Review of [theoretical] models

"State of the art of the models and simulations of galaxies in groups and clusters"

Goal:

- Overview of current models of different types
- Scope of physical ingredients in each
- (Limitations and inherent assumptions)
- Comparison of numerical approaches, regimes of applicability, classes of objects, etc.

Not:

- Extensive review of the scientific results of the topics of this workshop as addressed by models
- Focused on details of feedback (tomorrow)

Review of [theoretical] models

- Bruno Henriques
  - SAMs
- Stephanie Tonnesen & Elke Roediger
  - Idealized & wind-tunnels
- Annalisa Pillepich
  - Cosmological hydro sims
- Dylan Nelson
  - … in the context of Illustris / TNG
- Yannick Bahé
  - ... in the context of EAGLE
- Collective discussion

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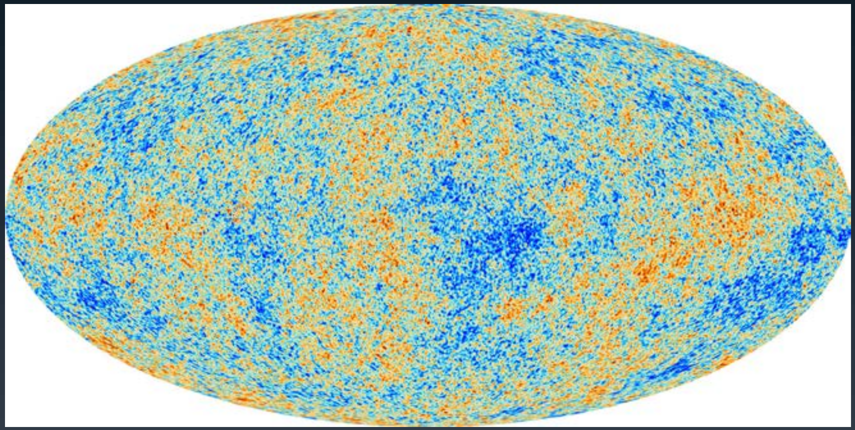
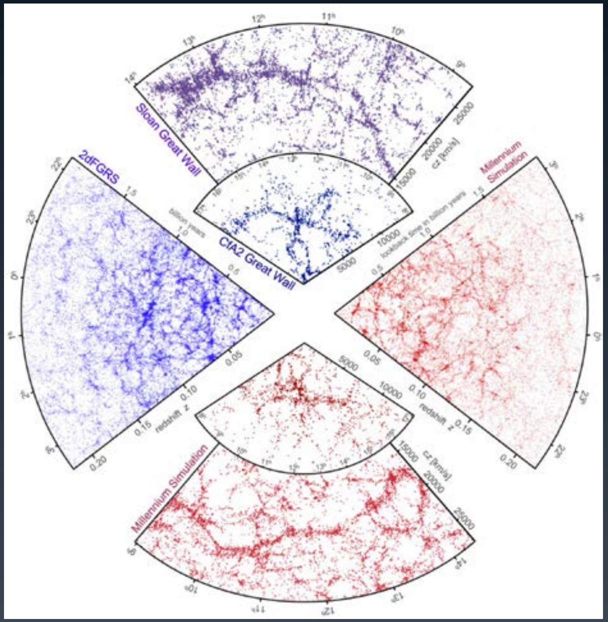
Challenges in galaxy formation theory

Bruno Henriques (Zwicky Fellow, ETH Zurich)

Simon White, Peter Thomas, Simon Lilly
Raul Angulo, Scott Clay, Benoit Fournier, Qi Guo,
Gerard Lemson, Volker Springel, Rob Yates

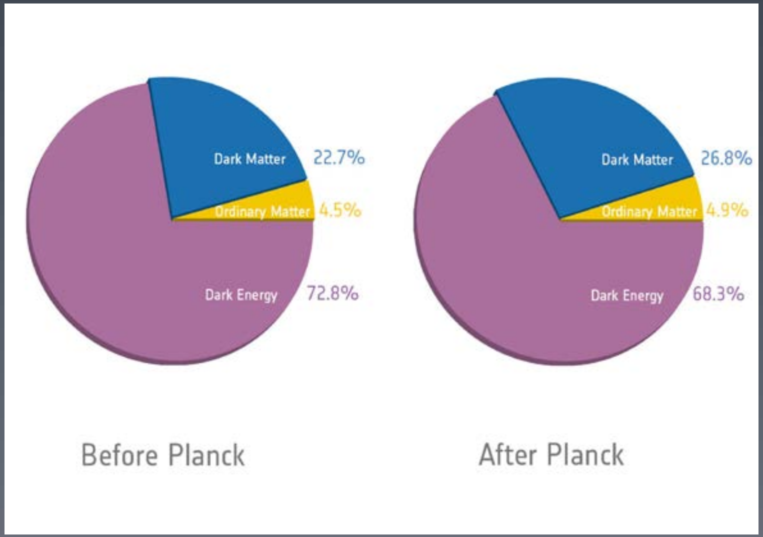
Basic principle of SAMs: Gravity



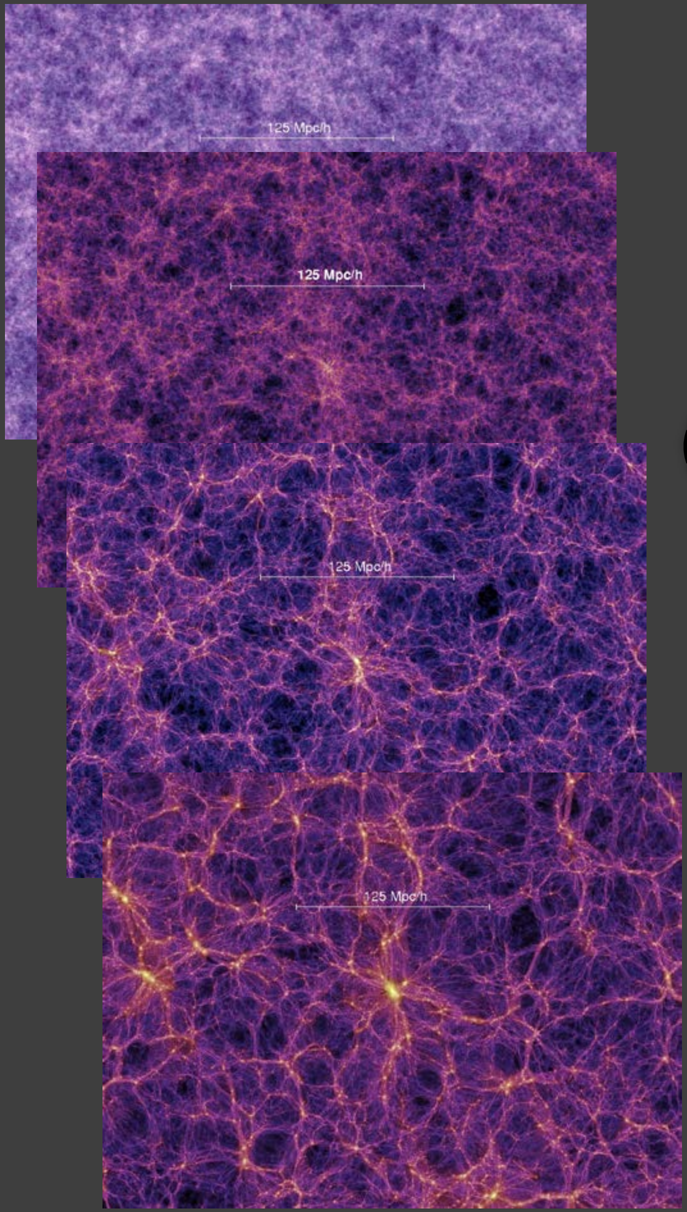


Content of the Universe known to a few percent!!!

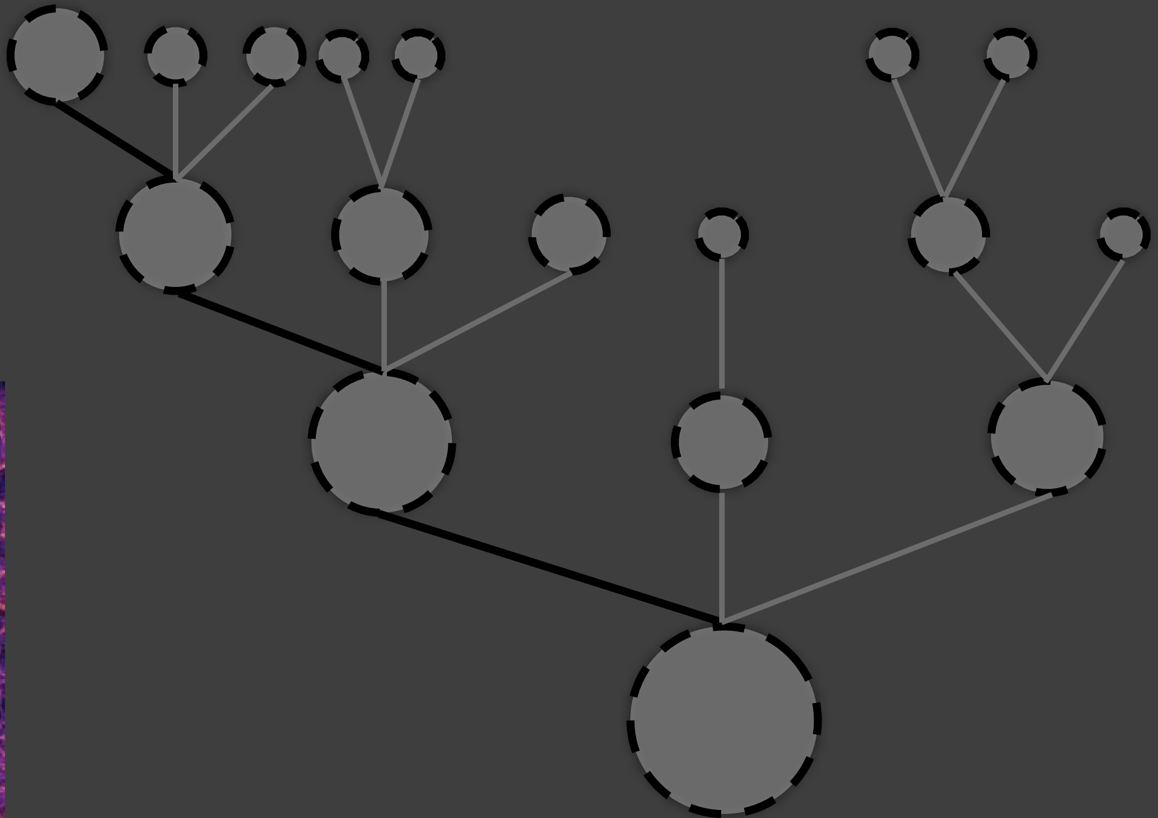
We have a working model of the universe in which <u>85% of matter only interacts through gravity</u>



Evolution of structures is "fully known"



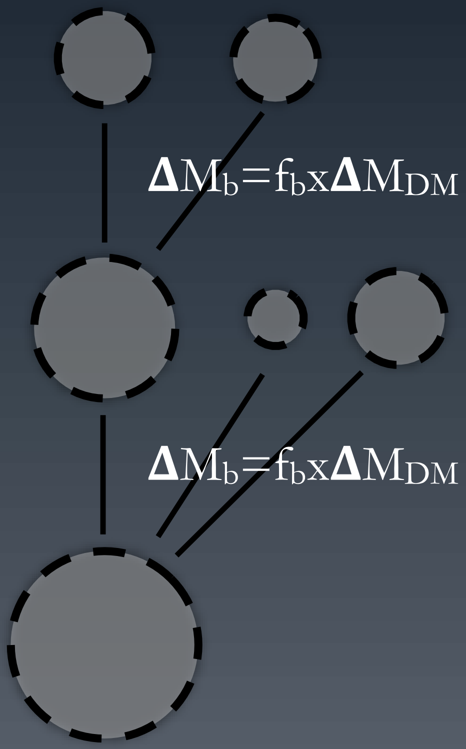
masses, sizes, temperatures, positions and velocities of dark matter haloes are "known"

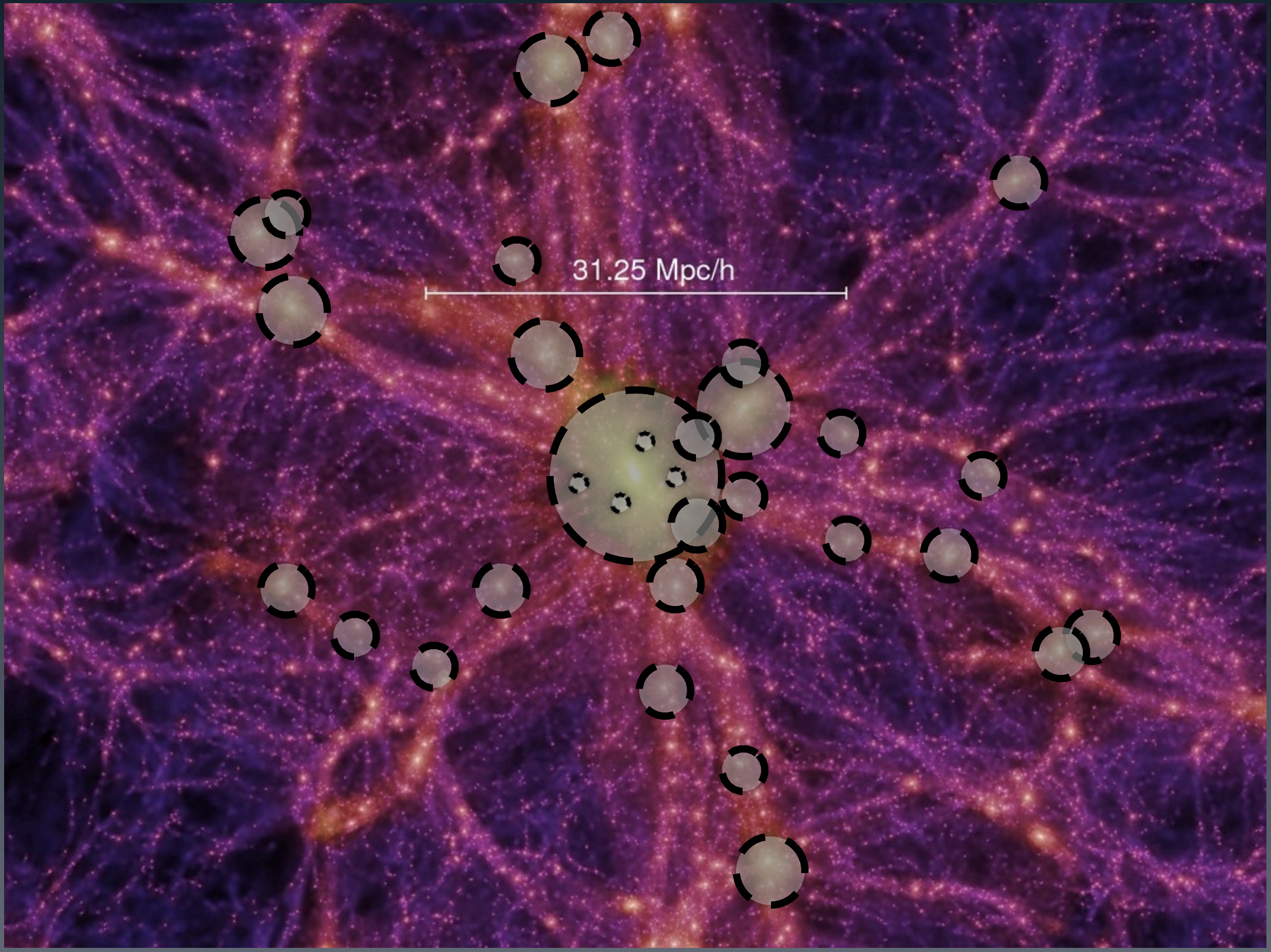


Accretion

baryonic mass is given by cosmology:

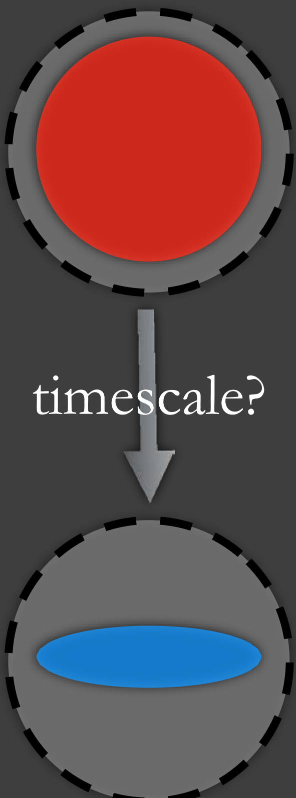
$M_b = f_b x M_{DM}$





Cooling

What happens to the baryons? hot atmosphere vs rapid cooling



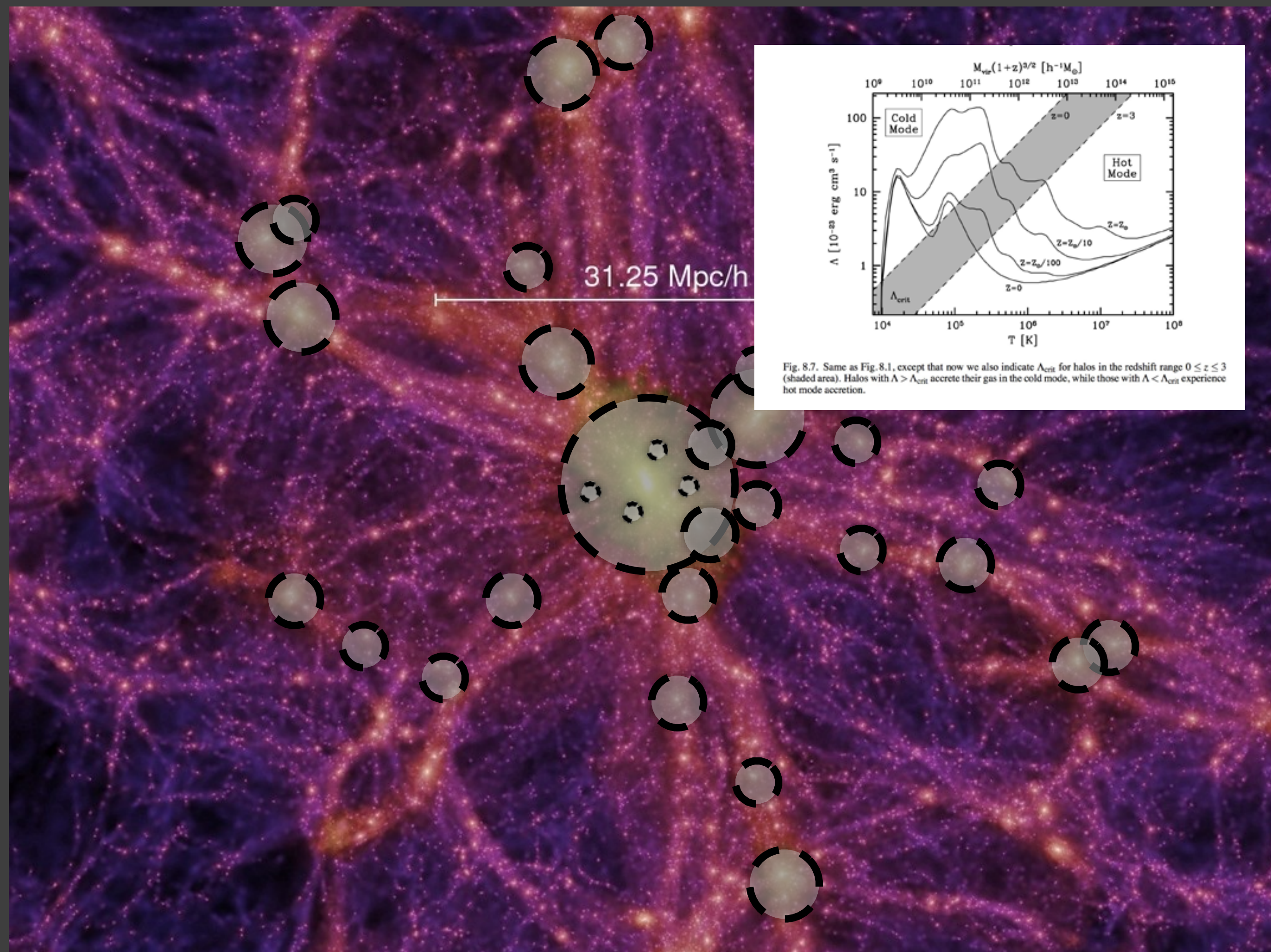
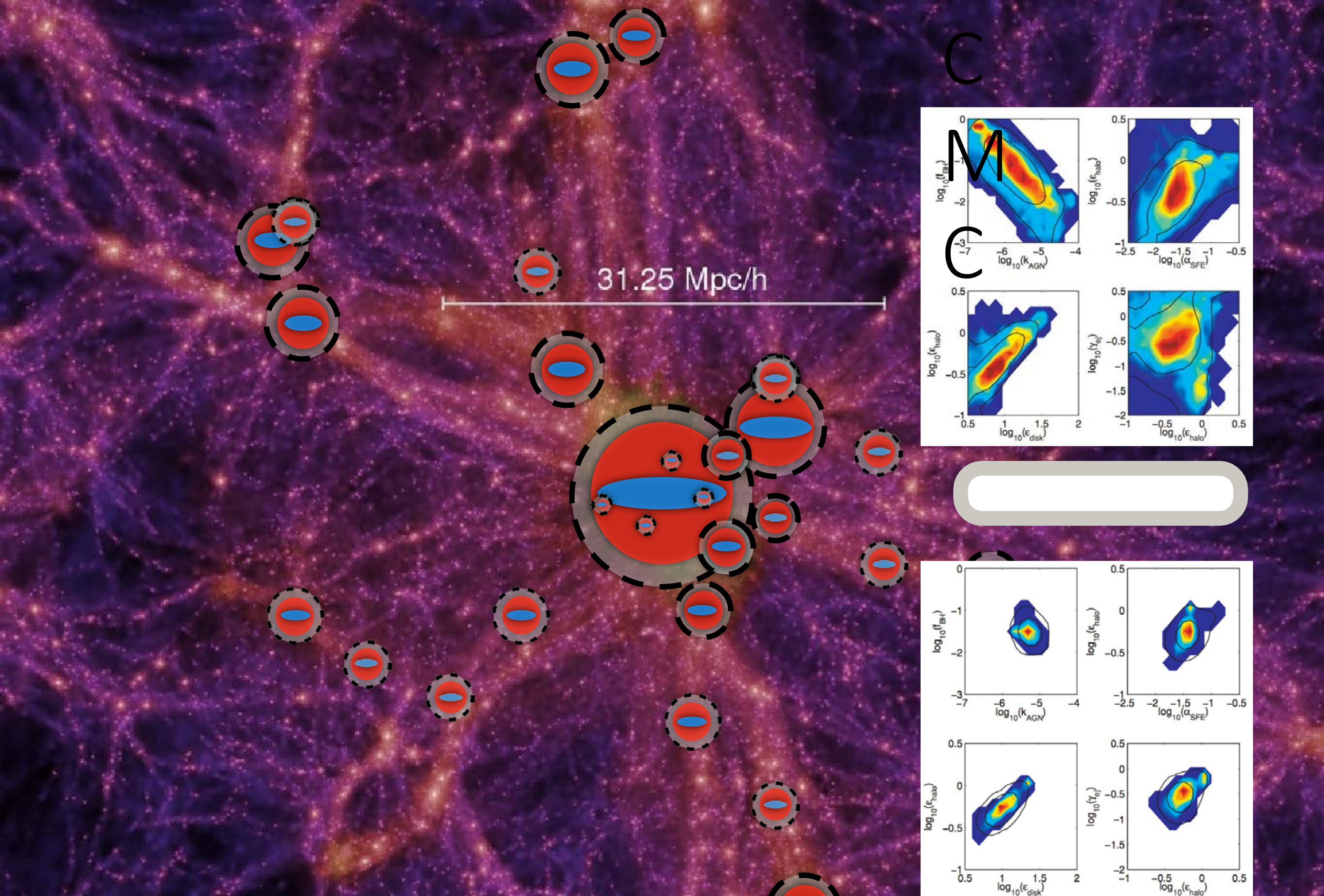
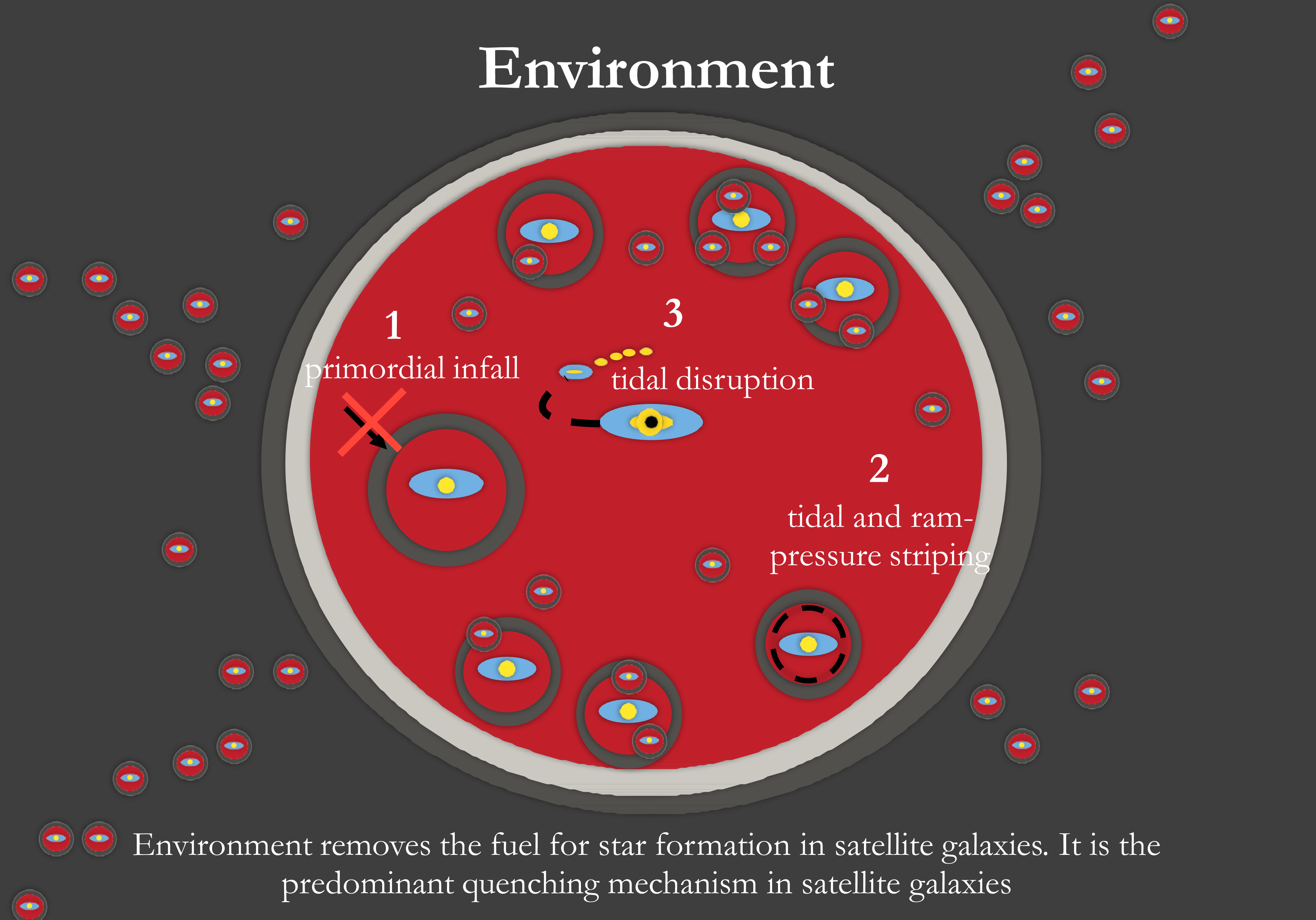


Fig. 8.7. Same as Fig. 8.1, except that now we also indicate Λ_{crit} for halos in the redshift range $0 \leq z \leq 3$ (shaded area). Halos with $\Lambda > \Lambda_{crit}$ accrete their gas in the cold mode, while those with $\Lambda < \Lambda_{crit}$ experience hot mode accretion.



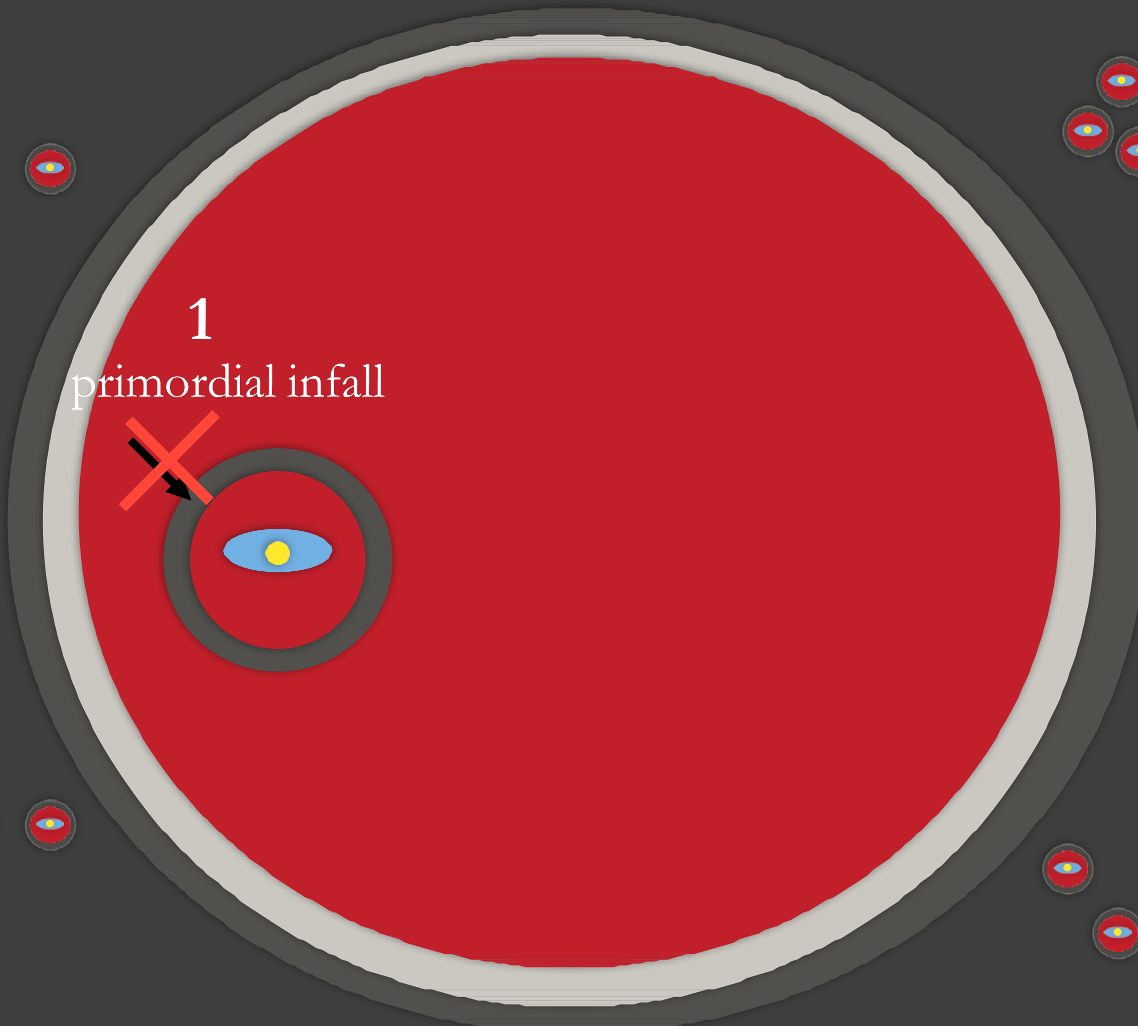
Henriques, Thomas, Oliver & Roseboom (2009), Henriques & Thomas (2010), Henriques et al. (2013), Henriques et al. (2015)

Environment



Environment removes the fuel for star formation in satellite galaxies. It is the predominant quenching mechanism in satellite galaxies

Lack of Primordial Infall



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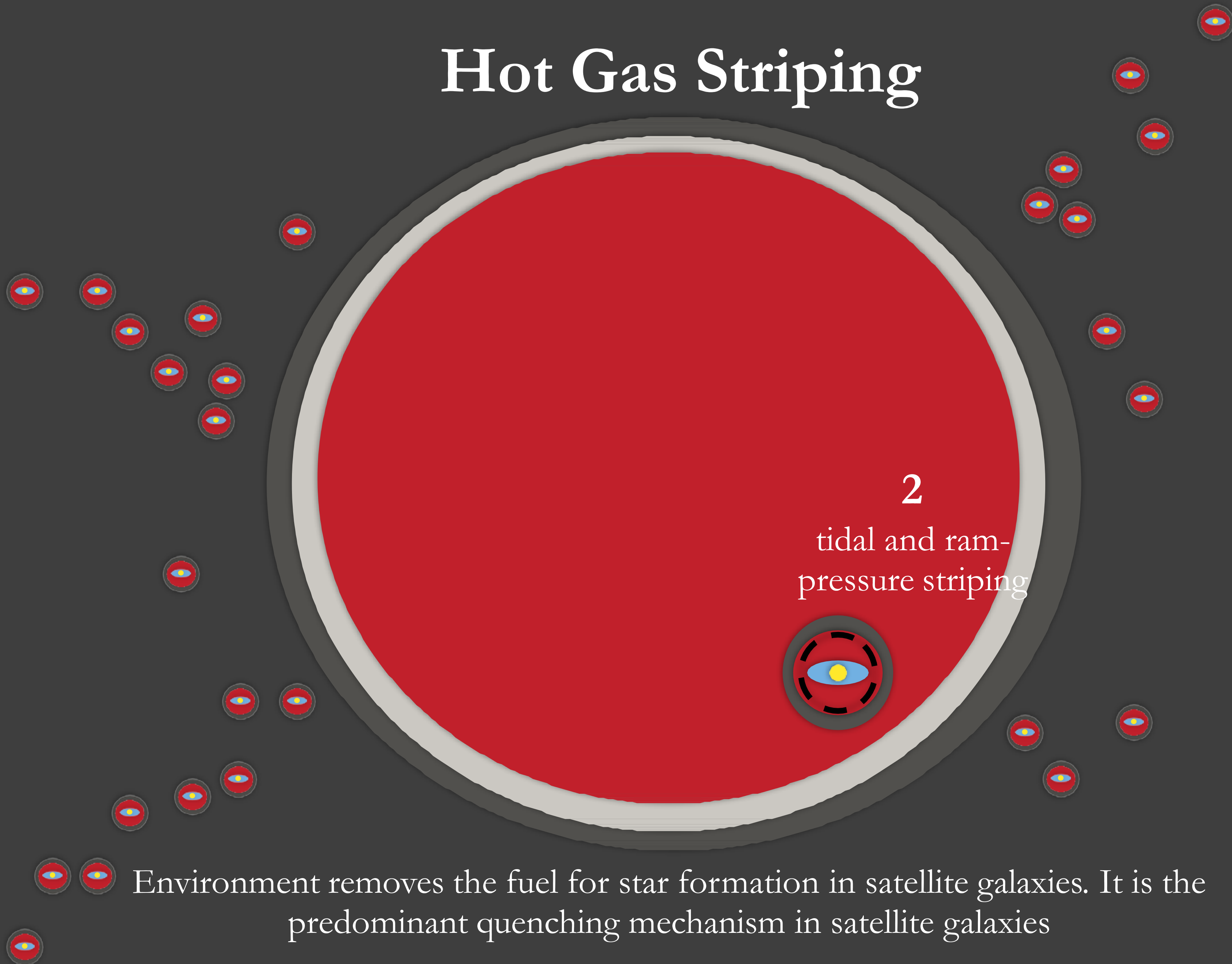
Hot Gas Striping



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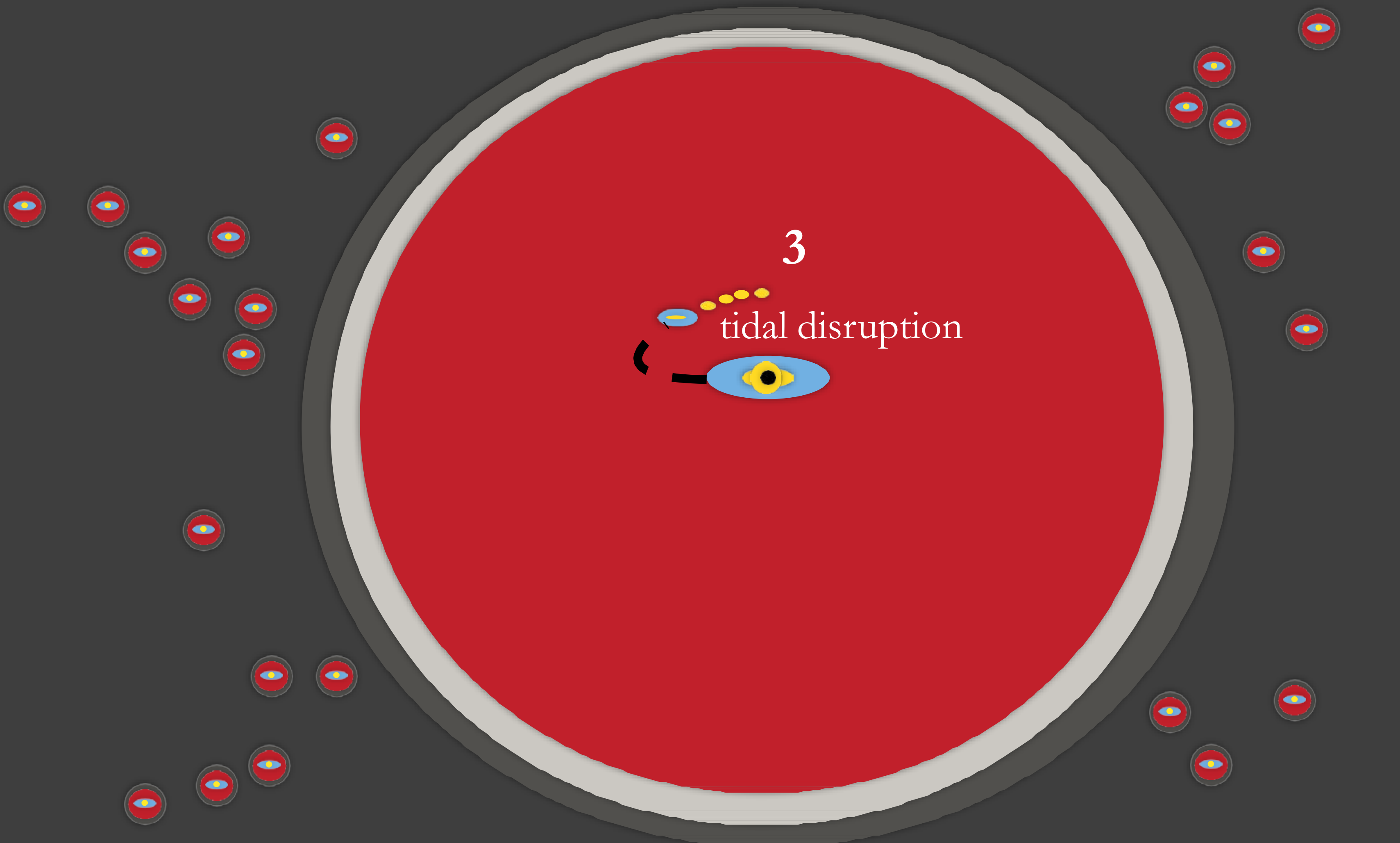
Tidal disruption of cold gas and stars



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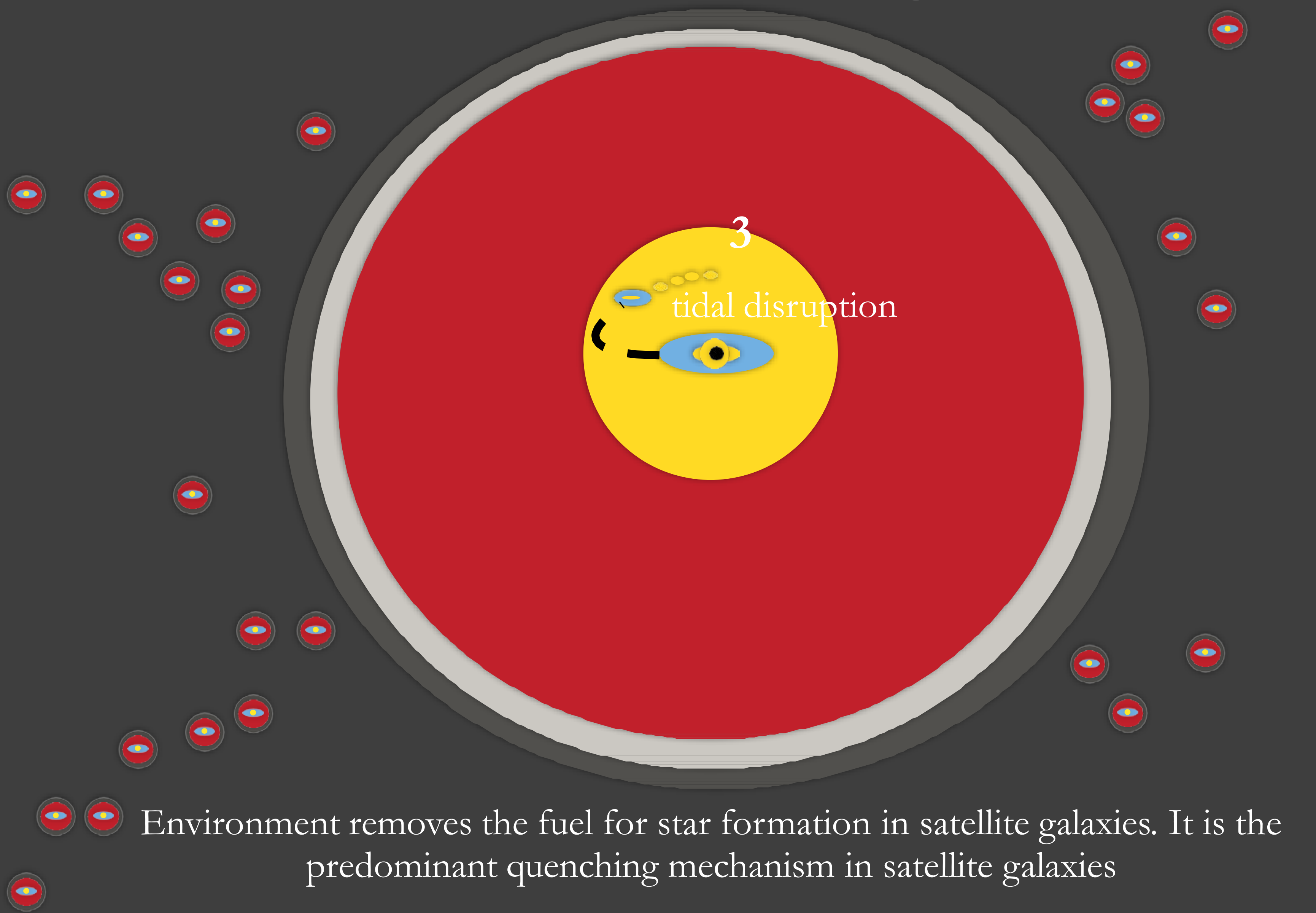
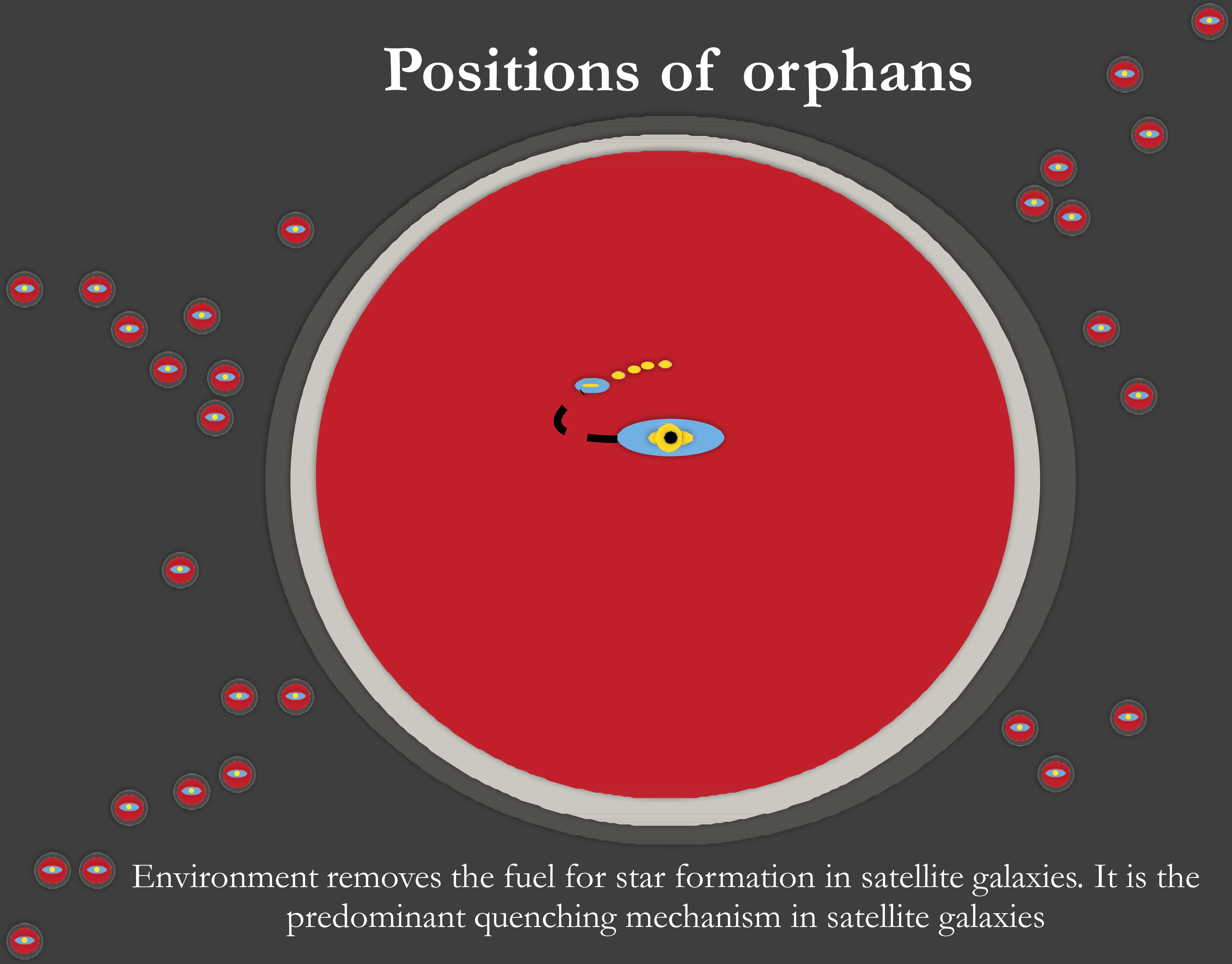
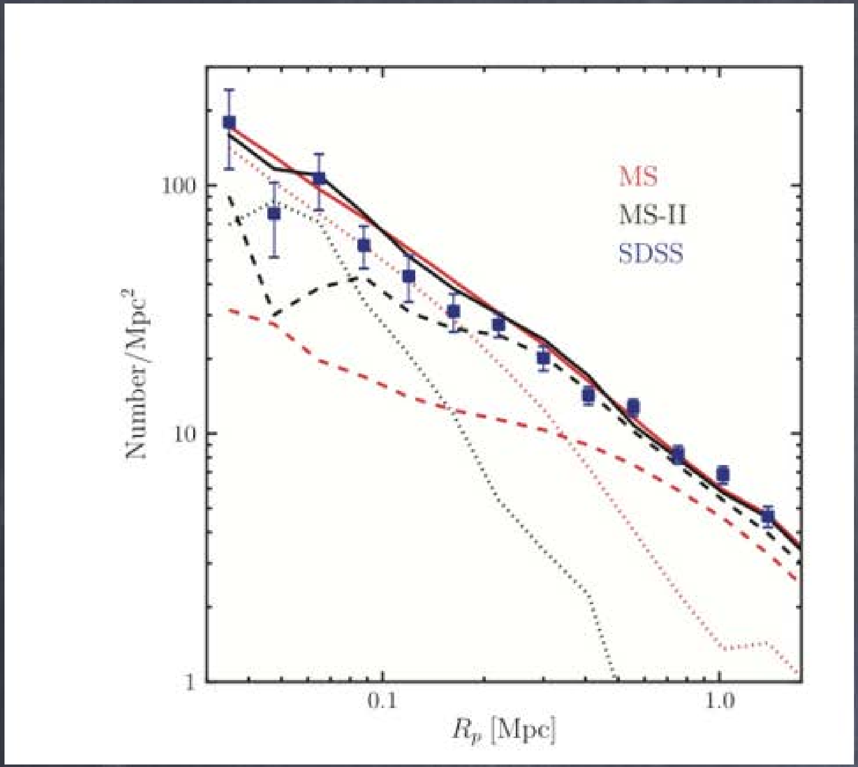


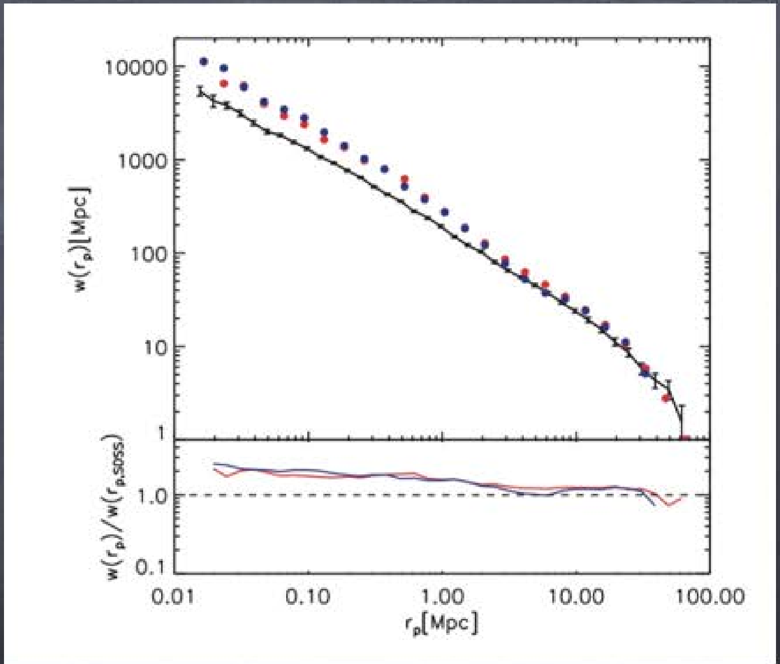
Environment removes the fuel for star formation in satellite galaxies. It is the predominant quenching mechanism in satellite galaxies

Positions of orphans



Environment removes the fuel for star formation in satellite galaxies. It is the predominant quenching mechanism in satellite galaxies

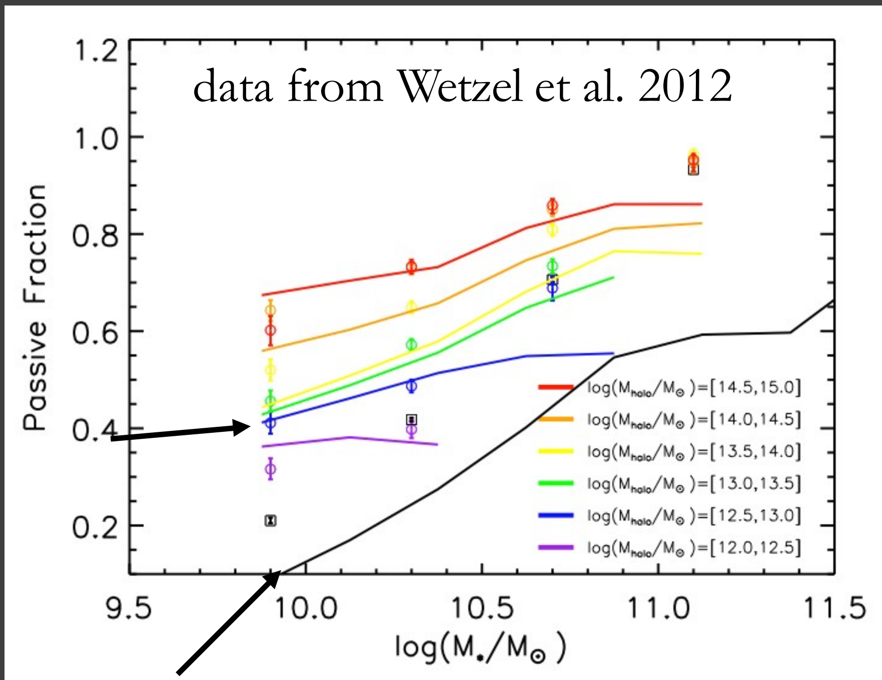




Environment removes the fuel for star formation in satellite galaxies. It is the predominant quenching mechanism in satellite galaxies

AGN and Environment Quenching

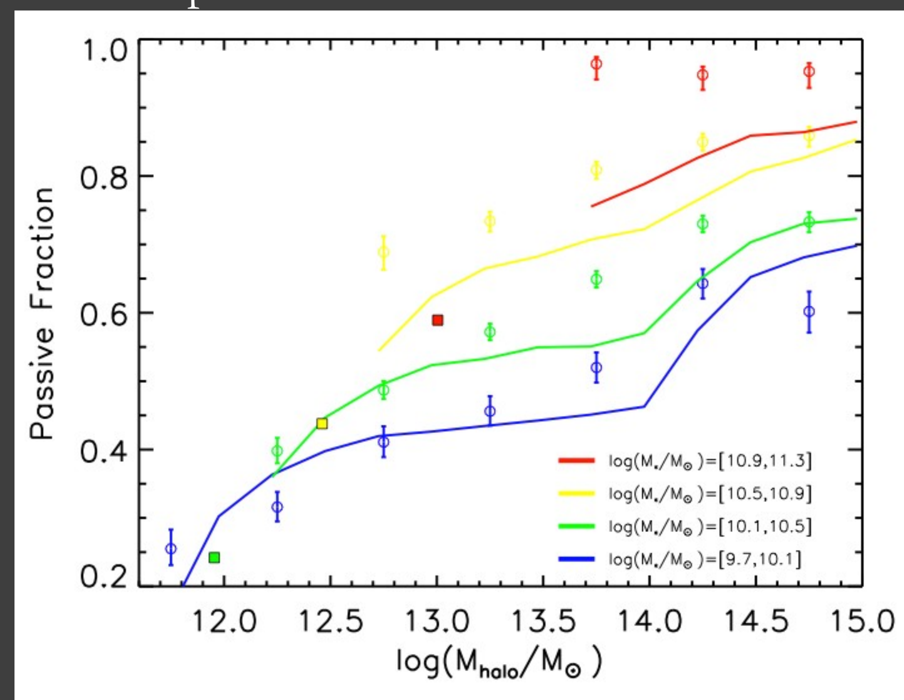
passive fraction vs stellar mass



higher quenched fractions for higher higher stellar masses and denser environments

- massive galaxies quenched due to AGN
- most low mass galaxies are star-forming centrals
- 40% of low mass galaxies are satellites of which ~50% are quenched (20% quenched low mass)

passive fraction vs halo mass



Galaxy Formation in the Planck Cosmology IV; Henriques, White, Thomas, et al.; 2017

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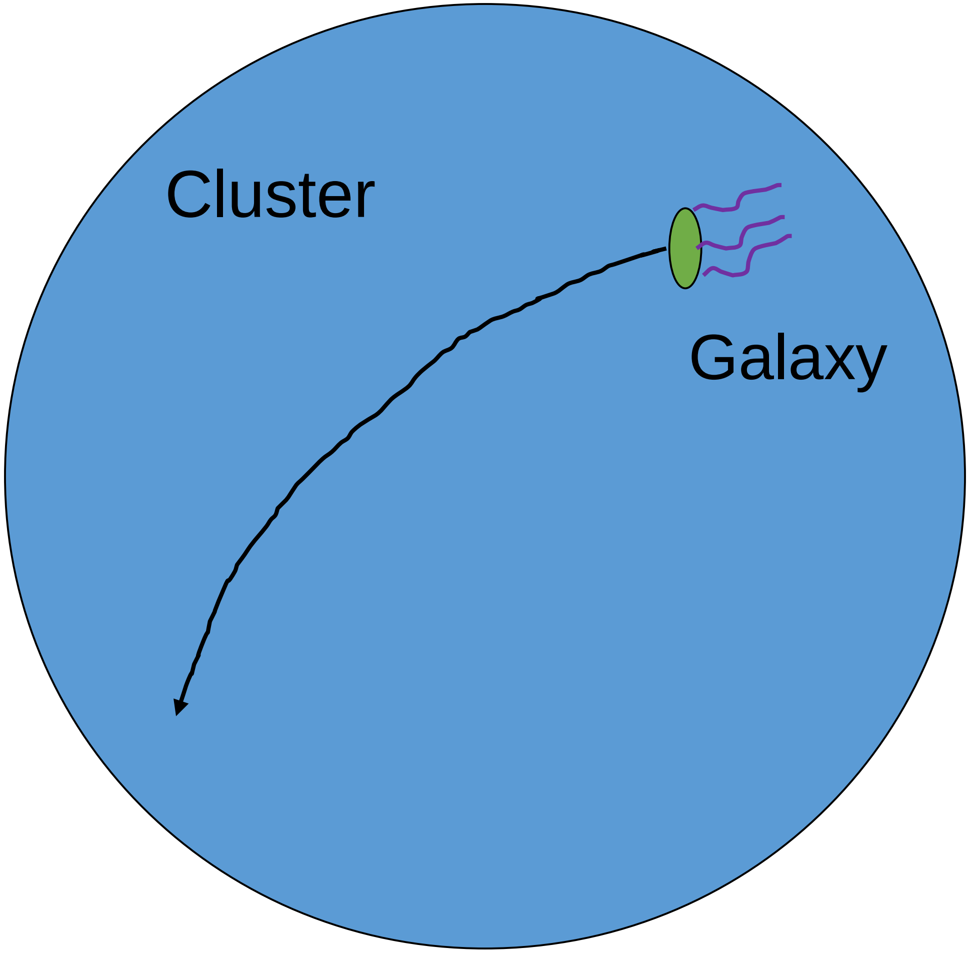
Gas-related environment effects on cluster galaxies = ram pressure stripping = gas stripping = ICM stripping



General idea: ICM head wind strips galaxy' s gas.
Does it work? Yes!

$P_{ram} \sim g\, \Sigma_{gas}$ *(Gunn&Gott 72)*

$P_{ram} \sim P_{ICM} \sim P_{ISM}$

Gas stripping – the devils in the details

Most simple idea: Object in a wind, head wind

Shape factor: sphere / disk / inclination angle
Variation of head wind / ram pressure during cluster passage

consens
us

For disk galaxies:

huge dynamic range in gas T, ρ, spatial and time scales

Proper SF and stellar feedback

remains
hard

Turbulent ISM, ICM, bulk motions in ICM

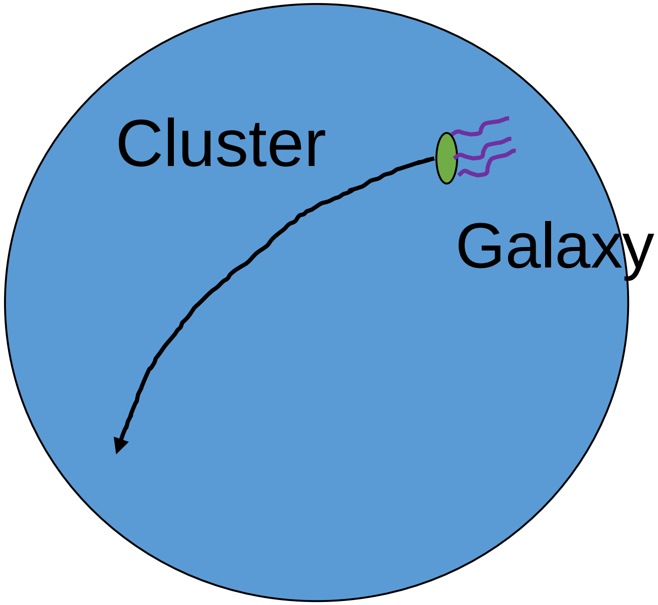
Magnetic fields in ICM, in ISM

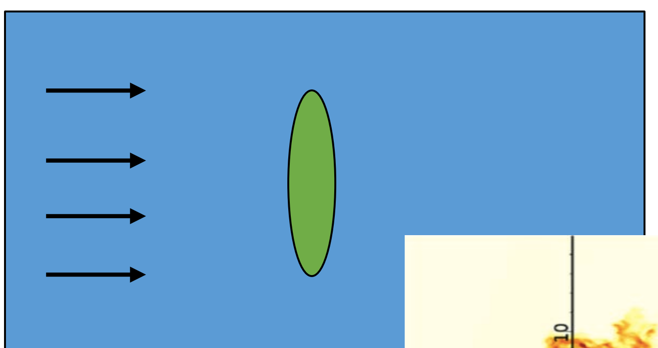
"Gas model" for ICM? Hydro/MHD/Kinetic code or ???, two-temperature? Mixing?

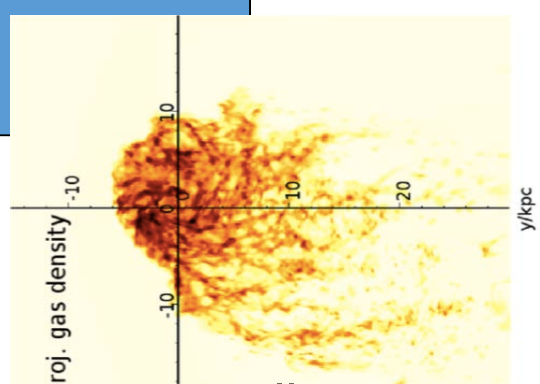
Proper radiative transfer to heat and cool the cool gas embedded in hot ICM

Proper radiative transfer to make mock observations

Idealized simulations





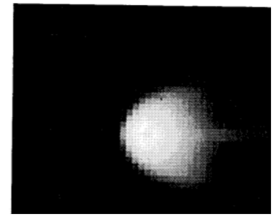
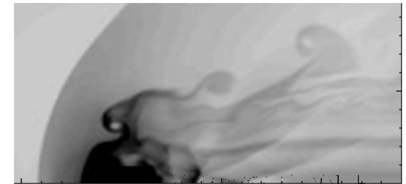


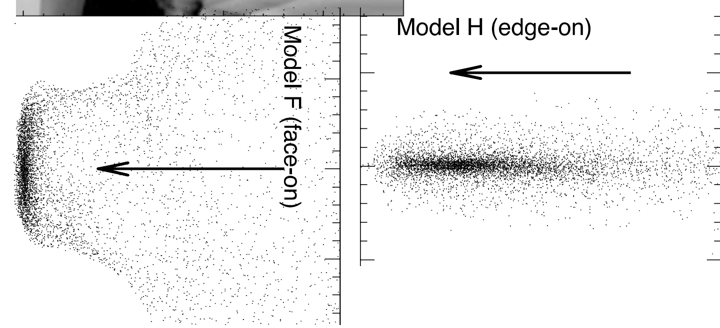
Roediger+ 2014

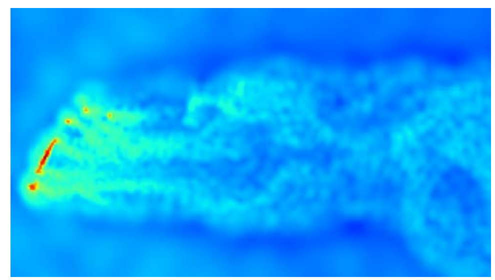
- Single/few galaxies
- Non-cosmological
- Choose the physics implemented, well controlled!
- Manual initial conditions (DM, stellar, gas, ICM wind, …)
- Scan parameter space
- Can be high resolution

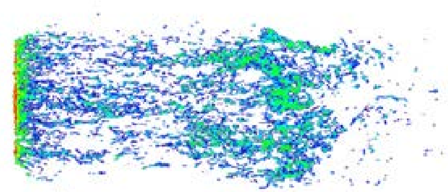
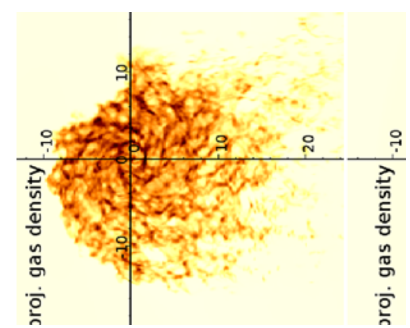
Consensus reached:

- Gas stripping works, truncated galactic gas, head-tail structure
- Gunn&Gott criterion / pressure comparison is decent prediction of *TRUNCATION* of galactic gas, almost independent of inclination
- Actual gas removal takes time – still-bound gas in tail region, fall-back





Takeda+84, Stevenson+99, Abadi+99, Schulz+01, Vollmer+ …, Innsbruck group, Tonnesen+ …, Roediger+…, and more!

Harder questions: impact on SF

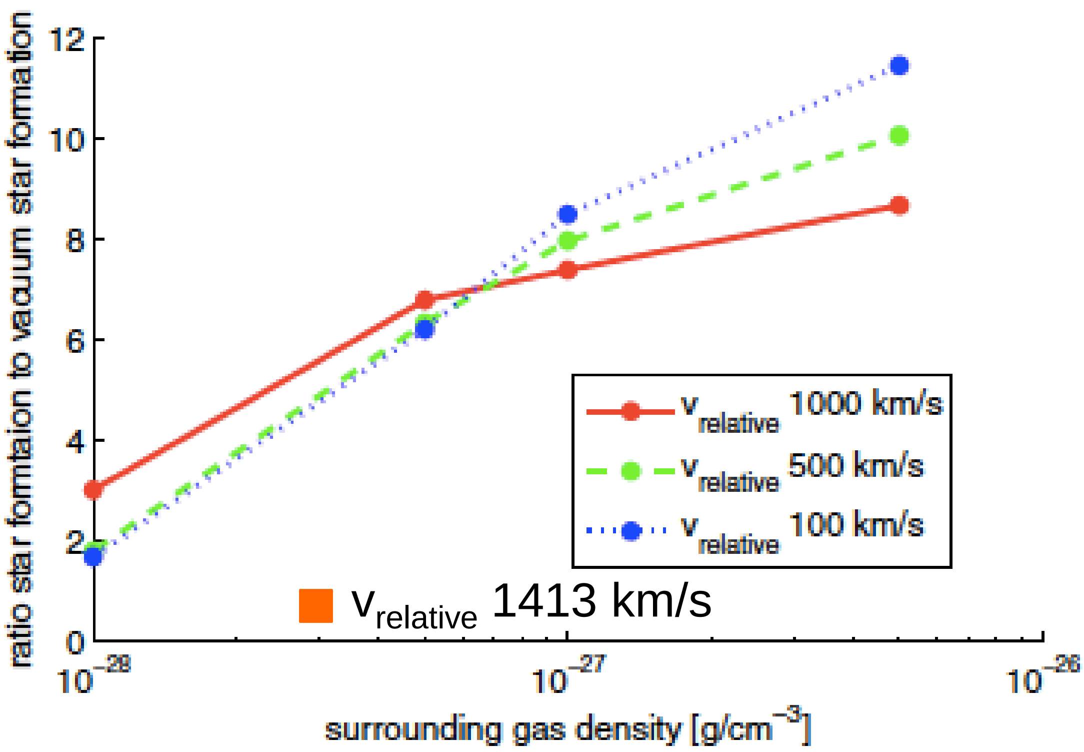


Fig. 5. Ratio of the star formation of the different simulations to the star formation integrated over 500 Myr for the isolated evolving galaxy.

Kapferer+ 2009:

Less massive disk
More gas-rich
Different resolution
Different SF recipe

Harder questions: impact on SF

Tonnesen	Kapferer	Roediger
No Enhancement.	Enhancement factor 2-10, A lot of SF in the tail	Strong enhancement of gas that is stripped immediately afterwards
AMR	SPH	AMR
cells in disk~$5x10^7$	particles in disk: $2x10^5$	cells in disk~$5x10^6$
Mass refine: 4900 M_{sun}	particle Mass: $3.4x10^4$ M_{sun}	Fully refine to 30 kpc
cooling: 300 K	cooling: 10^4 K	cooling: 10^4 K
T_{SF}: $1.1x10^4$ K	T_{SF}: 10^6 K	T_{SF}: $1.5x10^4$ K
ρ_{SF}: 3.85 x 10^{-25} g cm^{-3}	ρ_{SF}: ~7 x 10^{-26} g cm^{-3} (?)	ρ_{SF}: 3. x 10^{-24} g cm^{-3}

Caution

consider resolution and star formation recipes

Tonnesen	Kapferer	Roediger
AMR	SPH	AMR
cells in disk~5×10^7	particles in disk: 2×10^5	cells in disk~5×10^6
Mass refine: 4900 M_{sun}	particle Mass: 3.4×10^4 M_{sun}	Fully refine to 30 kpc
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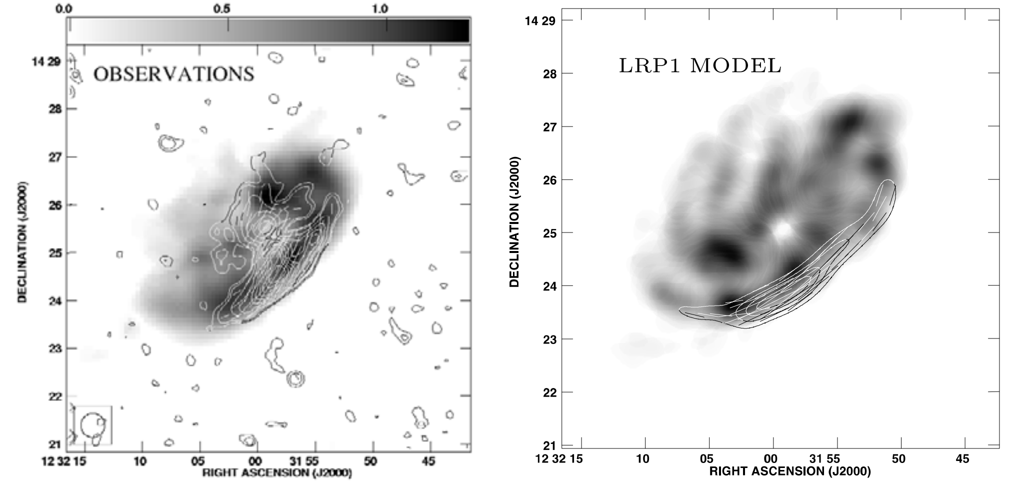
ρ_{SF}: 3.85 x 10^{-25} g cm^{-3}	ρ_{SF}: ~7 x 10^{-26} g cm^{-3} (?)	ρ_{SF}: 3. x 10^{-24} g cm^{-3}

Although SF in the disk will also depend on the gas surface density profiles assumed,
Kapferer sees much more SF in the tail!

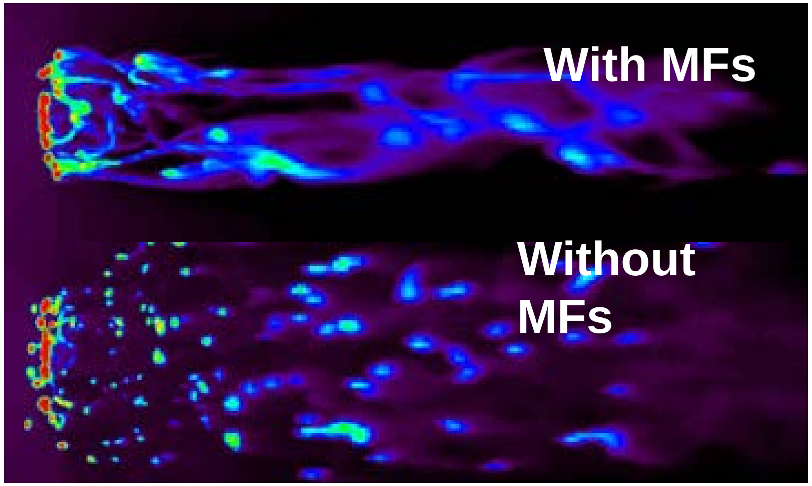
Harder questions: Magnetic fields

- MFs in ICM, in galaxy
- Polarisation of galactic MFs on front edge

Vollmer, Otmianowska-Masur



- Draping of ICM MFs, protects tail from fragmentation (idealised initial conditions)



Ruszkowski+ 14

Caution

Caution must be taken when posing questions and interpreting results!

Generalizations of "How RPS affects galaxies" are dangerous!!

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The underlying numerical and physical ingredients

Cosmological

Gravity

MHD

Uniform Volume

Sims for

Galaxy Physics

The underlying numerical and physical ingredients

Cosmological

Gravity

MHD

Uniform Volume

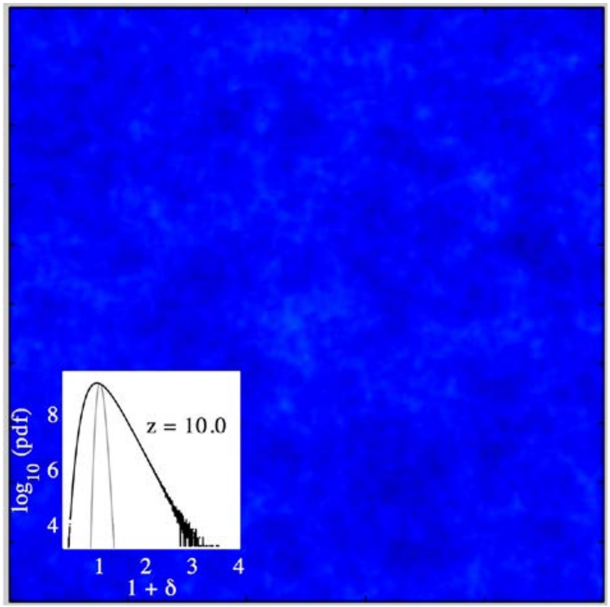
Sims for

Galaxy Physics

Working Assumption:
LCDM => Initial Conditions

Components:
Dark Matter (Ω_m articles)
Dark Energy (global evolution)

~250 Mpc (matter density projection)



Pillepich et al. 2008

The underlying numerical and physical ingredients

Cosmological

Gravity

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Uniform Volume

Sims for

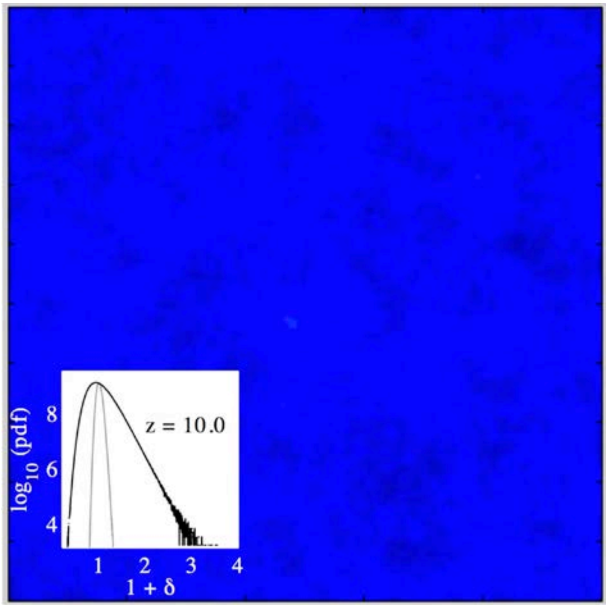
Galaxy Physics

Working Assumption:
LCDM => Initial Conditions

Components:
Dark Matter (Ω_m articles)
Dark Energy (global evolution)

Newtonian Equations
in an expanding universe
(non linear gravitational collapse)

~250 comoving Mpc (matter density projection)



Pillepich et al. 2008

The underlying numerical and physical ingredients

Cosmological

Gravity

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Uniform Volume

Sims for

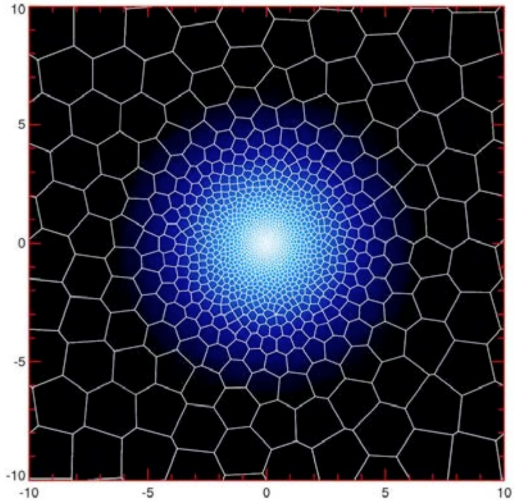
Galaxy Physics

Hydrodynamics:

+ **Gas** (Ω_b)

(H/He at the initial conditions)

Euler Equations



Rotating Gaseous Disk + Gas Mesh

Spoon in a coffee pot: mixing two fluids

Credits: Springel (code: AREPO)

The underlying numerical and physical ingredients

Cosmological

Gravity

MHD

Uniform Volume

Sims for

Galaxy Physics

Hydrodynamics:

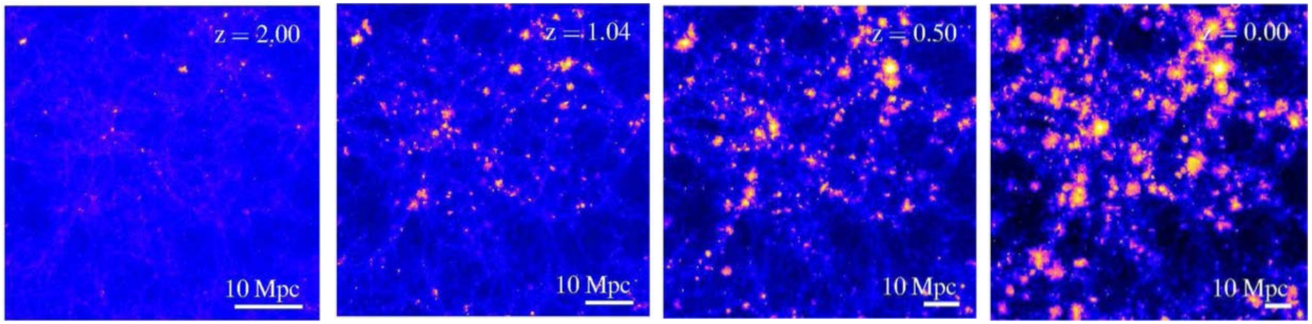
+ **Gas** ( )

(H/He at the initial conditions)

Euler Equations

+ **Seed Cosmic Magnetic Fields**

i.e. Maxwell Equations for perfect conductors



Magnetic Field Strength, amplified from an initial 10^-14 Gauss to a few microGauss

Pakmor et al. 2013, 2014, 2017

Marinacci et al. 2016

The underlying numerical and physical ingredients

Cosmological

Gravity

MHD

Uniform Volume

Sims for

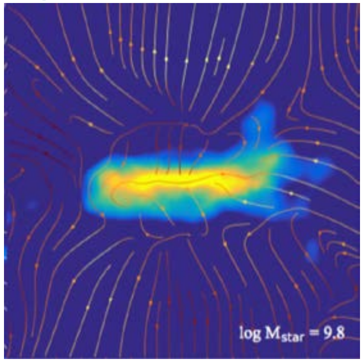
Galaxy Physics

+ STARS and BLACK HOLES

Formation and evolution of stars (SNIa, SNII, AGBs) & their pollution of the inter-stellar medium

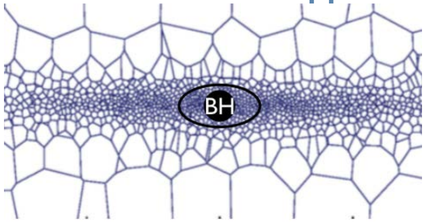
(H, He, C, N, O, Ne, Mg, Si, and Fe)

Feedback from stars => galactic outflows



Pillepich et al. 2017

Feedback from SMBHs => galactic outflows & suppression of SF



Cooling & Heating of the gas
(via tables and including collisional excitation, collisional ionization, recombination, dielectric recombination and free–free emission) + UV background + metal line cooling

....

The underlying numerical and physical ingredients

● = *particles*

Cosmological
Gravity
MHD
Uniform Volume
Sims for
Galaxy Physics

resolution elements

- ● DARK MATTER
- *GAS - cells*
- ● STARS
- ● BLACK HOLES

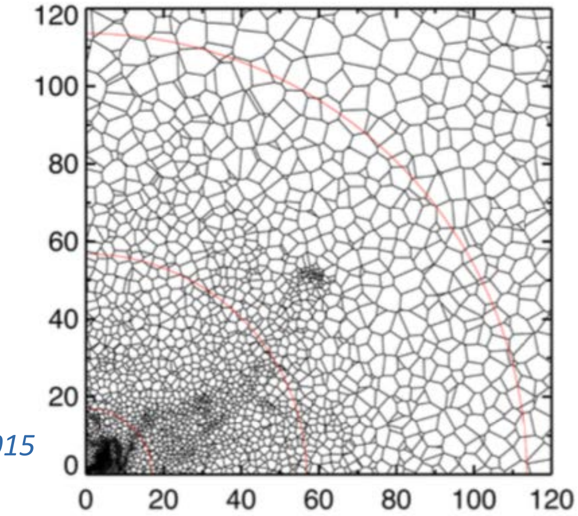
AREPO approach

Same resolution element mass across the whole box
(e.g. DM particles mass = ~10^6 Msun)

Full spatial and time resolution adaptivity

Thousands of galaxies and haloes!

Gas Mesh in a cosmological gas halo



Nelson et al. 2015

The underlying numerical and physical ingredients

Credits: Genel & Illustris Team

Cosmological

Gravity

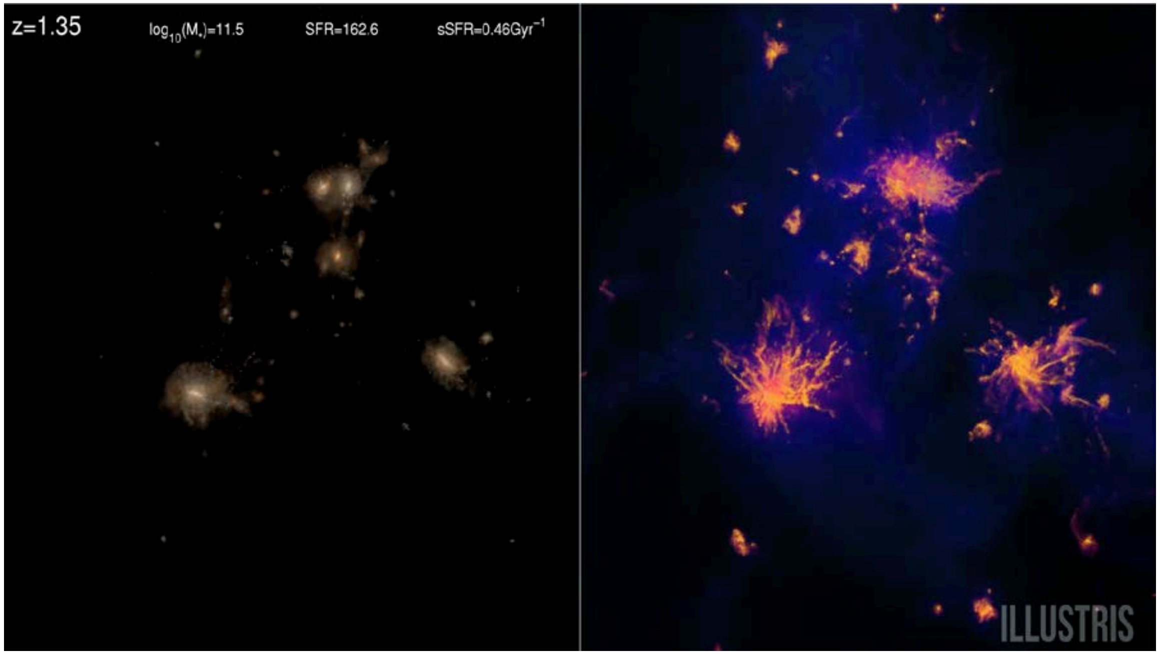
MHD

Uniform Volume

Sims for

Galaxy Physics

STELLAR LIGHT



GAS DENSITY

THE HIERARCHICAL GROWTH OF GALAXIES, GALAXY MERGERS, COSMIC GAS ACCRETION INTO HALOES, TIDAL AND RAM PRESSURE STRIPPING, DYNAMICAL FRICTION etc ARE ALL "EMERGING" PROCESSES IN SIMULATIONS LIKE ILLUSTRIS/TNG

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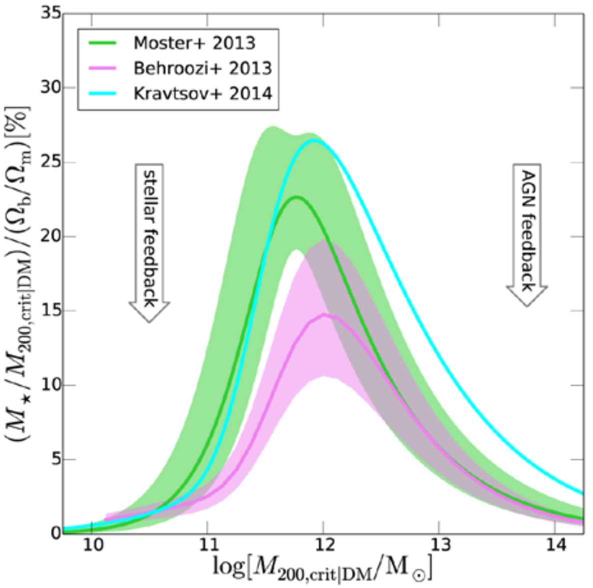
The original Illustris simulation:

- AREPO code (TreePM+Voronoi Hydro)
- 100 Mpc cosmological volume
- Resolution: 1 kpc (10^6 M_{sun} baryon)
- Galaxy mass range: > 10^9 M_{sun}
- Halo mass range: < 10^{14} M_{sun}
- ‘Comprehensive physical model’



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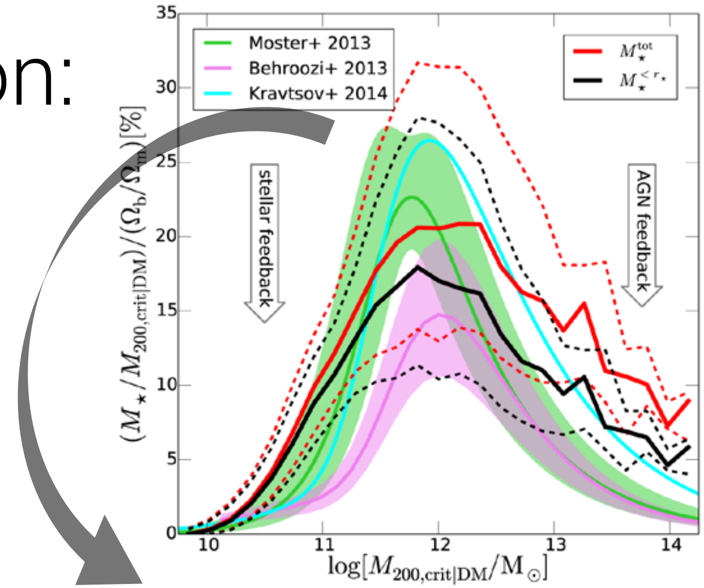
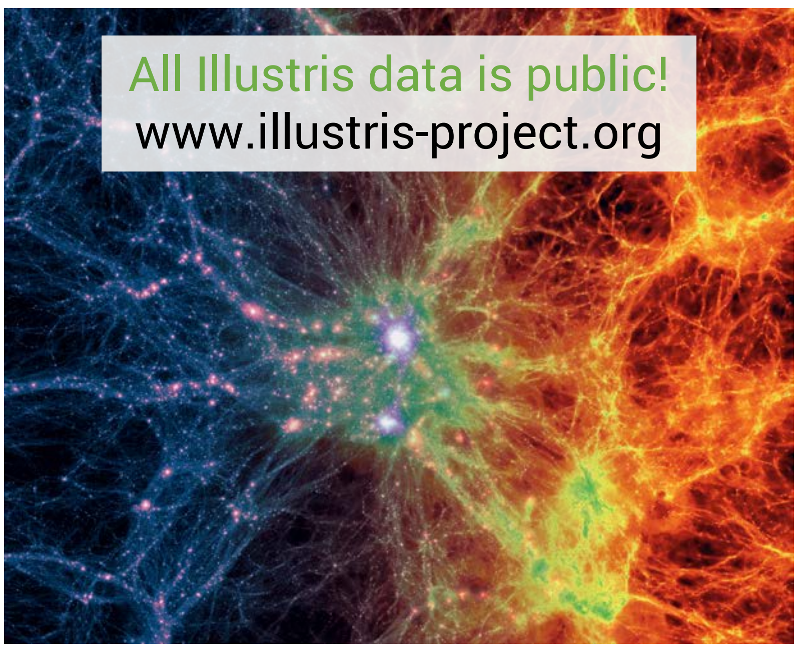
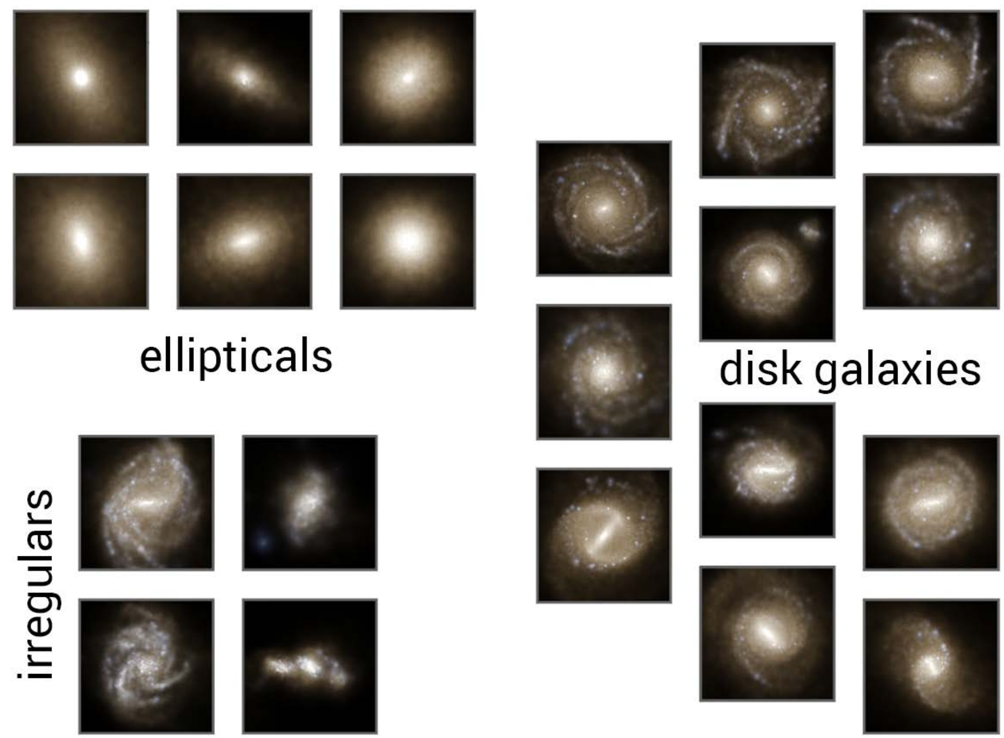






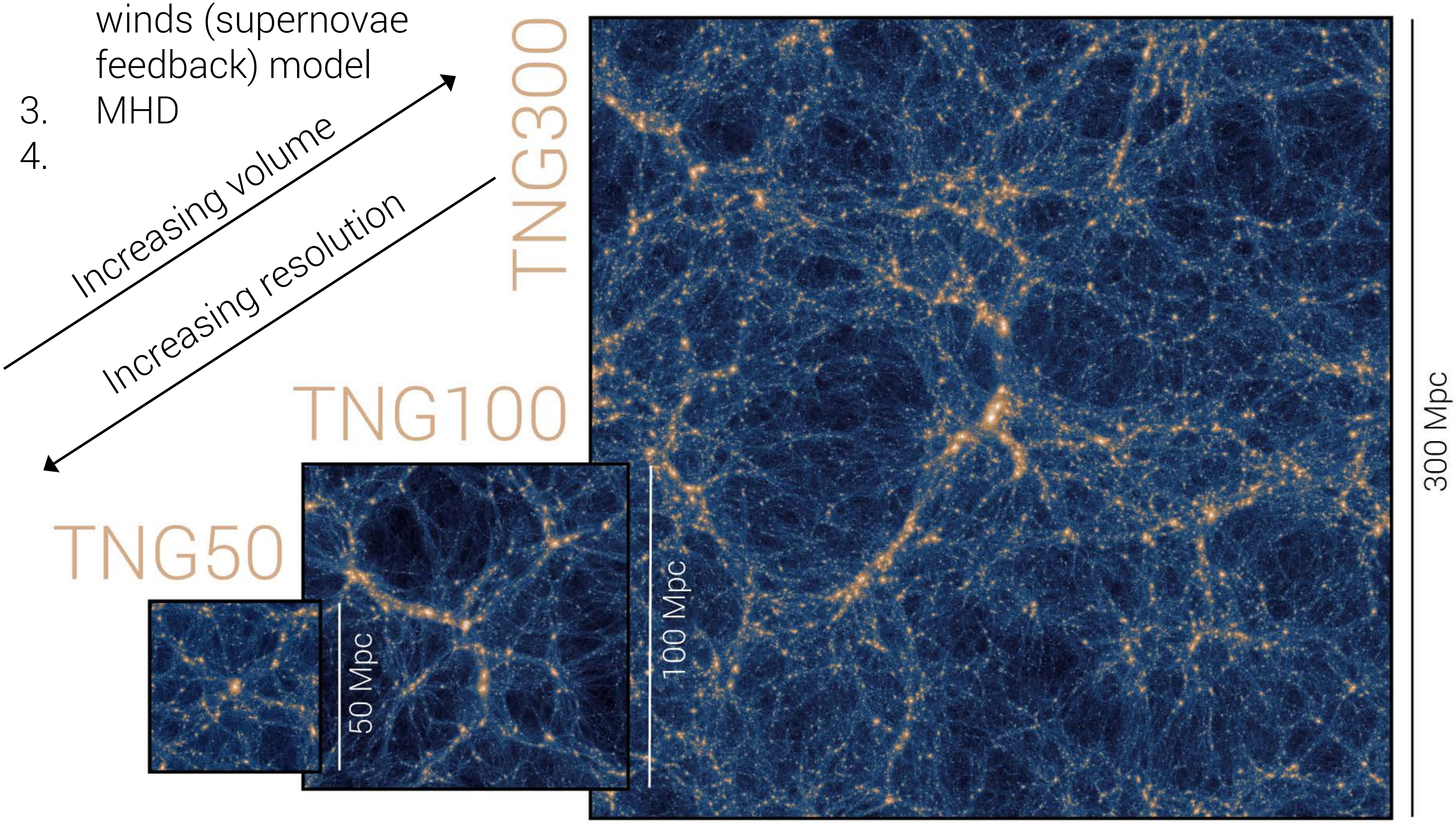
Mark Vogelsberger
Volker Springel
Shy Genel
Debora Sijacki
Paul Torrey
Dylan Nelson
Greg Snyder
Simeon Bird
Dandan Xu
Lars Hernquist

IllustrisTNG
‘the next generation’

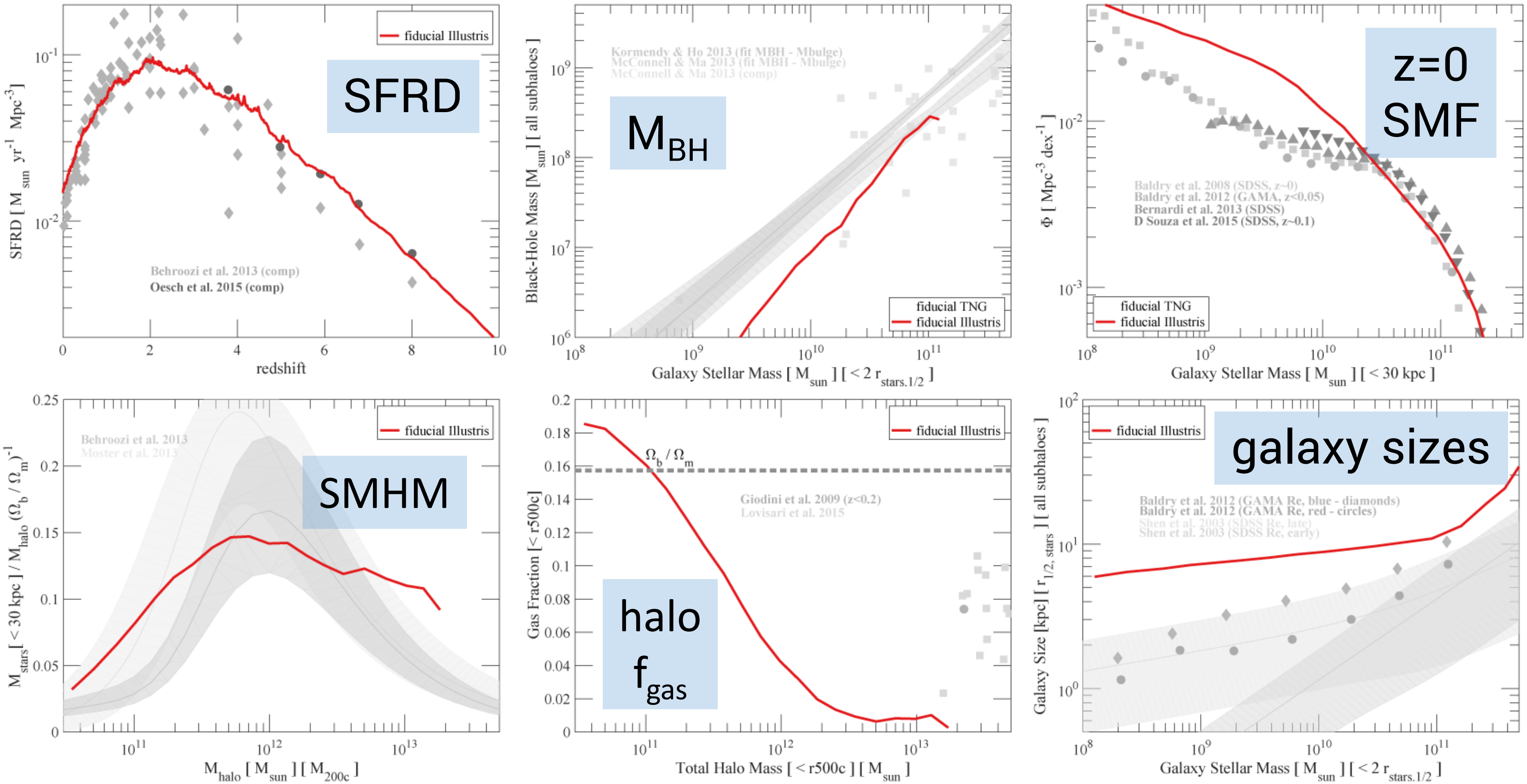
Volker Springel
Lars Hernquist
Annalisa Pillepich
Ruediger Pakmor
Dylan Nelson
Rainer Weinberger
Federico Marinacci
Jill Naiman
Mark Vogelsberger
Shy Genel
Paul Torrey

Takeaway differences:

1. New BH feedback model: kinetic wind
2. Revised galactic winds (supernovae feedback) model
3. MHD
4.

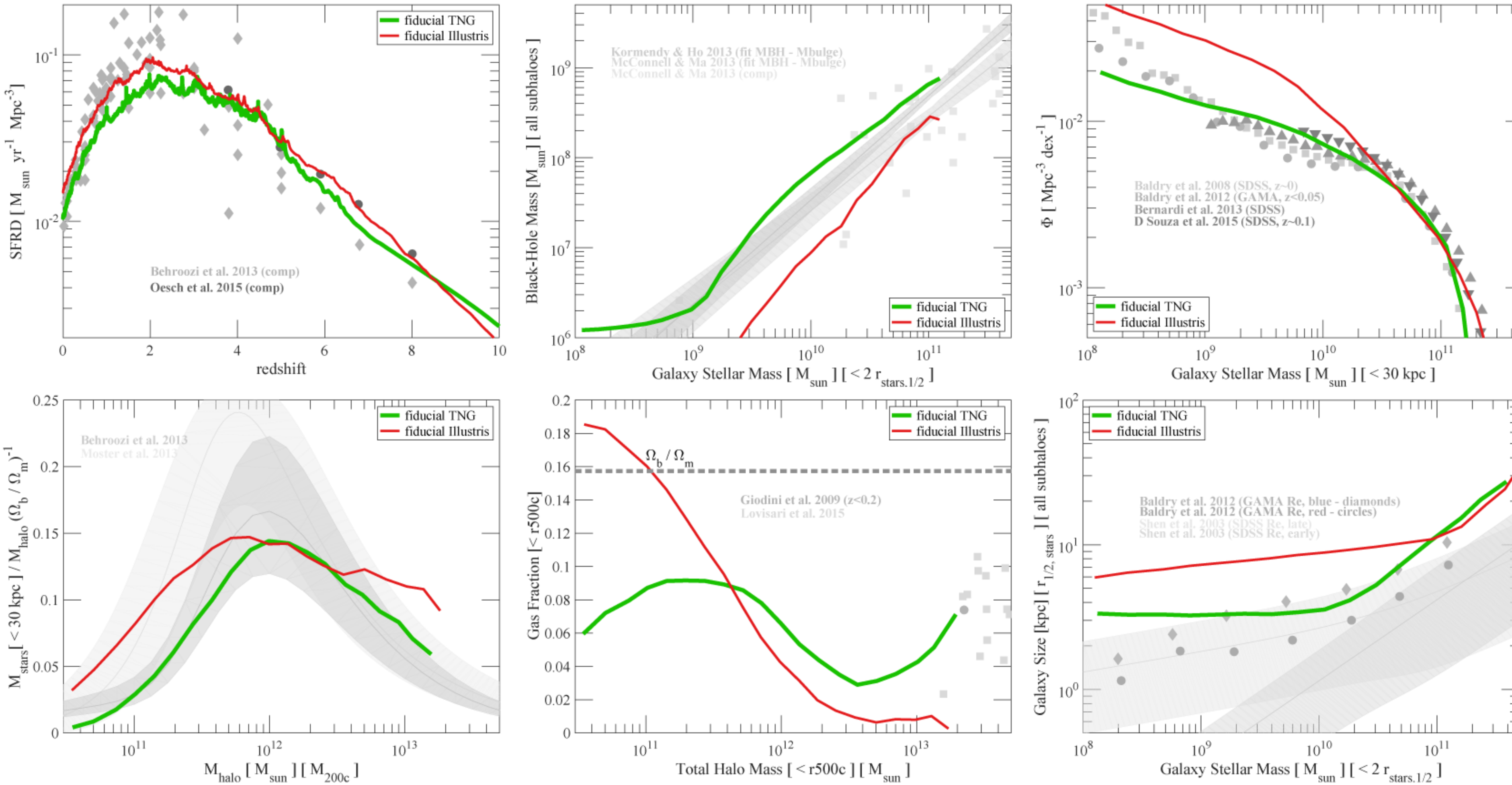


IllustrisTNG: are the results realistic?



Pillepich et al. (2017) – TNG 'methods' paper

IllustrisTNG: are the results realistic?

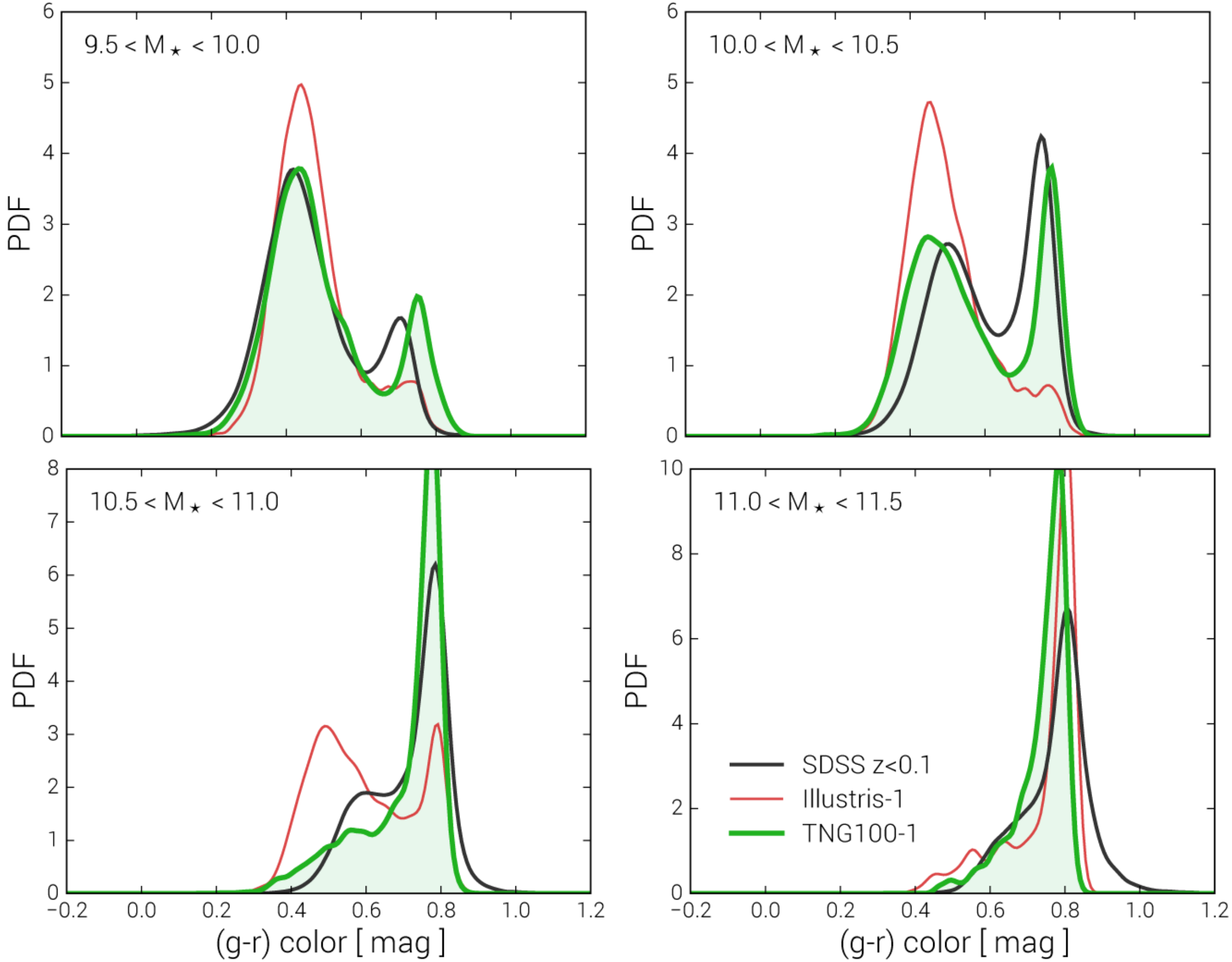


Pillepich et al. (2017) – TNG 'methods' paper

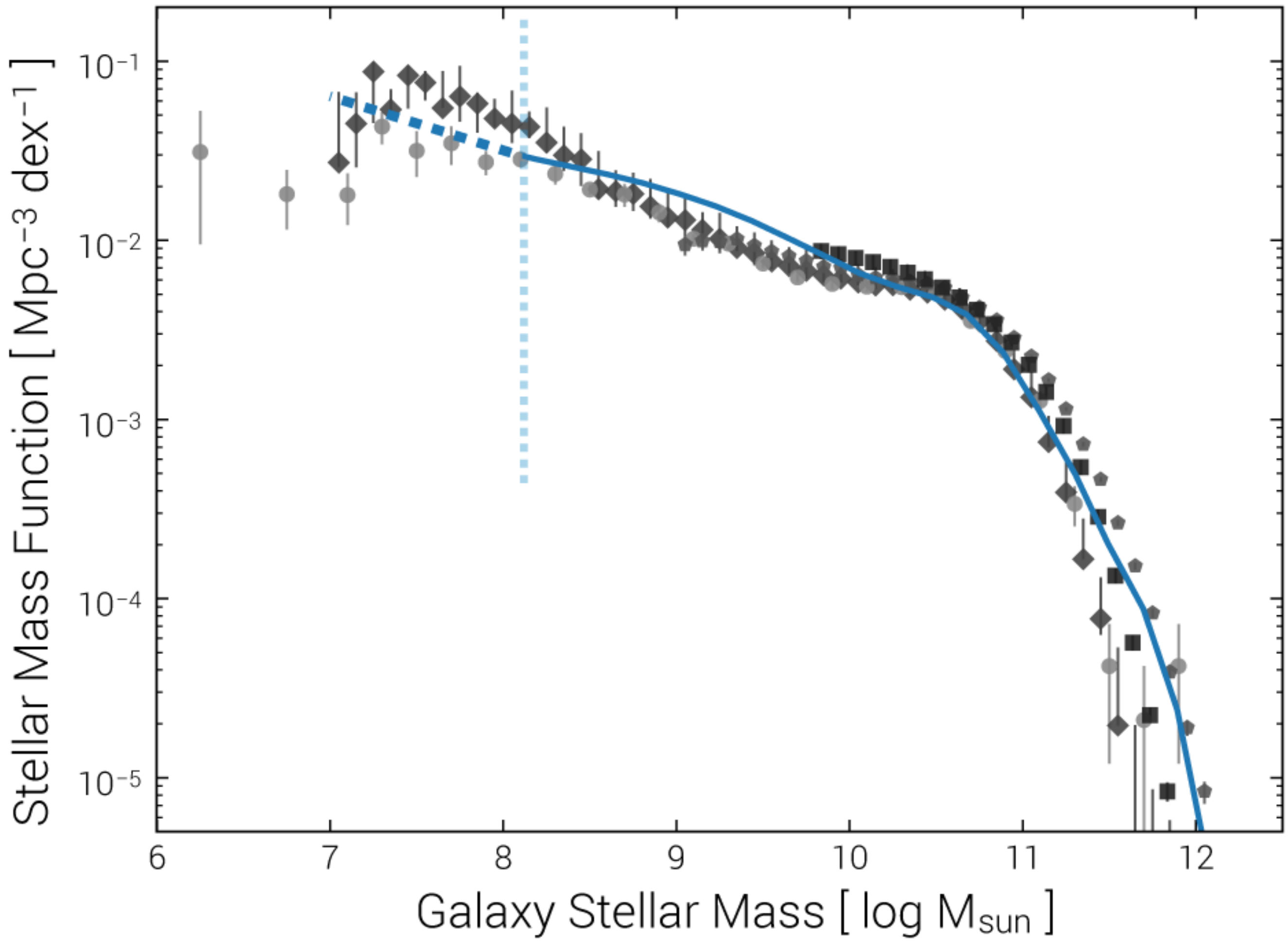
IllustrisTNG: are the results realistic?

Galaxy color bimodality vs. SDSS (z ~ 0)

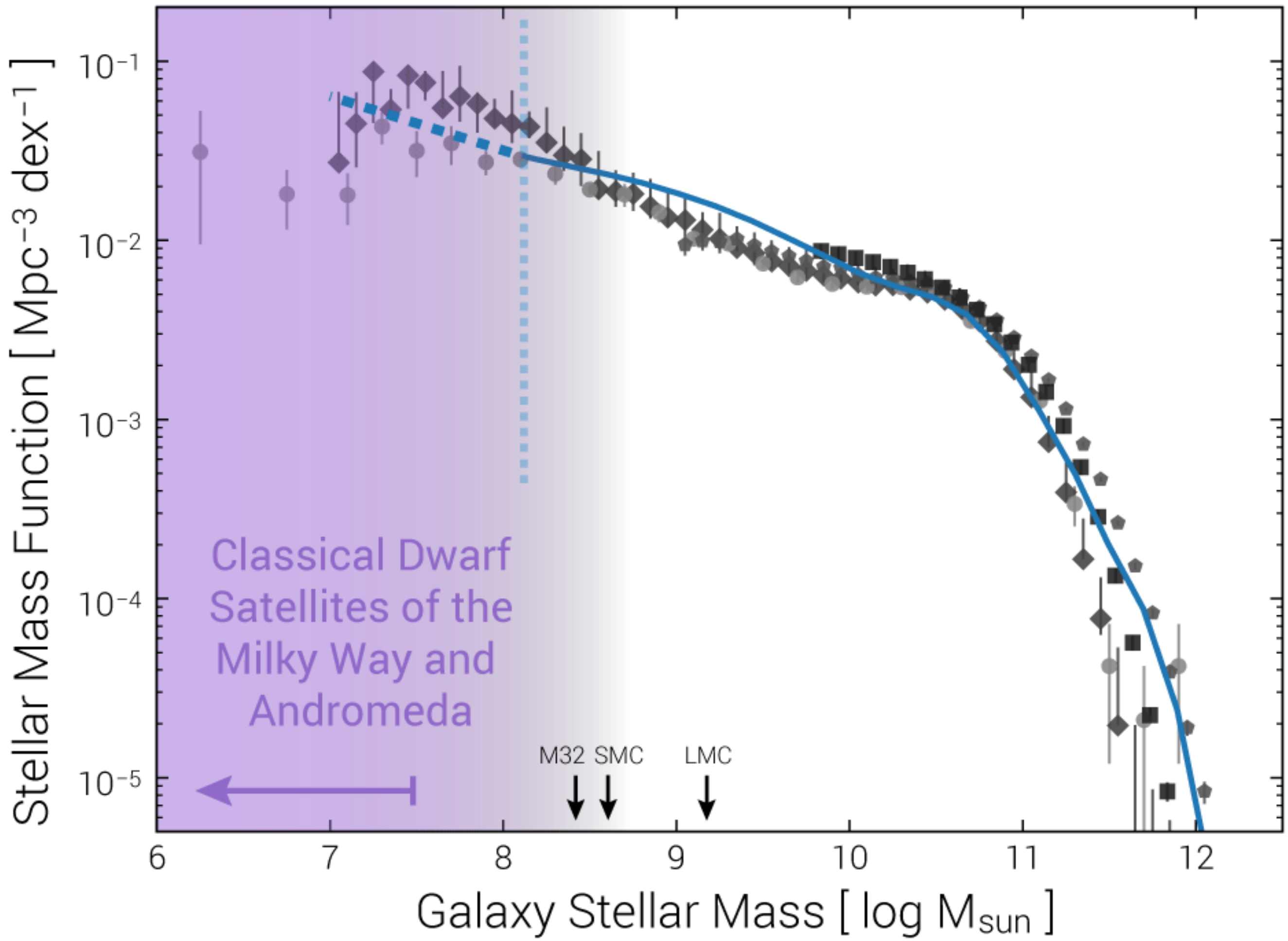
Nelson et al. (2017)



Galaxy evolution in Groups and Clusters: Prospects with TNG50

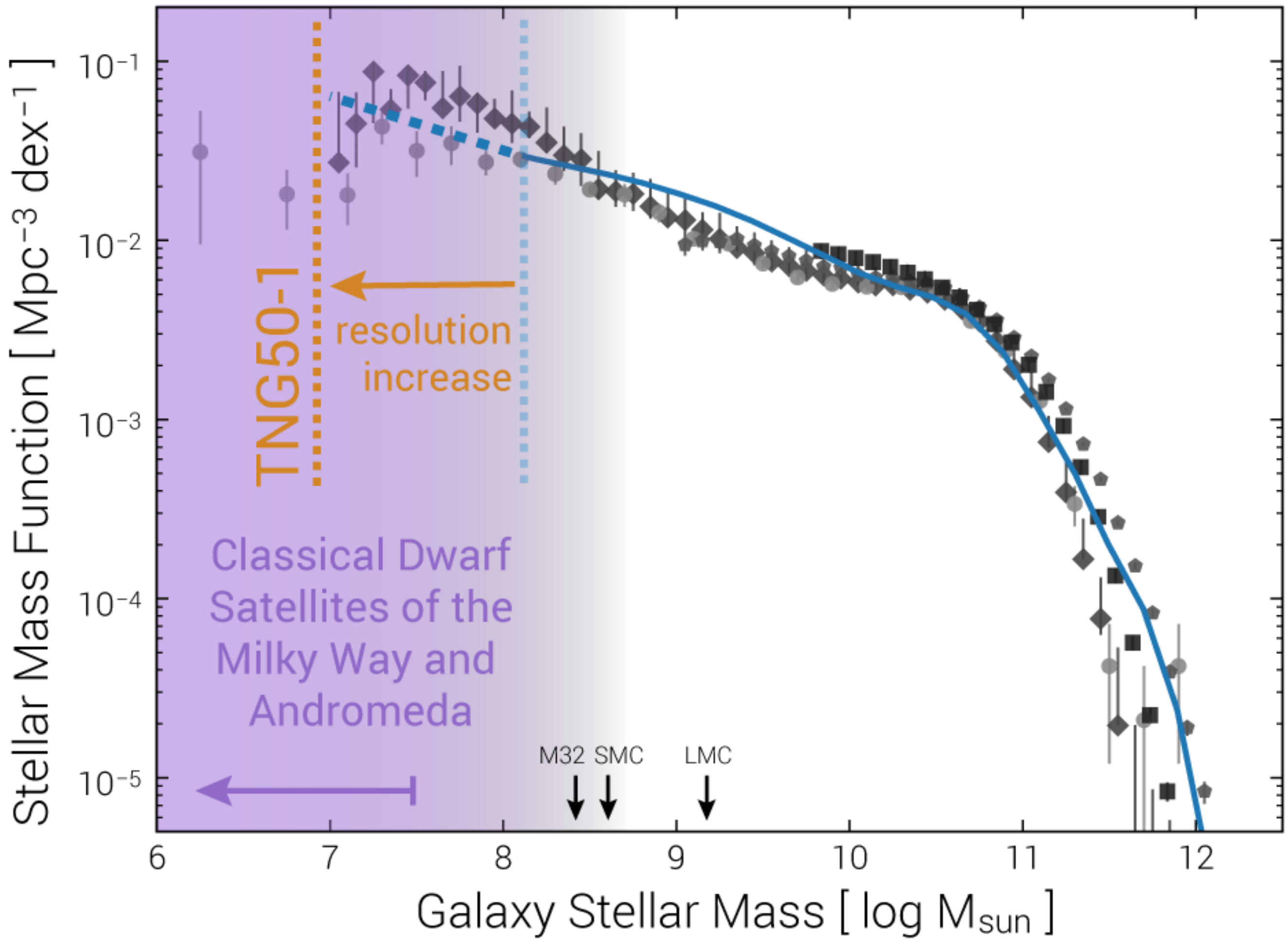


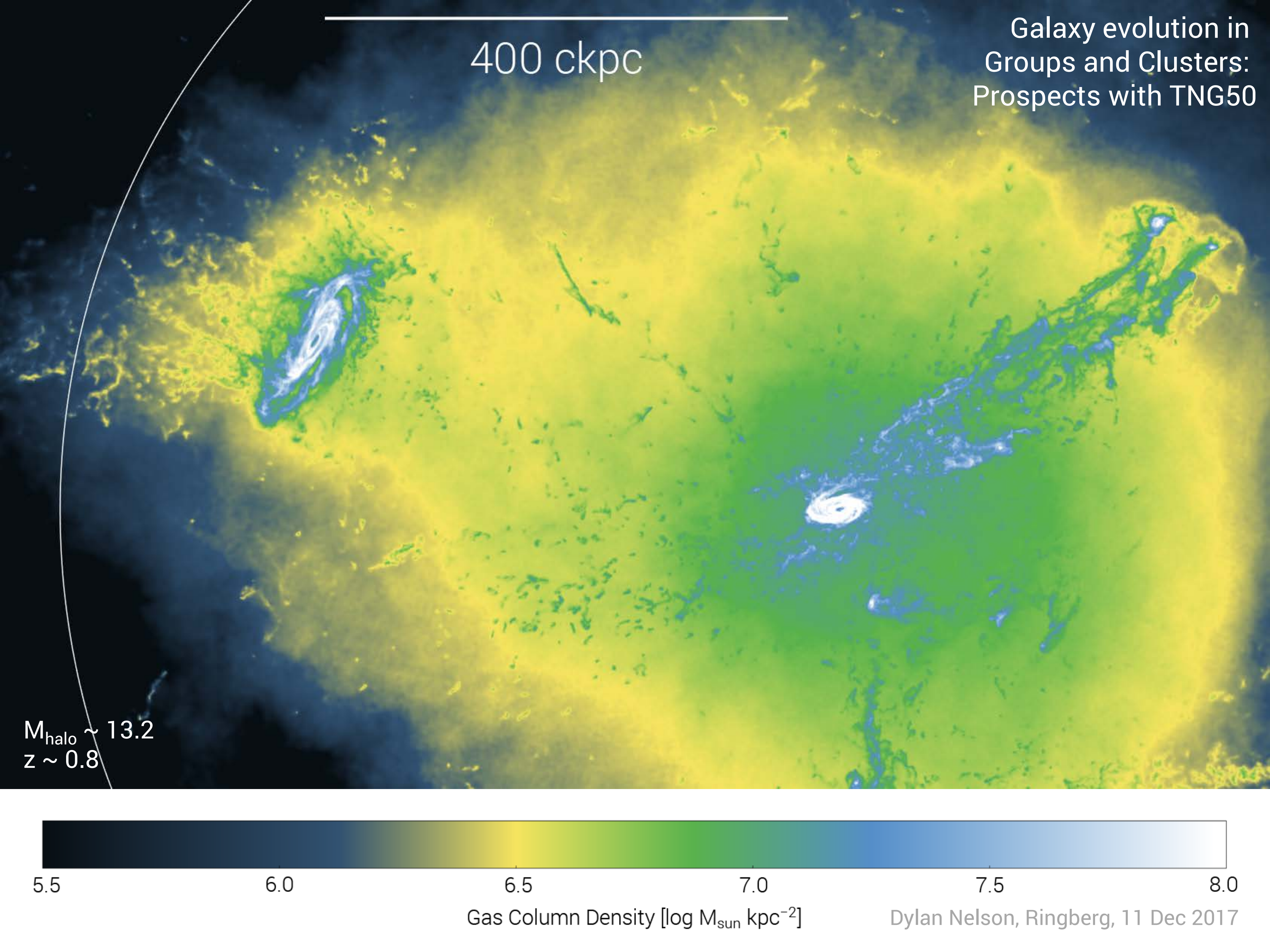
Galaxy evolution in Groups and Clusters: Prospects with TNG50

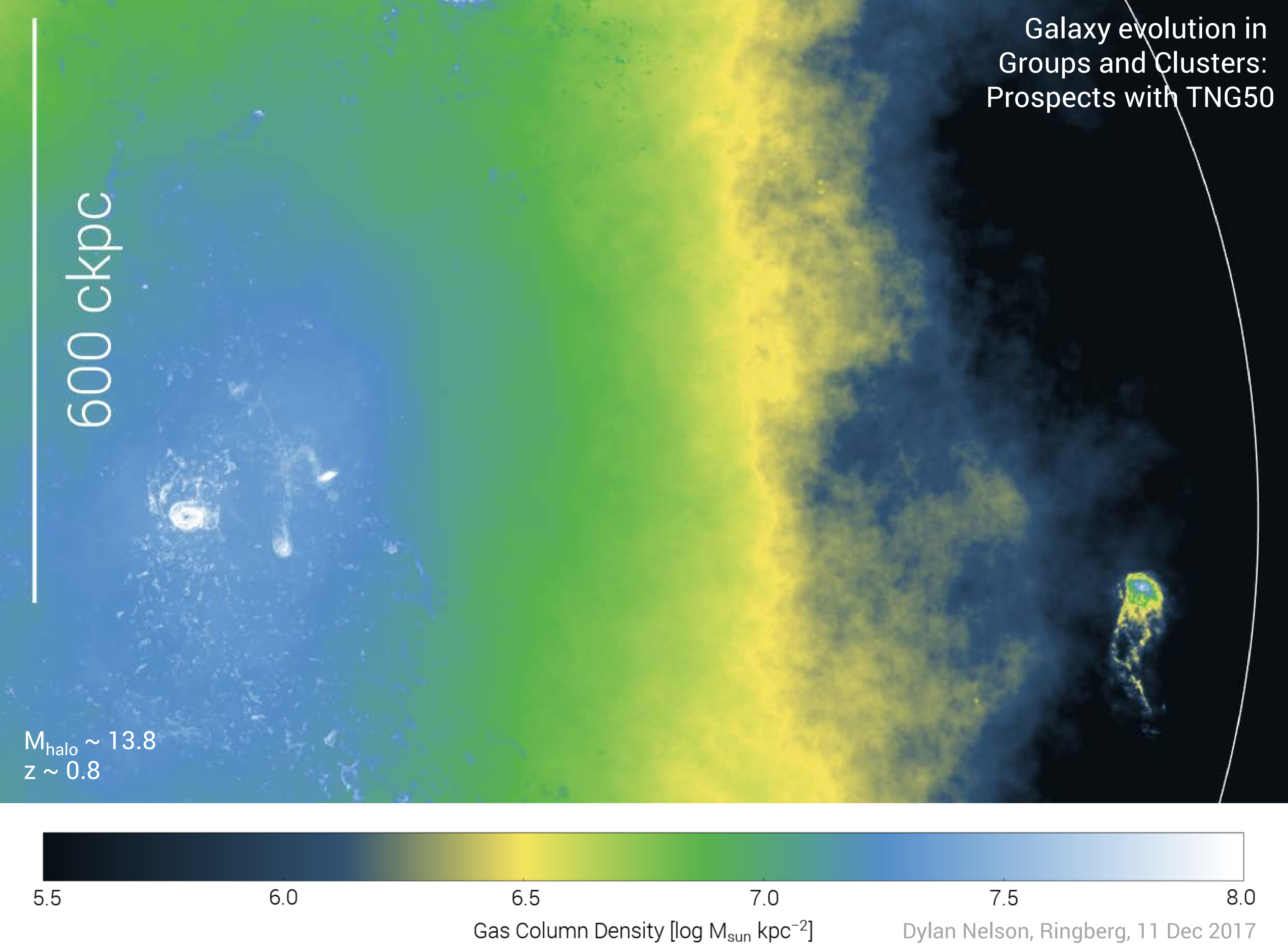


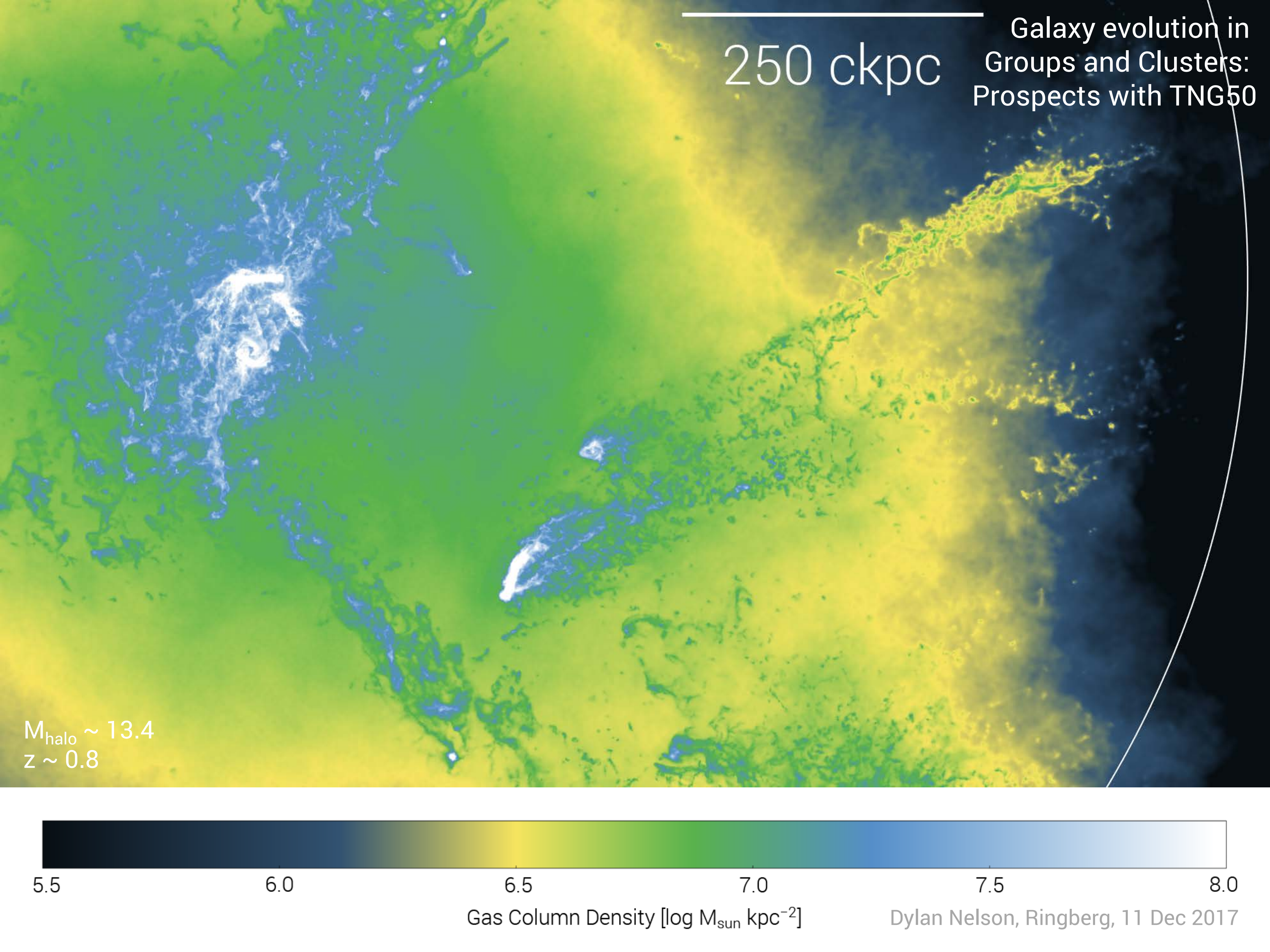
Dylan Nelson, Ringberg, 11 Dec 2017

Galaxy evolution in Groups and Clusters: Prospects with TNG50




400 ckpc
Galaxy evolution in
Groups and Clusters:
Prospects with TNG50
M_{halo} ~ 13.2
z ~ 0.8
5.5
6.0
6.5
7.0
7.5
8.0
Gas Column Density [log M_{sun} kpc^{-2}]
Dylan Nelson, Ringberg, 11 Dec 2017


Galaxy evolution in
Groups and Clusters:
Prospects with TNG50
600 ckpc
M_halo ~ 13.8
z ~ 0.8
5.5
6.0
6.5
7.0
7.5
8.0
Gas Column Density [log M_sun kpc^-2]
Dylan Nelson, Ringberg, 11 Dec 2017

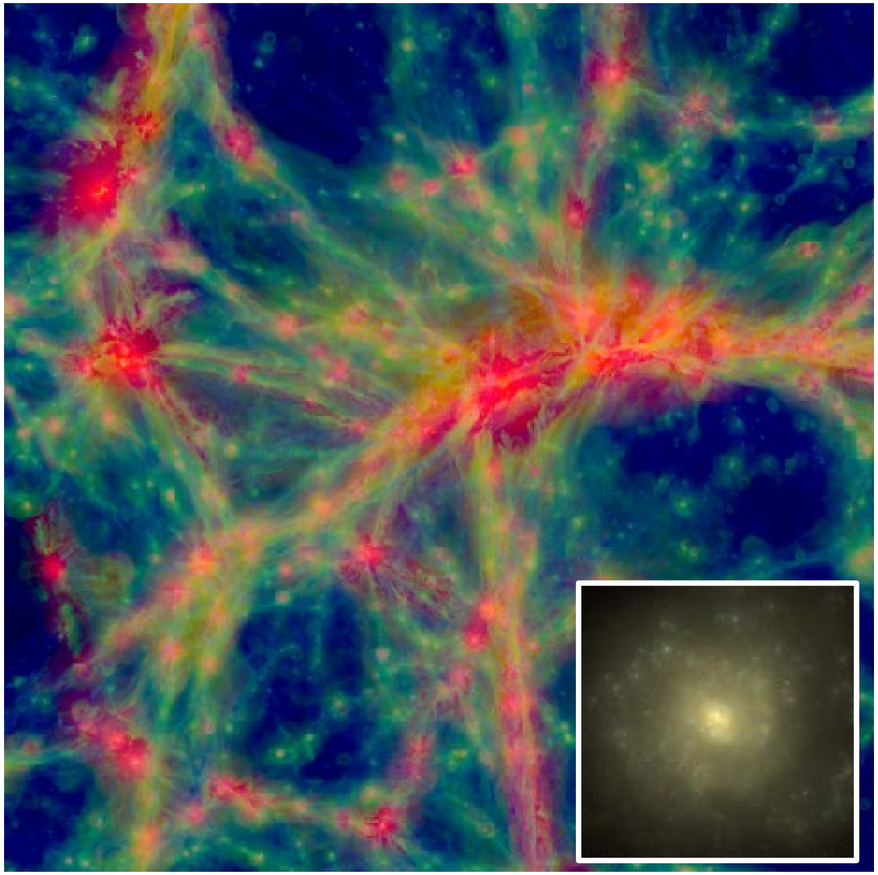

Galaxy evolution in
Groups and Clusters:
Prospects with TNG50
250 ckpc
M_halo ~ 13.4
z ~ 0.8
5.5
6.0
6.5
7.0
7.5
8.0
Gas Column Density [log M_sun kpc^-2]
Dylan Nelson, Ringberg, 11 Dec 2017

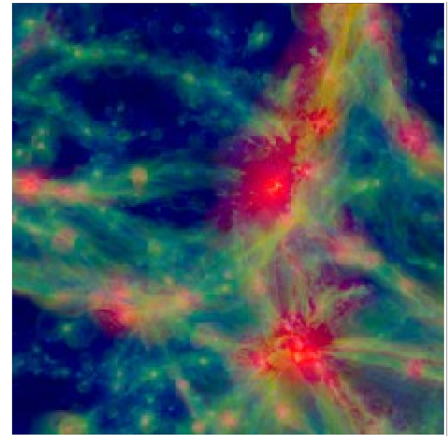
Review of [theoretical] models

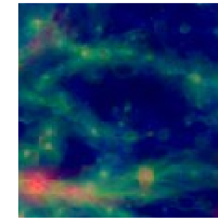
- Stephanie Tonnesen & Elke Roediger
  - Idealized & wind-tunnels
- Bruno Henriques
  - SAMs
- Annalisa Pillepich
  - Cosmological hydro sims
- Dylan Nelson
  - … in the context of Illustris / TNG
- Yannick Bahé
  - … in the context of EAGLE
- Collective discussion

The EAGLE simulations

Schaye et al., 2015
Crain et al., 2015







Largest simulation: (100 cMpc)³

- Resolution of ~2 x 10^6 $M_\odot$ (baryons)
- One “Reference" simulation model
- Some (poor) clusters

Many additional 50 and 25 cMpc simulations

- Expore variations in supernova / BH feedback and other subgrid parameters.
- Some groups in 50 cMpc volume

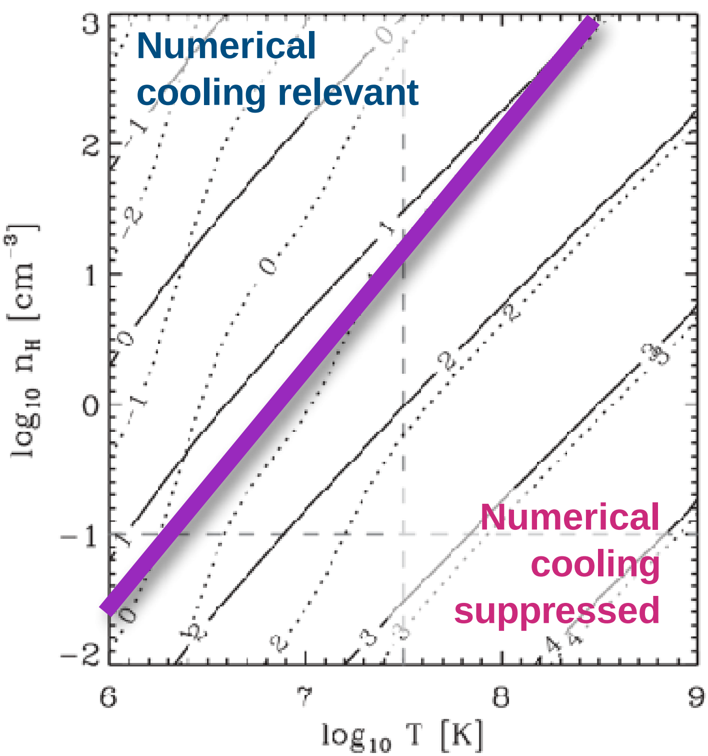
+ spin-off simulations of galaxy clusters

—> See talks on Thursday and Friday

Supernova feedback in EAGLE

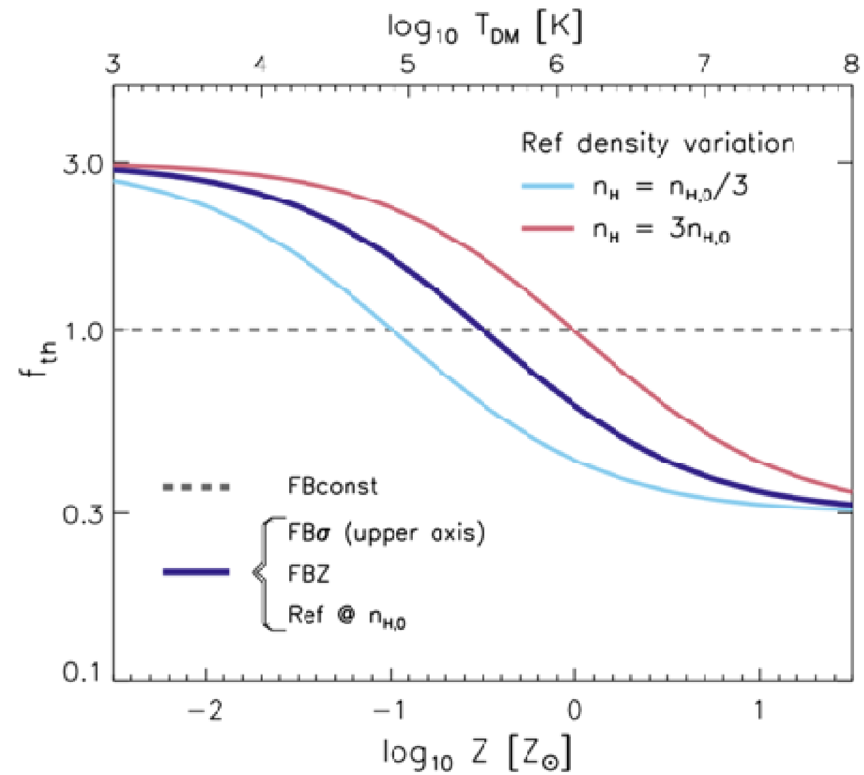
log (t_{cool} / $t_{cross, kernel}$)

(Dalla Vecchia & Schaye, 2012)



SN efficiency scalings

(Crain et al., 2015)



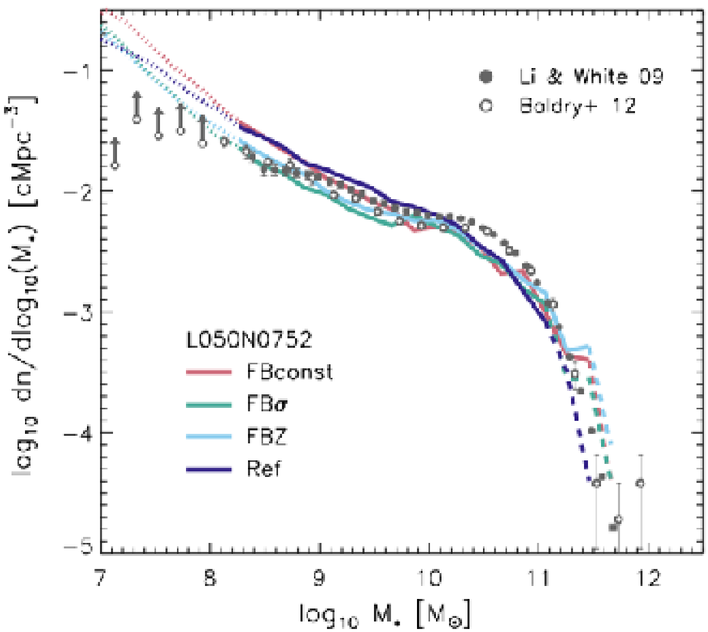
Thermal stochastic feedback

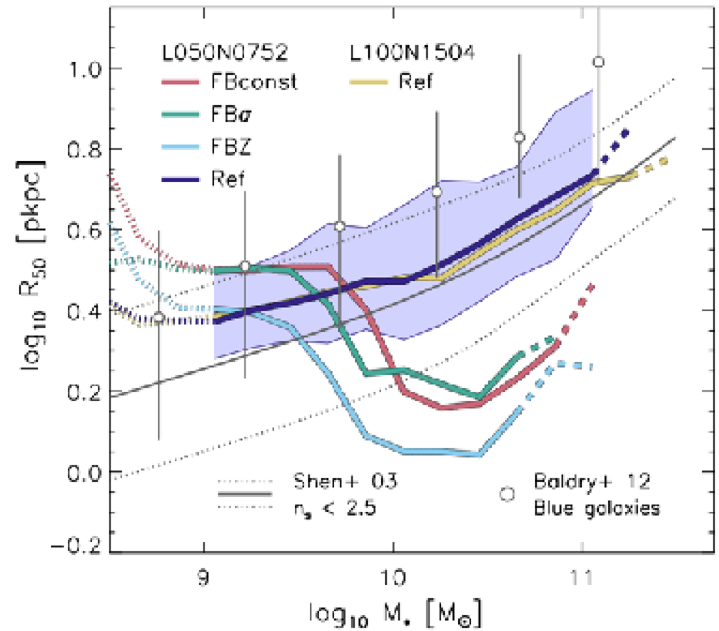
Energy is stored up until gas can be heated to a temperature that is high enough for numerical cooling to be suppressed

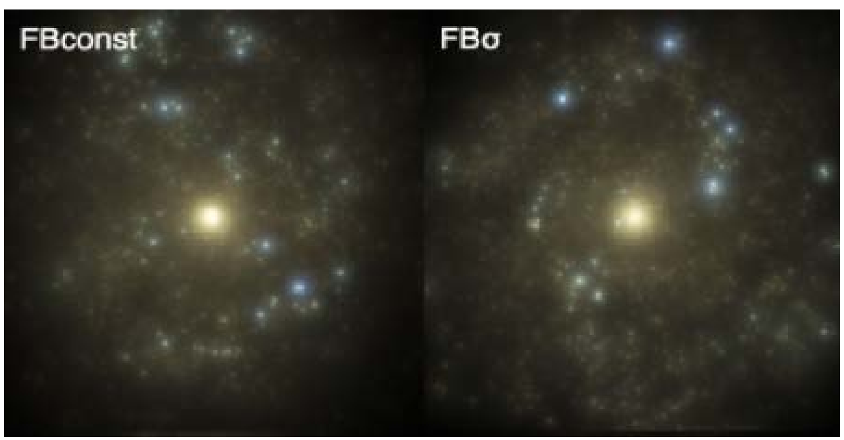
Feedback efficiency scaled with local quantities

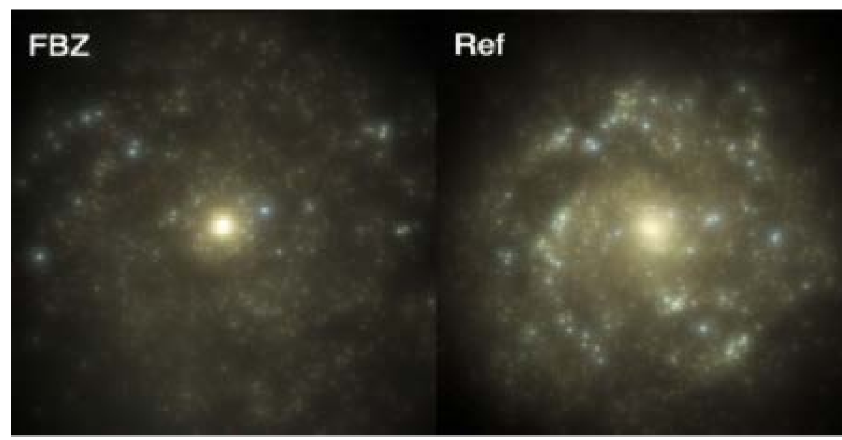
To overcome remaining numerical cooling, feedback is made more efficient in high-density gas. Variation with metallicity models physical cooling losses.

Supernova feedback in EAGLE





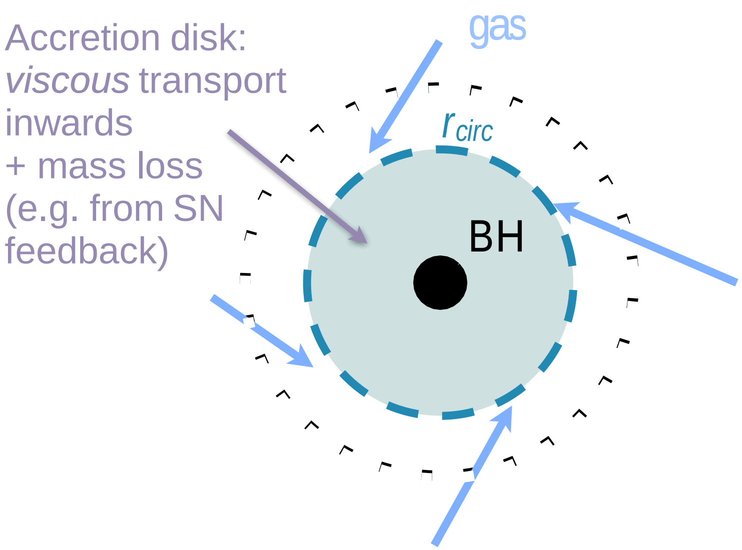




GSMF not sensitive to feedback scaling, but **galaxy sizes** are

Crain et al., 2015

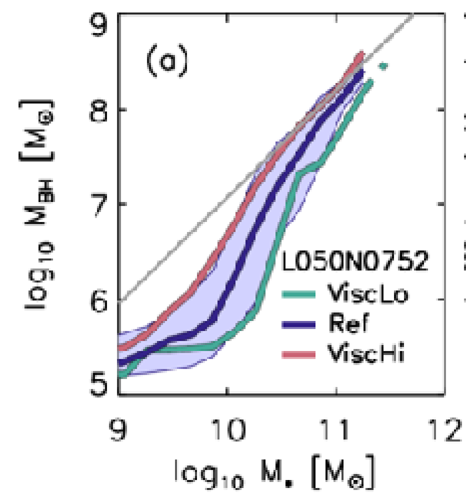
EAGLE BH growth and feedback



Modified Bondi accretion limit:

$$\dot{m}_{\rm accr} \sim \frac{M_{\rm disc}}{t_{\rm visc}} \sim \frac{\dot{m}_{\rm Bondi}\, t_{\rm Bondi}}{t_{\rm visc}}$$

$$\frac{t_{\rm Bondi}}{t_{\rm visc}} = \frac{r_{\rm Bondi} c_{\rm s}^{-1}}{C_{\rm visc}[r_{\rm Bondi} V_\phi]^3 [G M_{\rm BH}]^{-2}} = \frac{1}{C_{\rm visc}} \frac{c_{\rm s}^3}{V_\phi^3}.$$



Free parameter Cvisc

Describes unresolved structure of accretion disc (default $C_{\rm visc}$ = 2π).

Higher $C_{\rm visc}$: *lower* viscosity, delayed BH growth

Rosas-Guevara et al., 2015
Schaye et al., 2015
Crain et al., 2015

BH feedback:

10% of accreted mass converted to energy, with assumed 15% coupling efficiency to gas

Black hole feedback is stochastic (like SN)

But heating temperature is higher (default: **Δ**T = $10^{8.5}$ K) because gas density around black holes is typically higher than in SF regions.

Review of [theoretical] models

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- Bruno Henriques
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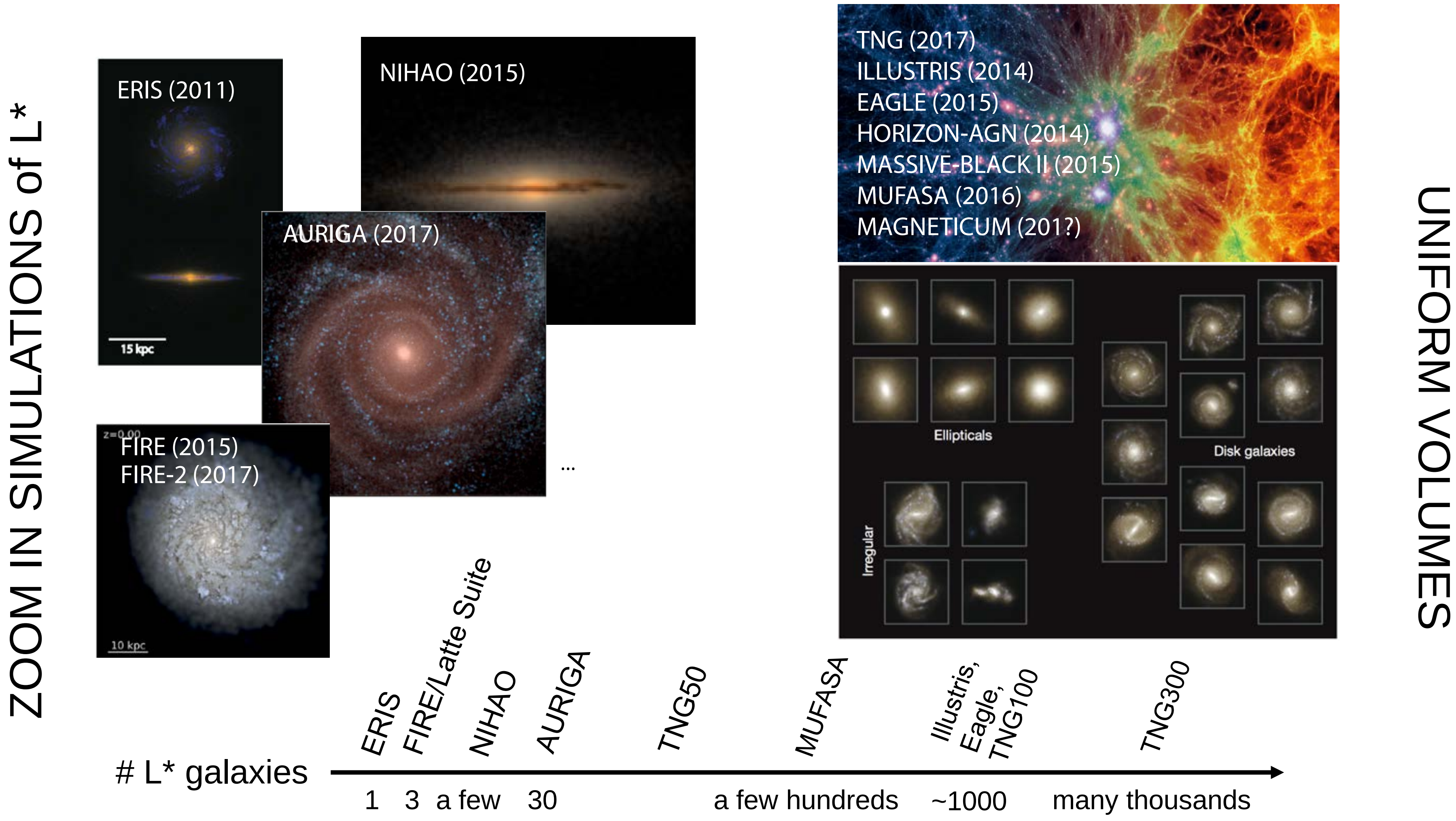
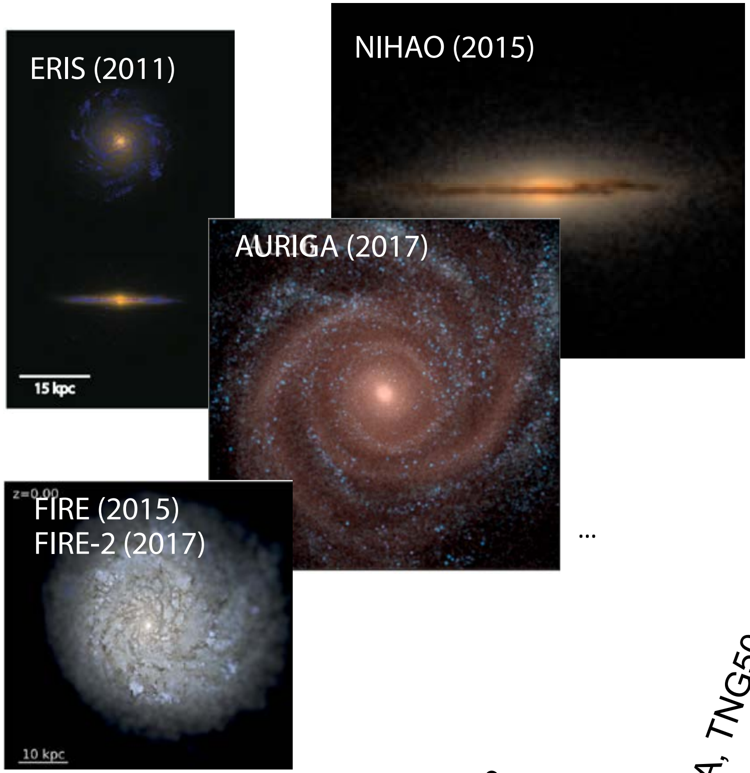
- Dylan Nelson
  - … in the context of Illustris / TNG
- Yannick Bahé
  - ... in the context of EAGLE
- Current landscape -> collective discussion

The Landscape of (Current) Cosmological (M)HD Simulations

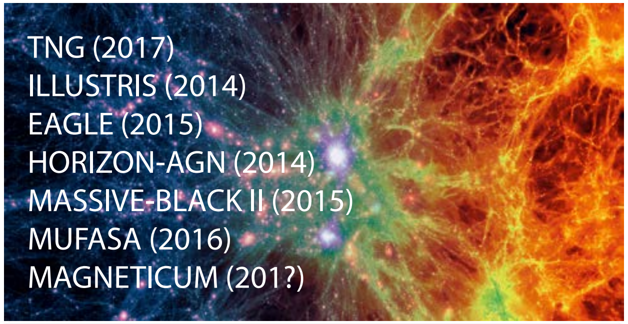


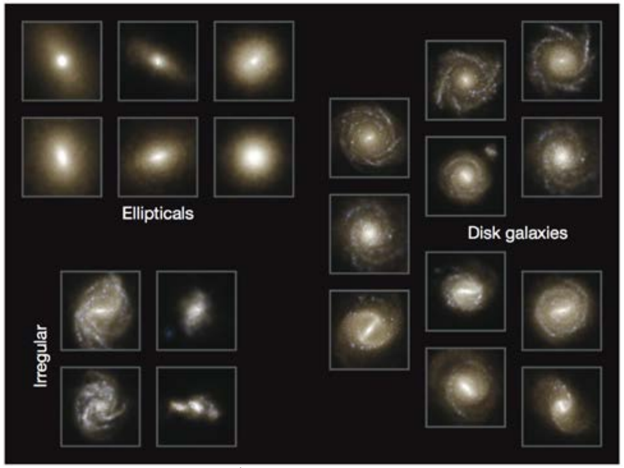
The Landscape of (Current) Cosmological (M)HD Simulations

ZOOM IN SIMULATIONS of L*



...





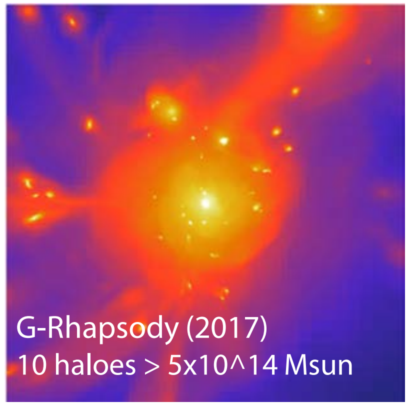
UNIFORM VOLUMES

resolution:
baryonic mass in Msun
(for L* sims)

FIRE-2	ERIS	AURIGA, TNG50	NIHAO	Illustris, Eagle TNG100	Mass-BlackII	MUFASA TNG300
~7e3	1e4	5e4	3e5	~1-2e6	~3e6	2e7

The Landscape of (Current) Cosmological (M)HD Simulations

ZOOM IN SIMULATIONS of CLUSTERS



Yonsei Clusters (2016)

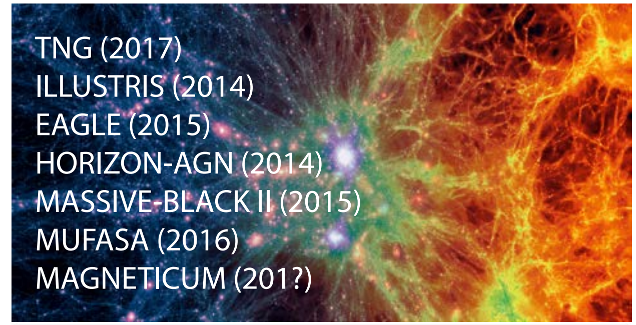
16 halos > 10^14 Msun

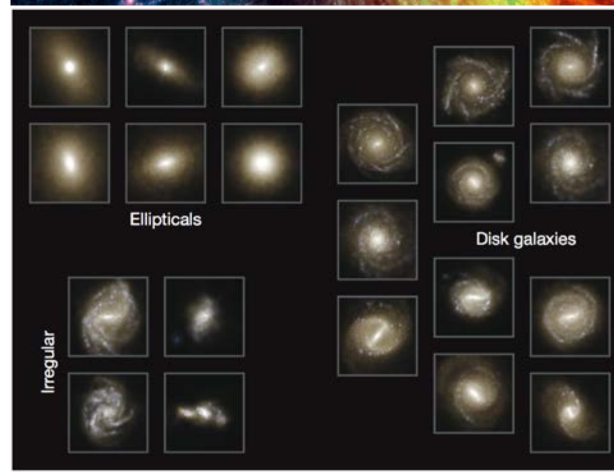
\+

DMO Zooms

Adiabatic Runs

Too-low res samples to study galaxies

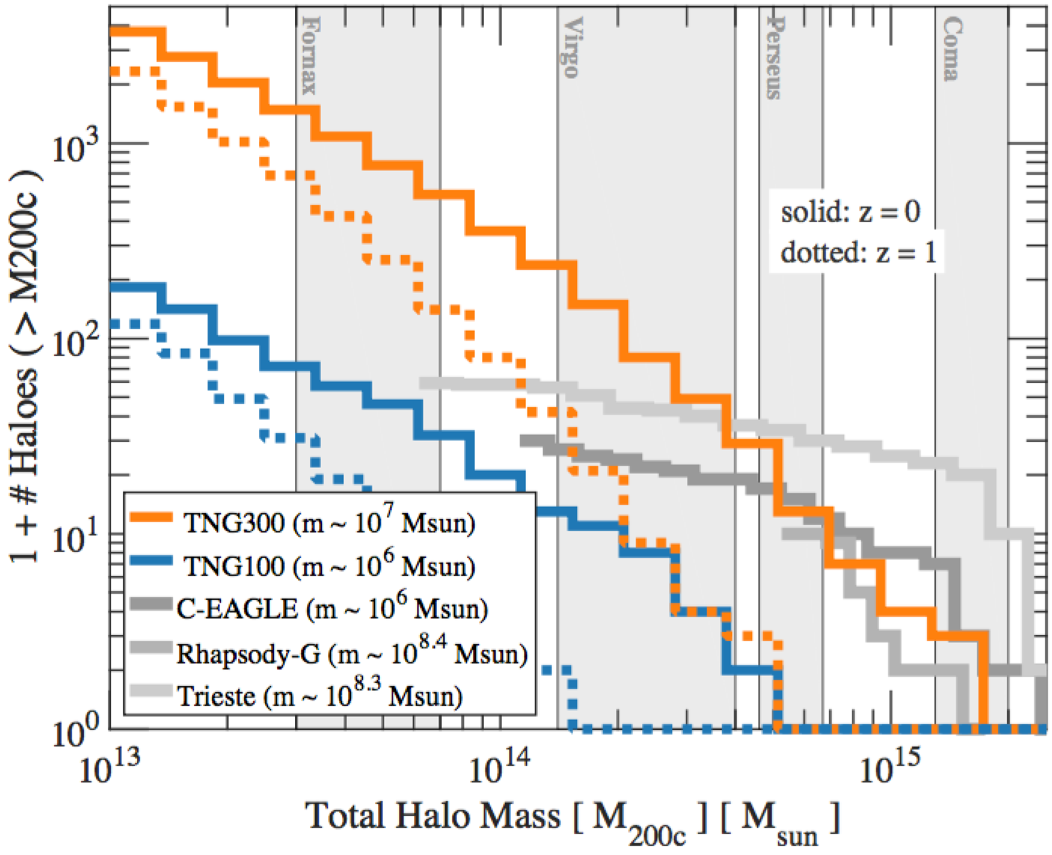




UNIFORM VOLUMES

It is hard to simulate very **massive objects** including the resolution and the physics ingredients that are needed to model also their member **galaxies (and not just the central)**

The Landscape of (Current) Cosmological (M)HD Simulations



Pillepich, Nelson, Hernquist et al. 2018

The mass regime of **Fornax** is not too much explored in zoom-in cosmological hydro simulations.

In simulations like Illustris, EAGLE and the new TNG100, we have many tens of Fornax-like haloes and ~10

In projects like C-EAGLE, there are 7 haloes more massive than 10^15 Msun, so a few comparable to **Coma**.

In TNG50, we will have ~10 Fornax-like haloes with galaxies resolved with m_res ~ a few 10^4 Msun and one Virgo mass-like object.

Theory model questions (that we are asking ourselves, or that you should be asking us):

- What are the strengths and weaknesses of current models in general?
    - For insights into galaxy evolution? For cluster galaxy members?
    - Are feedback models (i.e. AGN/ICM interaction) good enough, or too crude?
    - Are gas-dynamical models good enough, or too crude (i.e. ICM/ISM interaction)?
    - Can we do better: bridging the *(res.)* gap (i.e. zooms <-> boxes, idealized <-> SAMs)
- Can models explain both 'quiet gas stripping' (gradual truncation) and 'spectacular gas stripping' (jellyfish, peri-center SF bursts) *simultaneously*?
- What are the most important caveats in making obs. comparisons? Should we at all?
- Are there un-considered obs. we should use to better constrain the models, or do the models have enough on their hands already?
    - Do group/cluster member constraints provide more than 'field' constraints?
- Stepping back: do we understand DM sub-structure formation (& disruption!) processes enough to even model baryonic effects on top?

Science questions (we) would like answers to:

- How do different environmental effects impact satellite *quenching* (vs. mass/redshift)?
- When (what distance) do satellites start to experience env. effects?
- Does env. quenching depend on host halo mass, or not? (Just cosmic starvation?)
    - How does FB from central galaxies effect satellites? Directly, indirectly?
    - What direct evidence exists for the role of AGN FB? Distinguishable from SF FB?
- What aspects of galaxies are affected by their environment? (e.g. AGN activity?)
    - Morphological evolution of satellites: important or not?
    - Metal enrichment of satellites: most important processes? Predictions?