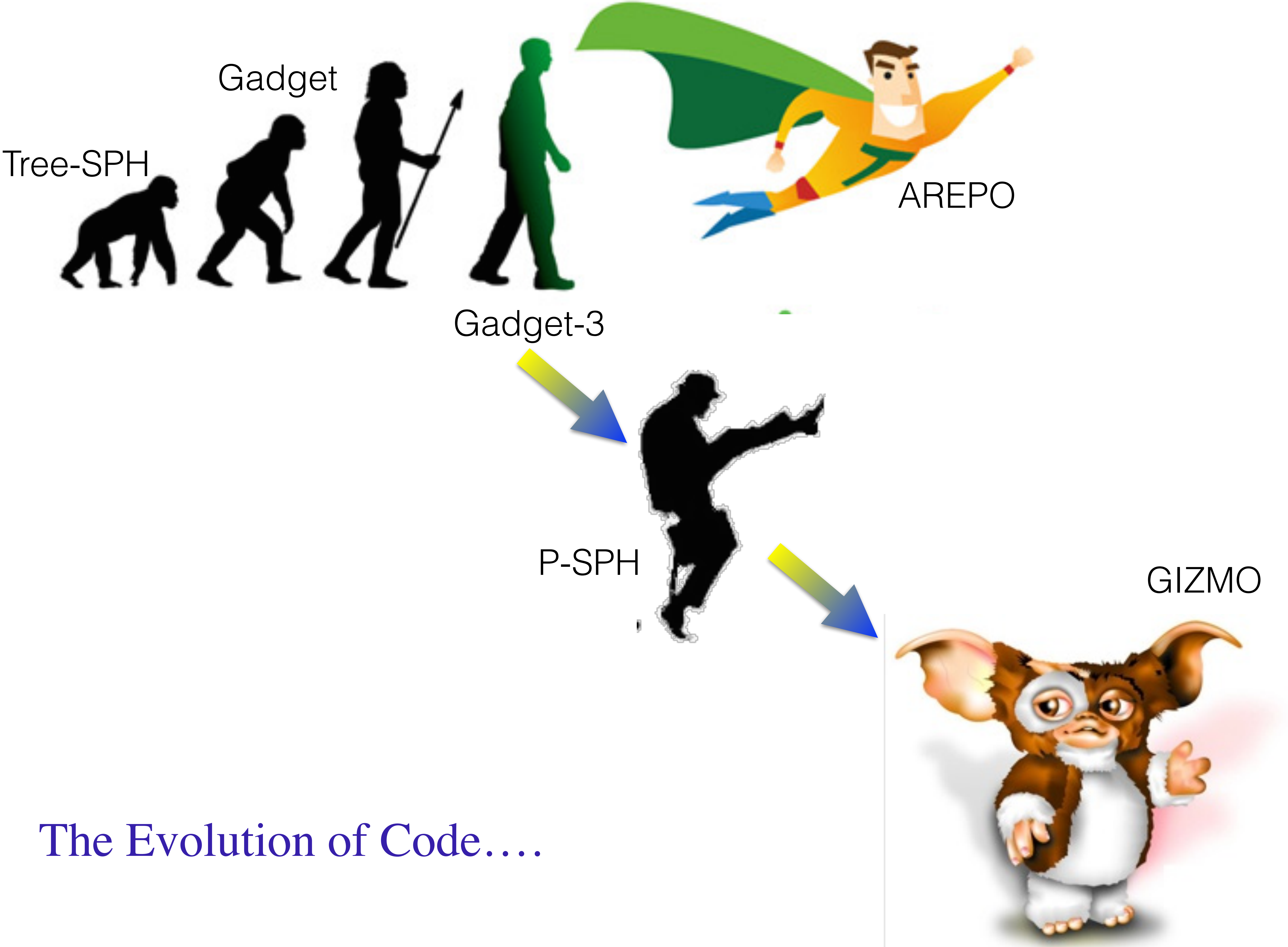
Numerics, Resolution, Physics

Towards Predictive Galaxy Formation Simulations

Phil Hopkins
Caltech

Numerical Methods

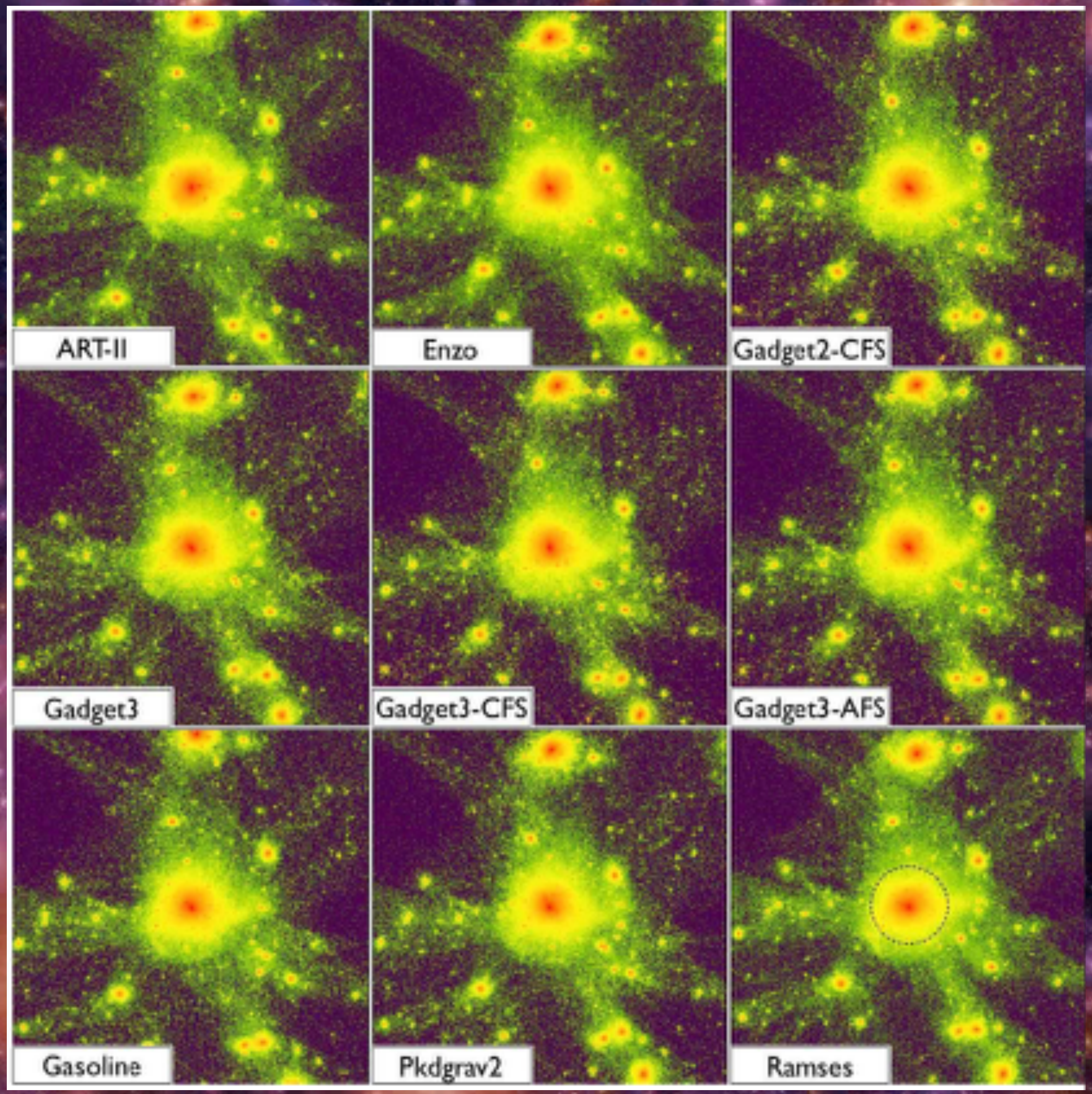
(aka: why did we switch from SPH?)



The Evolution of Code….

Gravity (Large Scales): Looks Pretty Good!

Kim et al. 2013 (AGORA Collaboration)



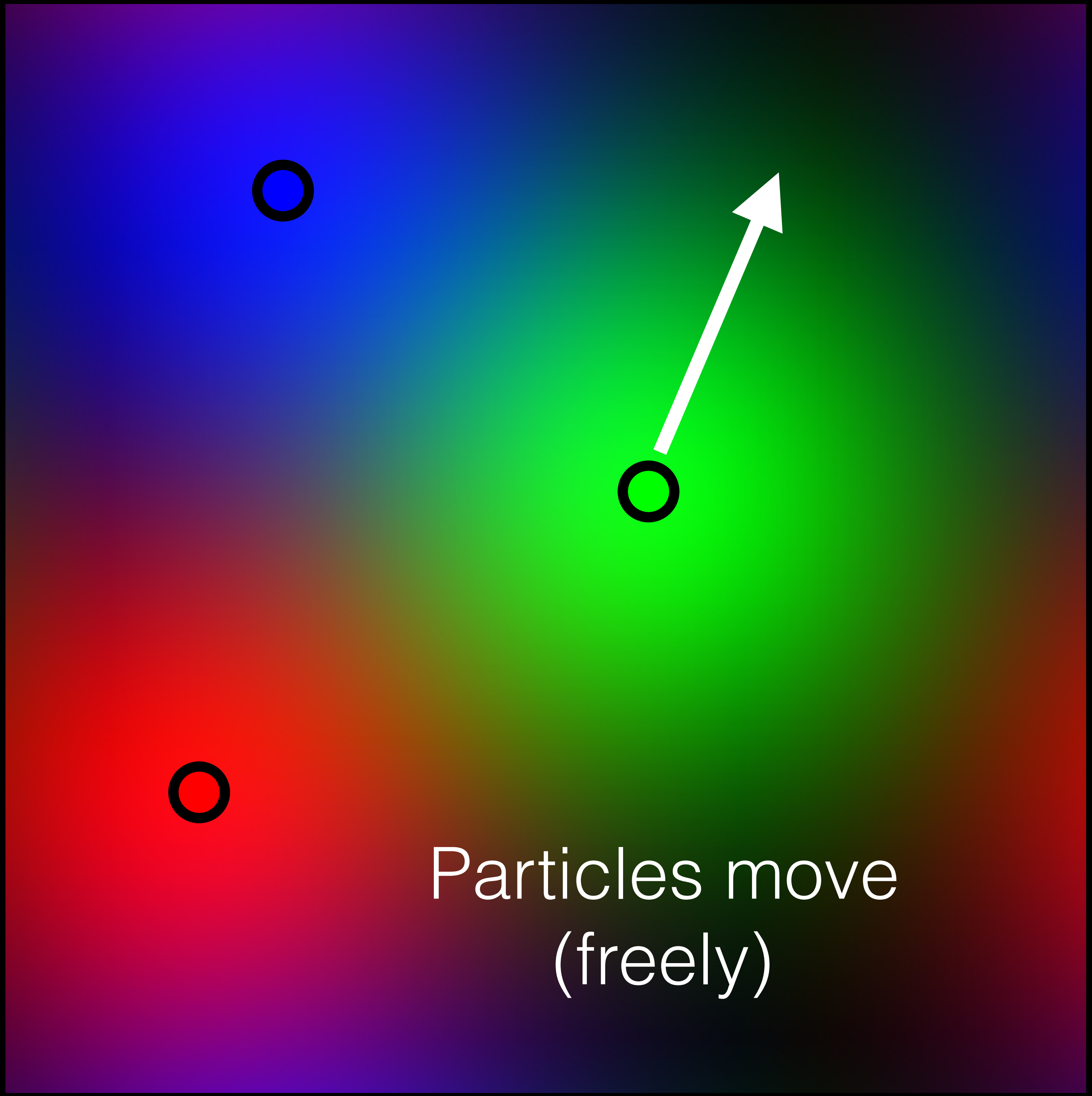
Challenge:

POPULAR METHODS FOR HYDRODYNAMICS HAVE PROBLEMS

Lucy 77, Gingold & Monaghan 77
Reviews by: Springel 11, Price 12

Smoothed-Particle Hydrodynamics

- Lagrangian, adaptive, simple, conservative

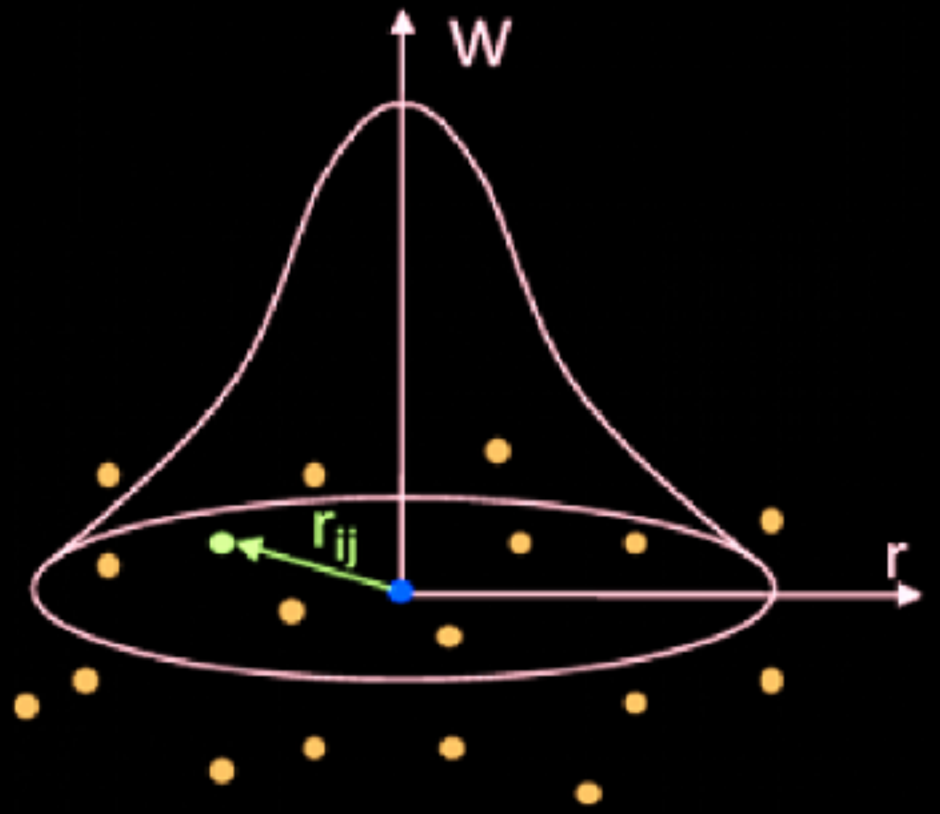


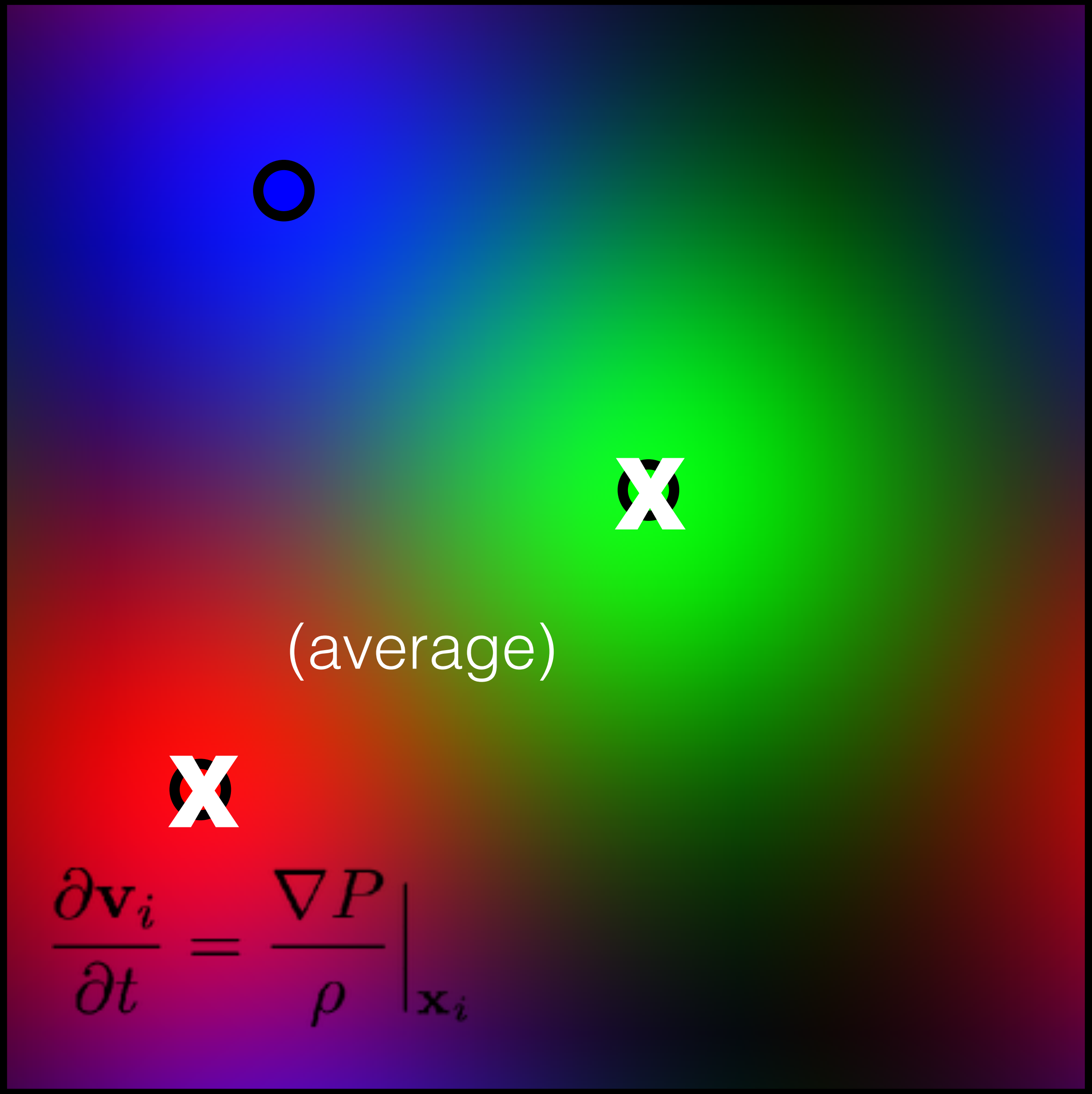
Challenge:
POPULAR METHODS FOR HYDRODYNAMICS HAVE PROBLEMS

Lucy 77, Gingold & Monaghan 77
Reviews by: Springel 11, Price 12

Smoothed-Particle Hydrodynamics

- No volume partition: point-like particles smoothed into fields [ok in “continuum limit”]



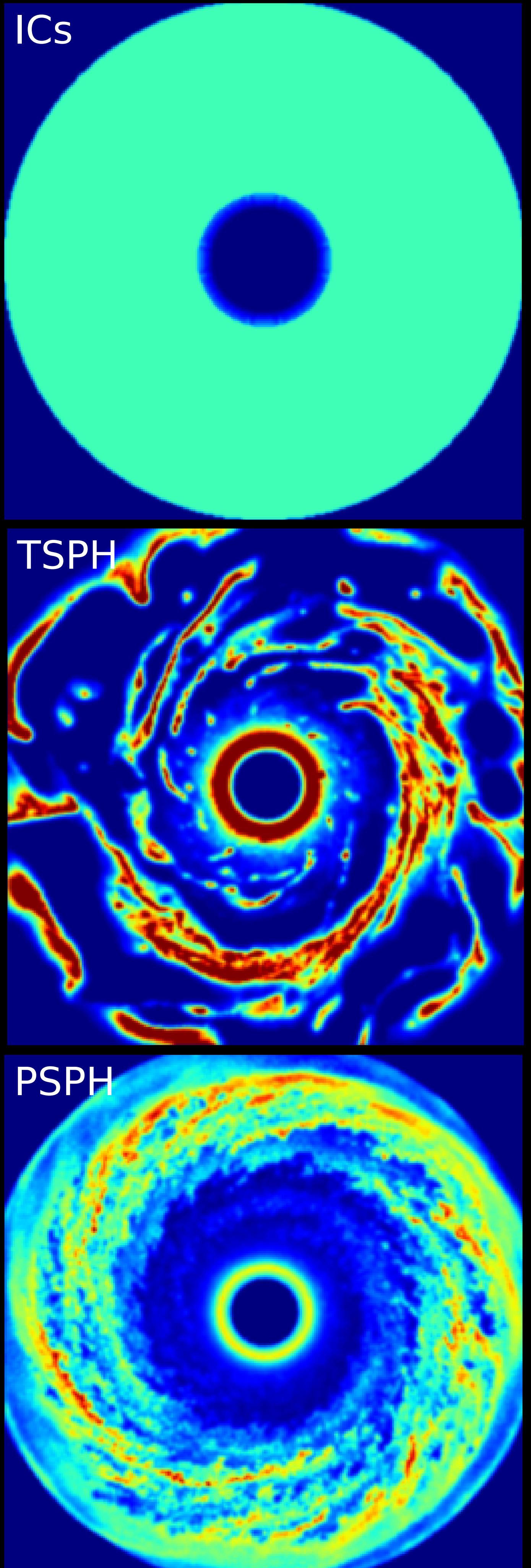


- Solve EOM at particle locations (stabilize with artificial diffusion)

Challenge:

POPULAR METHODS FOR
HYDRODYNAMICS HAVE PROBLEMS

Keplerian disk/ring
(should conserve ICs)



Smoothed-Particle Hydrodynamics

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

"old" SPH
(Springel 02)
(after 20 orbits)

"new" SPH
(Hopkins 13)

Morris 97, Okamoto 03,
Cullen & Dehnen 10, Bauer & Springel 12

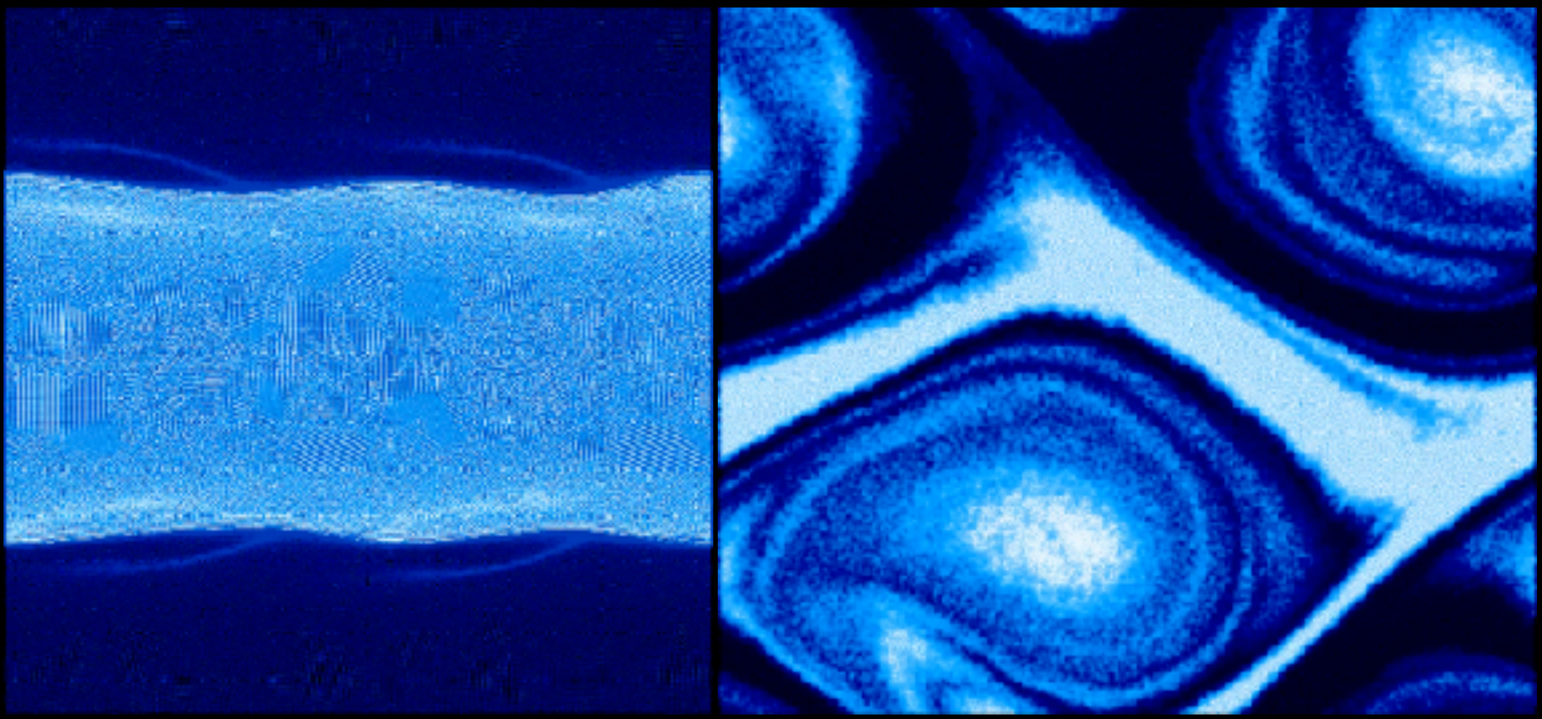
Challenge:
POPULAR METHODS FOR
HYDRODYNAMICS HAVE PROBLEMS

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

- **"Traditional SPH"**
  - GADGET/(old)GASOLINE
  - ~32 neighbors (cubic spline)
  - constant artificial viscosity
  - "density" formulation

- **"Modern SPH"**
  - P-SPH/SPHS/PHANTOM
  - ~128-500 neighbors (alt. kernels)
    (many people: Read, Dehnen)
  - high-order switches
    (Cullen+Dehnen)
  - "pressure" formulation
    (Hopkins, Saitoh+Makino)
  - artificial diffusion for entropy
    (Price, Wadsley)

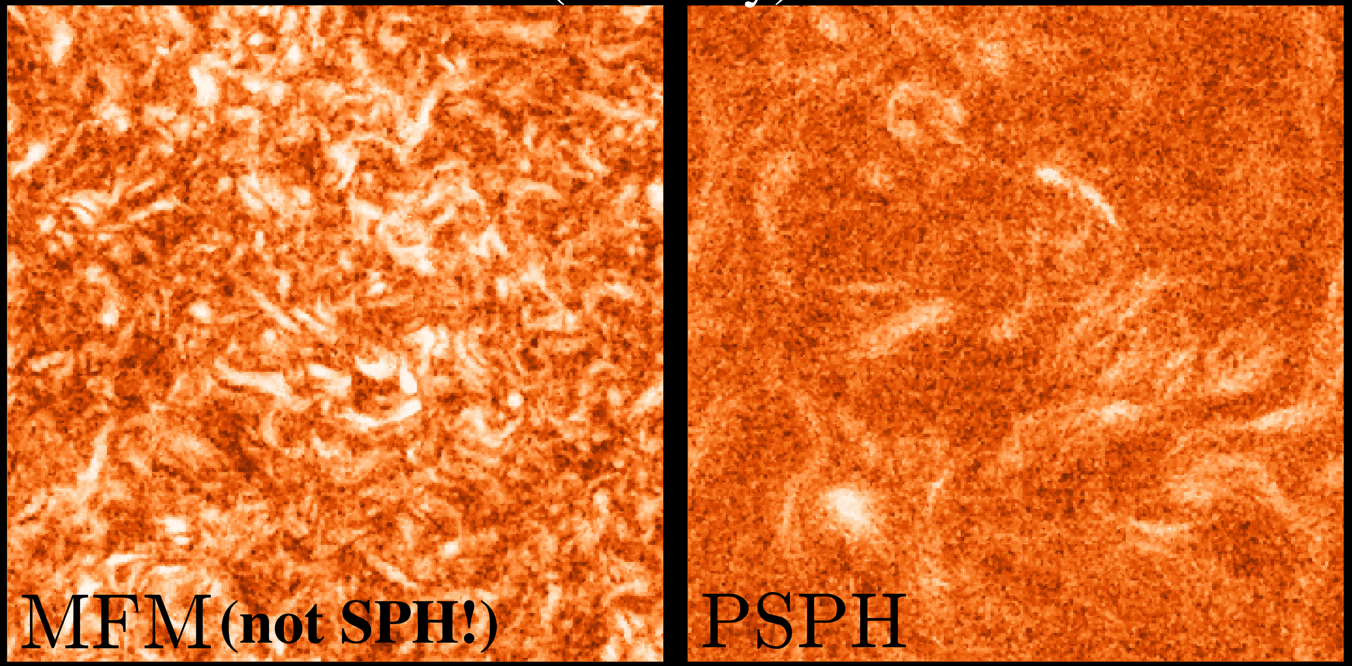
Kelvin-Helmholtz Instabilities



"old" SPH
(Springel 02)

"new" SPH (PSPH)
(Hopkins '13): >>100 neighbors

Sub-sonic turbulence (vorticity)

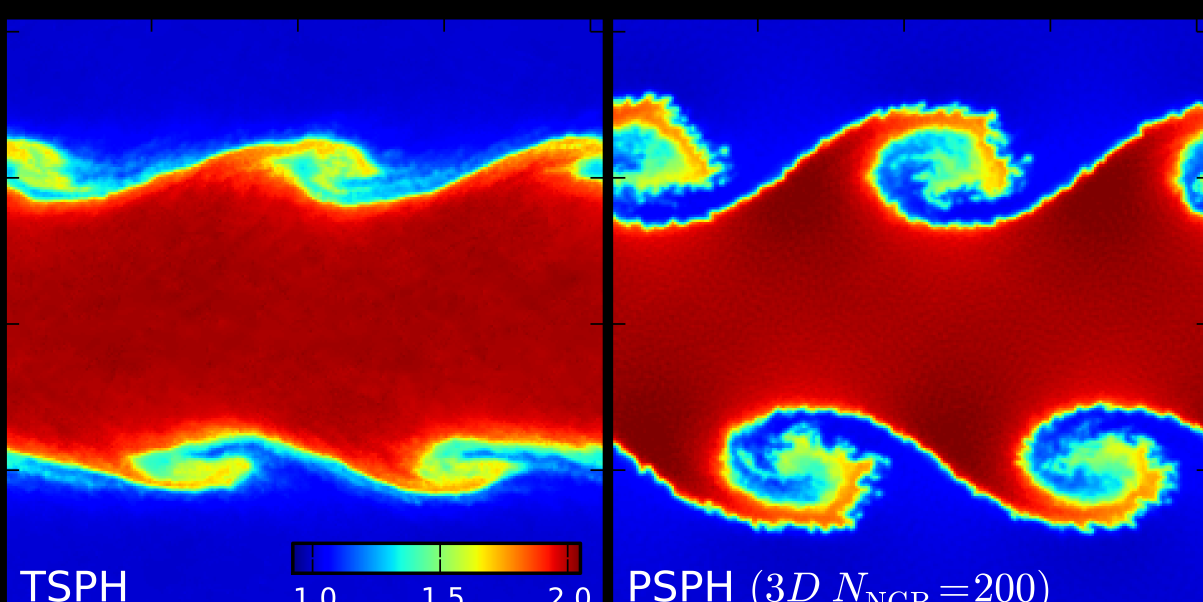


Challenge:

POPULAR METHODS FOR HYDRODYNAMICS HAVE PROBLEMS

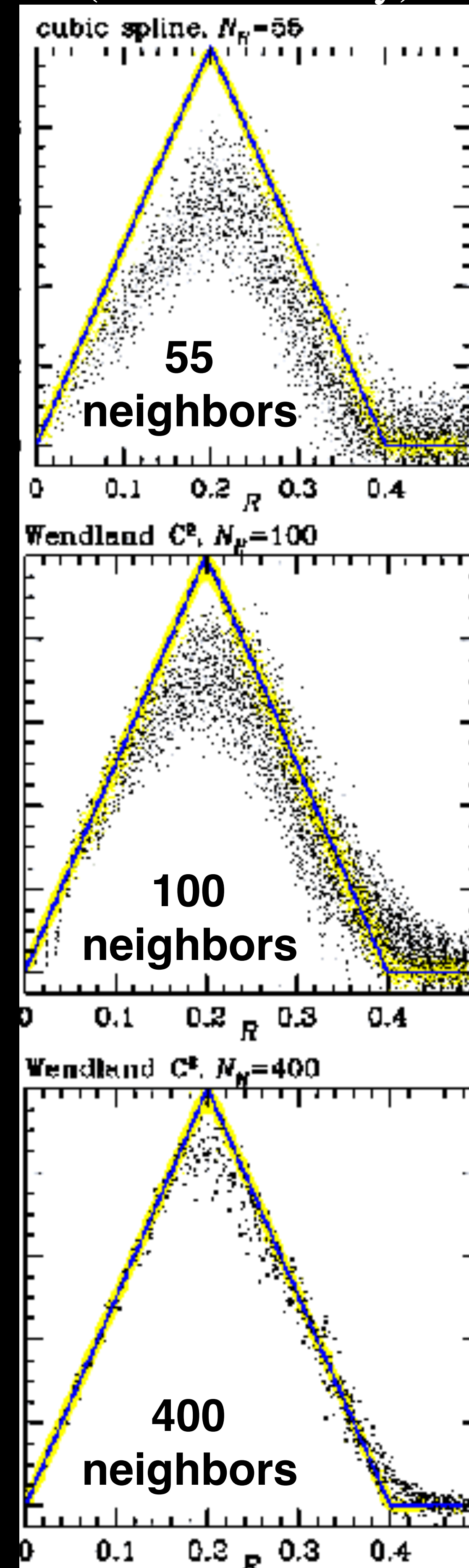
- Fundamental low-order errors:
  - converge slowly:
    "beat down" by
    increasing kernel size,
    but this is *not efficient!*

- MHD & anisotropic
  diffusion operators ill-posed

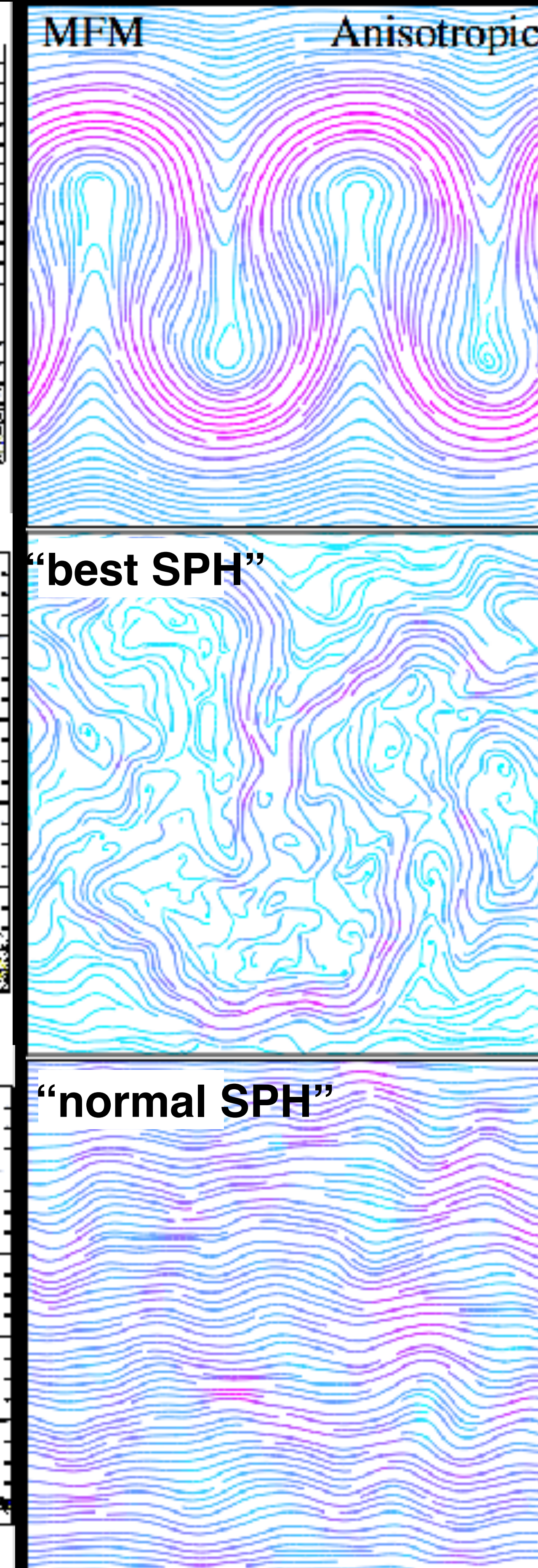


Dehnen & Aly, Rosswog, Hopkins, Tricco & Price, Read

Gresho vortex (Dehnen & Aly)



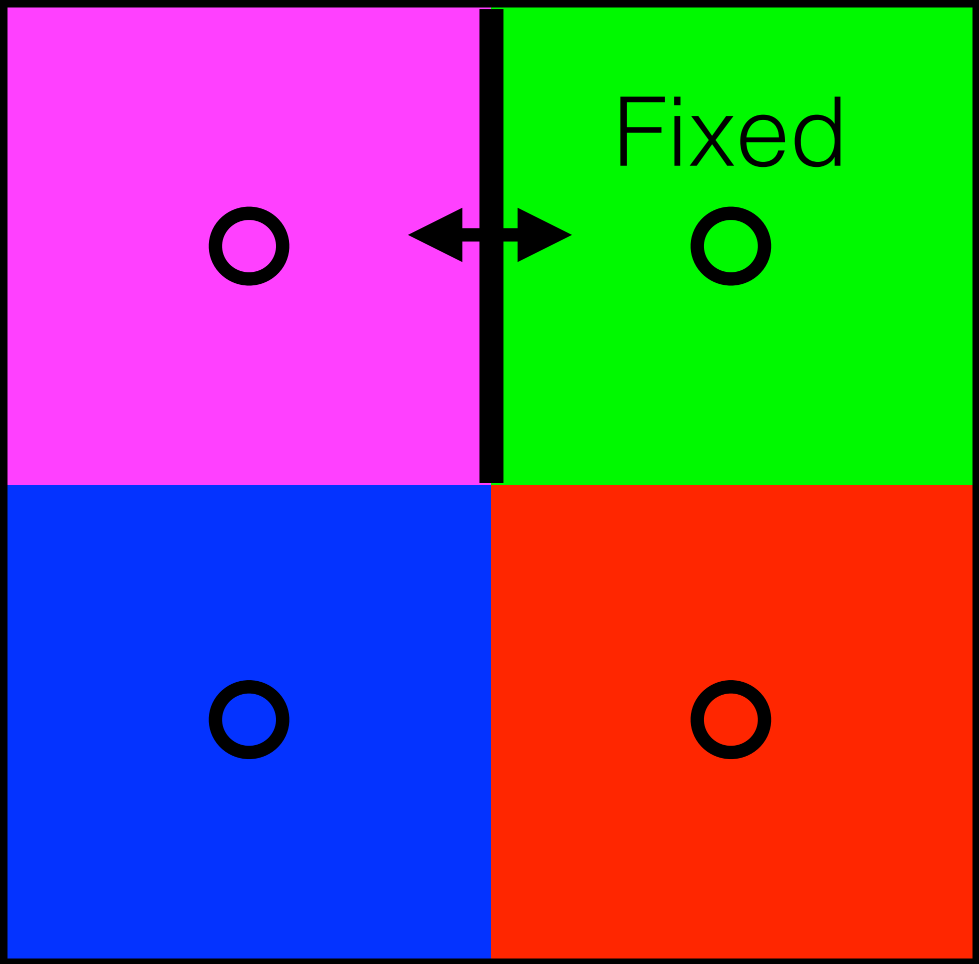
Anisotropic Conduction (MTI, HBI, Hall MRI)



Challenge:

POPULAR METHODS FOR HYDRODYNAMICS HAVE PROBLEMS

Berger & Colella 89 (& others)
Reviews by: Teyssier 14



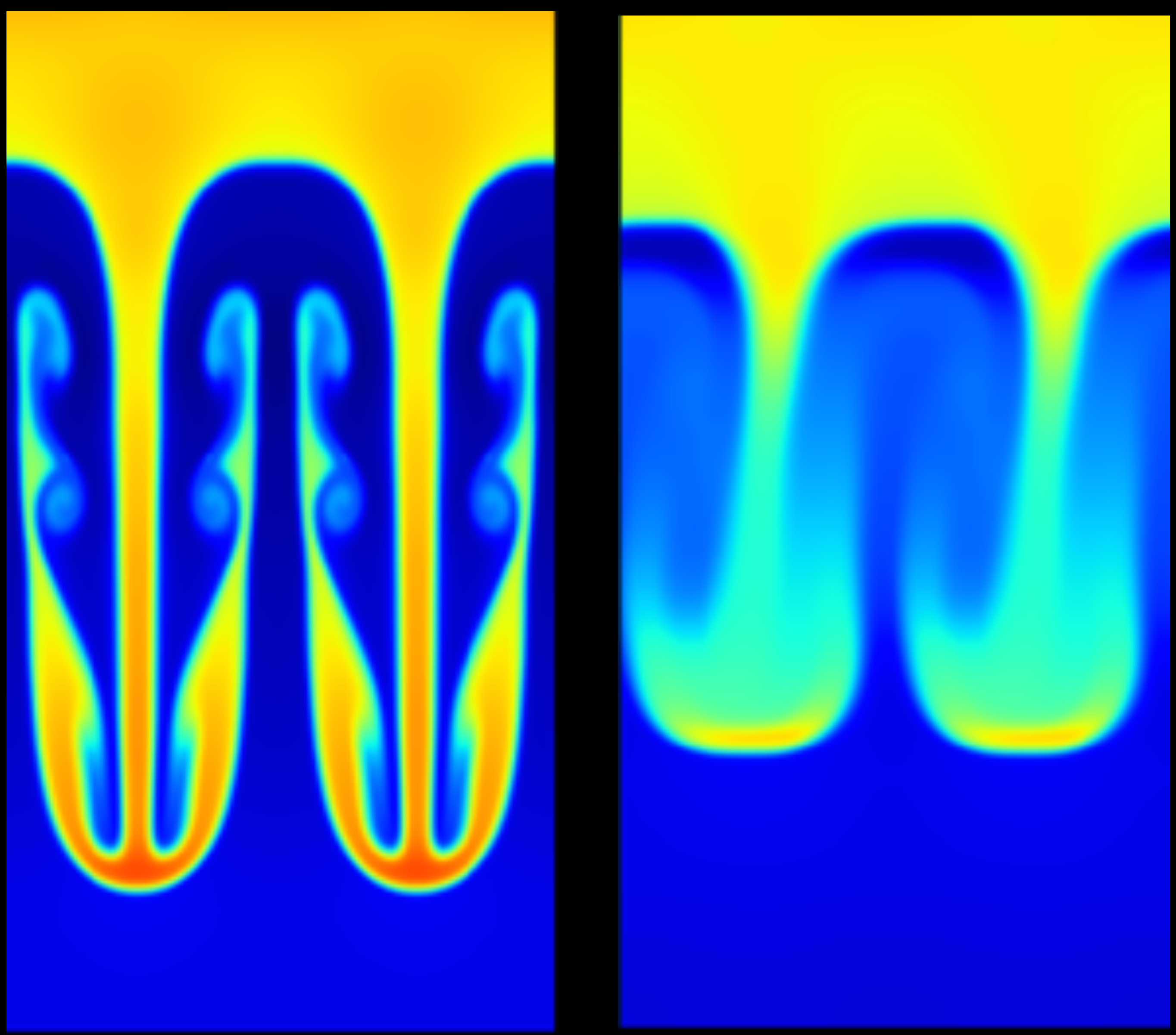
Adaptive Mesh Refinement

- Eulerian, well-studied, high-order
- Each cell carries conserved quantities inside volume V_i
- Solve Reimann problem between geometric faces

Adaptive Mesh Refinement (AMR)

CHALLENGE: POPULAR METHODS HAVE PROBLEMS

Rayleigh-Taylor instability
(AMR, 256^2)



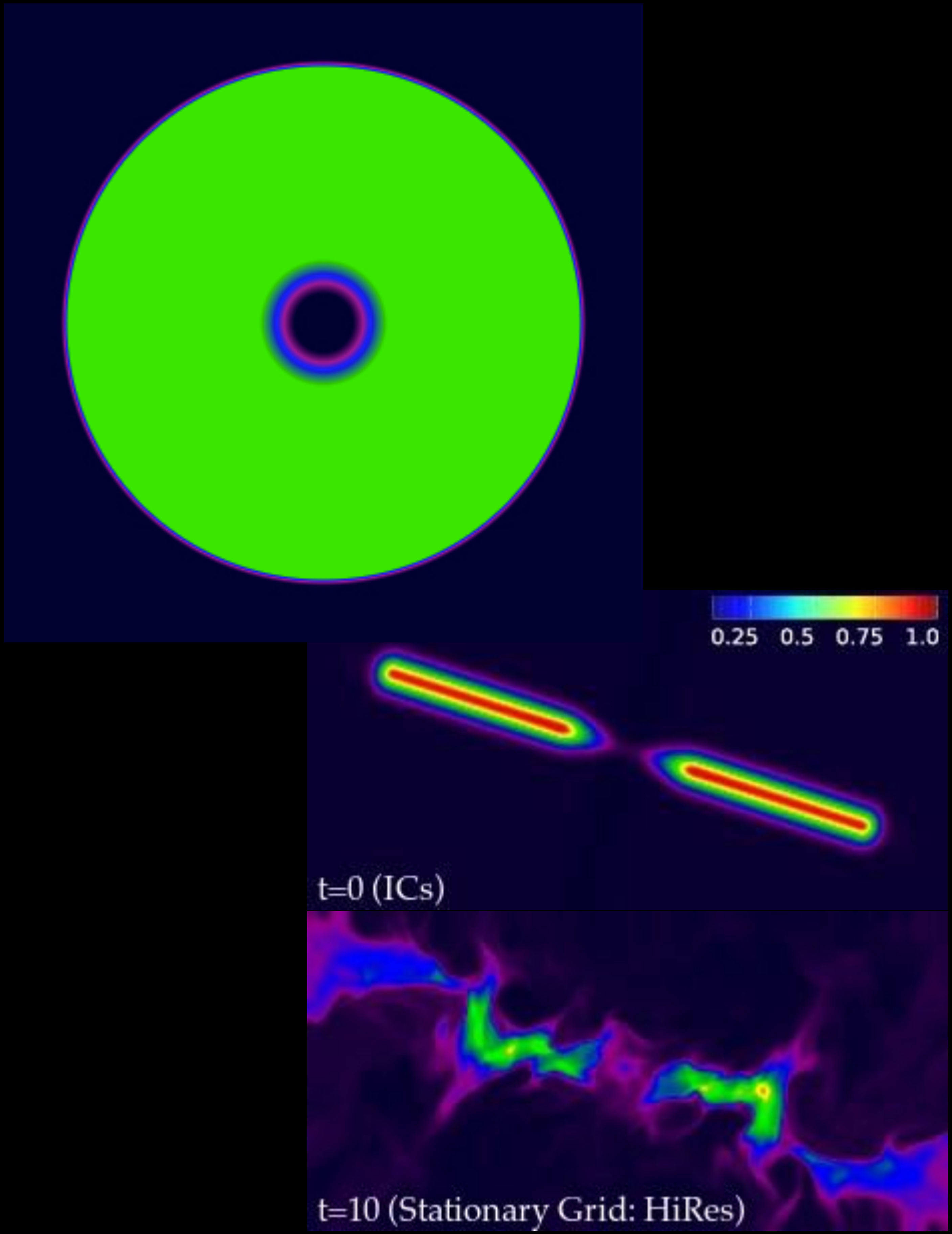
(no bulk motion) Mach 5 boost

- Eulerian, well-studied, high-order
- Excessive mixing/diffusion
  when fluid moves over cells

Bryan 95, Wadsley 08,
Tasker & Bryan 08, Springel 10

Adaptive Mesh Refinement (AMR)

CHALLENGE: POPULAR METHODS HAVE PROBLEMS

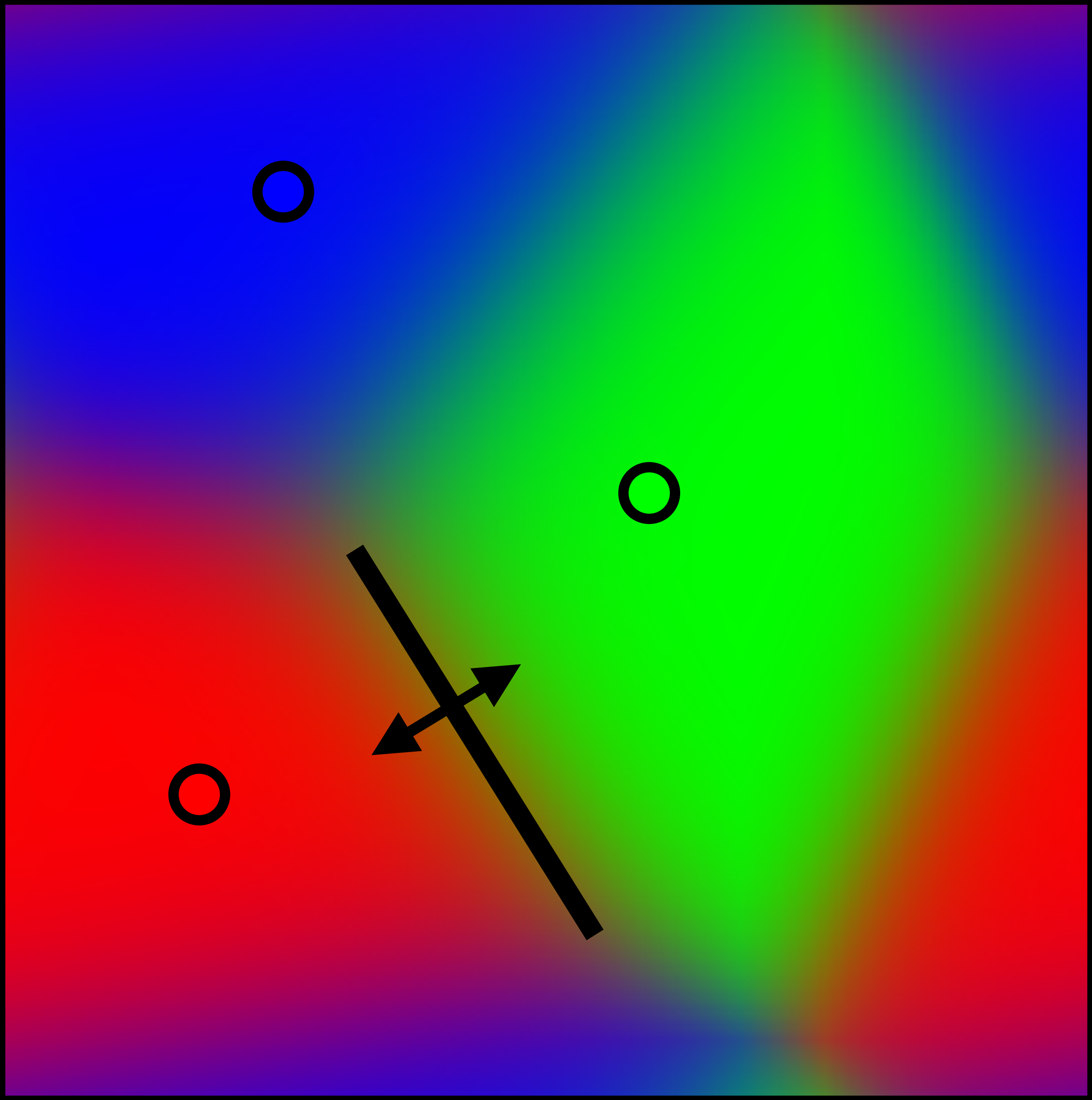


- Eulerian, well-studied, high-order
- Excessive mixing/diffusion
  when fluid moves over cells
- Geometric effects:
  - carbuncle instability (shocks)
  - loss of angular momentum
  - grid-alignment (disks)
- Also "beaten down" with resolution, but *expensive*
  - Hahn '10: >>512^2 resolution to avoid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

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

Challenge:

POPULAR METHODS FOR
HYDRODYNAMICS HAVE PROBLEMS



New Methods Combine (some) Advantages of Both

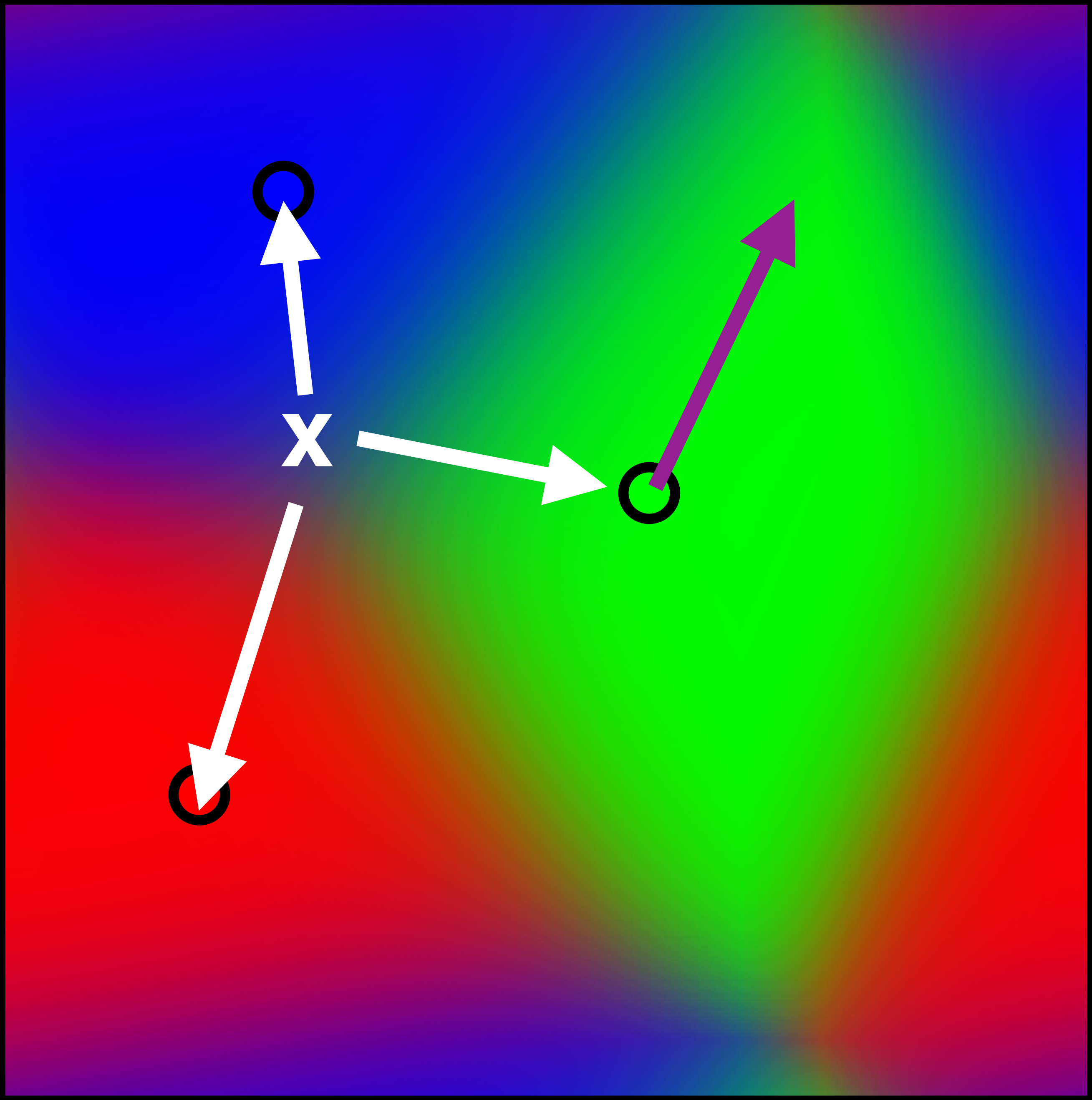
- Moving-meshes (AREPO), meshless finite-volume (GIZMO), high-order ALE methods
- Move with flow, no preferred geometry, but also accurate, high-order, and shock-capturing
- Less well-tested **!**

AREPO: Springel 2010
TESS/DISCO: Duffel 2011
FVMHD3D: Gaburov 2012
GIZMO: Hopkins 2015 (arXiv:1409.7395)

Challenge:

POPULAR METHODS FOR HYDRODYNAMICS HAVE PROBLEMS

Lanson & Vila 2008
Gaburov & Nitadori 2011
PFH 2014, 2015, 2016



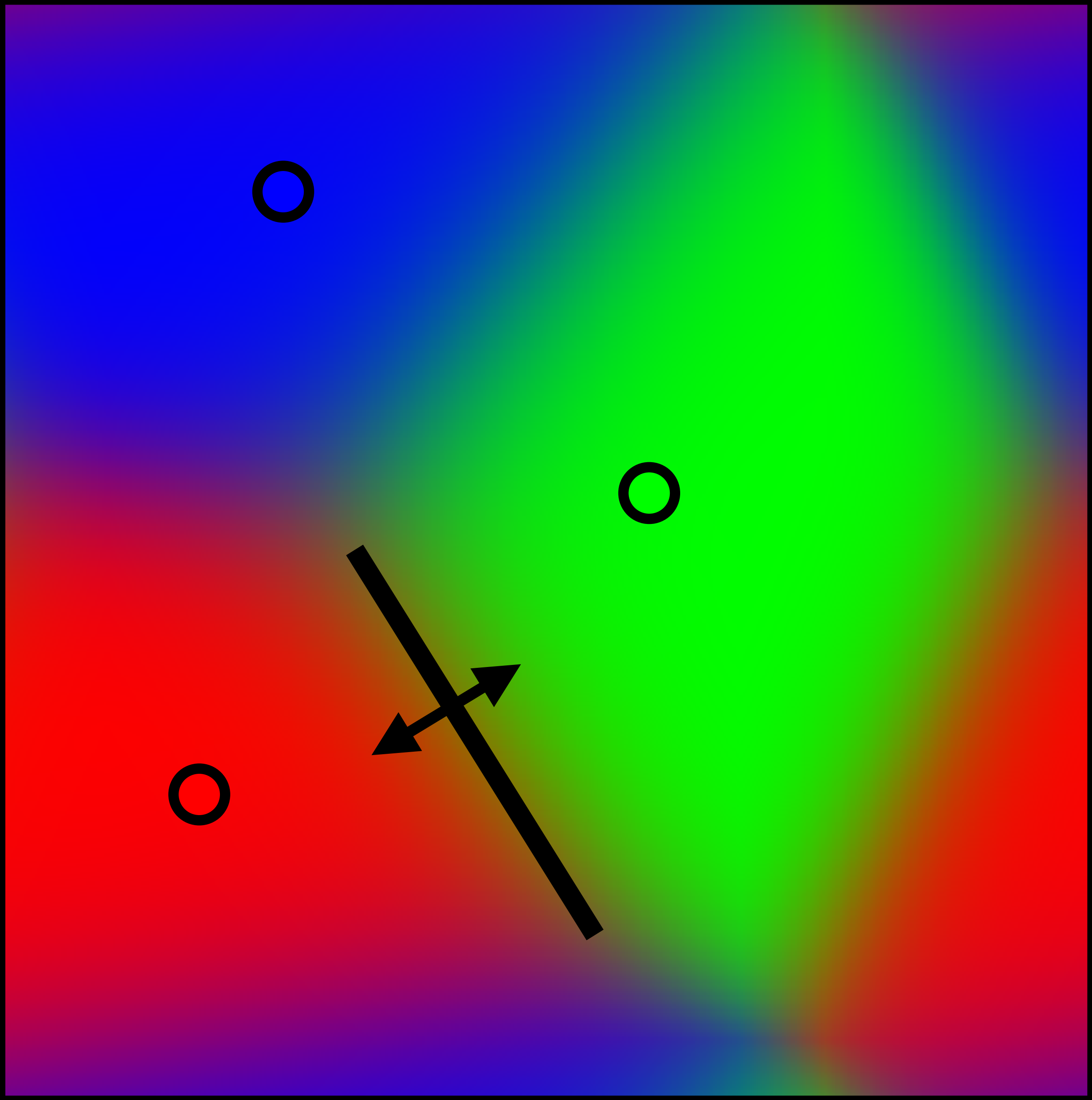
- Mesh-generating points move (if desired)
- Volume is "partitioned" with a continuous kernel (MFM/MFV) or step function (moving-mesh)

$$d\mathrm{Vol}_{i,j,k} = d^3\mathbf{x}\,\frac{W(\mathbf{x}-\mathbf{x}_{i,j,k})}{\sum W_{i,j,k}}$$

Challenge:

POPULAR METHODS FOR HYDRODYNAMICS HAVE PROBLEMS

Lanson & Vila 2008
Gaburov & Nitadori 2011
PFH 2014, 2015, 2016



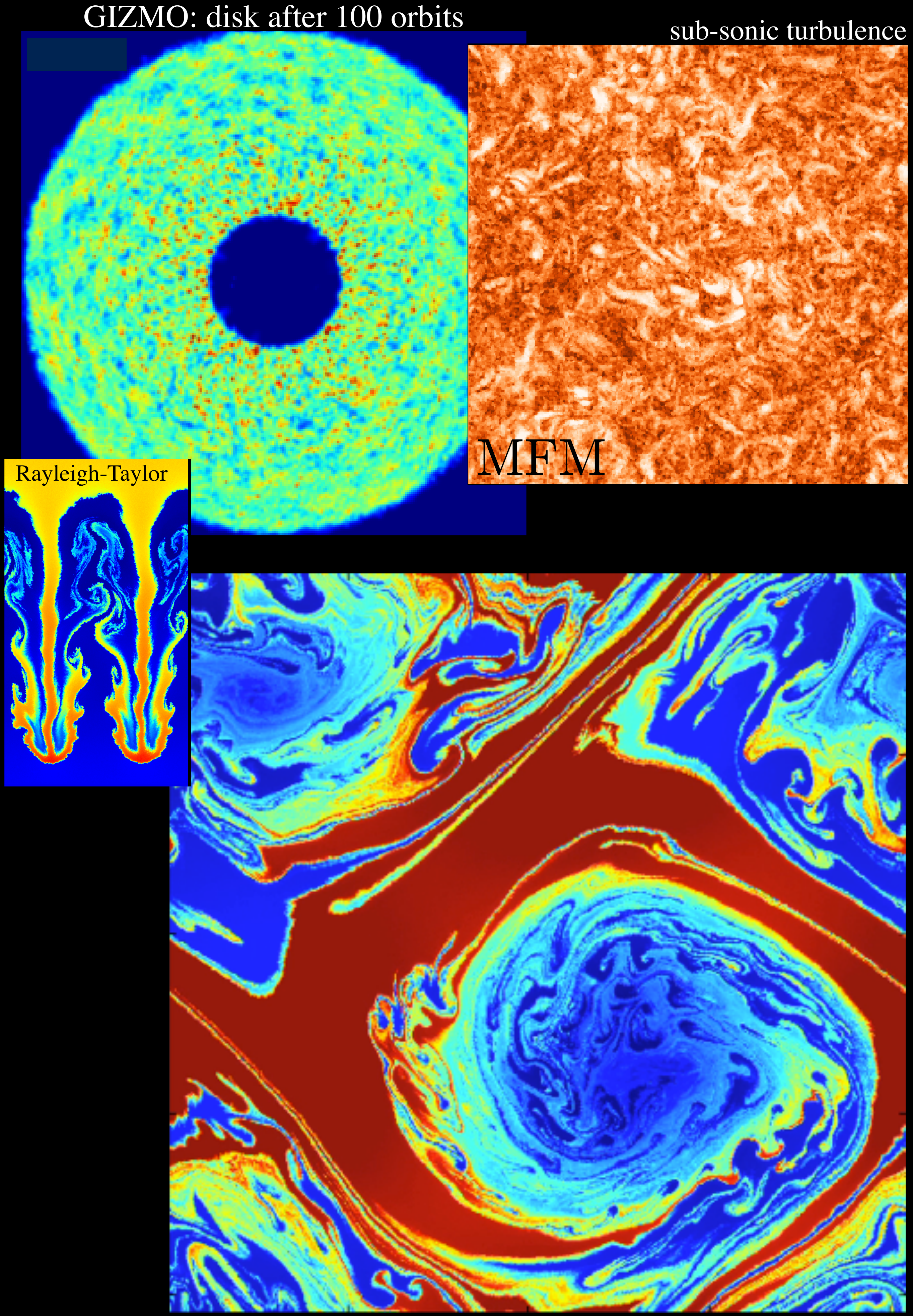
- Integrate EOM over volume: equivalent to Reimann problem at “effective face” (quadrature)

$$\Delta m_i = \int_{\rm vol} \frac{\partial \rho}{\partial t} d^3\mathbf{x} = -\int_{\rm vol} \nabla \cdot (\rho\,\mathbf{v})\, d^3\mathbf{x}$$

New Methods Combine (some) Advantages of Both:

(BUT REMAIN LESS WELL-TESTED)

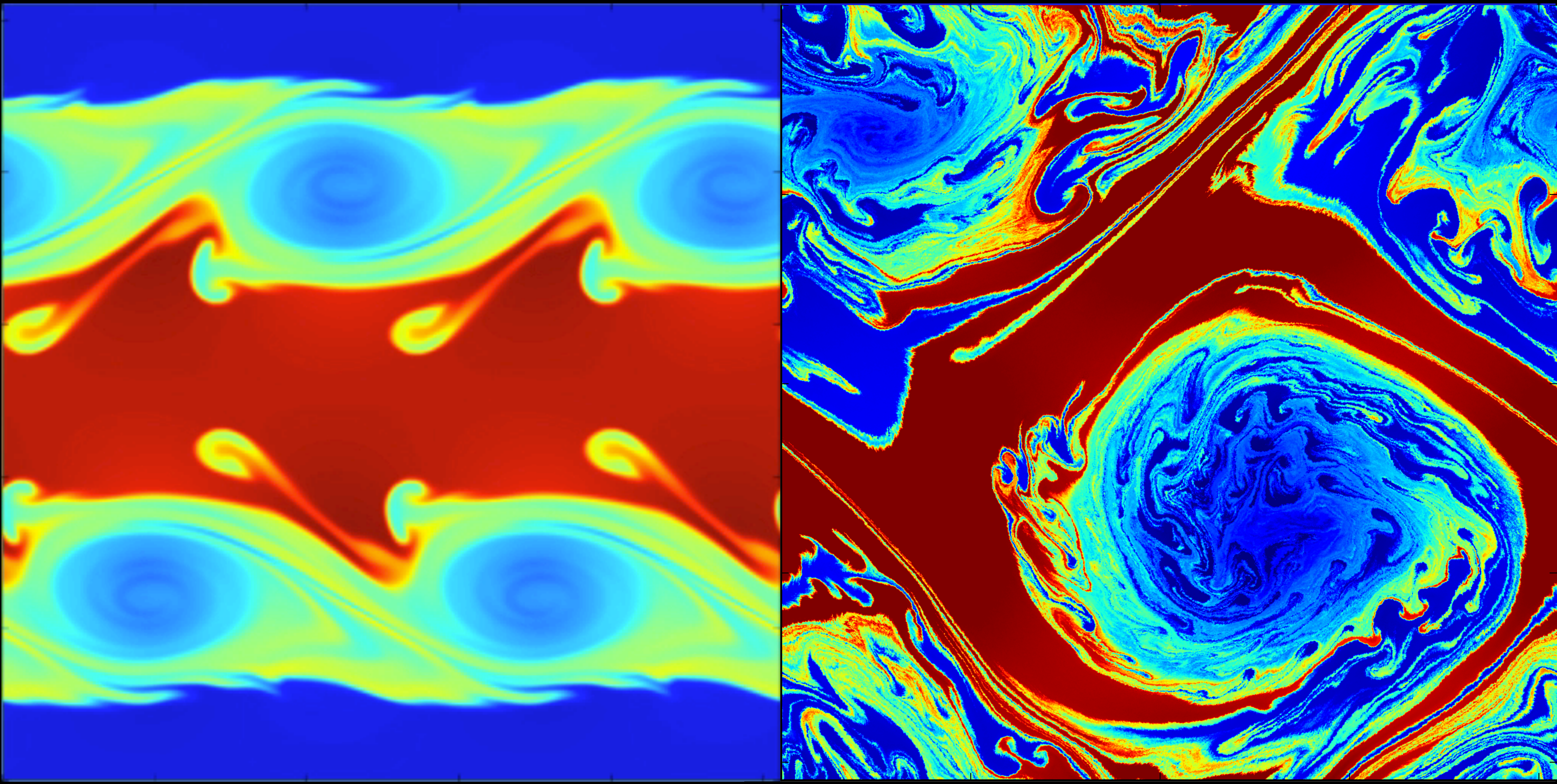
- Moving-meshes (AREPO), meshless finite-volume (GIZMO), high-order ALE methods
- Move with flow, no preferred geometry, but also accurate, high-order, and shock-capturing
- Grid noise is more severe



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

GIZMO: New Meshless Methods & Fluid Mixing

(www.tapir.caltech.edu/~phopkins)



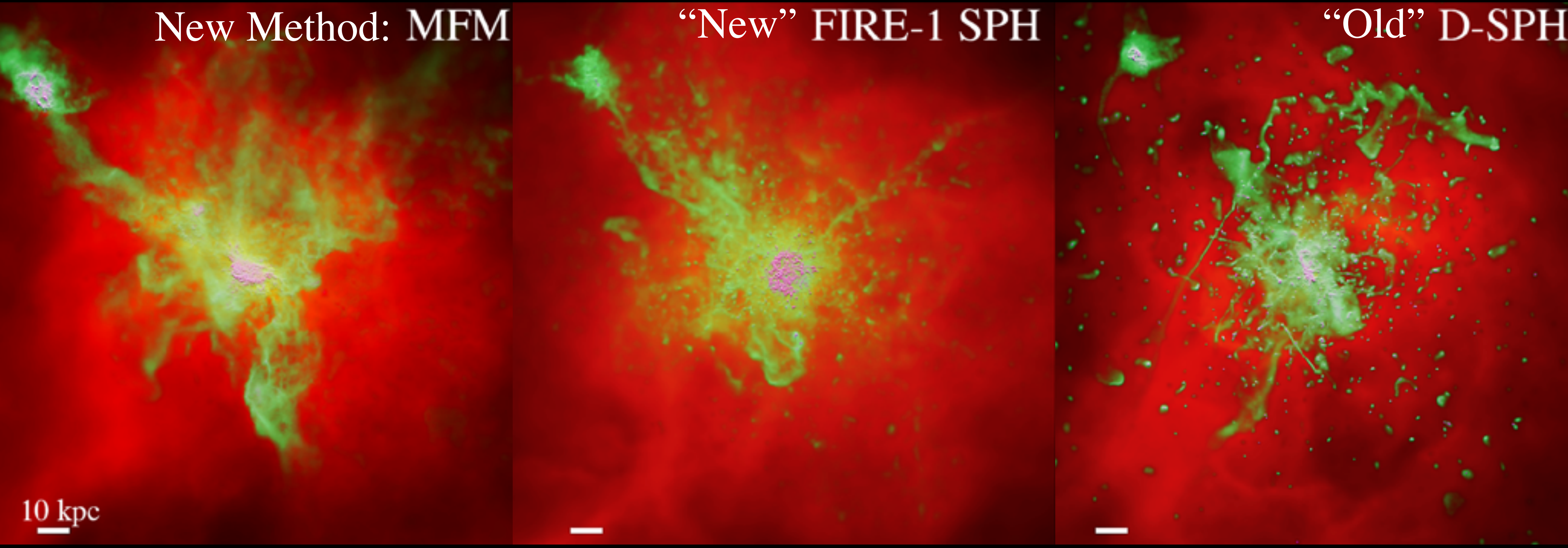
Cartesian Grid

Meshless Finite Volume

Hopkins 2015 (arXiv:1409.7395)

Getting the Hydro Right Can Matter

BUT IT DEPENDS ON WHAT YOU CARE ABOUT



Agertz 07 & many others

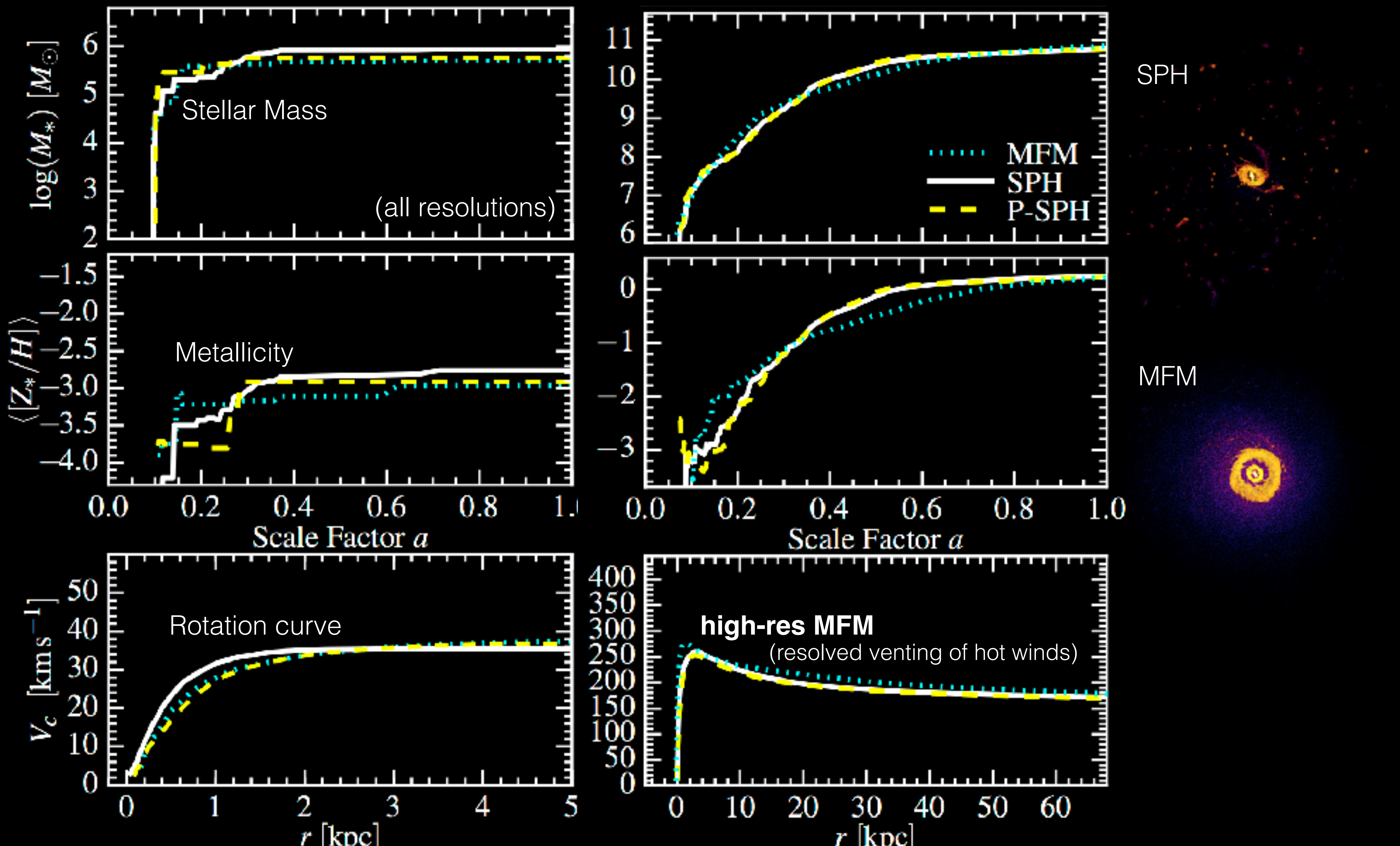
BUT only factor ~1.5 difference in mass!

Getting the Hydro Right Can Matter

DEPENDS ON WHAT YOU CARE ABOUT

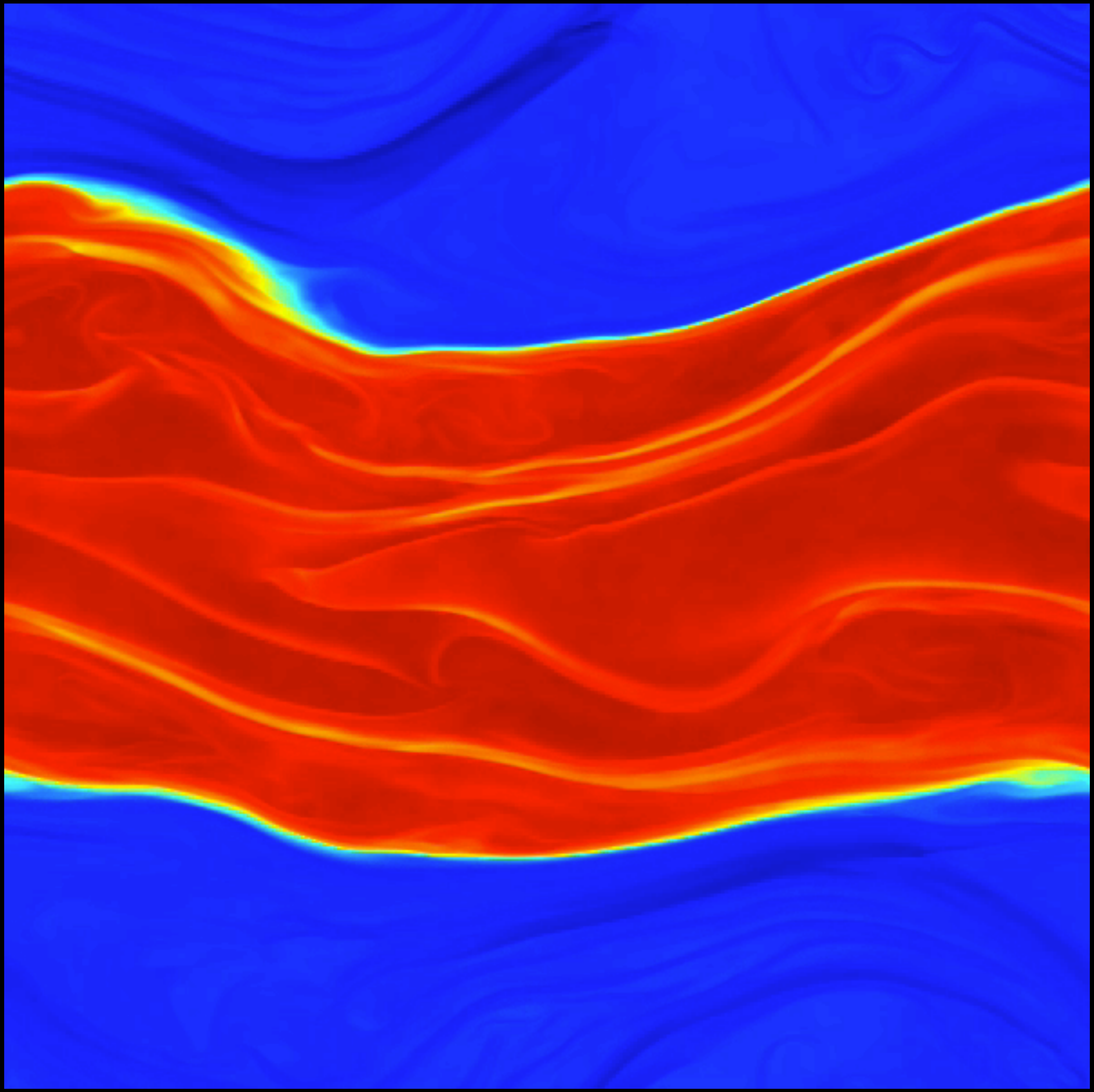
Dwarfs ("cold mode"): no effects

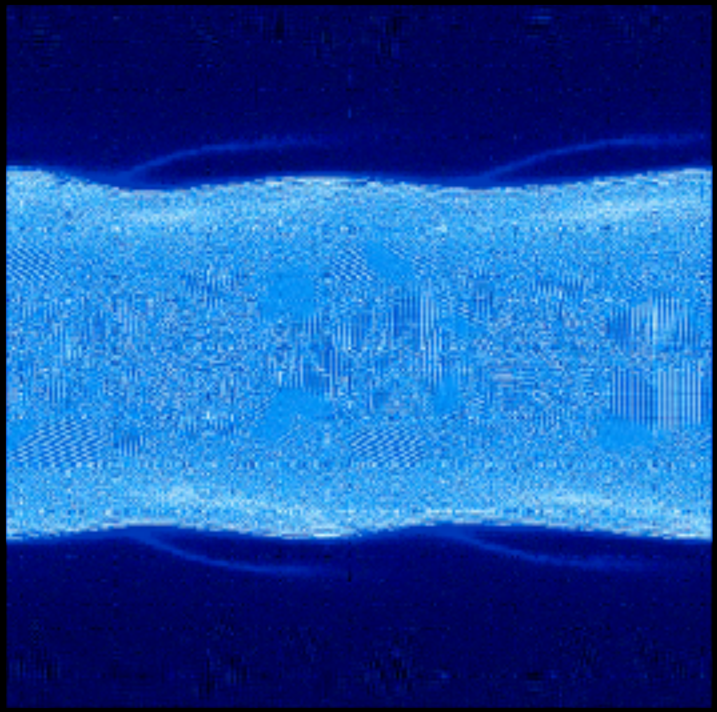
Massive Galaxies ("hot mode"): cooling & wind "venting"



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

DON’T MISTAKE NUMERICAL PRECISION FOR PHYSICAL ACCURACY



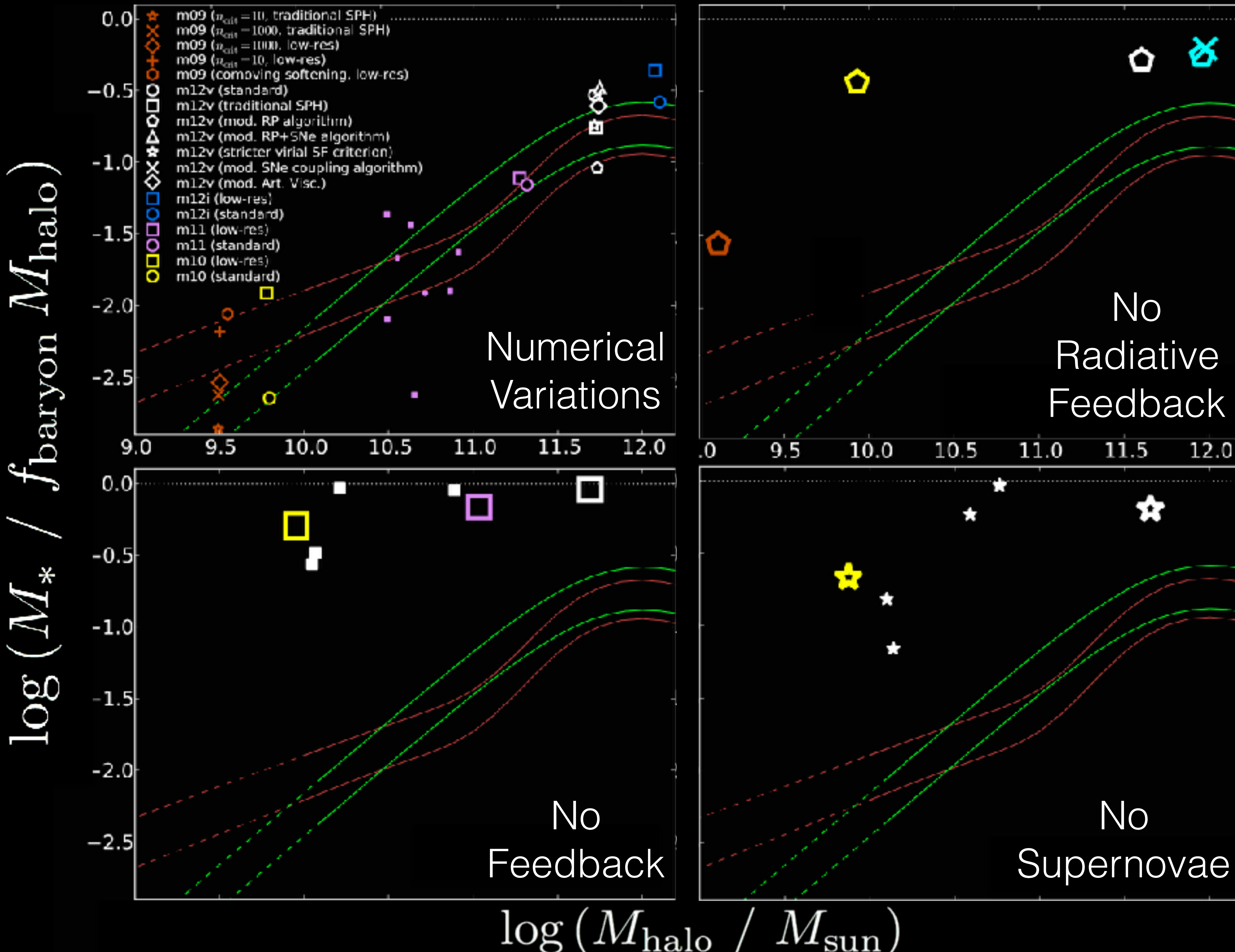


“old” SPH
(Springel 02)

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

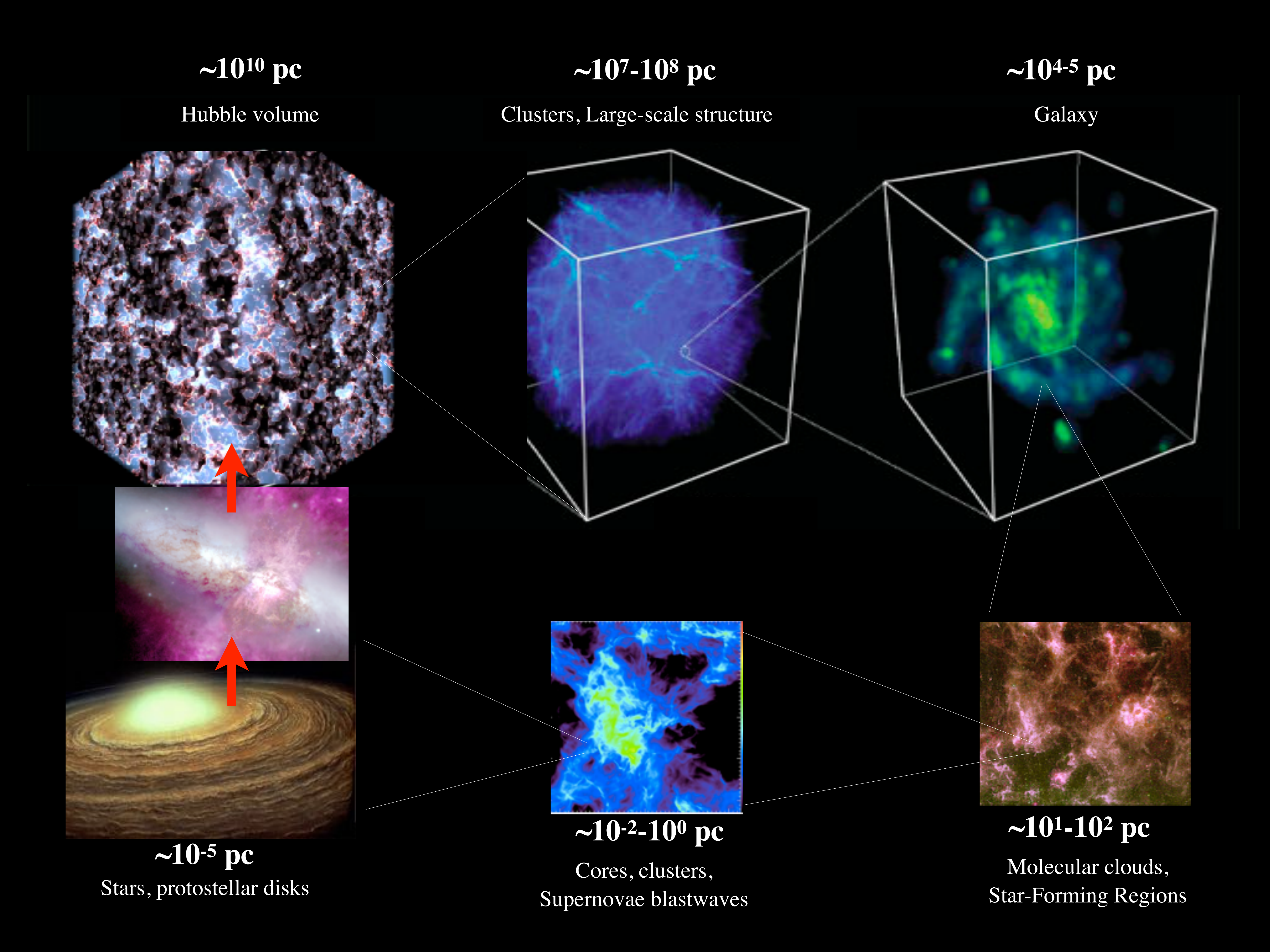
Getting the Hydro Right Can Matter

DEPENDS ON WHAT YOU CARE ABOUT



Resolution

(how to get more of it)


~10^10 pc
Hubble volume
~10^7-10^8 pc
Clusters, Large-scale structure
~10^4-5 pc
Galaxy
~10^-5 pc
Stars, protostellar disks
~10^-2-10^0 pc
Cores, clusters,
Supernovae blastwaves
~10^1-10^2 pc
Molecular clouds,
Star-Forming Regions

Previous “State of the Art”

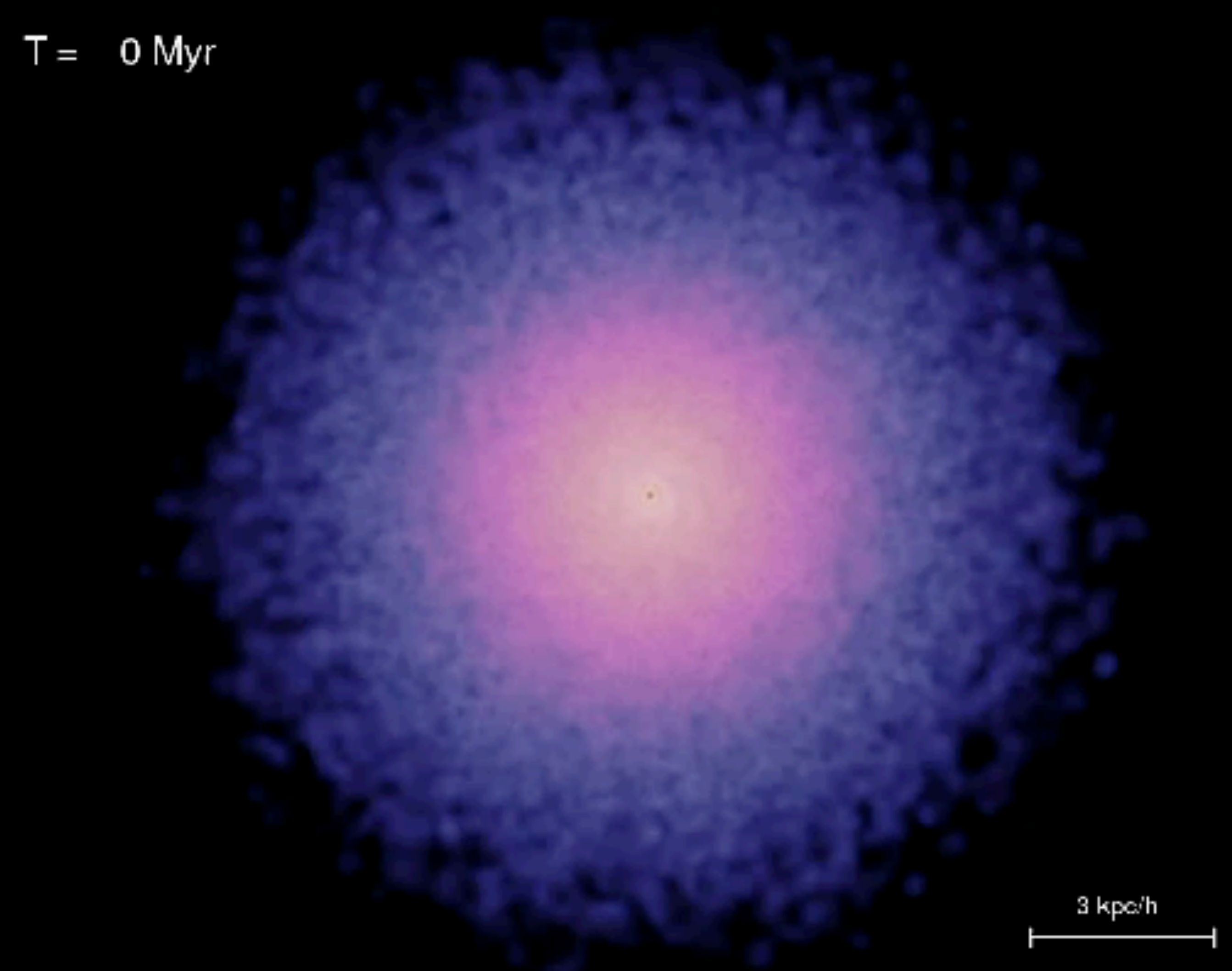
Resolution:
~kpc
$\sim 10^6\ M_{sun}$

Interstellar Medium:
single, ideal fluid

Winds?
“sub-grid” (cheat a bit)

- turn off cooling
- throw out mass “by hand”

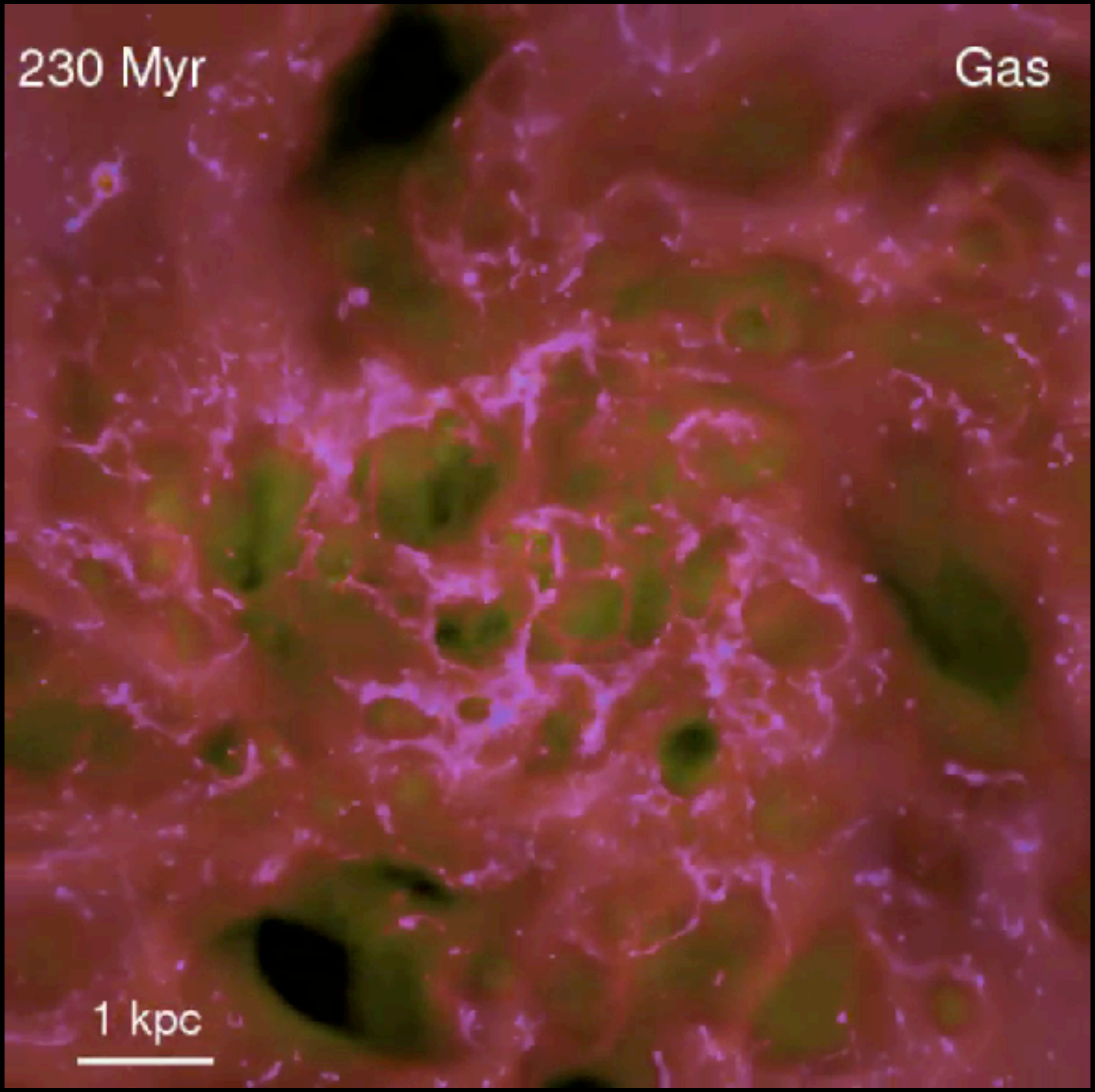
$$M_{\rm wind} = ({\rm fudge}) \times M_{\rm stars}$$



e.g. “Illustris”, “OWLS,” “EAGLE,”
…anything I wrote before 2012…

The FIRE Project

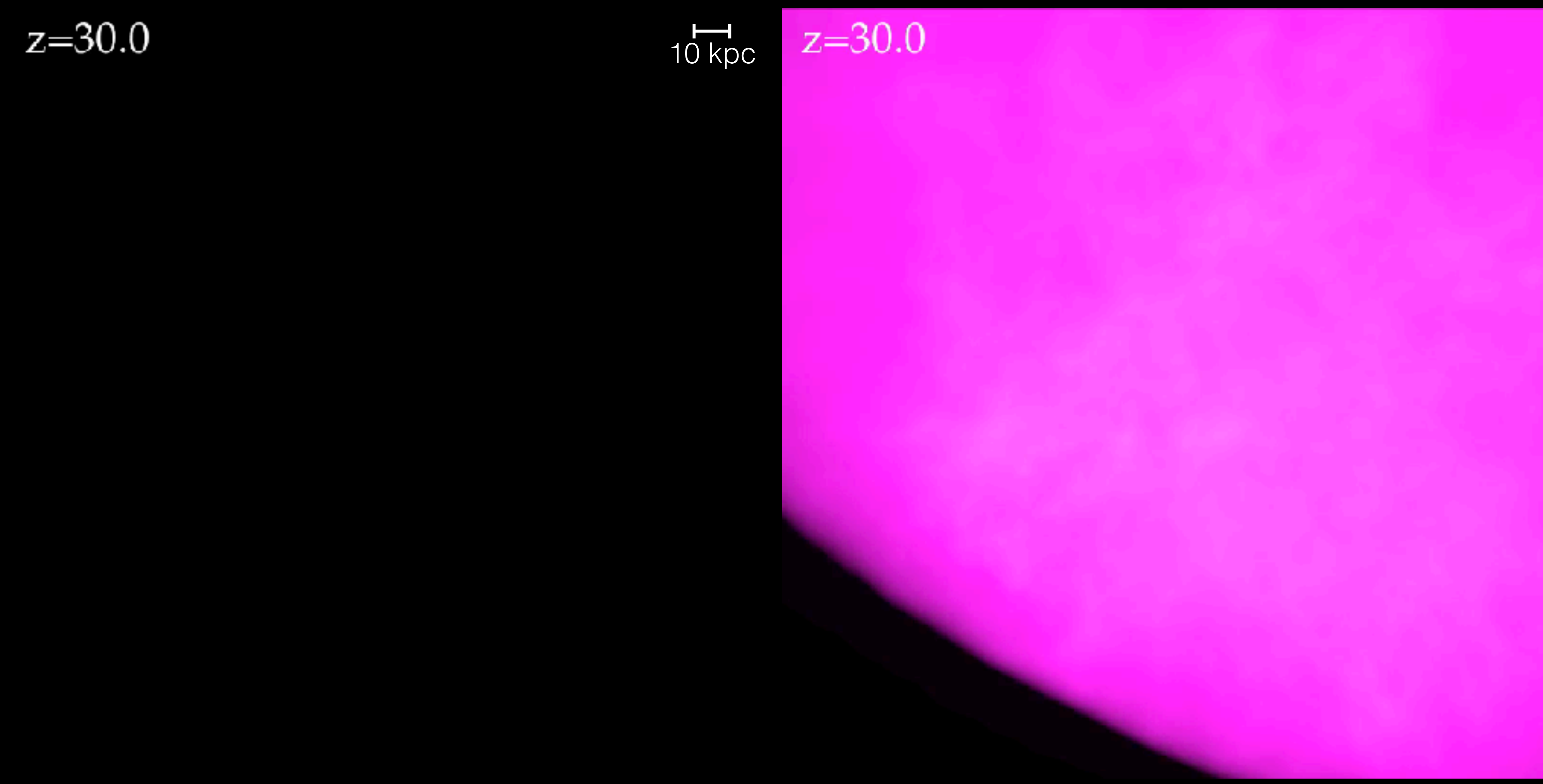
Feedback In Realistic Environments



Yellow: hot (>10^6 K) Pink: warm (ionized, ~10^4K) Blue: cold (neutral <10-8000 K)

- Resolution ~pc
  Cooling & Chemistry ~10 - 10^{10} K
- **Feedback:**
  - SNe (II & Ia)
  - Stellar Winds (O/B & AGB)
  - Photoionization (HII regions) & Photo-electric (dust)
  - Radiation Pressure (IR & UV)
  - now with…
    - Magnetic fields
    - Anisotropic conduction & viscosity
    - Cosmic rays

(movies at fire.northwestern.edu)



Stars (Hubble image):

Blue: Young star clusters

Red: Dust extinction

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

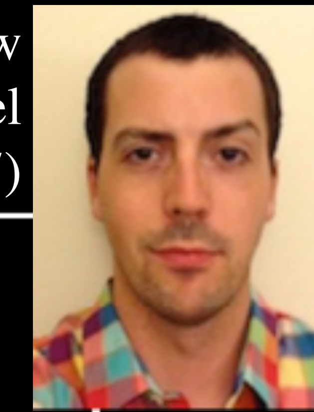
Green: warm (ionized)

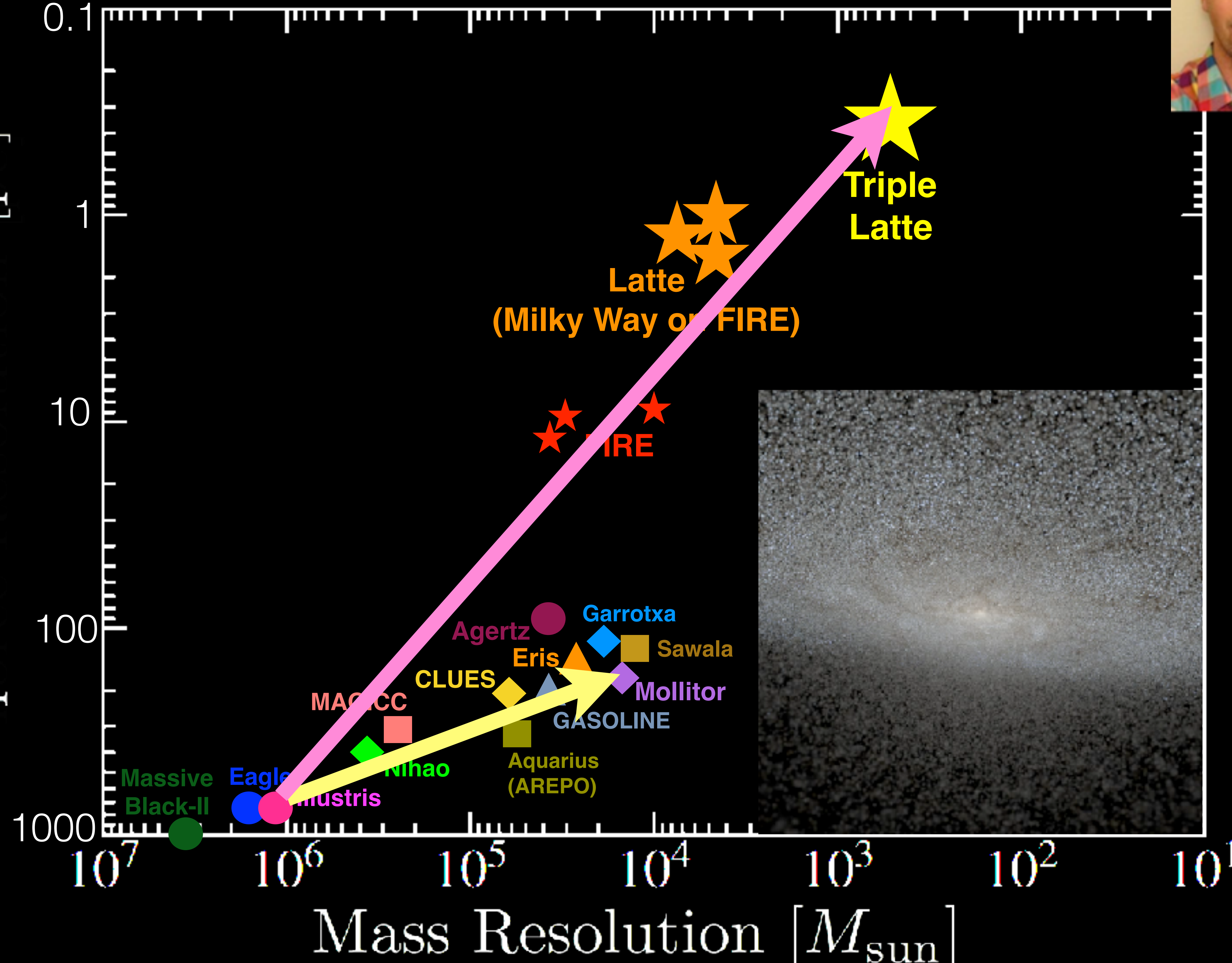
Red: hot $(> 10^6\ K)$

The Future is Now

ALGORITHMIC BREAKTHROUGHS ENABLE NEW PHYSICS

Andrew
Wetzel
(arXiv:1602.05957)

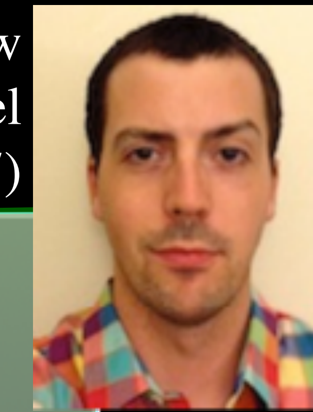


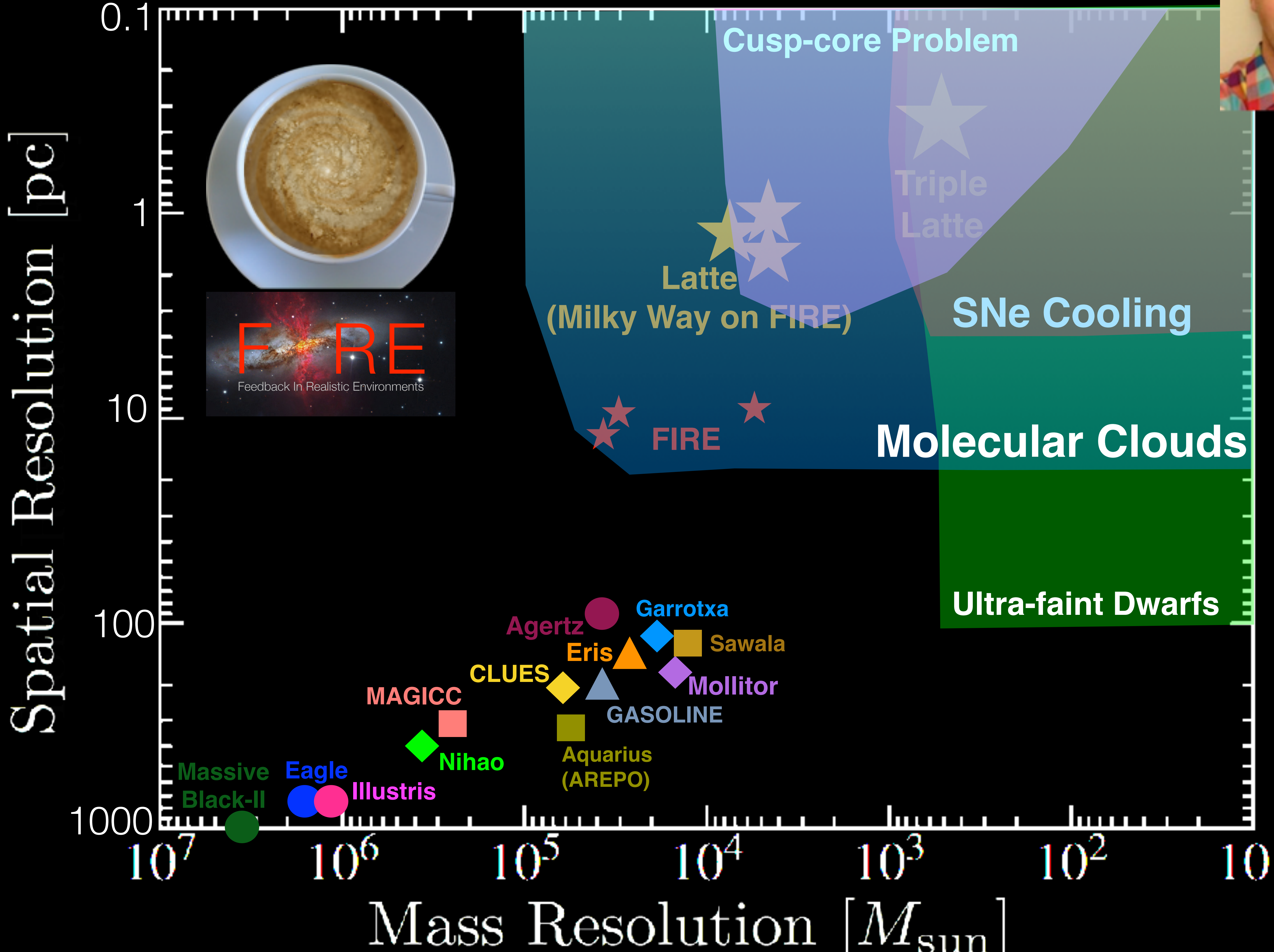


The Future is Now

NEW PHYSICS AT NEW SCALES

Andrew
Wetzel
(arXiv:1602.05957)



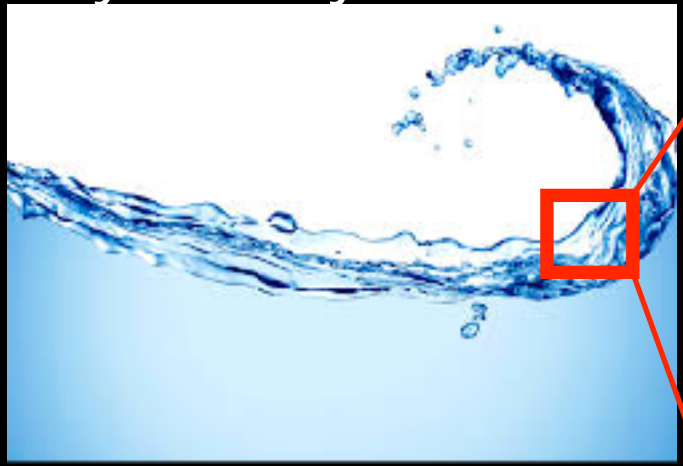


Physics

(a question of philosophy)

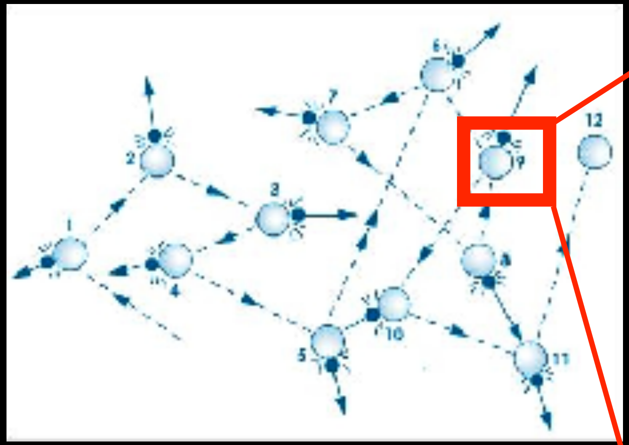
Everything is sub-grid

Hydrodynamics



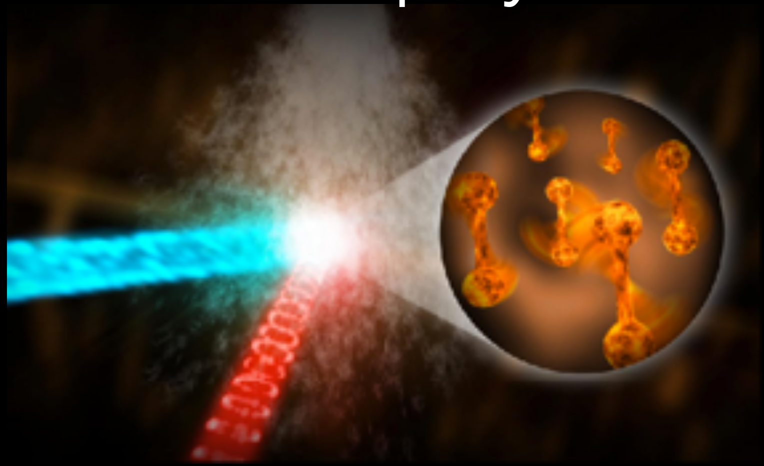
$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{v}$$

Statistical mechanics



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

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

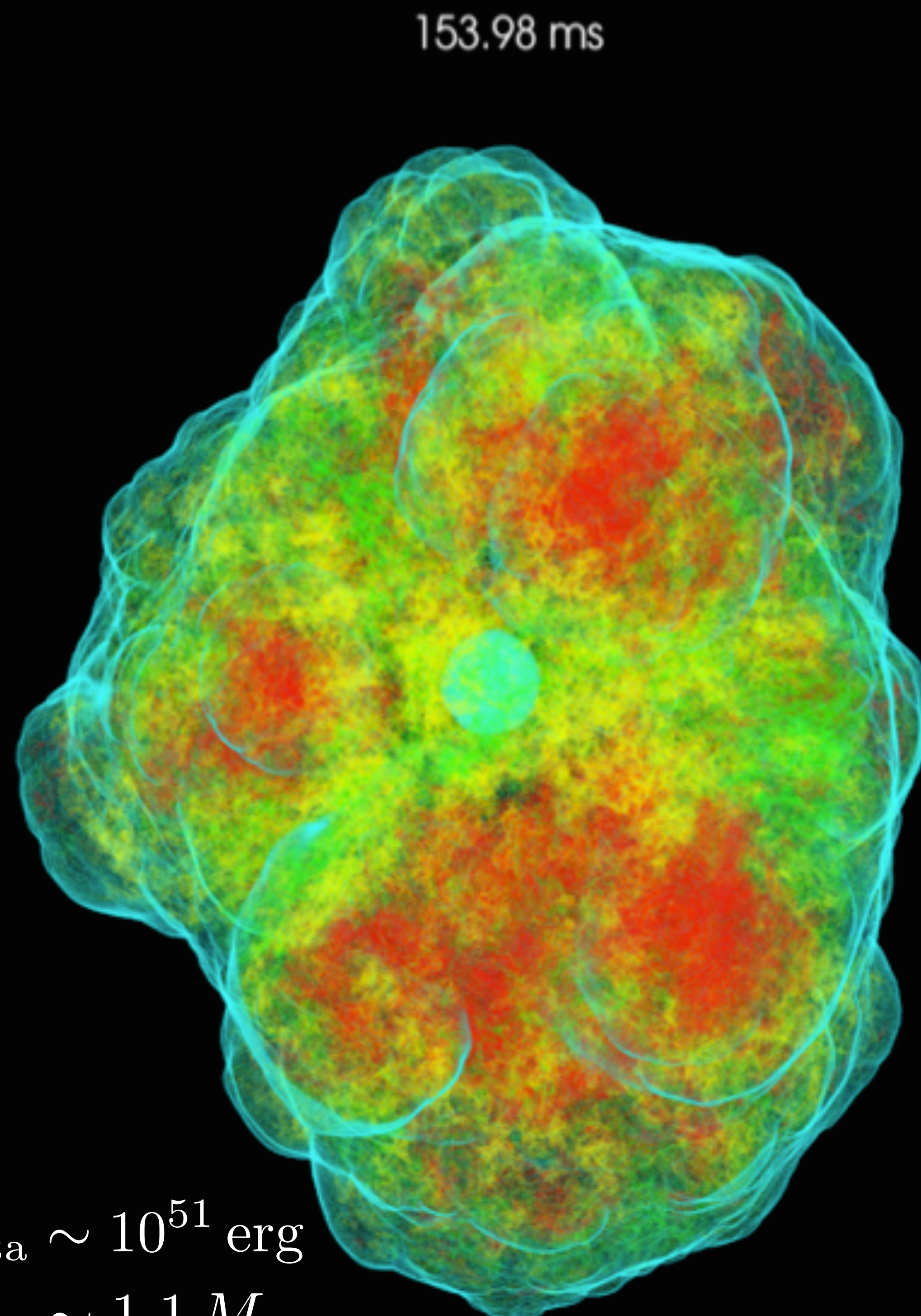
(building up a sub-grid model)

Example: SNe

Resolution:

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

Predict: Explosion



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

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

$$\ldots$$

Moesta et al. '14

Sub-grid physics:

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

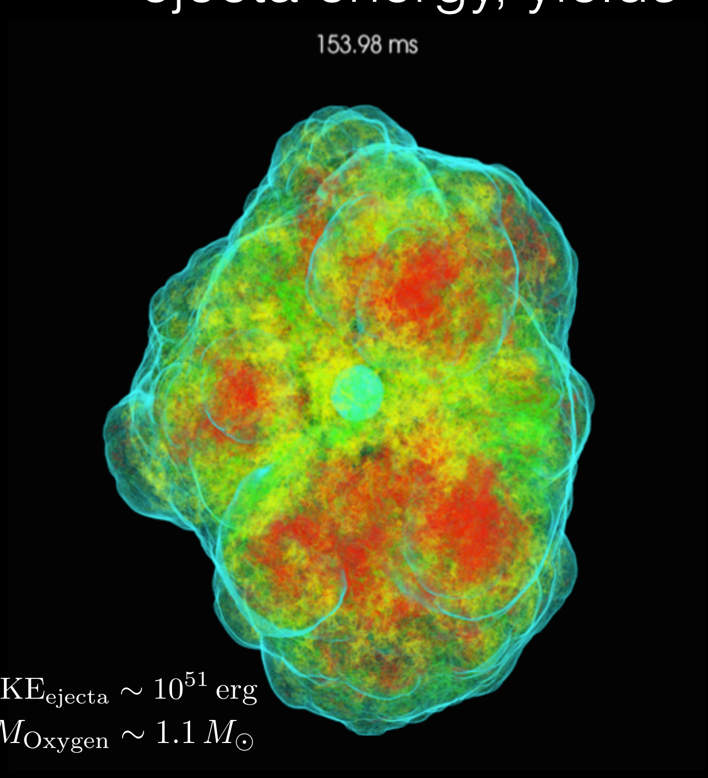
Example: SNe

Resolution:

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

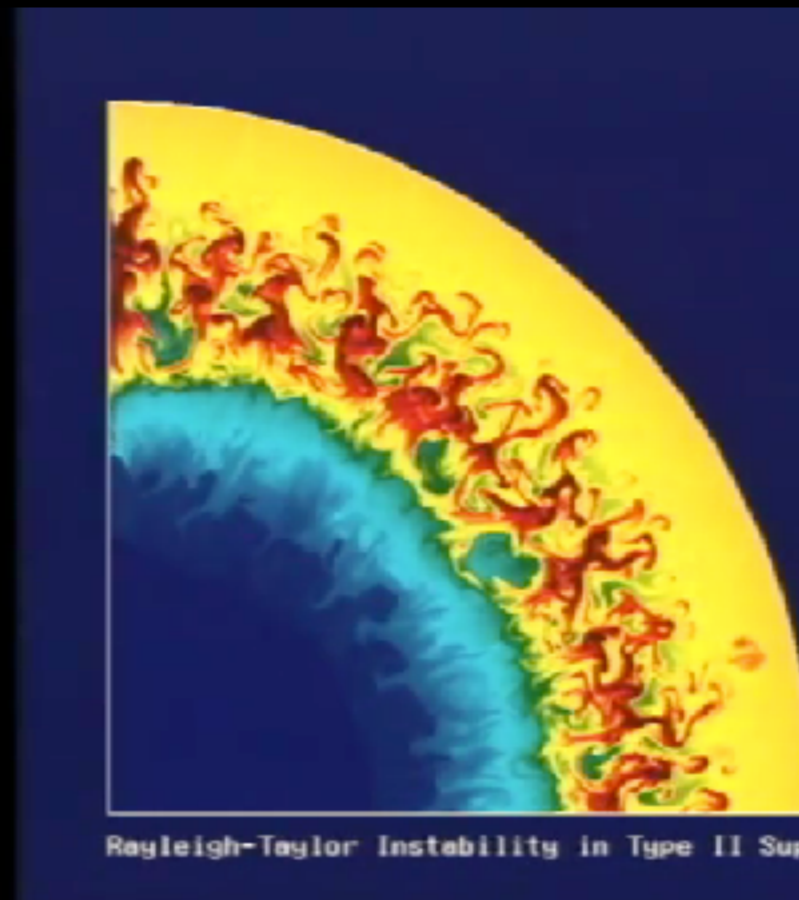
Sub-grid physics:

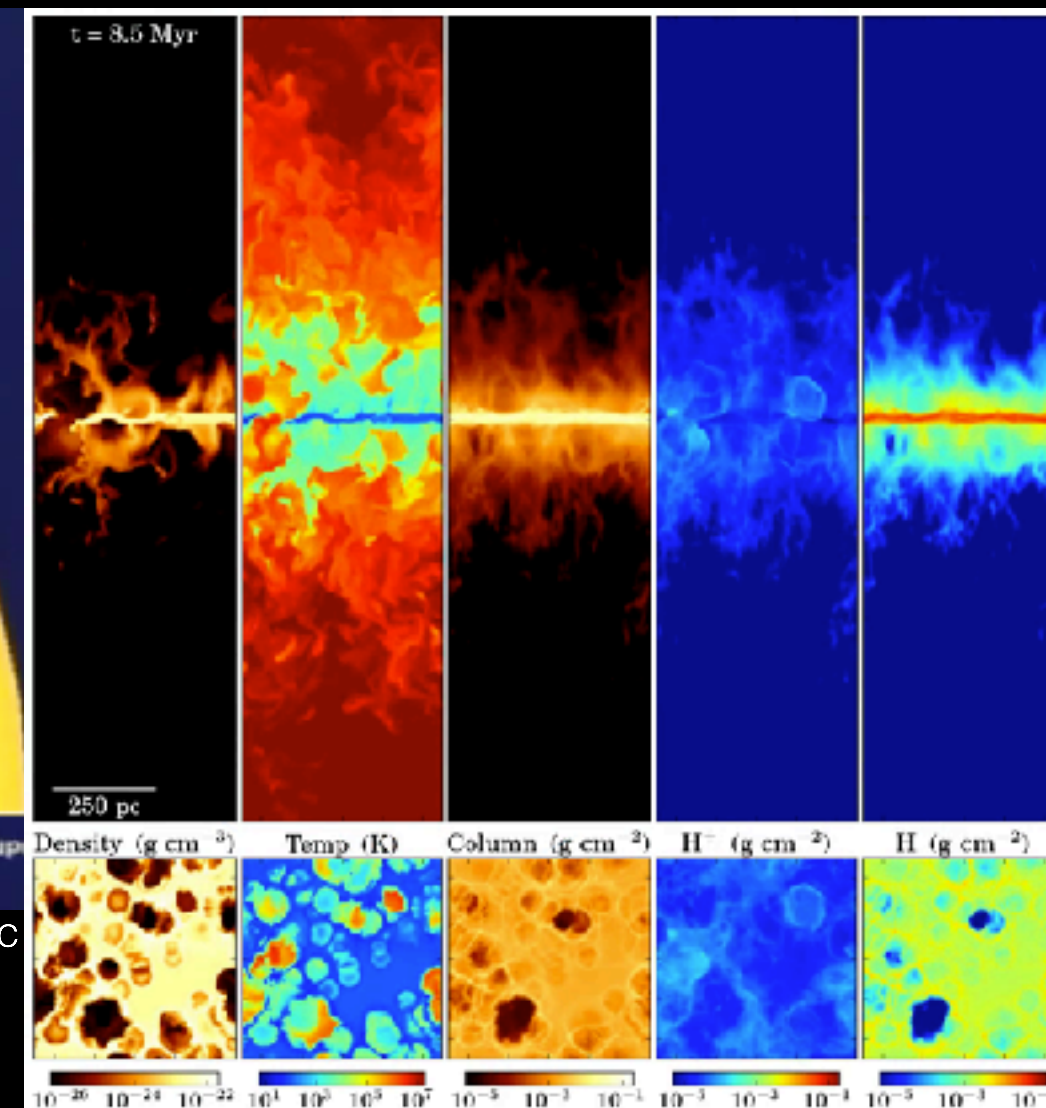
- SNe explosion
- ejecta energy, yields



$\mathrm{KE}_{\mathrm{ejecta}} \sim 10^{51}\,\mathrm{erg}$
$M_{\mathrm{Oxygen}} \sim 1.1\, M_\odot$
...

Predict: Blastwave Evolution/ISM Interaction





Walch, Martizzi, Barnes, Cioffi, etc

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

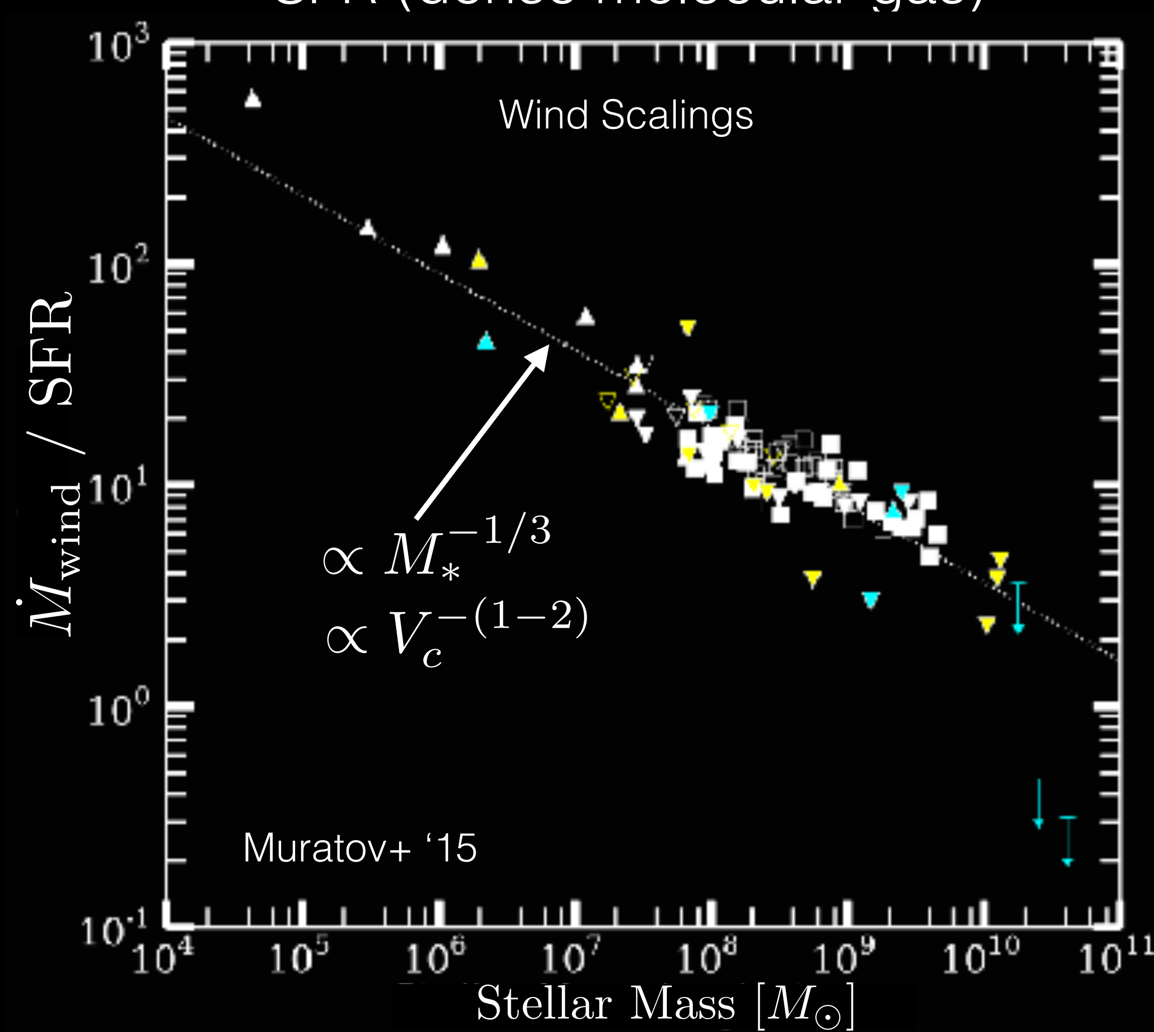
Predict: Overlap: super-bubbles & winds

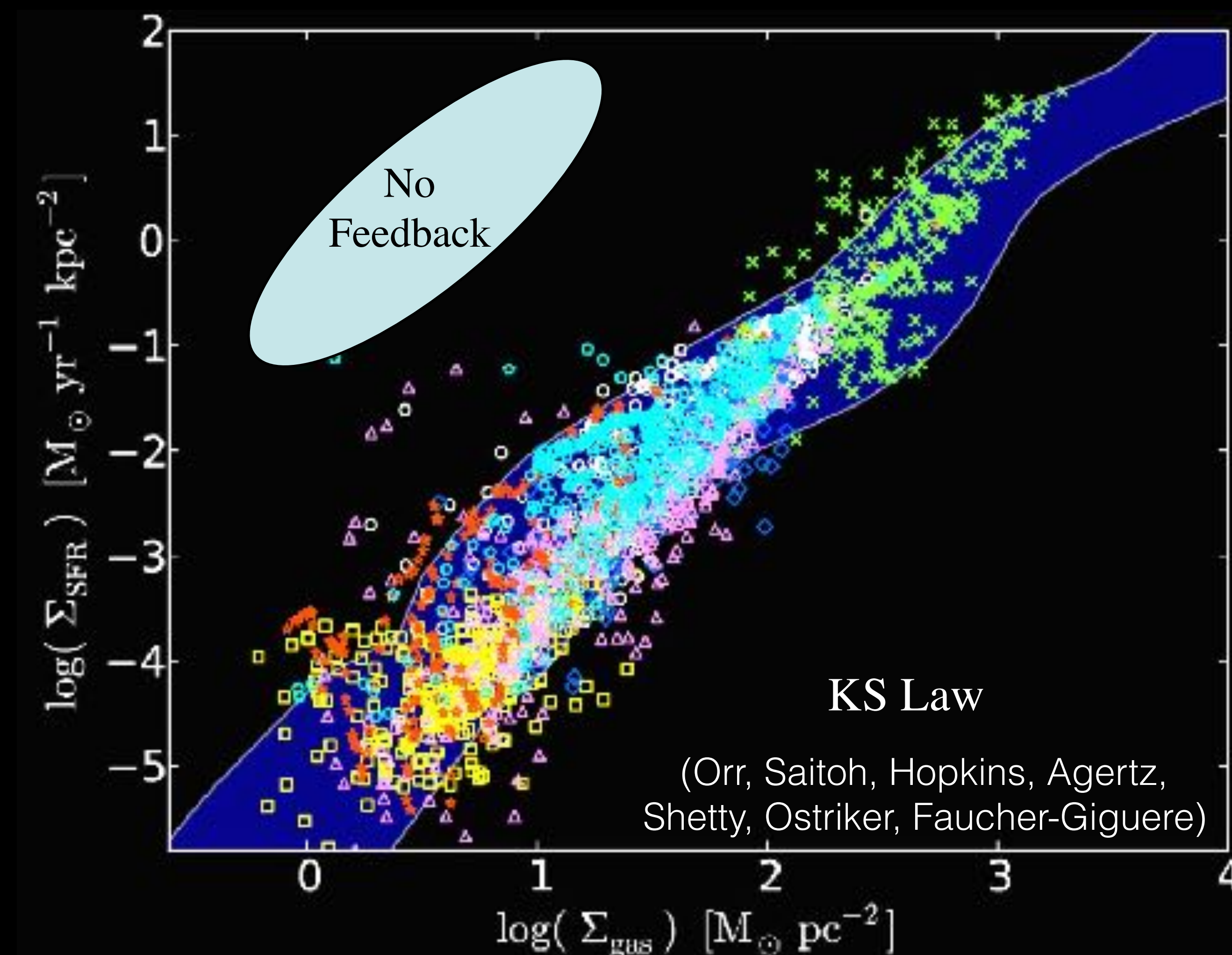
Resolution:

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

Sub-grid physics:

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

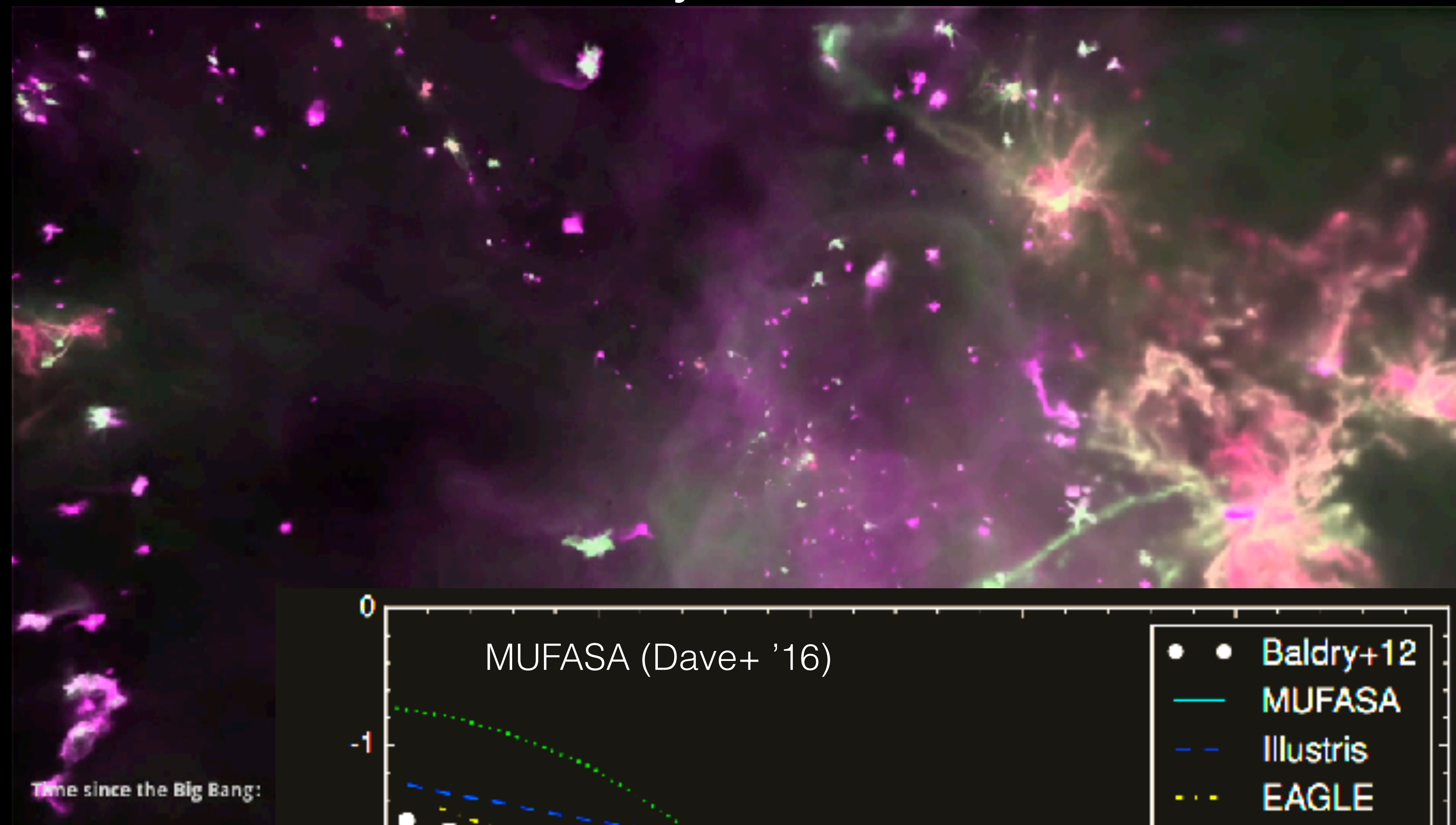




FIRE

Example: SNe

Predict: Galaxy SFHs, IGM enrichment

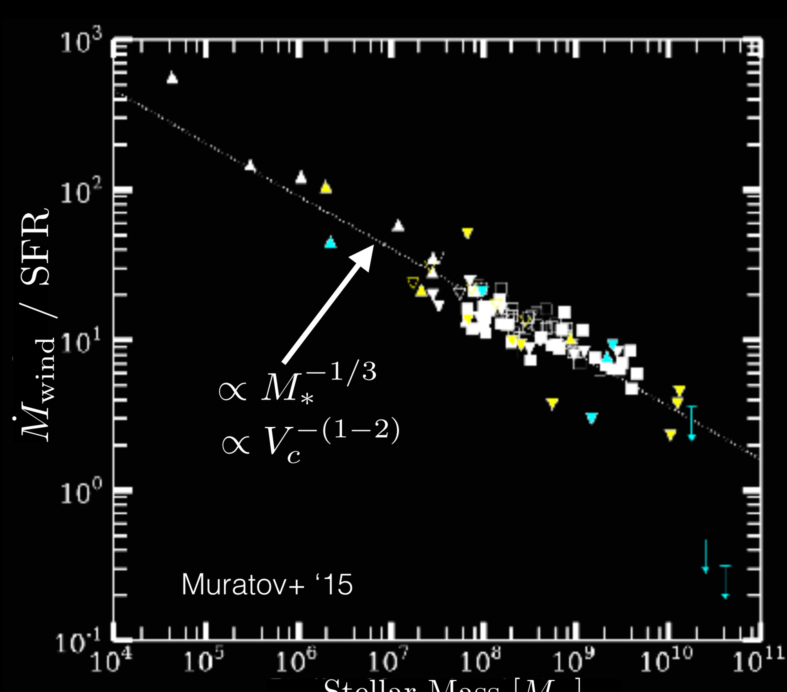


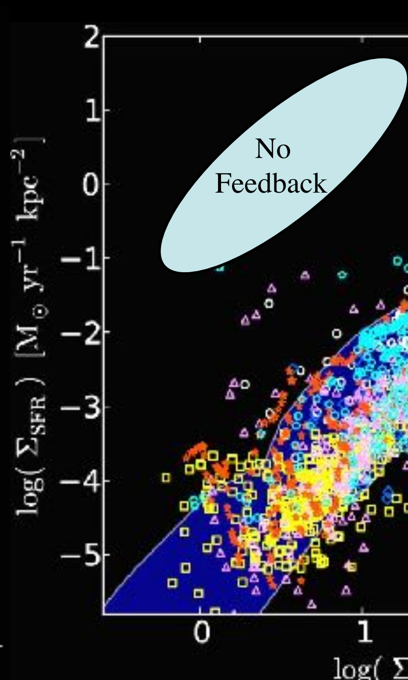
Resolution:

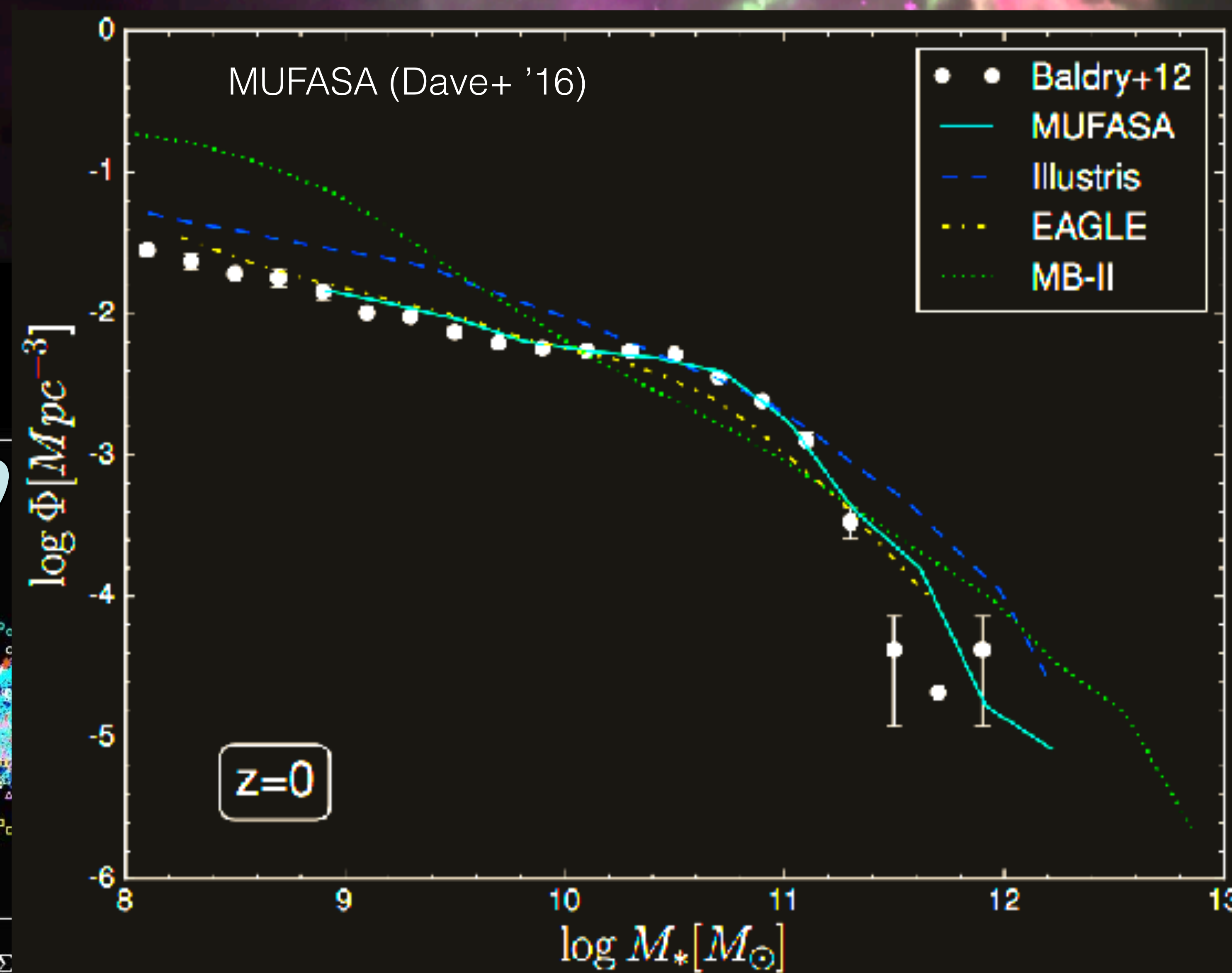
$$m_i \gtrsim 10^6 \, M_\odot$$

Sub-grid physics:

- ~~SFR (kpc/low-density gas)~~
- wind scalings (galaxy-scale)



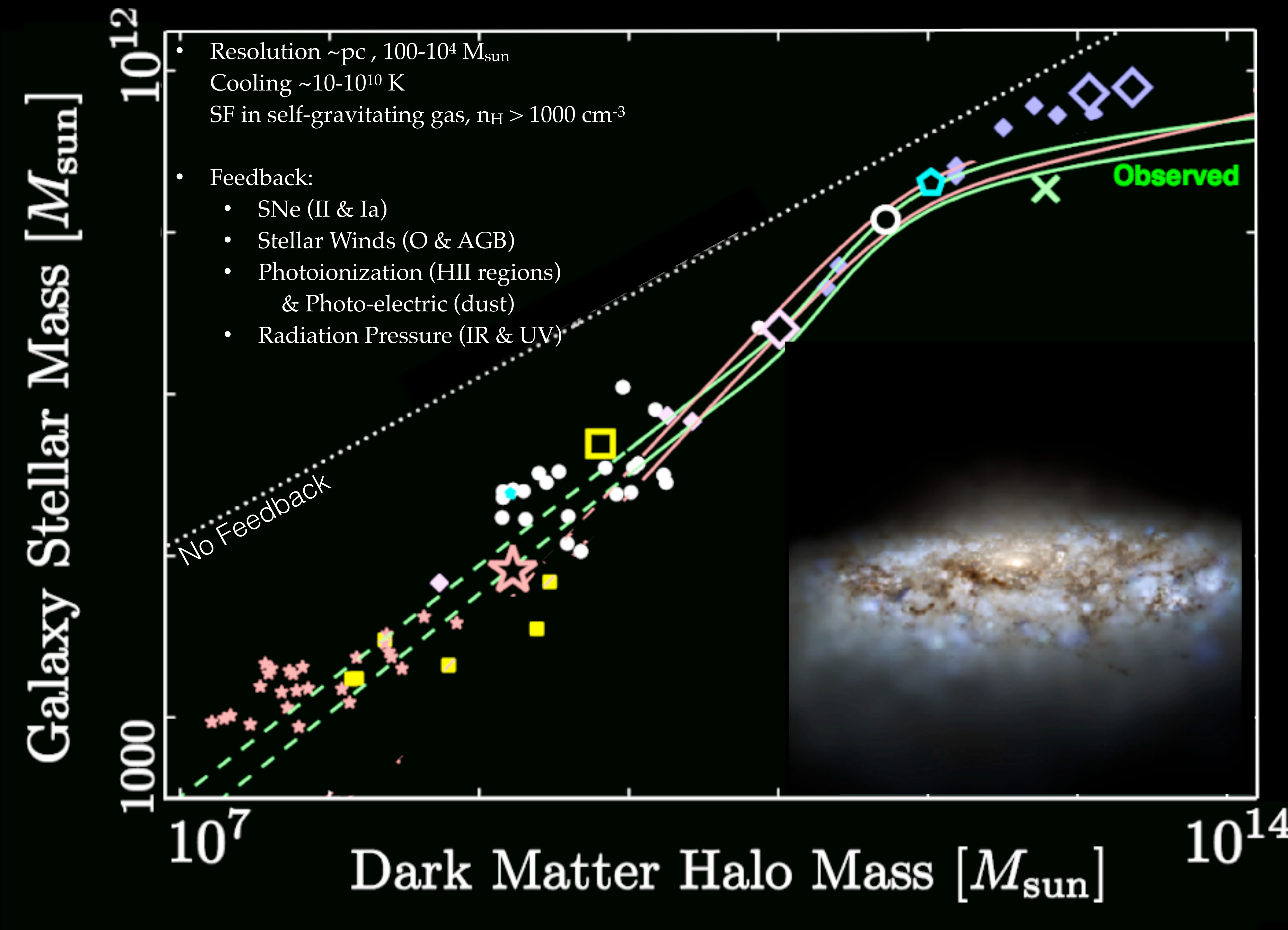




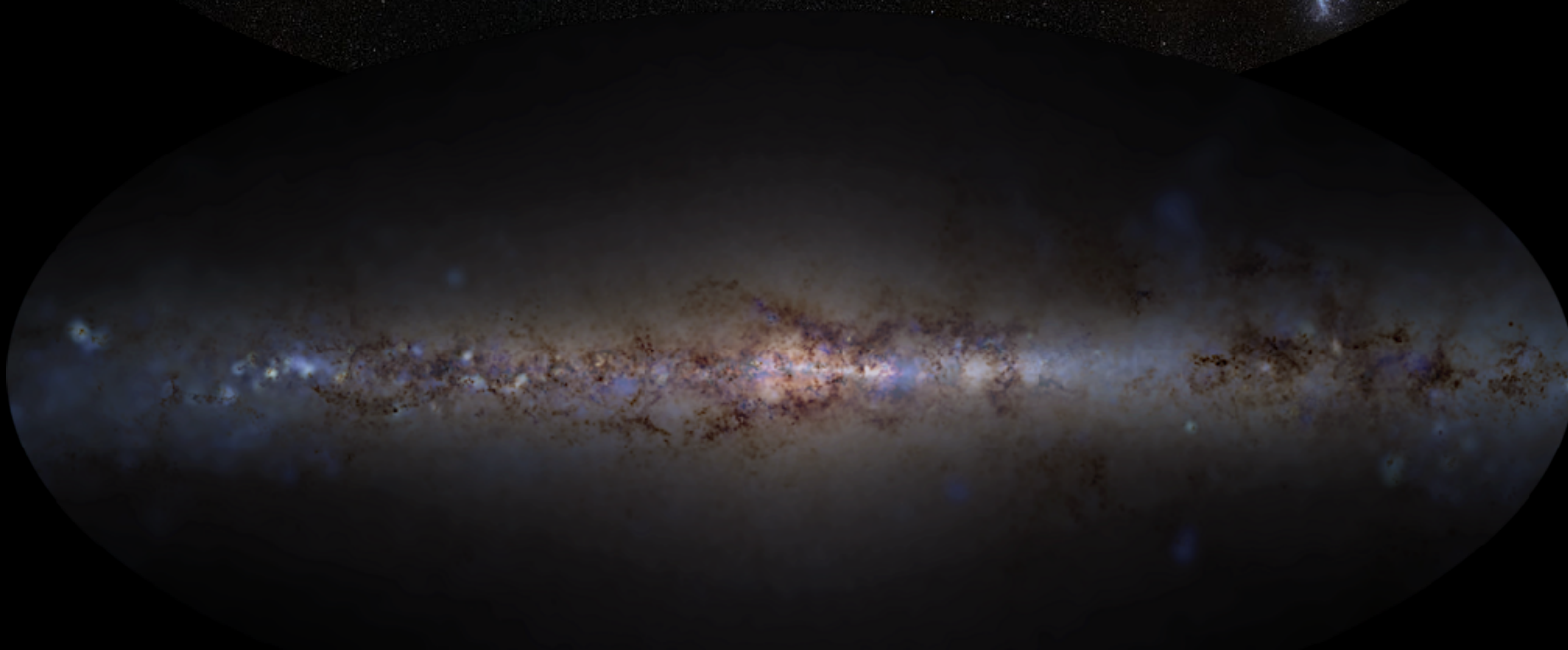
It Works!

THIS APPROACH IS PRODUCING REALISTIC GALAXIES

PFH et al.
(arXiv:1311.2073)



The Milky Way

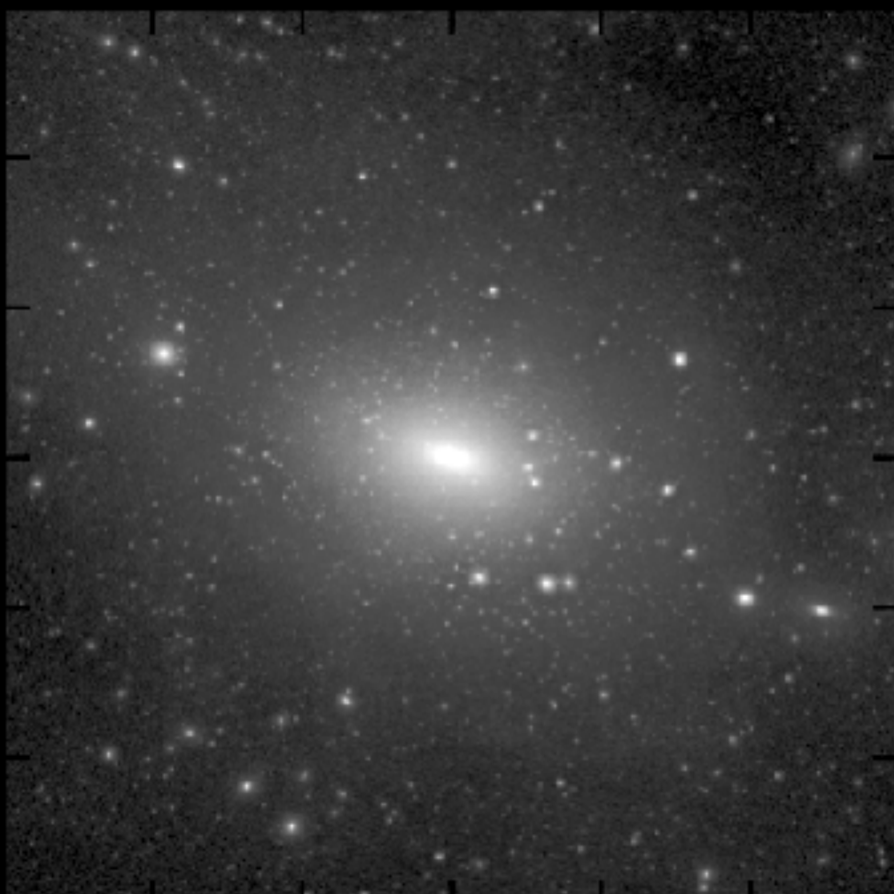


Failures No More

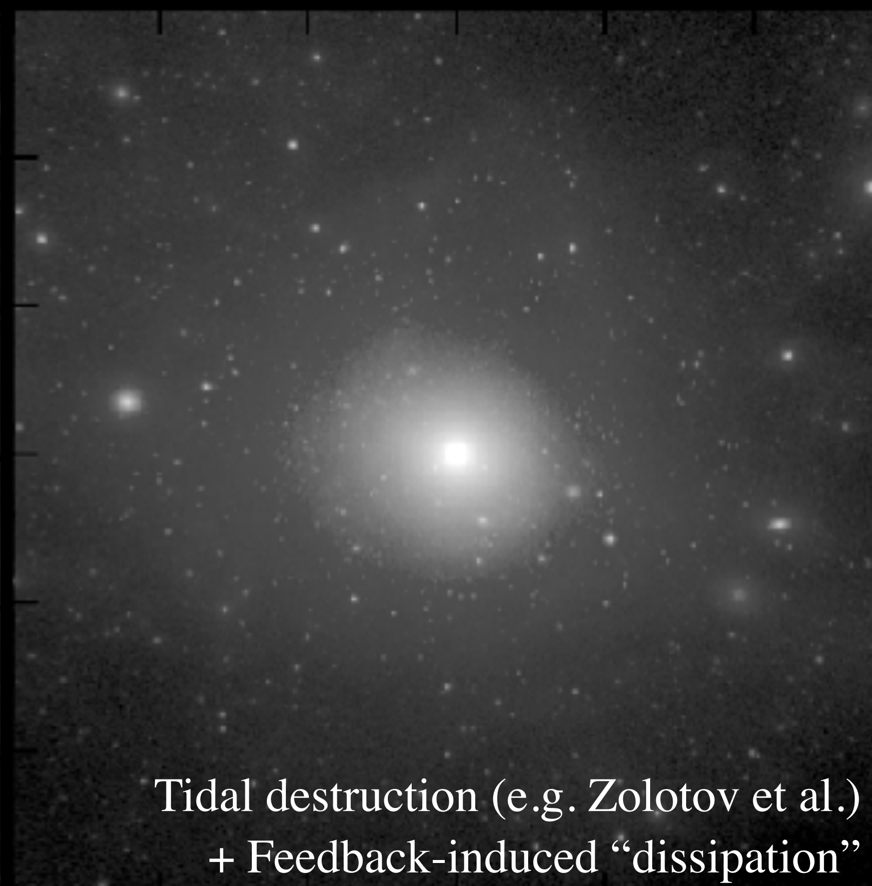
FEEDBACK EXPLAINS WHY SATELLITES ARE “MISSING”

Andrew
Wetzel
(arXiv:1602.05957)

Dark matter only simulation
(dark matter)



+ baryons & feedback
(dark matter)



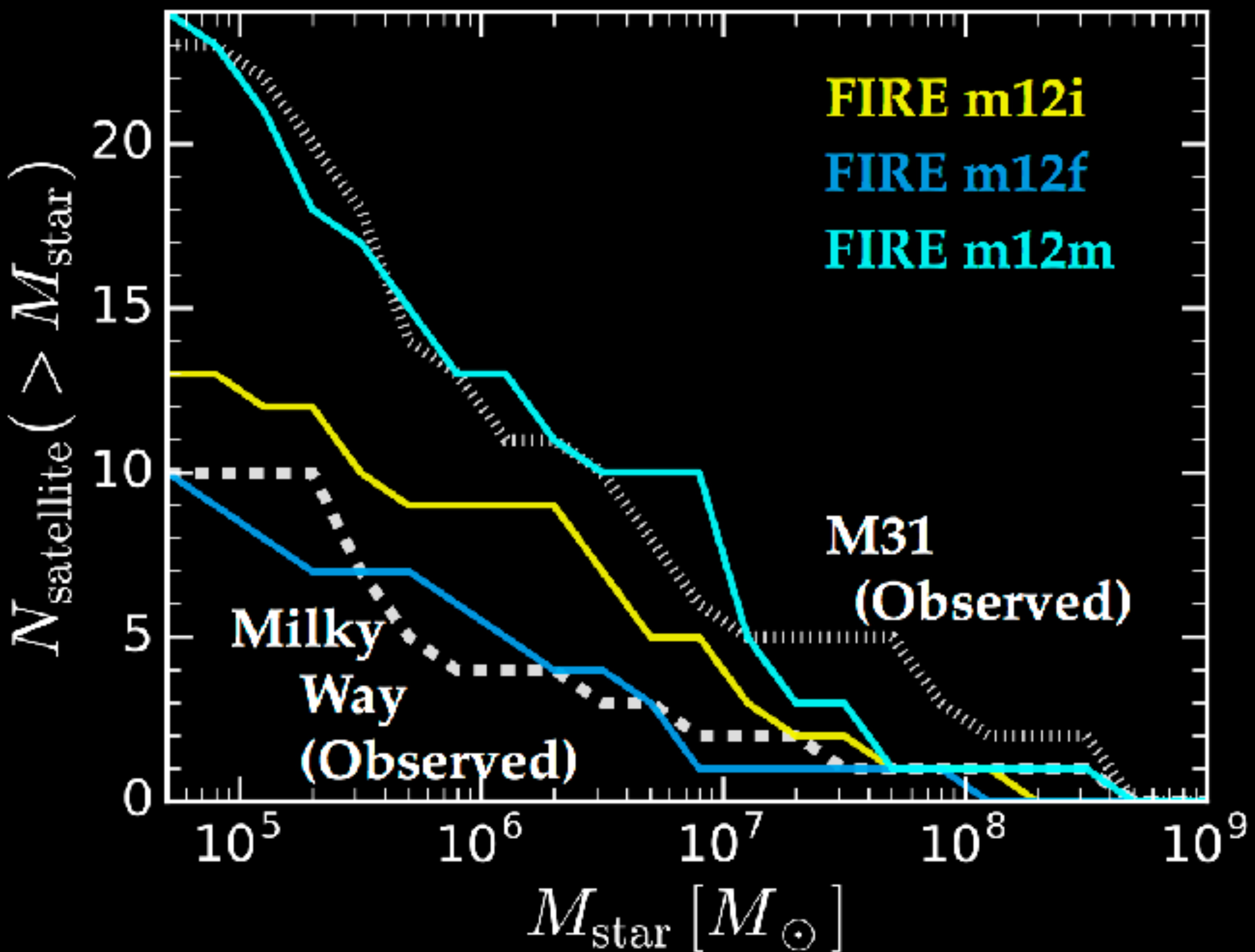
+ baryons & feedback
(stars)

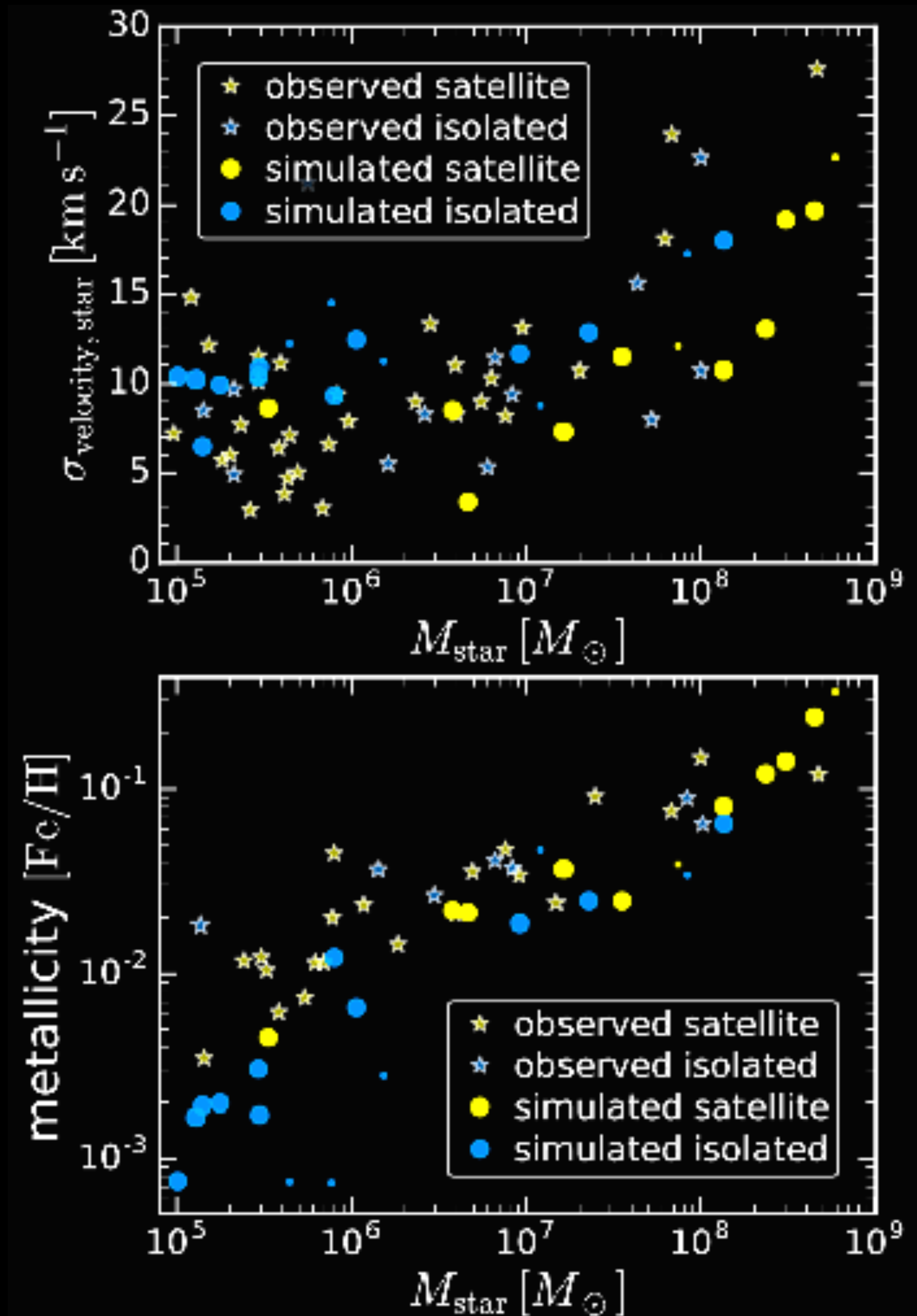
600 kpc

Failures No More

FEEDBACK SUPPRESSES STAR FORMATION AND DENSITIES

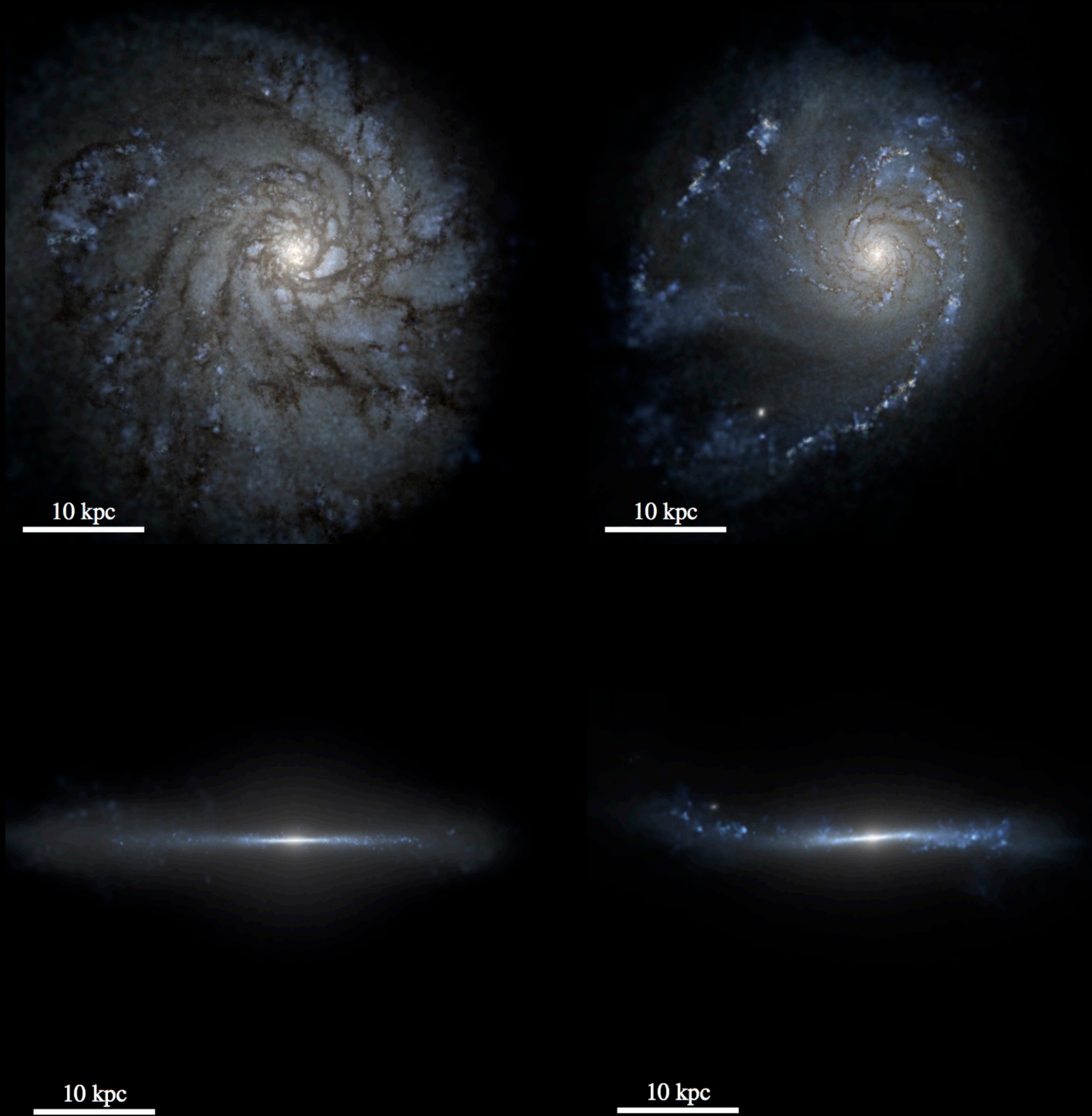
Wetzel + I. Escala (prep)



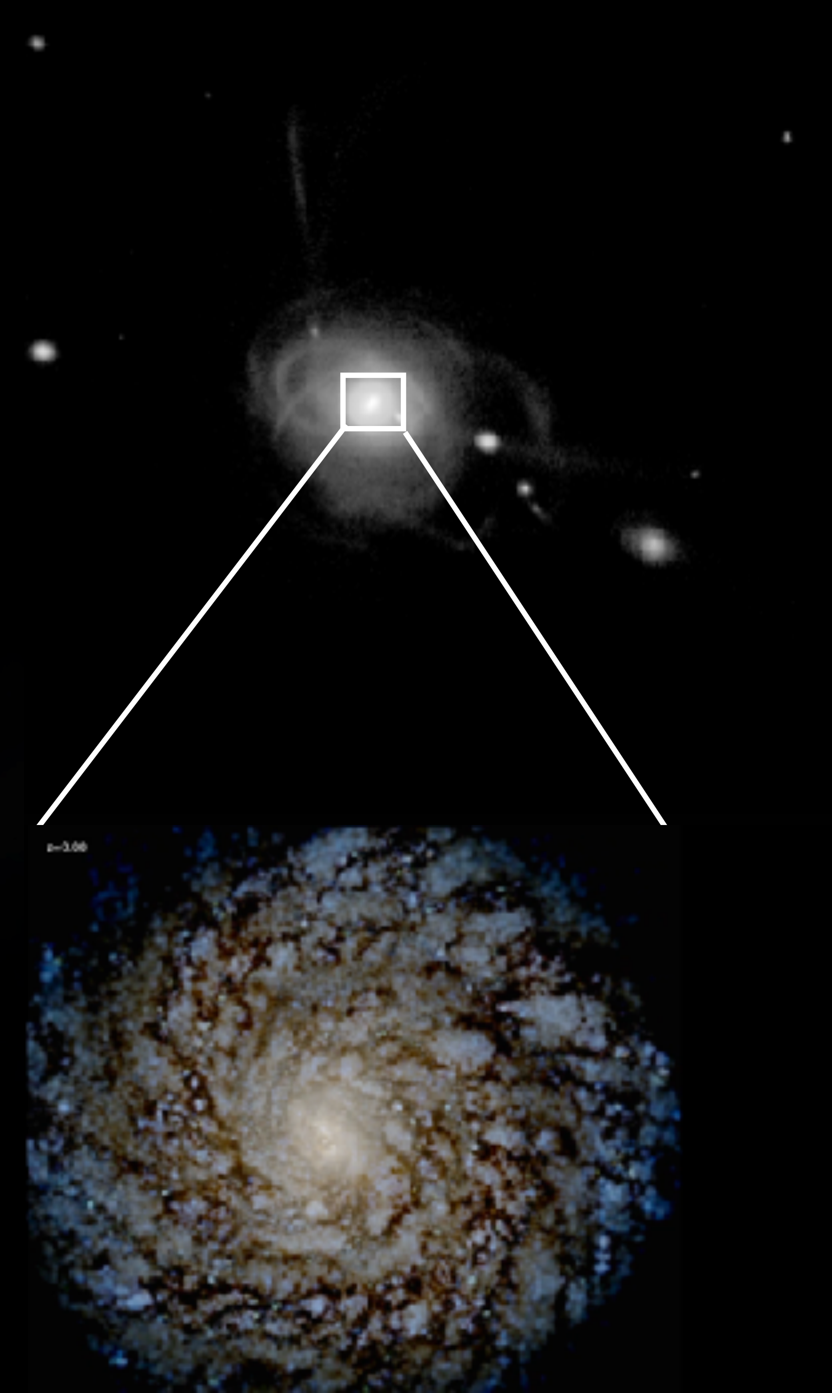


Thin Disks Emerge Naturally

Garrison-Kimmel et al., in prep

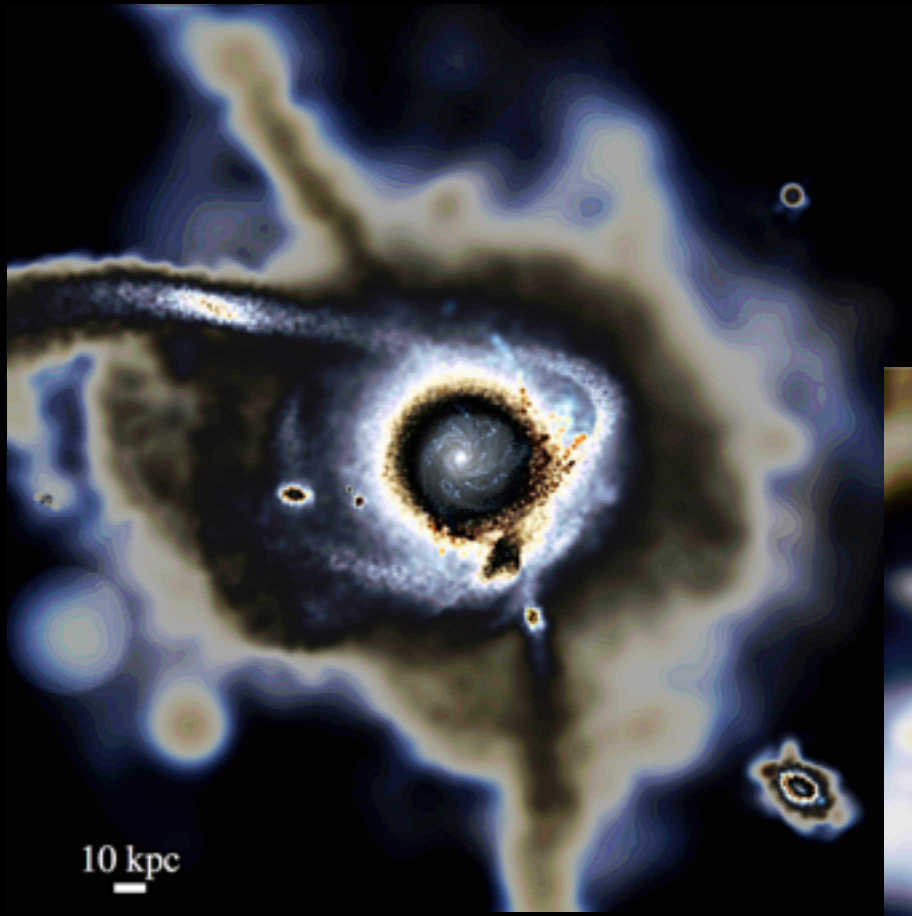


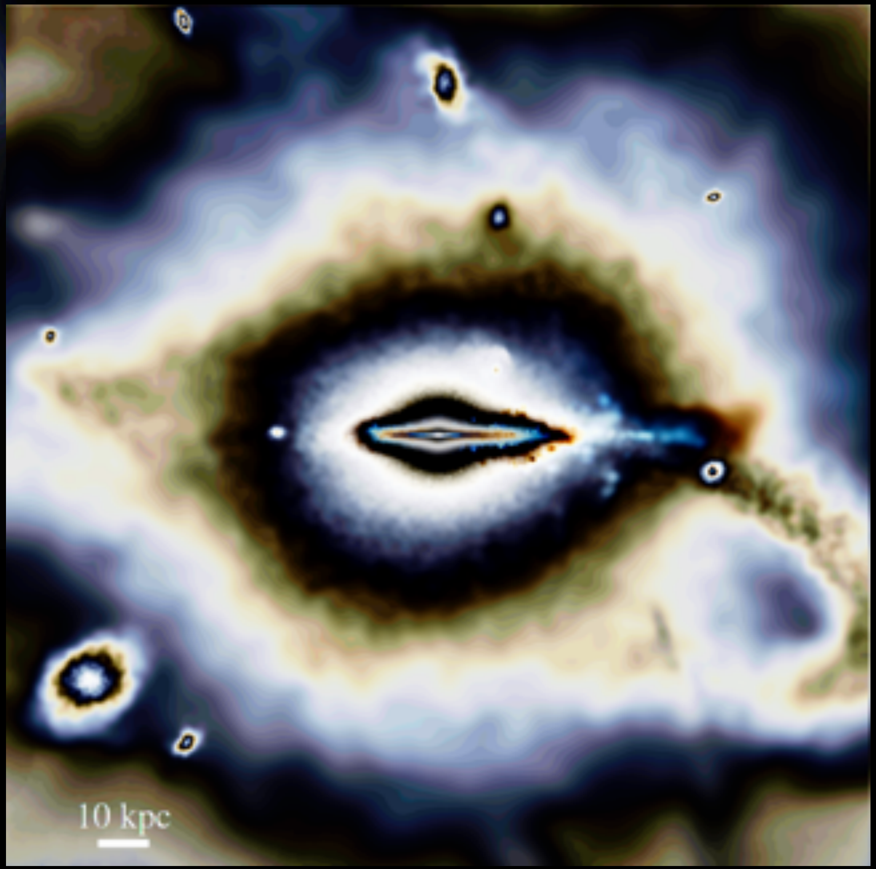
+ baryons & feedback (stars)



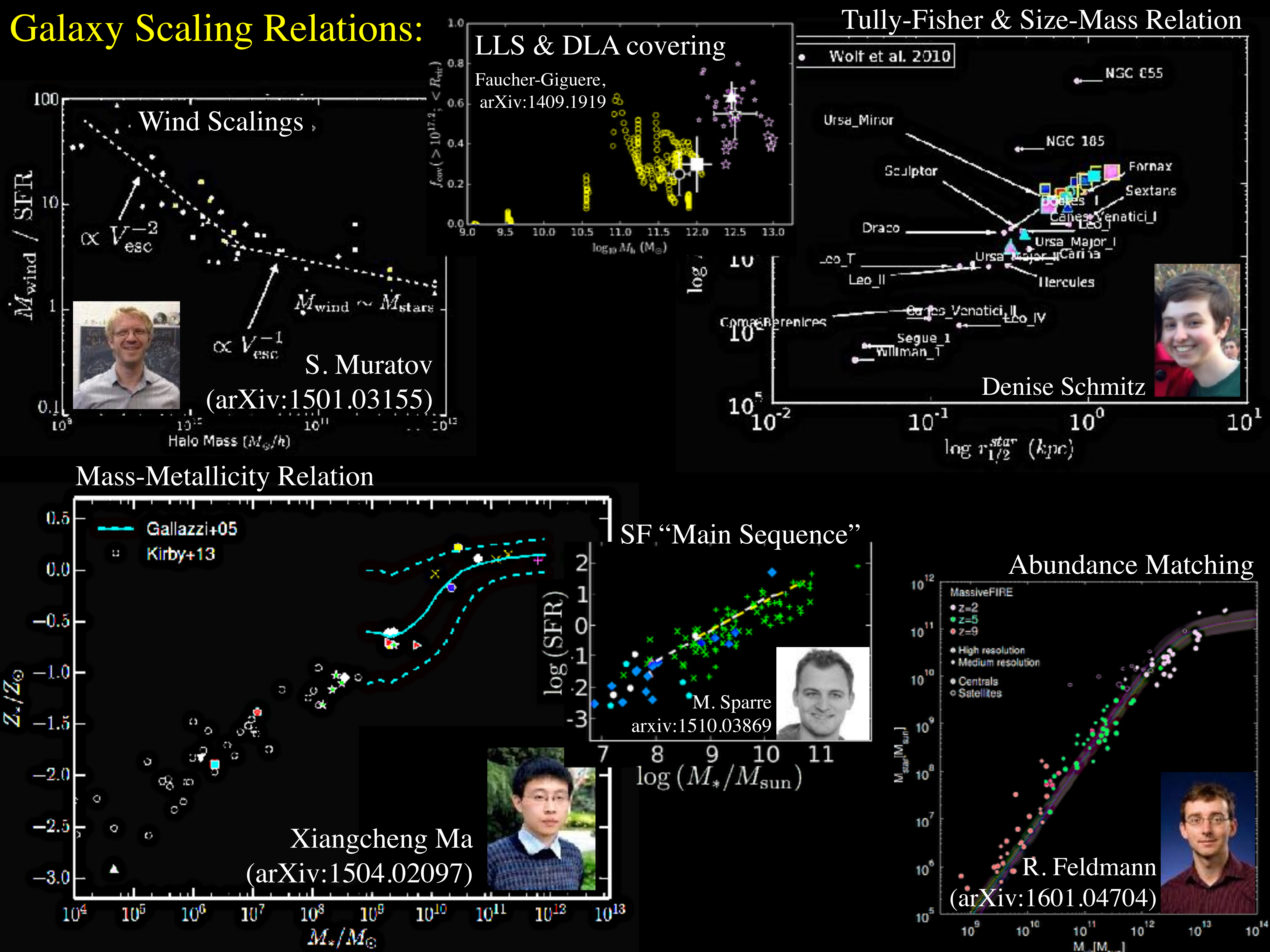
Halo Structure

A NEW GENERATION OF MODELS FOR STELLAR STRUCTURE SURVEYS





Sanderson et al. (in prep)

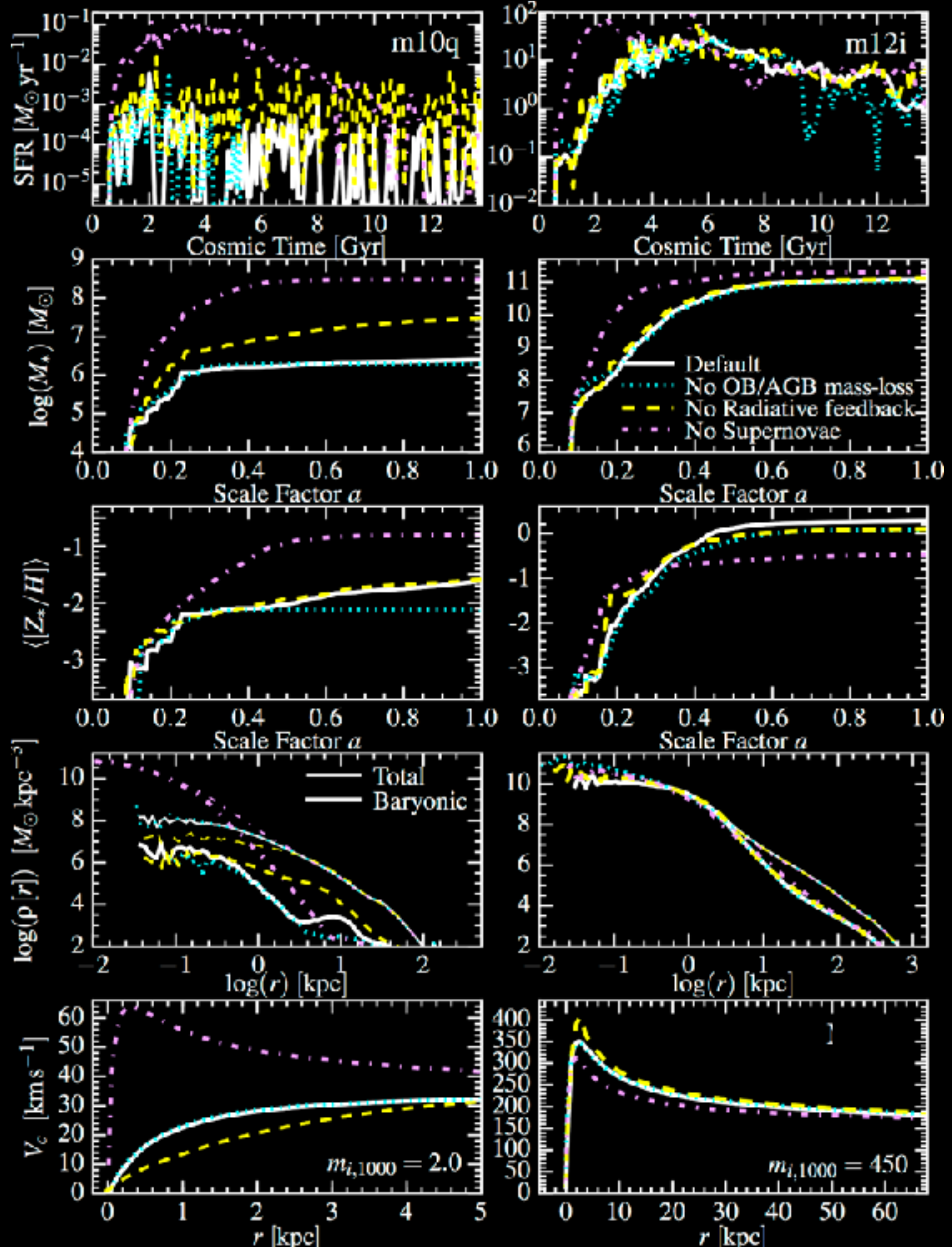

Galaxy Scaling Relations:
Wind Scalings
$\dot{M}_{\rm wind}$ / SFR
$\propto V_{\rm esc}^{-2}$
$\propto V_{\rm esc}^{-1}$
$\dot{M}_{\rm wind} \sim M_{\rm stars}$
Halo Mass ($M_\odot/h$)
S. Muratov
(arXiv:1501.03155)
LLS & DLA covering
Faucher-Giguere,
arXiv:1409.1919
$\log_{10} M_h$ ($M_\odot$)
Tully-Fisher & Size-Mass Relation
Wolf et al. 2010
NGC 655
Ursa_Minor
NGC 185
Sculptor
Fornax
Sextans
Draco
Leo_I
Ursa_Major_I
Carina
Leo_T
Leo_II
Hercules
Coma Berenices
Canes_Venatici_II
Leo_IV
Segue_1
Willman_1
Denise Schmitz
log $r_{1/2}^{star}$ (kpc)
Mass-Metallicity Relation
Gallazzi+05
Kirby+13
$Z_*/Z_\odot$
$M_*/M_\odot$
Xiangcheng Ma
(arXiv:1504.02097)
SF "Main Sequence"
log (SFR)
log ($M_*/M_{\rm sun}$)
M. Sparre
arxiv:1510.03869
Abundance Matching
MassiveFIRE
z=2
z=5
z=9
High resolution
Medium resolution
Centrals
Satellites
R. Feldmann
(arXiv:1601.04704)

What Matters?

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

Feedback Matters!

OBVIOUSLY!



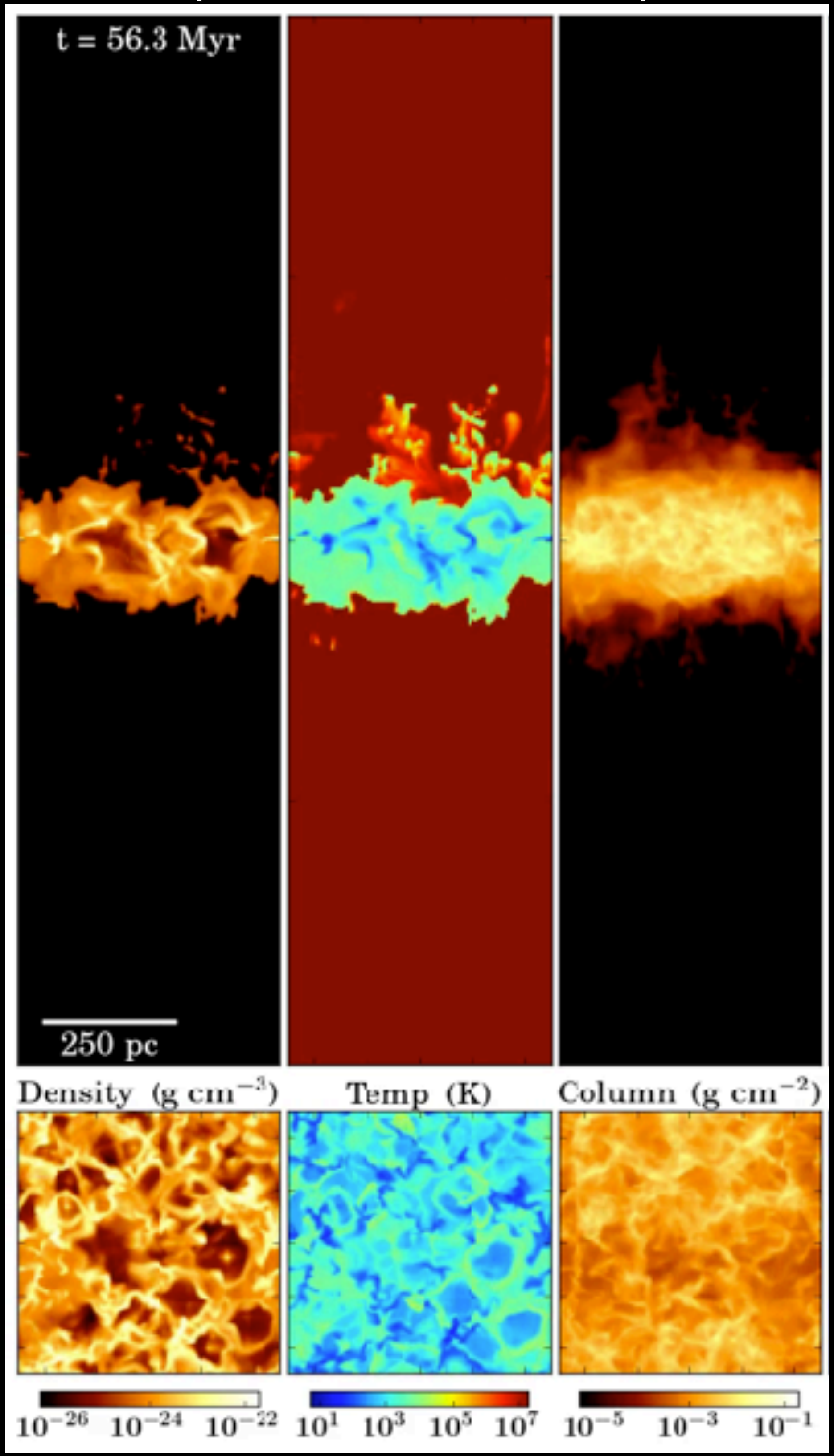
Doing the "sub-grid" right can matter

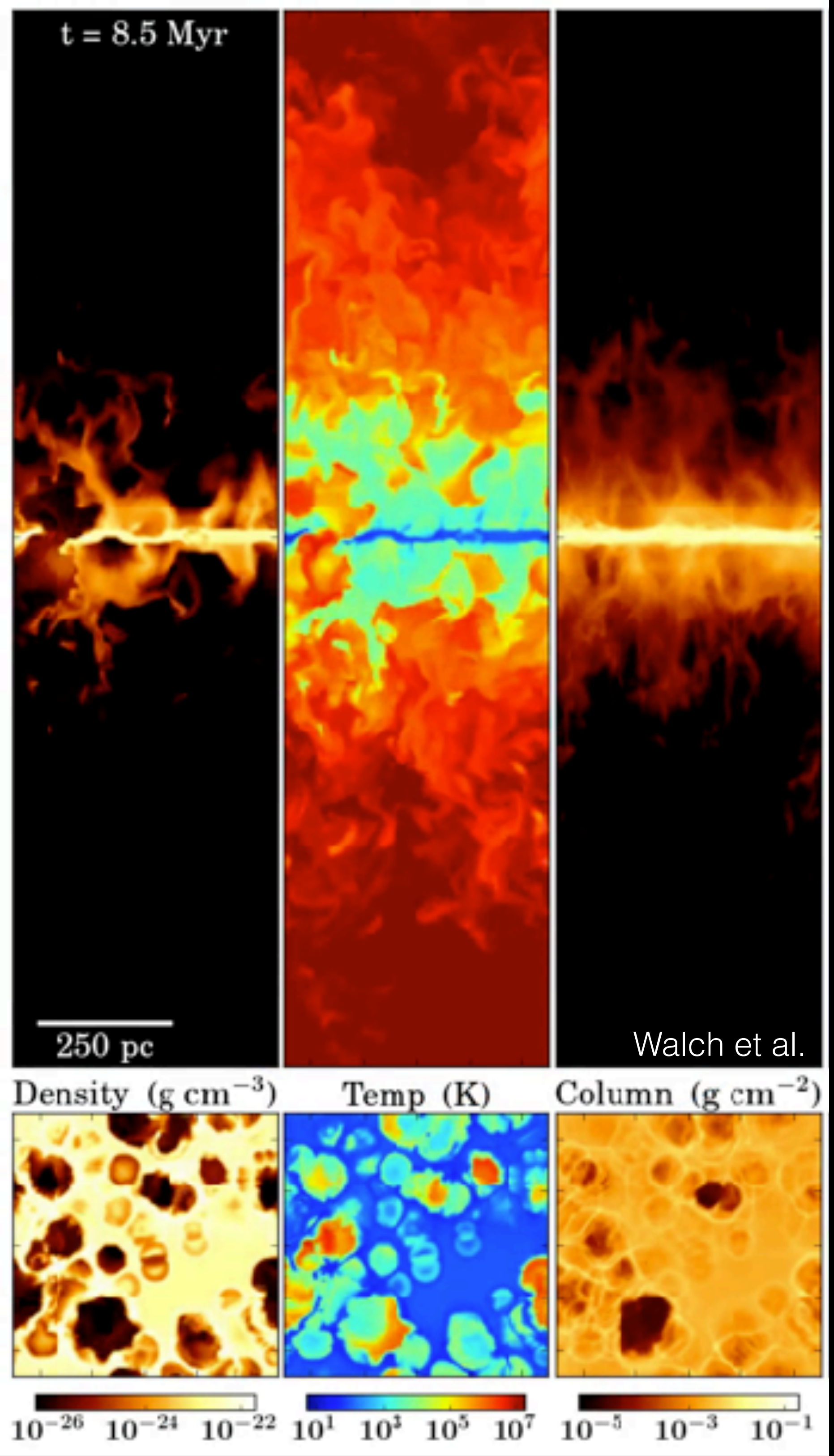
IF RESOLVE DENSE GAS, NEED PHYSICS FOR IT!

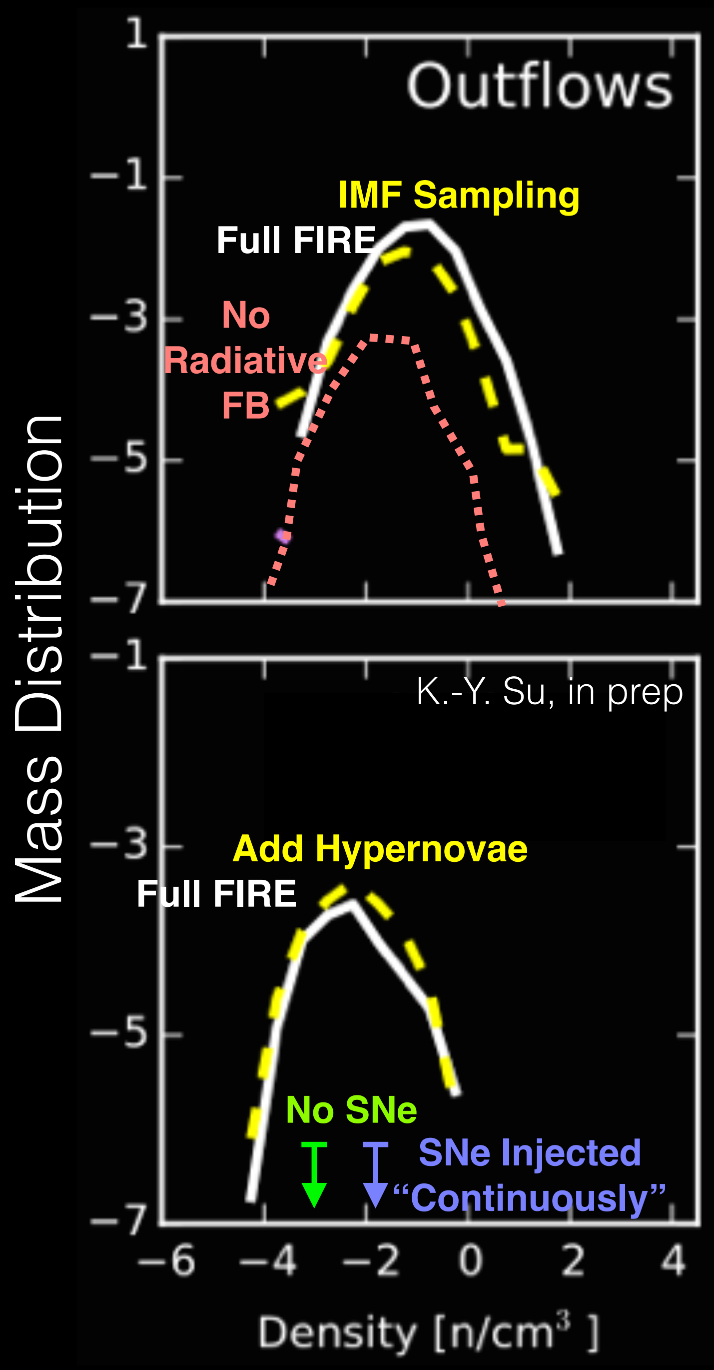
Murray+, Martizzi+, Walch+, Barnes+
Hopkins+, Hayward+, Shetty+, Hennebelle+

SNe Explode in Density Peaks (no radiative feedback)

SNe Clustered & Off-Peak (with radiative feedback)





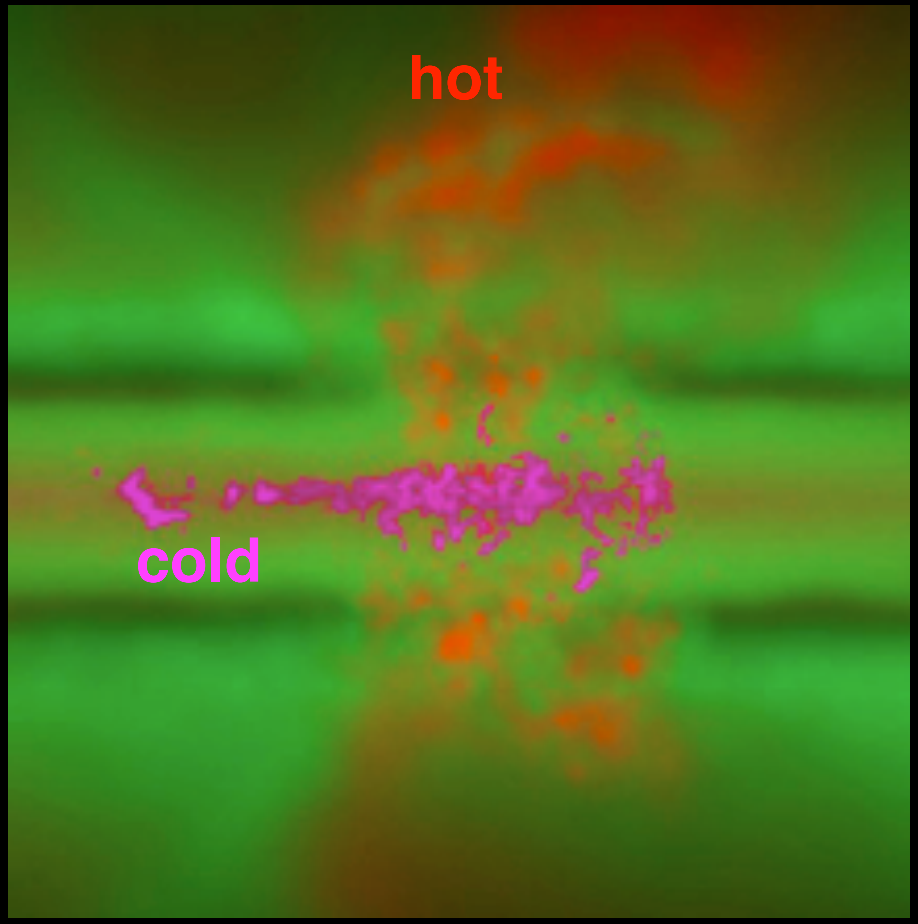


Doing the "sub-grid" right can matter

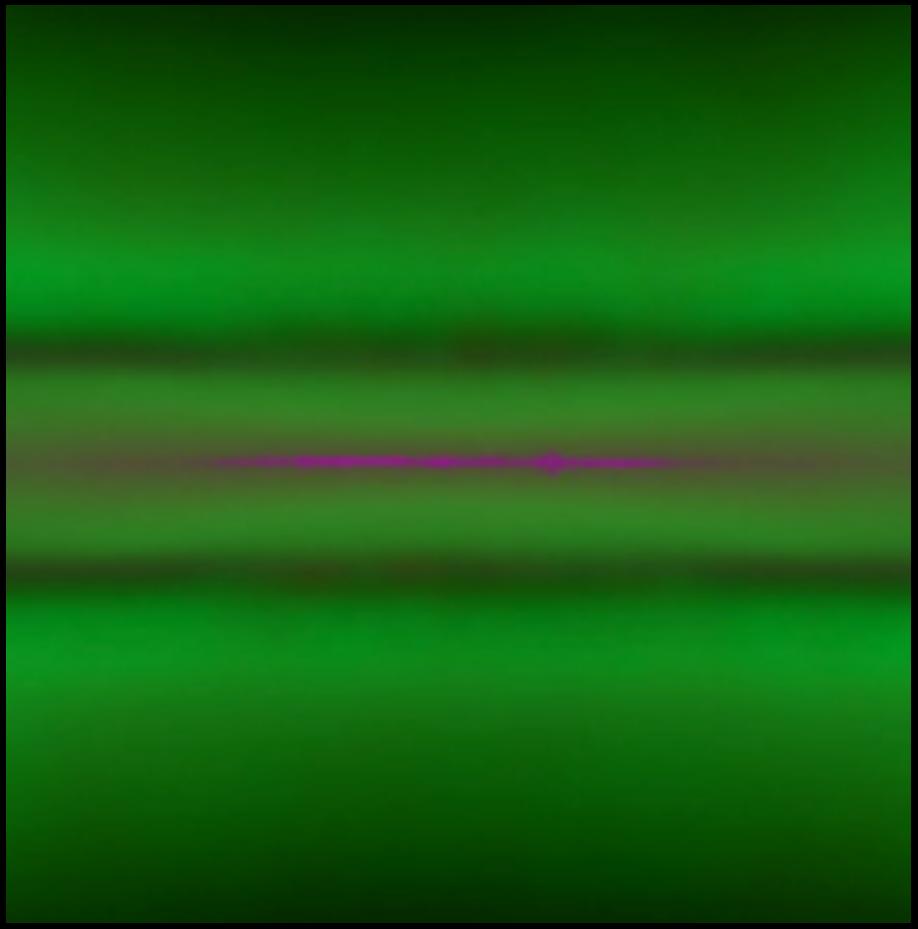
IF RESOLVE BUBBLES, NEED PHYSICS FOR IT!

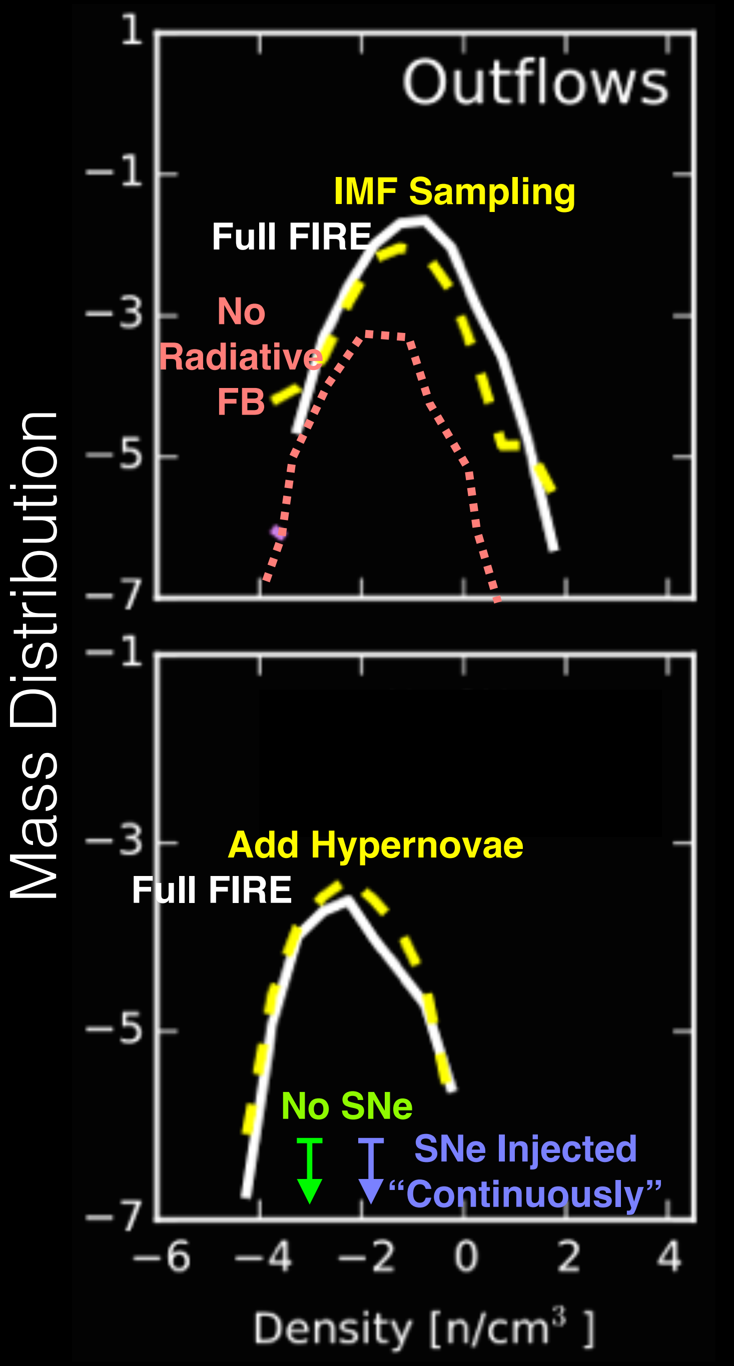
Klessen+, Ostriker+
Hopkins+
K.-Y. Su, in prep

Treat each SNe explicitly following resolved explosion



Continuously dump thermal energy ~SFR





Doing the "sub-grid" right can matter

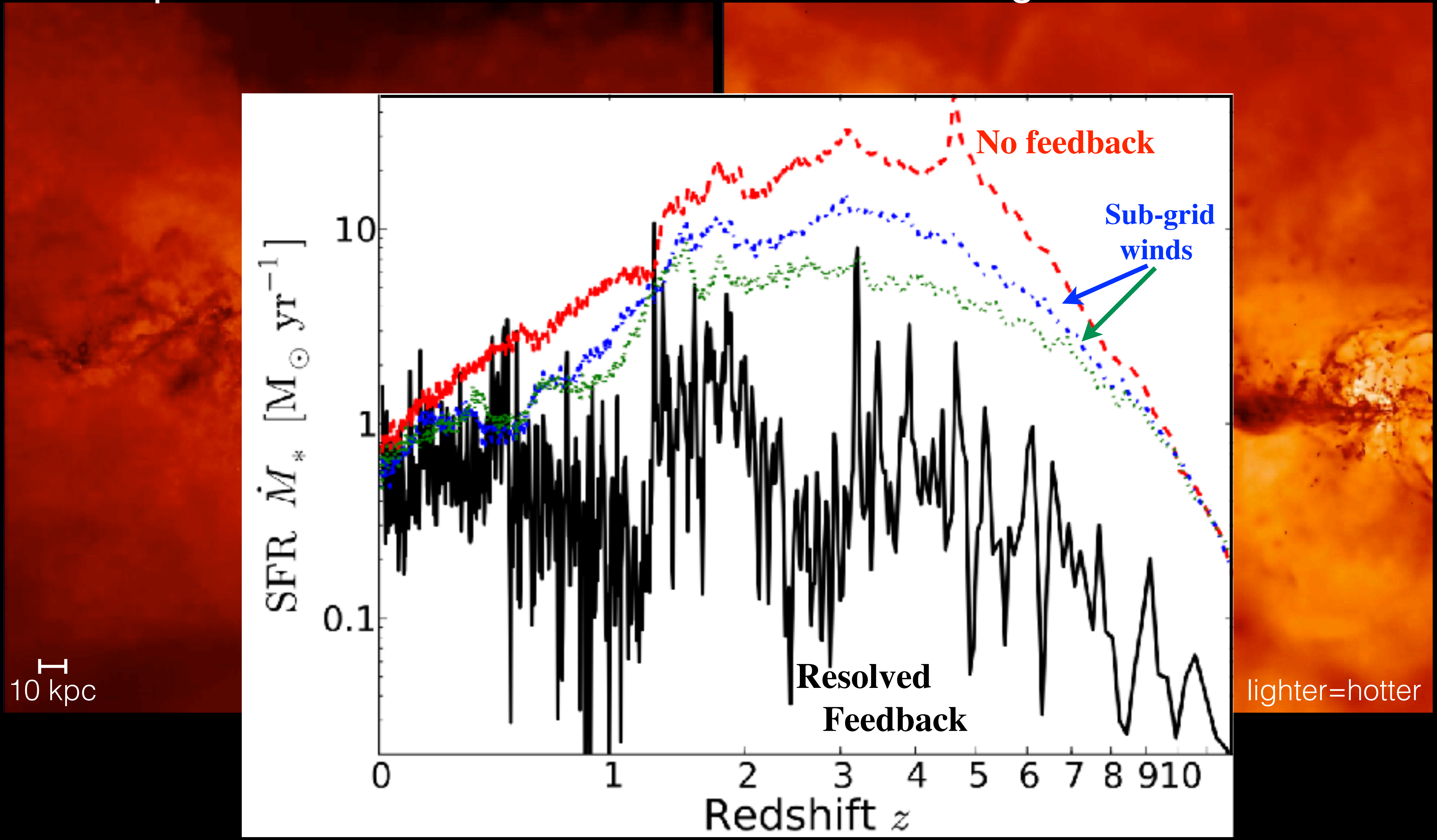
DANGERS OF ONLY FITTING MASSES

M. Sparre
arxiv:1510.03869

Proto-Milky Way: Gas Temperature:

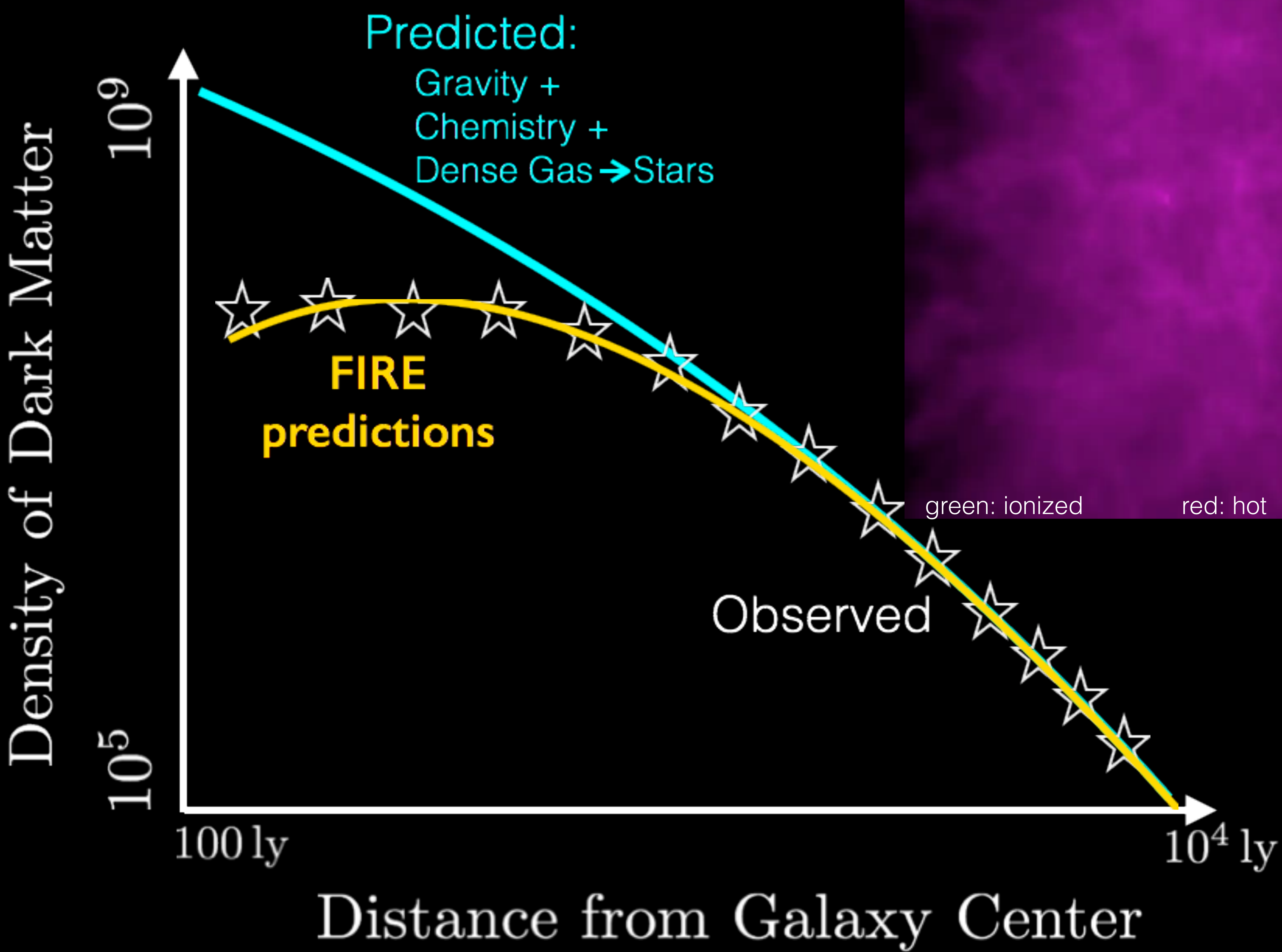
Simple Sub-Grid $(\dot{M}_{\rm wind} = \eta\, \dot{M}_*)$

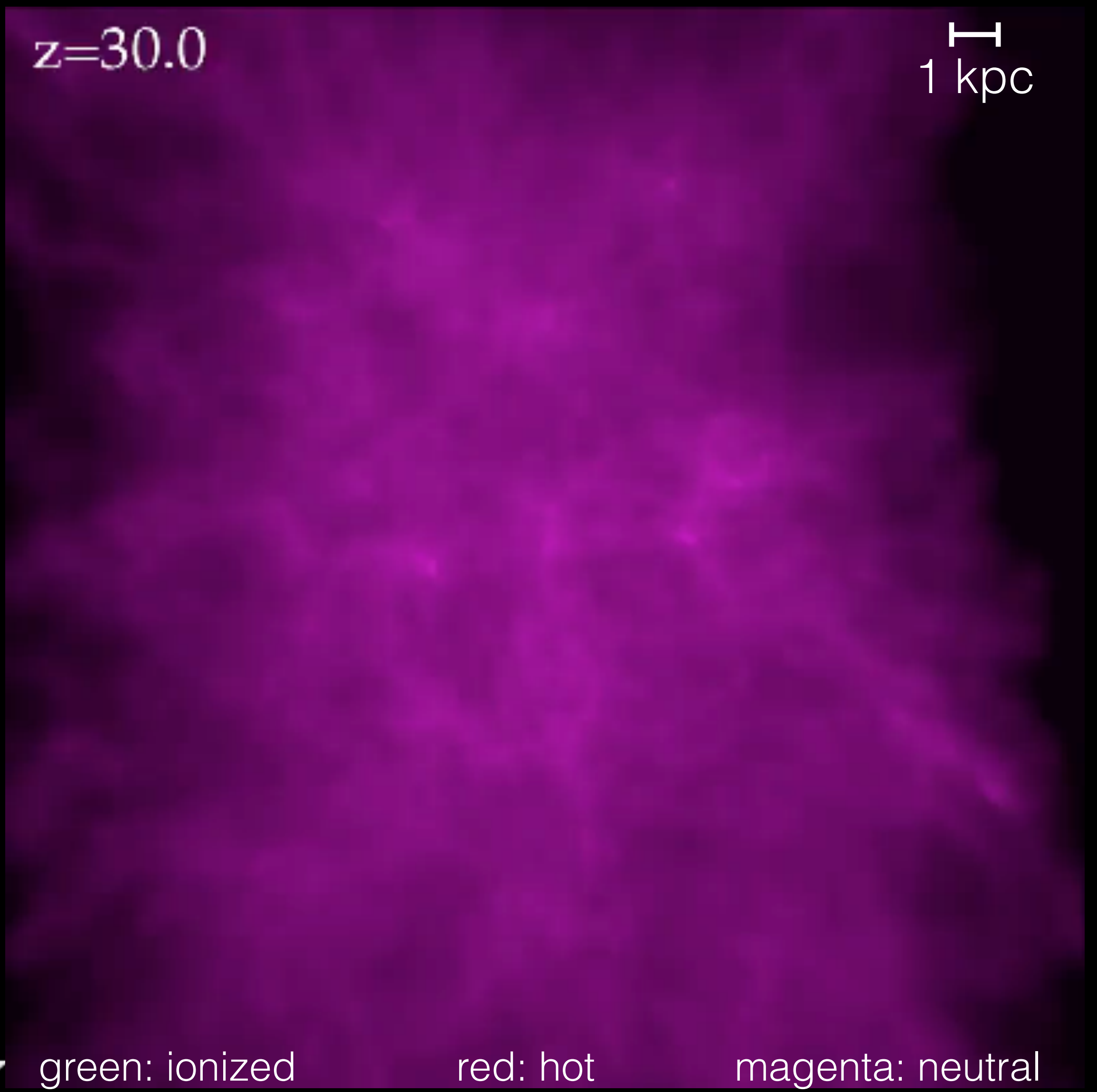
Following Full Feedback



Feedback Saves Cold Dark Matter?

NO EXOTIC PHYSICS NECESSARY





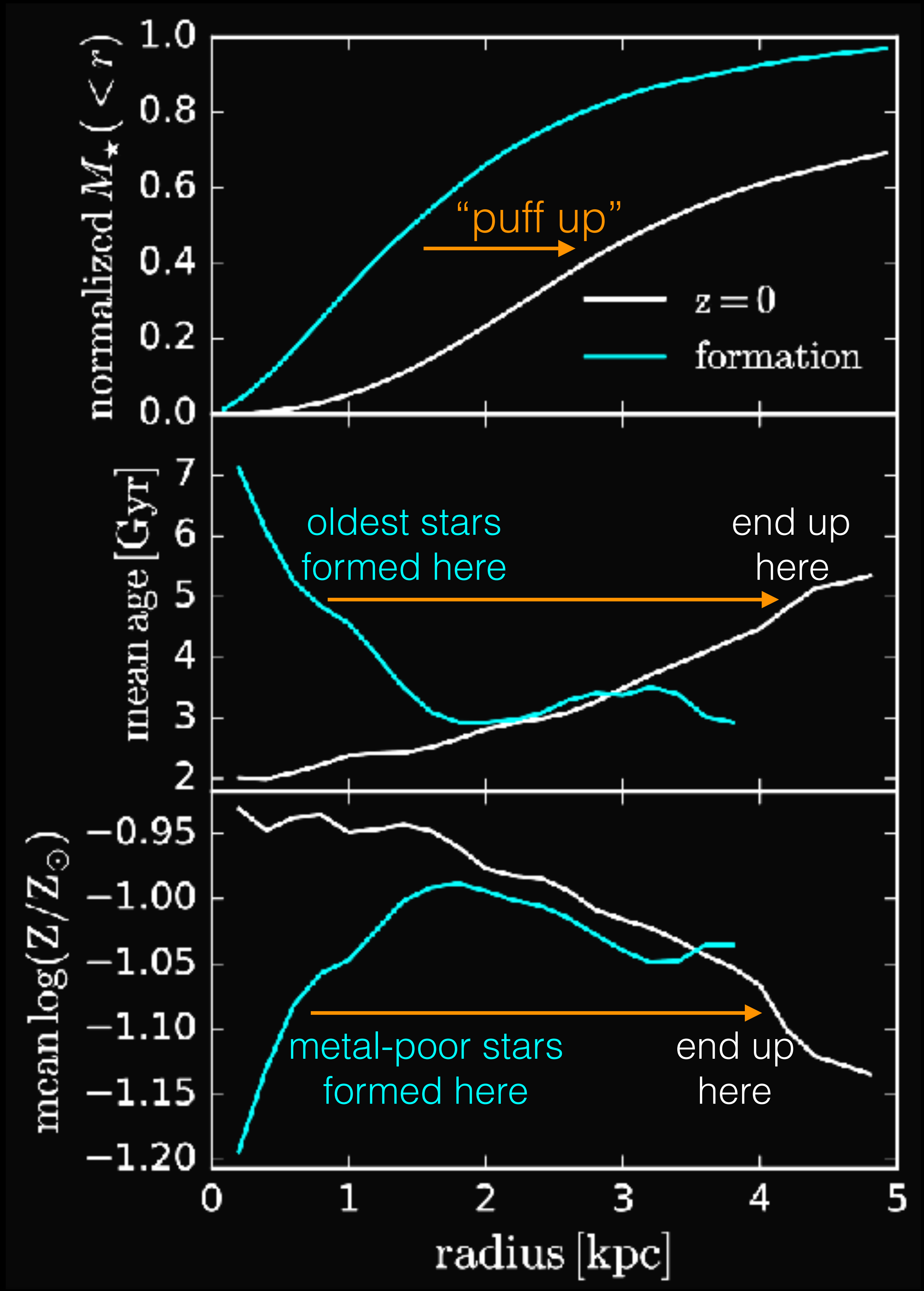
Onorbe et al.
(arXiv:1502.02036)
Chan et al.
(arXiv:1507.02282)
Wheeler et al.
(arXiv:1504.02466)

Direct Consequences for Structure

K. El-Badry, arXiv:1512.01235

BURSTY SF = STARS MIXED, JUST LIKE DM

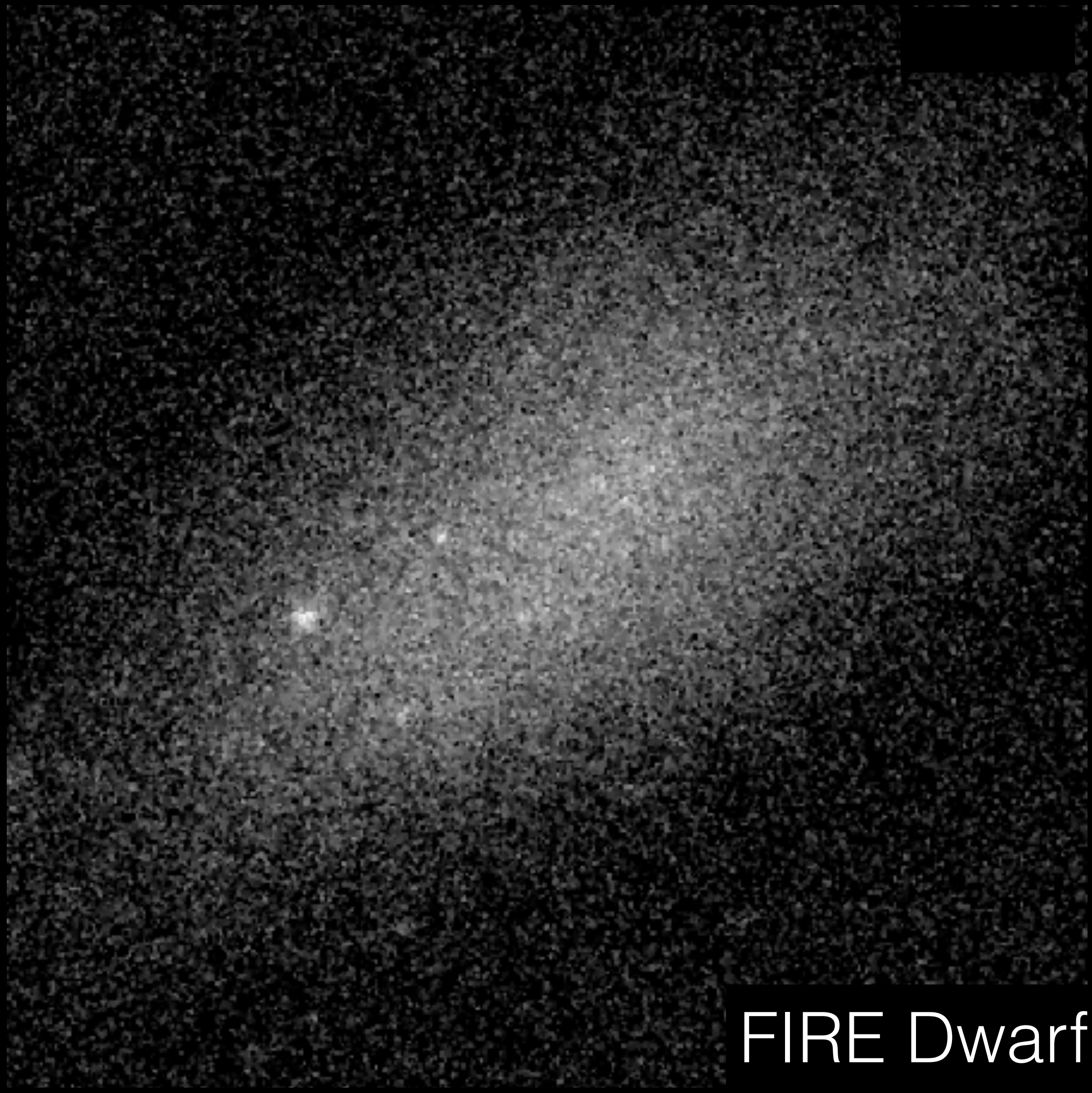
- If DM orbits perturbed, stars are too!
  - Radial anisotropy
  - Gradients "wiped out"
  - Galactic radii *oscillate*



Predicts New Classes of Galaxies

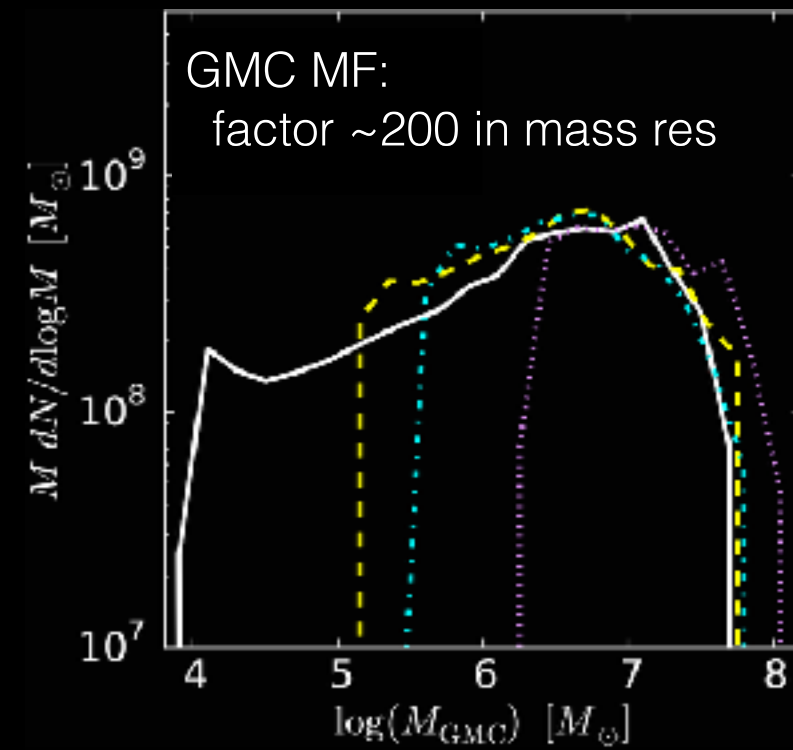
ULTRA-DIFFUSE SYSTEMS: THE NEW "NORMAL"

K. El-Badry
(arXiv:1512.01235)
+ TK Chan (prep)



Resolution: Needs to Match Your Physics!

DIFFERENT PREDICTIONS REQUIRE DIFFERENT RESOLUTION



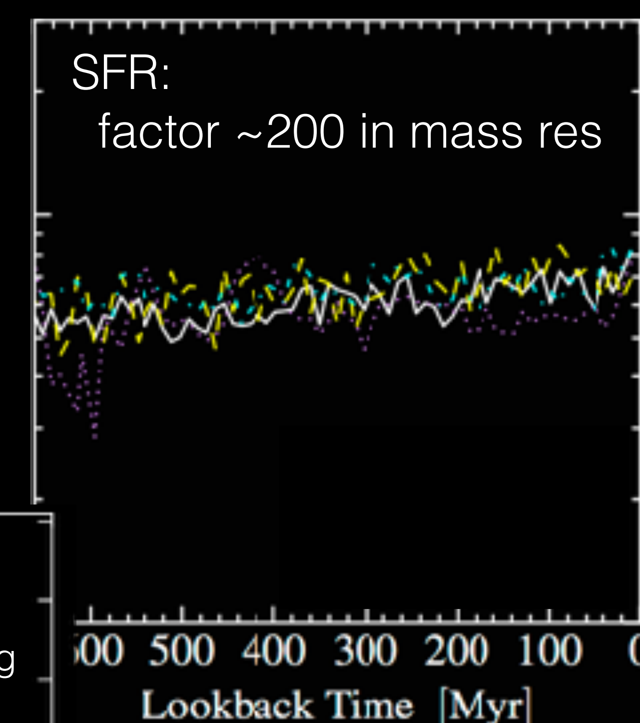
Fragmentation / GMCs / Dense Gas:

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

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

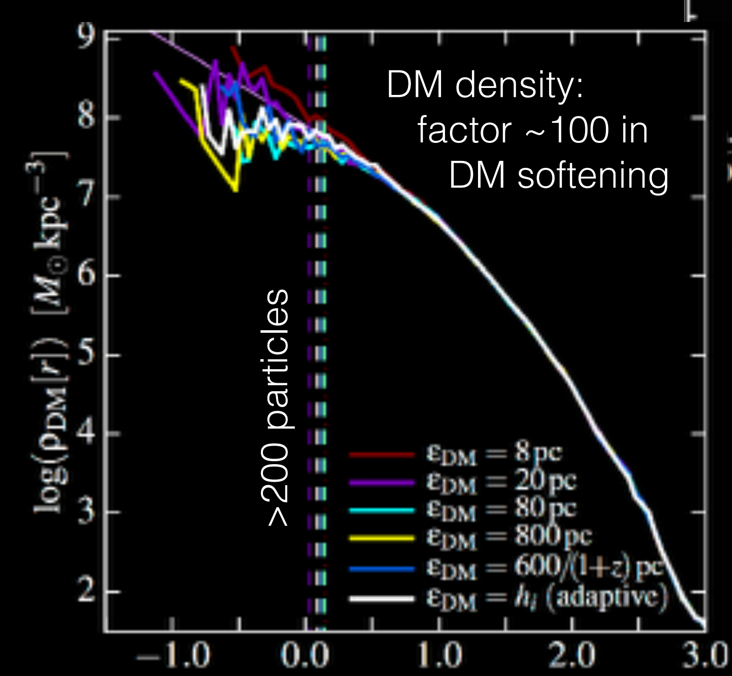
Super-bubbles / overlaps / chimneys:

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



Individual SNe (no sub-grid SNe momentum):

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

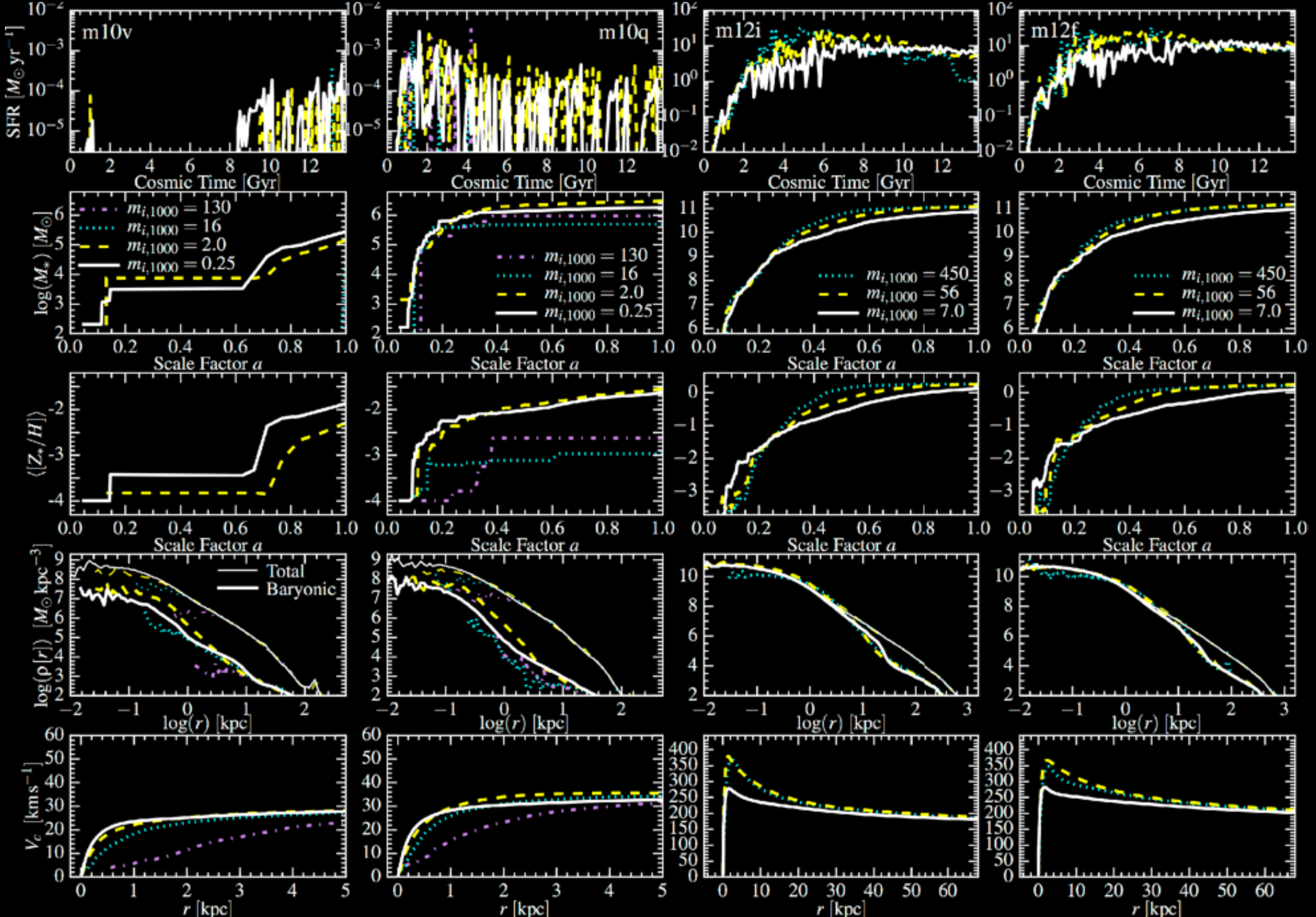


Dwarf galaxy "bursty-ness":

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

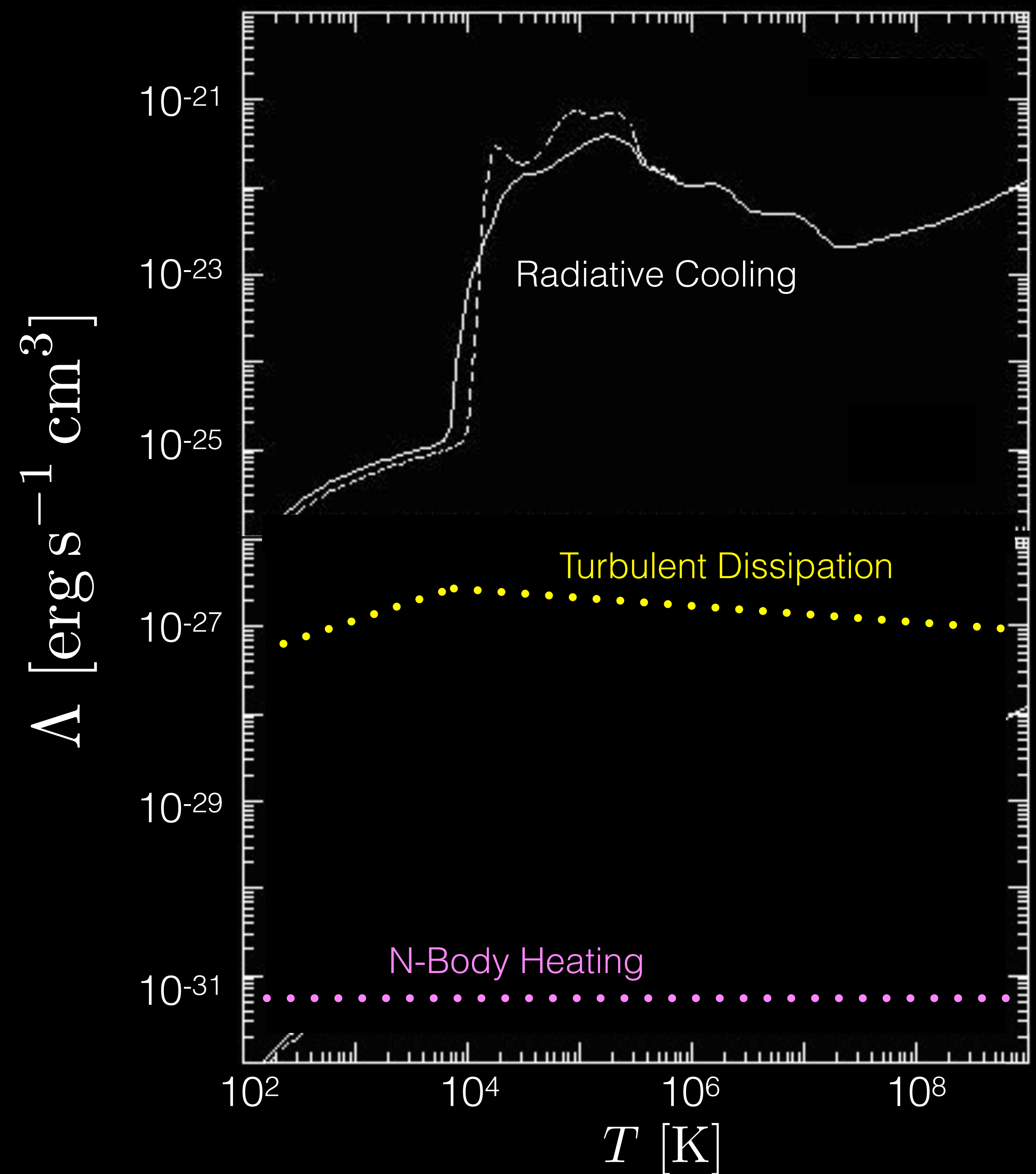
Resolution: Needs to Match Your Physics!

DIFFERENT PREDICTIONS REQUIRE DIFFERENT RESOLUTION



N-Body Heating is Totally Negligible

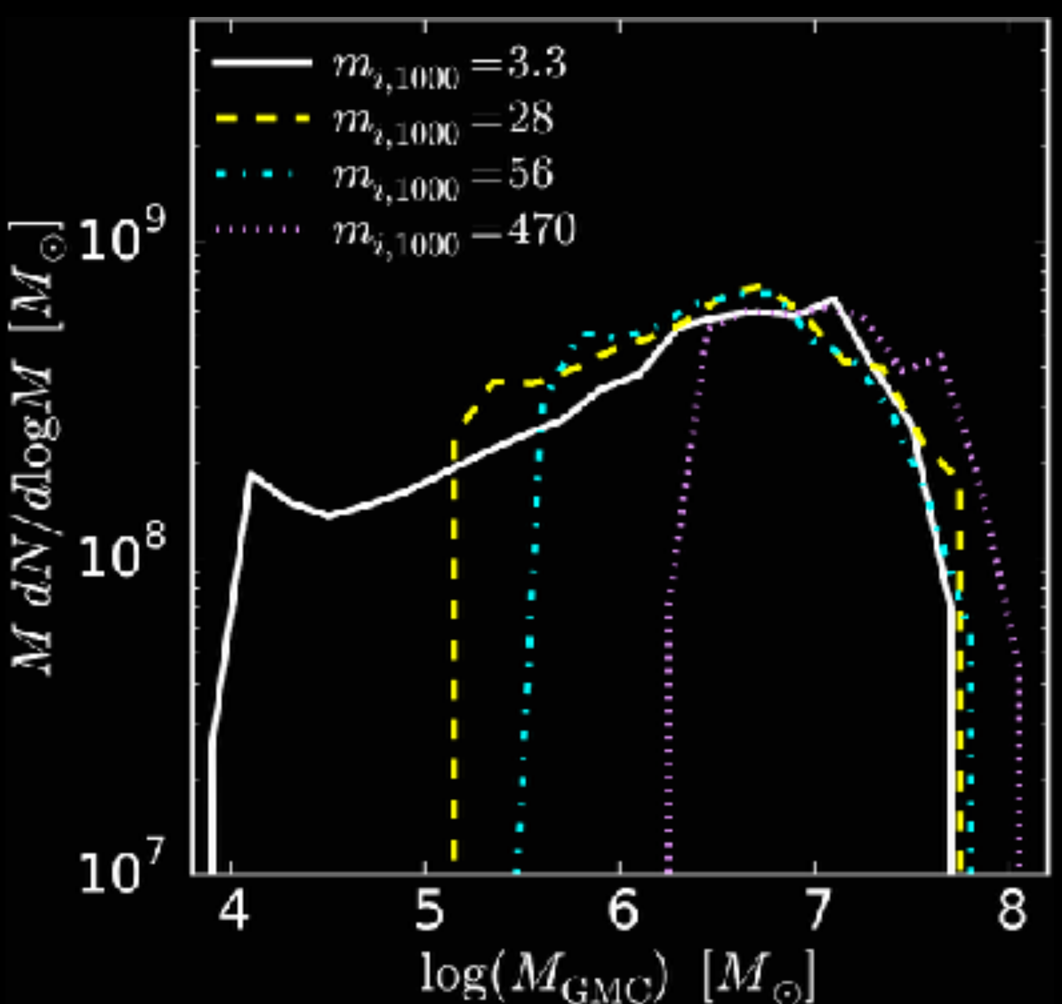
EVEN FOR EXTREME SOFTENINGS



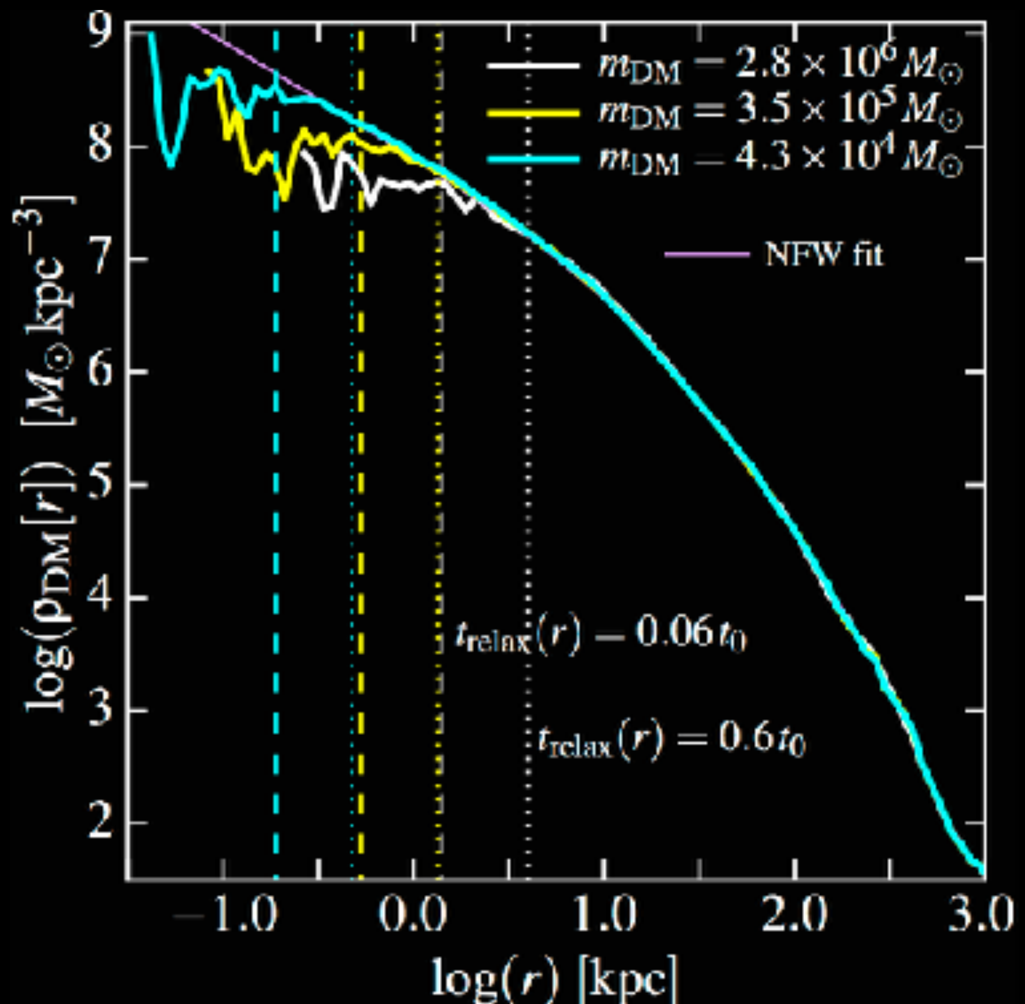
Resolution: Needs to Match Your Physics!

DIFFERENT PREDICTIONS REQUIRE DIFFERENT RESOLUTION

Fragmentation / GMC MF / clump existence:
<10 particles/clump



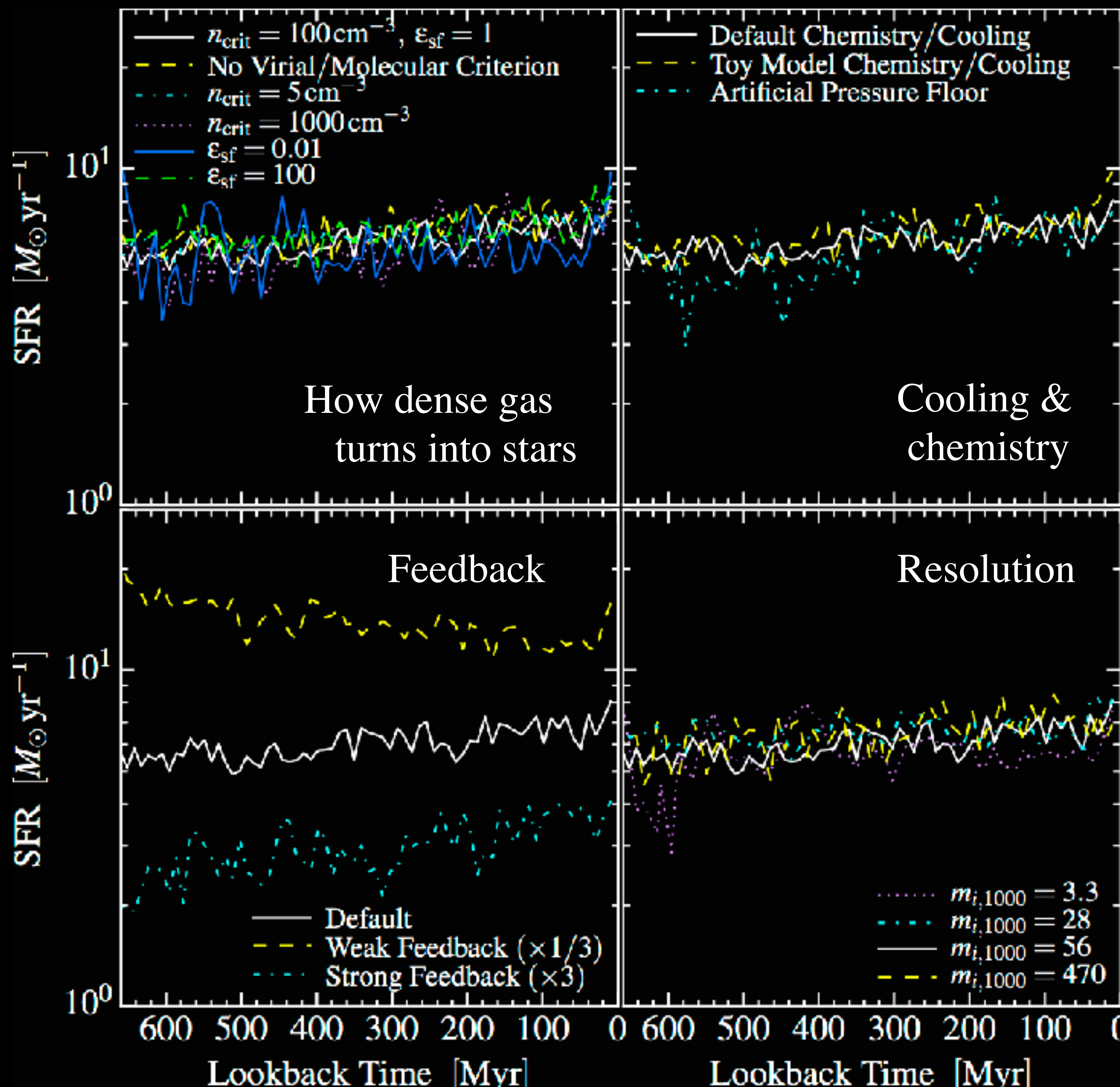
Mass profiles: < 200 particles



What Doesn't Matter?

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

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

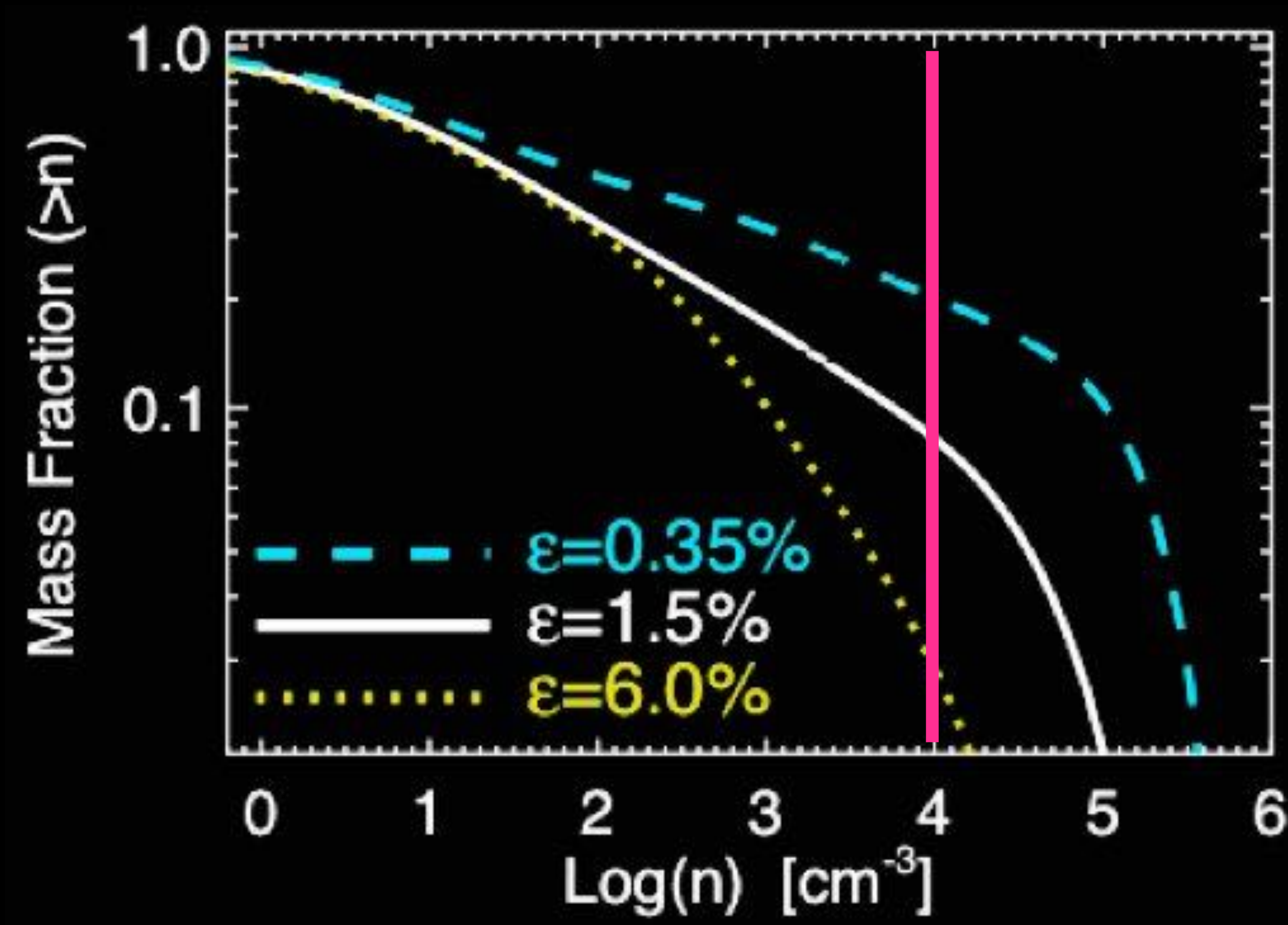


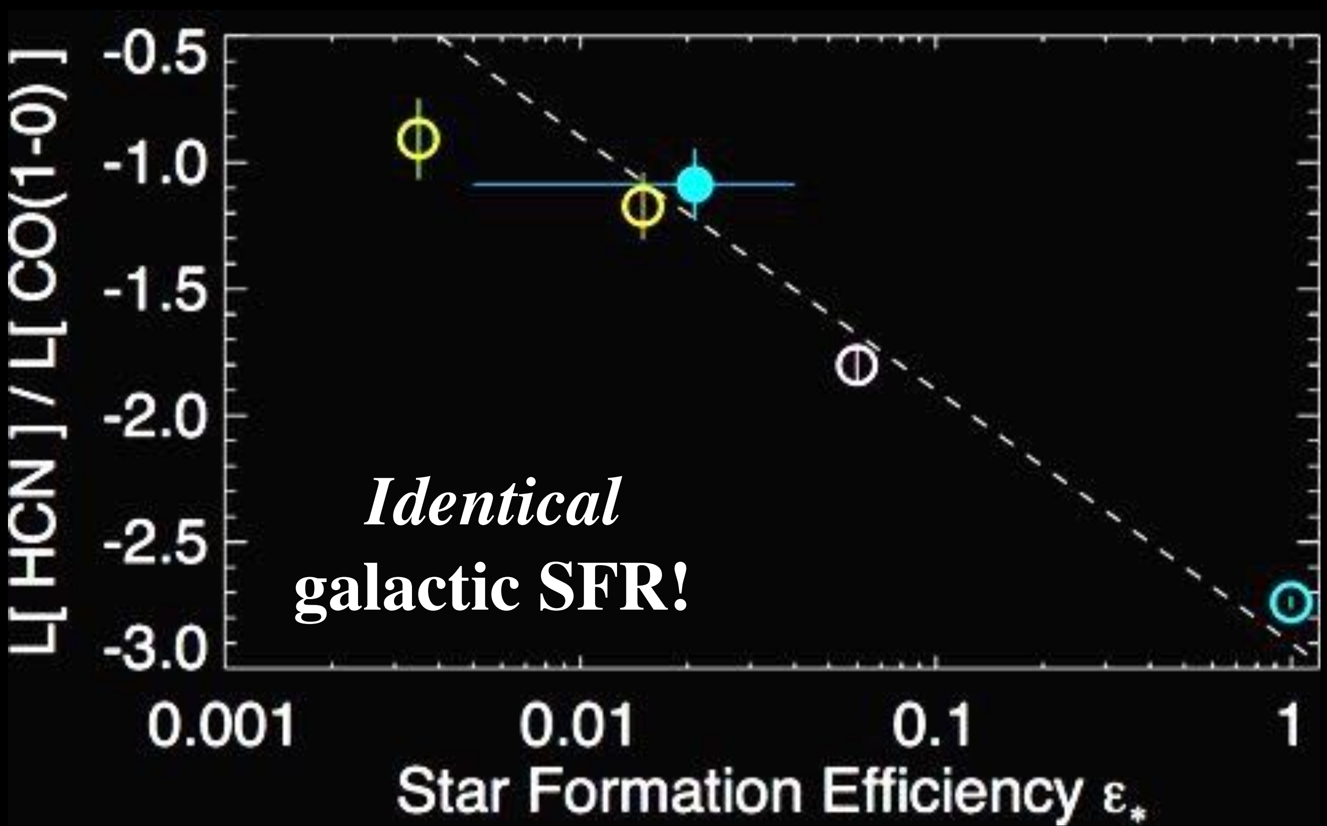
Matt Orr (in prep)
Saitoh+ 11
Hopkins+ 11,12,14
Agertz+14

Dense Gas *Does* Change

SELF-REGULATES TO "NEEDED" SFR LEVEL

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





Identical
galactic SFR!

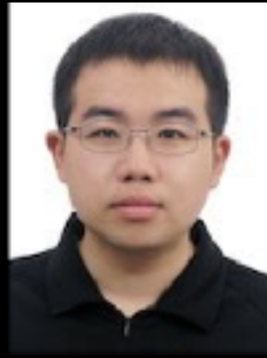
(molecular gas)

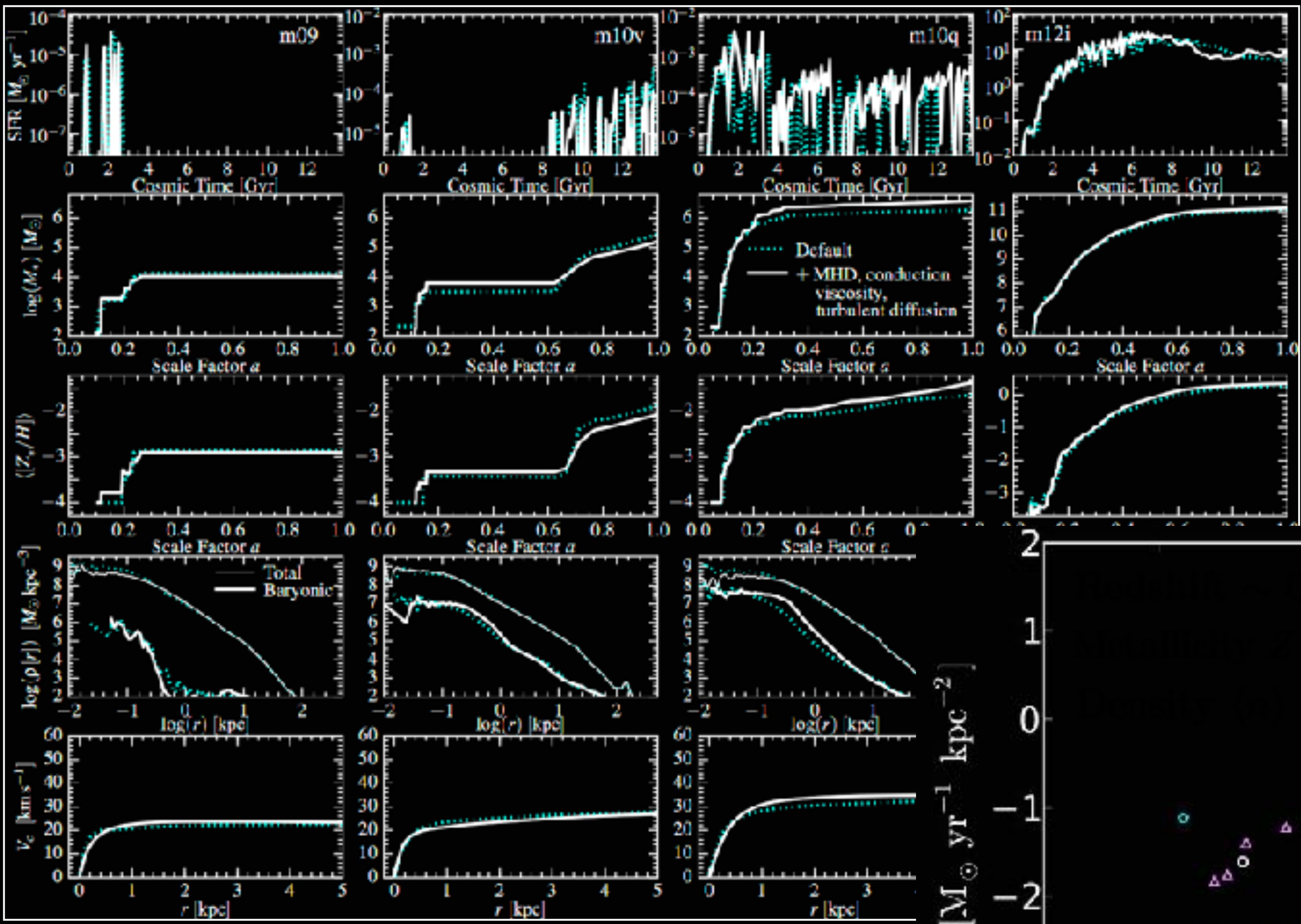
Matt Orr (in prep)
Hopkins+ 11,12,14
Shetty+ 14
Narayanan+ 13

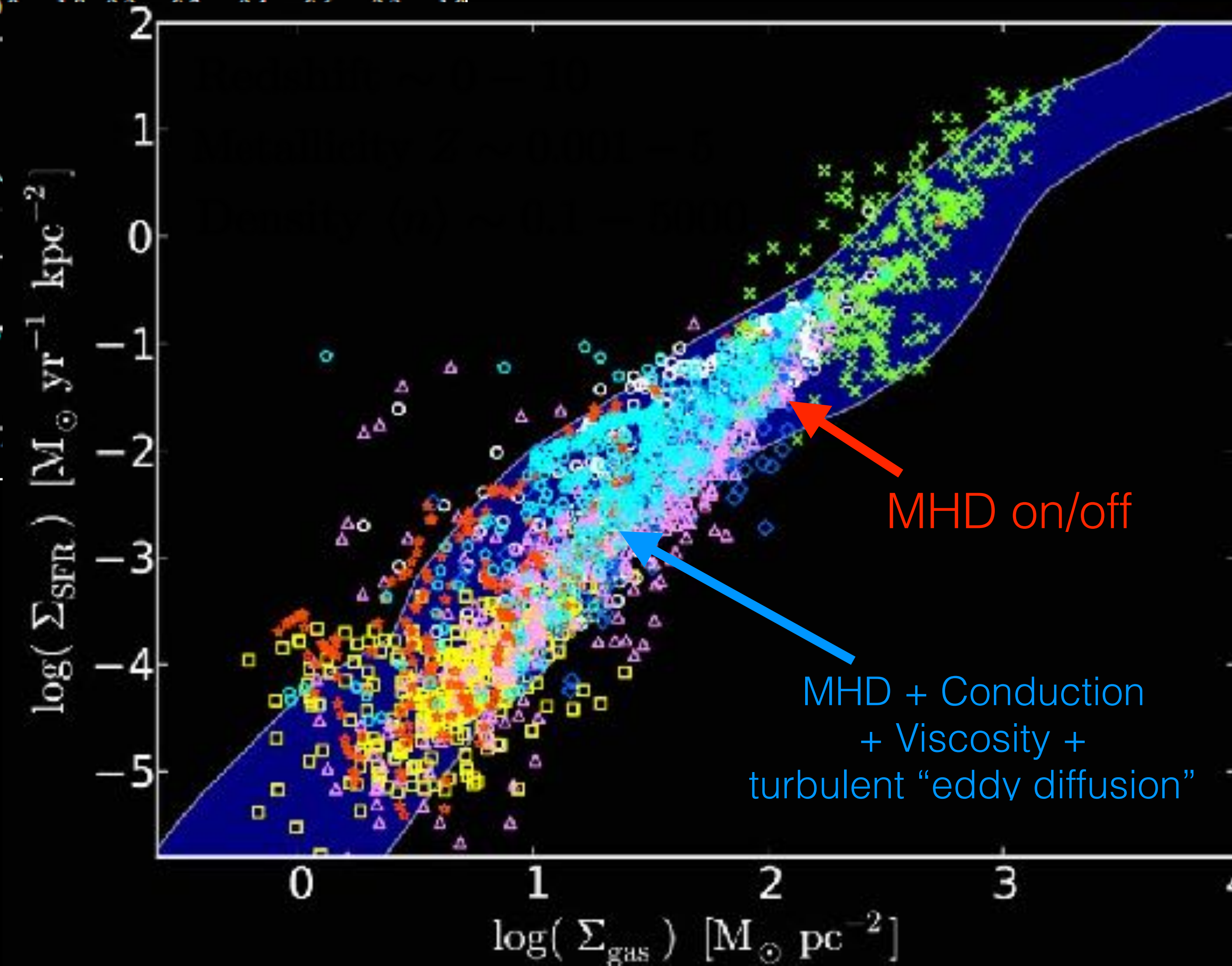
Galaxy SFRs (sub-L*) independent of MHD+diffusion

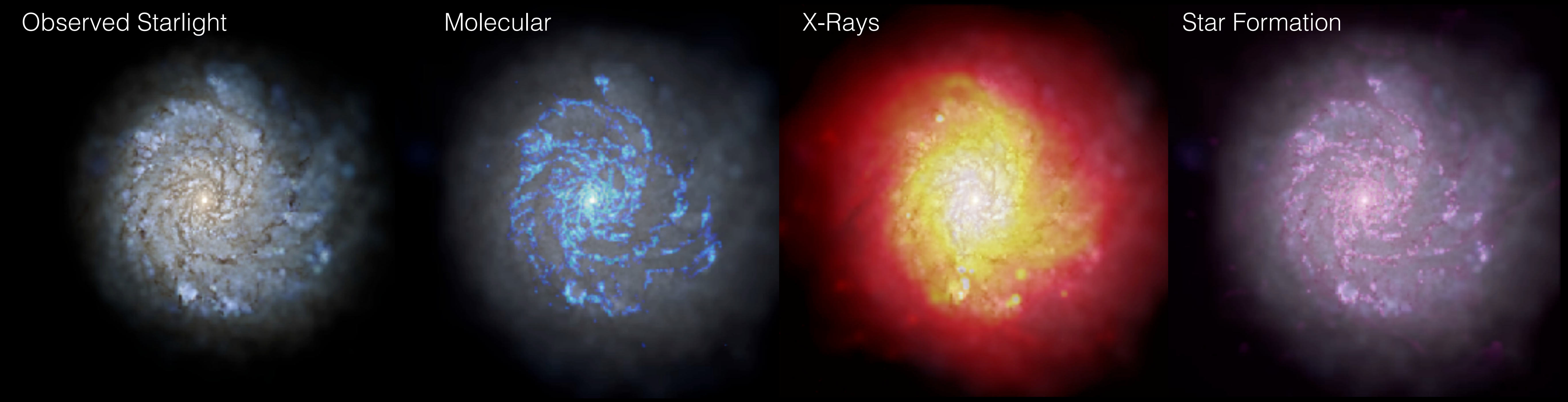
MAY NOT APPLY TO COOLING IN HOT HALOS!

Kung-Yi Su
(in prep.)









- **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