Gravitational instability II

- Initial spectrum of fluctuations (Harrison-Zeldovich)
- Initial conditions for numerical calculations
- Interpretation of cosmological simulations
- Some illustrative examples
- Dwarf galaxy problem

Two fluid instability
Simplified

We use our equation for single fluid instability. Fluids are not interacting directly but only “through gravitation”. The term reads:

$$\frac{4\pi G}{c^2}(\delta\epsilon + 3\delta P) = \frac{4\pi G}{c^2}\left((\epsilon_\gamma + \epsilon_B)(1+3c_B^2)(1+w_B)\delta_B + \epsilon_X(1+3c_X^2)(1+w_X)\delta_X\right)$$

So it is the same as before but from two sources. The pressure to energy density ratio and the sound velocity (in *c* units) are:

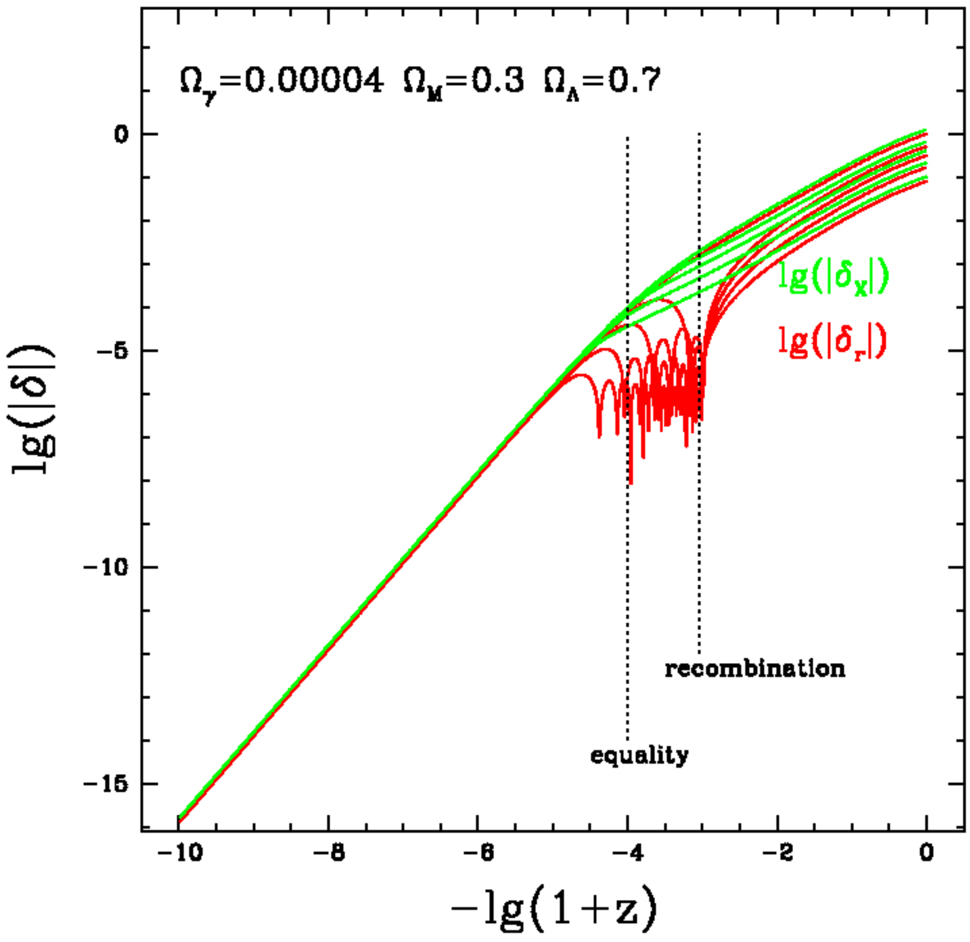
$$\begin{aligned} w_B &= \frac{P_\gamma}{\epsilon_\gamma + \epsilon_B} = \frac{\frac{1}{3}\Omega_\gamma(1+z)^4}{\Omega_\gamma(1+z)^4 + \Omega_B * (1+z)^3} = \frac{1}{3}\frac{\Omega_\gamma(1+z)}{\Omega_\gamma(1+z) + \Omega_B} \\ c_B^2 &= \frac{dP/dz}{d\epsilon/dz} = \frac{1}{3}\frac{4\Omega_\gamma(1+z)}{4\Omega_\gamma(1+z) + 3\Omega_B} \end{aligned}$$

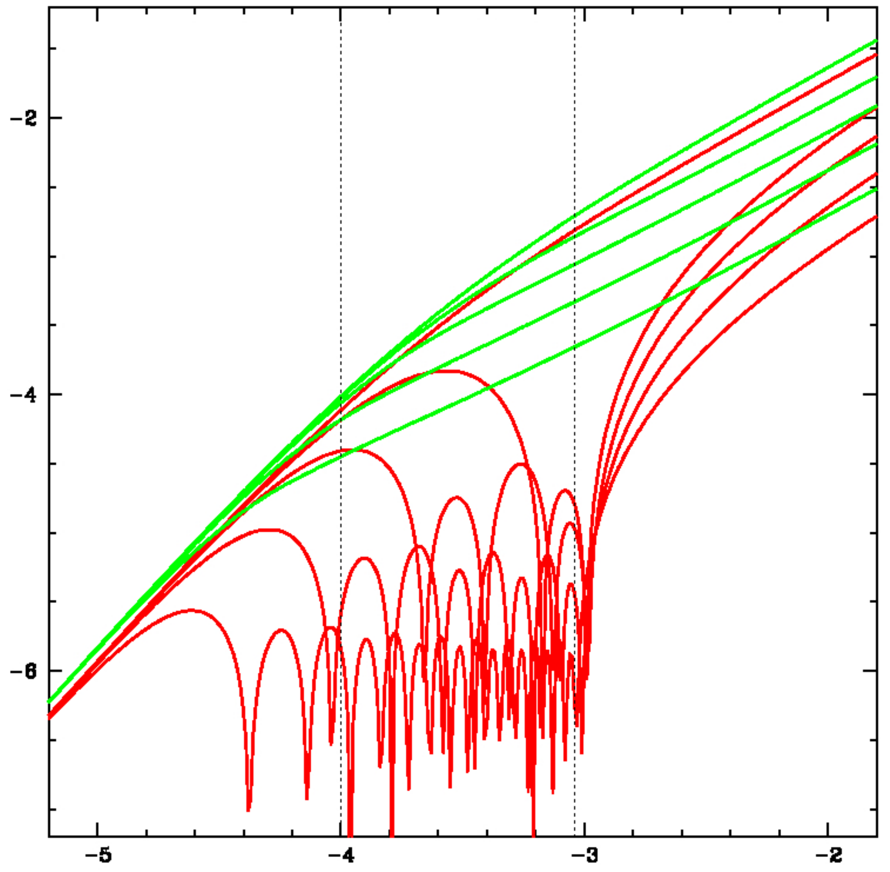
And for dark matter both vanish. Our set of equations:

$$\boxed{\begin{aligned} \ddot{\delta}_B + 2\frac{\dot{a}}{a}\dot{\delta}_B &+ \left[\frac{k^2 c_B^2 c^2}{a^2}\delta_B - \frac{4\pi G}{c^2}\left((\epsilon_\gamma + \epsilon_B)(1+3c_B^2)(1+w_B)\delta_B + \epsilon_X(1+3c_X^2)(1+w_X)\delta_X\right)\right] = 0 \\ \ddot{\delta}_X + 2\frac{\dot{a}}{a}\dot{\delta}_X &+ \left[\frac{k^2 c_X^2 c^2}{a^2}\delta_X - \frac{4\pi G}{c^2}\left((\epsilon_\gamma + \epsilon_B)(1+3c_B^2)(1+w_B)\delta_B + \epsilon_X(1+3c_X^2)(1+w_X)\delta_X\right)\right] = 0 \end{aligned}}$$

It may be applied to any two fluids not directly interacting, with different sound velocities. For dark matter we use c_X=w_X=0. Using the trick delta_B=A_B*f, delta_x=A_X*f and logarithmic independent variable we get the solutions.

Two fluid instability

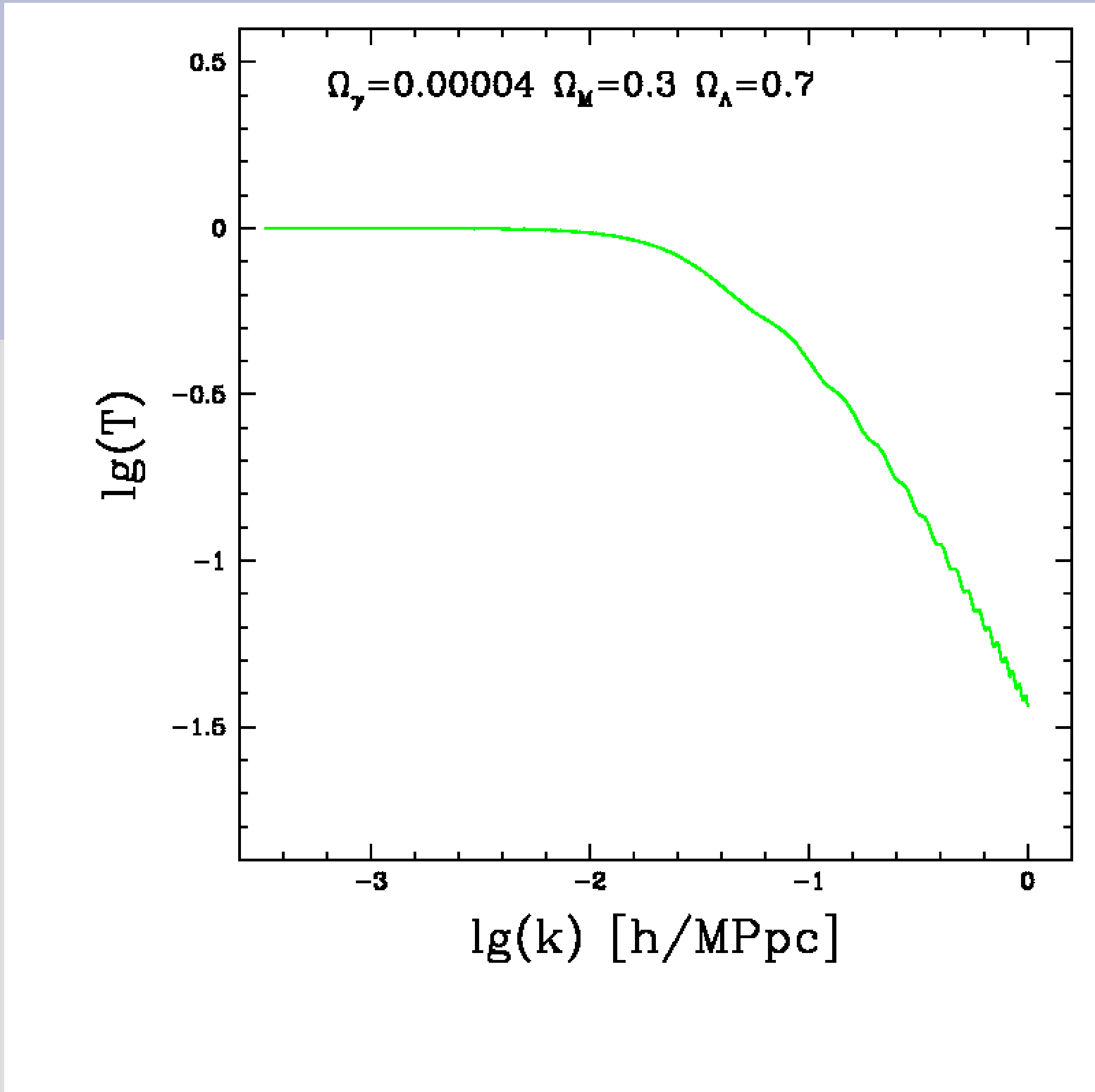




Instability of two fluids (before *equality:* relativistic gas + cold dark matter, after *recombination:* cold baryons + cold dark matter)

(Fast “improvements” to an old single-fluid program)

Two fluid instability



Instability of two fluids: transmission factor. Small scales (large wave numbers) are “filtered out” (“low pass filter” - not very sharp)

Spectrum of fluctuations

Any function (with some conditions) can be expressed as Fourier transform:

$$\delta(\vec{x}) = \int d_3 k \delta_{\vec{k}} \exp(-i\vec{k}\vec{x})$$

Where *delta* describes relative fluctuations of matter density. Average fluctuation is zero, but average square is not:

$$\frac{1}{V}\int_V d_3x|\delta^2(\vec{x})| =$$
$$\frac{1}{V}\int_V d_3x \int d_3k'\delta_{\vec{k}'} \exp(-i\vec{k}'\vec{x}) \int d_3k''\delta^*_{\vec{k}''} \exp(+i\vec{k}''\vec{x})$$
$$\rightarrow \int d_3k'\delta_{\vec{k}'} \int d_3k''\delta^*_{\vec{k}''}\delta_{\mathrm{Dirac}}(\vec{k}' - \vec{k}'')$$
$$= \int d_3k|\delta^2_{\vec{k}}| \approx 4\pi \int \frac{dk}{k} k^3|\delta^2_k|$$

Dirac's delta results from space integration at $V \rightarrow$ *infinity*. 3D → 1D integration results from the assumed isotropy: anything can depend on $|k|$ but not on its direction. The function integrated over ln(k) is called *power spectrum of density fluctuations*:

$$P_\delta(k) \equiv k^3|\delta^2(k)|$$

Harrison – Zeldovich spectrum

$$P_\delta(k) \equiv k^3|\delta^2(k)| \qquad P_{\delta\Phi}(k) \equiv k^3|\delta\Phi^2(k)|$$

(Similarly potential fluctuations have some power spectrum). Zeldovich and Harrison postulated independently that the spectra should be of a power-law form (since there is no natural scale in the early Universe and no way to propose more complicated function):

$$|\delta_k^2| \sim k^n$$

$$\triangle\delta\Phi_{\vec{k}} = -k^2\delta\Phi_{\vec{k}} = 4\pi G\rho_0\delta_{\vec{k}}$$

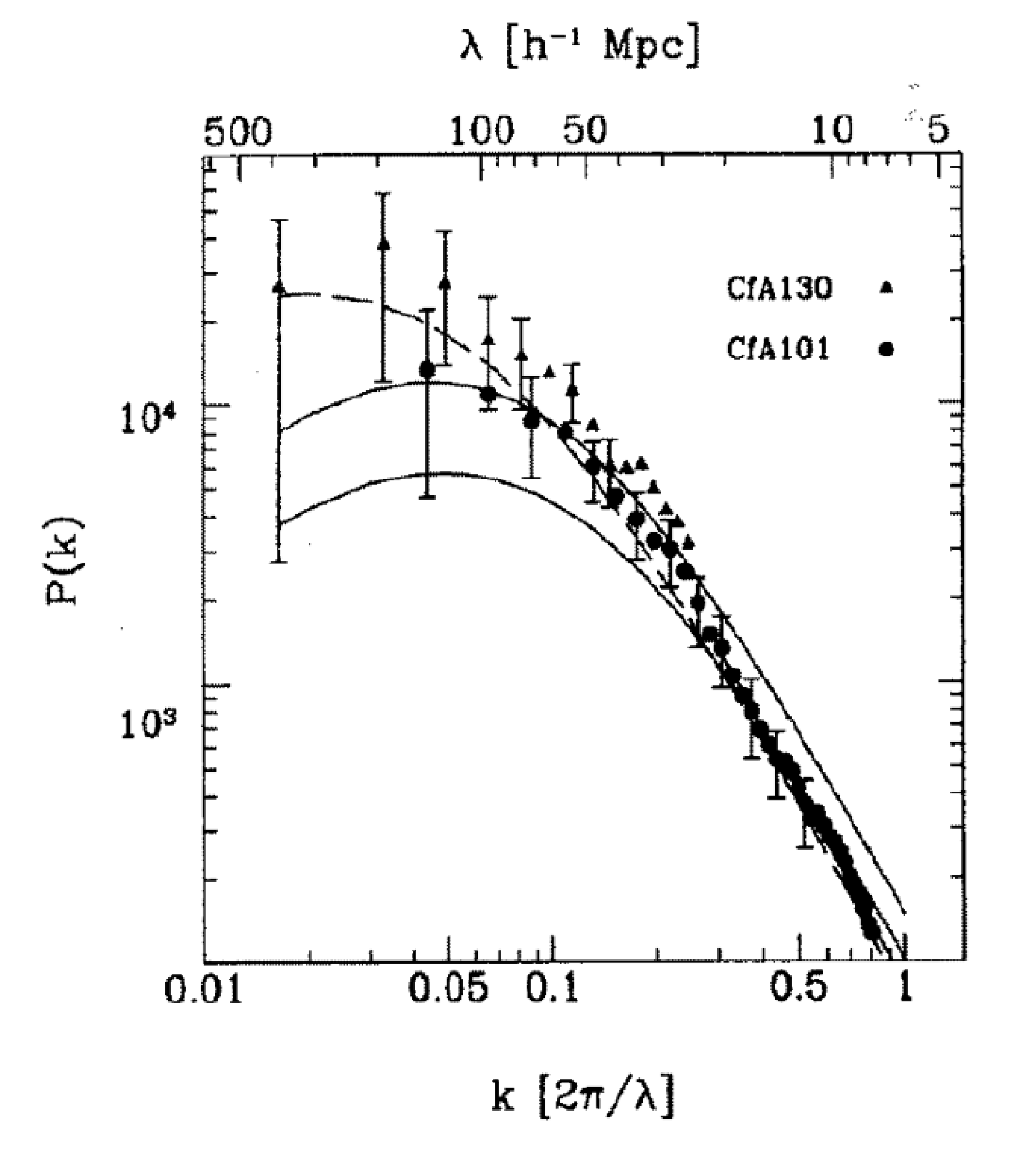
$$P_{\delta\Phi}(k) \sim k^3\frac{|\delta_k^2|}{k^4} = \frac{|\delta_k^2|}{k}$$

The Poisson equation gives the relation between density and potential fluctuations which gives the spectrum of potential perturbations. Power law functions become infinite at zero or infinity, depending on the power index. Exception: power index=0. One would not like potential spectrum becoming infinite at small scales, which would mean the presence of many low mass black holes in the Universe. Strong very large scale fluctuation may lead to the gravitational collapse of the Universe as whole. To avoid both extremes one postulates:

$$\frac{|\delta_k^2|}{k} \sim k^0 \qquad |\delta_k^2| \sim k^1 \qquad n = 1$$

Which is the Harrison – Zeldowich initial spectrum of density fluctuations. The amplitude is not given, must be fitted to observations.

Fluctuations spectrum: examples



CfA observations of galaxy distribution in space compared with some theoretical predictions.

Expected fluctuation in a sphere

$$\delta_R(\vec{k}) = \frac{1}{4/3\pi R^3} \int_{|\vec{r'}| \leqslant R} d_3 r'^3 \delta_{\vec{k}} \exp\left(i\vec{k}(\vec{r}_0 + \vec{r'})\right)$$

Above: averaged fluctuation in a sphere of radius *R* around r_0 induced by a single Fourier component. Integrating:

$$\frac{3}{4\pi R^3} \int_0^R r'^2 dr' \int_{-1}^{+1} d\mu \int_0^{2\pi} d\phi \exp\left(ik\mu r'\right)$$

$$= \frac{3 * 4\pi}{4\pi R^3} \int_0^R r'^2 dr' \frac{\sin\left(kr'\right)}{kr'} = 3\frac{\sin\left(kR\right) - kR\cos\left(kR\right)}{(kR)^3}$$

$$= 3\frac{j_1(kR)}{kR} \equiv W(kR)$$

W(kR) is a low pass filter: |W(x)|<3/x^2. Small scale fluctuations (k>>1/R) have little influence on the sphere-averaged density.

Expected square fluctuation in a sphere

Averaging over many sphere of radius *R* positions we calculate mean square fluctuation

$$\frac{1}{V}\int_V d_3 r_0 \int d_3k' W(k'R)\delta_{\vec{k}'} \int d_3k'' W(k''R)\delta_{\vec{k}''} \exp\left(i(\vec{k}' - \vec{k}'\right.$$

$$= \int d_3k' W(k'R)\delta_{\vec{k}'} \int d_3k'' W(k''R)\delta_{\vec{k}''}\delta_{Dirac}(\vec{k}' - \vec{k}'')$$

$$= \int d_3k\,\delta_k^2 W^2(kR) \approx 4\pi \int_0^{x_0/R} k^2 dk\,\delta_k^2 \qquad (63)$$

Where x_0 is the first zero of spherical Bassel function *j_1(x)* .
Calculating the above expression for *R*=8 Mpc/h one gets parameter *sigma_8* which can also be measured in the real galaxy distribution.

Velocity perturbations

As shown already the velocity and density perturbations are related:

$$\vec{v} = \frac{\dot{a}}{a}\vec{r} + \delta\vec{v} \qquad \dot{\delta} + \frac{1}{a}\nabla_{\vec{x}}\delta\vec{v} = 0$$

If we assume that velocity perturbations are *potential* i.e. is a gradient of some function

$$\delta\vec{v} = -\nabla\delta\chi$$

Then for a growing mode of density fluctuations one gets (after some calculations):

$$\delta\vec{v} = -\frac{afH}{4\pi}\int d_3x' \frac{\delta(\vec{x}')(\vec{x} - \vec{x}')}{|\vec{x} - \vec{x}'|^3} \qquad f \approx \Omega^{0.6}$$

So the density distribution defines the velocity perturbation distribution. The *f* factor calibrates the relation. In principle measuring the velocity field and the density distribution one can find *f* and *Omega* it depens on

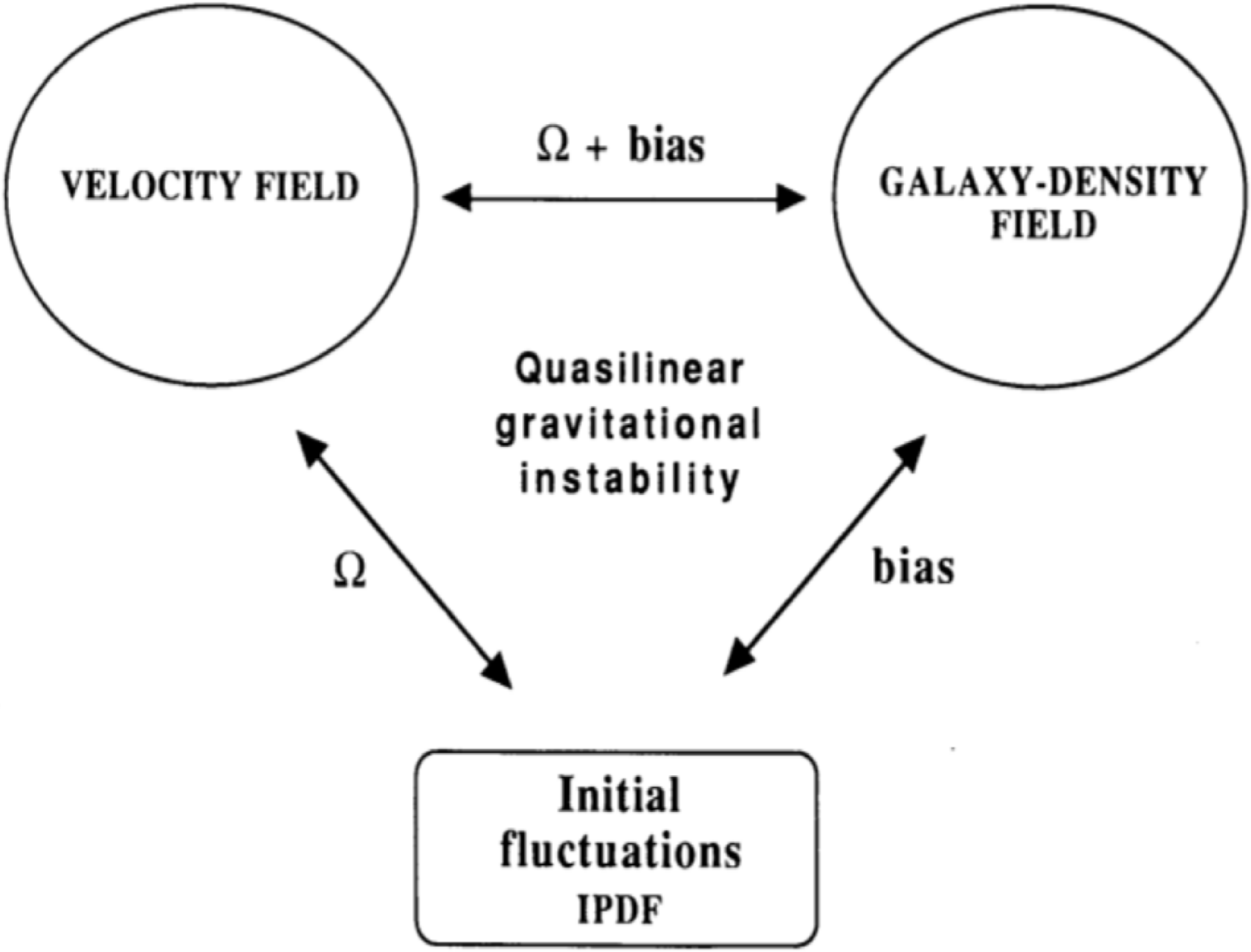


FIG. 6.—Relationships between observations and theoretical ingredients

Nusser & Dekel (1993) ApJ, 405, 437

Velocity perturbations

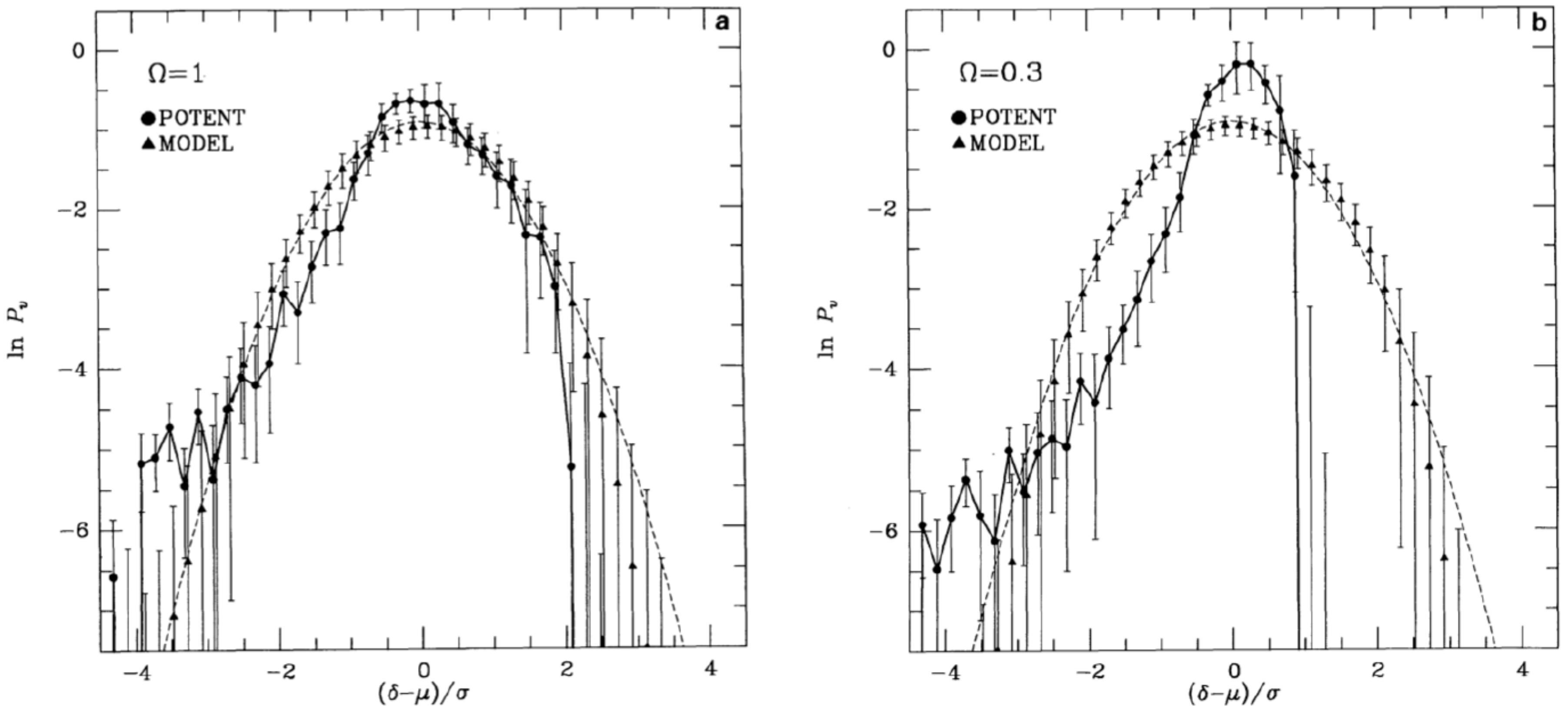


FIG. 4.—Density IPDF recovered from the POTENT velocity field of observed velocities (*solid line*) compared with Gaussian (*short-dash line*) and with the IPDF recovered from the velocity field of Gaussian CDM simulations (*triangles*). The assumed Ω is 1 or 0.3, and the models are of $\Omega_0 = \Omega$ accordingly. The error bars attached to the data are measurement errors, and the error bars attached to the model are due to the limited volume sampled by POTENT. The total error is roughly the sum in quadrature of the two errors.

Nusser & Dekel (1993) ApJ, 405, 437

The authors claimed the Universe was ~flat with ~critical density, which was giving a better agreement between their data analysis and theoretical models.

Velocity perturbations

Evidence for a low density Universe
from the relative velocities of galaxies

R. Juszkiewicz*§, P. G. Ferreira*‖¶, H. A. Feldman#,

A. H. Jaffe**, M. Davis**

Theory →

$$v_{12}(r) = -\tfrac{2}{3}\, H\, r\, \Omega^{0.6} \bar{\bar{\xi}}(r)[1 + \alpha \bar{\bar{\xi}}(r)]$$

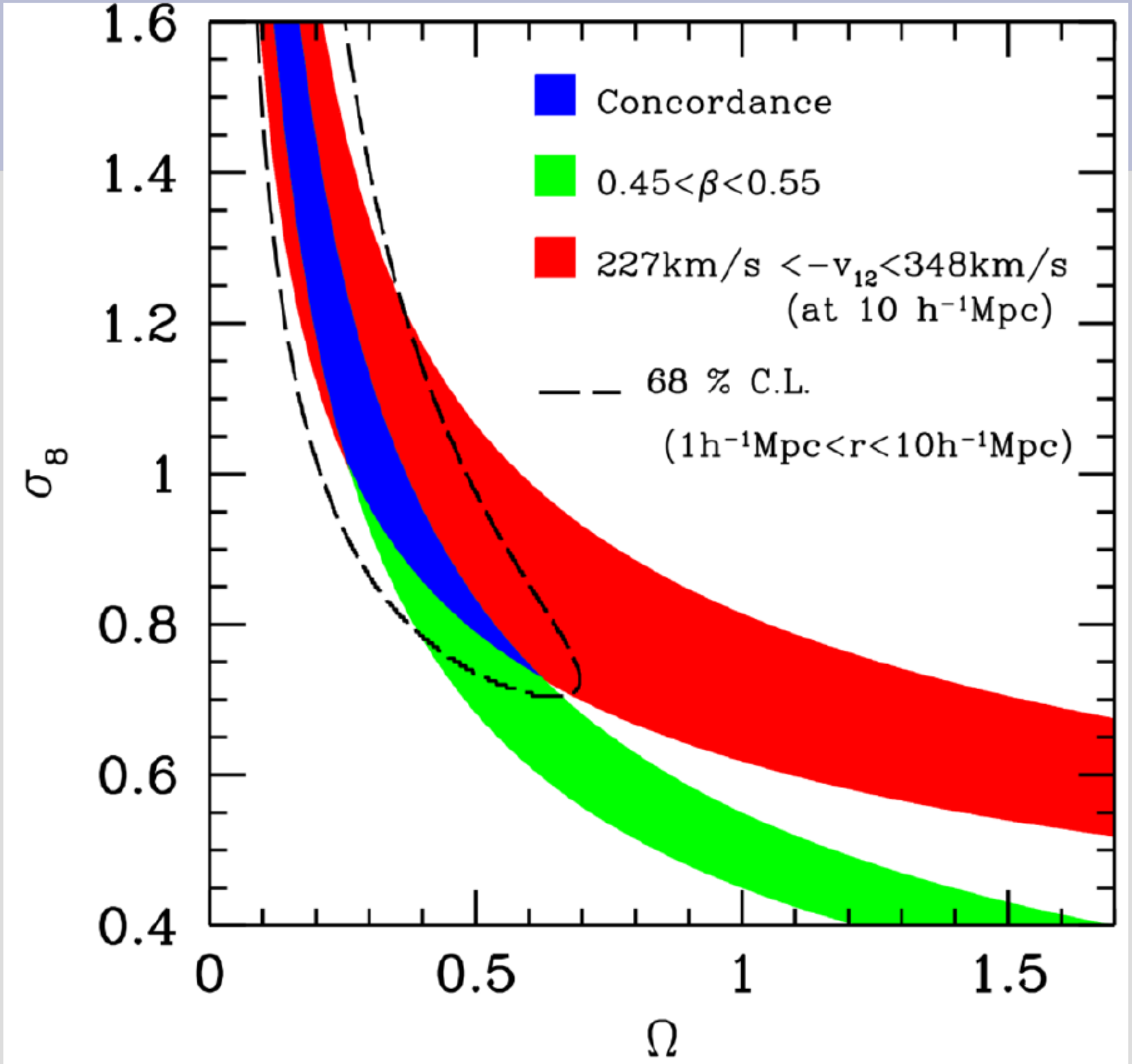
$$\bar{\bar{\xi}}(r) = \frac{3 \int_0^r \xi(x)\, x^2\, dx}{r^3\, [1 + \xi(r)]} ,$$

Measurement →

$$v_{12}(r) = \langle (\vec{v}_1 - \vec{v}_2) \cdot \hat{r} \rangle_\rho = \langle (\vec{v}_1 - \vec{v}_2) \cdot \hat{r}\, w_{12} \rangle$$

The authors used the relation between relative velocity of two galaxies and their autocorrelation function calculated in the second order.

Velocity perturbations



Conclusion: the Universe is *low density*.

Initial conditions for nonlinear calculations

The linear approach valid at high *z* (>100?) allows to find the power spectrum of fluctuations at some “z_switch”

$$k^3\delta_k^2(z_{sw}) = k^3\delta_k^2(\mathrm{prim}) * T^2(k)$$

At *recombination* the approach is still valid so

$$P_\delta(k) \quad \Rightarrow \quad \left(\frac{\delta T}{T}\right)_{prim} \quad \Rightarrow \quad C^2(l)$$

has low cost

Simulation cube with *periodic boundary conditions*:

$$\delta(x+jL, y+mL, z+nL) = \delta(x,y,z)$$

$$k_{min} = \frac{2\pi}{L} \qquad k_{max} \approx N^{1/3} k_{min}$$

Using Fourier we get:

$$\delta(x,y,z) = \sum_{jmn} \delta_{jmn} e^{2\pi i(jx+my+nz)/L}$$

$$|\vec{k}(j,m,n)| = \frac{2\pi}{L}\sqrt{j^2+m^2+n^2}$$

But delta_jmn are not given...

Initial conditions for nonlinear calculations

Power spectrum gives only rms of the expected amplitude for a given wave vector. It is commonly assumed that the distribution of amplitudes is Gaussian and of phases uniform. Each set of initial conditions – realisation of a random process:

$$\delta_{\vec{k}} = X * \exp(2\pi i Y)\sqrt{\langle \delta_k^2 \rangle}$$
$$p(X) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}X^2\right)$$
$$p(Y) = 1 \qquad 0 \leq Y \leq 1$$

Density fluctuations real → condition for amplitudes:

$$\delta(-\vec{k}) = \delta^*(\vec{k})$$

Only 1/2 of amplitudes has to be drawn (for j>0, say). The other are calculated from the above condition.

Gaussianity: sofisticated problem. Some data (or rather fits to the data, data analysis) suggest non-Gaussianity but with low confidence.

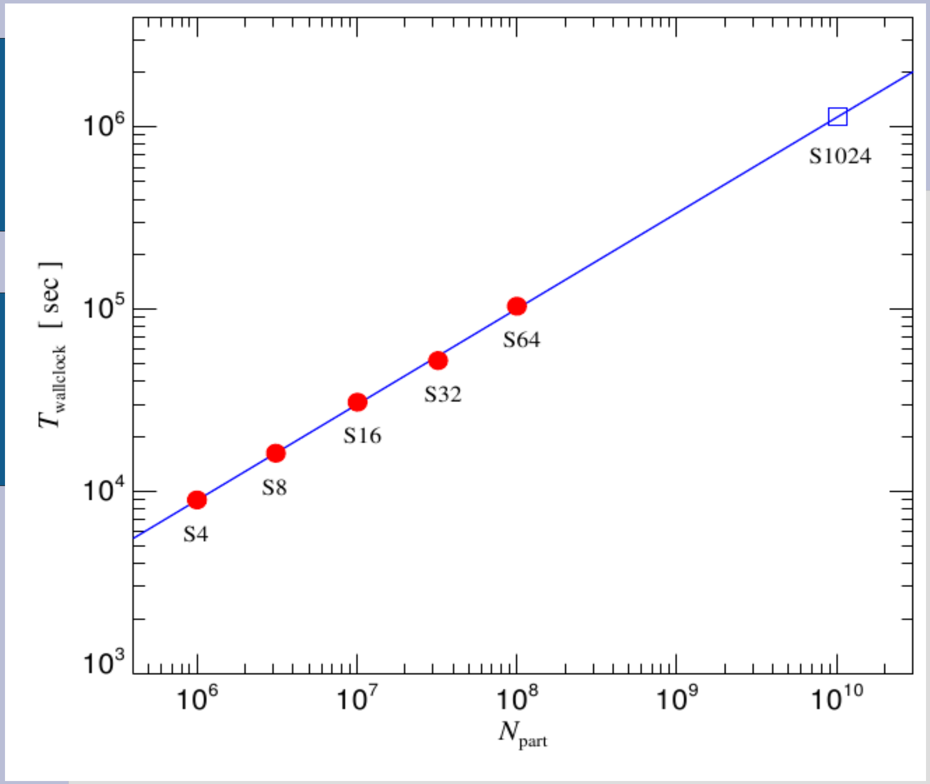
Initial conditions
for nonlinear calculations

Drawing *delta_k* → *delta(x,y,z);* 1+*delta(x,y,z)* may be interpreted as probability distribution for finding a particle in any location. Accompanying velocity field gives velocities to particles

N-body code. Particles = chunks of mass (in reality each 10^6 – 10^9 solar depending on *L* and *N;* Millennium: L=500/h Mpc, N=1820^3, IllustrisTNG L=(50-100-300)/h Mpc N=2*(1820-2500)^3 plus tracing particles plus hydrodynamics)

So: continuous density distribution [*1+delta(x,y,z)*] is represented by a finite number of *particles* which can map the density field only with limited resolution. The same applies to velocity: it is given only at particles' positions.

Calculation time



[Springel, V. (2005) MN, 364, 1105]

Processors time: ~40%
Sending data between processors ~60%

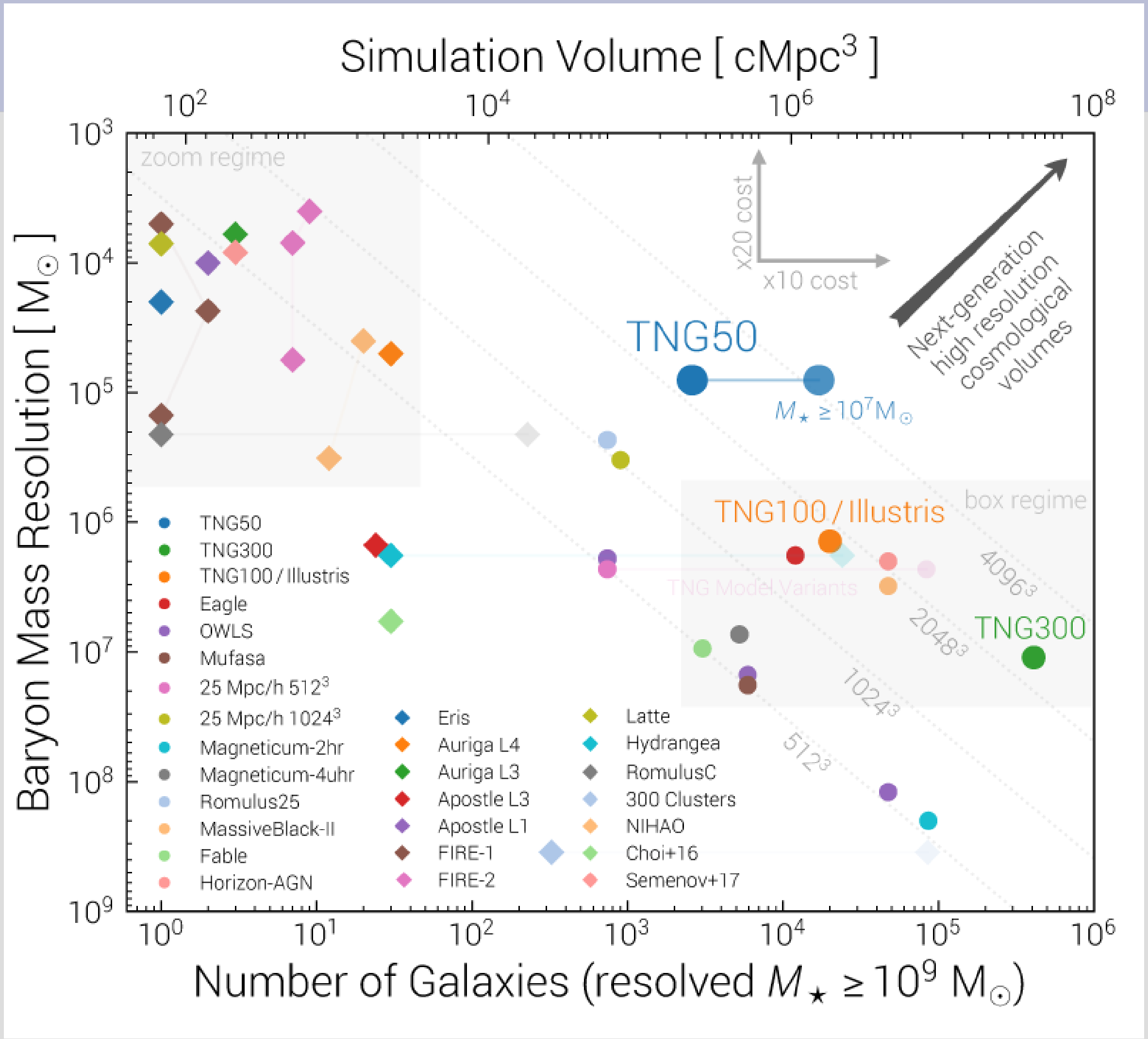
← Expectations (2005)

Illustris TNG news:
21 Oct, 2020:
“The date for the public release of the TNG50 simulation has been set for Feb 1, 2021”

23 Apr, 2019:
“After 26 months, the TNG50 simulation reaches z=0 on the Hazel Hen supercomputer”

(2160^3 DM+2160^3 gas +2160^3 trace
(2160^3=10^10)

Calculation time:
resolution / volume



Resolution – Volume compromise

[https://www.tng-project.org/about/]

Simulation results: interpretation

- Each run is a realization of a random process used to set the initial data
- As in the argument for the Universe uniformity: results of a simulation should statistically reproduce some of the real Universe properties
- Gravitation and pressure gradients are given (more or less) by the *first principles*
- Star formation is introduced in a heuristic way. (Example: when the density in a gas cell is over ... star formation begins with some *IMF, SFR* etc depending on metallicity and enviroment)
- Radiation transfer is taken into account to some extent.
- The agglomeration of DM and gas (caused mostly by gravitation) gives realistic mass function for galaxies and clusters
- History of gravitationaly bound systems and their growth by mergers is something one cannot observe from the beginning. It tells something about the *early* and *unseen*.
- There are many synthetic galaxies → some should resemble the Milky Way, some groups should resemble the Local Group. Finding them may illustrate the possible history of our Galaxy its satellites etc.

Simulation results: interpretation

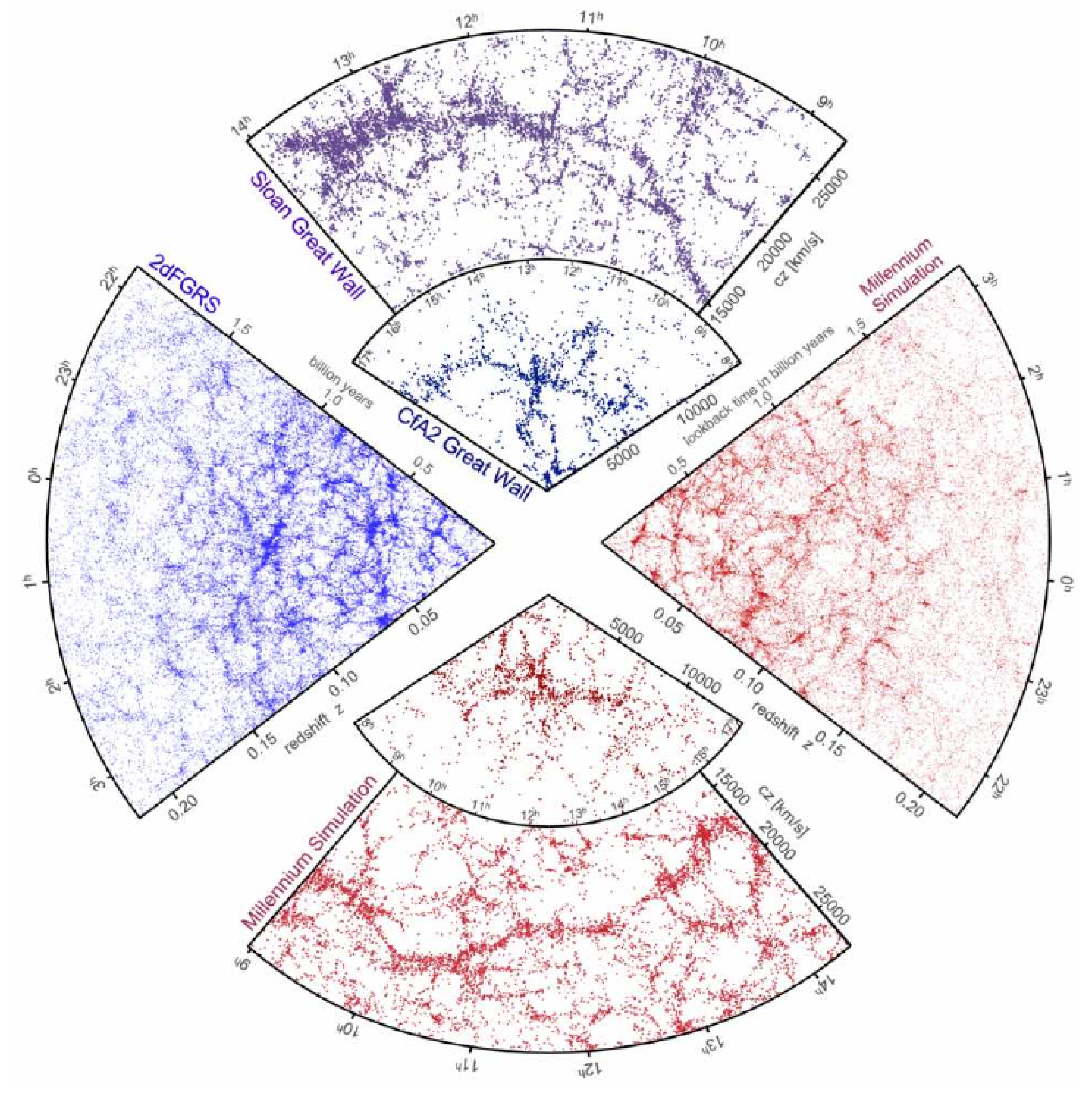
- **Halo**. Average distance between particles is b=L/N^{1/3}. Assume two particles closer then b/5 to be friends. Look for FoF (friends of friends). If you find a group of >20 friends, check if the system is gravitationaly bound. If it is call it a *halo*.
- **Galaxy**. If there is bound gas in the halo and after the first generation of stars there remains some gas for the next generation, halo becomes a *galaxy.* (Small haloes may become dark; a galaxy should provide enviroment for the next generations of stars.)
- **Groups and clusters**. Knowing which haloes are galaxies and using definitions from the real world one may classify synthetic galaxy systems.
- **Voids**. Regions of space devoid of synthetic galaxies (with synthetic galaxy number density much (..) lower than the average).
- **Mergers**. Intuitions from double/triple systems of point masses are inadequate. Unbound double system remains unbound, unless it interacts with the third body (or 3rd, 4th, ..., but the 3rd only is most probable). To bound a double some energy must be sent away (to the 3rd?). Haloes are themselves systems of point masses. During an encounter with similar system there is a possiblity to transform some of the *orbital* energy into *internal energy* and eject some of the particles to *infinity*. Thus conserving the total energy and loosing some mass from the final system it is possible that an *encounter* becomes a *merger*.

Simulation results: interpretation

- **Major merger** (if mass ratio>1/3). Stars from discs go to sferoidal component of the new object, all the gas goes to the new disc whose axis of rotation is defined by angular momentum conservation. Mergers speed up star formation: in major merger up to 40% of gas is used to form stars immediately after the encounter. Population synthesis based on Bruzual with Chabrier IMF → galaxy colors. SN → ejection of gas, SN+PN → metals, AGN → gas heating (slowing down star formation?)
- **Minor merger** (with much smaller object). *Big* galaxy remains basically unchanged. Stars from *small* go to the spheroidal component of *big*. They may be seen as *streams* based on kinematics and metallicity. Gas goes to the *big* disc and may speed up the star formation in proportion to its amount, so the effect is much less pronounced than in major mergers. Astrophysical processes inside – as above
- **SMBH**. It is believed that every massive enough galaxy has a super-massive black hole in its center. In Illustris a BH of mass ~10^5 sun is seeded whenever galaxy M_stars>1.5*10^10 and then grows at the cost of gas falling into the center (or some other *rules*; individual stars are not followed but their input to accretion may be treated statistically).
- **Binary SMBH?** The trajectories of SMBHs can be followed → the parameters of double BH after the merger can be calculated. (Hope of GW community?)

Example: Millennium

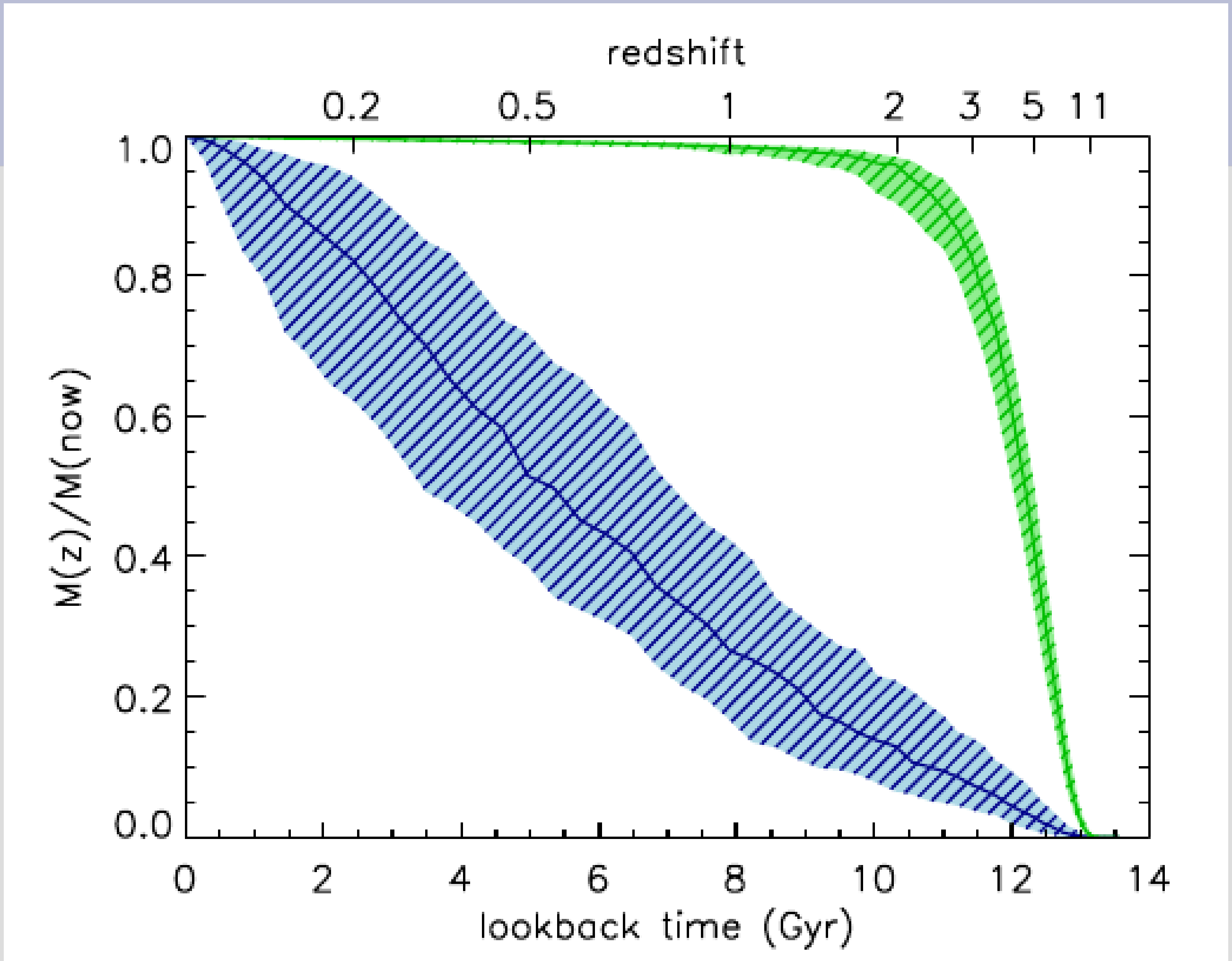
Subjective similarities ? →



Springel, Frenk & White (2006) Nature, 440, 1137

Example: Millennium

Most luminous galaxies in clusters:
 Where do the stars come from?



Assembly **Formation**

DeLucia & Blaizot (2007) MN, 375, 2

Example: Illustris

Introducing the Illustris Project: Simulating the coevolution of dark and visible matter in the Universe

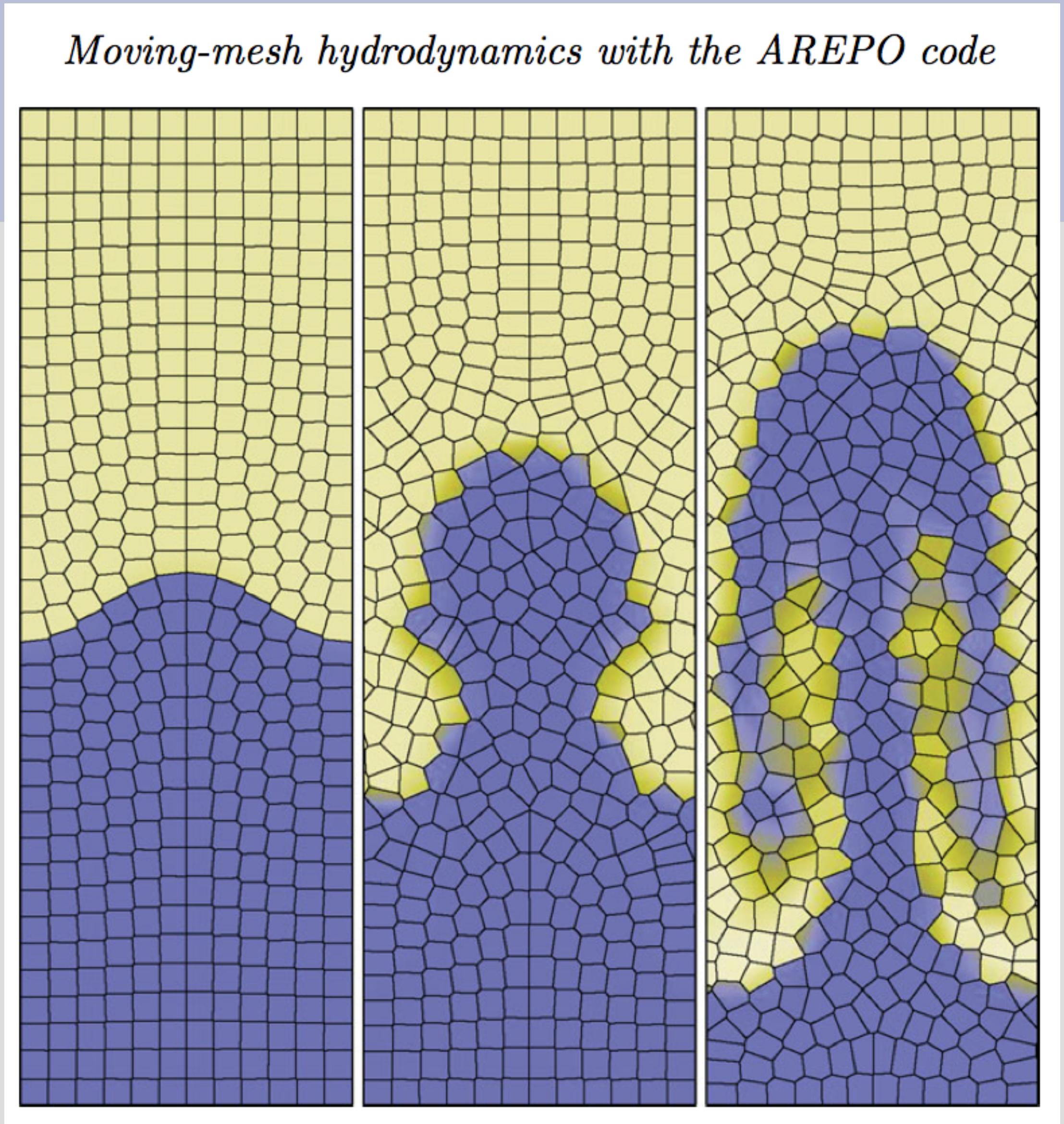
(2014) MNRAS, 444, 1518

Mark Vogelsberger[1], Shy Genel[2], Volker Springel[3,4], Paul Torrey[2], Debora Sijacki[5], Dandan Xu[3], Greg Snyder[6], Dylan Nelson[2] , and Lars Hernquist[2]

name	volume $[(\mathrm{Mpc})^3]$	DM particles / hydro cells / MC tracers	$\epsilon_{\mathrm{baryon}}/\epsilon_{\mathrm{DM}}$ [pc]	$m_{\mathrm{baryon}}/m_{\mathrm{DM}}$ $[10^5\ \mathrm{M}_\odot]$	$r_{\mathrm{cell}}^{\mathrm{min}}$ [pc]	$m_{\mathrm{cell}}^{\mathrm{min}}$ $[10^5\ \mathrm{M}_\odot]$	description
Illustris-1	106.5^3	$3 \times 1,820^3 \cong 18.1 \times 10^9$	$710/1,420$	$12.6/62.6$	48	0.15	full physics
Illustris-2	106.5^3	$3 \times 910^3 \cong 2.3 \times 10^9$	$1,420/2,840$	$100.7/501.0$	98	1.3	full physics
Illustris-3	106.5^3	$3 \times 455^3 \cong 0.3 \times 10^9$	$2,840/5,680$	$805.2/4008.2$	273	15.3	full physics
Illustris-Dark-1	106.5^3	$1 \times 1,820^3$	$710/1,420$	$-/75.2$	–	–	DM only
Illustris-Dark-2	106.5^3	1×910^3	$1,420/2,840$	$-/601.7$	–	–	DM only
Illustris-Dark-3	106.5^3	1×455^3	$2,840/5,680$	$-/4813.3$	–	–	DM only
Illustris-NR-2	106.5^3	$2 \times 910^3 \cong 1.5 \times 10^9$	$1,420/2,840$	$100.7/501.0$	893.8	6.6	no cooling/SF/feedback
Illustris-NR-3	106.5^3	$2 \times 455^3 \cong 0.2 \times 10^9$	$2,840/5,680$	$805.2/4008.2$	2322.8	39.4	no cooling/SF/feedback

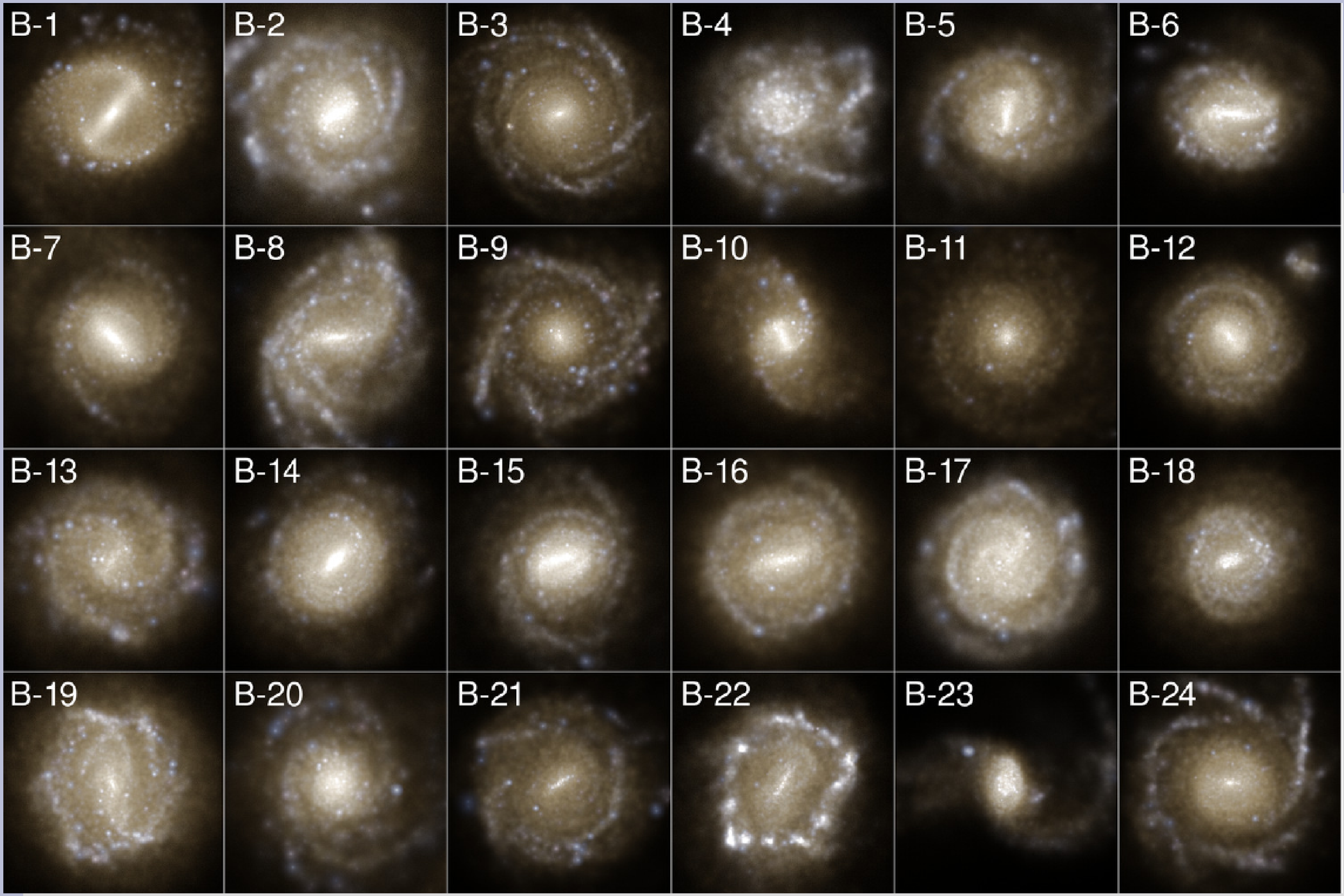
Table 1. Details of the Illustris simulation suite. Illustris-(1,2,3) are hydrodynamical simulations including our model for galaxy formation physics. Illustris-Dark-(1,2,3) are DM-only versions of the original Illustris simulations. They have the same initial conditions but do not include baryonic matter. Illustris-NR-(2,3) include baryons, but do not account for any feedback or cooling processes (non-radiative). Illustris-1 follows the evolution of $12,057,136,000$ DM particles and hydrodynamical cells in total with the smallest fiducial cell size ($r_{\mathrm{cell}}^{\mathrm{min}}$) below 50 pc and the least massive cells having masses of a few times $10^4\ \mathrm{M}_\odot$ ($m_{\mathrm{cell}}^{\mathrm{min}}$). In addition, we follow the evolution of $1,820^3$ Monte-Carlo tracer particles (MC tracers).

Example: Illustris



Hydrodynamics: “moving mesh”. Above: application to Rayleigh-Taylor instability. Gas cells conserve mass. Deformations allow to avoid topological problems ...

Illustris



Blue “galaxies”

Illustris

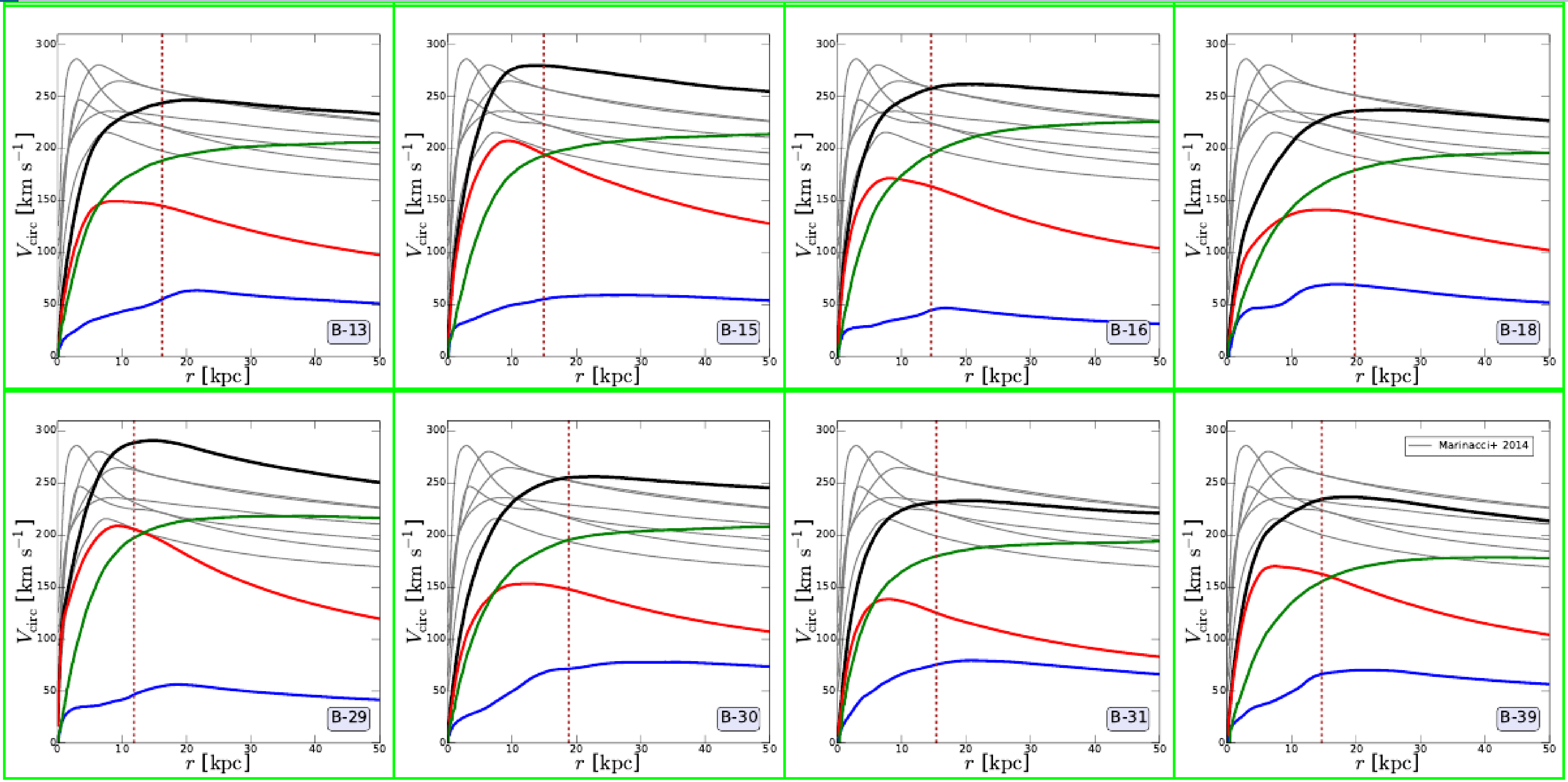
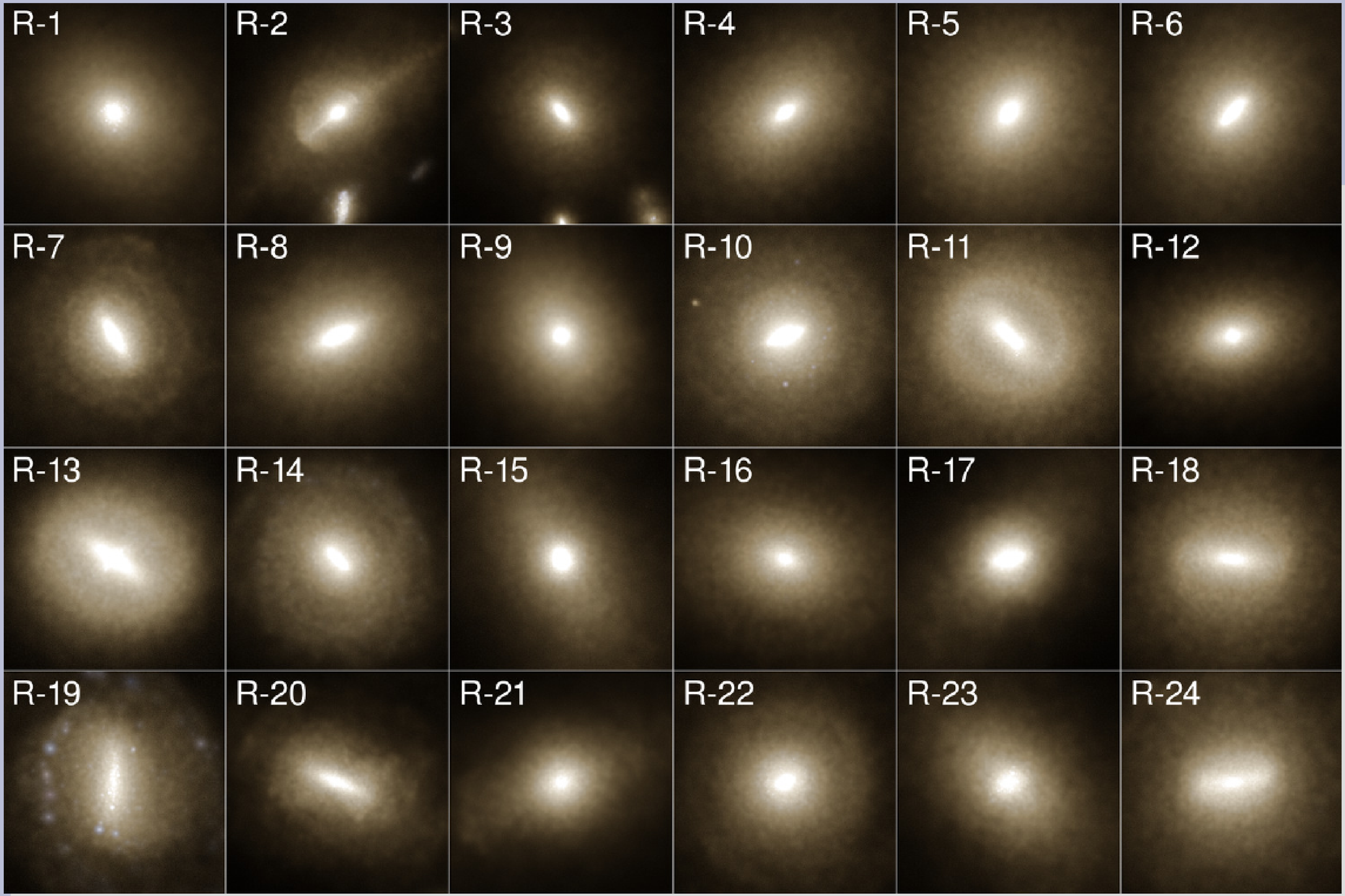


Figure 22. Circular velocity curves of a few selected disk galaxies from the sample presented in Figure 20. All of these galaxies show a steeply rising and then nearly flat circular velocity curve (black line), which is characteristic of late-type spiral galaxies. The different lines show the contributions from different mass components: gas (blue), stars (red), and DM (green). The gas contribution is typically small with maximum circular velocities around $\sim 70\,{\rm km\,s^{-1}}$ for some cases, and for most systems around $\sim 50\,{\rm km\,s^{-1}}$. The dashed brown vertical lines shows our fiducial galaxy radius $r_\star$, i.e. twice the stellar half-mass radius. This is the radius where we measure the circular velocity for the construction of the baryonic Tully-Fisher relation (see below). We also show in each panel the eight circular velocity curves for the Aquila haloes taken from Marinacci et al. (2014a) (gray thin lines). We note that those are based on the level-5 Aquarius haloes; i.e. sampled at higher spatial and mass resolution than the samples selected from the Illustris volume.

Rotation curves of blue “galaxies”

Illustris

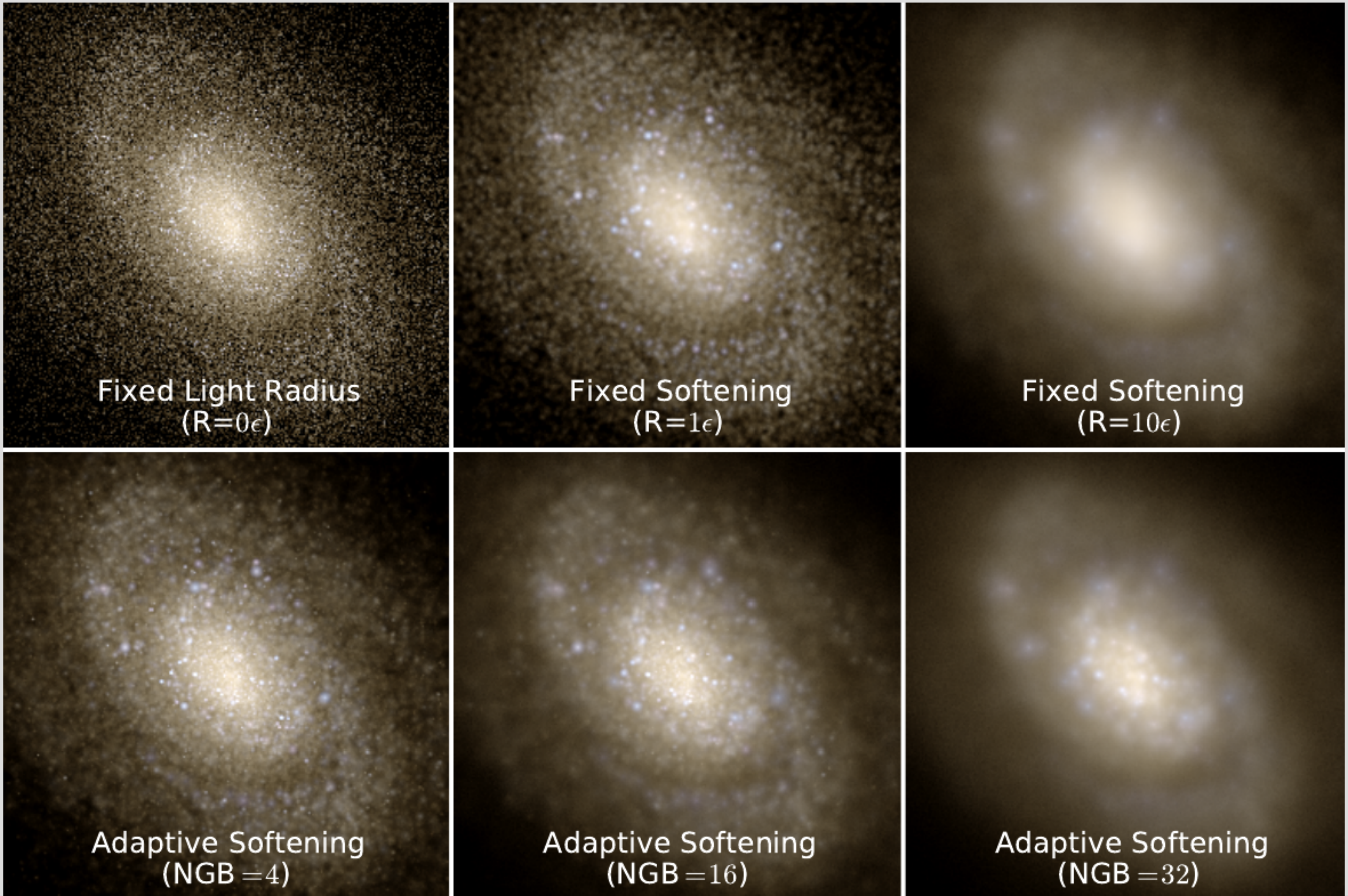


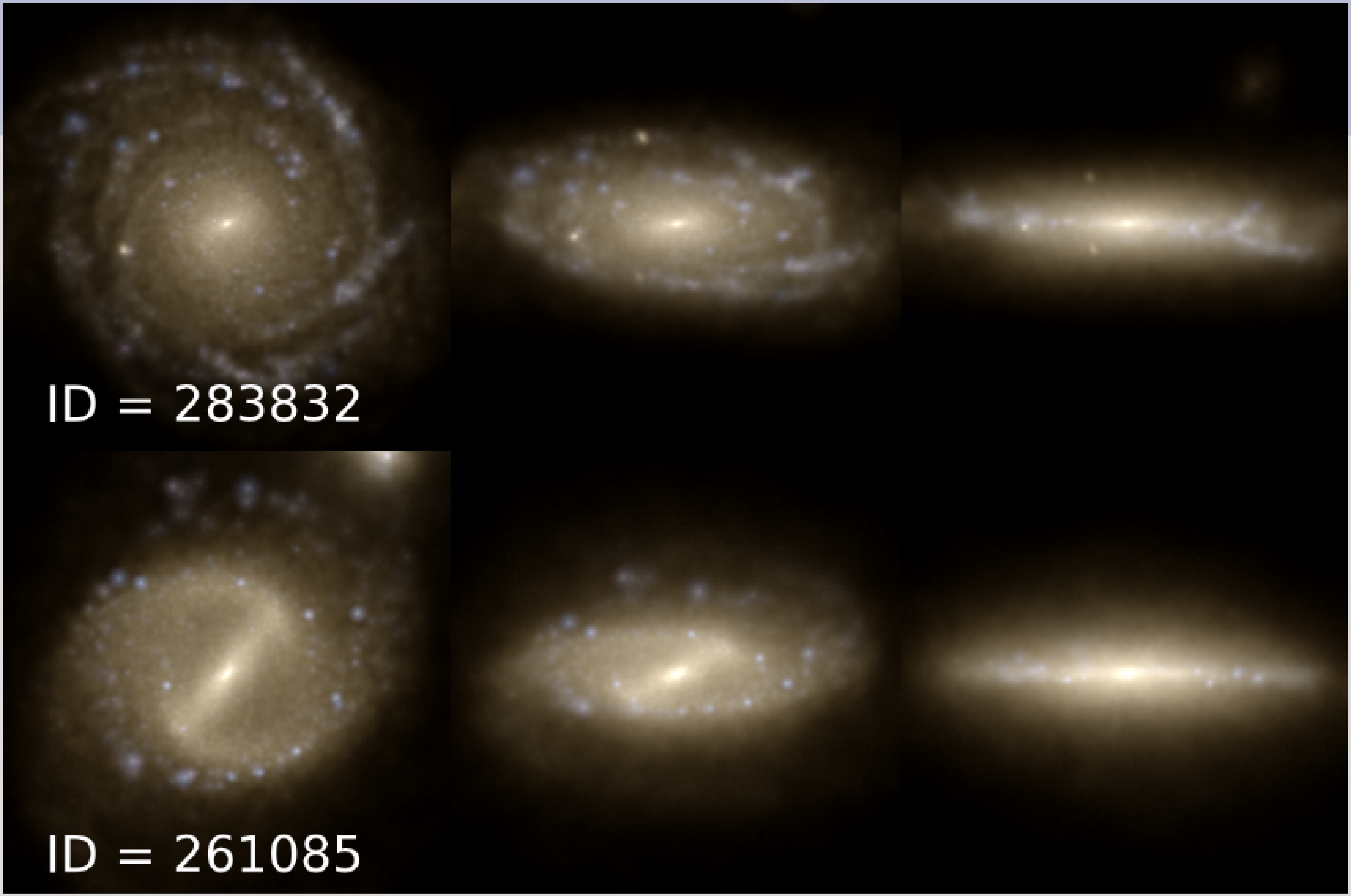
Red “galaxies”

Synthetic Galaxy Images and Spectra from the Illustris Simulation

(Simulations of observations)

Paul Torrey[1,2,3⋆], Gregory F. Snyder[4], Mark Vogelsberger[2], Christopher C. Hayward[1,3,5†], Shy Genel[1], Debora Sijacki[6], Volker Springel[5,7], Lars Hernquist[1], Dylan Nelson[1], Mariska Kriek[8], Annalisa Pillepich[1], Laura V. Sales[1], and Cameron K. McBride[1]

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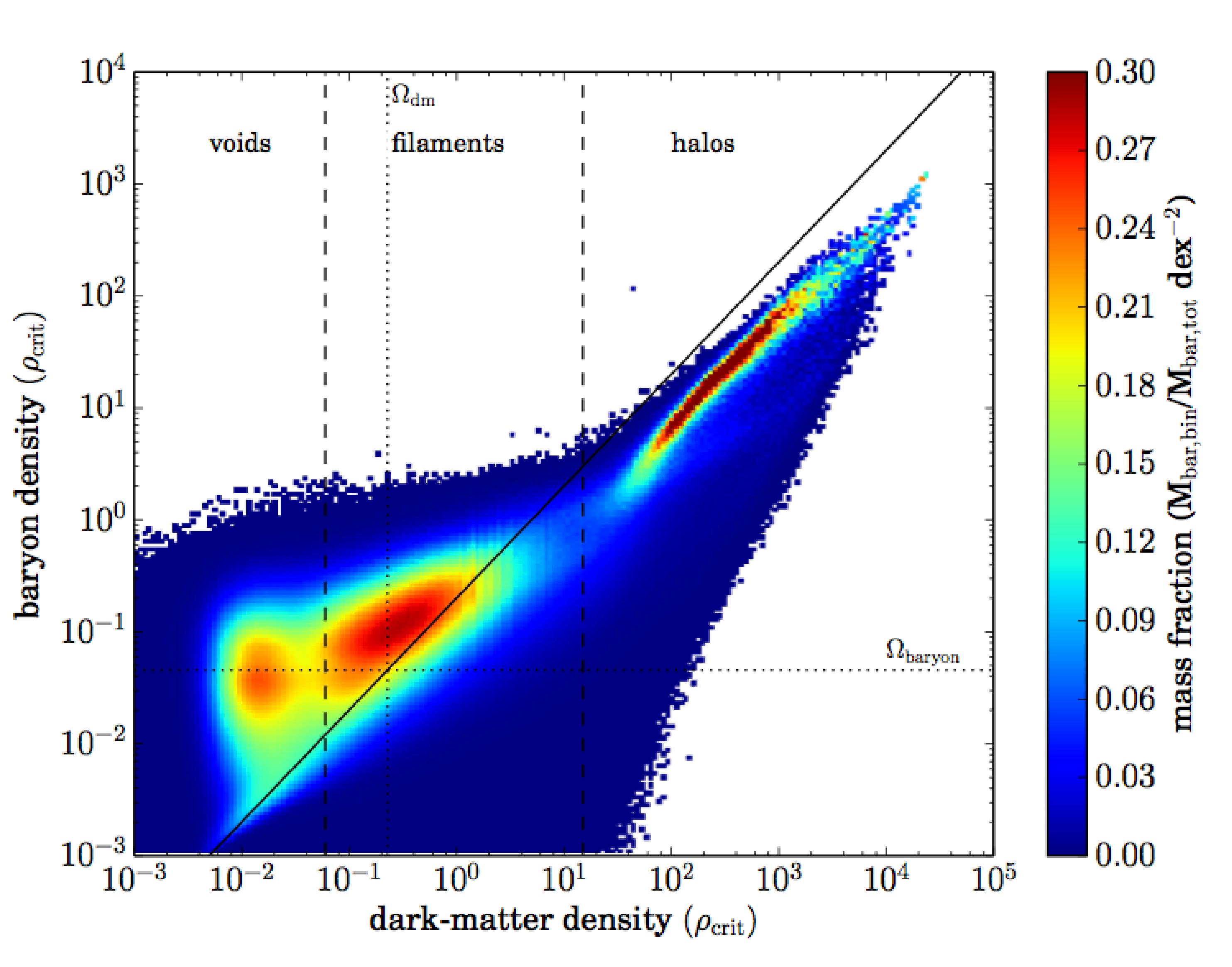
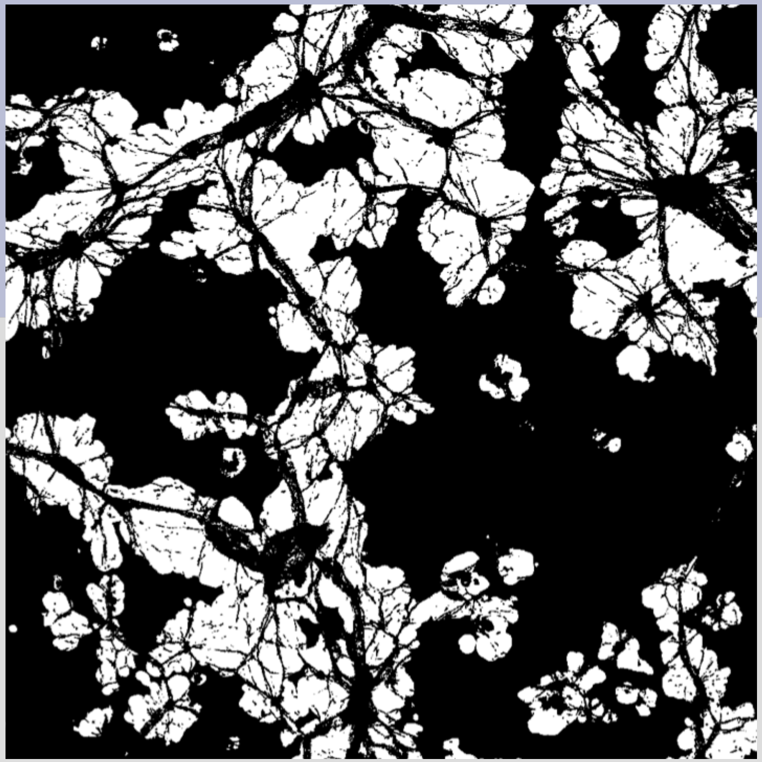
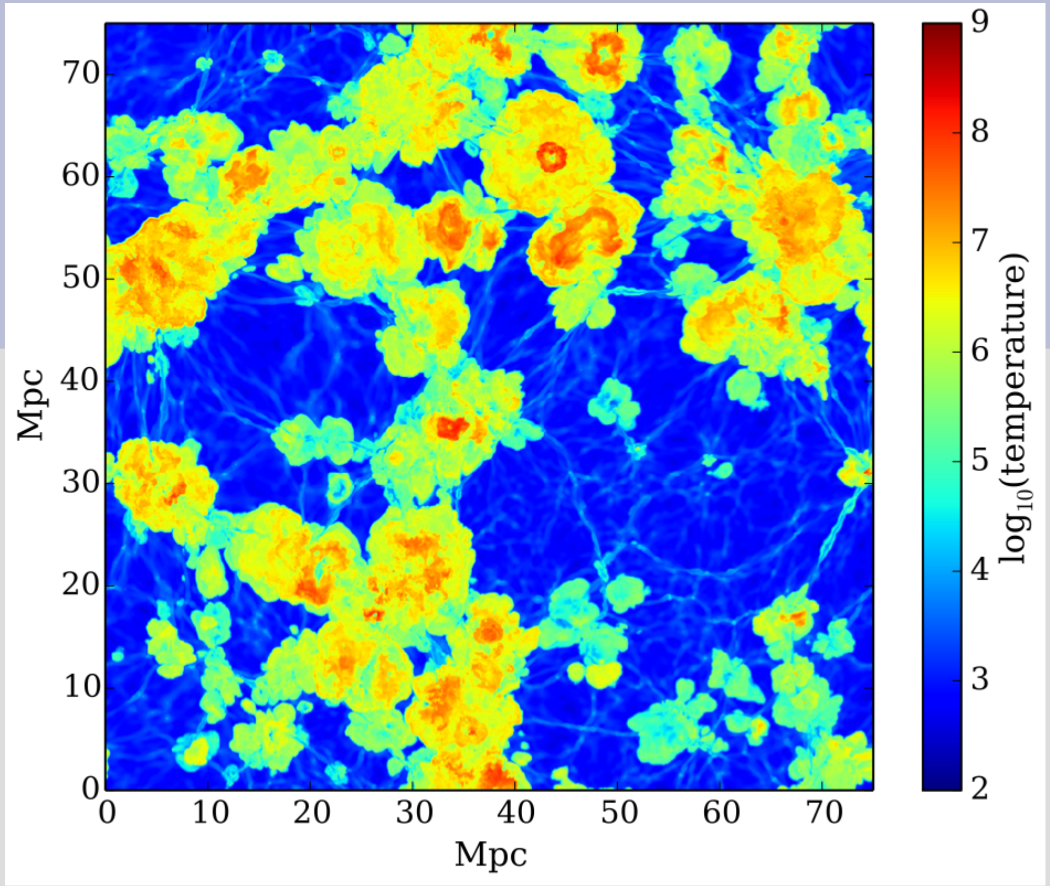


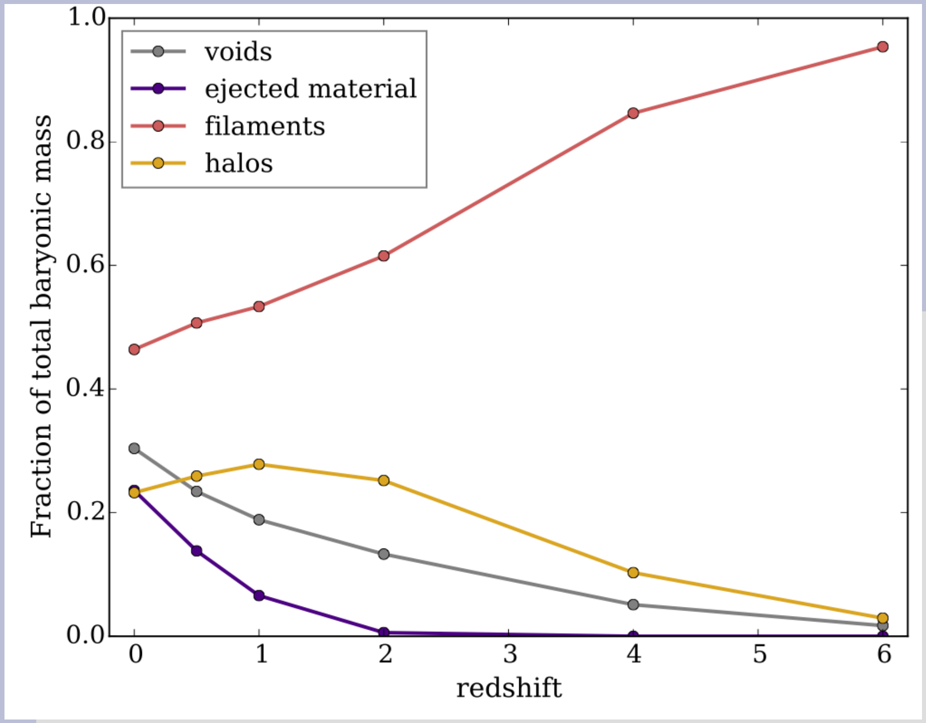
Distributions of baryons (B) and dark matter (DM) in regions of different densities. The solid line shows the average ratio of B:DM. In haloes DM is over-represented; in voids: B

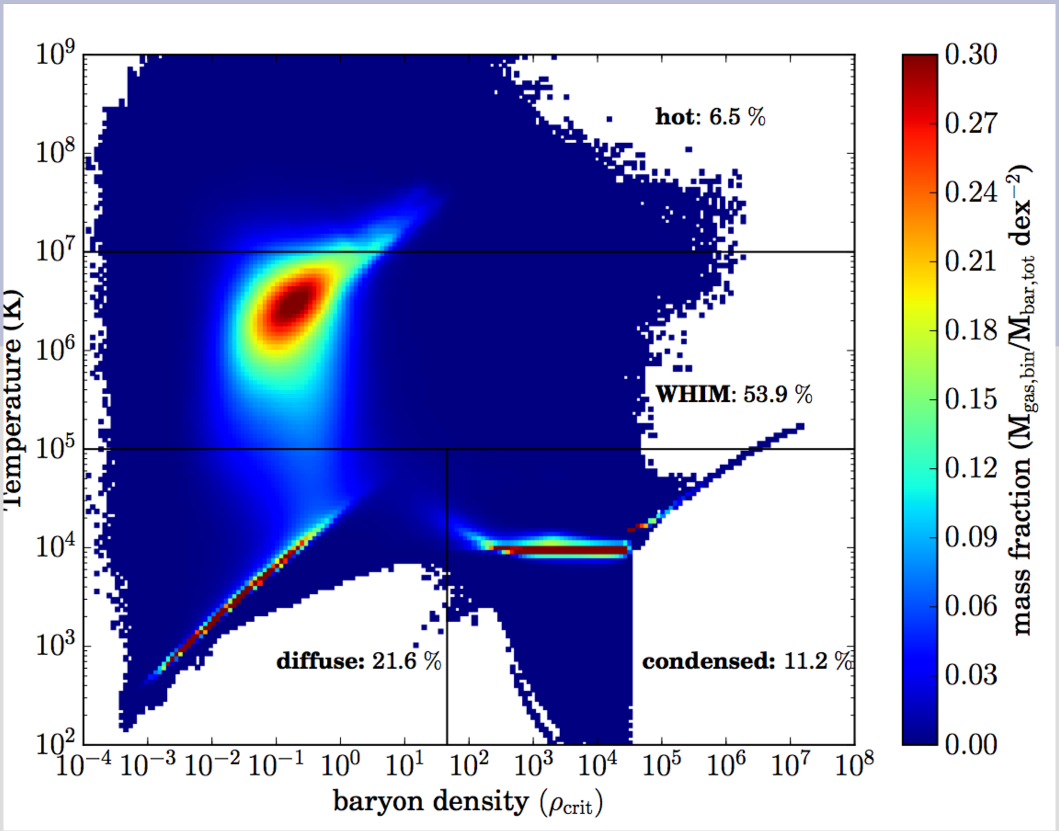


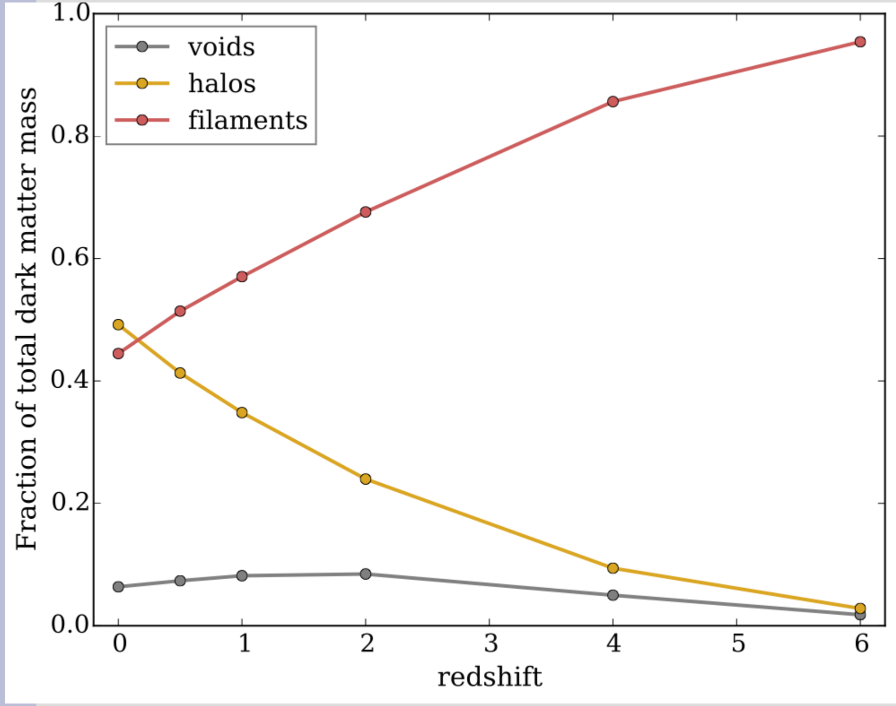


Above: spatial distribution and temperature of the gas ejected into voids (example)
Below: B and DM statistics

component	dark matter density region (ρ_{crit})	% of total dark matter mass	% of total baryonic mass	% of total mass	% of total volume
haloes	> 15	49.2 %	23.2 %	44.9 %	0.16 %
filaments	0.06 - 15	44.5 %	46.4 %	44.8 %	21.6 %
voids	0 - 0.06	6.4 %	30.4 %	10.4 %	78.2 %
ejected material inside voids	0 - 0.06	2.6 %	23.6 %	6.1 %	30.4 %







Here and on few preceding slides: Results of Illustris. Not observed directly (But the presence of ionized gas indirectly confirmed by dispersion measures of some FRBs)

The stellar mass assembly of galaxies in the Illustris simulation: growth by mergers and the spatial distribution of accreted stars

Vicente Rodriguez-Gomez,[1⋆] Annalisa Pillepich,[1] Laura V. Sales,[1,2] Shy Genel,[3†] Mark Vogelsberger,[4] Qirong Zhu,[5,6] Sarah Wellons,[1] Dylan Nelson,[1,7] Paul Torrey,[4,8] Volker Springel,[9,10] Chung-Pei Ma,[11] and Lars Hernquist[1]

"RULES":

- Whenever n_H>0.13/cm^3 → star formation
- Stochastic process
- Time scale ~2.2 bln y/rho^{1/2}
- IMF=Chabrier (2003)
- Evolution of star populations → SN, PN
- H He C N O Ne Mg Si Fe followed
- If halo lg(M)>10.2 → BH, accretion, radiation, interaction with gas

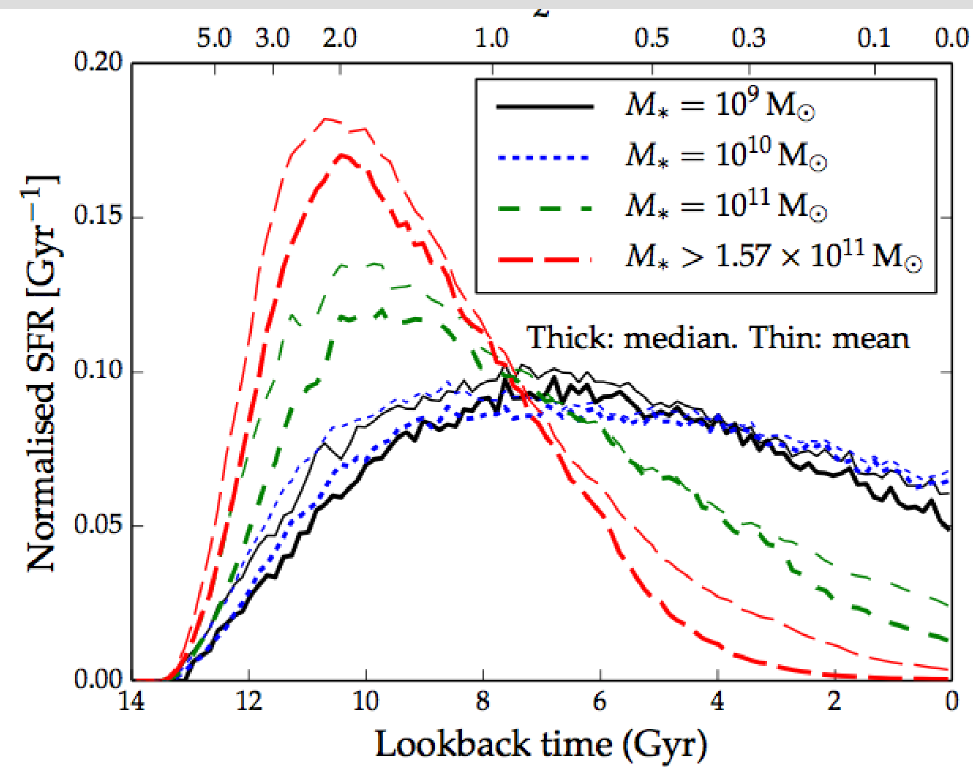
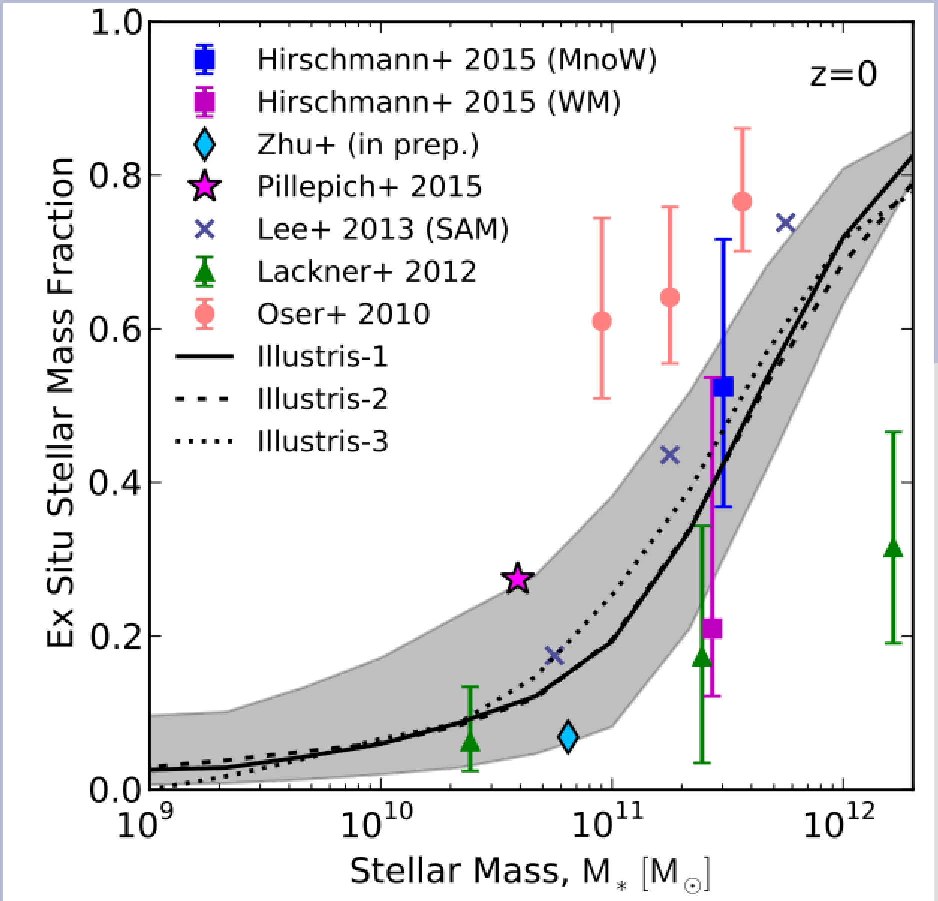
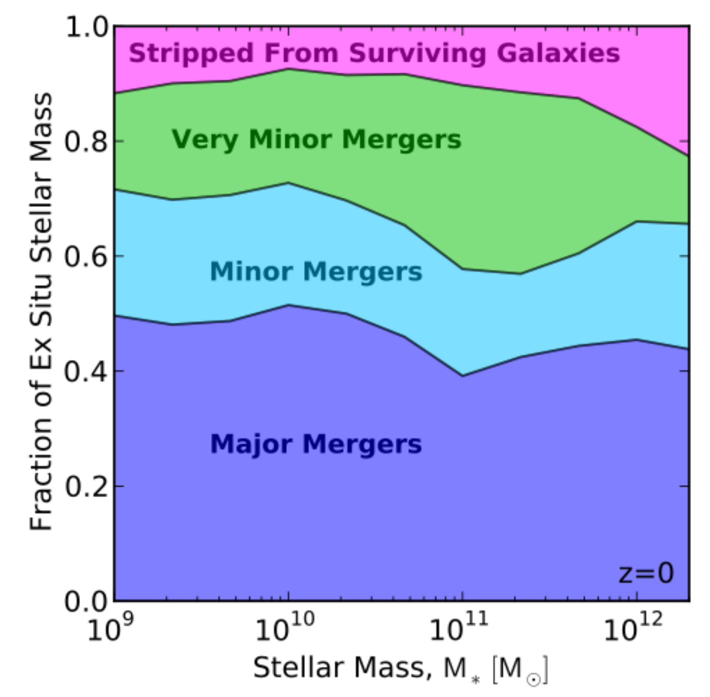
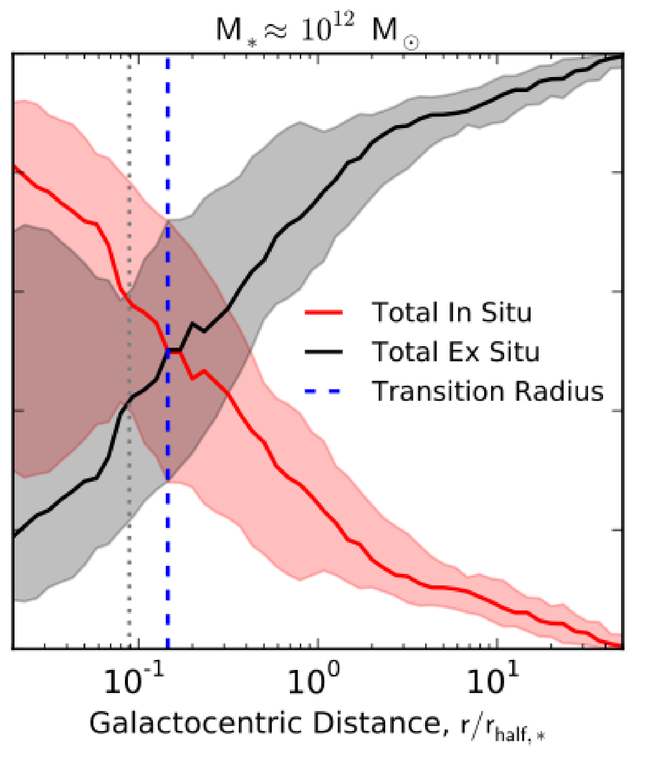


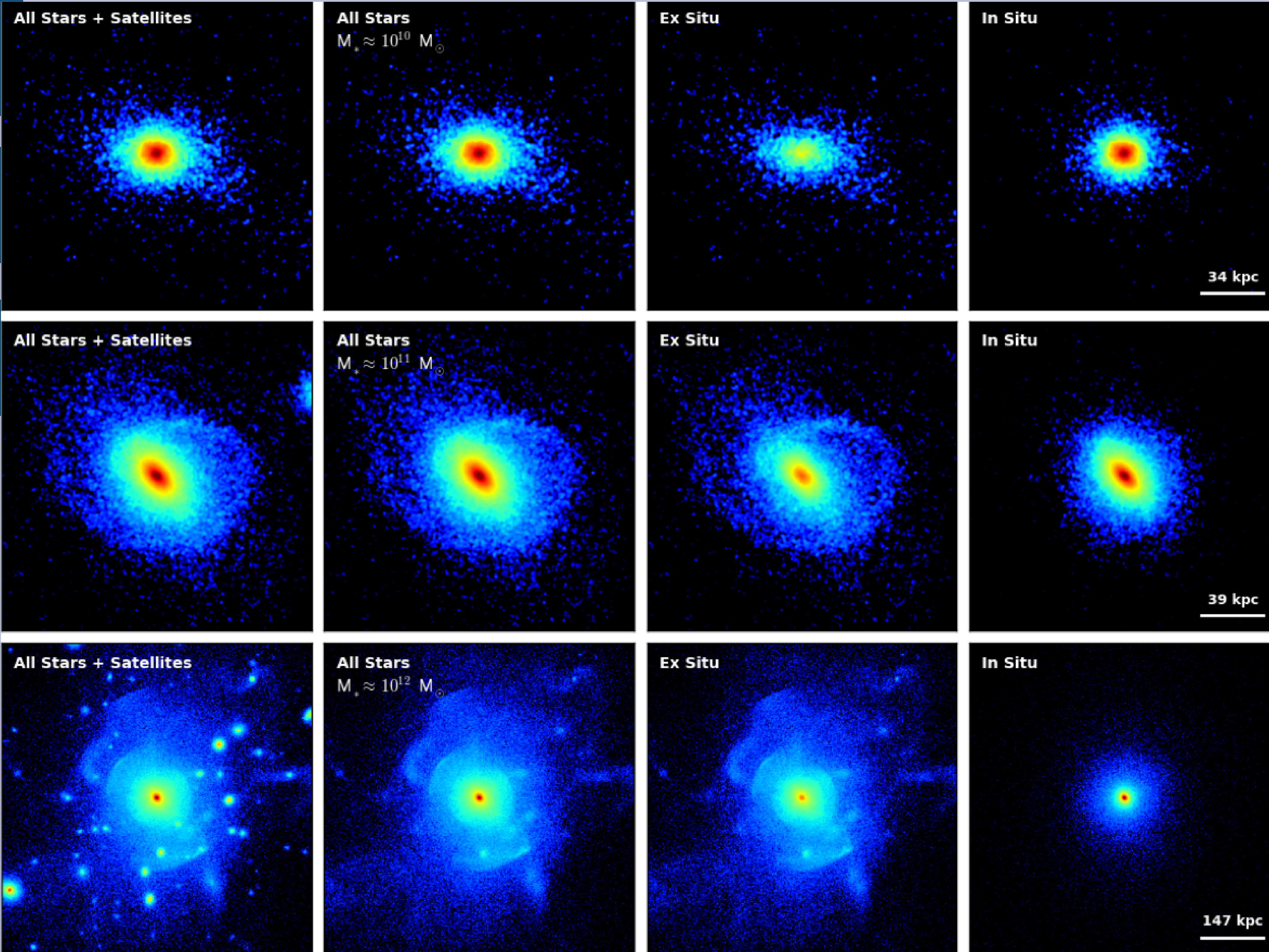
Figure 9. Mean and median (thin and thick lines, respectively) star formation histories of galaxies in the four different stellar mass ranges (see Table 2). The star formation rates are normalised so that $\int \mathrm{SFR}(t)\mathrm{d}t = 1$.







Where do the stars come from:
The more massive galaxy the larger distance from the center, the larger proportion of stars formed outside the galaxy)


All Stars + Satellites
All Stars
$M_* \approx 10^{10}$ $M_\odot$
Ex Situ
In Situ
34 kpc
All Stars + Satellites
All Stars
$M_* \approx 10^{11}$ $M_\odot$
Ex Situ
In Situ
39 kpc
All Stars + Satellites
All Stars
$M_* \approx 10^{12}$ $M_\odot$
Ex Situ
In Situ
147 kpc

The Illustris Simulation: Public Data Release☆

Dylan Nelson[a,*], Annalisa Pillepich[a], Shy Genel[b,a,1], Mark Vogelsberger[c], Volker Springel[d,e], Paul Torrey[c,g], Vicente Rodriguez-Gomez[a], Debora Sijacki[f], Gregory F. Snyder[h], Brendan Griffen[c], Federico Marinacci[c], Laura Blecha[j,2], Laura Sales[i], Dandan Xu[d], Lars Hernquist[a]

- Www.illustris-project.org
- Raw data (hundreds TB)
- JupyterLab Workspace and
- Simple browser scripts templates to analyze the data

Known problems:

- SFR too large at z<1 (ineffective switchtching out by SN, BH etc???)
- SMF too large for the lowest and the highest masses at z<1
- Galaxies with   M_stars < 5*10^10 “too big”
- Distribution of galaxy colors in disagreement with observations
- Rings in disc galaxies
- Too little gas in high mass galaxies
- Coronas of S more luminous in X-rays than for E (opposite to observations)

Example: IllustrisTNG

The Hubble Sequence at $z \sim 0$ in the IllustrisTNG simulation with deep learning

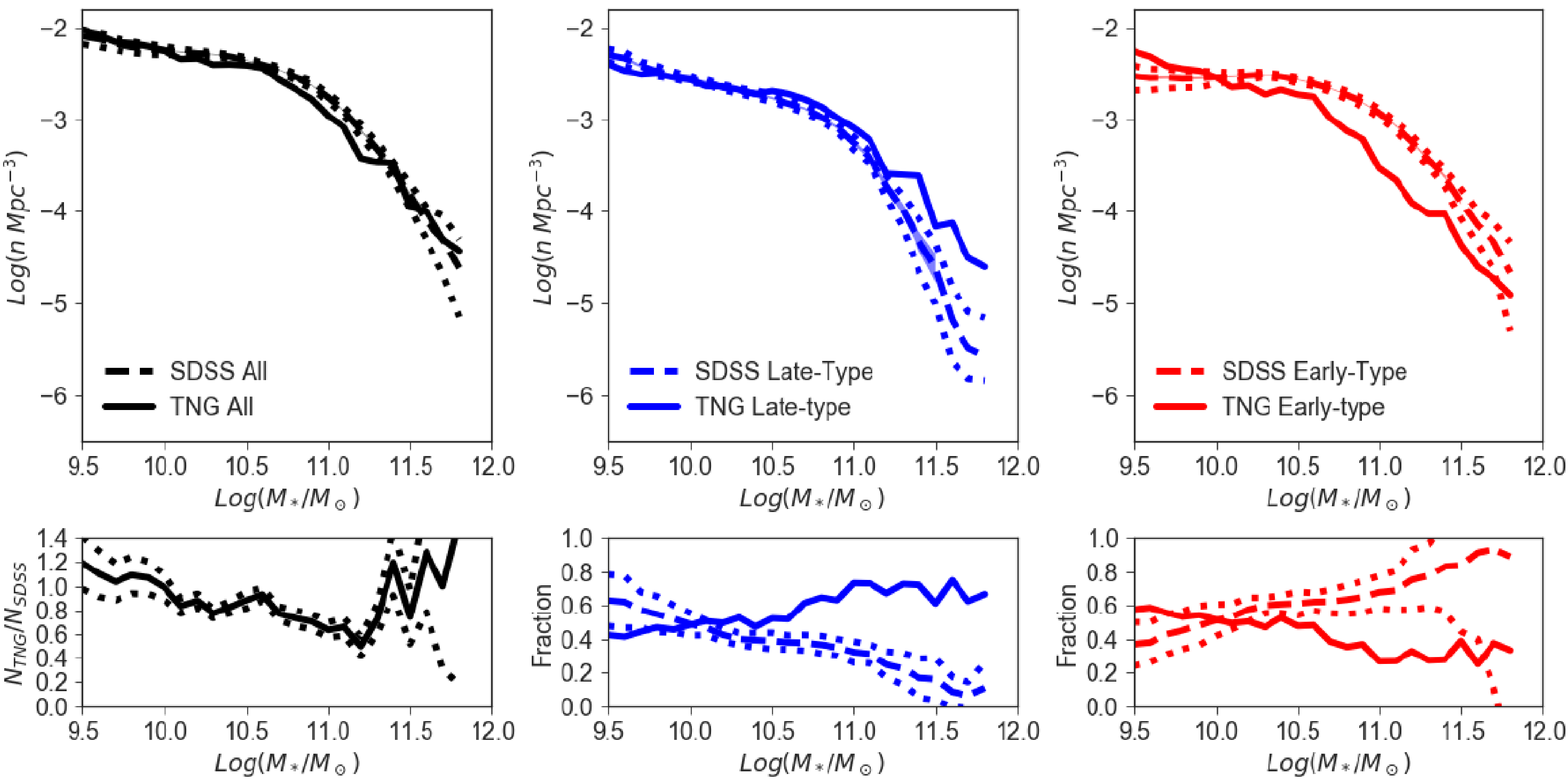
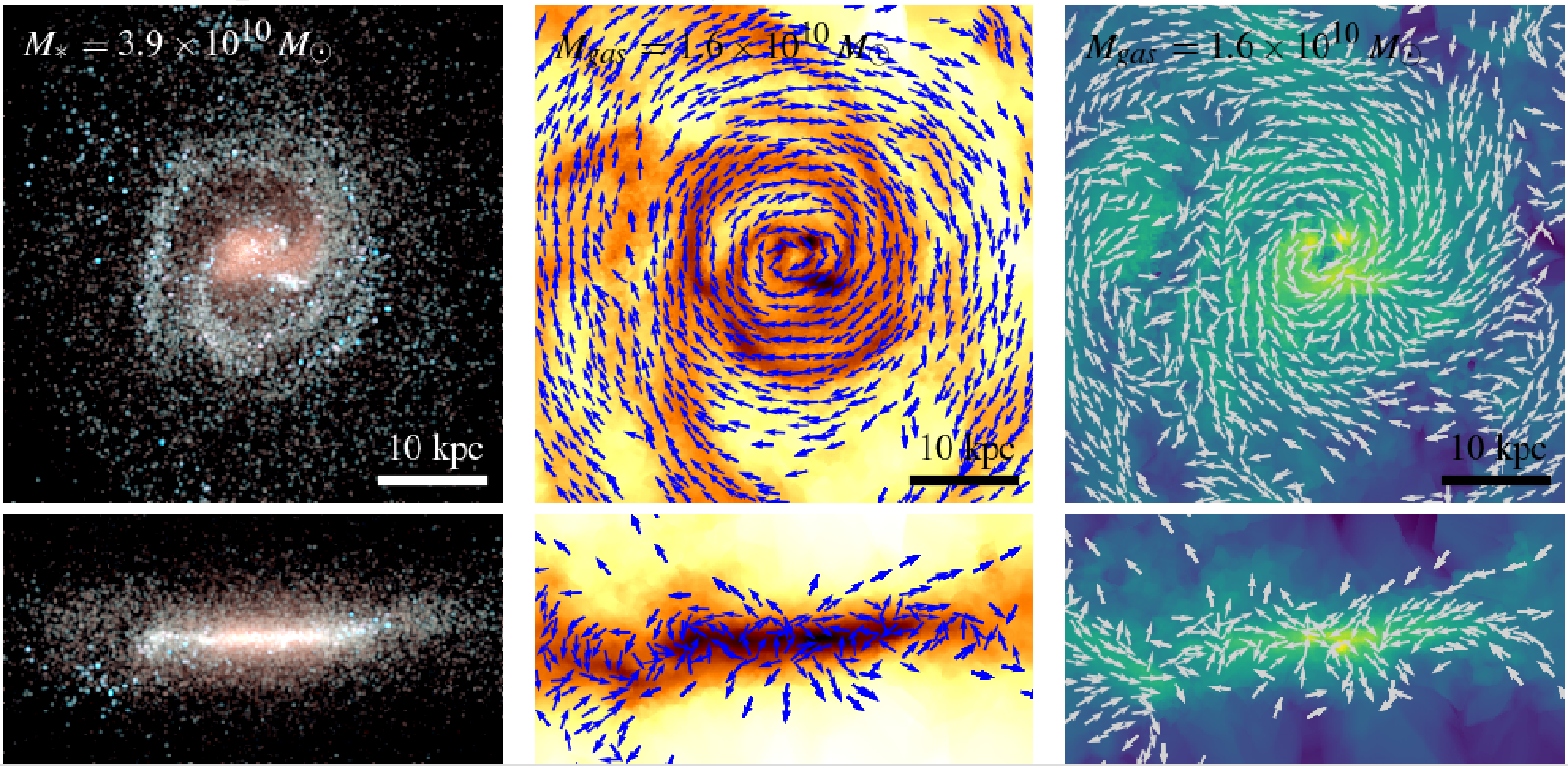


Figure 11. Stellar Mass Functions of all (top left panel), early (top right panel) and late-Type (top middle panel) galaxies. The

First results from the IllustrisTNG simulations: radio haloes and magnetic fields

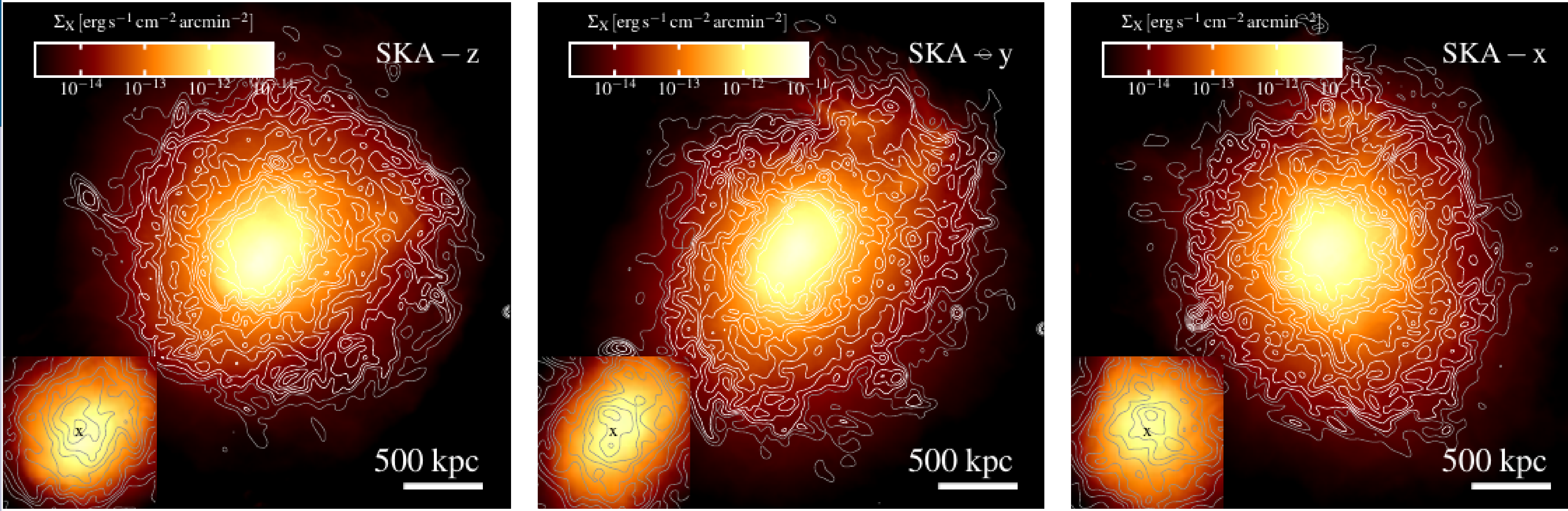
Federico Marinacci[1★], Mark Vogelsberger[1], Rüdiger Pakmor[2], Paul Torrey[1], Volker Springel[2,3], Lars Hernquist[4], Dylan Nelson[5], Rainer Weinberger[2], Annalisa Pillepich[6], Jill Naiman[4], Shy Genel[7,8]



Maps of stars distribution, B mass-weighted and B volume-weighted

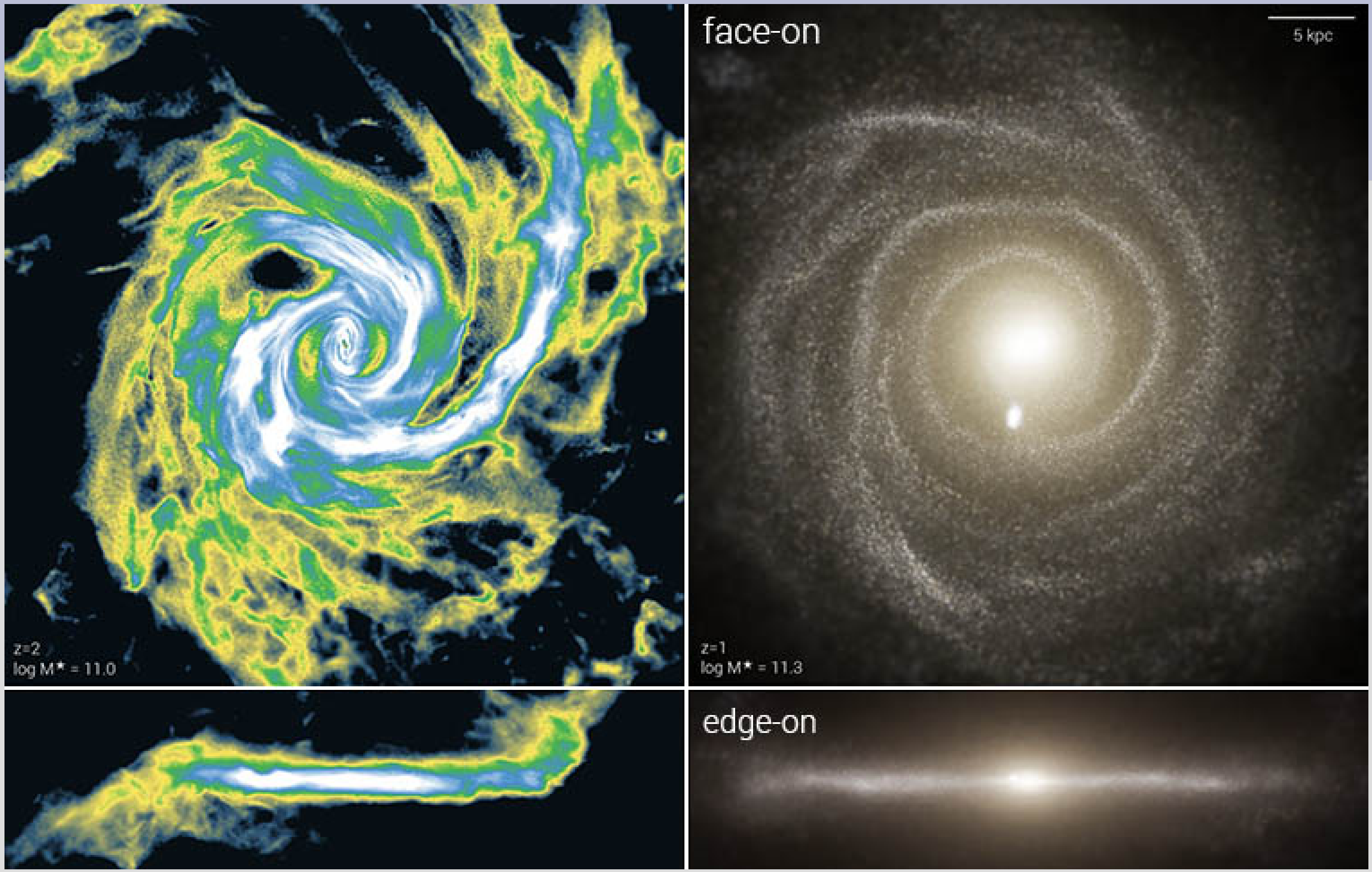
First results from the IllustrisTNG simulations: radio haloes and magnetic fields

Federico Marinacci[1★], Mark Vogelsberger[1], Rüdiger Pakmor[2], Paul Torrey[1], Volker Springel[2,3], Lars Hernquist[4], Dylan Nelson[5], Rainer Weinberger[2], Annalisa Pillepich[6], Jill Naiman[4], Shy Genel[7,8]



X-rays (color) and synchrotron (contours) maps for the most massive halo of TNG-300. Three projections are presented assuming sensivity of a 200 cm^2 X-ray telescope and SKA respectively.

Example: TNG50

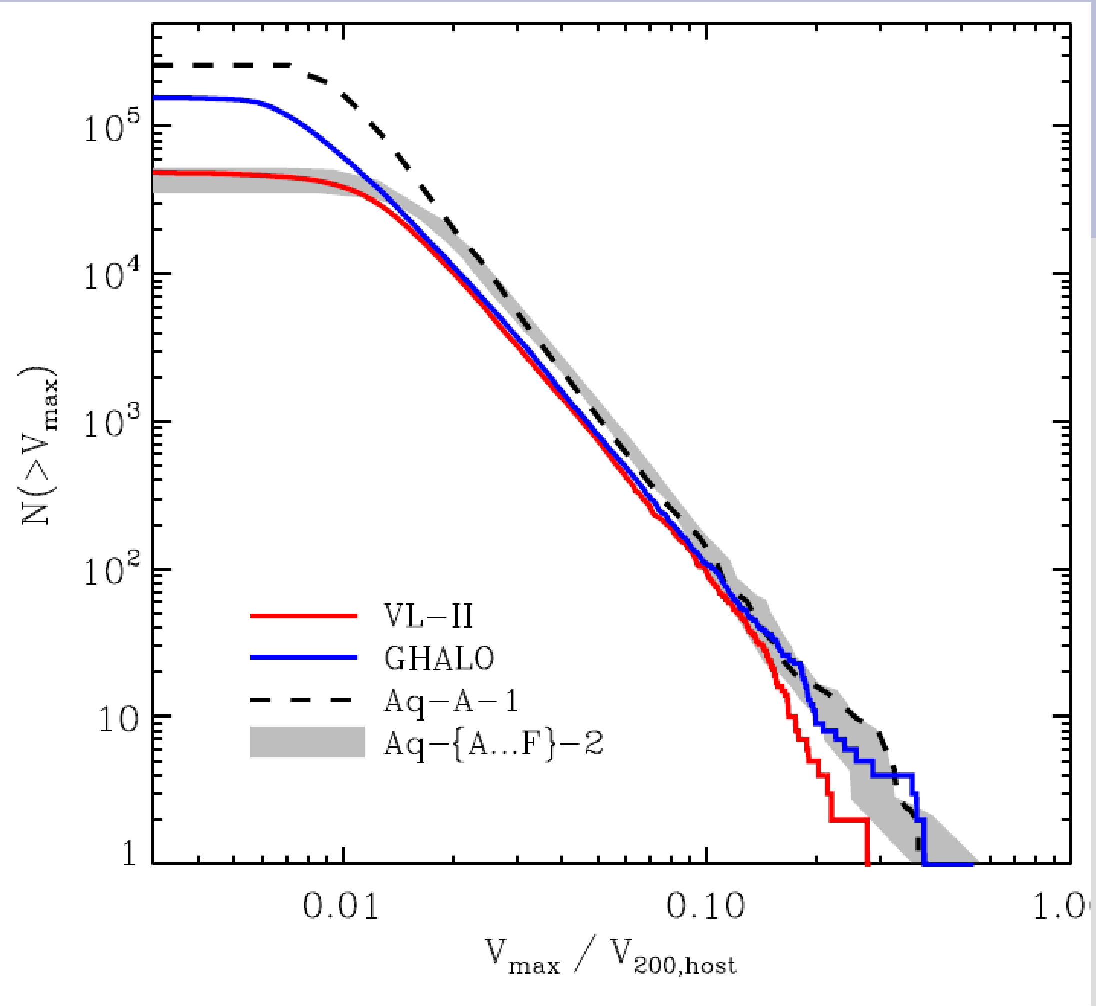


[https://www.tng-project.org/about/]

TNG50 product: one of ~100 synthetic objects similar to Milky Way

TNG50: gas cell 8*10^4 solar, baryon spatial resolution ~140 pc

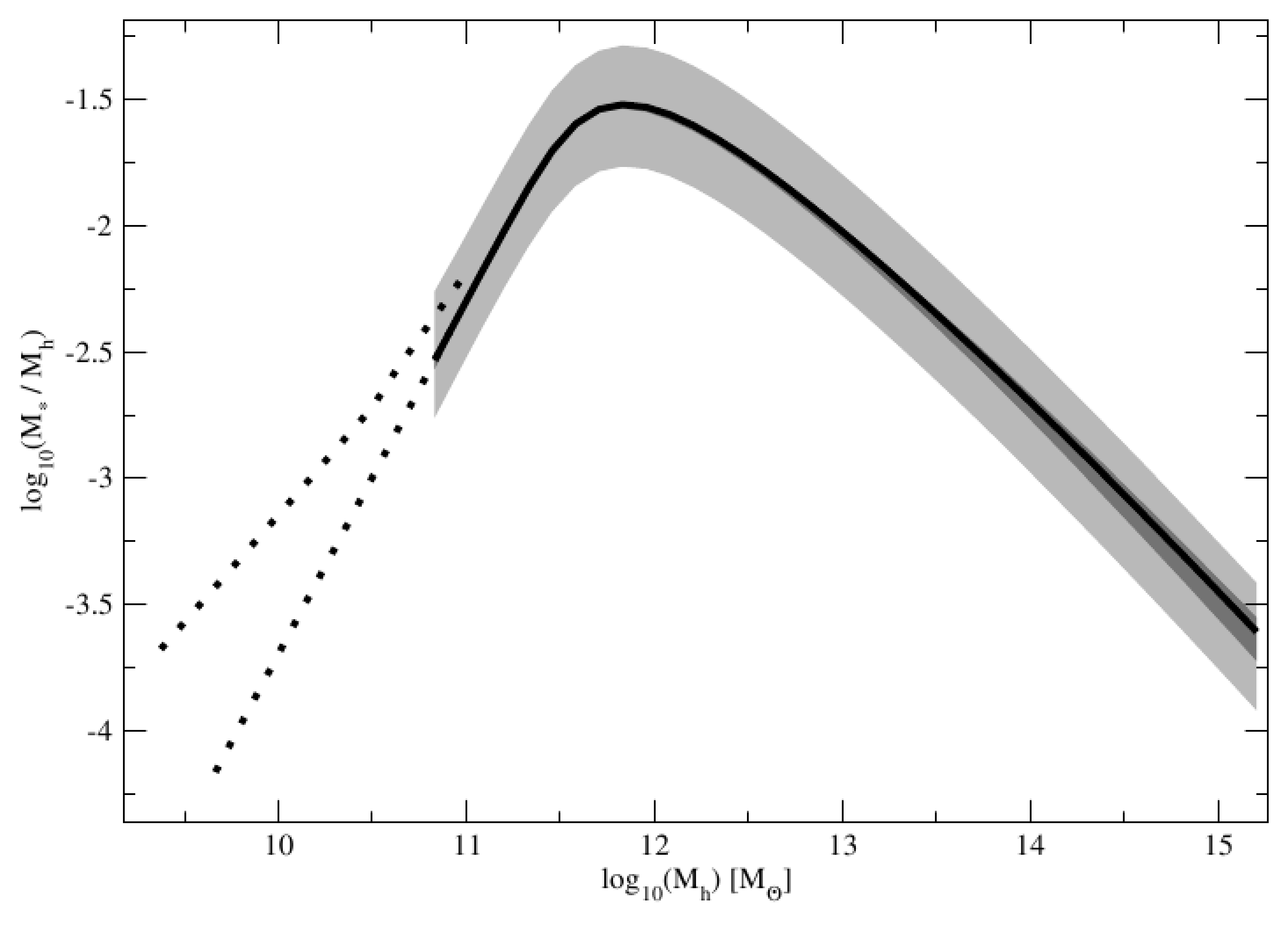
Dwarf galaxy (old) problem



[Bullock (2010) arXiv:1009.4505]

Simulations: MW should be surrounded by ~350 dwarf satellites with velocity dispersions >10km/s

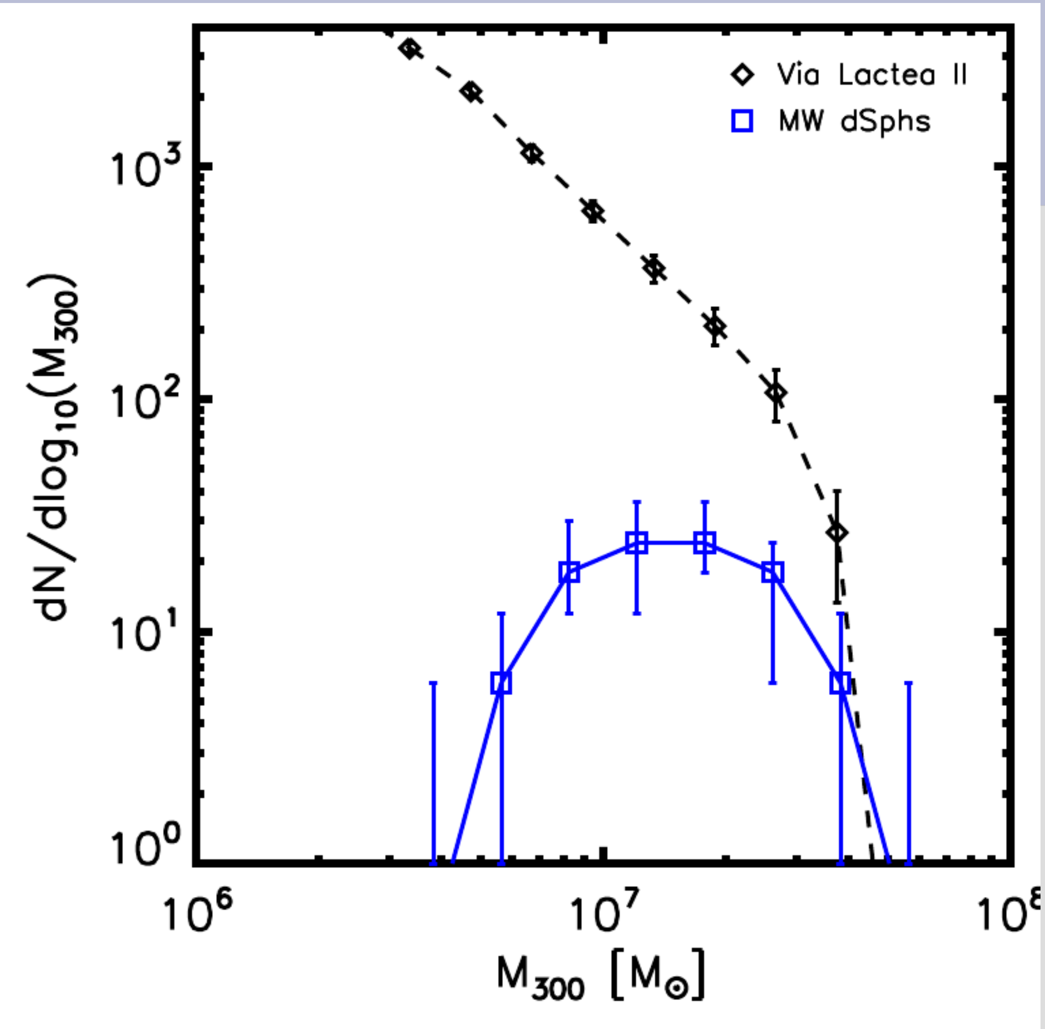
Dwarf galaxy (old) problem



[Bullock (2010) arXiv:1009.4505]

What part of total mass can be assigned to stars?

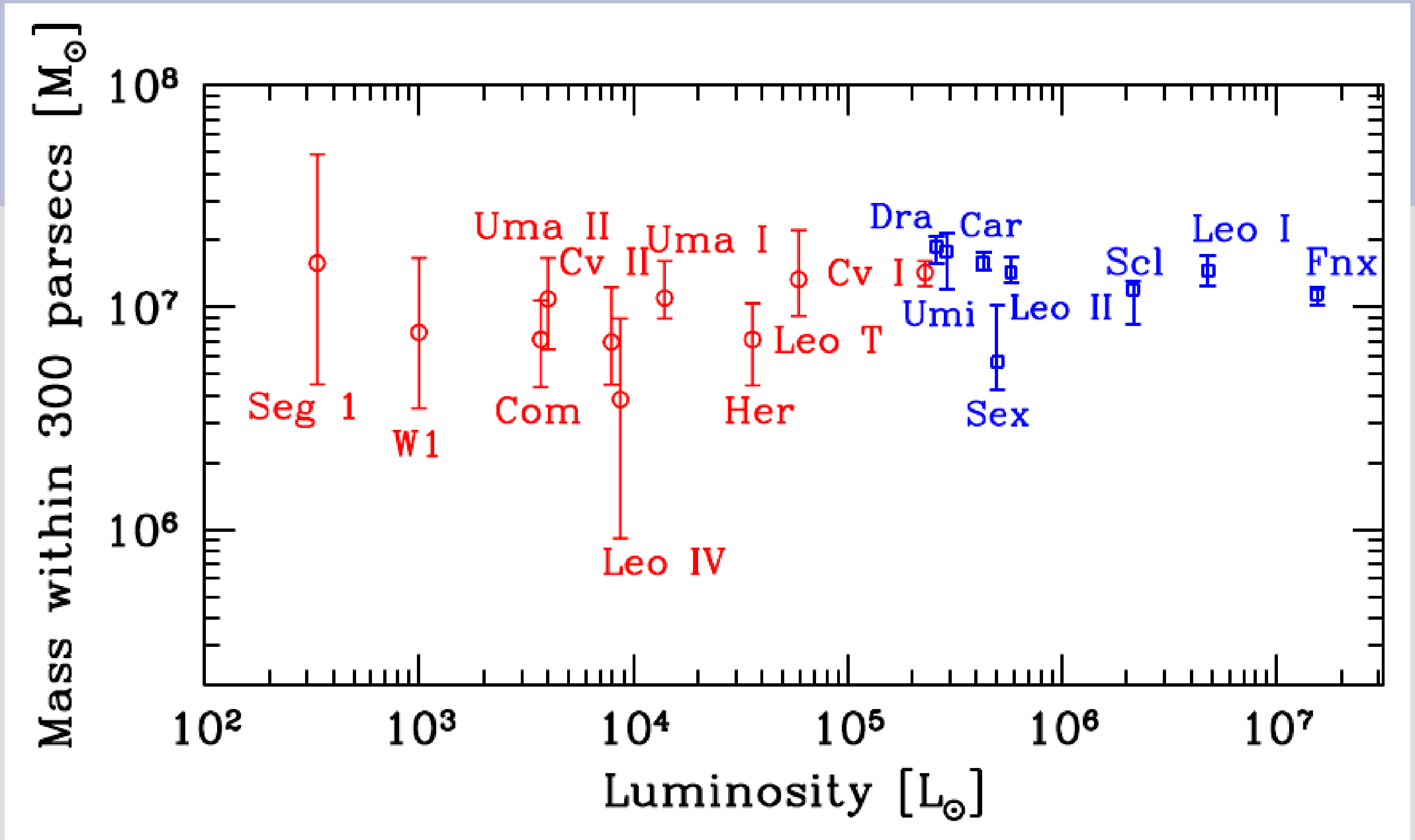
Dwarf galaxy (old) problem



[Bullock (2010) arXiv:1009.4505]

Blue: observed number of dSph around MW
Black: expected number from simulations

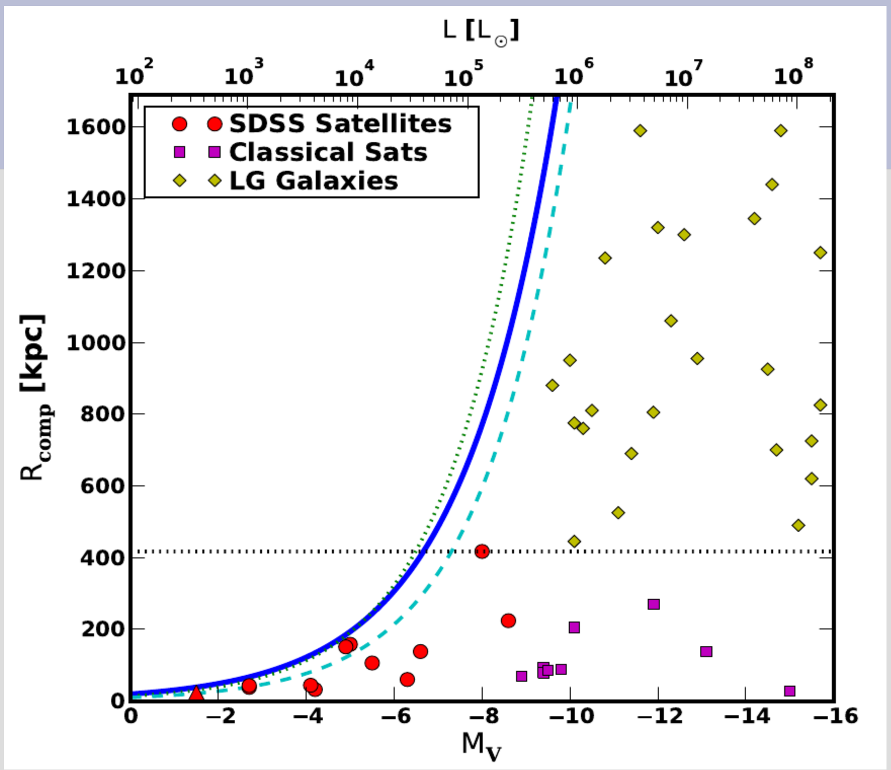
Dwarf galaxy (old) problem

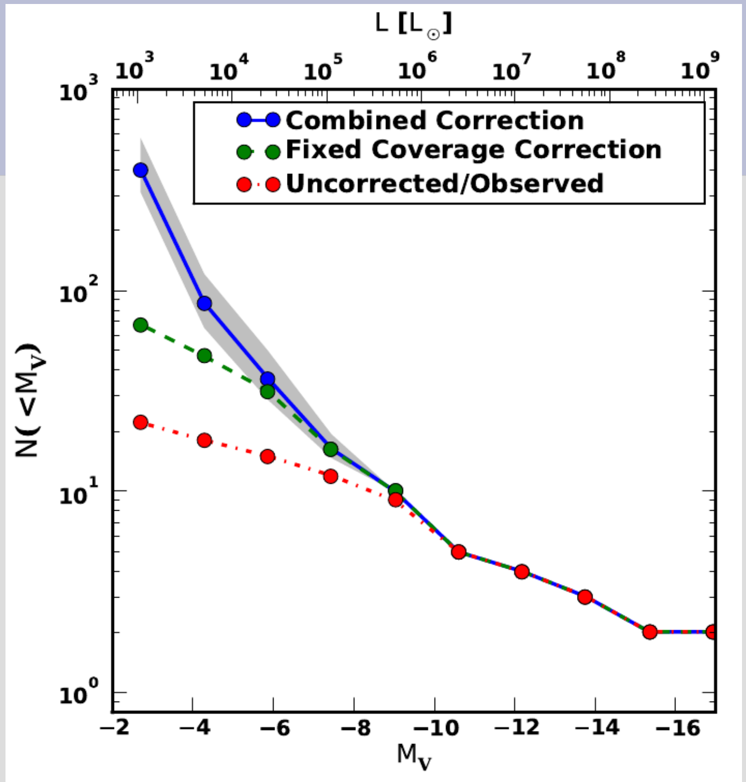


[Bullock (2010) arXiv:1009.4505]

Classic (pre- SDSS) and very dim MW satellites
(another ~20 discovered 2016 not shown)

Dwarf galaxy (old) problem



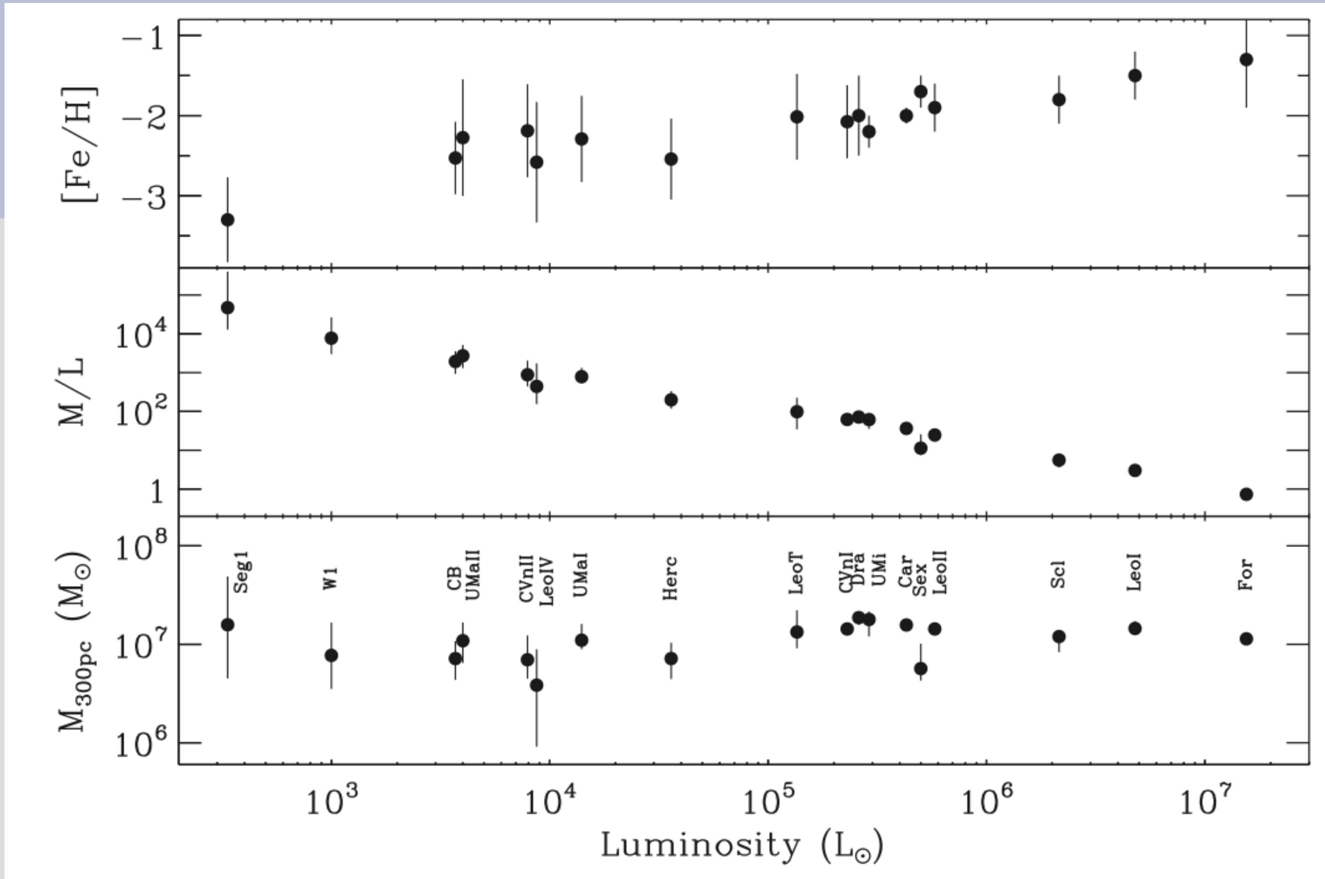


[Bullock (2010) arXiv:1009.4505]

Some too big, having too low surface brightness dwarfs may be unobservable with SDSS. Also: SDSS observes ~ 1/5 of the sky

Corrections for incompleteness and sky coverage give much larger number of dwarfs (LSST will check it ?)

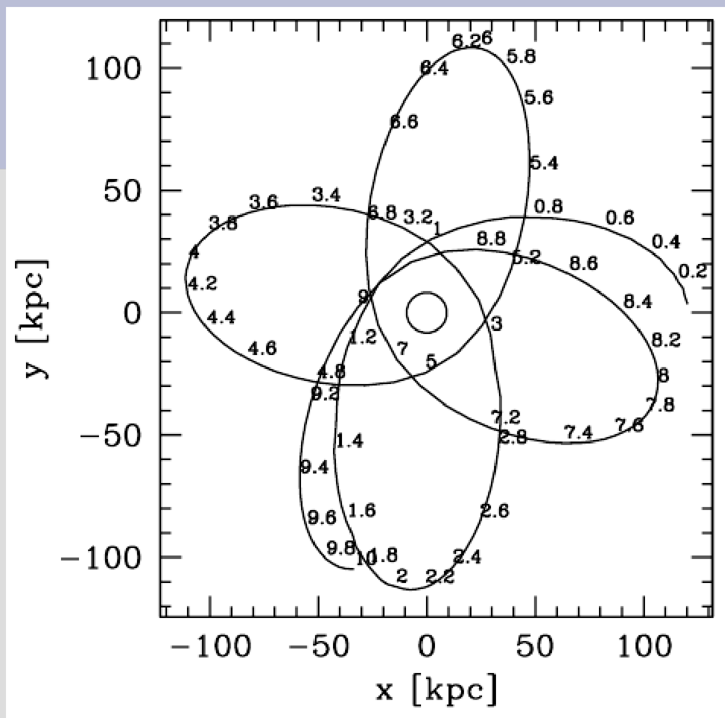
MW dwarfs

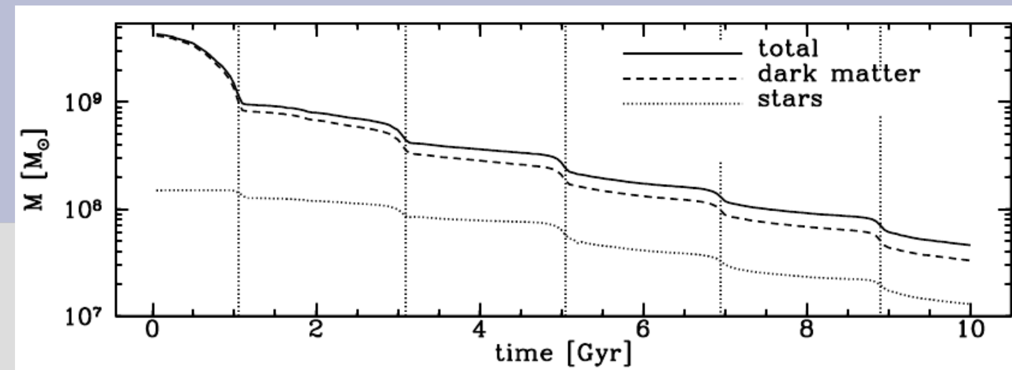


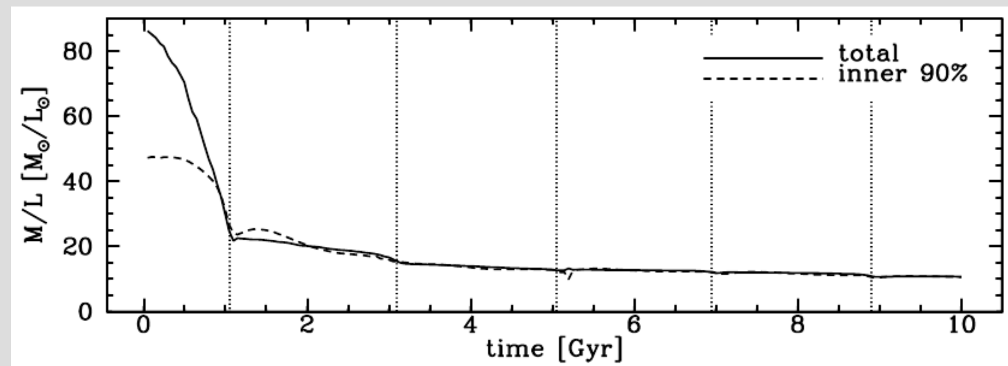
[Geha et al. (2009) ApJ, 692, 1464]

Some Galactic satellite dwarfs have very high range of luminosity while their total masses do not differ much. (This implies wide range of M/L ratio > 4 orders of magnitude) WHY ?

MW dwarfs tidal destruction







Klimentowski et al. (2009) MN, 397, 2015

Some 10 bilion years history of MW tidal forces disrupting orbiting dwarf

Similar topics are still investigated by Professor Ewa Łokas and collaborators:

Tidally induced warps of spiral galaxies in IllustrisTNG

Marcin Semczuk,[1,2] Ewa L. Łokas,[2] Elena D'Onghia,[3,4] E. Athanassoula,[5] Victor P. Debattista,[6] Lars Hernquist[7]

Preprint 18 February 2020

The APOSTLE simulations: solutions to the Local Group's cosmic puzzles

Till Sawala[1,2*], Carlos S. Frenk[1], Azadeh Fattahi[3], Julio F. Navarro[3,4], Richard G. Bower[1], Robert A. Crain[5], Claudio Dalla Vecchia[6,7], Michelle Furlong[1], John. C. Helly[1], Adrian Jenkins[1], Kyle A. Oman[2], Matthieu Schaller[1], Joop Schaye[8], Tom Theuns[1], James Trayford[1] and Simon D. M. White[9]

•EAGLE code based on Gadget-3 (Gadget-2: Millennium)
• Gravitation + hydrodynamics
• Radiation transfer, cooling, ionization, recombination
• Stellar evolution, SN, winds, BH, AGN
• APOSTLE: 12 fragments of simulation in (100Mpc)^3 chosen in a way to guarantee the presence of 2 haloes with masses close to MW+M31, at a distance ~ 800 kpc, approaching each other with the velocity 0-250 km/s
• Parameters of WMAP-7
• Evolution since first stars until "today"
• First stars z~17 inside the predecessors of MW and M31
• At z~11.5 ionization, star formation halt until the formation of the high mass halo

Dwarf galaxy (old) problem
numerical solution ?

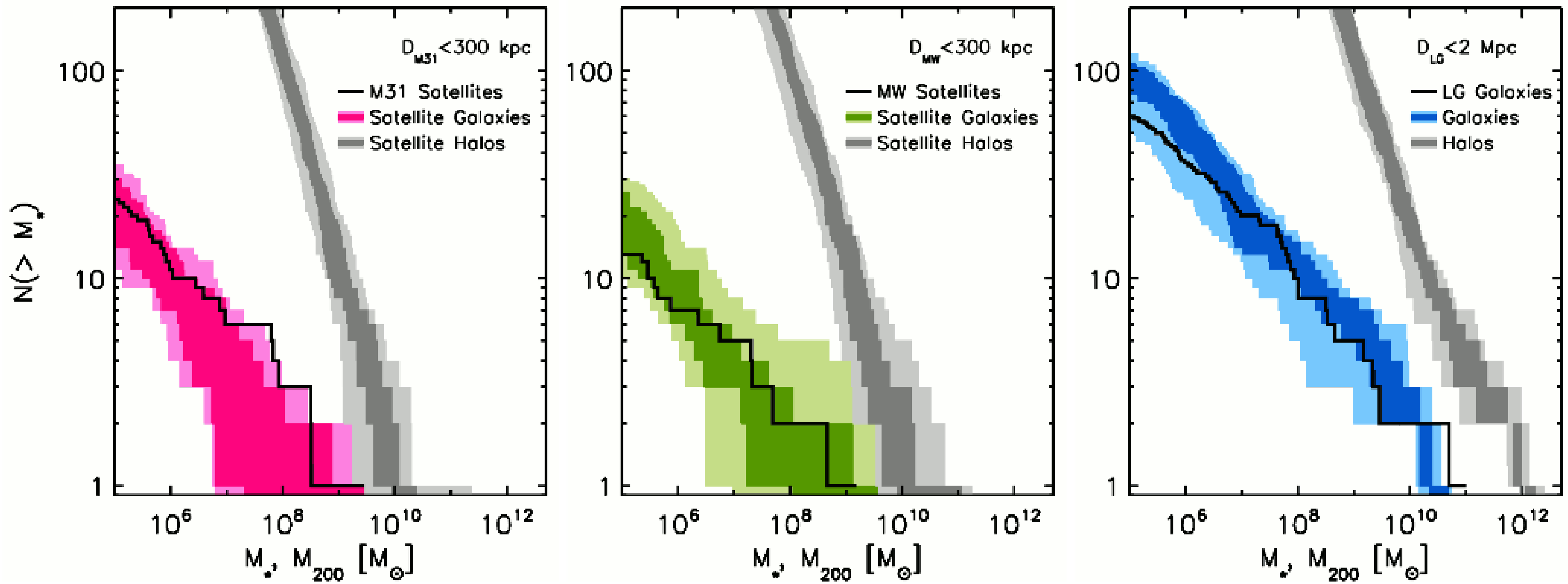


Figure 3. Stellar mass functions from 12 APOSTLE simulations at resolution L2 compared to observations. In the left and centre, shaded regions show the mass functions of satellites within 300 kpc of each of the primary (left) and secondary (centre) of the two main Local Group galaxies from each simulation volume, while lines show the observed stellar mass function within 300 kpc of M31 (left) and the MW (centre). In the right, the shaded region shows all galaxies within 2 Mpc of the Local Group barycentre in the simulations, while

- Not in every halo star formation is efficient enough that it becomes observable as a galaxy
- Cause: internal processes (SN → winds, BH → winds and other) enviroment (tidal disruption, ionization by external radiation)