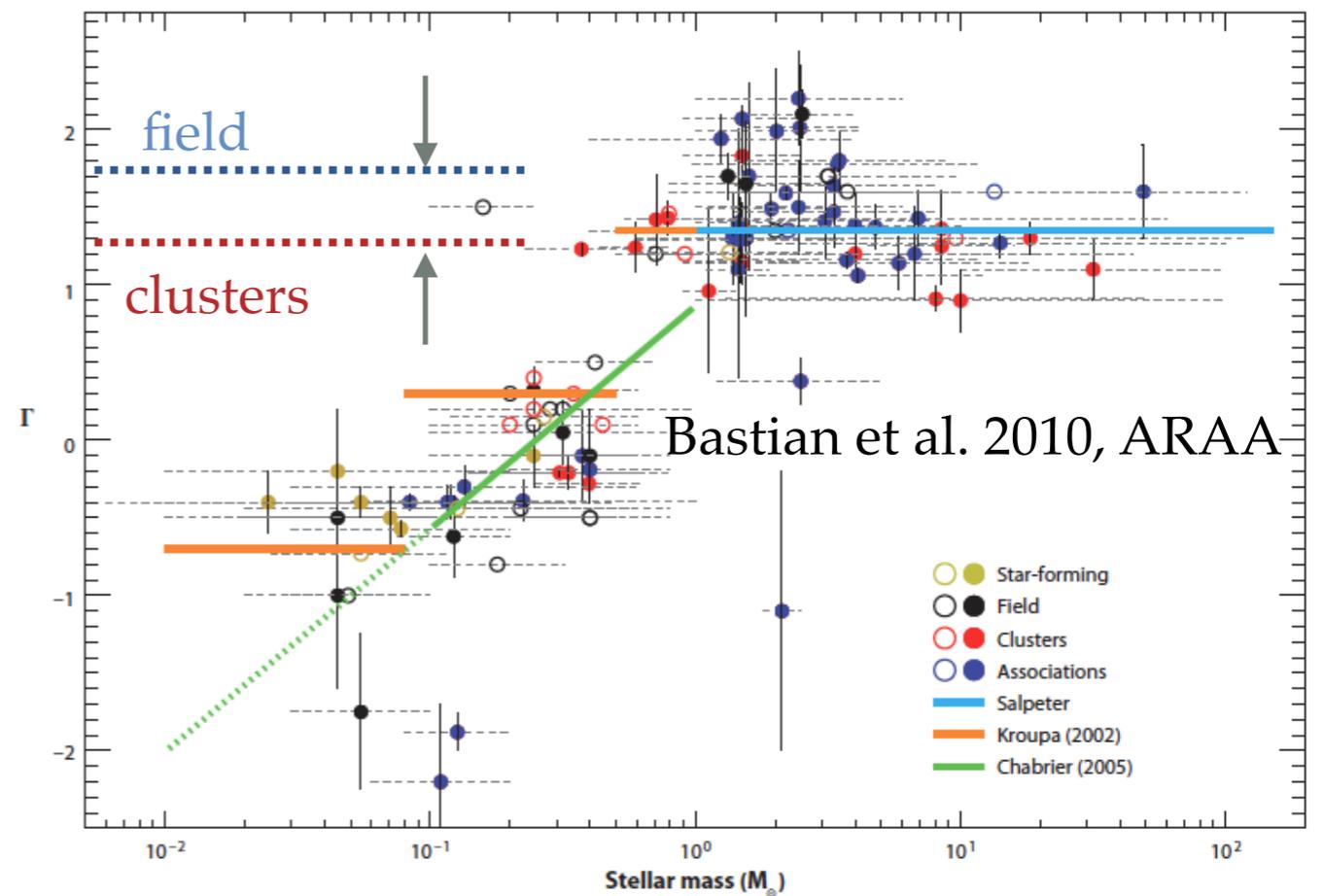
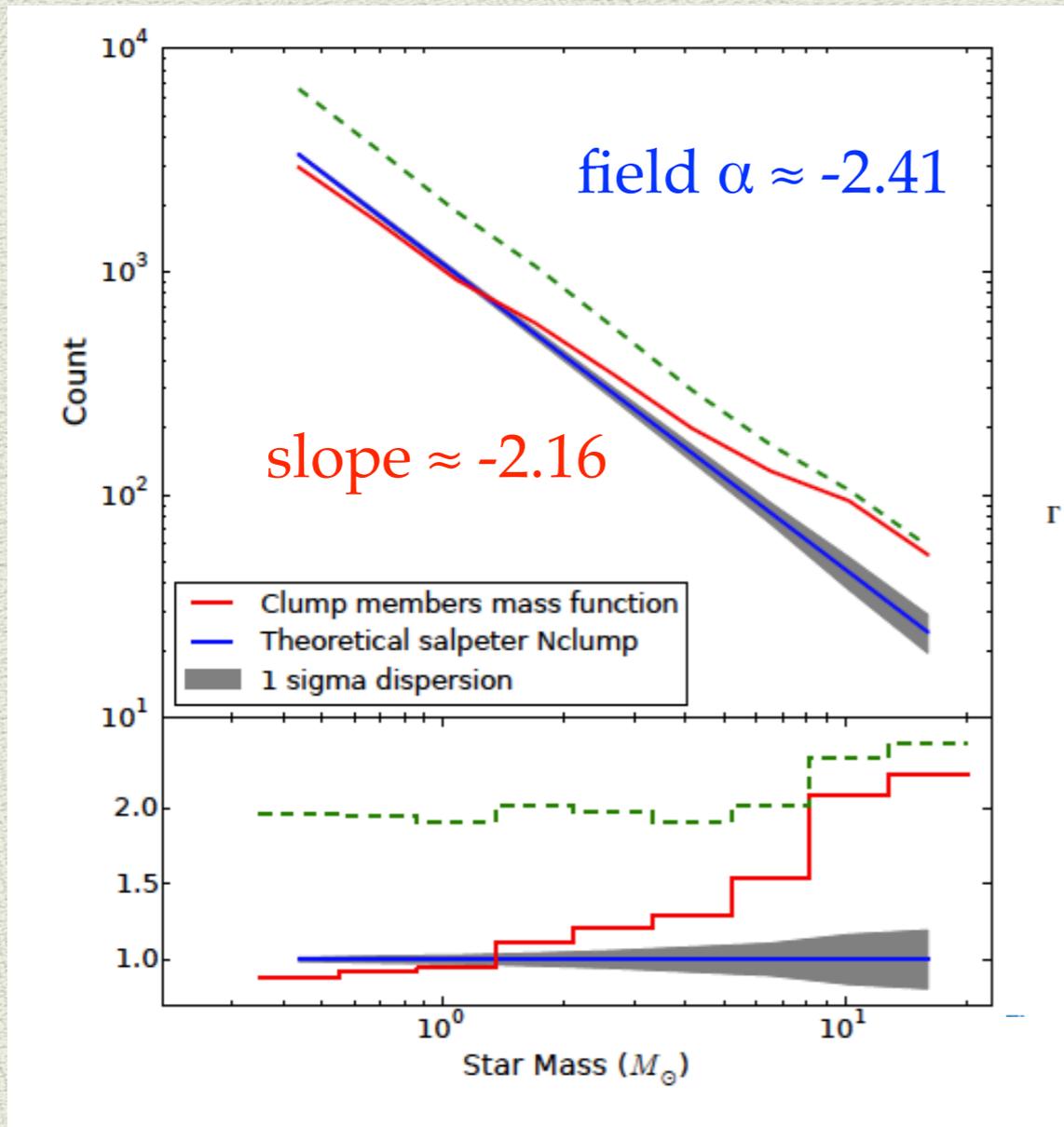
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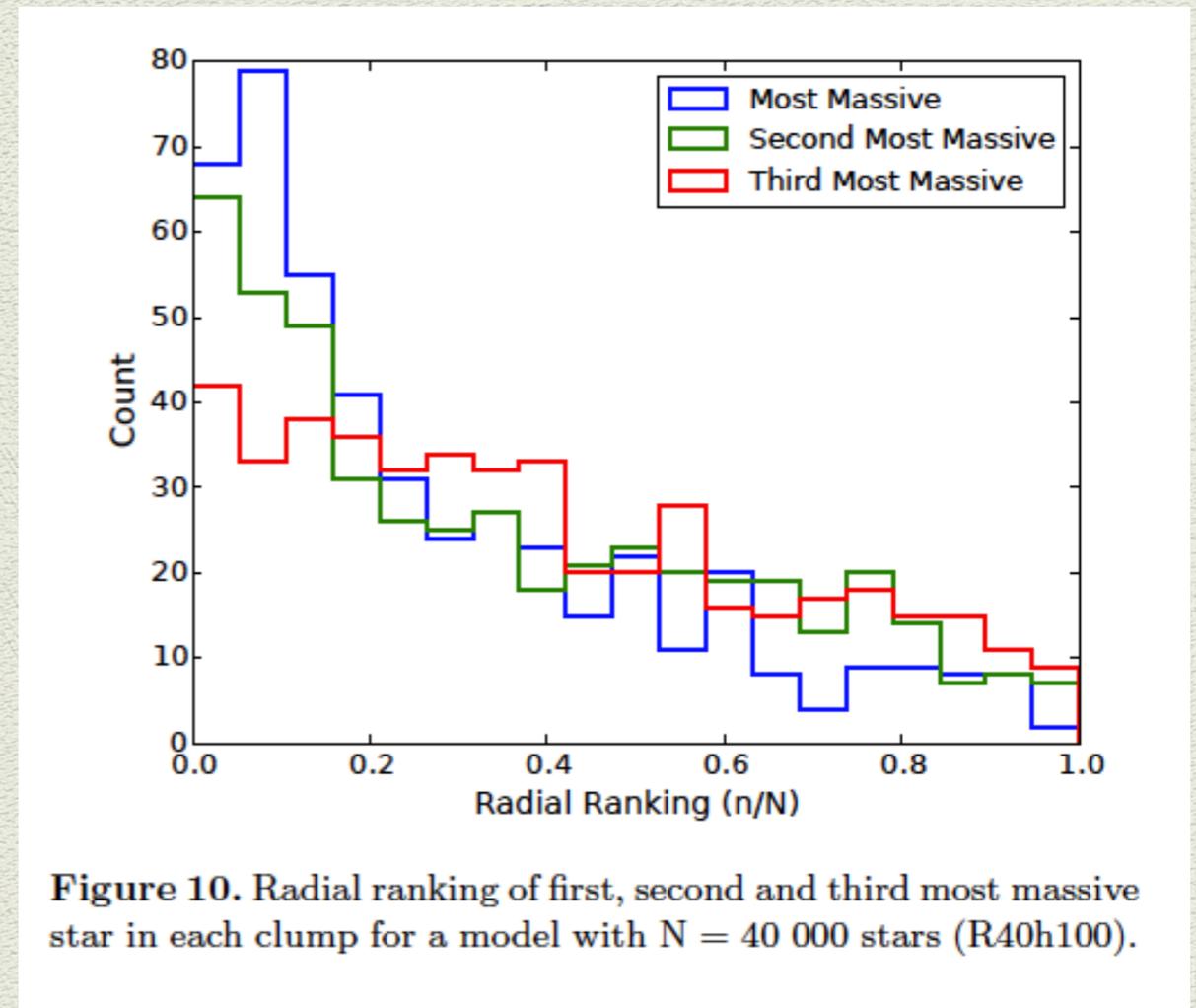
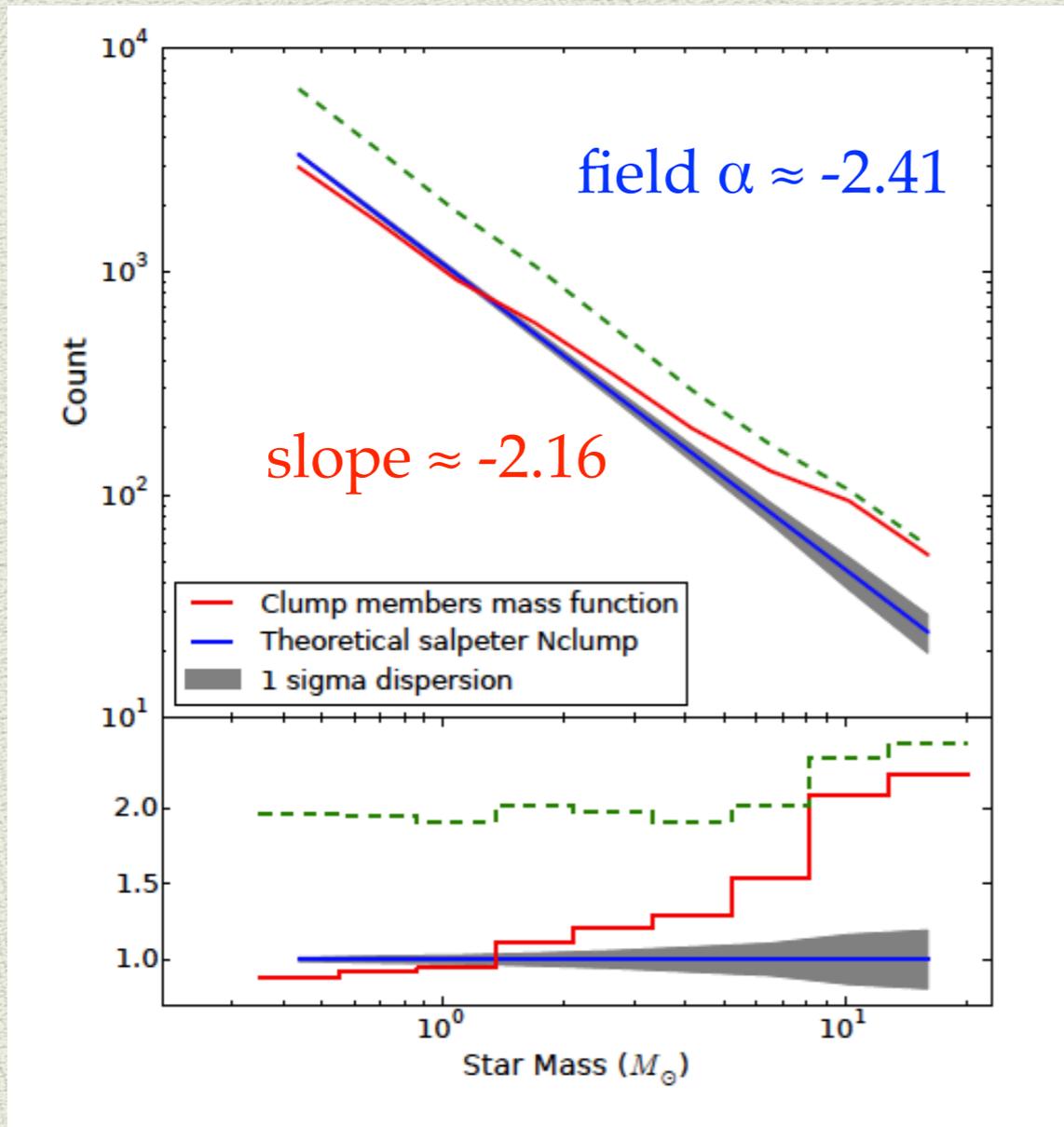


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2010

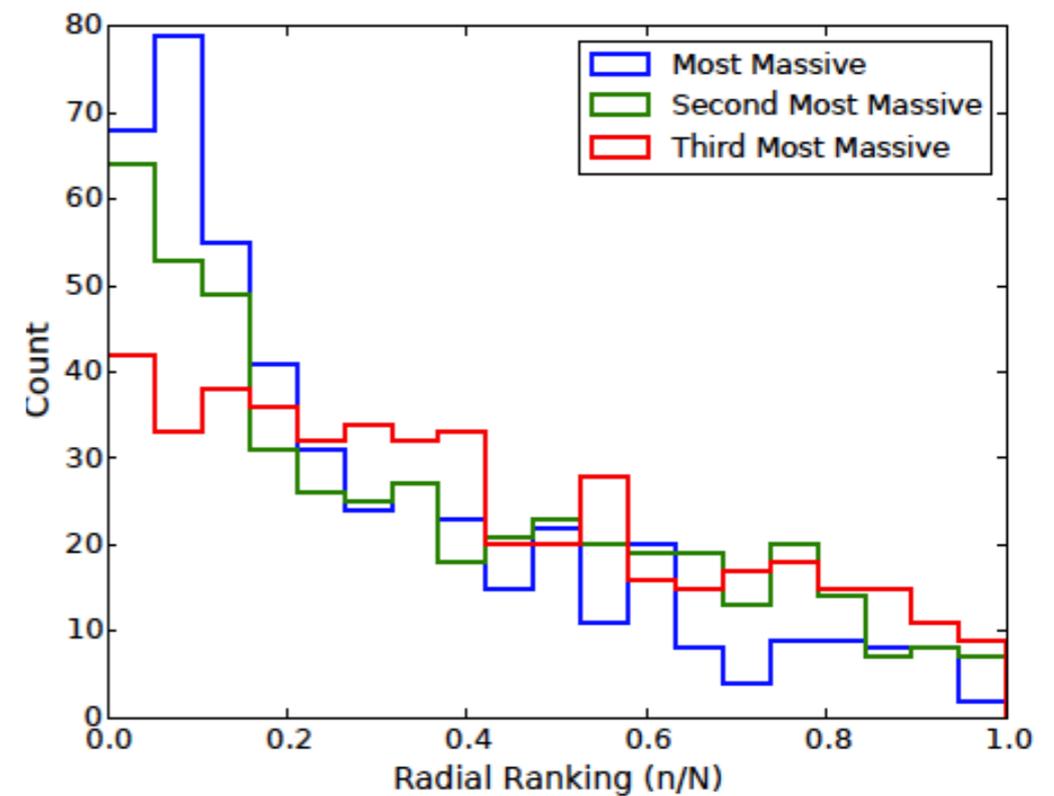
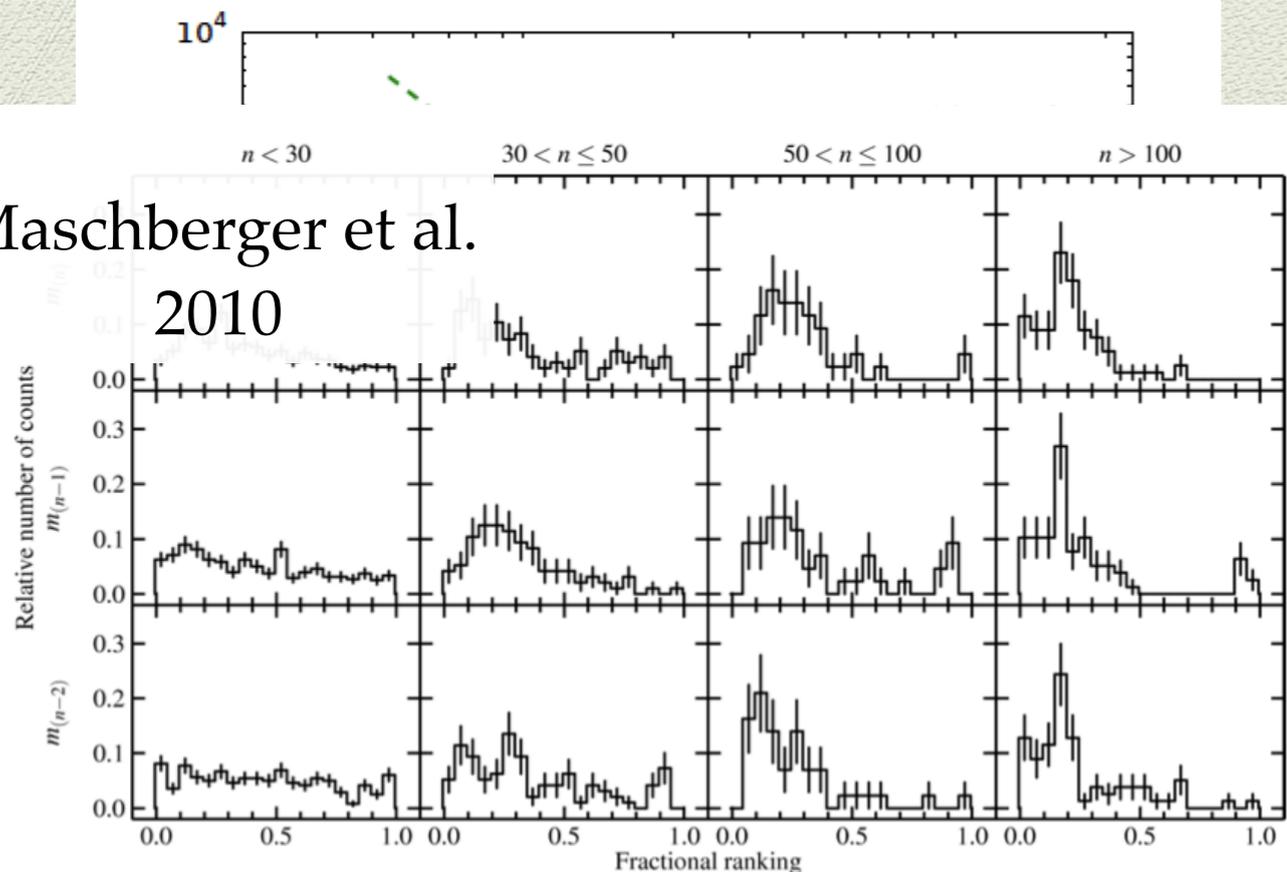


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Initial conditions : the

Most Valuable Paper .. 😊

MVP approach

A DYNAMICAL ORIGIN FOR EARLY MASS SEGREGATION IN YOUNG STAR CLUSTERS

STEPHEN L. W. McMILLAN AND ENRICO VESPERINI

Department of Physics, Drexel University, Philadelphia, PA; steve@physics.drexel.edu, vesperin@physics.drexel.edu

AND

SIMON F. PORTEGIES ZWART

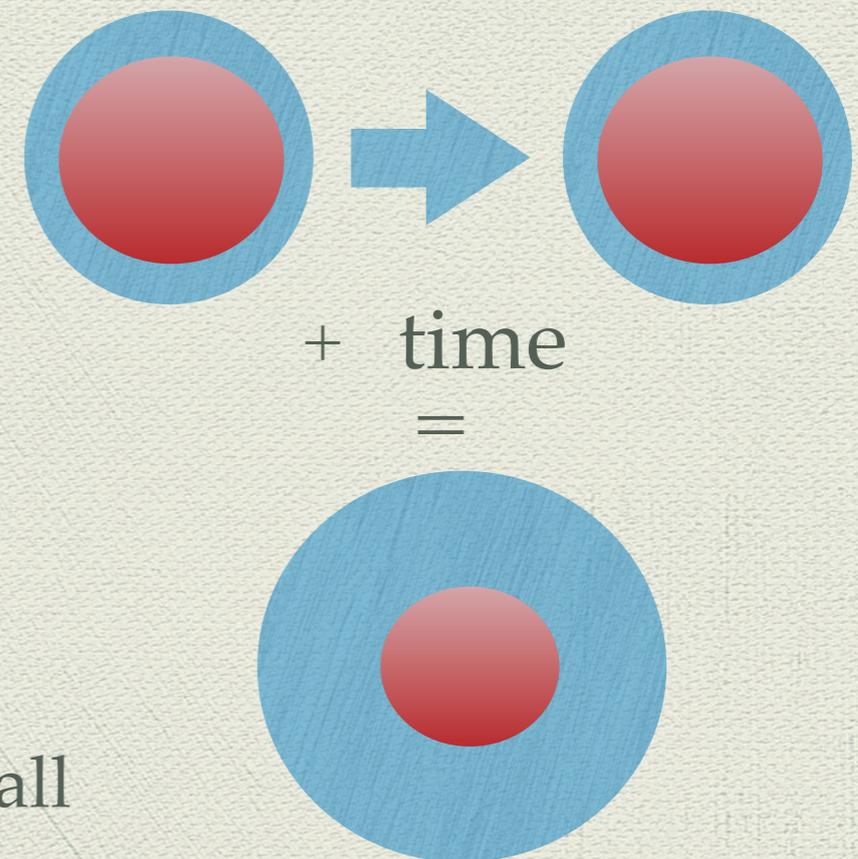
Astronomical Institute "Anton Pannekoek" and Section Computational Science, University of Amsterdam, Kruislaan 403, Amsterdam, Netherlands; spz@science.uva.nl

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, ..

Initial conditions : the

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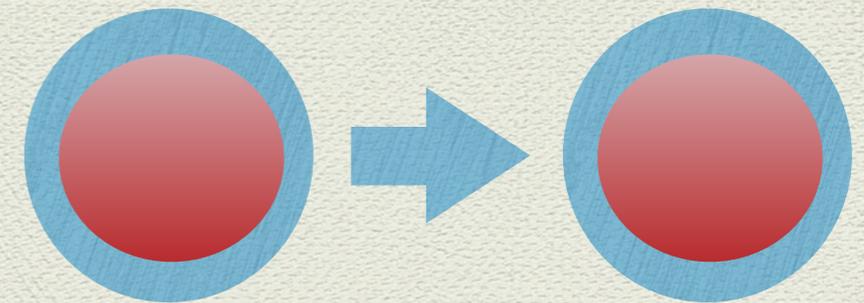
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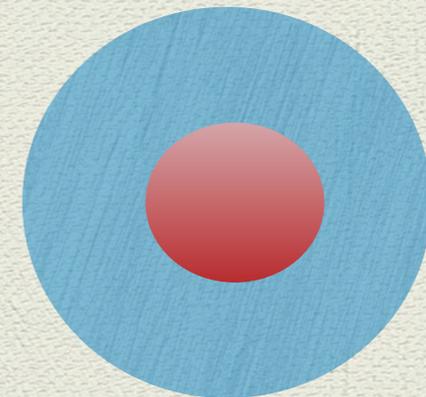
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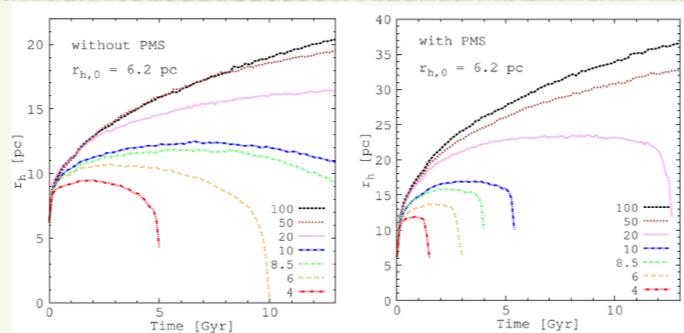
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+ time
=



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

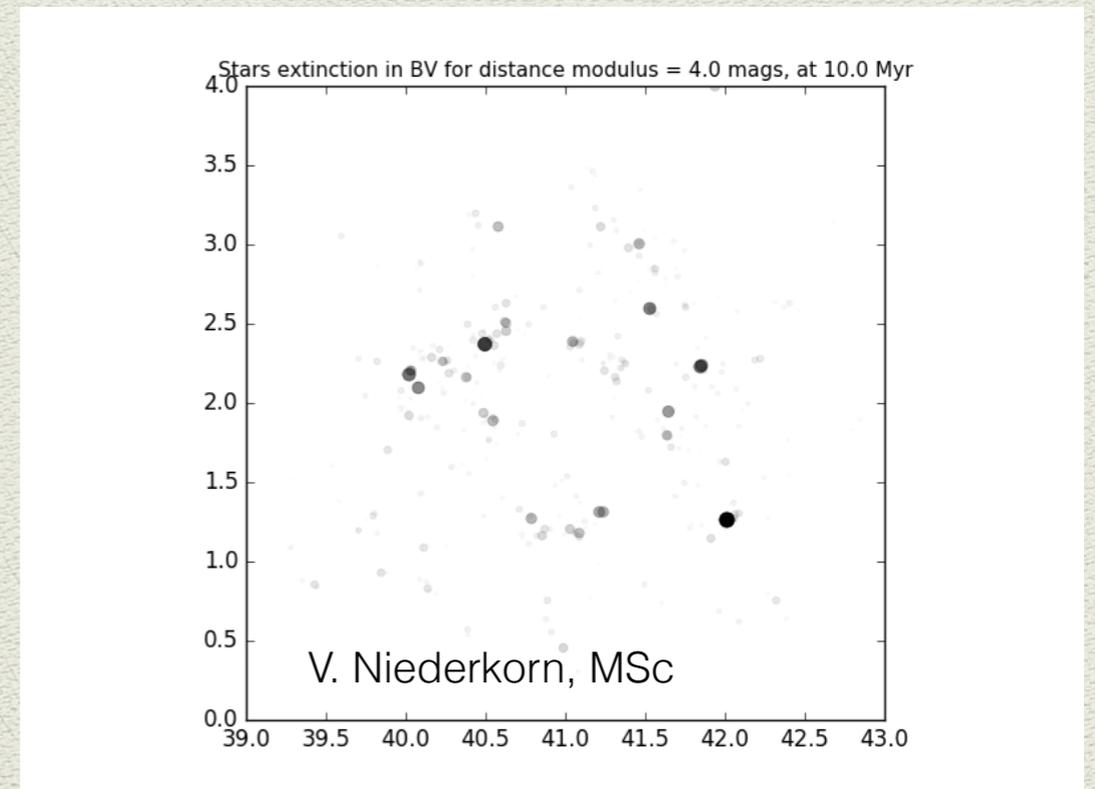
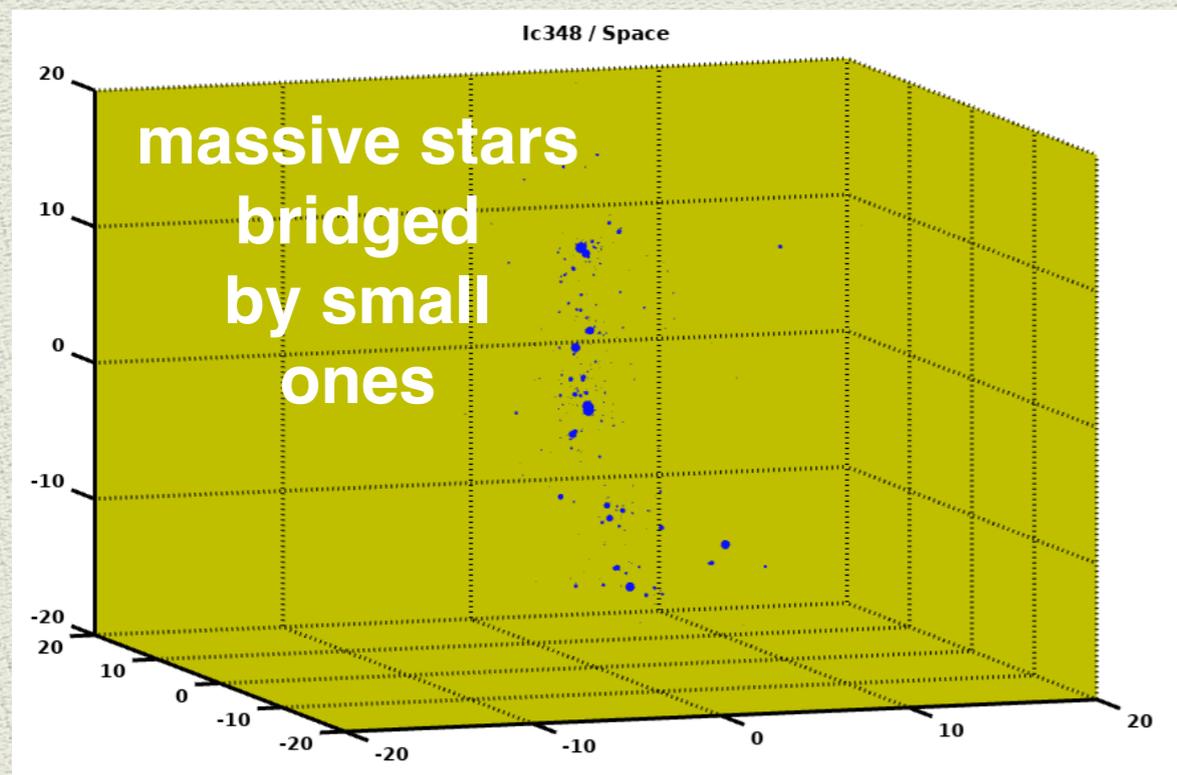


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Also : Allison et al. 2009, R. Parker, ..

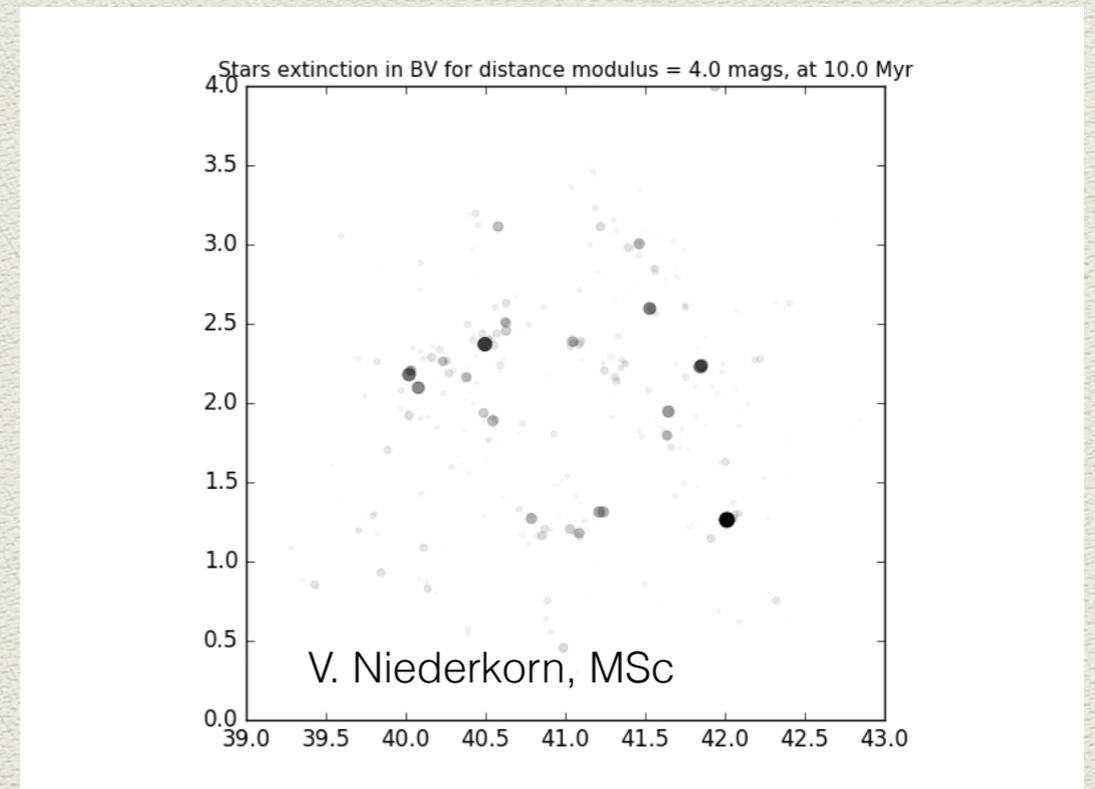
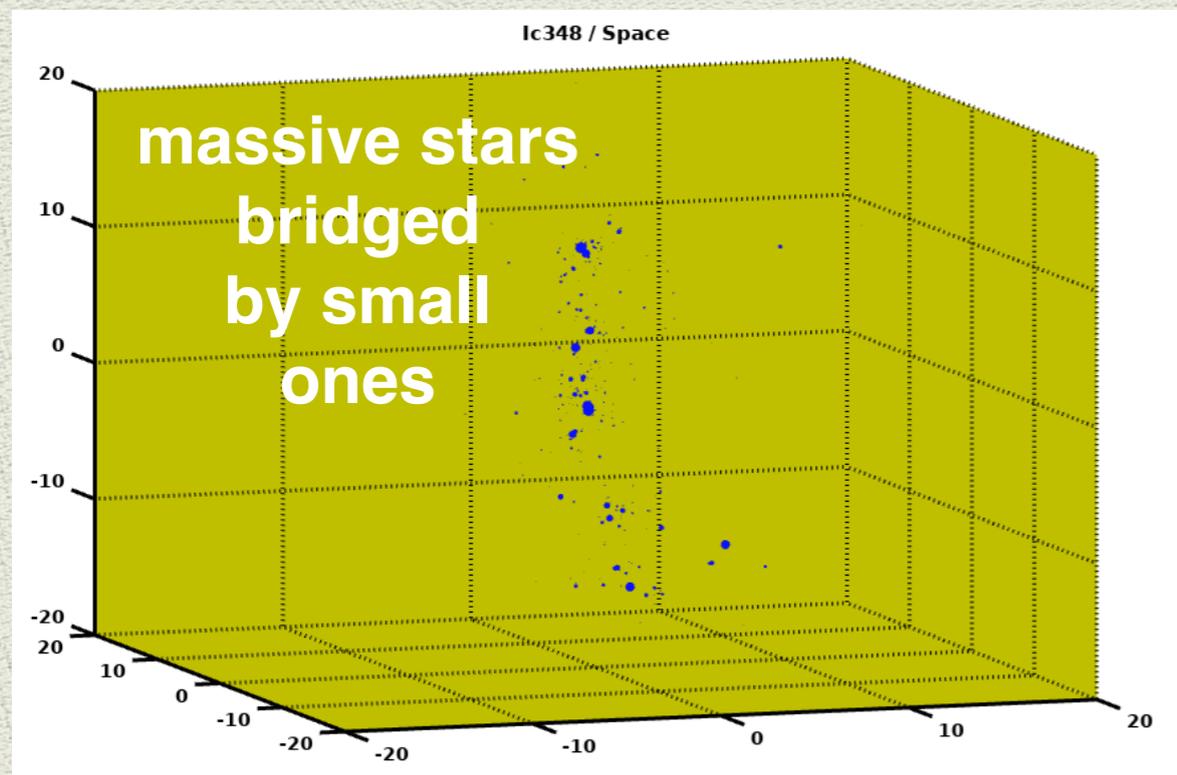
Morphology - The Minimum Spanning Tree approach

- ◆ 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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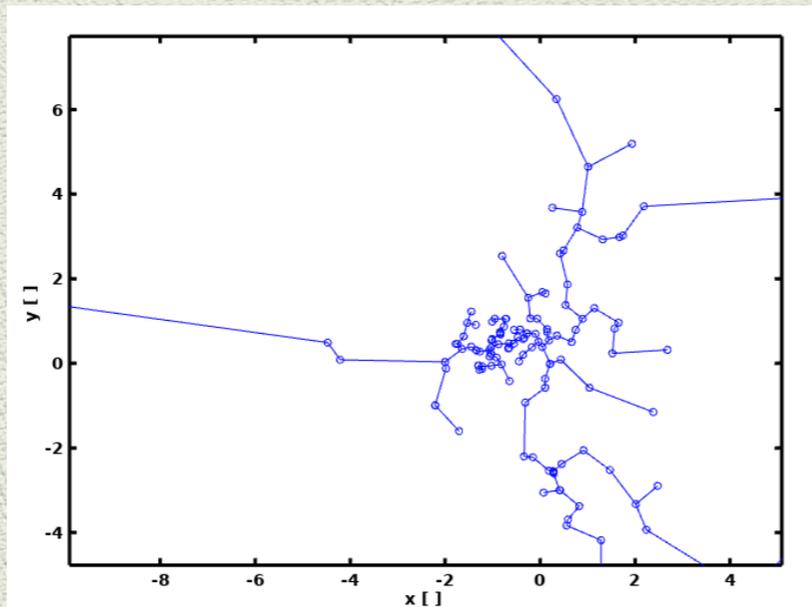
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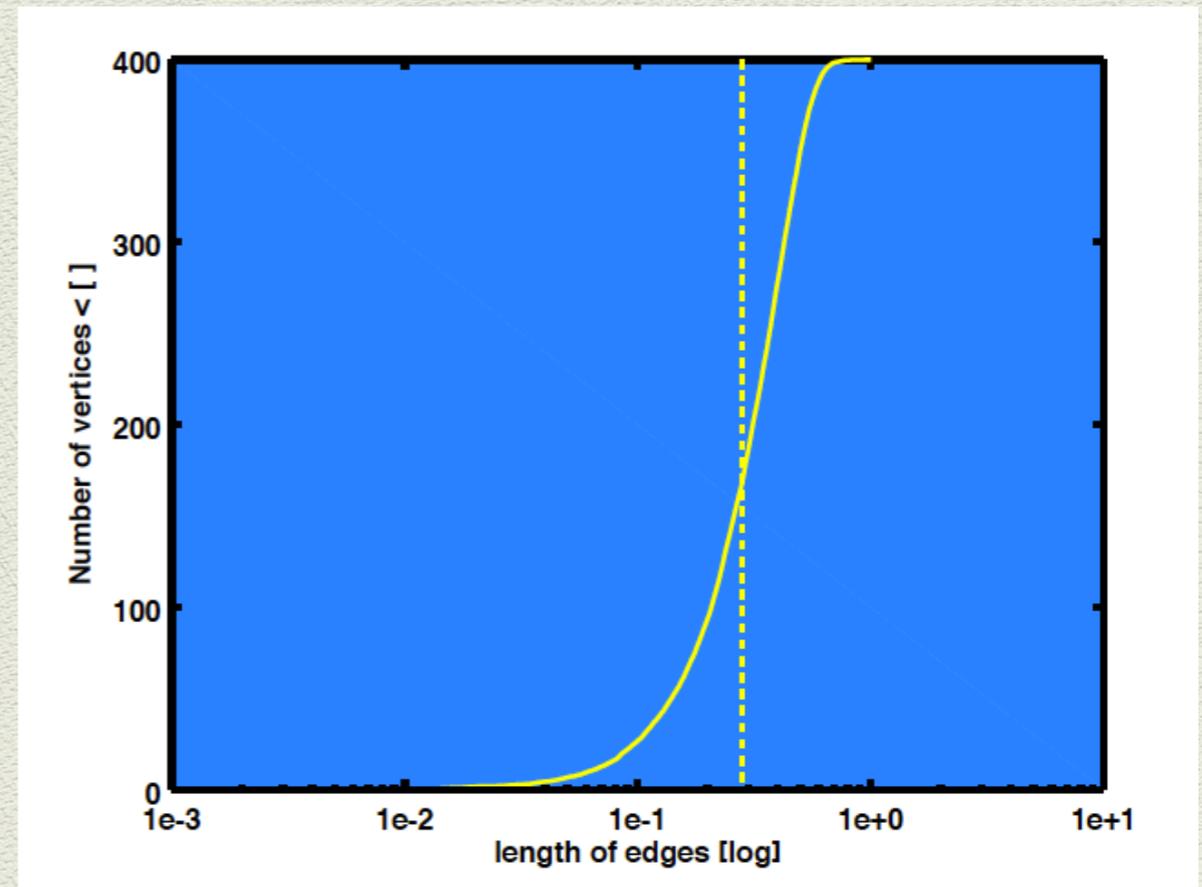
MST: distribution of edges

- ◆ Distribution differs if selected stars are “packed” together
- ◆ Useful to determine relative mass segregation (Alison, Parker ..)
- ◆ Cumulative distribution

MST
reconstruction
(zoom)

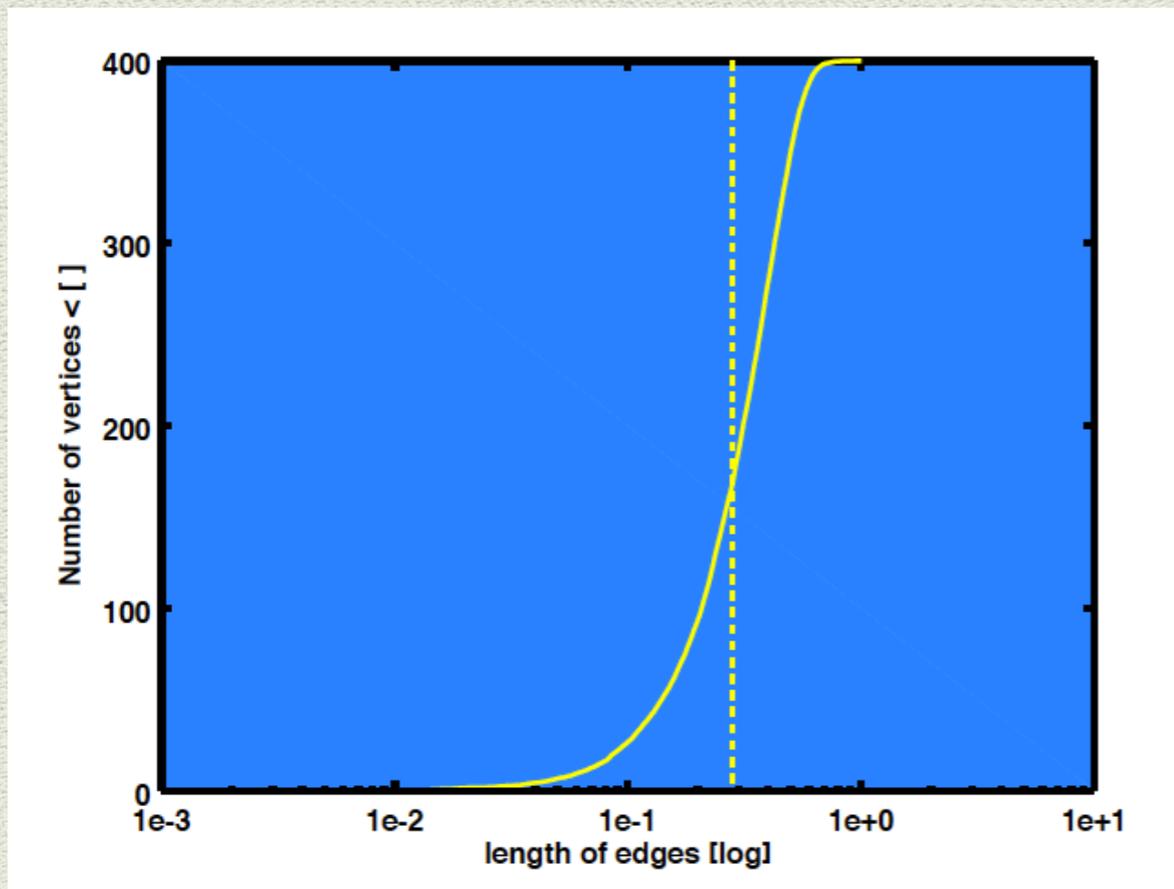


Uniformly sampled
surface / normalized

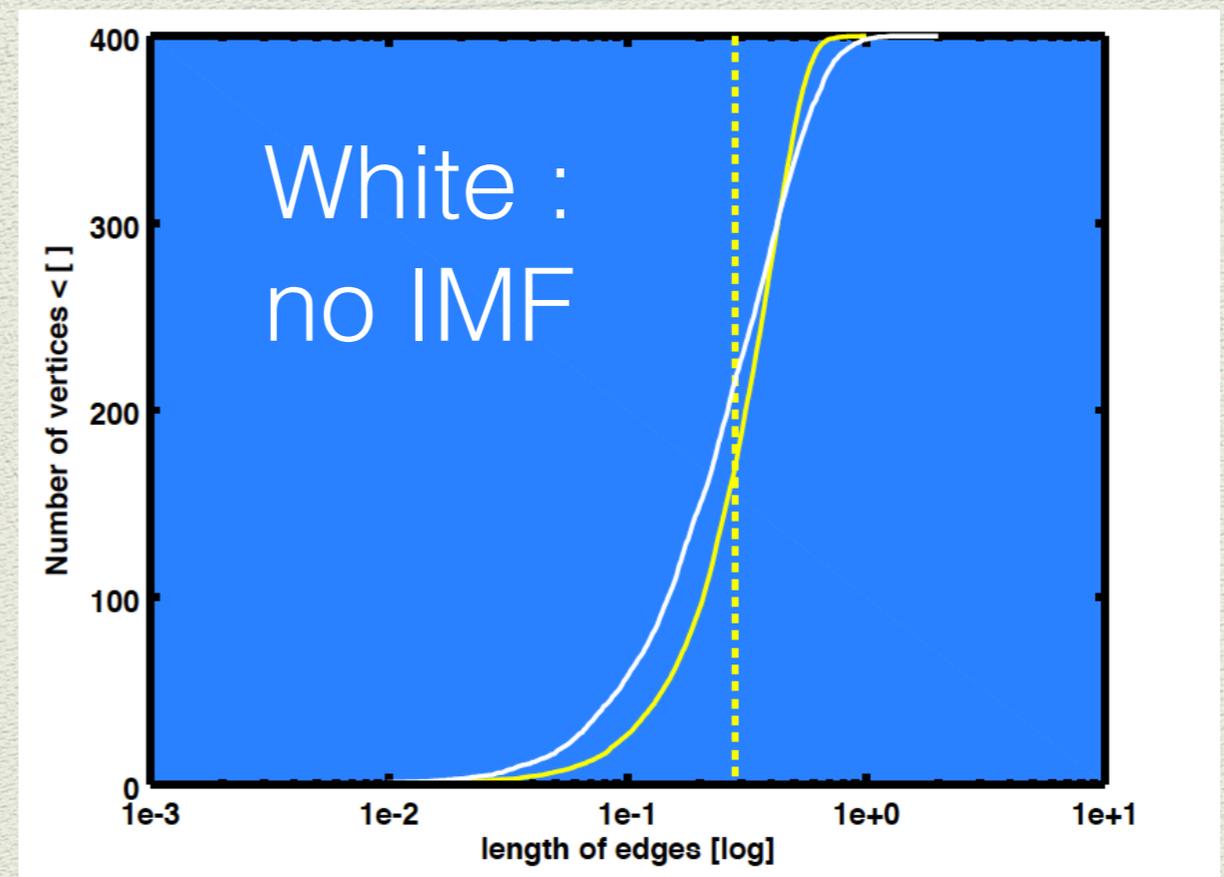


MST: distribution of edges

Uniformly sampled
surface / normalized

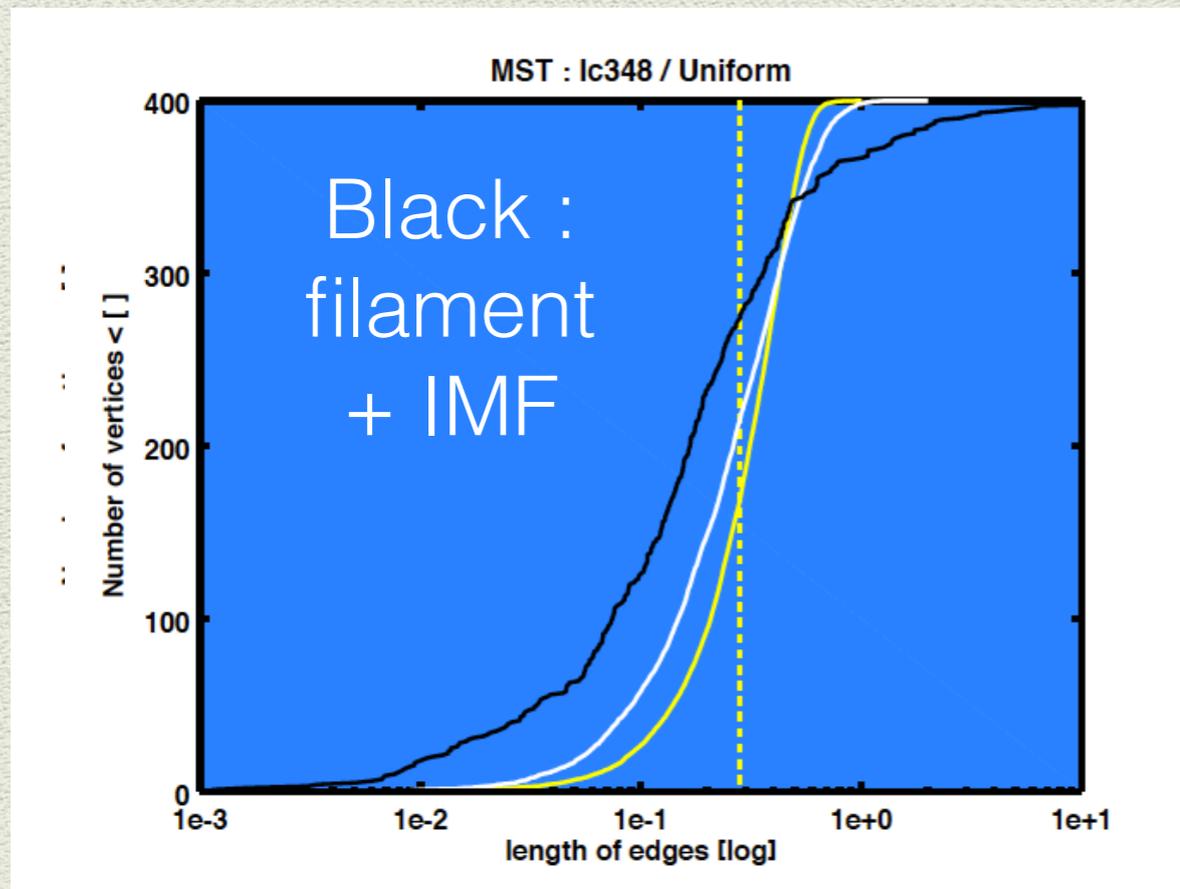


Uniformly sampled
+ fragmented model

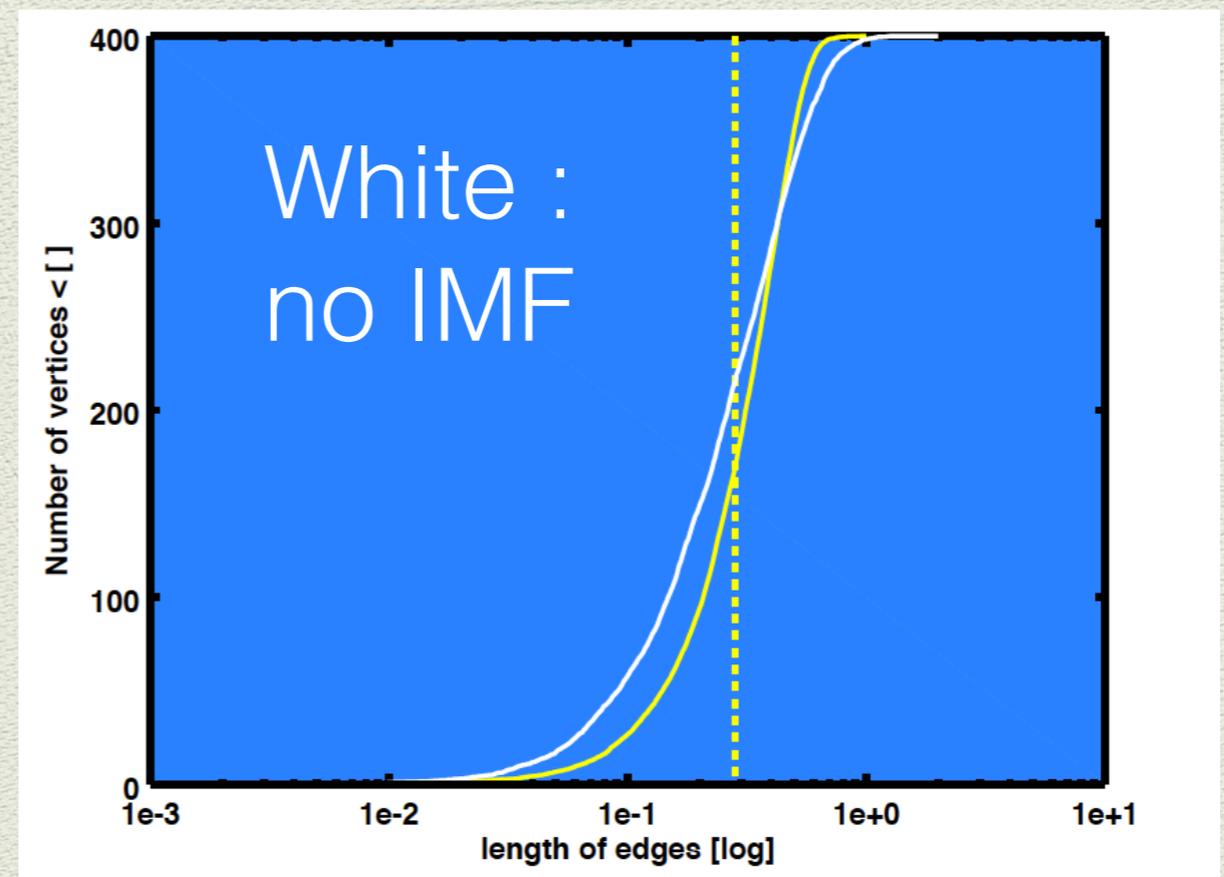


MST: distribution of edges

Uniformly sampled
surface / normalized

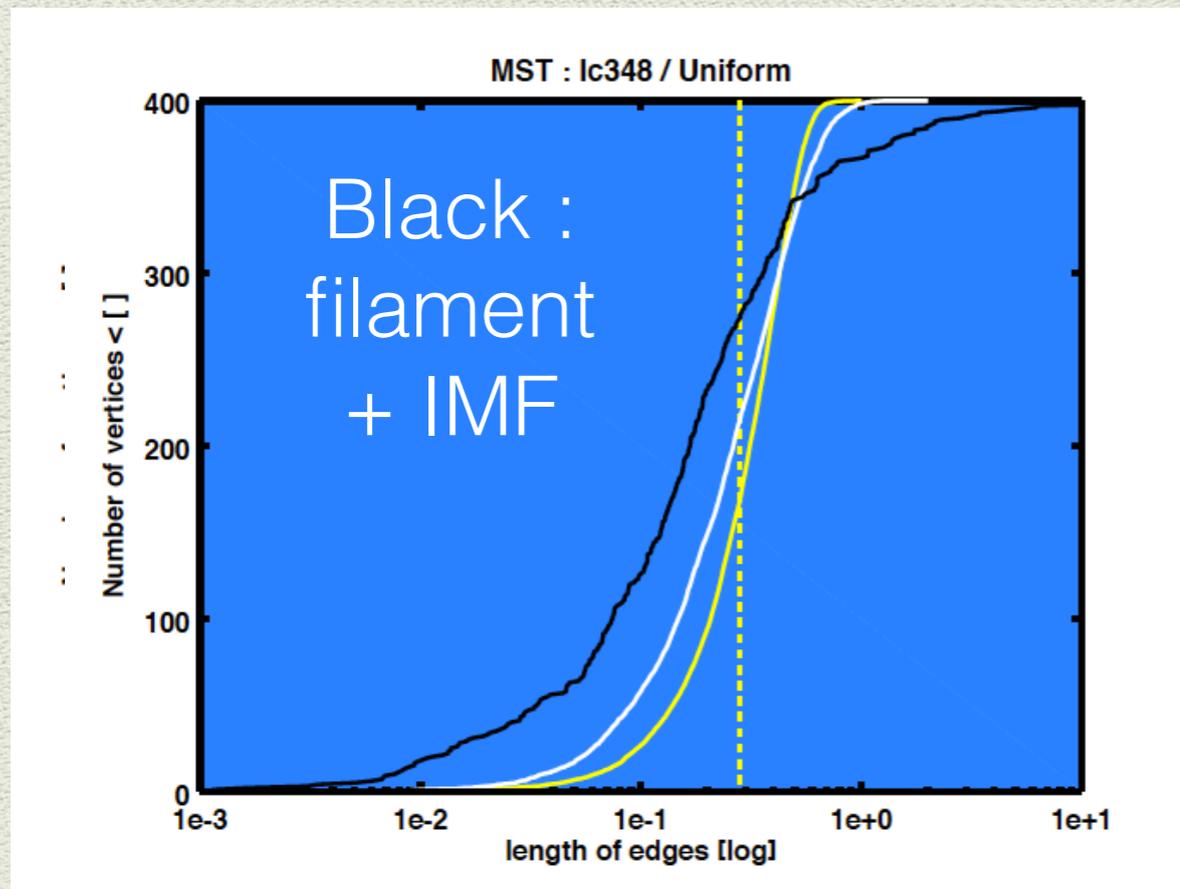


Uniformly sampled
+ fragmented model

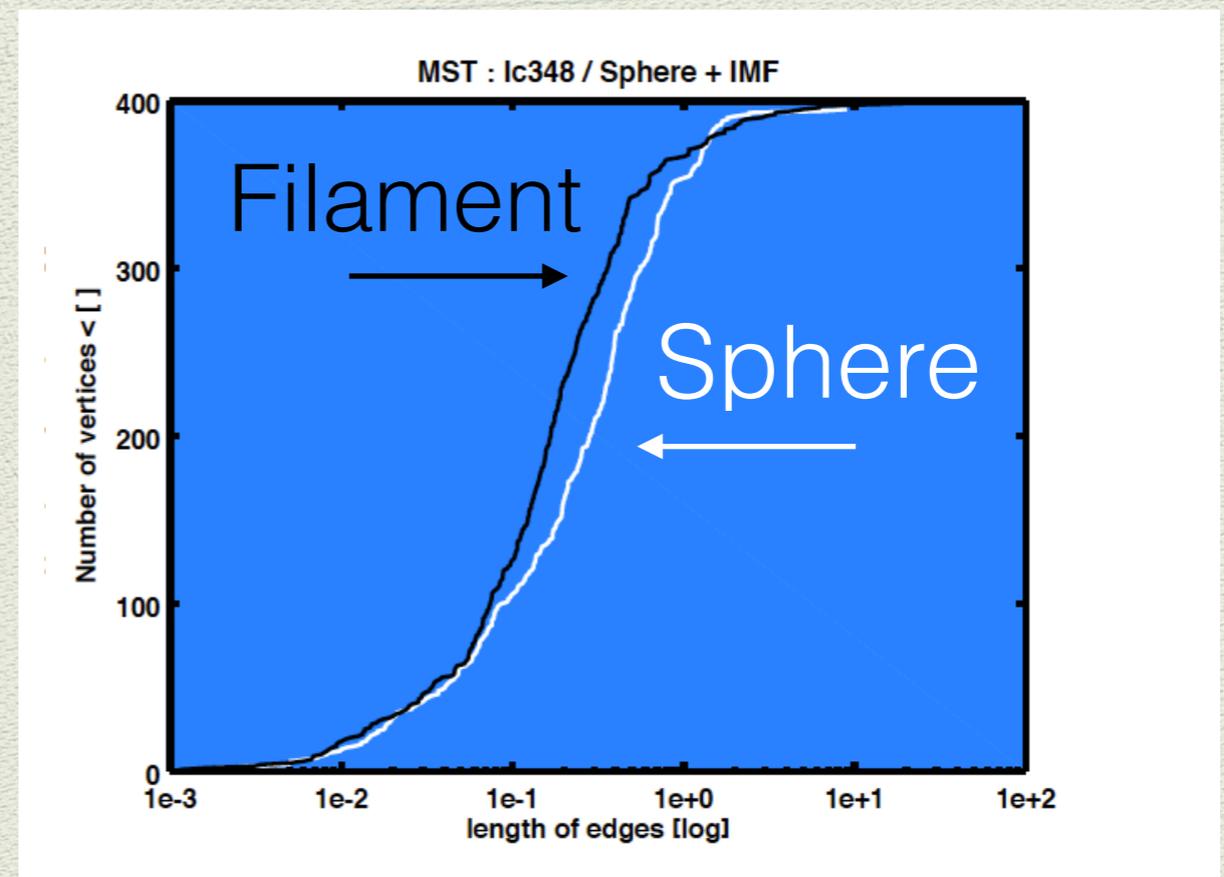


MST: distribution of edges

Uniformly sampled
surface / normalized



Uniformly sampled
+ fragmented model

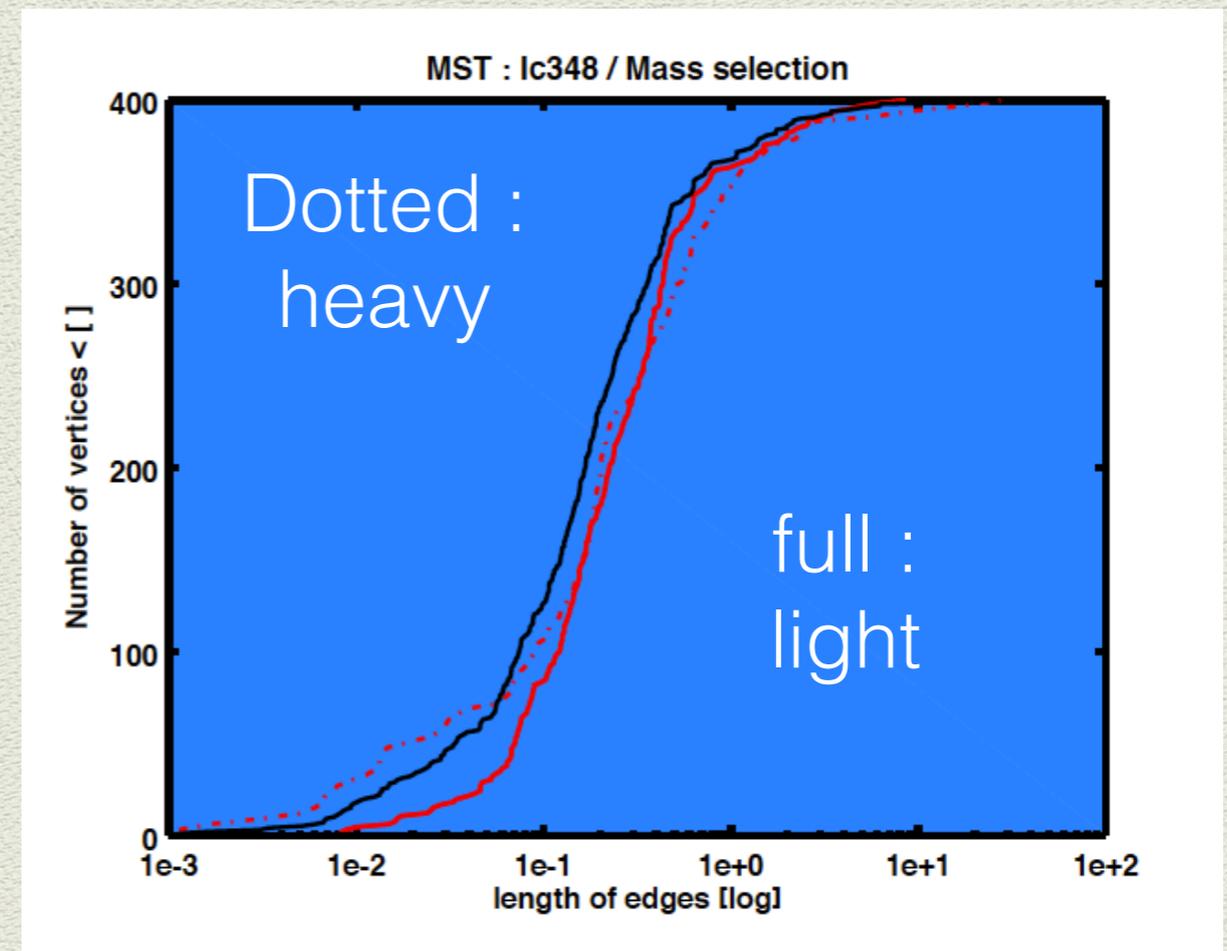
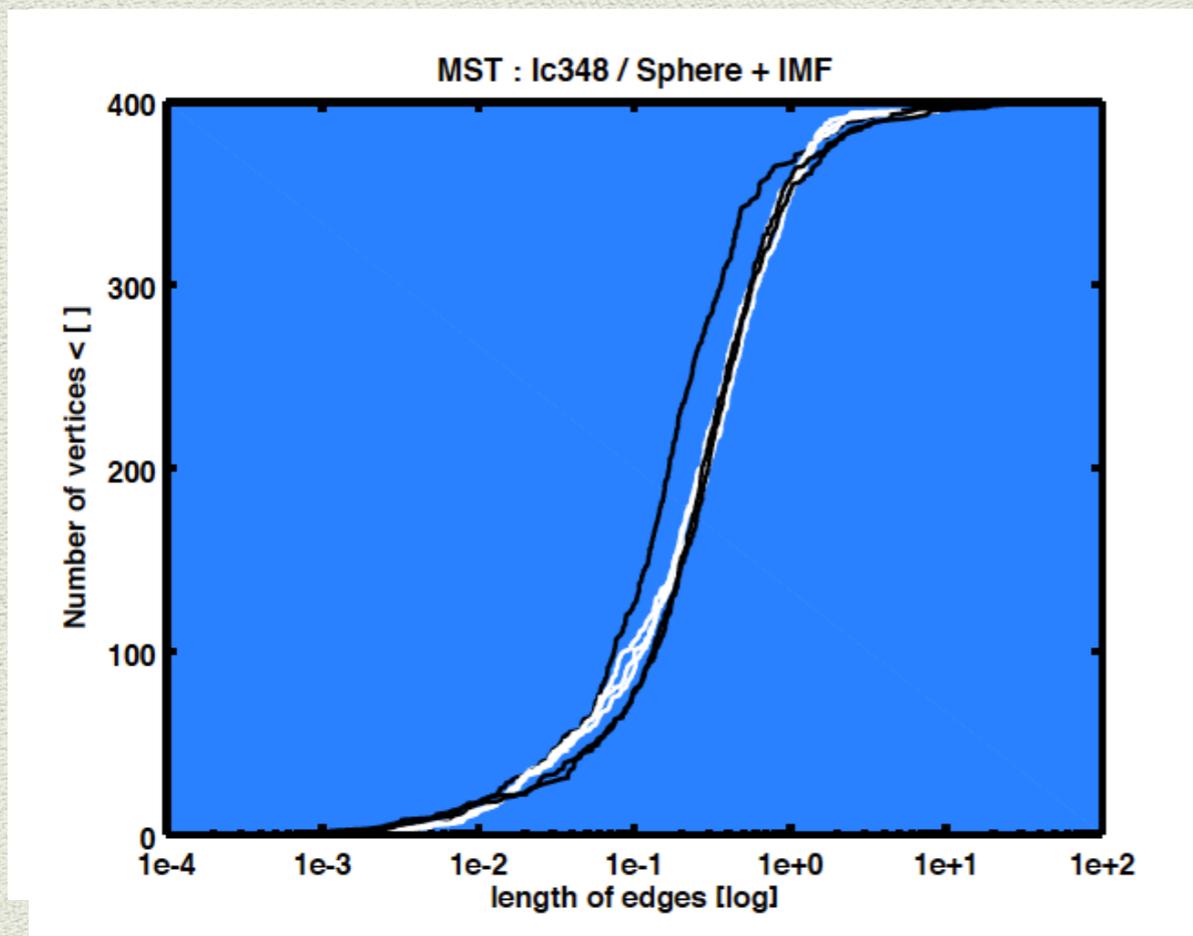


Effect of global geometry

MST: distribution of edges

Different projection angles

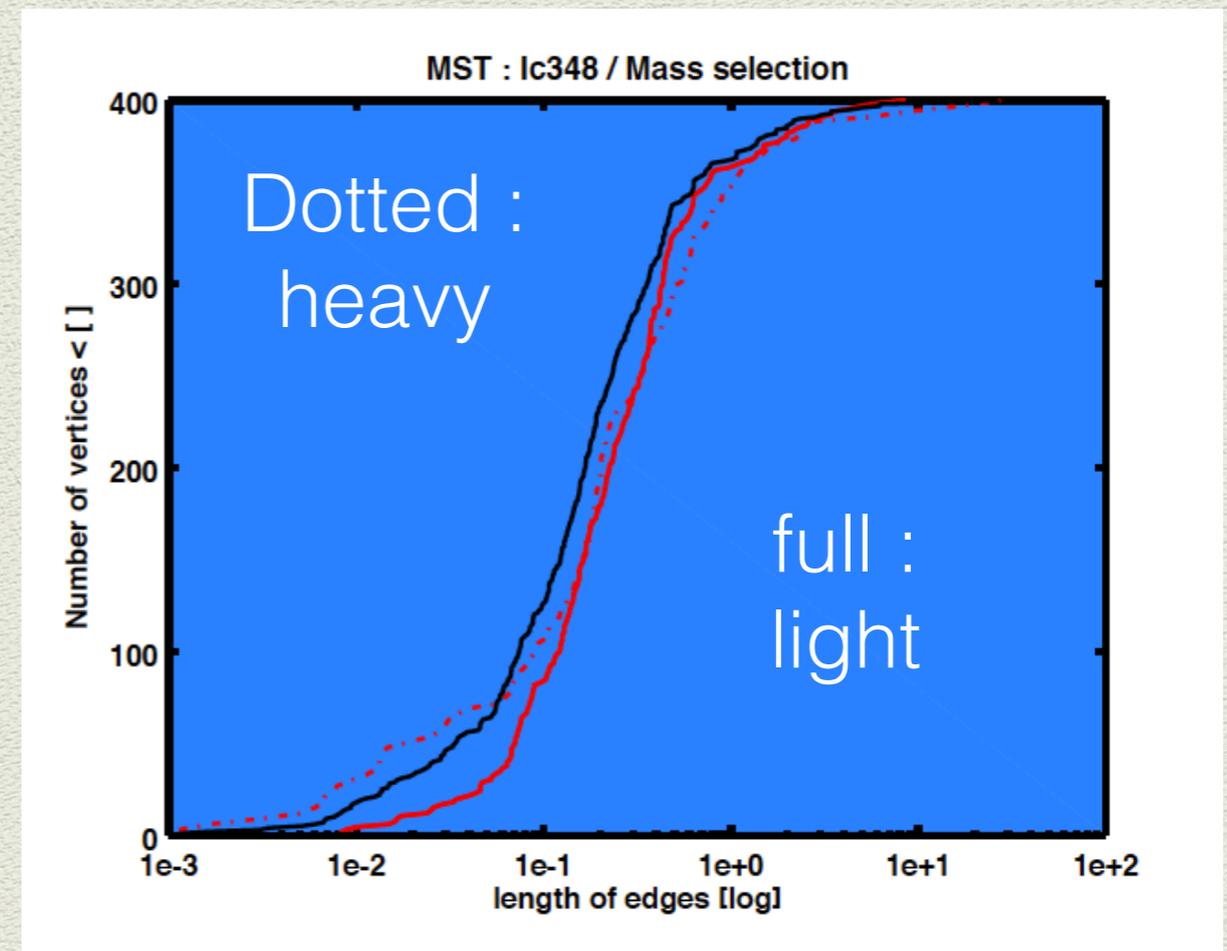
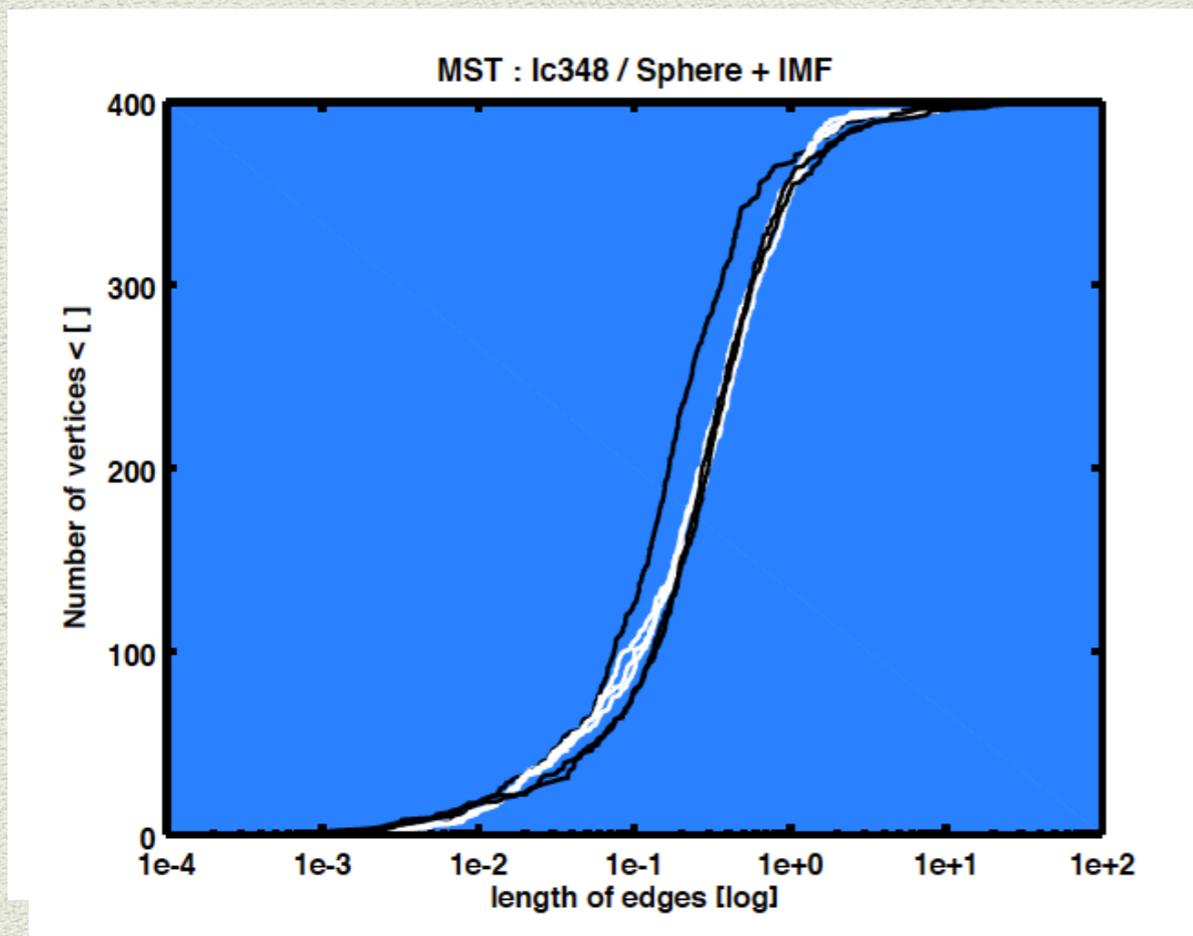
Selection by mass / renormalized



MST: distribution of edges

Different projection angles

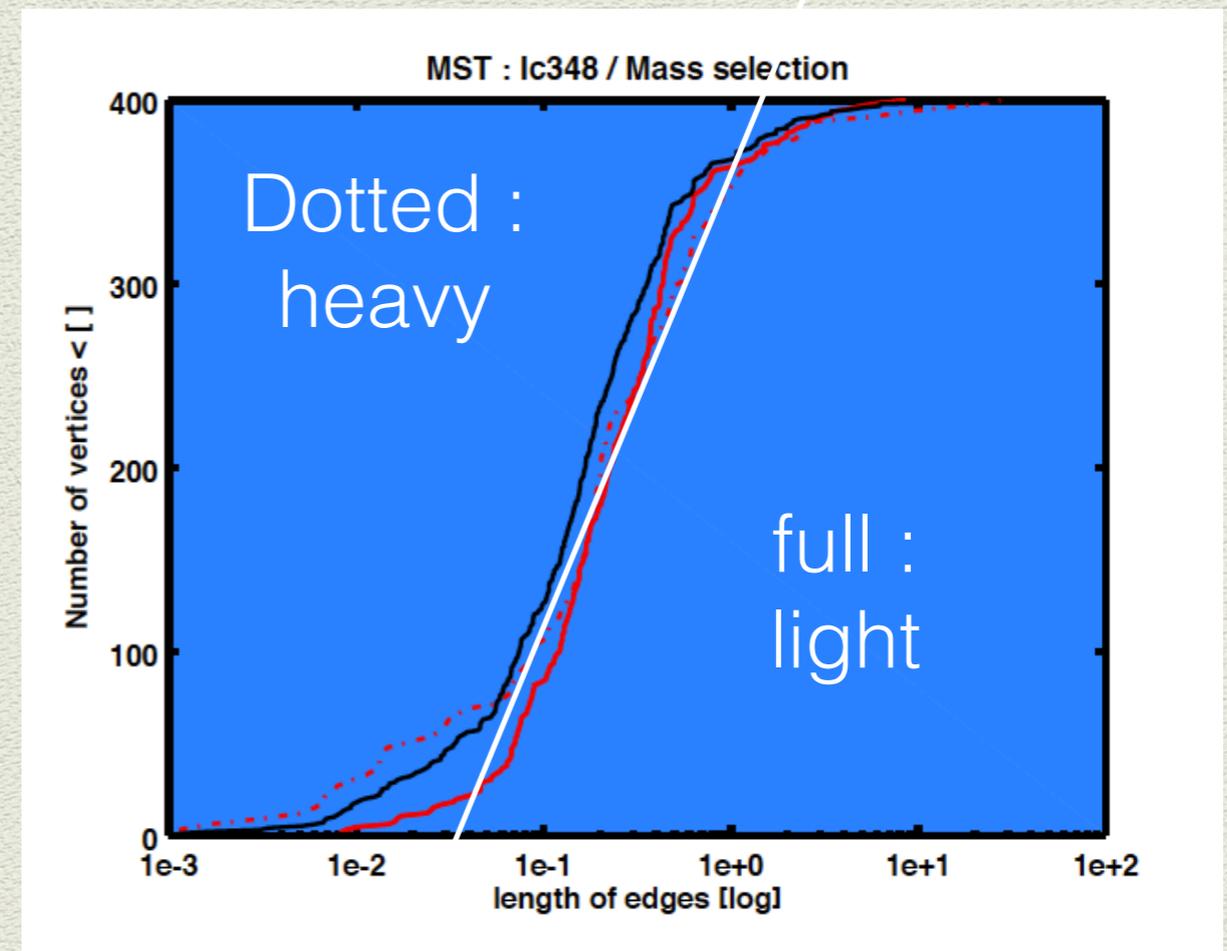
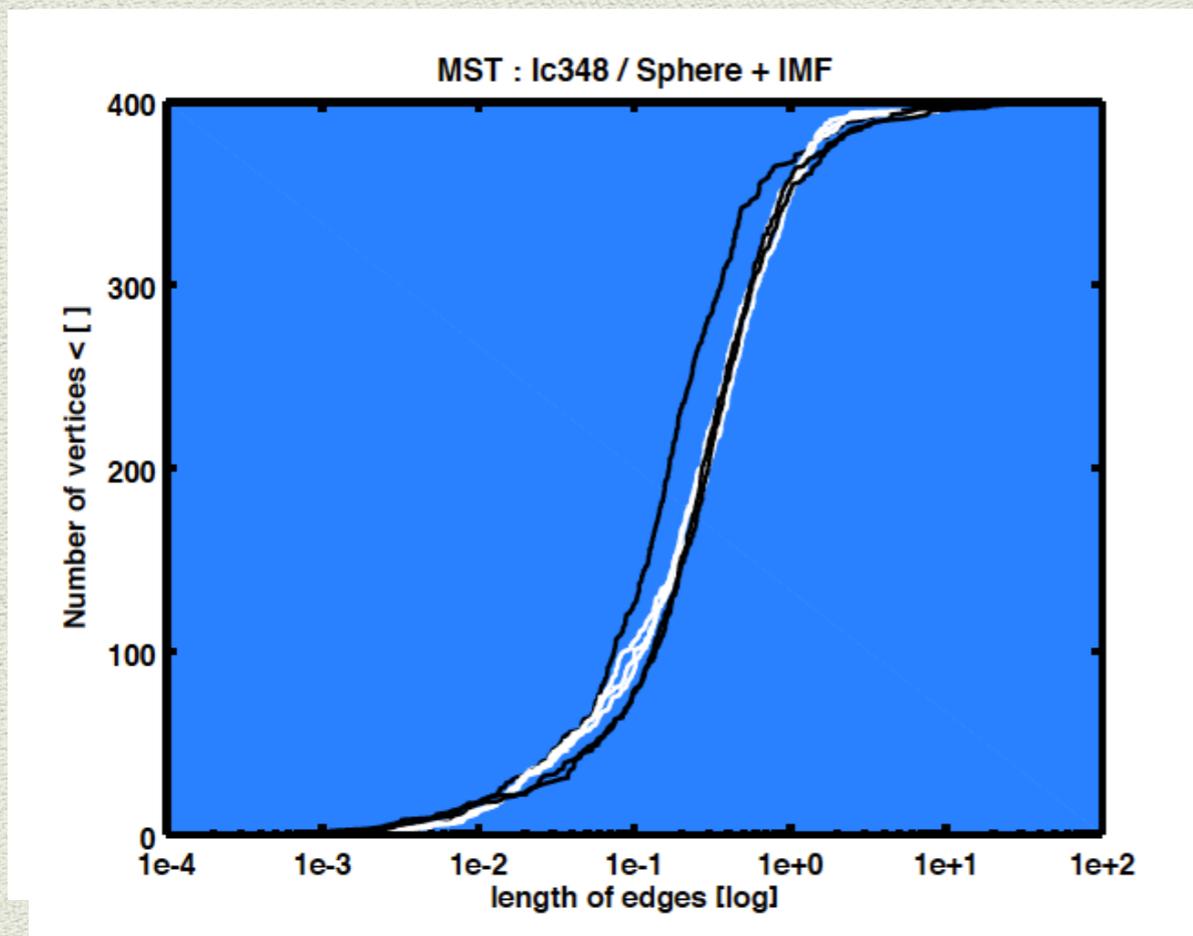
Selection by mass / renormalized



MST: distribution of edges

Different projection angles

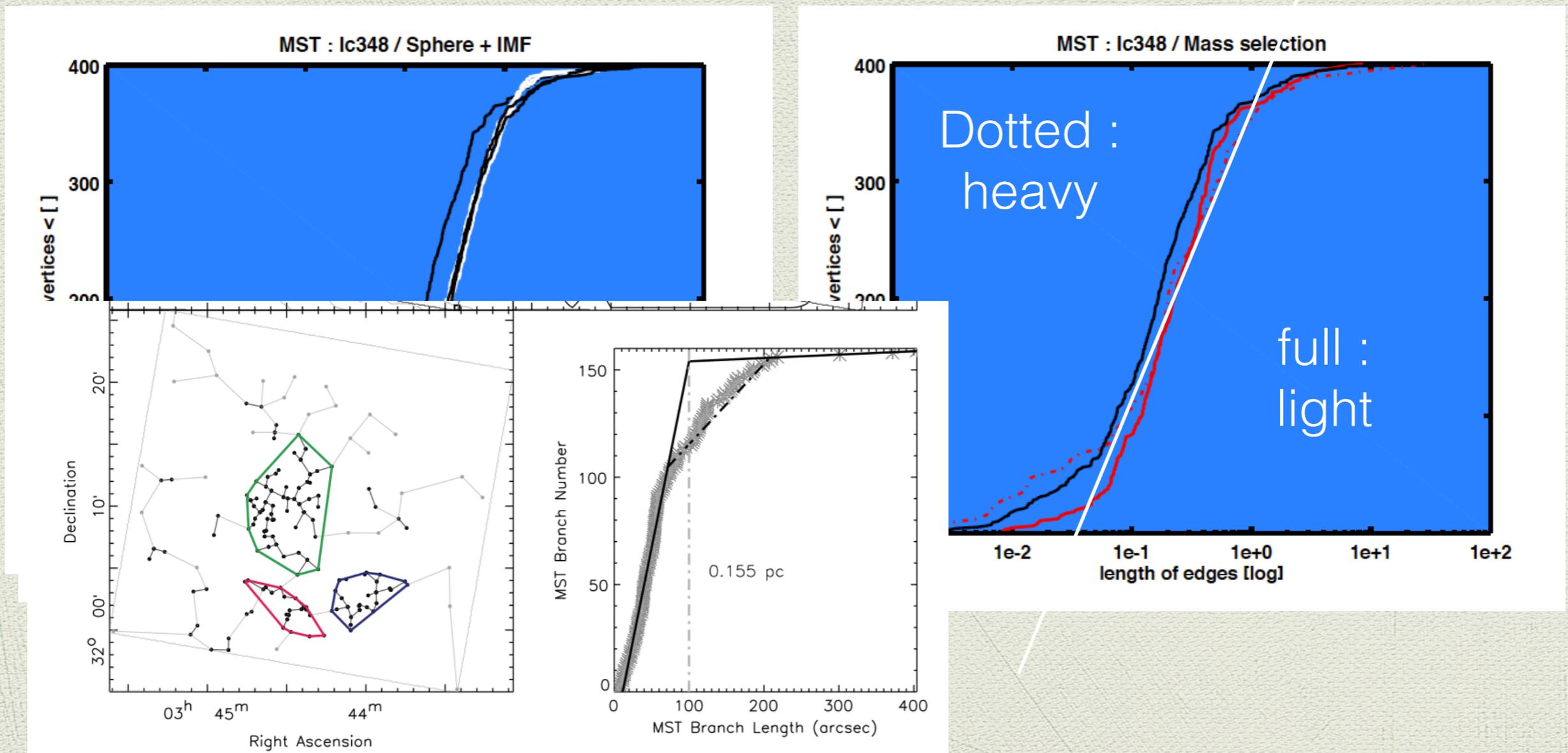
Selection by mass / renormalized



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 ($\gg 1 \text{ pc}^2$)
- The stellar clumps are top-heavy with respect to field stars ;
- The dynamics along filaments enhances breaks in the MST statistics.