The Eagle HI Universe

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

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The study of cosmic gas is assuming an ever greater role in extragalactic astronomy

< 10% of today's baryons are in stars

Gas traces a broad range of physical conditions, and encodes much information

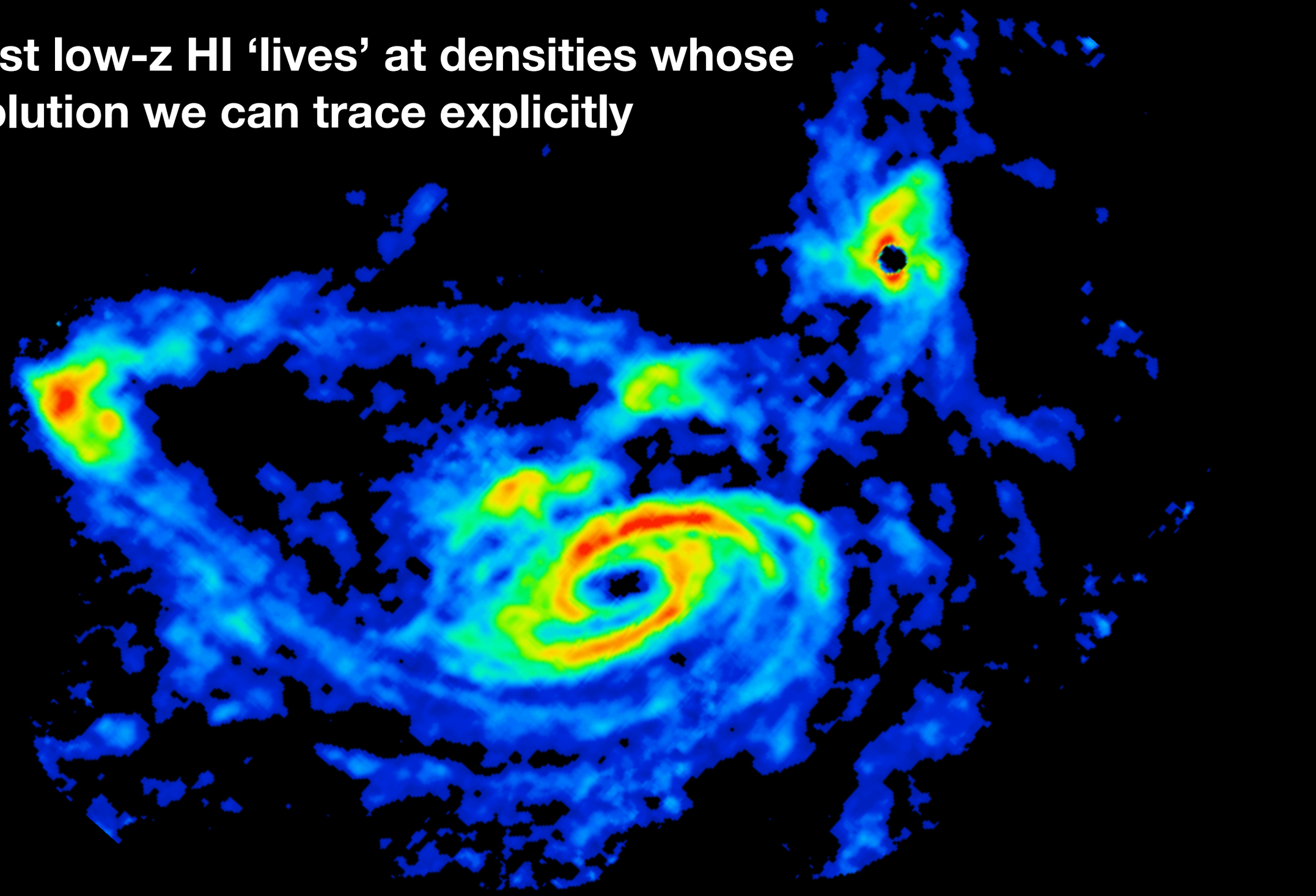
Realising the full potential of these richer data demands a commensurate increase in the complexity of our models.

In short, this means:

1) appealing to subgrid schemes on scales motivated by physics, not computational convenience

This structure is missed by semi-analytic models, yet we can readily follow the relevant equations.

Most low-z HI ‘lives’ at densities whose evolution we can trace explicitly



Yun+ (1994)

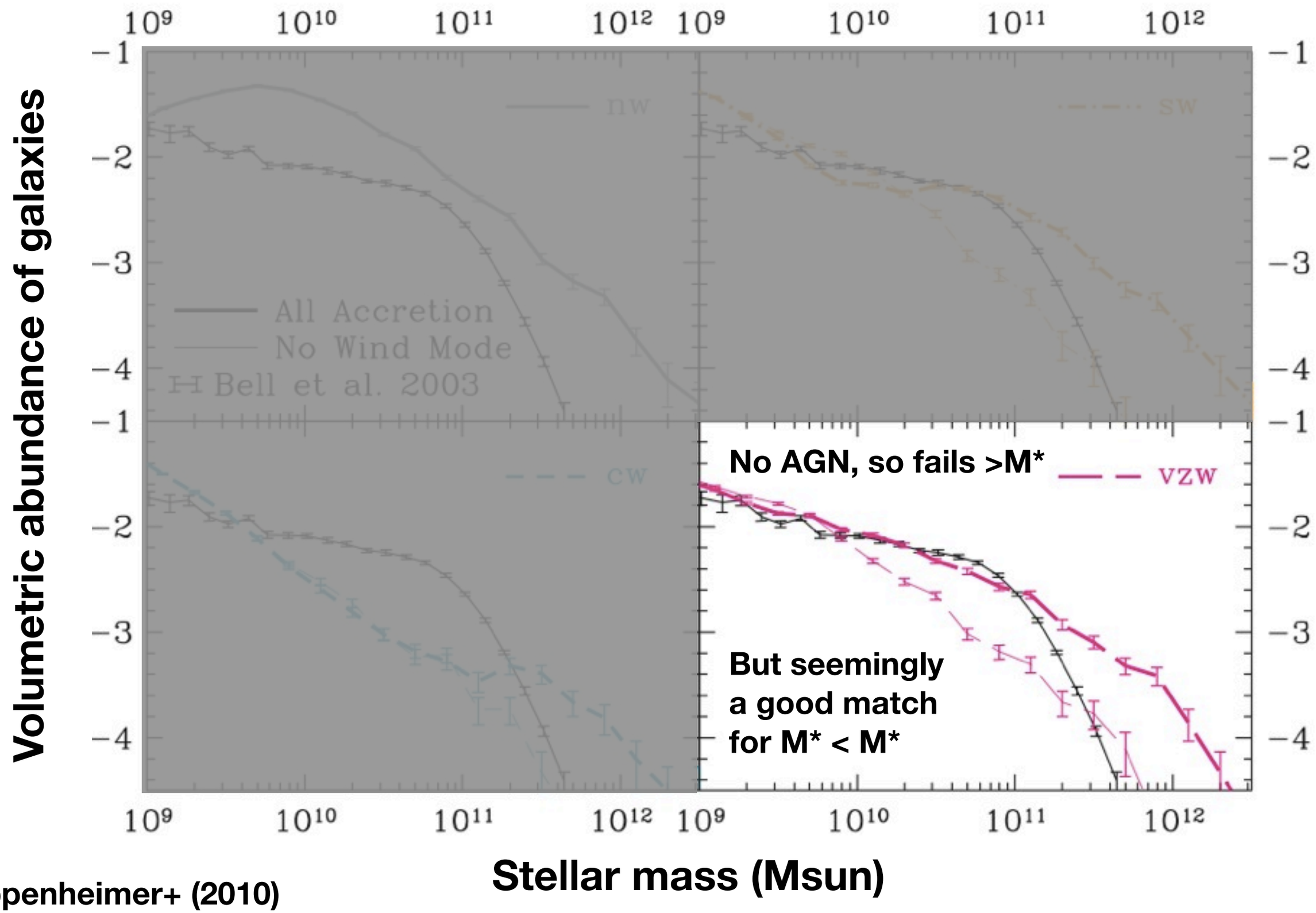
Realising the full potential of these richer data demands a commensurate increase in the complexity of our models.

In short, this means:

1) appealing to subgrid schemes on scales motivated by physics, not computational convenience

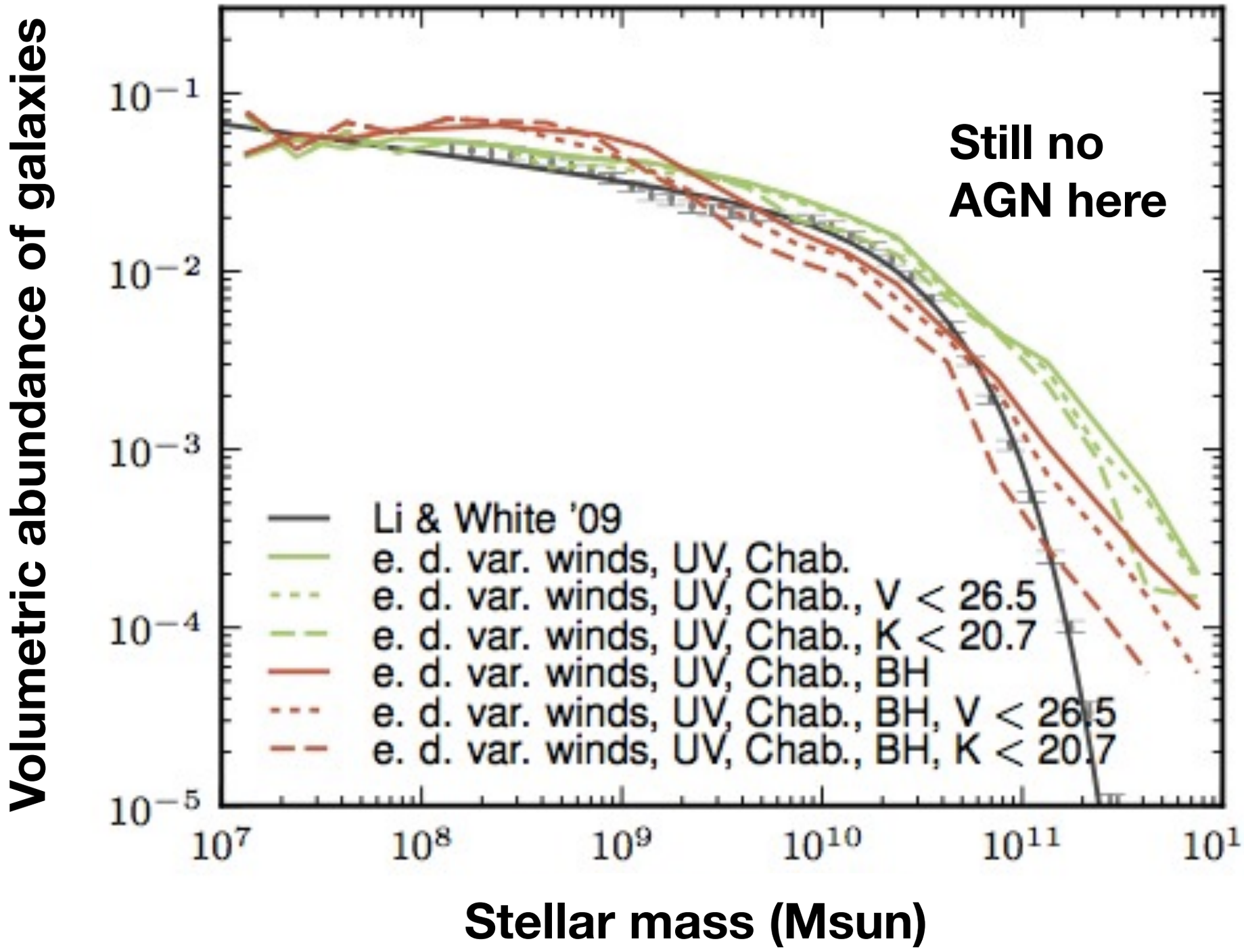
2) calibrating subgrid physics against measurements to ensure macroscopic results are meaningful

The galaxy stellar MF in ‘hydro’ runs



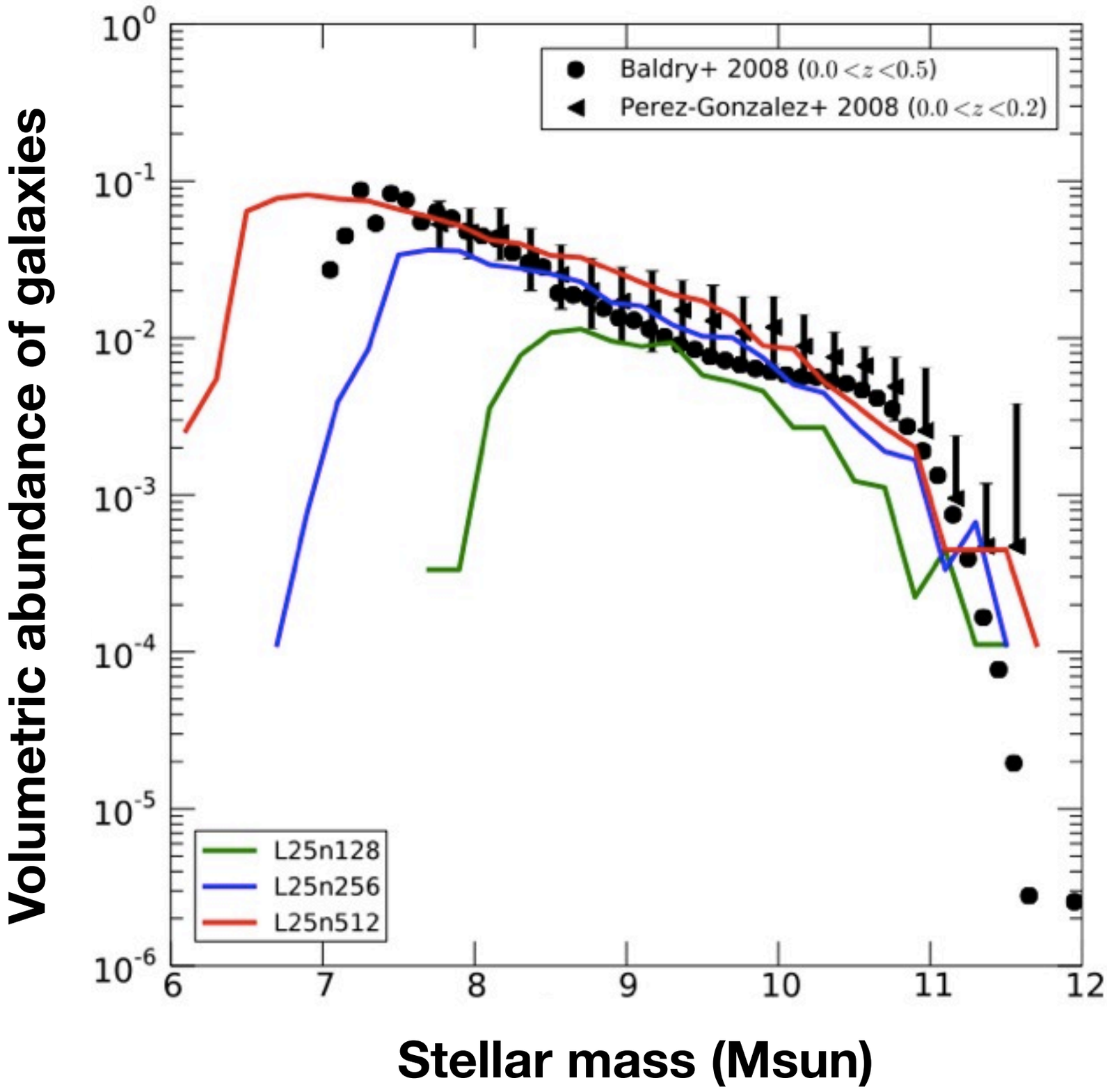
Oppenheimer+ (2010)

Corroborated with similar model...



Puchwein & Springel (2012)

...and moving mesh simulations (similar SNe feedback, + AGN)



Vogelsberger et al. (2013)

Realising the full potential of these richer data demands a commensurate increase in the complexity of our models.

In short, this means:

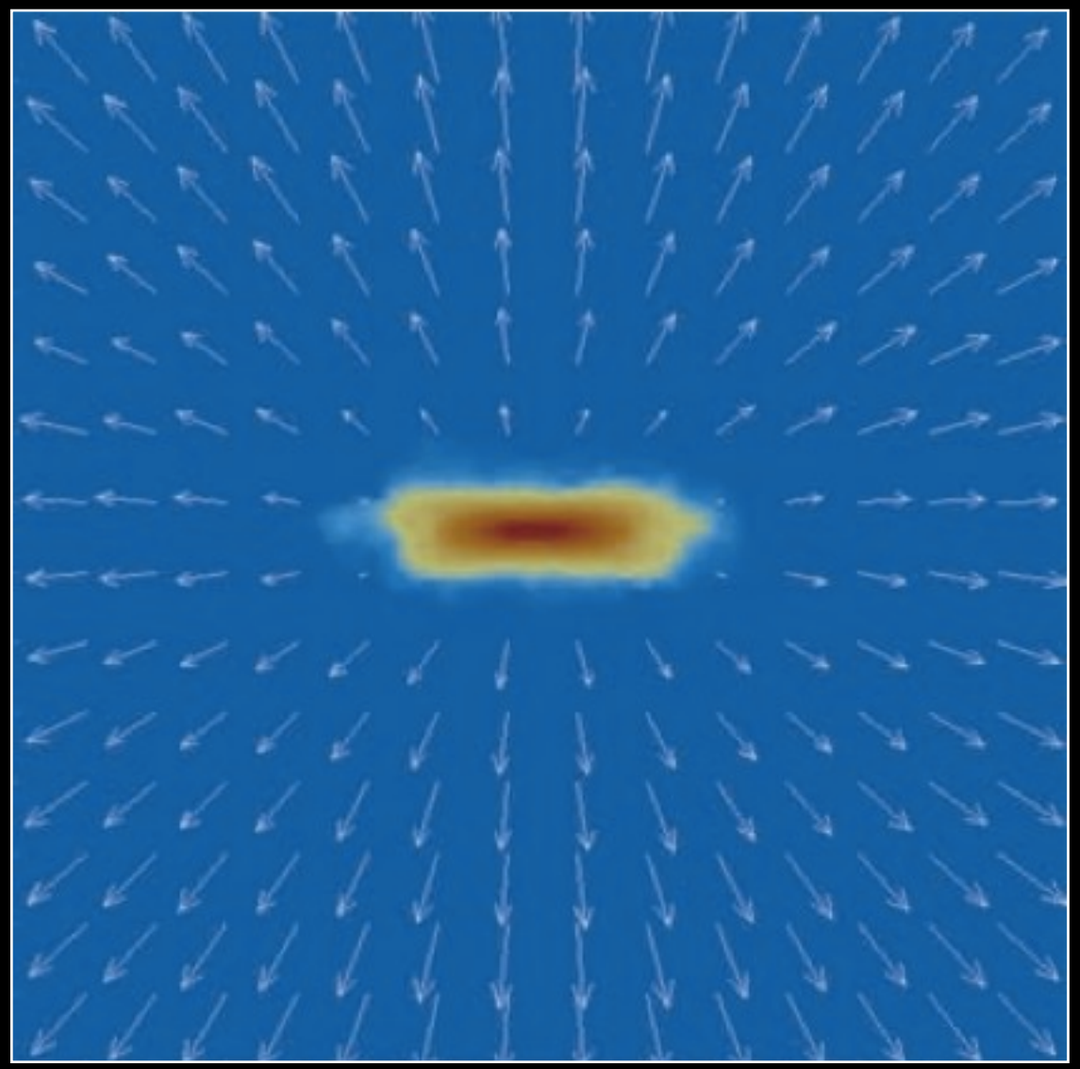
1) switching to subgrid schemes on scales motivated by physics, not computational convenience

2) calibrating subgrid physics against measurements to ensure macroscopic results are meaningful

3) avoiding unphysical treatments wherever possible

Surface density projection of edge-on dwarf galaxy

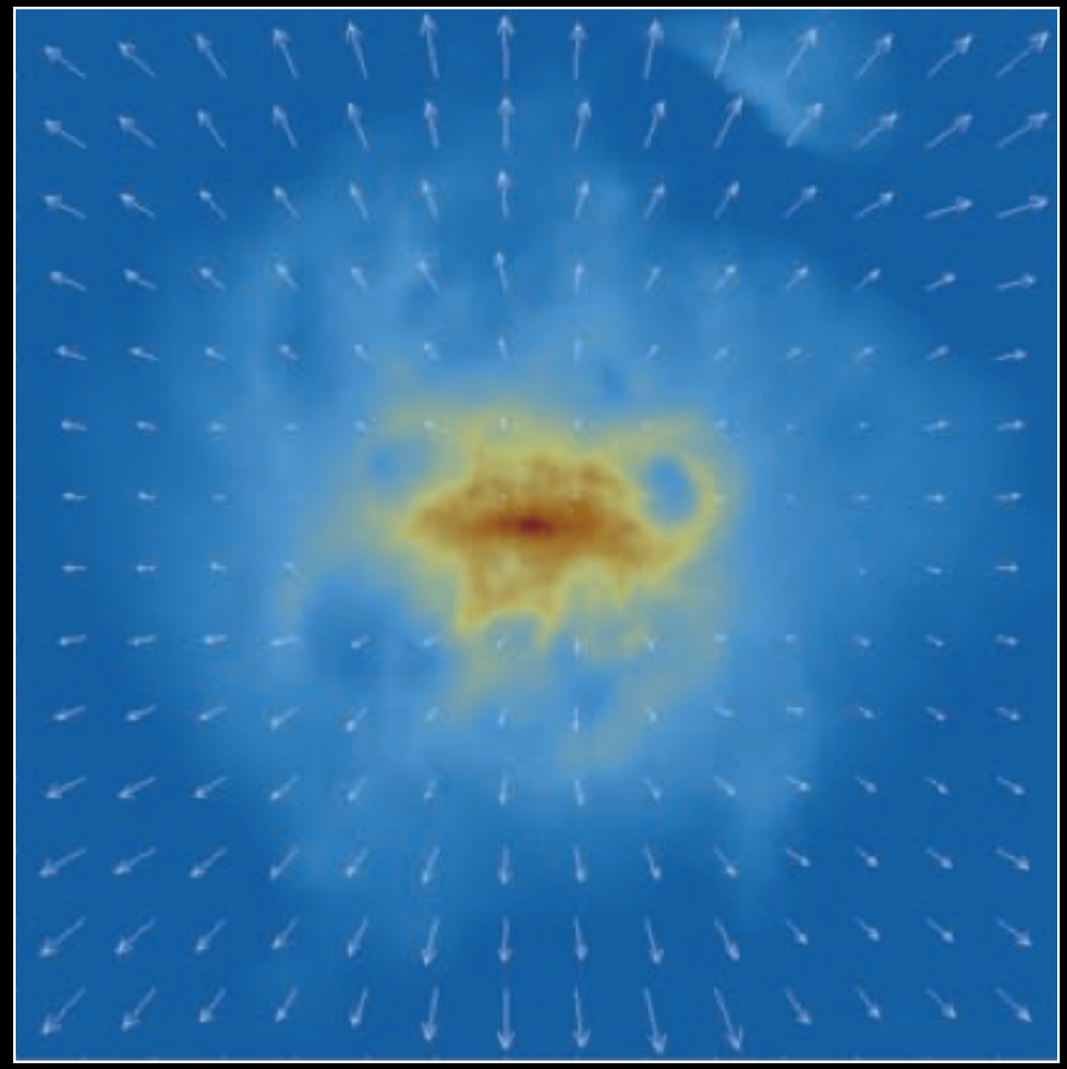
Hydro-decoupled winds



Offer precise control

Eases convergence criteria

Fully coupled winds



Better reflection of Nature...

Yields *prediction* of v_w, loading

Surface density projection of edge-on dwarf galaxy

Calibrated winds are the defining feature of ‘successful’ simulations.

Hydro decoupled winds

Fully coupled winds

...in the examples just shown, the winds were **decoupled** and scaled from **halo** properties.

- We can be confident that calibration of the feedback will yield an **accurate** mass function

- Next step is to achieve this without appealing to **unphysical** numerical aids, nor scaling from ‘**disconnected**’ quantities.

Dalla Vecchia & Schaye (2008)

Curie Tier-0 facility

Run by French atomic energy agency (CEA)

- 10,080 Intel SandyBridge processors
  ➡ 80,640 cores, peak 1.6Pflops, 2.2MW
- 315TB memory
- 5PB scratch storage
- 20PB archival storage
- 15th on TOP500 (June 2013)

PRACE 6th call

- Awarded 40 million core-hours

+ 2PB storage allocation at SARA, NL.

The Eagle Simulations

Evolution and **A**ssembly of **G**a**L**axies and their **E**nvironments

Hydrodynamical simulations of galaxy populations and the CGM/IGM, adopting the 1st-year Planck cosmogony:

➡ **Minimum resolution set by requirement that Jeans instability is well-resolved in the warm ISM.**

m_{gas} = 10^6 M_{sun} (int. res), 1.25×10^5 M_{sun} (high res)

➡ **Minimum volume set by requirement that galaxy stellar mass function is sampled beyond *L**.**

L ranges from 25 Mpc to 100 Mpc

Three key aspects...

1) **Eagle incorporates several updates that mitigate key shortcomings of SPH.**

➡ Generalised SPH, new kernels, improved shock detection, time-step limiting. Only latter significant at this resolution.

2) **The efficiency of SN+AGN feedback is calibrated to yield a broad match to the z~0 stellar mass function*.**

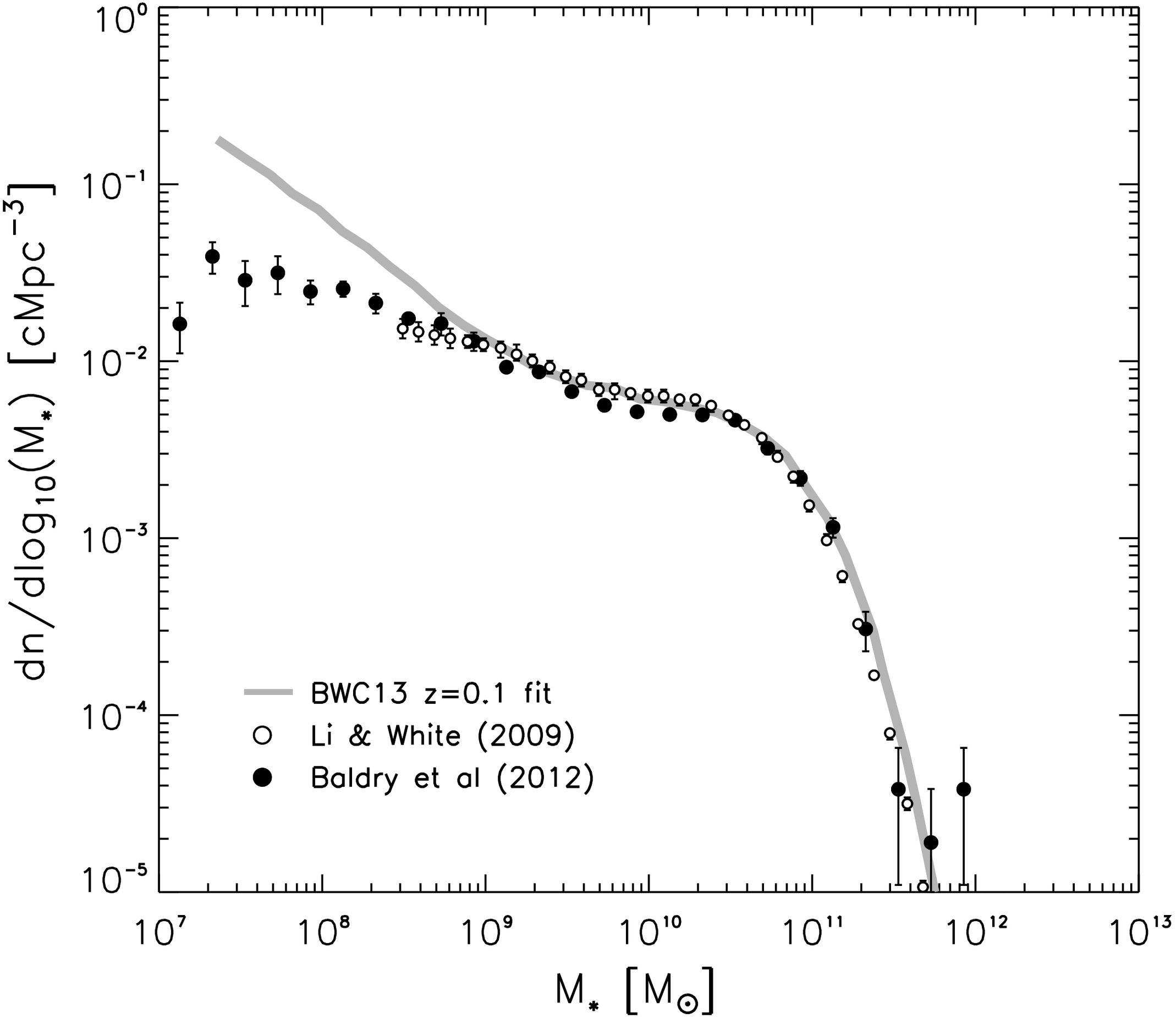
* Not a scientific aim, but a condition of playing the game!

3) **Eagle philosophy: scalings of processes only driven by localised, physically related quantities**.**

** The ISM doesn't know 'what redshift it is', or what its host halo's mass or velocity dispersion is.

Please see movie here:

http://home.strw.leidenuniv.nl/~crain/wordpress/wp-content/uploads/eagle_volume_rhoT.avi


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$dn/dlog_{10}(M_*)$ [cMpc^{-3}]
BWC13 z=0.1 fit
Li & White (2009)
Baldry et al (2012)
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
M_* [$M_\odot$]

EAGLE

z = 0.1

BWC13 z=0.1 fit

Li & White (2009)

Baldry et al (2012)

$dn/d\log_{10}(M_*)$ [cMpc^{-3}]

M_* [$M_\odot$]

Modelling HI in “optically thin” simulations

Ali Rahmati (MPA)

Post-process simulations to estimate HI fraction of gas particles.

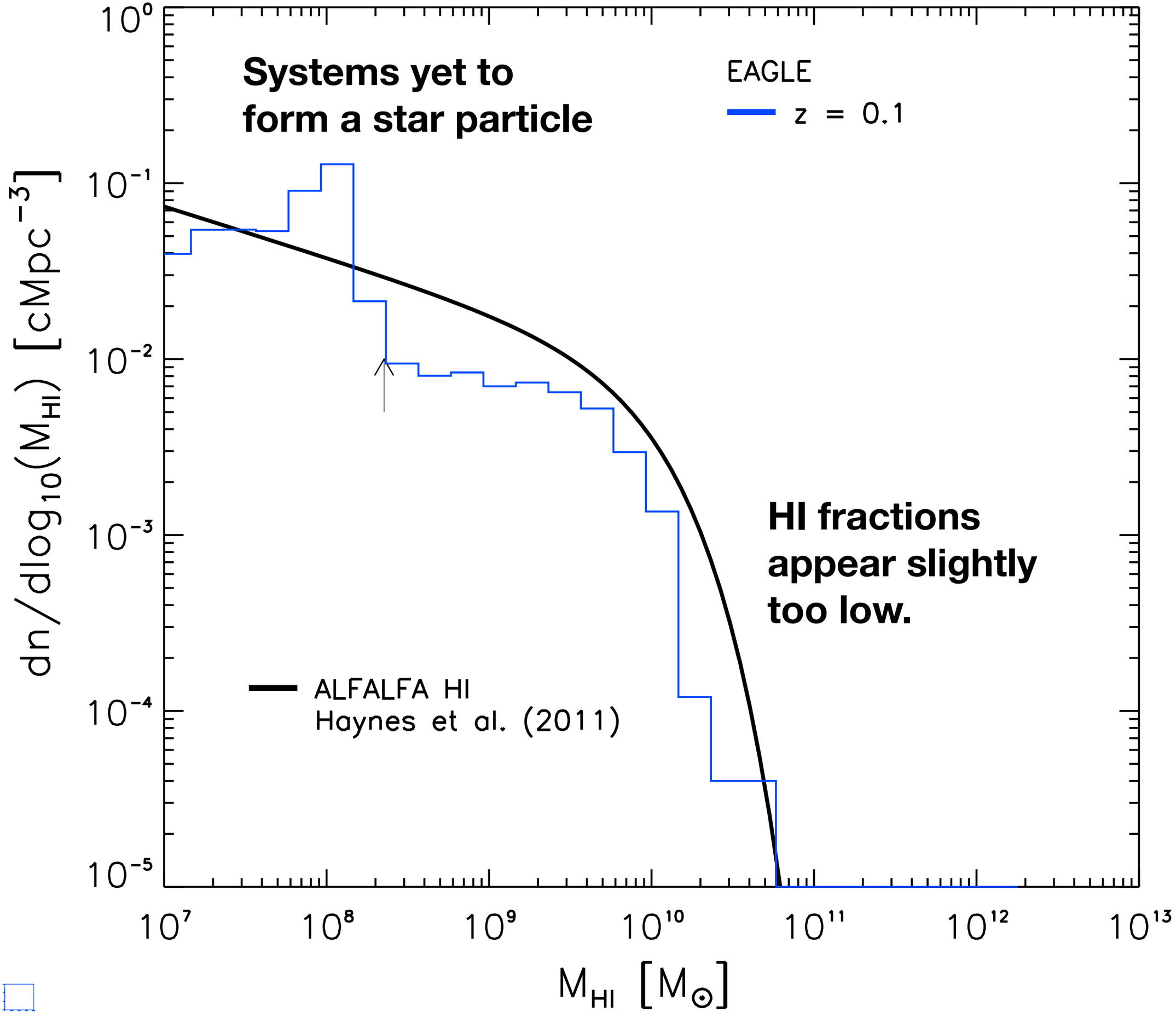
Rahmati et al. (2013a) present scaling relations for $f_{HI}(n_H,T,z)$ based on detailed radiation hydrodynamics calculations.

Molecular fraction from Blitz & Rosolowsky pressure law.
Appealing: we follow pressure explicitly.

Caveat: this relation is calibrated in the local Universe.

Please see movie here:

http://home.strw.leidenuniv.nl/~crain/wordpress/wp-content/uploads/galaxy_montage.avi


Systems yet to
form a star particle
EAGLE
z = 0.1
HI fractions
appear slightly
too low.
ALFALFA HI
Haynes et al. (2011)
dn/dlog10(MHI) [cMpc−3]
MHI [M⊙]
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^7
10^8
10^9
10^10
10^11
10^12
10^13

Mitigated at high-resolution

EAGLE (high res 12.5Mpc)
z = 0.1

ALFALFA HI
Haynes et al. (2011)

Larger volumes at high resolution now running

$dn/d\log_{10}(M_{HI})$ [cMpc^{-3}]

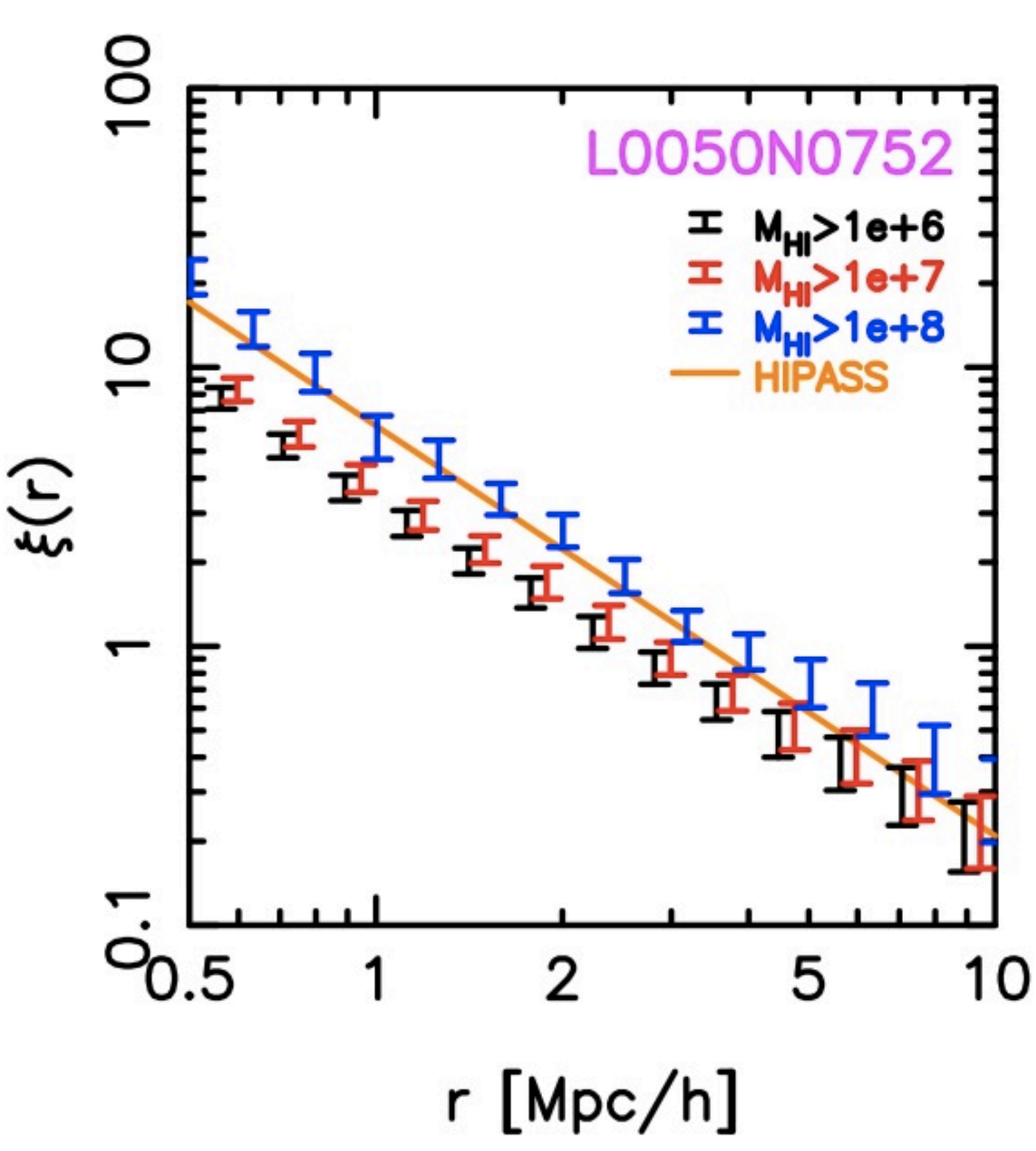
M_{HI} [$M_\odot$]

Chris Blake (Swinburne)

***** Very preliminary *****

Fundamental test: are we putting HI in the right place?

Likely a useful test of physics at faint-end of HI mass function (c.f. Kim et al. 2013)



Eagle galaxy HI profiles

*** *Very* preliminary (started last week!) ***

Confront with Bluedisk galaxies: 23 HI-rich + 25 ‘control’ galaxies mapped with WSRT (Wang+ 2013)

↓

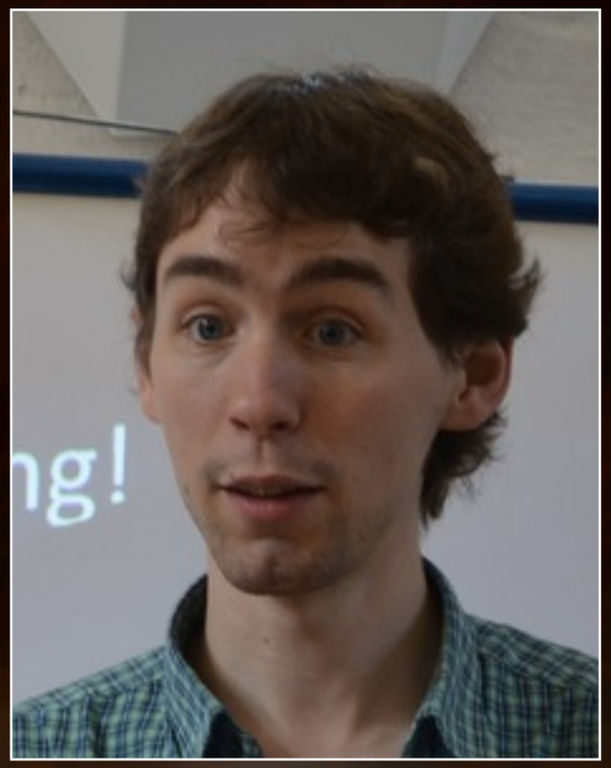
Extract roughly equivalent samples of HI-rich and control disc galaxies from Eagle.

↓

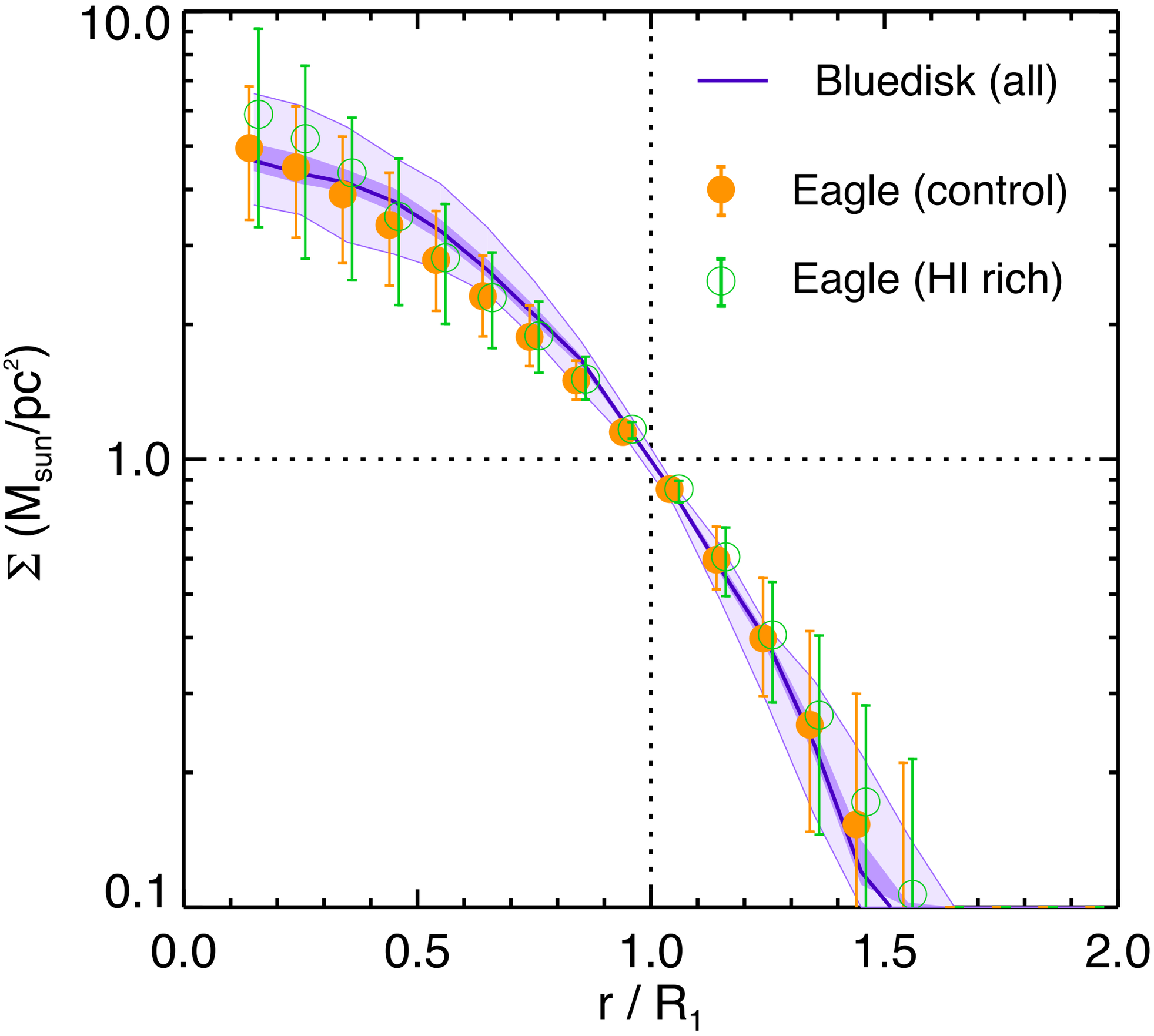
Construct SPH-smoothed HI images, convolve with elliptical beam (FWHM 14,9 kpc), clip at n_H threshold.

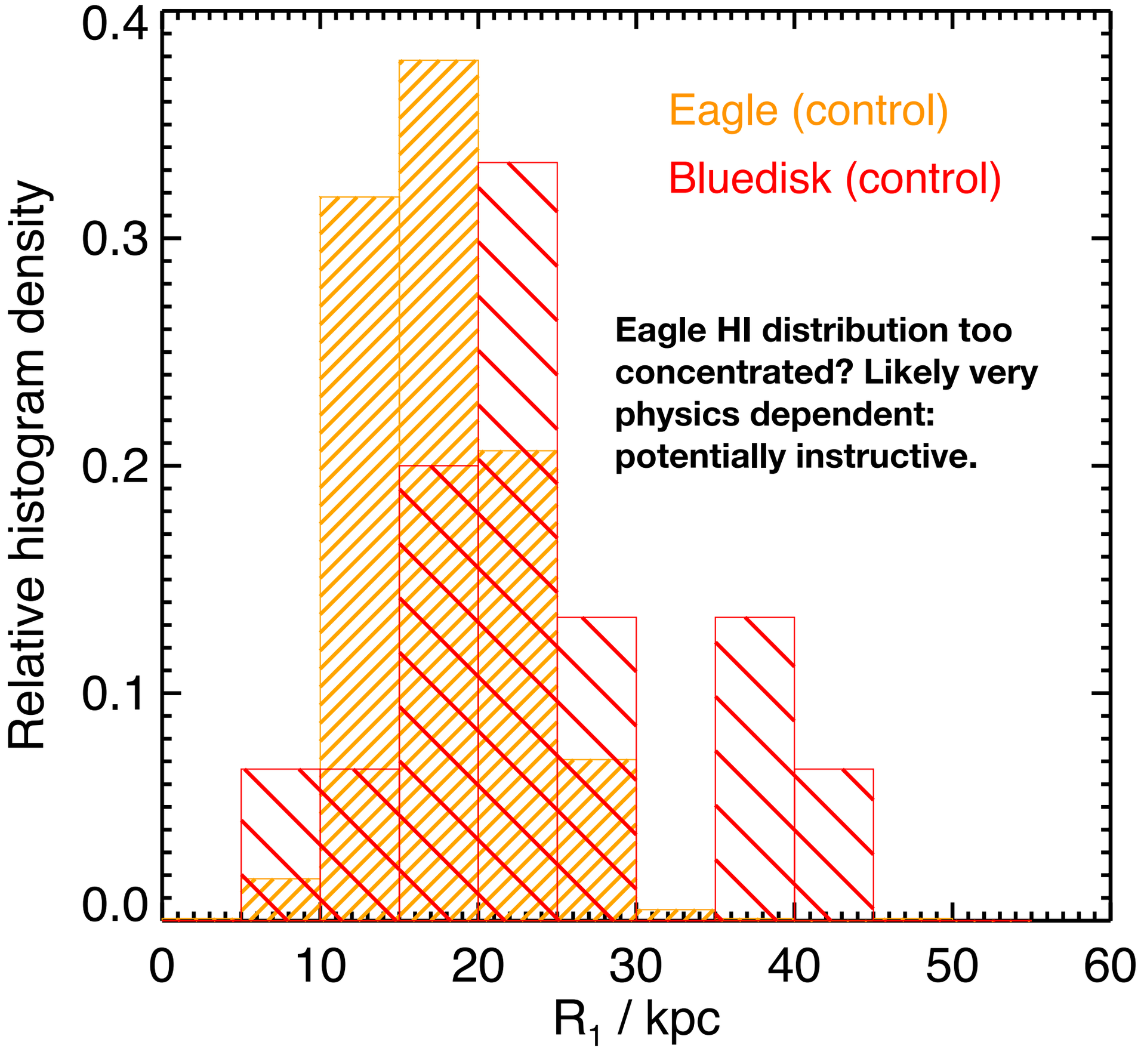
↓

Normalise to surface density of 1 M_{sun} pc^{-2} and clip at detection threshold of $N_{HI} \sim 10^{19.3}$ cm^{-2}.



Yannick Bahe (MPA)


10.0
1.0
0.1
0.0
0.5
1.0
1.5
2.0
Σ (M_sun/pc^2)
r / R_1
Bluedisk (all)
Eagle (control)
Eagle (HI rich)


Eagle (control)
Bluedisk (control)
Eagle HI distribution too concentrated? Likely very physics dependent: potentially instructive.
Relative histogram density
0.0
0.1
0.2
0.3
0.4
0
10
20
30
40
50
60
R1 / kpc

Summary

Cosmological hydro simulations can now reproduce galaxy populations with accuracy comparable to SAMs

- **Detailed modelling of ISM/CGM of relevance for gas surveys**

C.H. sims often appeal to approximations or techniques that impact significantly upon their predictions.

- **Eagle demonstrates that many are unnecessary**

Eagle is ideal testbed for interpreting gas-phase data and generating predictions for forthcoming instrumentation.

- **Several key HI constraints reproduced ‘out of the box’**
- **Further calibration against HI data may prove profitable**

Eagle galaxy catalogues will be publicly available (SQL) as per Millennium Simulation. Collaborative projects also welcome.