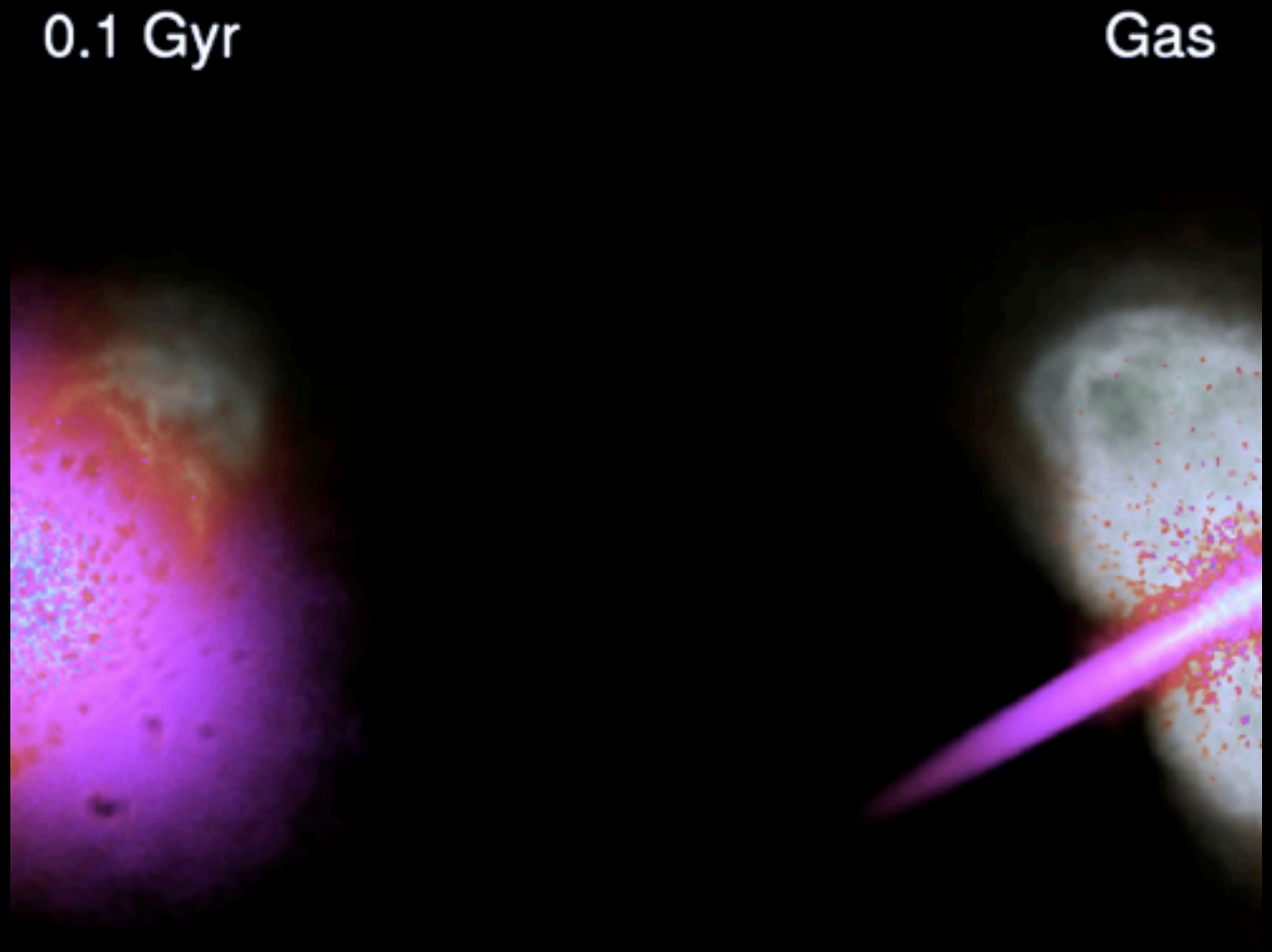
# Updates on FIRE:
# Feedback In Realistic Environments

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fire.northwestern.edu

# Stellar Feedback: How Can We Do Better?

- High-resolution (~1-10 pc), molecular/metal cooling (~10 K), SF at $n_H > 100$ cm$^{-3}$

- Energy/Mass/Metal Injection:
  - SNe (II & Ia)
  - Stellar Winds (O & AGB)
  - Photoionization (HII) & Photoelectric

- Momentum Flux:
  - Radiation Pressure

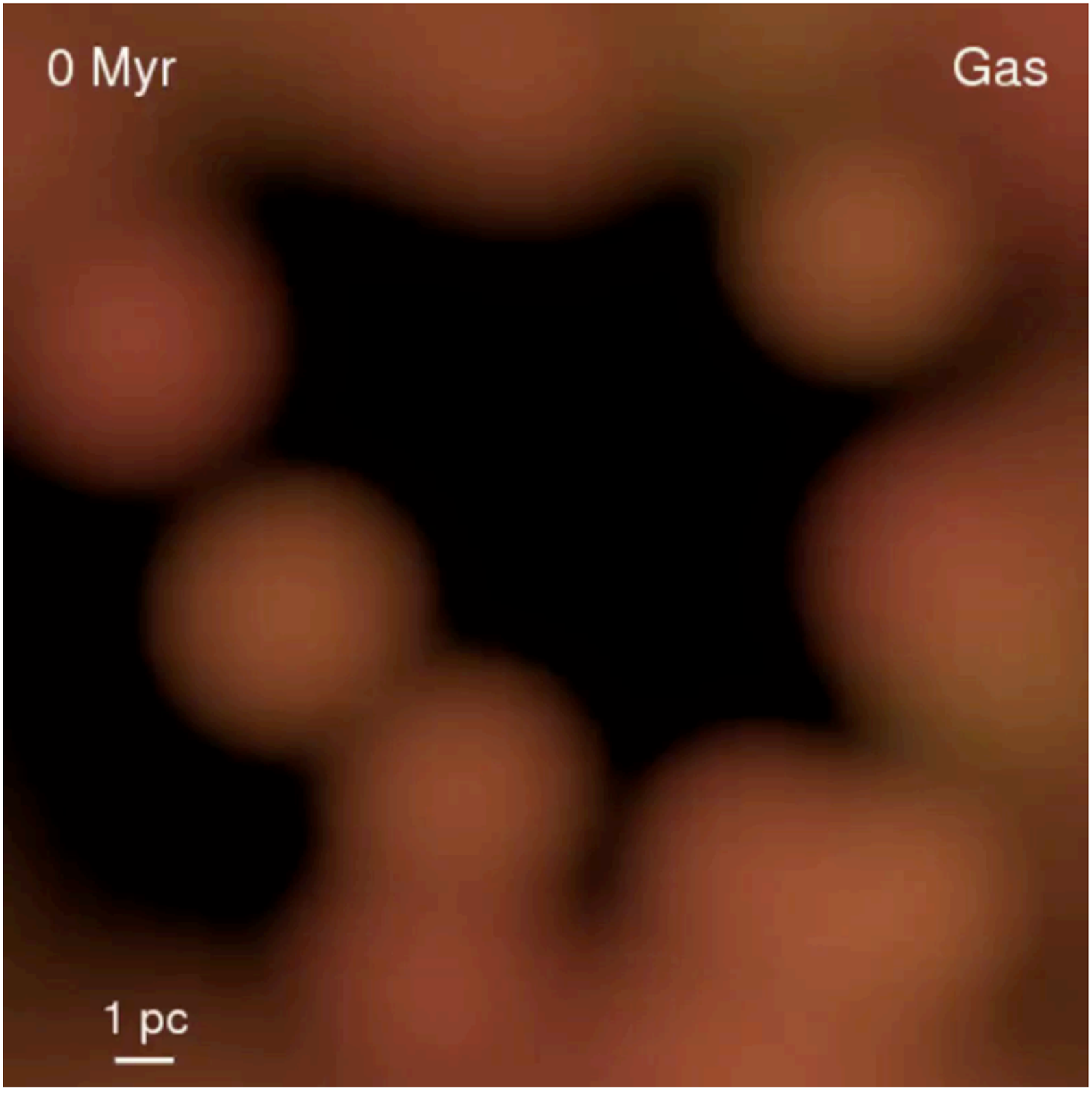
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

  - SNe

$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

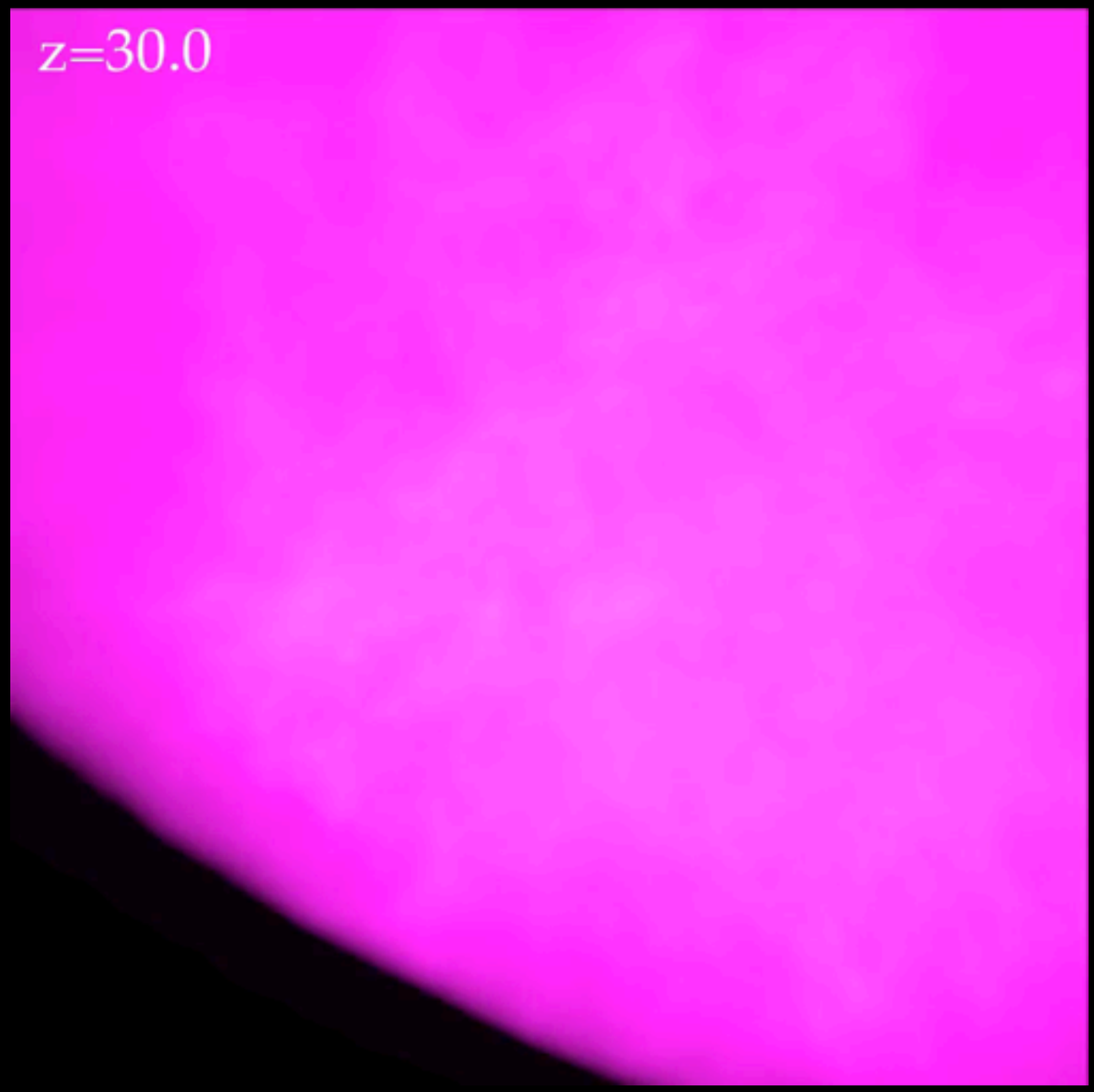
  - Stellar Winds

$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$




- (also MHD, anisotropic conduction, diffusion)

z=30.0




Stars (Hubble image):

Blue: Young star clusters

Red: Dust exinction

Gas: Magenta: cold $(< 10^4\ K)$

Green: warm (ionized)

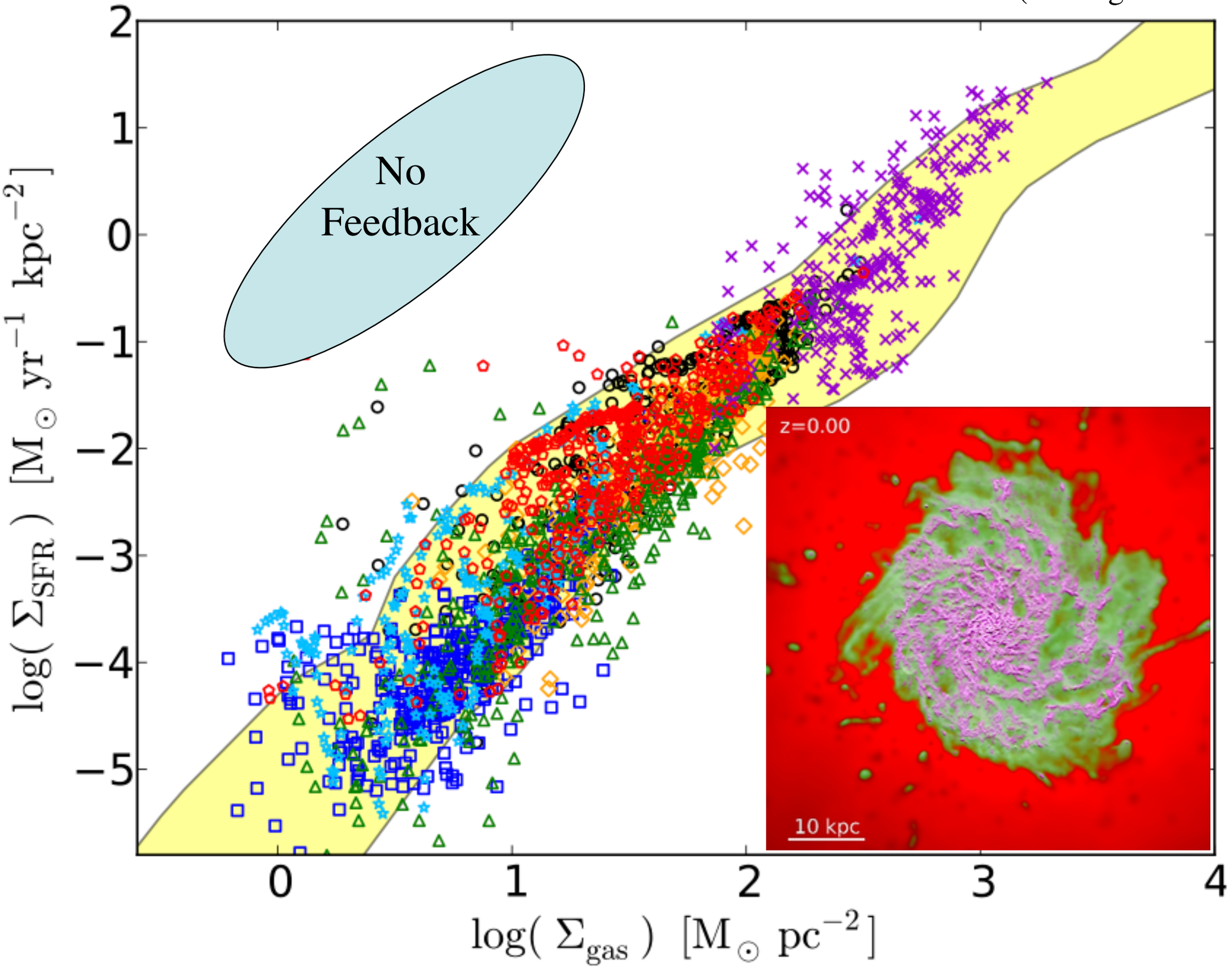
Red: hot $(> 10^6\ K)$

# The Kennicutt Law Emerges

*INDEPENDENT* OF SMALL-SCALE SF LAW

PFH et al. (arXiv:1311.2073)

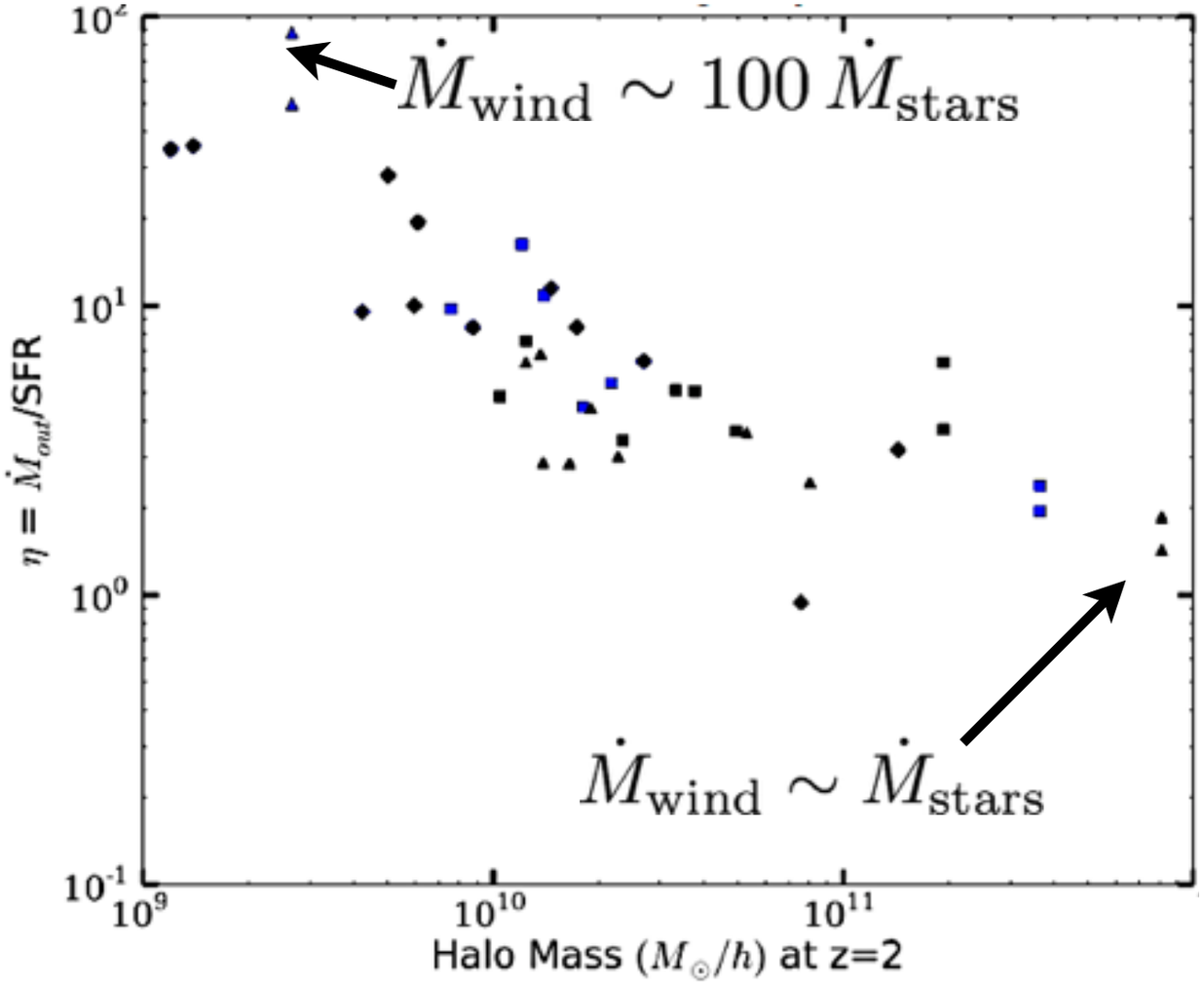
(also Agertz+ 1404.2613)

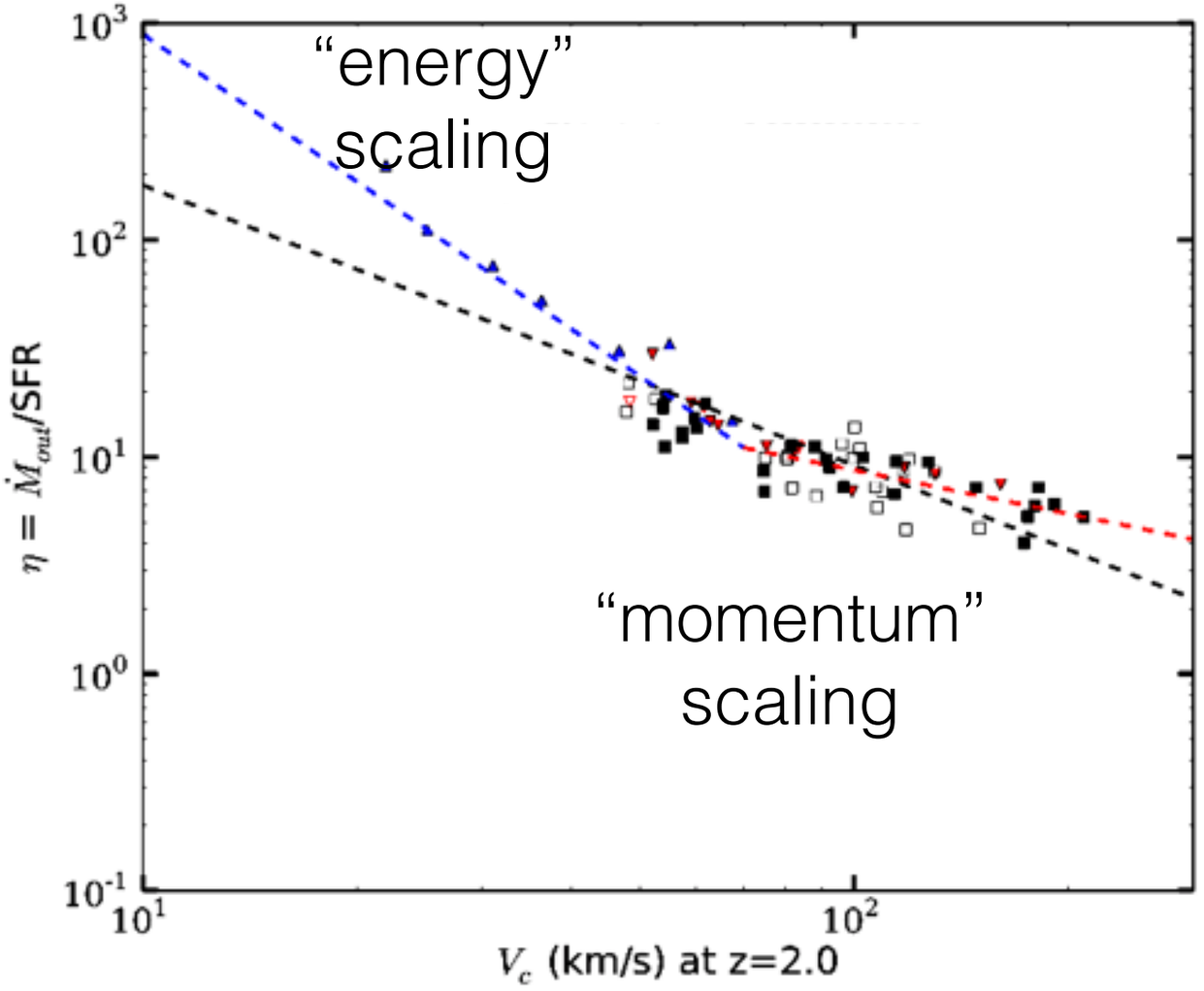


# How Efficient Are Galactic Super-Winds?

## WHAT MECHANISMS DRIVE THEM?

S. Muratov



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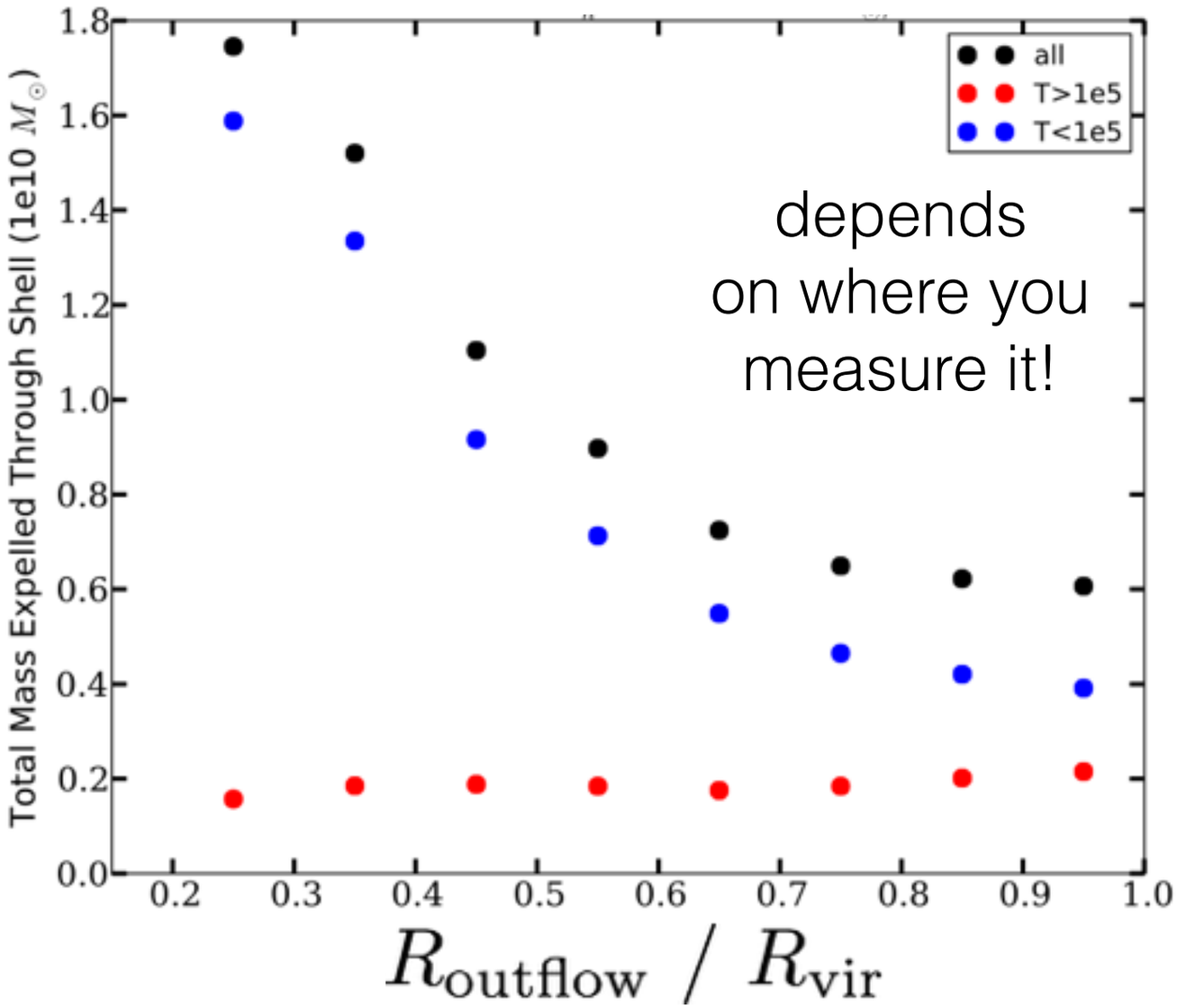
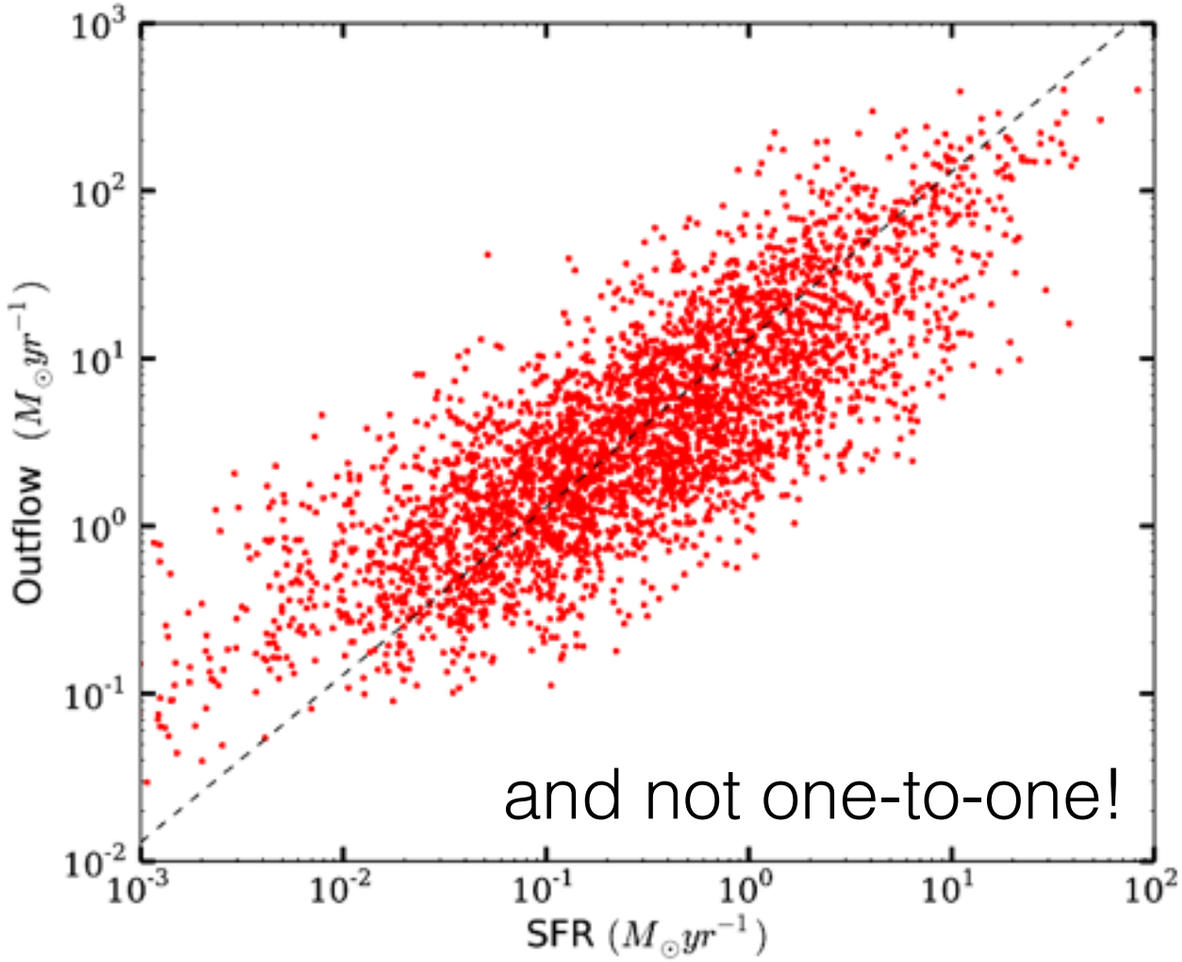
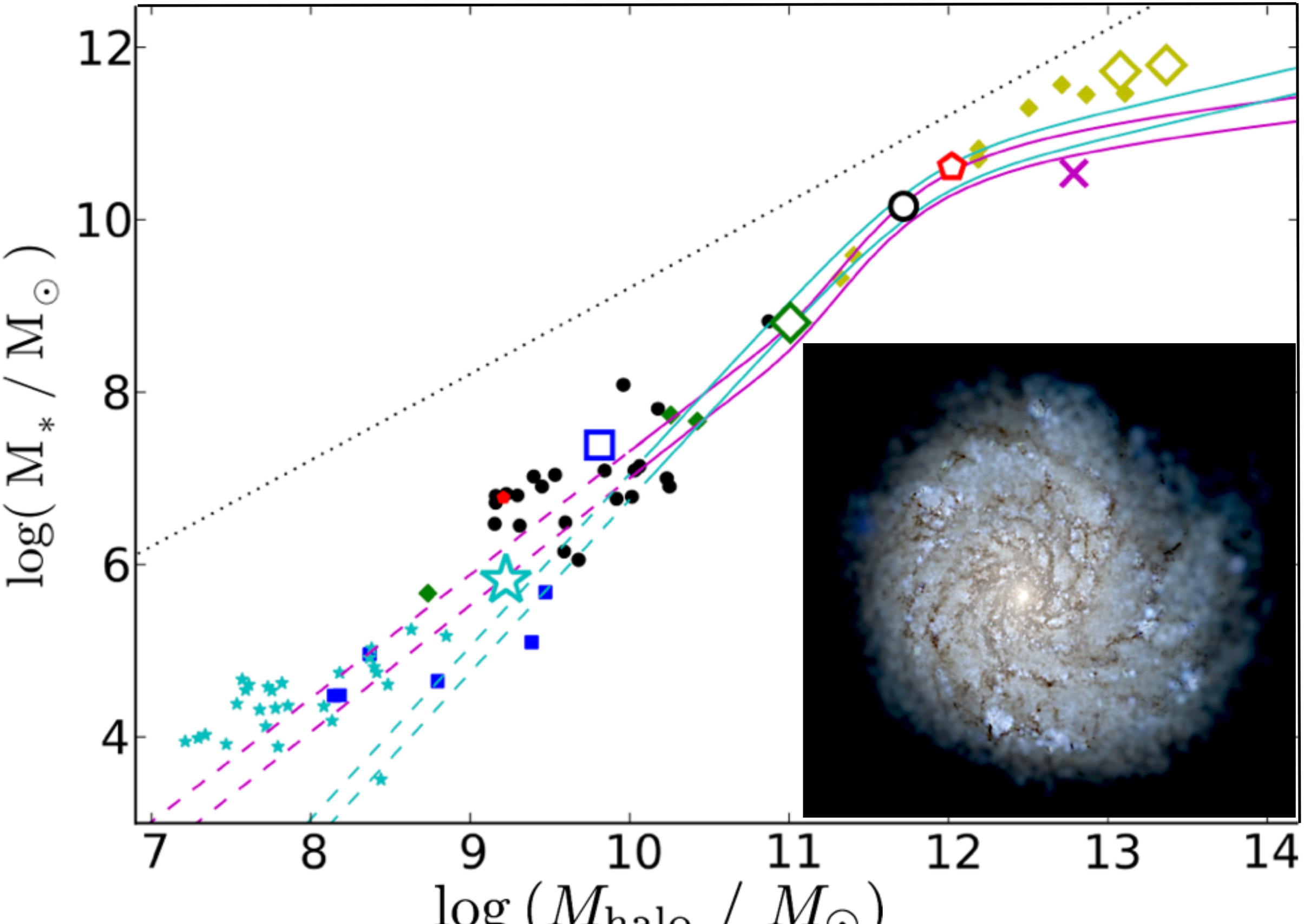


# Does Stellar Feedback Explain the Mass Function?

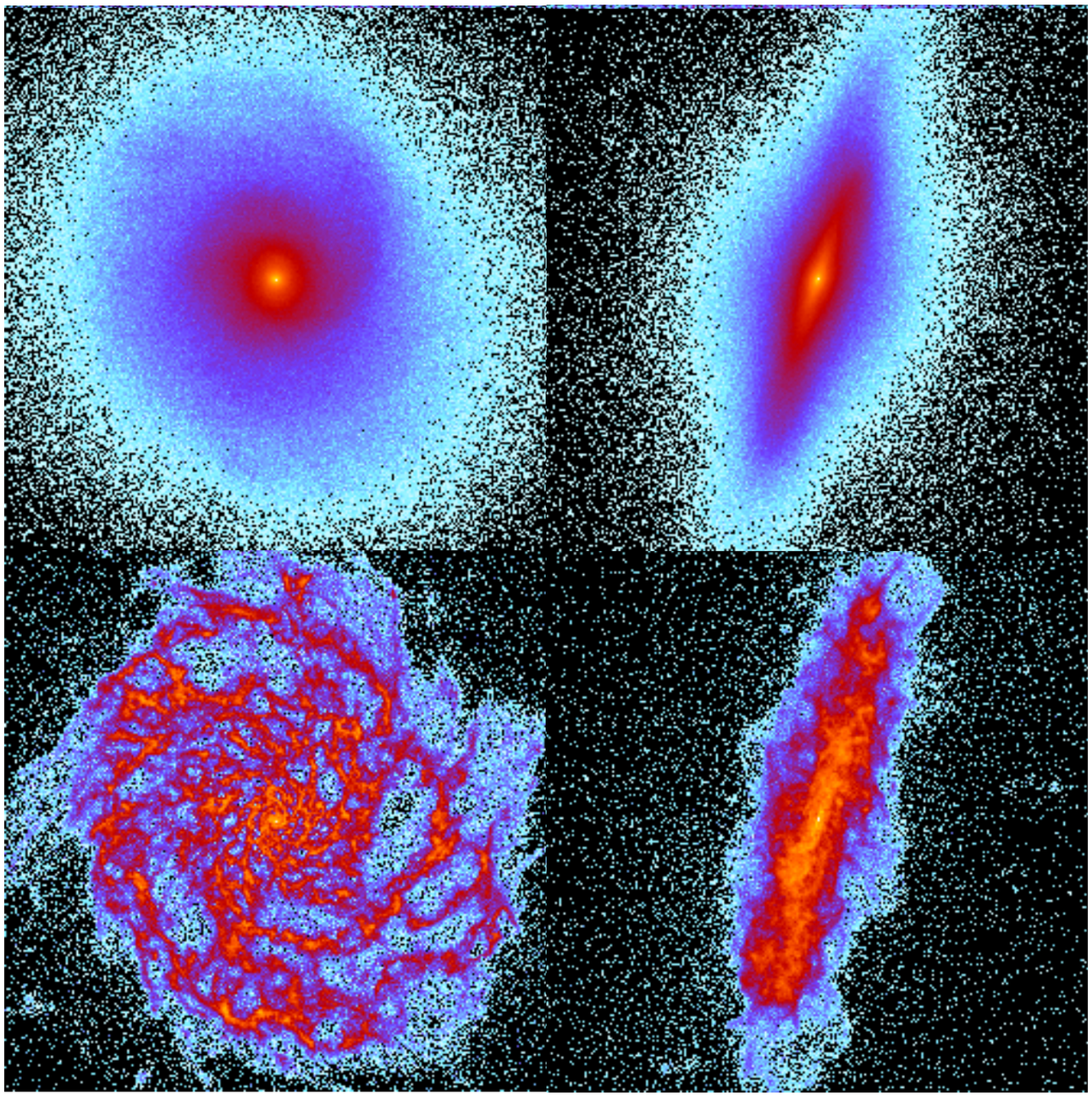
PFH et al. (arXiv:1311.2073)

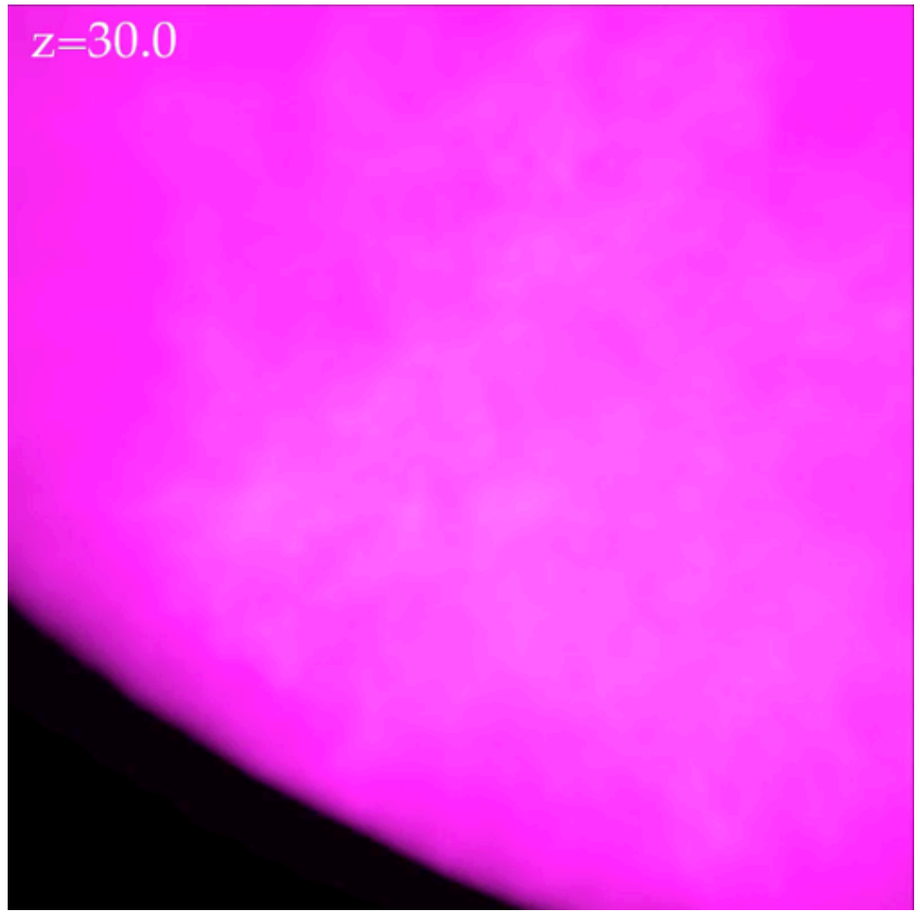
## HOW EFFICIENT ARE GALACTIC WINDS?

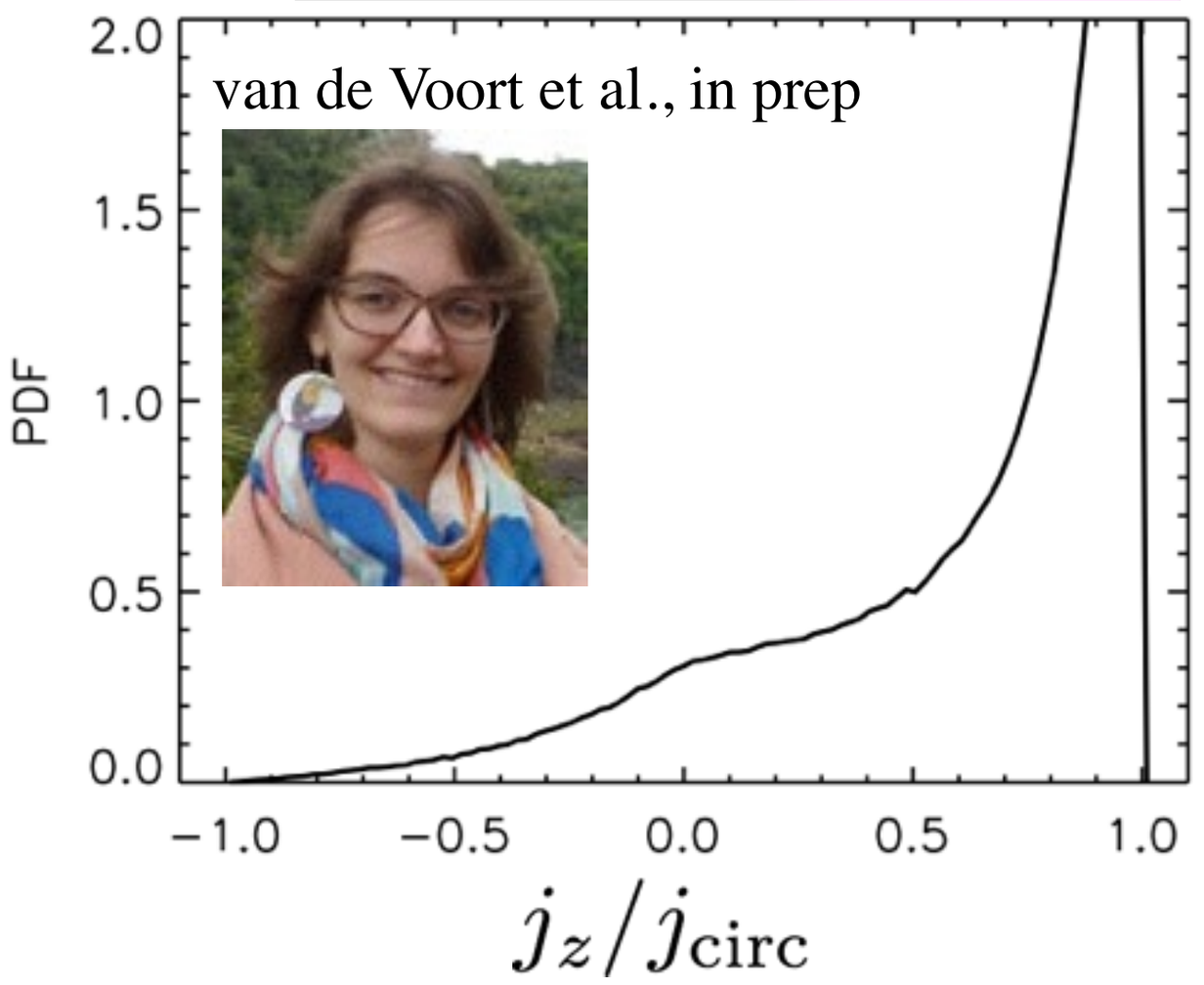


# You Can Have Feedback & Thin Disks

## *RESOLVED* MULTI-PHASE PHYSICS KEY



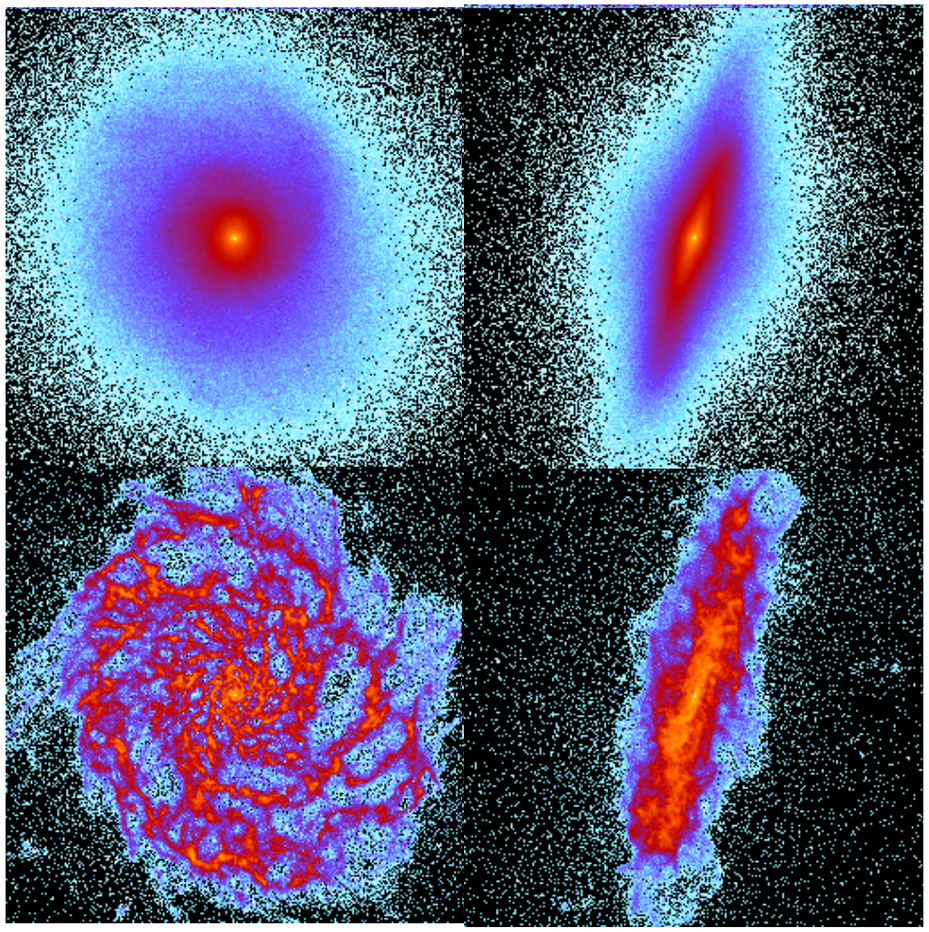


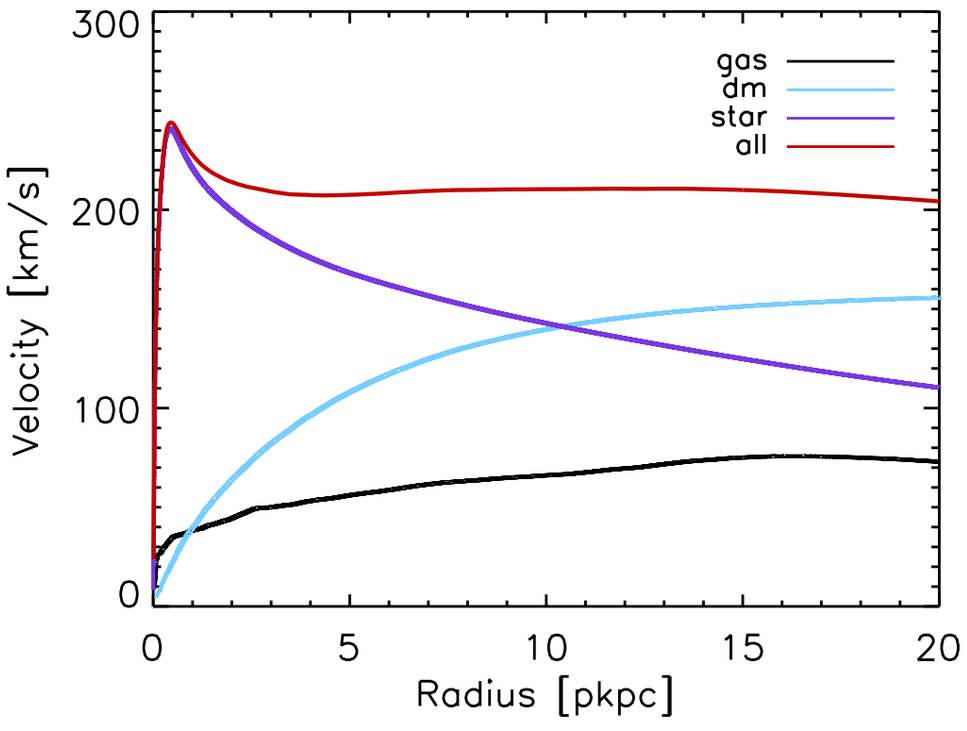



# But Feedback *Does* Matter

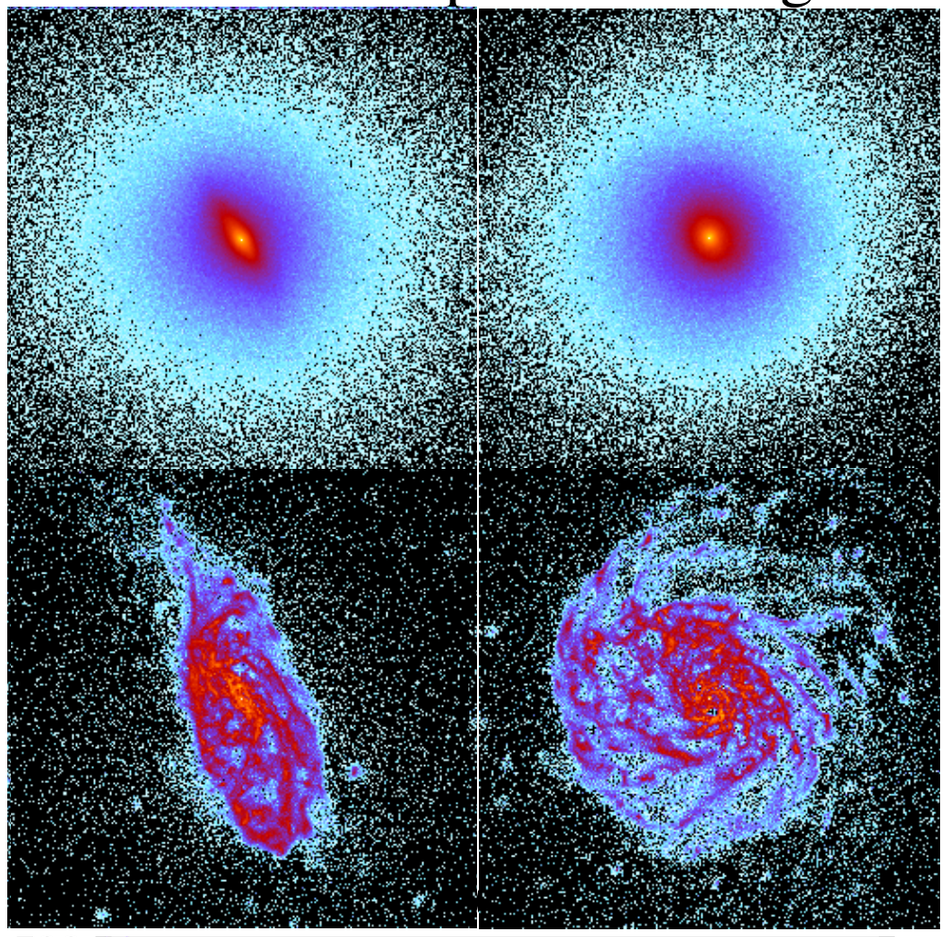
## DETAILS & MULTIPLE MECHANISMS IMPORTANT

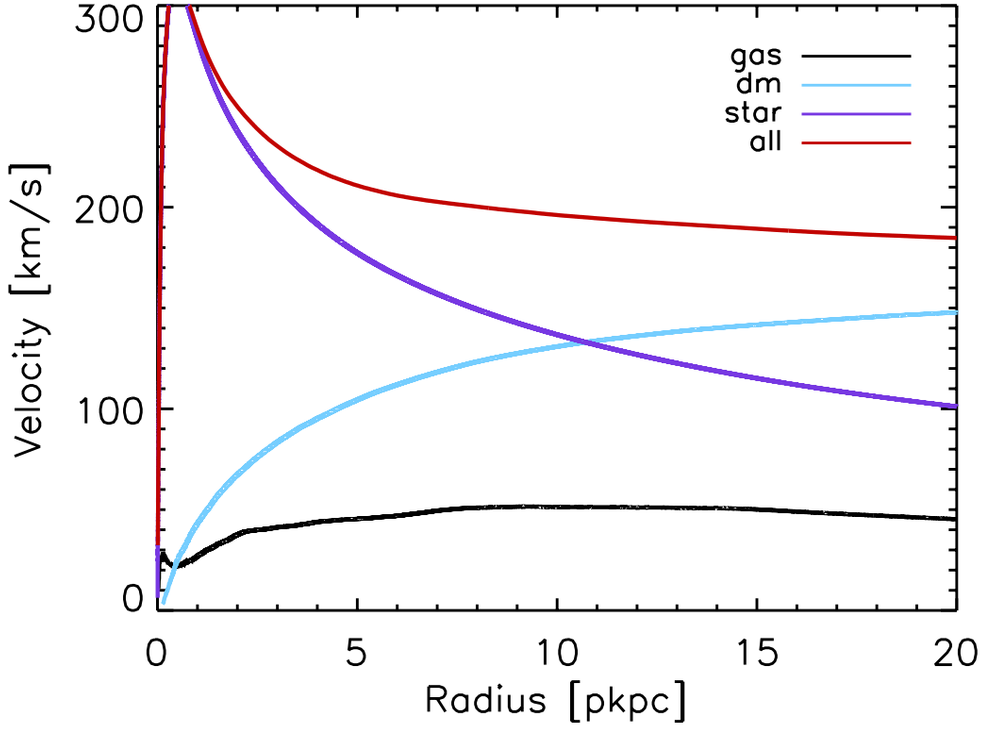
standard






no multiple-scattering






Denise Schmitz, van de Voort+

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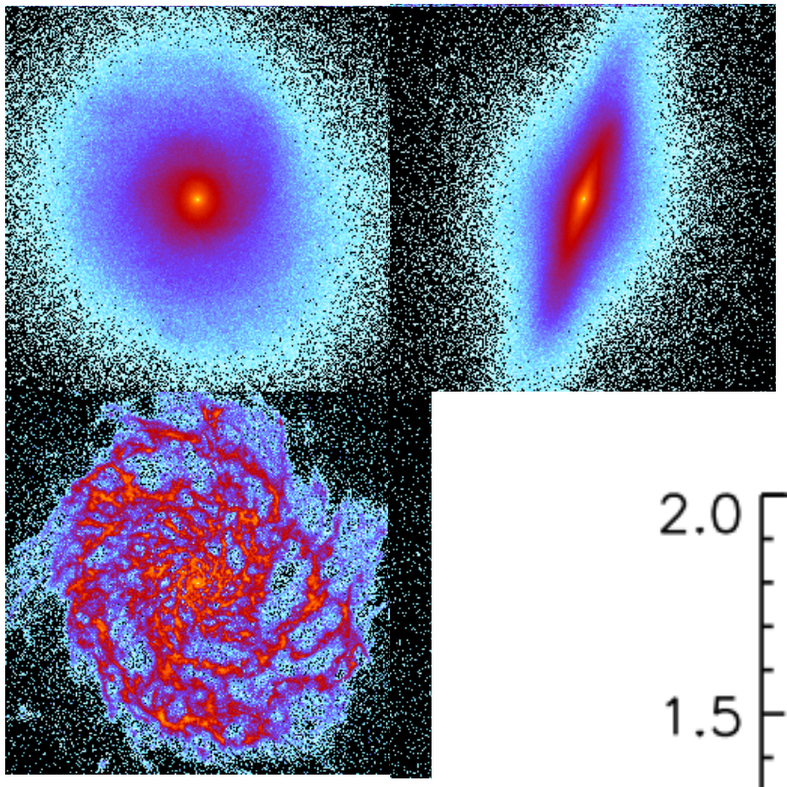
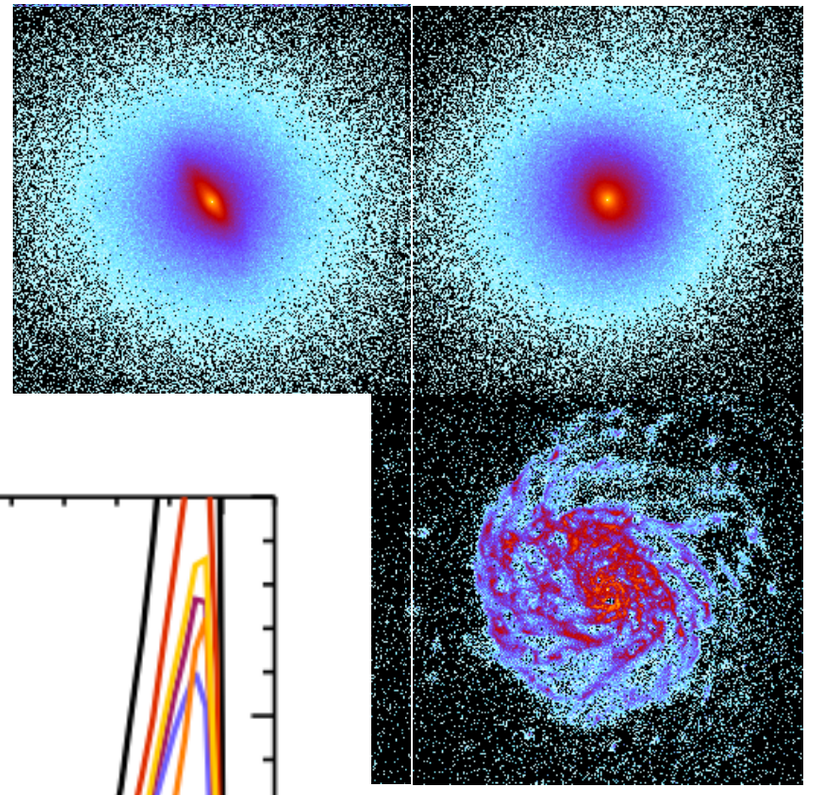
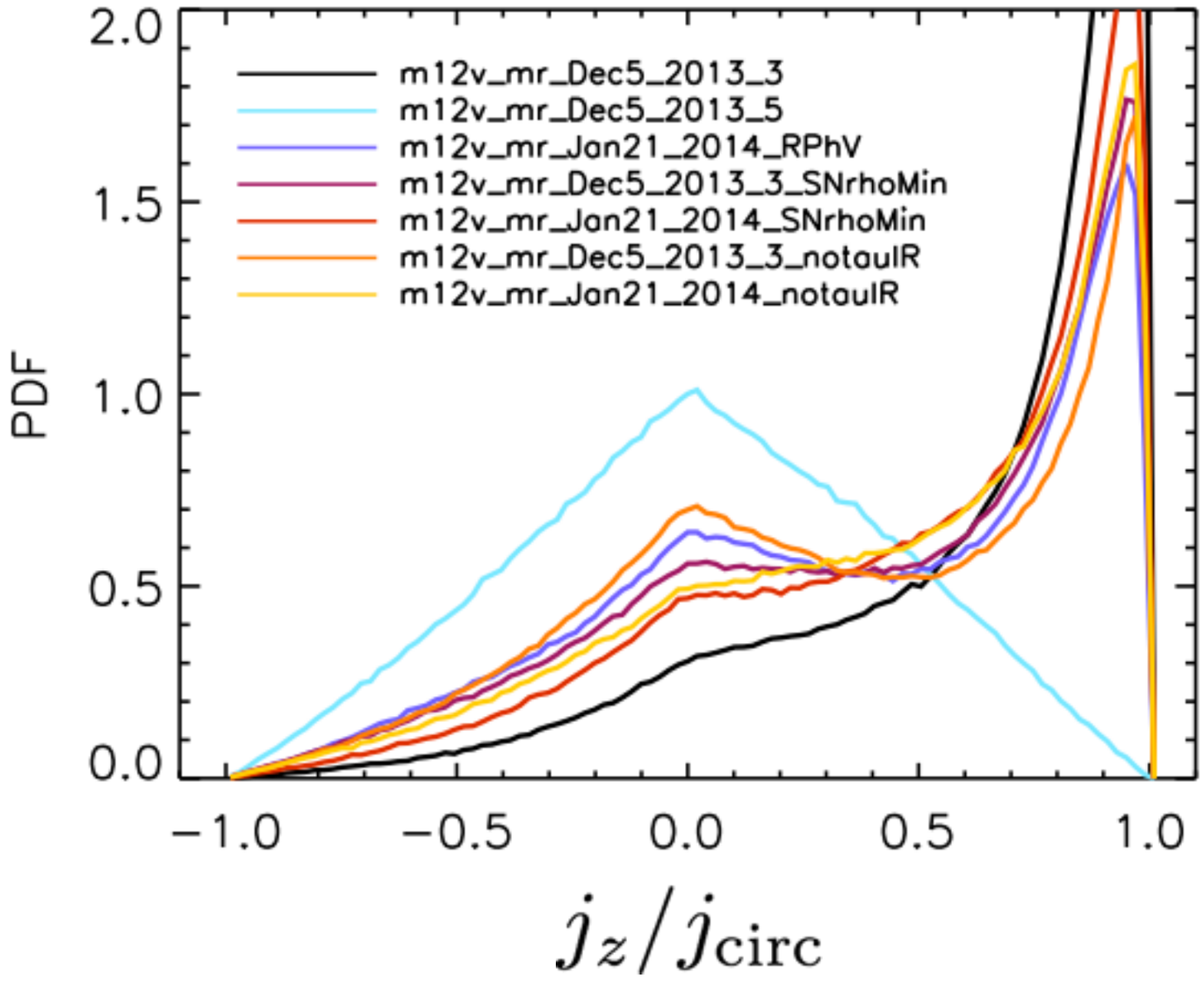


no multiple-scattering



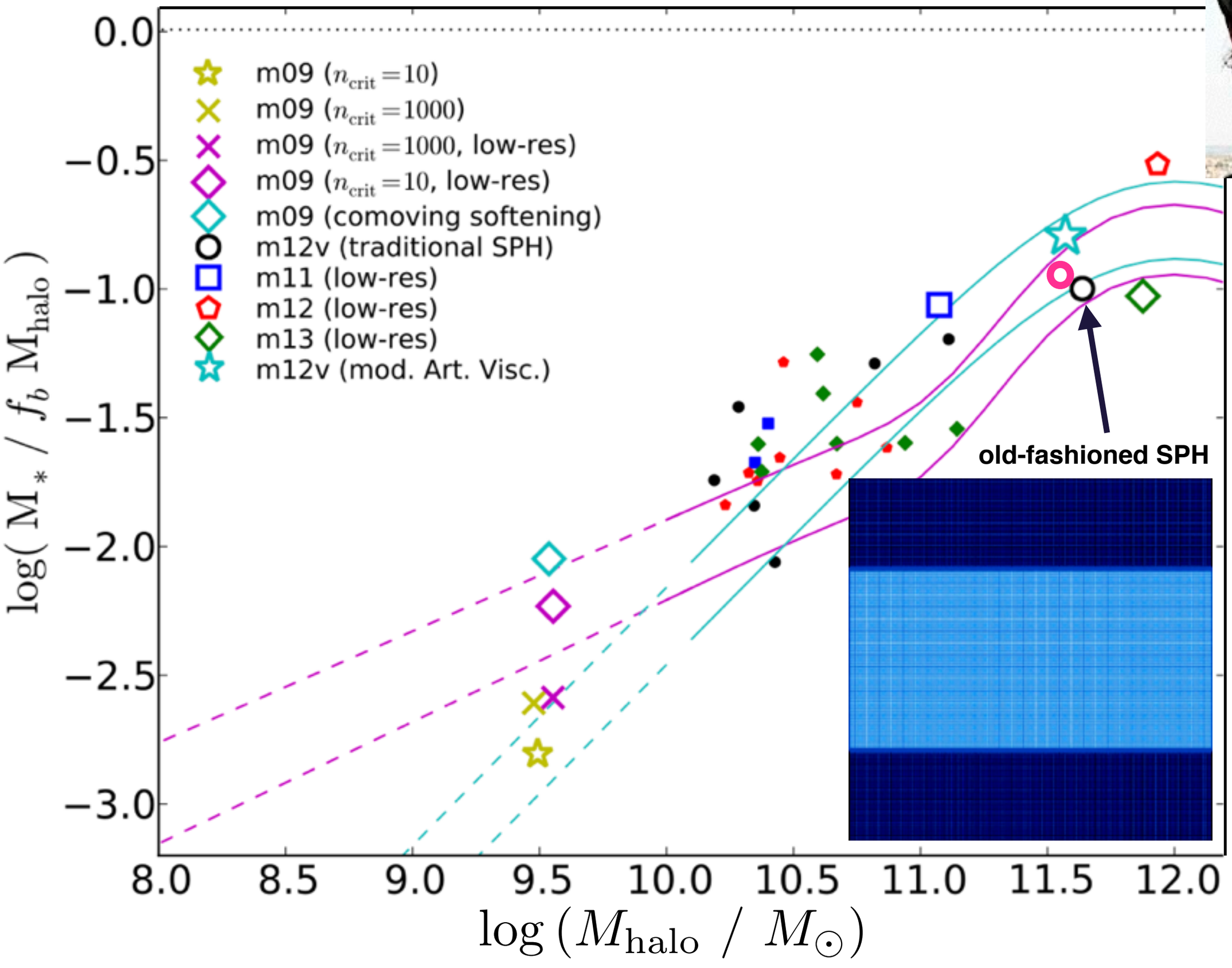



Denise Schmitz, van de Voort+

# Weak Numerical Dependence

## "ALGORITHMIC" CHOICES NOT DOMINANT

Keres et al., in prep



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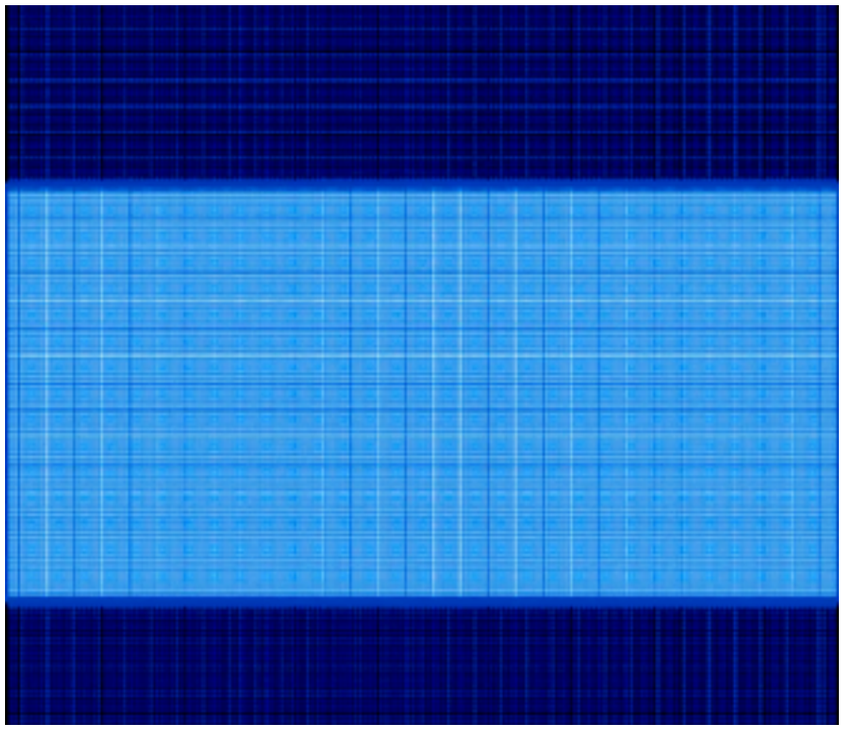
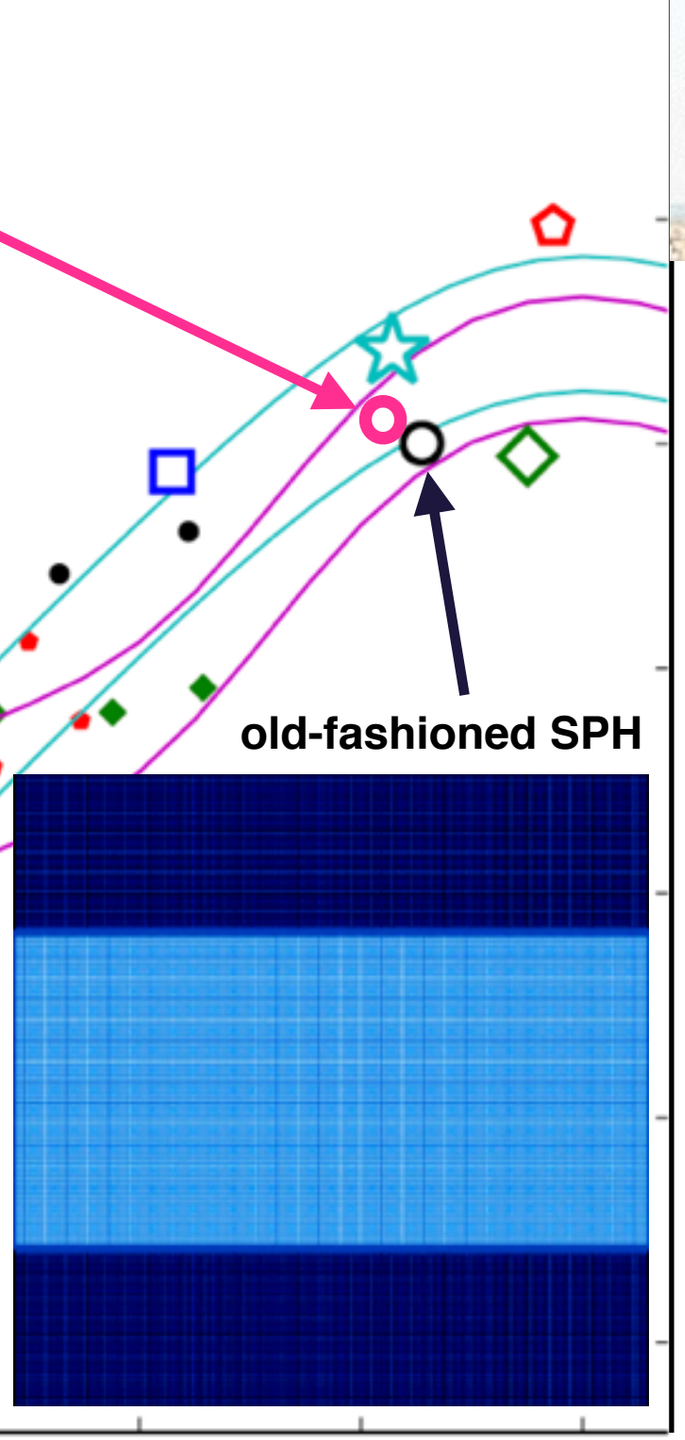
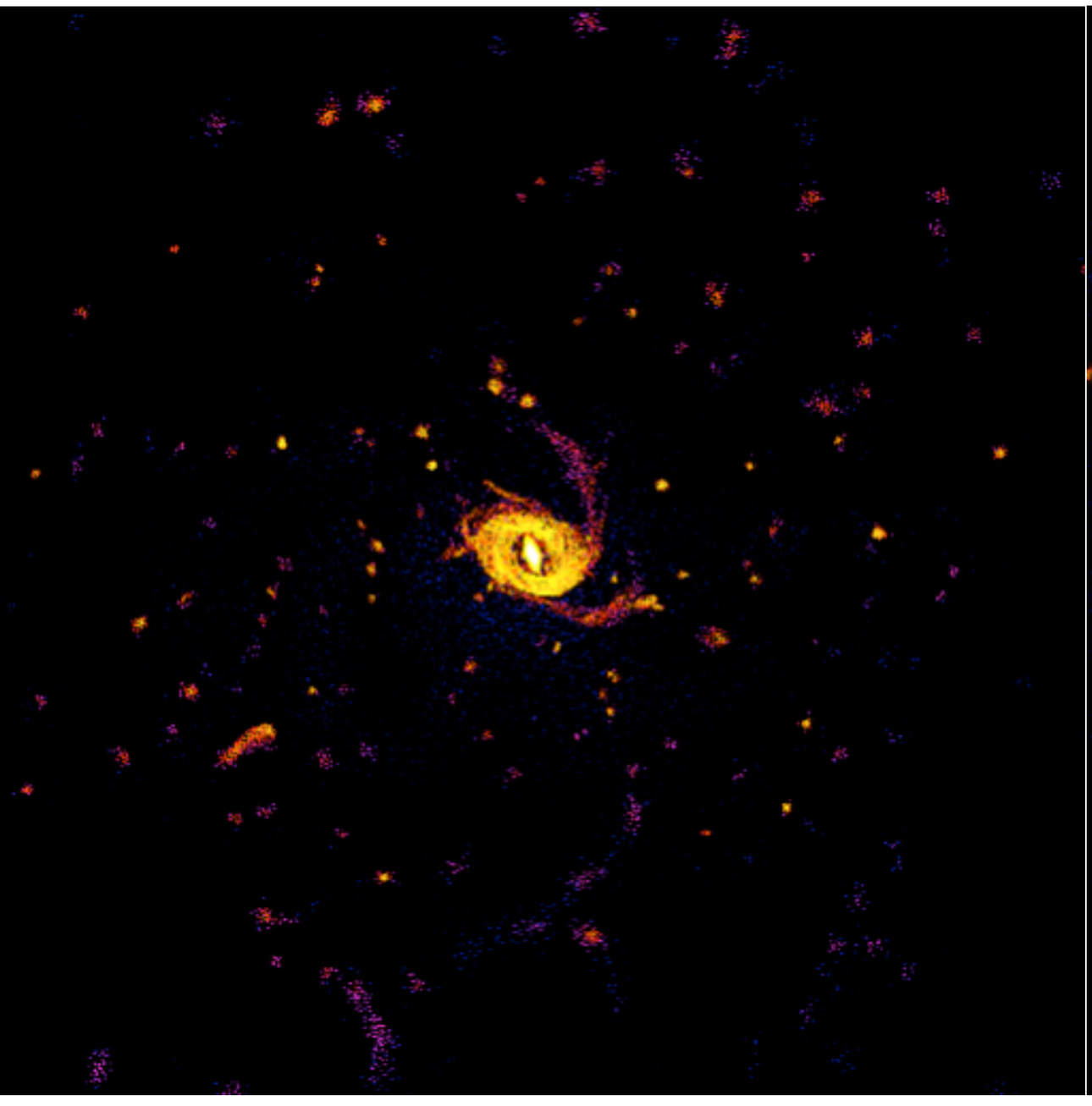




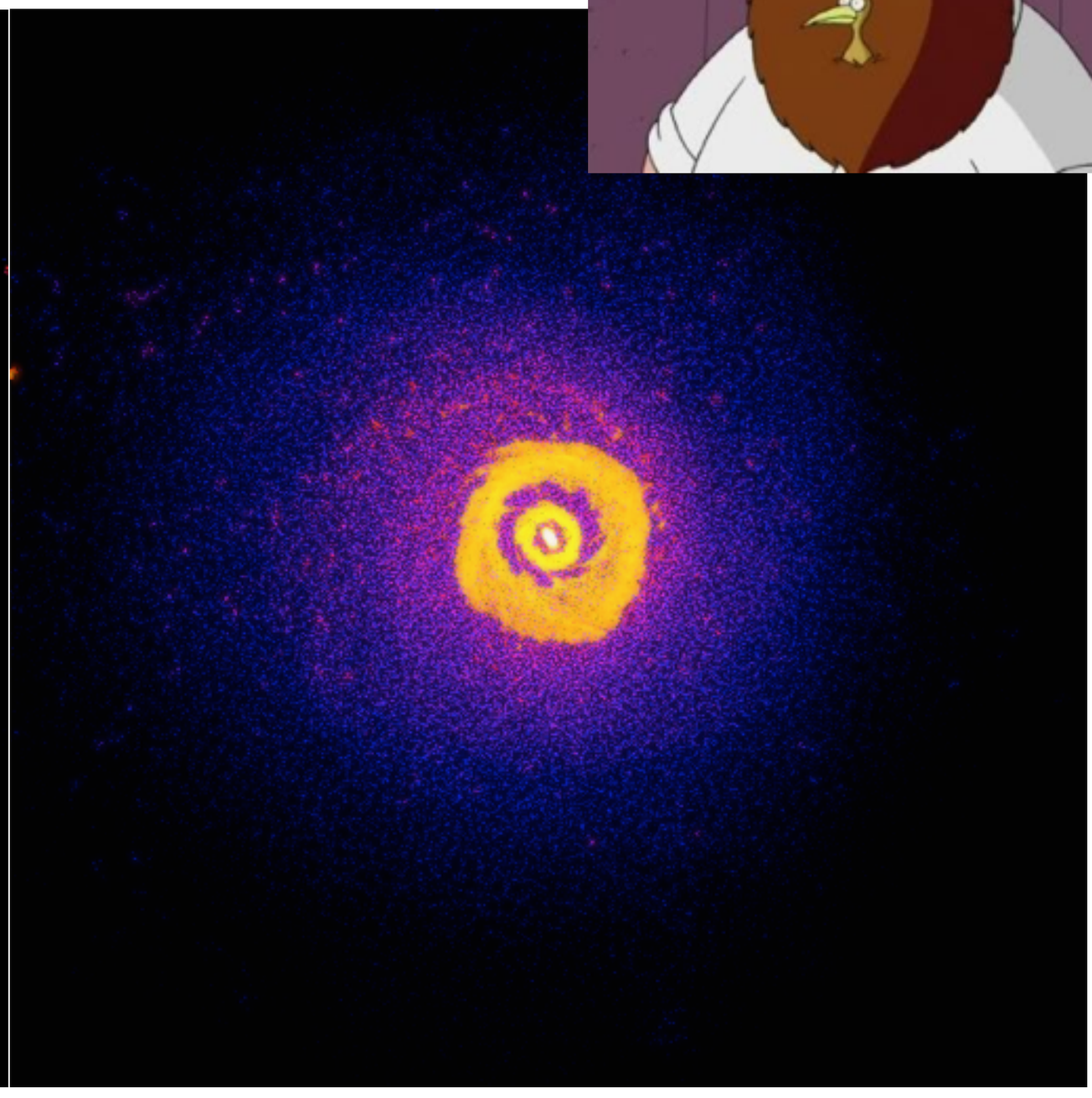
# Gravitational Heating & Mixing

## NOT AS MANY CLUMPS THESE DAYS!

Keres et al.,
(newer picture)



Density Formulation
("Old" GADGET)



Pressure-Entropy Formulation
(GIZMO)

Cooling from hot halo *is* sensitive to numerics

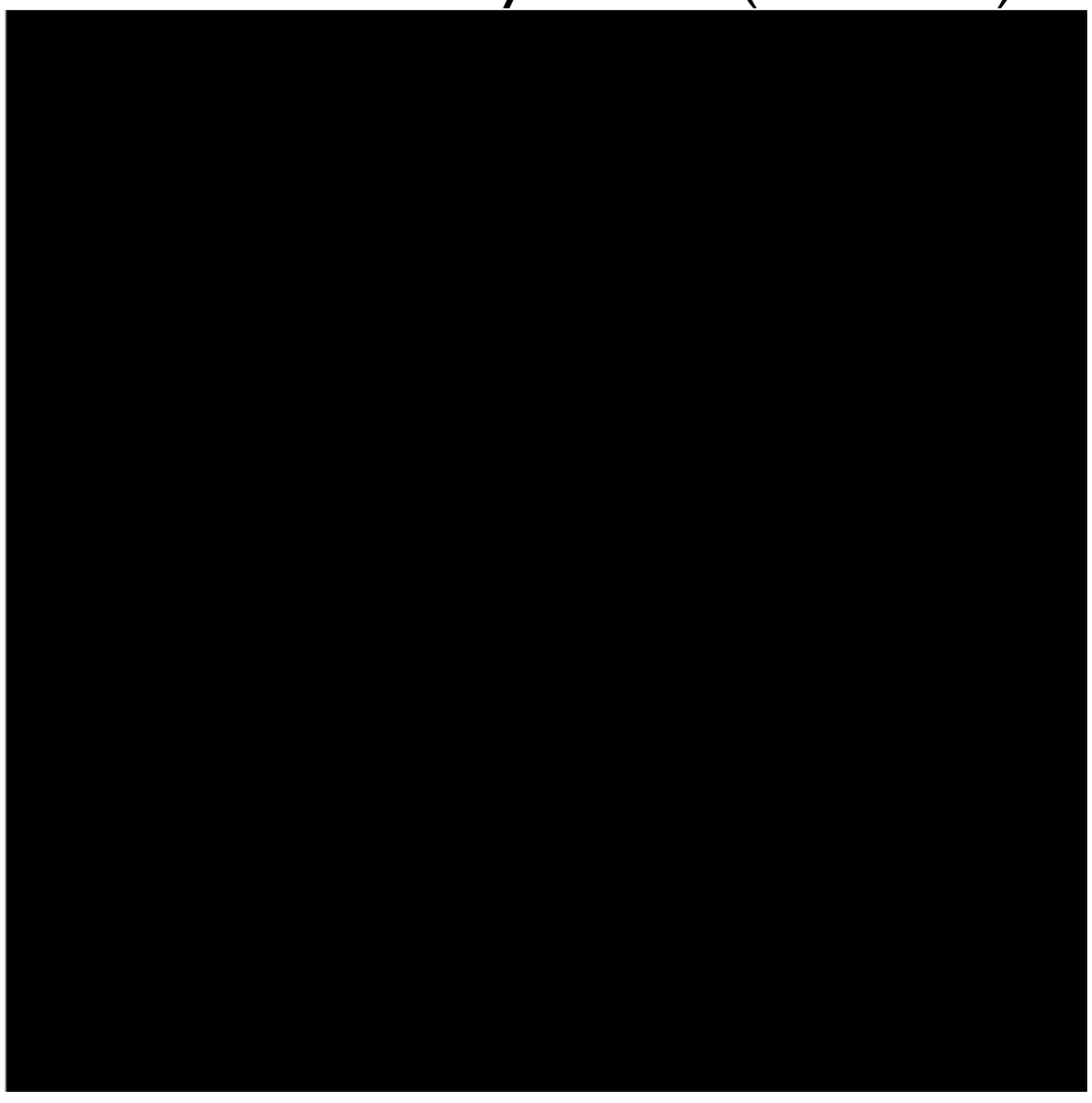
Sub-Grid Is Not Enough

WE NEED TO DO BETTER!

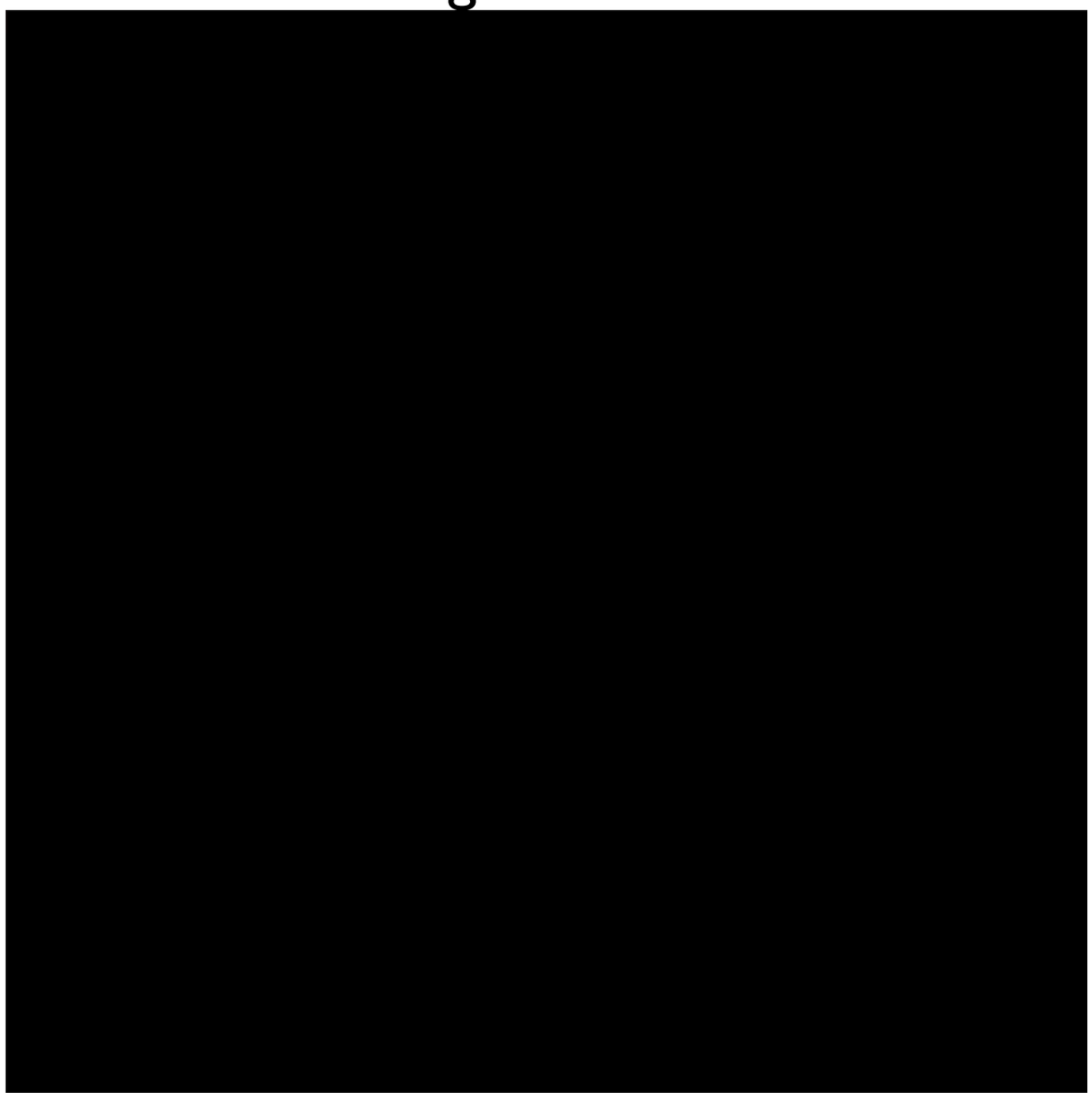
Faucher-Giguere, in prep

# Proto-MW: Gas Temperature:

Insert Winds "By Hand" (Sub-Grid)



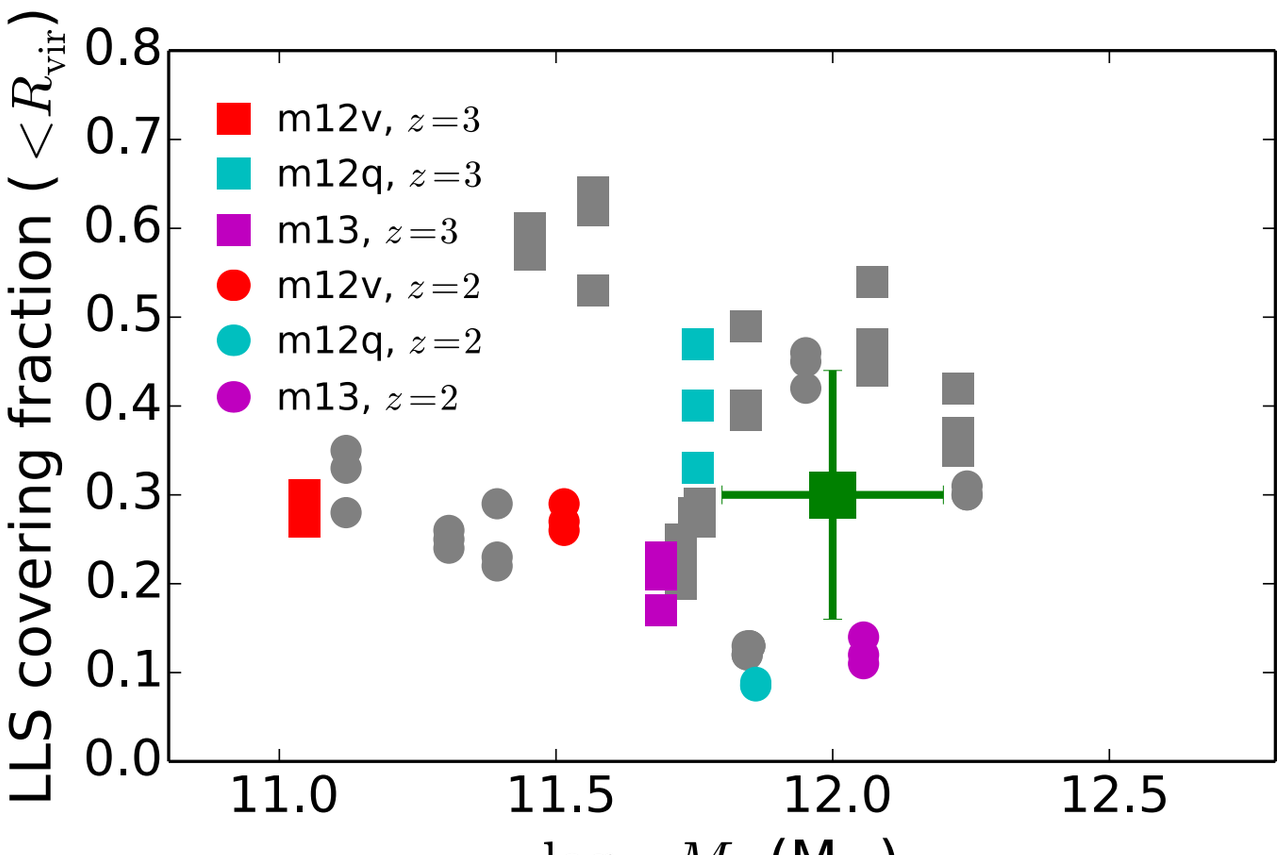
Following Full Feedback

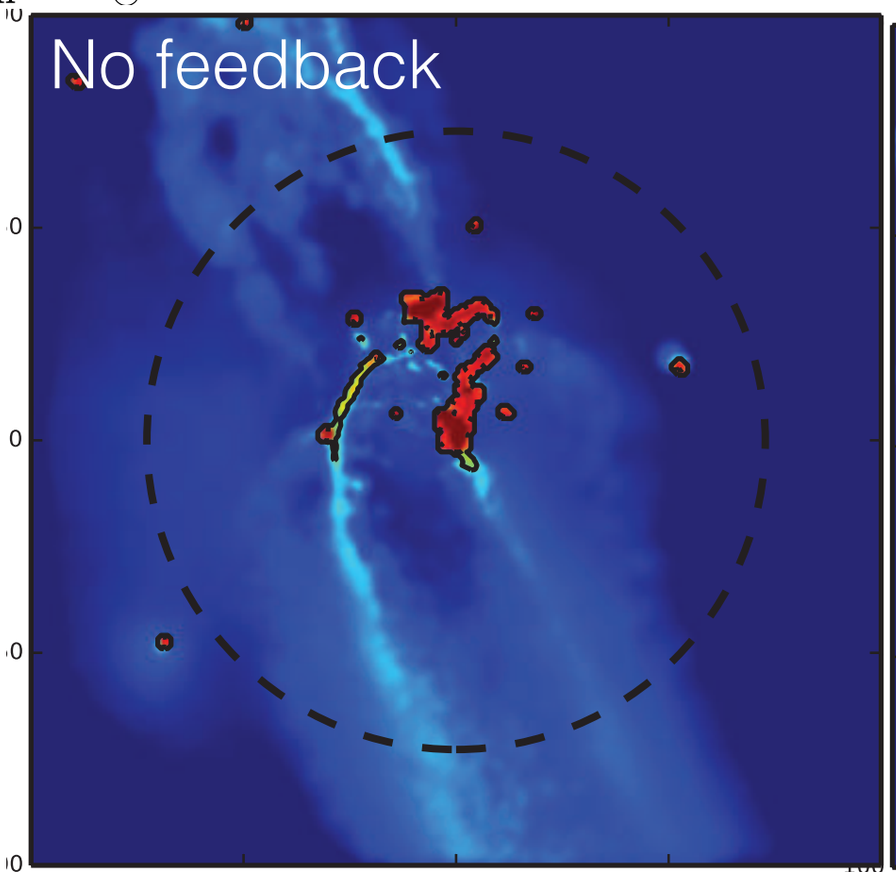


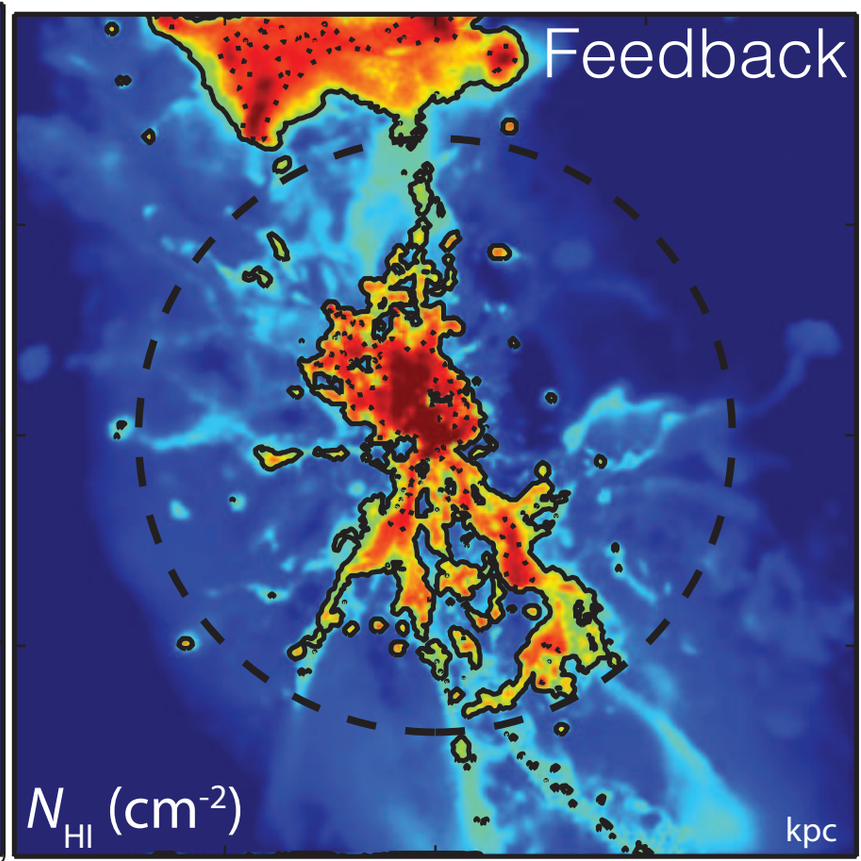
# Feedback Determines the Halo Gas Properties

## ABSORBERS FALL OUT NATURALLY… EXCEPT

Faucher-Giguere, in prep



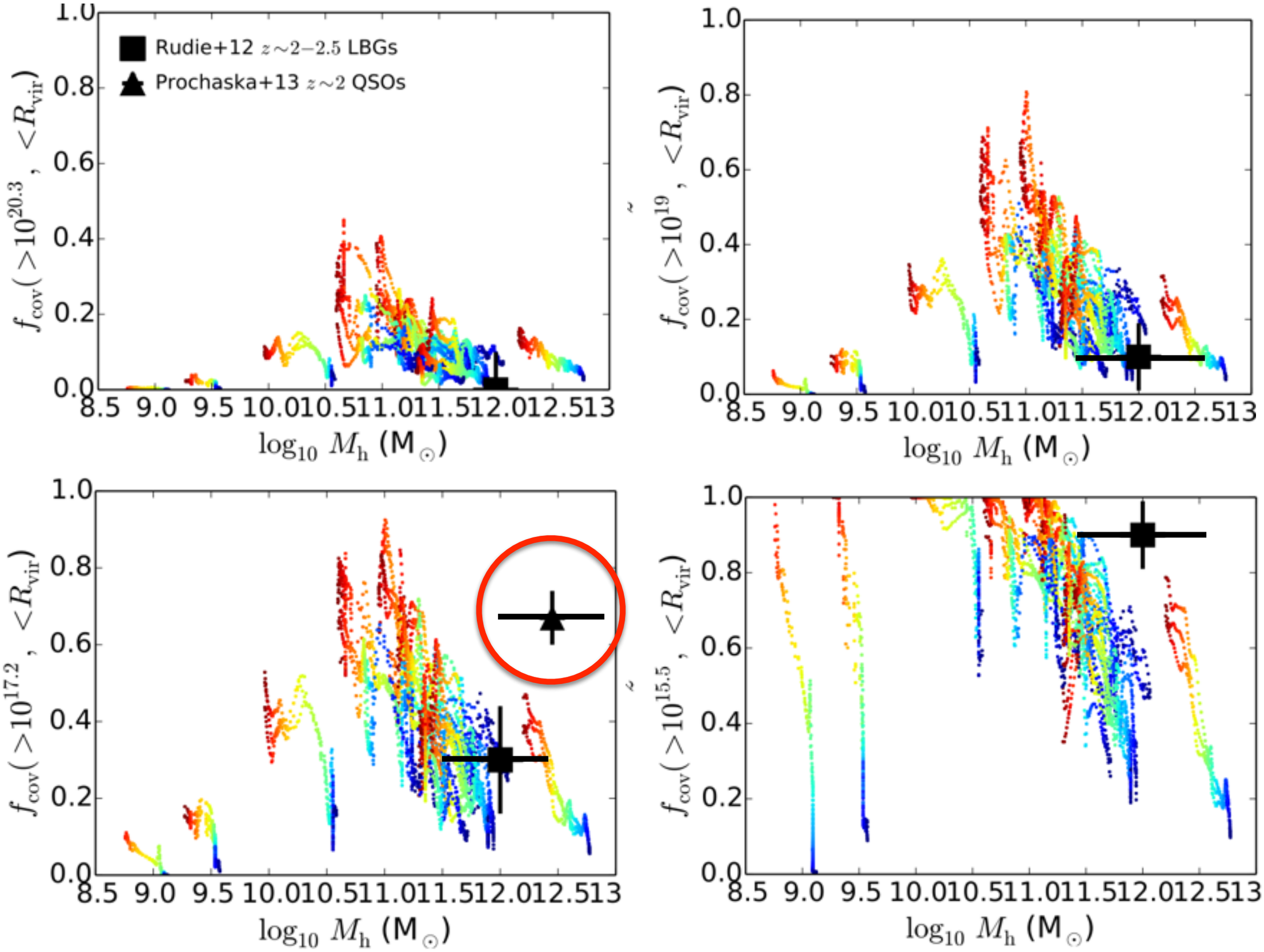



# Feedback Determines the Halo Gas Properties

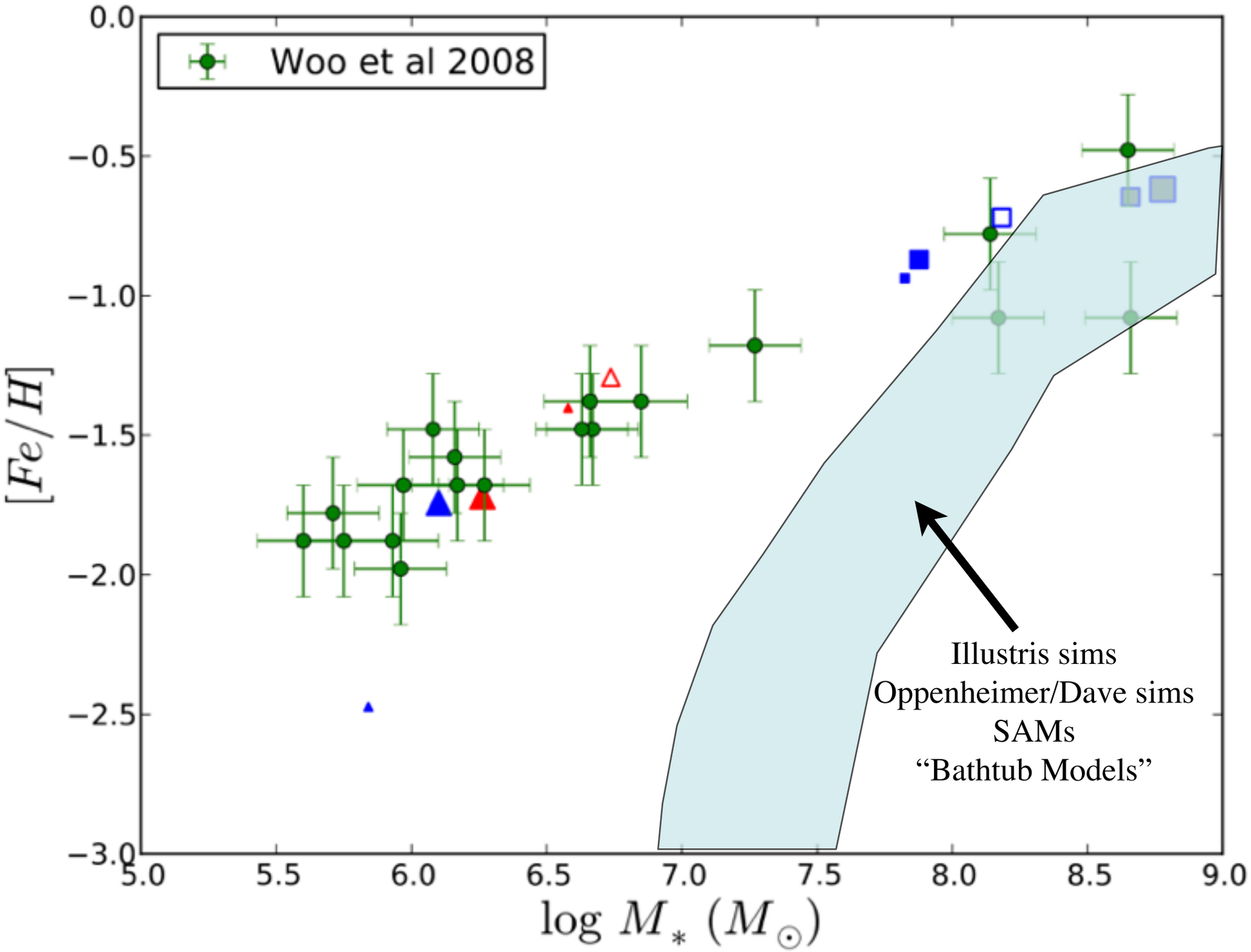
## ABSORBERS FALL OUT NATURALLY… EXCEPT QUASAR SYSTEMS

Faucher-Giguere, in prep



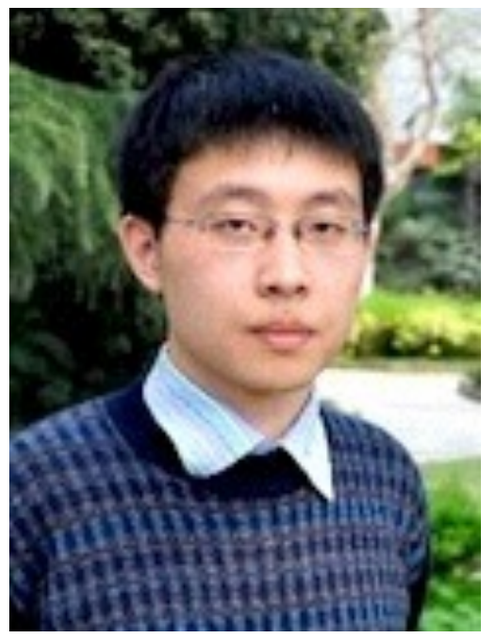
# Mass-Metallicity Relation is Sensitive to Feedback

*DETAILS* MATTER



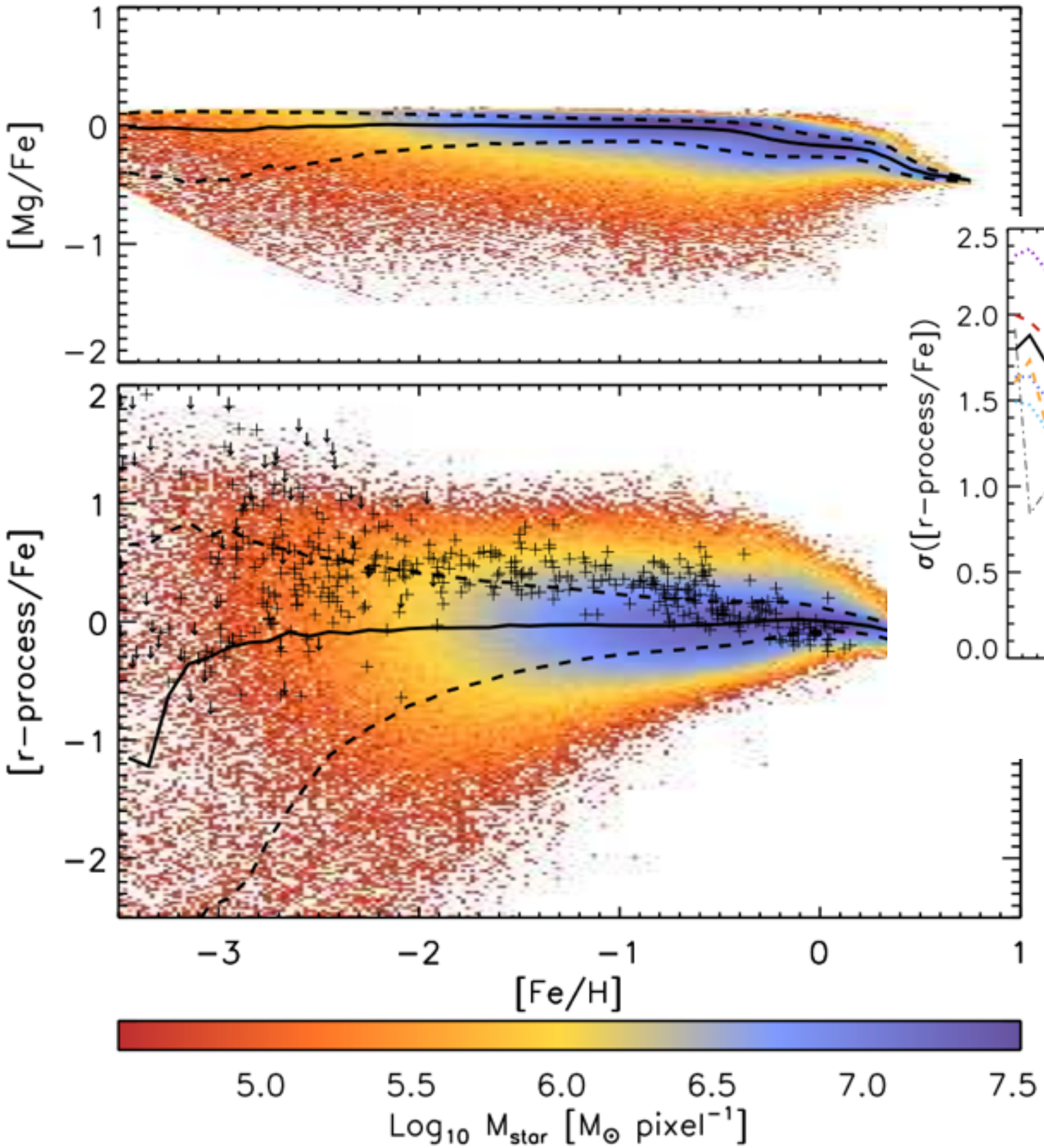

- Outflows suppress "new" infall of pristine material?
- Metal-rich gas preferentially re-accretes in fountains?

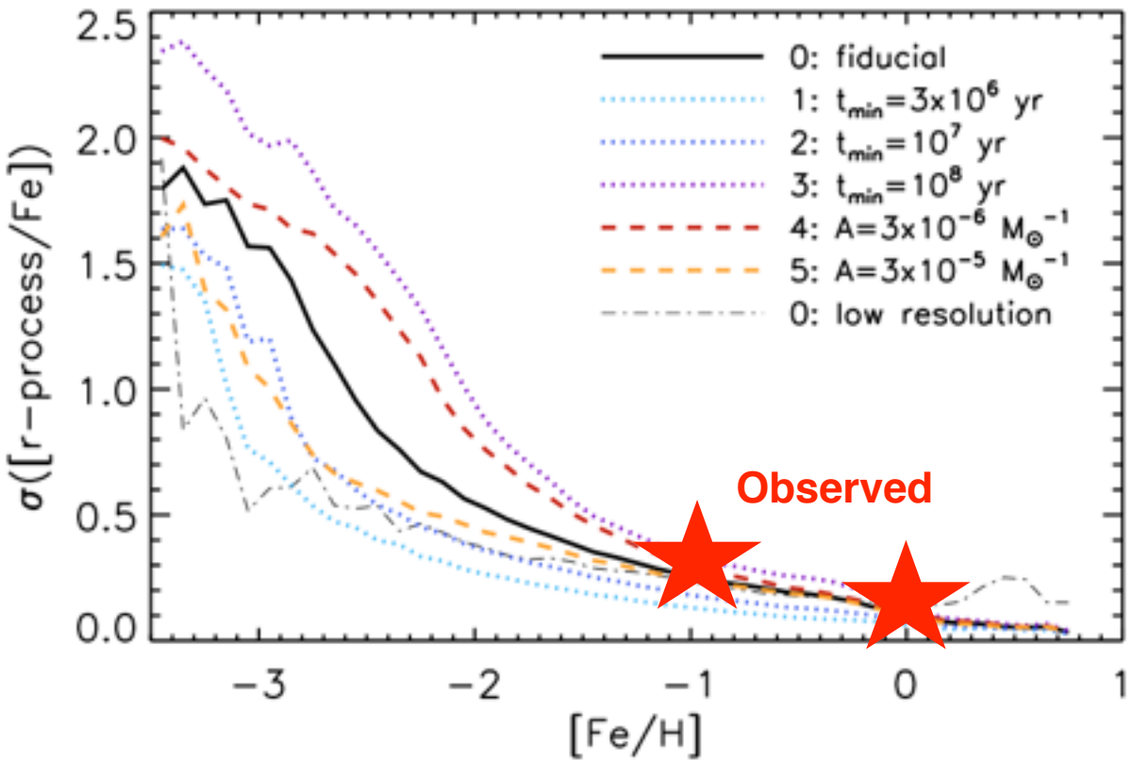
Xiancheng Ma



# Constraints on the Origins of R-Process Elements?

## CAN THEY COME FROM NEUTRON-STAR MERGERS?



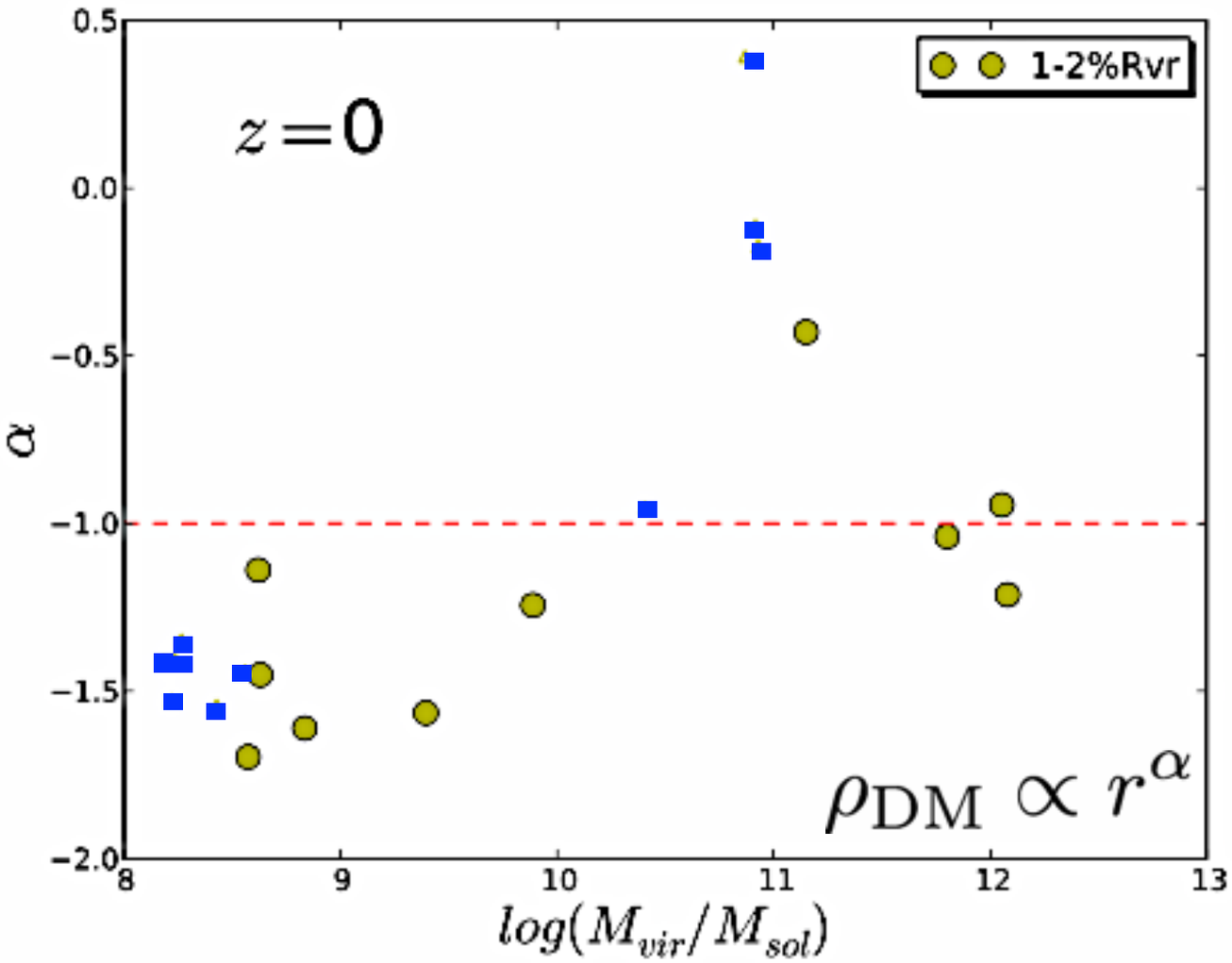



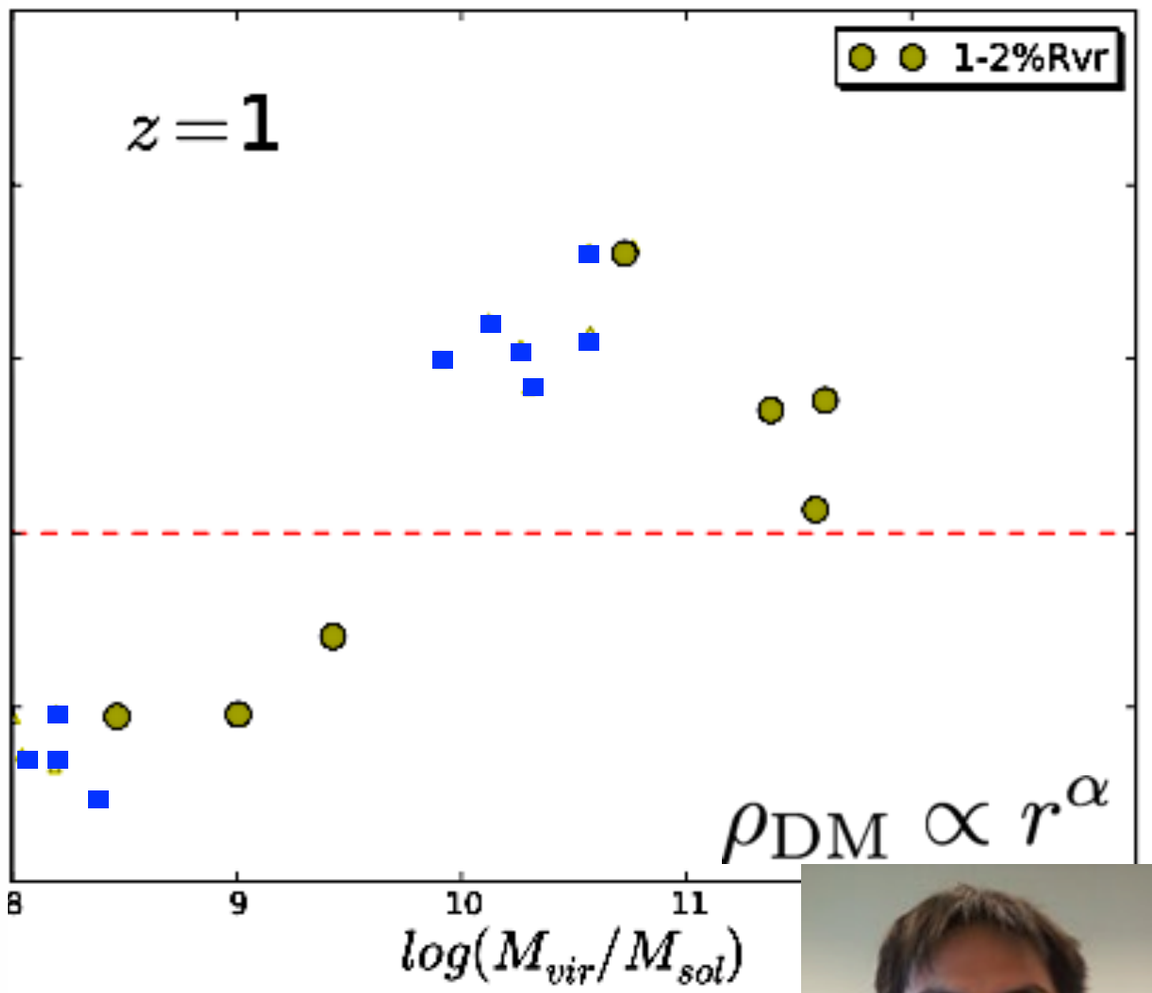

Freeke van de Voort

# Cusp or core?

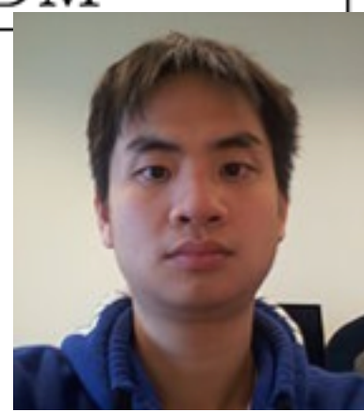
Overall in FIRE, cores form only in a limited range of halos masses:
~$10^{10}$-$10^{11}$Msun (halos hosting galaxies with $M_*$~$10^6$-$10^9$ Msun).

~MW mass halos are also affected: very little or no adiabatic contraction!



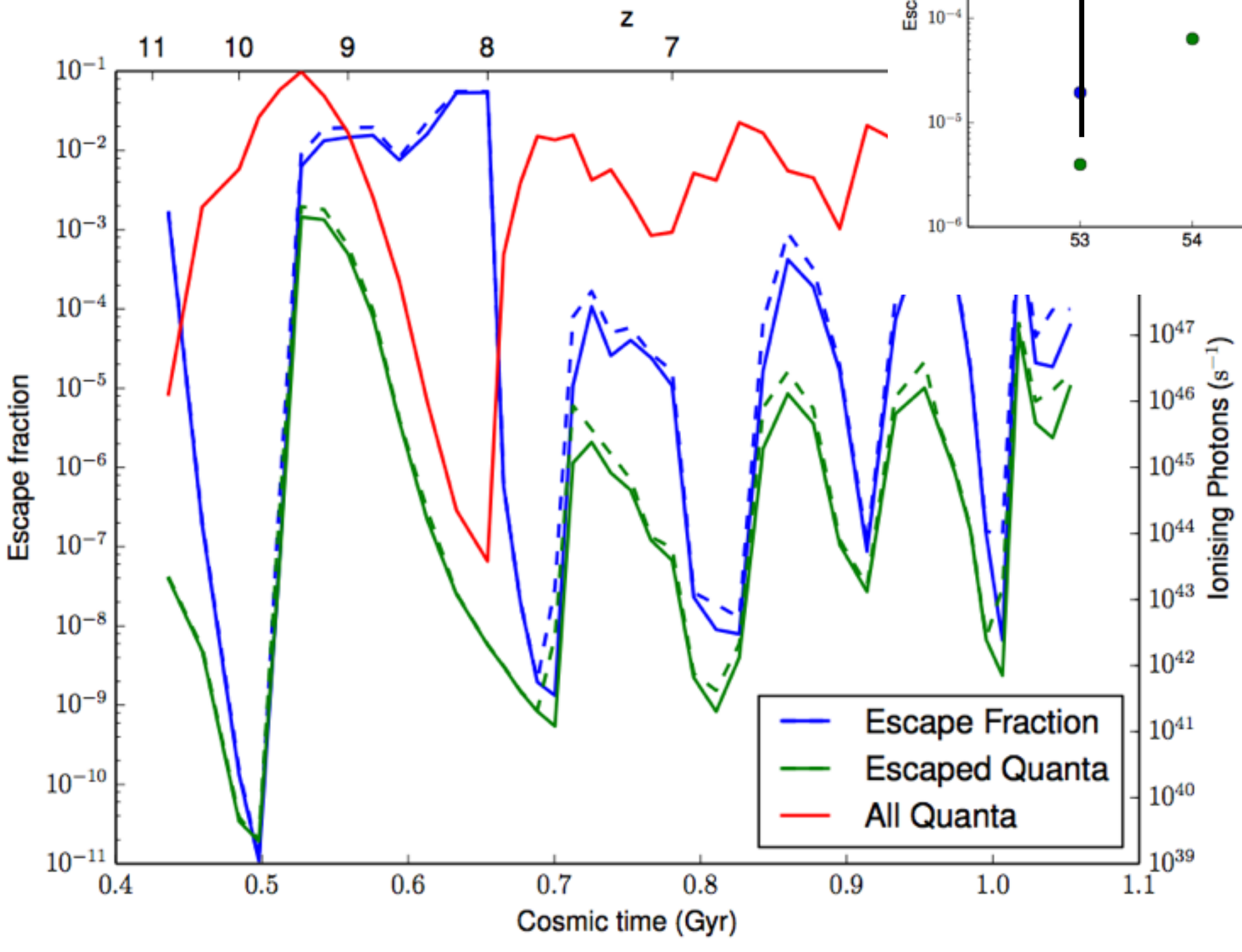

T.-K. Chan et al., in preparation

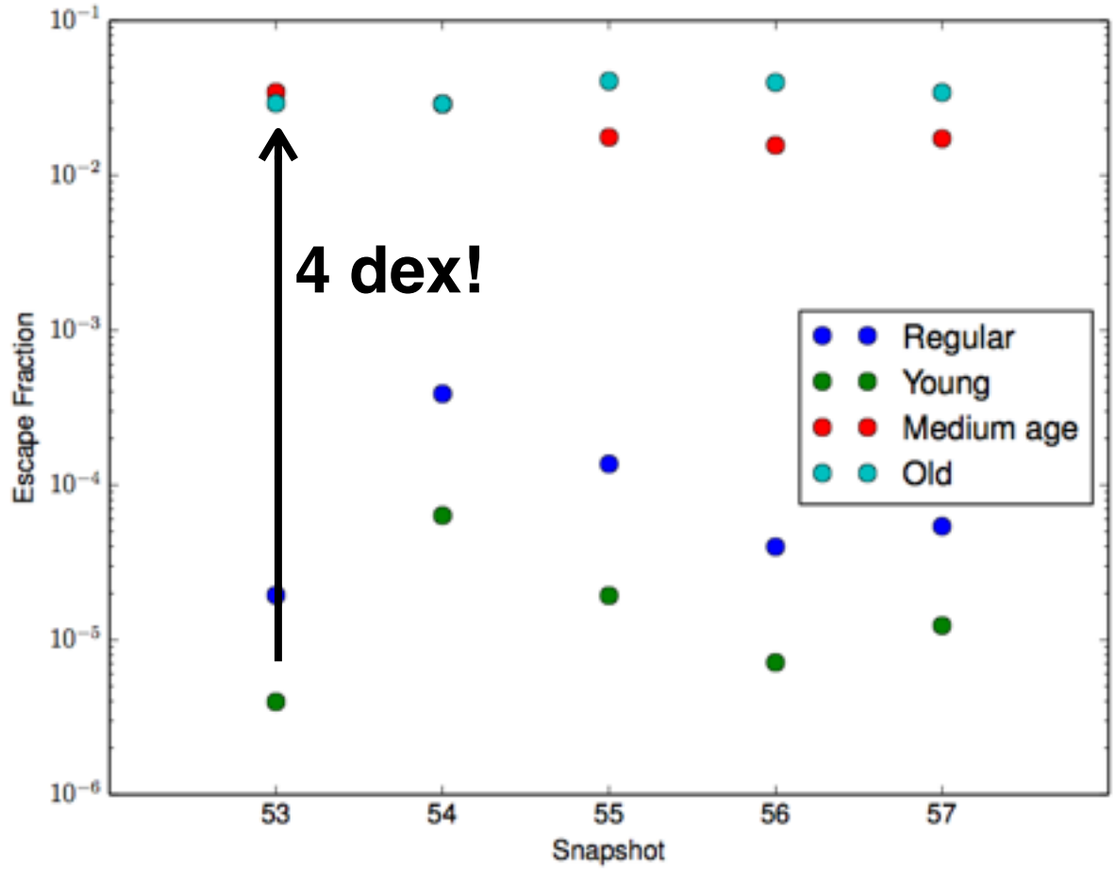


# Escape fractions of ionizing photons

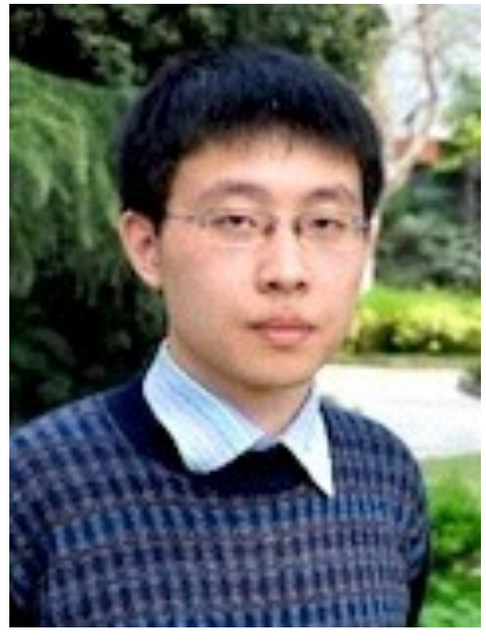
## ISM PHASE STRUCTURE MATTERS

resolution ~ 0.1 pc, ~$20\,M_\odot$



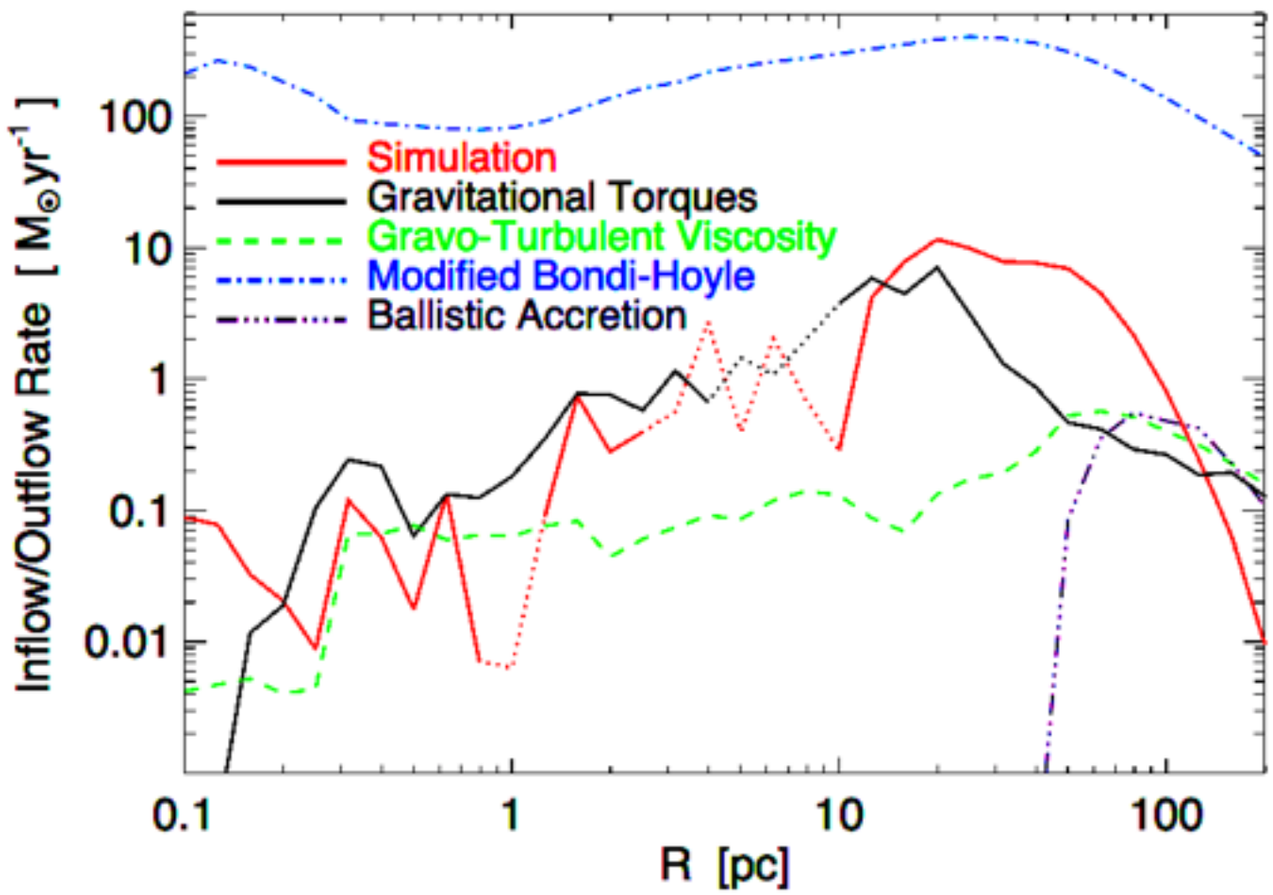

Xiancheng Ma

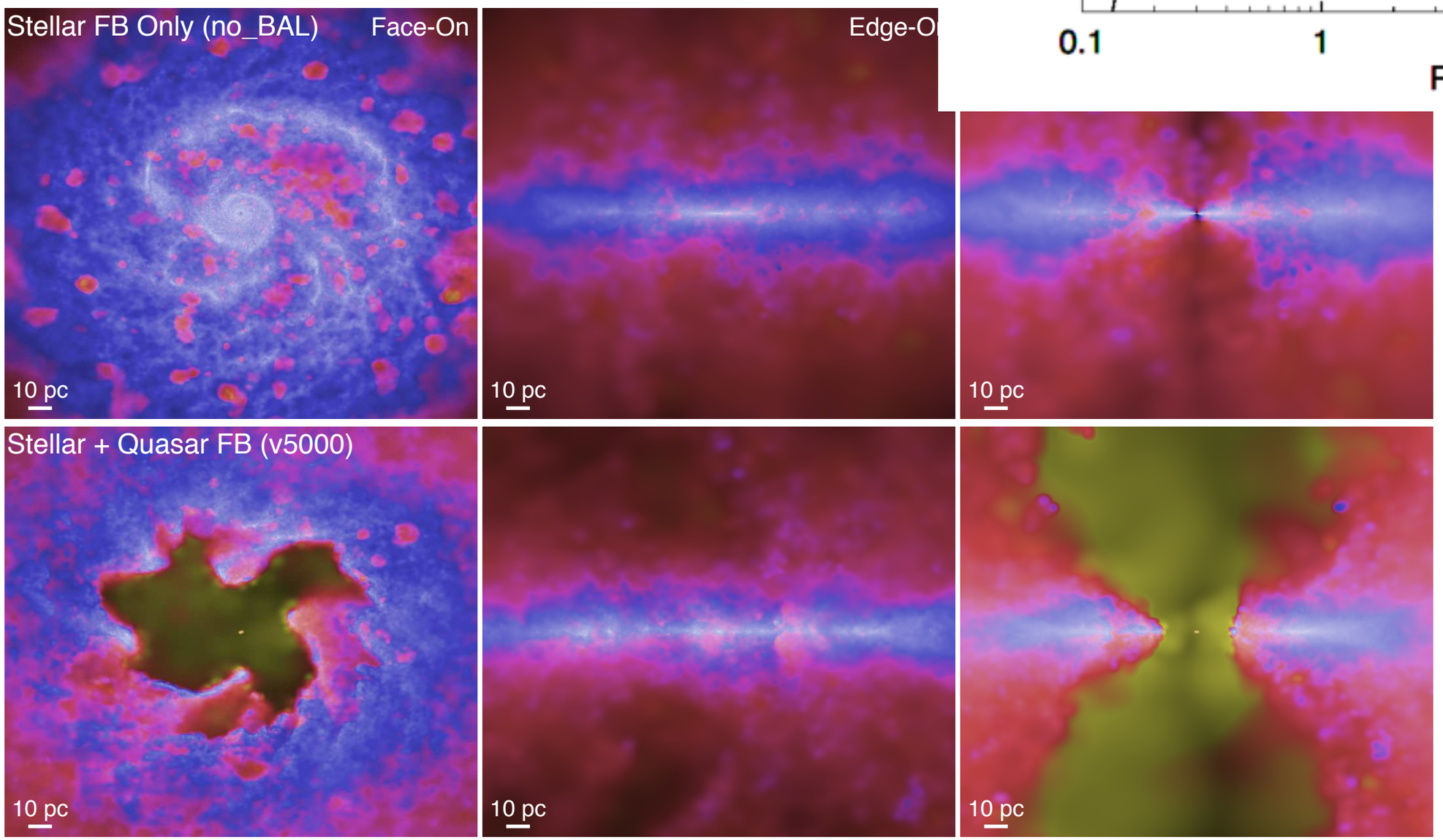


# Revisiting Accretion

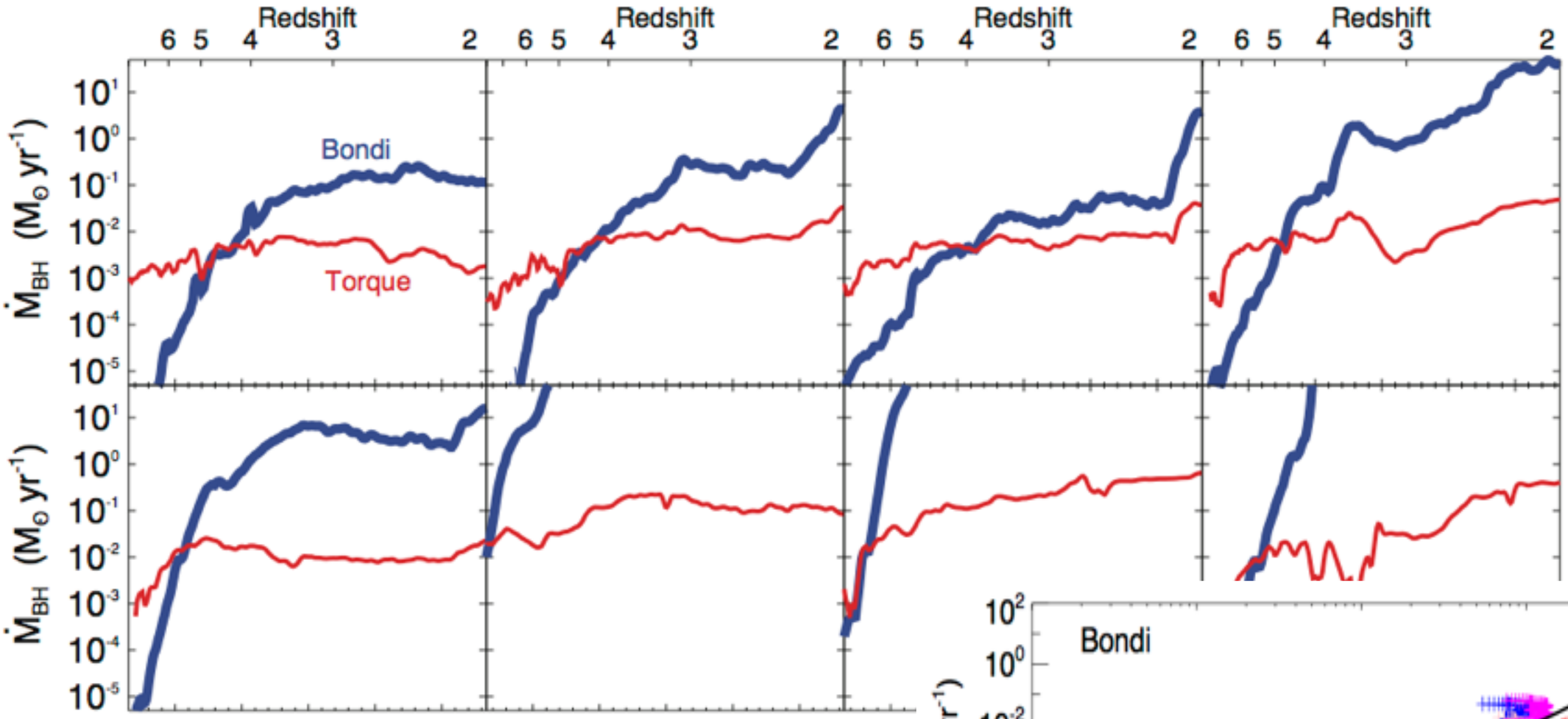
*INCLUDING:*

- *RESOLUTION = 0.01 pc, 10 Msun*
- *STELLAR FEEDBACK*
- *COOLING (10K - 1e10 K)*
- *COMPTON HEATING*
- *PHOTOIONIZATION FROM BH+STARS*
- *RADIATION PRESSURE*
- *ACCRETION DISK WINDS*



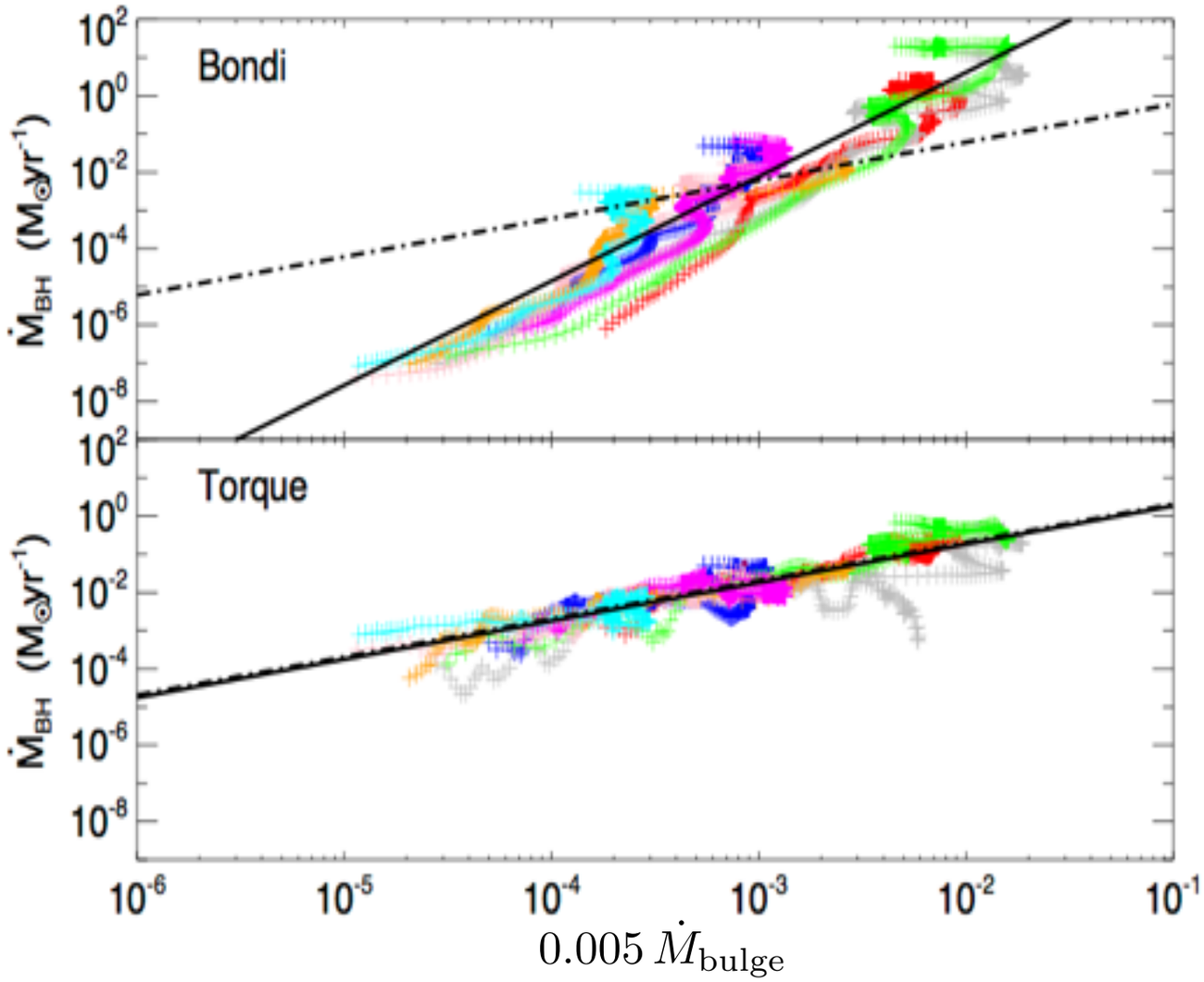

Paul Torrey




Gravitational Torques
vs.
Bondi

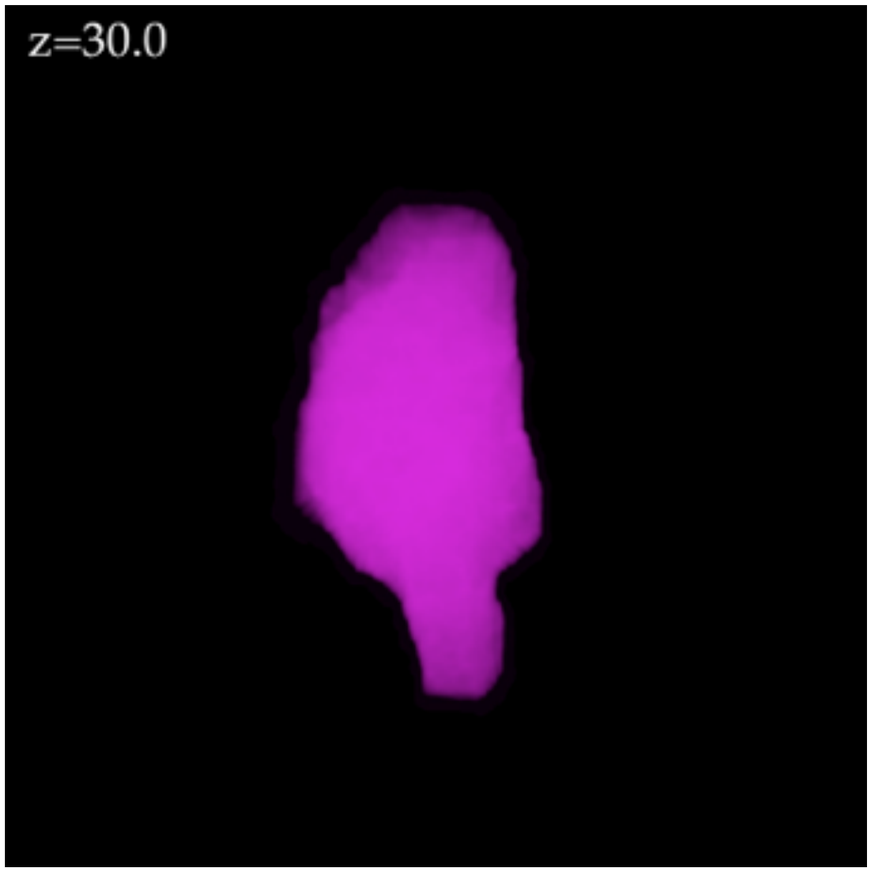
in cosmological sims

Angles-Alcazar et al. 2013

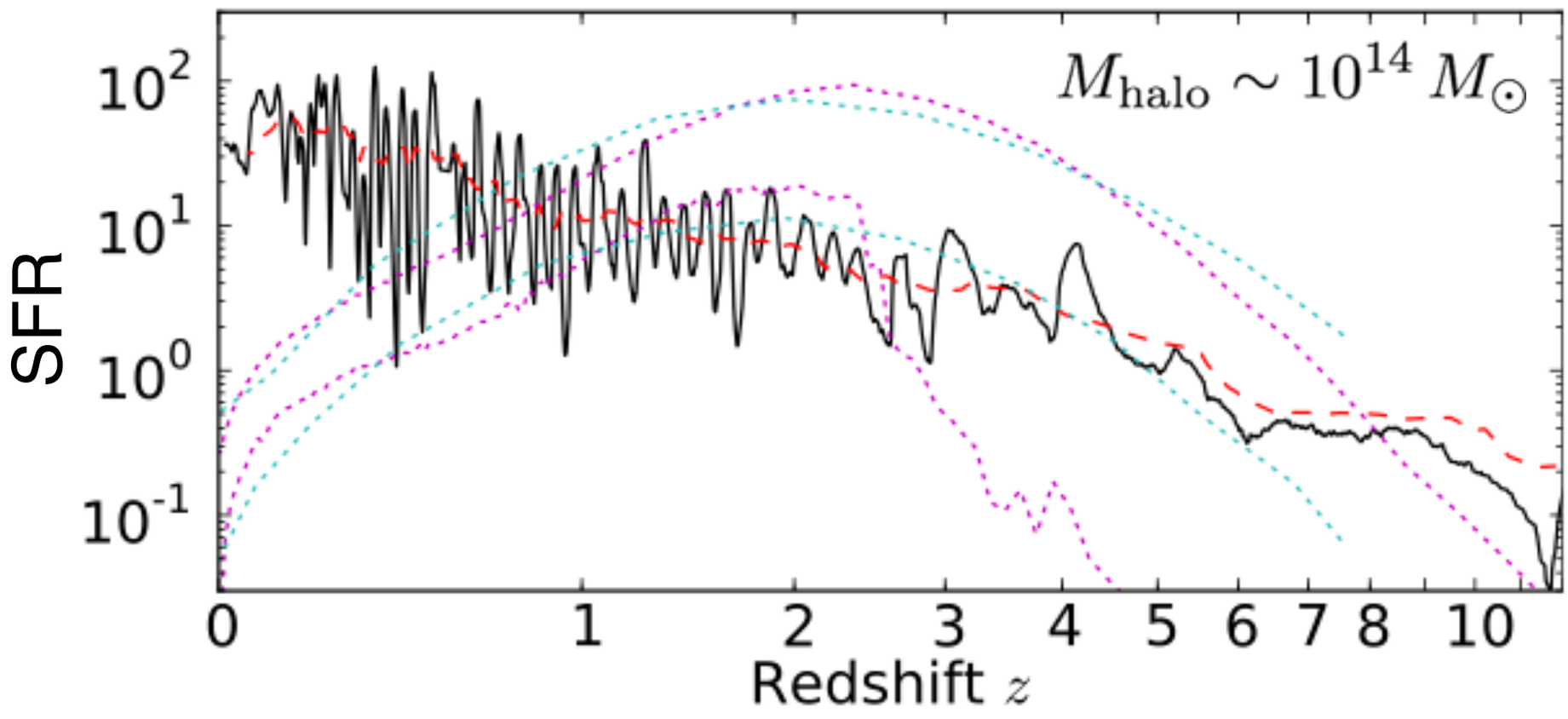


# Quenching: Non-AGN Mechanisms *FAIL*

## *MORE* THAN GRAVITY, COOLING, STARS, & MHD



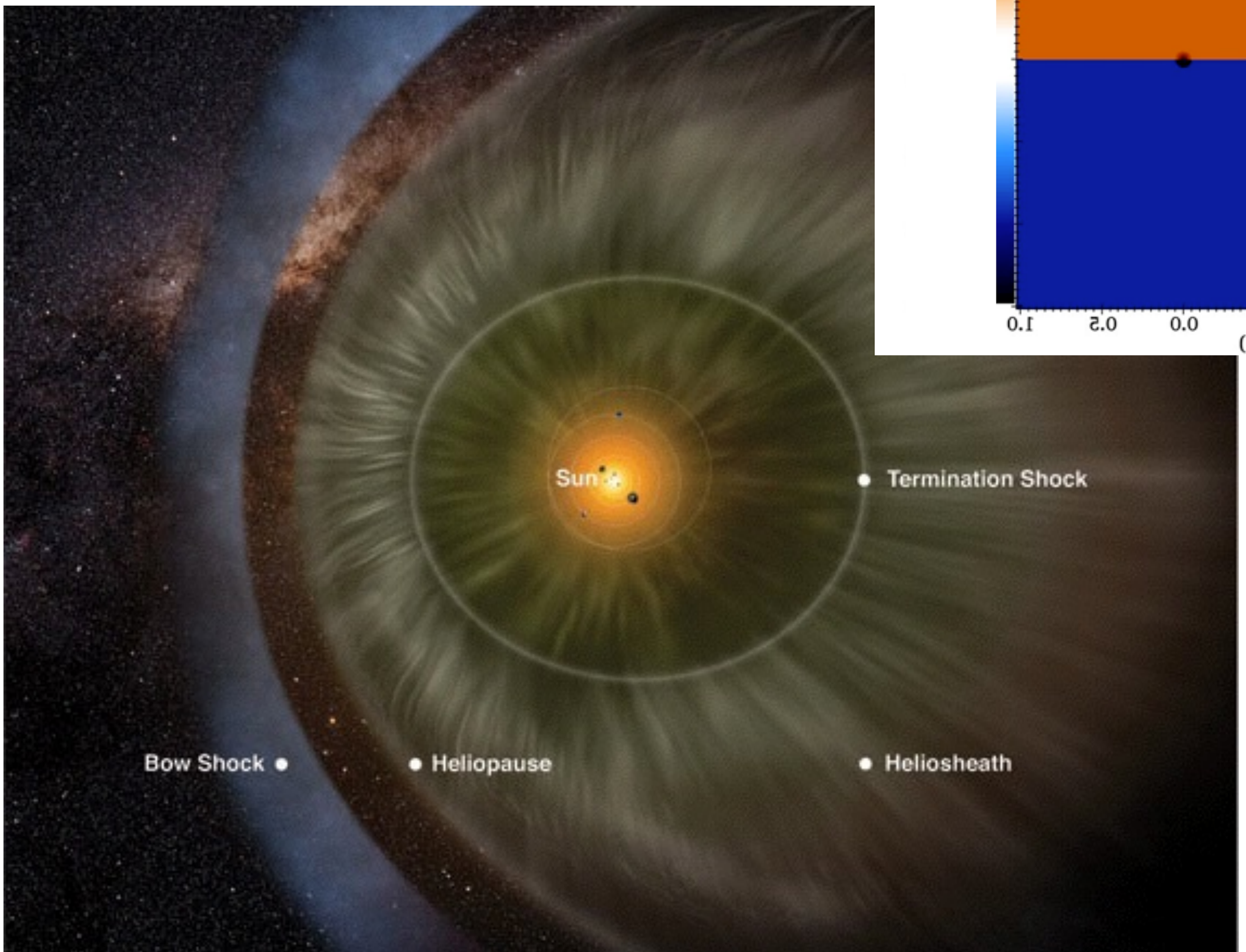

- **Morphology?** (**are** bulge-dominated)
- **Clumps/Gravity?** (resolution ~10^4 $M_{sun}$)
- **MHD/Conduction?** (new runs included)
- **Stars?** (late-time AGB/SNIa included)

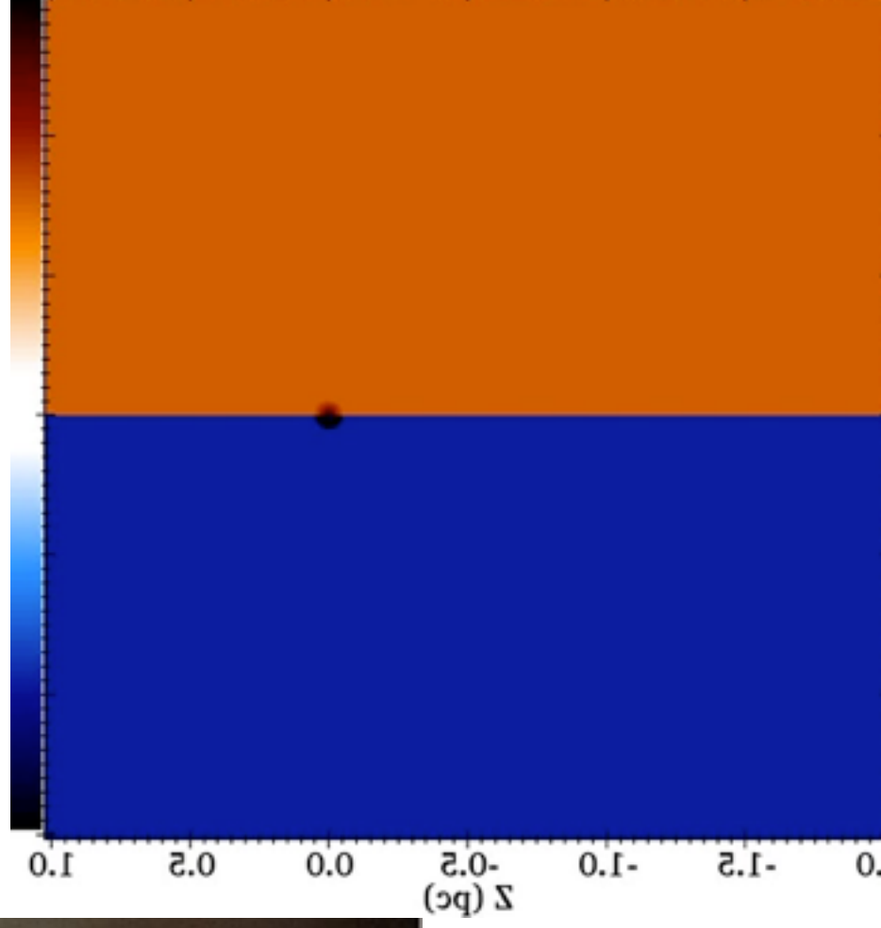


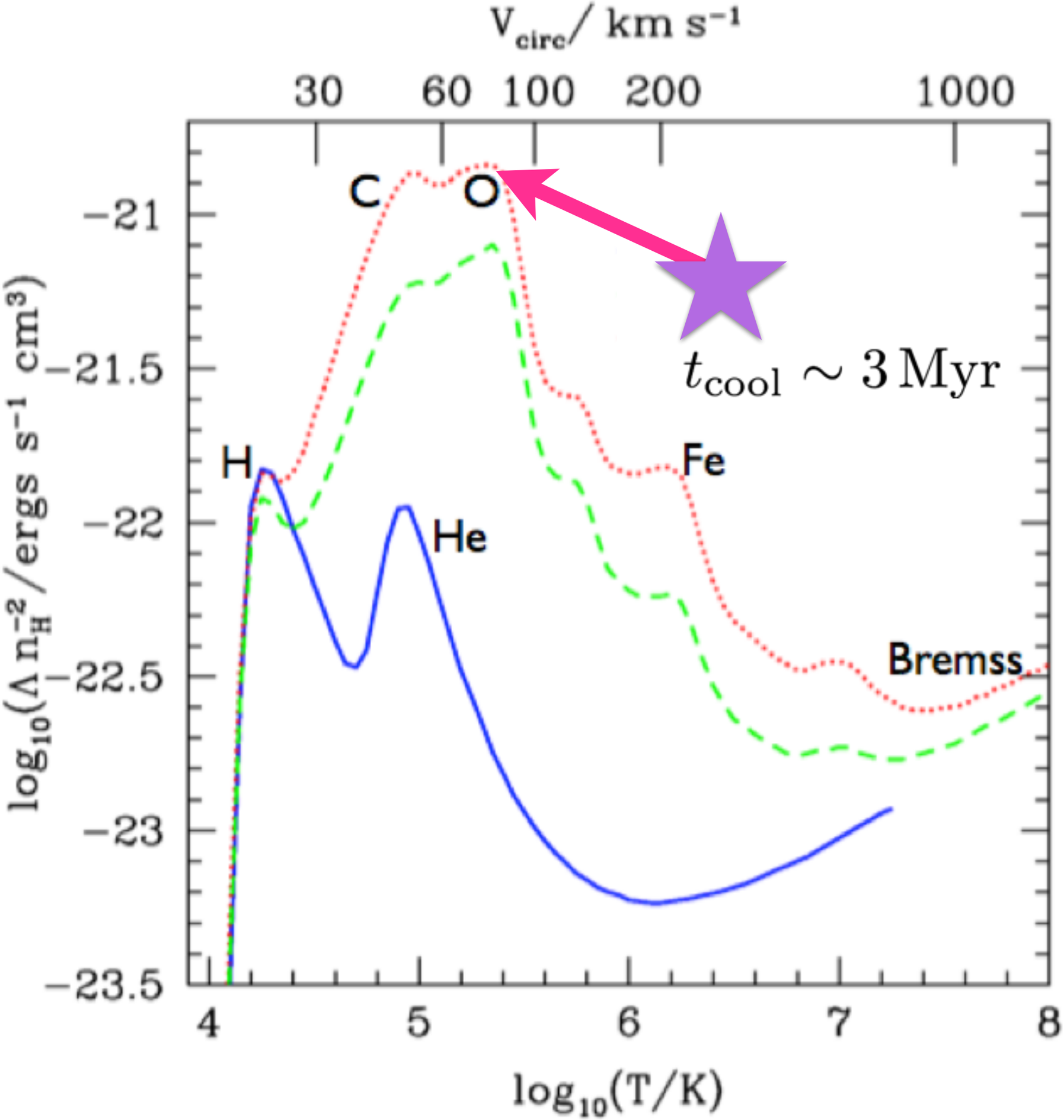

(more to come, Robert Feldmann)

# Can Stars Do It?

## SNIa, AGB (Conroy+, Ostriker, Novak)



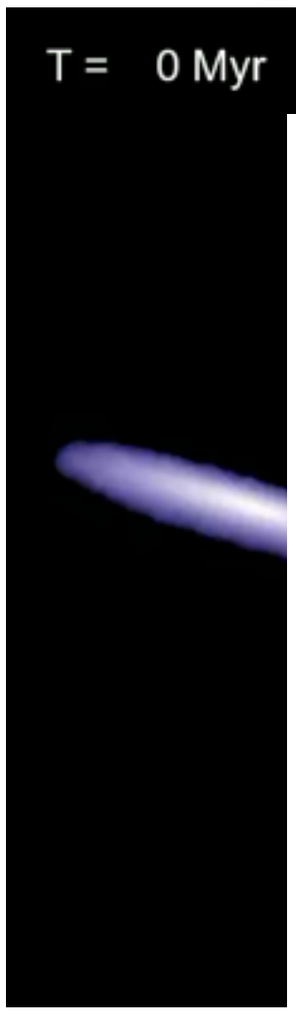

$V_{circ}$/ km s$^{-1}$
30
60
100
200
1000
C
O
H
He
Fe
Bremss
$t_{cool} \sim 3\,\mathrm{Myr}$
−21
−21.5
−22
−22.5
−23
−23.5
$\log_{10}(\Lambda\, n_H^{-2}$ /ergs s$^{-1}$ cm$^3$)
4
5
6
7
8
$\log_{10}$(T/K)

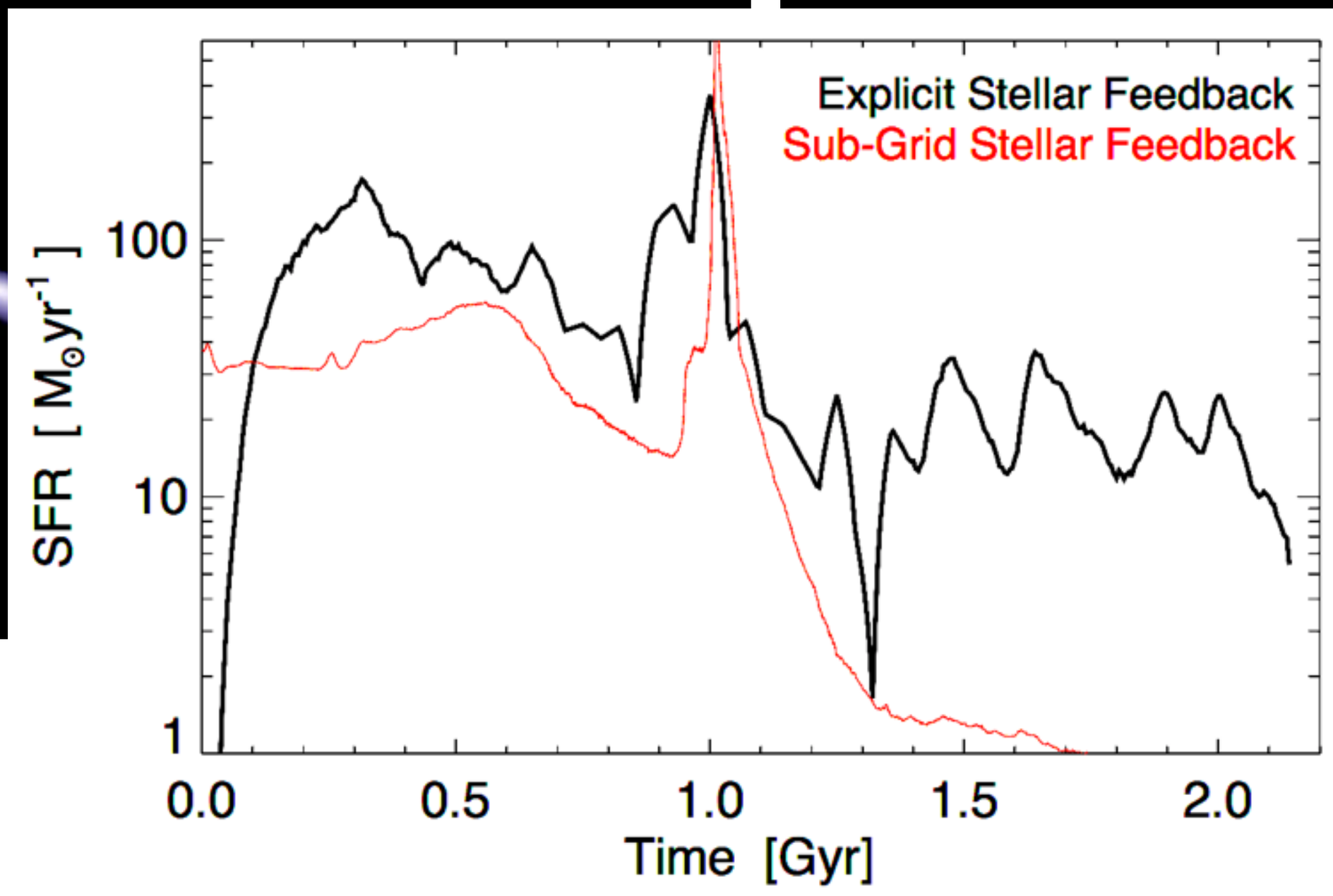
# Quenching: Don't Trust Models that Don't Do Stars Right

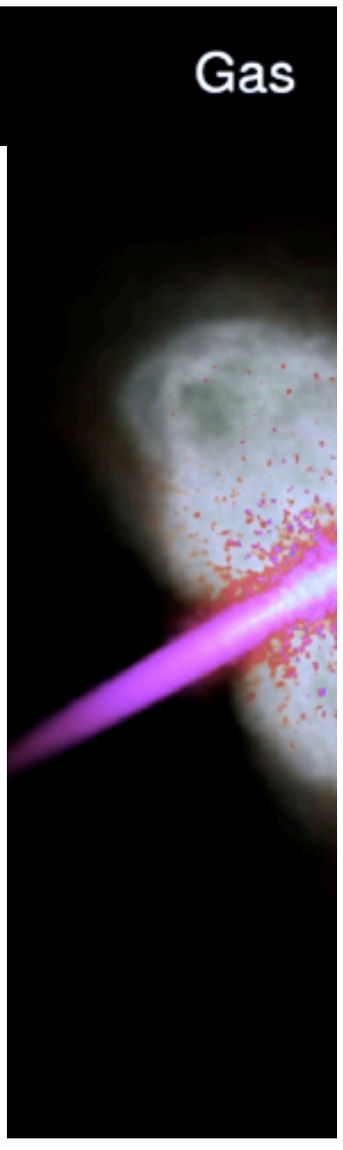
## SMALL GALAXIES BECOME BIG GALAXIES

"Decoupled Winds" (Sub-Grid)

Following Explicit Feedback



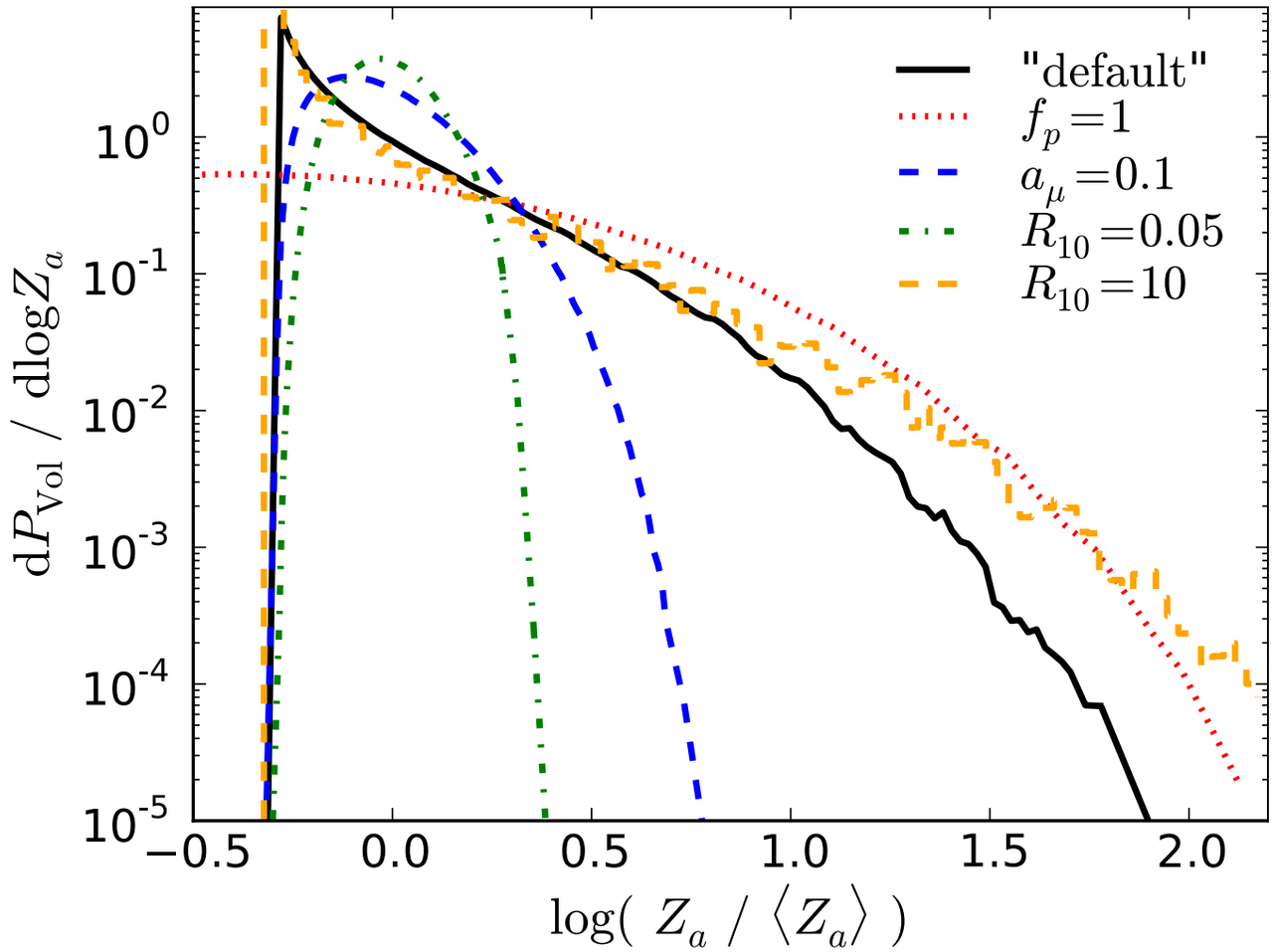



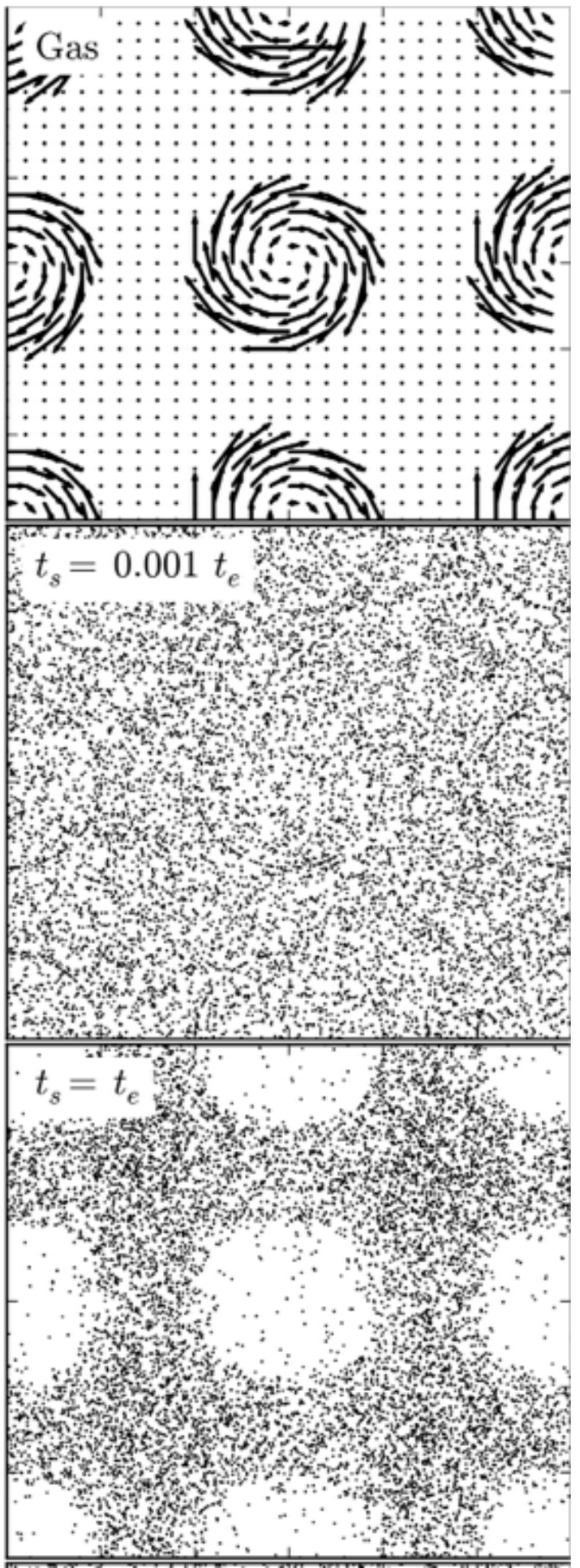



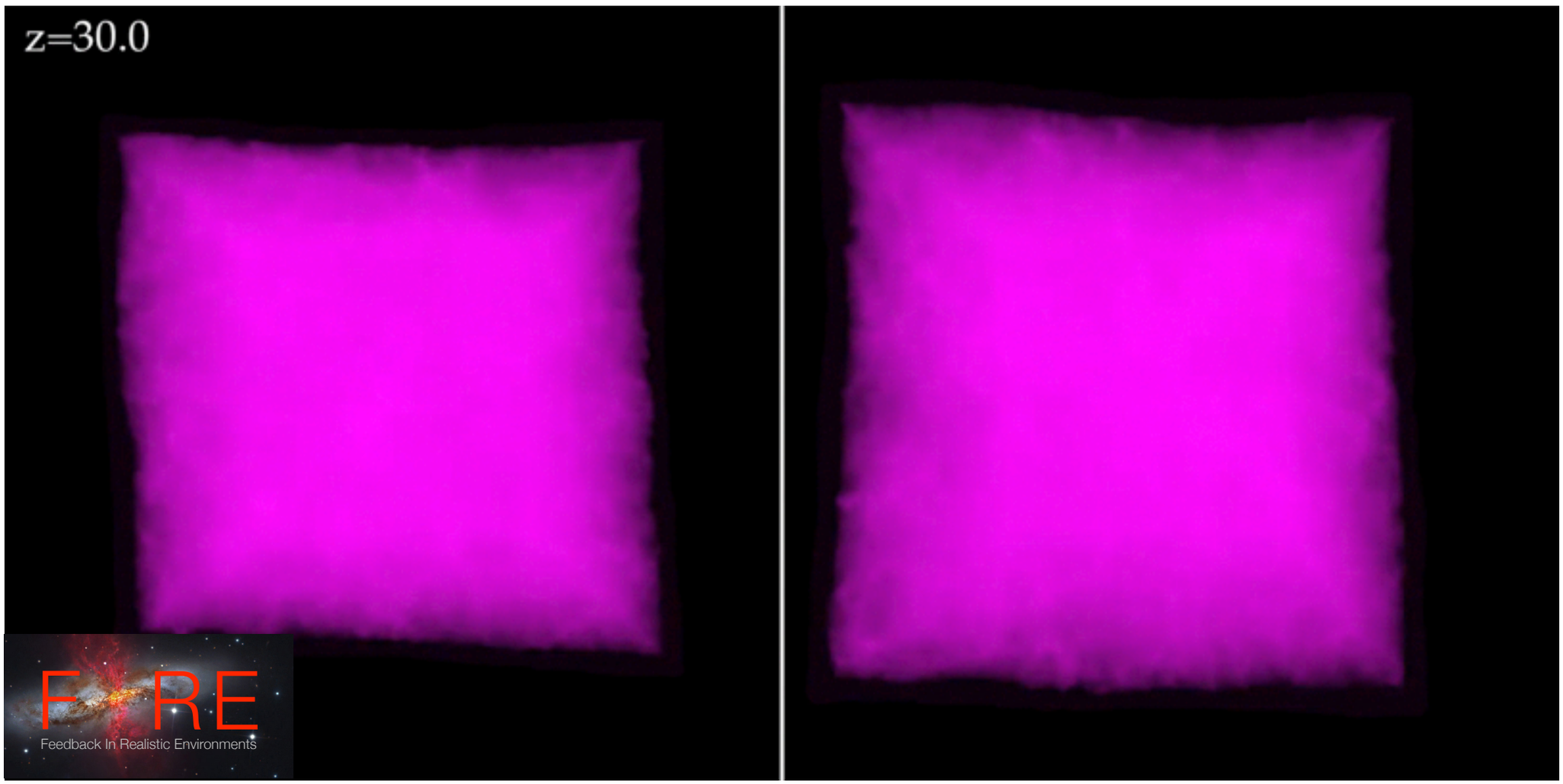
# Totally Metal Stars?

*(PFH, arXiv:1406.5509)*

- **Dust is not Gas**
  - Instabilities segregate gas and dust
  - Large core-to-core fluctuations in species in big grains (C,O)






- **Star formation is Feedback-Regulated**: *independent* of small-scale SF
- Cosmologically: ***Accretion does not regulate star formation***
  - **Winds** determine **IGM enrichment, temperature, & subsequent inflow**
  - **Resolved feedback ≠ sub-grid feedback**!
    - Mass-metallicity, SFHs, morphology *not the same*
- **New Physics (AGN?)** needed to "quench": **Stars *enhance* overcooling**

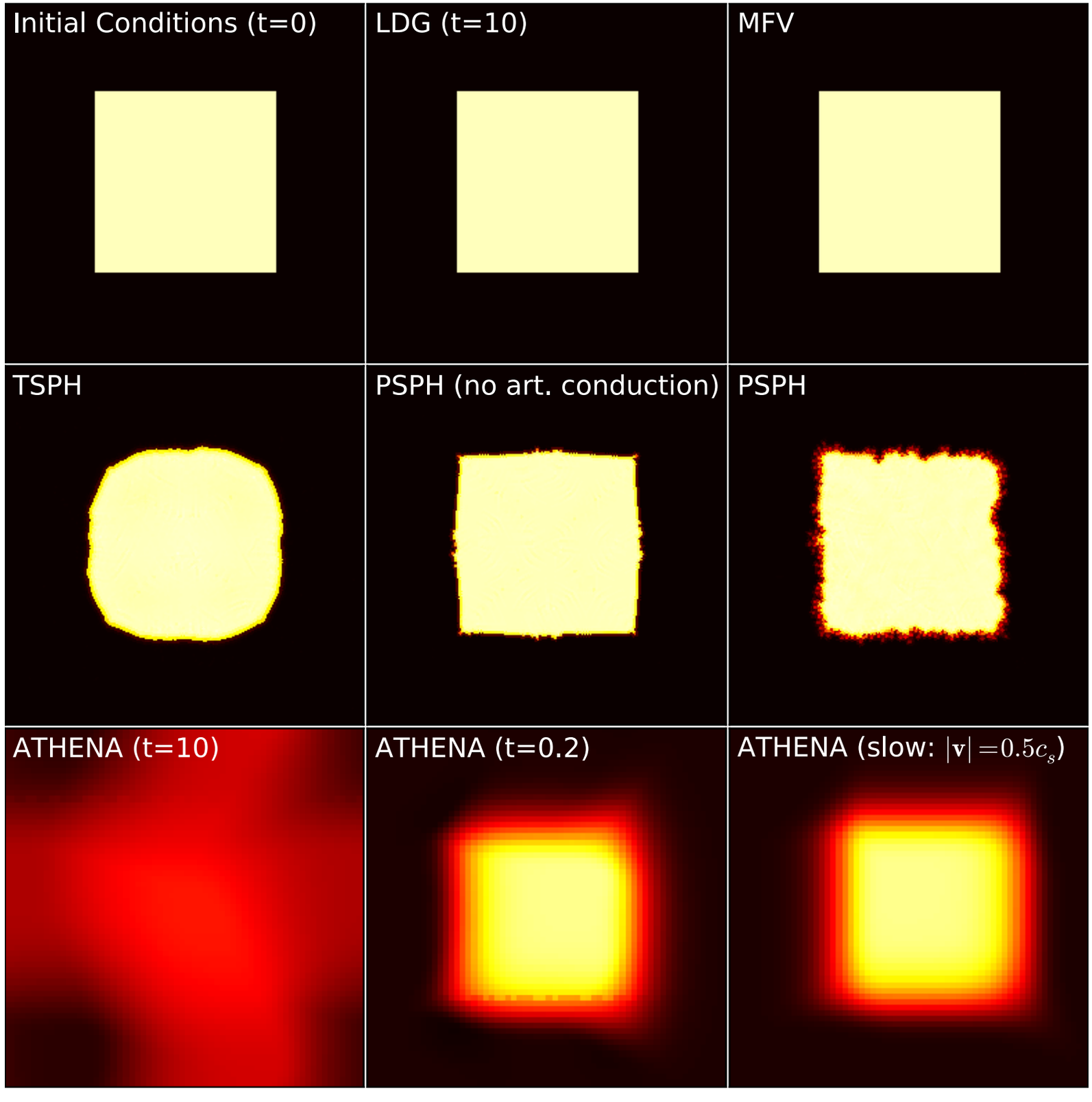
- **Lots of work in progress!** (stay tuned)

# GIZMO: A New, Public Gravity+Hydro Code

*(to appear very soon)*

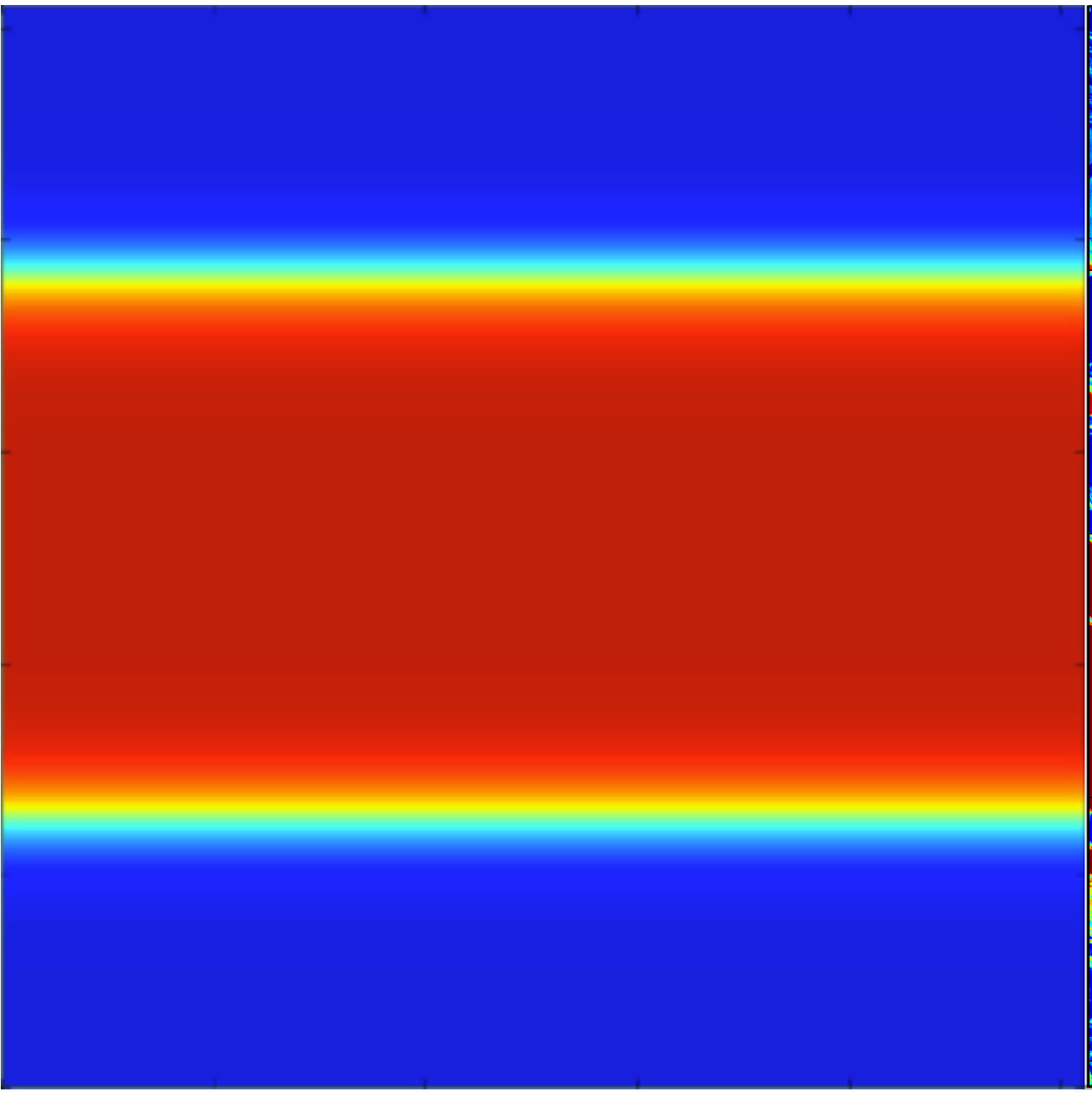
- **You choose:**
  - 'Traditional' SPH
  - 'Modern' P-SPH
  - Meshless Finite Volume
  - Finite-Mass Galerkin
  - Moving-Mesh (ongoing)

- **100% compatible** with GADGET ICs/snaps

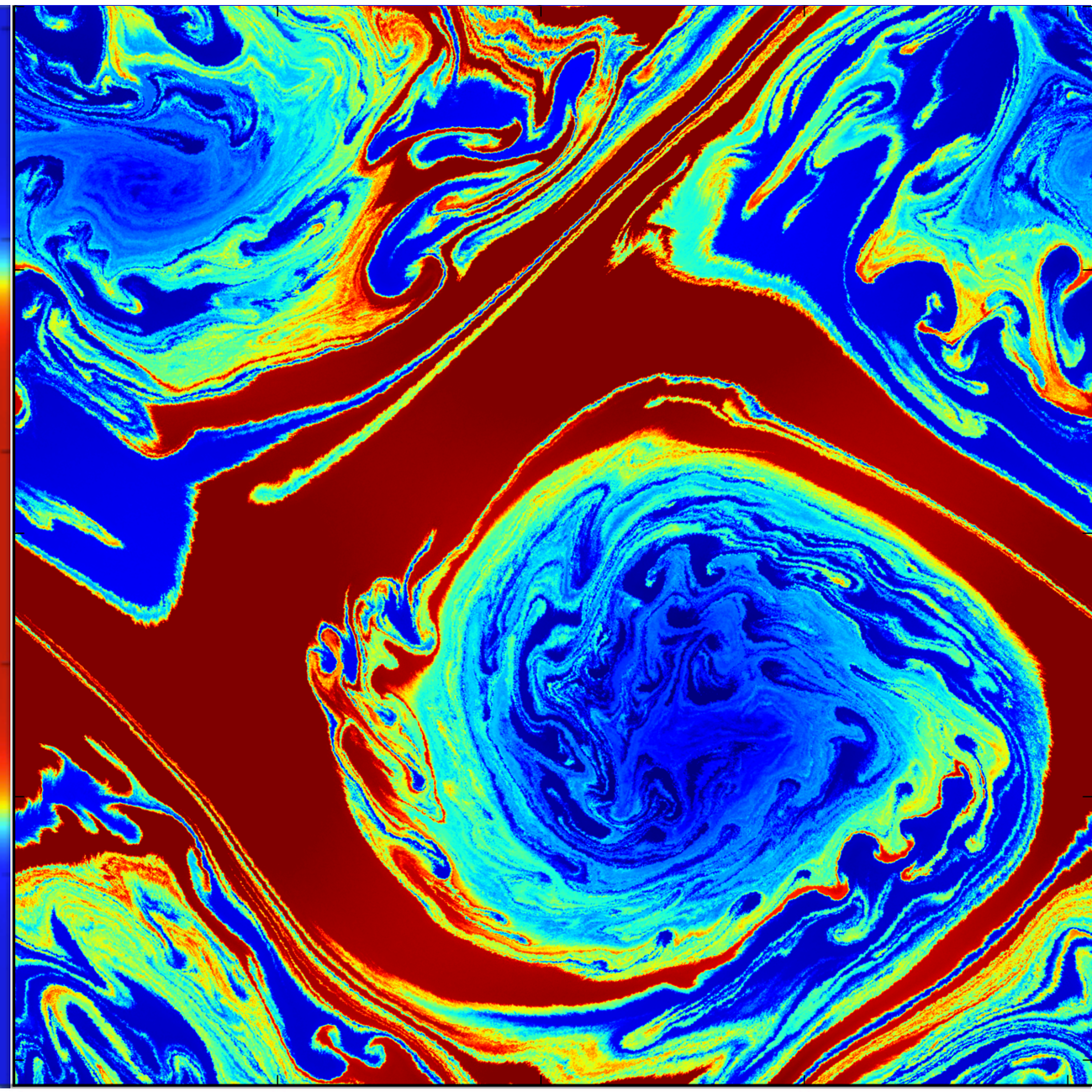


# GIZMO: A New, Public Gravity+Hydro Code

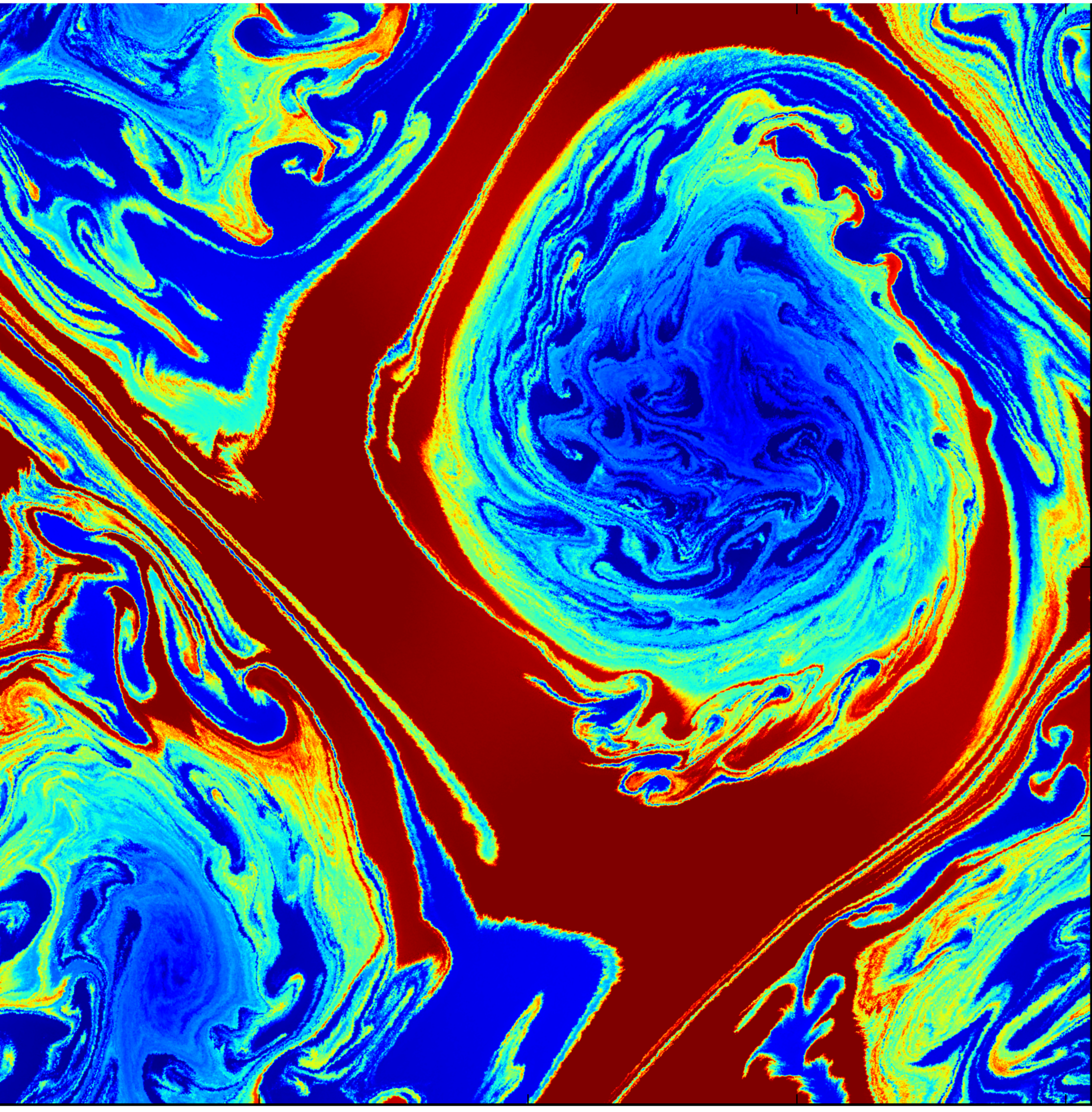
*(to appear very soon)*

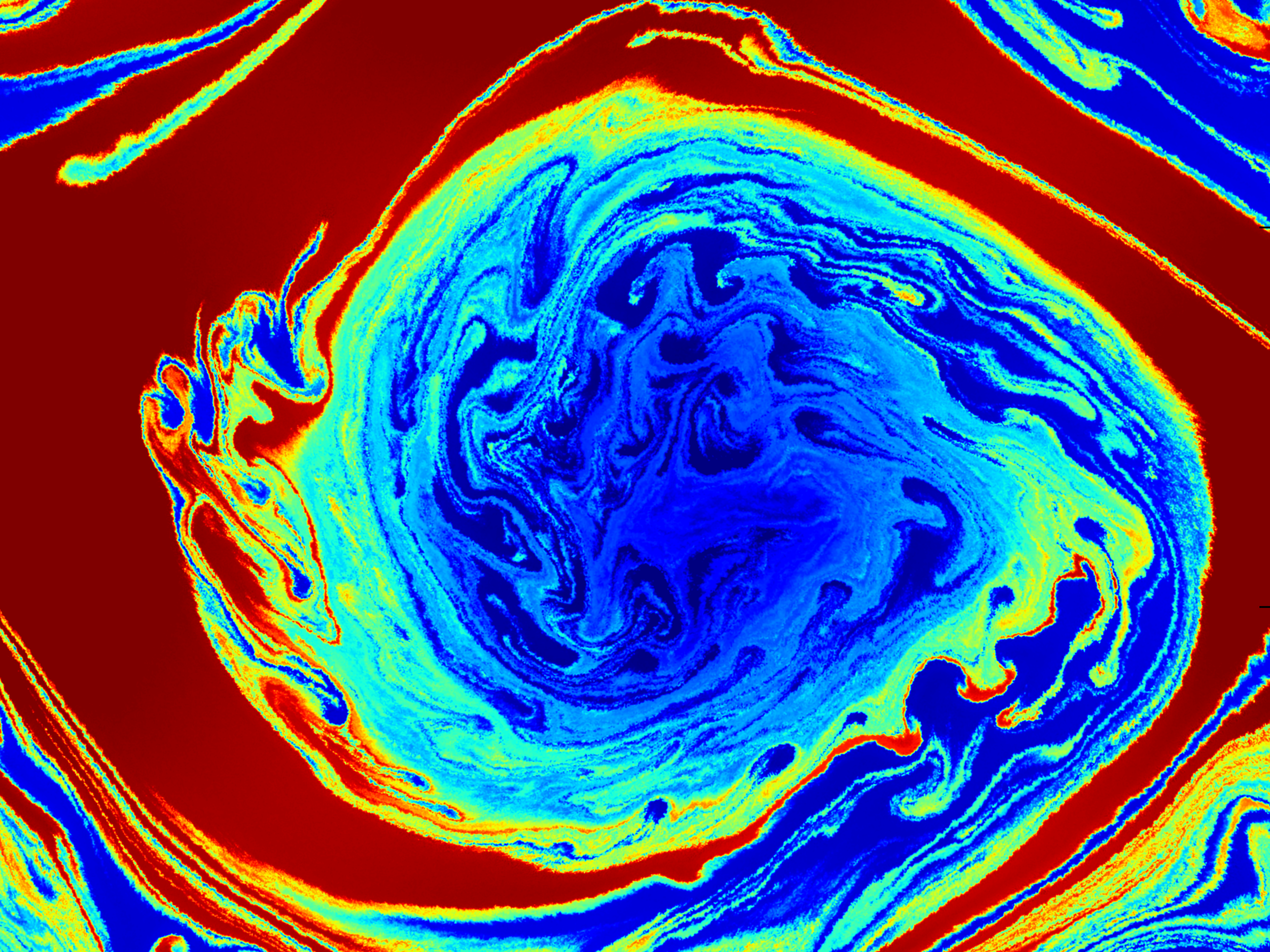


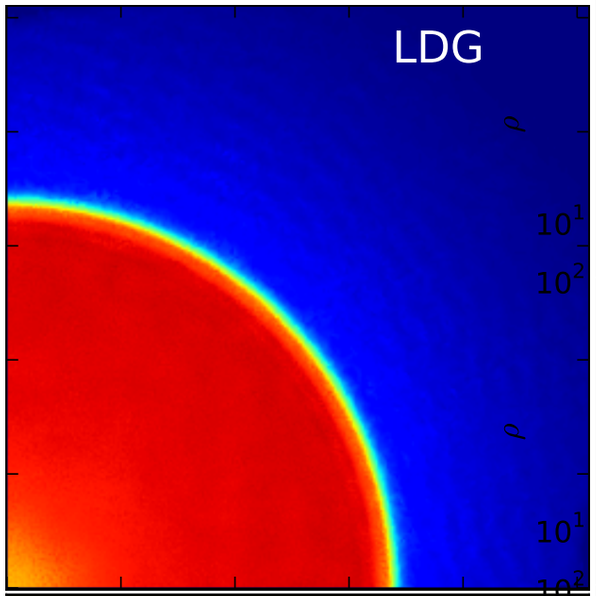
Cartesian Grid

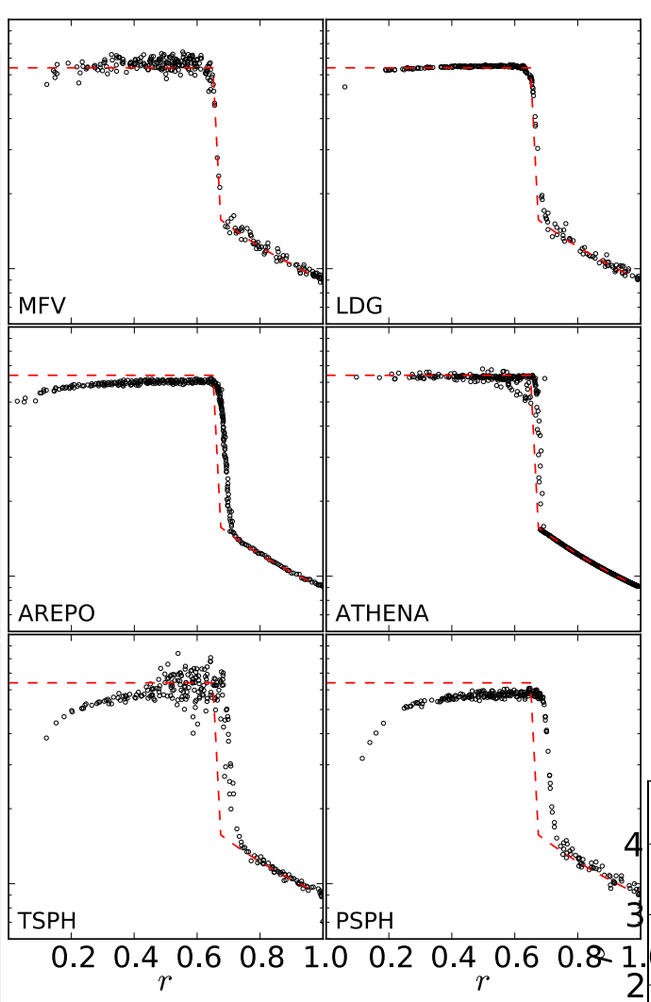


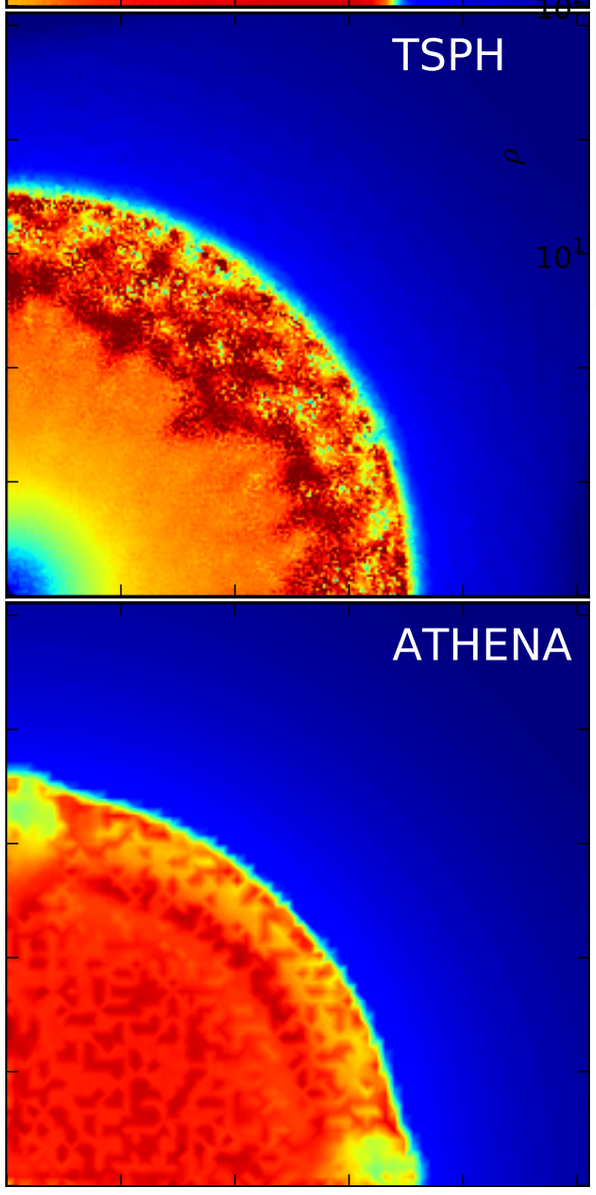
Meshless Finite Volume





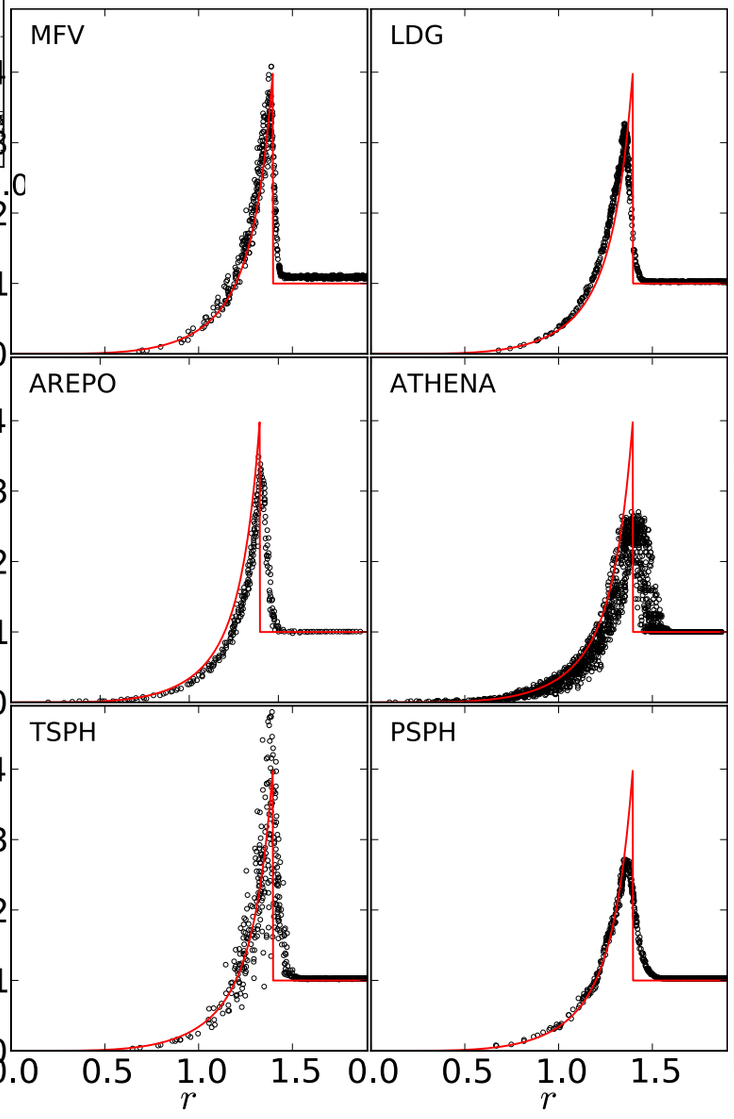


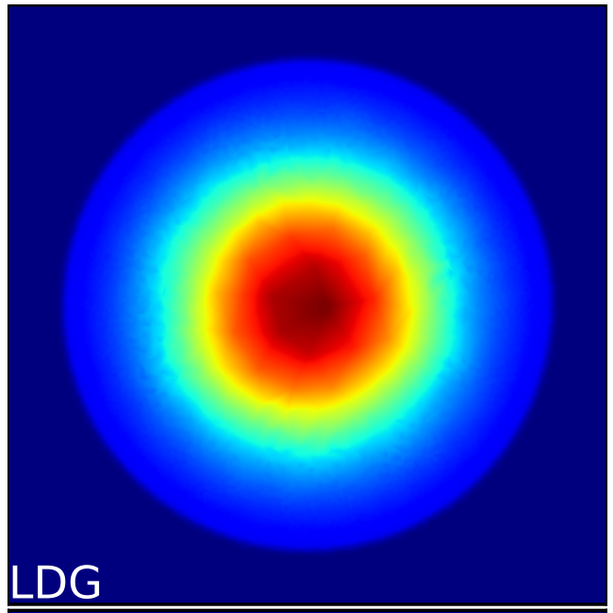



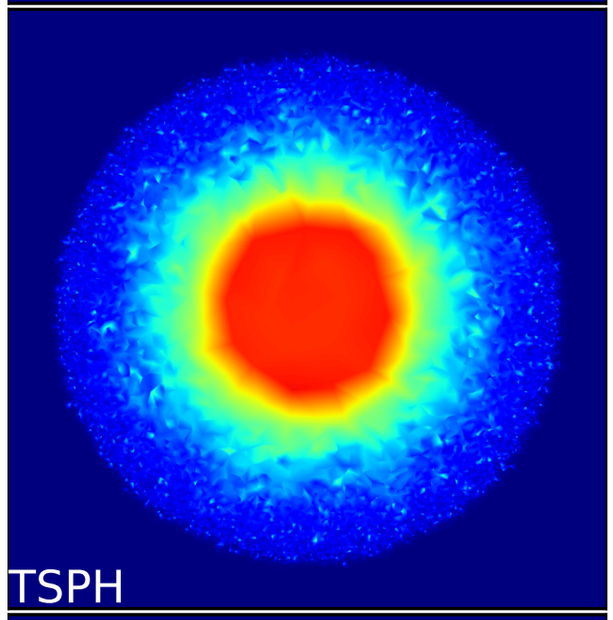



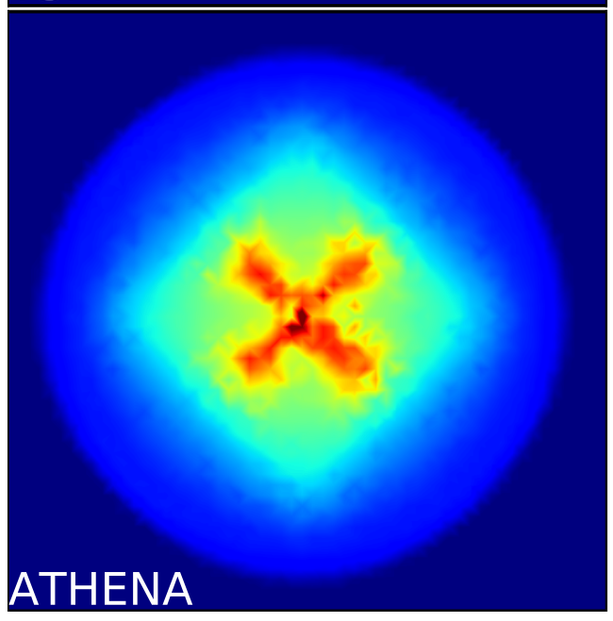

# Noh Implosion

# Sedov Explosion



# Comparing methods in GIZMO: Angular Momentum