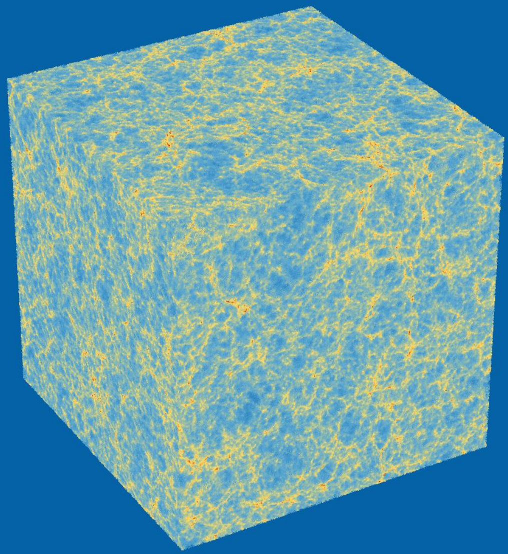
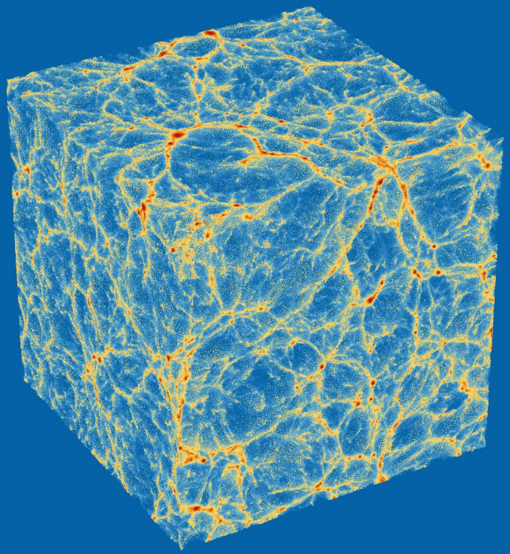
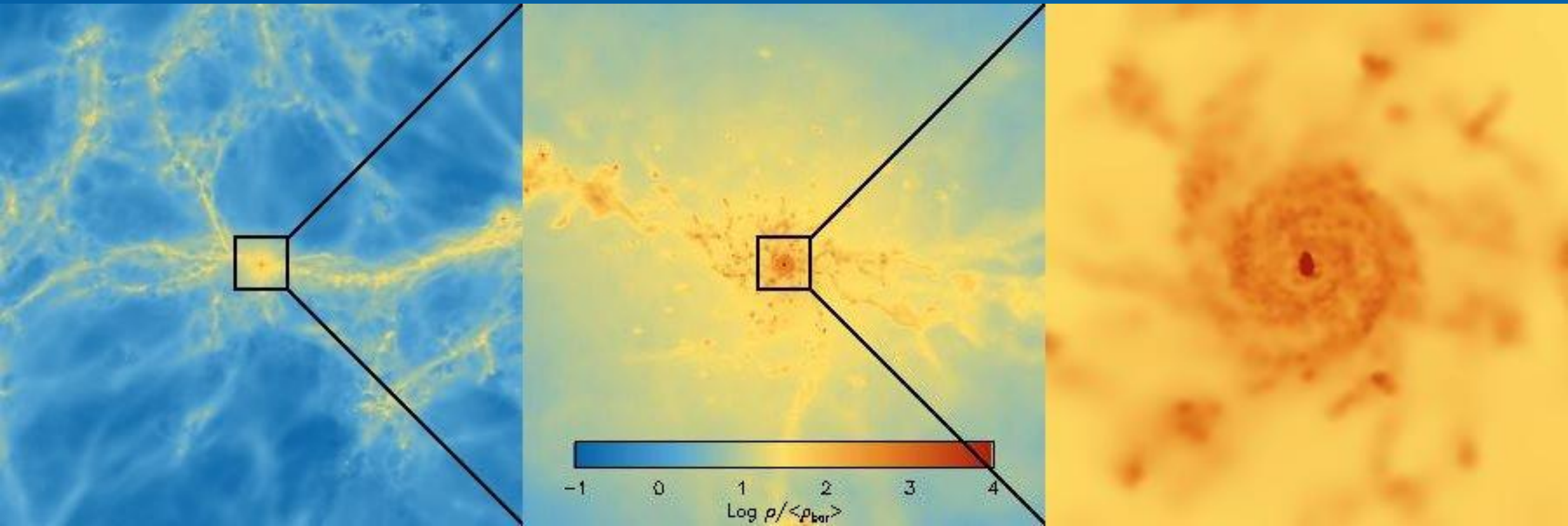
Cosmological SPH simulations of the formation and evolution of galaxies

Joop Schaye et al. (Leiden)
(Yope Shea)



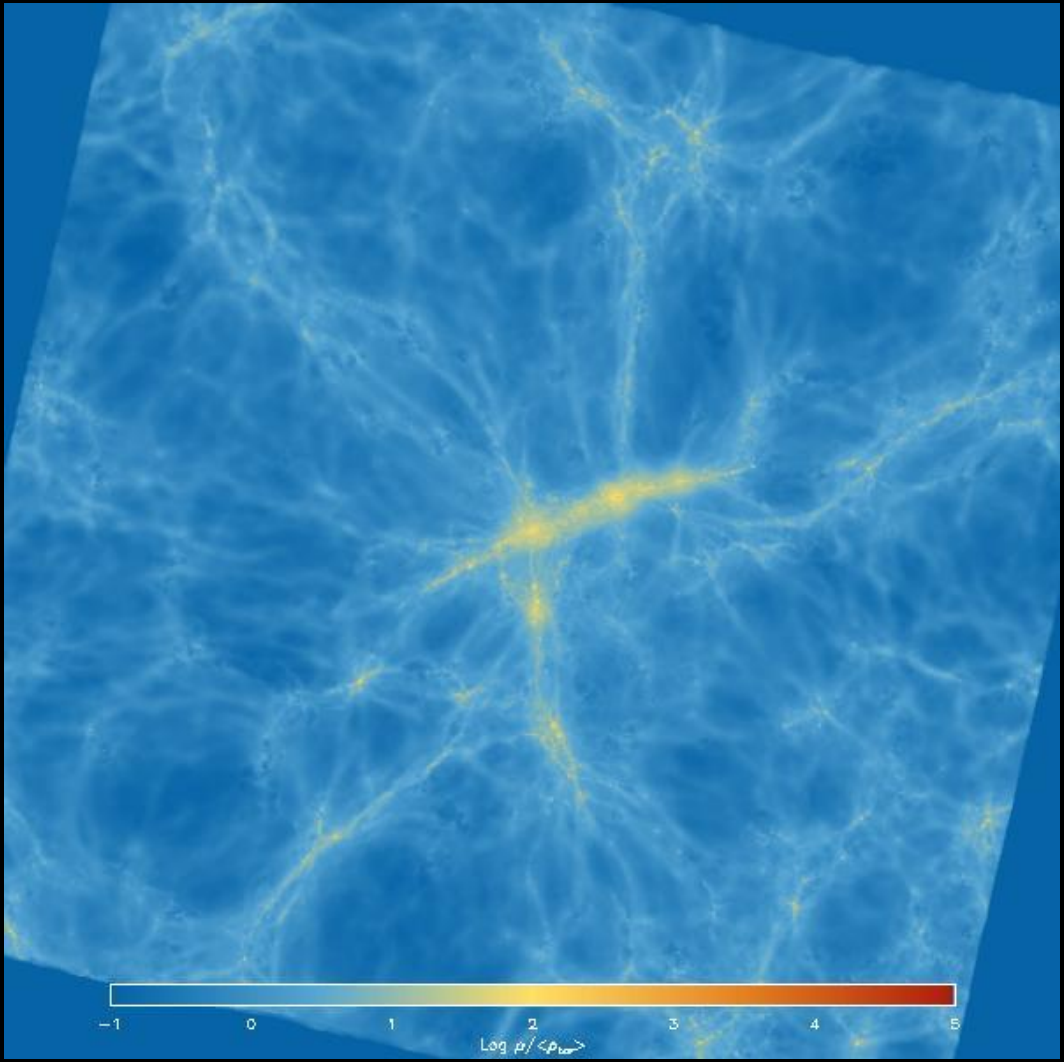




Cosmological hydro simulations

- 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, …)
- Scales ~< 10^3 pc to ~ 10^2 Mpc
- Sub-grid modules are a crucial part of the game

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:
REF
L025
N512

Basic resolution requirements

- Convergence requires resolving the Jeans scales:

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

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

- Modeling the cold ISM is still too demanding
- Transition from warm ($T \sim 10^4$ K) to cold ($T \ll 10^4$ K) ISM expected at $n_H \sim 10^{-2} - 10^{-1}$ cm^{-3}, with some metallicity dependence (JS 2004)
- Well-posed challenge:

  Resolve the Jeans scales down to the warm ISM

→ Need particle mass $\ll 10^7$ $M_\odot$

→ Need spatial resolution $\ll$ 1 kpc

Subgrid models for cosmological hydro simulations

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

Subgrid models: radiative cooling

- Standard assumptions:
  - Collisional ionization equilibrium
  - Solar relative abundances
- Recent developments (e.g. Wiersma, JS & Smith 2009):
  - UV background (optically thin limit)
  - Element-by-element cooling
- Future:
  - Non-equilibrium ionization
  - Full radiative transfer
  - Local radiation sources
  - Dust cooling
- Main limitation: uncertain elemental abundances

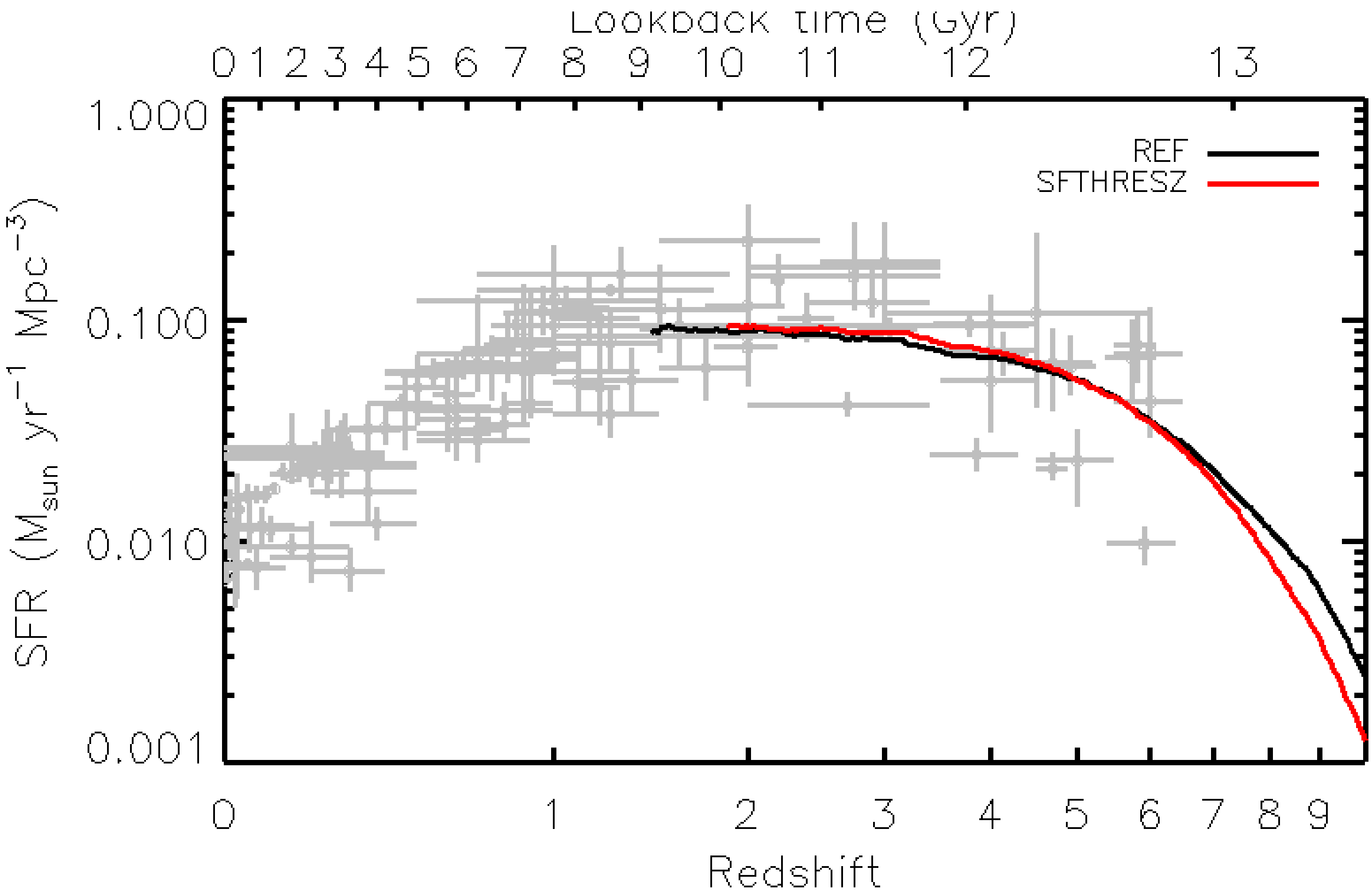
Sub-grid models: star formation

- Standard approach:
  - Schmidt volume density law with threshold $(\dot{\rho}_* \propto \rho^m)$
  - Parameters tuned to match observed Kennicutt-Schmidt surface density law $(\dot{\Sigma}_* \propto \Sigma_g^n)$
  - Stochastic implementation
  - Power-law EoS for gas above SF threshold
- Recent developments:
  - Pressure laws allow direct implementation of observed surface density laws (JS & Dalla Vecchia 2008)
  - Zoomed simulations:
    - Higher thresholds
    - Cold ISM physics
- Thanks to self-regulation, star formation rates are insensitive to the SF law (e.g. JS+ 2010, Hopkins+ 2011)

Metallicity-dependent SF

- Stars form from cold (molecular) gas (need small Jeans scale)
- Critical column required for transition from warm to cold gas depends on metallicity (dust shielding) (JS 2004; Krumholz+ 2009, 2011)
- Metallicity-dependent SF law could reduce SF efficiency in low-mass galaxies, particularly at high redshift (e.g. Gnedin & Kravtsov 2011; Feldmann+ 2011; Kuhlen+ 2011; Krumholz & Dekel 2011)

A metallicity-dependent SF law in OWLS



JS et al. (2010)

Metallicity-dependent SF

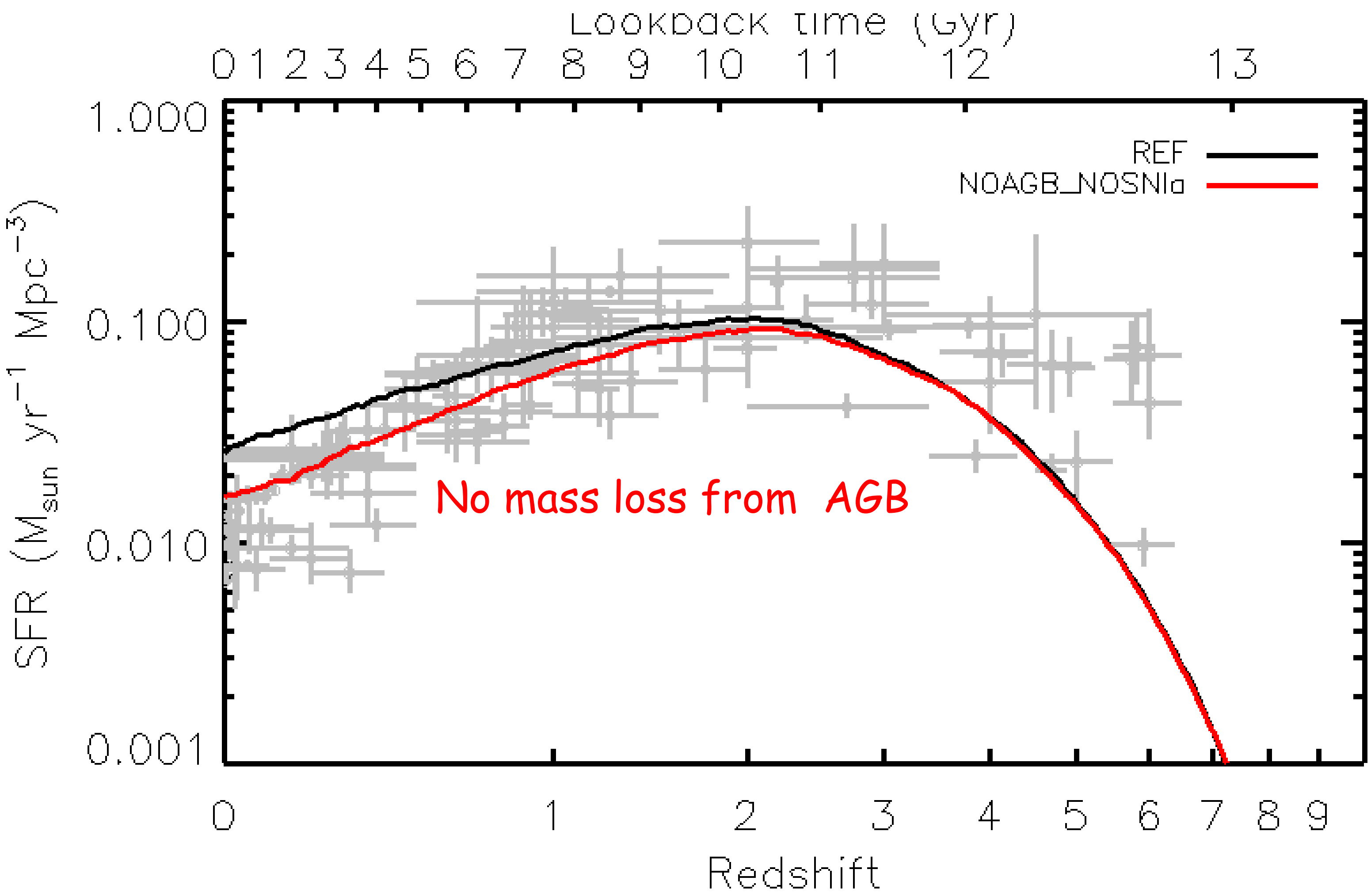
- OWLS predicts only a minor metallicity effect, also for fixed galaxy mass.
- SF in galaxies is self-regulating
  - Infall set by environment and redshift
  - SFR adjusts such that outflows balance infall

  → Higher (lower) SF efficiency → less (more) dense gas, but same SFR
- As a result of self-regulation, the SF law controls amount of high-density gas rather than the SFR

Subgrid models: chemodynamics

- Standard assumptions:
  - Solar relative abundances
  - Instantaneous recycling
- Recent developments (e.g. Wiersma, JS, et al. 2009):
  - SNII, SNIa and stellar mass loss
  - Individual elements tracked and used for cooling
- Main limitations:
  - Metal mixing unresolved
  - Nucleosynthetic yields highly uncertain
  - SNIa rates highly uncertain
  - IMF uncertain

Mass loss from AGB stars fuels SF

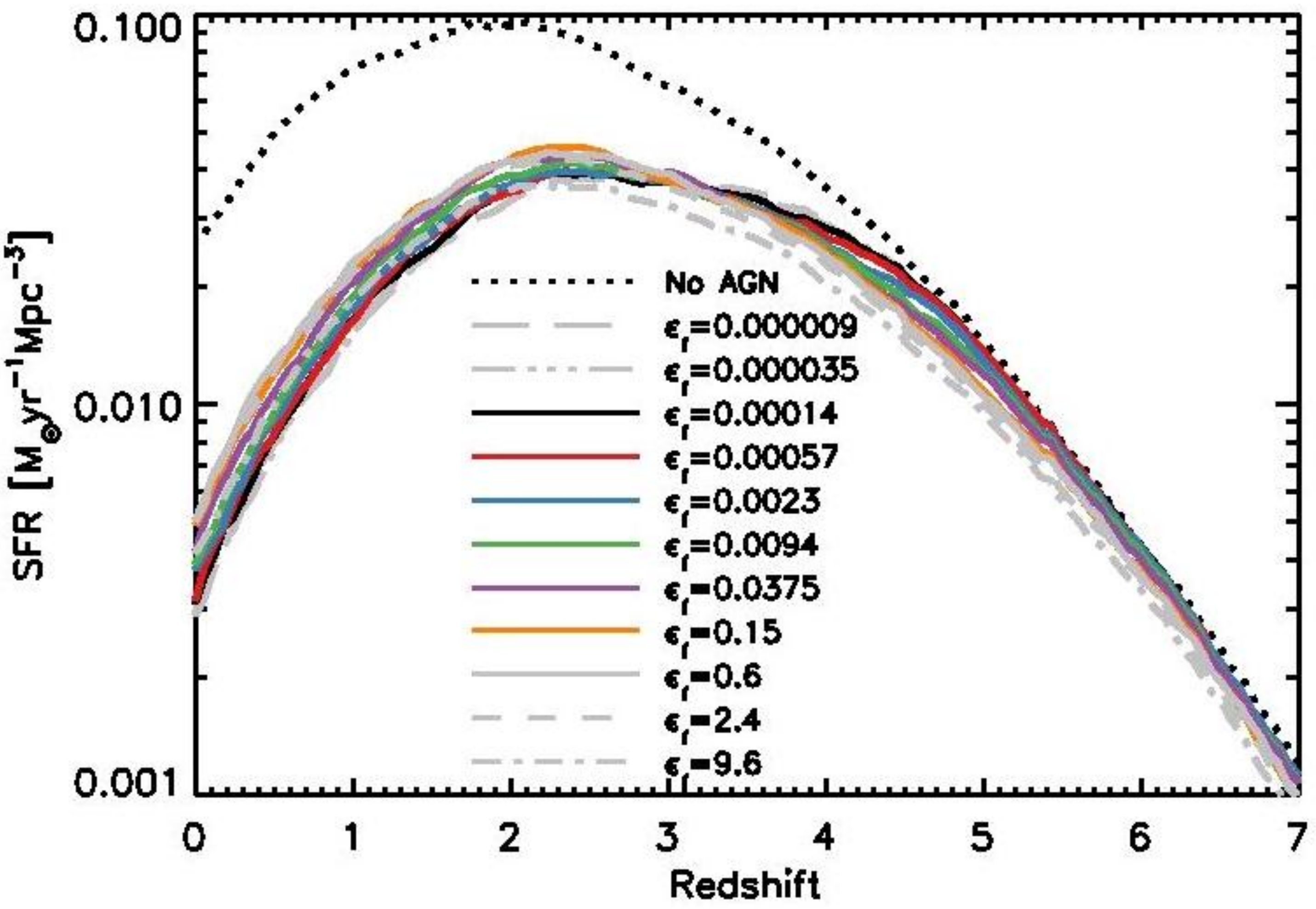


JS et al. (2010)

Subgrid models: supermassive black holes

- Standard approach (Springel+ 2005):
  - Massive seed BHs (~ 10^5 $M_\odot$)
  - Eddington-limited Bondi-Hoyle accretion times huge fudge factor (~ 10^2)
  - BHs pinned to bottom of potential well
  - Nearby, bound BHs merge
  - Local, thermal/kinetic feedback, efficiency ~ 1 %
  - Feedback efficiency tuned to reproduce normalization of local BH scaling relations, sets BH masses
- Recent developments: BH spin, more physical accretion models, recoils
- Main limitations:
  - Small length/time scales relevant for AGN variability unresolved
  - Mass scale above which AGN feedback becomes efficient determined by resolution and subgrid parameters
  - "Radio-mode" absent/poorly resolved
- Thanks to self-regulation, AGN feedback insensitive to accretion model and assumed efficiency (e.g. Booth & JS 2009, 2010)

Varying the efficiency of AGN feedback



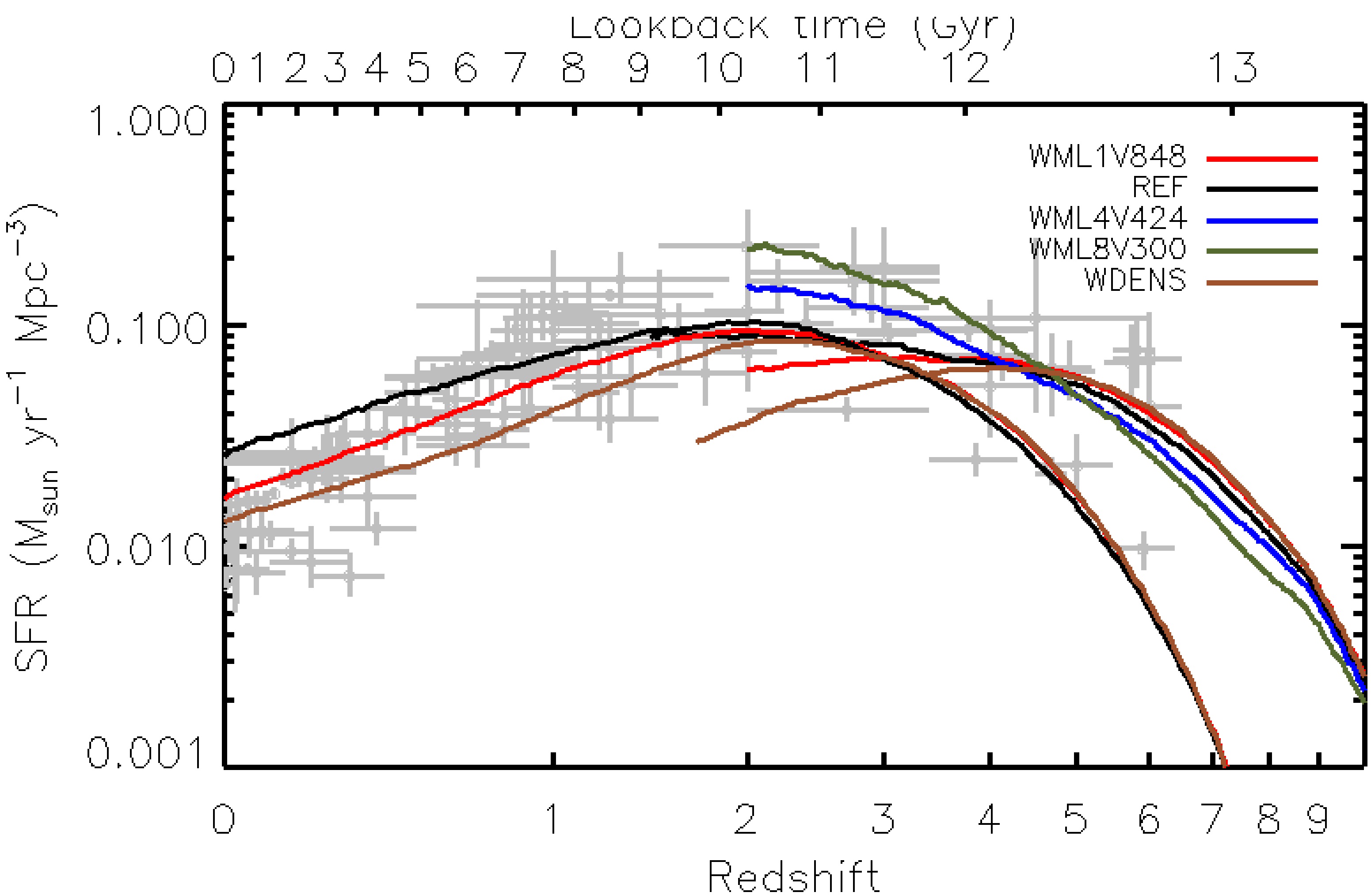
Self-regulation on scale of DM haloes! (Booth & JS 2010, 2011)

Booth & JS (2009)

Subgrid models: Galactic winds

- Standard approach
  - Most of the SNII energy injected in ISM
  - Cooling catastrophe avoided by:
    - Injecting kinetic energy
      - Initial mass loading
      - Initial velocity
    - Temporarily ignoring drag on wind particles (Springel & Hernquist 2003; see Dalla Vecchia & JS 2008 for discussion)
    - Temporarily turning off cooling
    - Very high resolution (zooms)
- Recent developments
  - "Momentum-driven" winds, but it now seems radiation pressure on dust is insufficient
  - Halo-dependent parameters: large mass loading in low-mass haloes, high velocities in high-mass haloes (e.g. Oppenheimer & Dave 2008)
- Main issues
  - Large amount of freedom has very important consequences
  - Poor observational constraints

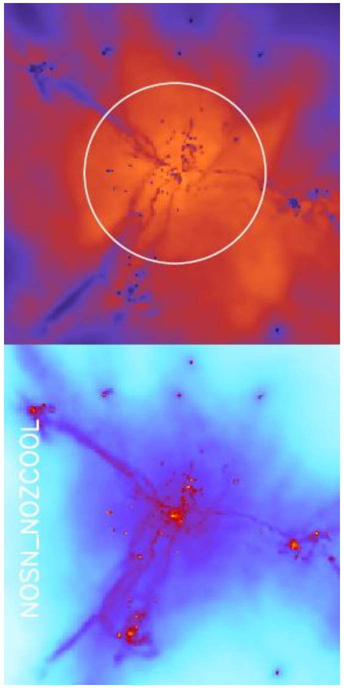
Varying the winds: constant energy



JS et al. (2010)

Cold streams in hot haloes: varying the feedback

No FB

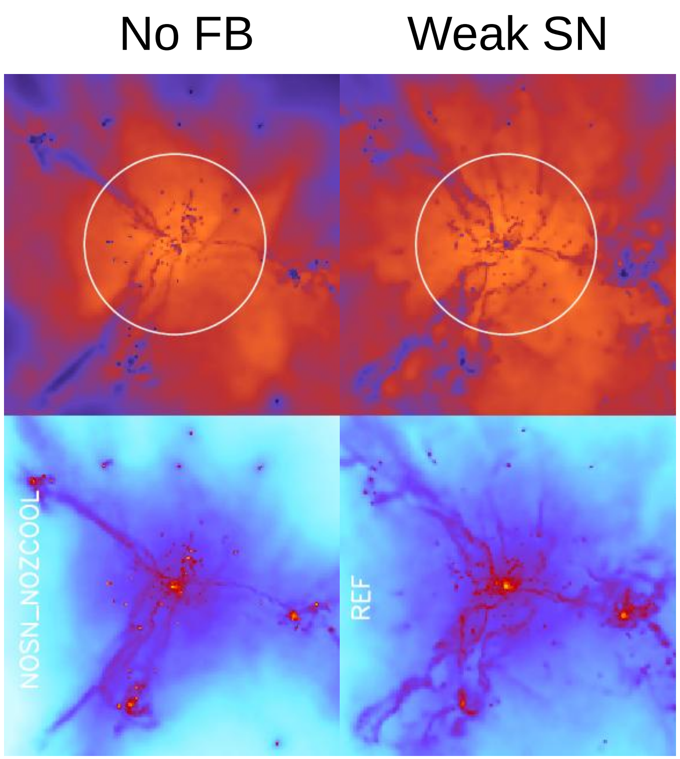


$$M_{\text{halo}} = 10^{12}\ \mathrm{M}_{\odot}$$

$$z = 2$$

Van de Voort, JS et al. (2011a)

Cold streams in hot haloes: varying the feedback



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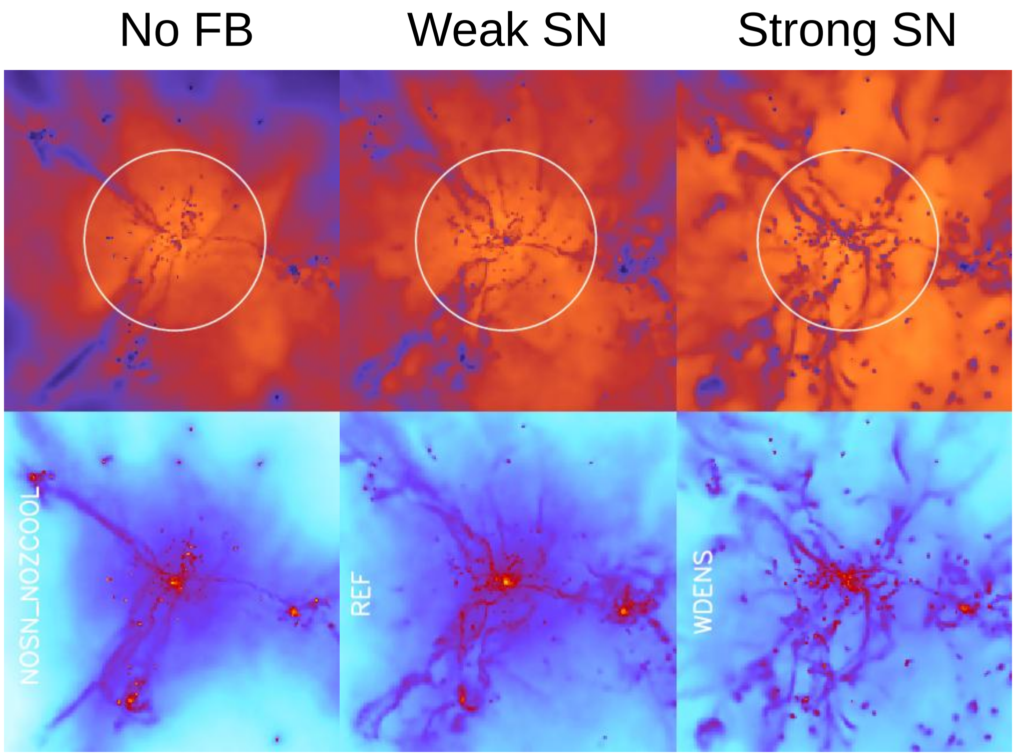

Same amount of SN energy

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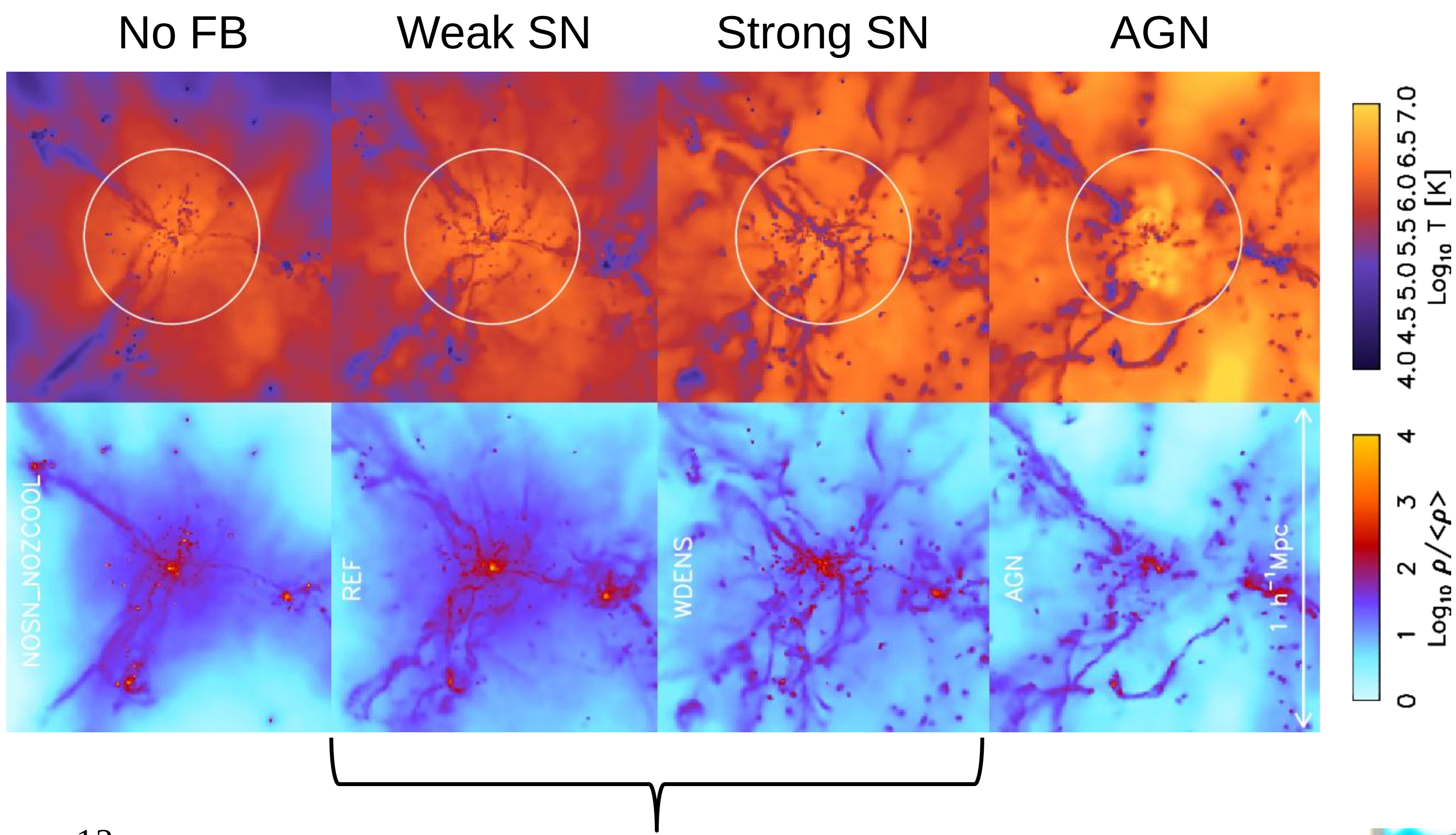

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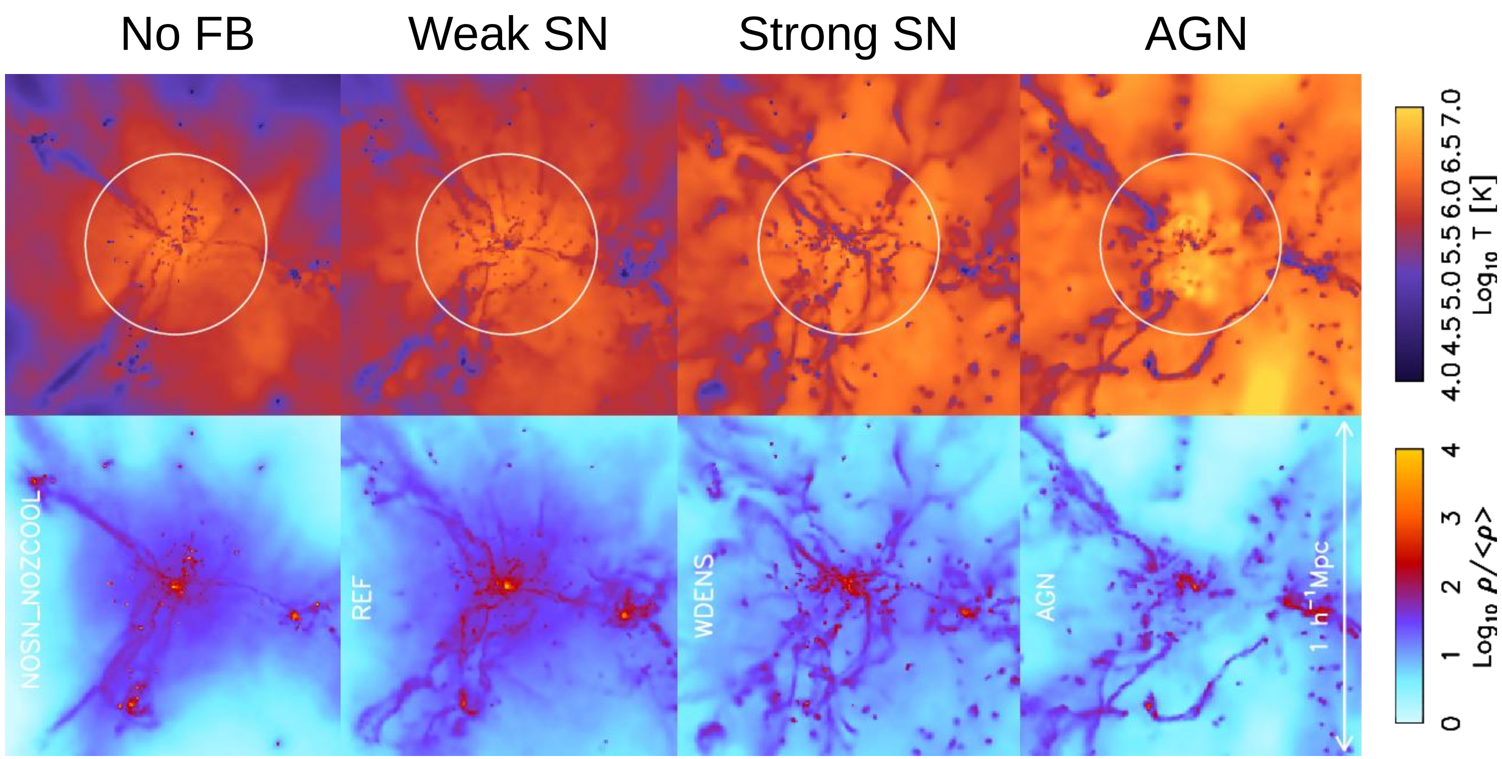
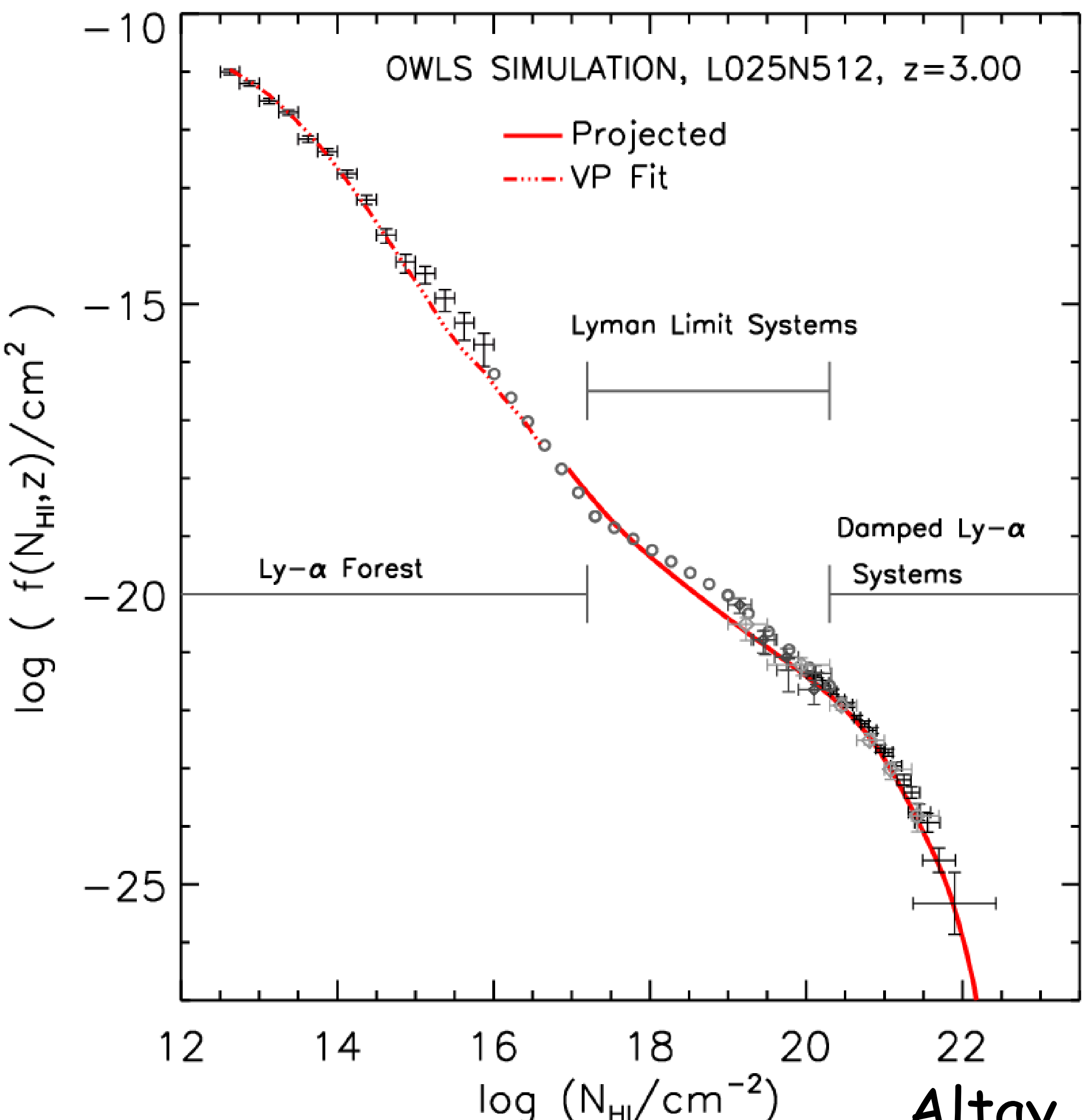


Used for studies of gas accretion

Reproduces z=0 groups

Van de Voort, JS et al. (2011a)

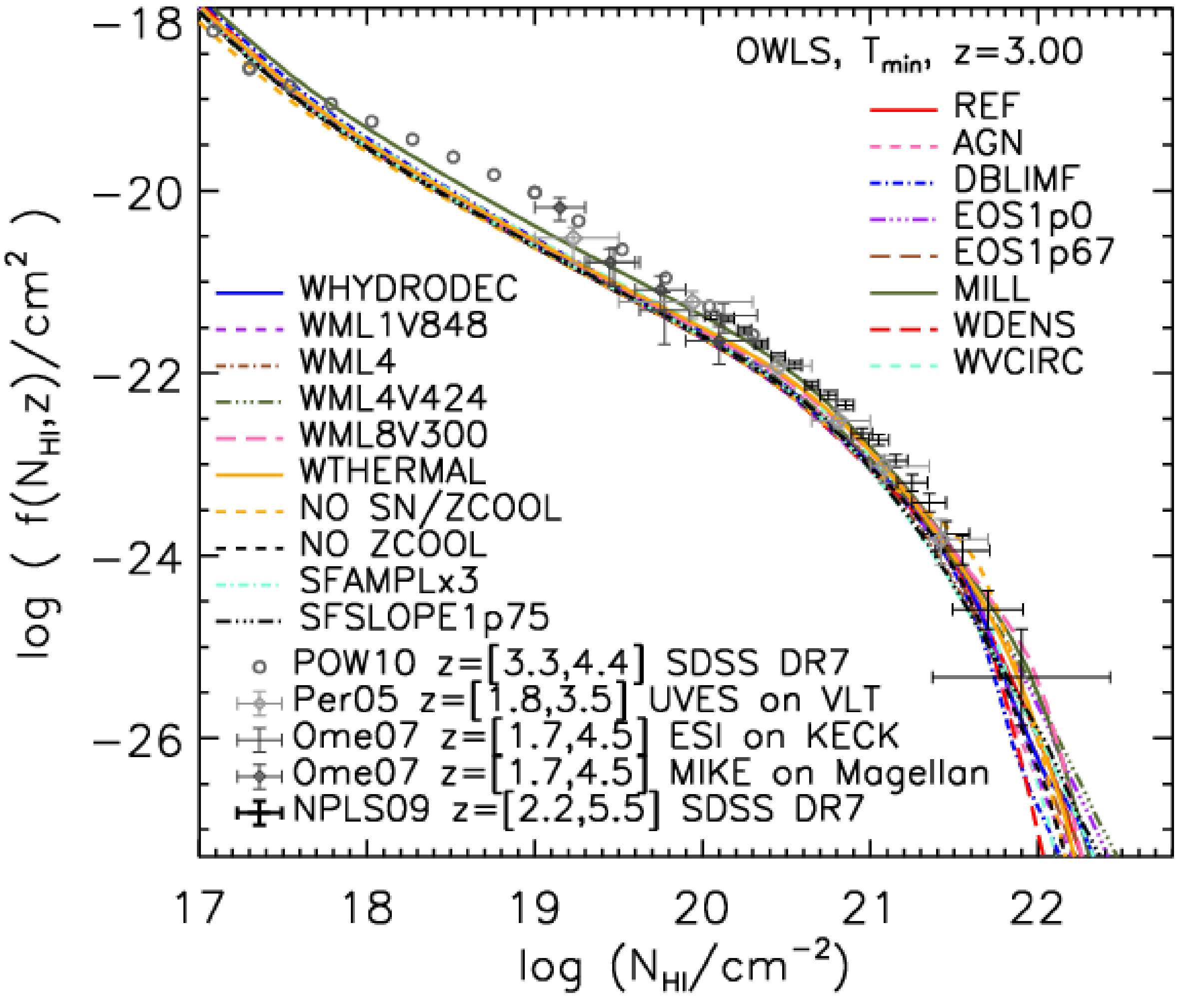
HI column density distribution at z=3



Amazing agreement!

Altay, Theuns, JS et al. (2011)

Effect of subgrid physics



Very robust!

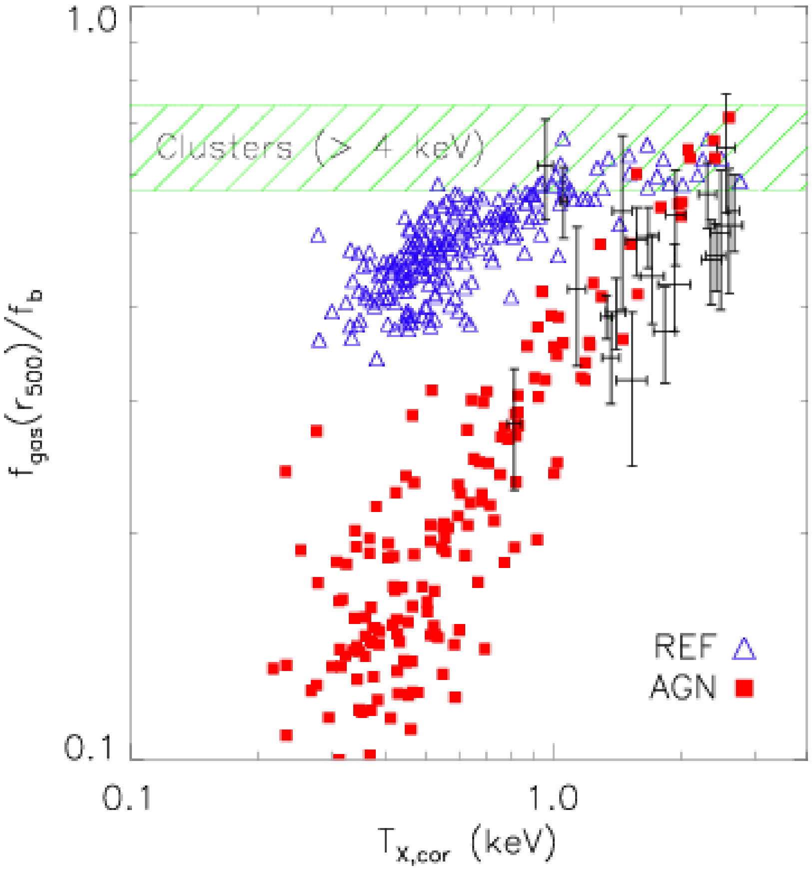
Altay et al. (in prep)

Why your cosmology colleagues should have been at this meeting

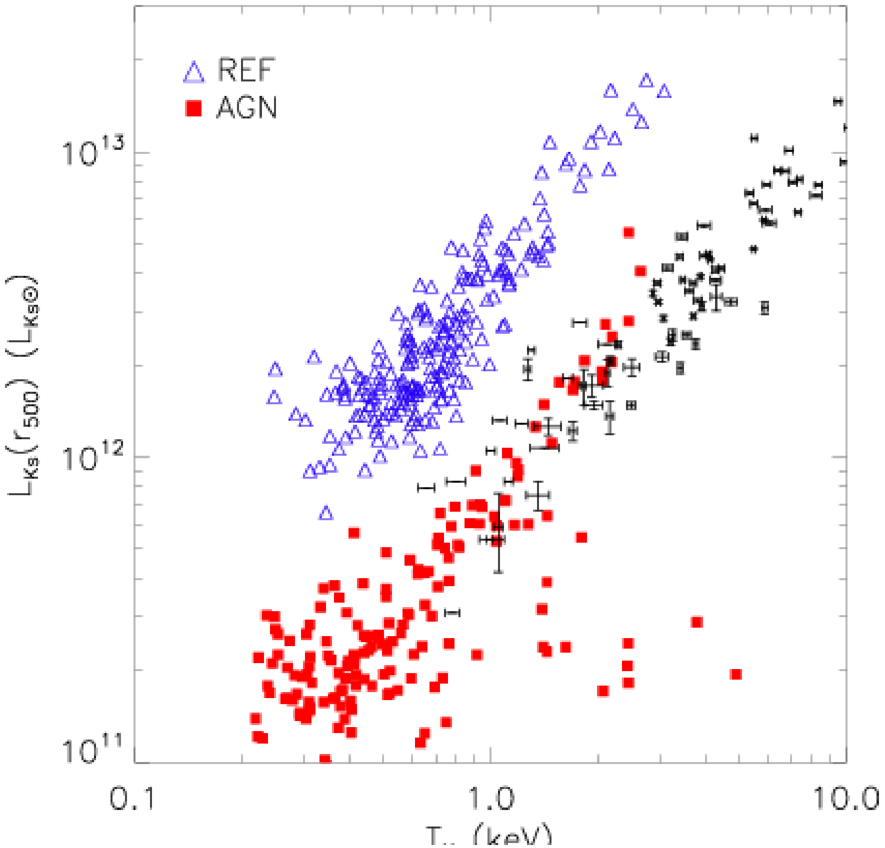
- Baryons change the large-scale distribution of matter.
- Cosmic shear is the driver for WFIRST and EUCLID.
- Previous work (e.g. Jing et al. 2006; Rudd et al. 2008; Guillet et al. 2009; Cassarini et al. 2010) suffered from overcooling, as is the case for the OWLS REF model.
- Overcooling was thought to be conservative: effect of baryons too strong.

Group gas and stellar contents

Gas fraction



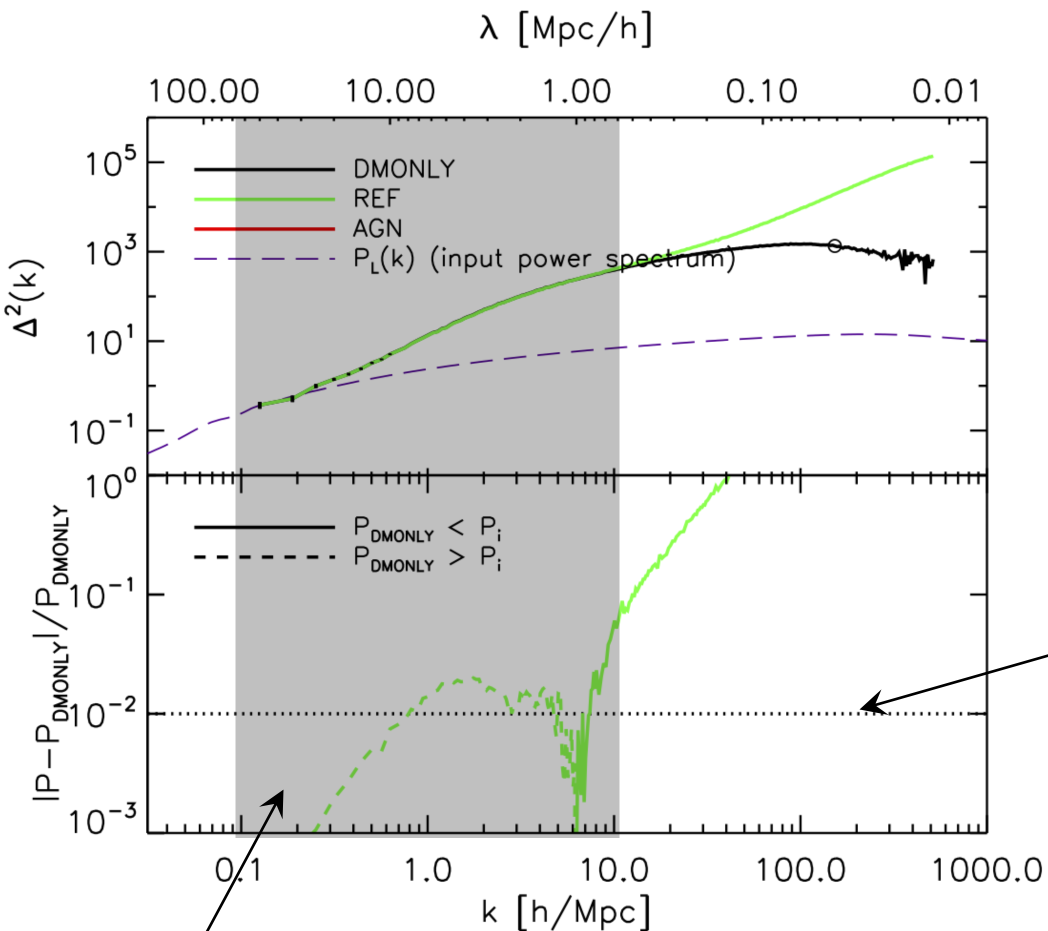
K-band luminosity



McCarthy, JS, et al. (2010)

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

Baryons and the matter power spectrum

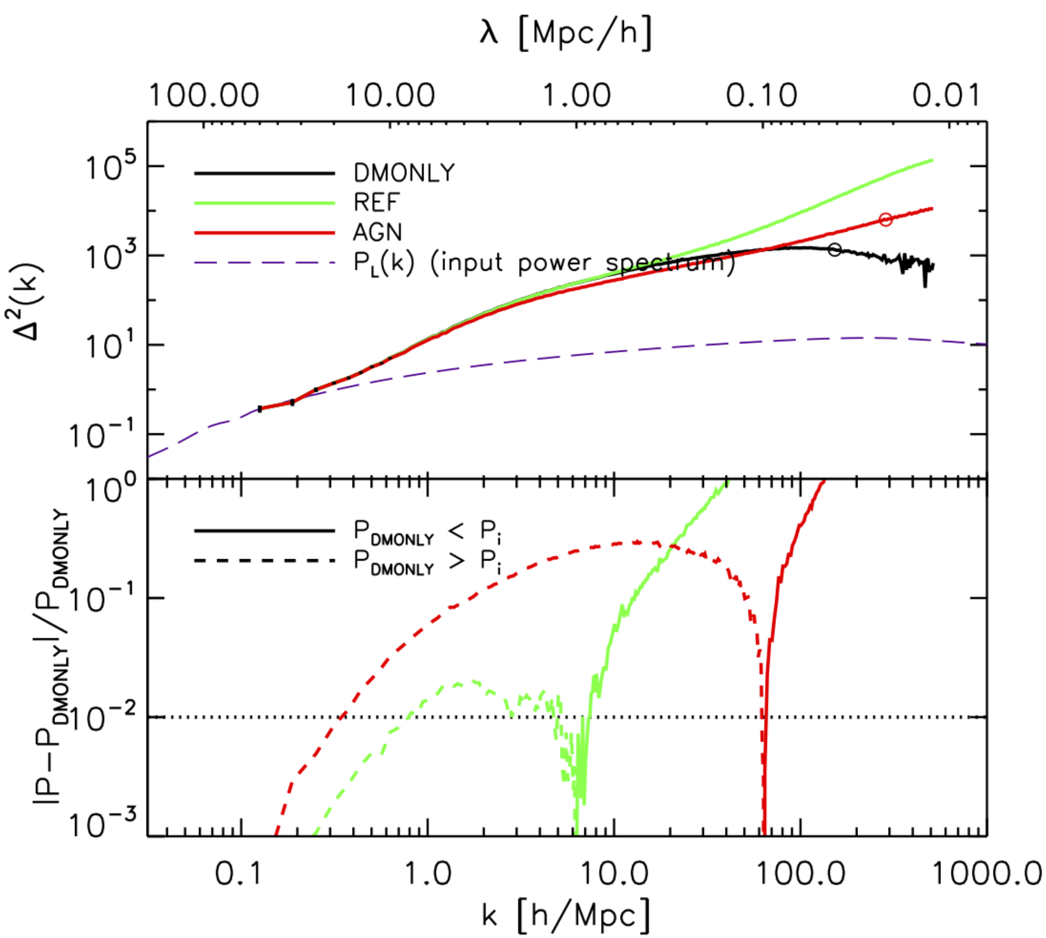


1% difference wrt dark matter only

Range of interest for cosmic shear

Van Daalen, JS, et al. (2011)

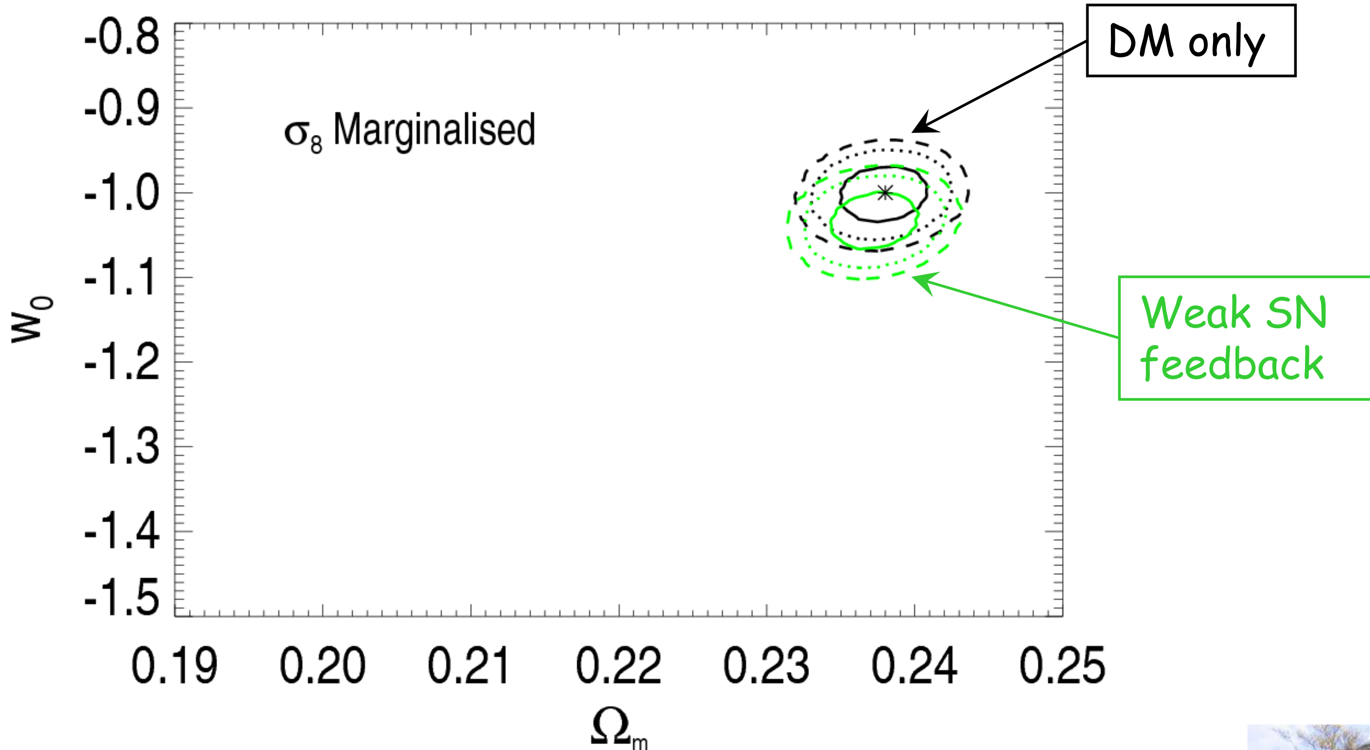
Baryons and the matter power spectrum



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

Van Daalen, JS, et al. (2011)

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



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

Semboloni, Hoekstra, JS, van Daalen, McCarthy (2011)

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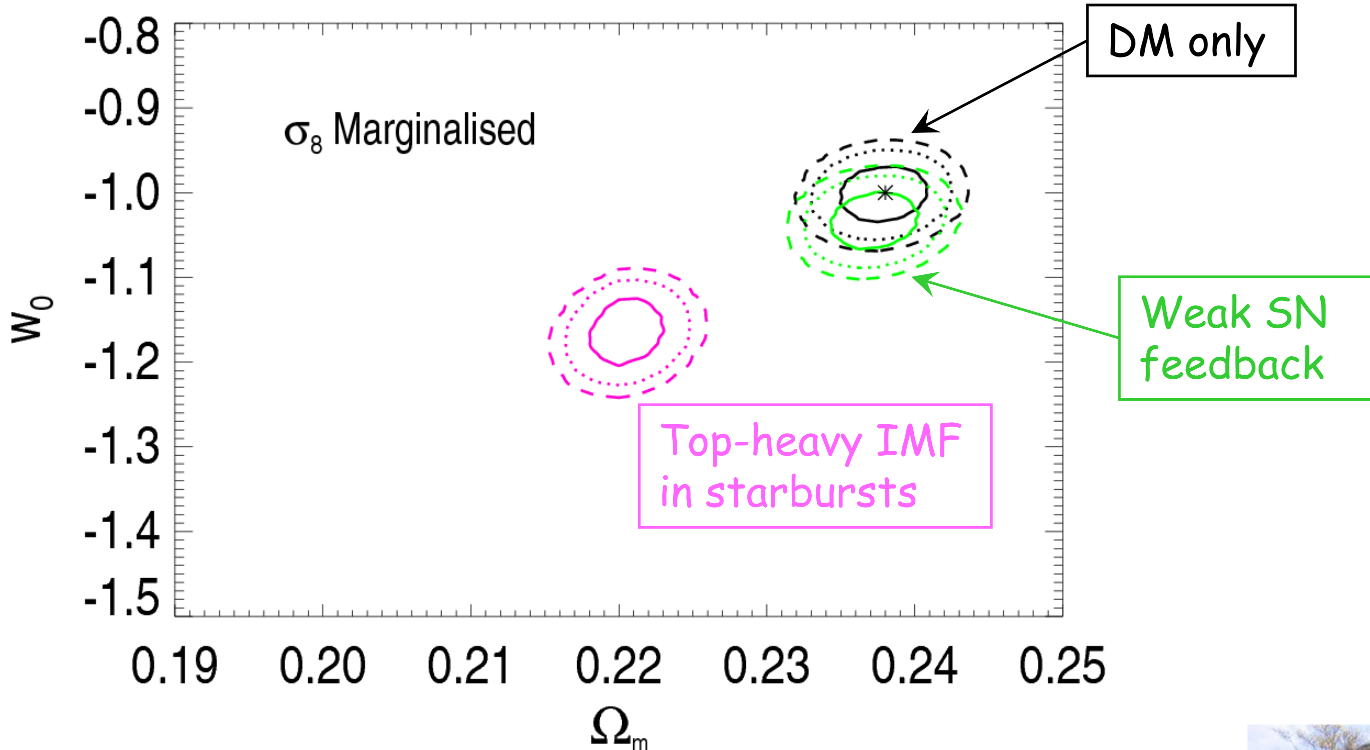

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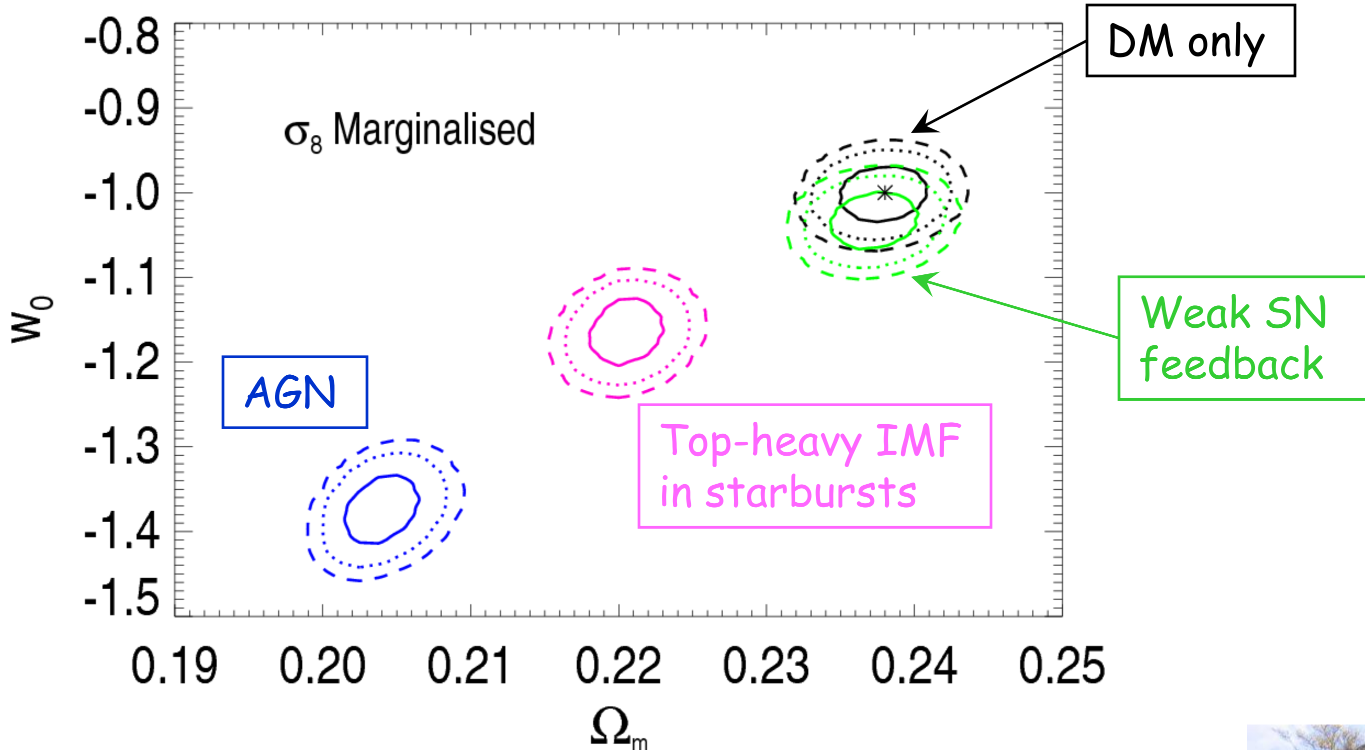

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Semboloni, Hoekstra, JS, van Daalen, McCarthy (2011)

Cosmological hydro: Status

- Predictions for stellar properties and for ISM/CGM are currently limited by subgrid physics, particularly galactic winds
  - → Need to be careful about what questions to ask
  - → SPH vs AMR secondary issue
  - → Much to be gained from:
    - Higher resolution
    - Fitting feedback to match obs. population stats
    - Observations of gas around galaxies
- Predictions for intergalactic gas are more robust and limited by "real" physics, e.g. radiative transfer.
- Cosmology on scales ~< 10 Mpc limited by galaxy formation → challenge and opportunities