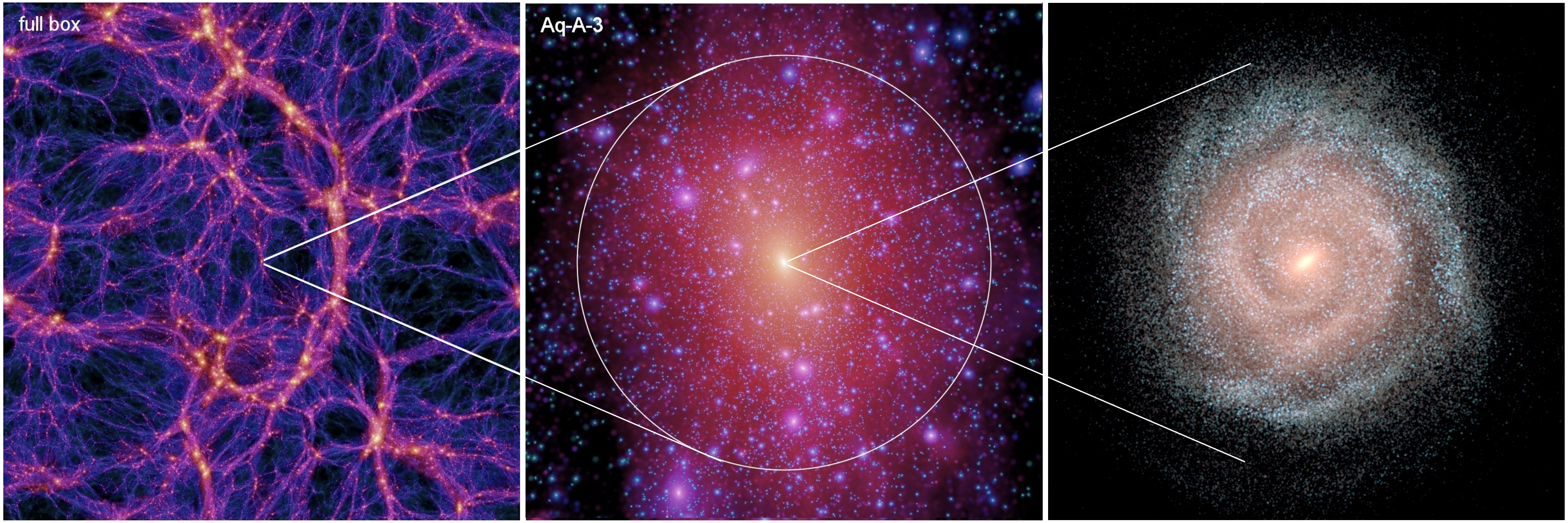
Supercomputer simulations of the dark and luminous matter in the Universe

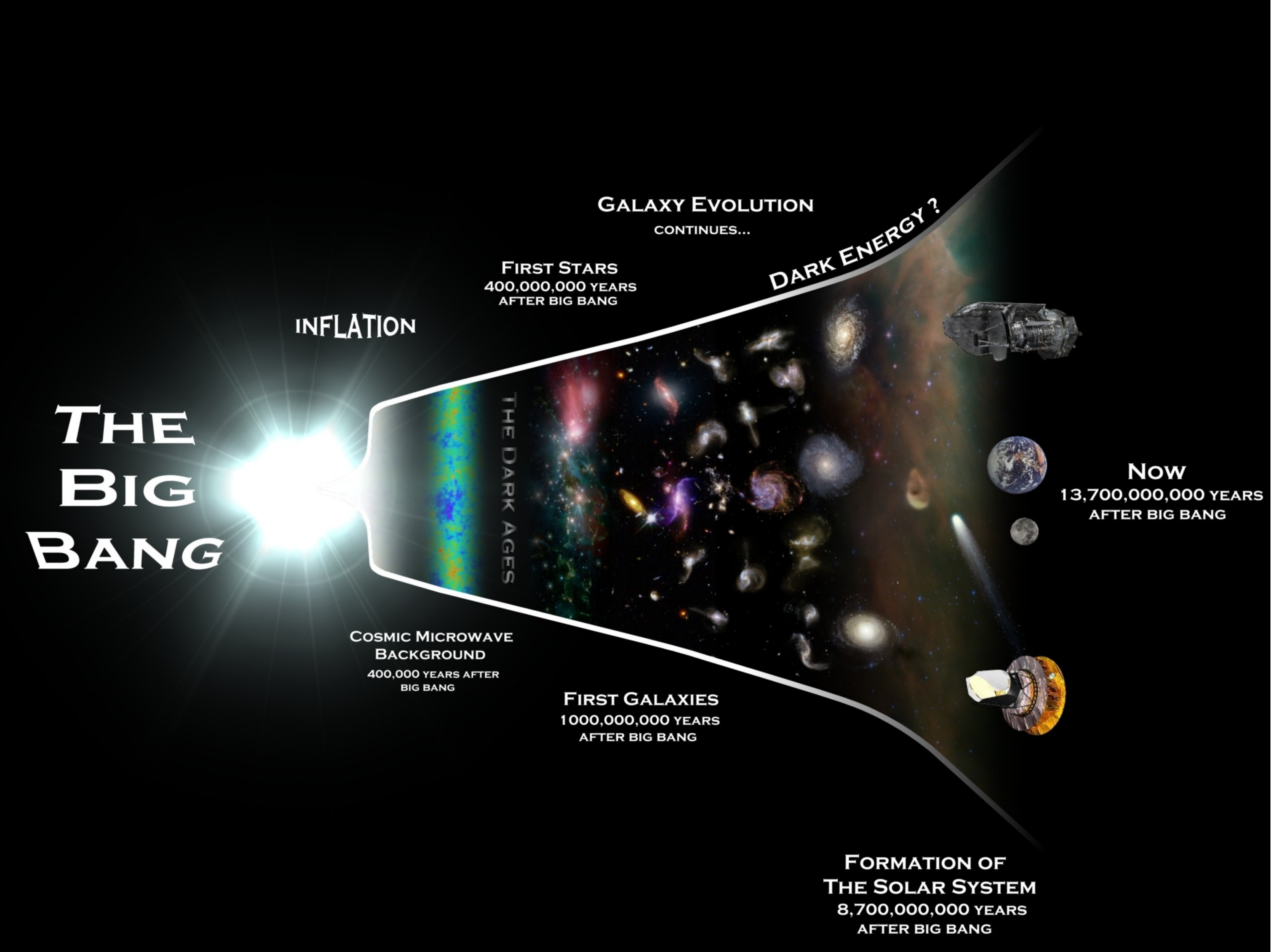
Volker Springel



- **Structure formation in a dark universe**
- **Old problems and recent progress in galaxy formation simulations**
- **Magnetic fields, cosmic rays, and other multi-scale challenges**

Heidelberg Institute for Theoretical Studies
HITS
Universität Heidelberg

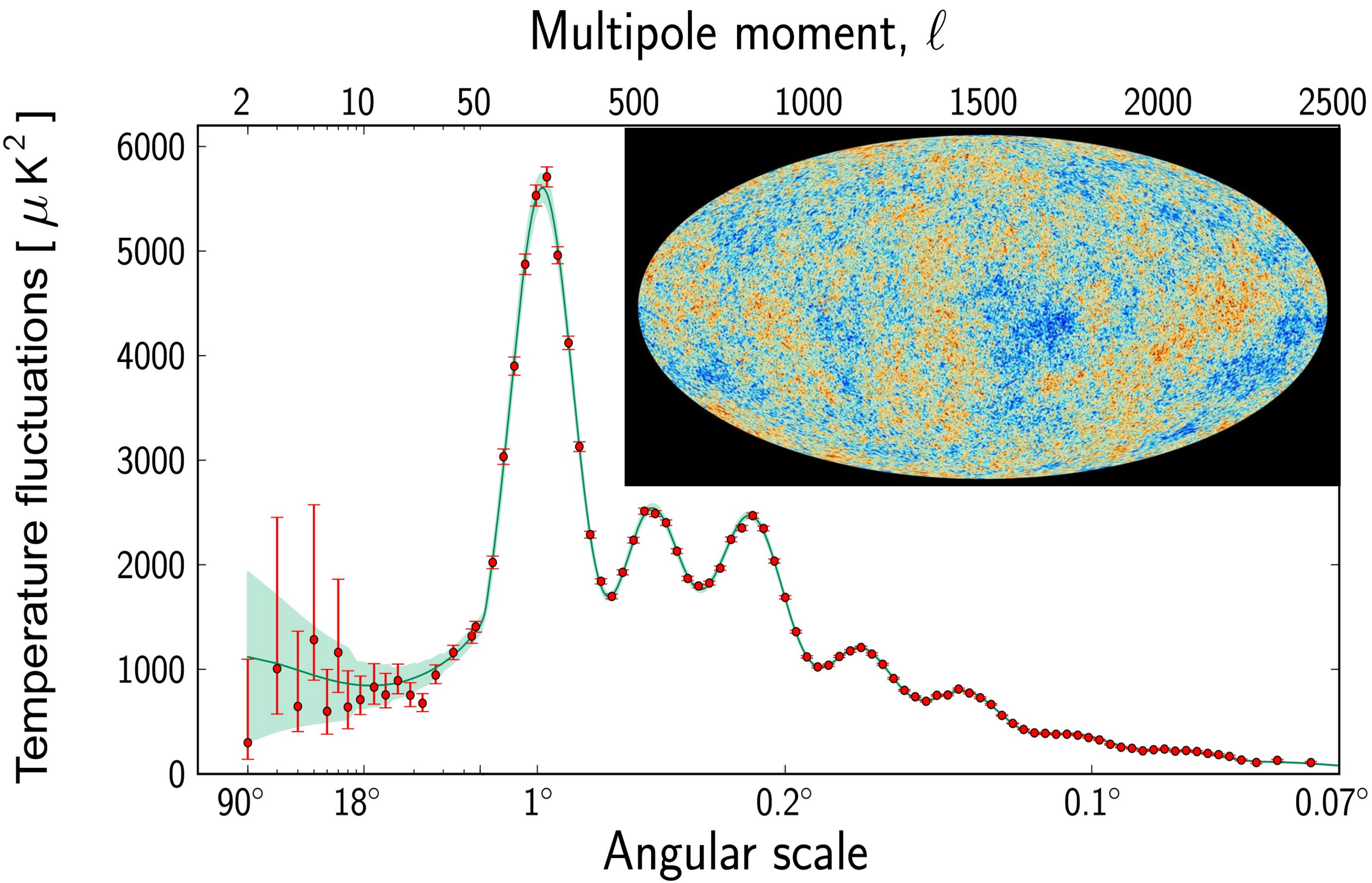
DESY
Physics Colloquium
Hamburg/Zeuthen, May 2017


THE BIG BANG
INFLATION
FIRST STARS
400,000,000 YEARS
AFTER BIG BANG
GALAXY EVOLUTION
CONTINUES...
DARK ENERGY ?
THE DARK AGES
COSMIC MICROWAVE
BACKGROUND
400,000 YEARS AFTER
BIG BANG
FIRST GALAXIES
1000,000,000 YEARS
AFTER BIG BANG
NOW
13,700,000,000 YEARS
AFTER BIG BANG
FORMATION OF
THE SOLAR SYSTEM
8,700,000,000 YEARS
AFTER BIG BANG

Amazing observational progress has specified the intial conditions

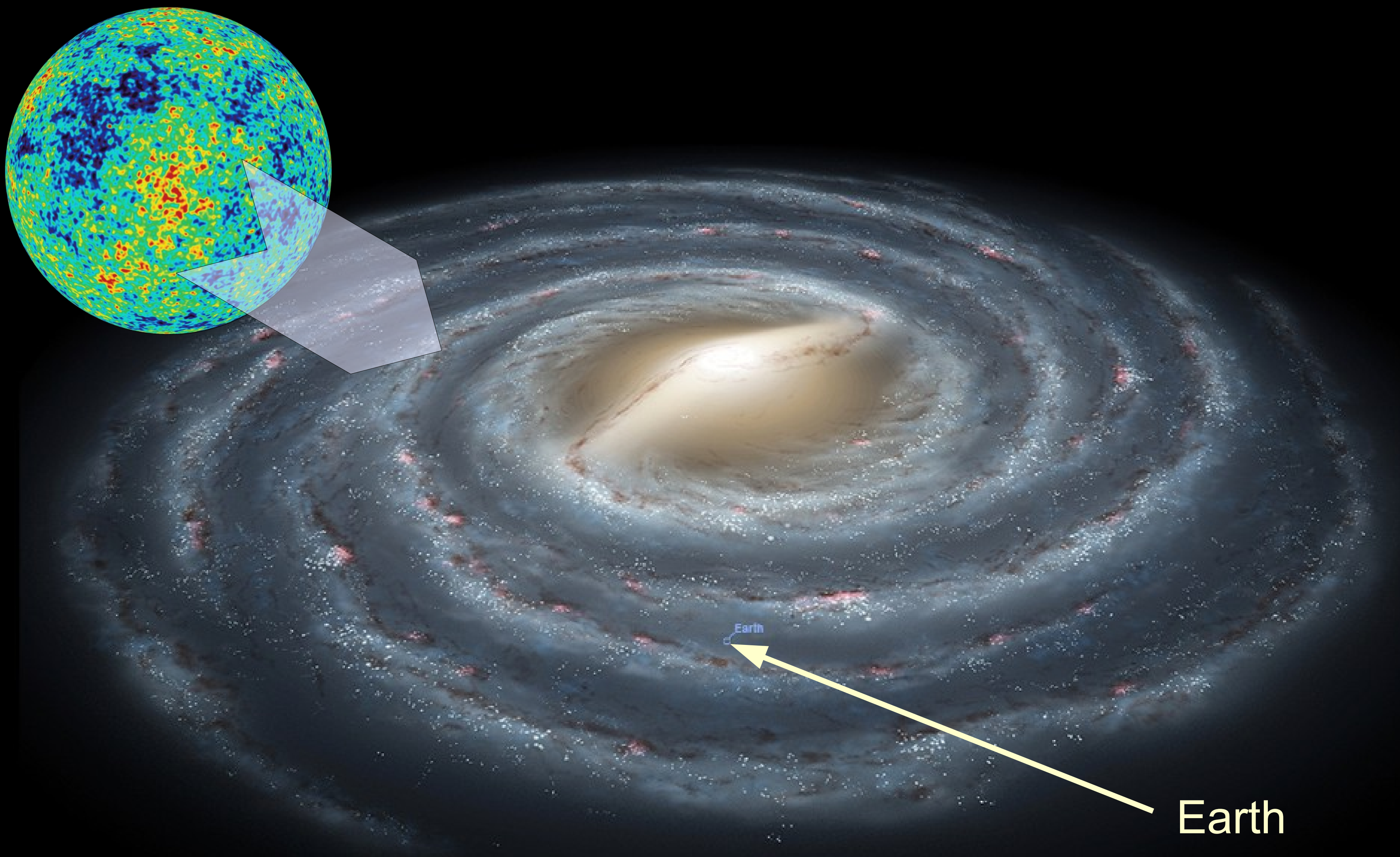
CMB CONTRAINTS TODAY AS SEEN BY PLANCK

Minimal, 6-parameter ΛCDM model is a great fit



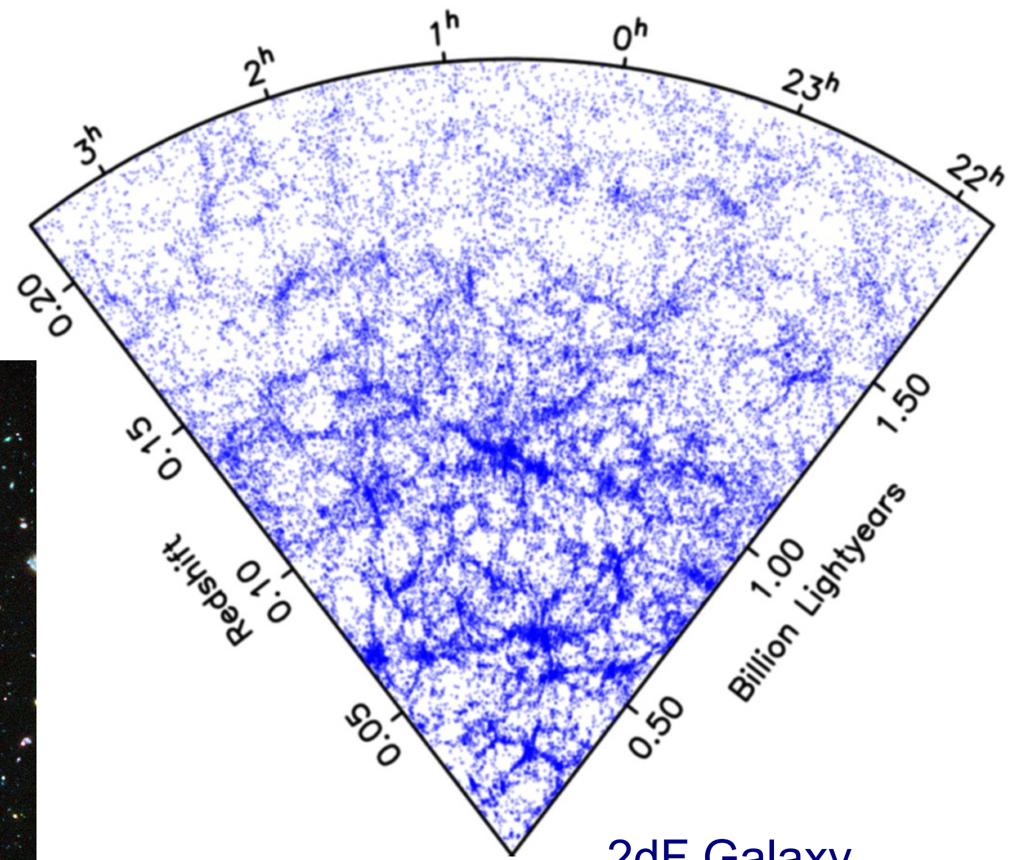
Planck Collaboration (2013)

Need to bridge 13.7 billion years of (non-linear) evolution

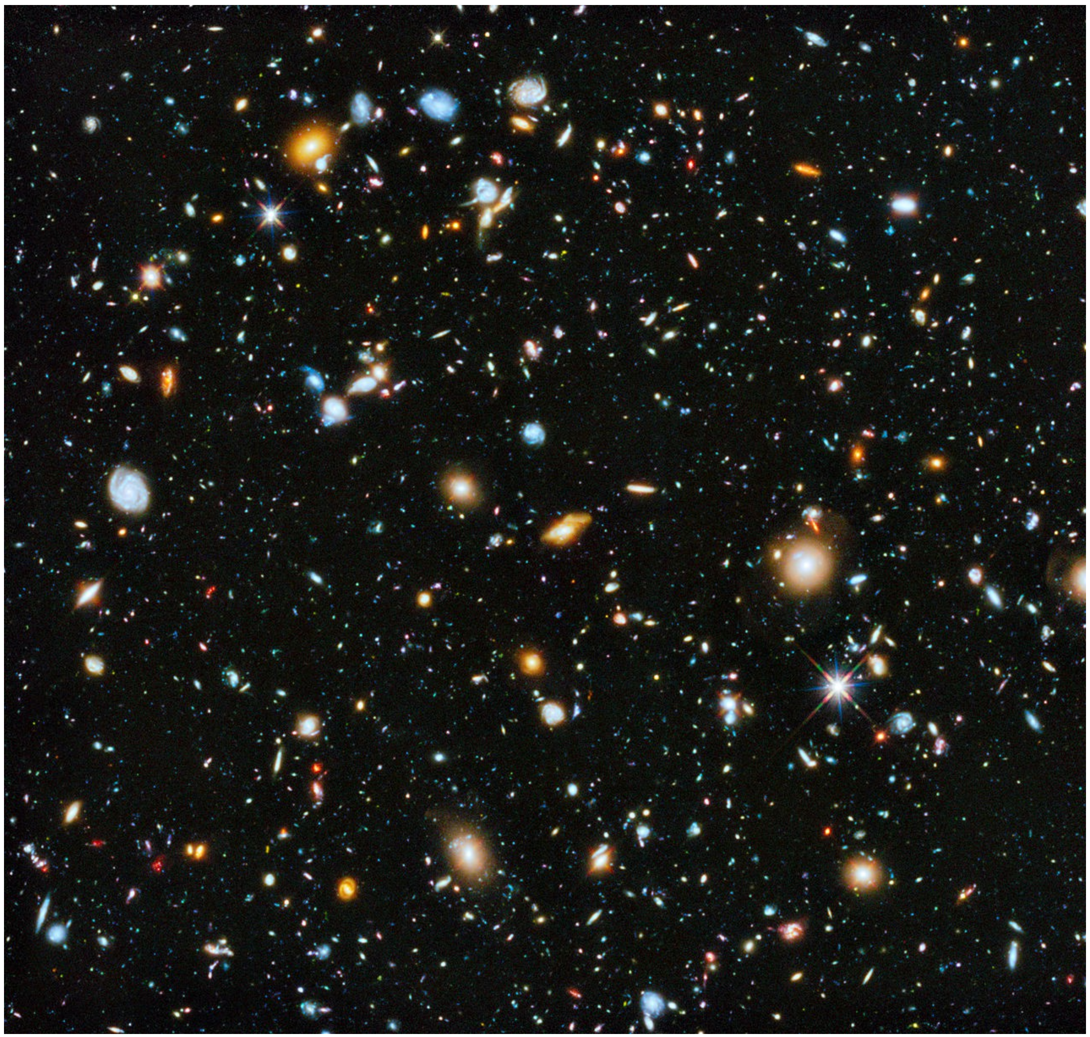


Redshift surveys and deep observations unveil how galaxies evolved, and how they are clustered in space

DEEP IMAGING AND REDSHIFT SURVEYS



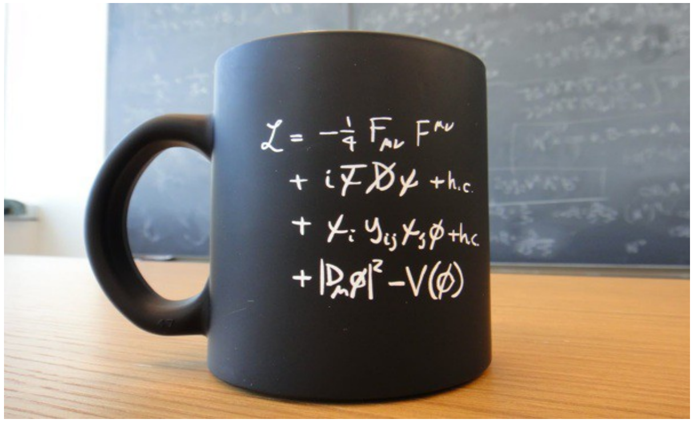
2dF Galaxy Redshift Survey



Hubble Ultra Deep Field

Much of astrophysics is described through systems of
Partial Differential Equations (PDEs)

THE PHYSICS IS NOT JUST THE EQUATIONS – IT'S ALSO THE SOLUTIONS



- Euler/Navier-Stokes equations
- Collisionless dynamics
- Radiative transfer
- MHD
- General relativity
- ….

hyperbolic conservation laws of fluid dynamics

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla(\rho \mathbf{v}\mathbf{v}^T + P) = \nabla \mathbf{\Pi}$$

$$\frac{\partial}{\partial t}(\rho e) + \nabla[(\rho e + P)\mathbf{v}] = \nabla(\mathbf{\Pi}\mathbf{v})$$

Poisson-Vlasov system

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \mathbf{v} + \frac{\partial f}{\partial \mathbf{v}} \cdot \left(-\frac{\partial \Phi}{\partial \mathbf{x}}\right) = 0$$

$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \int f(\mathbf{x}, \mathbf{v}, t)\, \mathrm{d}\mathbf{v}$$

The cost of 1 Gflop has dropped like a rock over the past decades

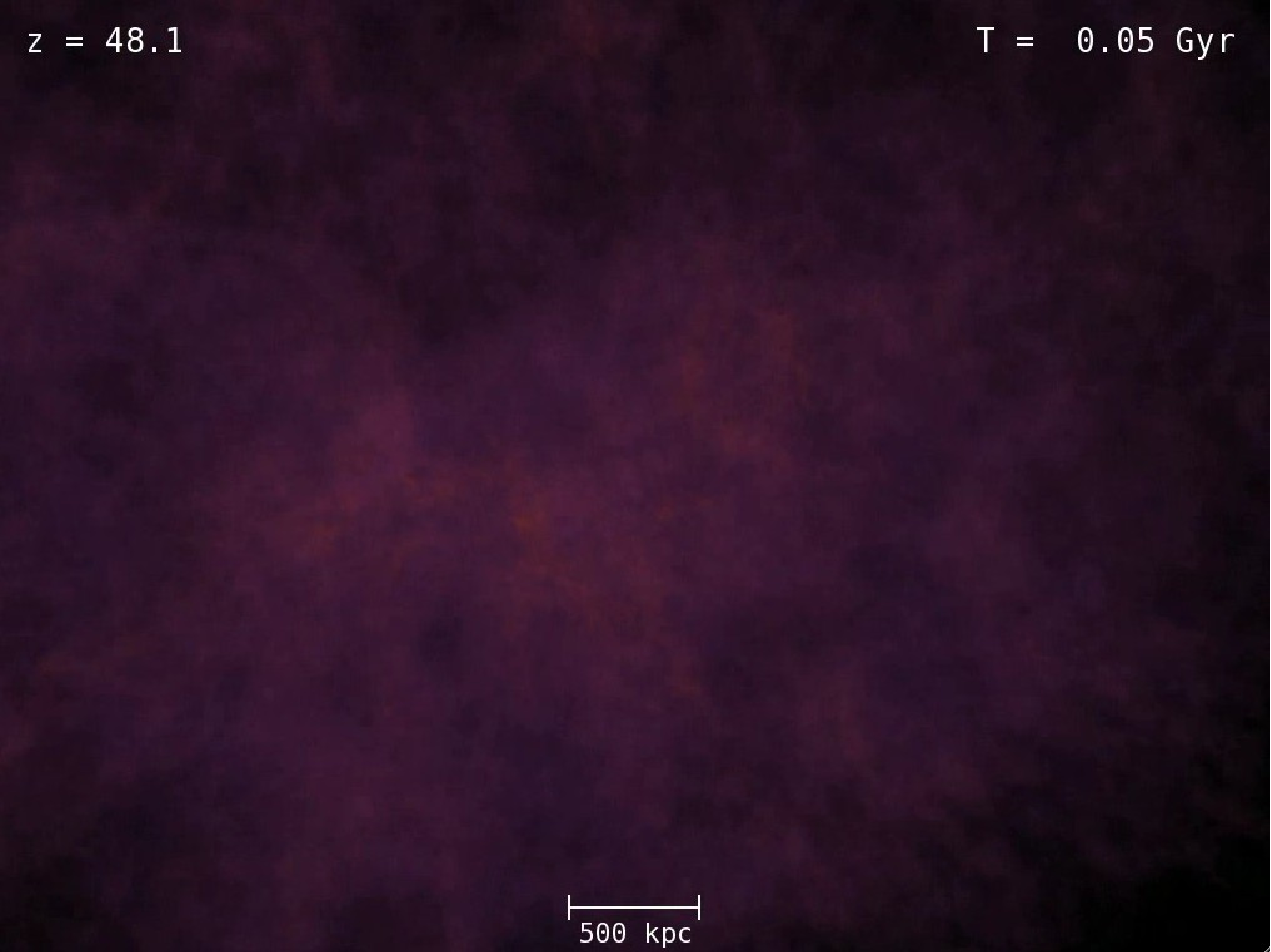
APPROXIMATE COST TO BUY A PERFORMANCE OF 1 GFLOP IN HARDWARE

a drop in price of ~8 orders of magnitude over the past 30 years

Date	Approximate cost per GFLOPS	Approximate cost per GFLOPS inflation adjusted to 2013 US dollars[45]	Platform providing the lowest cost per GFLOPS
1961	US $1,100,000,000,000 ($1.1 trillion)	US $8.3 trillion	About 17 million IBM 1620 units costing $64,000 each
1984	$18,750,000	$42,780,000	Cray X-MP/48
1997	$30,000	$42,000	Two 16-processor Beowulf clusters with Pentium Pro microprocessors[47]
April 2000	$1,000	$1,300	Bunyip Beowulf cluster
May 2000	$640	$836	KLAT2
August 2003	$82	$100	KASY0
August 2007	$48	$52	Microwulf
March 2011	$1.80	$1.80	HPU4Science
August 2012	$0.75	$0.73	Quad AMD7970 GHz System
June 2013	$0.22	$0.22	Sony Playstation 4
November 2013	$0.16	$0.16	AMD Sempron 145 GeForce GTX 760 System
December 2013	$0.12	$0.12	Pentium G550 R9 290 System

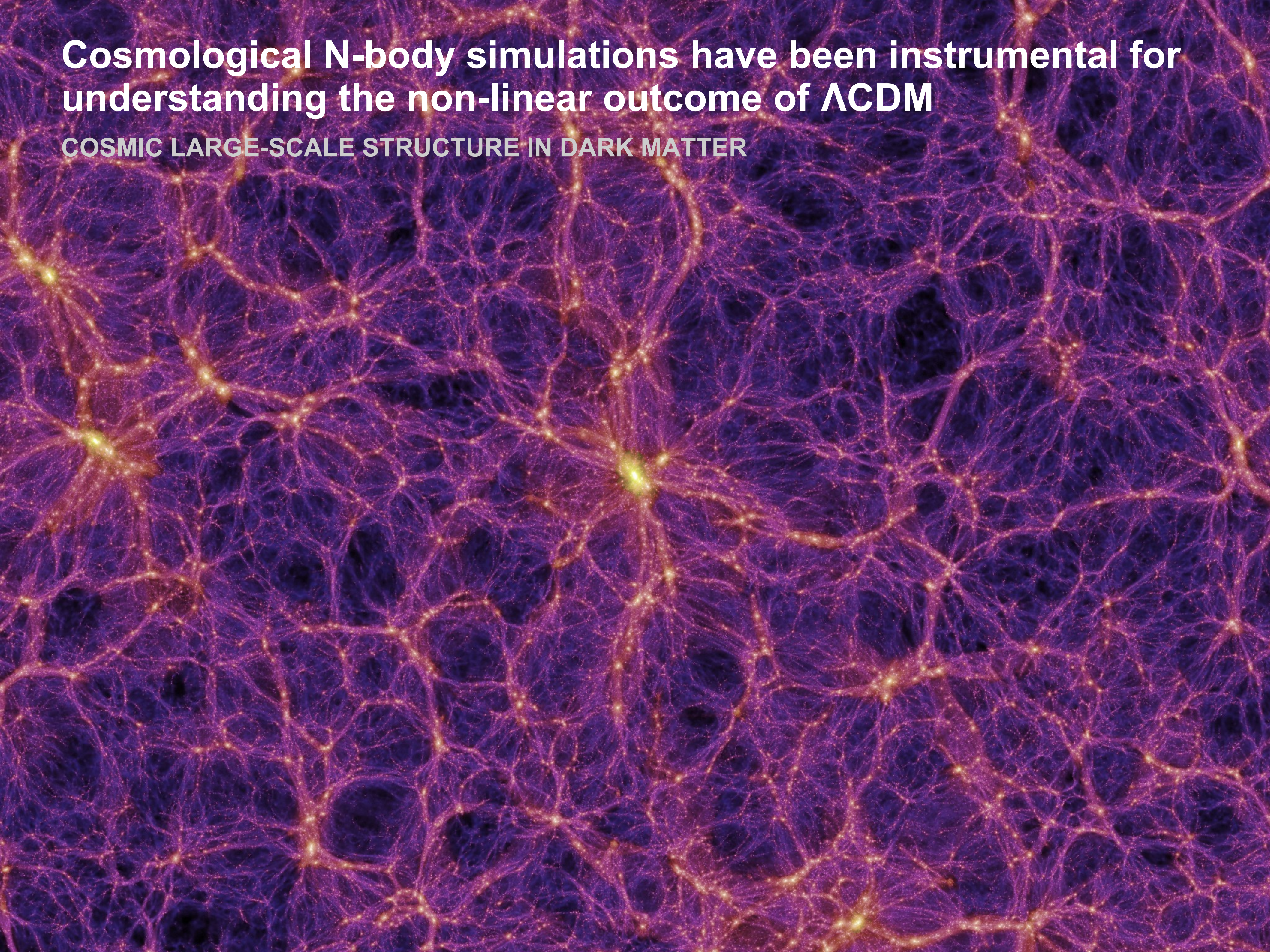
source: wikipedia

Numerical methods are often the only option to solve PDEs


z = 48.1
T = 0.05 Gyr
500 kpc

Cosmological N-body simulations have been instrumental for understanding the non-linear outcome of ΛCDM

COSMIC LARGE-SCALE STRUCTURE IN DARK MATTER



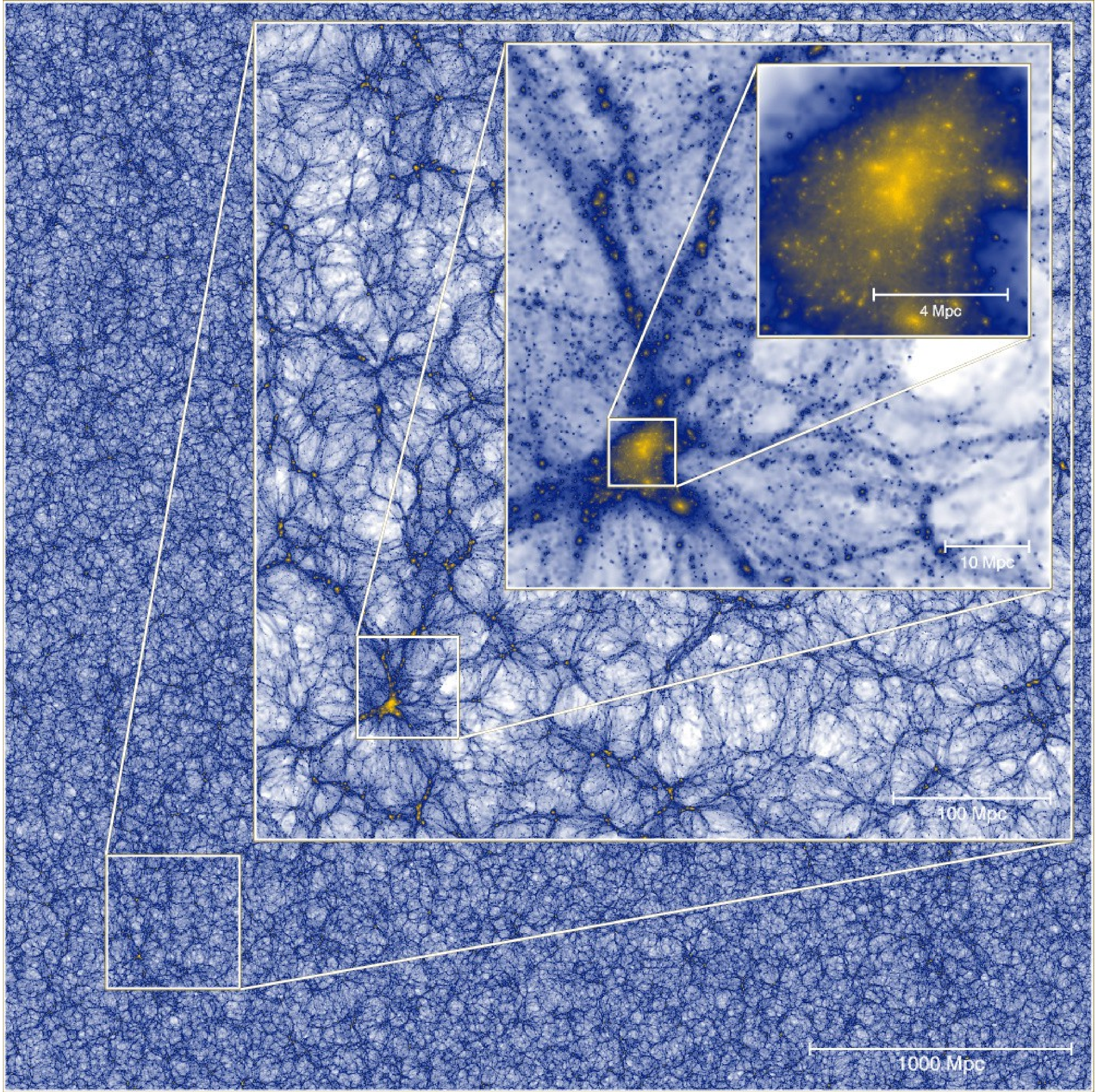
Millennium-XXL

303 billion particles

Largest high-resolution N-body simulation ever

Visualization example: understanding the structure of the non-linear mass distribution in the Universe

Angulo, Springel, White, Frenk et al. (2011)



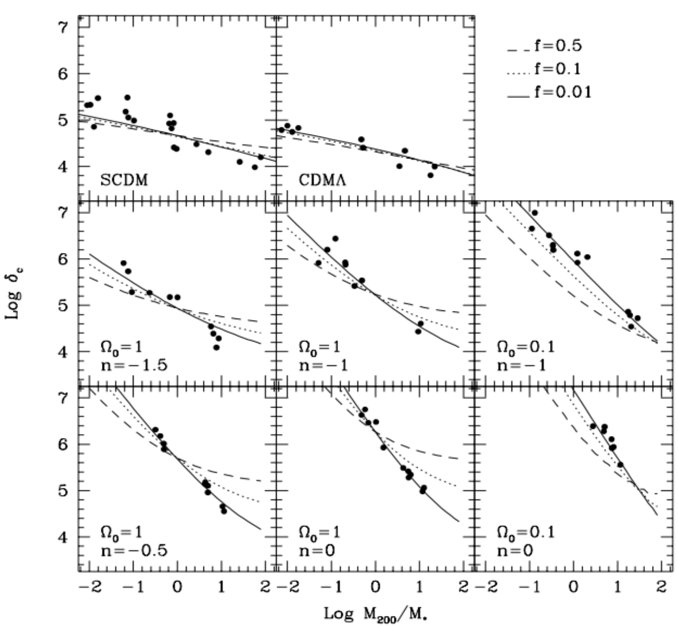
The structure of Cold Dark Matter Halos has been established by N-body simulations

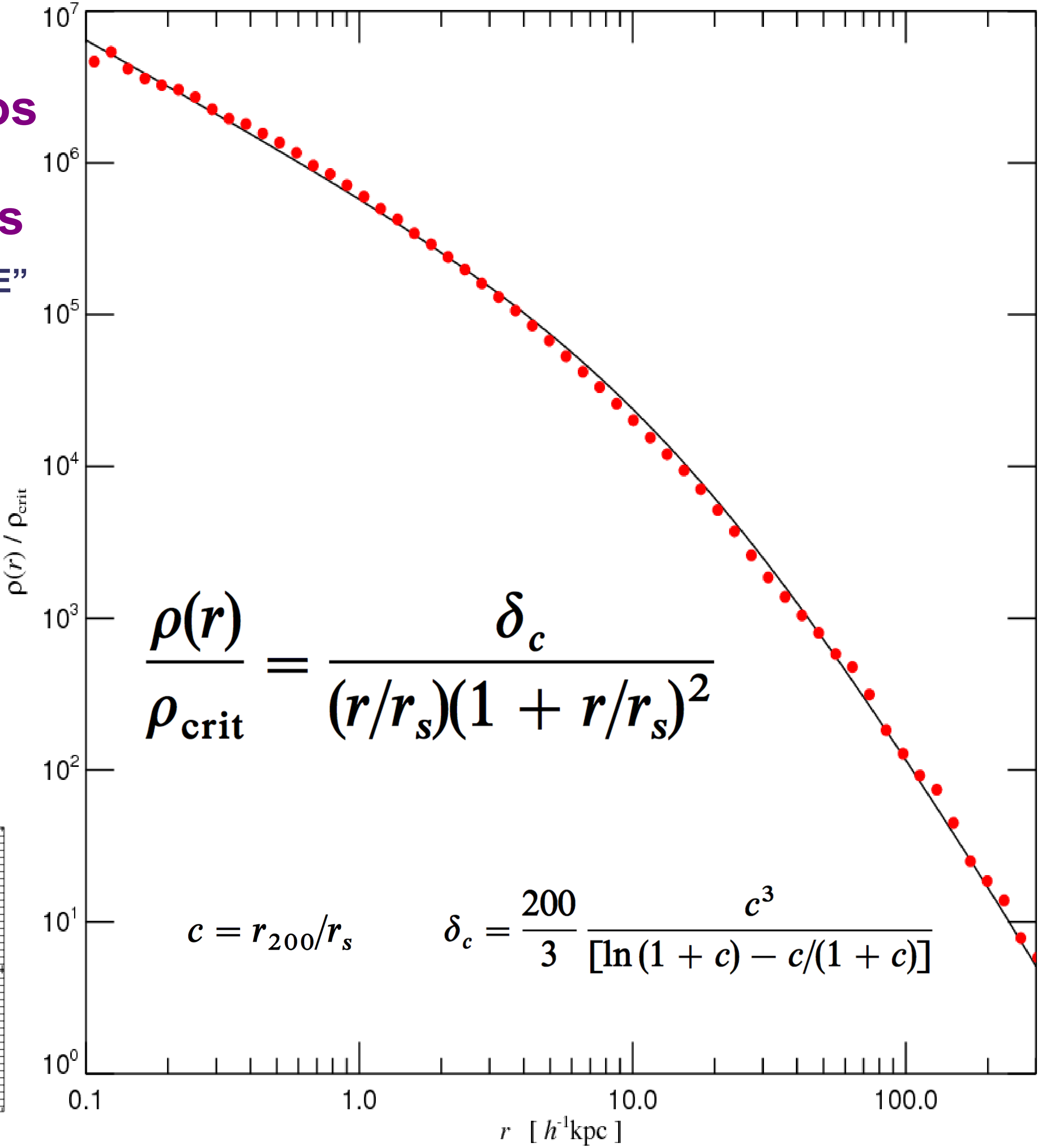
THE UNIVERSAL "NFW PROFILE"

Navarro, Frenk & White (1996, 1997)

already more than 10000 citations,

#2 and #1 most cited papers within astronomy/astrophysics in 1996/1997

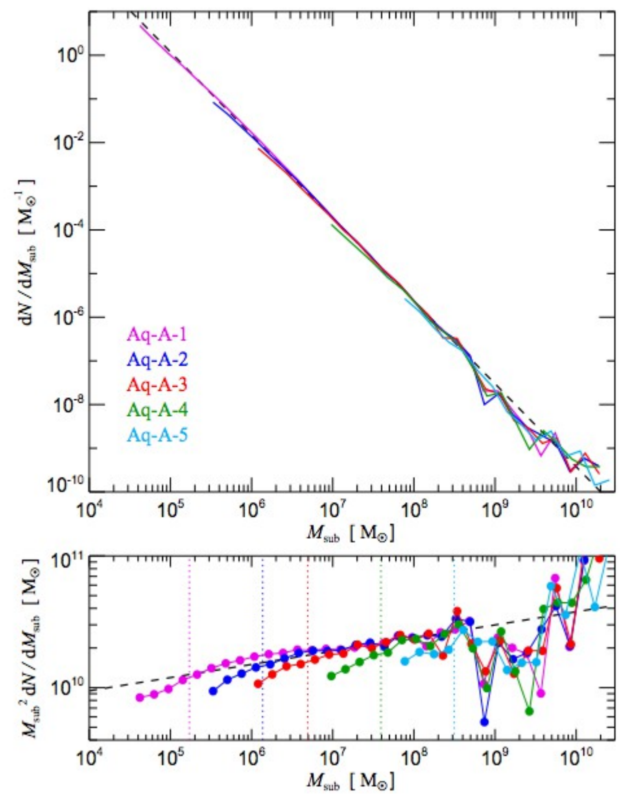




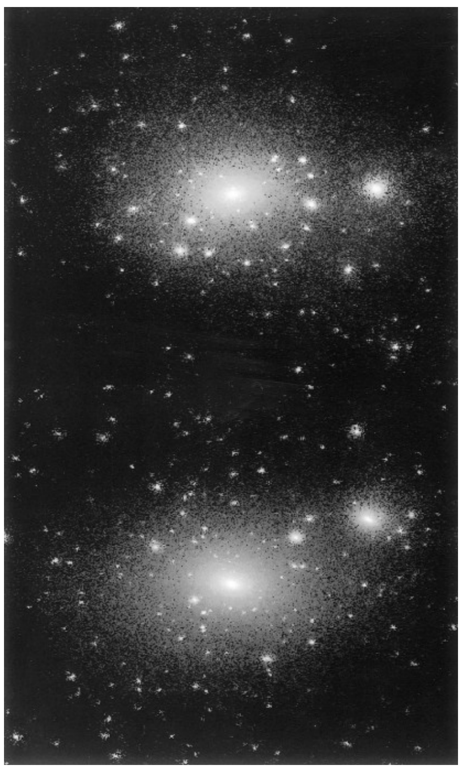
Cold dark matter halos are filled with a myriad of subhalos

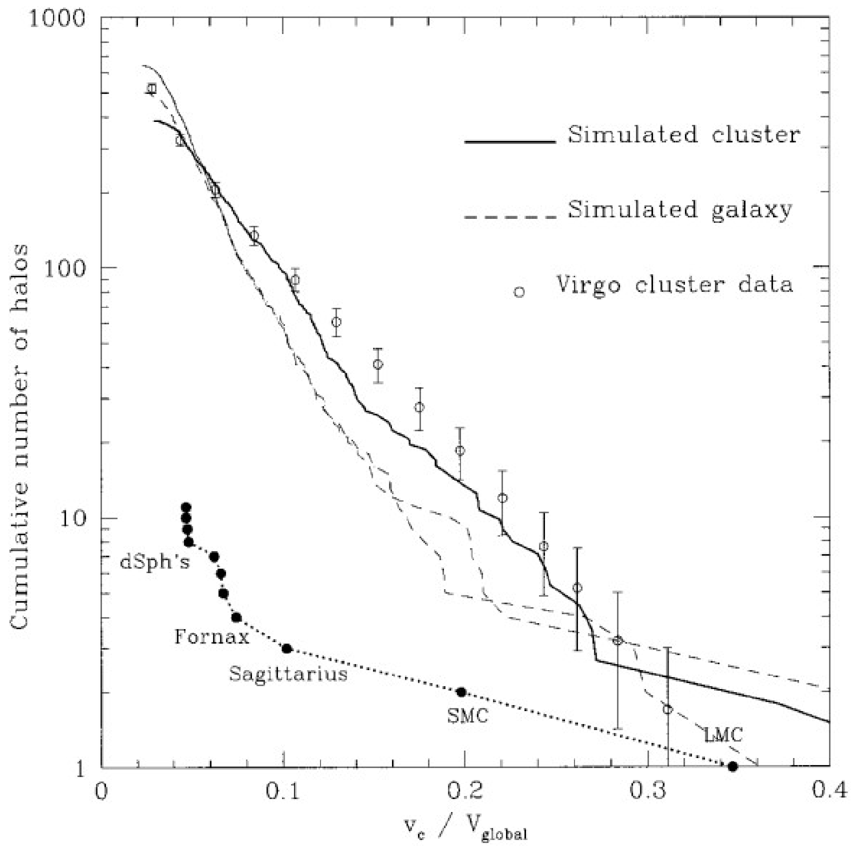
THE COMPLEX PHASE-SPACE OF DARK MATTER HALOS

Springel et al. (2008)



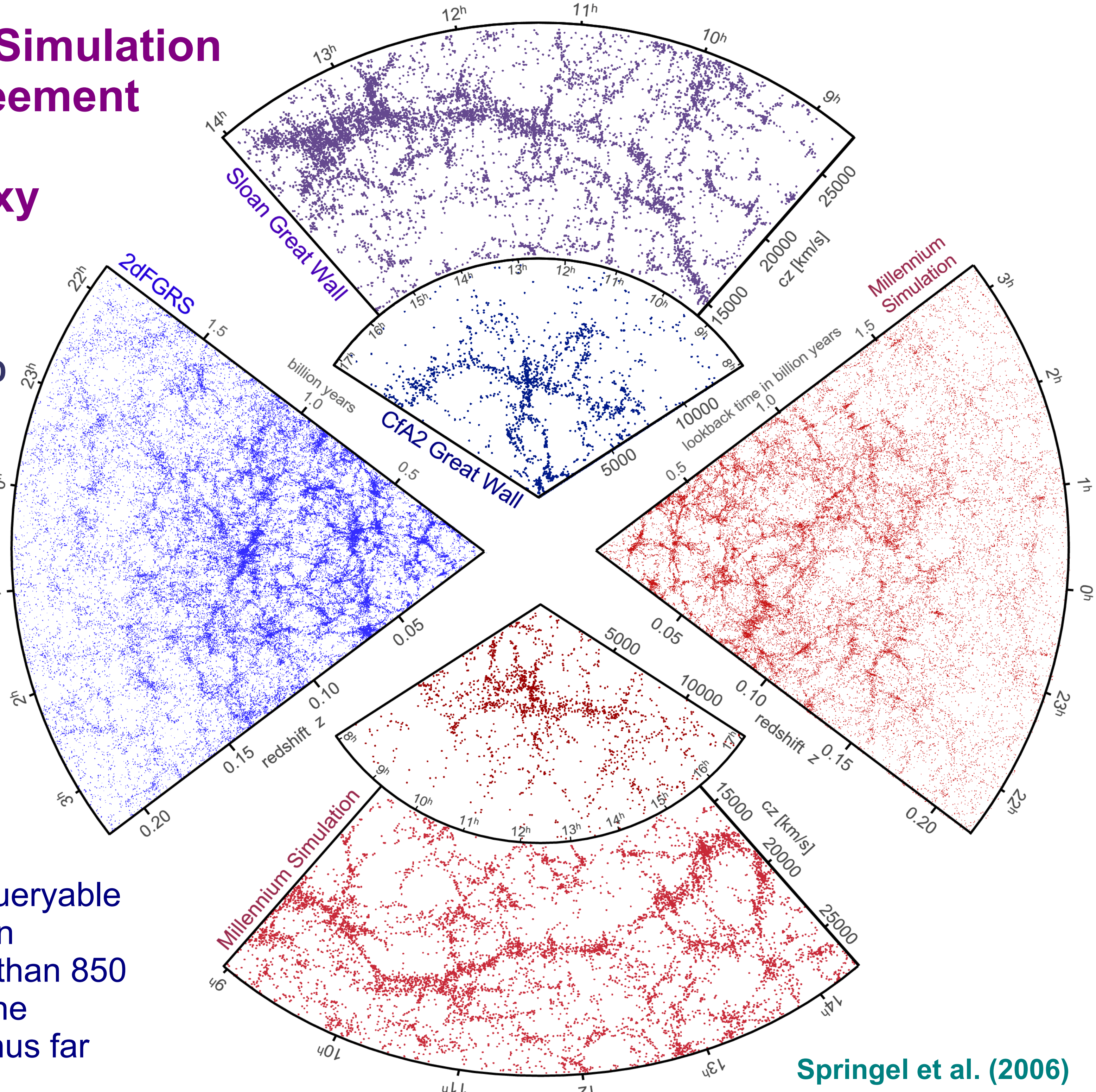
Moore et al. (1999)





The Millennium Simulation found good agreement of the predicted large-scale galaxy distribution with observations

VIRTUAL VS OBSERVED PIE DIAGRAMS

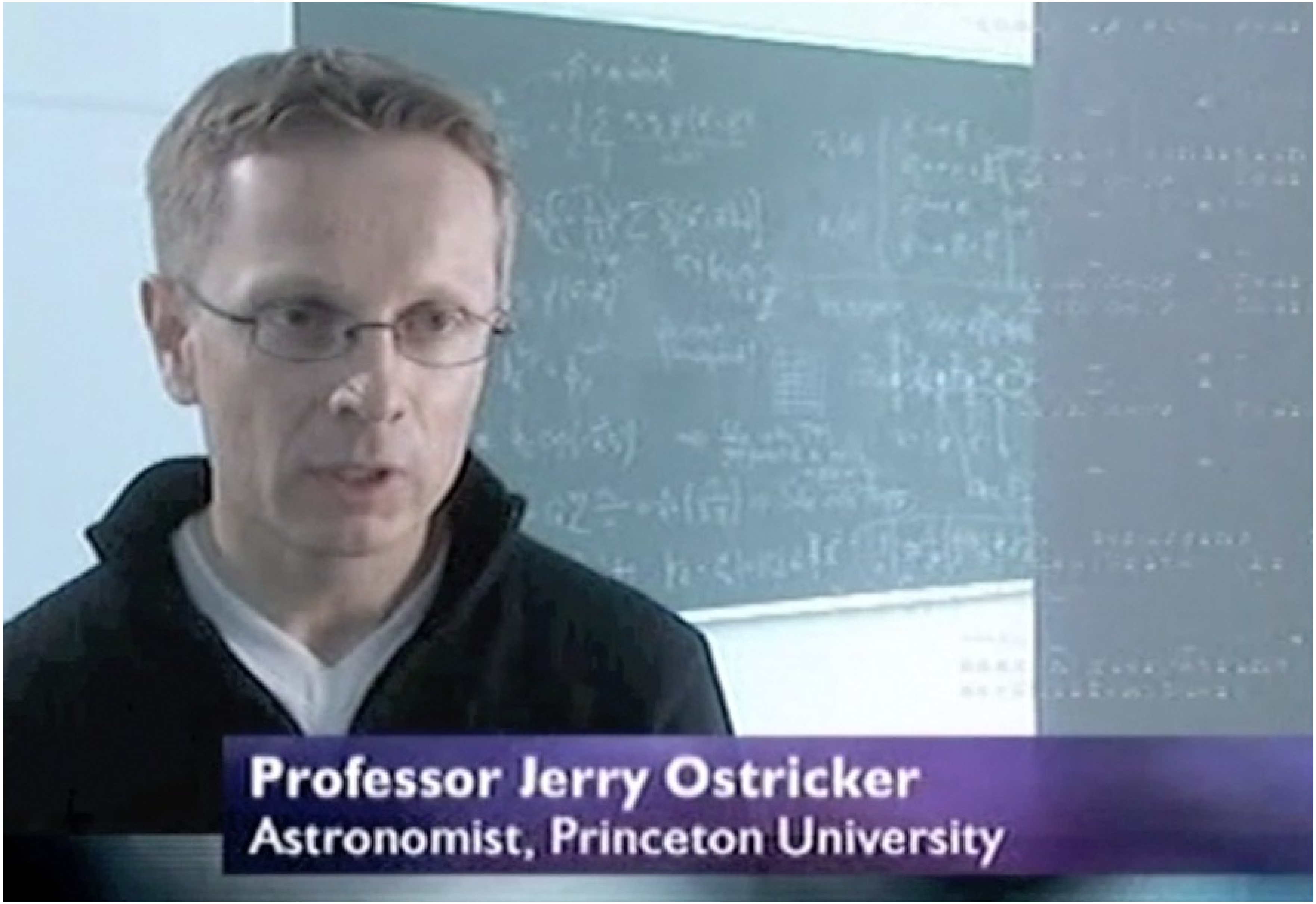


public access to SQL-queryable database with simulation predictions led to more than 850 publications based on the Millennium simulation thus far

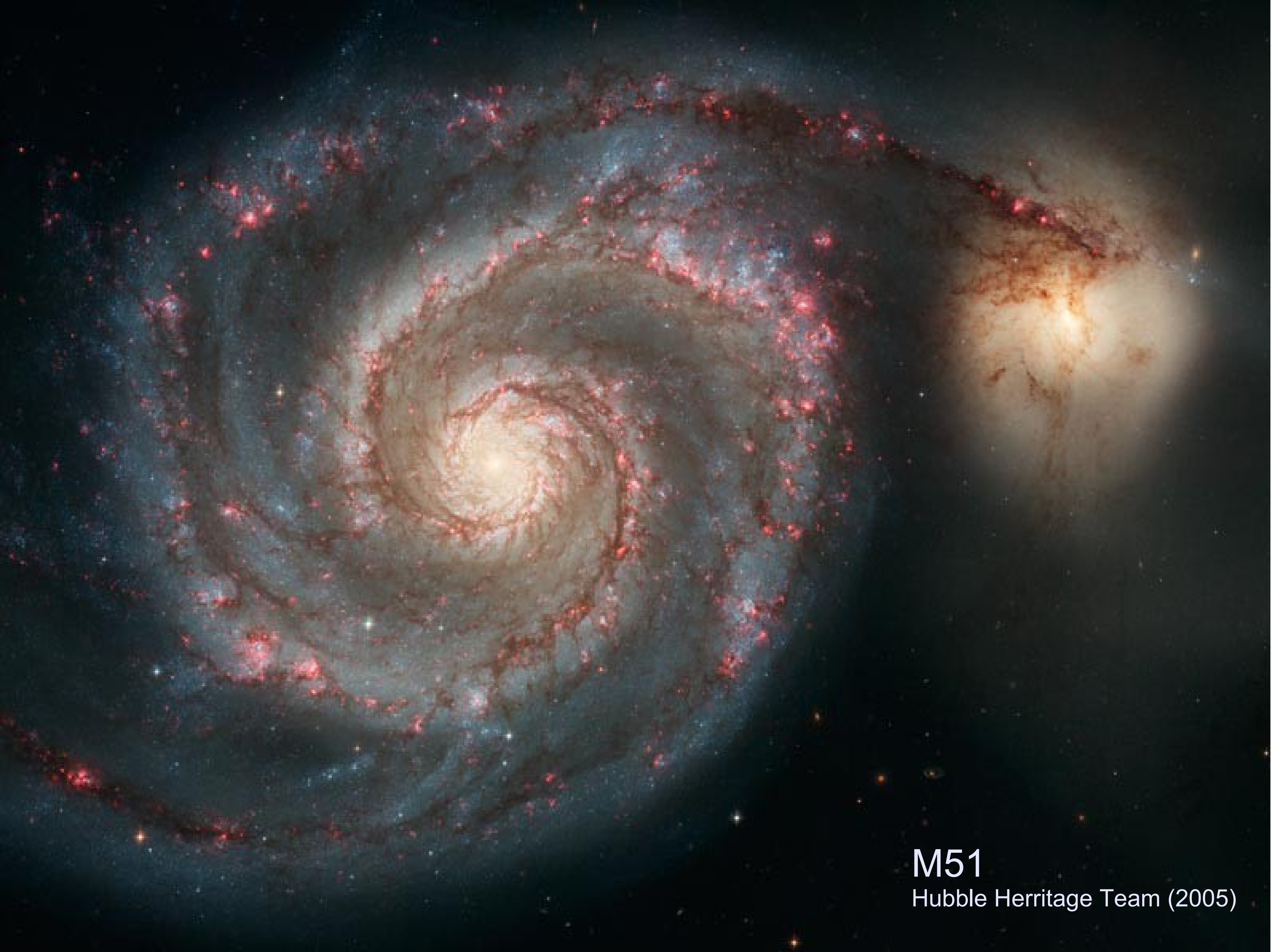
Springel et al. (2006)

This meant instant fame... :-)

BBC NEWSNIGHT, JUNE 2, 2005

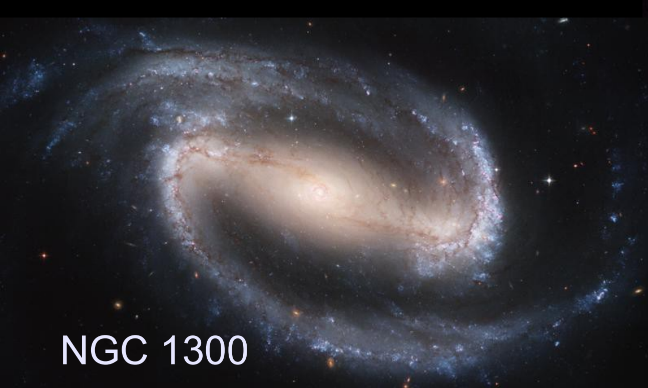


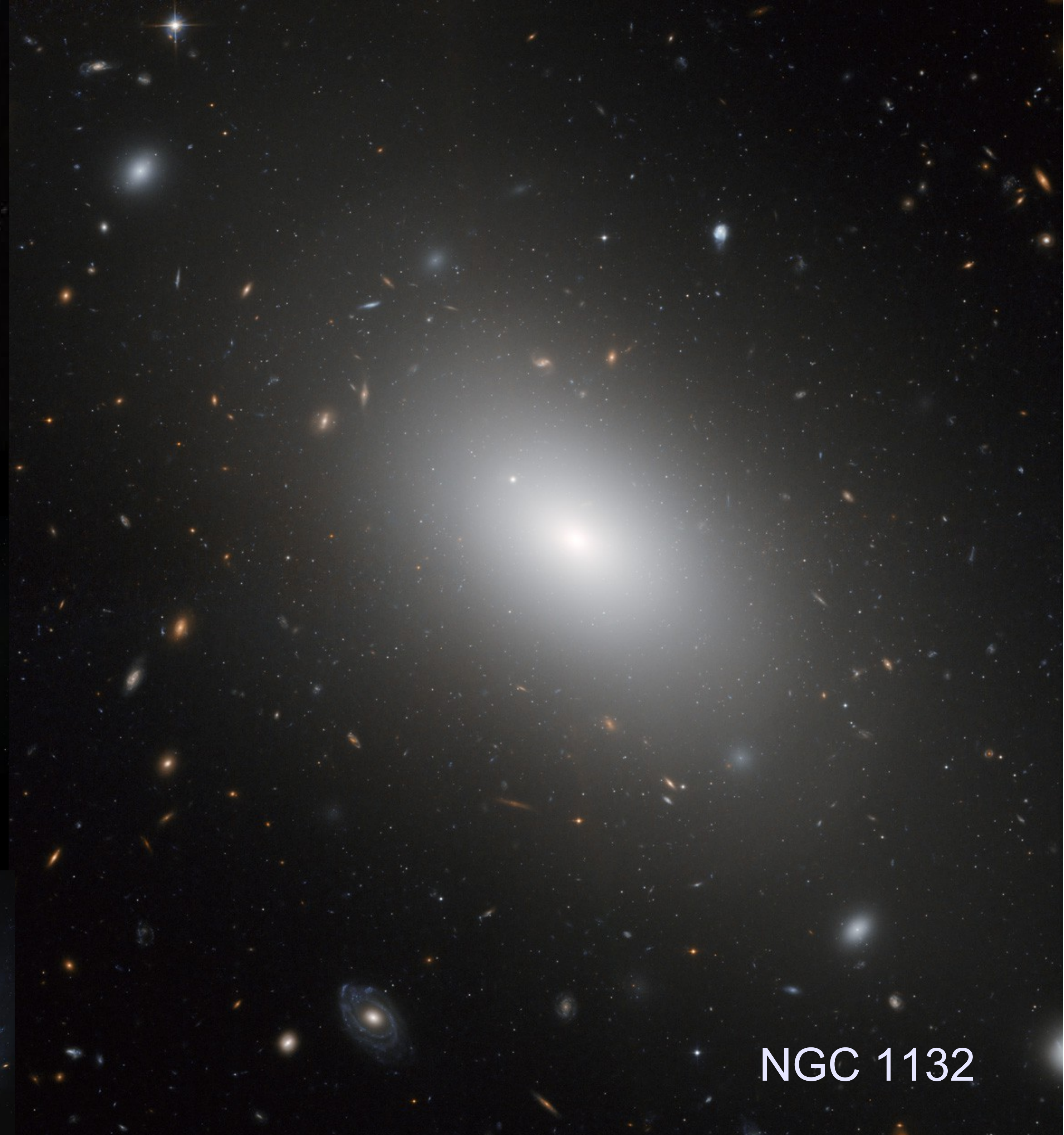
What is to be understood about galaxies?


M51
Hubble Herritage Team (2005)


Hoag's Object

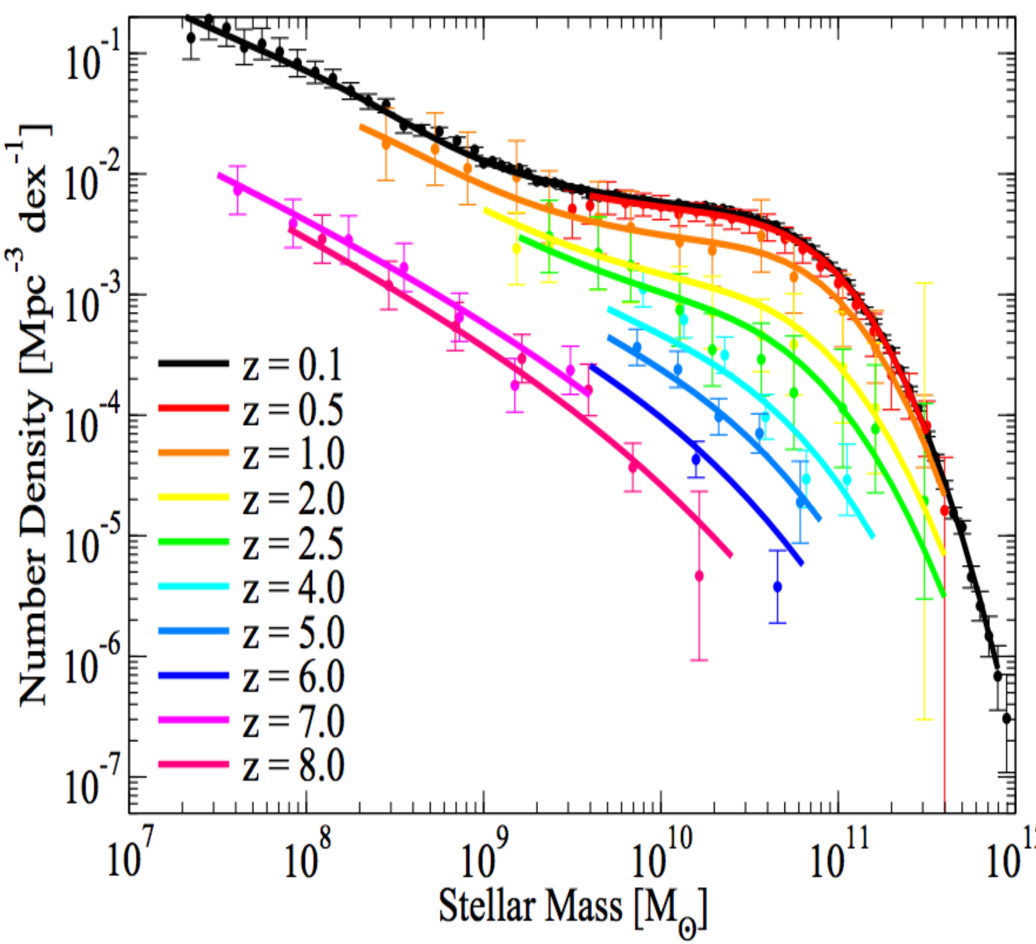

M104


NGC 1300

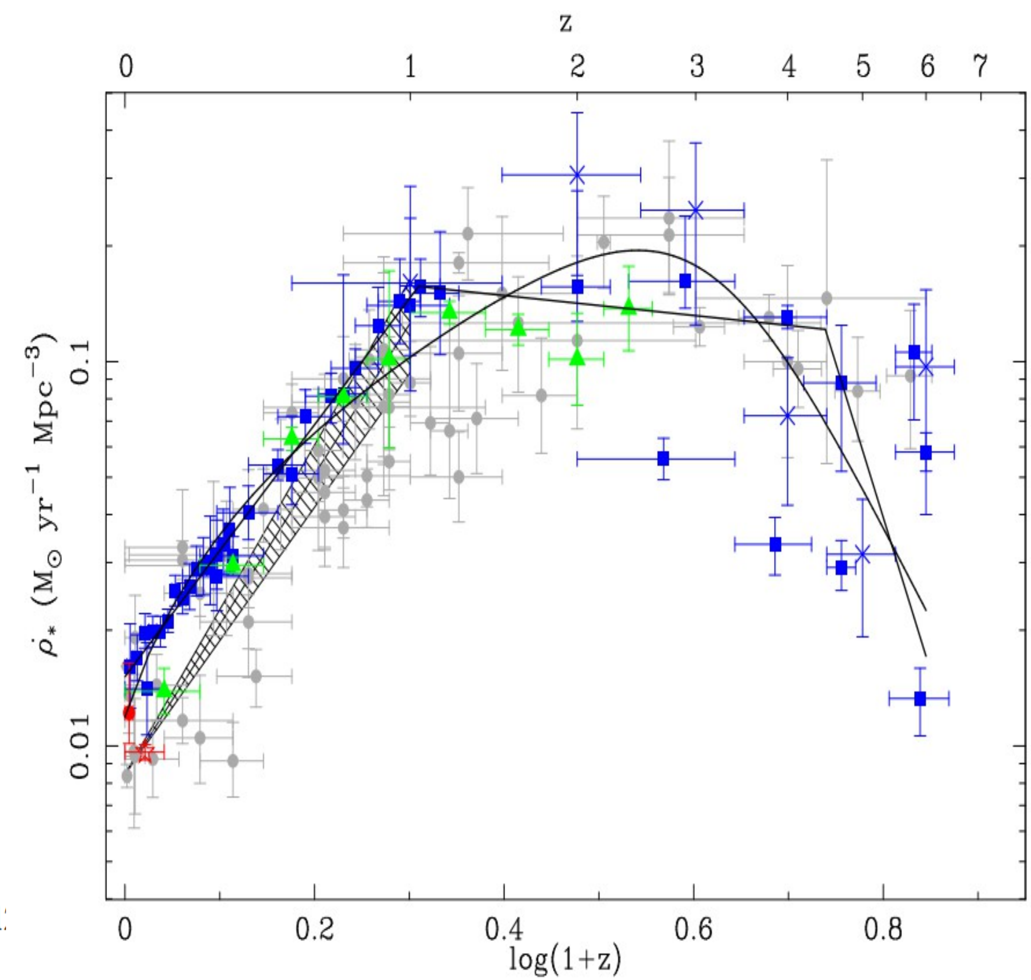

NGC 1132

Many statistical properties of galaxies and their history have now been accurately measured

GALAXY STELLAR MASS FUNCTION AND COSMIC STAR FORMATION HISTORY



Behroozi, Wechsler & Conroy (2013)



Hopkins & Beacom (2006)

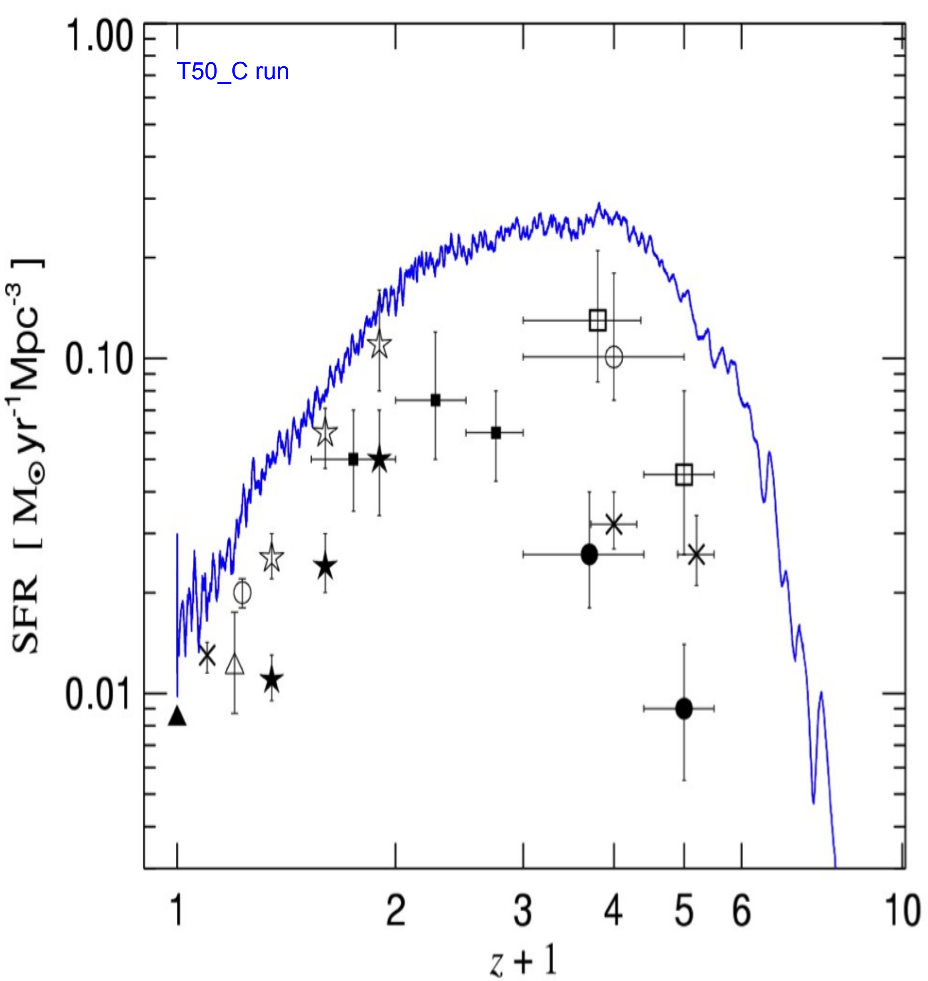
Traditional **failures** of hydrodynamical simulations of galaxy formation

The **overcooling problem** refers to excess star formation produced by hydrodynamic simulations on essentially all halo mass scales

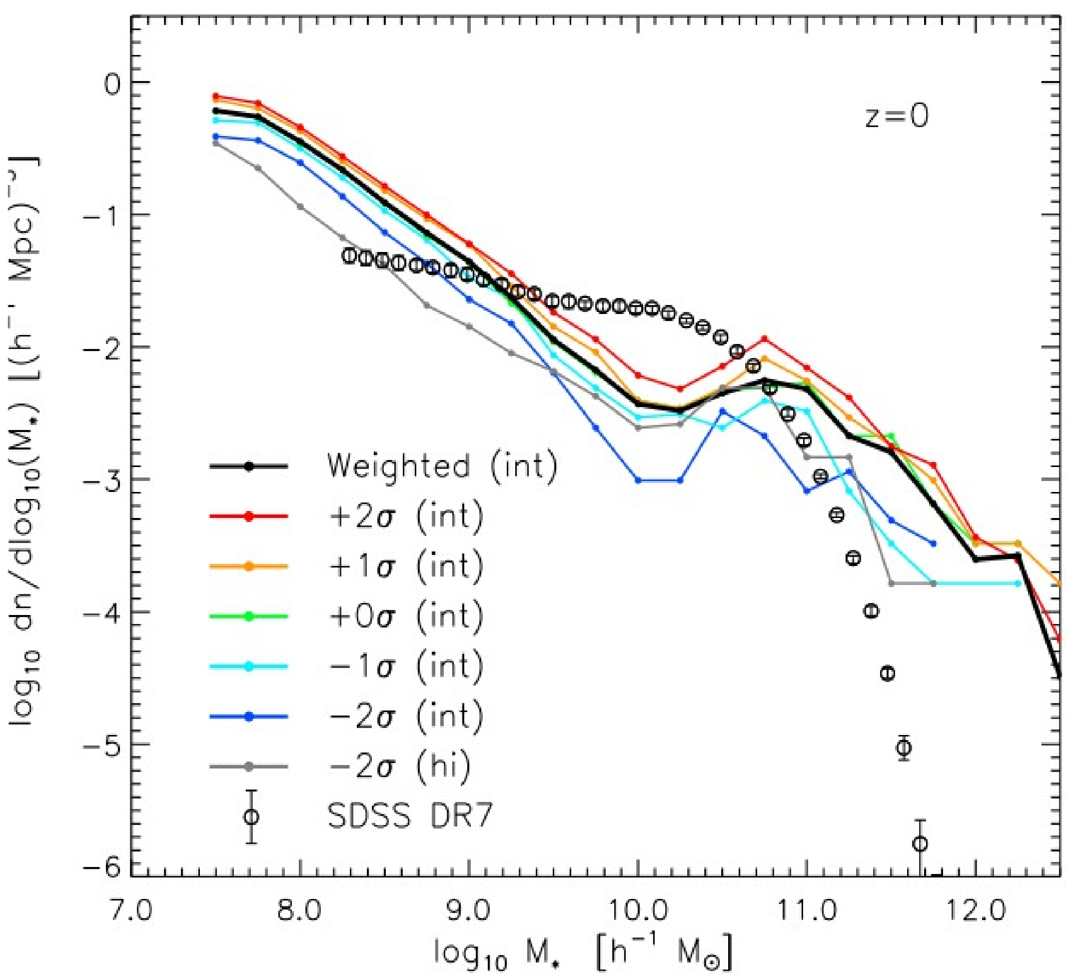
STAR FORMATION HISTORY AND LUMINOSITY FUNCTION FOR SIMULATIONS WITH WEAK/NO FEEDBACK

"Baryon conversion efficiency" without feedback excessively high (~ 30%-100%)

Springel & Hernquist (2003)



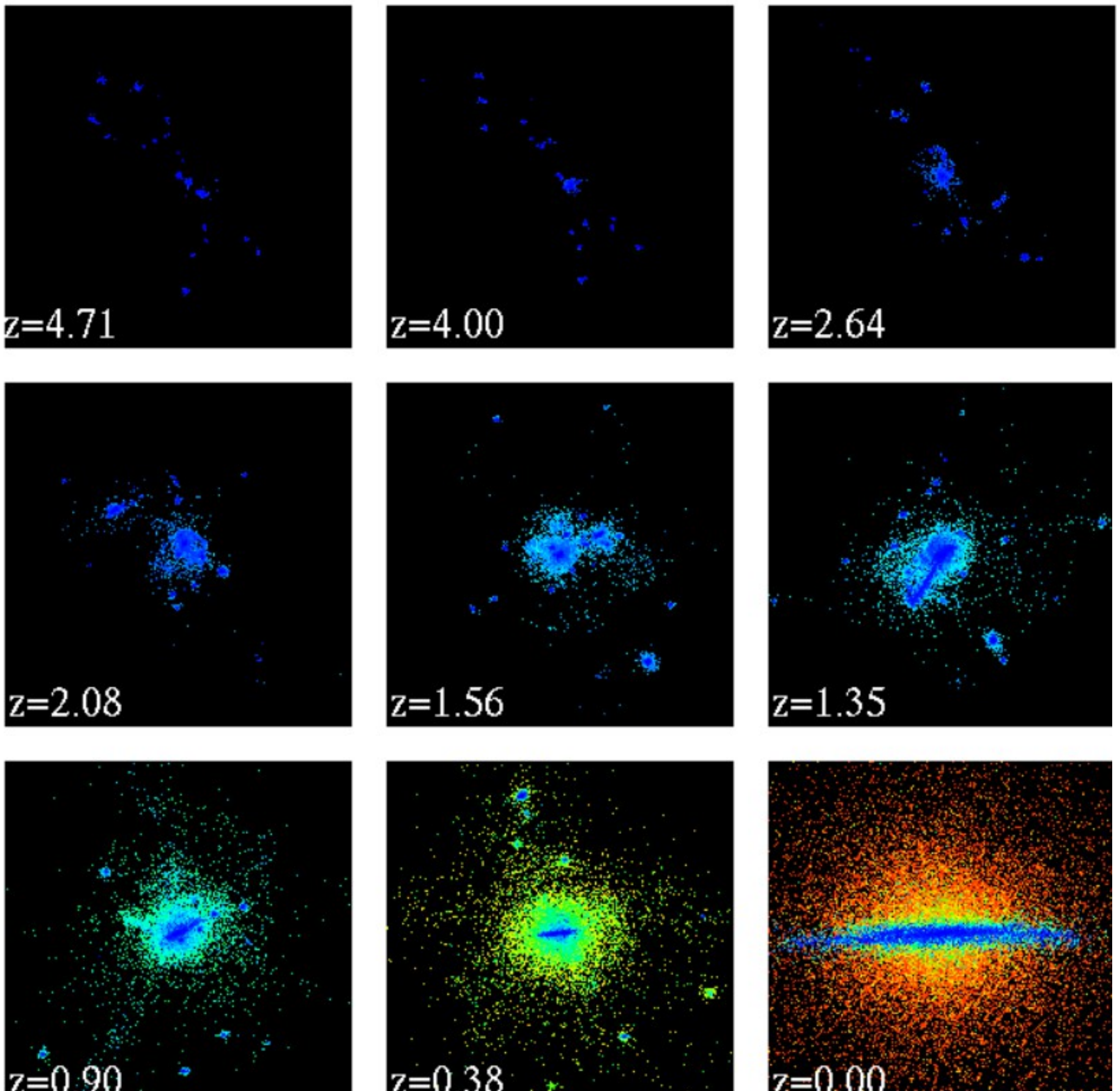
Crain et al. (2009)

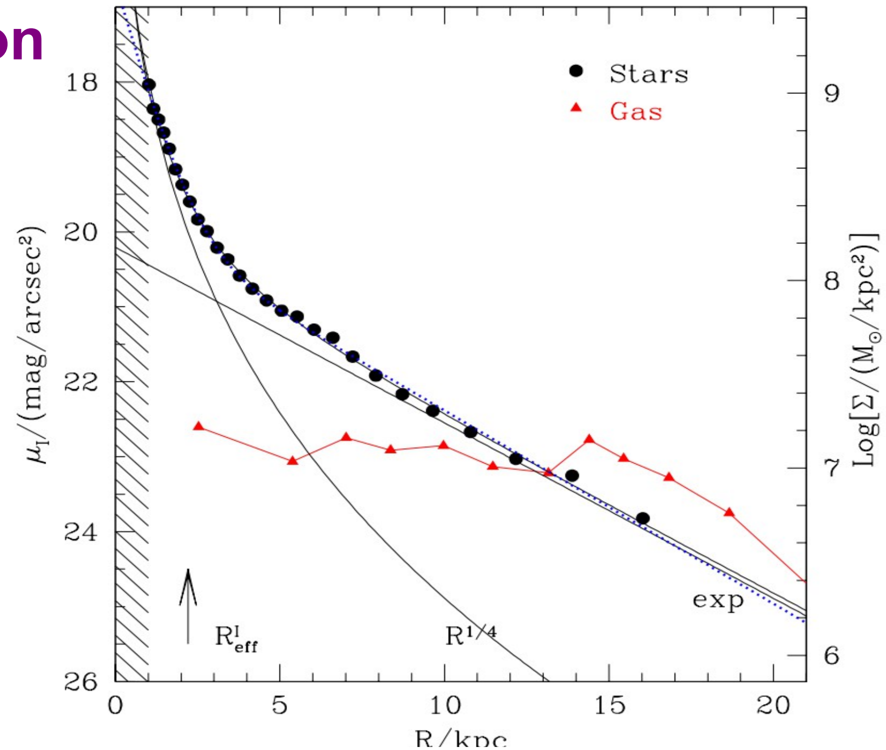


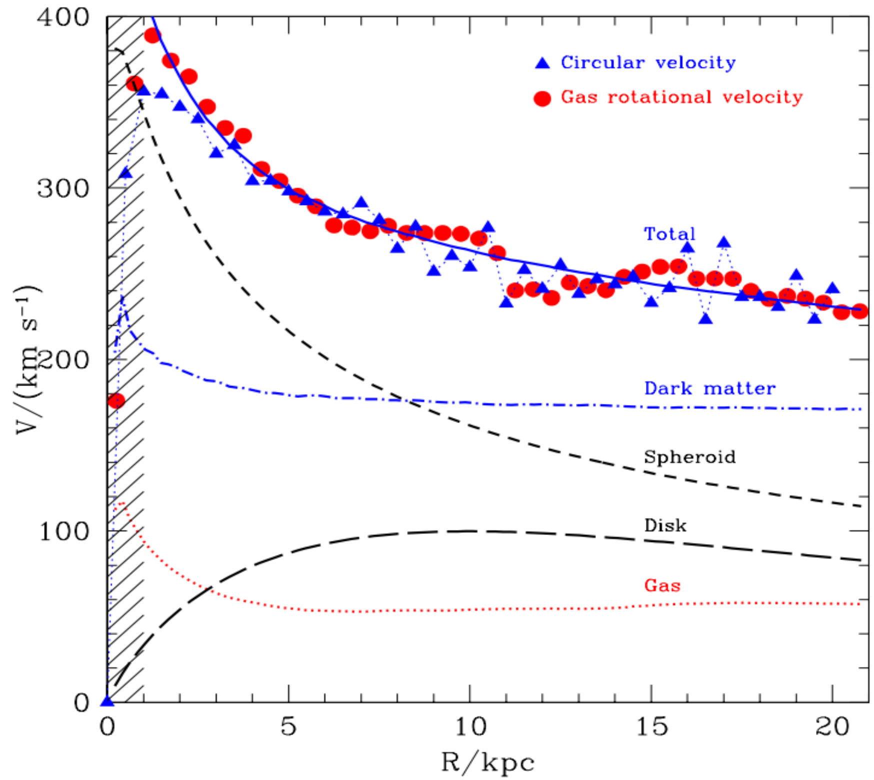
Massive bulges produce **unrealistic rotation curves** in simulations of disk galaxies

SPECIFIC ANGULAR MOMENTUM VS. CIRCULAR VELOCITY

Abadi et al. (2003)







The multifaceted need for **feedback**

Star formation in the interstellar medium (ISM) is surprisingly inefficient

THE GAS CONSUMPTION TIMESCALE OF STAR FORMATION

depletion time:

$$t_{\rm dep} \equiv M_{\rm gas}/\dot{M}_*$$

gravitational free-fall time:

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

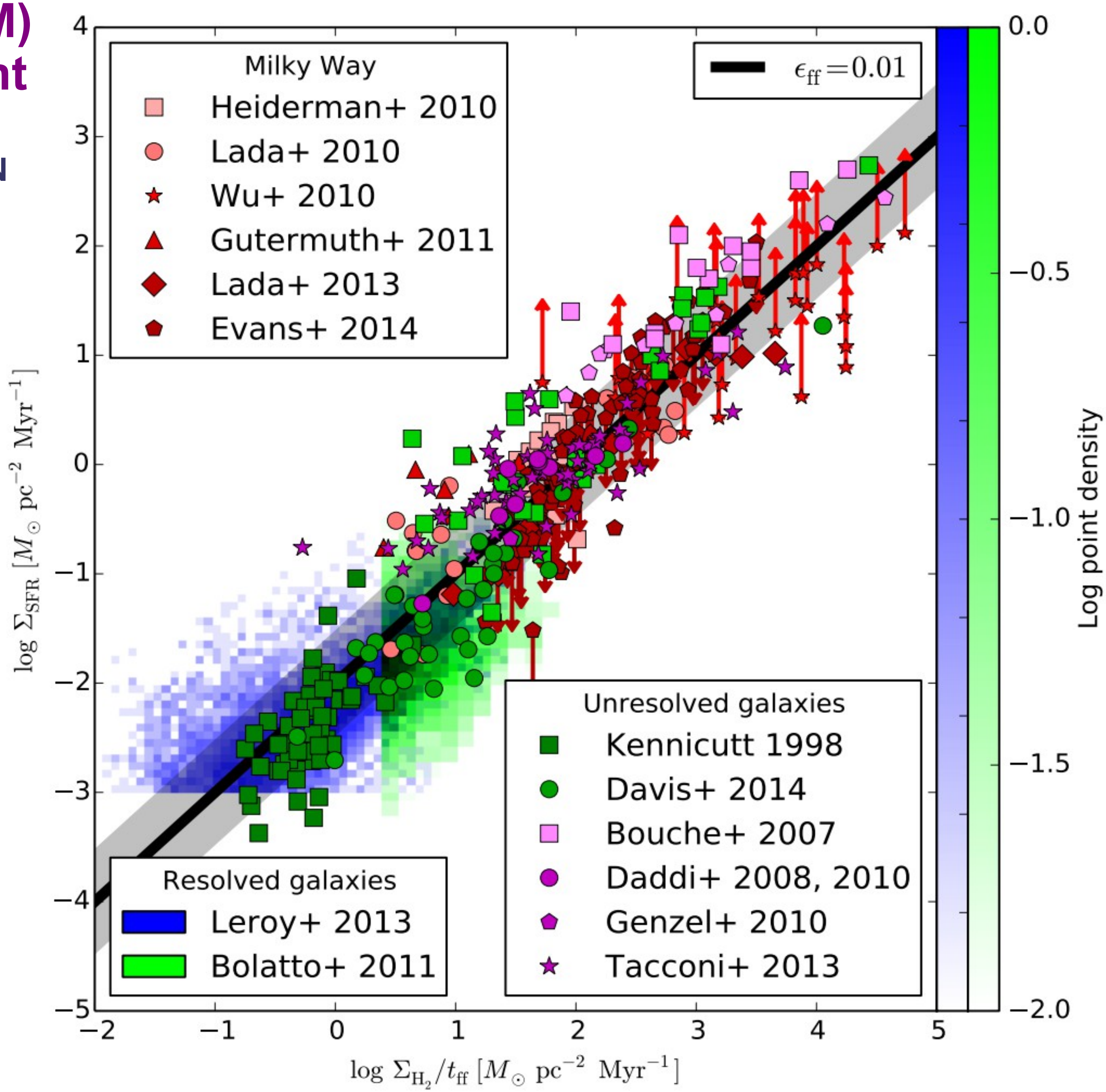
dimensionless "efficiency" of star formation:

$$\epsilon_{\rm ff} \equiv \frac{t_{\rm ff}}{t_{\rm dep}}$$

observed is:

$$\dot{\Sigma}_\star \simeq \epsilon_{\rm ff} \frac{\Sigma_{\rm H_2}}{t_{\rm ff}}$$

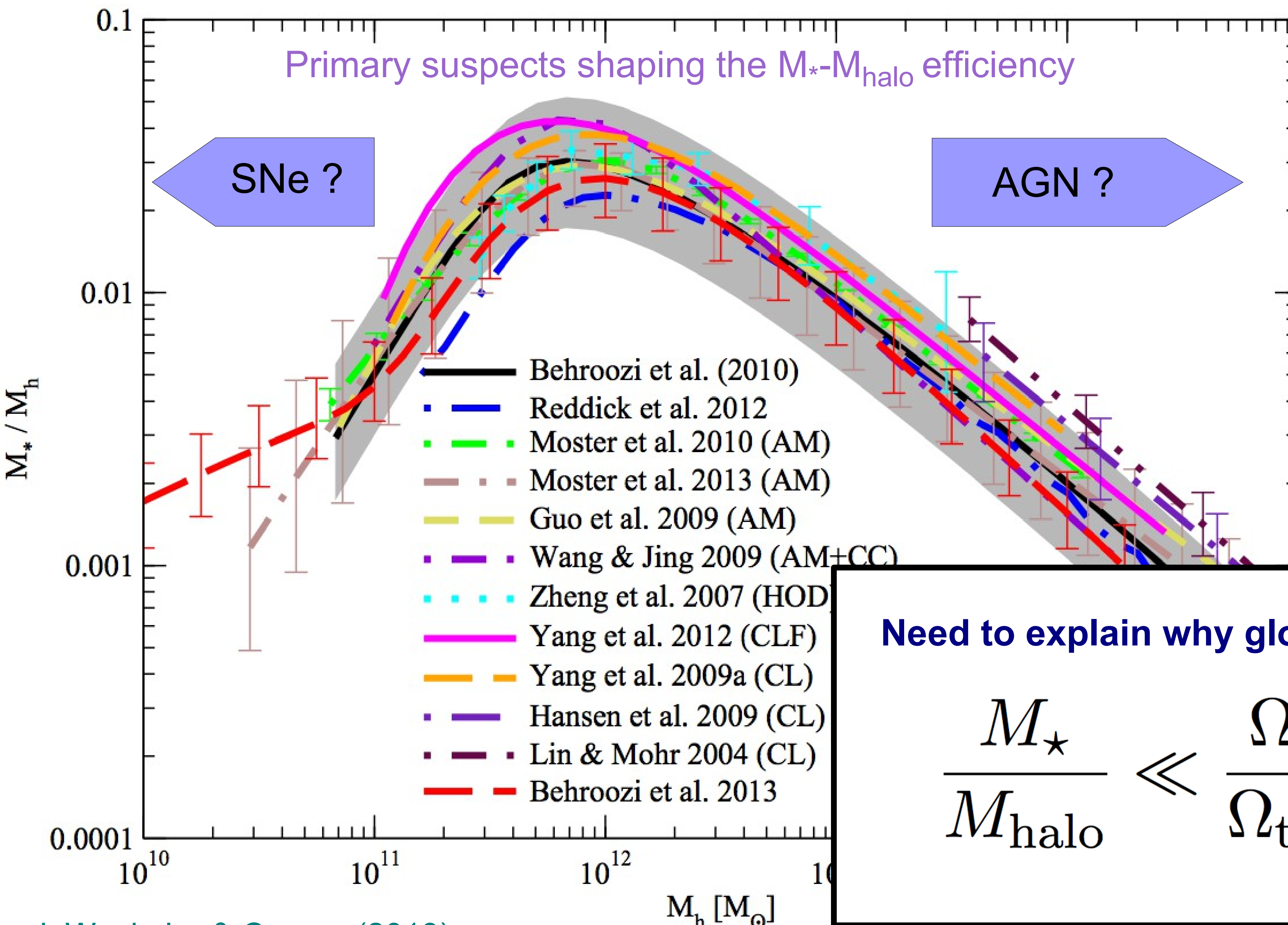
$$\epsilon_{\rm ff} \sim 0.01$$



Krumholz et al. (2014)

Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

MODULATION OF GLOBAL STAR FORMATION EFFICIENCY AS A FUNCTION OF HALO MASS



Need to explain why globally:

$$\frac{M_\star}{M_{\rm halo}} \ll \frac{\Omega_b}{\Omega_{\rm tot}}$$

Behroozi, Wechsler & Conroy (2013)

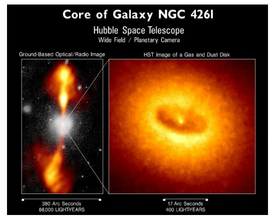
But what physics is responsible for feedback in the first place?

- **Supernova explosions (energy & momentum input)**

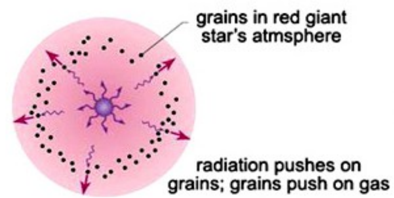
Kepler's Supernova

Bubble Nebula

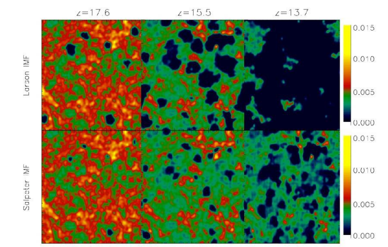
- **Stellar winds**



- **AGN activity**

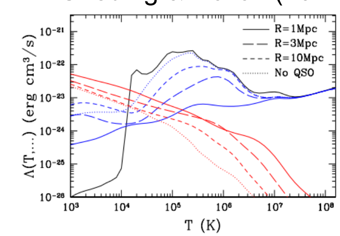


Ciardi al. (2003)



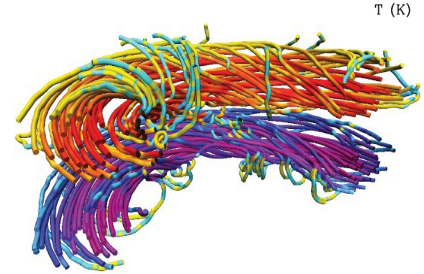
- **Radiation pressure on dust**
- **Photoionizing UV background and Reionization**

Gneding & Hollon (2012)

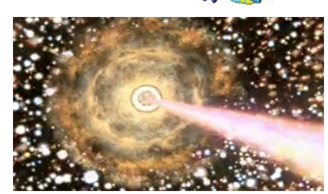


- **Modification of cooling through local UV/X-ray flux**
- **Photoelectric heating**

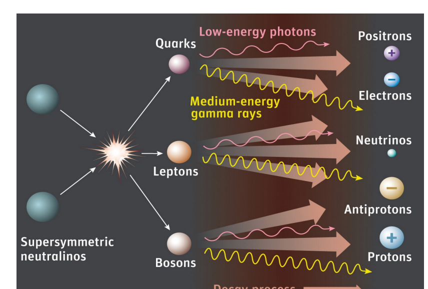
- **Cosmic ray pressure**



- **Magnetic pressure and MHD turbulence**

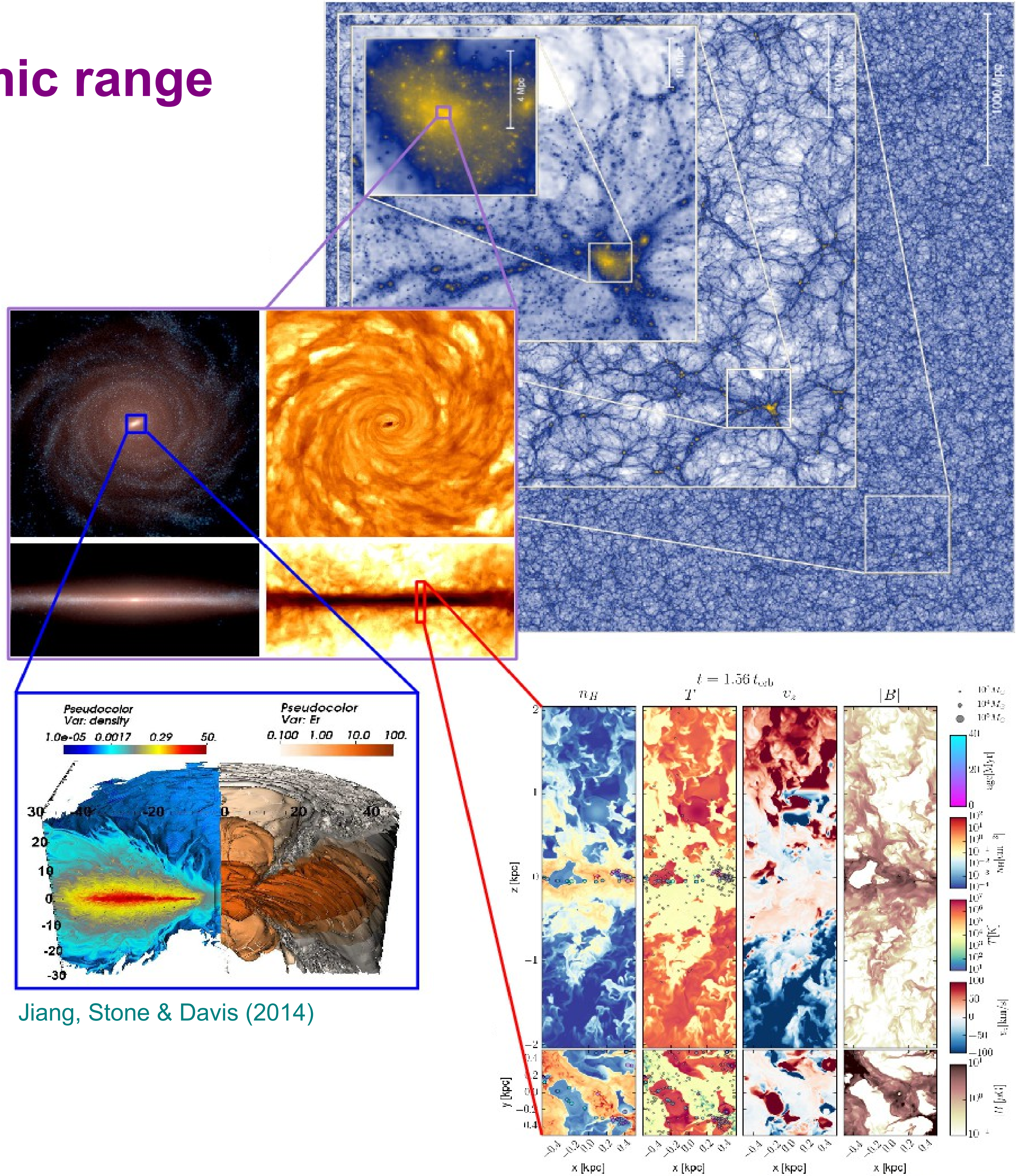


- **TeV-blazar heating of low density gas**



- **Exotic physics (decaying dark matter particles, etc.)**

The dynamic range challenge



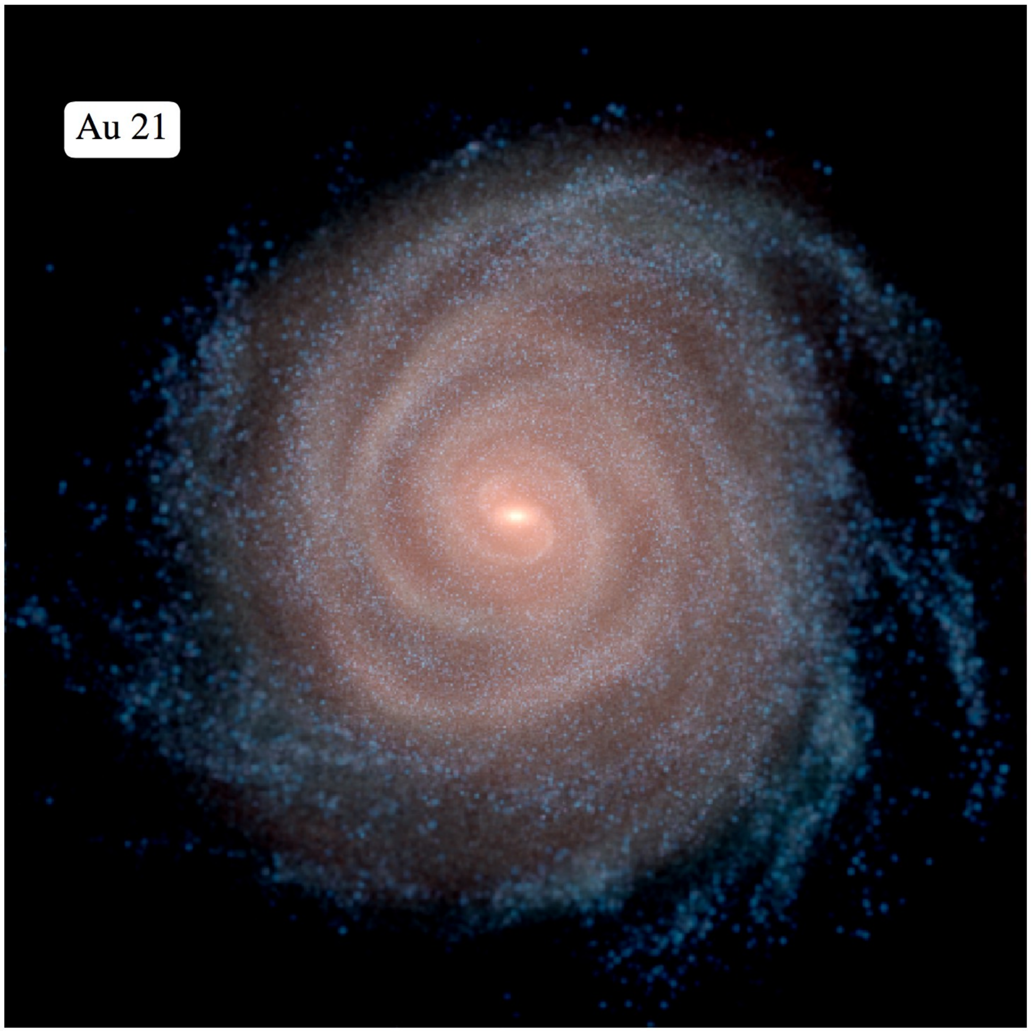
Angulo et al. (2012)

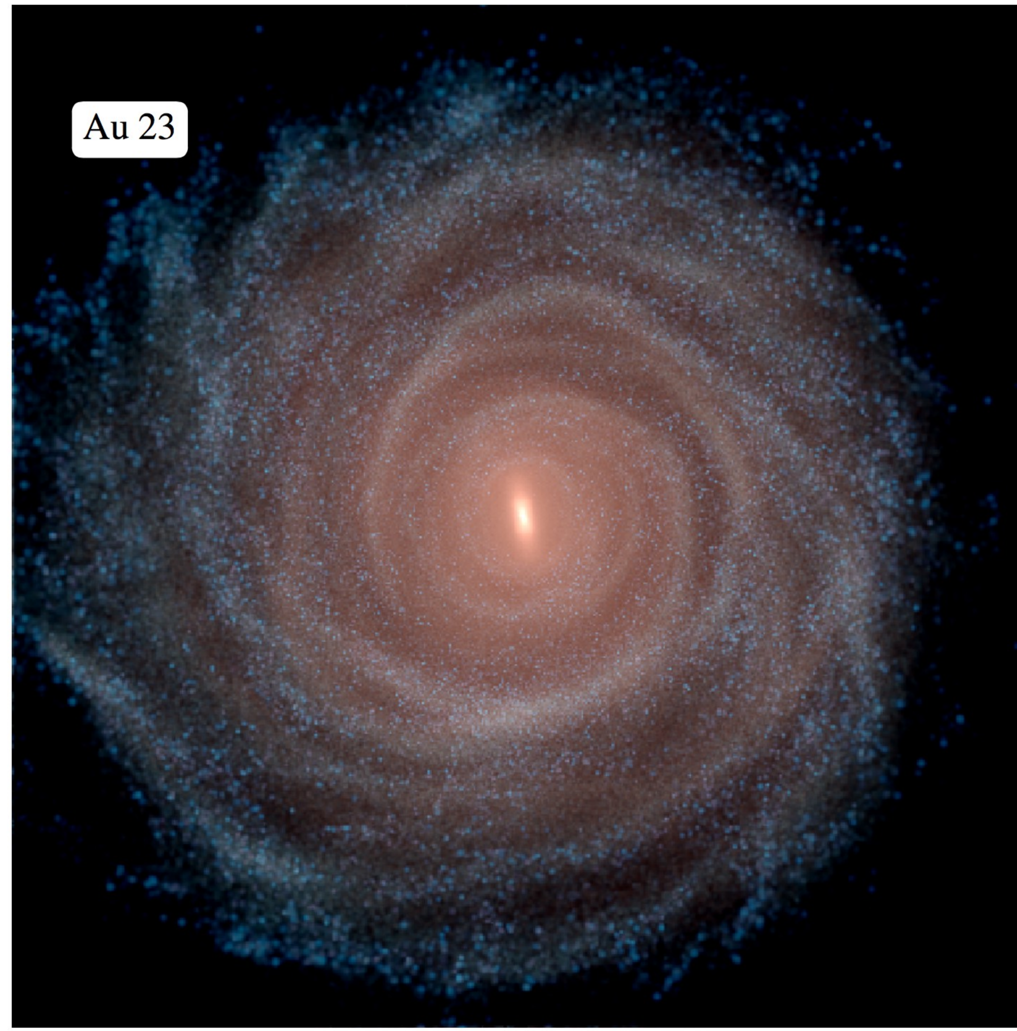
Grand et al. (2016)

Jiang, Stone & Davis (2014)

Kim & Ostriker (2016)

Recent progress – finally disk galaxies!





Grand, Springel, Pakmor, et al. (2017)

Progress on several fronts led to successful disk galaxy formation simulations

KEY REQUIREMENTS FOR ENABLING DISK FORMATION WITH SMALL BULGES

- ***Much stronger feedback physics*, kicking in already at high redshift**
- **Higher numerical resolution**
- **More accurate numerical methods**

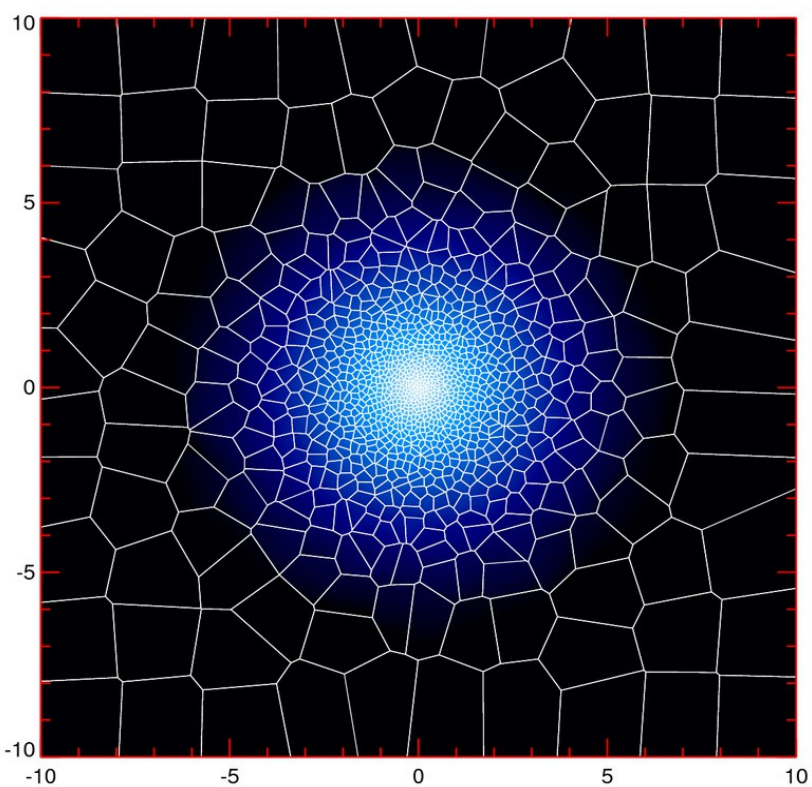
Big grain of salt:

Radically different assumptions about feedback can yield similar results.

The **moving-mesh hydrodynamics AREPO** is ideally matched to cosmology

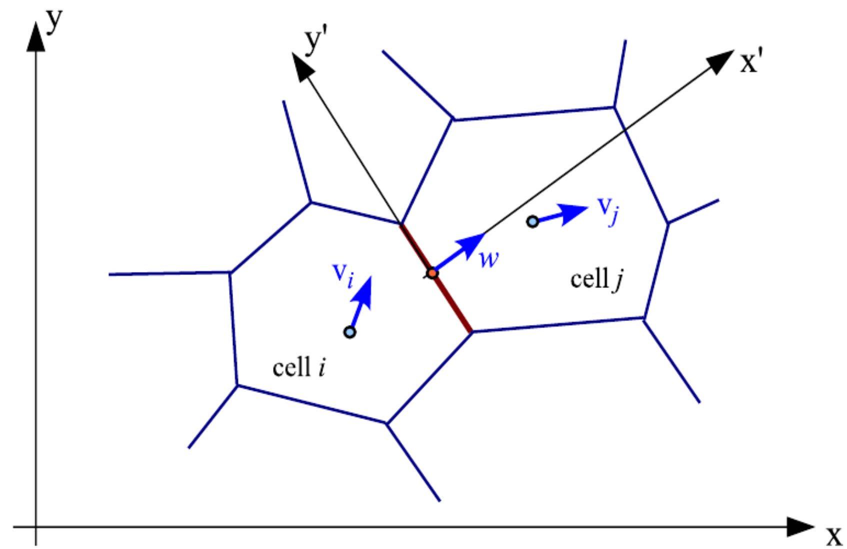
PRINCIPAL ADVANTAGES

- Low numerical viscosity, very low advection errors
- Full adaptivity and manifest Galilean invariance
- Makes larger timesteps possible in supersonic flows
- Crucial accuracy improvement over SPH technique

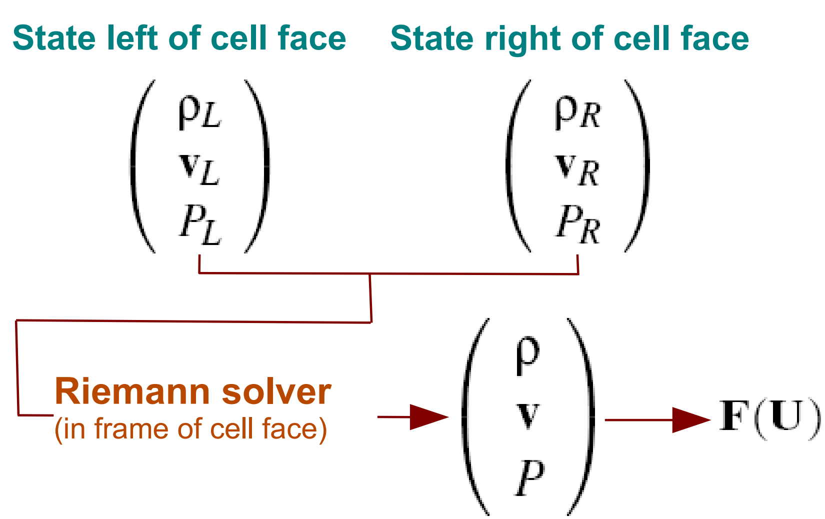


Springel (2010)

Sketch of flux calculation

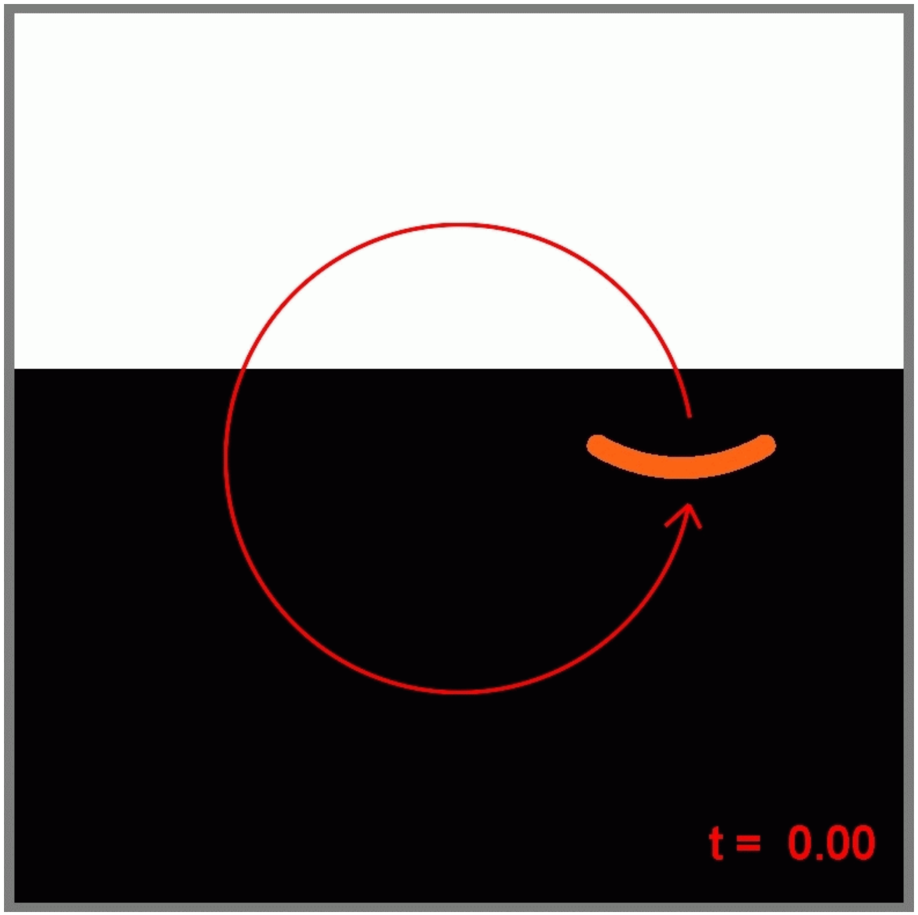


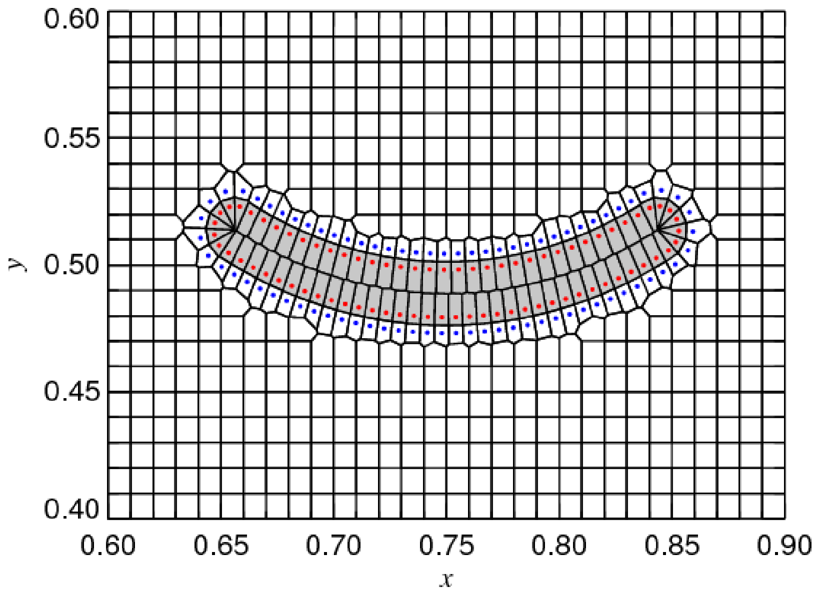
The motion of the mesh generators uniquely determines the motion of all cell boundaries

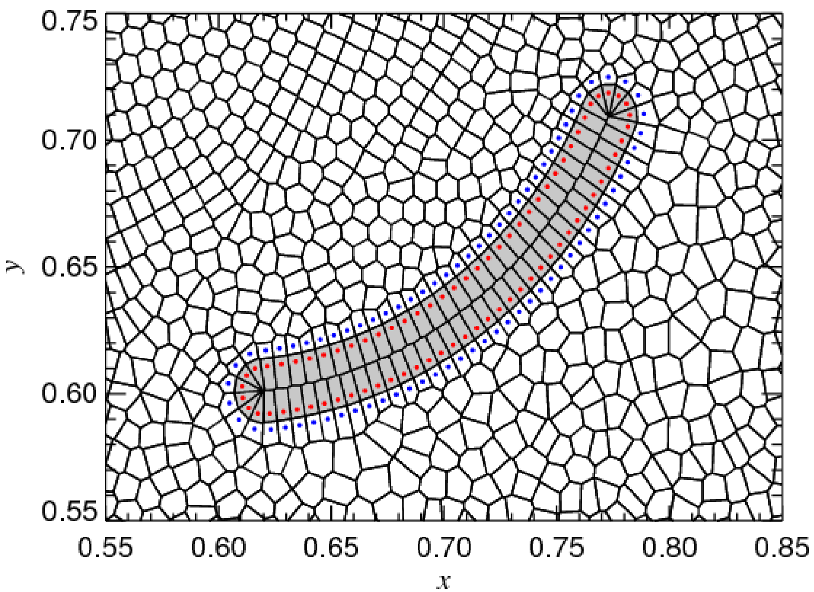


The moving-mesh approach can also be used to realize arbitrarily shaped, moving boundaries

STIRRING A COFFEE MUG







Springel (2010)

Galaxy formation physics for in the Illustris simulations

Cooling and metal enrichment

- Nine elements followed independently
- Mass and metal loss of stars treated continuously over time based on stellar population synthesis models (similar to Wirsma et al. 2009)
- Ionization balance and cooling from H and He followed with direct chemical network (Katz et al. 1996)
- Metal line cooling added through CLOUDY lookup tables in density, temperature and redshift
- Simple self-shielding correction (Rahmati et al. 2013)

Star formation and winds

- Variant of Springel & Hernquist (2003)
- Cold dense gas stabilized by an ISM equation of state
- Winds are phenomenologically introduced, with an energy given as a fixed fraction of the supernova energy
- The wind velocity is variable, the mass flux follows for energy-driven winds
- Fiducial model scales wind with local dark matter velocity dispersion
- Winds are launched outside of star-forming gas, and metal-loading can be reduced if desired

Black hole accretion and feedback

- Black hole seeding and accretion model (Springel et al. 2005)
- Quasar-mode feedback for high accretion rates
- Radio-mode feedback for low accretion rates based on bubble-heating model (Sijacki et al. 2006)
- Radiative AGN feedback (change in heating/cooling due to variation of UVB) in proximity to an active black hole
- Reduction of accretion rate in low-pressure/low-density regimes to avoid large hot bubbles around black holes in quiescent state
- Black holes tied to potential minimum of halos

Vogelsberger et al. (2013)

The Illustris Simulation

$3 \times 1820^3 = 18.1 \times 10^9$ cells / particles / tracers

106.5 Mpc boxsize

$M_{baryon} = 1.26 \times 10^6\ M_\odot$
$M_{dm} = 6.26 \times 10^6\ M_\odot$

~50 pc smallest cell size

16 (+3) million CPU hours

www.illustris-project.org

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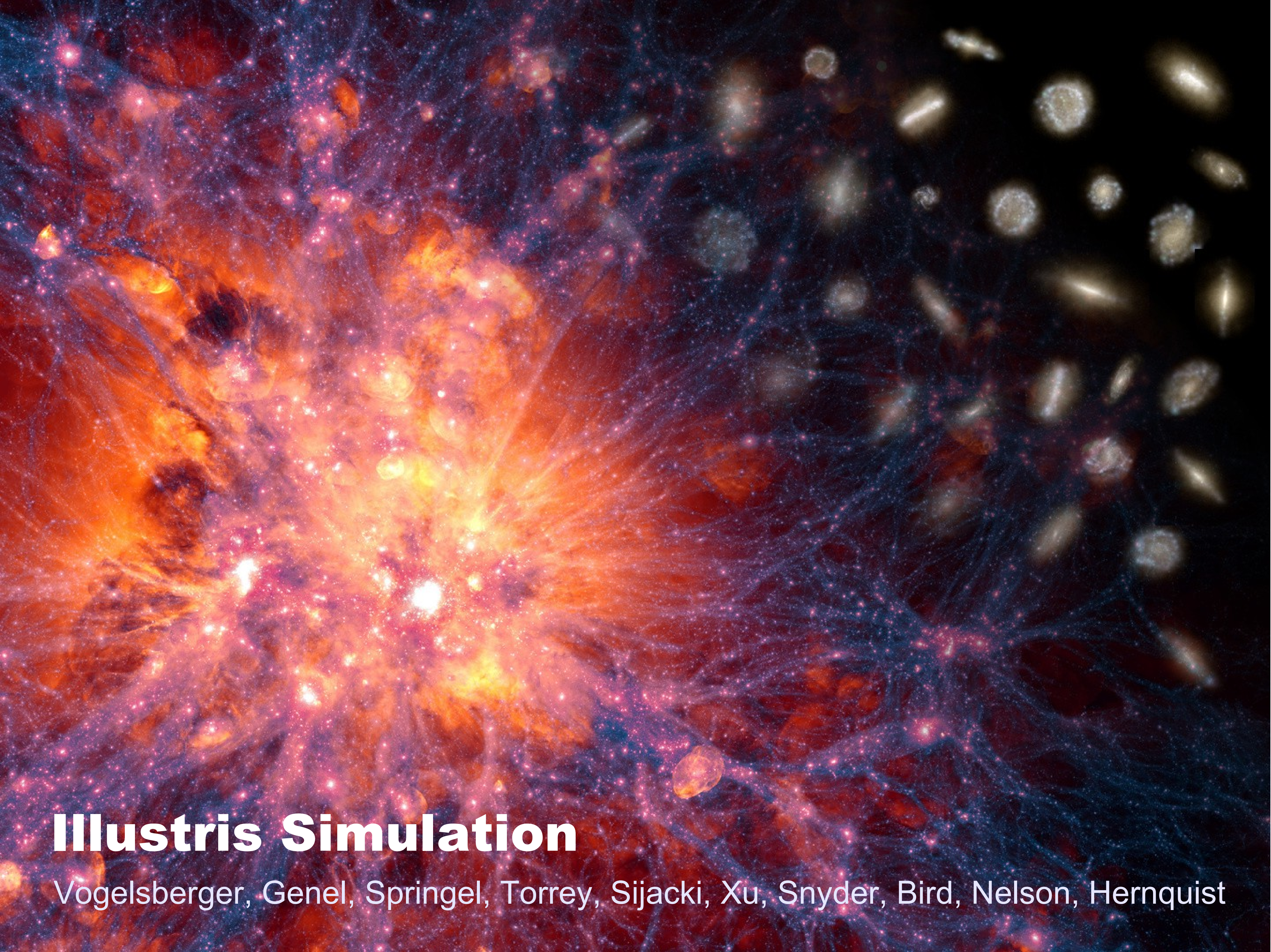
- ***Properties of galaxies reproduced by a hydrodynamic simulation***
  Vogelsberger et al., 2014, Nature, 509, 177
- ***Introducing the Illustris Project: Simulating the coevolution of dark and visible matter in the Universe***
  Vogelsberger et al., 2014, submitted to MNRAS, arXiv:1405.2921
- ***The Illustris Simulation: the evolution of galaxy populations across cosmic time***
  Genel et al., 2014, submitted to MNRAS, arXiv:1405.3749)
- ***Damped Lyman-alpha absorbers as a probe of stellar feedback***
  Bird et al., 2014, submitted to MNRAS, arXiv:1405.3994

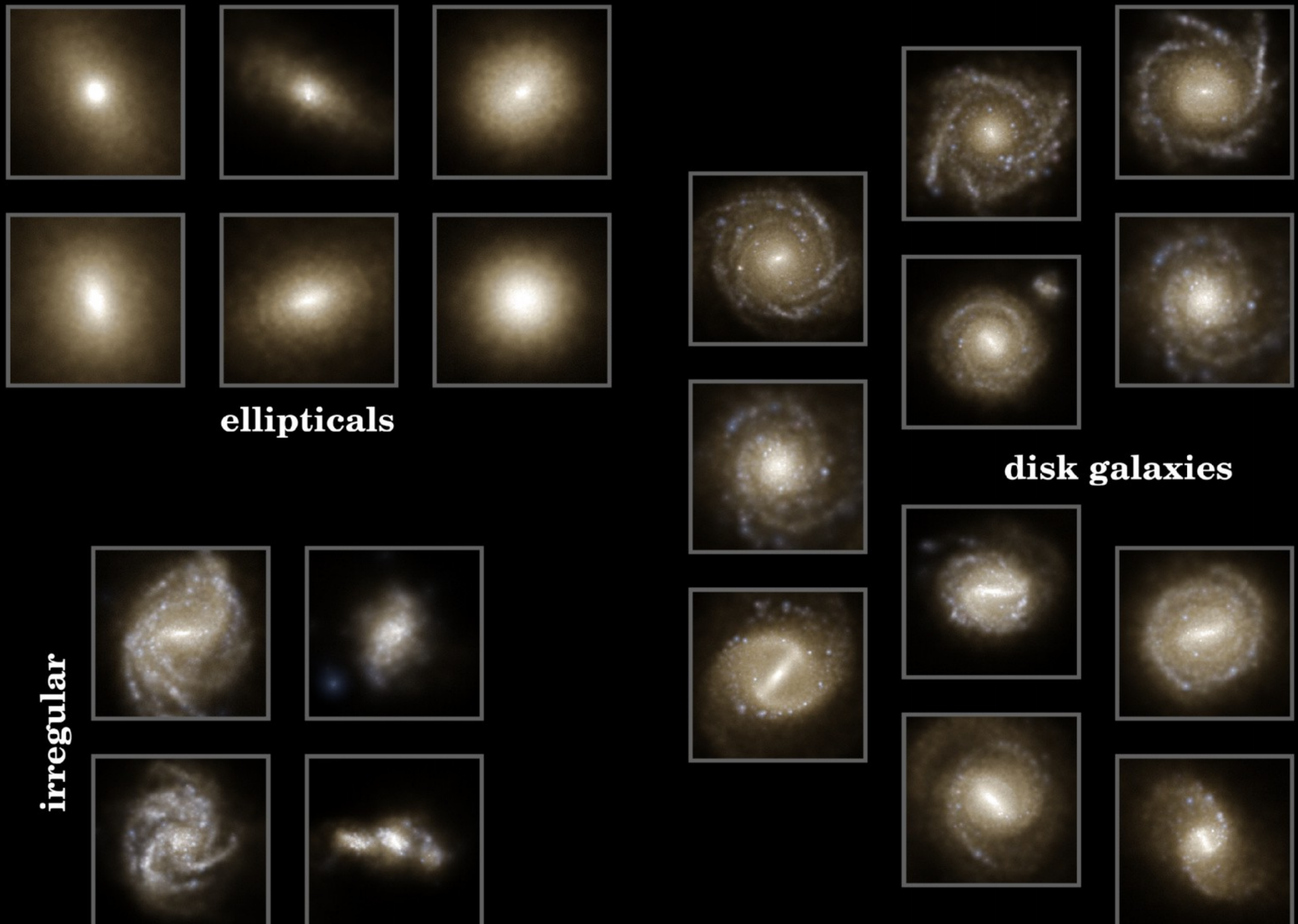


Illustris Simulation

Vogelsberger, Genel, Springel, Torrey, Sijacki, Xu, Snyder, Bird, Nelson, Hernquist

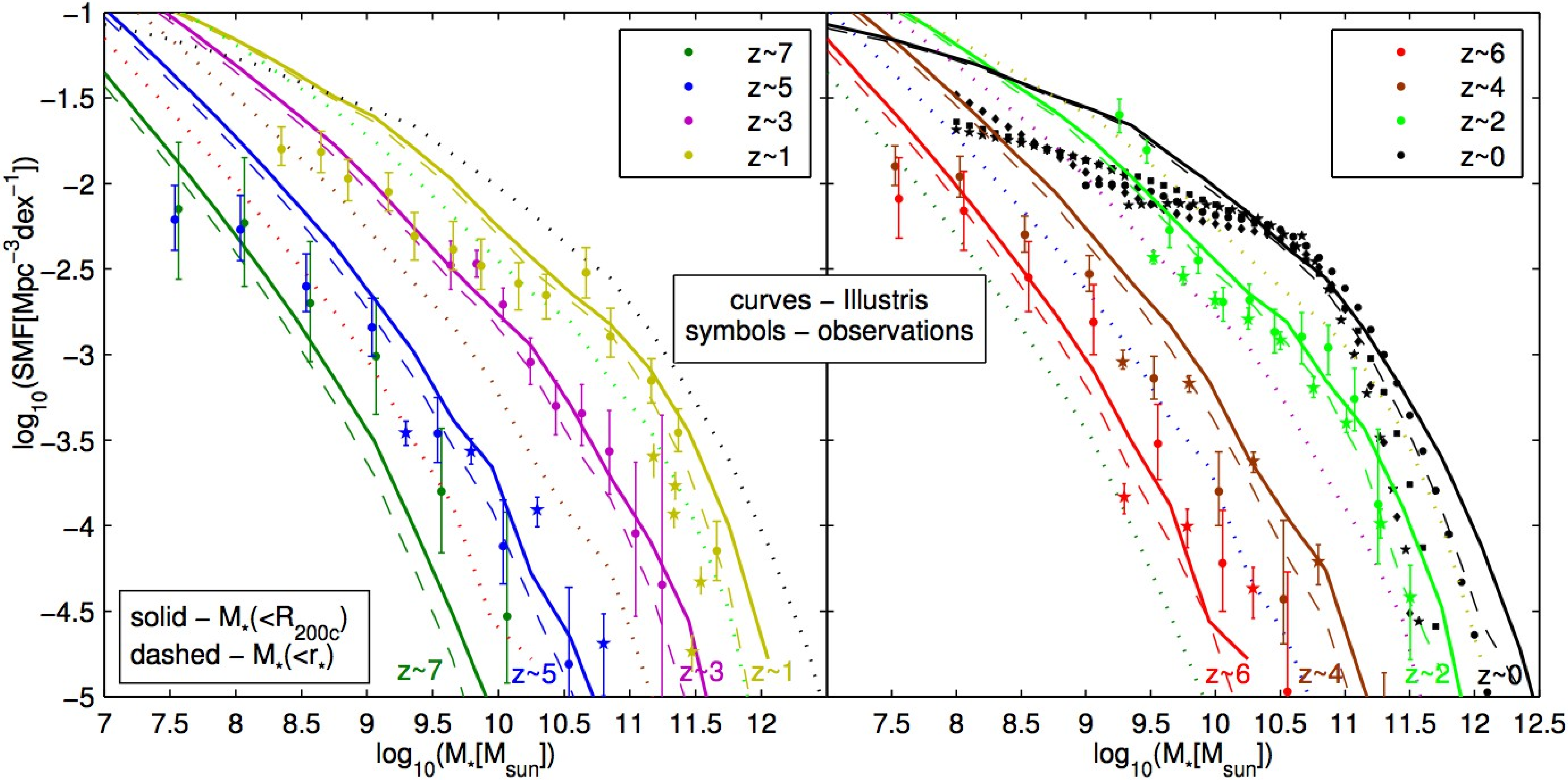
The Illustris simulation reproduces the morphological mix of galaxies

SIMULATED HUBBLE TUNING FORK DIAGRAM



The stellar mass functions match observations at high redshift well

STELLAR MASS FUNCTIONS OF ILLUSTRIS COMPARED TO HIGH-Z OBSERVATIONS



Genel et al. (2014)

Illustris was executed on CURIE (France) and SuperMUC (Germany)

~19 million CPU hours

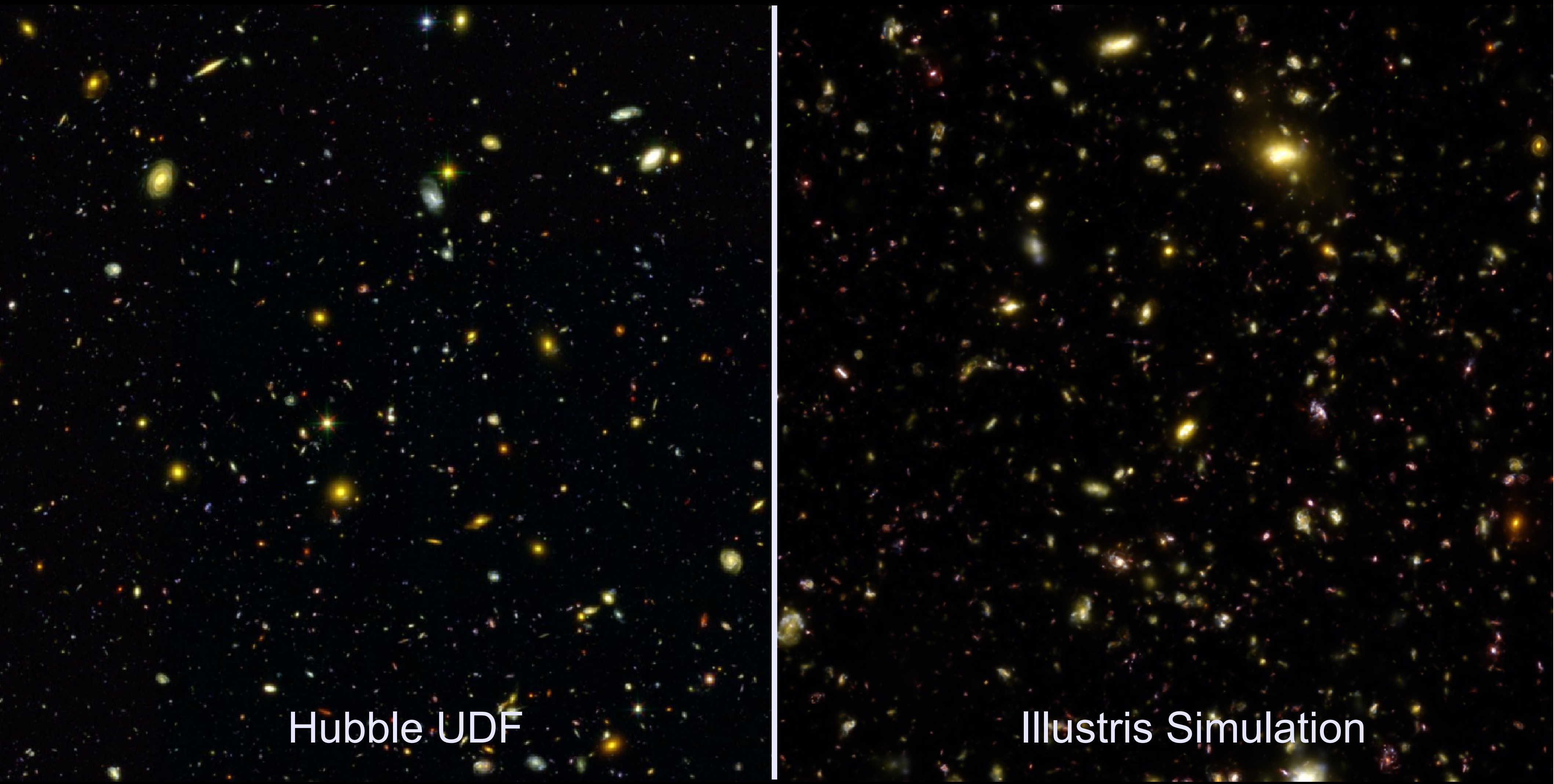
GCS
Gauss Centre for Supercomputing

PRACE

XSEDE
Extreme Science and Engineering Discovery Environment

Artificial light cone observations look rather similar to the real **Hubble Ultra Deep Field**

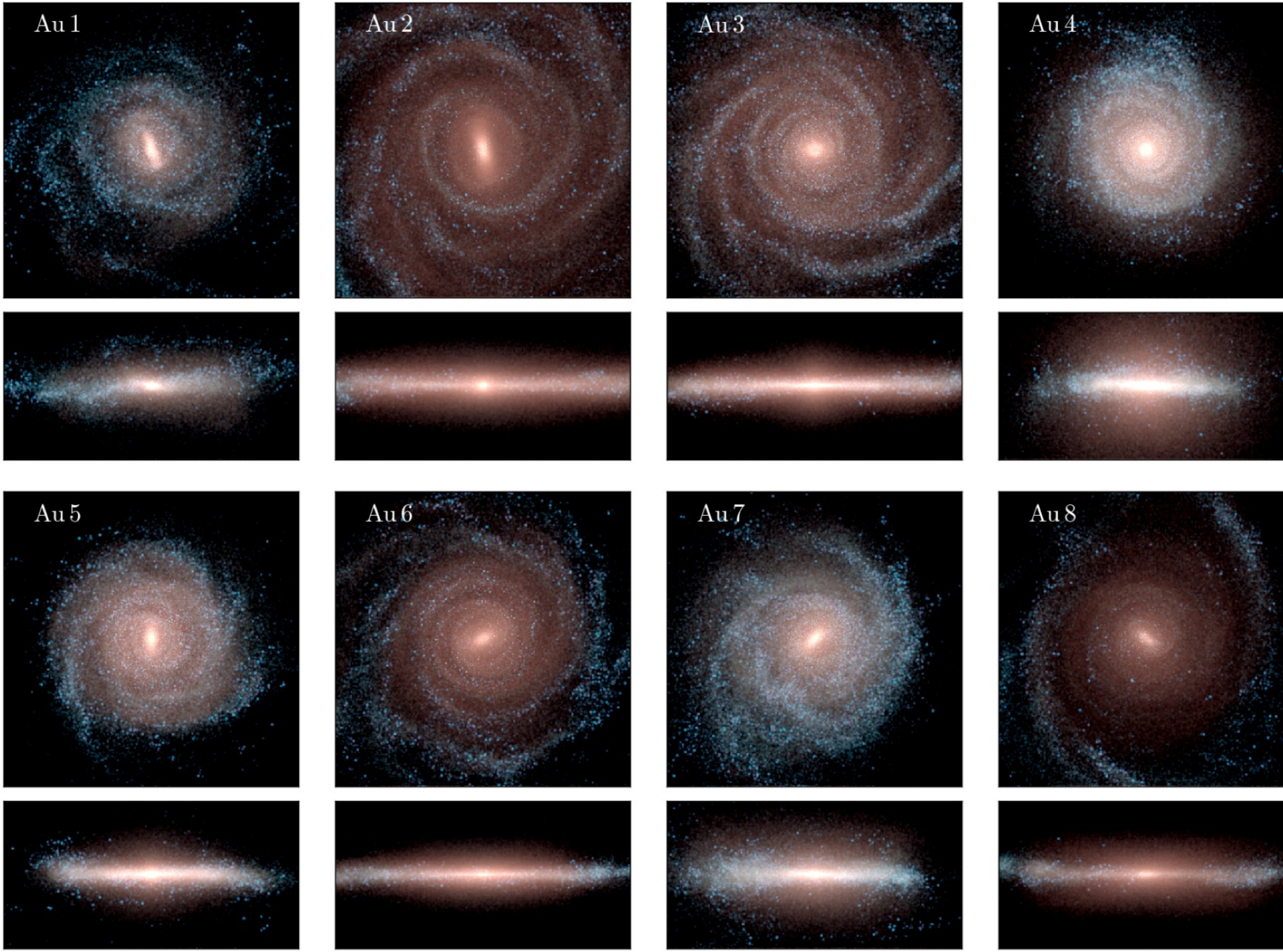
MOCK VS REAL UDF



“Auriga”
Milky Way-like galaxies

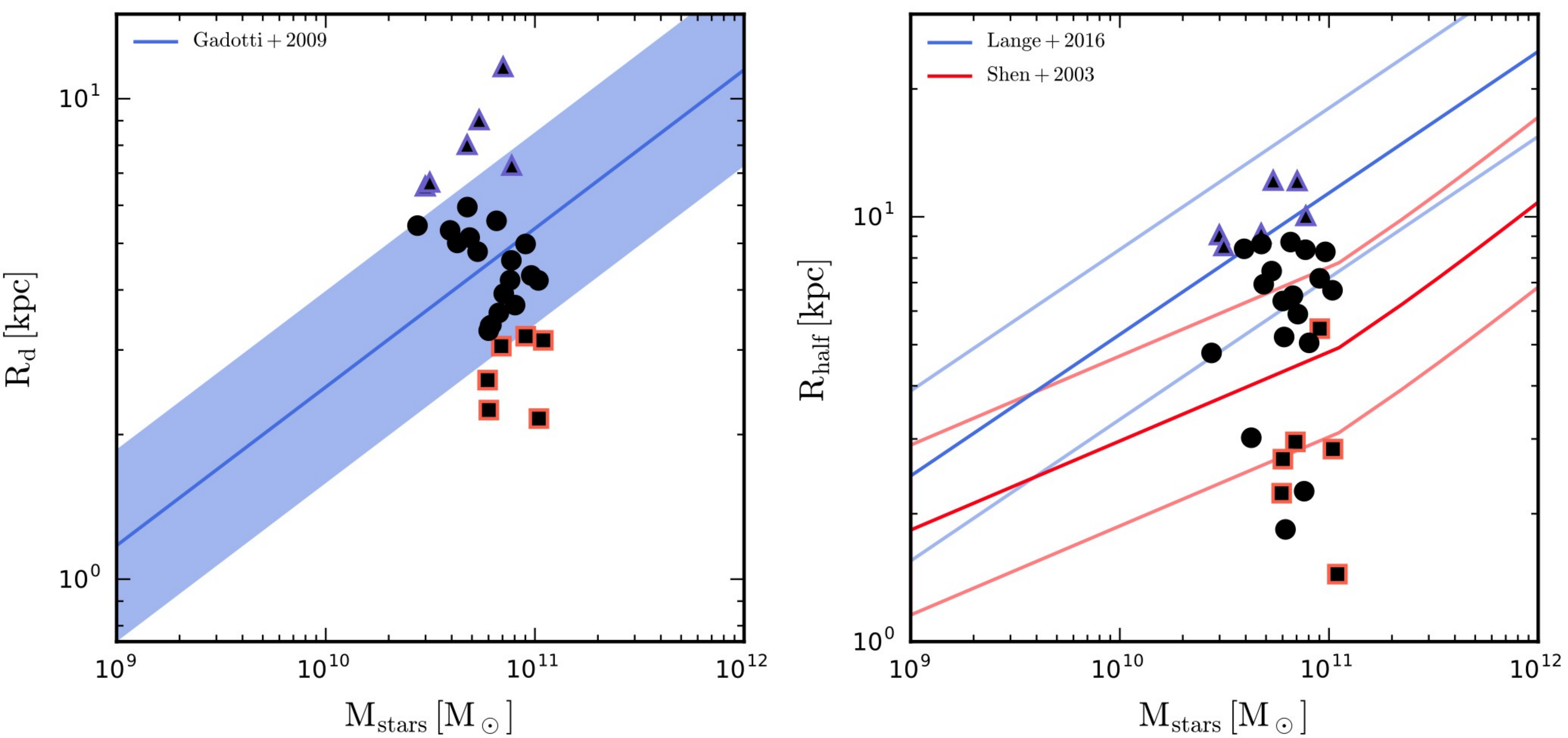
Results from AURIGA

30 HIGH-RESOLUTION MILKY WAY-SIZED HALOS



The disk sizes match observational constraints

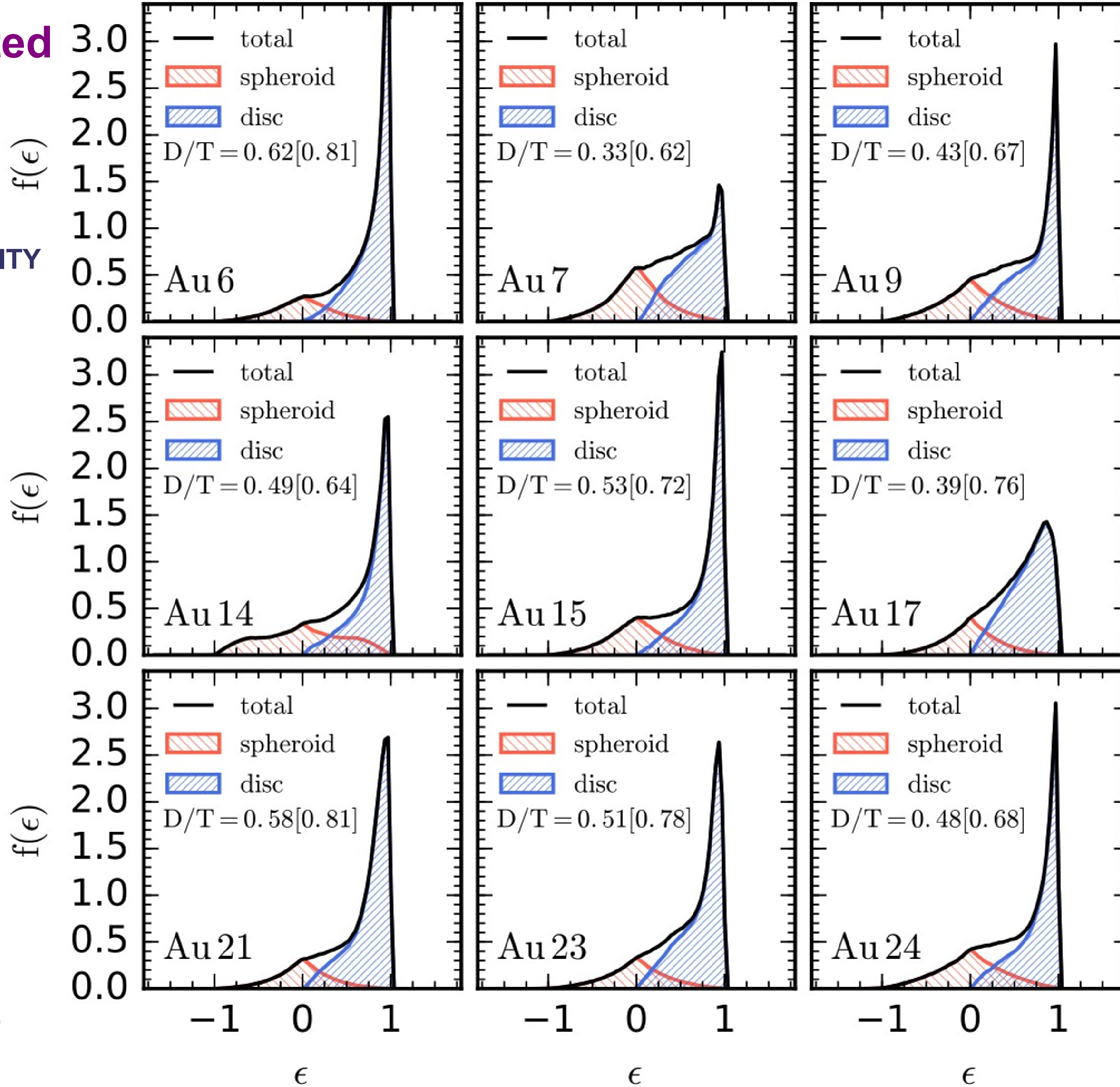
EXPONENTIAL DISK SCALE LENGTHS AND HALF-MASS RADII AS A FUNCTION OF STELLAR MASS



Grand et al. (2016)

Disk dominated systems with small bulges are formed

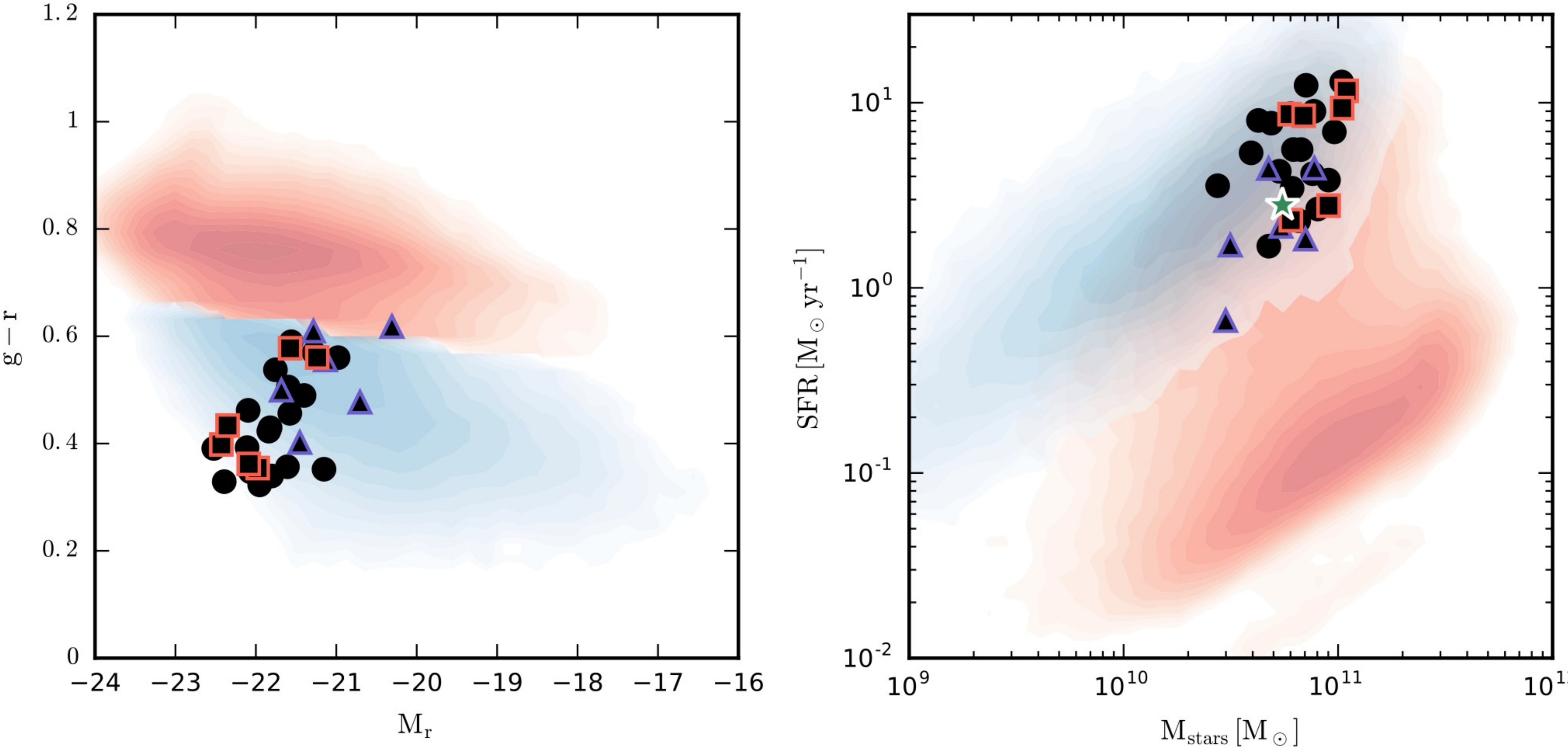
ORBITAL CIRCULARITY DISTRIBUTION



Grand et al. (2016)

The simulations are late-type, blue cloud star forming galaxies

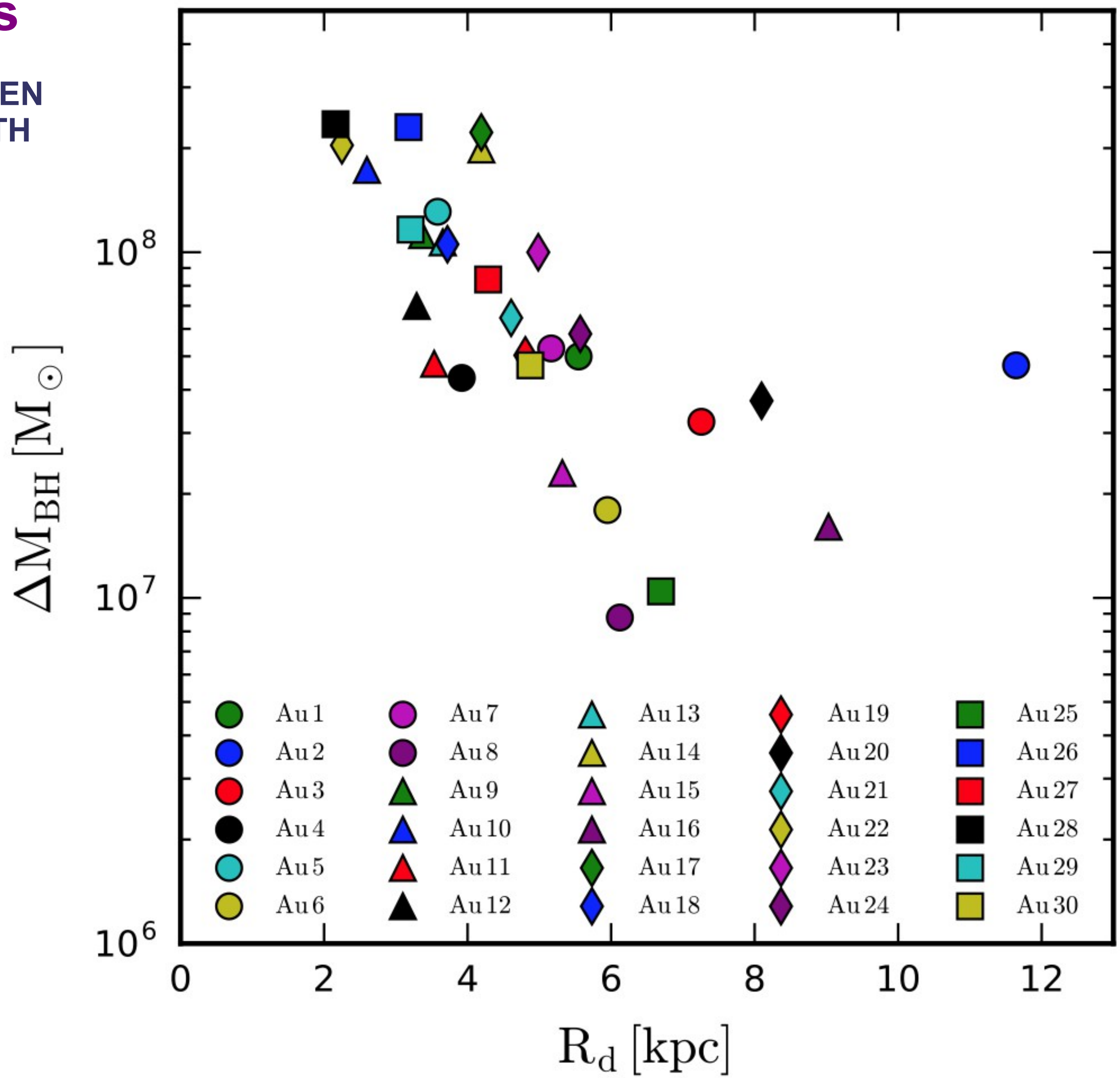
COLORS AND STAR FPRMATION RATES AS A FUNCTION OF MAGNITUDE OR STELLAR MASS



Grand et al. (2016)

Black hole growth influences disk sizes

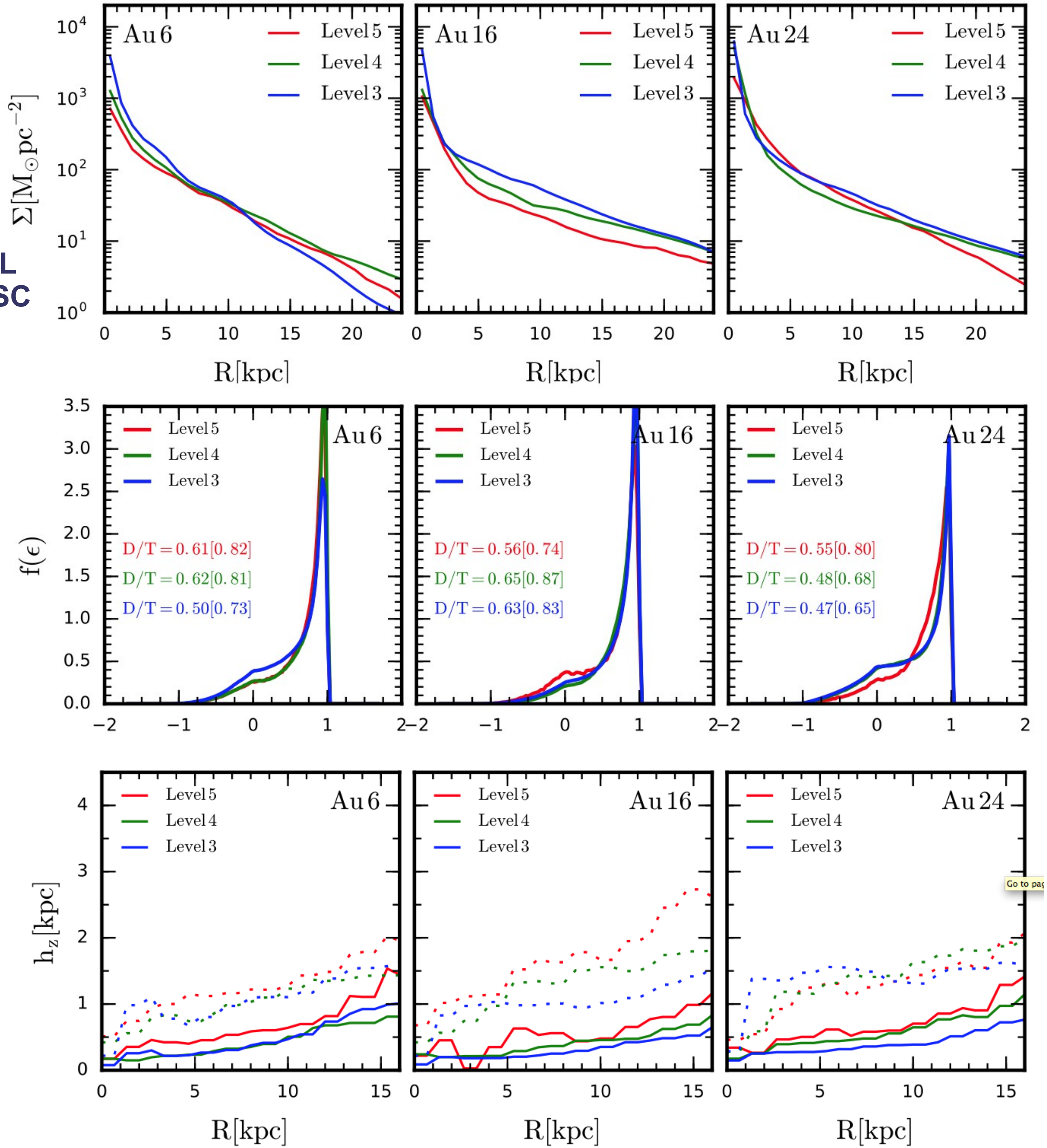
BLACK HOLE GROWTH BETWEEN Z=1 AND Z=0 CORRELATED WITH DISK SCALE LENGTHS



Grand et al. (2016)

The models converge reasonable well, ***for fixed model parameters***

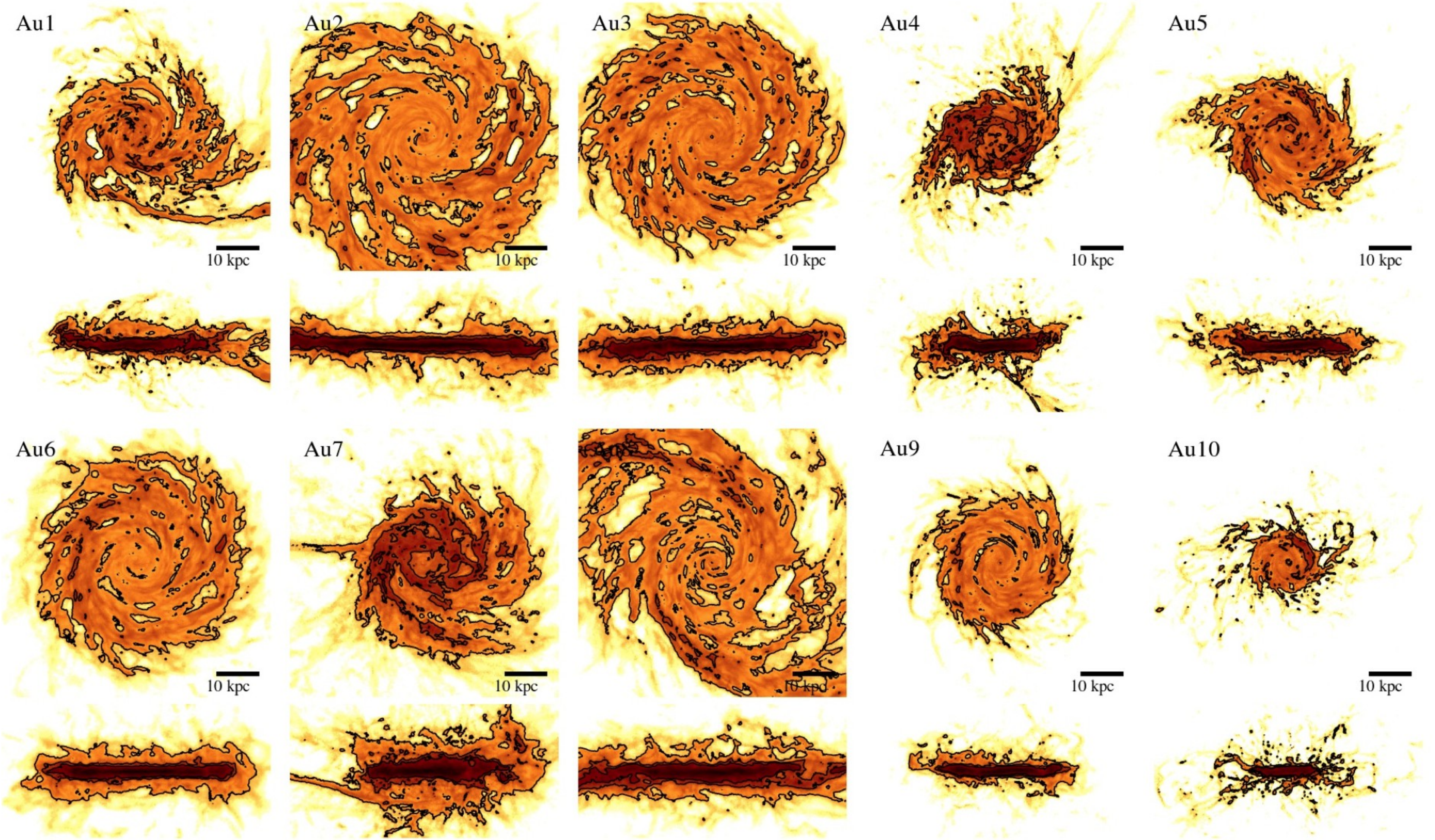
SURFACE BRIGHTNESS, ORBITAL CIRCULARITY AND VERTICAL DISC SCALE HEIGHT COMPARED AT VERY DIFFERENT NUMERICAL RESOLUTION



Grand et al. (2016)

The morphology of neutral gas is very different from the stars

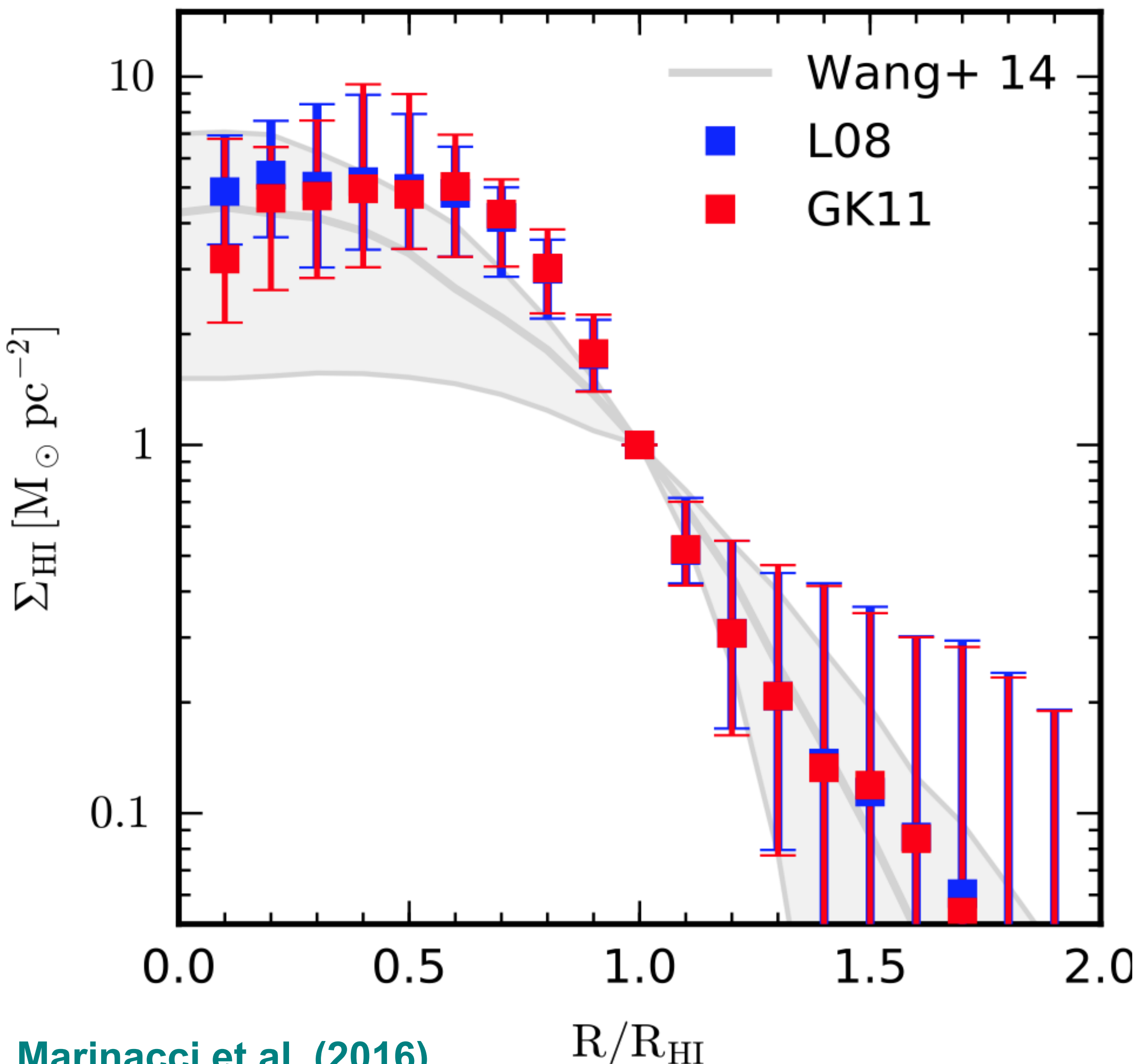
HI PROJECTIONS OF AURIGA GALAXIES

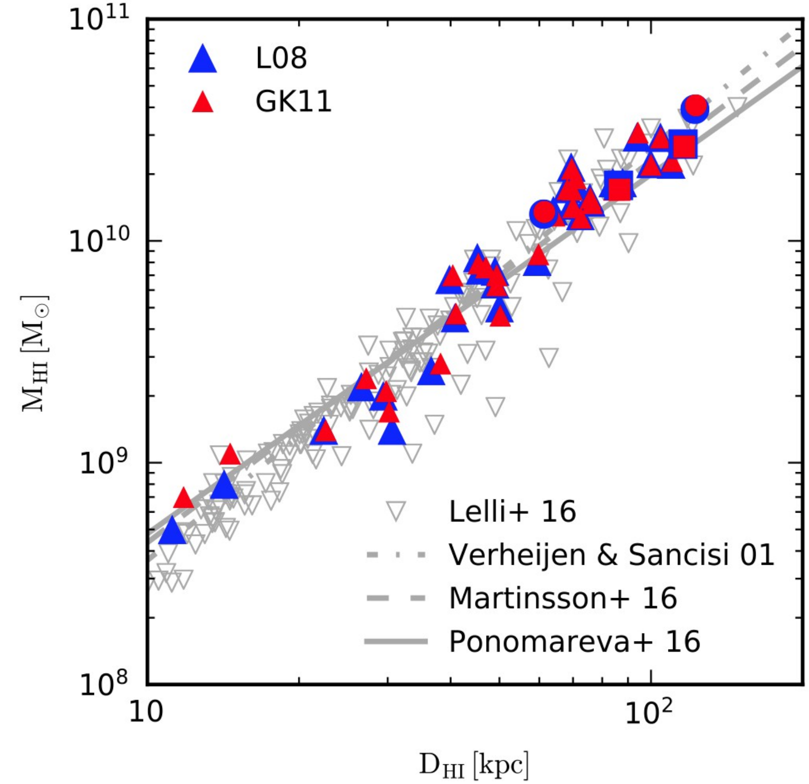


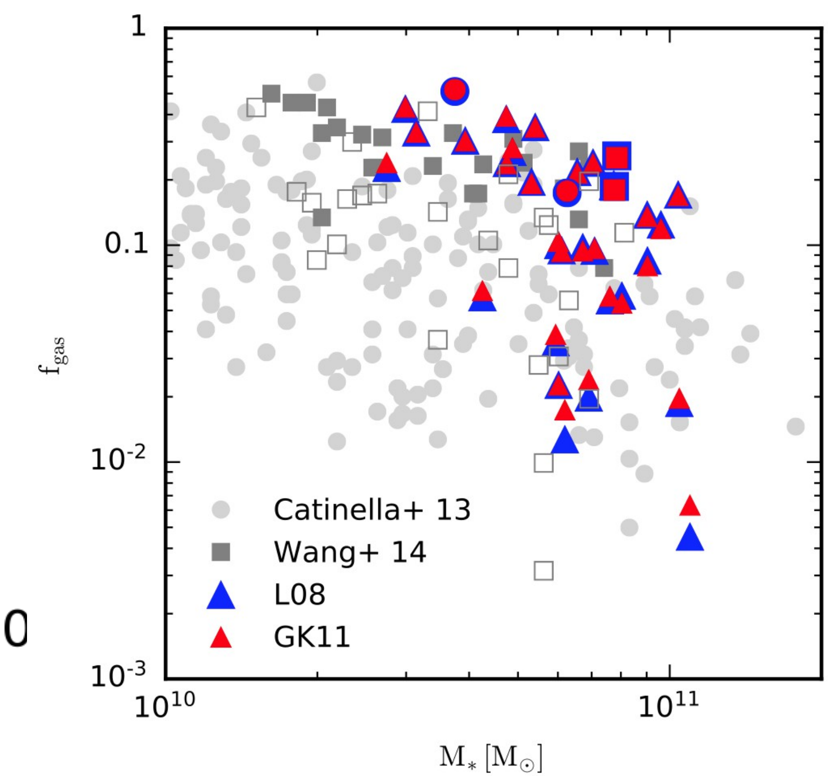
Marinacci et al. (2016)

HI properties are in broad agreement with observational constraints

HI SURFACE DENSITIES, HI MASSES, AND TOTAL GAS FRACTIONS OF SIMULATED DISKS COMARED TO DATA







Marinacci et al. (2016)

Magnetic fields

We have an ideal MHD implementation in AREPO that seems to work well

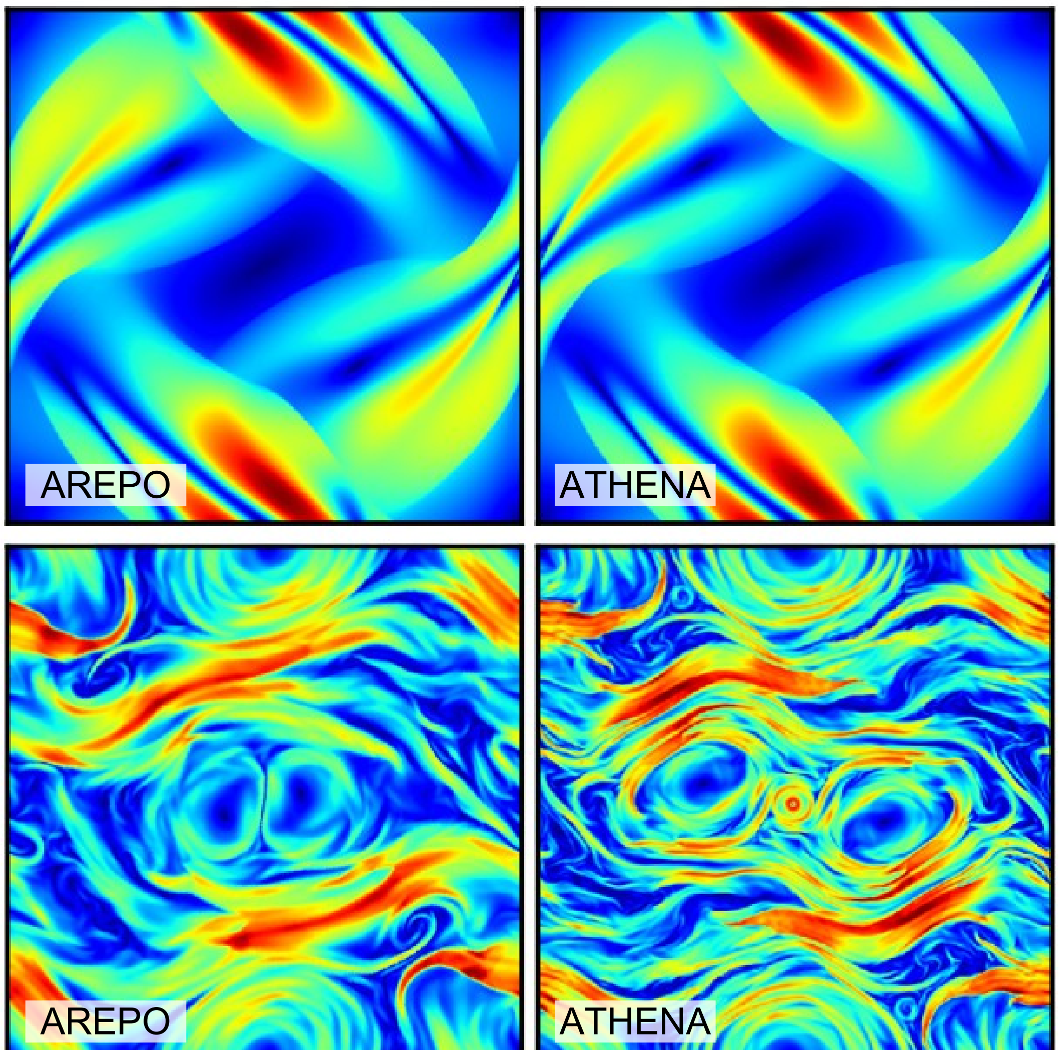
EQUATIONS AND SOME TESTS

Pakmor, Bauer & Springel (2011)

Pakmor & Springel (2013)

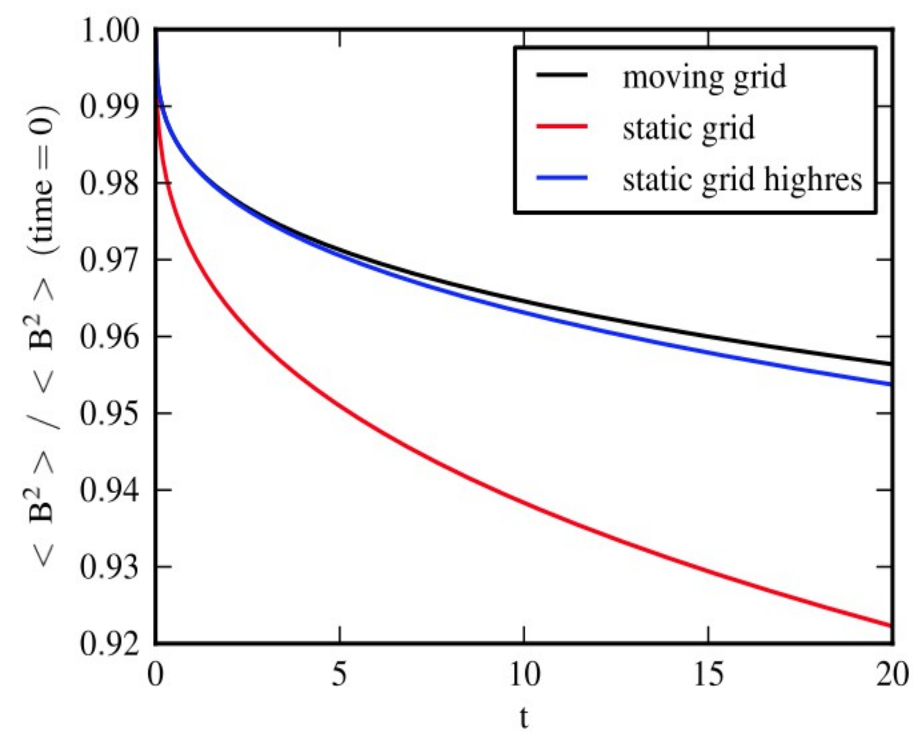
$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho\mathbf{v} \\ \rho e \\ \mathbf{B} \\ \psi \end{pmatrix} \qquad \mathbf{F}(\mathbf{U}) = \begin{pmatrix} \rho\mathbf{v} \\ \rho\mathbf{v}\mathbf{v}^T + p - \mathbf{B}\mathbf{B}^T \\ \rho e\mathbf{v} + p\mathbf{v} - \mathbf{B}\,(\mathbf{v}\cdot\mathbf{B}) \\ \mathbf{B}\mathbf{v}^T - \mathbf{v}\mathbf{B}^T + \psi I \\ c_h^2\mathbf{B} \end{pmatrix}$$

Orszag-Tang vortex test



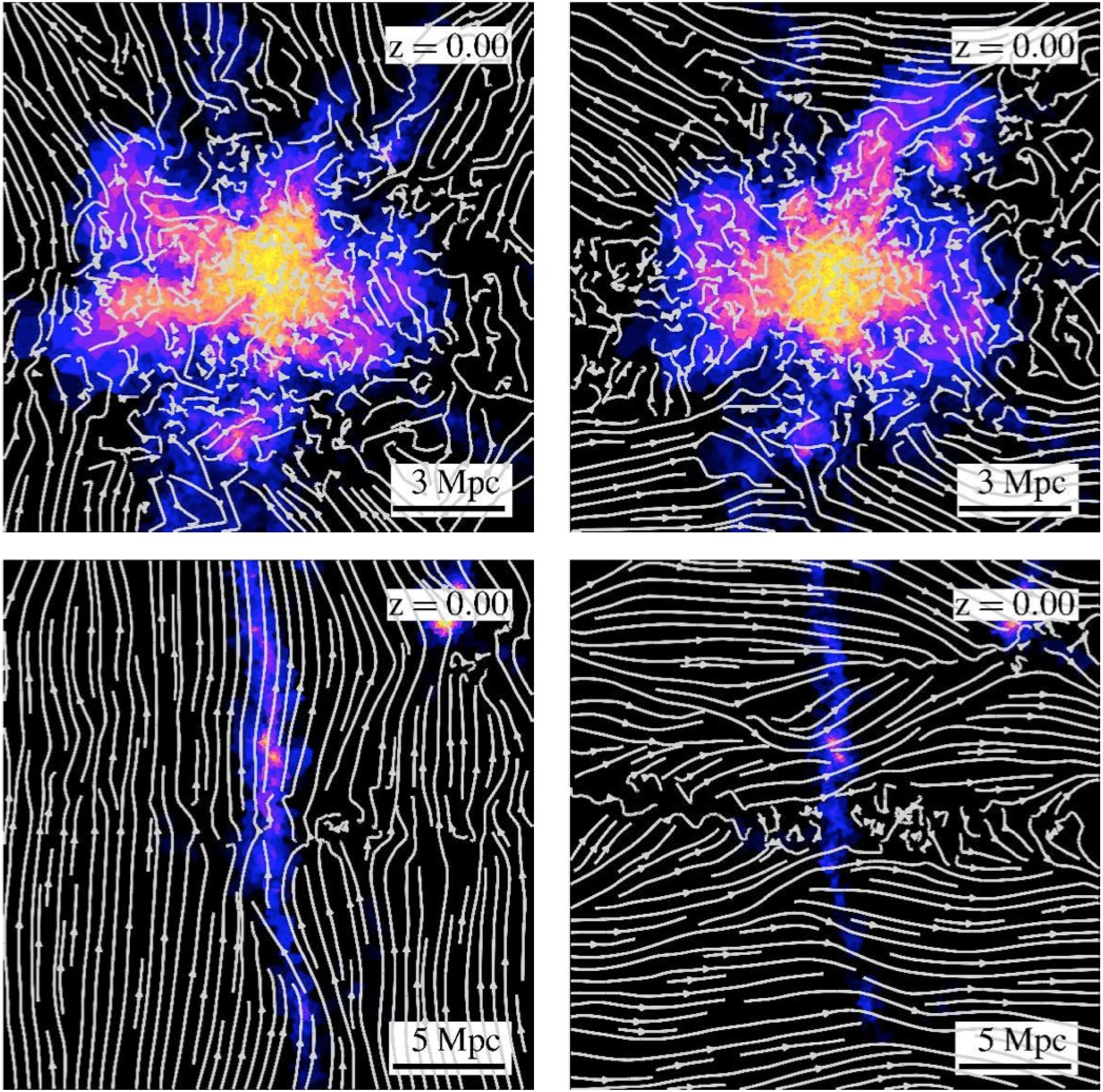
- 8-wave Powell scheme for divergence cleaning
- Approximate HLLD Riemann solver

Loss of magnetic energy in moving field loop



In filaments, memory of the initial field geometry is still kept, and this affects also the amplification

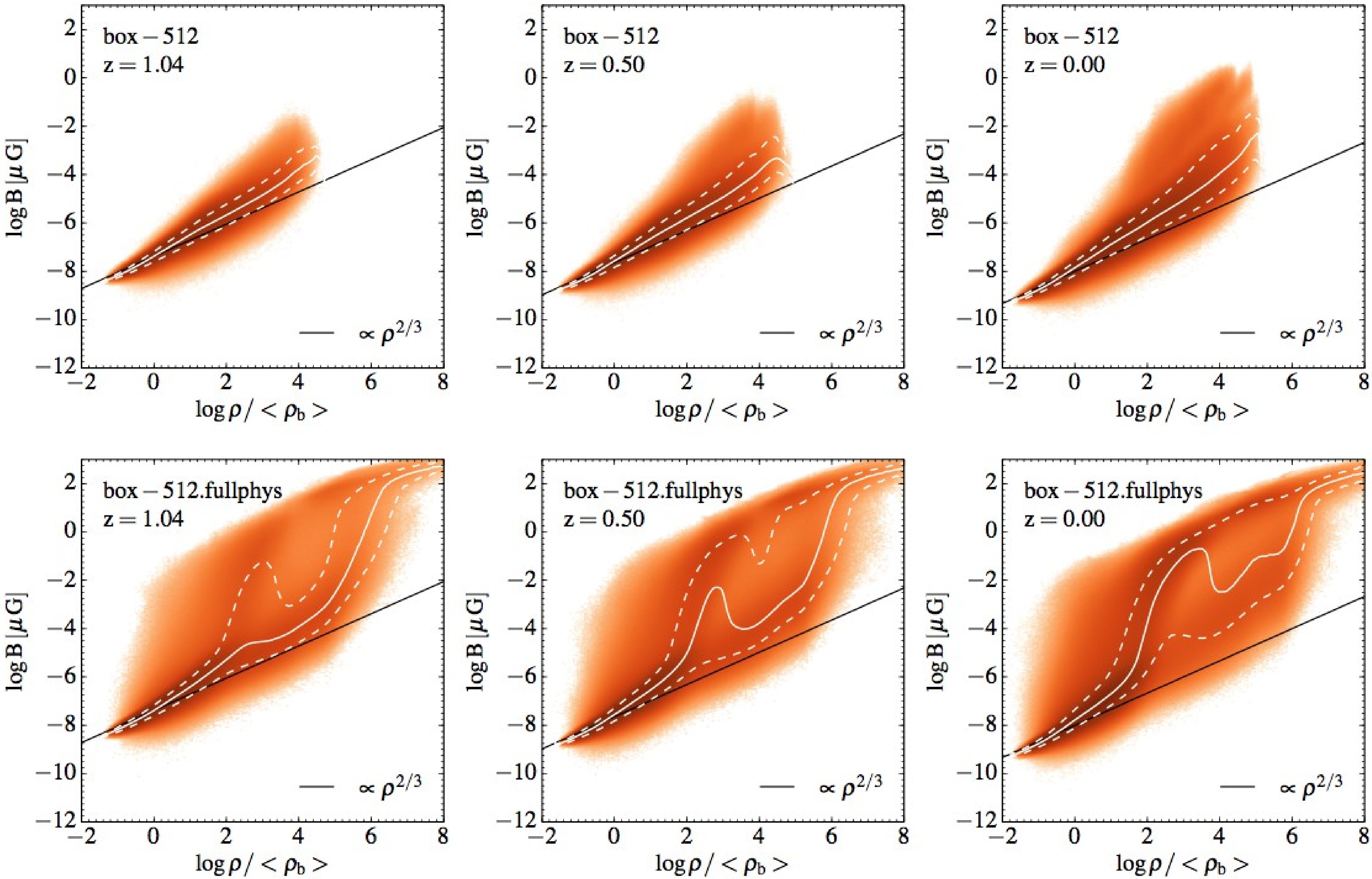
FIELD DISTRIBUTION IN TWO IDENTICAL SIMULATIONS WHERE THE INITIAL ORIENTATION OF THE B-FIELD WAS CHANGED



Marinacci et al. (2015)

The non-radiative and full physics simulations differ strongly in the B-field amplification in the dense gas

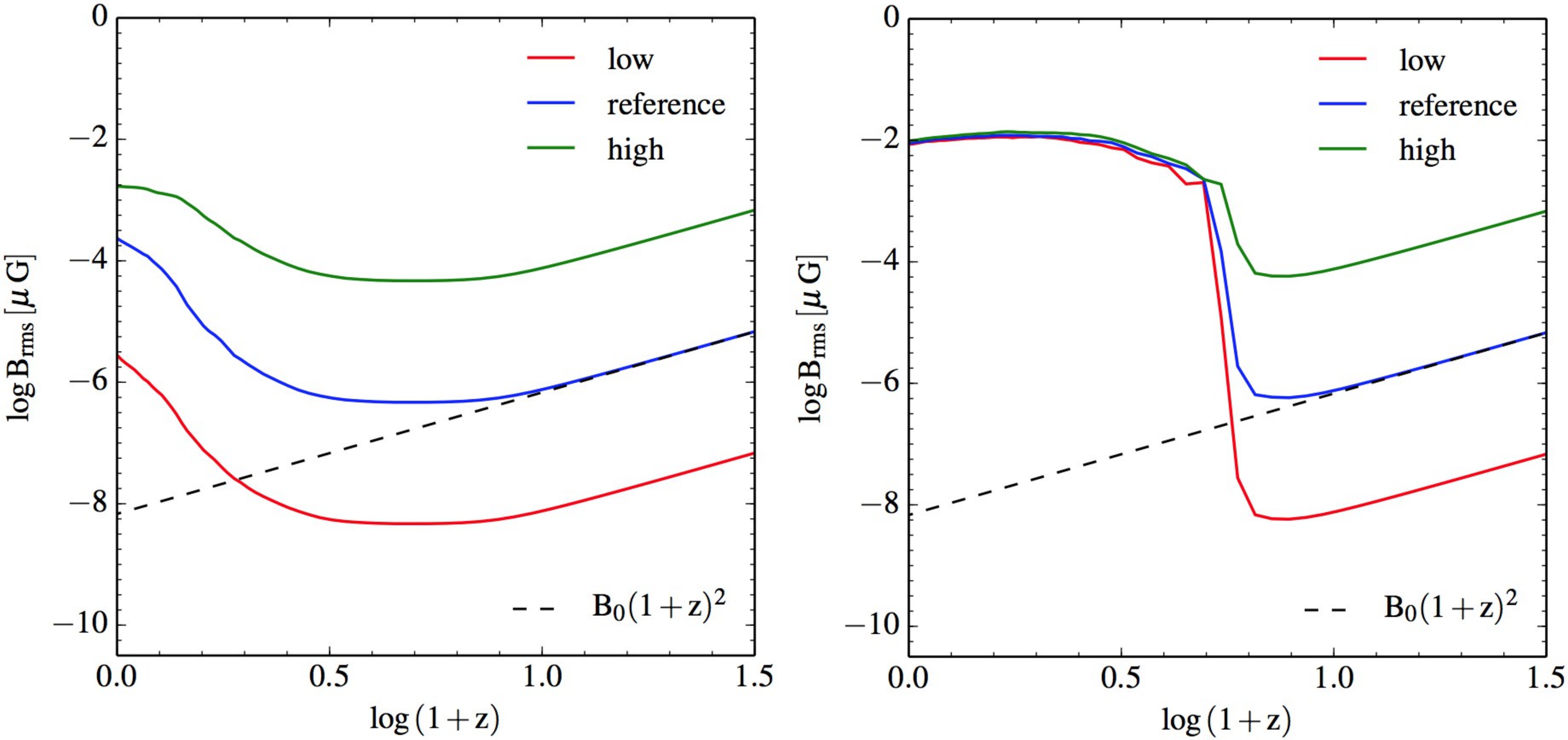
REDSHIFT EVOLUTON OF THE B-FIELD STRENGTH VS BARYON OVERDENSITY Marinacci et al. (2015)



The low redshift volume-weighted B-field strength in the full physics simulation is fairly independent of the seed field

EVOLUTON OF THE VOLUME-WEIGHTE B-FIELD FOR DIFFERENT SEED FIELDS AND PHYSICS

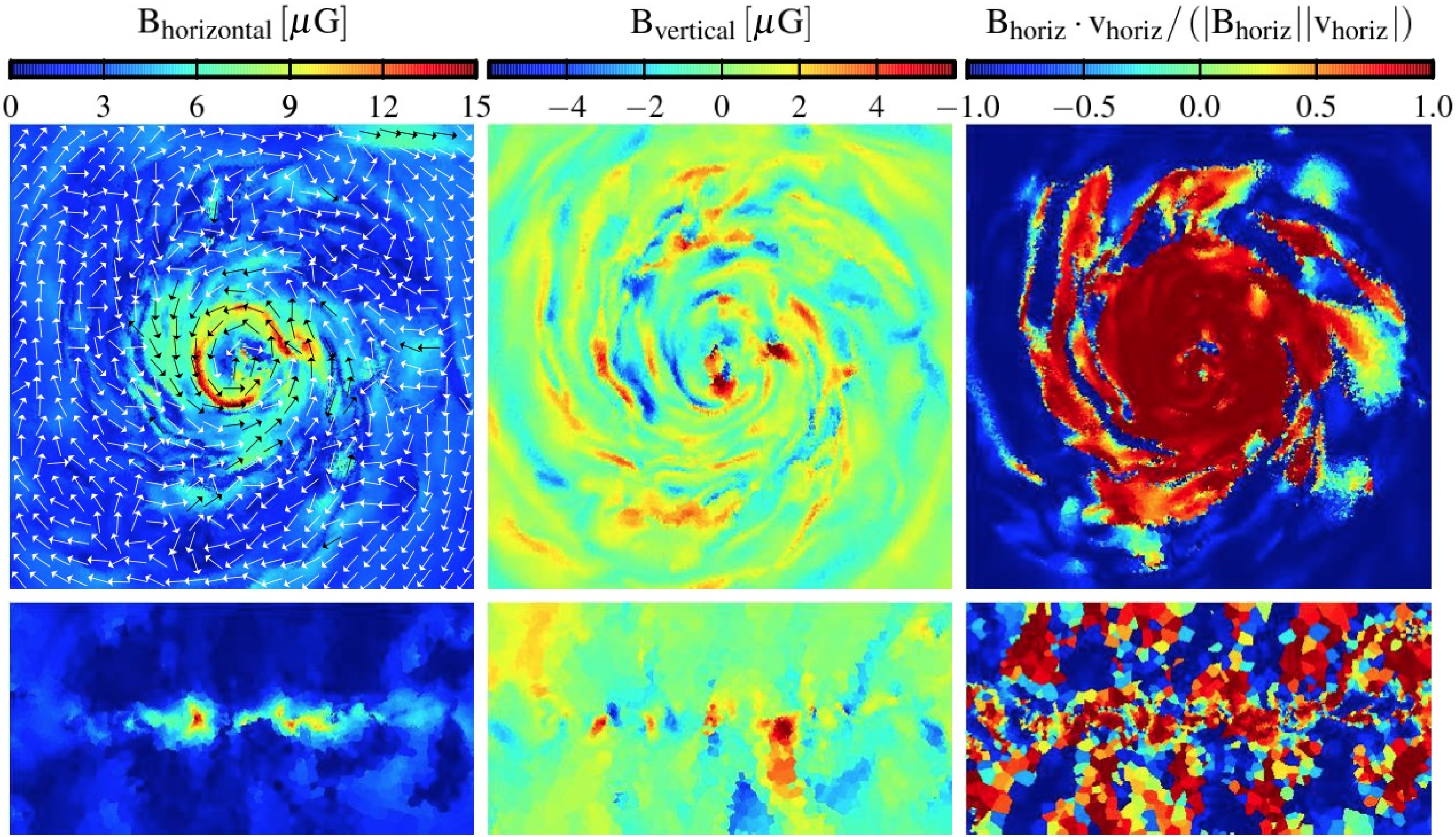
non-radiative **full physics**



Marinacci et al. (2015)

The predicted present-day B-field is largely toroidal

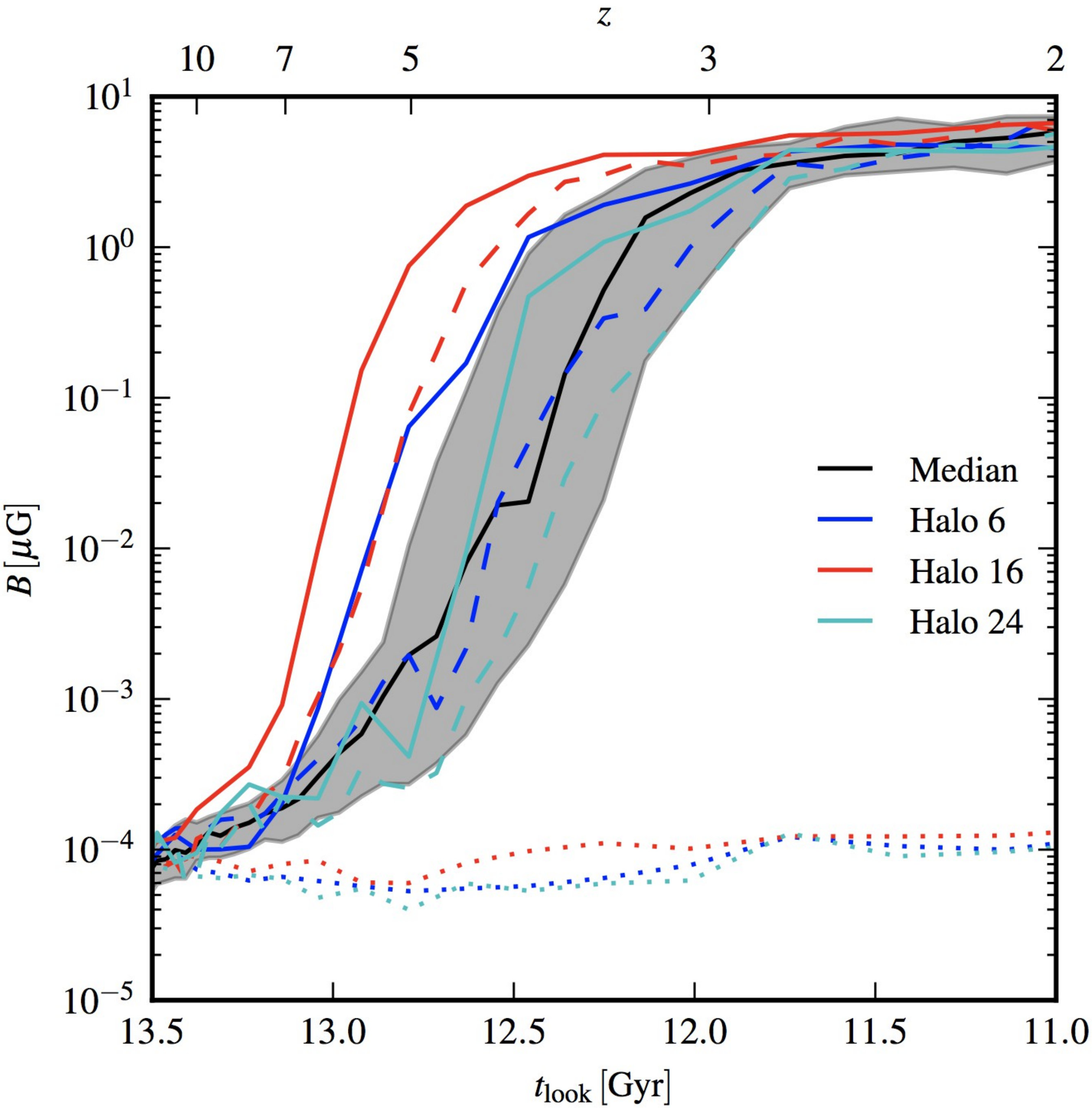
MAGNETIC FIELD IN THE DISK AT REDSHIFT Z=0



Pakmor et al. (2014)

A small-scale dynamo is active at very high redshift

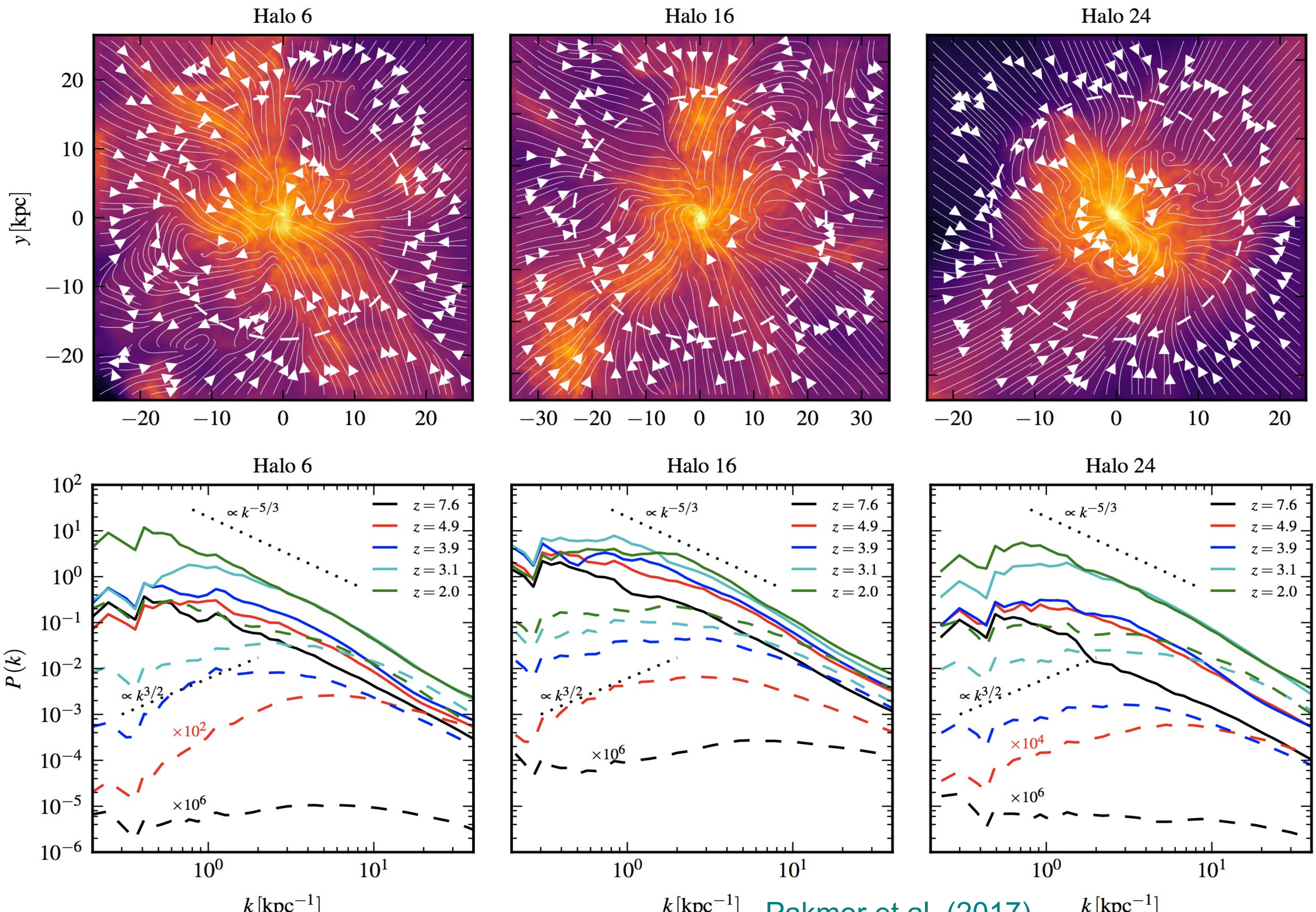
EVOLUTION OF THE VOLUME-WEIGHTED RMS B-FIELD STRENGTH INSIDE 10 KPC



Pakmor et al. (2017)

Amplification of B-field occurs through turbulent dynamo

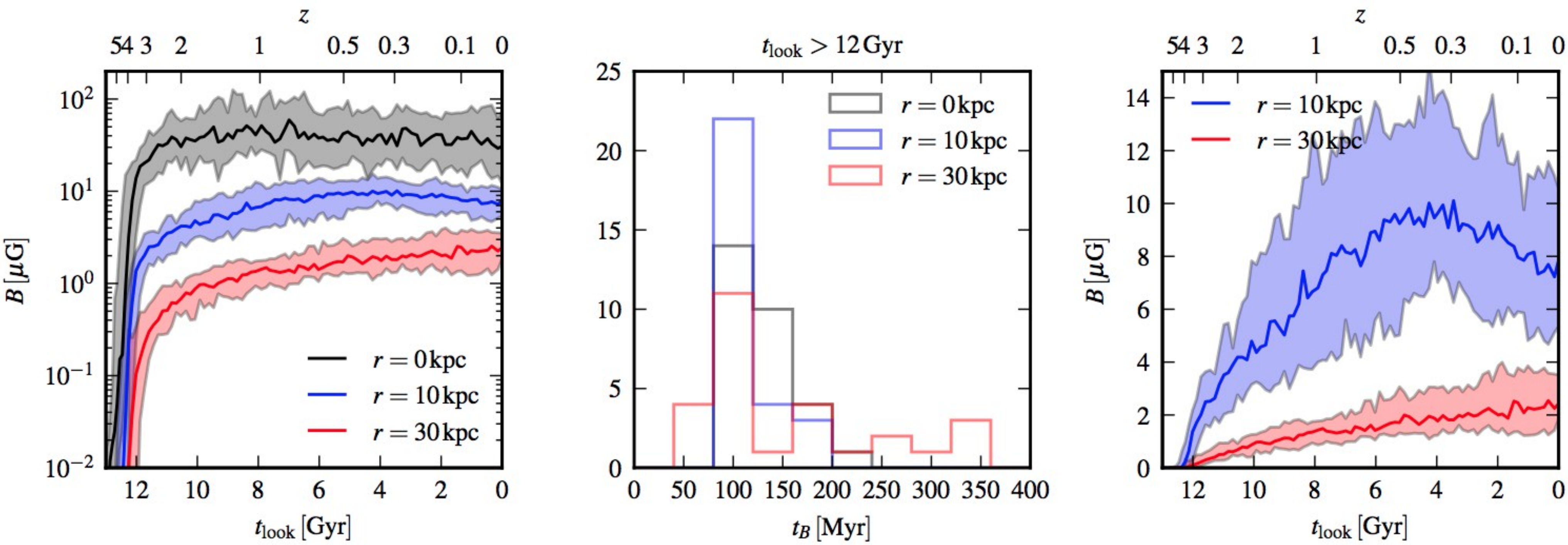
VELCOITY FIELD AND EVOLUTION OF VELOCITY AND B-FIELD POWER SPECTRA



Pakmor et al. (2017)

Little residual amplification happens in the disks themselves once the small-scale dynamo has saturated

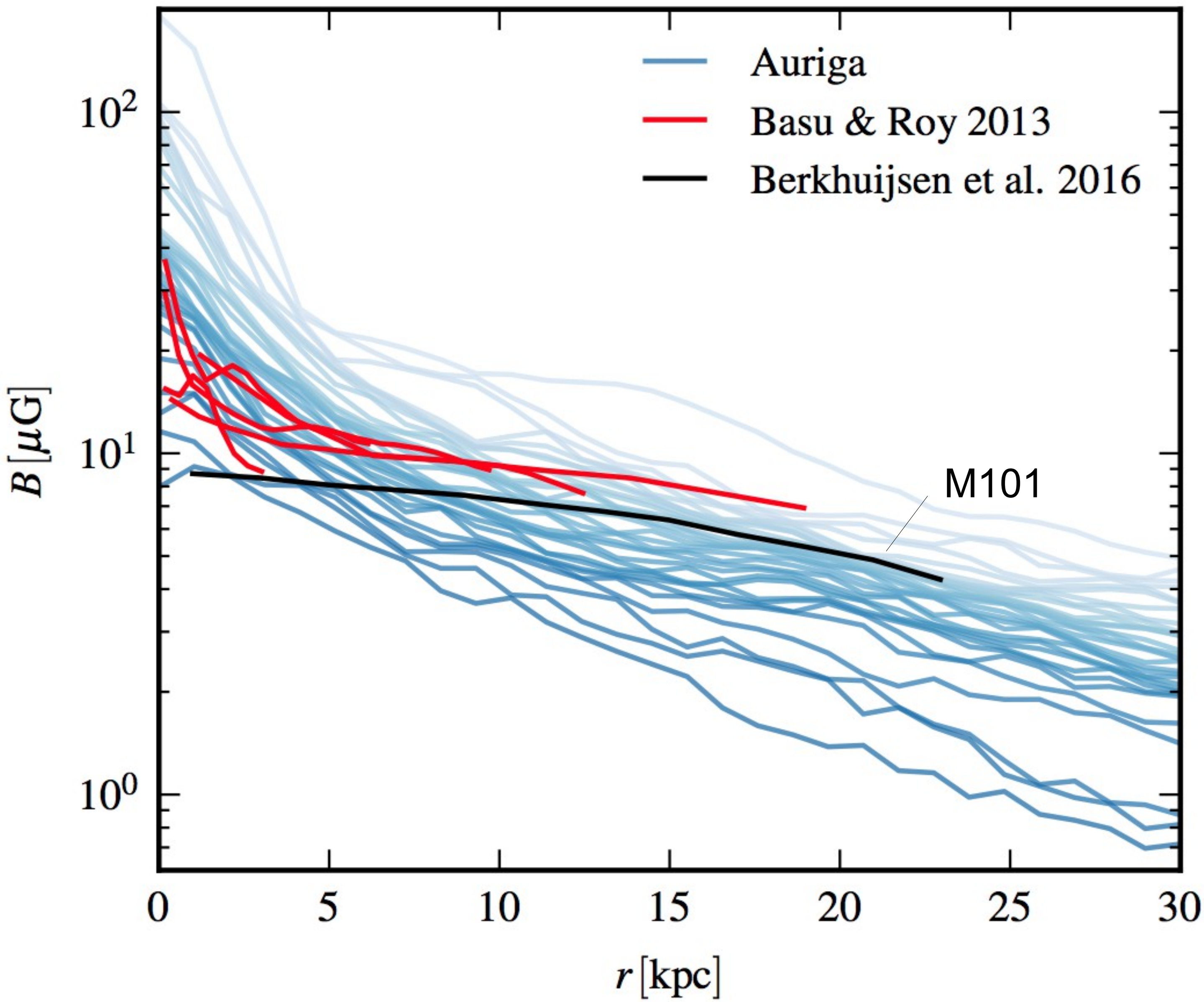
TIME EVOLUTION OF THE B-FIELD AVERAGED OVER ALL AURIGA GALAXIES



Pakmor et al. (2017)

The predicted magnetic field strength agrees quite well with observations

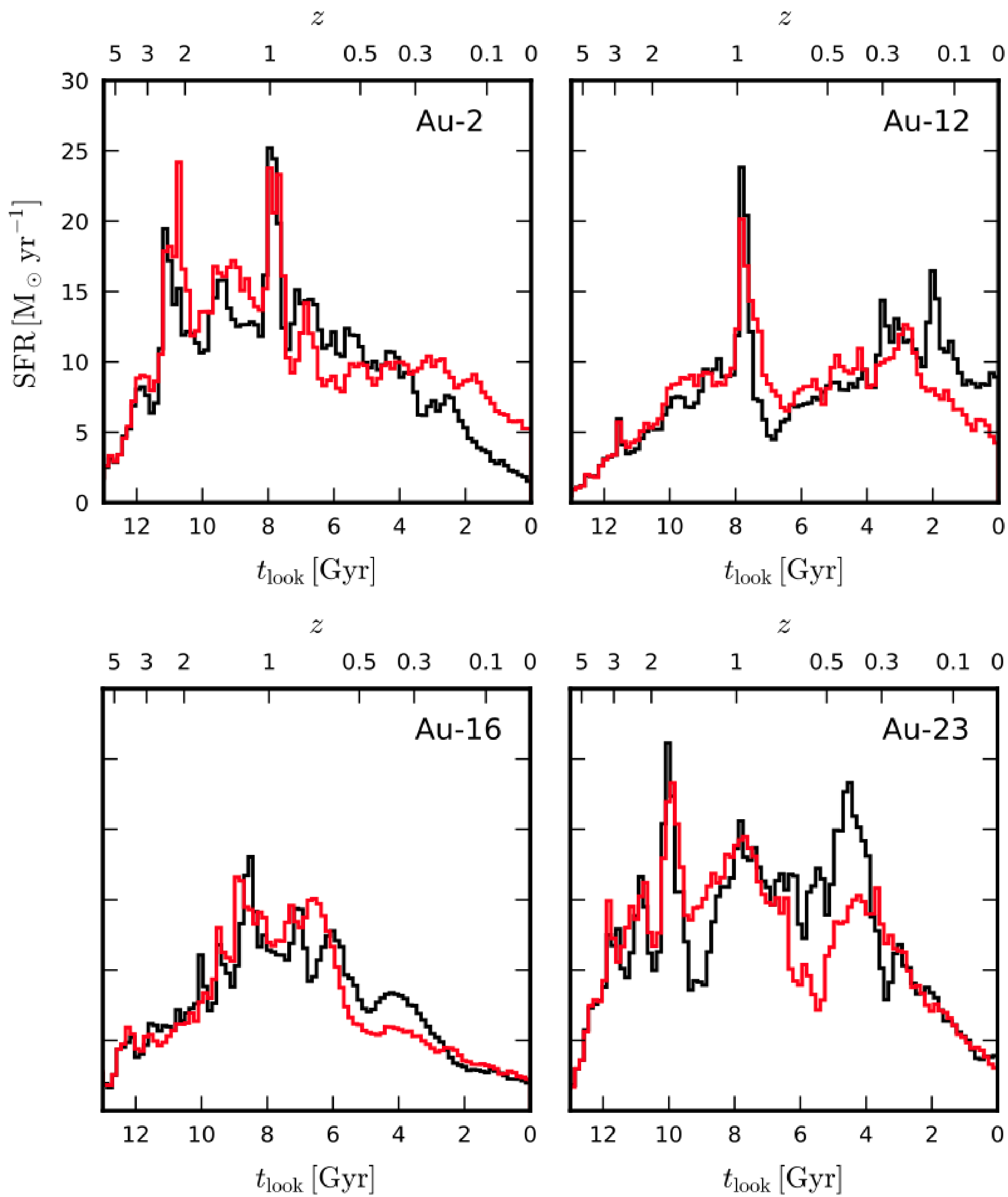
PROFILES OF MAGNETIC FIELD STRENGTH IN SIMULATIONS AND OBSERVATIONS



Pakmor et al. (2017)

Theres is little impact of magnetic fields on the star formation histories because equipartition is reached too late

COMPARISON OF SIMULATIONS WITH AND WITHOUT MAGNETIC FIELDS



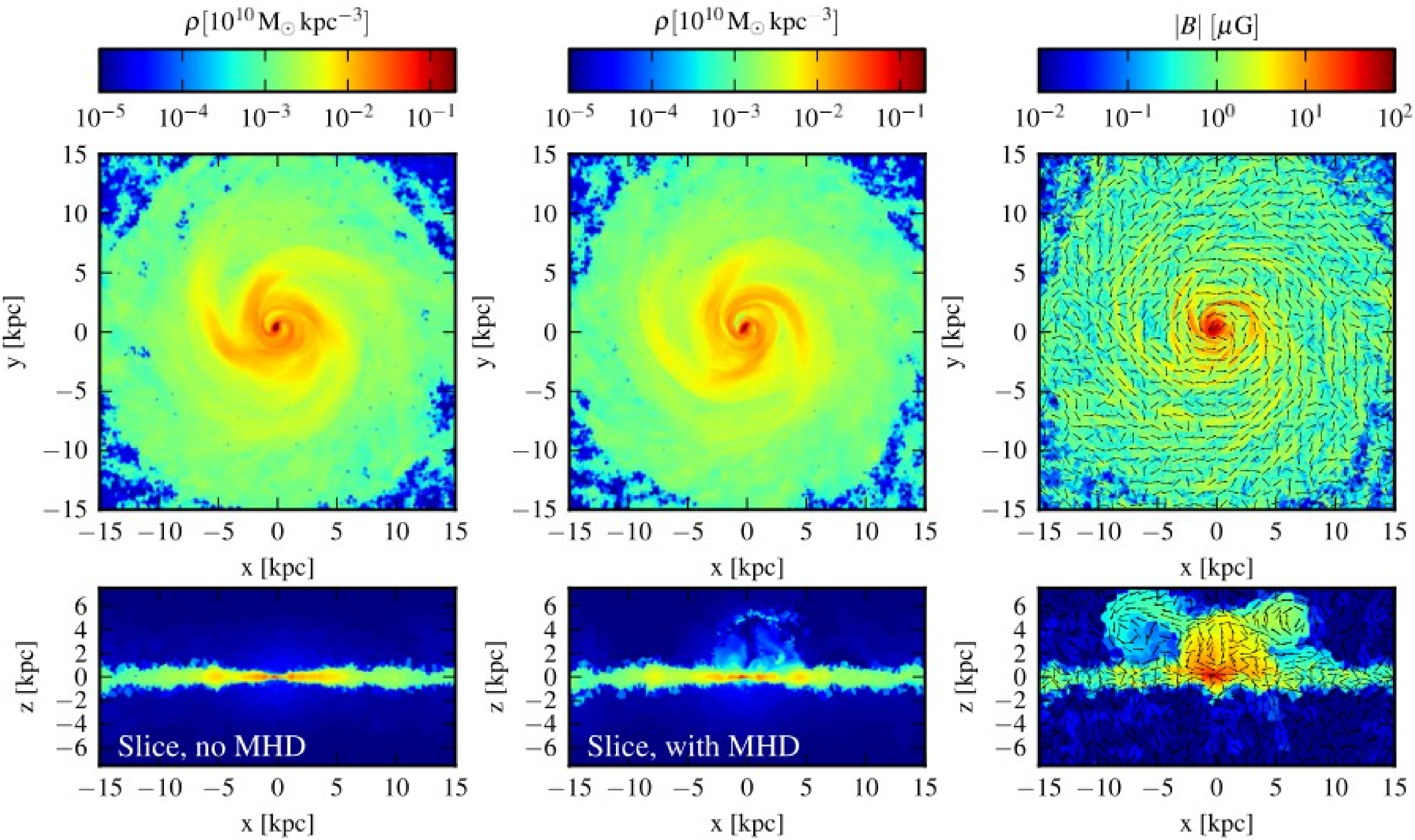
Black: with B-Fields

Red: without B-Fields

Pakmor et al. (2017)

In isolated disk galaxy formation simulations, magnetic fields drive magnetically driven small fountain like flows out of the disk

SLICES THROUGH THE GAS DENSITY AND THE MAGNETIC FIELD

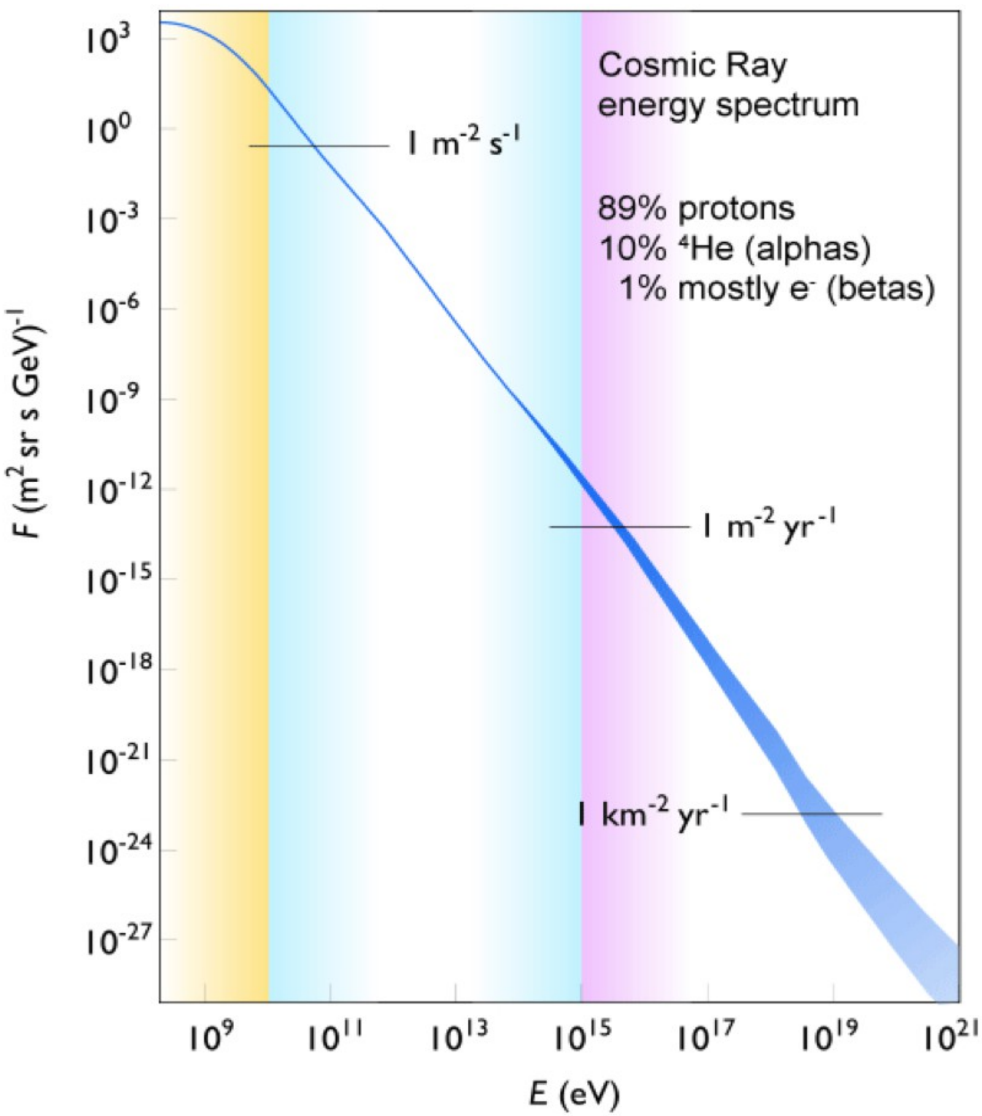


Pakmor & Springel (2012)

Cosmic rays

The Galactic cosmic ray energy spectrum provides a significant contribution to the total ISM pressure

GLOBAL PROPERTIES OF GALACTIC COSMIC RAYS



data compiled by Swordy

energy density in cosmic rays:
comparable to thermal and magnetic energy densities in ISM (equipartition)

main production mechanisms:

- supernova shocks (10-30% of the energy appears as CRs)
- large-scale structure formation shocks

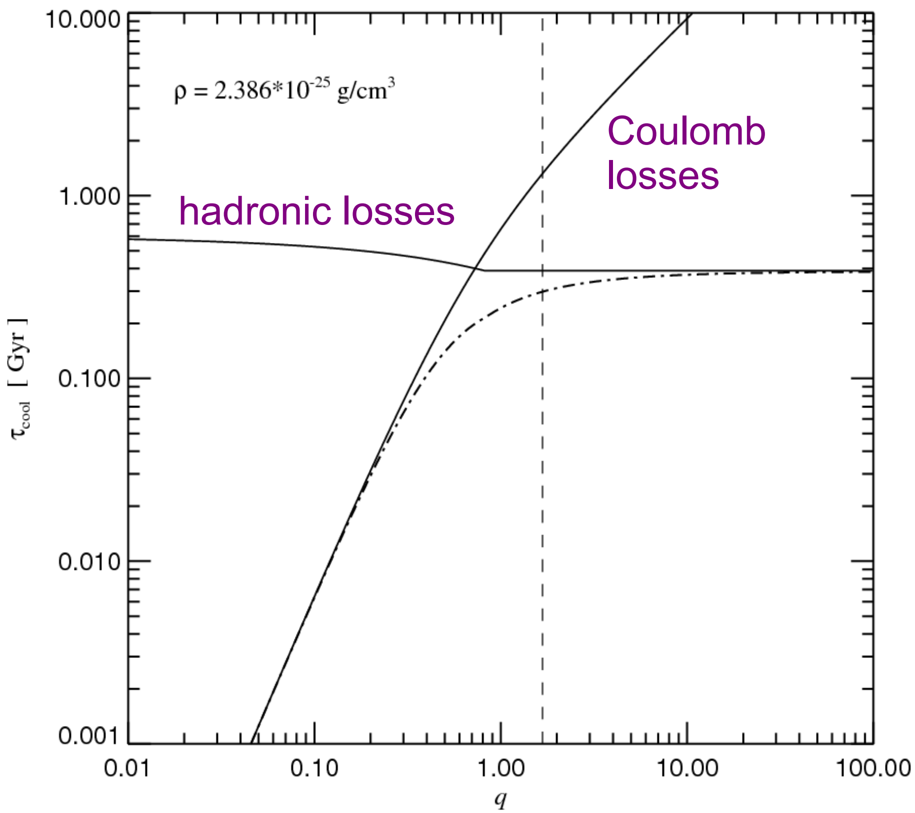
main dissipation mechanisms:

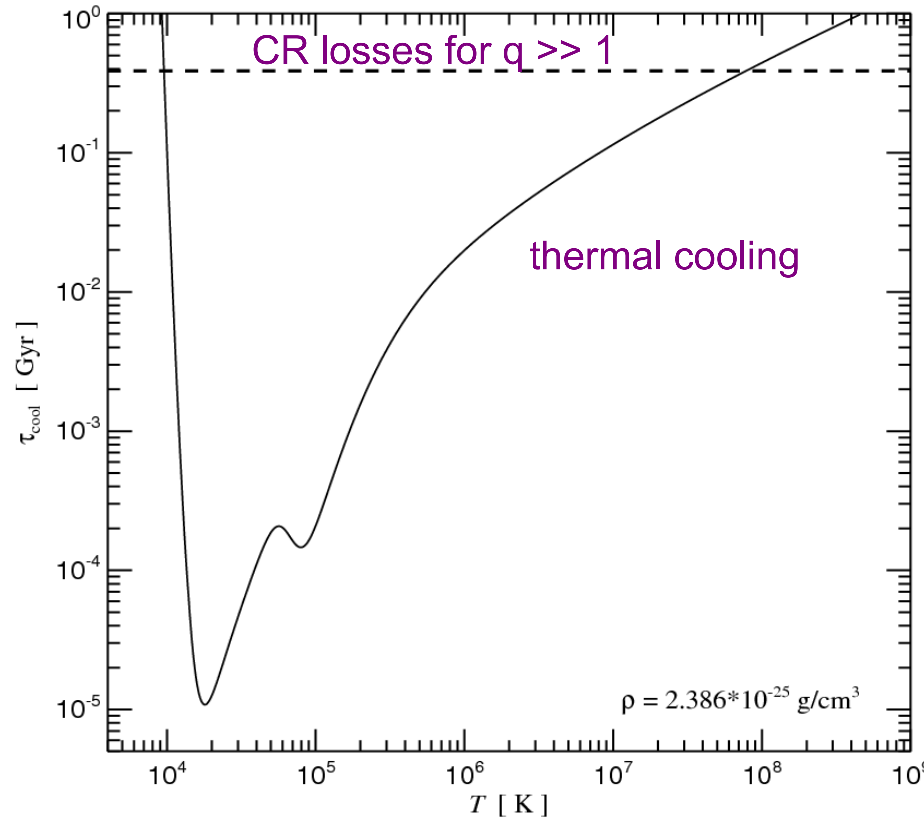
- Coulomb losses
- hadronic interactions, mostly pion production
- Bremsstrahlung (negligible for protons)

CRs have a larger dissipation timescale than thermal cooling, and the softer equation of states keeps the pressure high in outflows

COMPARISON OF DISSIPATION TIMESCALES

Jubelgas et al. (2006)





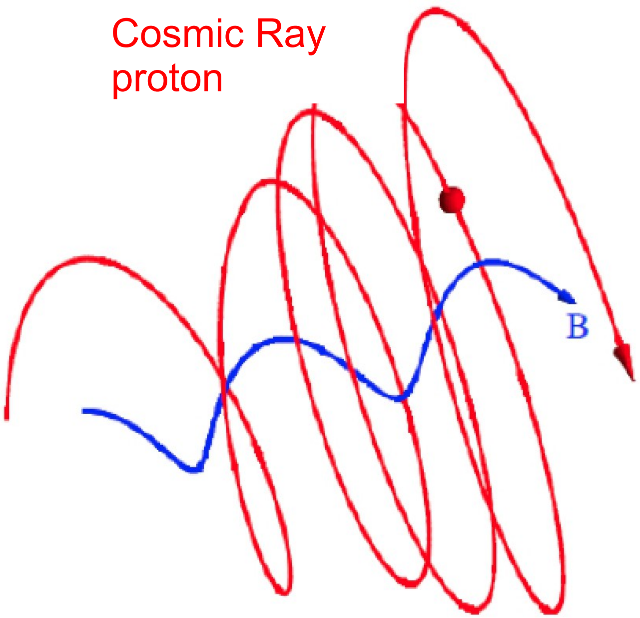
Also important: Softer equation of state, $P \sim \rho^{4/3}$ (buoyancy effects!)

And: CR dissipation dumped into thermal reservoir, increasing the pressure.

$$\Delta E/V = P/(\gamma - 1) = P_{\rm cr}/(\gamma_{\rm cr} - 1)$$

The CR dynamics is coupled to magnetic fields permeating the gas

INTERACTIONS OF COSMIC RAYS AND MAGNETIC FIELDS



Cosmic rays scatter on magnetic fields – this lets them exert a pressure on the thermal gas, and diffuse relative to its rest frame.

Streaming instability:

- CRs can in principle move rapidly along field lines (with c), which acts to reduce any gradient in their number density.
- But if $c_s > v_A$, CR excite Alfven waves (streaming instability)
- scattering off this wave field in turn limits the CR bulk speed to a much smaller, effective streaming speed v_{str}
- streaming speed: $$\mathbf{v}_{\rm str} = -v_{\rm str} \frac{\nabla P_{\rm cr}}{|\nabla P_{\rm cr}|}$$ $$v_{\rm str} = \lambda \max(c_S, v_A)$$ $$\lambda \sim 1$$

The CR transport complicates fluids dynamics considerable

COSMIC RAY DYNAMICS WITHOUT SOURCE AND SINK TERMS

$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla} \cdot \mathbf{F} = \boldsymbol{S}$$

$$\boldsymbol{U} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \varepsilon \\ \varepsilon_{\mathrm{cr}} \\ \boldsymbol{B} \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v}^{\mathrm{T}} + P\mathbf{1} - \boldsymbol{B}\boldsymbol{B}^{\mathrm{T}} \\ (\varepsilon + P)\boldsymbol{v} - \boldsymbol{B}\,(\boldsymbol{v}\cdot\boldsymbol{B}) \\ \varepsilon_{\mathrm{cr}}\boldsymbol{v} + (\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{st}} - \kappa_{\varepsilon}\boldsymbol{b}\,(\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\mathrm{cr}}) \\ \boldsymbol{B}\boldsymbol{v}^{\mathrm{T}} - \boldsymbol{v}\boldsymbol{B}^{\mathrm{T}} \end{pmatrix}, \quad \boldsymbol{S} = \begin{pmatrix} 0 \\ \mathbf{0} \\ P_{\mathrm{cr}}\,\boldsymbol{\nabla}\cdot\boldsymbol{v} - \boldsymbol{v}_{\mathrm{st}}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}} + \Lambda_{\mathrm{th}} + \Gamma_{\mathrm{th}} \\ -P_{\mathrm{cr}}\,\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}} + \Lambda_{\mathrm{cr}} + \Gamma_{\mathrm{cr}} \\ \mathbf{0} \end{pmatrix}$$

$$P = P_{\mathrm{th}} + P_{\mathrm{cr}} + \frac{\boldsymbol{B}^2}{2} \qquad \varepsilon = \varepsilon_{\mathrm{th}} + \frac{\rho \boldsymbol{v}^2}{2} + \frac{\boldsymbol{B}^2}{2} \qquad \boldsymbol{v}_{\mathrm{st}} = -\frac{\boldsymbol{B}}{\sqrt{\rho}}\,\mathrm{sgn}(\boldsymbol{B}\cdot\boldsymbol{\nabla}P_{\mathrm{cr}})$$

cosmic ray streaming, nasty(!) numerically

Energy equation:

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla}\cdot\left[\varepsilon_{\mathrm{cr}}(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}}) - \kappa_{\varepsilon}\boldsymbol{b}\,(\boldsymbol{b}\cdot\boldsymbol{\nabla}\varepsilon_{\mathrm{cr}})\right] = -P_{\mathrm{cr}}\,\boldsymbol{\nabla}\cdot(\boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}}) + \Lambda_{\mathrm{cr}} + \Gamma_{\mathrm{cr}}$$

anisotropic diffusion

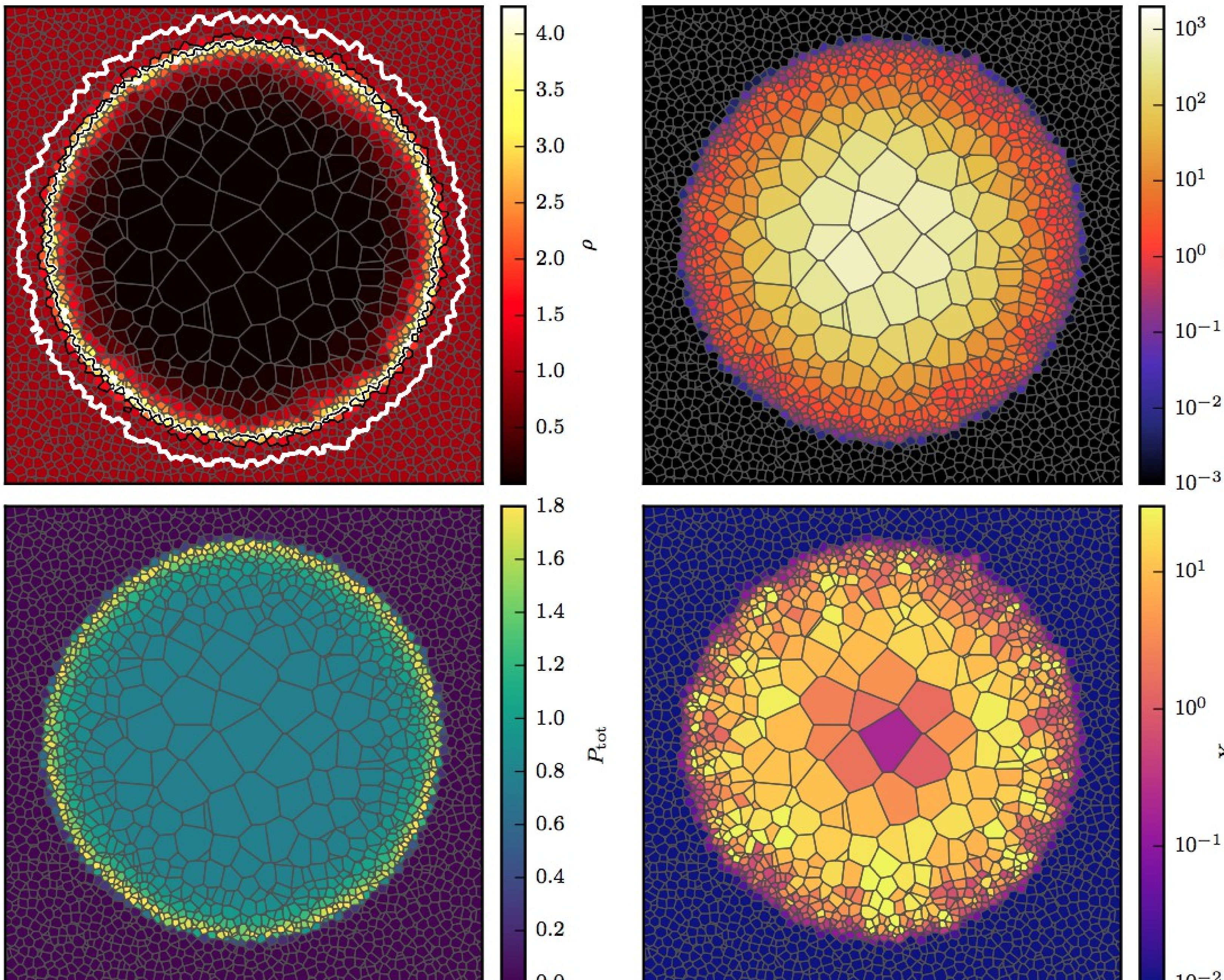
Cosmic ray poduction at a spherical blast wave

SLICES THROUGH THE CENTER

$\zeta = 0.5$

density and shock zone

total pressure



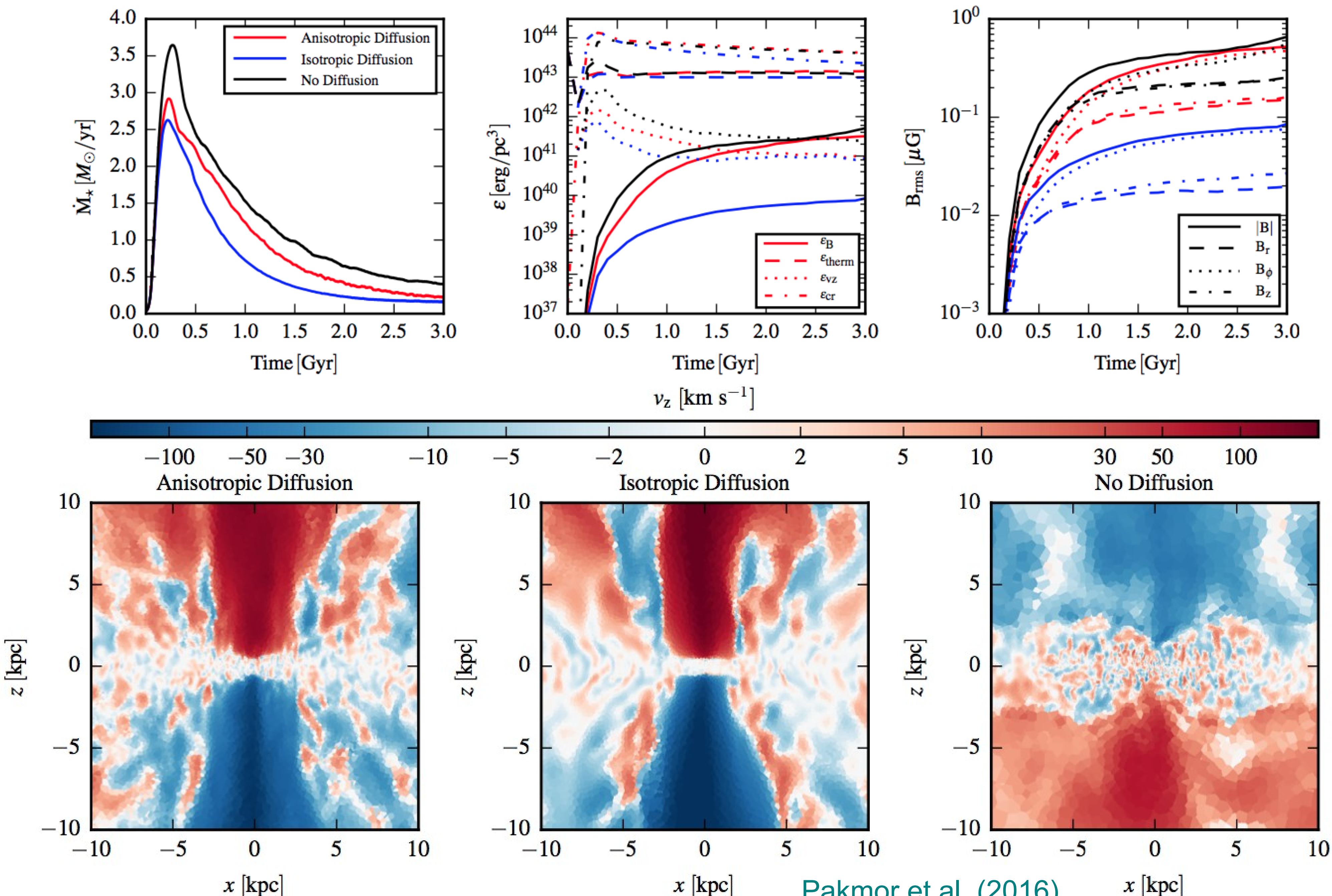
CR egy per mass

CR over thermal pressure

Pfrommer et al. (2016)

Transport processes of CRs are critical for driving their winds

COMPARISON OF DISK GALAXY EVOLUTION WITH DIFFERENT COSMIC RAY PHYSICS



Pakmor et al. (2016)

The runs with isotropic diffusion slow down the galactic dynamo

FIELD AMPLIFICATION IN RUNS WITH ISOTROPIC AND ANISOTROPIC DIFFUSION

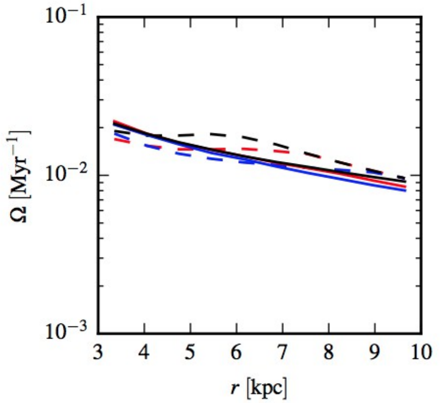
Dynamo in axisymmetric disk:
(neglecting Ohmic diffusion)

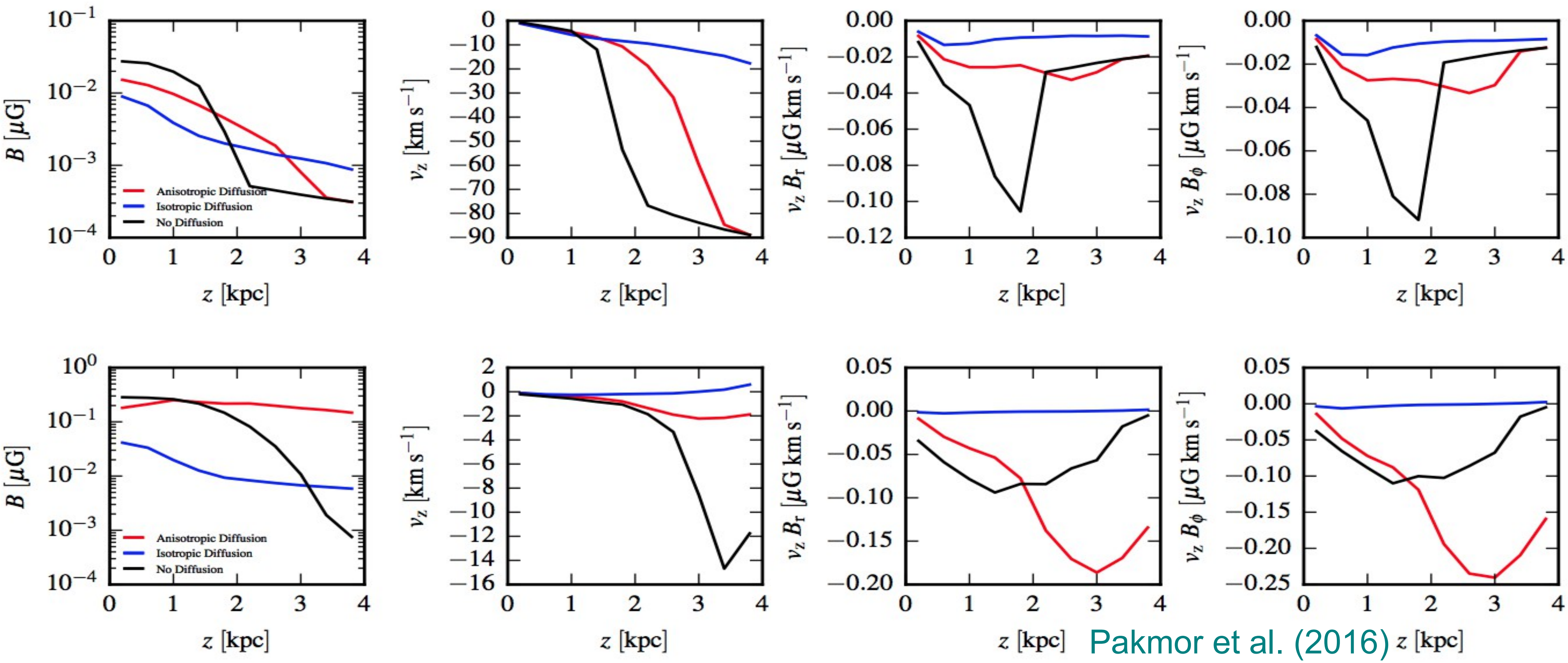
$$\frac{\partial \bar{B}_r}{\partial t} = -\frac{\partial}{\partial z}\left(\bar{v}_z \bar{B}_r + \mathcal{E}_\phi\right)$$

$$\frac{\partial \bar{B}_\phi}{\partial t} = -\frac{\partial}{\partial z}\left(\bar{v}_z \bar{B}_\phi + \mathcal{E}_r\right) + q\Omega_0 \bar{B}_r$$

Shukurov et al. (2006)

All terms similar, except that the gradients in the strength of the radial and vertical magnetic field are shallower for the isotropic diffusion run – this slows down the B-field amplification.





Pakmor et al. (2016)

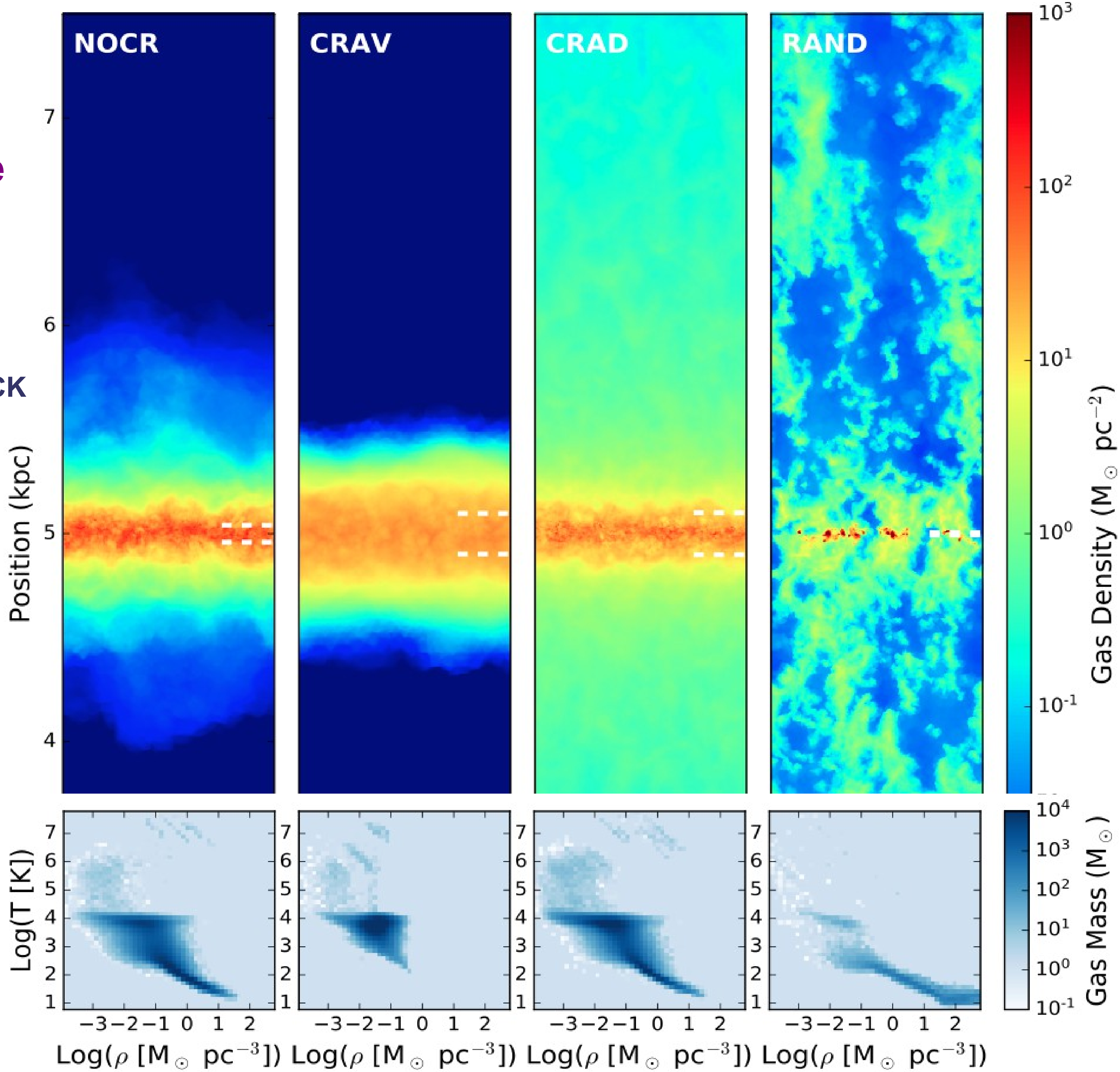
Stratified-box simulations of SN feedback demonstrate the importance of CRs for driving outlows

DIFFERENT MODES OF SUPERNOVA FEEDBACK

with gas self-gravity and stationary stellar potential

self-shielding with TreeCol

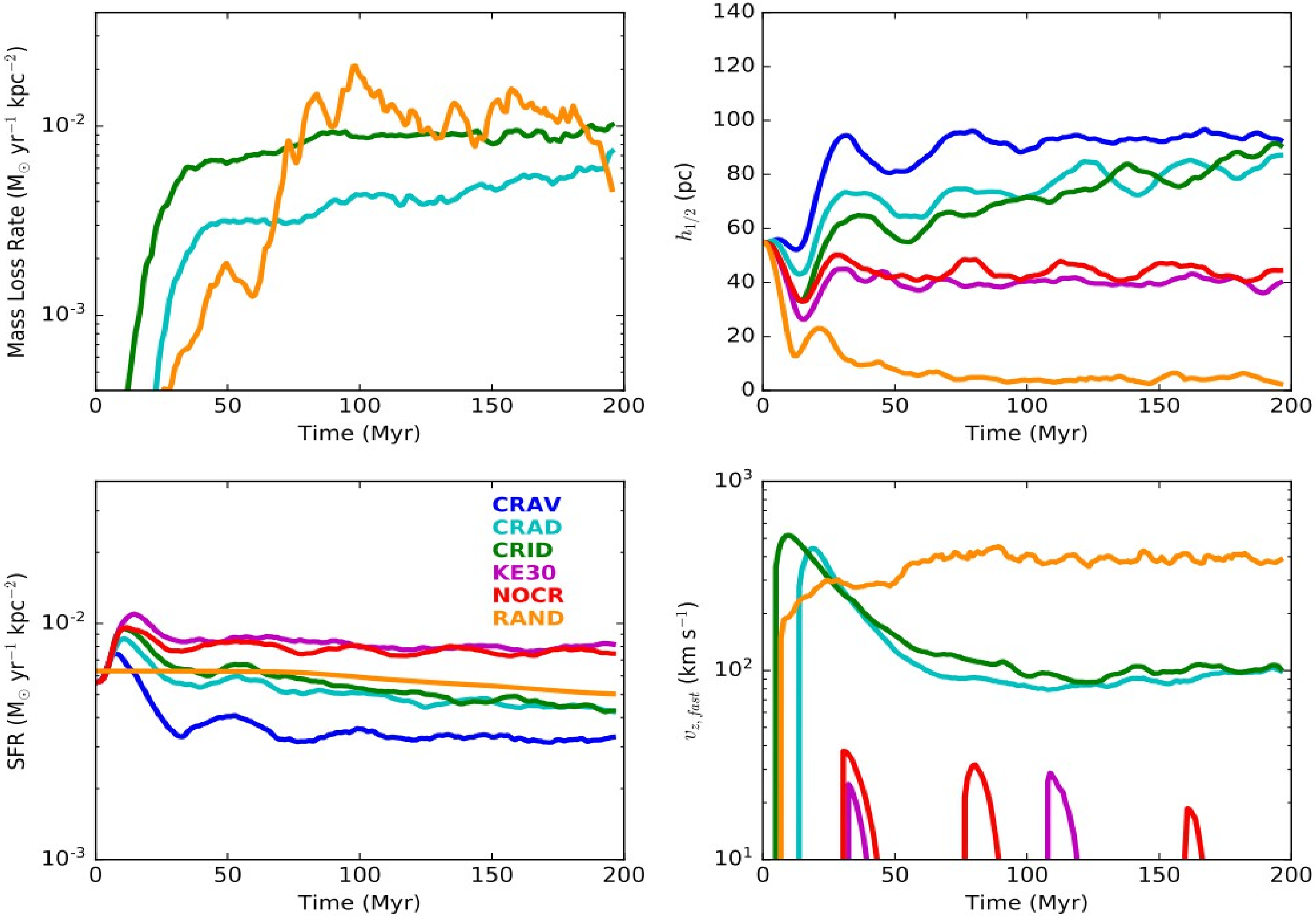
$$\Sigma_0 = 10\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}$$
$$f_g = 0.1$$
$$m_t = 10\ \mathrm{M}_\odot$$
$$\varepsilon = 0.165\ \mathrm{pc}$$



Simpson et al. (2016)

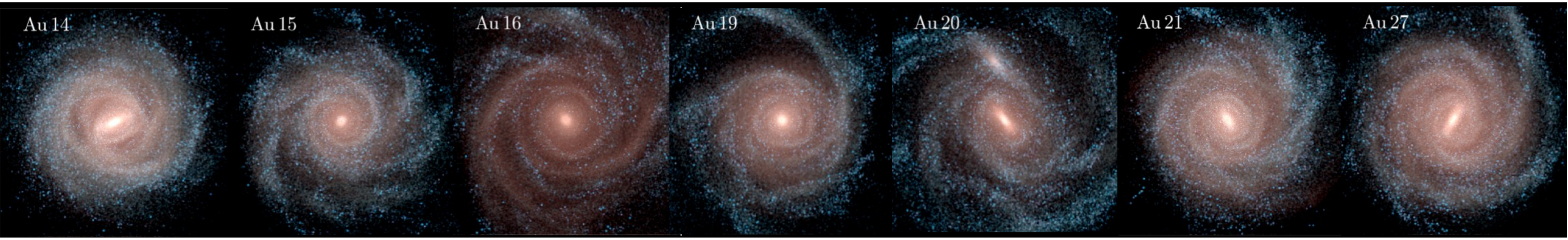
Cosmic ray transport processes reduce the star formation and sustain mass loaded winds

COMPARSON OF THE TIME EVOLUTION FOR DIFFERENT FEEDBACK MODELS



Simpson et al. (2016)

Summary: Lots of progress, but many open questions!



Stellar feedback

- Which physics regulates star formation?
- How important are cosmic rays, magnetic fields, and radiative effects?
- Does baryonic physics modify the dark matter distribution?
- What drives galactic winds and outflows?

Black hole impact on galaxy formation

- Where do supermassive black holes come from?
- What is the origin of BH – galaxy scaling relations?
- How does energy liberated by accretion couple to host galaxies?
- What is the expected merger rate of supermassive black holes?

Numerical techniques

- How we model in a single code a vast range in time- and length scales?
- How can we systematically couple theoretical models computed on different scales?
- Which numerical schemes are efficient and sufficiently accurate?