The CMF in Galactic Protoclusters

Paolo Padoan
(ICREA & Institute of Cosmos Sciences - University of Barcelona)

Lots of work by Veli-Matti Pelkonen & Mika Juvela

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

Royal Astronomical Society

MNRAS **522,** 3548–3567 (2023) https://doi.org/10.1093/mnras/stad1213
Advance Access publication 2023 April 24

Will ALMA reveal the true core mass function of protoclusters?

P. Padoan,[1,2★] V.-M. Pelkonen,[1★] M. Juvela,[3] T. Haugbølle[4] and Å. Nordlund[4]

[1]*Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB, Martí i Franqués 1, E08028 Barcelona, Spain*
[2]*ICREA, Pg. Lluís Companys 23, E-08010 Barcelona, Spain*
[3]*Department of Physics, University of Helsinki, PO Box 64, 00014, Helsinki, Finland*
[4]*Niels Bohr Institute, University of Copenhagen, Øster Voldgade 5-7, DK-1350 Copenhagen, Denmark*

Accepted 2023 April 15. Received 2023 April 3; in original form 2023 January 19

The origin of the stellar IMF

Chabrier's range <1 M⊙ (***lognormal turnover***):
understood as mapping of the density pdf from supersonic turbulence

Salpeter's range >1 M⊙ (***power law***):
probably turbulence, but no real solid theory

Observational evidence from the prestellar CMF

The CMF gives some support to the lognormal turnover range *(Motte et al. 1998, …)*.

What about the CMF at larger masses? Harder to establish, we need to:

- Select regions that (can) form massive stars
- Reach few kpc distance, hence resolution 0.5”

This is ALMA territory.

ALMA-IMF Large Program, *Motte et al. (2022, I)*

They select the 15 most massive clouds from *Csengeri et al. (2017)*, which is a catalog of the 200 most massive APEX/ATLASGAL clumps.

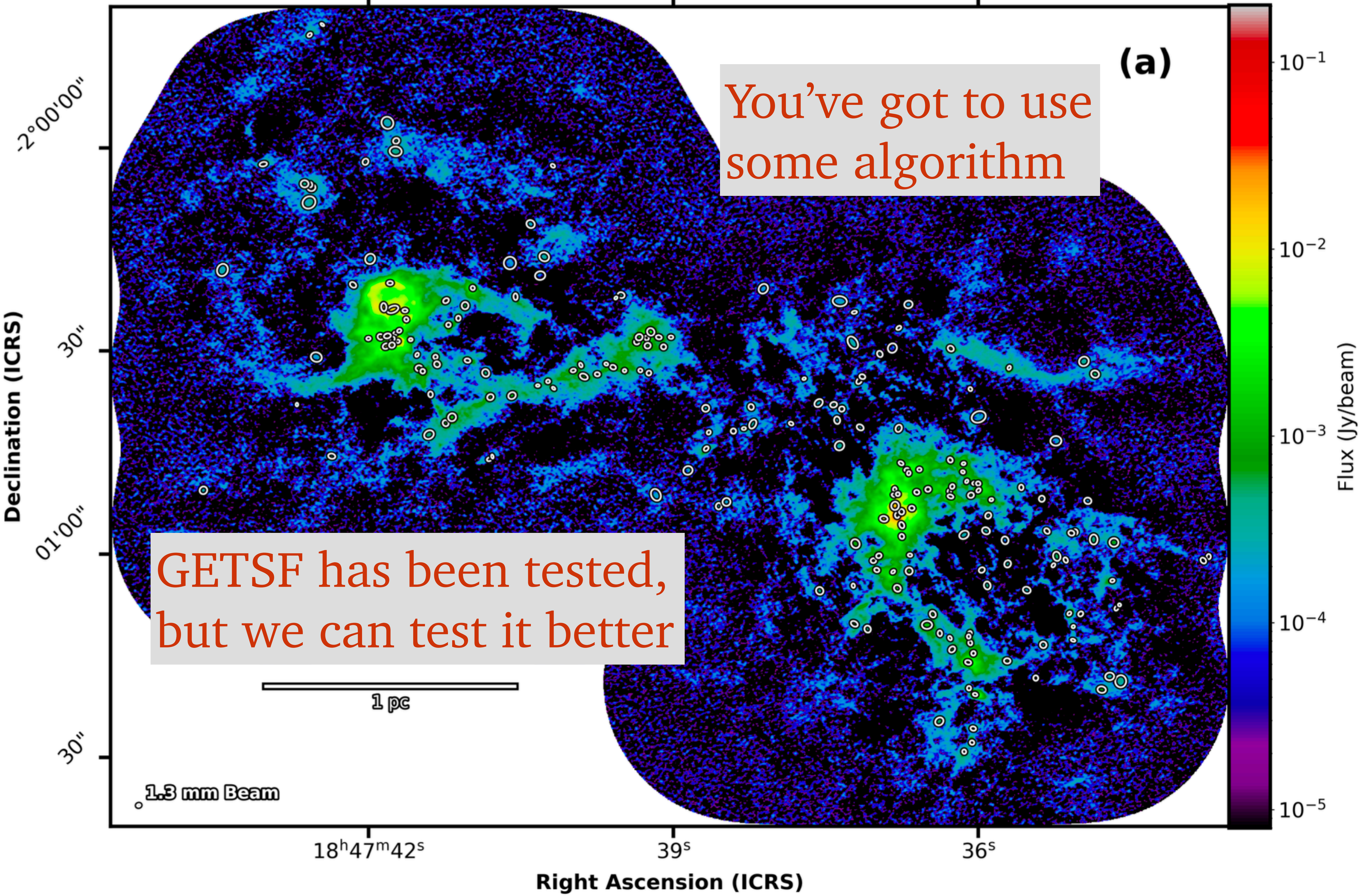
- Distances: 2 - 5.5 pc
- Masses: 500 - 10,000 $M_\odot$
- Sizes (FWHM): 0.21 - 0.58 pc

Typical ALMA map: 2x2 pc size, 0.5” resolution, 0.1 mJy/beam noise

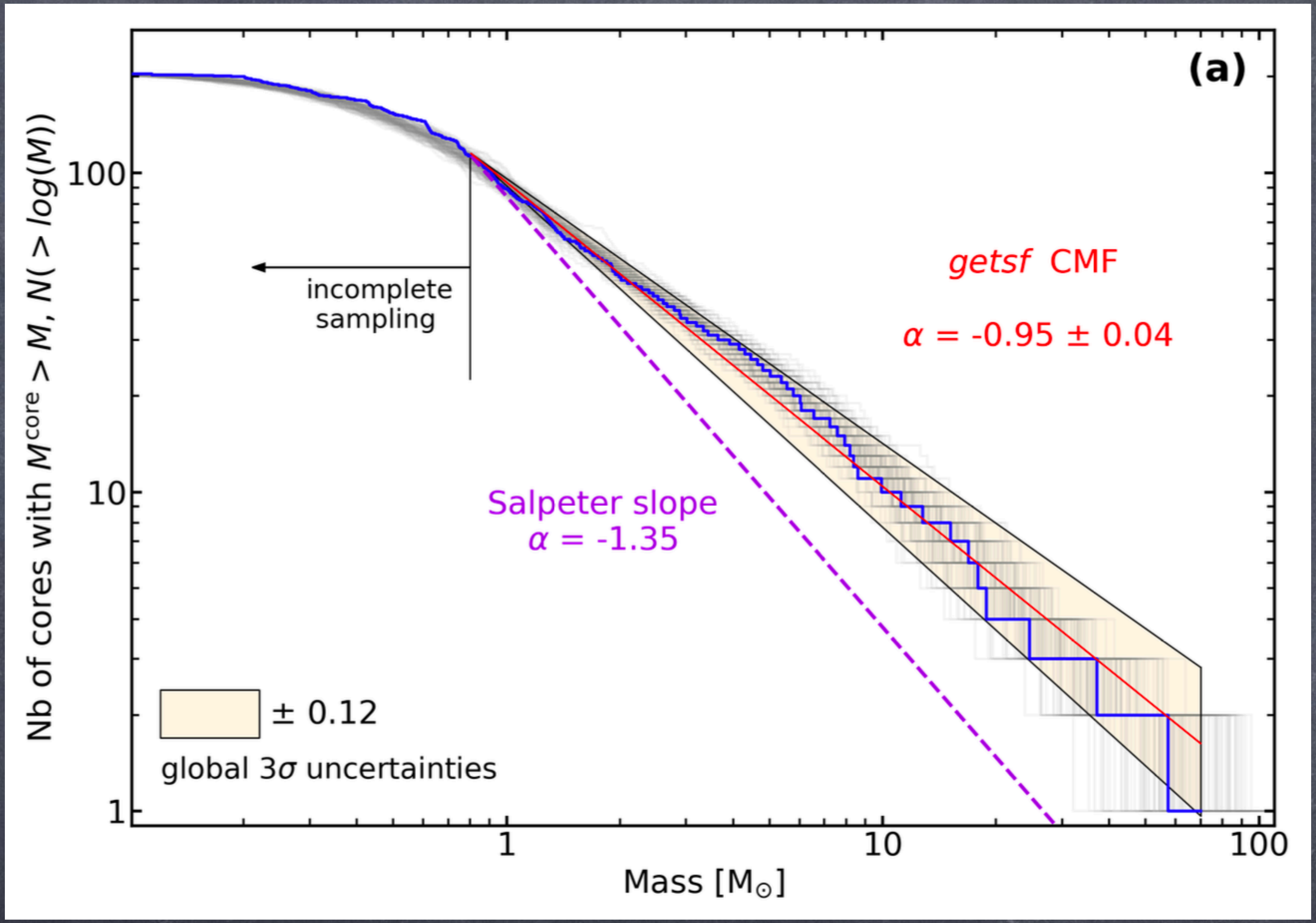
Constant resolution of 2,000 AU and 0.6 $M_\odot$

Maps are not spectacular: ***the cores don’t really jump to your eyes…..***

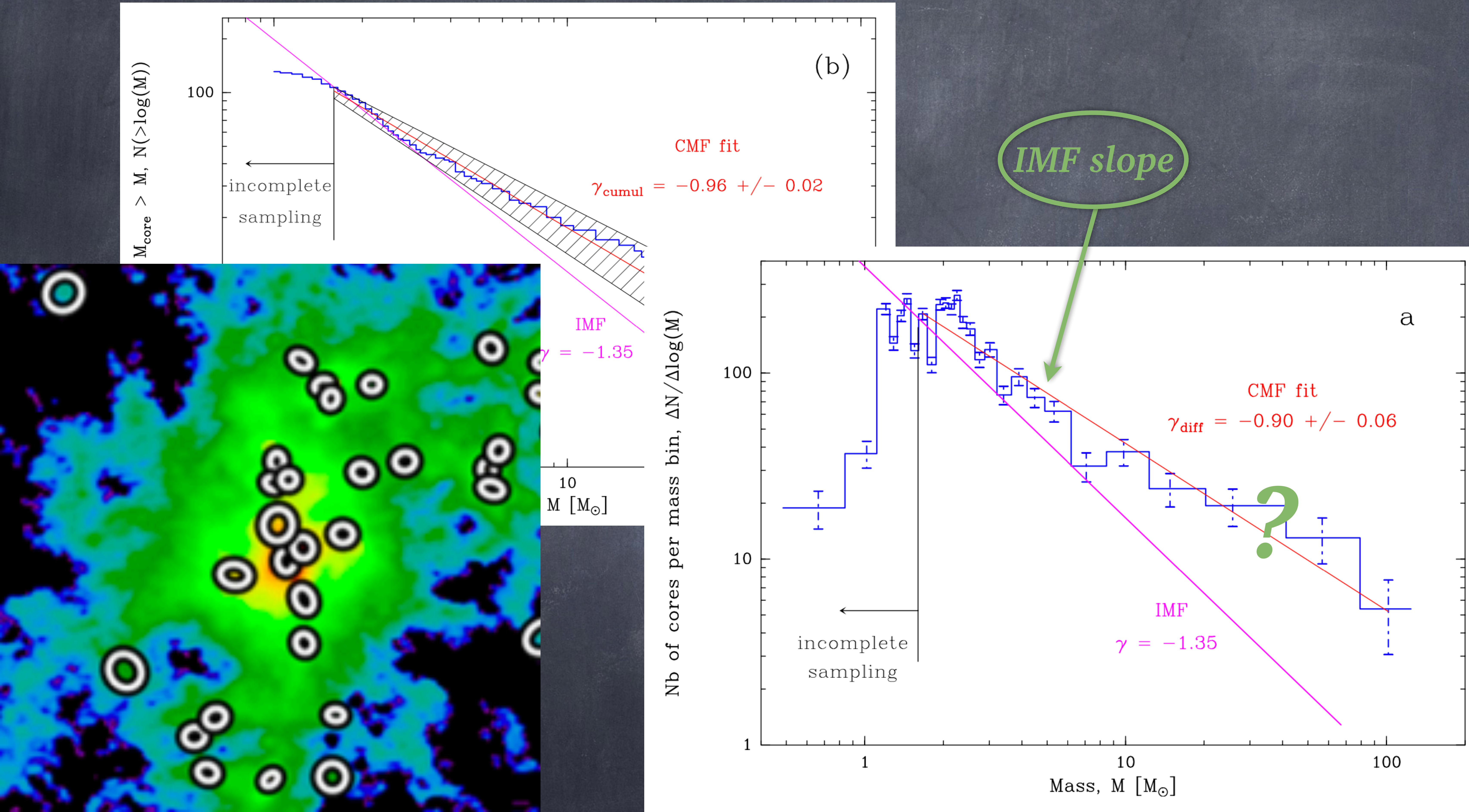
Y. Pouteau et al.: ALMA-IMF III: Top-heavy core mass function in the W43-MM2&MM3 mini-starburst



Pouteau et al. (2022), II: **Top-heavy CMF** in W43 MM2 and MM3
Motte et al. (2018): Top-heavy CMF in W43 MM1



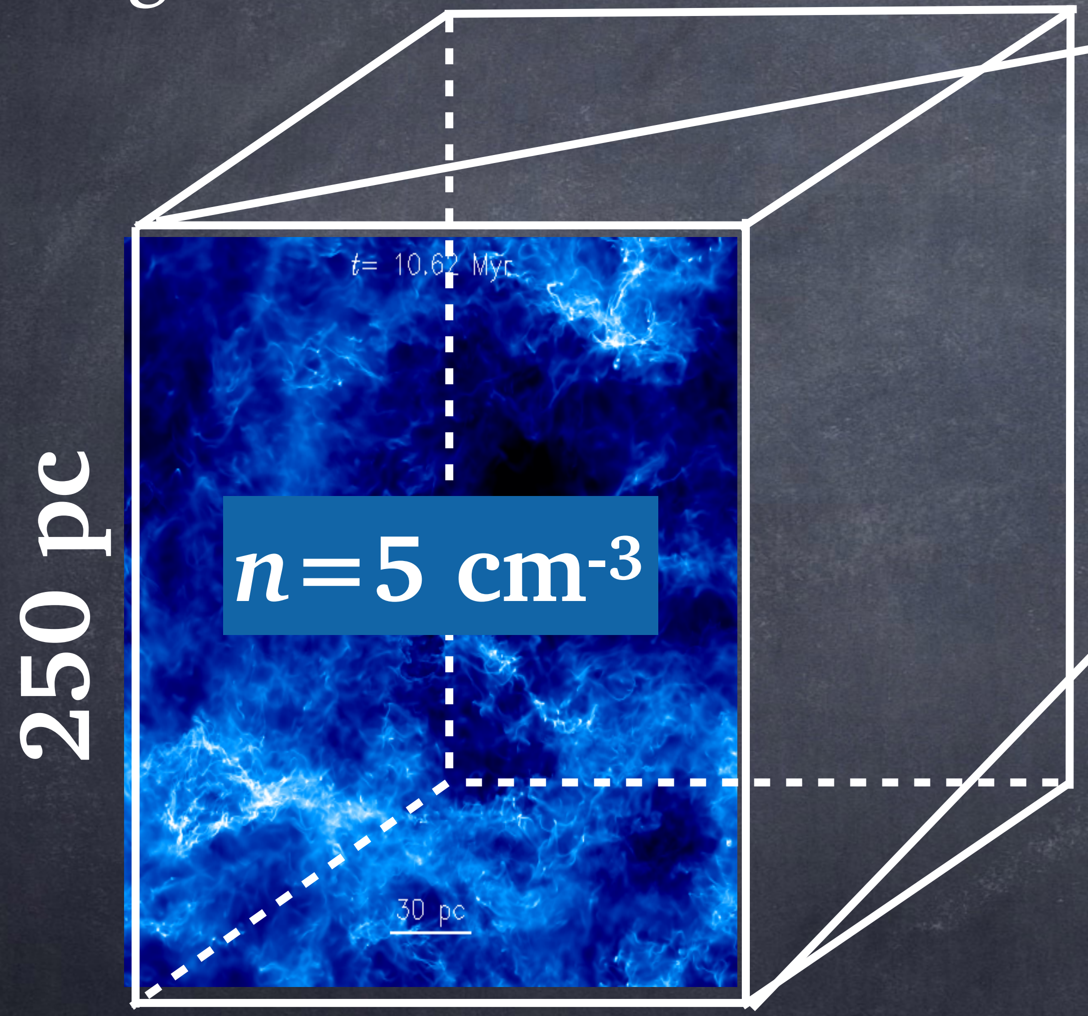
Cumulative MF: what if the MF is not an extended single power law?

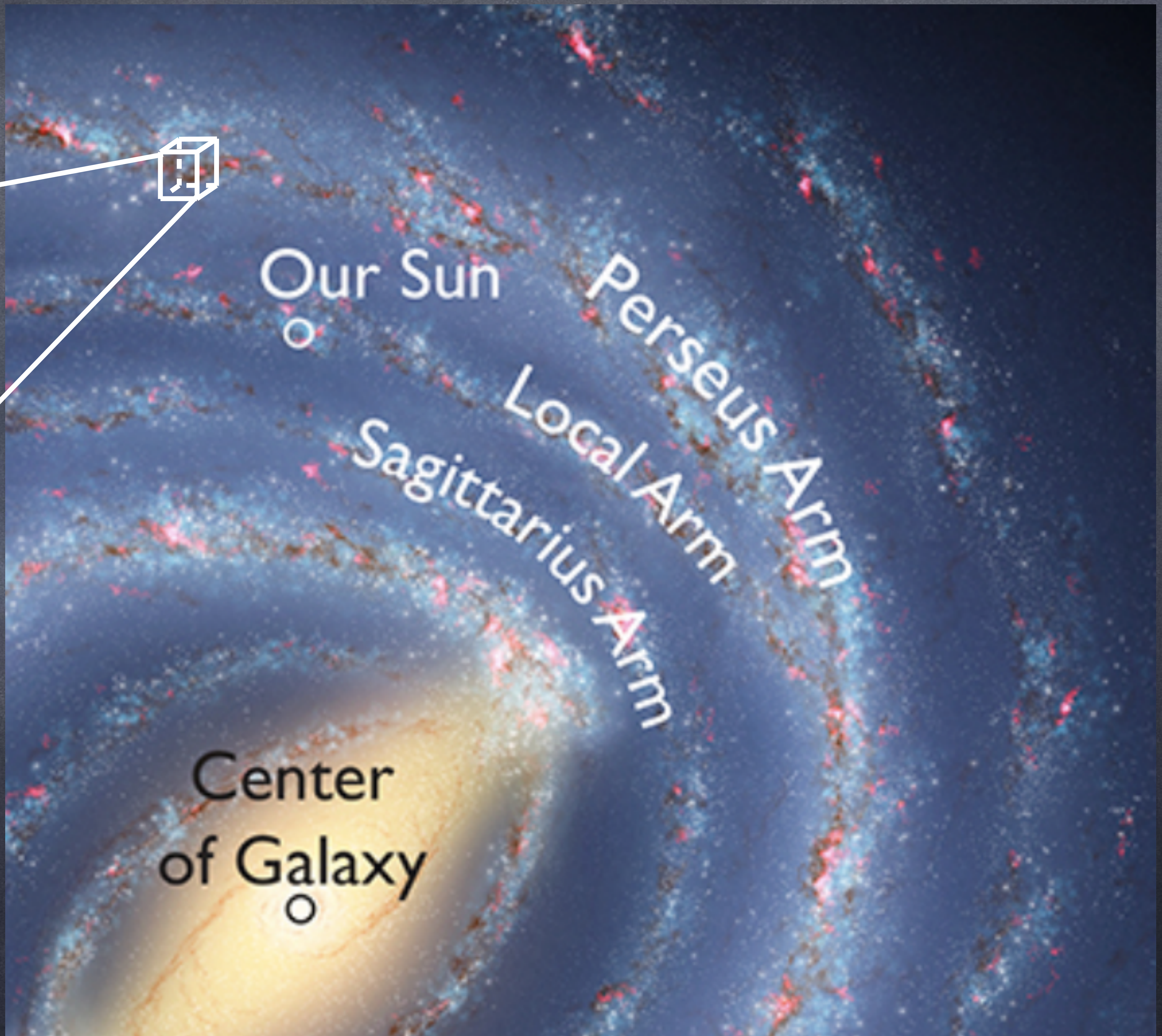


(b)
100
10
$M_{core} > M$, $N(>\log(M))$
CMF fit
γ_{cumul} = −0.96 +/− 0.02
incomplete
sampling
IMF
γ = −1.35
M $[M_\odot]$
IMF slope
a
CMF fit
γ_{diff} = −0.90 +/− 0.06
IMF
γ = −1.35
incomplete
sampling
?
Nb of cores per mass bin, $\Delta N/\Delta\log(M)$
1
10
100
Mass, M $[M_\odot]$

We simulate a 250 pc (*periodic*) 2.e6 M⊙ chunk of a spiral arm

Outer scale ≲ 100 pc, so going much above 250 pc is a waste of dynamic range.





First random SNe, ~6 SNe/Myr

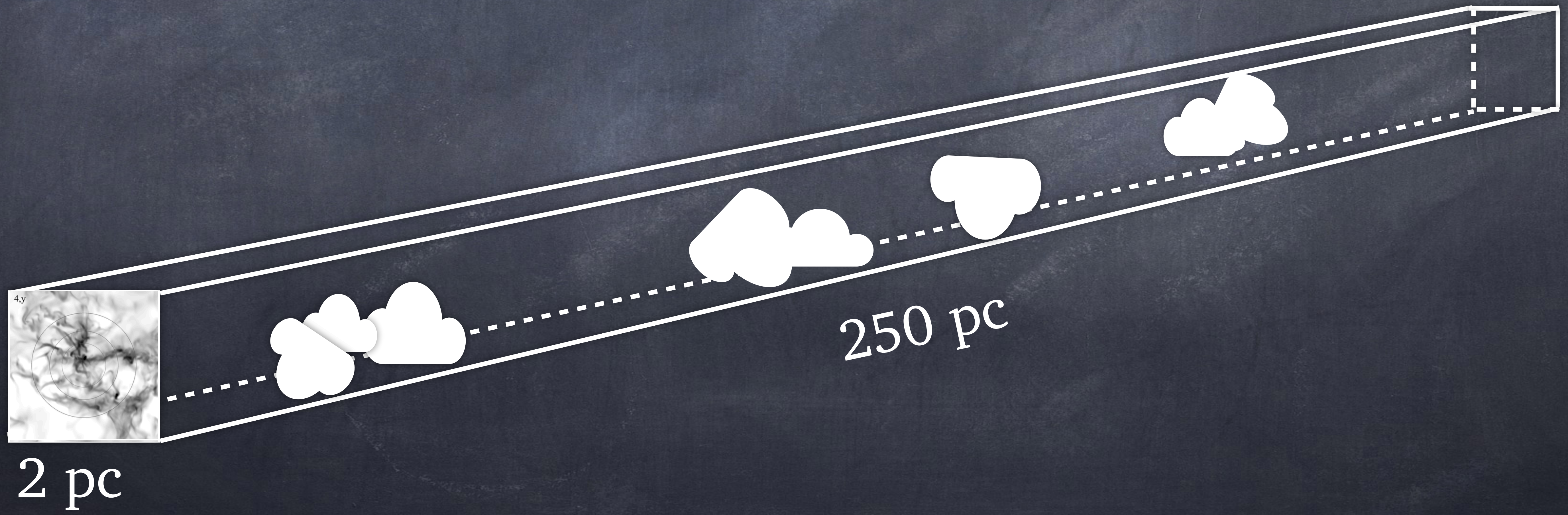
<u>Then **real SNe** from resolved stars</u>

We search for the densest regions in the simulation, at a resolution of 0.5 pc (a bit like ATLASGAL clumps)

We select 12 clumps and 'map' them at the full resolution of 0.0076 pc

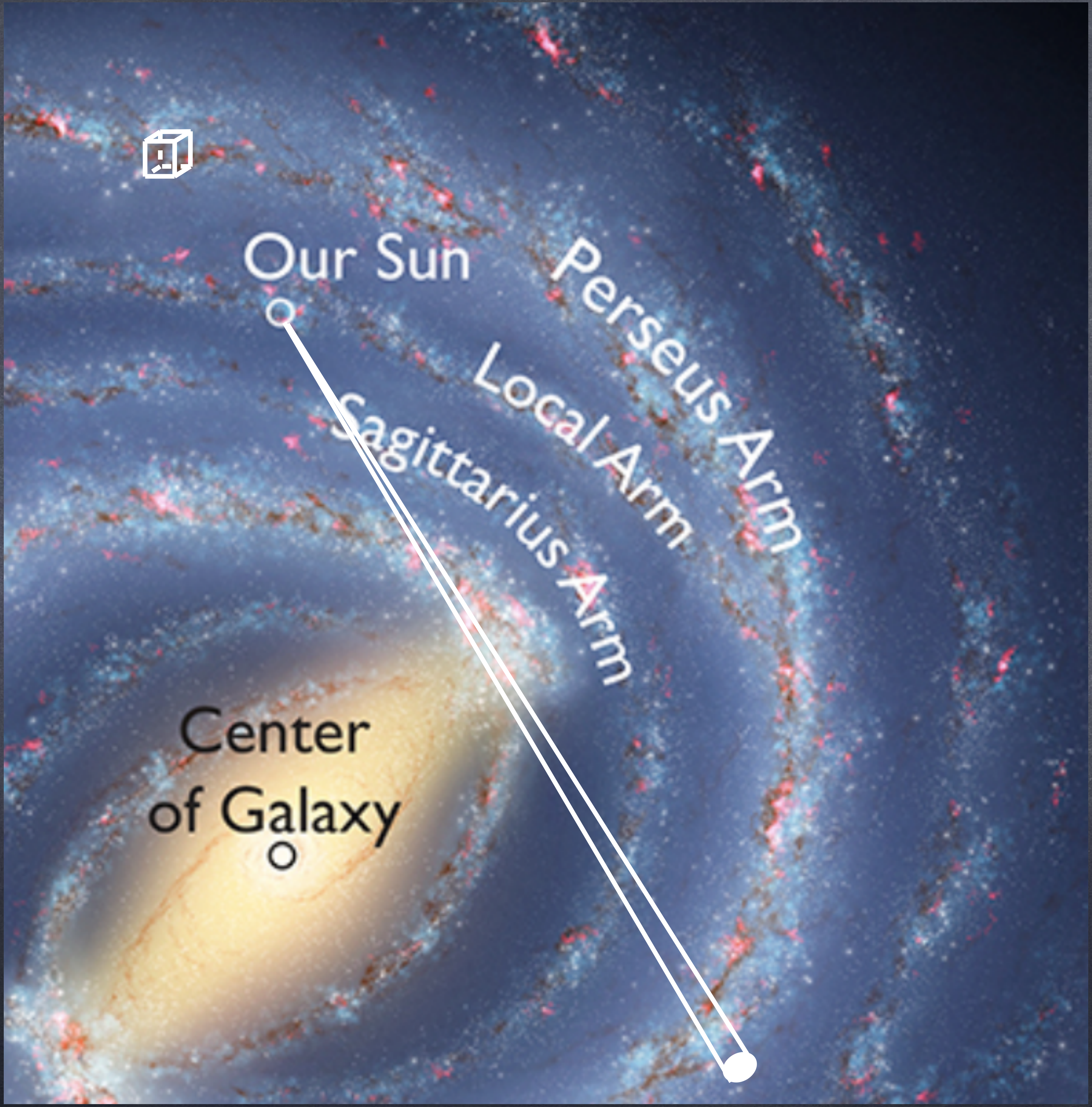
2 x 2 pc maps, from 2 x 2 x **250** pc volume

Huge aspect ratio! Very different from small-scale simulations:



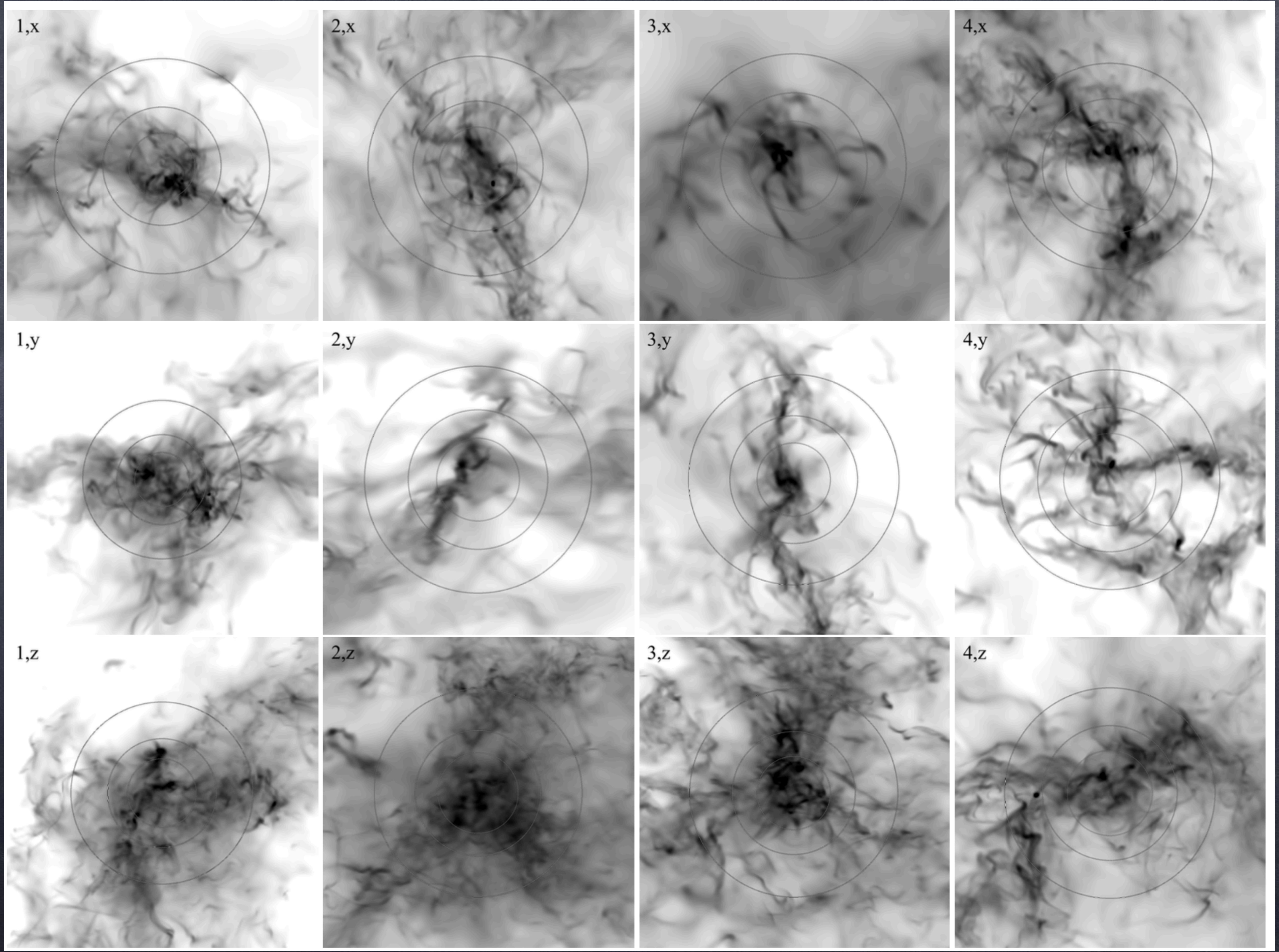
Simulation:

- 0.25 kpc
- 1 spiral arm



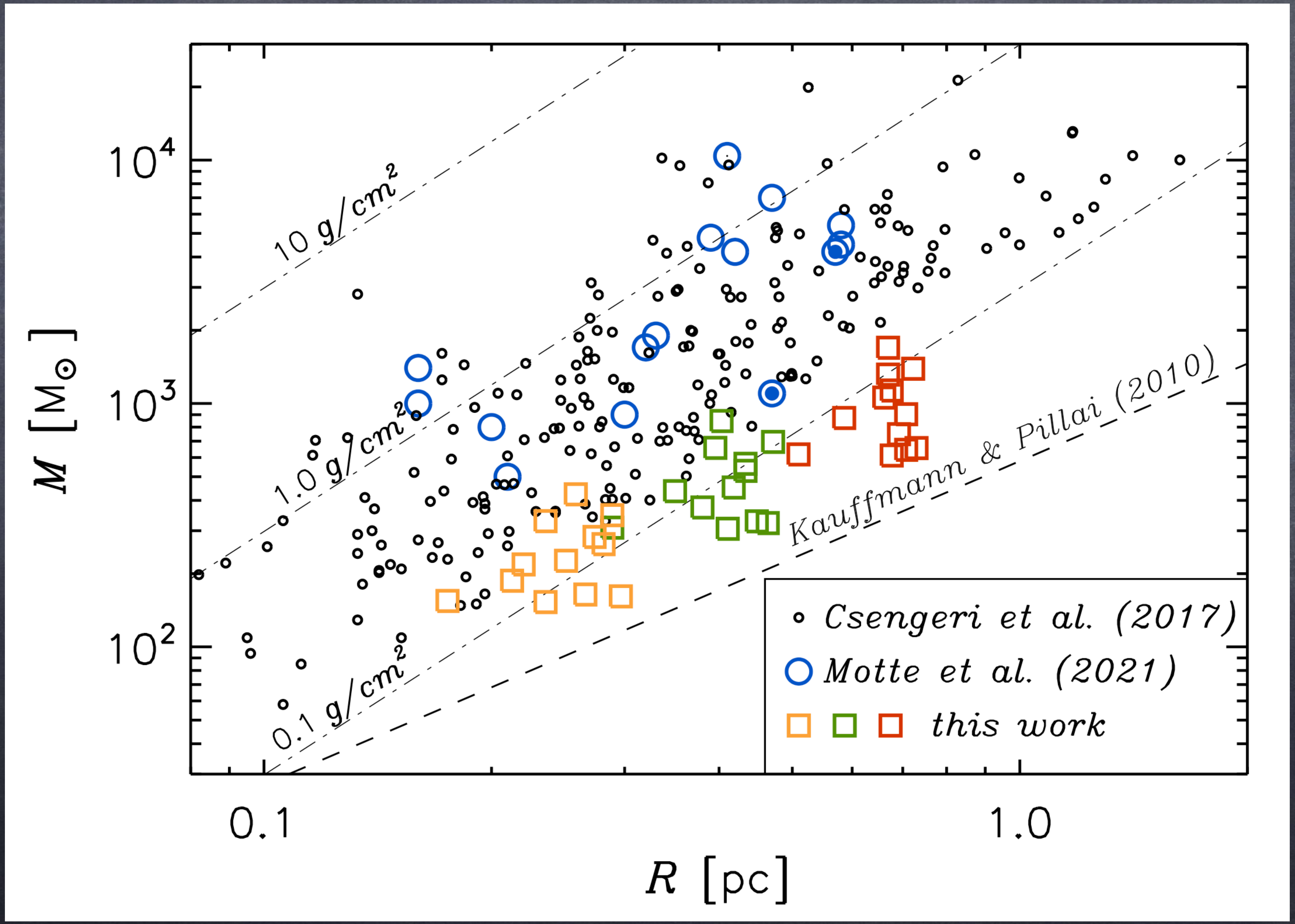
Observations:

- >10 kpc
- > 5 spiral arms

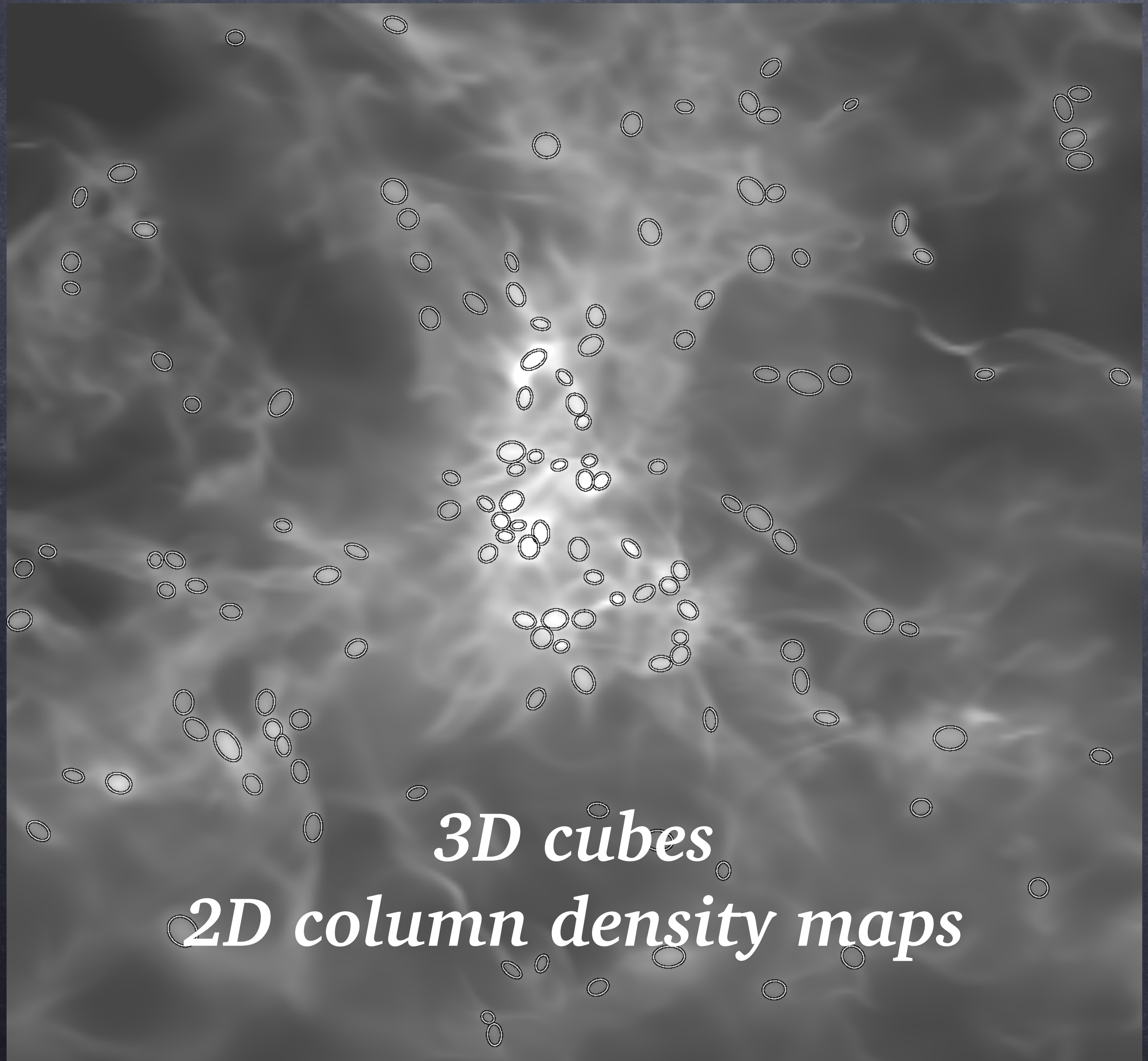

1,x
2,x
3,x
4,x
1,y
2,y
3,y
4,y
1,z
2,z
3,z
4,z

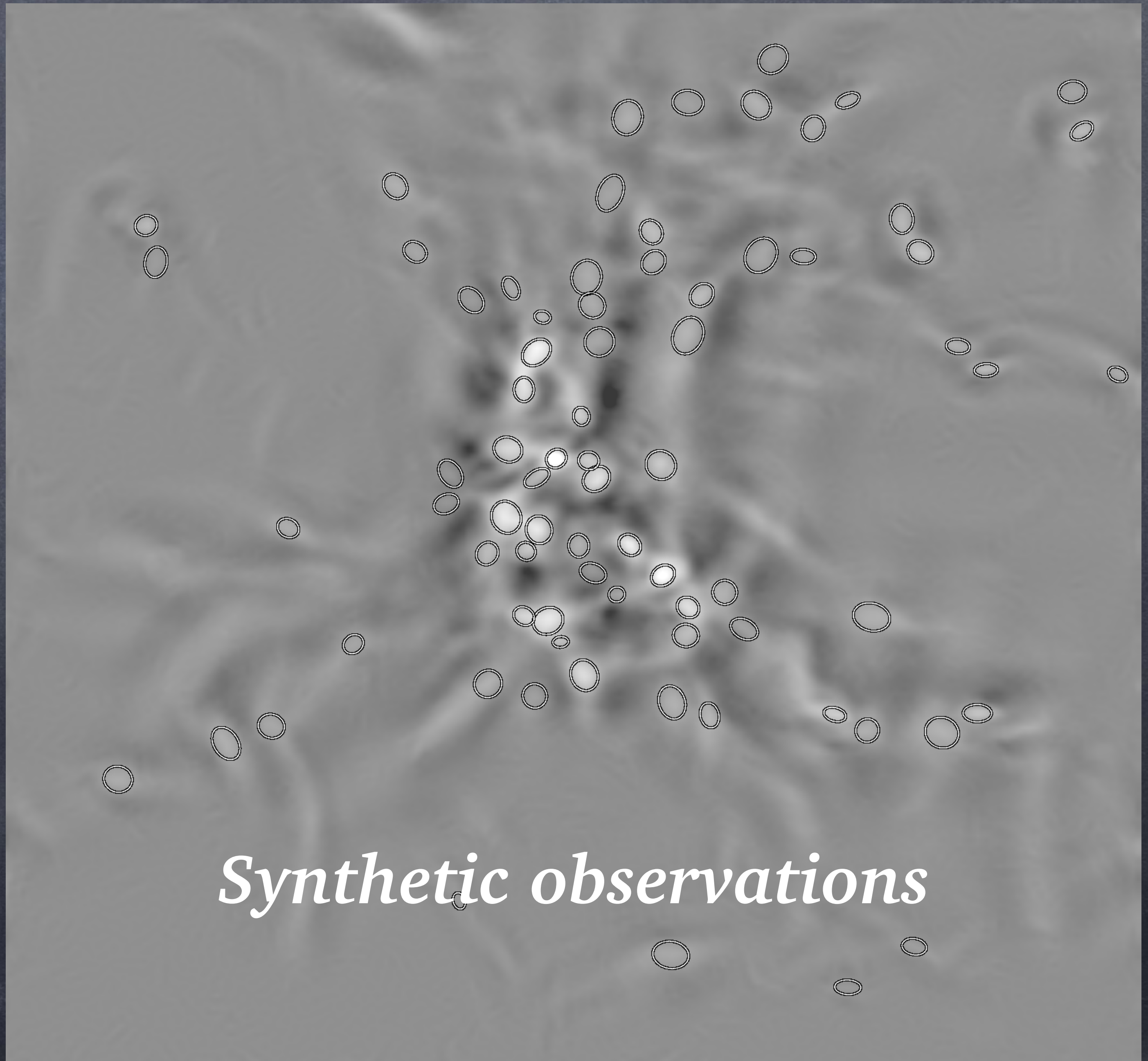
Mass-size relation: ATLASGAL, ALMA, this work.

- Our column densities are on the low side, but partially overlap
- We are well above the threshold for massive SF (Kauffmann & Pillai 2017)
- We know these regions are forming massive stars in the simulation.



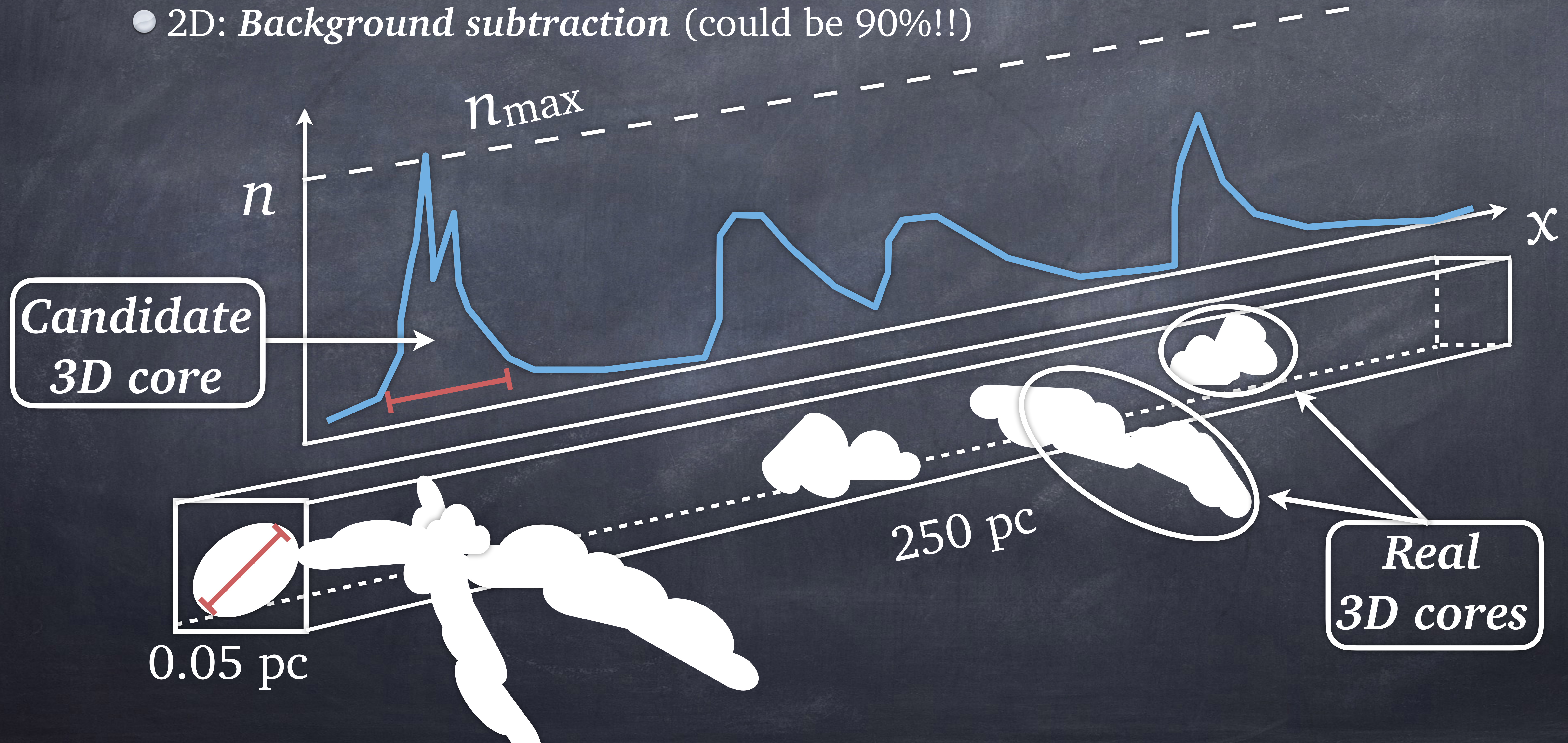
- Radiative transfer with the SOC code *(Juvela 2019)*
- General ALMA-IMF pipeline *(Ginsburg et al. 2022, II)*
- Noise reduction MNGSEG code *(Robitaille et al. 2019)*
- 2D core selection with the GETSF code *(Men'shchikov 2021)*
- 3D core selection with the DENDRO code *(Padoan et al. 2007)*





2D versus 3D and CANDIDATE cores

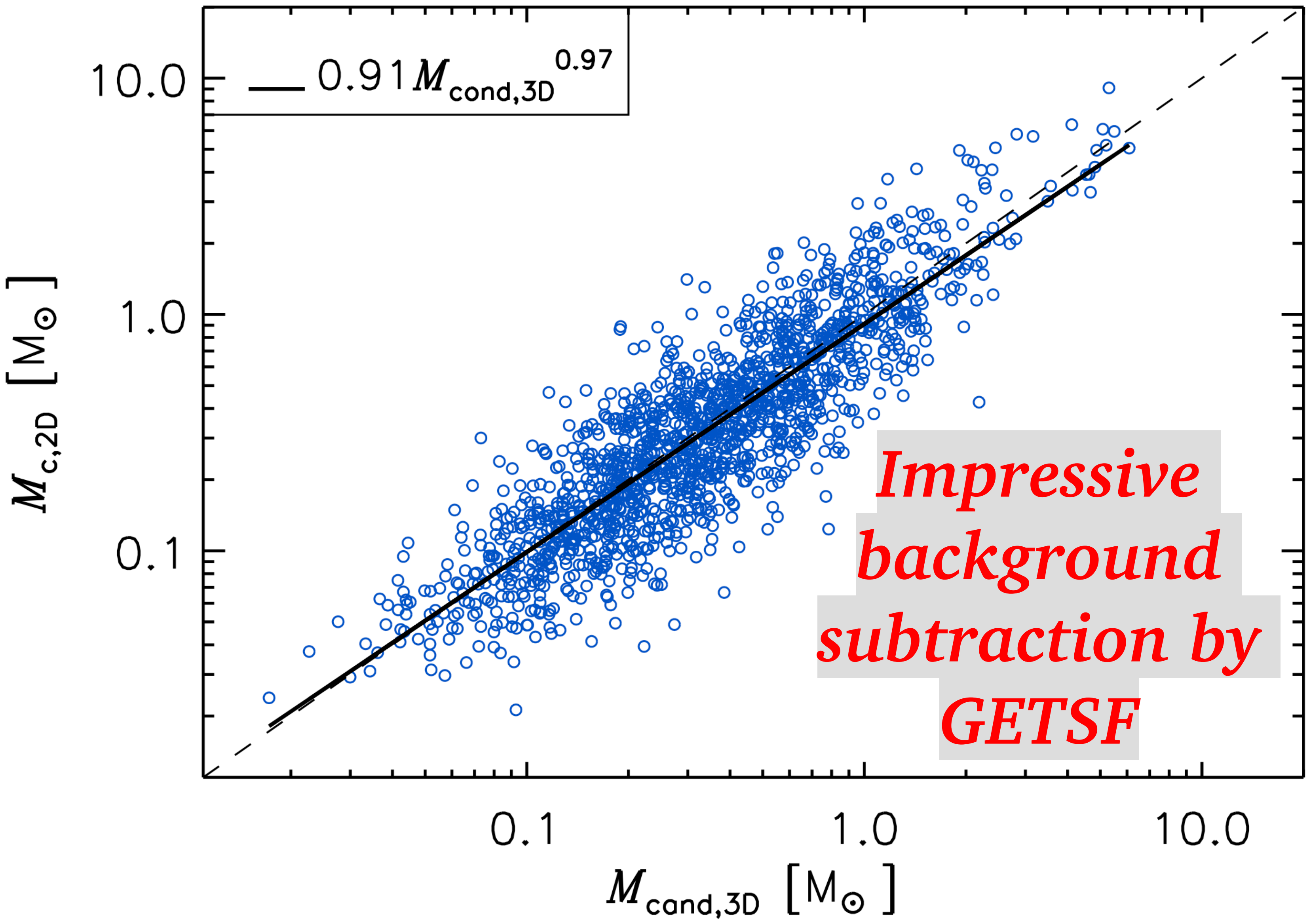
- 3D: Clear ***physical*** definition (background subtraction is meaningless!!)
- 2D: ***Background subtraction*** (could be 90%!!)

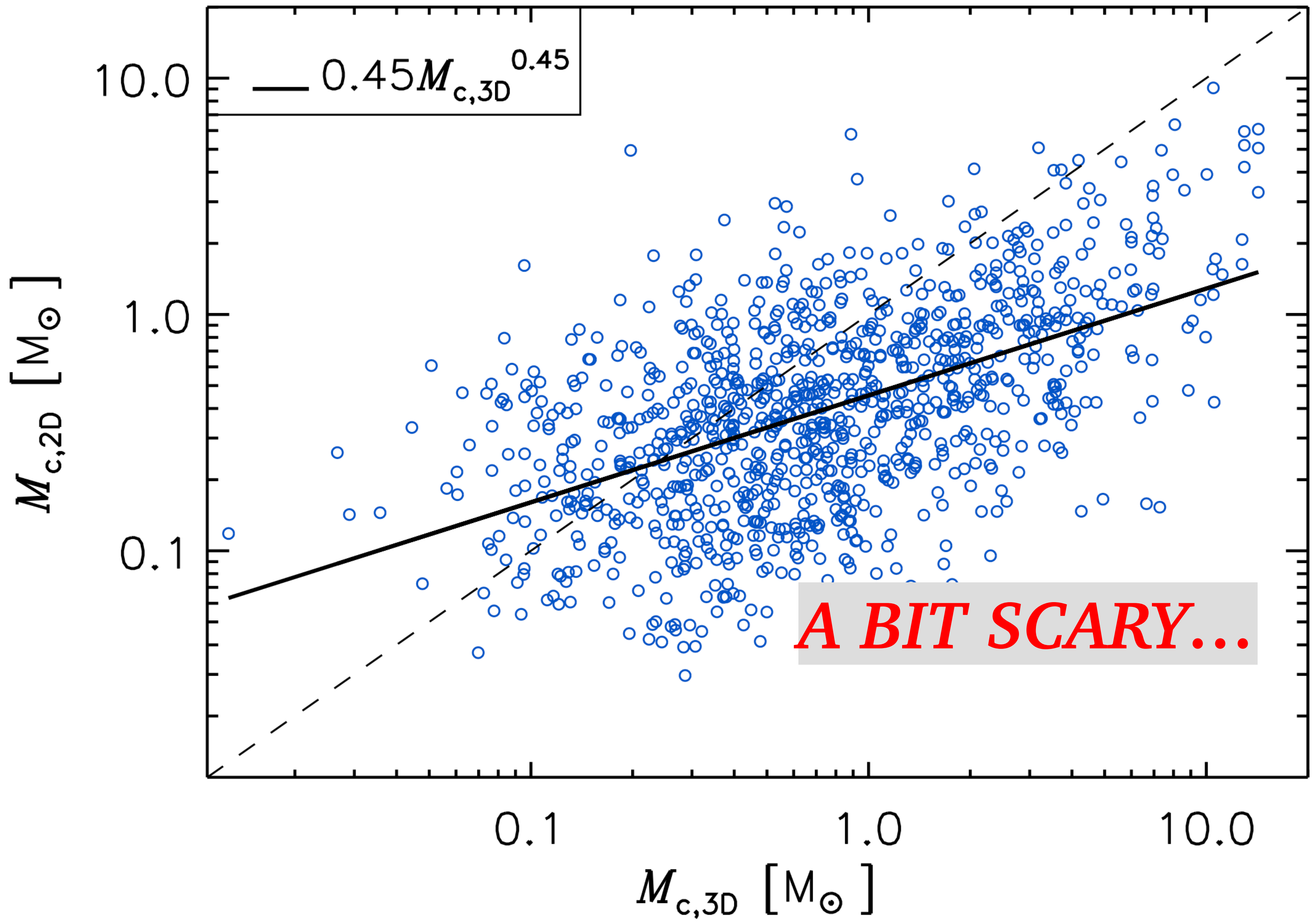


COLUMN-DENSITY MAPS

2D GETSF core masses are well correlated with candidate core masses.

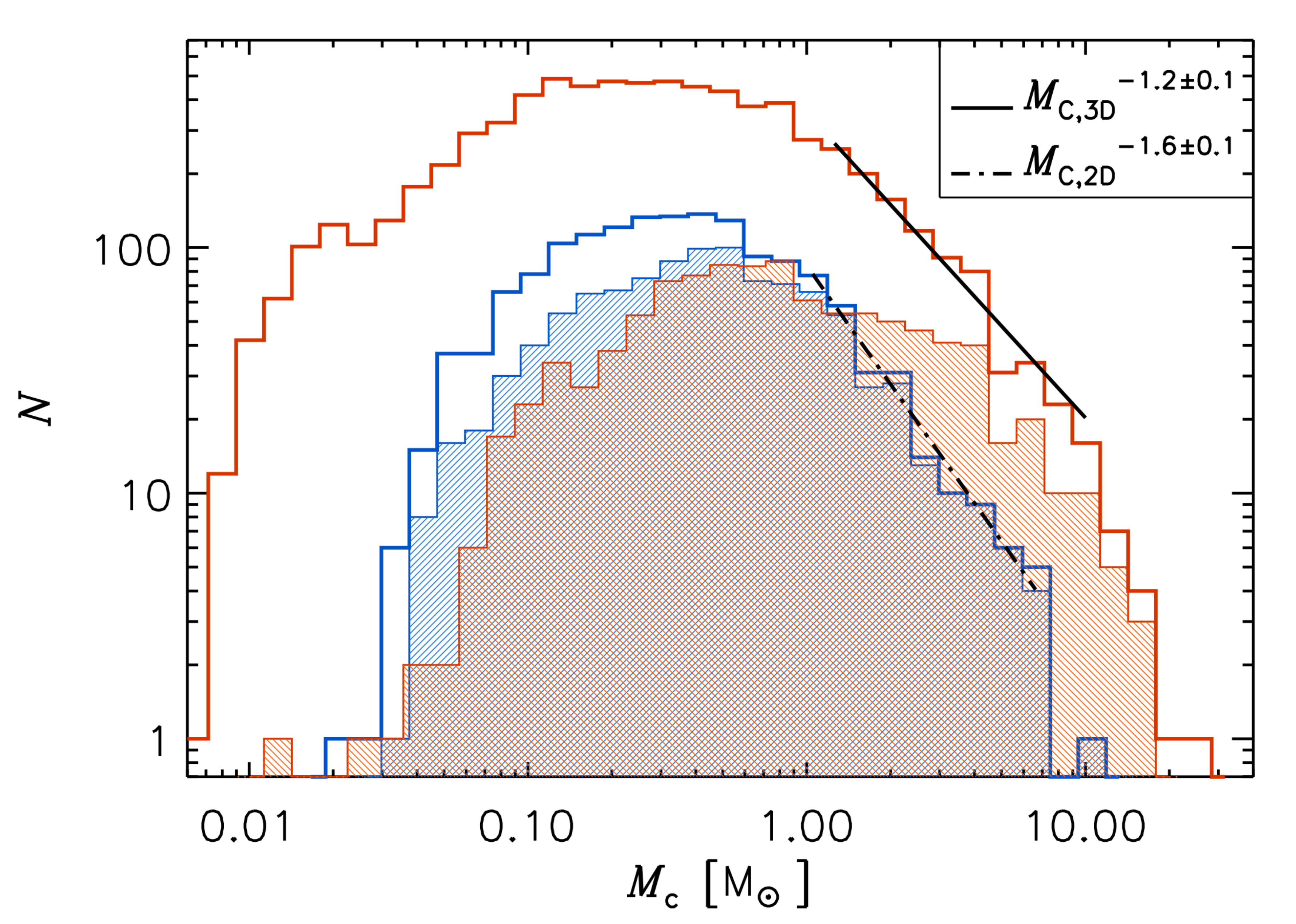
2D GETSF core masses are scarcely correlated with real 3D core masses.





COLUMN-DENSITY MAPS

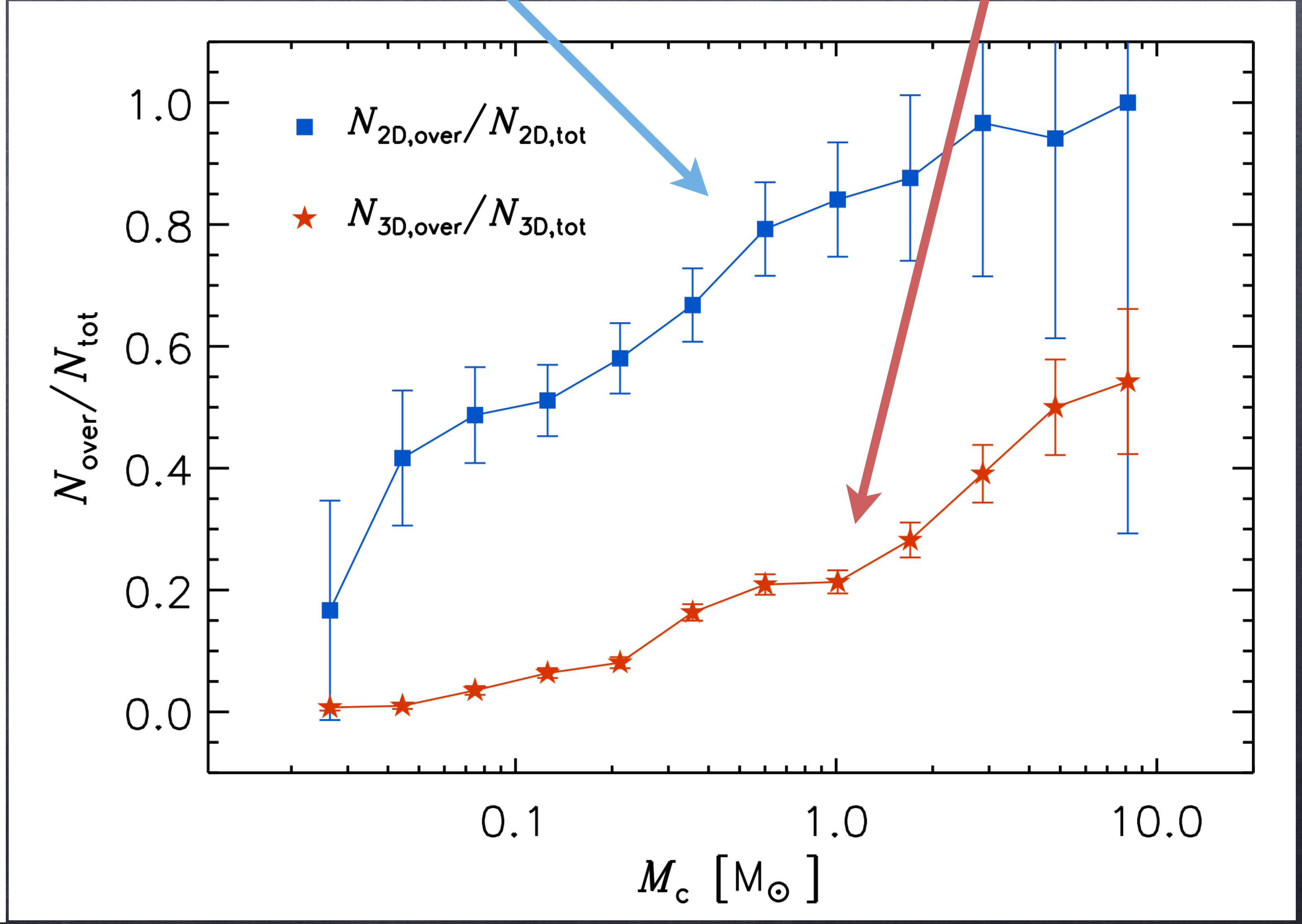
The CMF of GETSF cores is significantly steeper than that of real 3D cores.



Quite a few observational artifacts, and the CMF is incomplete at all masses.

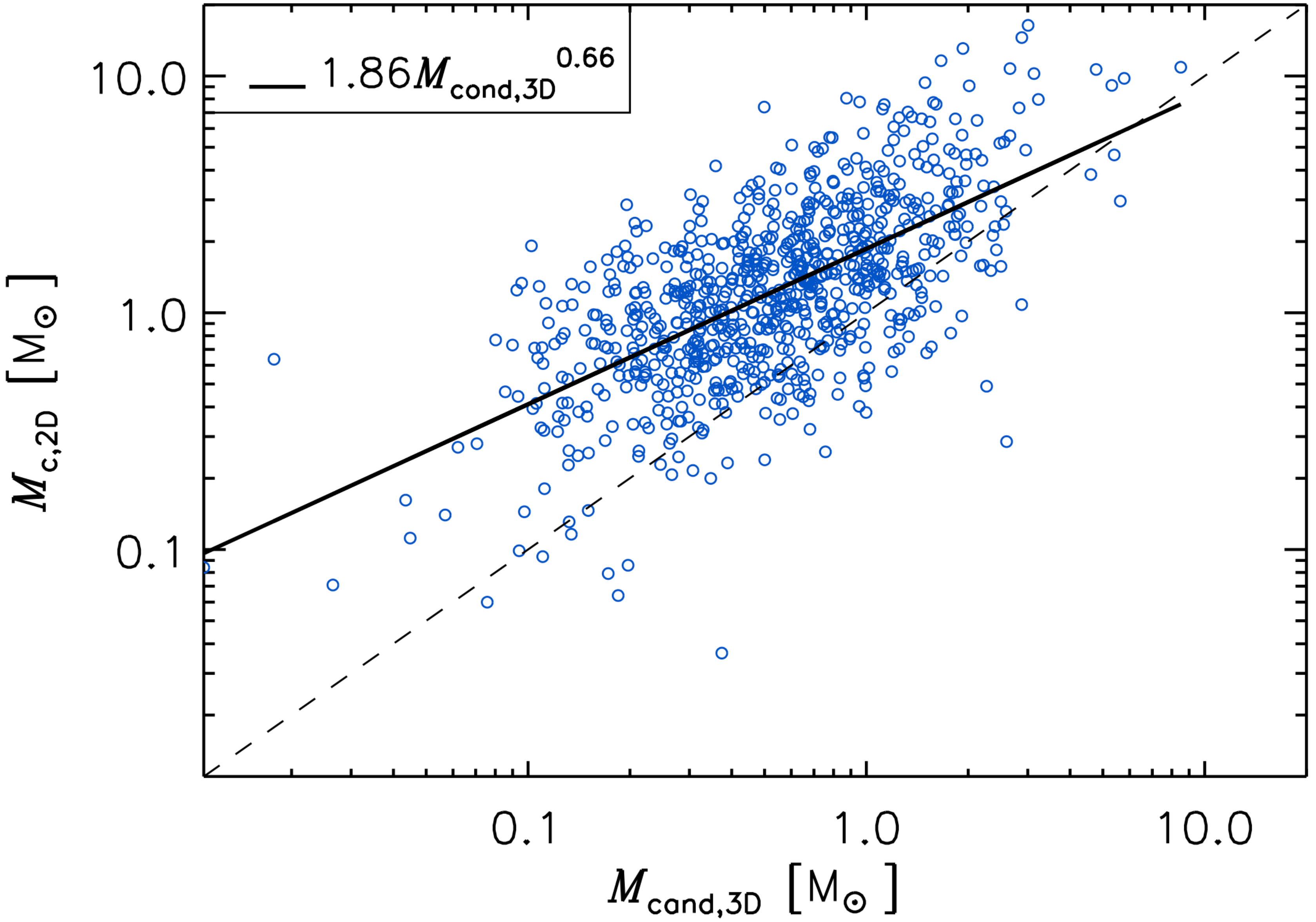
1-artifacts

completeness

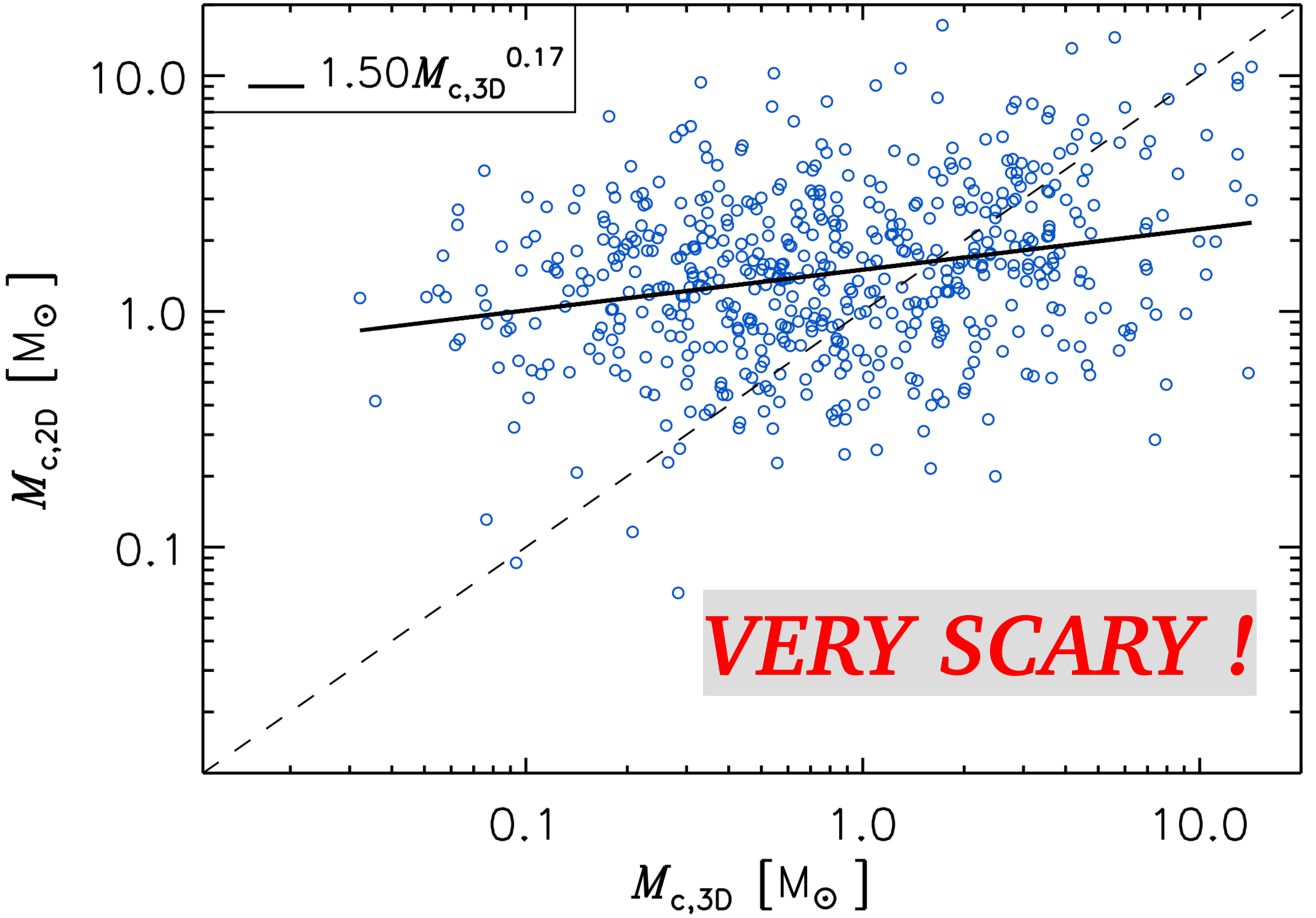


SYNTHETIC ALMA MAPS

The background subtraction is still OK with the synthetic maps.



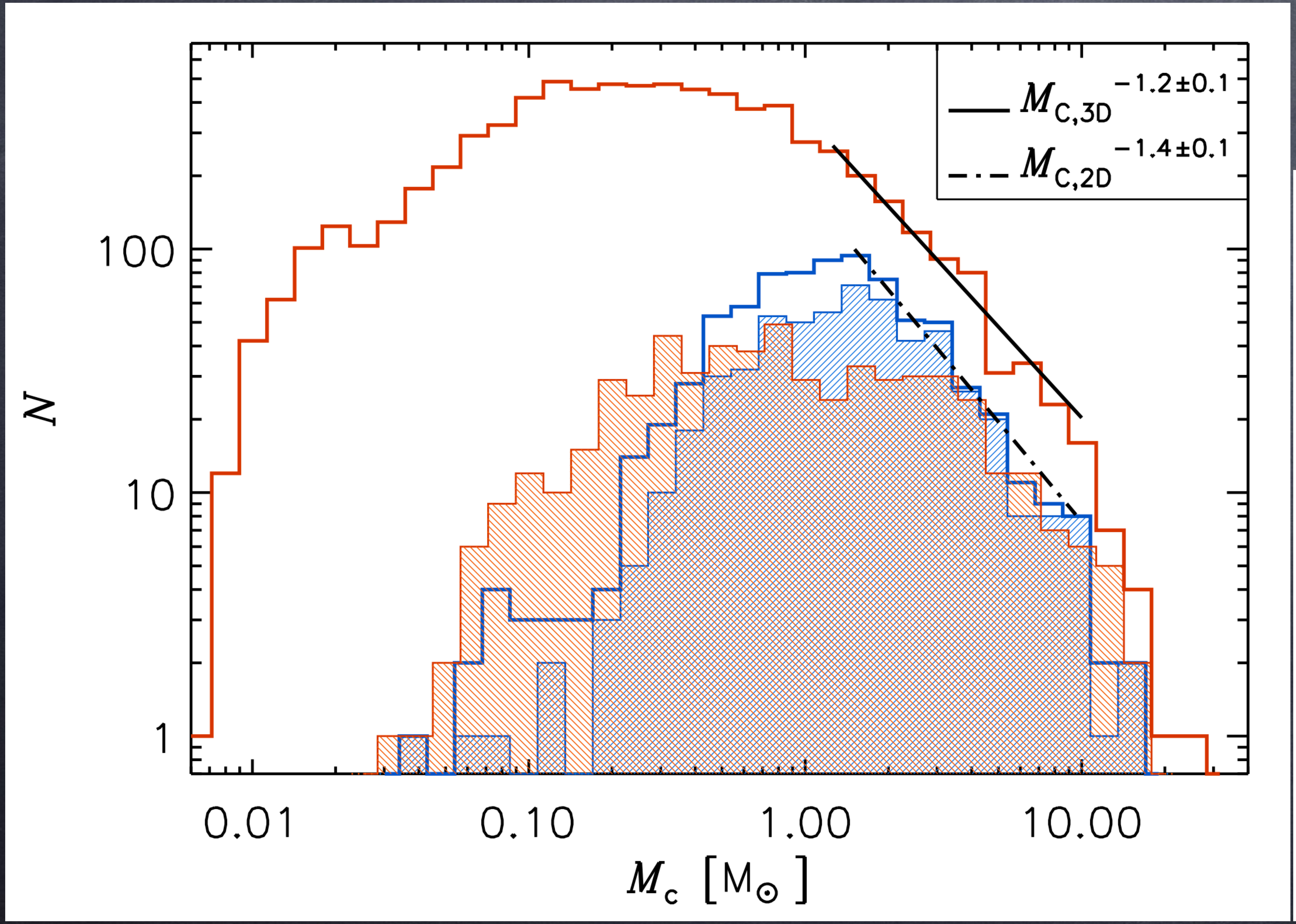
Very weak correlation between masses of 2D GETSF cores and real 3D cores.



SYNTHETIC ALMA MAPS

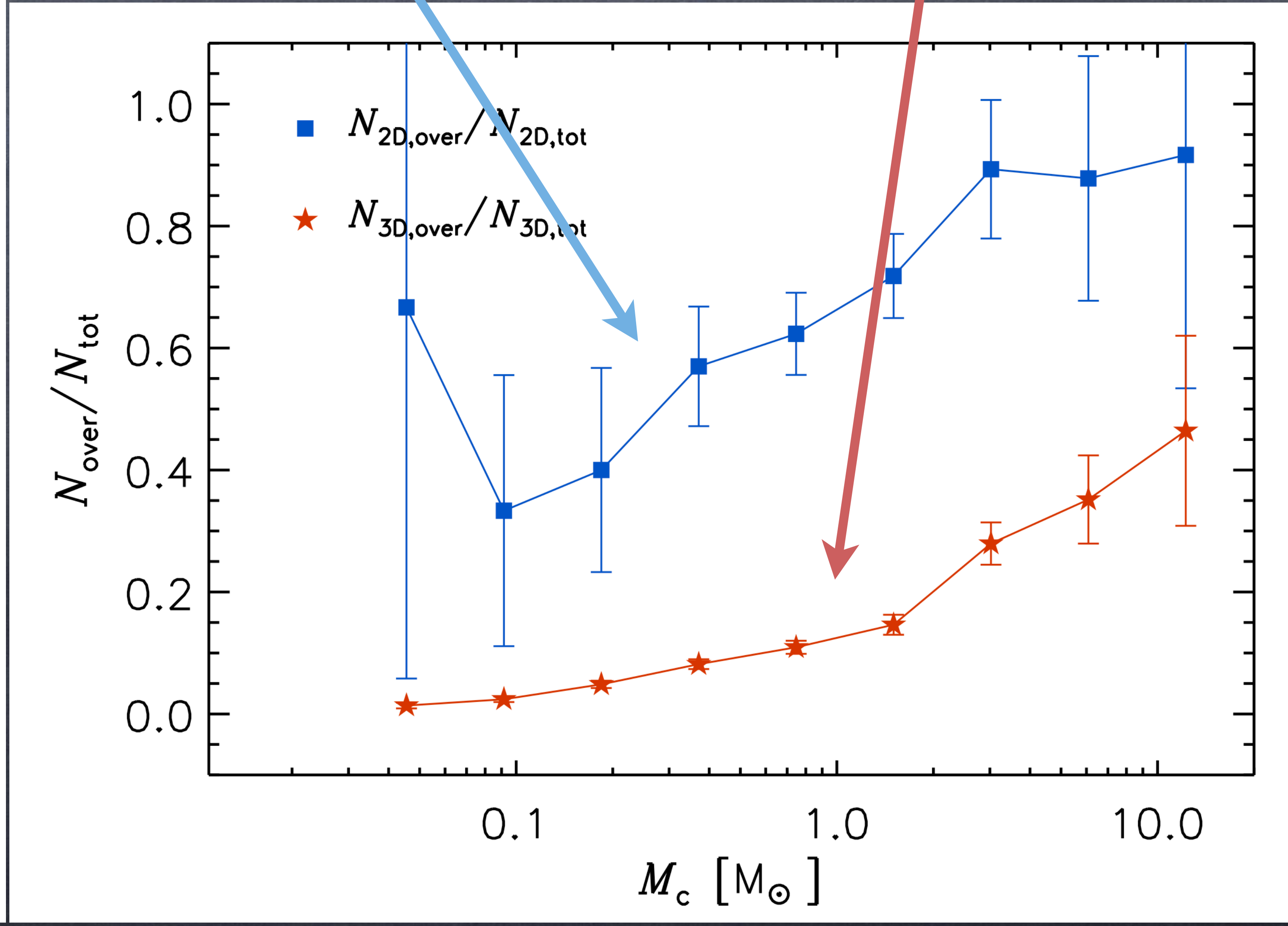
The CMF of GETSF cores has similar slope to that of real 3D cores.

Quite a few observational artifacts, and the CMF is incomplete at all masses.



1-artifacts

completeness



INDIVIDUAL EFFECTS

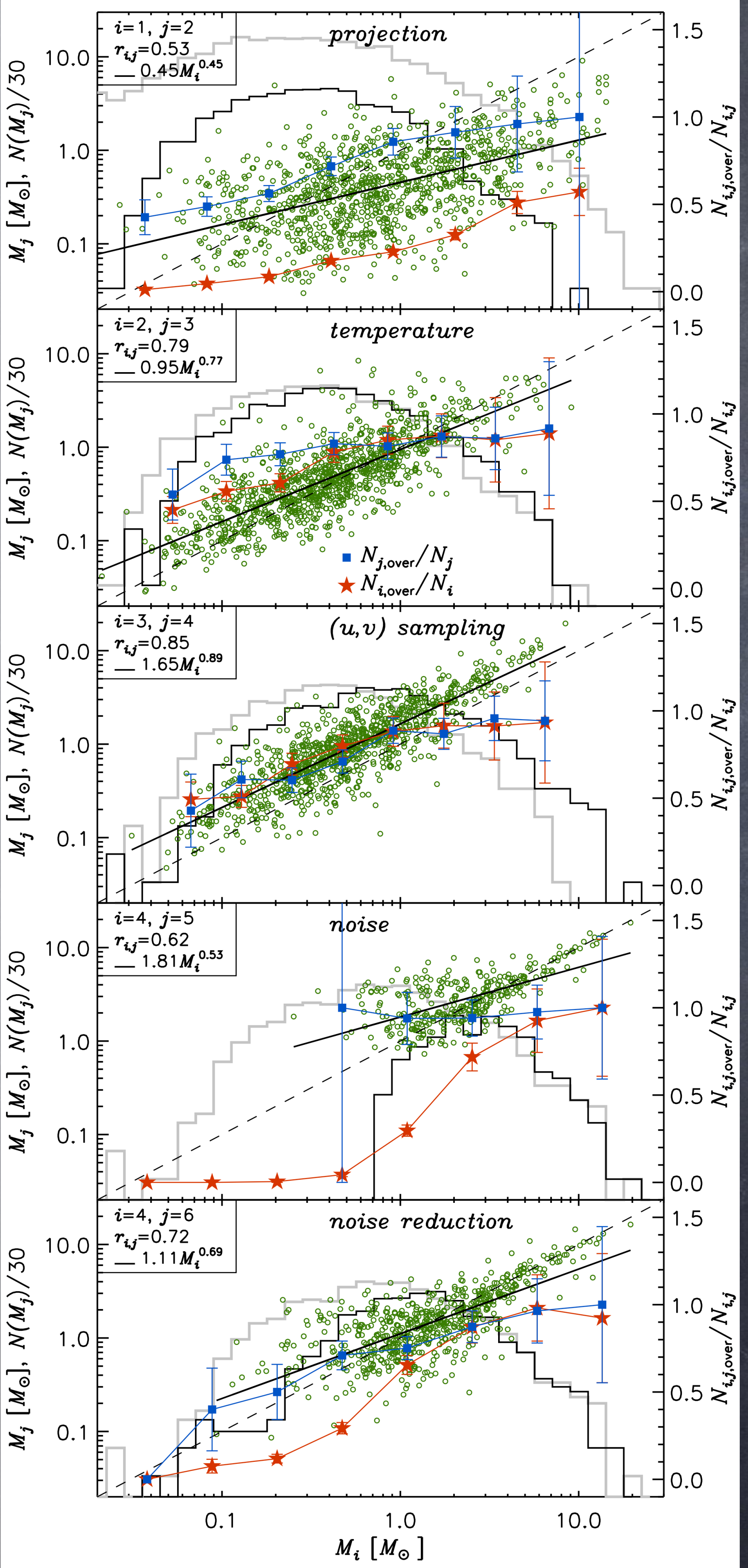
M_i	Extraction	Effect	r
M_1	3D cube		
		projection	0.53
M_2	column density		
		temperature	0.79
M_3	single dish		
		u,v sampling	0.85
M_4	interferometer		
		thermal noise	0.62
M_5	ALMA		
		denoising	0.72
M_6	ALMA denoised		

Correlation coefficient consistent with the product of individual steps:

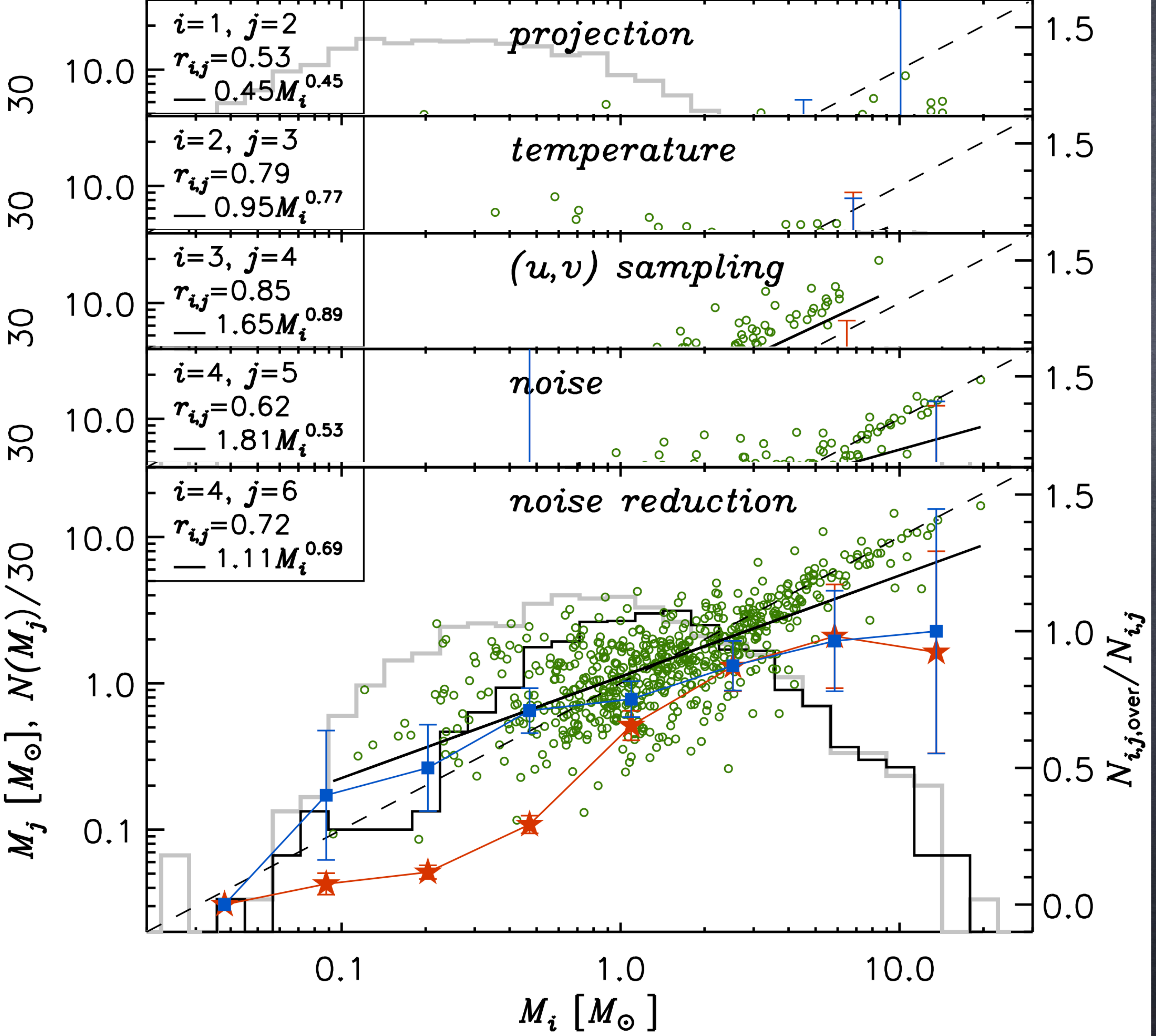
$$r_{1,6} = 0.251$$

$$r_{1,2}\, r_{2,3}\, r_{3,4}\, r_{4,6} = 0.255$$

Projection (incurable) & ***noise*** (costly to improve) are the strongest effects.



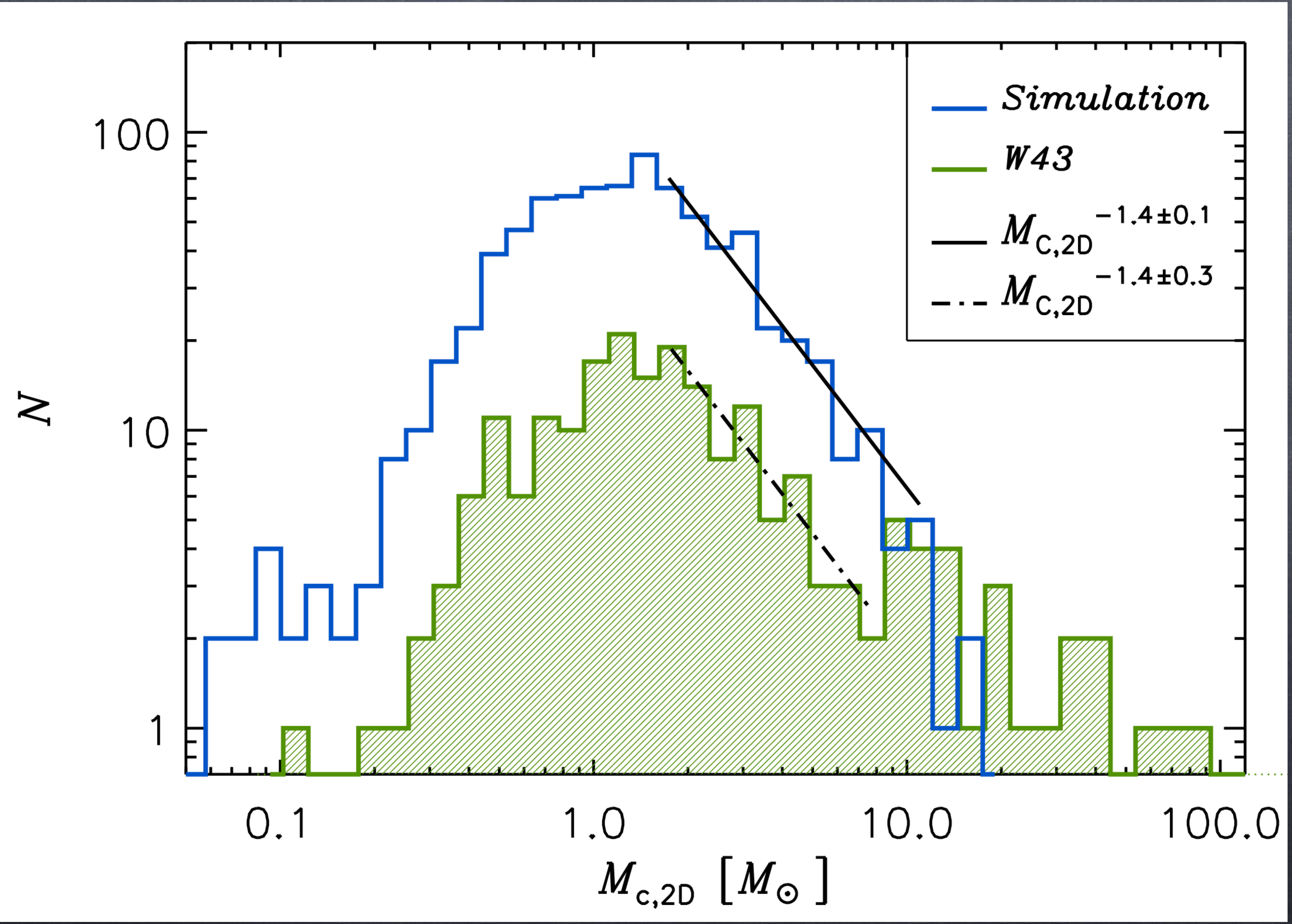
i=1, j=2
$r_{i,j}$=0.53
$0.45M_i^{0.45}$
projection
i=2, j=3
$r_{i,j}$=0.79
$0.95M_i^{0.77}$
temperature
$N_{j,over}/N_j$
$N_{i,over}/N_i$
i=3, j=4
$r_{i,j}$=0.85
$1.65M_i^{0.89}$
(u,v) sampling
i=4, j=5
$r_{i,j}$=0.62
$1.81M_i^{0.53}$
noise
i=4, j=6
$r_{i,j}$=0.72
$1.11M_i^{0.69}$
noise reduction
M_j [$M_\odot$], $N(M_j)/30$
$N_{i,j,over}/N_{i,j}$
M_i [$M_\odot$]



i=1, j=2
$r_{i,j}$=0.53
$0.45M_i^{0.45}$
projection
i=2, j=3
$r_{i,j}$=0.79
$0.95M_i^{0.77}$
temperature
i=3, j=4
$r_{i,j}$=0.85
$1.65M_i^{0.89}$
(u,v) sampling
i=4, j=5
$r_{i,j}$=0.62
$1.81M_i^{0.53}$
noise
i=4, j=6
$r_{i,j}$=0.72
$1.11M_i^{0.69}$
noise reduction
M_j [$M_\odot$], $N(M_j)/30$
$N_{i,j,over}/N_{i,j}$
M_i [$M_\odot$]

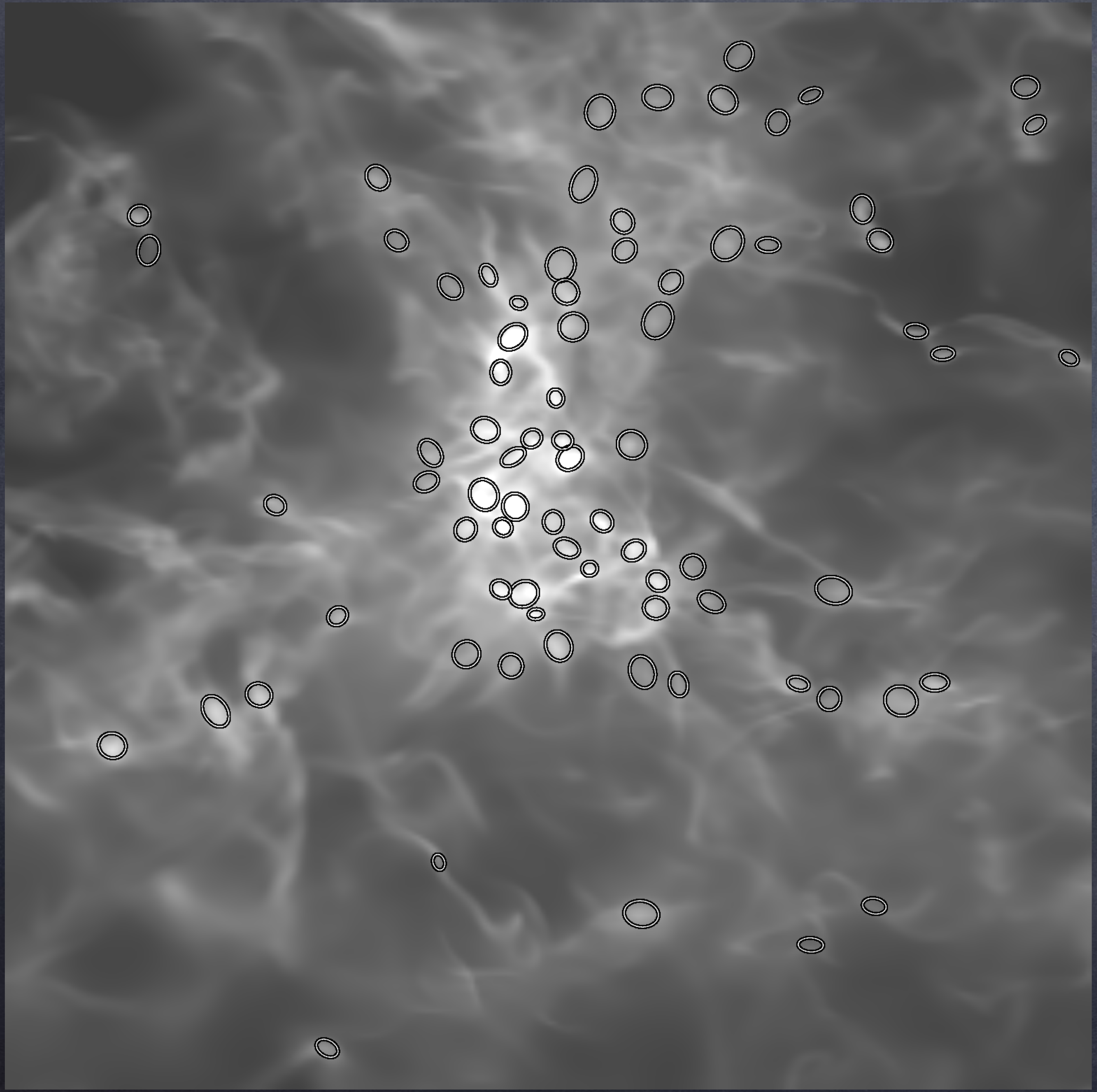
THE CMF IN W43

Is the CMF top heavy?   *Are they really prestellar cores?*

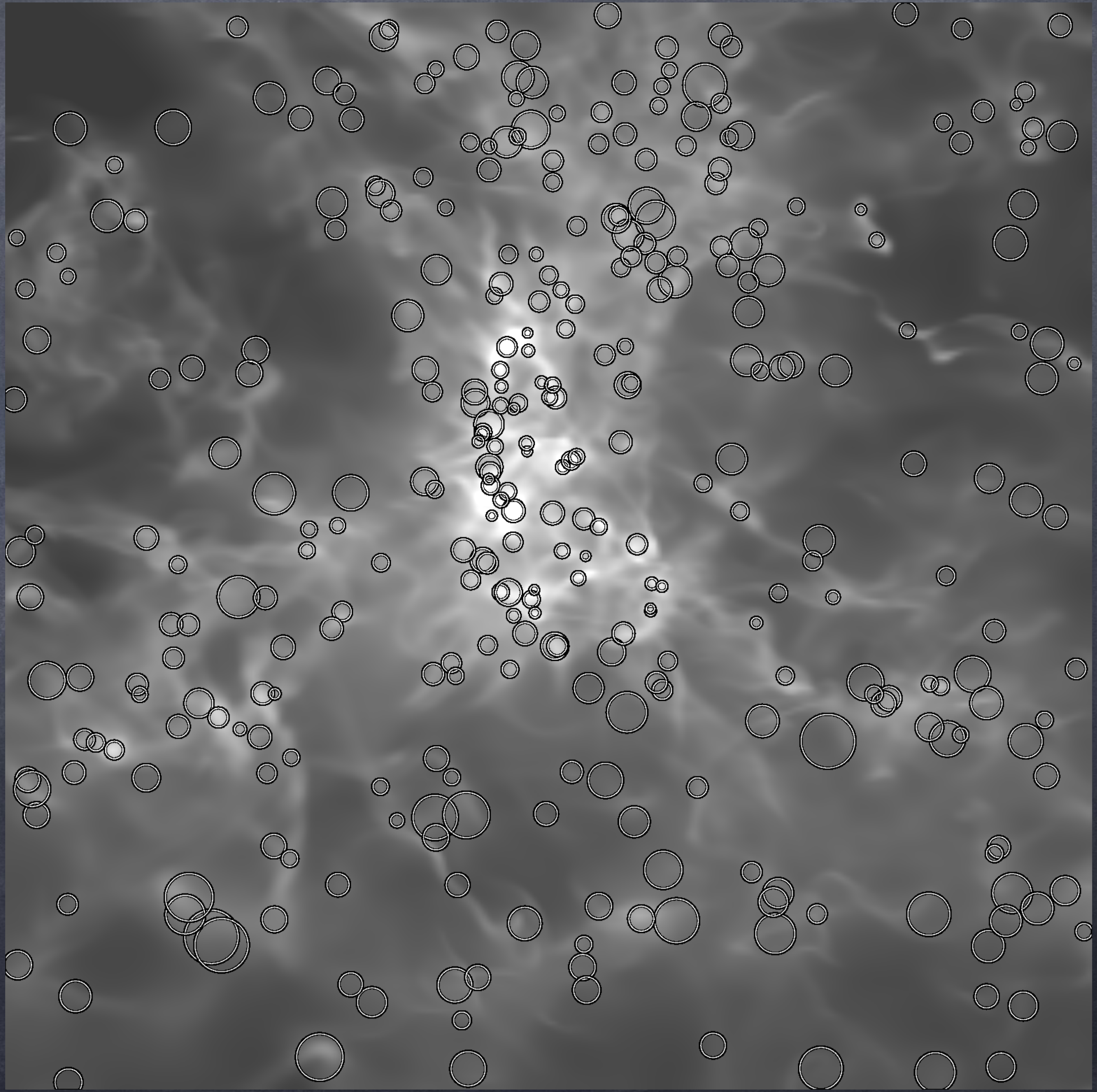


A lot of overlap of real 3D cores in the highest density regions:

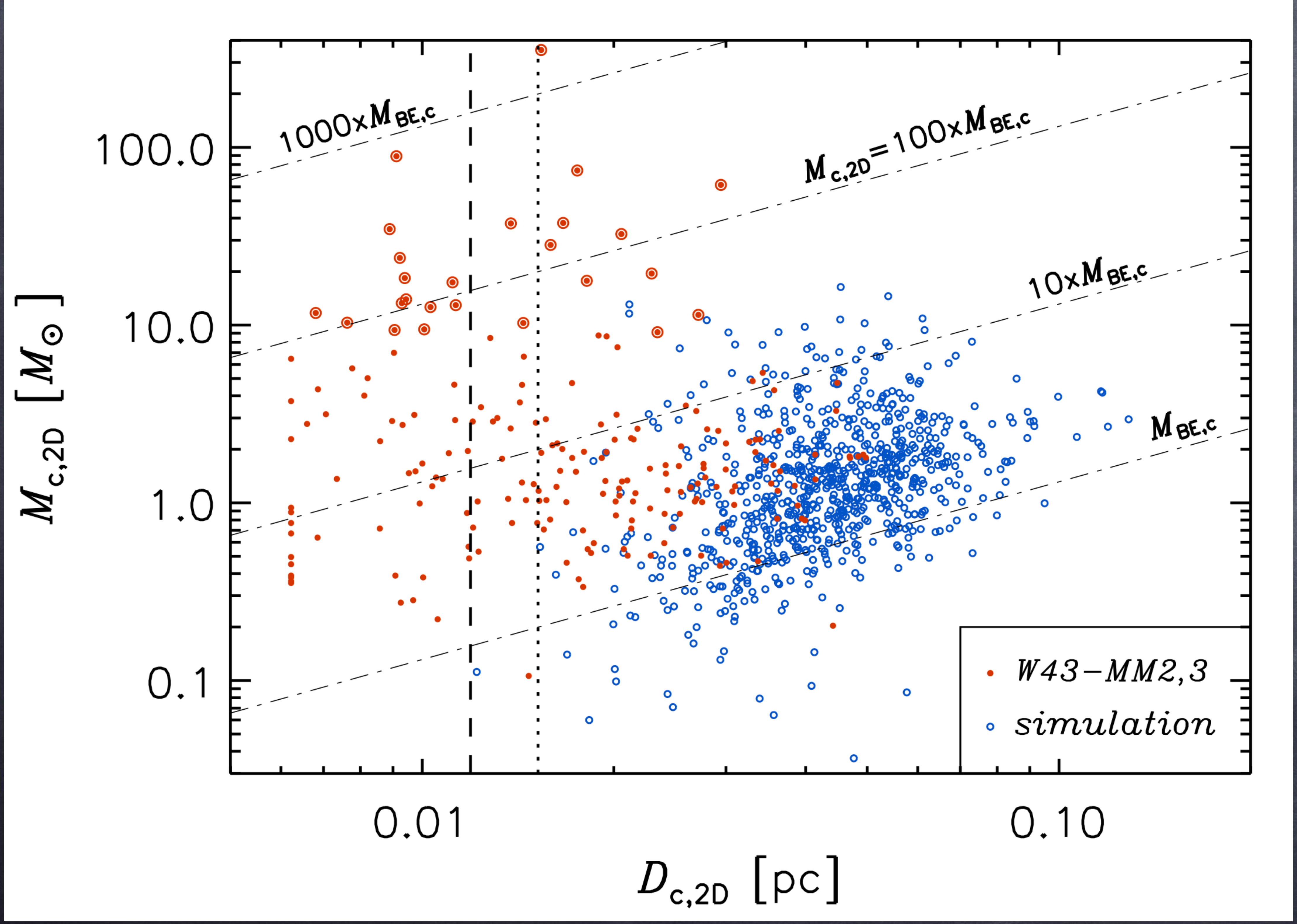
2D CORES



3D CORES (>0.5 M⊙)



100-1,000 $M_{BE,c}$? Definitely not prestellar!



Now confirmed by *Nony et al. (2023, V)*:

- they are protstellar
- the prestellar CMF is NOT top-heavy

SUMMARY

1. GTSF background subtraction works well: decent mass estimate of the main structure in the los.
2. The main core in the los is not always a real 3D cores, 30% of them are artifacts, only 10% > 3 $M_\odot$
3. Most real 3D cores are not detected. Massive ones can overlap (count 1 core instead of 5…)
4. The completeness fraction is monotonic with mass, from 40% at 10 $M_\odot$ to 15% at 1 $M_\odot$.
5. When a 3D counterpart is found, there is *a weak correlation* between the masses of the synthetic ALMA cores and those of the corresponding 3D cores.
6. Random mass error due to, in order of importance: projection, noise, temperature, (u,v) sampling.
7. The CMF slope >1 $M_\odot$ is -1.2 ± 0.1 for real 3D cores, -1.6 ± 0.1 for 2D cores from colum-density maps, and -1.4 ± 0.1 for 2D cores from the ALMA maps.
8. $T_{color} > T_{dust}$, but one can derive empirical relations with the simulations.
9. Most of the most massive cores in protoclusters are PROTOstellar, with mass likely overestimated.
10. We have no observational evidence of a top-heavy prestellar CMF in galactic protoclusters.

OPEN QUESTIONS

1. Are core temperatures overestimated? Alternatively, mass (hence density) could be overestimated, but the density is still large, and also the assumed opacity (0.01 cm2/g)
2. Why are protstellar cores more massive? Is the mass overestimated? Or is the CMF overestimated at high masses because protostellar cores are long-lived (constantly fed)?
3. Is the observed CMF slope always similar to that of real 3D cores? How does the relation depend on the environment, observational strategy, data analysis?
4. Can we even separate properly the PROTOstellar and PREstellar CMFs? Overlap from projection will always be a problem for the most massive cores.
5. If protostellar cores are fed over ~1 Myr to form a massive star, can we probe that phase from the (shallower) slope of the PROTOstellar CMF?
6. At high spatial resolution (~0.01 pc), shouldn’t we select PREstellar cores as extended objects rather than compact? Sure GETSF can get larger objects, but in practice…..