Introducing IllustrisTNG(*)

ANNALISA PILLEPICH
MPIA, Heidelberg

(*) TNG = The Next Generation

Time since the Big Bang: 0.4 billion years

ILLUSTRIS

Introducing IllustrisTNG(*)

ANNALISA PILLEPICH
MPIA, Heidelberg

(*) TNG = The Next Generation

Time since the Big Bang: 0.4 billion years

Scope of this Talk

Introduce you to IllustrisTNG, the newest example of

uniform-Volume Cosmological
Gravity+(M)HD Simulations
for Galaxy Formation and Evolution

1. Give an overview of the general ideas behind our simulations, baryonic haloes, and the included physics mechanisms
2. Showcase the many applications these calculations allow

The TNG Team

HITS

Max-Planck-Institut für Astrophysik

CfA

SIMONS FOUNDATION

Volker Springel

Lars Hernquist

Annalisa Pillepich

Rüdiger Pakmor

Dylan Nelson

Rainer Weinberger

Federico Marinacci

Jill Naiman

■ Original Illustris Team + Debora Sijacki et al.

Mark Vogelsberger

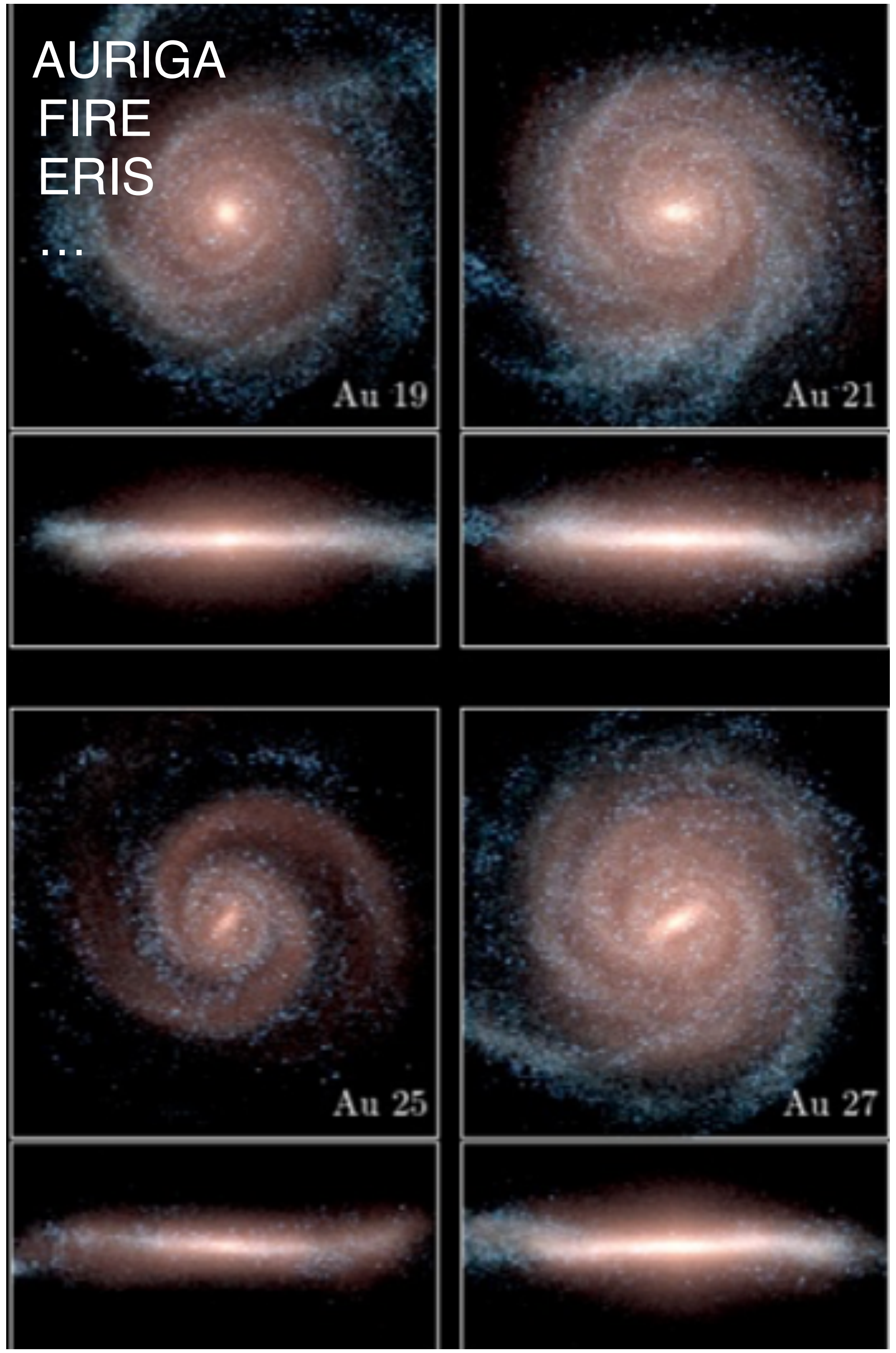
Shy Genel

Paul Torrey

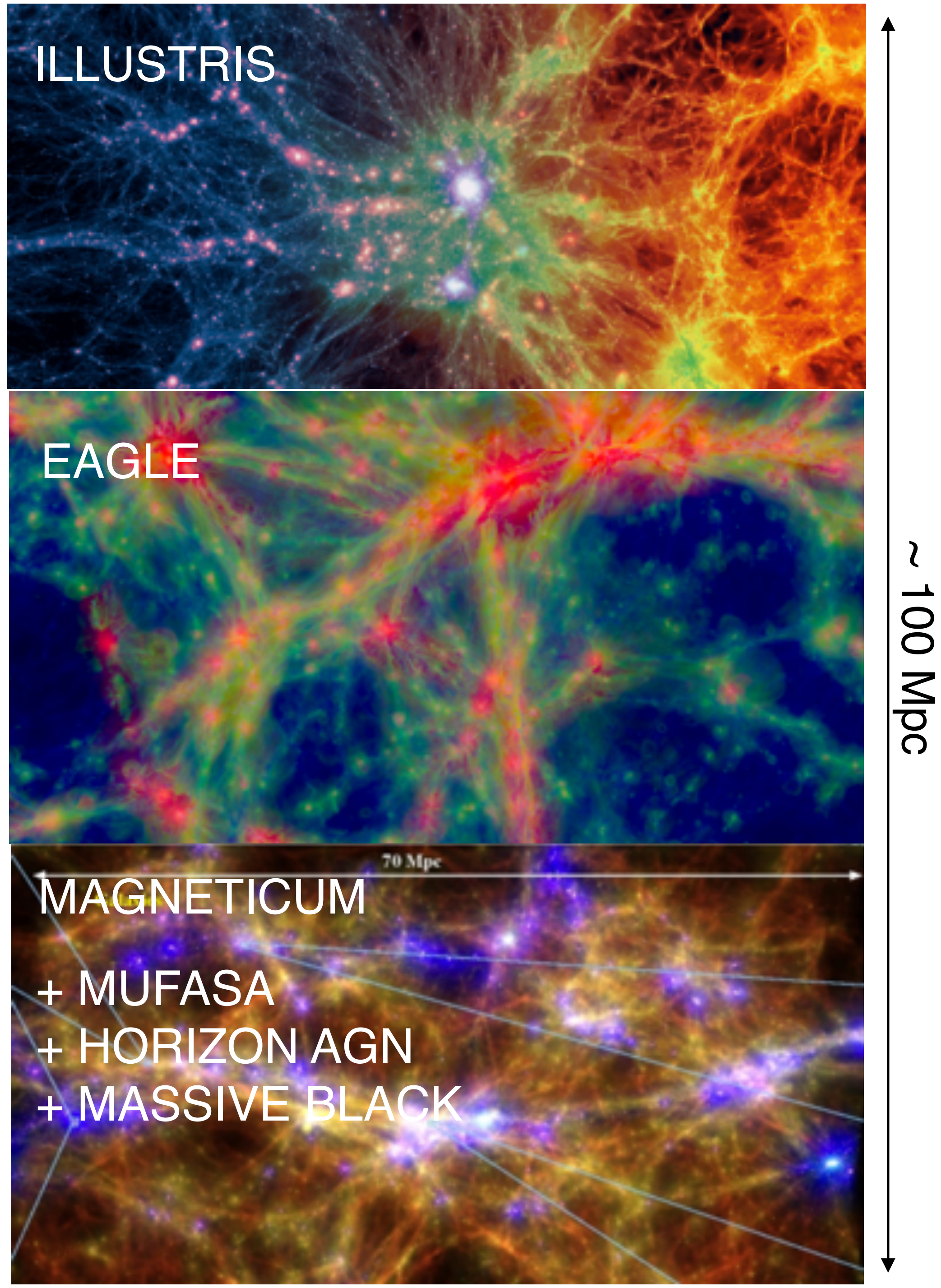
The Illustris Simulation

The Context

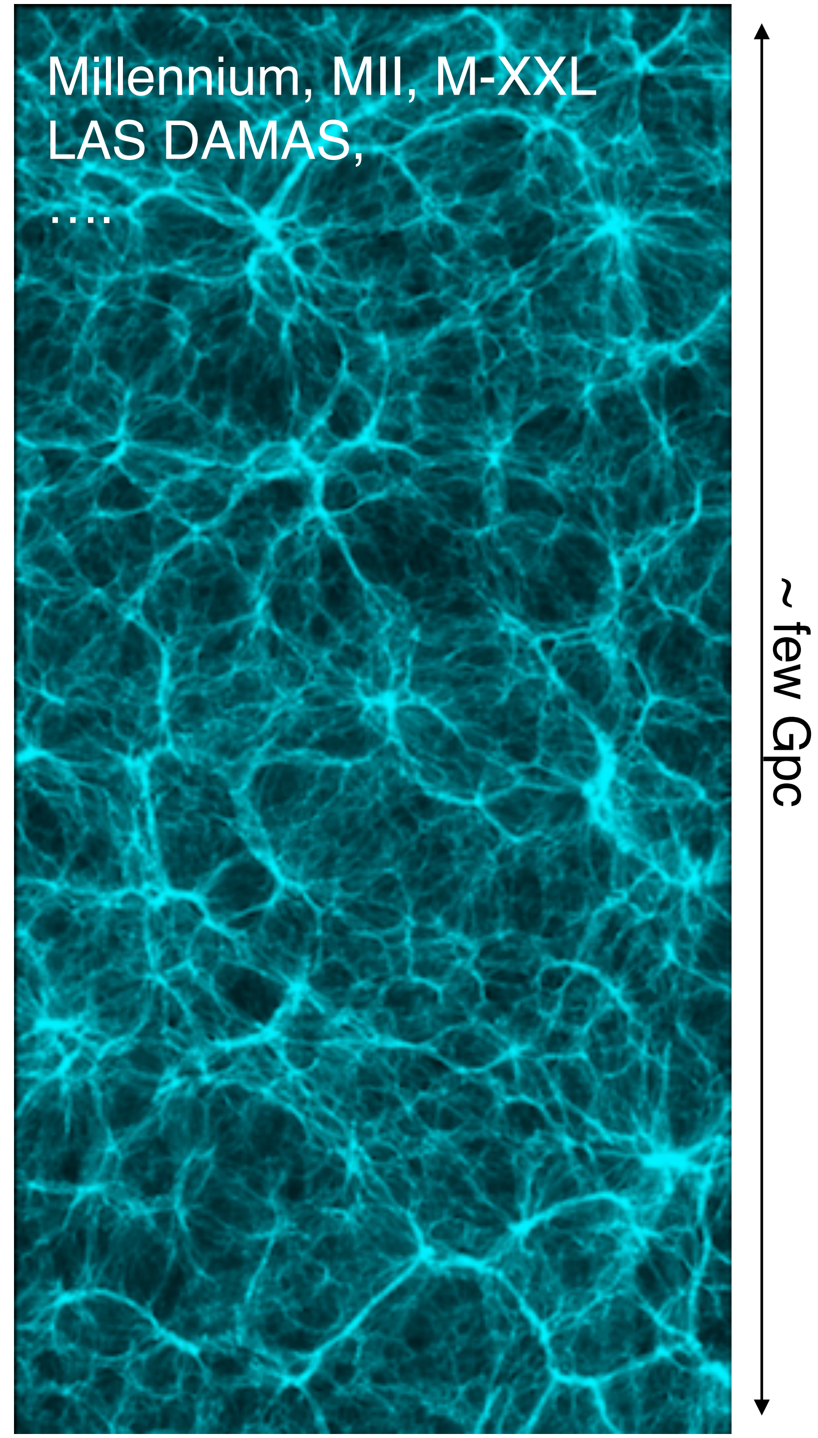
Zoom-ins: individual galaxies, <100pc res



Uniform Volumes with Baryonic Physics



Gravity-Only Uniform Volumes

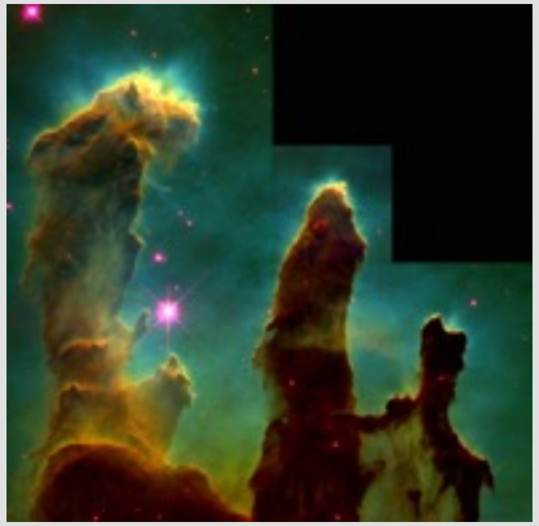


The Baryonic Ingredients…

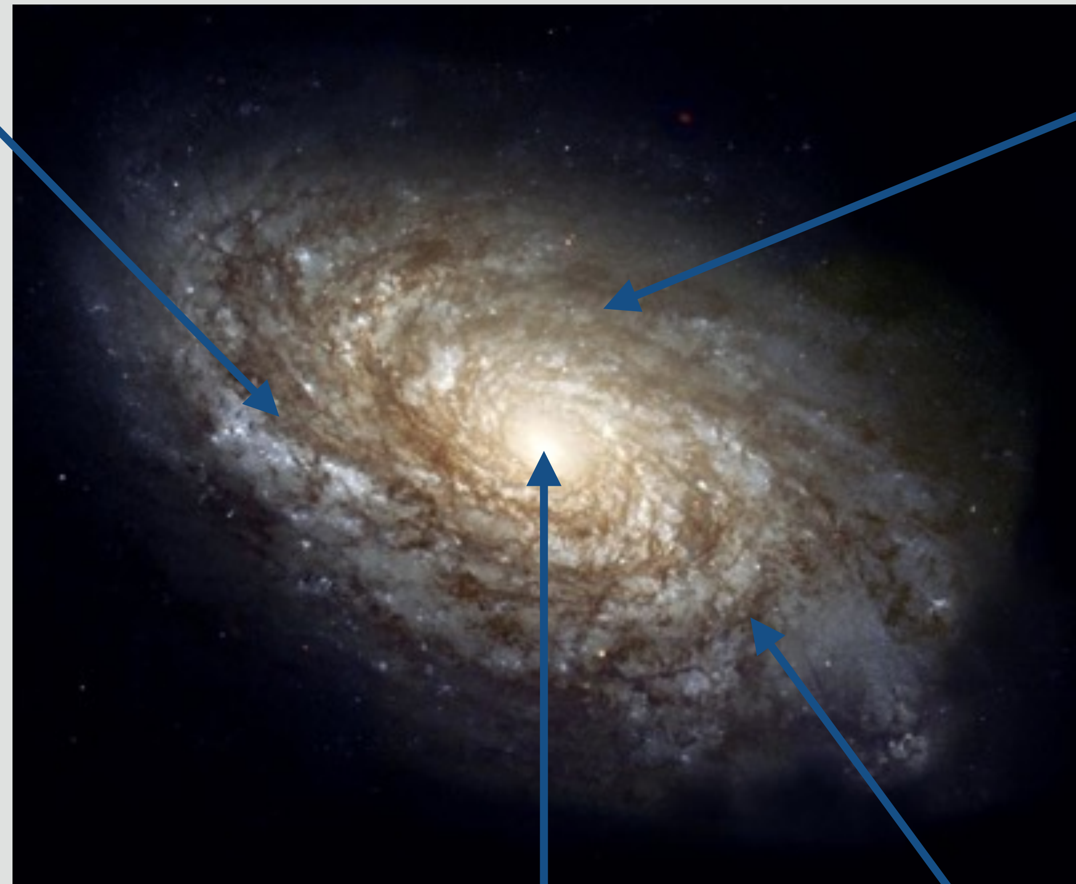
Gravity is not the only physical process governing galaxies….

THE LINK IS THE PHYSICS OF GAS AND OF THE
THE SO-CALLED FEEDBACK MECHANISMS

Formation and evolution of stars



Supernovae Explosions



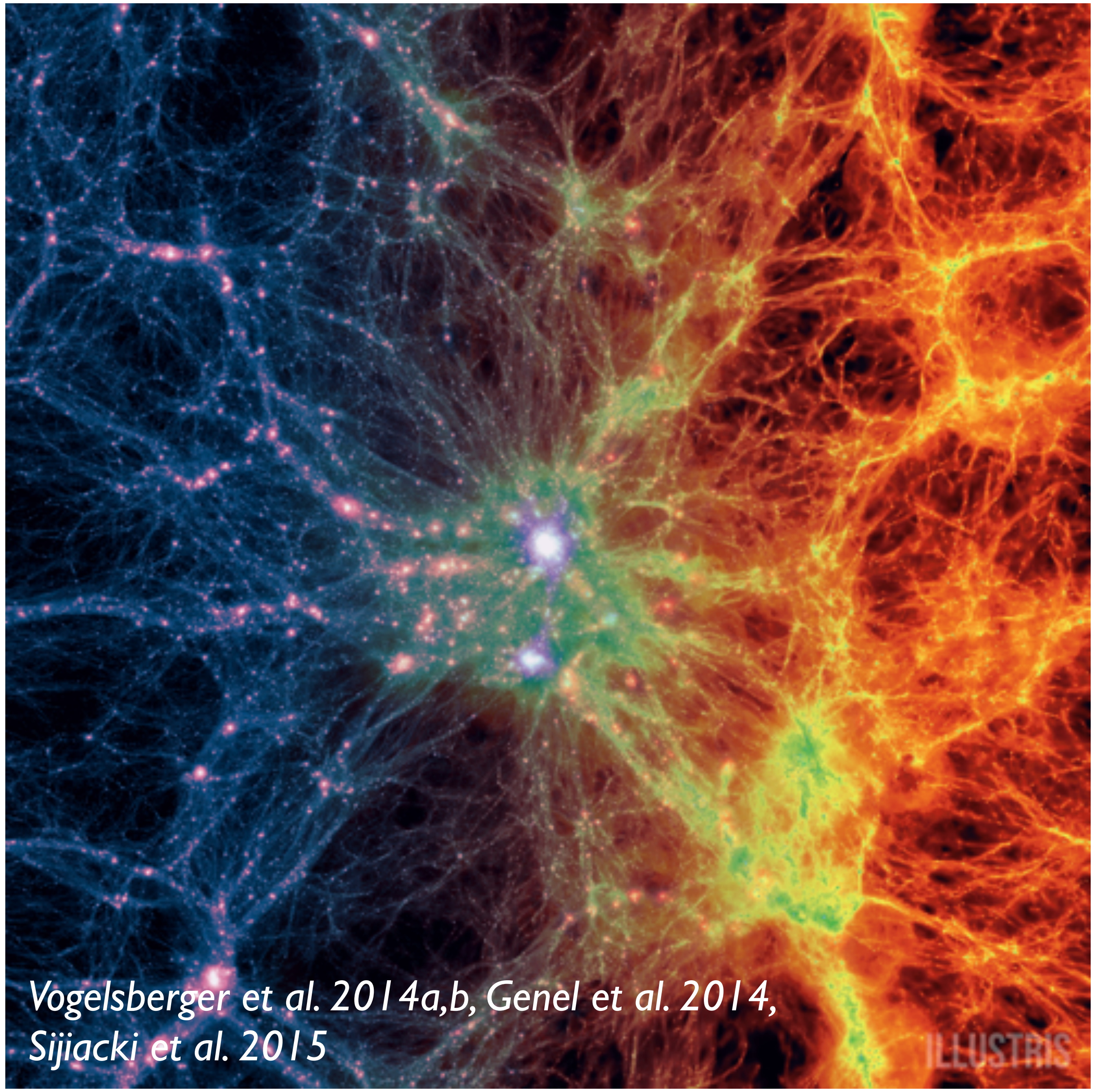
Gas and Dust:
Halo, Clouds, Winds

dark matter and gaseous halo

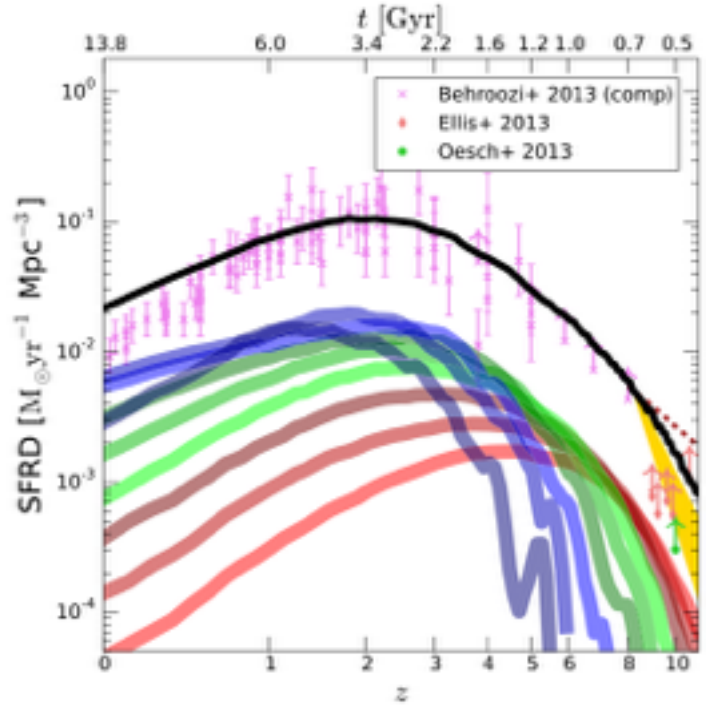
Supermassive Black Hole at the Center

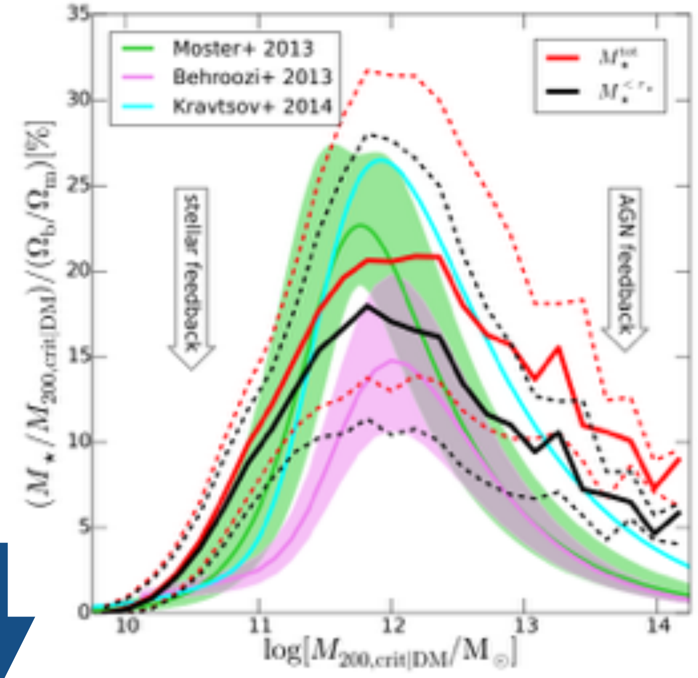
Illustris in one slide

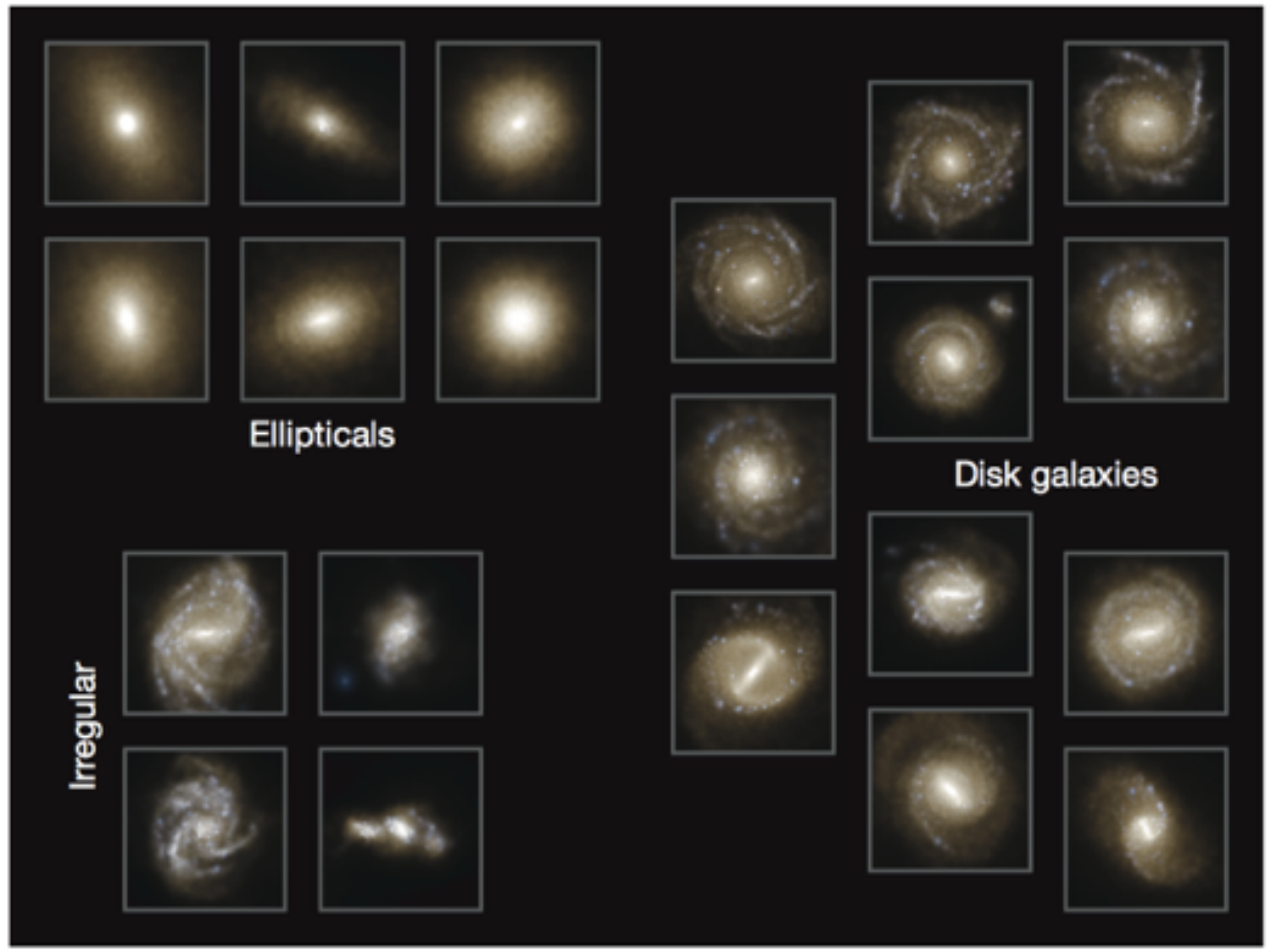
AREPO Code
106.5 Mpc Cosmological Box
Halo Mass Range: < 2x10^{14} Msun; Res: ~ 1 kpc, ~ 10^6 Msun



Vogelsberger et al. 2014a,b, Genel et al. 2014, Sijiacki et al. 2015





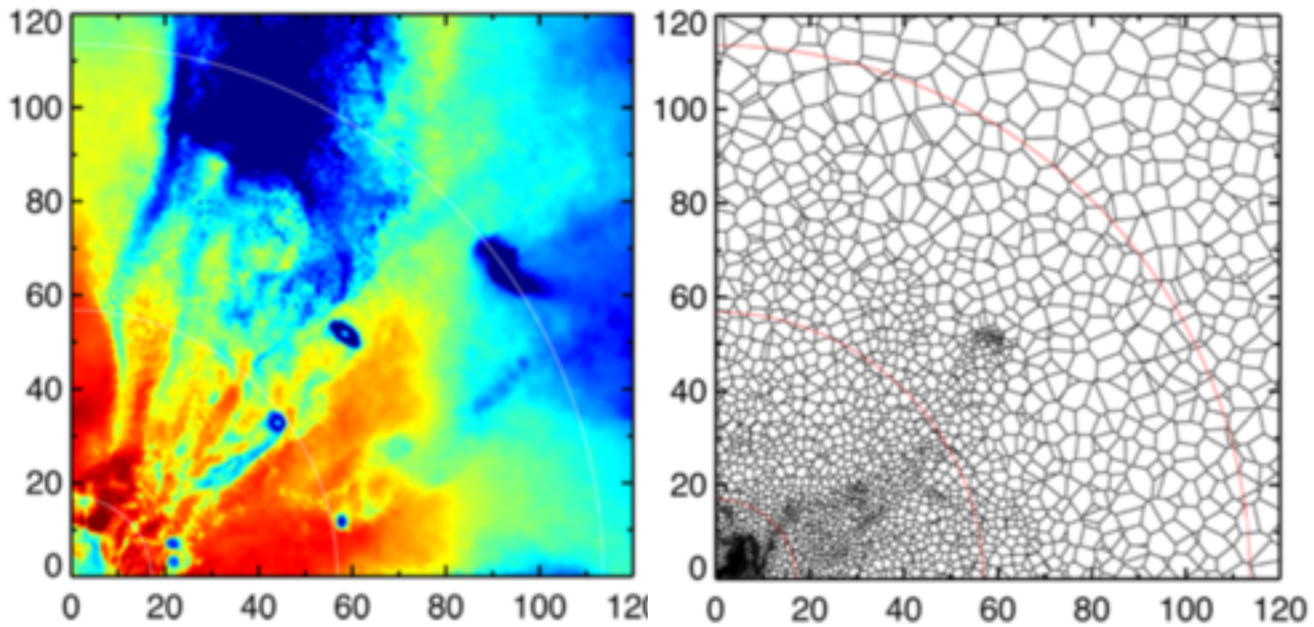


Vogelsberger et al. 2014a

The Codes of Cosmological (M)HD Simulations

AREPO (Springel 2010):
moving-mesh code

resolution elements	• DARK MATTER *GAS - cells* • STARS • BLACK HOLES
gravity	TreePM Solver
(Magneto-) hydrodynamics	Riemann Solver on Voronoi Mesh

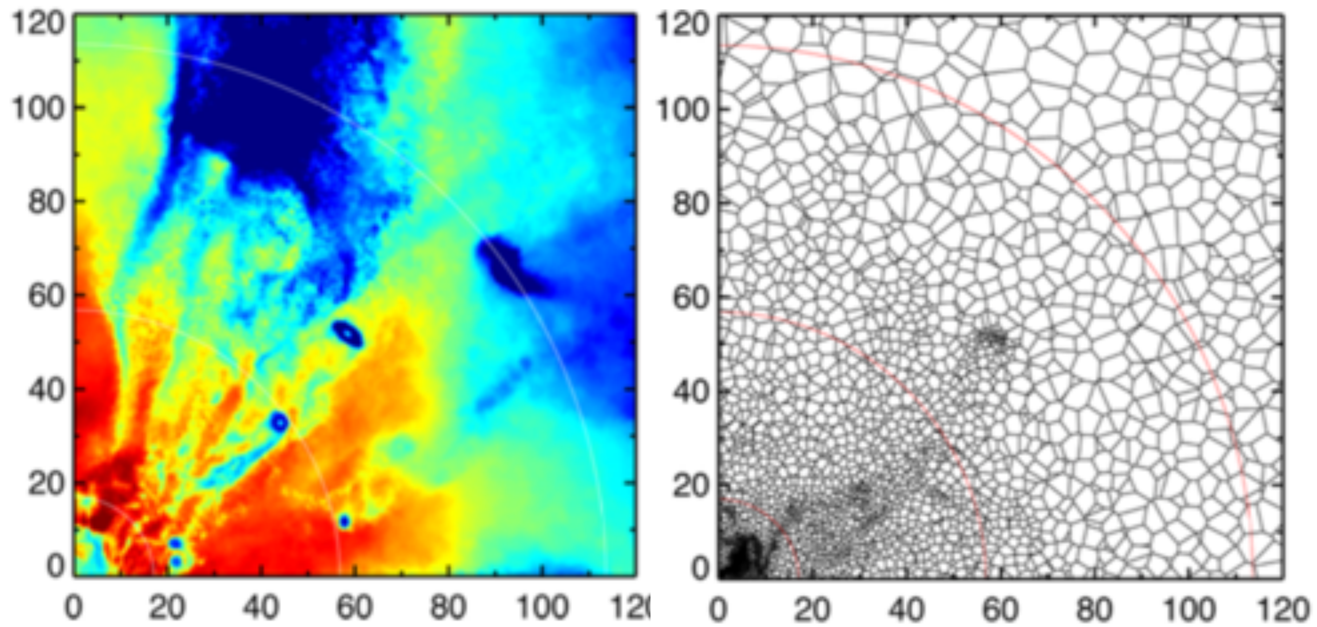


Nelson et al. 2015a

The Codes of Cosmological (M)HD Simulations

AREPO (Springel 2010):
moving-mesh code

resolution elements	DARK MATTER *GAS - cells* STARS BLACK HOLES
gravity	TreePM Solver
(Magneto-) hydrodynamics	Riemann Solver on Voronoi Mesh

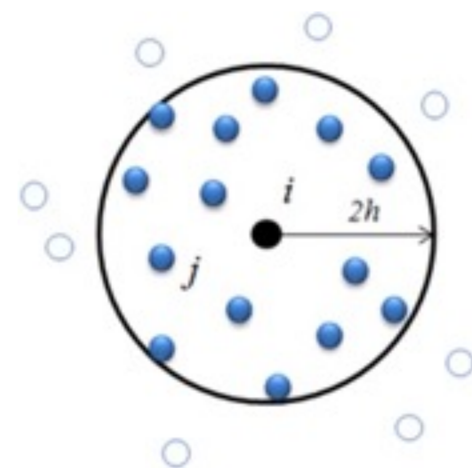


Nelson et al. 2015a

SPH/Particle Codes
(e.g. GADGET-n, GASOLINE, P-SPH)

All resolution elements are particles (also the gas)

Smooth Particle Hydrodynamics:



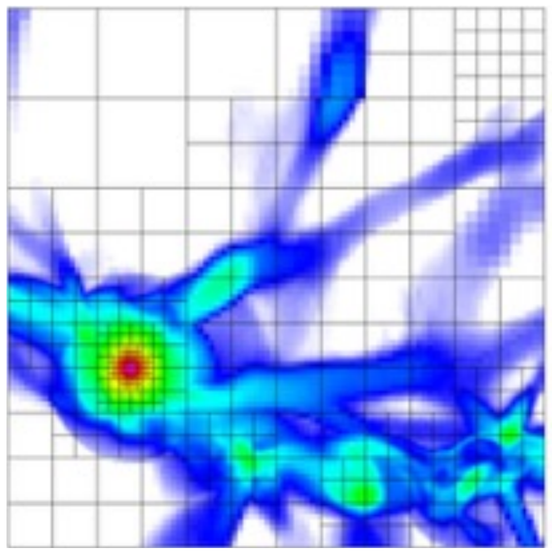
● = *particles*

The Codes of Cosmological (M)HD Simulations

GRID/AMR Codes
(e.g. RAMSES)

Gas (at least) is sampled by cells

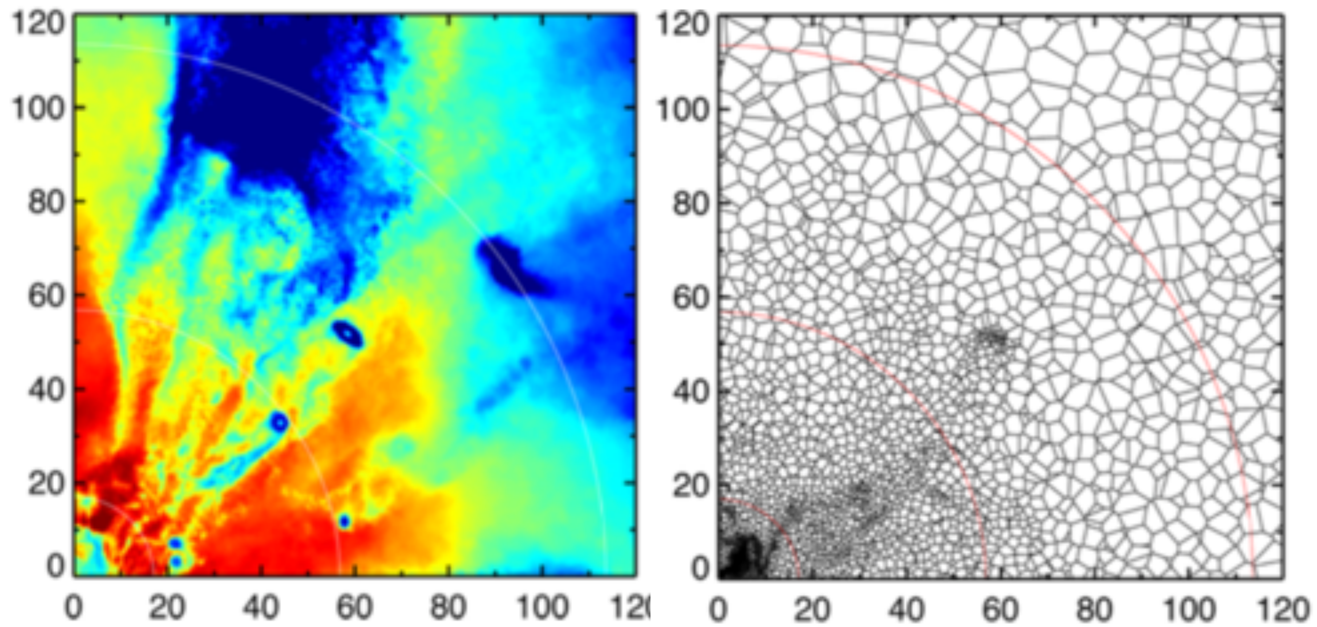
MHD is solved on a fixed cartesian grid, that is refined:



AMR = adaptive mesh refinement

AREPO (Springel 2010):
moving-mesh code

resolution elements	DARK MATTER *GAS - cells* STARS BLACK HOLES
gravity	TreePM Solver
(Magneto-) hydrodynamics	Riemann Solver on Voronoi Mesh

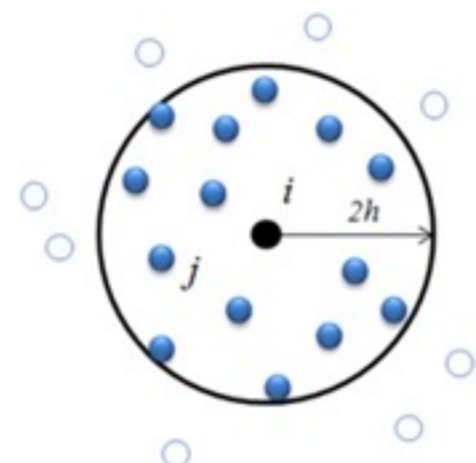


Nelson et al. 2015a

SPH/Particle Codes
(e.g. GADGET-n, GASOLINE, P-SPH)

All resolution elements are particles (also the gas)

Smooth Particle Hydrodynamics:

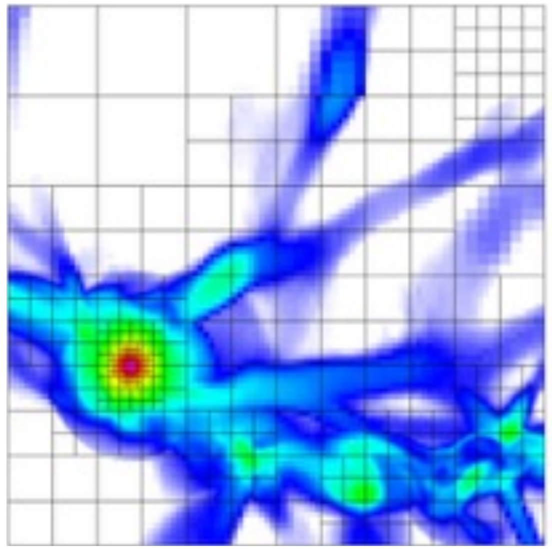


● = *particles*

The Codes of Cosmological (M)HD Simulations

GRID/AMR Codes
(e.g. RAMSES)

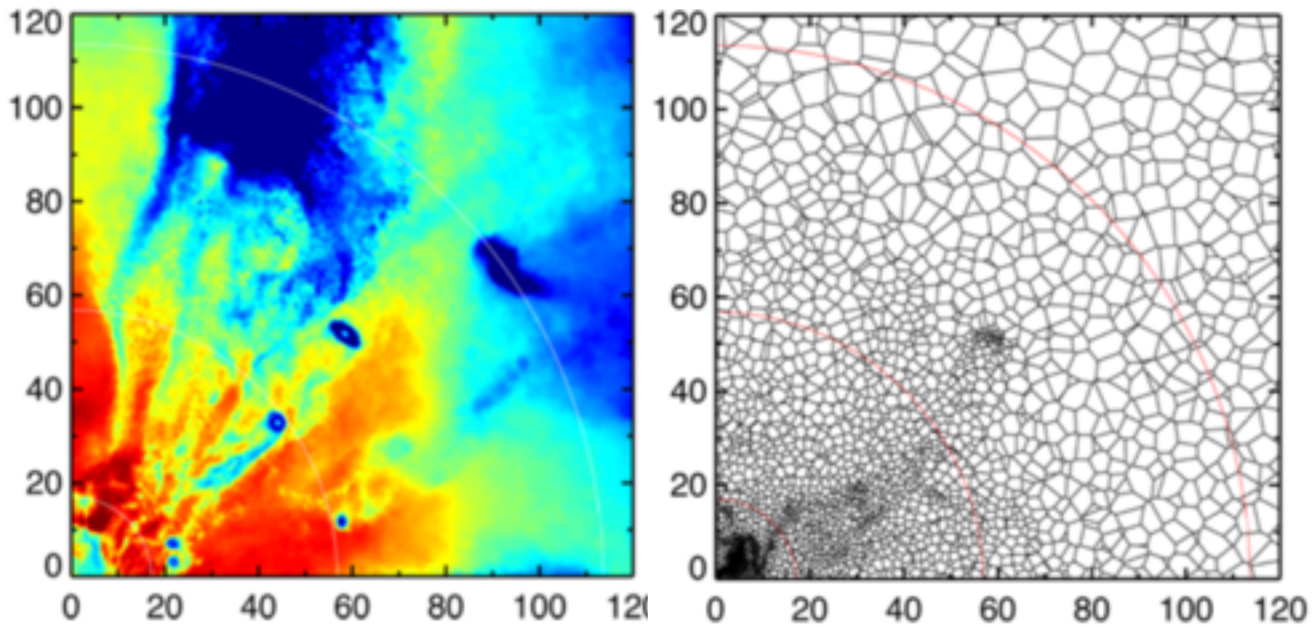
HORIZON-AGN



AMR = adaptive mesh refinement

AREPO (Springel 2010):
moving-mesh code

Illustris
IllustrisTNG
Auriga

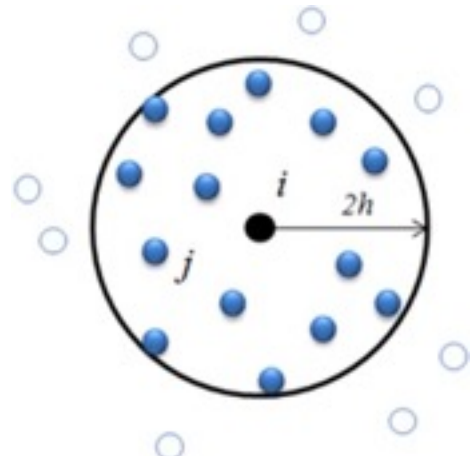


Nelson et al. 2015a

SPH/Particle Codes
(e.g. GADGET-n, GASOLINE, P-SPH)

EAGLE
Massive-Black
Magneticum
ERIS
NIHAO
FIRE
…

Smooth Particle Hydrodynamics:

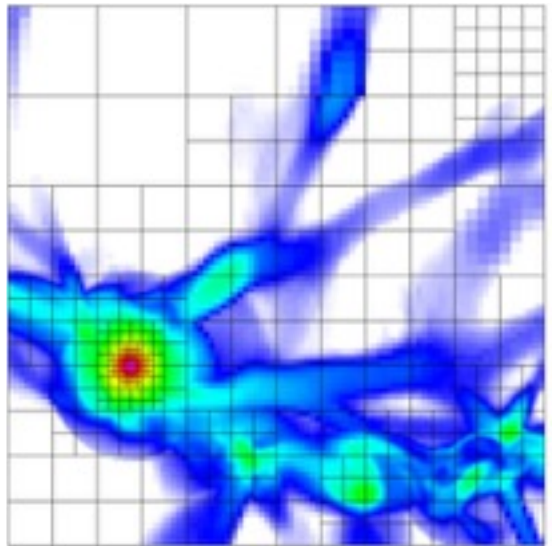


● = *particles*

The Codes of Cosmological (M)HD Simulations

GRID/AMR Codes
(e.g. RAMSES)

HORIZON-AGN



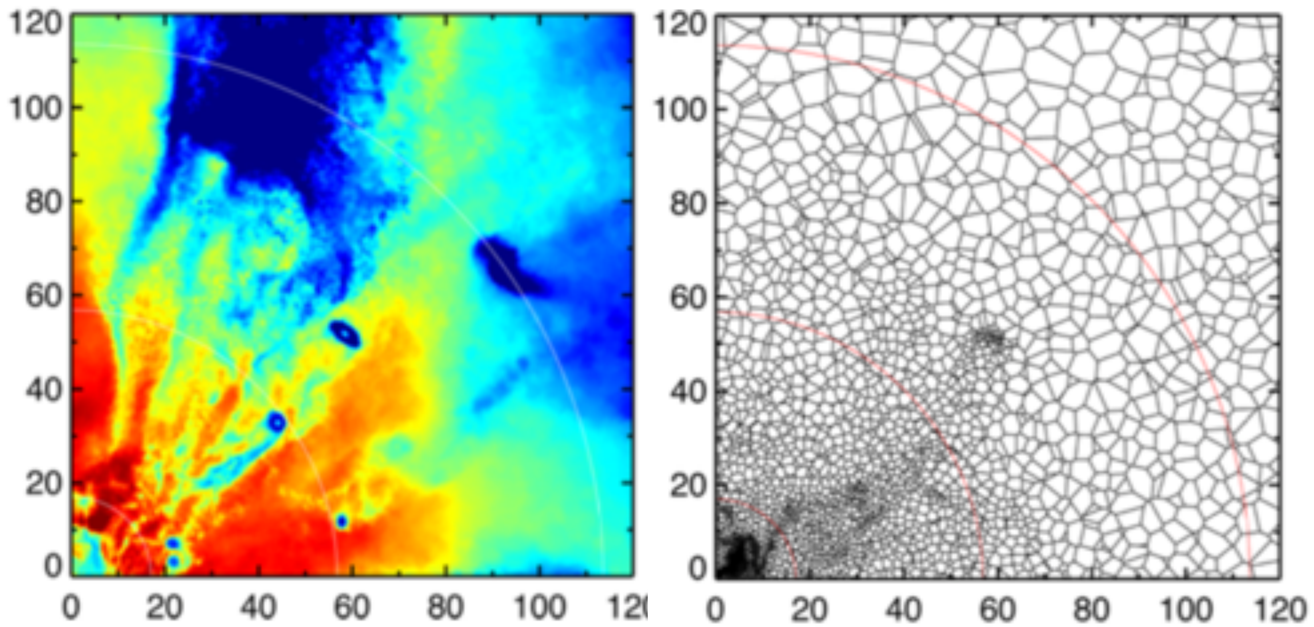
AMR = adaptive mesh refinement

AREPO (Springel 2010):
moving-mesh code

Illustris
IllustrisTNG
Auriga

GIZMO with
mesh-less finite mass Rieman solver

FIRE-2
MUFASA

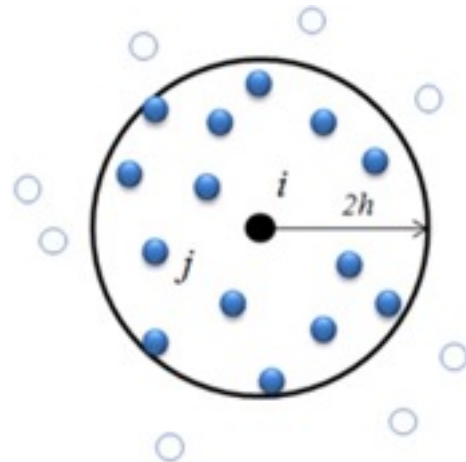


Nelson et al. 2015a

SPH/Particle Codes
(e.g. GADGET-n, GASOLINE, P-SPH)

EAGLE
Massive-Black
Magneticum
ERIS
NIHAO
FIRE
…

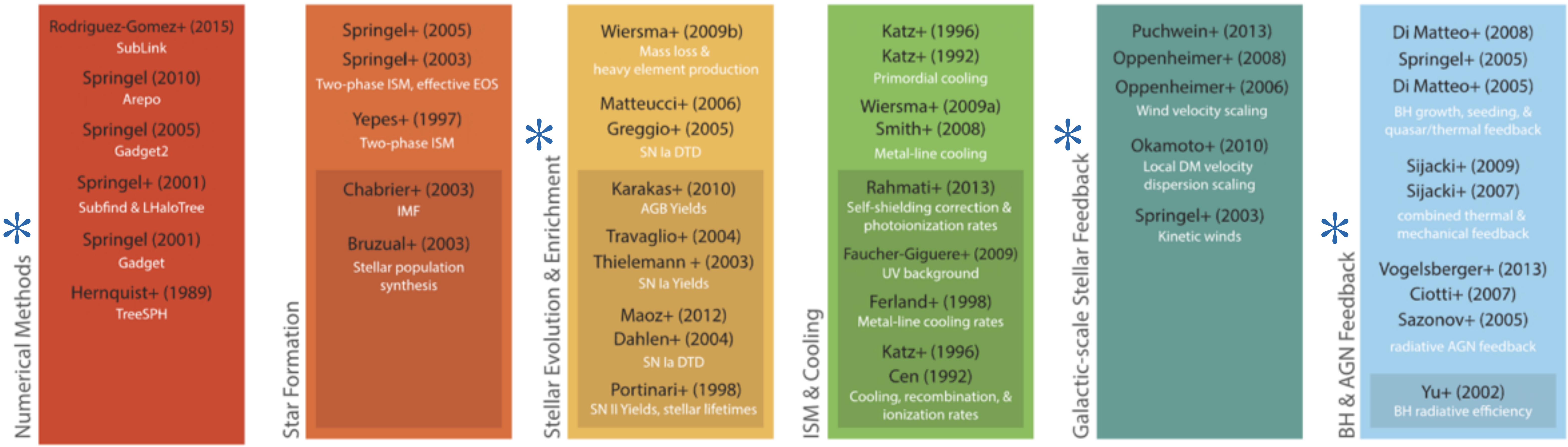
Smooth Particle Hydrodynamics:



● = *particles*

The Illustris Galaxy Physics Model

Vogelsberger et al. 2013, Torrey et al. 2014
Schematic from Nelson, Pillepich, Genel et al. 2015



The overall model is based on choices *inspired* by observations and by other, more detailed, "ab initio" theoretical studies of individual processes

It necessarily entails a subgrid treatment of phenomena acting on scales smaller than 10-1000 parsec, and hence many choices in the numerical implementation and free parameters

* TNG modifications

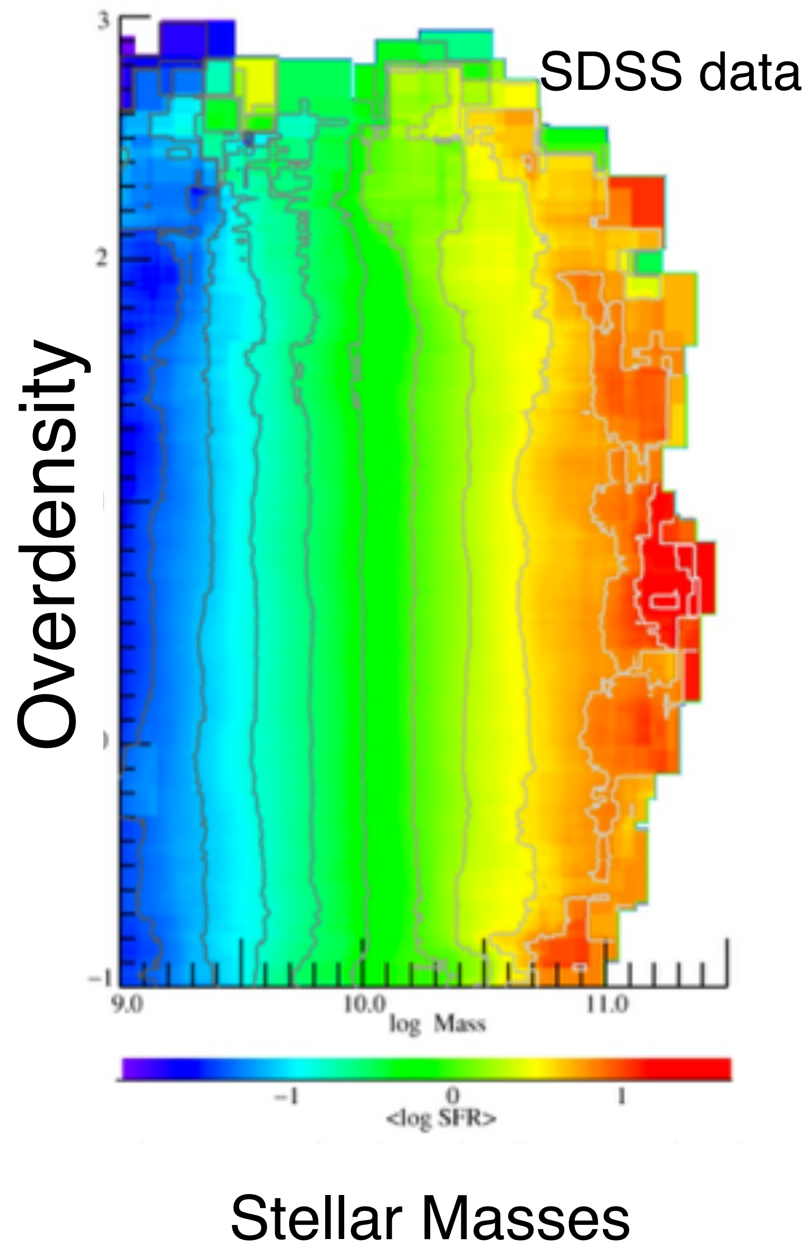
The overarching Idea

WORKING ASSUMPTION: LCDM as Cosmological framework => hierarchical growth of structure

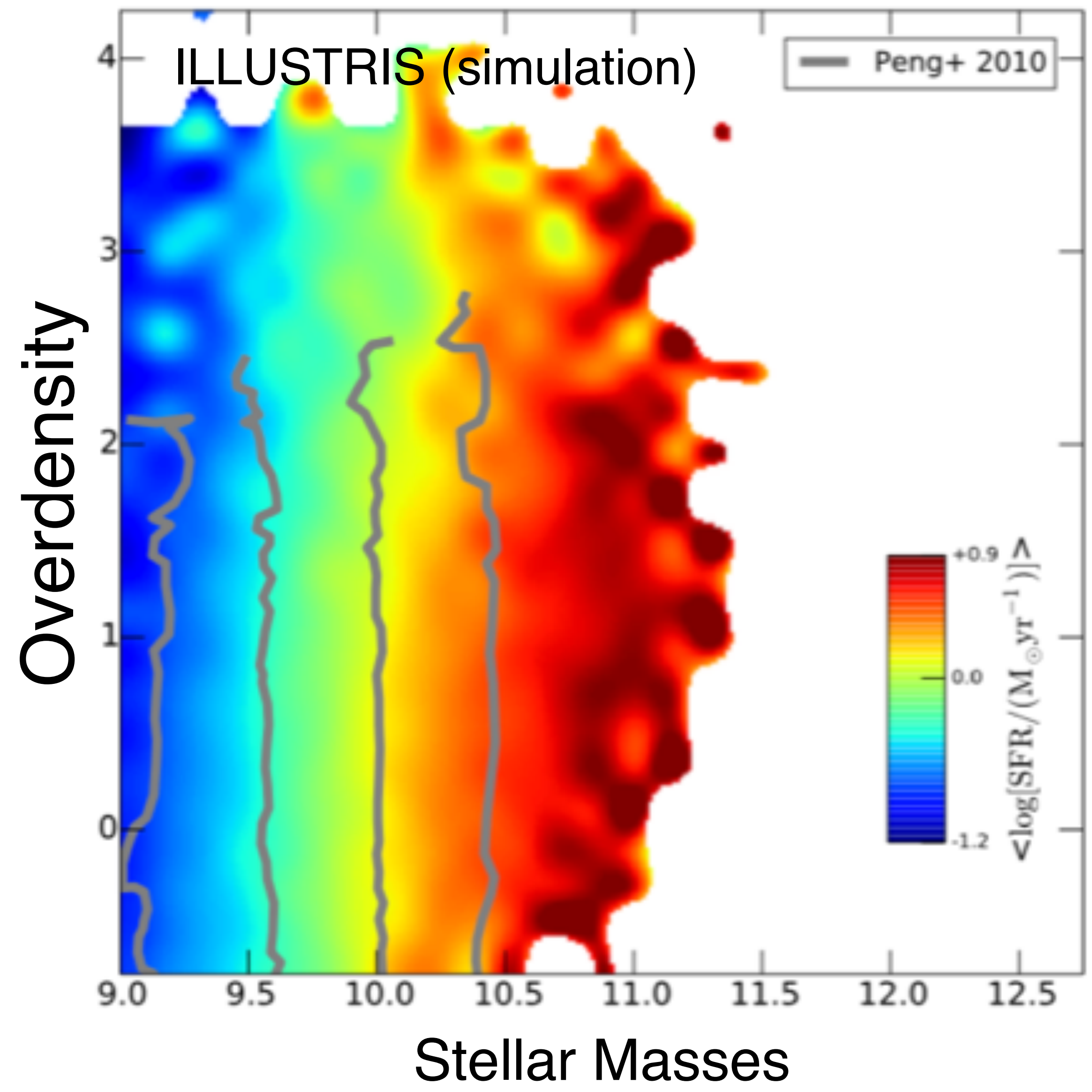
1. We are after an ***effective* theory** for galaxy formation that functions across the widest possible ranges of masses, redshifts, assembly histories, environments
2. We want not just to form galaxies, but also to take into account the effects of the **hierarchical growth of structure** (i.e. mergers, accretion, etc)
3. Once we get the **“average” galaxy population**, we want to use the simulation as exploration tool, e.g. to understand the physical origin of the galaxy-to-galaxy variations (the **scatter**) and the mechanisms behind the diverse galaxy pathways
4. A few observational constraints are used to *calibrate* the model,
   e.g. SFRD and/or the galaxy stellar mass function at z=0
5. To do so, we must simulate **thousands or tens of thousands of galaxies**
   => cosmological volumes with > tens Mpc side and sub grid prescriptions
6. Any *other* simulation outcome can be considered a **prediction, a gift** of the simulation
7. (All of those, collectively, must be contrasted to observations to ultimately **validate** (or not) the model)

Examples of predictions/gifts/applications: on galaxy quenching

Thousands of galaxies are needed to validate quenching theories



Peng et al. 2010

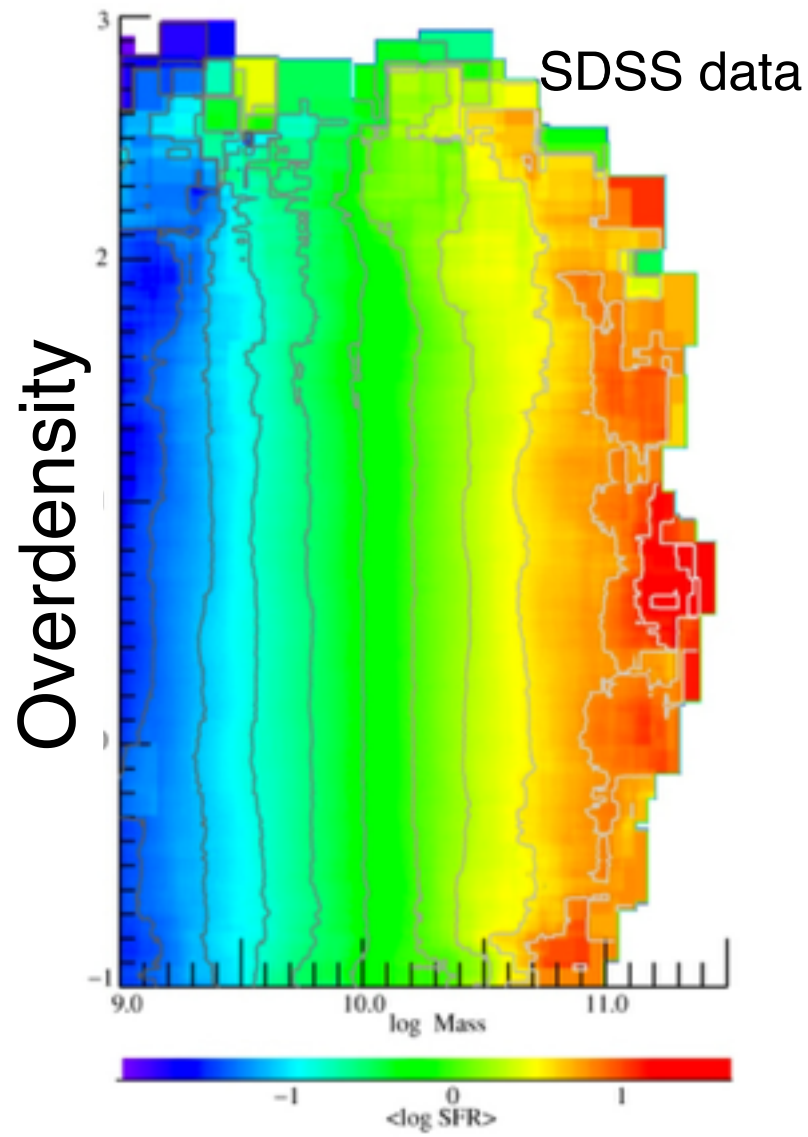


Vogelsberger et al. 2014

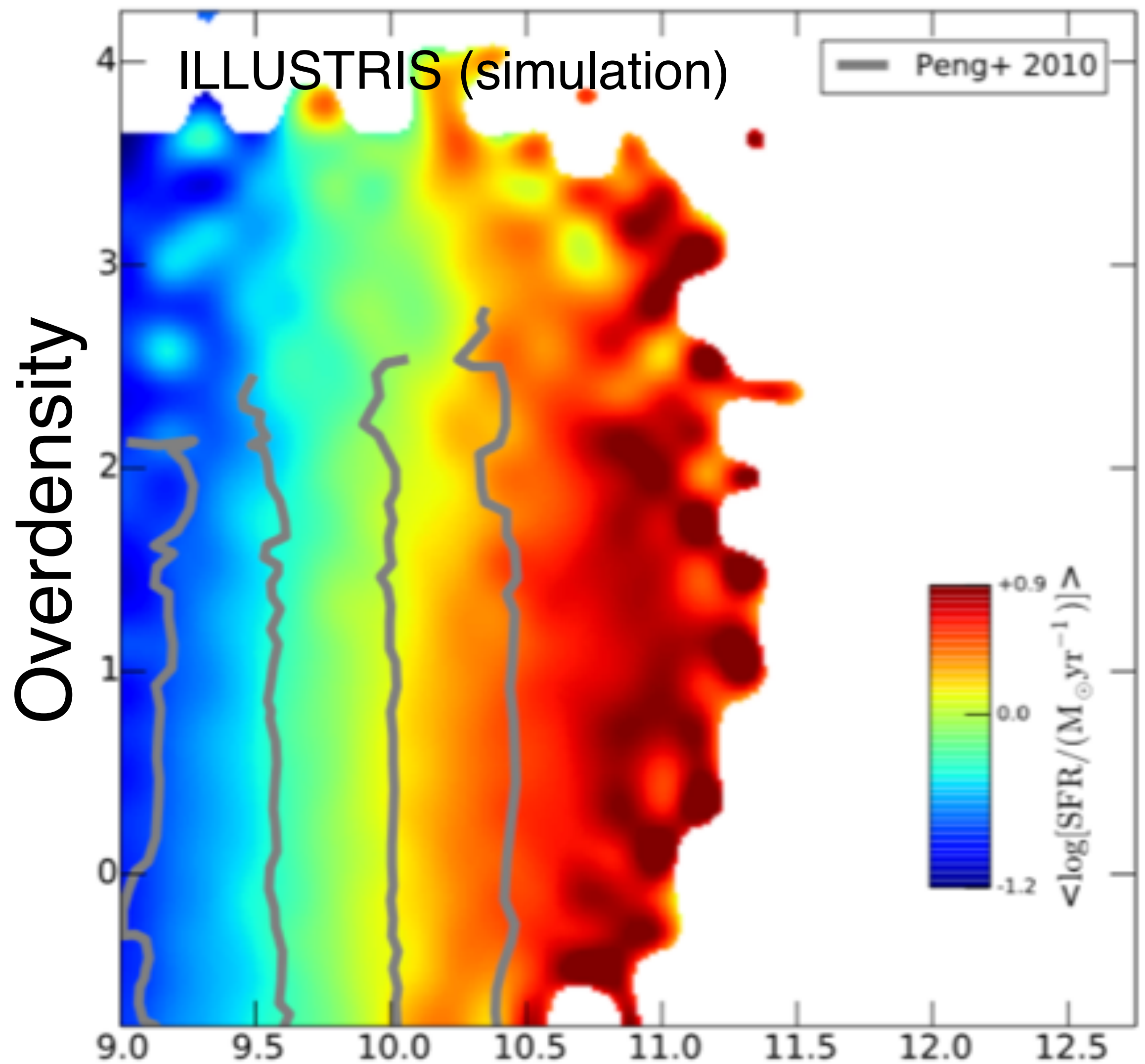
Examples of predictions/gifts/applications: on galaxy quenching

Thousands of galaxies are needed to validate quenching theories

Peng et al. 2010



Stellar Masses



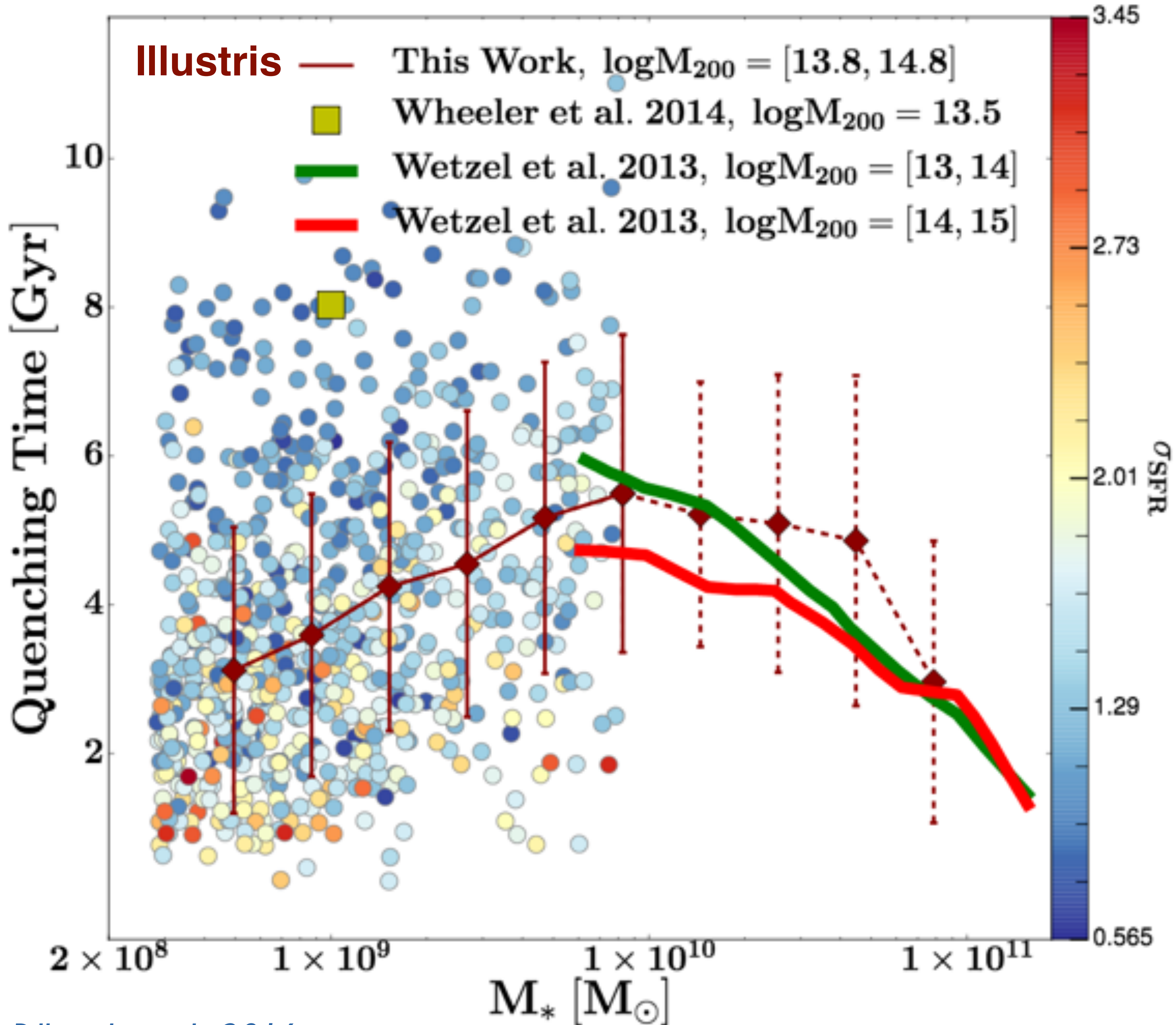
Stellar Masses

Vogelsberger et al. 2014

The SFRs of star forming galaxies do *not* depend on the density of their surroundings

Examples of predictions/gifts/applications: on quenching in clusters

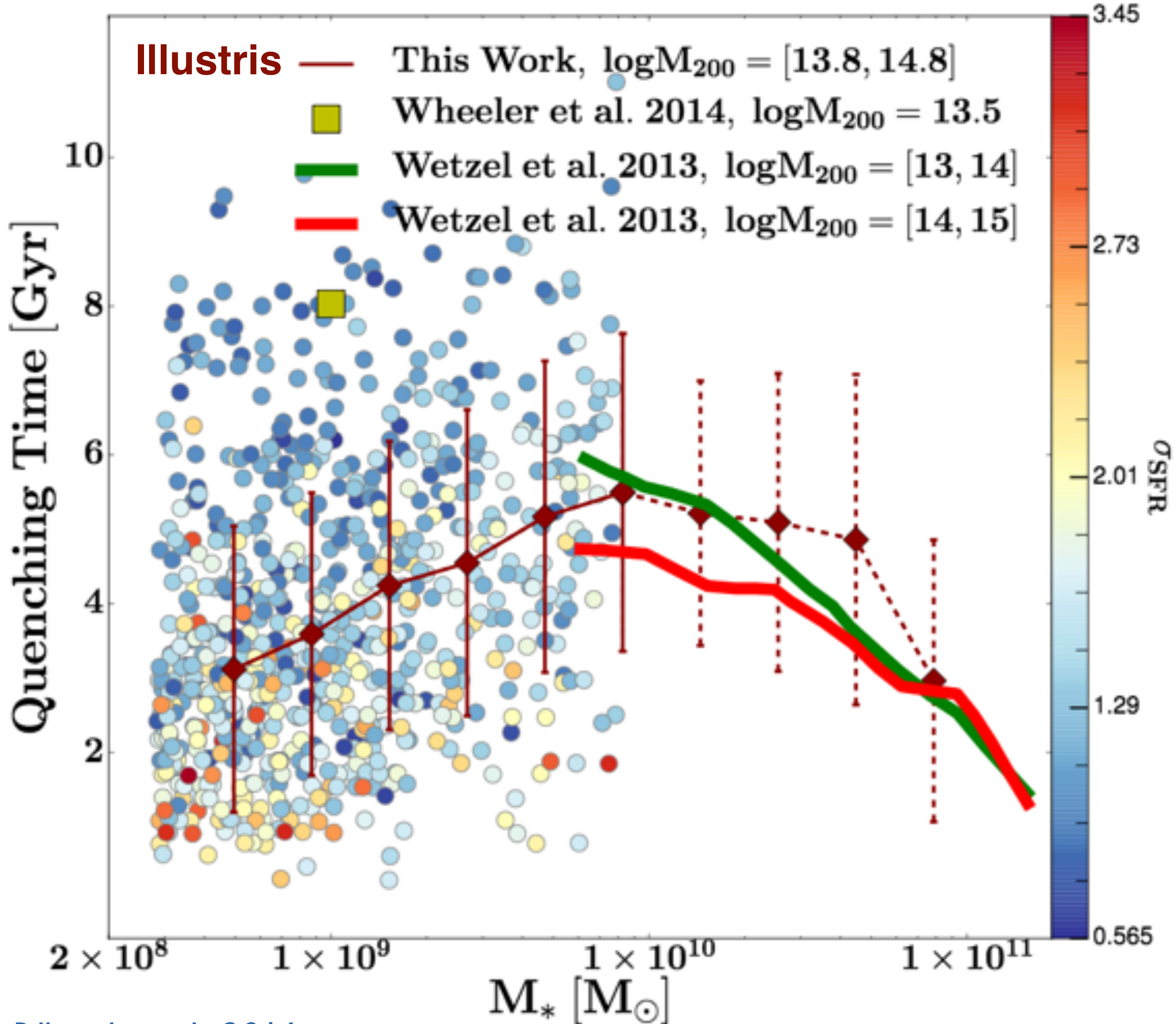
Hundreds of satellite galaxies are needed to understand quenching mechanisms in massive haloes, and those massive haloes need to exhibit sensible properties



Mistani, Sales, Pillepich et al. 2016

Examples of predictions/gifts/applications: on quenching in clusters

Hundreds of satellite galaxies are needed to understand quenching mechanisms in massive haloes, and those massive haloes need to exhibit sensible properties



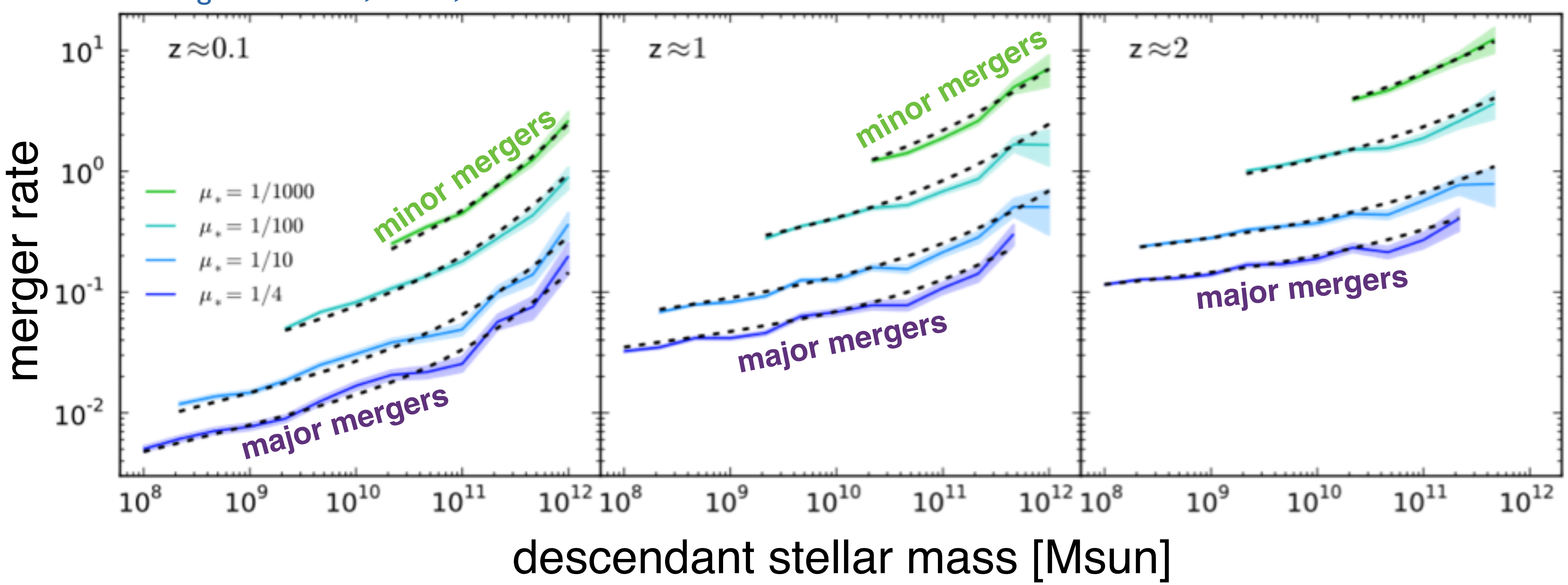
Mistani, Sales, Pillepich et al. 2016

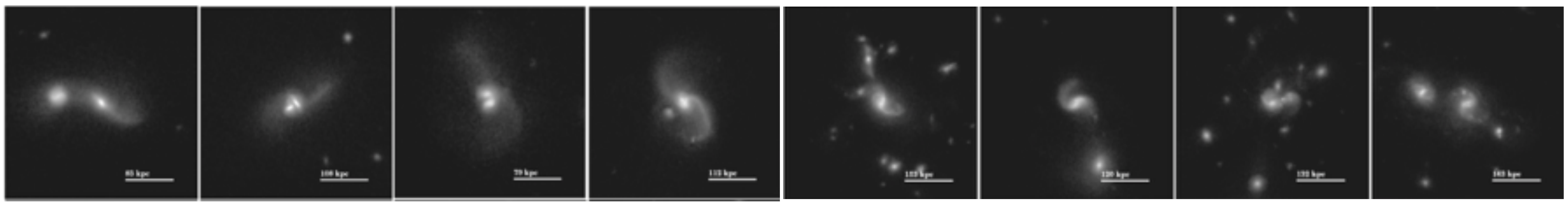
The time needed to quench a satellite's star formation depends on its mass and on the mass of its host.

But with huge galaxy-to-galaxy variations

Examples of predictions/gifts/applications: on merger rates

Rodriguez-Gomez, Genel, et al. 2015

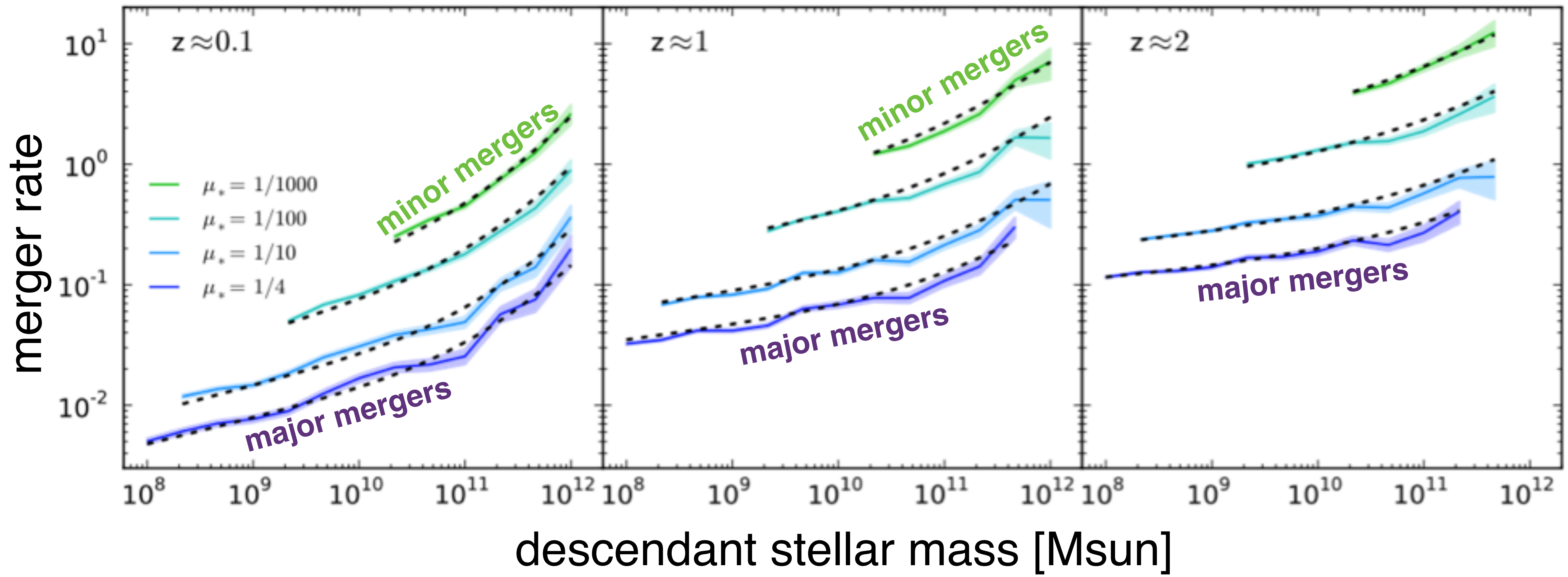




Credits: A. Pillepich

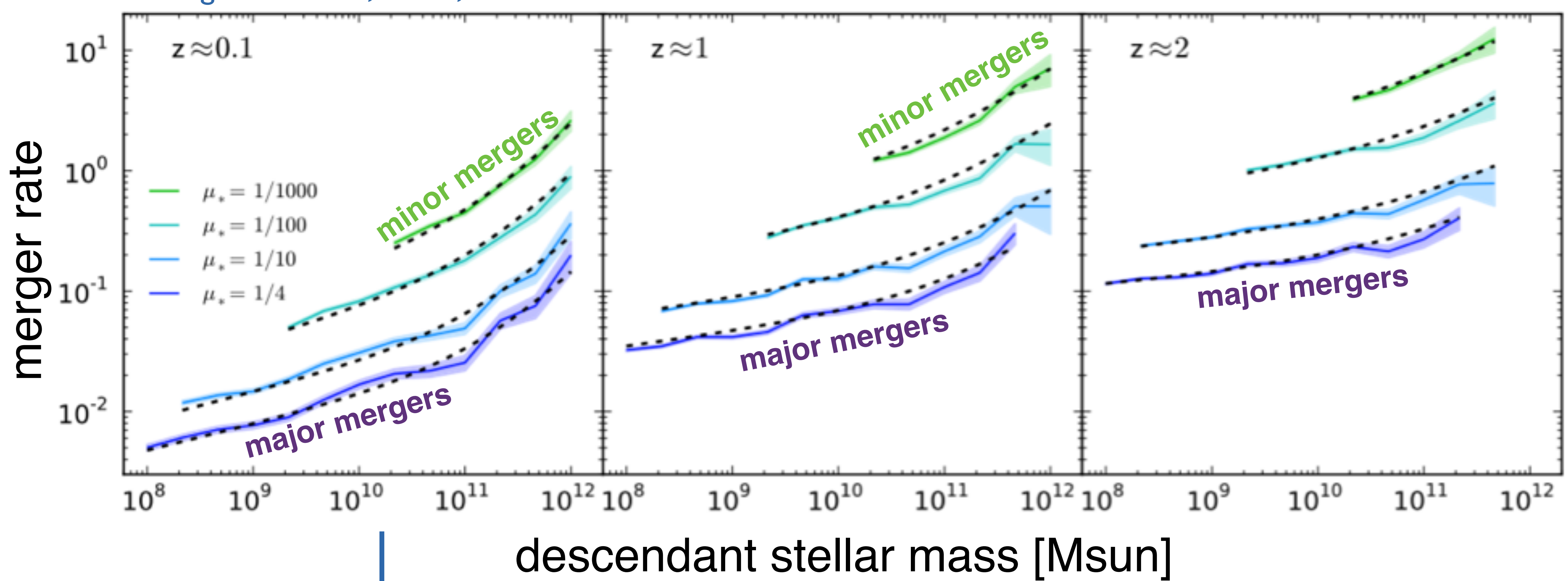
Examples of predictions/gifts/applications: on merger rates

Rodriguez-Gomez, Genel, et al. 2015



Examples of predictions/gifts/applications: on merger rates

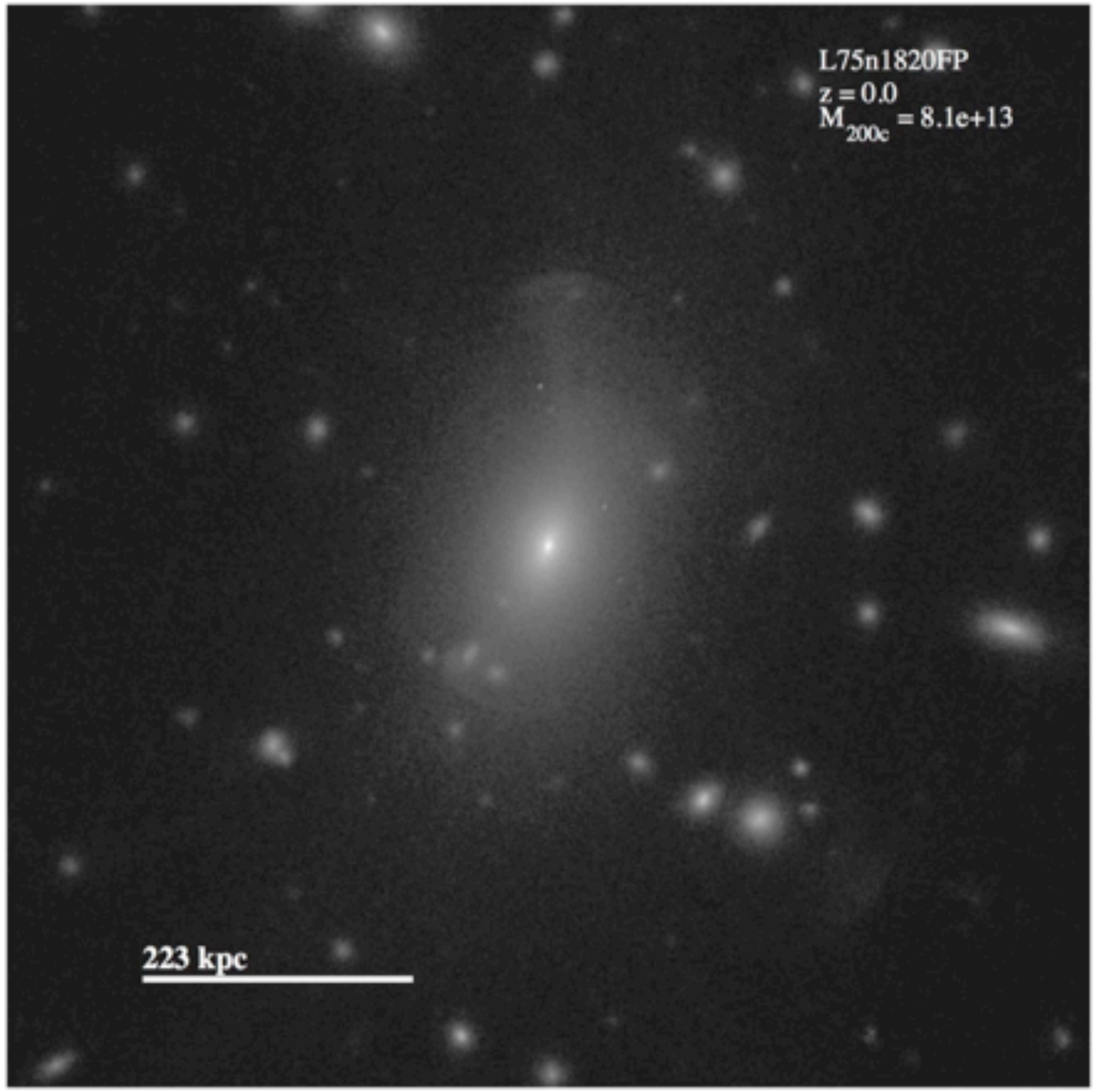
Rodriguez-Gomez, Genel, et al. 2015



At z~0, more massive galaxies have more frequent major mergers than less massive galaxies

Examples of predictions/gifts/applications: on stellar haloes

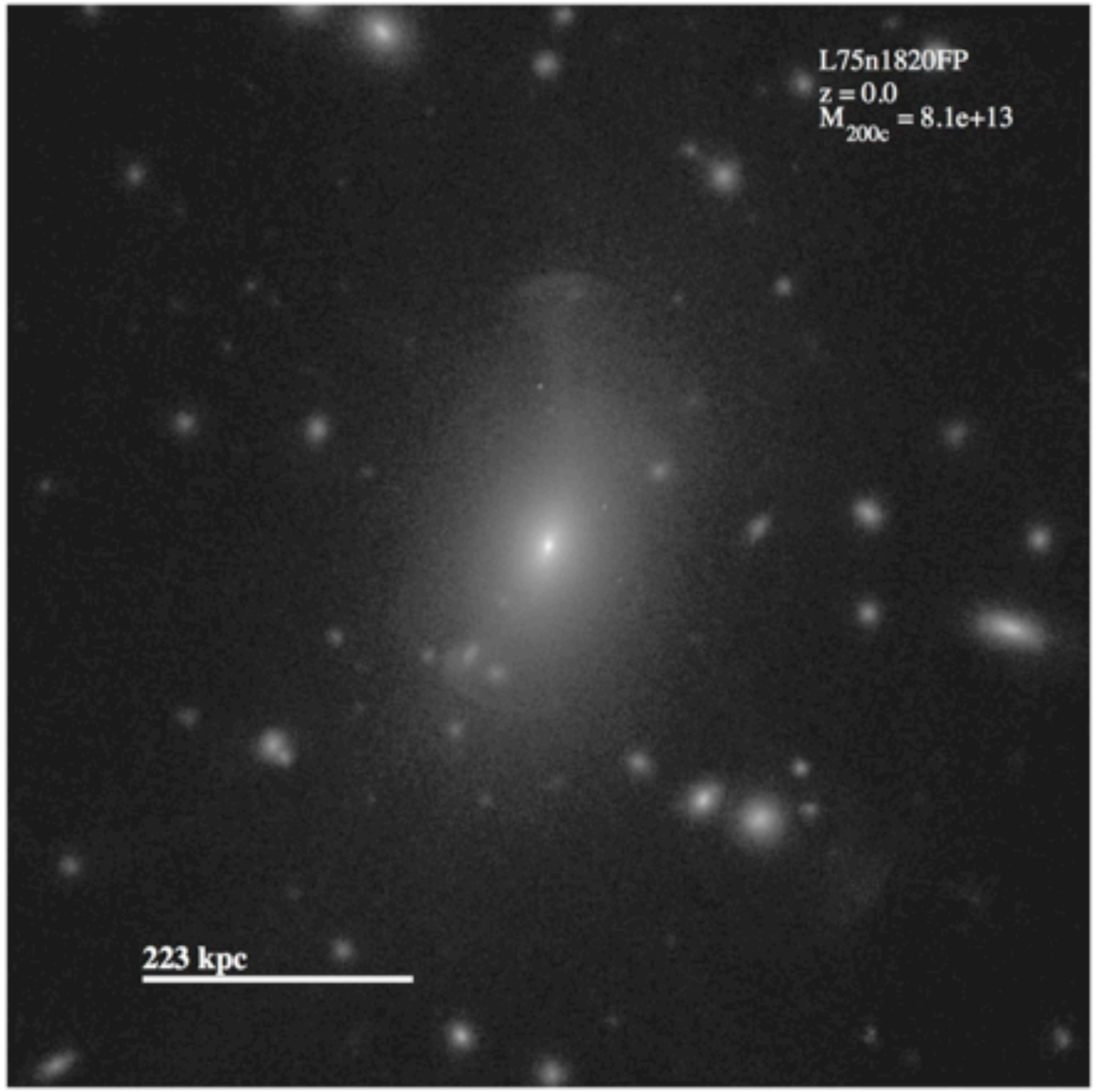
With Illustris, we could sample thousands of stellar haloes and predict the typical slope of the stellar mass density profiles at low surface brightness



Pillepich et al. 2014

Examples of predictions/gifts/applications: on stellar haloes

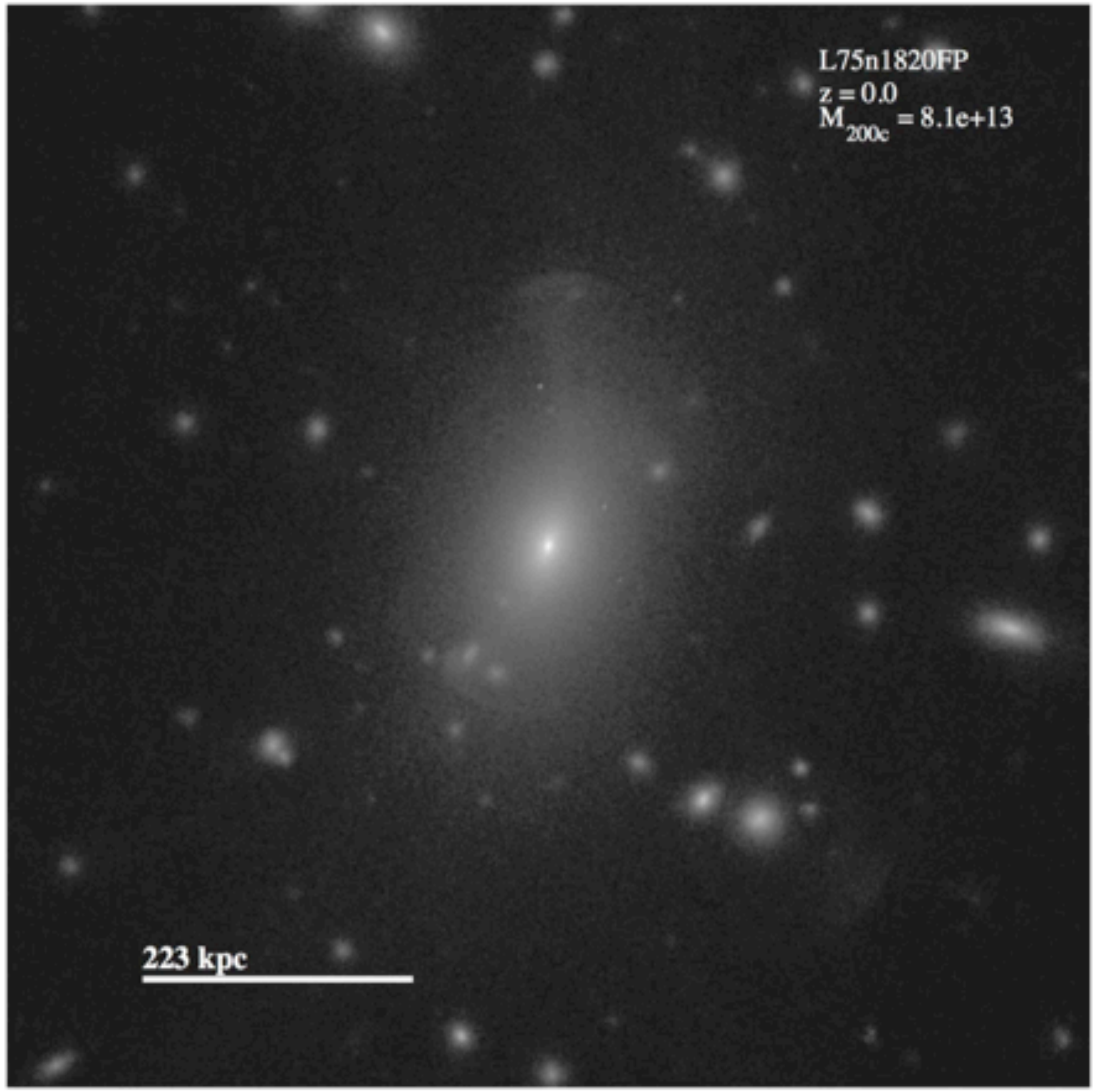
With Illustris, we could sample thousands of stellar haloes and predict the typical slope of the stellar mass density profiles at low surface brightness

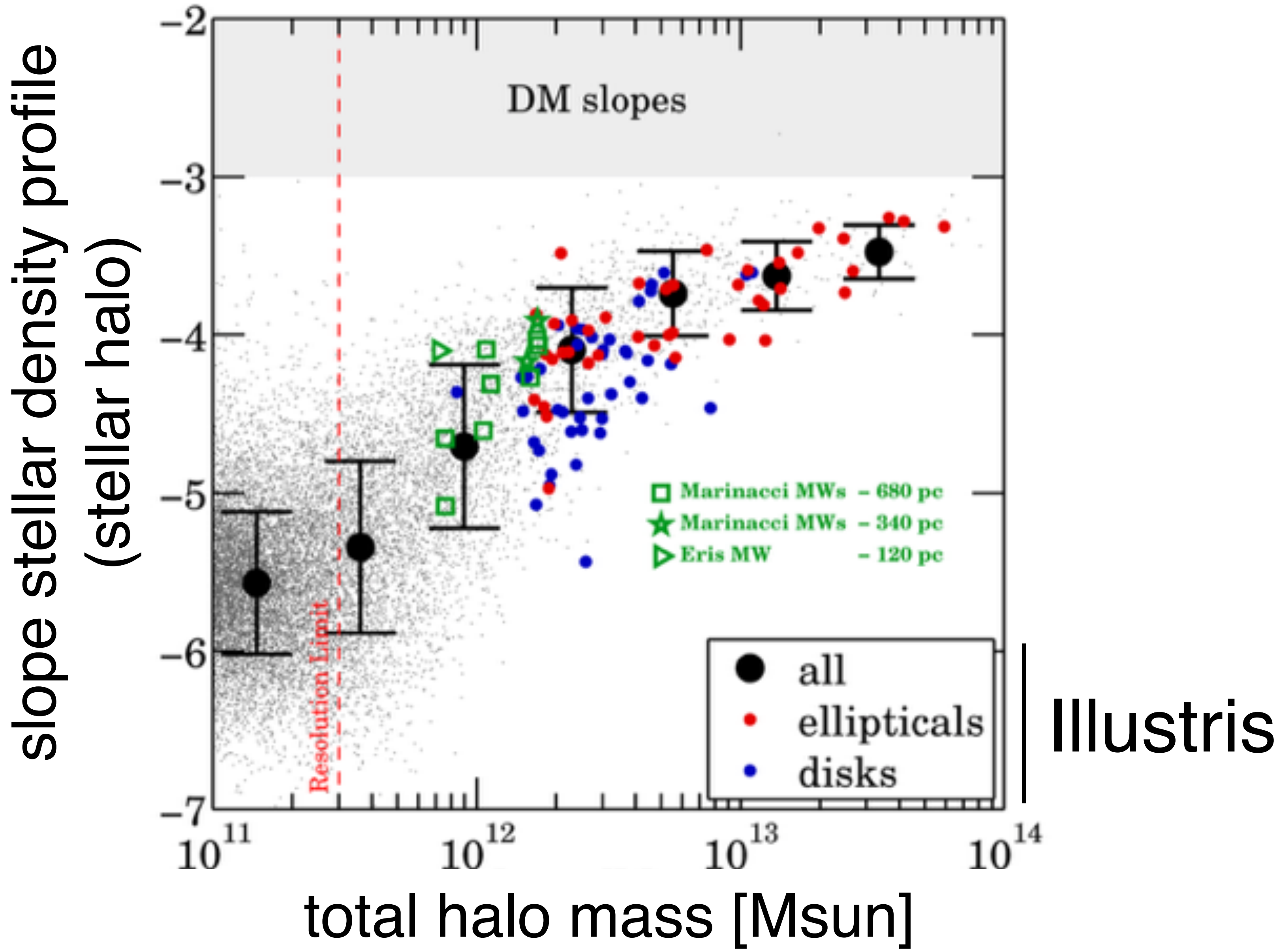


Pillepich et al. 2014

Examples of predictions/gifts/applications: on stellar haloes

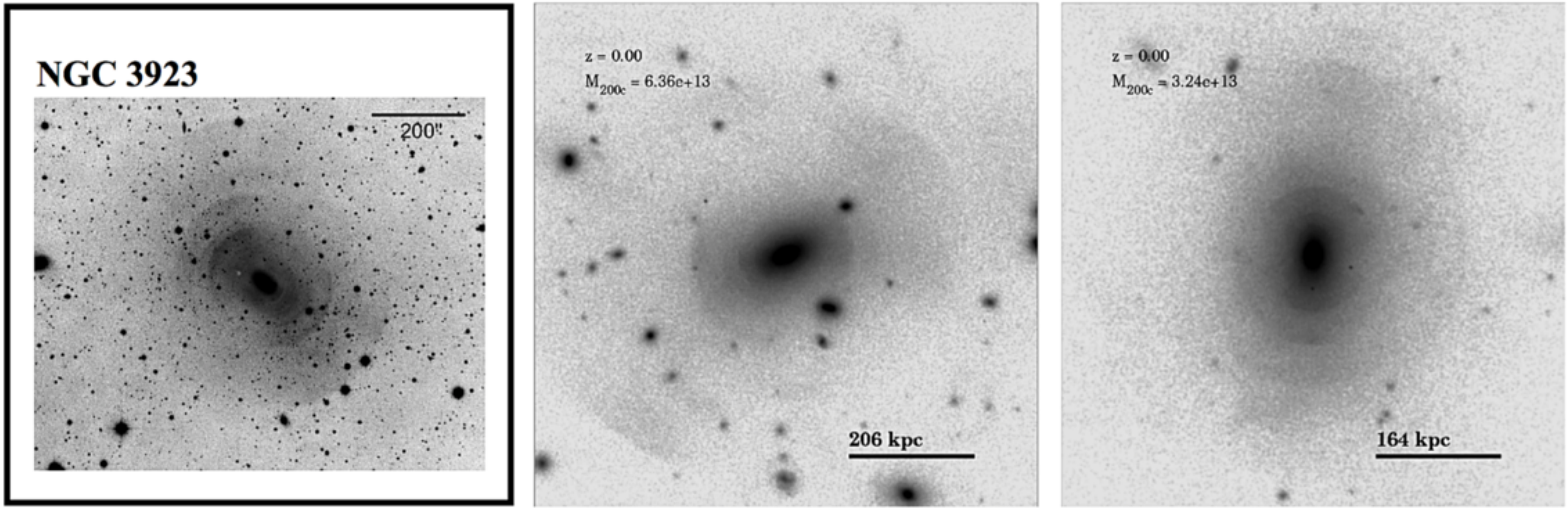
With Illustris, we could sample thousands of stellar haloes and predict the typical slope of the stellar mass density profiles at low surface brightness





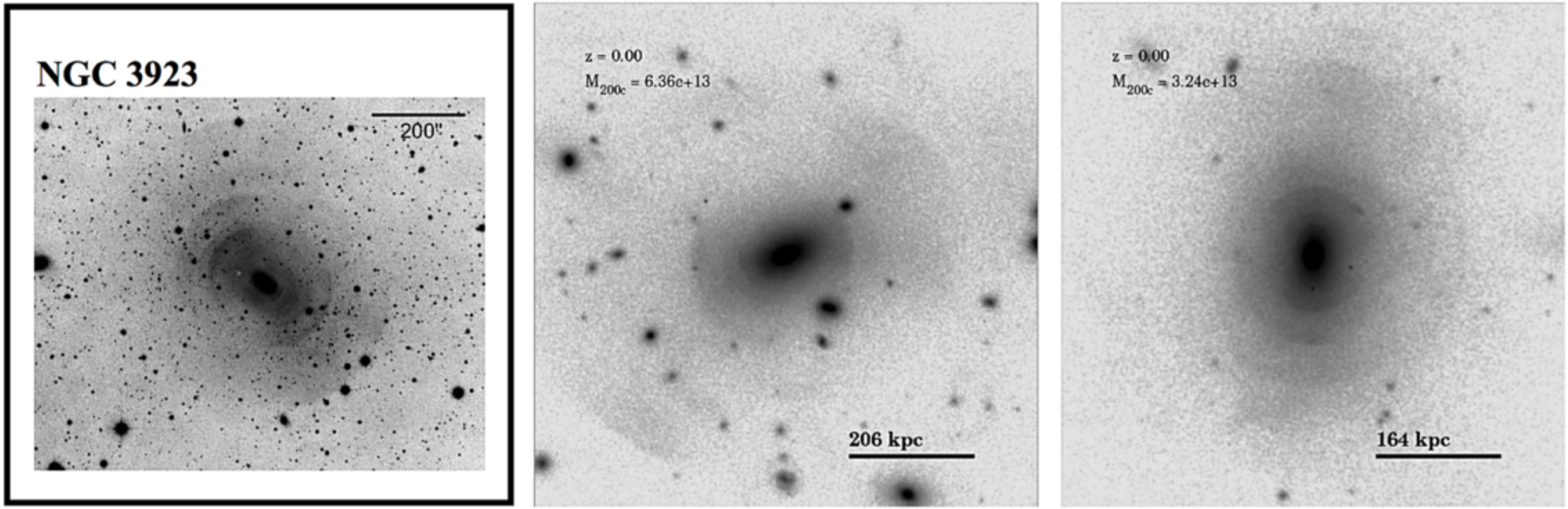
Pillepich et al. 2014

Examples of predictions/gifts/applications: on stellar haloes features



Pop, Pillepich et al. 2017

Examples of predictions/gifts/applications: on stellar haloes features

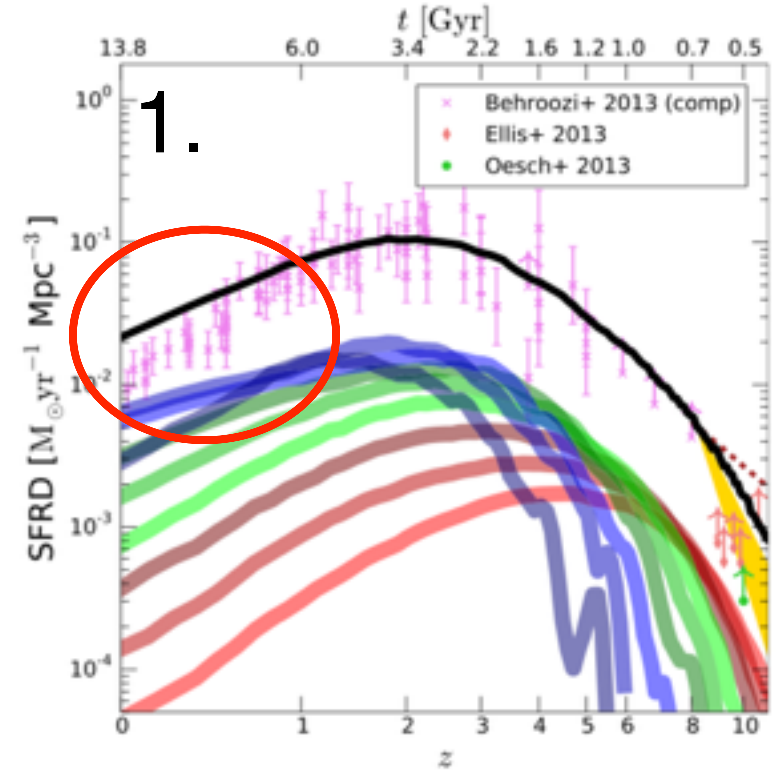


Prediction: about 18% of galaxies in haloes > 6x10^12 Msun should have stellar shells in their outskirts, at z=0

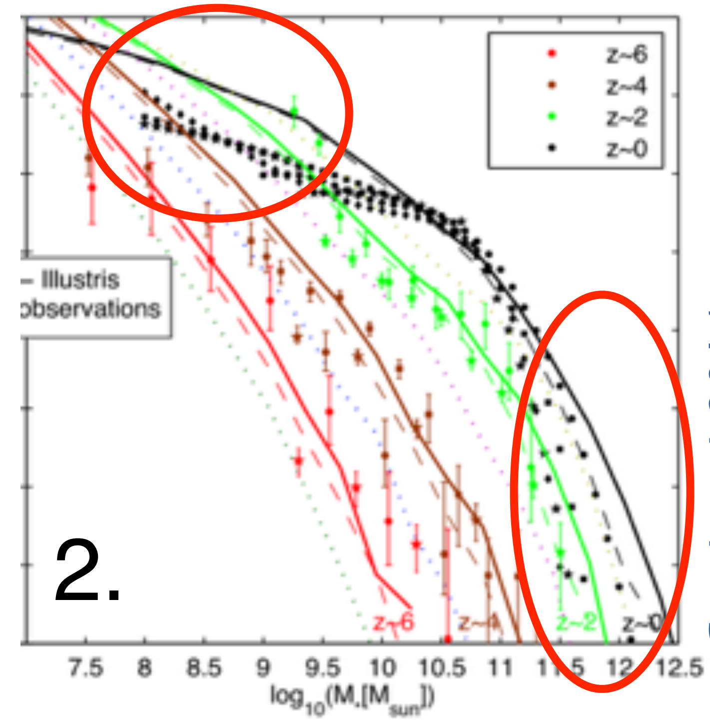
Pop, Pillepich et al. 2017

Illustris Limitations, i.e. issues identified in the Illustris galaxies

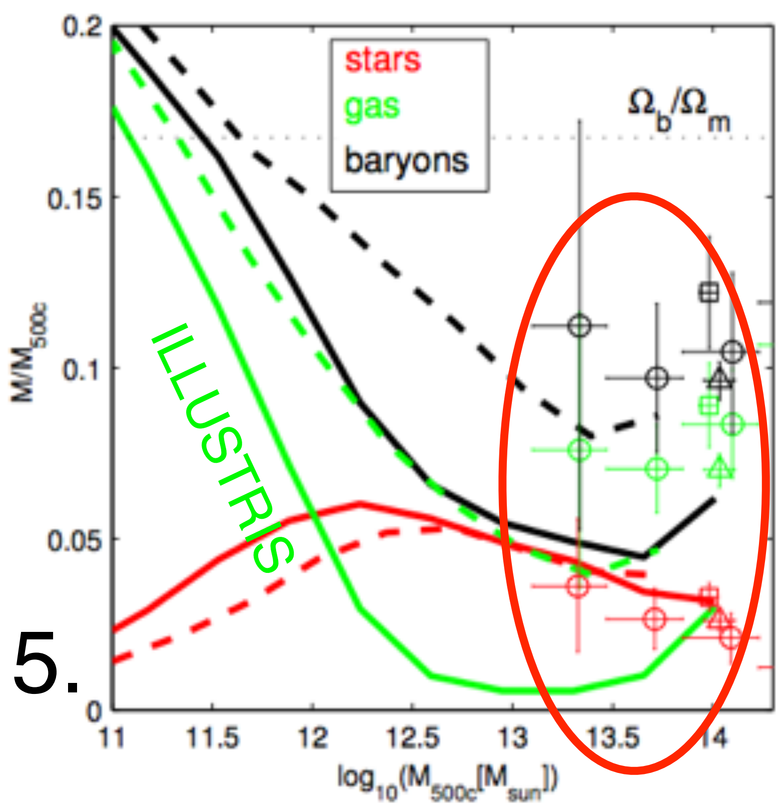
1. Too high Cosmic SFRD at z<1
2. Too high galaxy stellar mass function at z=0 at the low & high mass ends
3. Too extended stellar sizes for galaxies < 10^10 Msun
4. Spurious ring-like features at z=0
5. Too low halo gas fractions with R500 in haloes > 10^13.5 Msun
6. Not well enhanced galaxy color bimodality



Vogelsberger et al. 2014b

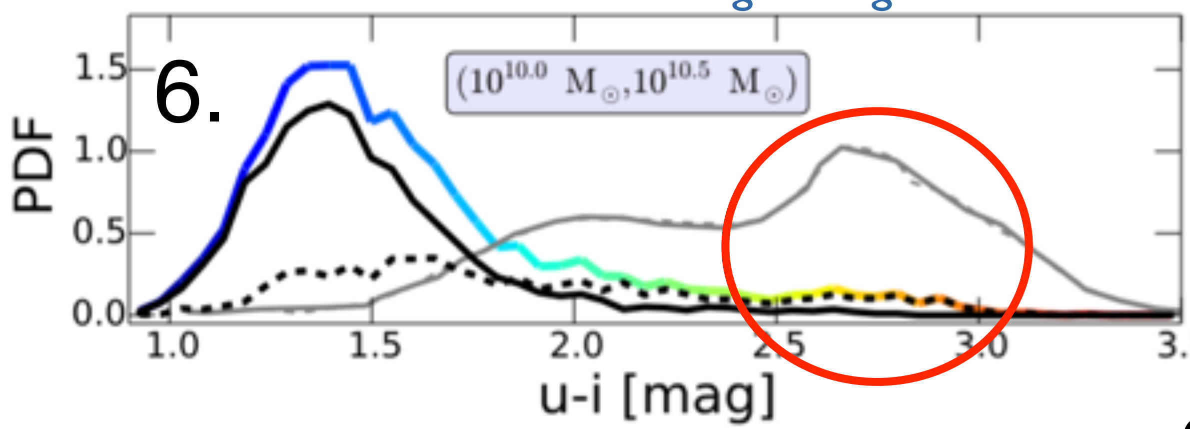


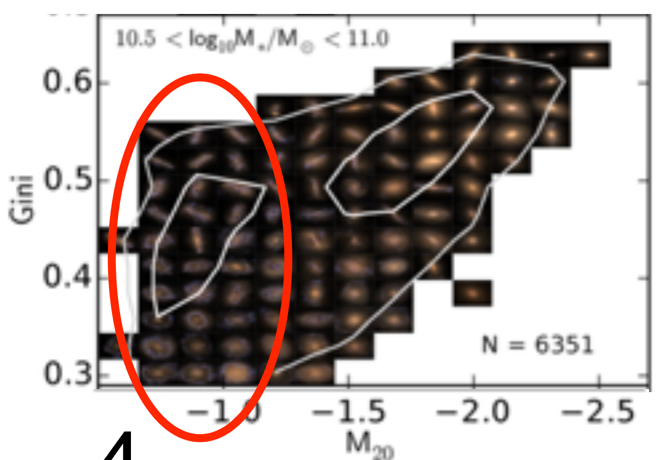
Genel et al. 2014

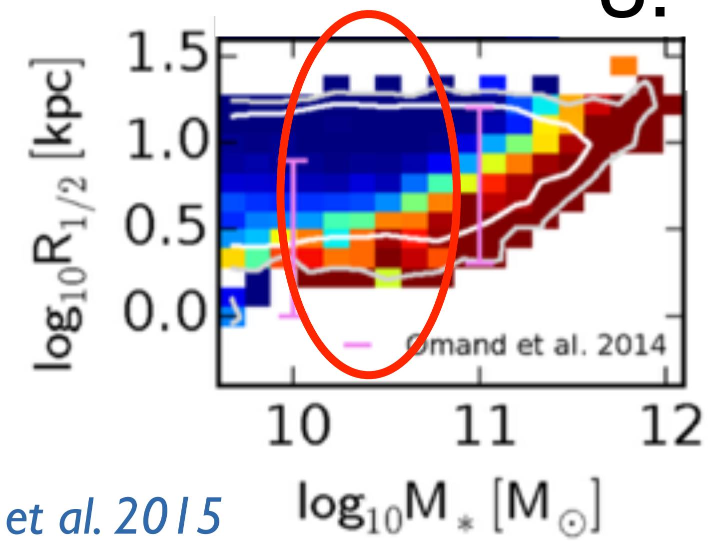


Genel et al. 2014

Vogelsberger et al. 2014







Snyder et al. 2015

The TNG Model
(and its ingredients)

The TNG Model (an *effective* model for galaxy physics)

Springel 2010, Vogelsberger 2013, Torrey 2014, Genel 2014

AREPO Code + Cosmological ICs + Illustris Framework

GRAVITY+HYDRODYNAMICS — DM HALO and LARGE SCALE STRUCTURE ASSEMBLY — COSMOLOGICAL GAS ACCRETION — Gas Cooling/Heating — Threshold-based star formation — Stellar Evolution — Metal Enrichment — Galactic Winds Feedback — Black Hole Seed and Growth — Black Hole Feedback

The TNG Model (an *effective* model for galaxy physics)

Springel 2010, Vogelsberger 2013, Torrey 2014, Genel 2014

AREPO Code + Cosmological ICs + Illustris Framework

GRAVITY+HYDRODYNAMICS — DM HALO and LARGE SCALE STRUCTURE ASSEMBLY — COSMOLOGICAL GAS ACCRETION — Gas Cooling/Heating — Threshold-based star formation — Stellar Evolution — Metal Enrichment — Galactic Winds Feedback — Black Hole Seed and Growth — Black Hole Feedback

Weinberger et al. 2017, Pillepich et al. 2017

- Numerical improvements

Pakmor et al. 2016, Springel et al.

- New physics and sub grid models:
  - **MHD** and evolution of Magnetic Fields — *Pakmor et al. 2011, Pakmor & Springel 2013*
  - New low-accretion BH feedback: pulsed kinetic **BH-driven winds**
  - **Refined galactic wind feedback**
  - Revised some stellar evolution choices and new yield tables

- Diagnostic tools:
  - On the fly cosmological shock finder — *Schaal & Springel 2015, Schaal et al. 2016*
  - Metal production tracking (all metals by SNIa, SNII, AGB + Fe by SNIa, SNII)
  - Subgrid model for neutron-star mergers, as r-process material sources (Europium)

The TNG Model (an *effective* model for galaxy physics)

Springel 2010, Vogelsberger 2013, Torrey 2014, Genel 2014

AREPO Code + Cosmological ICs + Illustris Framework

GRAVITY+HYDRODYNAMICS — DM HALO and LARGE SCALE STRUCTURE ASSEMBLY — COSMOLOGICAL GAS ACCRETION — Gas Cooling/Heating — Threshold-based star formation — Stellar Evolution — Metal Enrichment — Galactic Winds Feedback — Black Hole Seed and Growth — Black Hole Feedback

Weinberger et al. 2017, Pillepich et al. 2017

- Numerical improvements

Pakmor et al. 2016, Springel et al.

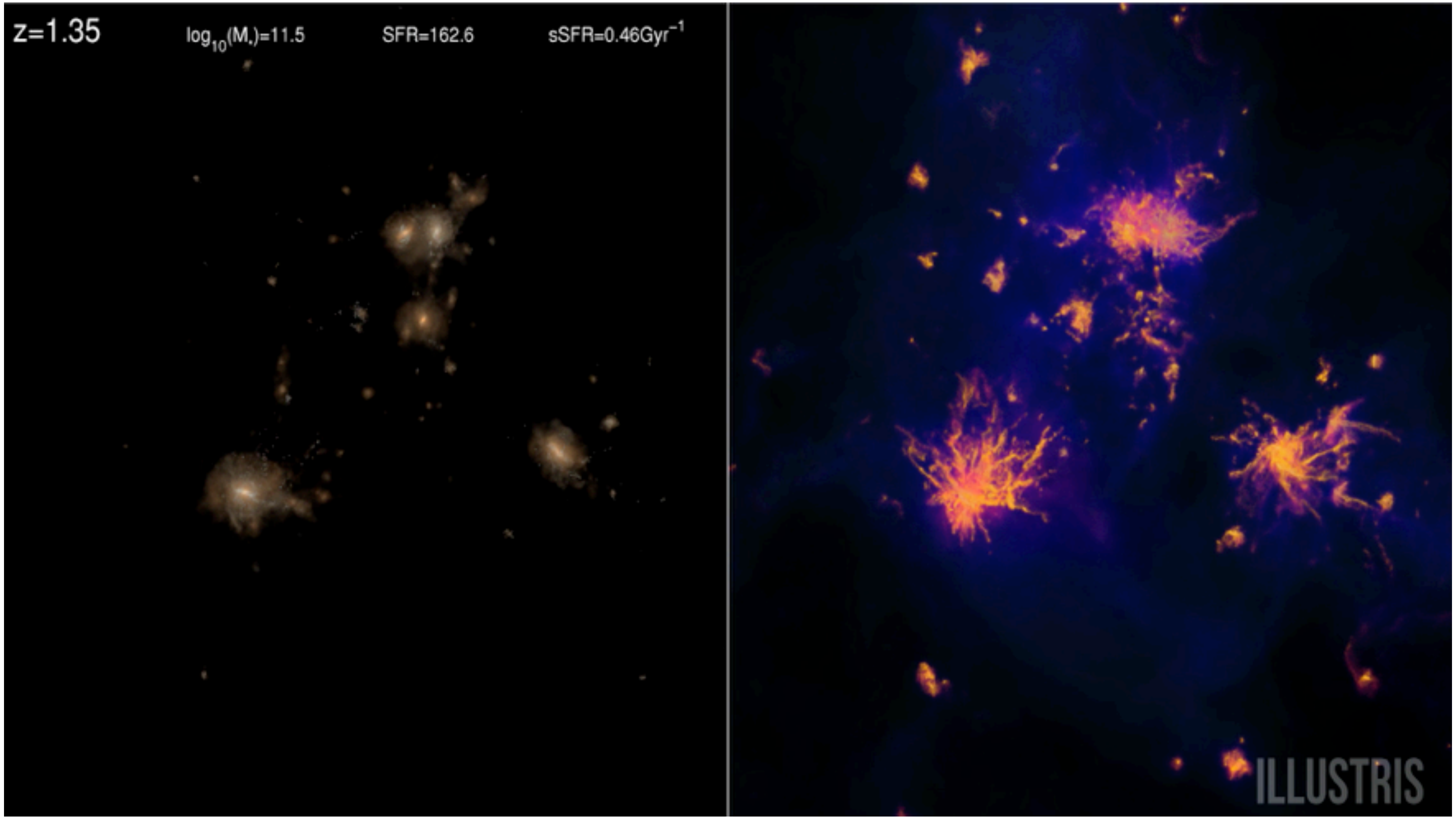
- New physics and sub grid models:
  - **MHD** and evolution of Magnetic Fields *Pakmor et al. 2011, Pakmor & Springel 2013*
  - New low-accretion BH feedback: pulsed kinetic **BH-driven winds**
  - **Refined galactic wind feedback**
  - Revised some stellar evolution choices and new yield tables

- Diagnostic tools:
  - On the fly cosmological shock finder *Schaal & Springel 2015, Schaal et al. 2016*
  - Metal production tracking (all metals by SNIa, SNII, AGB + Fe by SNIa, SNII)
  - Subgrid model for neutron-star mergers, as r-process material sources (Europium)

On the Cosmological Ingredient: Hierarchical Growth of Galaxies

credits: Shy Genel

STELLAR LIGHT

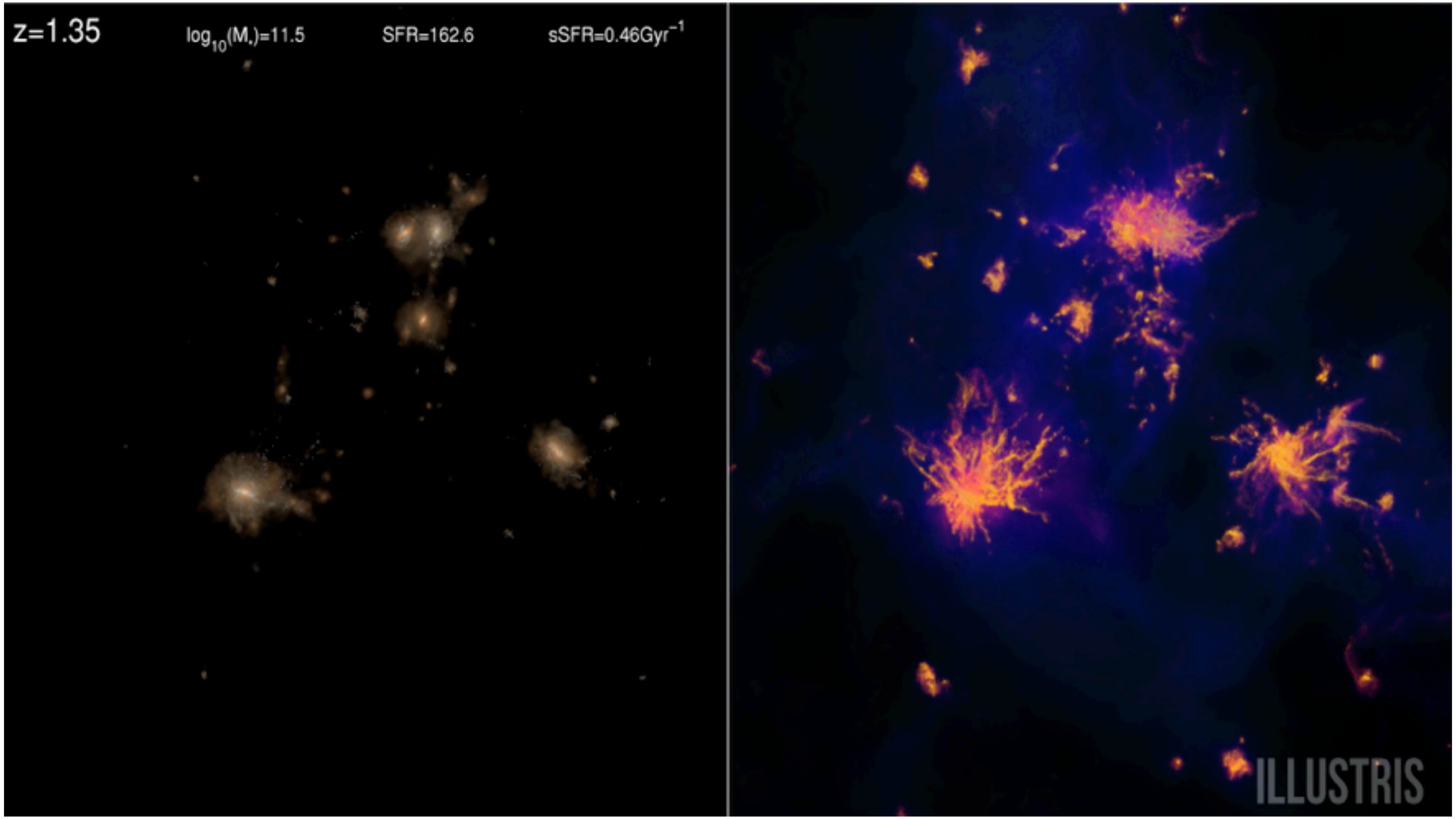


GAS DENSITY

THE HIERARCHICAL GROWTH OF GALAXIES, TIDAL AND RAM PRESSURE STRIPPING, DYNAMICAL FRICTION etc ARE ALL “EMERGING” PROCESSES IN SIMULATIONS LIKE ILLUSTRIS/TNG

On the Cosmological Ingredient: Hierarchical Growth of Galaxies

credits: Shy Genel



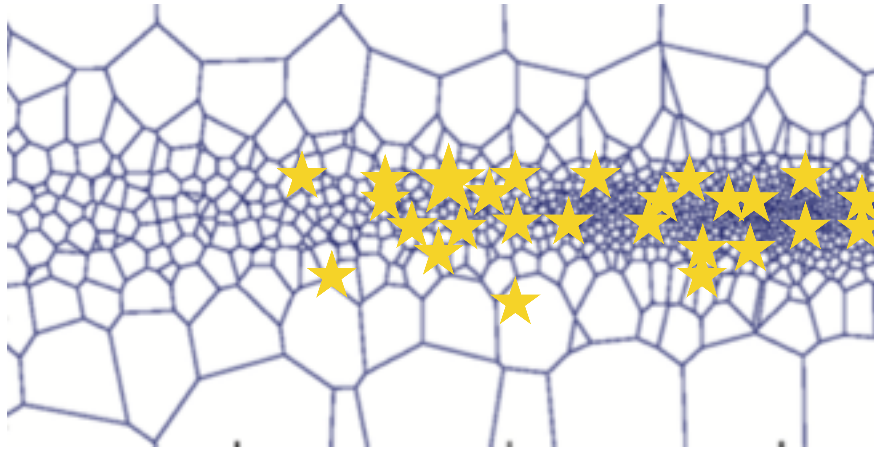
STELLAR LIGHT

GAS DENSITY

THE HIERARCHICAL GROWTH OF GALAXIES, TIDAL AND RAM PRESSURE STRIPPING, DYNAMICAL FRICTION etc ARE ALL “EMERGING” PROCESSES IN SIMULATIONS LIKE ILLUSTRIS/TNG

On Star Formation and the Interstellar Medium

In galaxy simulations, the conversion of gas into stars is also sub grid.



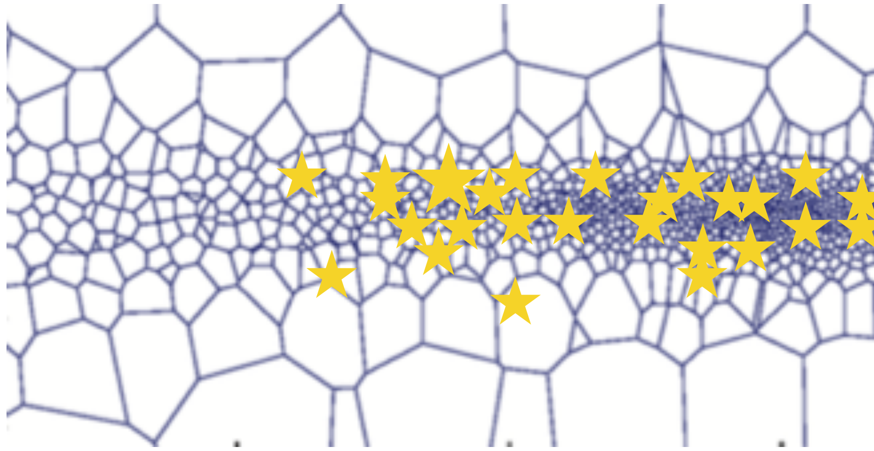
The limited resolution does not allow to resolve the very dense and cold (T << 10^4K) gas:

- In Illustris/TNG, if n_H > 0.1 cm^-3 => gas mass goes into stars with a certain SF time scale
- Stellar particles represent single age stellar populations with a given IMF
- In practice, the gas is imposed a pressure floor, i.e. is placed “by hand” onto an effective equation of state (a relation between T and rho)

Additional Ingredients:
DE FACTO, among our calibrator there is also the Kennicut-Schmidt Relation

On Star Formation and the Interstellar Medium

In galaxy simulations, the conversion of gas into stars is also sub grid.



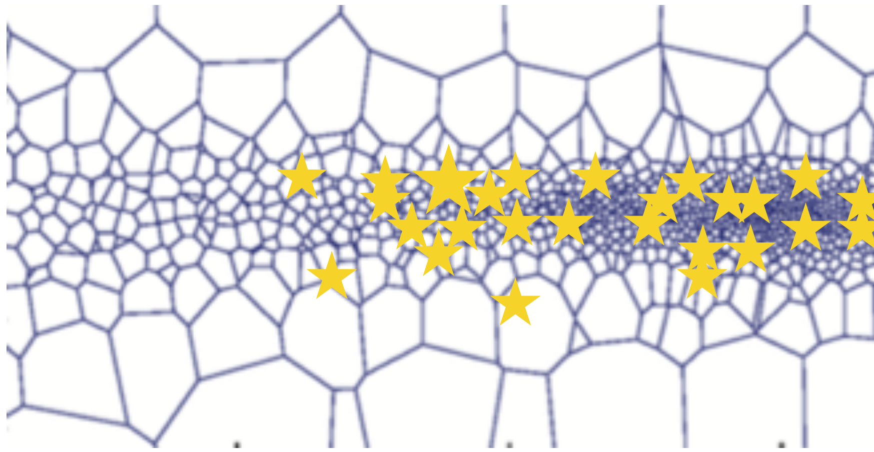
The limited resolution does not allow to resolve the very dense and cold (T << 10^4K) gas:

- In Illustris/TNG, if n_H > 0.1 cm^-3 => gas mass goes into stars with a certain SF time scale
- Stellar particles represent single age stellar populations with a given IMF
- In practice, the gas is imposed a pressure floor, i.e. is placed "by hand" onto an effective equation of state (a relation between T and rho)

Additional Ingredients:
DE FACTO, among our calibrator there is also the Kennicut-Schmidt Relation

On Star Formation and the Interstellar Medium

In galaxy simulations, the conversion of gas into stars is also sub grid.



The limited resolution does not allow to resolve the very dense and cold (T << 10^4K) gas:

- In Illustris/TNG, if n_H > 0.1 cm^-3 => gas mass goes into stars with a certain SF time scale
- Stellar particles represent single age stellar populations with a given IMF
- In practice, the gas is imposed a pressure floor, i.e. is placed "by hand" onto an effective equation of state (a relation between T and rho)

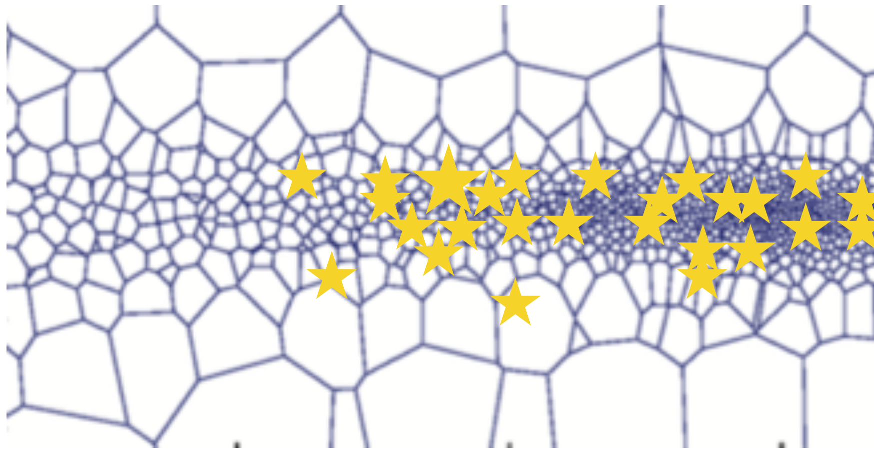
About the SF threshold:

- Different sims assume different values (e.g. in Eris has n = 5 cm^-3)
- In Eagle, n is Z dependent
- In FIRE, it is the molecular gas that matters + gas must be self gravitating

Additional Ingredients:
DE FACTO, among our calibrator there is also the Kennicut-Schmidt Relation

On Star Formation and the Interstellar Medium

In galaxy simulations, the conversion of gas into stars is also sub grid.



The limited resolution does not allow to resolve the very dense and cold (T << 10^4K) gas:

- In Illustris/TNG, if n_H > 0.1 cm^-3 => gas mass goes into stars with a certain SF time scale
- Stellar particles represent single age stellar populations with a given IMF
- In practice, the gas is imposed a pressure floor, i.e. is placed "by hand" onto an effective equation of state (a relation between T and rho)

Possibly with different shapes in different models (e.g. EAGLE)

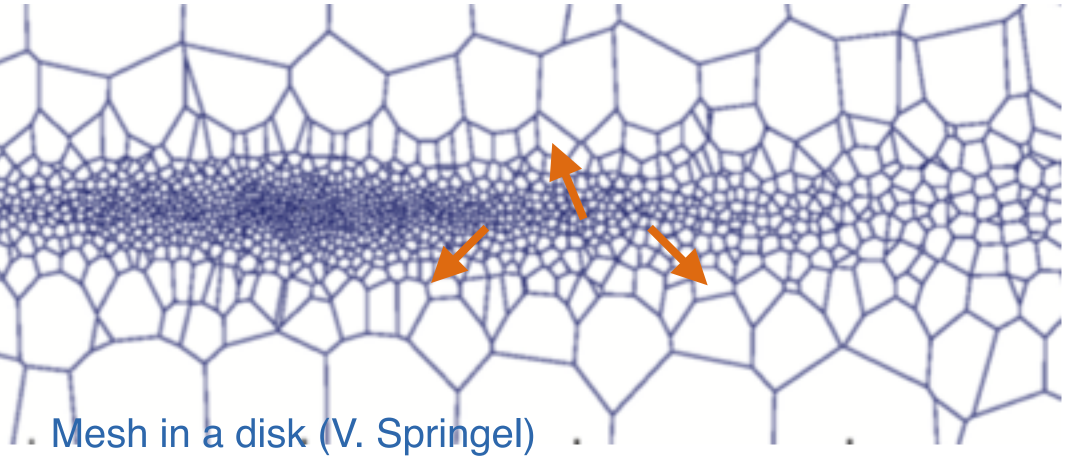
About the SF threshold:

- Different sims assume different values (e.g. in Eris has n = 5 cm^-3)
- In Eagle, n is Z dependent
- In FIRE, it is the molecular gas that matters + gas must be self gravitating

Additional Ingredients:
DE FACTO, among our calibrator there is also the Kennicut-Schmidt Relation

Pillepich, Springel, Nelson et al. 2017

Stellar Feedback: Subgrid Implementation in Illustris/TNG


Mesh in a disk (V. Springel)

Wind particles are spawned from star forming gas cells, decoupled from the hydro

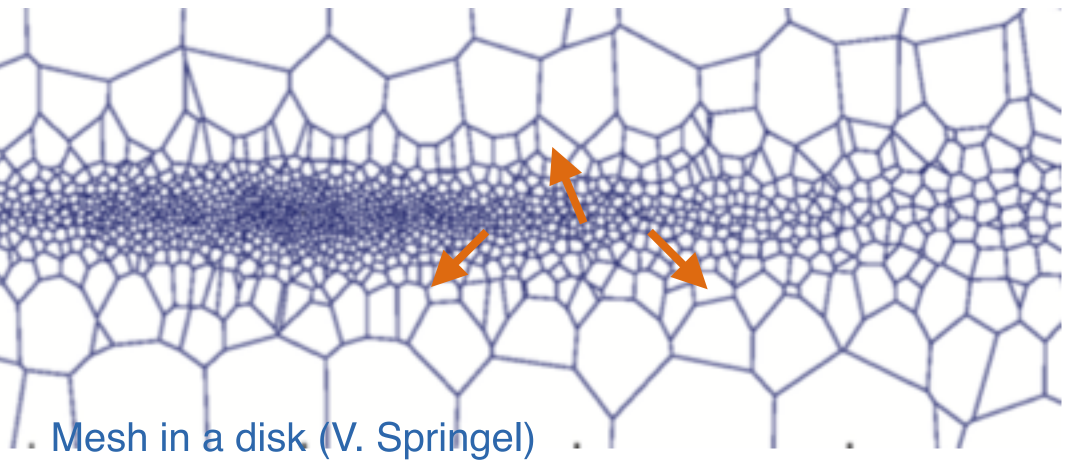
Choices at injection: velocity, mass loading/ energy, thermal content

$$\boxed{\dot{E}_w = e_w \dot{M}_{\rm SFR}; \quad e_w \propto N_{\rm SNII}\, E_{\rm SNII,51}\, 10^{51}\, {\rm erg}\, {\rm M}_\odot^{-1},}$$

\propto

Pillepich, Springel, Nelson et al. 2017

Stellar Feedback: Subgrid Implementation in Illustris/TNG


Mesh in a disk (V. Springel)

Wind particles are spawned from star forming gas cells, decoupled from the hydro

Choices at injection: velocity, mass loading/ energy, thermal content

$$\dot{E}_w = e_w \, \dot{M}_{\rm SFR},$$

\propto

$$N_{\rm SNII} \, E_{\rm SNII,51} \, 10^{51} \, \text{erg} \, \text{M}_\odot^{-1},$$

ILLUSTRIS

Galactic Winds

ILLUSTRIS		TNG
non local, from sf-ing gas	General Approach	non local, from sf-ing gas
bipolar	Directionality	isotropic
cold	Thermal Content	warm
$\propto$ local $\sigma_{\rm DM}$	Injection Velocity	$\propto$ local $\sigma_{\rm DM}$ with H(z) scaling
-	Injection Mass Loading	gas-metallicity (Z) dependent
no	Injection Velocity Floor	yes: 350 km/s

TNG

Phenomenology of the Illustris issues: Illustris galactic winds are not effective enough at high redshifts and in small galaxies (haloes < 10^12 Msun)

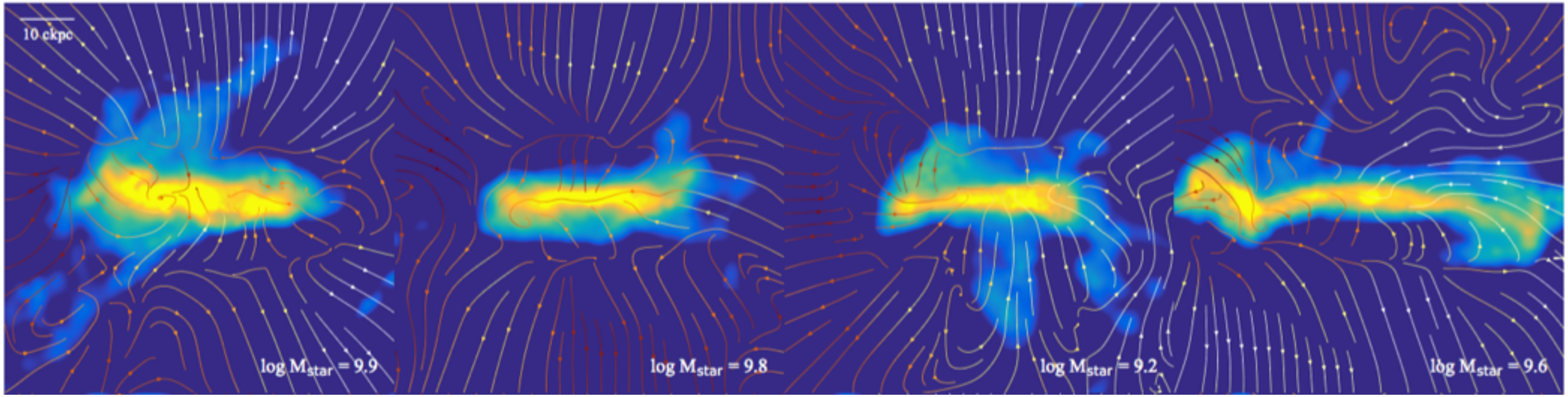
TNG Solution: Overall faster winds at all masses and redshifts, energy of the winds relatively larger in low mass systems in comparison to MW-like haloes

Stellar Feedback: Effects in Illustris/TNG

Random galaxies at z~2 from L25 Mpc/h box

Pillepich, Springel, Nelson et al. 2017

TNG (isotropic)



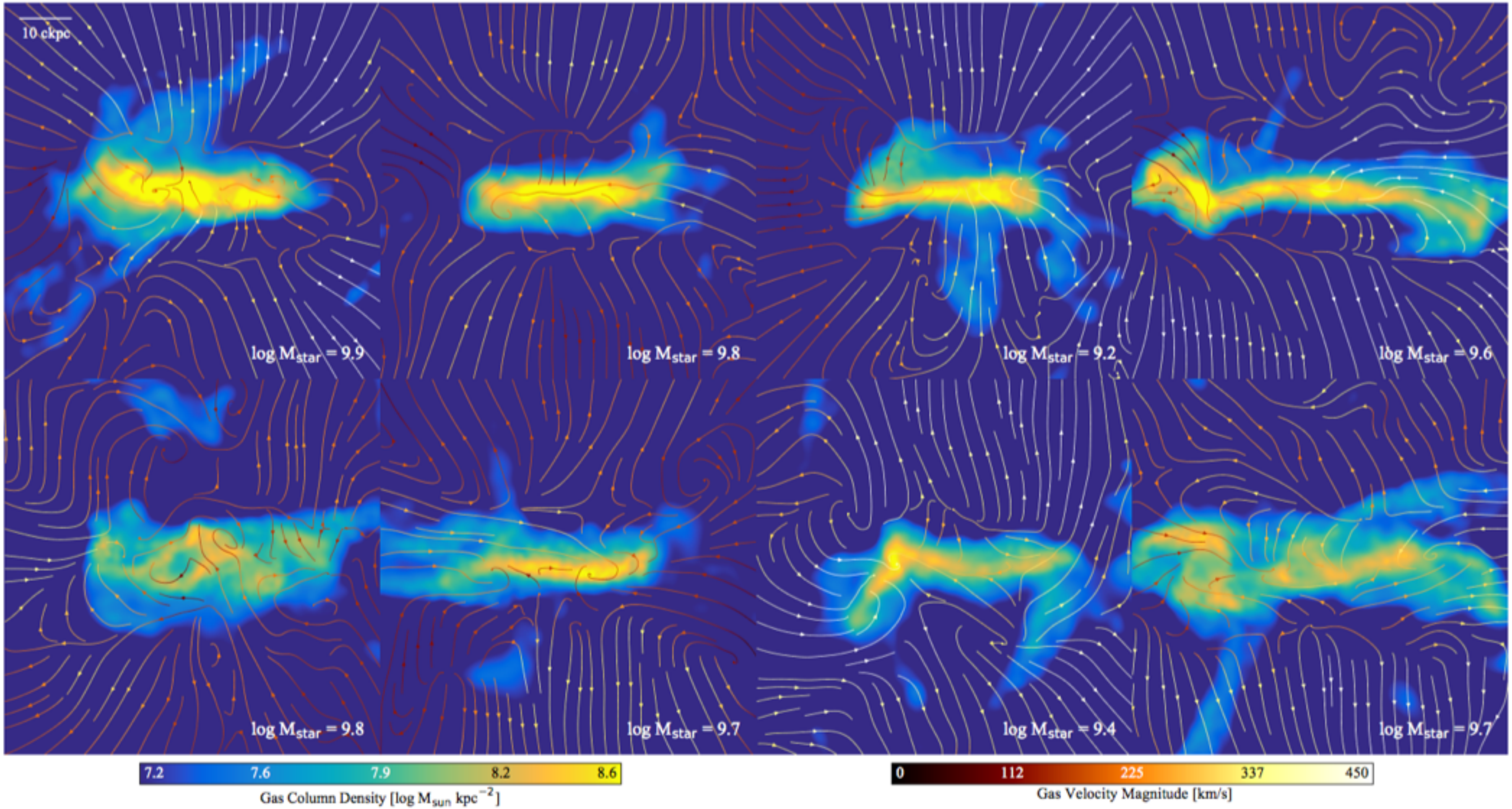
Stellar Feedback: Effects in Illustris/TNG

Random galaxies at z~2 from L25 Mpc/h box

Pillepich, Springel, Nelson et al. 2017

TNG (isotropic)

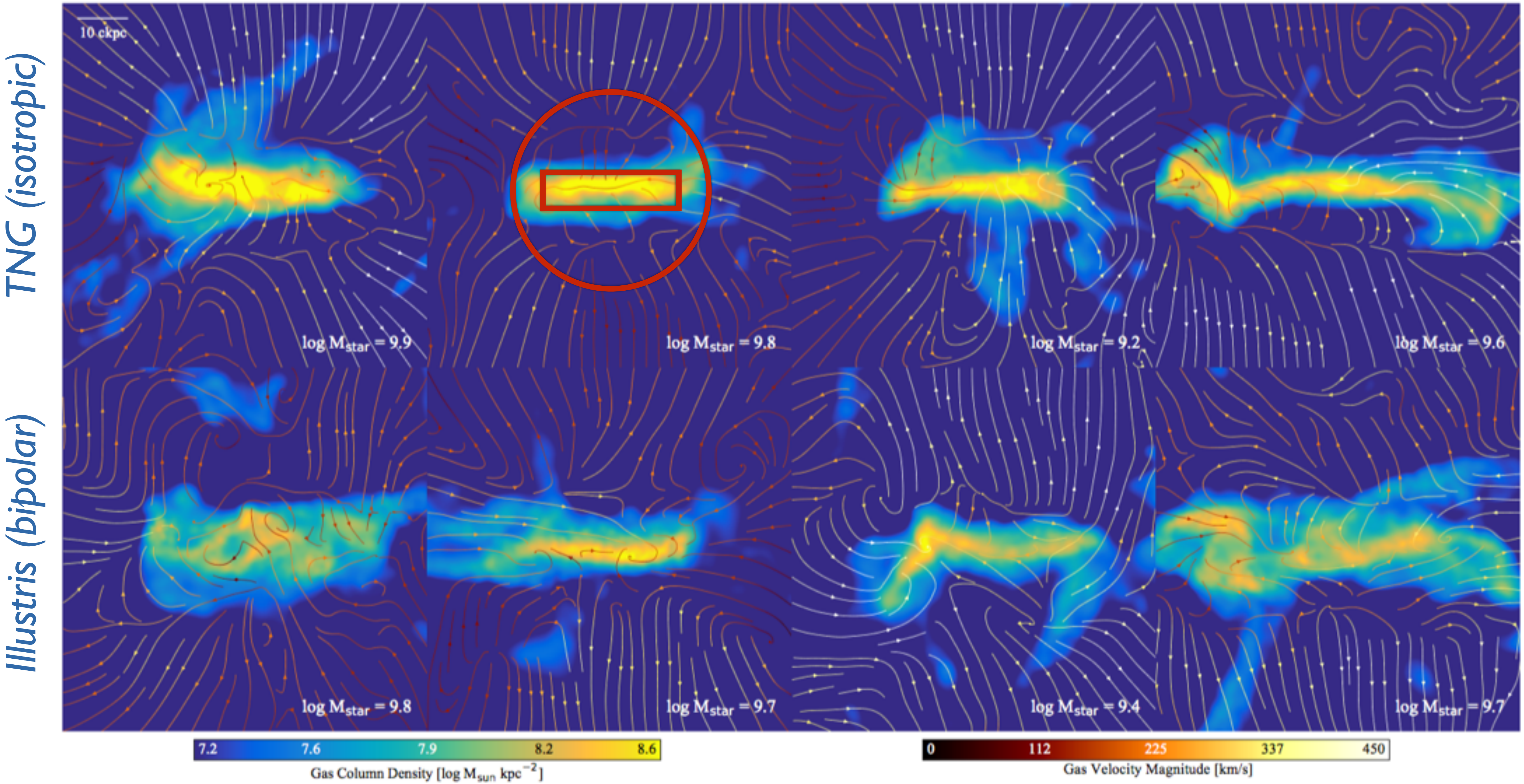
Illustris (bipolar)



Stellar Feedback: Effects in Illustris/TNG

Random galaxies at z~2 from L25 Mpc/h box

Pillepich, Springel, Nelson et al. 2017

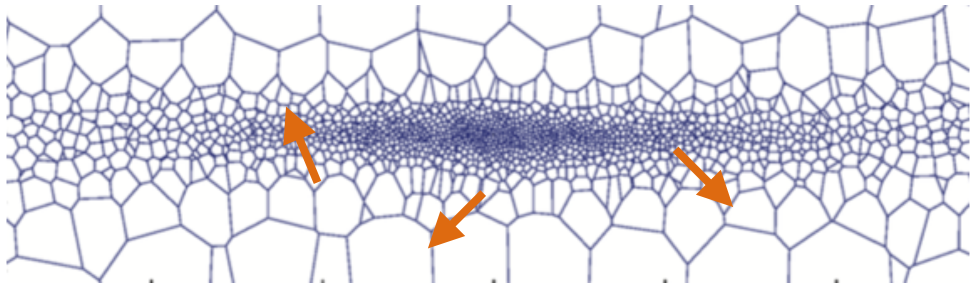


Stellar Feedback: Other Implementations on the Market

Galactic Winds/ Winds Launch

e.g. Illustris, IllustrisTNG, Auriga (see above)

e.g. MUFASA, with FIRE-inspired scalings!

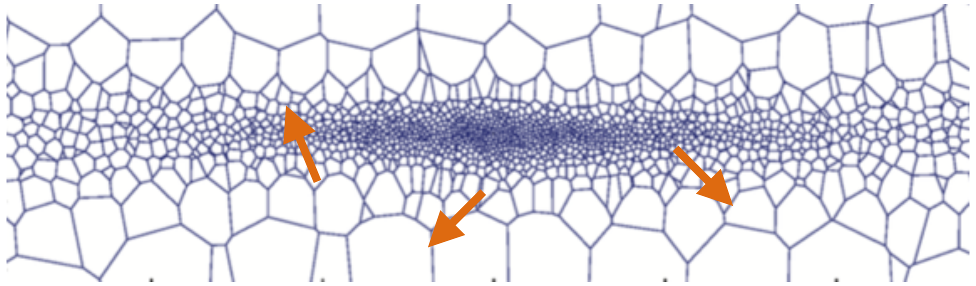


Stellar Feedback: Other Implementations on the Market

Galactic Winds/ Winds Launch

e.g. Illustris, IllustrisTNG, Auriga (see above)

e.g. MUFASA, with FIRE-inspired scalings!



SN Bubbles aka Thermal Energy Injections “around” stellar particles

Also to mimic and connected to SNII explosions

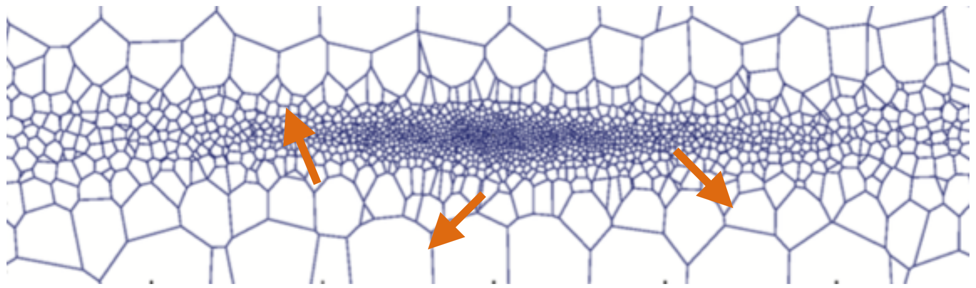
- With shut-off of the cooling of the heated gas?
  Yes, e.g. in Eris, NIHAO
- With energetic depending on ISM metallicity? EAGLE
- In addition to a kick of the surrounding gas? FIRE

Stellar Feedback: Other Implementations on the Market

Galactic Winds/ Winds Launch

e.g. Illustris, IllustrisTNG, Auriga (see above)

e.g. MUFASA, with FIRE-inspired scalings!



SN Bubbles aka Thermal Energy Injections “around” stellar particles

Also to mimic and connected to SNII explosions

- With shut-off of the cooling of the heated gas? Yes, e.g. in Eris, NIHAO
- With energetic depending on ISM metallicity? EAGLE
- In addition to a kick of the surrounding gas? FIRE

. . .

+ “Early” Stellar Feedback

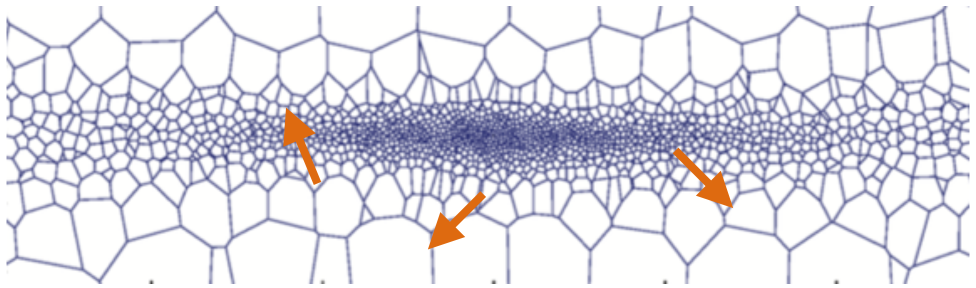
Ionizing feedback from massive stars before their explosions e.g. NIHAO, FIRE

Stellar Feedback: Other Implementations on the Market

Galactic Winds/ Winds Launch

e.g. Illustris, IllustrisTNG, Auriga (see above)

e.g. MUFASA, with FIRE-inspired scalings!



SN Bubbles aka Thermal Energy Injections “around” stellar particles

Also to mimic and connected to SNII explosions

- With shut-off of the cooling of the heated gas?
  Yes, e.g. in Eris, NIHAO
- With energetic depending on ISM metallicity? EAGLE
- In addition to a kick of the surrounding gas? FIRE

• • •

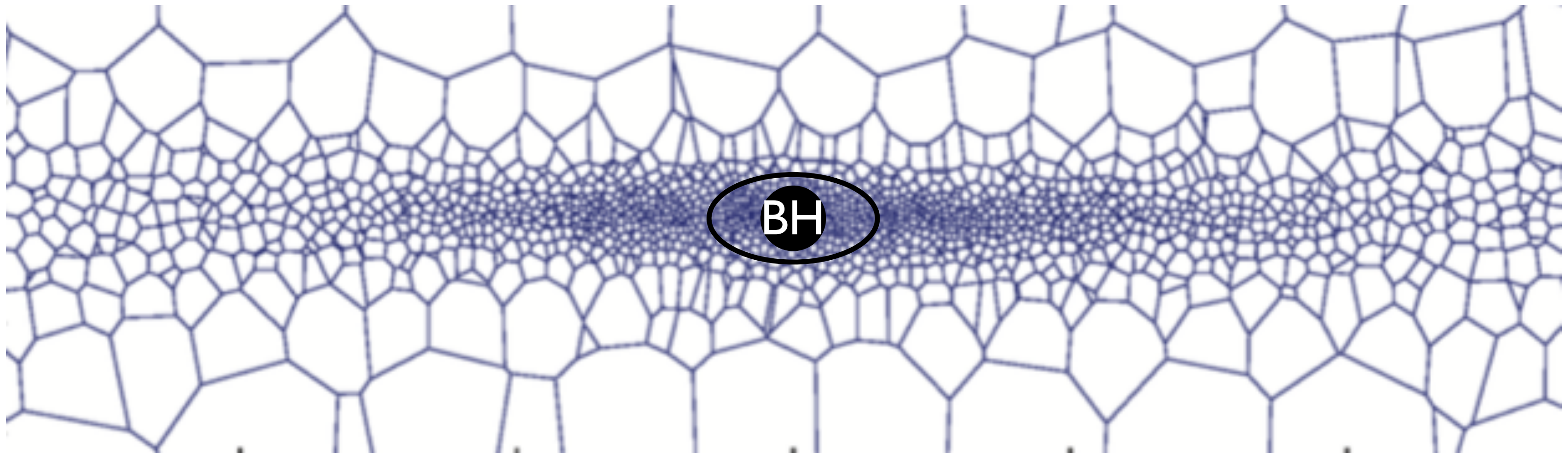
+ “Early” Stellar Feedback

Ionizing feedback from massive stars before their explosions
e.g. NIHAO, FIRE

Burstyness vs. smoothness of SF Histories

BH Feedback: BH seeding and accretion

BHs are usually placed by hand as “sink particles”:
they can grow in mass by `accreting` material from the surroundings



Mesh in a disk (V. Springel)

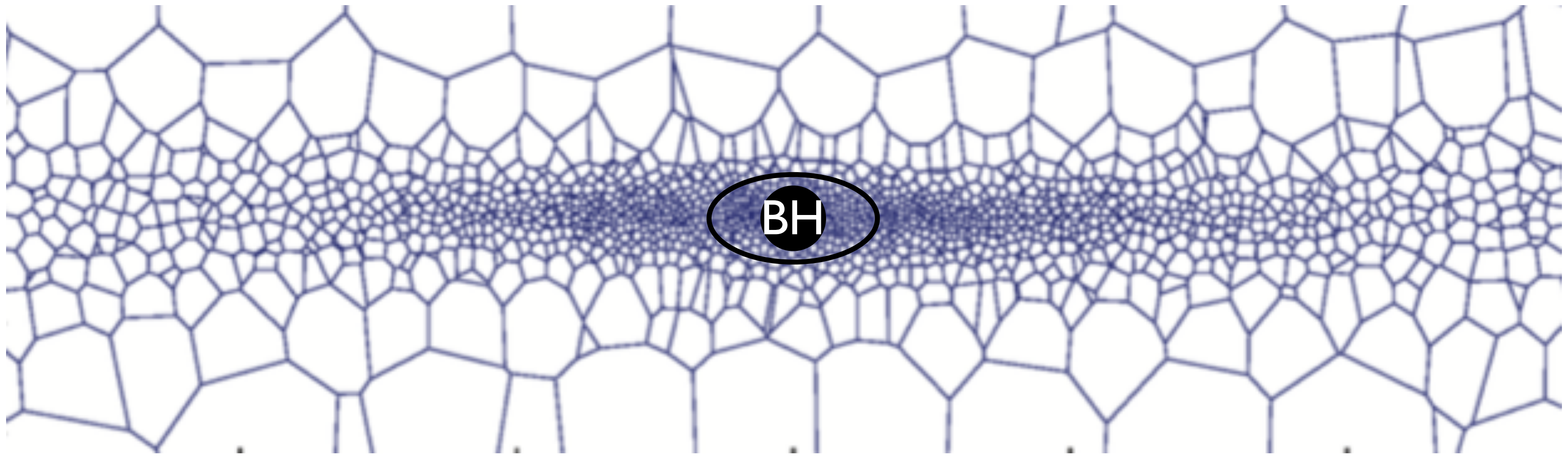
ILLUSTRIS

BH Seed Mass
FoF Halo Mass for BH seeding
BH Accretion
BH Accretion
BH Positioning

TNG

BH Feedback: BH seeding and accretion

BHs are usually placed by hand as “sink particles”:
they can grow in mass by `accreting` material from the surroundings



Mesh in a disk (V. Springel)

ILLUSTRIS		TNG
$1 \times 10^5 h^{-1} \mathrm{M}_\odot$	BH Seed Mass	$8 \times 10^5 h^{-1} \mathrm{M}_\odot$
$5 \times 10^{10} h^{-1} \mathrm{M}_\odot$	FoF Halo Mass for BH seeding	$5 \times 10^{10} h^{-1} \mathrm{M}_\odot$
$\alpha = 100$ Boosted Bondi-Hoyle	BH Accretion	Un-boosted Bondi-Hoyle (w/ v_A)
parent gas cell, Eddington limited	BH Accretion	nearby cells, Eddington limited
fixed to halo potential minimum	BH Positioning	fixed to halo potential minimum

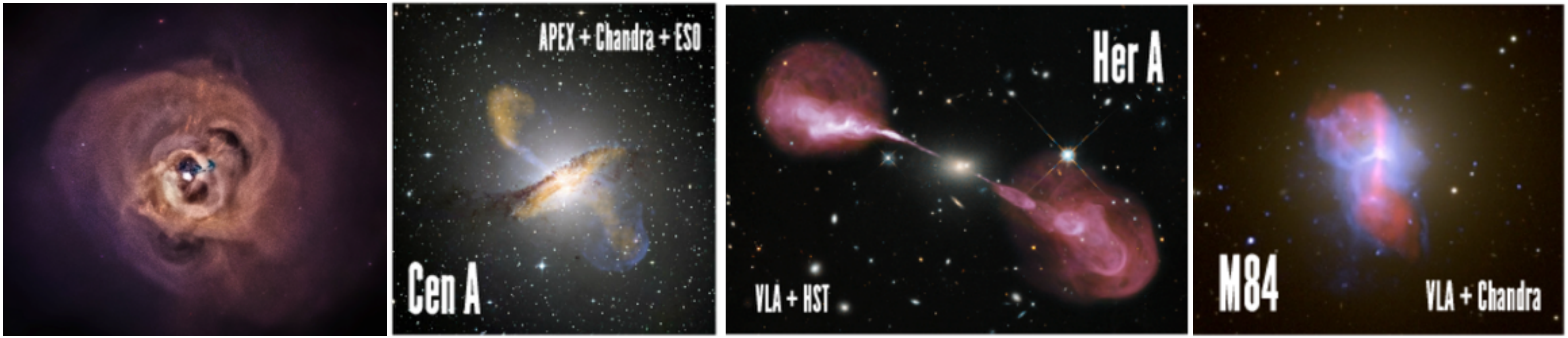
$$\dot{M}_{\rm BH} = \frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho}{\left(c_s^2 + v^2\right)^{3/2}}$$

$$\dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_{\rm r} \sigma_{\rm T} c}$$

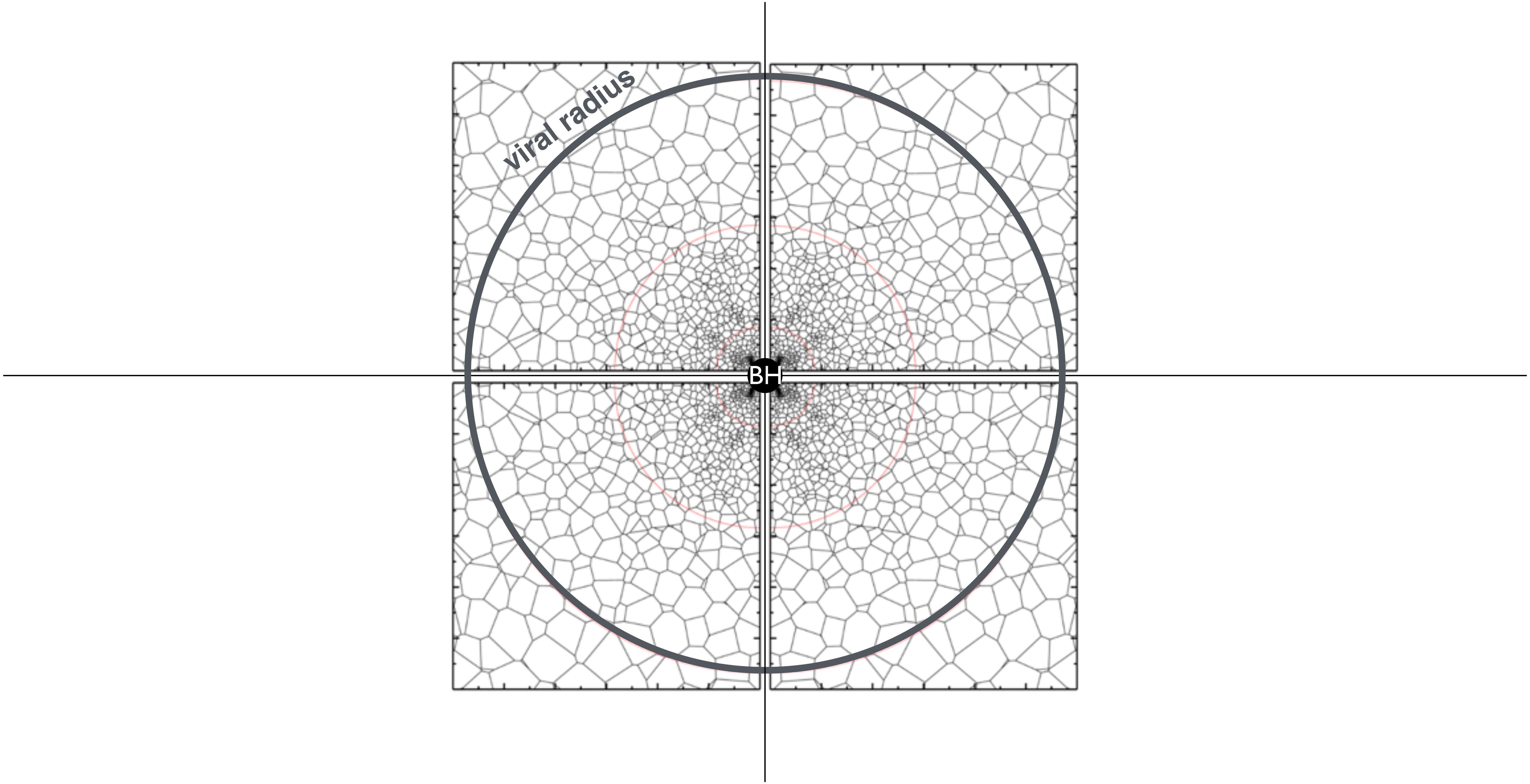
BH Feedback: Subgrid Implementation

Goal: to exchange energy and/or momentum from the central BH to the surrounding medium

Possibly, with outcomes that resemble what we think we see in reality

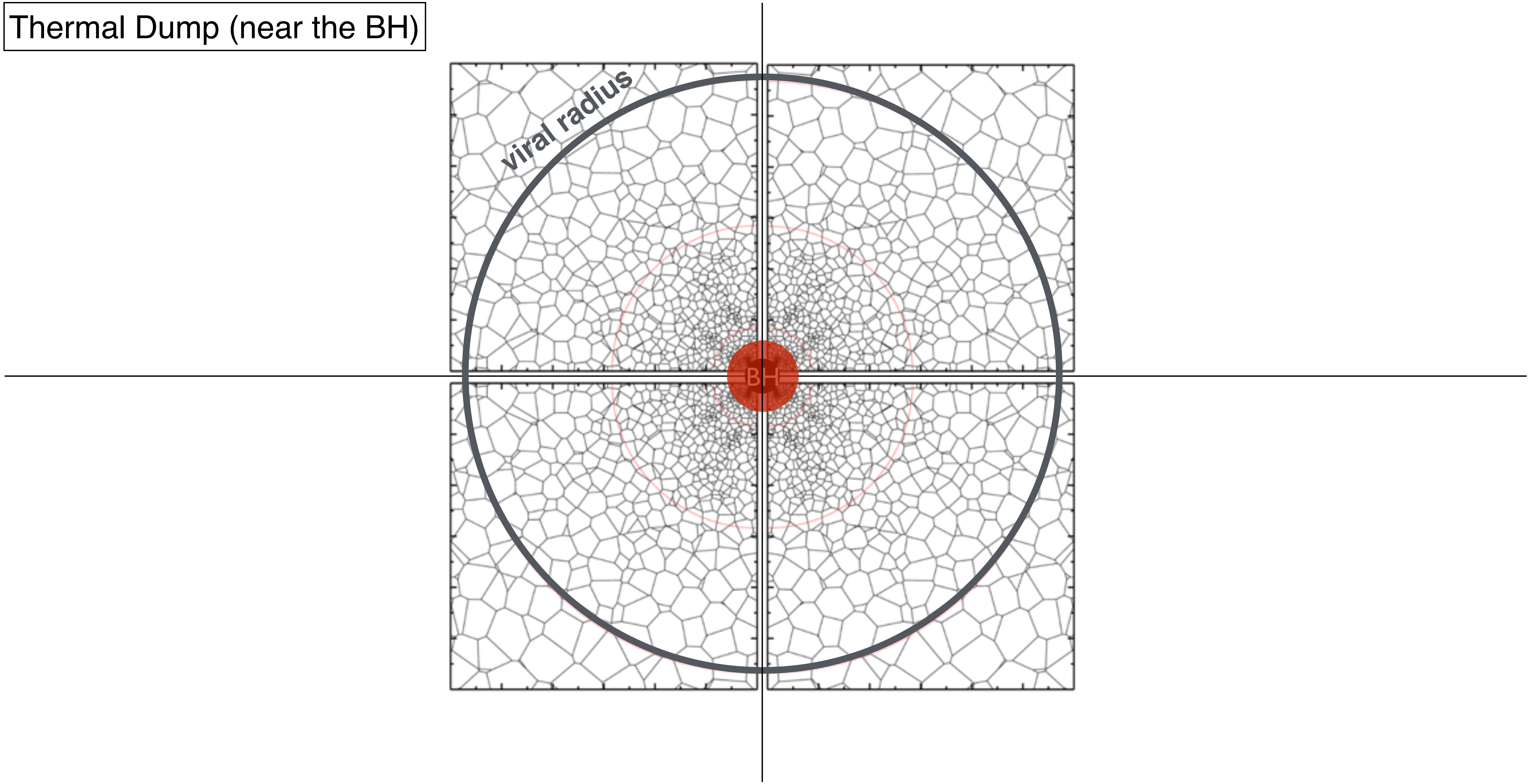


BH Feedback: Subgrid Implementation



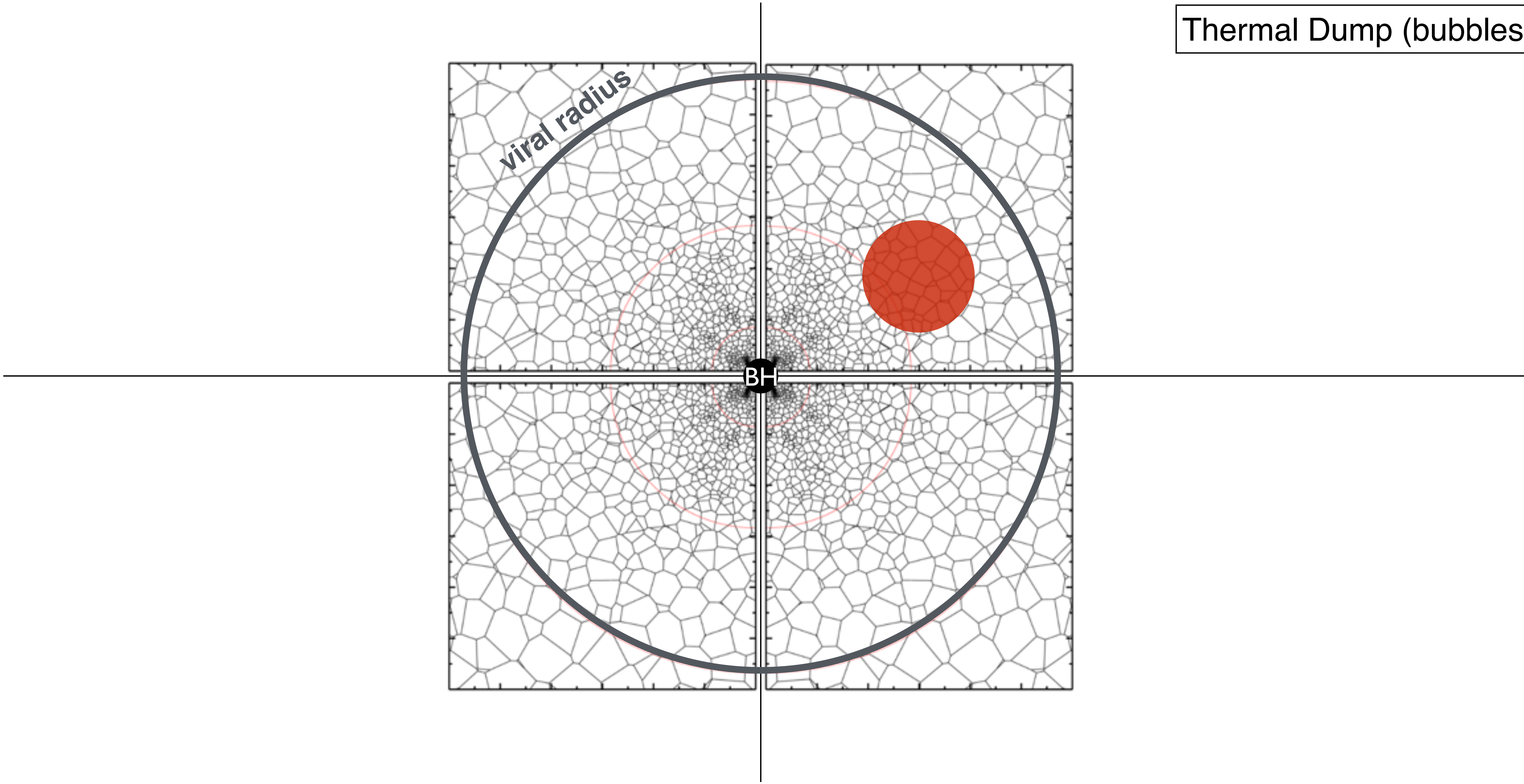
BH Feedback: Subgrid Implementation

Thermal Dump (near the BH)



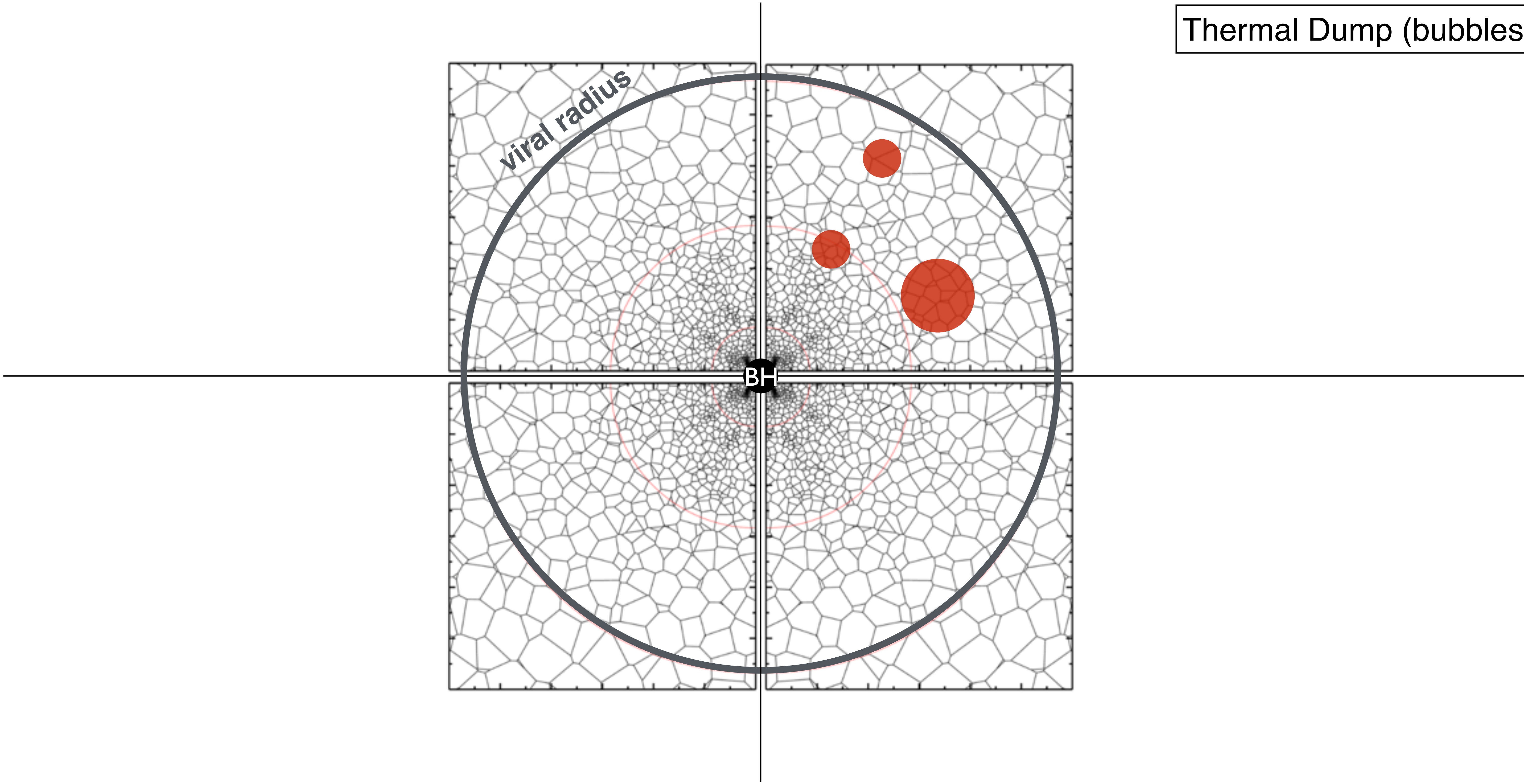
BH Feedback: Subgrid Implementation

Thermal Dump (bubbles)

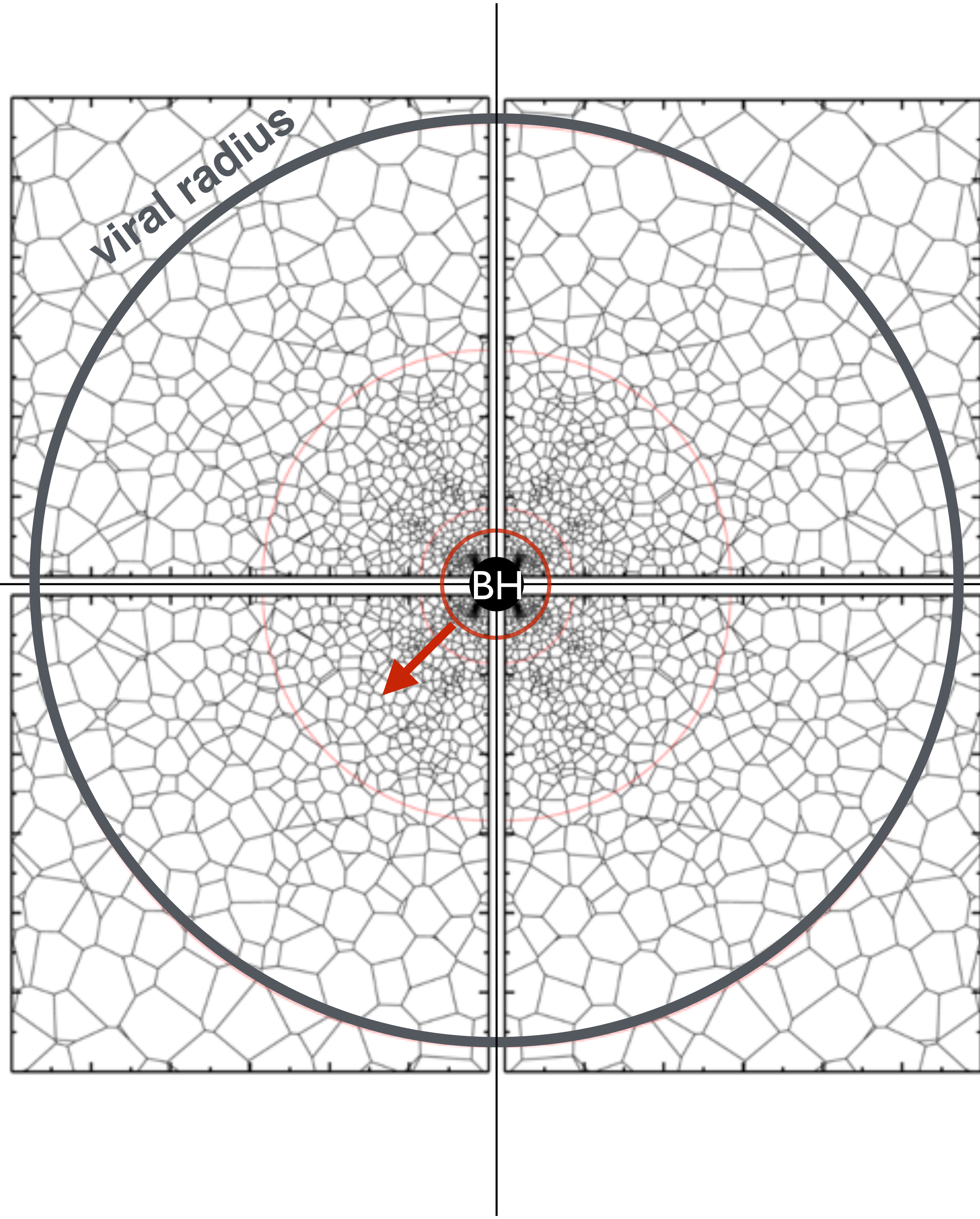


BH Feedback: Subgrid Implementation

Thermal Dump (bubbles)

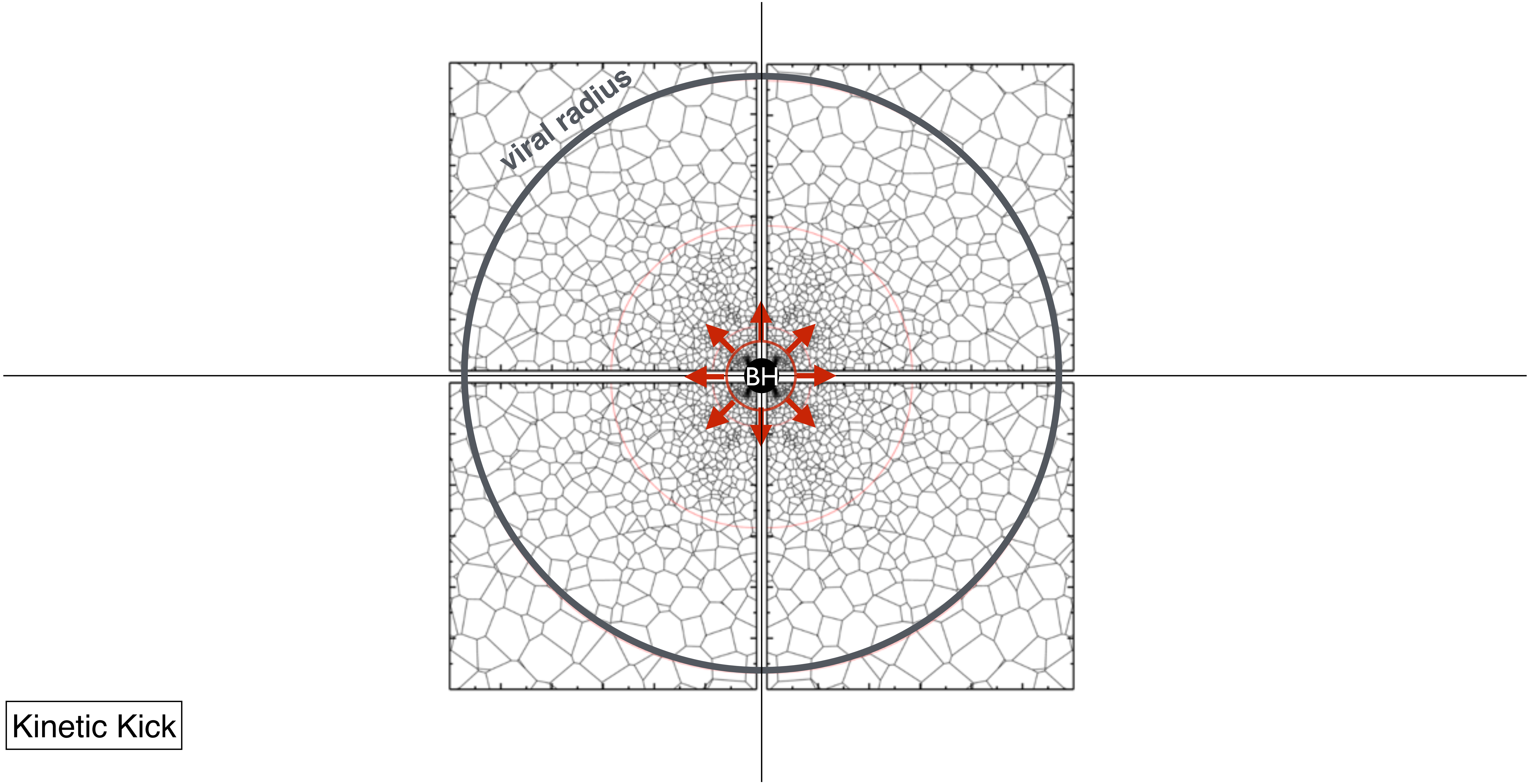


BH Feedback: Subgrid Implementation



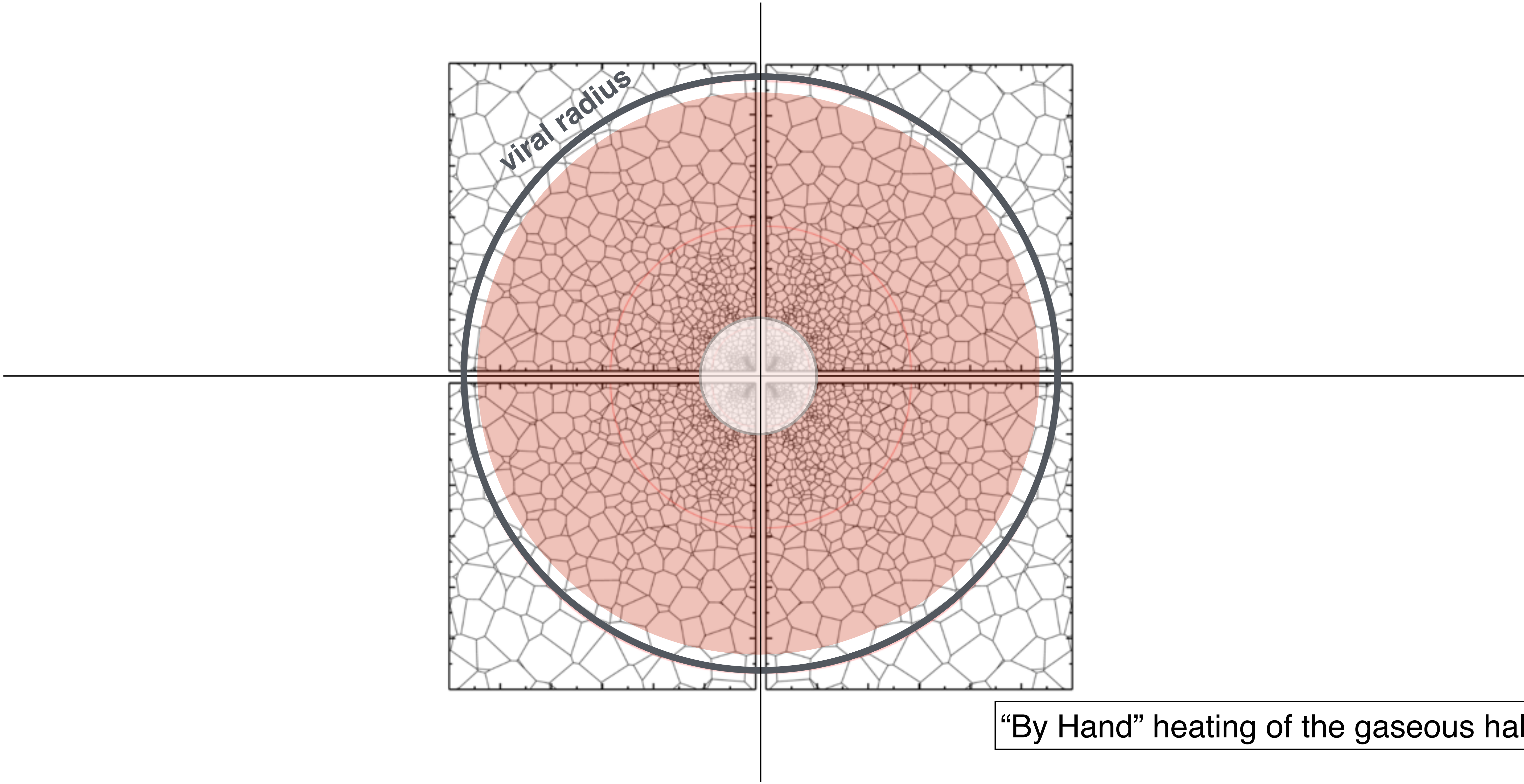
Kinetic Kick

BH Feedback: Subgrid Implementation



Kinetic Kick

BH Feedback: Subgrid Implementation



“By Hand” heating of the gaseous halo

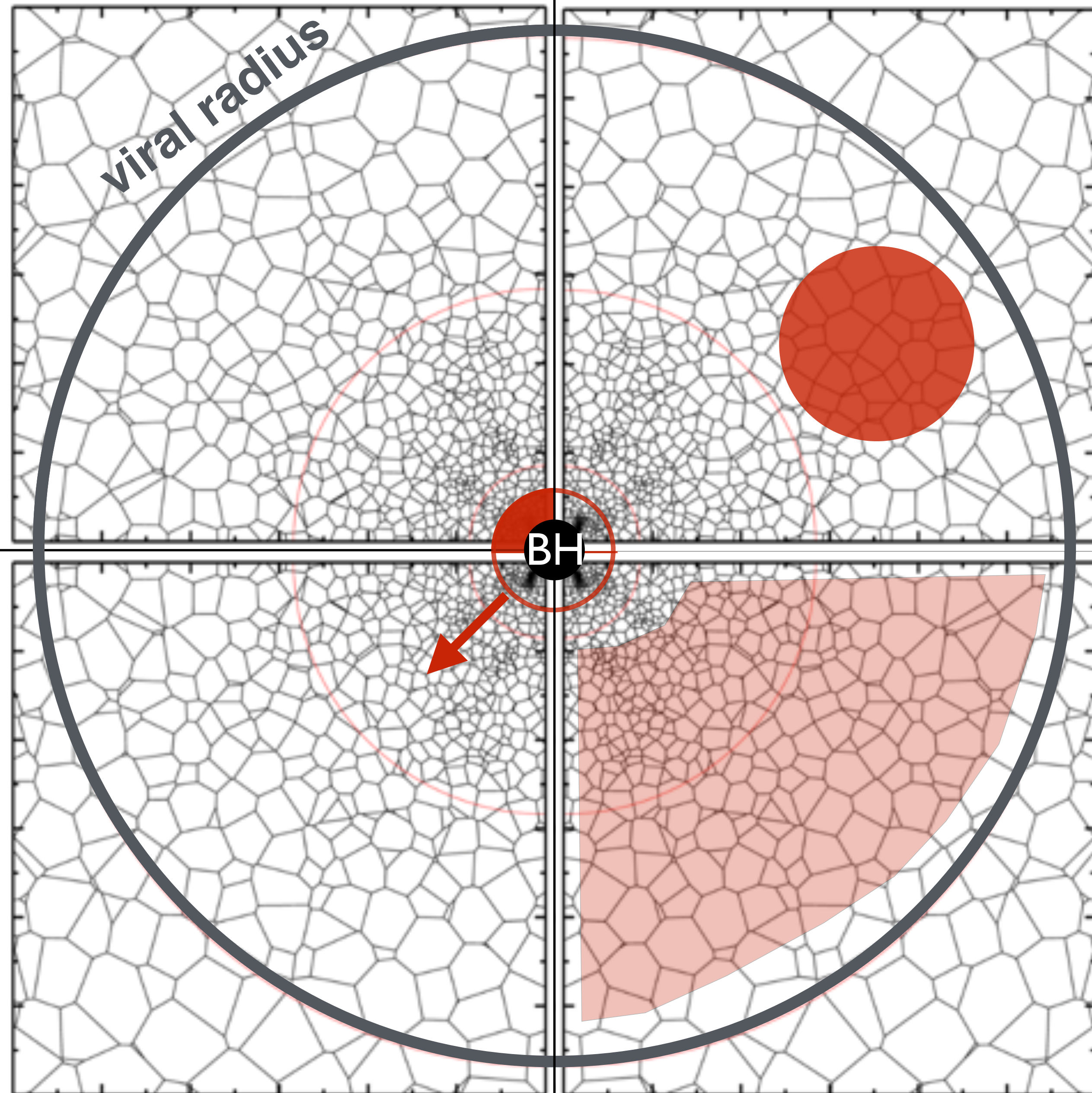
BH Feedback: Subgrid Implementation

Thermal Dump (near the BH)

Continuous?
- yes e.g. Illustris, HorizonAGN
- no e.g. Eagle

Only at high accretion rates?
- yes e.g. Illustris
- no e.g. Eagle (all the time)

aka QUASAR MODE



aka RADIO MODE

Thermal Dump (bubbles)

Very sporadic, energetic bubbles: Illustris
More frequent, “smaller bubbles”: Auriga

Only at low accretion rates?
- yes e.g. Illustris
- no e.g. Auriga (all the time)

Isotropic?
- no e.g. TNG, each time in different dirs
- no: bipolar e.g. HorizonAGN

Continuous?
- ~ e.g. TNG, each time in different dirs

Only at low accretion rates?
- yes e.g. TNG, HorizonAGN

Kinetic Kick

See also Choi et al. 2012, 2014, 2015; Dubois et al. 2010, 2012; Weinberger et al 2017

Affecting only non-self shielded gas
e.g. Mufasa, NIHAO variations

“By Hand” heating of the gaseous halo

BH Feedback: Subgrid Implementation in TNG

Weinberger, Springel, Hernquist, et al. 2016

ILLUSTRIS

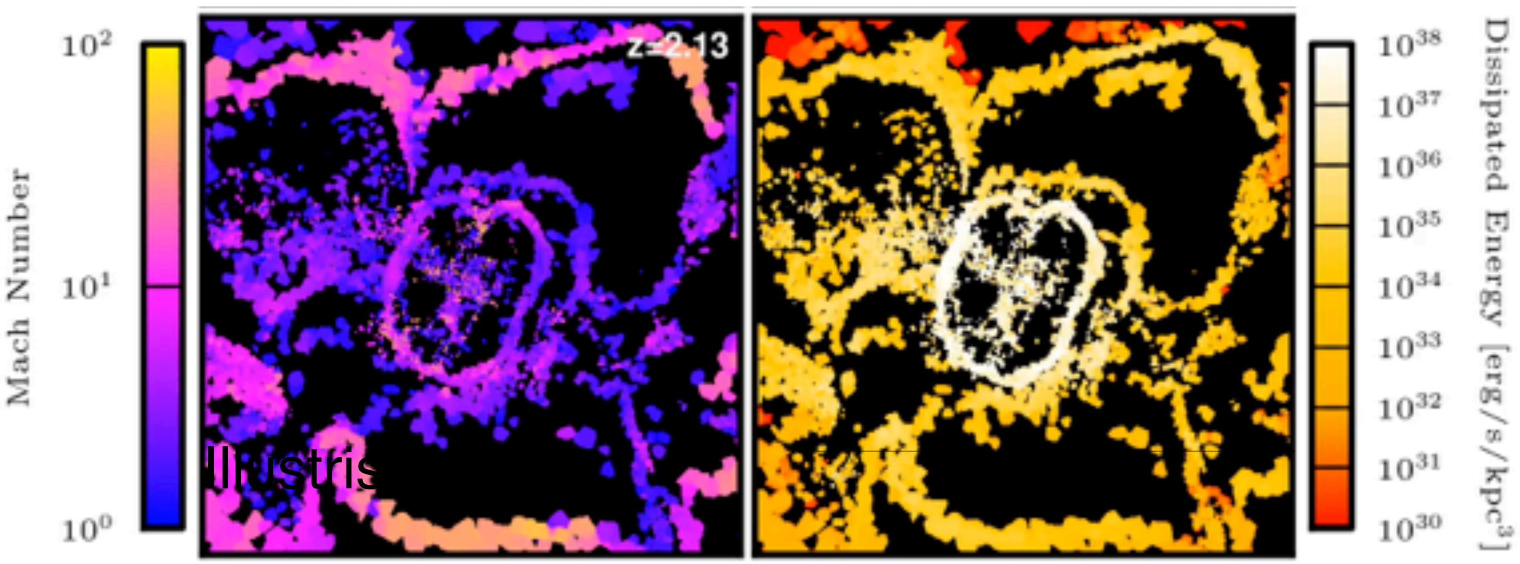
ILLUSTRIS		TNG
Two: "Quasar/Radio"	BH Feedback Modes	Two: "High/Low Accretion State"
Thermal Injection around BHs	High-Accr-Rate Feedback	Thermal Injection around BHs
Thermal 'Bubbles' in the ICM	Low-Accr-Rate Feedback	BH-driven kinetic wind
constant: 0.05	Low/High Accretion Transition: χ	BH-mass dependent, $\leqslant 0.1$
0.2	Radiative efficiency: ϵ_r	0.2
$\epsilon_f \epsilon_r$, with $\epsilon_f = 0.05$	High-Accr-Rate Feedback Factor	$\epsilon_f \epsilon_r$, with $\epsilon_f = 0.1$
$\epsilon_m \epsilon_r$, with $\epsilon_m = 0.35$	Low-Accr-Rate Feedback Factor	$\epsilon_{f,\mathrm{kin}} \leqslant 0.2$
yes	Radiative BH Feedback	yes

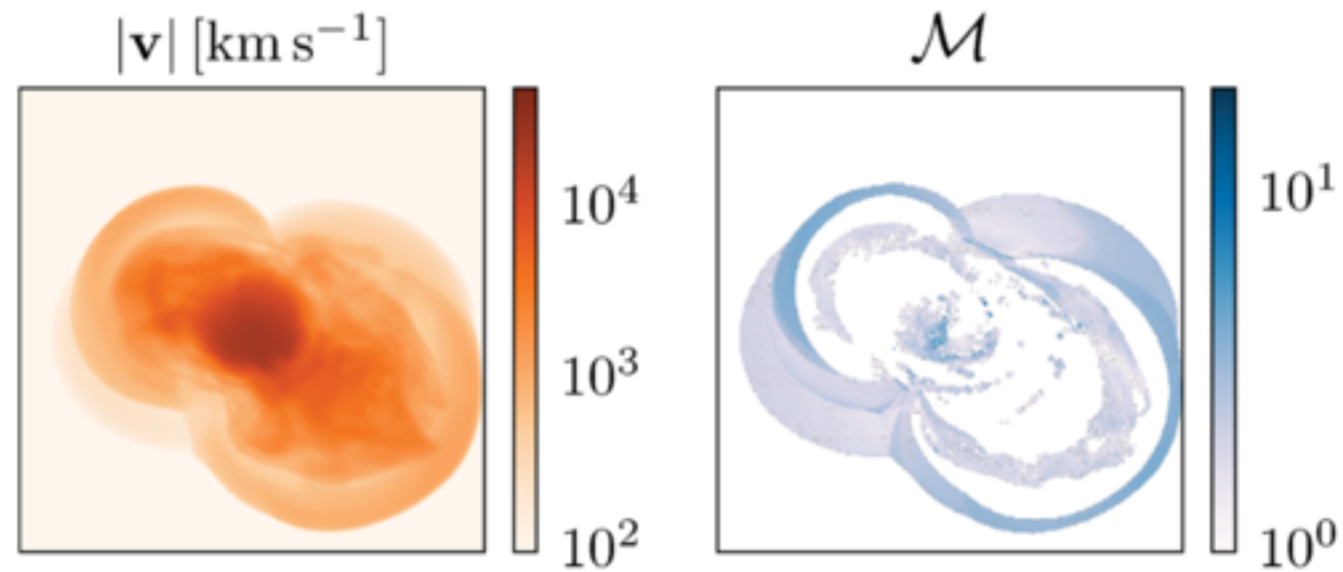
$$\chi = \min\left[\chi_0 \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^\beta, 0.1\right]$$

TNG

Phenomenology of the Illustris issues: Illustris BH feedback is too violent, removes all the gas from the halo and yet does not quench the central galaxies

Schaal, Springel et al. 2016





Weinberger, Springel, et al. 2016 (idealised setup, n~0.1 cm^-3)

BH Feedback: Subgrid Implementation in TNG

Weinberger, Springel, Hernquist, et al. 2016

ILLUSTRIS

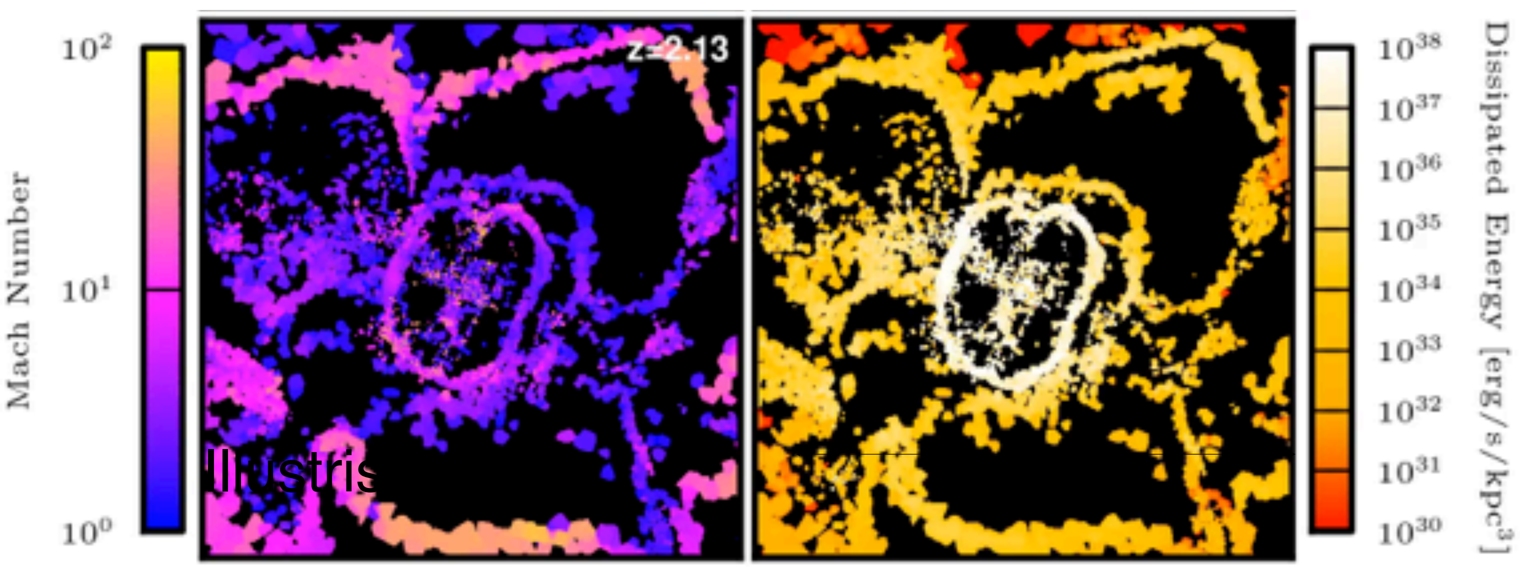
Two: "Quasar/Radio"	BH Feedback Modes	Two: "High/Low Accretion State"
Thermal Injection around BHs	High-Accr-Rate Feedback	Thermal Injection around BHs
Thermal 'Bubbles' in the ICM	Low-Accr-Rate Feedback	BH-driven kinetic wind
constant: 0.05	Low/High Accretion Transition: χ	BH-mass dependent, $\leqslant 0.1$
0.2	Radiative efficiency: ϵ_r	0.2
$\epsilon_f \epsilon_r$, with $\epsilon_f = 0.05$	High-Accr-Rate Feedback Factor	$\epsilon_f \epsilon_r$, with $\epsilon_f = 0.1$
$\epsilon_m \epsilon_r$, with $\epsilon_m = 0.35$	Low-Accr-Rate Feedback Factor	$\epsilon_{f,\mathrm{kin}} \leqslant 0.2$
yes	Radiative BH Feedback	yes

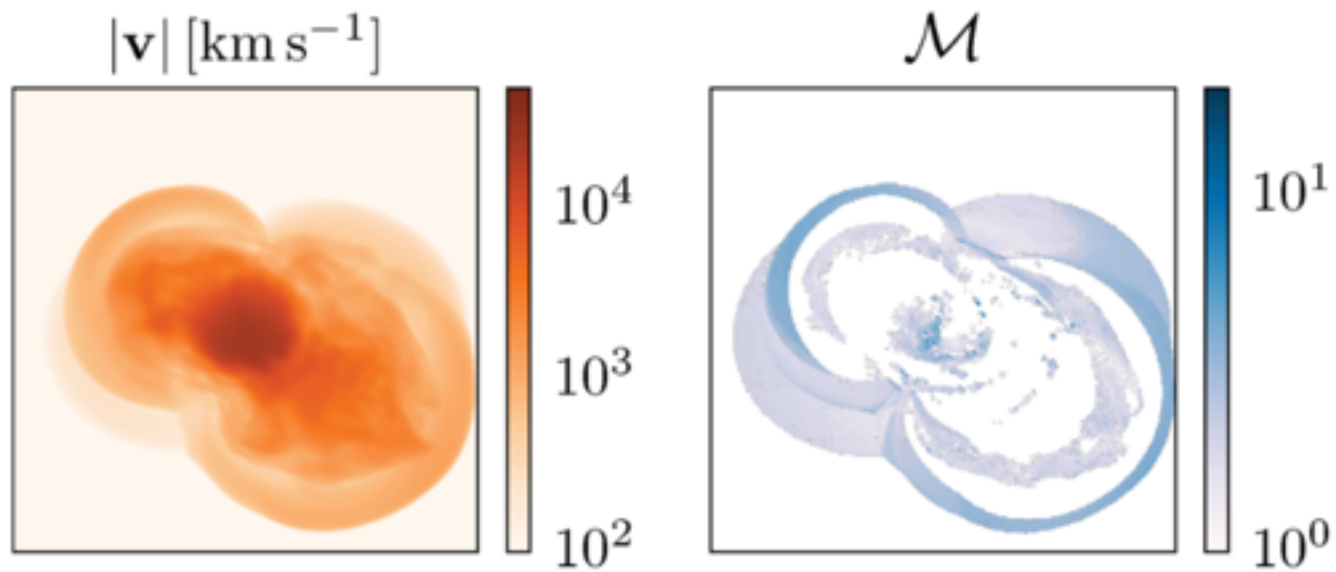
$$\chi = \min\left[\chi_0 \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^\beta, 0.1\right]$$

TNG

Phenomenology of the Illustris issues: Illustris BH feedback is too violent, removes all the gas from the halo and yet does not quench the central galaxies

Schaal, Springel et al. 2016





Weinberger, Springel, et al. 2016 (idealised setup, n~0.1 cm^-3)

BH Feedback: Effects

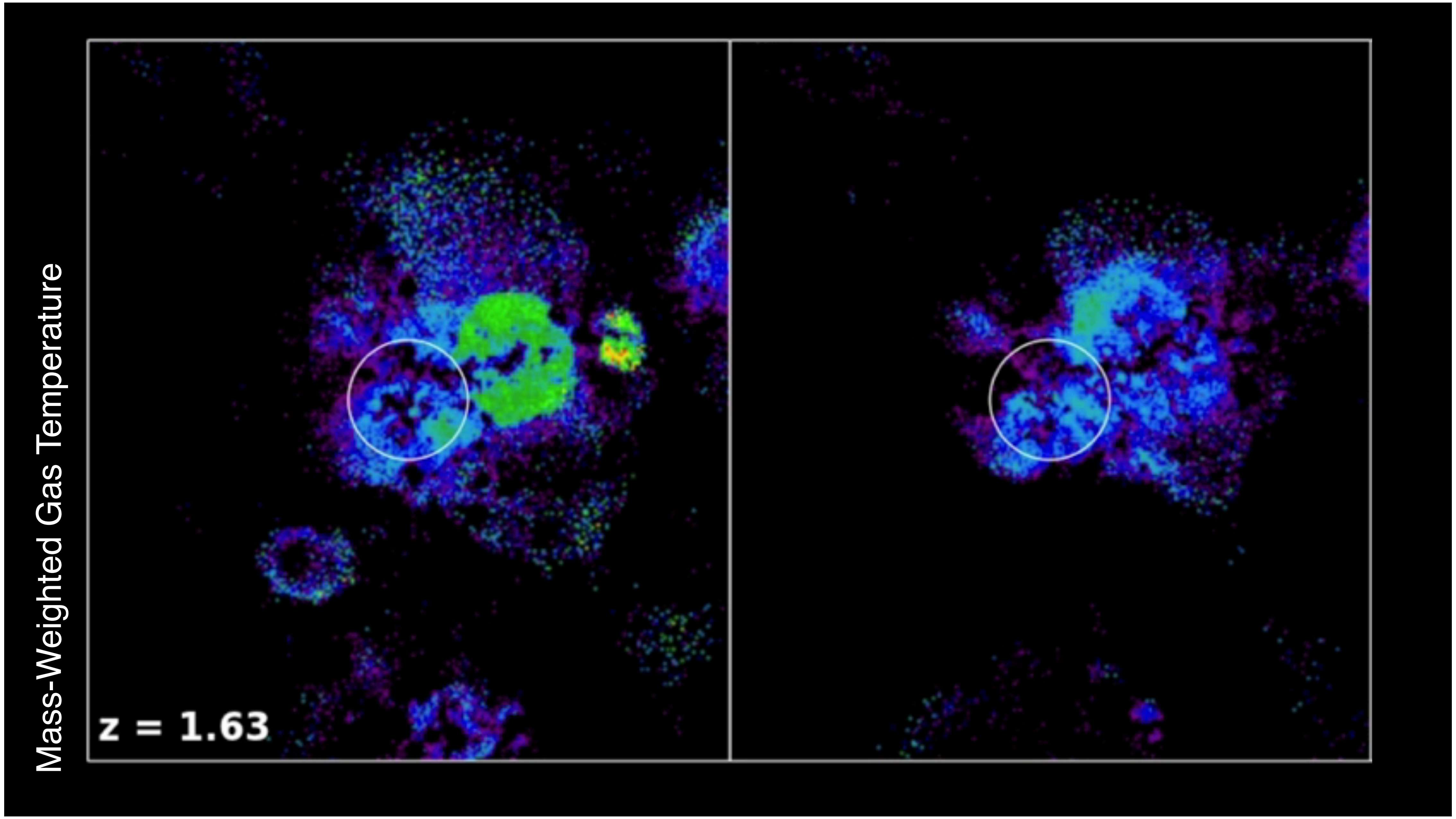
Zoom Cluster 2: 4x10^{13} Msun

Illustris

Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

TNG

Kinetic feedback
kicks in random directions to neighboring gas cells



Credits C. Popa

BH Feedback: Effects

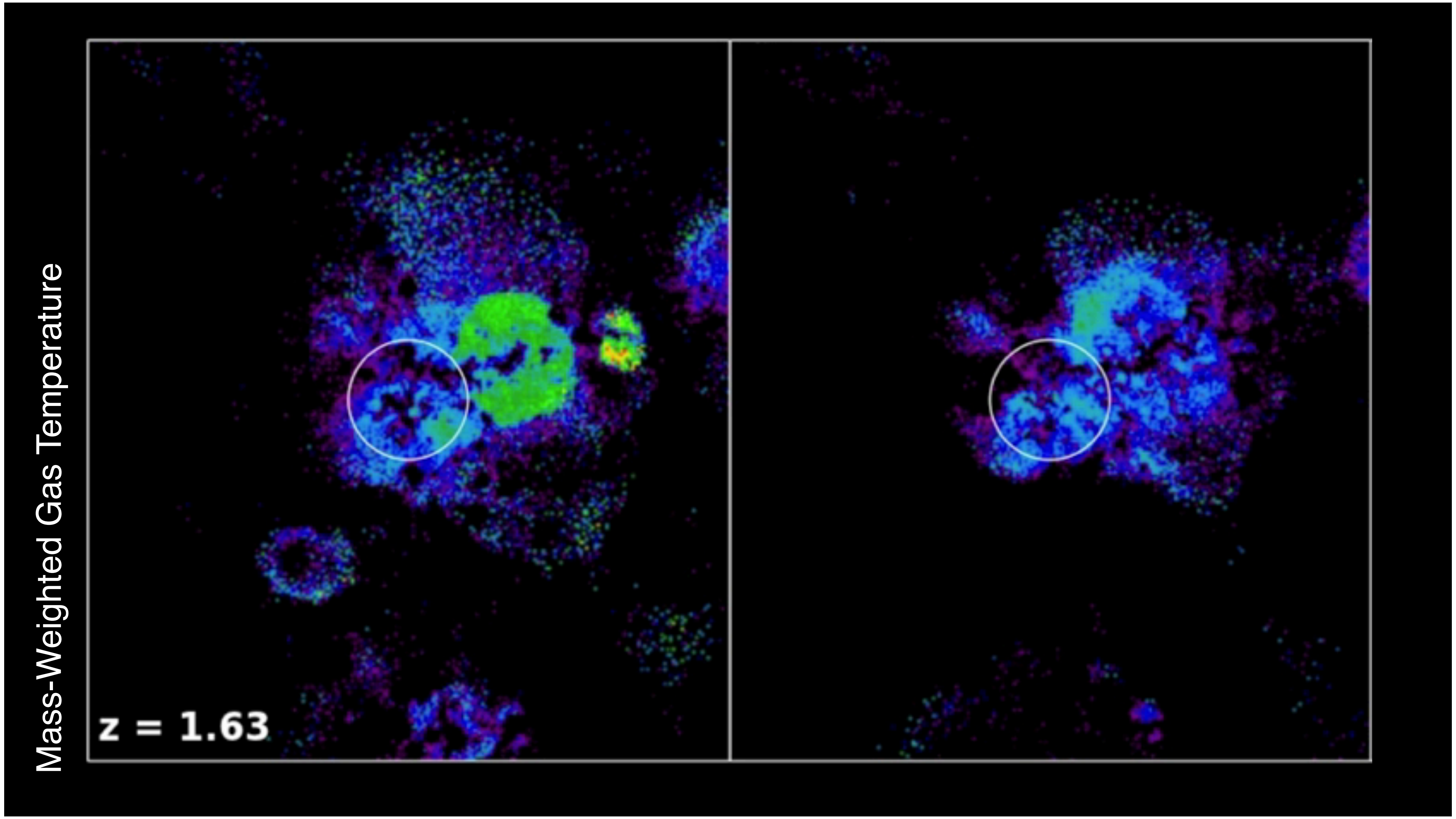
Zoom Cluster 2: 4x10^{13} Msun

Illustris

Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

TNG

Kinetic feedback
kicks in random directions to neighboring gas cells



Credits C. Popa

BH Feedback: Effects

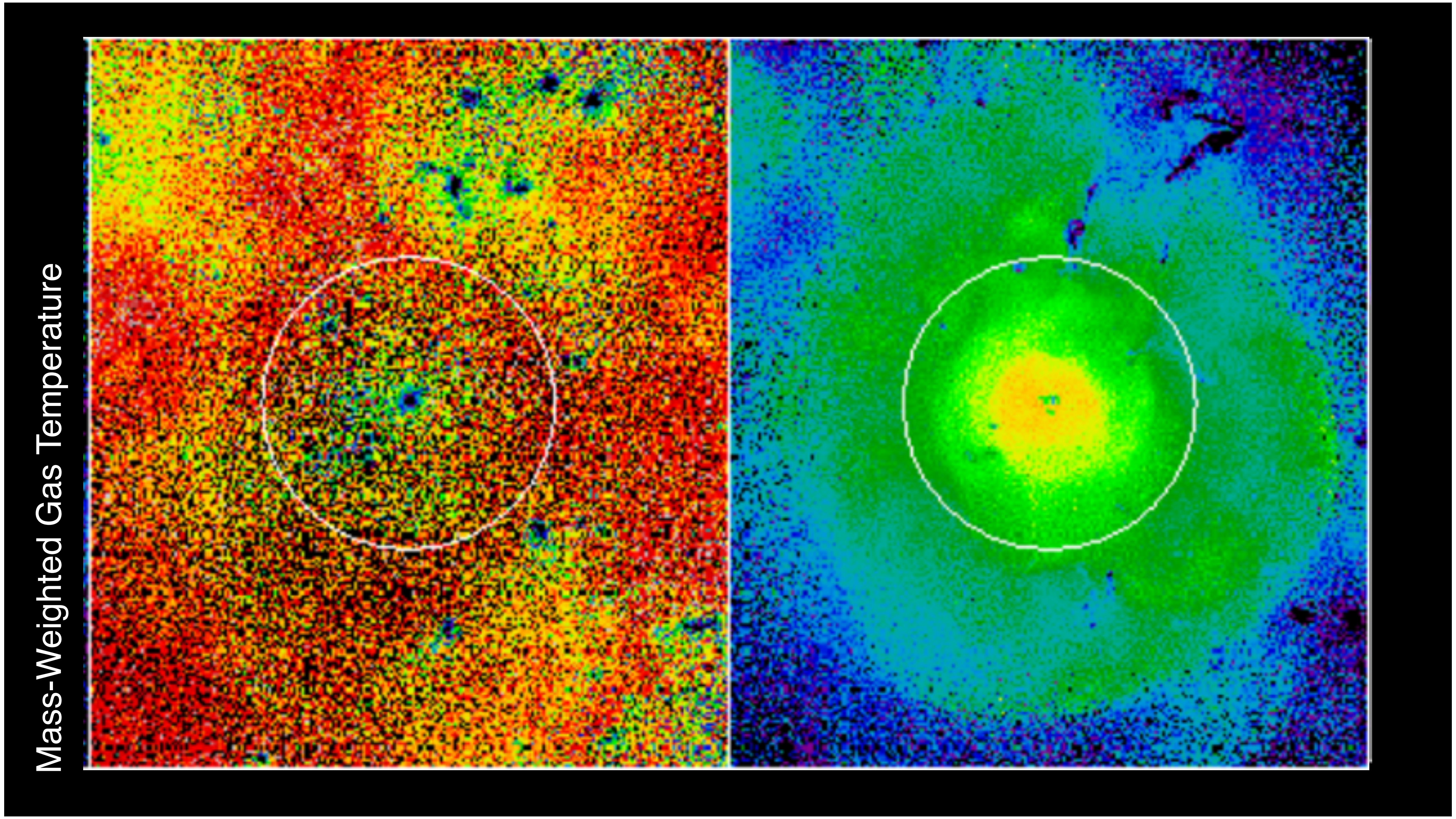
Zoom Cluster 1: $2x10^{13}$ Msun

Illustris

Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

TNG

Kinetic feedback
kicks in random directions to neighboring gas cells



Credits C. Popa

BH Feedback: Effects

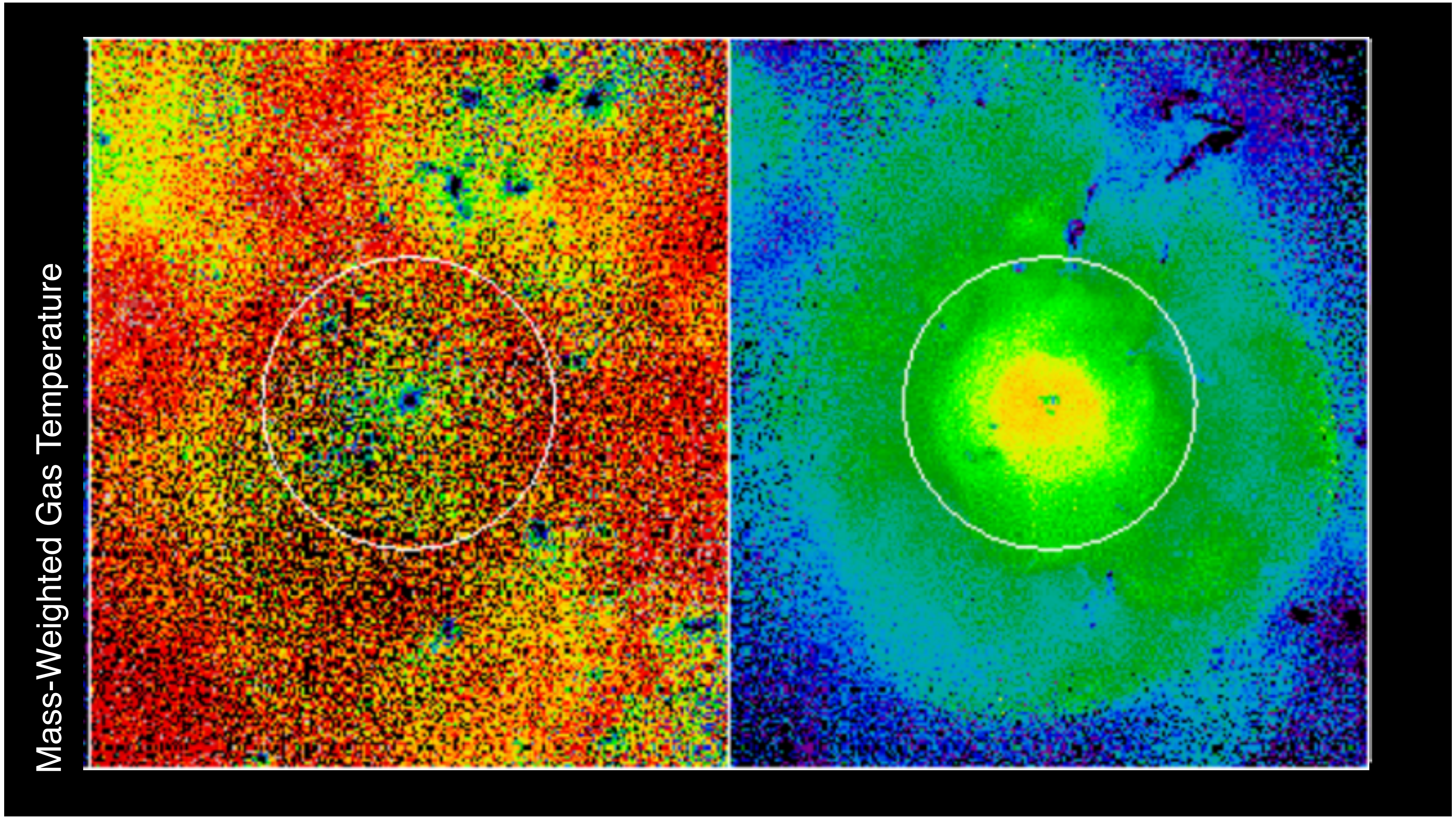
Zoom Cluster 1: 2×10^{13} Msun

Illustris

Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

TNG

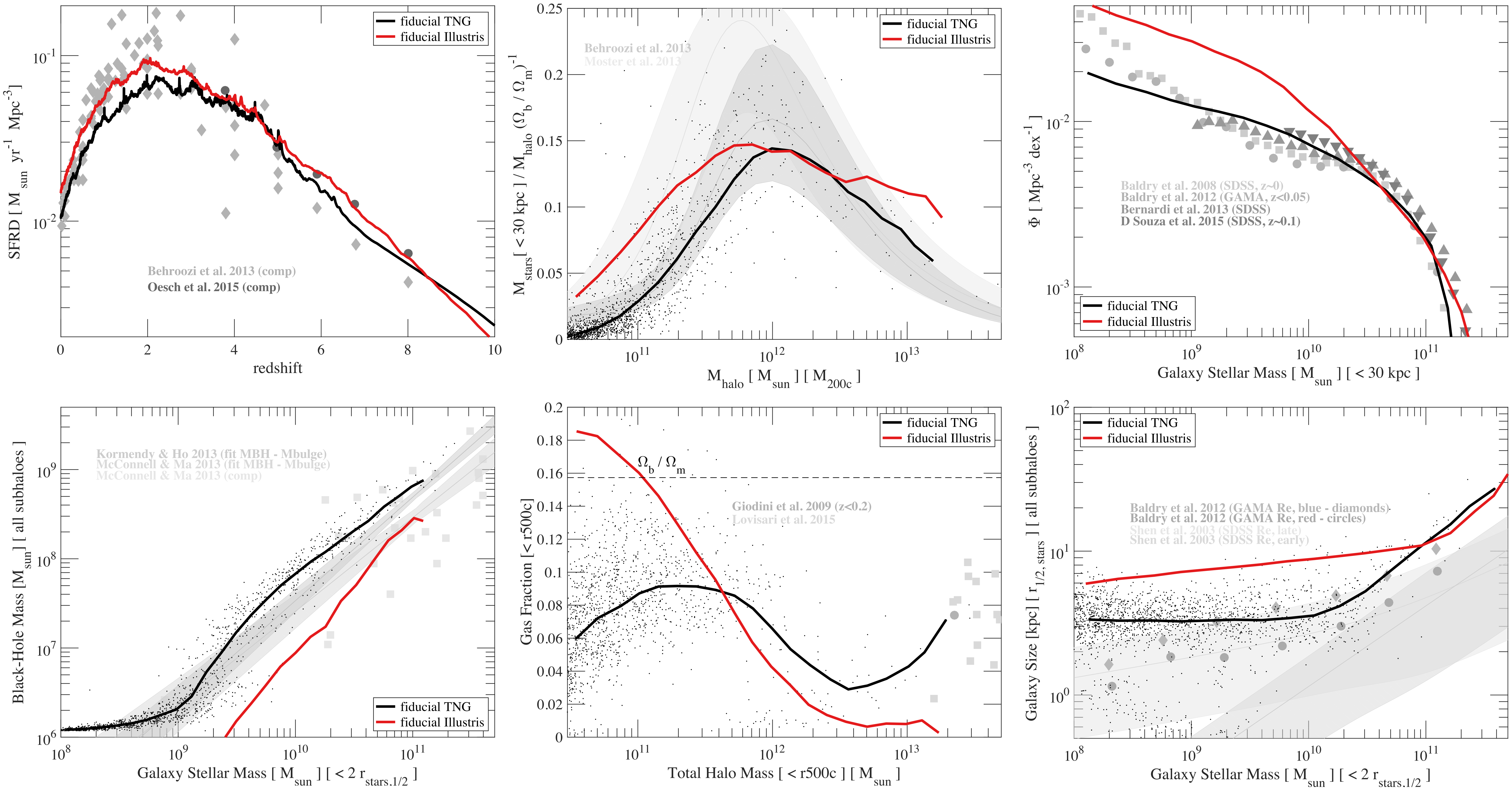
Kinetic feedback
kicks in random directions to neighboring gas cells



Credits C. Popa

The desired outcome with the TNG Model

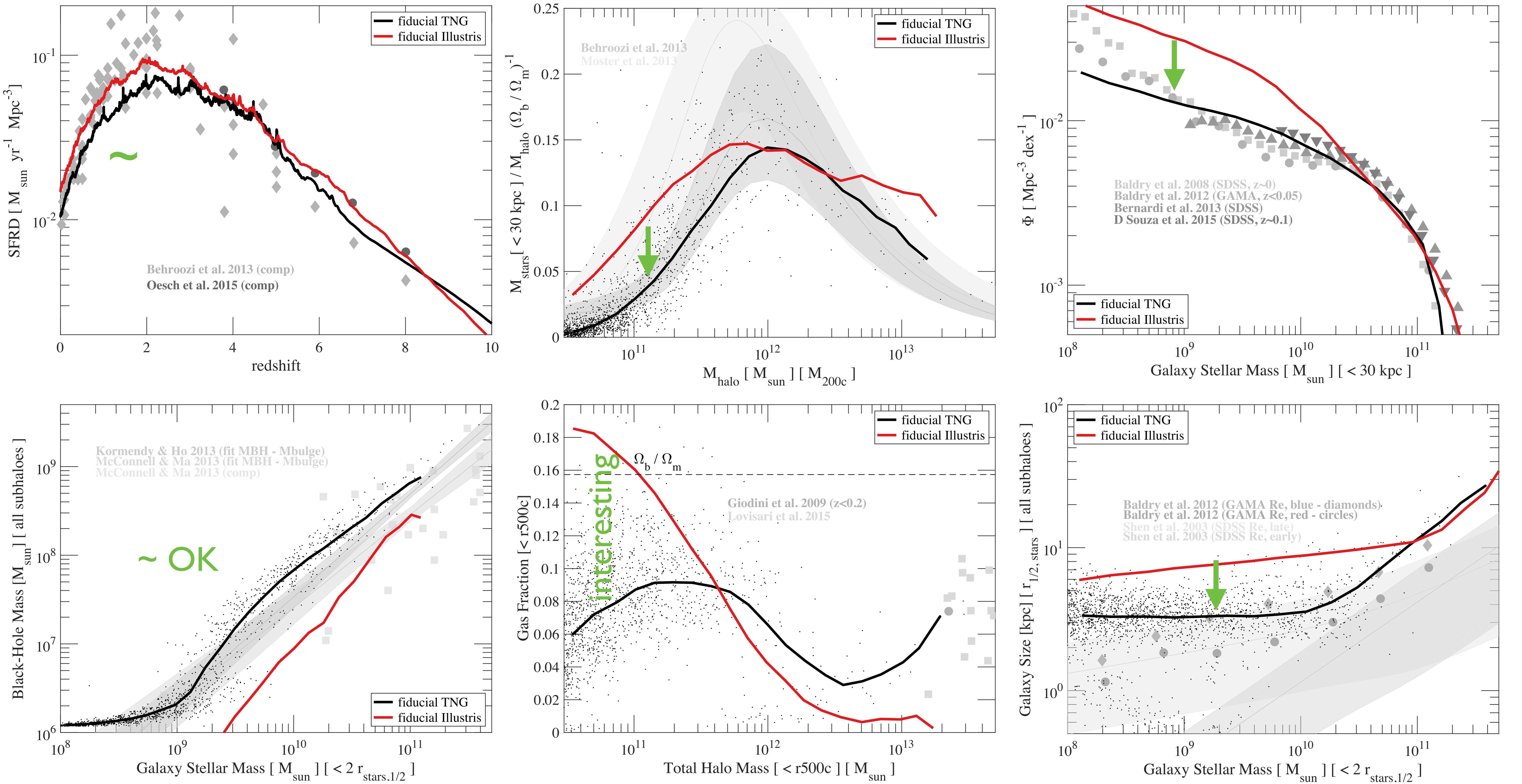
Pillepich, Springel, Nelson et al. 2017
[L25n512 box]



The desired outcome with the TNG Model

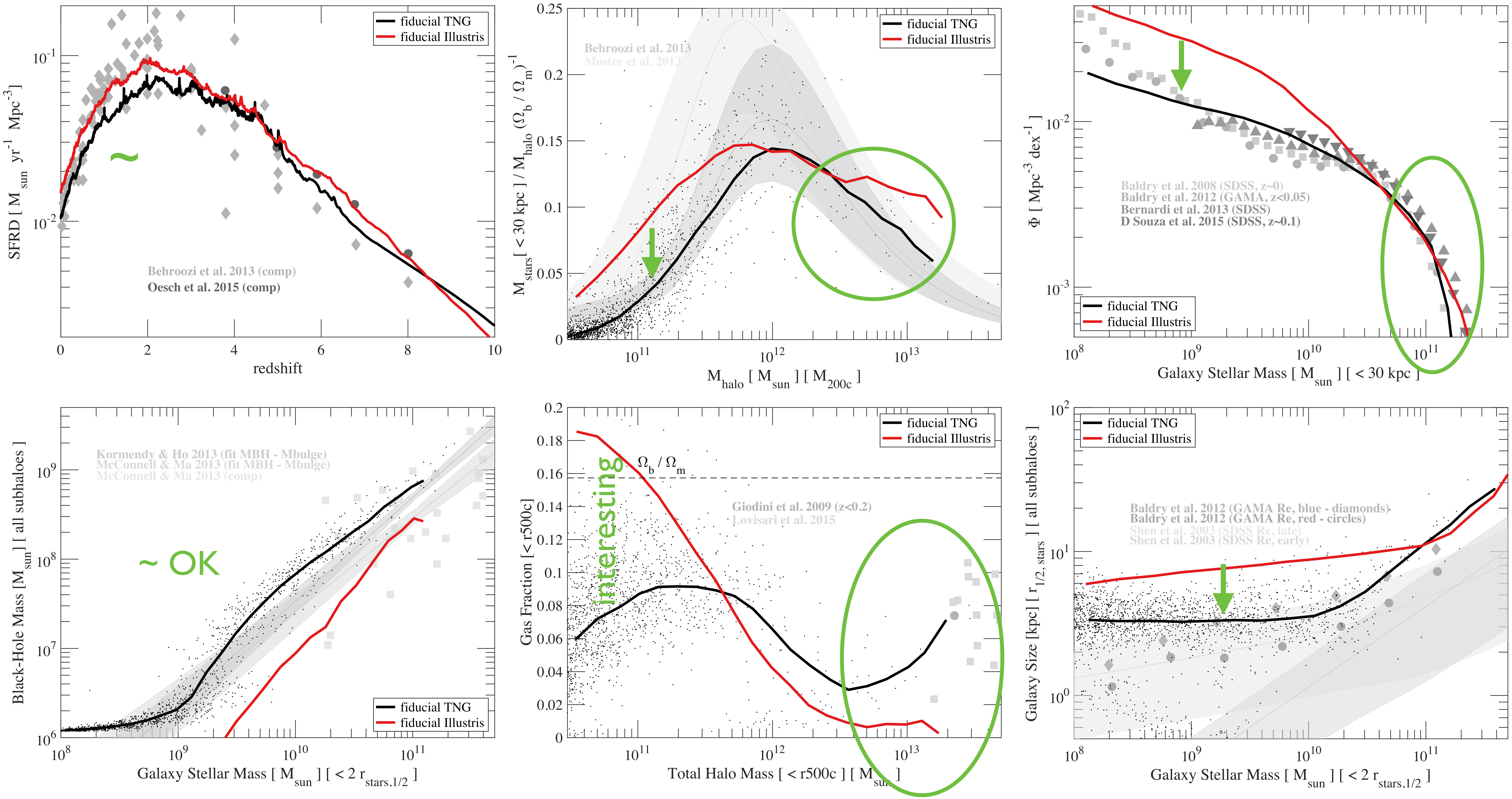
Pillepich, Springel, Nelson et al. 2017

[L25n512 box]



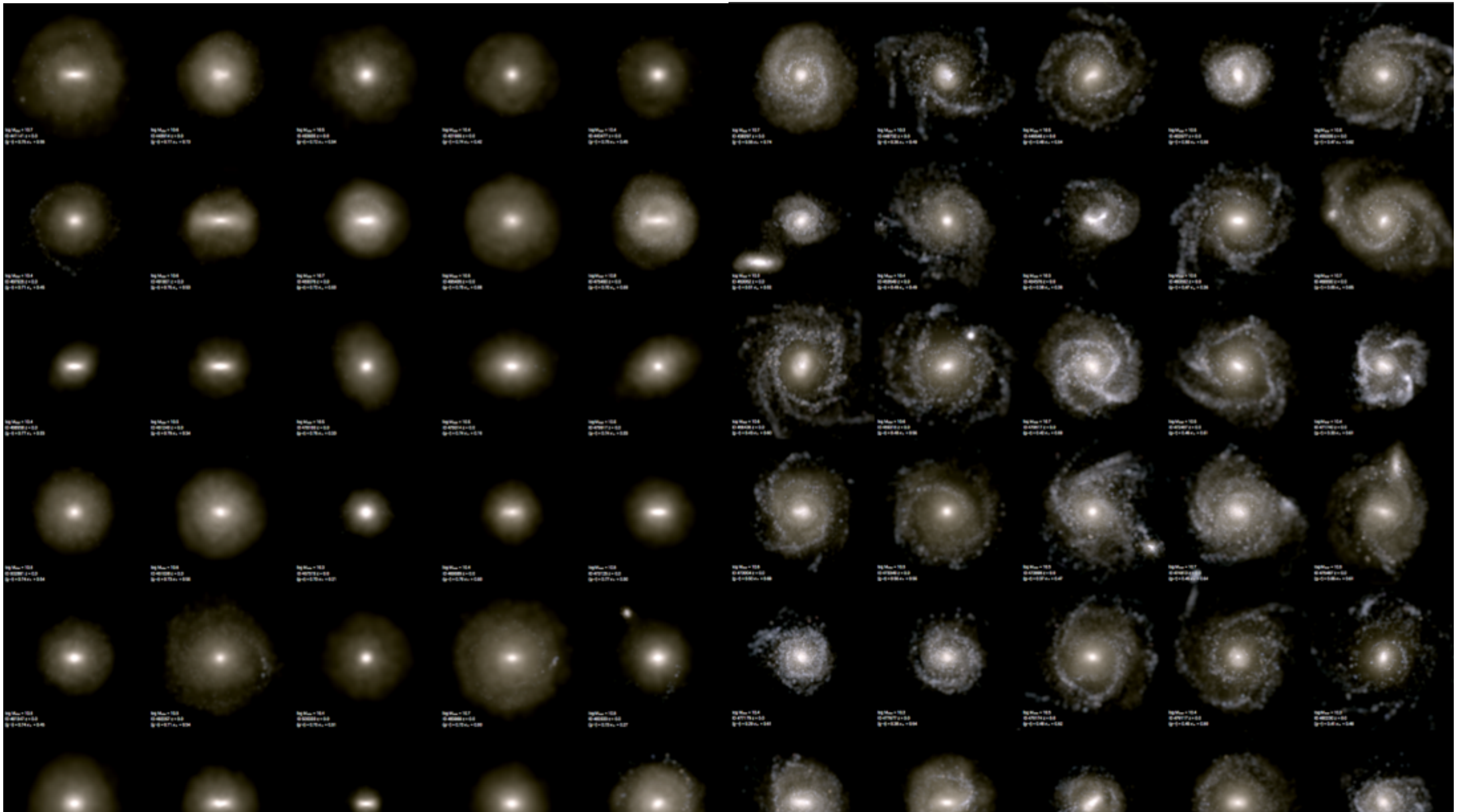
The desired outcome with the TNG Model

Pillepich, Springel, Nelson et al. 2017
[L25n512 box]



The desired outcome with the TNG Model

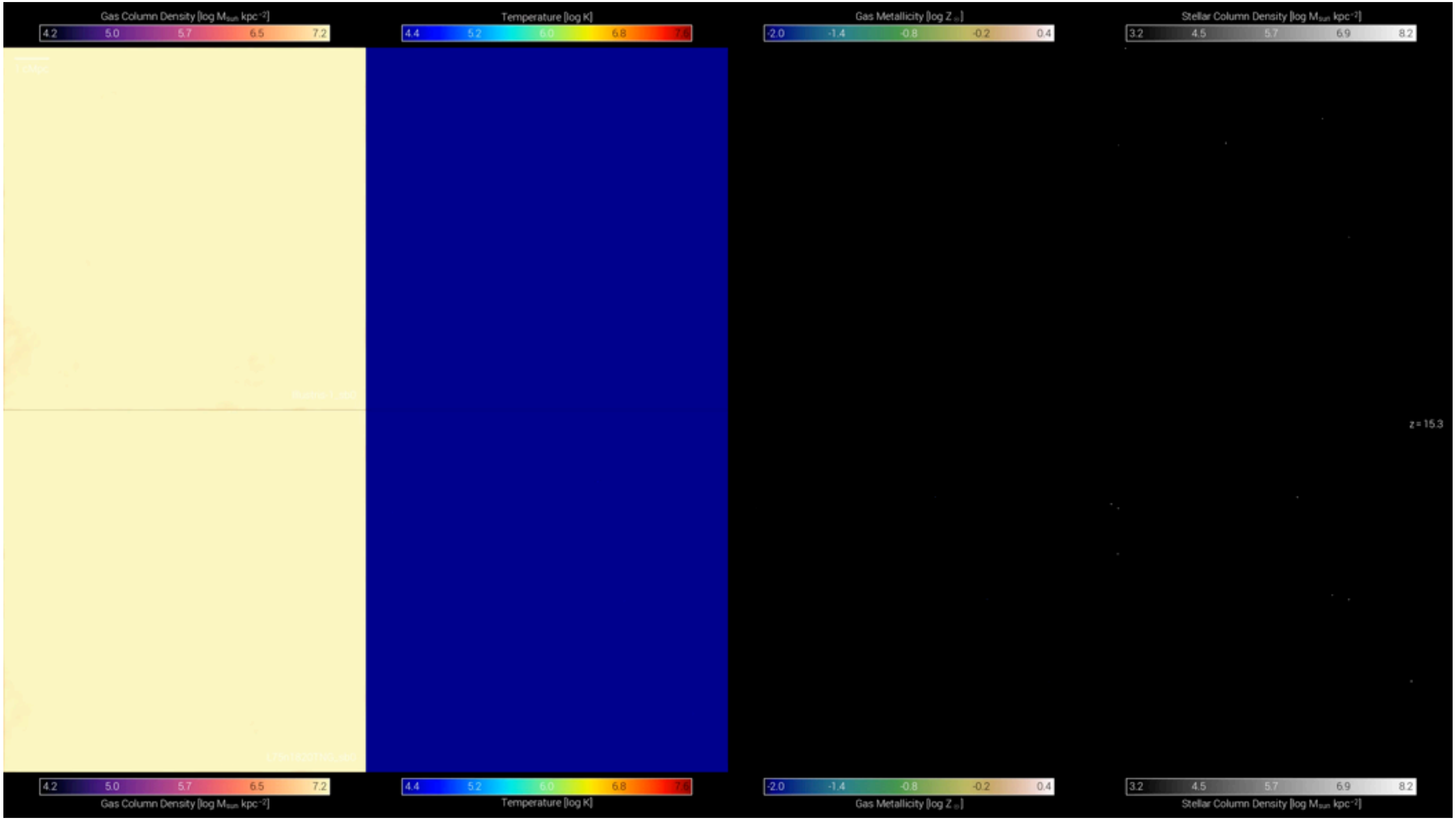
Nelson, Pillepich, Springel, 2017



What about beyond galaxies? On the need of Volumes!

Illustris Model

TNG Model

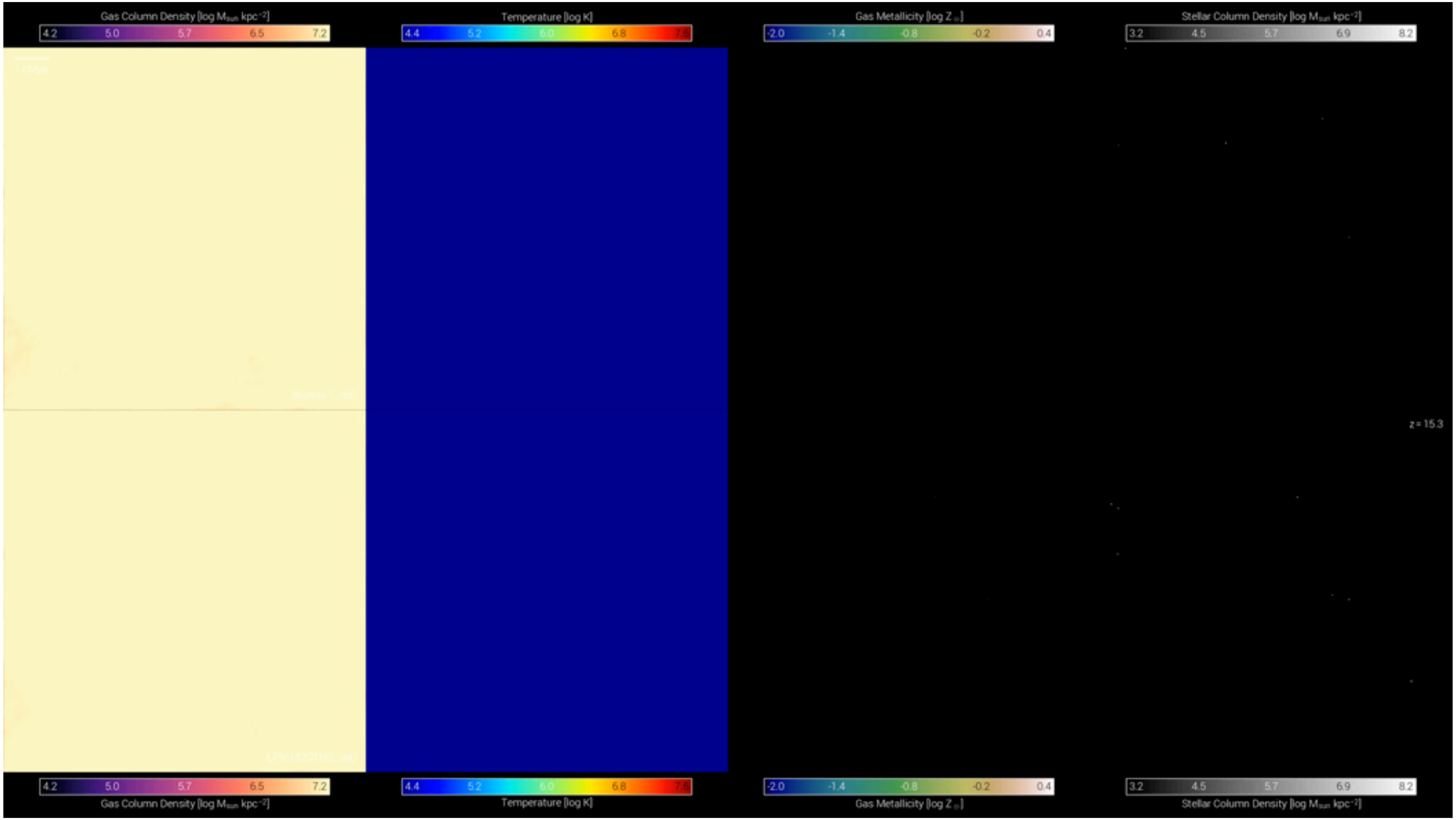


Credits: Dylan Nelson (MPA) & IllustrisTNG Team

What about beyond galaxies? On the need of Volumes!

Illustris Model

TNG Model



Credits: Dylan Nelson (MPA) & IllustrisTNG Team

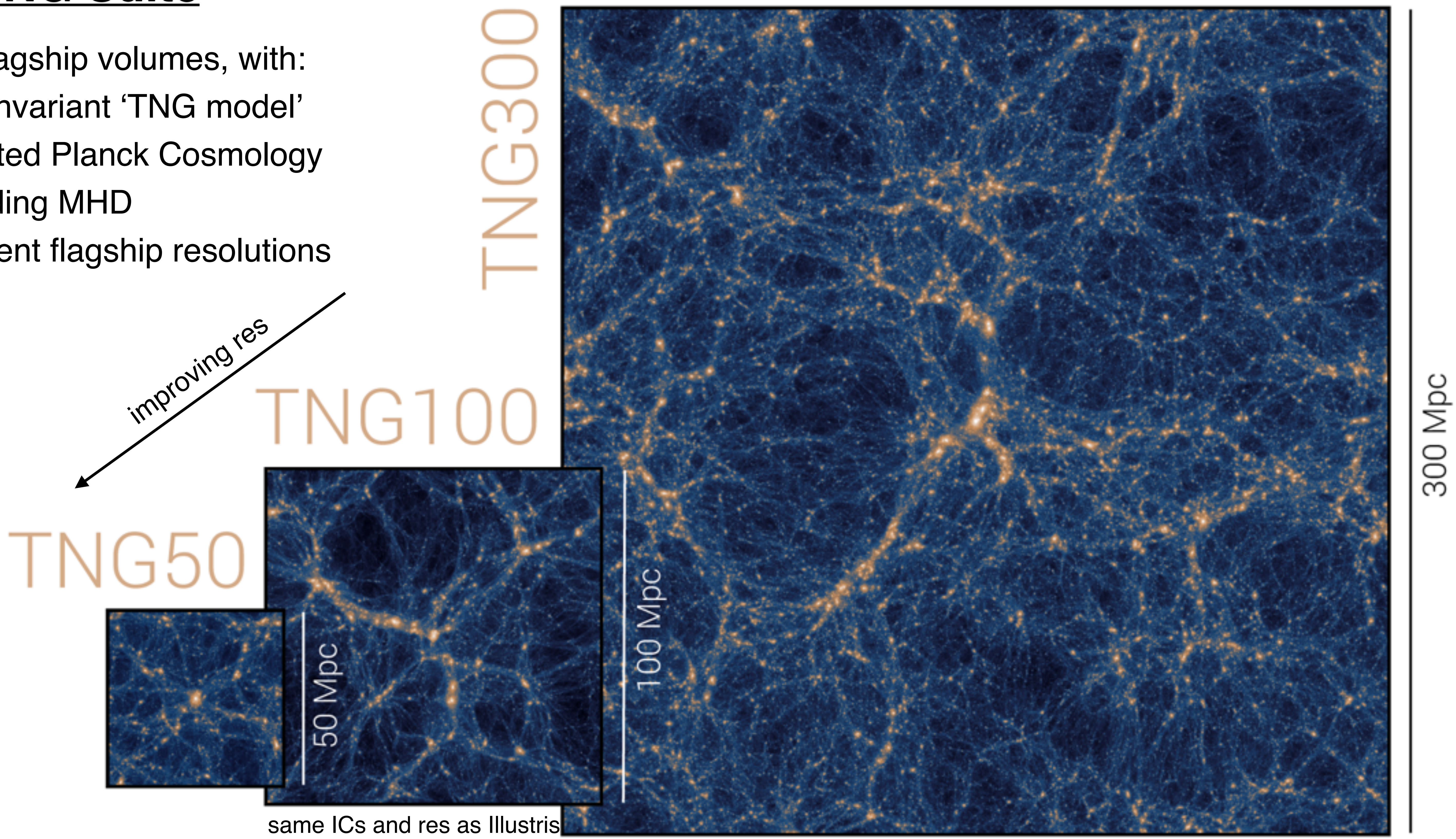
The TNG Simulations

The TNG Suite

www.tng-project.org

Three flagship volumes, with:

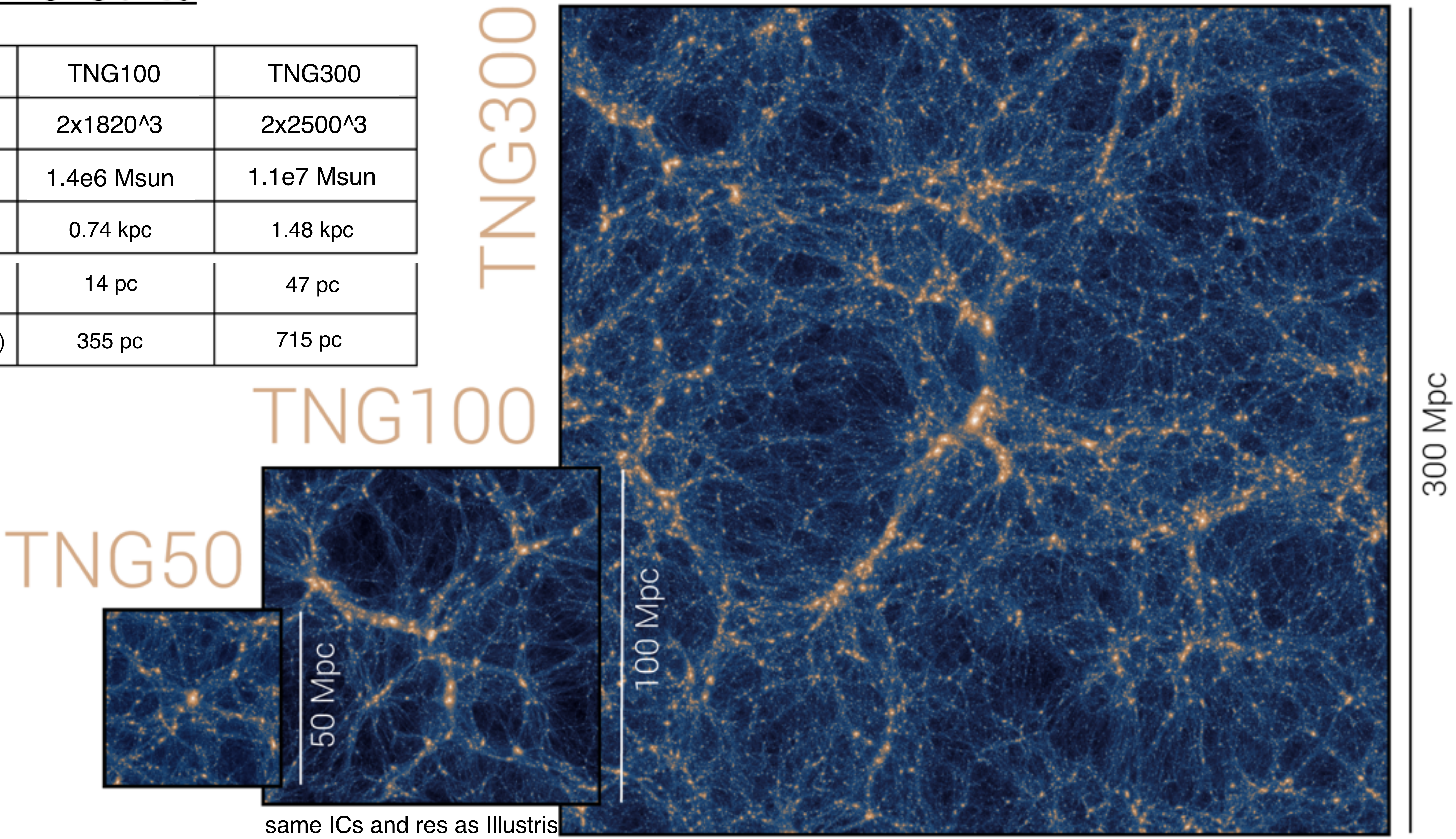
- new invariant ‘TNG model’
- Updated Planck Cosmology
- Including MHD
- Different flagship resolutions



The TNG Suite

www.tng-project.org

Box	TNG100	TNG300
# res el	2x1820^3	2x2500^3
m_stars	1.4e6 Msun	1.1e7 Msun
DM soft	0.74 kpc	1.48 kpc
min(r_cell)	14 pc	47 pc
avg(r_cell,sf)	355 pc	715 pc

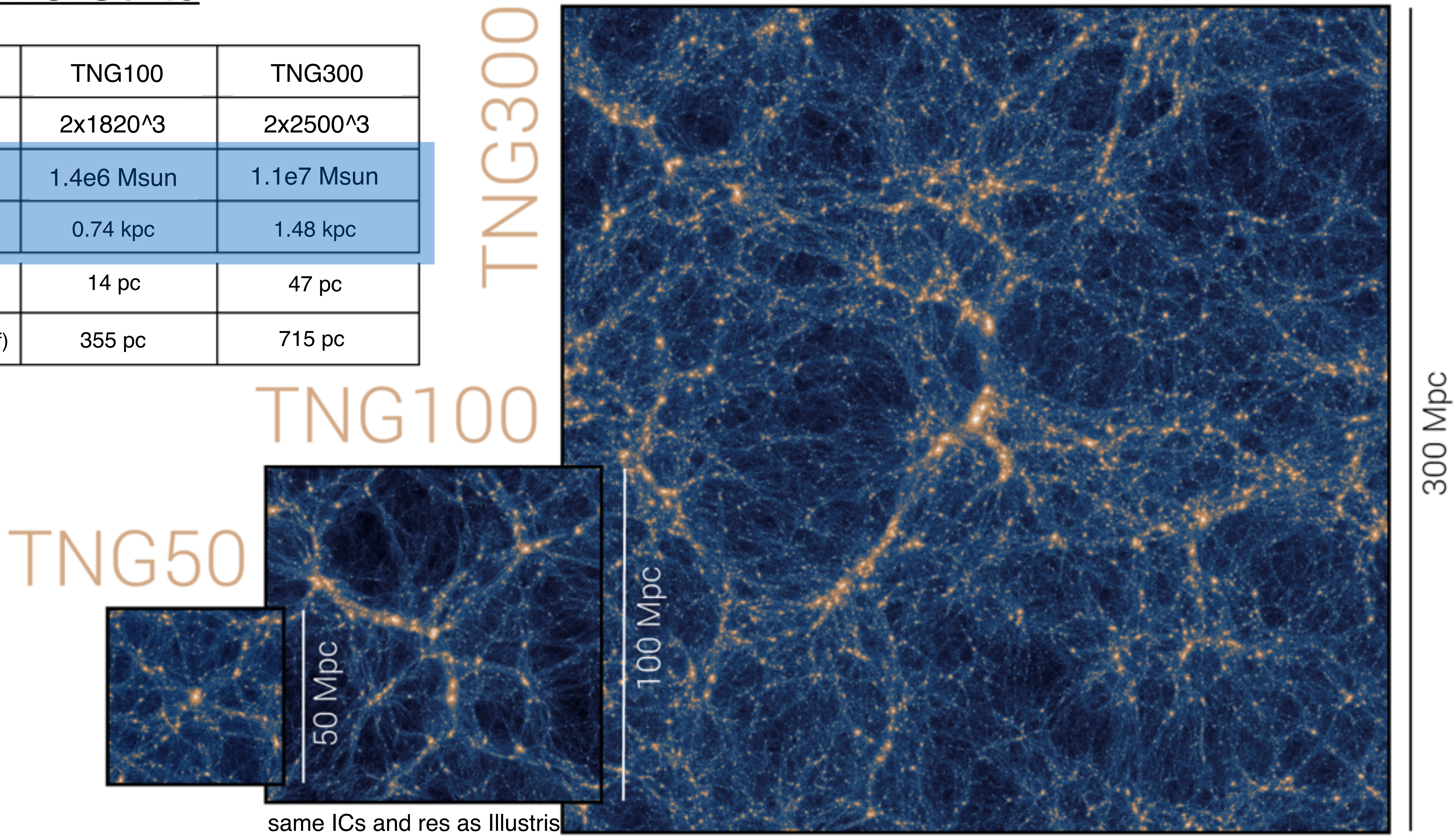


same ICs and res as Illustris

The TNG Suite

www.tng-project.org

Box	TNG100	TNG300
# res el	2x1820^3	2x2500^3
m_stars	1.4e6 Msun	1.1e7 Msun
DM soft	0.74 kpc	1.48 kpc
min(r_cell)	14 pc	47 pc
avg(r_cell,sf)	355 pc	715 pc

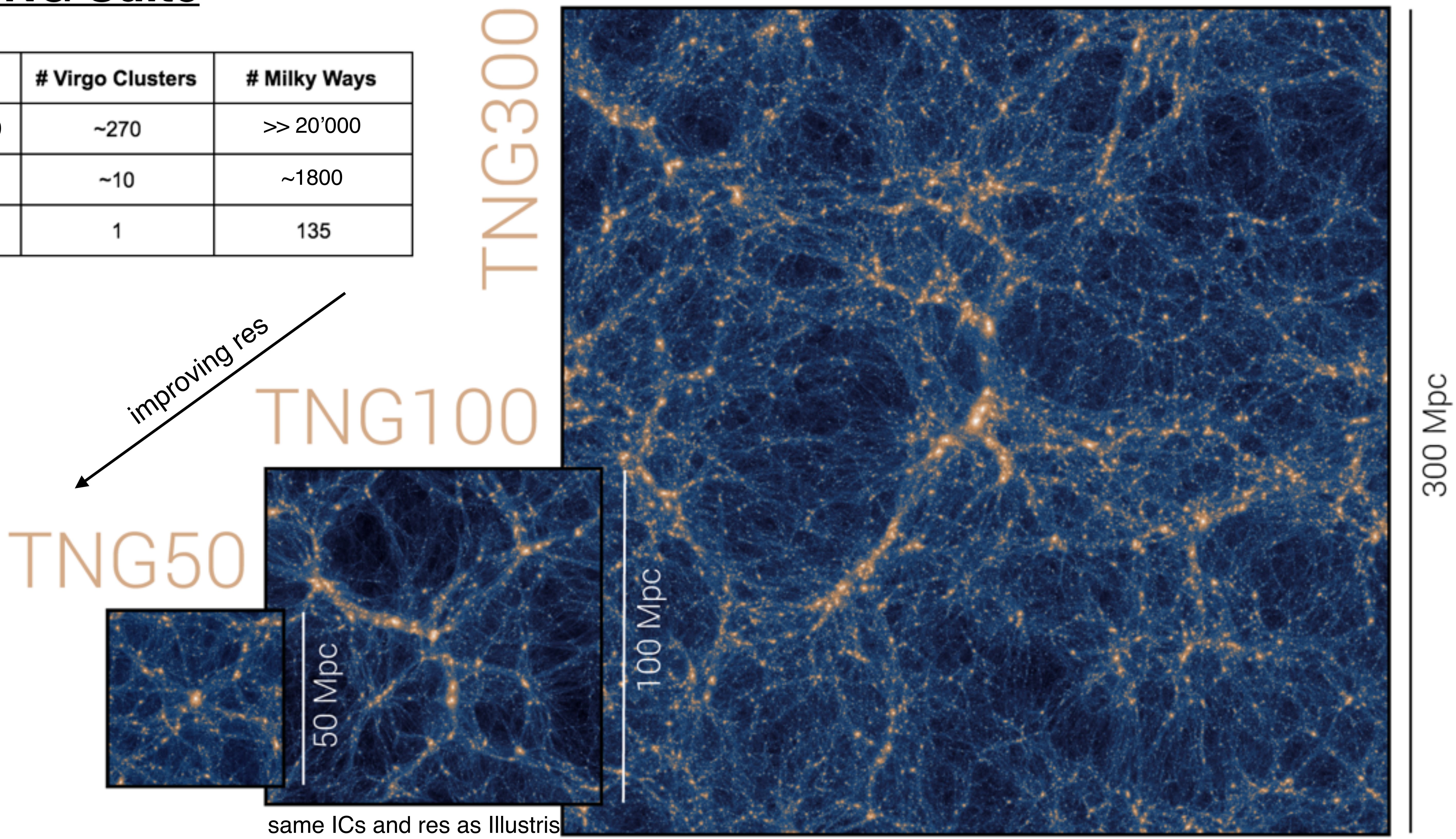


same ICs and res as Illustris

The TNG Suite

www.tng-project.org

Box	# Virgo Clusters	# Milky Ways
TNG300	~270	>> 20'000
TNG100	~10	~1800
TNG50	1	135



Running the Simulations

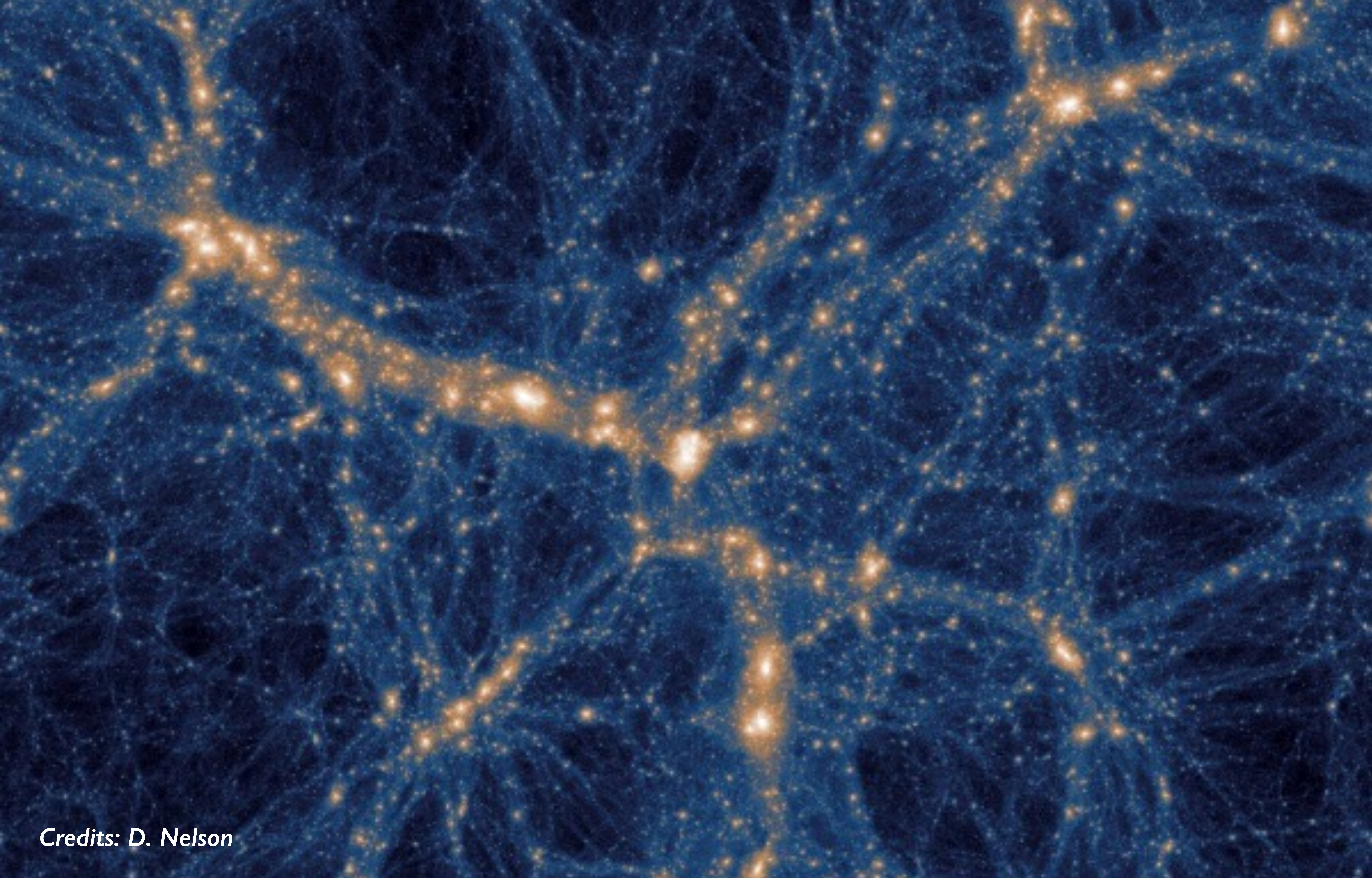
@ Hazelhen (Stuttgart)
Cray Cluster
7712 nodes with 24 cores/node
5.3GB of memory per core!

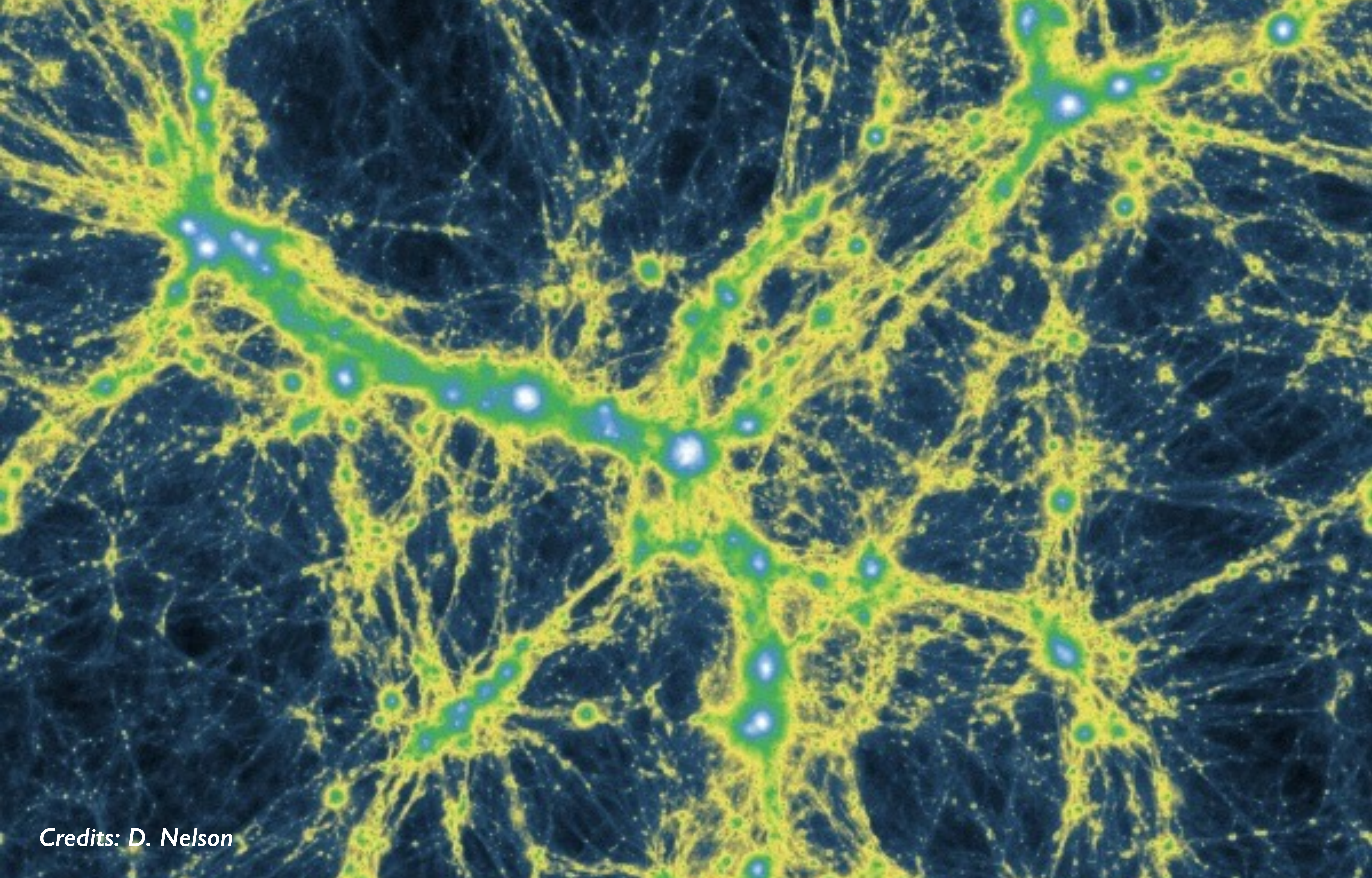
Flagship Runs	TNG100	TNG300	TNG50
Box Size	106 Mpc	303 Mpc	52 Mpc
# Resolution Elements	> 2x1820^3	> 2x2500^3	> 2x2160^3
# Computing Cores	10'752	24'000	16'320
Current Redshift	0	0	~ 1

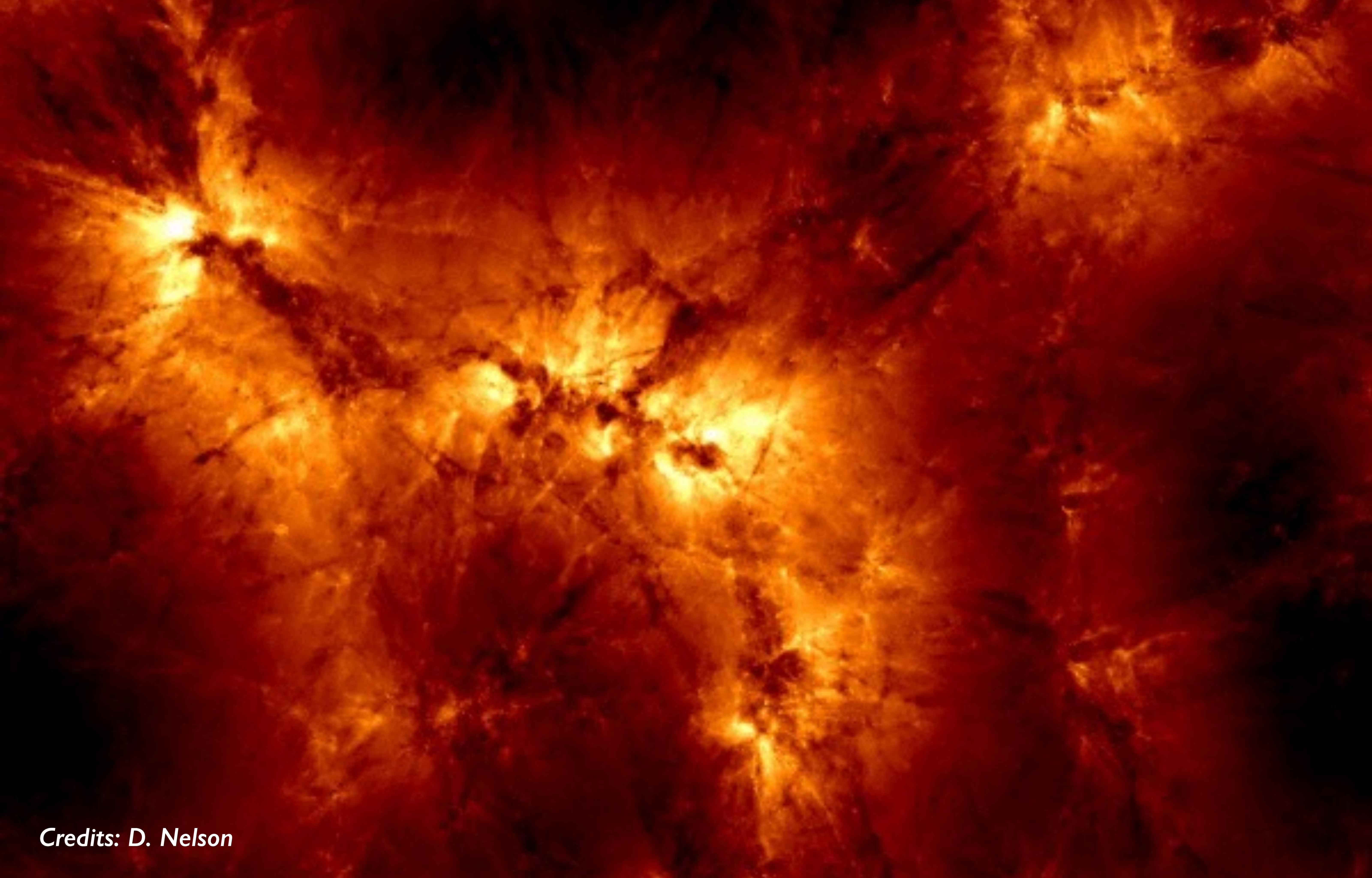
Springel:2017
Pillepich:2017b
Nelson:2017 +
Marinacci:2017 *Genel:2017*
Naiman:2017 *Vogelsberger:2017*

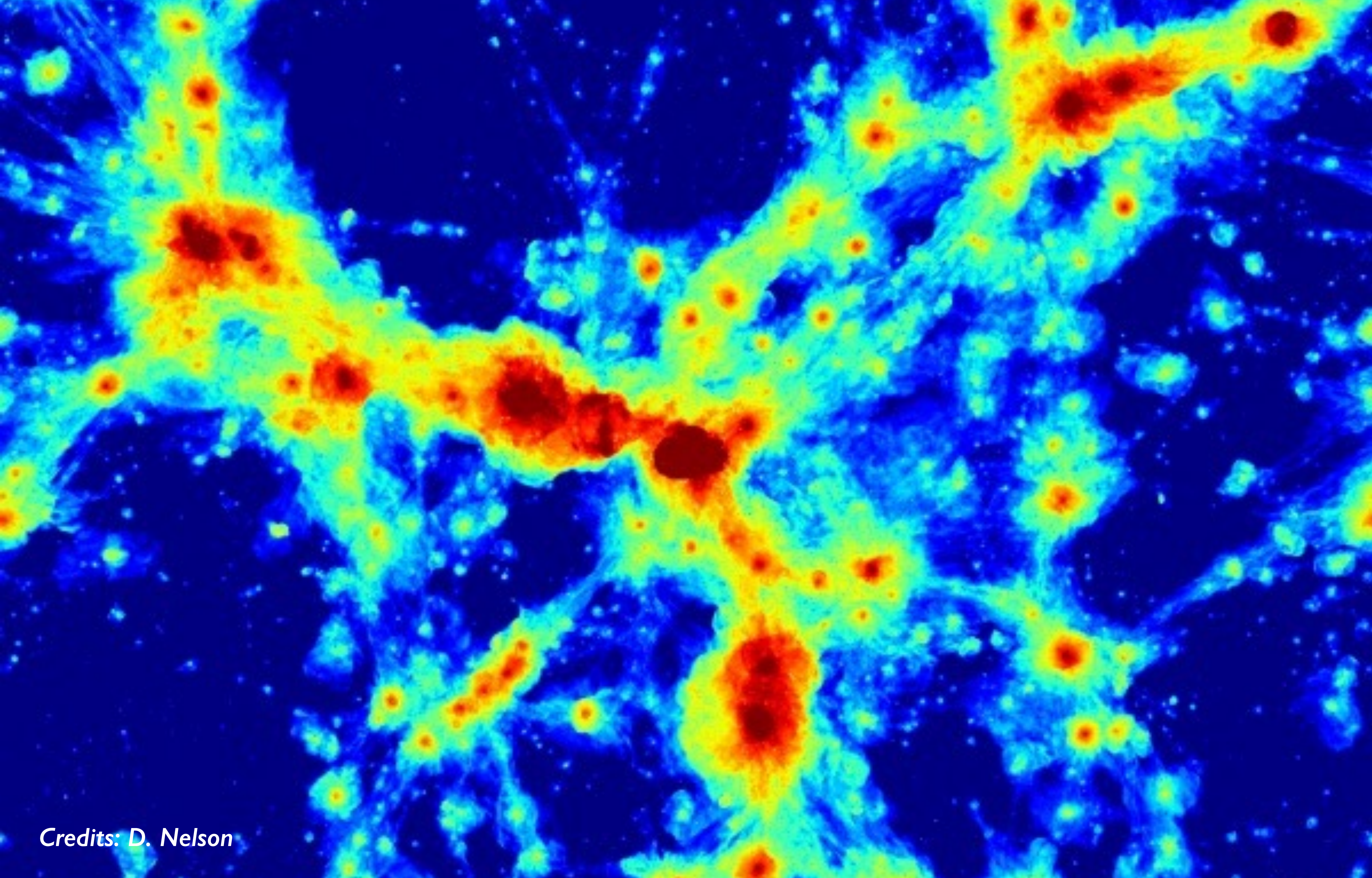
TNG100 and TNG 300 are done!
TNG50 requires many more months to arrive to z=0

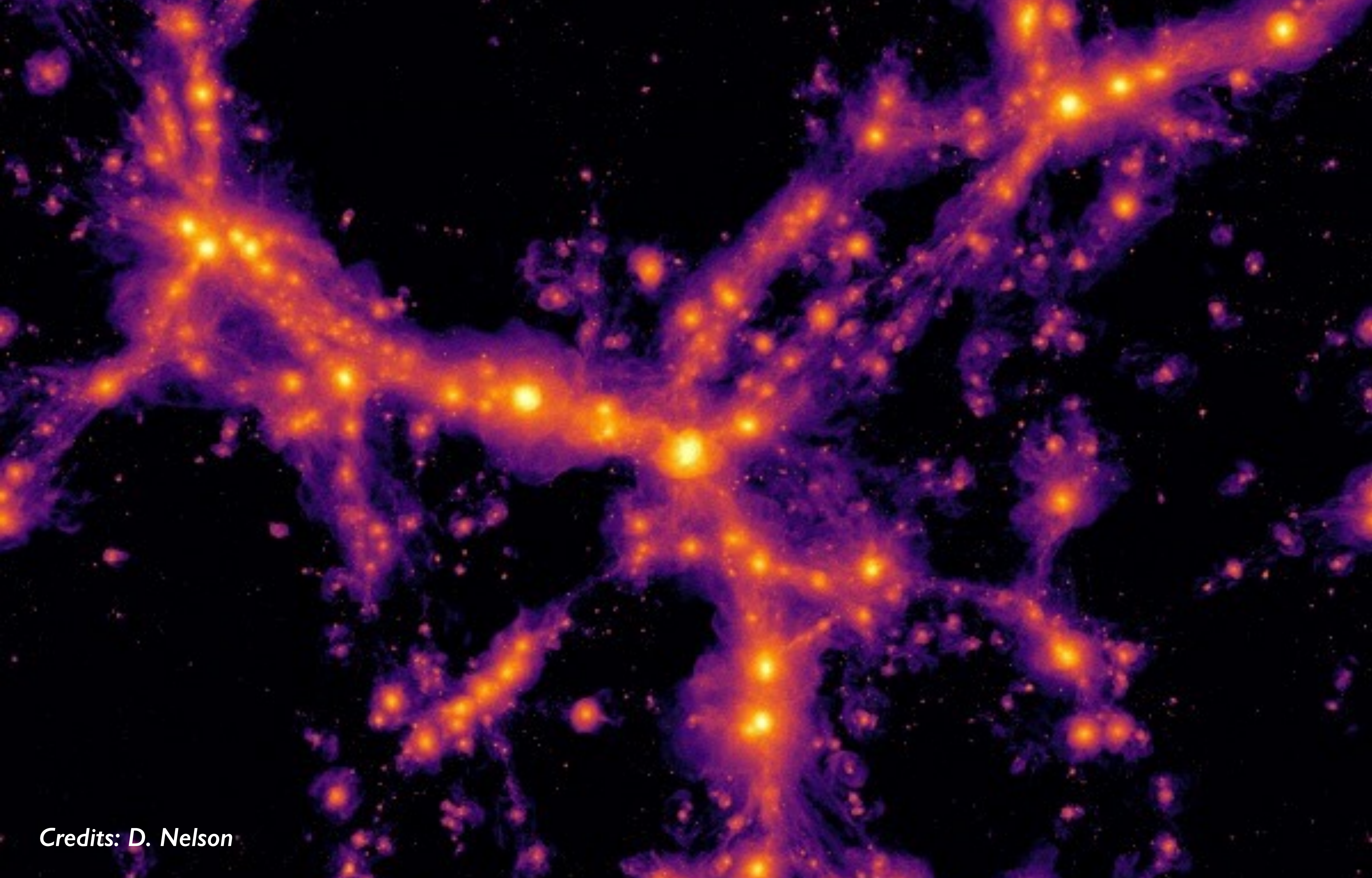
Explorations

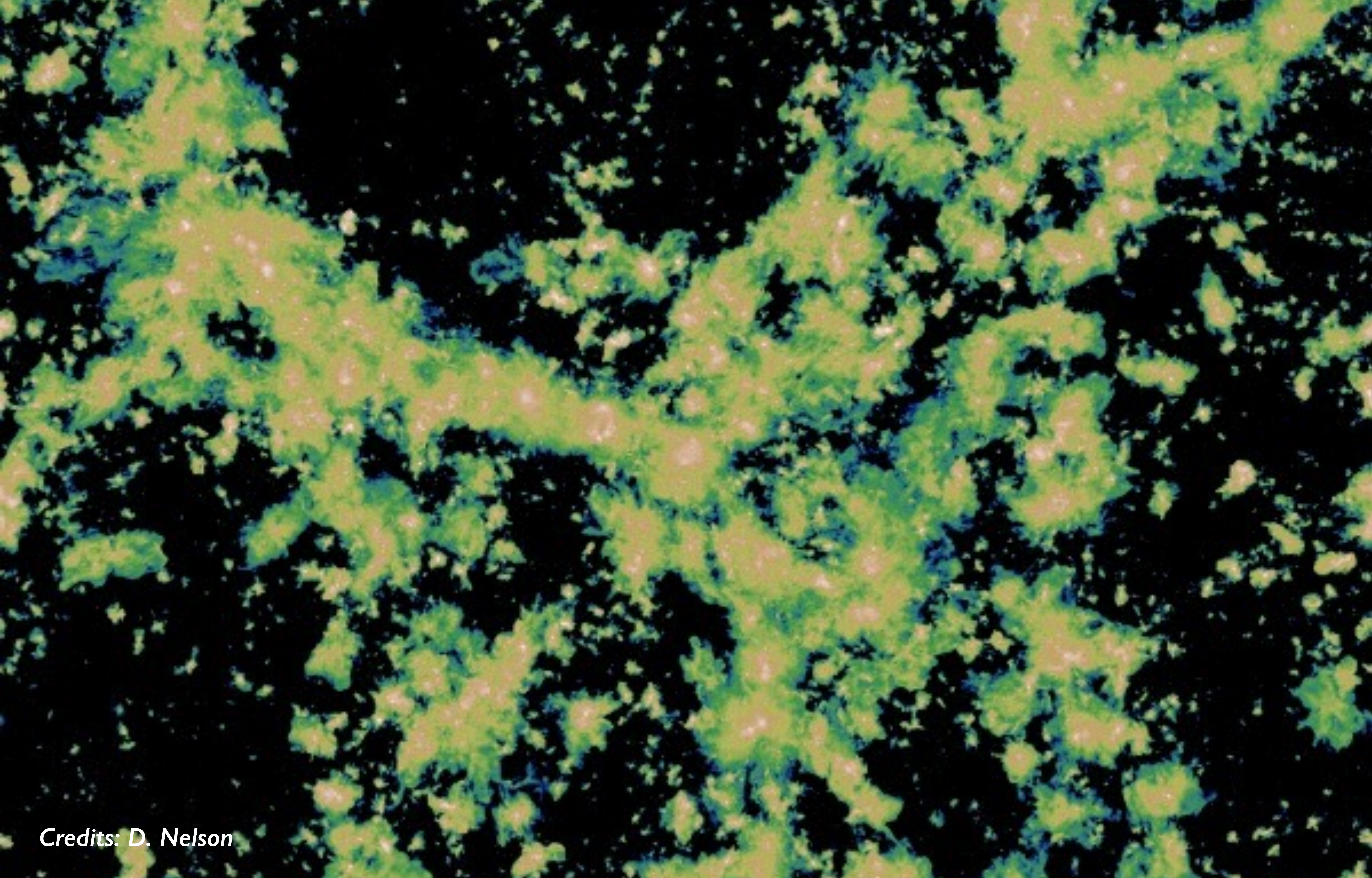

Credits: D. Nelson

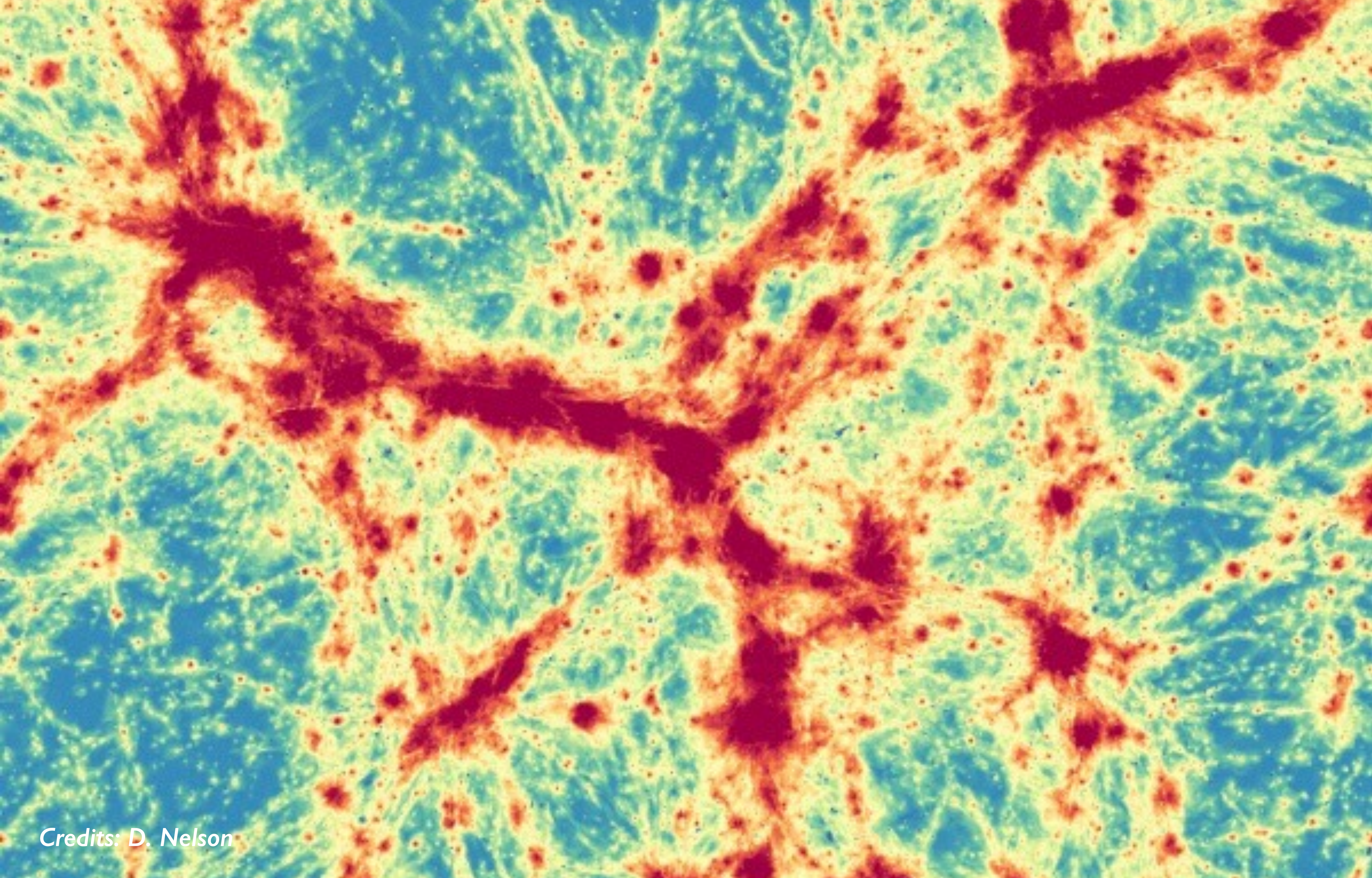

Credits: D. Nelson

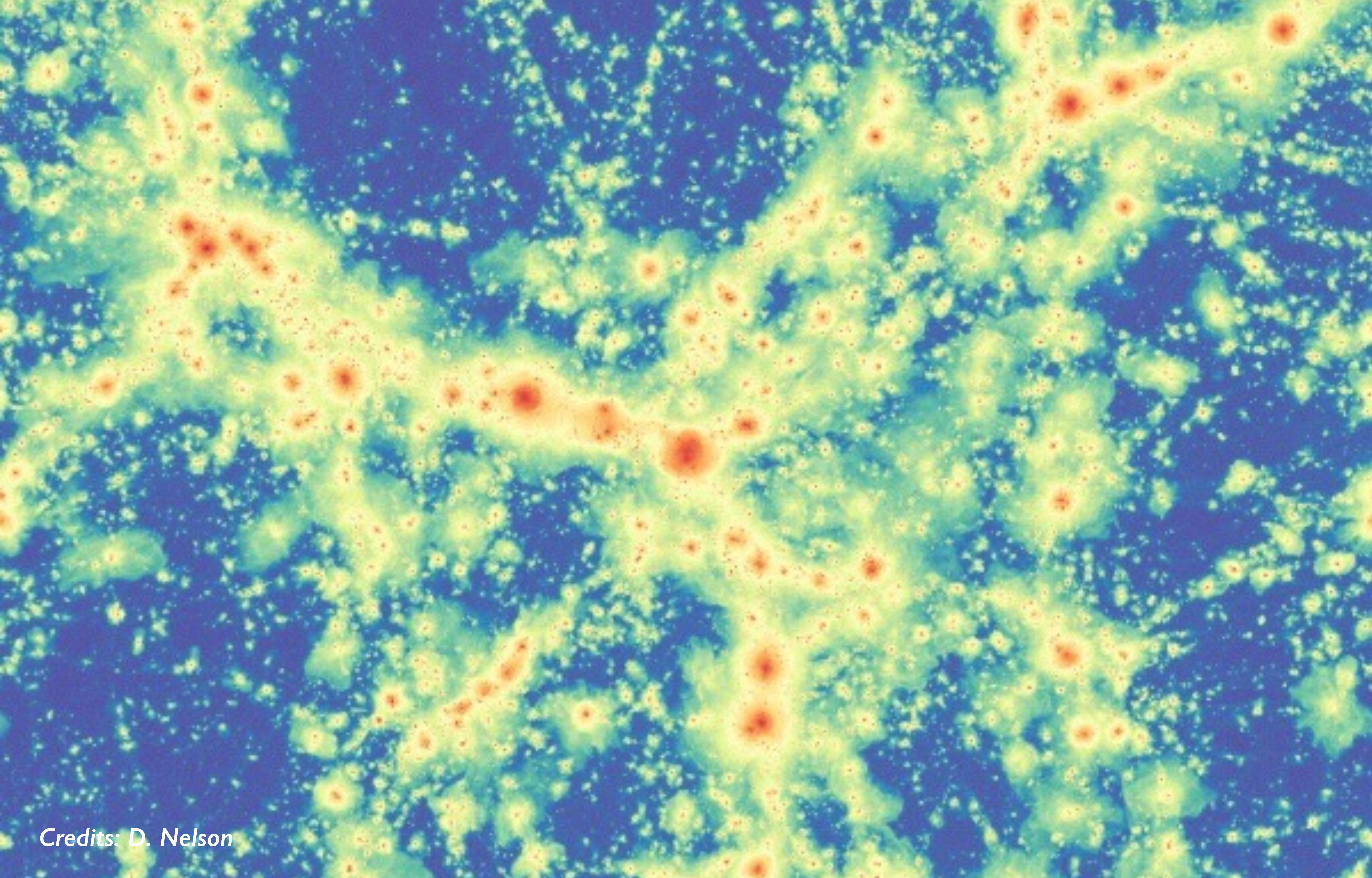

Credits: D. Nelson

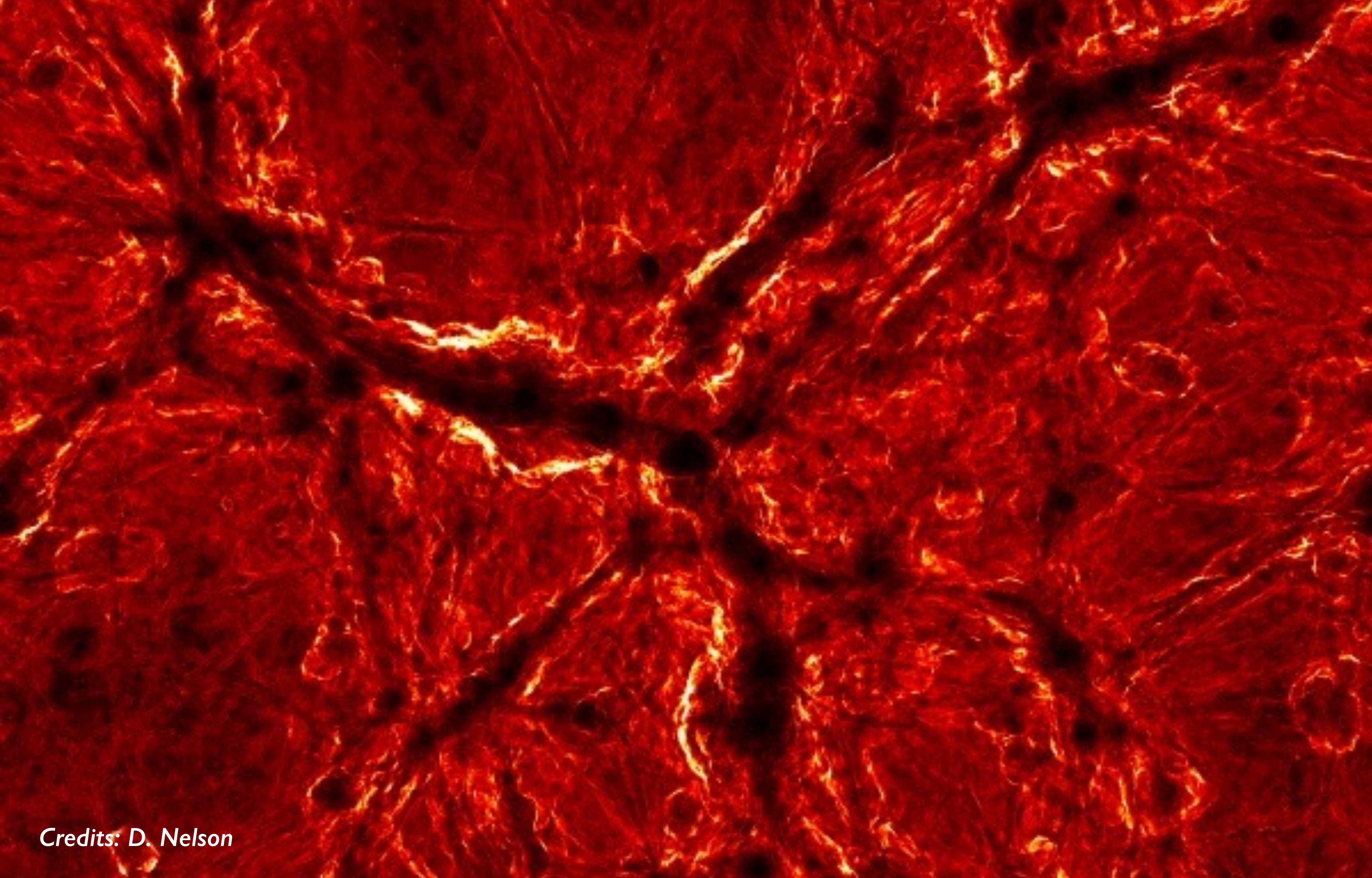

Credits: D. Nelson

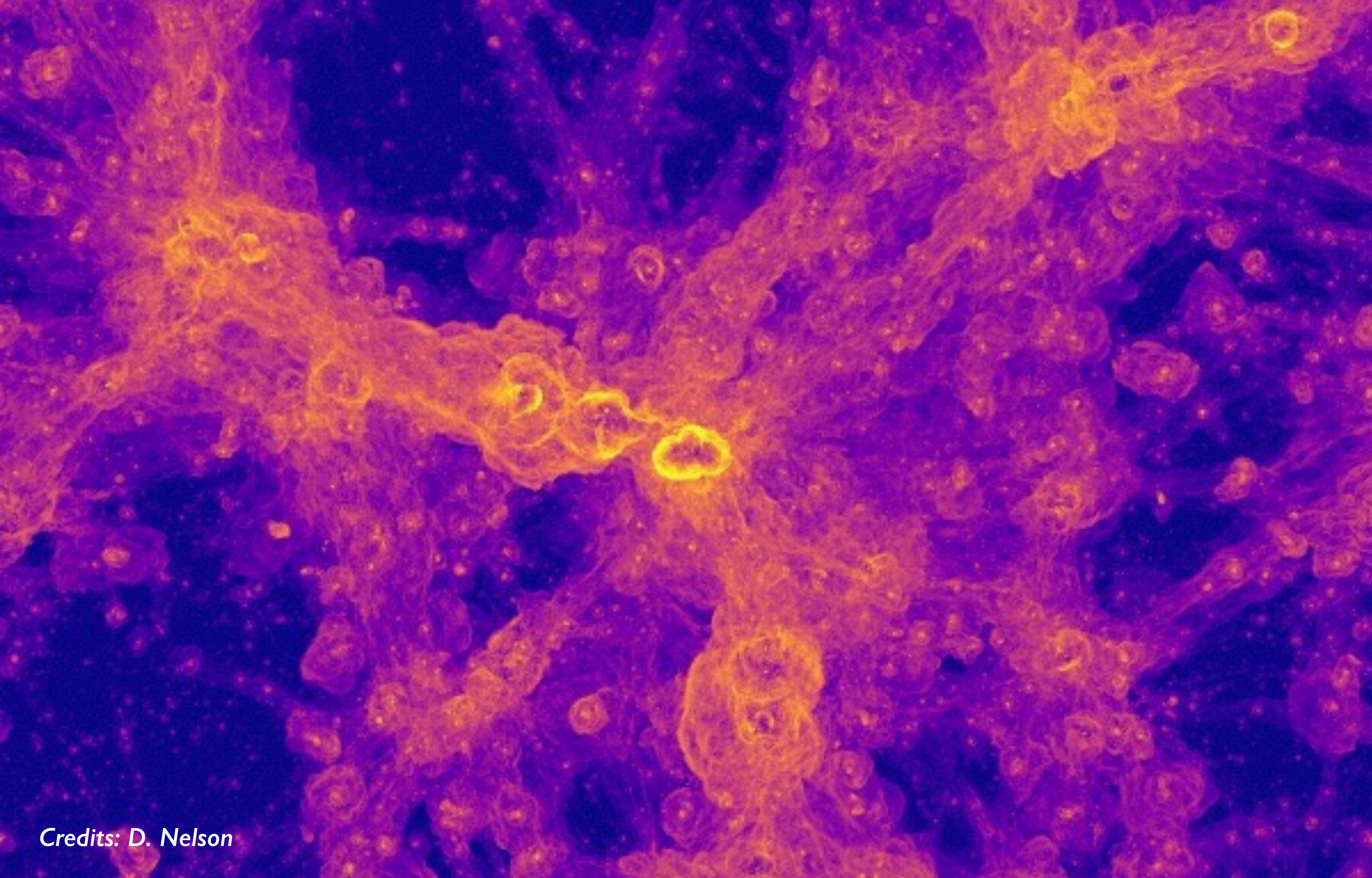

Credits: D. Nelson

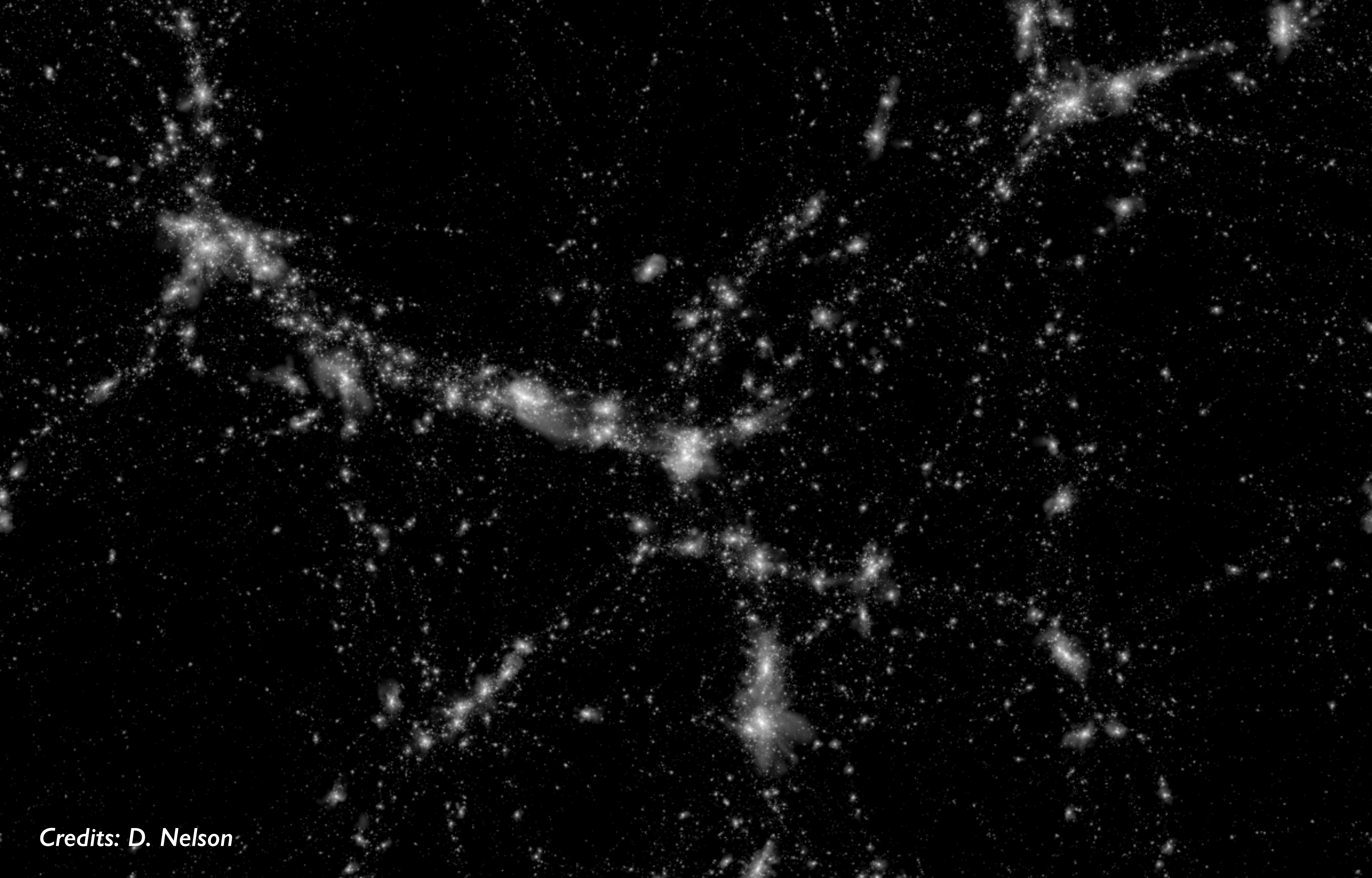

Credits: D. Nelson


Credits: D. Nelson

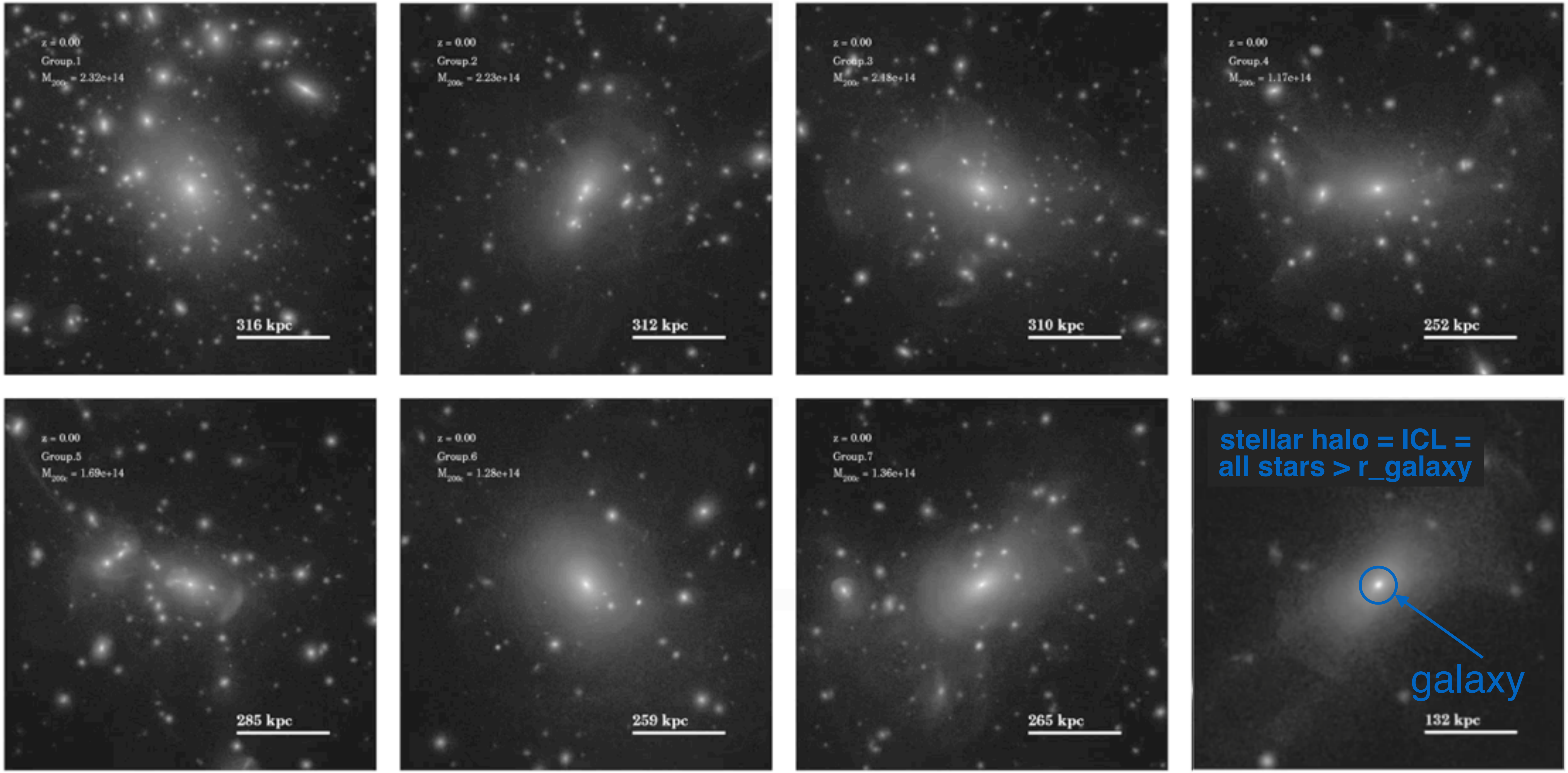

Credits: D. Nelson


Credits: D. Nelson


Credits: D. Nelson

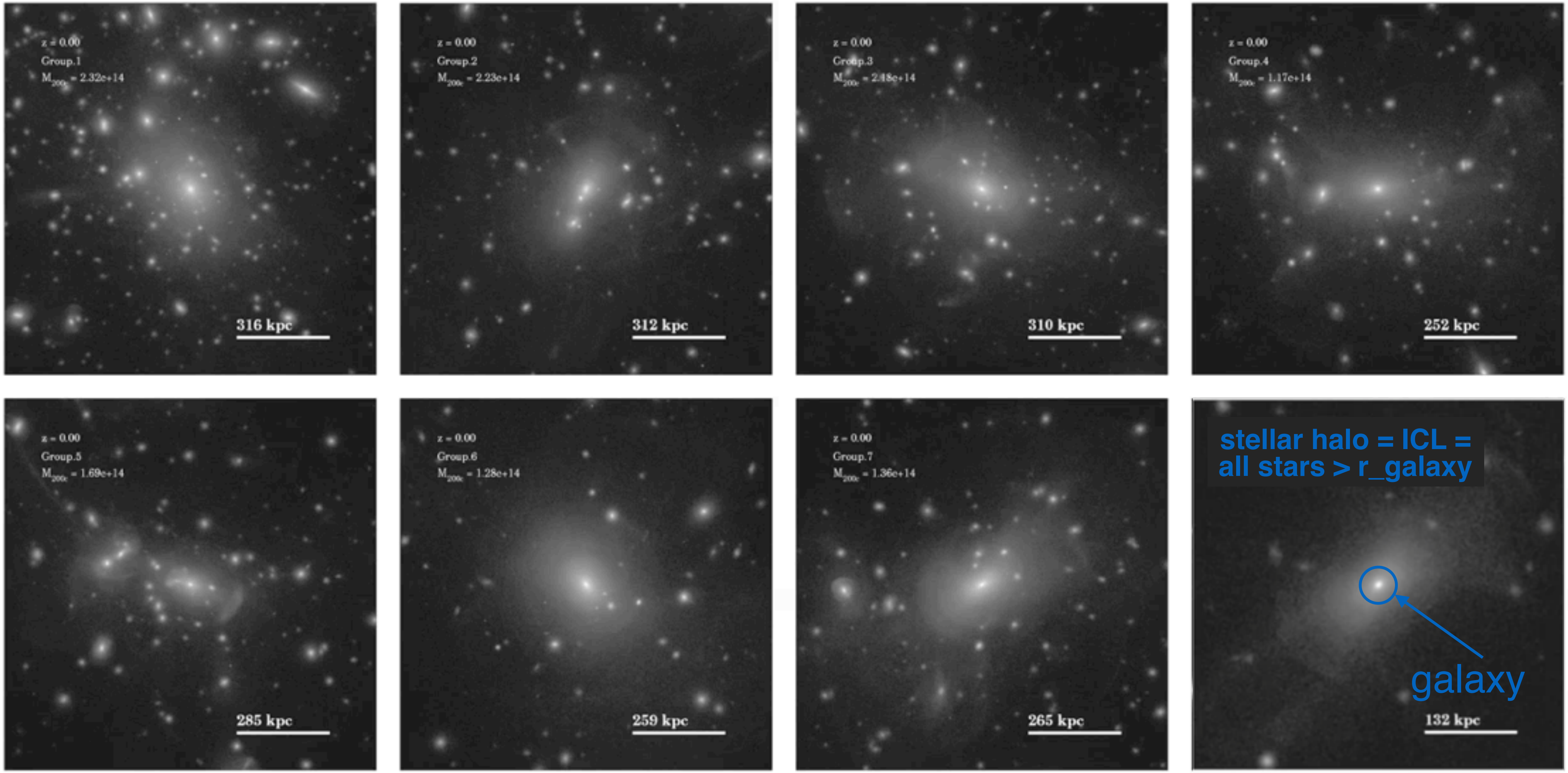

Credits: D. Nelson

#1: With TNG, we sample thousands of massive galaxies with their ICL



Pillepich, Nelson, Hernquist et al. 2017

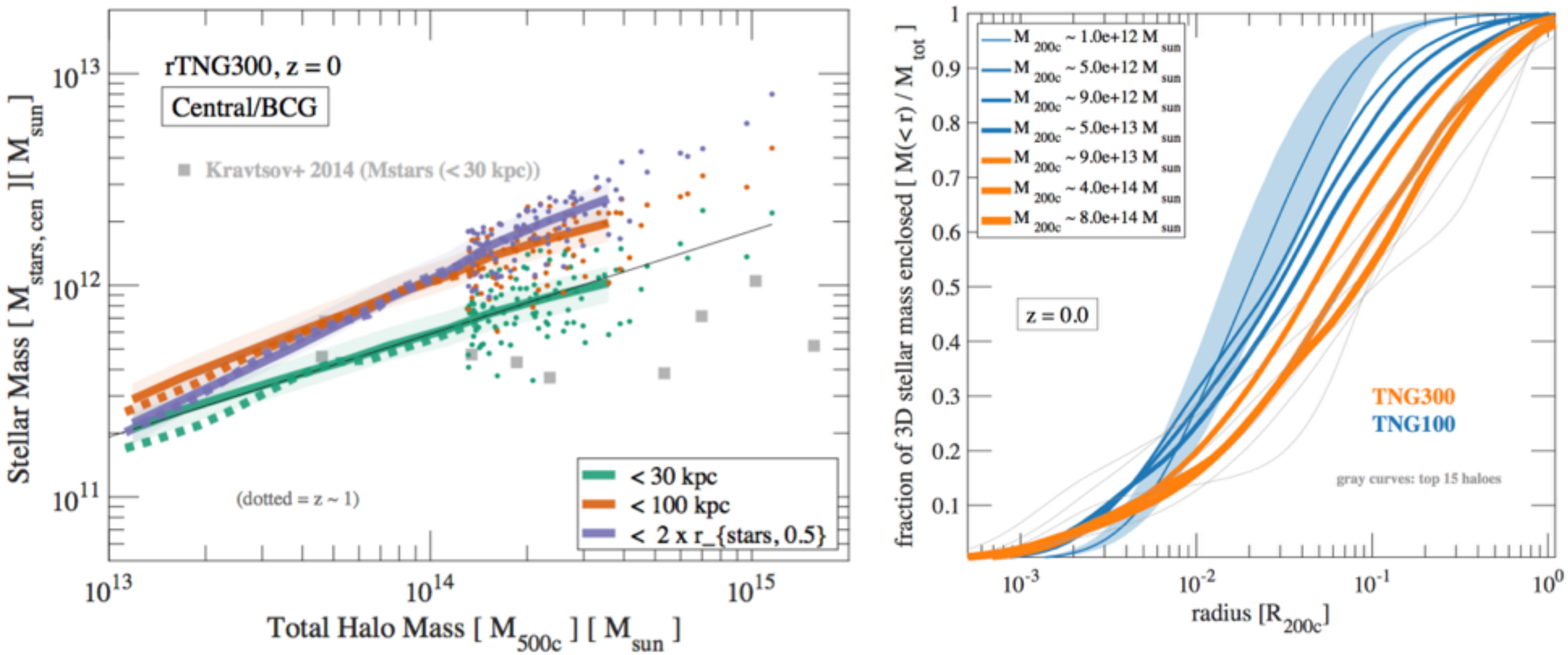
#1: With TNG, we sample thousands of massive galaxies with their ICL



Pillepich, Nelson, Hernquist et al. 2017

#2: Halo Mass predicts Stellar Mass and … Stellar Mass Profiles!

For galaxies in haloes > a few 10^12 Msun and for r > a few kpc:



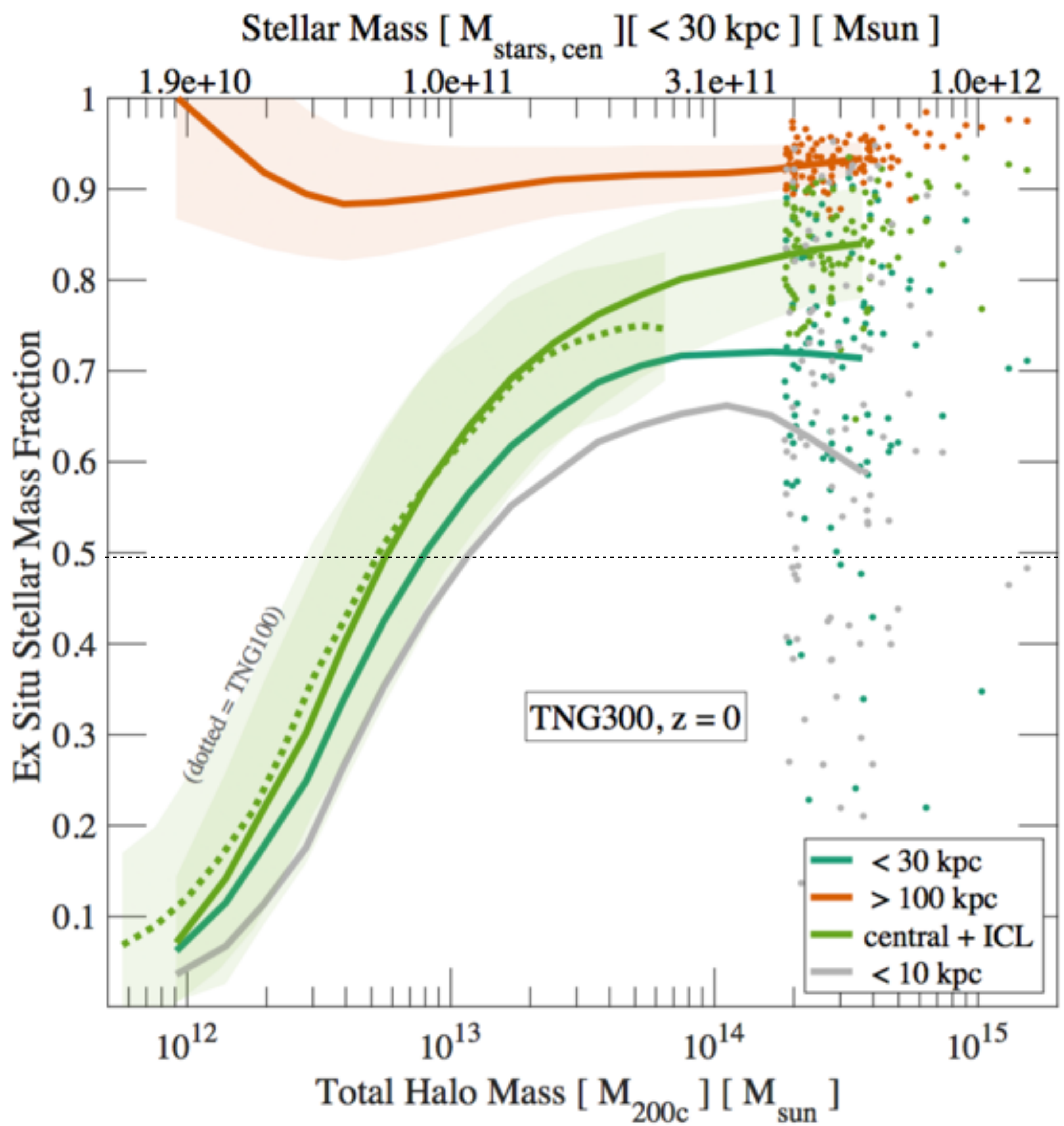
M_stars = f(MHalo) at better than ~0.15 dex uncertainty

Stellar Mass Profiles (> a few kpc) exhibit (on average) the same shape at all Halo Masses!

Pillepich, Nelson, Hernquist et al. 2017

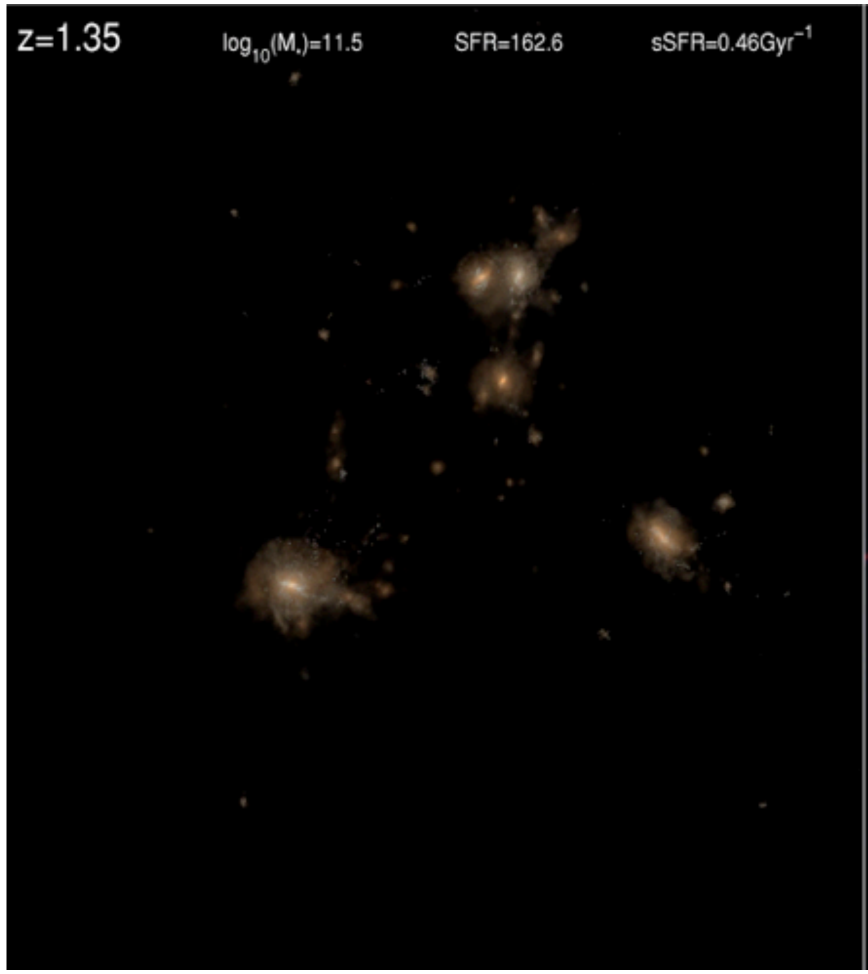
#3: Much of the stellar mass in big haloes has been "stolen"

Fraction of ever Accreted Stars



Pillepich, Nelson, Hernquist et al. 2017

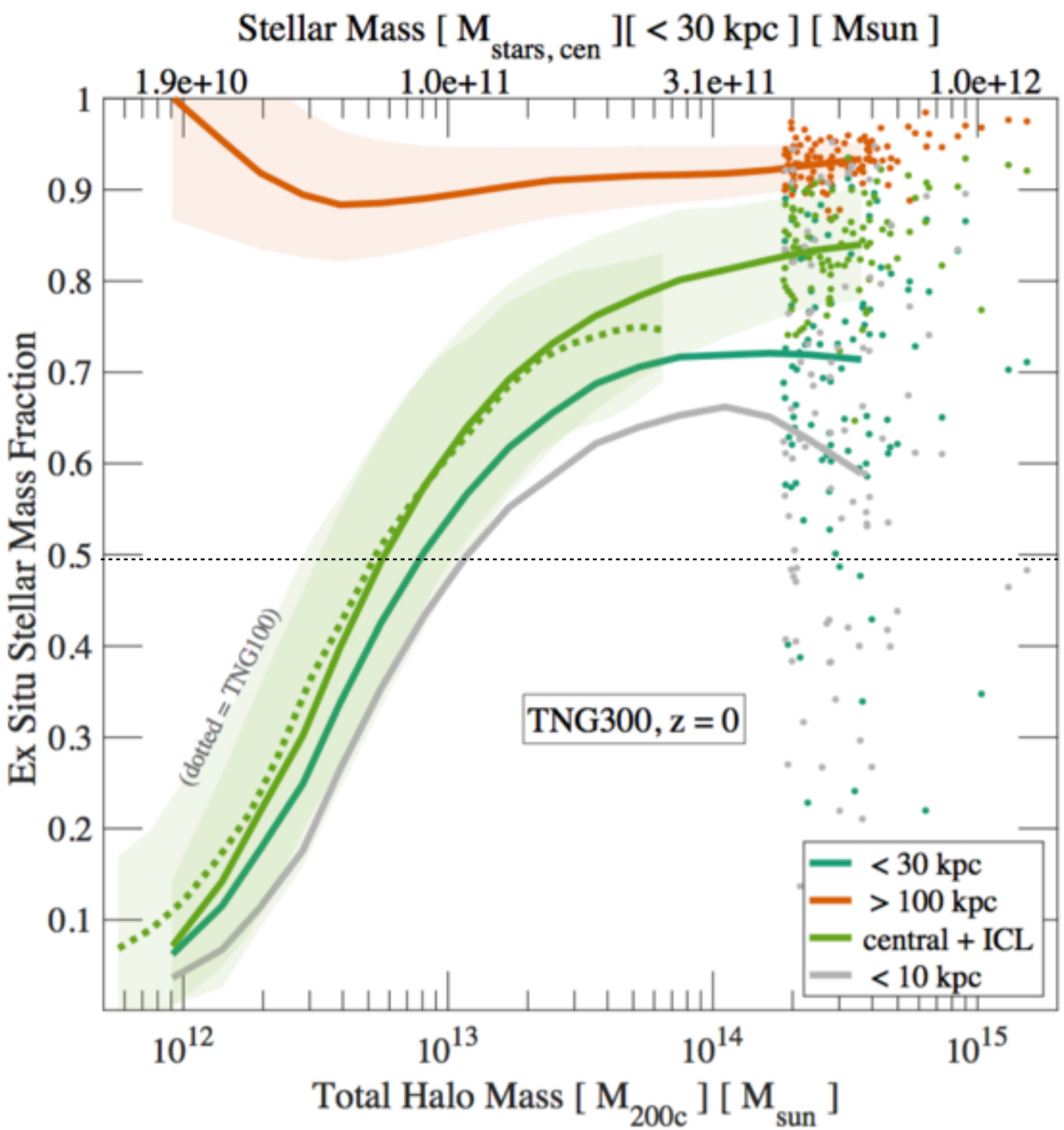
Credits: Shy Genel



More massive galaxies have assembled **more than half of their stars by accreting satellites and merging** rather than making star formation

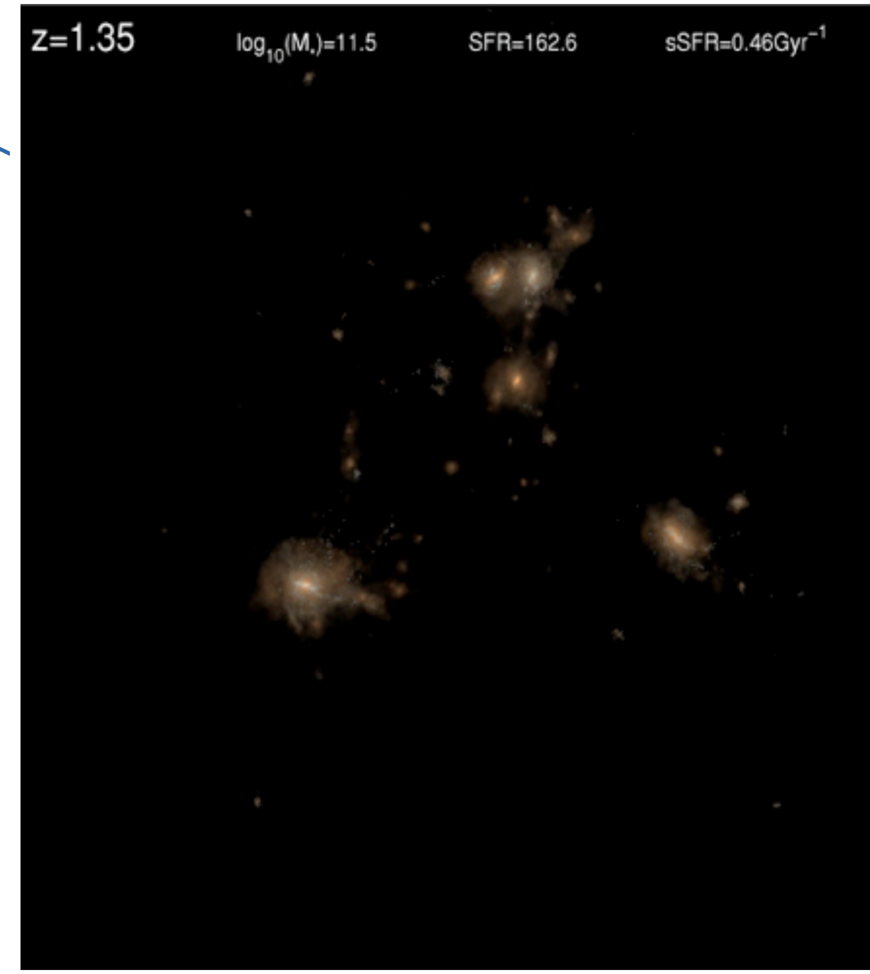
#3: Much of the stellar mass in big haloes has been “stolen”

Fraction of ever Accreted Stars



Pillepich, Nelson, Hernquist et al. 2017

Credits: Shy Genel

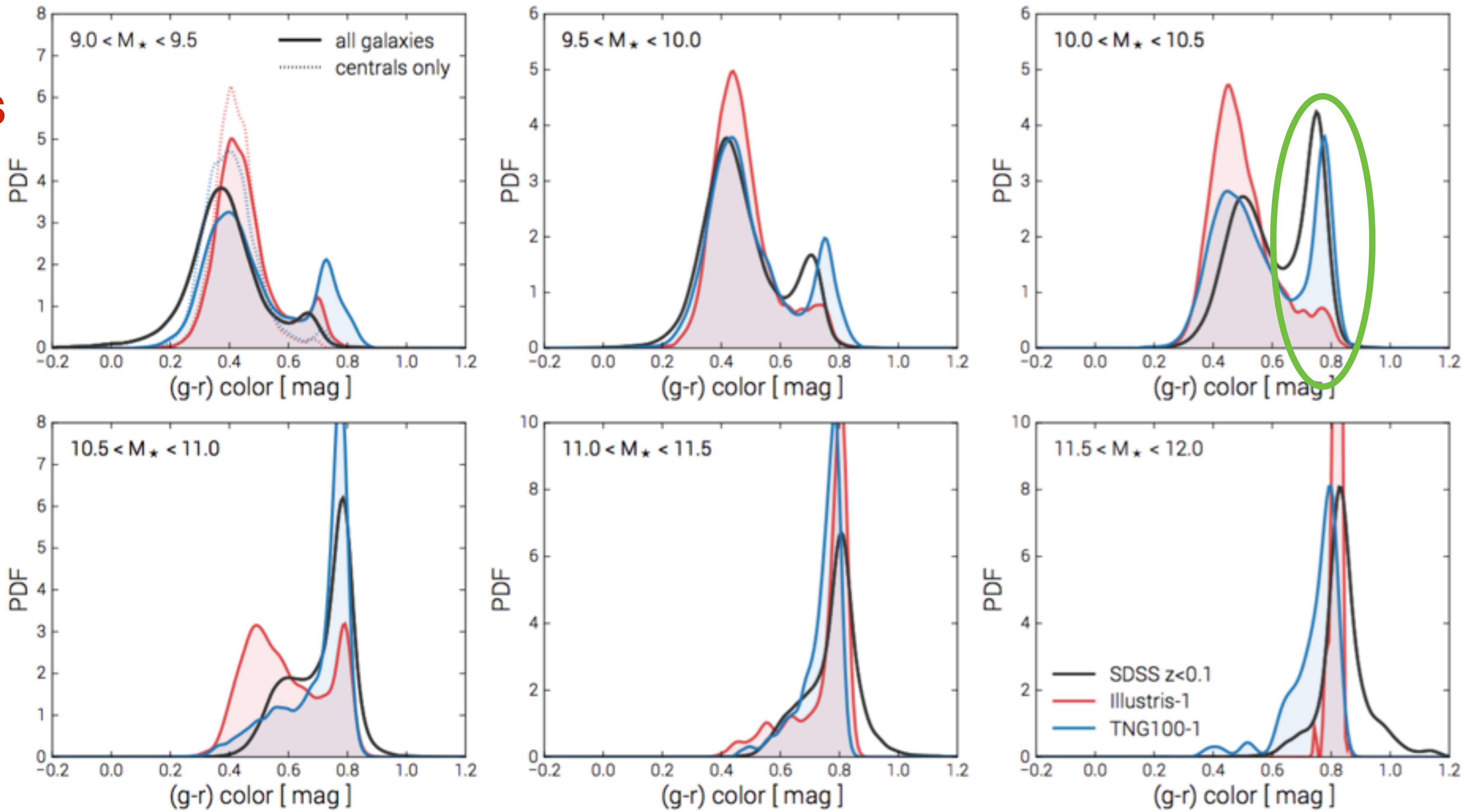


More massive galaxies have assembled **more than half of their stars by accreting satellites and merging** rather than making star formation

#4: The TNG color bimodality is in *quantitative* agreement with SDSS

SDSS
Illustris
TNG

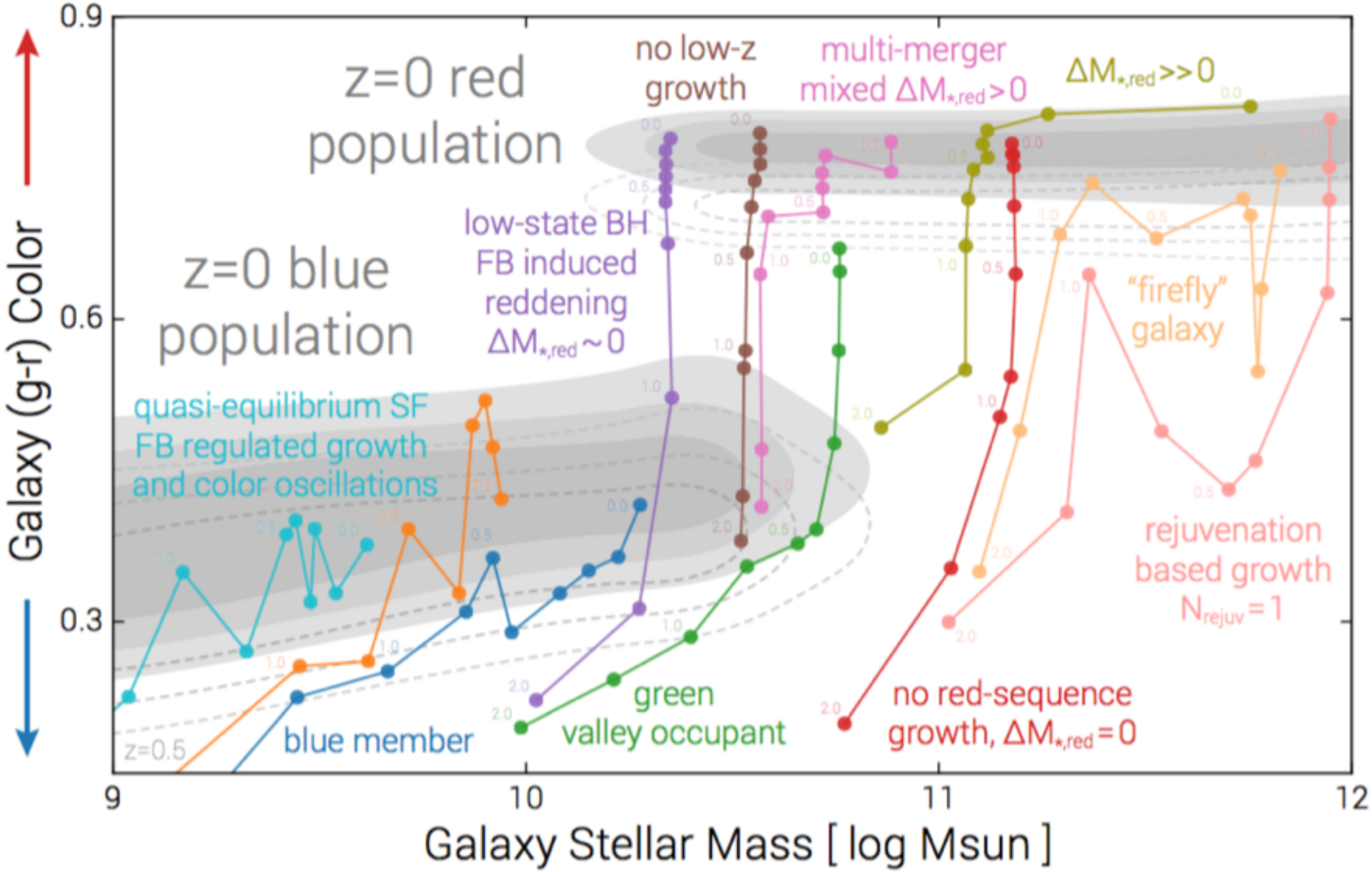
with dust reddening!



We have solved the lack of red galaxies which affected Illustris in certain mass ranges

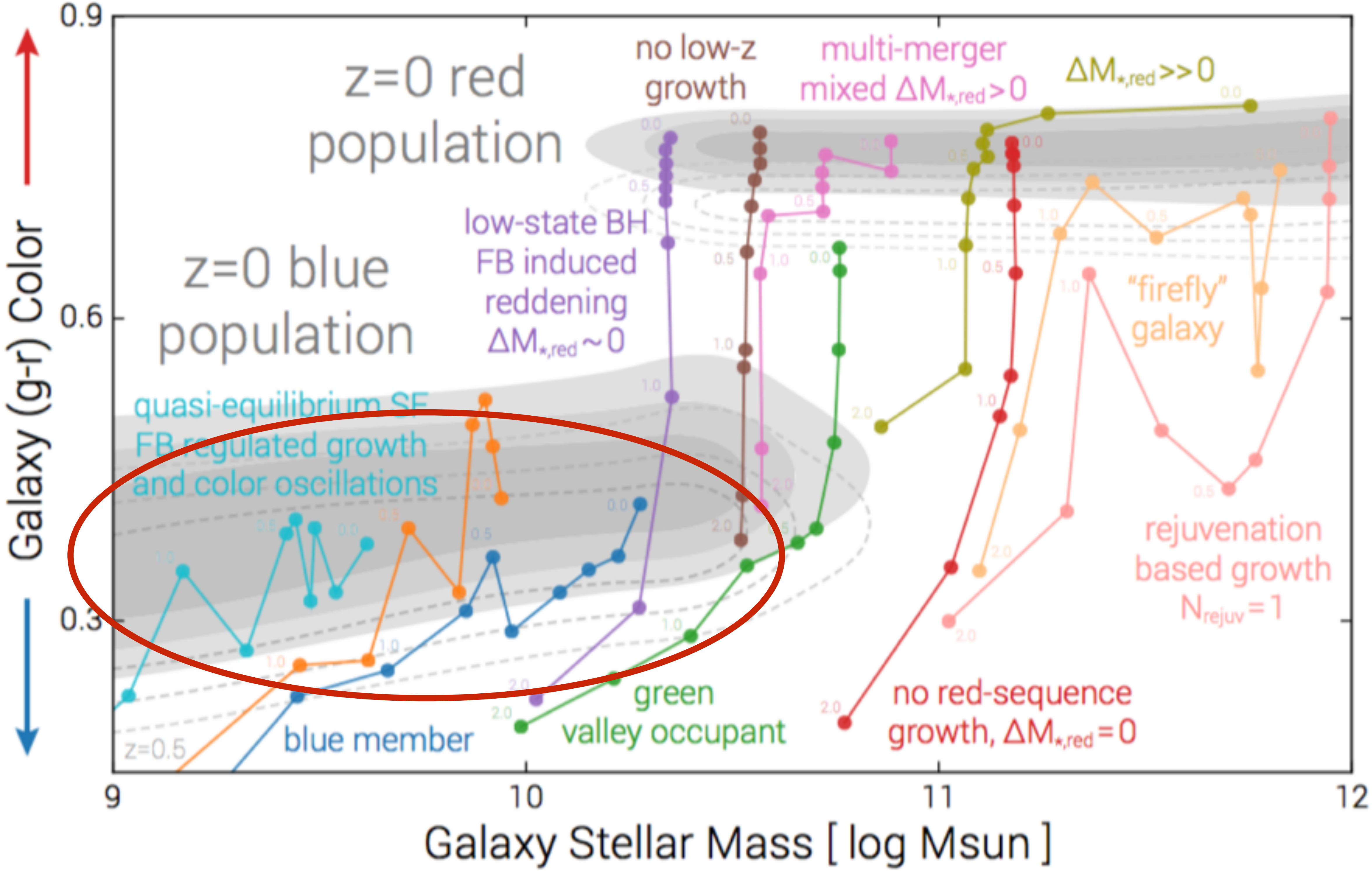
Nelson, Pillepich, Springel, et al. 2017

#5: We can explore (and time) all possible pathways…



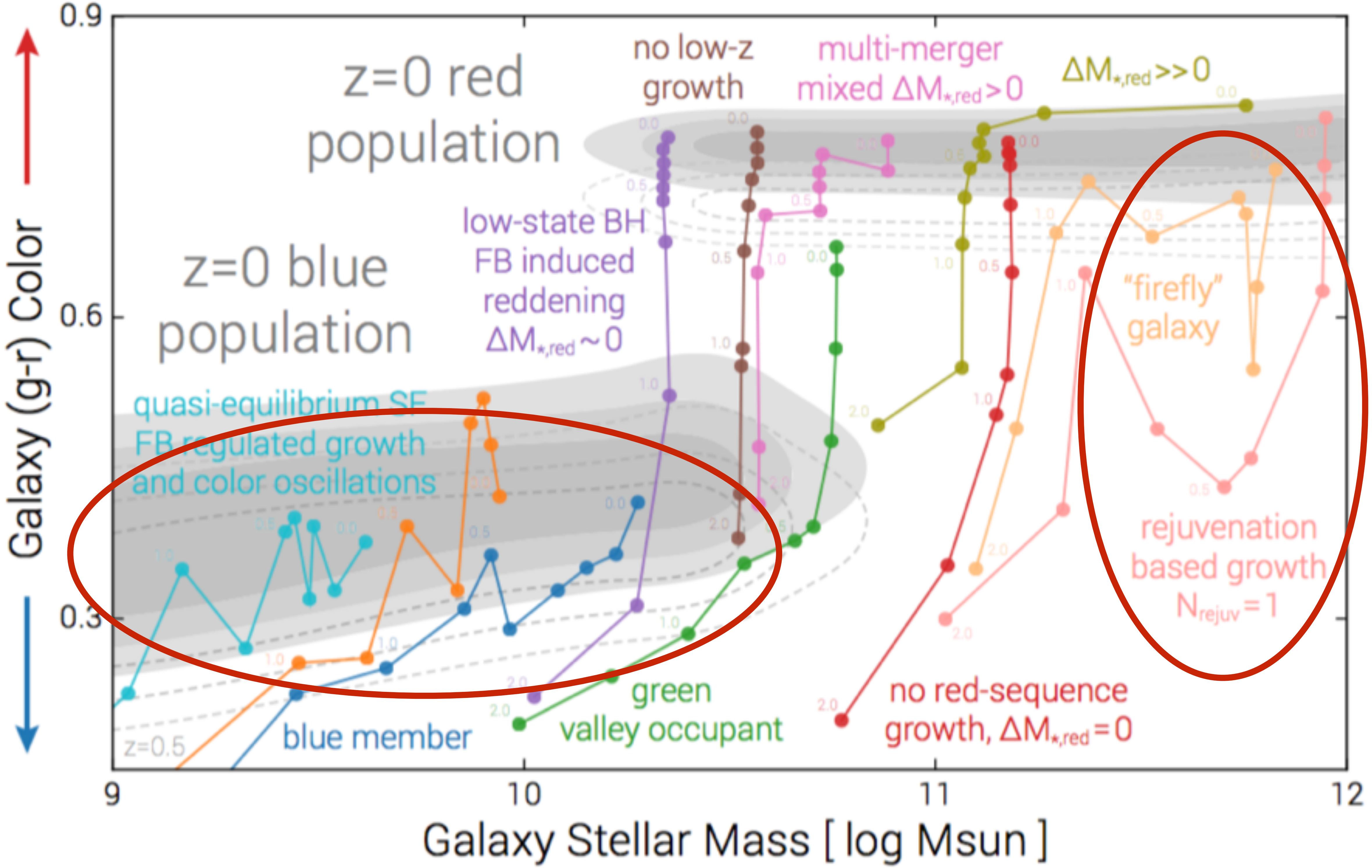
Nelson, Pillepich, Springel, et al. 2017

#5: We can explore (and time) all possible pathways…



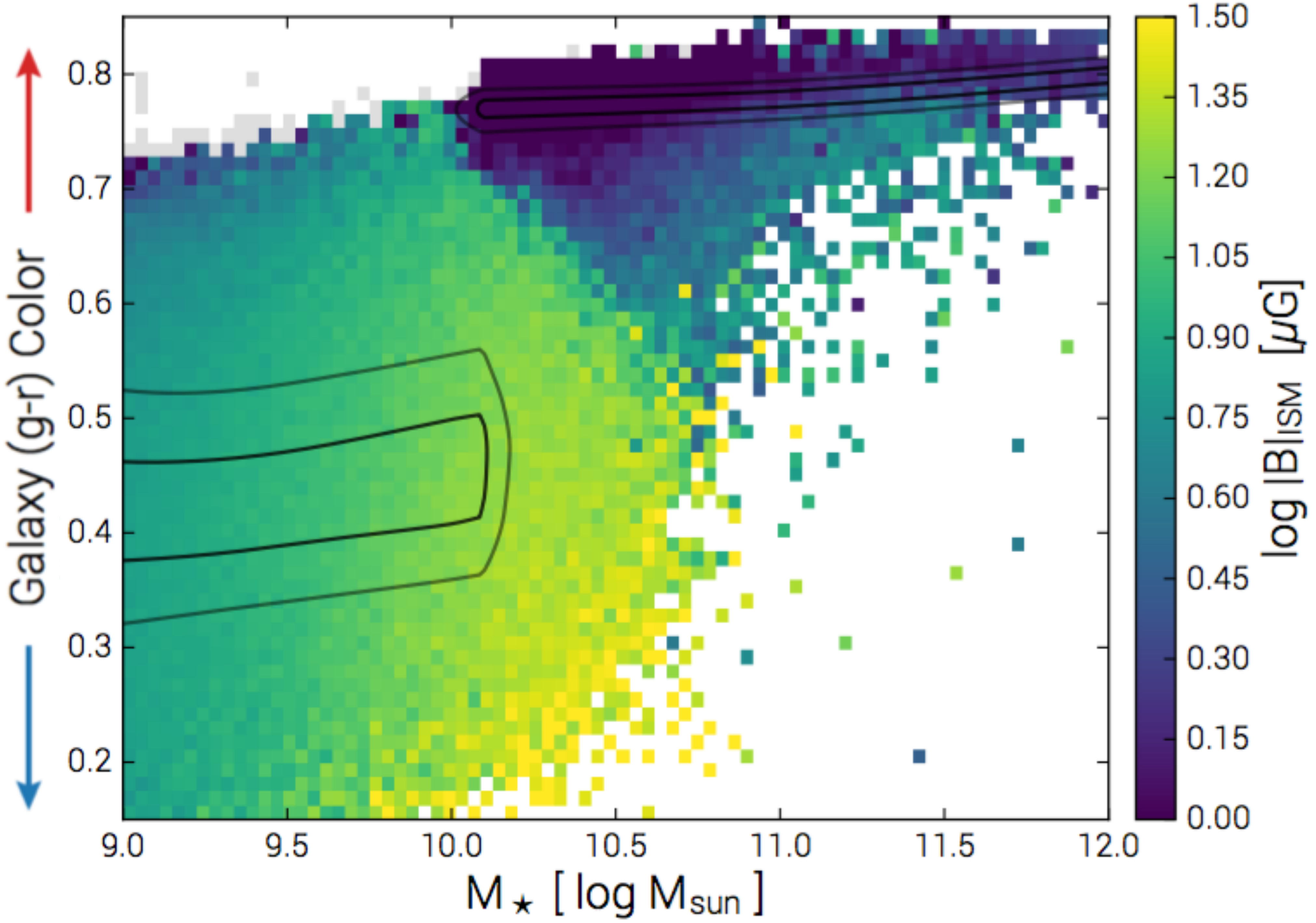
Nelson, Pillepich, Springel, et al. 2017

#5: We can explore (and time) all possible pathways...



Nelson, Pillepich, Springel, et al. 2017

#6: Magnetic Fields in/around galaxies “know” their color



Magnetic Field Strength:

Blue galaxies:
10-30 microGauss
Red Galaxies:
< 1 microGauss

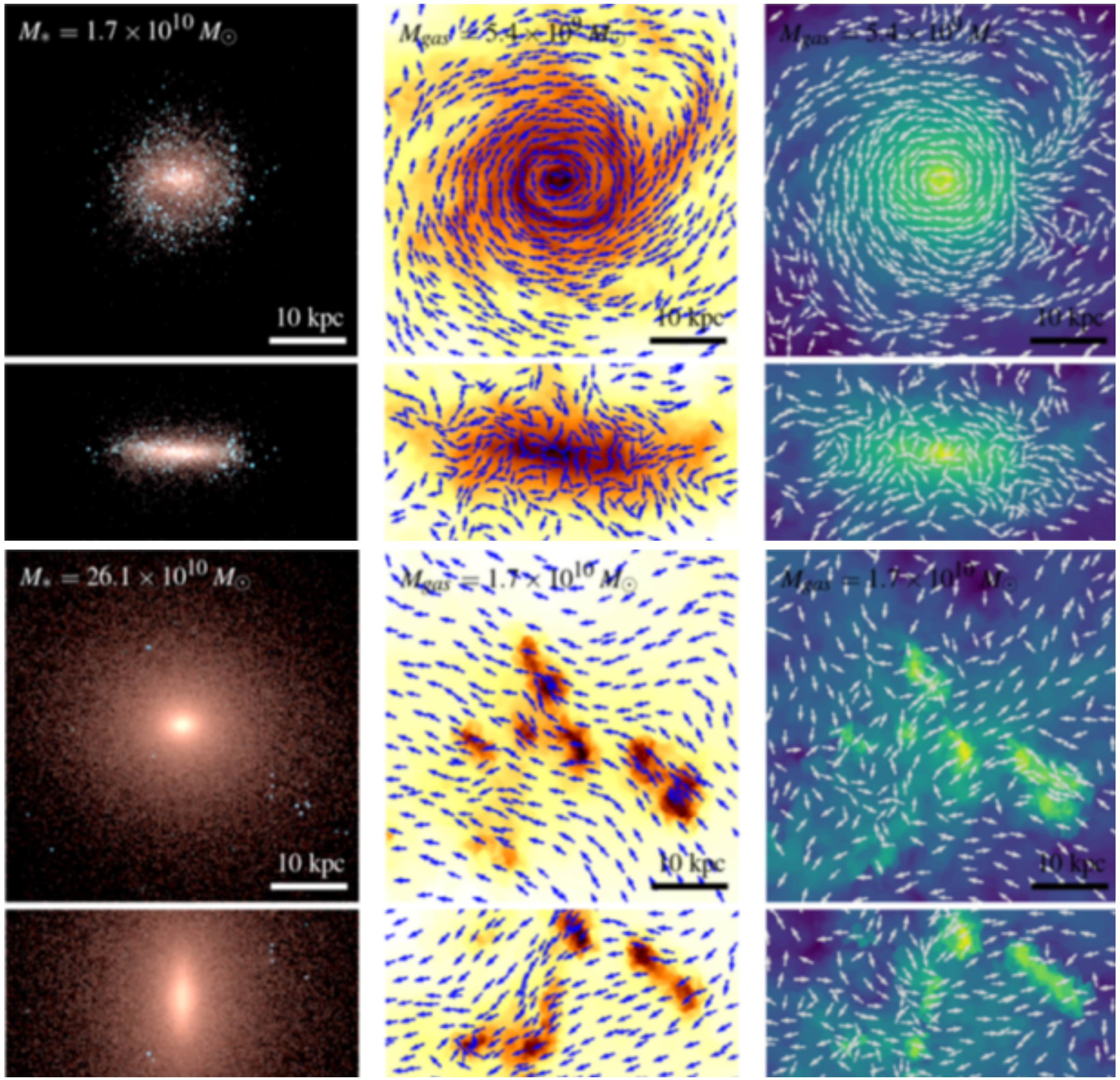
(not a causation!)

Nelson, Pillepich, Springel, et al. 2017

#7: Magnetic Fields in/around galaxies "know" their type

DISK

ELLIPTICAL



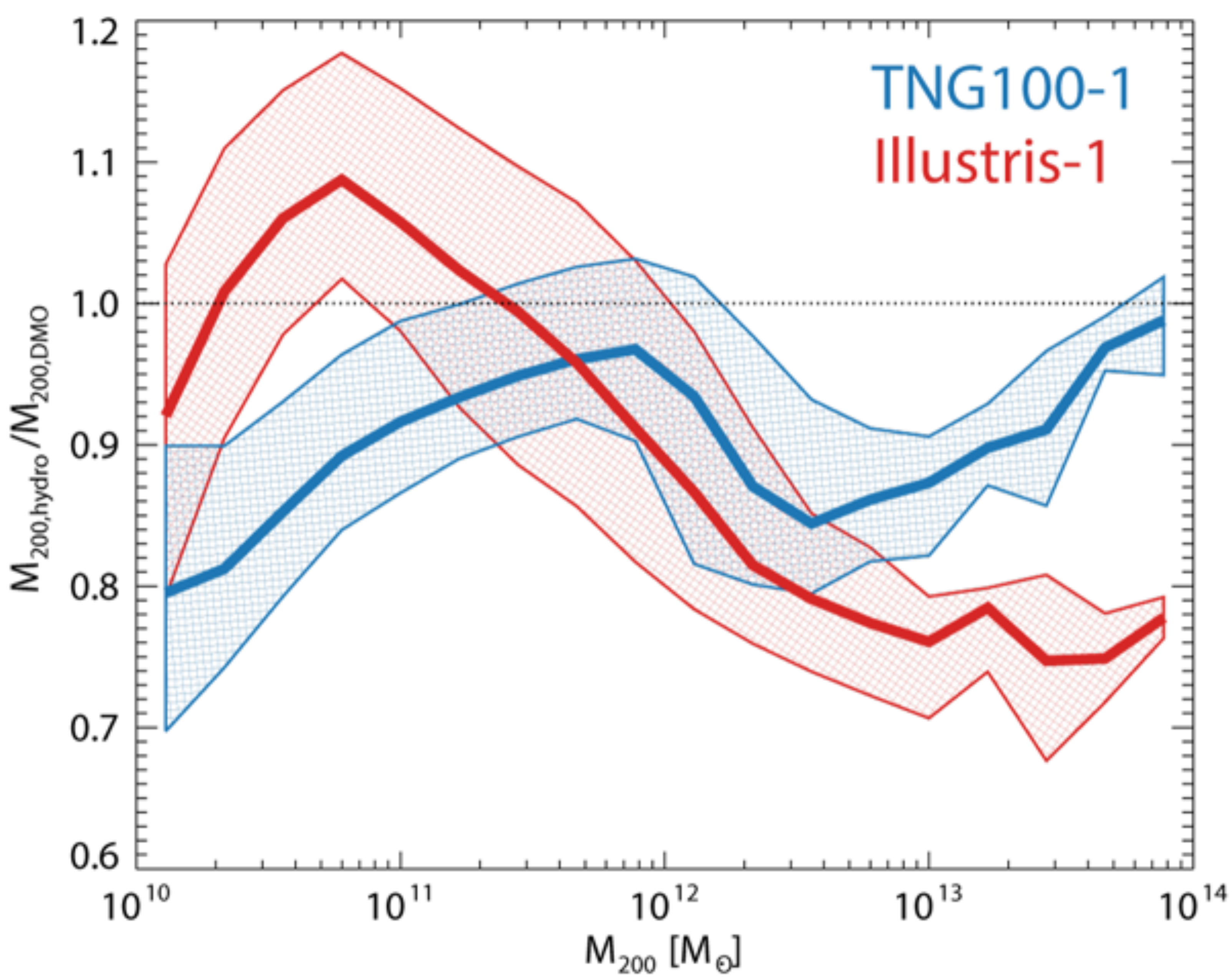
Magnetic Field Topology:

Disk galaxies: well ordered in the disk place

Elliptical Galaxies: field orientation not well defined

Marinacci, Vogelsberger, Pakmor et al. 2017

#8: Baryonic physics may alter the meaning itself of “halo mass”

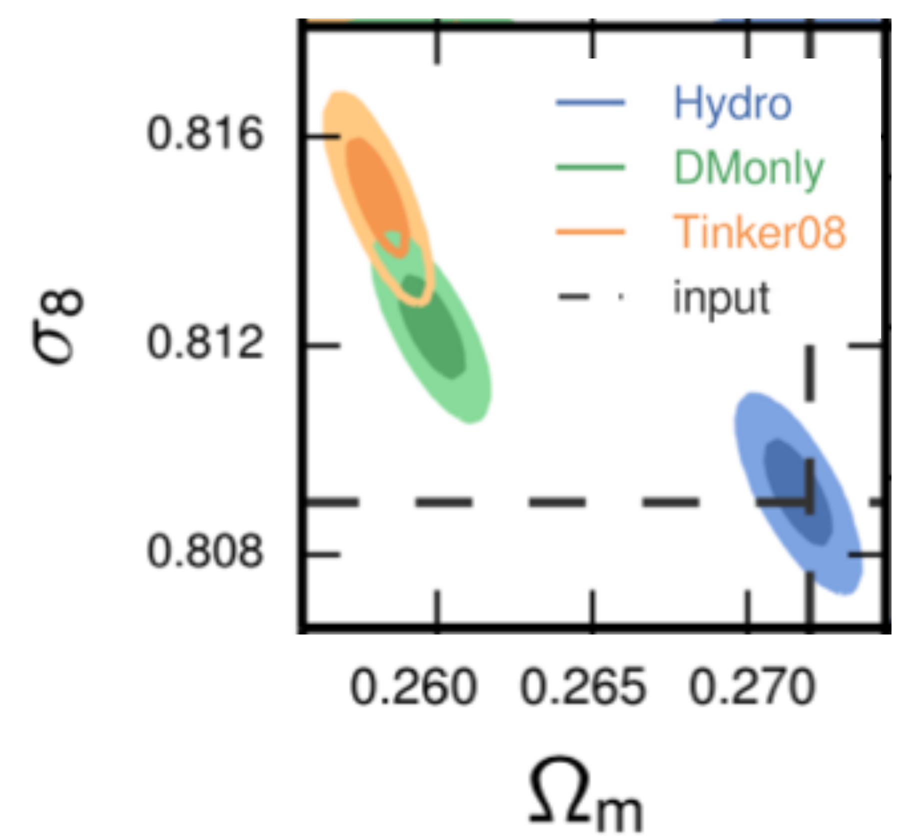


BUT, different models provide different quantitative expectations

Lovell, Pillepich et al. in prep

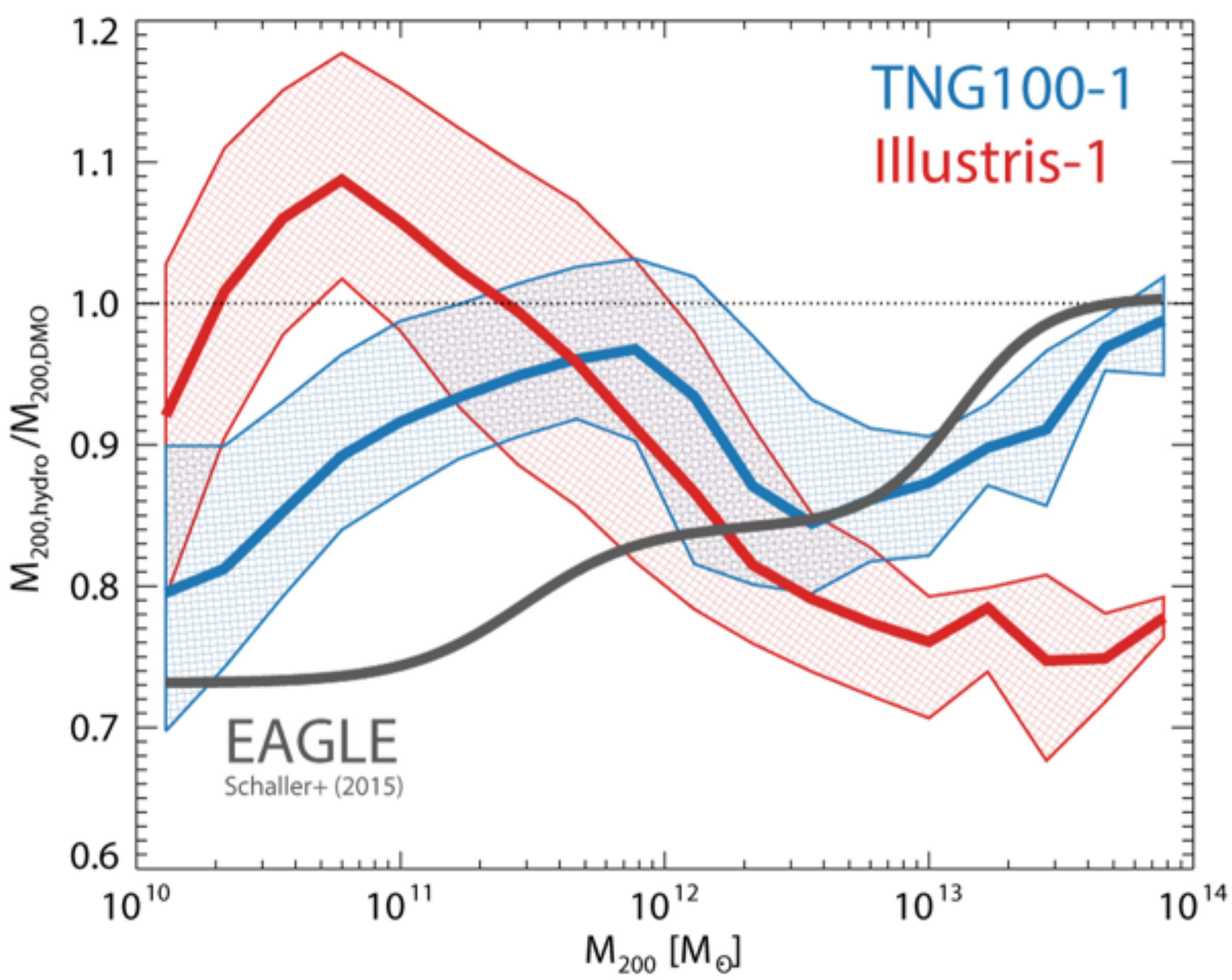
The presence of stars and gas change the “meaning/definition” of total halo mass. This implies different theoretical parameterisations of the DM halo mass functions

The implications for Cosmology are sobering:



Bouquet et al. 2016 (MAGNETICUM) eROSITA Cluster Constraints

#8: Baryonic physics may alter the meaning itself of "halo mass"

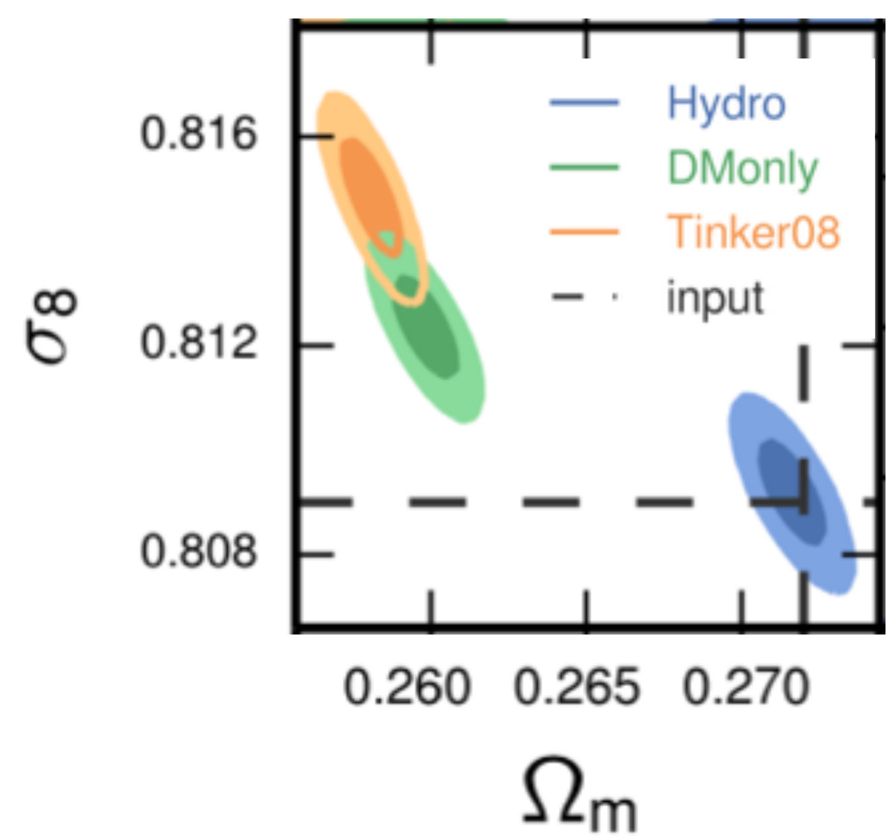


BUT, different models provide different quantitative expectations

Lovell, Pillepich et al. in prep

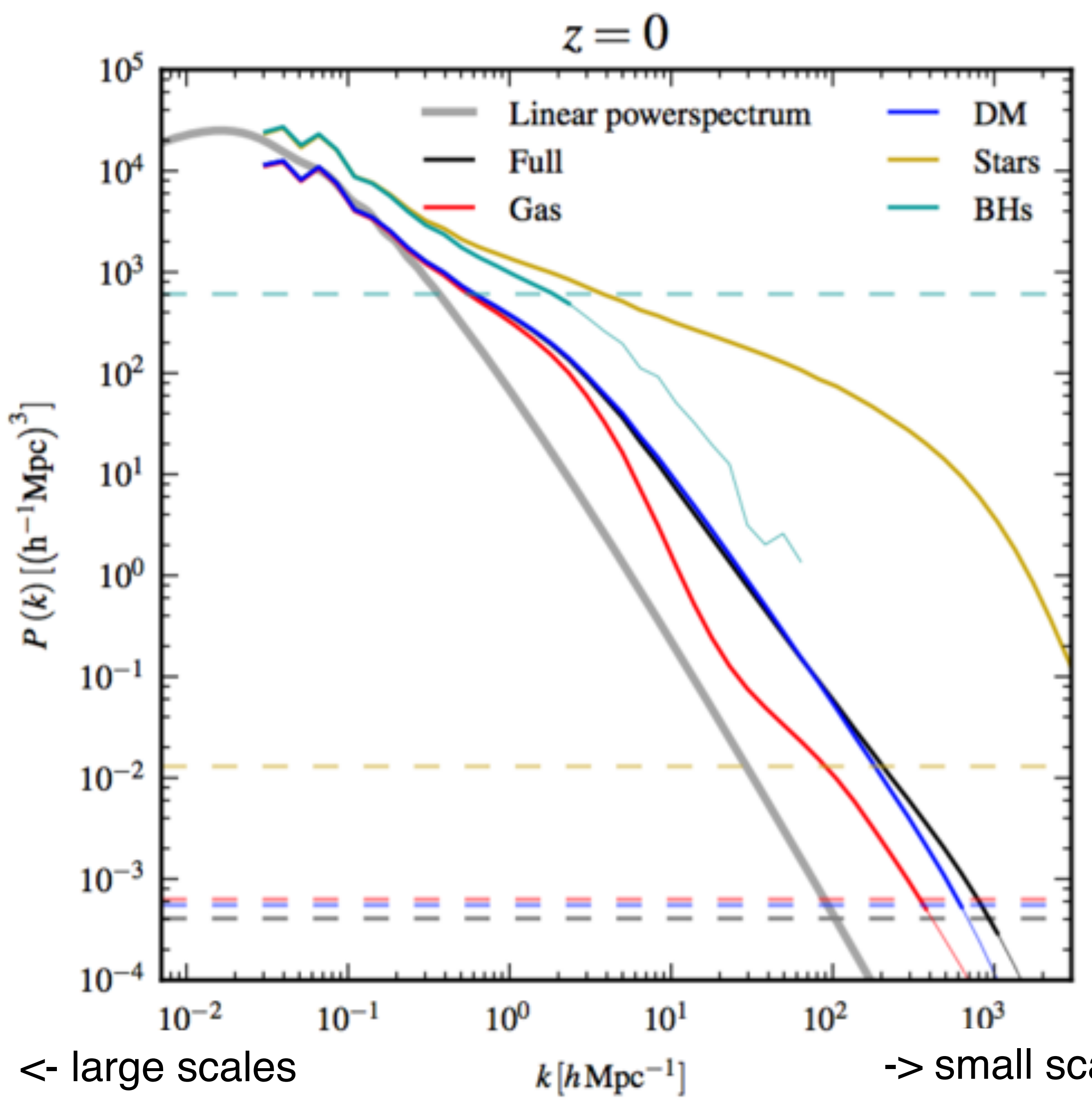
The presence of stars and gas change the "meaning/definition" of total halo mass. This implies different theoretical parameterisations of the DM halo mass functions

The implications for Cosmology are sobering:

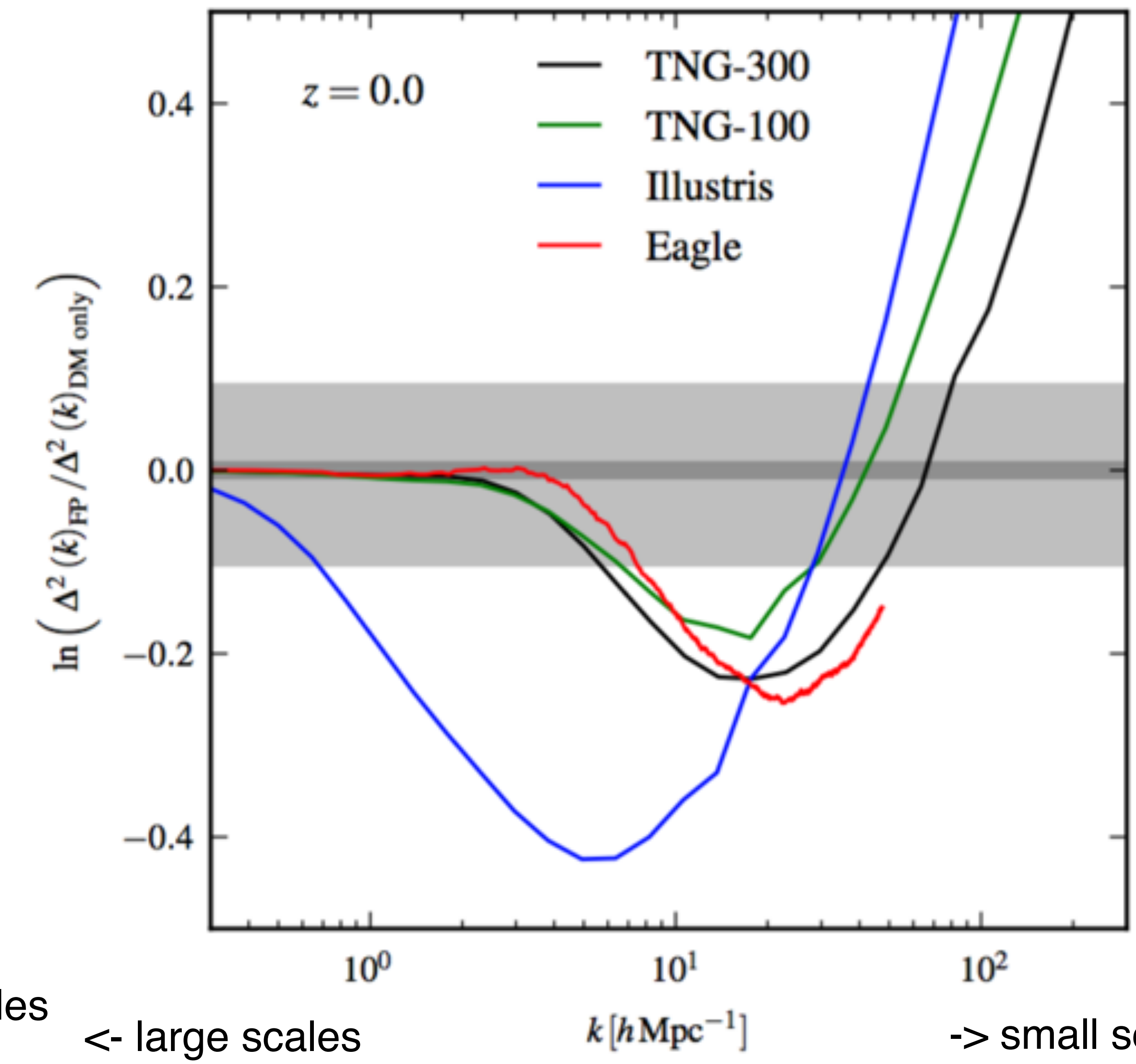


Bouquet et al. 2016 (MAGNETICUM) eROSITA Cluster Constraints

#9: Gravity-only matter distribution formulas may need revision



<- large scales -> small scales

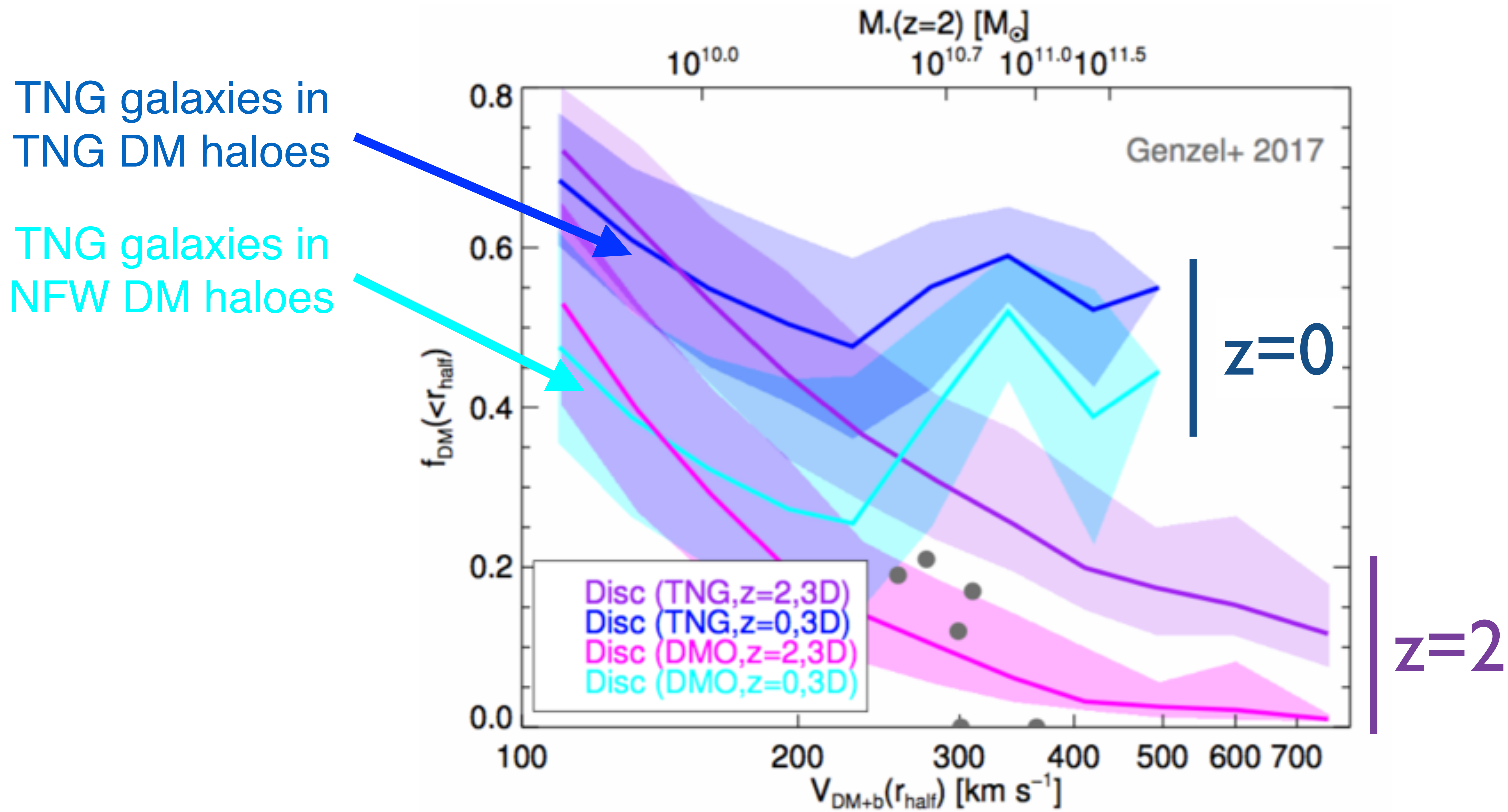


<- large scales -> small scales

The different matter components are differently clustered
The presence of galaxies and gas affects the clustering of the matter

Springel, Pakmor, Pillepich et al. 2017

#10: Baryonic physics may alter the underlying DM: DM fractions



The fraction of DM within galaxies would be smaller if baryonic physics did not produce an **enhancement of DM** in comparison to DMO haloes

Lovell, Pillepich et al. in prep

Conclusions

www.illustris-project.org

1. Cosmological simulations for galaxy formation and evolution are reaching ever more mature **levels of realism and physical complexity**

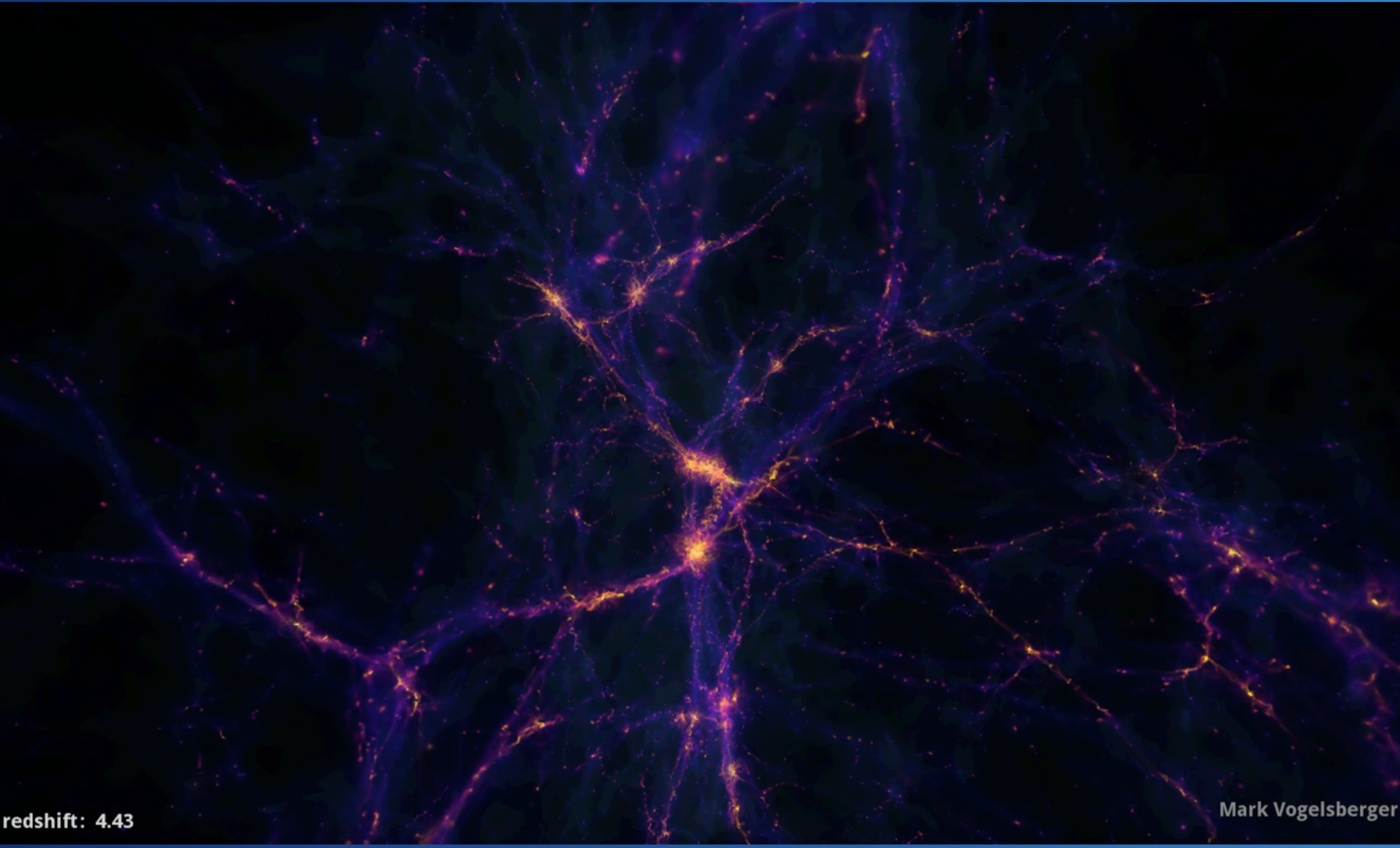
2. They are becoming progressively more reliable tools to **predict** a plethora of mechanisms and processes in cosmology and astronomy

3. In particular, I have described to you **IllustrisTNG**. Its goals:
   - To **address all the physical model issues** identified in Illustris galaxies and haloes
   - To introduce new sub grid treatments, **new physics,** and numerical improvements
   - To significantly **expand upon the scope** of volume sims and include new diagnostic tools

4. Illustris is fully public, IllustrisTNG will be released by end 2018

www.tng-project.org


redshift: 4.43
Mark Vogelsberger


redshift: 4.43
Mark Vogelsberger