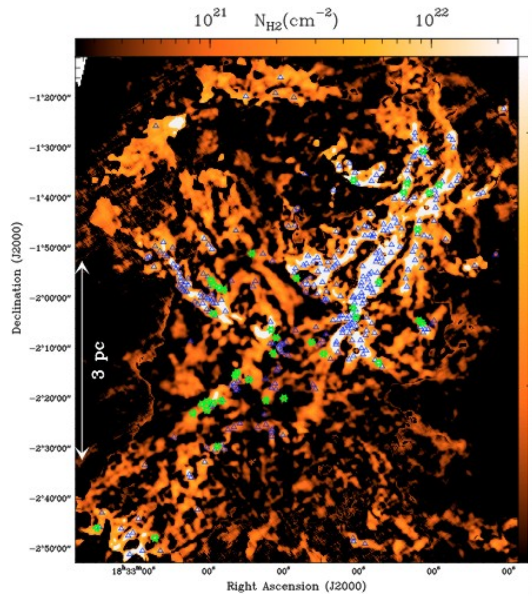

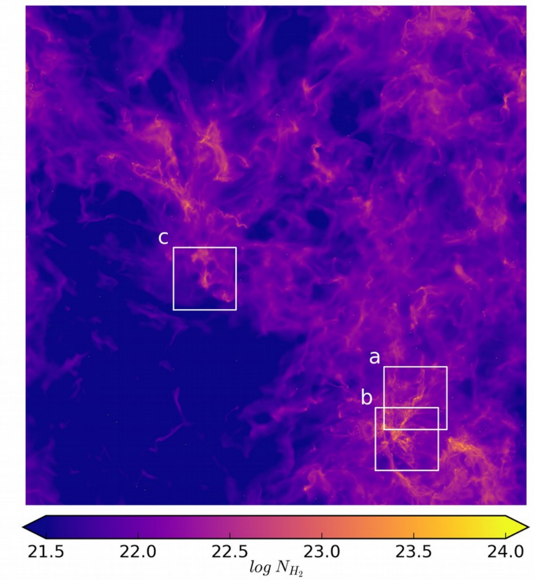

From the CMF to the IMF: Beyond the Core-Collapse model

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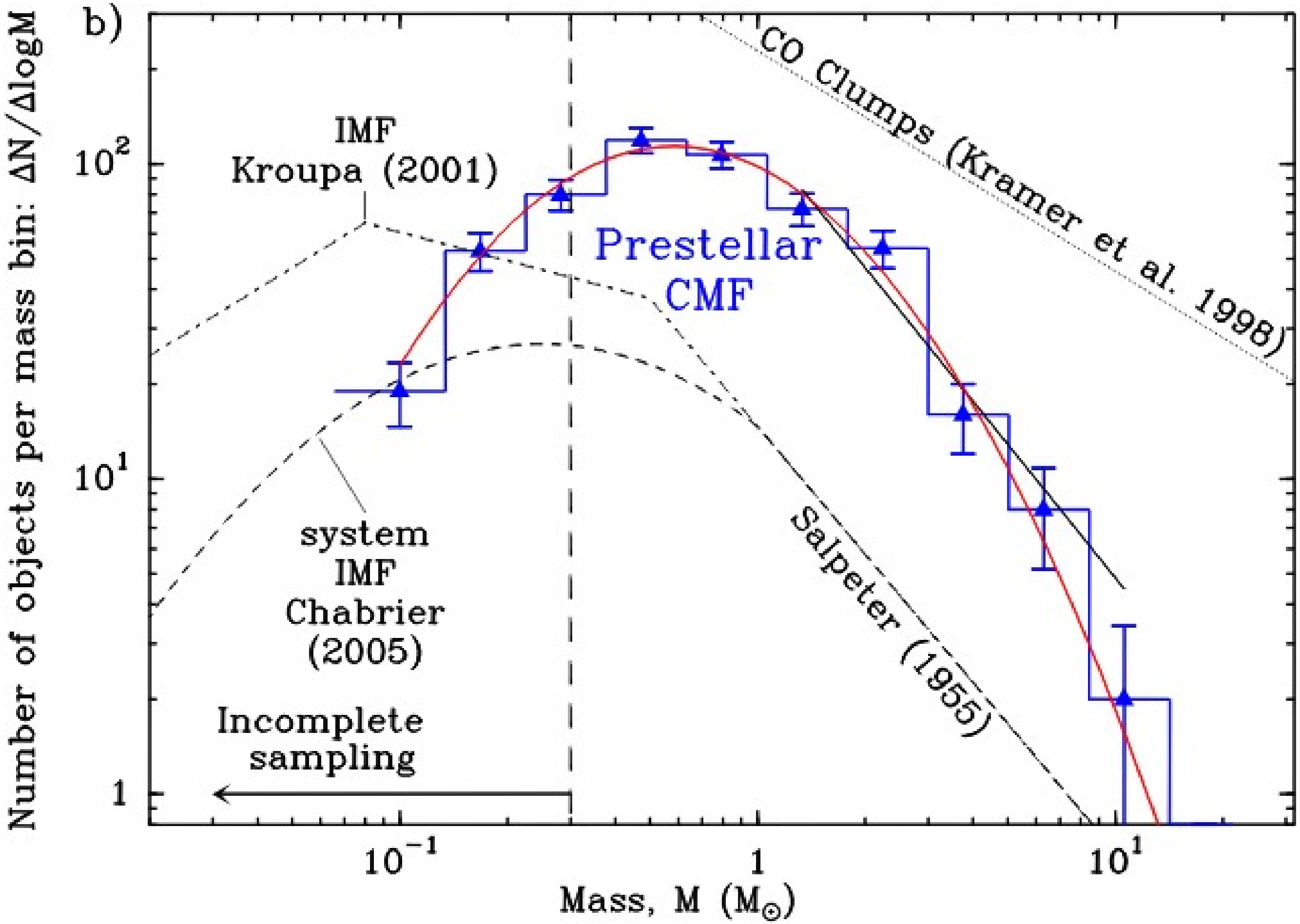
Star formation scenarios

1. Turbulent core collapse (monolithic collapse, McKee and Tan 2003)
   - Single core collapses under its gravity and forms a star (or a multiple system). M_star = efficiency * M_core.
2. Clump collapse (competitive accretion, Bonnell at al. 2001, 2004)
   - Stars form in clusters, and the whole cluster collapses globally. The gravitational potential is highest in the center → more accretion → high-mass star in the center.
3. **Inertial-Inflow (Padoan et al. 2017, 2020)**
   - Rather than gravity working alone, turbulence plays a key role. Converging flows build up nodes which may collapse. Prestellar cores do not suddenly stop accreting, and turbulence can feed more mass into the forming star even after the collapse has started → wide range of final masses.

CMF and IMF

- CMF: Core Mass Function, a census of prestellar cores/clumps
- IMF: Initial Mass Function, a census of zero-age Main Sequence Stars



- Andre et al. (2014): Herschel observations of Aquila (Könyves et al. 2010, Andre et al. 2010) found efficiency 0.2-0.4 in CMF → IMF; similarity implies one-to-one relation for low-mass stars.

Do low-mass stars form by core-collapse?

Motivation:

There is mounting observational evidence that high-mass stars continue to accrete outside their progenitor cores: the lack of high-mass prestellar cores (e.g., Sanhueza et al. 2019), and observations of parsec-scale mass streams (e.g., Peretto et al. 2013). Simulations show this as well (e.g., Padoan et al. 2020).

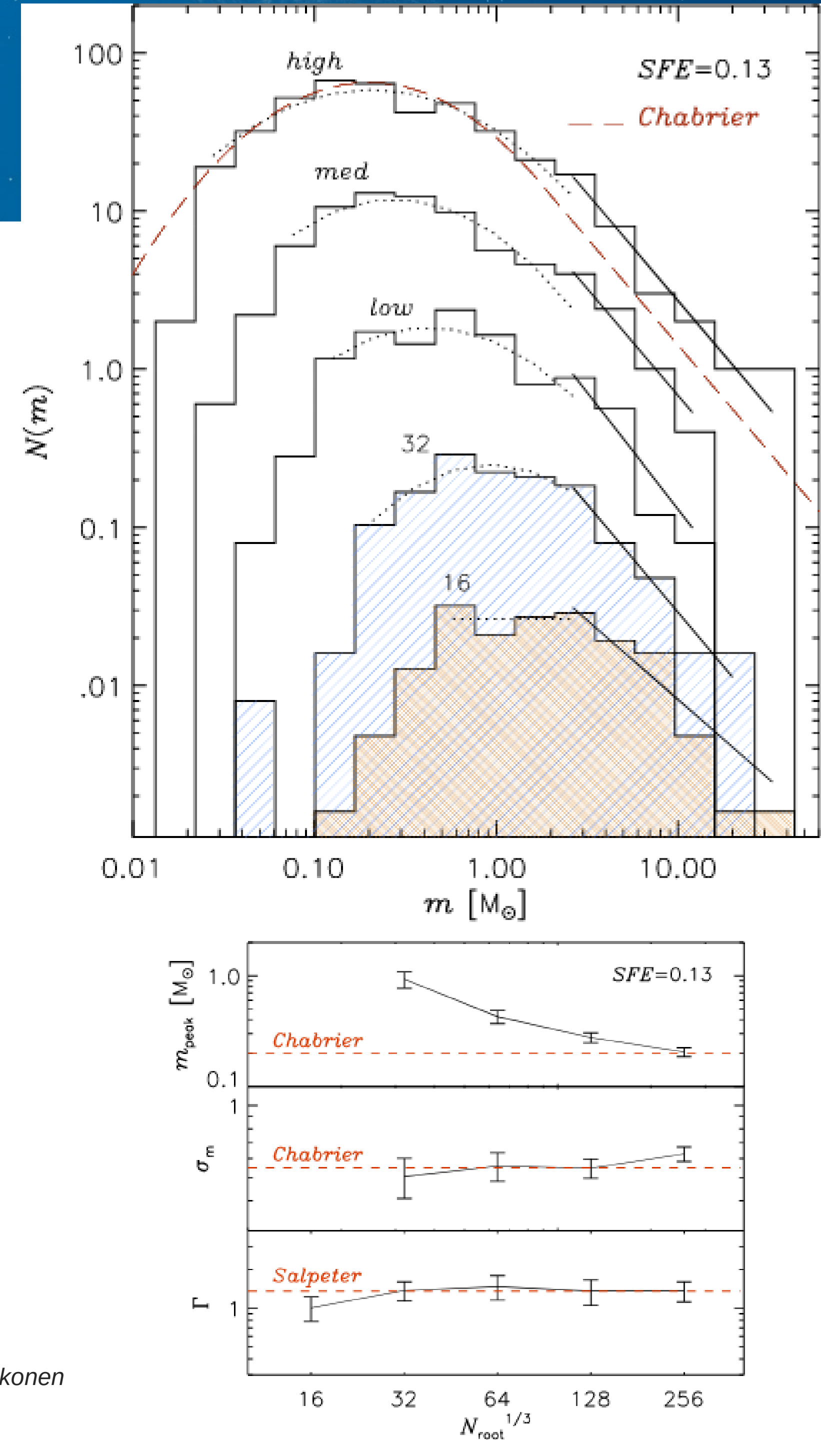
However, there are plenty of potential low-mass progenitor cores, and low-mass star formation is often considered to be the 'simple' case in comparison. Could they be formed by a monolithic, turbulent core collapse?

Method:

MHD simulation with sink (star) particles. Find the bound cores at the time of the sink formation and see if M_star = efficiency*M_core.

MHD simulation of a star-forming cloud

- Detailed in Haugbølle et al. 2018
- Calculated with RAMSES AMR MHD
- 4pc periodic box with a mass of 3000 Msun, mean number density 795 cm^{-3}
- 256 root-grid, AMR → 50 AU
- Sink particles are formed ($\rho_s = 1.7\times10^9$ cm^{-3}, efficiency 50% subgrid feedback 'model') and mass tracer particles are tracked
- Randomly driven supersonic turbulence
- ~2.5 Myr with self-gravity → a realistic IMF is obtained



Clumpfind

- 3D clumpfind (PPP). Reference: Padoan et al. (2007)
- Density field is scanned for overdensities in discrete density levels with amplitude $\delta\rho/\rho = f$, around density maximums. Once the initial tree is constructed, the connected regions over each density level are added if they are bound: $E_g >= E_t + E_k$. Overdensities are split up into separate cores if smaller cores would be bound, too. Otherwise, the larger, bound core is kept intact: overdensities which are not bound can be subsumed by larger overdensities. Mass is followed down to the minimum level or when the overdensity would become unbound, whichever comes first.
- Parameters: f, minimum density level, minimum size of the region.
- Setup: 0.5pc subcubes ($1024^3 \rightarrow$ 100 AU) around each sink as it forms, to catch the prestellar clump just at the collapse. f = 2%, minimum level = $10 * n_{mean}$ = 7950 cm^{-3}, minimum size = 4 cells.

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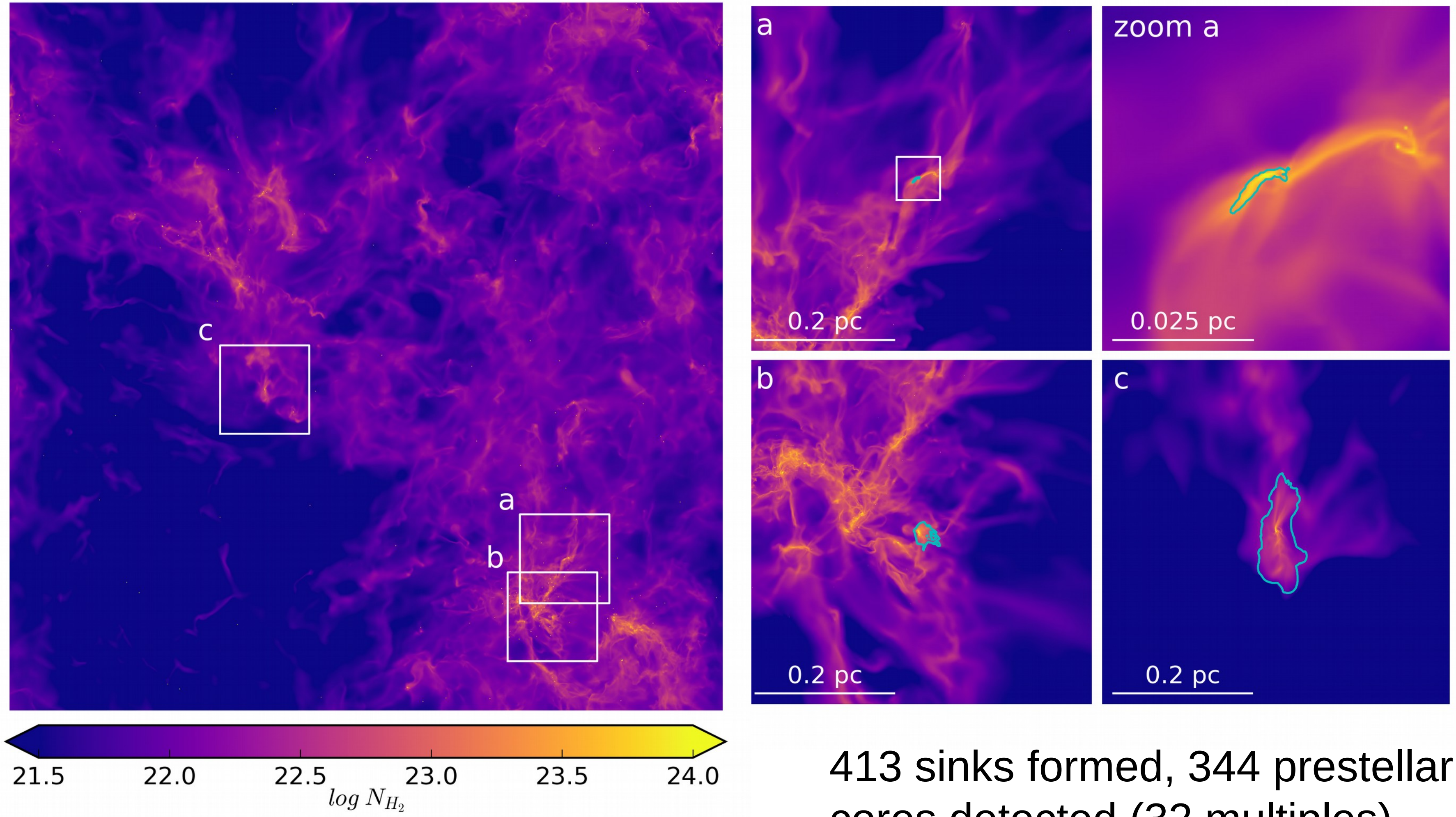
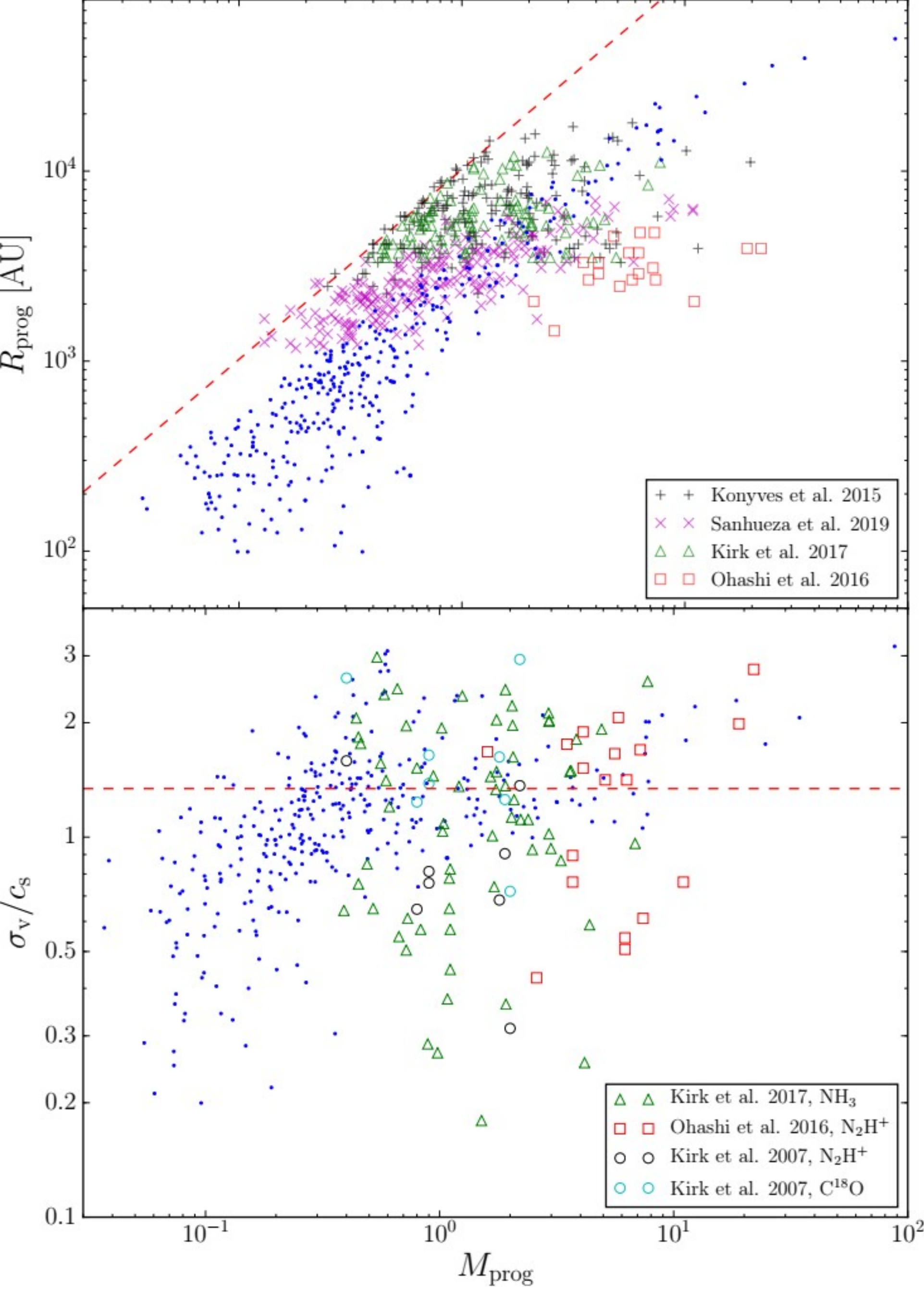
Progenitor clumps



413 sinks formed, 344 prestellar cores detected (32 multiples).

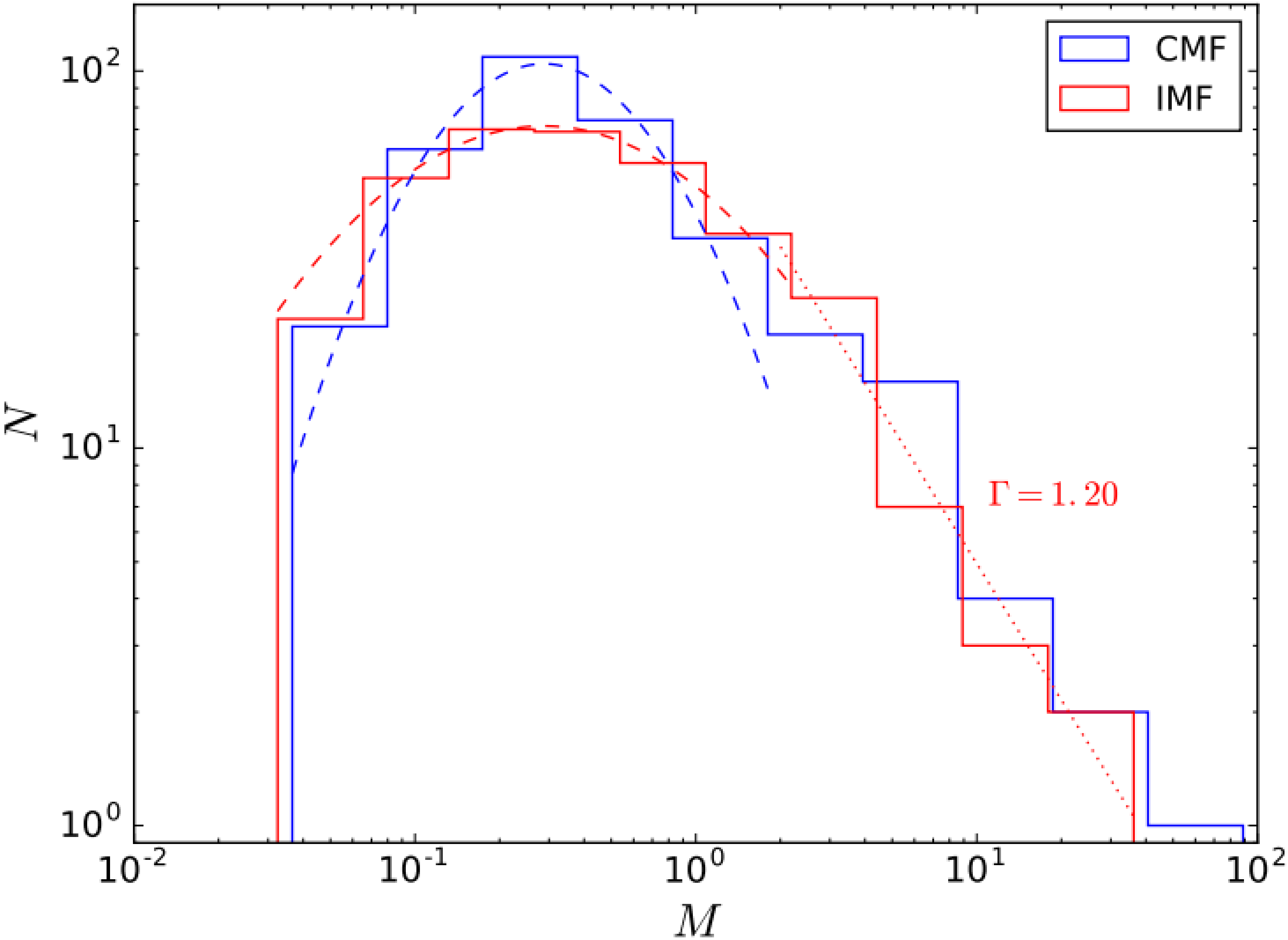
R, M, sonic Mach



Comparison with the observations shows that our progenitor clumps overlap with the observations (resolution limited ~ 1000 AU).

As our progenitors are technically selected after the collapse has already started (the sink was created during the previous 22 kyr timestep), they may be more condenced than true prestellar cores. However, they should still contain all of their original bound mass and indeed should be even more bound (as well as maybe have accumulated more mass).

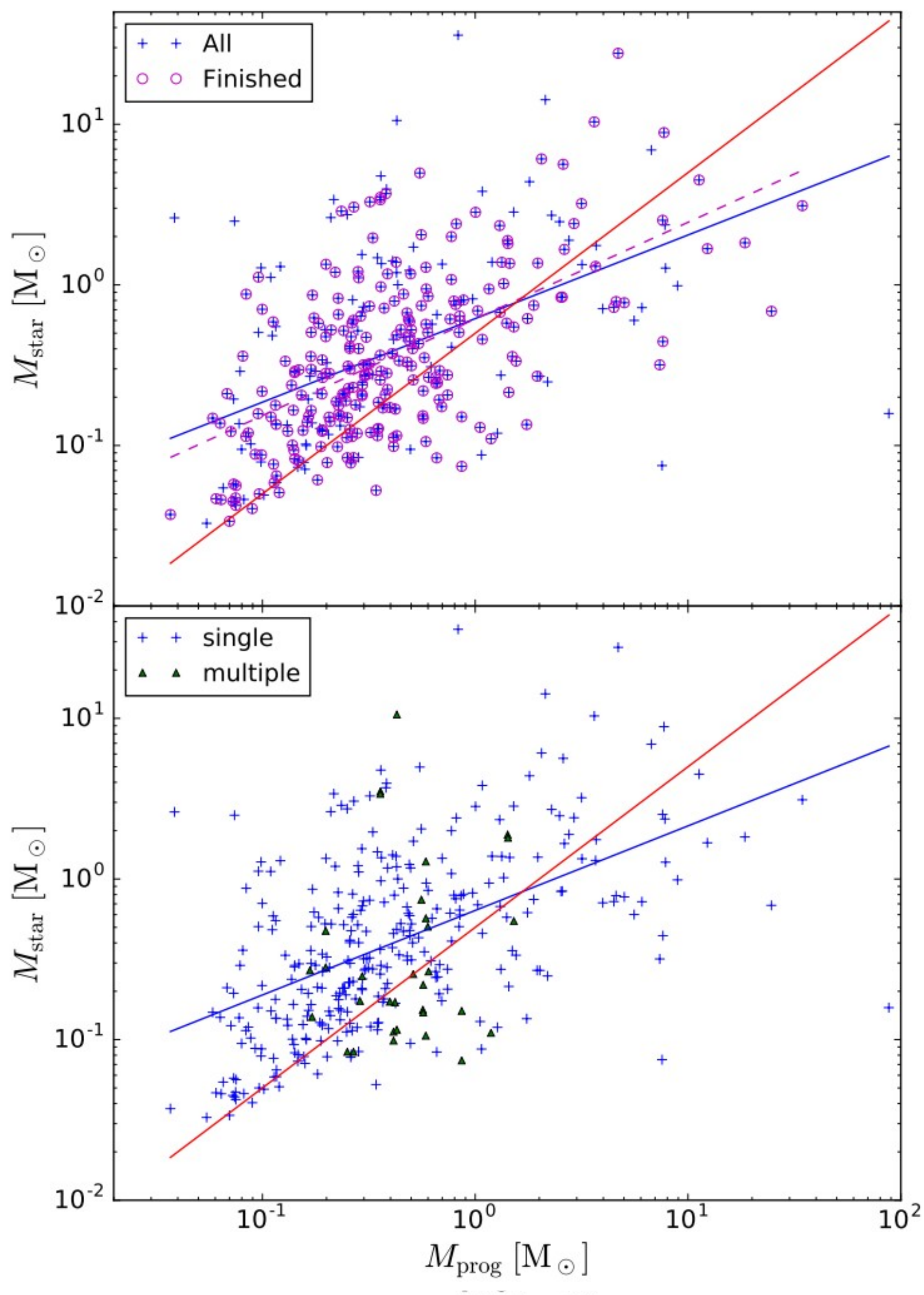
Progenitor clumps vs. sink (star) masses



Statistical similarity but no offset.

Mass peak for both ~0.3 Msol, but converges towards 0.17 (IMF) and 0.26 Msol (CMF) with resolution.

However, this does not mean one-to-one relationship from a core to a star.



Progenitor vs. Star

- Constant 50% efficiency (red line) would require a slope of 1 (in loglog plot).
- Instead, the slopes are 0.5 – 0.6, with the Pearson's correlation coefficient about the same.
- High-mass progenitors (> 5 Msol) generally subfragment into several smaller cores later on. But we have many sinks that are much more massive than what their initial bound mass reservoir would allow.

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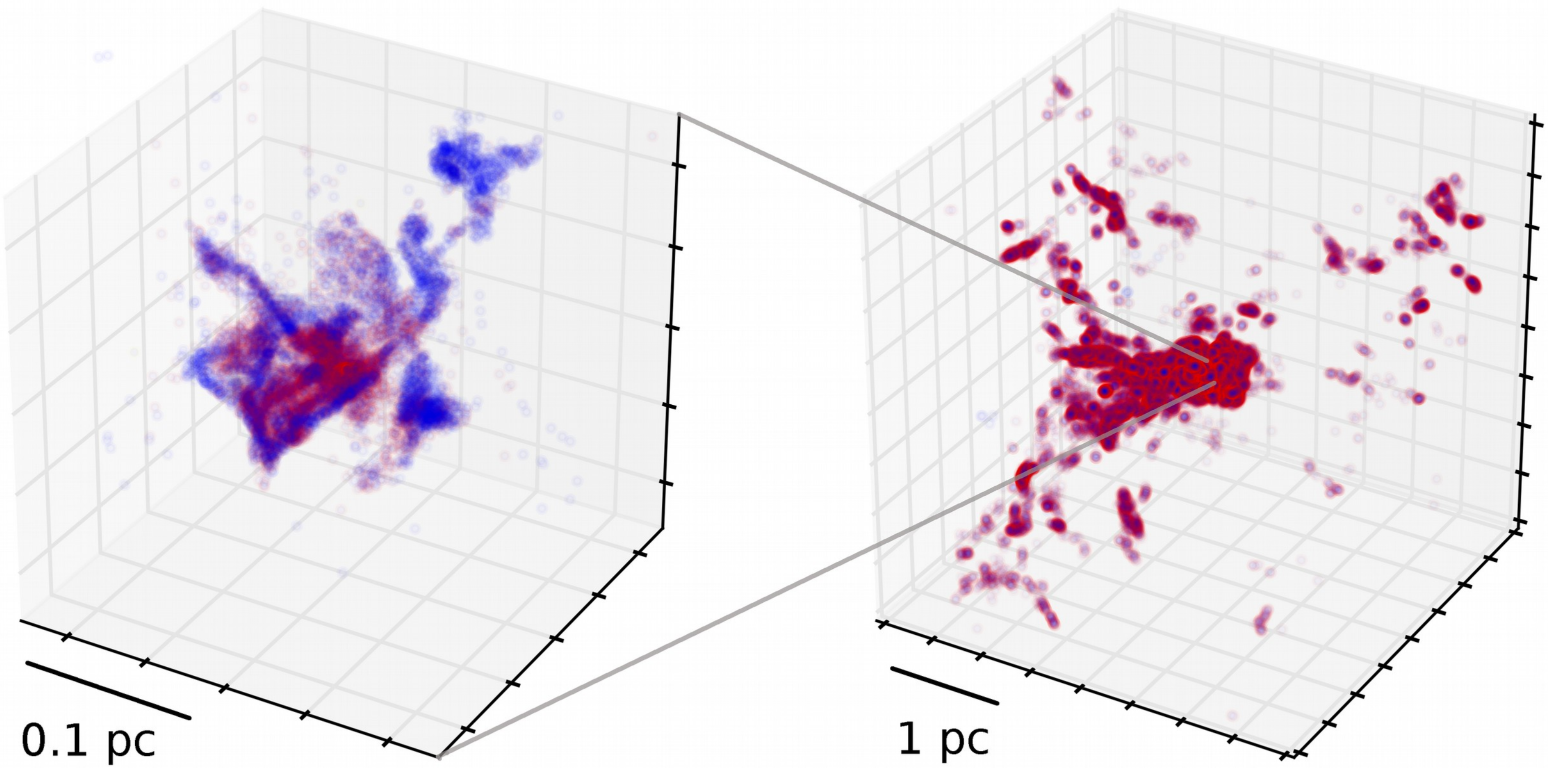
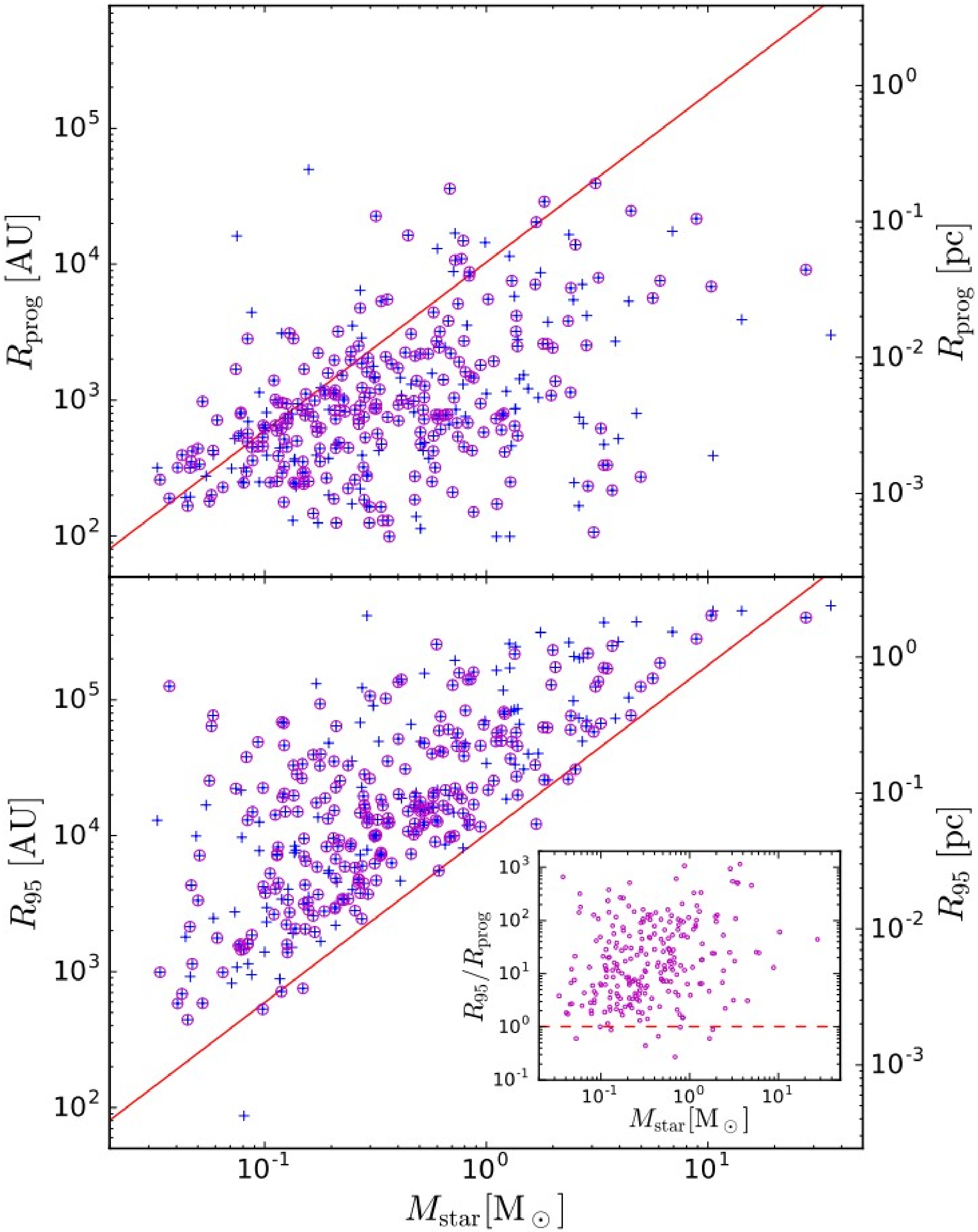
Accretion of mass: tracers



- Left: Example progenitor core and tracers assigned to it, shown in a 0.25 pc subcube. Red dots (~60%) are tracers that will end up in the sink, while blue dots end up in some other sink.
- Right: The tracers (red) are accreted from the whole 4 pc MHD box (centered on the sink). Over 90% of the final star mass is still outside the progenitor core.



Inflow region

Inflow region:
R_{95} = the radius within which 95% of the mass is accreted.

Red line (Padoan et al. 2020):
$R_{95} = 0.05pc * (M_{star}\ [Msol])^{1.24}$
(fitted to highest accretion sources, which match R_{95} lower envelope, 2 – 60 Msol)

Inset: The ratio of the accretion radius to the bound progenitor radius. There is no correlation with stellar mass, and clearly the majority of the stars are accreting at least some mass outside of their progenitor radius.

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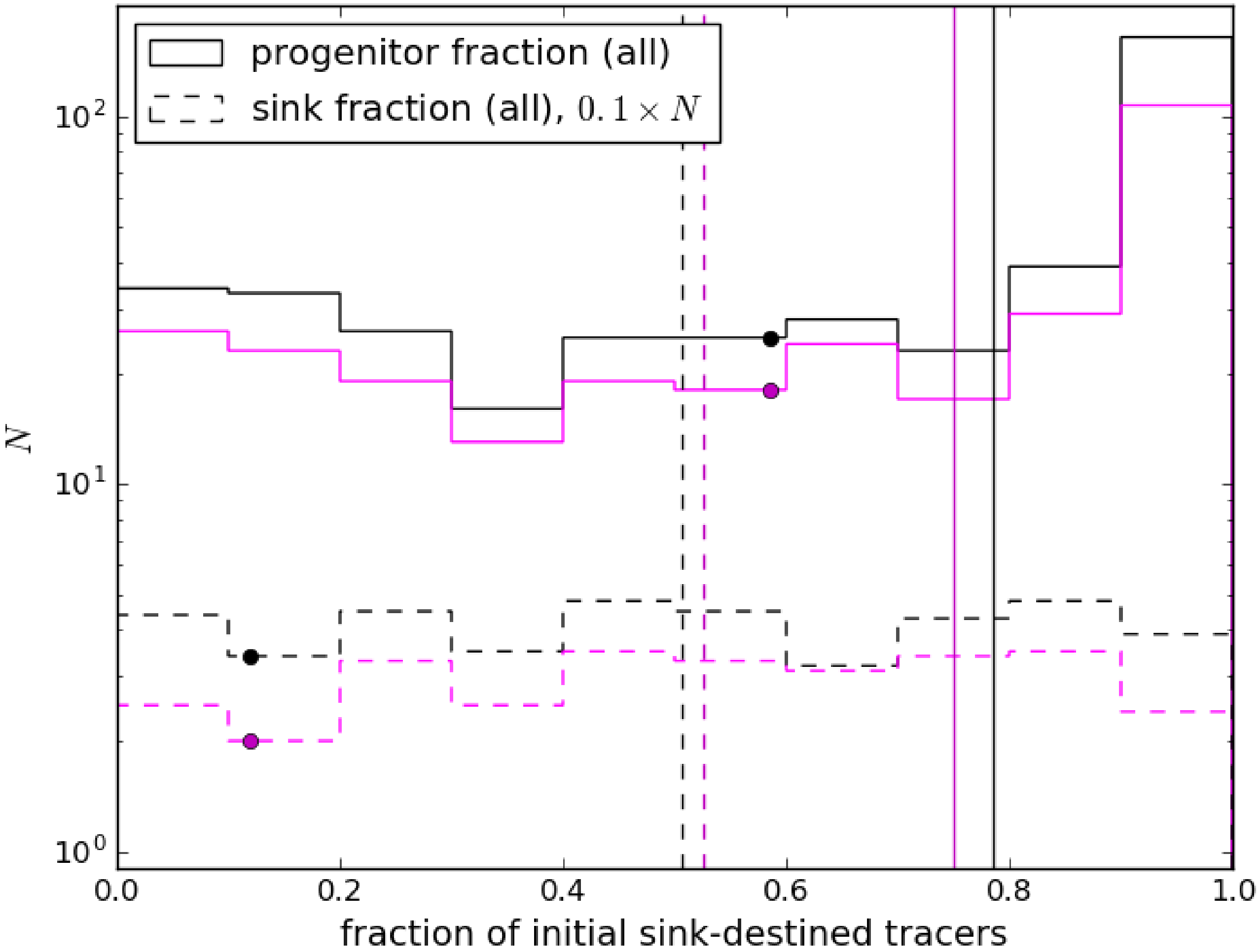
Accretion of mass: tracers



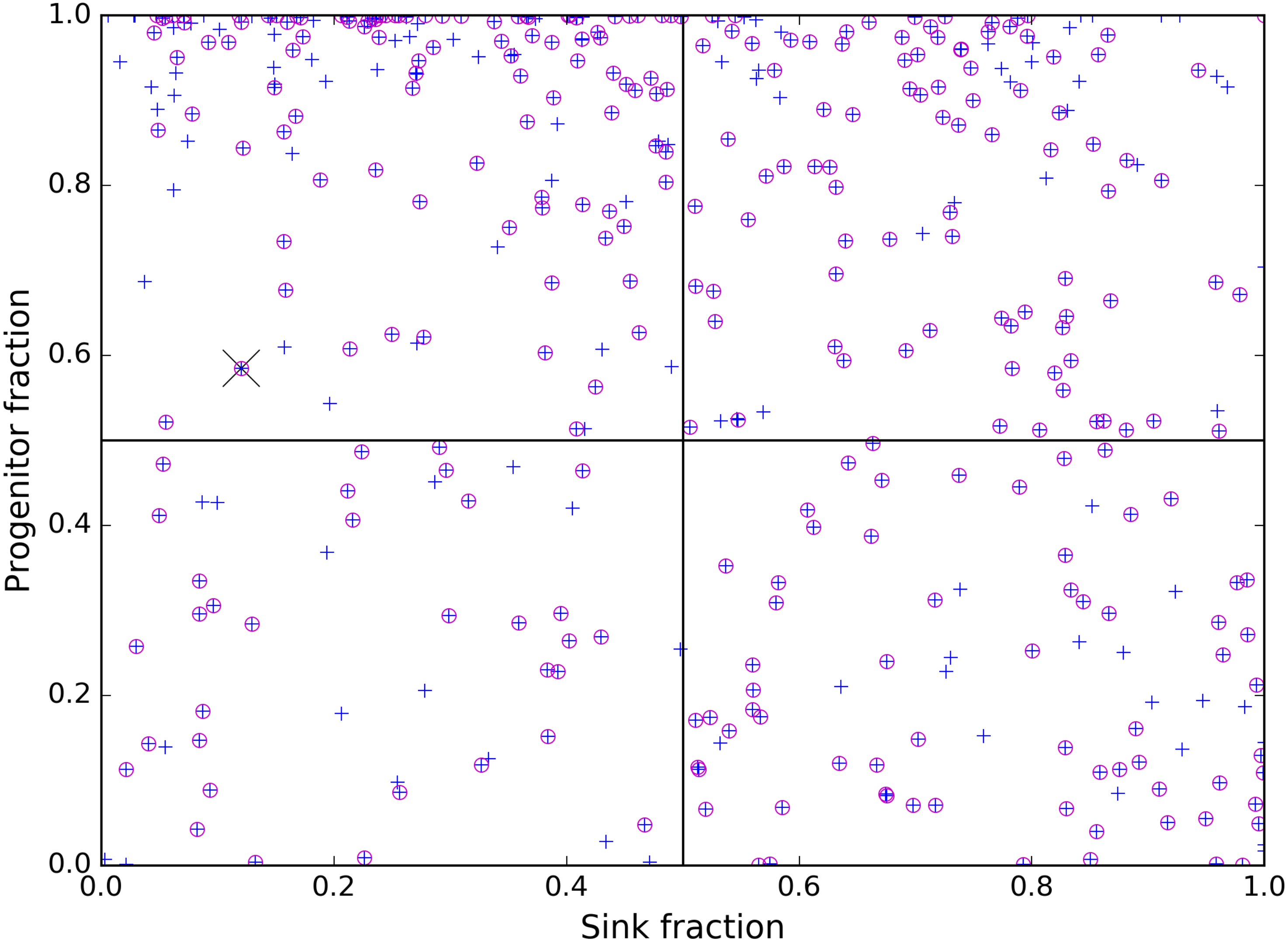
Tracer fraction histograms. Vertical lines are medians.

Solid: the fraction of tracers of the initial progenitor that will be accreted by the sink. Most of the progenitor mass is accreted.

Dashed: The fraction of final sink mass already in the progenitor (initial sink-destined tracers divided by final ones); more mass is often accreted from outside.

Color: black = all, magenta = sinks that have finished accreting by the end of the simulation.

Accretion of mass: tracers



Tracer fractions as a scatterplot.

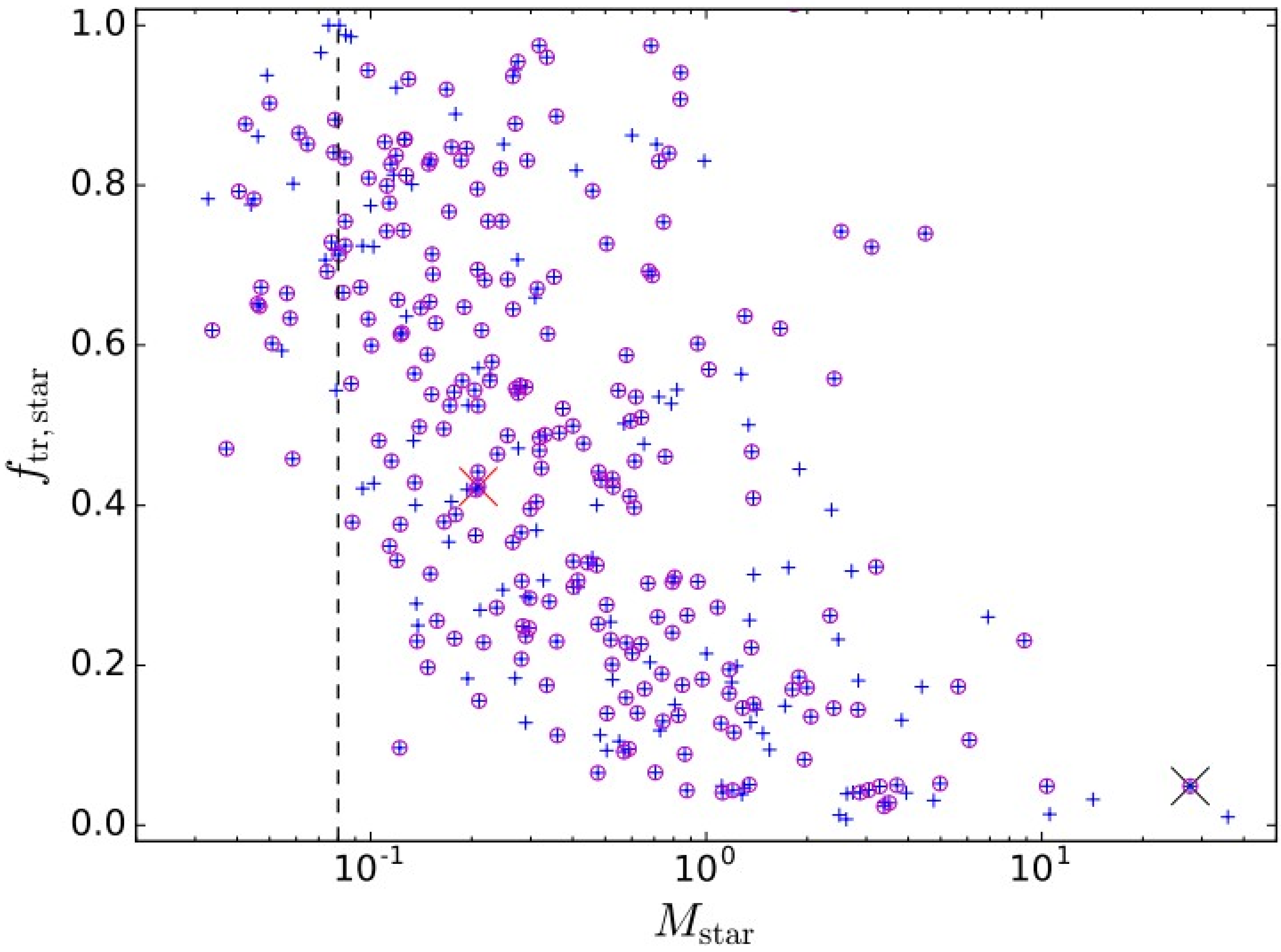
The upper right quadrant is where we have >50% of the progenitor going into the sink and representing >50% of the final sink mass.

All (blue crosses): 30% in upper right quadrant

Finished (magenta circles): 31% in upper right quadrant

Black cross is the example progenitor.

Accretion of mass: tracers



The fraction of final stellar mass already in the progenitor as a function of final stellar mass.

For stars less than 1 Msol, ~50% of the stellar mass originates outside the core.

This increases to ~90% for intermediate-mass stars (2 < M / Msol < 5).

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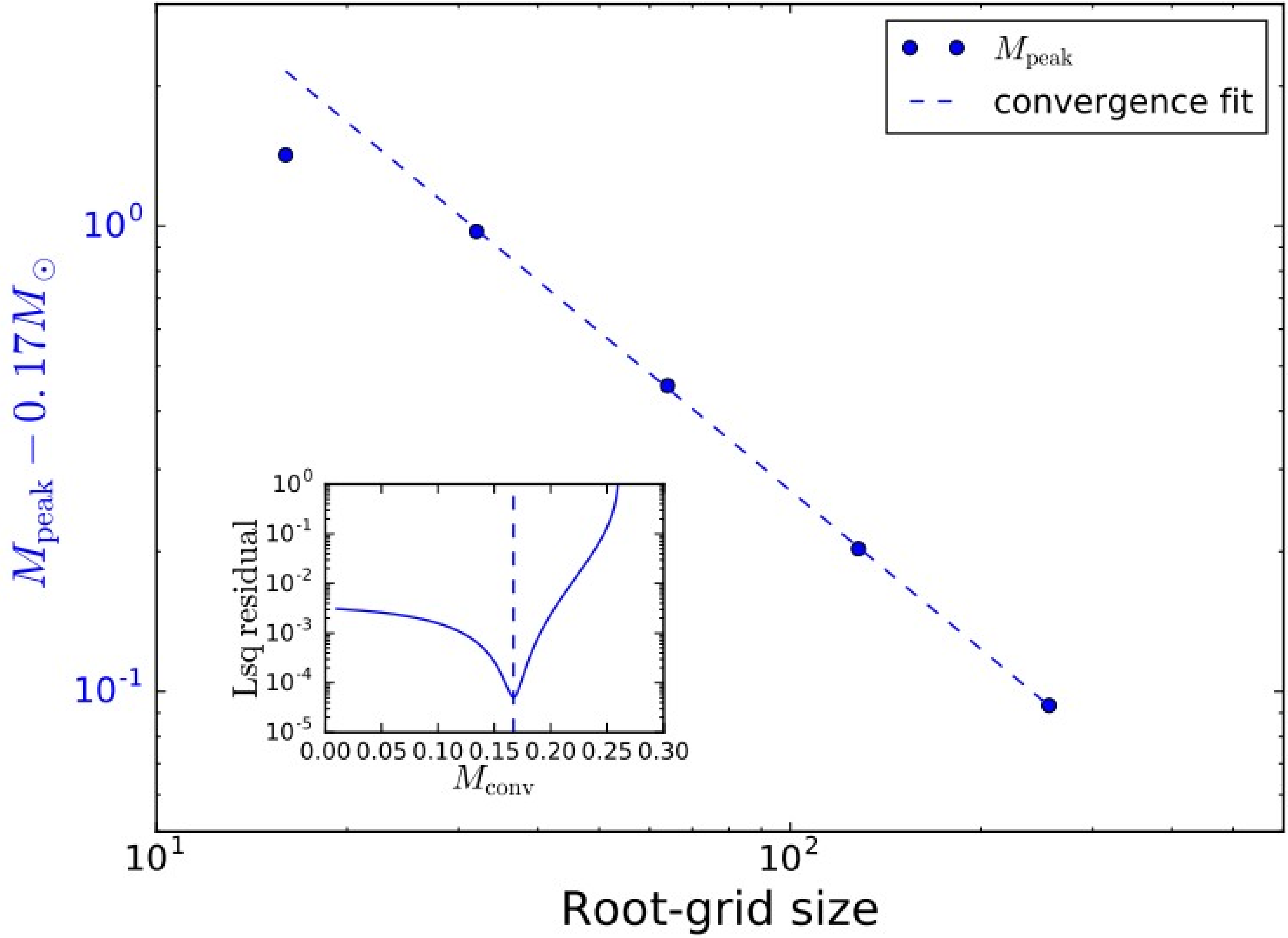
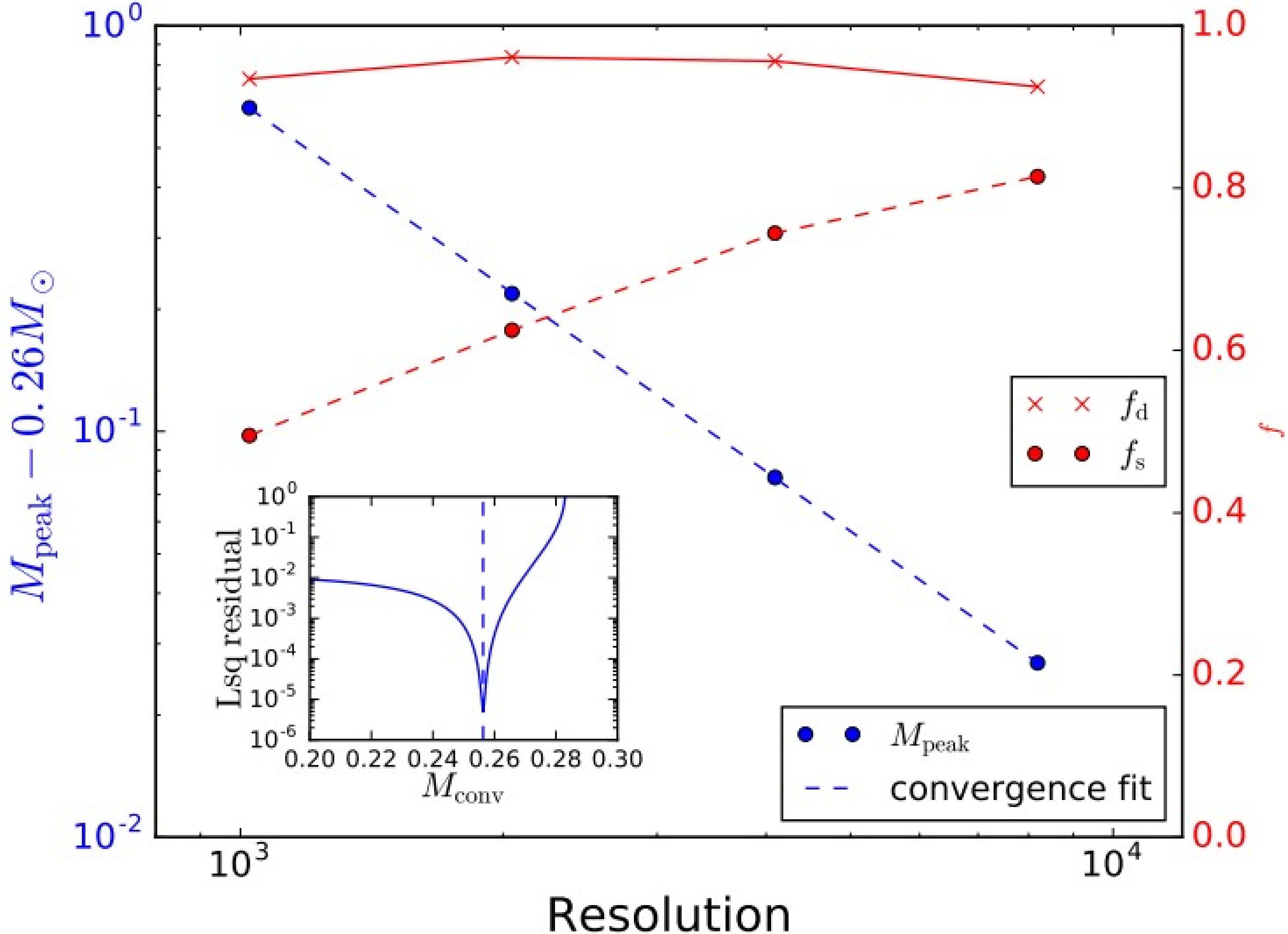
Resolution: IMF convergence



Resolution: Progenitors

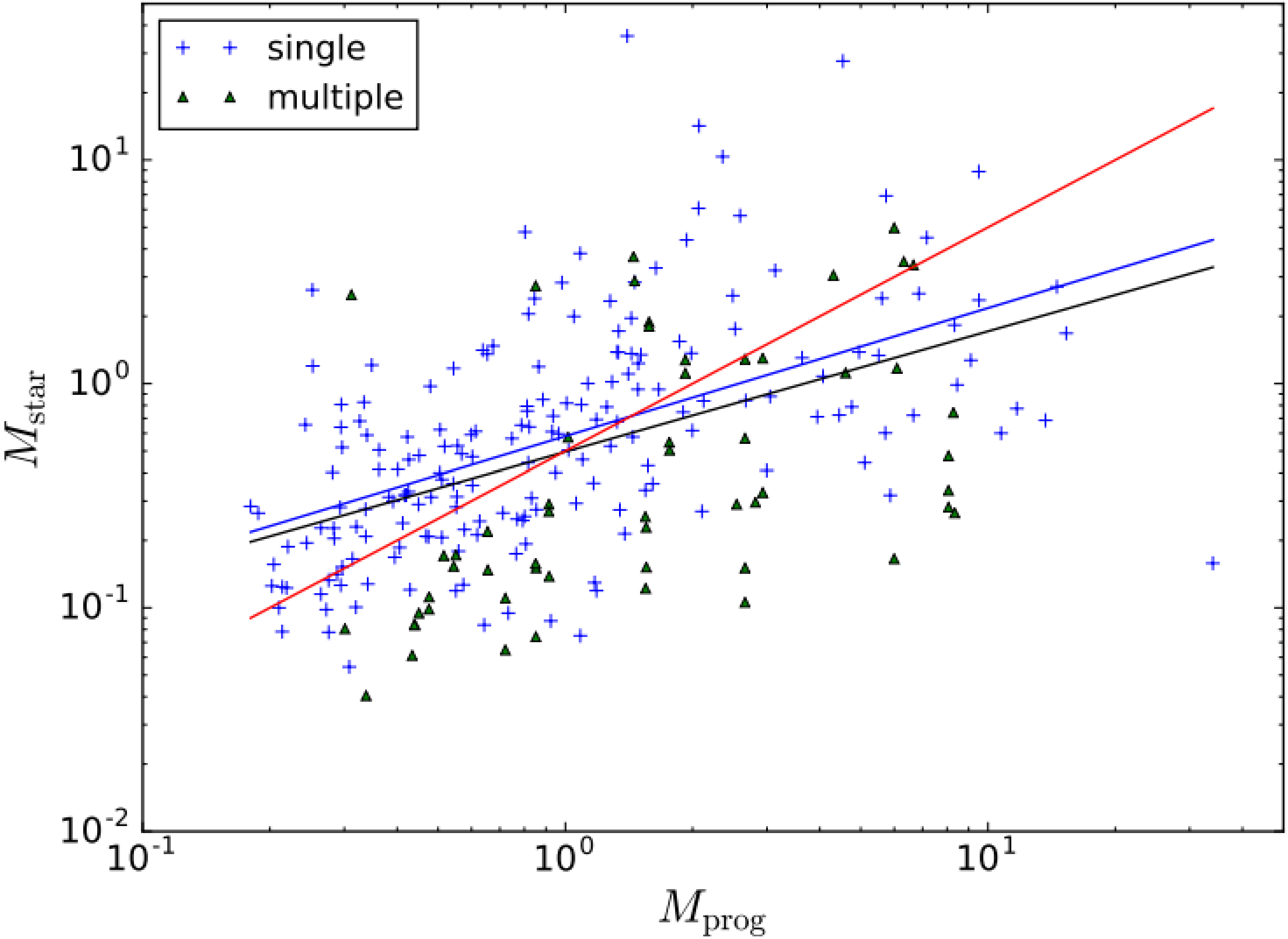


Blue: the shift of the mass peak with resolution.

Red (solid): fraction of detected sinks vs. all 413 sinks in the simulation

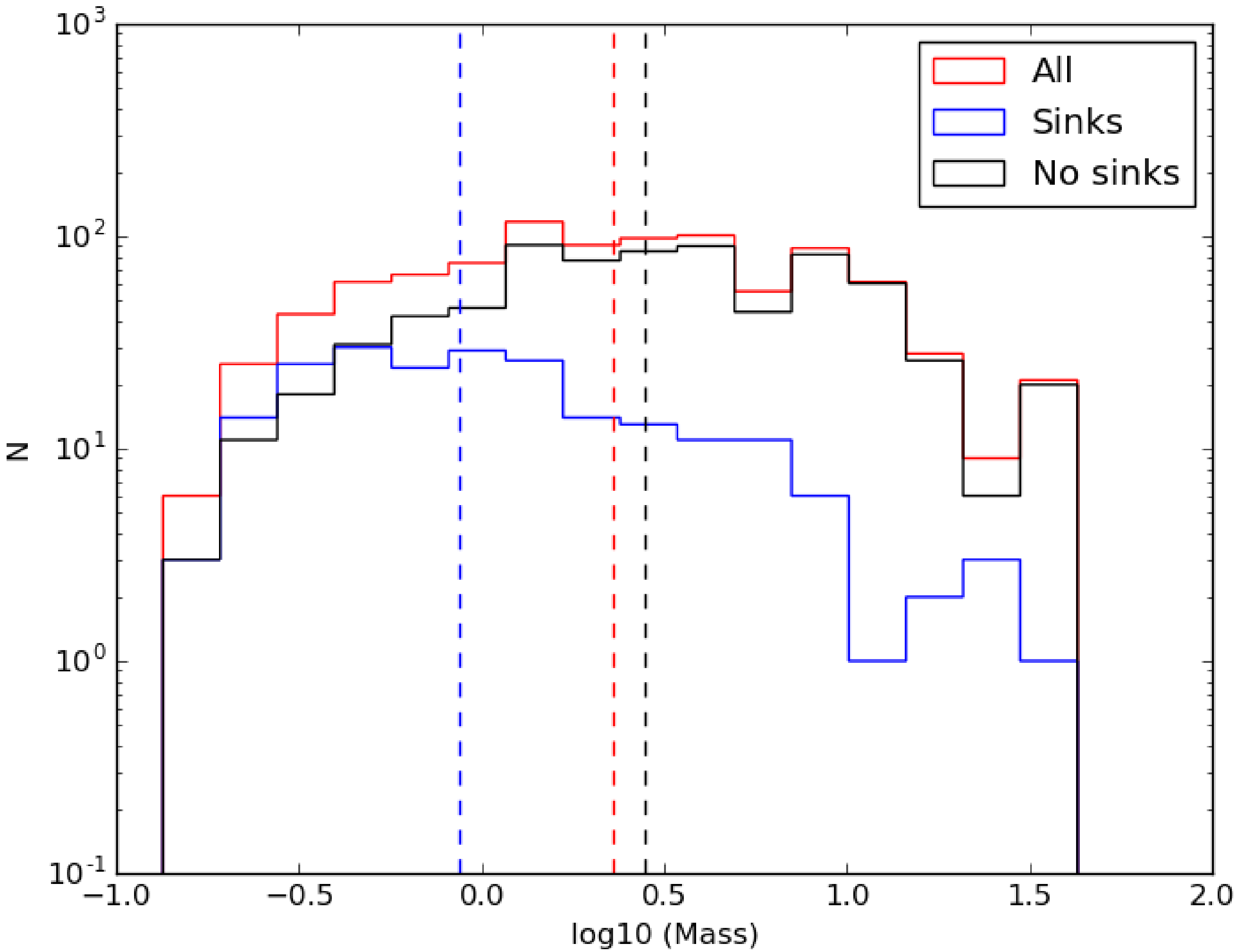
Red (dashed): fraction of single-sink progenitors vs. all detected progenitors.

Resolution: Progenitors



As previously, but with 1024^3 resolution. Fewer single-sink progenitors, and the scatter is even more, resulting in the Pearson correlation coefficient of 0.48 (black line). Blue line (single-sink progenitors) has comparable slope and correlation as before.

Prestellar CMF vs. Progenitor CMF



Selection done on the full 4pc box in each snapshot at 1024^3 resolution, without a priori knowledge of the sink particles.

A posteriori classification based on sink particles: protostellar (contain older sinks, not shown here), prestellar with sinks (our progenitor cores) and prestellar without sinks.

The median mass of all prestellar cores is about 2.5-3 times higher than just for progenitor cores. Catching the progenitors of progenitors before they start to subfragment?

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Conclusions

1) The progenitor CMF converges with resolution, with a peak moving from 0.66 Msol to 0.28 Msol using resolutions from 800AU to 100AU. The estimated converged peak (0.26 Msol) is close to the IMF peak (0.17 Msol), which is contradictory to the core-collapse model.

2) The CMF derived from the simulation is very similar to the stellar IMF from the same simulation. Irrespectively, we find no direct correlation between the progenitor core mass and the final stellar mass for individual stars, contrary to the hypothesis of the core-collapse model.

3) A significant fraction of the mass reservoir of stars is generally outside of the progenitor cores. This applies across the whole IMF. For stars less than 1 Msol, ~50% of the stellar mass originates outside the core. This increases to ~90% for intermediate-mass stars ($2 < M / Msol < 5$).

4) The inflow region that contains 95% of the mass reservoir of a star is generally much larger than the size of the progenitor core. The ratio between the inflow radius and the core radius has a median value of 14 and its largest values are ~1000. This size ratio shows no significant correlation with the final stellar mass.

5) The competitive-accretion model is also ruled out: the inflow region is not gravitationally bound, hence the Bondi-Hoyle accretion rate would be too small to explain the actual accretion rates.

6) The similarity between observed CMFs and the stellar IMF is confirmed by the simulation. However, observed CMFs should in principle result in a larger core mass on average (limitations in resolution and no a priori knowledge of which cores will form stars). Inclusion of unbound cores in the observed CMFs may have the opposite effect.

Take-home message

1) Low-mass star formation is more complex, not a simple monolithic turbulent core collapse with a constant efficiency factor.

2) There is a robust statistical connection -- that can come from no other place than the fact that turbulence is generic -- between the cores where the stars form, and what turbulence chooses to bring close enough to a growing star, so it can accrete that mass.

References:
Pelkonen et al. 2020, https://arxiv.org/abs/2008.02192v2
(For massive stars: Padoan et al. 2020, ApJ, 900, 82P)