How feedback shapes the galaxy stellar mass function

Eagle, owls and other Gimics

Tom Theuns
Institute for Computational Cosmology
Ogden Centre for Fundamental Physics
Durham University, UK
and
University of Antwerp
Belgium

1

Outline:

- Motivation
- Introduction
  - cosmology 101: forming structures
  - cosmology 102: forming galaxies.
  - The need for “subgrid” physics
- EAGLE subgrid physics implementation in Gadget
  - star formation, cooling, and feedback (SNe and AGN)
- Lessons learned from the precursors: Owls and Gimic
- (How) Do supernova regulate starformation?
- Parameter selection (tuning)
  - methodology

Galaxy formation

Aims:

- How do galaxies form?
- How do they evolve?
- Which physical processes operate?

Basic paradigm

- Dark haloes form
- Cool(ed) gas forms discs
- Discs fragment to form stars

Multi-scale/complex/rich problem

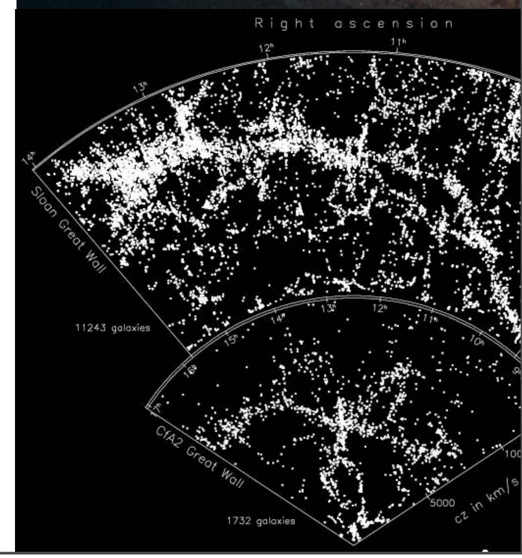
2 pc

x 10000

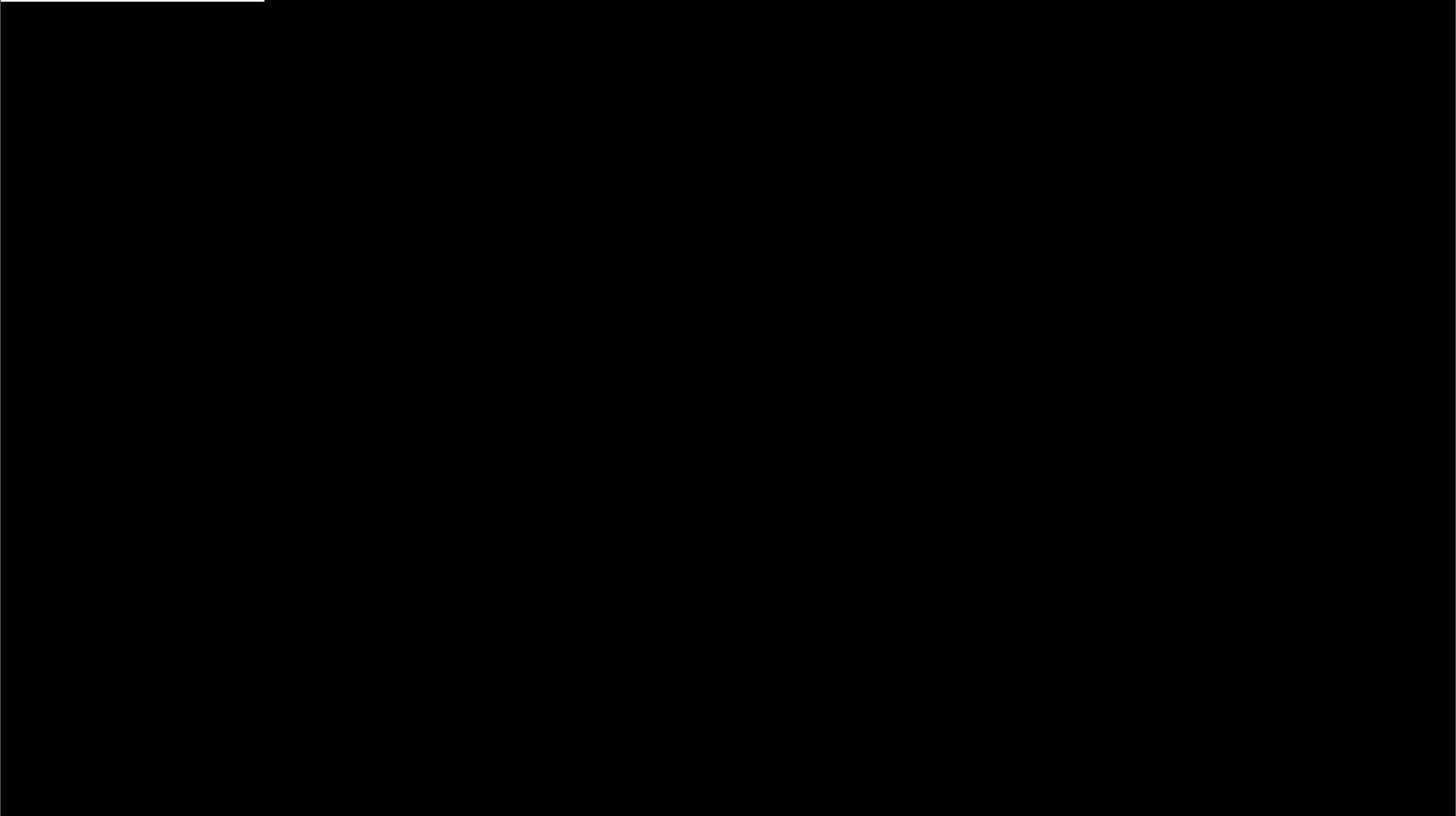
20 kpc

x 10000

200 Mpc

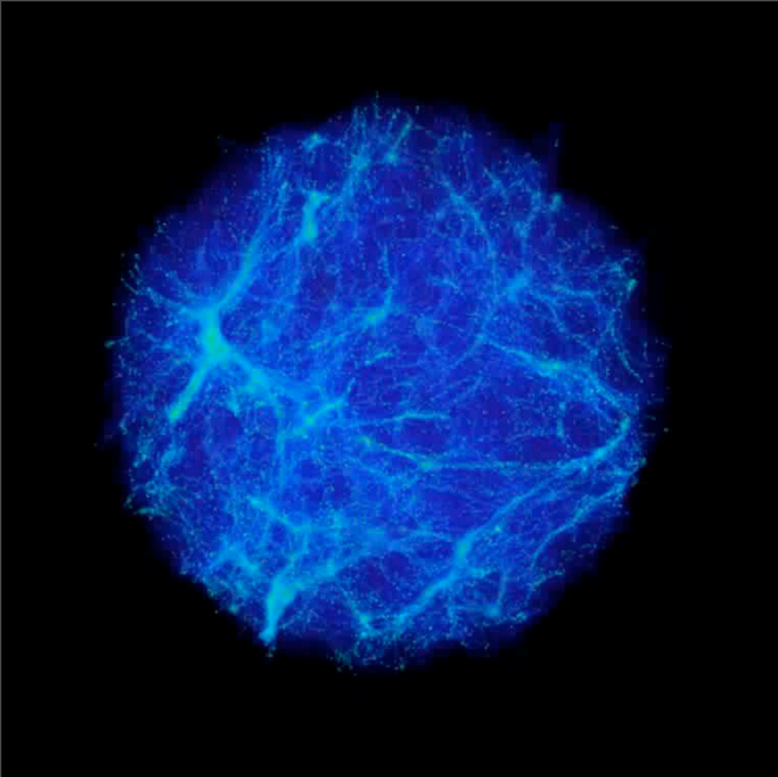


Motivation

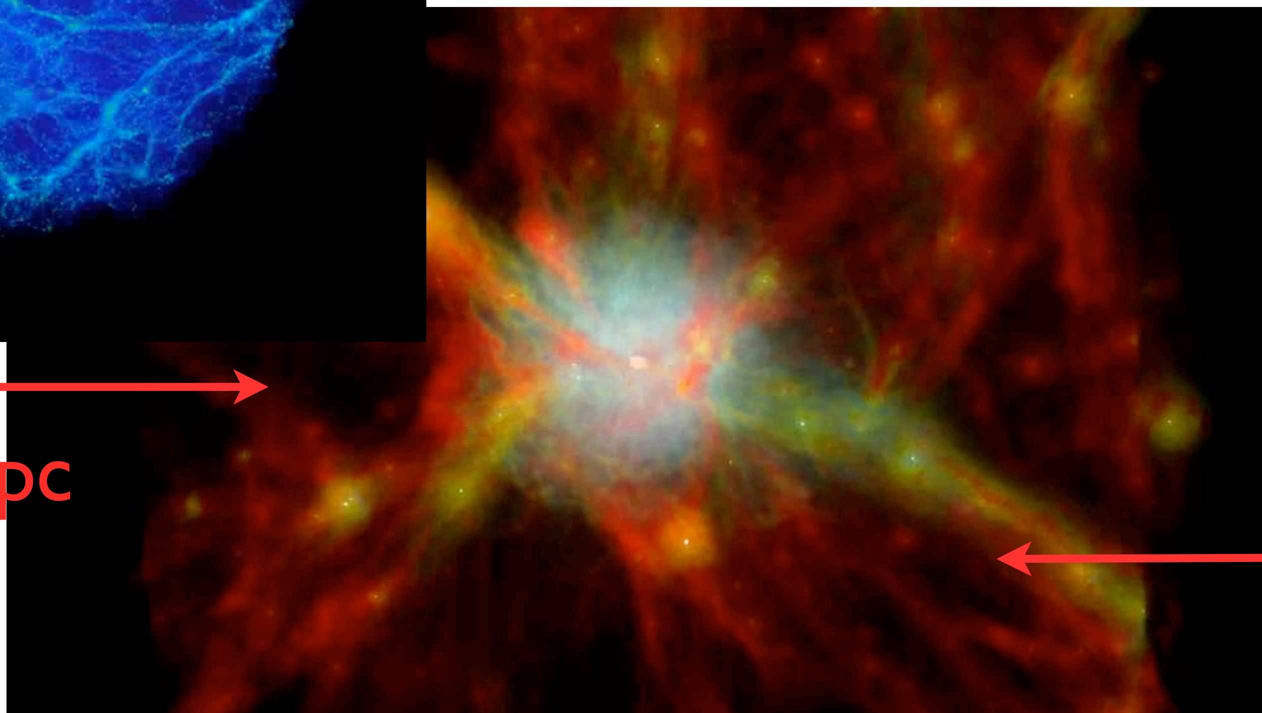


- Simulations follow evolution
- Physical understanding
- Which modelling needs improving?

Multi-scale/complex/rich problem



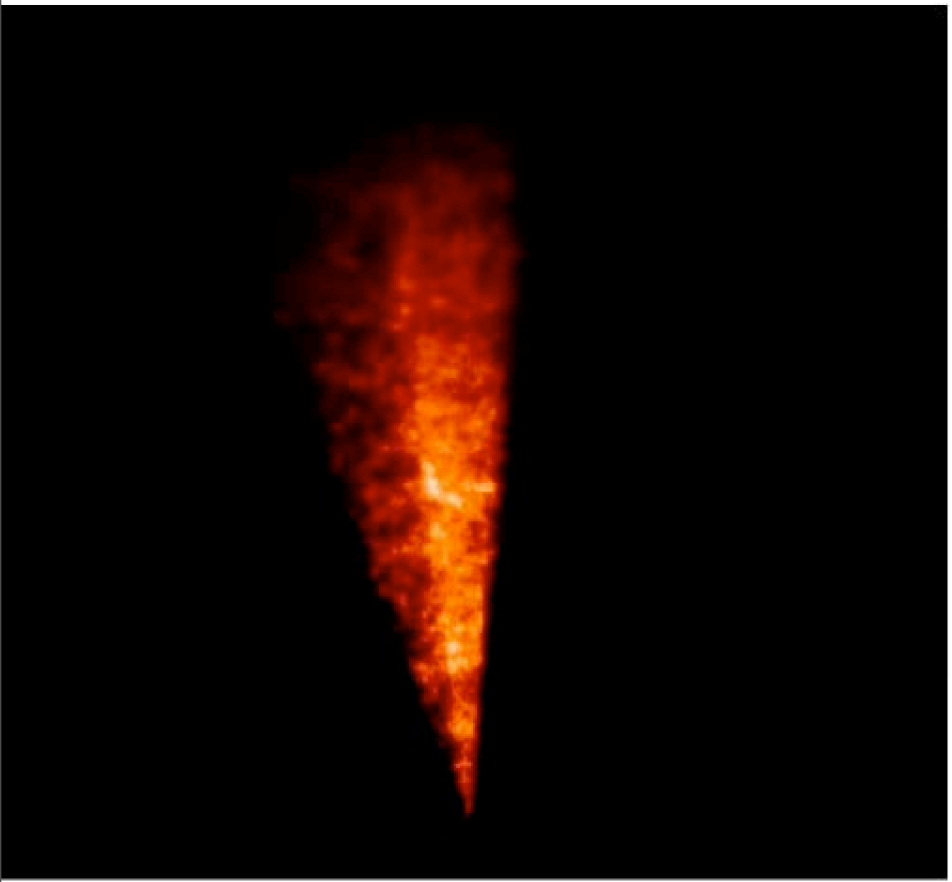
2 Mpc



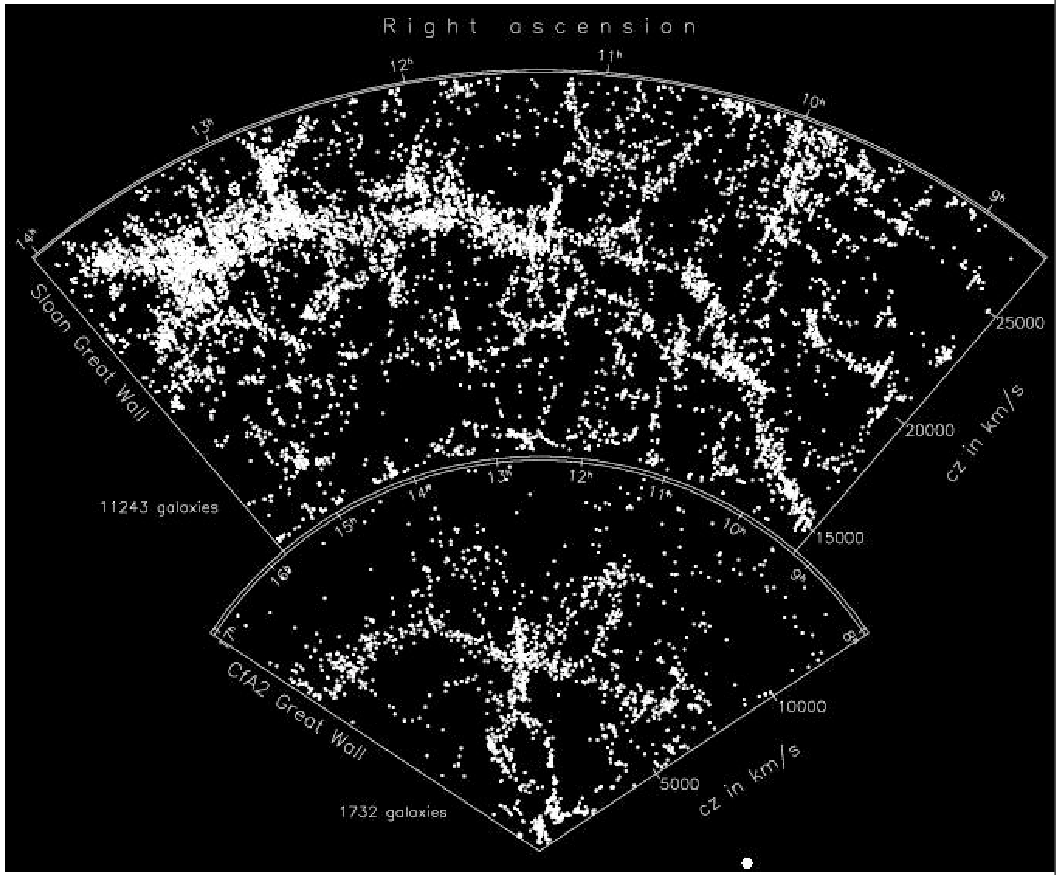
40 Mpc

20 kpc

Observed distribution of galaxies



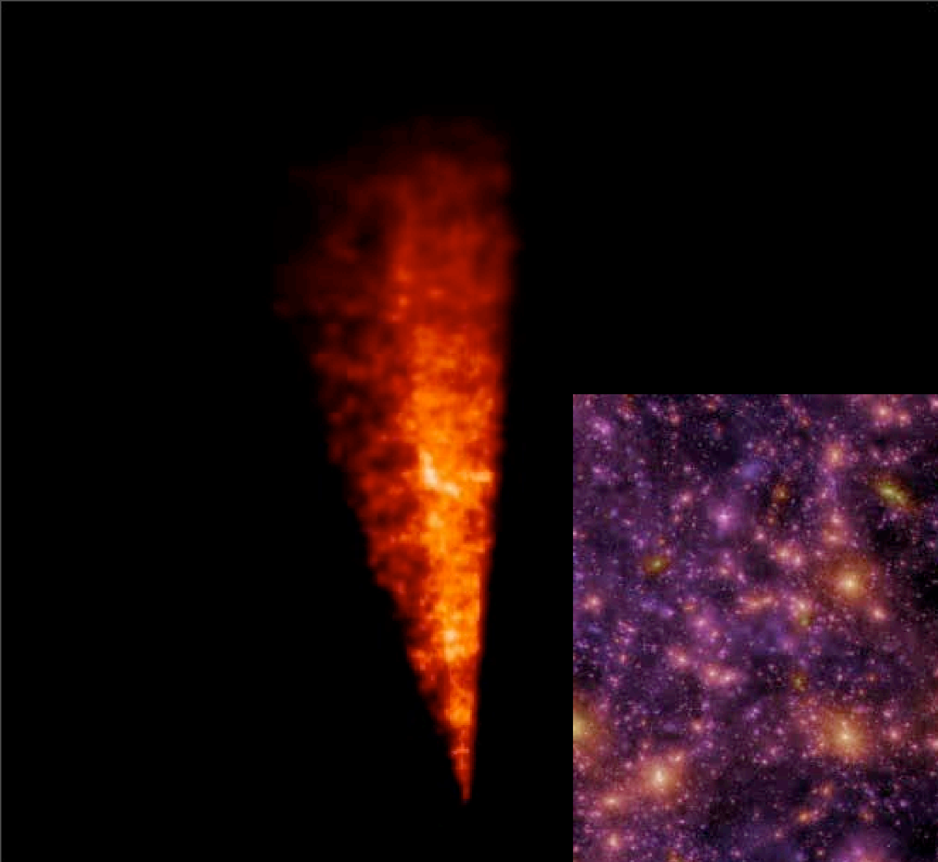
Anglo-Australian 2-degree field redshift survey

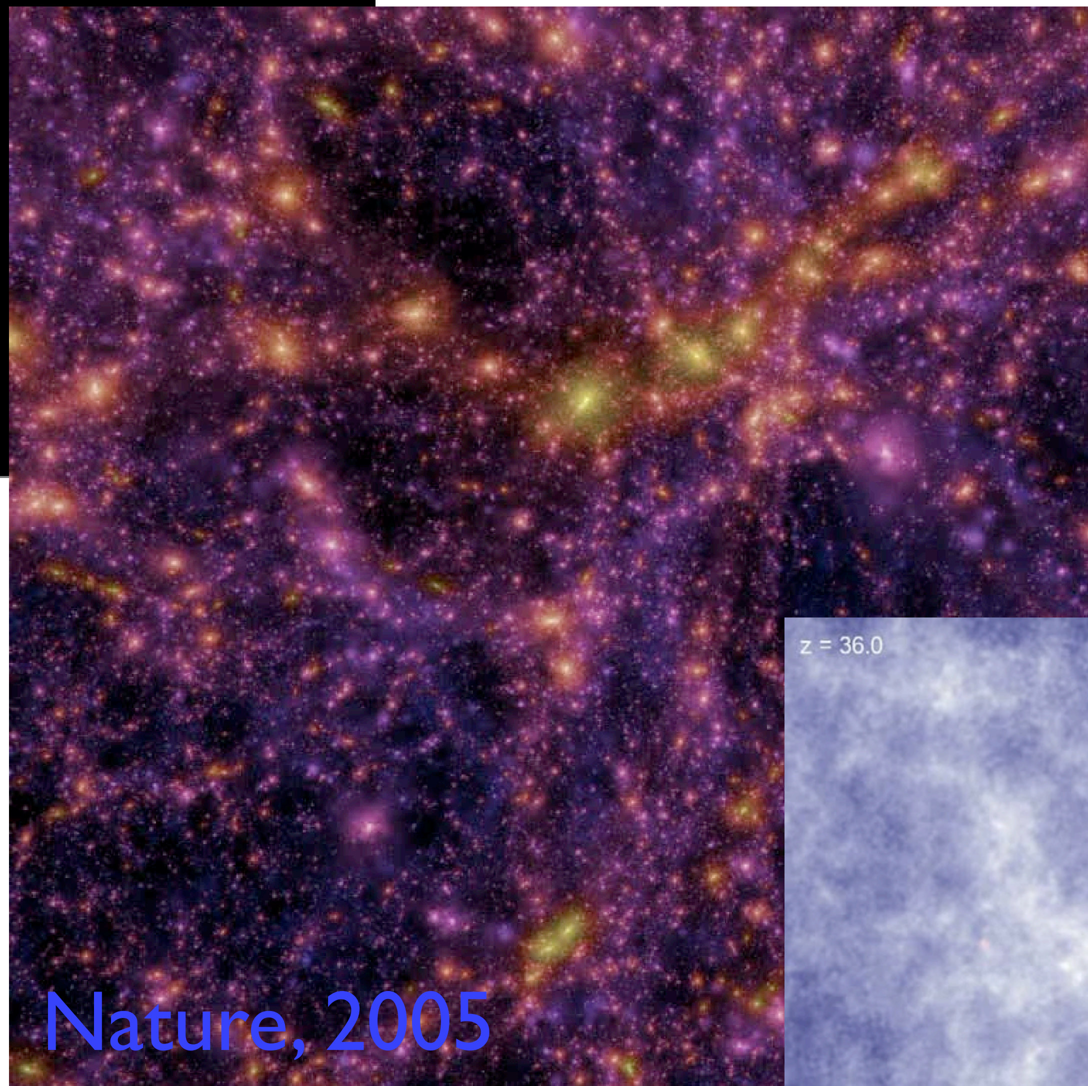


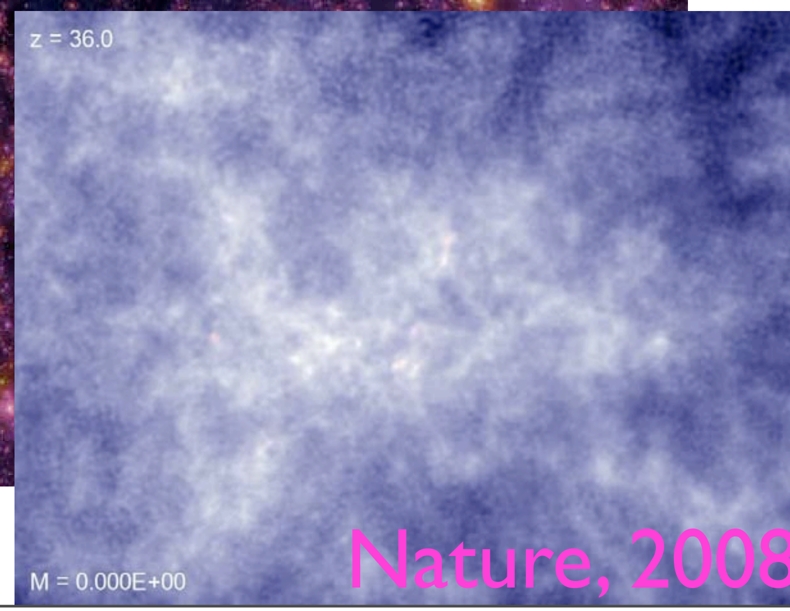
CfA survey

Millennium simulation + semi-analytical model

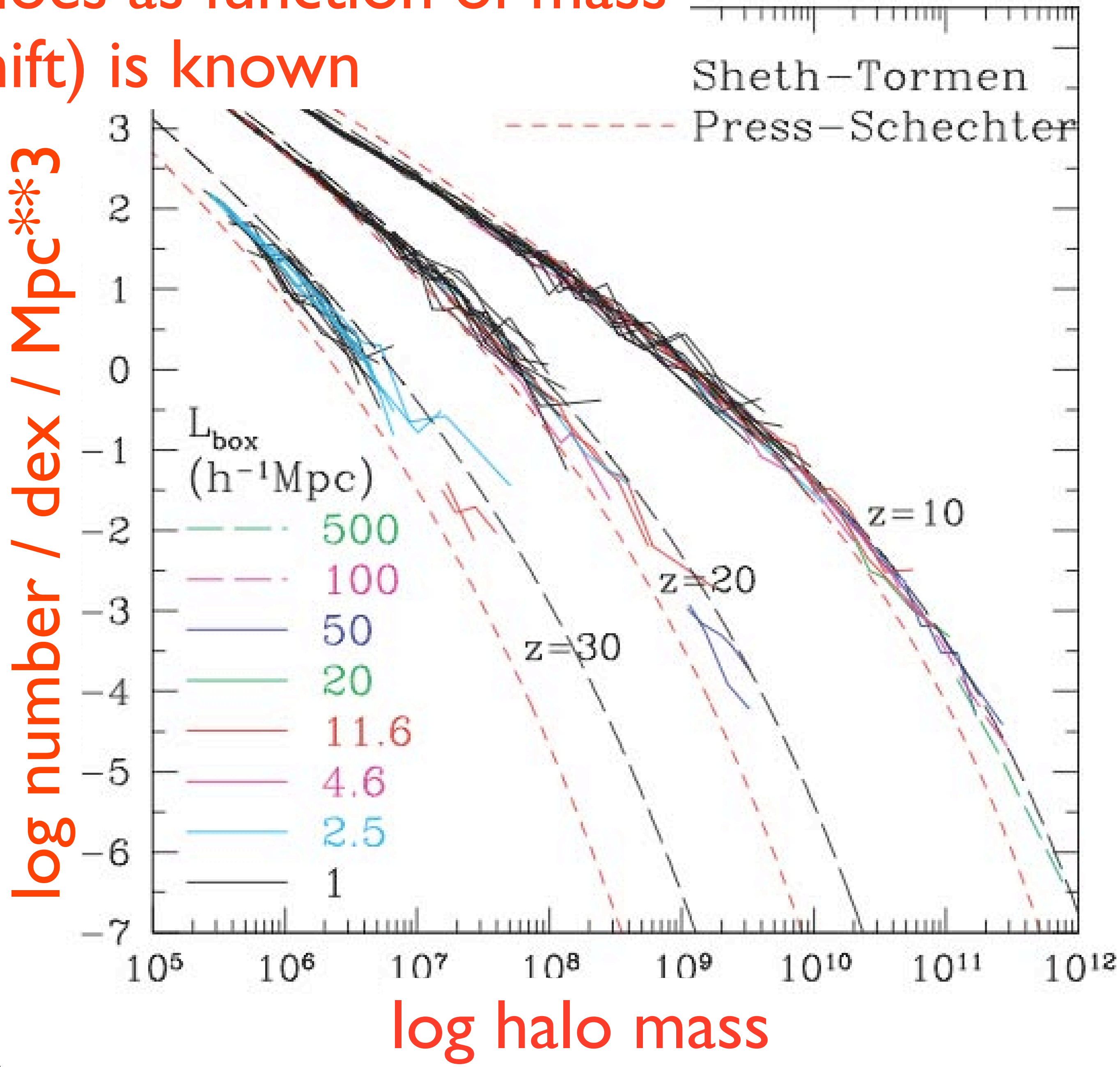
Gravitational build-up of dark matter structures is “solved” problem







The abundance of haloes as function of mass (and redshift) is known



Mon. Not. R. Astron. Soc. **374,** 2–15 (2007)

The halo mass function from the dark ages through the present day

Darren S. Reed,[1★] Richard Bower,[1] Carlos S. Frenk,[1] Adrian Jenkins[1] and Tom Theuns[1,2]

Springel+05,Heitmann+13,

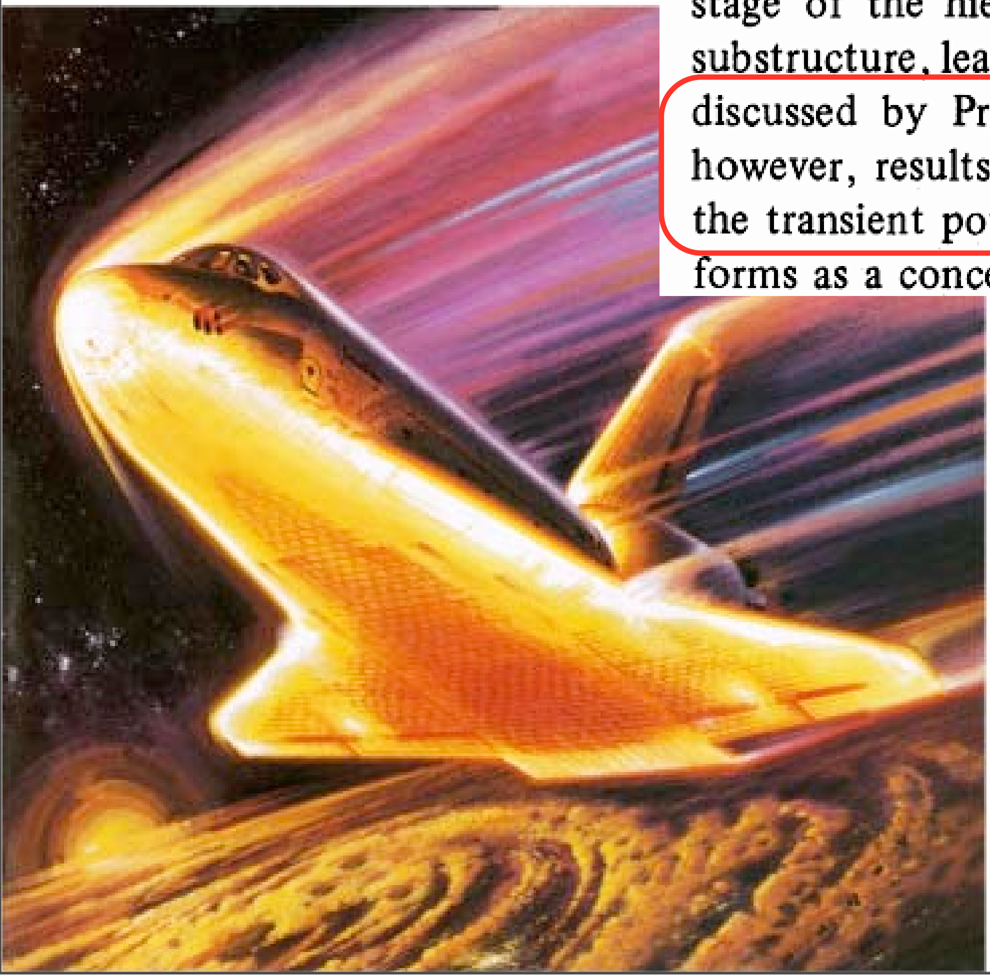
How do galaxies form inside their halo?

Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

Mon. Not. R. astr. Soc. (1978) **183**, 341–358

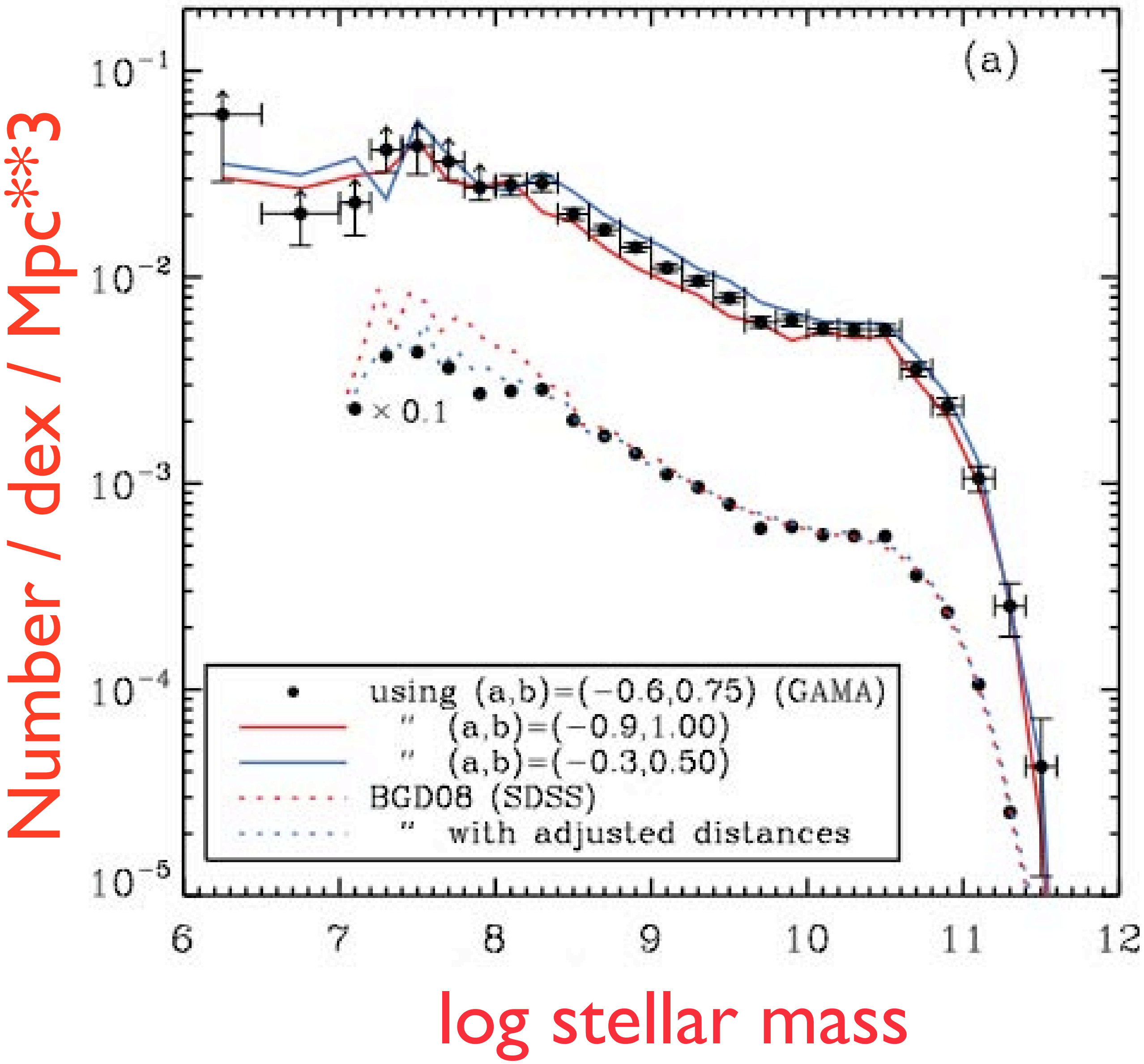
White & Rees '78

present scale we infer from the large-scale distribution of galaxies. As each stage of the hierarchy forms and collapses, relaxation effects wipe out its substructure, leading to a self-similar distribution of bound masses of the type discussed by Press & Schechter. The entire luminous content of galaxies, however, results from the cooling and fragmentation of residual gas within the transient potential wells provided by the dark matter. Every galaxy thus forms as a concentrated luminous core embedded in an extensive dark halo.



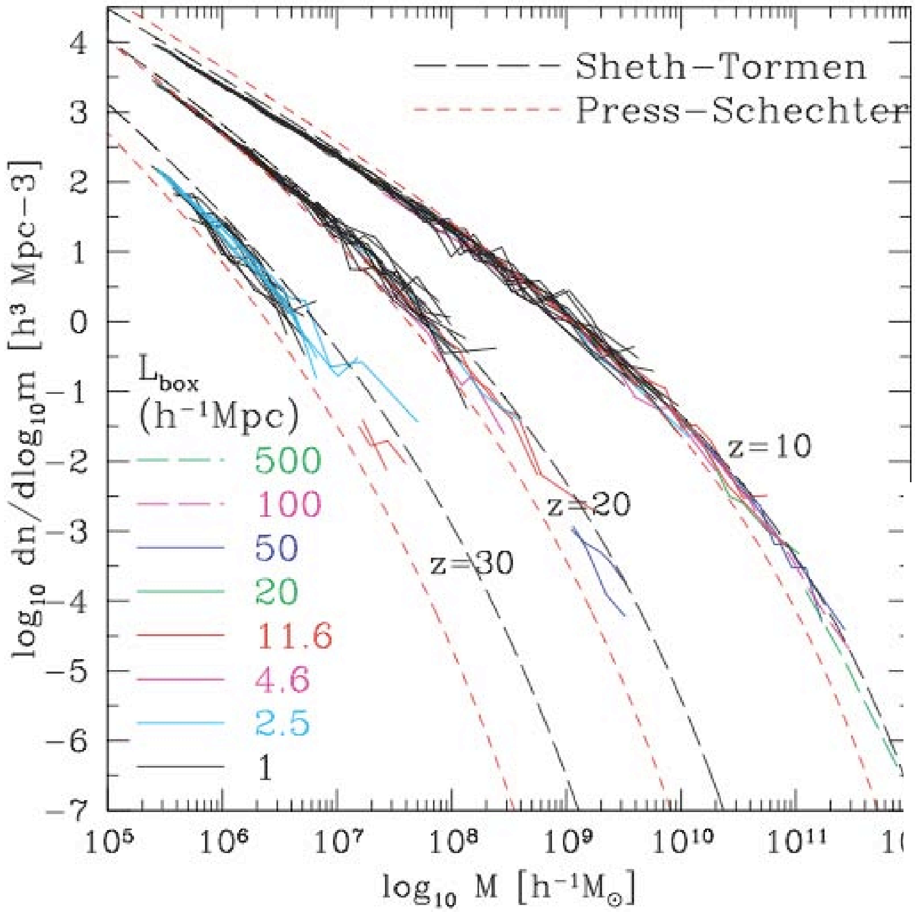
Tom Theuns

Galaxy And Mass Assembly (GAMA): the galaxy stellar mass function at $z < 0.06$



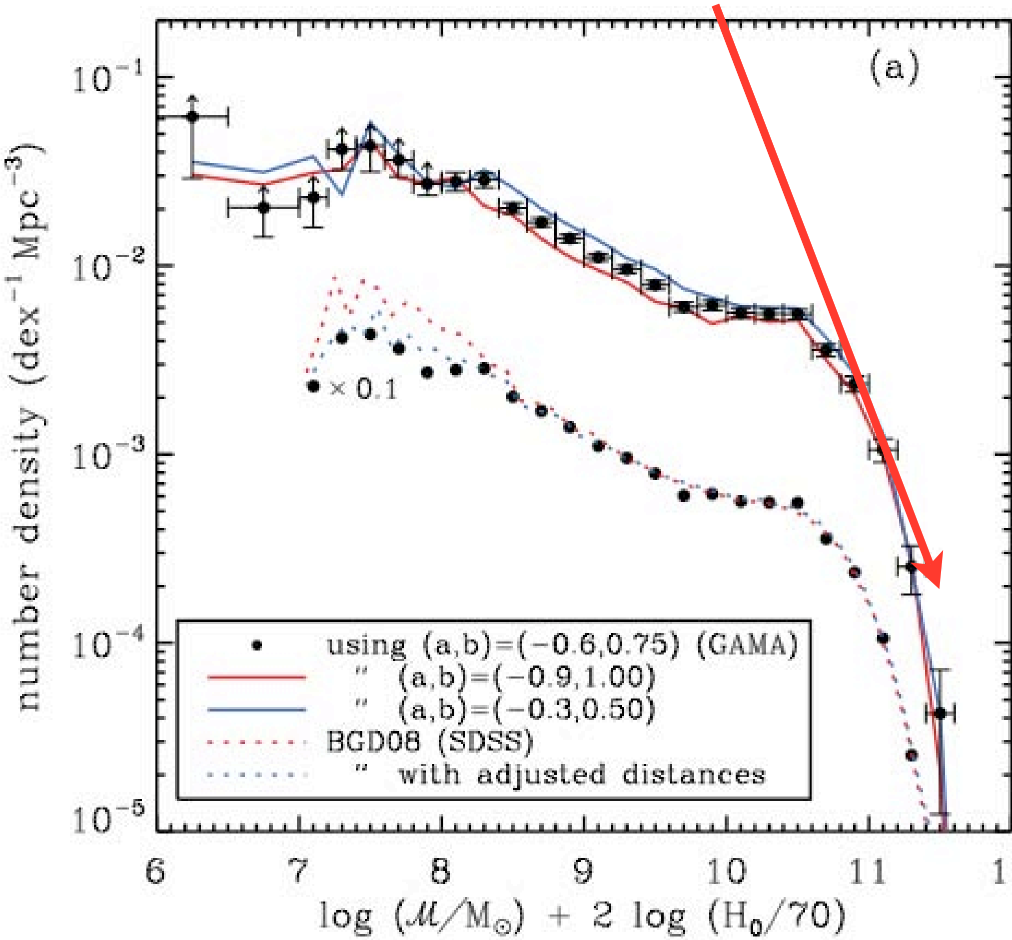
Baldry+12

Abundance matching



Reed+07

Too hot to cool?



Baldry+12

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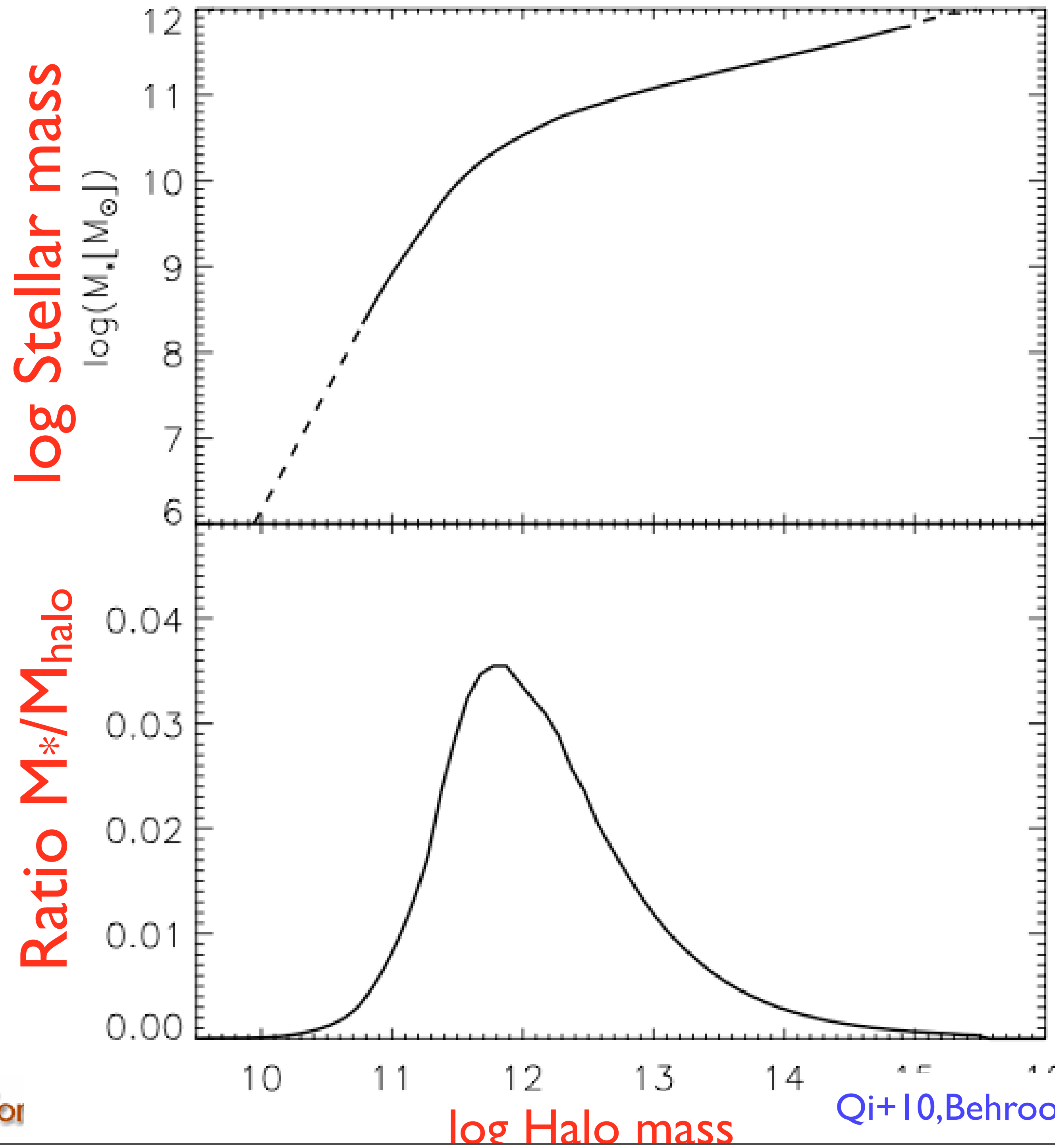
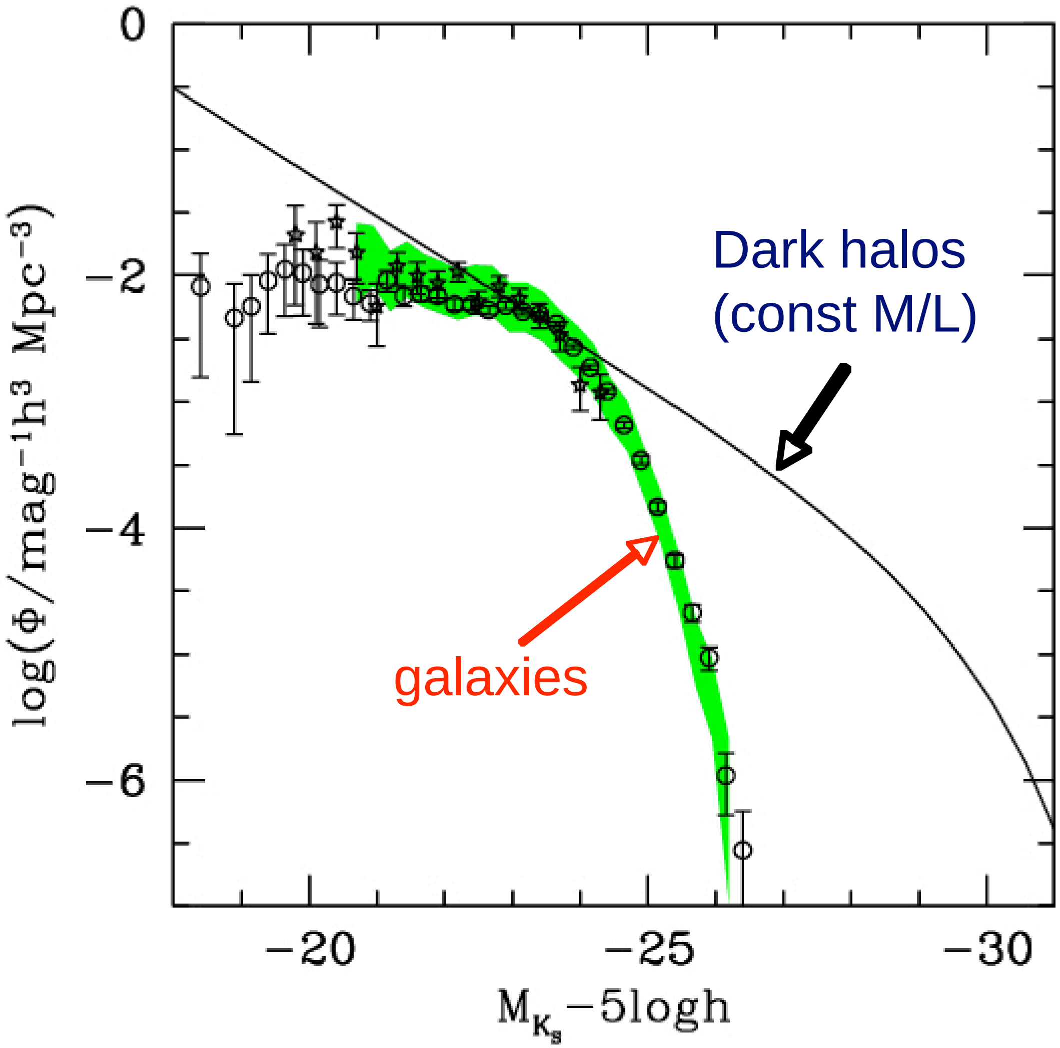


Qi+10,Behroozi+, Leauthaud+

ICC Institute for

Durham University

Halo mass function and galaxy luminosity functions have very different shapes



Feedback or gastrophysics is key

Tom Theuns

ICC Institute for Computatio

Benson+

Galaxy formation

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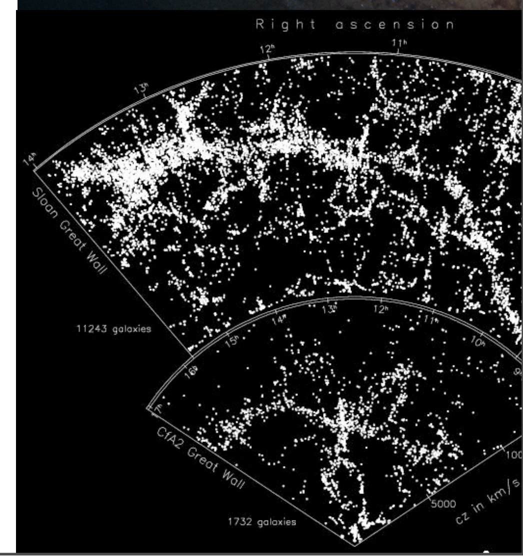

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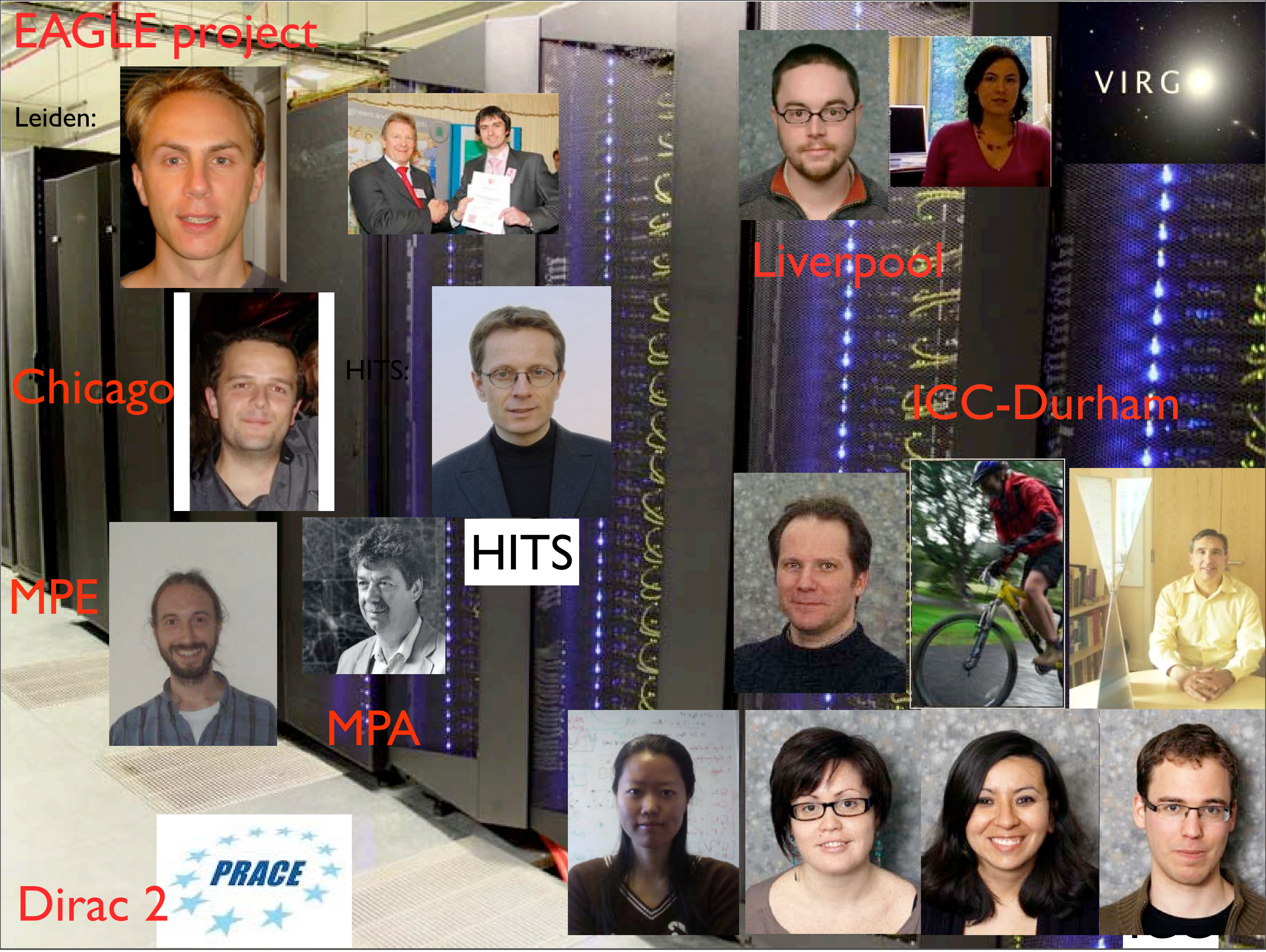
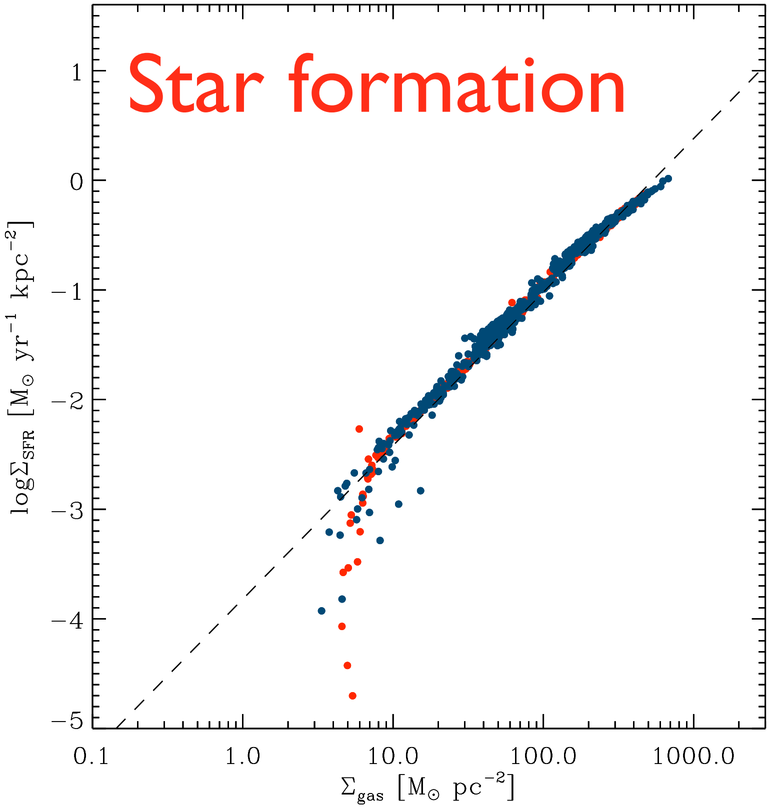
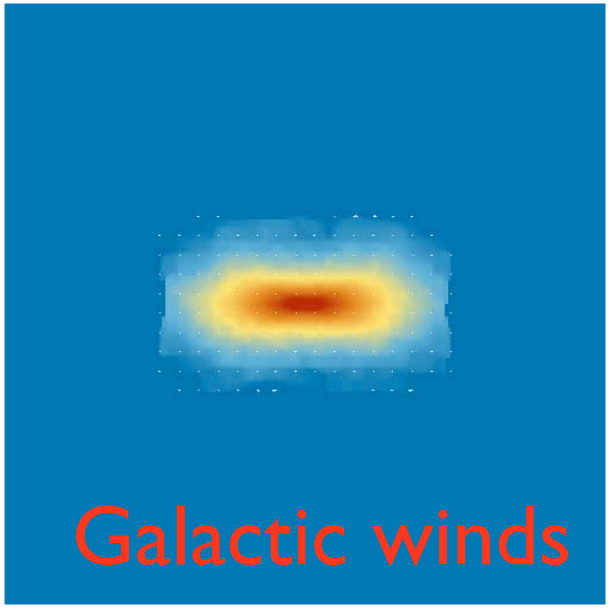
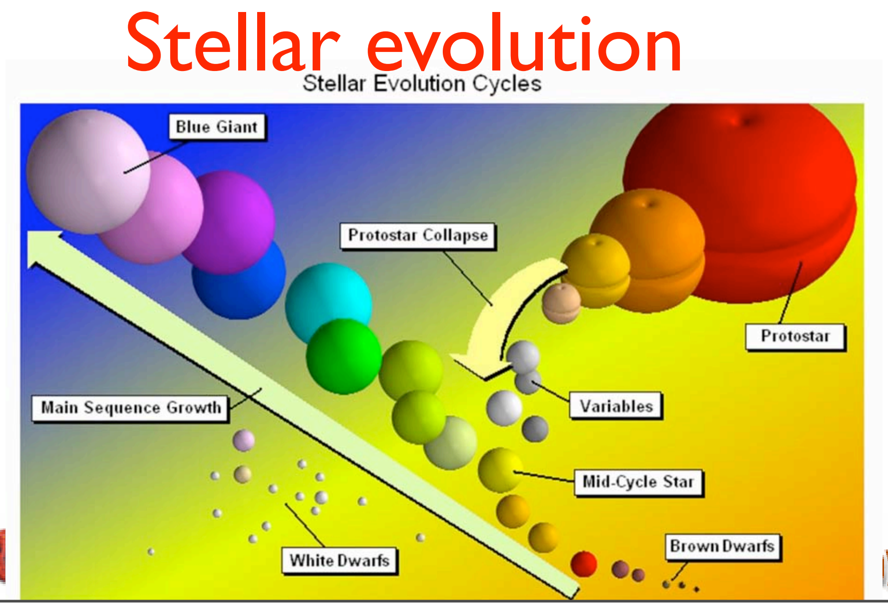
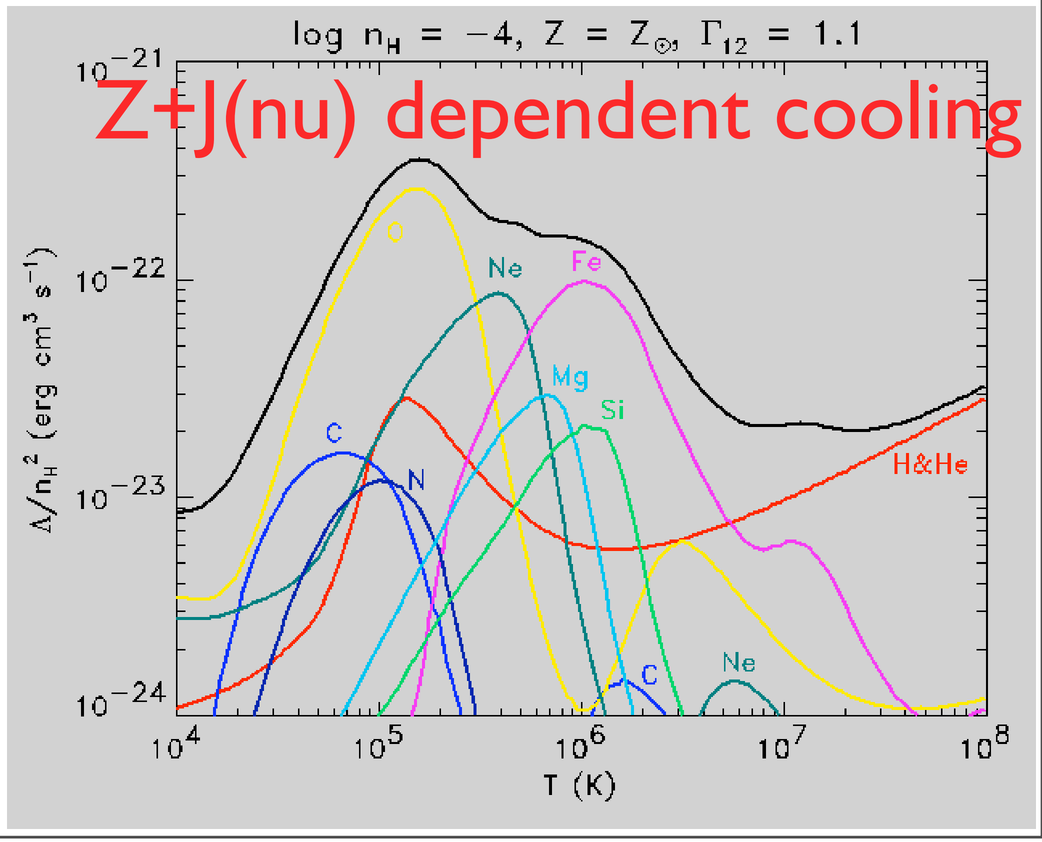

EAGLE project
Leiden:
VIRG
Liverpool
Chicago
HITS:
ICC-Durham
HITS
MPE
MPA
PRACE
Dirac 2

subgrid physics added to Gadget-3



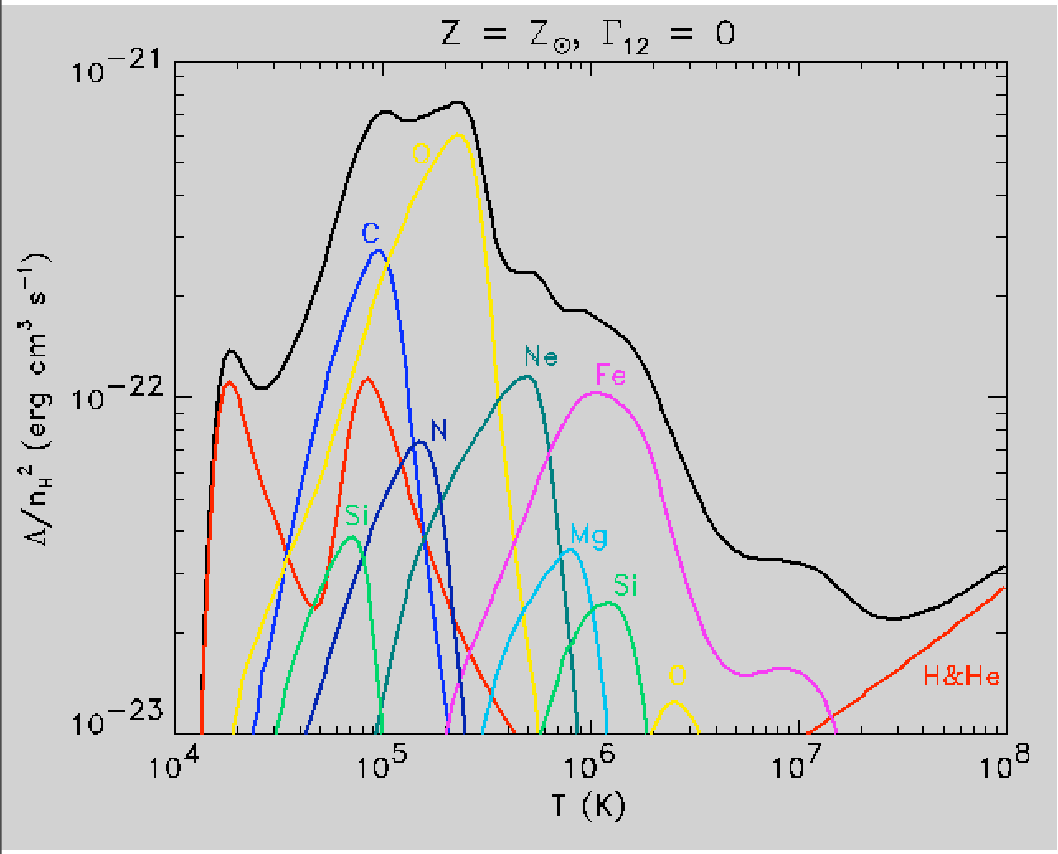






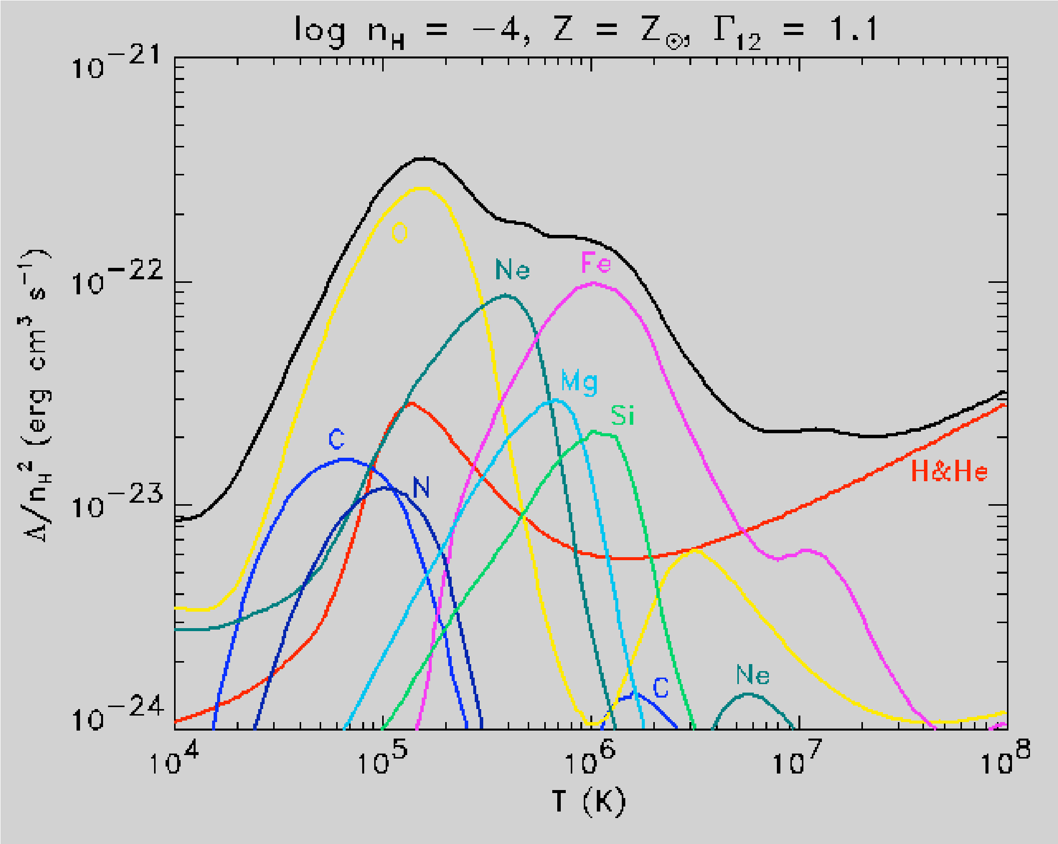
Commercial break: your talk will continue in 20 seconds

1. Element-by-element cooling (and heating) in the presence of UV/X-ray background



Without ionizing background

With ionizing background from gals & AGN



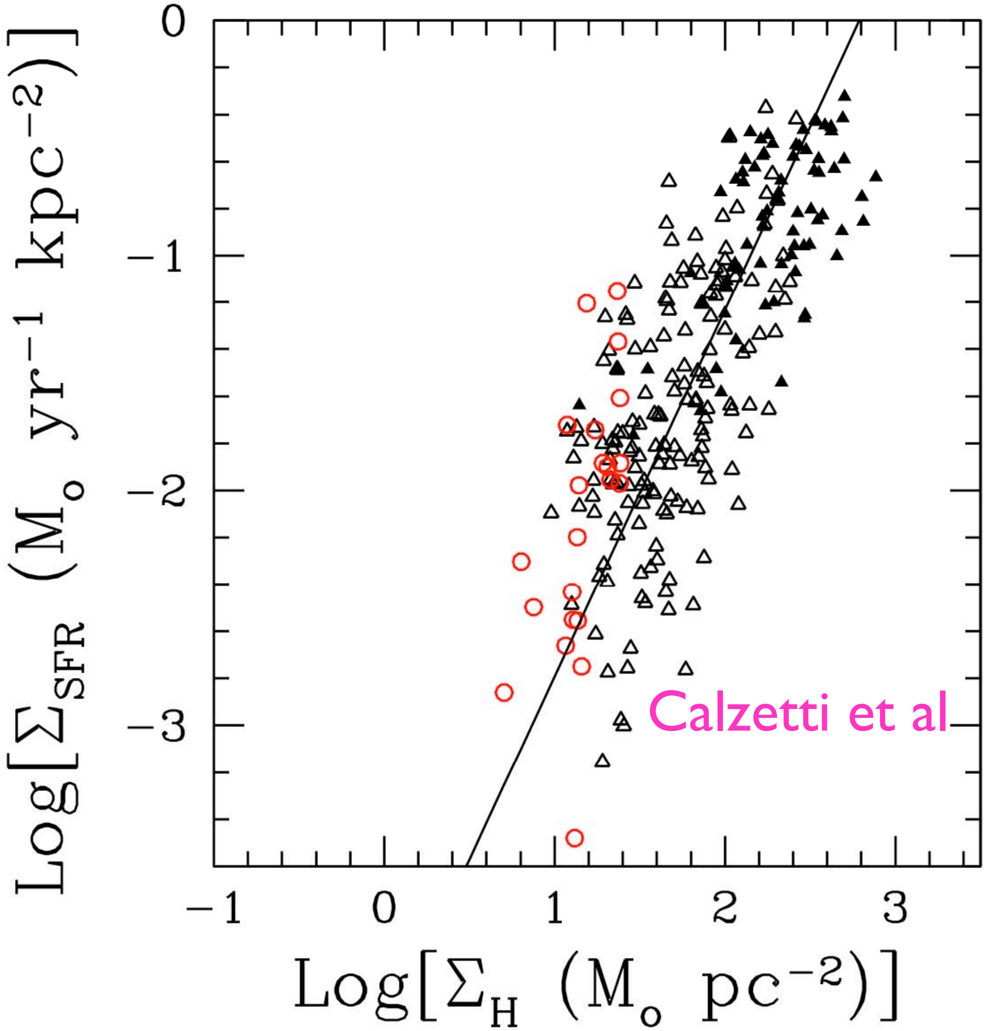
Wiersma et al ‘08

Durham University

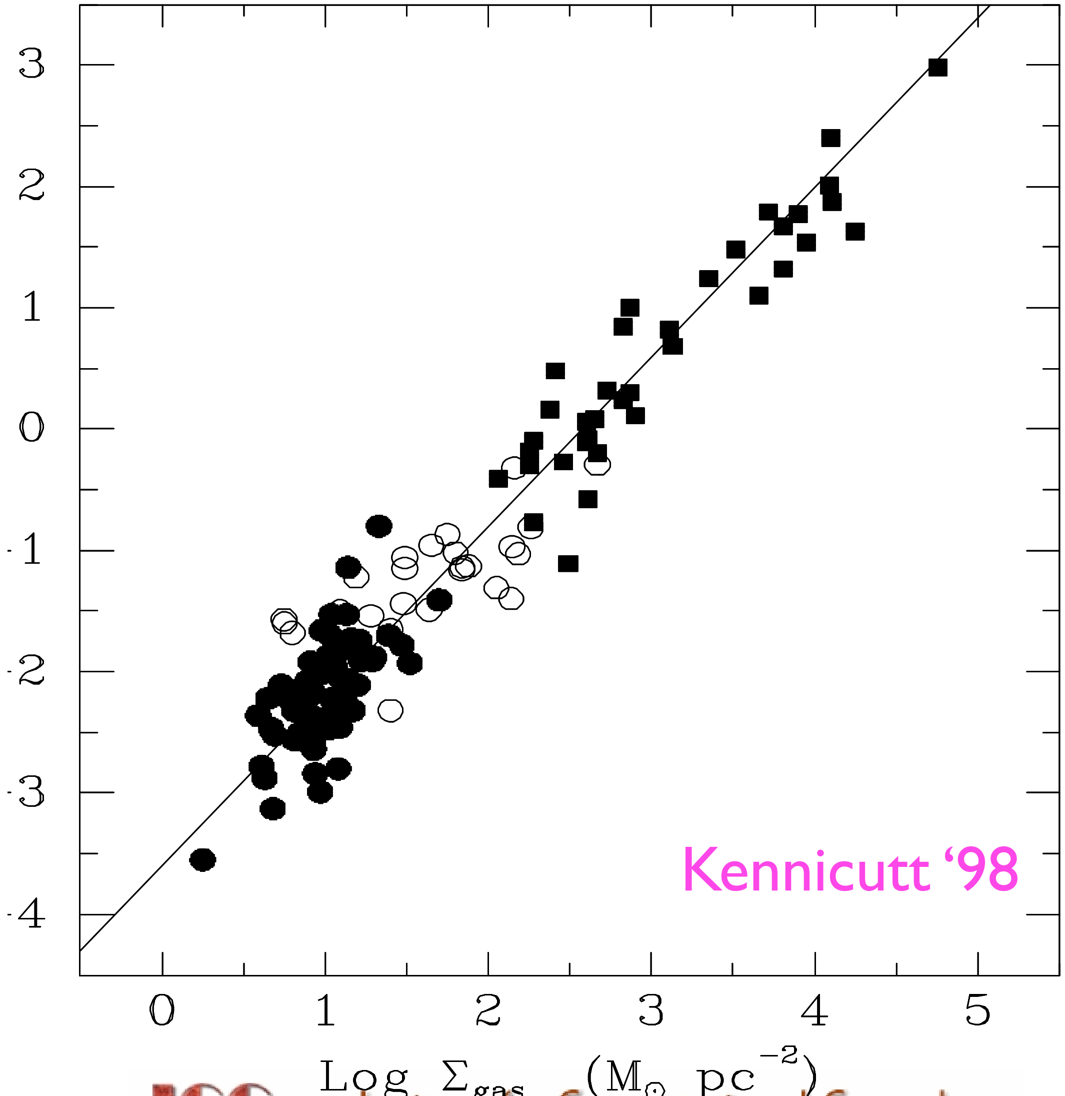
2. Star formation implementation (and the origin of the Kennicutt-Schmidt law)

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{n} \quad (n = 1.4 \pm 0.15)$$

Local: same galaxy

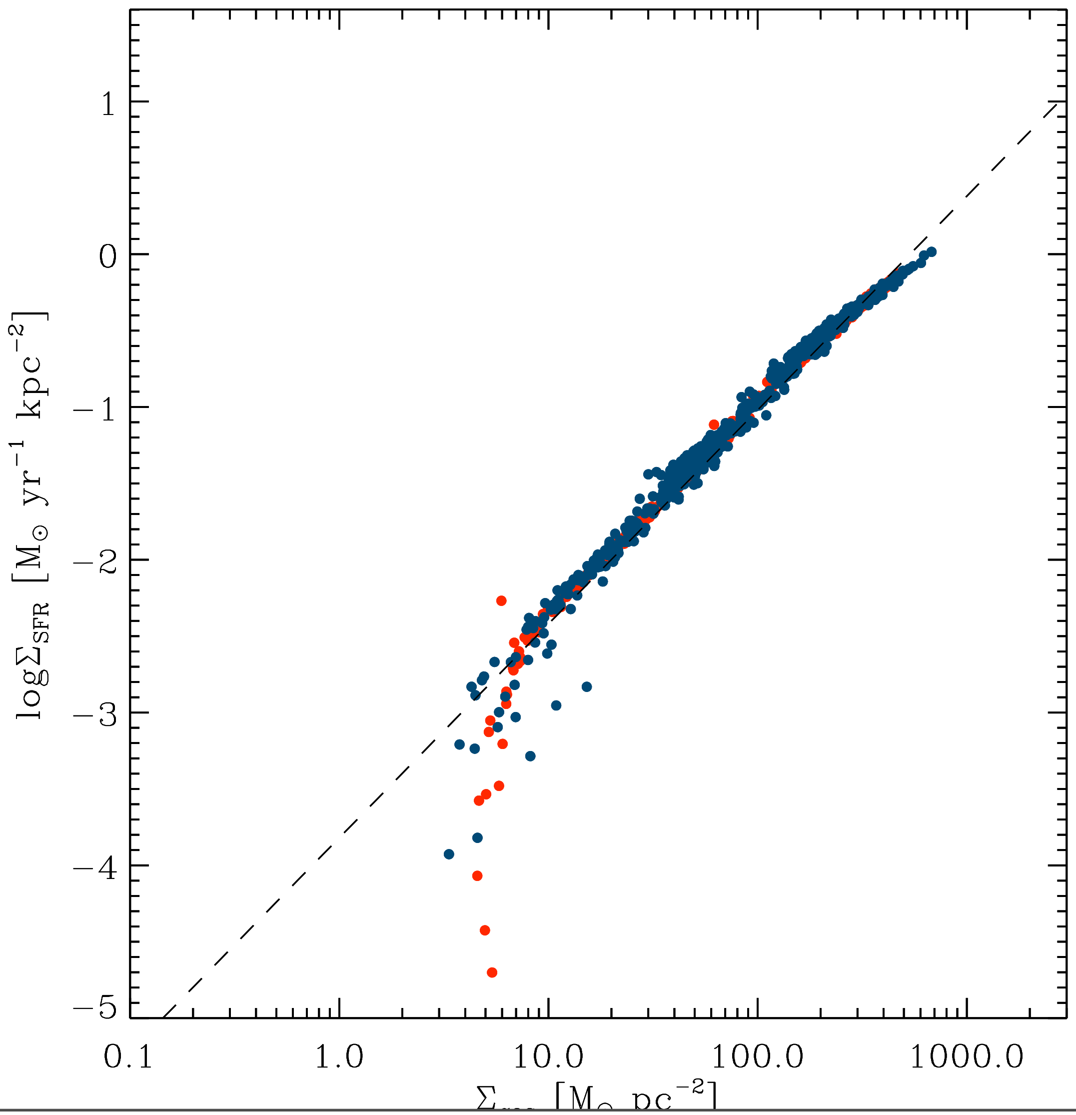


Global: different galaxies



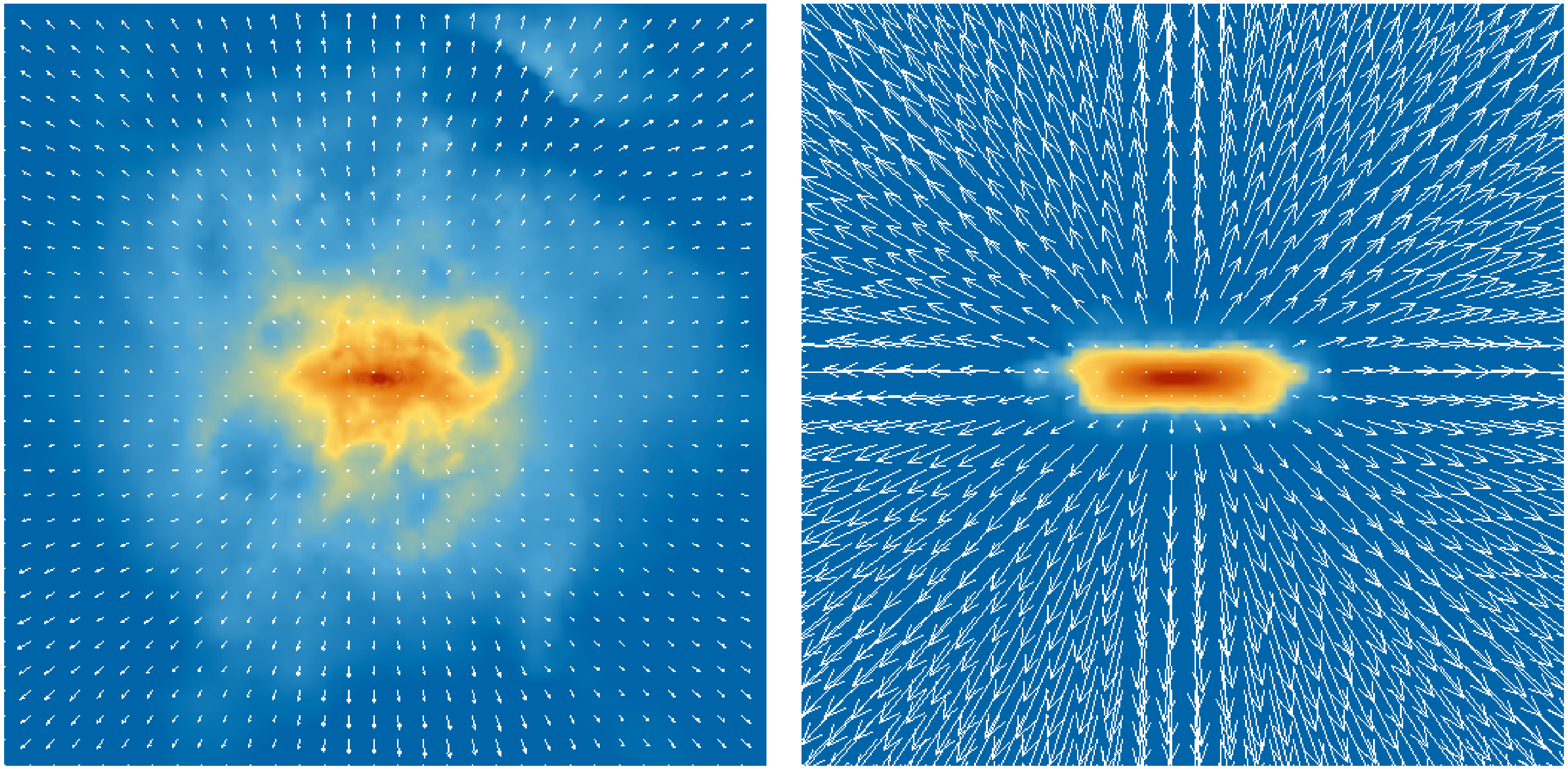
ICC Institute for Computational Cosmology

Star formation guarantees the simulated galaxies follow the imposed Kennicutt-Schmidt law



Schaye 04

3. Implementation of winds:

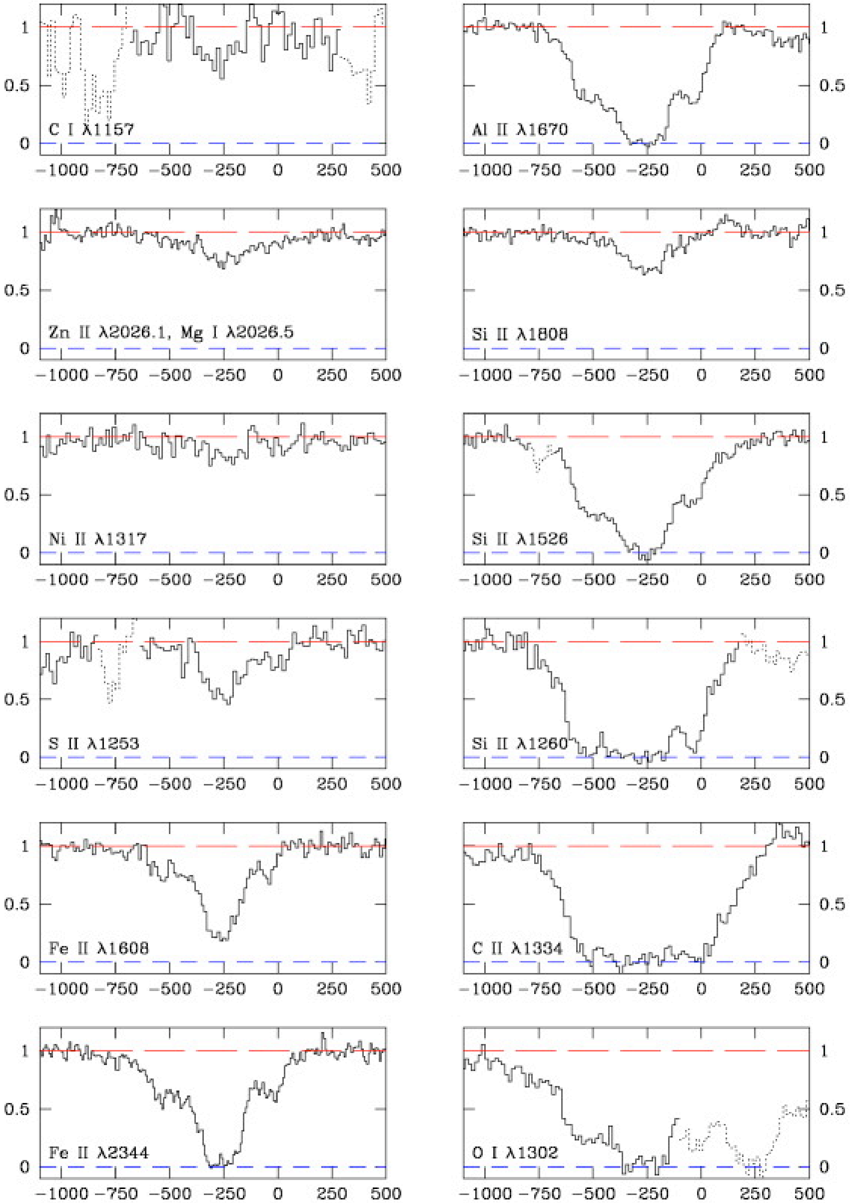


Schaye & Dalla Vecchia 08, 12

Springel, Kay+, Scanapiecco+,Oppenheimer+,Kawata+,Tornatore+,Teyssier+

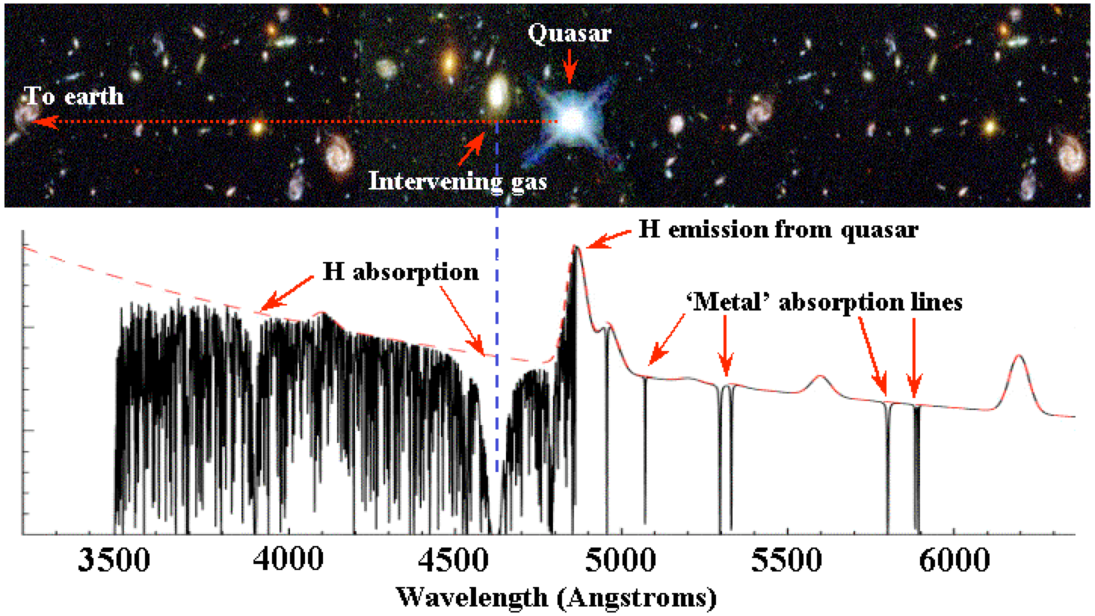
for Computational Cosmology

Evidence for galactic winds:



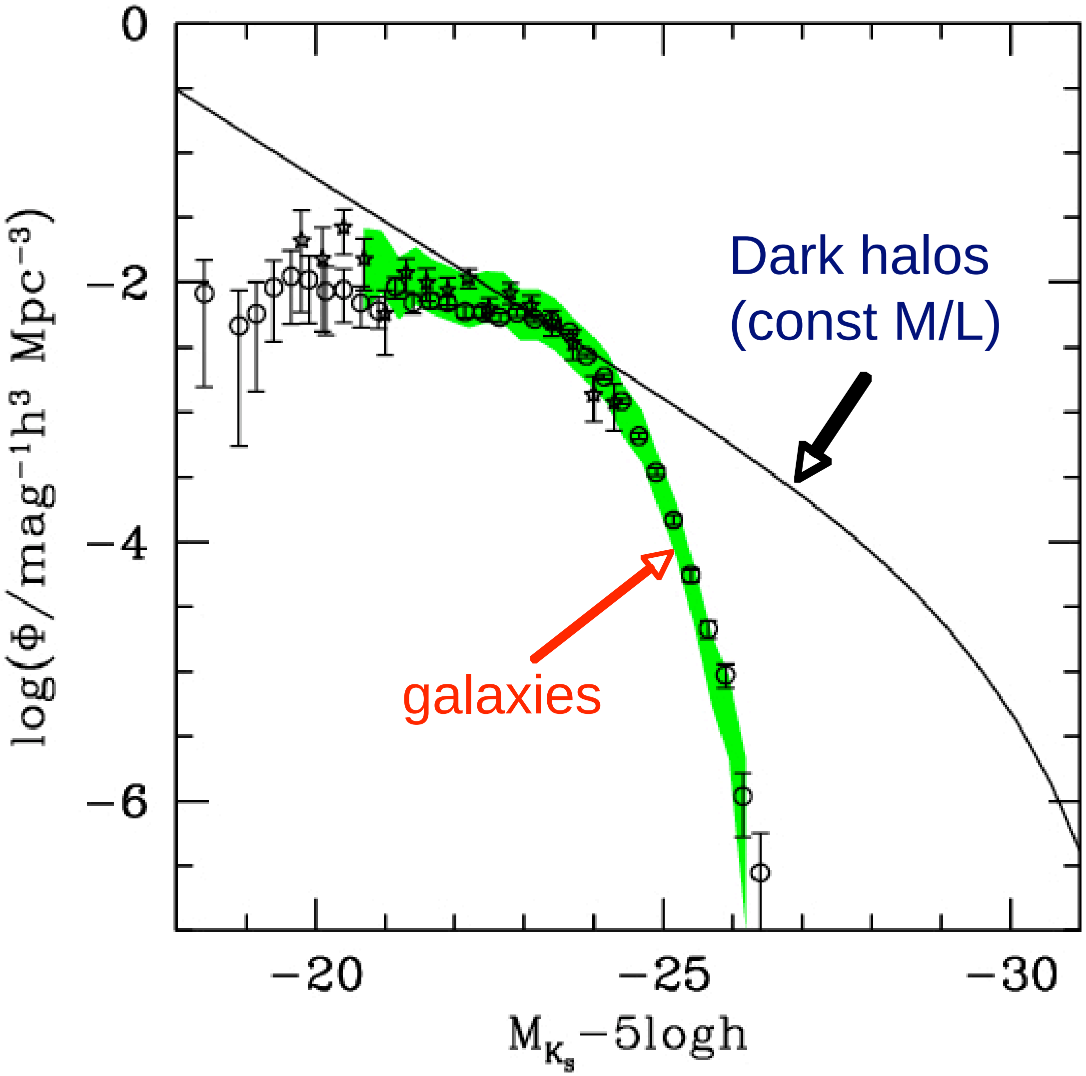
At high z: Pettini et al 02

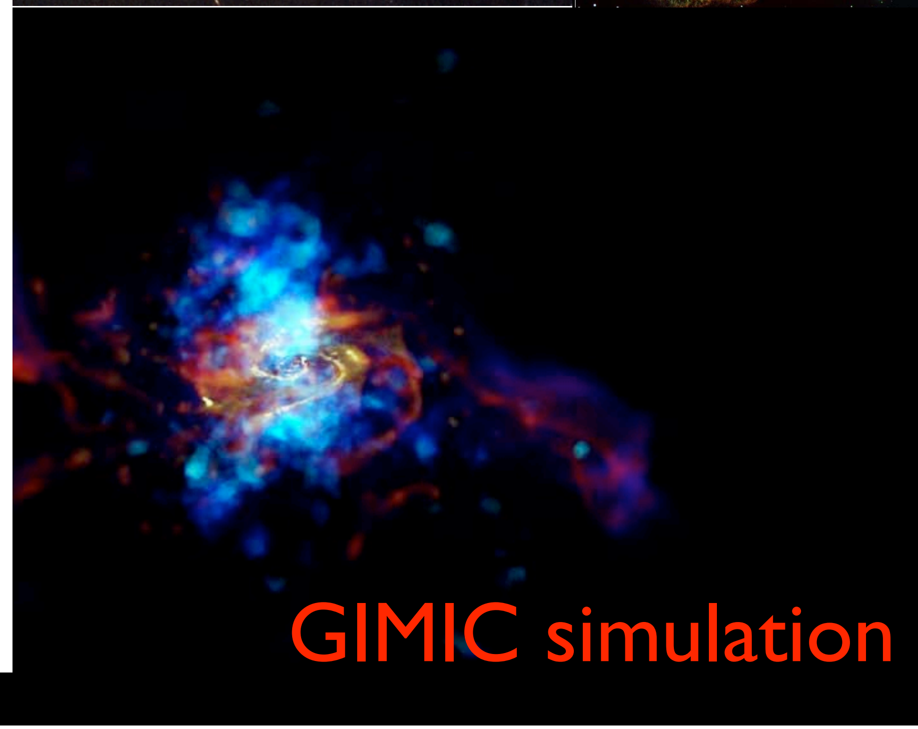
At low z: M82



In absorption

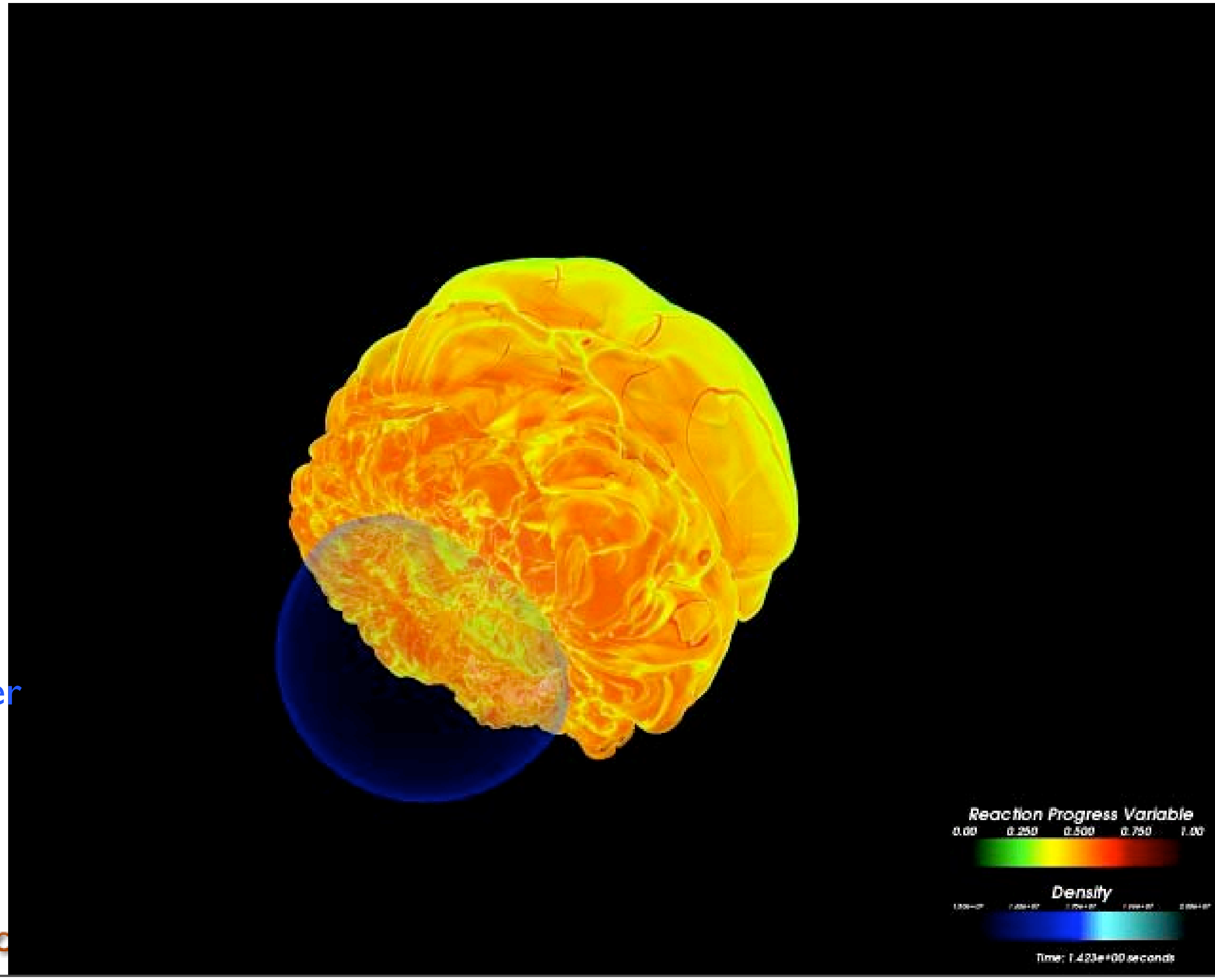
Supernova feedback leads to expulsion of gas out of galaxy





4. Stellar evolution

- Stellar initial initial mass function (Chabrier)
- Stellar lifetimes
- Luminosities (BC models)
- Stellar yields
  - Type I SNe
  - Type II SNe
  - AGB stars



Few+12,Tornatore+07,Oppenheimer+06,Kawata+13,Scannapieco+09

5: AGN implementation

Dark matter haloes determine the masses of supermassive black holes

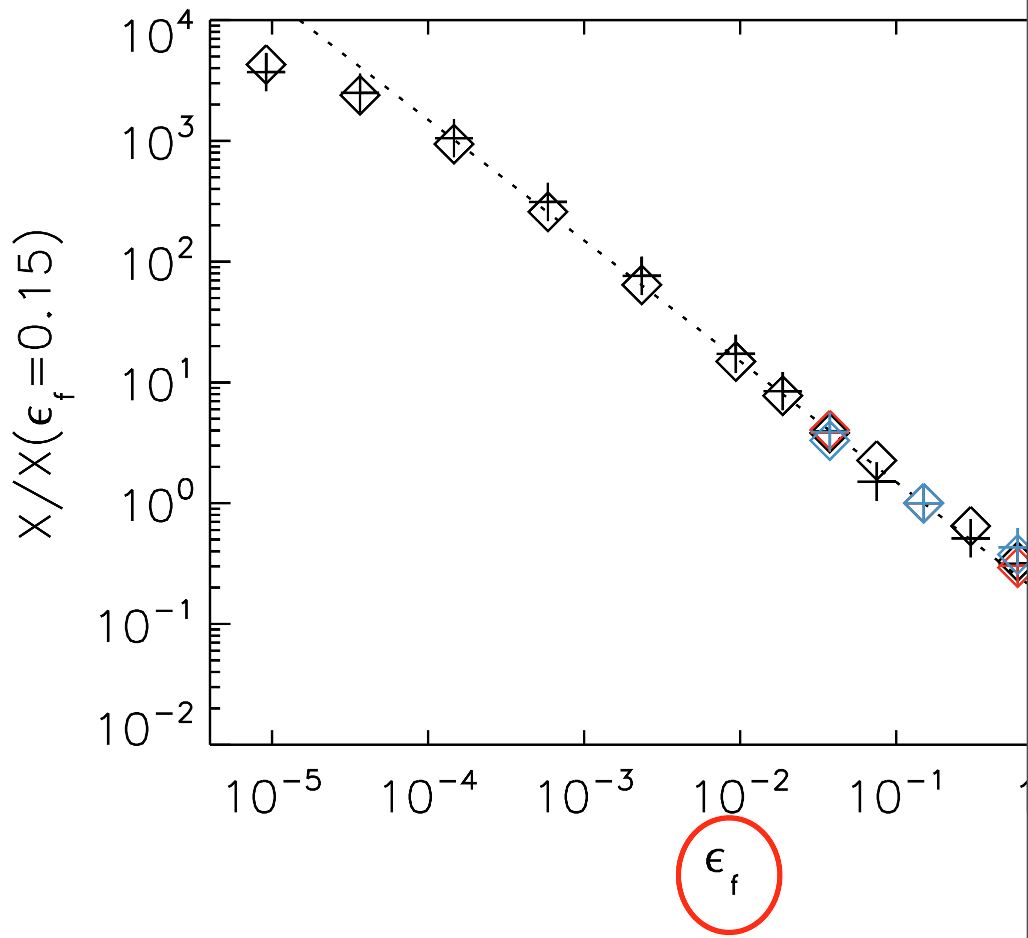
C. M. Booth[1*] and Joop Schaye[1] MN, 2010

BH grows such that it produces a constant amount of feedback

$$\dot{E} = \epsilon_f \epsilon_r \dot{m}_{\rm accr} c^2 = \frac{\epsilon_f \epsilon_r}{1-\epsilon_r} \dot{m}_{\rm BH} c^2 \,,$$

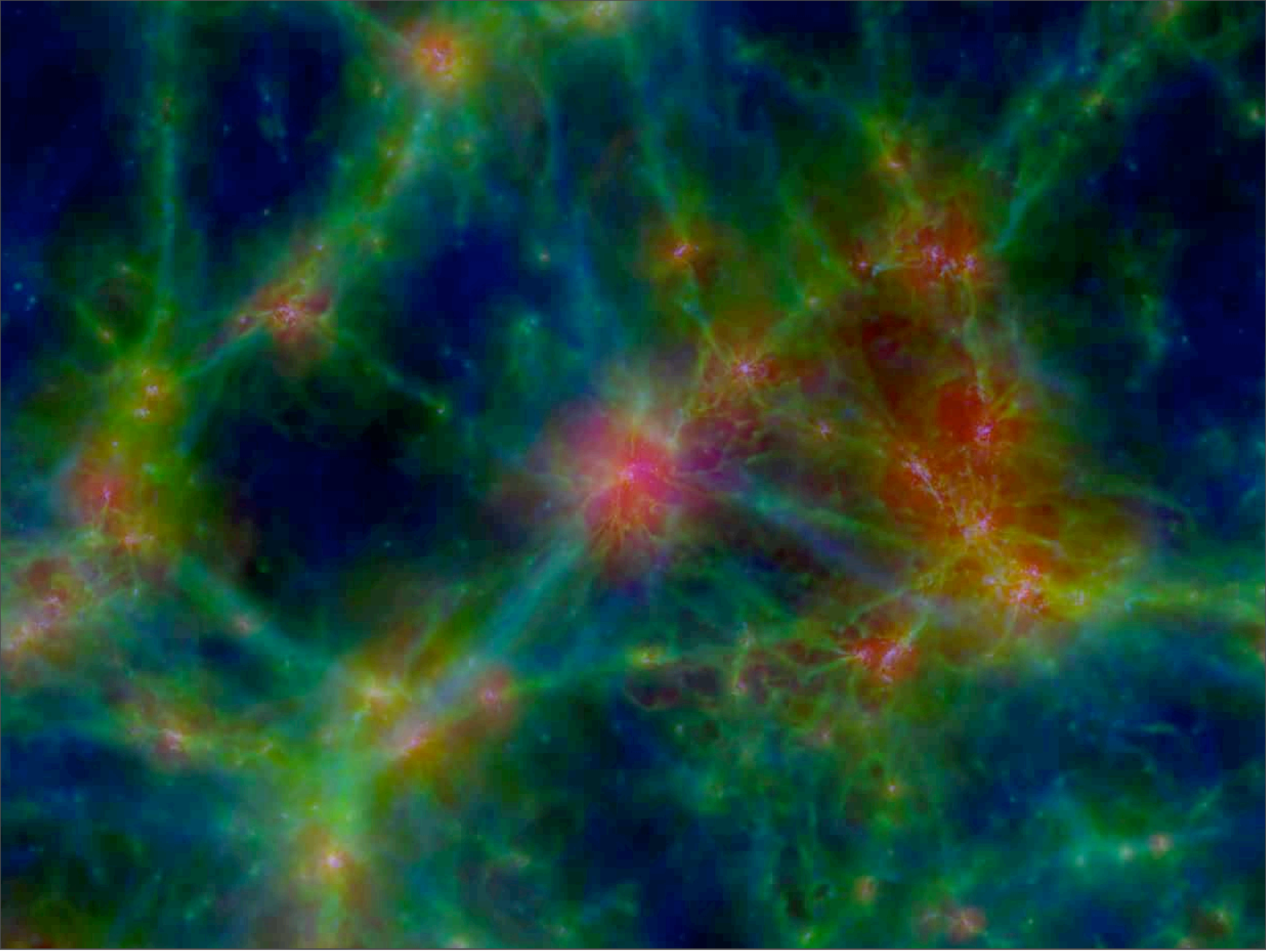
BH accretion rate

energy from accreting BH injected into surrounding gas



Mass of BH is not set by accretion rate, but by its feedback efficiency

Di Matteo+08



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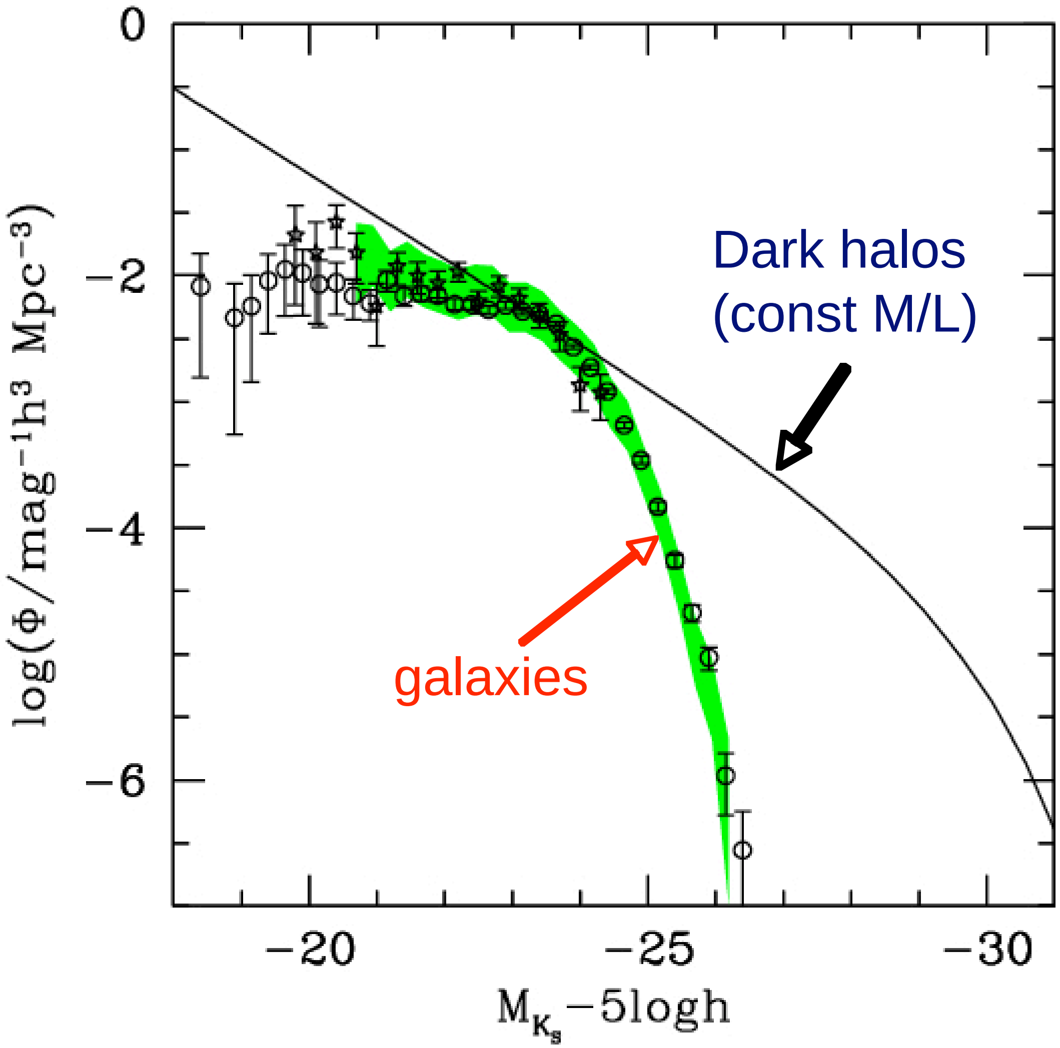

Feedback or gastrophysics is key

Subgrid parameters

- Heating/cooling
  - Epoch of reionisation, UV/X-ray background, self-shielding
- Star formation
  - KS-parameters, threshold, H_2 - Z dependence?
- Stellar evolution
  - Stellar initial mass function, yields, life-times
- Supernova feedback
  - Coupling SNe to gas, heating/wind parameters
- AGN feedback
  - Seed mass, accretion rate, feedback efficiency

The challenges of theory/numerical simulations:

Scales:

- Box Size = 50 Mpc, bulge size = 1kpc
  - need (500 000)^3 resolution elements
- Mean density = 10^{-7} cm^{-3}, star formation starts at 100 cm^{-3}
  - 10^9 density contrast
- Age of Universe 13.7 Gyr, sound-crossing time bulge: 1 Myr
  - require 10^4 steps

Physics:

- Gas cooling
  - follow synthesis of elements, effects of radiation
- star formation
  - magnetic fields, dust, shielding
- feedback from stars
- supernovae, cosmic rays
- Black-hole formation
  - feedback from black holes
- Observables!

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“ .. as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns -- the ones we don't know we don't know."

The physics driving the cosmic star formation history

Joop Schaye,[1*] Claudio Dalla Vecchia,[1] C. M. Booth,[1] Robert P. C. Wiersma,[1]
Tom Theuns,[2,3] Marcel R. Haas,[1] Serena Bertone,[4] Alan R. Duffy,[1,5]
I. G. McCarthy,[6] and Freeke van de Voort[1]

Schaye+10

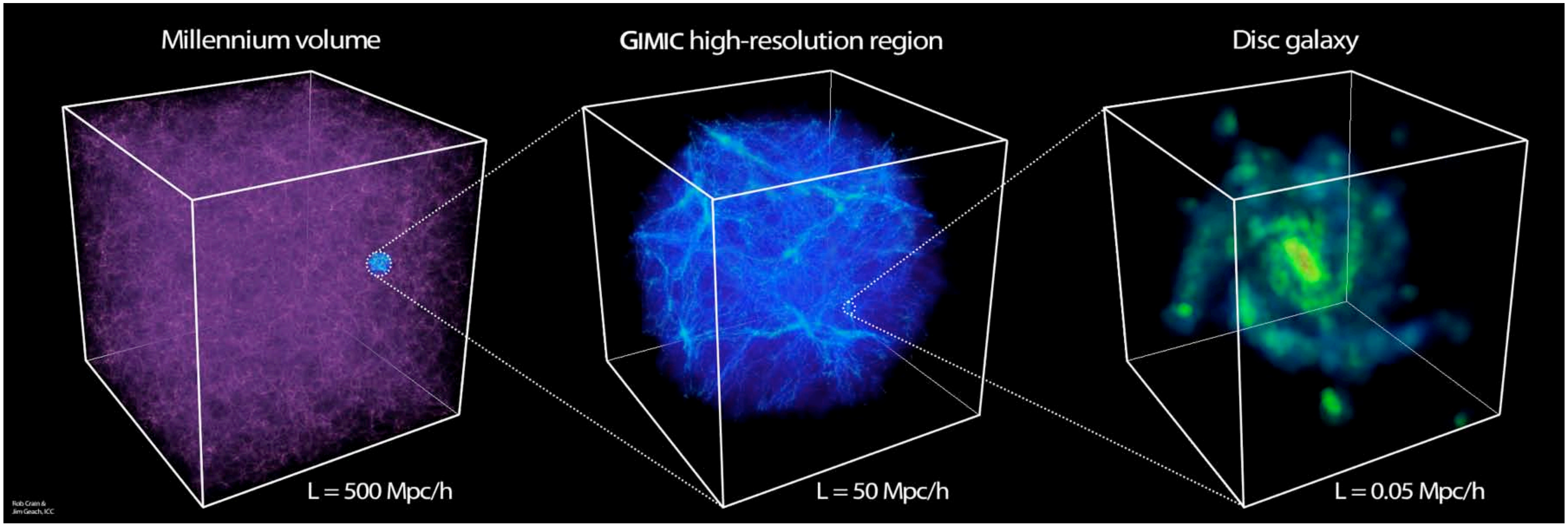
Galaxies-Intergalactic Medium Interaction Calculation –I. Galaxy formation as a function of large-scale environment.

Robert A. Crain[1,2⋆], Tom Theuns[1,3], Claudio Dalla Vecchia[4], Vincent R. Eke[1], Carlos S. Frenk[1], Adrian Jenkins[1], Scott T. Kay[5], John A. Peacock[6] Frazer R. Pearce[7], Joop Schaye[4], Volker Springel[8], Peter A. Thomas[9], Simon D. M. White[8] & Robert P. C. Wiersma[4] (The Virgo Consortium)

Crain+09

Suite of simulations: GIMIC/OWLS

Galaxy-Intergalactic Medium Interaction Calculation



Zoomed simulations of 5 spheres picked from the Millennium Simulation

Combine LSS with high numerical resolution

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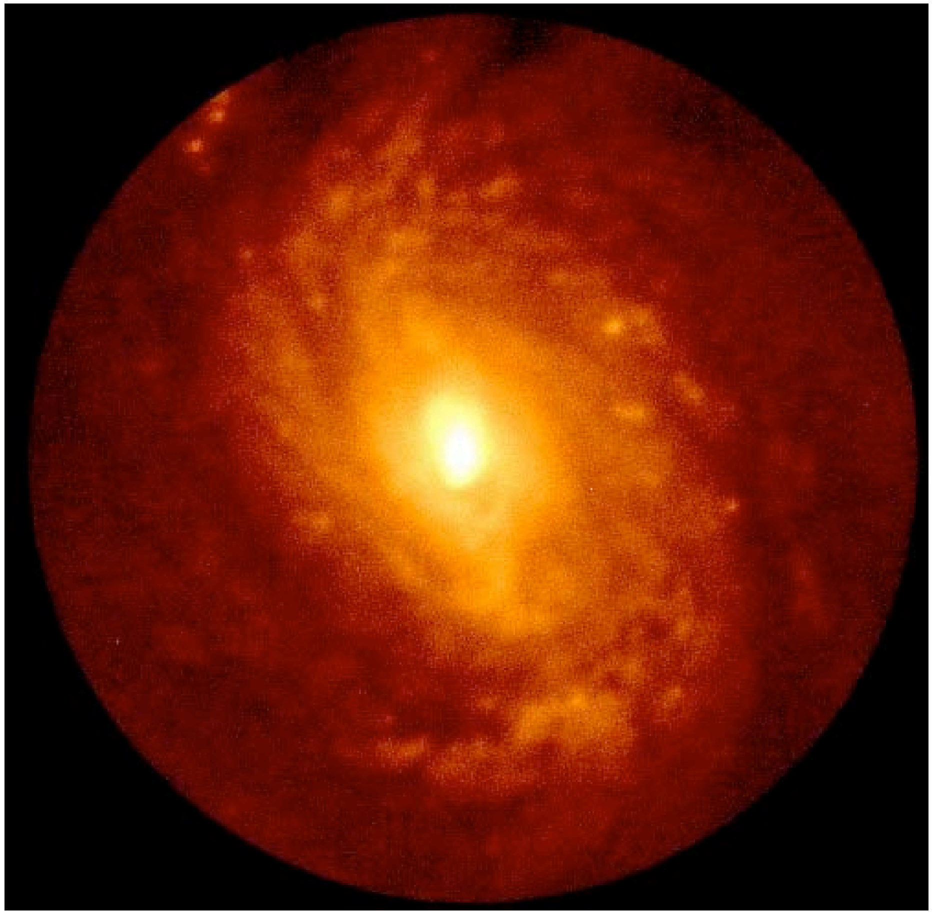
OverWhelmingly Large Simulations:
periodic boxes (25,100Mpc) with
range of physics (50+models)

Name	Box Size (Mpc/h)	Comment
DBLIMFCONTSFV1618	100/25	Top-heavy IMF above $n_{\rm H} > 30\ {\rm cm}^{-3}$, $v_{\rm w} = 1618\ {\rm km\,s}^{-1}$
DBLIMFV1618	100/25	Top-heavy IMF above $n_{\rm H} > 30\ {\rm cm}^{-3}$, $v_{\rm w} = 1618\ {\rm km\,s}^{-1}$, $\dot{\Sigma}_*(0) = 2.083 \times 10^{-5} {\rm M}_\odot {\rm yr}^{-1} {\rm kpc}^{-2}$
DBLIMFCONTSFML14	100/25	Top-heavy IMF above $n_{\rm H} > 30\ {\rm cm}^{-3}$, $\eta = 14.545$
DBLIMFML14	100/25	Top-heavy IMF above $n_{\rm H} > 30\ {\rm cm}^{-3}$, $\eta = 14.545$, $\dot{\Sigma}_*(0) = 2.083 \times 10^{-5} {\rm M}_\odot {\rm yr}^{-1} {\rm kpc}^{-2}$
REFERENCE	100/25	
EOS1p0	100/25	Isothermal equation of state, particles with $n_{\rm H} > 30\ {\rm cm}^{-3}$ are instantaneously converted into stars if they are on the equation of state
EOS1p67	25	Equation of state $p \propto \rho^{\gamma_*}$, $\gamma_* = 5/3$
IMFSALP	100/25	Salpeter IMF, SF law rescaled
MILL	100/25	Millenium cosmology (WMAP1): $(\Omega_m, \Omega_\Lambda, \Omega_b h^2, h, \sigma_8, n, X_{He}) = (0.25, 0.75, 0.024, 0.73, 0.9, 1.0, 0.249)$
NOAGB_NOSNIa	100	AGB & SNIa mass & energy transfer off
NOHeHEAT	25	No He reheating
NOSN	100/25	No SNII winds, no SNIa energy transfer
NOSN_NOZCOOL	100/25	No SNII winds, no SNIa energy transfer, cooling uses initial (i.e., primordial) abundances
NOZCOOL	100/25	Cooling uses initial (i.e., primordial) abundances
REIONZ06	25	Redshift reionization = 6
REIONZ12	25	Redshift reionization = 12
SFAMPLx3	25	$\dot{\Sigma}_*(0) = 4.545 \times 10^{-4} {\rm M}_\odot {\rm yr}^{-1} {\rm kpc}^{-2}$
SFAMPLx6	25	$\dot{\Sigma}_*(0) = 9.09 \times 10^{-4} {\rm M}_\odot {\rm yr}^{-1} {\rm kpc}^{-2}$
SFSLOPE1p75	25	$\gamma_{\rm KS} = 1.75$
SFTHRESZ	25	Metallicity-dependent SF threshold
SNIaGAUSS	100	Gaussian SNIa delay distribution (efficiency: 2.56 %)
WDENS	100/25	Wind mass loading and velocity determined by the local density
WML1V848	100/25	$\eta = 1$, $v_{\rm w} = 848 {\rm km\,s}^{-1}$
WML4	100/25	$\eta = 4$
WML8V300	25	$\eta = 8$, $v_{\rm w} = 300 {\rm km\,s}^{-1}$
WPOT	100/25	Momentum driven wind model (scaled with the potential)
WPOTNOKICK	100/25	Momentum driven wind model (scaled with the potential) without extra velocity kick = 2 x local velocity dispersion
WVCIRC	100/25	Momentum driven wind model (scaled with the resident halo mass)

- The basics.
- What do we want?
- What can we do?
- Does it work?
- What did we learn?
- Where do we go from here?

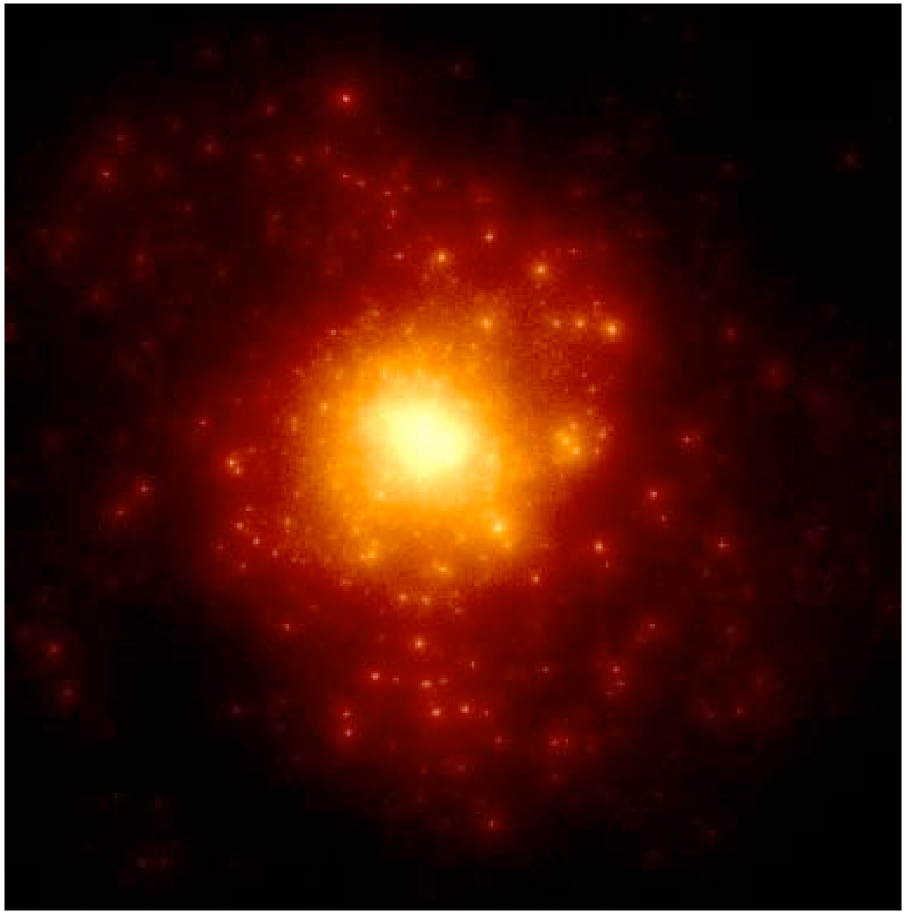
Observed

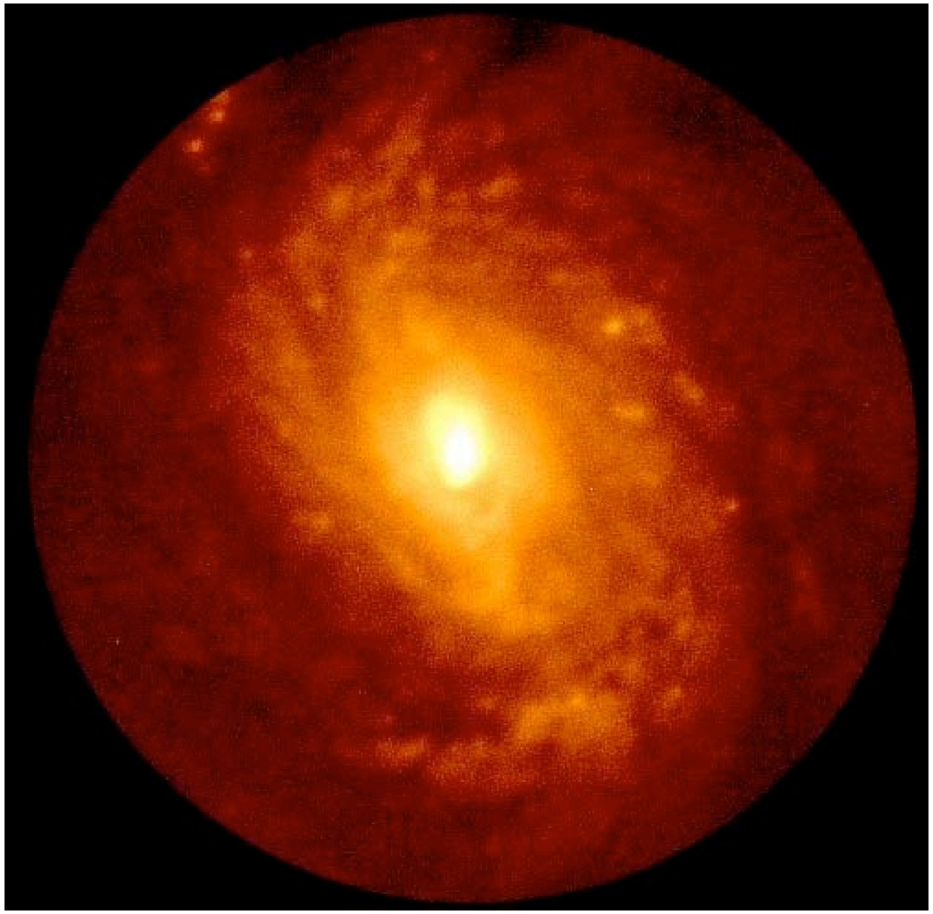


NGC 1068

Simulated

Observed





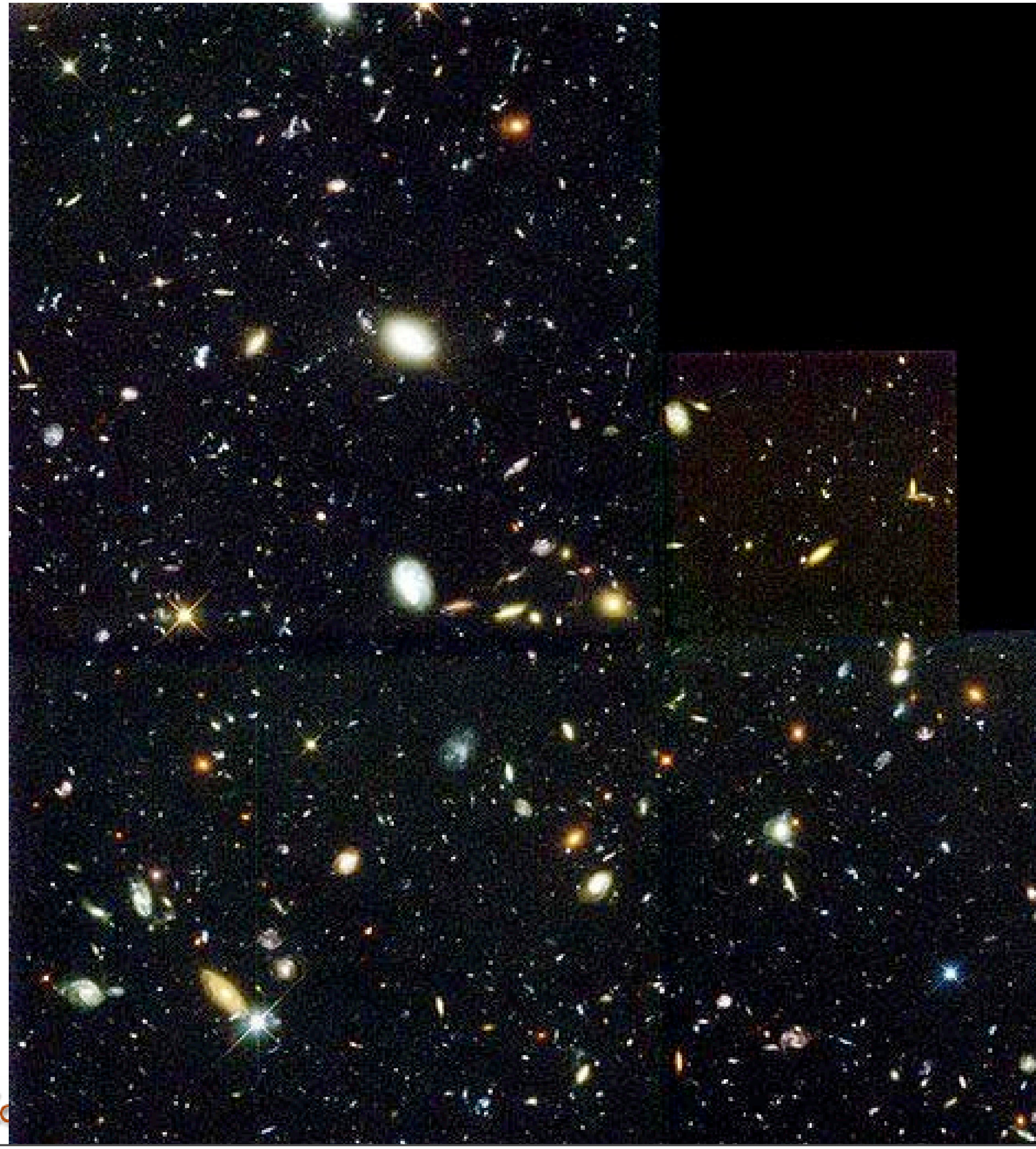
Gadget simulation

NGC 1068

SKIRT + EAGLE

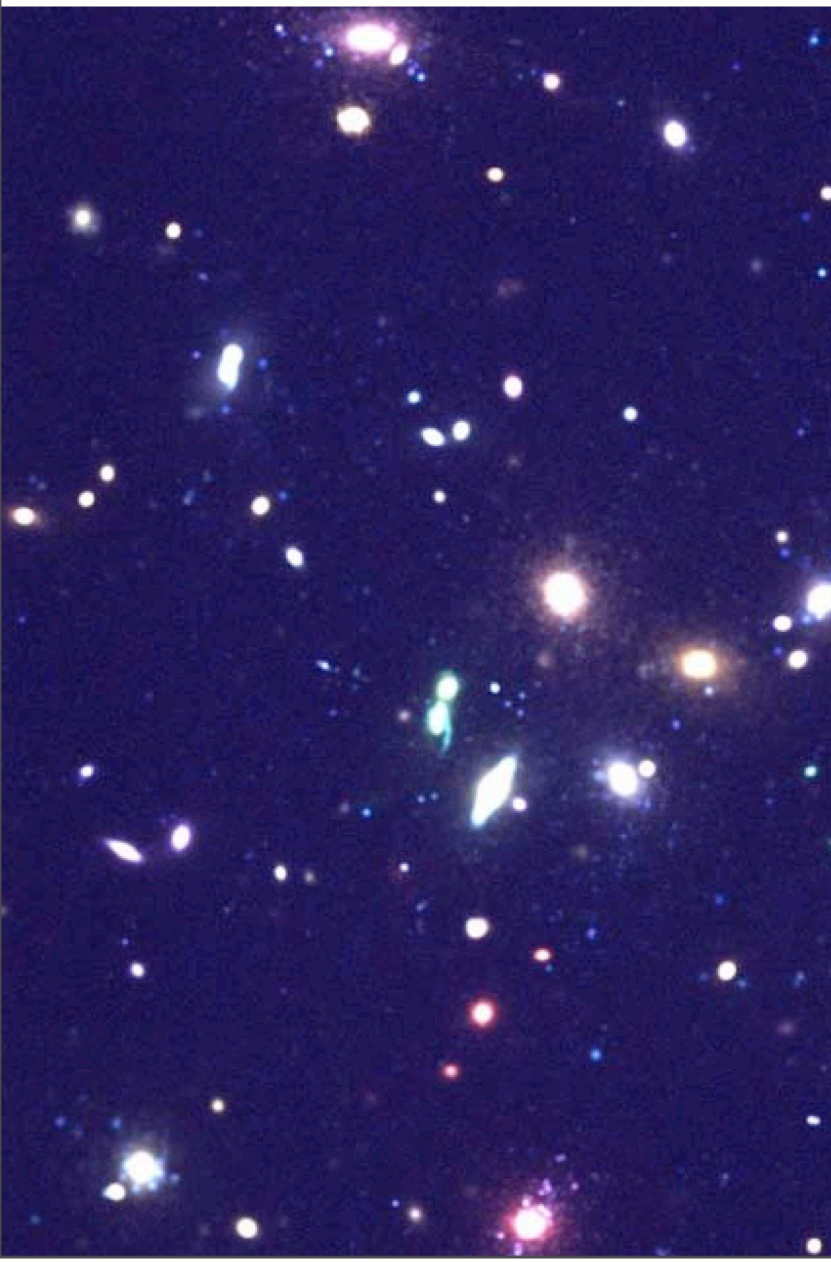
M Baes (Gent)

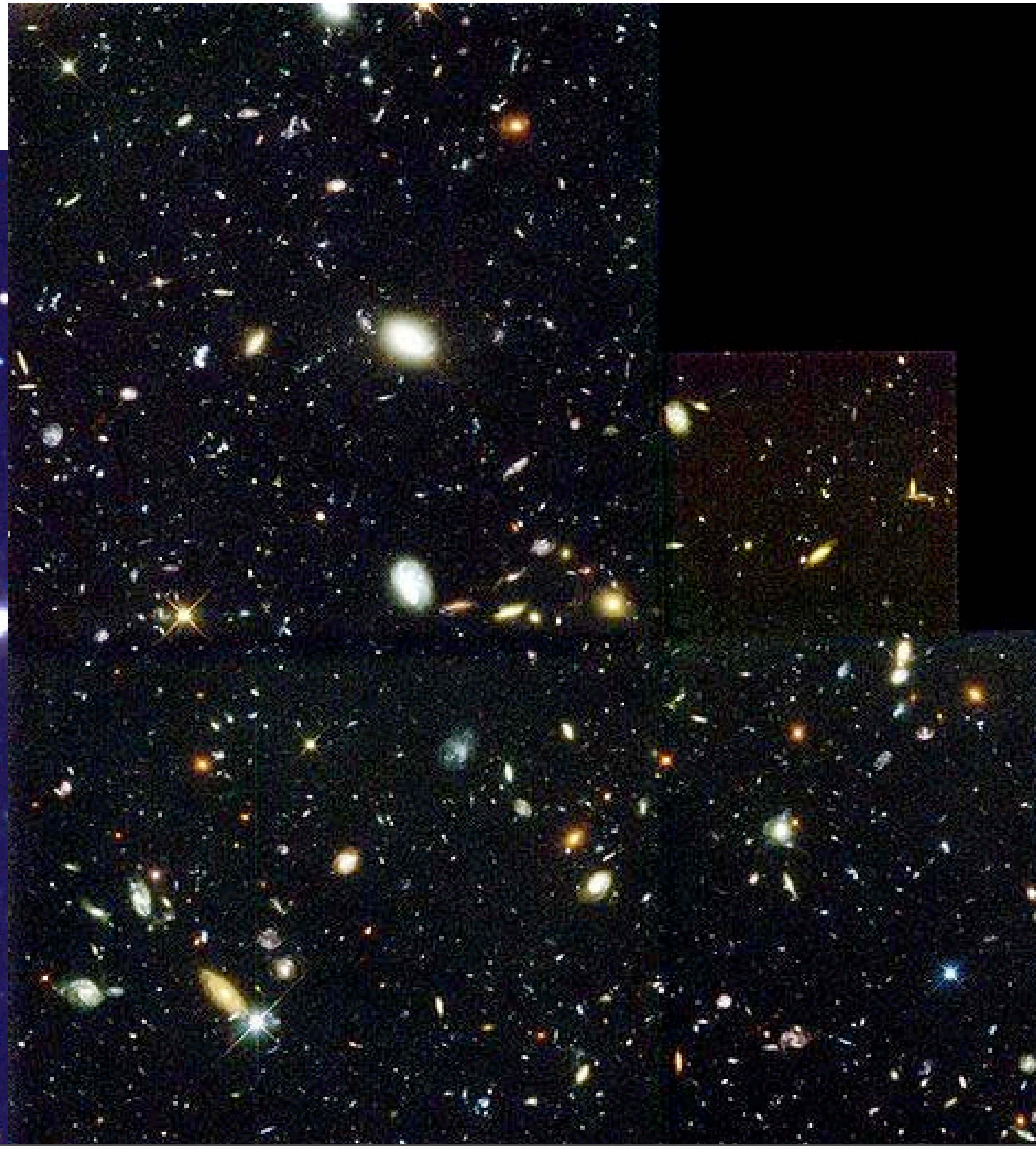
Hubble Deep Field



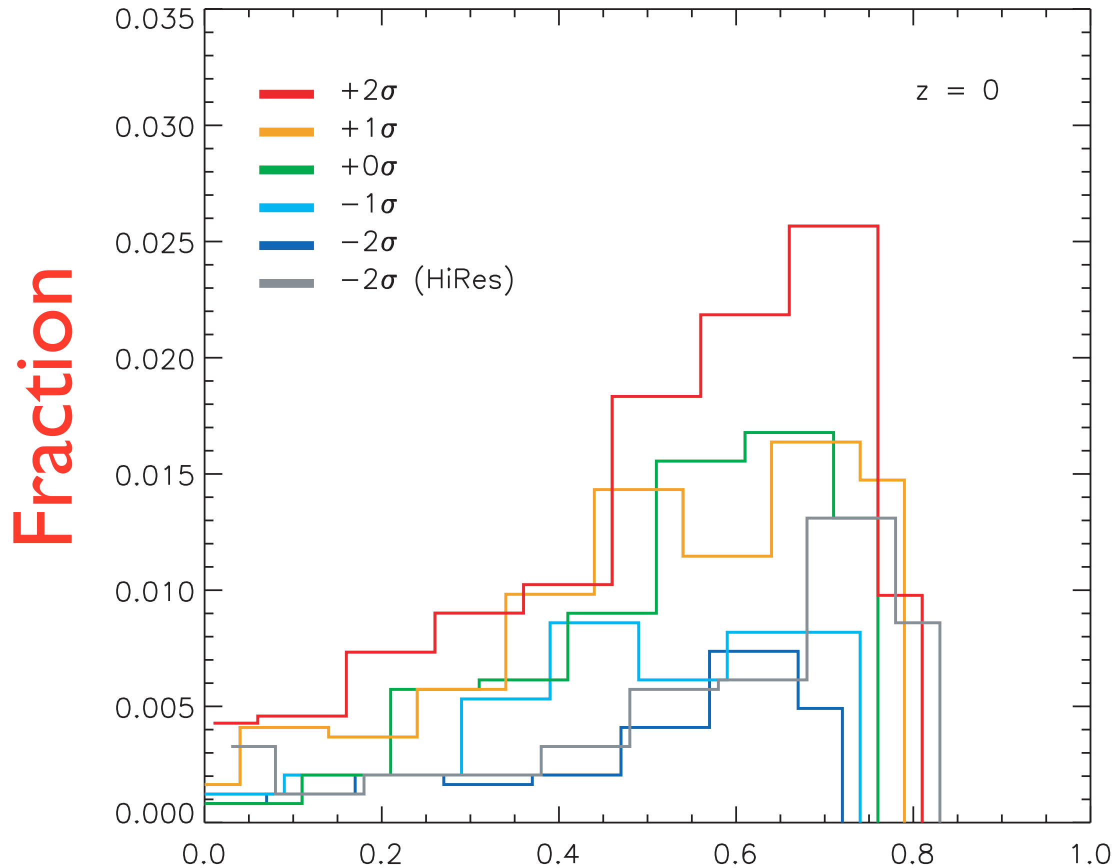
Hubble Deep Field

Gadget deep field





We have a Hubble sequence!



but why?

Bulge-dominated

Disc/total

Disc-dominated

Simulations have > 400 galaxies of MW mass and more, with 10^5 or more particles in them each.

euns

We have a Hubble sequence!

but how do you classify simulated galaxies?

- bulge-disc decomposition on image?
- bulge-disc decomposition?
- colours?

Why do we have a Hubble sequence?

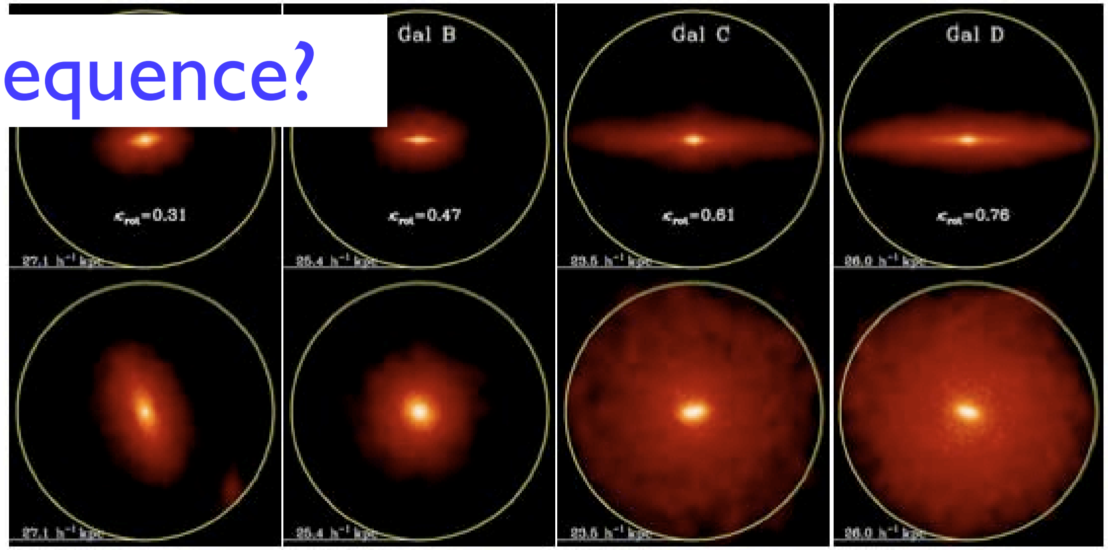
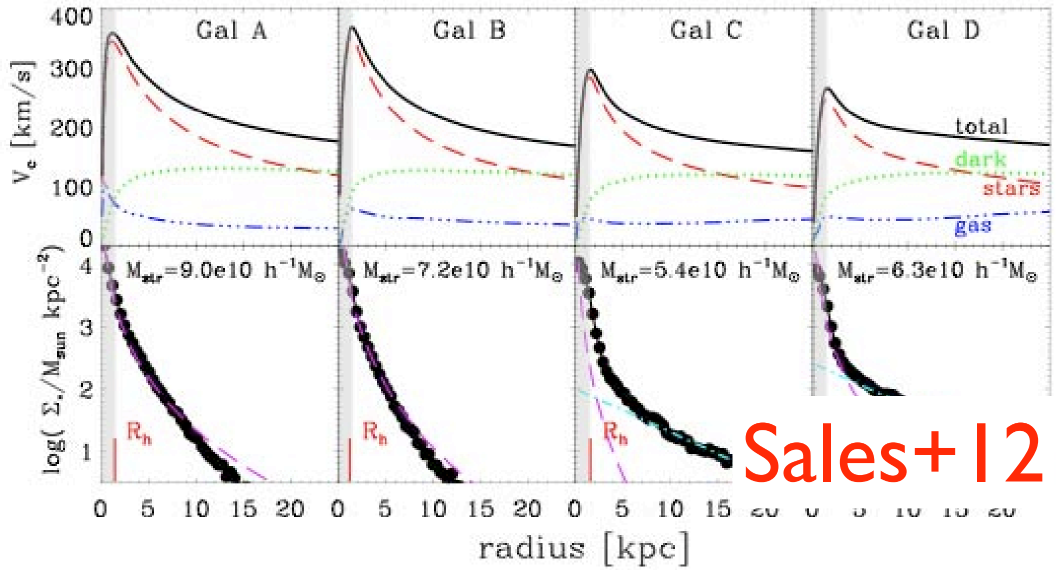


Figure 2. Illustration of the structure of four galaxies in our sample with increasing degree of rotational support (left to right). The first and second row edge-on and face-on projections of the stellar distribution. The yellow circle marks the radius, $r_{gal} = 0.15\, r_{200}$, used to define the galaxy.



Sales+12

Martig+12

The Origin of Disks and Spheroids in Simulated Galaxies

Laura V. Sales[1], Julio F. Navarro[2], Tom Theuns[3,4], Joop Schaye[5], Simon D. M. White[1],

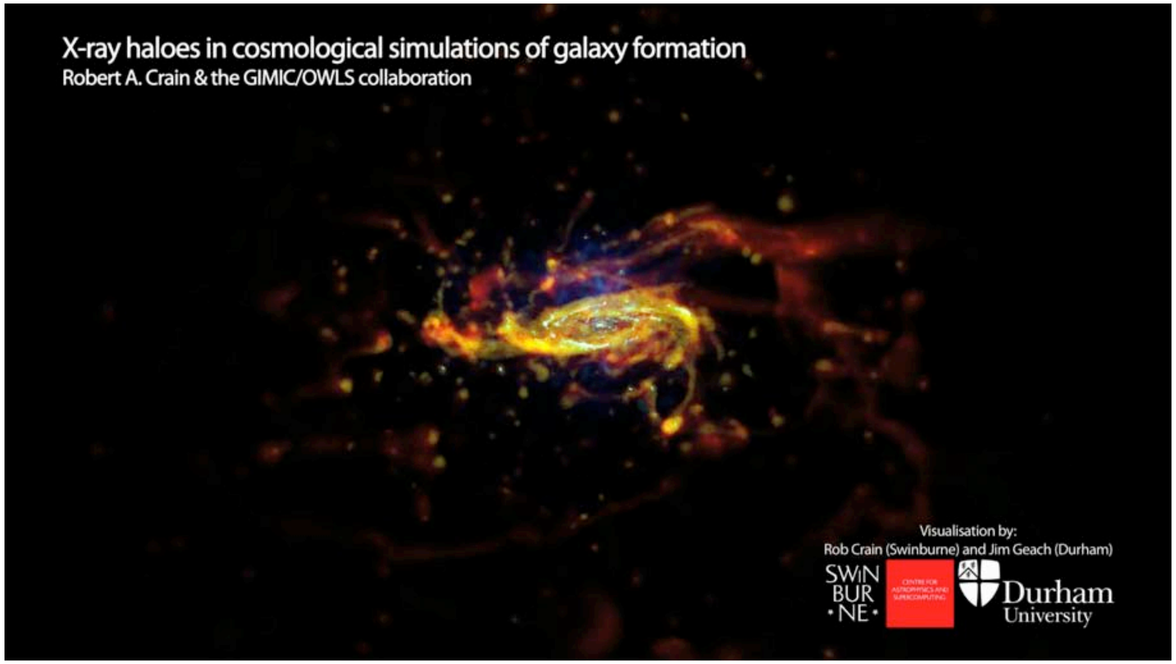
key: alignment of angular momentum in forming galaxy

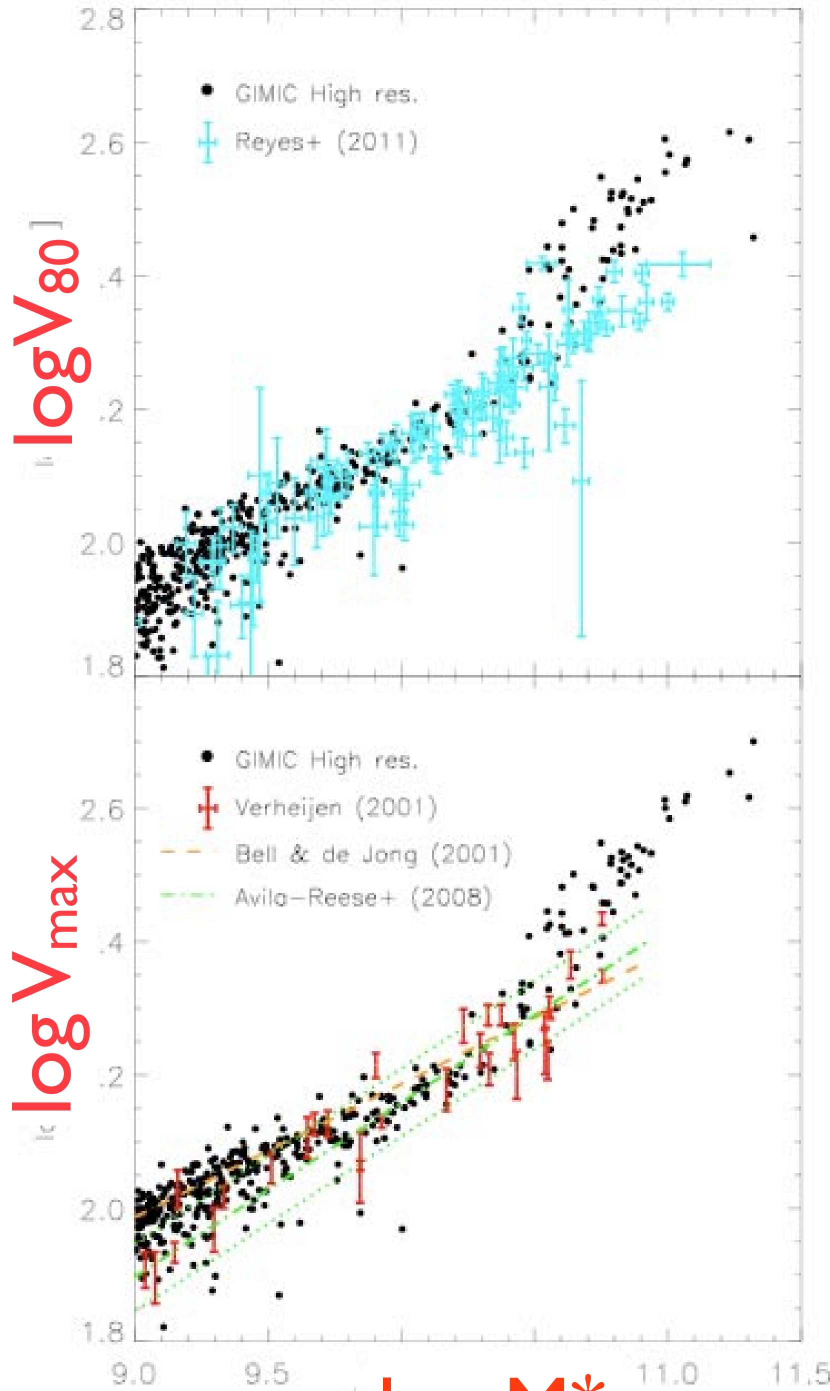
Theuns

Tully-Fisher relation

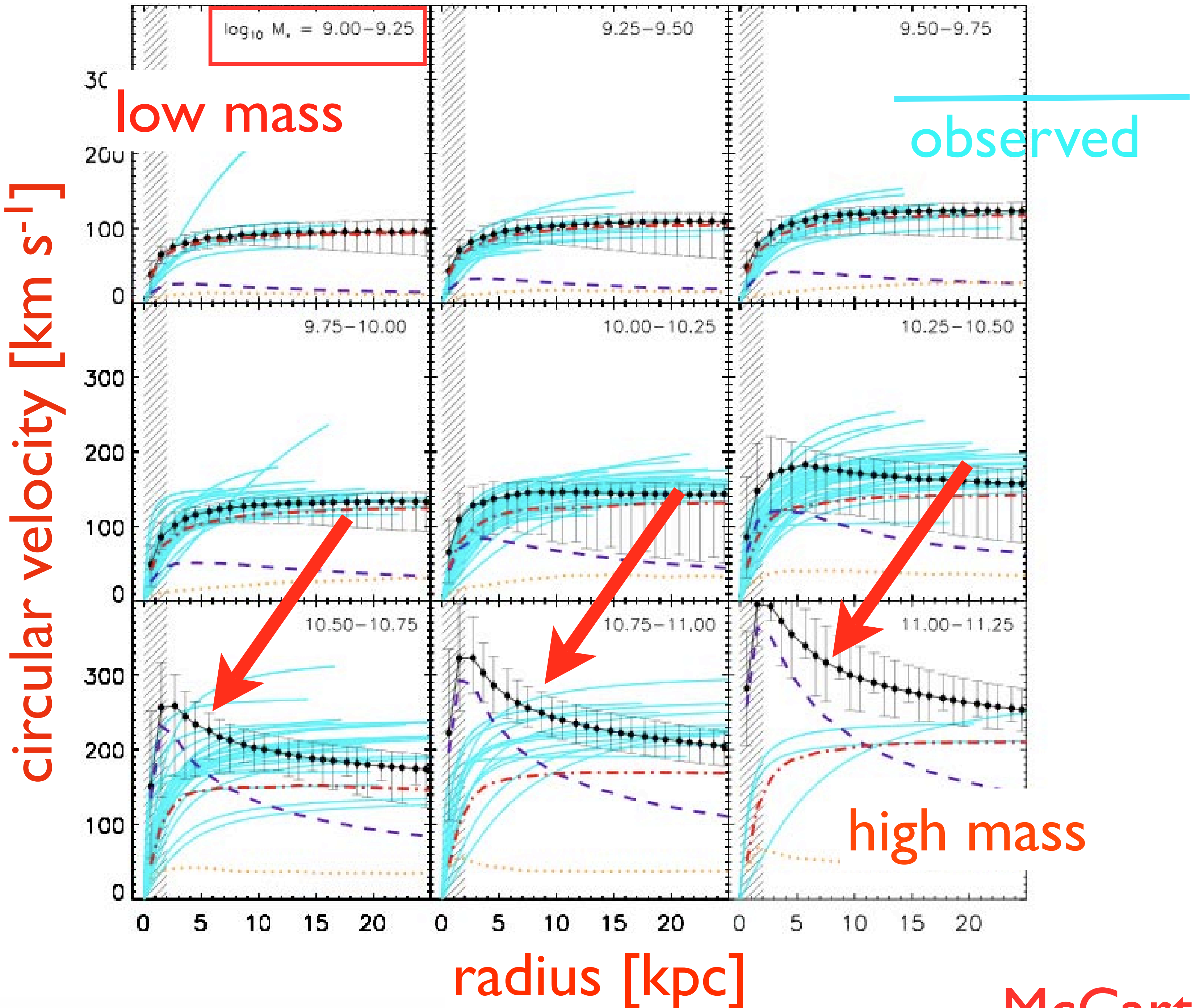
Rotation rates, sizes, and star formation efficiencies o representative population of simulated disc galaxies

I. G. McCarthy[1,2⋆], J. Schaye[3], A. S. Font[1], T. Theuns[4,5], C. S. Frenk[4], R. A. Crain[3], C. Dalla Vecchia[6]





Shapes of rotation curves



McCarthy+12

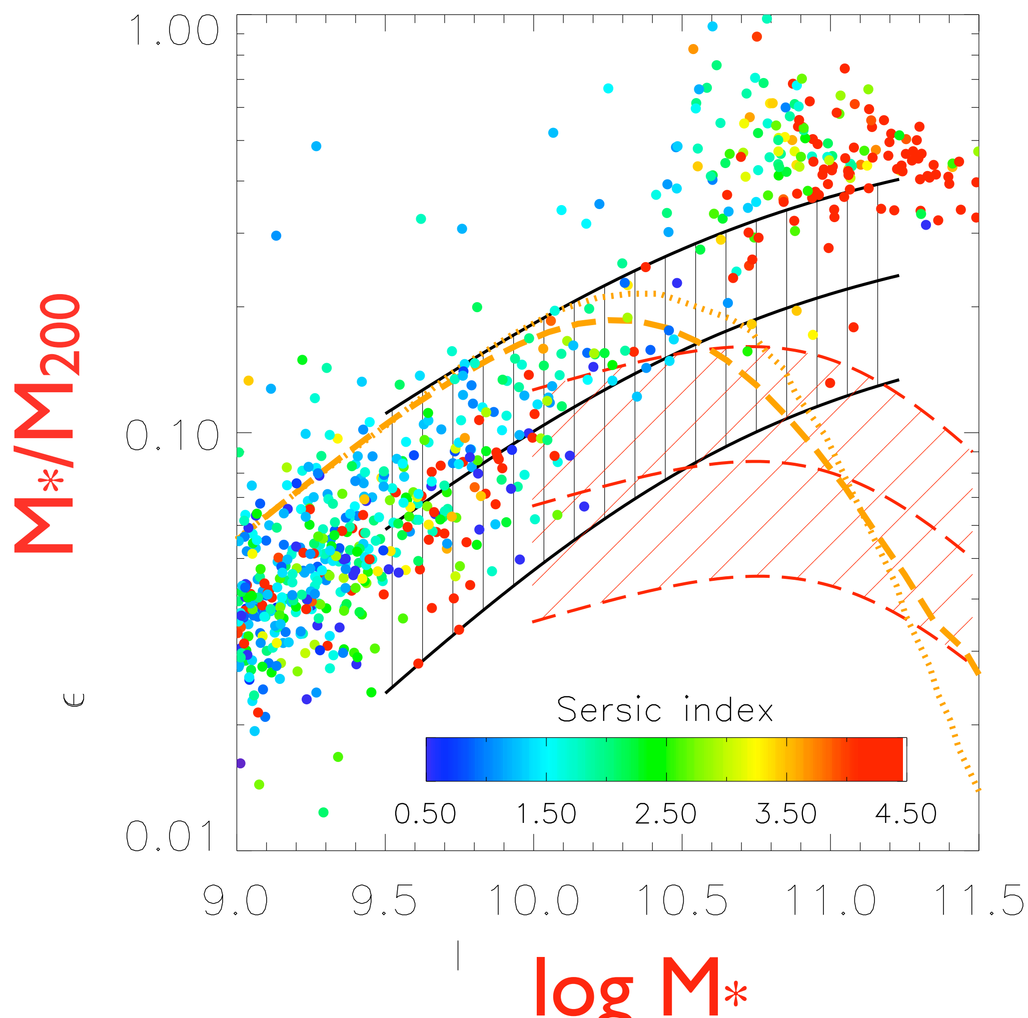
Why do simulated galaxies follow a TF-relation?

$$\frac{dn}{M_{200}} \propto M_{200}^{-1.9}$$

$$\frac{dn}{dM_\star} \propto M_\star^{-\alpha}$$

$$\epsilon_{\rm SF} \equiv \frac{M_\star}{M_{200}} \propto M_\star^{(1.9-\alpha)/0.9}$$

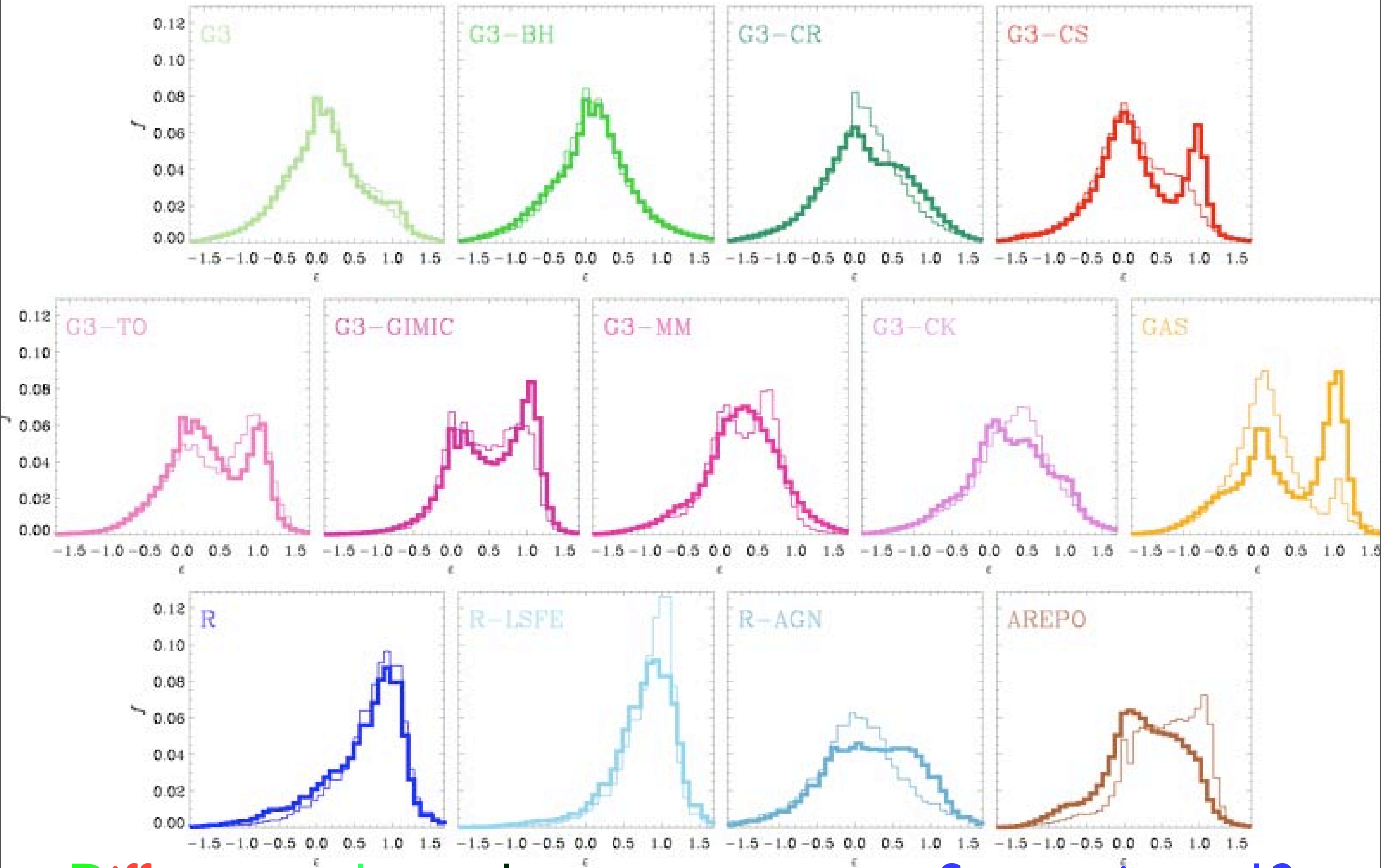
$$V_{\rm rot} \propto M_\star^{(\alpha-1)/2.7}$$



key: correct efficiency, efficient feedback

McCarthy+12

Diskyness of Aquila galaxies



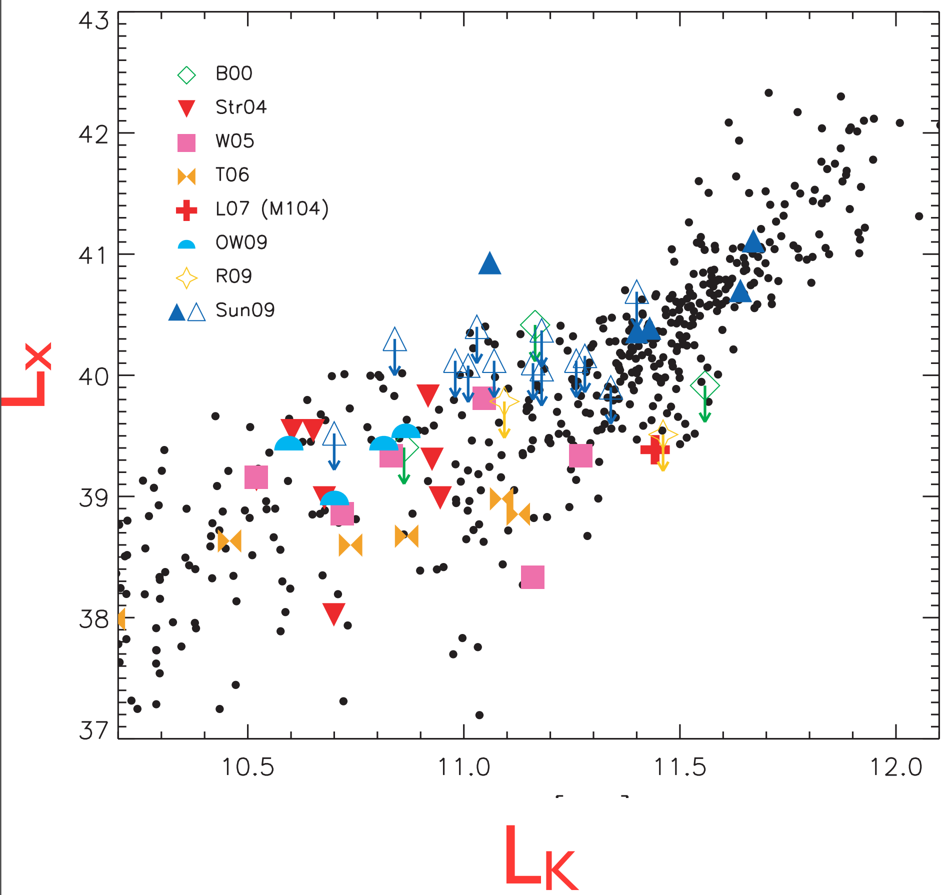
Different codes codes

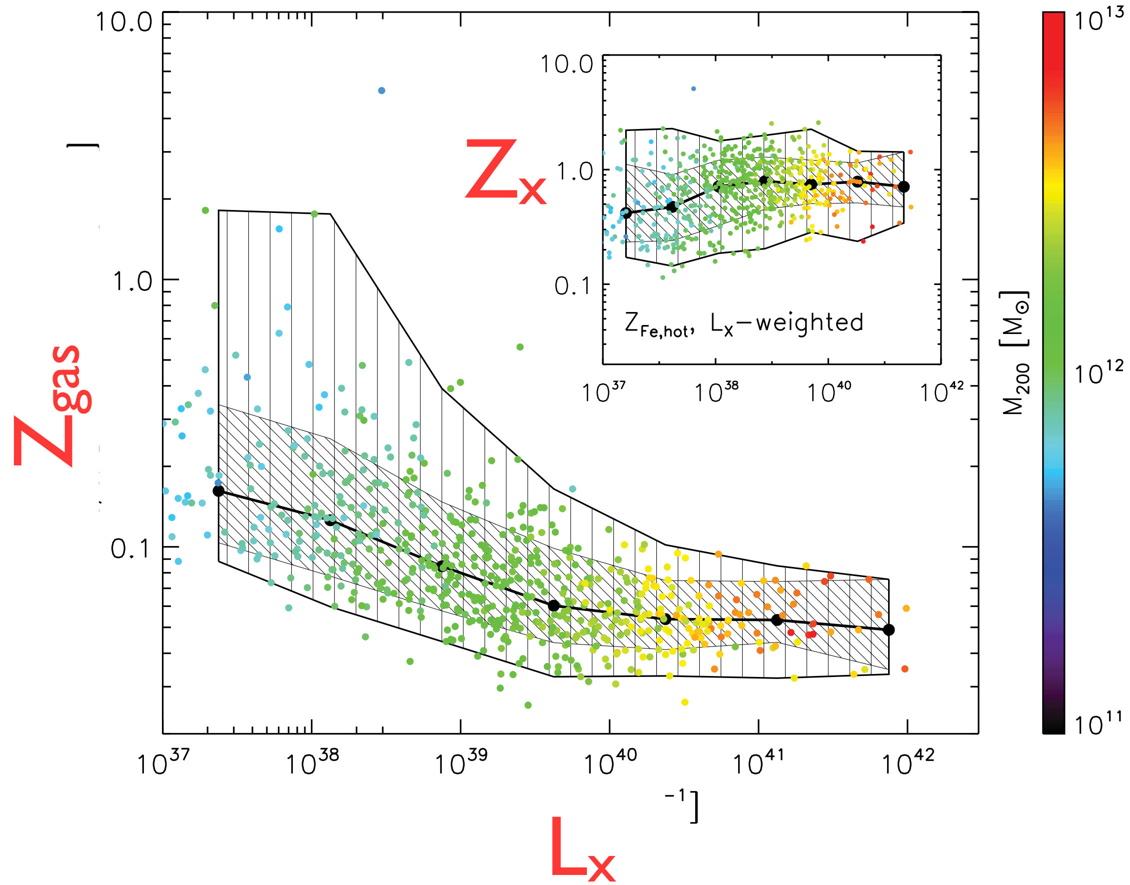
Scannapieco+12

X-ray haloes of MW-like galaxies

Gas in haloes of spirals has a reasonable X-ray luminosity and metallicity

(long a stumbling block in semi-analytical models)

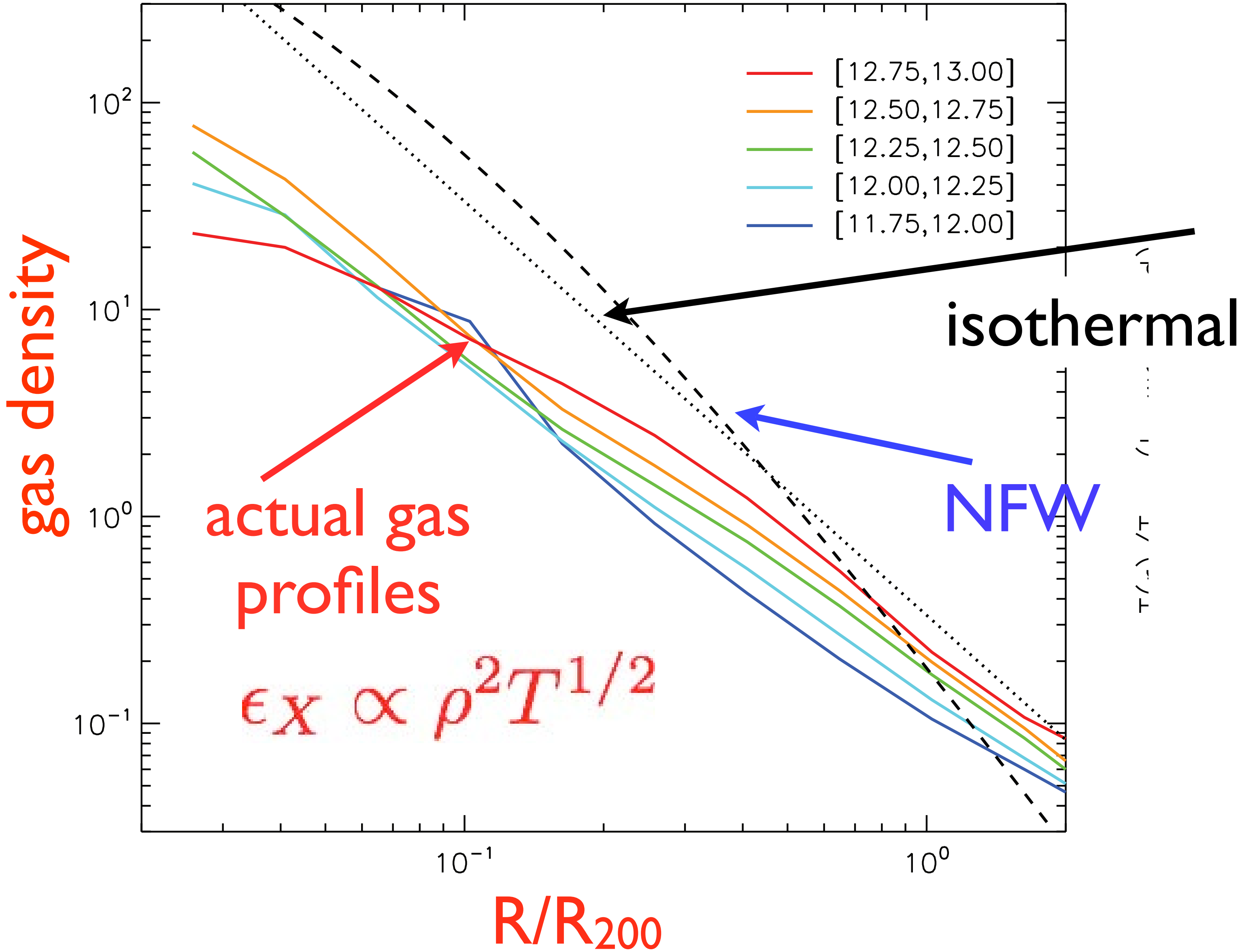




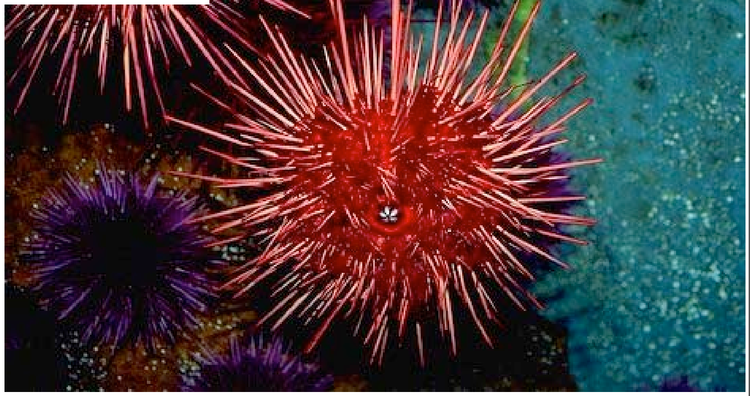
Crain+10 itute for Computational Cosmology 50

Crain+12

Why does gas in haloes of spirals have a reasonable X-ray luminosity and metallicity?

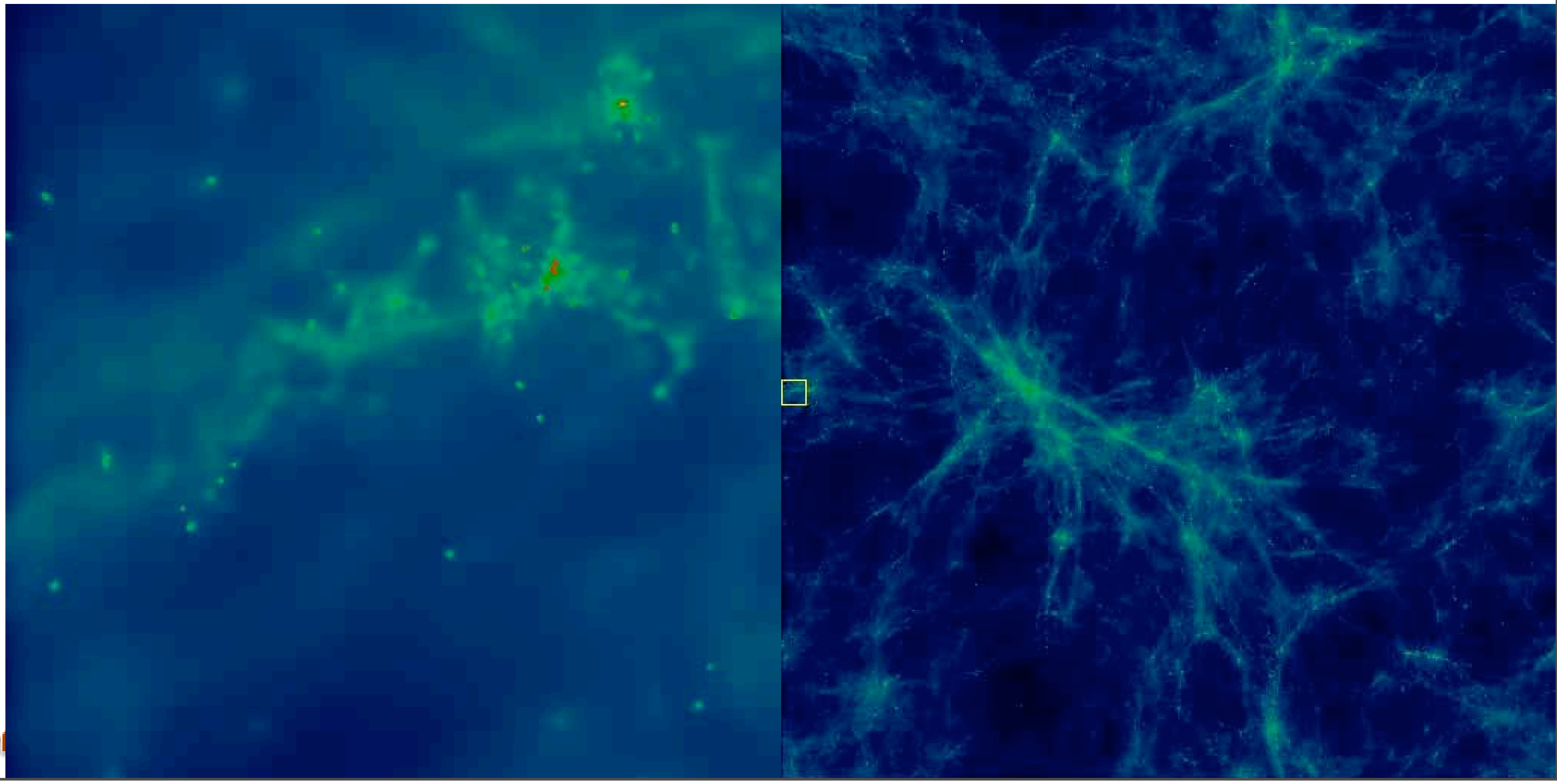


The Universe in (HI) absorption



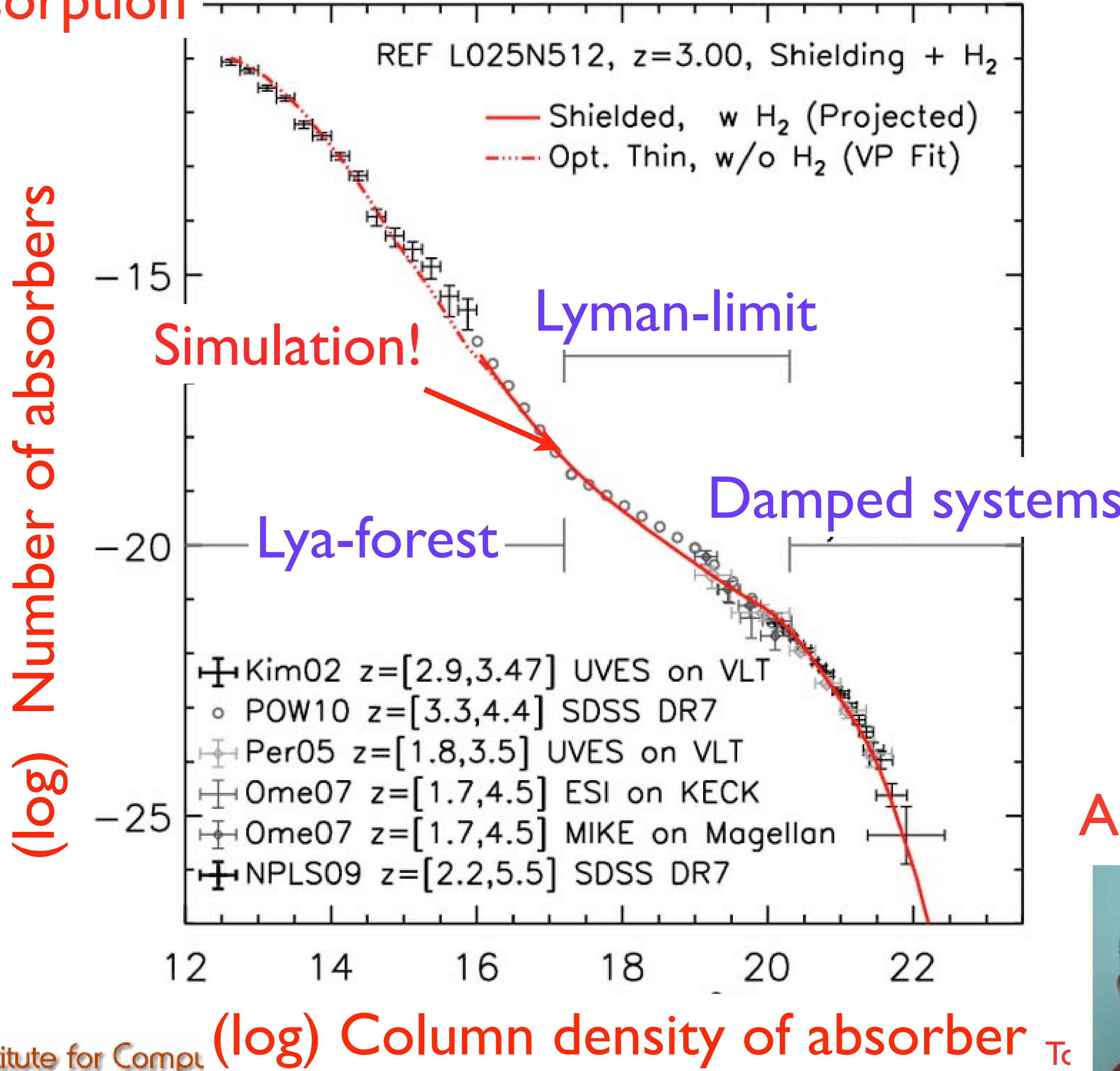
Through Thick and Thin - HI Absorption in Cosmological Simulations

Gabriel Altay[1], Tom Theuns[1,2], Joop Schaye[3], Neil H. M. Crighton[4,5] and Claudio Dalla Vecchia[3,6]



ICC Institute for Co

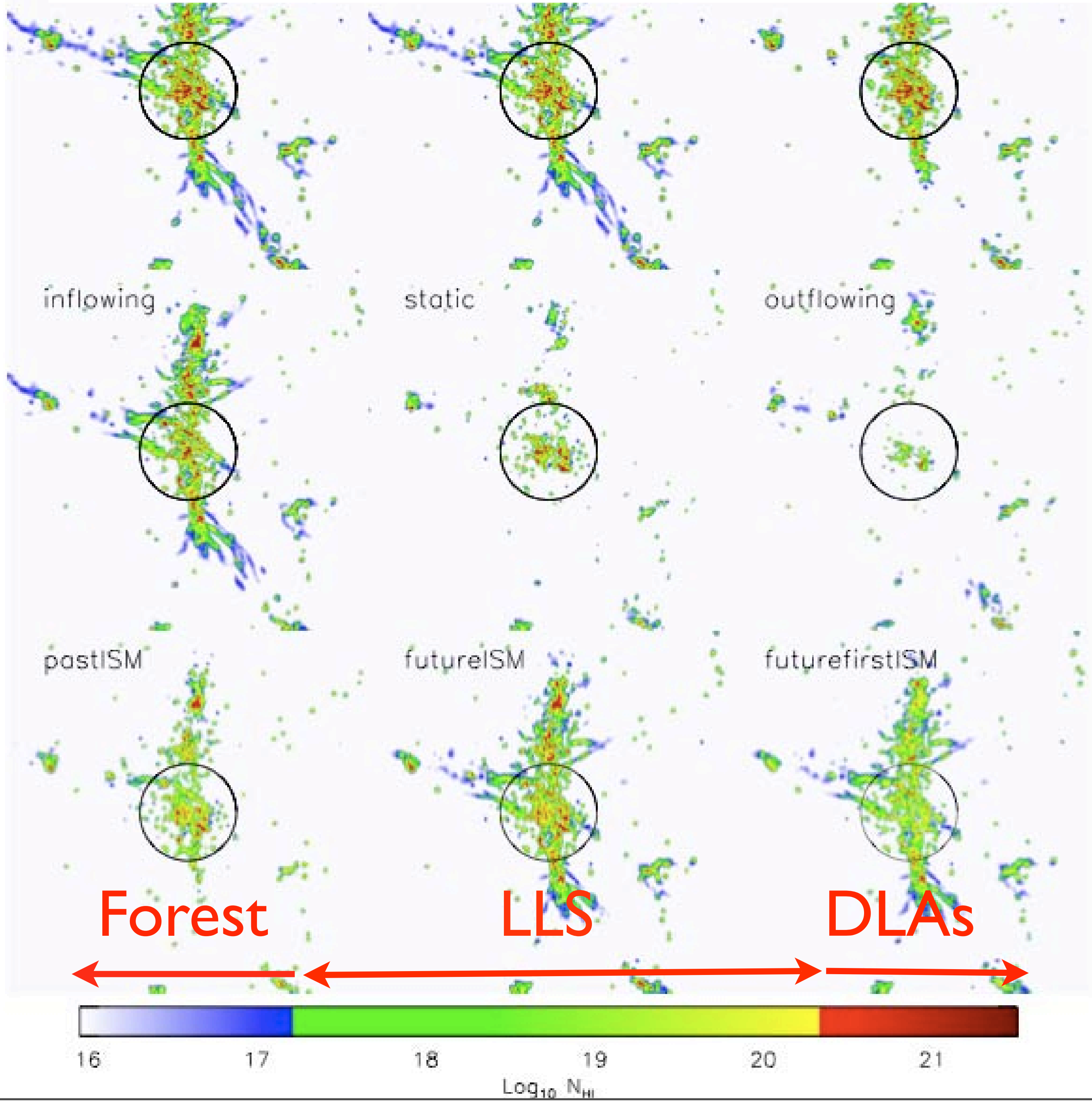
HI in absorption



Altay +

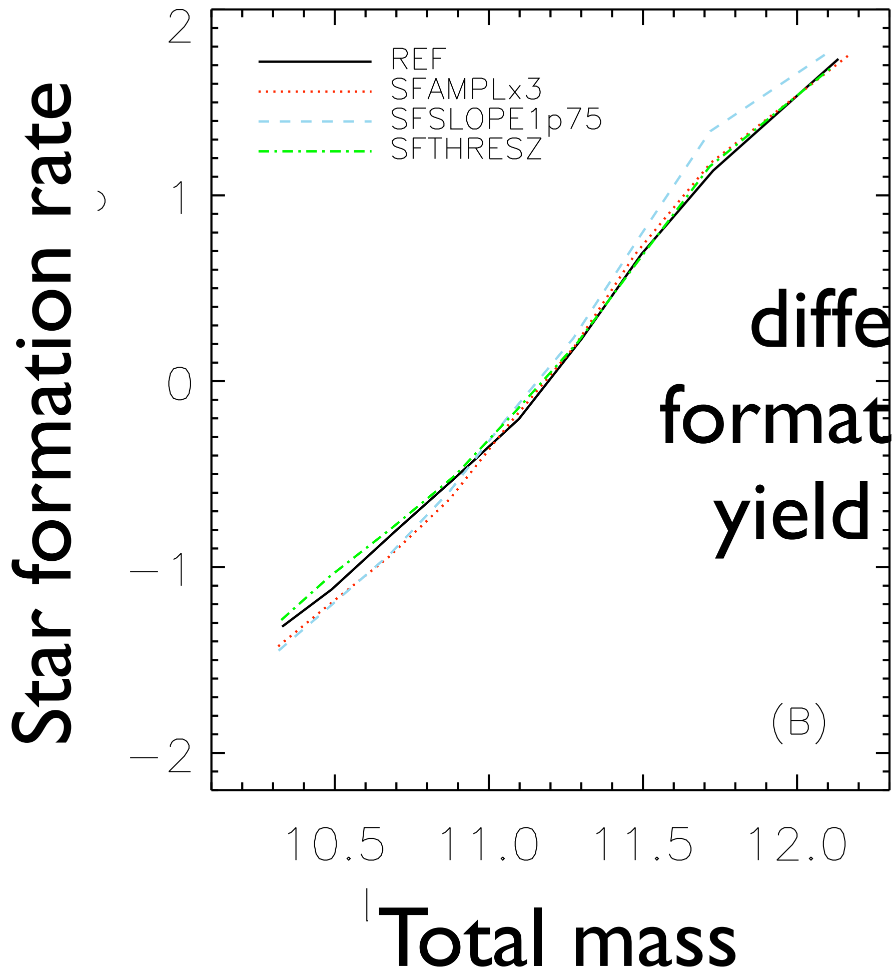
Institute for Compu

Cold accretion flows and the nature of high column density H I absorption at redshift 3



Van de Voort+12

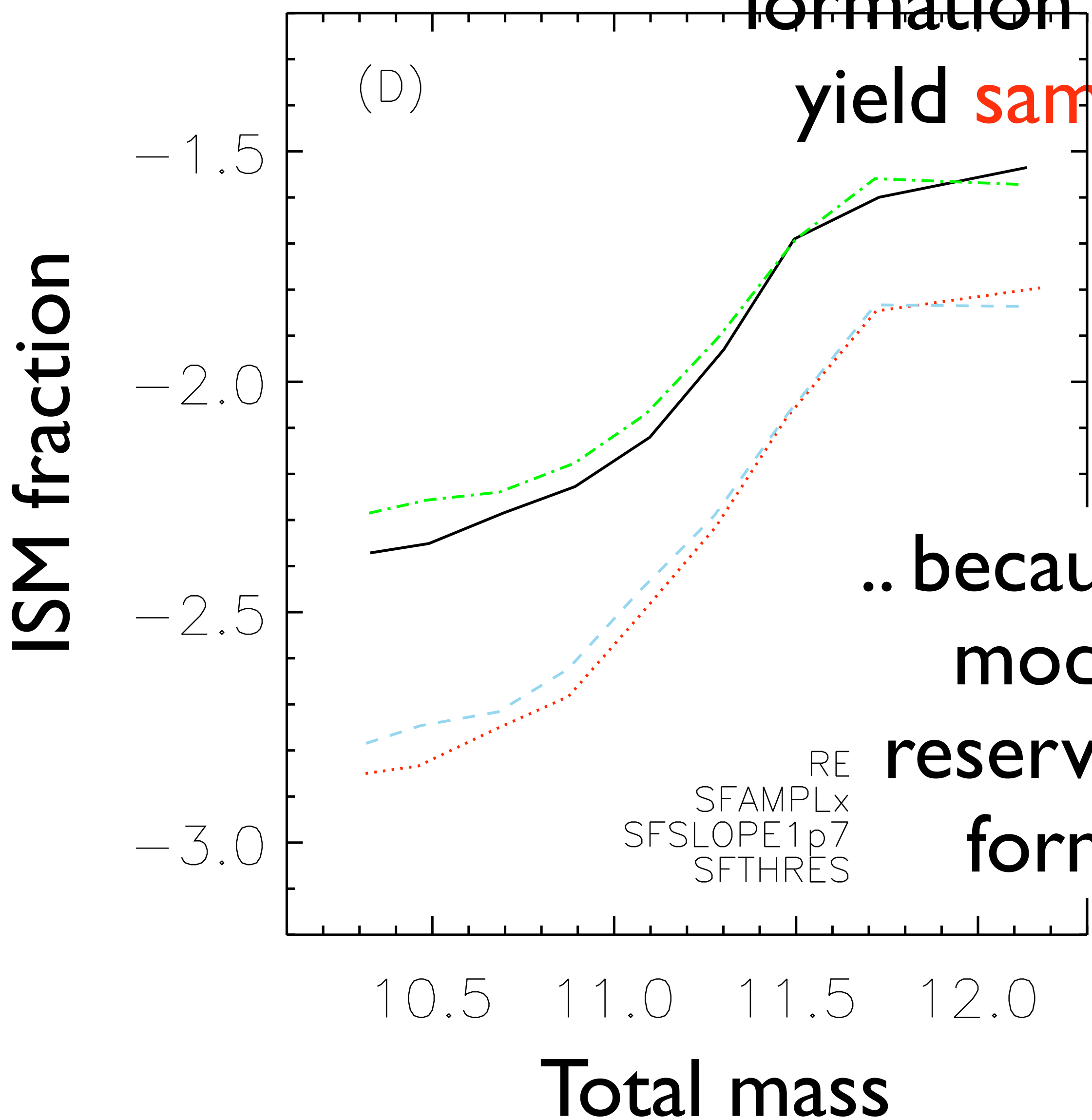
Star formation is self-regulating by feedback



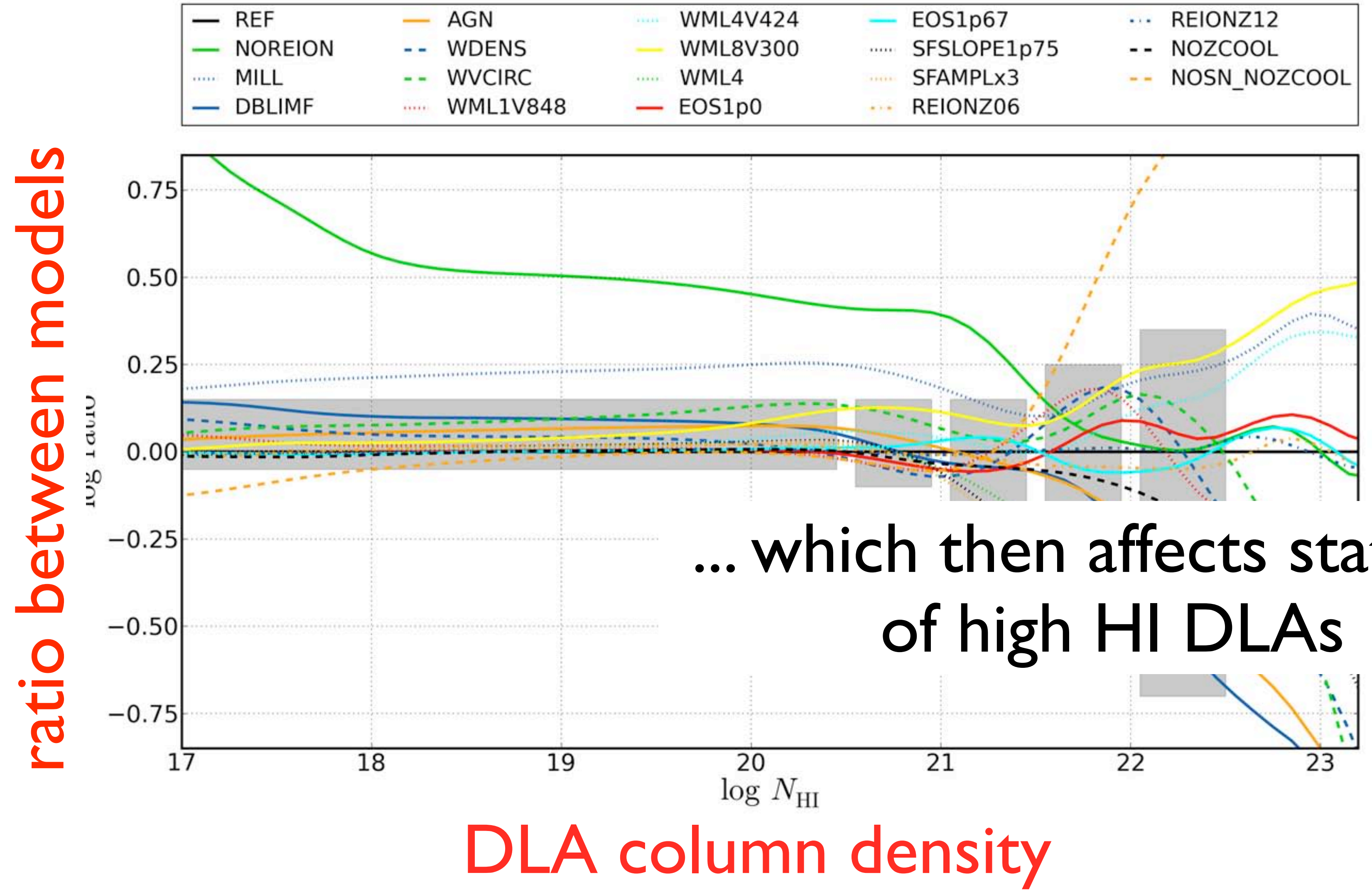
different star formation choices yield same SFR

Haas+12

different star formation choices yield same SFR



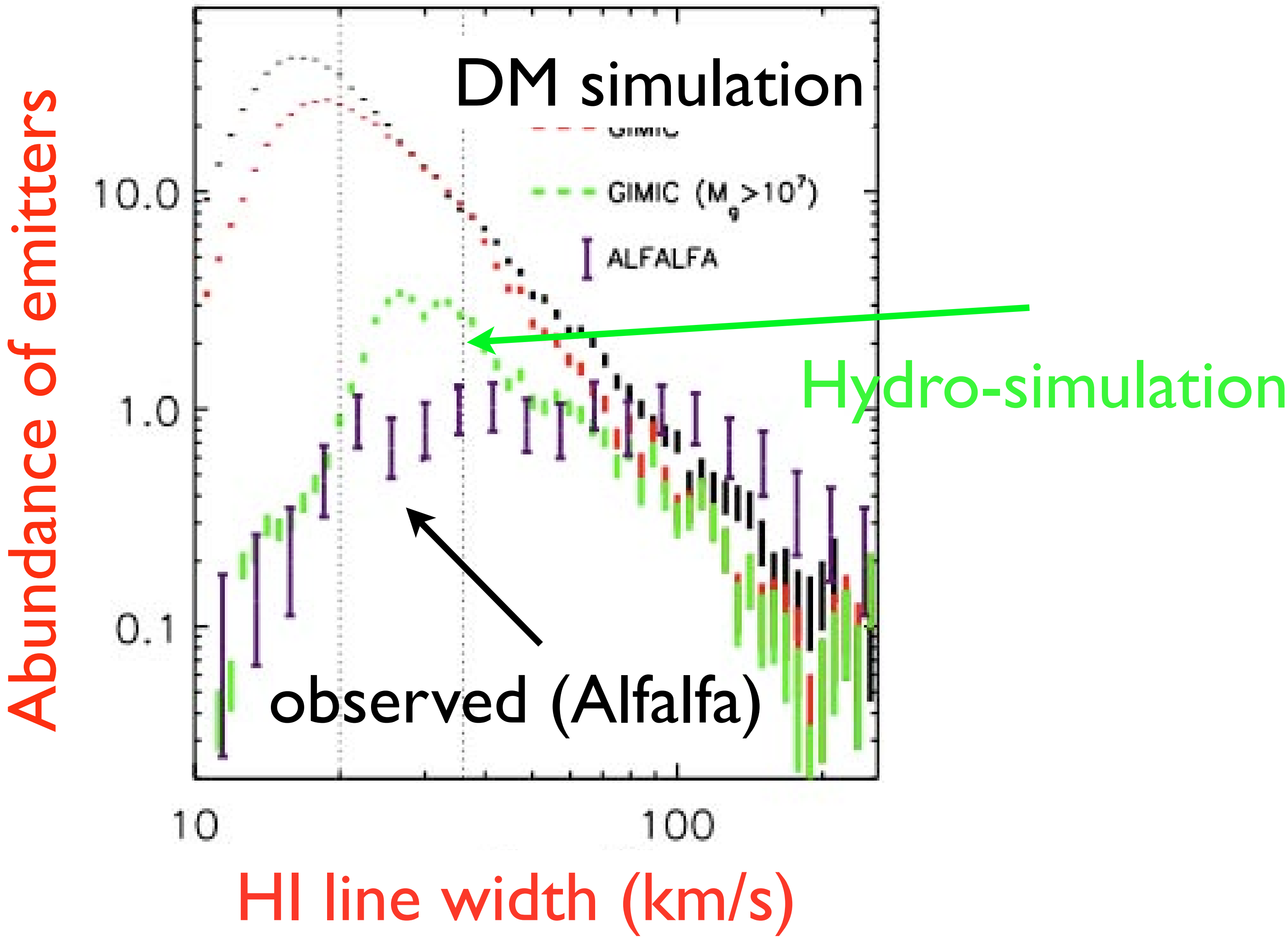
.. because galaxies modify their reservoir of star forming gas



... which then affects statistics of high HI DLAs

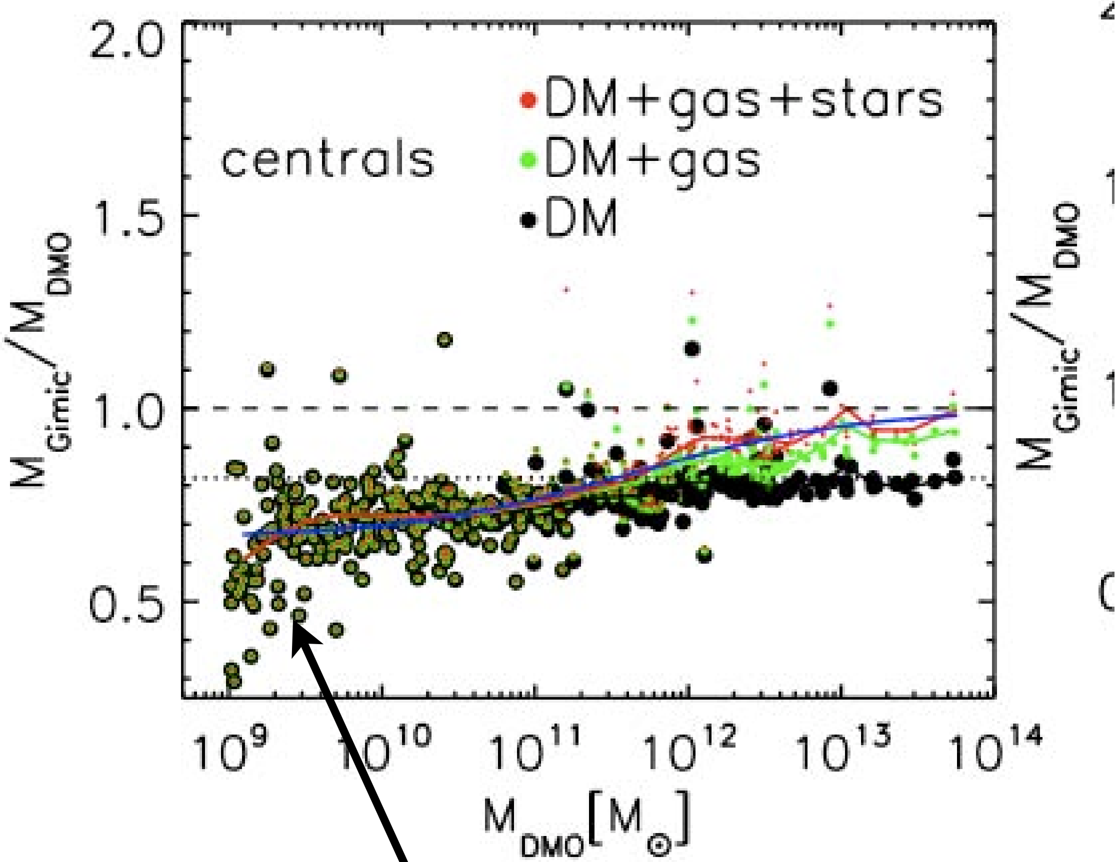
Altay+13

Simulations give correct abundance of HI emitters



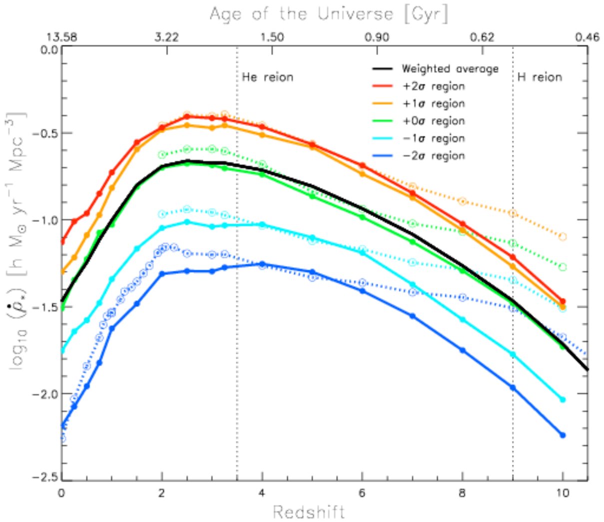
Sawala+12

Why do simulations give correct abundance of HI emitters?

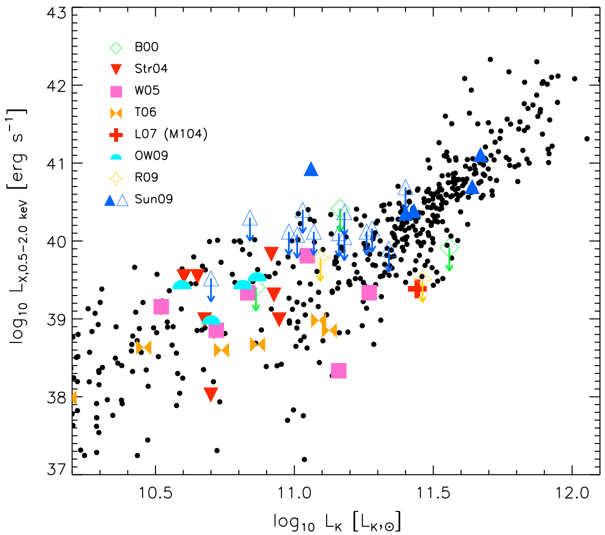


low-mass haloes lose baryons and dark matter mass due to feedback

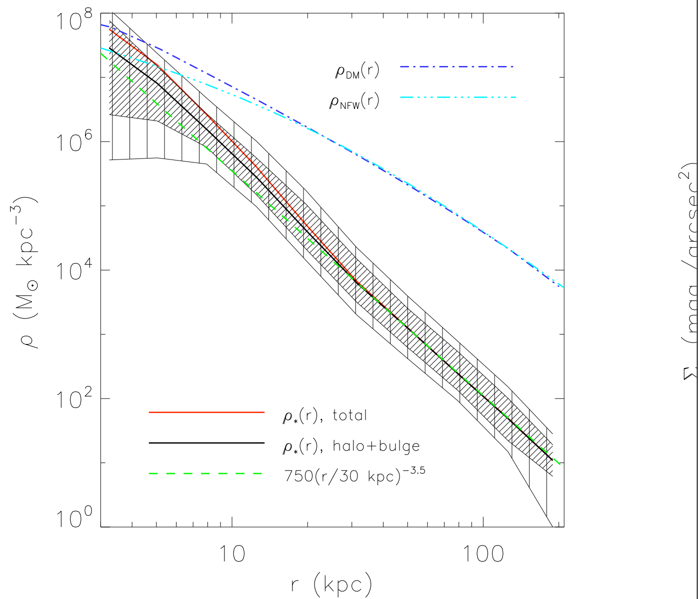
Sawala+12



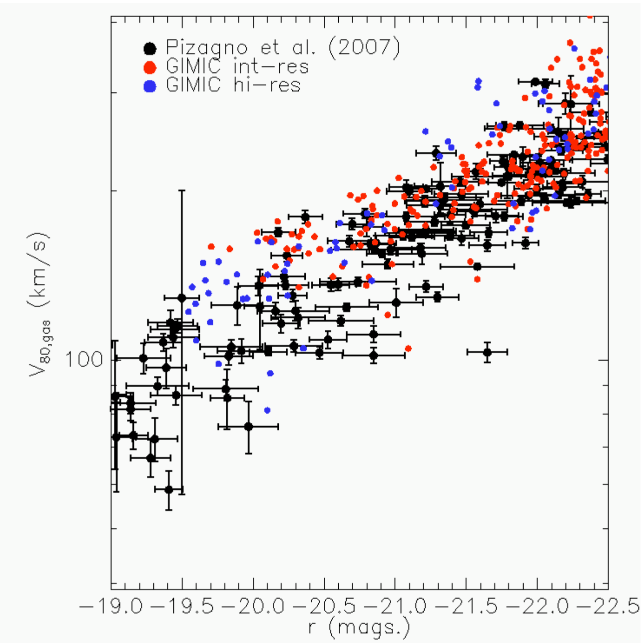
Mass function



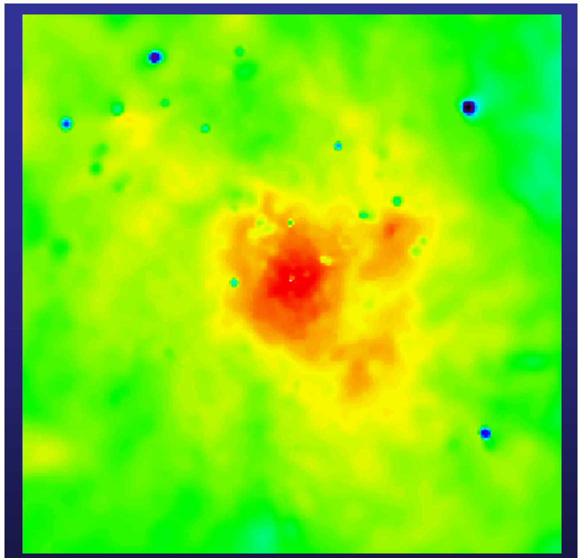
Lx-Lk



Stellar halo

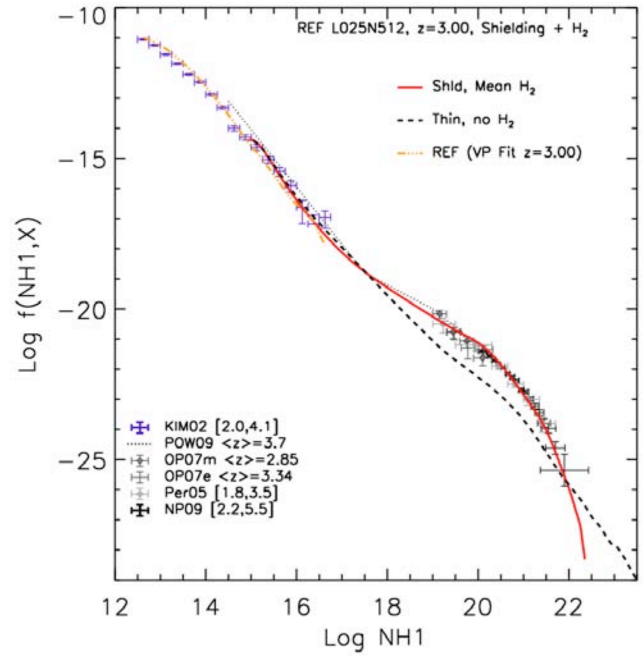


Tully-Fisher



X-ray spectroscopic-like temperature map [0.5-7.0 keV band]

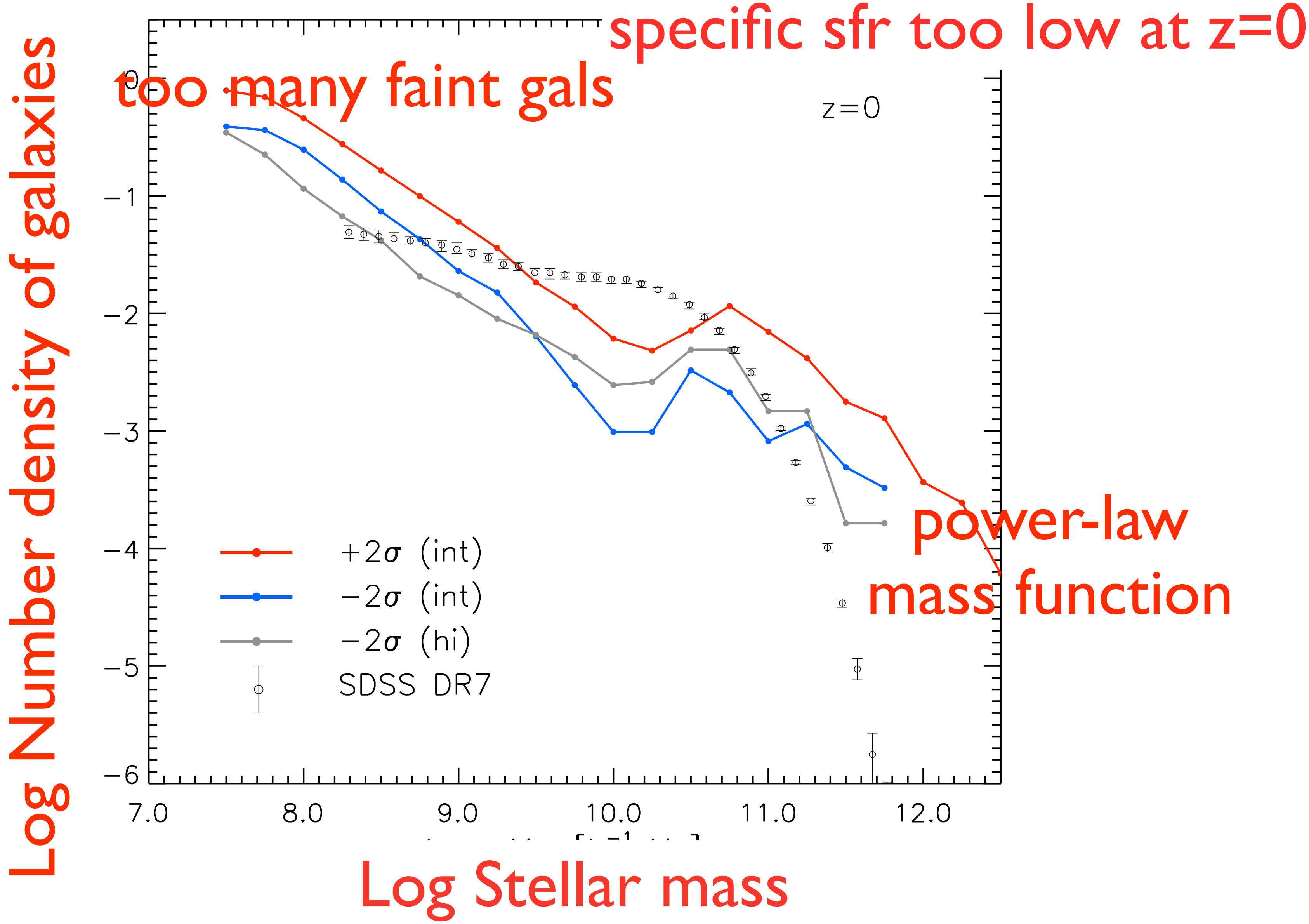
AGN in groups



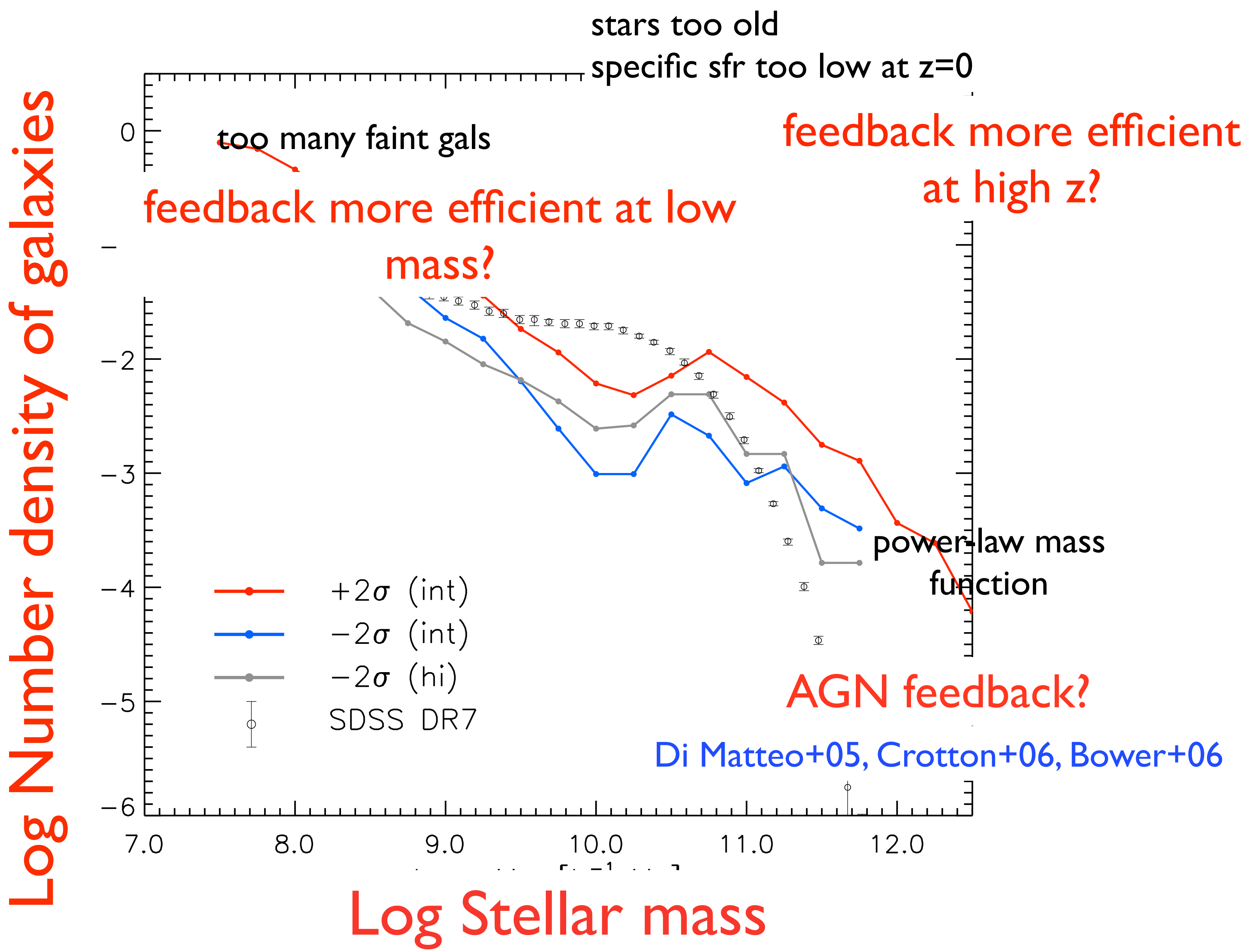
HI distribution

Simulation issues: stellar mass function

stars too old
specific sfr too low at z=0



Tune feedback to shape galaxy stellar mass function



in all cases: efficient feedback is key

- low mass galaxies: SNe
- in higher mass galaxies: AGN
- feedback more efficient at high z

- Does feedback behave like this?
- Why?

EFFECTS OF SUPERNOVAE ON THE EARLY EVOLUTION OF GALAXIES

Richard B. Larson

(Received 1974 July 5)

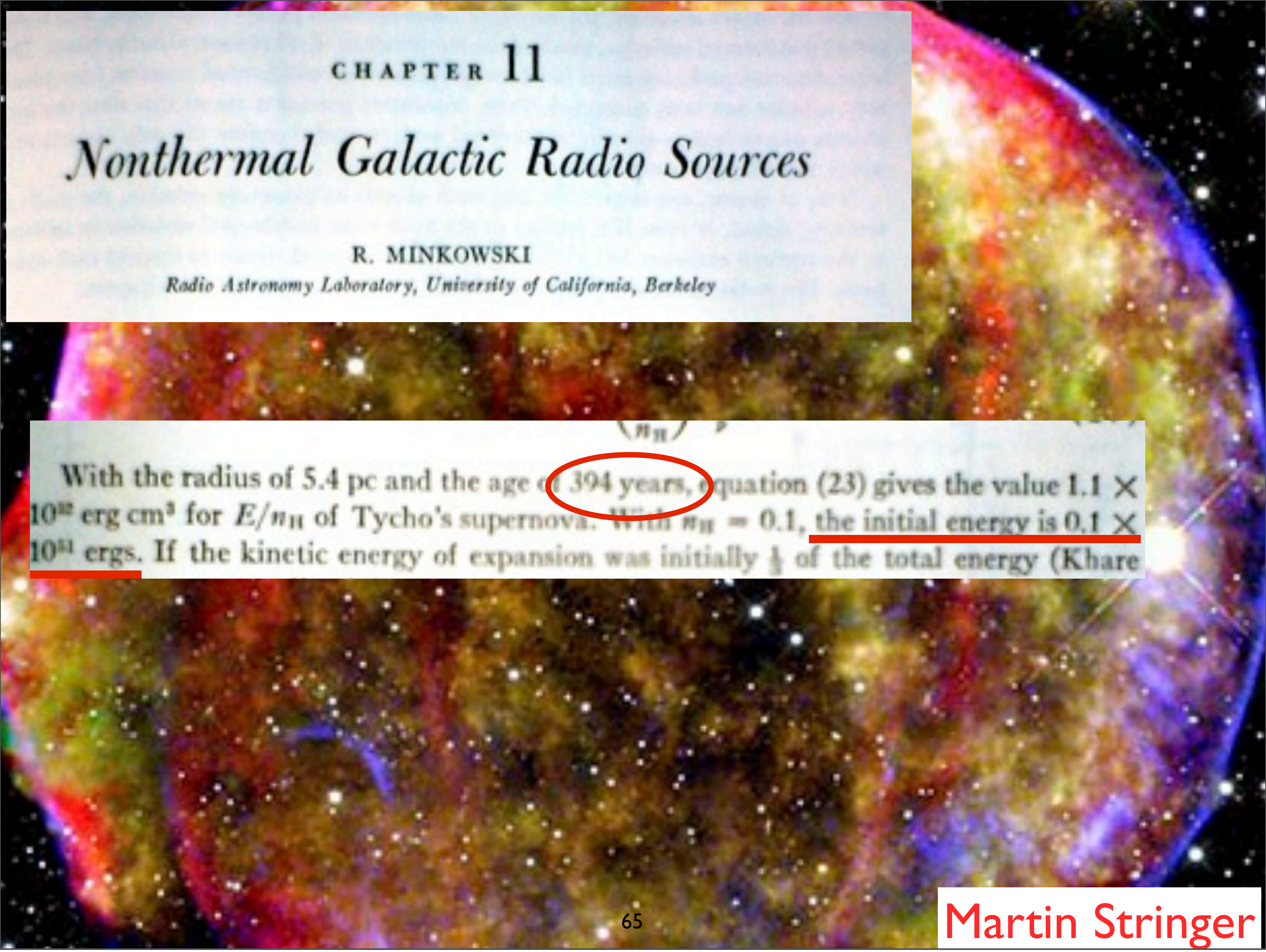
SUMMARY

During the early evolution of an elliptical galaxy, some of the residual interstellar gas is heated to high temperatures by supernova explosions and is driven out of the galaxy in a galactic wind. The energy supplied per supernova is typically reduced about an order of magnitude by radiative cooling of supernova remnants, but the remaining energy is still sufficient to cause significant gas loss, particularly for small galaxies. In galaxies of smaller mass, gas loss begins earlier and carries away a larger fraction of the initial mass, owing to the lower escape velocity. Model collapse calculations show that the effect of early gas loss is to cause galaxies of smaller mass to have less condensed nuclei, smaller average metal abundances, and smaller metal abundance gradients, in qualitative agreement with the observations.

escape energy. In reality, the gas is probably not lost all at once, but we would obtain approximately the same prediction for the total amount of gas lost by assuming only that all of the available energy of $\sim 0{\cdot}1\ E_0$ per supernova is expended in removing gas from the galaxy.

White & Rees 78, Dekel & Silk 86

Martin Stringer



CHAPTER 11

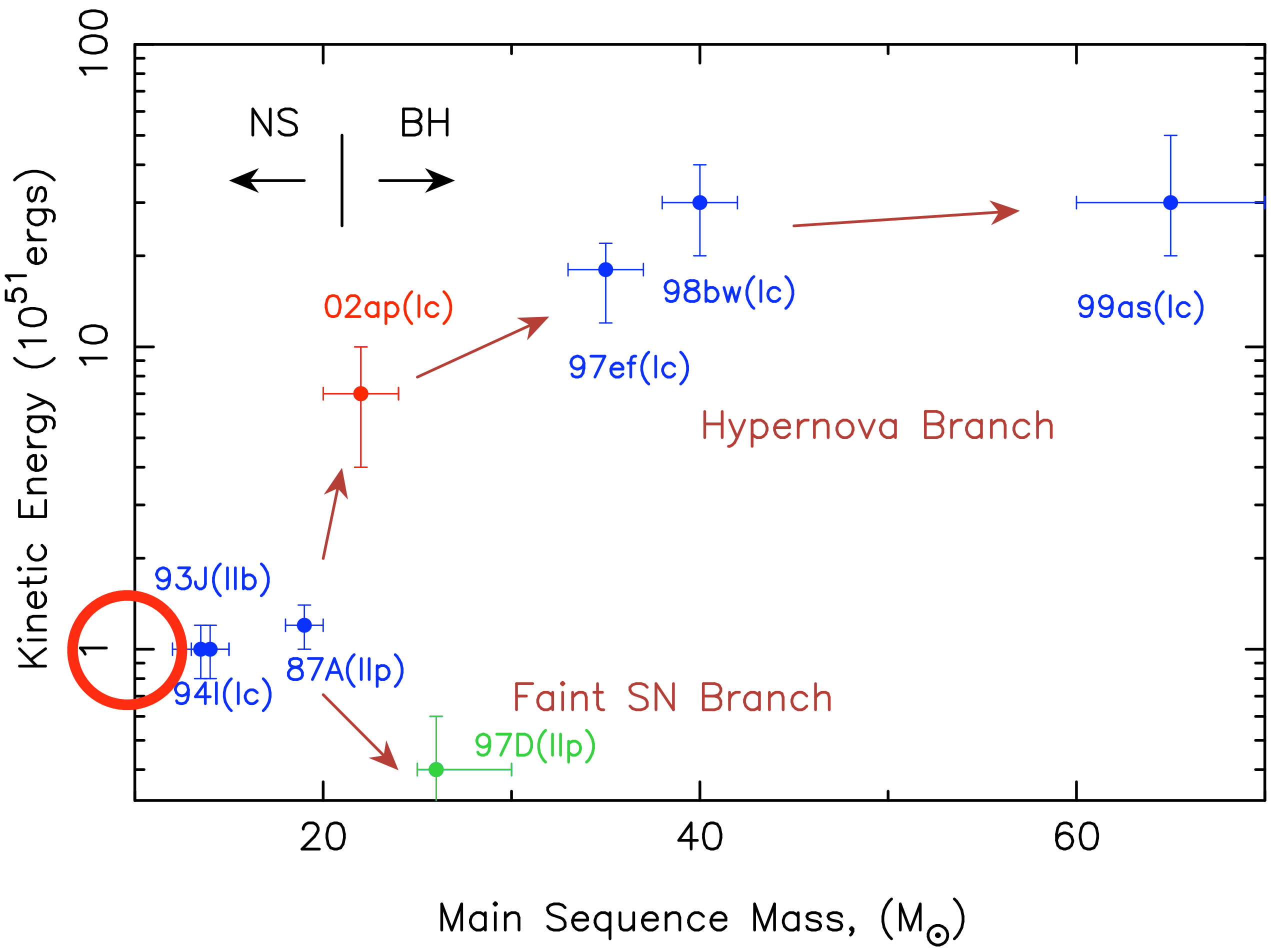
Nonthermal Galactic Radio Sources

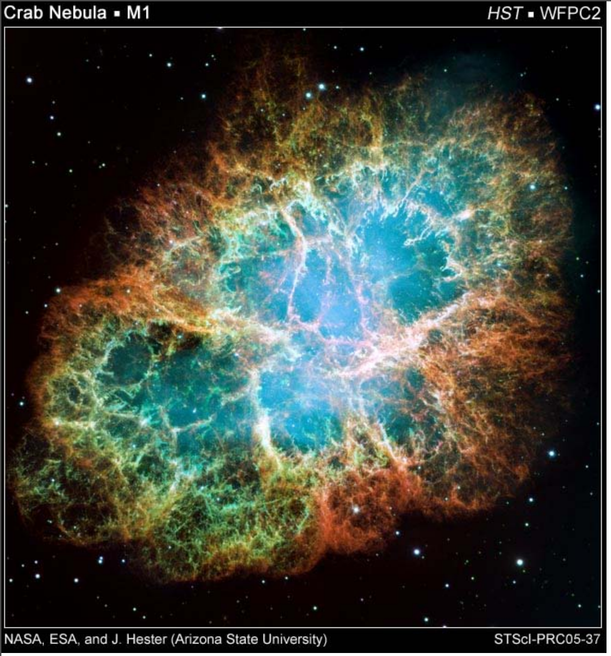
R. MINKOWSKI
Radio Astronomy Laboratory, University of California, Berkeley

With the radius of 5.4 pc and the age of 394 years, equation (23) gives the value 1.1×10^{52} erg cm^3 for E/n_H of Tycho's supernova. With $n_H = 0.1$, the initial energy is 0.1×10^{51} ergs. If the kinetic energy of expansion was initially $\frac{1}{2}$ of the total energy (Khare

HYPERNOVAE AND OTHER BLACK-HOLE-FORMING SUPERNOVAE

Ken'ichi Nomoto,[1,2] Keiichi Maeda,[1] Paolo A. Mazzali,[2,3] Hideyuki Umeda,[1]
Jinsong Deng,[1,2] Koichi Iwamoto,[4]

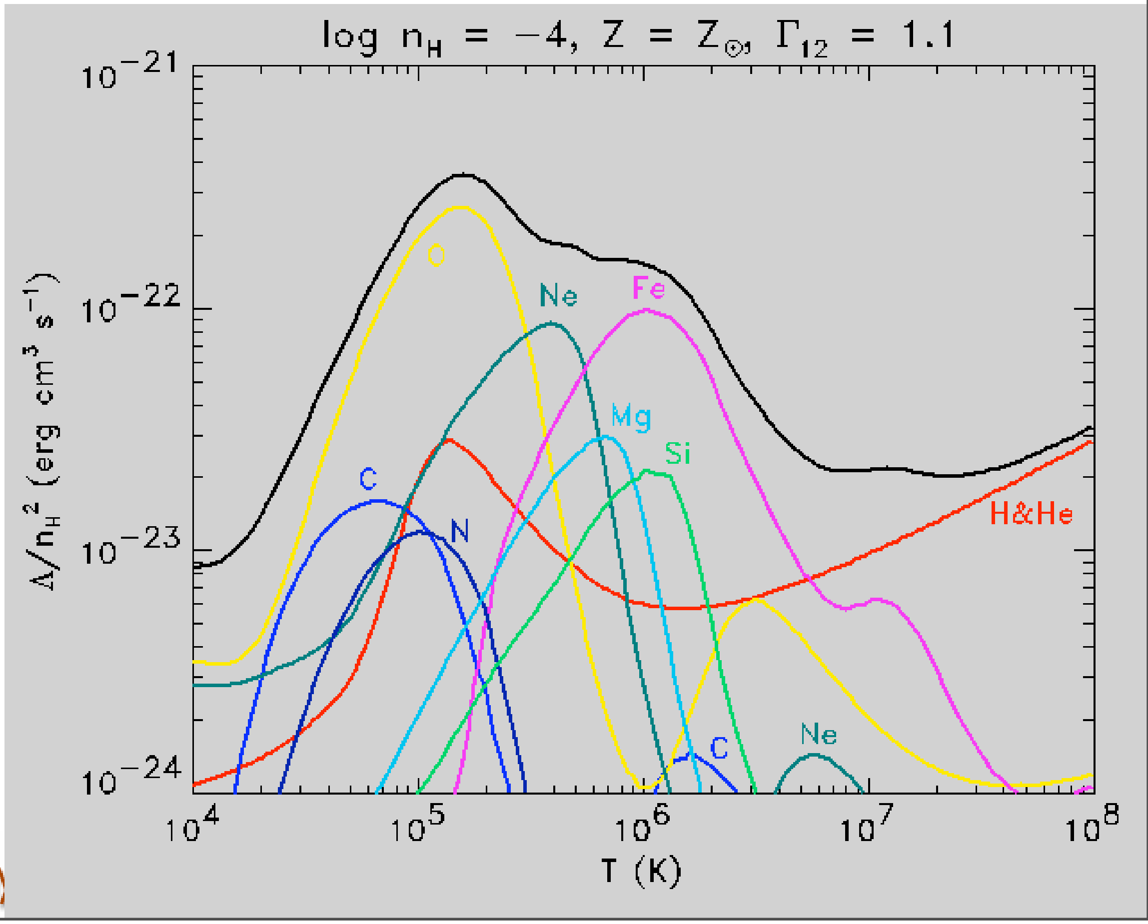




$$\Delta M_\star \rightarrow \Delta E_\star = \frac{\Delta M_\star}{100 M_\odot} 10^{51}\,\mathrm{erg}$$

Inject energy as hot gas?
As a wind?
Some combination?

cooling rate depends strongly on density and temperature



Naive implementation depends directly on numerical scheme

- cooling rate strongly dependent on density (and hence resolution)
- how much is the heating temperature?

$$\Delta M_\star \rightarrow \Delta E_\star = \frac{\Delta M_\star}{100 M_\odot} 10^{51}\,\mathrm{erg}$$

Give all energy to 1 particle-> T=2 10^7 K
SPH: give energy to 48 particles -> T= 0.5 10^6 K

cooling rates differ by factor 10!

Physics of SN blast wave

(cold) ejecta

reverse shock: thermally driven shell

interior and shell cool: snowplough

$$\frac{10^{51}\mathrm{ergs}}{100\,M_\odot} = 2\times10^{7}\mathrm{K}$$ Arbitrary re-heating

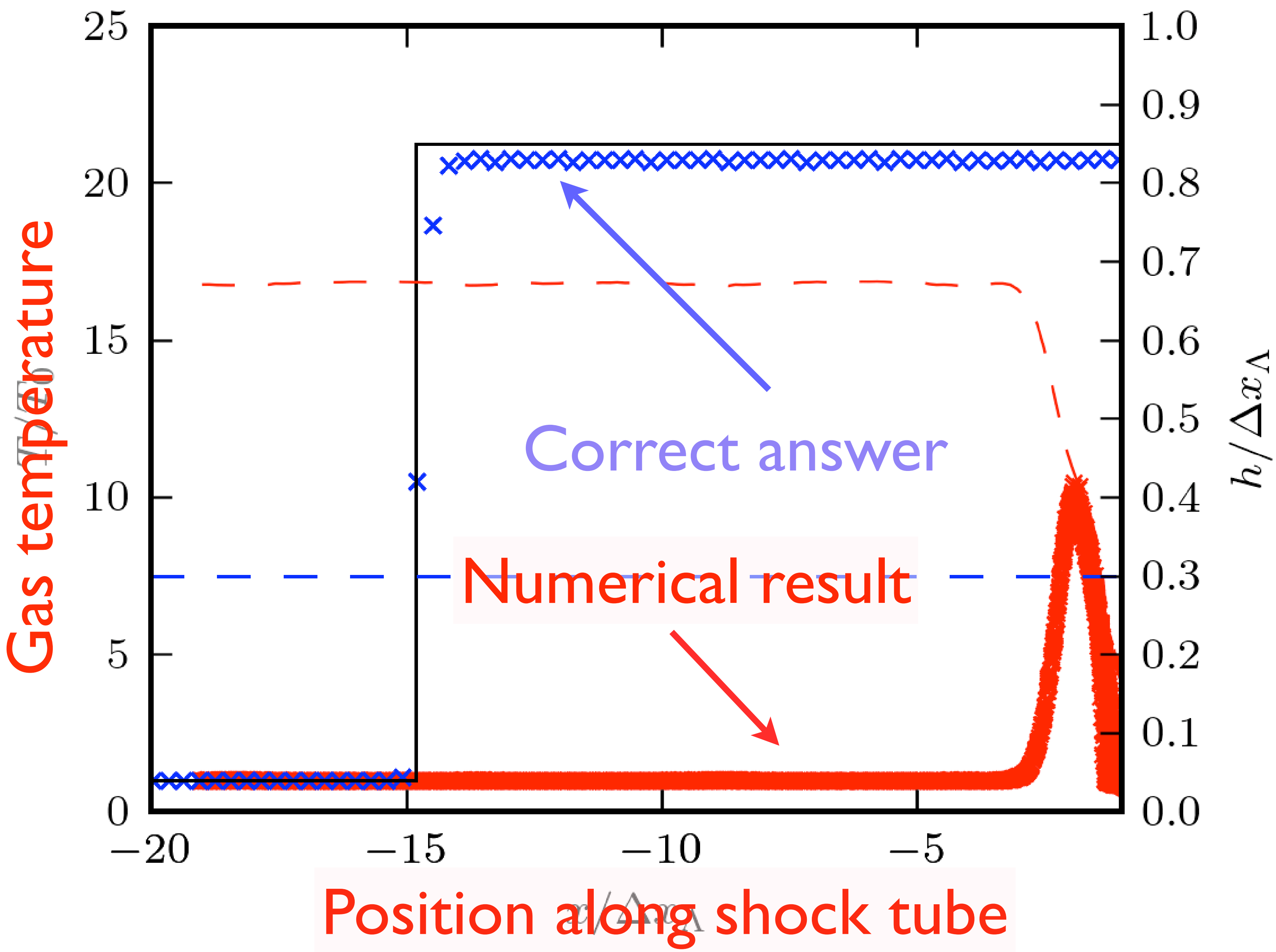
$$\frac{10^{51}\mathrm{ergs}}{10\,M_\odot} = 2\times10^{8}\mathrm{K}$$ Heat just stellar ejecta

Sedov: similarity solution depends only on injected energy

But: amount of cooling determines transition to snowplough and hence effectiveness of feedback

Numerical overcooling makes problem worse (Creasey+11)

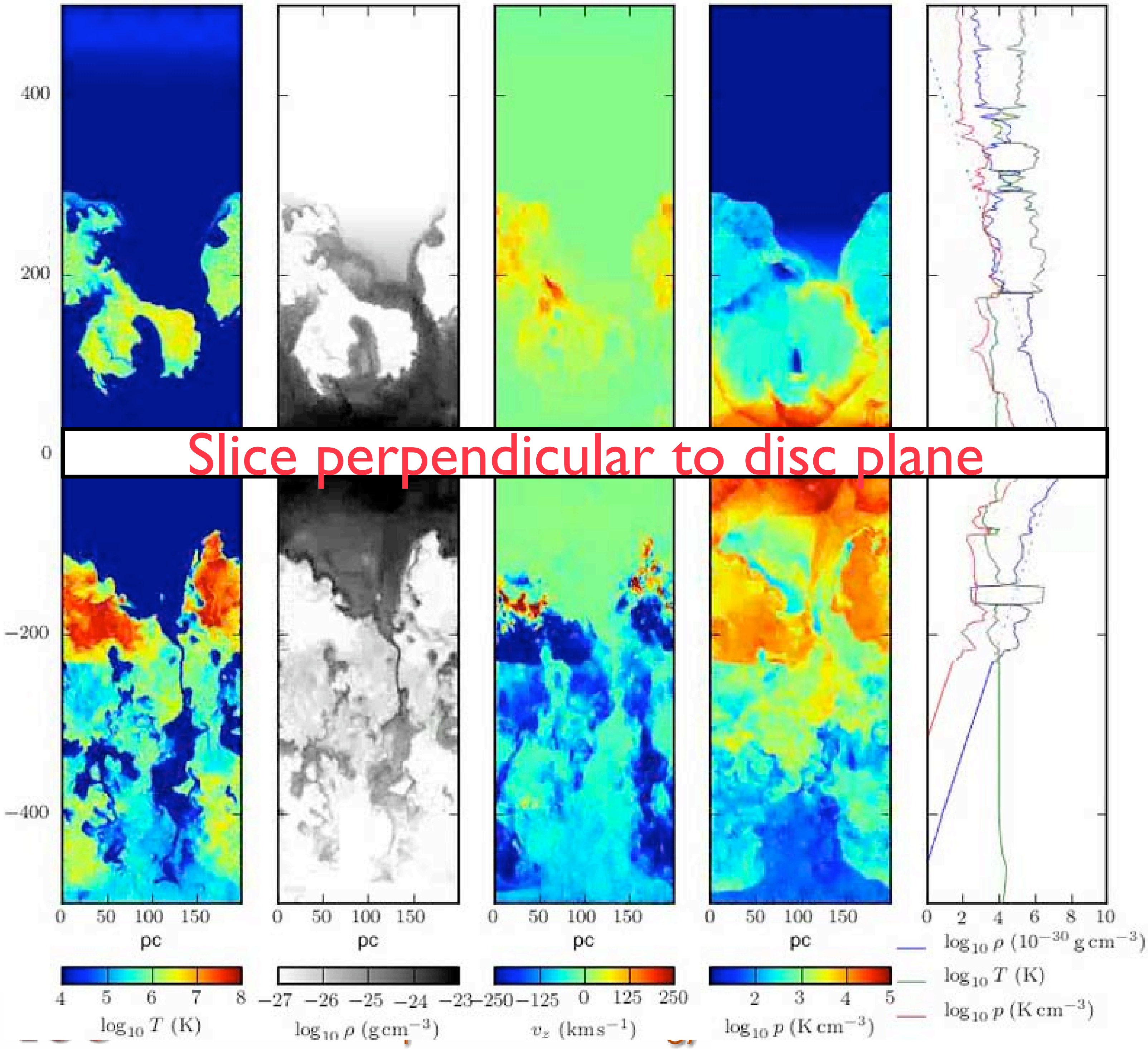
“Sod” shock similarity solution with cooling



Creasey+, 11

30 Jupiter mass resolution

Computational volume of 10^9 cells has same mass as single Eagle particle

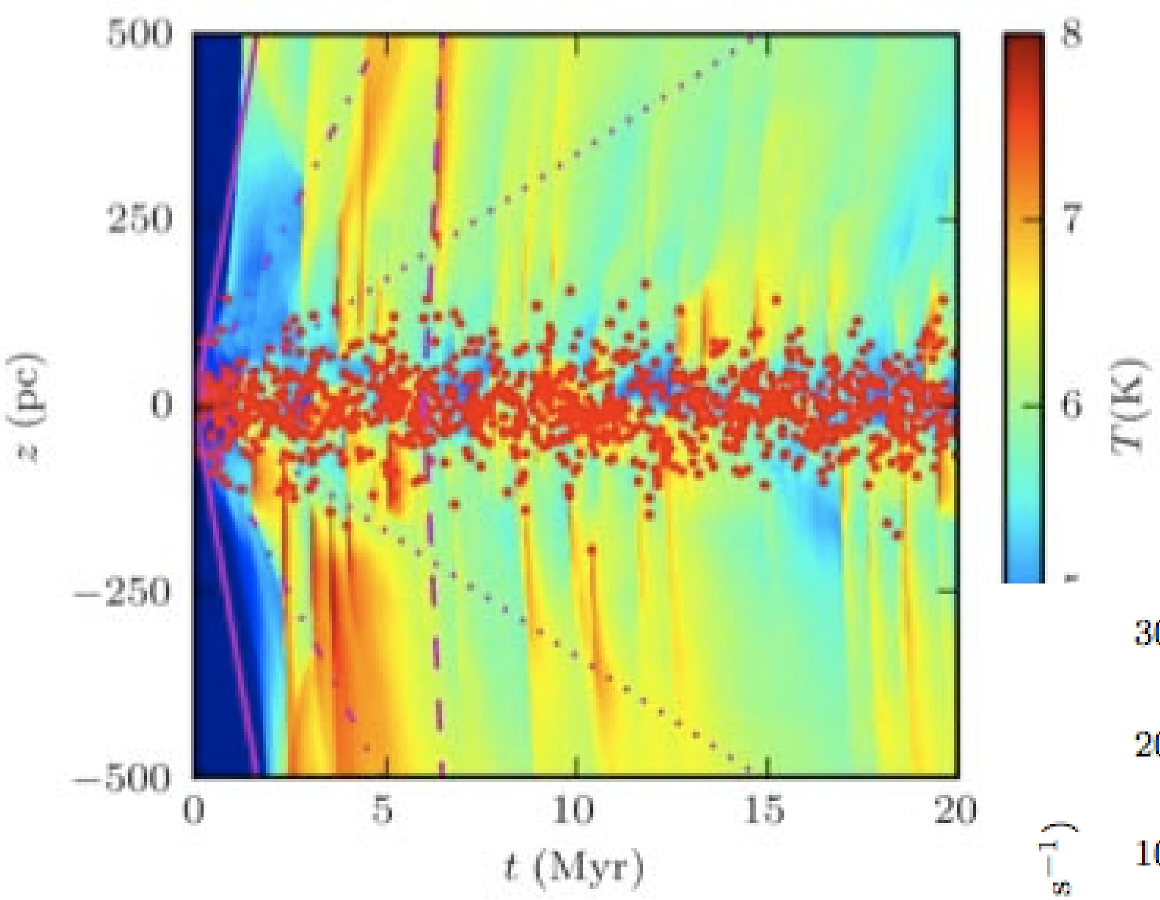


Creasey+13

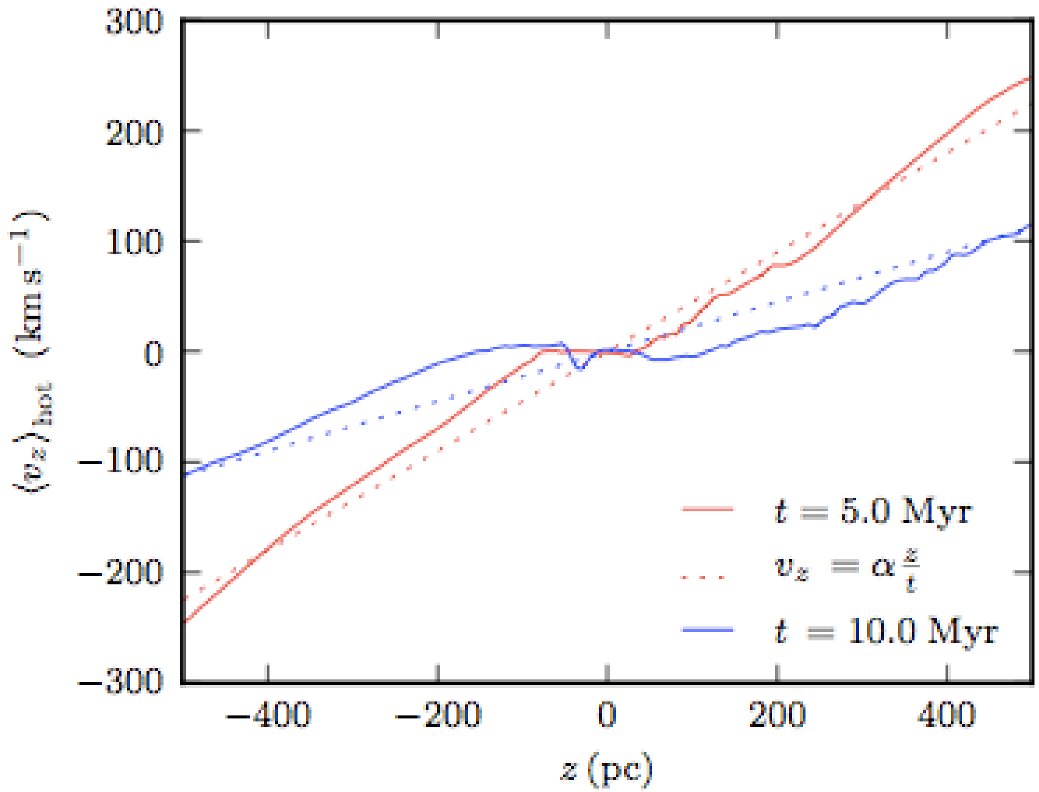
FLASH

Tom Theuns

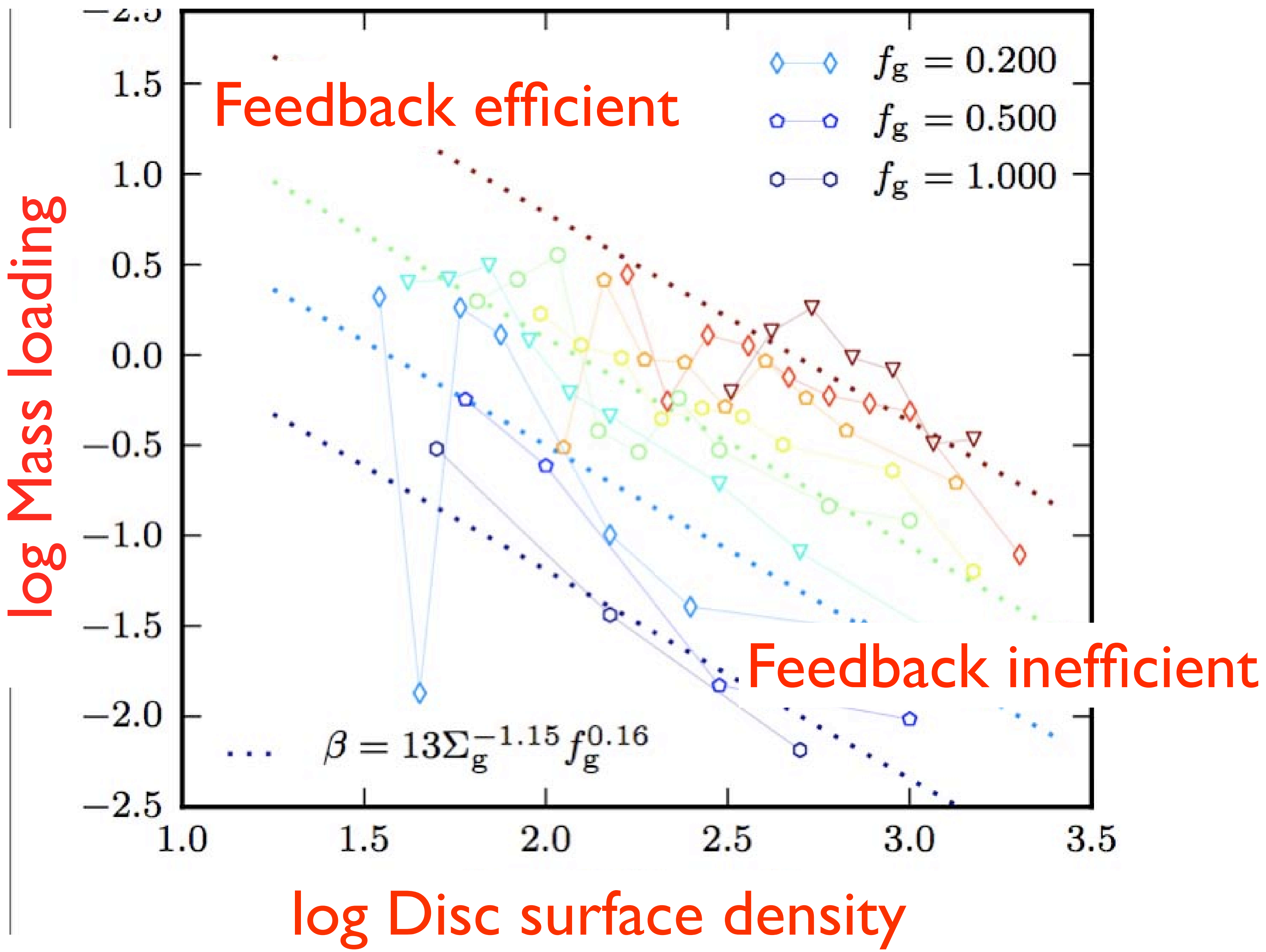
"Wind" is a series of overlapping rare faction waves



Wind "accelerates" away from plane due to thermal driving



Creasey+12



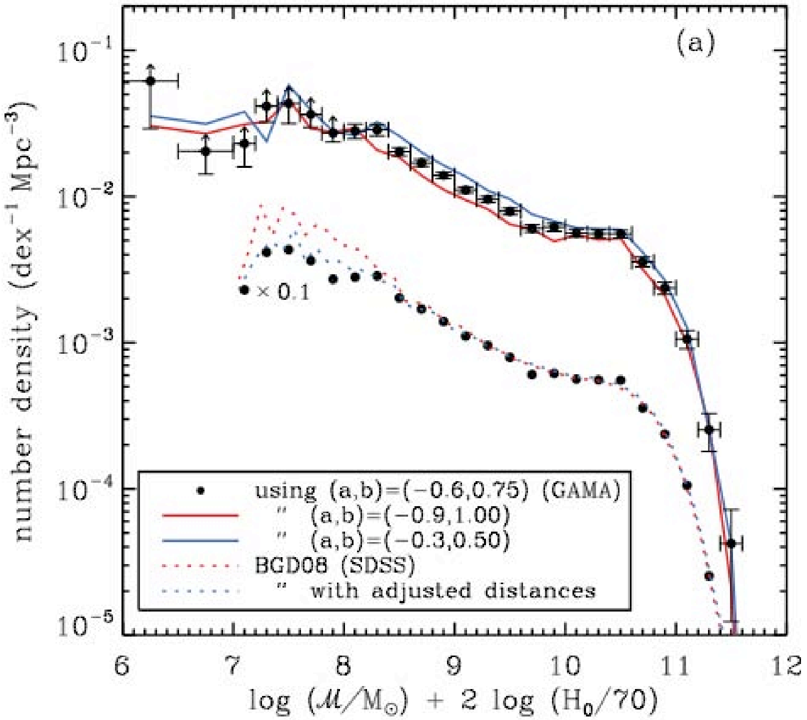
Feedback efficient
Feedback inefficient
log Mass loading
log Disc surface density
$f_g = 0.200$
$f_g = 0.500$
$f_g = 1.000$
$\beta = 13\Sigma_g^{-1.15} f_g^{0.16}$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
1.0
1.5
2.0
2.5
3.0
3.5

Creasey+13

dense disc: SNe feedback inefficient

sparse disc: SNe feedback efficient

$$\frac{\dot{M}_{\rm w}}{\dot{M}_\star} \approx 13\,\frac{\epsilon}{100}\left(\frac{\Sigma_{\rm gas}}{10M_\odot{\rm pc}^{-2}}\right)^{-8/11}\left(\frac{f_{\rm gas}}{0.1}\right)^{4/11}\left(\frac{\Lambda}{10^{-22}{\rm erg\,s}^{-1}}\right)^{-6/11}$$



$$\frac{\dot{M}_{\rm w}}{\dot{M}_\star} \propto V_{\rm d}^{-3.4}$$

exponent depends on disc model

SN feedback (much) less efficient in big discs

Creasey+, 13

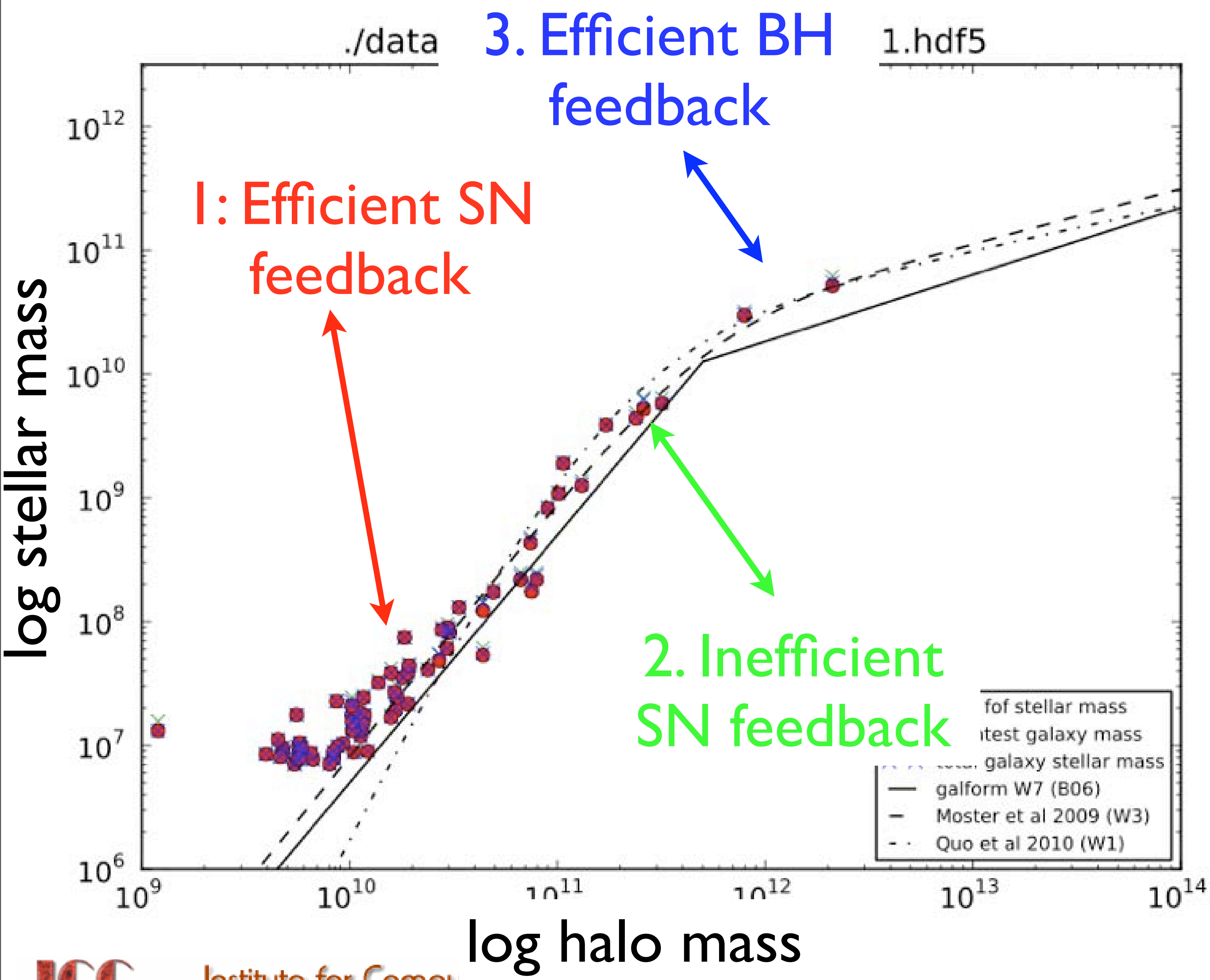
Summary:

- Introduction
  - cosmology 101: forming structures
  - cosmology 102: forming galaxies.
  - The need for "subgrid" physics
- EAGLE subgrid physics implementation in Gadget
  - star formation, cooling, and feedback (SNe and AGN)
- Lessons learned from the precursors: Owls and Gimic
- (How) Do supernova regulate starformation?
- Parameter selection (tuning)
  - methodology

Subgrid parameters

- Heating/cooling
  - Epoch of reionisation, UV/X-ray background, self-shielding
- Star formation
  - KS-parameters, threshold
- Stellar evolution
  - Stellar initial mass function, yields, life-times
- Supernova feedback
  - Coupling SNe to gas, heating/wind parameters
- AGN feedback
  - Seed mass, accretion rate, feedback efficiency

Parameter turning: re-heating T, and efficiency-M_{halo} relation



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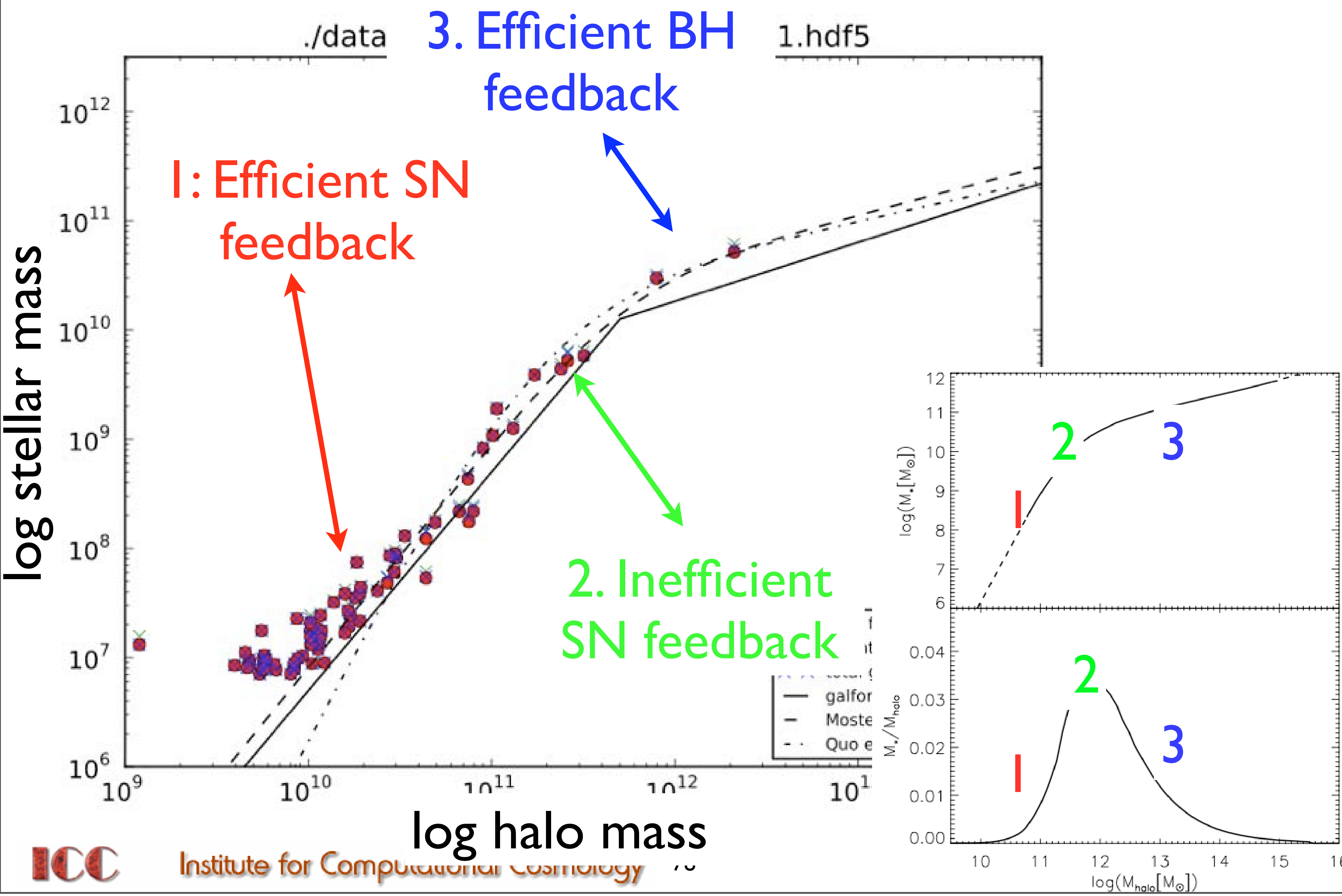
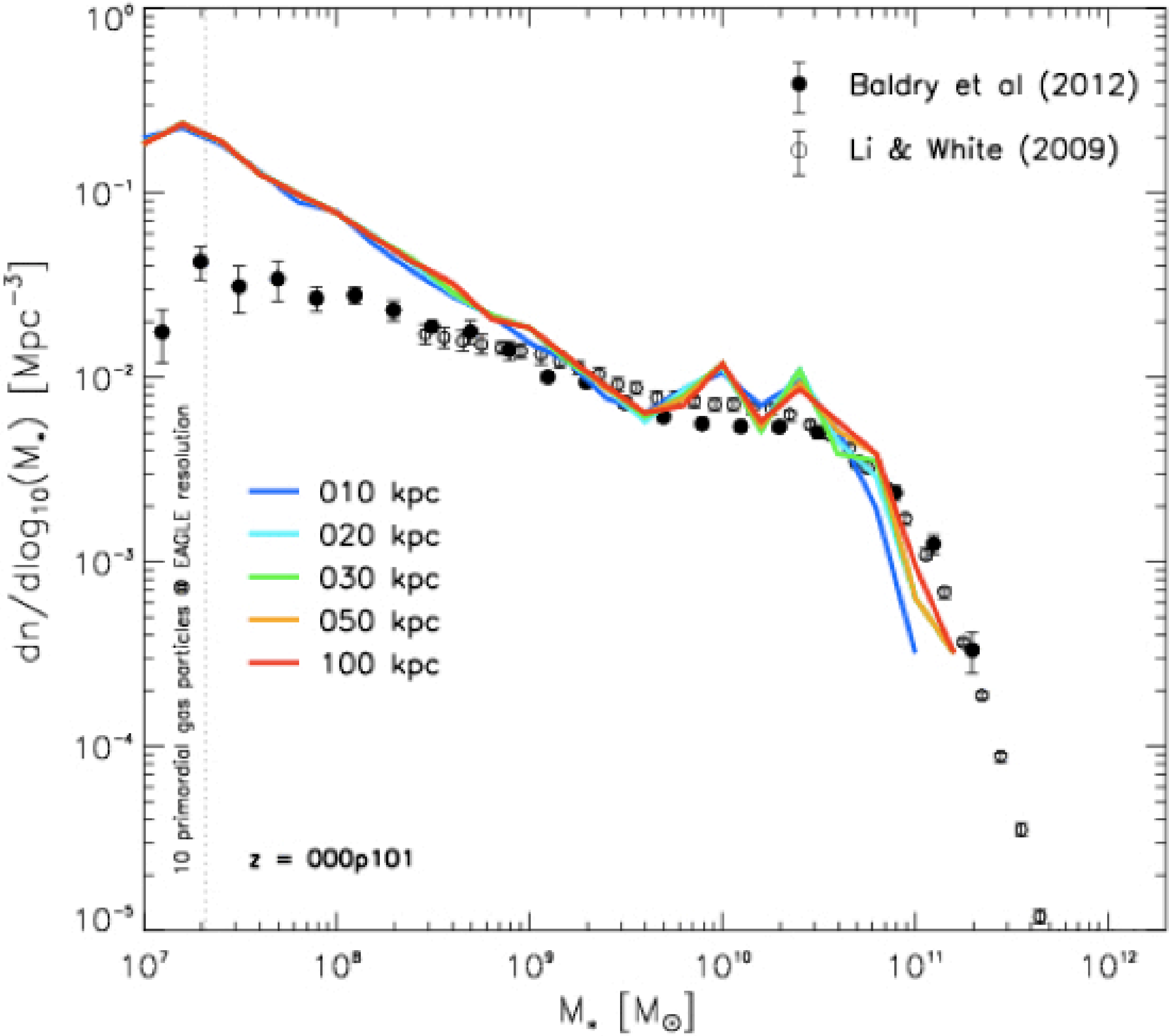


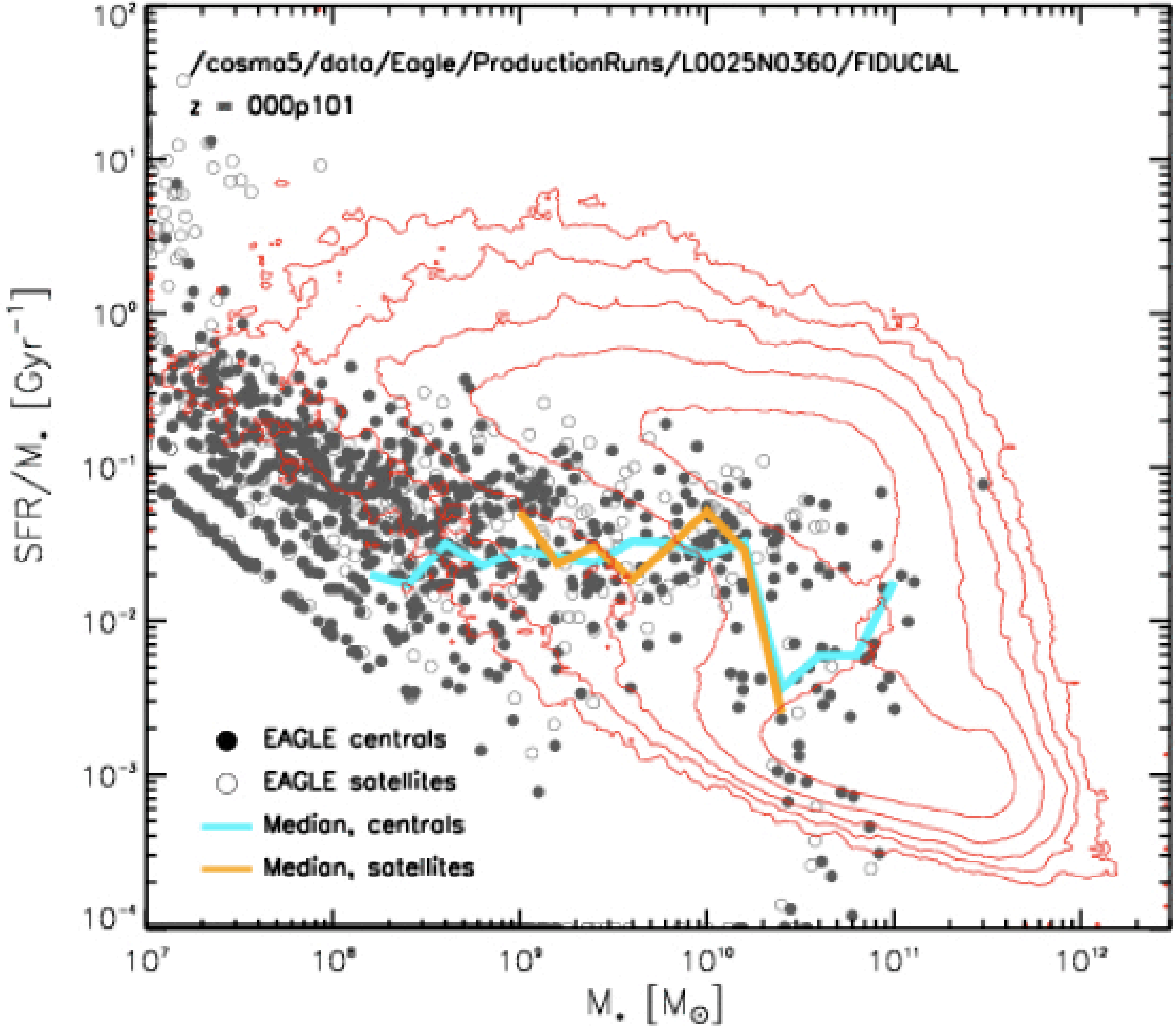
Eagle: Stellar mass function

Eagle: Stellar mass function



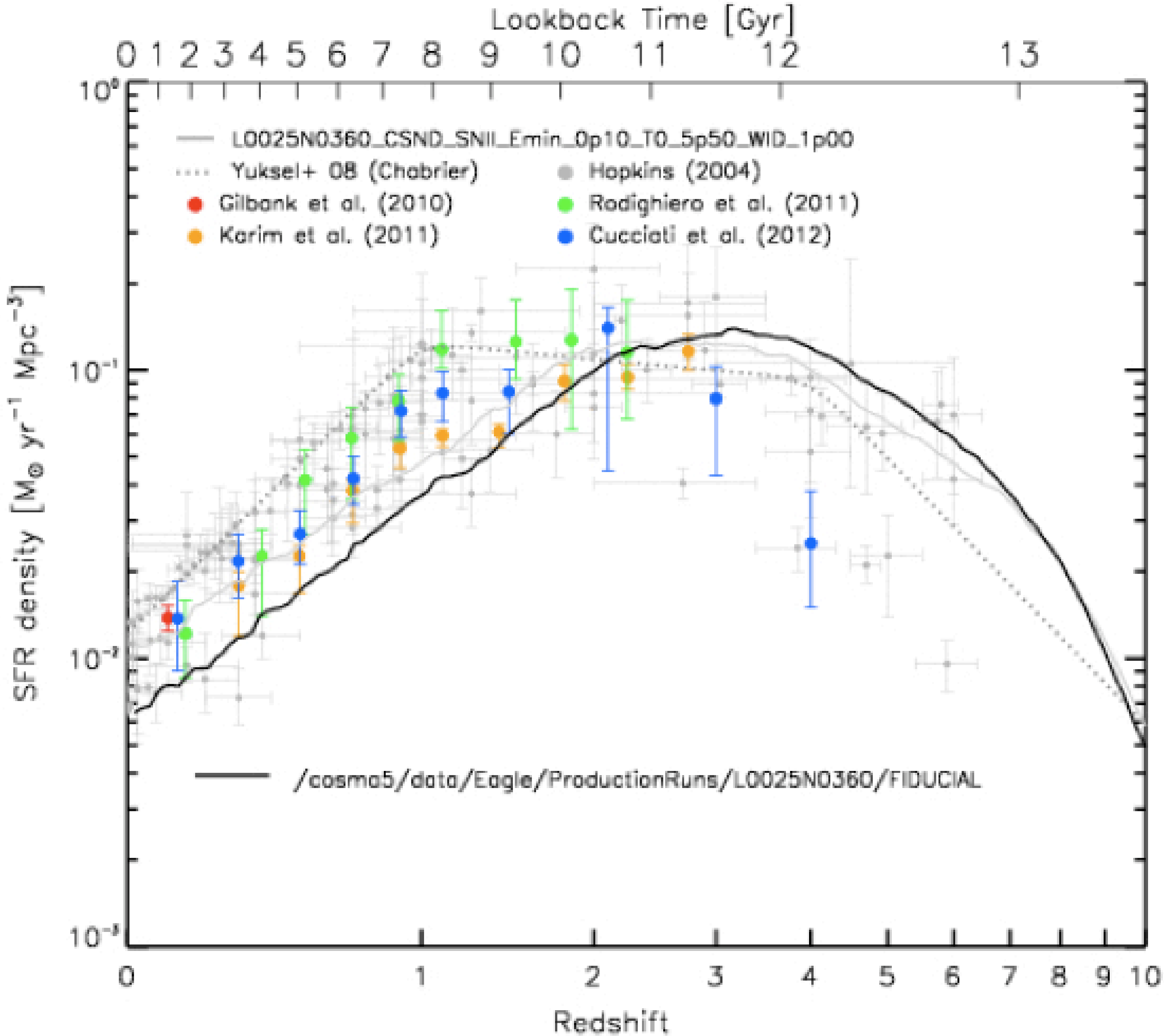
Eagle: Specific star formation rate

Eagle: Specific star formation rate



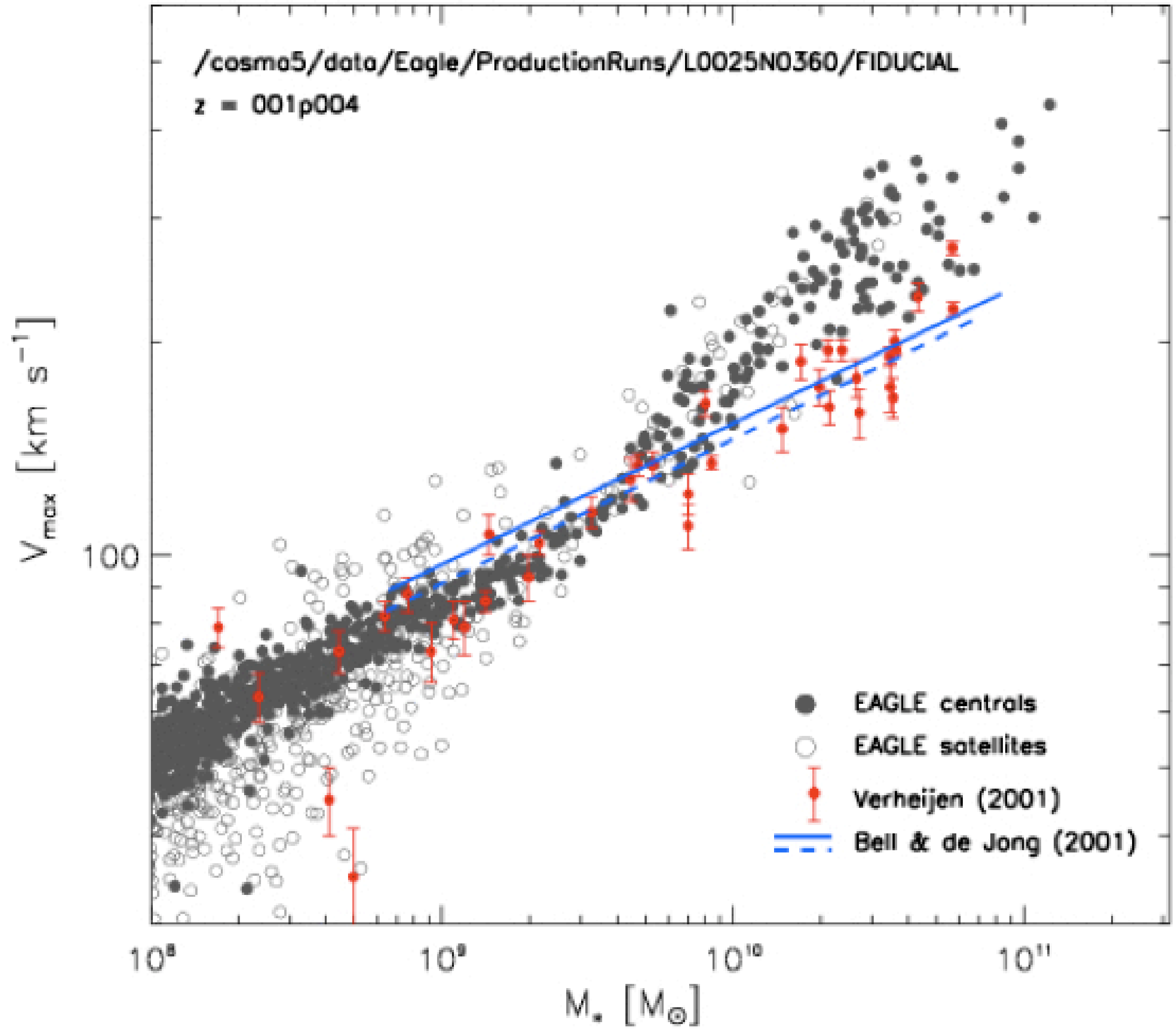
Eagle: star formation history

Eagle: star formation history



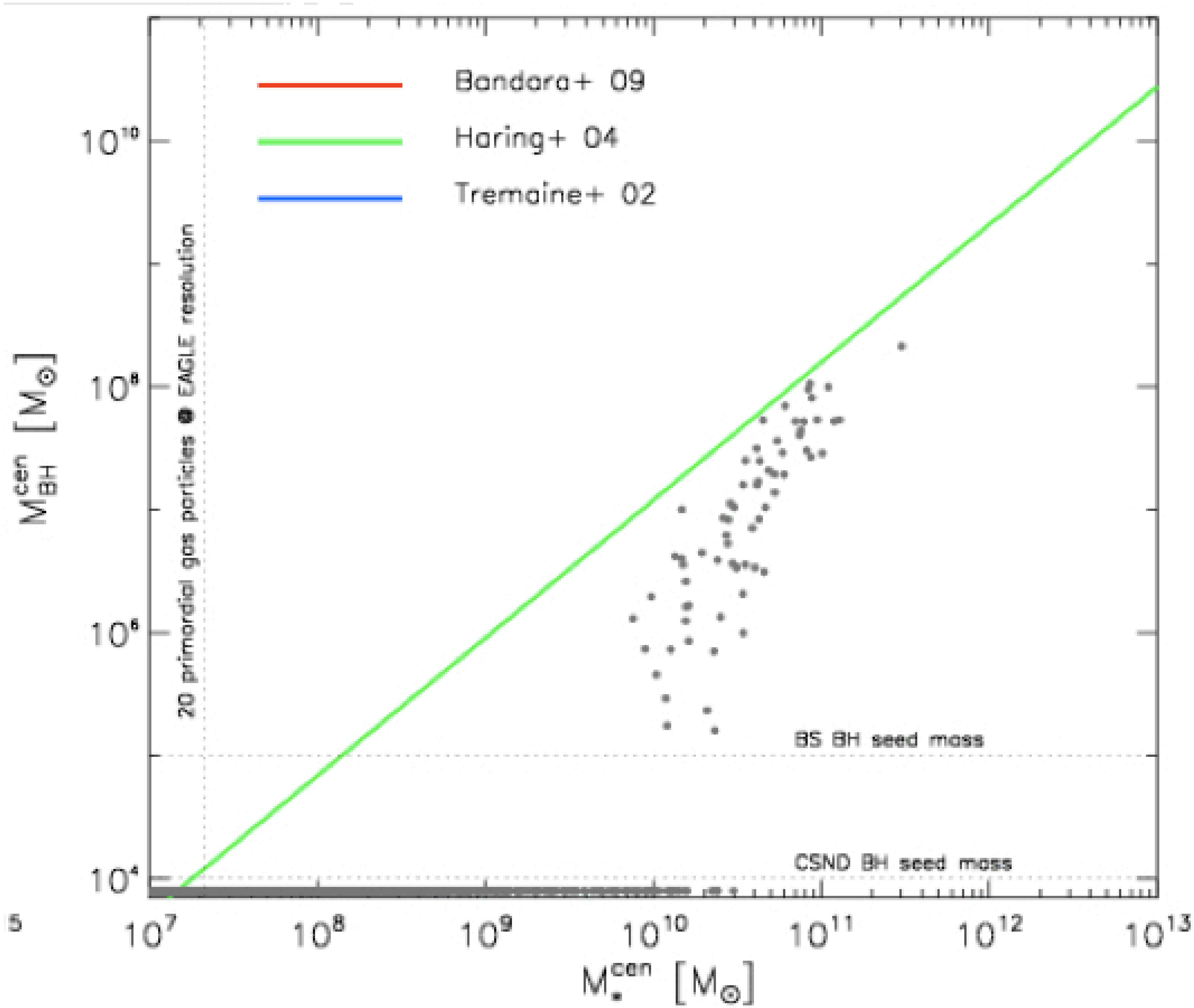
Eagle: Tully-Fisher relation

Eagle: Tully-Fisher relation



Eagle: M_* versus BH-mass

Eagle: M* versus BH-mass



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