Simulations of Pop III Star Formation: What's Next?

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The Big Question: What is the IMF of Population III stars?

More specifically:

- What have we learned thus far?
- Where are we now?
- Where do we need to go next?

Pop III star formation simulations

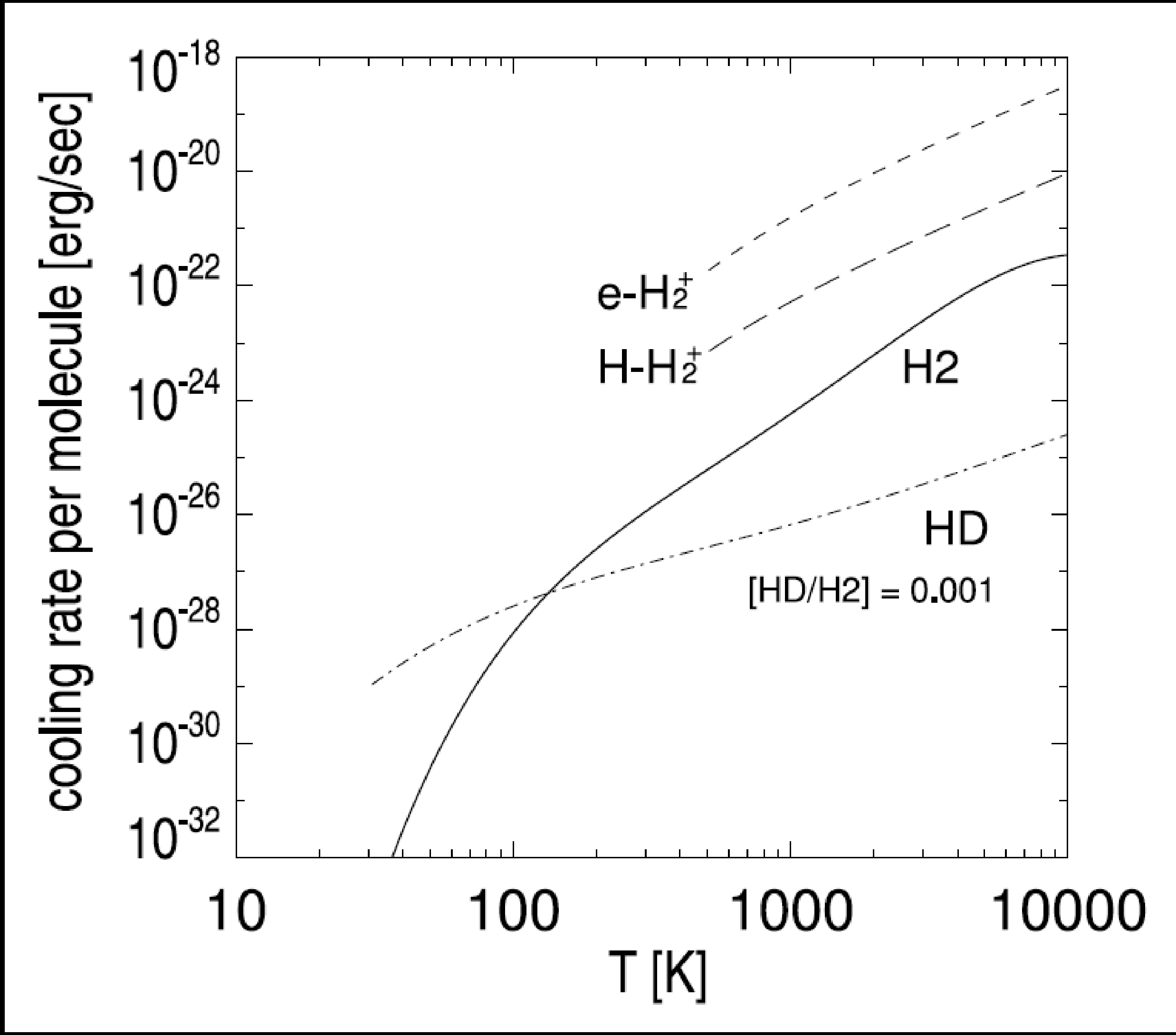
(an incomplete list)

- Abel, Bryan & Norman 2000, 2002
- Bromm, Coppi & Larson 2002; Bromm & Loeb 2004; Johnson & Bromm 2006
- Yoshida et al. 2006; Gao et al. 2007
- O'Shea & Norman 2006, 2007
- Omukai & Palla 2003; Omukai & Yoshii 2003
- Susa & Umemura 2006; Susa 2007

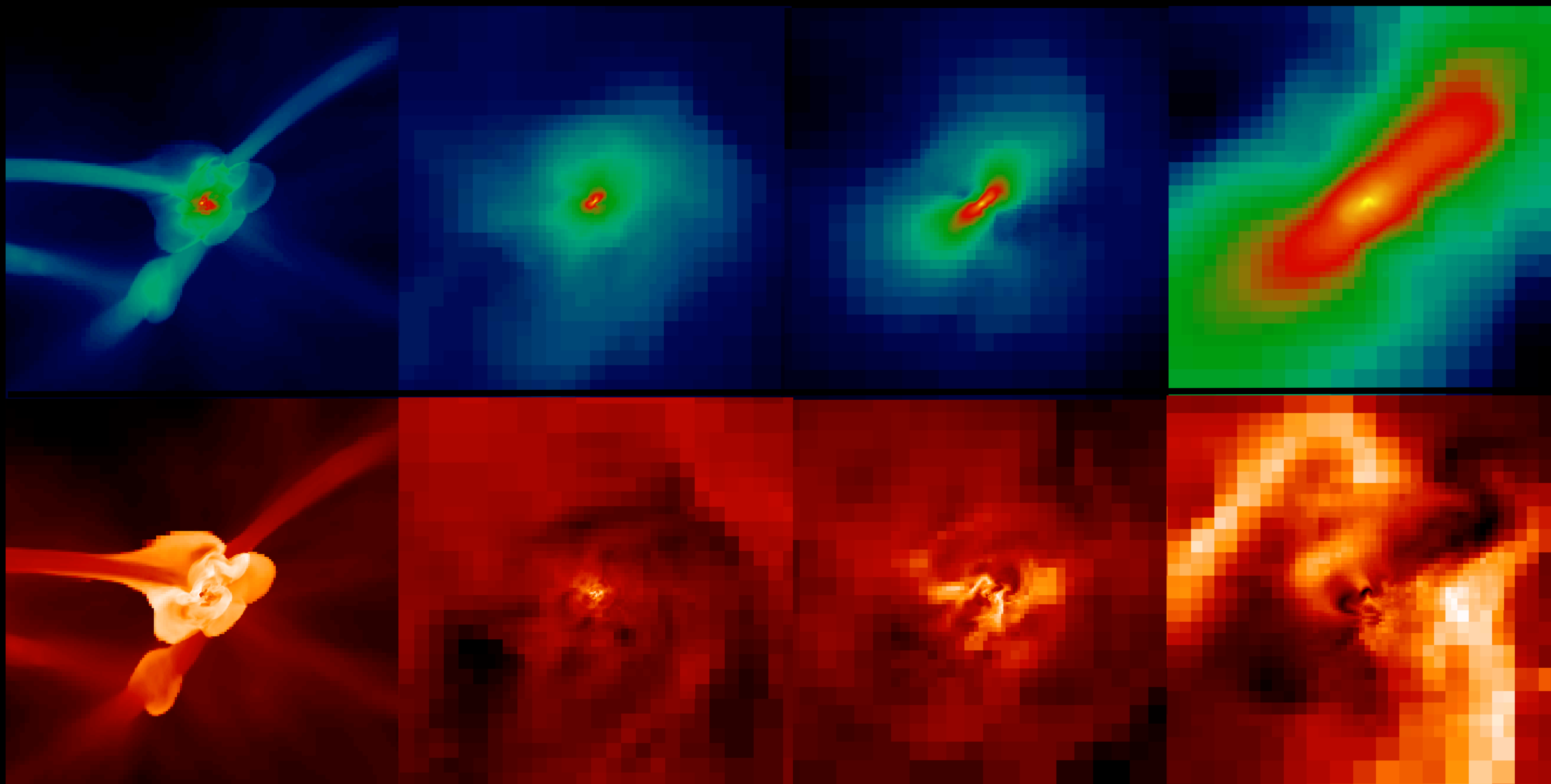
What have we learned?

- The chemistry and cooling of molecular hydrogen (including HD) suggests more massive stars than in our galaxy

From Yoshida et al. 2007, ApJ, 663, 687



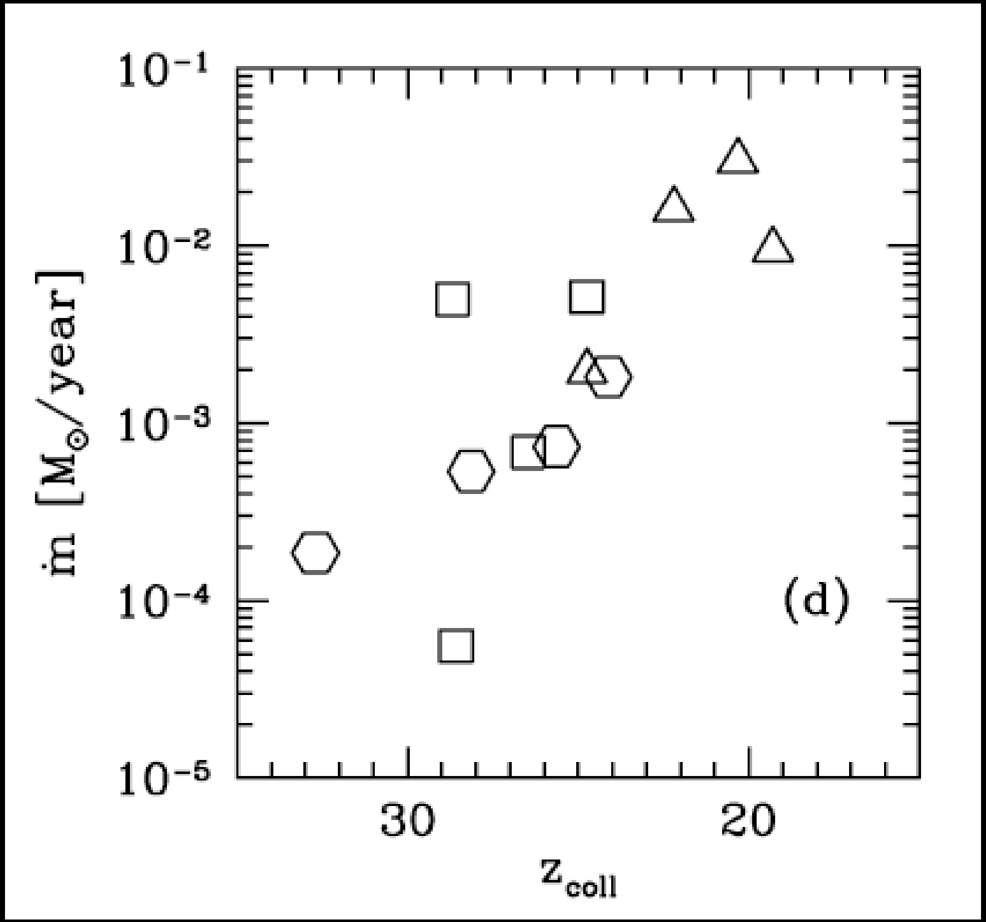
- It is important to simulate the formation of Population III stars in an appropriate context: within cosmological structure!

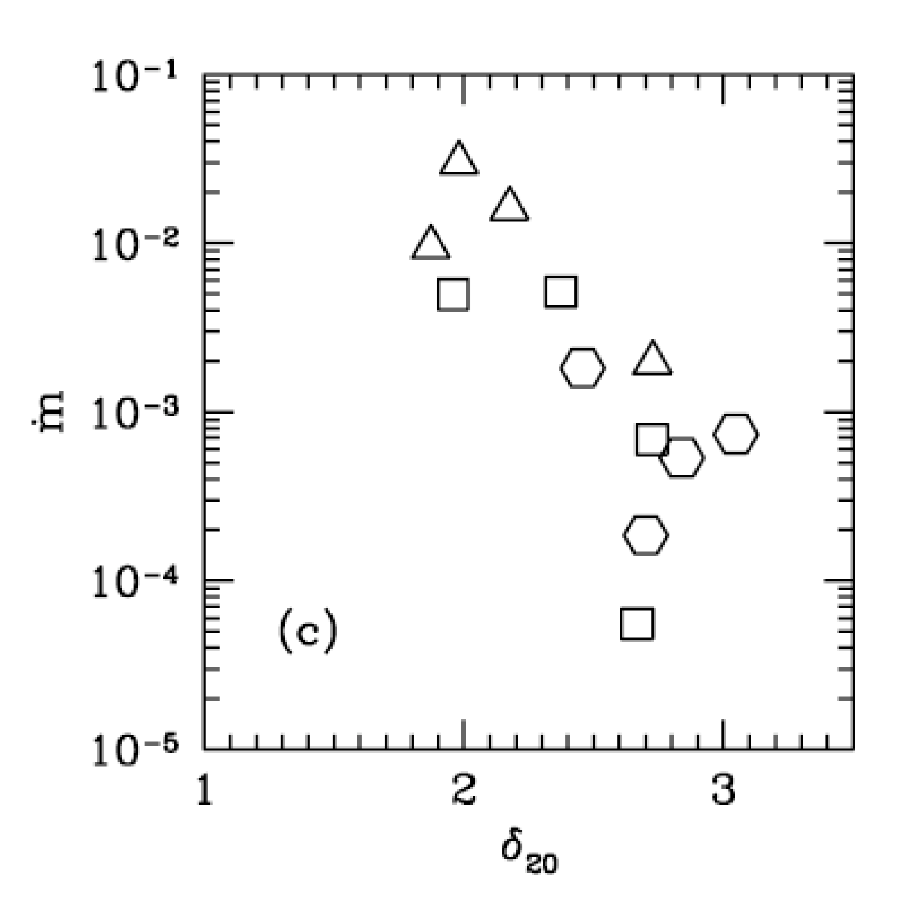


1 kpc | 5 pc | 0.5 pc | 0.05 pc

O’Shea & Norman 2007, ApJ, 654, 66-92

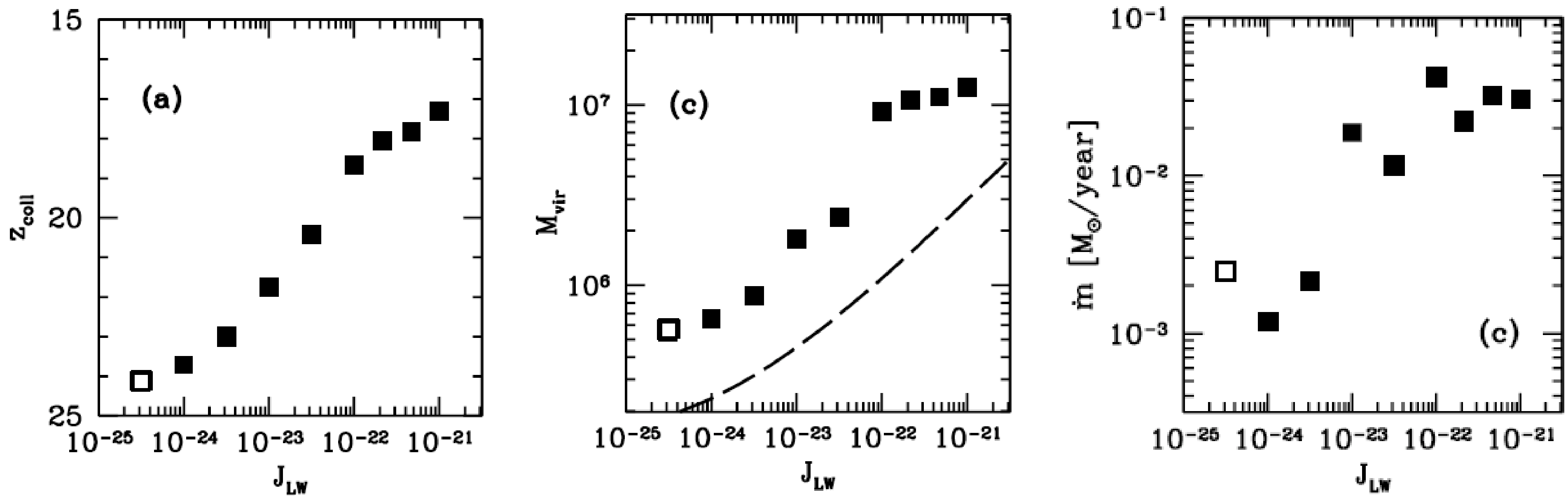
- Lots of variation in formation redshifts, halo environments - translates to varied accretion rates





O'Shea & Norman 2007, ApJ, 654, 66-92

- Feedback from previous generations of Pop III stars (photodissociating and photoionizing radiation, cosmic rays, etc.) can be important



O'Shea & Norman 2007, ApJ, accepted (arXiv:0706.4416)
Also see Wise & Abel, ApJ, submitted (arXiv: 0707.2059)

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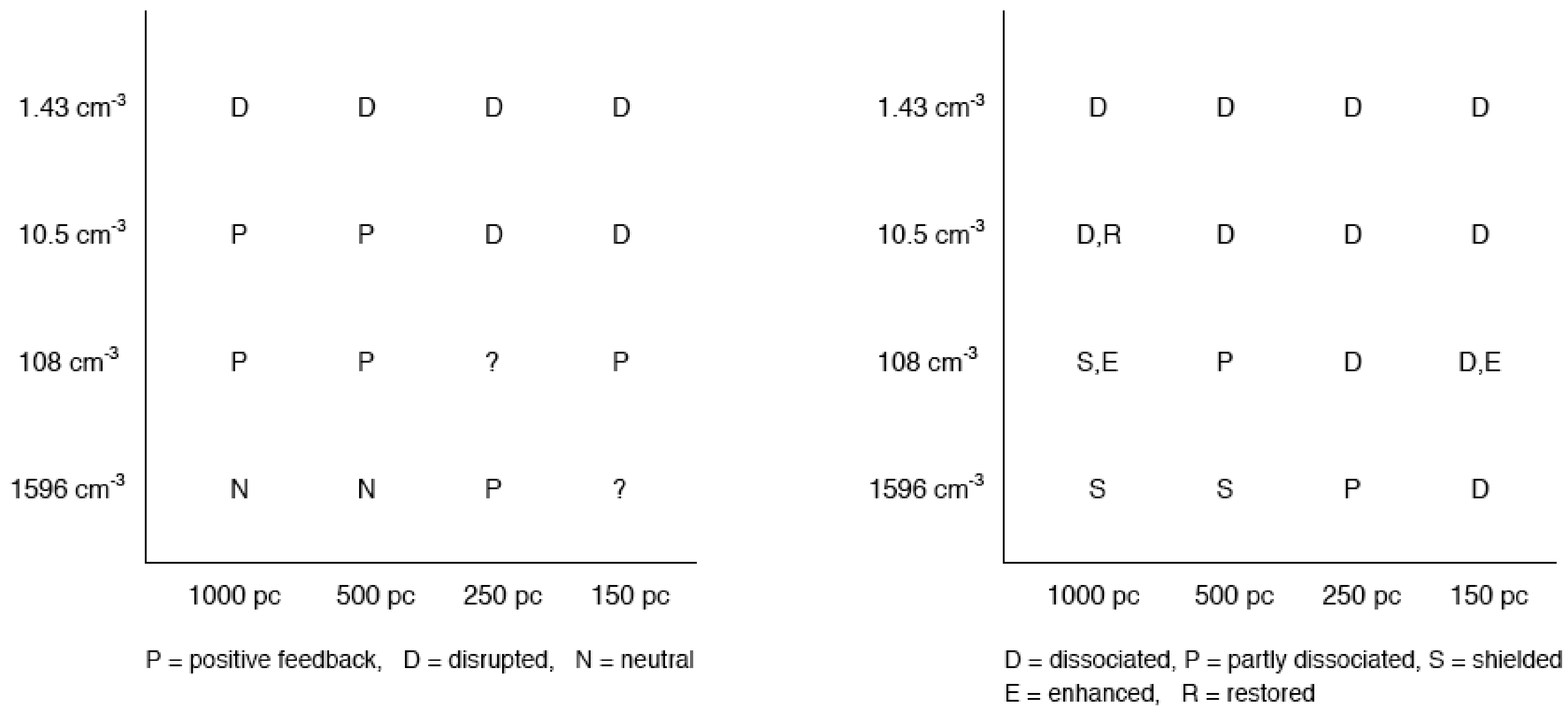


Fig. 17.— Radiative feedback on star formation (left) and dissociation of the core of the halo (right) in each of the photoevaporation models.

Whalen, O'Shea, Smidt & Norman 2007, ApJ, submitted (arXiv: 0708.1603)
But, also see Ahn & Shapiro 2007, MNRAS, 375, 881

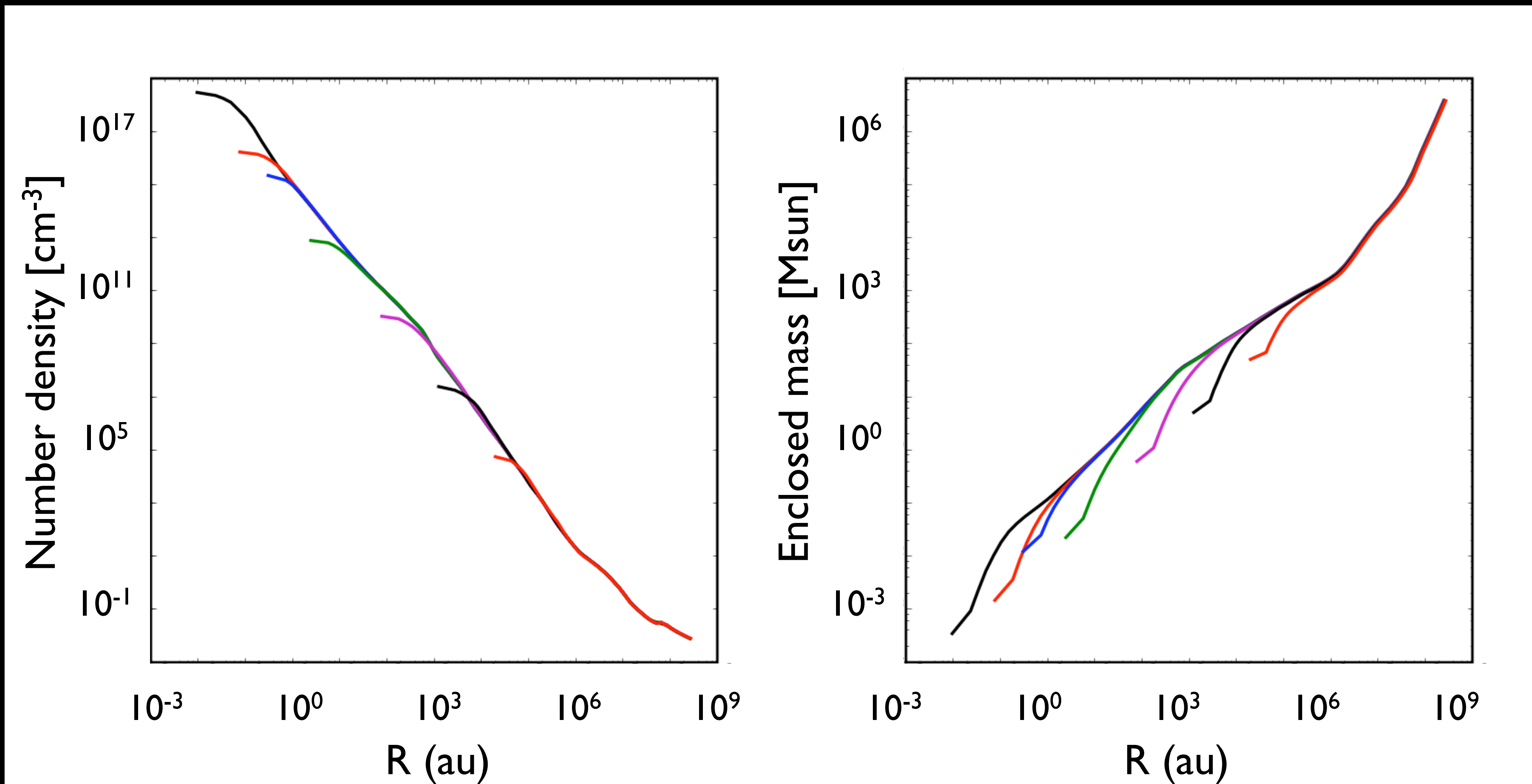
Where are we now?

The current state-of-the art: Turk, Abel & O'Shea 2007 (in prep.)

- Extension of Abel, Bryan & Norman 2002, using the Enzo code (http://lca.ucsd.edu/portal/software/enzo)
- New physics:
  - Improved primordial chemistry (goes to $\sim 10^{22}$ cm^{-3}), including H_2 formation heating at $n_H > 10^8$ cm^{-3}
  - New EOS at high density: Saumon et al. 1995
  - Take into account opacity to lines, continuum at $n_H > 10^{12}$ cm^{-3} (reduces cooling rates)
- New numerics: extended floating point position - up to (at least) 42 levels of AMR!

The current state-of-the art: Turk, Abel & O'Shea 2007 (in prep.)

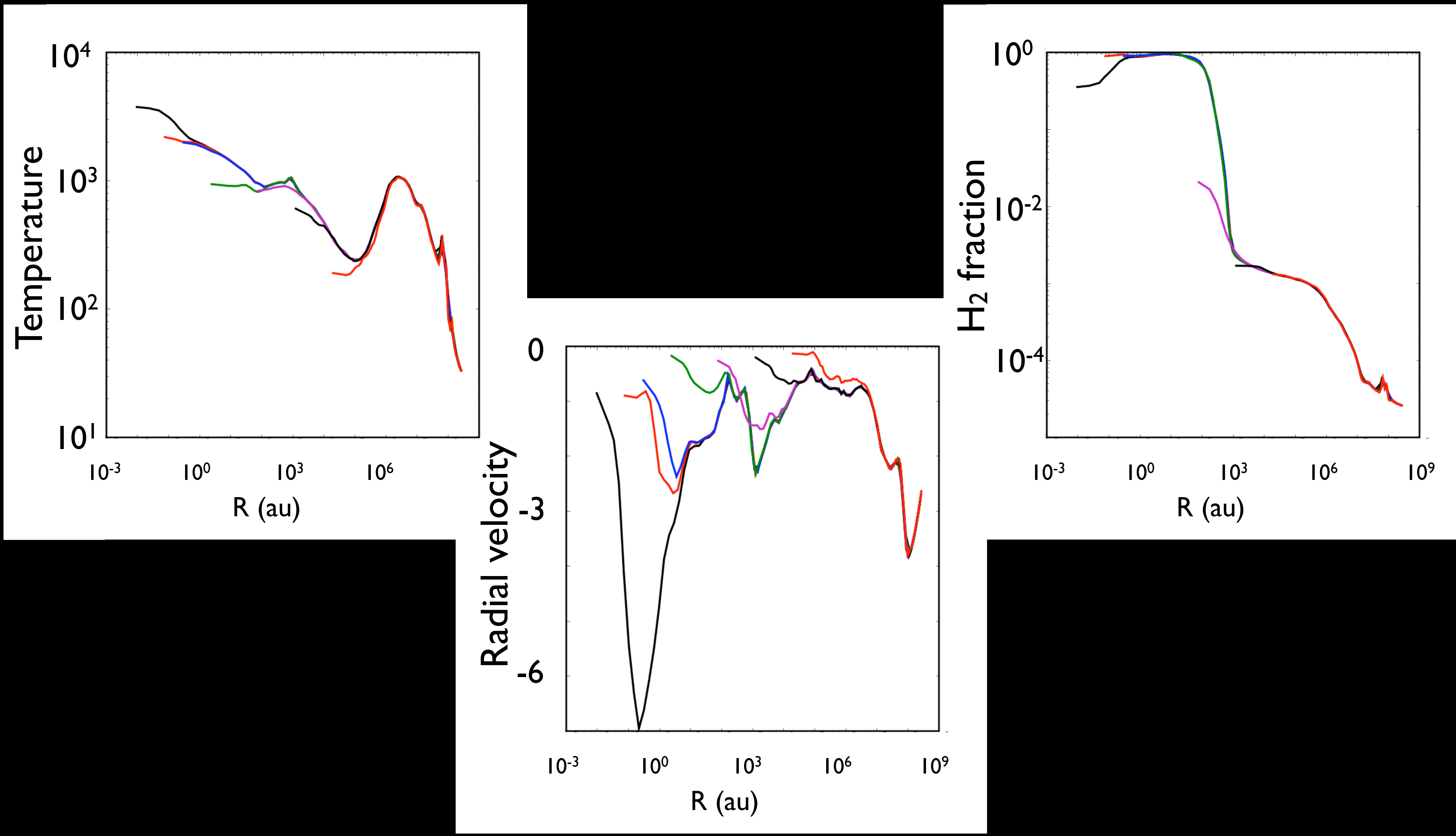
- 0.3 Mpc/h box (comoving), 128^3 root grid w/2 static nested grids, centered on Lagrangian volume of most massive halo in box at z=15
- Initialize at z=166 assuming WMAP III model (approximately) + sigma8 = 0.9
- Follow with up to 35 levels of resolution until collapse of gas at the center of this halo at z ~ 28
- Final output: n_{max} = 3e21 cm^{-3}, dx = 1.8e9 cm (0.026 R_{sun}), m_{res}(L=35) = 2.2e-8 M_{sun}



Number density

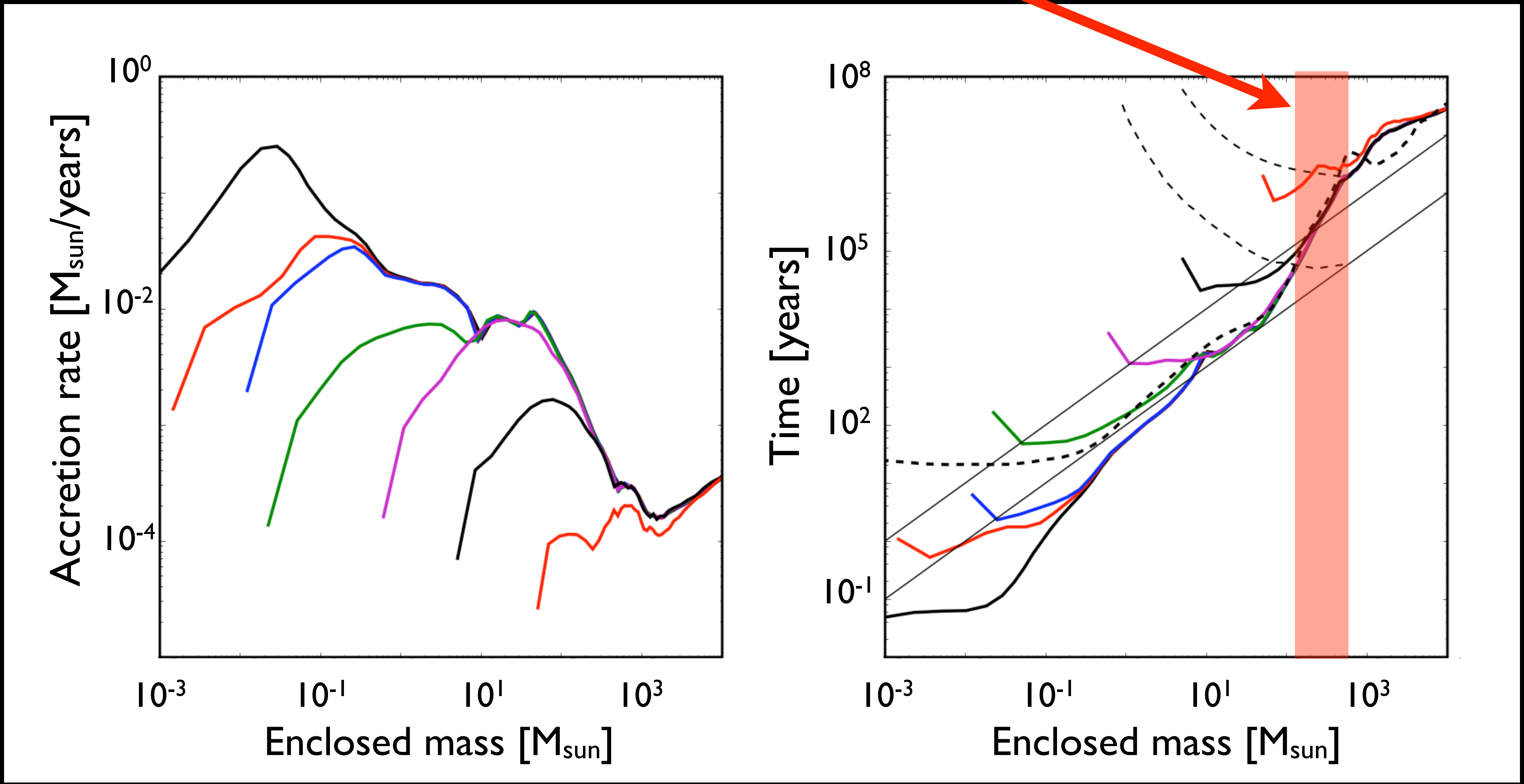
Enclosed mass

Turk, Abel & O'Shea 2007 (in prep)

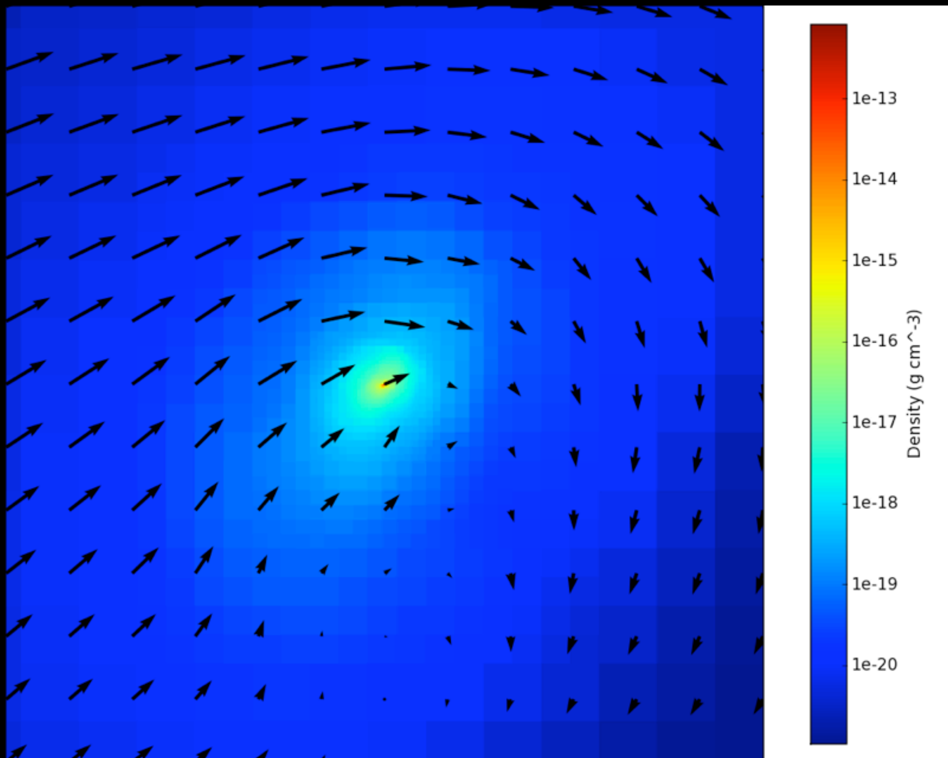


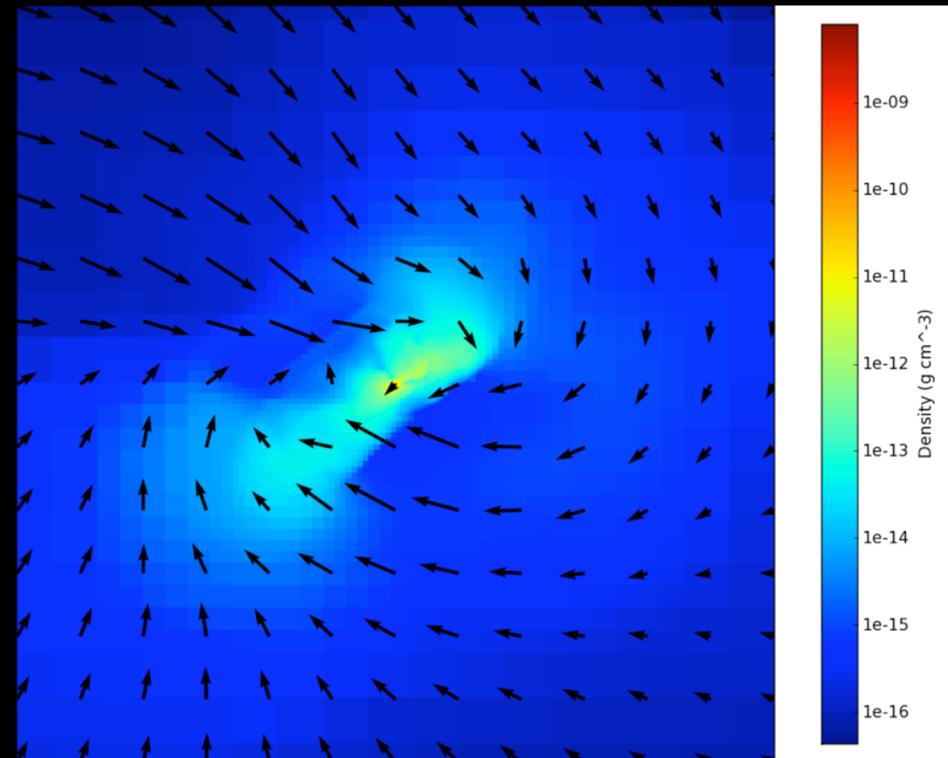
Turk, Abel & O'Shea 2007 (in prep)

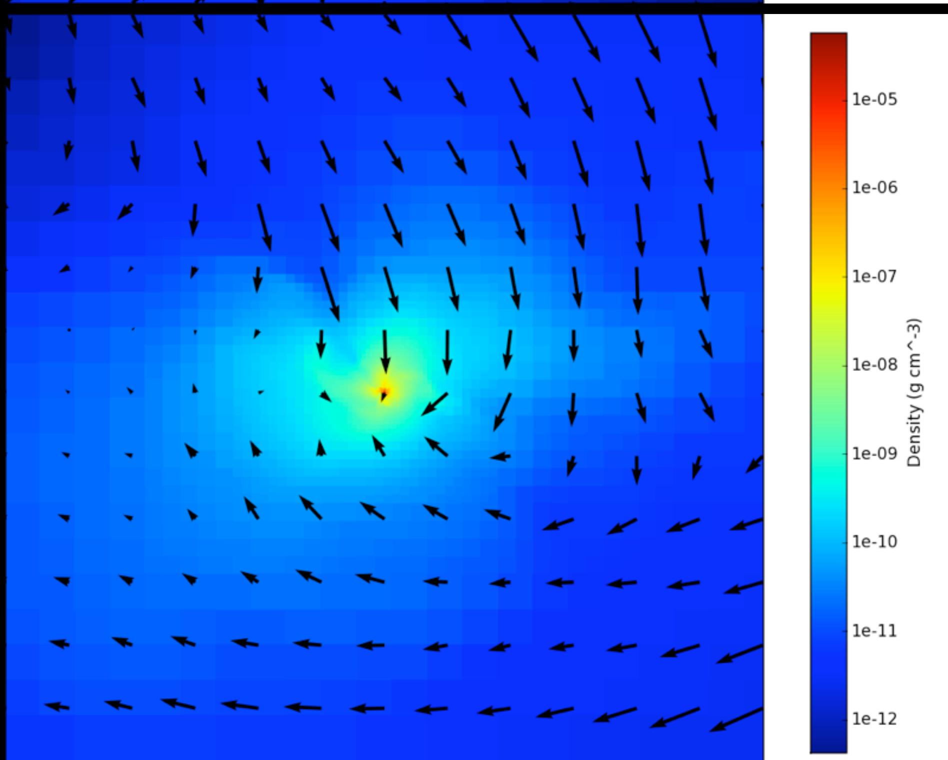
Estimated mass: hundreds of M_{sun}!



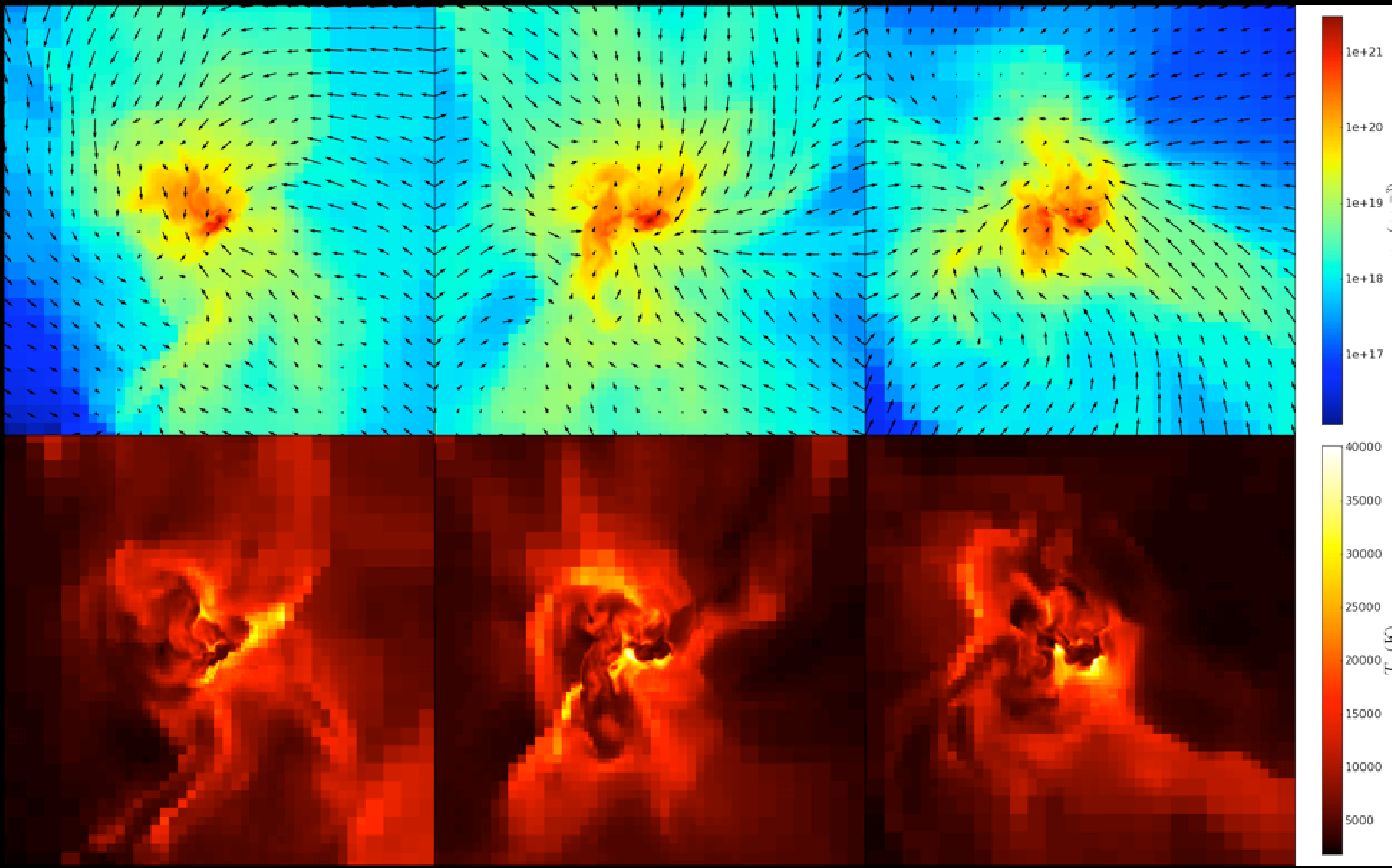
Turk, Abel & O'Shea 2007 (in prep)



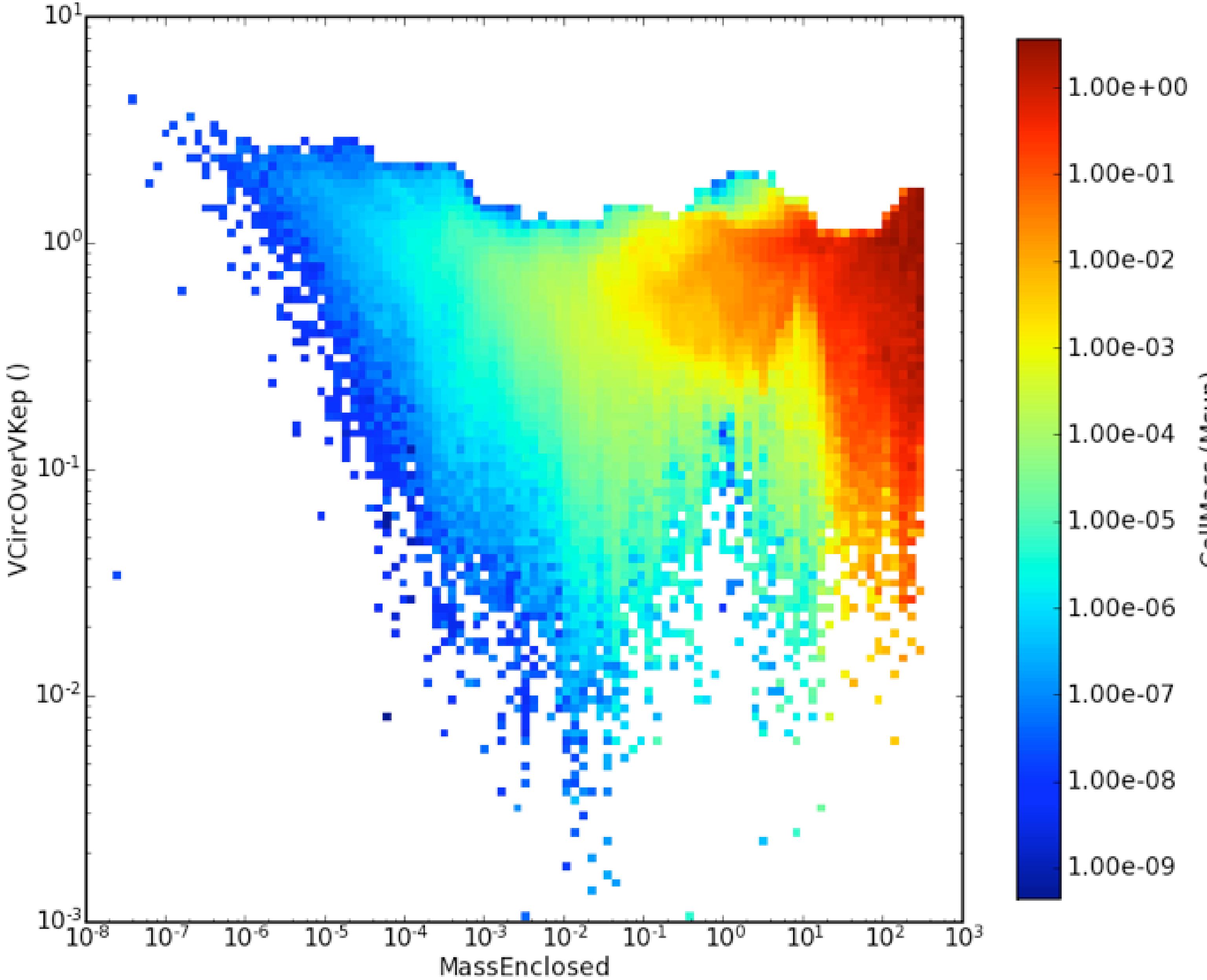




Above left: 1 pc (M_{enc} = 332 M_{sun})
Above: 2000 au (M_{enc} = 23 M_{sun})
Left: 20 au (M_{enc} = 0.63 M_{sun})



10 R_{sun}, M_{enc} = 0.023 M_{sun}



10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
VCircOverVKep ()
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
MassEnclosed
1.00e+00
1.00e-01
1.00e-02
1.00e-03
1.00e-04
1.00e-05
1.00e-06
1.00e-07
1.00e-08
1.00e-09
CellMass (Msun)

What’s next?

What do we assume when calculating mass from our sims?

- We look at the final snapshot (with 1e-3 M_{sun} protostar), not a massive protostar
- We assume spherical symmetry
- We assume angular momentum, radiation feedback are unimportant

None of these things can be ignored!
See Tan & McKee 2004, ApJ, 603, 383
(and McKee & Tan 2007, in prep.)

What physics have we been ignoring that needs to be included?

- Radiation transport with point and diffuse sources (multigroup/multifrequency, coupled to chemistry)
- MHD (non-ideal?)
- Better non-ideal EOS at high density
- Good 0d/1d models of protostellar/stellar evolution
- Accreting and radiating sink particles

We need to throw away cosmology!

- L_{box} = 0.3 Mpc/h (comoving)
- Area of interest: ~2 pc across (proper)
- Volume of interest: 1e-12 of total simulation volume!
- Central ~parsec is effectively decoupled from the rest of the universe!

Cosmology machinery is unneeded:
this is an astrophysics problem!

Conclusions

- We simulate scales ranging from megaparsecs to fractions of a parsec, including all of the relevant physics and with good agreement between methods
- A variety of accretion rates onto Pop III stars are inferred: all indicate massive stars. But how massive?
- Our current fundamental problem is lack of physics in our simulation, not lack of resolution
- We need to really understand the "last parsec" problem - we have to move past our current n-body + hydro cosmology codes!