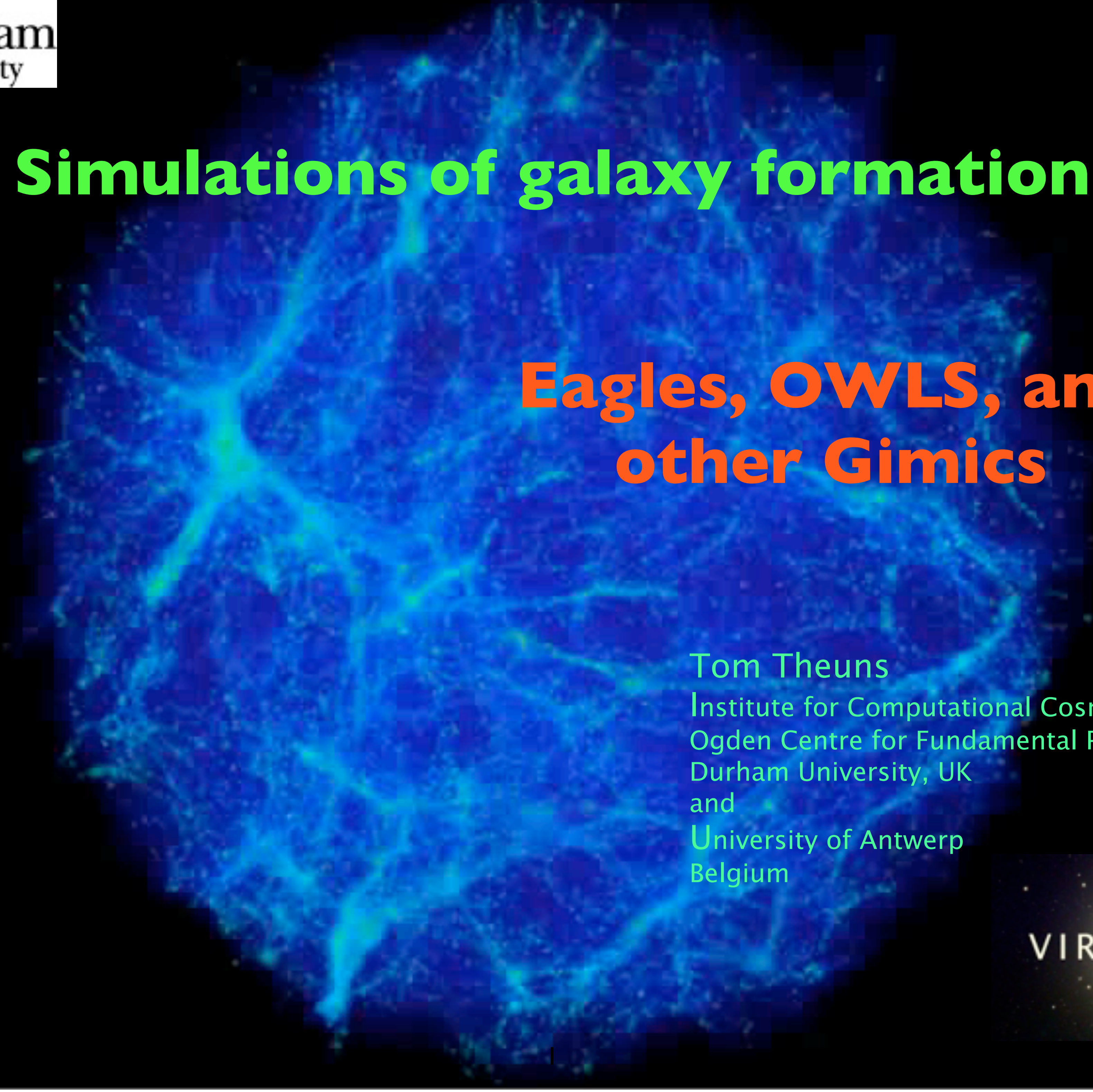
Simulations of galaxy formation



Eagles, OWLS, and other Gimics

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

Contents:

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

Contents:

- The basics (you know this already)
- What do we want? (rather obvious)
- What can we do? (limitations)
- Does it work? (sometimes)
- What did we learn?
- Where do we go from here?

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

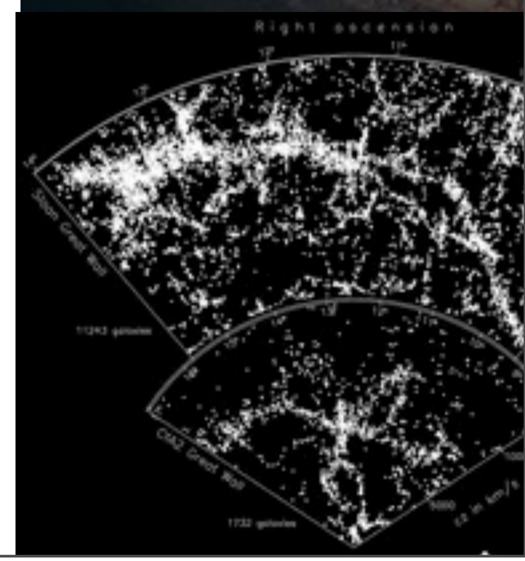
2 pc

x 10000

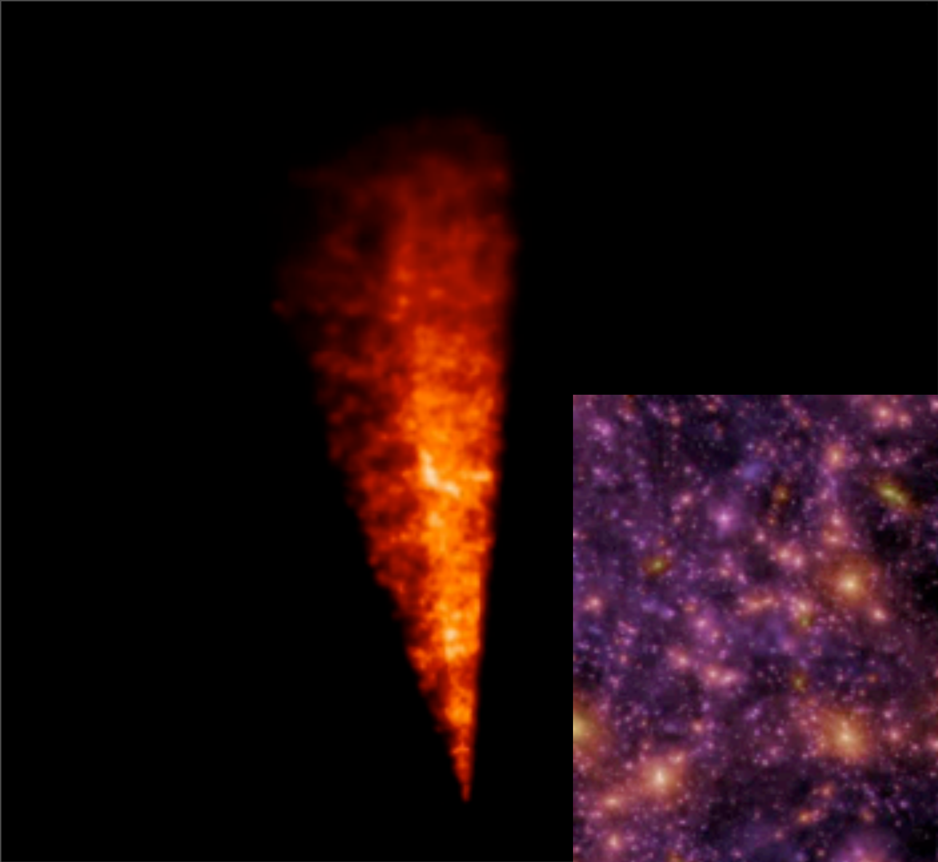
20 kpc

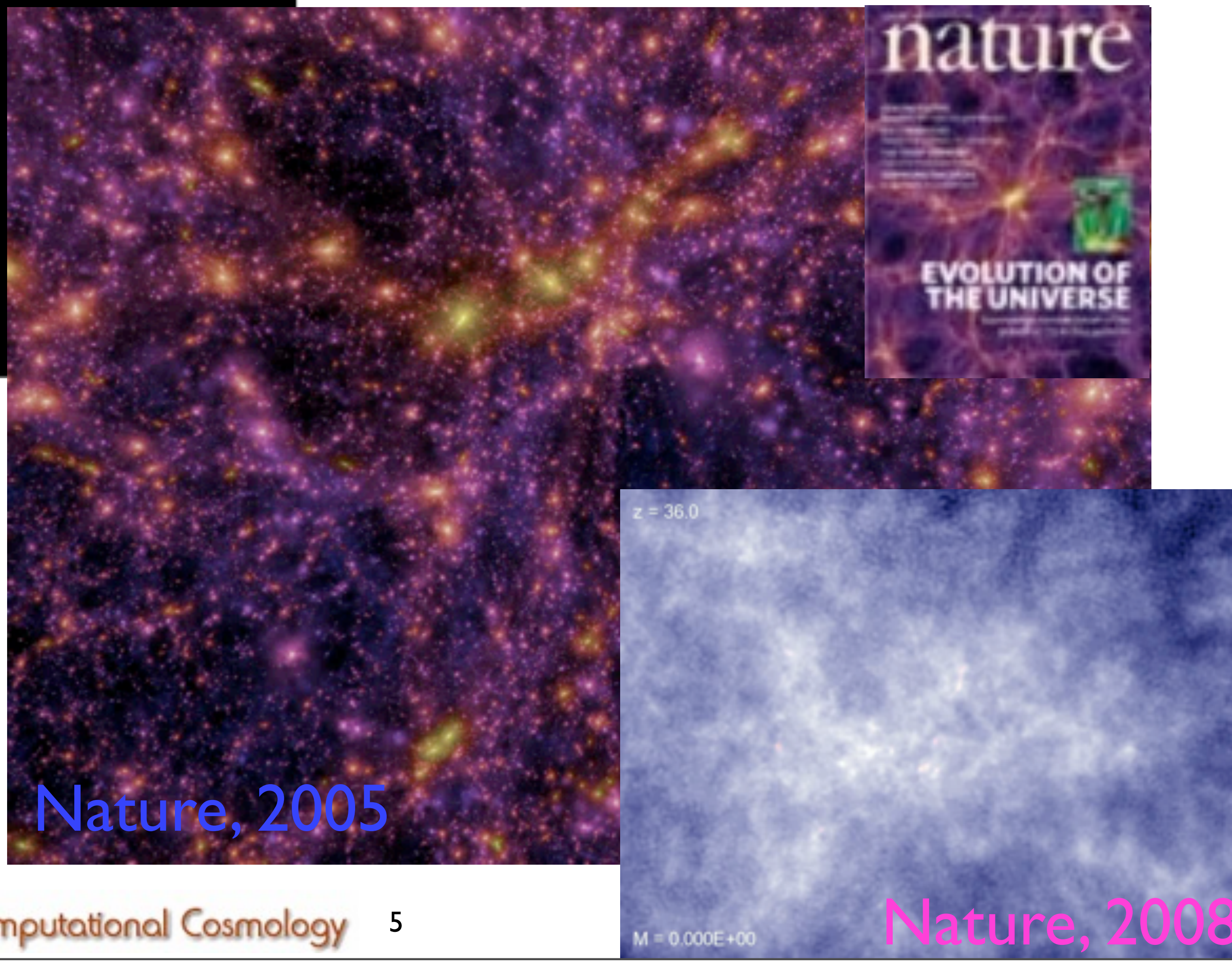
x 10000

200 Mpc



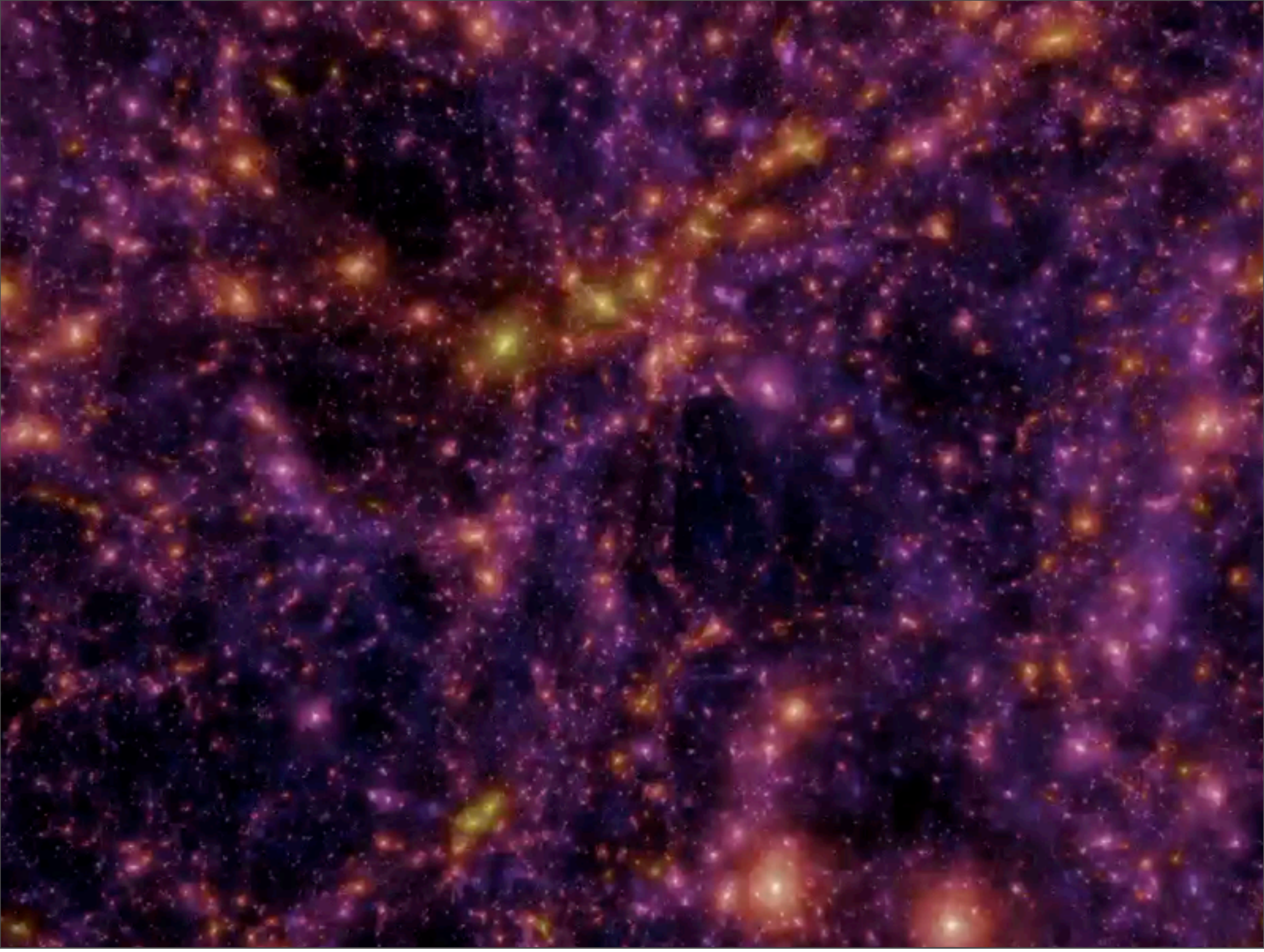
Gravitational build-up of dark matter structures is "solved" problem



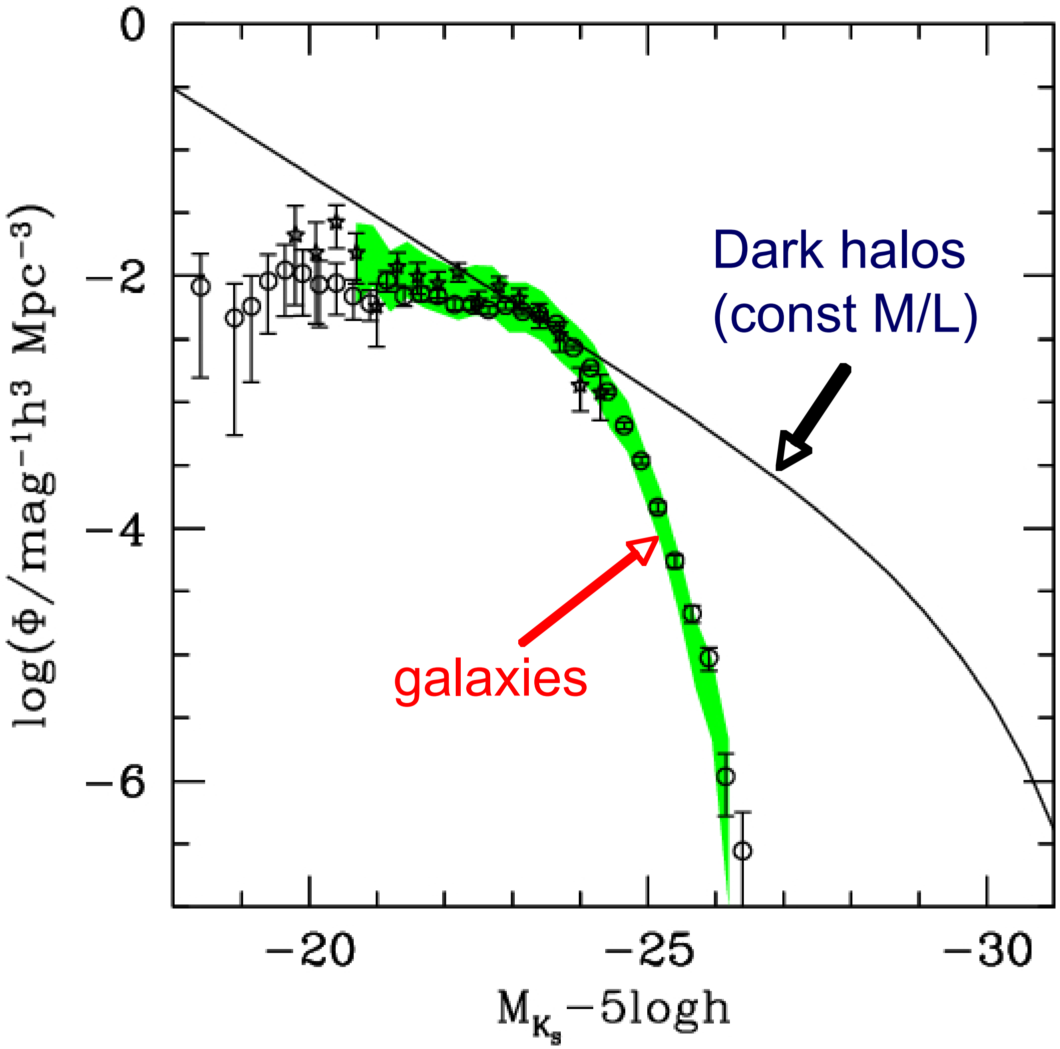


How do galaxies form inside these haloes?

How do galaxies form inside these haloes?



Halo mass function and galaxy luminosity functions have different shape

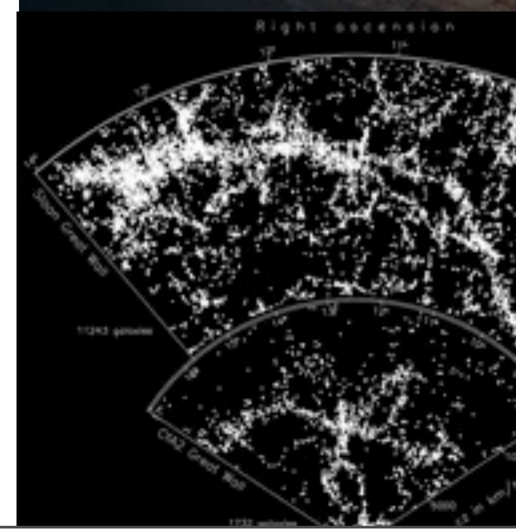


Feedback or gastrophysics is very important

Transfer of power

baryonic physics

Gravity



The challenges of theory/numerical simulations:

Scales:

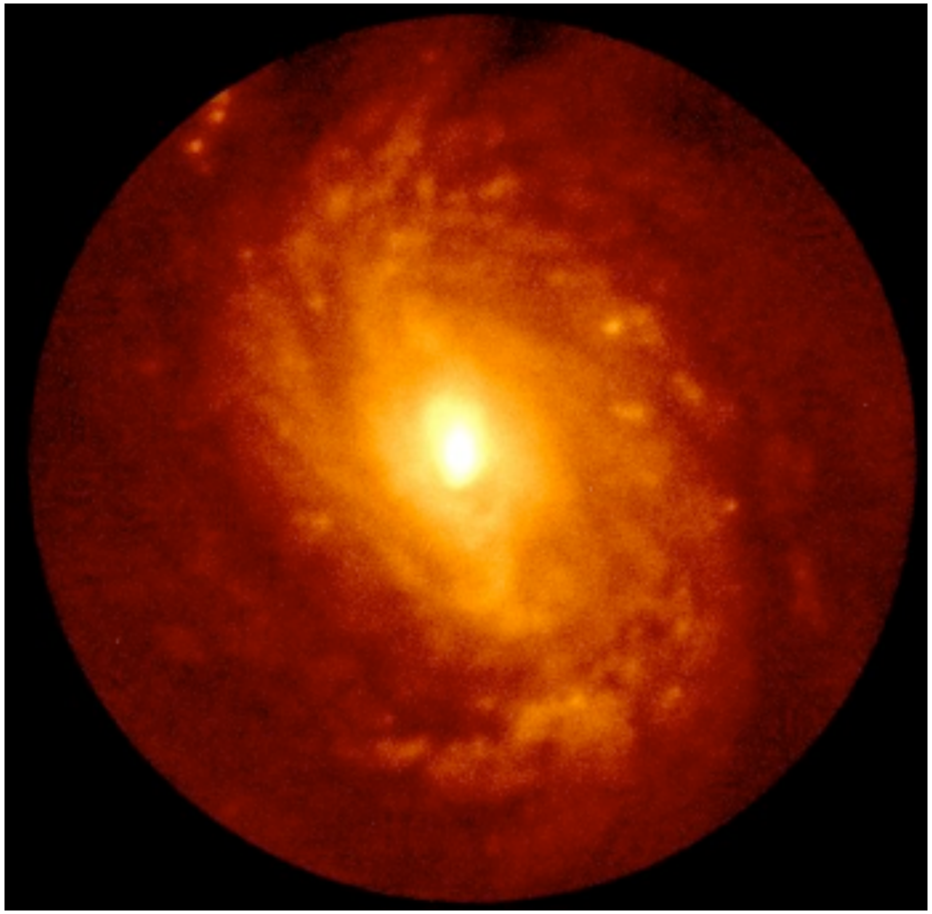
- Box Size = 50 Mpc, bulge size = 1kpc
  - need (500 000)^3 resolution elements
- Mean density = 10^{-7} cm^{-3}, star formation starts at 100 cm^{-3}
  - 10^9 density contrast
- Age of Universe 13.7 Gyr, sound-crossing time bulge: 1 Myr
  - require 10^4 steps

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!

“ .. 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."

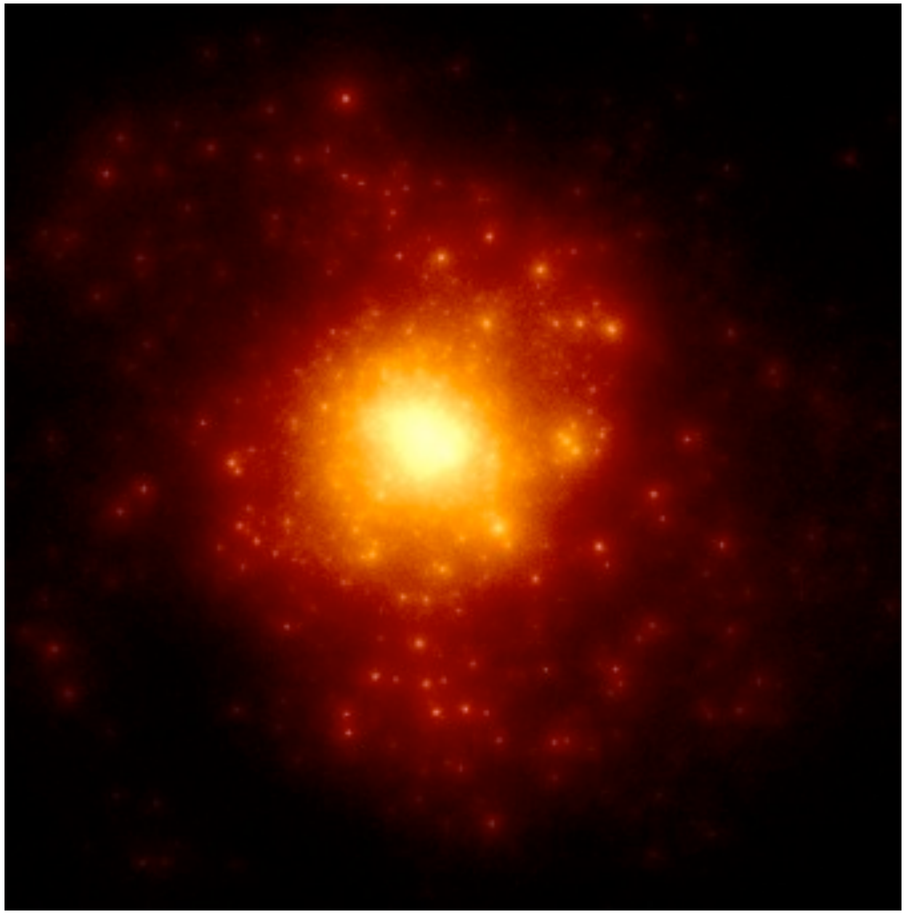
Observed

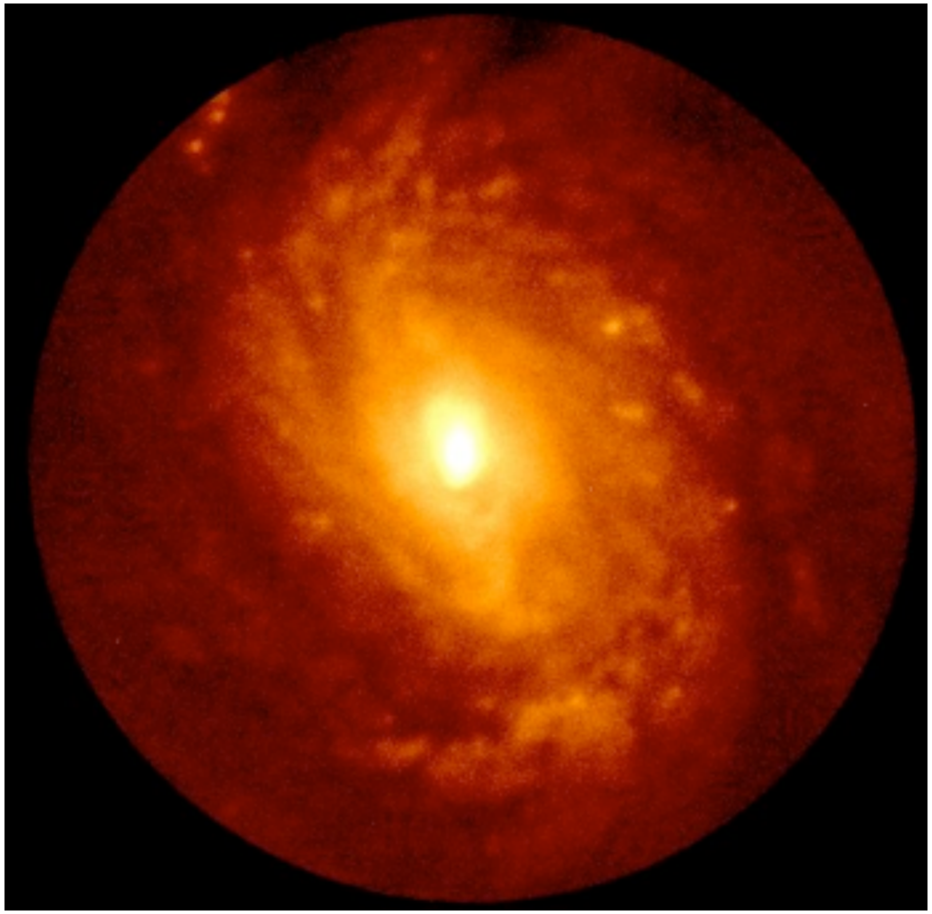


NGC 1068

Simulated

Observed

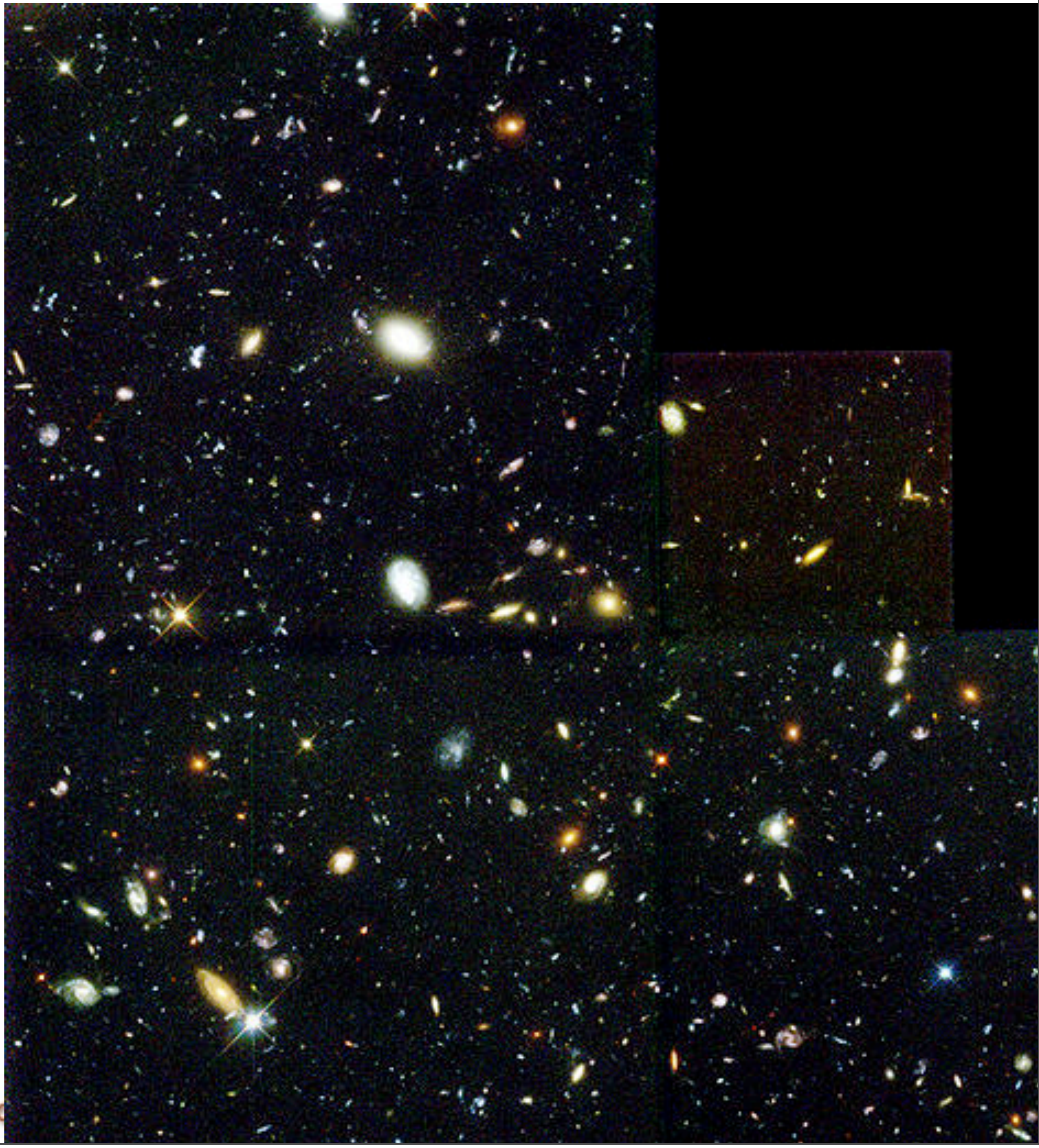




Gadget simulation

NGC 1068

Hubble Deep Field



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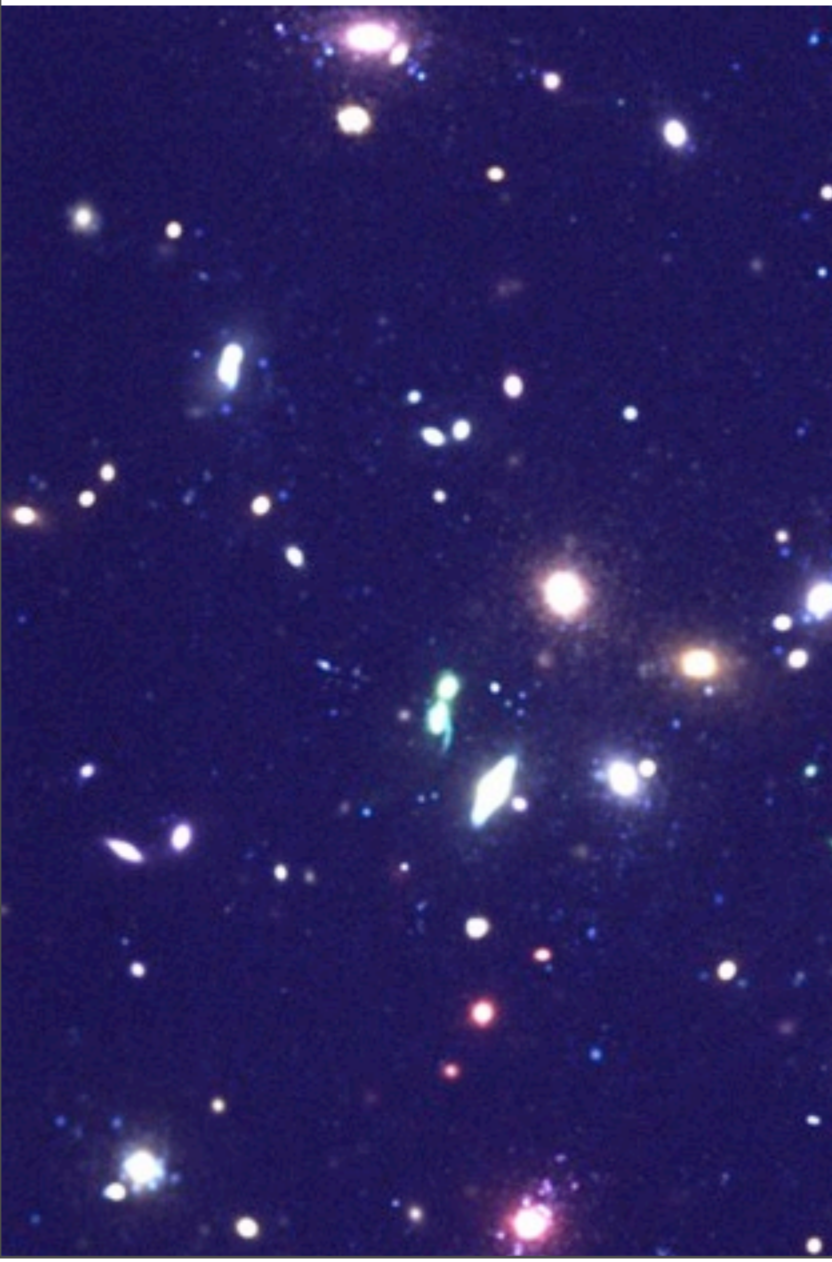
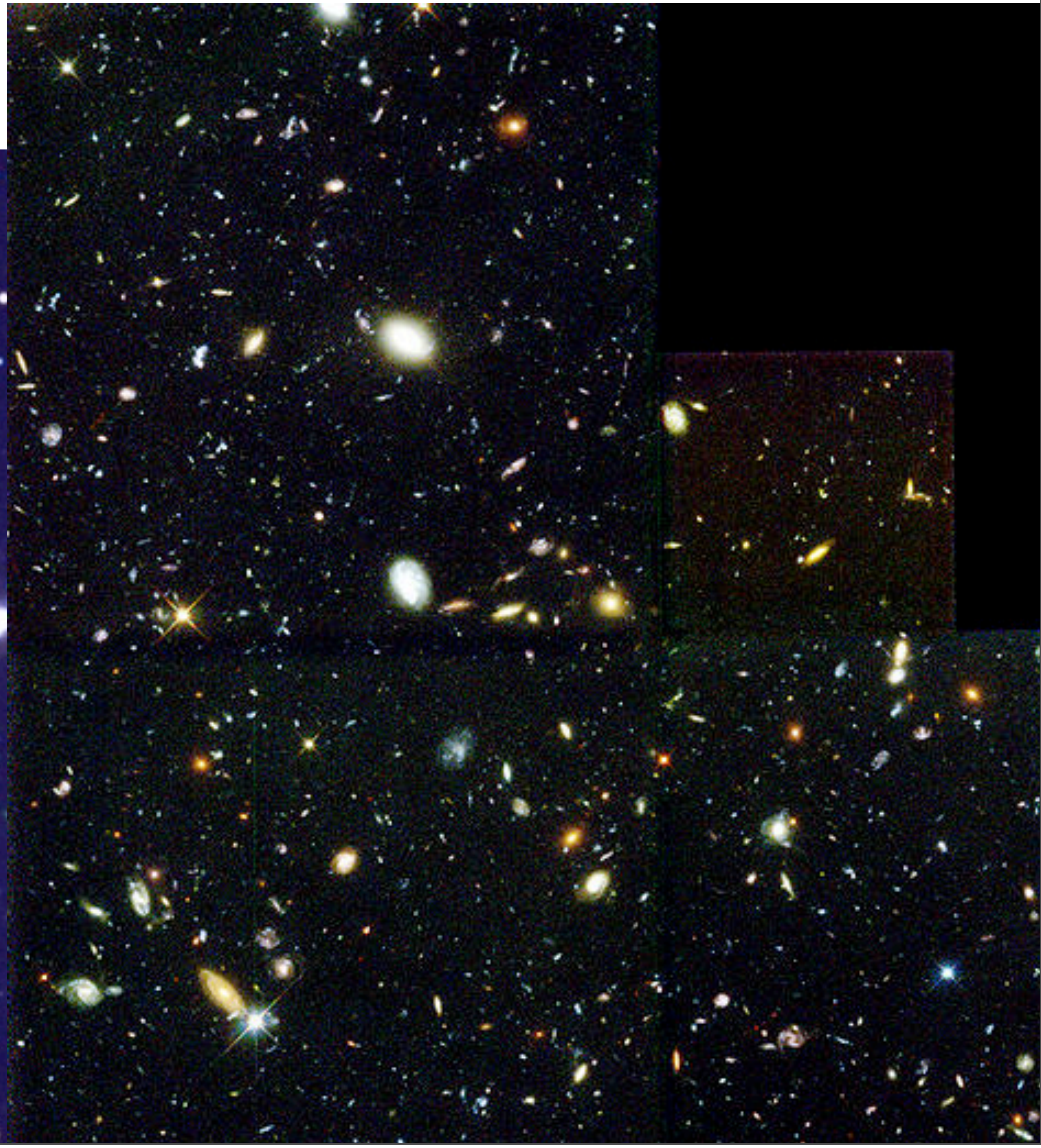
Hubble Deep Field

Gadget deep field





GIMIC/OWL (EAGLE) projects

Leiden:
Claudio Dalla Vecchia
Joop Schaye

Crain, Robert

Trieste:
Luca Tornatore

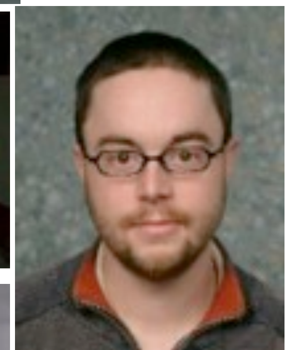
Aims:
- simulate IGM and galaxies together
- investigate numerical/physical uncertainties

MPA:
Volker Springel

- Gadget 3
- Star formation guarantees Schmidt law
- Stellar evolution
- Galactic winds
- Metal-dependent cooling

GIMIC/OWLS project

Leiden:



Trieste:

HITS:

MPE

ICC

om Theuns

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

Galaxy-Intergalactic Medium Interaction Calculation re-simulations within Millennium box with a single choice of parameters

+


GIMIC

=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“Sub-grid physics” needed:

- star formation (resolved densities << densities at which stars form)
- feedback: resolution >> supernova blast wave

→ use effective “phenomenological” description

“Numerical convergence”

→ modelling parameters depend on resolution

holistic approach:

need to investigate all aspects of model

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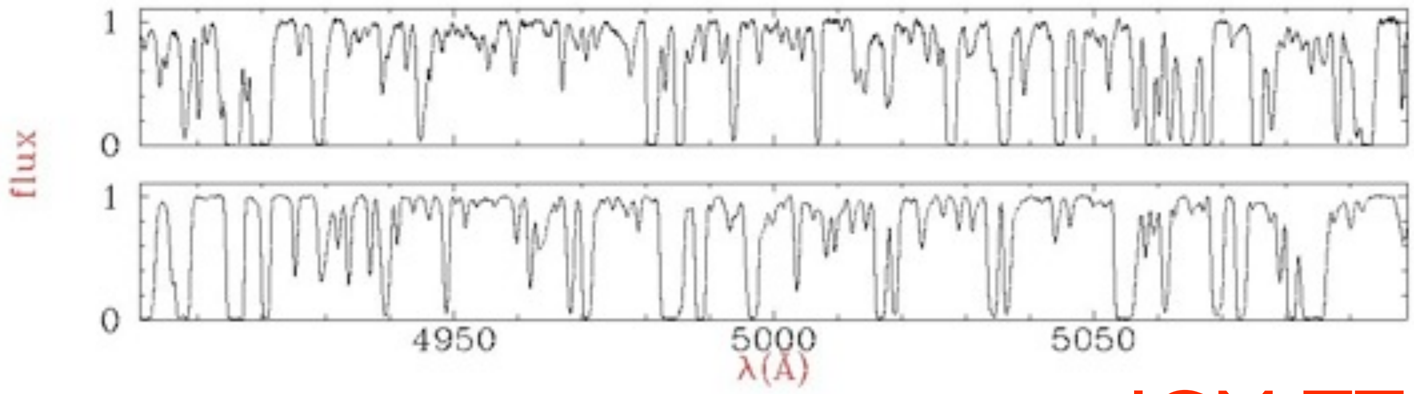
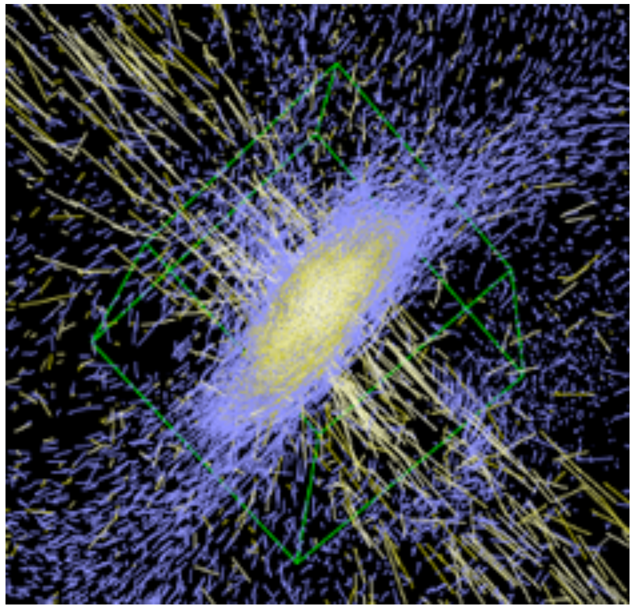
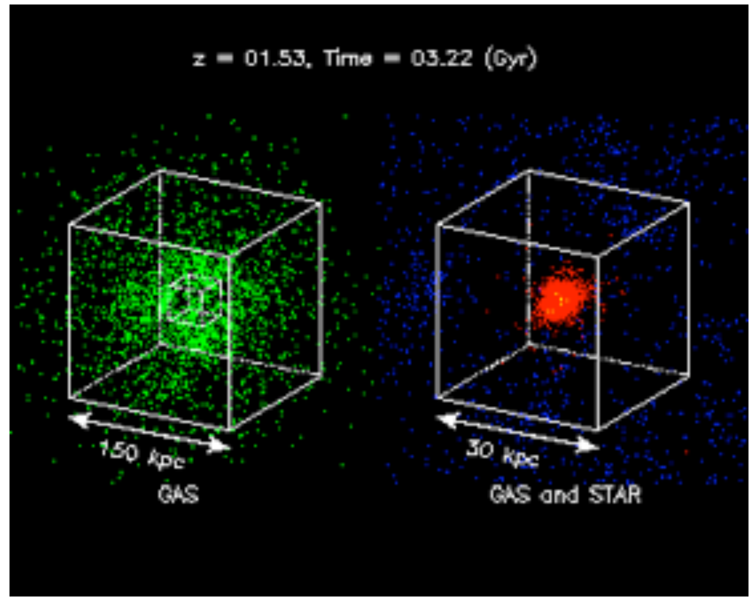


IGM: TT

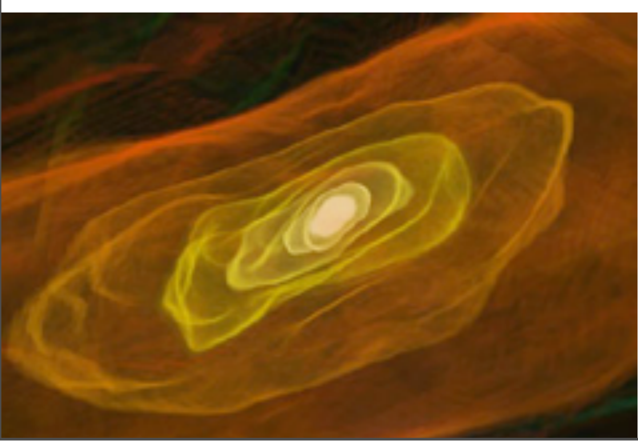
X-ray cluster:
Borgani et al





Galaxy: Springel

Dwarf Galaxy:
Kawata



First star: Abel et al

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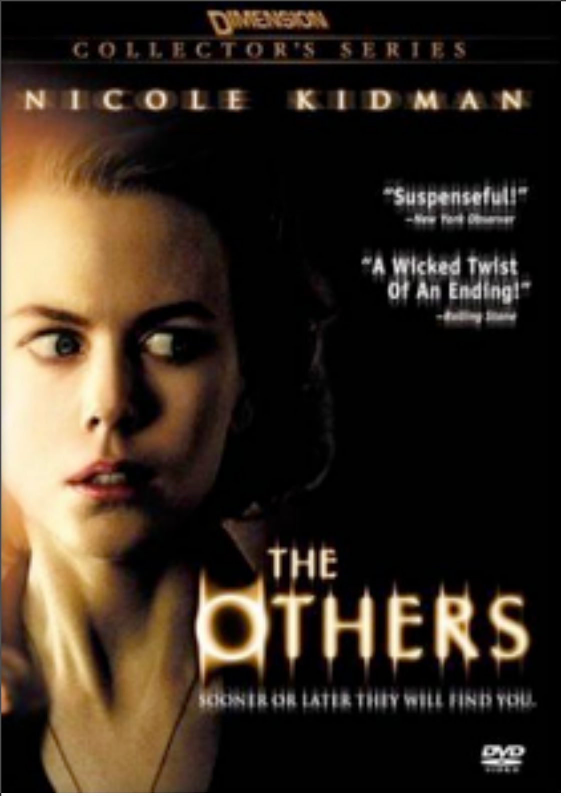


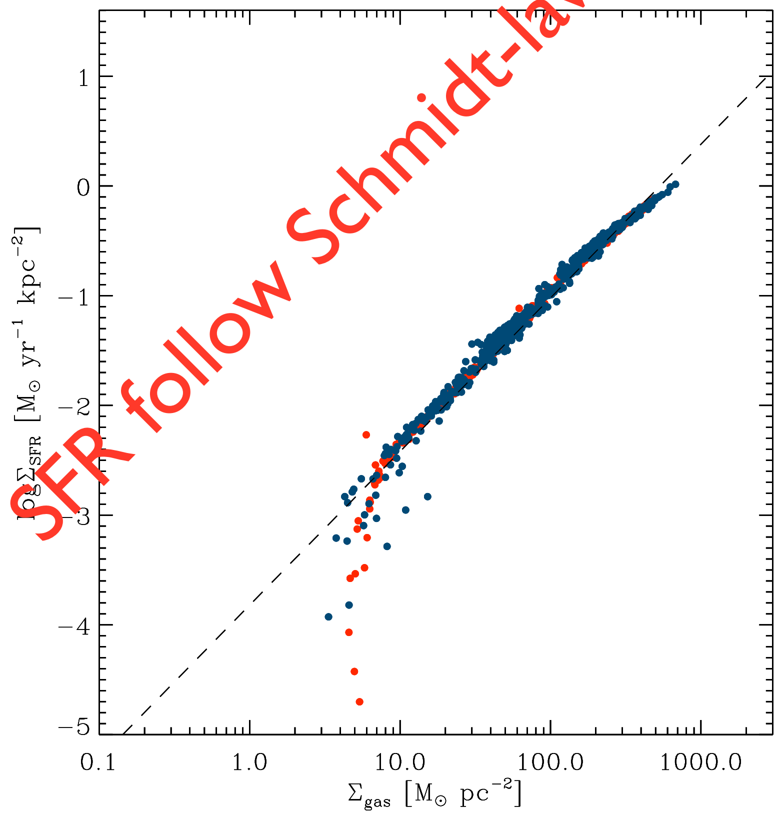
or, our competitors

- Gadget: SPH + TreePM
- Gasoline: SPH + TreePM
- Ramses (AMR)
- Enzo (AMR)
- Art
- Arepo (moving mesh)

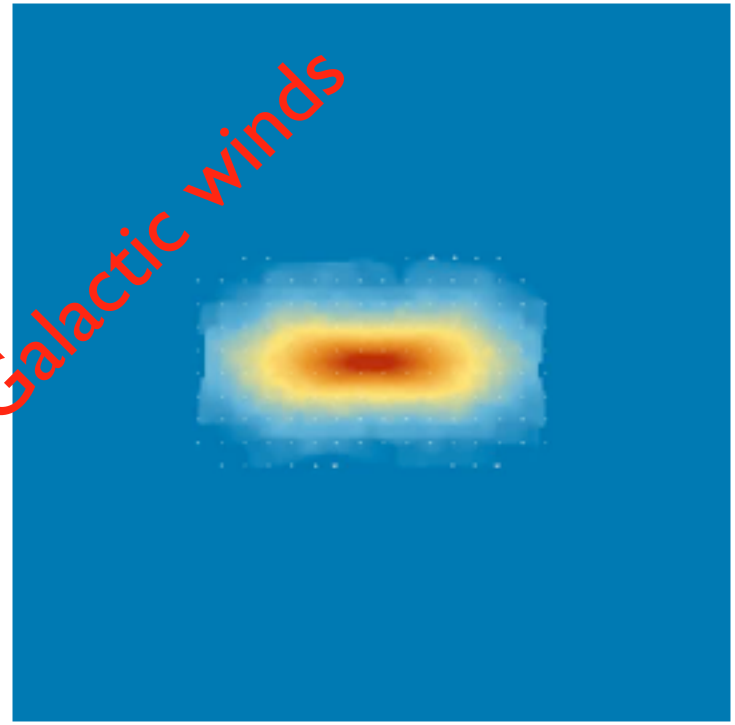
- Dave, Oppenheimer +.Gadget ++
- Hernquist +: Gadget+, Arepo
- Other Gadget+ groups
- Seattle group: Gasoline (SPH)
- Teyssier+: Ramses (AMR)
- Gnedin+
- Hopkins +: Gadget

Subgrid physics

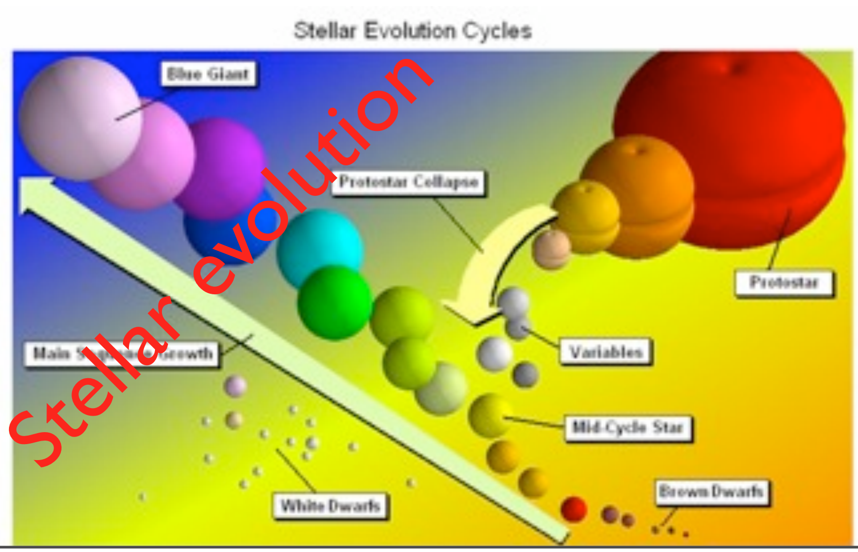
SFR follow Schmidt-law



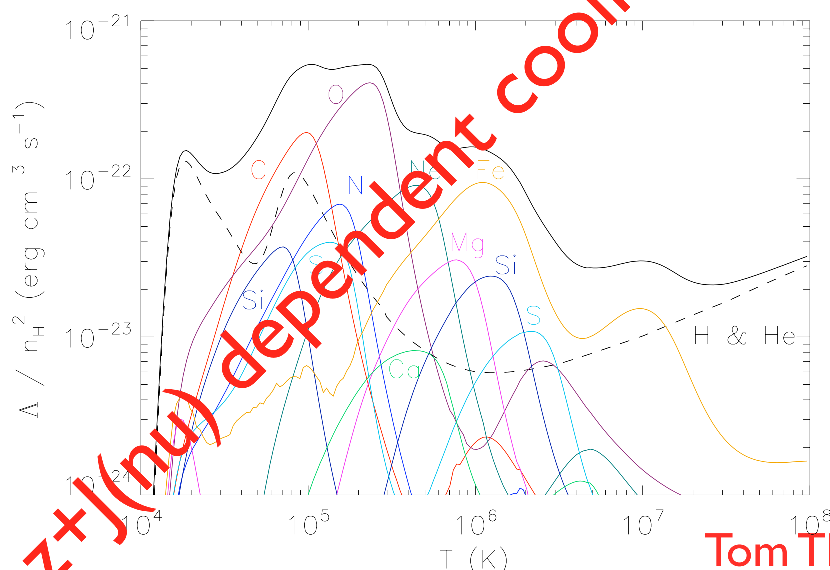
Galactic winds



Stellar evolution



z+J(nu) dependent cooling

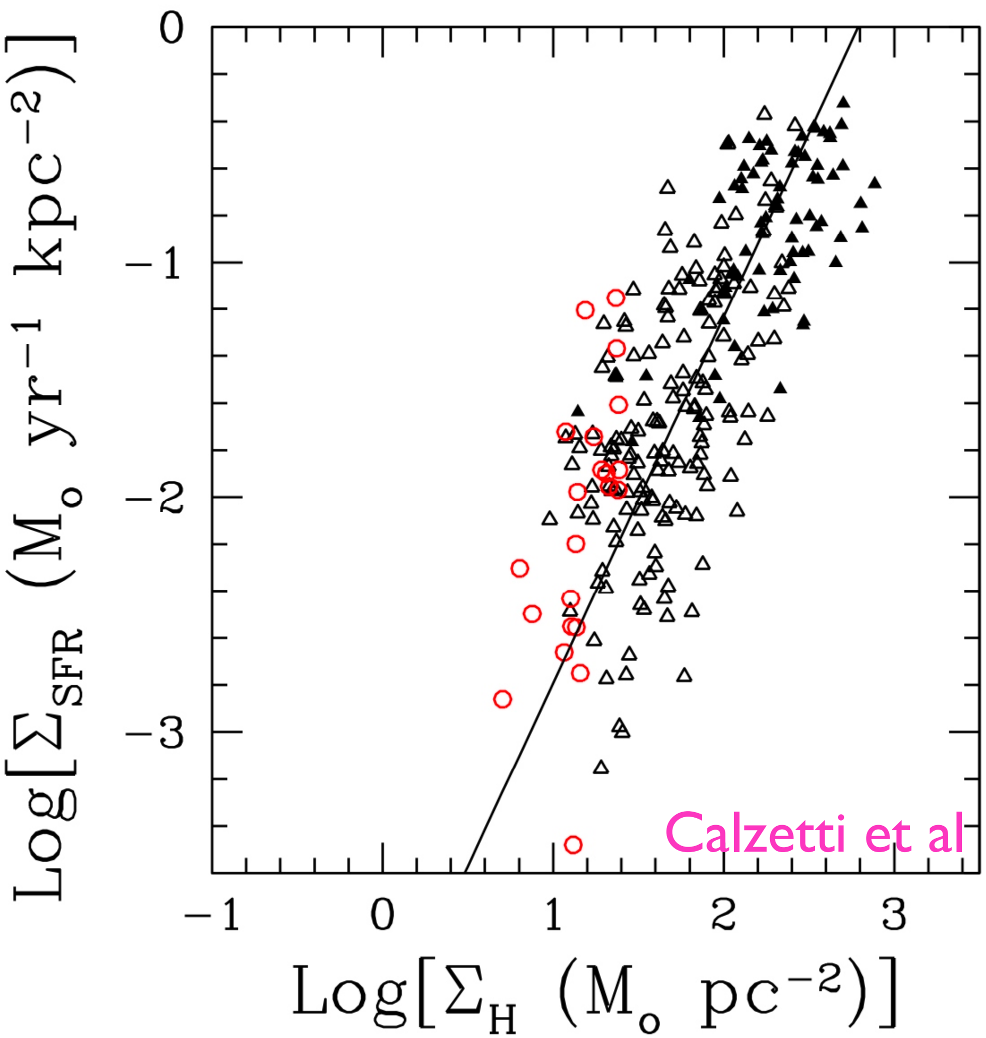


Tom Theuns

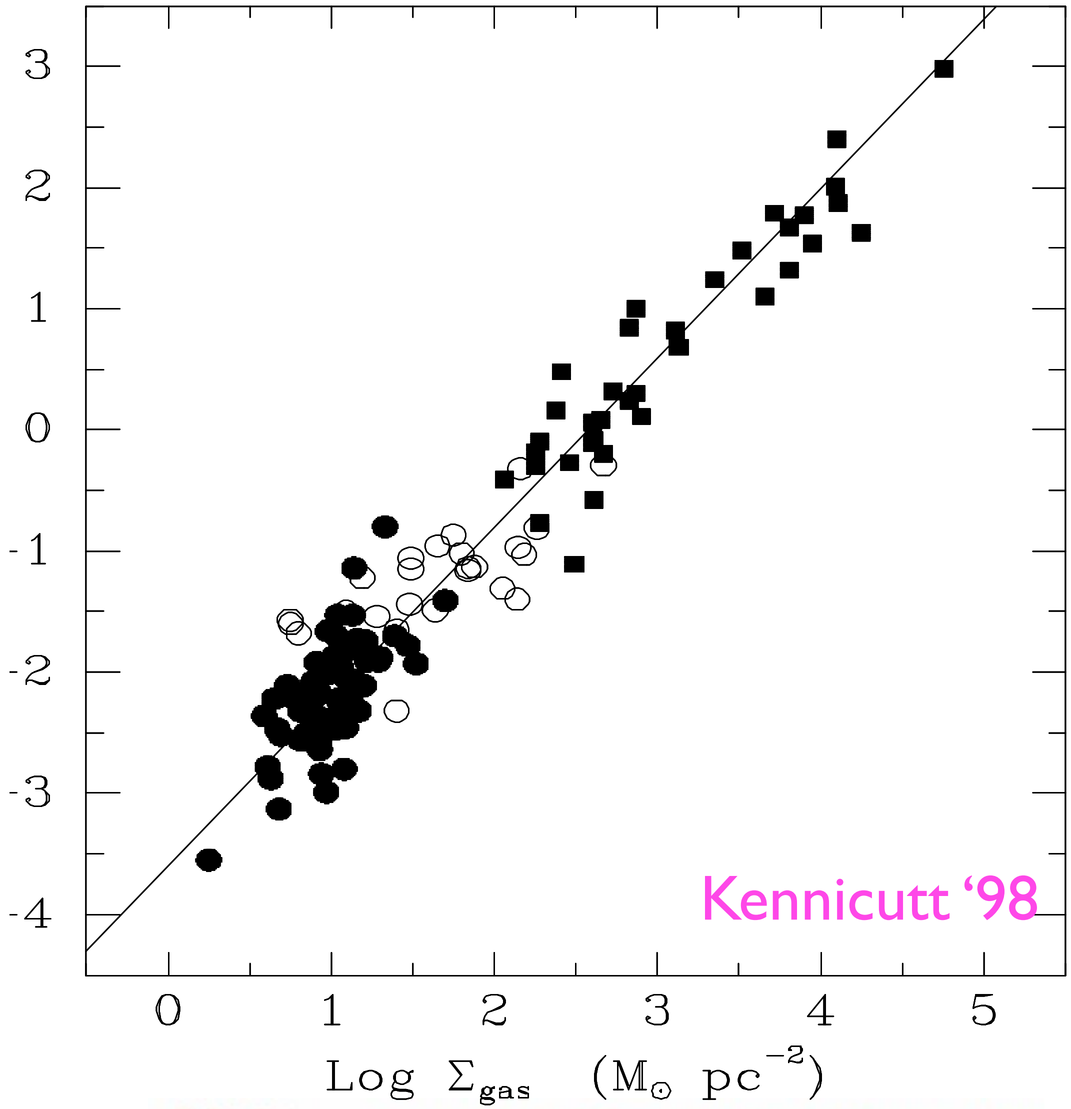
Star formation: what we want: Schmidt law

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

Local: same galaxy



Global: different galaxies



Tom Theuns

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How to obtain Schmidt law? Sub-grid model for SF and ISM

- Insufficient resolution to model multiphase ISM
- Need effective pressure of unresolved, multiphase ISM
- Need star formation law that reproduces observed threshold and Schmidt law with the minimum number of free parameters
- We do not want to simulate more than we can

J Schaye

Sub-grid model for SF and ISM

- What goes in

  Effective equation of state (gives the pressure of the gas)

$$P \propto \rho_{\rm gas}^{\gamma_{\rm eff}} \quad (\rho_{\rm gas} > \rho_{\rm thr})$$

  Schmidt law (surface densities)

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{n}$$

  Surface density threshold

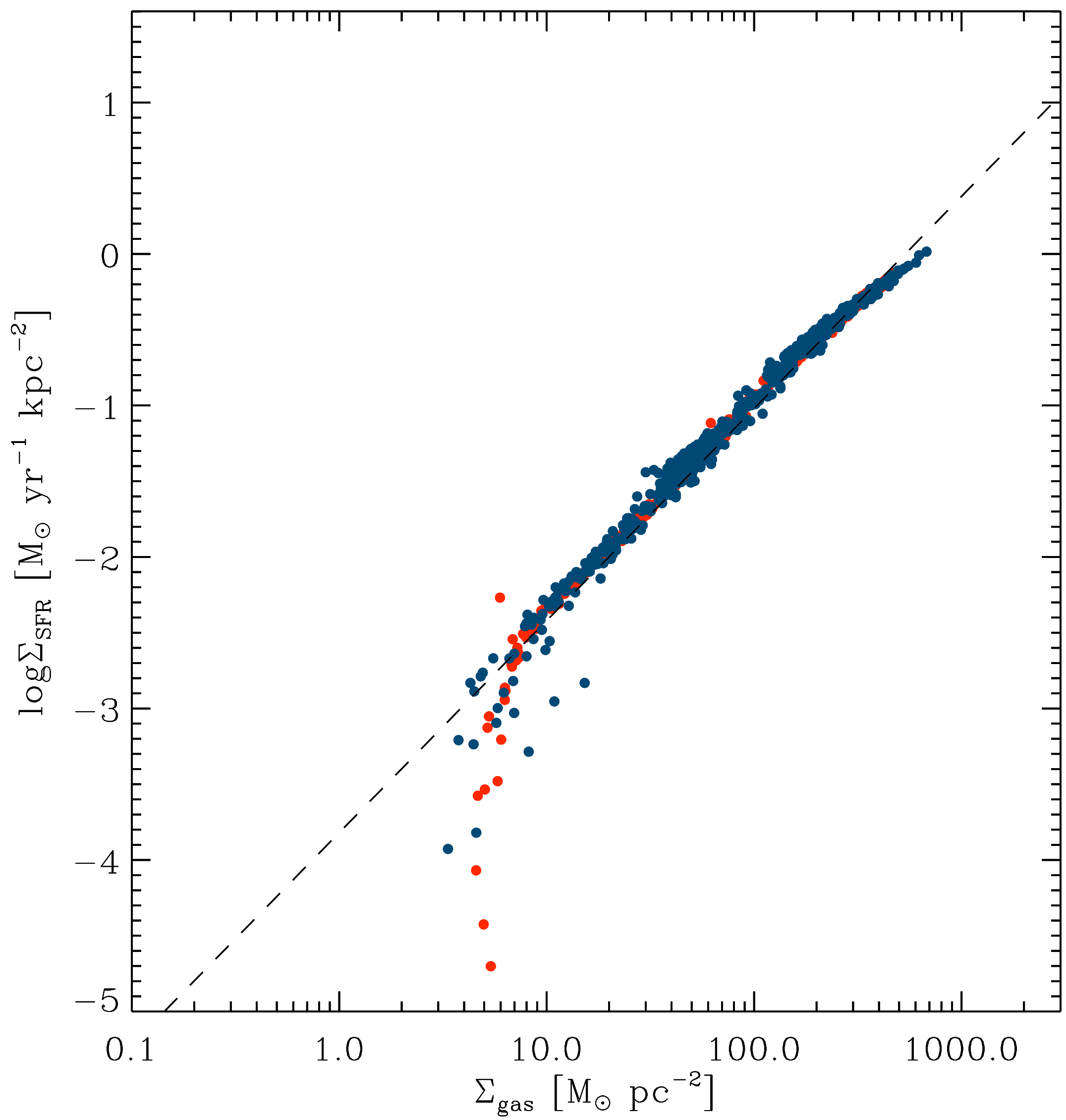
- What comes out

  Volume density star formation law

  Volume density threshold

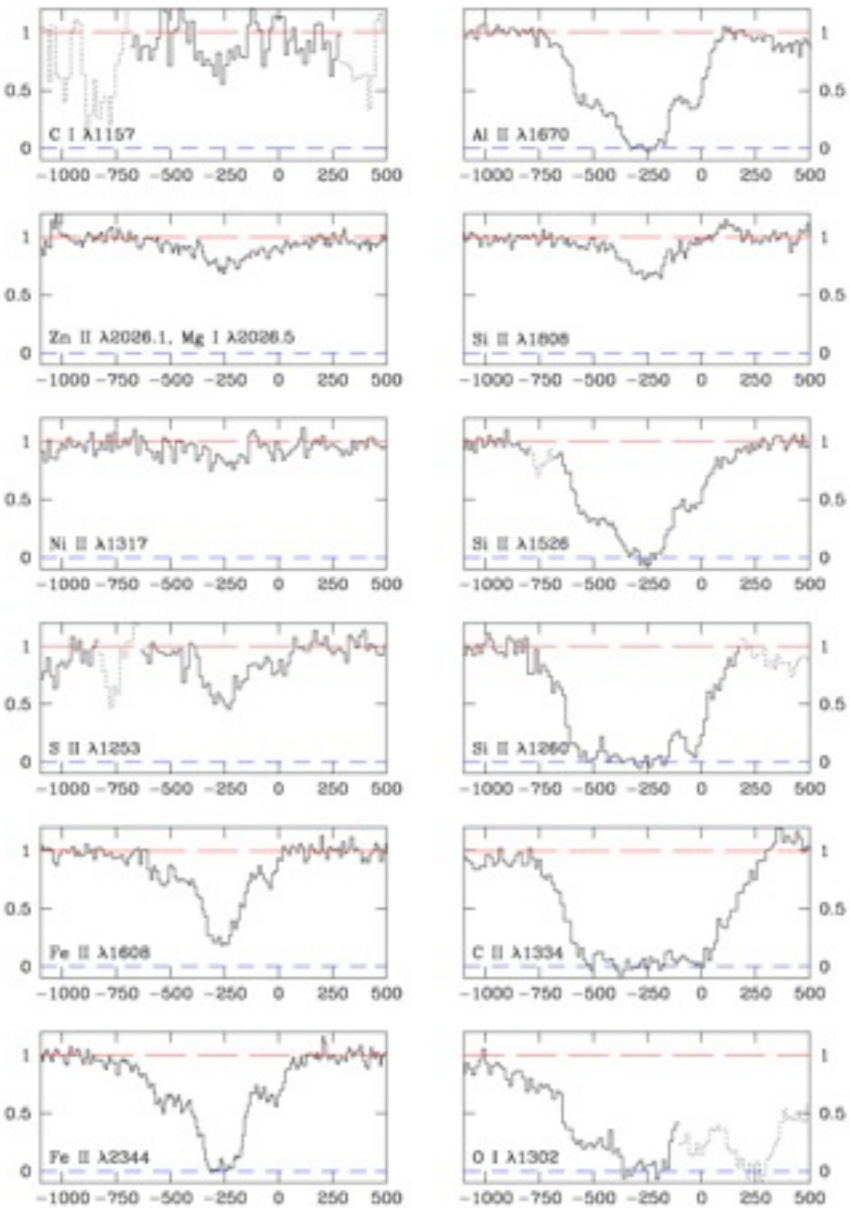
J Schaye

Implementation guarantees a Schmidt law



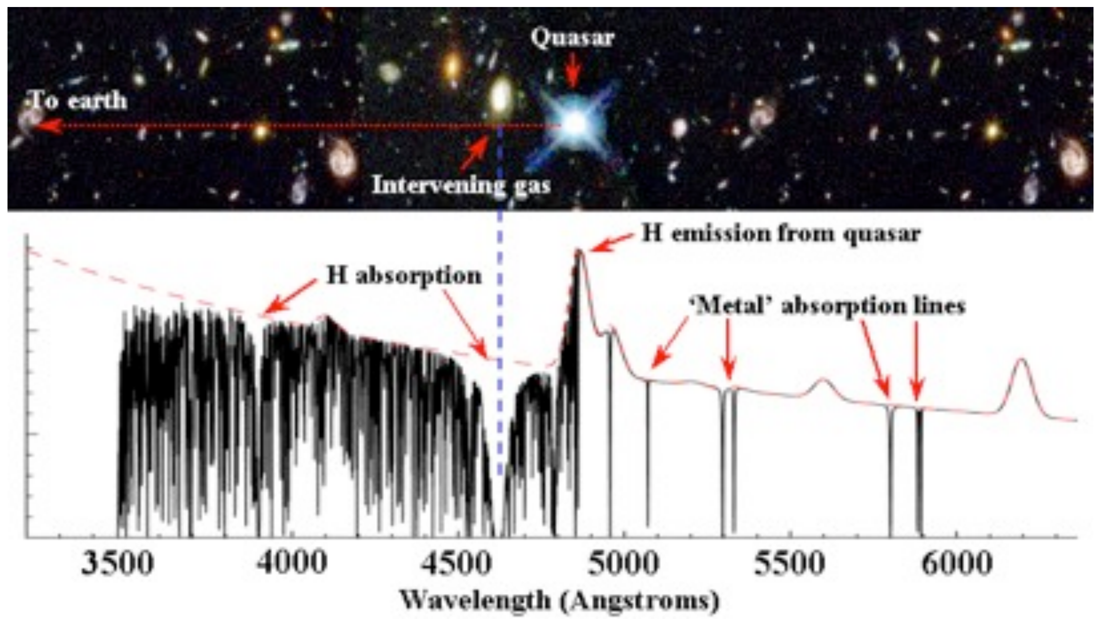
Schaye 04

Evidence for galactic winds:



At high z: Pettini et al 02

At low z: M82



In absorption

Energetics of galactic wind

newly formed → $\Delta M_\star$; SN energy total → $\Delta E_\star$; SNe/stellar mass → $\frac{1}{100 M_\odot}$; 1 SN → 10^{51} erg

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

$$\dot{E}_\star = \eta_{\rm T}\,\epsilon_{100} \frac{10^{51}\,\mathrm{erg}}{100\,M_\odot} \dot{M}_\star = \eta_{\rm T}\,\epsilon_{100}\,(710\,\mathrm{km\,s^{-1}})^2$$

$$\Delta E_{\rm wind} = \frac{1}{2} M_{\rm wind}\, v_w^2 + M_{\rm wind} u_{\rm wind}$$

$$\frac{1}{2}\dot{M}_{\rm wind}\, v_{\rm wind}^2 = \dot{E}_\star$$

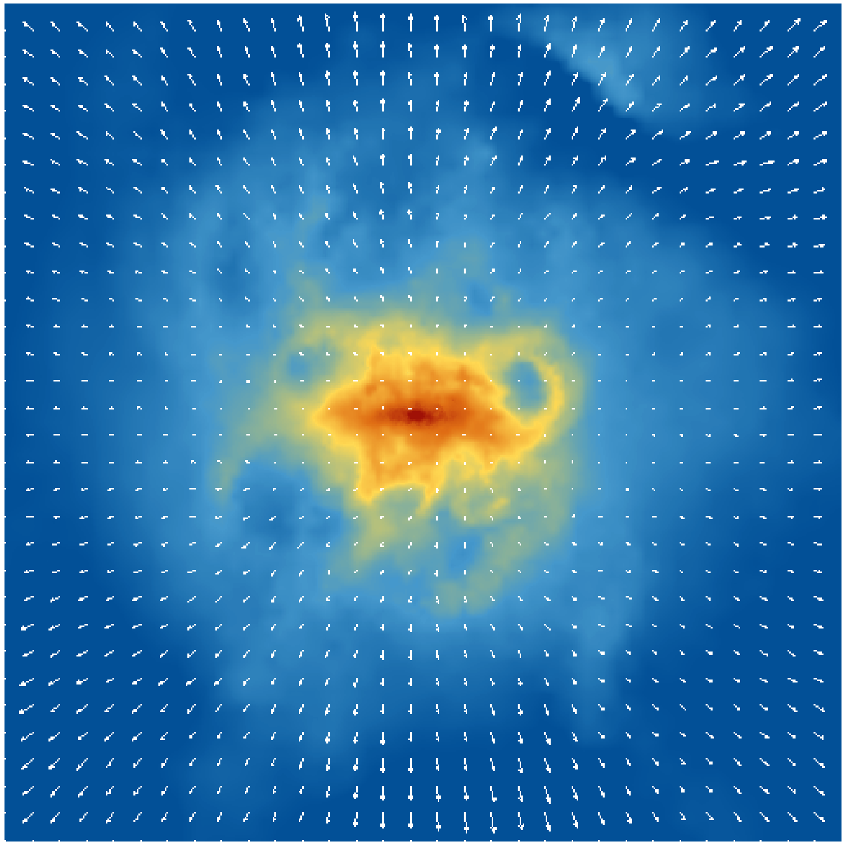
Energetics of galactic wind

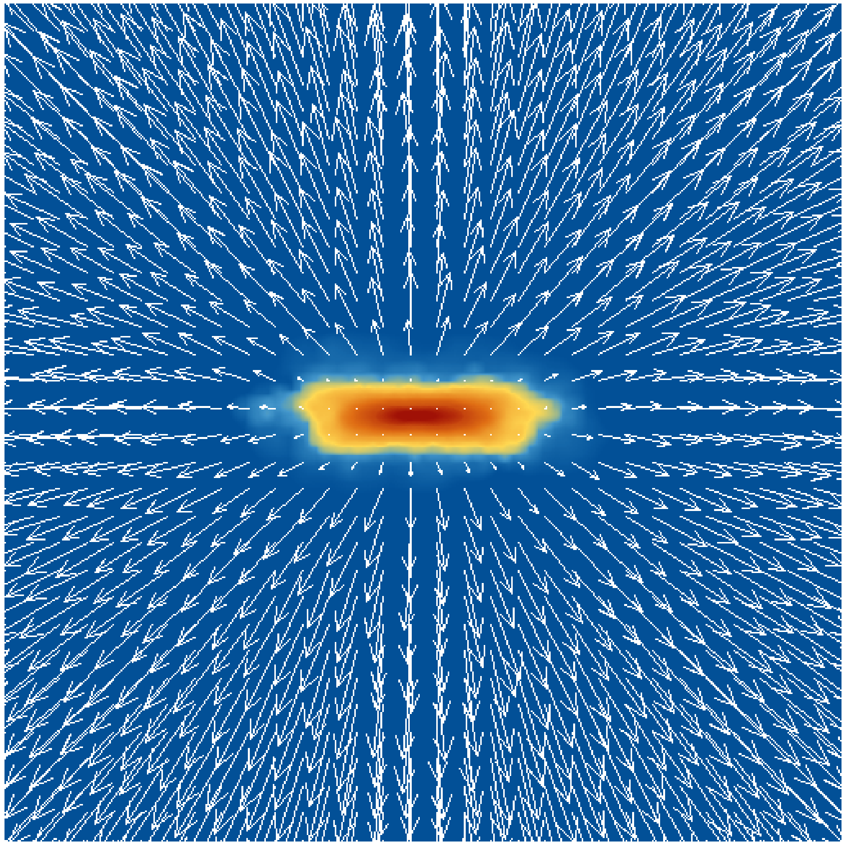
$$\beta \equiv \frac{\dot{M}_{\rm wind}}{\dot{M}_\star} = 2\eta_{\rm T}\,\epsilon_{100}\,(710\,{\rm km\,s^{-1}})^{-2}$$

- Phenomenological model: how to choose mass-loading/ wind speed?
- Want significant mass loading (beta>1): hence feedback becomes inefficient in galaxies a few times more massive than the MW (AGN?)
- Feedback could be very efficient in small galaxies, but only if wind speed comparable to escape speed. But why would this be the case? (beta depends on halo?)

Durham University

Implementation of winds:





Schaye & Dalla Vecchia 08

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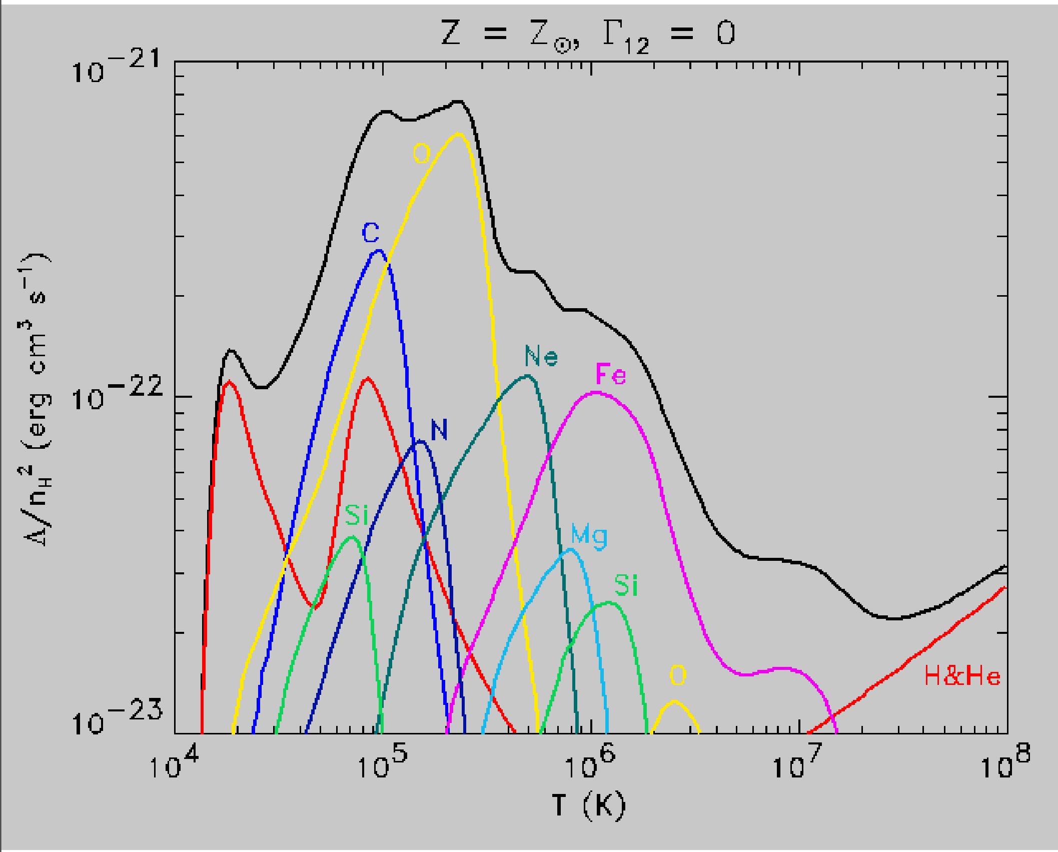
Tom Theuns

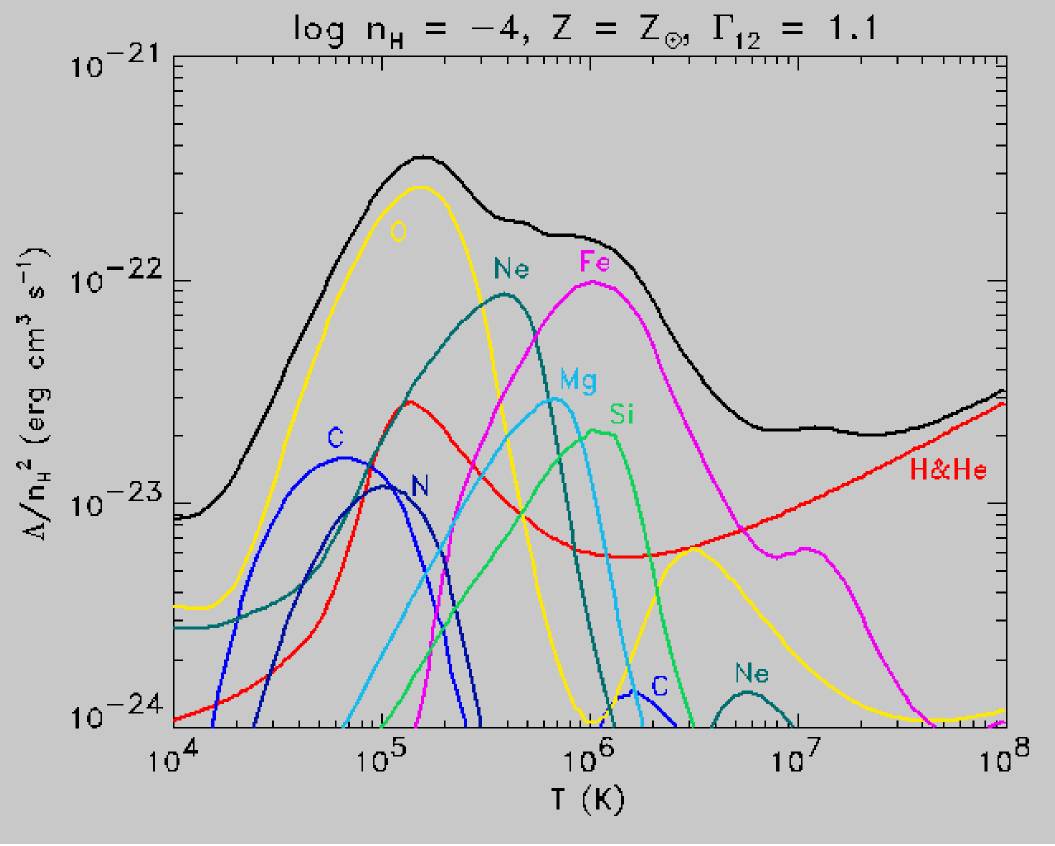
Durham University

Metal cooling and the UV-background
Cooling rate



Without ionizing background

With ionizing background from gals & AGN



Wiersma et al ‘08

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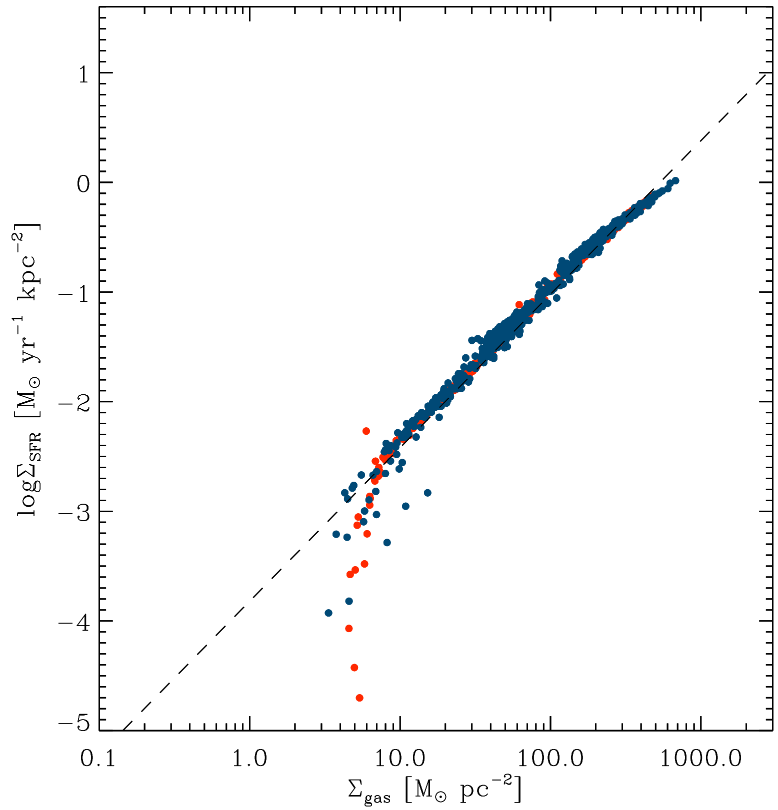
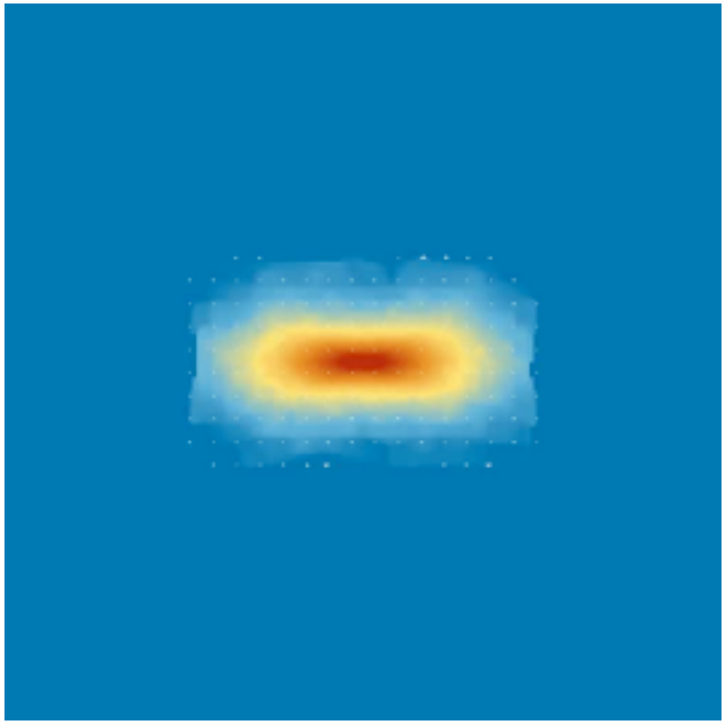
Code in brief

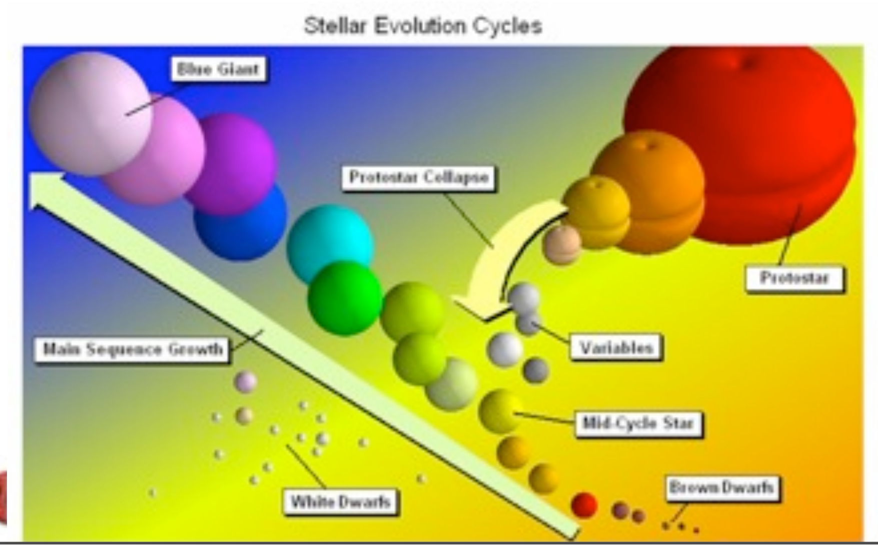
SFR follow Schmidt-law



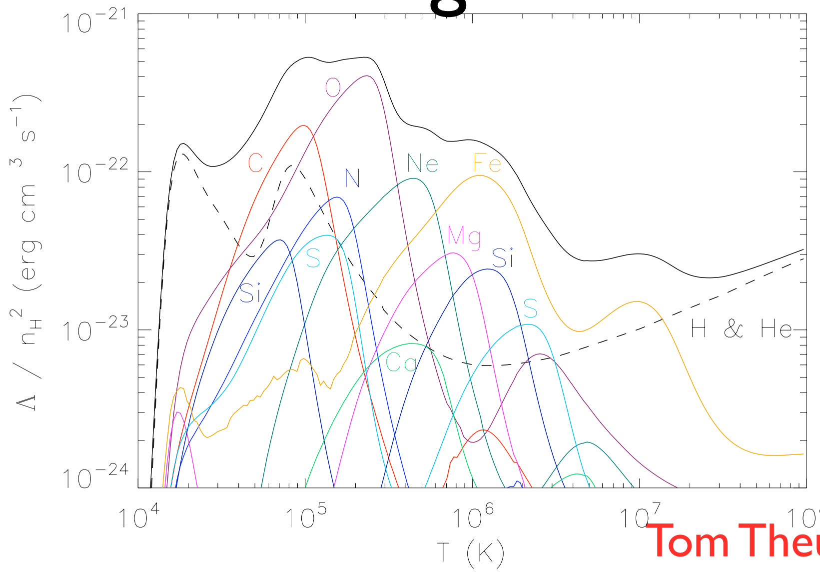
Galactic winds



Stellar evolution



Z+J(nu) dependent cooling



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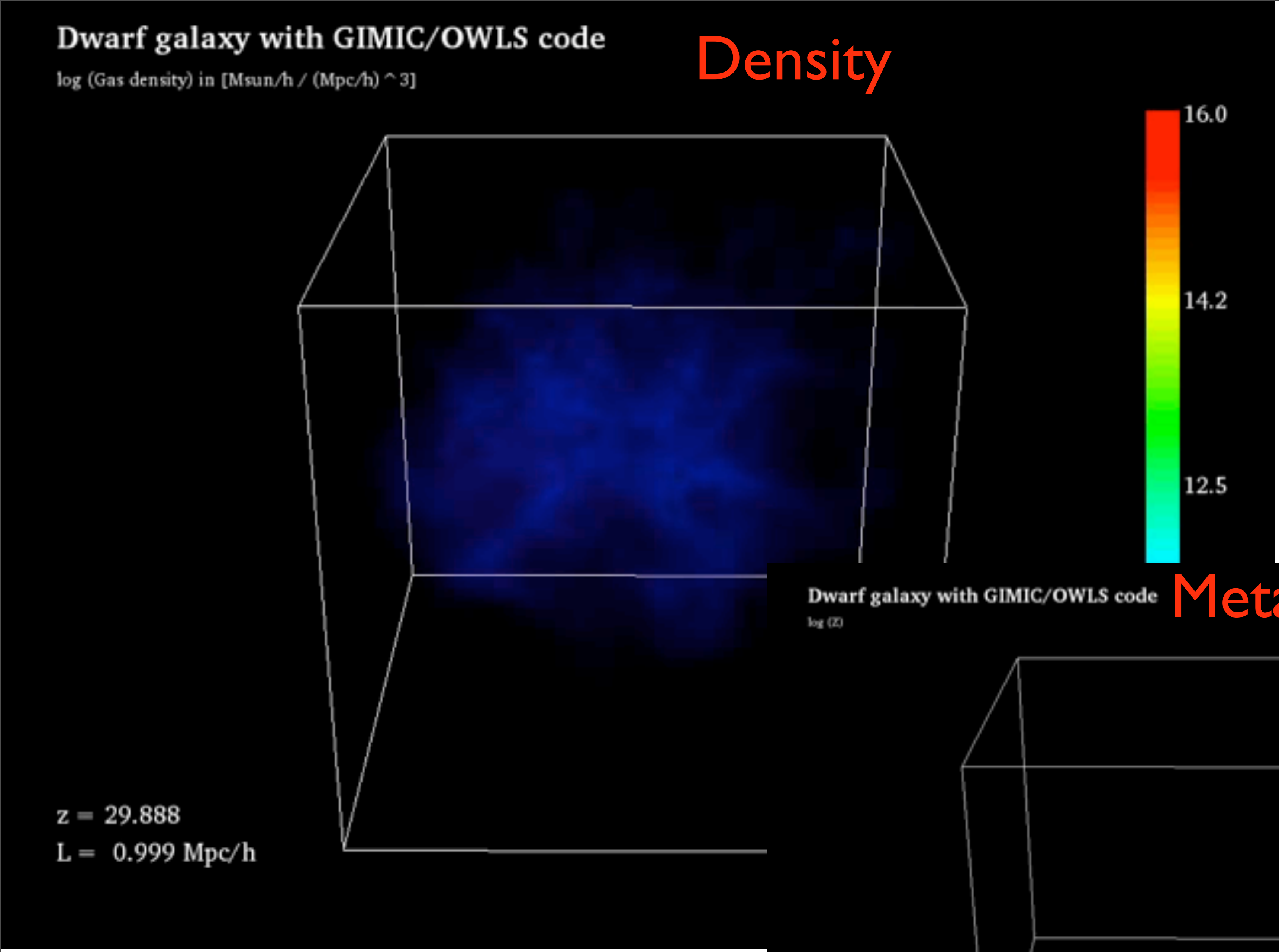

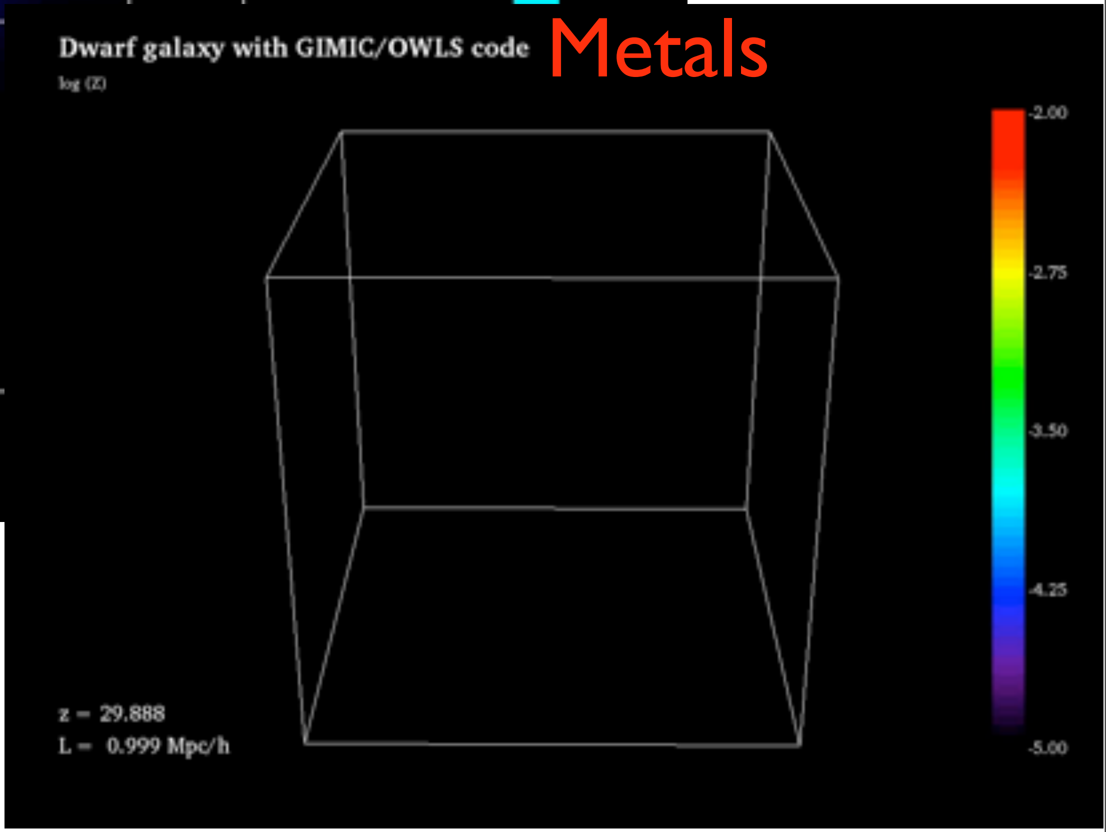

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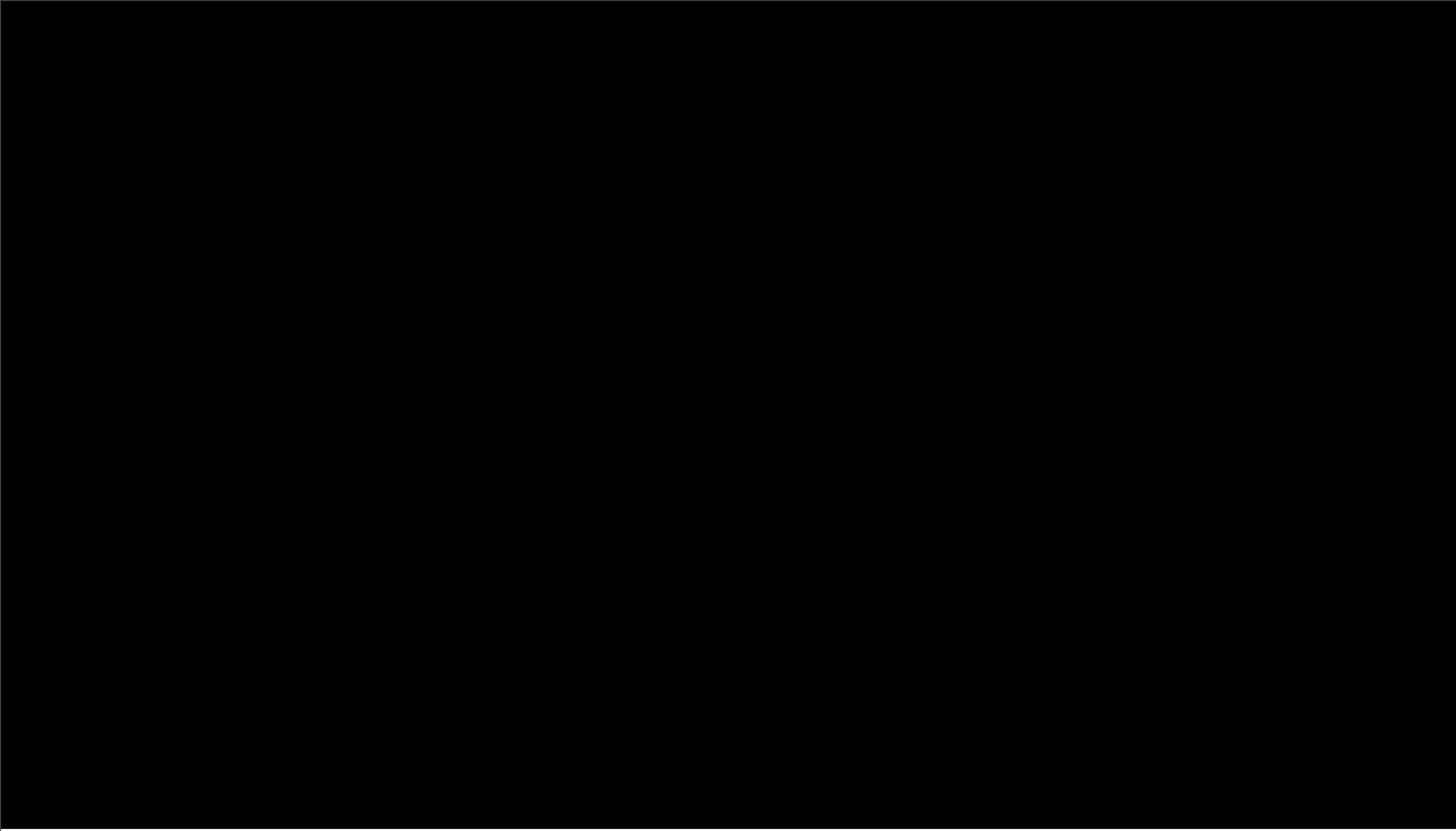

Formation of Milky Way-like galaxy

X-ray coronae in simulations of galaxy formation

Robert A. Crain[1⋆], Ian G. McCarthy[2], Carlos S. Frenk[3], Tom Theuns[3,4]
& Joop Schaye[5]
Tom Theuns

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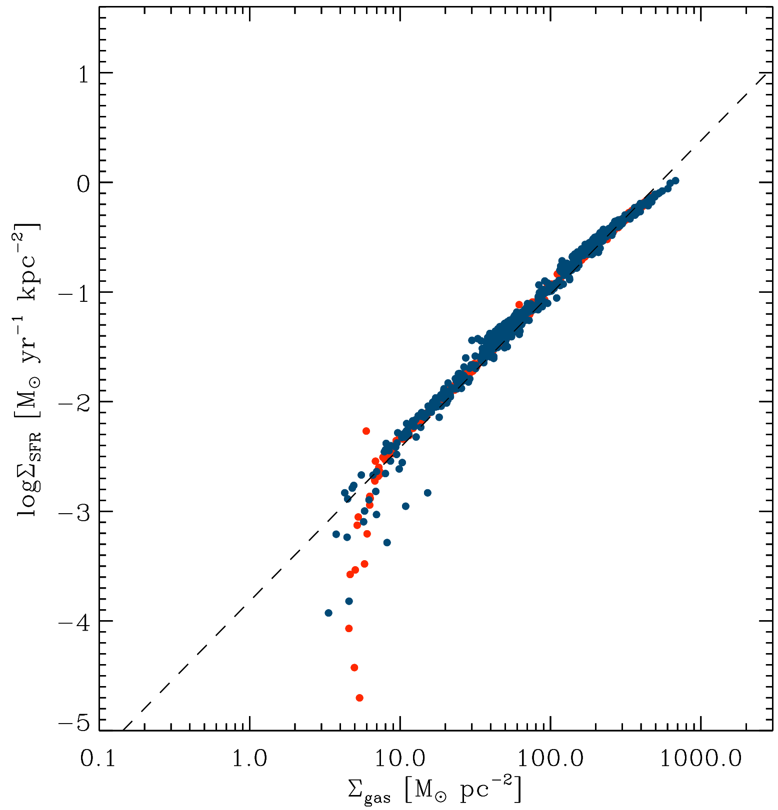
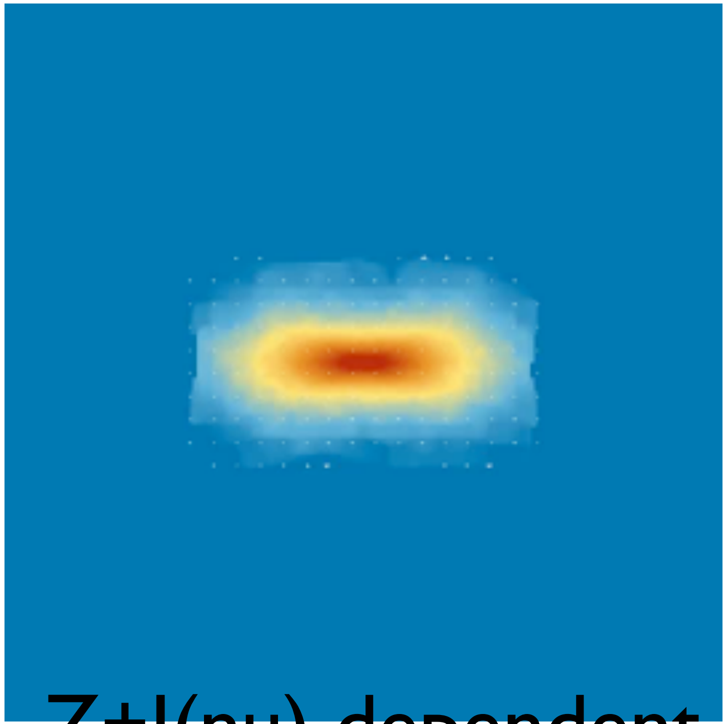
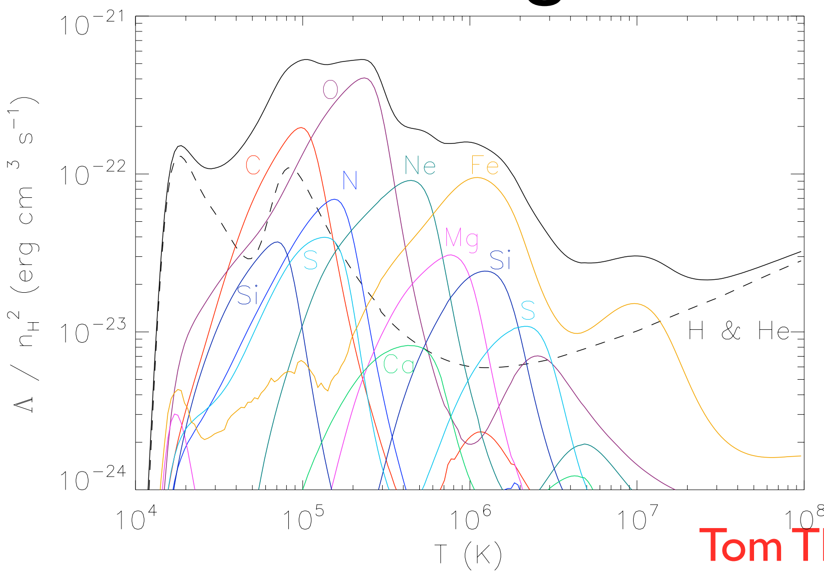
"GIMIC" deep field

SFR follow Schmidt-law **Code in brief** Galactic winds

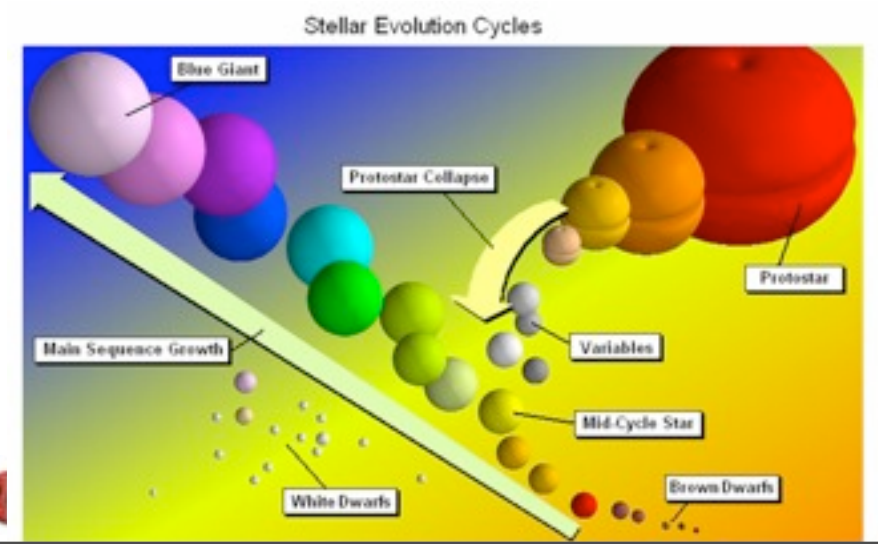




Z+J(nu) dependent cooling



Stellar evolution



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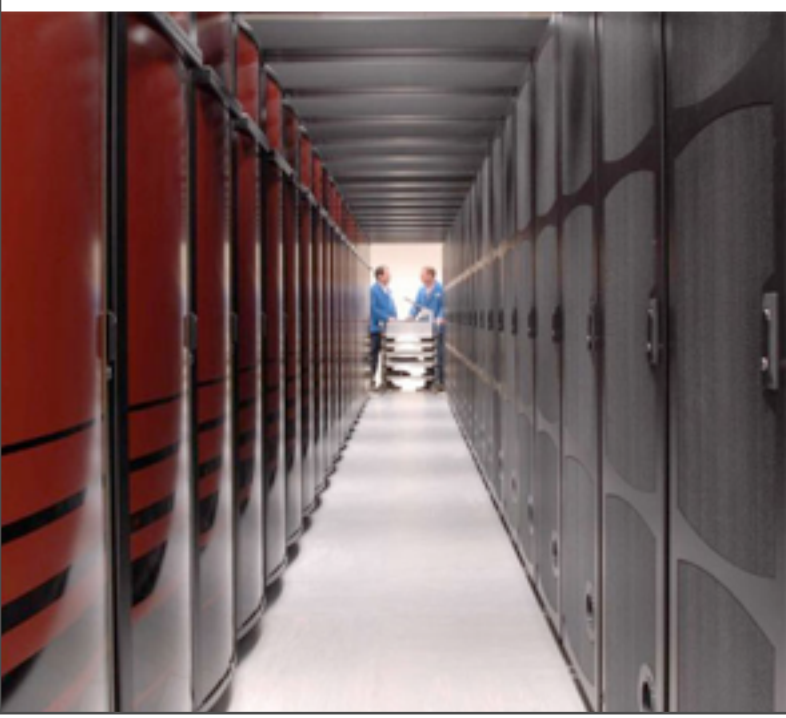
Tom Theuns

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)

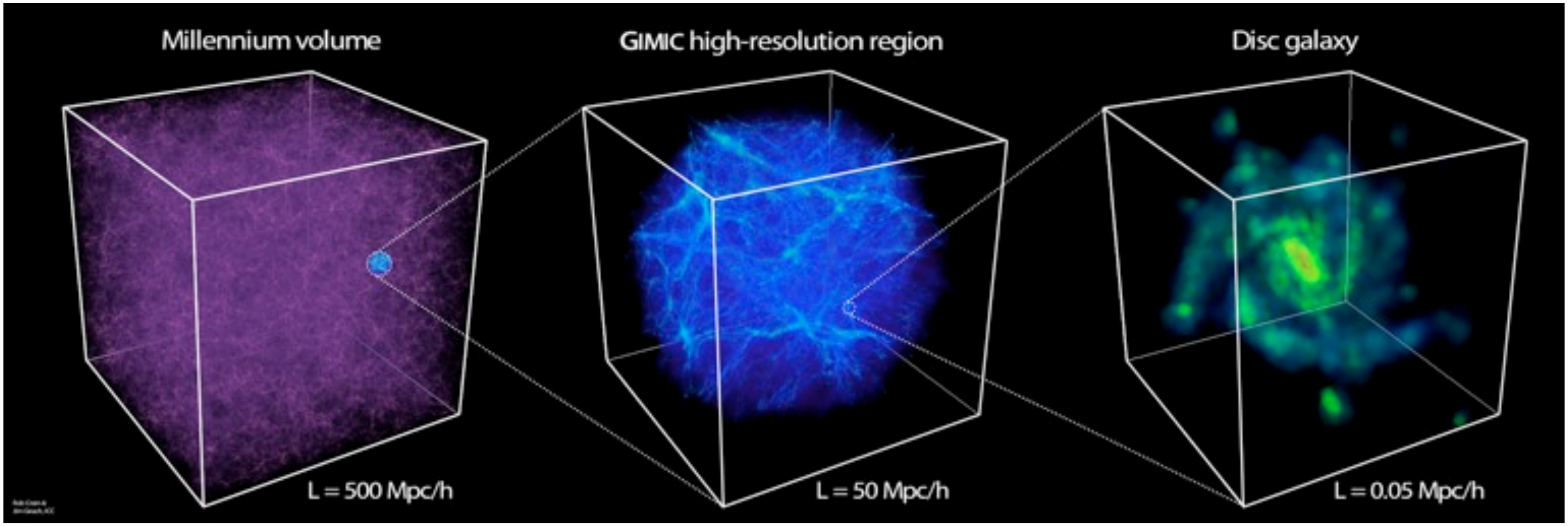


Distributed
European
Infrastructure for
Supercomputing
Applications

GIMIC

Suite of simulations:
GIMIC/OWLS

Galaxy-Intergalactic Medium Interaction Calculation



Zoomed simulations of 5 spheres picked from the Millennium Simulation

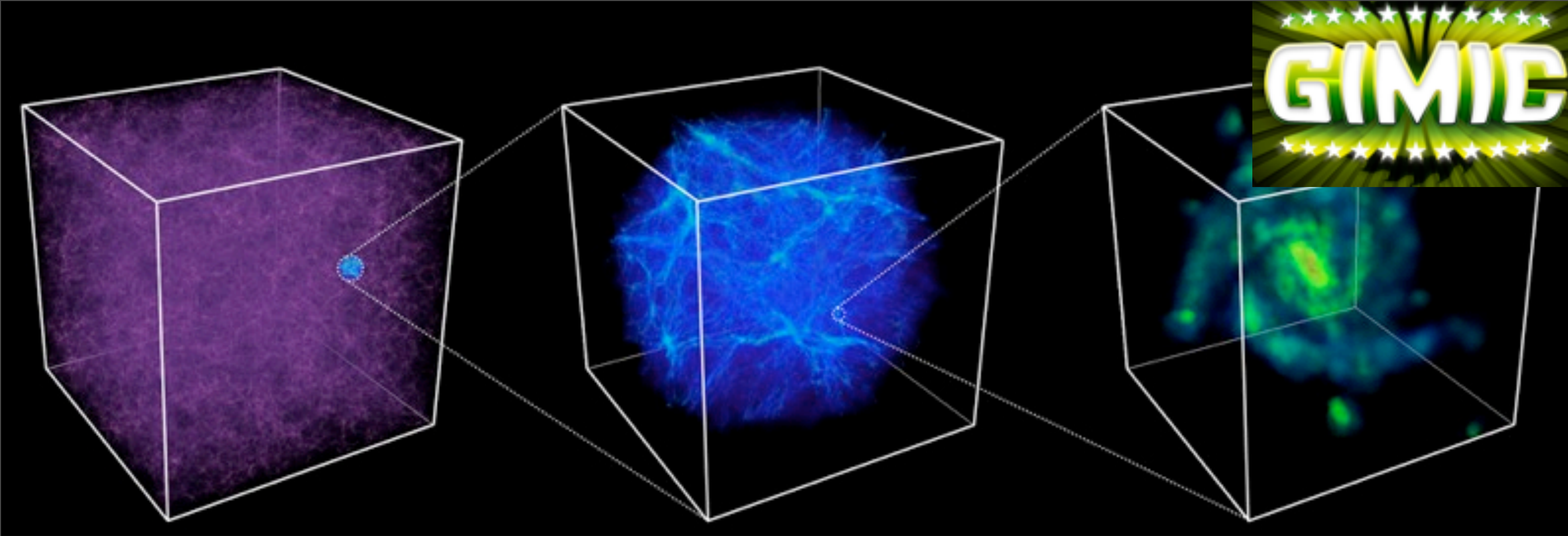
Combine LSS with high numerical resolution

Tom Theuns

ICC Institute for Computational Cosmology

Motivation for GIMIC:

- include (very) large-scale structure
- good numerical resolution yet able to reach redshift z=0
- formation of unusual objects (massive cluster, deep void)



Millennium volume:

- box is 500 Mpc/h on a side
- cosmology $(\Omega_m, \Omega_\Lambda, \Omega_b, h, \sigma_8, n) = (0.25, 0.75, 0.045, 0.73, 0.9, 1)$
- Springel et al '05

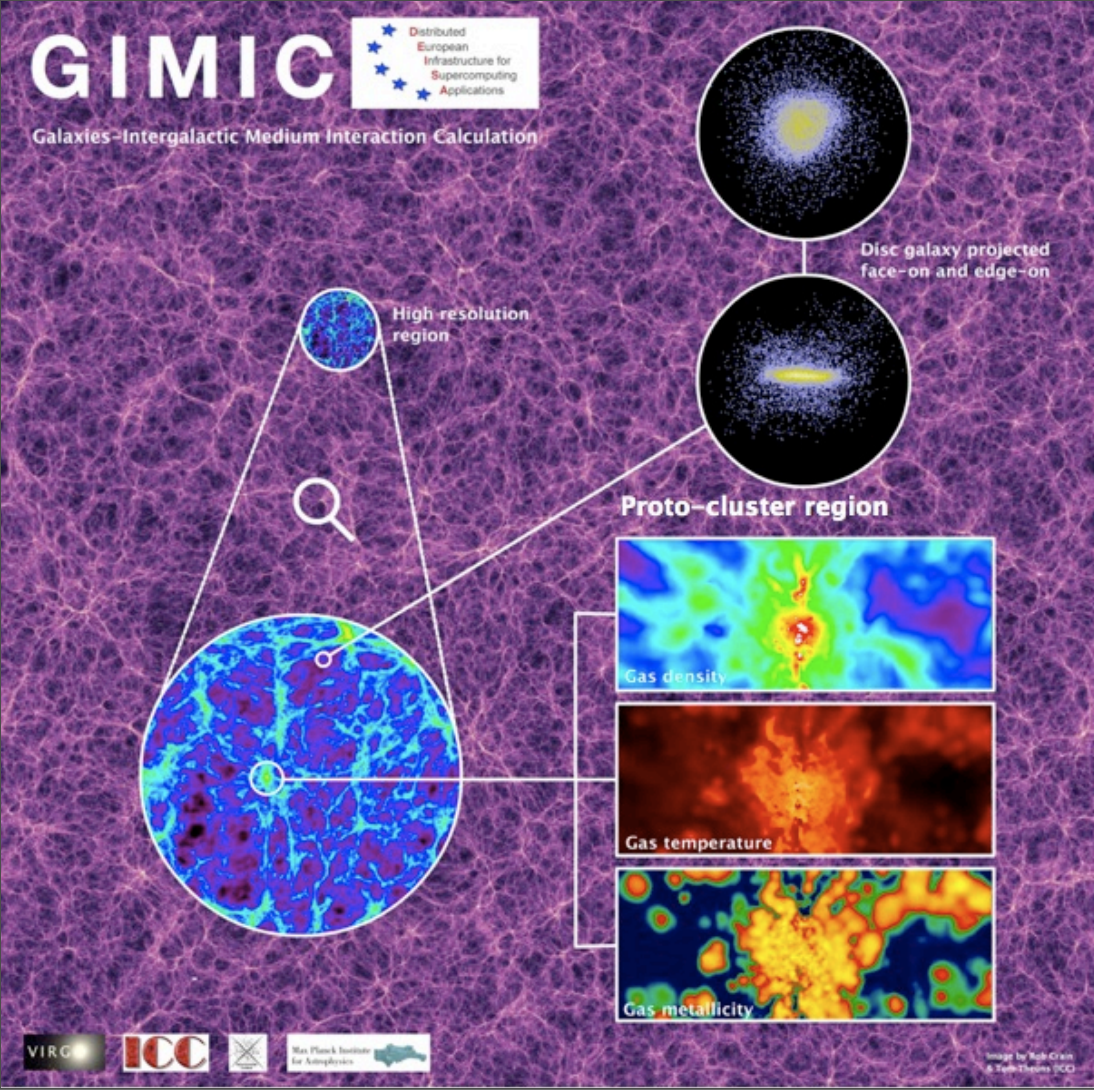
Distributed European Infrastructure for Supercomputing Applications

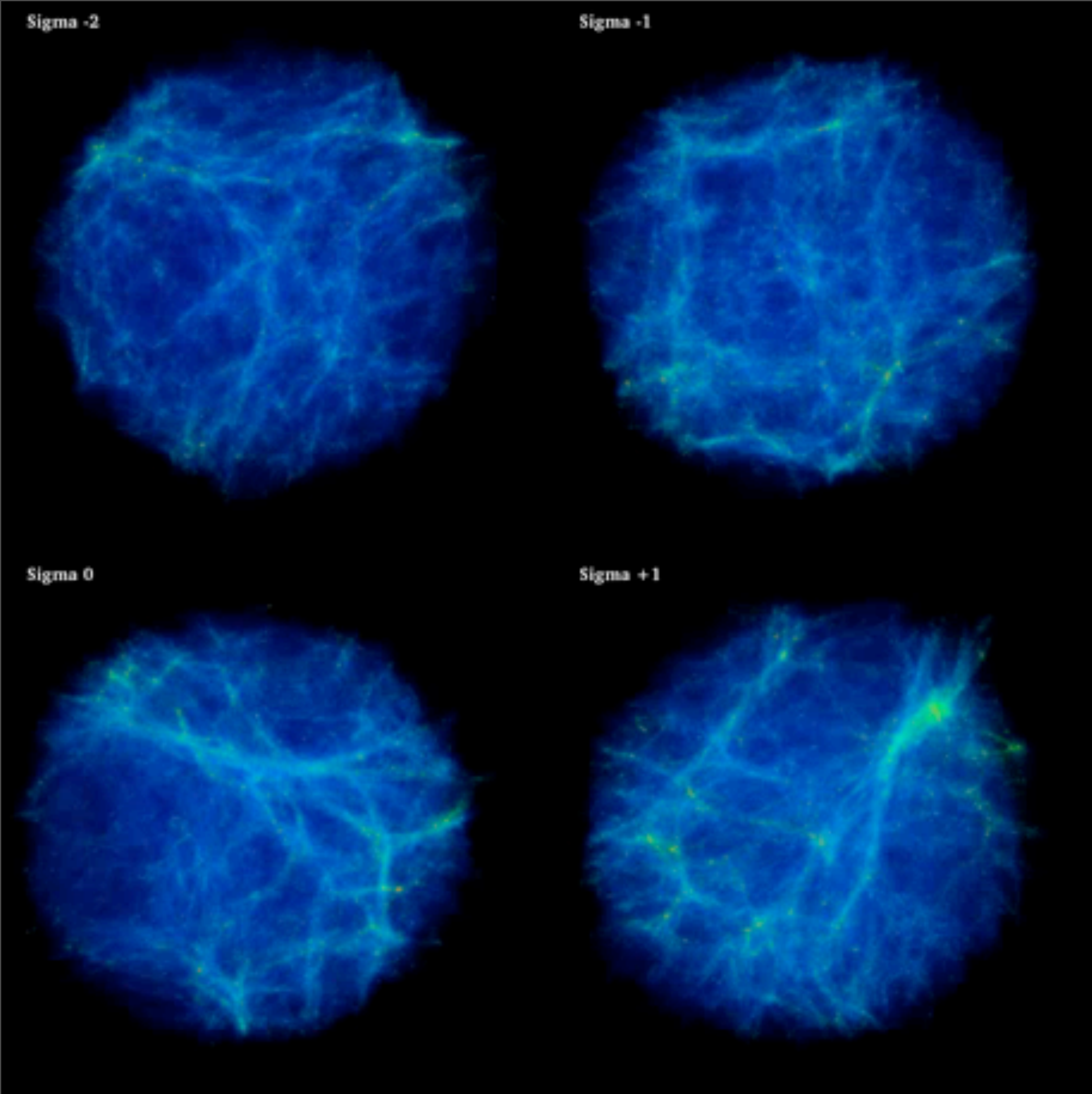
5 regions:

- (-2,-1,0,1,2) sigma
- radius 18 Mpc/h (at z=1.5)
- $m_{\rm gas} = 1.45 \times 10^6 \, h^{-1} \, M_\odot$

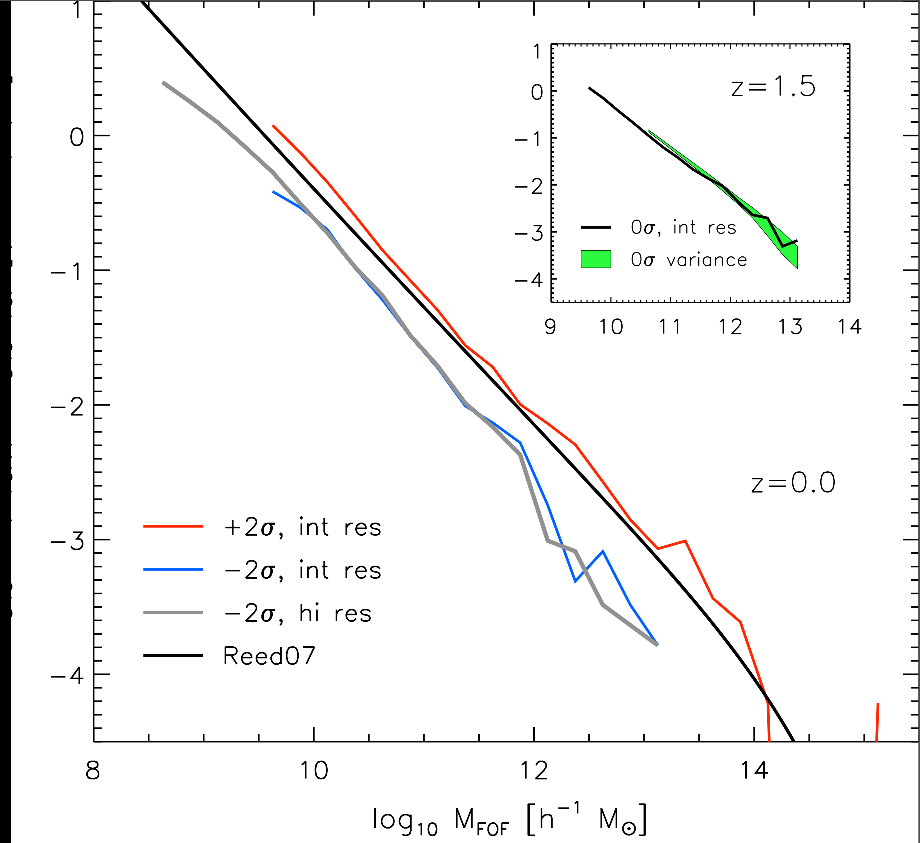
ICs: A Jenkins

VIRGO


GIMIC
Distributed
European
Infrastructure for
Supercomputing
Applications
Galaxies–Intergalactic Medium Interaction Calculation
Disc galaxy projected
face-on and edge-on
High resolution
region
Proto–cluster region
Gas density
Gas temperature
Gas metallicity
ICC



Sigma -2
Sigma -1
Sigma 0
Sigma +1

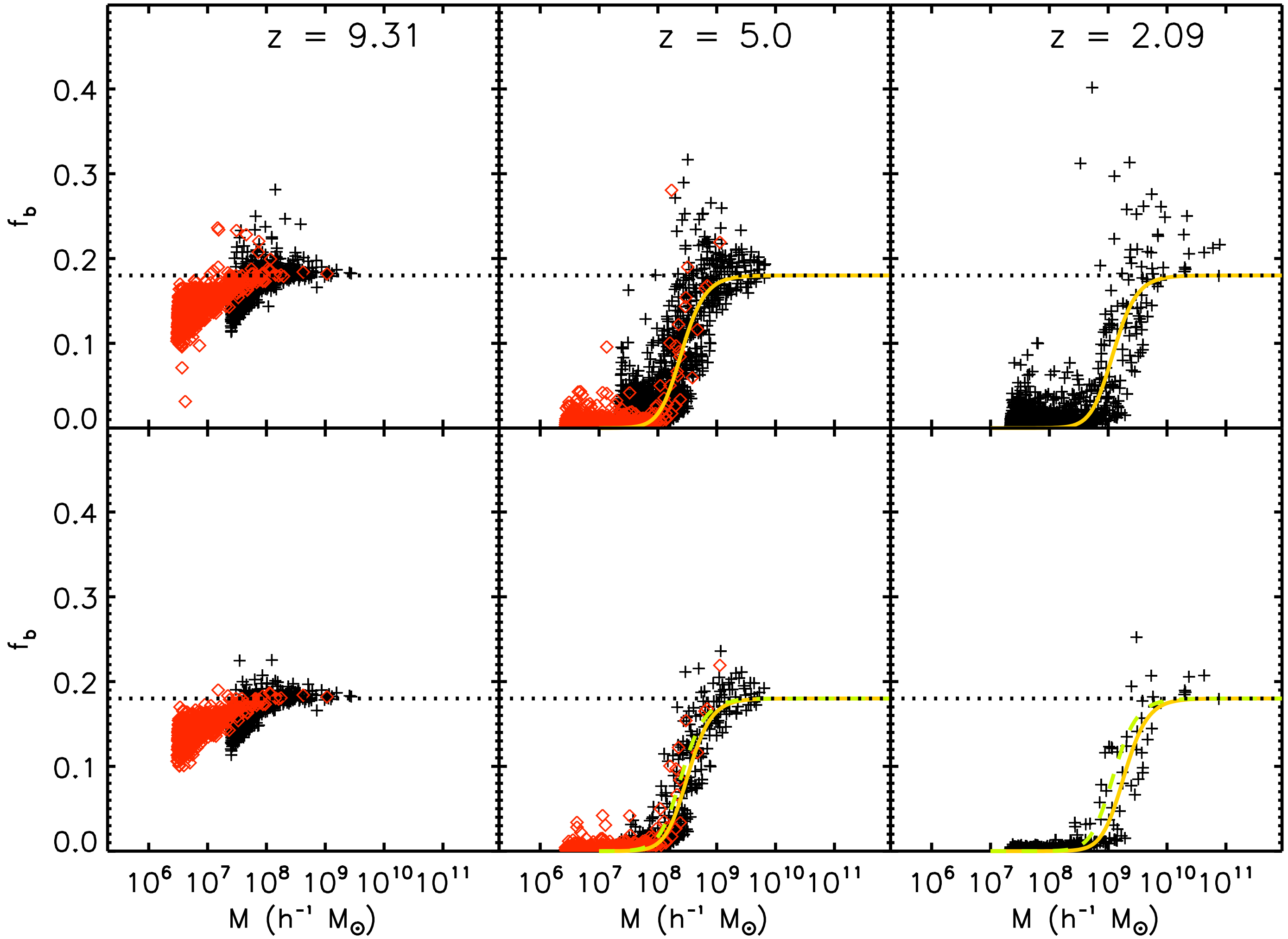


z=1.5
0σ, int res
0σ variance
z=0.0
+2σ, int res
−2σ, int res
−2σ, hi res
Reed07
log10 MFOF [h−1 M⊙]

Massloss of galaxies due to a UV-background

Takashi Okamoto[1⋆], Liang Gao[1,2] and Tom Theuns[1,3]
[1] Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham, DH1 3LE
[2] National Astronomical Observatories, Chinese Academy of Science, Beijing, 100012, China
[3] Department of Physics, University of Antwerp, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerp, Belgium

Baryon fraction



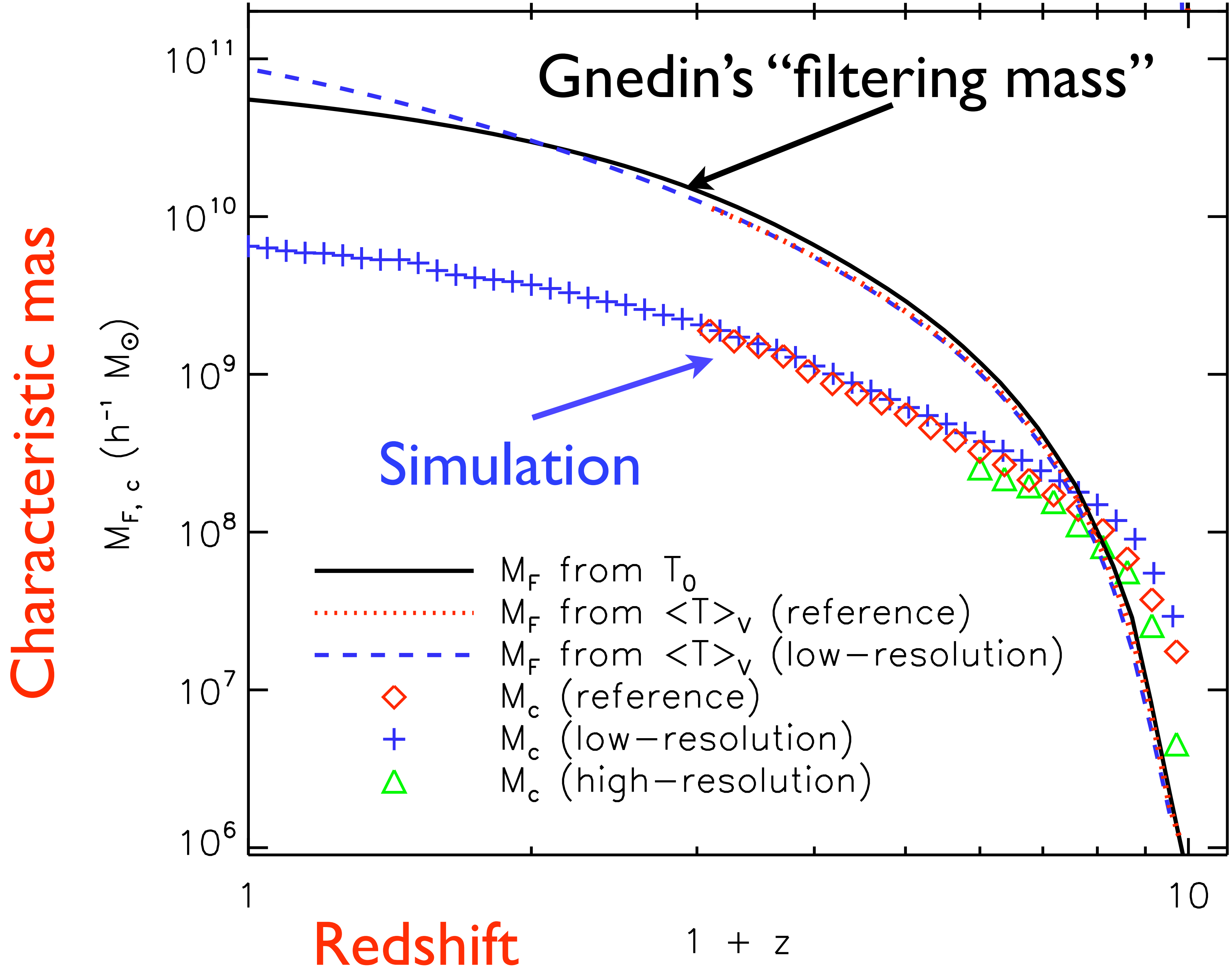
all haloes

"Isolated" haloes

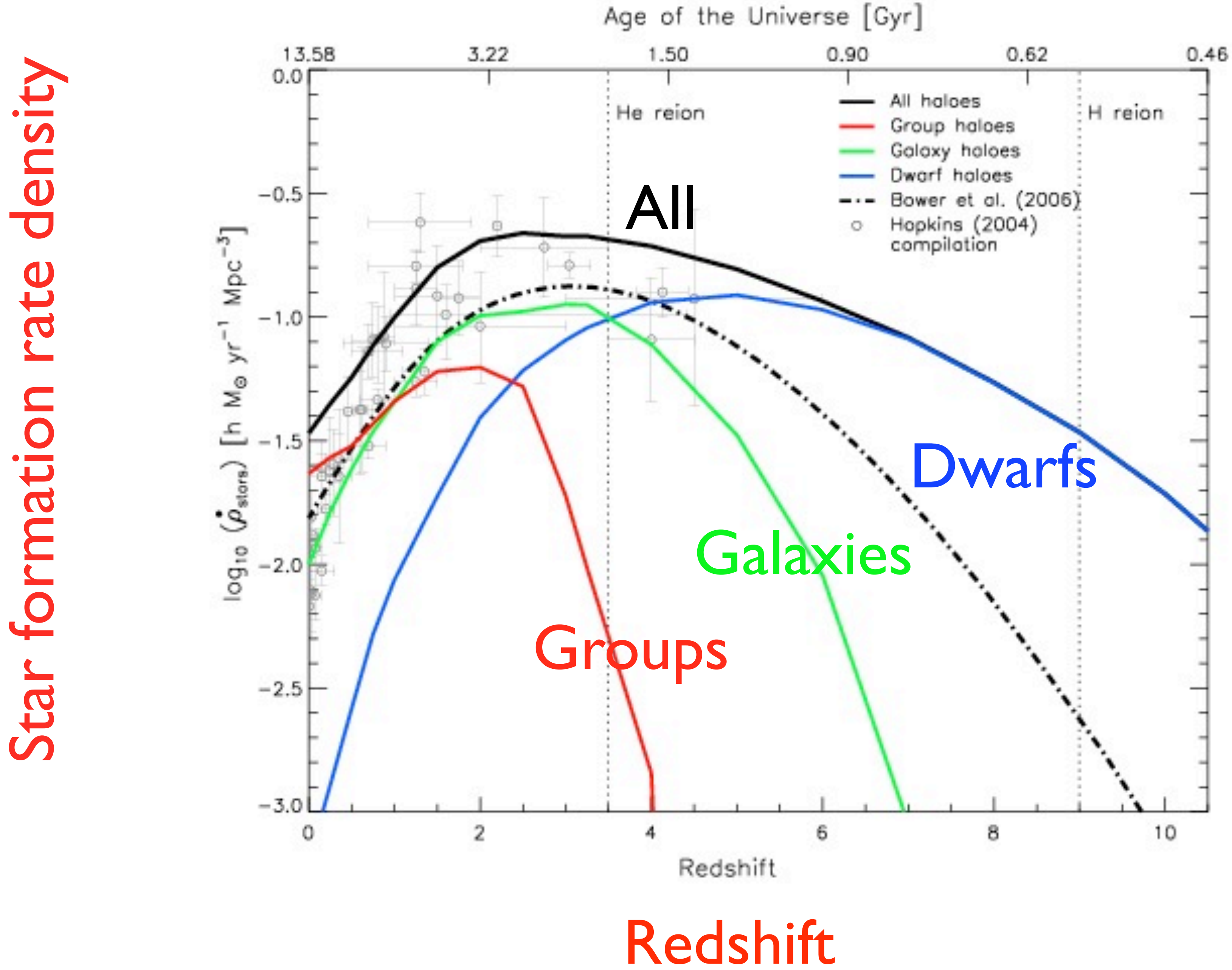
Halo mass

crosses: individual haloes

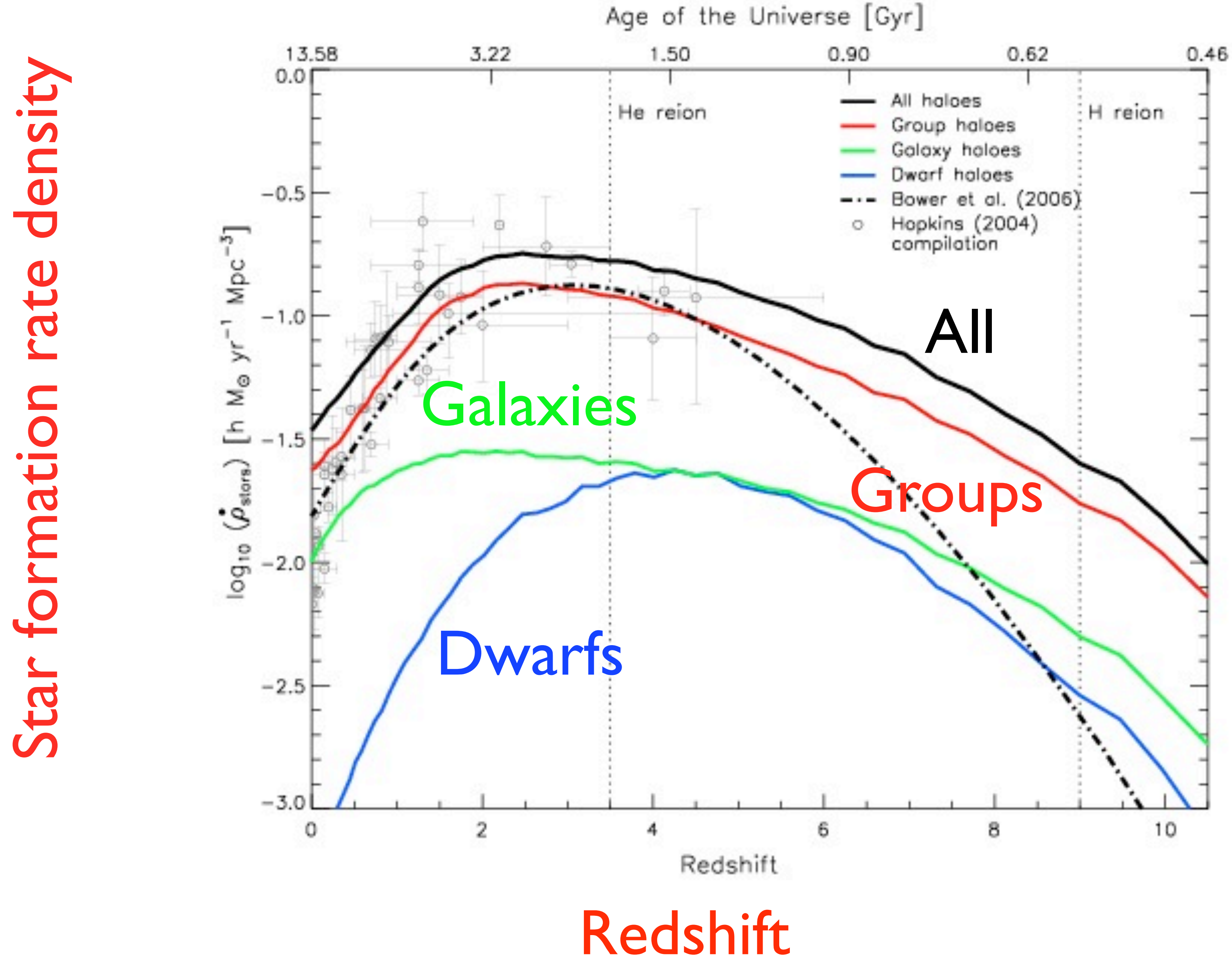
Characteristic mass is much smaller than Gnedin's filtering mass



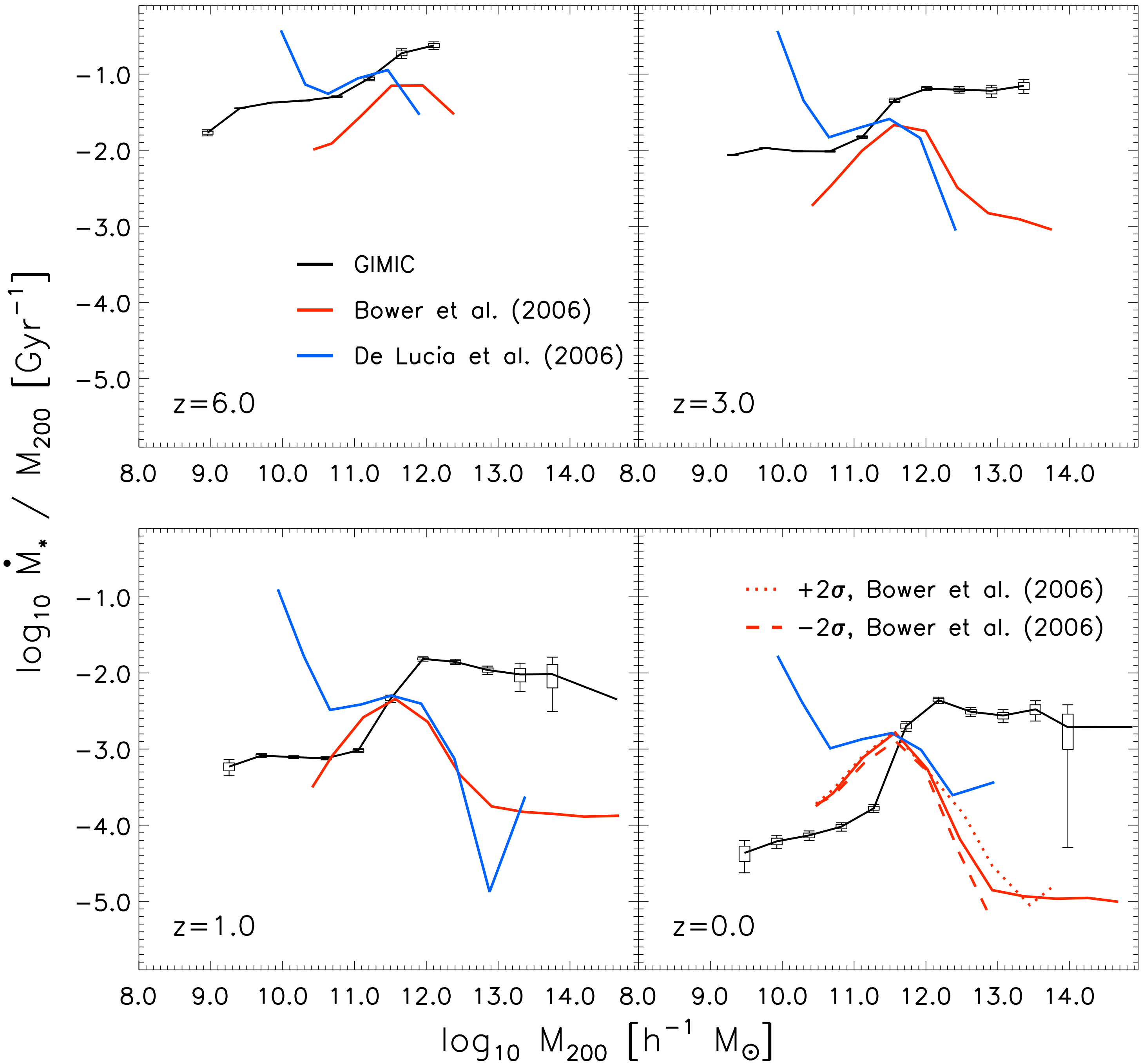
Star formation as function of halo mass then



Star formation as function of halo-mass now

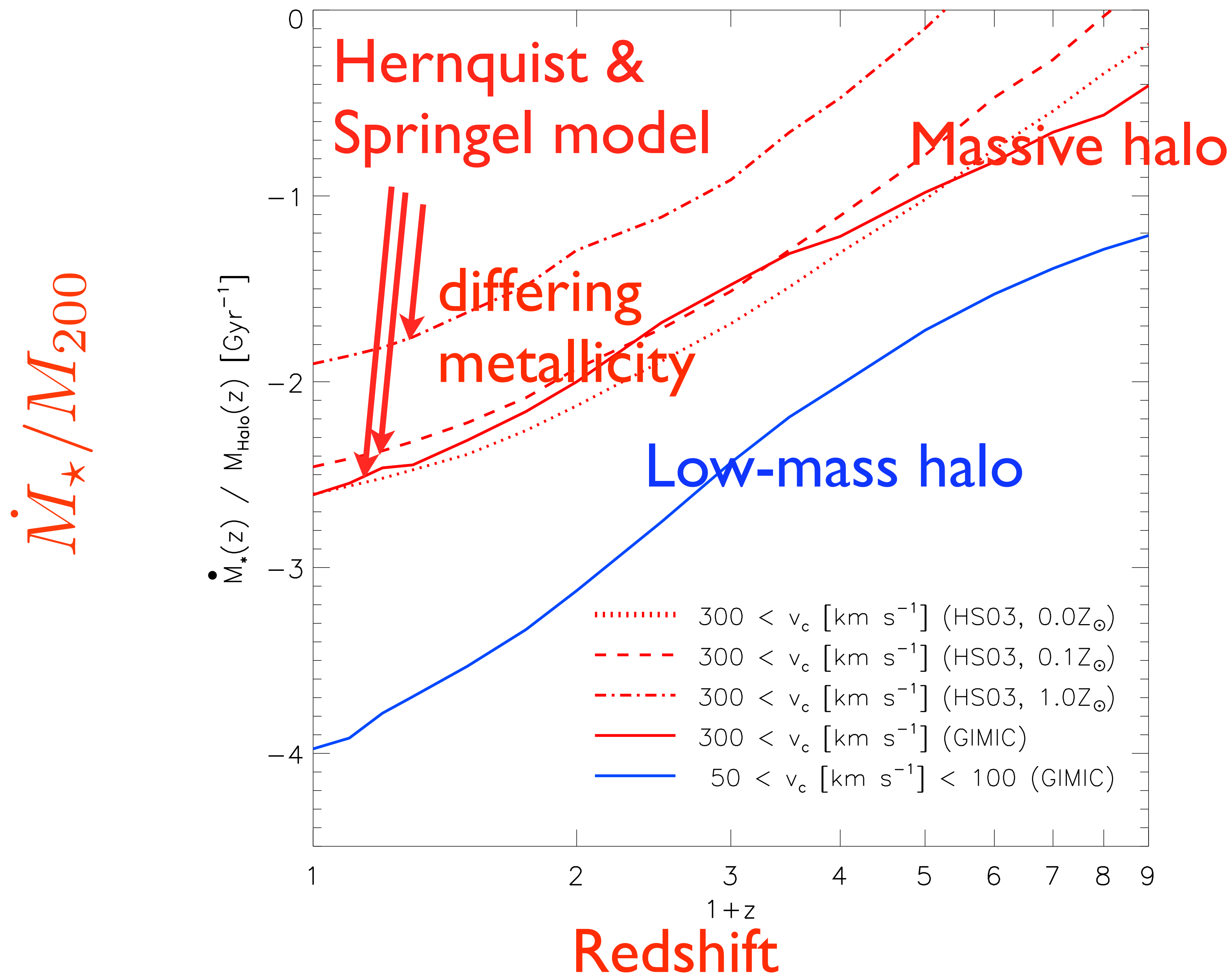


Gimic vs semi-analytical models



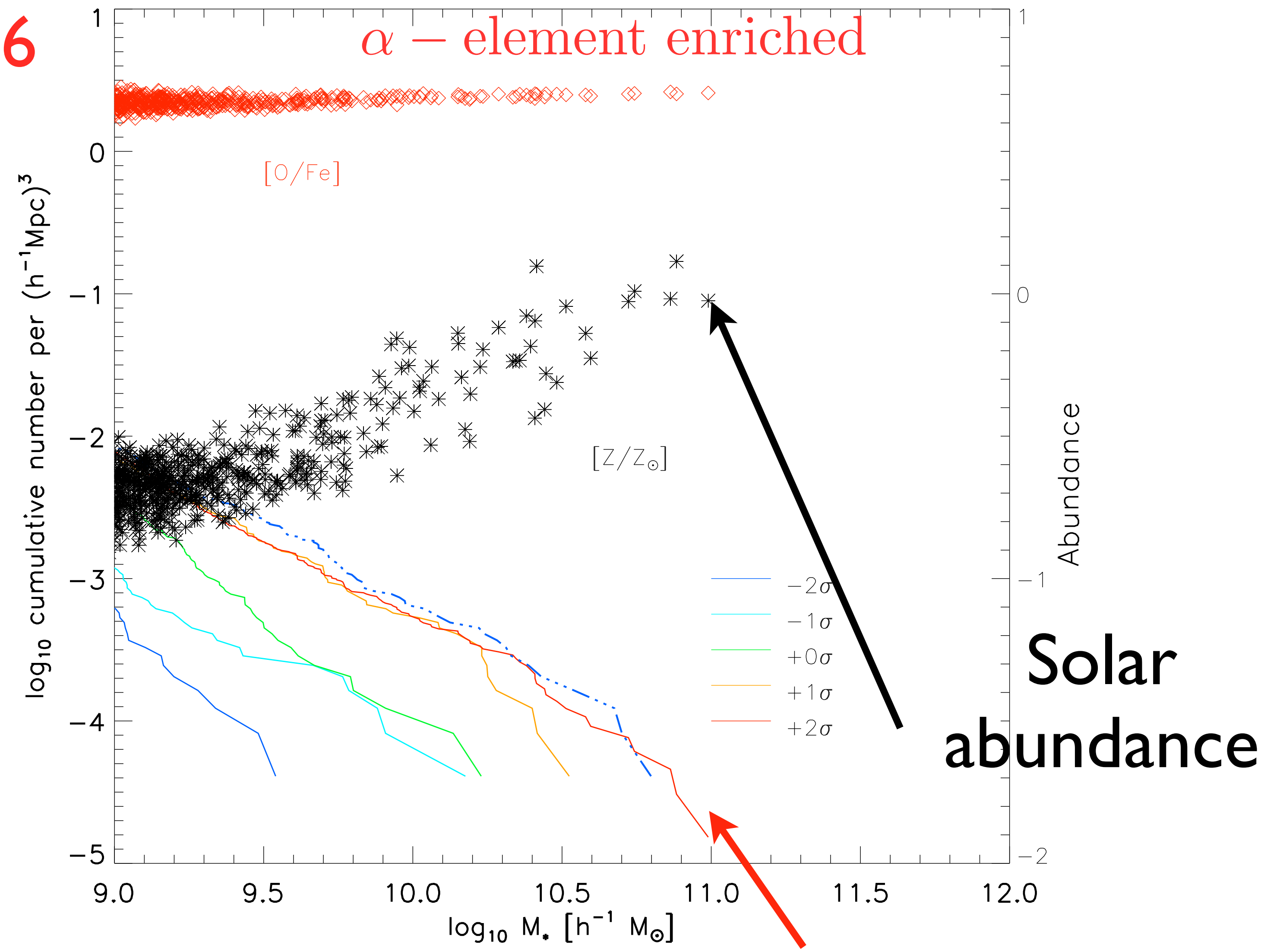
GIMIC
Bower
De Lucia

sSFR as function of redshift



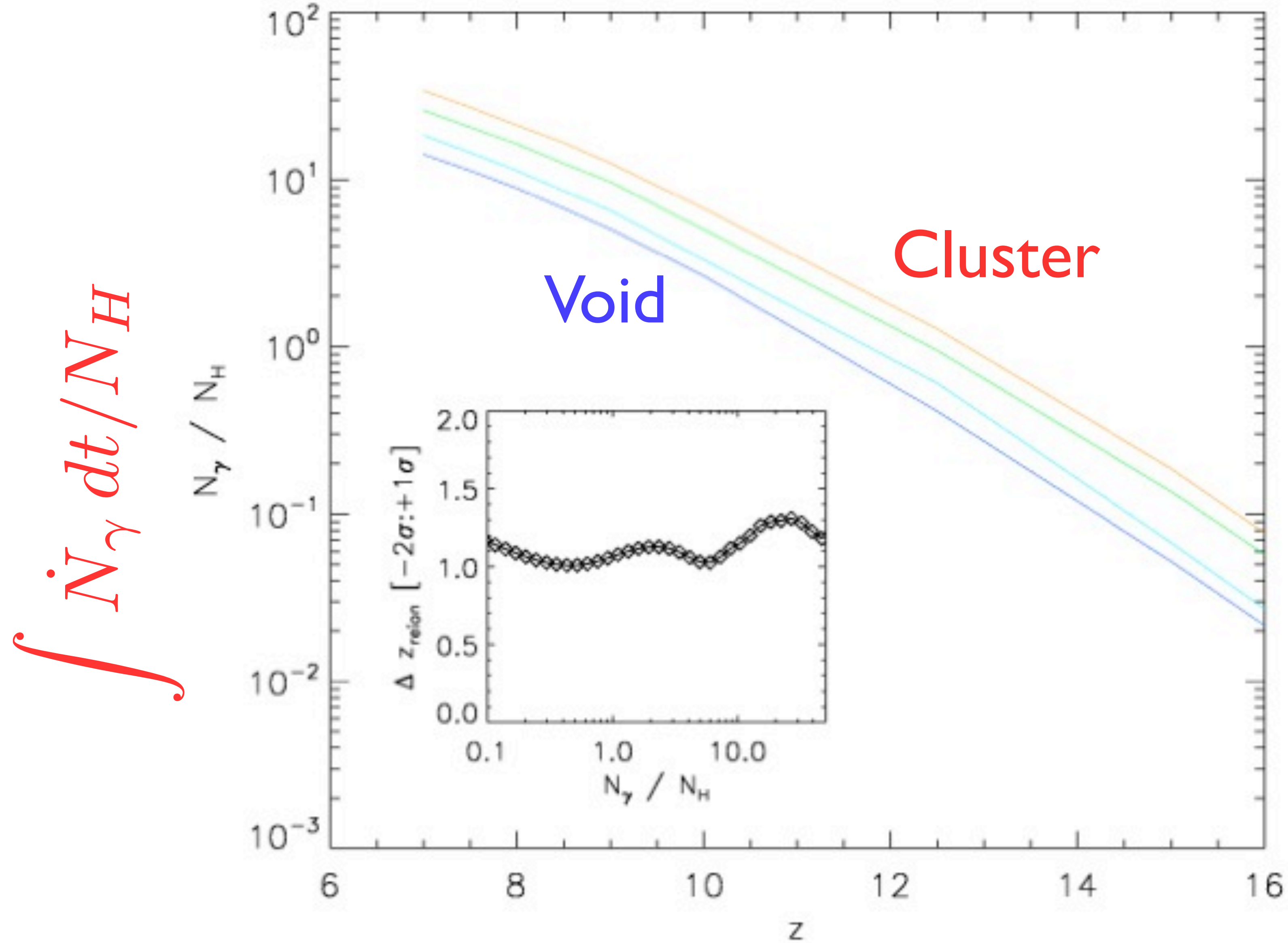
Reionization as function of environment

Stellar mass function z=6



$M_\star = 10^{11}\,M_\odot$ solar-abundance galaxy

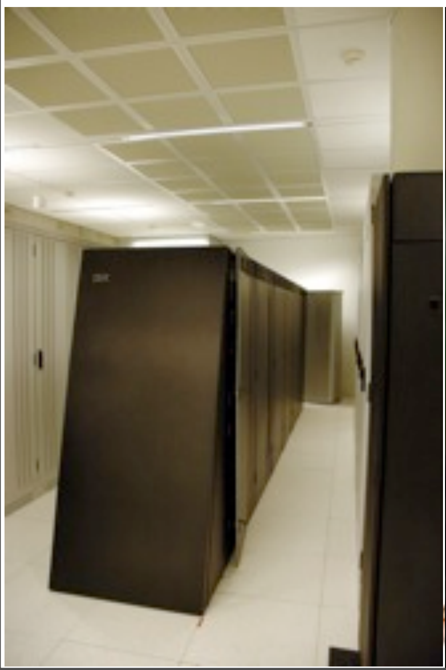
Reionization as function of environment



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]

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




Z= 14.72

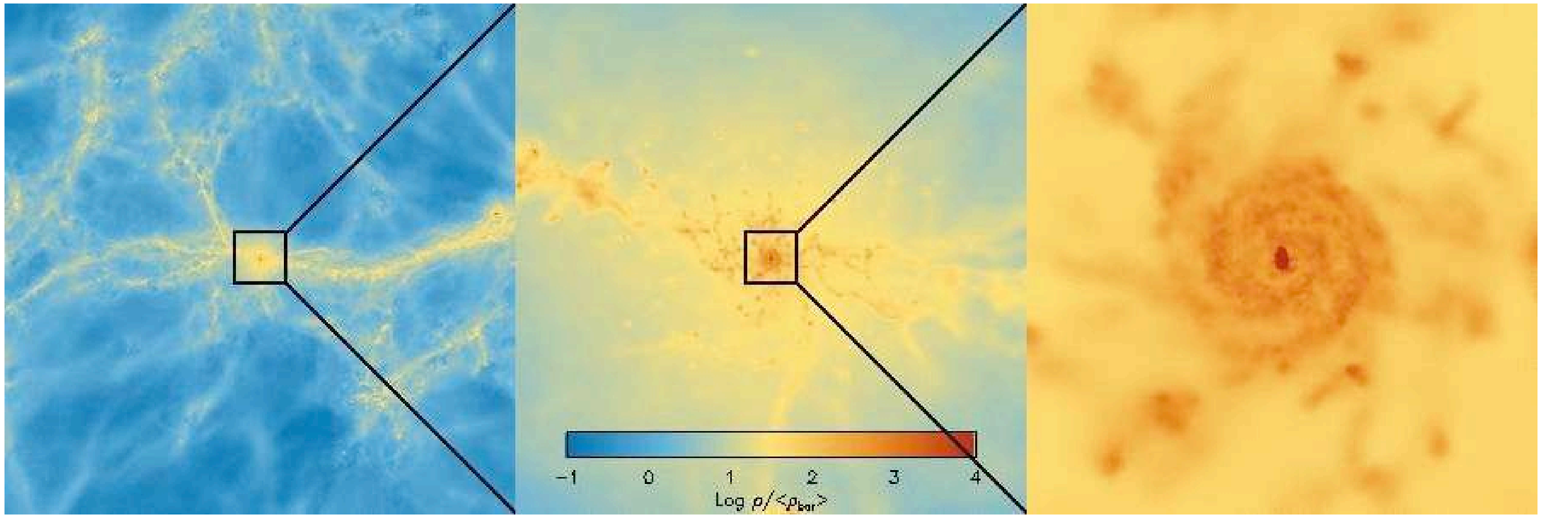


Figure 1. Zoom into a $M_{200} = 10^{12.2}$ $M_\odot$ halo at $z = 2$ in the *REF_L025N512* simulation. From left-to-right, the images are 10, 1, and 0.1 h^{-1} Mpc on a side. All slices are 1 h^{-1} Mpc thick. Note that the first image shows only a fraction of the total simulation volume, which is cubic and 25 h^{-1} Mpc on a side. The color coding shows the projected gas density, $\log_{10} \rho / \langle \rho_b \rangle$, and the color scale ranges from -1 to 4 (which is lower than the true maximum of the image). The coordinate axes were rotated to show the galaxy face-on. This halo is the 10th most massive in the simulation. About half of the haloes in this mass range host extended disk galaxies, while the other half have highly disturbed morphologies due to ongoing mergers.

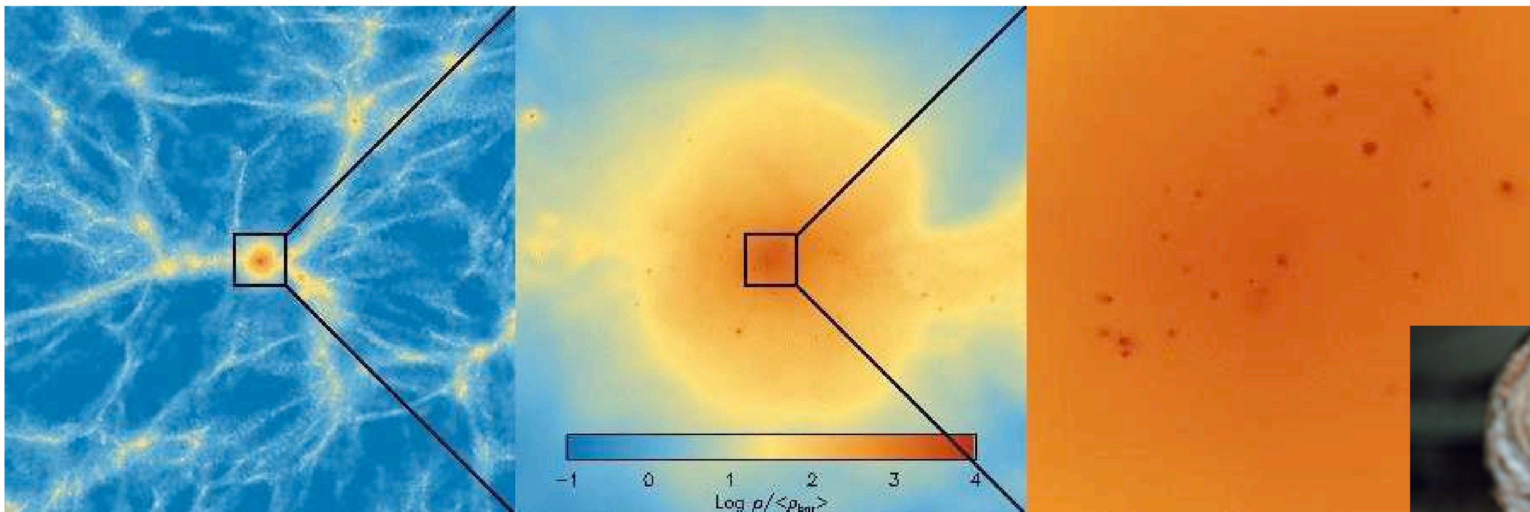


Figure 2. Zoom into a $M_{200} = 10^{14.2}$ $M_\odot$ halo at $z = 0$ in the *REF_L100N512* simulation. From left-to-right, the images ar
0.4 h^{-1} Mpc on a side. All slices are 1 h^{-1} Mpc thick. Note that the first image shows only a fraction of the total simulati
which is cubic and 100 h^{-1} Mpc on a side. The color coding shows the projected gas density, $\log_{10} \rho / \langle \rho_b \rangle$, and the color s
from -1 to 4 (which is lower than the true maximum of the image). This halo is the 10th most massive in the simulation.

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)

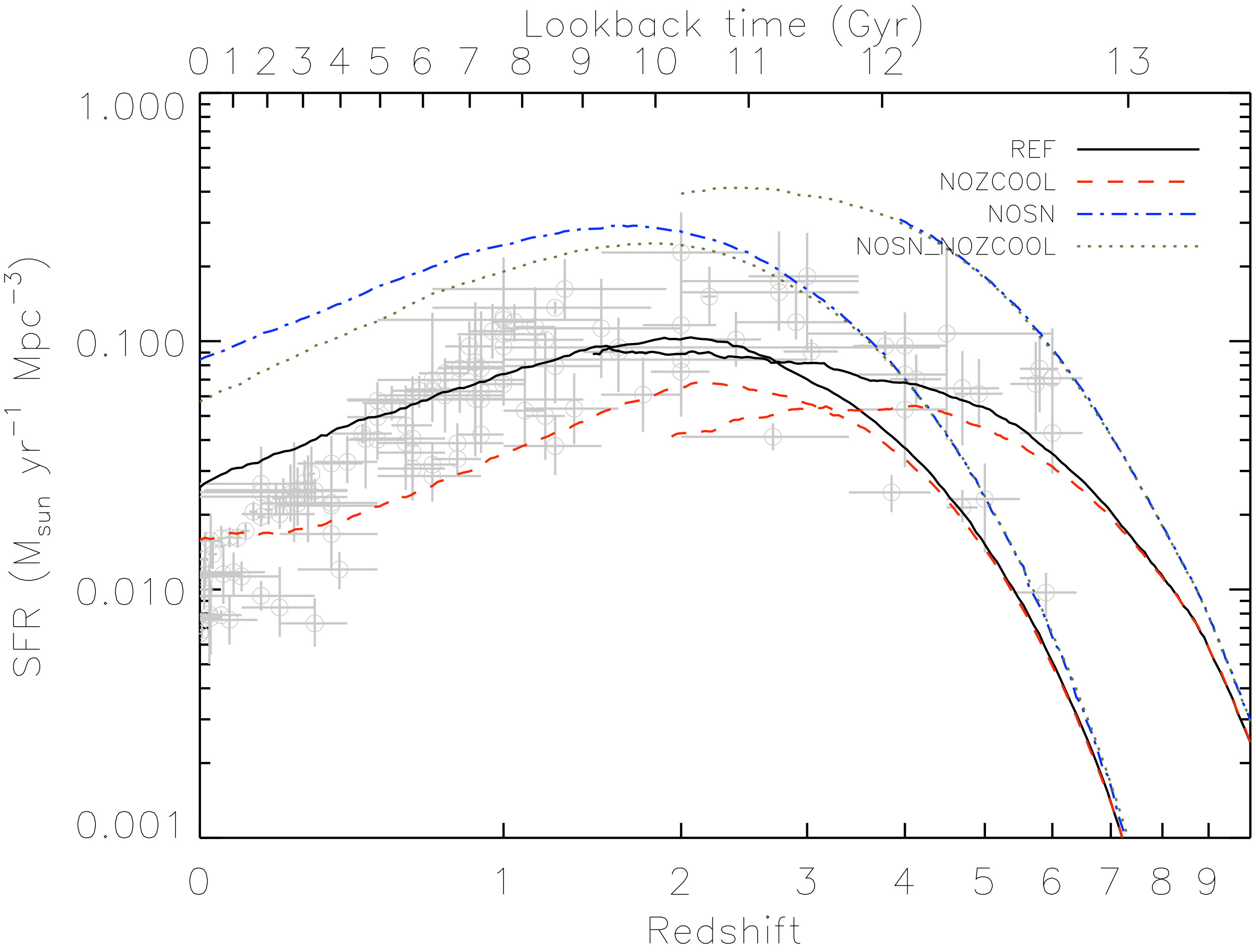
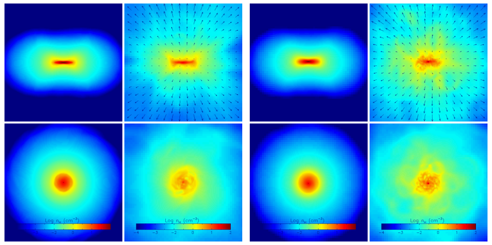


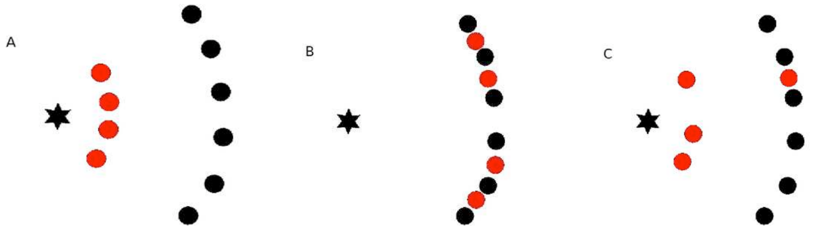
Figure 6. As Fig. 5, but comparing the SFHs for models with and without metal-line cooling, both in the presence and absence of SN-driven winds. Except at very high redshift, metal-line cooling strongly increases the SFR. The boost due to metal-line cooling is greater when SN feedback is included, which implies that metals radiate away a significant fraction of the energy injected by SNe.

Intermezzo: does your code integrate the relevant equations accurately (enough)?

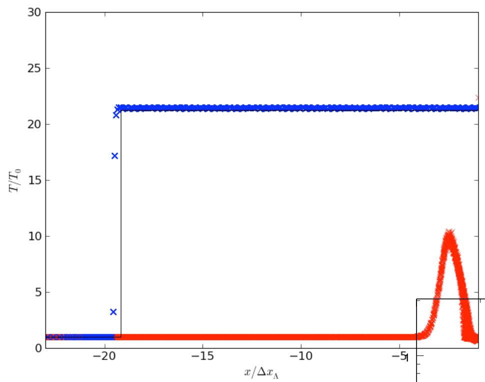
Numerical aspects: SPH vs AMR



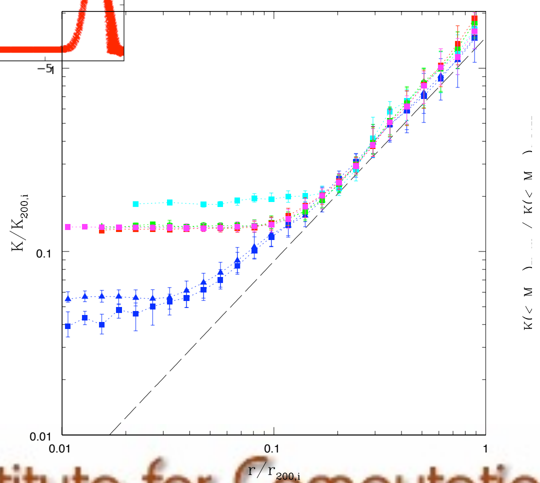
Isolated galaxies



(metal) mixing



Radiative cooling



Entropy profiles

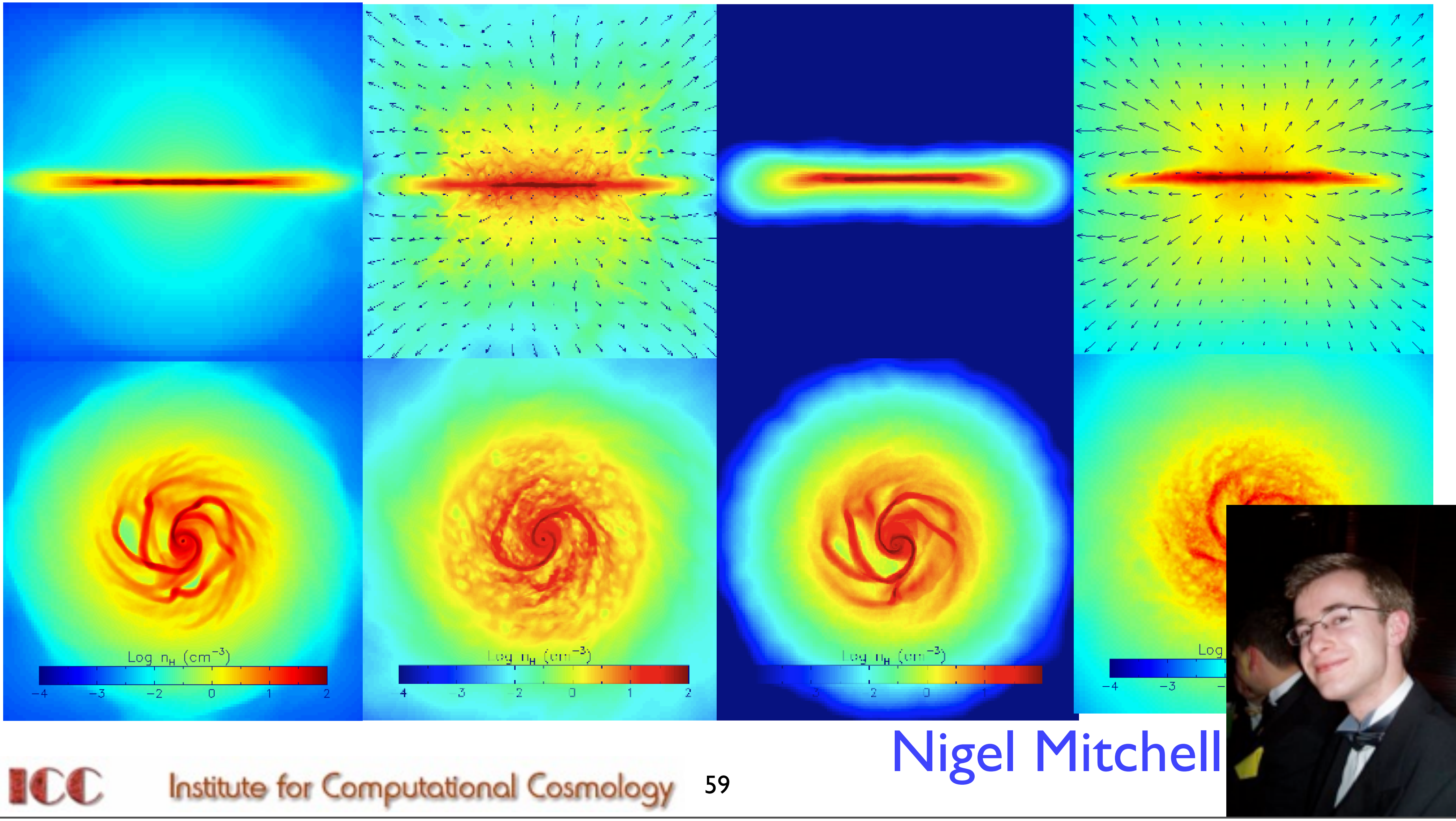
Tom Theuns

Institute for Computational Cosmology

Massive galaxy

Flash | Gadget

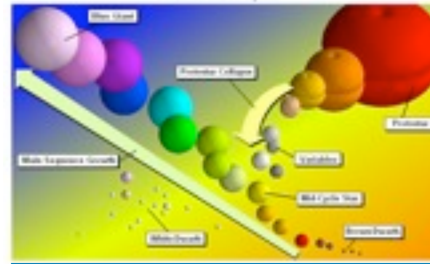
without feedback | with feedback | without feedback | with feedback

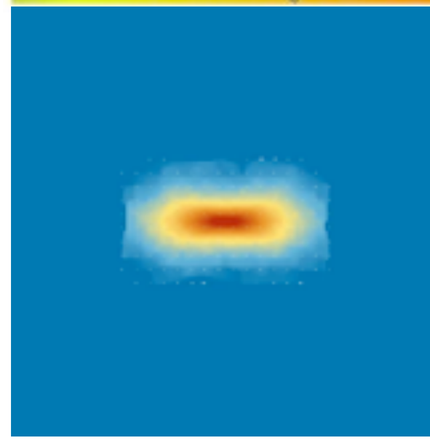


Nigel Mitchell

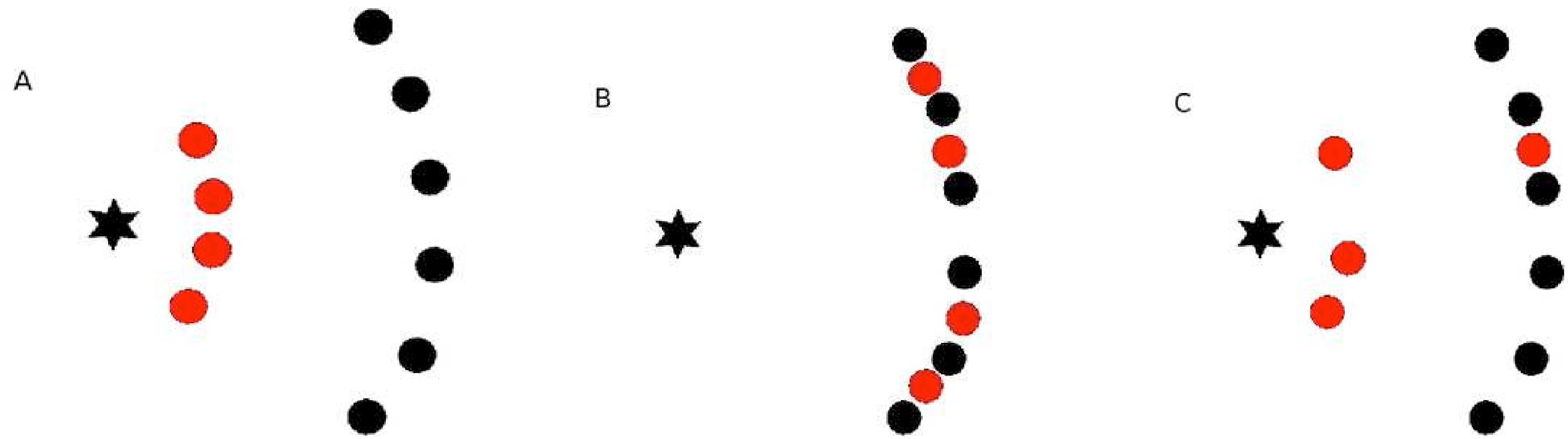
Chemical enrichment in cosmological, smoothed particle hydrodynamics simulations

Robert P. C. Wiersma,[1⋆] Joop Schaye,[1] Tom Theuns,[2,3] Claudio Dalla Vecchia,[1] and Luca Tornatore[4,5]

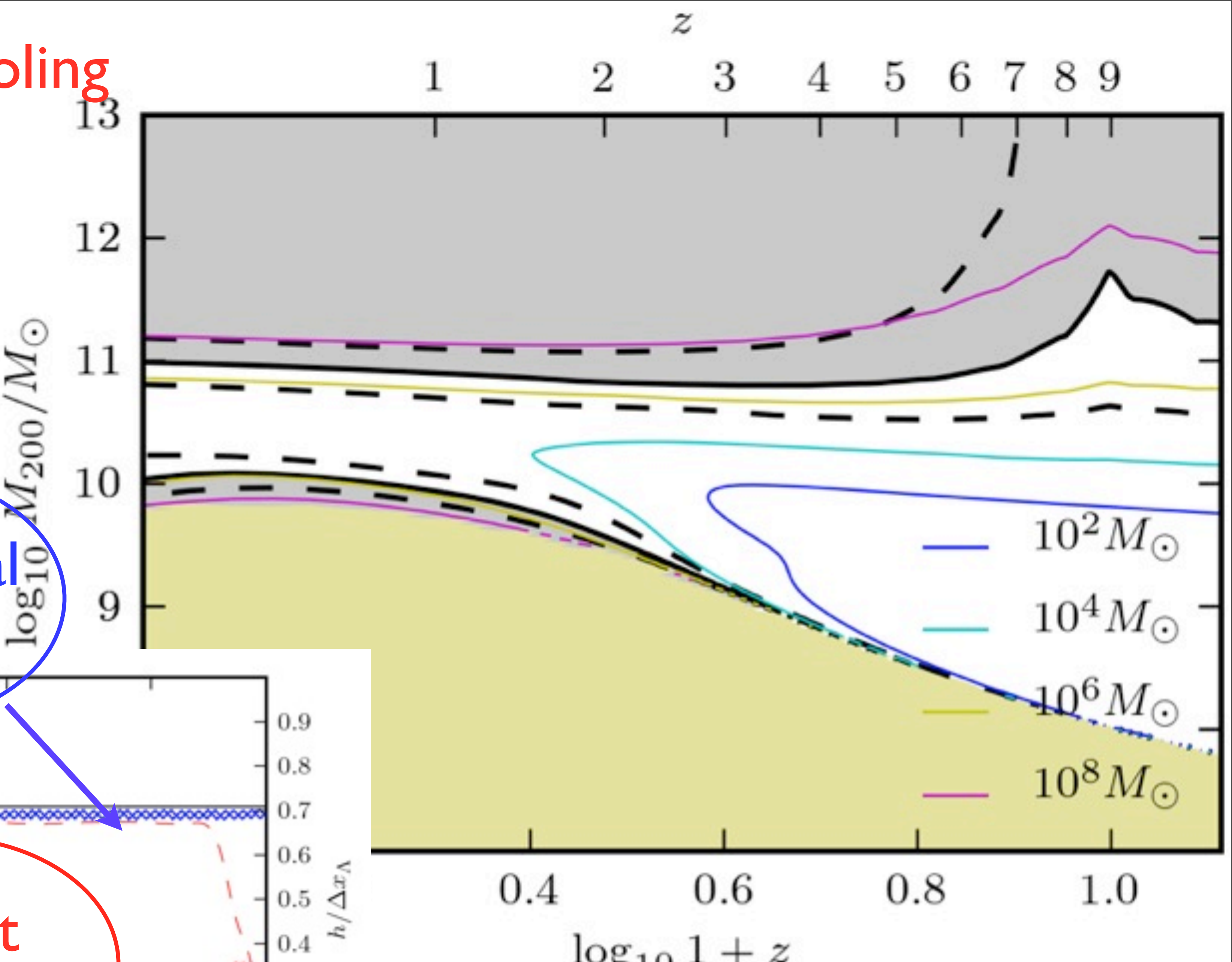


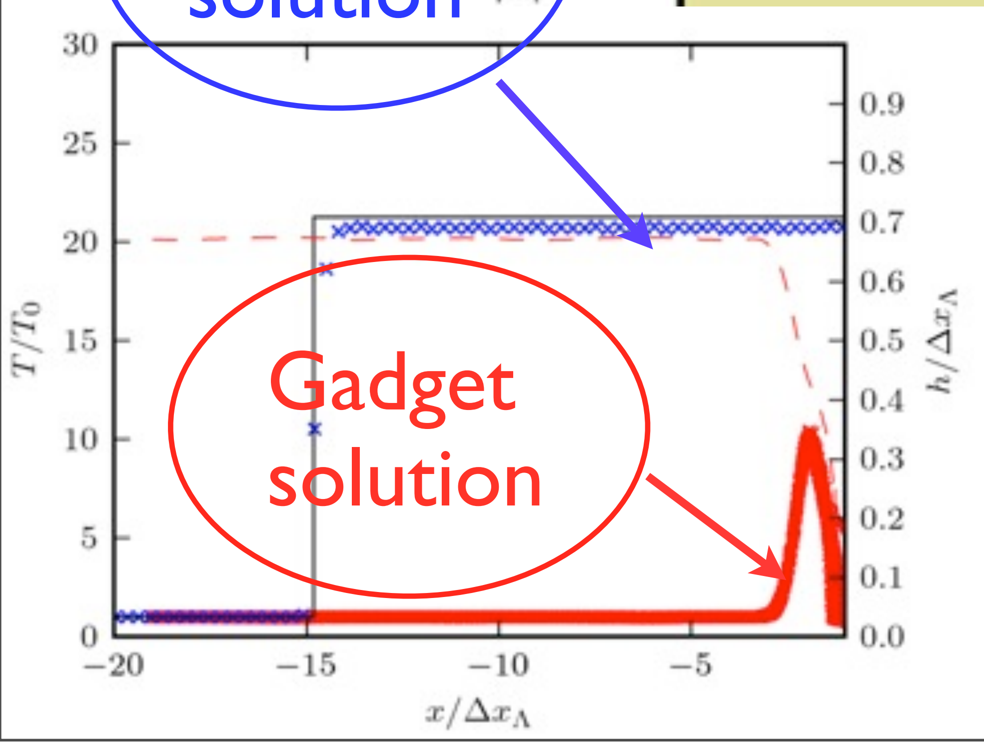


Enrichment in SPH



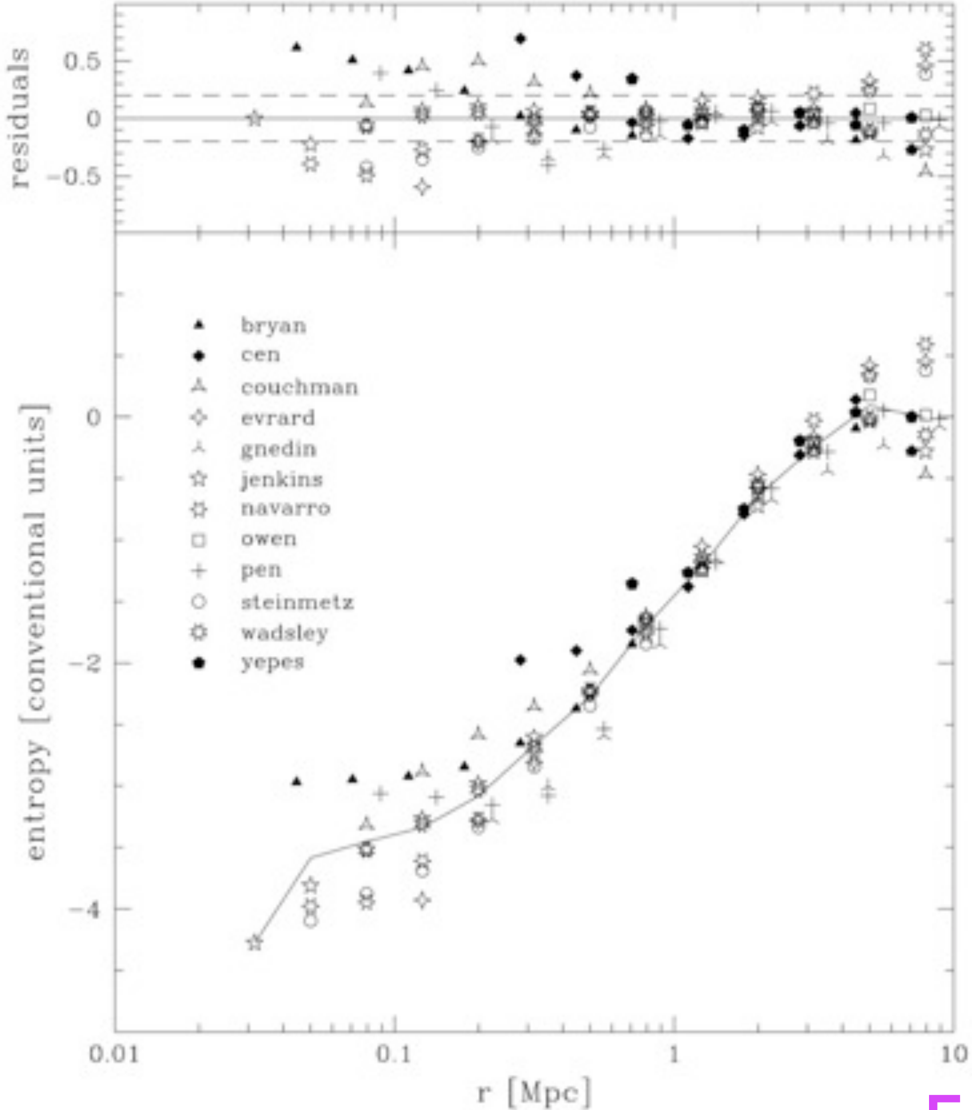
Radiative cooling





Creasey+, 2011

The Santa Barbara Cluster Comparison Project: A Comparison of Cosmological Hydrodynamics Solutions



Frenk et al '99

Tom Theuns

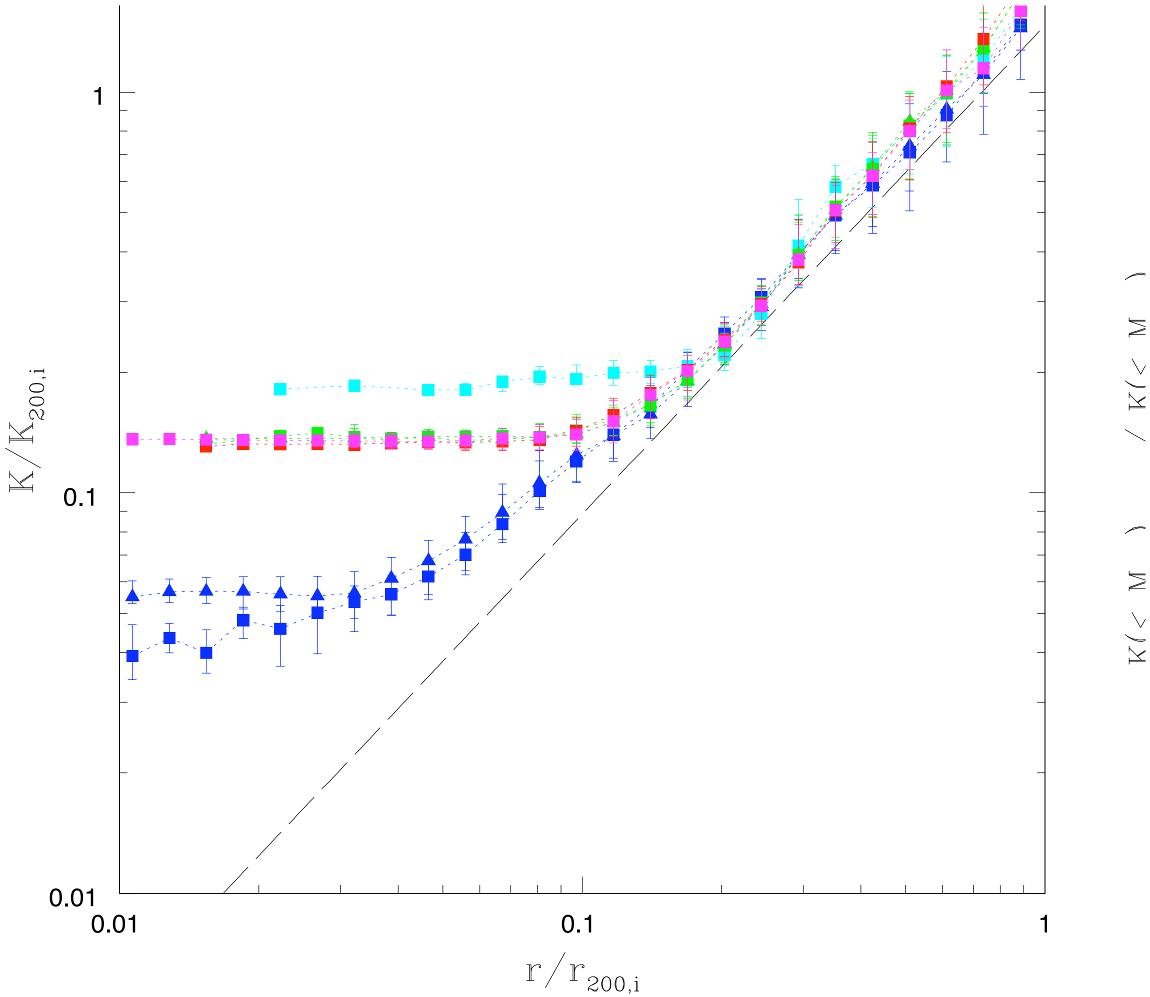
Institute for Computational Cosmology

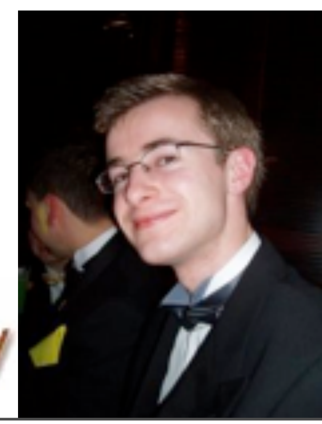
On the Origin of Cores in Simulated Galaxy Clusters

N. L. Mitchell[1⋆], I. G. McCarthy[1], R. G. Bower[1], T. Theuns[1,2], R. A. Crain[1]

[1] *Department of Physics, Durham University, South Road, Durham, DH1 3LE*
[2] *Department of Physics, University of Antwerp, Campus Groenenborger, Groenenborgerlaan 171, B-2020 Antwerp, Belgium*

Non-cosmological cluster mergers

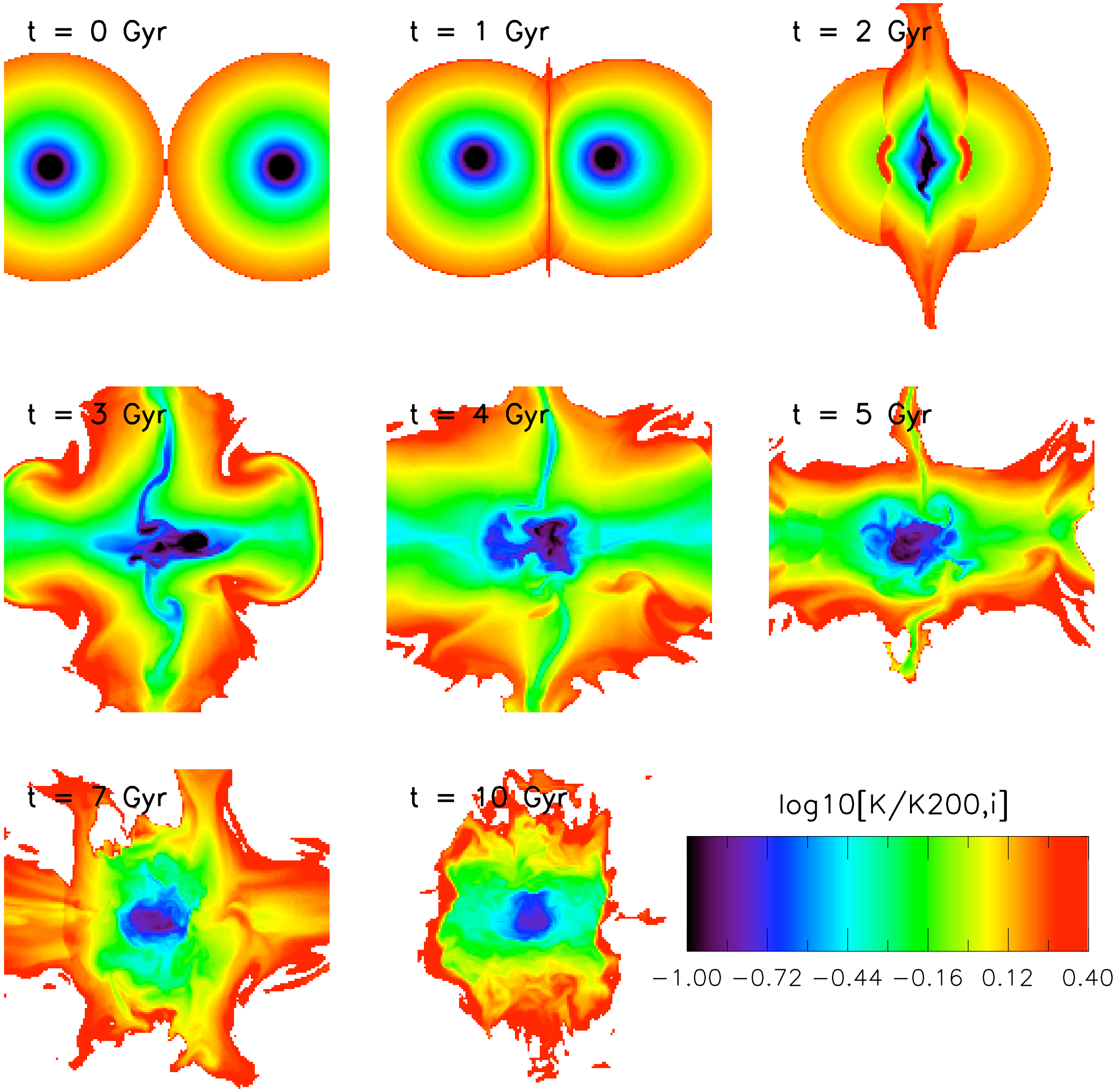




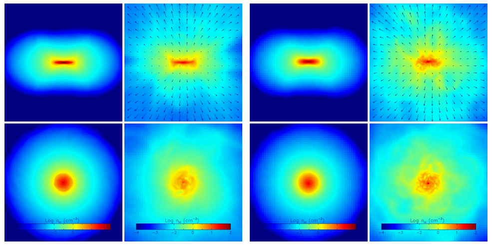
Tom Theuns

ICC Institute for Computational Cosmology

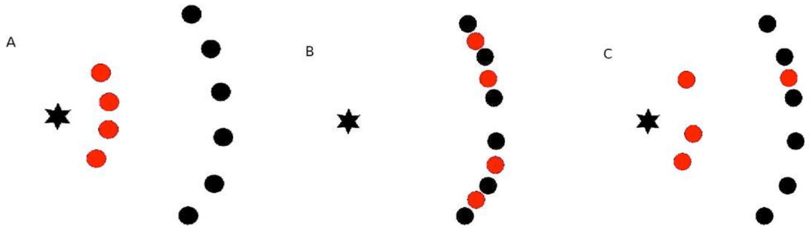
Generation of entropy (FLASH)



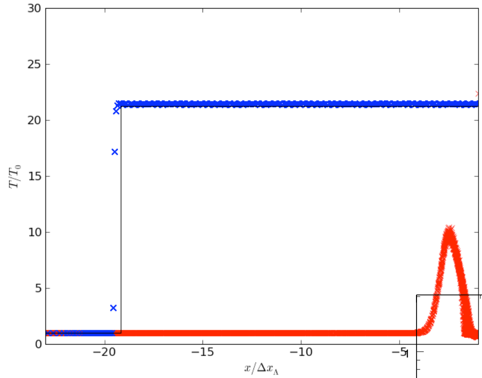
Numerical aspects: SPH vs AMR



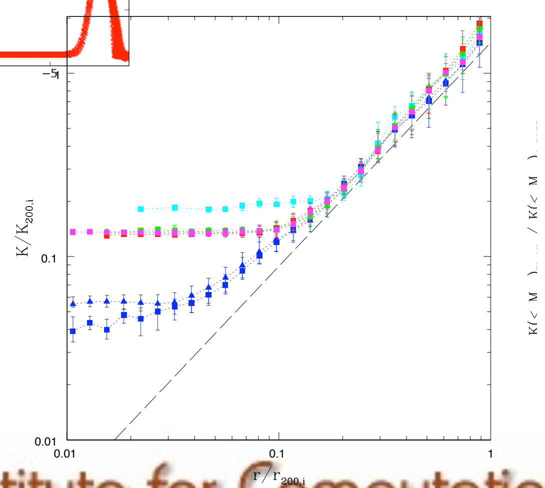
Isolated galaxies



(metal) mixing



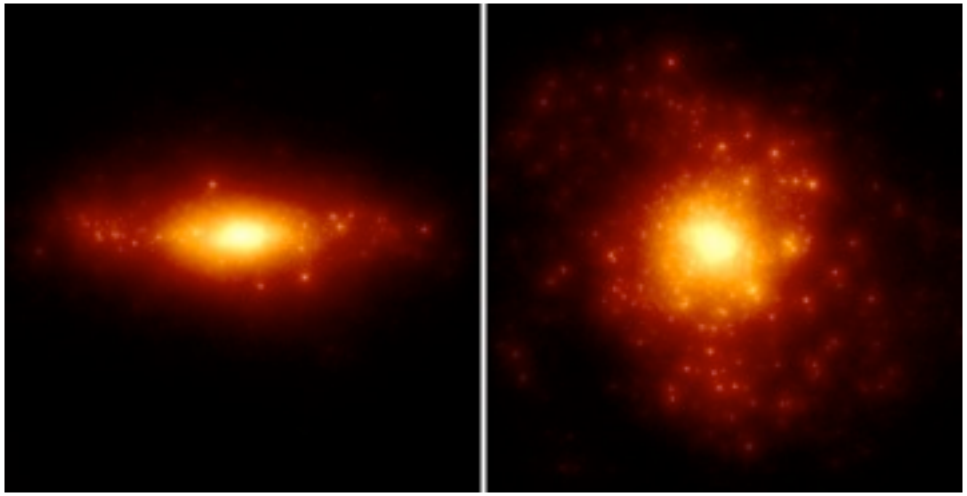
Radiative cooling



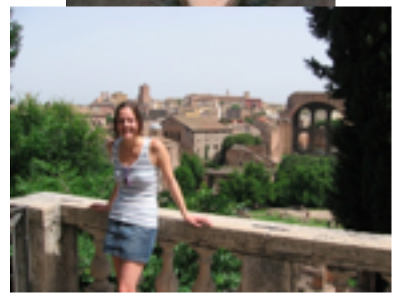
Entropy profiles

Institute for Computational Cosmology

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



Milky Ways et al



Tulluy-Fisher and M*/M200 relations: McCarthy+

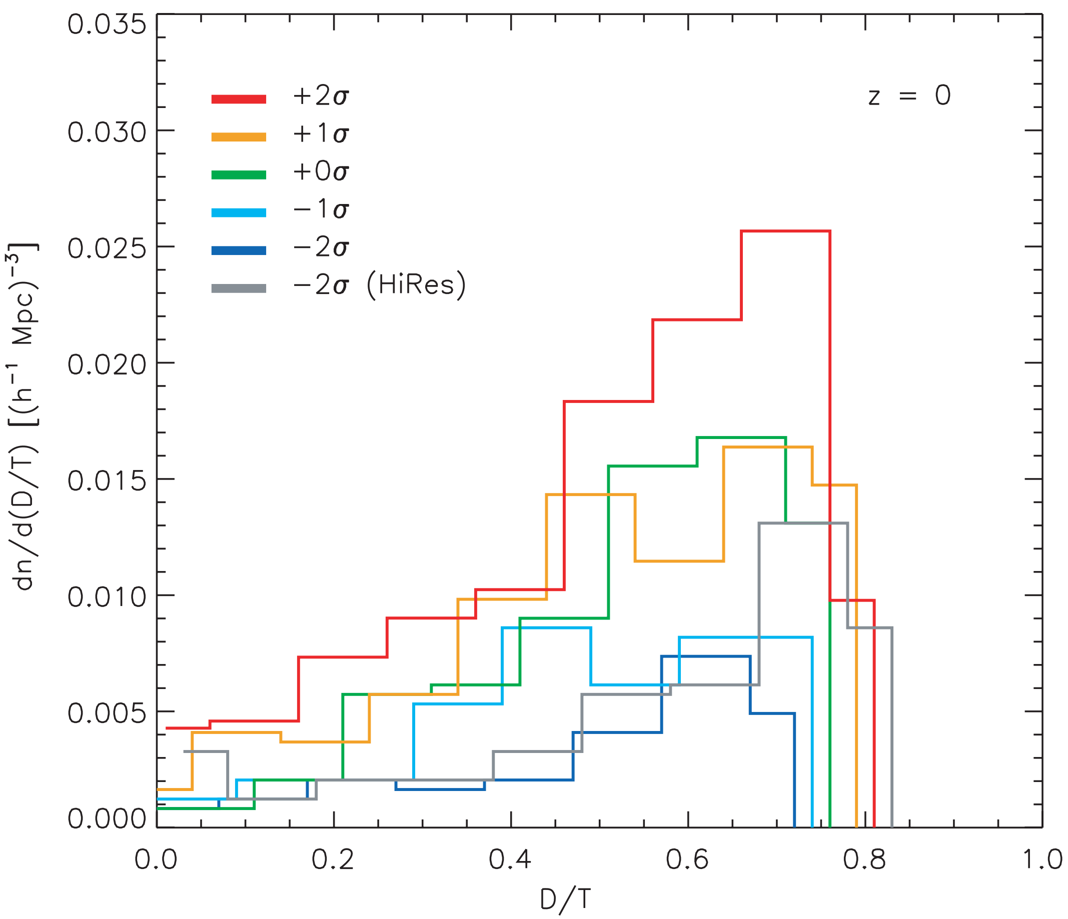
Global structure and kinematics of stellar haloes, McCarthy +

Mismatch and Misalignment: Dark haloes and Satellites of Disc Galaxies, Deason +

Cosmological simulations of the formation of stellar haloes around disc galaxies, Font +

X-ray coronae in simulations of disc galaxy formation, Crain+

The good: We have a Hubble sequence!



Bulge-dominated

Disc-dominated

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

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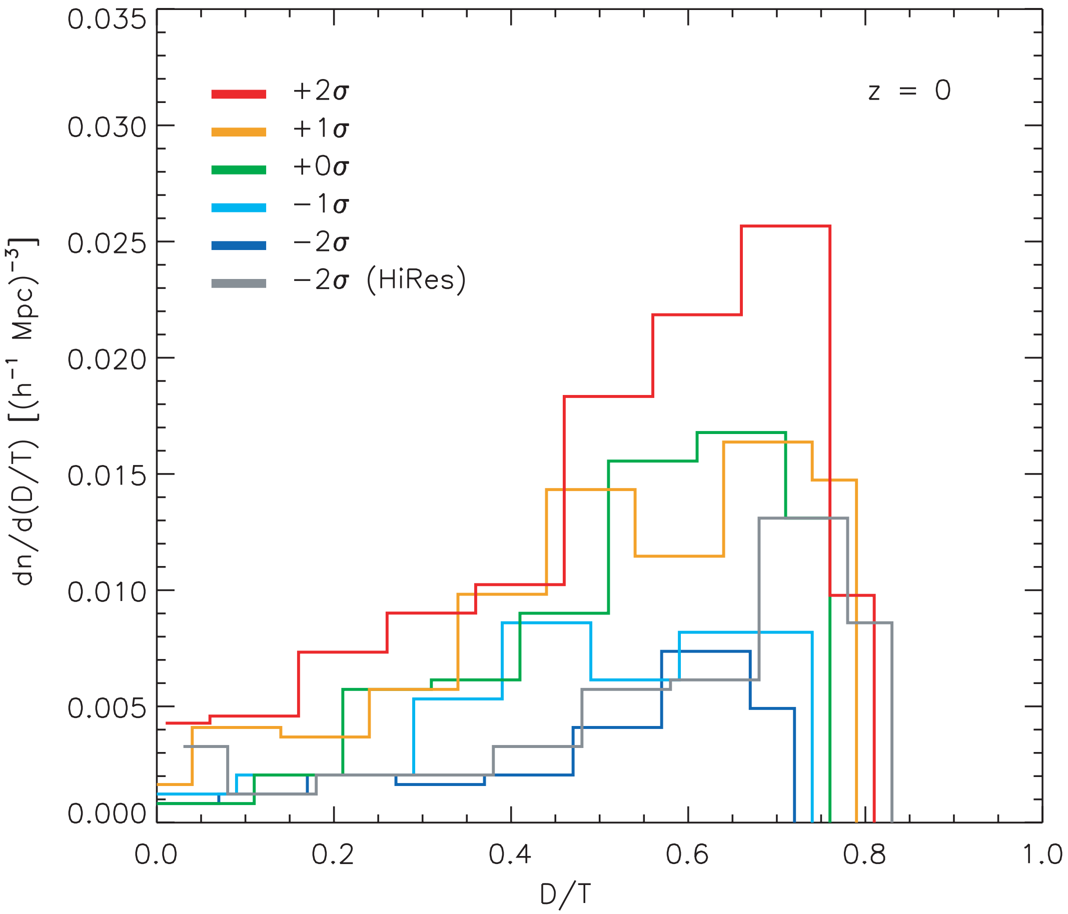
The good: We have a Hubble sequence!



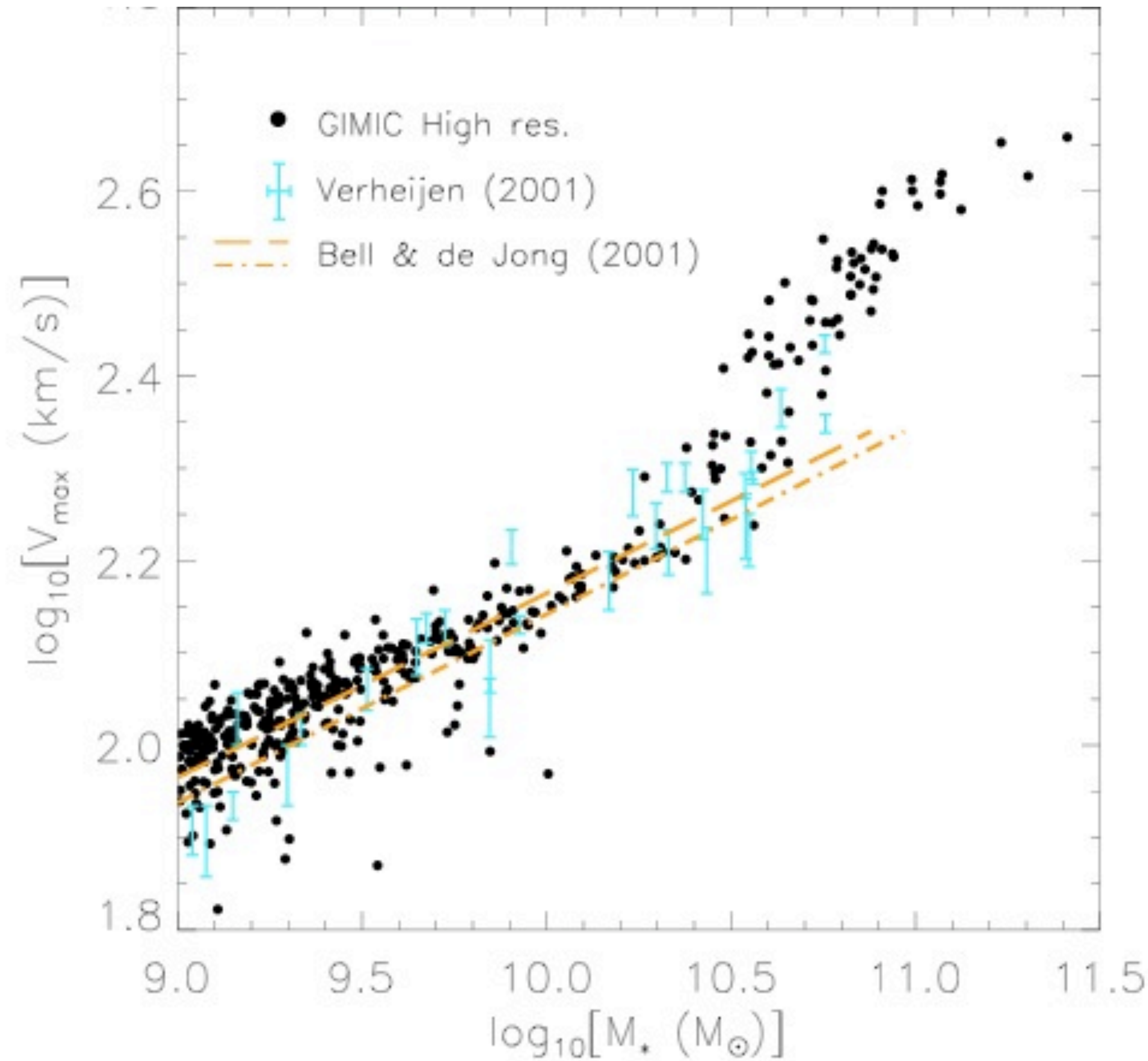
Bulge-dominated

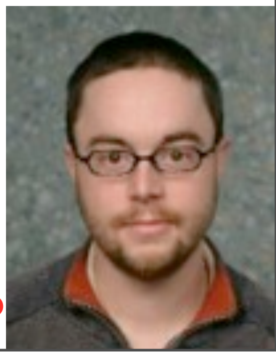
Disc-dominated

The Origin of Disks and Spheroids in Simulated Galaxies

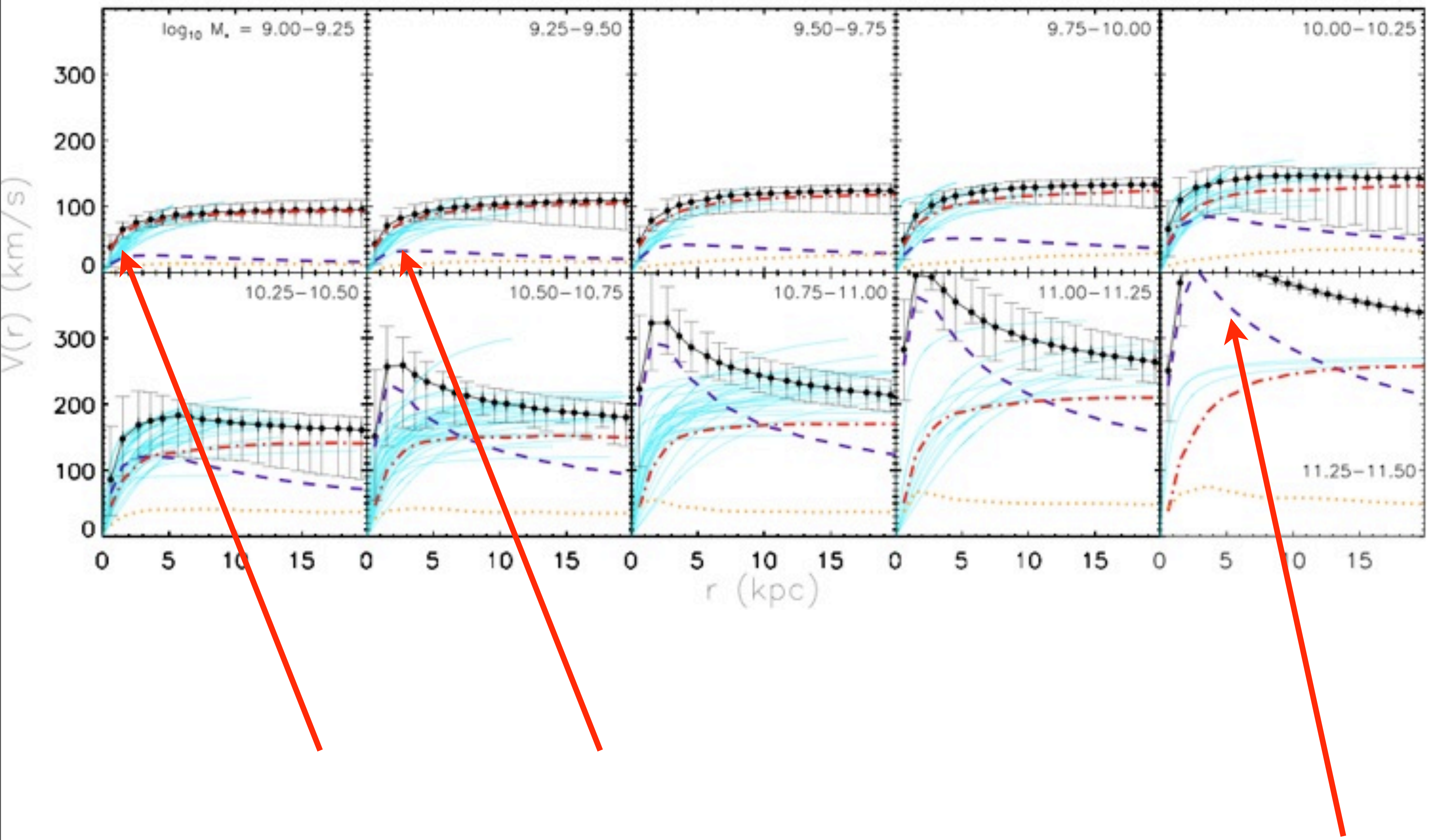
arXiv:1112.2220

Spirals have rotation curves with reasonable shapes, and follow the Tully-Fisher relation!

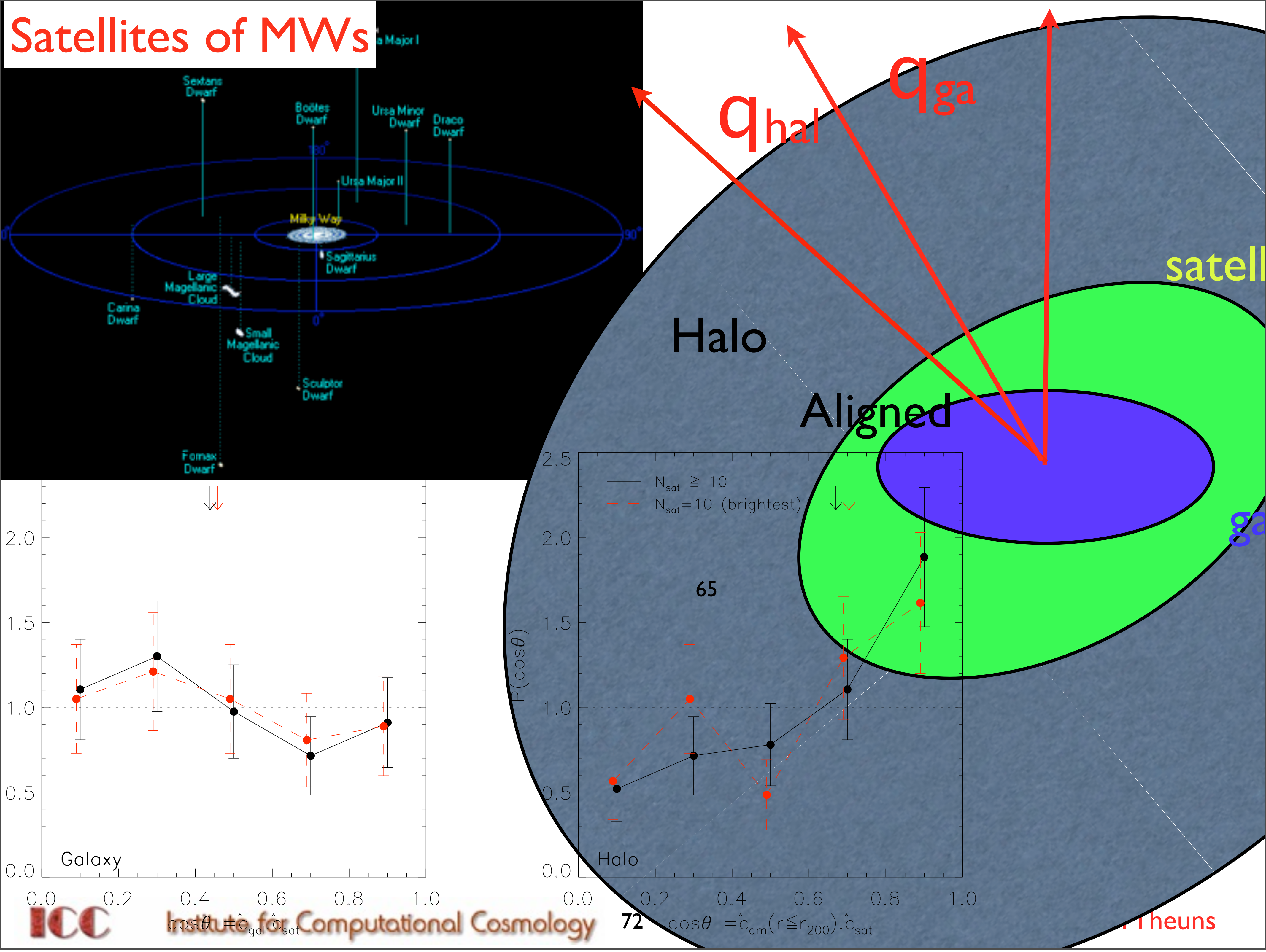




To


log$_{10}$ M$_*$ = 9.00–9.25
9.25–9.50
9.50–9.75
9.75–10.00
10.00–10.25
10.25–10.50
10.50–10.75
10.75–11.00
11.00–11.25
11.25–11.50
V(r) (km/s)
r (kpc)

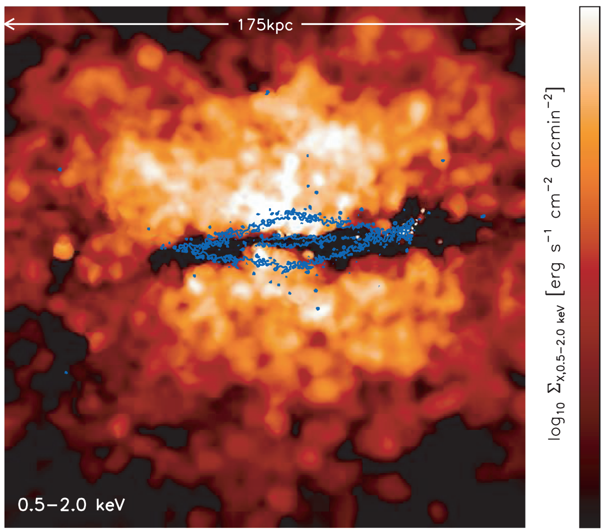
Tom Theuns

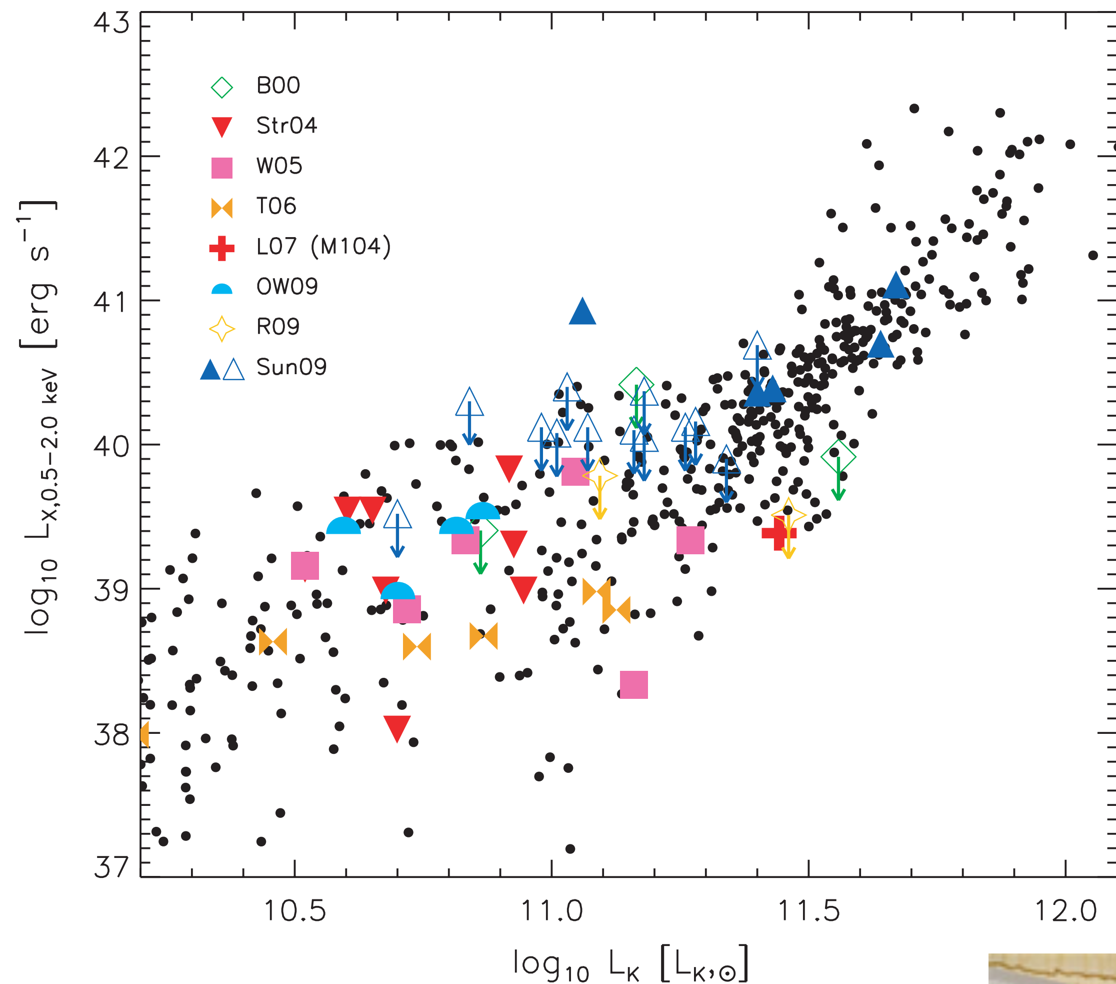


Satellites of MWs
Sextans Dwarf
Boötes Dwarf
Ursa Minor Dwarf
Draco Dwarf
Ursa Major II
Milky Way
Sagittarius Dwarf
Large Magellanic Cloud
Carina Dwarf
Small Magellanic Cloud
Sculptor Dwarf
Fornax Dwarf
q_{hal}
q_{ga}
Halo
Aligned
satell
$N_{sat} \geq 10$
$N_{sat}=10$ (brightest)
65
$P(\cos\theta)$
Galaxy
Halo
$\cos\theta = \hat{c}_{gal}.\hat{c}_{sat}$
$\cos\theta = \hat{c}_{dm}(r \leq r_{200}).\hat{c}_{sat}$
Institute for Computational Cosmology
72
Theuns

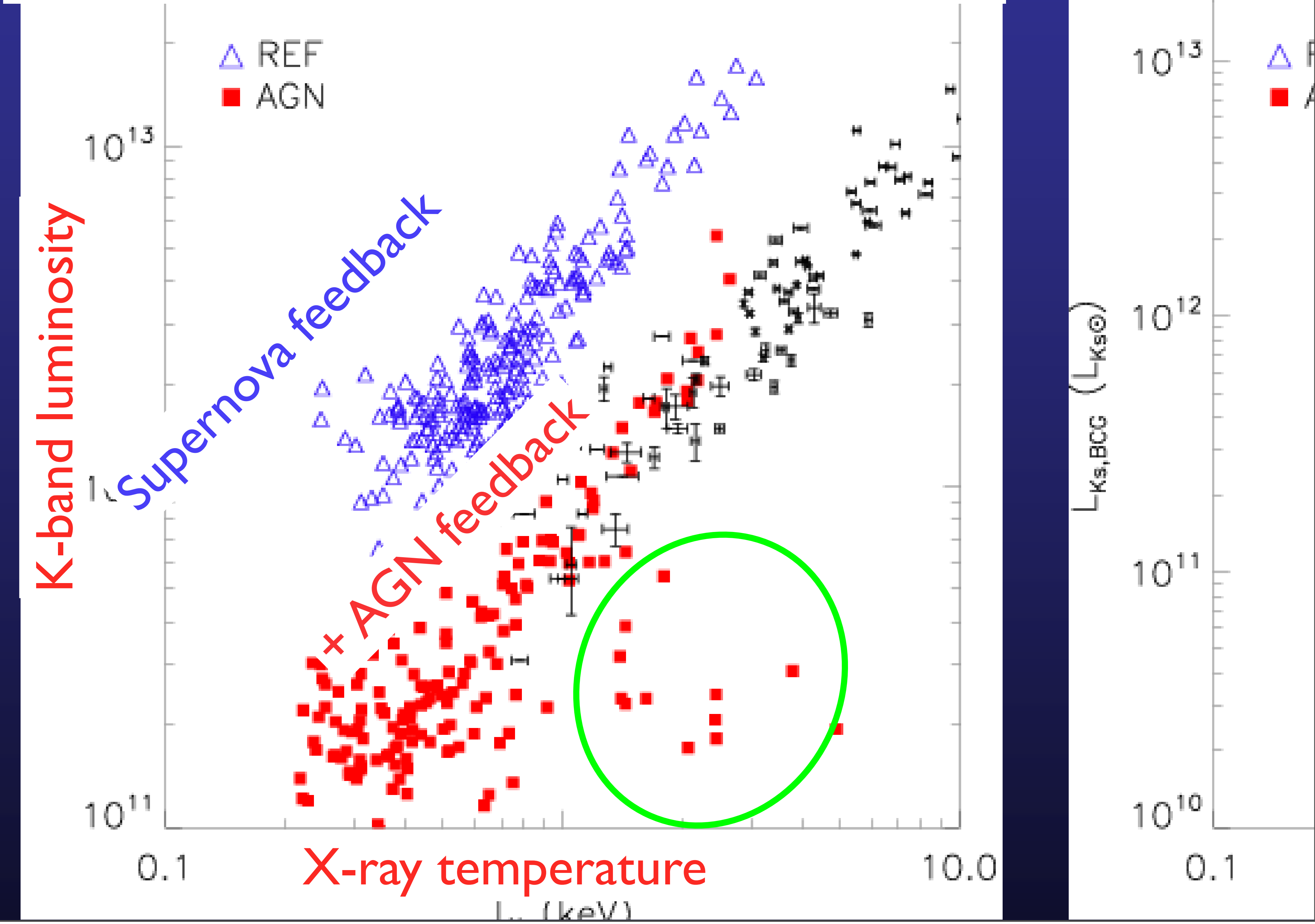
X-ray haloes of MW-like galaxies

Gas in haloes of spirals has a reasonable X-ray luminosity (long a stumbling block in semi-analytical models)



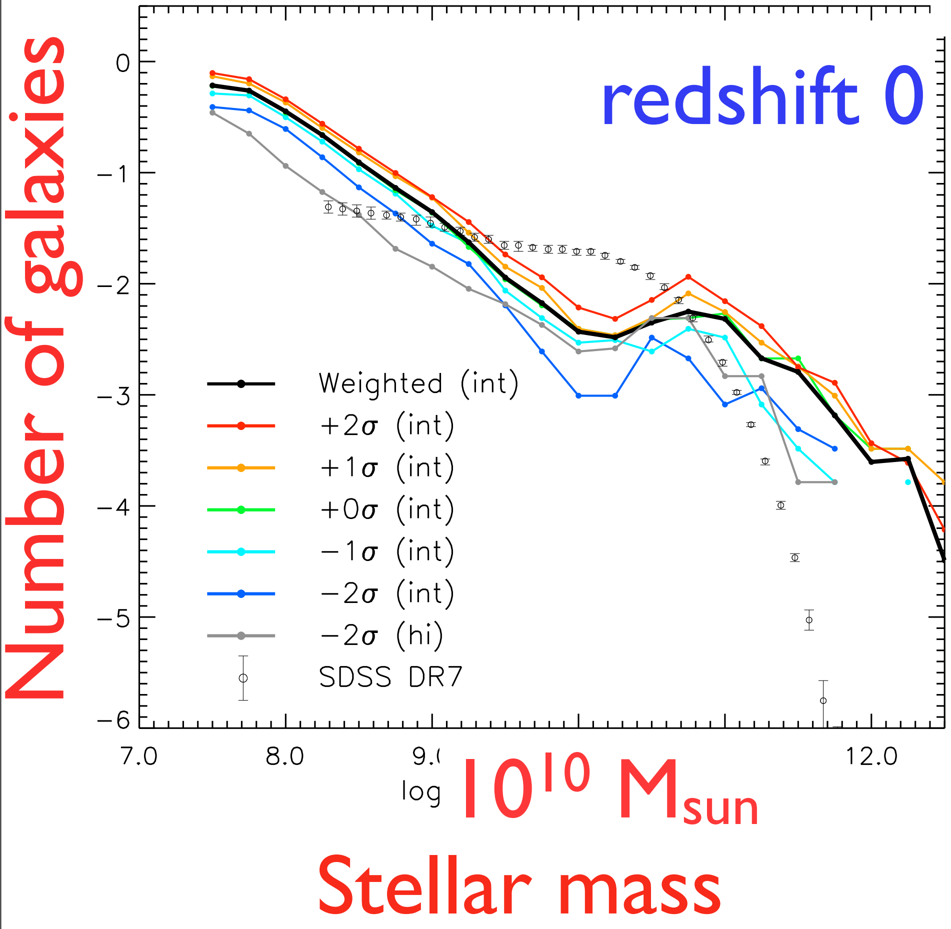


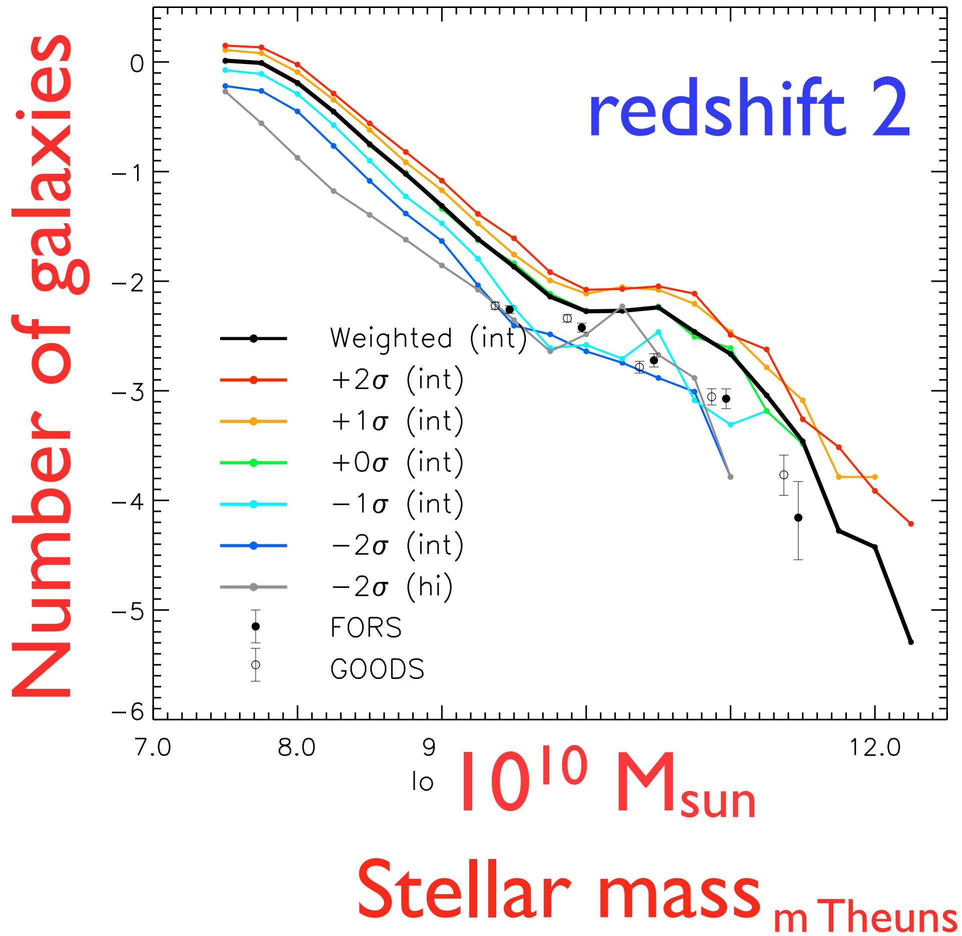
The bad: groups



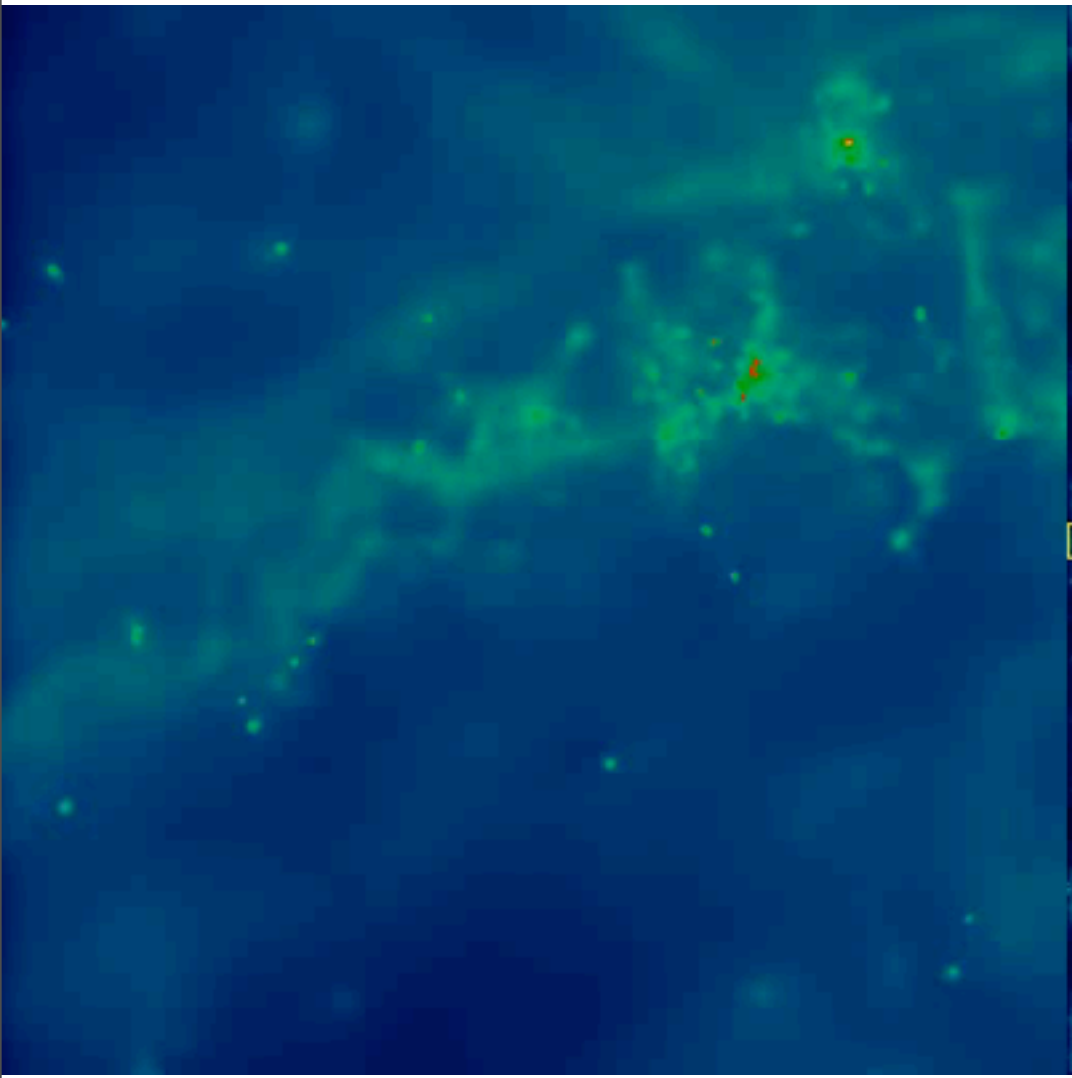
The Ugly: stellar mass function

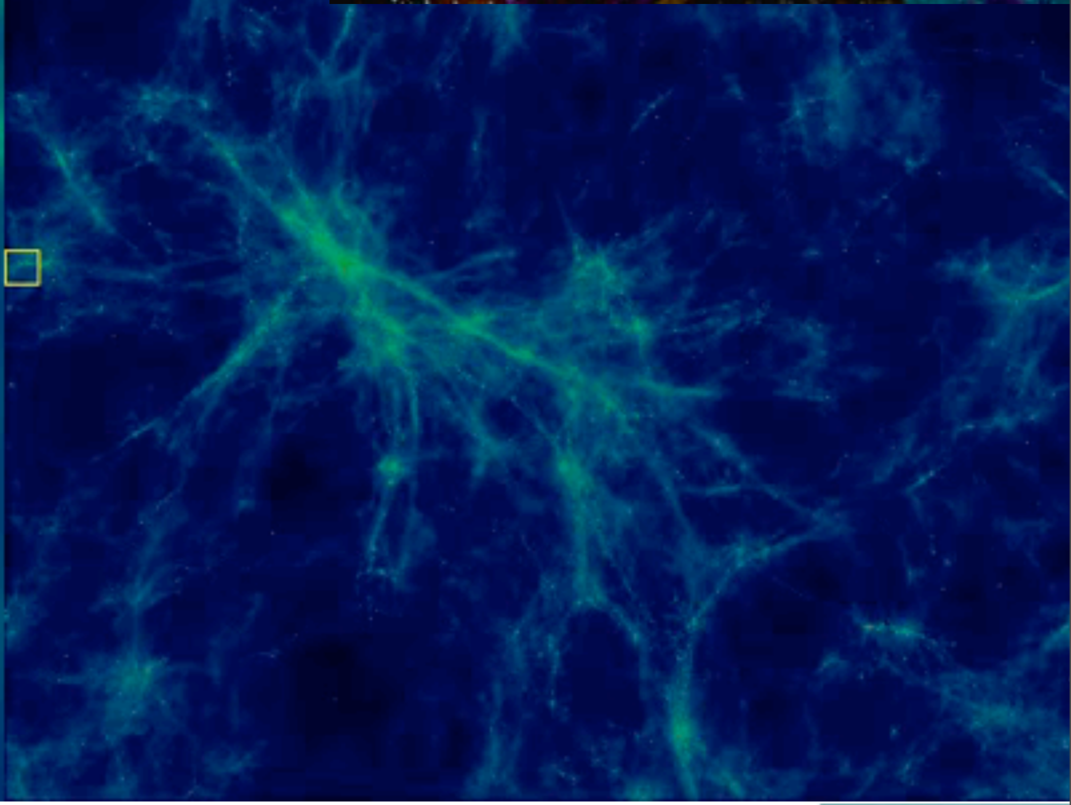
$$\dot{M}_{\rm wind}\left(\frac{v_{\rm wind}}{710\,{\rm km\,s^{-1}}}\right)^2 = \epsilon\,\eta\,\dot{M}_{*}$$





The good (again): HI in absorption





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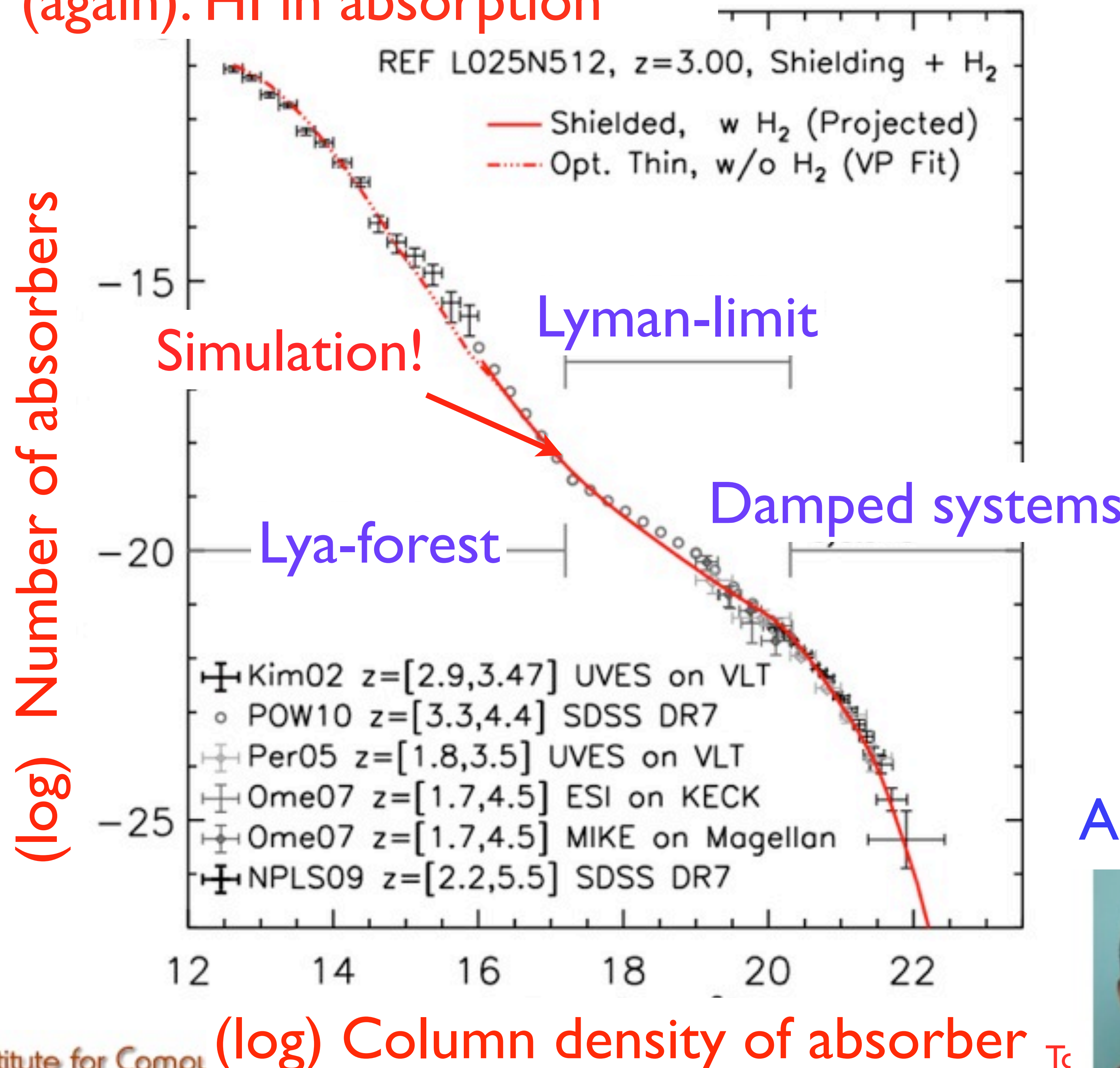
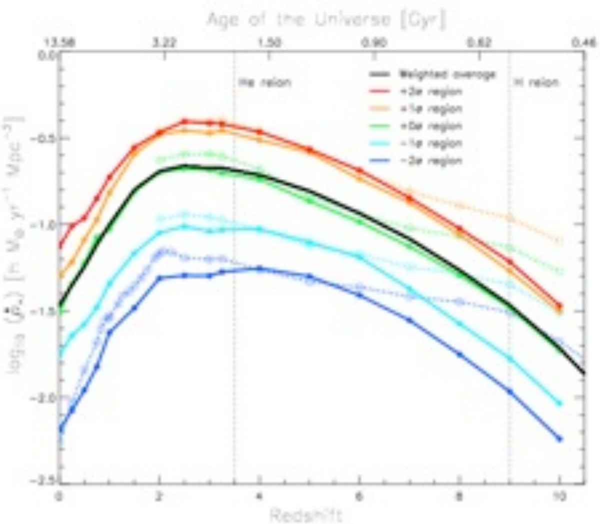
Tc

The good (again): HI in absorption

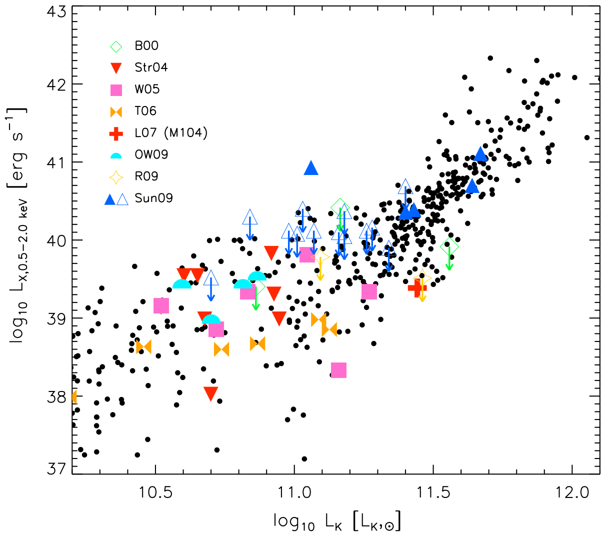


Altay +

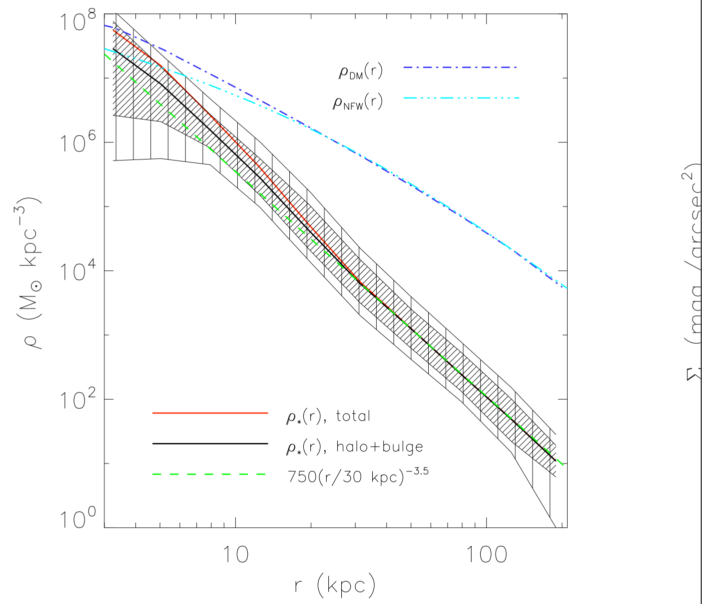
ICC Institute for Compu



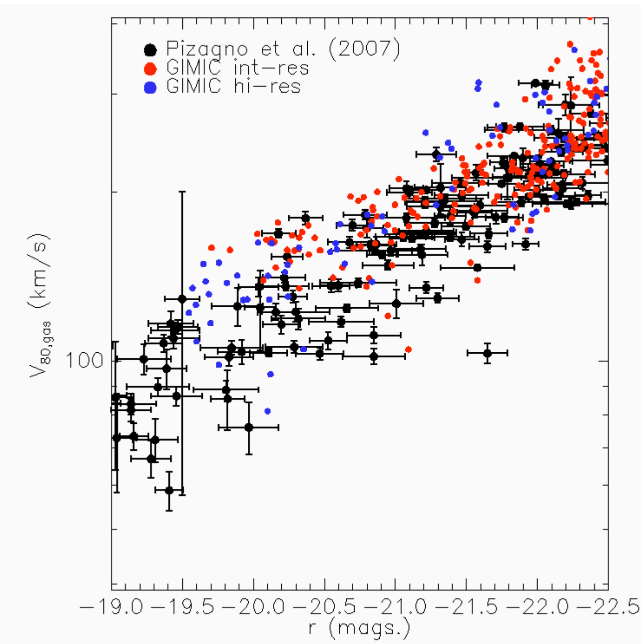
Mass function



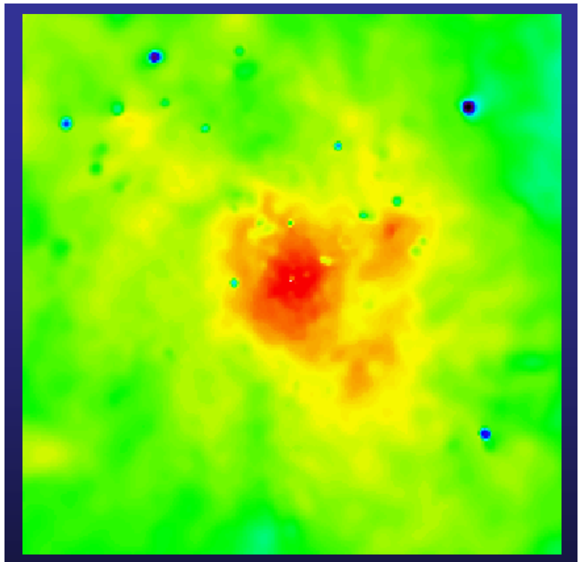
L_X-L_K



Stellar halo

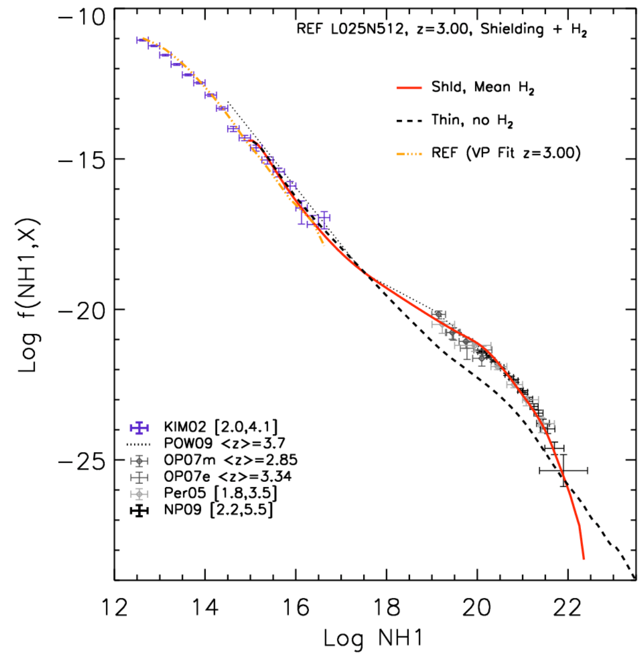


Tully-Fisher



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

AGN in groups



HI distribution

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

Good: Hubble sequence, rotation curves, MW-like galaxies, satellites, X-rays, HI

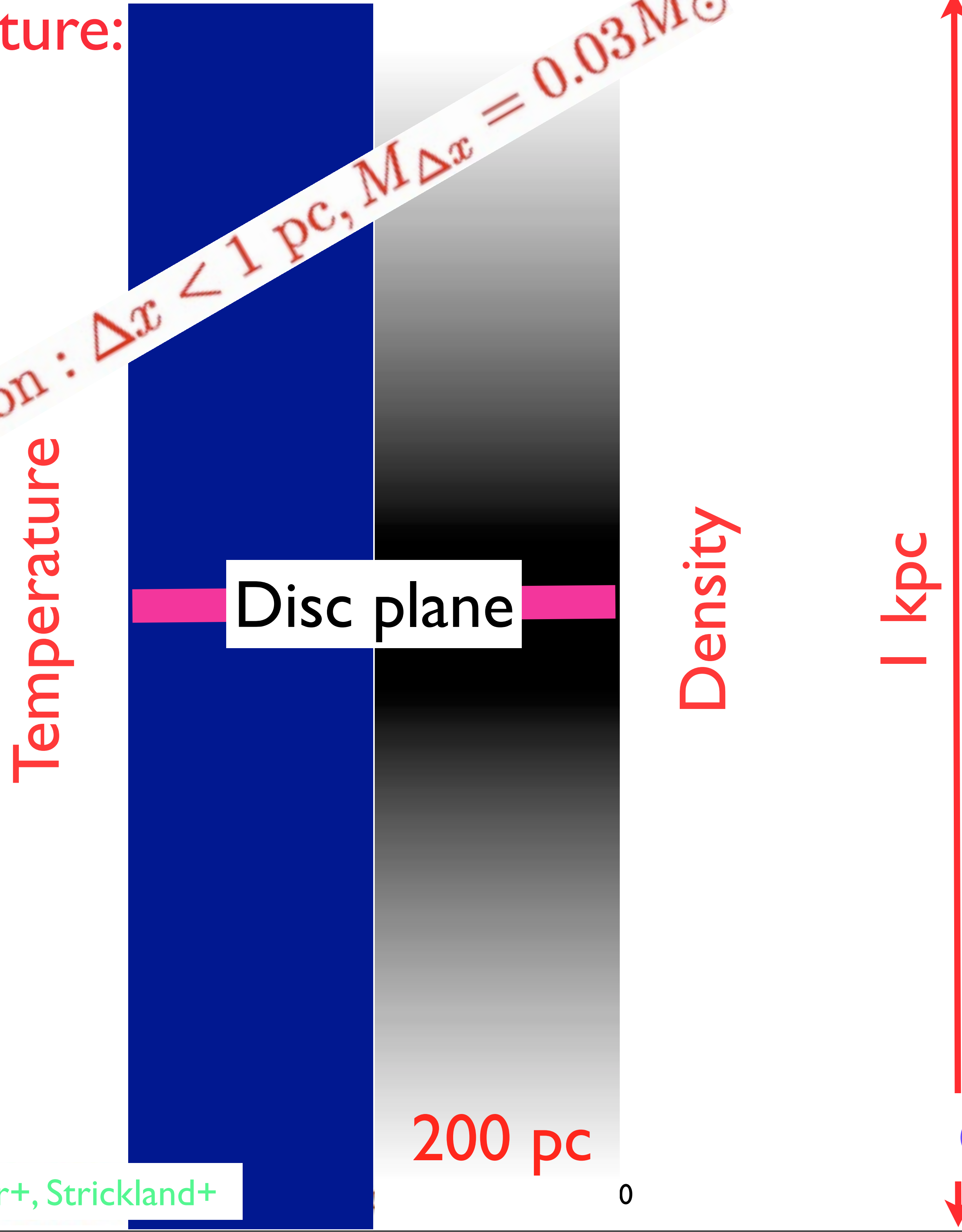
Bad (or not that good): need more physics (AGN)

Ugly: stellar mass functions

$$\dot{M}_{\rm wind}\left(\frac{v_{\rm wind}}{710\,{\rm km\,s^{-1}}}\right)^2 = \epsilon\,\eta\,\dot{M}_\star$$

The future:

resolution : $\Delta x < 1$ pc, $M_{\Delta x} = 0.03 M_{\odot}$



Also: Cooper+, Strickland+

Feedback superhero

Creasey+, in prep

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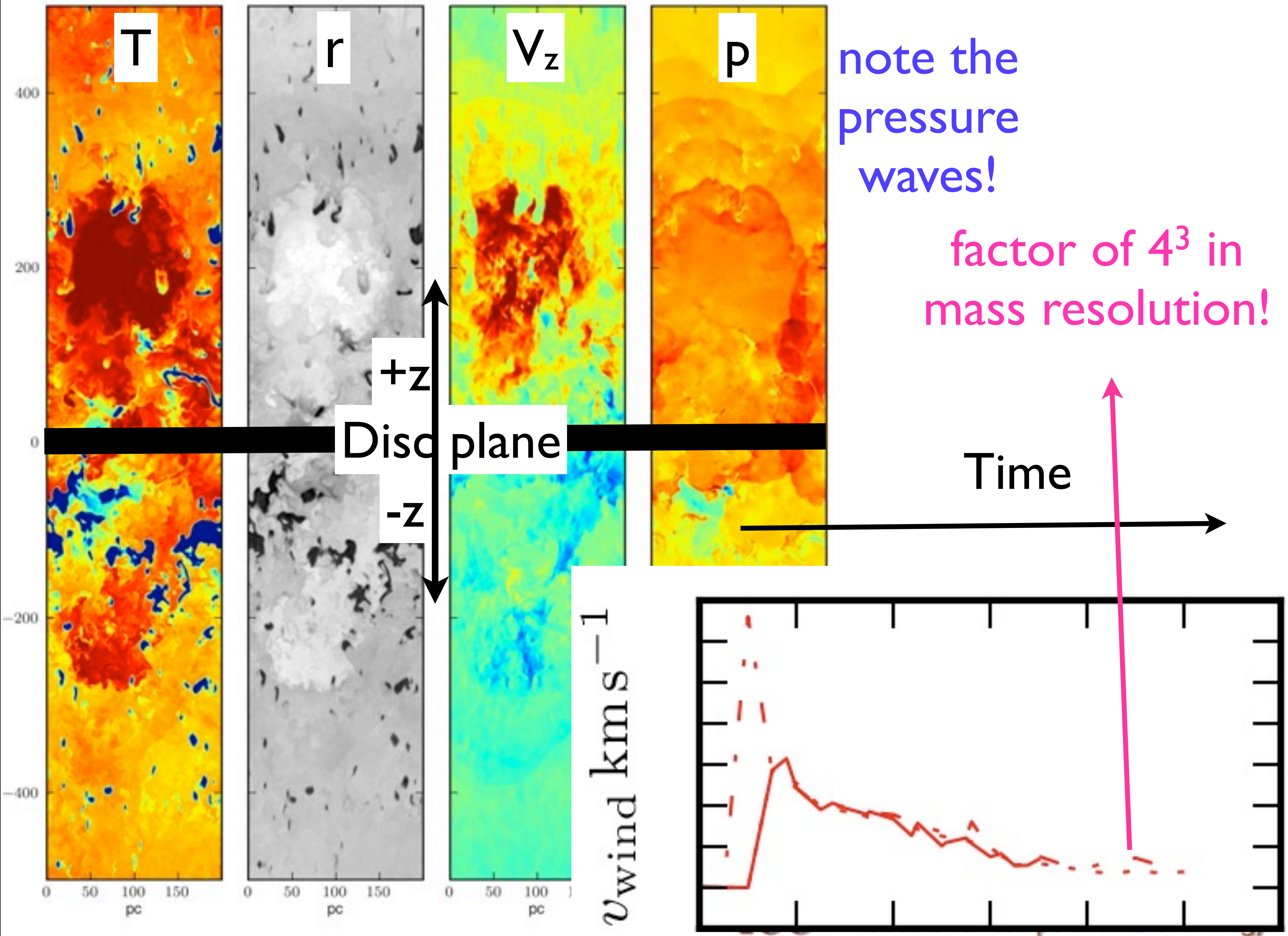
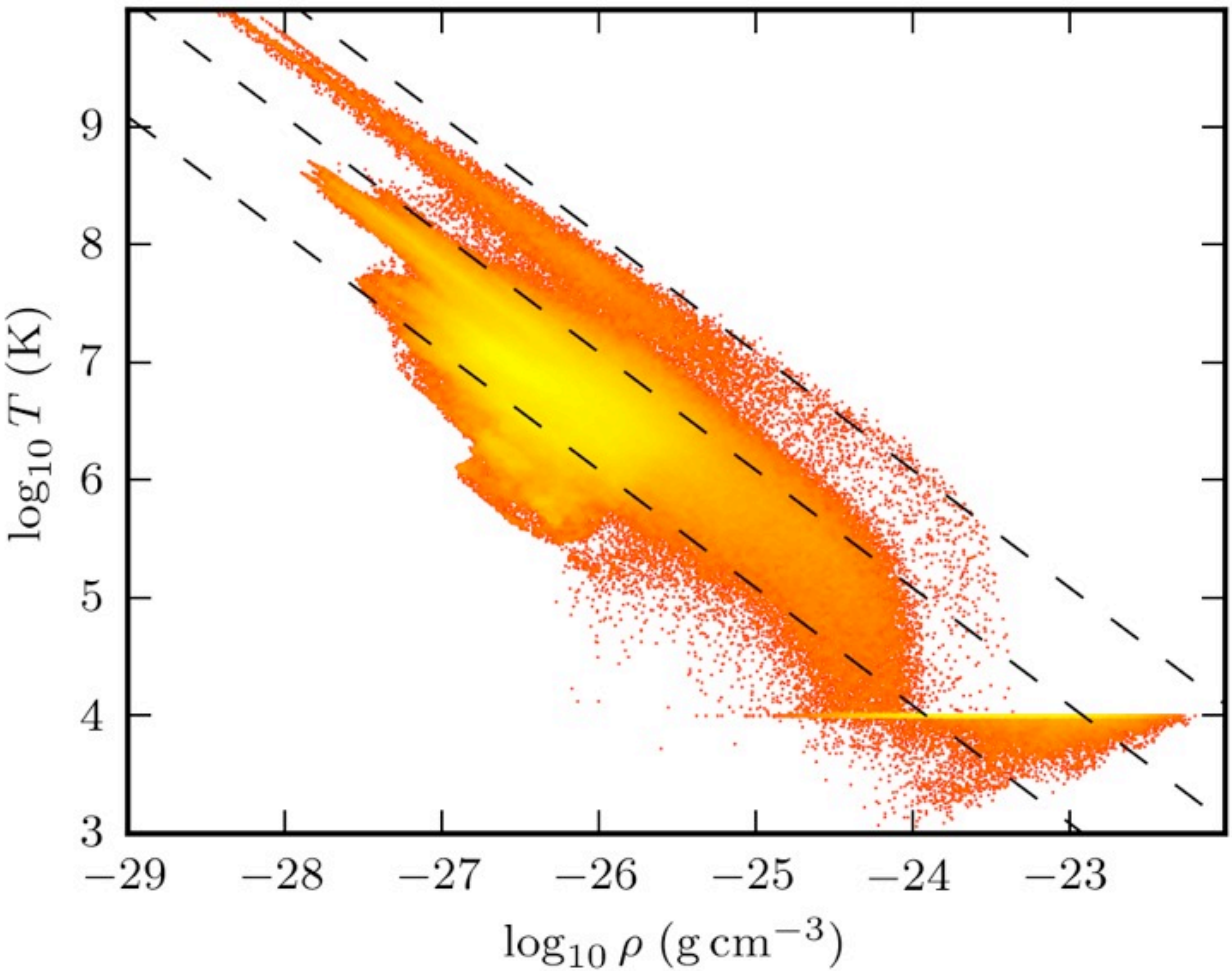
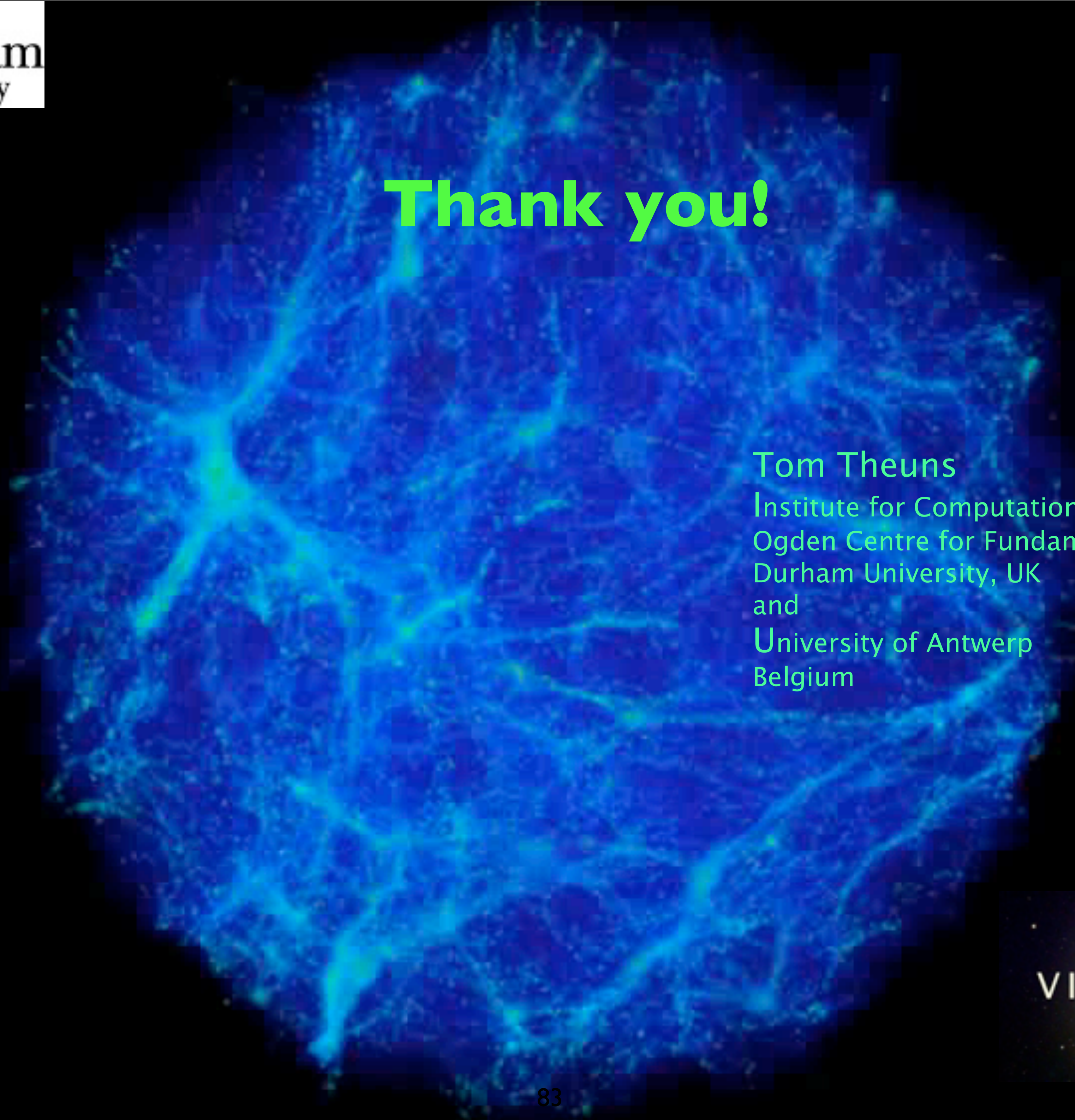

T
r
V_z
p
note the pressure waves!
factor of 4^3 in mass resolution!
+z
Disc plane
-z
Time
400
200
0
−200
−400
0
50
100
150
pc
v_{wind} km s^{-1}



9
8
7
6
5
4
3
$\log_{10} T$ (K)
−29
−28
−27
−26
−25
−24
−23
$\log_{10} \rho$ (g cm^{-3})



Thank you!

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