Numerics,Physics,Resolution

Towards Predictive Galaxy Formation Simulations

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Physics

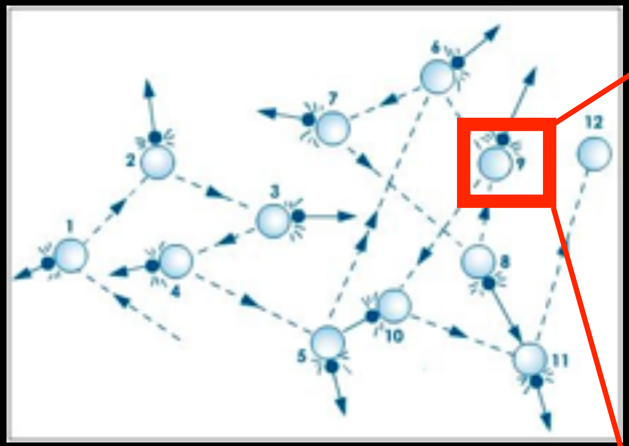
(a question of philosophy)

Everything is sub-grid

Hydrodynamics

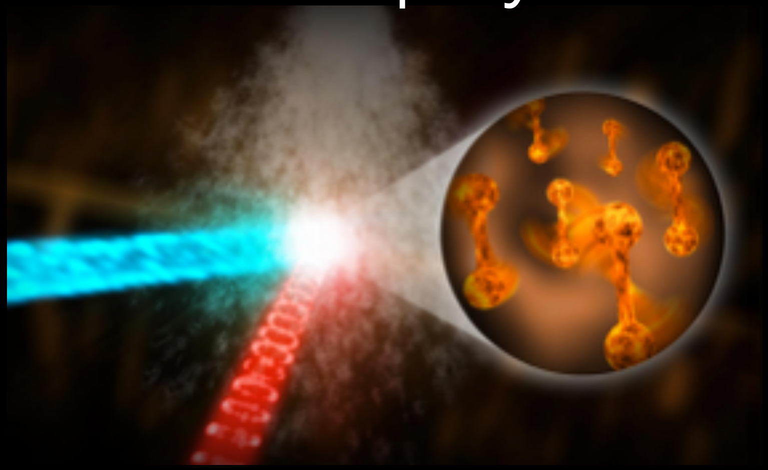
$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{v}$$

Statistical mechanics



$$\begin{aligned}
Q(t) &= f[t: g[Q]] = f^{(0)}[t: g^{(0)}[Q]] \\
&+ \varepsilon\left(\int \mathrm{d}s \frac{\delta f^{(0)}(t)}{\delta g^{(0)}(s)} g^{(1)}[s: Q] + f^{(1)}[t: g^{(0)}[Q]] \right) \\
&+ \varepsilon^2 \left(\int \mathrm{d}s \frac{\delta f^{(0)}(t)}{\delta g^{(0)}(s)} g^{(2)}[s: Q] \right. \\
&+ \frac{1}{2} \int \mathrm{d}s\, \mathrm{d}s' \frac{\delta^2 f^{(0)}(t)}{\delta g^{(0)}(s) \delta g^{(0)}(s')} g^{(1)}[s: Q] g^{(1)}[s': Q] \\
&+ \left. \int \mathrm{d}s \frac{\delta f^{(1)}(t)}{\delta g^{(0)}(s)} g^{(1)}[s: Q] + f^{(2)}[t: g^{(0)}[Q]] \right) + \mathrm{O}(\varepsilon^3)
\end{aligned}$$

Particle physics



$$\begin{aligned}
\mathcal{L}_{GWS} &= \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) + \\
&+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5) \Psi_f Z_\mu + \\
&- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu + \\
&- ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 + \\
&- \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 + \\
&- \frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 + \\
&+ \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta
\end{aligned}$$

2 philosophies of sub-grid:

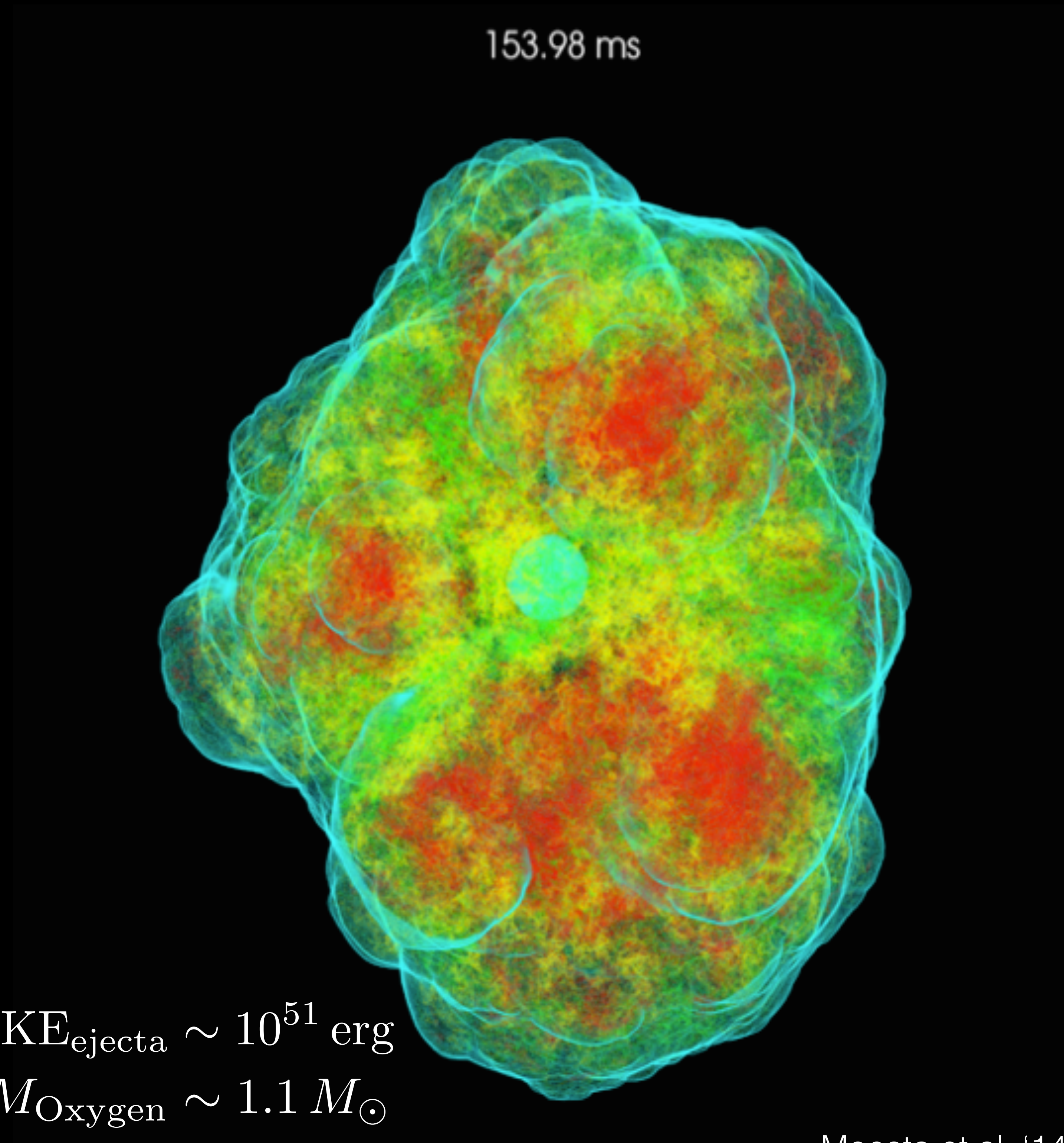
- 1. Parameterize unknowns, marginalize over them (fit to observations)
    - bias in BAO/LSS cosmology
    - MCMC SAMs / Illustris/Eagle philosophy
- 2. Derive from theory/observations on small scales, after “smoothing”
    - (magneto) hydrodynamics
    - FIRE philosophy: $M_{\rm wind}$ = (whatever the input physics predicts)

Example: Supernovae

(building up a sub-grid model)

Example: SNe

Predict: Explosion



Resolution:

$$m_i < 10^{-6}\, M_\odot$$

$$\mathrm{KE}_{\mathrm{ejecta}} \sim 10^{51}\,\mathrm{erg}$$

$$M_{\mathrm{Oxygen}} \sim 1.1\, M_\odot$$

$$\ldots$$

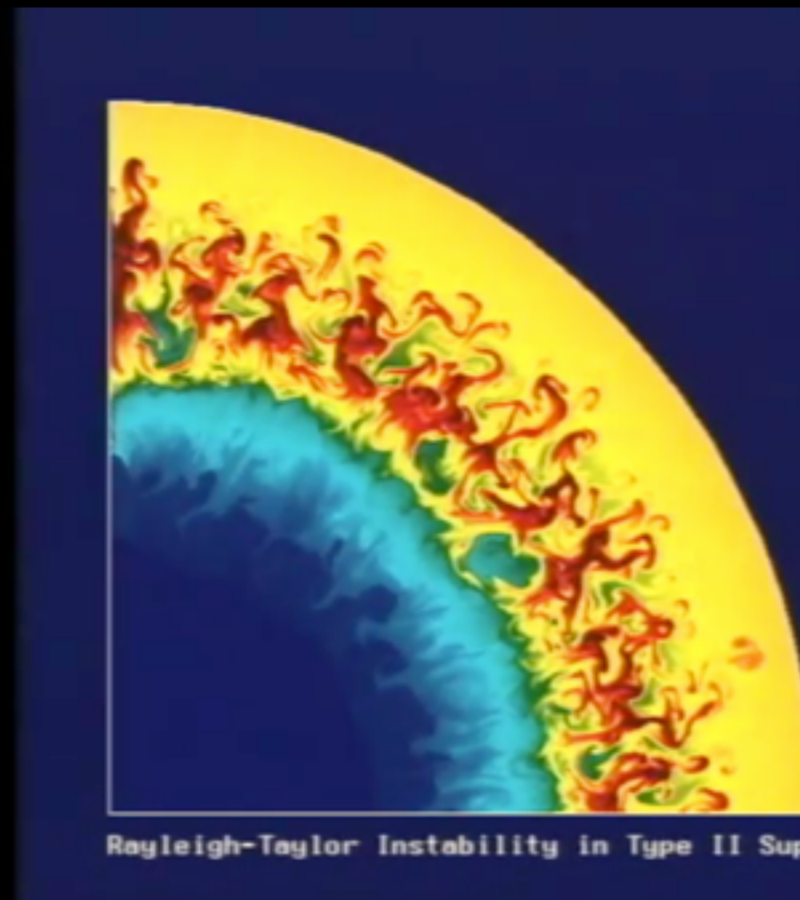
Moesta et al. '14

Sub-grid physics:

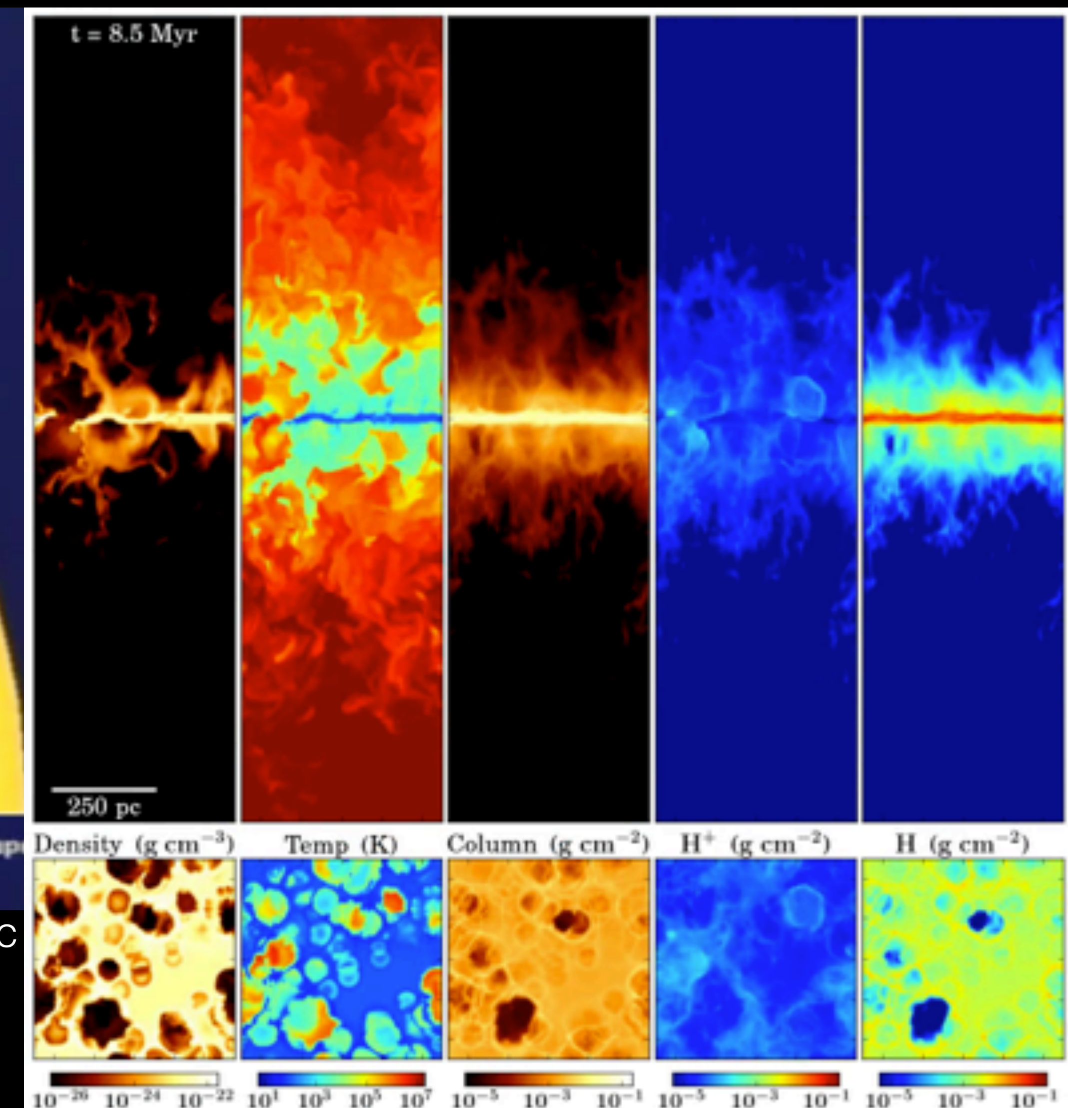
- (magneto) hydrodynamics
- nuclear Rx rates
- neutrino transfer

Example: SNe

Predict: Blastwave Evolution/ISM Interaction



Walch, Martizzi, Barnes, Cioffi, etc

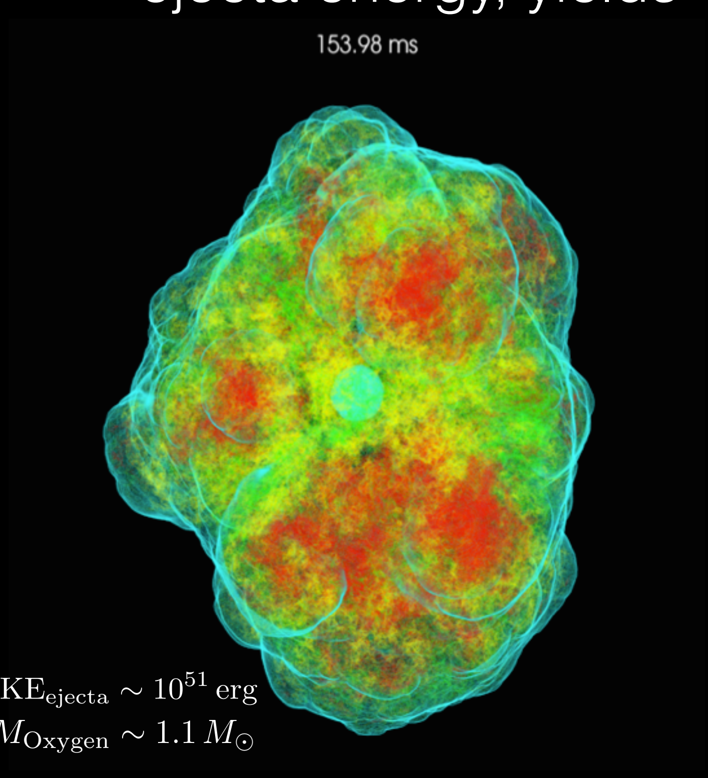


Resolution:

$$m_i \sim 1 - 100\, M_\odot$$

Sub-grid physics:

- SNe explosion
- ejecta energy, yields



End of energy-to-momentum (single SNe):

$$M_{\mathrm{snowplow,\, final}} \sim 3000\, M_\odot$$

Final momentum:

$$\langle M_s\, v_s \rangle_{\mathrm{final,\, SNr}} \sim 10^{5.5}\, M_\odot\, \frac{\mathrm{km}}{\mathrm{s}}$$

Example: SNe

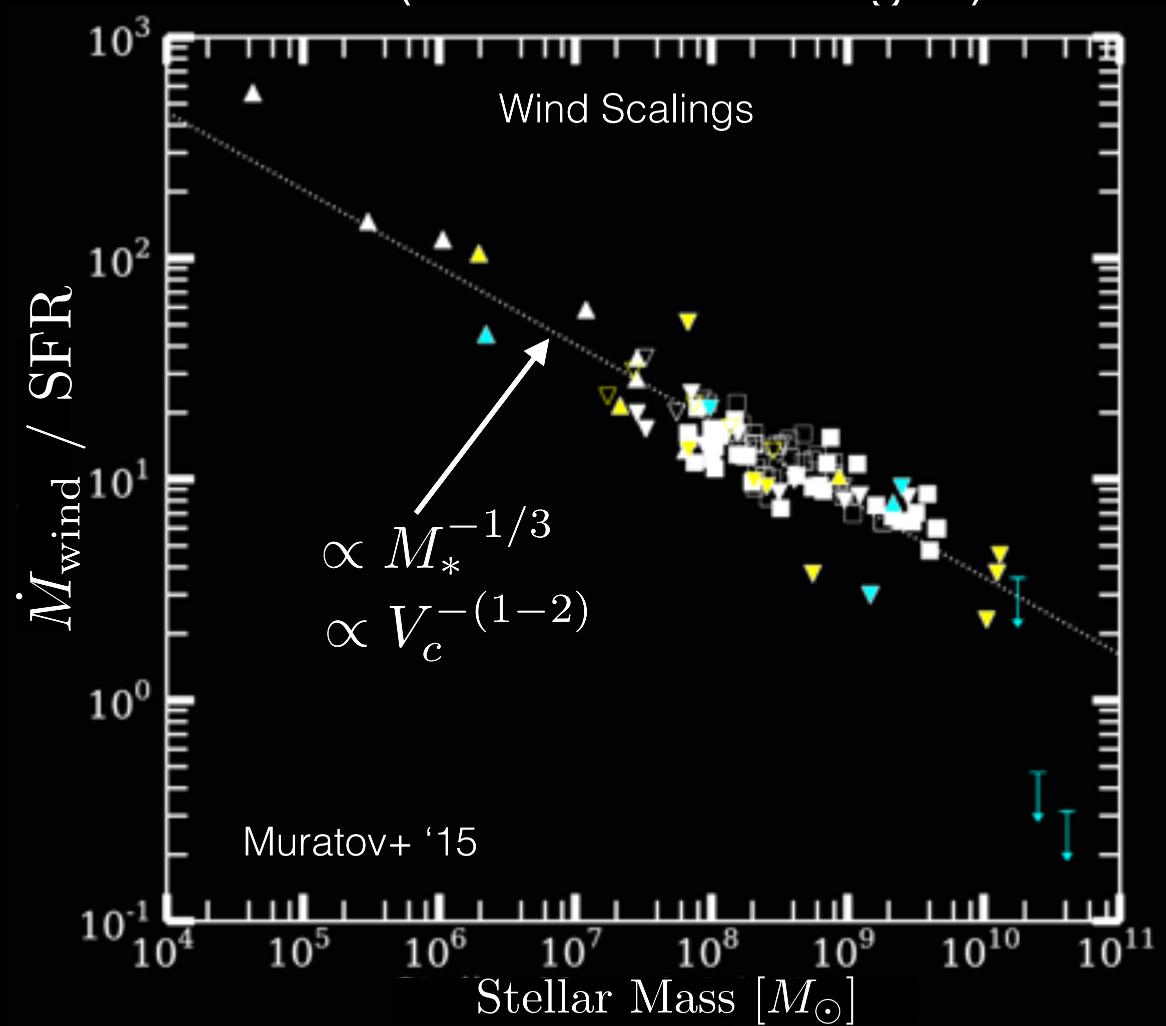
Predict: Overlap: super-bubbles & winds

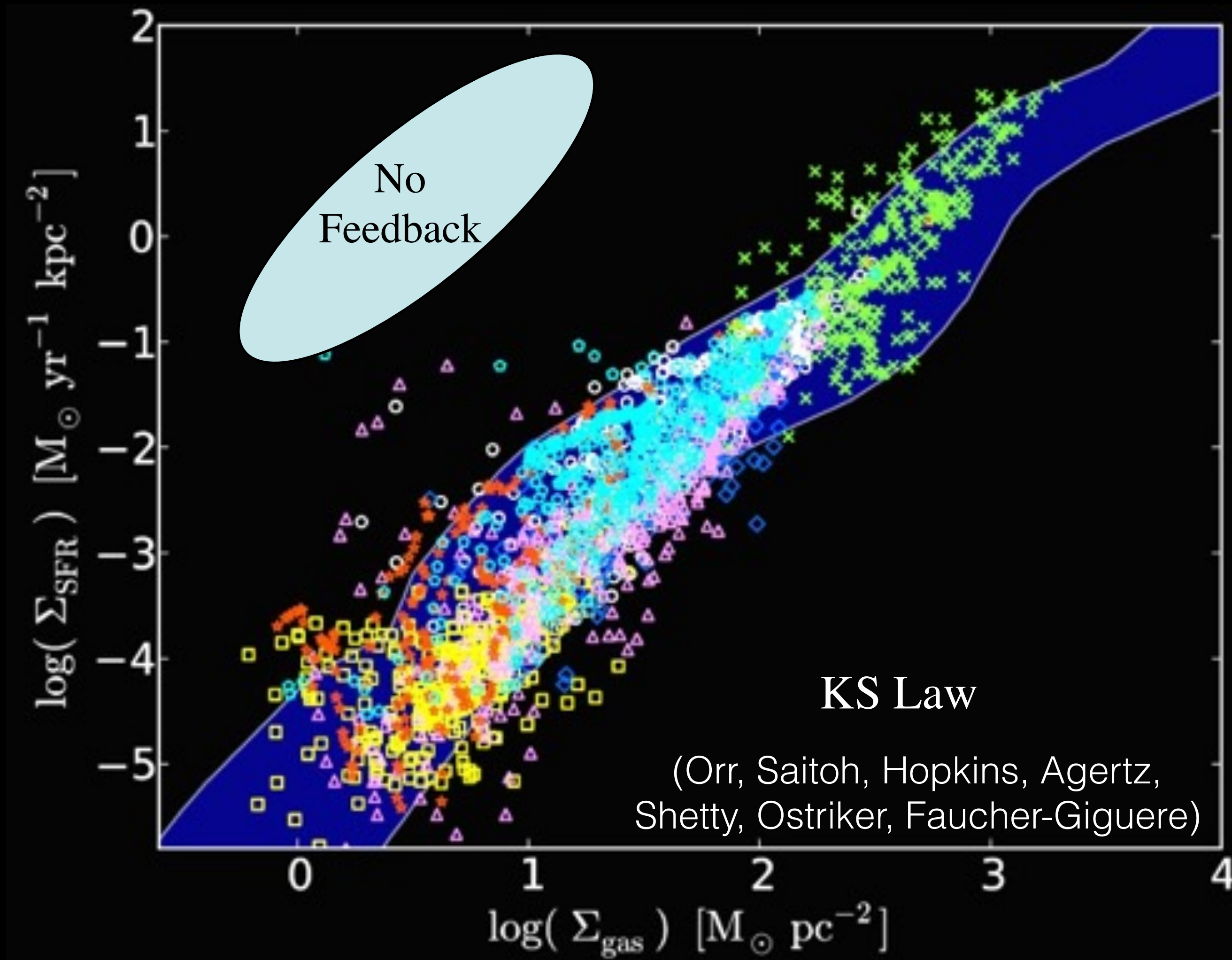
Resolution:

$$m_i \sim 10^{2-4}\,M_\odot$$

Sub-grid physics:

- single SNr evolution
- stellar evolution (rates)
- ~~SFR (dense molecular gas)~~





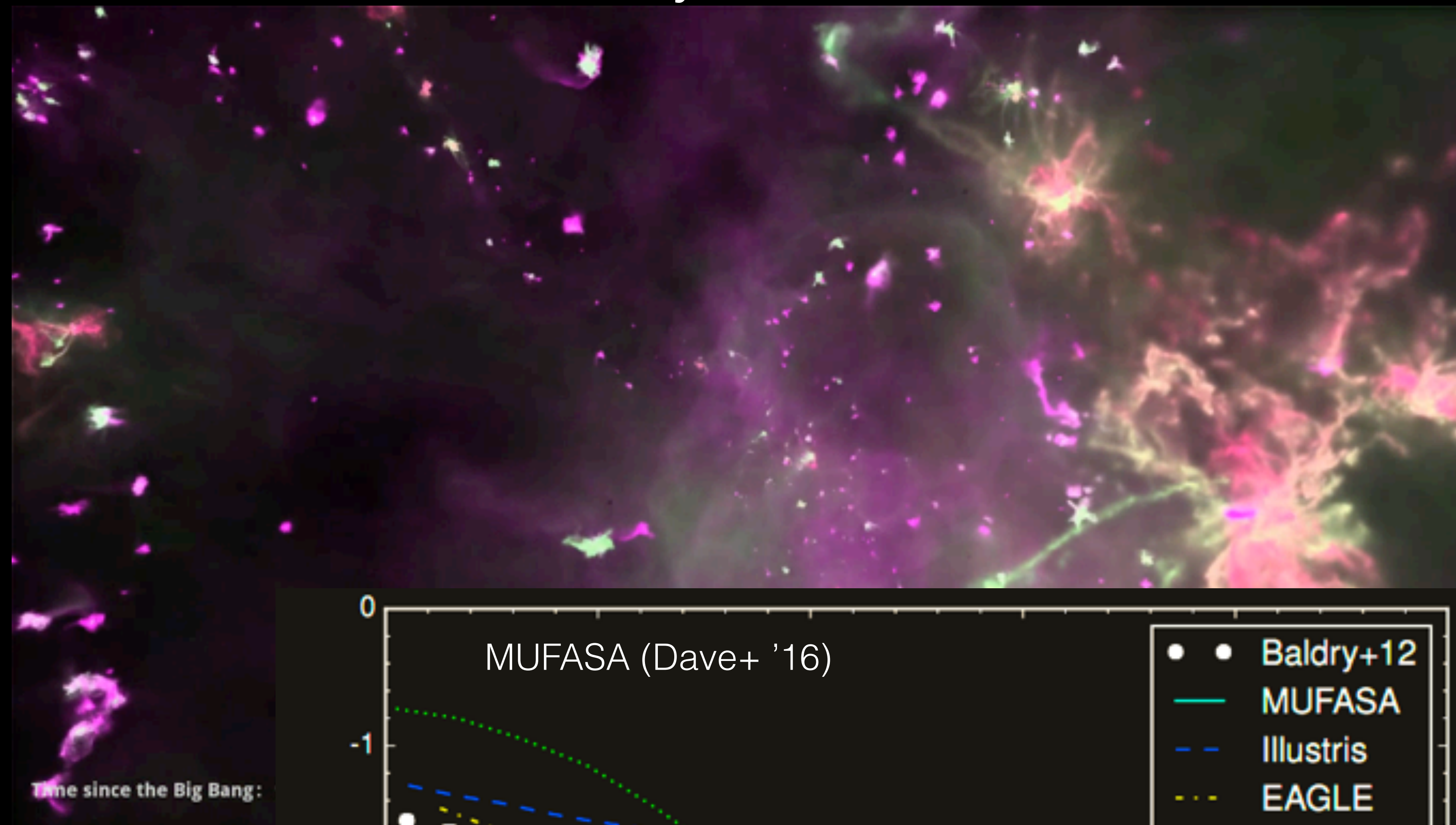
FIRE

Example: SNe

Predict: Galaxy SFHs, IGM enrichment

Resolution:

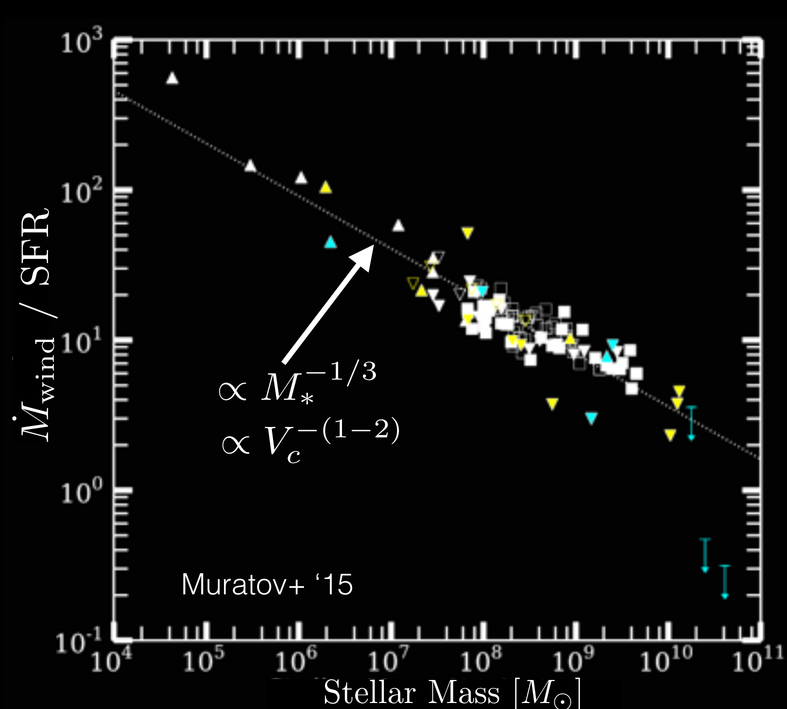
$$m_i \gtrsim 10^6\, M_\odot$$

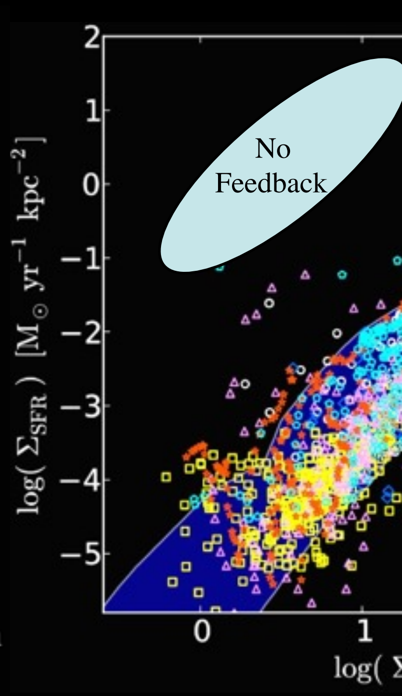


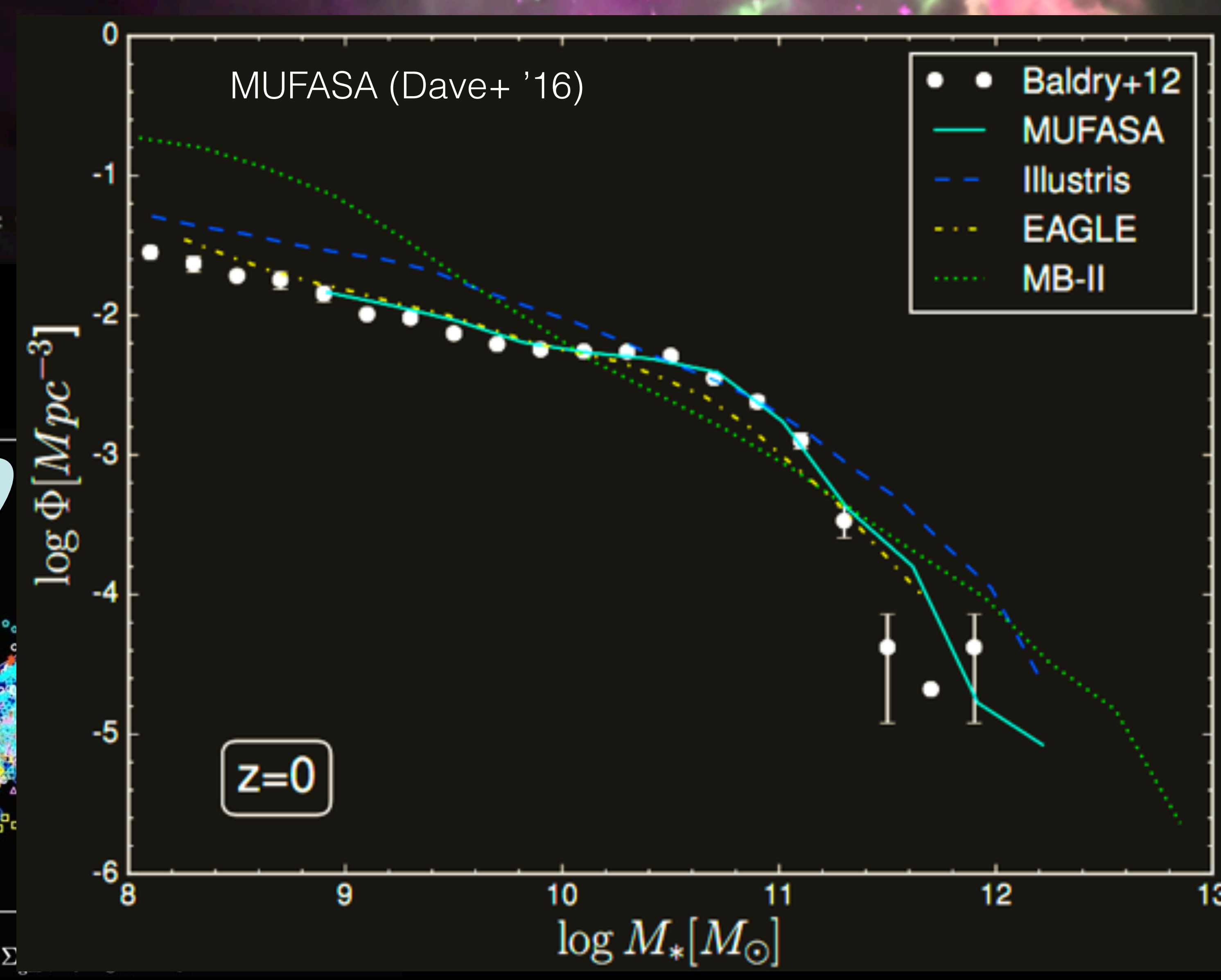
Sub-grid physics:

~~SFR (kpc/low-density gas)~~

- wind scalings (galaxy-scale)



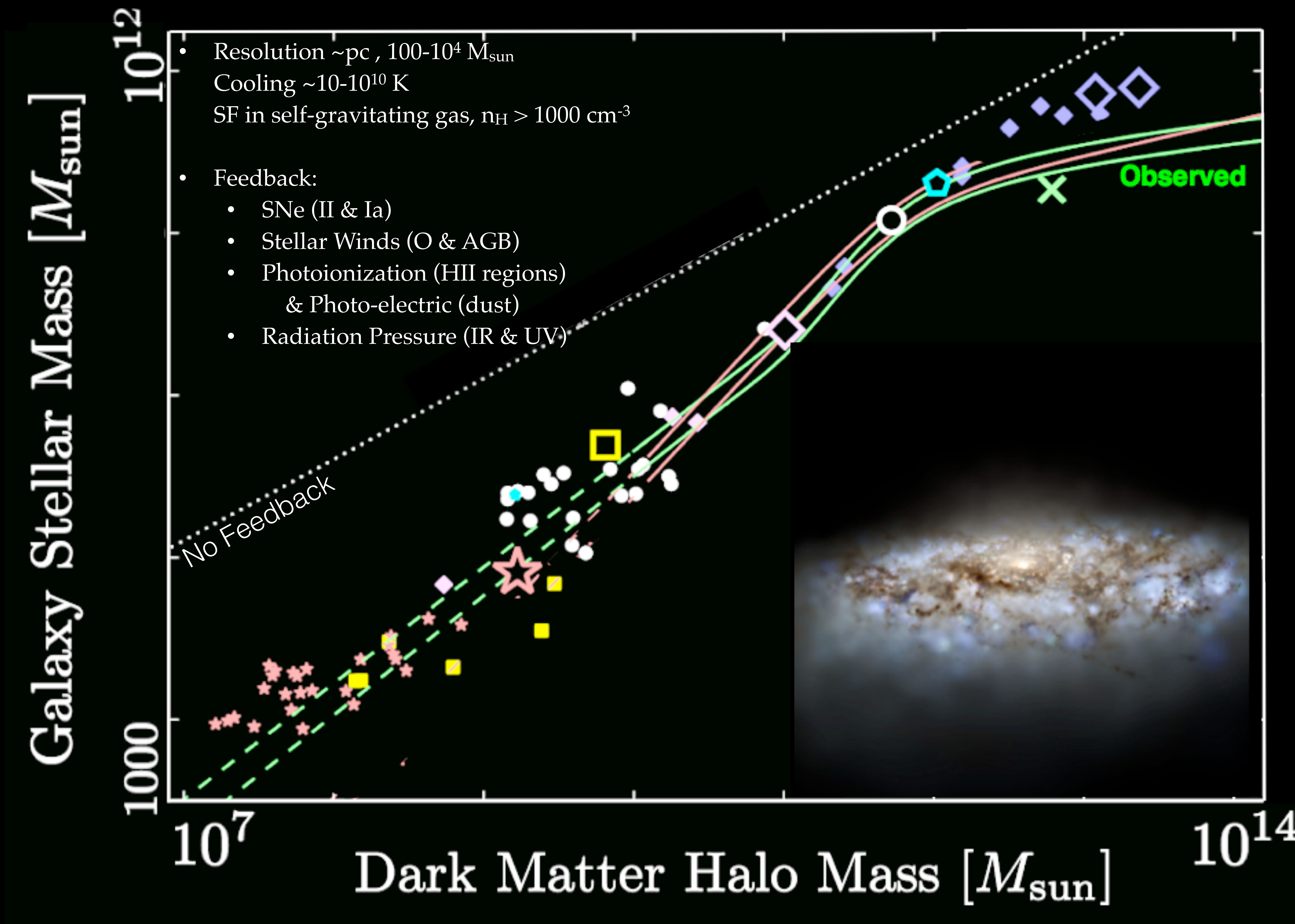




It Works!

THIS APPROACH IS PRODUCING REALISTIC GALAXIES

PFH et al.
(arXiv:1311.2073)



It Works!

- Resolution ~pc , 100-10^4 M_{sun}
  Cooling ~10-10^{10} K
  SF in self-gravitating gas, $n_H > 1000$

- Feedback:
  - SNe (II & Ia)
  - Stellar Winds (O & AGB)
  - Photoionization (HII regions)
    & Photo-electric (dust)
  - Radiation Pressure (IR & UV)

What Matters?

(depends 100% on *what you care about predicting*)

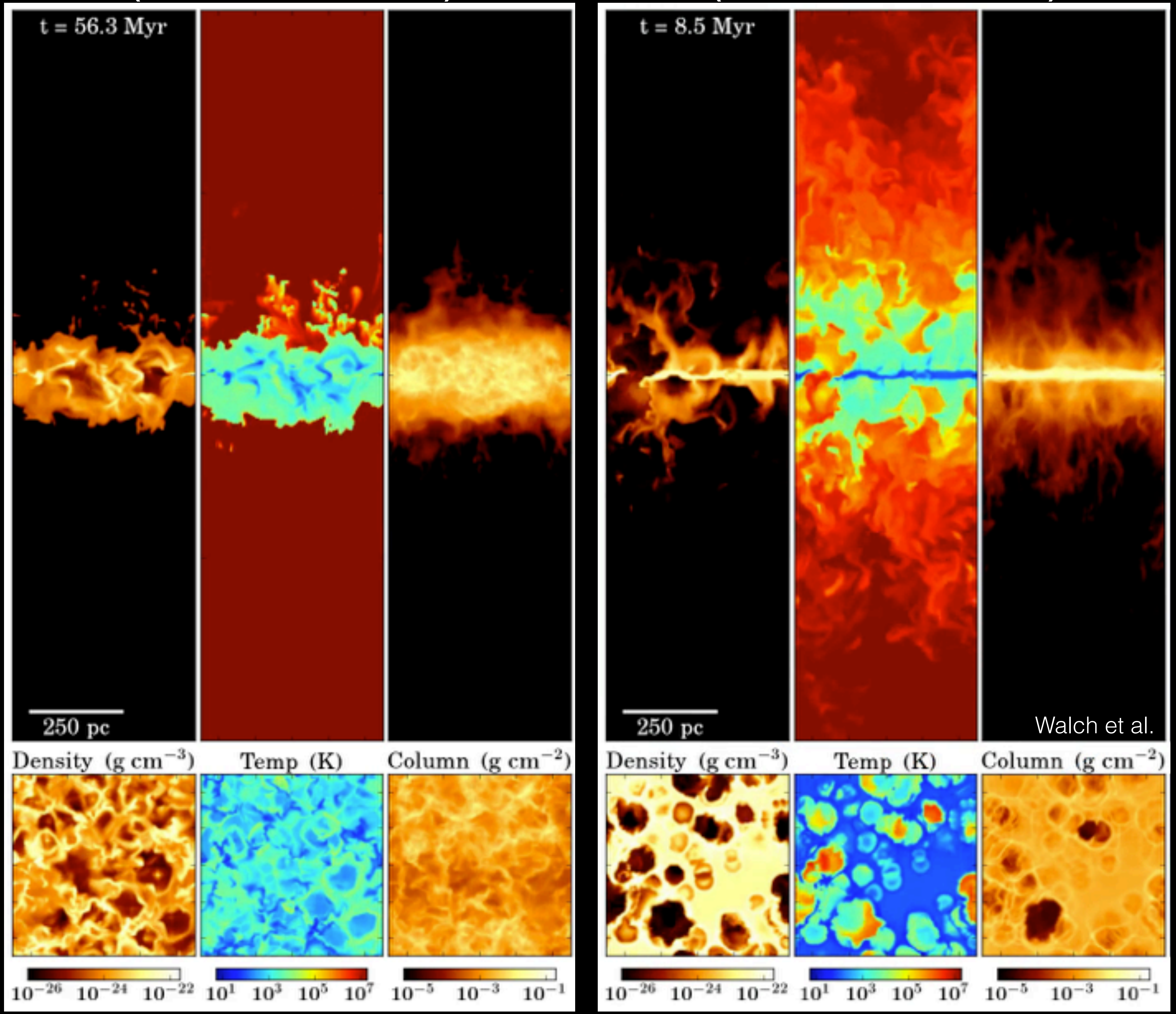
Doing the "sub-grid" right can matter

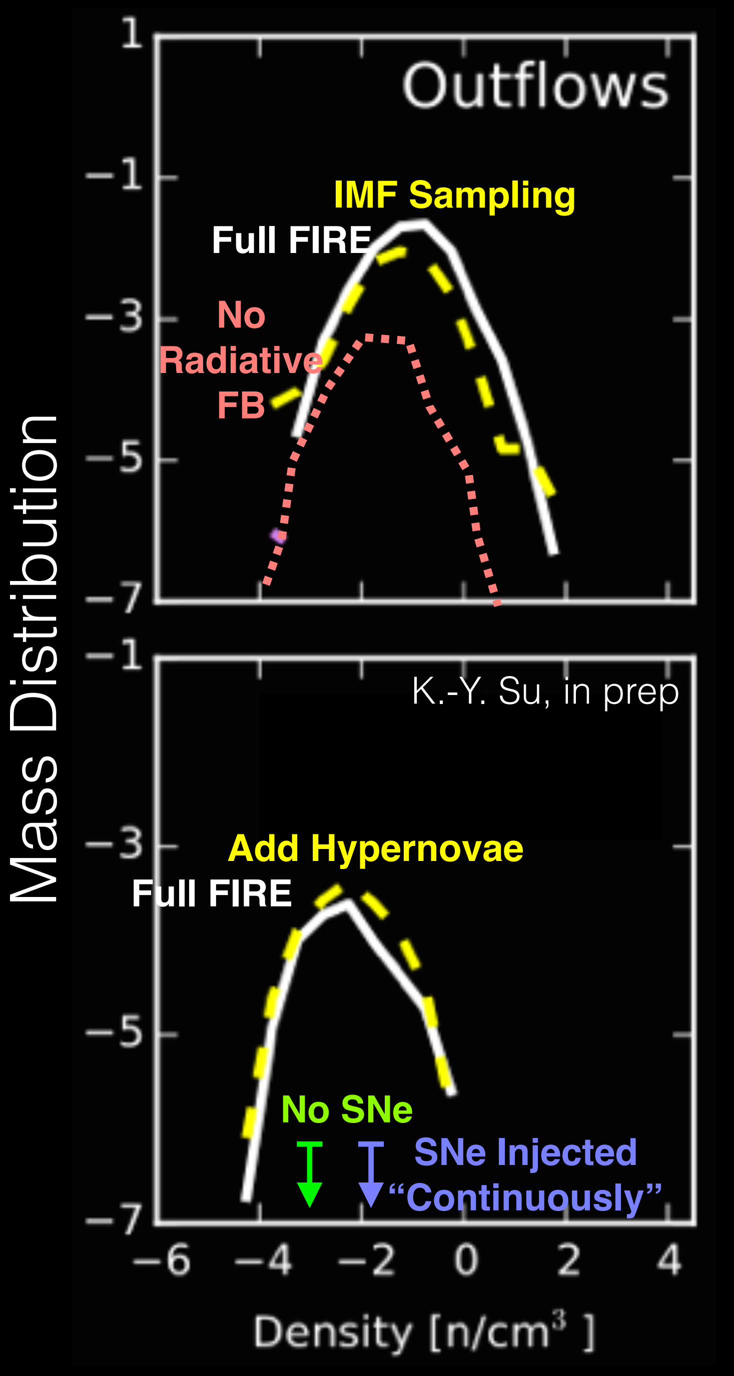
IF RESOLVE DENSE GAS, NEED PHYSICS FOR IT!

Murray+, Martizzi+, Walch+, Barnes+ Hopkins+, Hayward+, Shetty+, Hennebelle+

SNe Explode in Density Peaks (no radiative feedback)

SNe Clustered & Off-Peak (with radiative feedback)



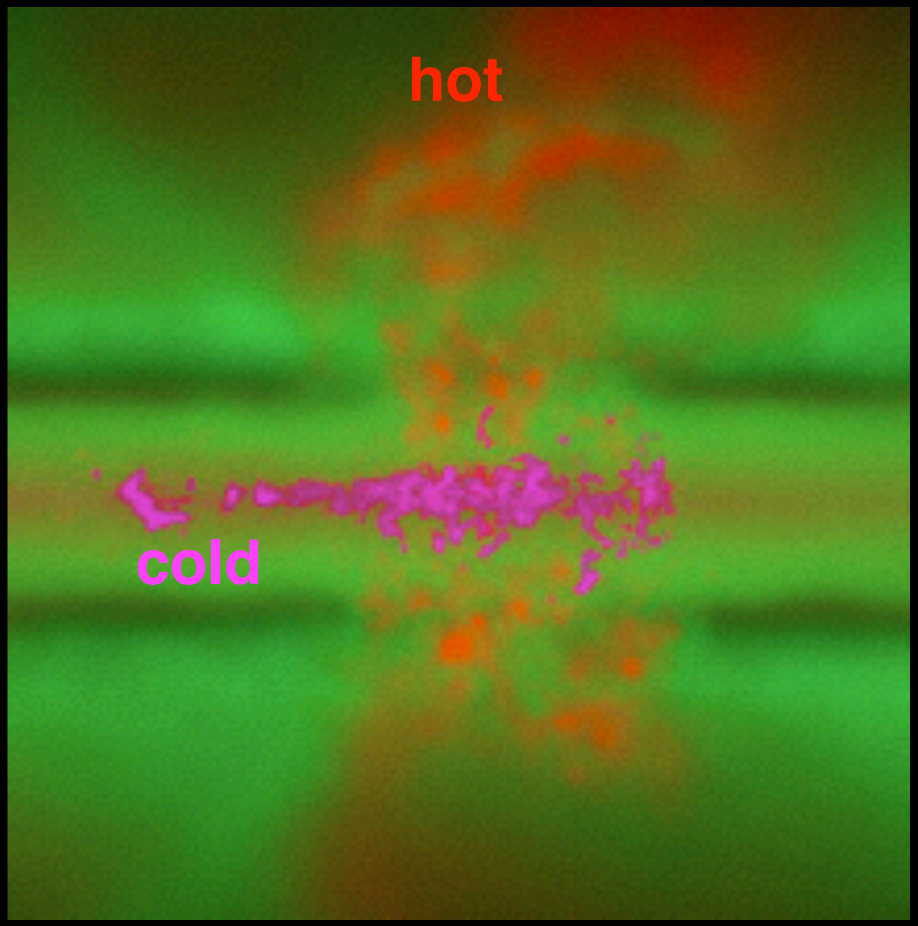


Doing the "sub-grid" right can matter

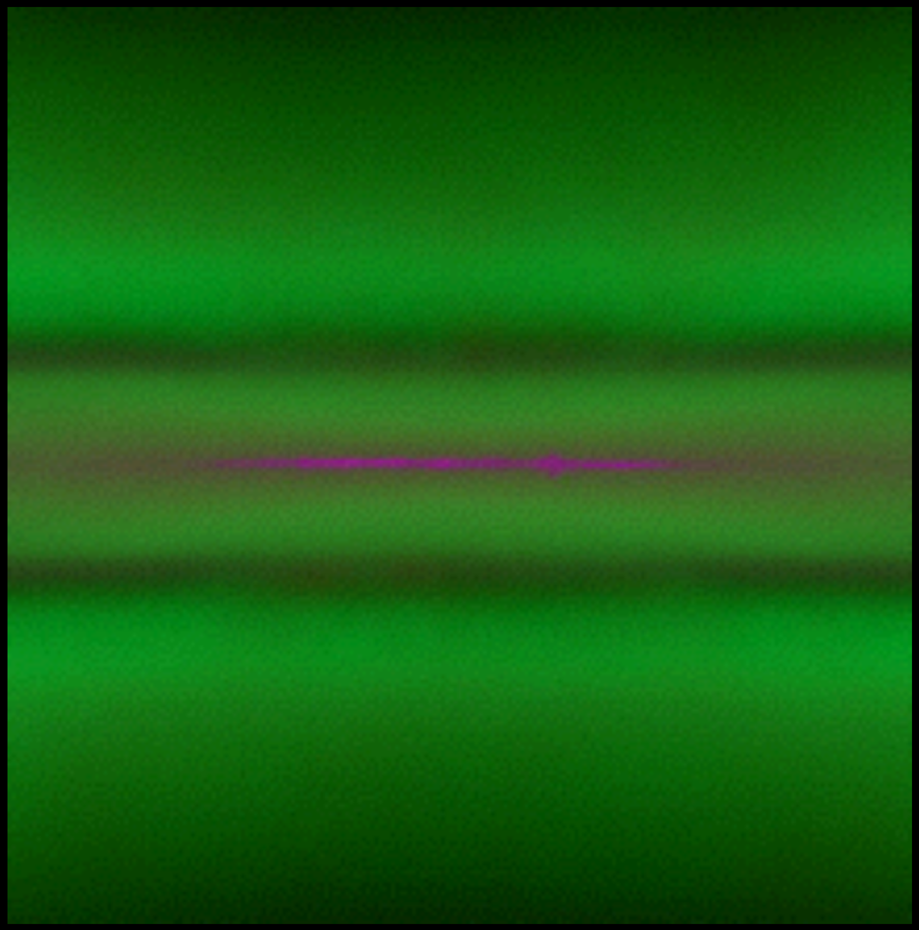
IF RESOLVE BUBBLES, NEED PHYSICS FOR IT!

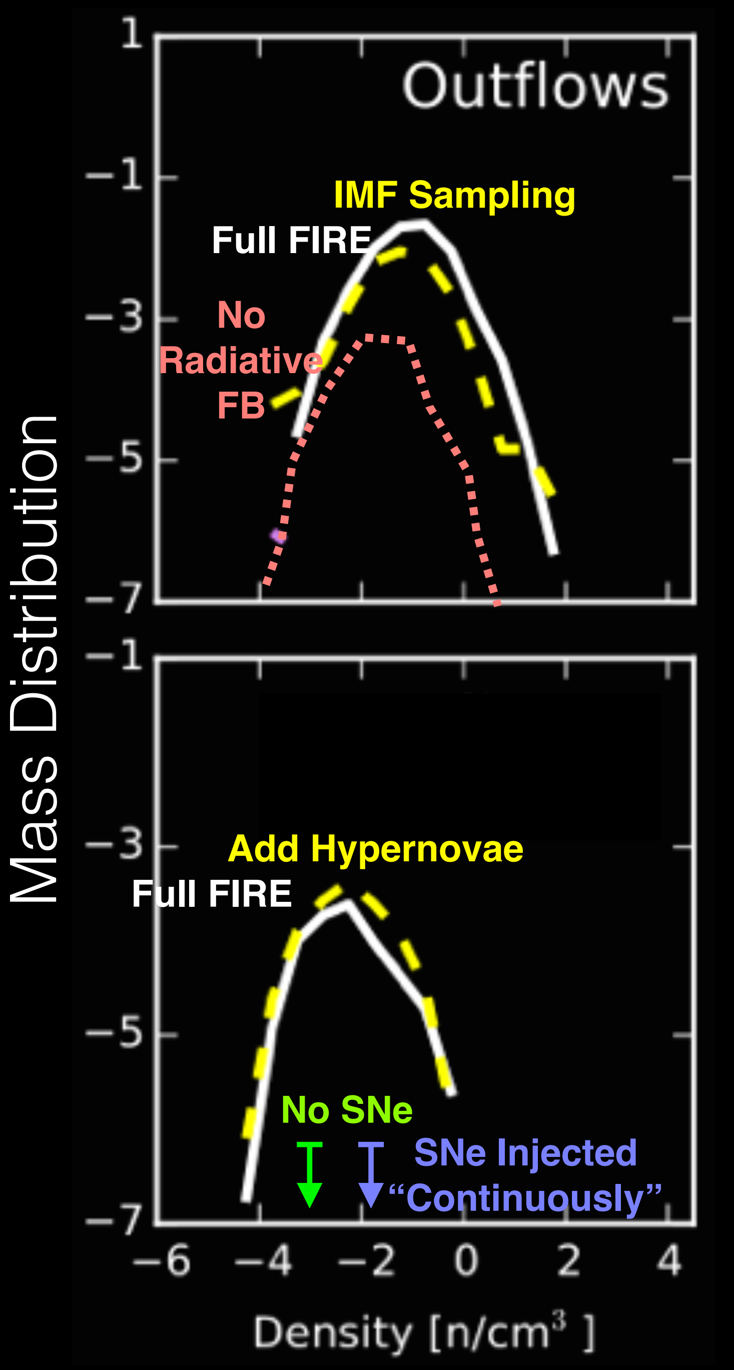
Klessen+, Ostriker+
Hopkins+
K.-Y. Su, in prep

Treat each SNe explicitly following resolved explosion



Continuously dump thermal energy ~SFR





Doing the "sub-grid" right can matter

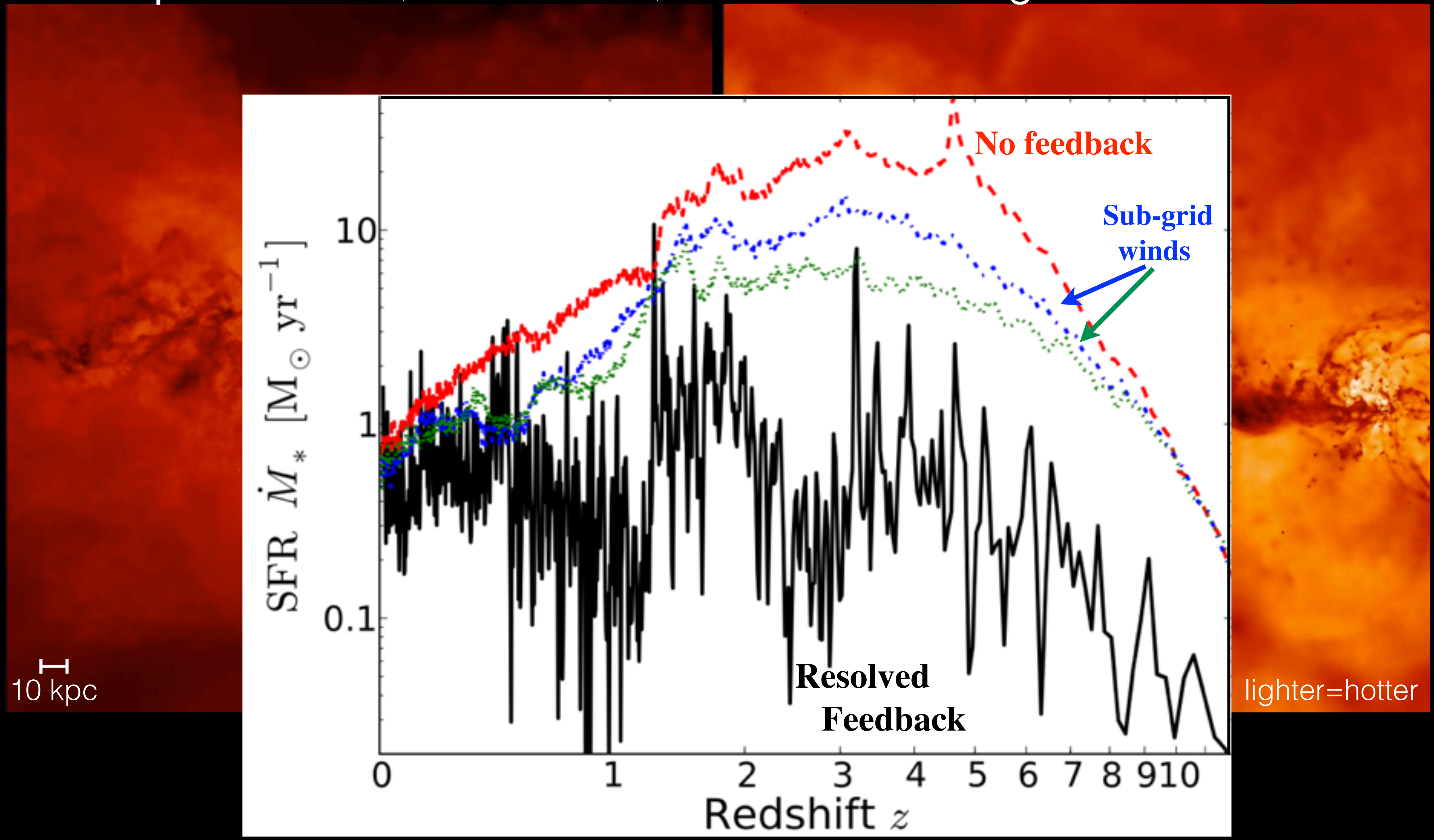
DANGERS OF ONLY FITTING MASSES

M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

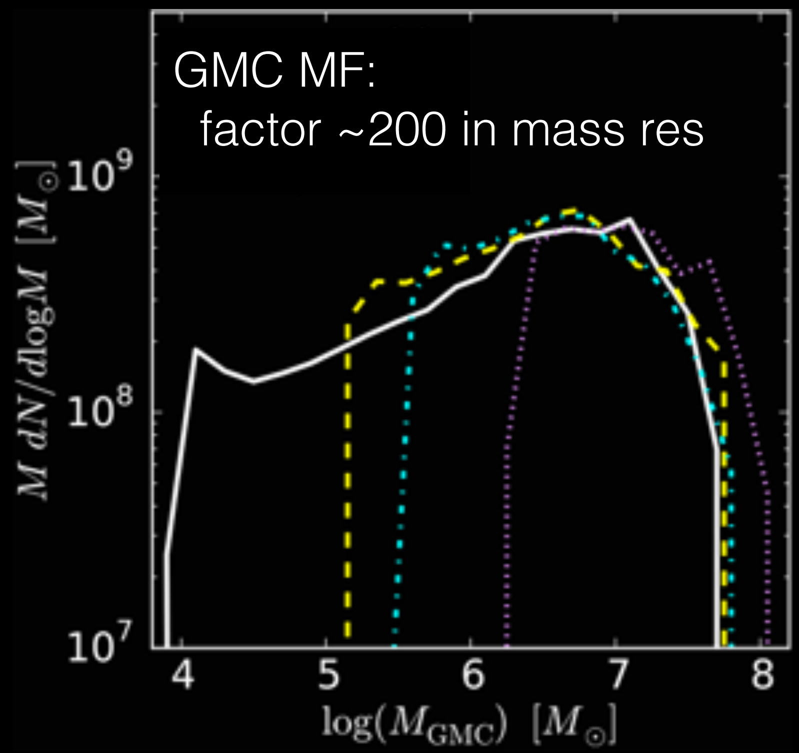
Simple Sub-Grid $(\dot{M}_{\rm wind} = \eta\,\dot{M}_*)$

Following Full Feedback



Resolution: Needs to Match Your Physics!

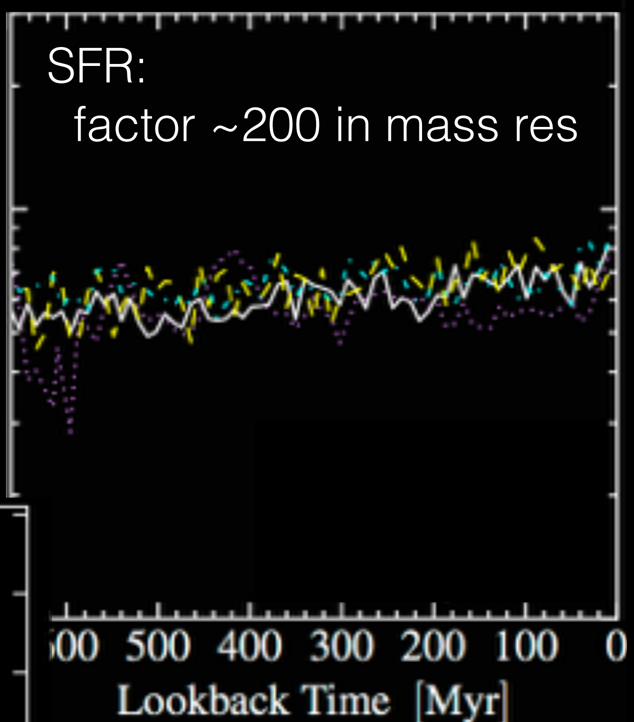
DIFFERENT PREDICTIONS REQUIRE DIFFERENT RESOLUTION



Fragmentation / GMCs / Dense Gas:

$$m_i \lesssim 10^5\,M_\odot \ll M_{\rm Toomre}$$

$$\epsilon_{\rm grav}^{\rm min} \ll 100\,{\rm pc}$$ [guaranteed if adaptive]

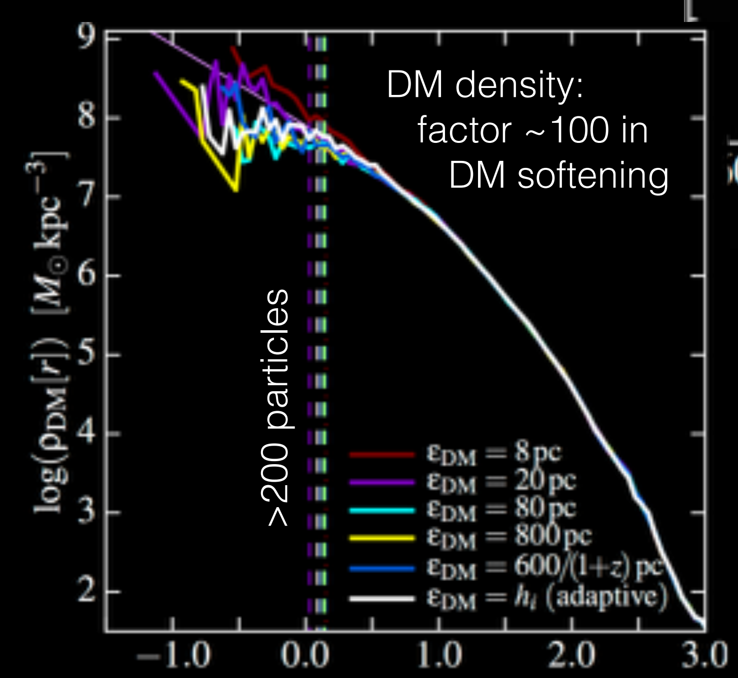


Super-bubbles / overlaps / chimneys:

$$m_i \lesssim 10^5\,M_\odot \ll M_{\rm Bubble}$$

Individual SNe (no sub-grid SNe momentum):

$$m_i \lesssim 10^3\,M_\odot \ll M_{\rm Cooling}$$



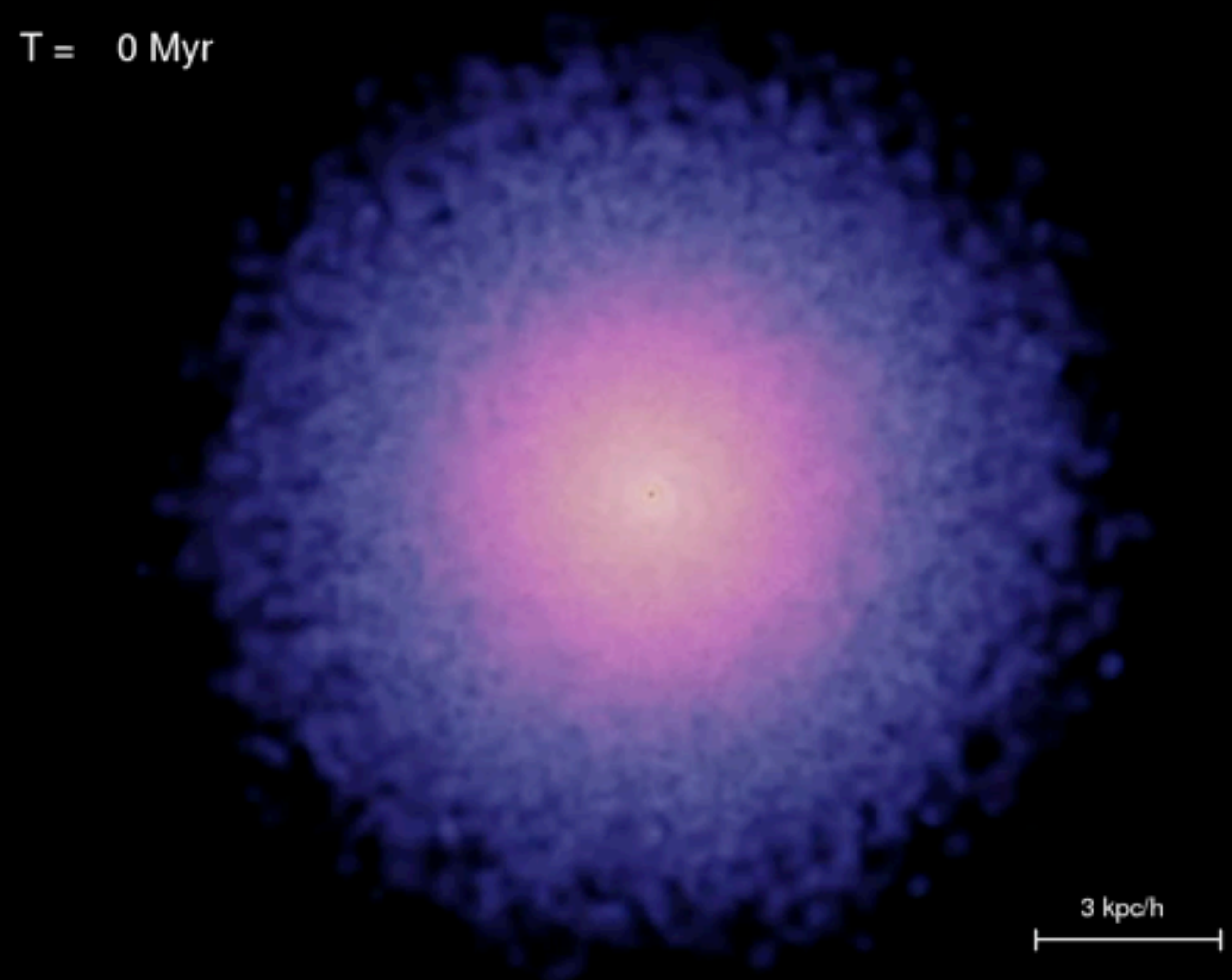
Dwarf galaxy "bursty-ness":

$$m_i \lesssim 10^{-6}\,M_{\rm halo}$$

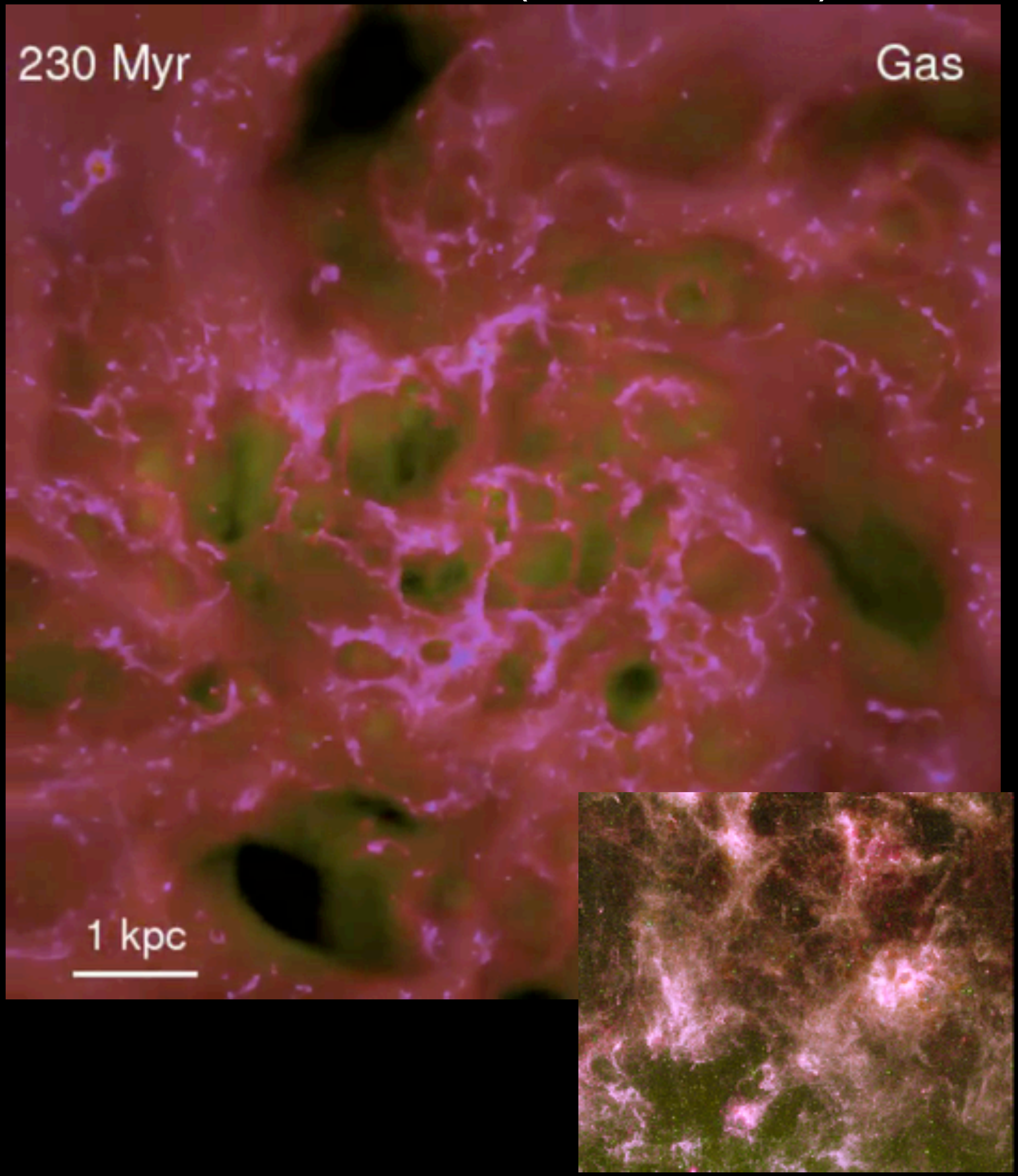
Doing the "sub-grid" right can matter

NEED PHYSICS TO PUSH BEYOND YOUR SUB-GRID SCALE

Sub-Grid ISM (Illustris, Eagle)



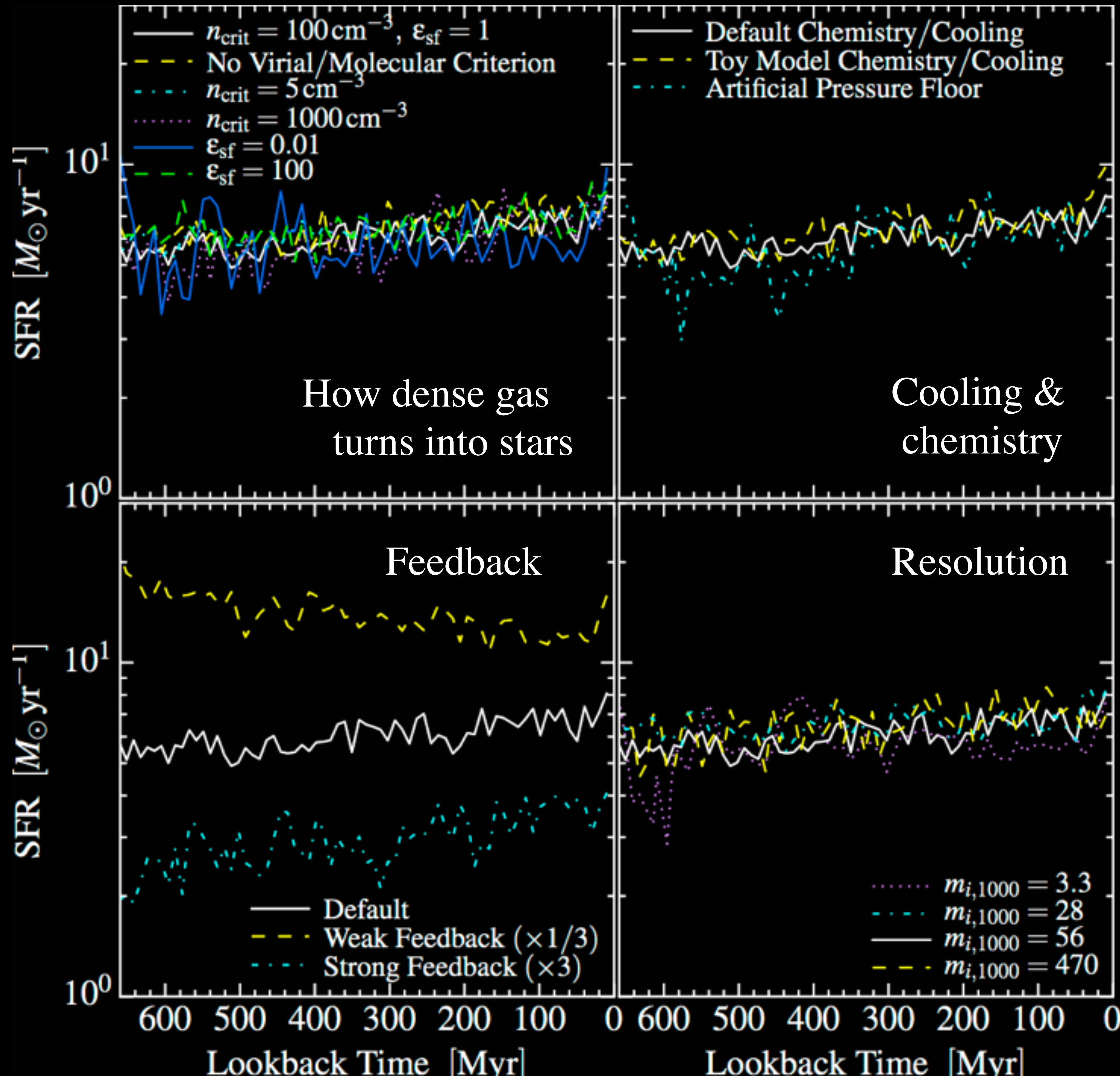
Resolved ISM (FIRE, SILCC)



What Doesn’t Matter?

(depends 100% on *what you care about predicting*)

(Galactic) Star Formation Rates are *INDEPENDENT* of how stars form!

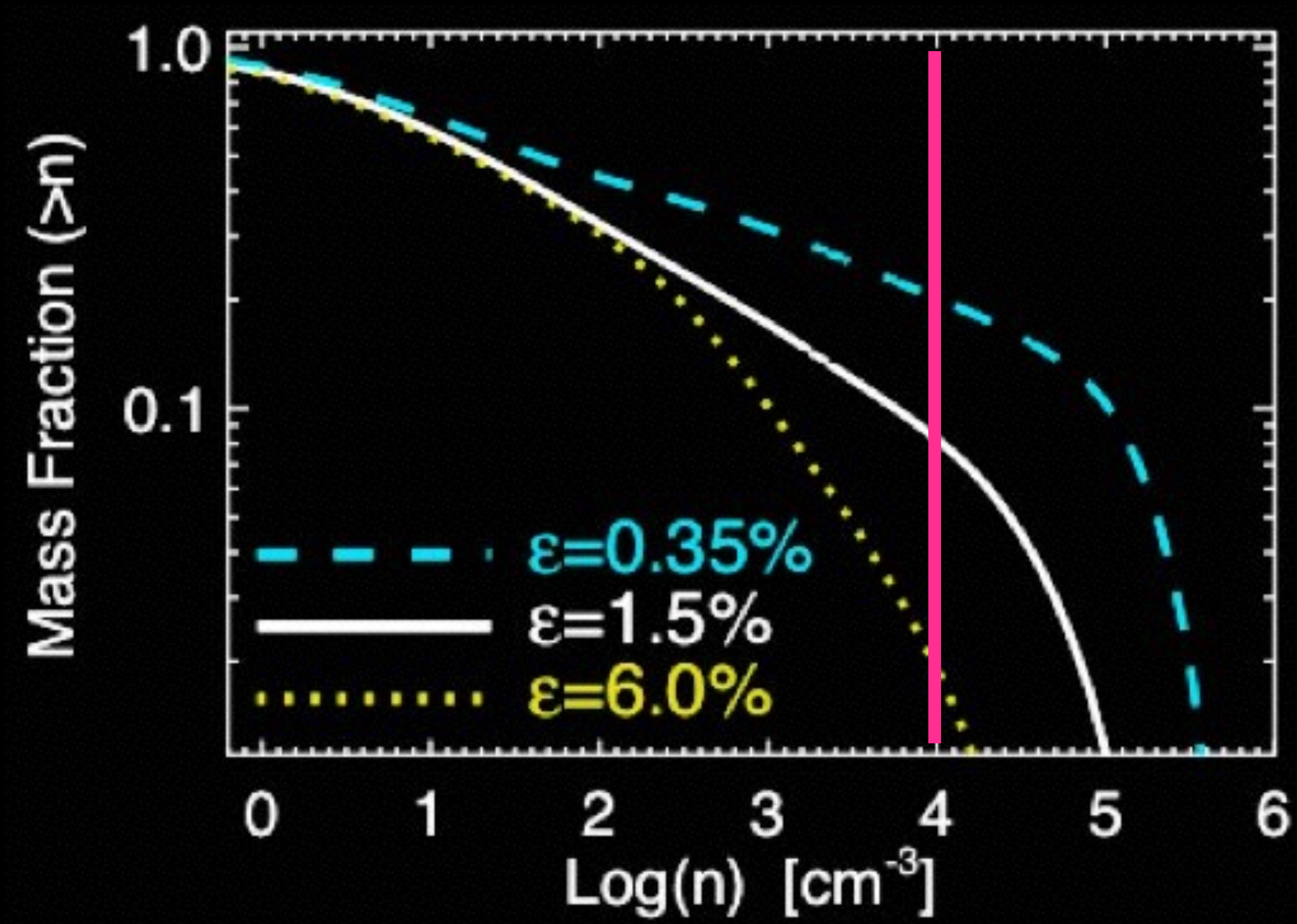


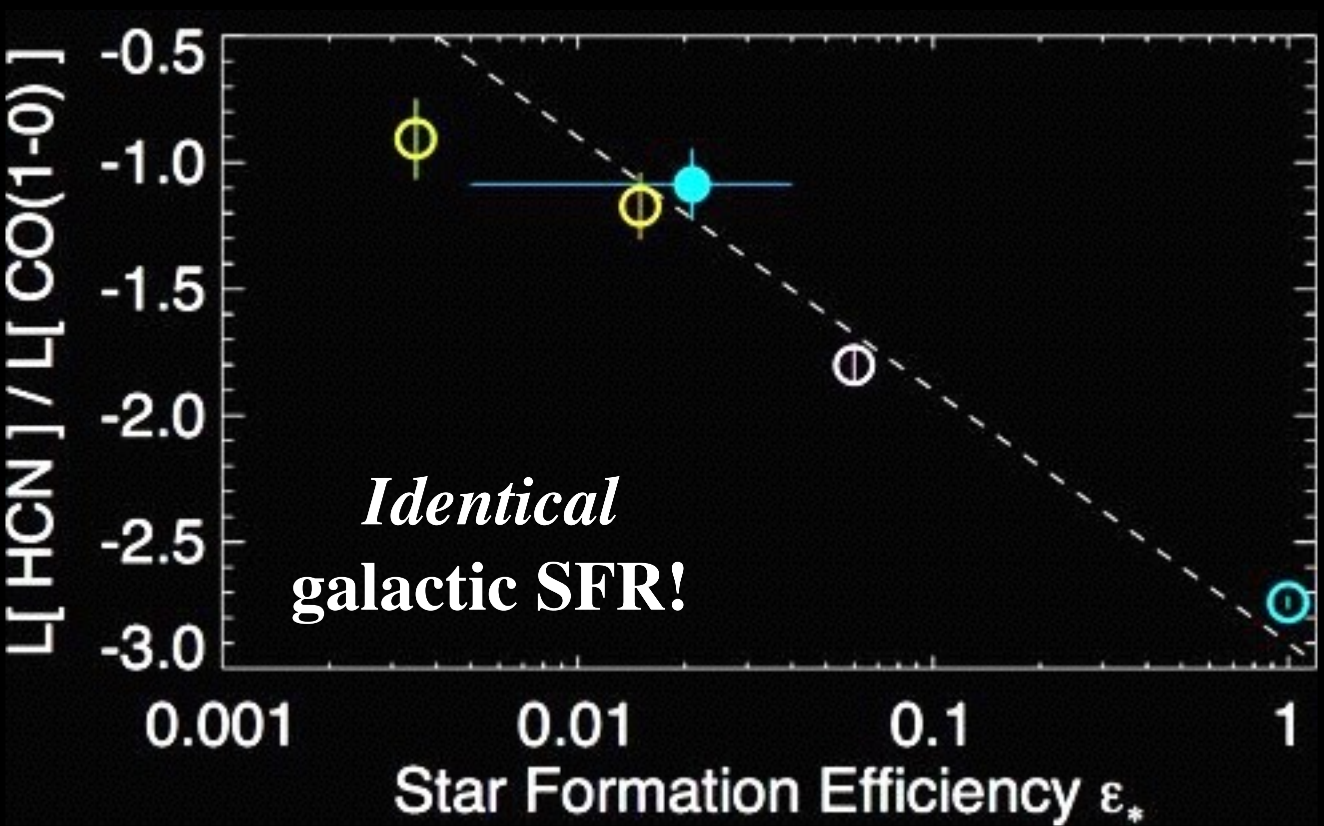
Matt Orr (in prep)
Saitoh+ 11
Hopkins+ 11,12,14
Agertz+14

Dense Gas *Does* Change

SELF-REGULATES TO "NEEDED" SFR LEVEL

Efficiency (SF per t_{dyn}) in *dense* gas





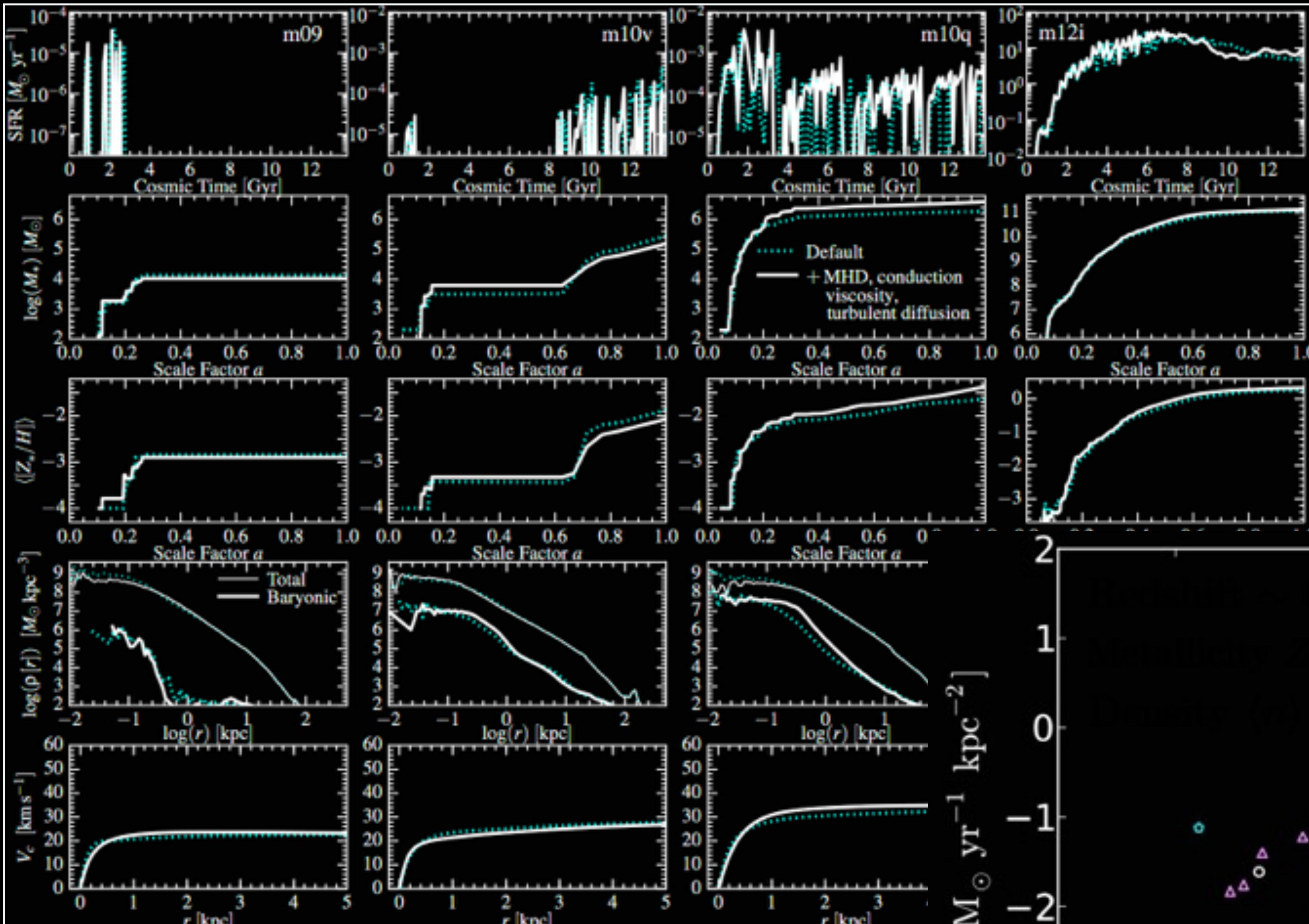
(molecular gas)

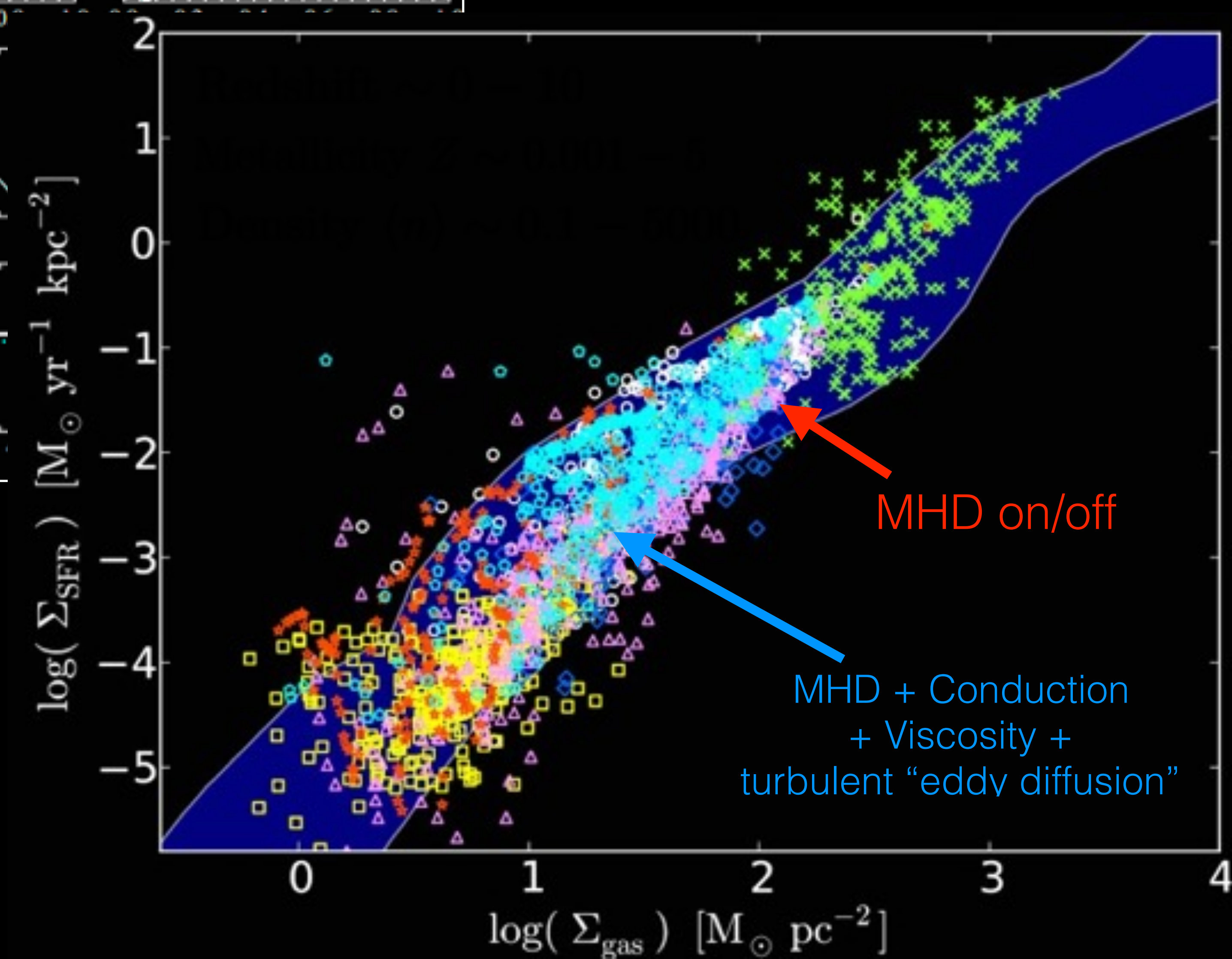
Matt Orr (in prep)
Hopkins+ 11,12,14
Shetty+ 14
Narayanan+ 13

Galaxy SFRs (sub-L*) independent of MHD+diffusion

MAY NOT APPLY TO COOLING IN HOT HALOS!

Kung-Yi Su
(in prep.)





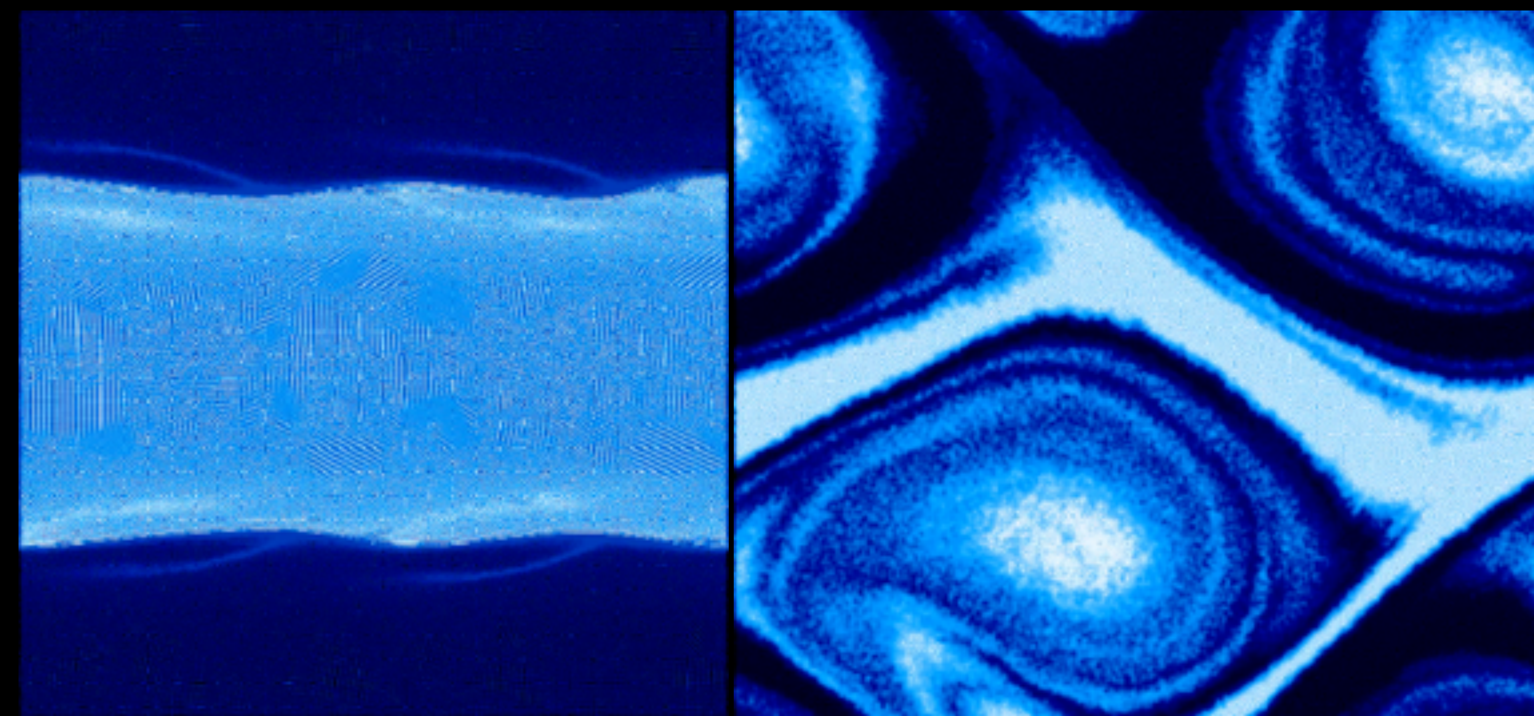
Numerical Methods

(aka: why did we switch from SPH?)

Smoothed-Particle Hydrodynamics (SPH)

CHALLENGE: POPULAR METHODS HAVE PROBLEMS

Kelvin-Helmholtz Instabilities

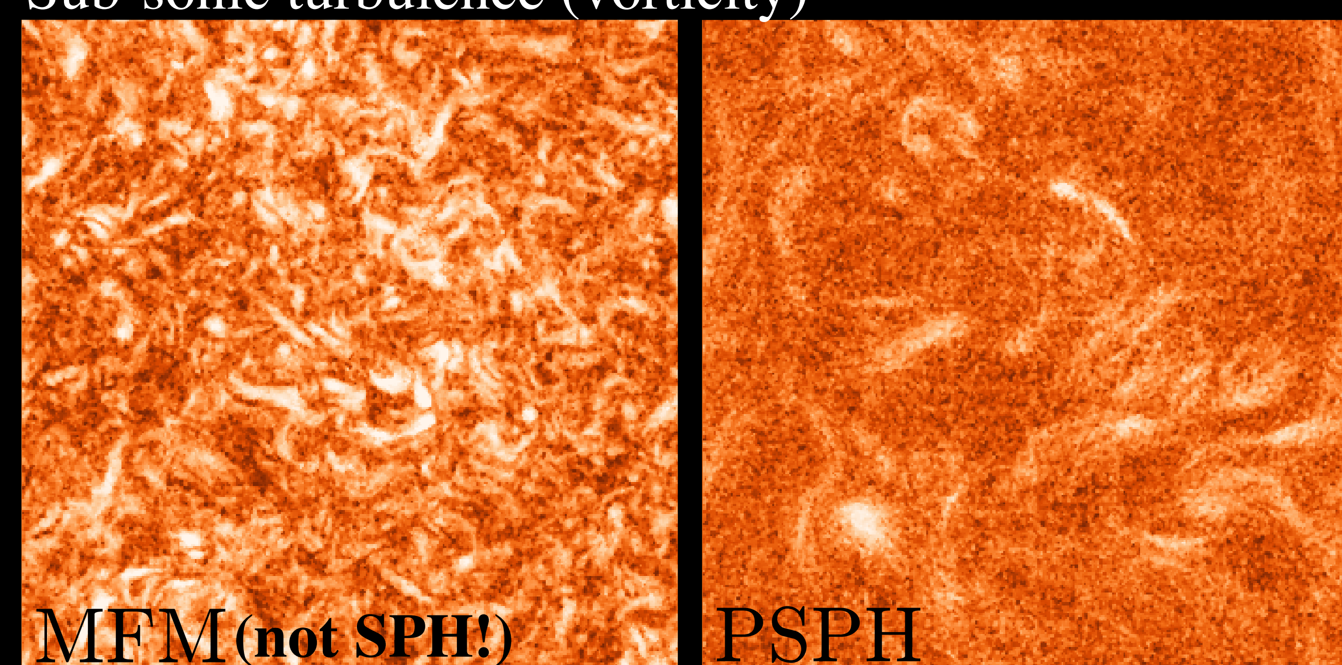


“old” SPH
(Springel 02)

“new” SPH (PSPH)
(Hopkins ’13): >>100 neighbors

- Lagrangian, adaptive, simple, conservative
- Artificial diffusion terms:
  - excess diffusion, viscosity

Sub-sonic turbulence (vorticity)



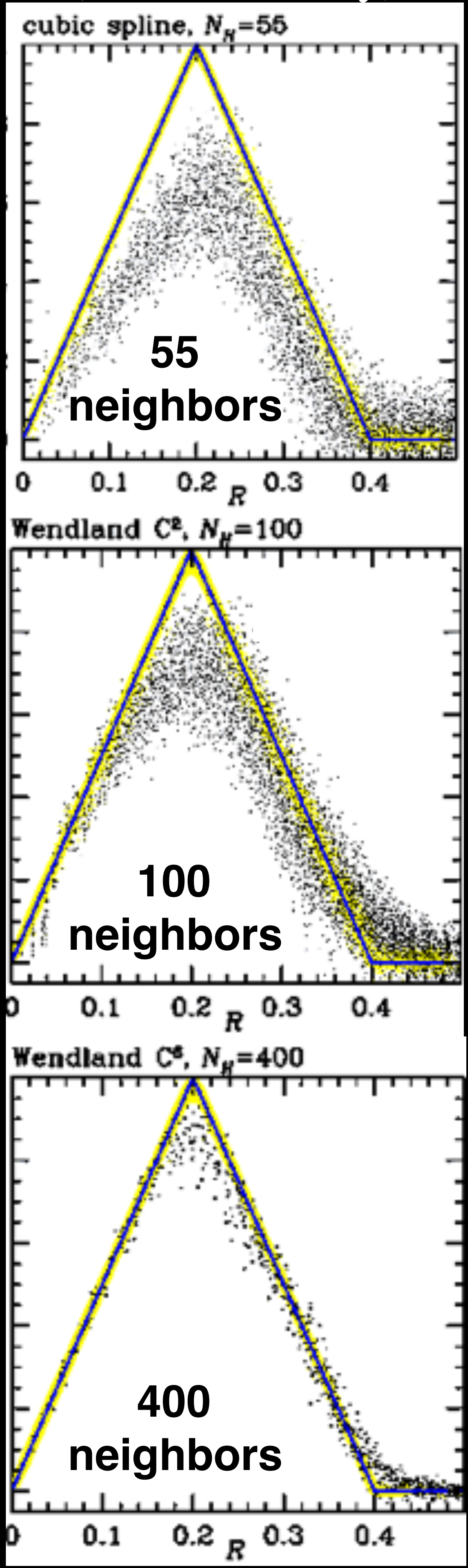
Ritchie & Thomas 01, Agertz 07,
Price 12, Read 12

Smoothed-Particle Hydrodynamics (SPH)

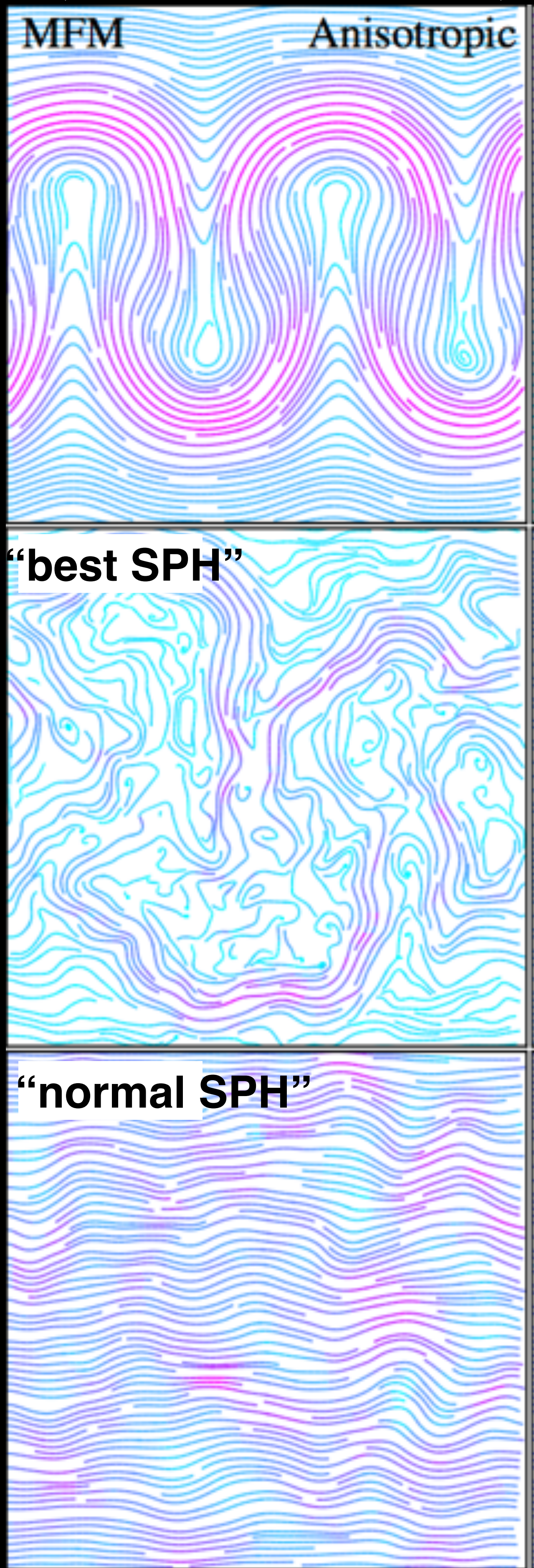
CHALLENGE: POPULAR METHODS HAVE PROBLEMS

- Fundamental low-order errors:
  - converges slowly:
    "beat down" by increasing kernel size, but this is *not efficient!*

Gresho vortex (Dehnen & Aly)



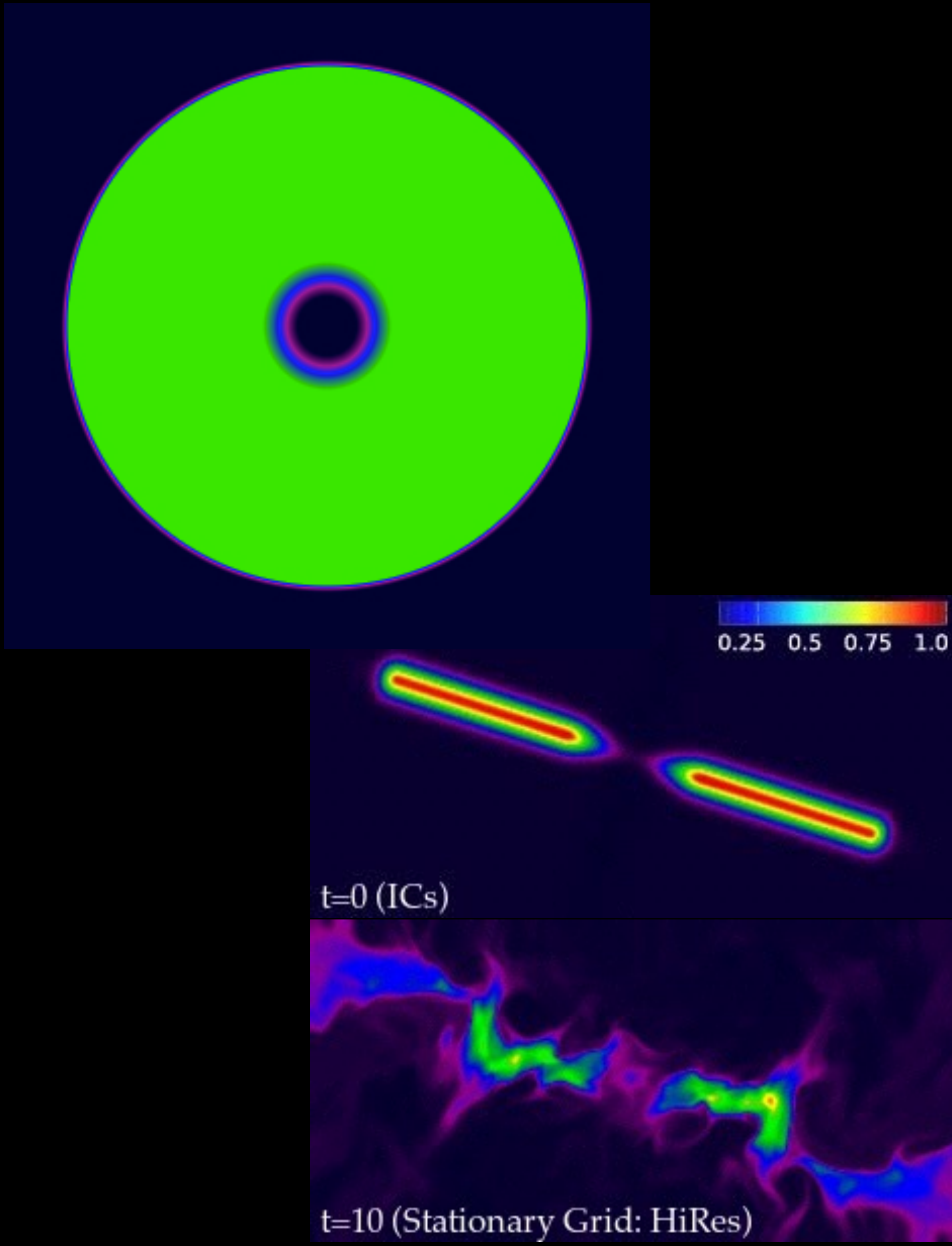
Anisotropic Conduction (MTI, HBI, Hall MRI)



Dehnen & Aly, Rosswog, Hopkins, Tricco & Price, Read

Adaptive Mesh Refinement (AMR)

CHALLENGE: POPULAR METHODS HAVE PROBLEMS



- Eulerian, well-studied, high-order
- Excessive mixing/diffusion
  when fluid moves over cells
- Geometric effects:
  - carbuncle instability (shocks)
  - loss of angular momentum
  - grid-alignment (disks)
- Also “beaten down” with resolution, but *expensive*
  - Hahn ’10: >>512^2 resolution to avoid grid-alignment

Peery & Imlay 88,
Mueller & Steinmetz 95, Hahn 10

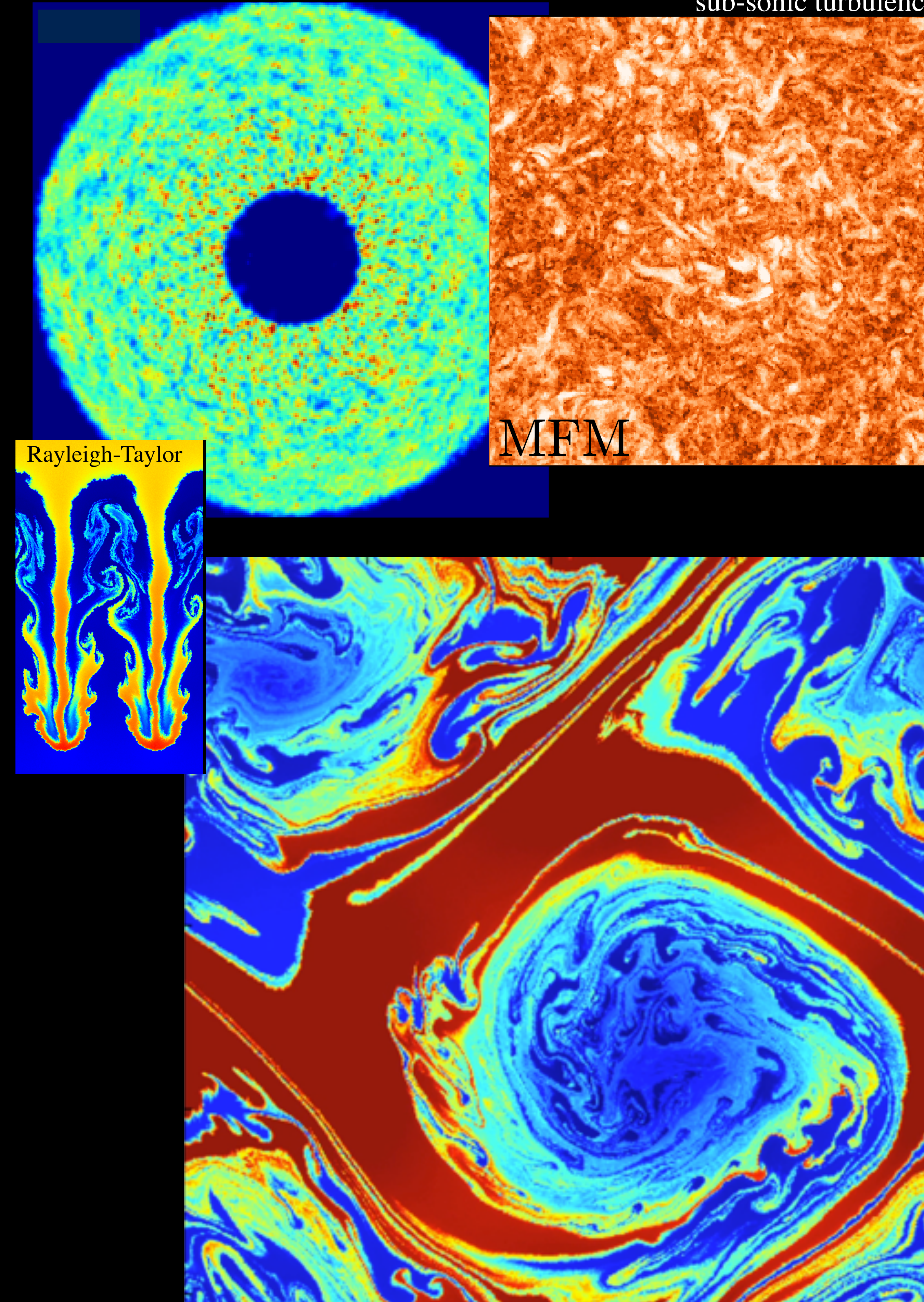
New Methods Combine (some) Advantages of Both:

(BUT REMAIN LESS WELL-TESTED)

- Moving-meshes (AREPO), meshless finite-volume (GIZMO), high-order ALE methods
- Move with flow, no preferred geometry, but also accurate, high-order, and shock-capturing
- Grid noise is more severe

GIZMO: disk after 100 orbits

sub-sonic turbulence

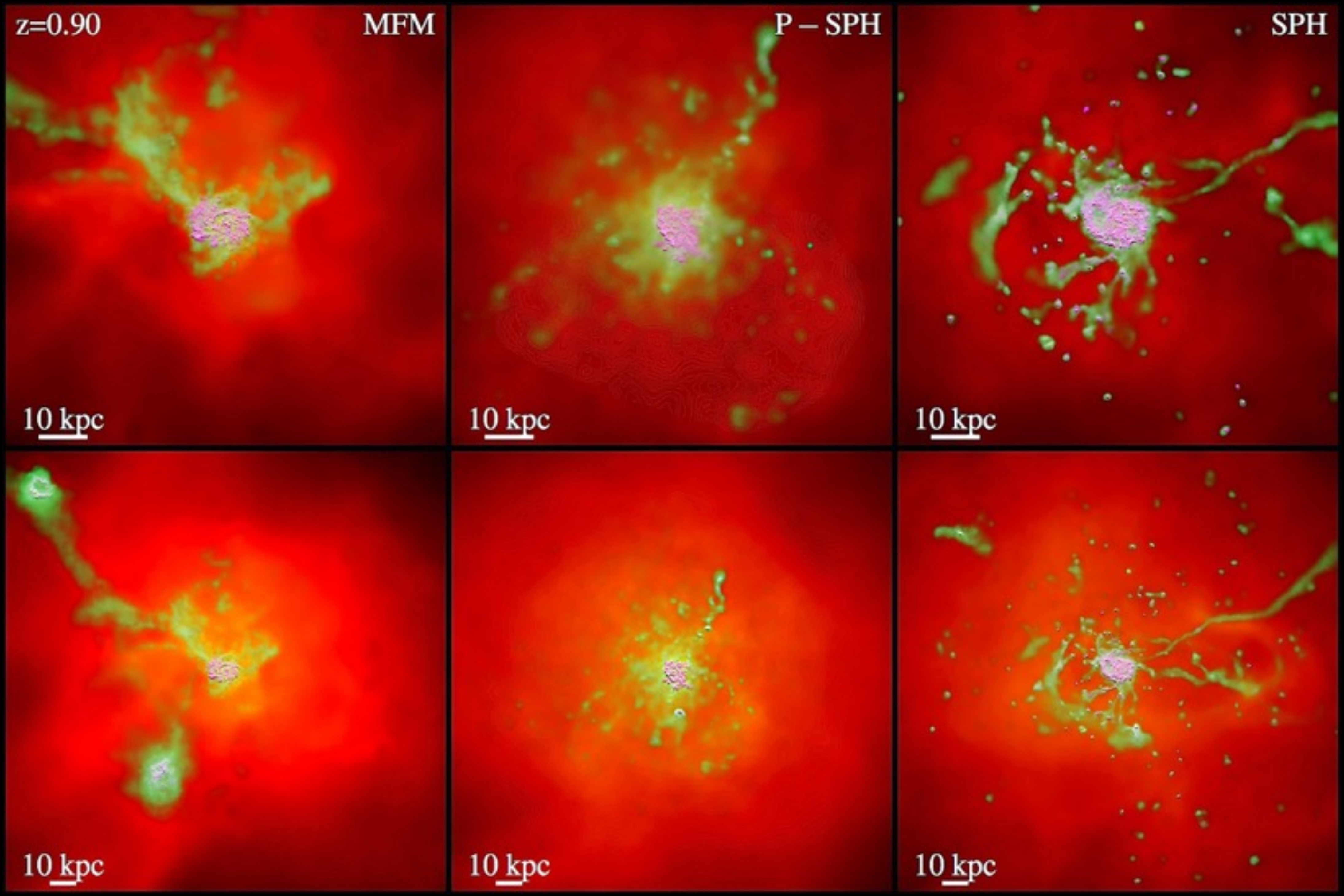


AREPO: Springel 2010
TESS/DISCO: Duffel 2011
FVMHD3D: Gaburov 2012
GIZMO: Hopkins 2015

Getting the Hydro Right Can Matter

BUT IT DEPENDS ON WHAT YOU CARE ABOUT

New Methods (GIZMO) | "New" SPH | "Old" SPH



Agertz 07 & many others

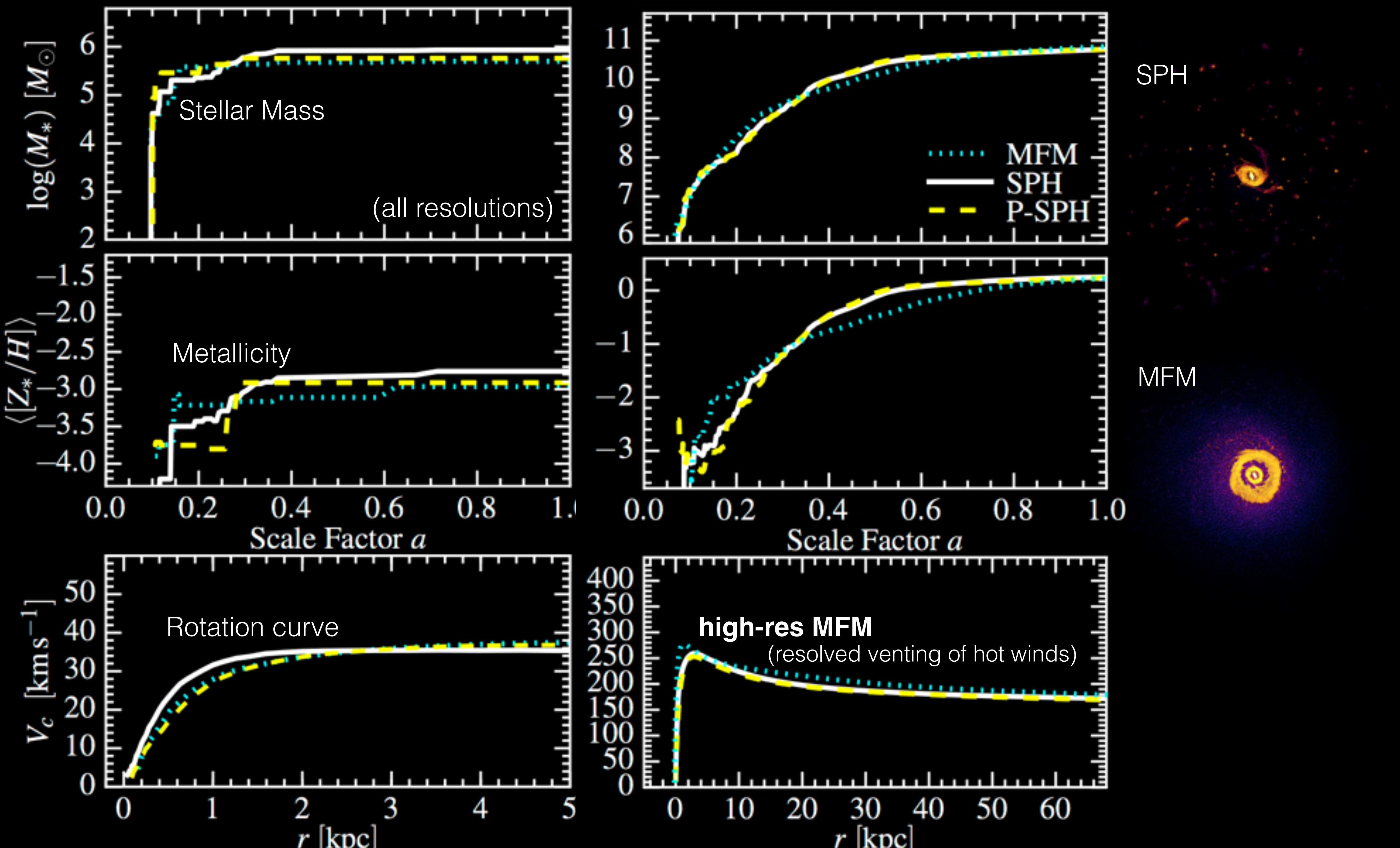
BUT only factor ~1.5 difference in mass!

Getting the Hydro Right Can Matter

DEPENDS ON WHAT YOU CARE ABOUT

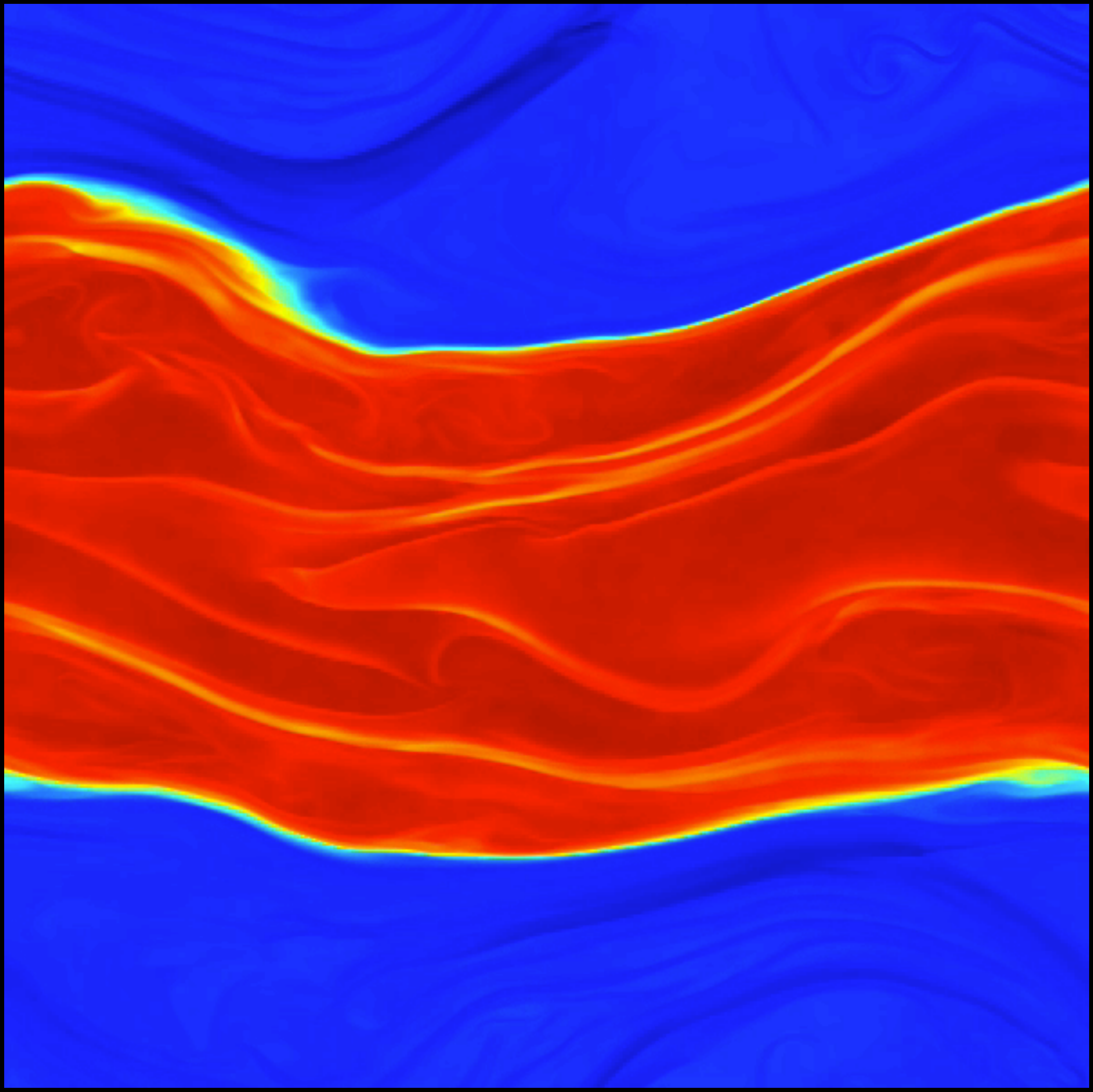
Dwarfs ("cold mode"): no effects

Massive Galaxies ("hot mode"): cooling & wind "venting"

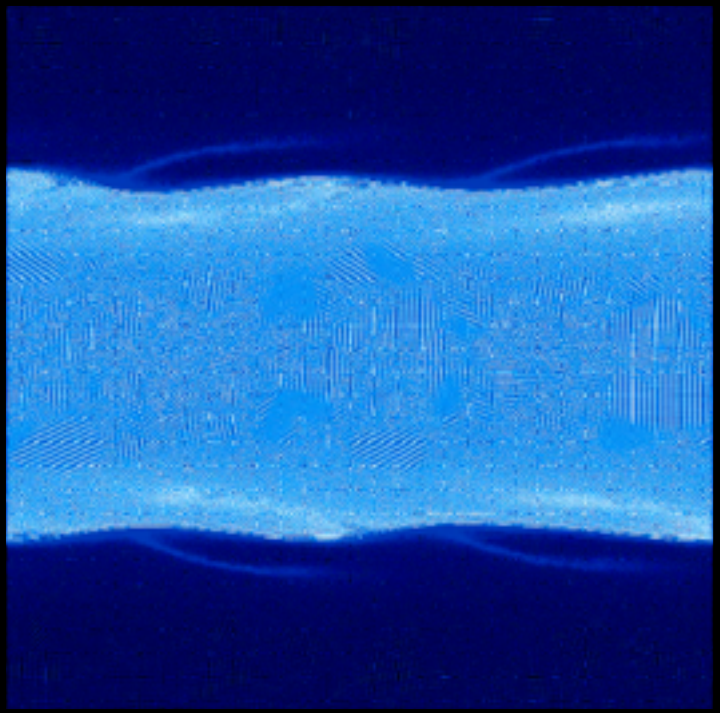


A Caution: You can get the “right” answer for the wrong reasons

DON’T MISTAKE NUMERICAL PRECISION FOR PHYSICAL ACCURACY



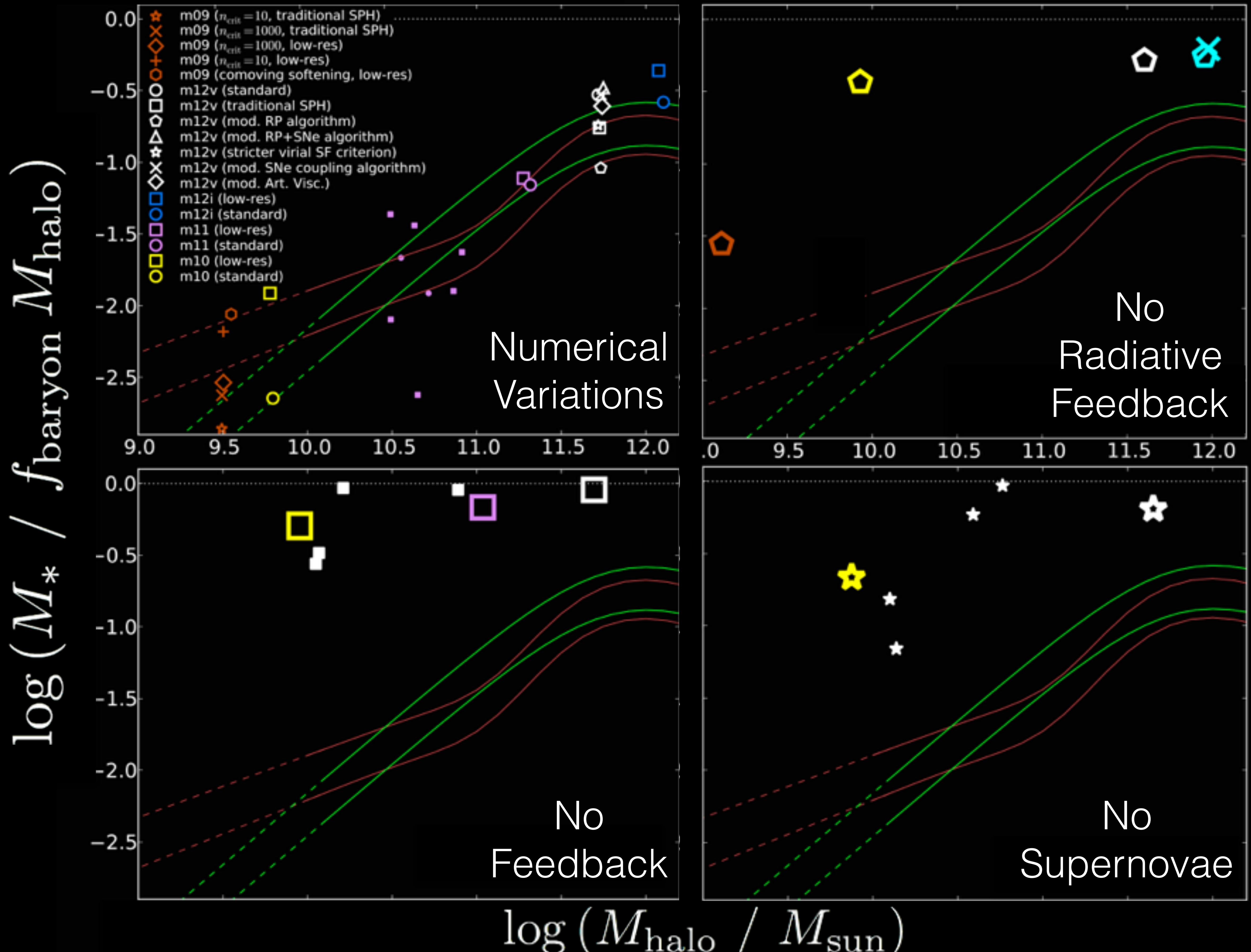
Magnetic KH
(Equipartition field)
with a “good” code

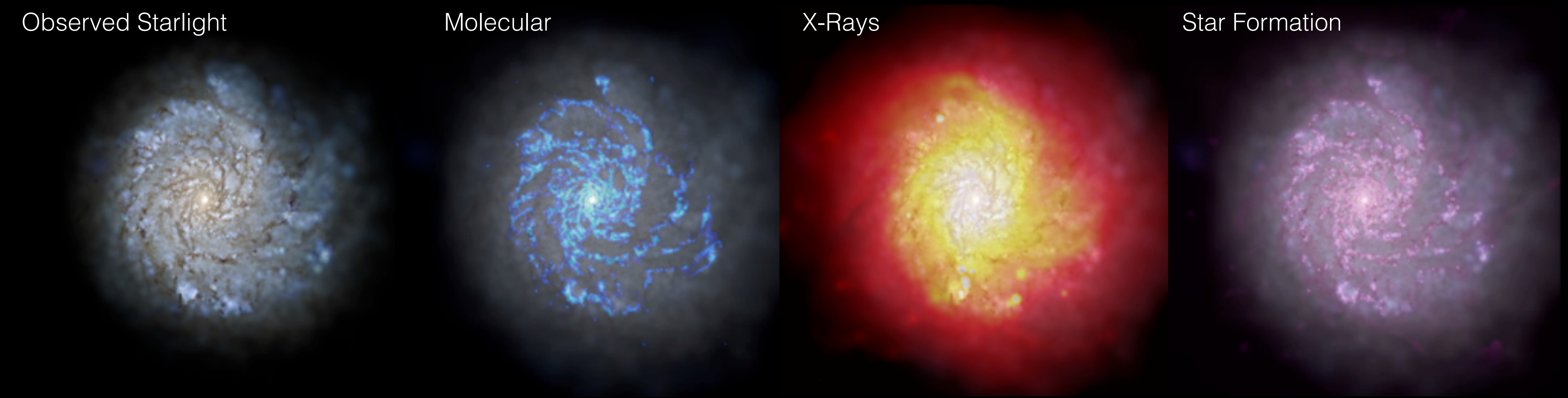


“old” SPH
(Springel 02)

Getting the Hydro Right Can Matter

DEPENDS ON WHAT YOU CARE ABOUT





- **Numerics can be important**
  - SPH: is high N_{NGB} worth it? MHD, conduction, RT, issues: significant differences in "hot halos"
  - Quasi-Lagrangian schemes: "grid noise" at very low Mach numbers (<0.01)
  - ***Physics*** usually dominates

- **Everything is sub-grid: but there are "good" and "bad" models, and different philosophies**
  - FIRE: trying to "build up" from small scales: works surprisingly well!
  - Need resolution to match your physics, but also need ***physics*** to match your resolution (no meaning in resolving scales you don't have the physics for)

- **What is needed? Depends 100% on what you want to predict**
  - Resolve dense gas: resolve fragmentation (Toomre), ***physics*** for GMC destruction (radiative FB)
  - Resolve SNe overlaps/bubbles: need to treat them explicitly, account for unresolved cooling
  - SFR surprisingly insensitive to small-scale SF physics, MHD, diffusion: ***feedback*** dominates