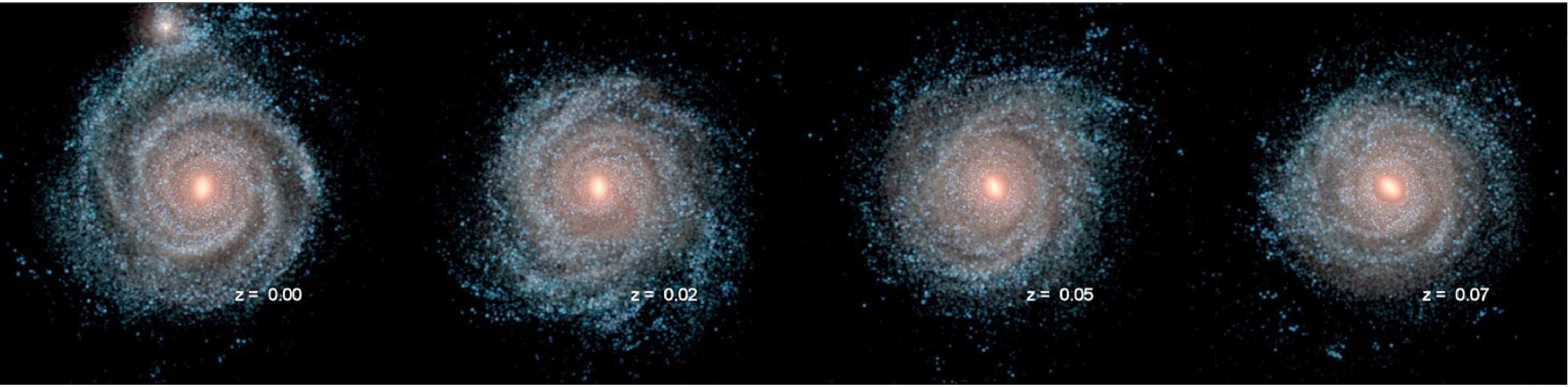
Winds and their impact in simulations of Milky Way-sized galaxies

Volker Springel



- A cosmological subgrid feedback model (winds driven by hand)
- Some results for Milky Way-sized galaxies
- Adding magnetic fields

Heidelberg Institute for Theoretical Studies
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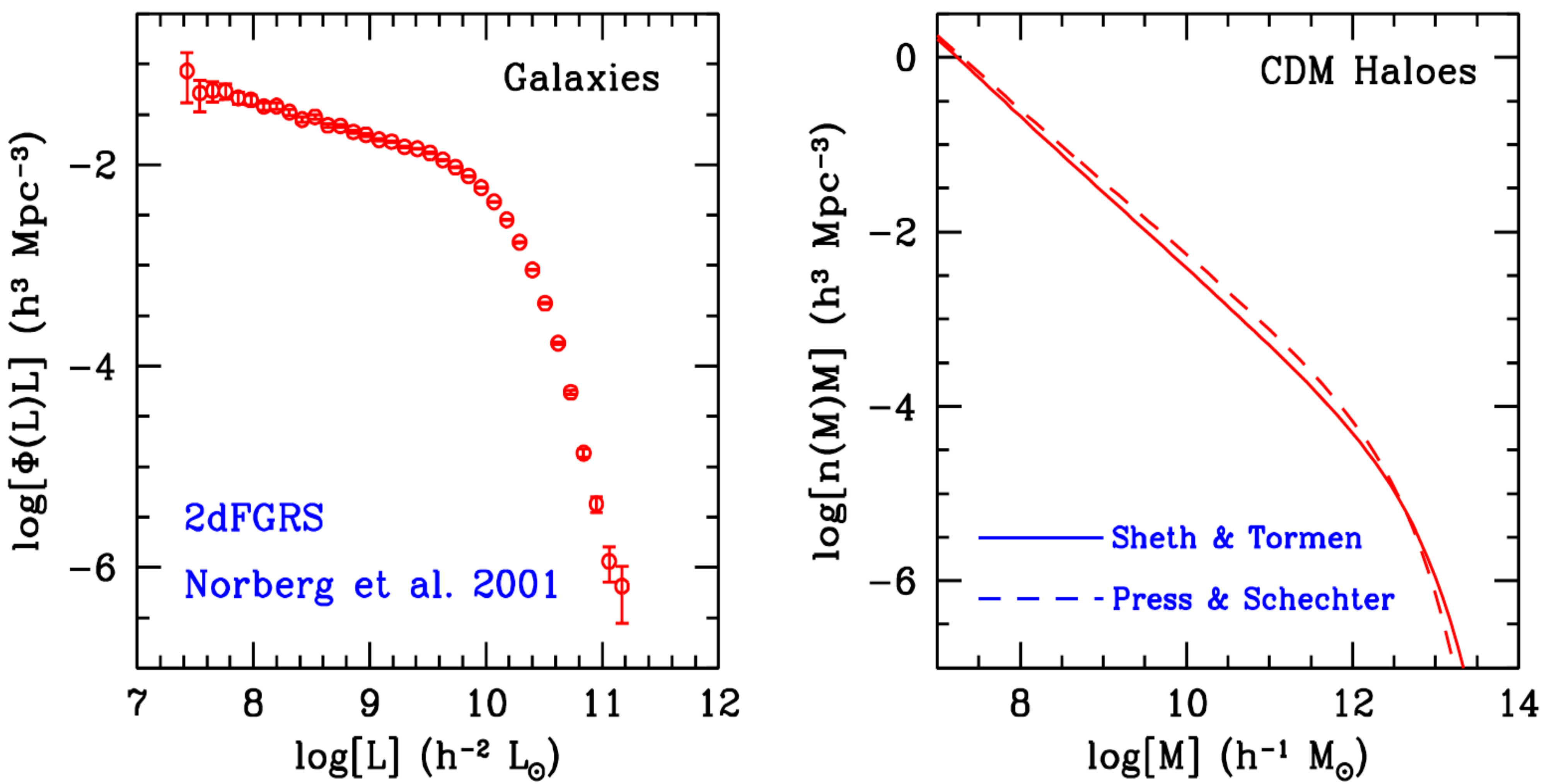
"Fire Down Below" Conference
Santa Barbara, April 2014

A long standing issue in galaxy formation theory: The shapes of the CDM halo mass function and the galaxy luminosity function are very different

THE OBSERVED LF COMPARED TO THE SHAPE OF THE CDM HALO MASS FUNCTION

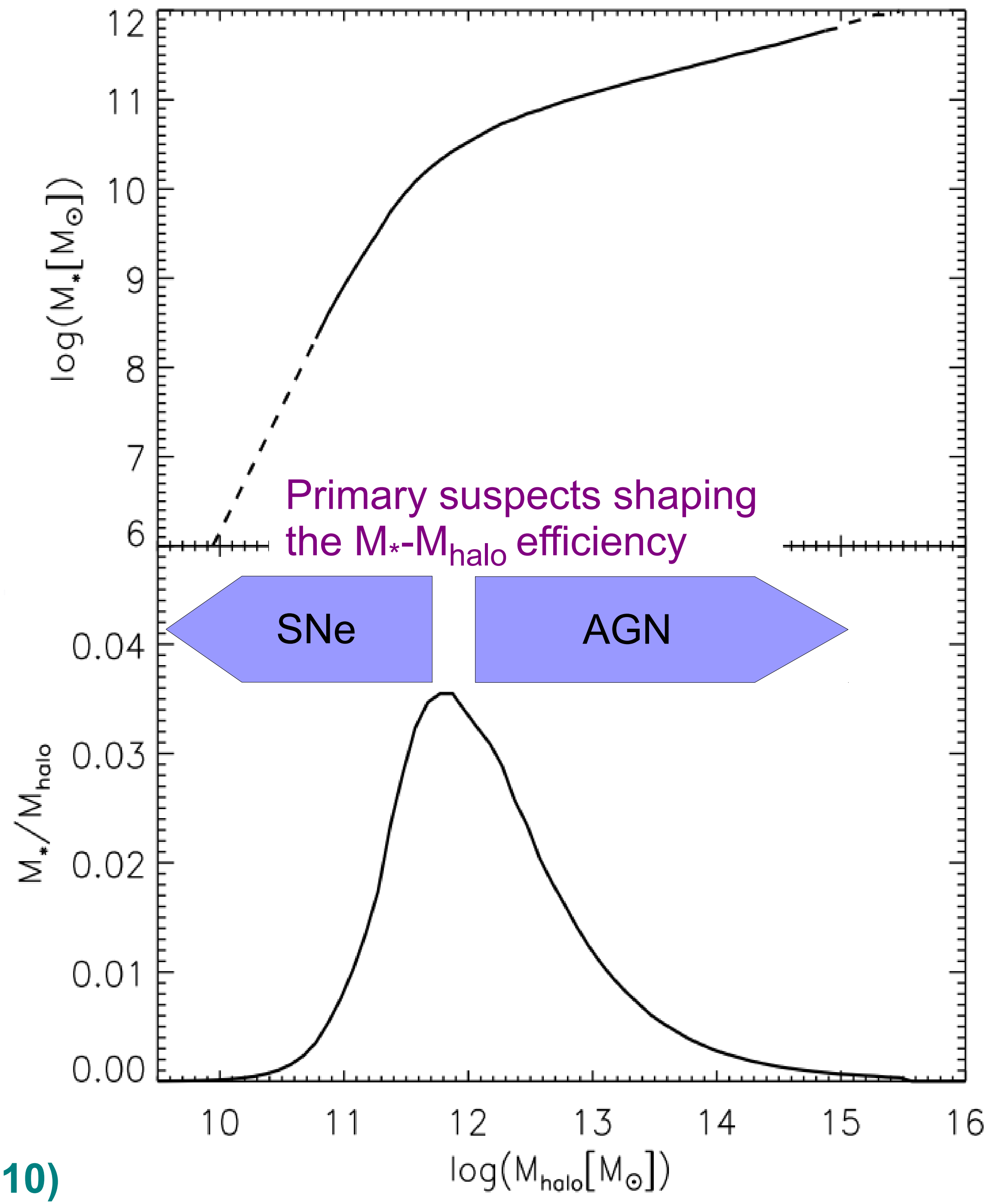


van den Bosch et al. (2004)

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

STELLAR MASSES FROM SDSS/DR7 MATCHED TO ΛCDM SIMULATION EXPECTATIONS

Assumption:
Stellar mass is monotonically increasing with halo mass



Guo, White & Boylan-Kolchin (2010)

Galaxy formation physics for cosmological simulations in AREPO

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)

Motivation for an **explicit subresolution treatment** of star formation and feedback

SUBRESOLUTION MODELS AS A NECESSARY INTERMEDIATE STEP FOR GALAXY FORMATION SIMULATIONS

Goals:

- Allow truly cosmological simulations of galaxy formation in which the global galaxy population and its relation to dark matter and diffuse cosmic gas can be studied.
- Inform about the required properties of small-scale physics for keeping ΛCDM viable.
- Constrain physical model building on small-scale, in particular help to identify the most crucial physics regulating galaxy formation.

Approach:

- Introduce a physically motivated but parameterized treatment of subgrid (feedback) processes to capture their backreaction onto larger, resolved scales.

Pros:

- Makes problem tractable.
- Obtain numerically well-posed boundary between sub-grid and resolved scales, allows numerically resolved/converged results.

Cons:

- Does not help at all to understand the "micro-physics" of feedback creation, can hence only be an intermediate step.

This is complementary to attempts to push the subresolution scale down to ISM scales even in cosmological zoom-in simulations.


Vogelsberger et al. (2013)

Parameterization of wind feedback

ENERGY AND MOMENTUM DRIVEN WINDS

Basic parameterization of energy flux in wind:

$$\frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 = \epsilon_{\rm SN,w} \dot{M}_*$$

Mass loading factor:

$$\eta \equiv \dot{M}_{\rm w} / \dot{M}_*$$

(Springel & Hernquist 2003)

We assume a wind speed proportional to the local potential well depth:

$$v_{\rm w} = \kappa_{\rm w}\, \sigma_{\rm DM}^{1D}$$

In general, one may assume an energy- or momentum scaling of the wind:

$$\eta_{\rm w} = \frac{1}{v_{\rm w}^2}\left({\rm egy}_{\rm w} + \sqrt{{\rm egy}_{\rm w}^2 + v_{\rm w}^2\, {\rm mom}_{\rm w}^2}\right)$$

(see also Openheimer & Dave 2006)

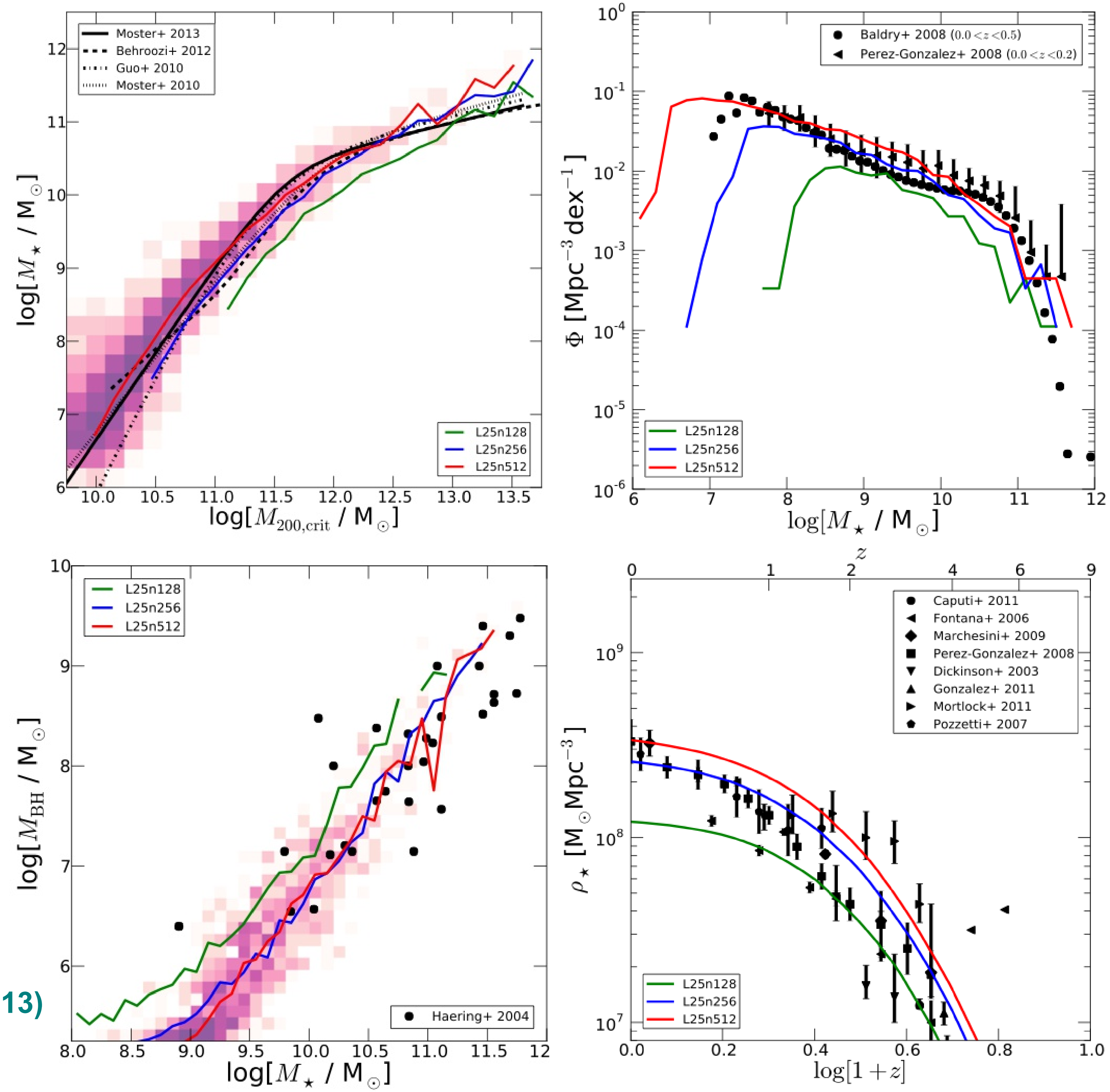
We however achieve the best results with a pure energy-scaling.
(Puchwein & Springel 2013, Vogelsberger et al. 2013)

The two parameters of the model, wind-speed scaling coefficient and energy fraction in the wind are tuned to obtain a reasonable stellar mass function.

Our “Illustris”-Projekt parameters are: $\kappa_{\rm w} = 3.7$ wind kinetic energy flux per supernova: 1.09×10^{51} erg

Our new physics models match a large range of key observables quite well and produce a consistent galaxy population in ΛCDM

STELLAR MASS FUNCTION, BLACK HOLE/STELLAR MASS RELATION, AND CUMULATIVE SFR HISTORY

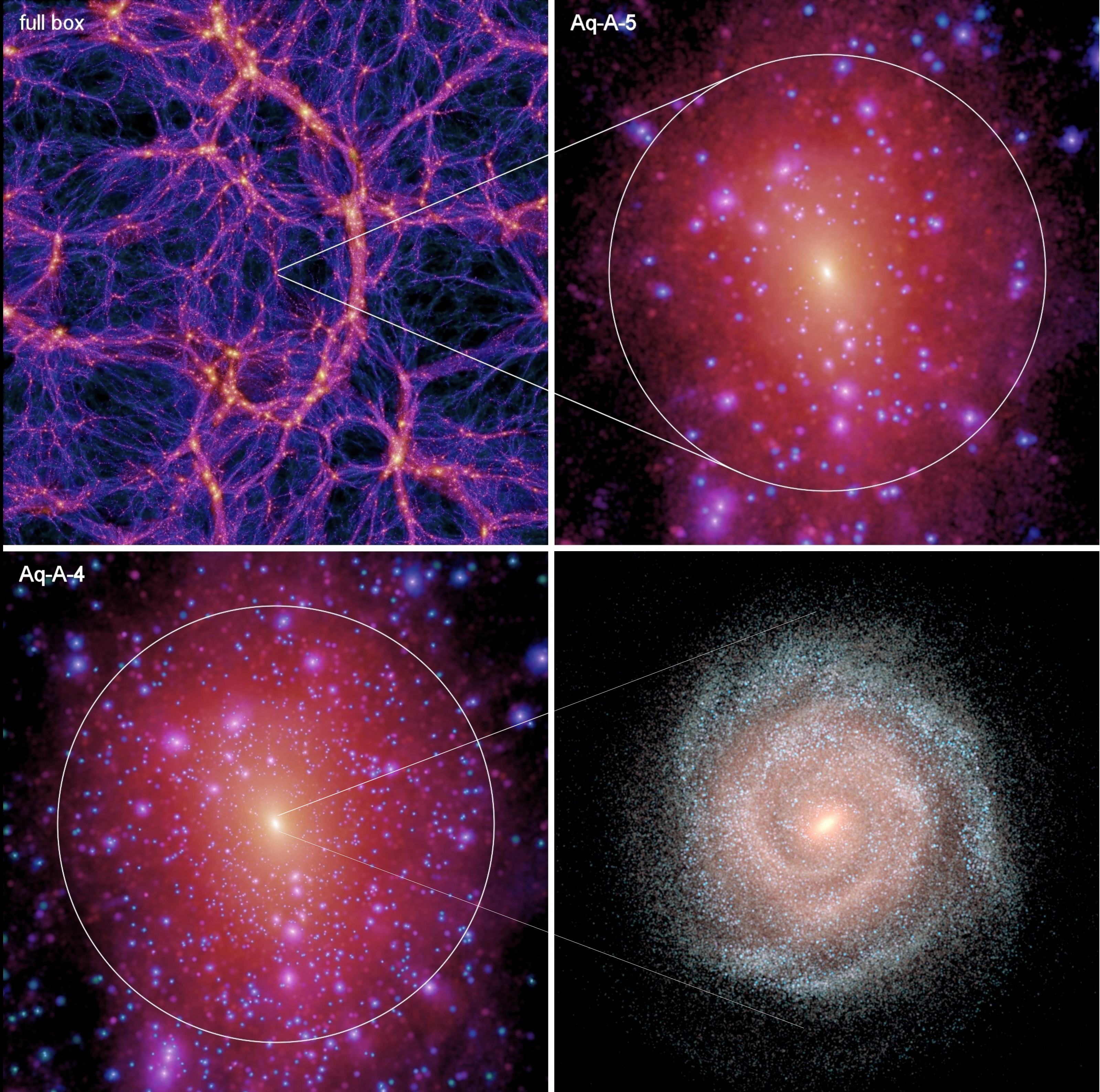


Vogelsberger et al. (2013)

Torrey et al. (2014)

We have applied the Illustris model also to zoom-in simulations of the Aquarius systems

STELLAR DISTRIBUTION AT THE CENTRE OF THE Aq-C-4 HALO



We have applied the physics parameterization developed for “Illustris” to the Aquarius zoom-in initial conditions of Milky Way-sized galaxies

PRIMARY NUMERICAL PARAMETERS OF SIMULATED HALOS AT Z=0

Run	R_{vir} (kpc)	M_{tot} ($10^{10}M_\odot$)	M_{gas} ($10^{10}M_\odot$)	$M_\star$ ($10^{10}M_\odot$)	M_{dm} ($10^{10}M_\odot$)	N_{cells}	$N_\star$	N_{dm}	m_{gas} ($10^5M_\odot$)	m_{dm} ($10^5M_\odot$)	f_b
Aq-A-5	239.0	169.13	11.21	4.95	152.95	203822	152476	579342	5.03	26.40	0.55
Aq-B-5	183.0	75.93	4.08	4.88	66.97	108806	234310	444557	3.35	17.59	0.70
Aq-C-5	234.5	159.74	7.09	7.00	145.64	163726	273124	674547	4.11	21.59	0.51
Aq-D-5	240.2	171.67	7.59	12.10	151.97	159591	442966	657760	4.40	23.10	0.68
Aq-E-5	206.3	108.74	3.58	8.75	96.39	101041	431167	550757	3.33	17.50	0.67
Aq-F-5	209.0	113.05	8.65	8.86	95.51	331692	620784	791829	2.30	12.06	0.96
Aq-G-5	204.4	105.83	11.43	6.00	88.40	346061	328784	708979	2.83	14.88	1.03
Aq-H-5	183.1	76.06	2.95	5.01	68.10	91792	273228	525235	2.96	15.56	0.61
Aq-C-6	235.5	161.82	9.86	5.95	146.00	28702	26803	84525	32.90	172.73	0.57
Aq-C-4	234.4	159.48	8.39	5.31	145.71	1526514	1637981	5399079	0.51	2.70	0.49

halos loose “only” up to half their baryons due to outflows, and some none

Initial analysis papers:

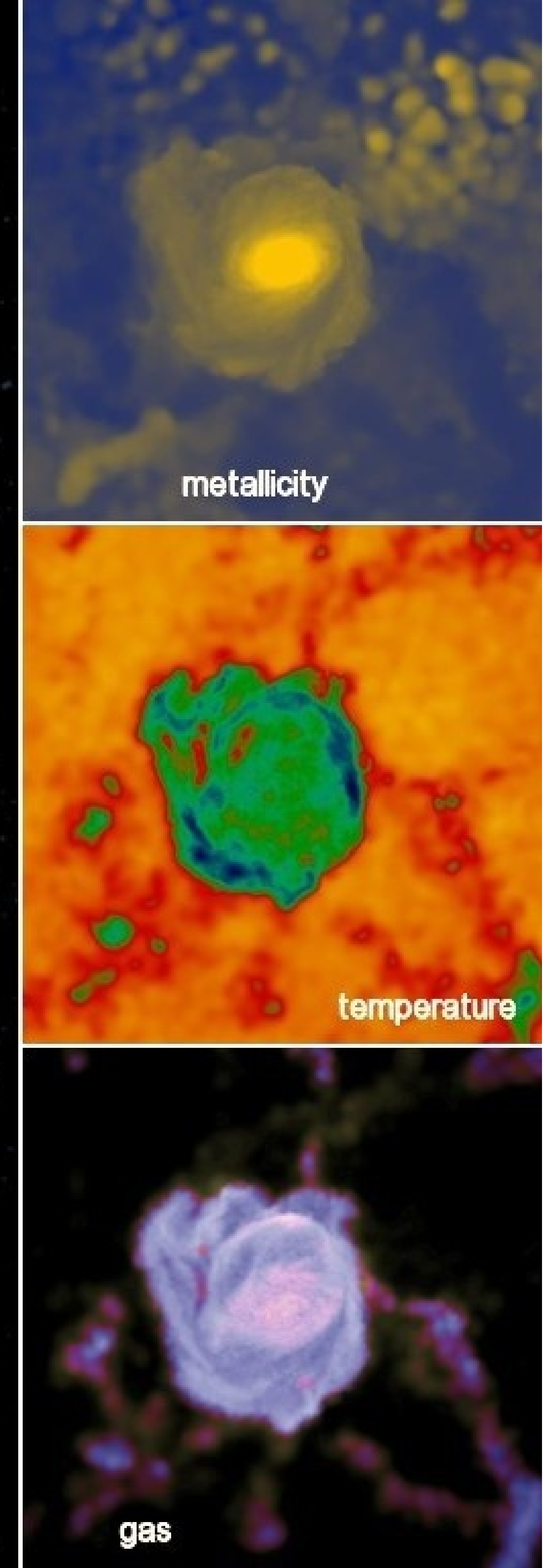
Marinacci, Pakmor & Springel (2014, MNRAS, 437, 1750)
Marinacci, Pakmor, Springel & Simpson (2014, arXiv:1403.4934)

Additional runs with magnetic fields:

Pakmor, Marinacci & Springel (2014, ApJL, 783, L20)

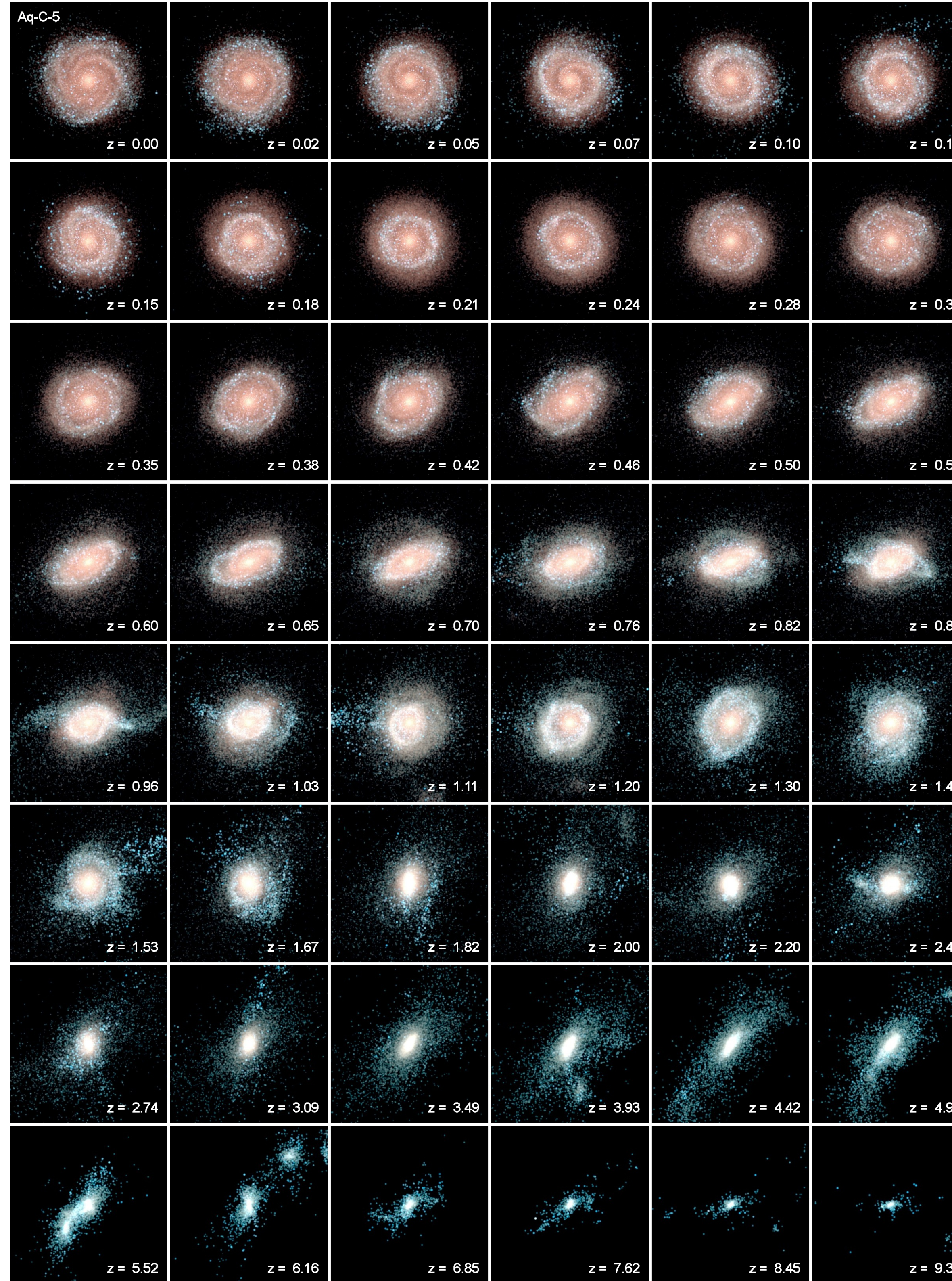
Visualizing the formation of a galaxy over time highlights the complexity of its dynamics over many dynamical times

AQ-C-5 SIMULATION (WITH TOO FEW OUTPUTS TIMES...)



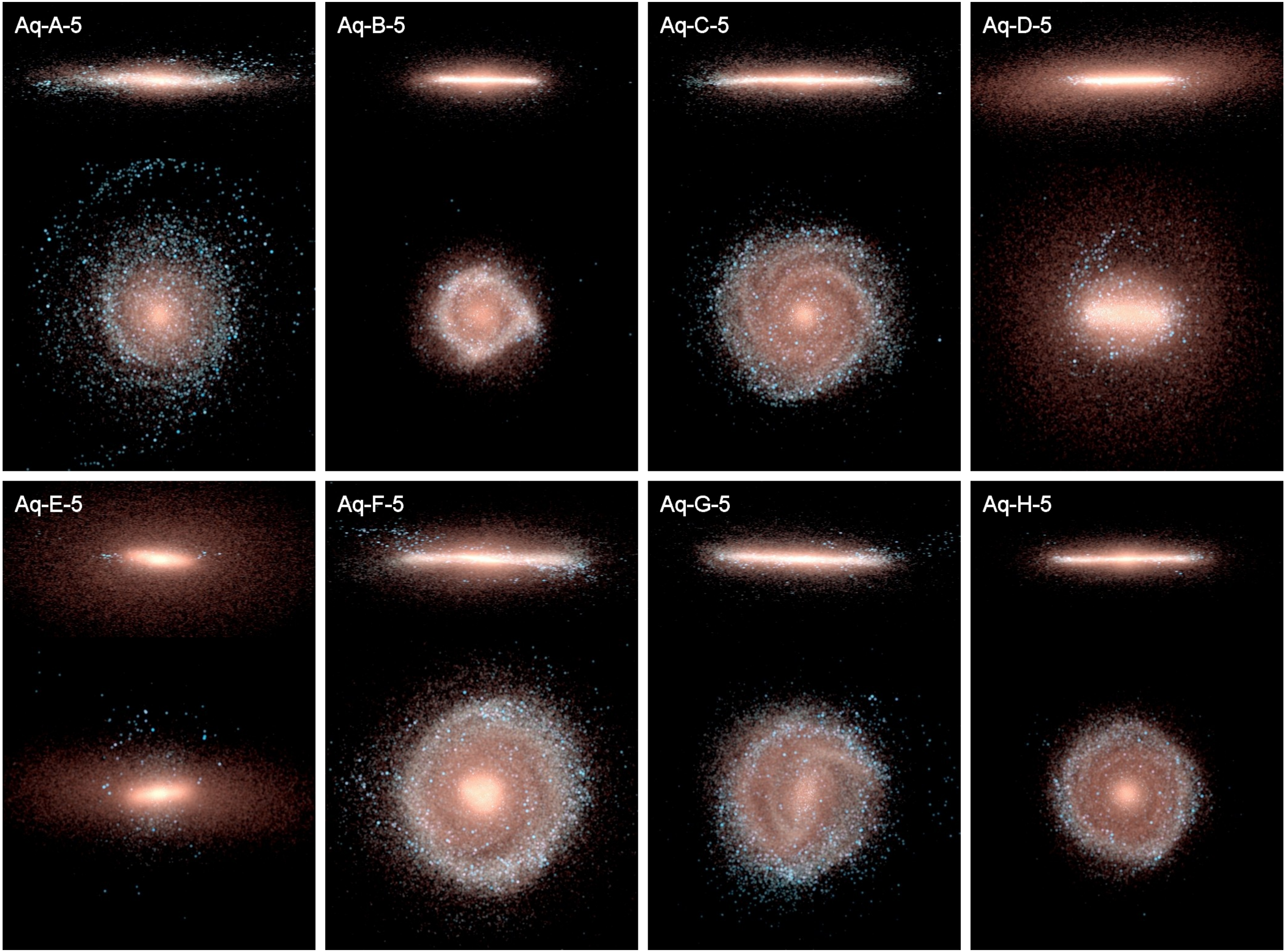
They heyday of blue disc formation lies between redshifts z=0.5 and 1.5

STELLAR DISTRIBUTION OF A FORMING MILKY WAY LIKE GALAXY



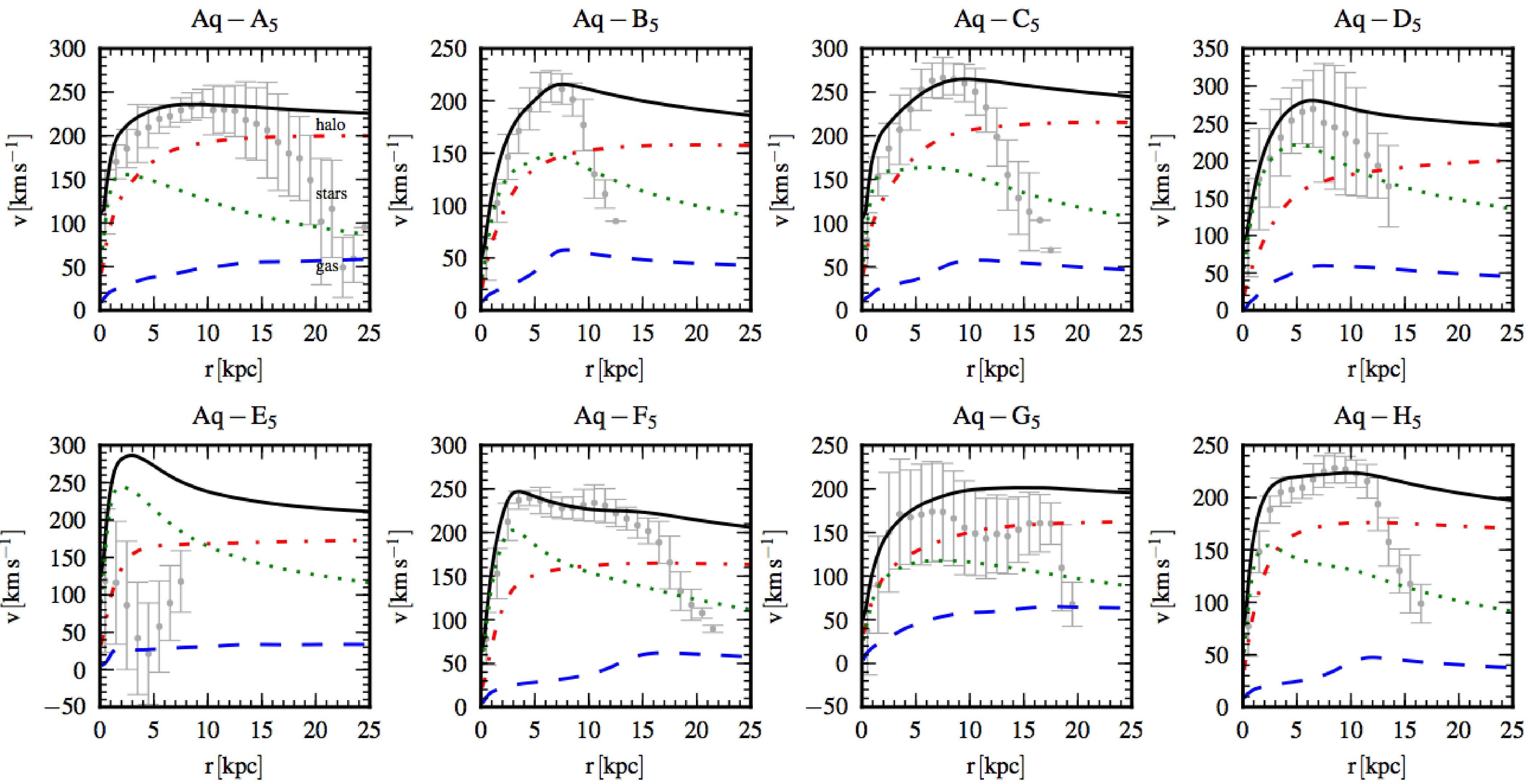
Marinacci, Pakmor & Springel. (2013)

Our set of 8 galaxies formed in Milky Way sized dark matter halos



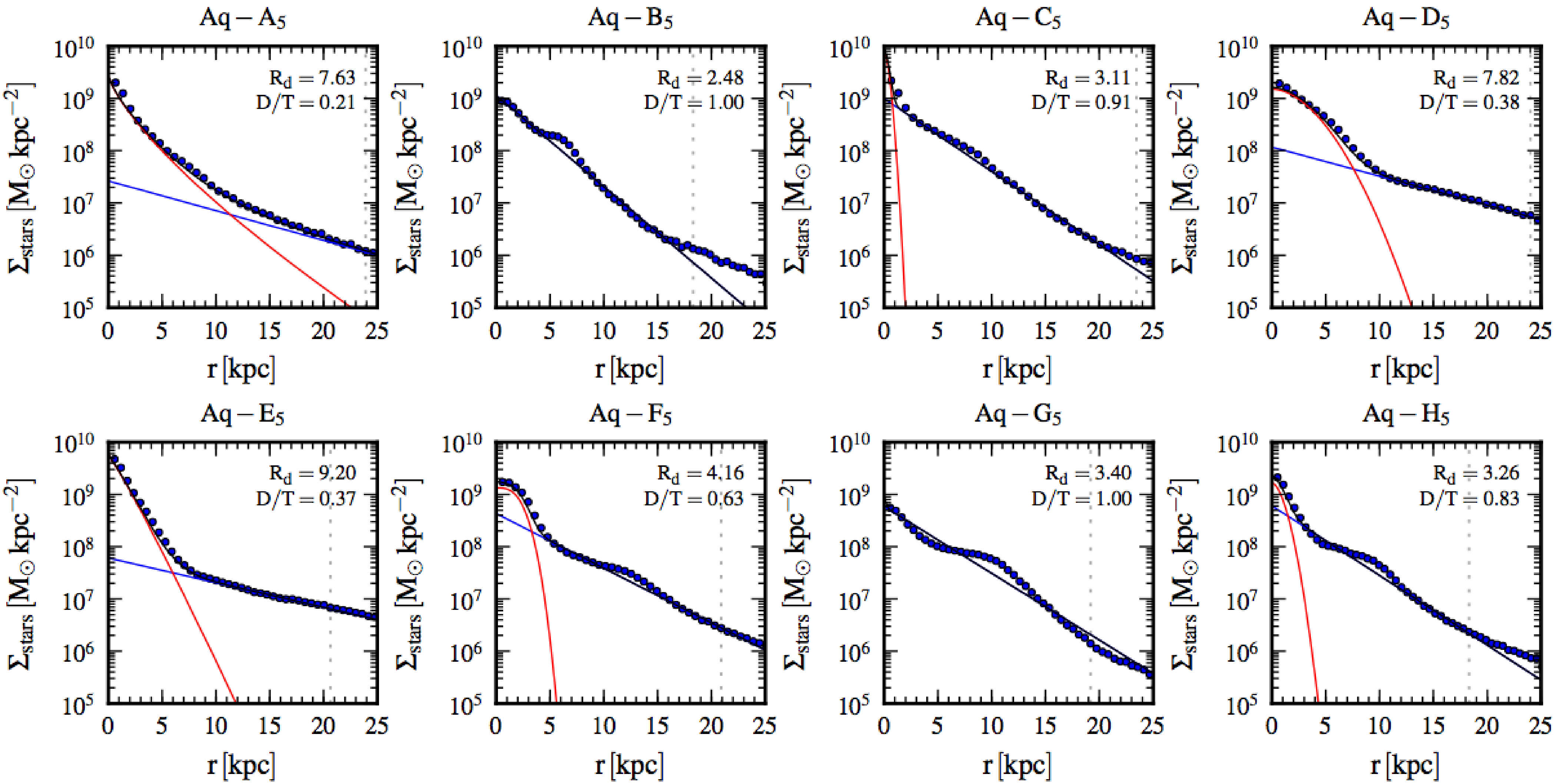
The rotation curves have reasonable shapes, most of them are (almost) flat

ROTATION CURVES OF OUR SIMULATED MILKY WAY-SIZED GALAXIES



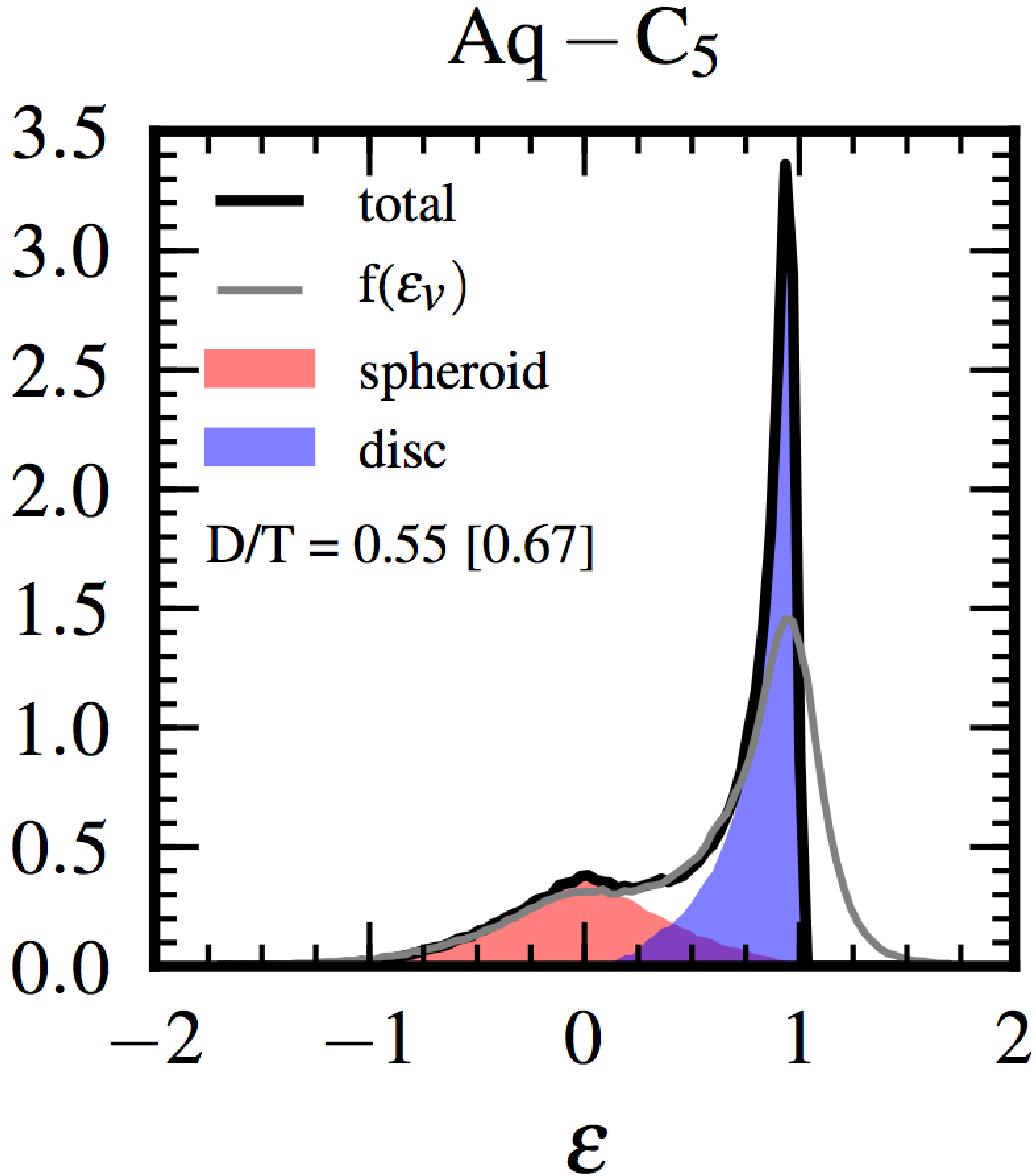
The stellar surface density profiles are close to exponential, with (sometimes) an obvious bulge component

STELLAR SURFACE DENSITY PROFILES WITH EXPONENTAL AND SERSIC FITS



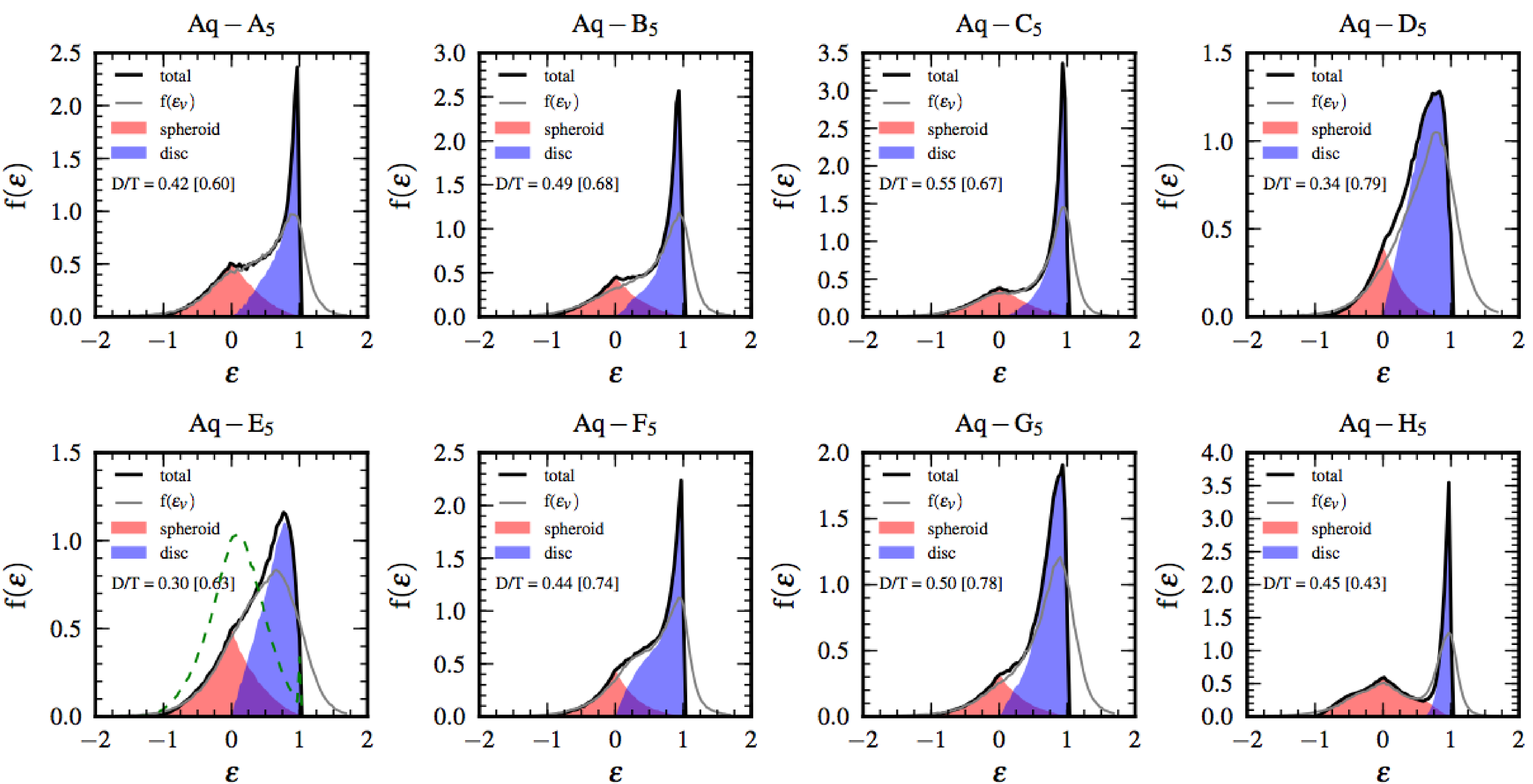
A kinematic analysis can be used to reliably quantify the relative amount of disk and bulge stars

ECCENTRICTY DISTRIBUTION FOR ALL STARS IN THE AQ-C SYSTEM



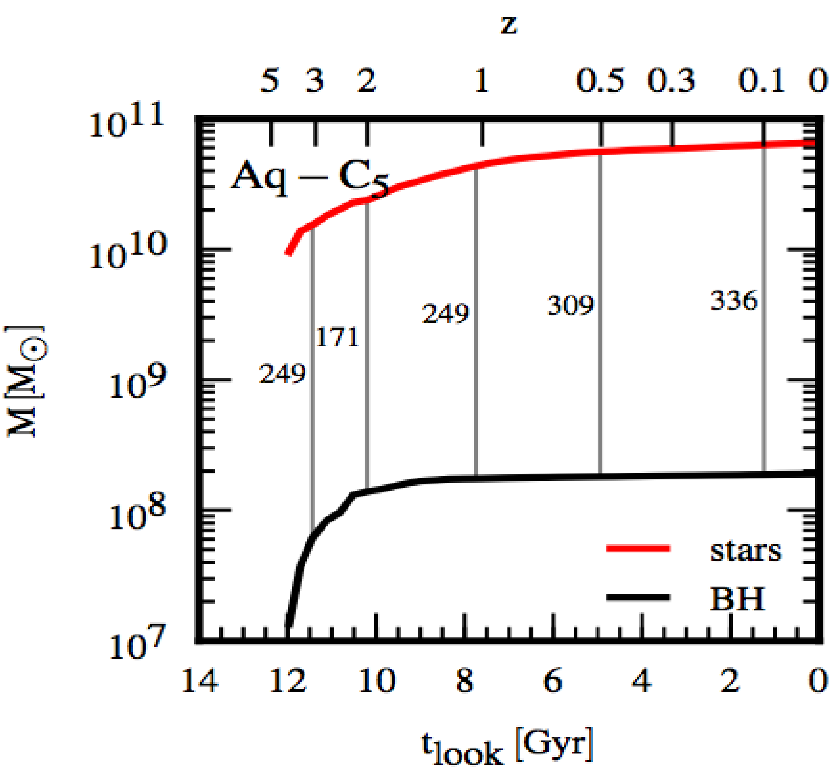
All our galaxies show a significant disc component with a subdominant bulge

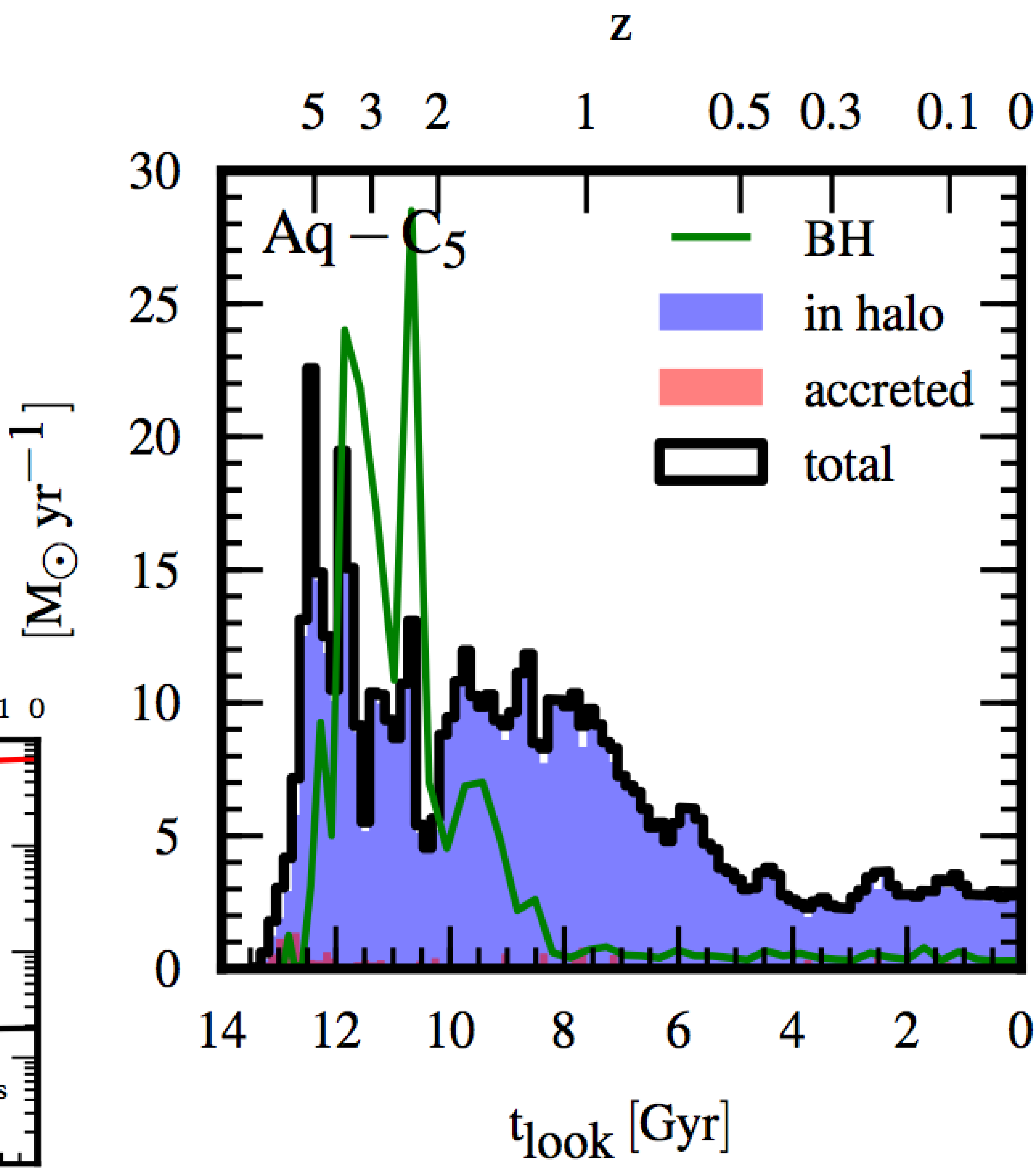
ECCENTRICTY DISTRIBUTIONS STARS IN THE AQUARIUS SYSTEMS



Starbursts at high redshift correlate with episodic black hole growth

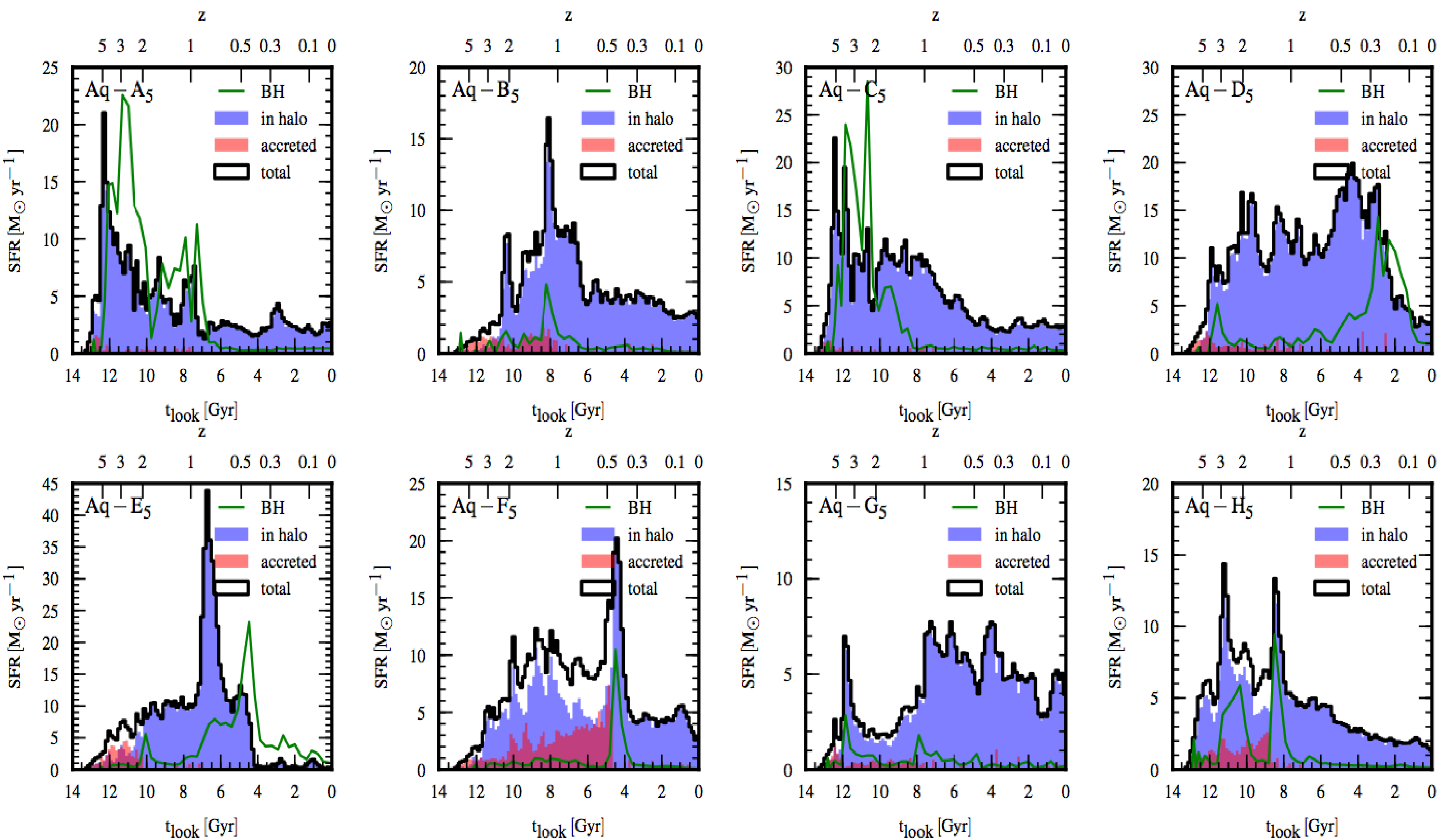
STAR FORMATION HISTORY OF THE AQ-C SYSTEM





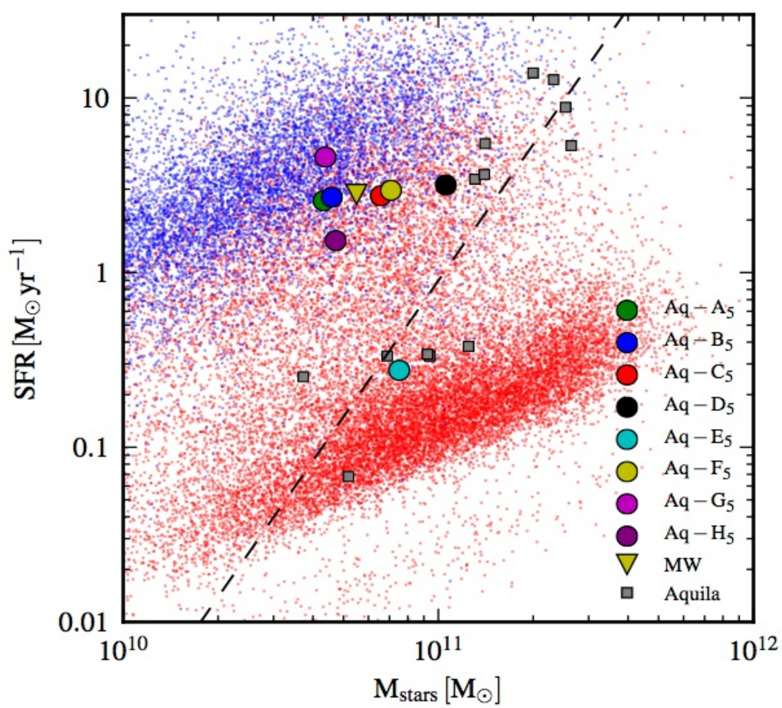
Most stars form “in-situ”, and the black hole growth is largely over by z~1

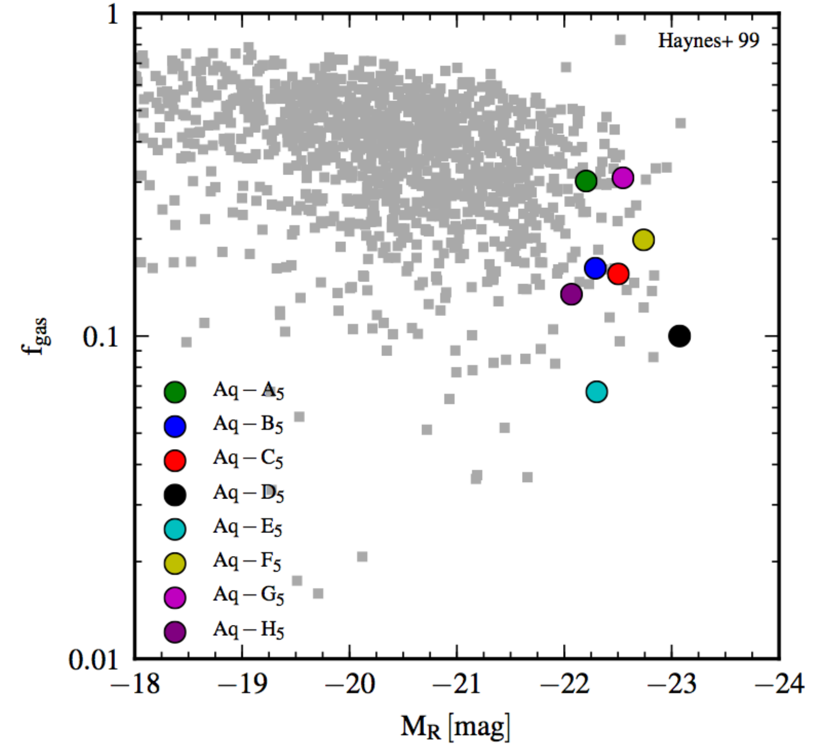
STAR FORMATION RATE AND BLACK HOLE ACCRETION RATE AS A FUNCTION OF LOOKBACK TIME

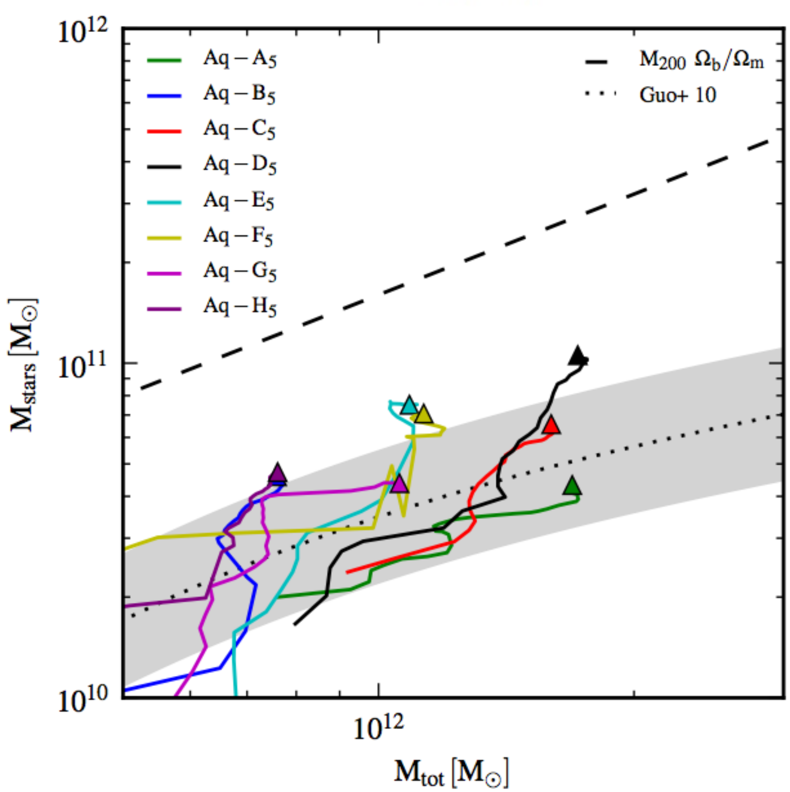


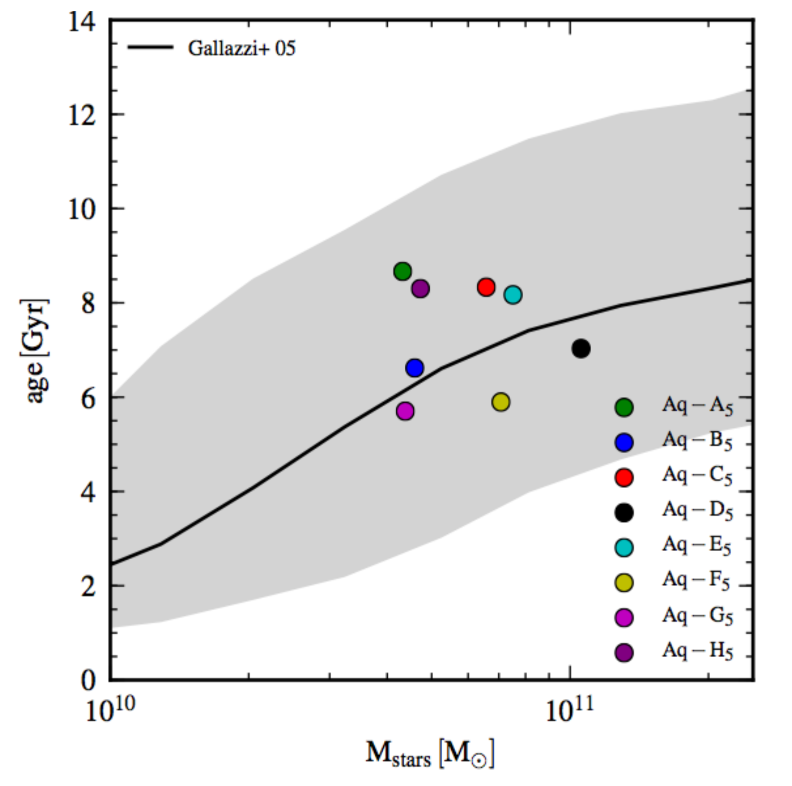
For the first time, simulated disc galaxies match the properties of the Milky Way

VARIOUS PROPERTIES OF THE AQ-C GALAXY



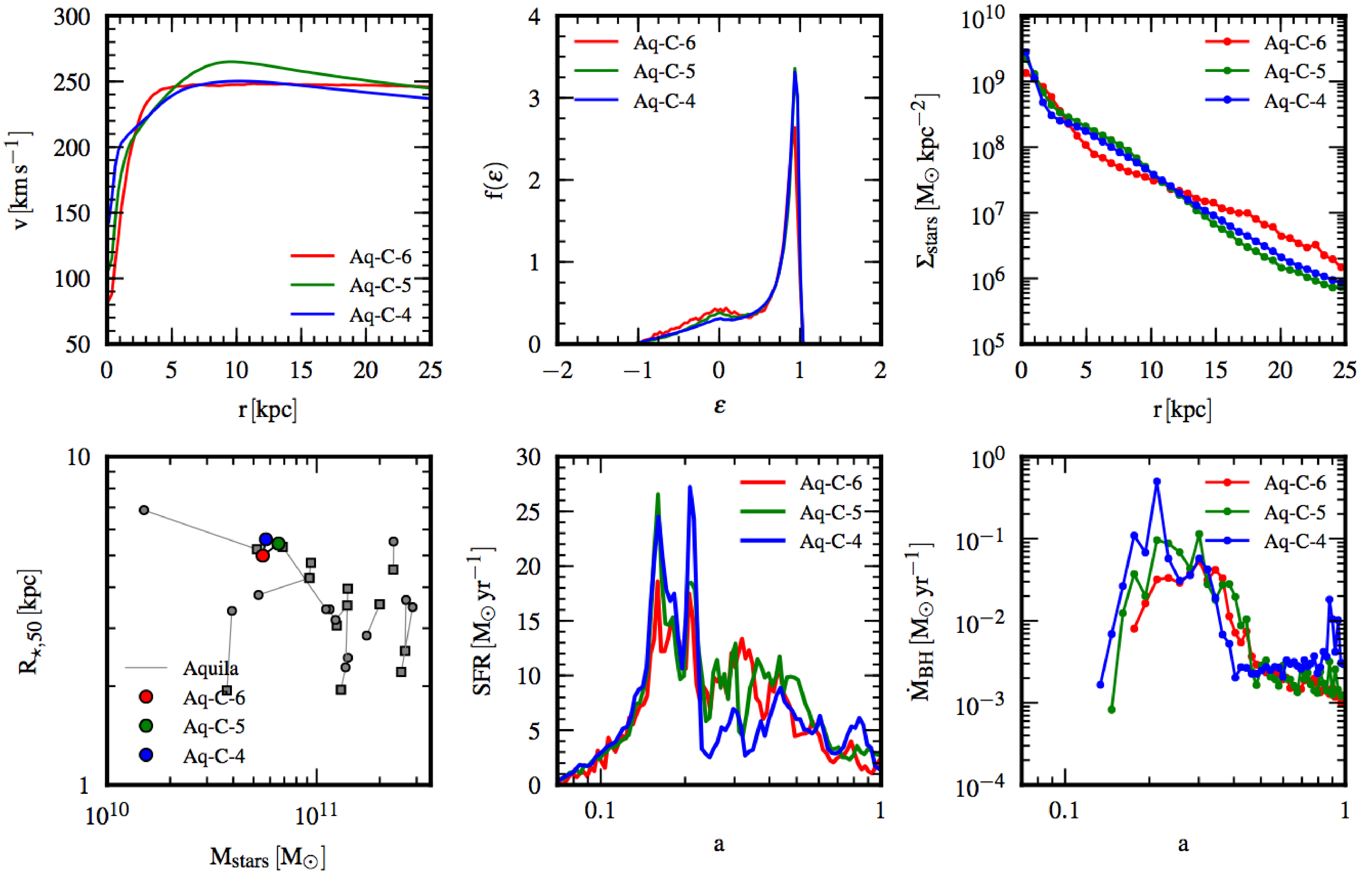






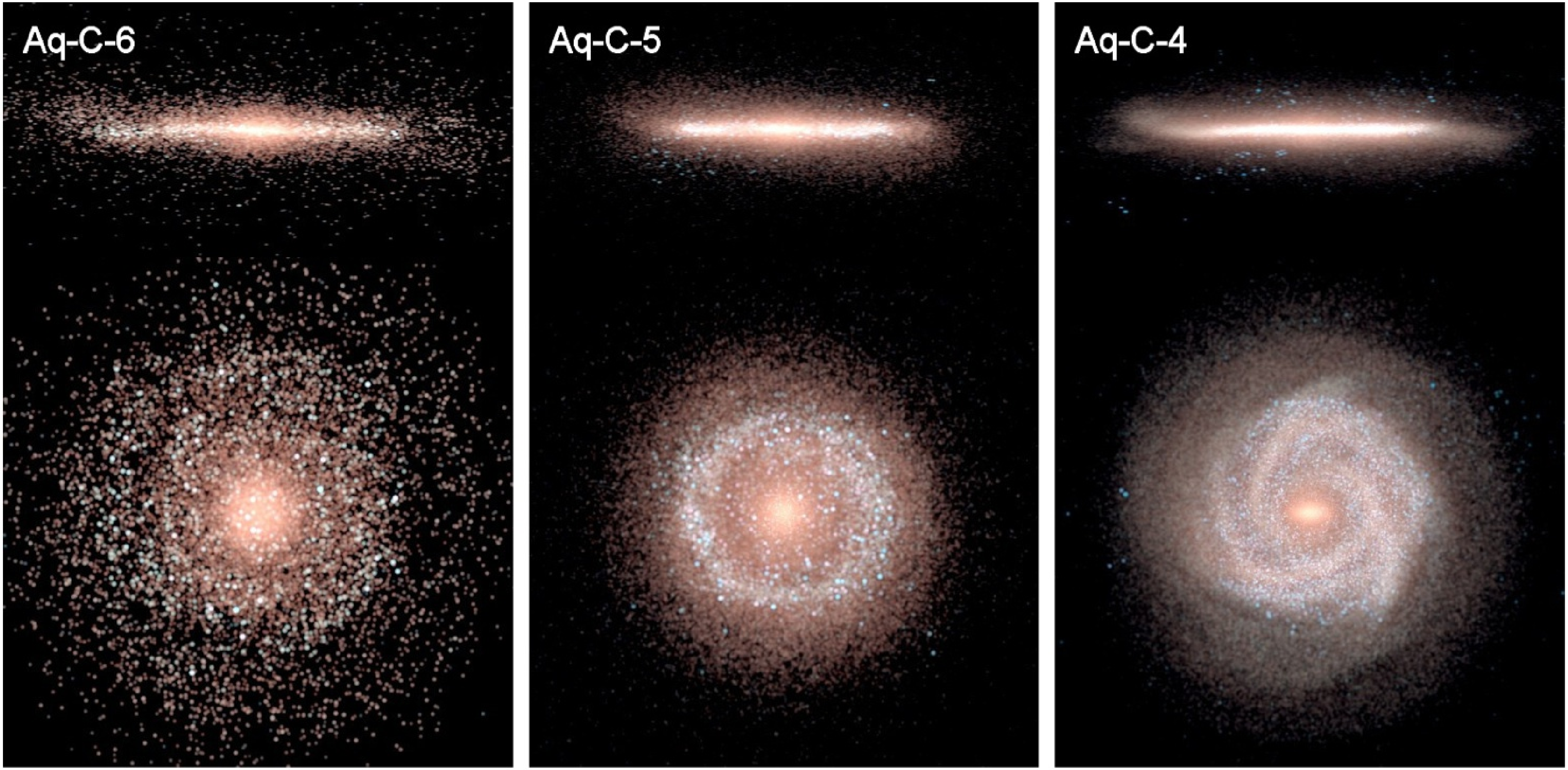
Our modelling of sub-grid physics is numerically well posed and leads to converged results

RESOLUTION COMPARISON OF KEY QUANTITIES FOR RESOLUTION LEVELS AQ-C-4, AQ-5 AND AQ-C-6



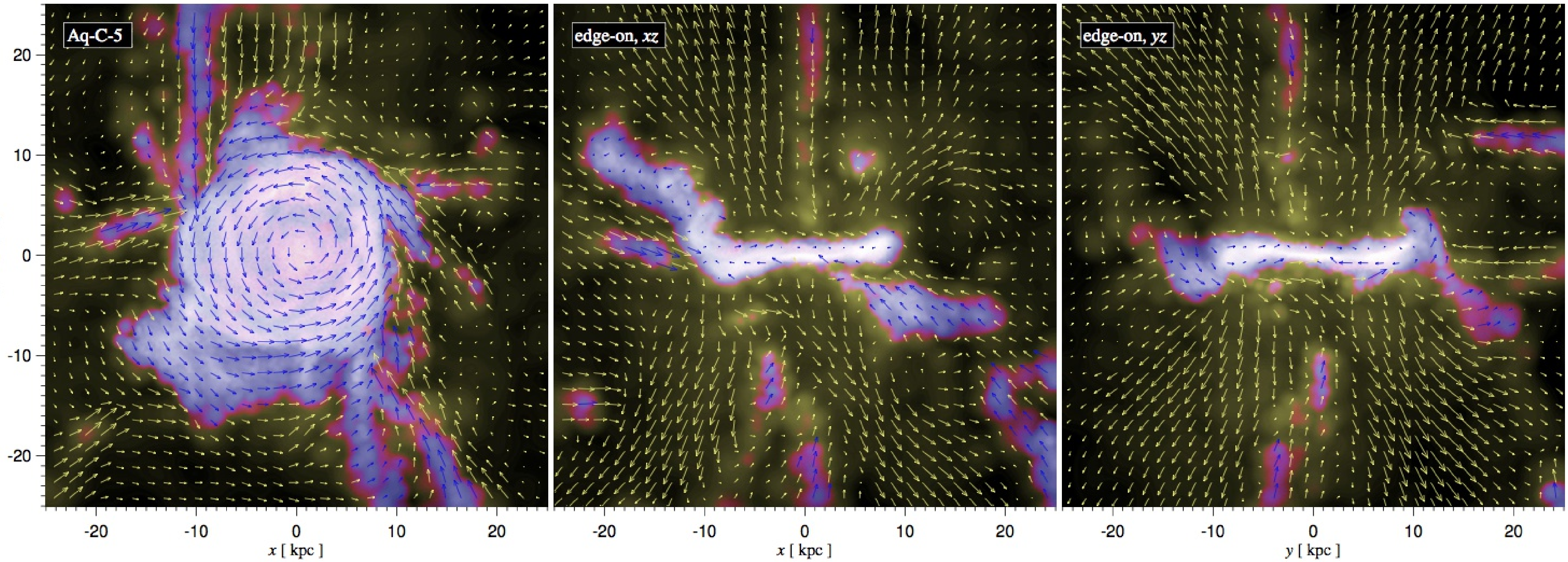
The visual galaxy morphology agrees well even for drastic resolution changes

STELLAR DENSITY DISTRIBUTION FOR AQ-C, OVER A RANGE OF 64 IN MASS RESOLUTION



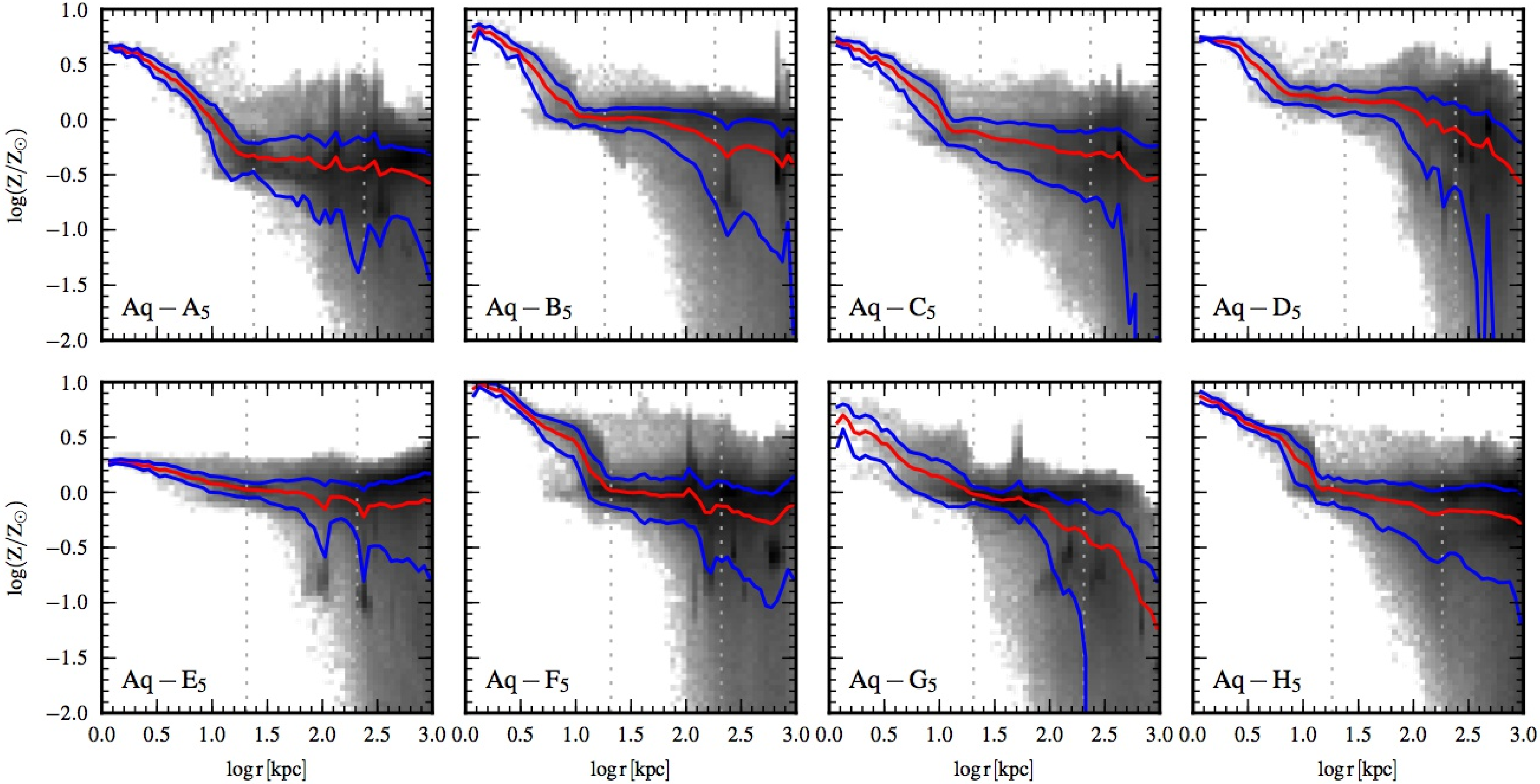
The gas flows around the disks are complex, with both inflow and outflow occuring in the circumgalactic medium

GASEOUS DENSITY AND VELOCITY FIELD IN FACE-ON AND EDGE-ON PROJECTIONS



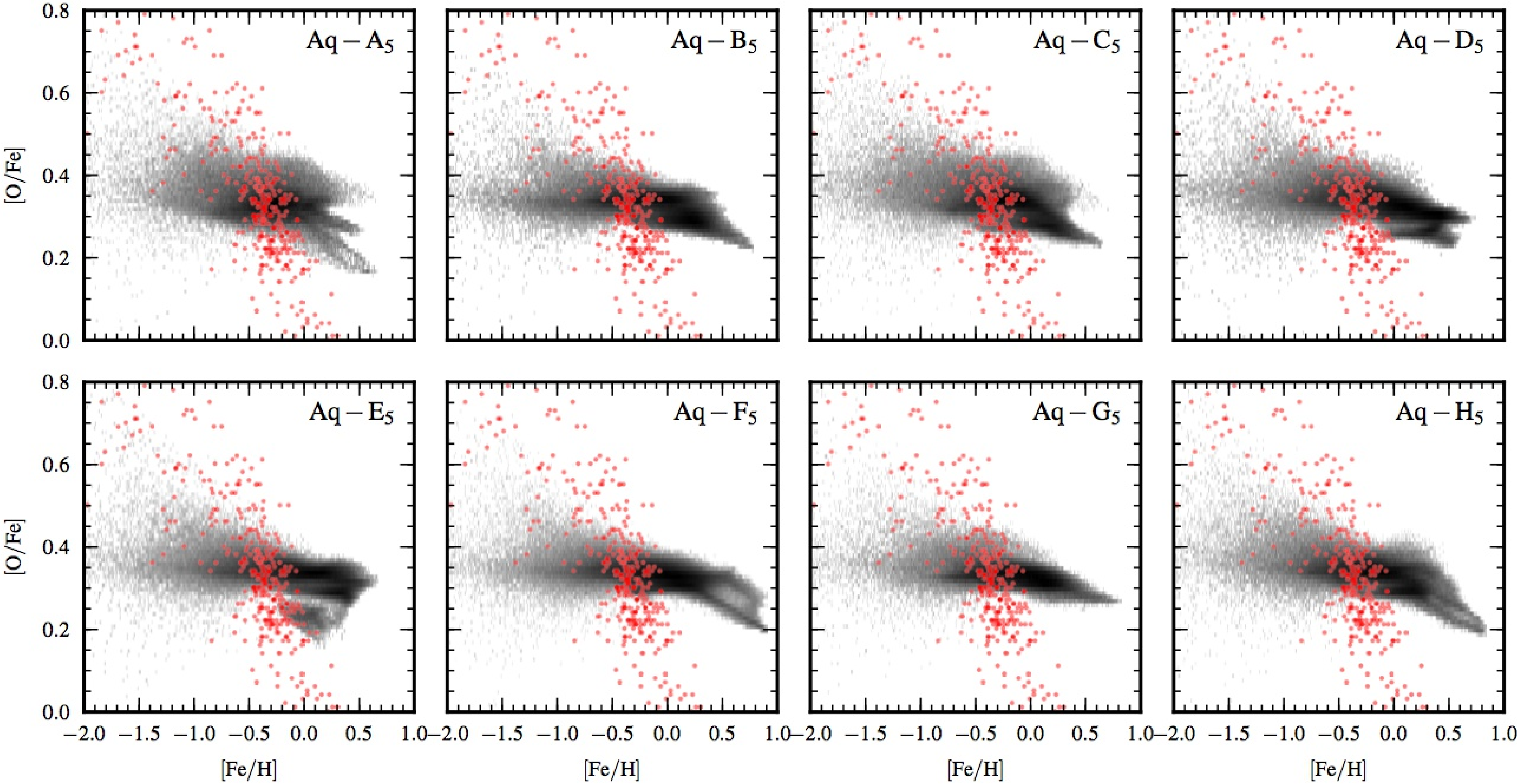
The winds induce substantial enrichment of the CGM and beyond, with only a mild metallicity gradient in the galactic halos gas

SPHERICALLY AVERAGED METALLICITY PROFILES AROUND OUR EIGHT PRIMARY GALAXIES



Our default runs do not reproduce the observed trend of oxygen abundance as a function of metallicity

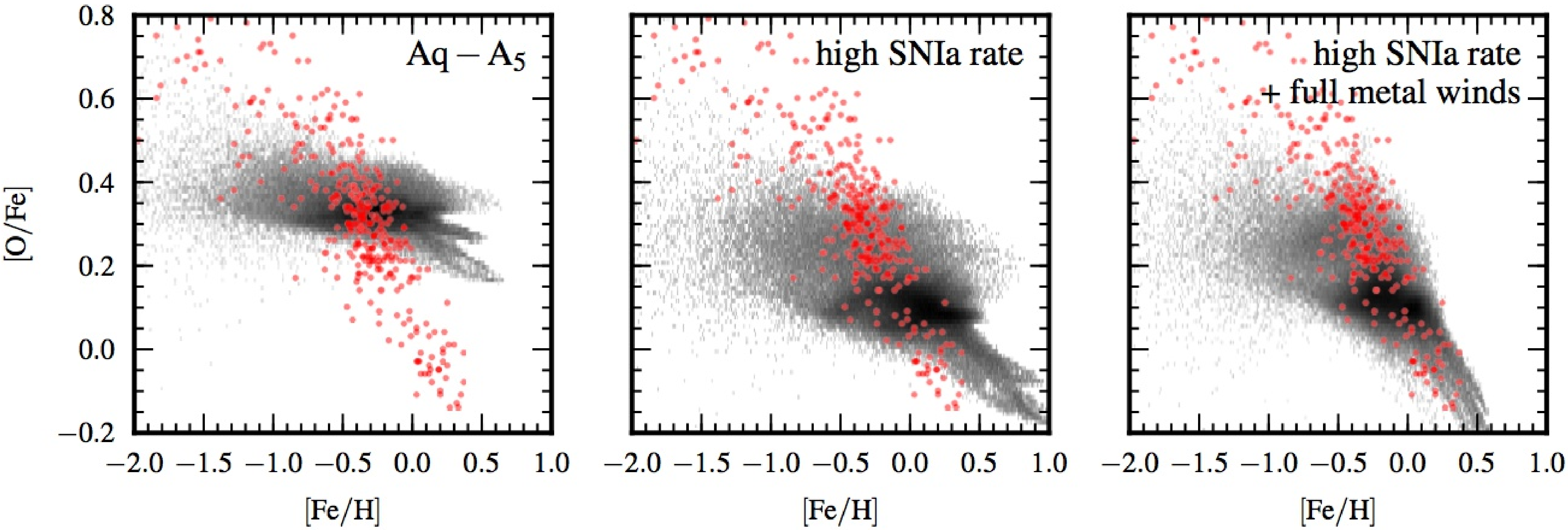
COMPARISON OF [O/Fe] VERSUS IRON ABUNDANCE TO THE MILKY WAY (RED POINTS)



→ underproduction of iron relative to oxygen

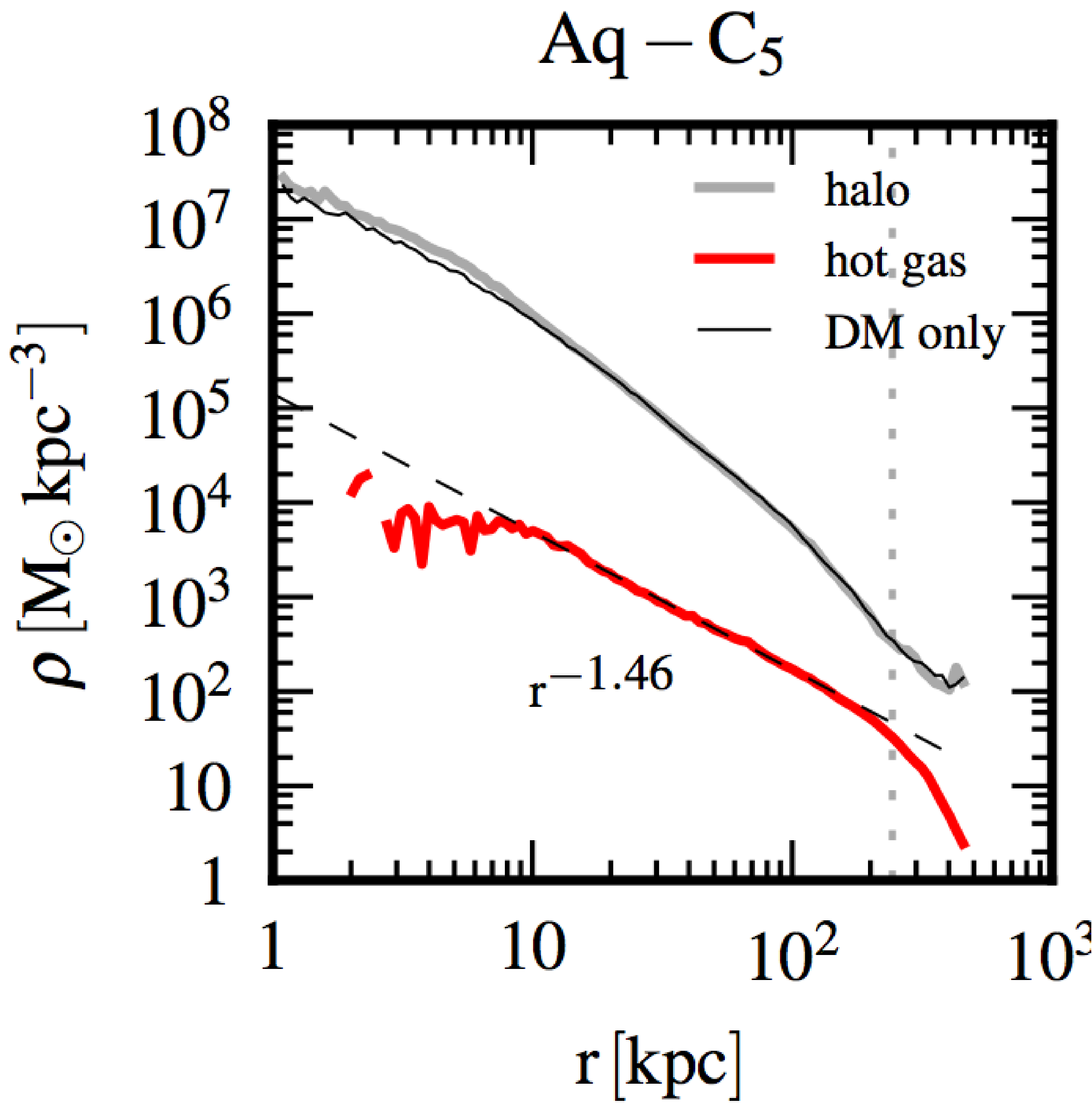
Detailed abundance ratio data provide important constraints on wind models and supernova type Ia rate parameterizations

OXYGEN ABUNDANCE VERSUS METALLICITY FOR DIFFERENT MODEL VARIANTS



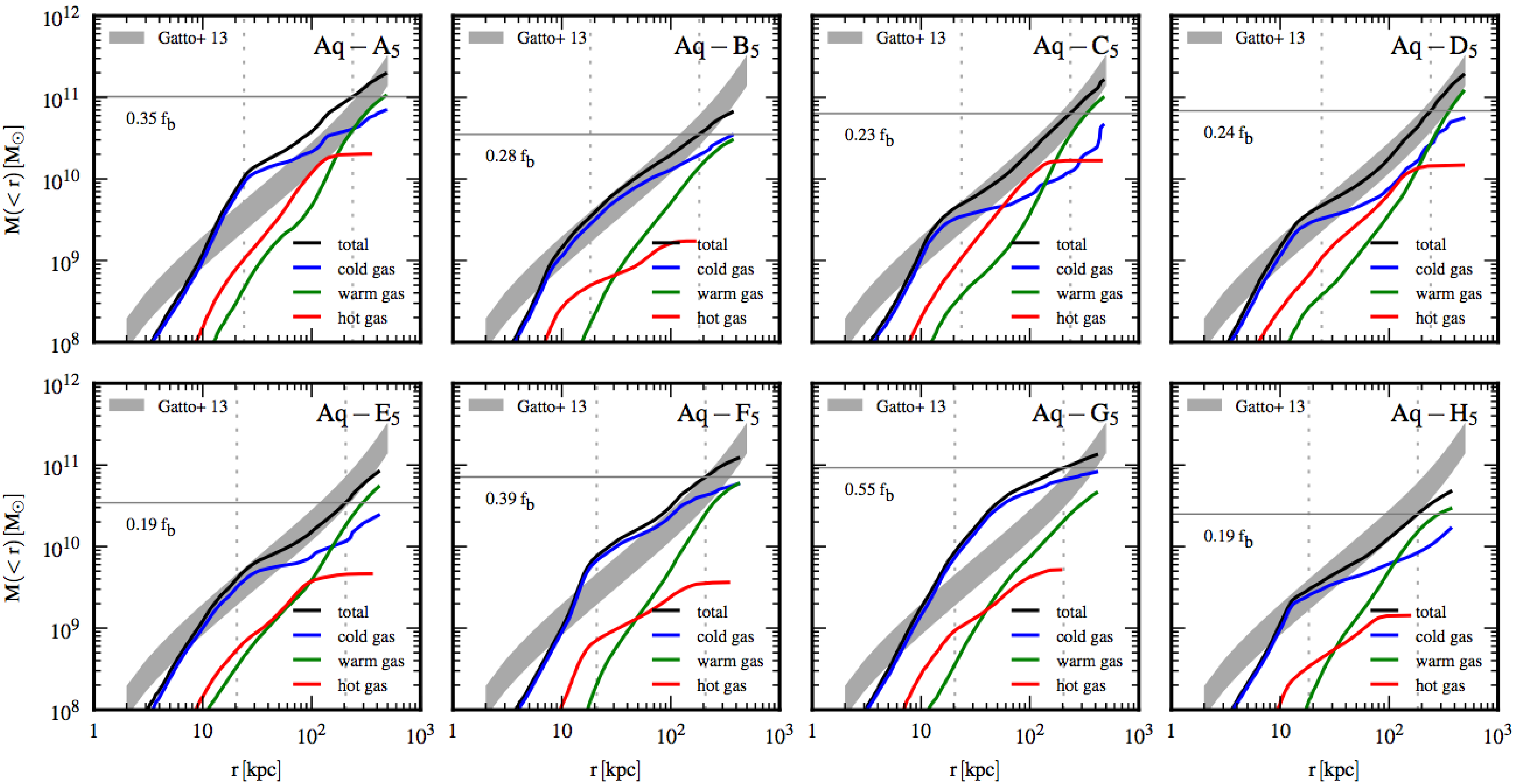
Baryonic physics leads to a slight compression of the dark matter in our runs – no core formation seen in these models

SPHERICALLY AVERAGED DENSITY PROFILES OF DARK MATTER AND HOT GAS



Most of the diffuse gas in our galactic halos is in cold form

CUMULATIVE MASS PROFILES OF DIFFUSE GAS IN DIFFERENT TEMPERATURE PHASES



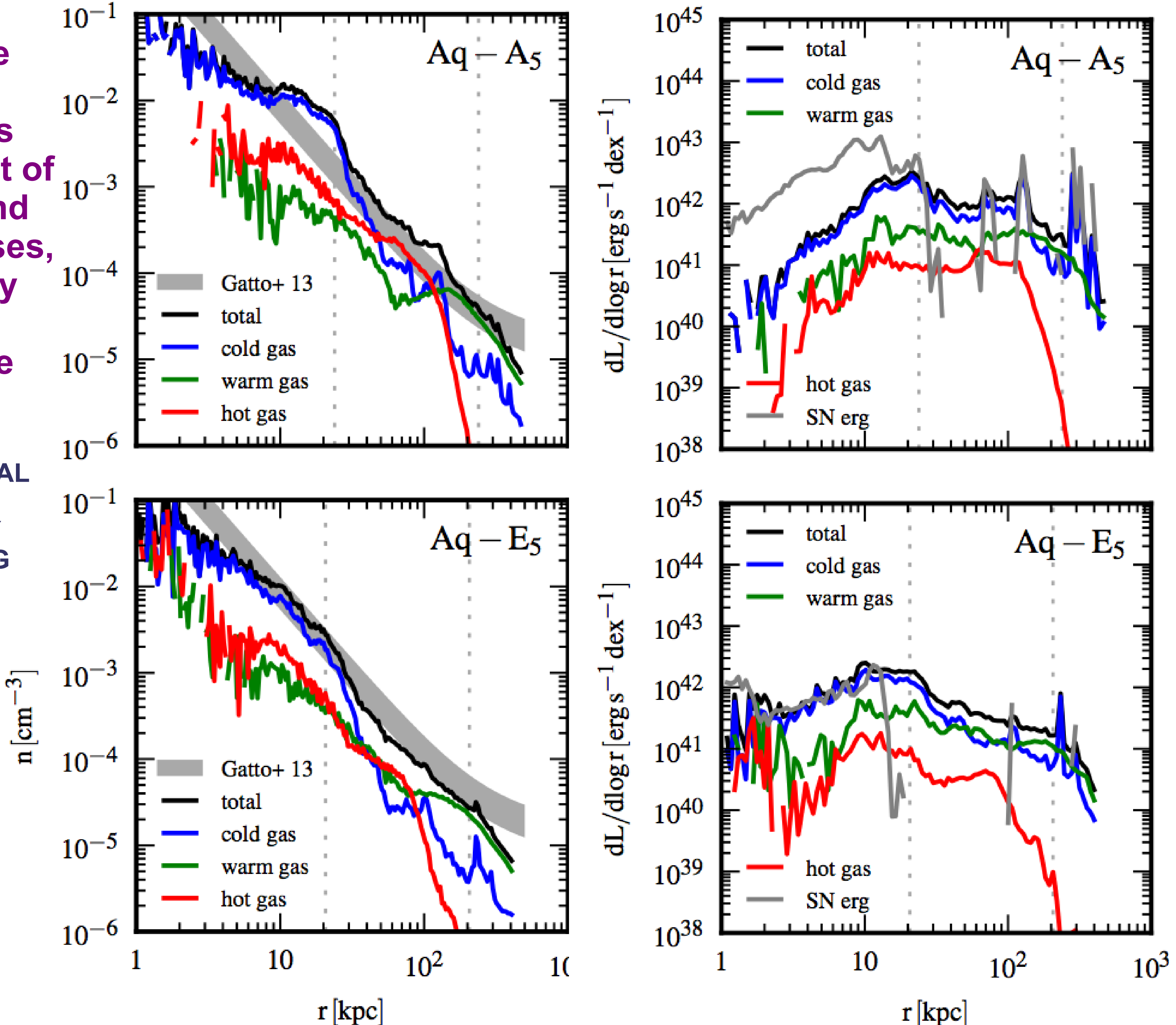
cold: $T < 10^5$ K

warm: 10^5 K $< T < 10^6$ K

hot: $T > 10^6$ K

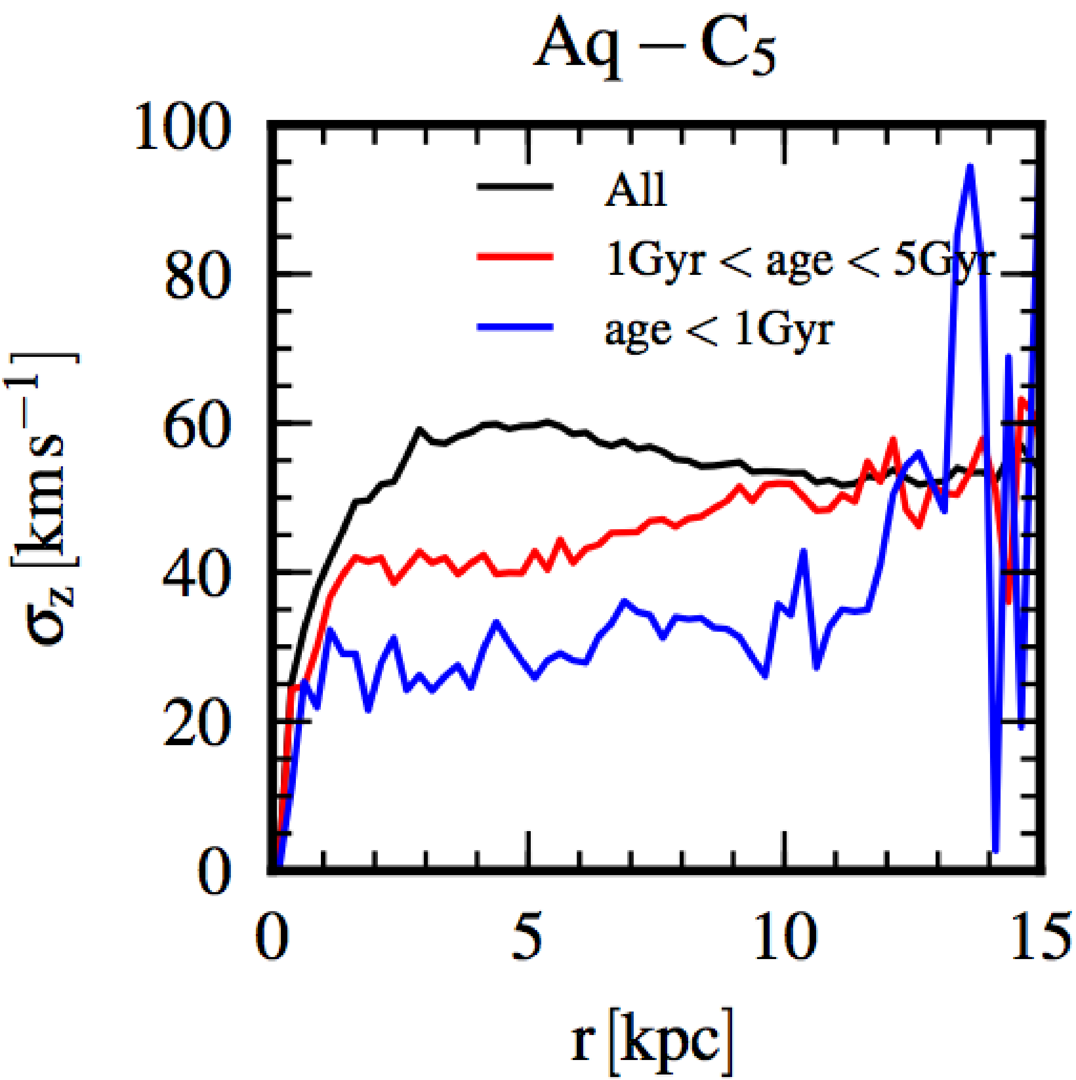
Most of the cooling emission is coming out of the cold and warm phases, powered by the energy input of the winds

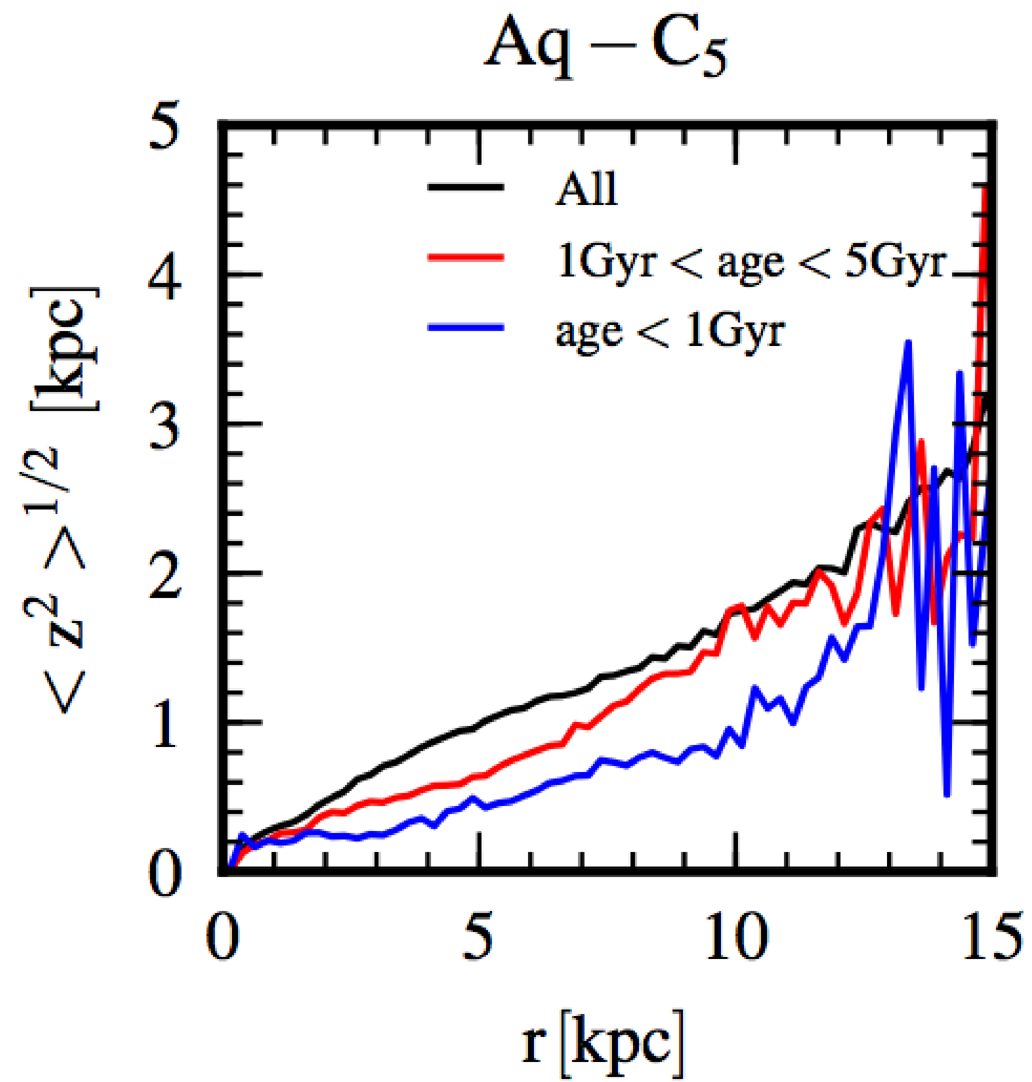
SDIFFERENTIAL PROFILES OF GAS DENSITY AND COOLING EMISSION



The disks we form are too thick overall, at least when the old disk stars are included

VERTICAL VELOCITY DISPERSION AND SCALE HEIGHT OF DISK STARS AS A FUNCTION OF RADIUS





Several important physical processes are still neglected in these disc formation simulations – and others are pushed to sub-grid modelling

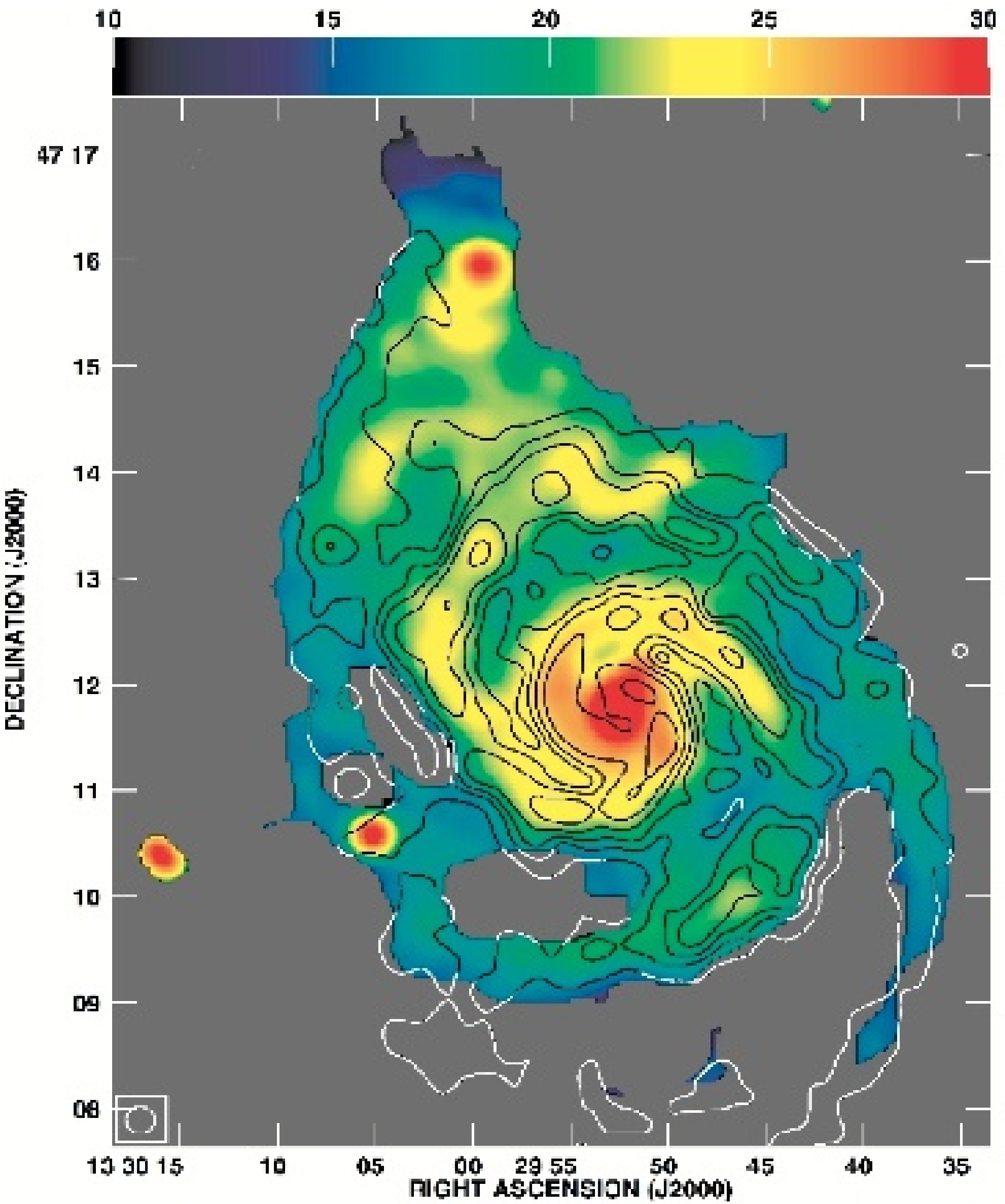
PARTIAL LIST OF MISSING PHYSICS

- self-consistent radiative transfer
- magnetic fields
- cosmic ray physics
- molecular chemistry
- dust

Magnetic fields may play an important role in galaxy formation

MAGNETIC FIELD STRENGTH IN M51

- Galaxies are magnetized
- Typical field strengths in spirals of ~10μG
- Assumed to be in equipartition with thermal gas pressure & cosmic rays
- Dynamically important (?)



Fletcher et al. (2011)

We have a new ideal MHD implementation in AREPO that works well

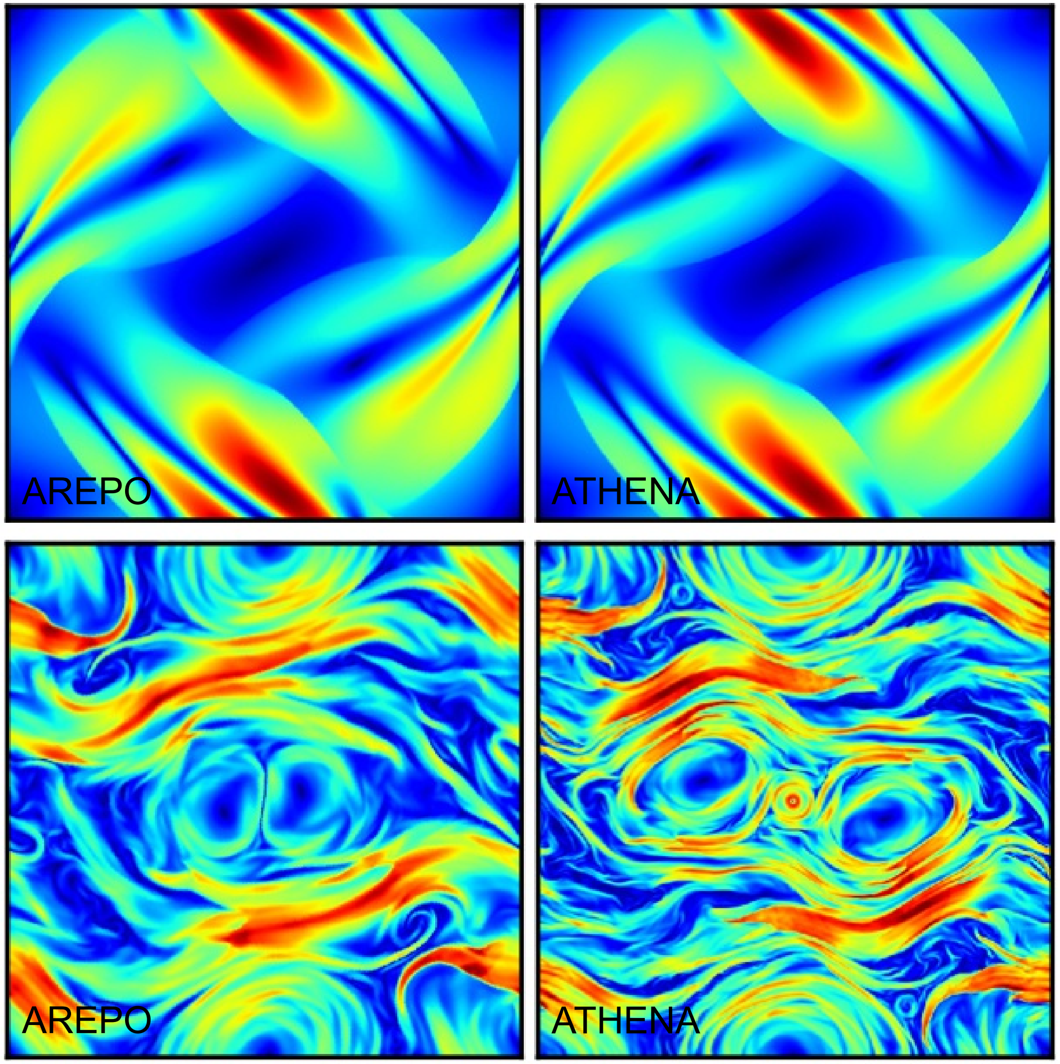
EQUATIONS AND SOME TESTS

Pakmor, Bauer & Springel (2011)

Pakmor & Springel (2013)

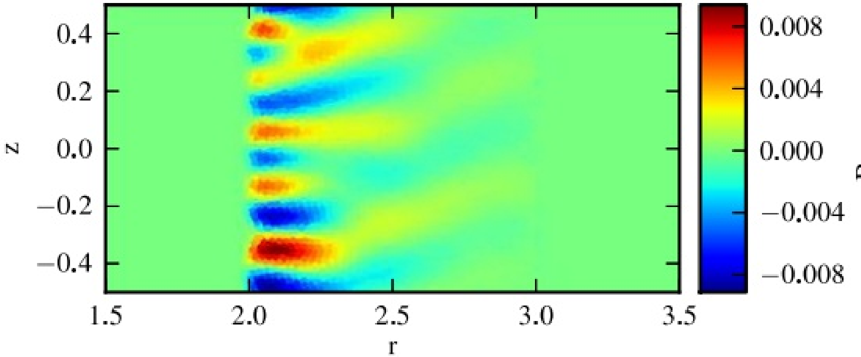
$$\mathbf{U} = \begin{pmatrix} \rho \\ \rho \mathbf{v} \\ \rho e \\ \mathbf{B} \\ \psi \end{pmatrix} \qquad \mathbf{F}(\mathbf{U}) = \begin{pmatrix} \rho \mathbf{v} \\ \rho \mathbf{v}\mathbf{v}^T + p - \mathbf{B}\mathbf{B}^T \\ \rho e \mathbf{v} + p\mathbf{v} - \mathbf{B}\left(\mathbf{v}\cdot\mathbf{B}\right)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

Orszag-Tang vortex test



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

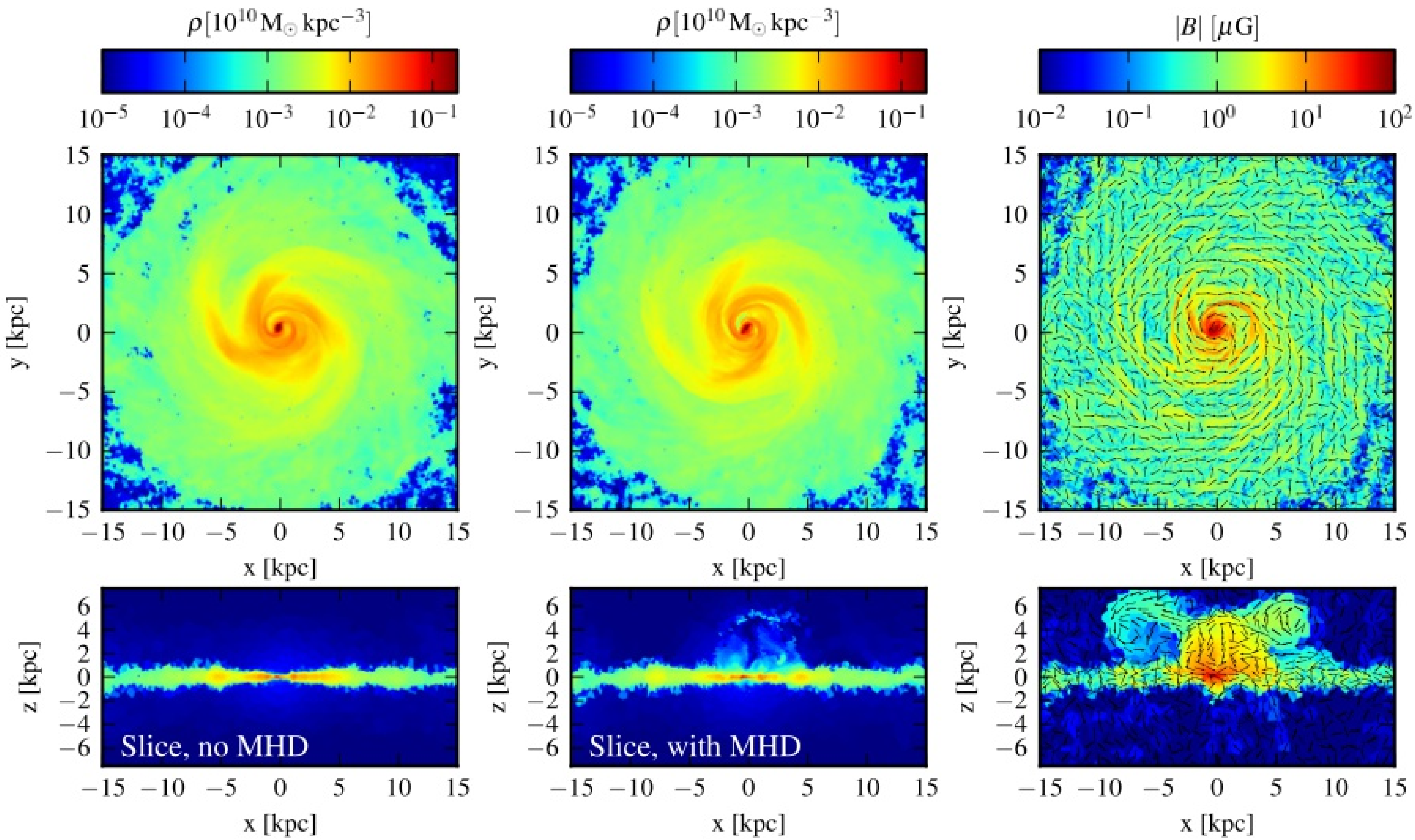
Magneto-rotational instability in 3D



→ we get the correct linear growth rate

In isolated disk galaxy formation simulations, magnetic fields produce weak magnetically driven fountain flows out of the disk

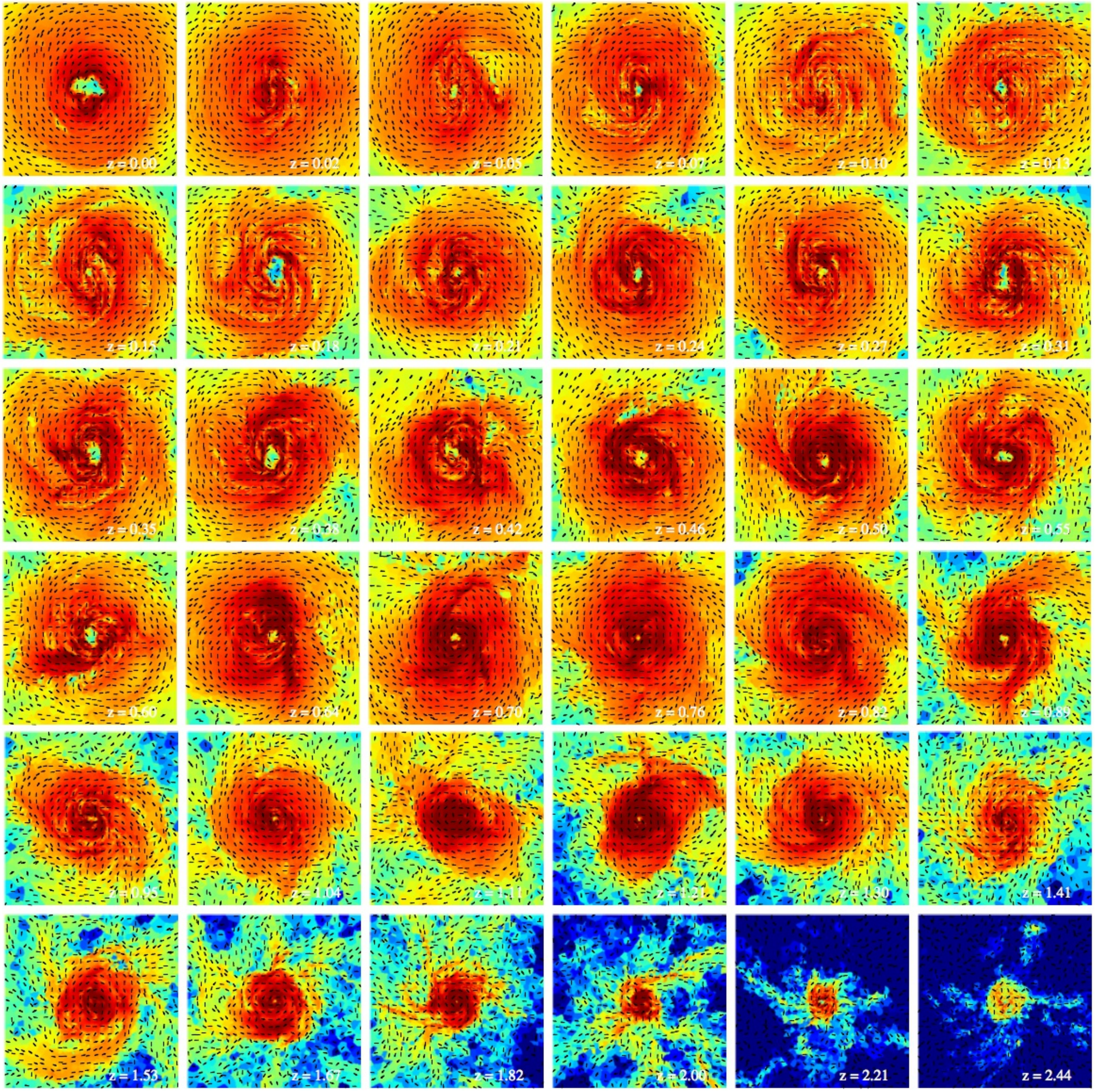
SLICES THROUGH THE GAS DENSITY AND THE MAGNETIC FIELD



Pakmor & Springel (2012)

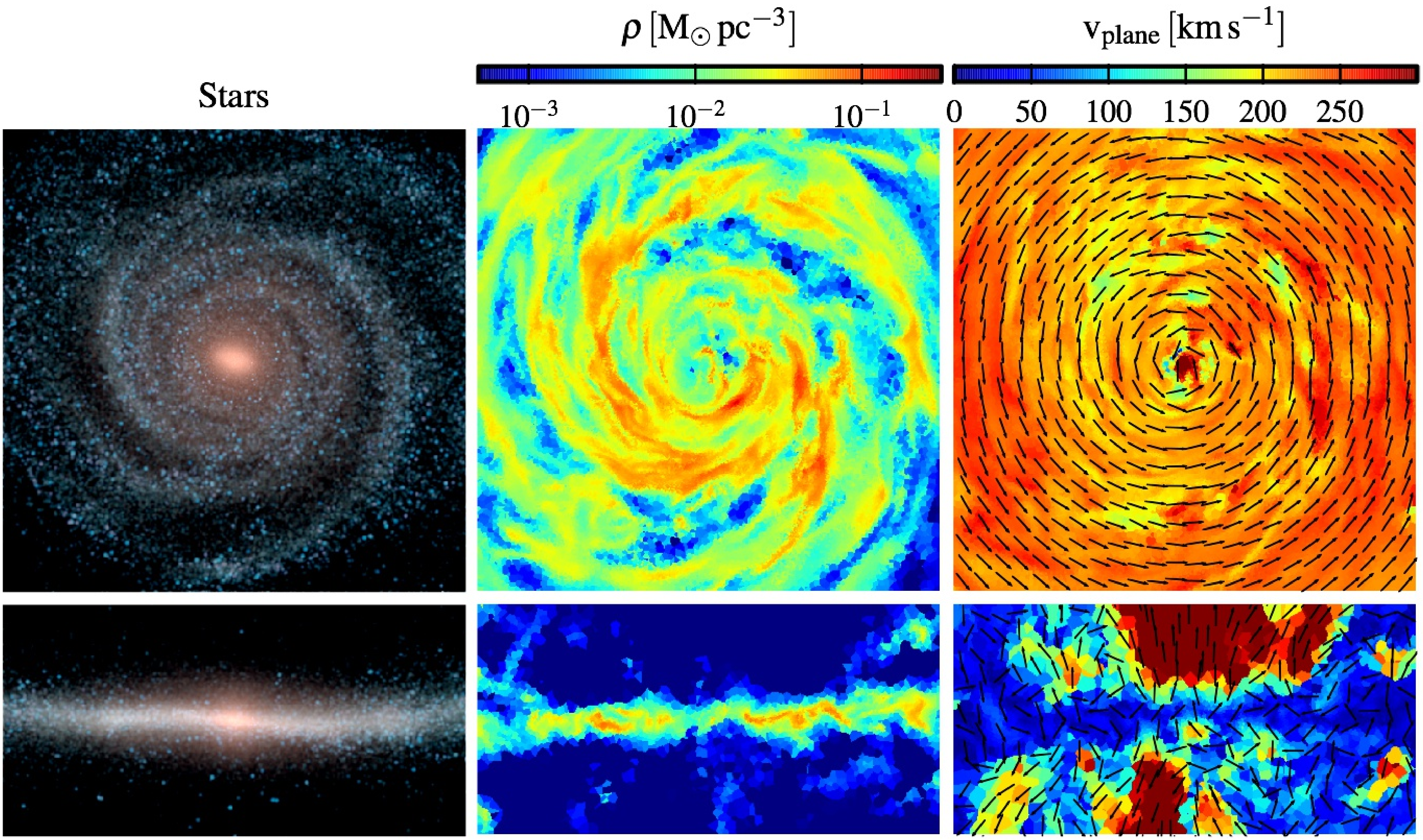
An azimuthal magnetic field builds up as soon as there is a well defined gas disc

MAGNTIC FIELD IN SLICES THROUGH THE DISC MID-PLANE OF AQ-D AT DIFFERENT TIMES



Simulations with magnetic fields produce similar disk galaxy morphologies

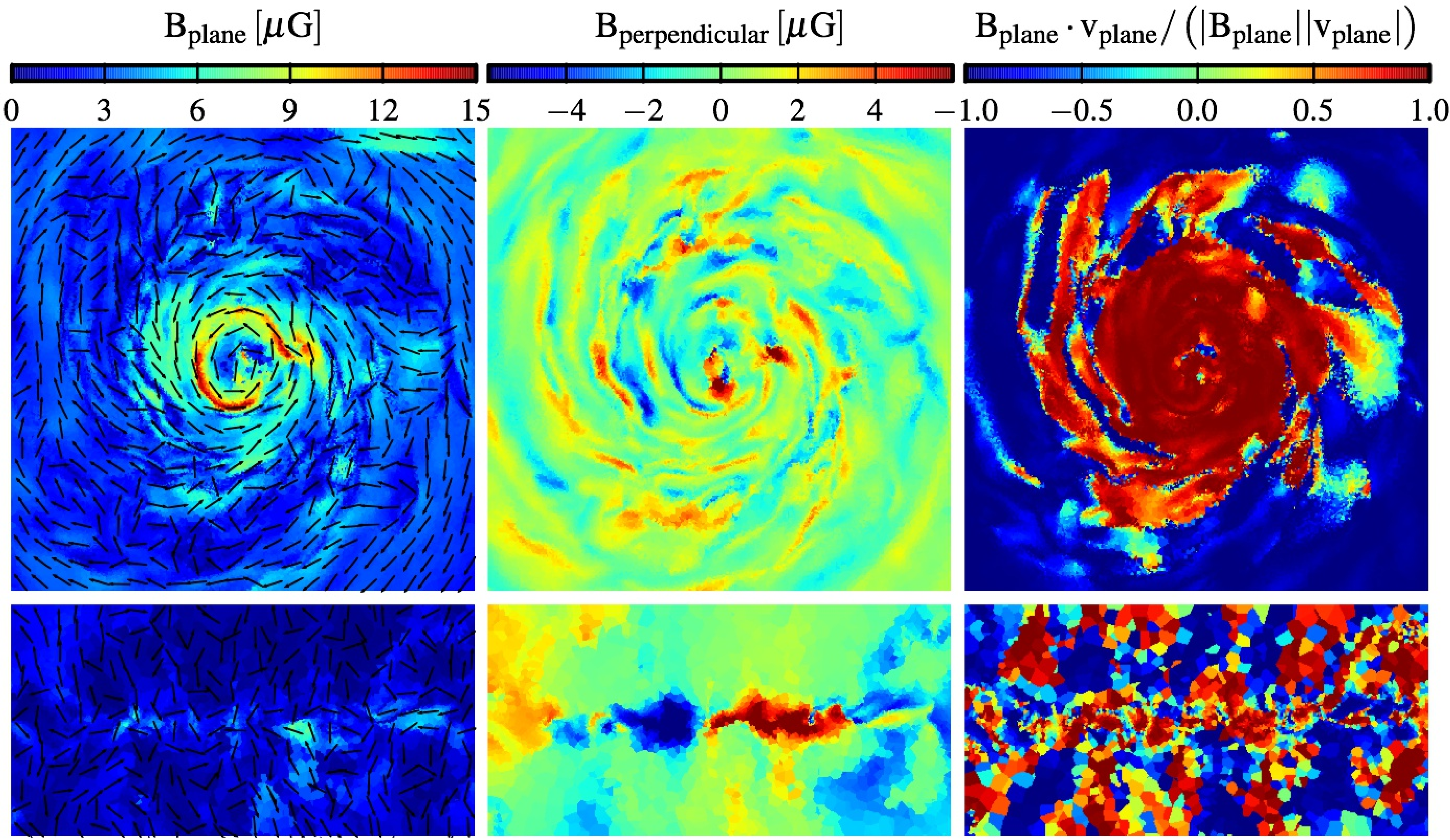
PROJECTED FACE-ON AND EDGE-ON MAPS OF ONE OF THE AQUARIUS GALAXIES



Pakmor et al. (2013)

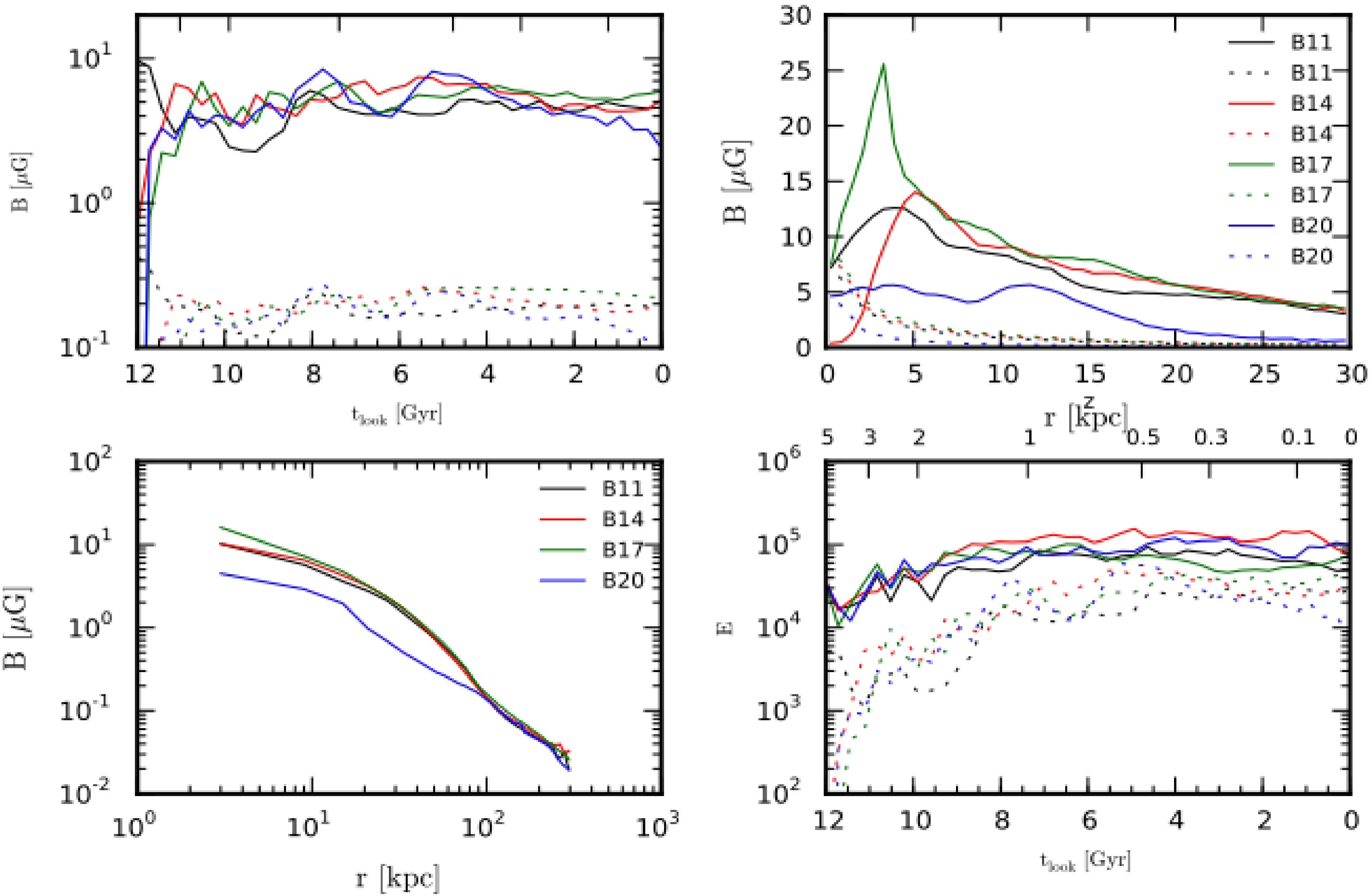
But now we also predict the build-up of an azimuthal magnetic field

MAGNETIC FIELD IN SLICES THROUGH THE DISC MID-PLANE



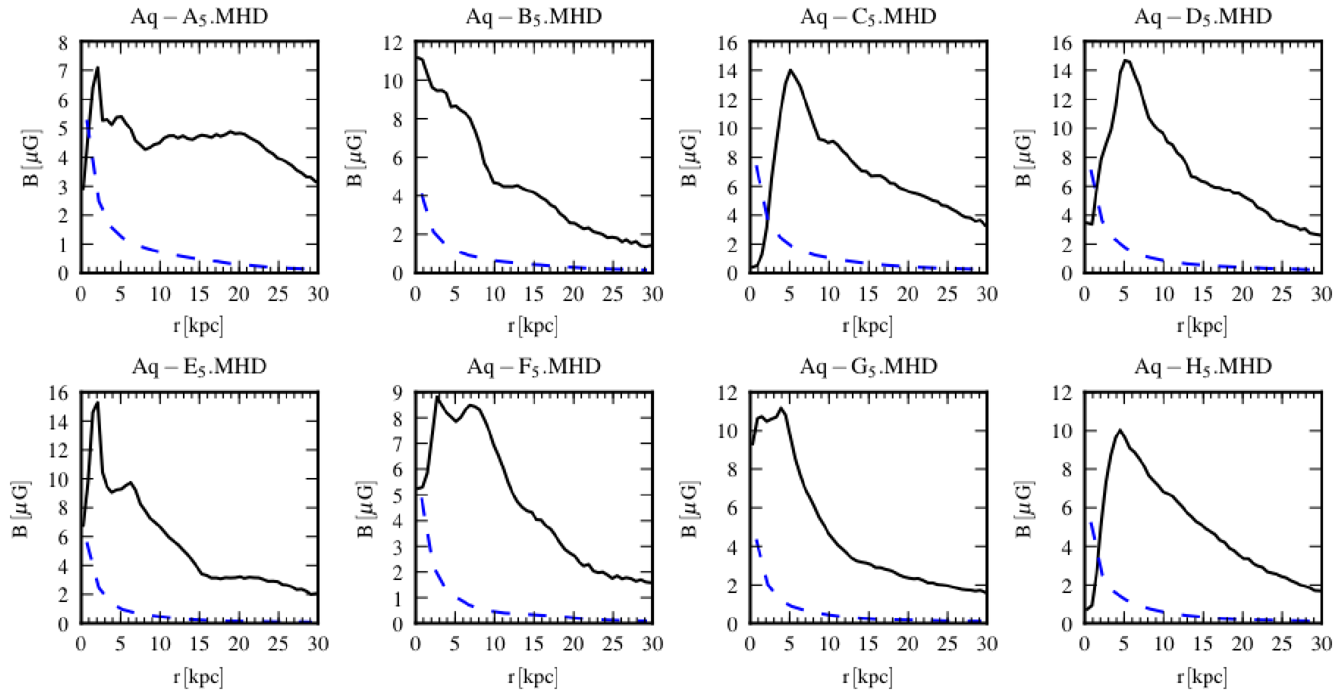
The results are insensitive to the magnetic seed field strength

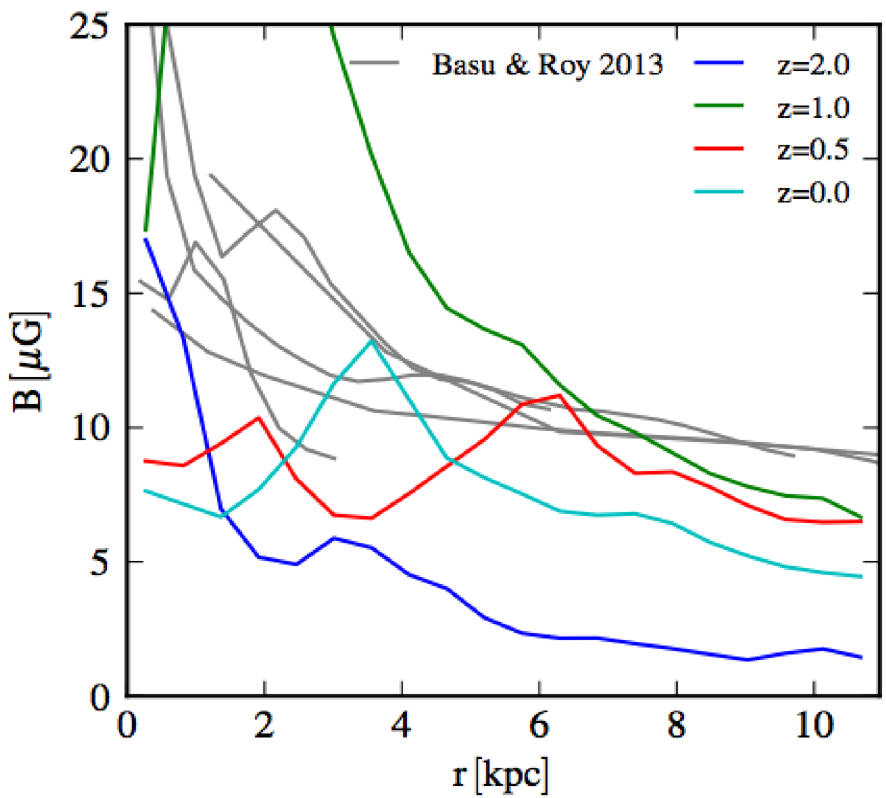
PREDICTED GALACTIC FIELD STRENGTHS FOR DIFFERENT SEED FIELDS

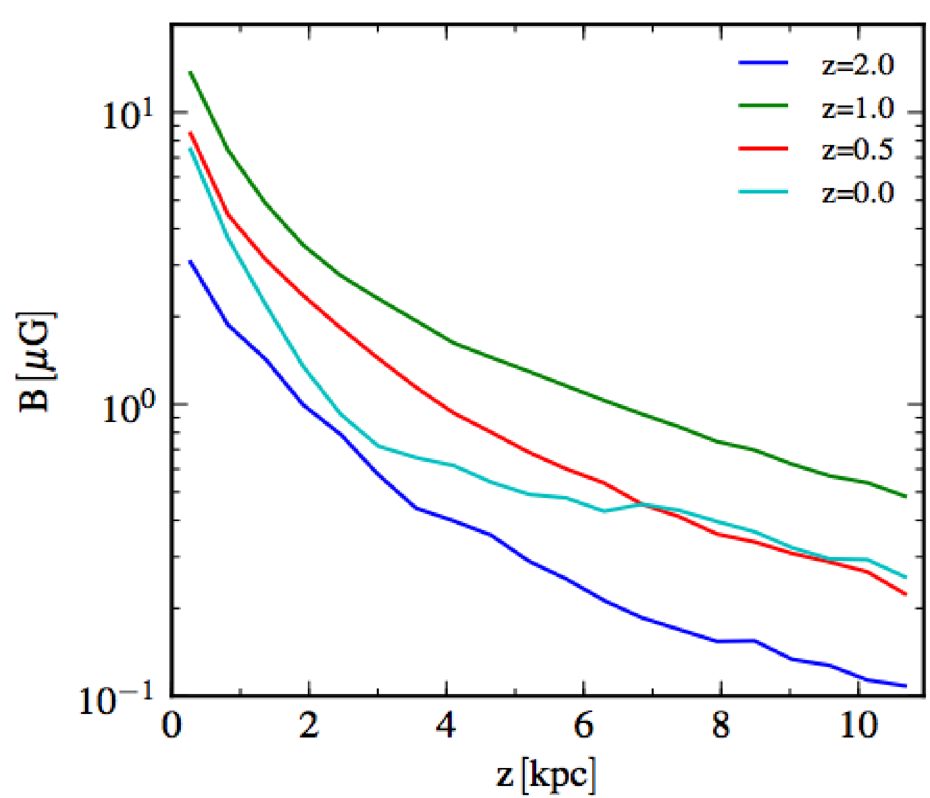


The predicted magnetic field strength agrees quite well with observations

RADIAL PROFILE OF MAGNETIC FIELD STRENGTH IN SIMULATIONS AND OBSERVATIONS

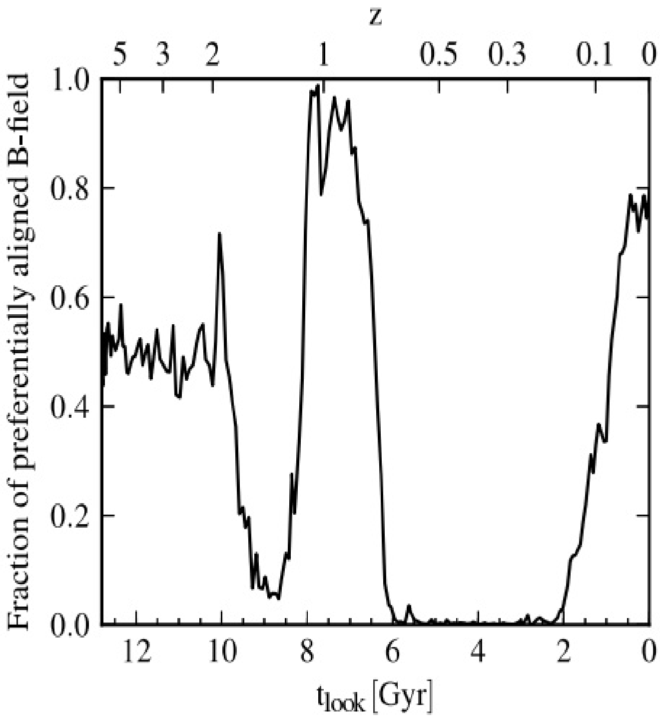


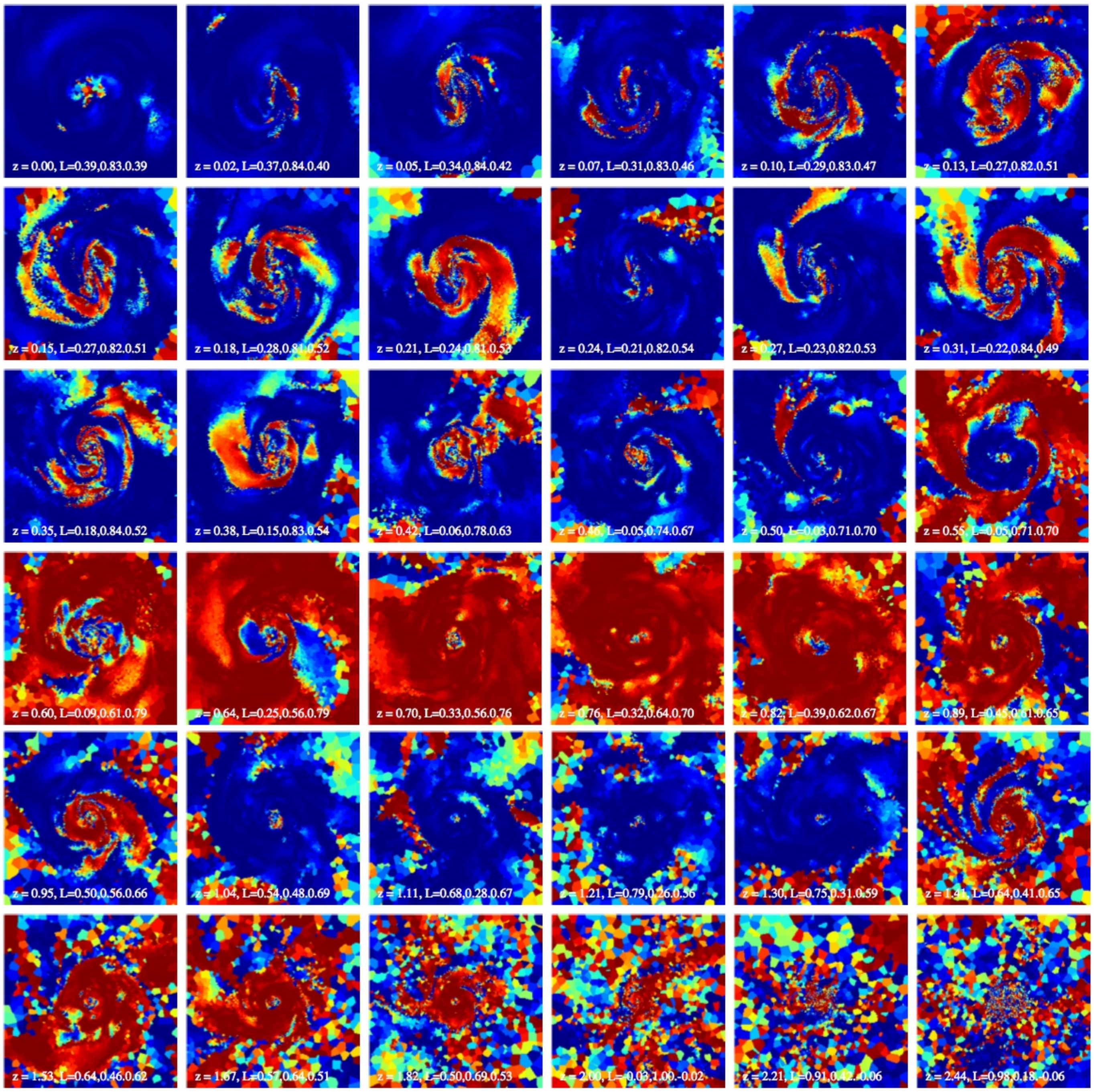




Interestingly, the magnetic pitch angle in the discs is predicted to occasionally flip every couple of gigayears

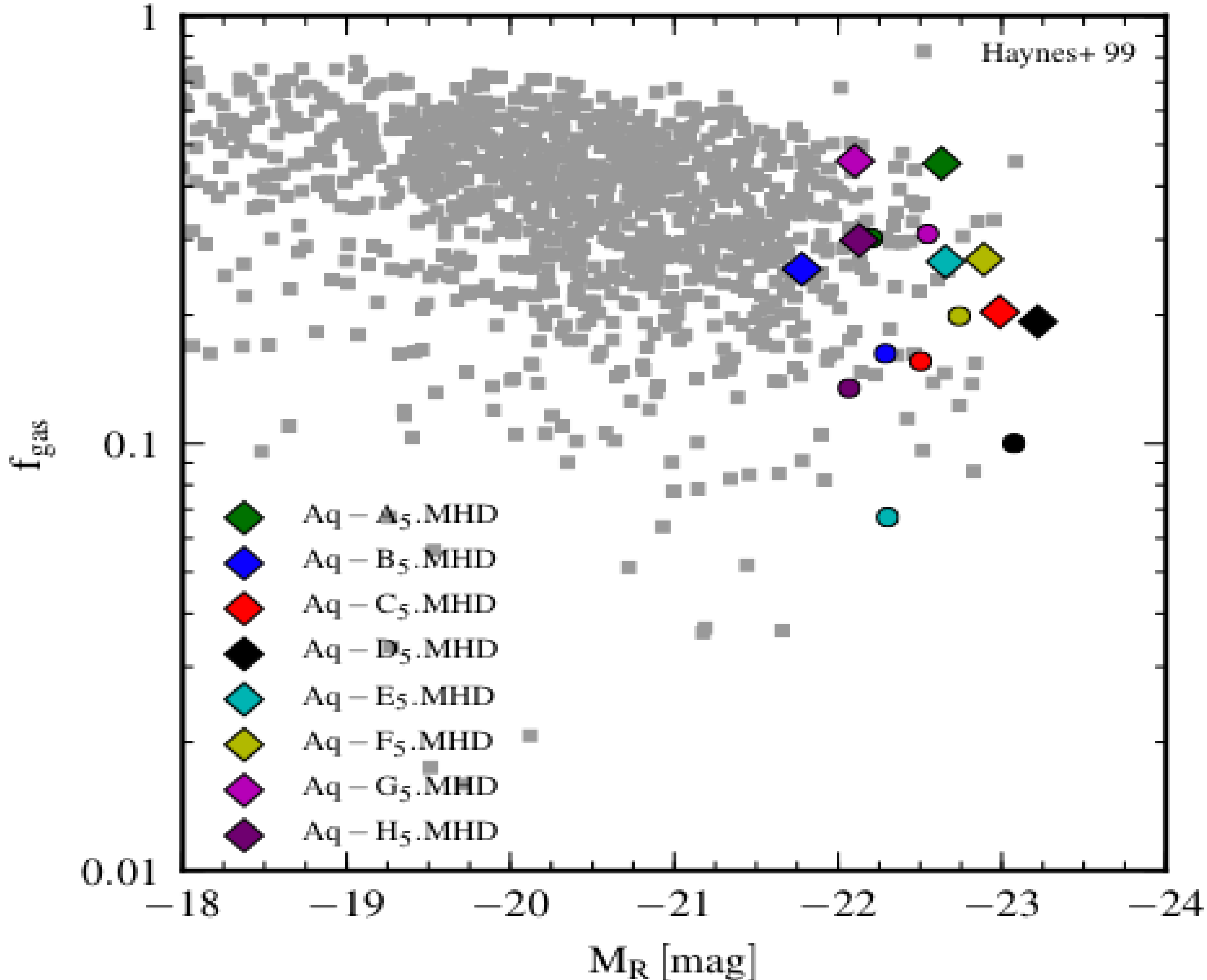
TIME EVOLUTION OF THE PITCH ANGLE IN THE AQ-A SIMULATION





The largest changes in the structural galaxy properties when magnetic fields are included occur for the gas fractions

GAS FRACTION FOR DISC GALAXIES SIMULATED WITH AND WITHOUT MAGNETIC FIELDS AT Z=0



Summary points

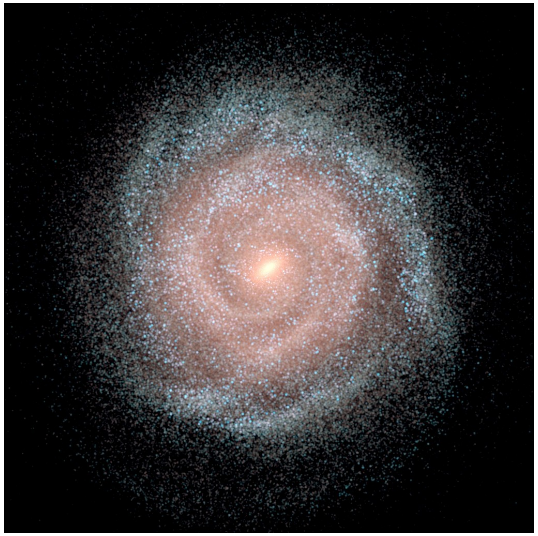
- Zoom-in simulations of Milky Way-sizes halos with AREPO and a sub-grid treatment of galaxy formation physics produce disk galaxies with reasonable properties.

- Our numerical methods converge quite well, including galaxy morphology. The largest differences with varying resolution occur for the central black holes masses.

- The coronal gas is predicted to be in a highly metal enriched state, but still has reasonable structure compared to models for the Milky Way corona. The cooling luminosity is dominated by cold/warm gas, and ultimately powered by the wind energy injection.

- We are able to take magnetic fields into account in cosmological simulations of disc galaxy formation.

- Disc galaxies with magnetic fields show a slight suppression of star formation and higher gas fractions. Magnetic field strengths saturate at 10 μG in the center, decline to a few μG in outer regions of the disk, and are independent of the seed field strength.



Some questions for discussion at this meeting...

- What are appropriate values for density threshold and efficiency of star formation? Does it matter at all once the resolution and feedback treatment are good enough?

  (There seem to be conflicting results/opinions about this...)

- What crucial physics is still missing in the simulations of Hopkins et al., Agertz et al.? Will this change the results qualitatively, quantitatively, or not at all?

- Are the new, “modern” versions of SPH able to resolve all problems associated with this technique?

- What are the most important properties of galaxies to look at besides stellar mass for constraining galaxy formation physics? Is morphology a good discriminator?

- How do we get thin enough stellar disks?

Identified problems of SPH and their solution – time for all-clear?

FALLACIES OF JUDGING THE ACCURACY OF SPH

New flavors of SPH behave a lot better on test problems than traditional SPH

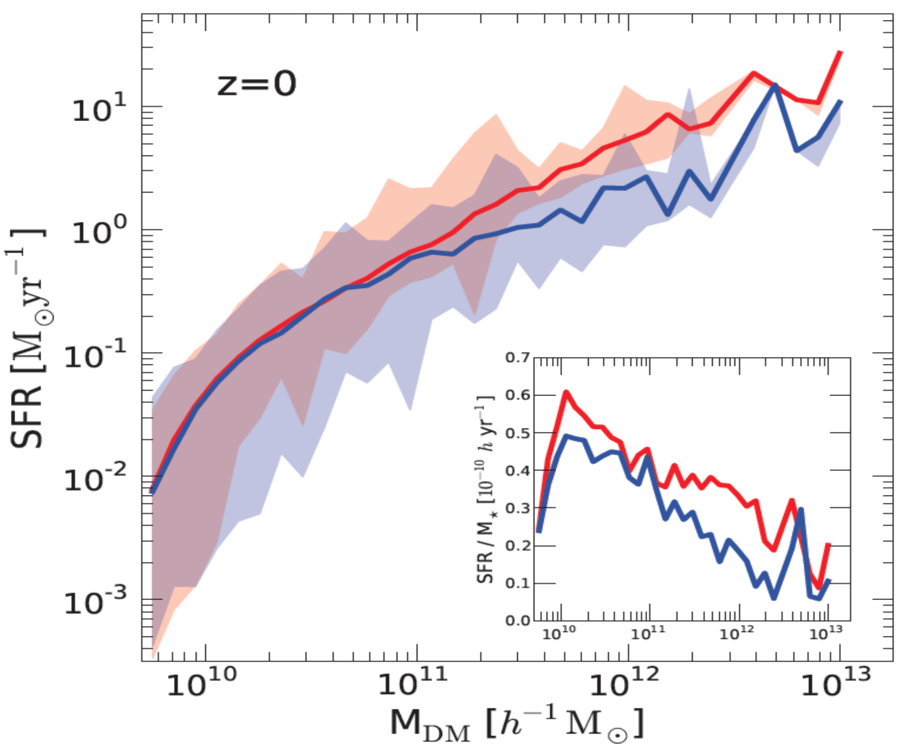
New SPH gives very similar results as old SPH in Hopinks et al. simulations, as well as in some other works

Can we conclude from this:

SPH is fixed,
"new" SPH can be trusted ?

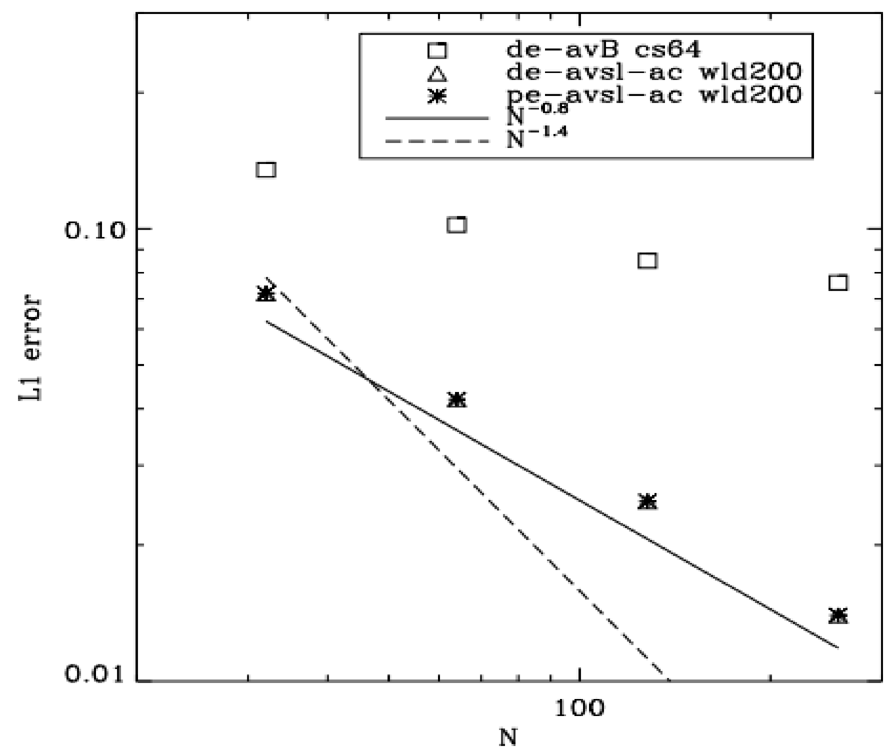
Cautionary note: Not addressed/tested are at least two things, for example:

cooling in large halos



Vogelsberger et al. (2012)

convergence rate of SPH



Hu, Naab, et al. (2013)