The morphology and evolution of Star Forming Regions & Binary Stars

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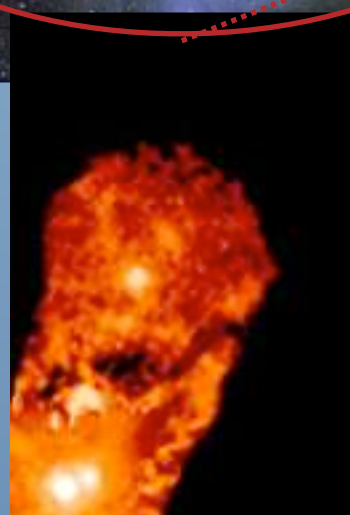
Aarseth meeting / Prague Czech Rep / December 12-15 2017

Observations ..

NGC604 in M33

Orion



Wide range of star forming regions:

- $\varrho \approx 10^1$ - 10^7 M_{Sun} / pc^3
- M_{cloud} 10 to ≈ few $\times 10^6$ M_o
- $\sigma \approx 30$ km/s @ 1 pc

Credits: image lifted from NASA / PotD ++

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

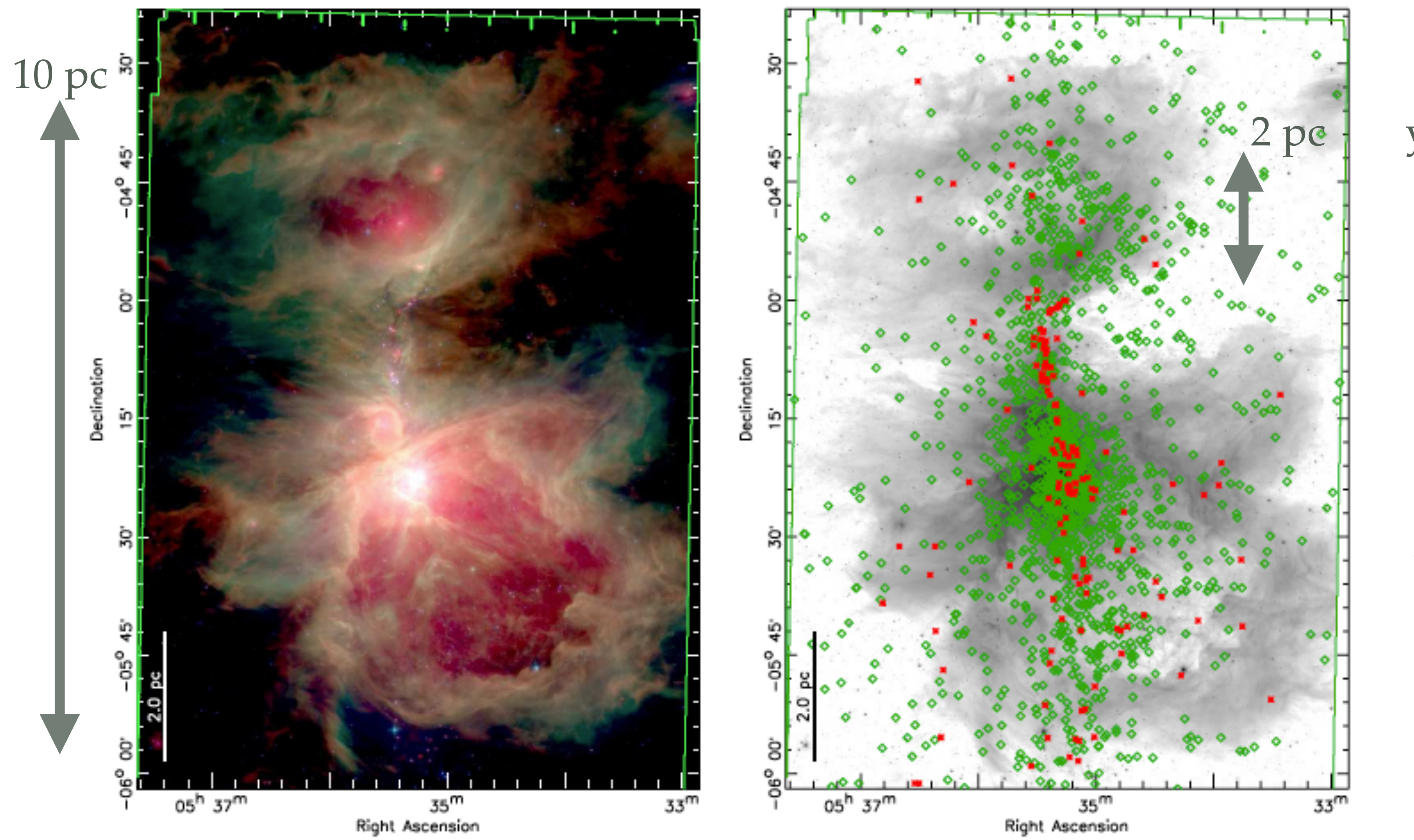
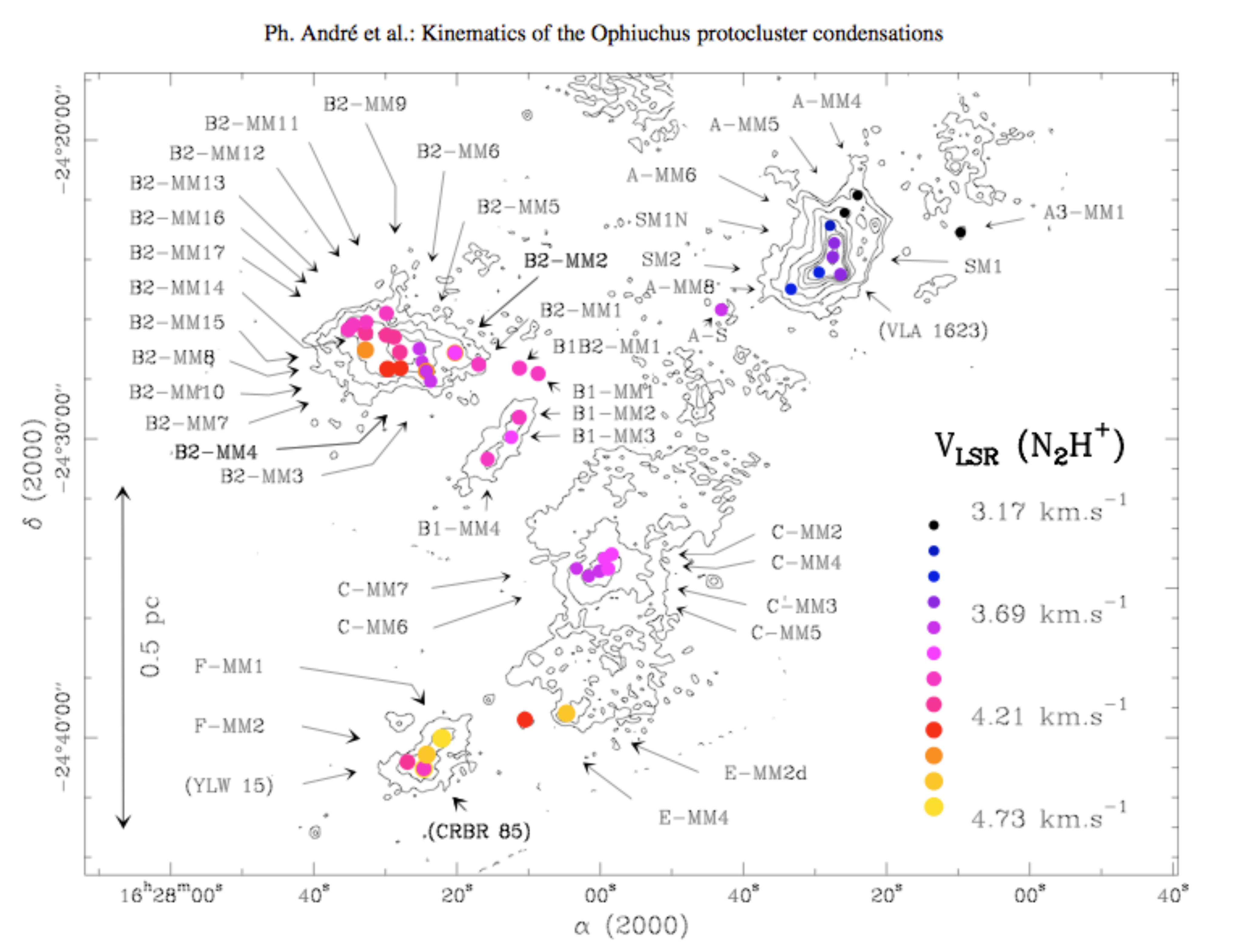


Figure 14. Left: mosaic of the ONC field. Blue is 4.5 μm, green is 5.8 μm, and red is 24 μm. Right: 4.5 μm image with the positions of dusty YSOs superimposed. Green diamonds are young stars with disks, red asterisks are protostars (including the faint candidate protostars and the 10 red candidate protostars 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. T. Megeath et al. 2012, 2015



Kinematics in the ϱOphiuchus region (IRAM 30 m data)

credits : Ph. André et al. 2007, AA

<u>Building up by cooling & accreting:</u> hydrodynamical fragmentation

:: Start from smooth density + randomly-seeded turbulent v-field

(from Bonnell, Bate et al. 2003++, others ..)

- Isothermal gas, FLASHv3
- rotational : $\nabla \cdot \underline{f} = 0$
- compressive : $\nabla \times \underline{f} = 0$
- Stochastic Kolmogorov spectrum
- Shocks, dissipation .. drivers ?

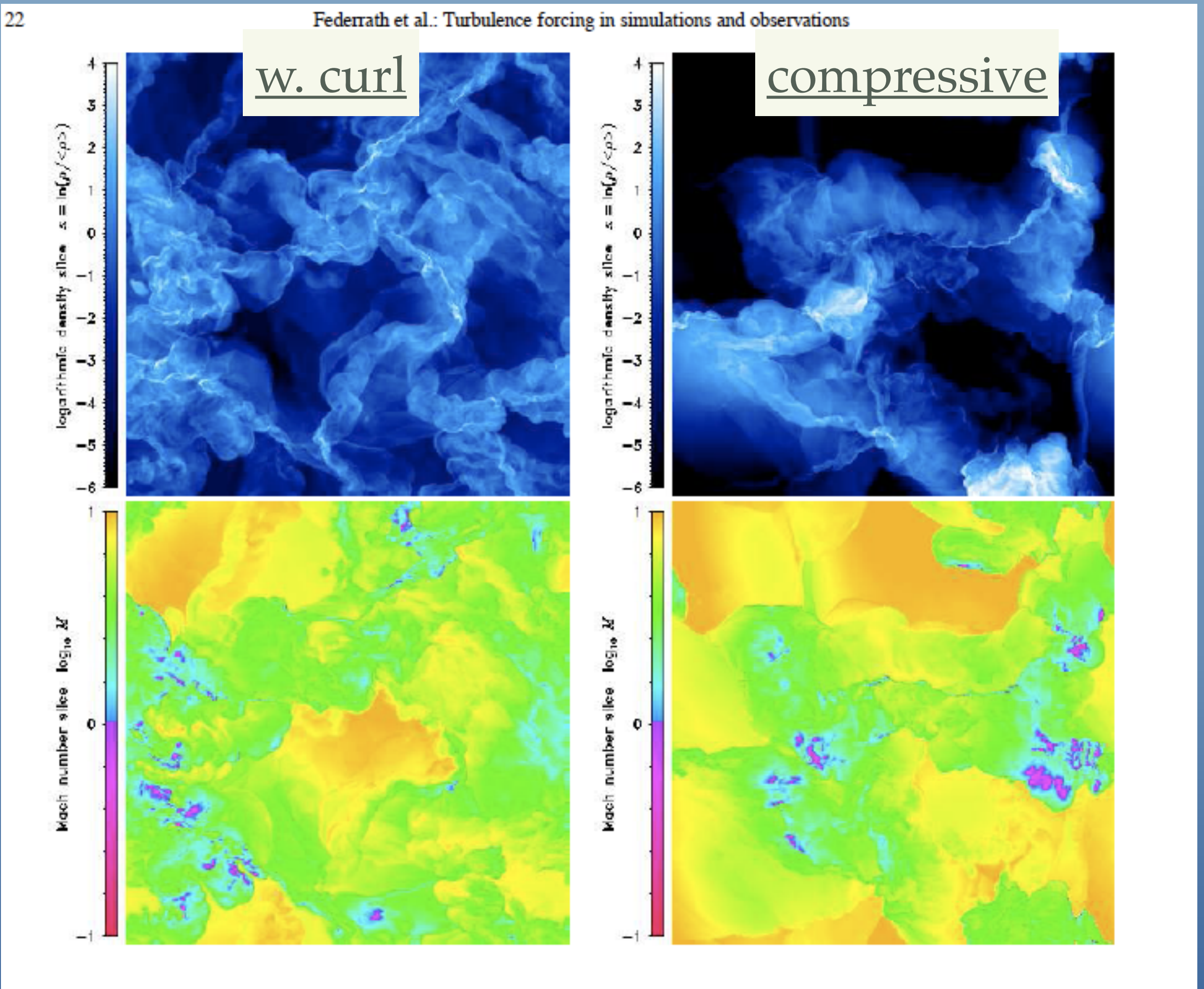


Fig. 16. *z*-slices through the local density (*top panels*) and Mach number fields (*bottom panels*) at $z = 0$ and $t = 2\,T$ for solenoidal forcing (*left*), and compressive forcing (*right*). Regions with subsonic velocity dispersions (Mach < 1) are distinguished from

from Federrath et al. 2010

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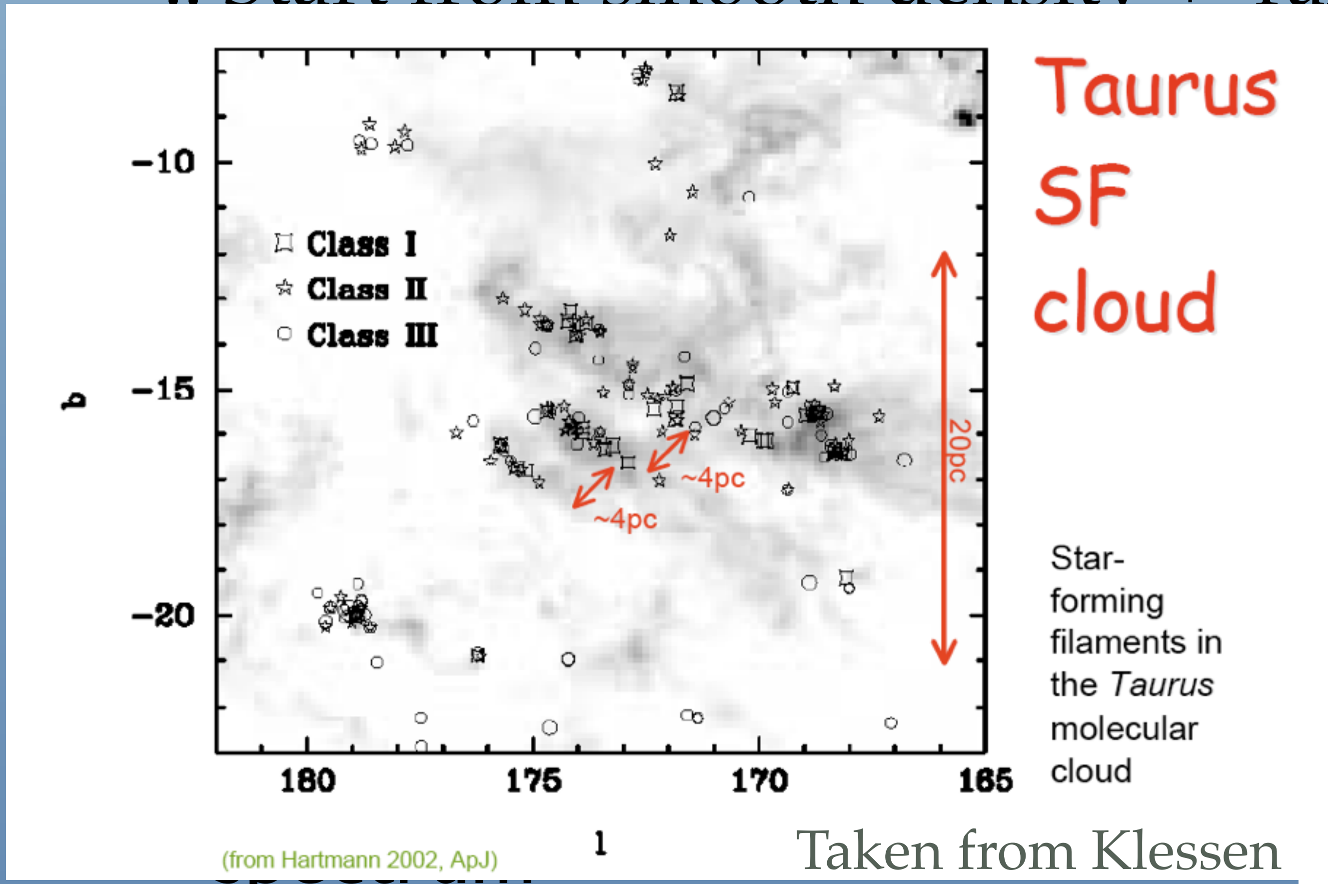

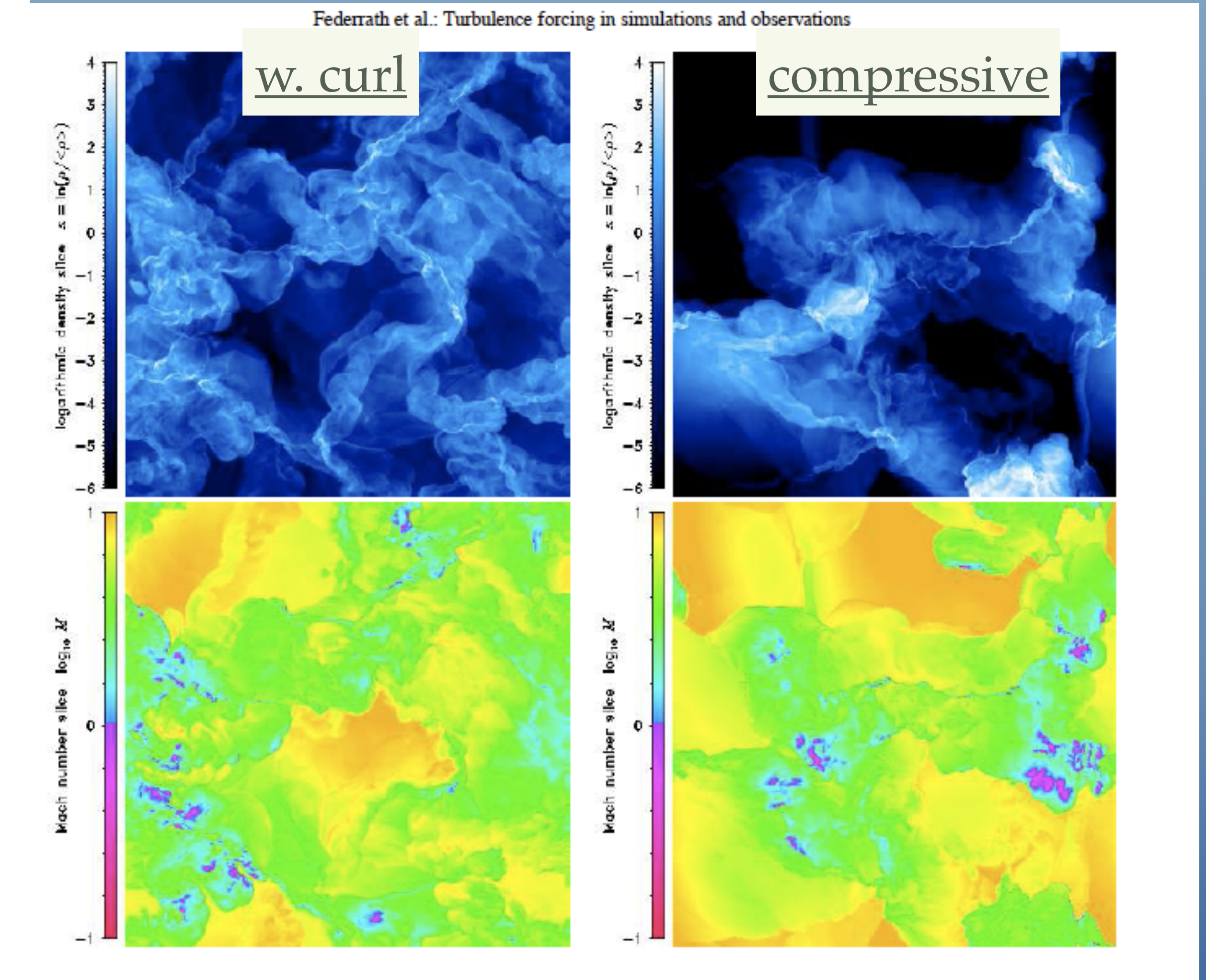

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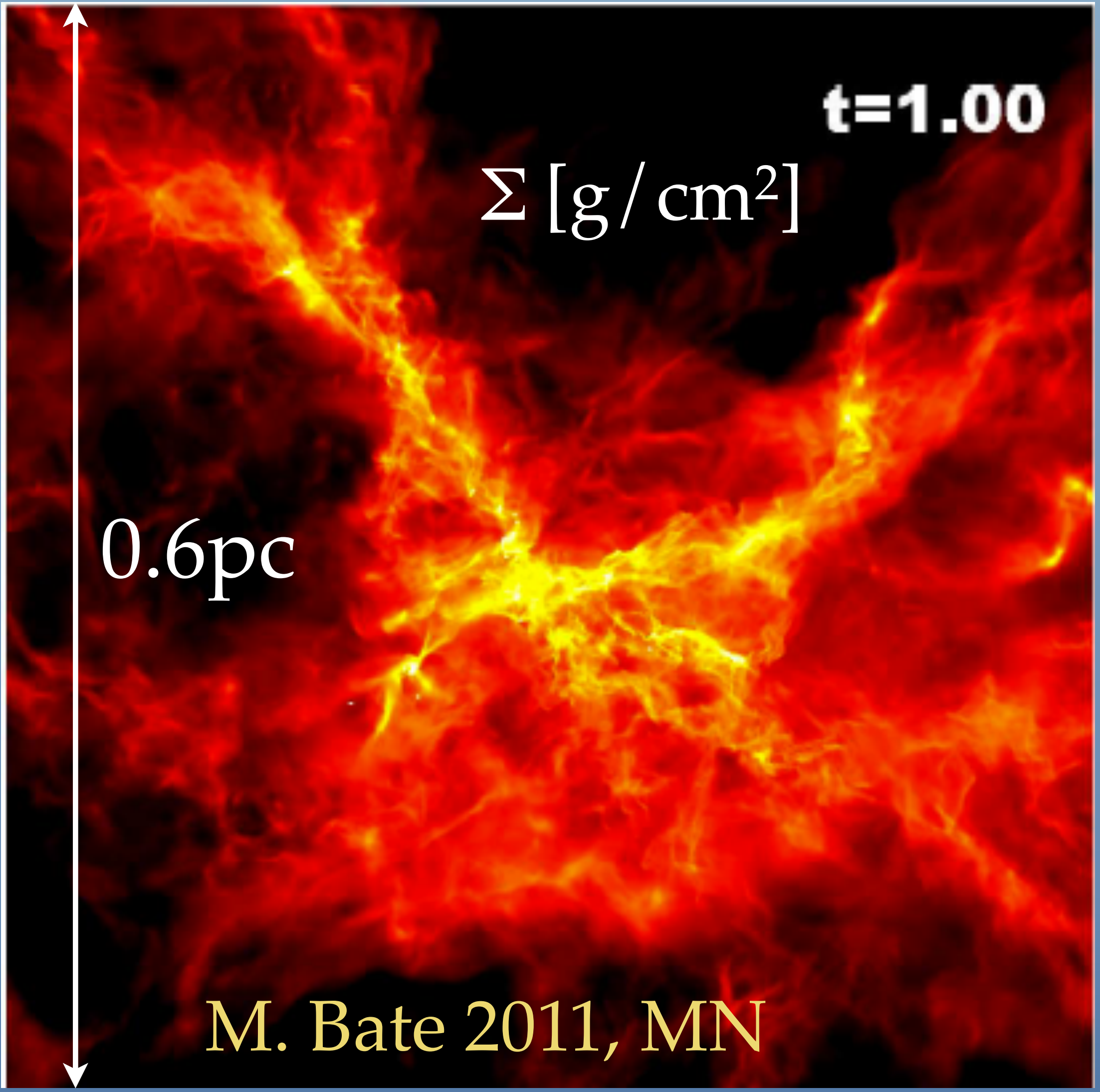
Fragmentation in star-formation calculations

- 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

  ($\varrho \approx 1.8 \times 10^3\ M_{Sun}$ / pc^3 initially)
- $M = 500\ M_{Sun}$, $R_o \approx 1/2$ pc $T \approx 10$ K
- Linear resolution ~ 0.5 AU



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; S. McMillan, op. recit.) ▷ 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])
- *Global* phase-mixing and relaxation on a time-scale well exceeding the star-formation time-scale

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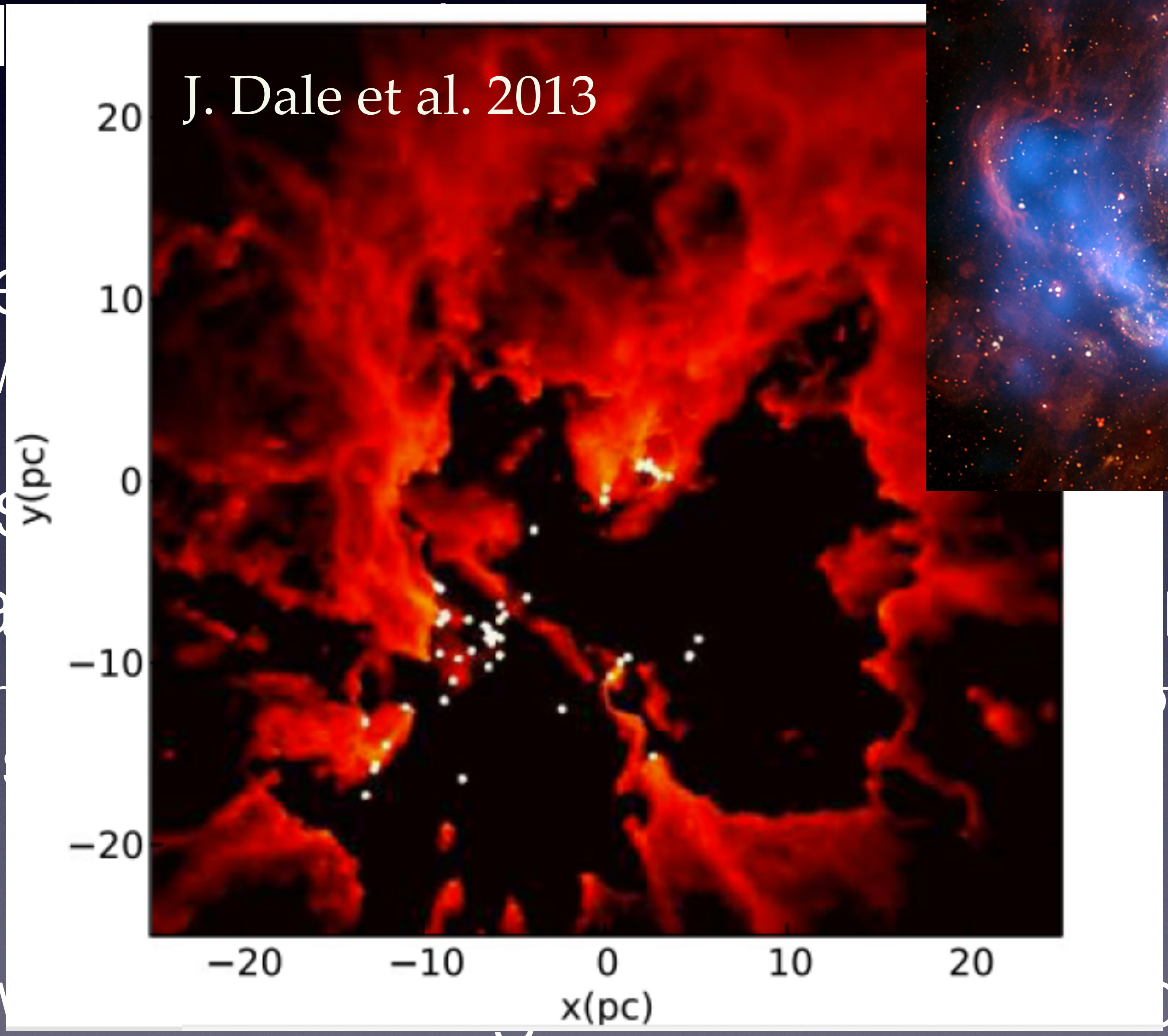
- *Global* … …n a time-scale w… …on time-scale



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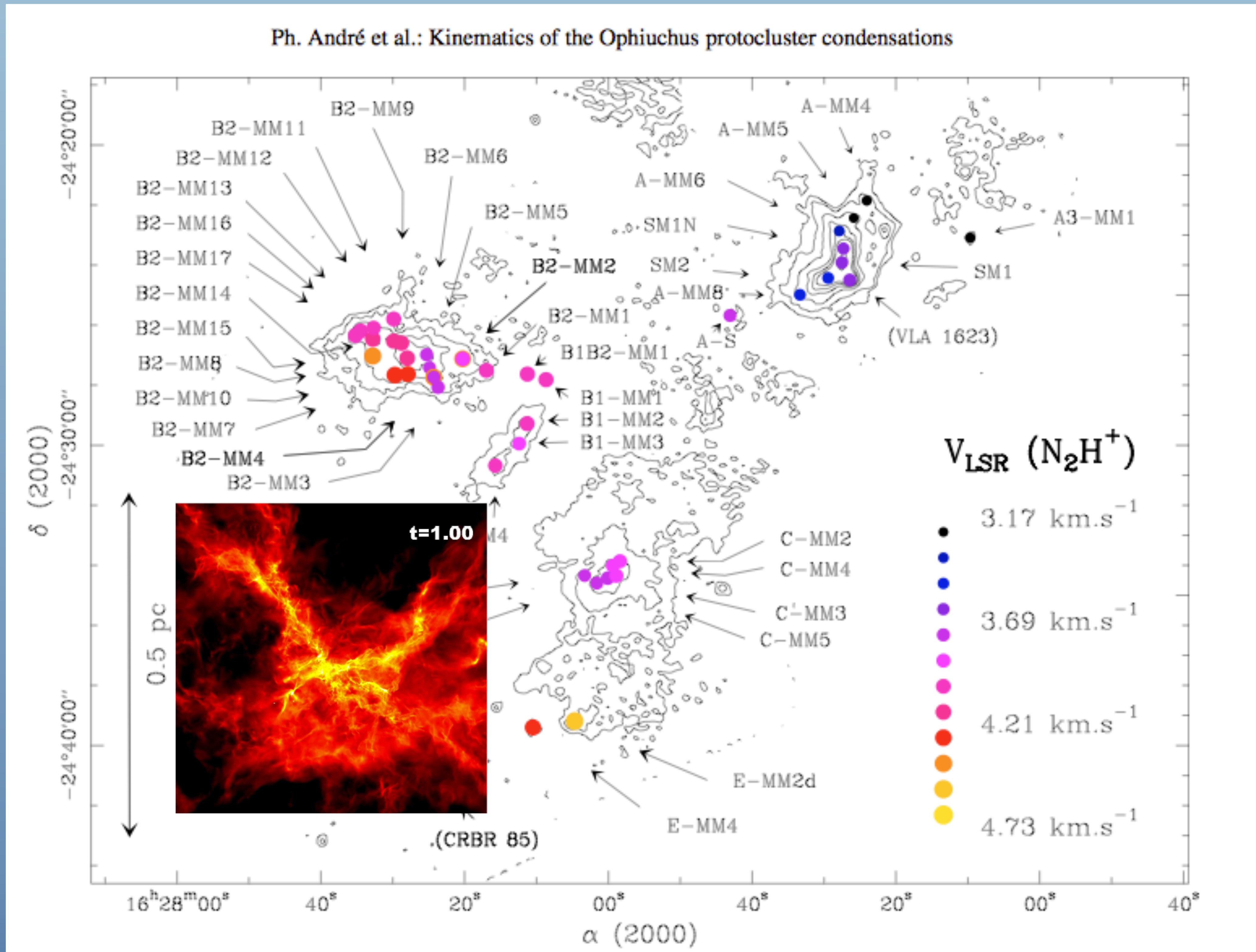

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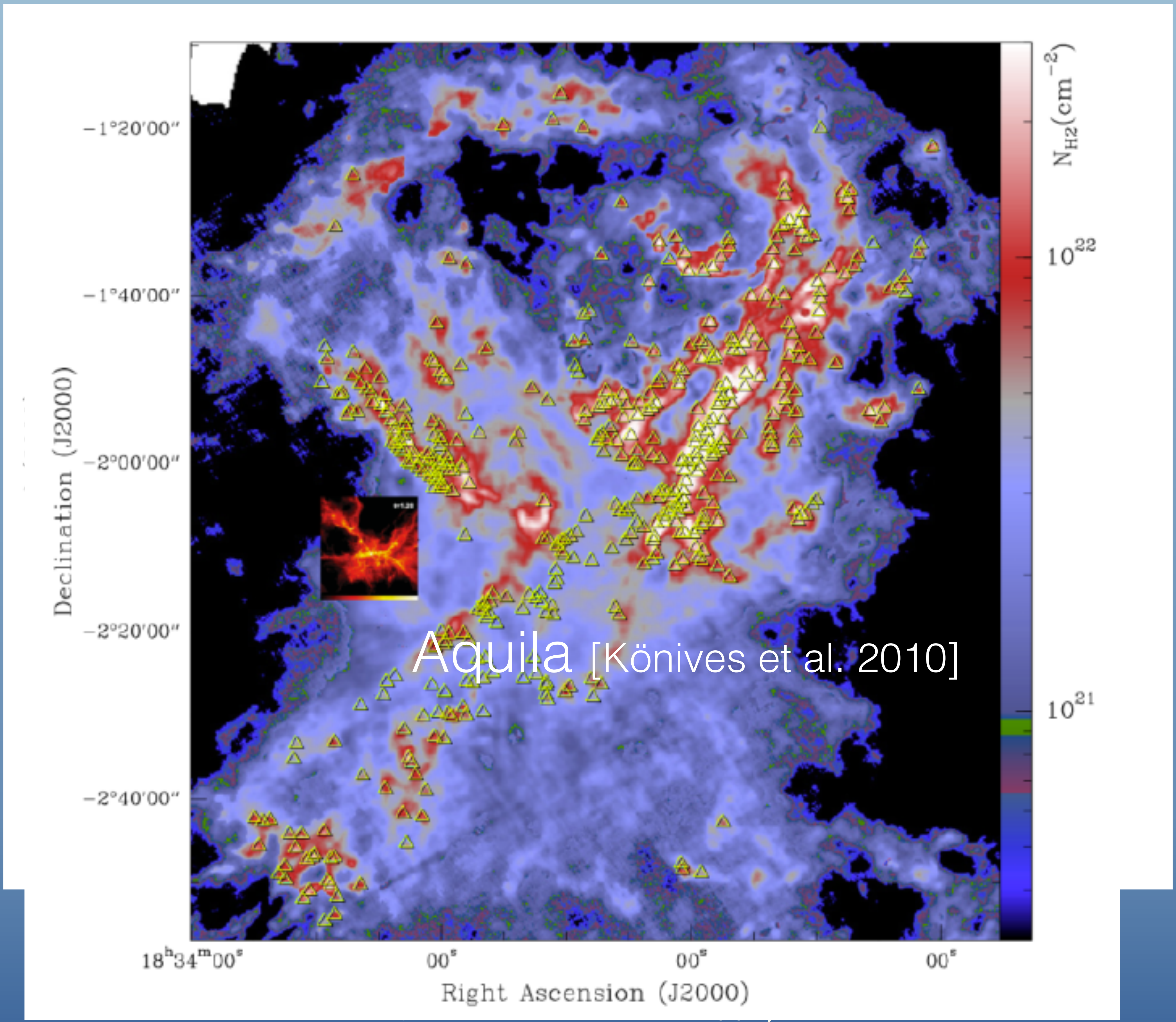

−1°20′00″
−1°40′00″
−2°00′00″
−2°20′00″
−2°40′00″
Declination (J2000)
18h34m00s
00s
00s
00s
Right Ascension (J2000)
NH2(cm−2)
10^22
10^21
Aquila [Könives et al. 2010]

Initial conditions for stellar dynamics: different approaches

- Classic argument: stars are *as cool/cold as* gas is $\sigma^2 \approx k_\beta T$
- 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, ..)

Initial conditions for stellar dynamics:

- Cla… $k_{\beta}T$
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  se, …
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  dra… 4, ..)
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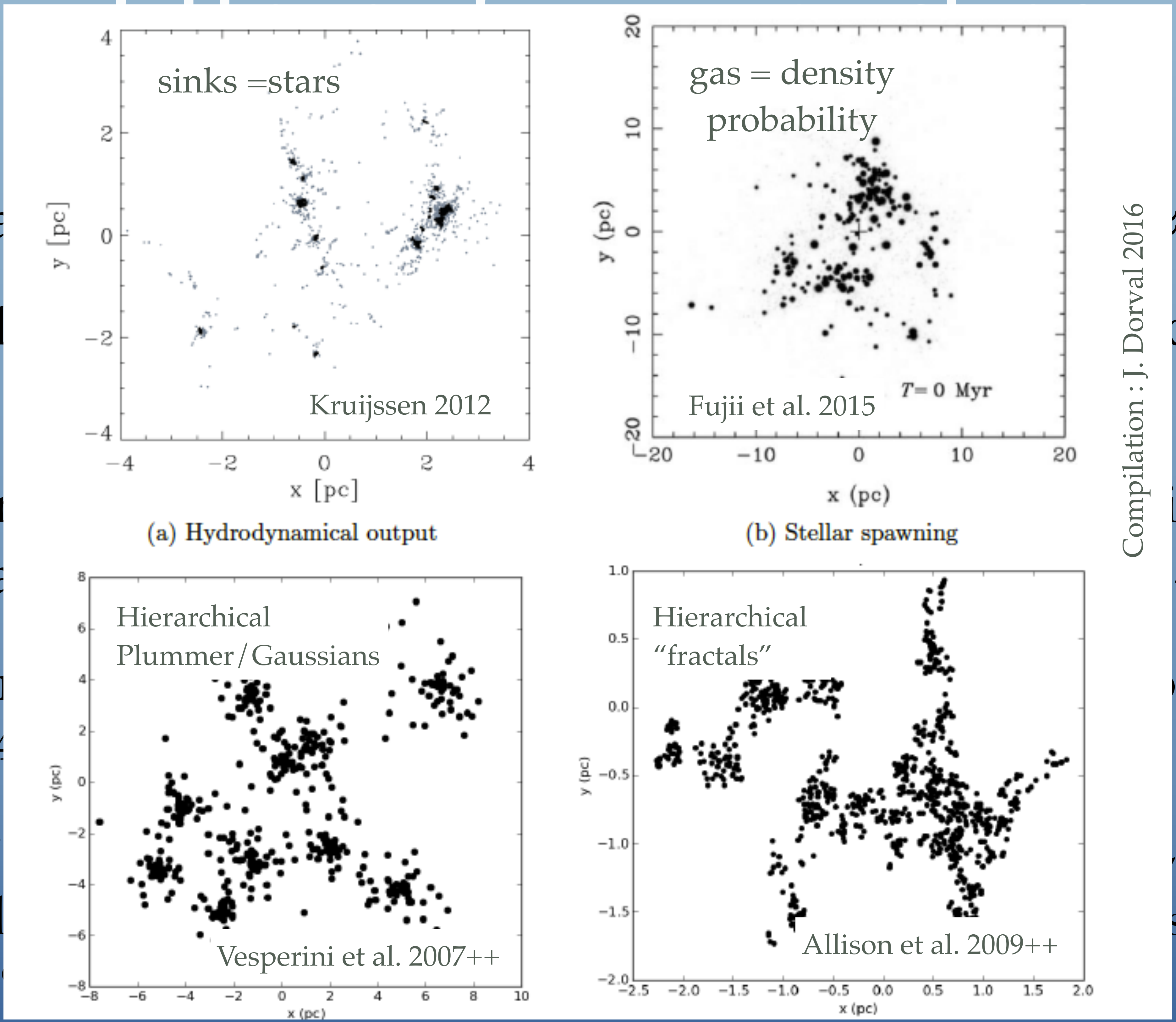

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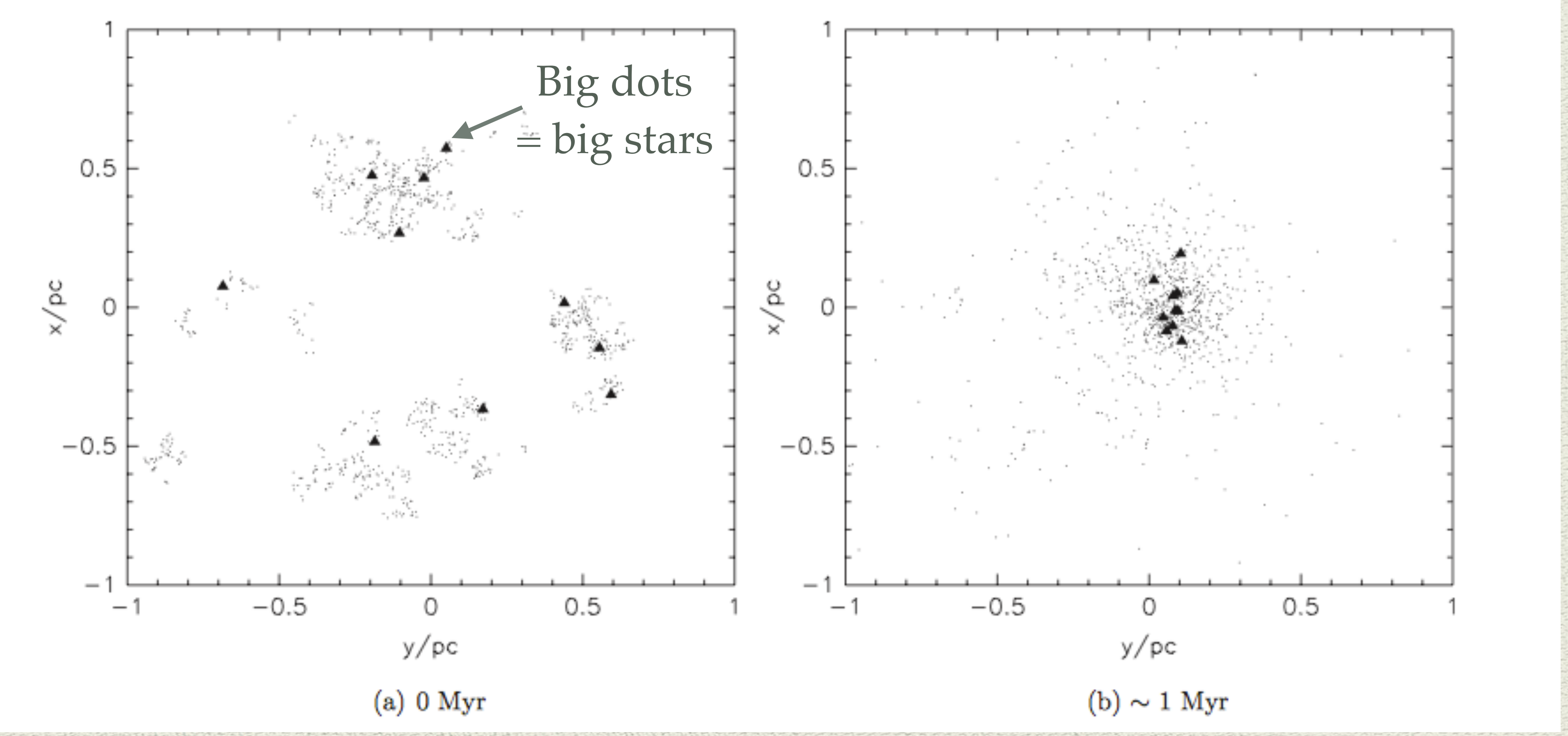


:: Mass segregation enhanced during relaxation (Vesperini et al 2007, '12,'15)

Segregation in young stellar populations : OB star in Carina

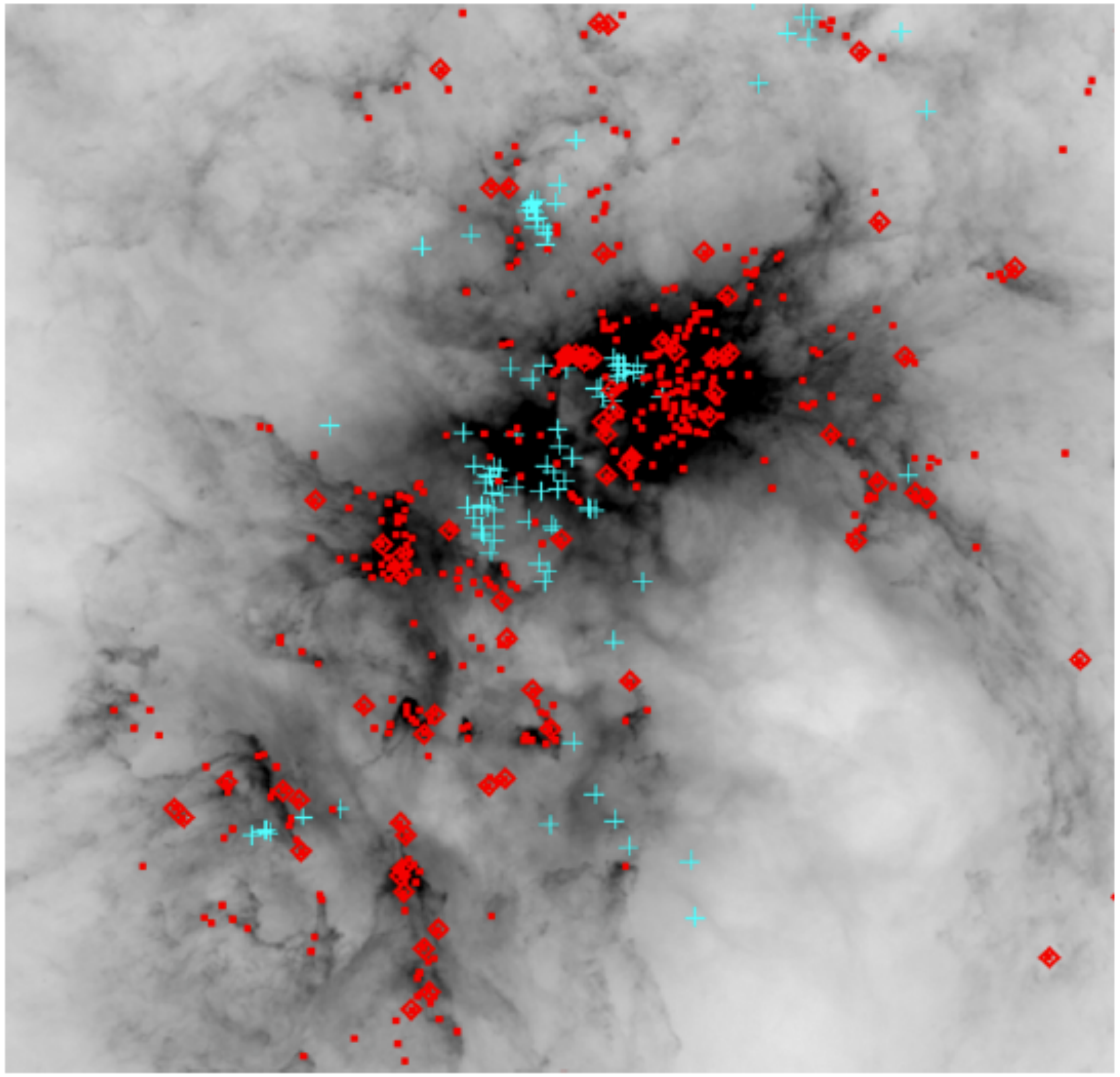


Figure 1.8: Herschel IR 70m observations of the Carina Nebula, with YSOs as red points and diamonds. Cyan crosses show OB stars. Both the gas and prestellar objects follow a substructured distribution. The figure was extracted from Gaczkowski et al. (2013).

Initial conditions: it's bottom up++

Fragmentation modes + *collisional* evolution

- Cooling leads to drop in Jean length and the growth of fragmentation modes
- Cooling by gravity = two-body diffusion of E_k *or* expansion of entire system (▷ analogy only, not thermal v; ok with a hard wall [gas pressure])
- $TdS = dU + P\,dV = 0$ :: dU ↓ if dV ↑

:: Mass segregation develops *during* the fragmentation process

→ collisional integrator: nb6/++, phiGPU: narrow mass range ok

:: Seek out a *fragmented* configuration with consistent v-field

:: Adiabatic cooling time = star formation time-scale (constraint)

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

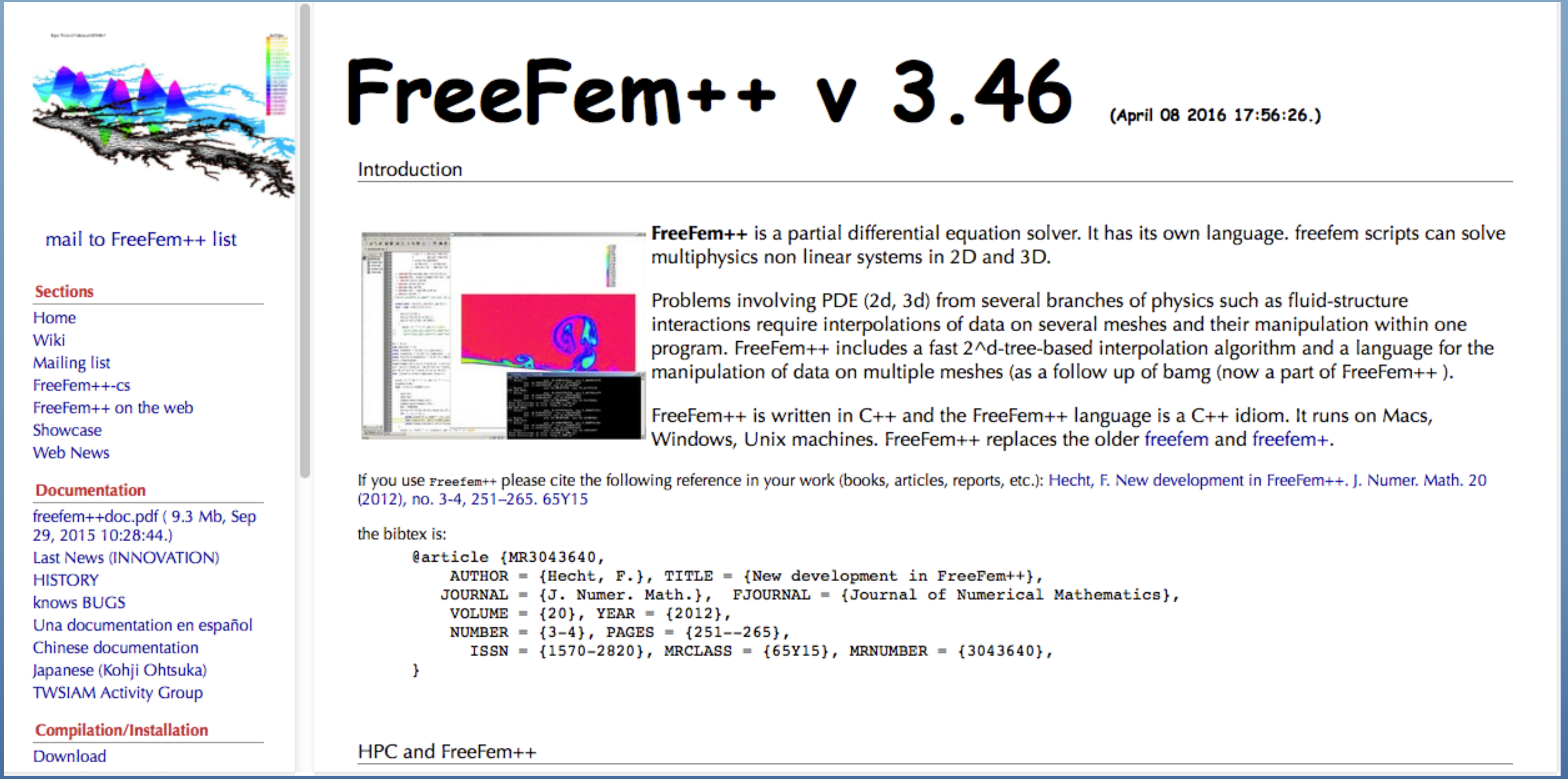
$$\frac{d^2}{dt^2} r' = -\nabla_{r'}(\Phi + \delta\Phi)$$

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

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



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Compilation/Installation

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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:

```
@article {MR3043640,
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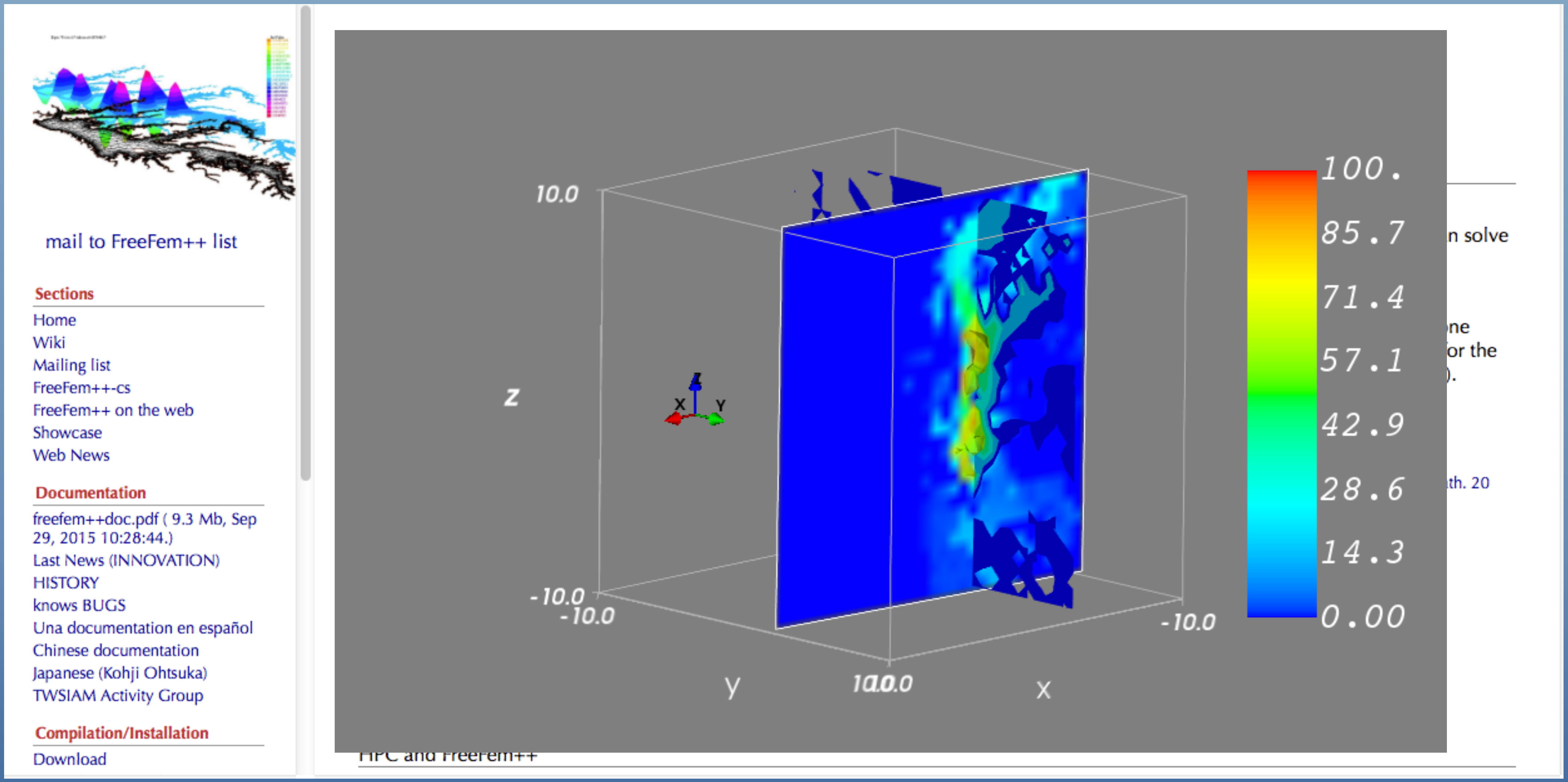
HPC and FreeFem++

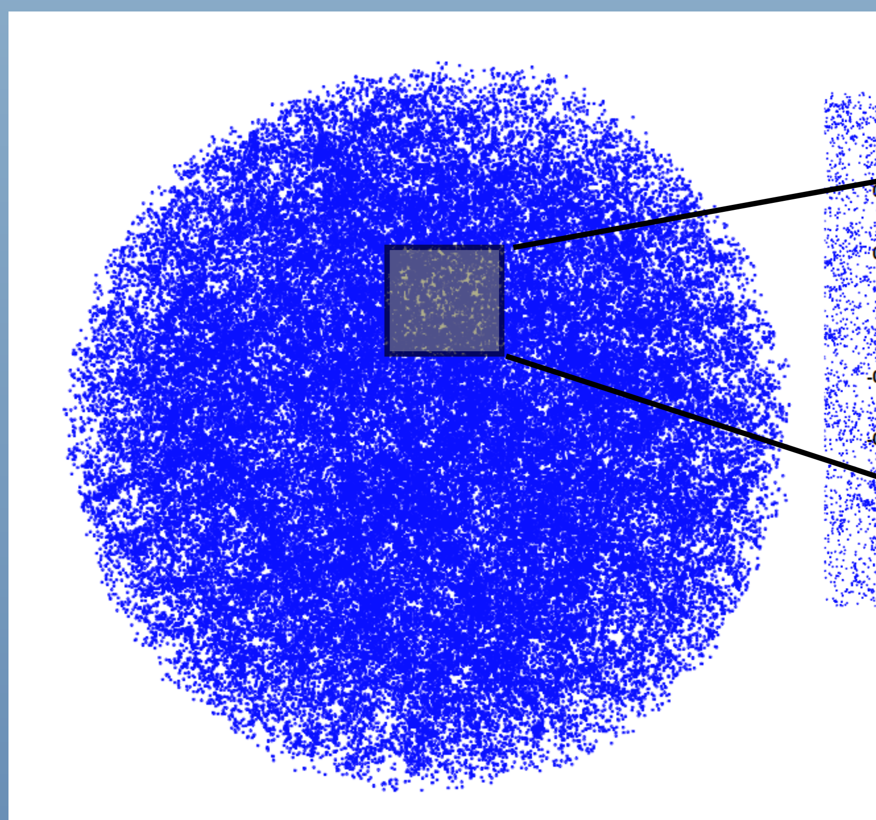
Fragmentation of self-gravitating fluids

- http://www.freefem.org

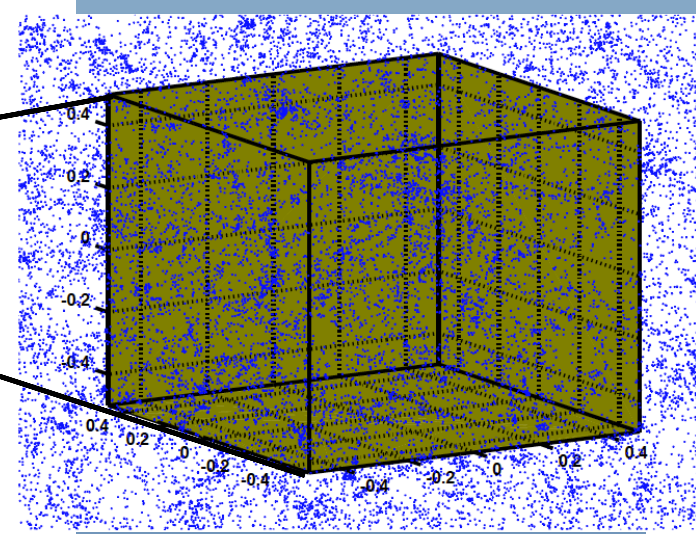


Procedure - avoid boundaries

Dorval et al. 2016 MNRAS, 2017

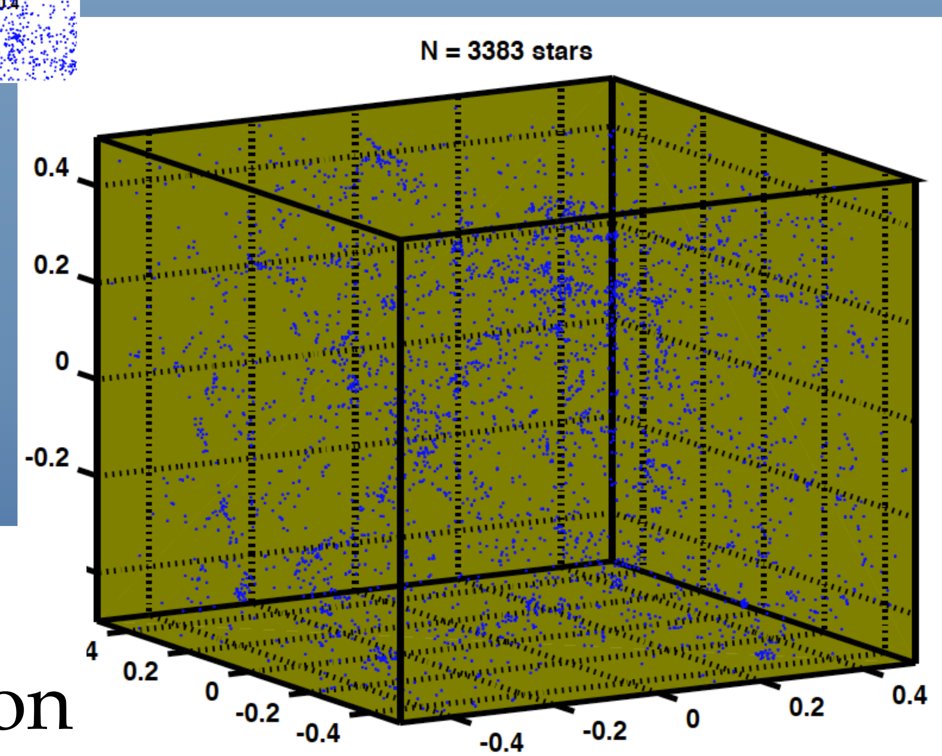


N ~ 100k stars



N ~ 3k
Rich open
cluster

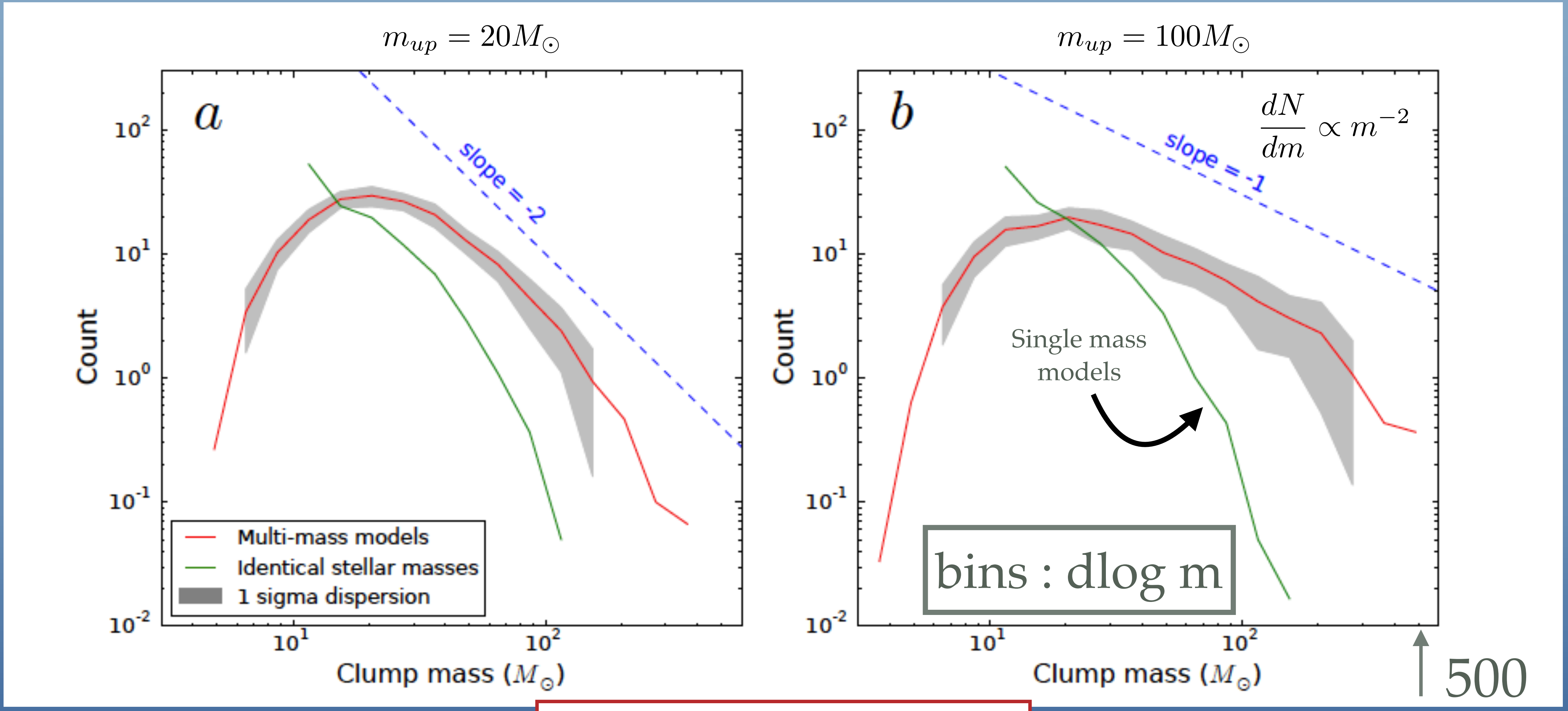
Extract
subset of
stars
clumps: MST technique



- Draw stars from IMF (Salpeter)
- Form binaries with primary-★ correlation

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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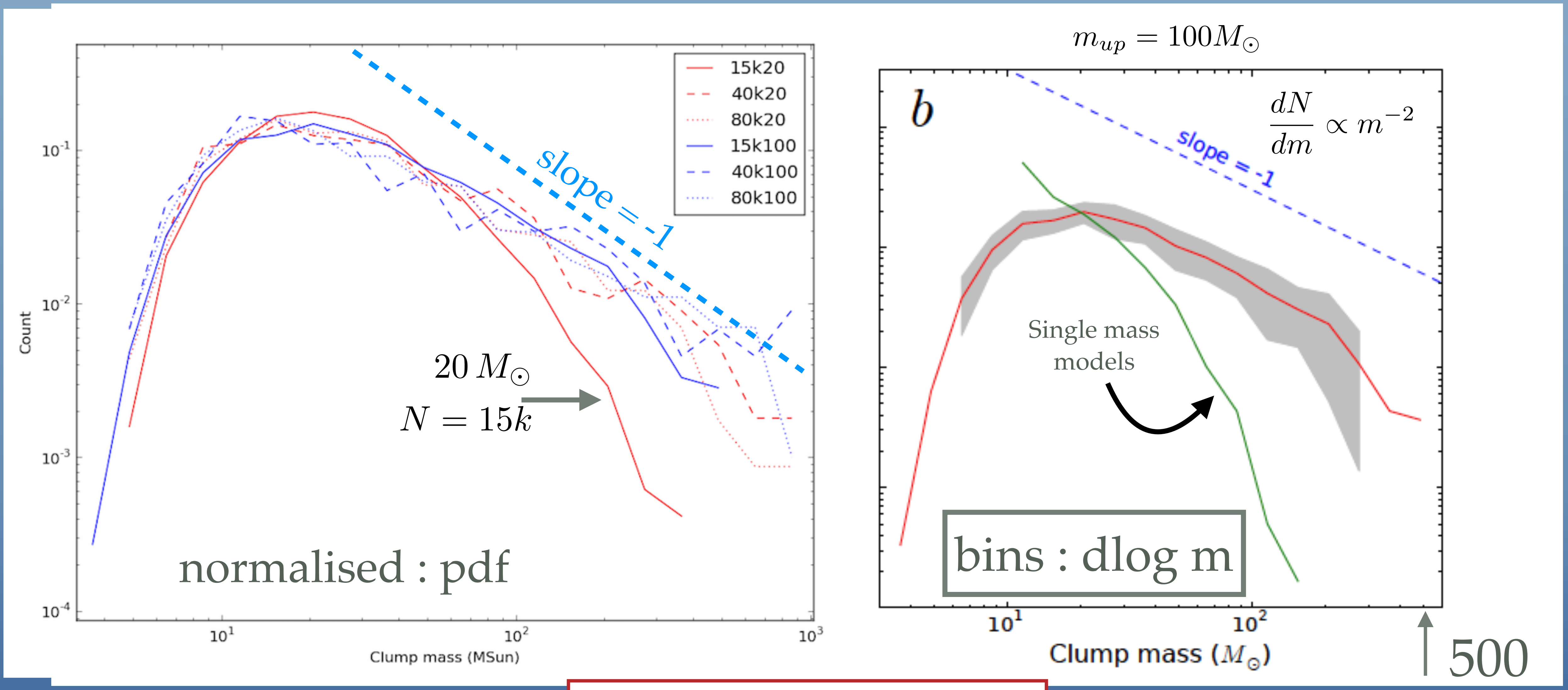
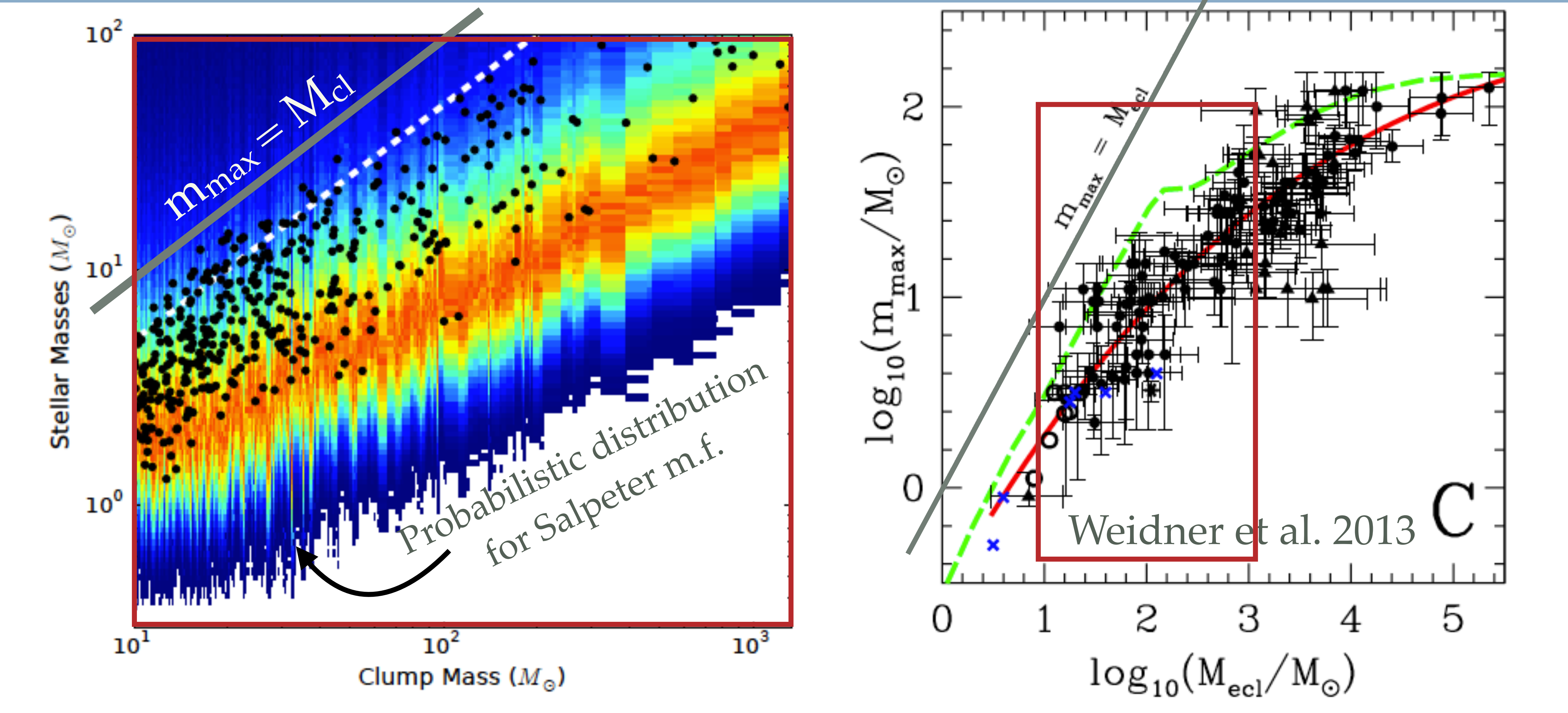


Runs with N = 15k

Stellar clumps:

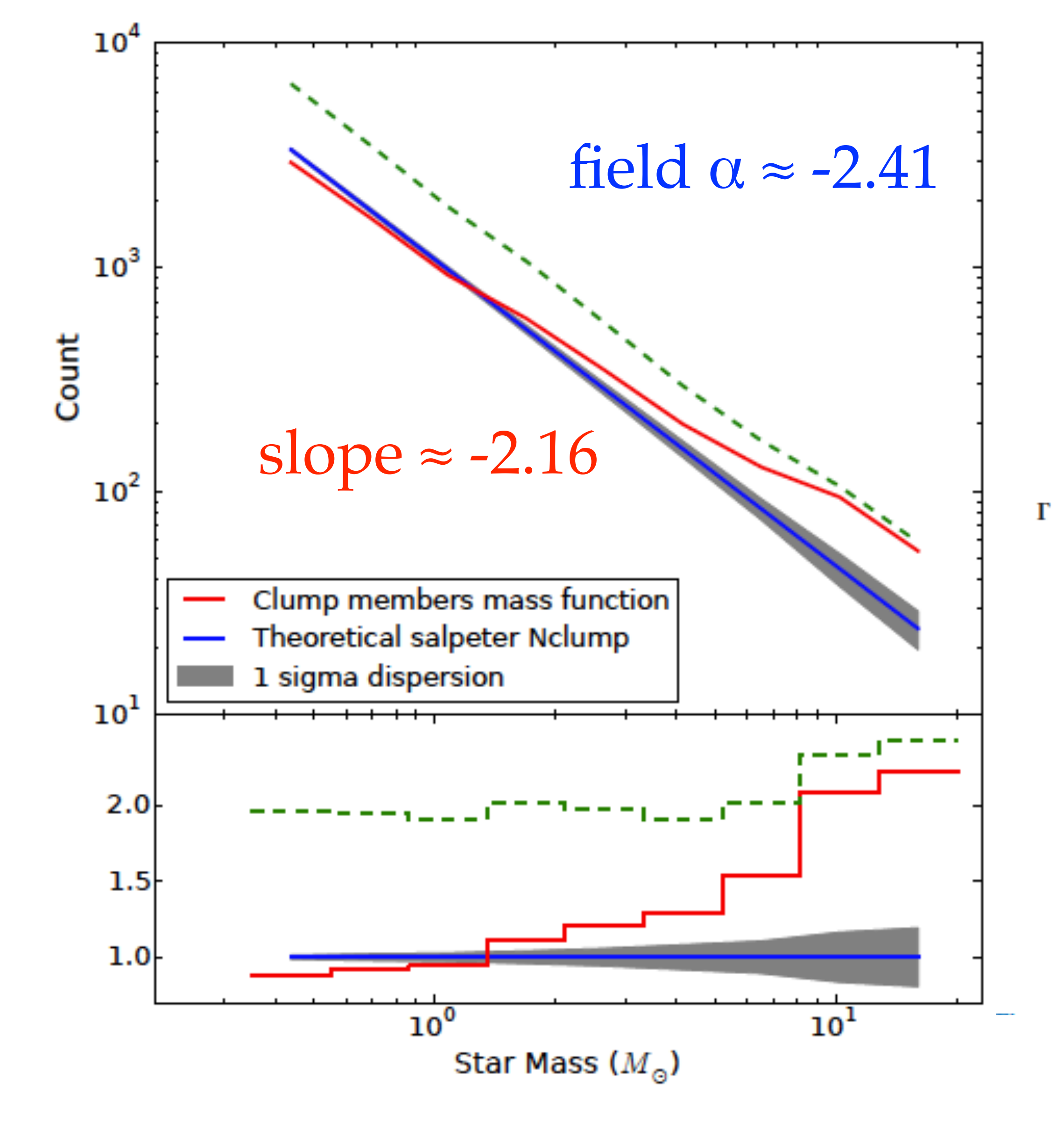
correlation with max{$m_\star$}

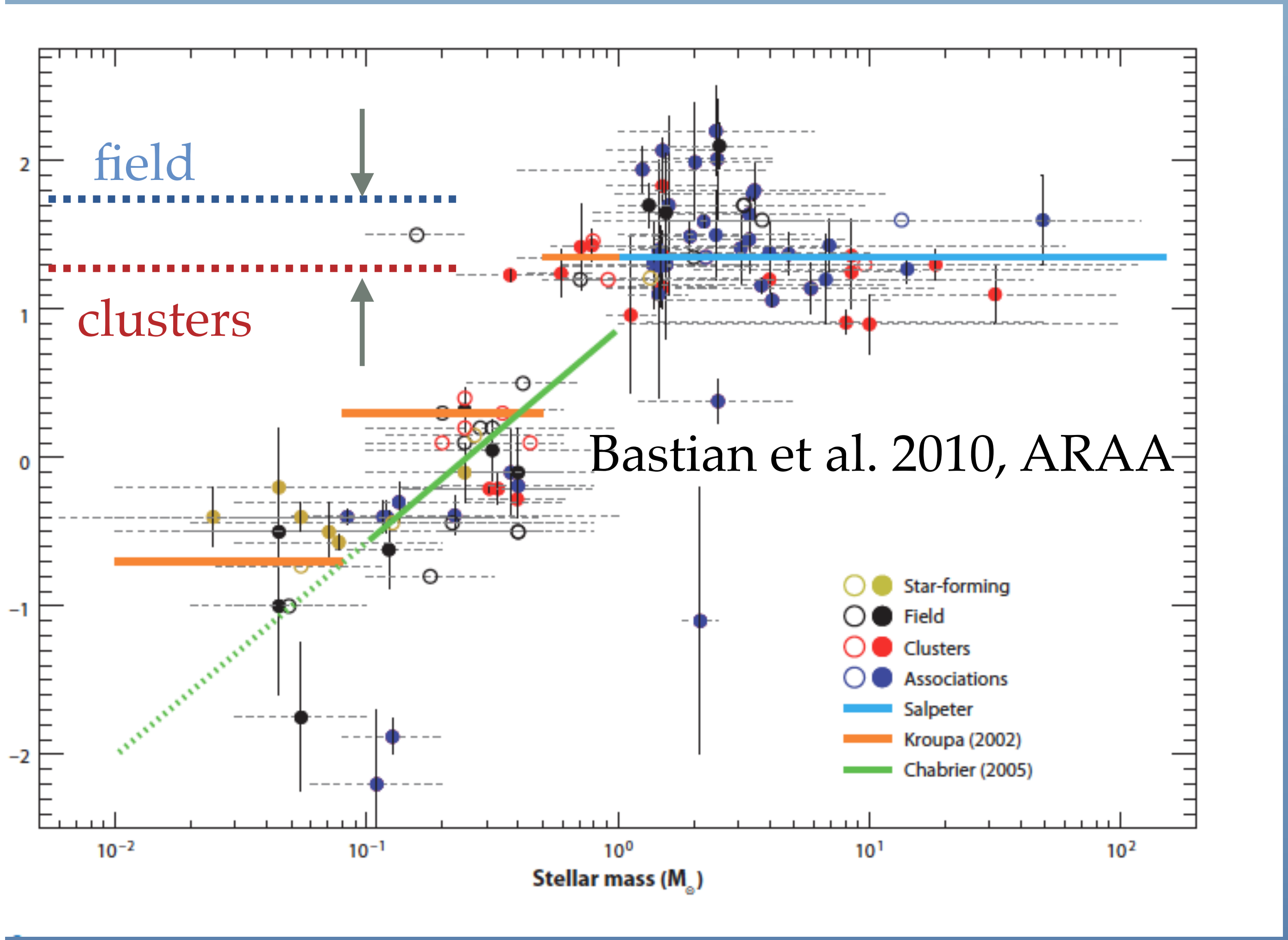


:: white dash: prediction from «radius of influence» of most massive star in clump

Stellar clumps: 50% of all stars

top-heavy, segregated ..





:: blue / grey : Salpeter (ensemble averaging)

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Maschberger et al. 2010

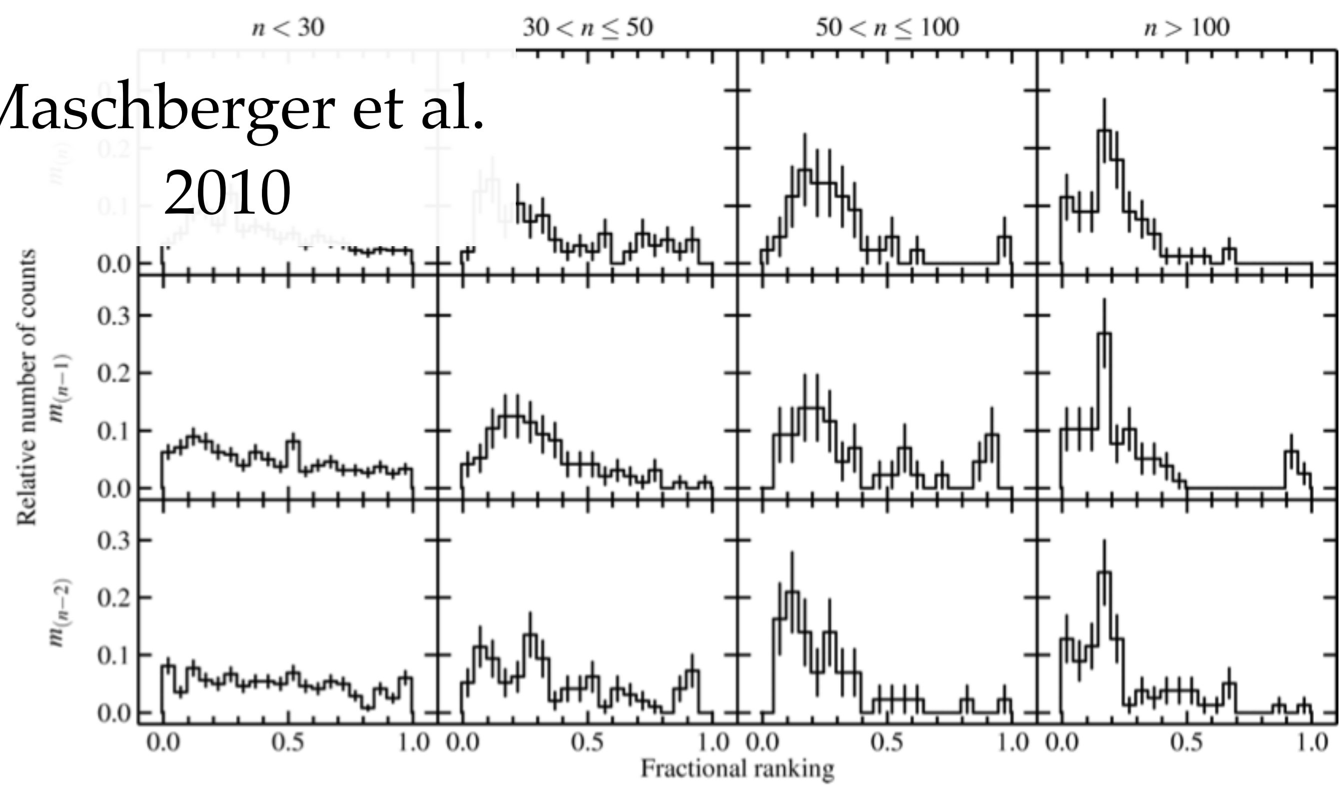

Figure 13. Histogram of the fractional radial ranking of the most massive (top), second most massive (middle) and third most massive (bottom) sink pa
its associated subcluster, split up by the number of sinks in the subcluster. The composite population of the 10^4 $M_\odot$ calculation is used to make the hist
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
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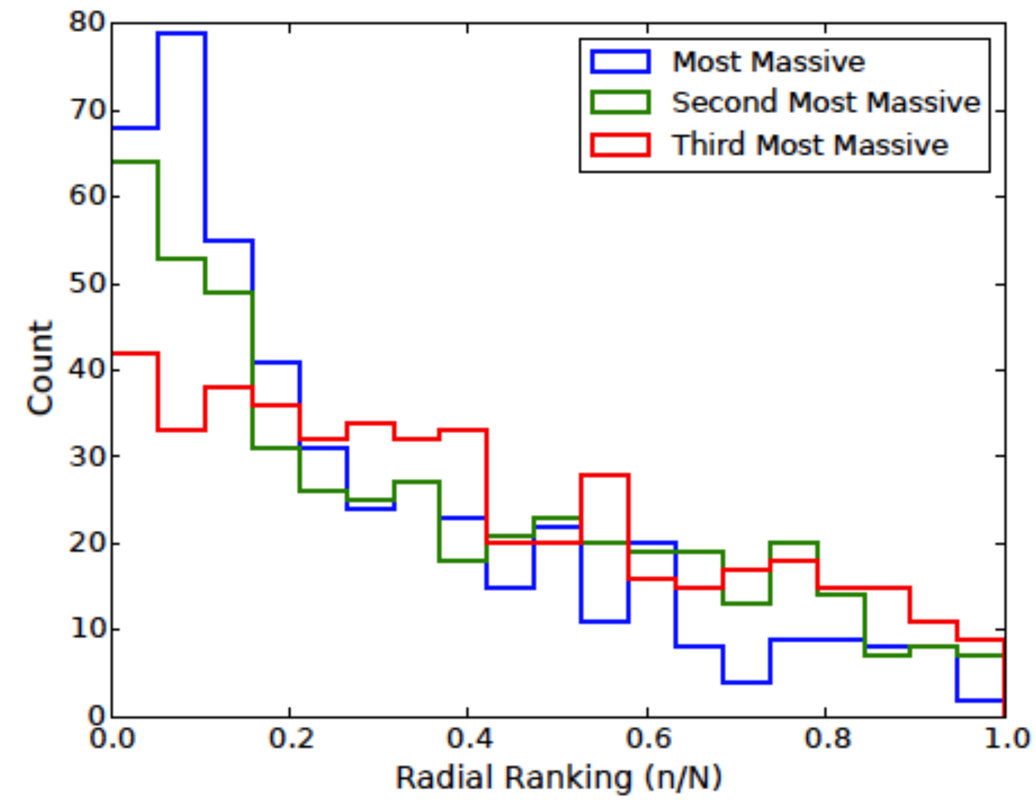

Figure 10. Radial ranking of first, second and third most massive star in each clump for a model with N = 40 000 stars (R40h100).

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

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

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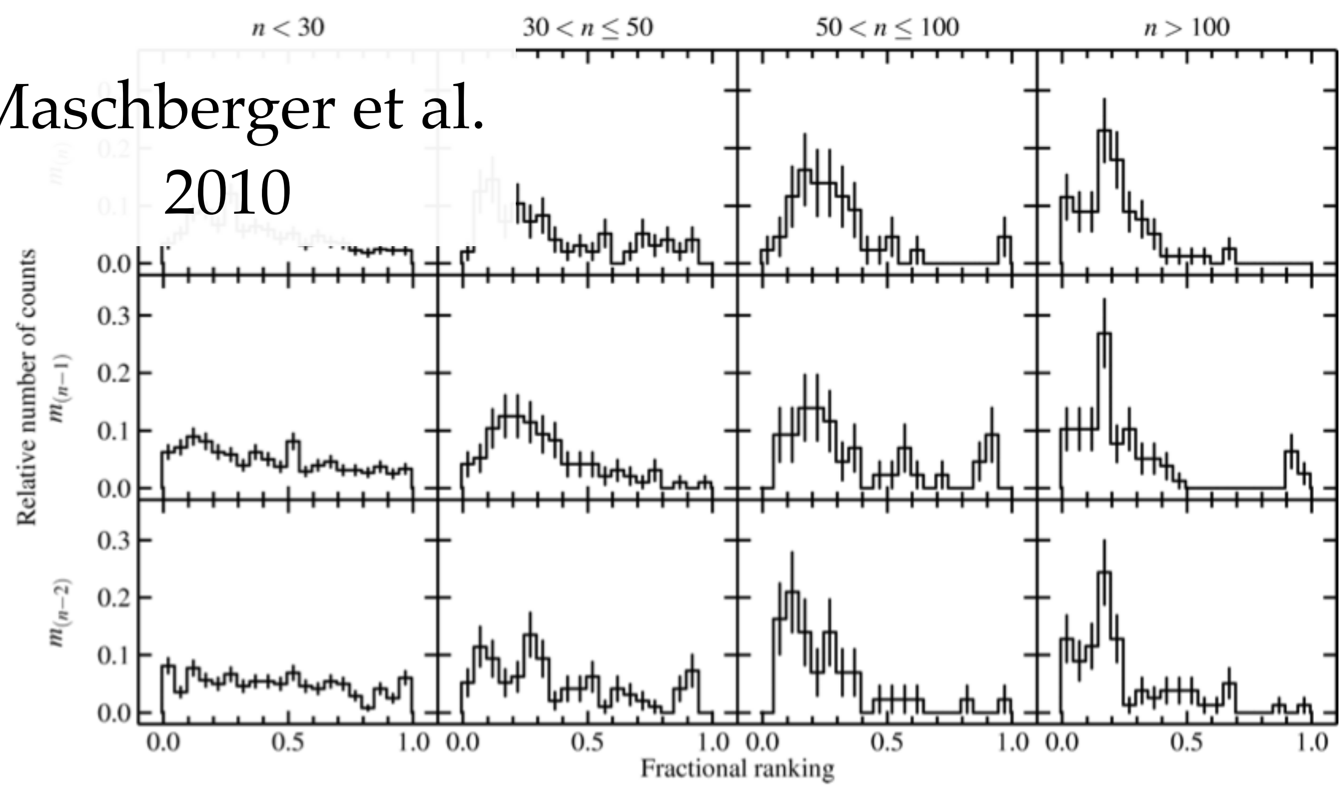

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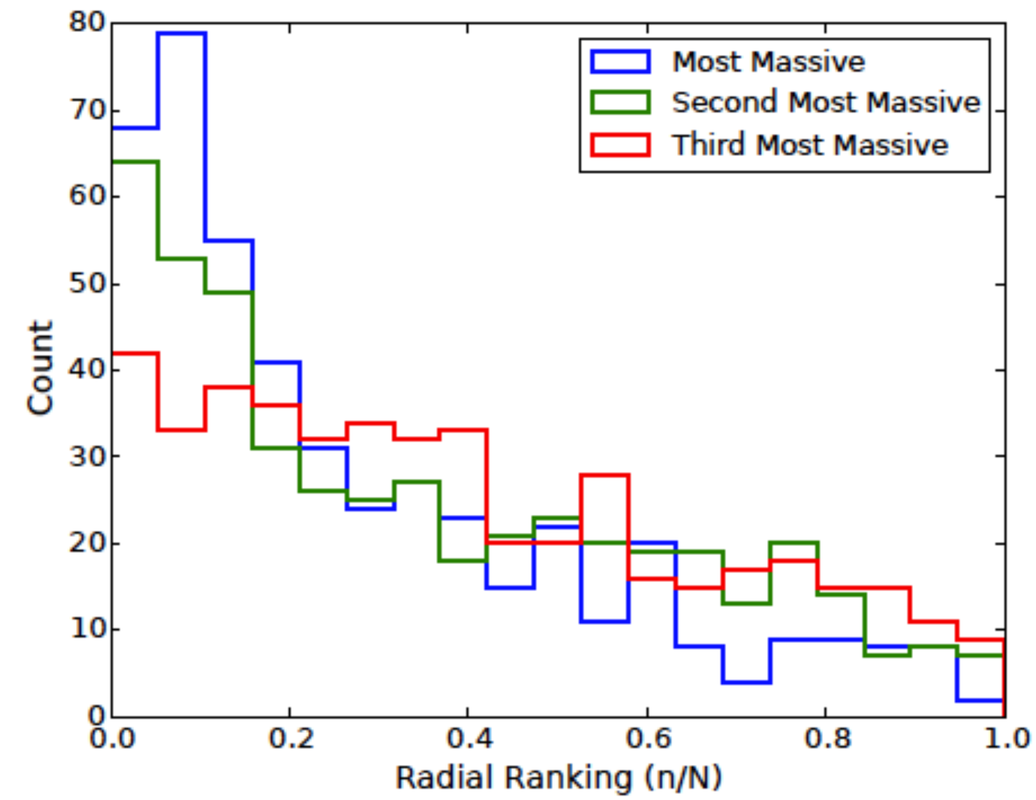

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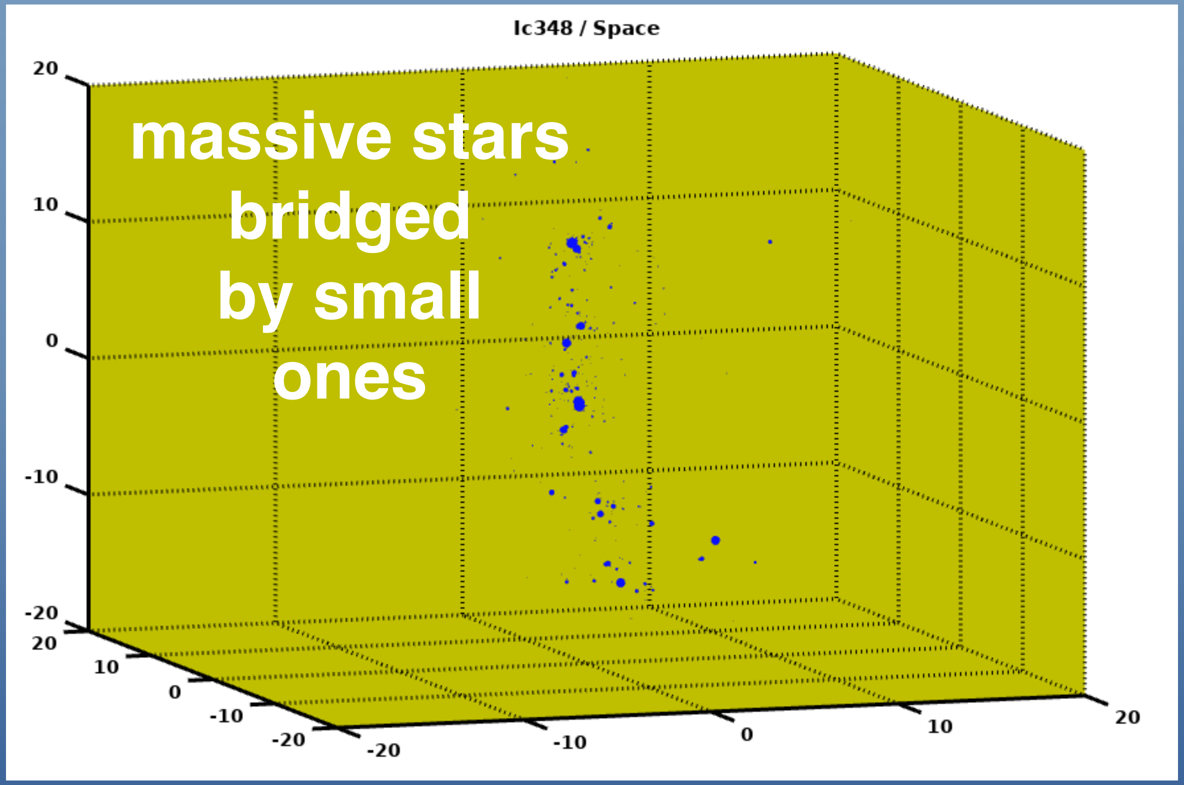
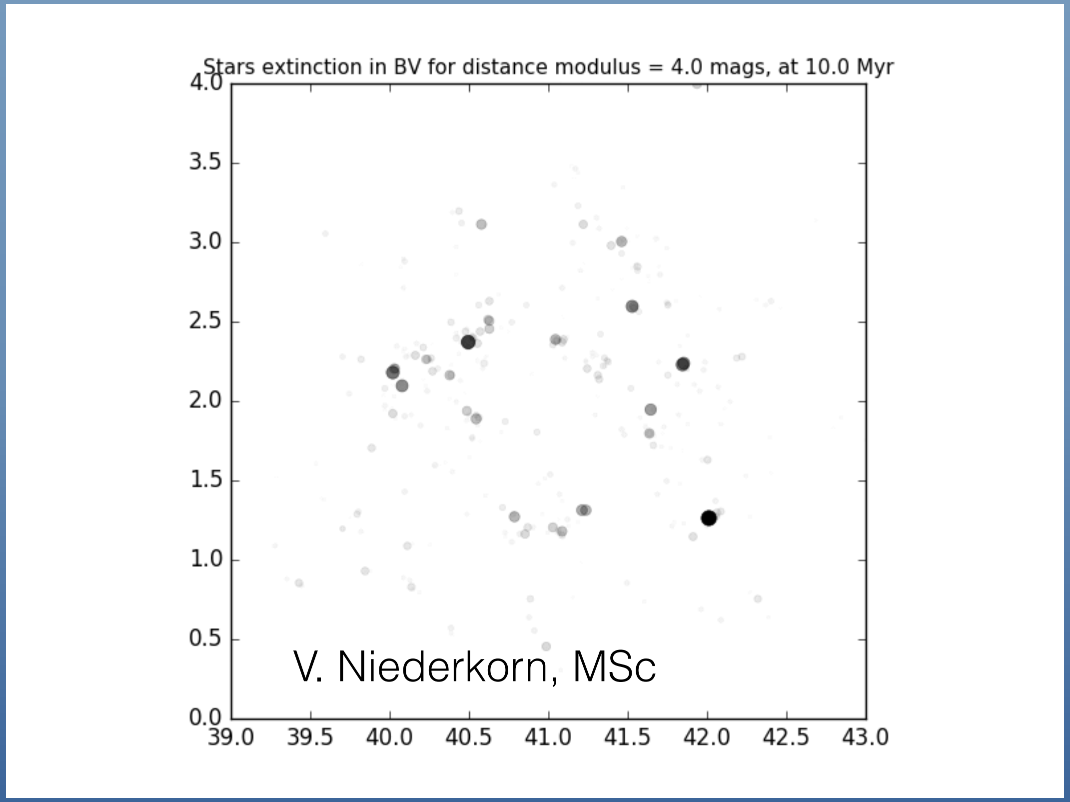
Exploring morphology using the Minimum Spanning Tree approach

- Morphology : apparent vs real .. selection, extinction
- Use the Pan-Starrs 1 extinction map (Green et al. 2015, ..)
- Set up a clump with N ~ 400 stars (e.g. Ic348)
- Photometry, bolometric corrections: set the object at different DM





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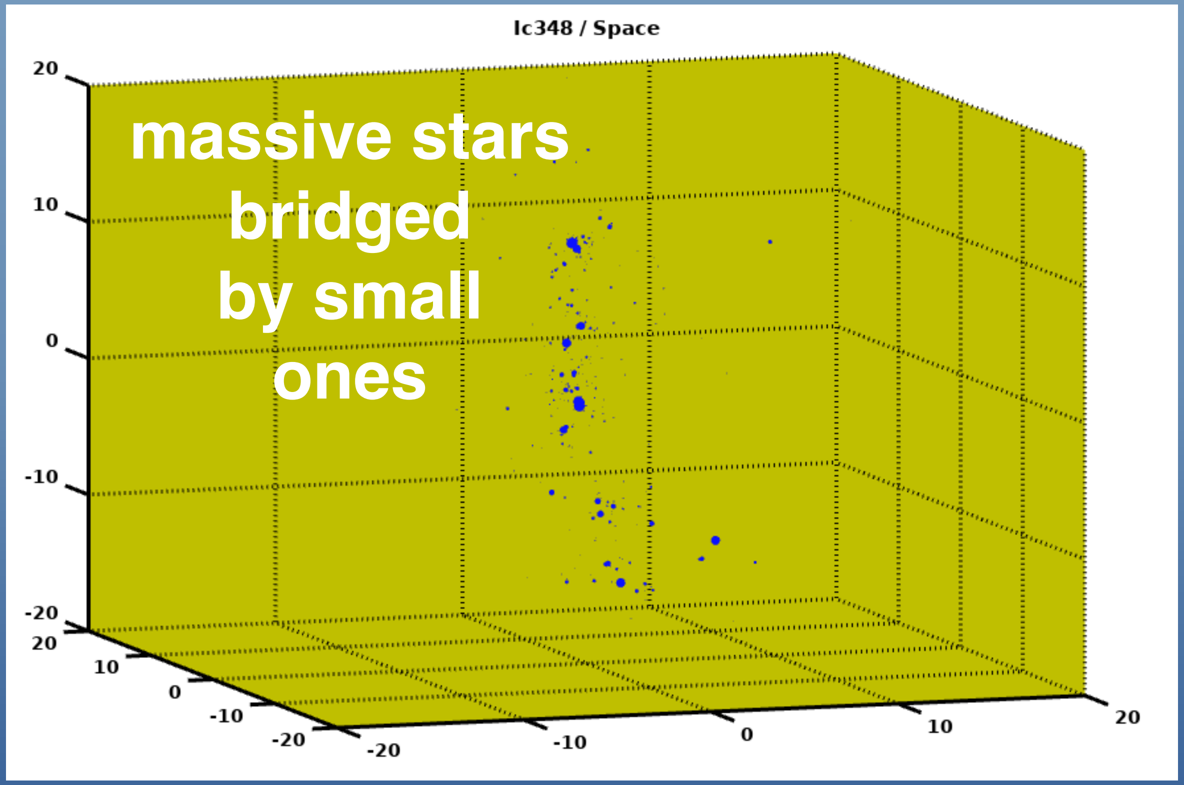
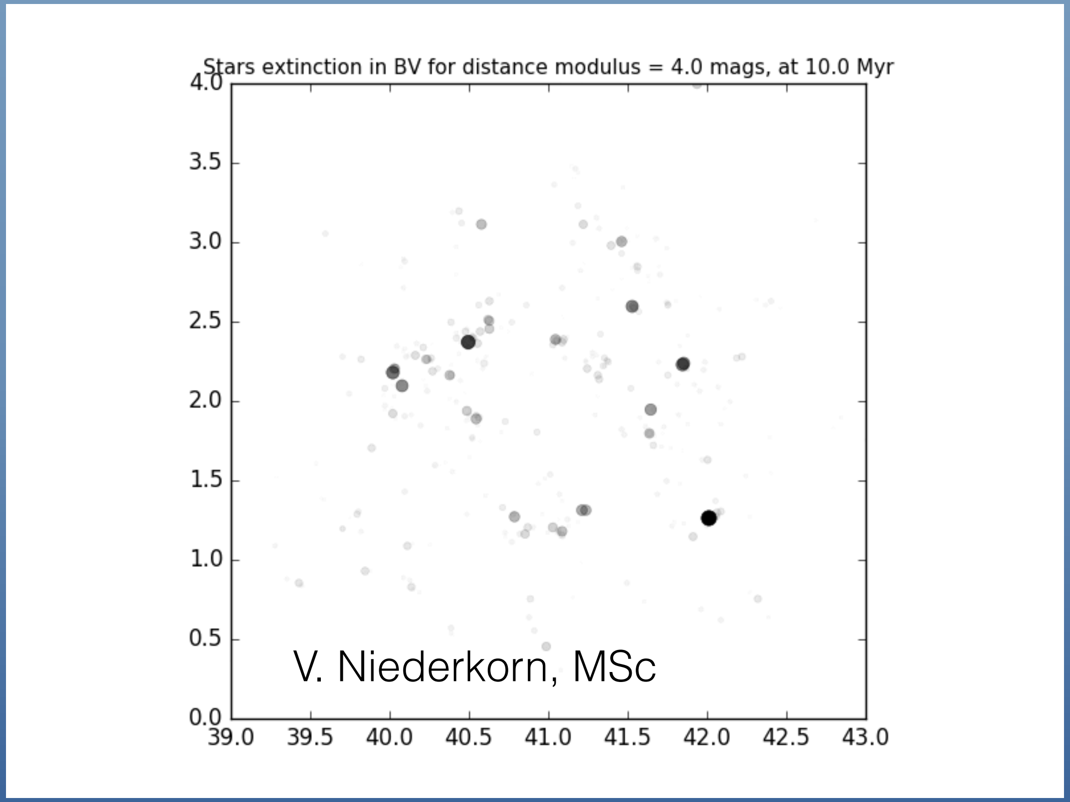
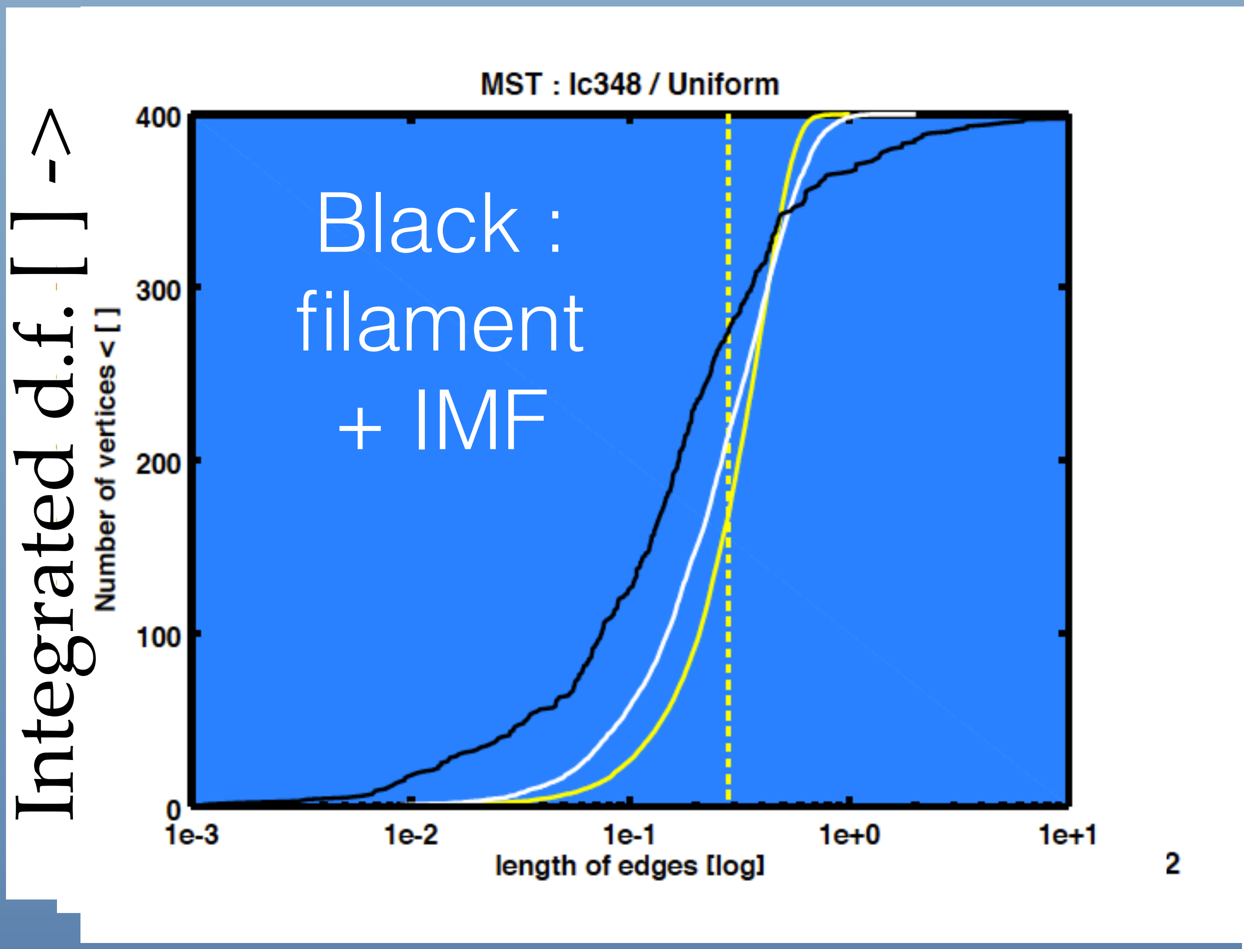


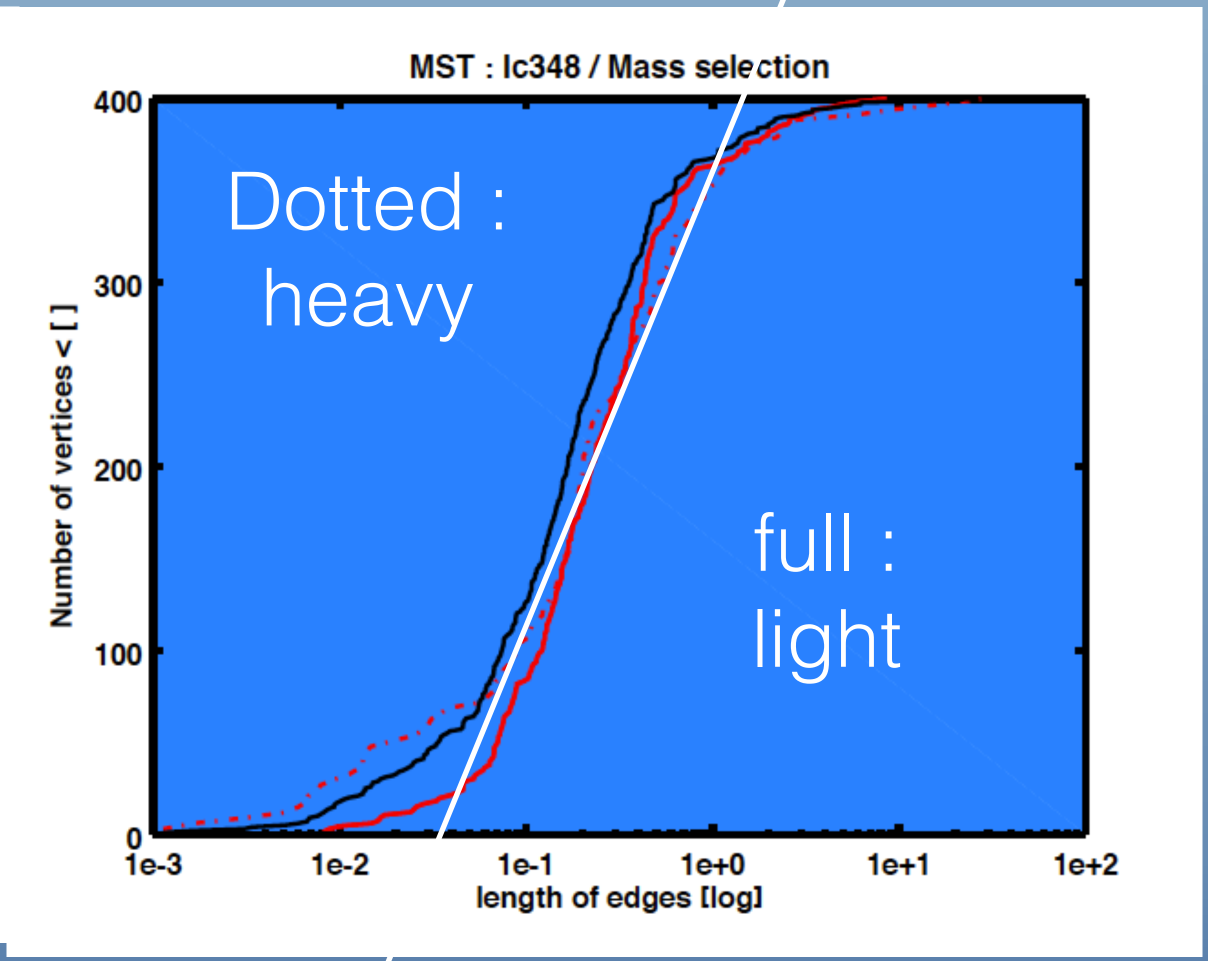


Exploring morphology using the Minimum Spanning Tree, all member stars

Different projection angles

Selection by mass / renormalized



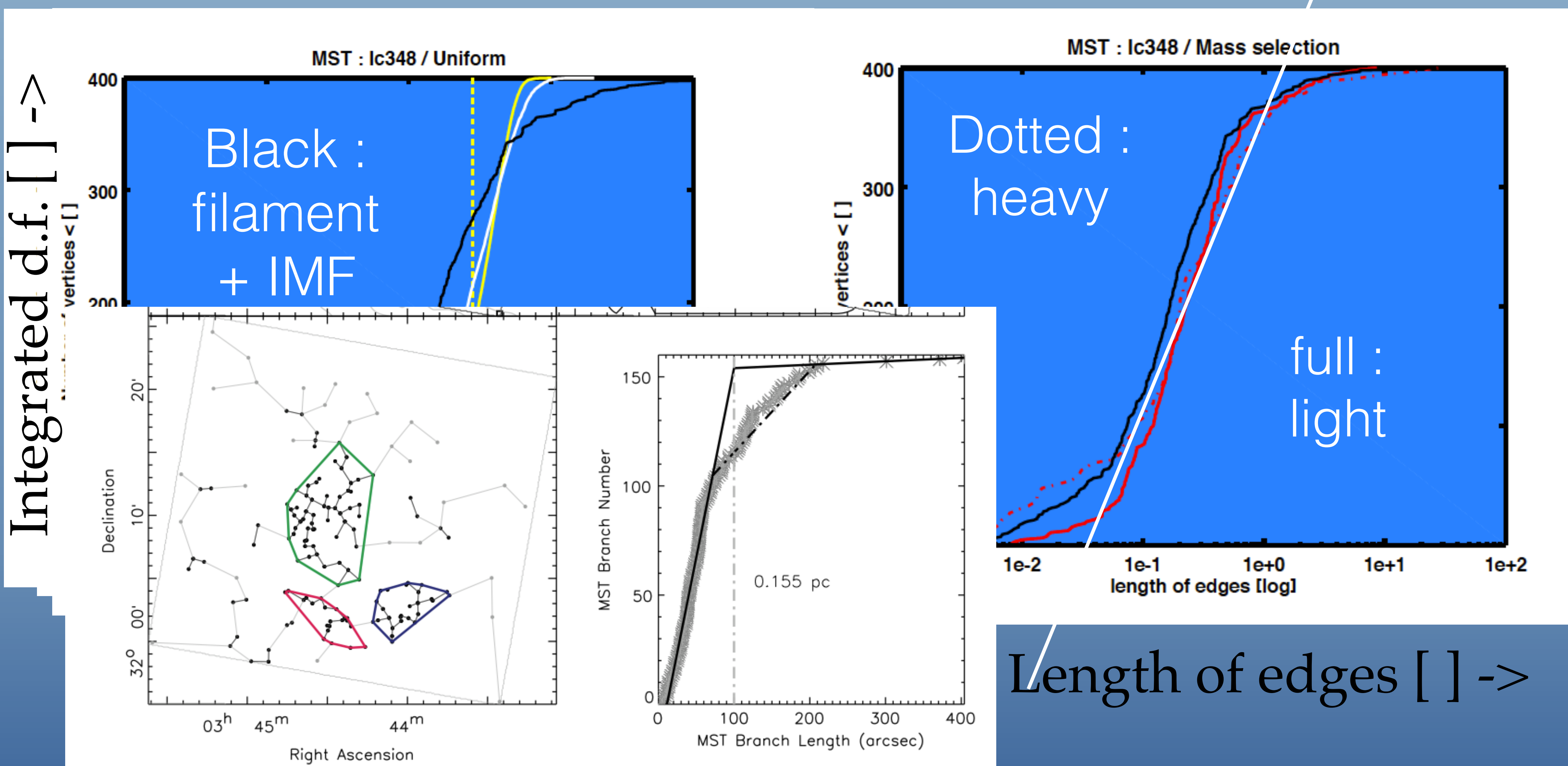


Length of edges [ ] ->

Exploring morphology using the Minimum Spanning Tree, all member stars

Different projection angles

Selection by mass / renormalized



Guthermut et al. 2009, ApJS

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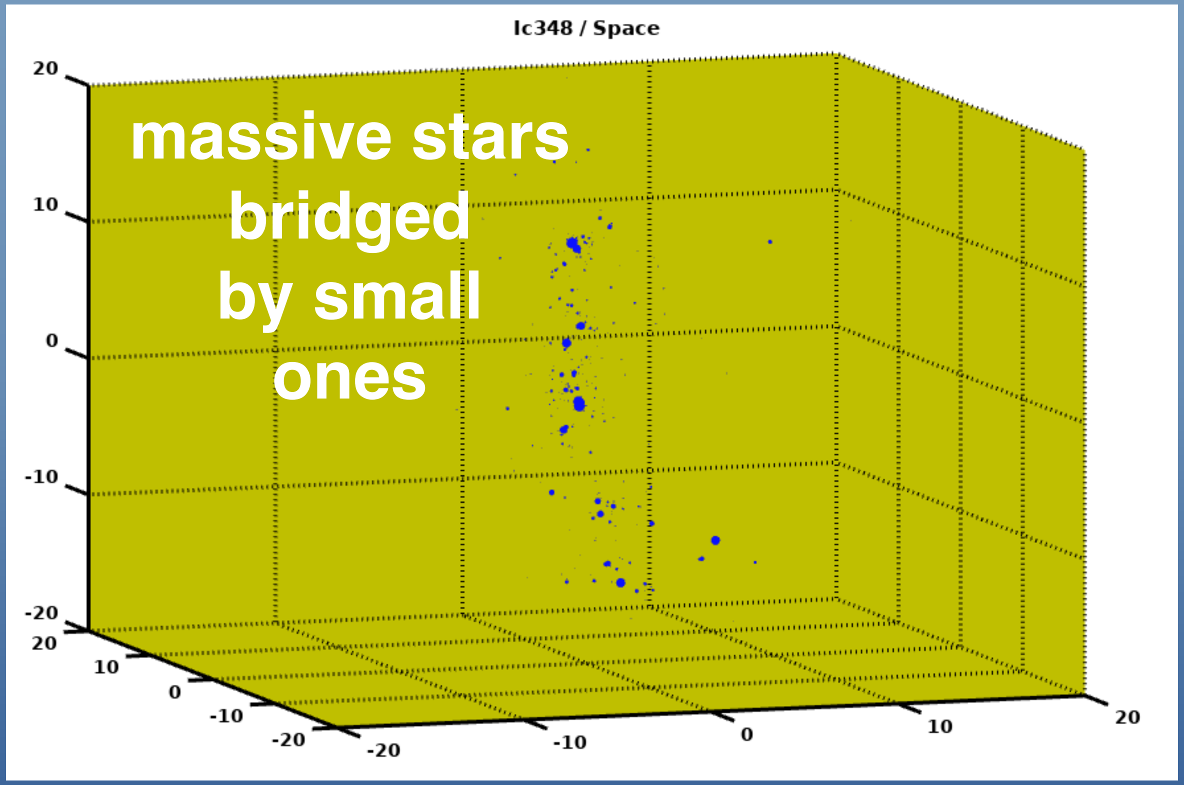
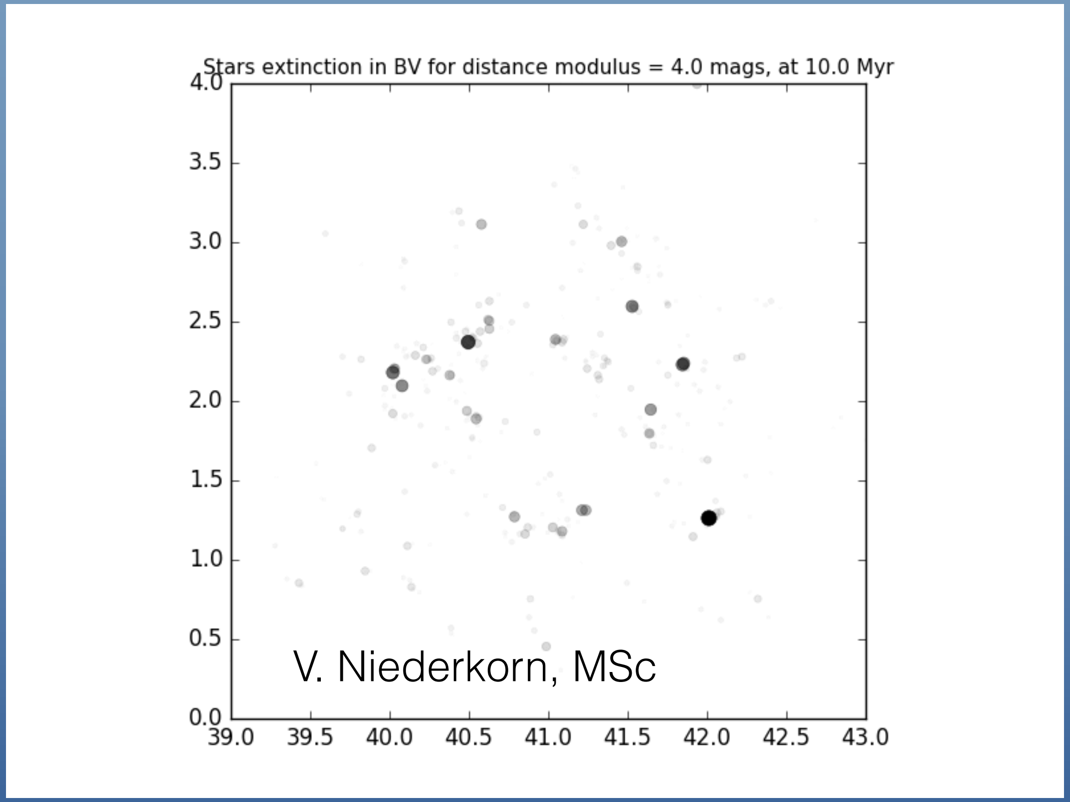
- Explore the impact of extinction on the appearance of the skeleton





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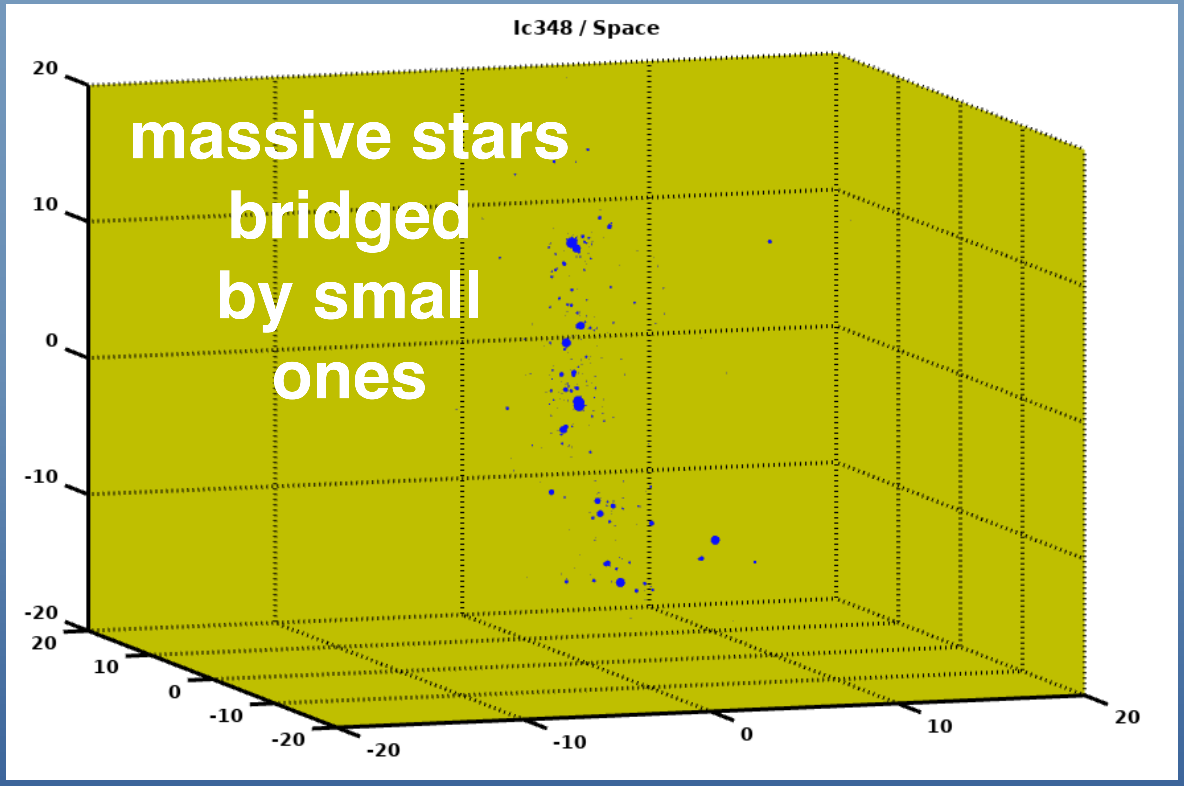
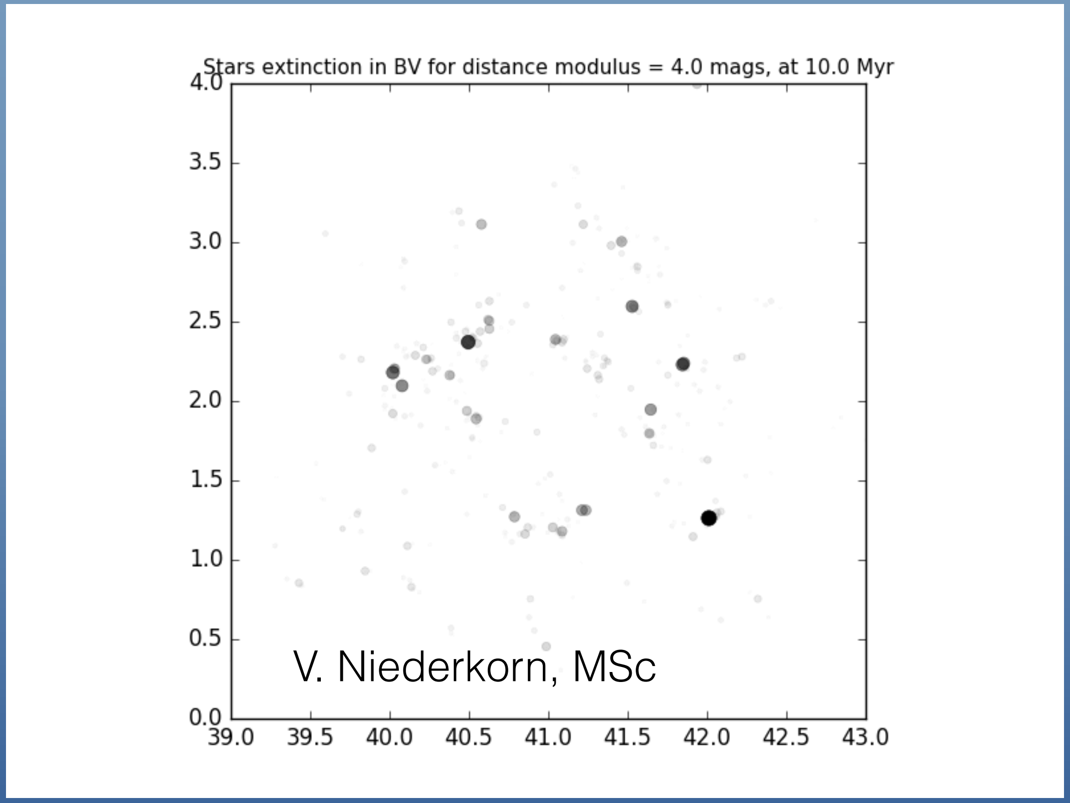
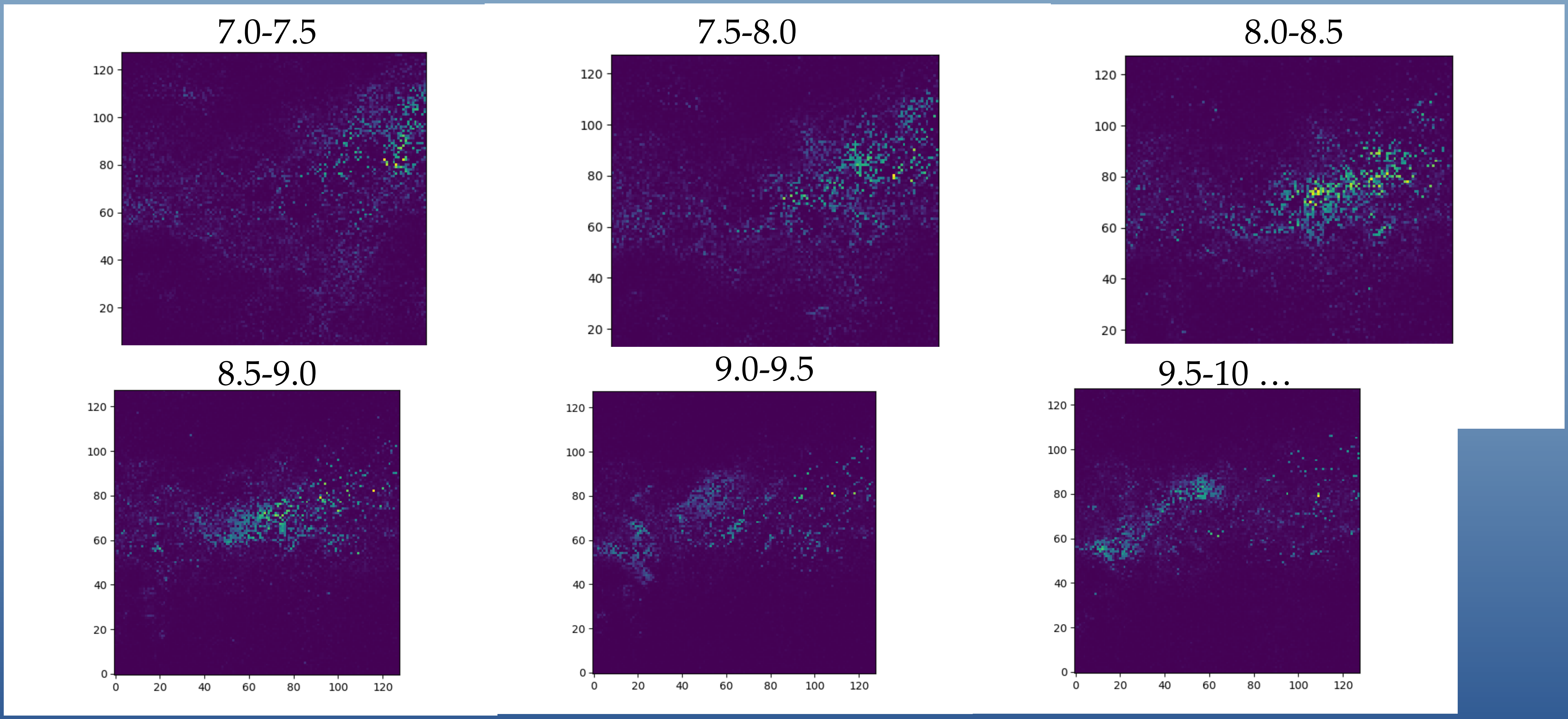




Exploring morphology using the Minimum Spanning Tree approach

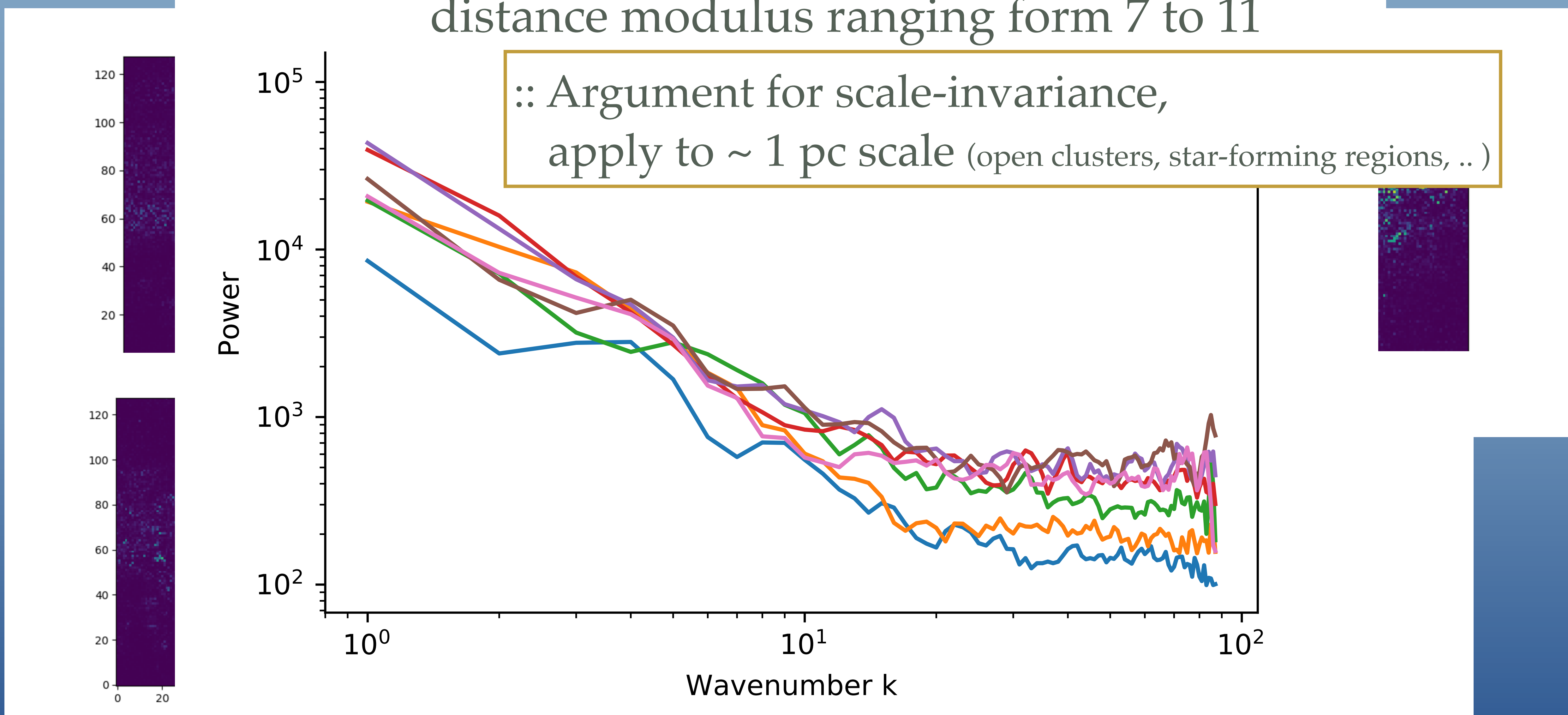
- Use the Pan-Starrs 1 extinction map (Green et al. 2015, ..)
- Set up maps at different distance scales (DM), same angular size



Exploring morphology using the <u>Minimum Spanning Tree approach</u>

- Use the Pan-Starrs 1 extinction map (Green et al. 2015, ..)
- Set … ular size

FFT power spectrum : fixed direction on the sky, distance modulus ranging form 7 to 11



Exploring morphology using the Minimum Spanning Tree approach

- Morphology : apparent vs real .. selection, extinction
- Use the Pan-Starrs 1 extinction map (Green et al. 2015, ..)
- Extinction (= distance effect) : shift on MST statistics
- Set up a clump with N ~ 400 stars (e.g. Ic348)
- K-band extinction / bolometric correction : ± 20% completeness @ $M_K = 21$

Exploring morphology using the Minimum Spanning Tree approach

- Morphology : ... inction
- Use the Pan-St ... al. 2015, ..)
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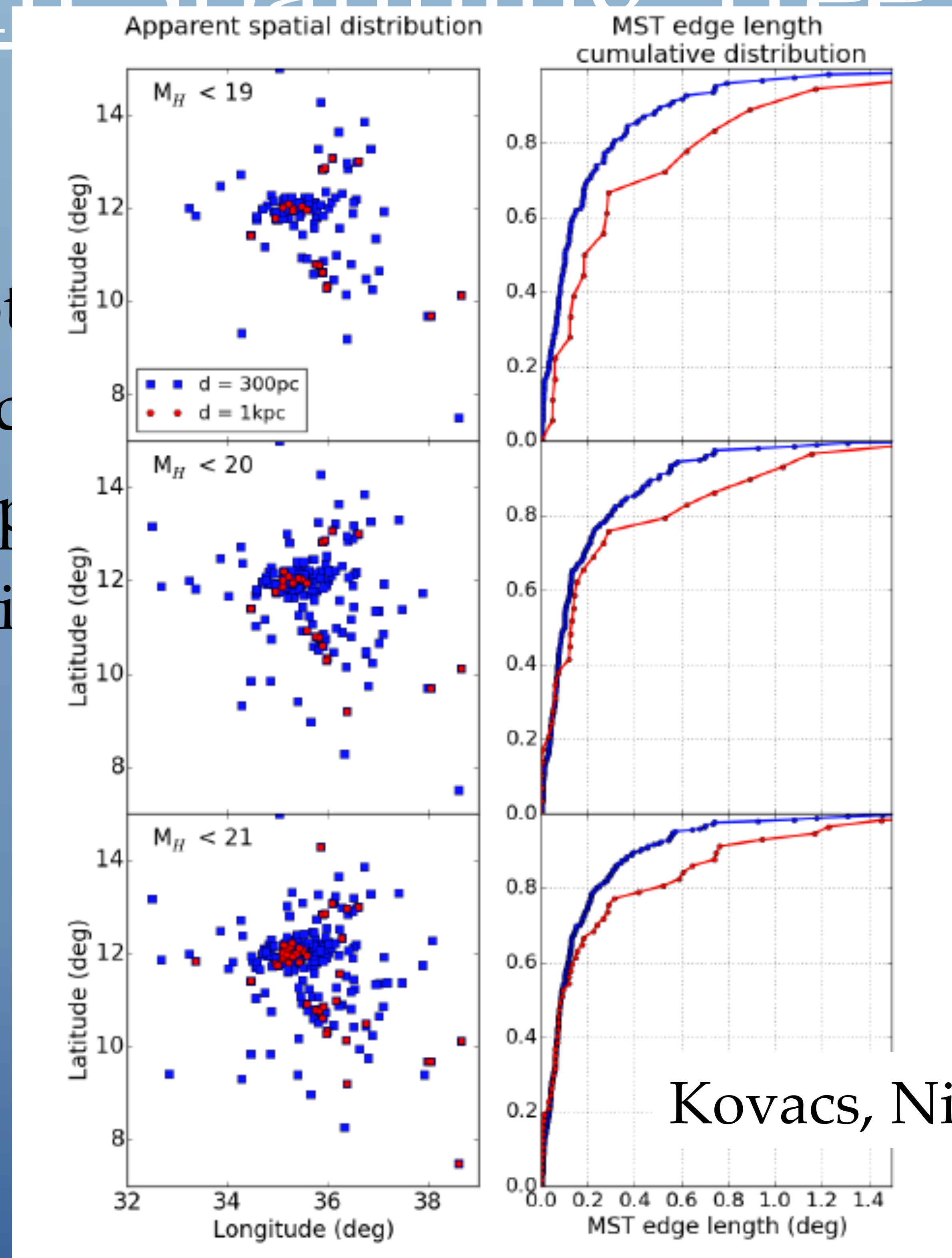
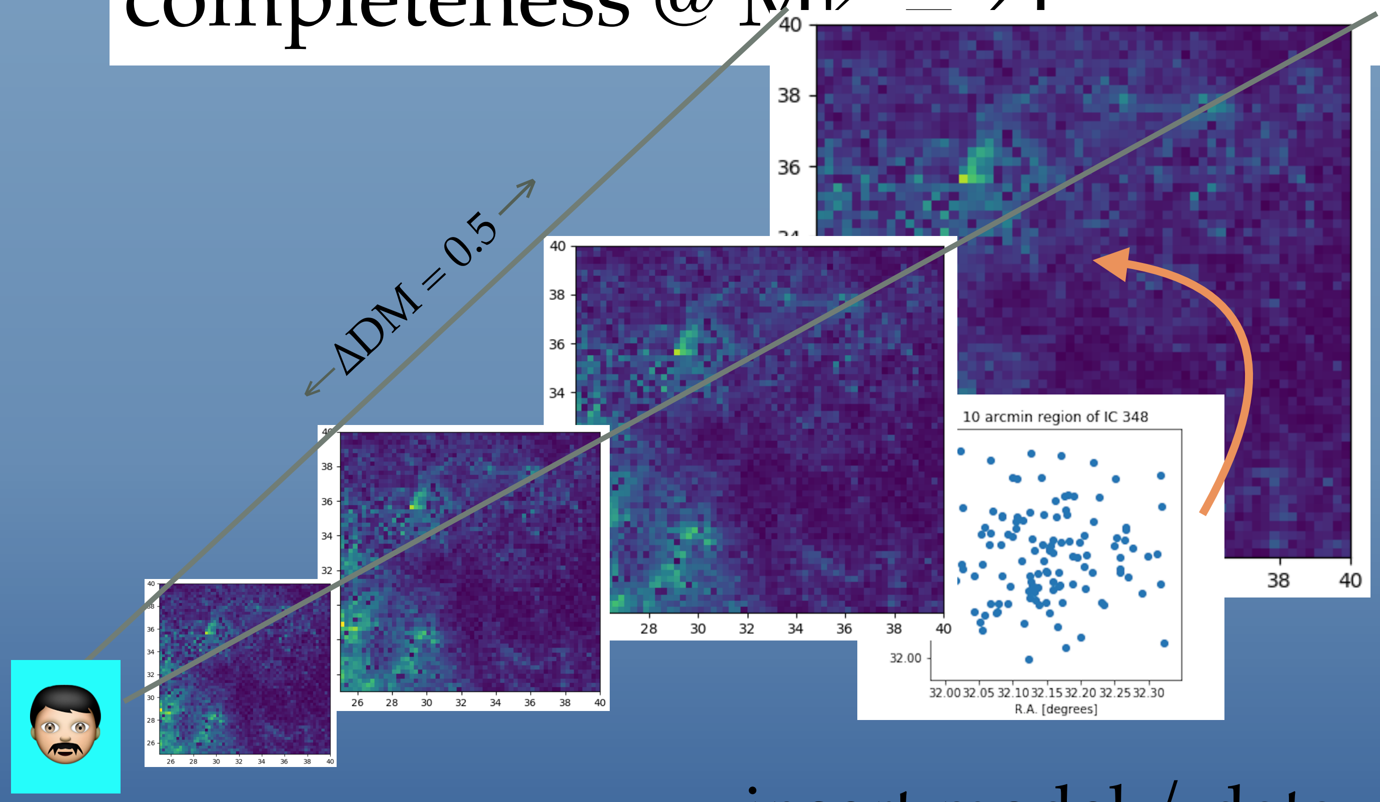
- Set up a clump
- K-band extincti ... % completeness @ $M_K = 21$



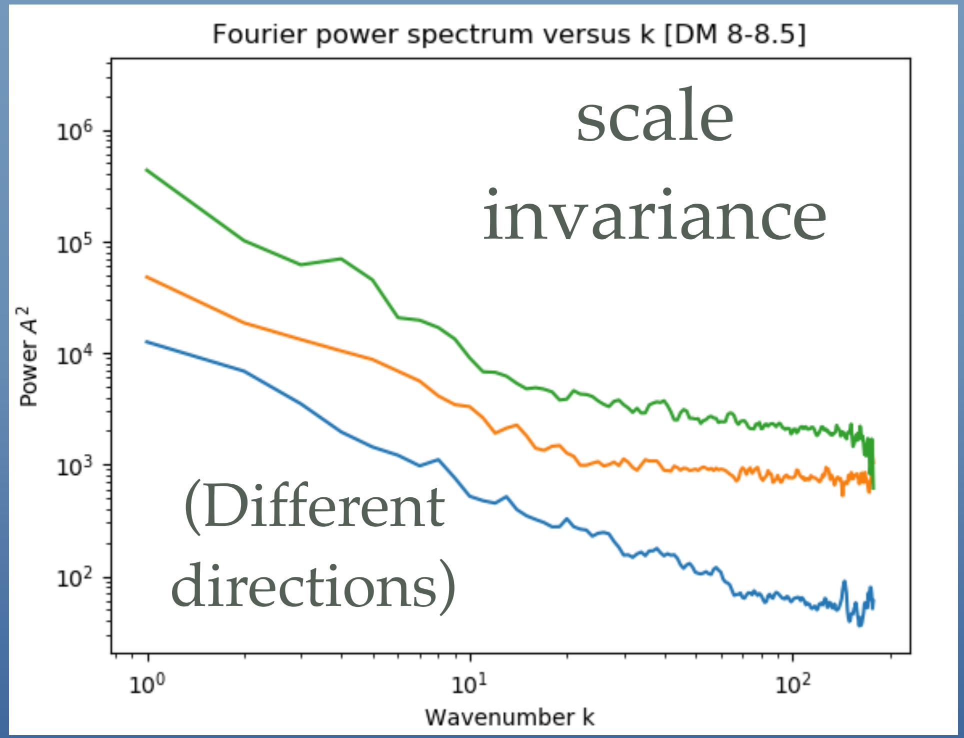
Kovacs, Niederkorn, Dorval, ..

Exploring morphology using the
Minimum Spanning Tree approach

- Morphology : apparent vs real .. selection, extinction
- Use the Pan-Starrs 1 extinction map (Green et al. 2015, ..)
- Fourier transform : phase mixing on ~ 1 pc scale in ~ 1 Myrs
- K-band extinction / bolometric correction : ± 20%
  completeness @ M_K = 21



insert model / data



Exploring morphology using the Minimum Spanning Tree approach

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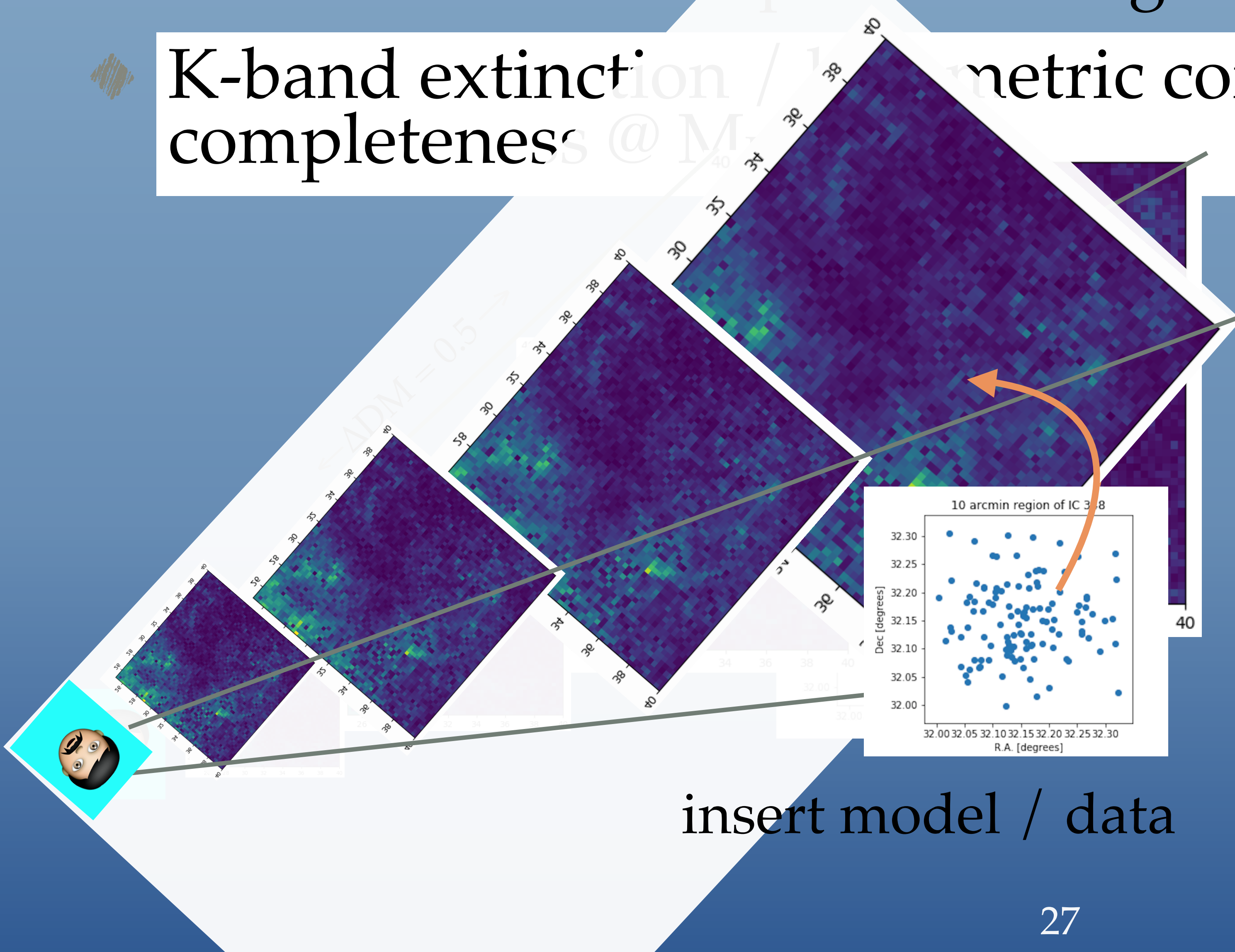
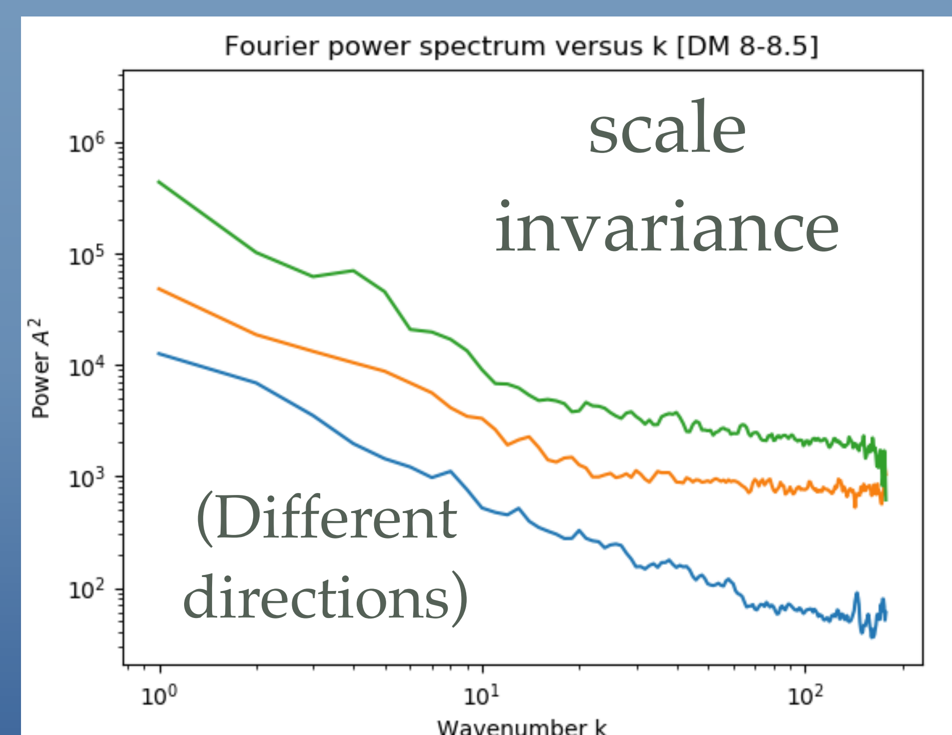


insert model / data



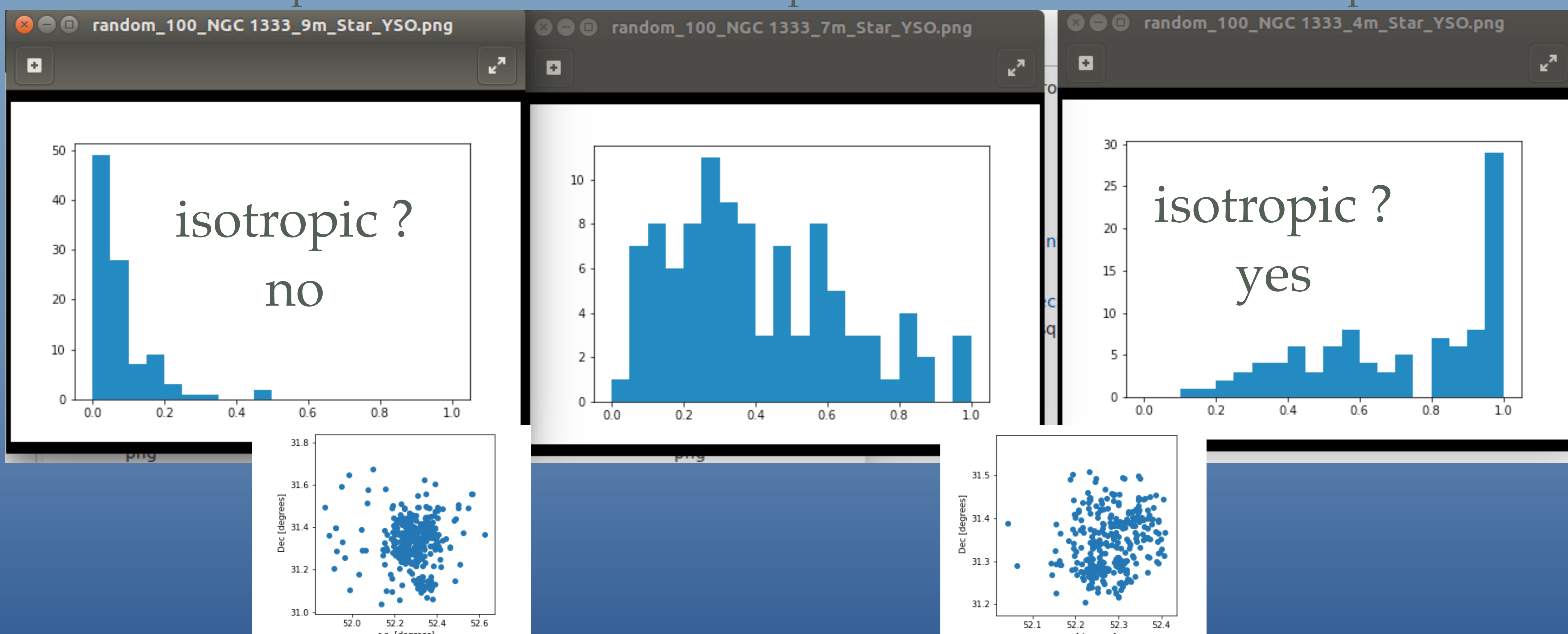
Exploring morphology using the Minimum Spanning Tree approach

.. or not :

example of an Kolmogorov-Smirnov statistics applied to NGC 1333.

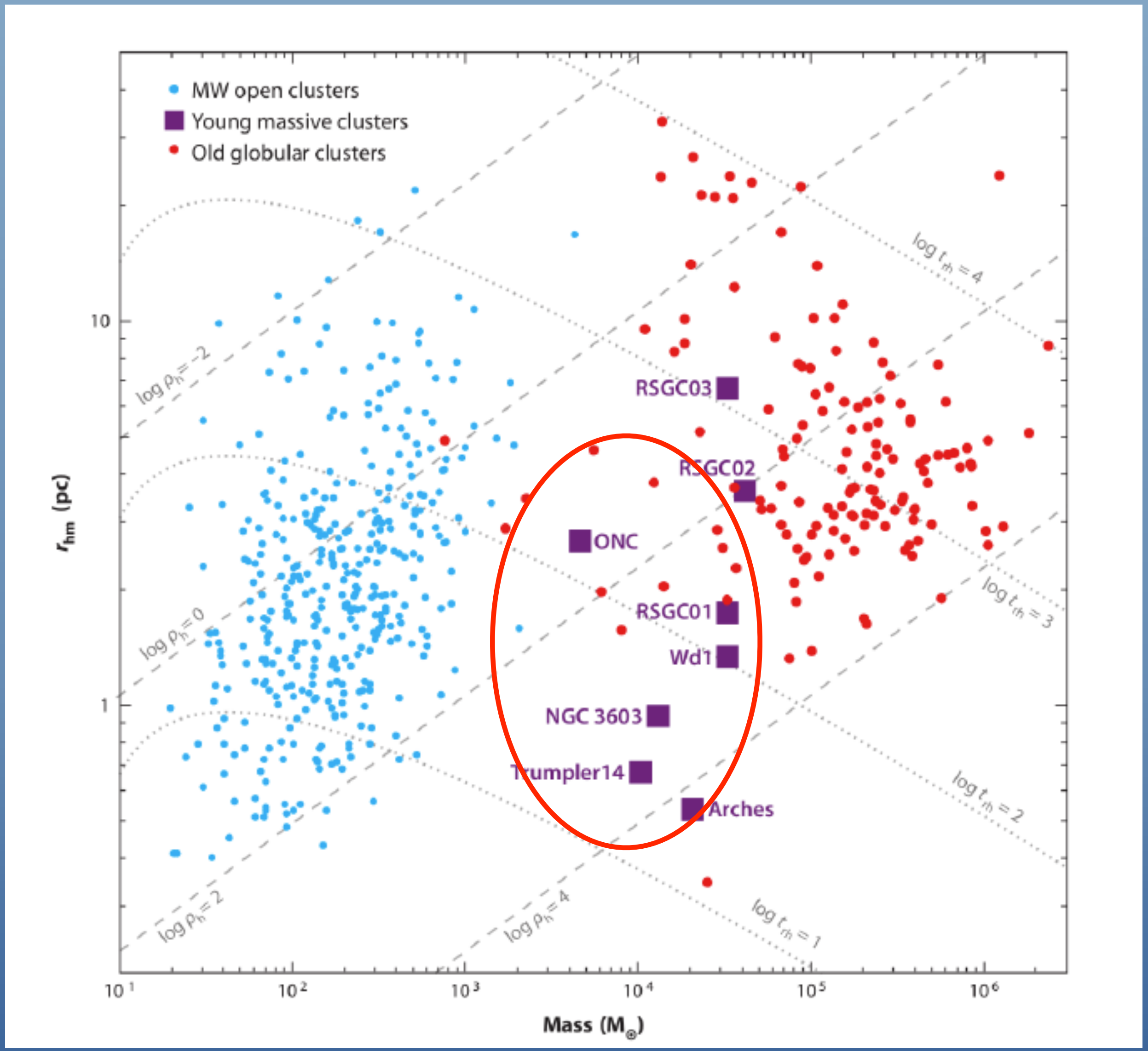
To do: compare actual clusters with embedded models

9 arcmin aperture 7 arcmin aperture 4 arcmin aperture



Exploring morphology
Orion (ONC), Wd1, ..

Possible multiple pops in ONC (de Marchi et al. 2017)
Un-relaxed embedded cores (Forster et al. 2015)



Integrated binary d.f. F(-E):
dynamical evolution, heating, disruption

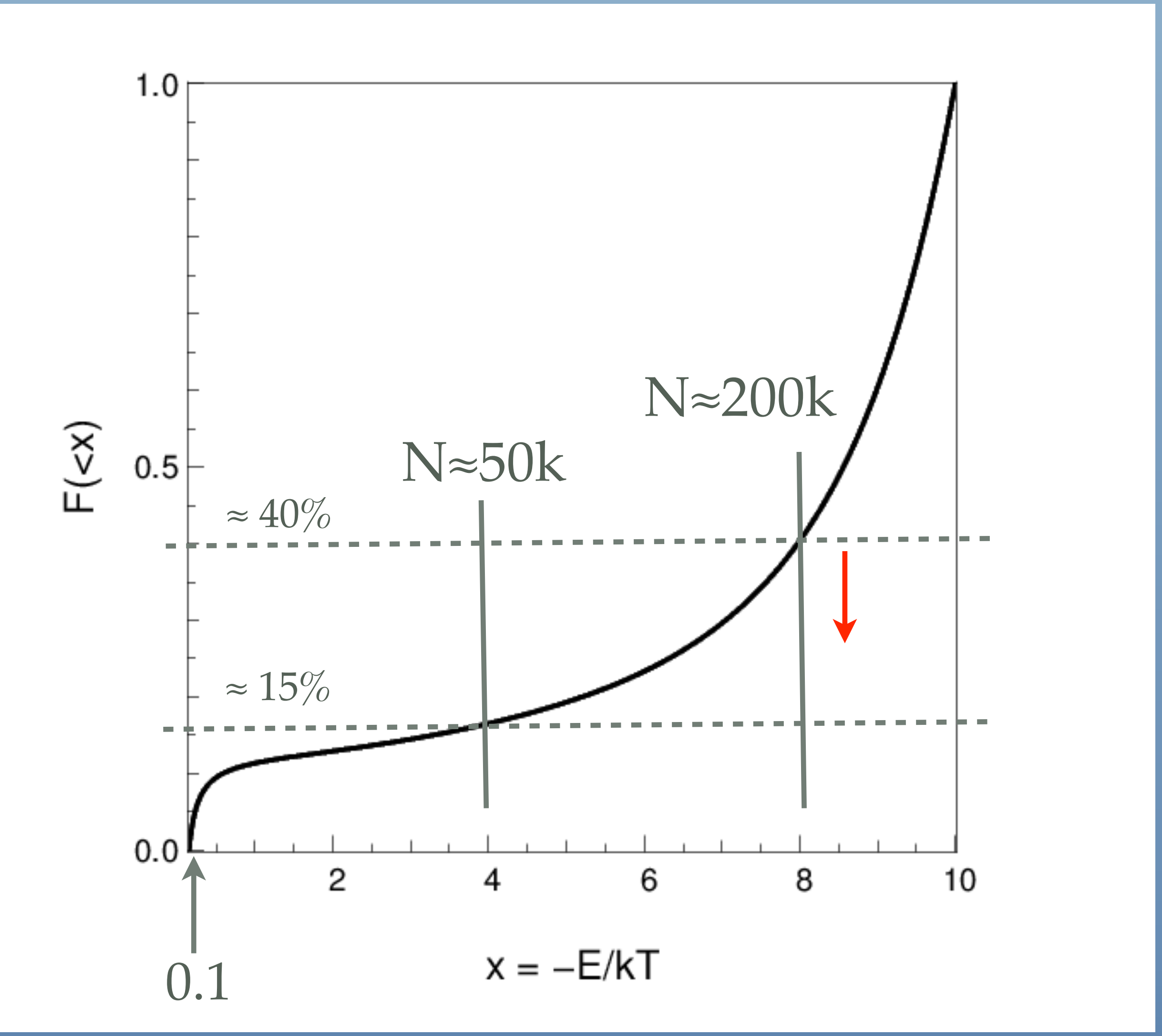
- "Thermalised" equilibrium d.f. in binding energy E = - G Mμ/a

$$f(-E) = K\exp(-\beta E)/(-E)^{5/2}$$

- The Boltzmann factor

$$\beta = \frac{1}{k_\beta T} = \frac{1}{\frac{1}{2}m\sigma^2}$$

- The fraction of binaries heated at formation time scales with √N, the number of (proto) stars formed

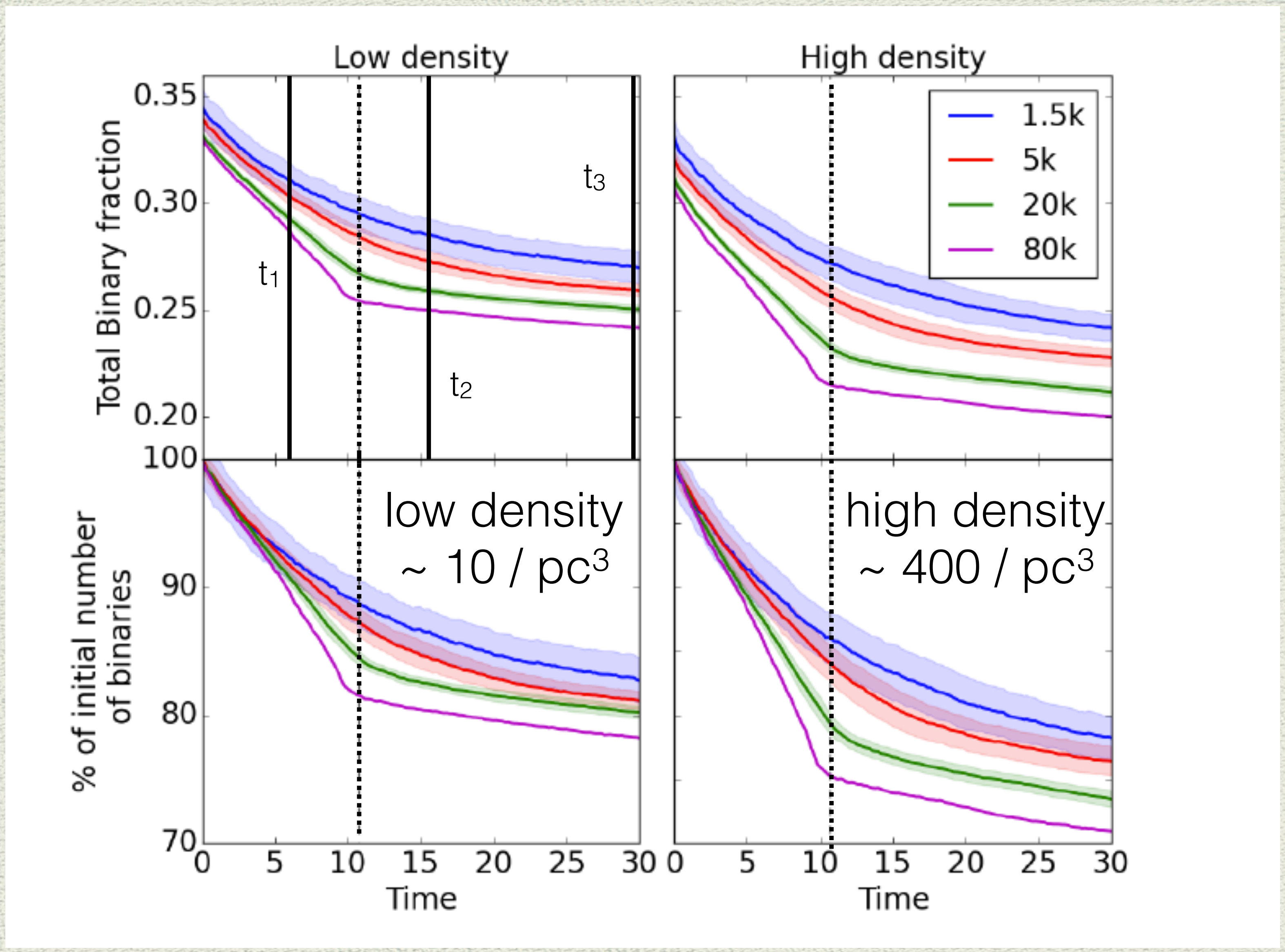


$$\frac{\delta W}{k_\beta T} \simeq \frac{25\pi}{4}\sqrt{\frac{5}{6}} \times 10^{-5}\,\frac{a_{bin}[AU]}{R_o[0.5pc]}\sqrt{N}$$

Lower-limit on R_o

Stellar clumps:

Internal dynamics of multiple stars significant



Evolution up to global mixing / relaxation

t_1 : internally, clumps
dotted : violent in-fall
t_2 : mixing (~1 Myr)
t_3 : end (~ 4 Myr)

Processing of binary stars for models with different N but same IMF + binary population

:: Survival rate weakly dependent on N, sharp transition at the bounce (t = dots)

cf. Dorval PhD + et al. 2017

Stellar clumps:

Internal dynamics of multiple stars significant

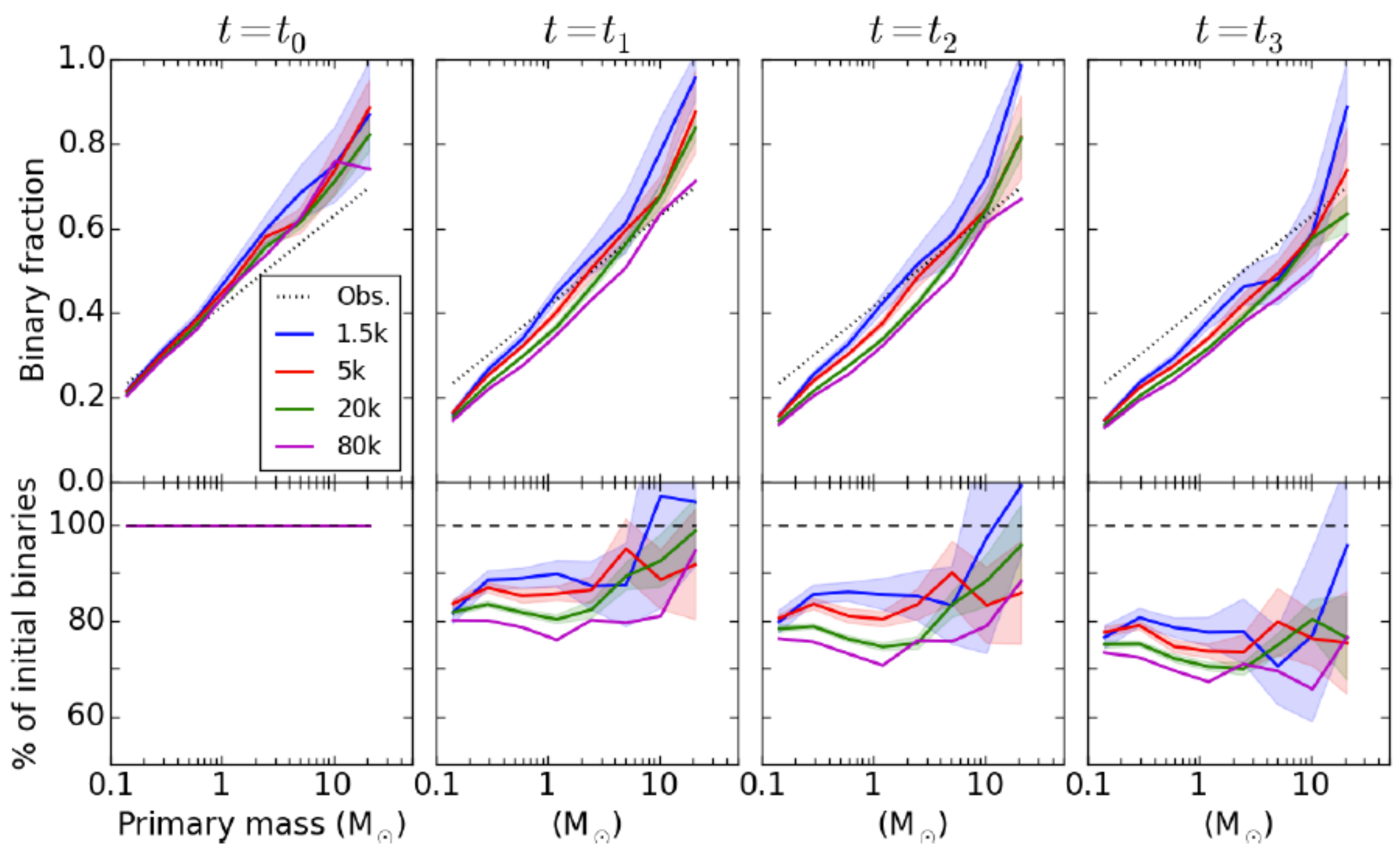


Figure 7.4: Same key as Fig. 7.3. The data are from high density models.

Processing of binary stars less severe in open clusters (heavy primaries)

Erosion @ la Marks-Kroupa (2011,12)

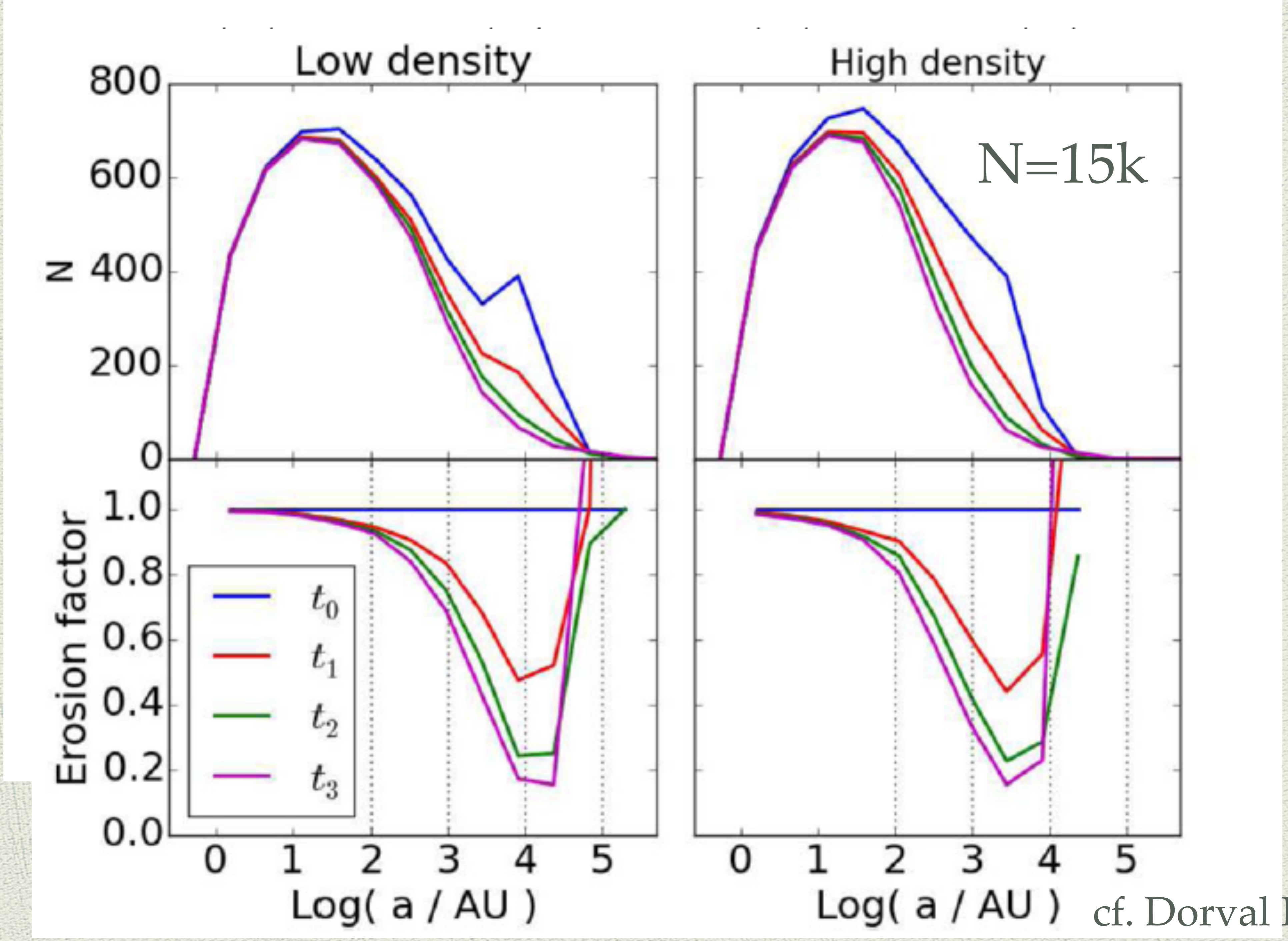
Collusion @ la Kouwenhoven et a.l (2010)

:: different dissolution rates wrt to primary mass

cf. Dorval PhD + et al. 2017

Stellar clumps:

Internal dynamics of multiple stars significant



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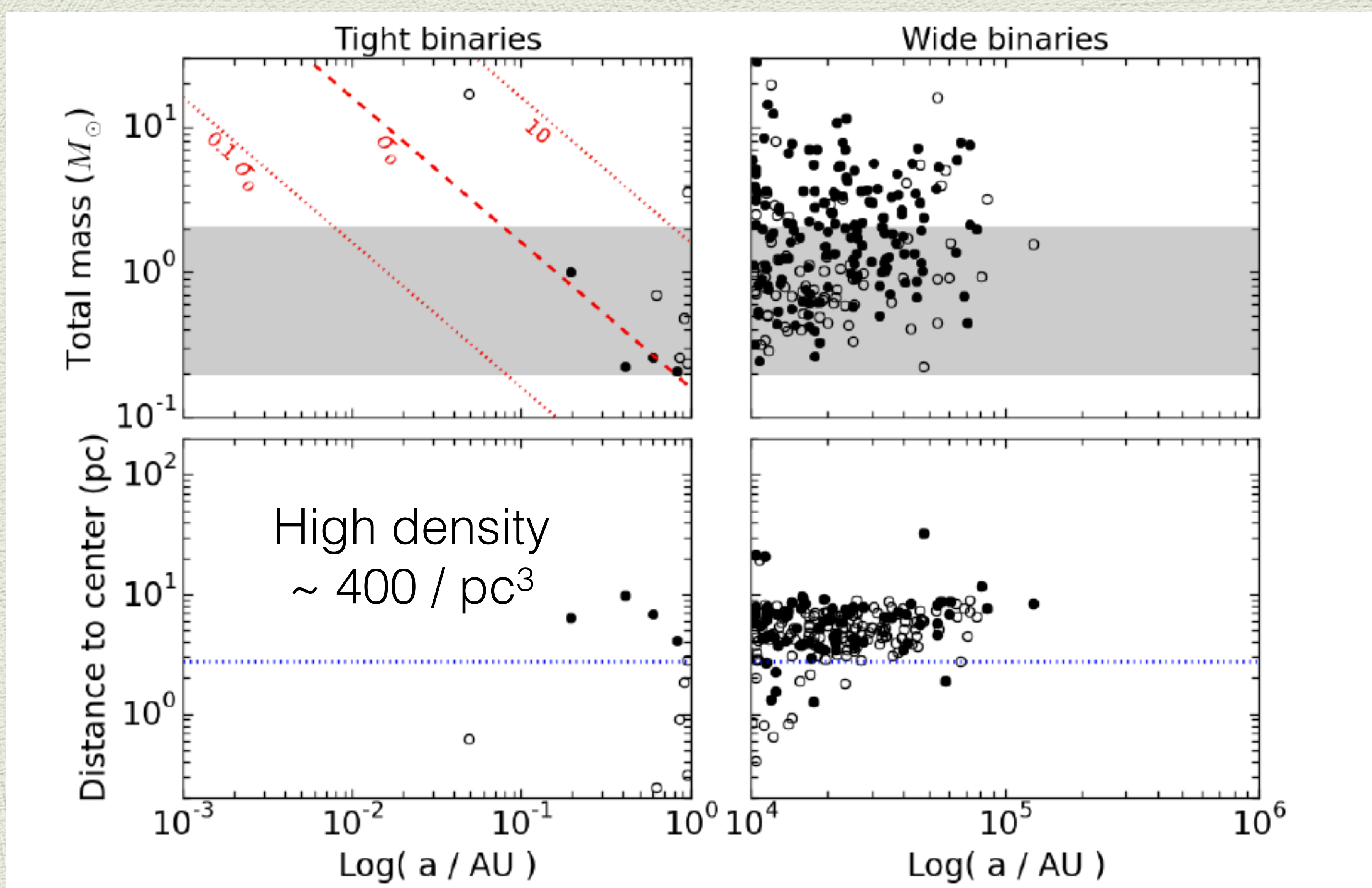
Stellar clumps:

The formation of tight binaries linked to environment



Exchange takes place within clumps *"time allowing"*

cf. Leigh & Geller 2015

The formation of tight binaries by binary-binary *exchange collisions* linked directly to the global mean density !

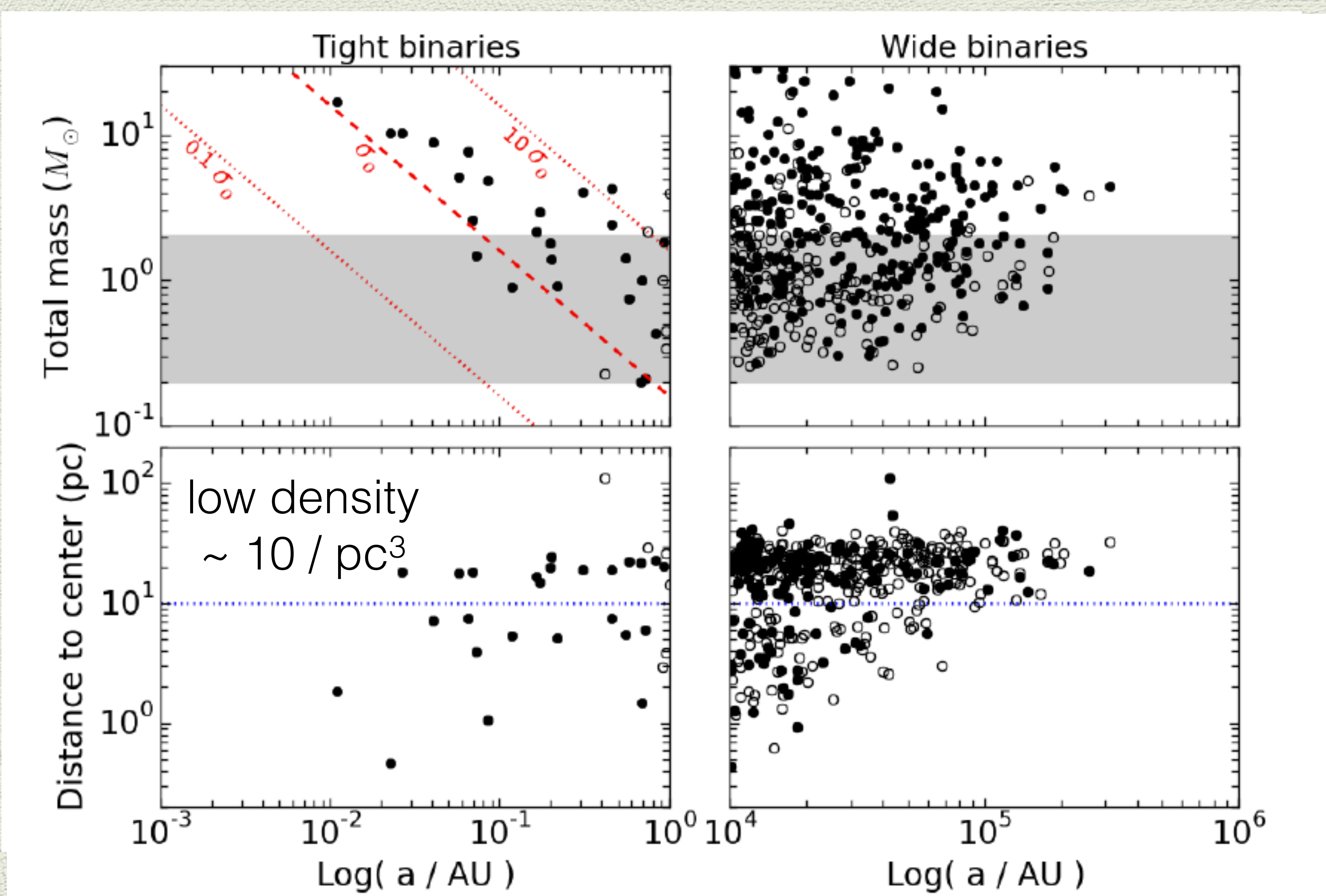
:: Collision rate for destruction

When θ > 100 : gravitational focusing important

$$\tau_{coll}^{-1} = 16\sqrt{\pi}n\sigma a^2\Theta$$
$$= 8\times10^{-4}\ \mathrm{Myr}^{-1}\left(\frac{n}{700\mathrm{pc}^{-3}}\right)\left(\frac{0.5\mathrm{km.s}^{-1}}{\sigma}\right)\left(\frac{a}{\mathrm{AU}}\right)\left(\frac{M}{2\mathrm{M}_\odot}\right)$$

Stellar clumps:

The formation of tight binaries linked to environment



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Summary

- Young clusters (open, rich) start out with odd geometry and sub-virial global velocities
- They should mix quickly yet have time to form stars first ..
- The stellar clumps are top-heavy with respect to field stars ;
- Outflows lead to wide-binaries forming [:: phase-space correlations]
- bi-bi exchanges + tight binaries favoured in low-density environment [:: amplification by gravitational focusing]
- surrounding gas may yet lead to isolated tight binaries merging
- Extinction maps scaled down to map out the low-mass stars, explore morphology, dynamics