Cosmological simulations of galaxy formation

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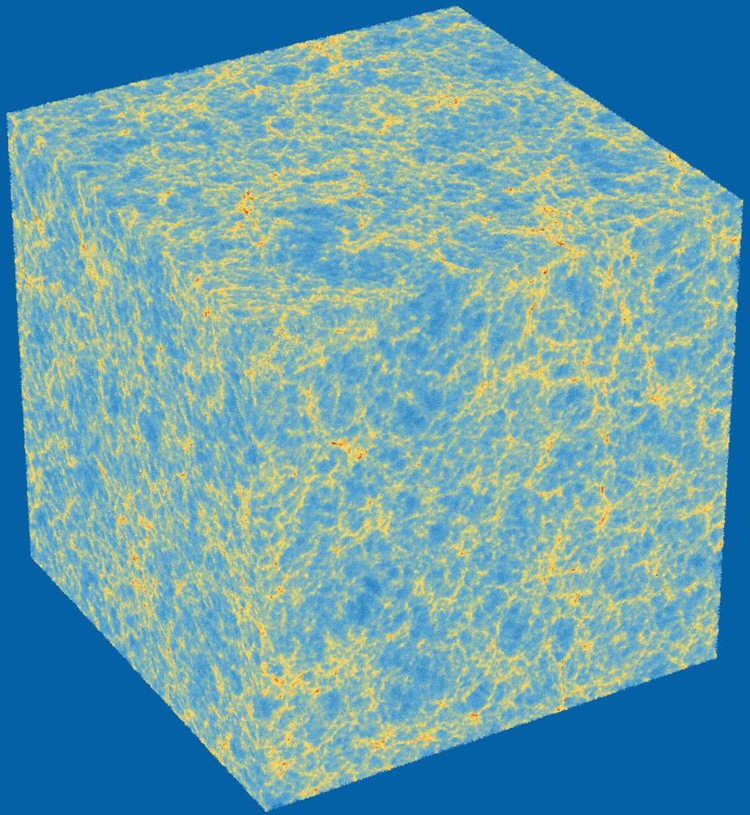
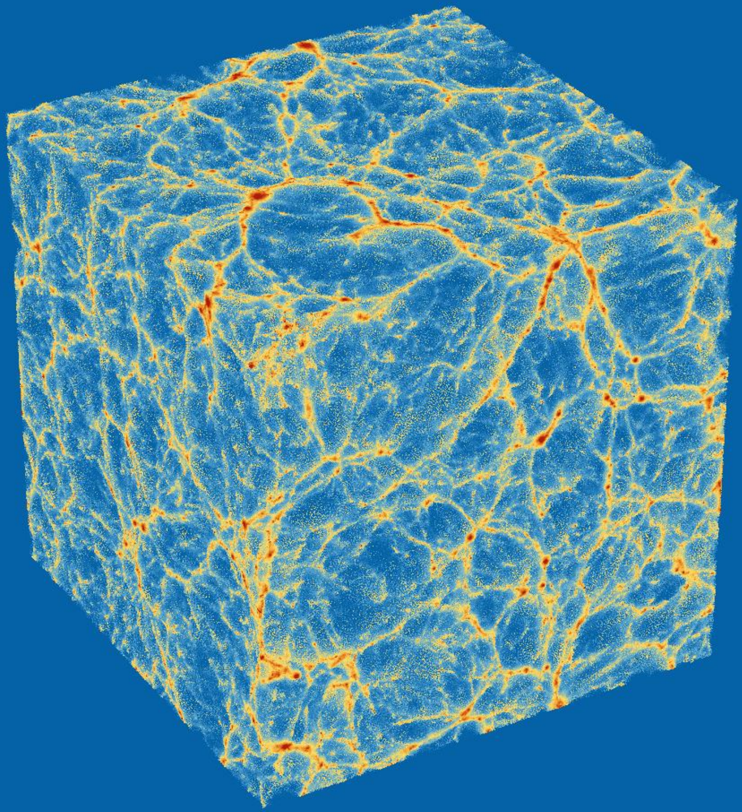
(Yope Shea)





Cosmological hydro simulations

- Evolution from z>~100 to z ~< 10 of a representative part of the universe
- Expansion solved analytically and scaled out
- Initial conditions from the CMB & LSS
- Boundary conditions: periodic
- Components: cold dark matter, gas, stars, radiation (optically thin)
- Discretizaton: time, mass (SPH) or length (AMR)
- Gravity and hydro solvers (and MHD, RT, …)
- Sub-grid modules are a crucial part of the game

Length Scales (cm)

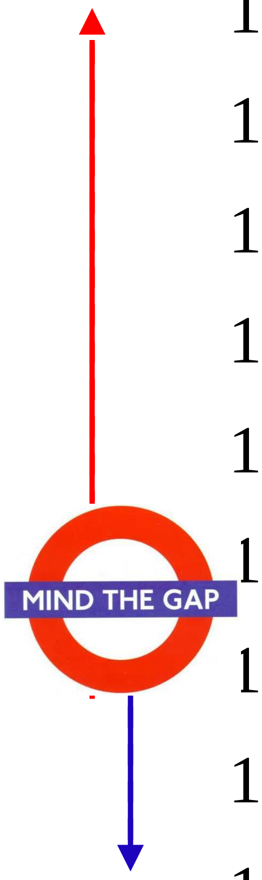
10^{-8}	interparticle distance in stars
10^{0}	interparticle distance in ISM
10^{2}	interparticle distance in IGM
10^{11}	stellar radii
10^{18}	interstar distance
10^{20}	star clusters
10^{22}	galaxies
10^{24}	clusters of galaxies
10^{28}	observable universe

Subgrid models

Cosmological simulations

Length Scales (cm)

Subgrid models



Cosmological simulations

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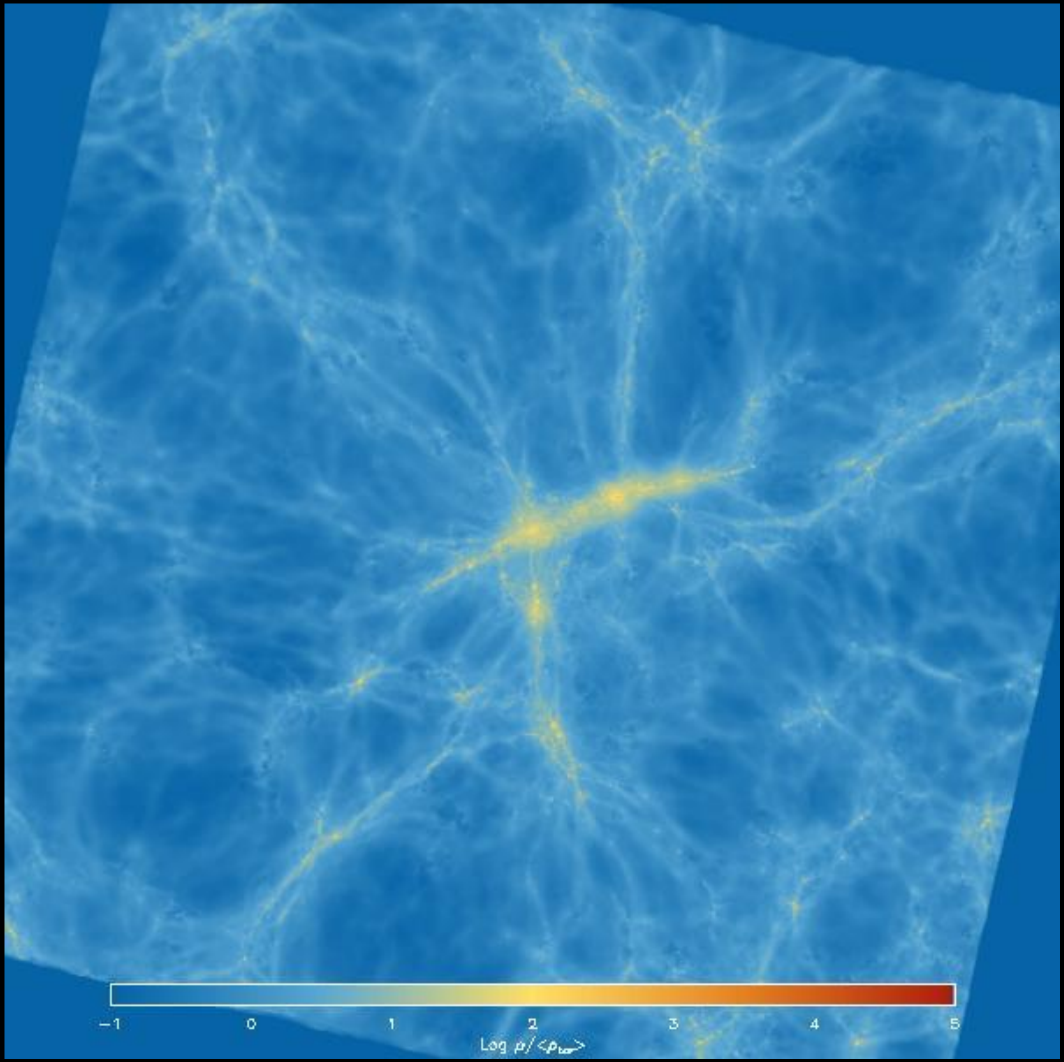
Zooming into a massive galaxy at z=2: Gas density



25 Mpc/h

Depth: 2 Mpc/h

Log M = 12.6
Log M* = 11.5

Simulation:
OWLS REF
L025
N512

Where to put the gap?

Transition from warm ($T \sim 10^4$ K) to cold, molecular ($T \ll 10^4$ K) ISM expected at $\Sigma_H \sim 10\ M_\odot pc^{-2}$ ($n_H \sim 10^{-2} - 10^{-1}$ cm^{-3} in warm phase).

- Determined by (dust) column needed to shield UV
- Associated with sharp reduction in Jeans scale → star formation
- Threshold decreases with metallicity and increases with UV

(JS 04, Gnedin+ 09, Krumholz+ 09, 11, Gnedin & Kravtsov 11, Feldmann+ 11, Glover & Clark 12, Clark & Glover 13, …)

Well-posed challenge:

Resolve the Jeans scales in the warm ISM

Basic resolution requirements

- Convergence requires resolving the Jeans scales:

$$M_{\rm J} \approx 1\times10^7\,h^{-1}\,{\rm M}_\odot\,f_{\rm g}^{3/2}\left(\frac{n_{\rm H}}{10^{-1}\,{\rm cm}^{-3}}\right)^{-1/2}\left(\frac{T}{10^4\,{\rm K}}\right)^{3/2}$$

$$L_{\rm J} \approx 1.5\,h^{-1}\,{\rm kpc}\;f_{\rm g}^{1/2}\left(\frac{n_{\rm H}}{10^{-1}\,{\rm cm}^{-3}}\right)^{-1/2}\left(\frac{T}{10^4\,{\rm K}}\right)^{1/2}$$

- Resolving the warm phase requires:
  - Particle mass << $10^7\,M_\odot$
  - Spatial resolution << 1 kpc
- Resolving gas with $n_H \sim 10^1\,cm^{-3}$ and $T \sim 10^2$ K requires :
  - particle mass << $10^3\,M_\odot$
  - spatial resolution << 10 pc
  - Radiative transfer
  - Complex chemistry

The cold phase is still too demanding for cosmological simulations

MIND THE GAP

MIND THE GAP

But we are about to cross the gap in simulations of individual galaxies!

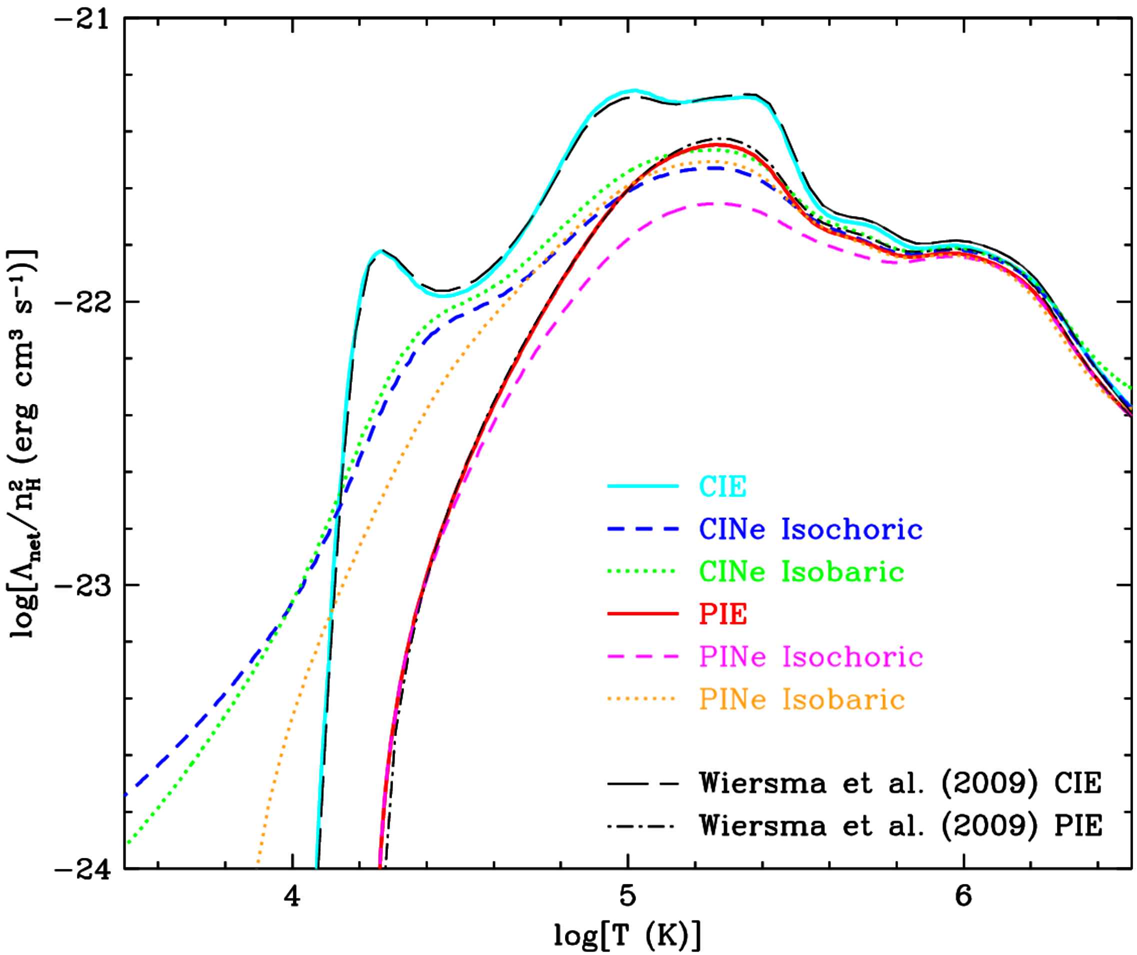
Subgrid models for cosmological hydro simulations

- **Radiative cooling**/heating
- Star formation
- Chemodynamics/stellar evolution
- **Galactic winds driven by feedback from SF**
- Black holes and AGN feedback
- Less conventional things. E.g.:
  - Turbulence (incl. mixing)
  - Cosmic rays
  - Dust

Radiative cooling

- Standard assumptions:
  - H & He in photo-ionisation equilibrium (optically thin, UV background only)
  - Metals in collisional ionisation equilibrium (though many studies still assume primordial abundances!)
- Recent developments (e.g. Wiersma, JS & Smith '09; Shen+ '10; Vogelsberger+ '13, Aumer+ '13):
  - Metals also in photo-ionisation equilibrium
  - Relative abundance variations
- Cutting edge/future:
  - Non-equilibrium ionization
  - Radiative transfer
  - Local radiation sources
  - Molecules
  - Dust

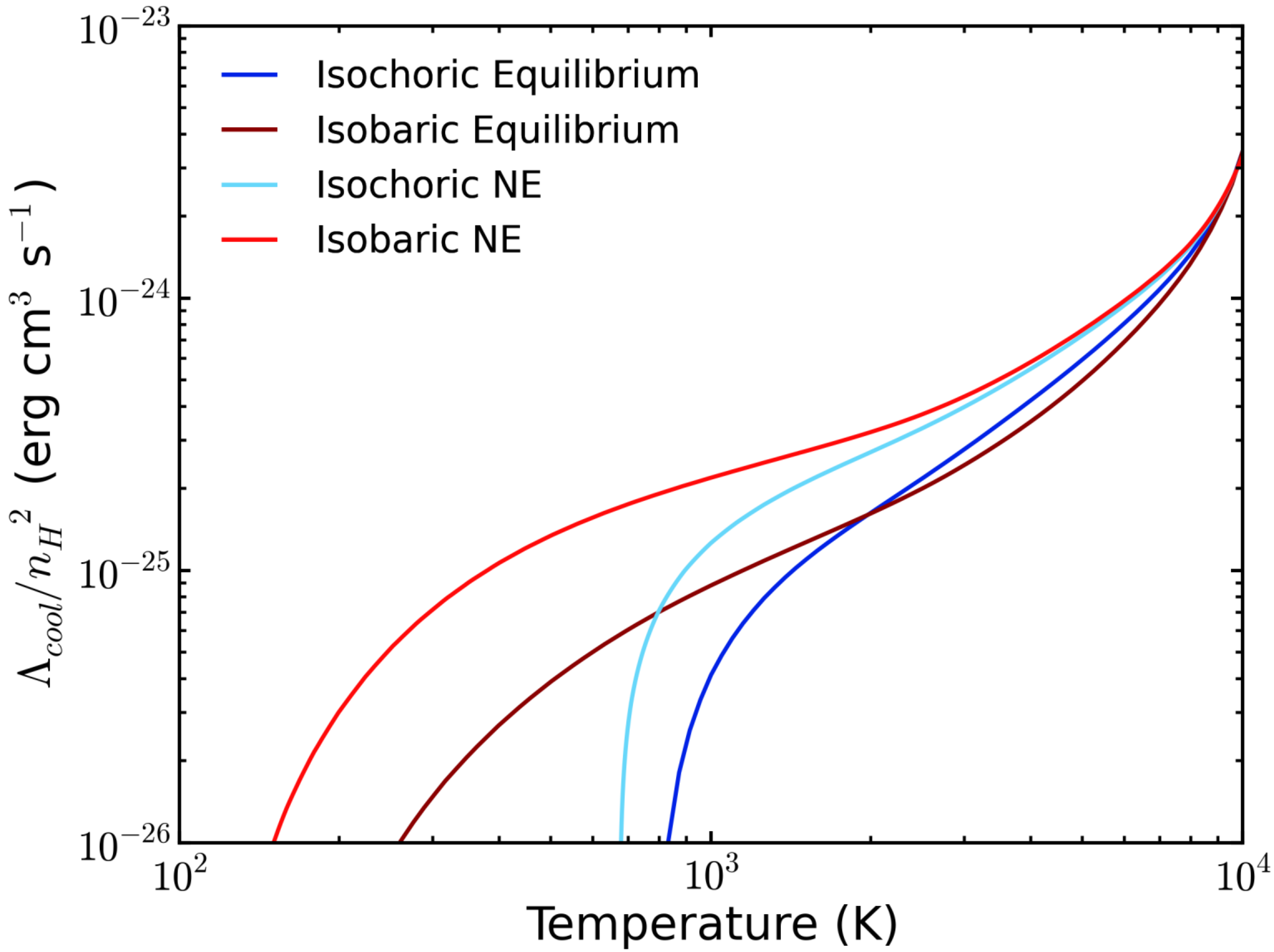
Cooling: effect of non-equil. and photo-ionisation



$n_H = 10^{-4}$ cm^{-3}, z=1, $Z = Z_\odot$

Oppenheimer & JS (2013a)

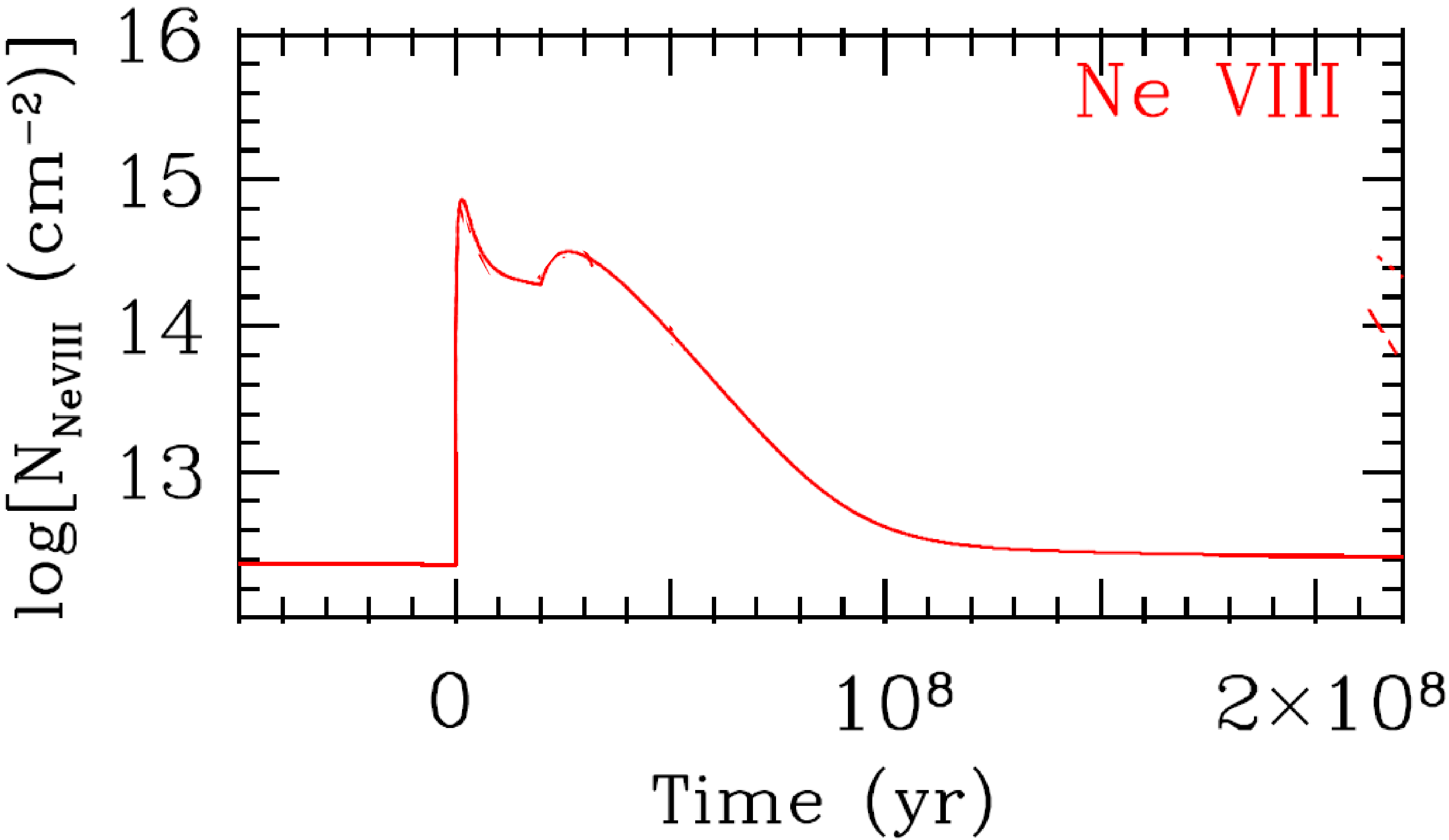
Cooling: effect of non-equil. at T < 10^4 K



n_H=1 cm^{-3}, Z=$Z_\odot$

Richings, JS & Oppenheimer (in prep)

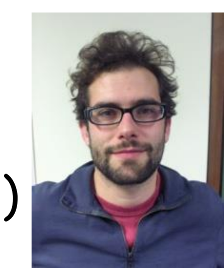
AGN proximity zone fossils



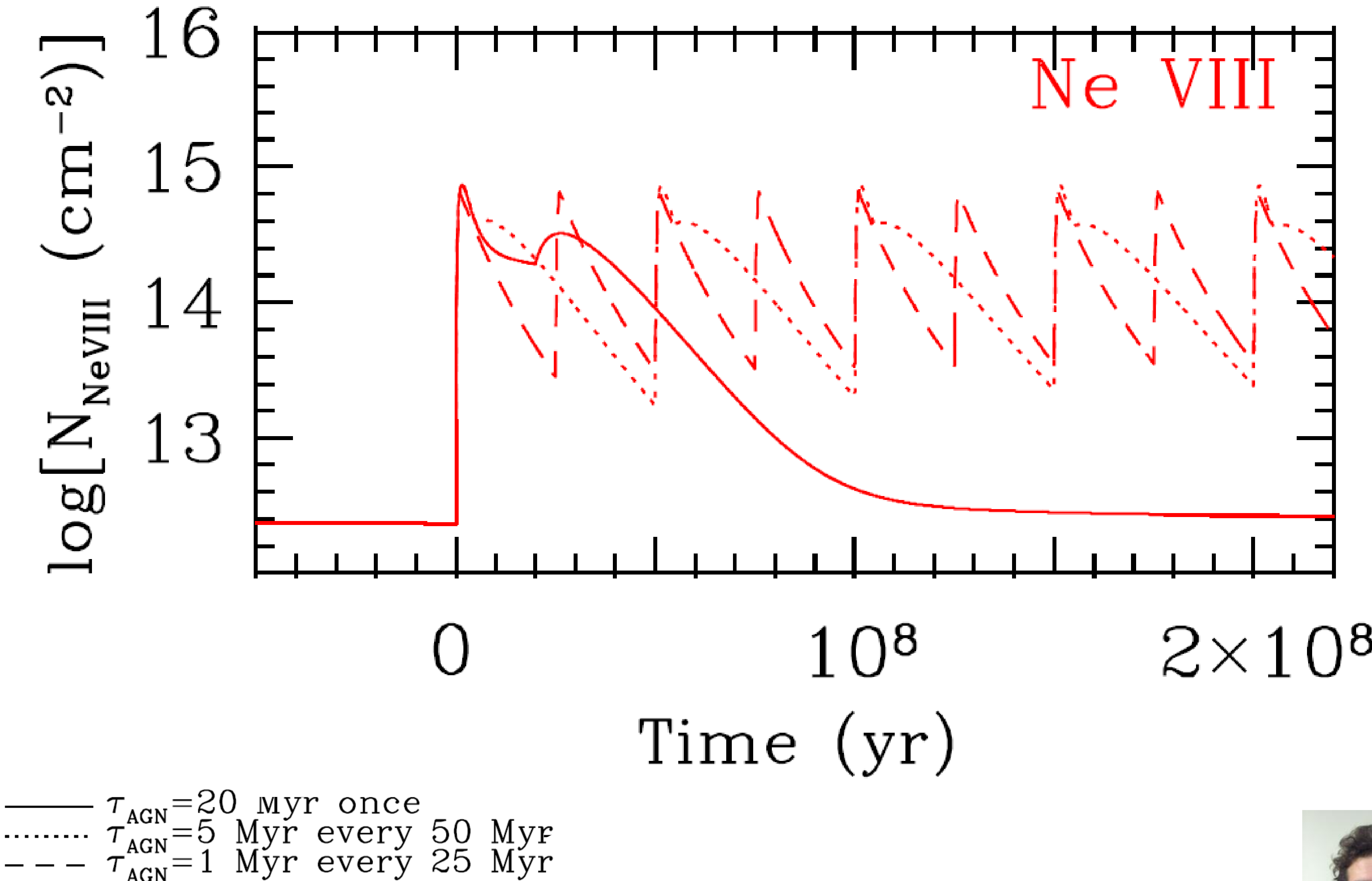
—— τ_{AGN}=20 Myr once

$n_H=10^{-4}$ cm^{-3}, T = 10^4 K, z=1, Z=Z$_\odot$

Oppenheimer & JS (2013b)



AGN proximity zone fossils

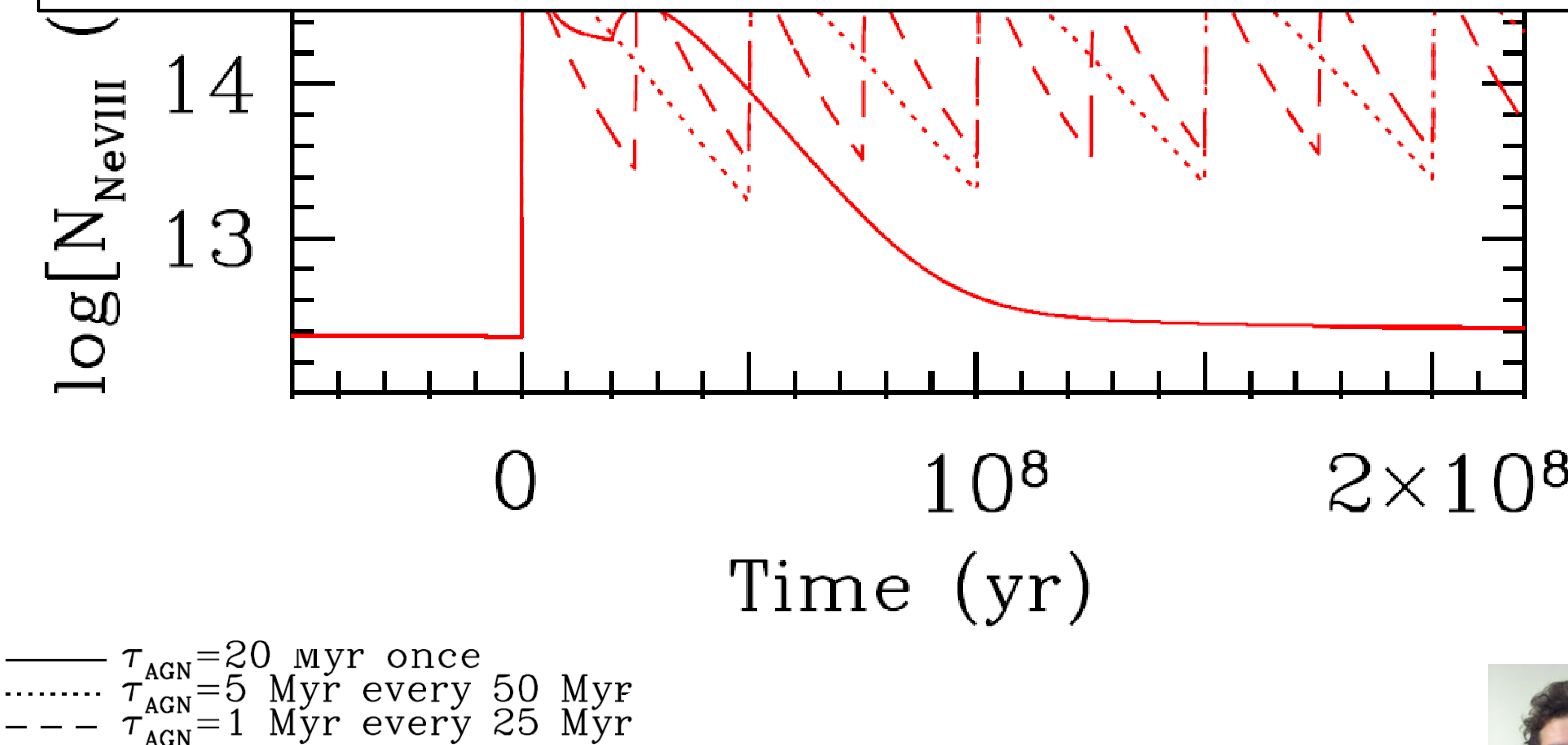


$n_H=10^{-4}$ cm^{-3}, T = 10^4 K, z=1, Z=Z$_\odot$

Oppenheimer & JS (2013b)

AGN proximity zone fossils

Most intergalactic metals may reside
in out-of-equilibrium AGN fossil zones!



$n_H=10^{-4}$ cm^{-3}, T = 10^4 K, z=1, Z=Z$_\odot$

Oppenheimer & JS (2013b)

Galactic winds driven by SF

- Winds may be:
  - Energy-driven
  - Momentum-driven
  - Both
- Sources of energy/momentum:
  - Supernovae
  - Radiation pressure:
    - On dust
    - From photo-ionisation
    - From trapping of Lya
  - Stellar winds
  - Cosmic rays
  - Combination of the above

Galactic winds driven by SF: WARNINGS

- Efficient feedback is required to match observations
- Feedback is often inefficient due to the numerical implementation…
- … but inefficient feedback is sometimes interpreted as a need for different physical processes
- Nearly all implementations are extremely crude (e.g. radiation pressure w/o radiative transfer)
- At the current resolution, the different feedback processes are hardly distinguishable
- Many hydro simulations use tricks that make them more like SAMs than you may think. E.g.:
  - Wind velocity depends on halo mass or dark matter velocity dispersion (e.g. Okamoto+, Davé/Oppenheimer+, Viel+, Vogelsberger+)
  - Temporarily turn off hydro for winds (e.g. Springel/Hernquist, Davé/Oppenheimer, Viel, Vogelsberger)
  - Temporarily turn off radiative cooling (nearly everyone else)

Implementing FB: recognized problems

Simplest recipe: star particles inject thermal energy into surroundings (e.g. Katz+ '96)

Recognized problems:

- Much of the mass in the ISM is in the cold phase ($T \ll 10^4$ K)
- Simulations do not model cold phase
  - → intercloud density too high
    - → cooling rate too high
    - → feedback too inefficient
  - → SF insufficiently clustered
    - → feedback too inefficient

Driving winds: brute force solution

- Allow for a cold phase
- Increase SF threshold (only sensible for cold phase)
- Still require subgrid recipe, but on smaller scale

Problem: need very high resolution

→ Can only model a small number of galaxies (zoomed simulations)

→ Need to pick initial conditions (e.g. merger history)

(e.g. Ceverino & Klypin '07, Hopkins+ '12, Ceverino+ '13)

Driving winds: subgrid recipes

- Multiphase particles (e.g. Marri & White '93, Scannapieco, Murante, Aumer/White)
- Suppress cooling by hand (e.g. Gerritsen '97, Thacker, Stinson/Brook/Gibson/Governato/Maccio/Mayer/Wadsley/…)
- Inject momentum (i.e. kinetic feedback) (e.g. Navarro & White '93, Springel/Hernquist, Davé/Oppenheimer, Teyssier, OWLS/GIMIC, Vogelsberger, …)
  - Most relevant advantage: can decrease initial mass loading
- Temporarily decouple winds from the hydrodynamics (e.g. Springel/Hernquist '03, Davé/Oppenheimer, Viel, Vogelsberger, …)
- Multiple feedback processes (e.g. Hopkins+, Stinson+ '13, …)

Implementing FB: less recognized problems

- Reality: SNe (or BHs) inject lots of energy in very little mass
  - → High temperatures
  - → Long cooling times
  - → Efficient feedback
- Simulations: inject energy in large gas mass
  - → Low heating temperatures
  - → Short cooling times
  - → Inefficient feedback

e.g. Kay+ '03; Booth & JS '09; Creasey+ '11; Dalla Vecchia & JS '12

Implementing FB: less recognized problems

- The SNII of an SSP of mass m_* can heat a mass $m_{g,heat}$ by
  $\Delta T = 4 \times 10^7$ K $(m_*/ m_{g,heat})$
- Reality: $m_* \gg m_{g,heat}$ initially
  → $\Delta T \gg 10^8$ K
  → $t_c \gg 10^8$ yr $(n_H/1 \text{ cm}^{-3})^{-1}$
- In simulations: $m_* \sim 0.01 - 0.1\ m_{g,heat}$
  → $\Delta T \sim 10^6$ K
  → $t_c \sim 10^5$ yr $(n_H/1 \text{ cm}^{-3})^{-1}$
  → overcooling
- Note that in SPH simulations $(m_*/ m_{g,heat})$ is independent of resolution!

Dalla Vecchia & JS (2012)

Implementing thermal FB: requirements

- FB only efficient if heated resolution elements expand faster than they cool radiatively:

  $t_c \gg t_s = h/c_s$

  where h is the spatial resolution
- Adiabatic expansion does not change t_c / t_s (assuming Brehmsstrahlung)
- Required T depends on density and resolution

$$\frac{t_{\rm c}}{t_{\rm s}} = 2.8 \times 10^2 \left(\frac{n_{\rm H}}{1~{\rm cm}^{-3}}\right)^{-1} \left(\frac{T}{10^{7.5}~{\rm K}}\right) \left(\frac{h}{100~{\rm pc}}\right)^{-1}$$

$$\frac{t_{\rm c}}{t_{\rm s}} \simeq 98 \left(\frac{n_{\rm H}}{1~{\rm cm}^{-3}}\right)^{-2/3} \left(\frac{T}{10^{7.5}~{\rm K}}\right) \left(\frac{\langle m \rangle}{7 \times 10^4~{\rm M}_\odot}\right)^{-1/3}$$

Dalla Vecchia & JS (2012)

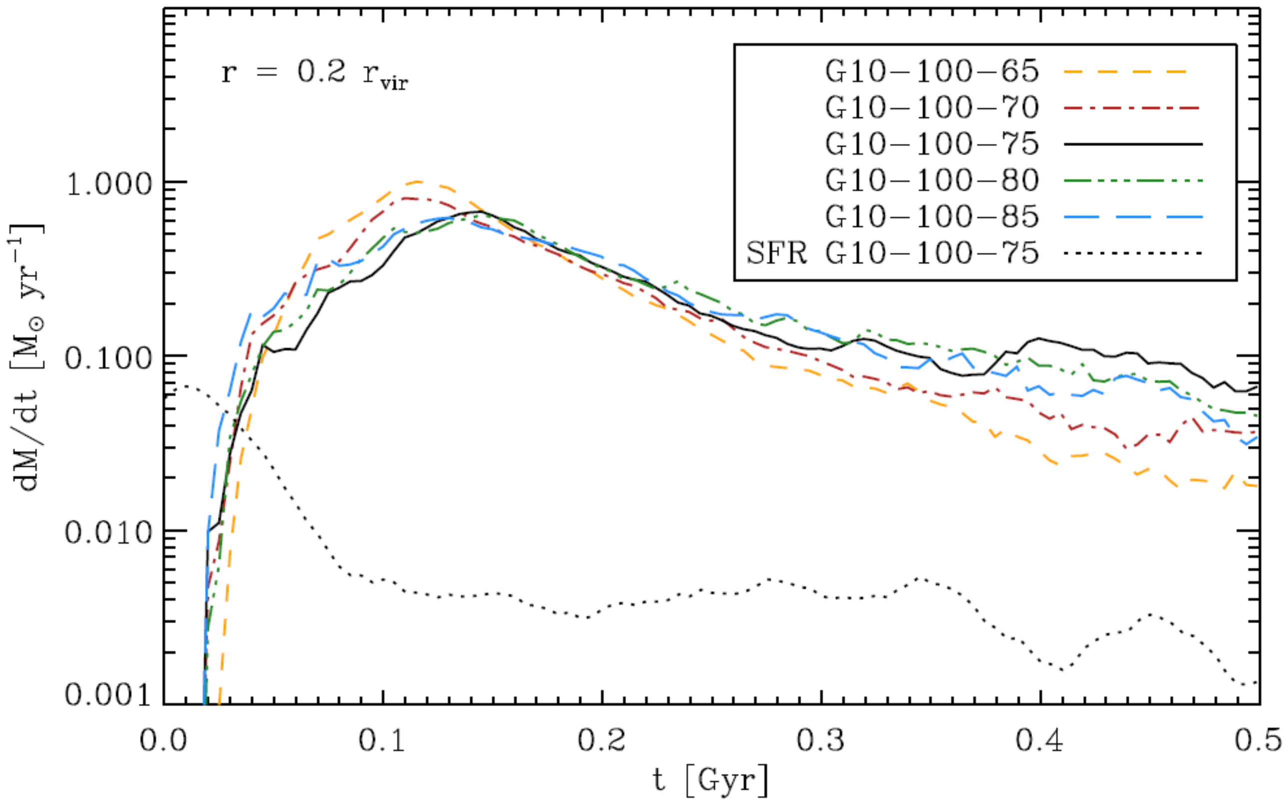
Implementing efficient thermal FB:

- ΔT determined by resolution
- Stochastic FB
  - → given ΔT, fraction of available energy that is injected, f_{th}, determines heating probability
- f_{th} not predicted, unresolved thermal losses need to be calibrated

Dalla Vecchia & JS (2012)

Mass outflow rate: 10^{10} M⊙ halo

- Particle mass 7×10^2 M⊙ → $\frac{t_c}{t_s} \cong 5\times10^2 \left(\frac{n_H}{1\,\mathrm{cm}^{-3}}\right)^{-2/3} \left(\frac{\Delta T}{10^{7.5}\,\mathrm{K}}\right)$
- Max $n_H \sim 10^2$ cm^{-3} → insensitive to ΔT for $\Delta T \geq 10^{6.5}$ K

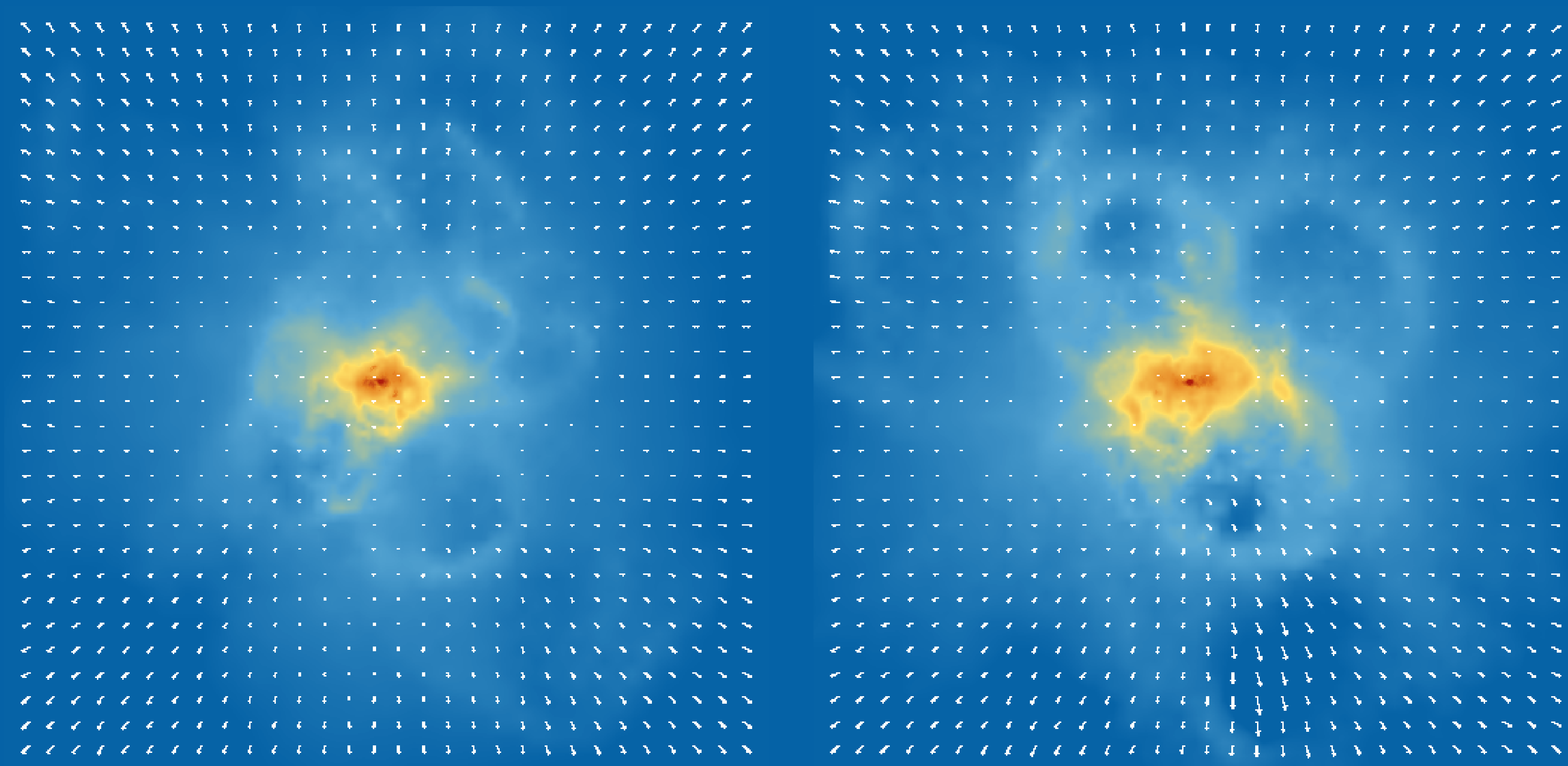


Dalla Vecchia & JS (2012)

10^{10} M⊙ halo, edge-on, gas density

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

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

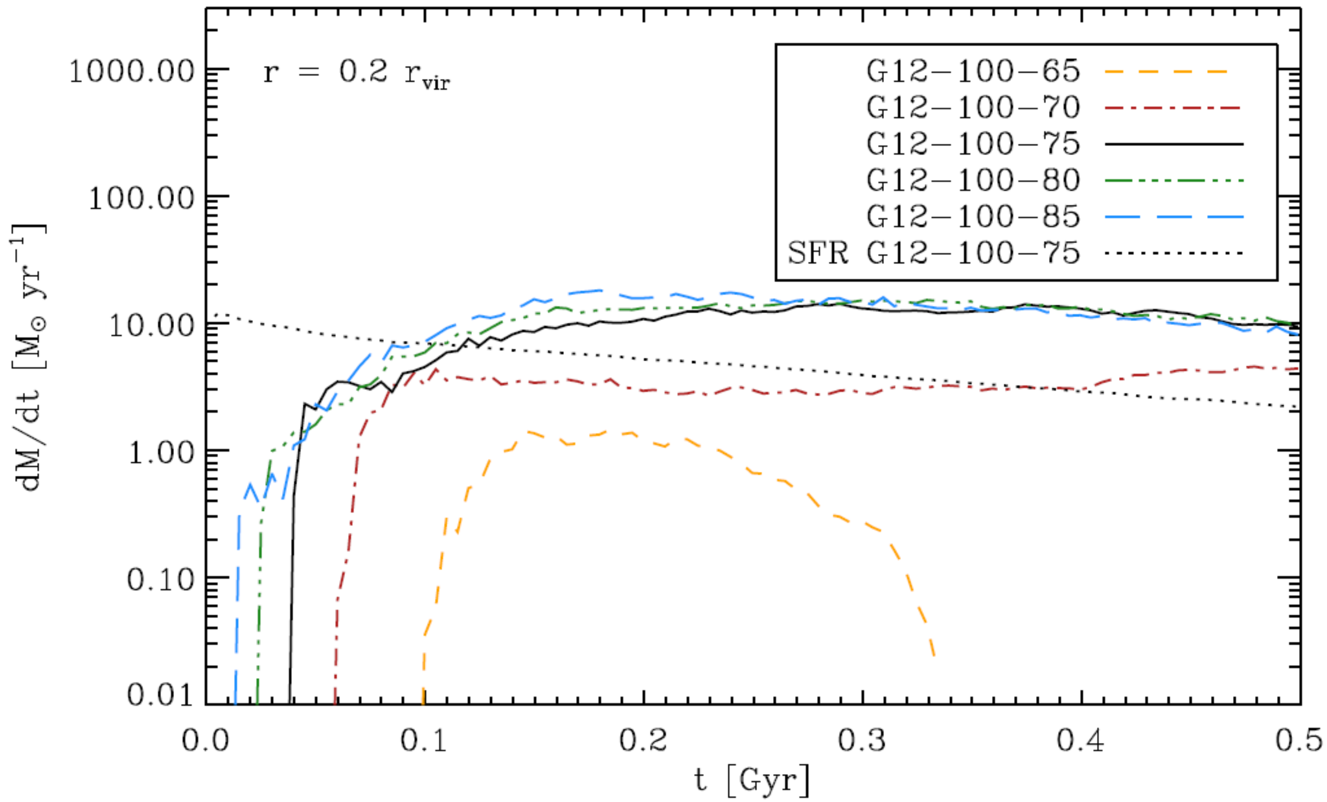


17.5 kpc/h

Dalla Vecchia & JS (2012)

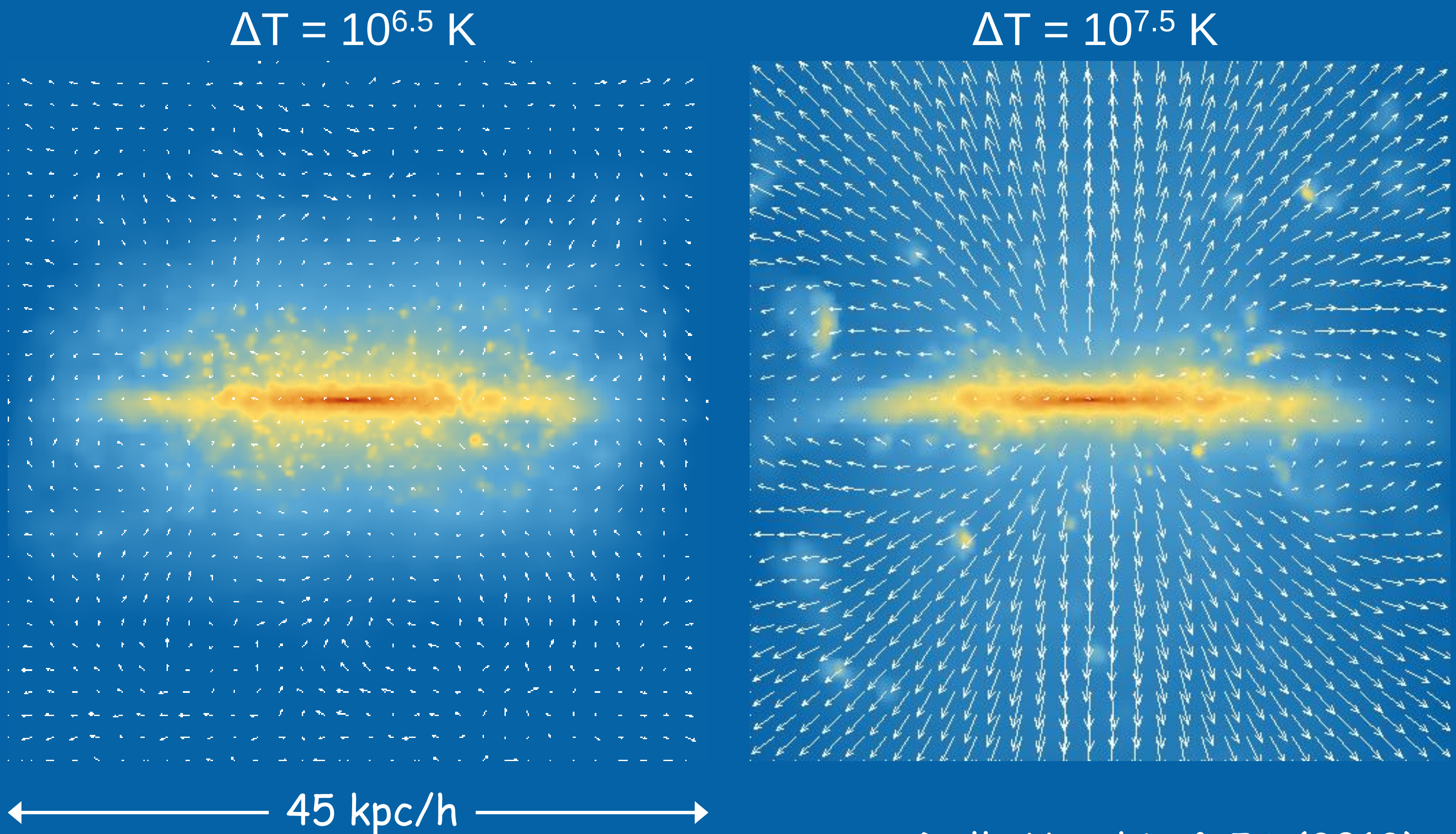
Mass outflow rate: 10^{12} M$_\odot$ halo

- Particle mass 7×10^4 M$_\odot$ → $\frac{t_c}{t_s} \cong 1\times10^2 \left(\frac{n_H}{1\,\mathrm{cm}^{-3}}\right)^{-2/3} \left(\frac{\Delta T}{10^{7.5}\,\mathrm{K}}\right)$
- Max $n_H \sim 10^3$ cm^{-3} → insensitive to ΔT for $\Delta T \geq 10^{7.5}$ K



Dalla Vecchia & JS (2012)

10^{12} M$_\odot$ halo, edge-on, gas density



Dalla Vecchia & JS (2012)

Self-regulated galaxy formation

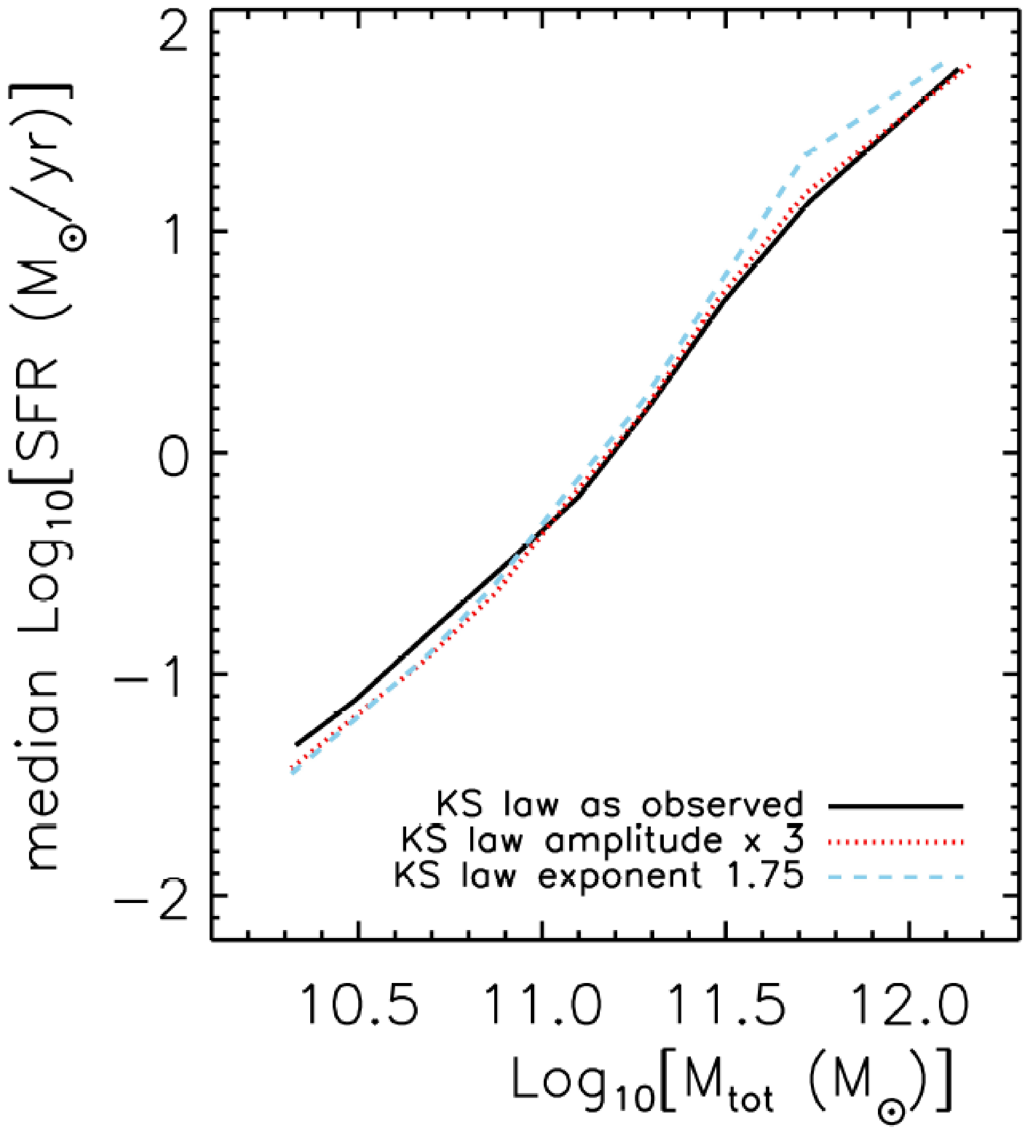
- Feedback too weak compared to accretion
  - Gas density increases
  - Star formation /BH growth rate increases
  - Feedback increases
- Feedback too strong compared to accretion
  - Gas density decreases
  - Star formation/BH growth rate decreases
  - Feedback decreases

Consequences of self-regulated GF

Outflow rate is determined by inflow rate. Hence, it is independent of:

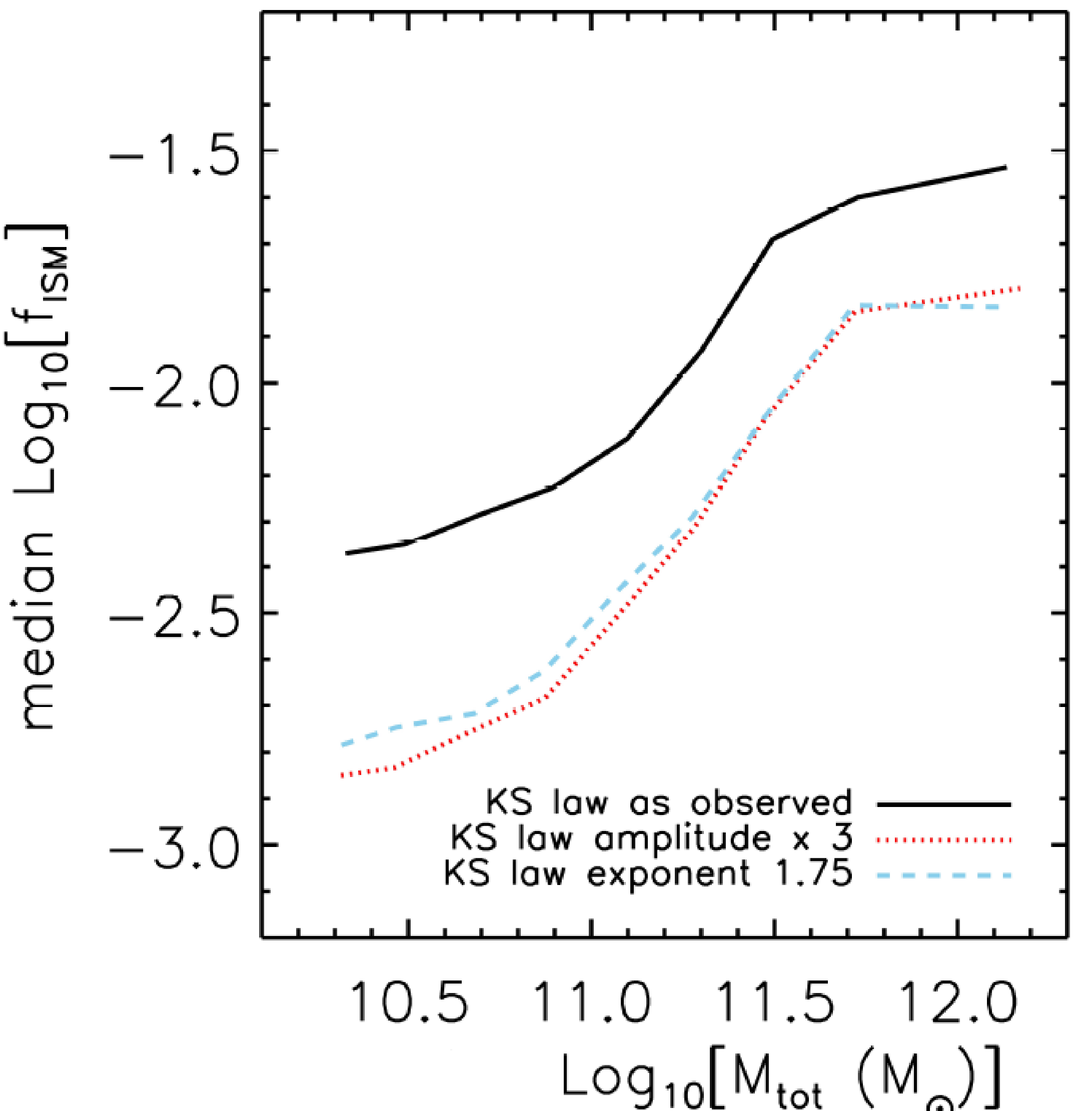
- SF law
  - SFR independent of SF law
    - SF law determines the amount of gas that is involved in SF ("gas fraction")

Varying the SF law: SFR(M)



Haas, JS, et al. (2013a)

Varying the SF law: Gas fraction



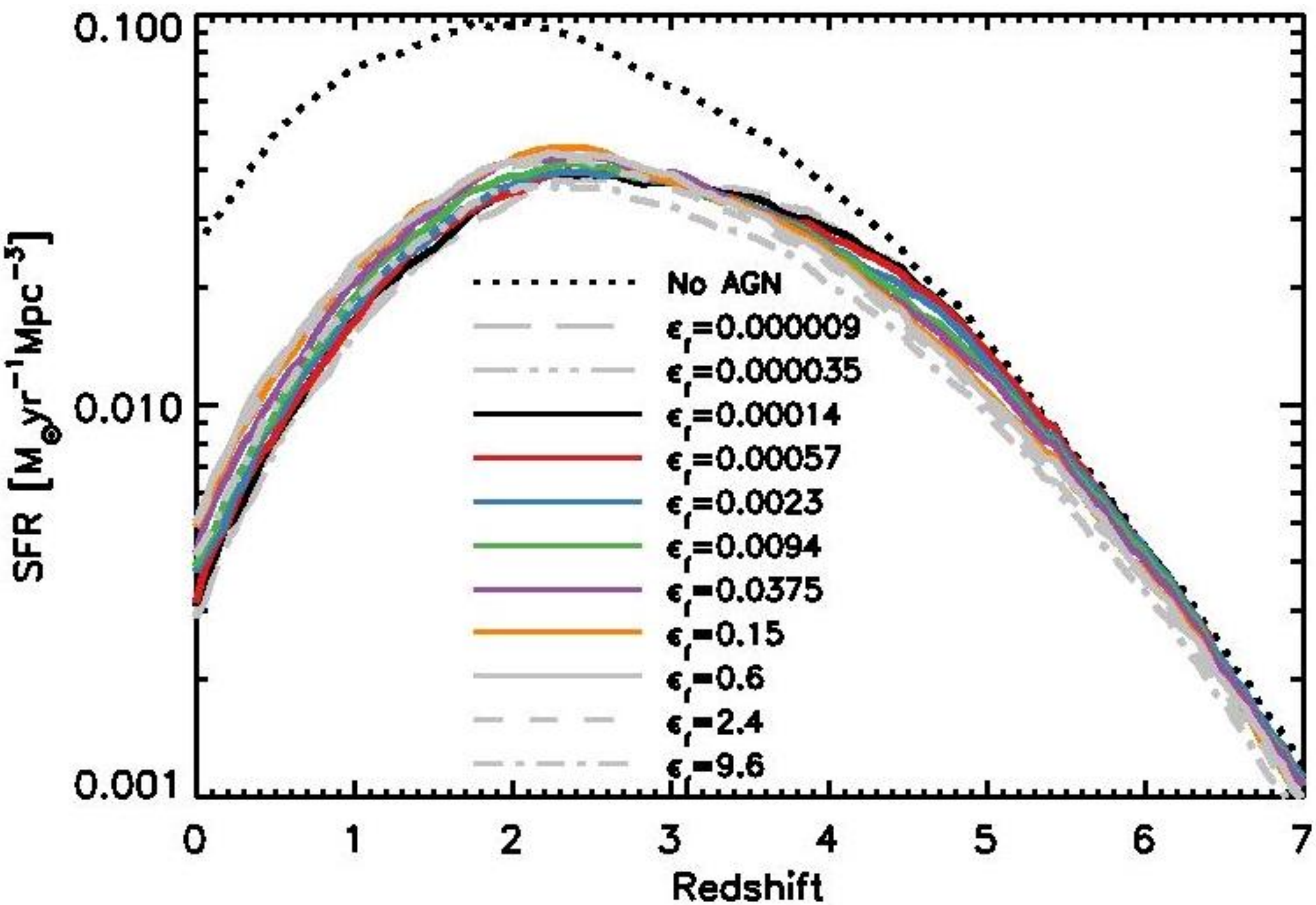
Haas, JS, et al. (2013a)

Consequences of self-regulated GF

Outflow rate is determined by inflow rate. Hence, it is independent of:

- SF law
  - SFR independent of SF law
    - SF law determines the amount of gas that is involved in SF ("gas fraction")
- SF feedback efficiency
  - SFR, and hence M_*, inversely proportional to efficiency of SF feedback
- AGN feedback efficiency
  - BH accretion rate, and hence M_{BH}, inversely proportional to efficiency of AGN feedback
  - SFR independent of AGN feedback efficiency

Varying the efficiency of AGN feedback

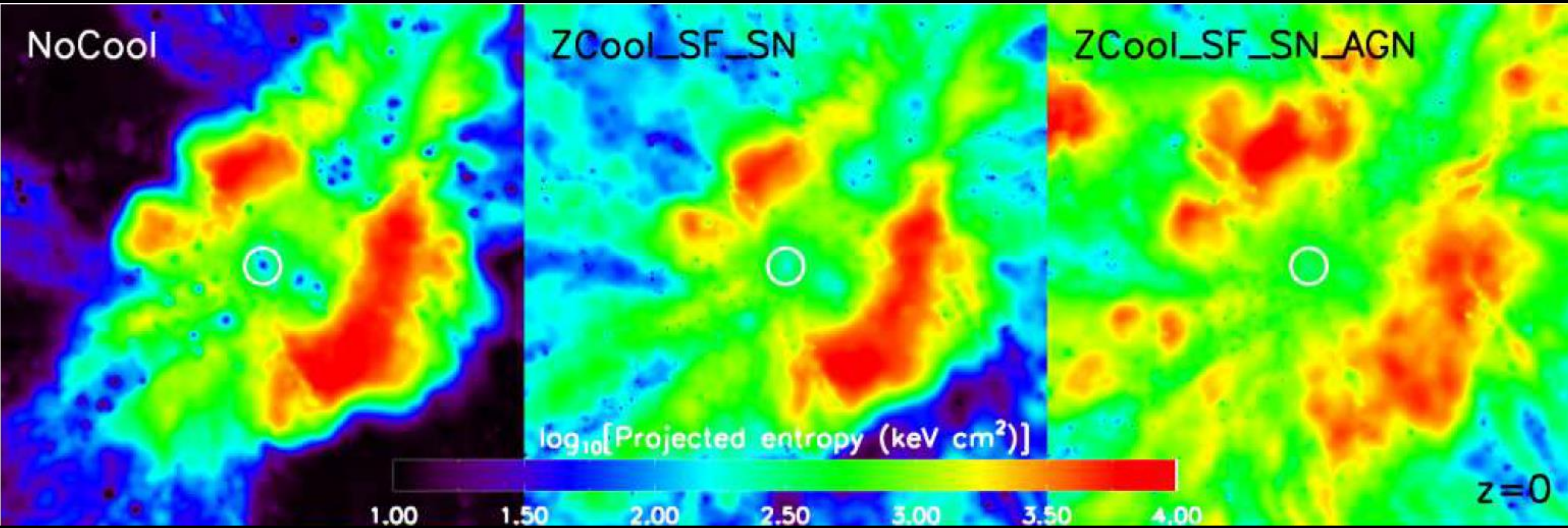


Self-regulation on scale of DM haloes! (Booth & JS 2010, 2011)

Booth & JS (2009)

The effect of baryons on the distribution of matter

Adiabatic | Cooling, SF, SN | Cooling, SF, SN, AGN



← 10 Mpc/h →

McCarthy, JS+ (2011)

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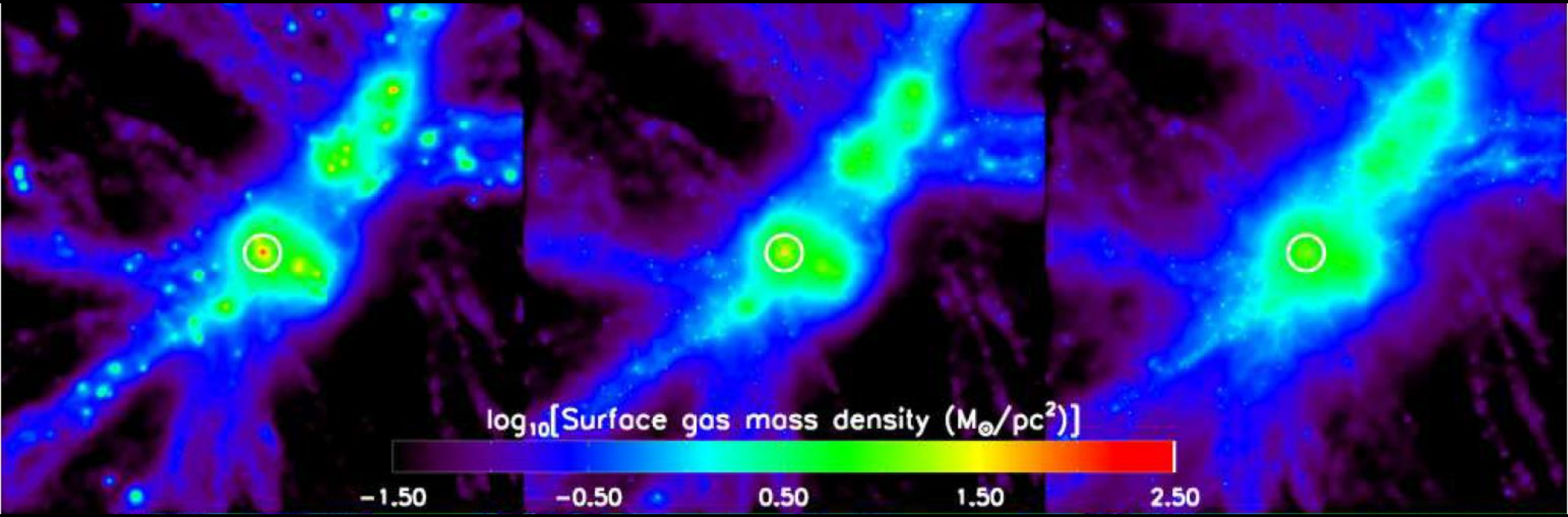
Adiabatic | Cooling, SF, SN | Cooling, SF, SN, AGN

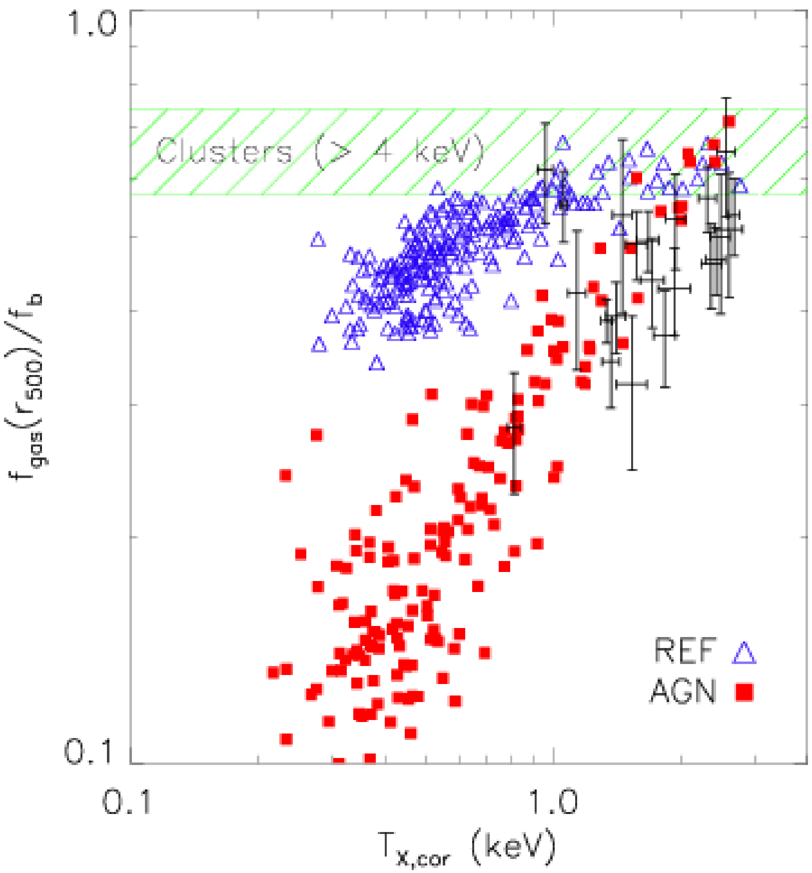


← 10 Mpc/h →

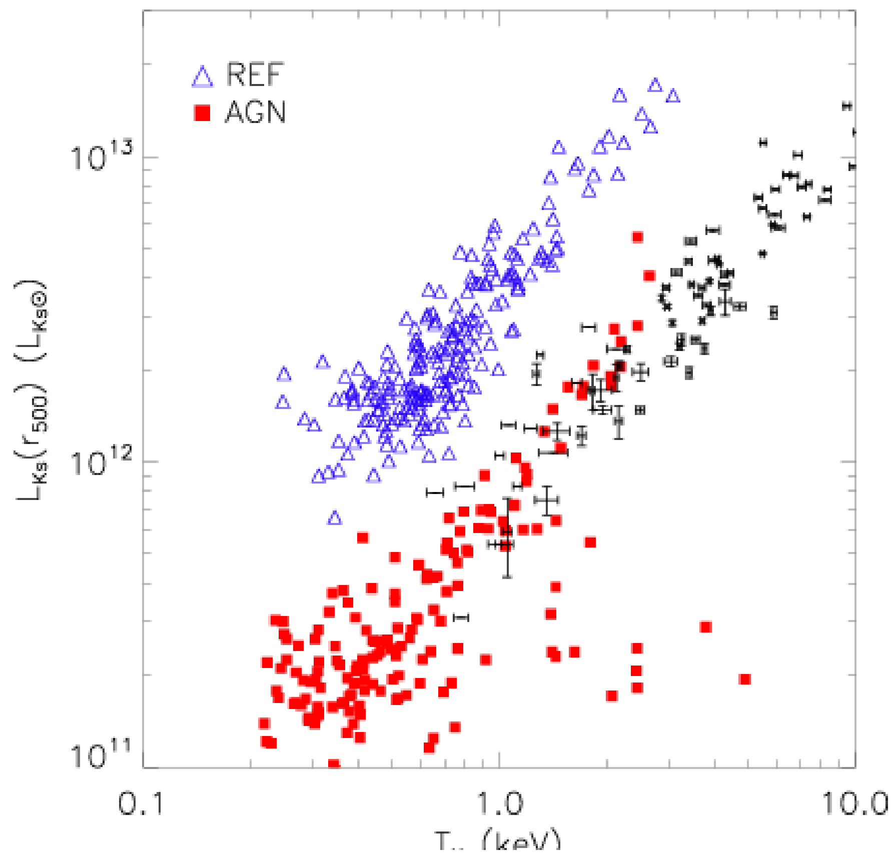
McCarthy, JS+ (2011)

Group gas and stellar contents

Gas fraction vs T



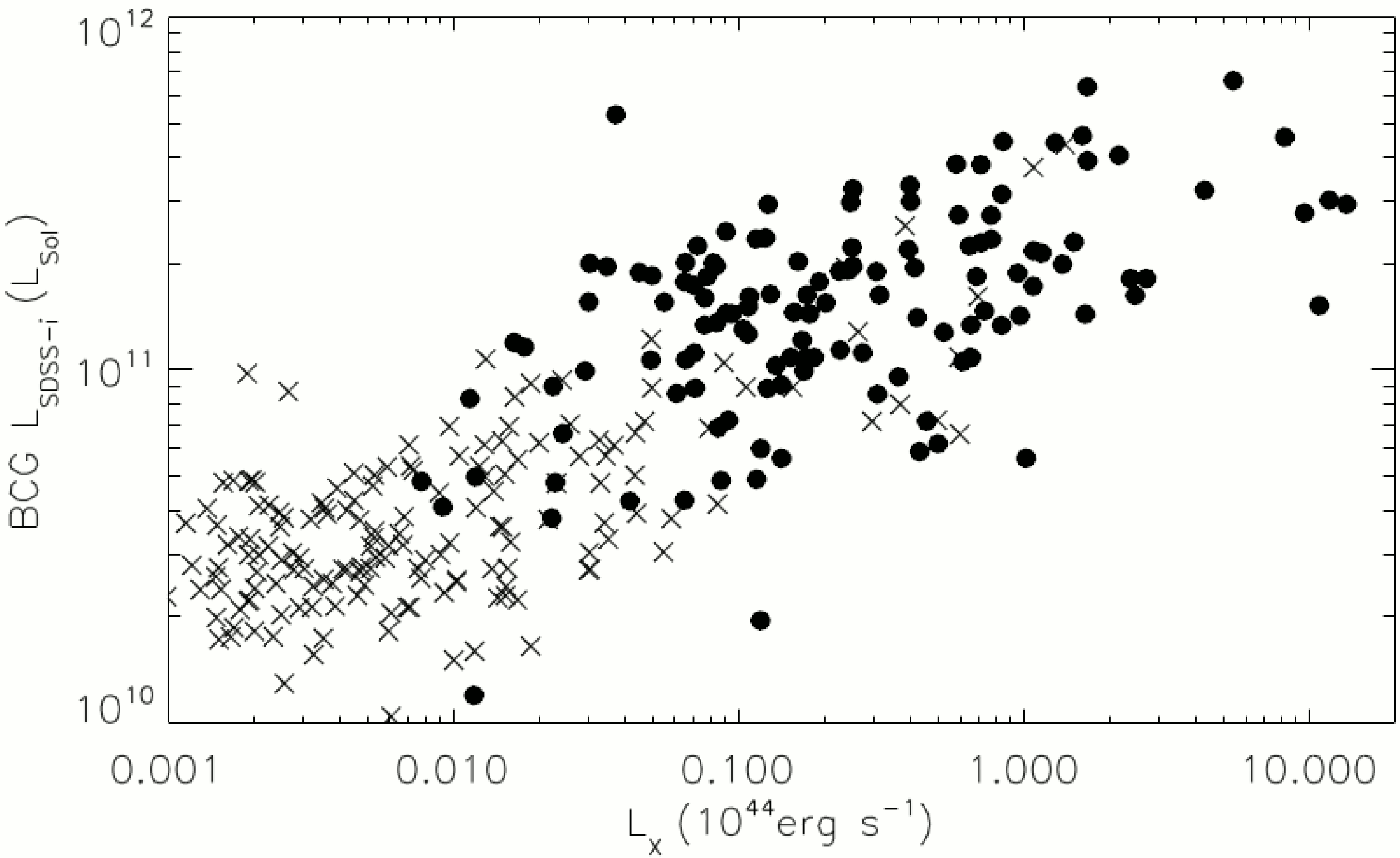
K-band luminosity vs T



McCarthy, JS+ (2010)

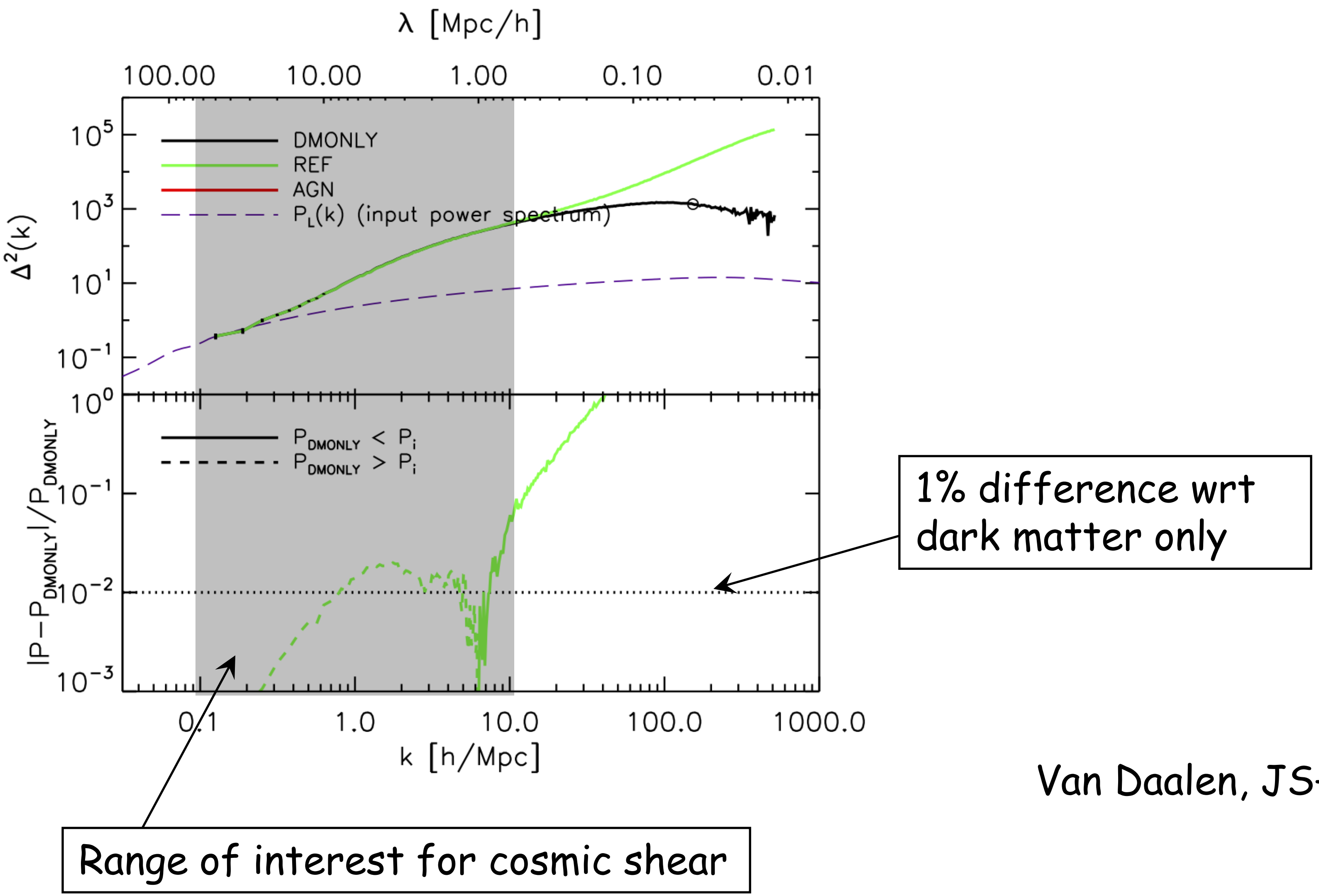
Observations: Lin & Mohr 2004, Horner 2001,
Rasmussen & Ponman (2009)

Optical vs X-ray luminosity



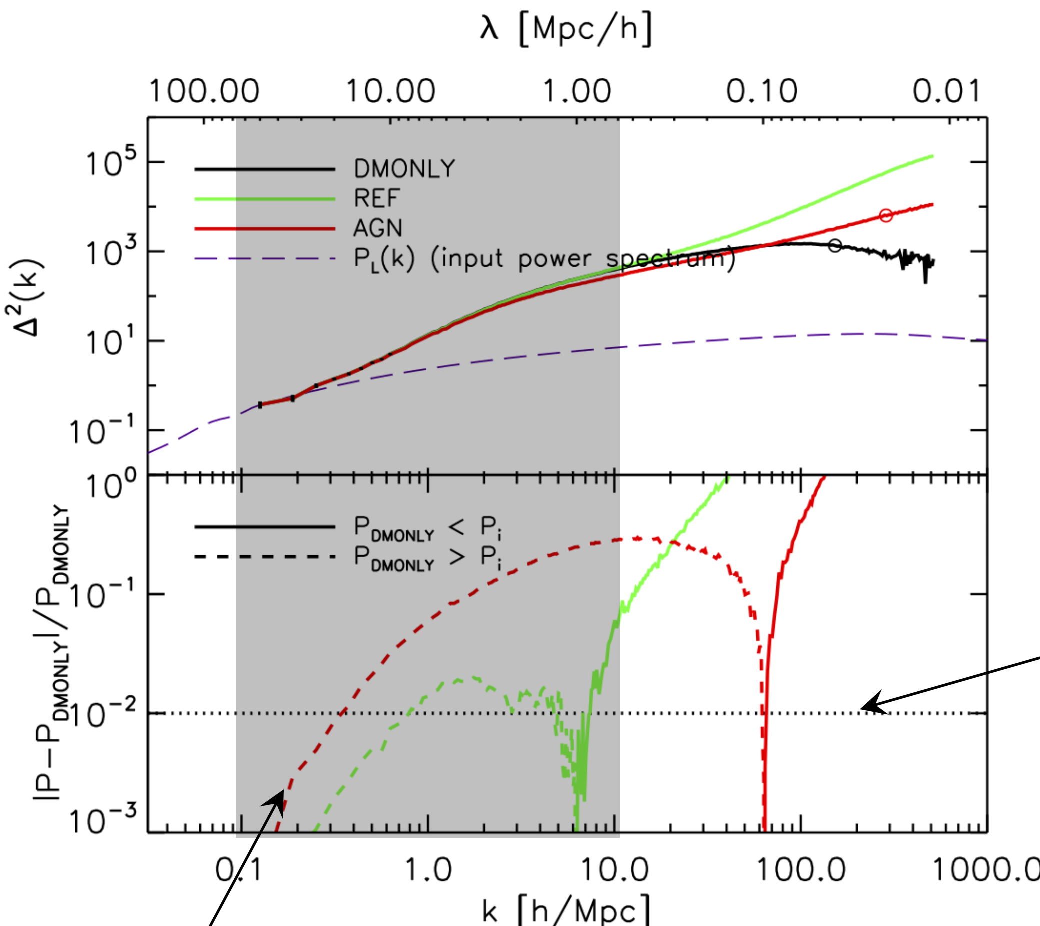
Stott+ (2012)

Baryons and the matter power spectrum



Van Daalen, JS+ '11

Baryons and the matter power spectrum



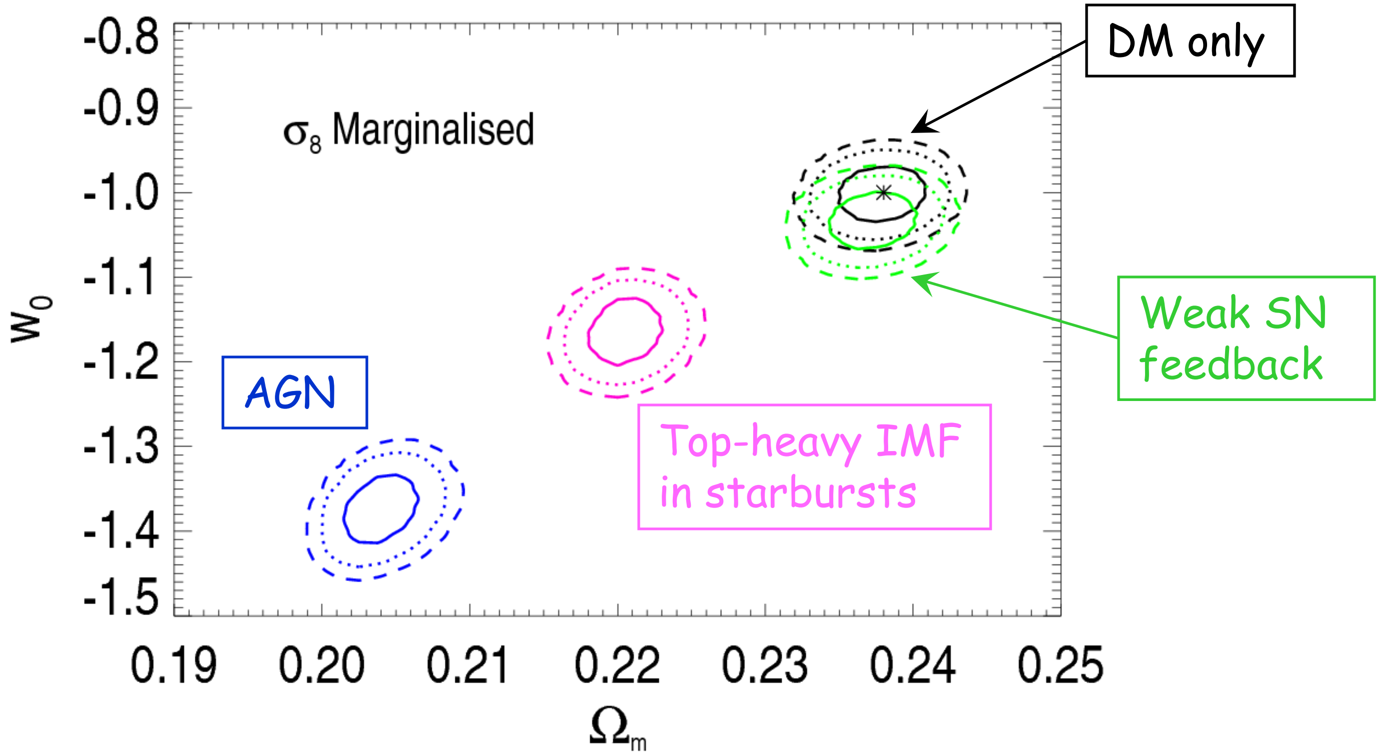
The feedback required to solve the overcooling problem suppresses power on large scales

1% difference wrt dark matter only

Range of interest for cosmic shear

Van Daalen, JS+ '11

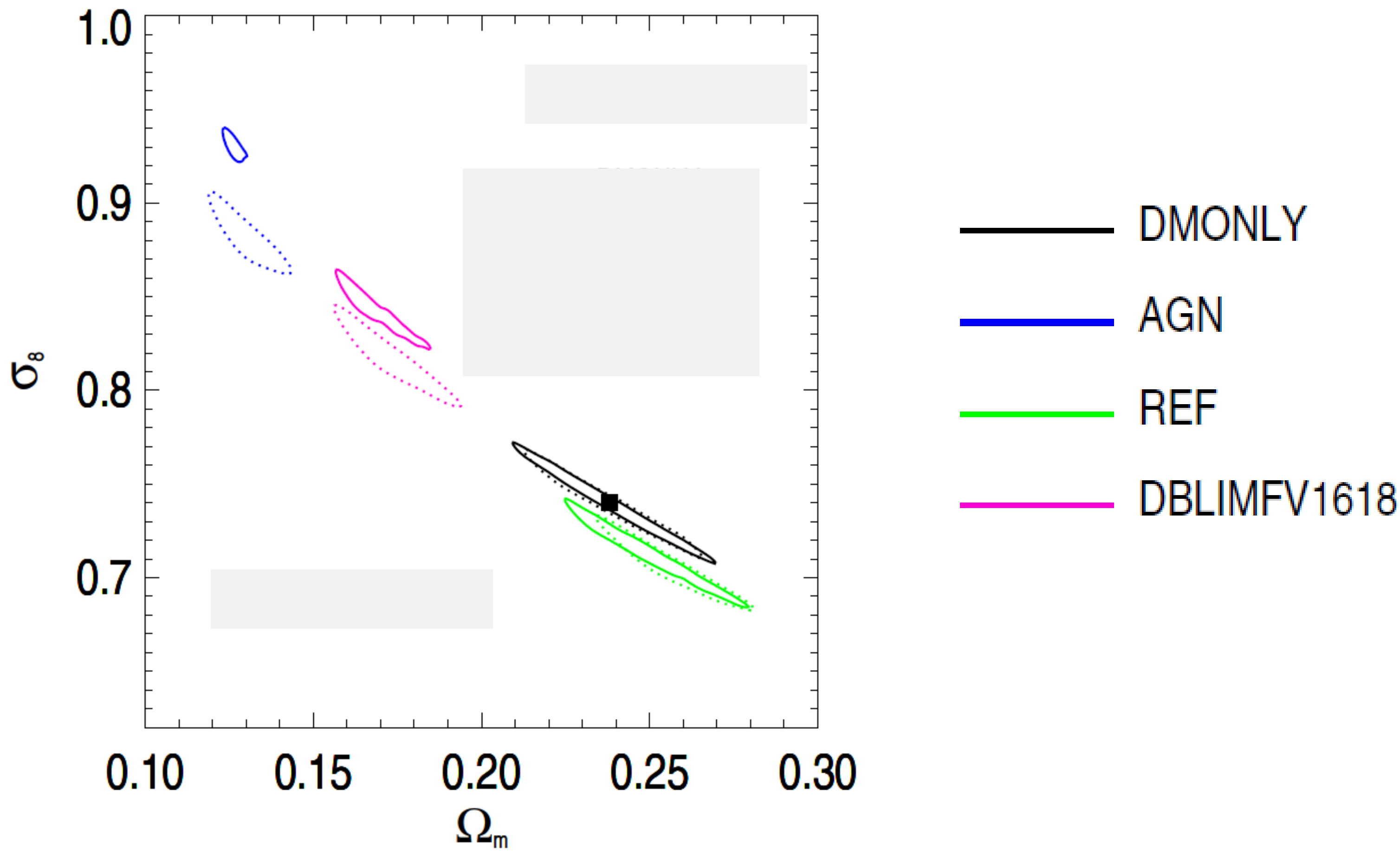
Biases due to galaxy formation for a Euclid-like weak lensing survey



Galaxy formation provides a challenge (target?) for weak lensing

Semboloni+ (2011)

Two and three point statistics

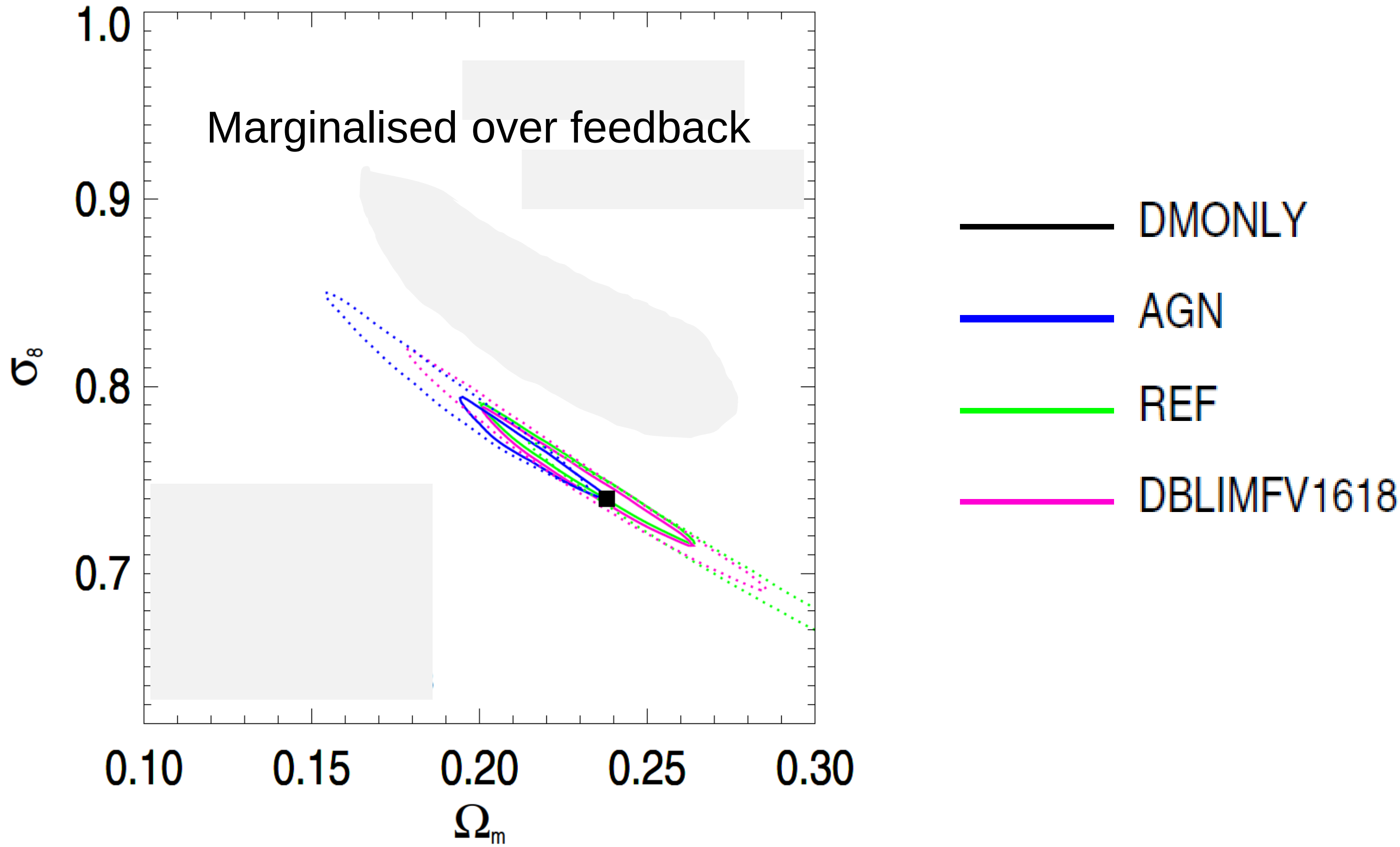


Semboloni, Hoekstra, JS '13

Euclid

w_0 marginalised

Two and three point statistics



Semboloni, Hoekstra, JS '13

Euclid

w_0 marginalised

Cosmic shear

- Baryonic effects can be dramatic (bias for Euclid ~10s of per cent if untreated)
- Power spectrum affected up to very large scales ($k > 0.3$ h/Mpc)
- Impact on bispectrum even higher
- Effects dominated by gas ejection
  - → Underestimated by models suffering from overcooling
  - → Calibration should use gas rather than star fractions
- Modified halo models can capture most of the effects, but currently use input from simulations

What next for galaxy simulations?

- Resolve cold ISM down to 10^2 K in individual (dwarf) galaxy
- Non-equilibrium chemistry including molecules
- Radiation-hydrodynamics

What next for cosmological simulations?

EAGLE:

Evolution and Assembly of GaLaxies and their Environments

- 100 Mpc volume
- 2×1504^3 particles
- To $z = 0$
- Resolves warm ISM
- Subgrid recipes dependent only on local hydro quantities
- Feedback efficiency calibrated to match mass function

EAGLE