Lecture 13

Monday 19 January 2015

Hydrodynamical Simulations of Galaxy Formation

Methods, recent progress, and results from the EAGLE project

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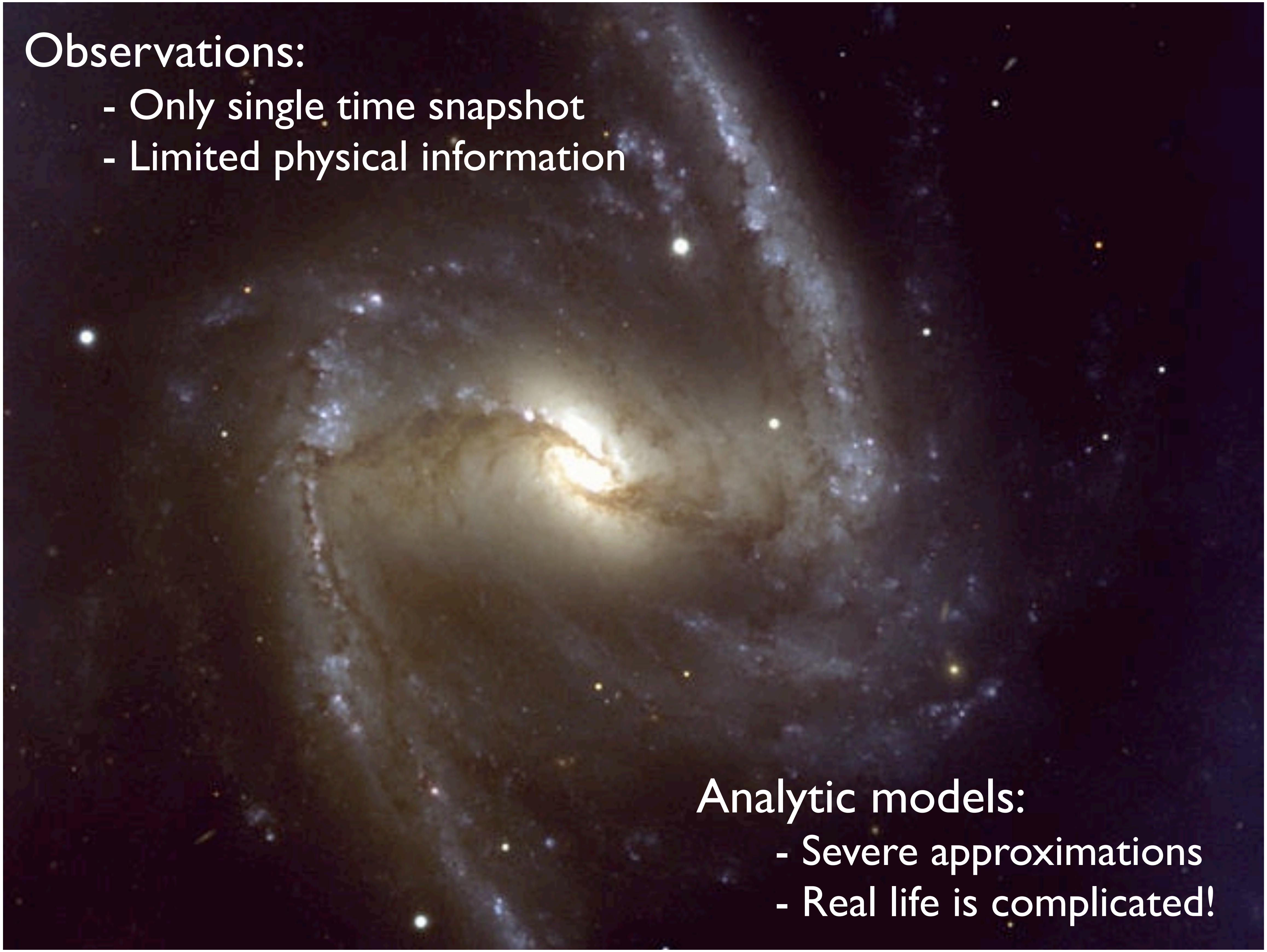
Motivation for simulations



Simulating DM / gravity only

Brief recap:

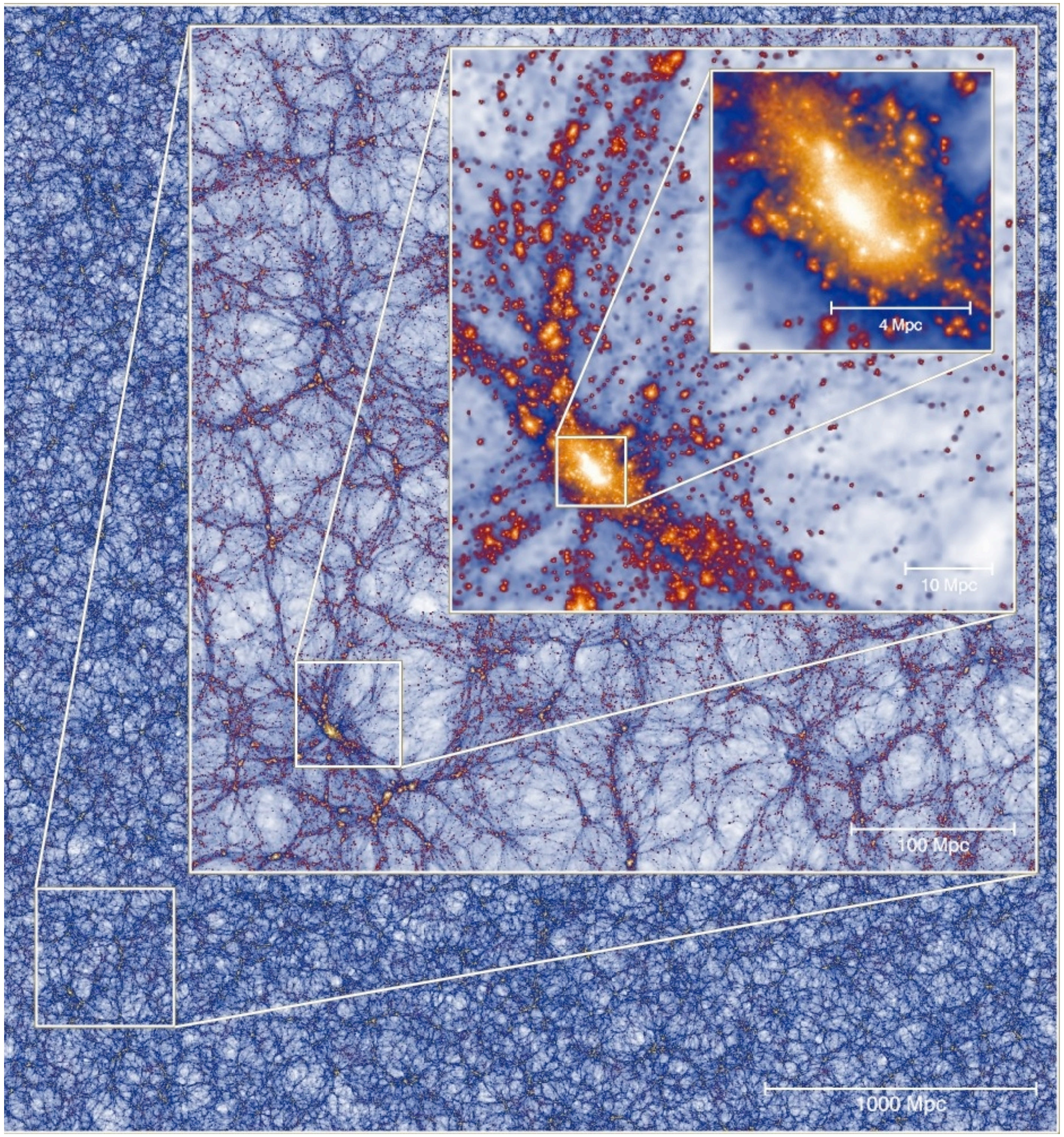
- Gravity is the dominant force over long distances
- "N-body simulations"
- Example: MXXL

Advantages:

- Relatively simple
- Physics "understood"
- Large volumes possible

Disadvantages:

- No galaxies (!!)
- Ignore effect of baryon physics on dark matter

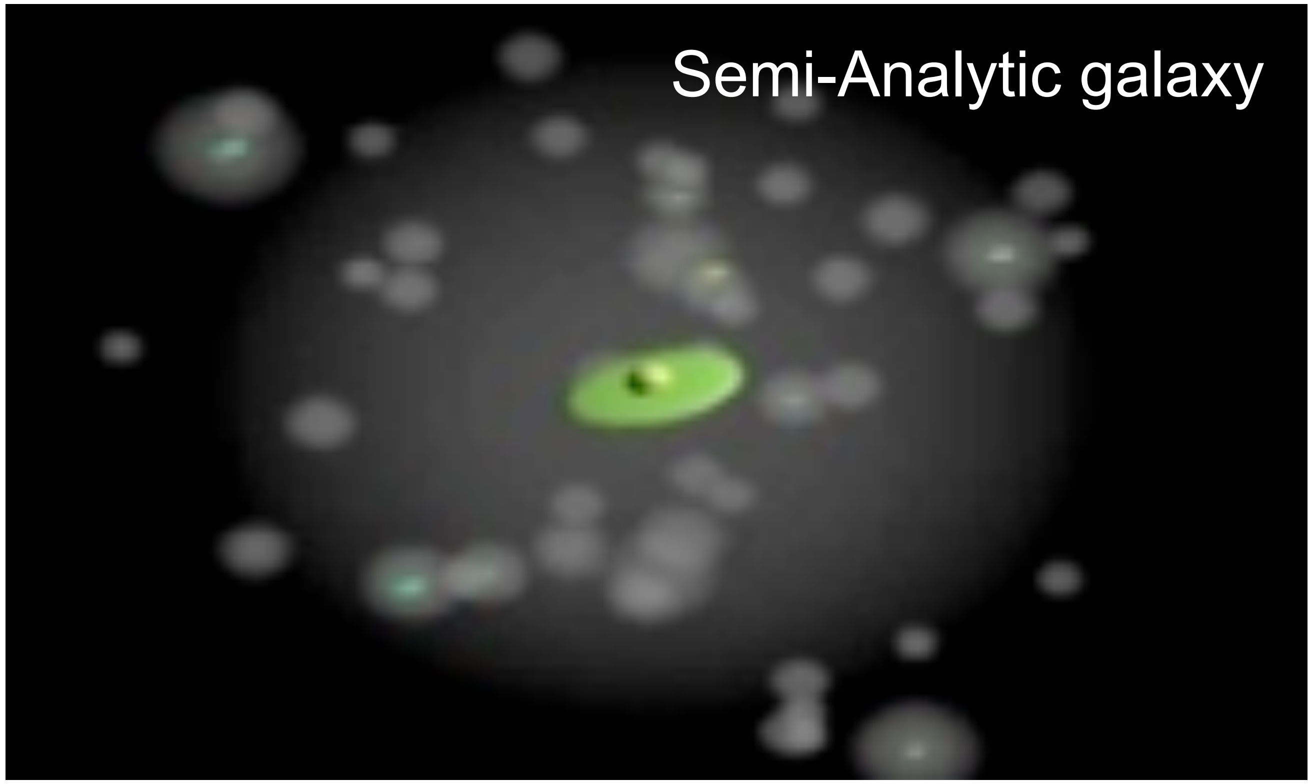


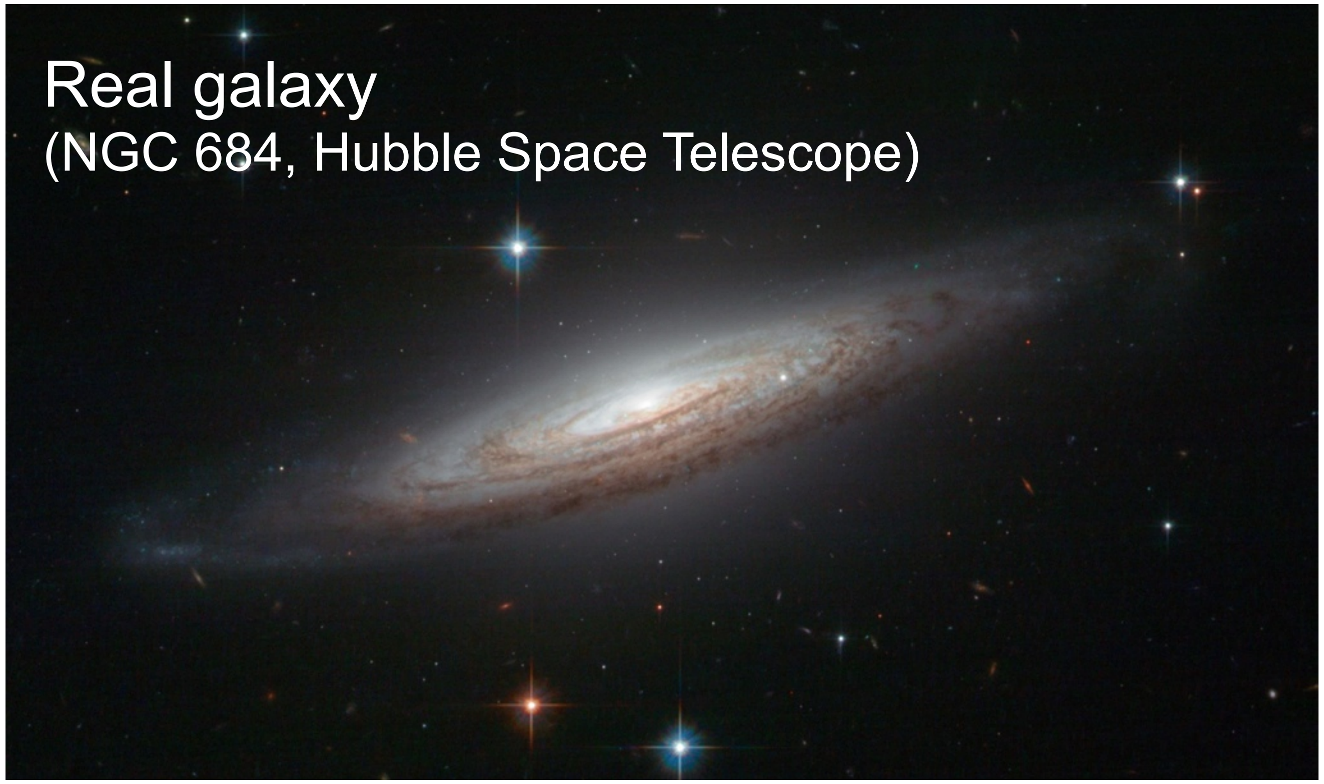
Matter density in MXXL simulation
(R. Angulo et al., 2012, MNRAS 426, 2046)

Semi-Analytic models

Deals with problem 1: Galaxies included into DM simulations “by hand” (see Lecture 11)

- Analytic prescriptions for galaxy evolution processes (Star formation, feedback, mergers, AGN, ...)
- Quick to run
- Easy to explore model variations
- But: severely simplified
- Baryons cannot influence DM
- No predictions about the inter-galactic medium





Hydrodynamical simulations

More fundamental approach: Include baryons directly into simulation

- Two fundamental additions to DM-only simulations:
- 1.) Hydrodynamics: Gas responds to pressure as well as gravity
- 2.) Baryonic physics: Gas can do more than simply move around (star formation, chemical evolution, black holes, ...)

Need to treat gas as *fluid*: Not collisionless, mean free path is short. This requires a fundamentally different simulation technique from DM.

Relevant scales often unresolved: Need to implement as *sub-grid physics* modules

How to deal with fluids in simulations

Fluid simulation: Grid method

Basic idea: Parcel up the simulation *volume* into a finite number of *cells*

- Each cell has a finite volume and contains a finite gas mass: get density
- Compute fluxes between neighbouring cells and update masses
- Often combined with *adaptive mesh refinement* (AMR) to make cells smaller in densest areas

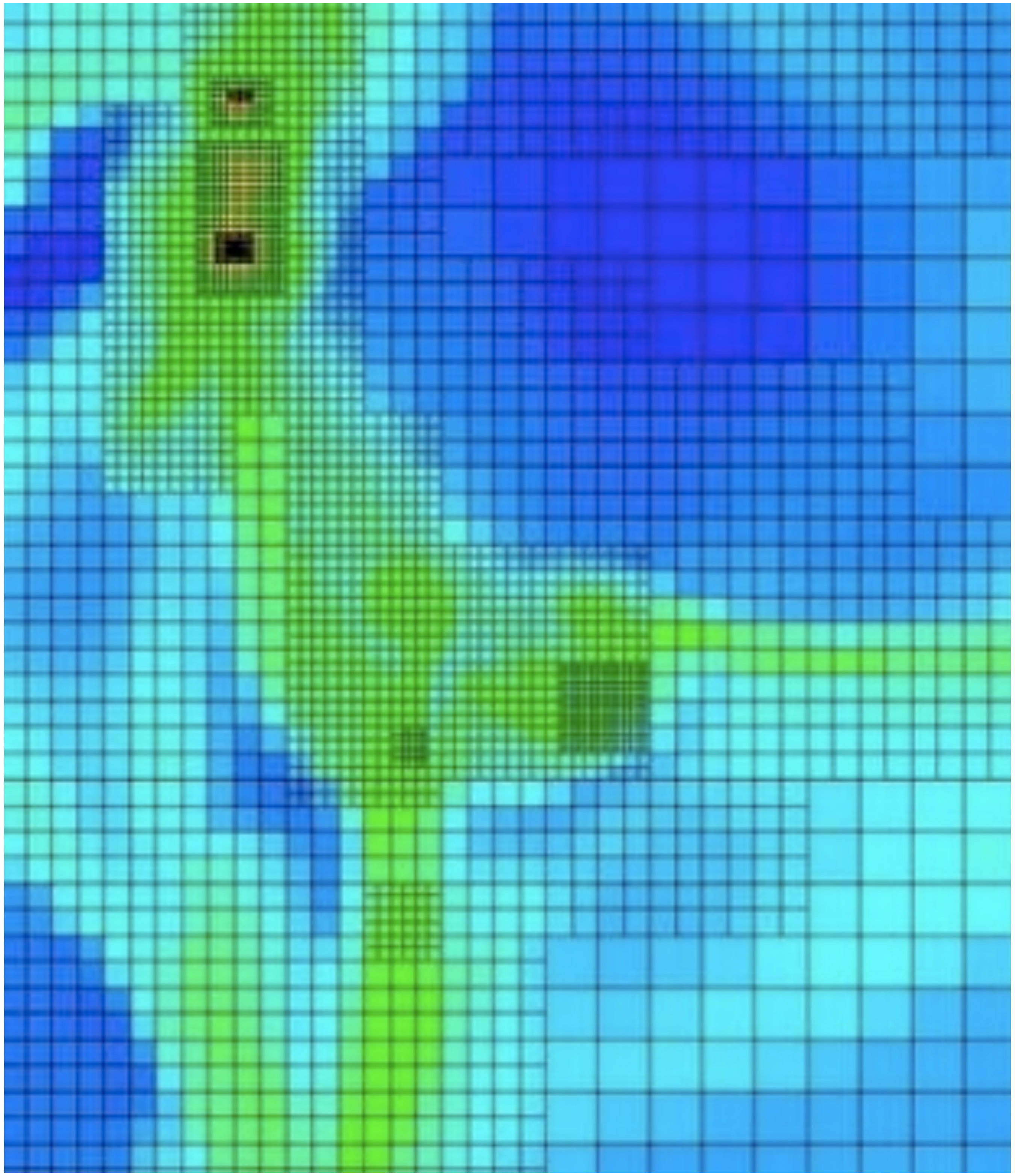
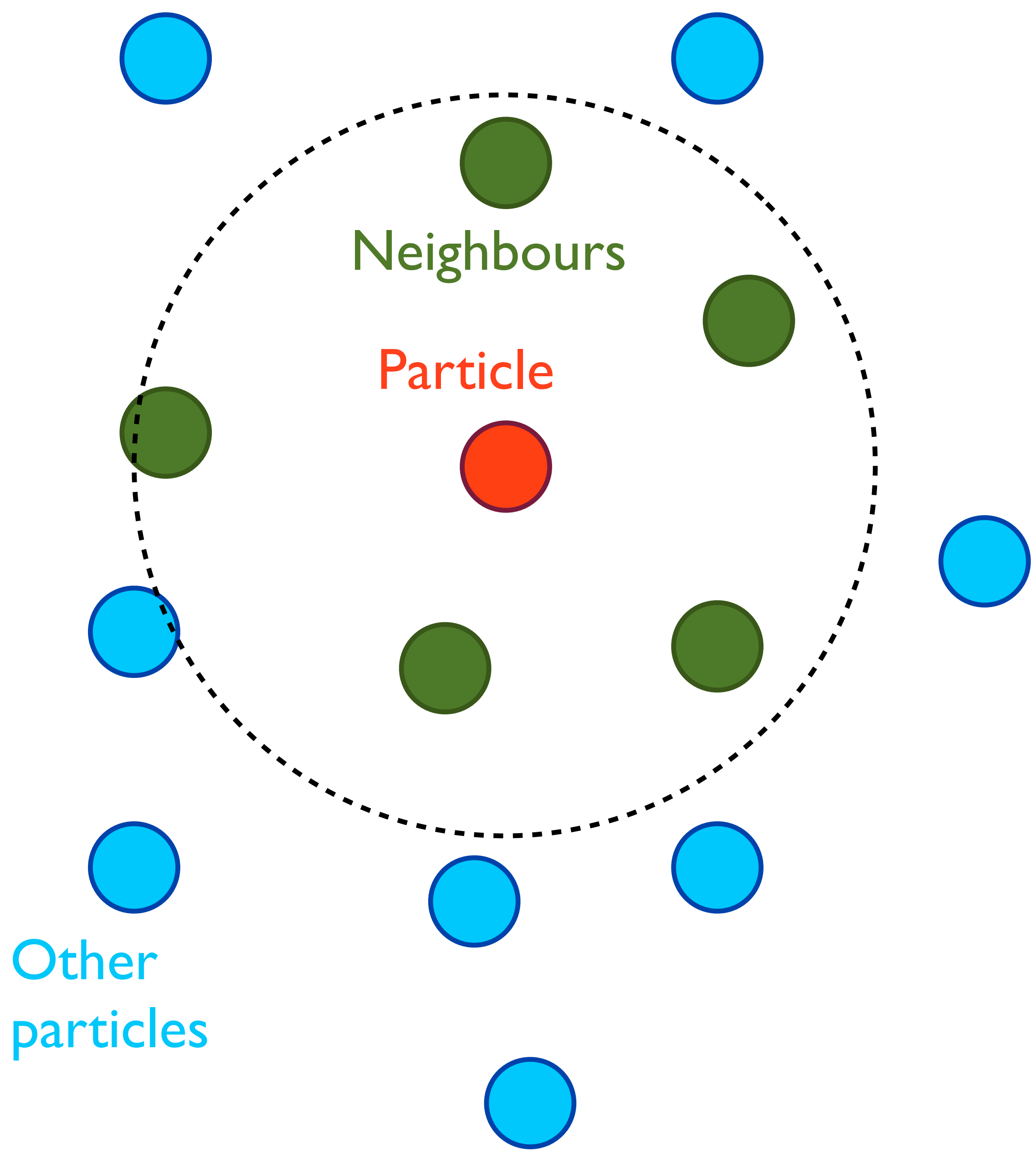


Illustration of AMR: Grid becomes finer in dense regions (yellow)

Fluid simulation: Particle method

Basic idea: Parcel up the simulation *mass* into a finite number of *particles*.

- Conceptually similar to DM-only simulation: Particles conserve mass and move through space.
- But particles occupy only infinitesimally small volume --> to find the local density, one must *interpolate* over neighbouring particles...



+Spatial resolution adapted *automatically*

+Galilean-invariant (no preferred frame or direction)

+Lagrangian: can trace individual particle's history

Smoothed Particle Hydrodynamics (SPH)

$$F_s(\mathbf{r}) = \int F(\mathbf{r}) W(\mathbf{r} - \mathbf{r}', h) \mathrm{d}\mathbf{r}'.$$

Some field F(**r**) Kernel W(**r**, h)

h is the characteristic width of the Kernel (normalized to unity)

$$W(\mathbf{r}, h) = w(\tfrac{|\mathbf{r}|}{2h}) \quad \text{with} \quad w_{3D}(q) = \frac{8}{\pi} \begin{cases} 1 - 6q^2 + 6q^3, & 0 \le q \le \frac{1}{2}, \\ 2(1-q)^3, & \frac{1}{2} < q \le 1, \\ 0, & q > 1, \end{cases}$$

Kernel is zero for $r \geq 2h$:
Integrate over finite volume

Assume we know the field values only at a finite set of points: $F_i = F(\mathbf{r}_i)$.
Each point has mass m_i and density $\rho_i \Rightarrow$ volume $\Delta\mathbf{r}_i \sim m_i / \rho_i$

$$F_s(\mathbf{r}) \simeq \sum_j \frac{m_j}{\rho_j} F_j W(\mathbf{r} - \mathbf{r}_j, h)$$

F_s defined everywhere and differentiable!

$$\rho_s(\mathbf{r}) \simeq \sum_j m_j W(\mathbf{r} - \mathbf{r}_j, h)$$

Want to have $h \geq d$ (mean interparticle separation):
Minimum of ~33 neighbours

(V. Springel, 2010, ARA&A 48, 391)

SPH in some more detail - gas dynamics

Euler equations in Lagrangian form:

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

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

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

Generating Lagrangian (Eckert 1960)

$$L = \int \rho\left(\frac{\mathbf{v}^2}{2} - u\right)\mathrm{d}V$$

discretize

$$L_{\mathrm{SPH}} = \sum_i \left(\frac{1}{2}m_i\mathbf{v}_i^2 - m_i u_i\right)$$

Pressure: $P_i = A_i\rho_i^\gamma = (\gamma - 1)\rho_i u_i$

Specific thermal energy: $u_i(\rho_i) = A_i\frac{\rho_i^{\gamma-1}}{\gamma - 1}$

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\sum_{j=1}^{N} m_j\left[f_i\frac{P_i}{\rho_i^2}\nabla_i W_{ij}(h_i) + f_j\frac{P_j}{\rho_j^2}\nabla_i W_{ij}(h_j)\right] \quad , \quad f_i = \left[1 + \frac{h_i}{3\rho_i}\frac{\partial\rho_i}{\partial h_i}\right]^{-1}$$

(V. Springel, 2010, ARA&A 48, 391)

SPH in some more detail - gravity

Also need to account for gravity!

This leads to an extra term in the equations of motions:

$$m_i \mathbf{a}_i^{\text{grav}} = -\frac{\partial E_{\text{pot}}}{\partial \mathbf{r}_i}$$
$$= -\sum_j G m_i m_j \frac{\mathbf{r}_{ij}}{r_{ij}} \frac{[\phi'(r_{ij}, \varepsilon_i) + \phi'(r_{ij}, \varepsilon_j)]}{2}$$
$$-\frac{1}{2} \sum_{jk} G m_j m_k \frac{\partial \phi(r_{jk}, \varepsilon_j)}{\partial \varepsilon} \frac{\partial \varepsilon_j}{\partial \mathbf{r}_i},$$

This term is only non-zero if the gravitational softening length is variable in space (usually not the case)

where E_{pot} is the potential energy:

$$E_{\text{pot}} = \frac{1}{2} \sum_i m_i \Phi(\mathbf{r}_i) = \frac{G}{2} \sum_{ij} m_i m_j \phi(r_{ij}, \varepsilon_j)$$

Final note:
SPH is by construction *inviscid* and cannot capture shocks!

⇒ "artificial viscosity"

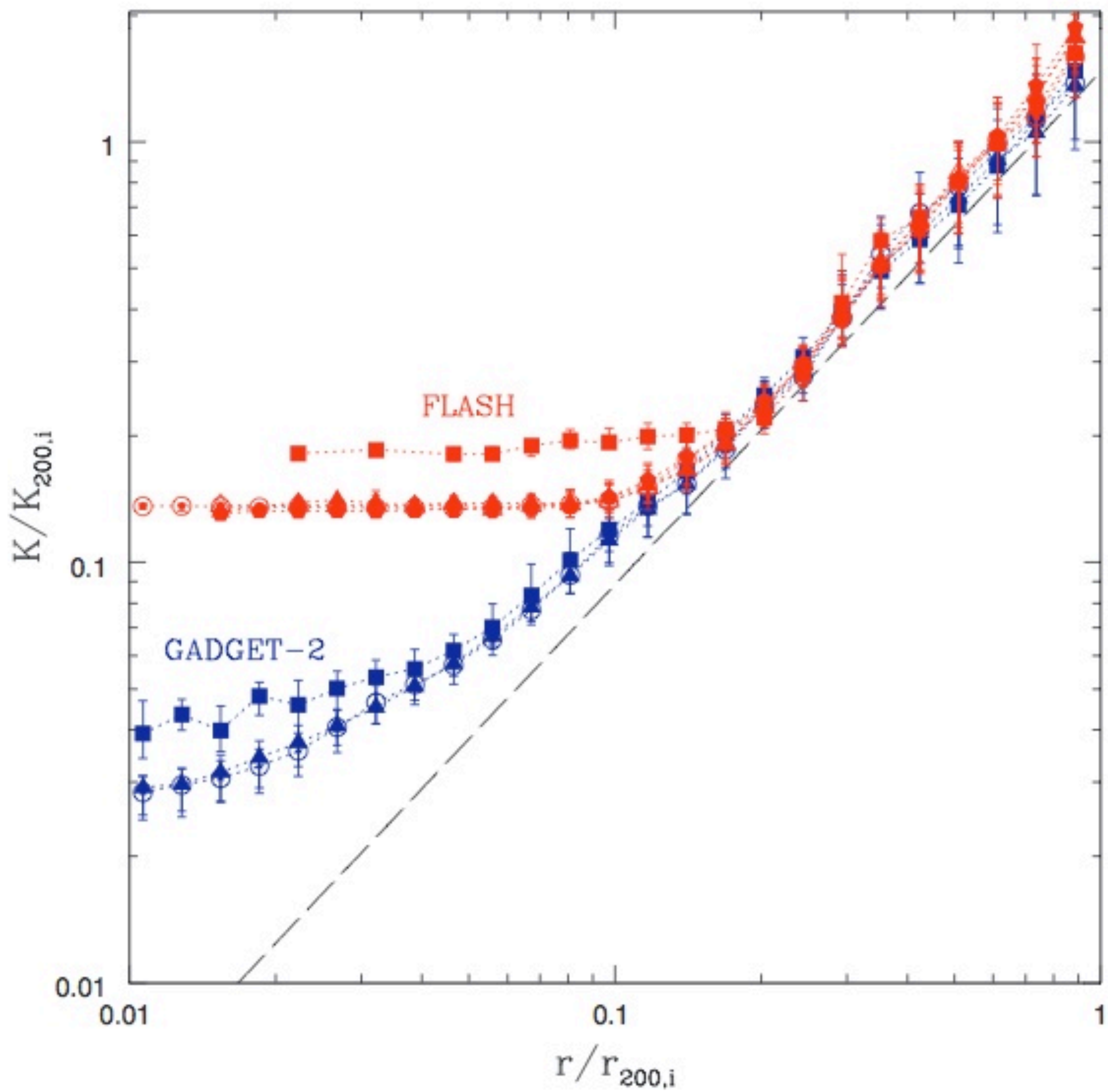
(convert kinetic into thermal energy when there is local convergence of the fluid flow)

(V. Springel, 2010, ARA&A 48, 391)

Fluid simulation: Method comparison

Two different schemes for same job: compare results!

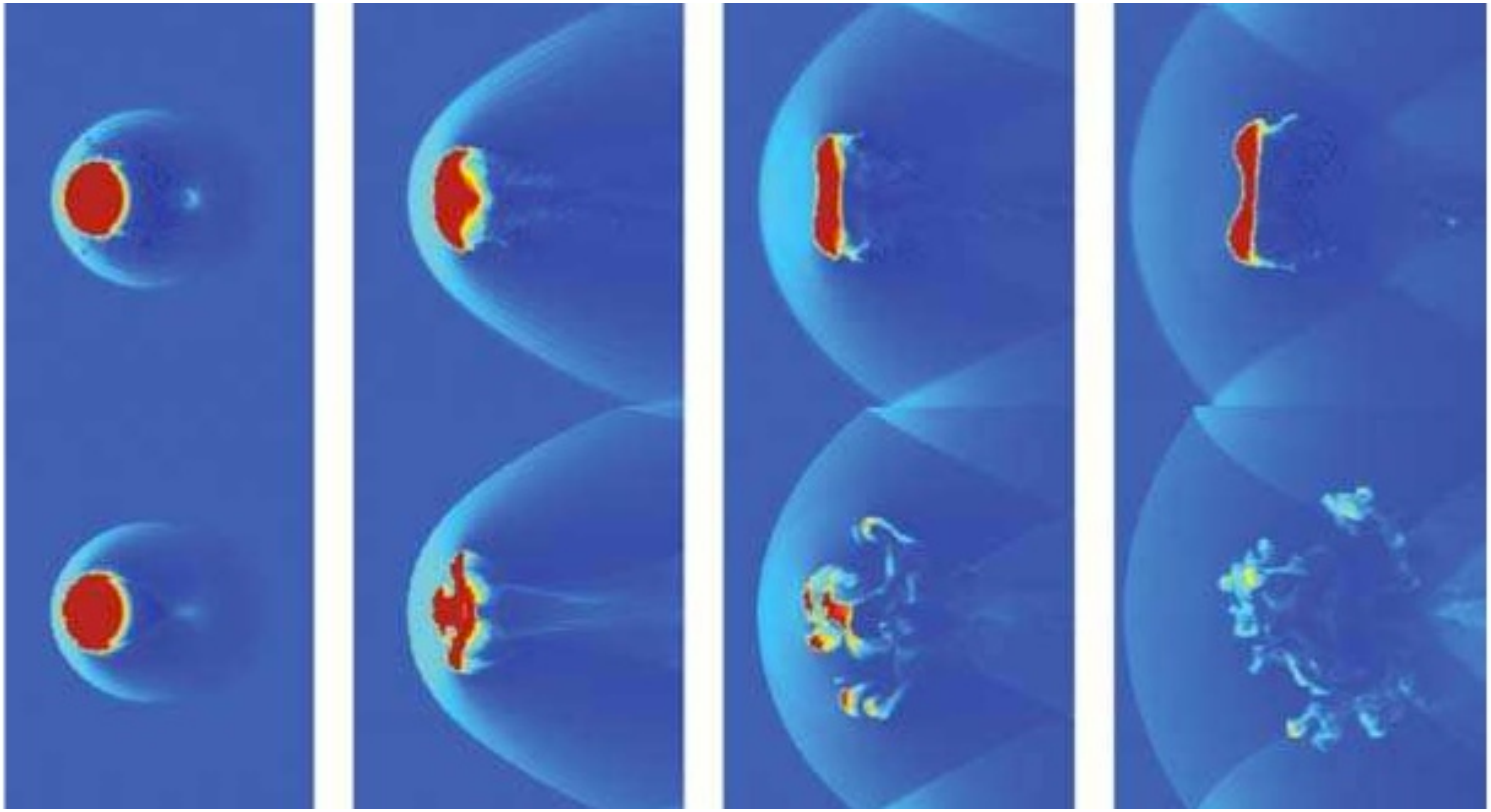
!!&@3!



Galaxy cluster entropy profiles: grid and SPH
(N. Mitchell et al., 2009, MNRAS 426, 2046)

Fluid simulation: Method comparison

Two different schemes for same job: compare results!



GADGET-2
(SPH)

ENZO
(grid)

Disruption of a gas blob in a supersonic flow
(O. Agertz et al., 2007, MNRAS 380, 963)

Result of calculation *can* depend strongly on numerical method (more later) !!

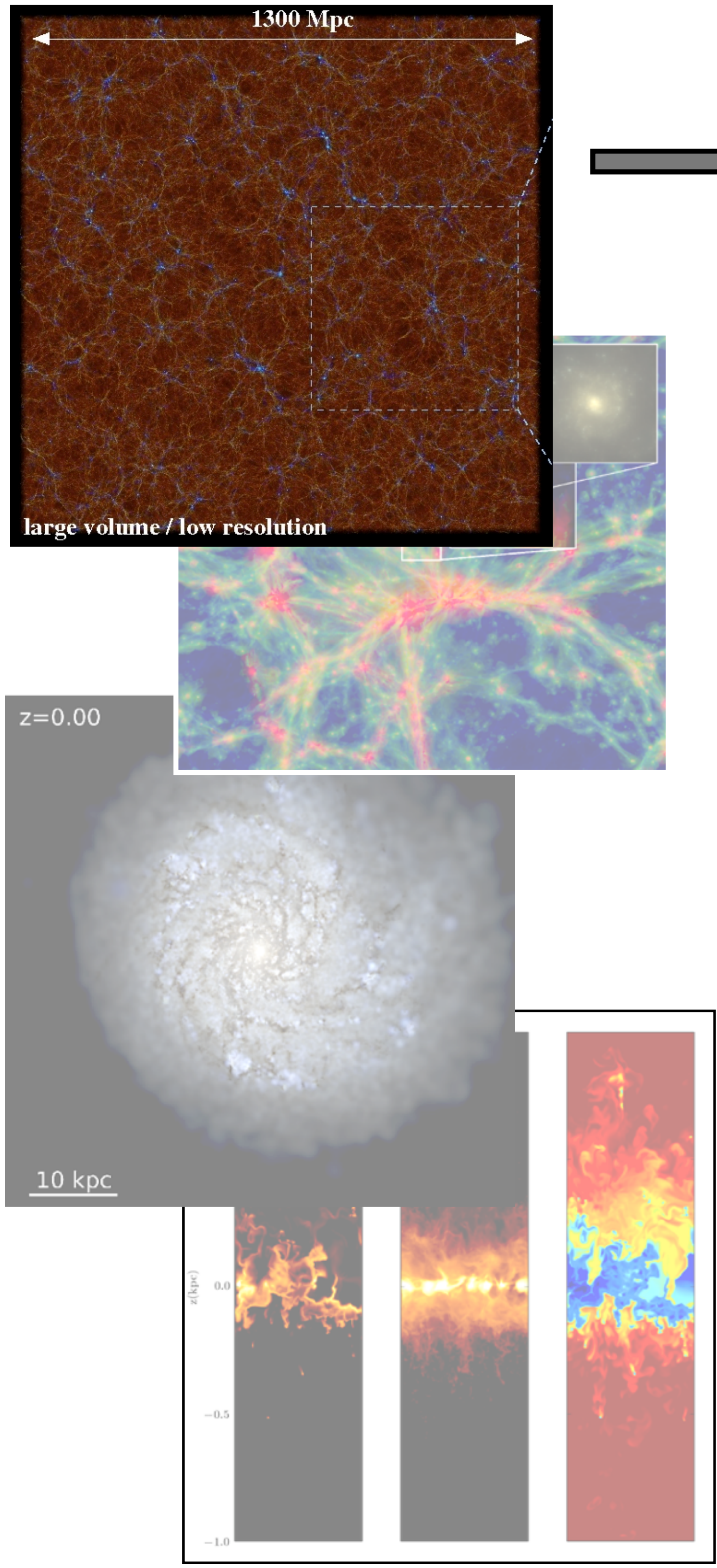
Note:

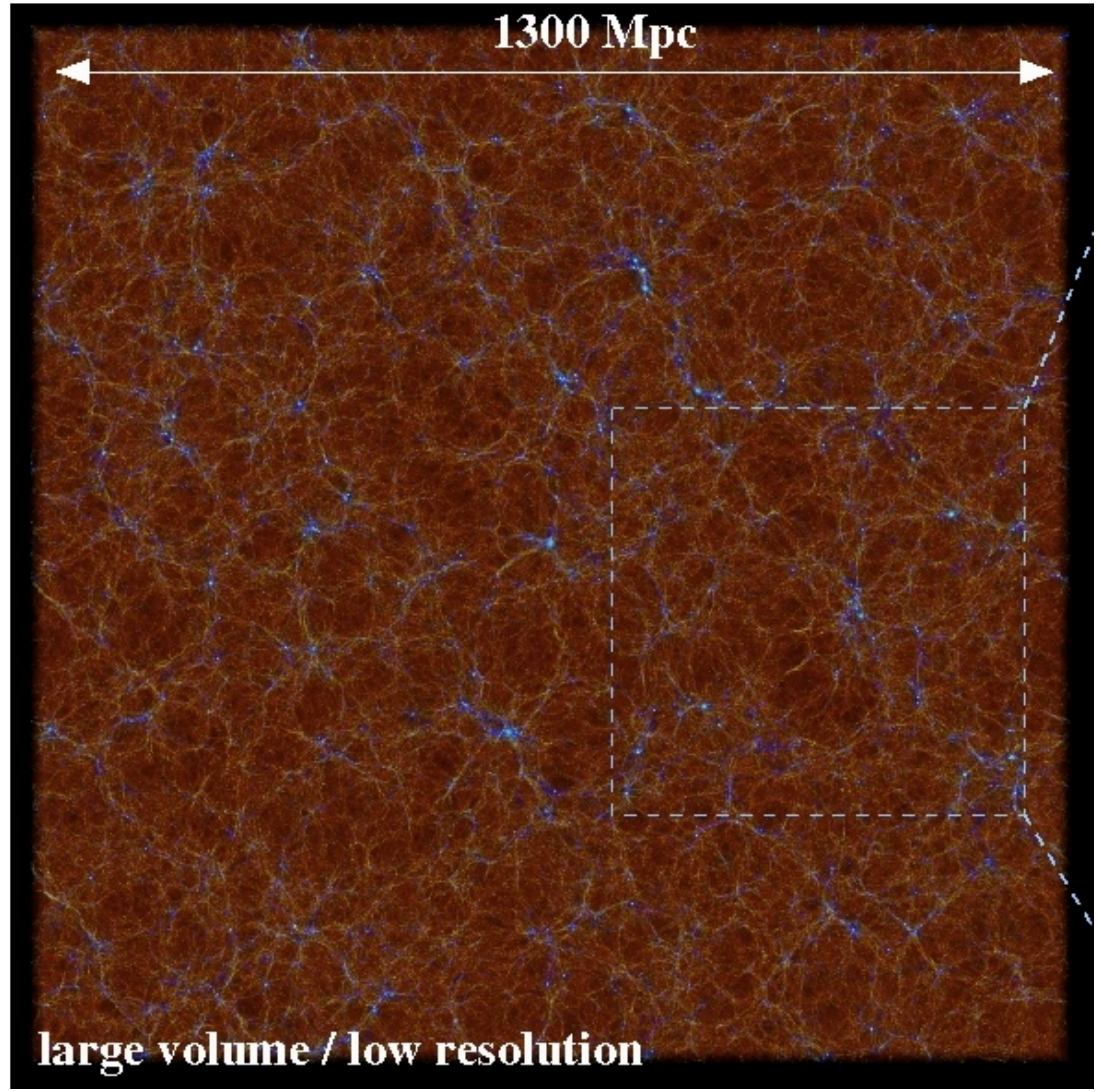
In recent years, much work has gone into solving these problems with the "traditional" SPH formalism. Details are beyond the scope of this course, but modern SPH codes are able to make accurate predictions about galaxy formation (see later).

(C.-Y. Hu et al., 2014, MNRAS 443, 1173)

How to deal with physics on unresolved scales: sub-grid modules

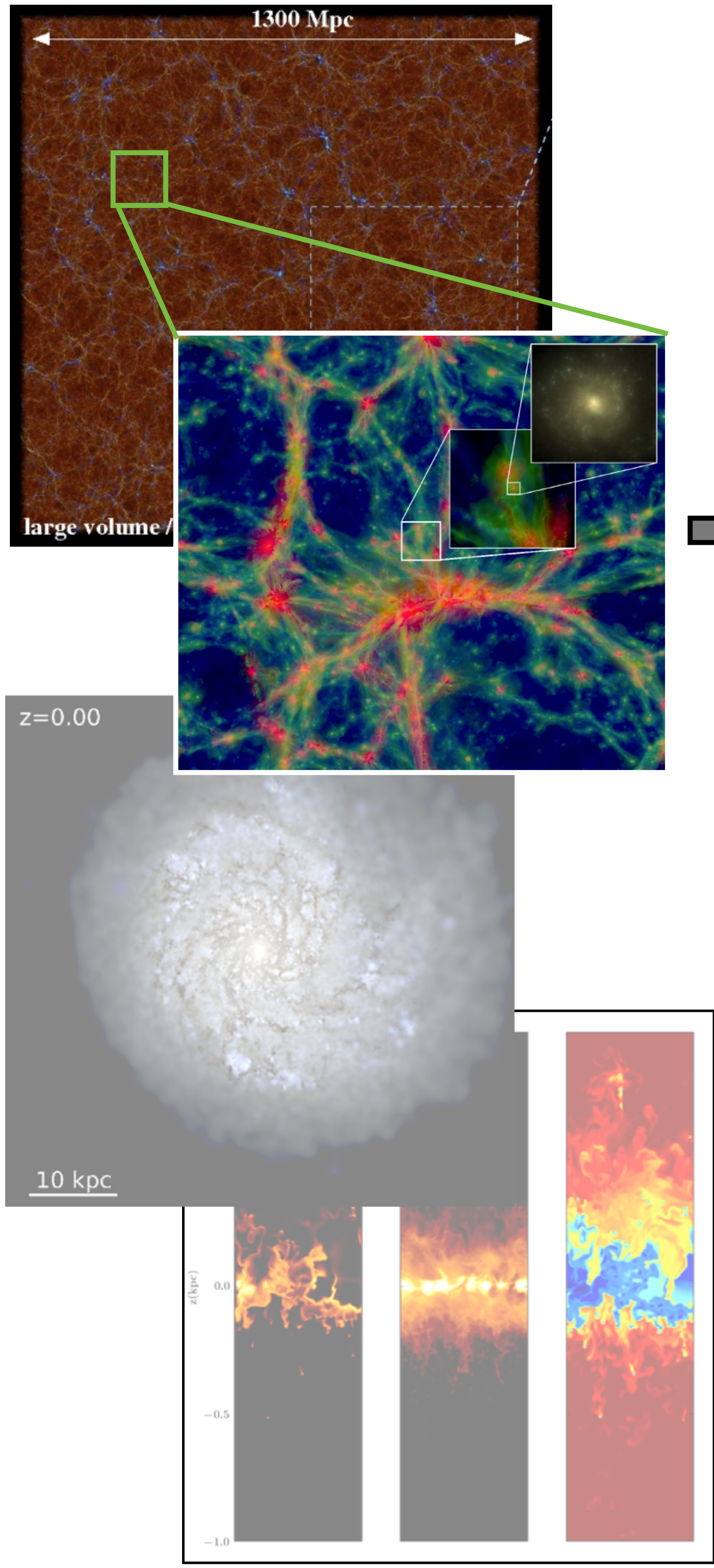
Hydro simulations on different scales

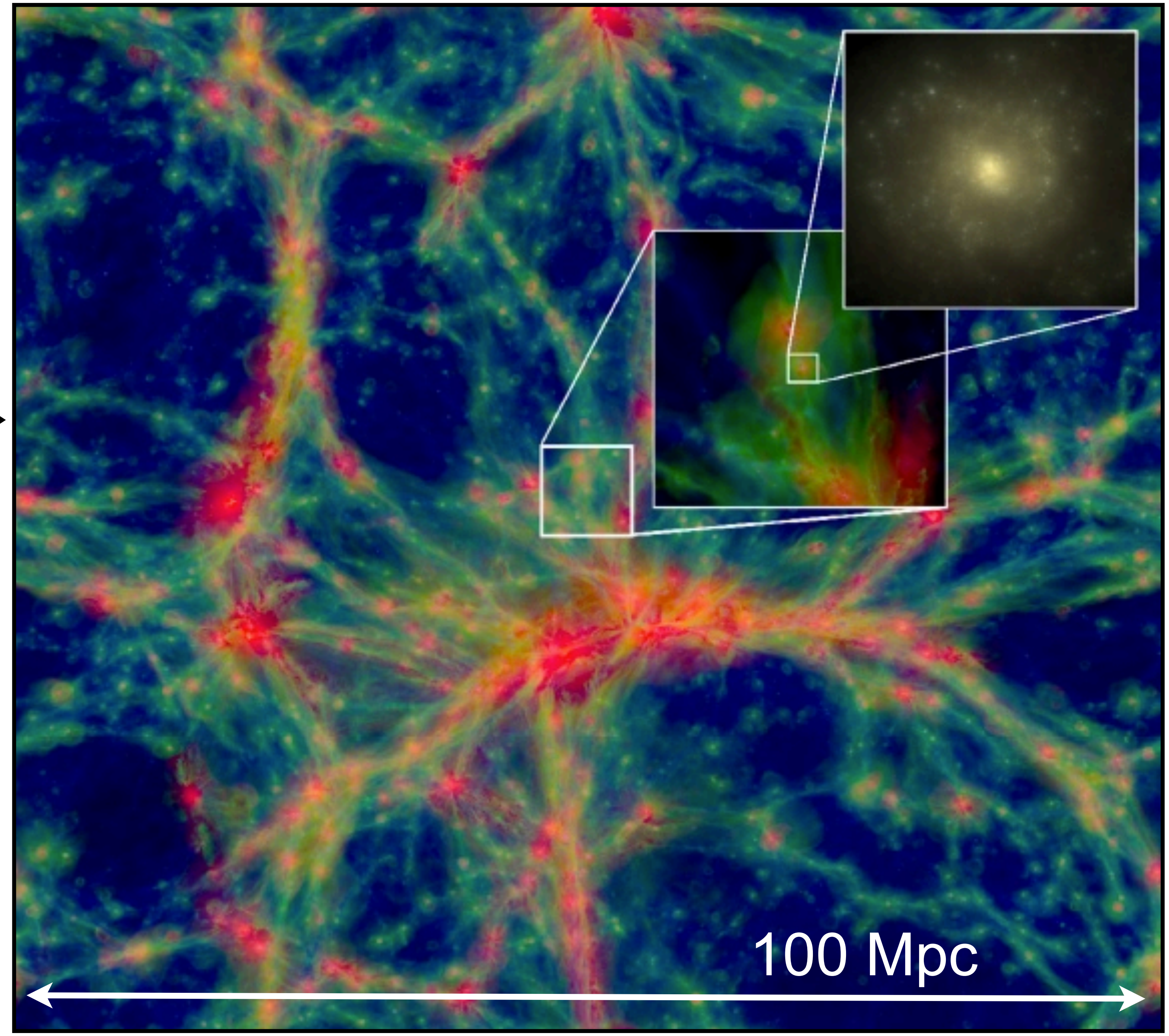




Large cosmological volumes, low res. (~10^{10} $M_{\odot}$)
(*MAGNETICUM*, K. Dolag et al., in prep.)

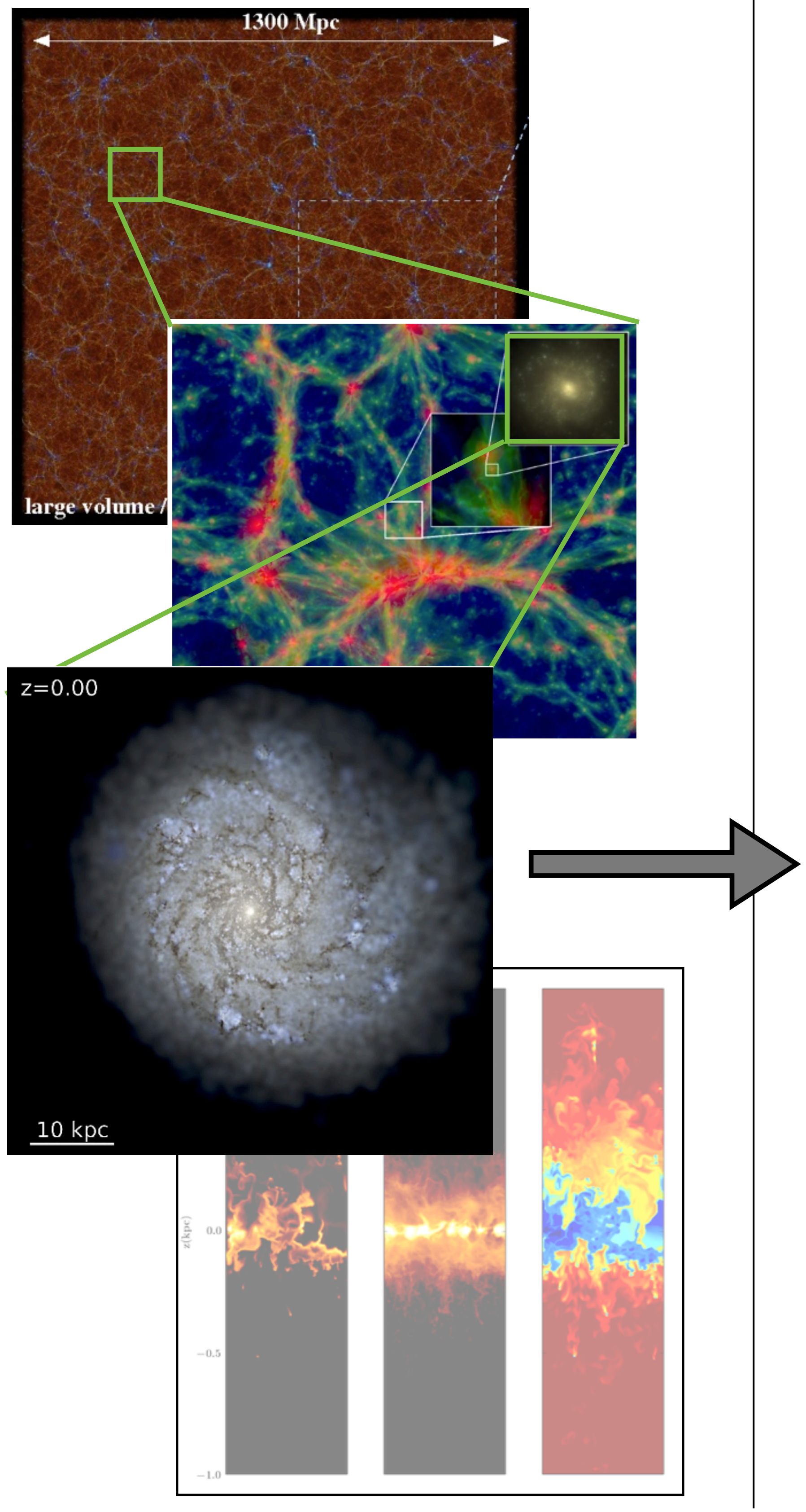
Hydro simulations on different scales

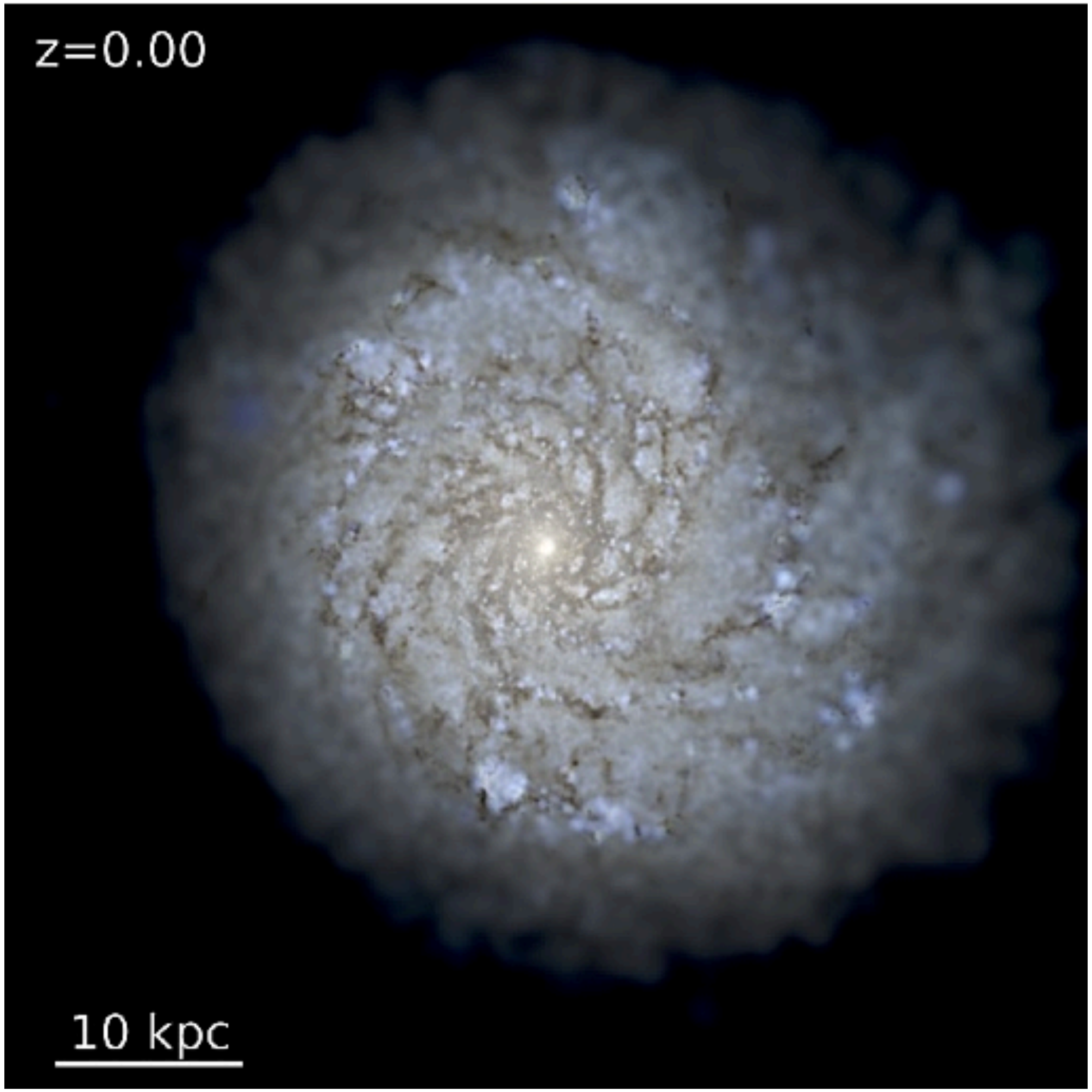




Small cosmological volumes, medium res. (~10^6 $M_\odot$)
(*EAGLE*, J. Schaye et al., 2015, MNRAS 446, 521)

Hydro simulations on different scales

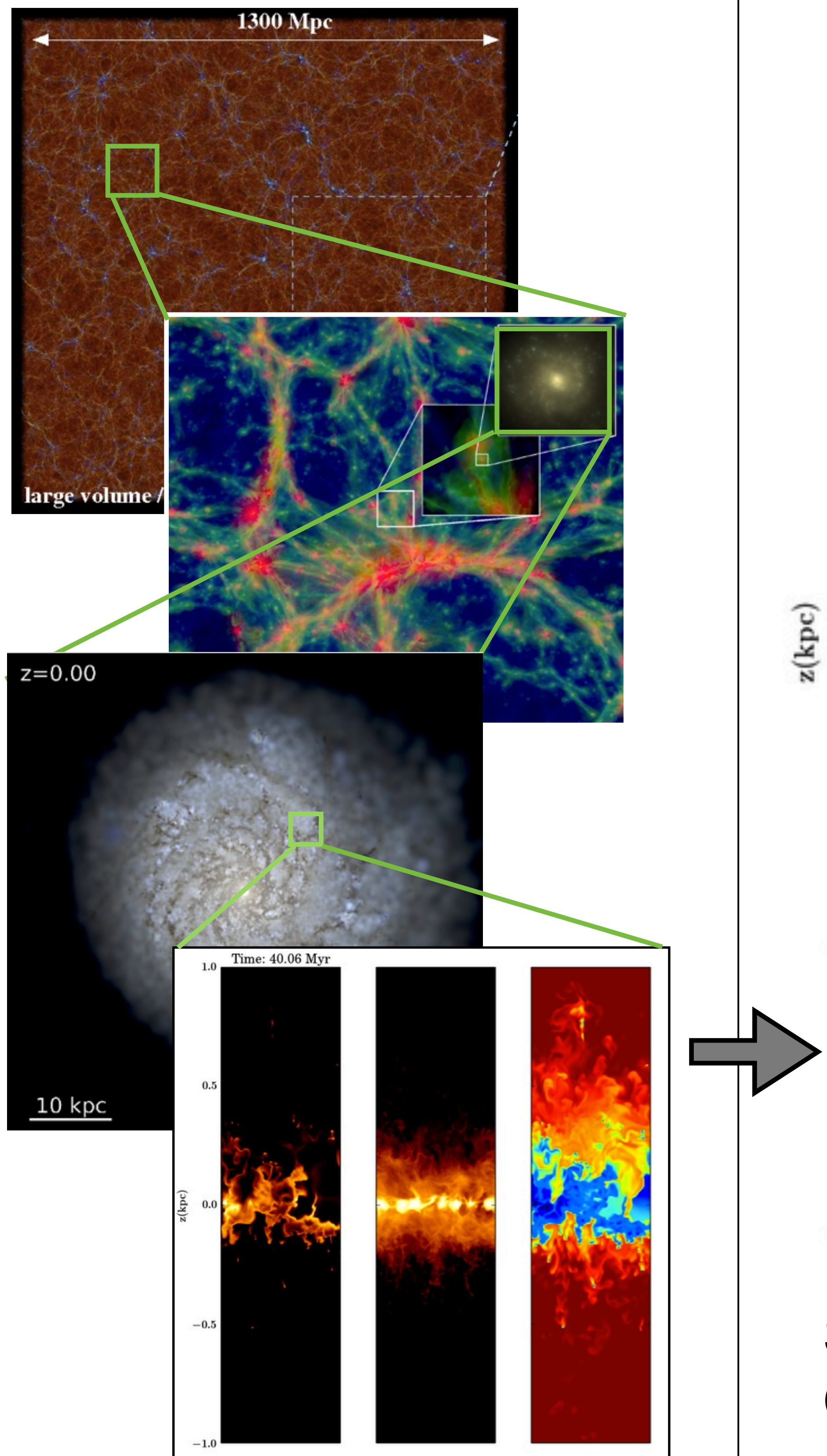


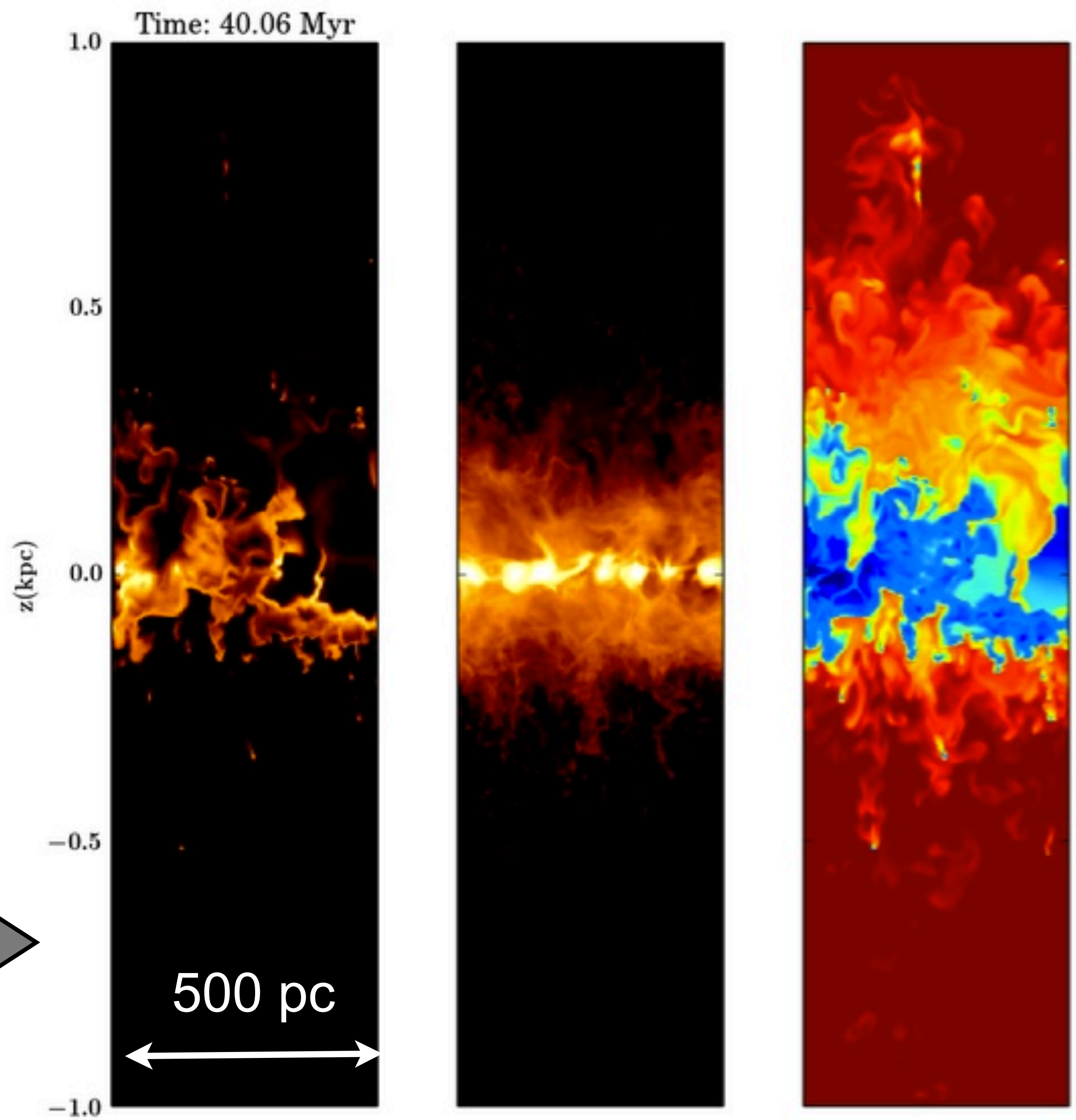


Individual galaxies, high res (~10^3 $M_\odot$)

(*FIRE* - P. Hopkins et al., 2014, MNRAS 445, 581)

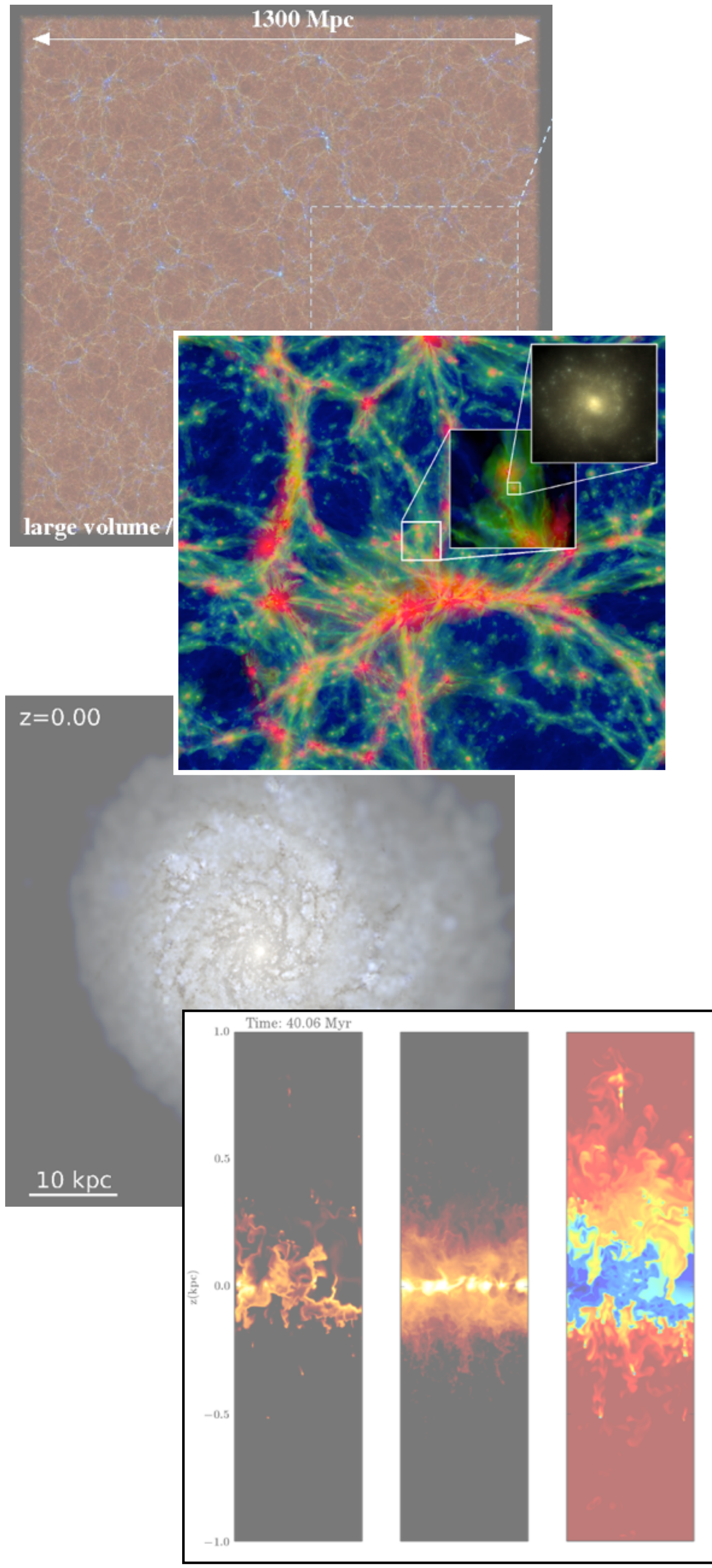
Hydro simulations on different scales





Slice through galactic disk, resolution 4 pc (~ 1 $M_\odot$)
(*SILCC* - S. Walch et al., 2014, arXiv:1412.2749)

Hydro simulations on different scales



Concentrate on this scale here: most useful for understanding the observed population of galaxies as a whole*

(Galaxies well-resolved at $M_{star} \gtrsim 10^9\ M_\odot$: 1000s of objects for robust comparisons to observations)

*: Except for those living in rare environments such as massive galaxy clusters (→ zoom simulations)

Which of these is a `typical' galaxy...?

Sub-grid modules: overview

Baryons are subject to physical effects beyond gravity and hydrodynamics. Broadly divide into three categories
[obviously heavily dependent on research interest!]

Directly interesting / observable	Impact on interesting quantities	Irrelevant
- Star formation	- Supernova feedback	- Planet formation
- Nucleosynthesis	- AGN feedback	- Chemistry
- SMBHs / Active Galactic Nuclei	- Cooling/ heating	- Biology / Life / ...

Need to be implemented into simulation

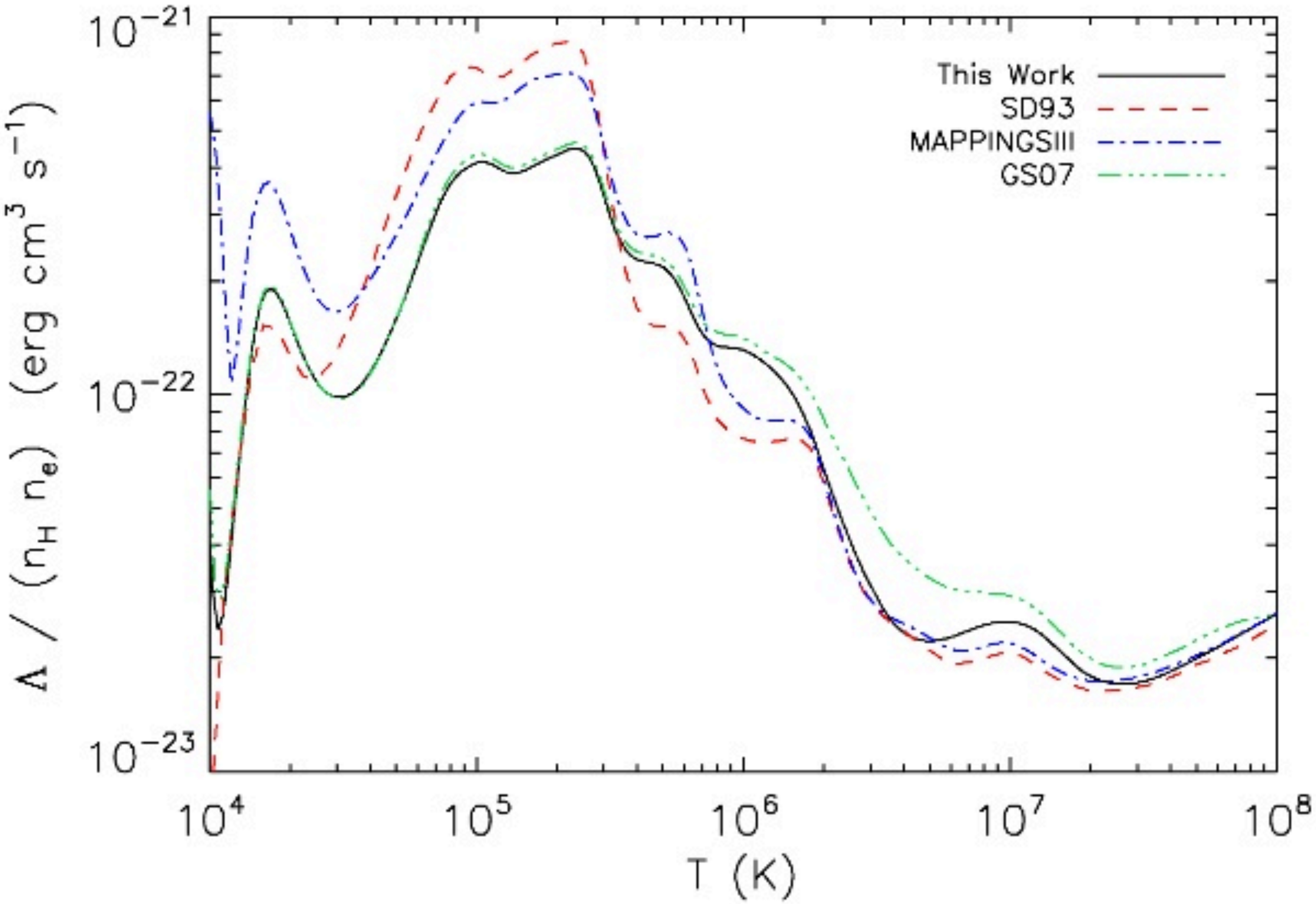
Important note:

This is an active area of research, and there are many different ways in which these effects can be implemented into a simulation.
Impossible to list them all!!

This lecture mostly follows the implementation in the EAGLE simulations.

I: Radiative cooling

Gas can radiate away its internal energy and cool: Essential for formation of dense structures like galaxies and stars.



Cooling function depends strongly on metallicity: H, He, C, N, O, Ne, Mg, Si, S, Ca and Fe

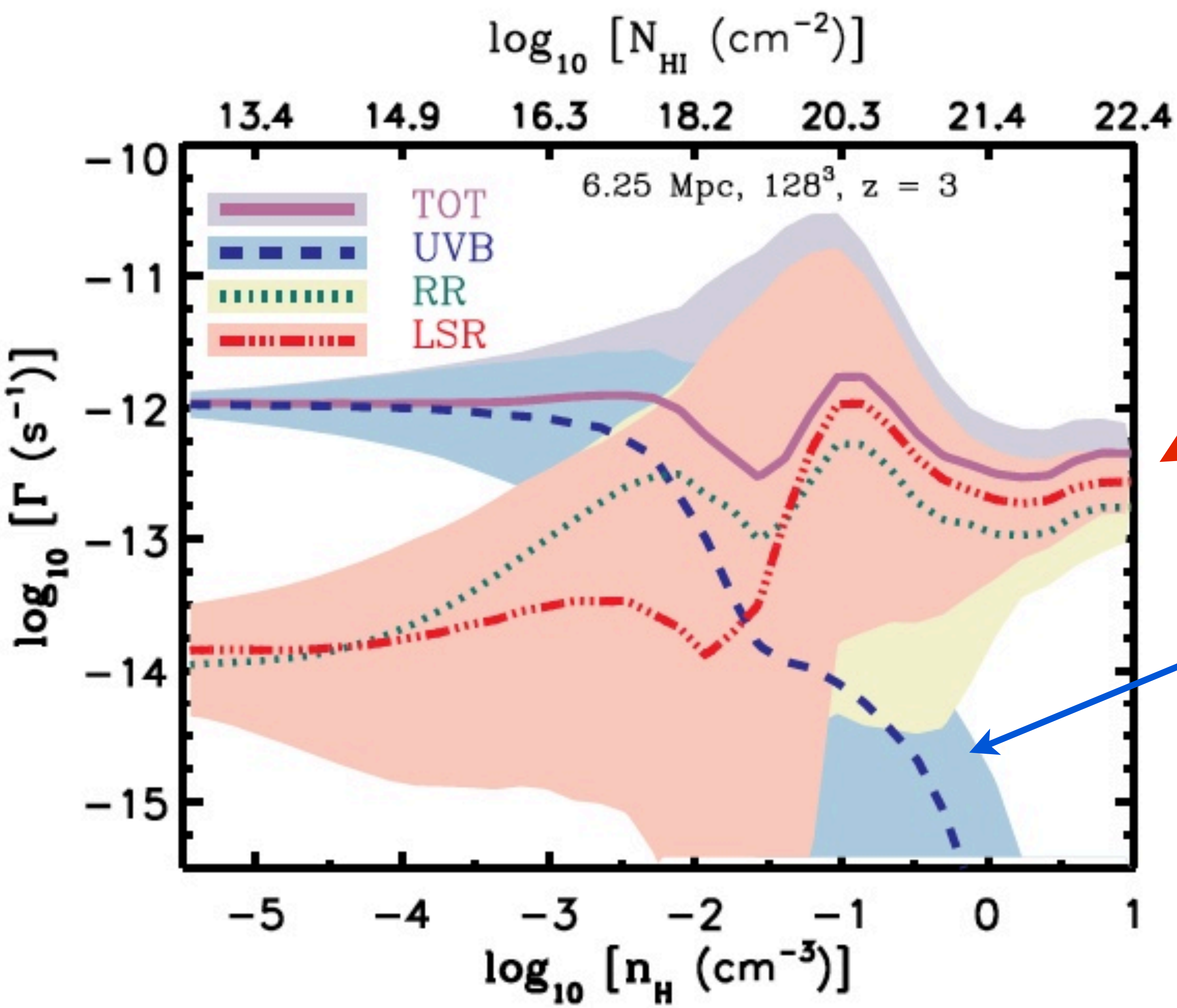
Look up tabulated cooling rates on element-by-element basis.

(R. Wiersma et al., 2009, MNRAS 393, 99)

I: Radiative cooling

Complications: Self-shielding against UV background, local stellar radiation

Usually ignored for simplicity



Ionization rate from local stellar radiation

Ionization rate from UV-background

(A. Rahmati et al., 2013, MNRAS 431, 2261)

Also: Cooling rates usually computed under assumption of ionization equilibrium...

II: Reionization

Include a time-dependent, but spatially uniform UV-background at $z \leq 11.5$ (consistent with Planck measurements).

Also inject 2 eV energy per proton mass to account for boost in photoheating rates during reionization

$\Rightarrow$ heats photoionized gas quickly to ~ 10^4 K

III: Star formation

Starting point: Observed Kennicutt-Schmidt law

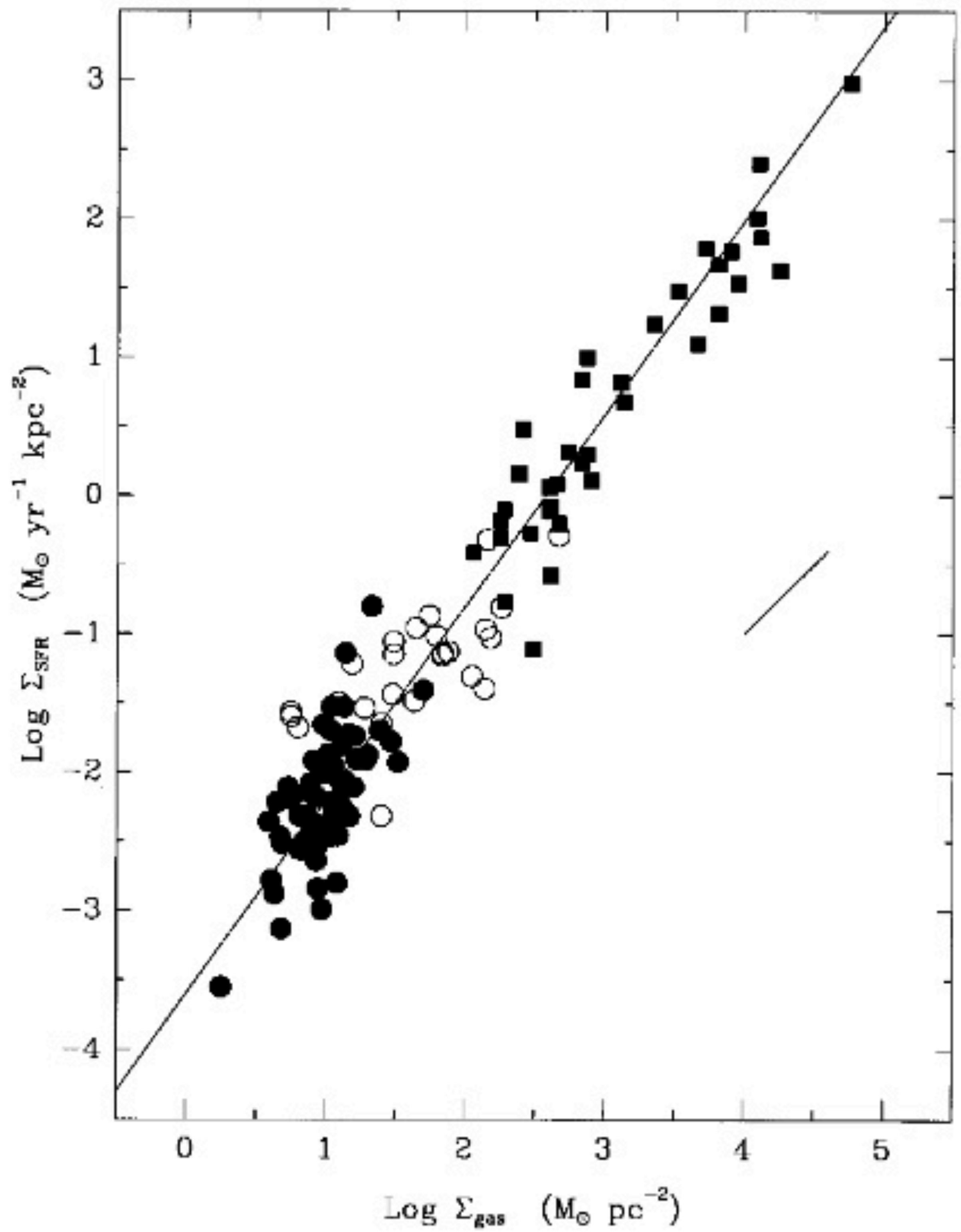
$$\dot{\Sigma}_* = A\left(\Sigma_g\, \mathrm{M}_\odot^{-1}\, \mathrm{pc}^2\right)^n$$

with A = 1.5 x 10^{-4} $M_\odot$ yr^{-1} kpc^{-2}
and n = 1.4

⇒ SFR from surface density

Implement *stochastically* with probability of gas→star given by particle's star formation rate

But this is *not* a "direct" variable of the simulation - would need to identify "galaxies", find disk orientation, ...



(R. Kennicutt, 1998, ApJ 498, 541)

III: Star formation as a pressure law

Assume that gas is self-gravitating:
disc scale-height ~ Jeans scale L_J

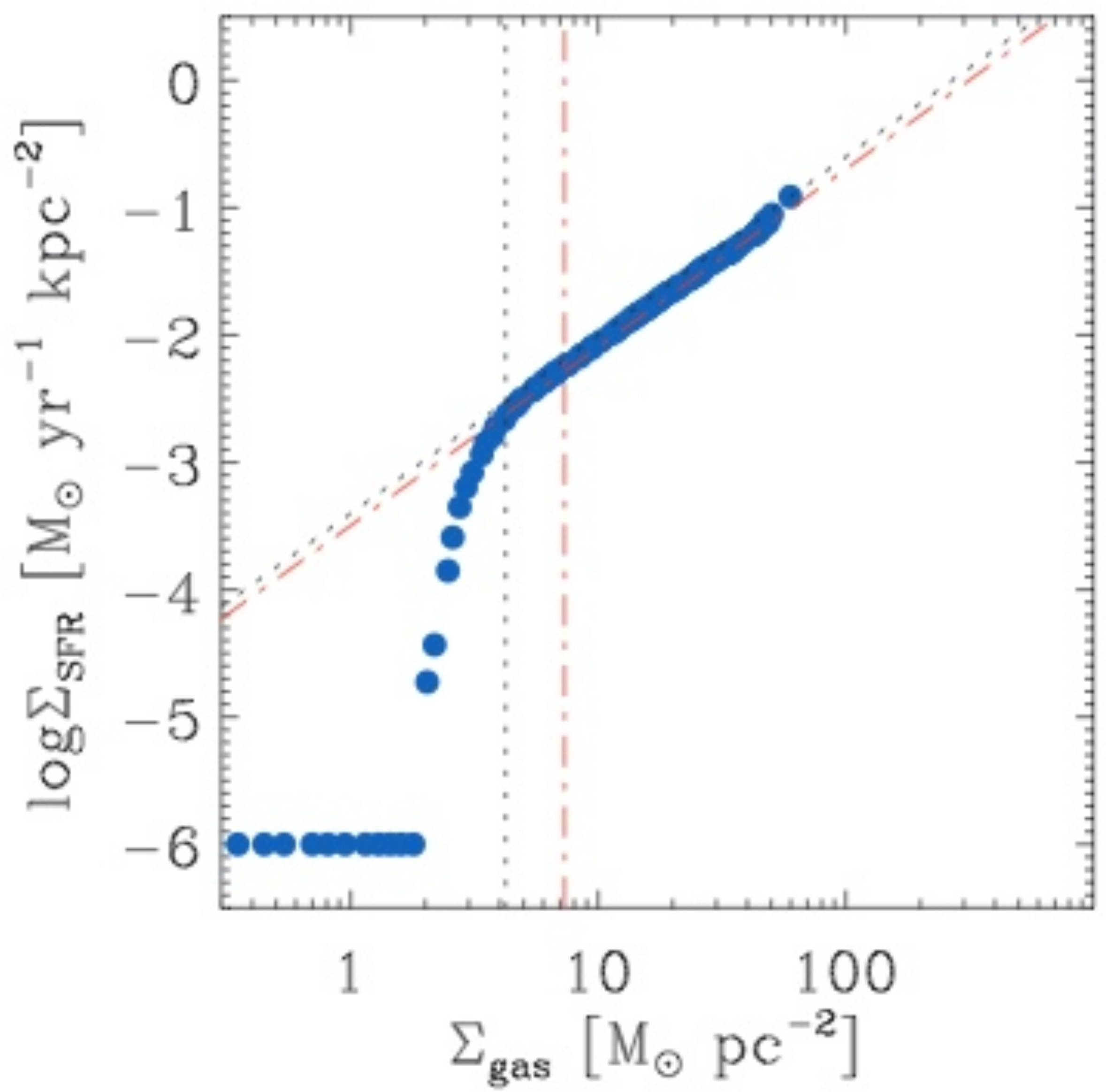
$$\Sigma_g \sim \Sigma_{g,J} \equiv \rho_g L_J,$$

$$= \left(\frac{\gamma k}{\mu G X}\right)^{1/2} (f n_H T)^{1/2},$$

$$= \left(\frac{\gamma}{G}\right)^{1/2} (f_g P_{tot})^{1/2},$$

So the KS law becomes:

$$\dot{m}_* = m_g A \left(1\,\mathrm{M_\odot\,pc^{-2}}\right)^{-n} \left(\frac{\gamma}{G} f_g P\right)^{(n-1)/2}$$



Test simulation reproduces original Kennicutt-Schmidt law

(J. Schaye & C. Dalla Vecchia, 2008, MNRAS 383, 1210)

III: Star formation threshold

Observationally, star formation (SF) occurs only in cold molecular gas ($T << 10^4$ K). Not modelled well in current simulations for resolution and physics reasons, so set the SF threshold at threshold density for cold phase formation:

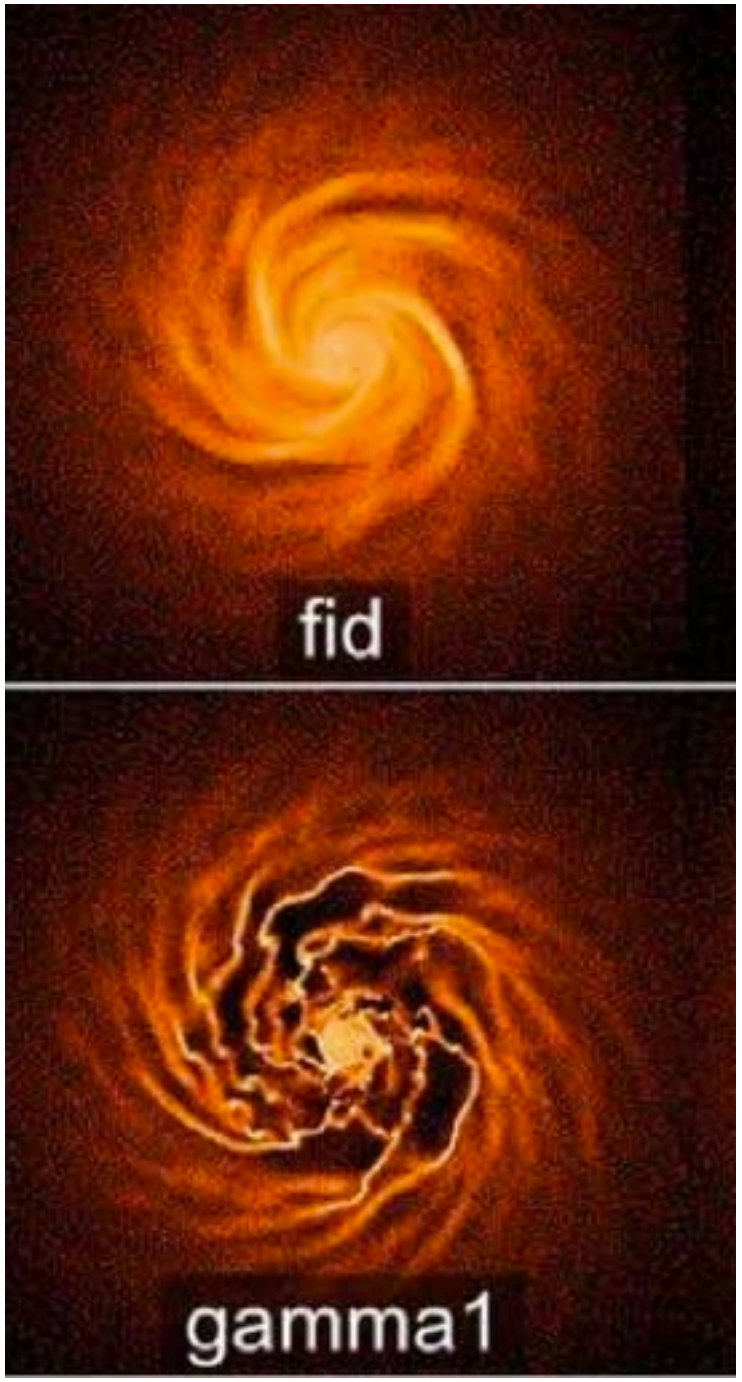
$$n_{\mathrm{H}}^{*}(Z) = 10^{-1}\,\mathrm{cm}^{-3}\left(\frac{Z}{0.002}\right)^{-0.64}$$

(Schaye, 2004)

[Higher Z → more dust → form cold molecular phase at lower density]

Impose *effective equation of state* above this threshold:

$$P_{\mathrm{tot}} = P_{\mathrm{tot,c}}\left(\frac{\rho_{\mathrm{g}}}{\rho_{\mathrm{g,c}}}\right)^{\gamma_{\mathrm{eff}}}$$ with $\gamma_{\mathrm{eff}} = 4/3$



$\gamma_{\mathrm{eff}} = 4/3$: Realistic disk galaxy

$\gamma_{\mathrm{eff}} = 1$: Artificial fragmentation of the disk

(J. Schaye & C. Dalla Vecchia, 2008, MNRAS 383, 1210)

IV: Stellar recycling

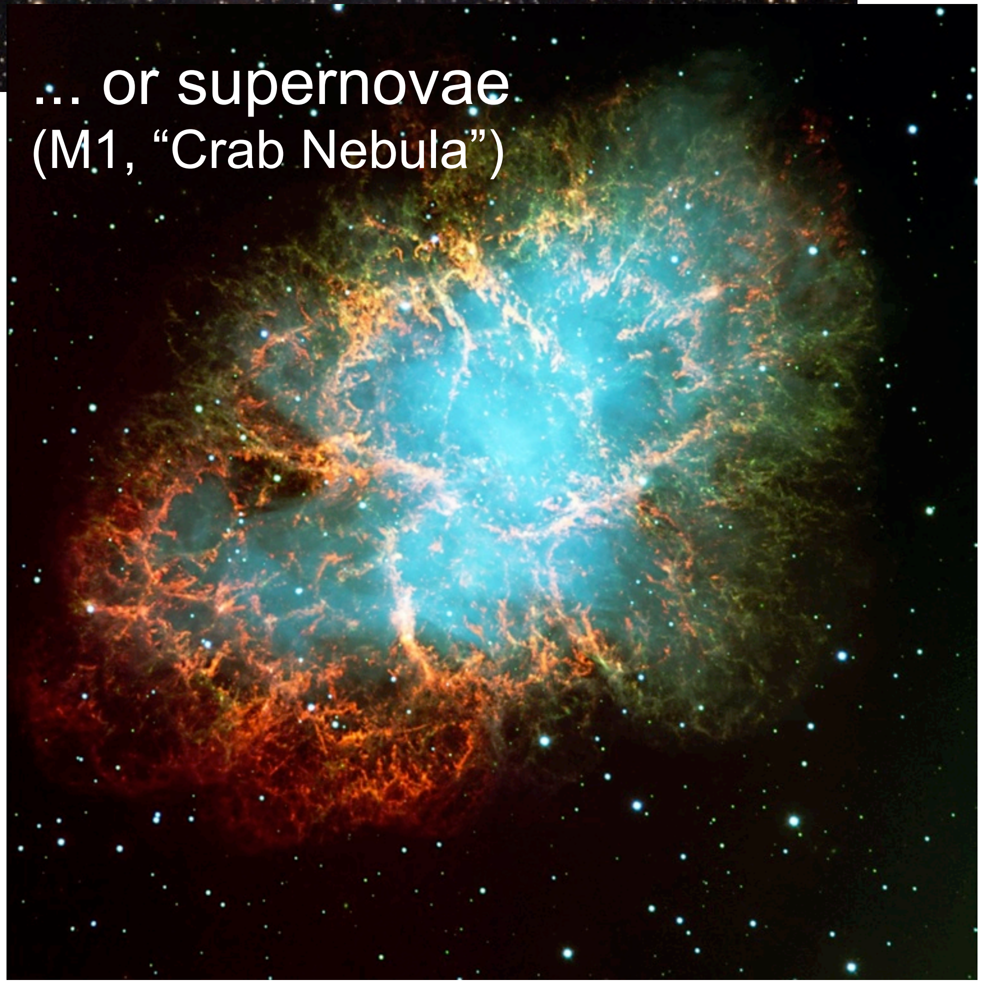
Stars do not lock up matter indefinitely: Significant fraction (~40%) *returned* to gas phase during star's life.

Important for two reasons:
(i) Significant contribution to gas mass
(ii) All elements except H and He produced in stars

⇒ Impact on large-scale structure

- Metallicity = observable test
- Cooling rates
- (Future) star formation

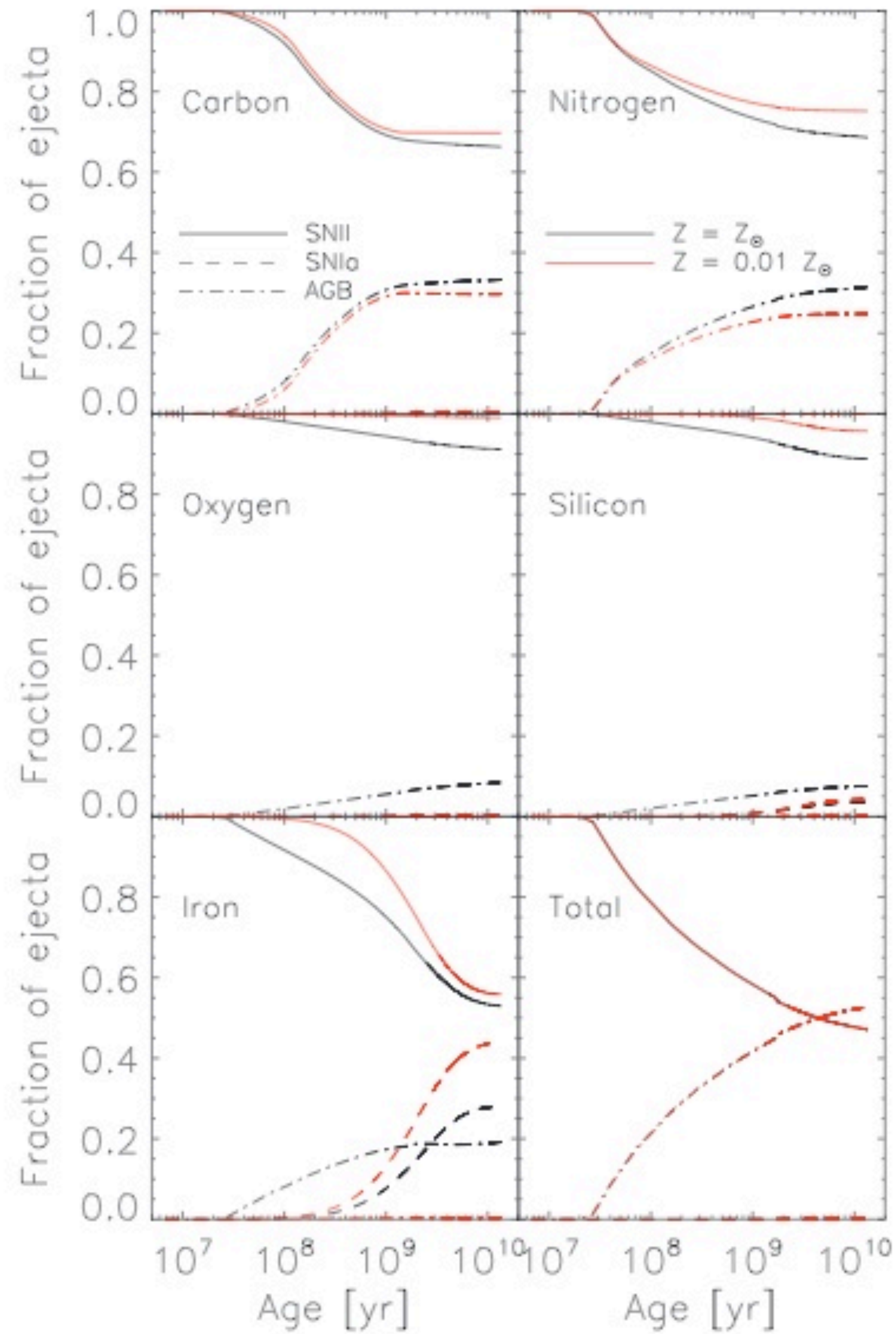
Requires both modelling of stellar evolution and implementation of recycling...



IV: Stellar recycling

- Current simulations have (mass) resolution of $\gtrsim 10^5\ M_\odot$
- Star particle = "Simple Stellar Population" (SSP)
- At each time step, compute which stellar masses leave the main sequence: these return mass
- AGB, SN II, SN Ia
- Masses of individual elements can be calculated to give detailed chemical composition of ISM
- Neighbouring gas particles increase their mass and metallicity

N.B.: "Mixing" of metals poorly modelled in SPH simulations!



(R. Wiersma et al., 2009, MNRAS, 399, 574)

V: Energy feedback from star formation

Stars inject energy into surrounding ISM through stellar winds, radiation, and supernovae

Naive implementation: Star particle heats up neighbouring gas particles

But energy is *radiated away far too quickly* and feedback does not have much effect...


Feedback in a real galaxy
(M82, HST)

Several routes to solve this:

(i) Inject energy *kinetically* (by giving nearby star particles velocity kicks). Need to specify details by hand.

(ii) Artificially disable cooling for some time, to allow conversion to kinetic energy.

(iii) Artificially decouple different thermal phases: Prolongues cooling time for SN ejecta.

(iv) Implement feedback stochastically...

V: Energy feedback from star formation

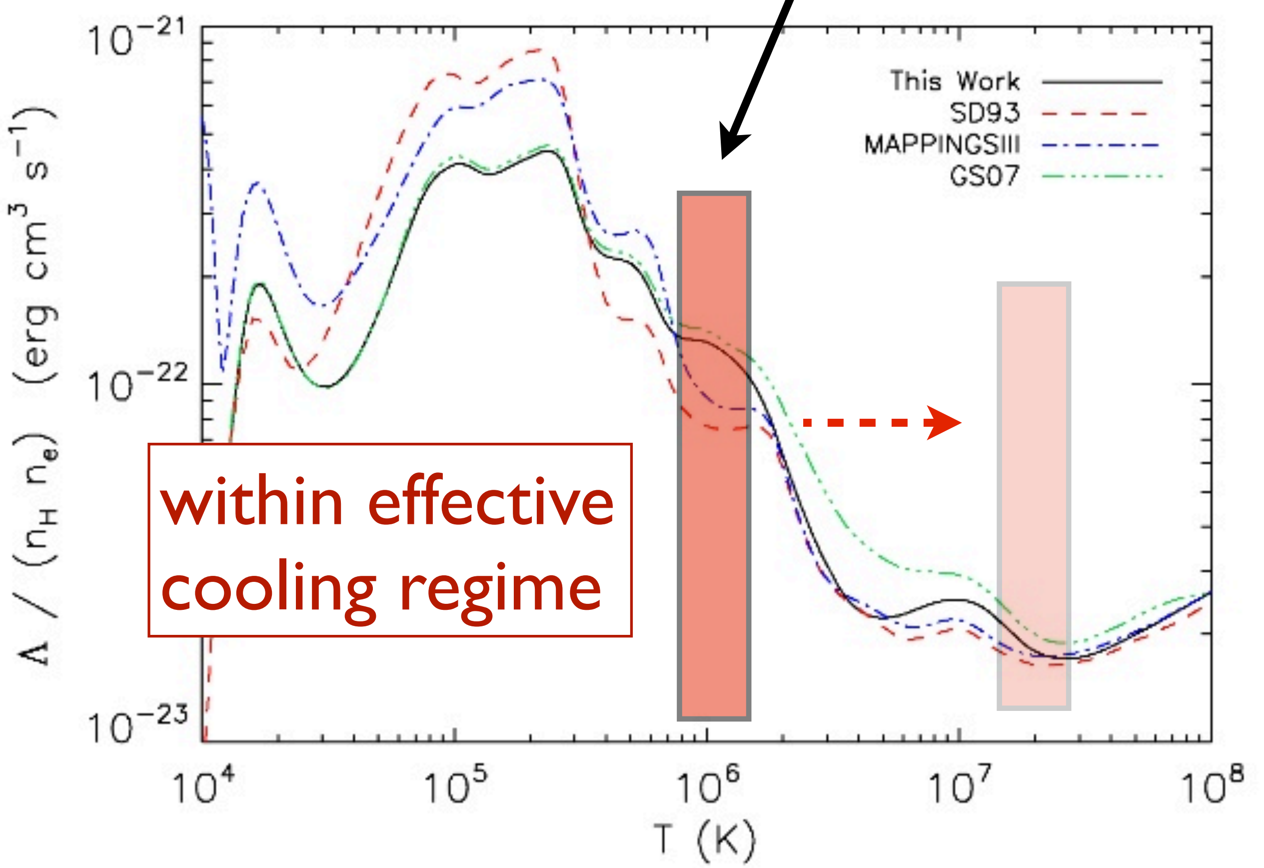
Reality:
Energy distributed over ~ 1 $M_\odot$ ejecta, so ratio M_{star} / M_{ej} is large (1 SN per 10^2 $M_\odot$ of new stars)

Simulation:
Energy from 1 star particle distributed over ~ 48 gas particles:
ratio of M_{star} / M_{ej} is small

$$\Delta T = (\gamma - 1)\frac{\mu m_{\rm H}}{k_{\rm B}} \epsilon_{\rm SN\,II} \frac{m_*}{m_{\rm g,heat}}$$
$$= 4.23 \times 10^7\,{\rm K} \left(\frac{n_{\rm SN\,II}}{1.736 \times 10^{-2}\,{\rm M}_\odot^{-1}}\right)\left(\frac{\mu}{0.6}\right)$$
$$\times E_{51} \frac{m_*}{m_{\rm g,heat}},$$

m_* / $m_{g,\,heat}$ = 1/48
⇒ ΔT~ 10^6 K

Reducing the heated gas mass would make feedback (much) more effective!



(C. Dalla Vecchia & J. Schaye, 2012, MNRAS 426, 140)

V: Energy feedback from star formation

Stochastic approach:

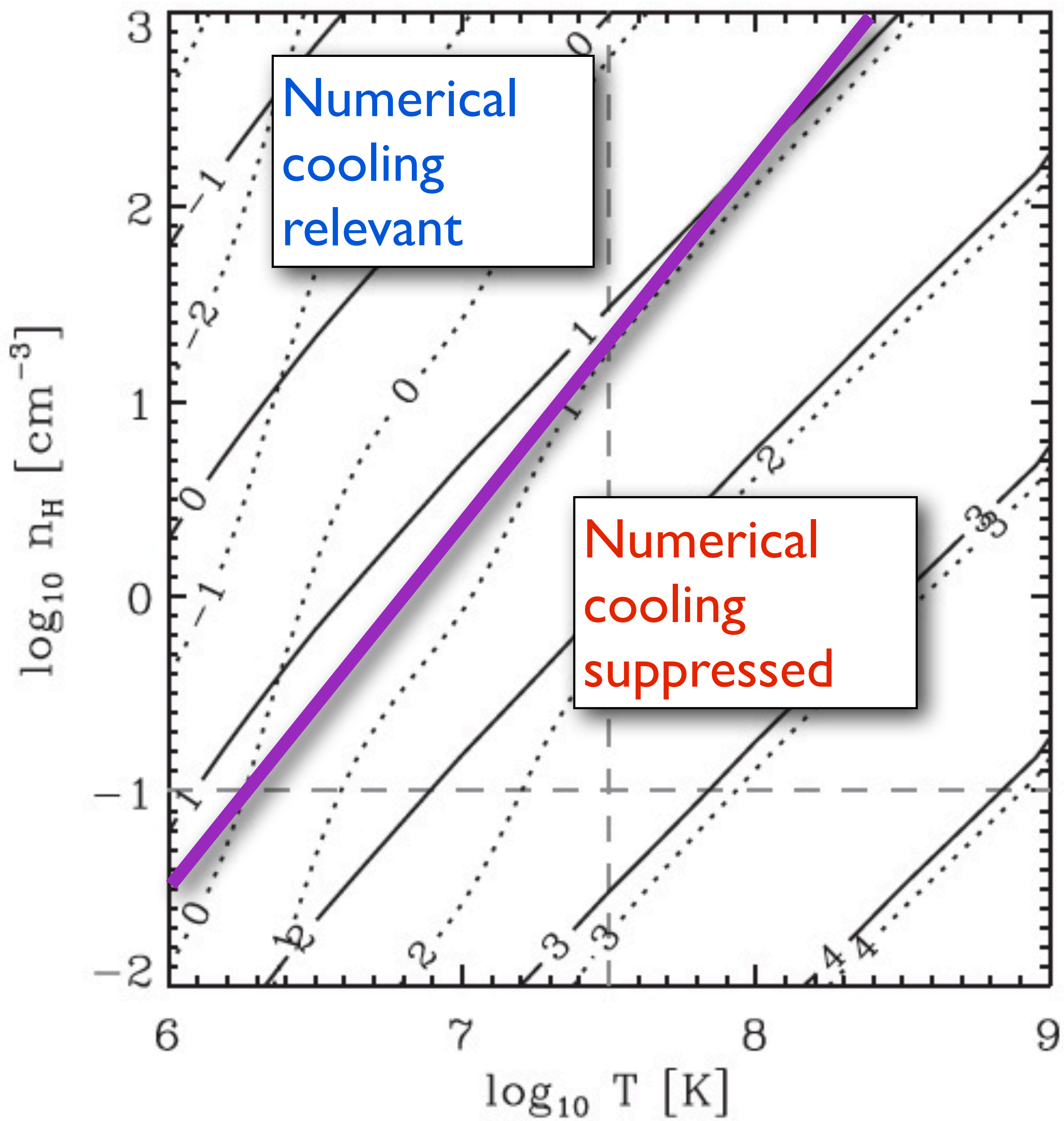
Specify desired heating temperature ΔT (specific energy $\Delta\varepsilon$) and calculate probability p that given gas particle is heated:

$$p = f_{\rm th} \frac{\epsilon_{\rm SN\,II}}{\Delta\epsilon} \frac{m_*}{\sum_{i=1}^{N_{\rm ngb}} m_i}$$

f_{th} = fraction of SN energy going into feedback

Constraint: p ≤ 1, so

$$\Delta\epsilon \geq f_{\rm th}\epsilon_{\rm SN\,II} \frac{m_*}{\sum_{i=1}^{N_{\rm ngb}} m_i} \simeq \frac{f_{\rm th}\epsilon_{\rm SN\,II}}{N_{\rm ngb}}$$

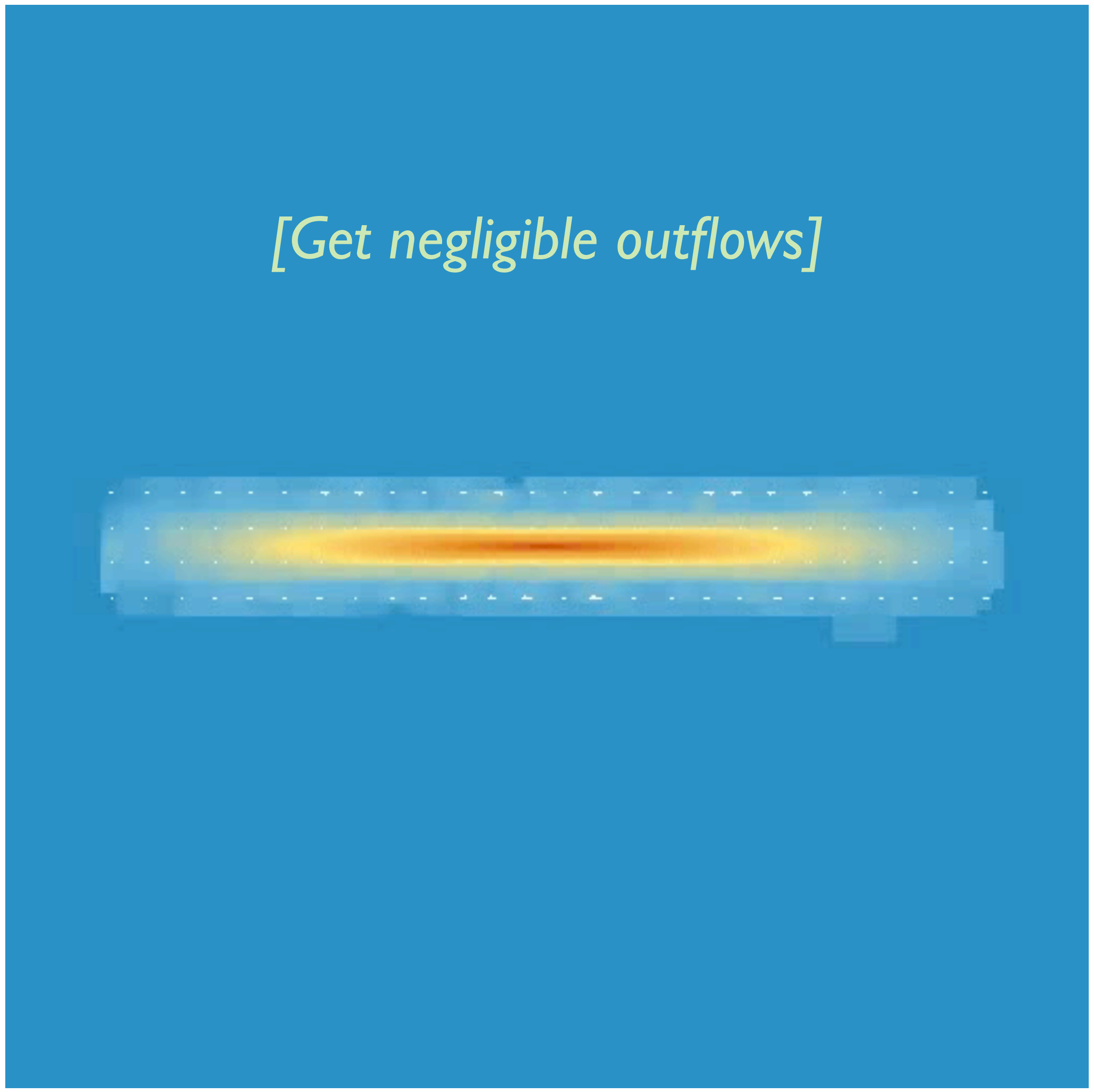


log t_{cool} / $t_{sound\text{-}crossing}$
(solid: primordial, dotted: solar)

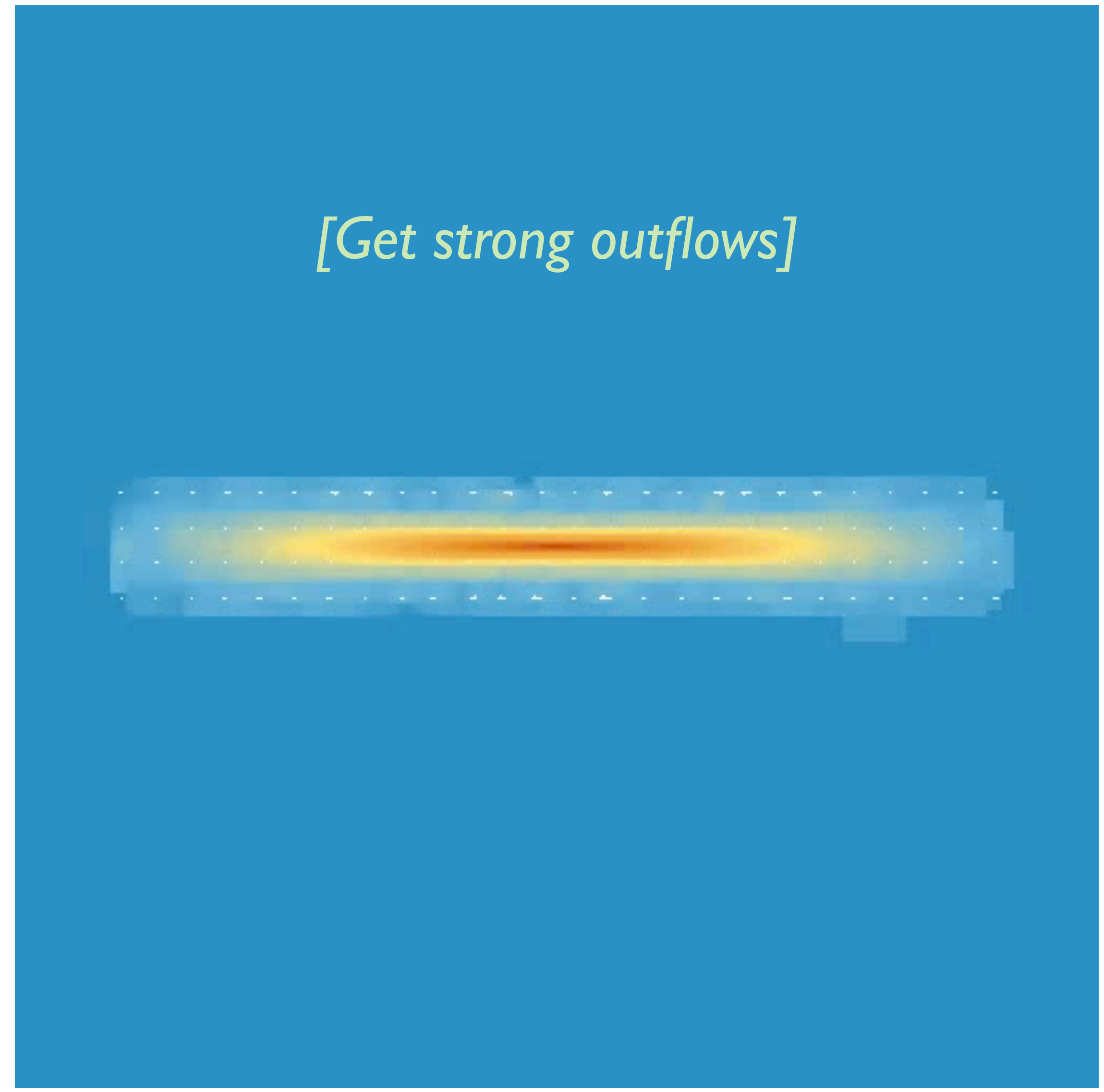
(C. Dalla Vecchia & J. Schaye, 2012, MNRAS 426, 140)

V: Energy feedback from star formation

Impact of heating temperature on outflows in 10^{12} $M_\odot$ galaxy



$\Delta T = 10^{6.5}$ K



$\Delta T = 10^{7.5}$ K

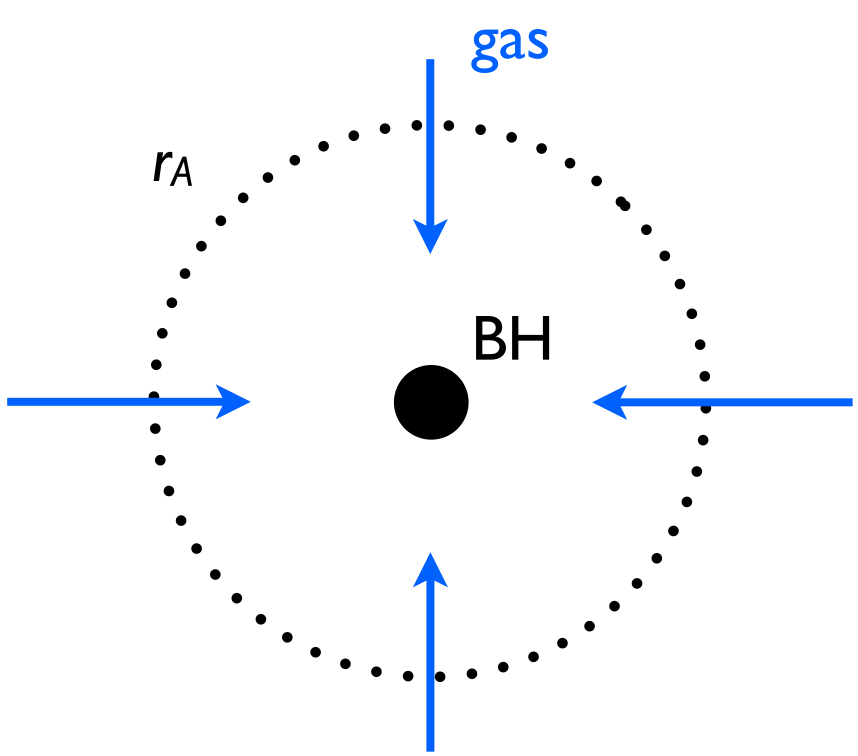
(C. Dalla Vecchia & J. Schaye, 2012, MNRAS 426, 140)

For the animations, see
http://www.strw.leidenuniv.nl/DS12/

VI: Black hole formation and AGN feedback

Two parts:
(i) BH formation and growth
(ii) Feedback effect on surrounding gas

"Seed" ~10^5 $M_\odot$ black holes in FOF haloes above threshold mass (10^{10} $M_\odot$)



BH "sphere of influence":

$|E_{pot}| > E_{internal}$
$r_A \sim GM_{BH} / c_s^2$

$$\dot{m}_{\rm BH} = 4\pi r_A^2 \rho_A c_s(r_A)$$

$$\dot{m}_{\rm Bondi} = \frac{4\pi G^2 m_{\rm BH}^2 \rho}{(c_{\rm s}^2 + v^2)^{3/2}}$$ x 100 (!!)

Also impose Eddington limit:

$$\dot{M}_{\rm Edd} = \frac{4\pi G m_{\rm p} M_{\rm BH}}{\sigma_{\rm T}\, c\, \epsilon_{\rm r}}$$

Stochastically swallow gas particles near black hole whenever subgrid BH mass has increased sufficiently

+ allow nearby BHs to merge

(V. Springel et al., 2005, arXiv:1312.0598;
C. Booth & J. Schaye, 2009)

VI: Black hole formation and AGN feedback

Two parts:
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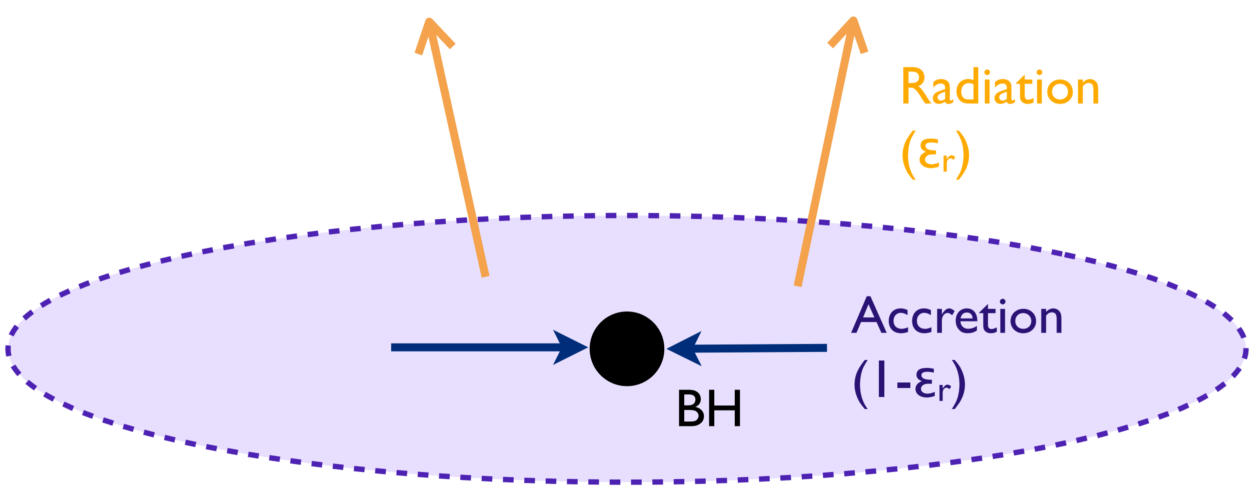
(ii) Feedback effect on surrounding gas



So that $\dot{m}_{\rm BH} = (1 - \epsilon_{\rm r})\dot{m}_{\rm accr}$

and $\dot{E}_{\rm BH} = \epsilon_f\, \epsilon_r\, \dot{m}_{\rm accr}\, c^2$

↑ Coupling between AGN and gas

(Y. Rosas-Guevara et al., 2013, arXiv:1312.0598)

Feedback implementation similar to SN feedback: Stochastically heat nearby gas particles by temperature ΔT_{AGN} (energy $\Delta\varepsilon_{AGN}$):

$$P = \frac{E_{\rm BH}}{\Delta\epsilon_{\rm AGN} N_{\rm ngb} \langle m_{\rm g}\rangle}$$

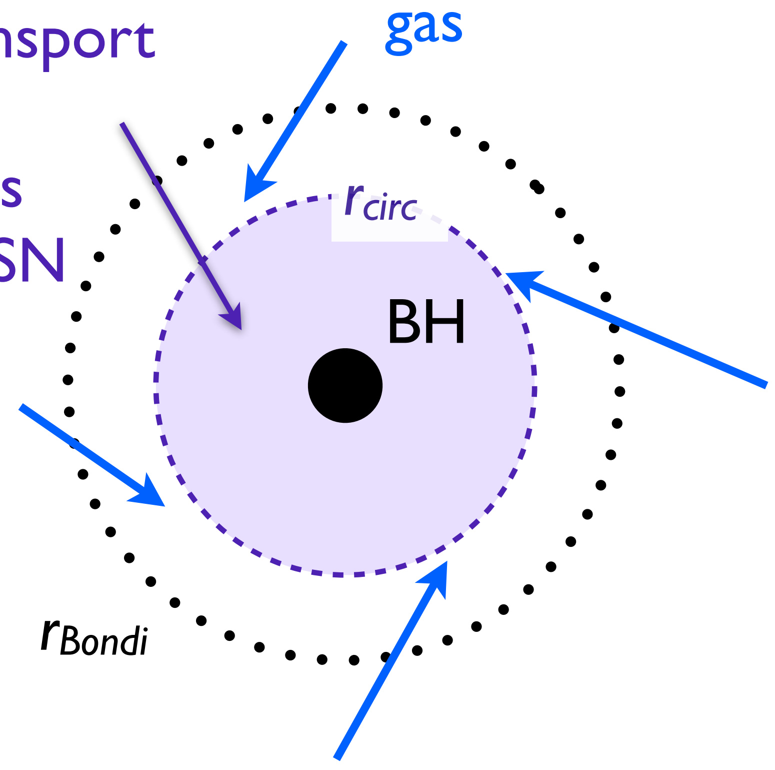
N.B.: Typically higher gas density than around newly formed star particles
⇒ higher ΔT

But: Too efficient in Milky-Way mass galaxies. Need to artificially limit impact in these cases ("radio-/quasar-mode")...

VI: Black hole formation and AGN feedback

... or take angular momentum of accreted gas into account!

Accretion disk:
viscous transport inwards
+ mass loss (e.g. from SN feedback)



$$r_{\rm circ} = \frac{j^2(r_{\rm circ})}{GM_{\rm BH}} = \frac{r_{\rm Bondi}^2 V_\phi^2}{GM_{\rm BH}} = GM_{\rm BH}\frac{V_\phi^2}{c_{\rm s}^4}$$

(Y. Rosas-Guevara et al., 2013, arXiv:1312.0598)

Additional limit on BH accretion rate:

$$\dot{m}_{\rm accr} \sim \frac{M_{\rm disc}}{t_{\rm visc}} \sim \frac{\dot{m}_{\rm Bondi}\, t_{\rm Bondi}}{t_{\rm visc}}$$

with $t_{\rm Bondi} = \frac{r_{\rm Bondi}}{c_{\rm s}} = \frac{GM_{\rm BH}}{c_{\rm s}^3}$

& $t_{\rm visc} = C_{\rm visc}\frac{r_{\rm circ}}{v_{\rm circ}} = C_{\rm visc}\frac{j^3}{G^2 M_{\rm BH}^2}$

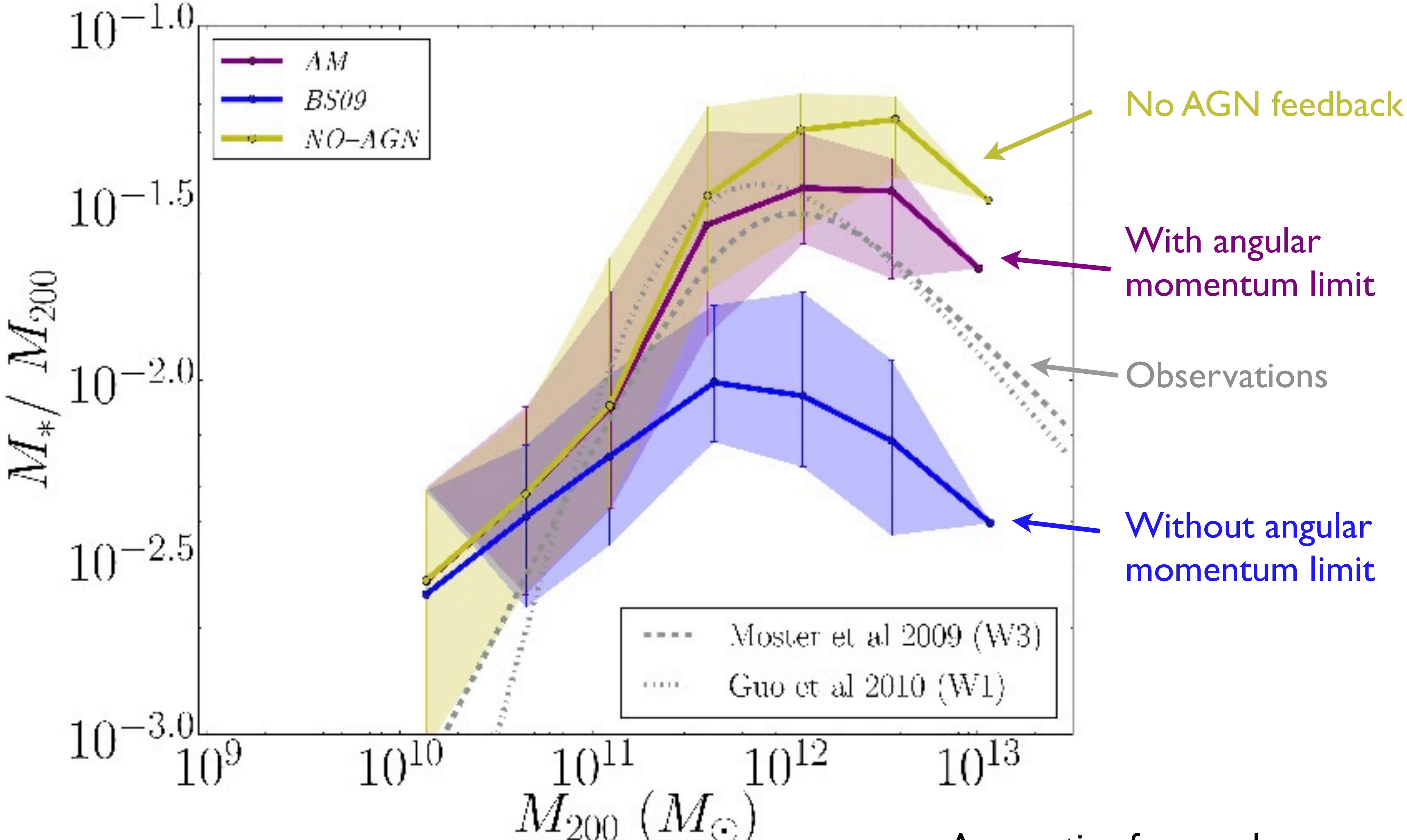
$$= C_{\rm visc}\frac{r_{\rm Bondi}^3 V_\phi^3}{G^2 M_{\rm BH}^2} = C_{\rm visc} G M_{\rm BH}\frac{V_\phi^3}{c_{\rm s}^6}$$

disk structure (unresolved)

$$\frac{t_{\rm Bondi}}{t_{\rm visc}} = \frac{r_{\rm Bondi} c_{\rm s}^{-1}}{C_{\rm visc}[r_{\rm Bondi} V_\phi]^3 [GM_{\rm BH}]^{-2}} = \frac{1}{C_{\rm visc}}\frac{c_{\rm s}^3}{V_\phi^3}.$$

Find V_Φ as $V_\phi = \left| \sum_{i=0}^{N_{\rm SPH}} \mathbf{r}_i \times \mathbf{v}_i\, m_i W(\mathbf{r}_i, h)\frac{1}{\rho h} \right|$

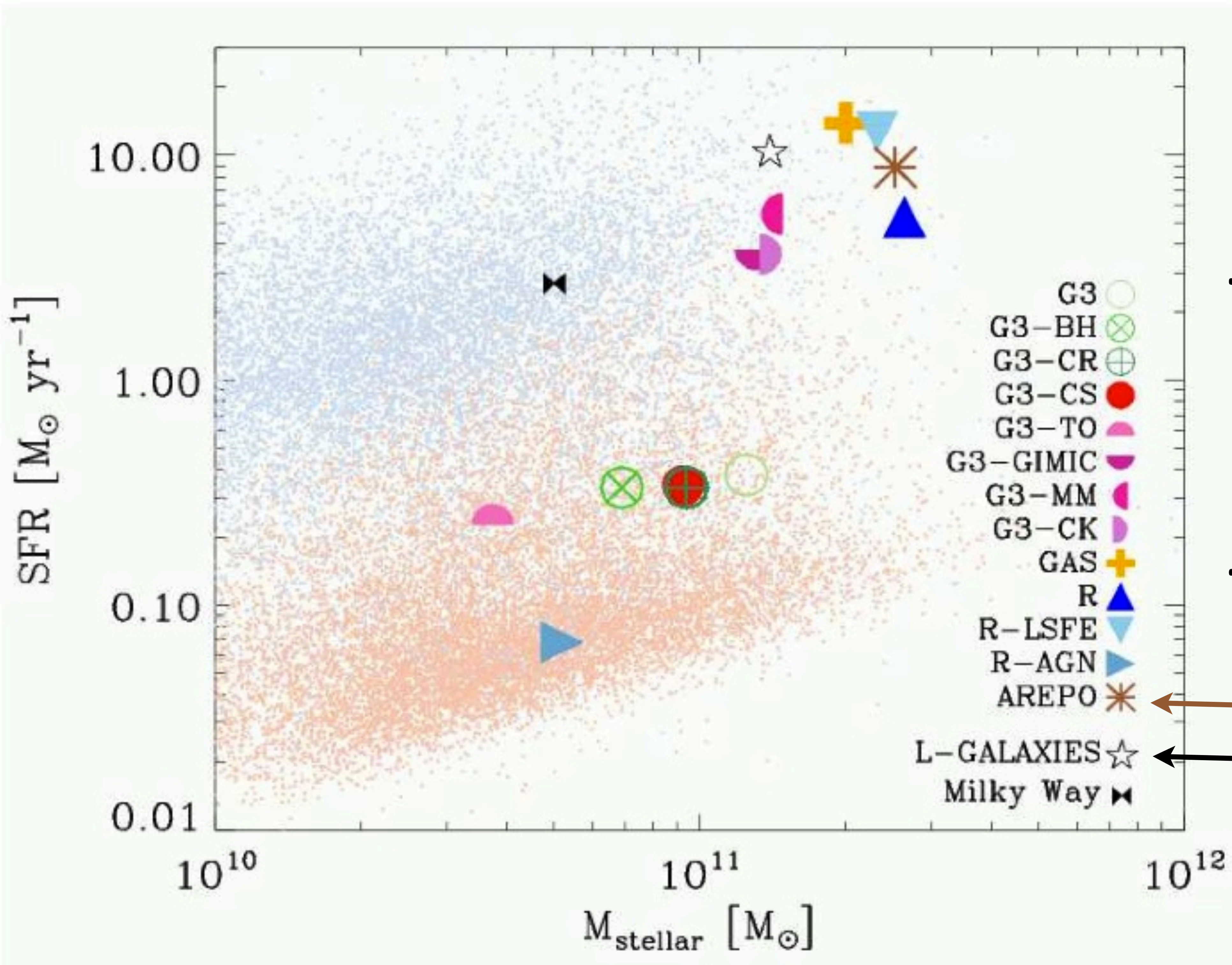
VI: Black hole formation and AGN feedback



(Y. Rosas-Guevara et al., 2013, arXiv:1312.0598)

Accounting for angular momentum limits AGN effect in massive haloes to observed level

Aside: sub-grid physics vs. hydro solver



"Aquila comparison project"

(1 galaxy, many codes)

SPH

(different sub-grid recipes)

AMR

hybrid

Semi-Analytic Model

Sub-grid physics has *much* larger effect

(C. Scannapieco, 2012, MNRAS 423, 1726)

The EAGLE Simulations

Evolution and Assembly of GaLaxies and their Environments

The EAGLE Simulations

Evolution and Assembly of GaLaxies and their Environments

N.B.: "Illustris" is another recent cosmological hydrodynamical simulation with similar results (and very different simulation code)

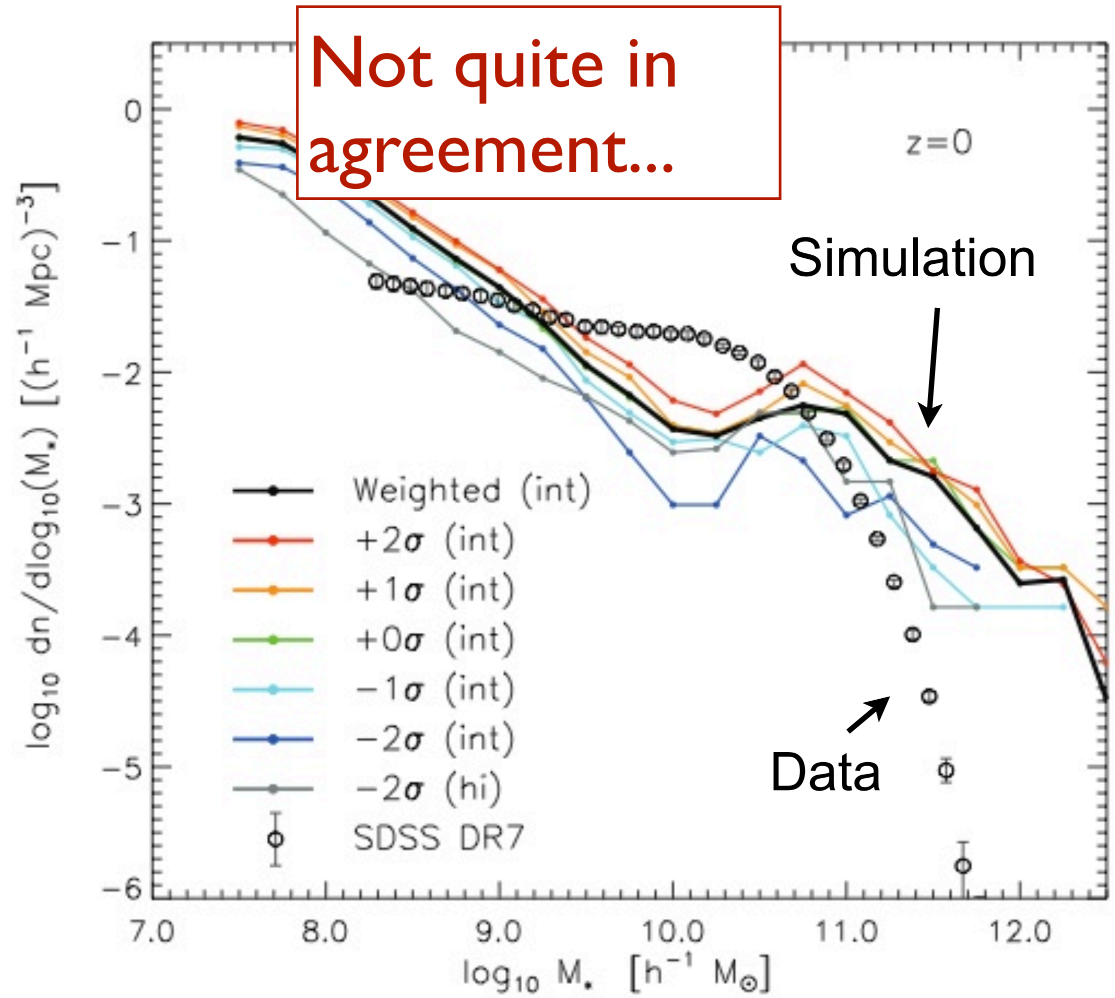
EAGLE: overview

Large suite of cosmological hydrodynamical simulations including all the subgrid recipes discussed above

Simulation aims:

- "Realistic" galaxy population: Especially match to observed galaxy stellar mass function
- Sub-grid physics only dependent on *physically motivated, local* quantities
- Resolve Jeans mass in warm ISM (i.e. $m_{gas} \approx 10^6$ M$_\odot$)

(J. Schaye et al., 2015, MNRAS 446, 521)



GSMF in GIMIC simulations
(R. Crain et al., 2009, MNRAS 399, 1773)

Not always the case: For example, SN-driven outflows often assumed to scale with velocity dispersion of DM halo

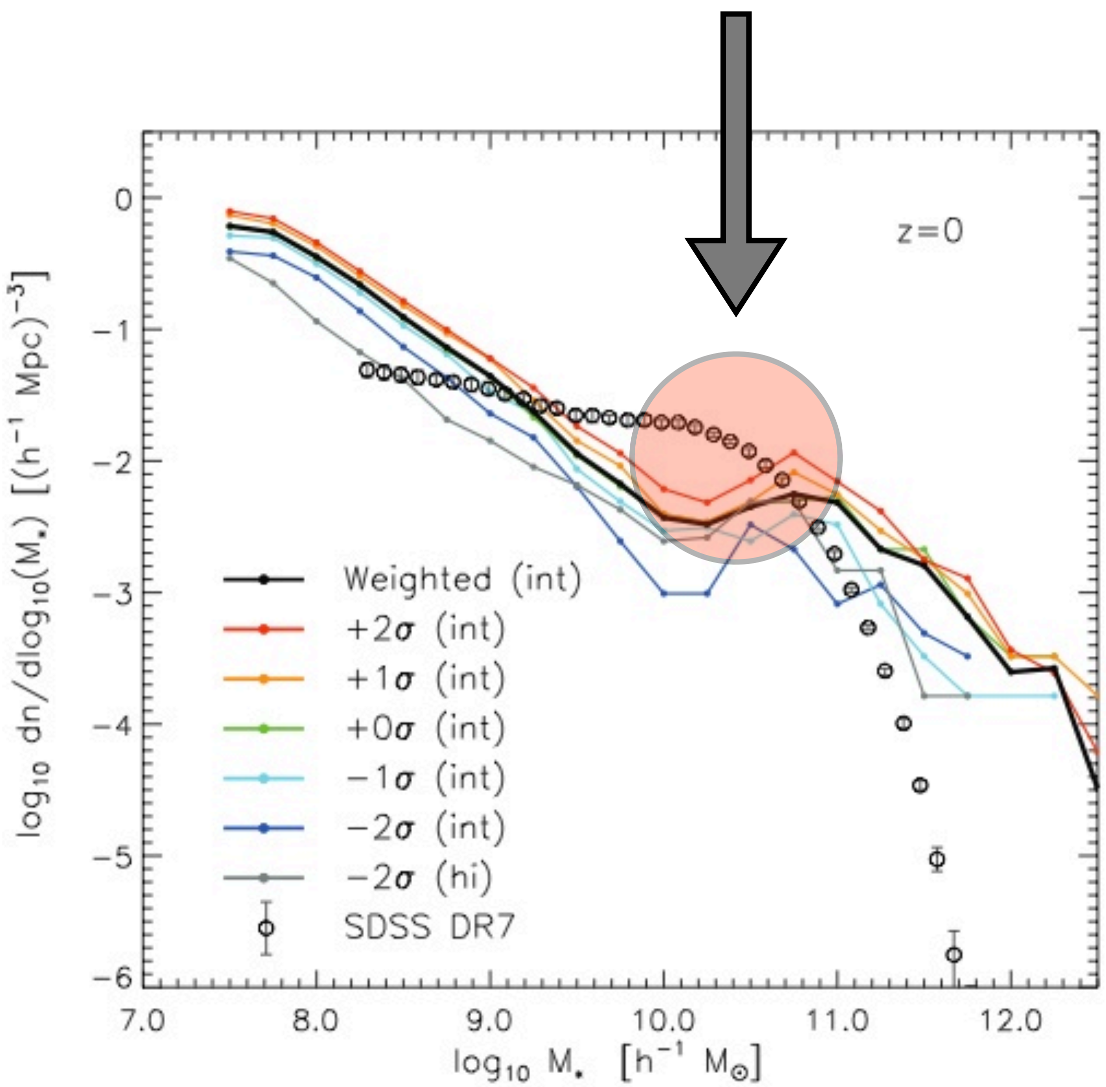
EAGLE: calibration

Main free parameters of above sub-grid models (i.e. not well-constrained by either observations or theory):

- Black hole heating temperature ΔT, efficiency ε_f, and viscosity parameter C_{Visc}
- Supernova feedback f_{th}

Strong influence only on most massive haloes (galaxy groups): $\Delta T = 10^{8.5}$ K & $\varepsilon_f = 0.15$ used as default

C_{Visc} calibrated to give break in GSMF at $M^* \sim 10^{10.5}\ M_\odot$



(J. Schaye et al., 2015, MNRAS 446, 521;
R. Crain et al., 2015, arXiv:1501.01311)

EAGLE: calibration

Main free parameters of above sub-grid models (i.e. not well-constrained by either observations or theory):

- Black hole heating temperature ΔT, efficiency ε_f, and viscosity parameter C_{Visc}
- Supernova feedback f_{th}

  Most influential parameter: calibrated to GSMF and stellar sizes

Strong influence only on most massive haloes (galaxy groups): $\Delta T = 10^{8.5}$ K & $\varepsilon_f = 0.15$ used as default

C_{Visc} calibrated to give break in GSMF at $M^* \sim 10^{10.5}\ M_\odot$

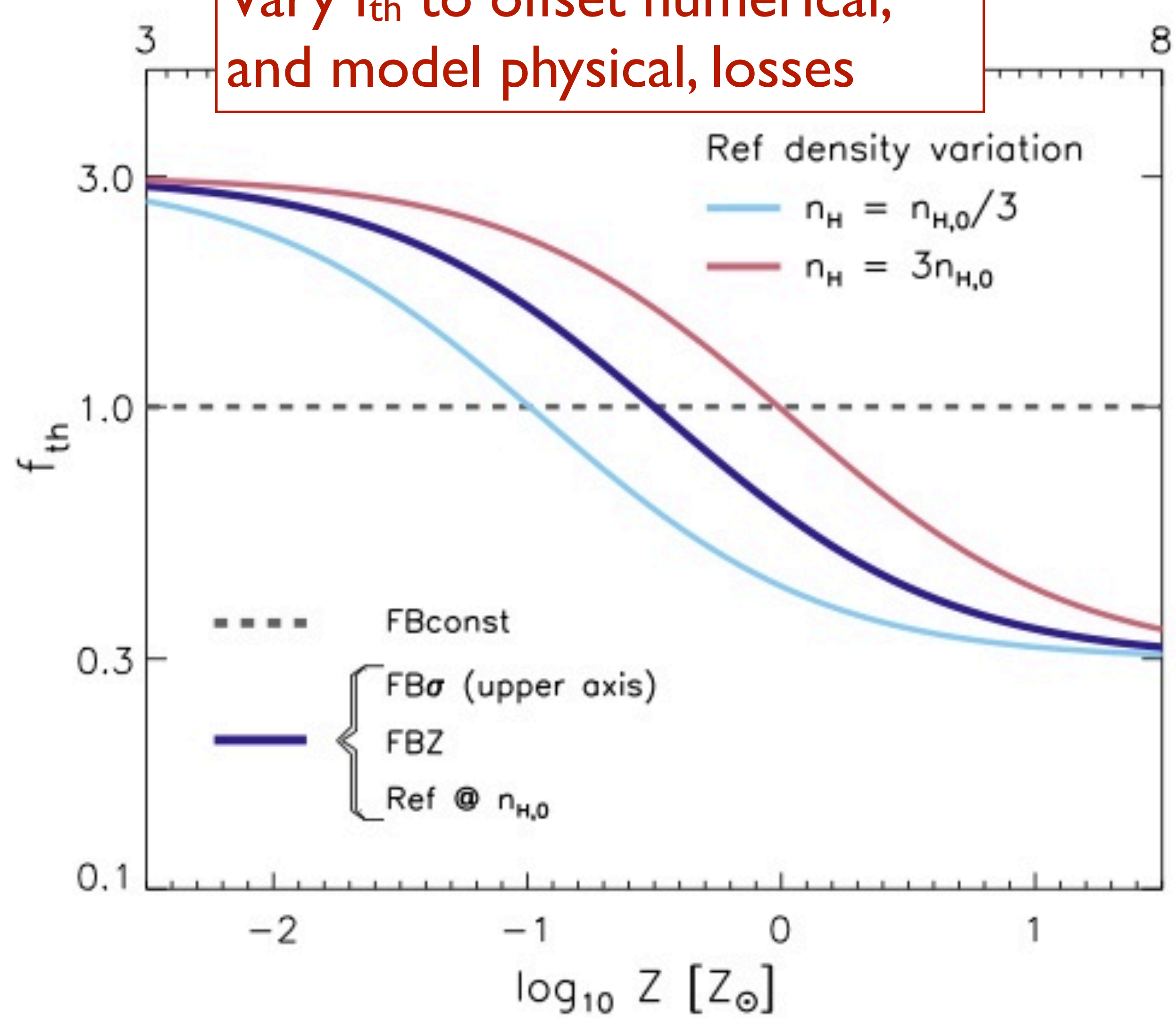
Vary f_{th} to offset numerical, and model physical, losses

$$f_{\rm th} = f_{\rm th,min} + \frac{f_{\rm th,max} - f_{\rm th,min}}{1 + \left(\frac{Z}{0.1\,Z_\odot}\right)^{n_Z} \left(\frac{n_{\rm H,birth}}{n_{\rm H,0}}\right)^{-n_n}}$$

$f_{th,\,min} = 0.3$ and $f_{th,\,max} = 3.0$

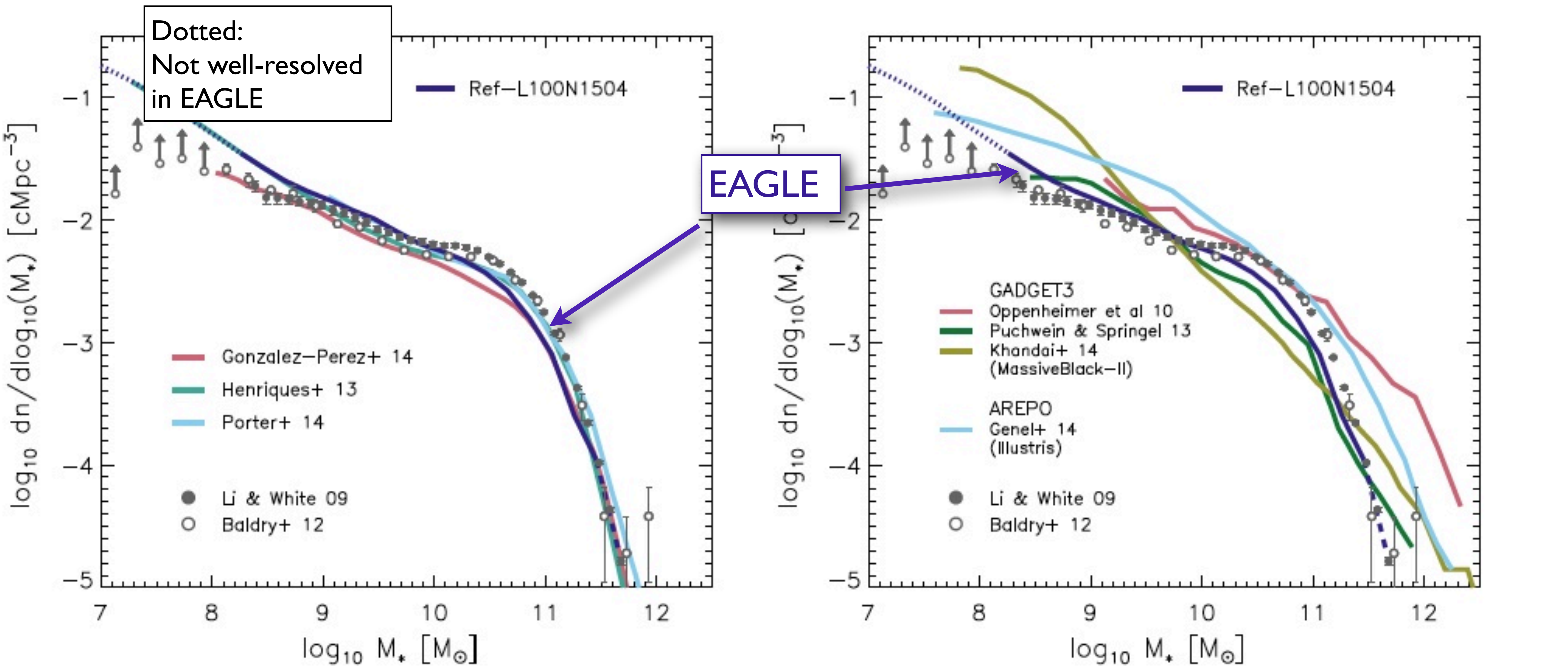
$n_Z = n_n \approx 1$

$n_{H,0} = 0.67\ cm^{-3}$



(J. Schaye et al., 2015, MNRAS 446, 521;
R. Crain et al., 2015, arXiv:1501.01311)

EAGLE results: Stellar masses

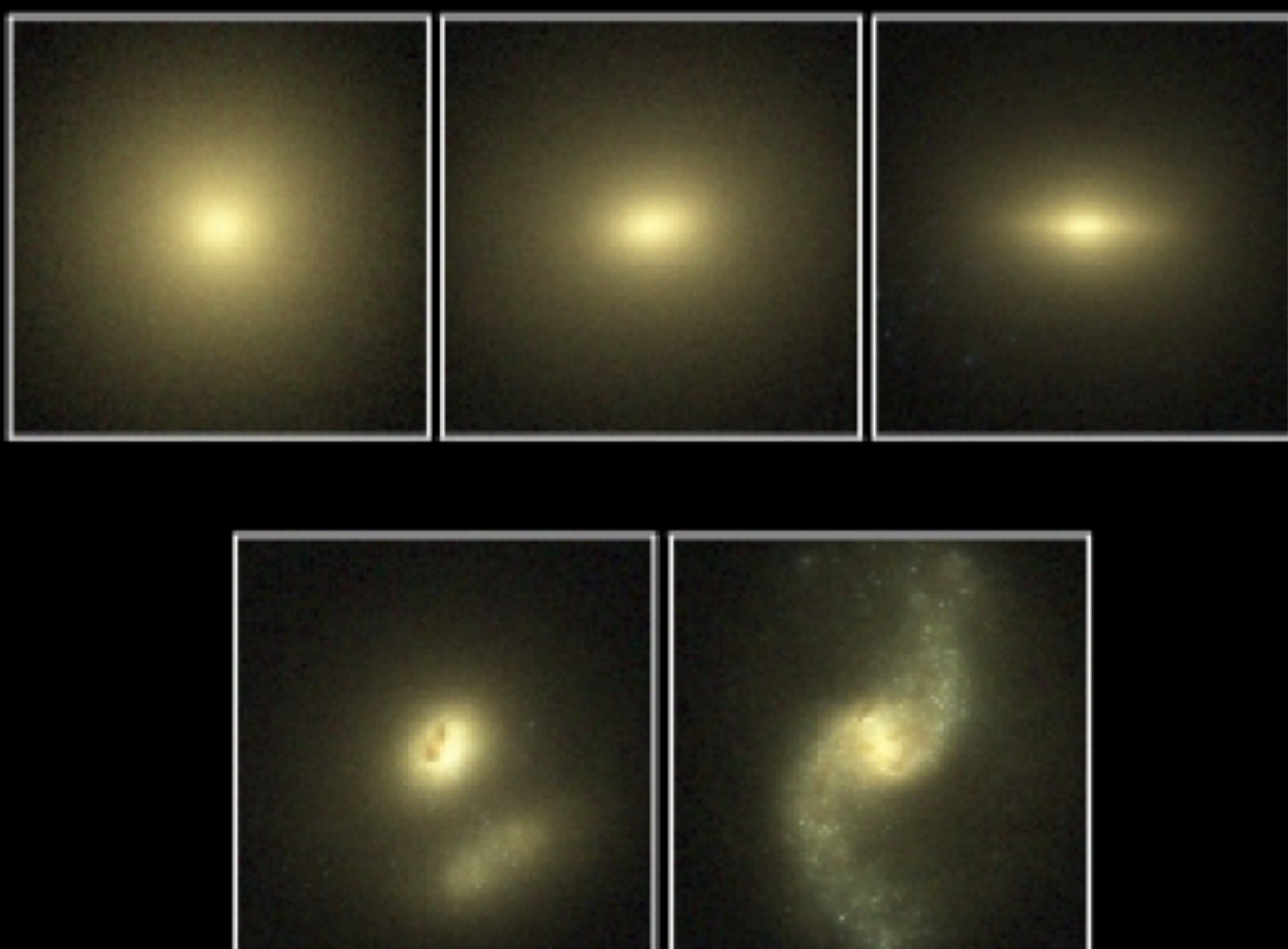


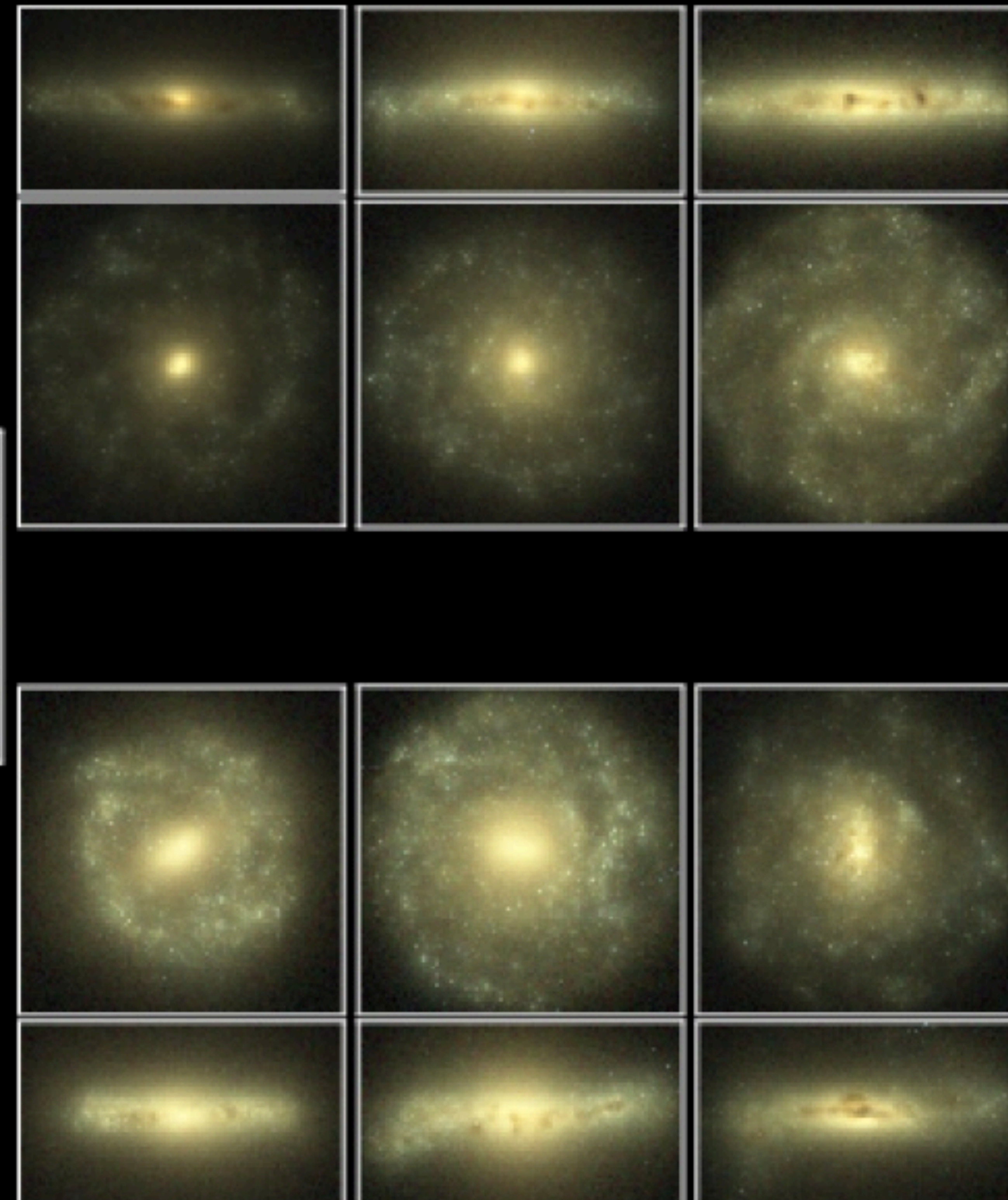
Galaxy Stellar Mass Function (GSMF) in EAGLE compared to two Semi-Analytic Models: **equally good fit to data**

EAGLE GSMF compared to other hydro simulations: **Significantly better fit**

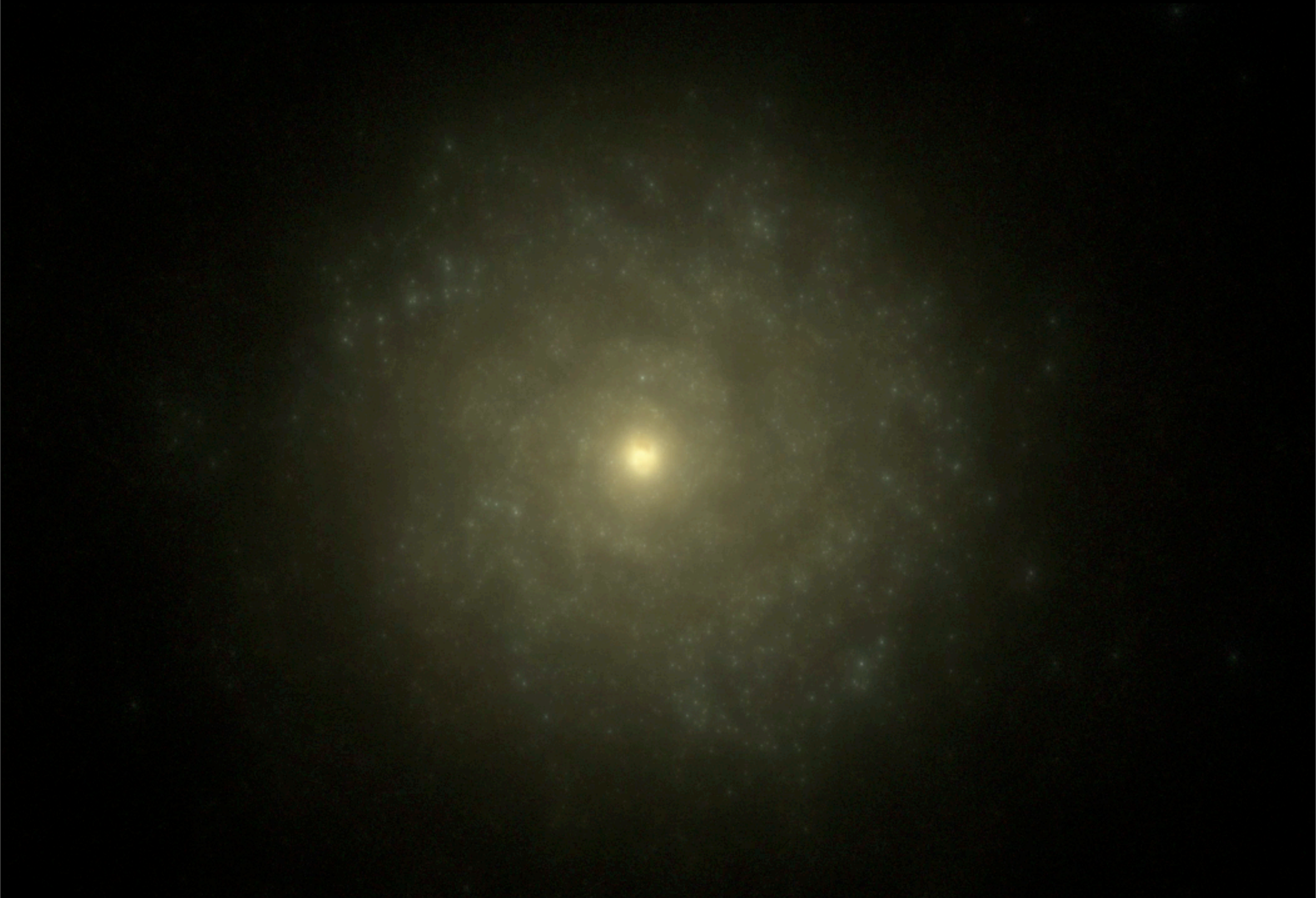
(J. Schaye et al., 2015, MNRAS 446, 521)

Mock images of EAGLE galaxies along the Hubble Sequence from SPS models + ray-tracing accounting for dust





(J. Schaye et al., 2015, MNRAS 446, 521)



See *http://eagle.strw.leidenuniv.nl/index.php/eagle-visualisation/*

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Summary

- Hydrodynamic simulations have made tremendous progress in last few years and now match observations as good as semi-analytic models, with far fewer free parameters.
- Fundamental difficulties are accurate modelling of hydrodynamics, and (especially) unresolved physical processes that influence structure formation on larger (resolved) scales
- Current simulations achieve resolution of $\sim 10^6\ M_\odot$ in boxes of ~100 Mpc sidelength: 1000s of galaxies like Milky Way

Together with simulations on larger and smaller scales, they are a very powerful tool to learn more about how the galaxies we observe formed and evolve

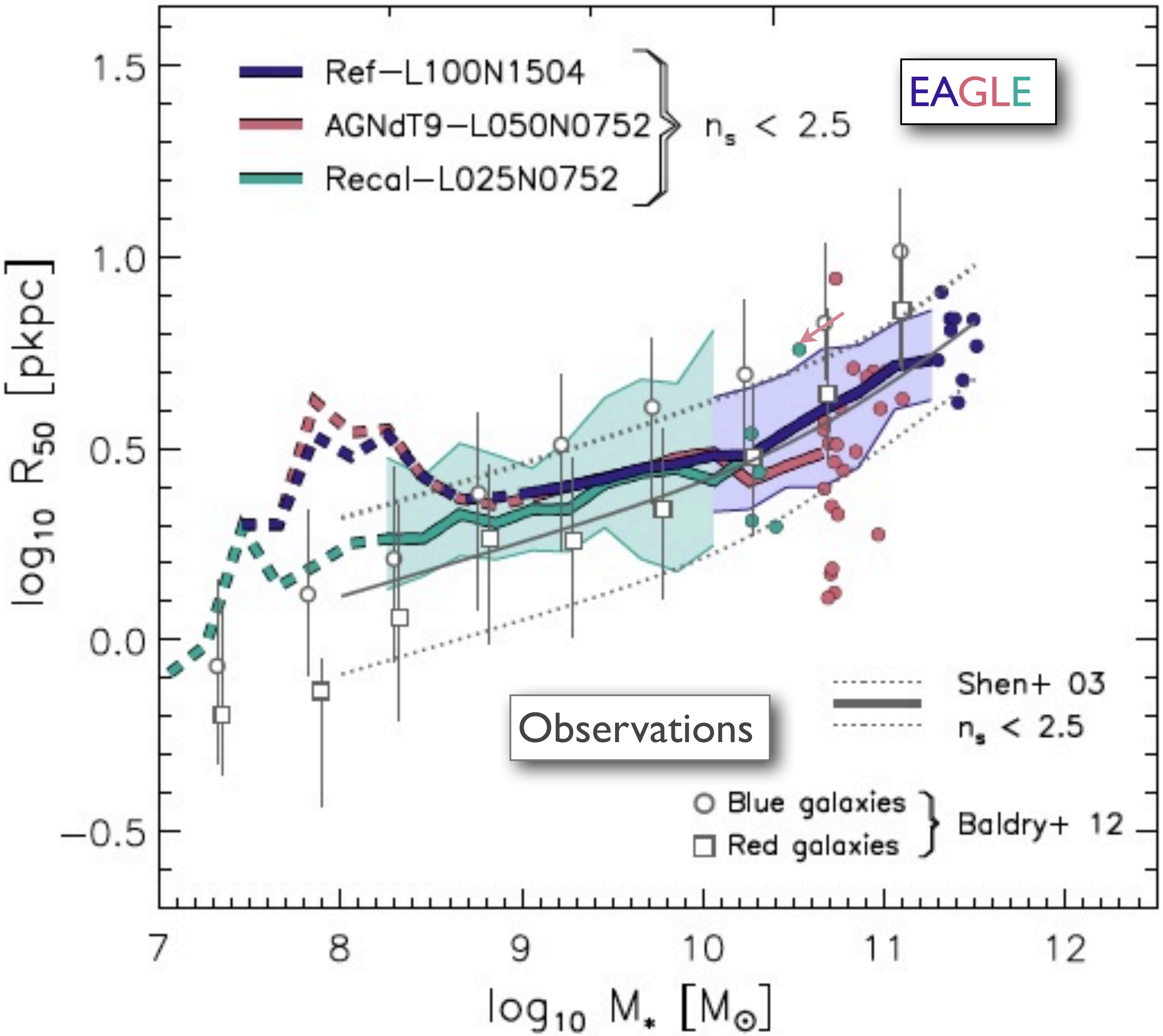
Rendered with
TYPHOON
Crain / Geach

Note:

The following slides were not shown in the lecture, but are nevertheless interesting.

They show a range of other predictions from the EAGLE simulations and the (generally very good) level of agreement with observations.

EAGLE results: Galaxy sizes



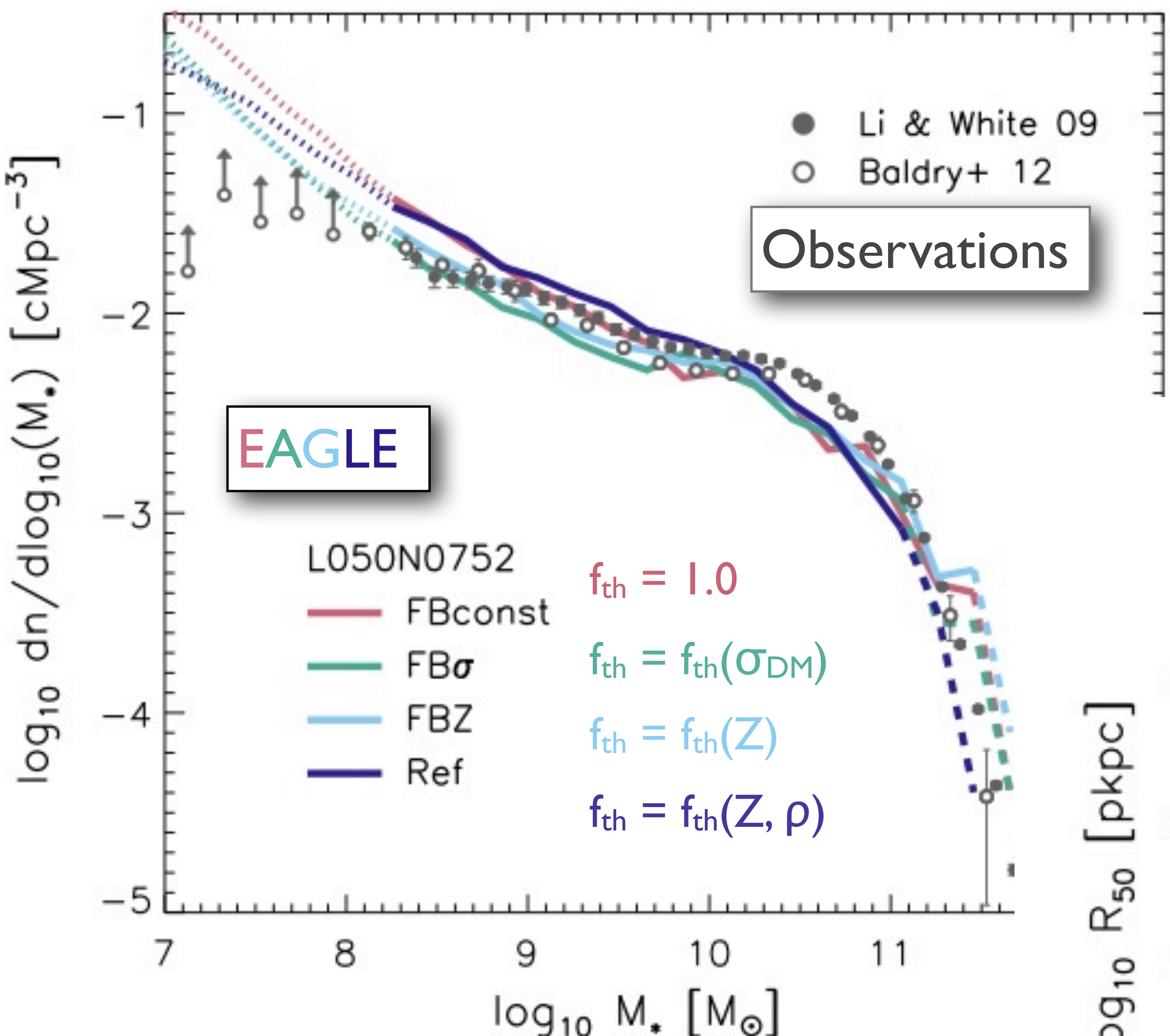
(J. Schaye et al., 2015, MNRAS 446, 521)

Simulated galaxies have the **right sizes**

(non-trivial success - recall angular momentum catastrophe)

N.B.: No fully "blind" prediction - stellar feedback model was chosen to reproduce this

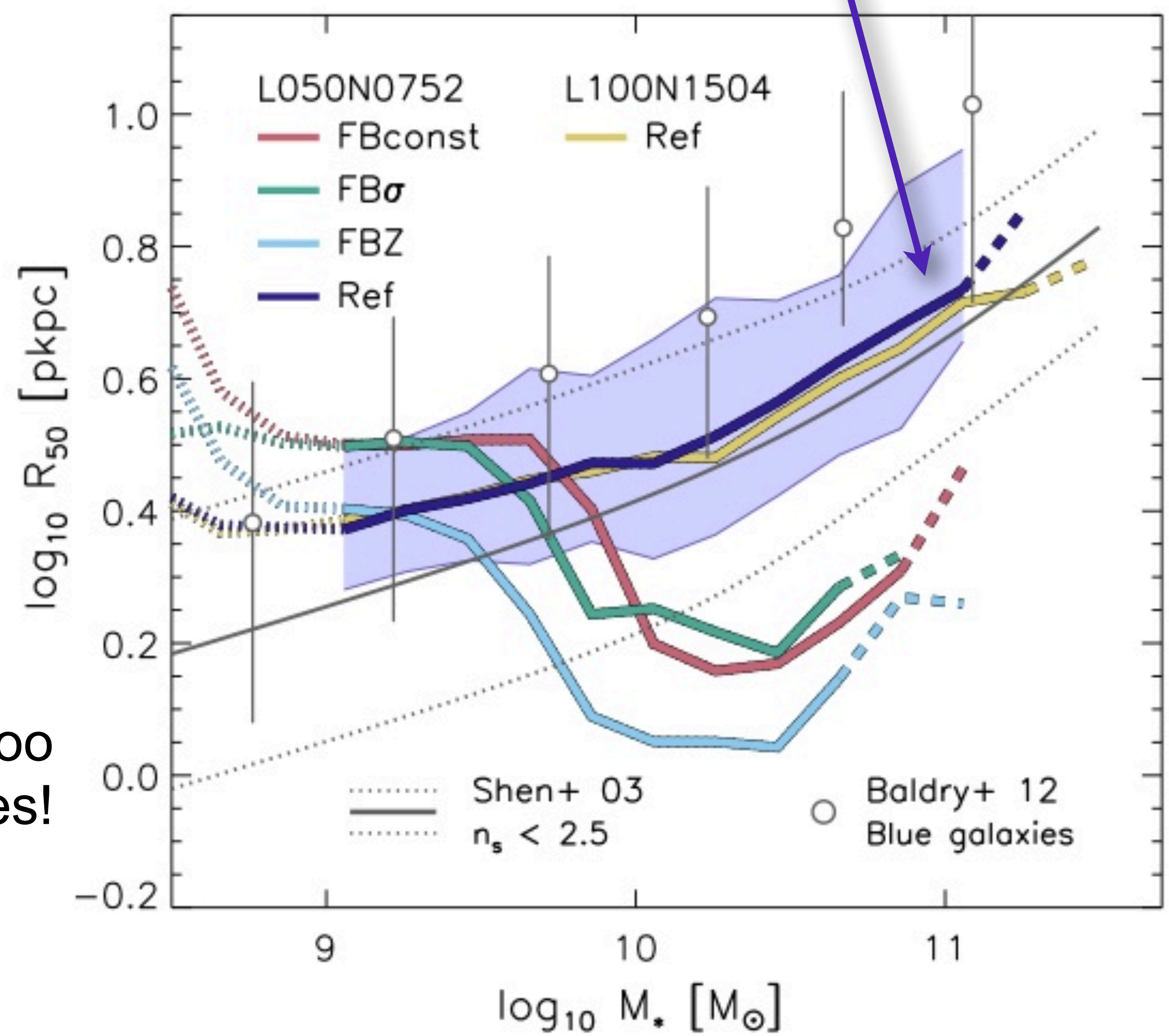
Calibration caveat: GSMF is not all!



All four models reproduce the GSMF...

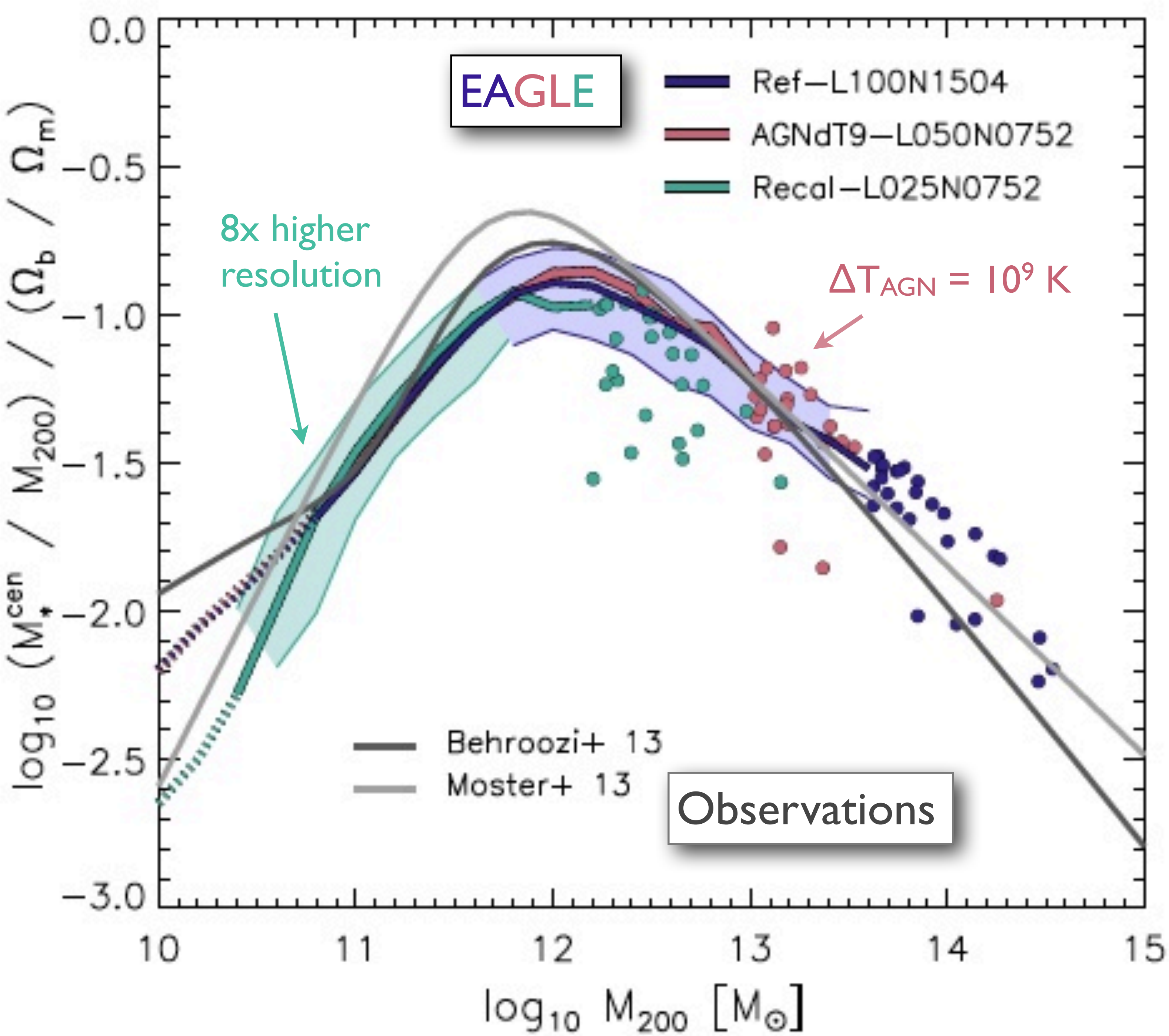
...but three produce too small galaxies!

Density dependence of f_{th} in "Ref" model compensates numerical energy loss in dense regions (see earlier)



(R. Crain et al., 2015, arXiv:1501.01311)

EAGLE results: M_{star}—M_{halo}

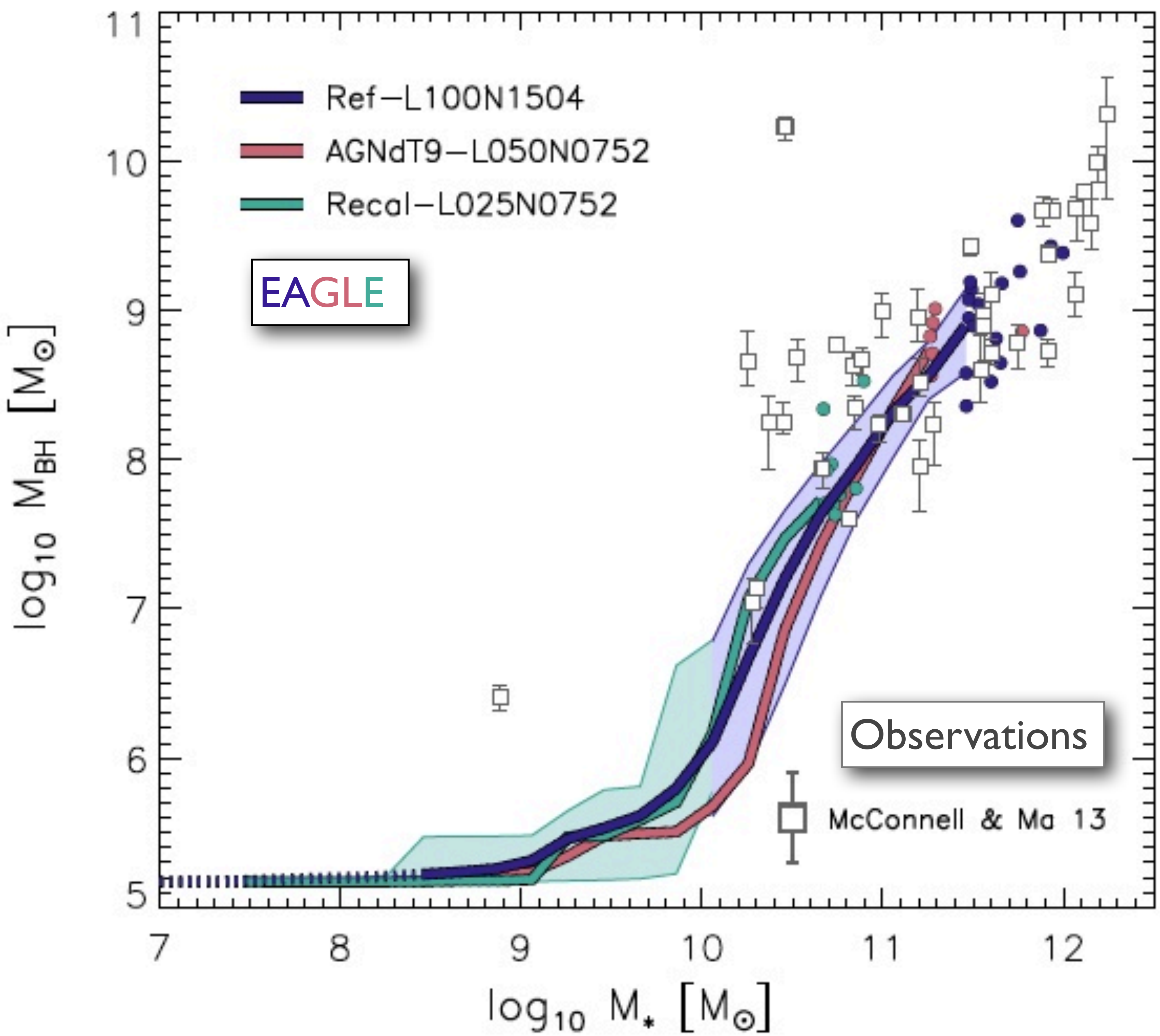


Relation between galaxy stellar mass and halo mass:

The right galaxies live in the right haloes

(J. Schaye et al., 2015, MNRAS 446, 521)

EAGLE results: Black hole masses



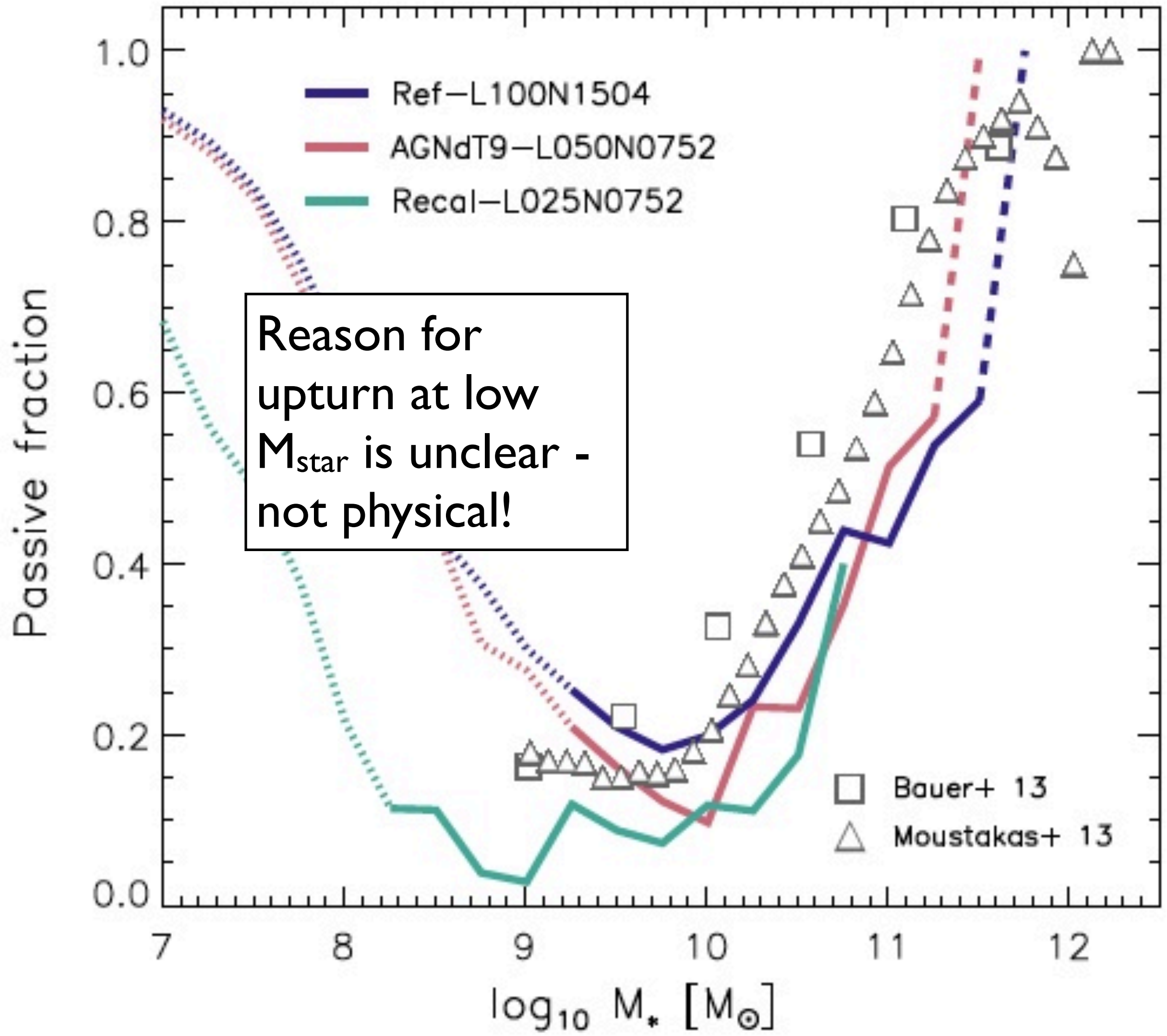
Large scatter in observations, but simulations generally produce **black holes of reasonable mass**

(Simulation volume too small to fully sample $M_{star} \gtrsim 10^{11}$ M⊙)

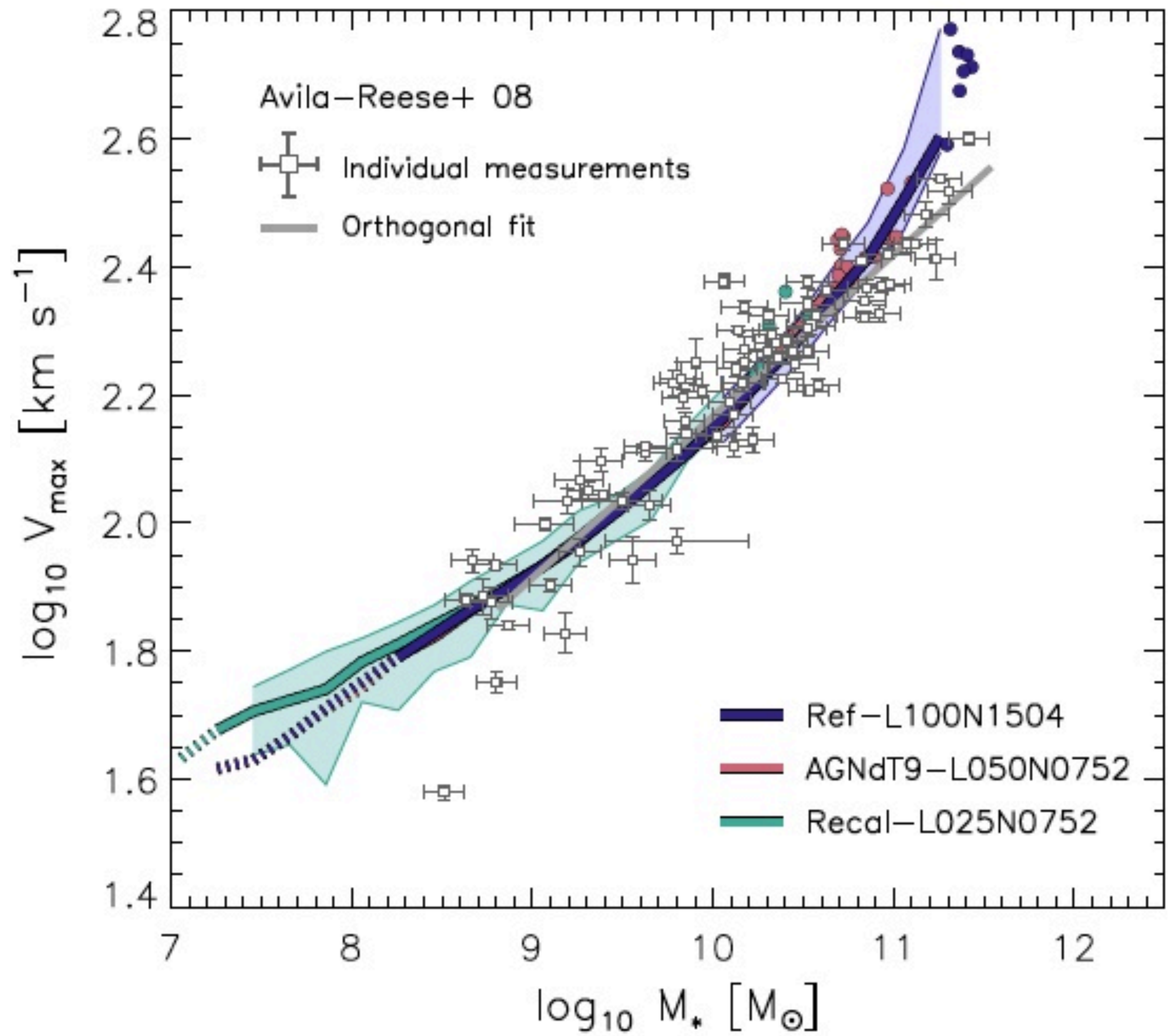
N.B.: Mostly influenced by ε_f

(J. Schaye et al., 2015, MNRAS 446, 521)

Some more EAGLE results...



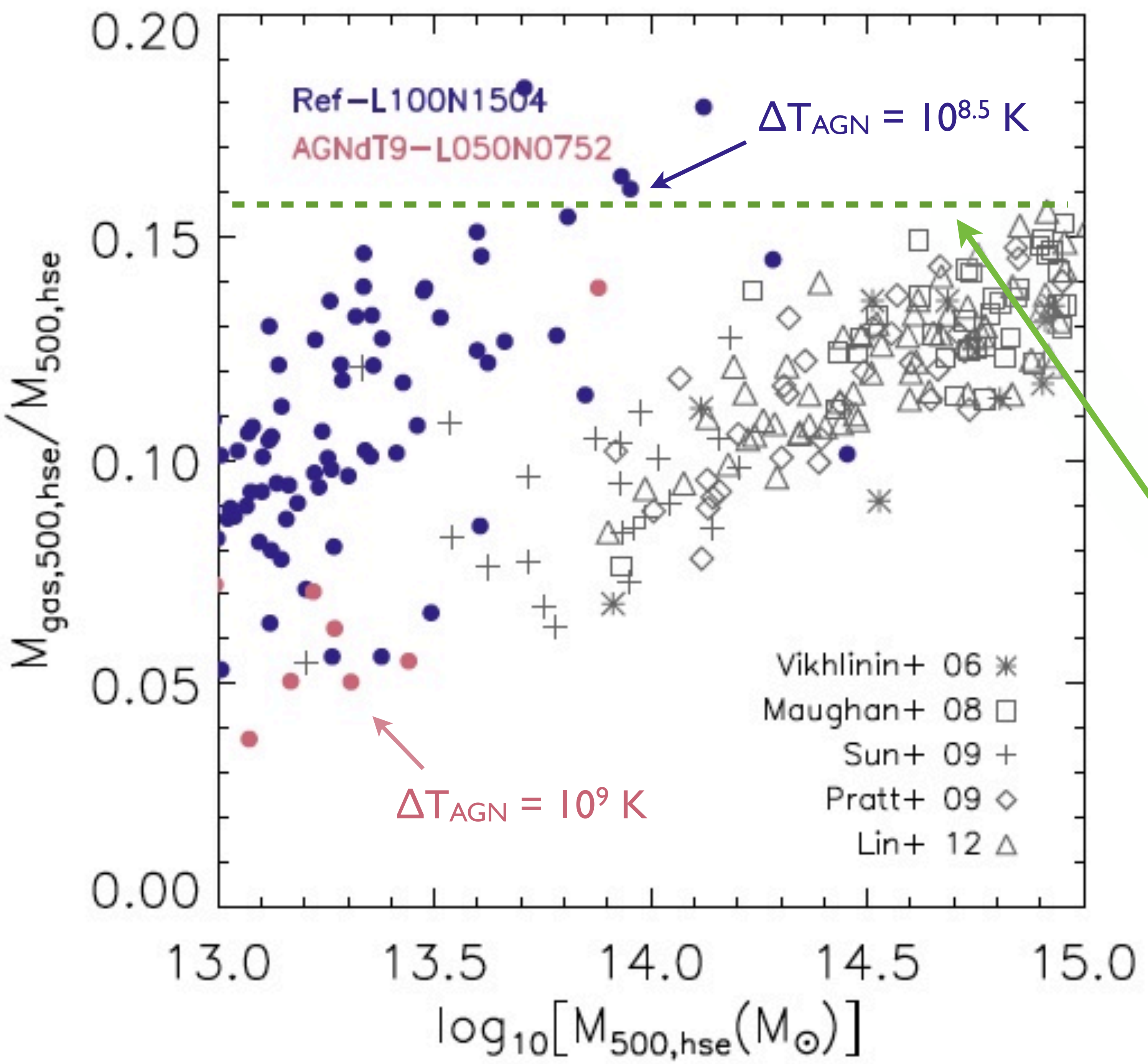
Fraction of passive galaxies ($SFR/M_{star} < 10^{-11}$ $M_\odot$ yr^{-1})



Tully-Fisher relation

(J. Schaye et al., 2015, MNRAS 446, 521)

EAGLE results: Galaxy groups



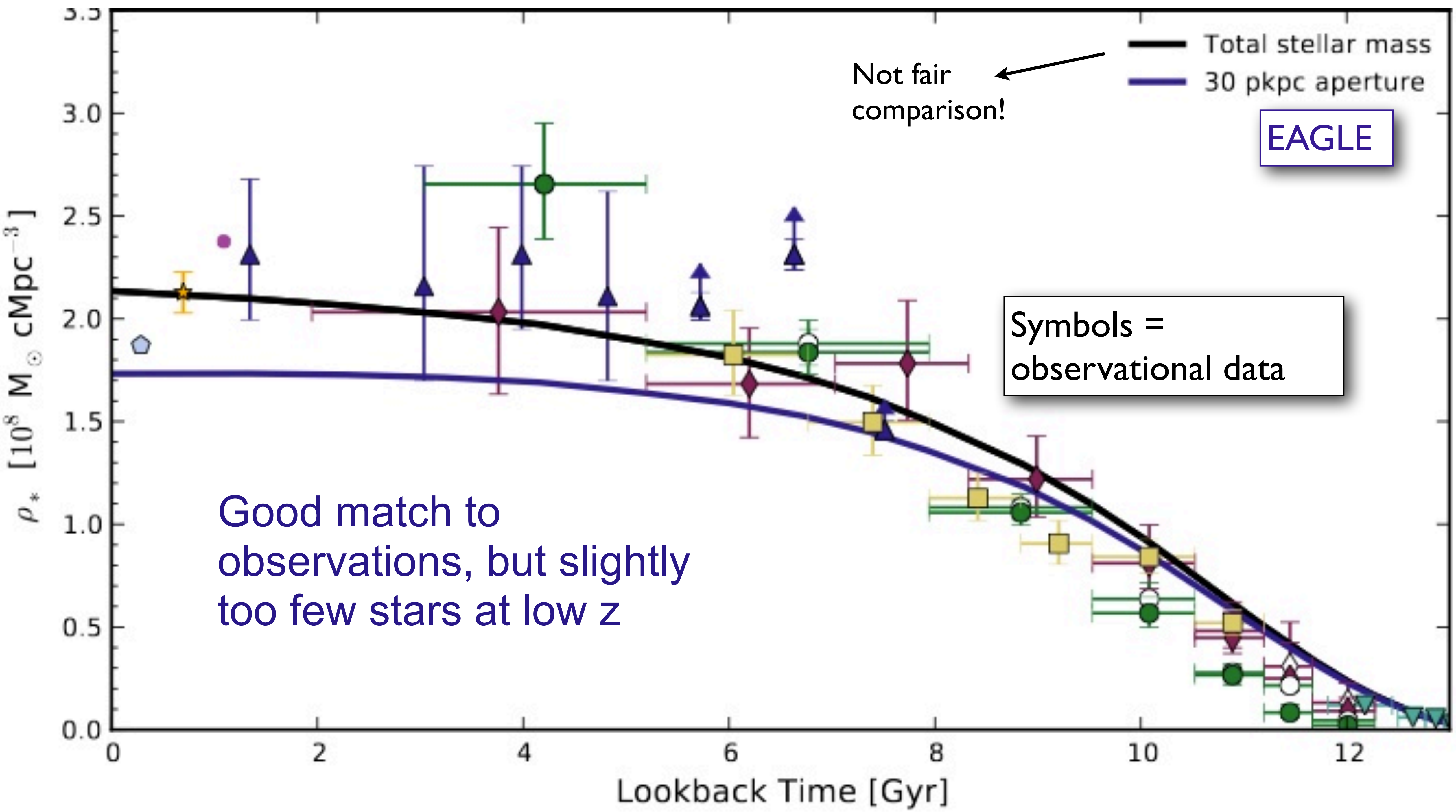
Significant effect of factor 3 increase in ΔT_{AGN}:

More realistic gas fractions in galaxy groups

N.B.: 10^9 K model only run in 50 Mpc box, so much fewer massive haloes.

(J. Schaye et al., 2015, MNRAS 446, 521)

EAGLE results: build-up of stellar mass



(M. Furlong et al., 2014, arXiv:1410.3485)