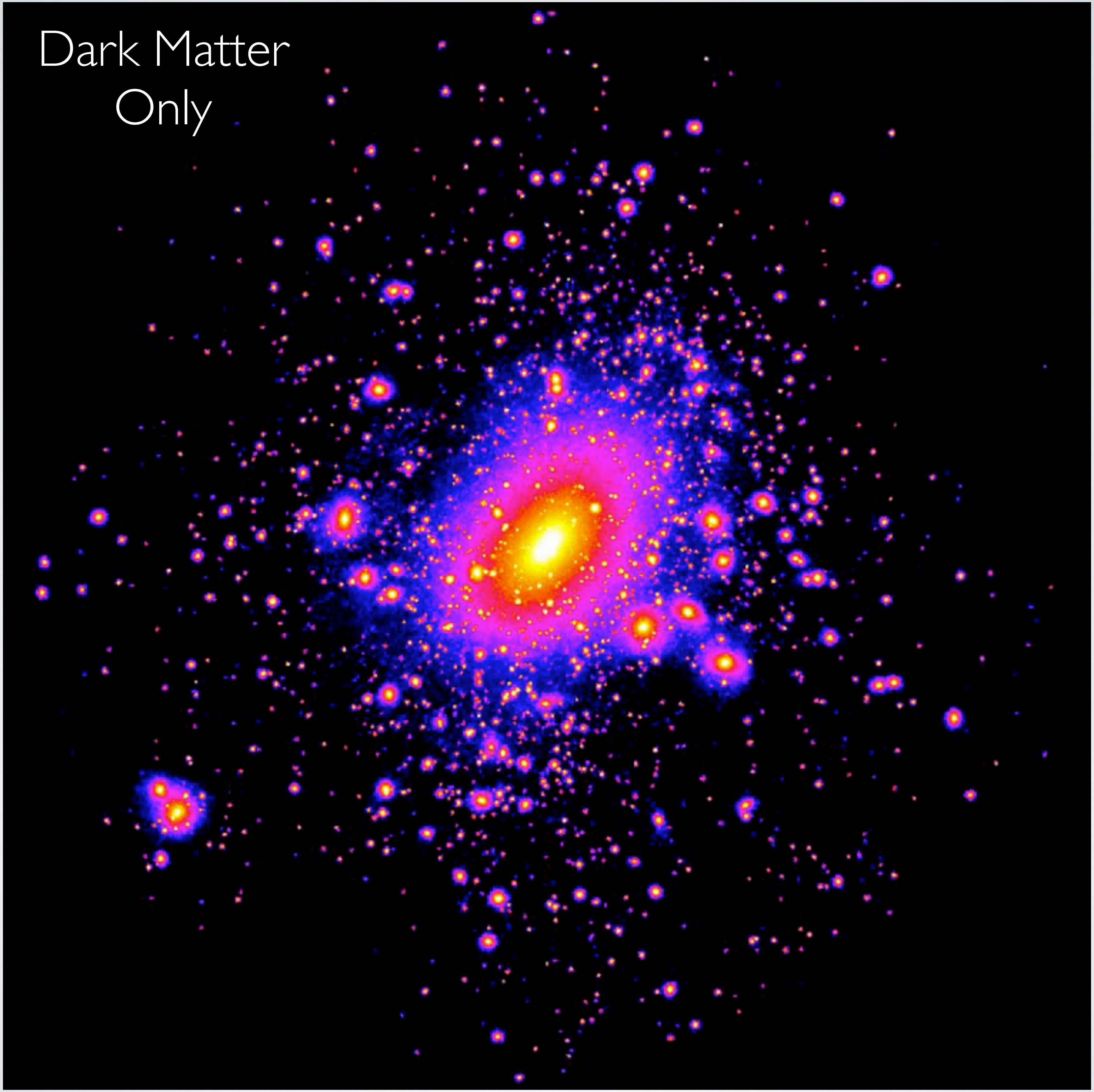
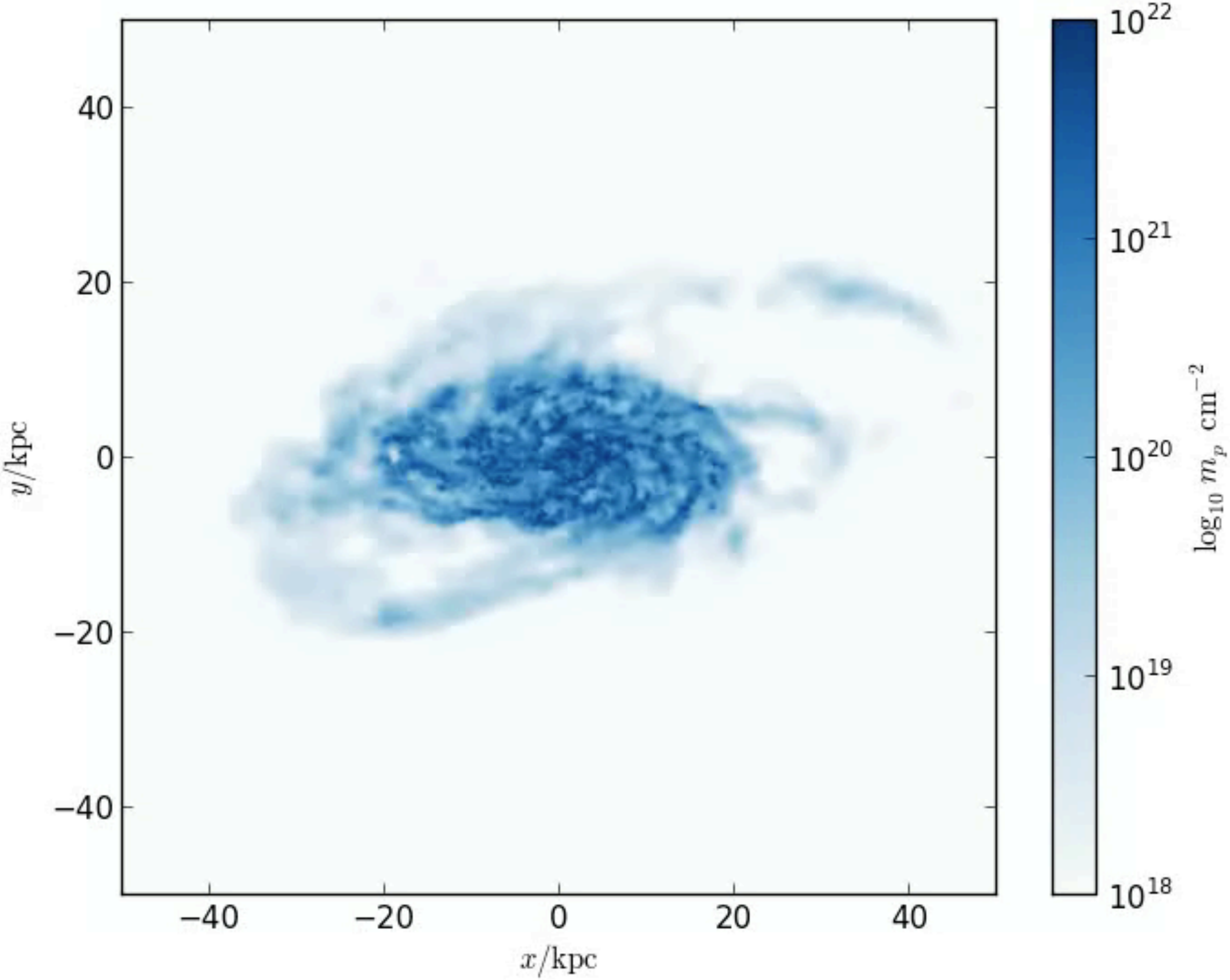
SIMULATIONS WITH BARYONIC PHYSICS

Greg Stinson (MPIA, Heidelberg)



from
Camilla
Penzo


M31:
Andromeda



40
20
0
−20
−40
y/kpc
−40
−20
0
20
40
x/kpc
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
$\log_{10}\,m_p\ \mathrm{cm}^{-2}$

GALAXY FORMATION OVERVIEW

GALAXY FORMATION INGREDIENTS

- Hydrodynamics
- Radiative gas cooling
- Star Formation
- Stellar Feedback

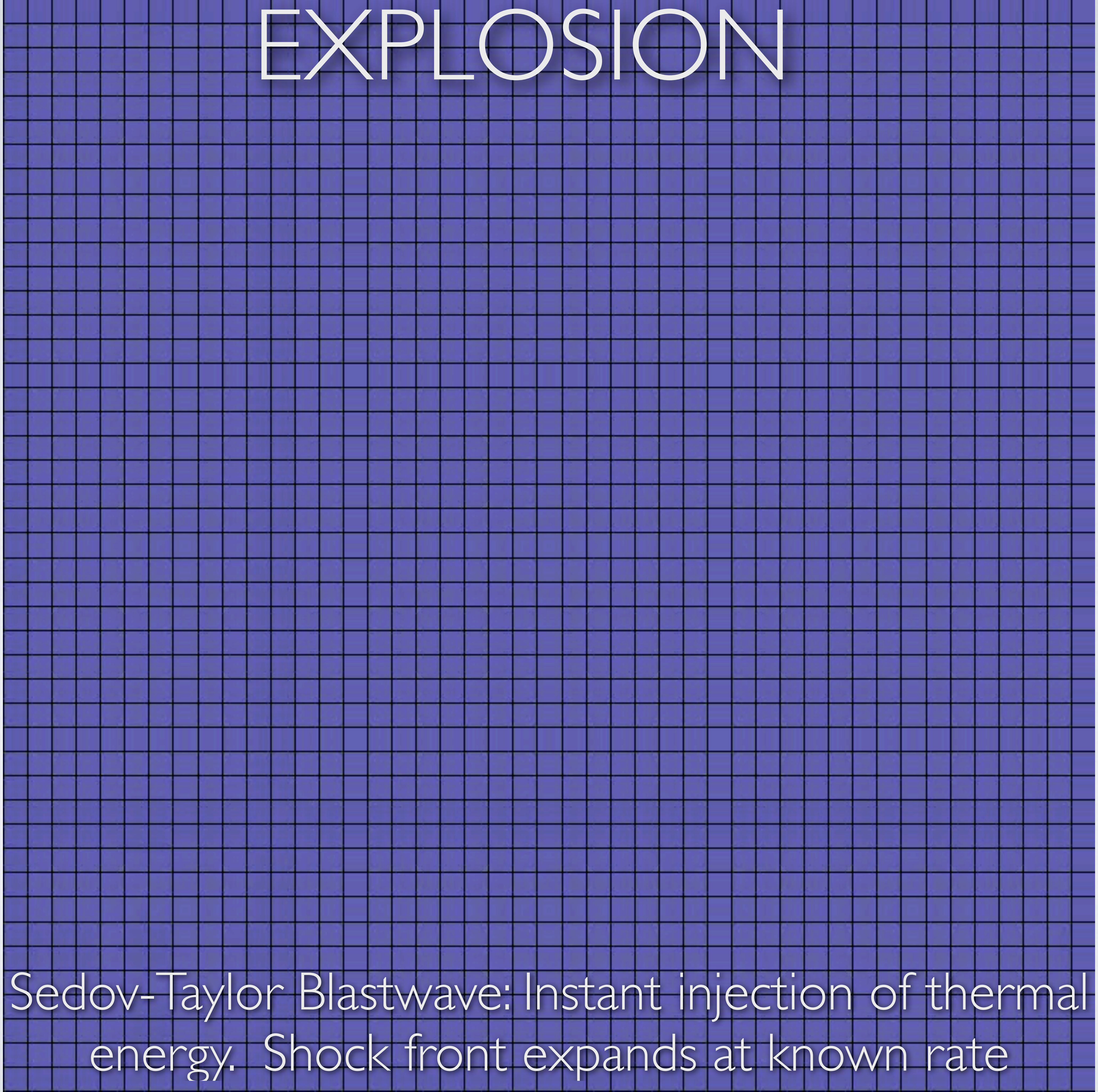
GALAXY FORMATION INGREDIENTS

- **Hydrodynamics**
- Radiative gas cooling
- Star Formation
- Stellar Feedback

HYDRODYNAMICS

- Ideally, we would simulate every subatomic particle in the Universe
- We cannot, so we make statistical approximations that we call density, pressure, viscosity, and turbulence
- Fundamental things that gas (baryonic fluid) does:
  - shocks when it collides
  - mixes when 2 phases are moving parallel to one another (shear)

EXPLOSION



cool

hot

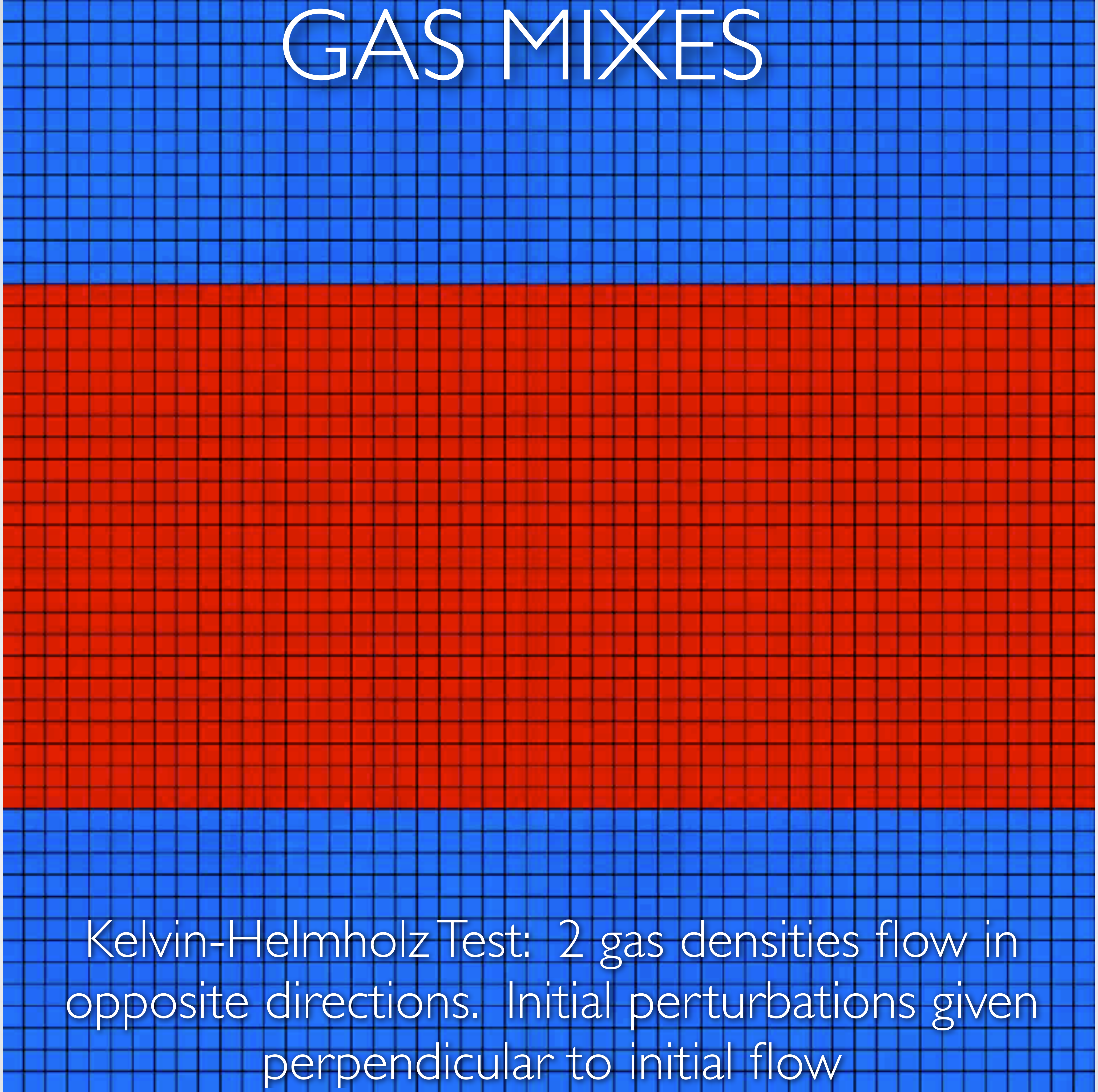
Springel
(2010)

Sedov-Taylor Blastwave: Instant injection of thermal energy. Shock front expands at known rate

GAS MIXES

low density

high density



Springel (2010)

Kelvin-Helmholz Test: 2 gas densities flow in opposite directions. Initial perturbations given perpendicular to initial flow

GAS MIXES

Rayleigh-Taylor Test: High density medium starts on top of low density medium and they mix (oil+vinegar)

HYDRODYNAMIC EQUATIONS

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

Gas moves
"Continuity"

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} + \frac{\boldsymbol{\nabla} P}{\rho} = 0$$

Pressure Pushes (F=ma)
"Euler"

$$\frac{D\epsilon}{Dt} = -\frac{P}{\rho}\vec{\nabla}.\vec{u} - \frac{1}{\rho}\vec{\nabla}.\vec{F} + \frac{1}{\rho}\Psi + \frac{\mathrm{H} - \Lambda}{\rho}$$

$$\frac{\mathrm{d}u}{\mathrm{d}t} + P \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

conduction
viscosity
heating/
cooling

Energy: Pressure heats
1st Law Thermodynamics

Solve these simultaneously

IDEAL SOLVER FOR GALAXY FORMATION

- High resolution (dynamic range)
- Accurate
- What will you follow?
  - volume
  - mass

DETERMINING DENSITY, PRESSURE, DIV(V)

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

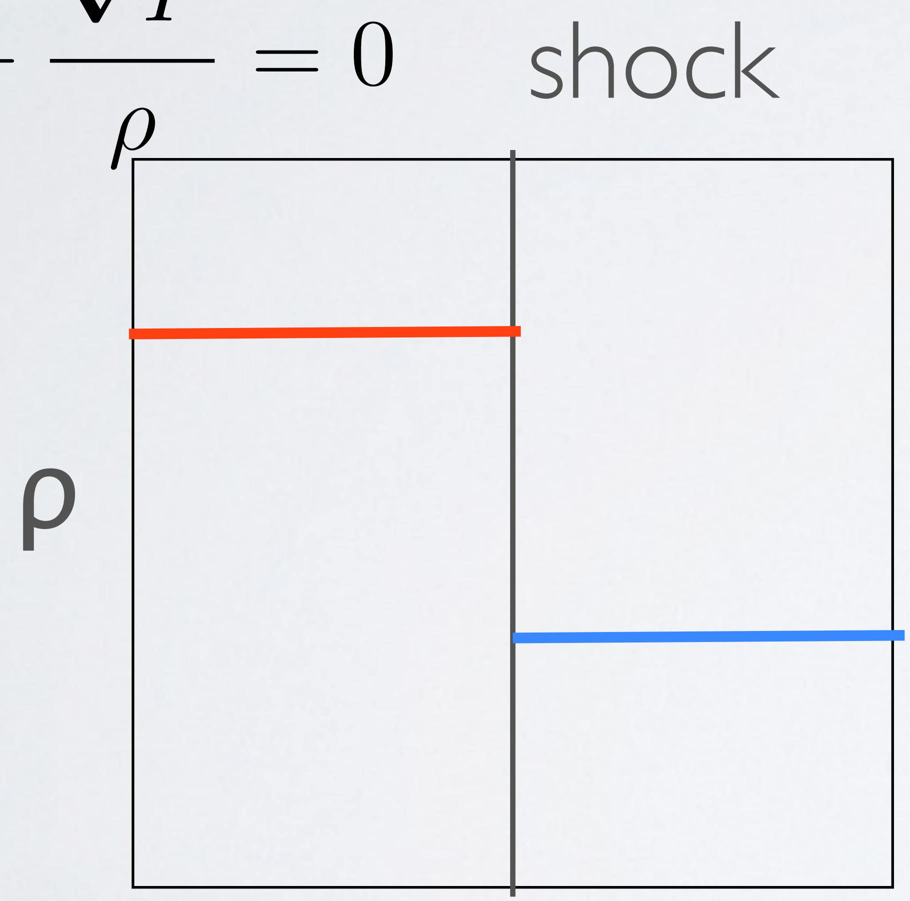
$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} + \frac{\boldsymbol{\nabla} P}{\rho} = 0$$

- When do you push versus get hot?
- Grid: Mass stored in each cell, *advected* from cell to cell
- SPH: Must find neighboring particles and determine what volume they fill

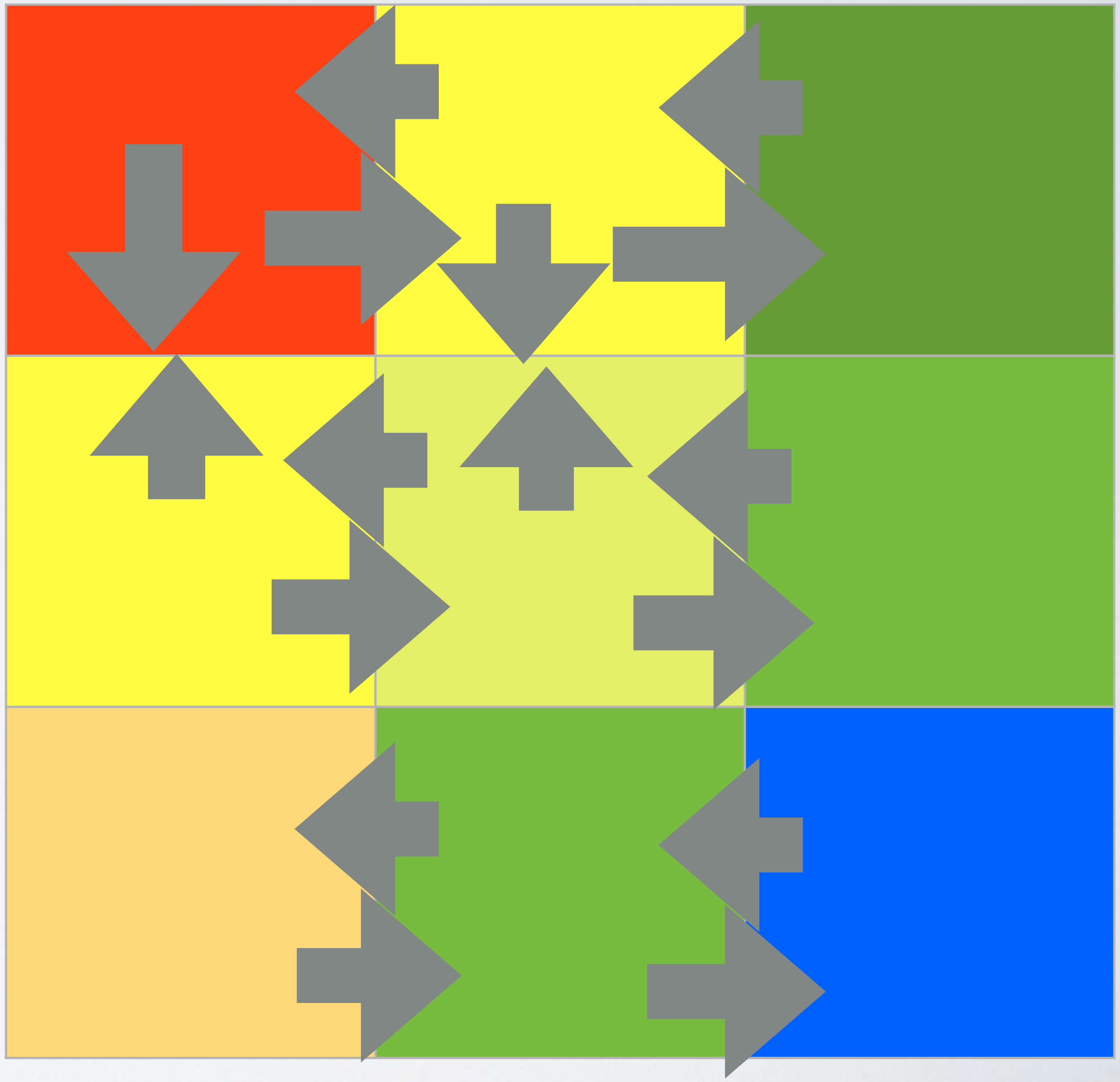
CALCULATING HYDRODYNAMICS ON GRID

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} + \frac{\boldsymbol{\nabla} P}{\rho} = 0$$



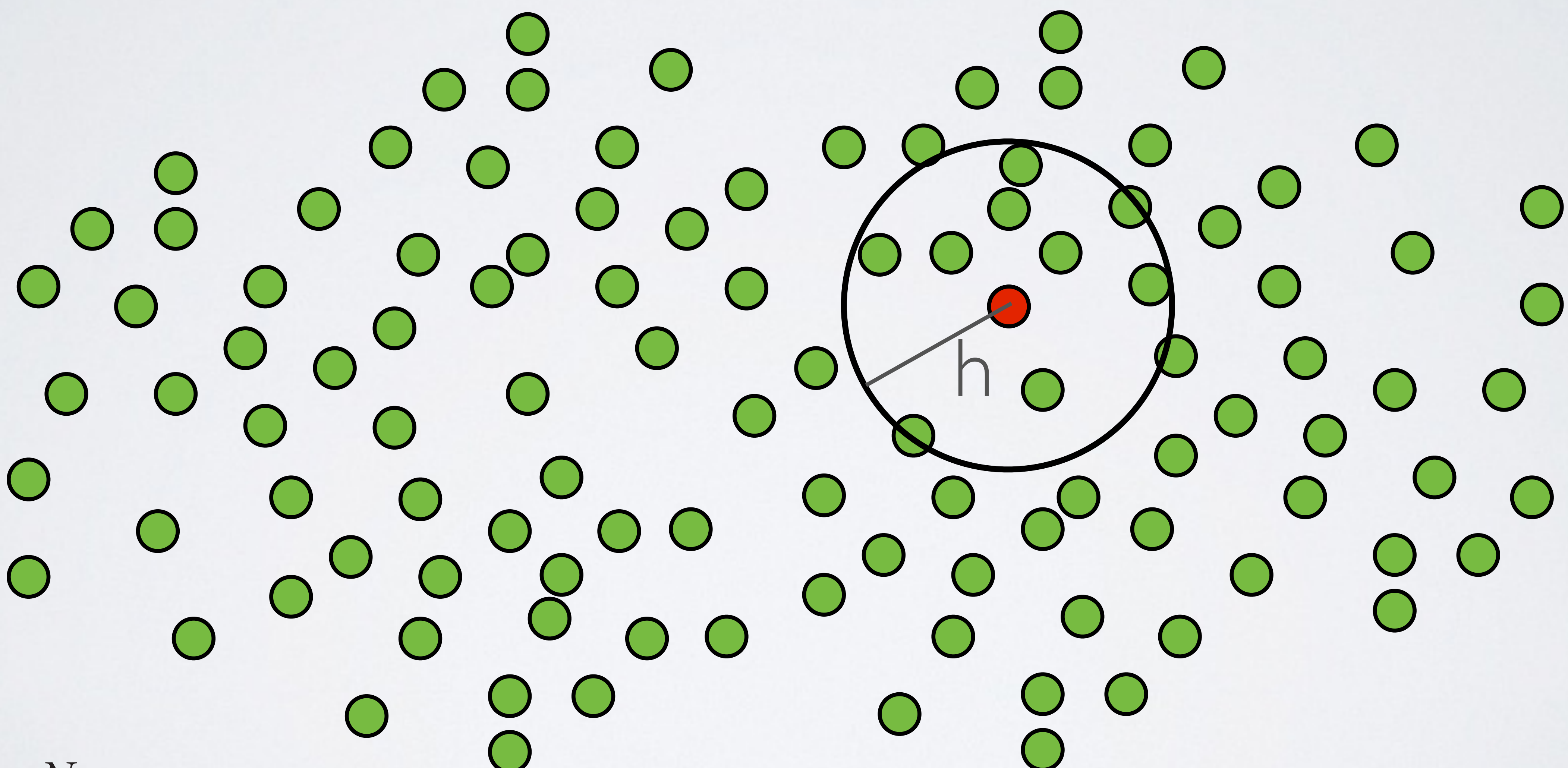
Riemann problem



SPH HYDRODYNAMIC CALCULATION

h: smoothing length - radius containing 32 nearest particles

W: Smoothing kernel - closer particles get more weighting



$$\rho_i = \sum_{j=1}^{N} m_j W(\mathbf{r}_i - \mathbf{r}_j, h_i)$$

$$(\nabla \cdot \mathbf{v})_i = \sum_j \frac{m_j}{\rho_j} \mathbf{v}_j \cdot \nabla_i W(\mathbf{r}_i - \mathbf{r}_j, h)$$

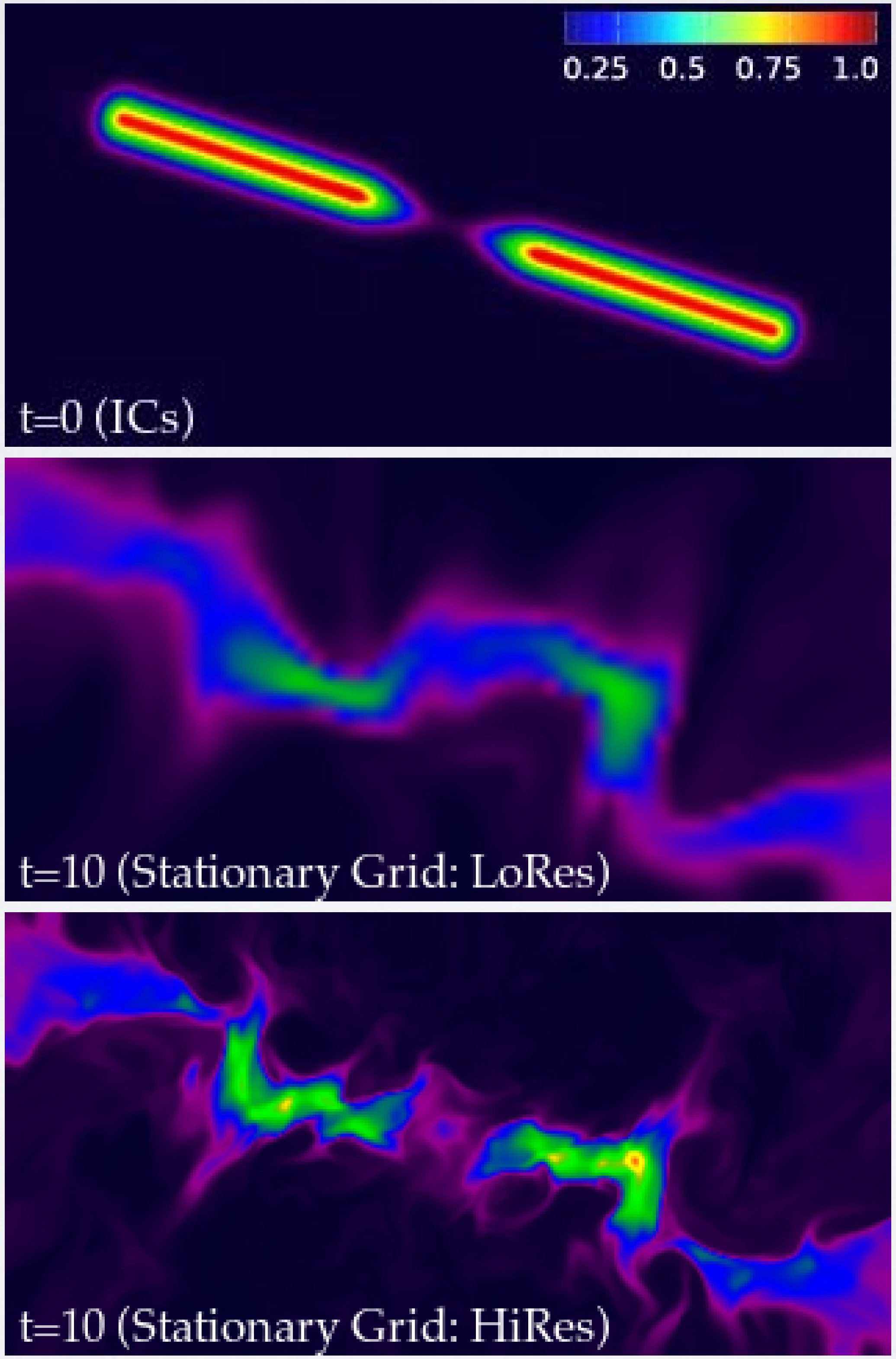
SOLVING THE EQUATIONS

- Grid: Solve the equations one by one for flux across cell boundaries
  - Discontinuities between cells resolved with Riemann shock equations
- SPH: Continuity and Force equation can be combined into one equation (Springel 2010 ARA&A)

PROBLEMS WITH METHODS

- Grid:
  - No “Galilean invariance”⇒moving changes solution
  - Grid imprints itself on solution

GRID PROBLEM



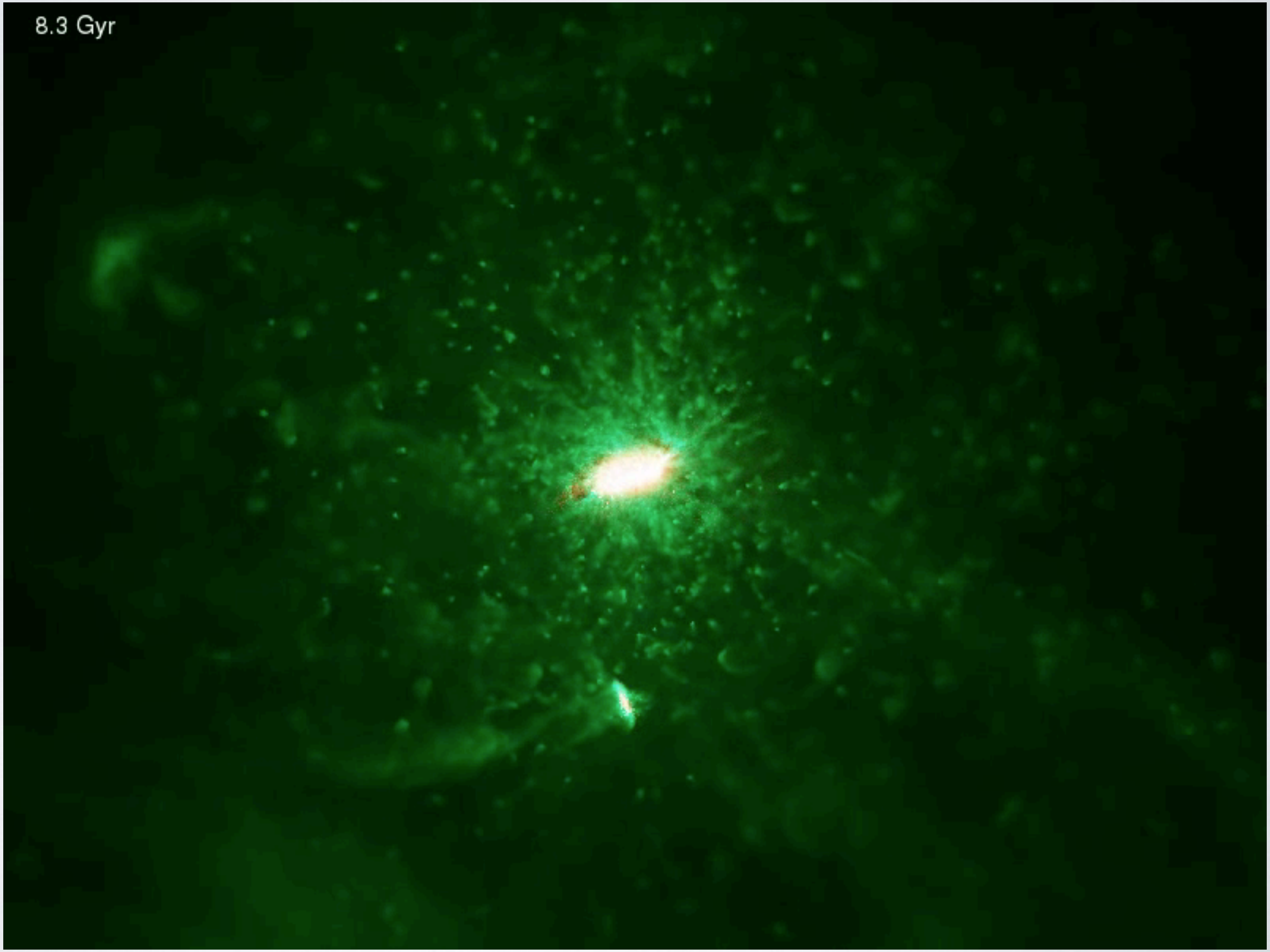
PROBLEMS WITH METHODS

- Grid:
  - No "Galilean invariance"⇒moving changes solution
  - Grid imprints itself on solution
- SPH:
  - Does not resolve shocks
  - Does not mix without encouragement: blob problem

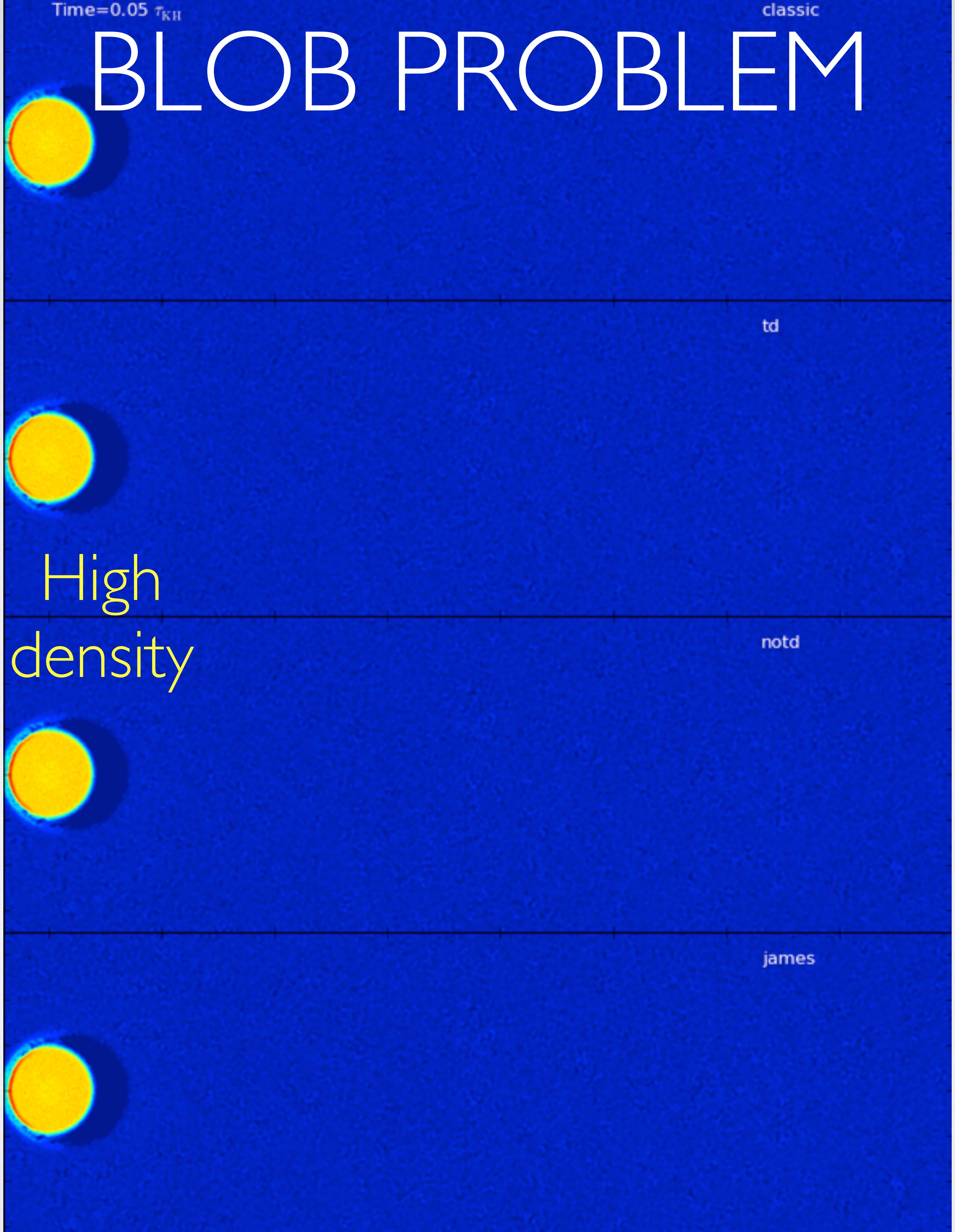
BLOB PROBLEM

10^7 particles inside r_{vir}

hot gas unstably cools



BLOB PROBLEM



old version

Low density

newest version

MOVING MESH

AREPO

GRID

Eulerian
Adaptive Mesh Refinement
(AMR)

PARTICLES

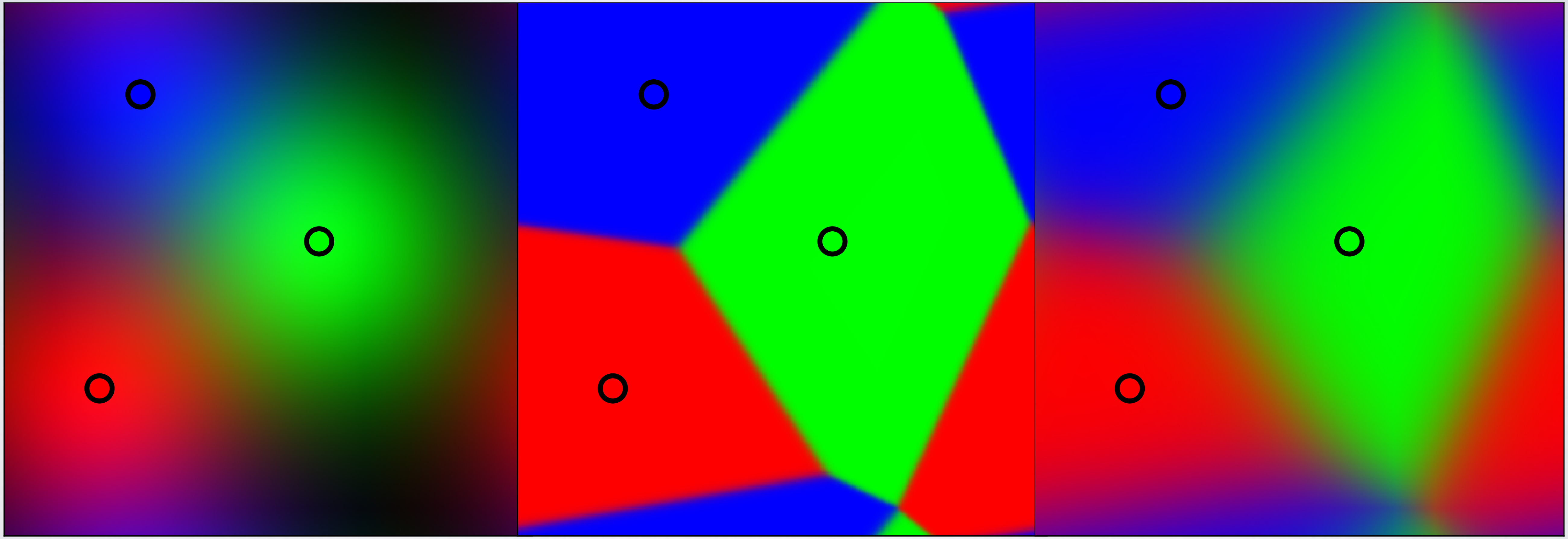
Lagrangian
Smoothed Particle
Hydrodynamics (SPH)

PROBLEMS WITH METHODS

- Grid:
  - No “Galilean invariance”⇒moving changes solution
  - Grid imprints itself on solution
- SPH:
  - Does not resolve shocks
  - Does not mix without encouragement: blob problem
- Moving Mesh:
  - Inaccuracies from solving equations on irregular cells

DIVIDING THE VOLUME

SPH AREPO Gizmo



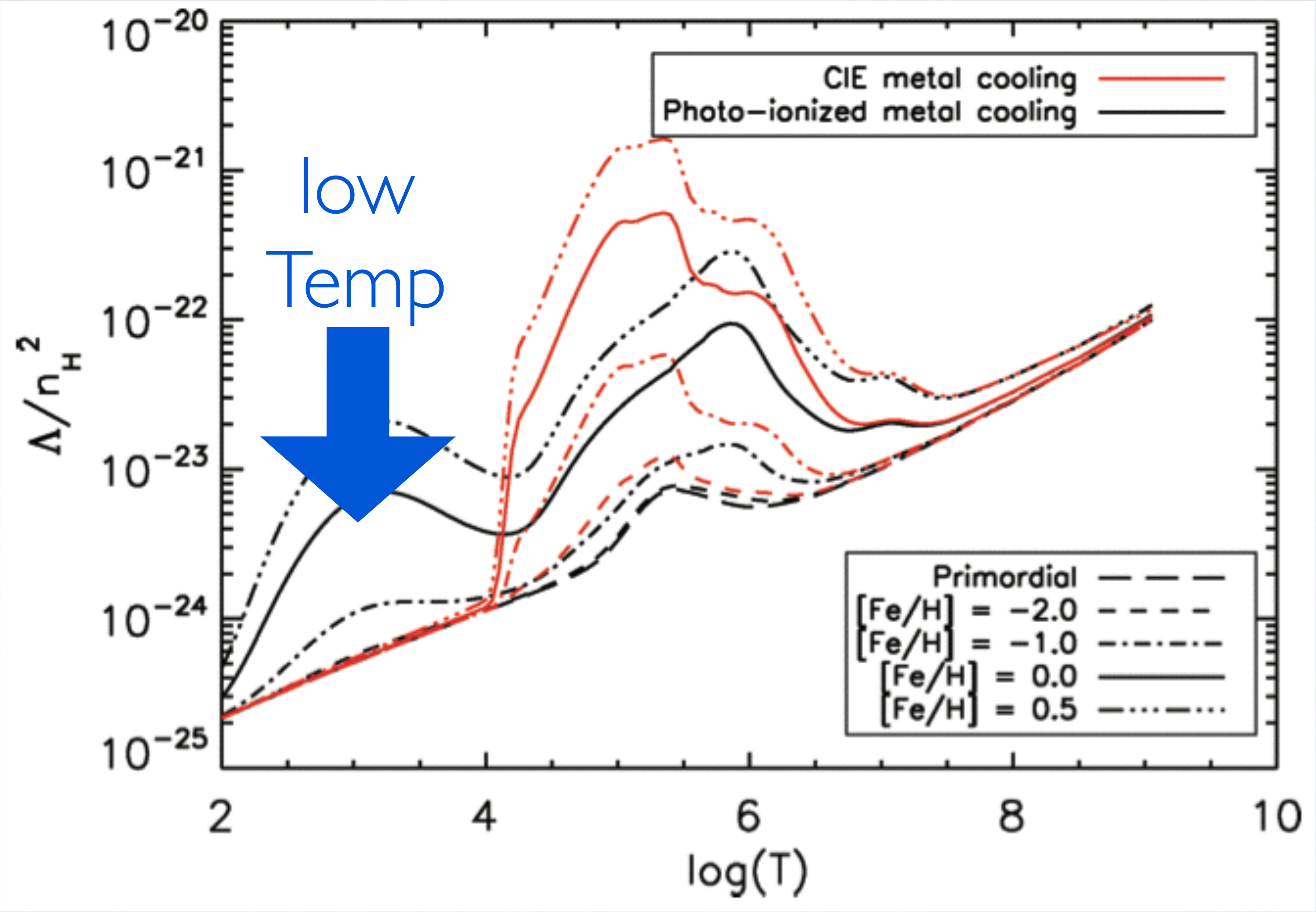
http://www.tapir.caltech.edu/~phopkins/Site/GIZMO.html

http://www.tapir.caltech.edu/~phopkins/Site/GIZMO_files/gizmo.pdf

GALAXY FORMATION INGREDIENTS

- Hydrodynamics
- **Radiative gas cooling**
- Star Formation
- Stellar Feedback

GAS COOLING CURVE

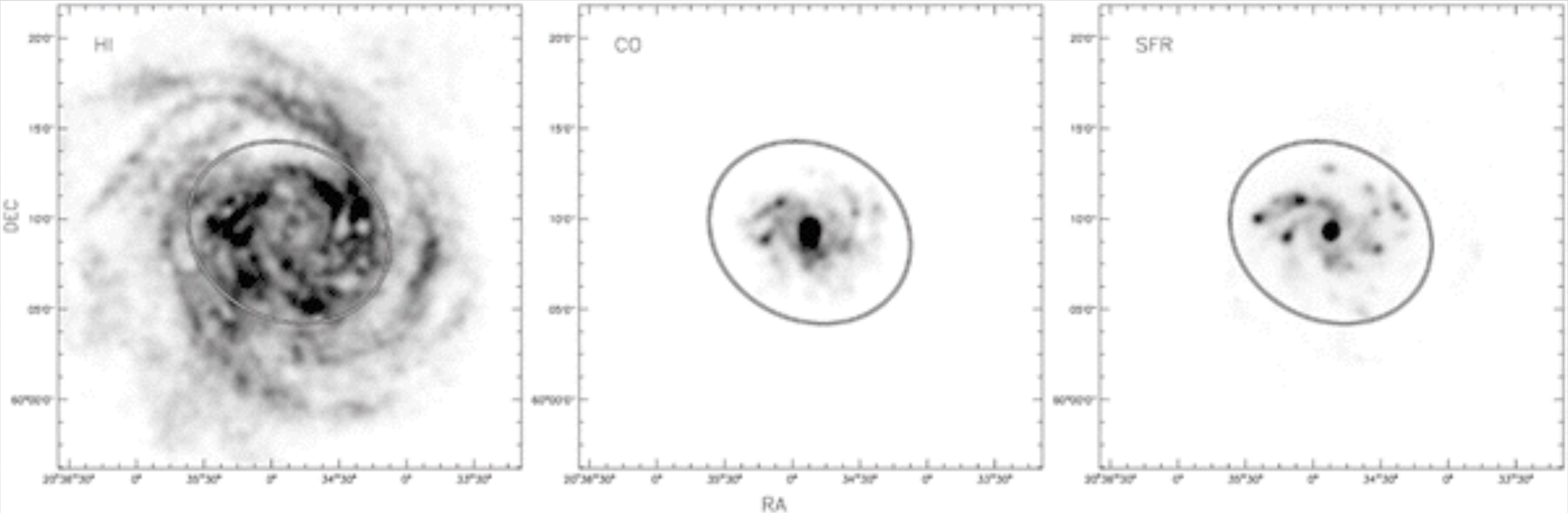


optically thin approximation: calculating radiative transfer is expensive!

GALAXY FORMATION INGREDIENTS

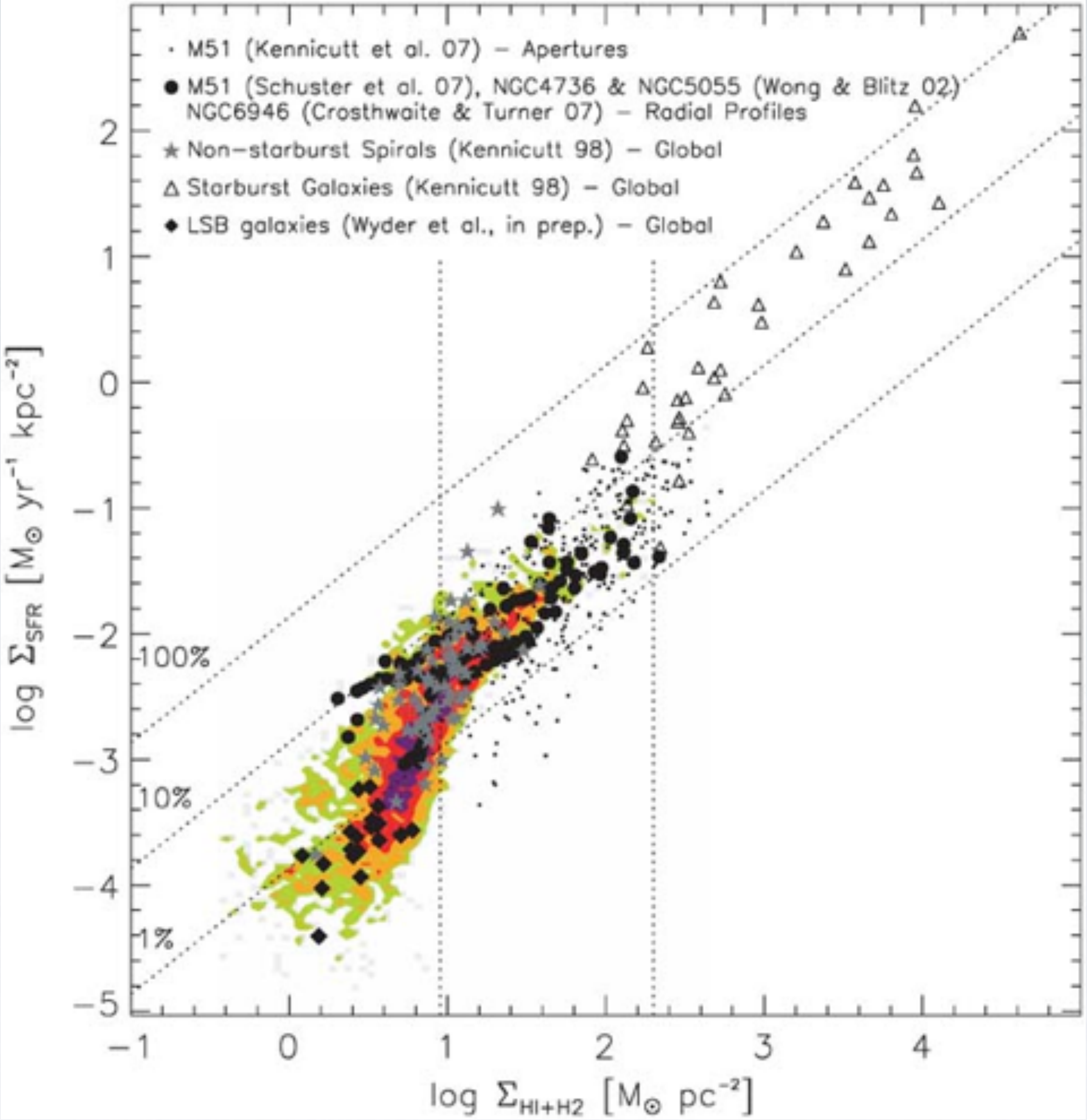
- Hydrodynamics
- Radiative gas cooling
- **Star Formation**
- Stellar Feedback

HI Molecular Gas Star Formation



GAS-STAR FORMATION SURFACE DENSITY RELATIONSHIP

Star Formation



Gas

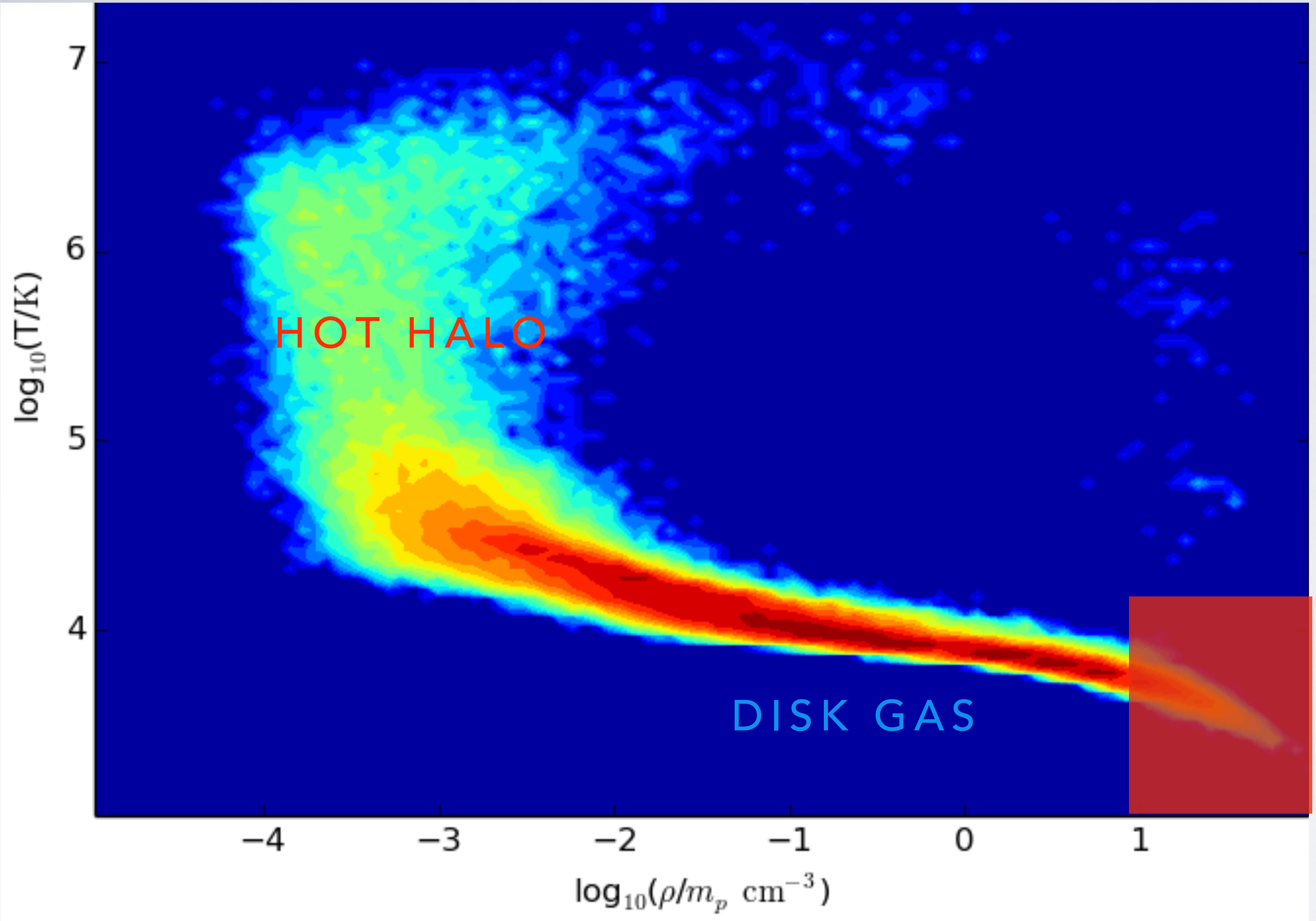
GAS-STAR FORMATION **SURFACE** DENSITY RELATIONSHIP

$$\frac{\Delta M_{\star}}{\Delta t} = c^{\star} \frac{M_{gas}}{t_{dyn}}$$

$$t_{dyn} \sim \frac{1}{\sqrt{G\varrho}}$$

$$\frac{\Delta \varrho_{\star}}{\Delta t} = c^{\star} \varrho_{gas}^{1.5} \qquad c^{\star} \sim 2\%$$

STAR FORMATION IN SIMULATION



highest resolved density

$$n_{th} = \frac{50 \times 10^5\ M_\odot}{(310\ \mathrm{pc})^3}$$

$n_{th} = 10\ \mathrm{cm}^{-3}$

STARS FORM FROM COOL, DENSE GAS

T_{max} = 15000 K; n_{min} = 10 cm-3 (resolved density)
Inherit kinematics and chemistry from parent gas

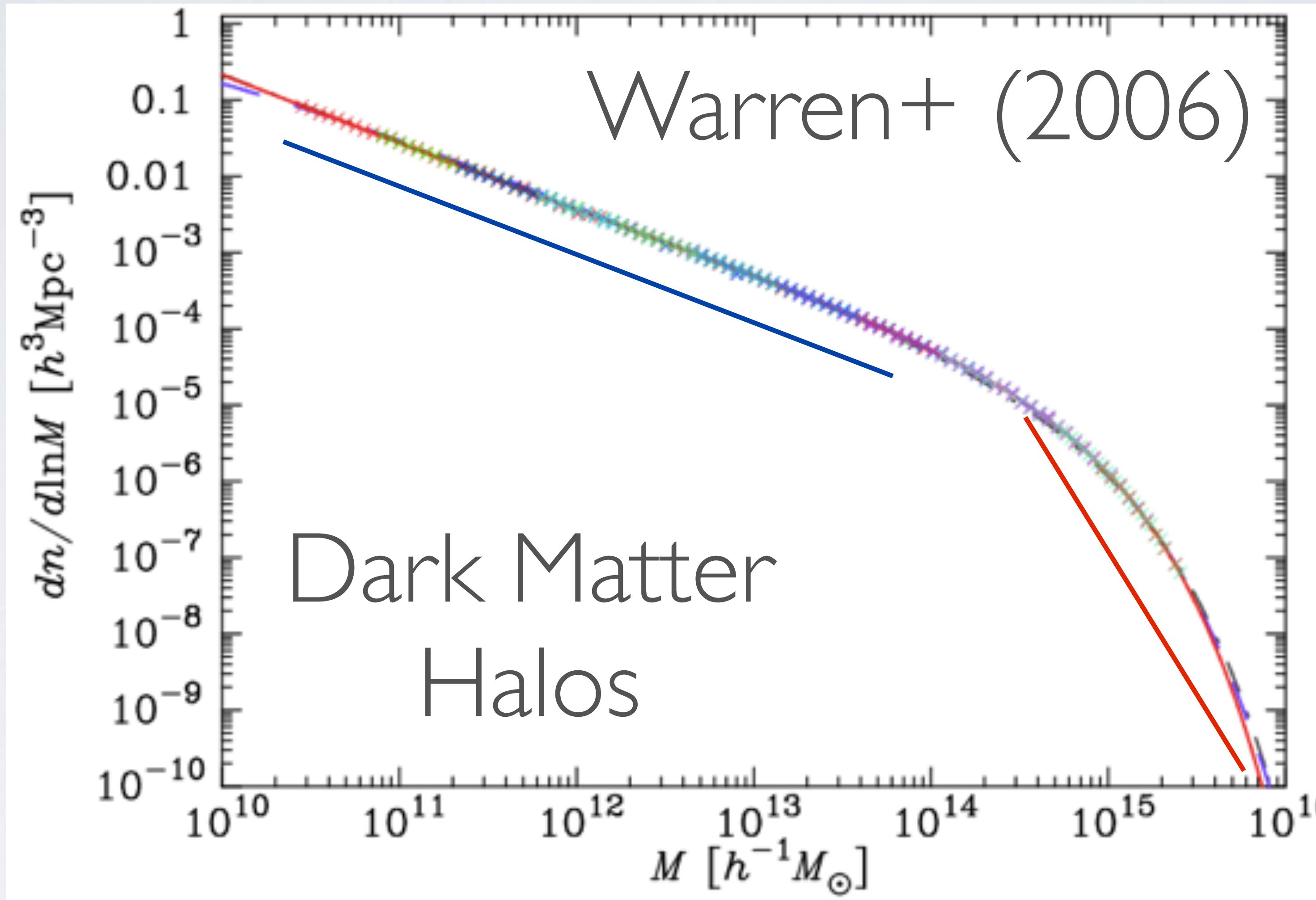
HOW DOES THAT WORK?

- Not well: Massive cooling instabilities lead to many unstable clumps

HOW EFFICIENT IS STAR FORMATION IN OBSERVED GALAXIES?

CONNECTING SIMULATIONS TO OBSERVATIONS

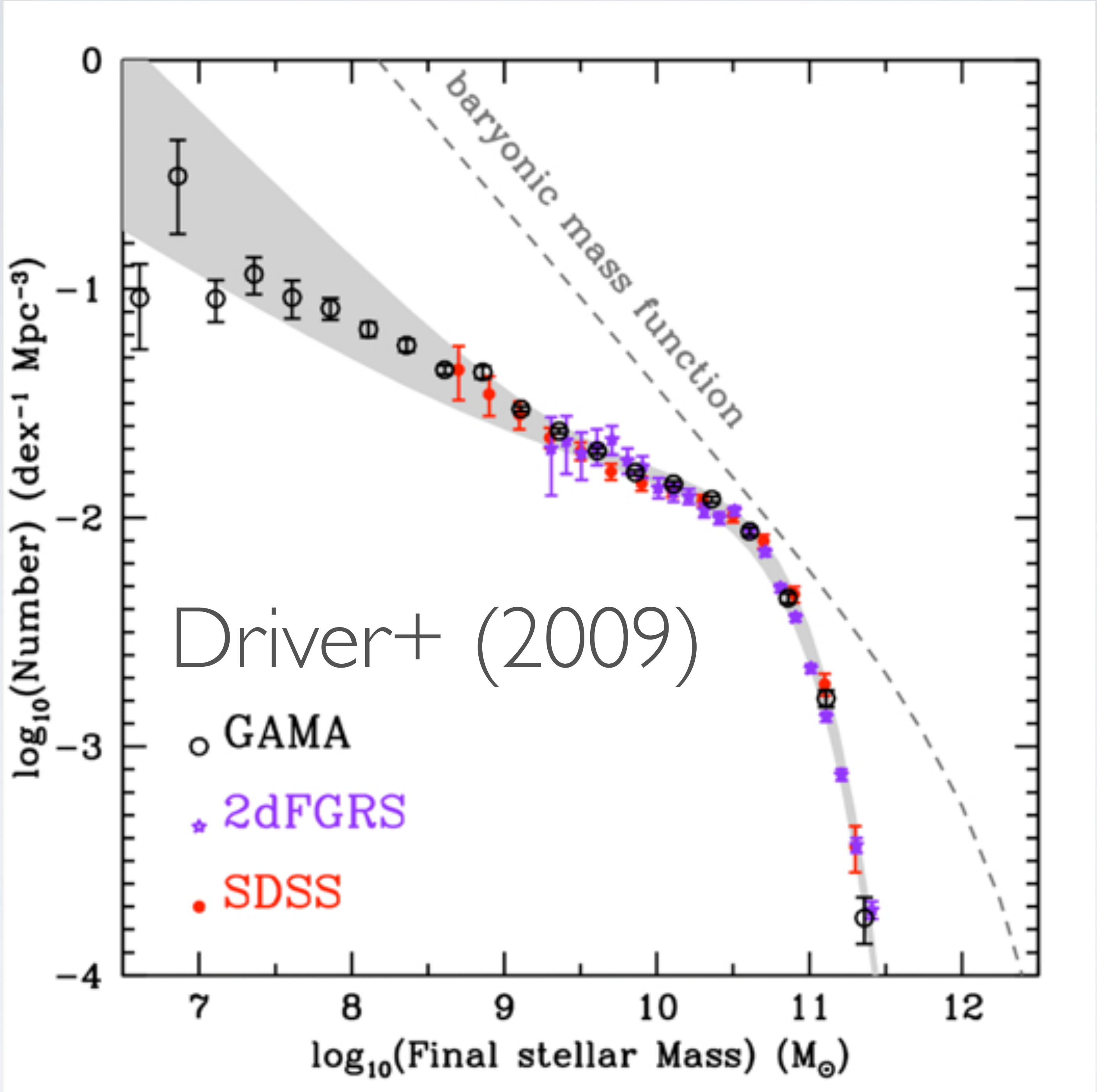
MASS FUNCTION



$$n_R(M) \propto M^{-1-\alpha} \exp\left[-\text{const.} \times \left(\frac{M^{1-\alpha}}{R}\right)^2\right]$$

power law + exponential

SLOAN DIGITAL SKY SURVEY



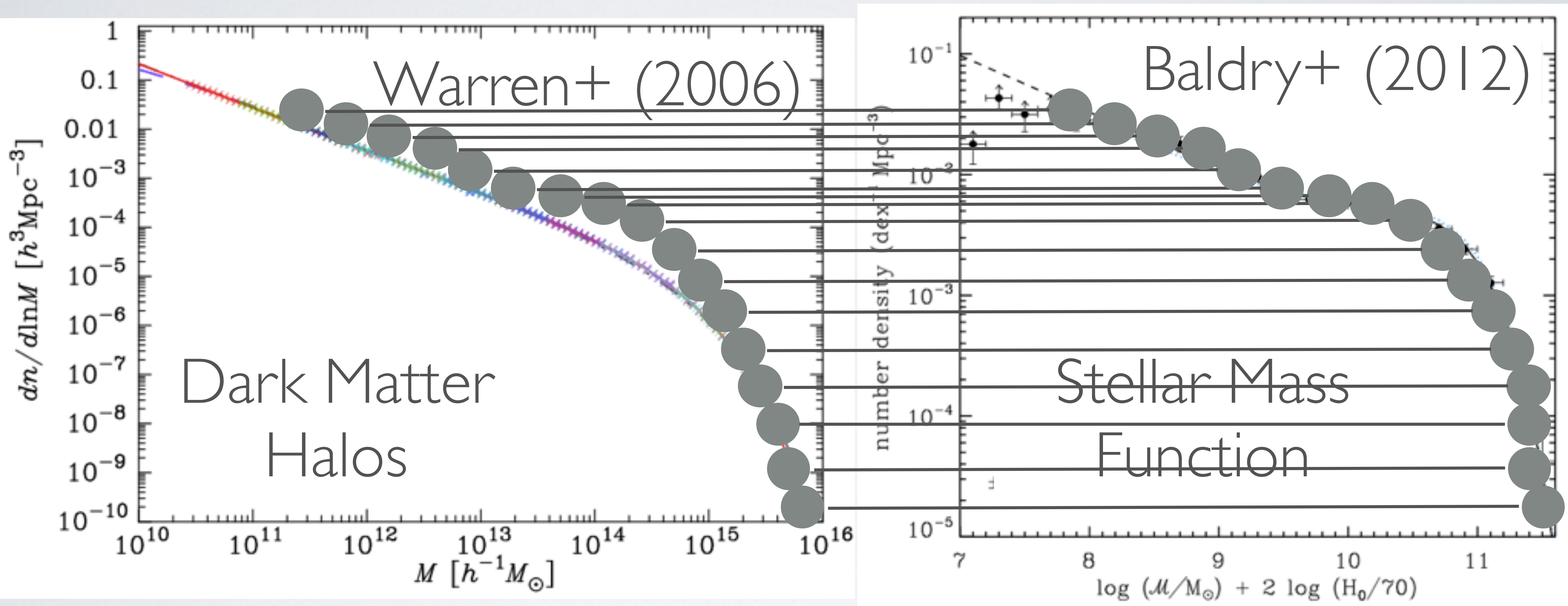
STELLAR MASS FUNCTION

luminosity translated to stellar mass

Different shape from halo mass function!

MASS VS LIGHT

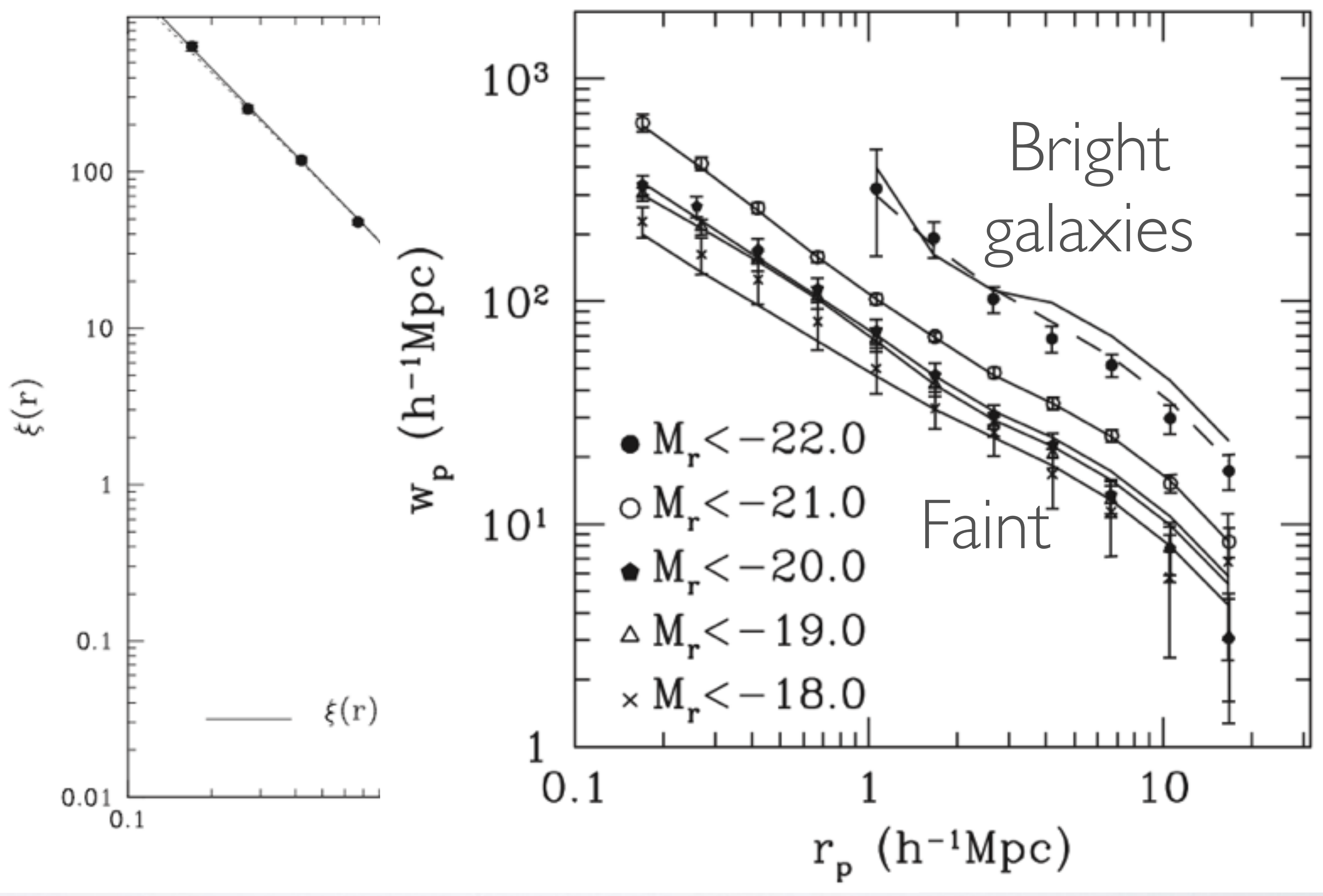
Put brightest galaxy into most massive DM halo



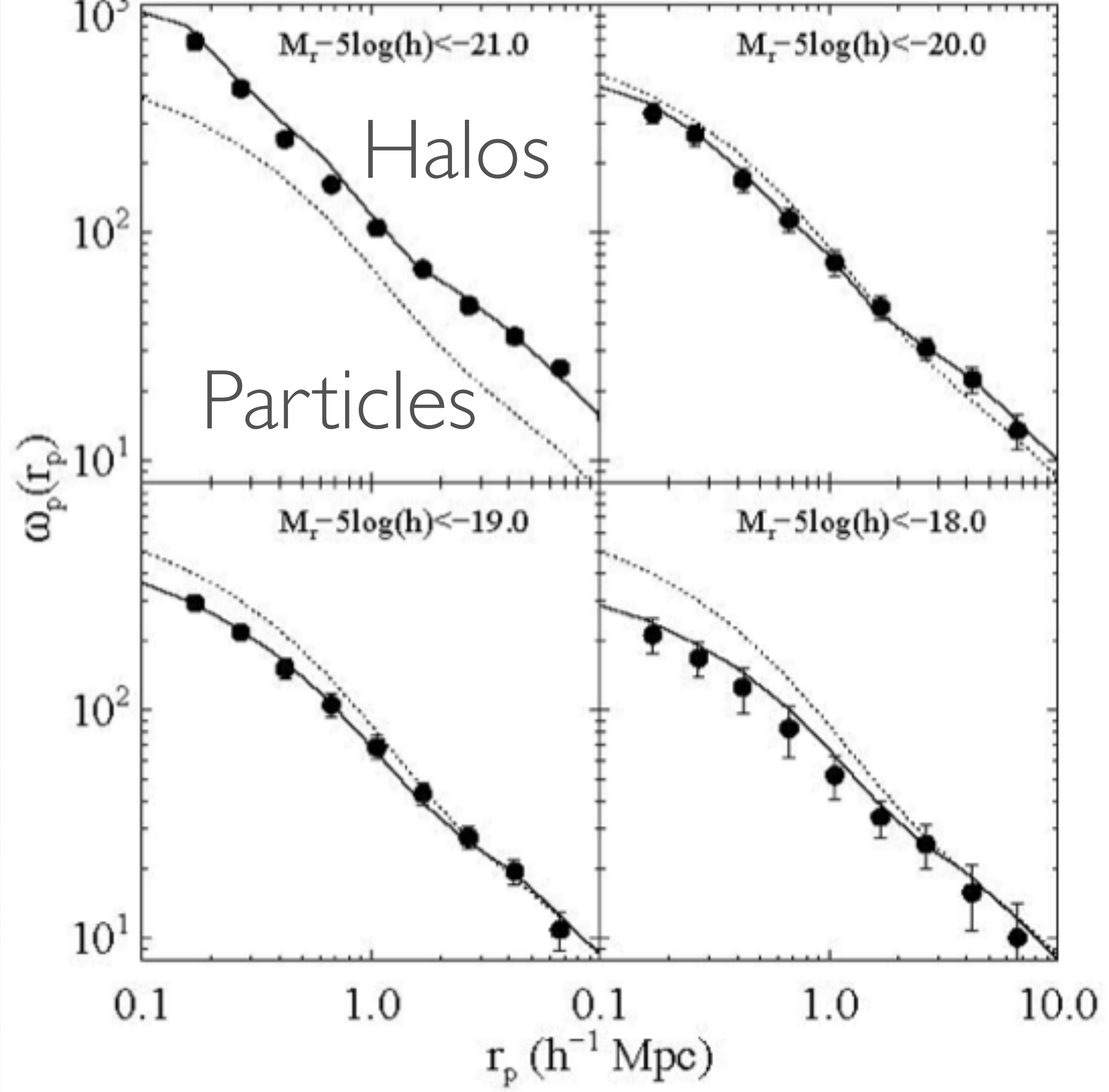
Abundance matching

How do we test? Clustering


CLUSTERING



CORRELATION FUNCTION



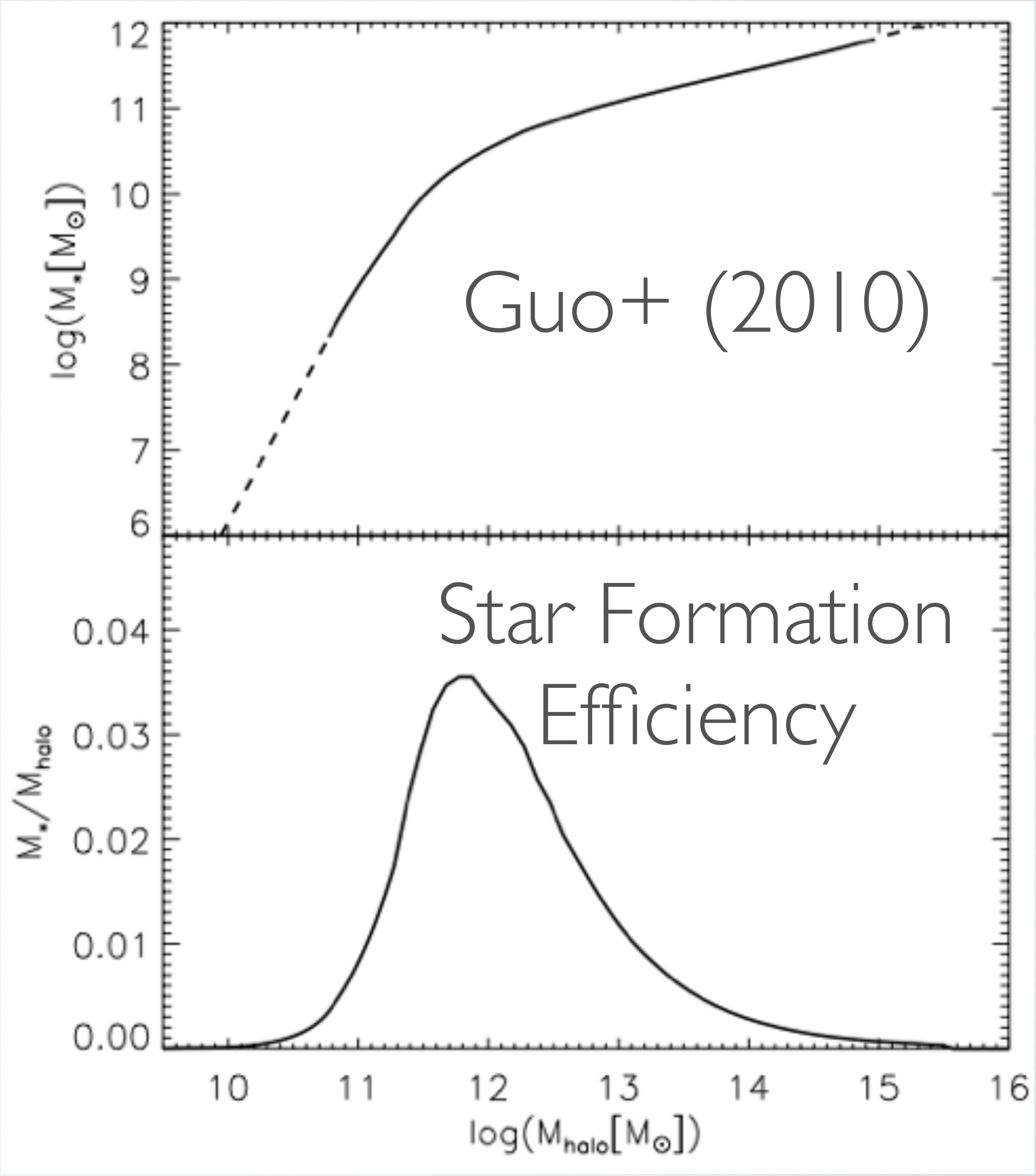
Conroy+ (2006)

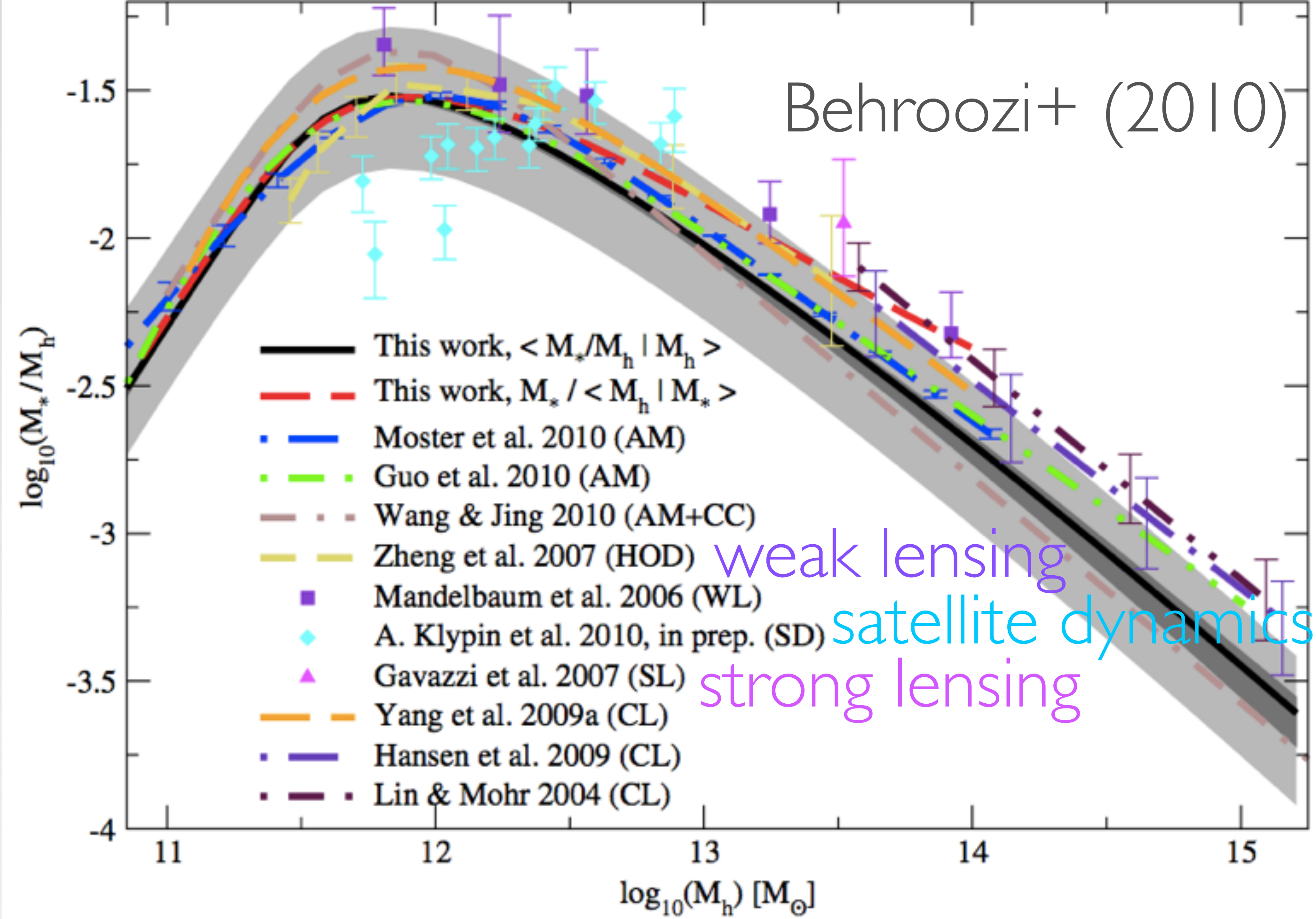
ABUNDANCE MATCHING

Clustering matches well!

ABUNDANCE MATCHING

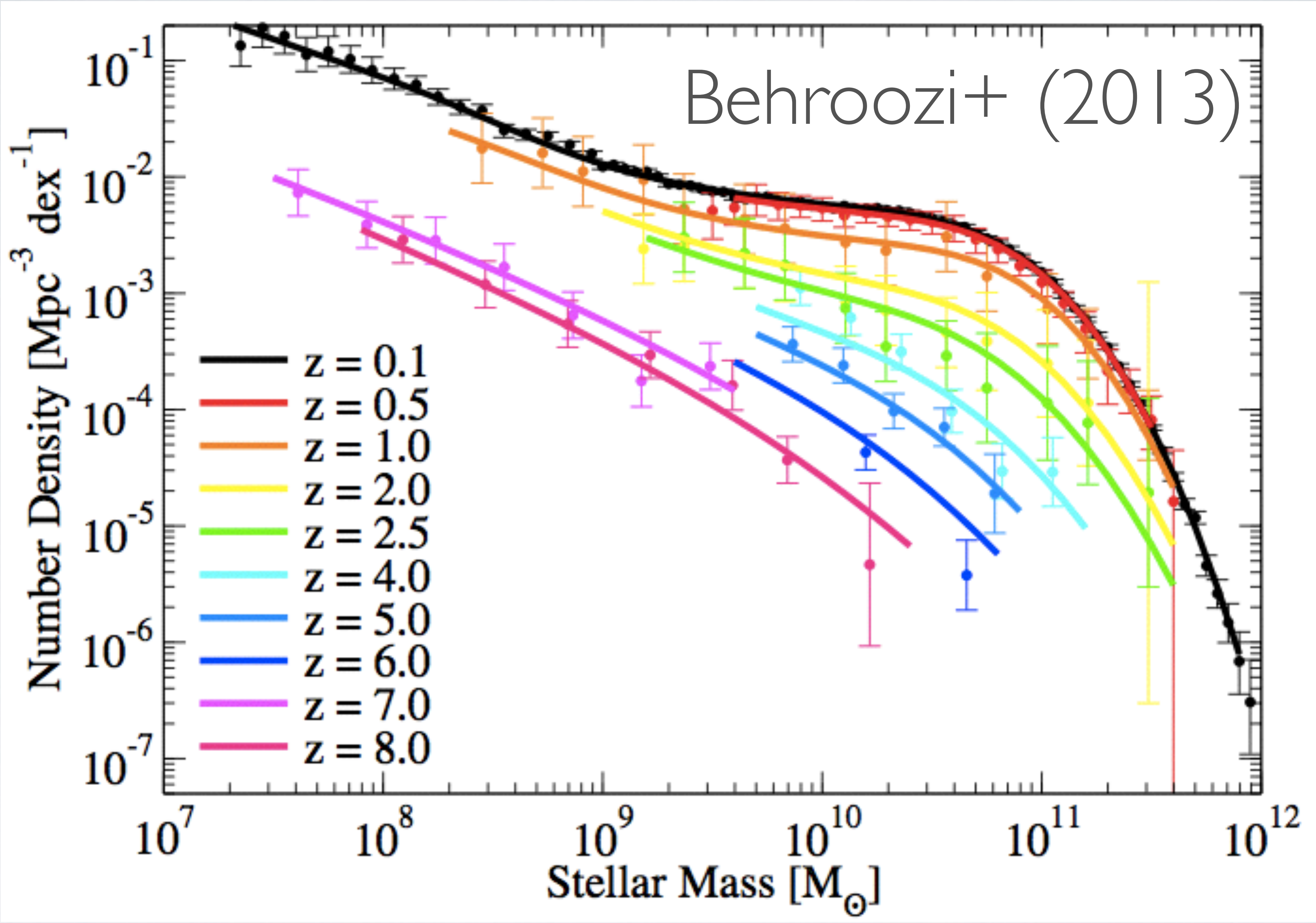
- Star formation is low efficiency at all masses (10-20% of baryons at peak: MW mass)
- Efficiency drops to low and high masses





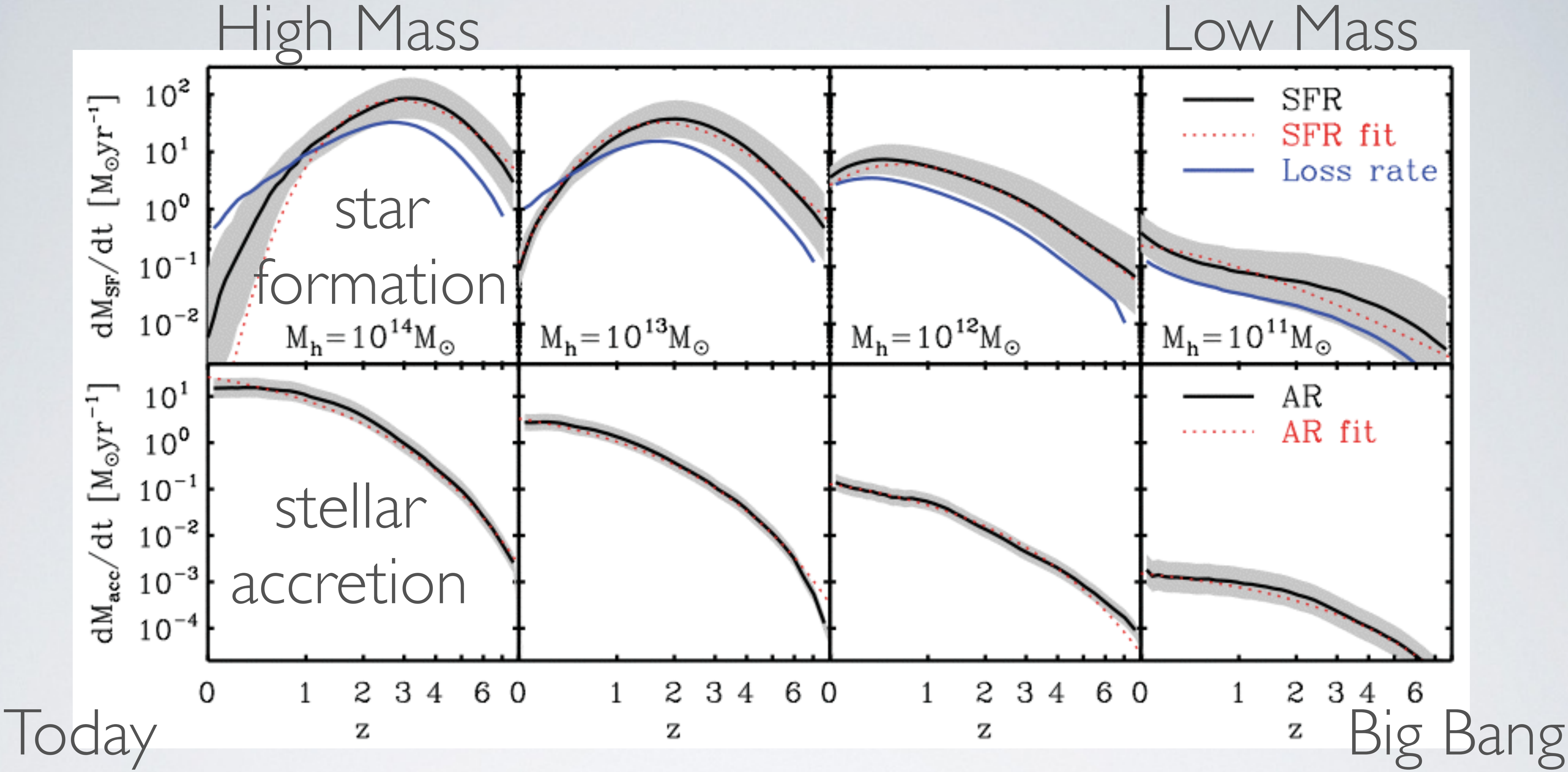
ABUNDANCE MATCHING COMPARED TO OTHER OBSERVATIONS


Hubble Ultra Deep Field
HST WFC3 IR
z = 0-10
LOOKING BACK THROUGH TIME



ABUNDANCE MATCHING EVOLUTION

Observed Luminosity Function evolution

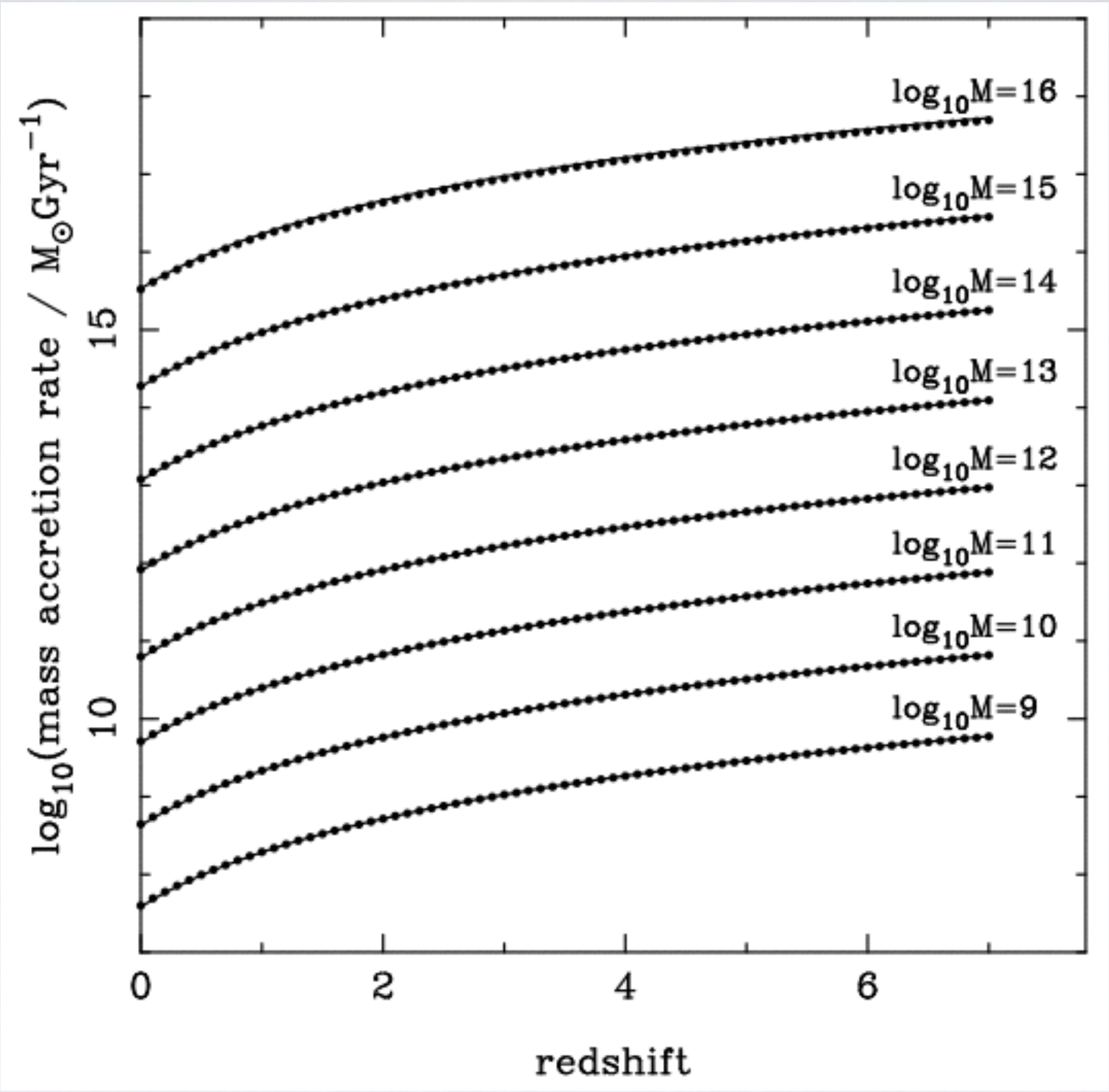


ABUNDANCE MATCHING EVOLUTION

Moster+ (2013)

star formation histories are mass dependent:

little galaxies form stars **late**



Miller+ (2006)

DARK MATTER ACCRETION

is **not** mass dependent in standard cosmology

TAKE AWAY

- In real galaxies, star formation is **inefficient**
- **When** stars forms depends on **halo mass**
- Star formation history does not follow dark matter accretion history

HOW TO LIMIT STAR FORMATION?

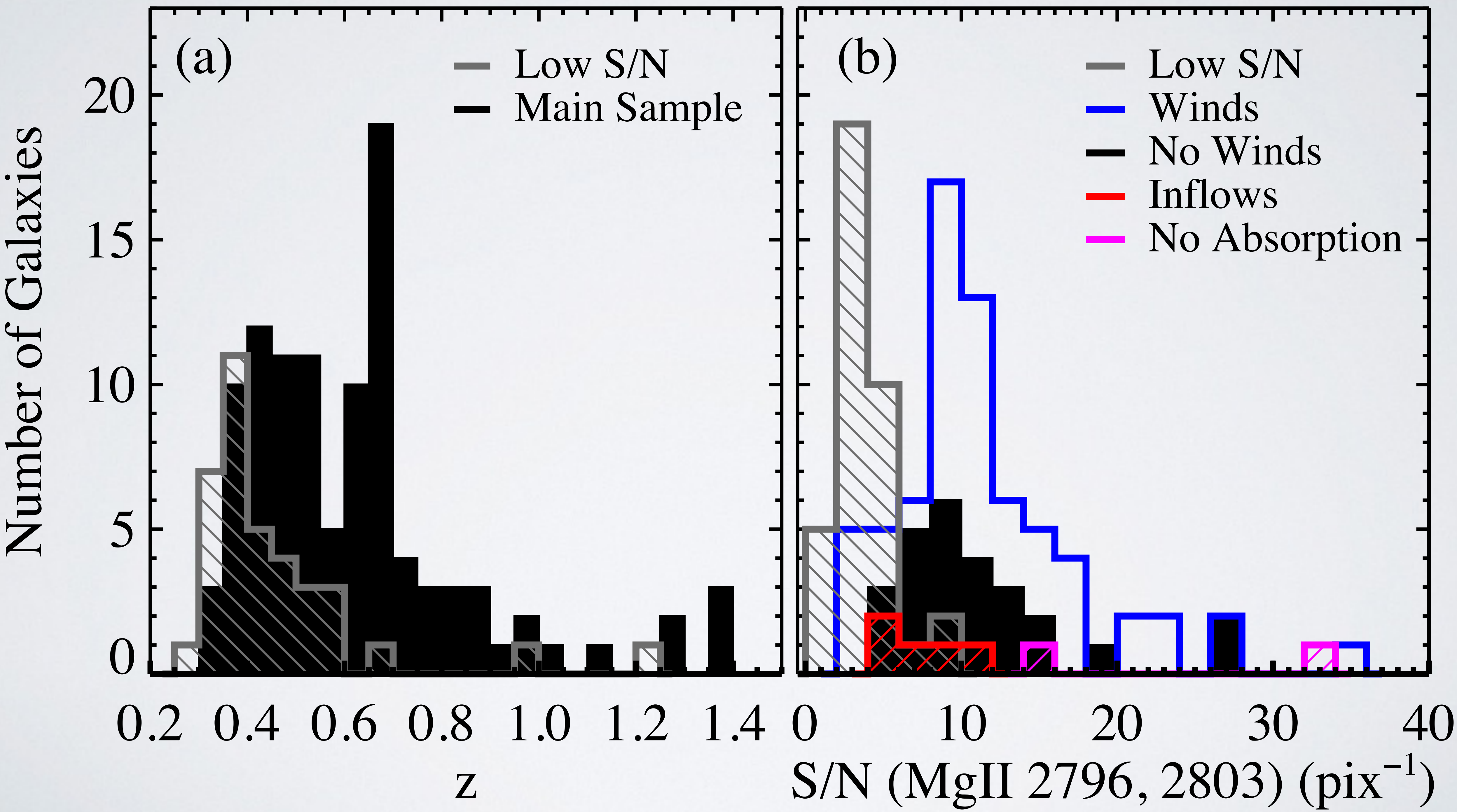
- You've got gas cooling into galaxy disk
- Two ways to stop it:
  - Stop gas from cooling so quickly
  - Blast gas away after it forms stars

OBSERVED OUTFLOWS

M82: the poster child for outflows

OBSERVED OUTFLOWS

They are observed frequently

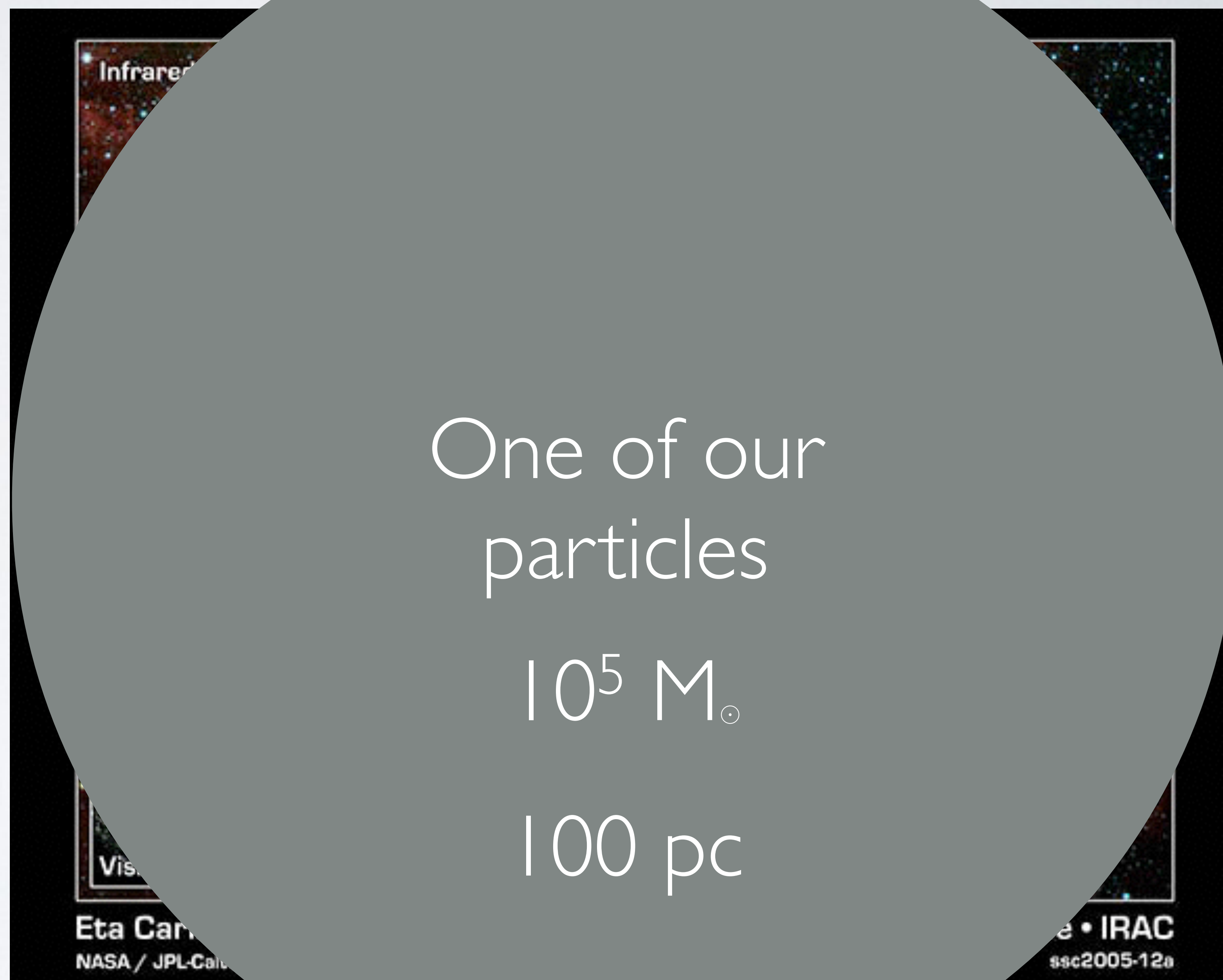


GALAXY FORMATION INGREDIENTS

- Hydrodynamics
- Radiative gas cooling
- Star Formation
- **Stellar Feedback**

HOW DO WE MODEL STELLAR FEEDBACK?

- Ideally, stellar feedback should do 3 things
  - Limit star formation
  - drive outflows
  - Provide turbulent pressure support in the disk



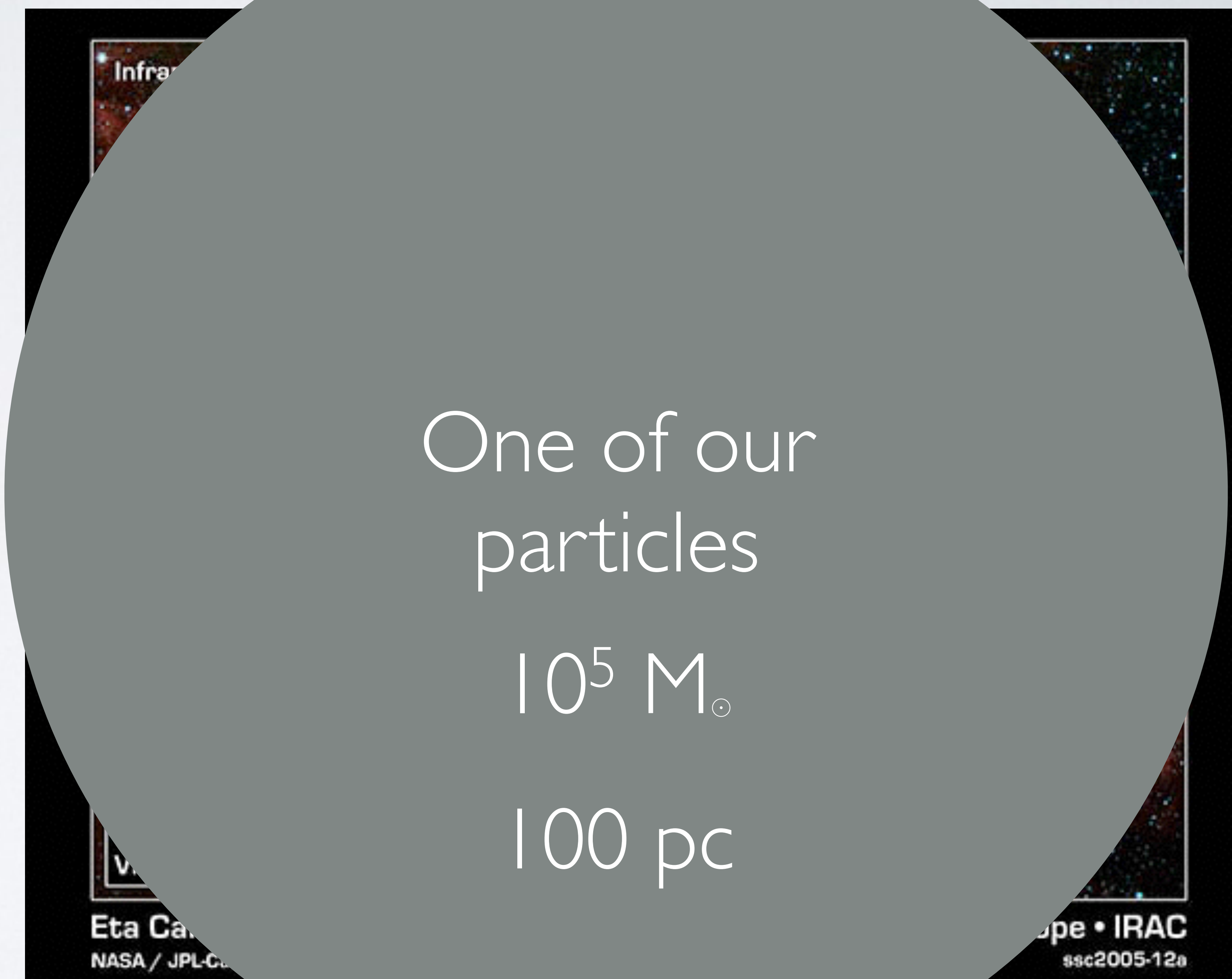
One of our particles

$10^5\ M_\odot$

100 pc

HOW DO WE MODEL STELLAR FEEDBACK?

- Problems
  - Dense gas cools fast ($t_{cool} < t_{dyn}$)
  - Small amount of hot gas has a large dynamical impact
  - How do you drive observed outflows?

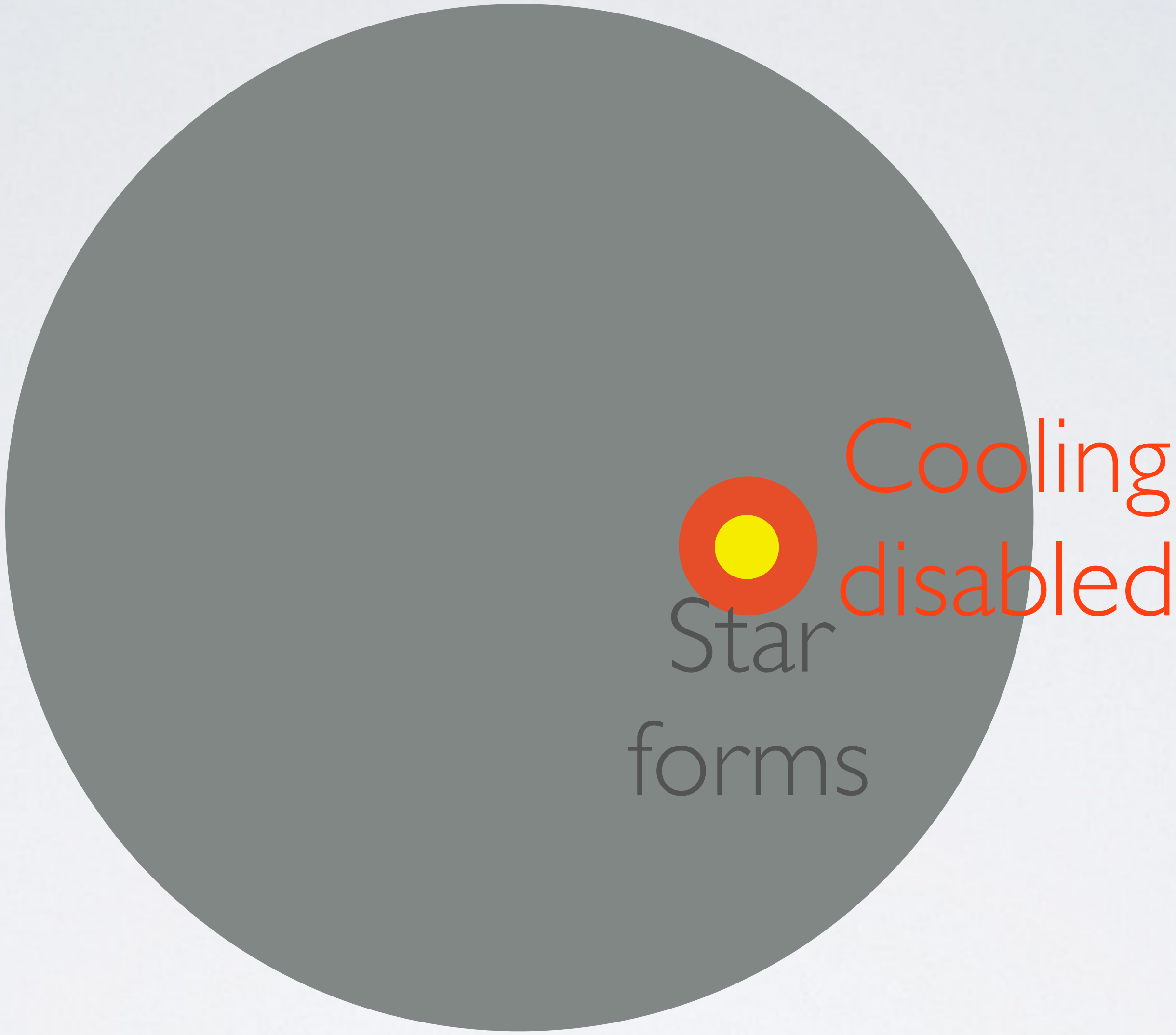


One of our particles

$10^5\ M_\odot$

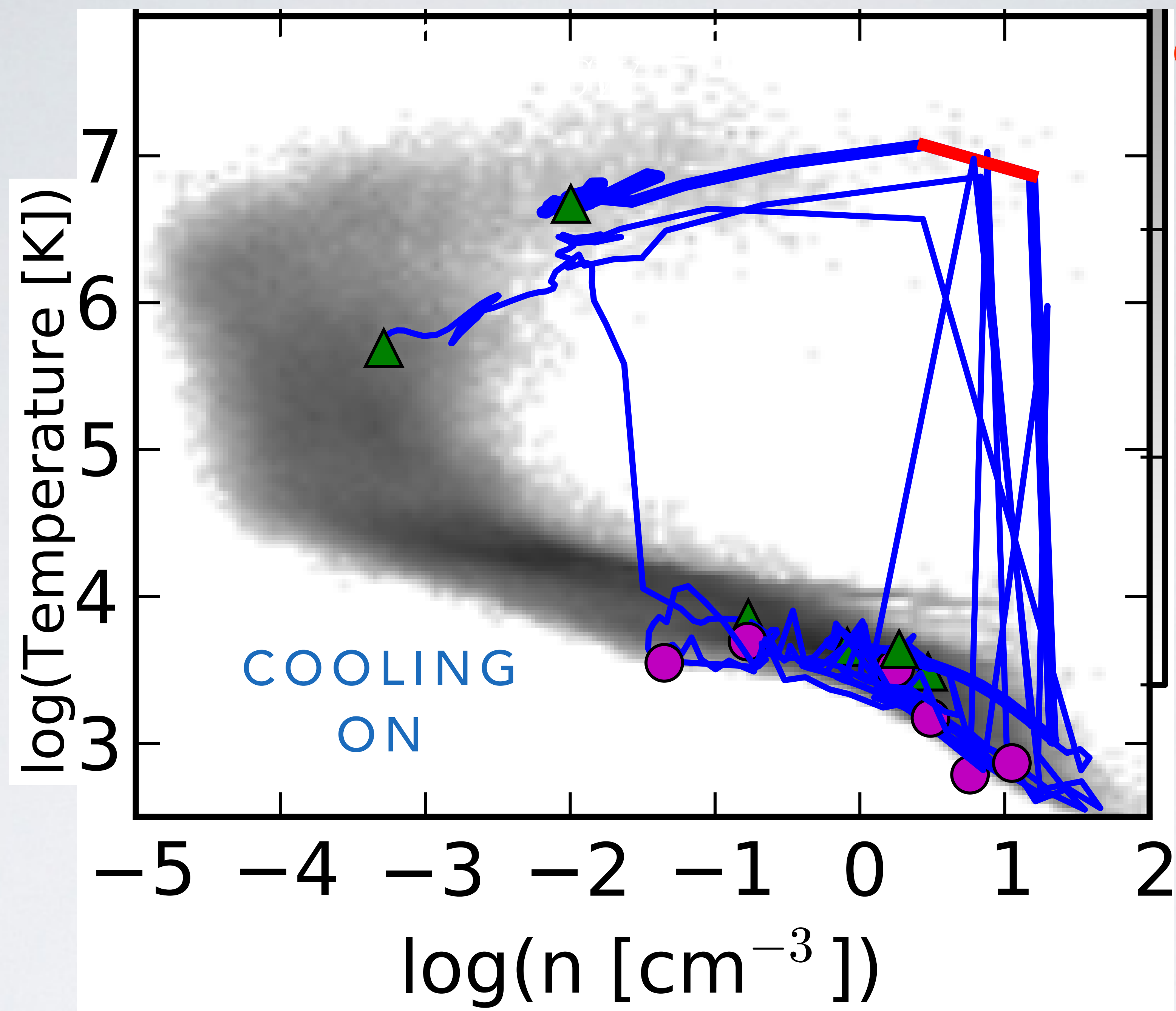
100 pc

Kinetic or Thermal Feedback



THERMAL ADIABATIC FEEDBACK

Artificially **delay cooling** while SNII explode
Thermal pressure causes outflows



All SN energy from 1 star particle input at the same time

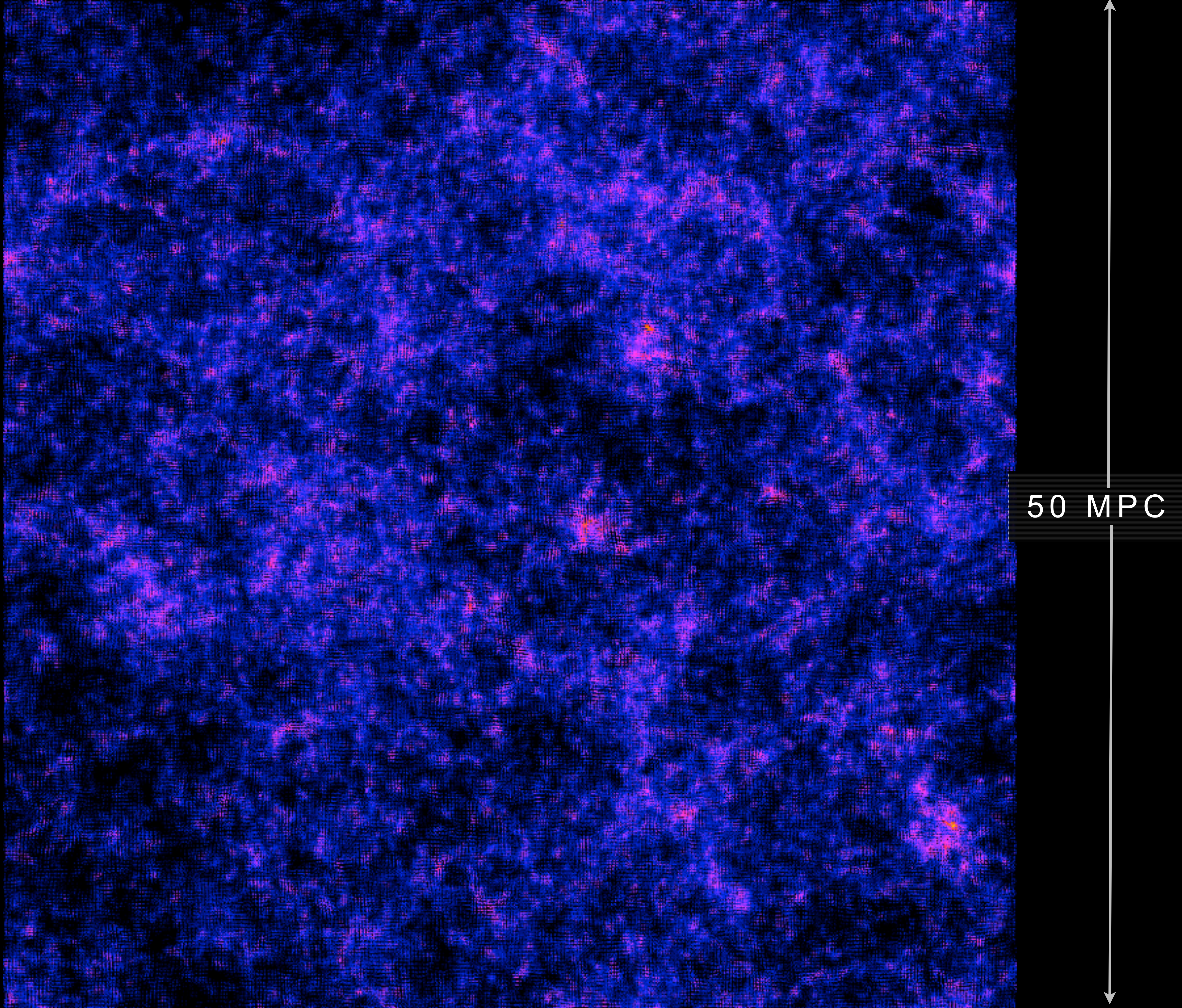
THERMAL FEEDBACK IN PHASE DIAGRAM

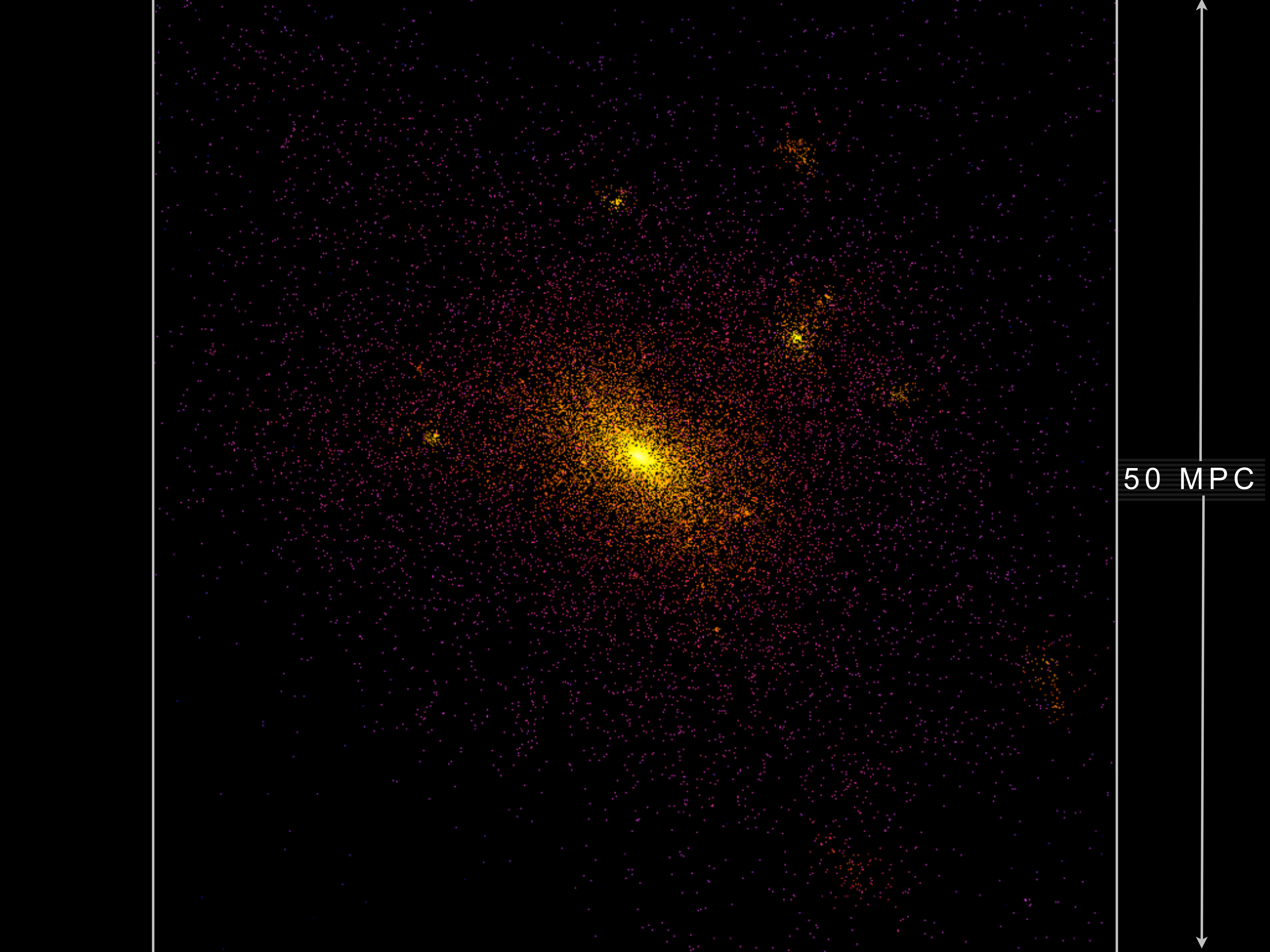
all SN energy packed into 1 particle at 1 time (Dalla Vecchia & Schaye 2012)

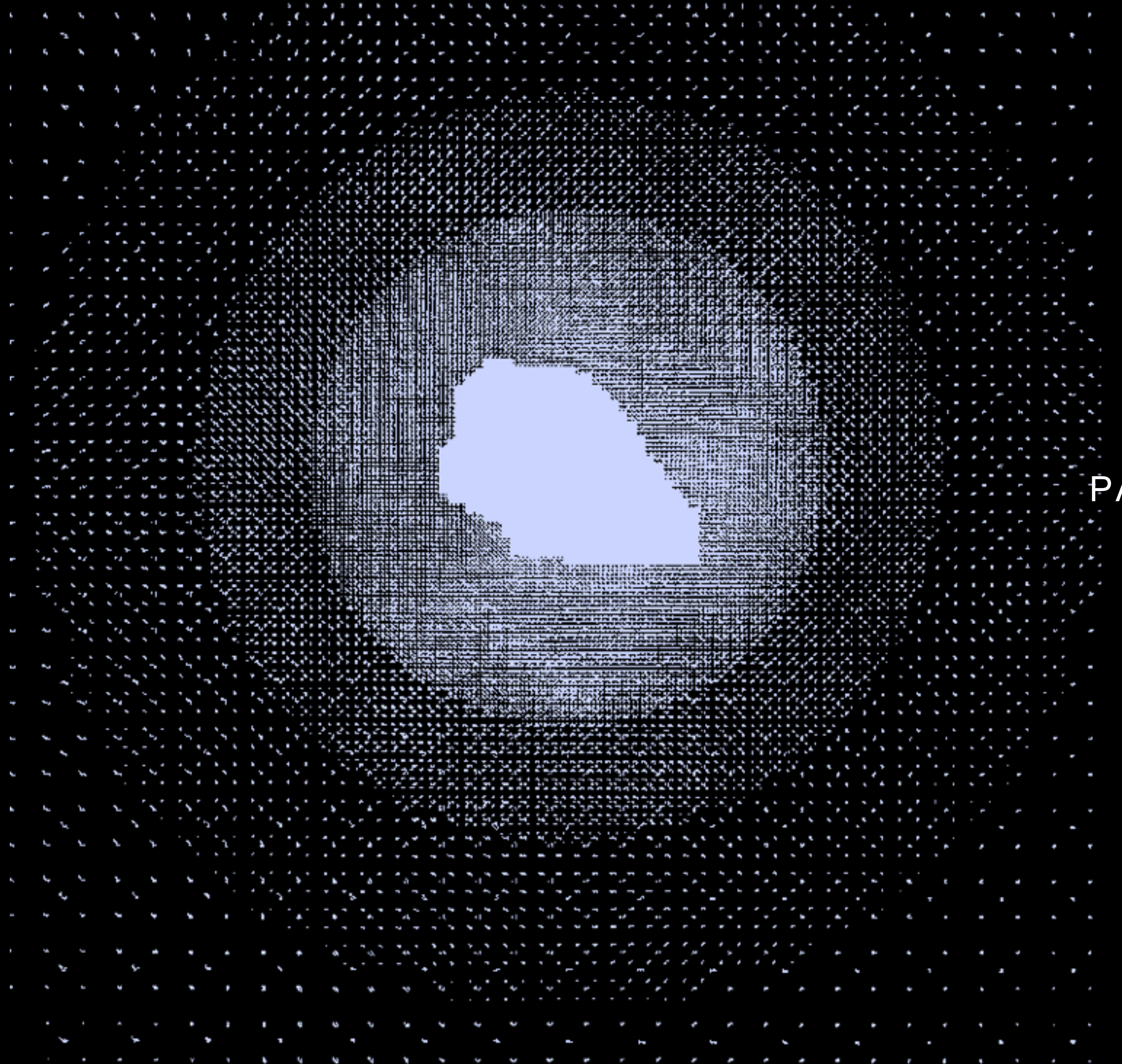
DALLA VECCHIA & SCHAYE (2012)

PUTTING HYDRODYNAMICS INTO COSMOLOGICAL SIMULATIONS

- Input Physics
  - Hydrodynamics, star formation, supernova feedback, other stellar feedback
- Run zoom simulations of Milky Way like galaxies

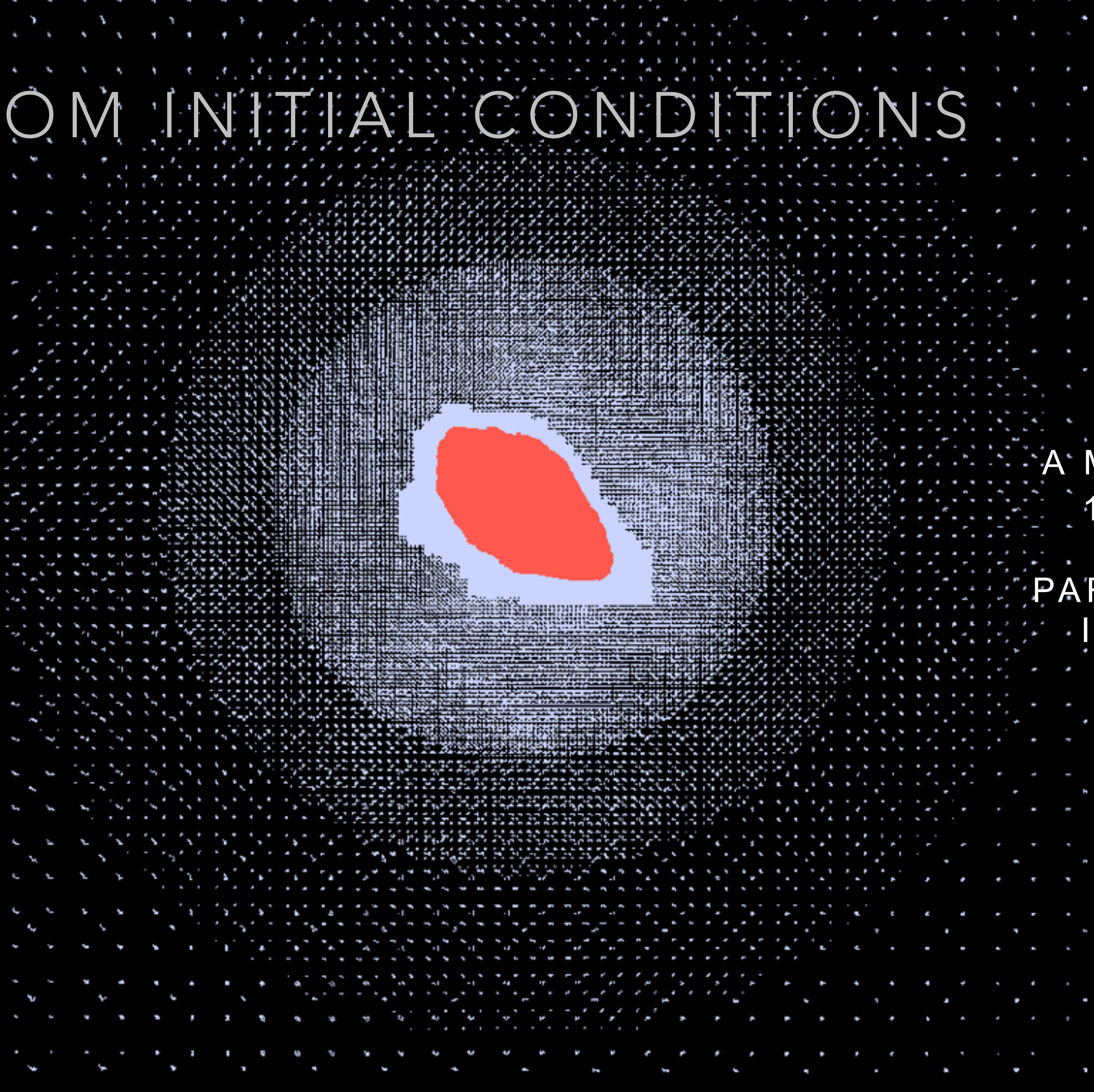

50 MPC


50 MPC



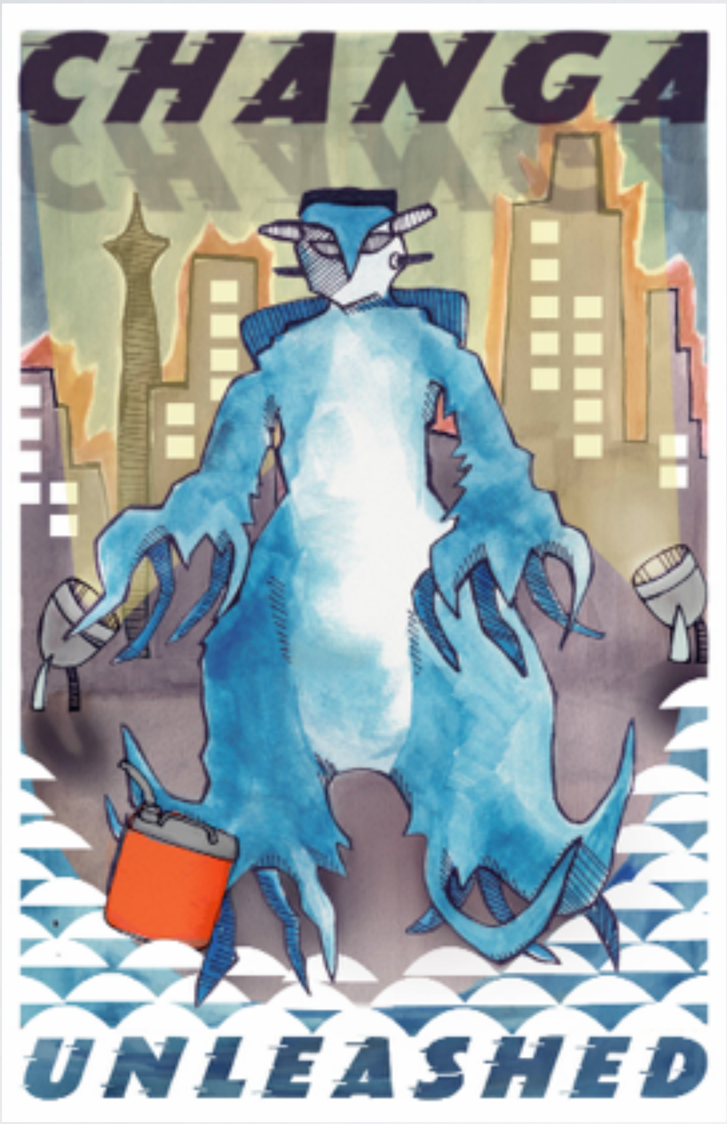
10^6 DM PARTICLES IN R_{VIR}

ZOOM INITIAL CONDITIONS

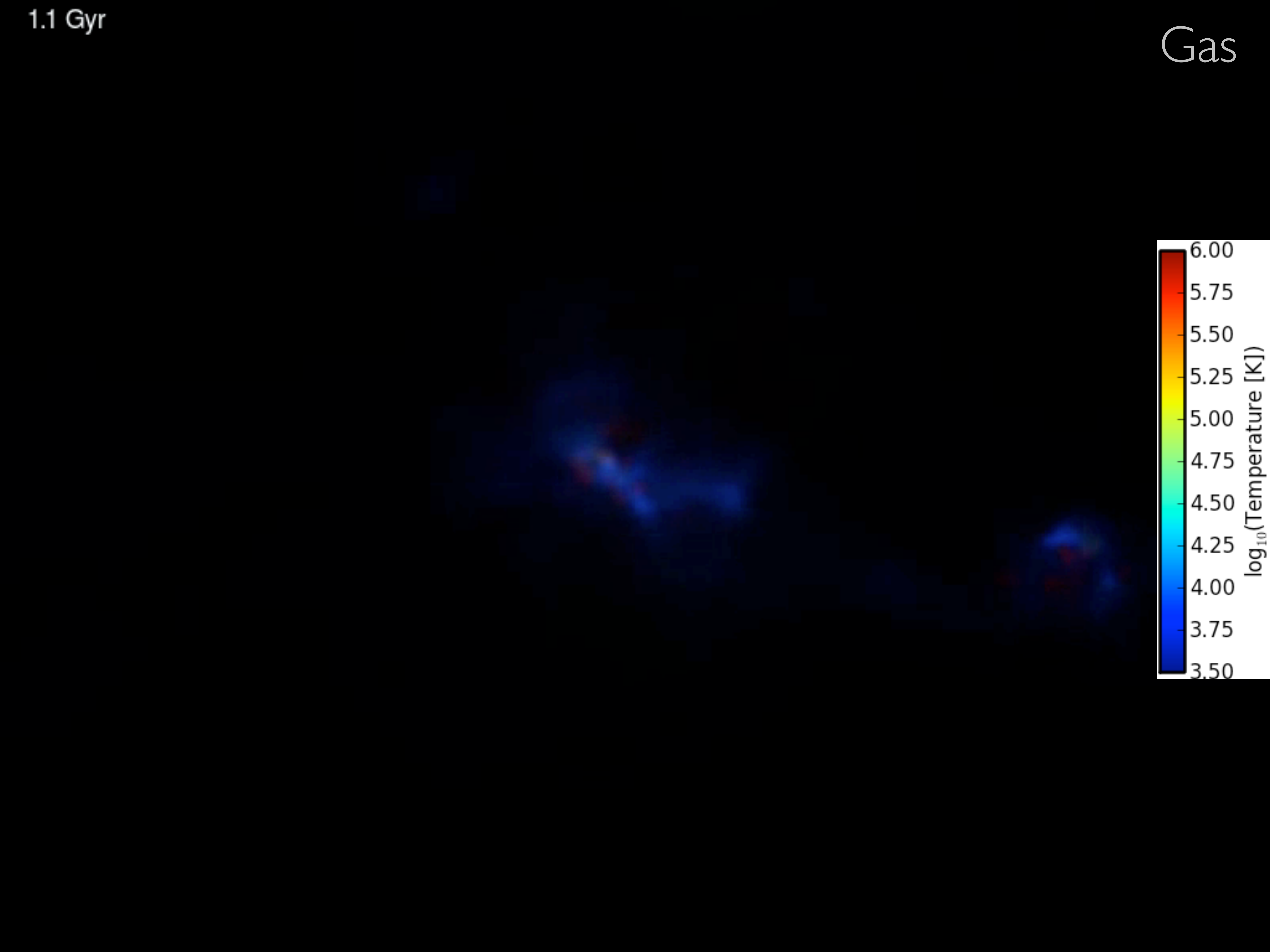


A MILLION
10^5 $M_\odot$
GAS
PARTICLES
IN R_{VIR}

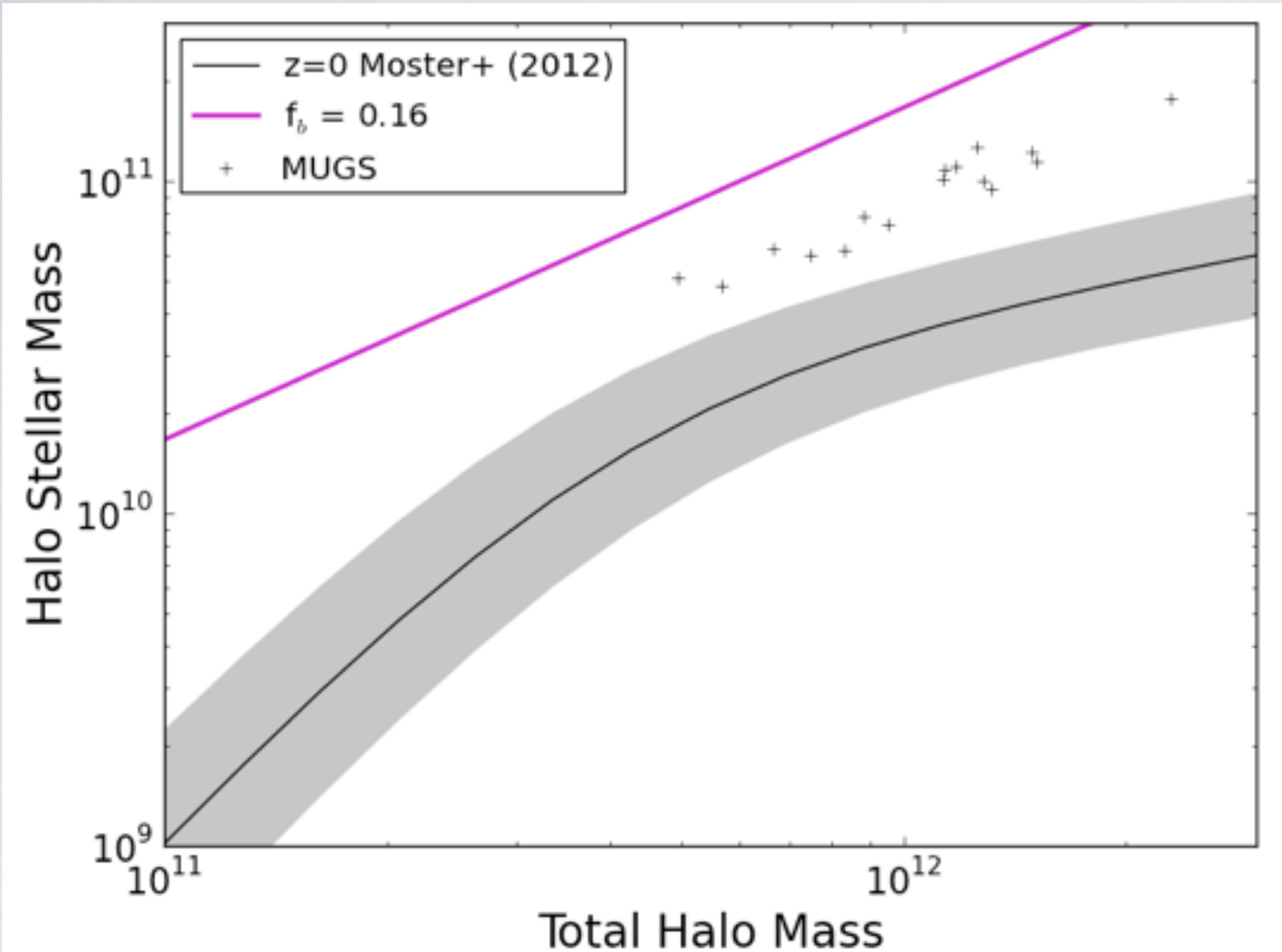
CHANGA



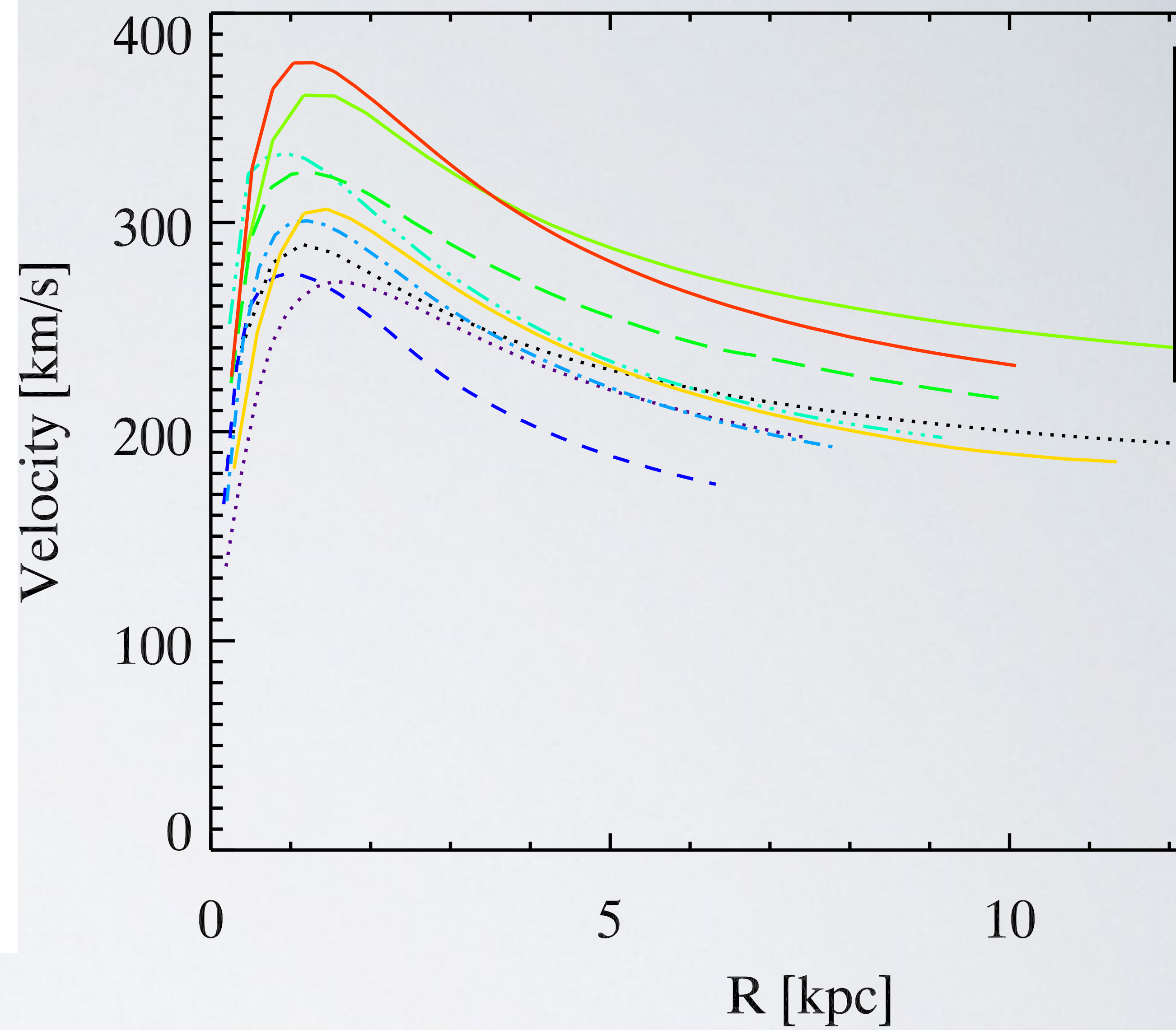
- Publicly available gravity + smoothed particle hydrodynamics solver
- Optically thin radiative gas cooling (Shen+ 2010)
- Star formation (Stinson+ 2006)
- Stellar feedback (Dalla Vecchia & Schaye 2012, Stinson+ 2013)


1.1 Gyr
Gas
6.00
5.75
5.50
5.25
5.00
4.75
4.50
4.25
4.00
3.75
3.50
log10(Temperature [K])

Too many stars form



primarily in the center



OVERCOOLING

MUGS Stinson et al (2010)

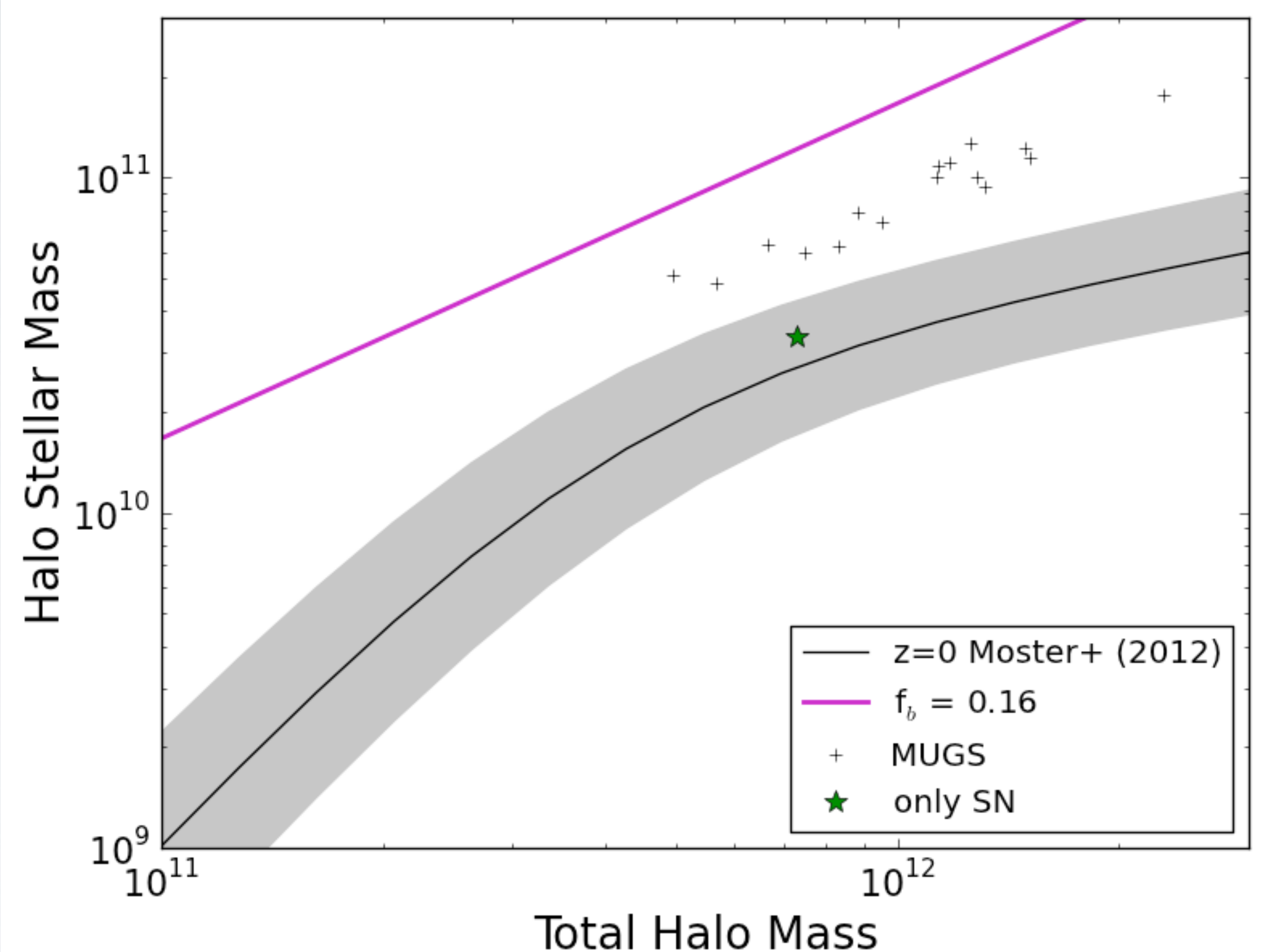
FROM MUGS TO MAGICC*

Increase SN feedback

Kroupa + (1993)
10% Mass SN
→
Chabrier (2003)
20% Mass SN

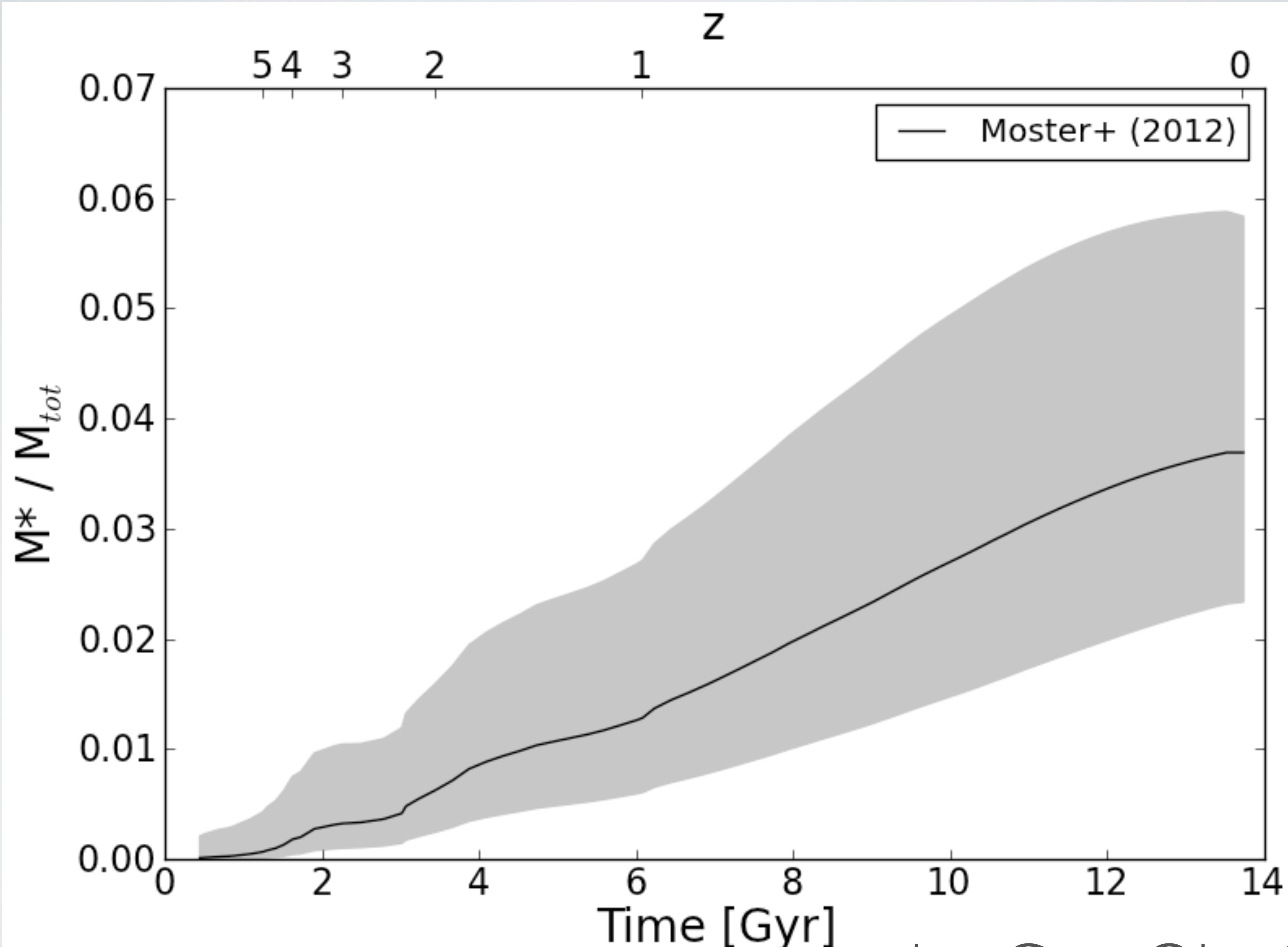
$E_{SN} = 0.4 \times 10^{51}$ ergs / SN → $E_{SN} = 10^{51}$ ergs / SN

* Making Galaxies in a Cosmological Context

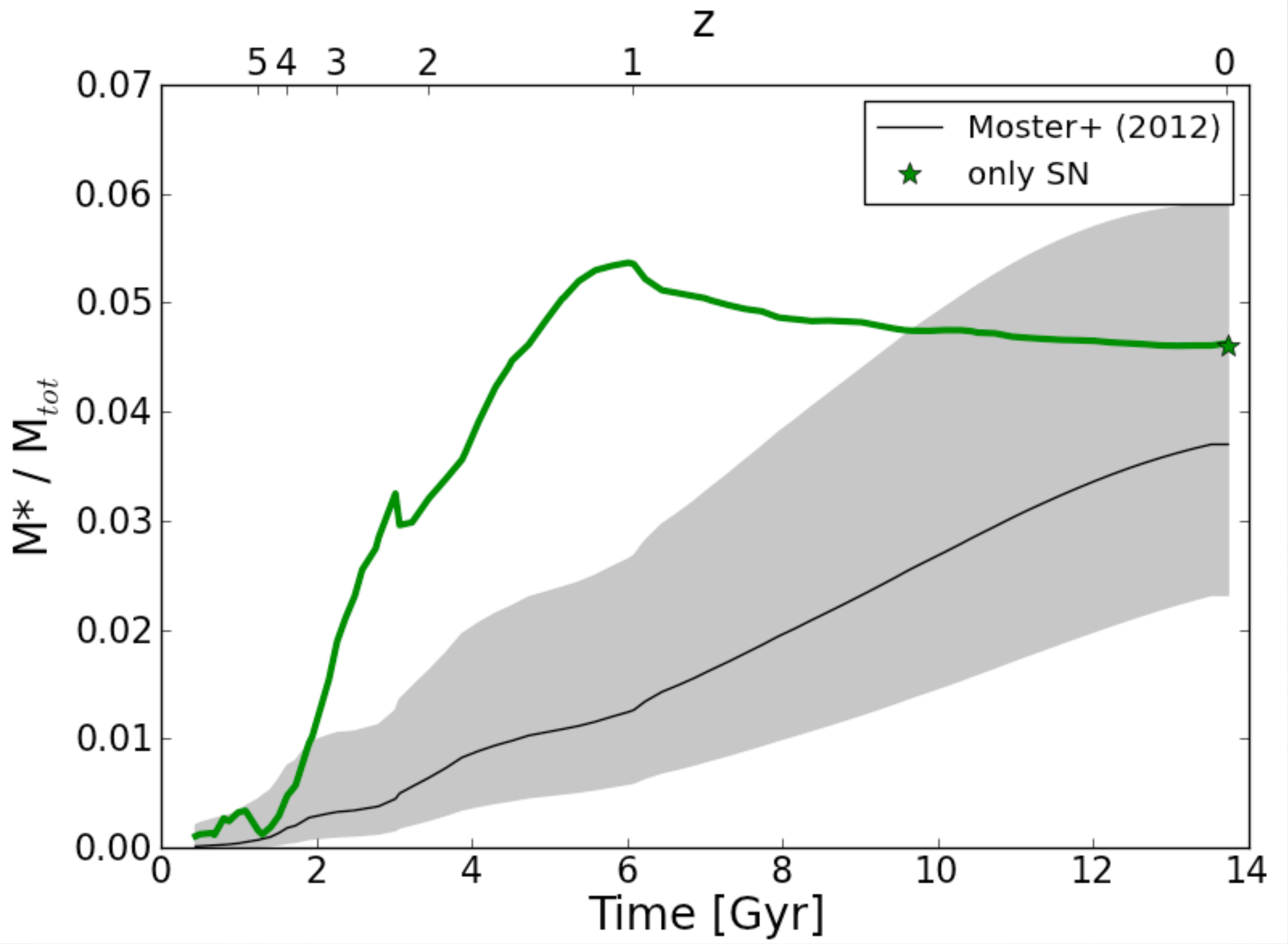


TURN UP FEEDBACK

100% Supernova Efficiency (10^{51} erg)

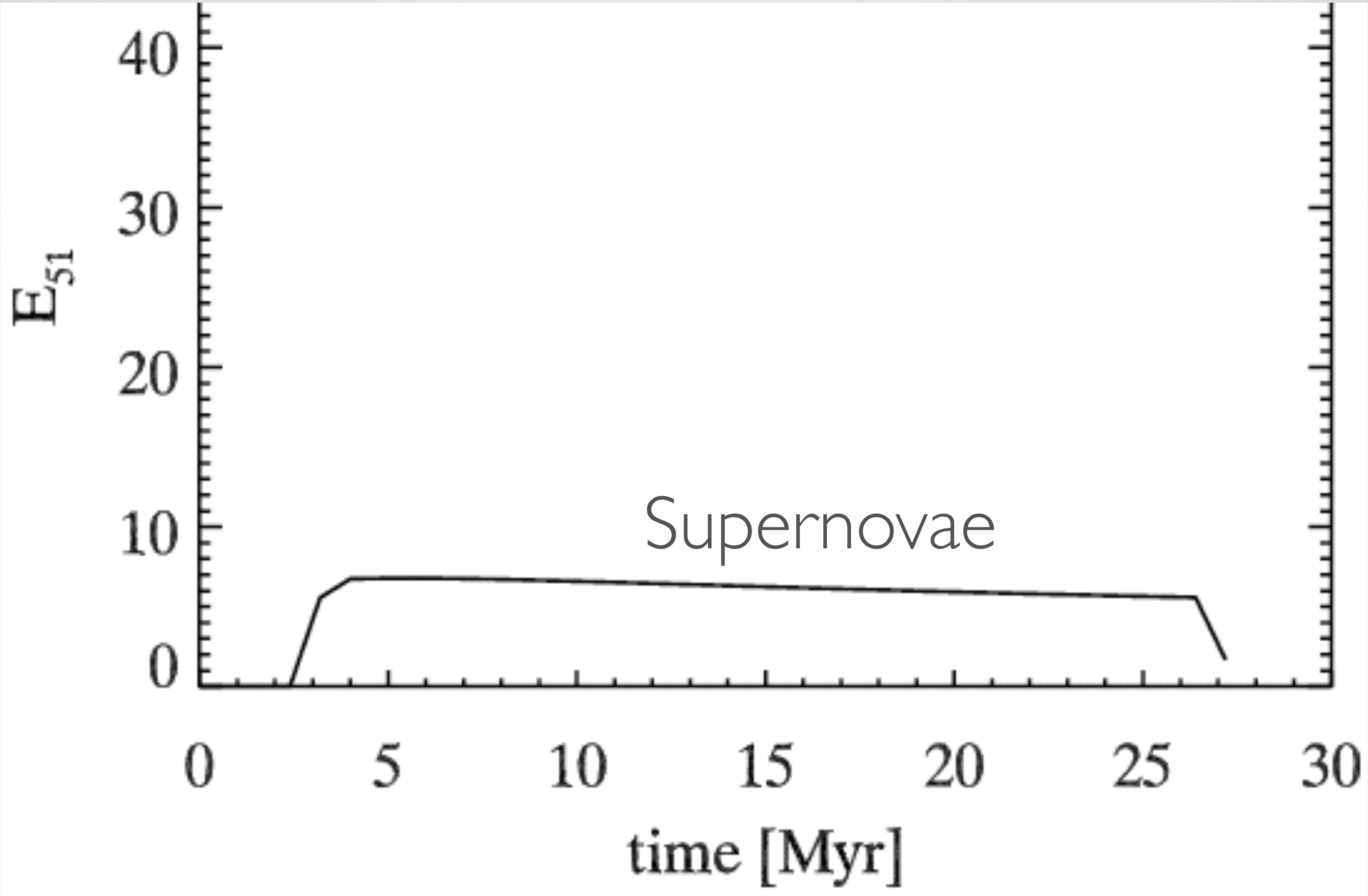


see also Guo, Qi+ (2011)
Behroozi+ (2012)



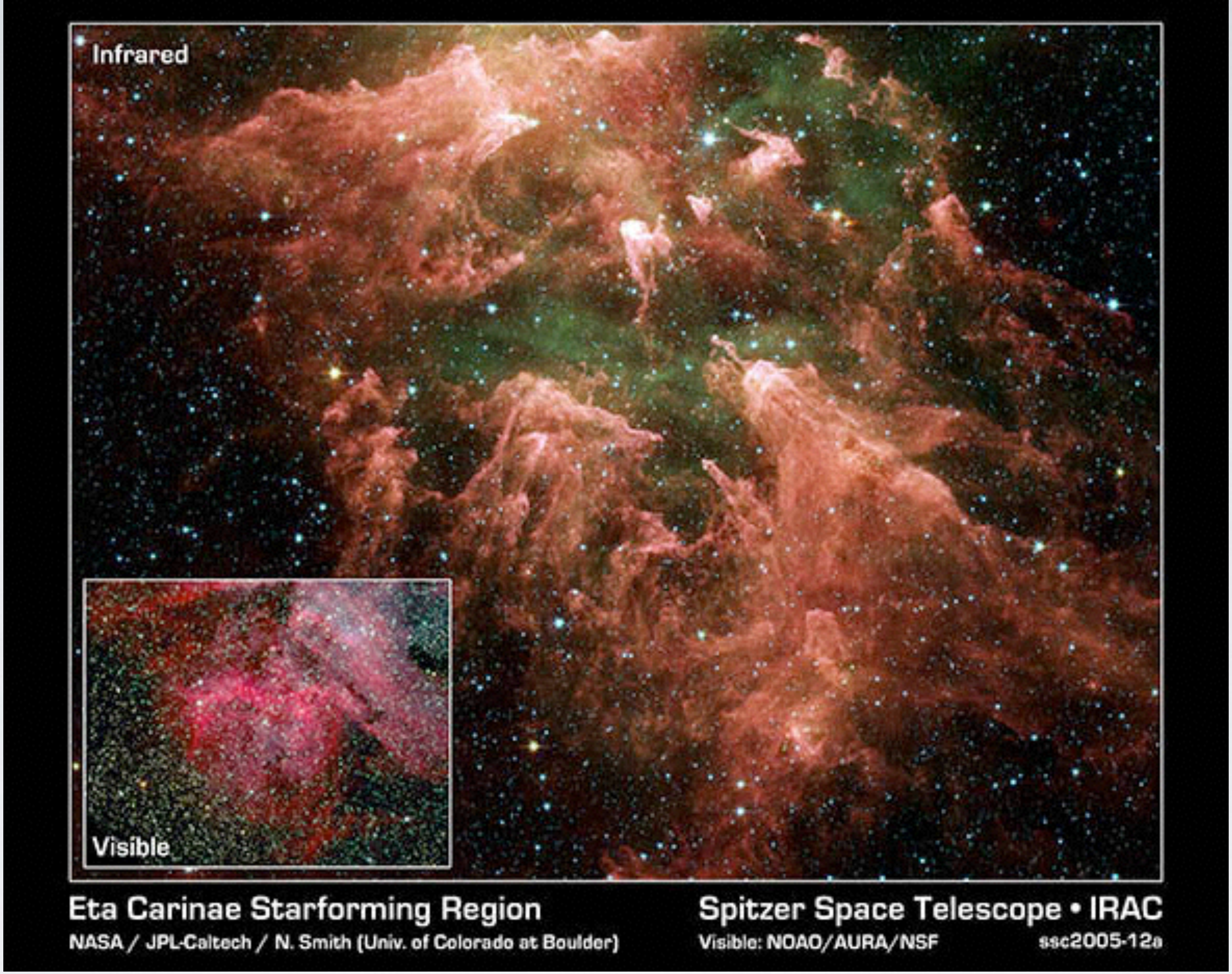
TURN UP FEEDBACK

100% Supernova Efficiency (10^{51} erg)



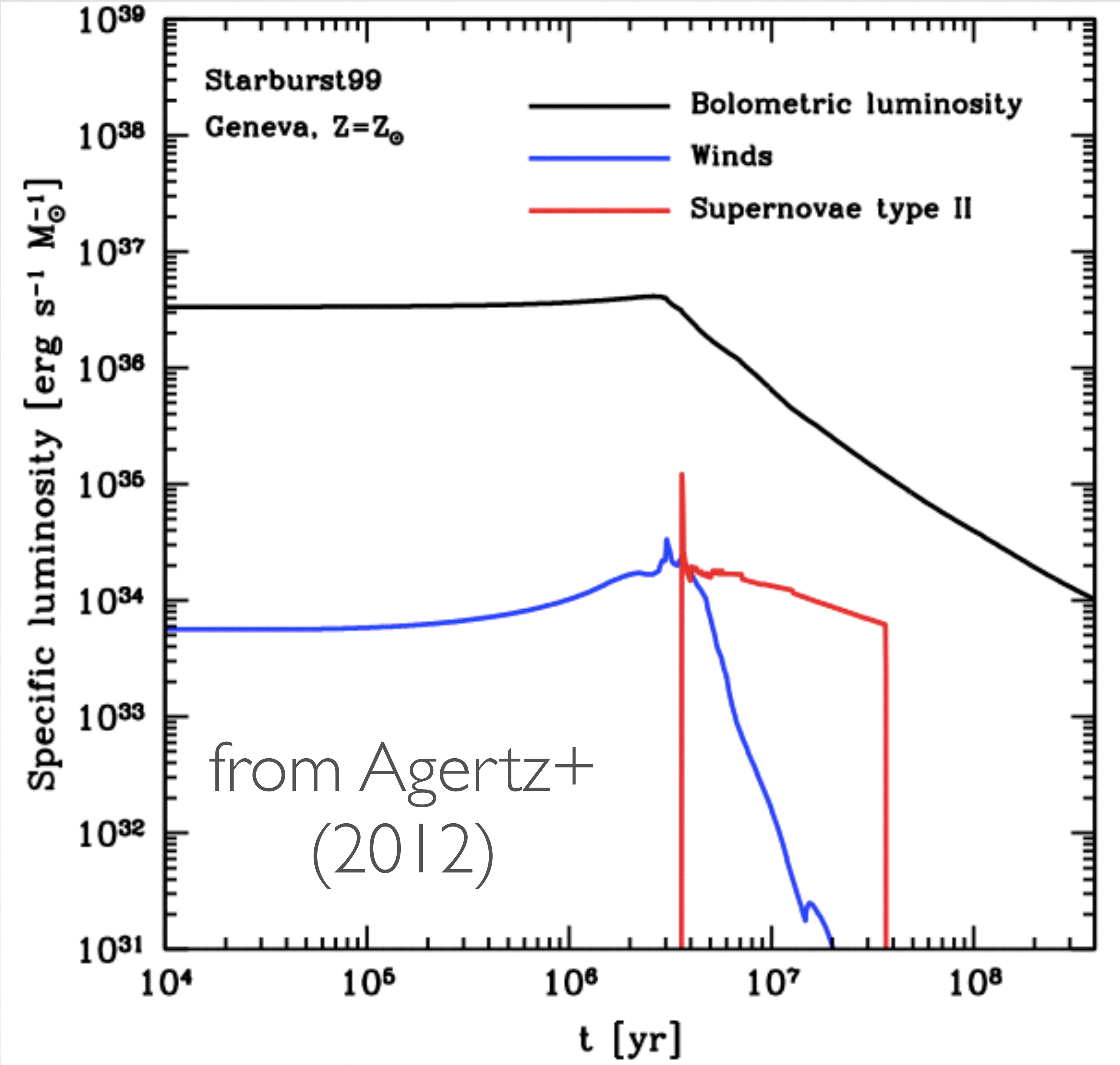
SUPERNOVA FEEDBACK

A hole

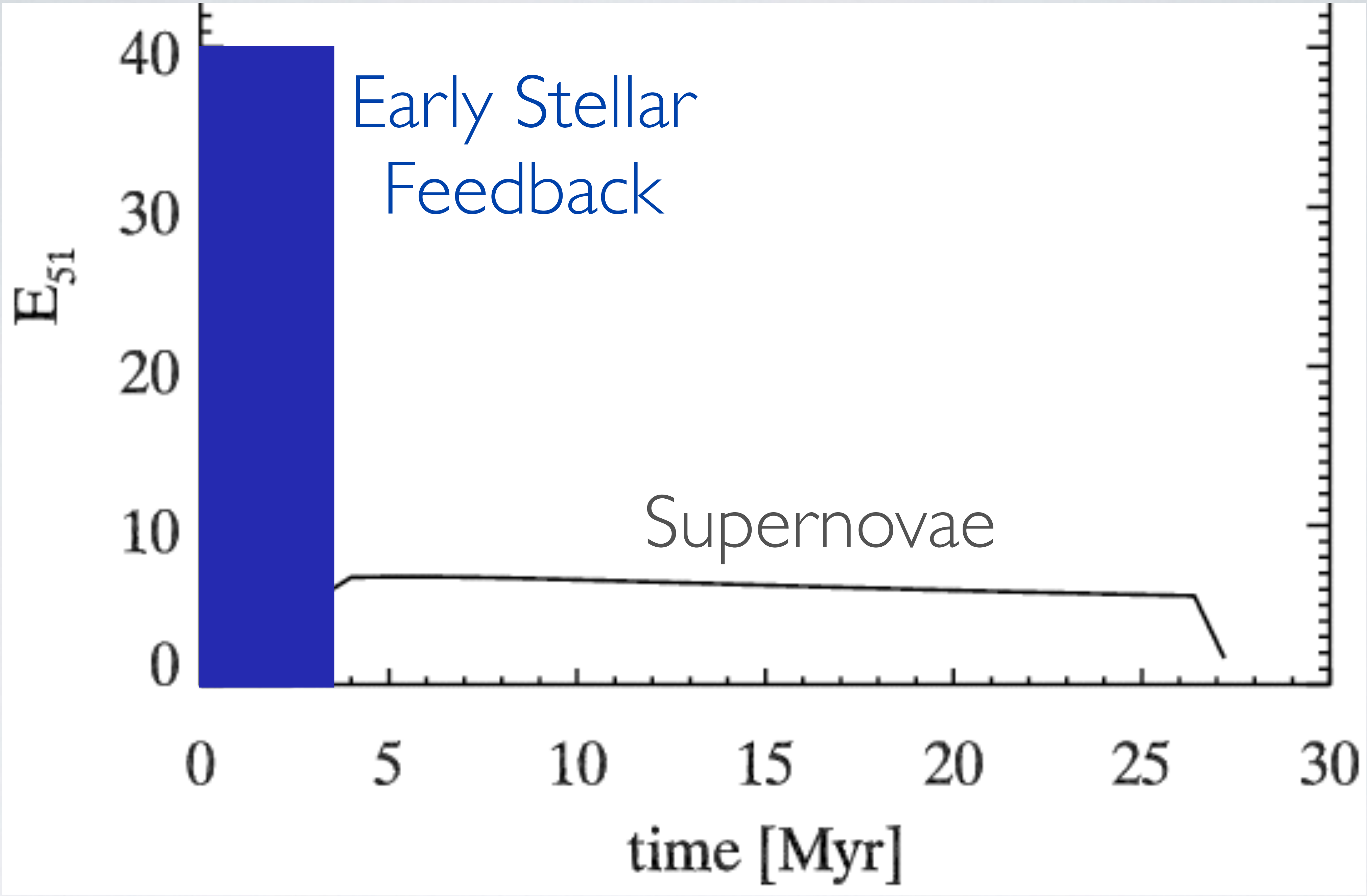


ETA CARINAE

< 3 Myr old, but stars already tearing gas apart

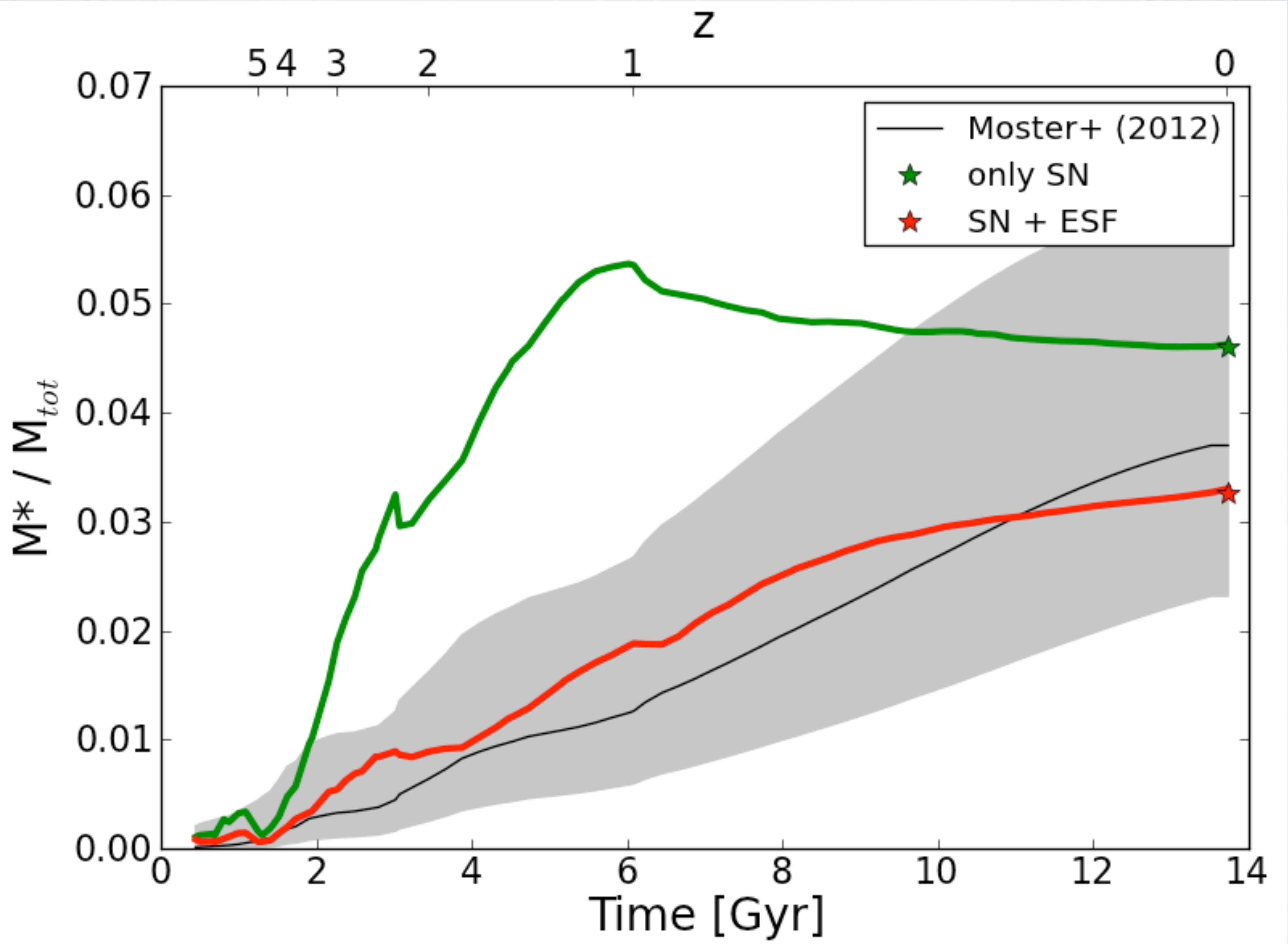


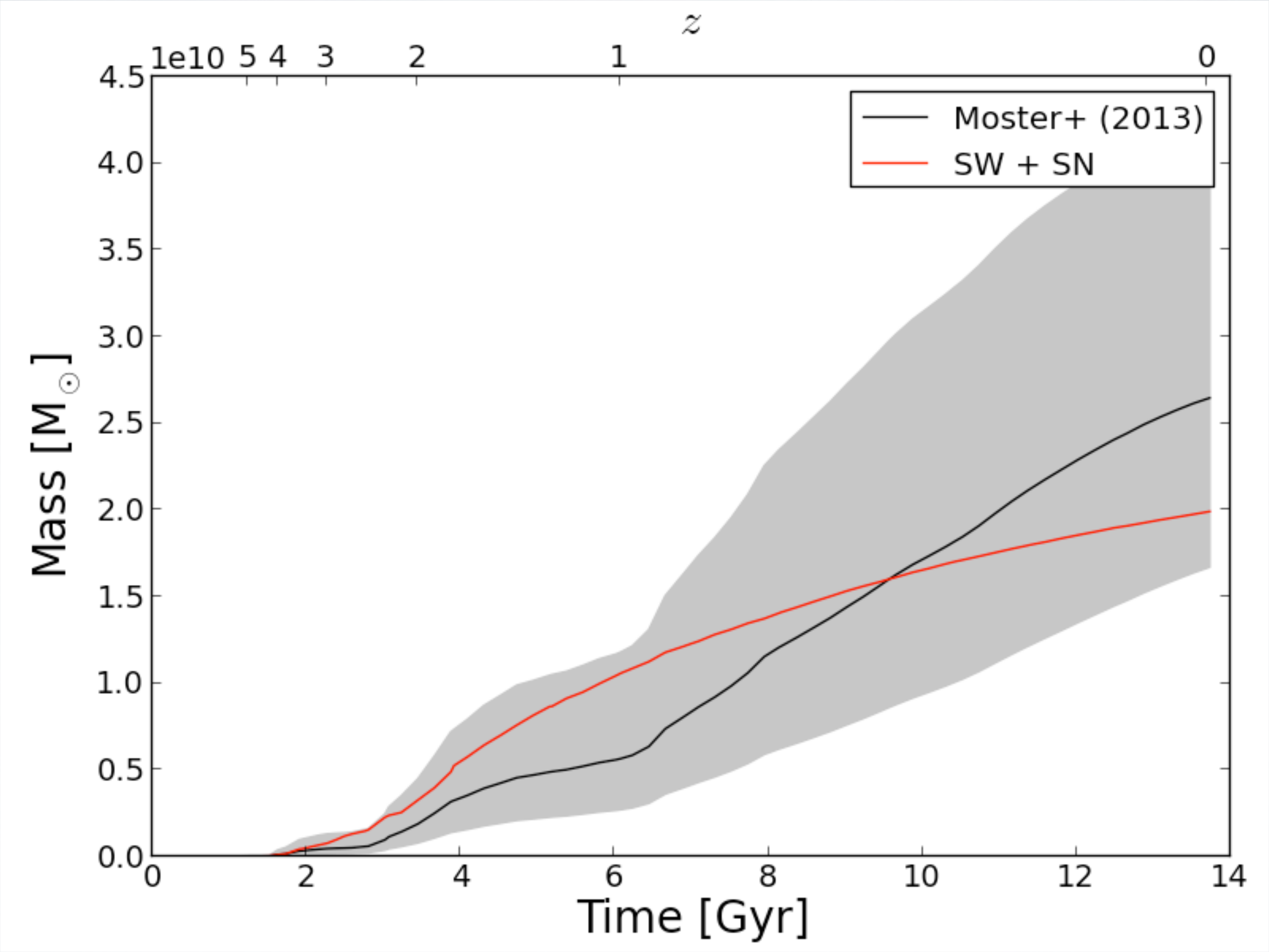
from Agertz+ (2012)



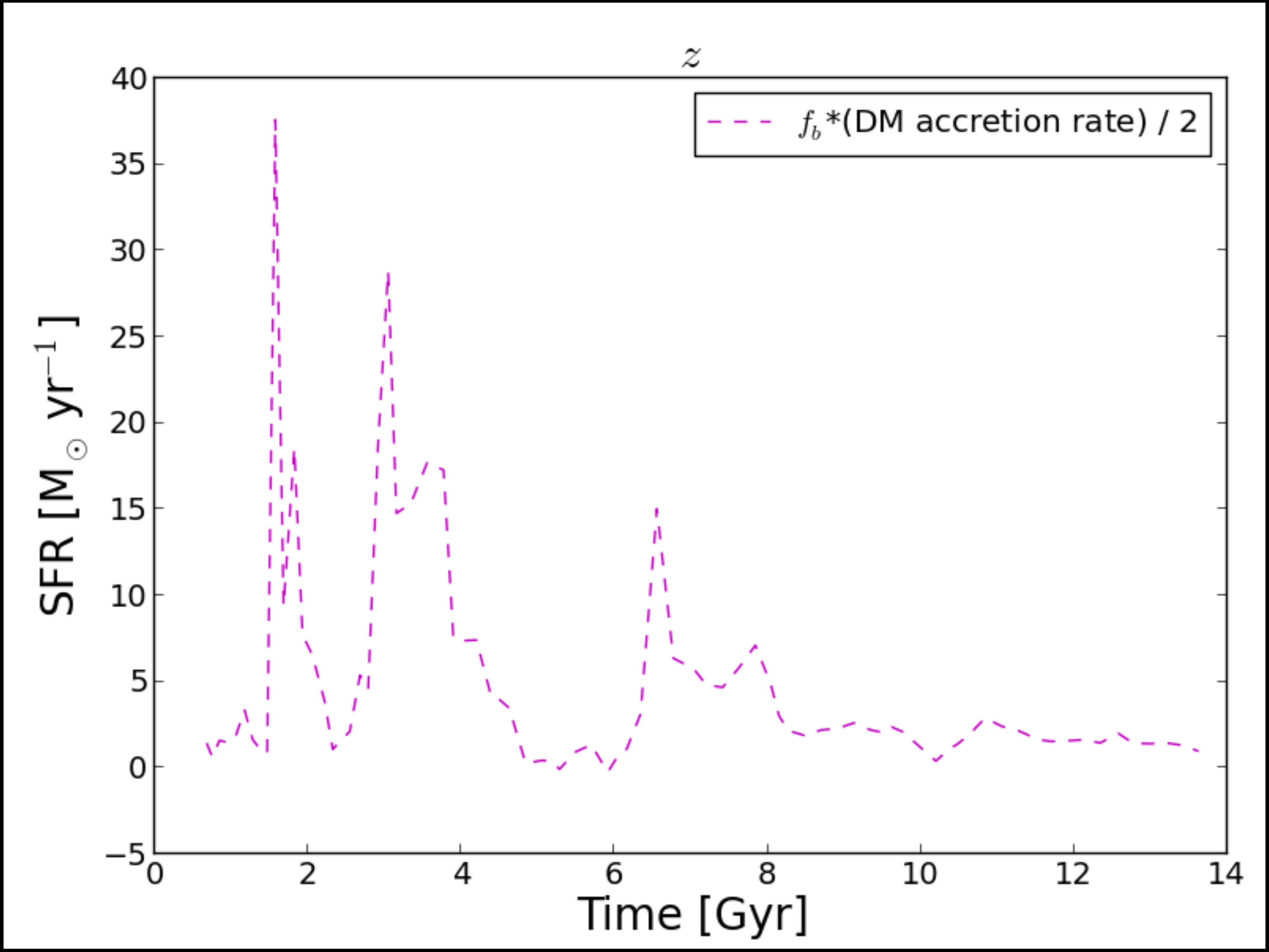
EARLY STELLAR FEEDBACK

A solution

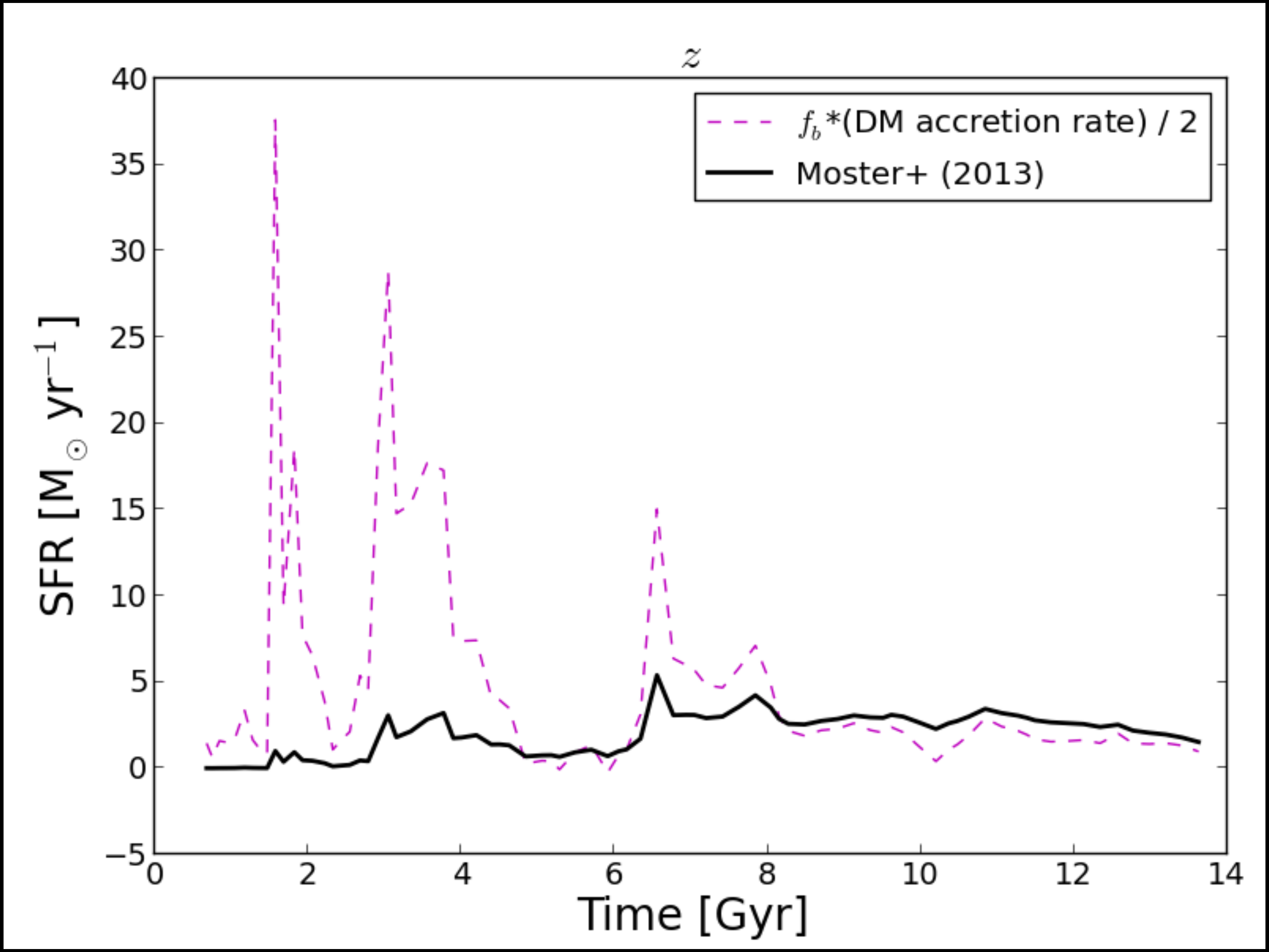

z
5
4
3
2
1
0
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
M* / M$_{tot}$
Moster+ (2012)
only SN
SN + ESF
0
2
4
6
8
10
12
14
Time [Gyr]



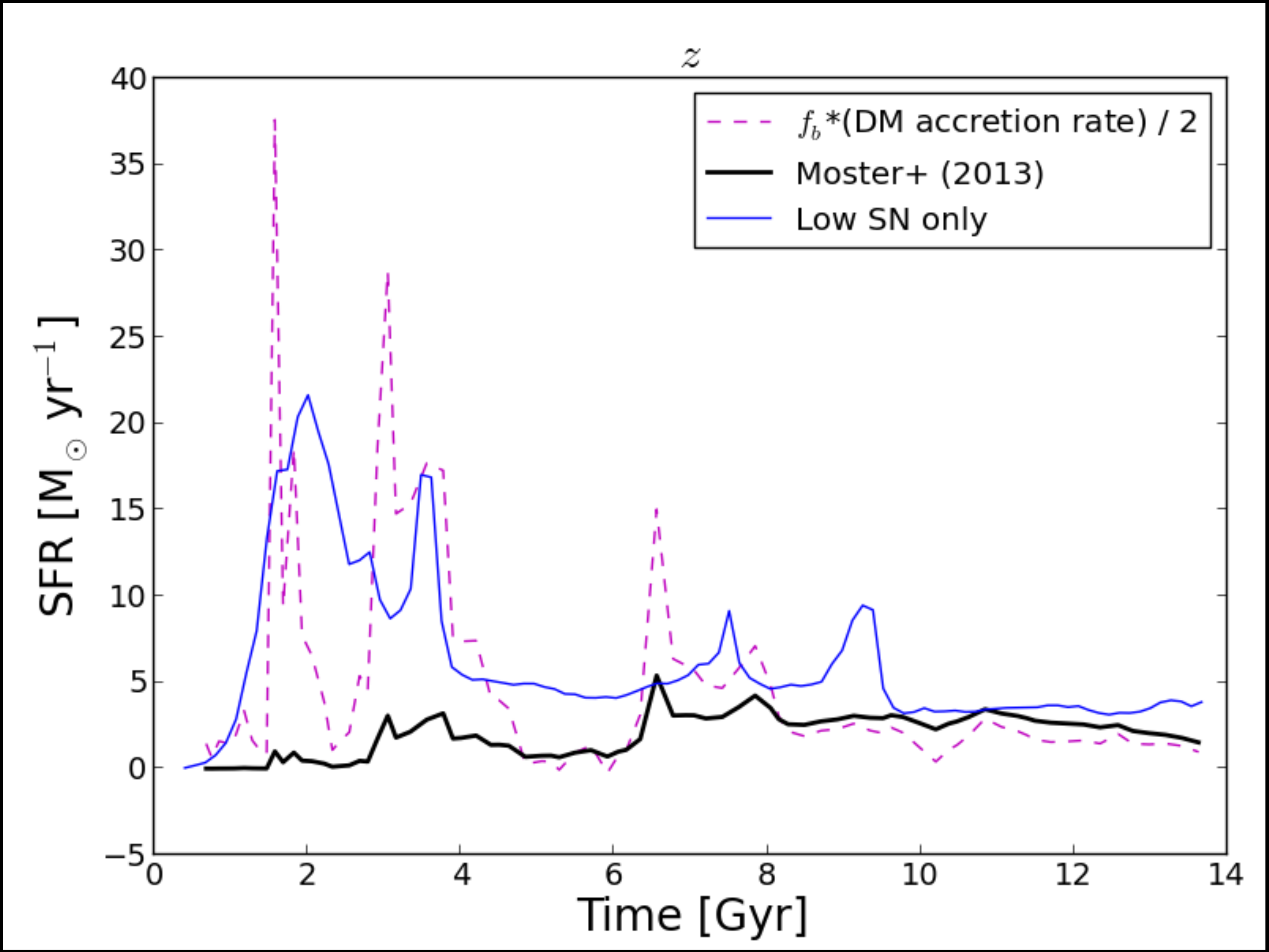
z
1e10 5 4 3 2 1 0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Mass [M☉]
0 2 4 6 8 10 12 14
Time [Gyr]
Moster+ (2013)
SW + SN



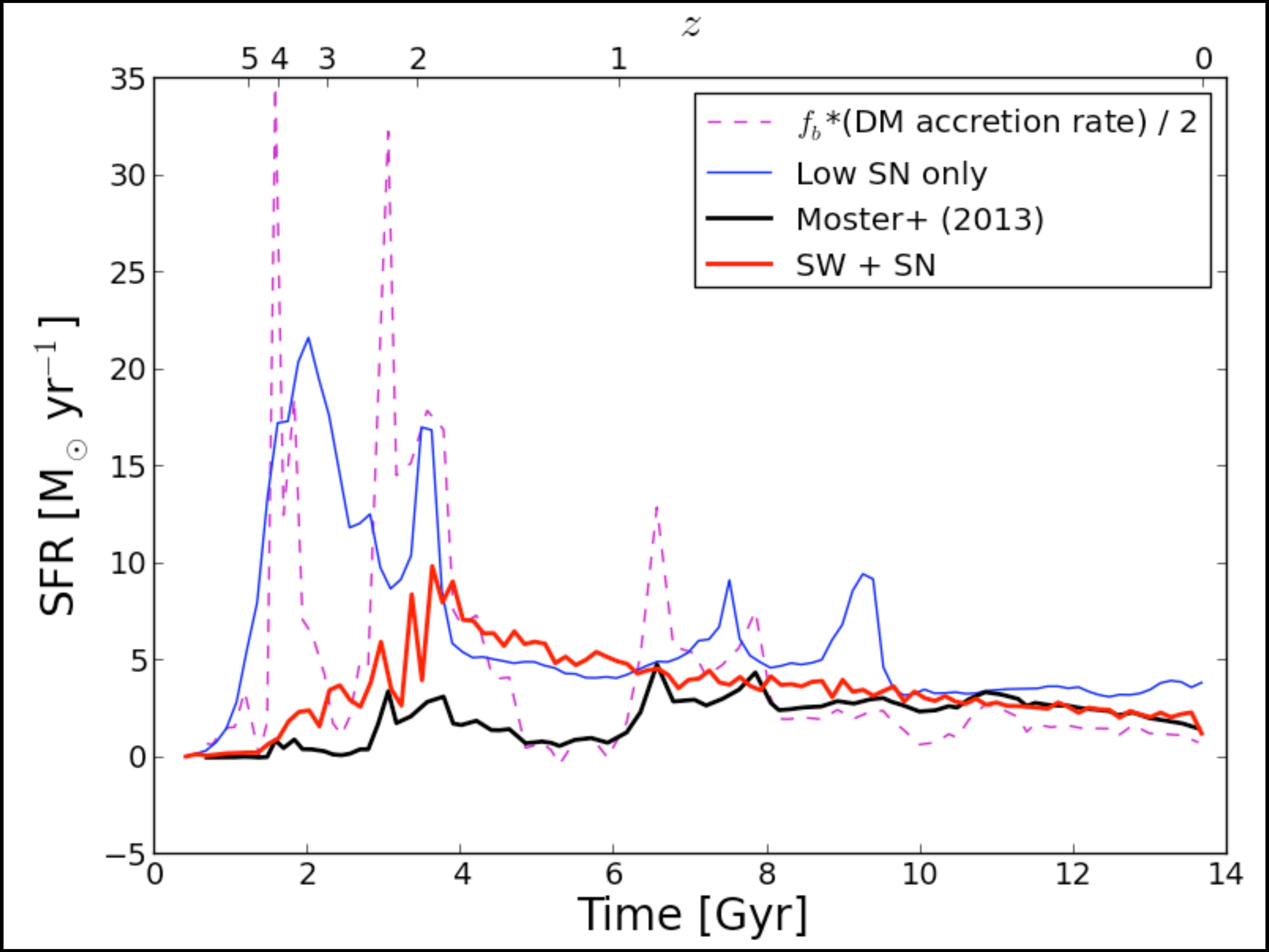
STAR FORMATION HISTORY



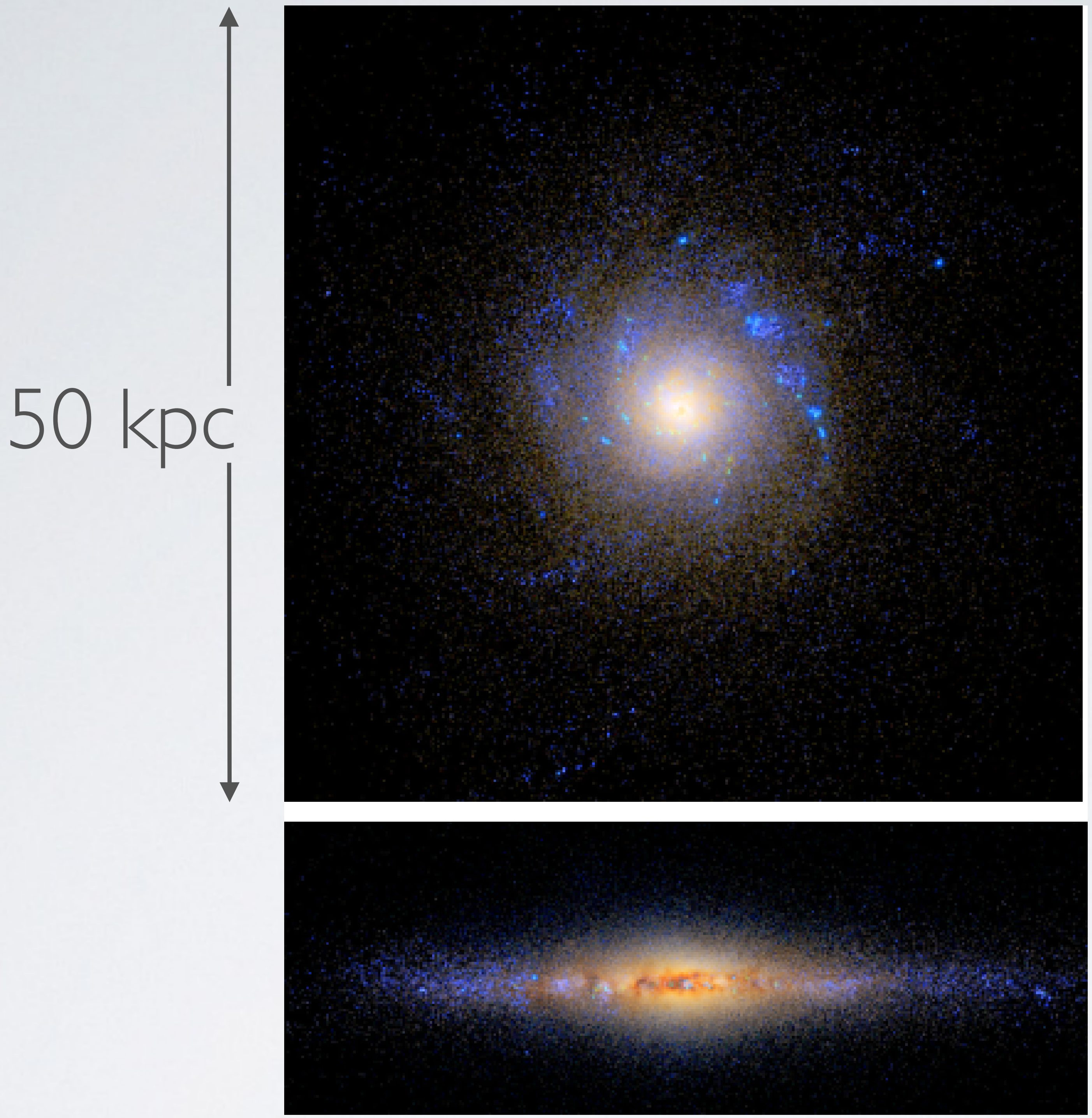
STAR FORMATION HISTORY



STAR FORMATION HISTORY



STAR FORMATION HISTORY



Movies at www.mpia.de/~stinson/magicc

THE MAGICC GALAXY

Match $M_\bigstar$-M_{halo} and see what happens

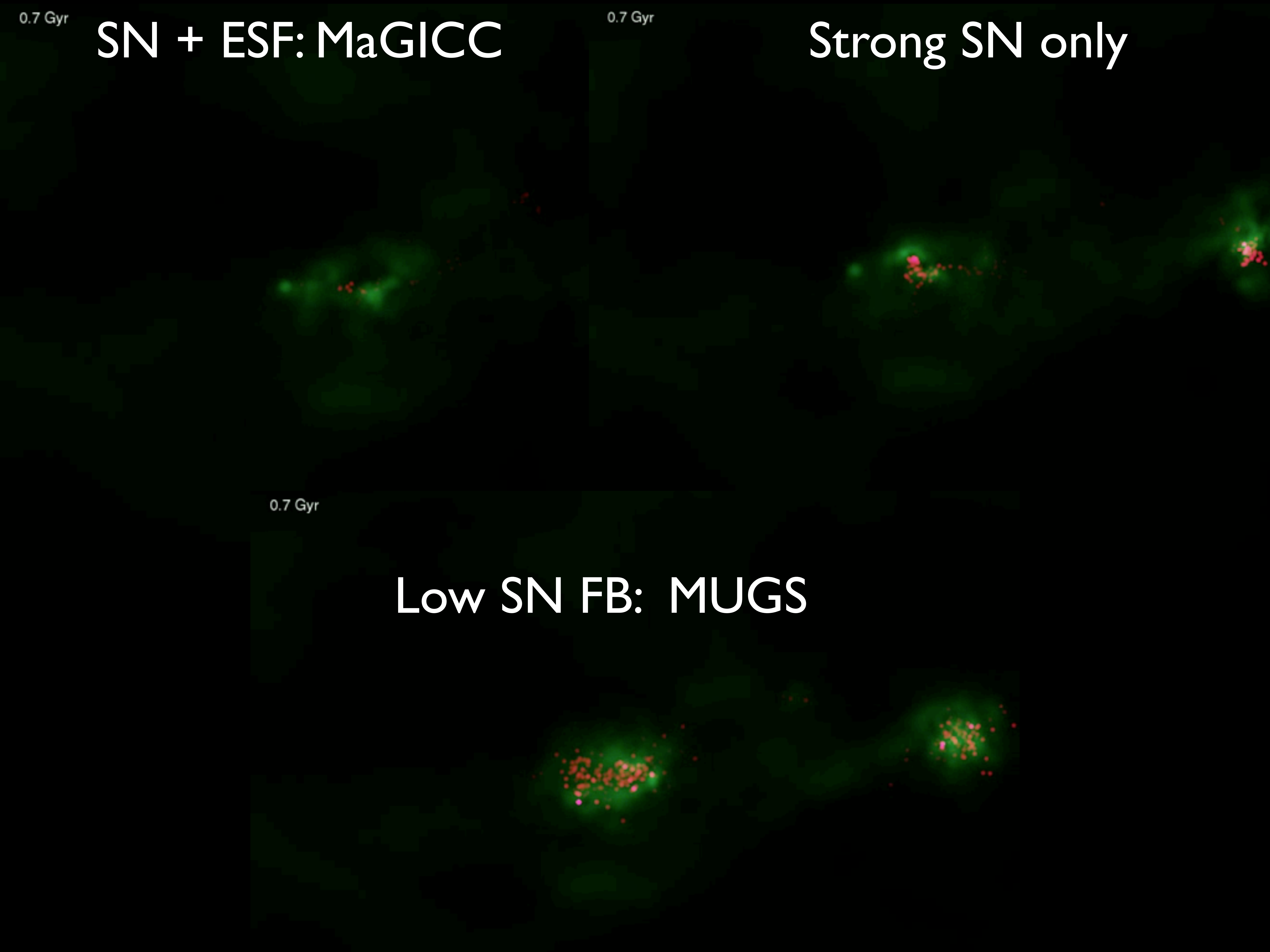
Stinson+ (2012b)

GALAXY FORMATION WITH HYDRODYNAMICS

- We are able to form realistic MW-like galaxies:
  - The right stellar mass
  - star formation history (different from DM accretion)

TOMORROW

- A wider selection of galaxy masses
- A look at how the baryons affect dark matter


0.7 Gyr
SN + ESF: MaGICC
0.7 Gyr
Strong SN only
0.7 Gyr
Low SN FB: MUGS