האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

GALAXY EVOLUTION: A GAS PERSPECTIVE

Jonathan Freundlich

Observations with: Françoise Combes, Philippe Salomé, Linda Tacconi, Reinhard Genzel, Roberto Neri, Santiago Garcia-Burillo & the PHIBSS consortium, Gianluca Castignani, Thierry Contini, Nicolas Bouché, Johannes Zabl & Ilane Schroeter

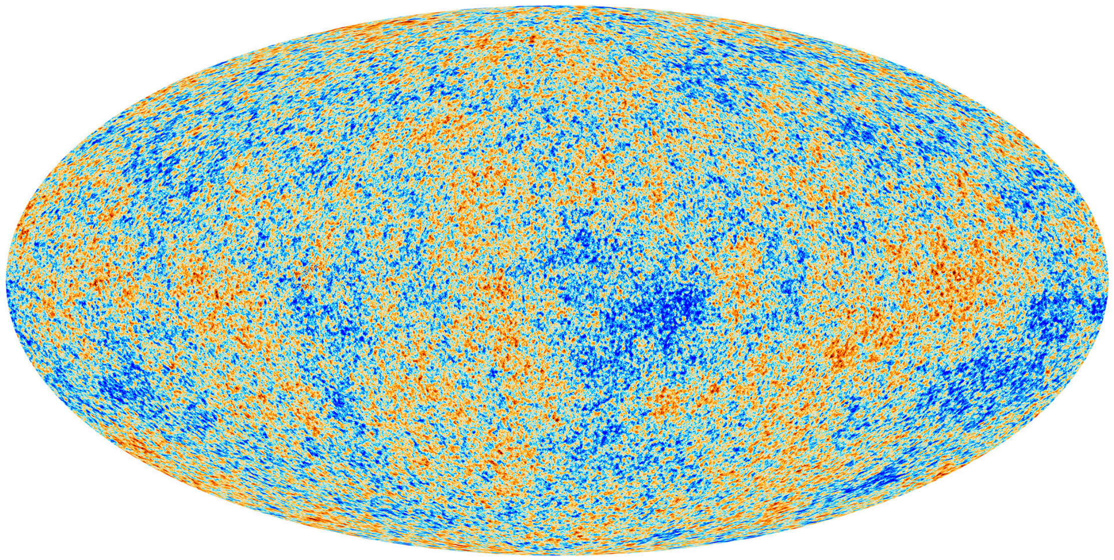
Theory with: Avishai Dekel, Fangzhou Jiang, Amr El-Zant, Andreas Burkert, Guy Ishai, Nicolas Cornuault, Sharon Lapiner, Aaron Dutton & Andrea Macciò

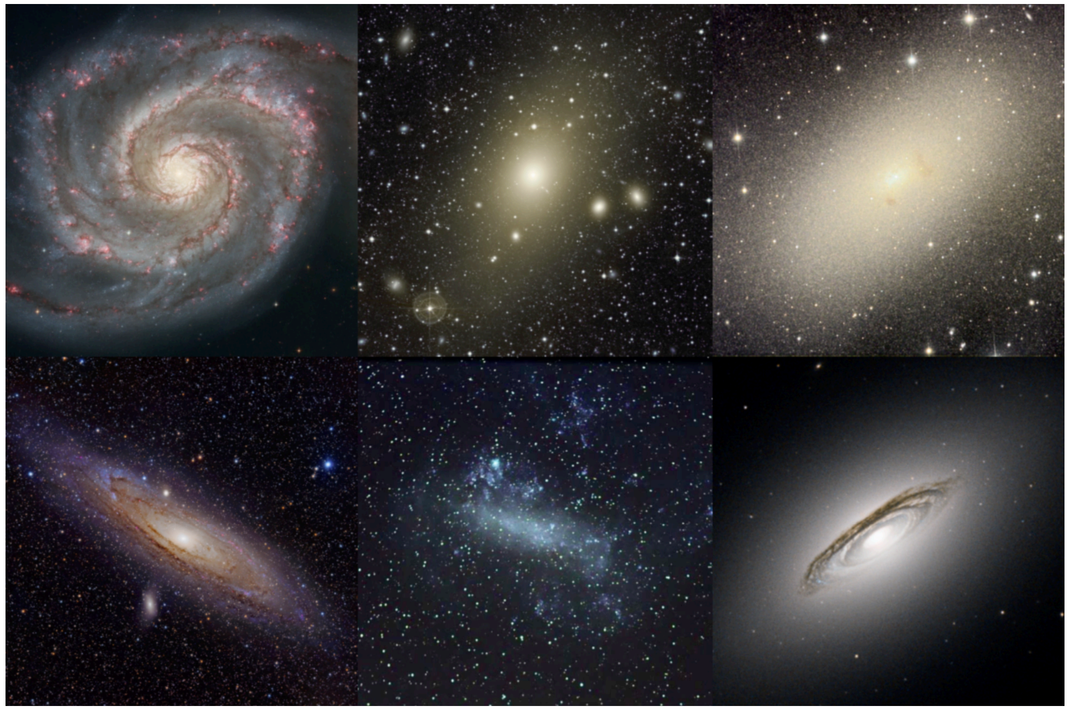
Outline

1. **Introduction:** the role of gas in galaxy evolution
2. **Gas and star formation:** molecular gas reservoirs across cosmic time
3. **Gas and dark matter:** core formation from outflow episodes

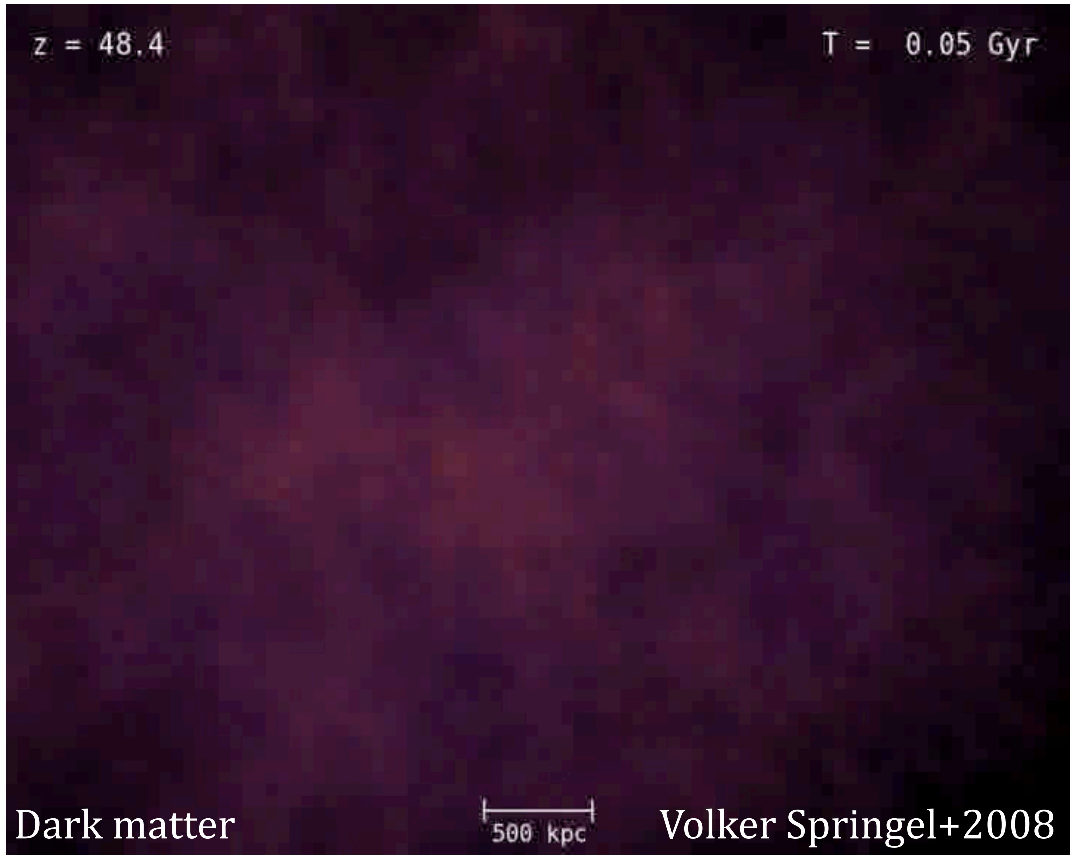
Galaxy formation in the ΛCDM model

From a very homogeneous early Universe to the current distribution of galaxies, clusters and voids...





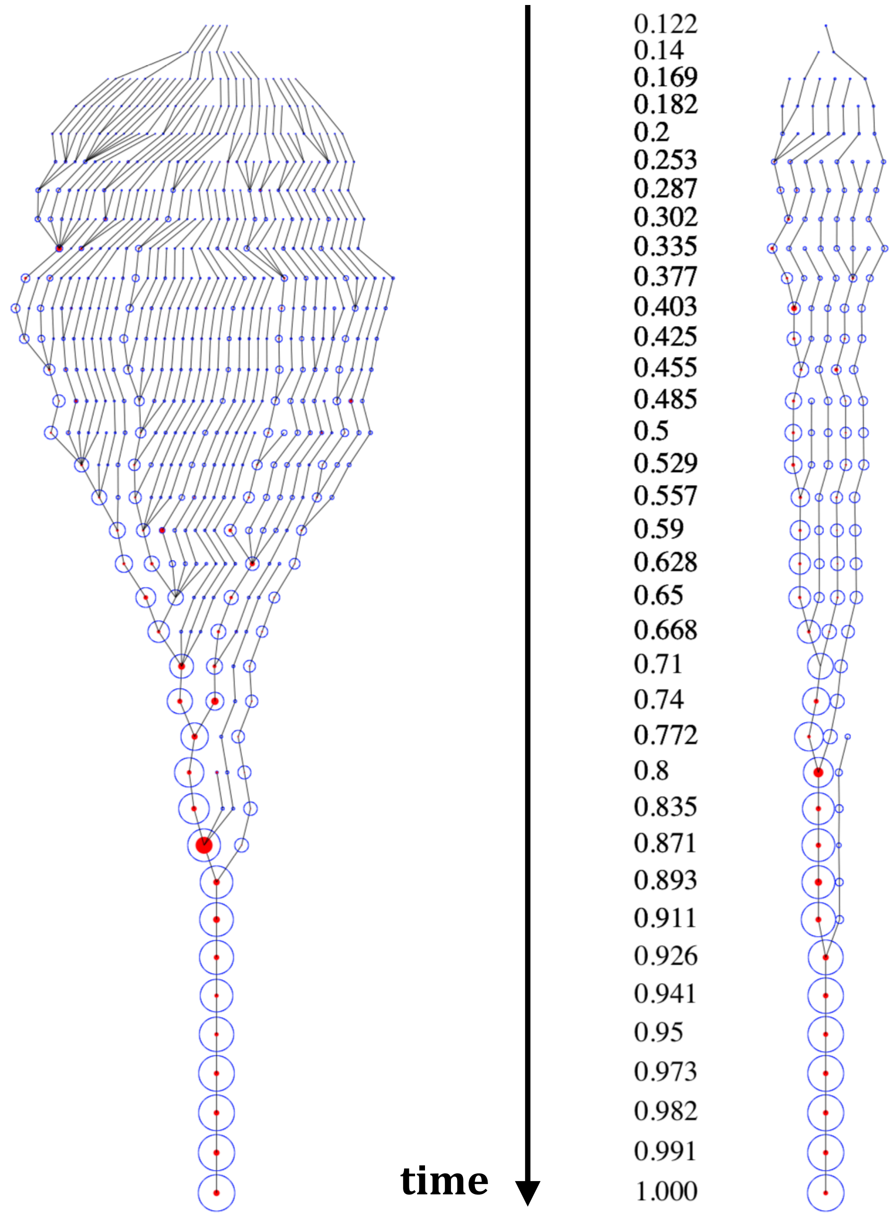
- ✦ **The standard ΛCDM cosmological model:**
  - 26% cold dark matter (CDM)
  - 5% baryons (ordinary matter)
  - 69% dark energy (accelerated expansion, Λ)
- ✦ **The Universe is initially very homogeneous** (cf. cosmic microwave background, 380 000 years after the Big Bang).
- ✦ **Gravitational attraction vs. the expansion of the Universe.**
- ✦ Hierarchical dark matter dynamics, baryons cool and contract within dark matter haloes.



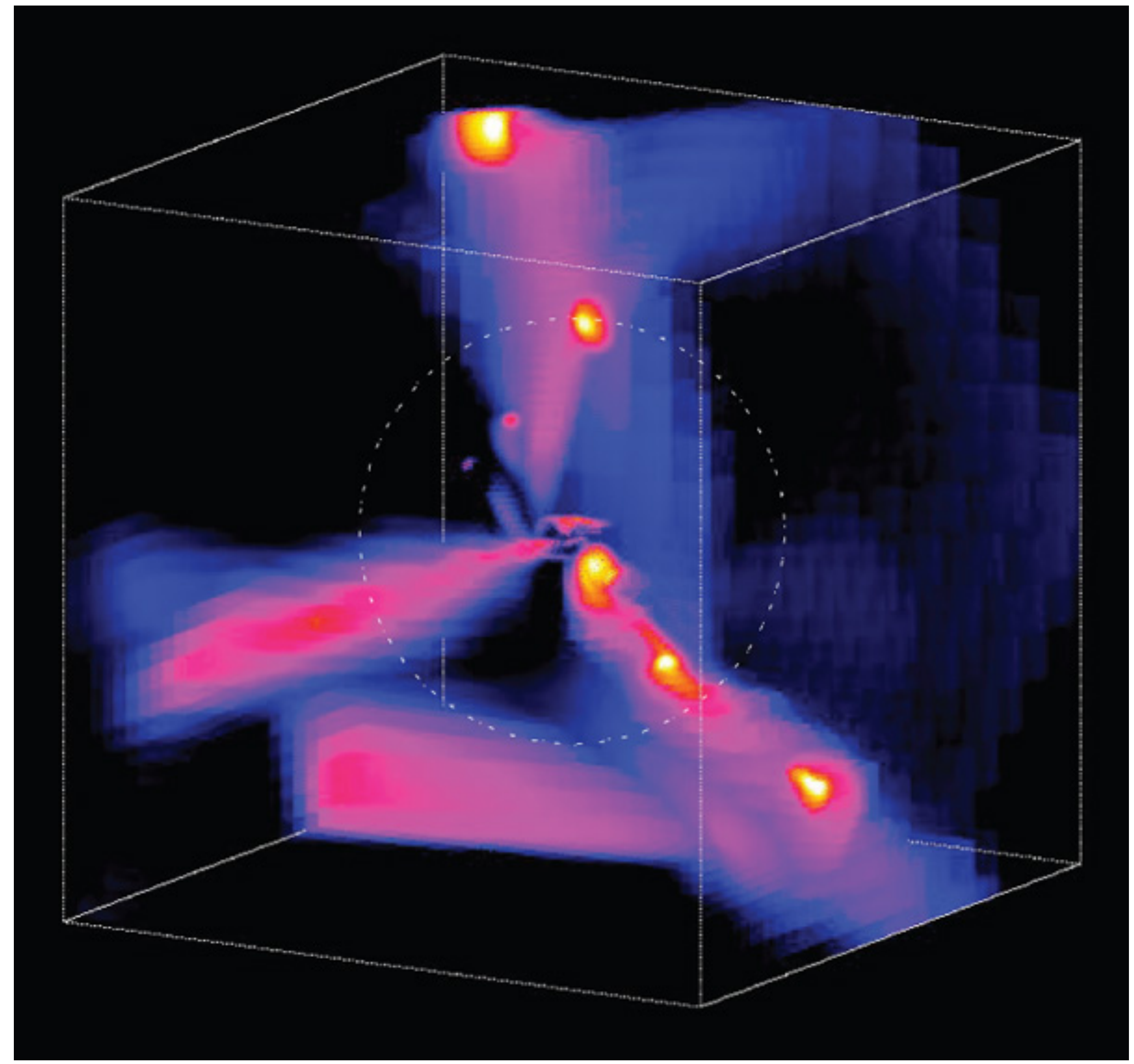
Images: ESA/Planck collaboration/C. Mihos/ESO/A. Block/NOAO/AURA/NSF/
A. Evans/NASA/S. Beckwith/Hubble Heritage Team/STScI/AURA/Skatebiker

How do galaxies get their gas?

Mergers vs. smooth accretion along the streams of the cosmic web



Wechsler+2002



Dekel, Birnboim, Engel, Freundlich+2009

Star formation

Stars form from cold giant molecular gas clouds in the interstellar medium

- ✦ Mostly composed of hydrogen, masses of 10^5-10^7 $M_\odot$, sizes over a few tens of parsec
- ✦ Gravitational collapse, fragmentation into high-density cores
- ✦ Inside the pre-stellar cores, temperature and pressure rise
- ✦ Nuclear fusion reactions and stellar stellar nucleosynthesis

(1 parsec = 3.09 10^{16} m)

The Orion nebula, a stellar nursery (NASA)

Feedback processes

Stellar feedback

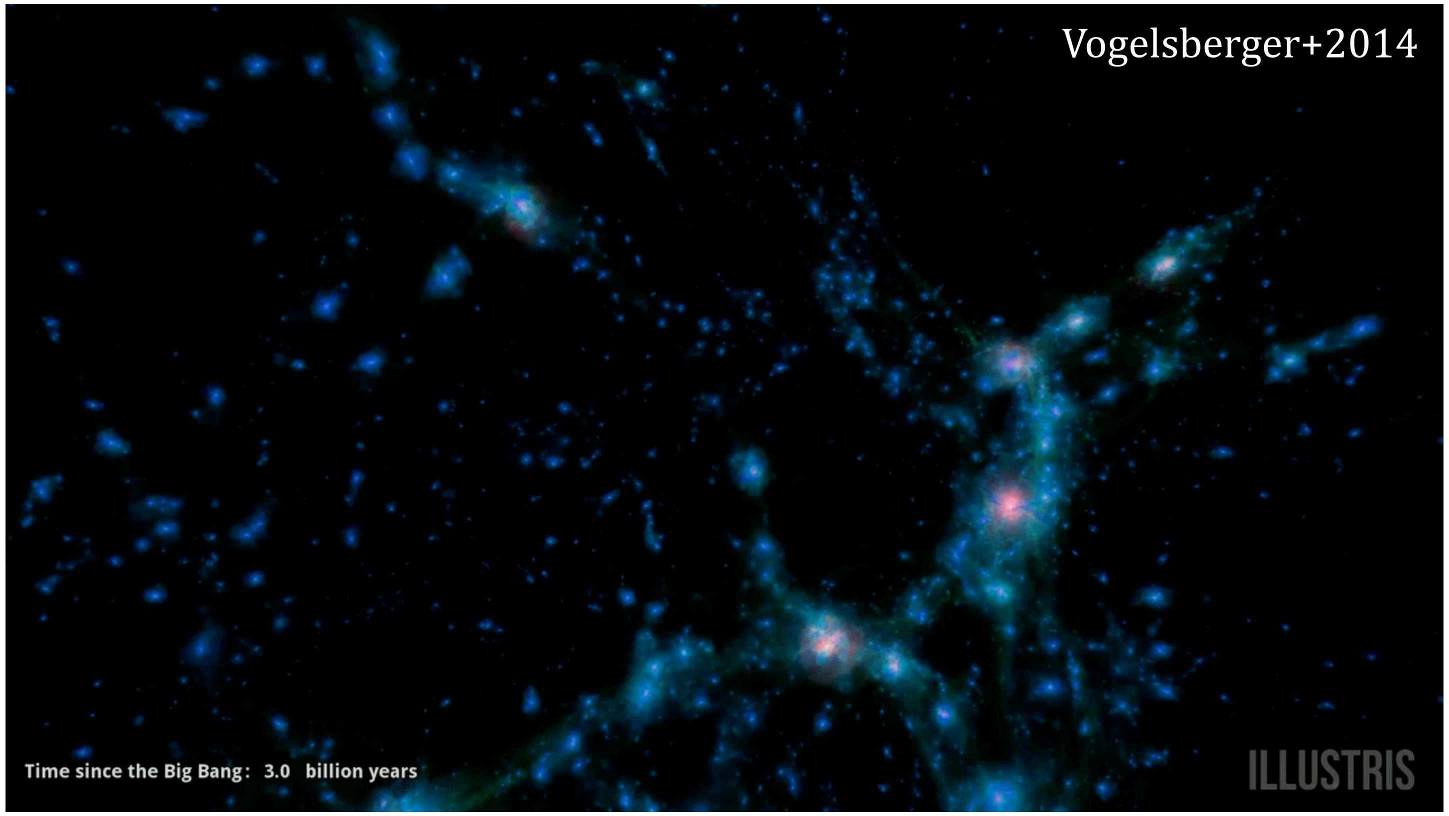
- ✦ Strong radiation fields:
  - UV ionising radiation
  - photoevaporation
  - radiation pressure
- ✦ Stellar winds
- ✦ Supernova explosions

Active galactic nuclei (AGN) feedback

- ✦ Radiation
- ✦ Outflowing winds
- ✦ Highly-collimated jets

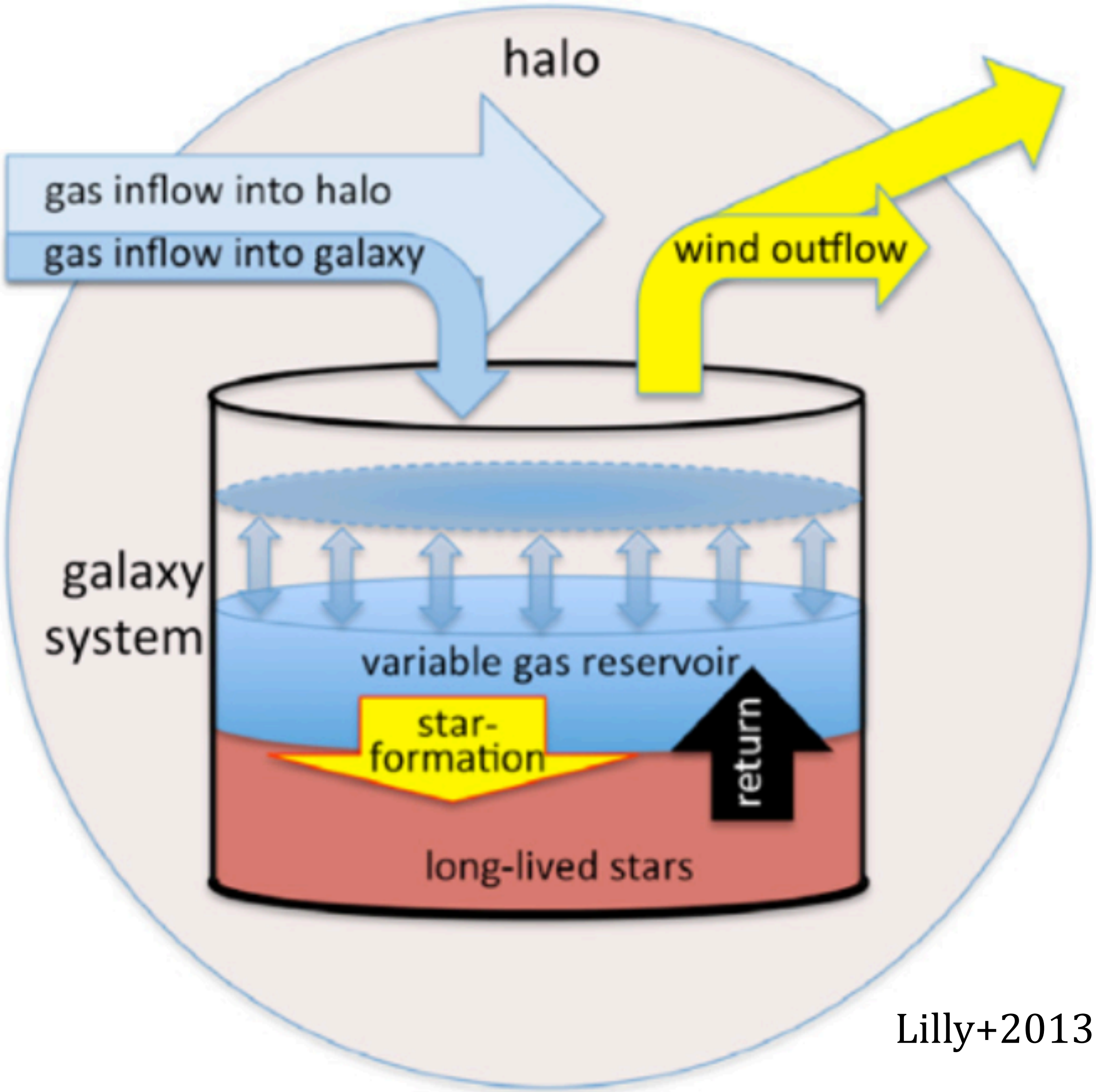
Positive feedback

- ✦ Heavy elements enhance cooling
- ✦ Compression waves



Galaxies as star factories

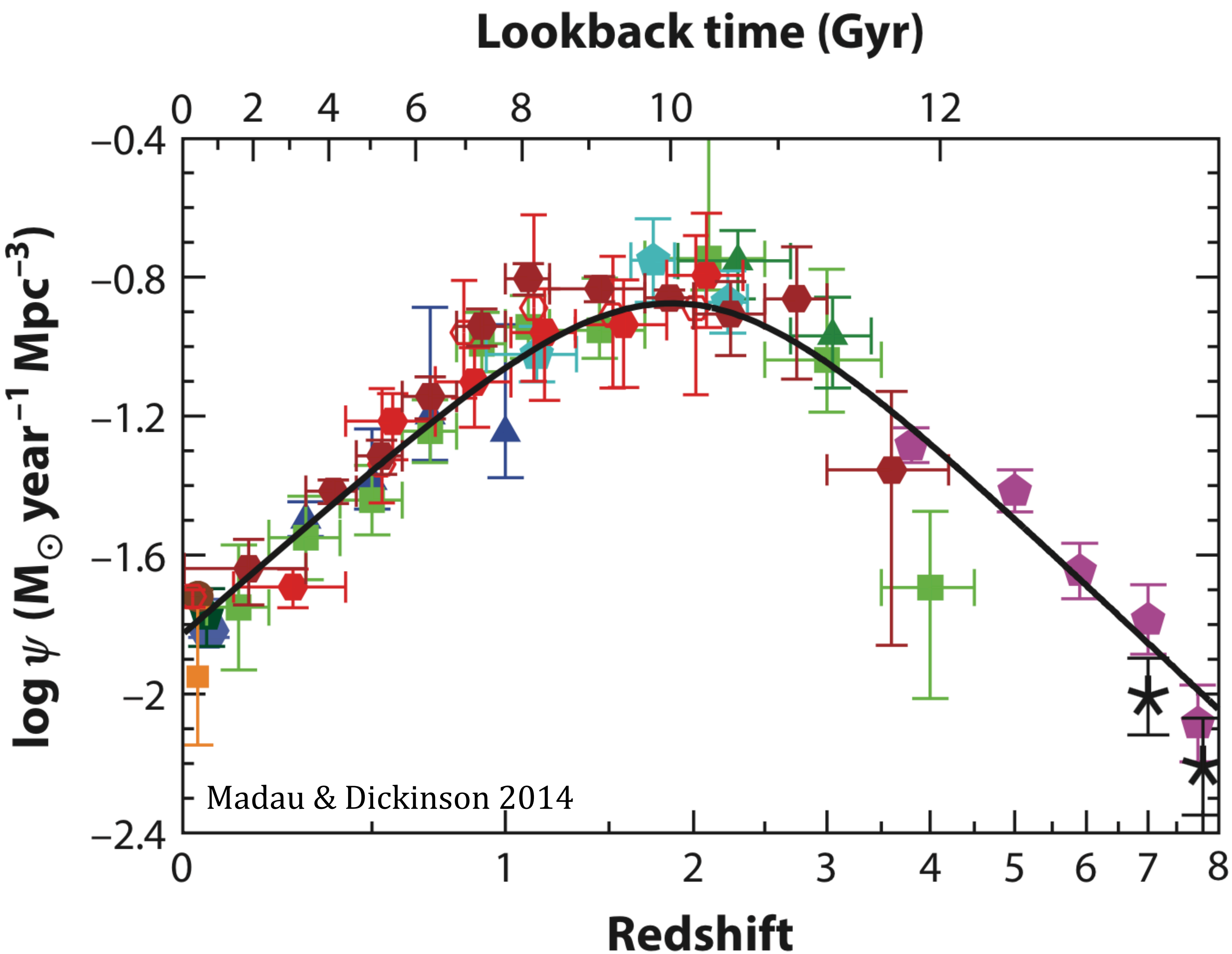
$$\underbrace{\dot{M}_{gas}}_{\text{gas reservoir}} = \underbrace{\dot{M}_{gas,in}}_{\text{inflows}} - \underbrace{\dot{M}_{stars}}_{\text{star formation}} - \underbrace{\eta \dot{M}_{stars}}_{\text{outflows}} + \underbrace{R\dot{M}_{stars}}_{\text{recycling}}$$



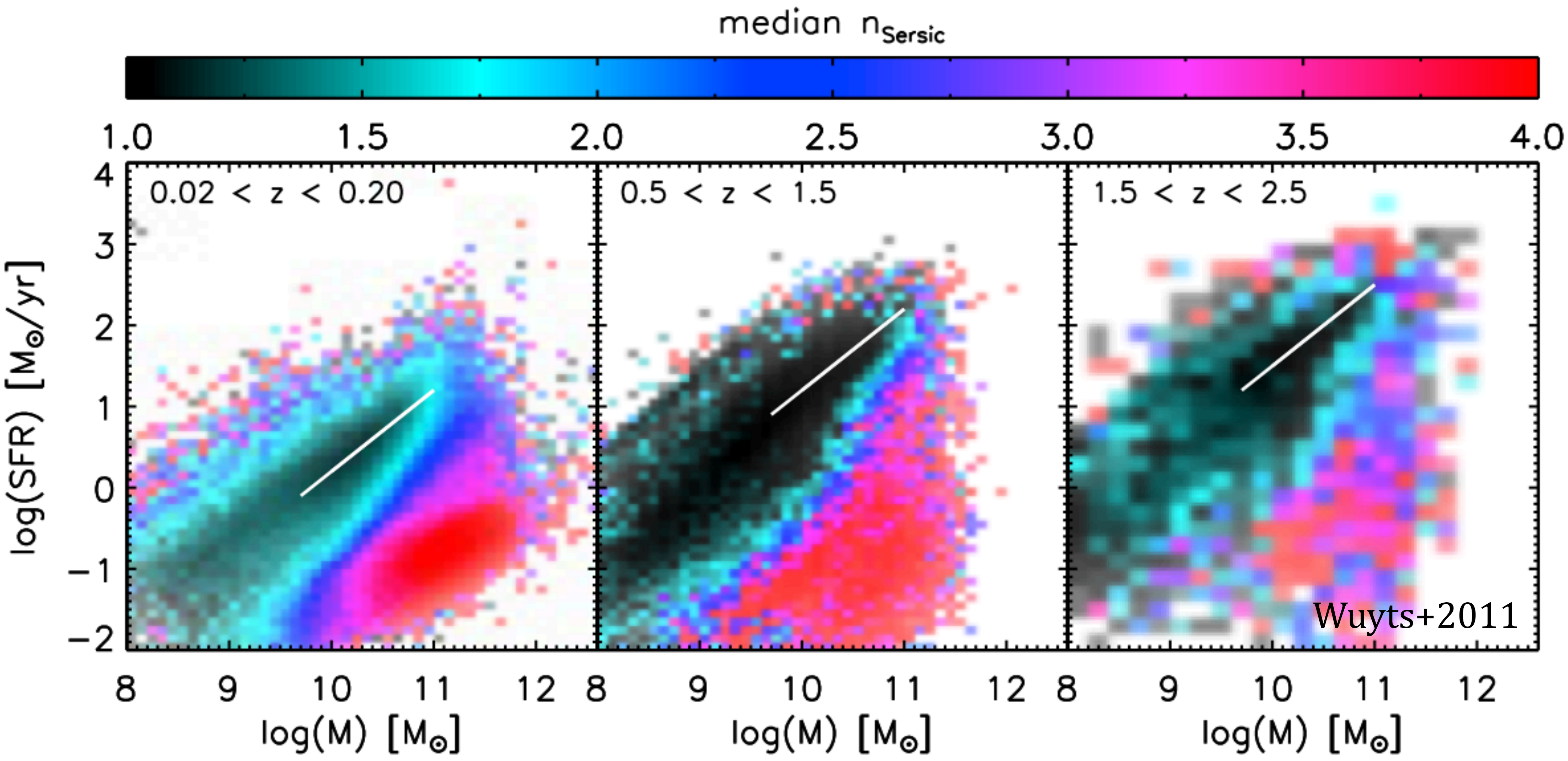
Lilly+2013

Star formation across cosmic time

Our Galaxy only forms a few stars per year, as most nearby galaxies. Ten billion years ago, between z=1-3, the star formation rate (SFR) could be up to 10-20 times higher.



The main sequence of star formation



- ✦ About 90% of the cosmic star formation history since *z=2.5* took place near the MS (Rodighiero+2011, Sargent+2012)
- ✦ At a given Mstar, the SFR on the MS drops by a factor ∼20 from z∼2 to the present time
- ✦ Tighness of the MS (0.3 dex): the evolution is not driven by mergers but by continuous processes

The Kennicutt-Schmit (KS) relation

Schmidt 1959

$\rho_{\mathrm{SFR}} \propto (\rho_{\mathrm{gas}})^n$

n~2 in our Galaxy

Kennicutt 1998

$\Sigma_{\mathrm{SFR}} \propto (\Sigma_{\mathrm{gas}})^N$

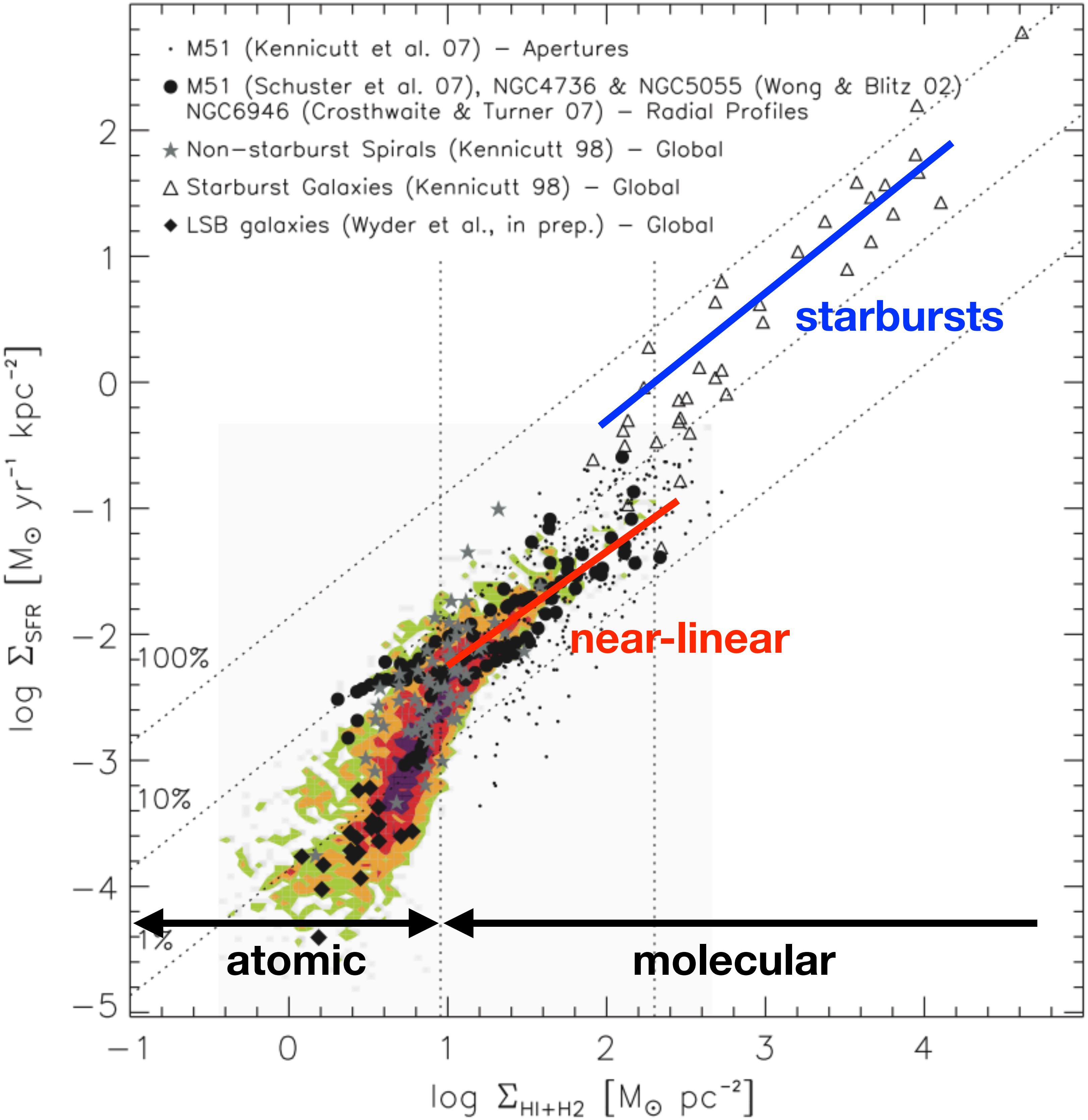
$N = 1.40 \pm 0.15$

in a sample of 61 spirals and 36 starbursts

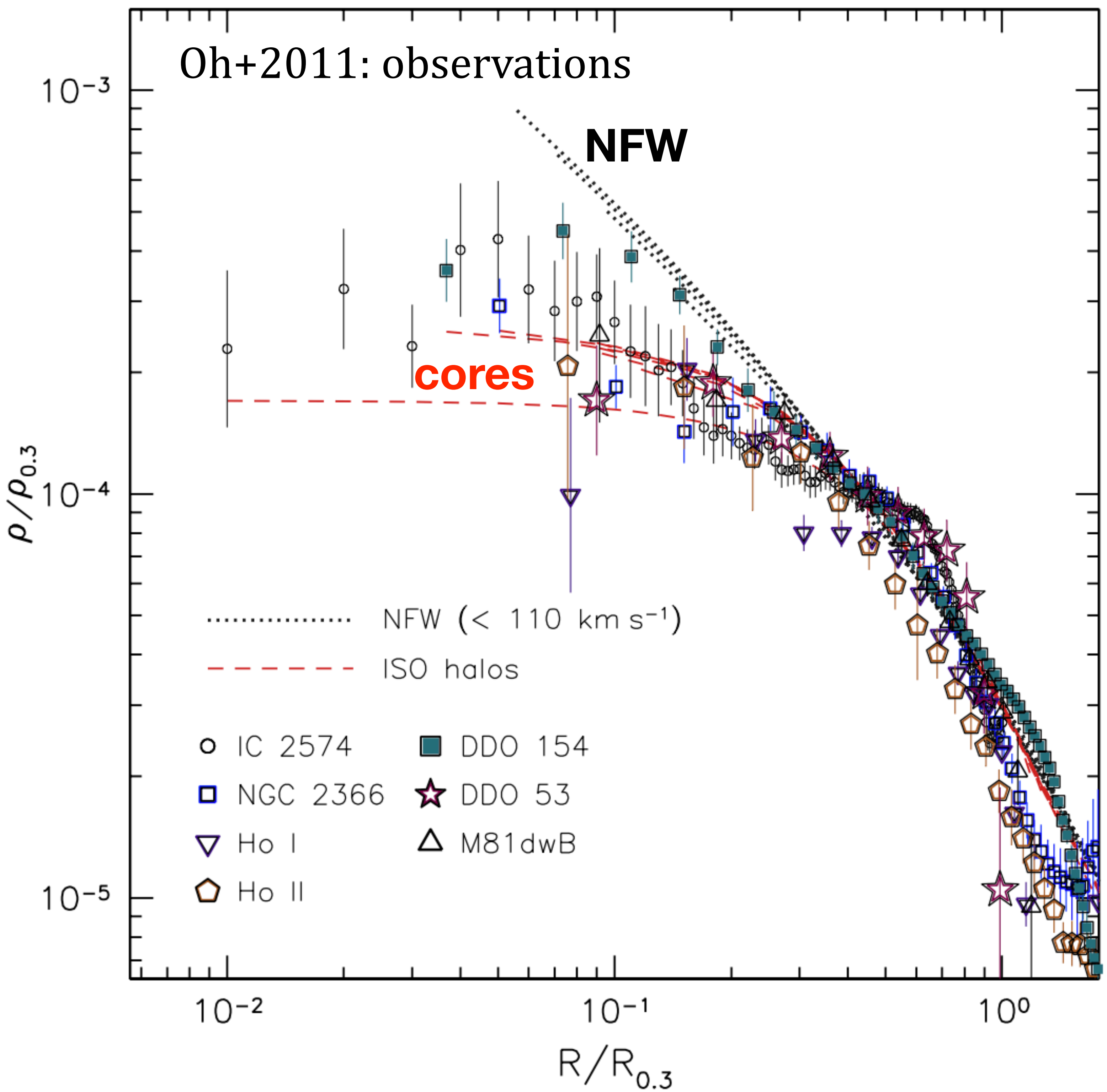
A linear relation indicates a constant **depletion time**

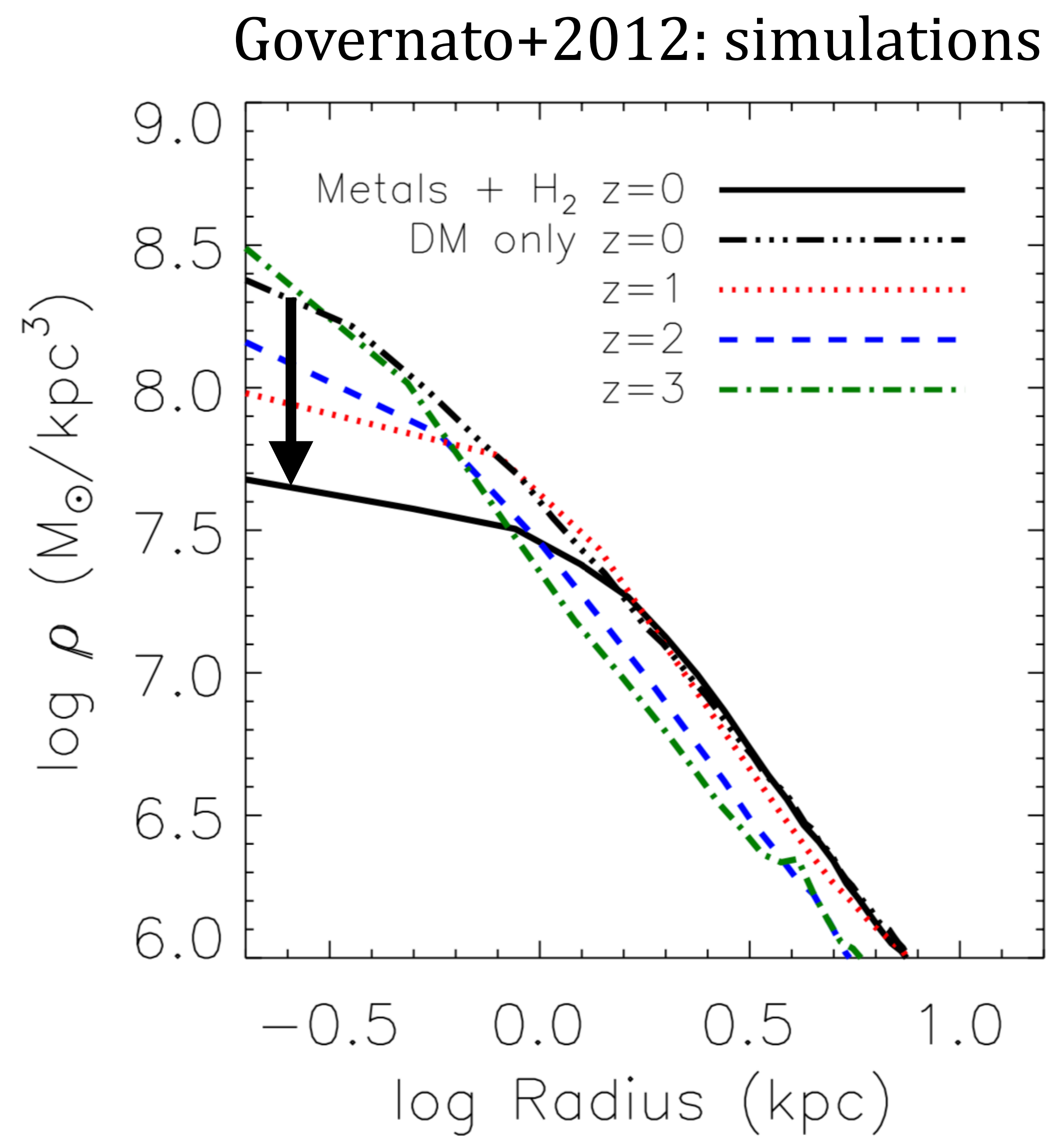
$t_{\mathrm{depl}} = M_{\mathrm{gas}}/\mathrm{SFR}$

Bigiel+2008



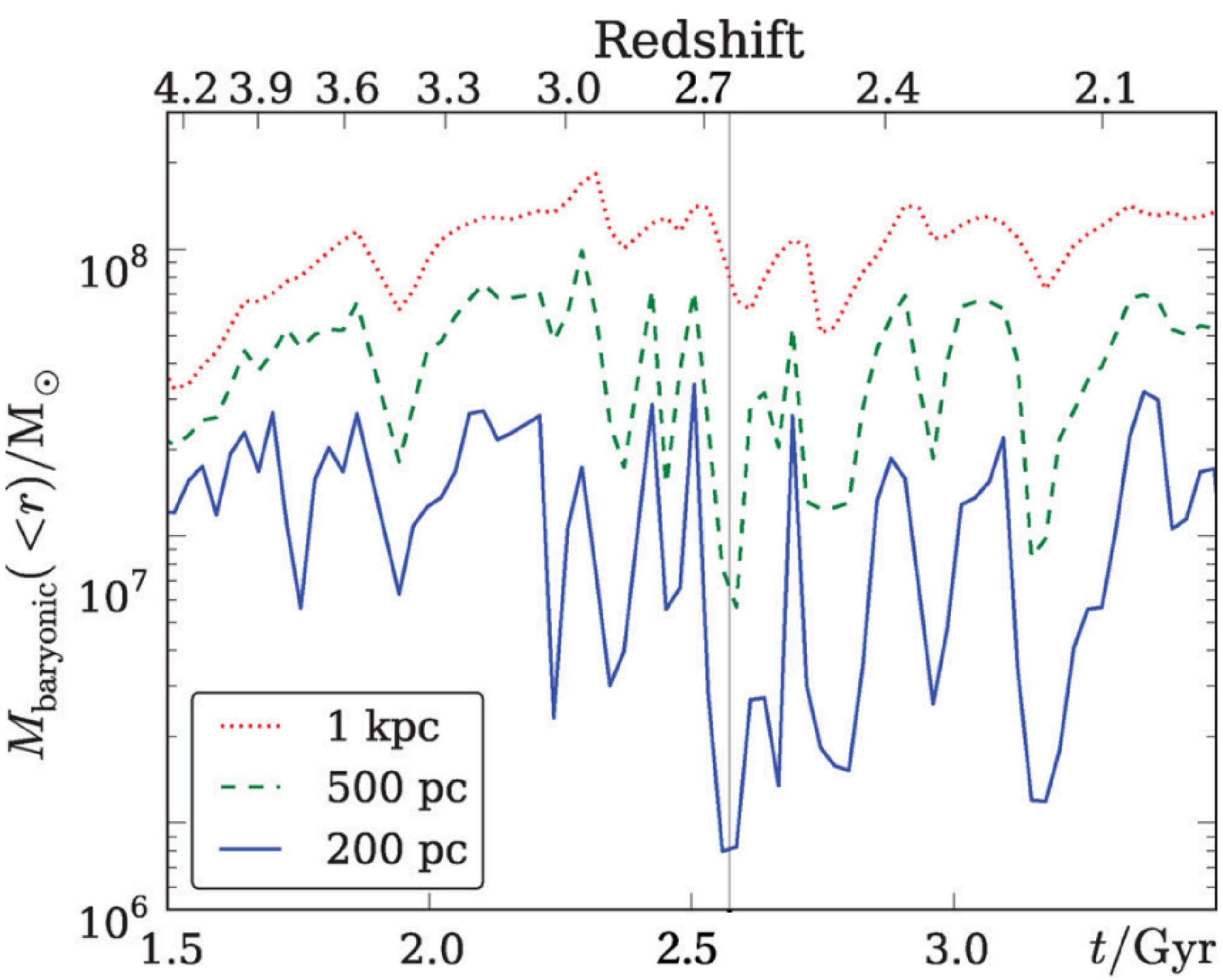
The cusp-core discrepancy

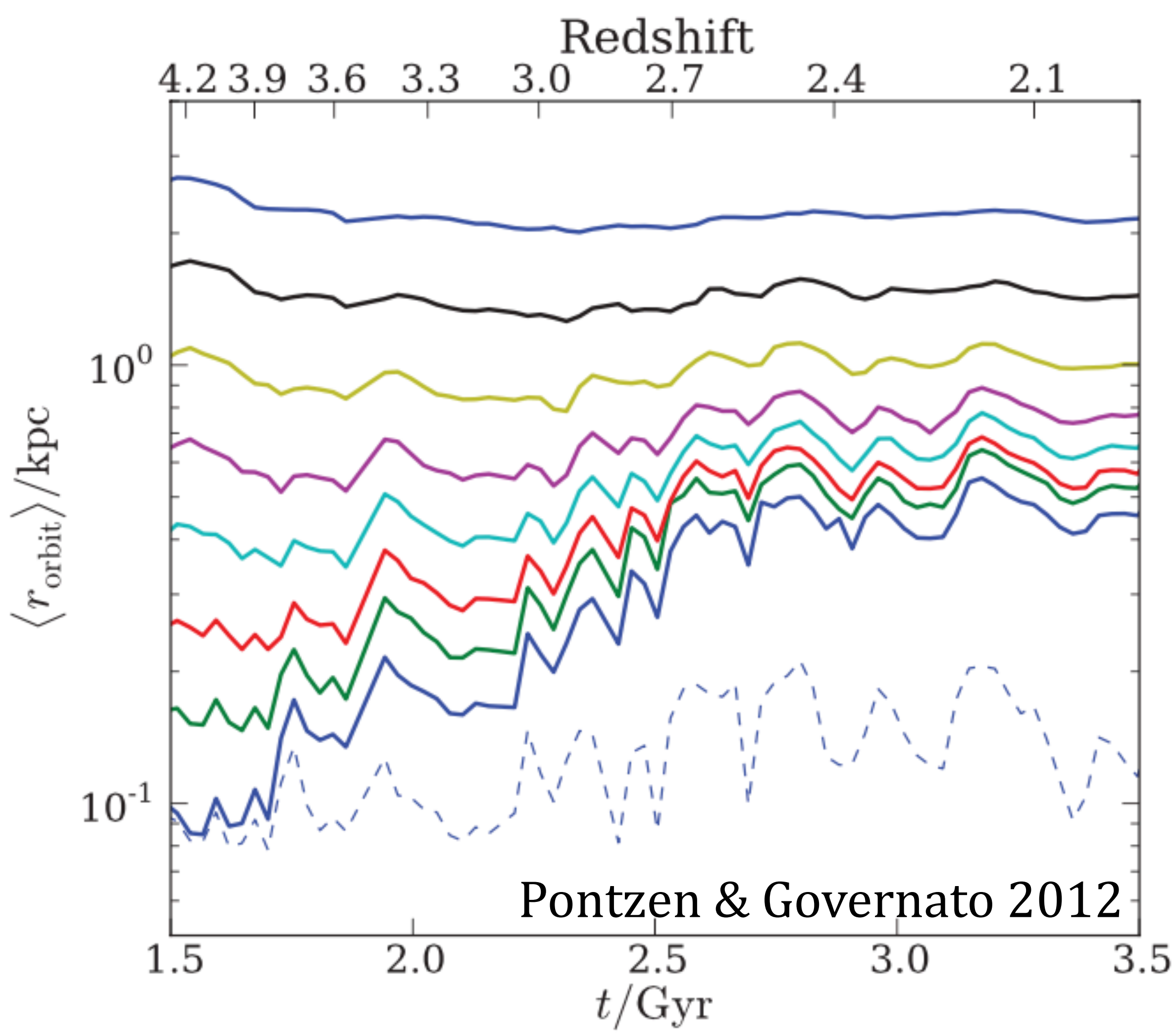




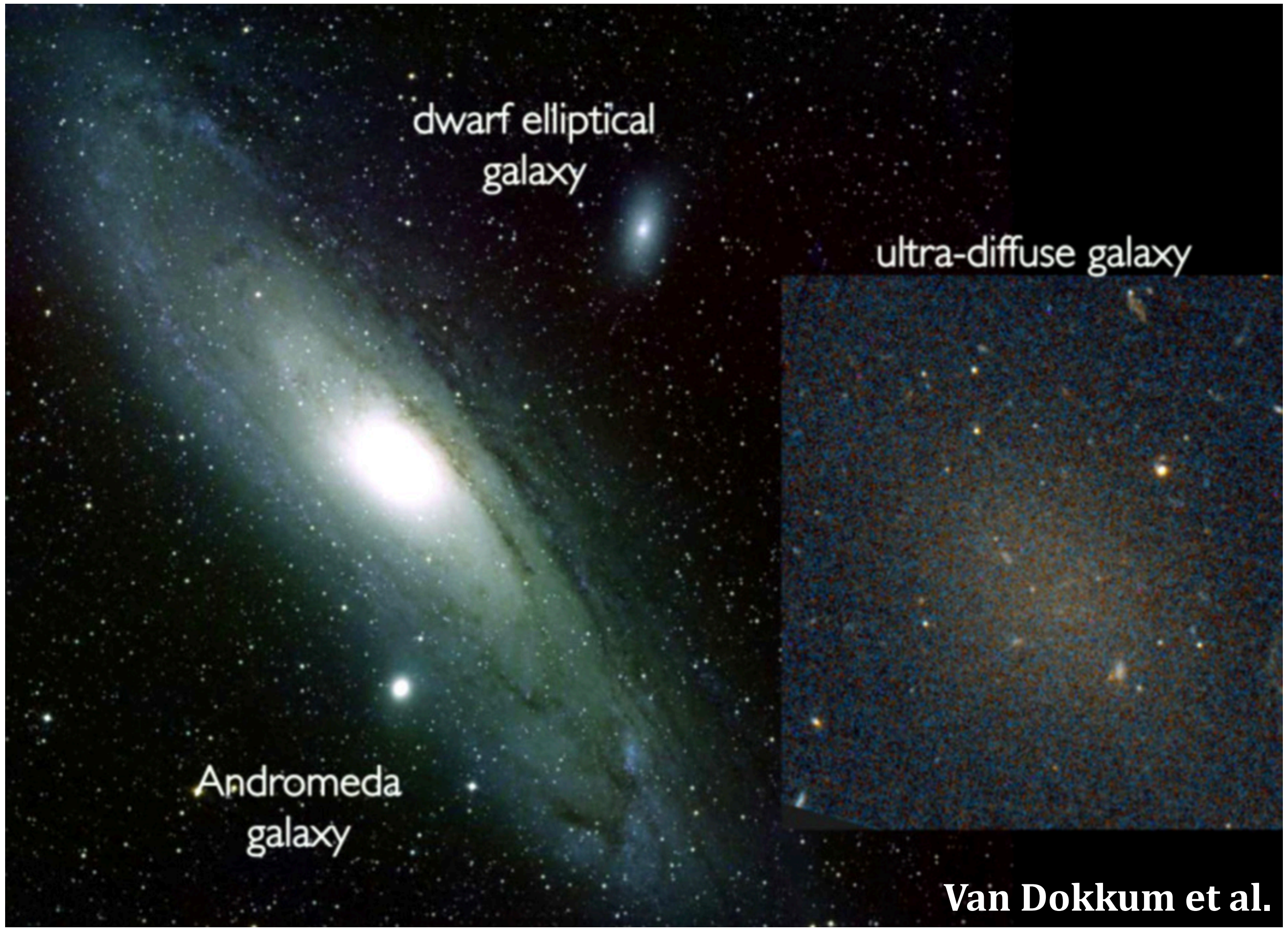
How can baryons affect the dark matter (DM) halo

- ✦ **Adiabatic contraction** (Blumenthal+1986)
- ✦ **Dynamical friction** (El-Zant+2001, 2004)
- ✦ **Repeated potential fluctuations from feedback processes** (Pontzen & Governato 2012)





Ultra Diffuse Galaxies (UDGs)

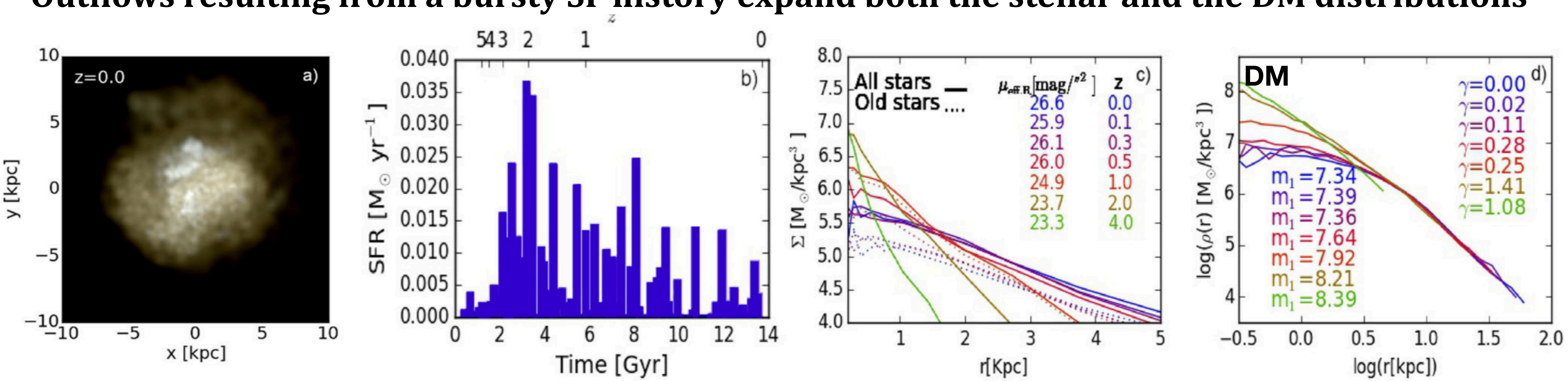


- ✦ **Stellar masses of dwarf galaxies**
  $7 < \log(M_{star}/M_{\odot}) < 9$
- ✦ **Effective radii of MW-sized objects**
  $1 < r_{eff}/\text{kpc} < 5$

Possible formation scenarii:

- ✦ **Failed MW-like galaxies** (Van Dokkum+2015)
- ✦ **High-spin tail** (Amorisco & Loeb 2016)
- ✦ **Tidal debris** (Greco+2017)
- ✦ **Stellar feedback outflows** (Di Cintio+2017)

Outflows resulting from a bursty SF history expand both the stellar and the DM distributions

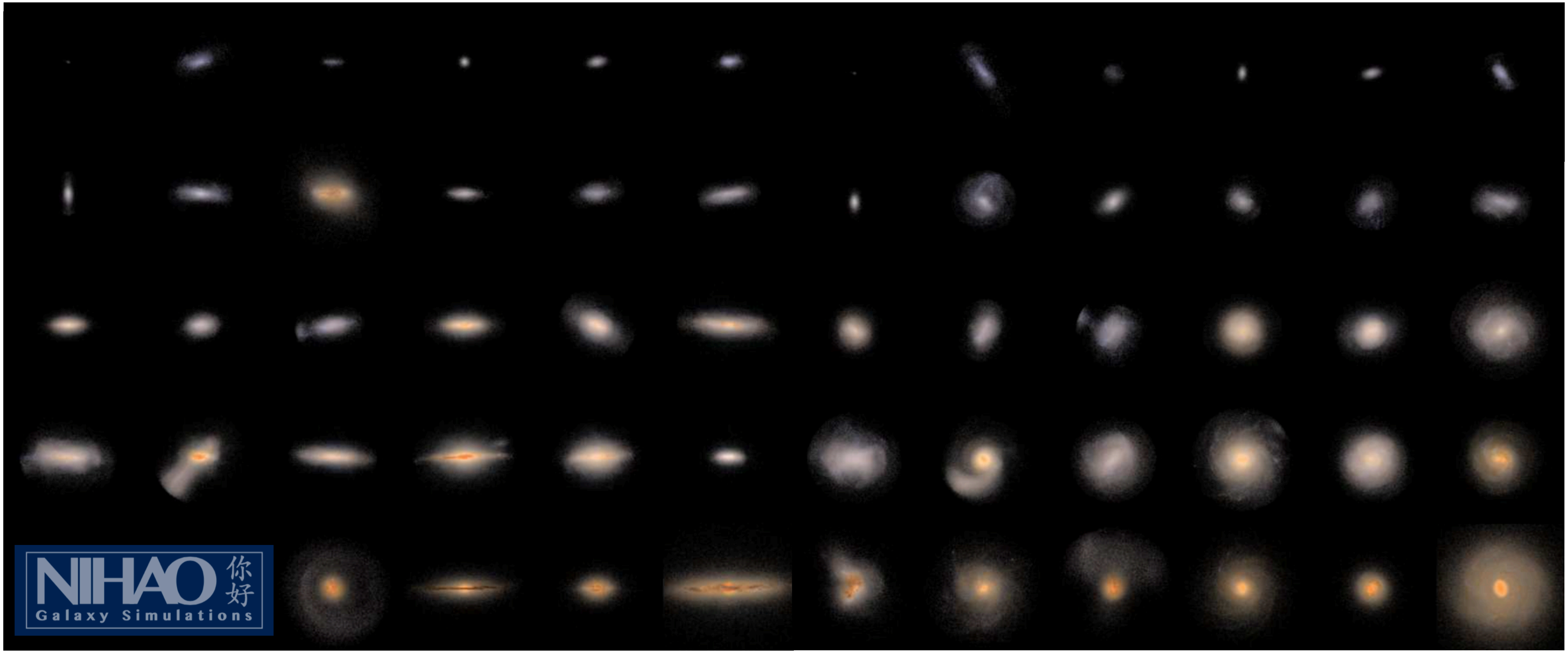


The NIHAO simulations

A set of ~100 cosmological zoom-in hydrodynamical simulations of galaxies

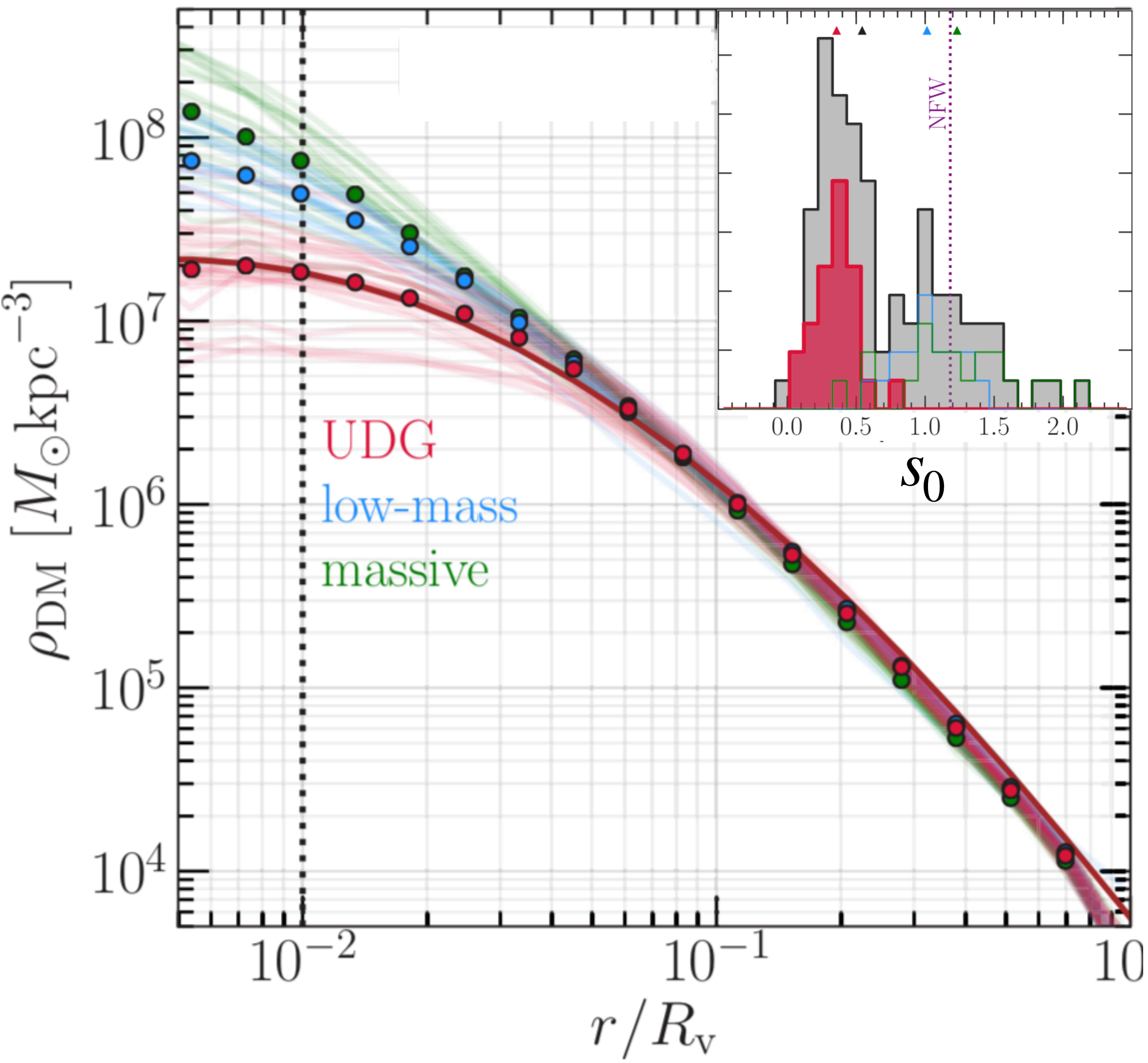
- ✦ Smoothed Particle Hydrodynamics code Gasoline2
- ✦ ΛCDM cosmology (Planck collaboration 2014)
- ✦ Turbulent mixing, cooling, UV background, star formation, chemical enrichment
- ✦ **Ionizing feedback from massive stars and blast-wave SN feedback**
- ✦ With and without baryons
- ✦ **Spatial resolution 1% of the virial radius**

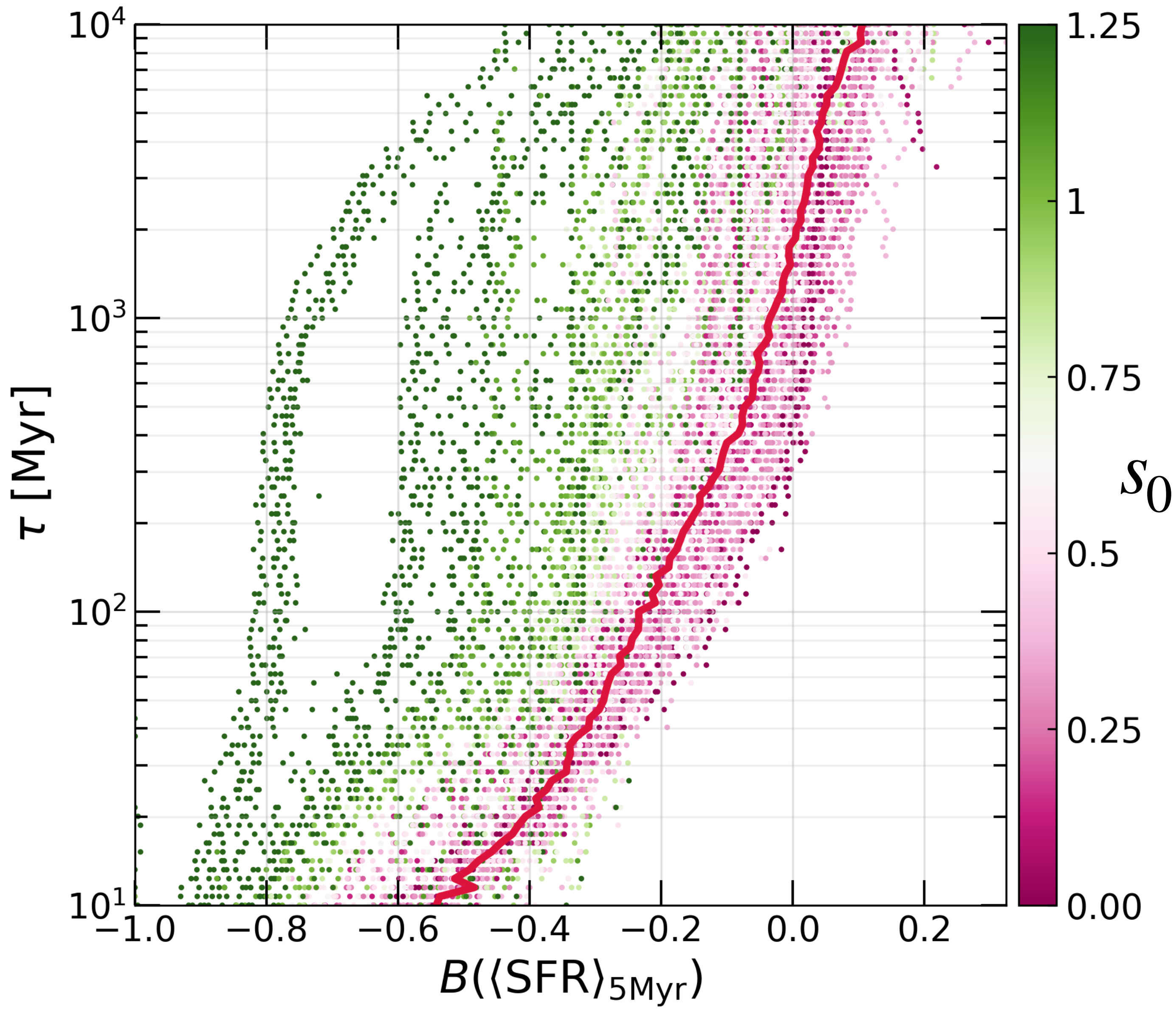
Wang+2015



Ultra-diffuse galaxies in the NIHAO simulations

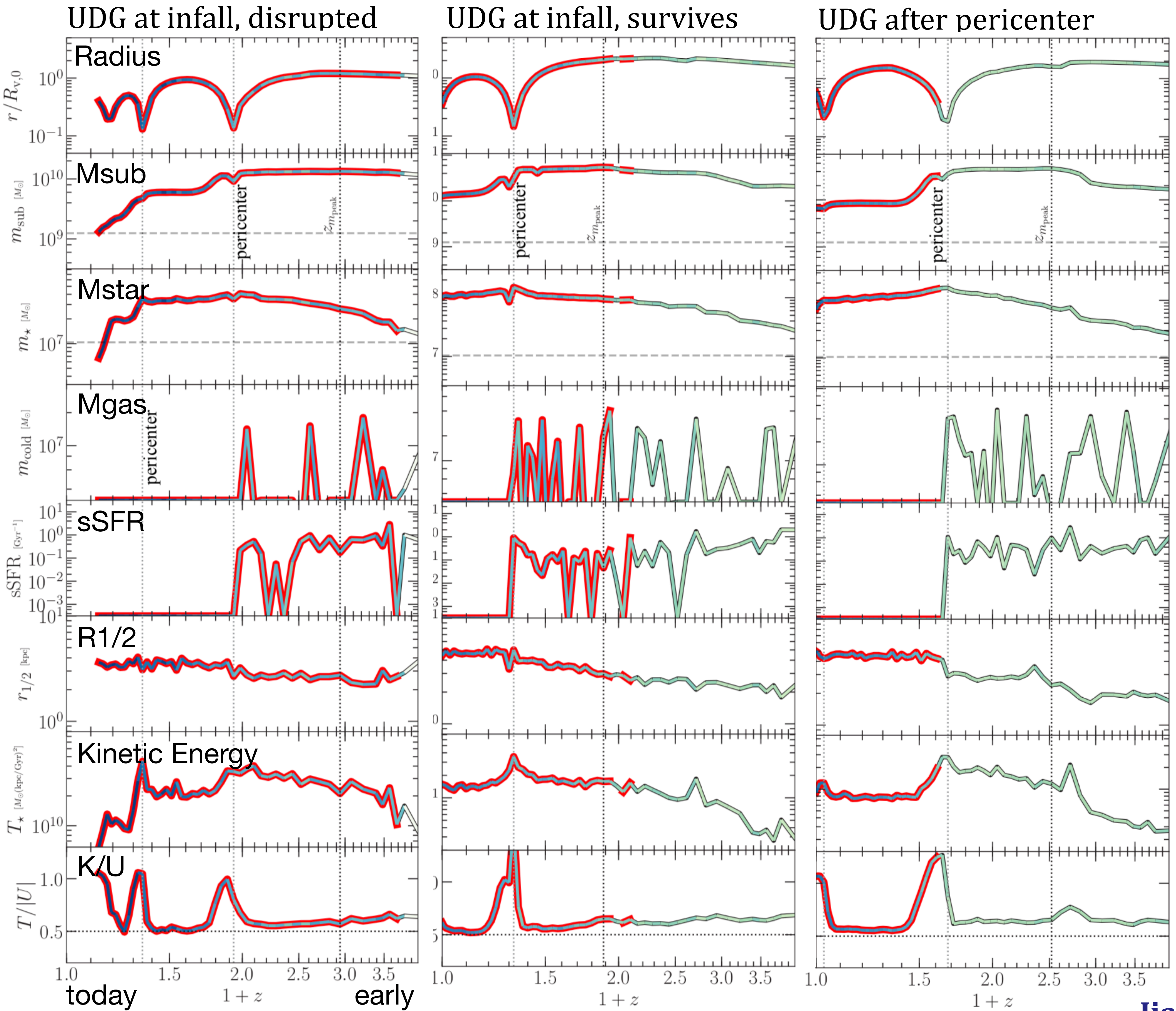
- ✦ **Cored** dark matter density profiles
- ✦ Inner slope s_0 related to the **burstiness** of the SF history $B(\tau) = \dfrac{\sigma_{\mathrm{SFR}}/\mu_{\mathrm{SFR}} - 1}{\sigma_{\mathrm{SFR}}/\mu_{\mathrm{SFR}} + 1}$



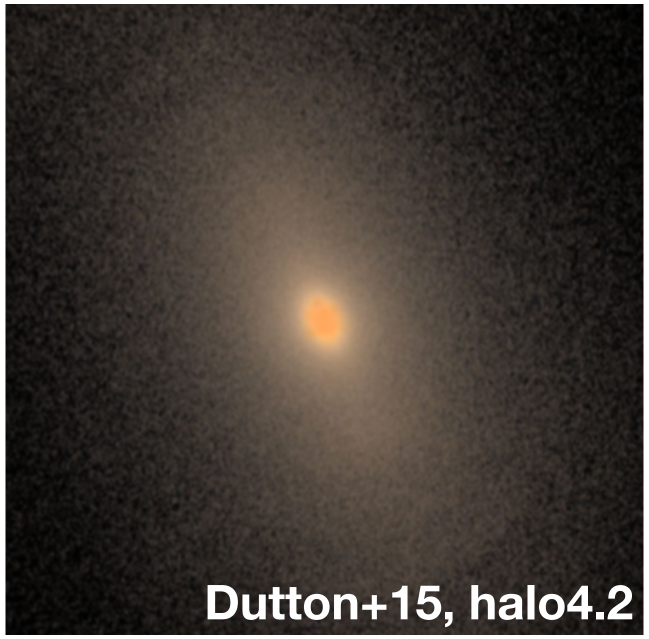


Jiang, Dekel, Freundlich+2019
Jiang, Freundlich, Dekel, Tacchella+, in prep.

Group UDGs in a NIHAO-like simulation



- ✦ About 20% of all group UDGs survive:
  - 50% accreted as UDGs
  - 50% became UDGs inside
- ✦ **Tidal puffing-up at pericenter**
  - DM loss
  - Small Mstar change
  - Size growth
  - Impulsive tidal heating
- ✦ **Gas removal by ram-pressure stripping**



Jiang, Dekel, Freundlich+2019

Outline

1. **Introduction:** the role of gas in galaxy evolution
2. **Gas and star formation:** molecular gas reservoirs across cosmic time
3. **Gas and dark matter:** core formation from outflow episodes

The IRAM PHIBSS survey (2010-2013)

IRAM **P**lateau de **B**ure **HI**gh-z **B**lue **S**equence CO(3-2) **S**urvey

- ✦ A statistical sample of main sequence (MS) galaxies near the peak epoch of star formation (*z=1-2*): 52 CO molecular gas detections
- ✦ 8 high-resolution follow-ups

Tacconi+2010, +2013, Genzel+2010, +2012, +**2013**, **Freundlich+2013**

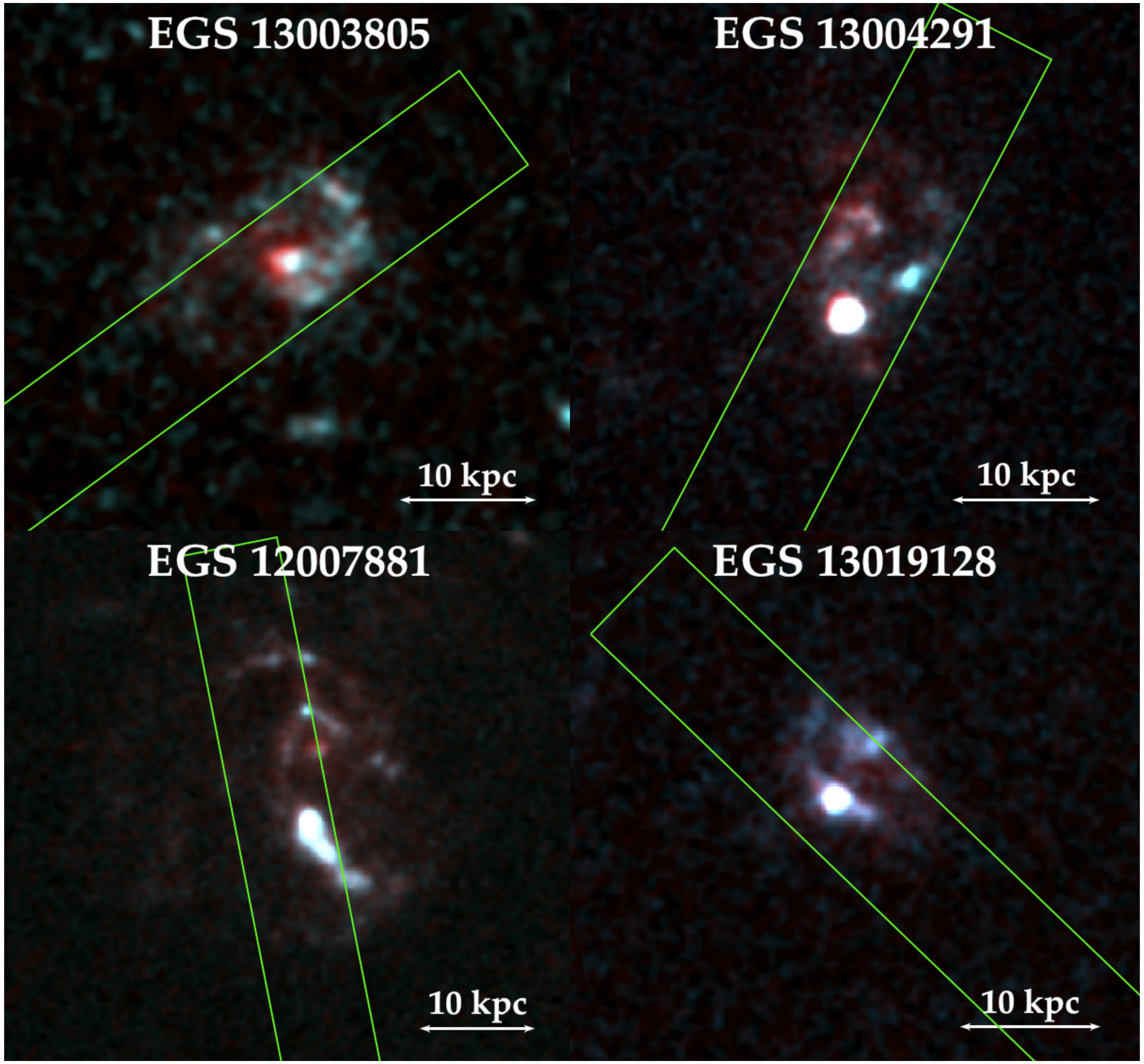
IRAM Plateau de Bure interferometer

Towards a resolved KS relation at high-z

✦ **A sample of four galaxies:**
- massive MS galaxies at $z=1.2$
- 0.5-1.5'' IRAM resolution
- no signs of major mergers

✦ **CO(3-2) molecular gas tracer**

✦ **Keck DEEP2 [OII] line spectra for the SFR**

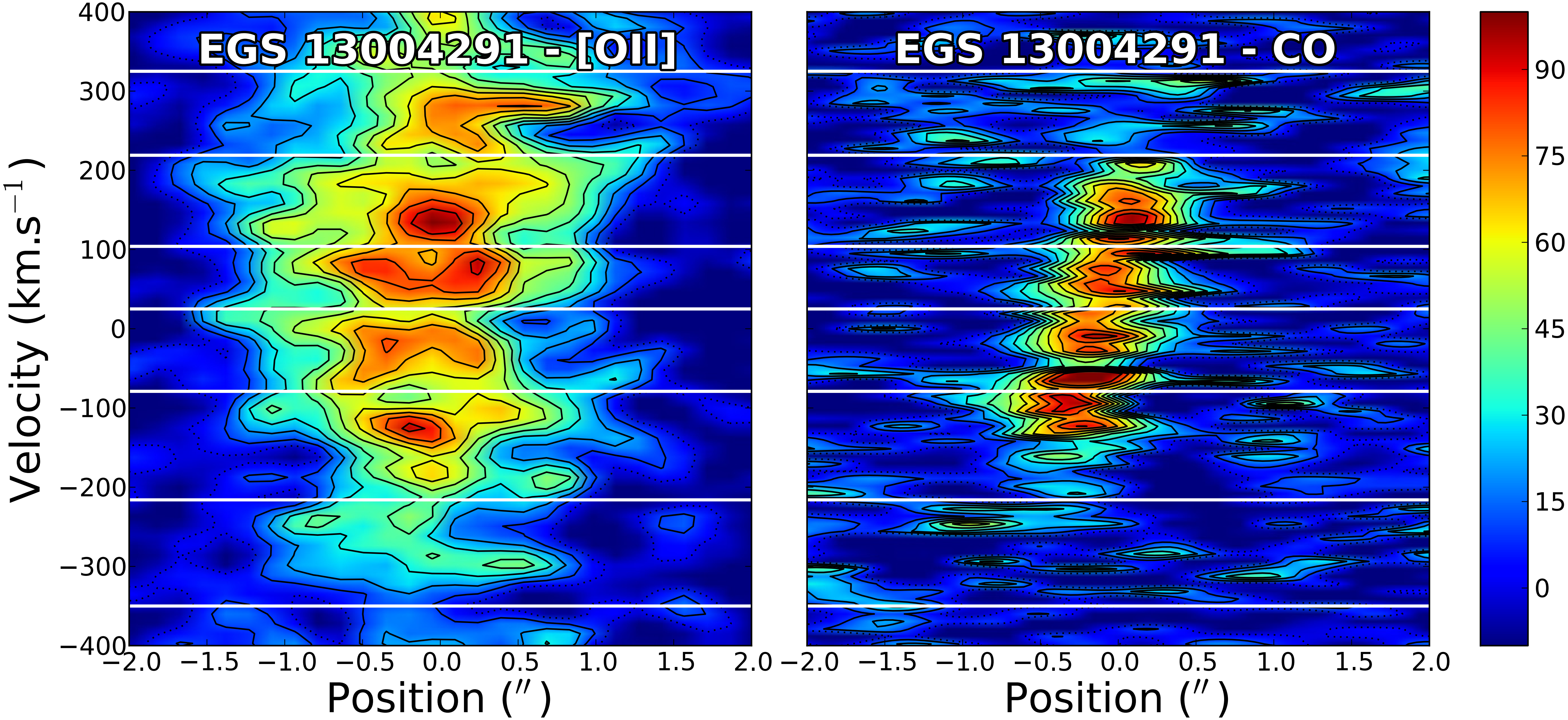


HST clumpy features smoothed out at DEEP2 and IRAM resolution (~1'')

➡ Resolving the substructures kinematically

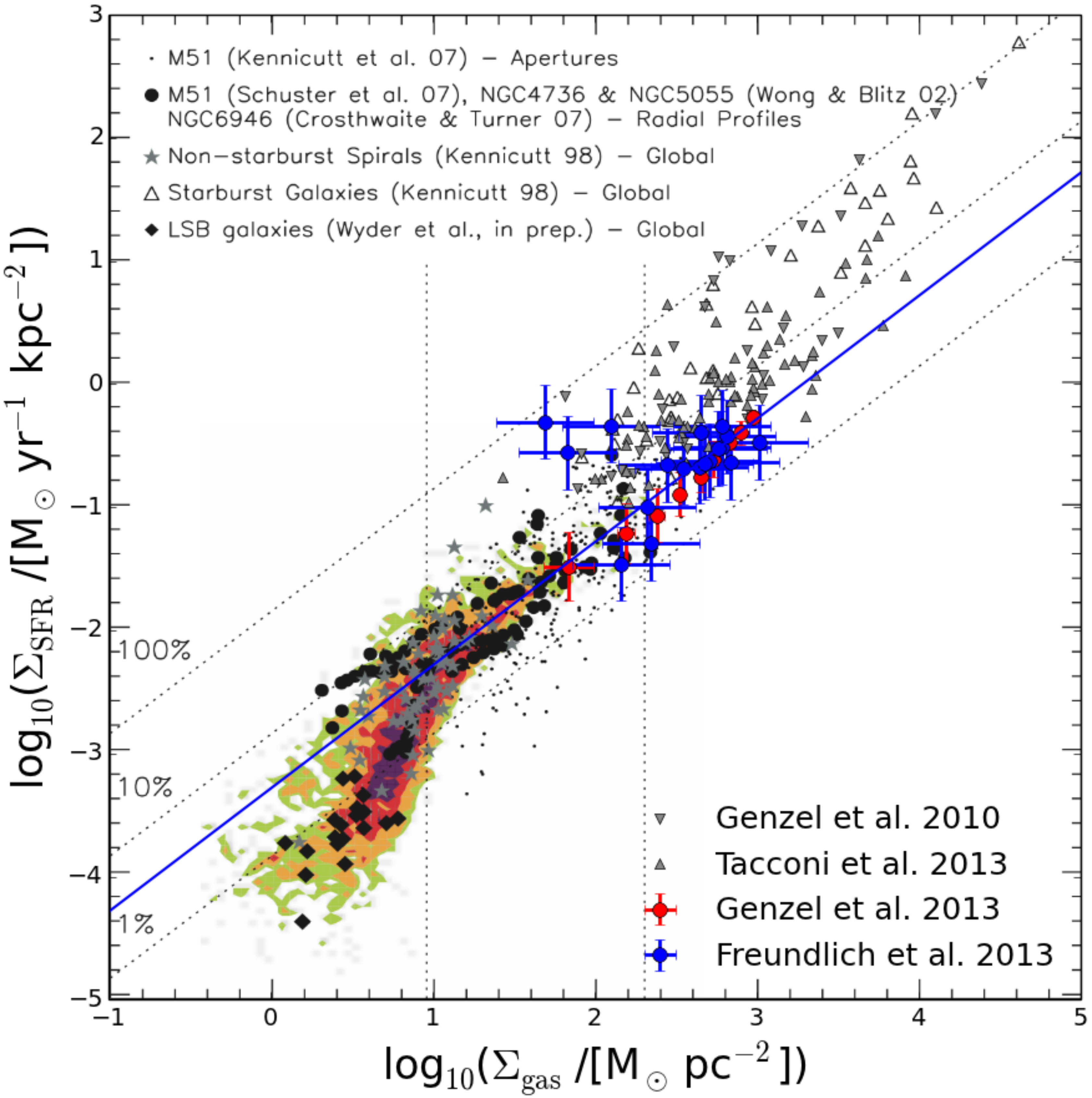
Freundlich+2013

Beating the resolution limit with the kinematics



Freundlich+2013

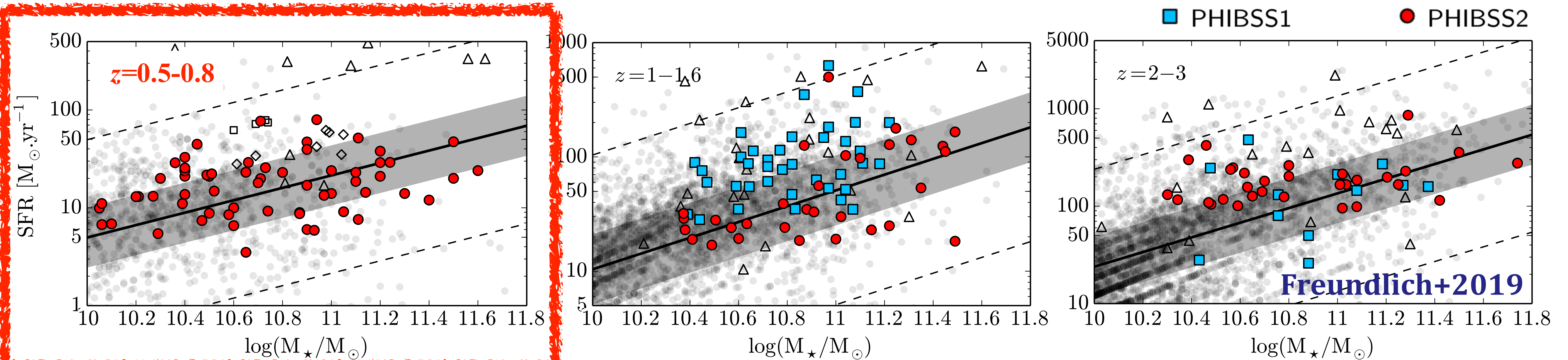
A resolved KS relation at high-z



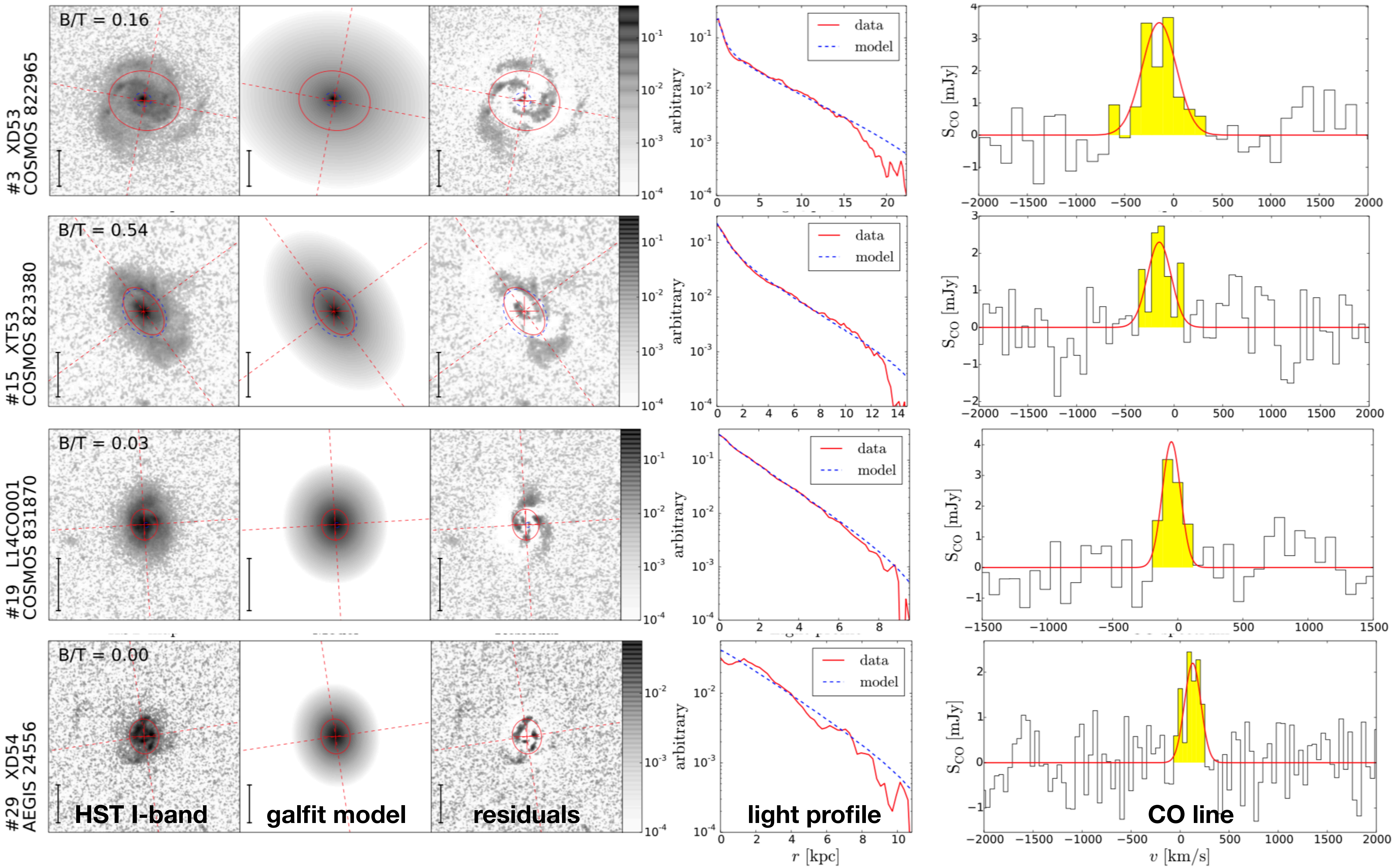
The IRAM PHIBSS2 legacy program (2013-2017)

- ✦ Covers the **build-up** (z=2-3), the **peak** (z=1-1.6) and the **winding-down** (z=0.5-0.8) of massive galaxy formation
- ✦ More than **120 targets**, including galaxies **on and below the MS**
- ✦ Enables to test the impact of AGNs, environment and morphology owing to a purely mass-selected sample

Genzel+2015, Tacconi+2018, Freundlich+2019

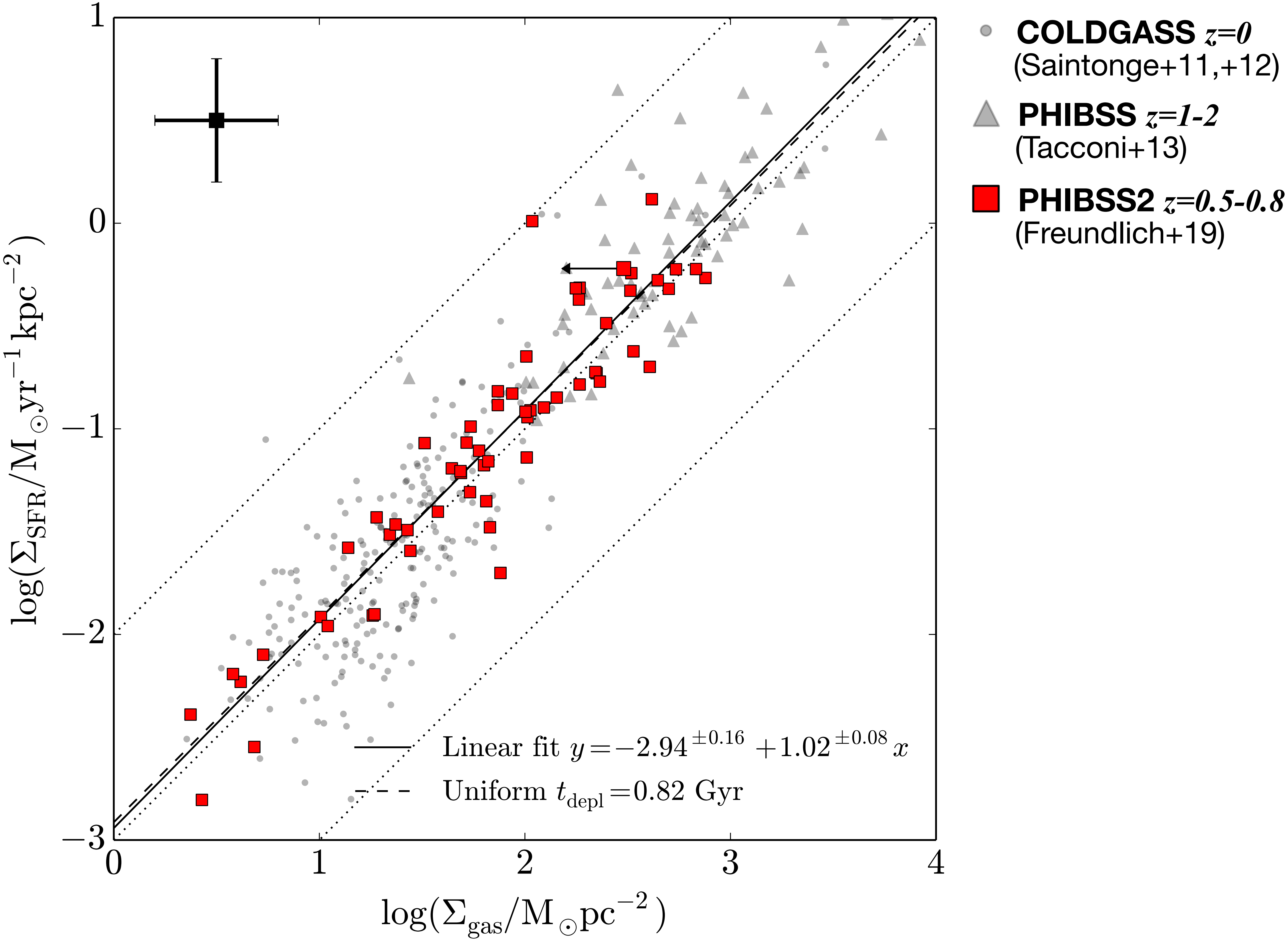


Examples of PHIBSS2 targets at z=0.5-0.8



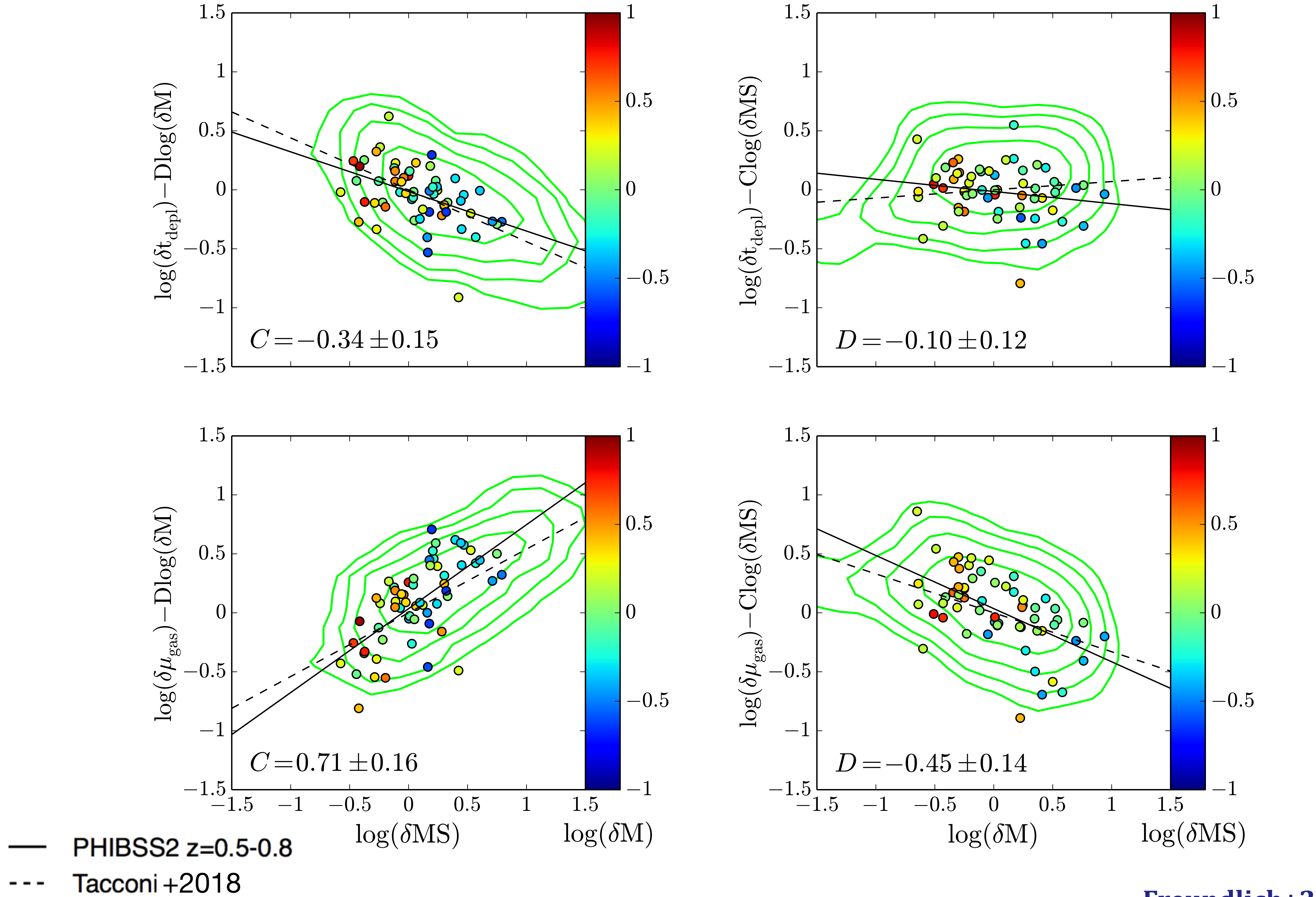
Freundlich+2019

KS relation at z=0.5-0.8



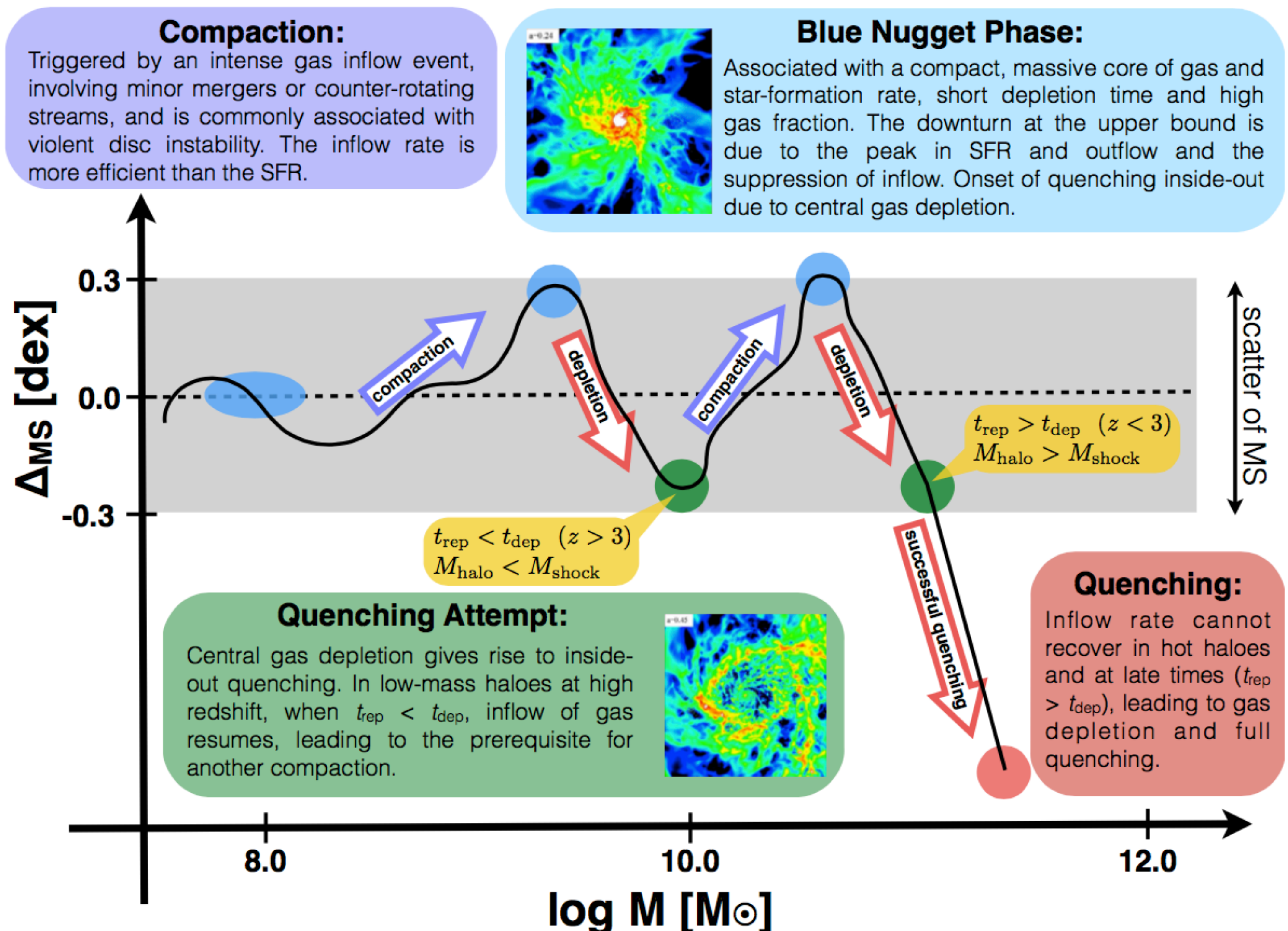
Freundlich+2019

Scaling relations at z=0.5-0.8



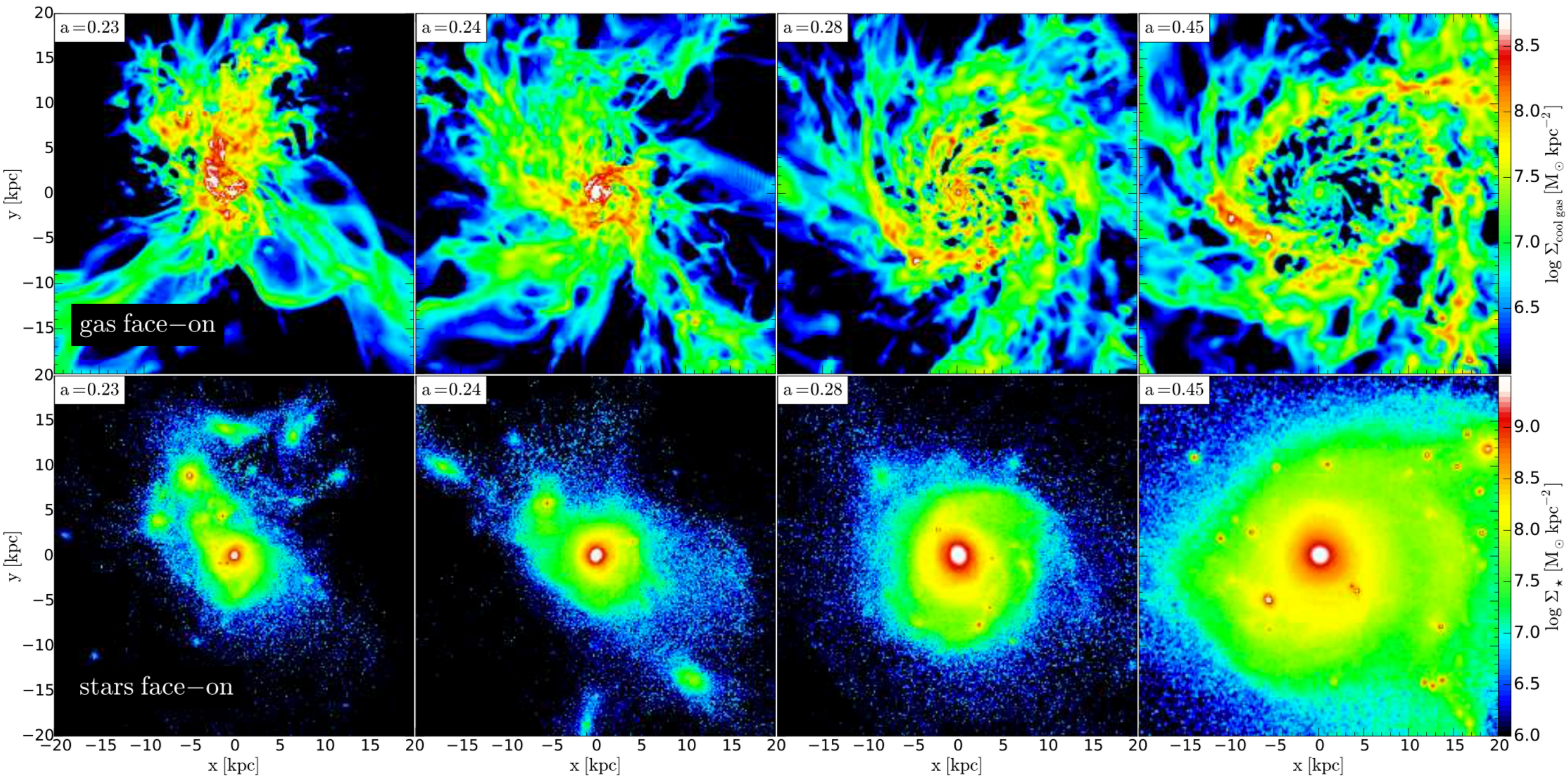
Freundlich+2019

Interpretation in terms of compaction and replenishment



Tacchella+2016

Interpretation in terms of compaction and replenishment

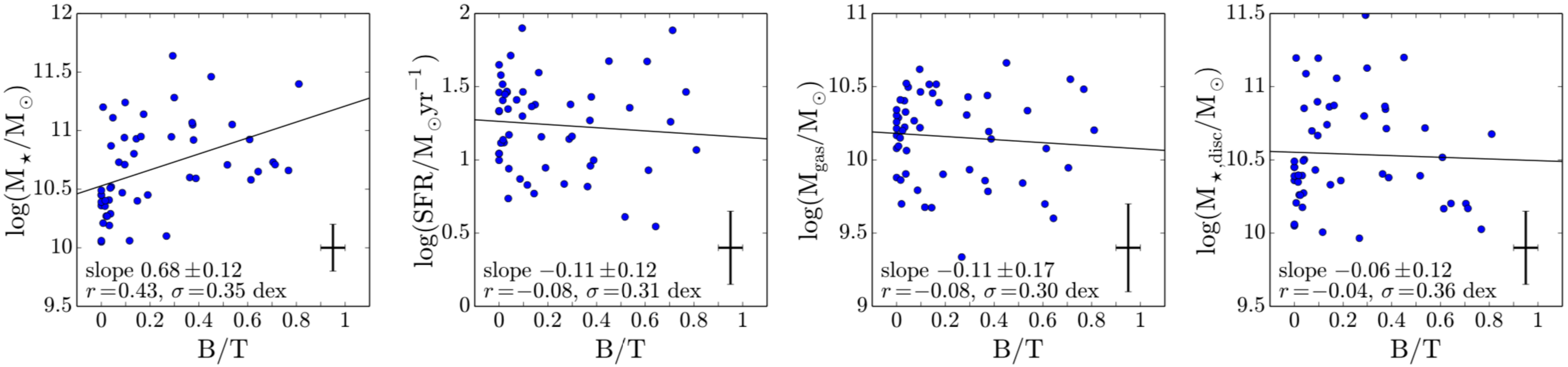


VELA cosmological zoom-in simulations (Ceverino+14)
— AMR ART code
— 25 pc resolution
— SN and radiative feedback

Dekel, Ginzburg, Jiang, Freundlich+ in prep.

Molecular gas and morphology at z=0.5-0.8

✦ **Dependences with the bulge-to-total luminosity ratio B/T**



✦ **Possible interpretations:**

- **Uniform star formation processes, irrespective of the past history:**
  - SFR, M_{gas} independent of B/T
  - No trace of morphological quenching (t_{depl} independent of B/T)
  - B/T traces old stars while $M_{star,disk}$ traces young stars
- **An evolutionary sequence:**
  - Bulge formation as M_{star} increases
  - Ongoing supply of molecular gas to maintain M_{gas} (accretion, HI to H_2 transformation)
  - Stellar migration towards the bulge (clump migration, bars, mergers)

Freundlich+2019

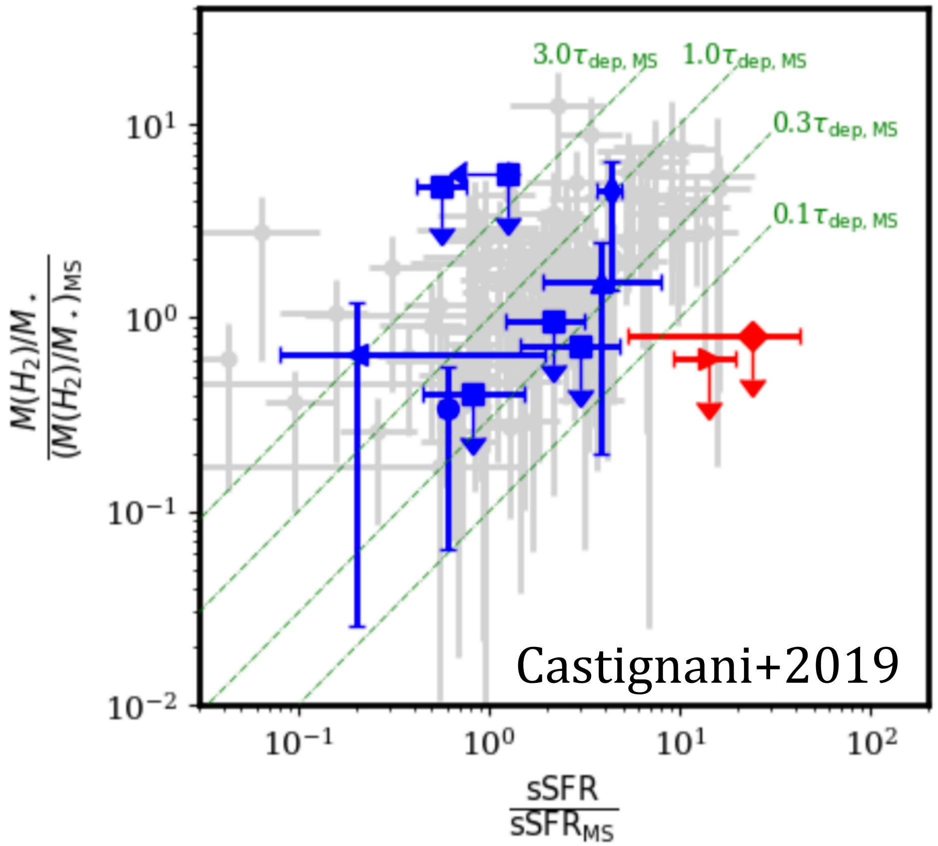
Perspective: molecular gas and environment

✦ **Brightest Cluster Galaxies**

— low molecular gas fractions

— potentially low depletion times

— compact morphology



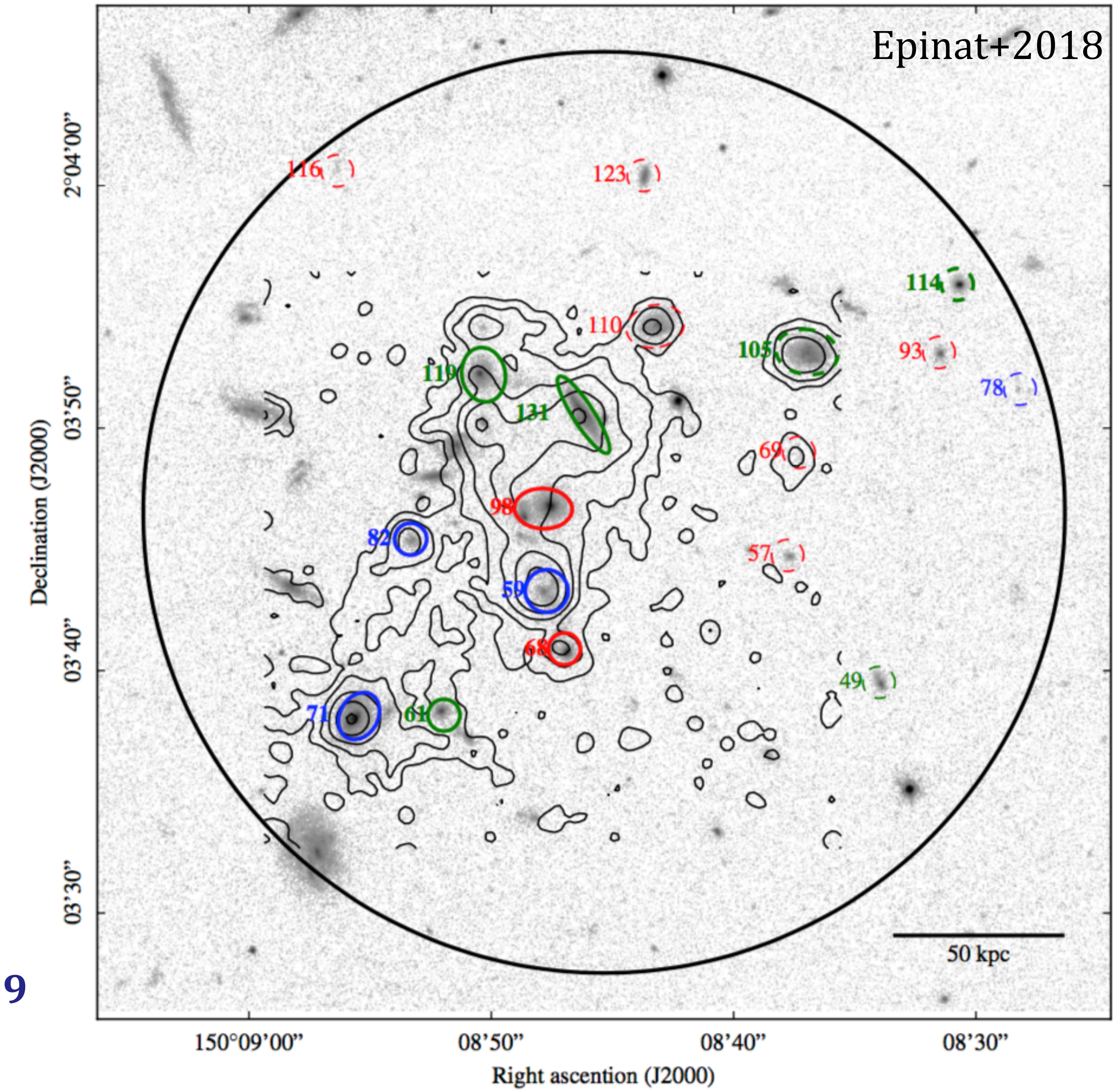
Castignani+2018

Castignani, Combes, Salomé & Freundlich 2019

✦ **Galaxy groups**

— molecular gas in a dense environment?

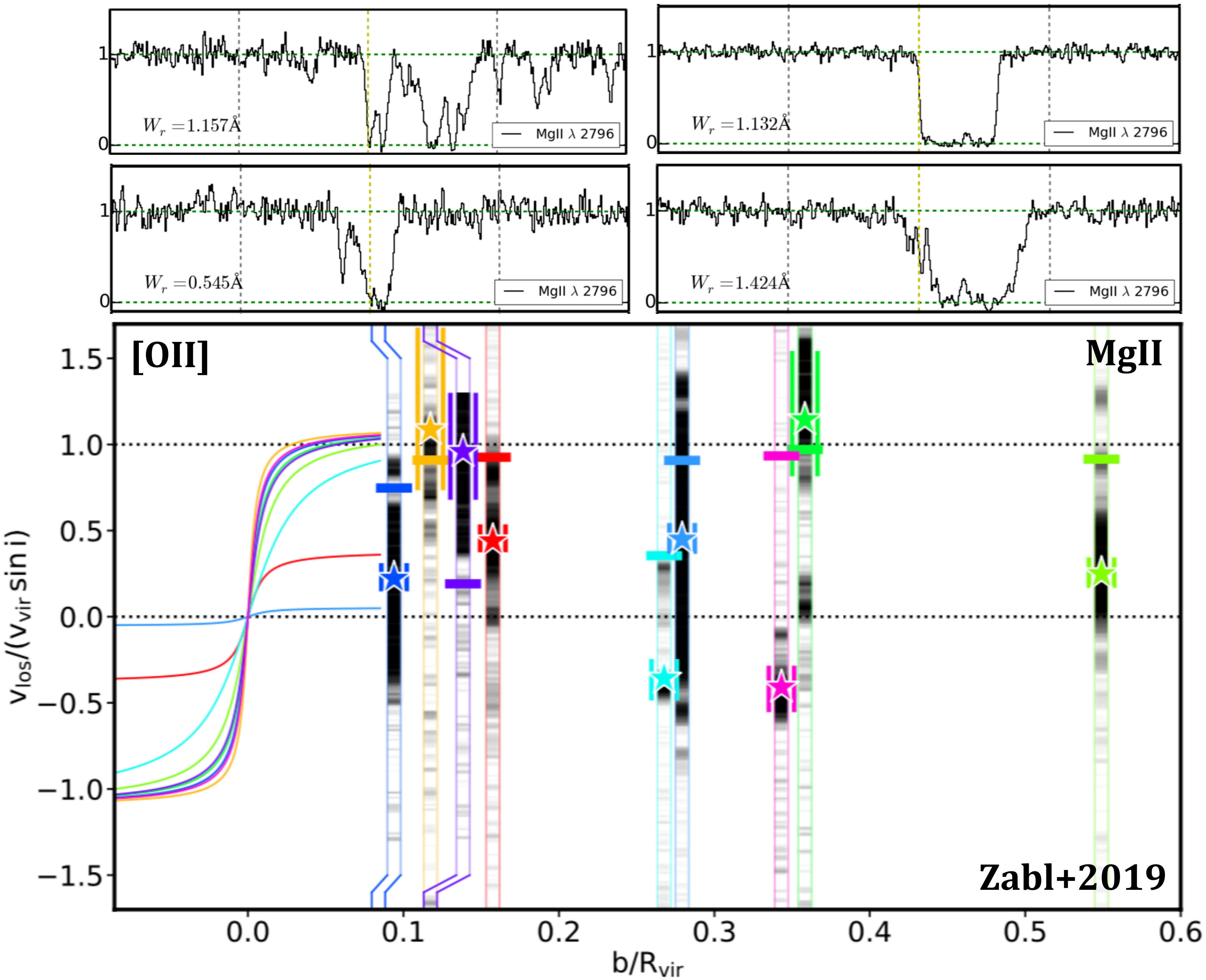
— diffuse molecular gas?

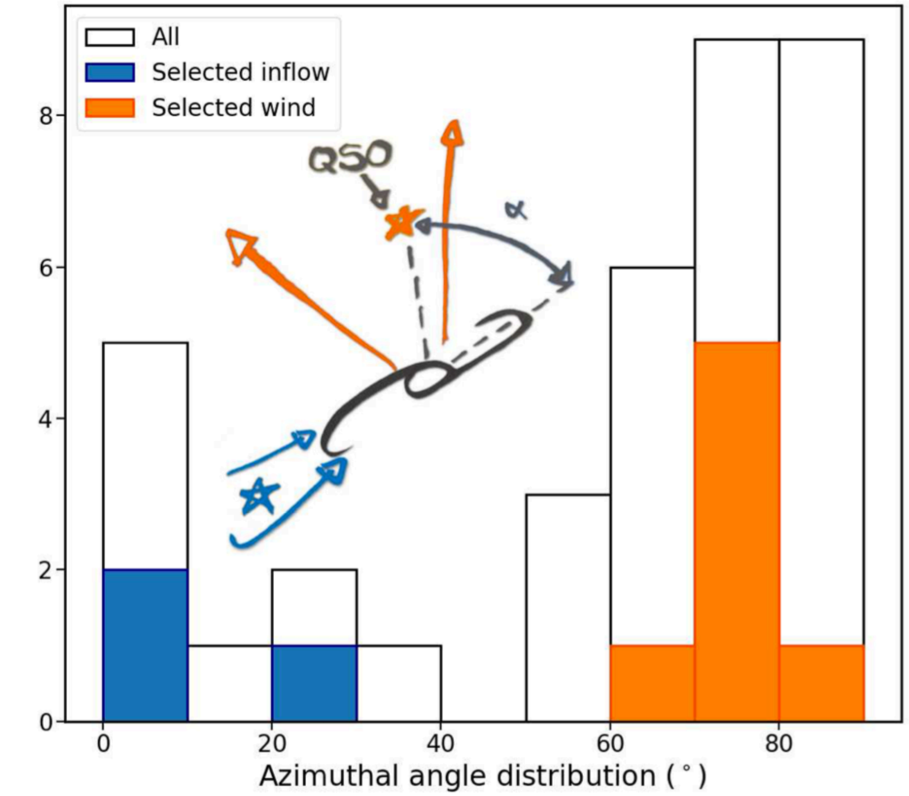


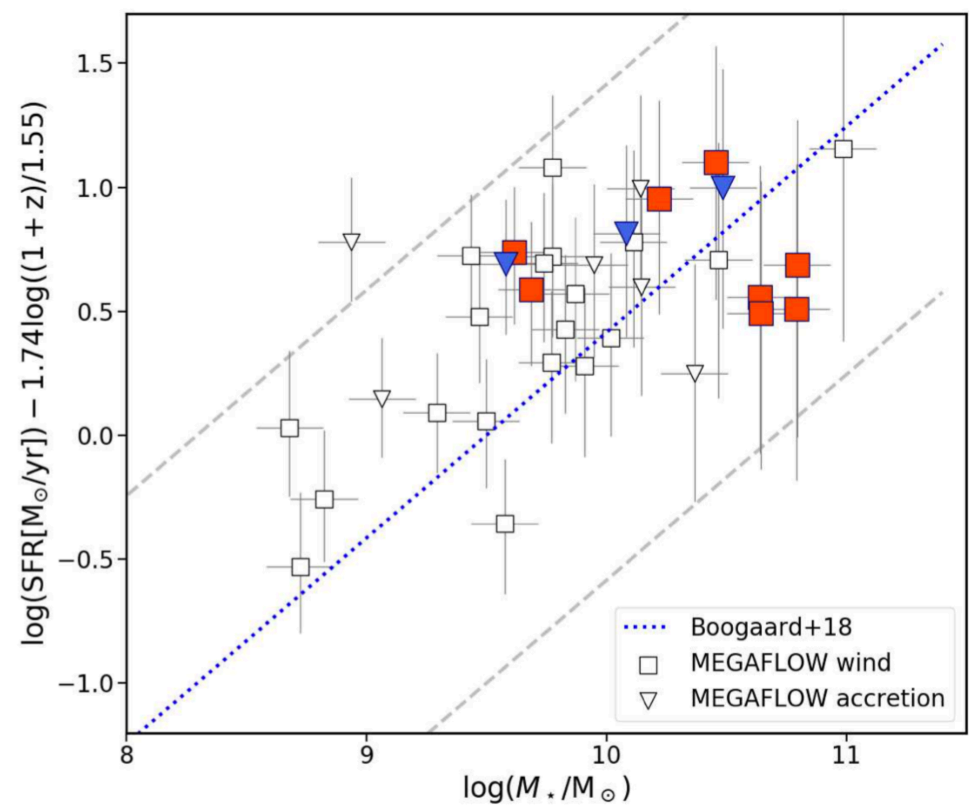
Perspective: molecular gas and environment

✦ **Galaxies and their surrounding — galaxies with gas flows**

- — MgII absorbers from the MEGAFLOW survey (MUSE)
- — Is the gas content related to the gas flows?
- — Test the gas regulator/bathtub model







Outline

1. **Introduction:** the role of gas in galaxy evolution
2. **Gas and star formation:** molecular gas reservoirs across cosmic time
3. **Gas and dark matter:** core formation from outflow episodes

Core formation from bulk outflows

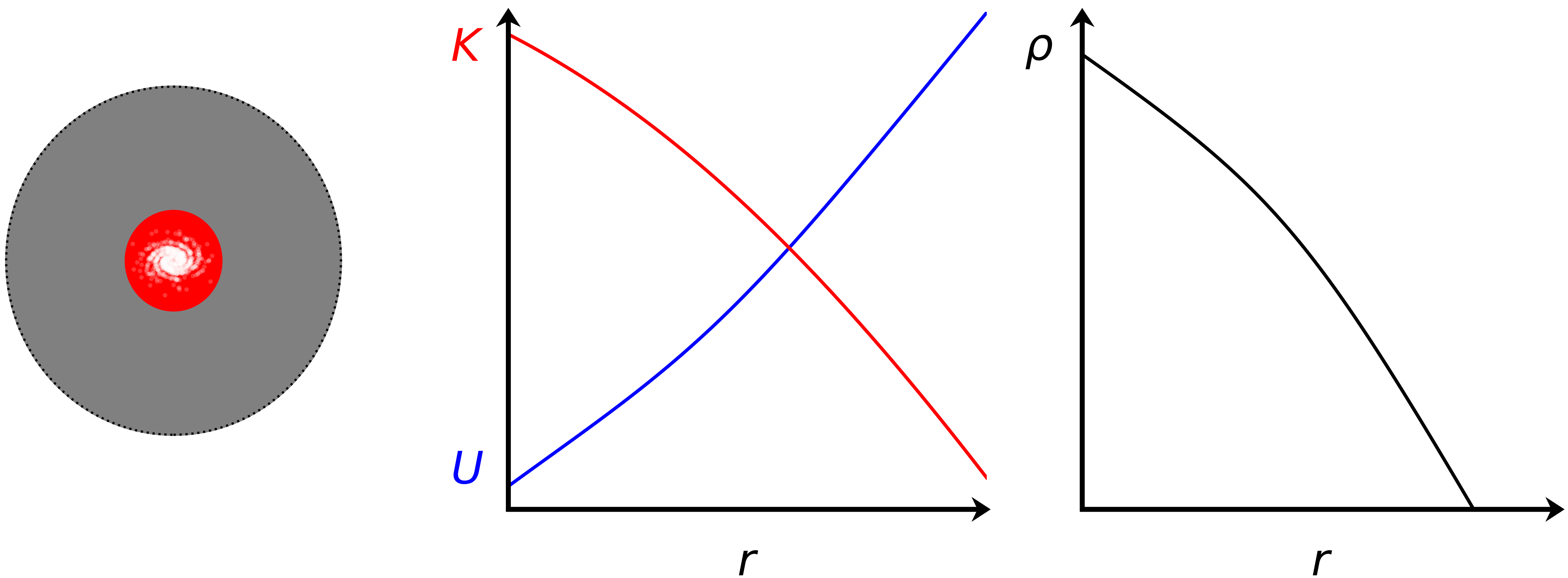
Evolution of a spherical shell encompassing a collisionless mass M when a baryonic mass m is removed (or added) at the center

✦ **Slow mass change**

Angular momentum conservation on circular orbits: $\frac{r_f}{r_i} = \frac{M}{M+m} = \frac{1}{1+f}$ with $f = \frac{m}{M}$

✦ **Instant mass change**

① Initial equilibrium $E_i(r_i) = U_i(r_i) + K_i(r_i)$



Freundlich, Dekel, Jiang+ 2019

Core formation from bulk outflows

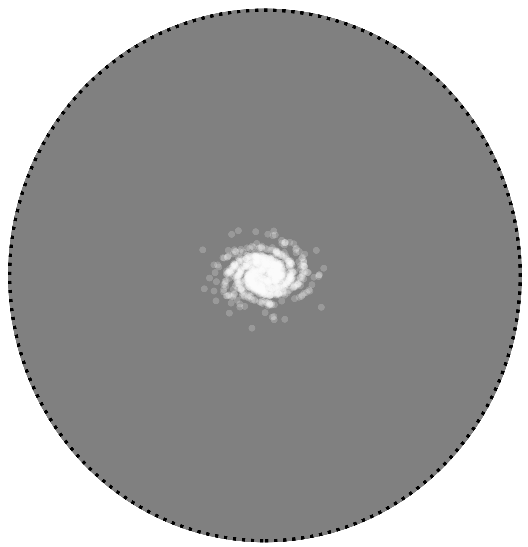
Evolution of a spherical shell encompassing a collisionless mass M when a baryonic mass m is removed (or added) at the center

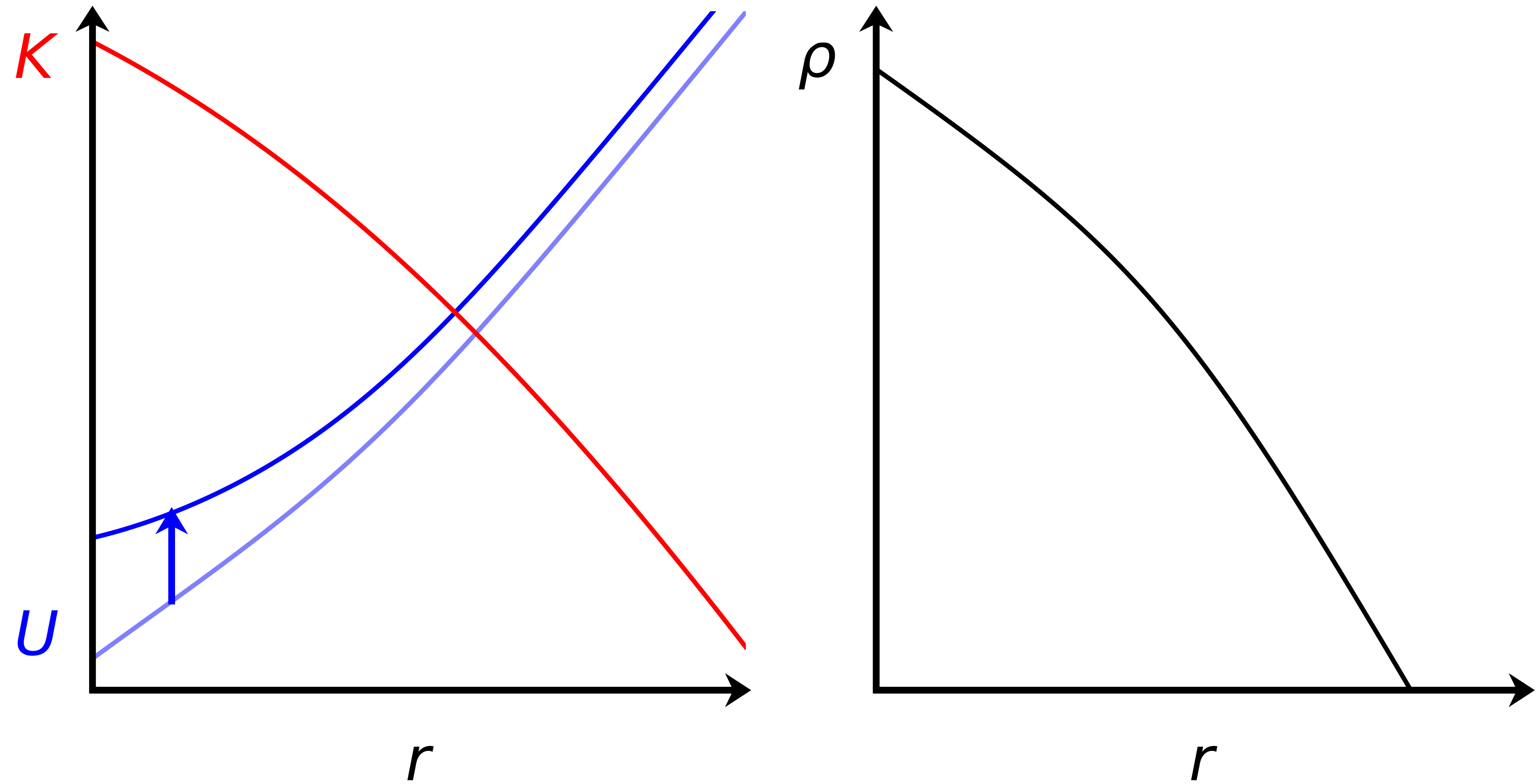
✦ **Slow mass change**

Angular momentum conservation on circular orbits: $\frac{r_f}{r_i} = \frac{M}{M+m} = \frac{1}{1+f}$ with $f = \frac{m}{M}$

✦ **Instant mass change**

② Sudden gas removal $E_t(r_i) = U_i(r_i) - Gm/r_i + K_i(r_i)$





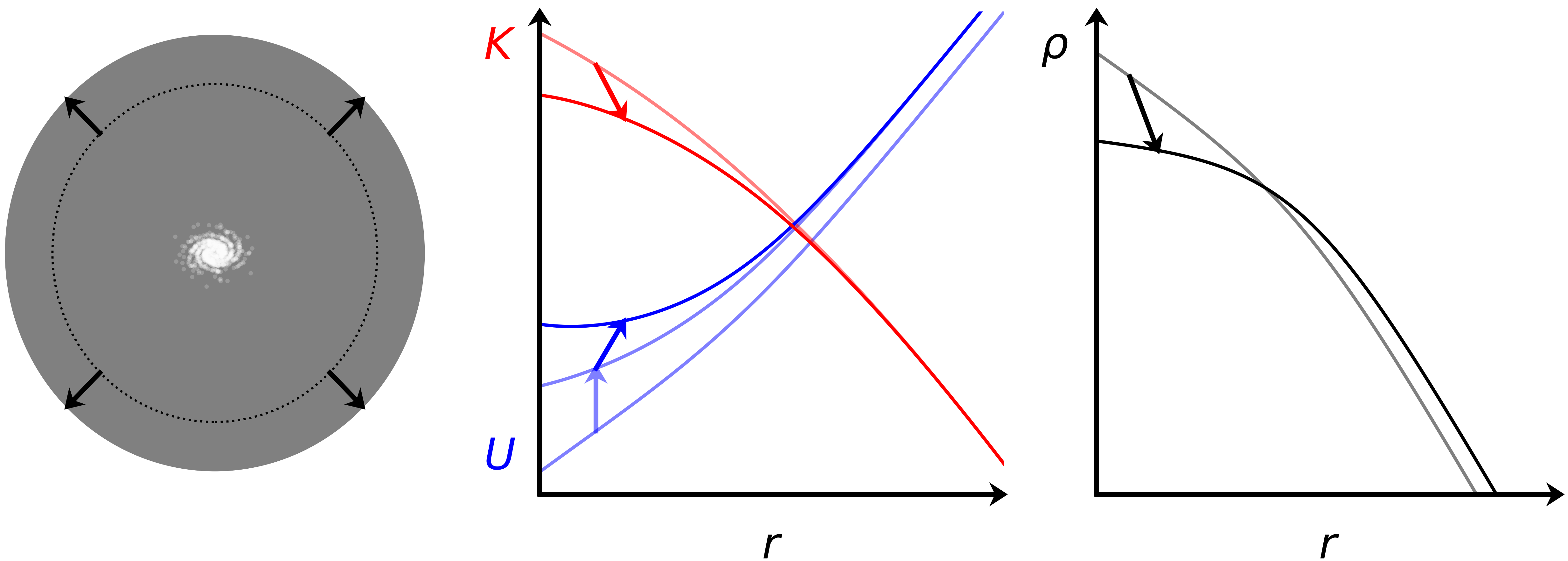
Freundlich, Dekel, Jiang+ 2019

Core formation from bulk outflows

Evolution of a spherical shell encompassing a collisionless mass M when a baryonic mass m is removed (or added) at the center

- ✦ **Slow mass change**
  Angular momentum conservation on circular orbits: $\frac{r_f}{r_i} = \frac{M}{M+m} = \frac{1}{1+f}$ with $f = \frac{m}{M}$
- ✦ **Instant mass change**

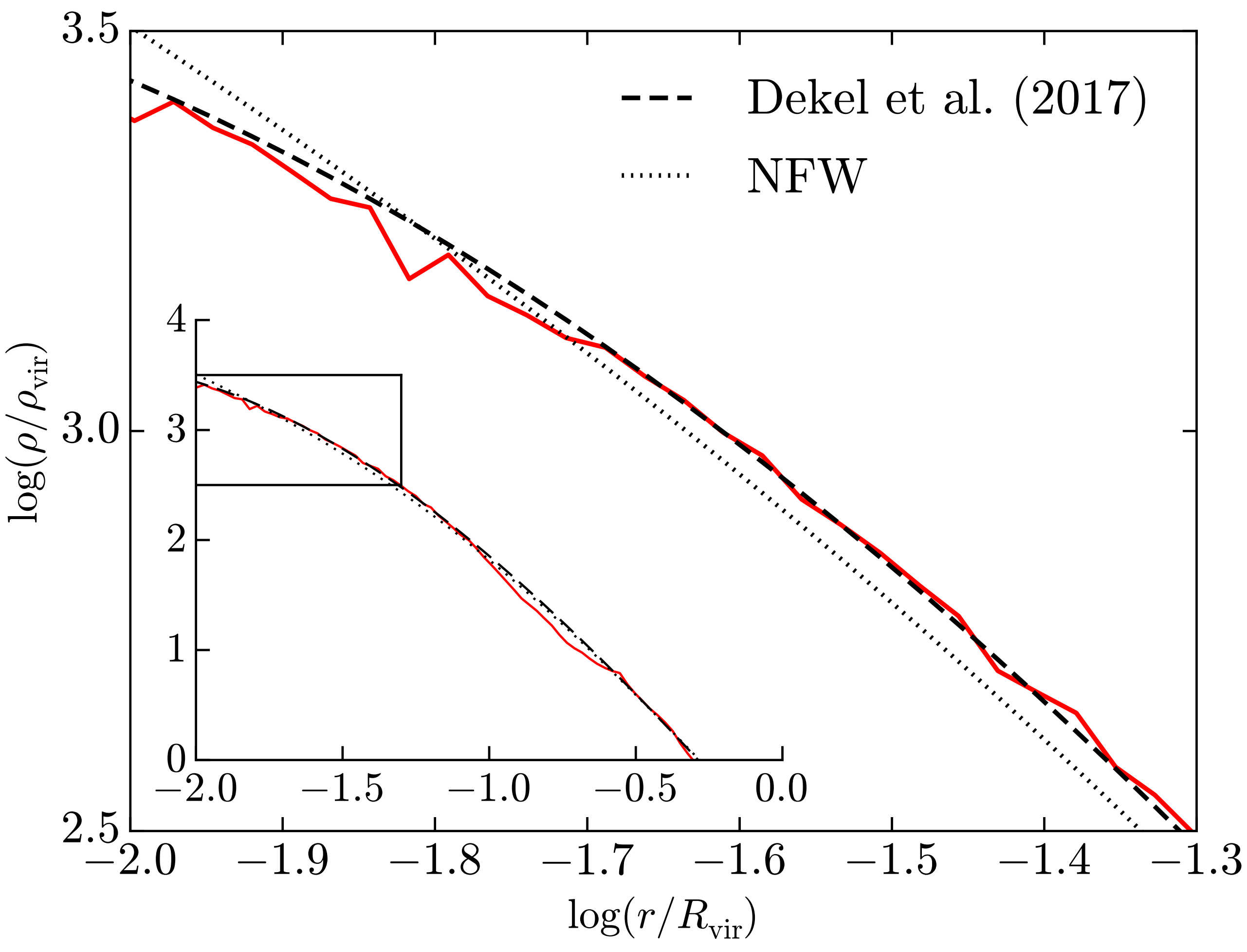
③ Relaxation $E_f(r_f) = U_f(r_f) - Gm/r_f + K_f(r_f)$

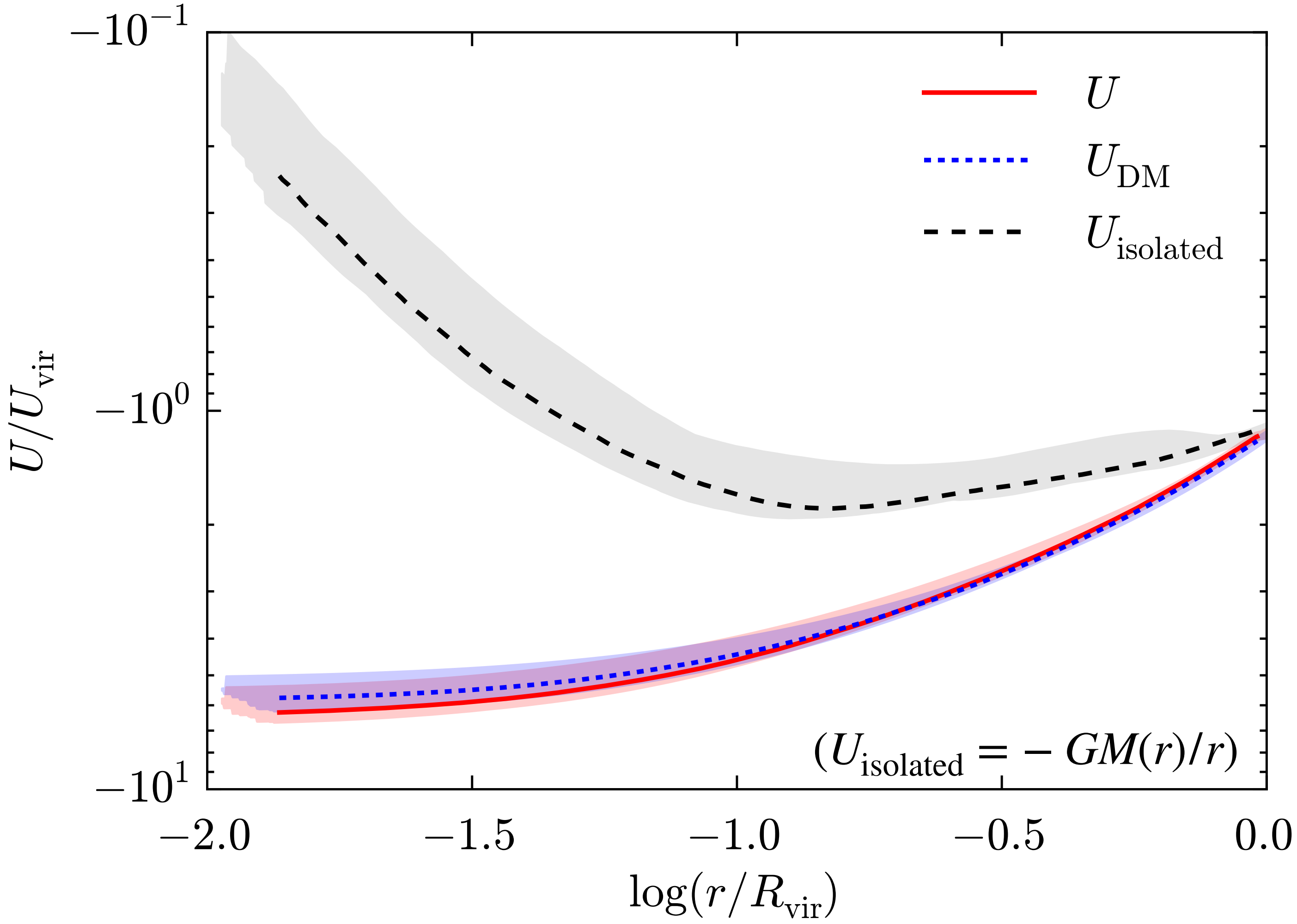


Given functional forms ***U(r;p,m)*** and ***K(r;p,m)***, **energy conservation** $E_f(r_f) = E_i(r_i)$ during relaxation yields the final state

Freundlich, Dekel, Jiang+ 2019

Parametrization of the density profile



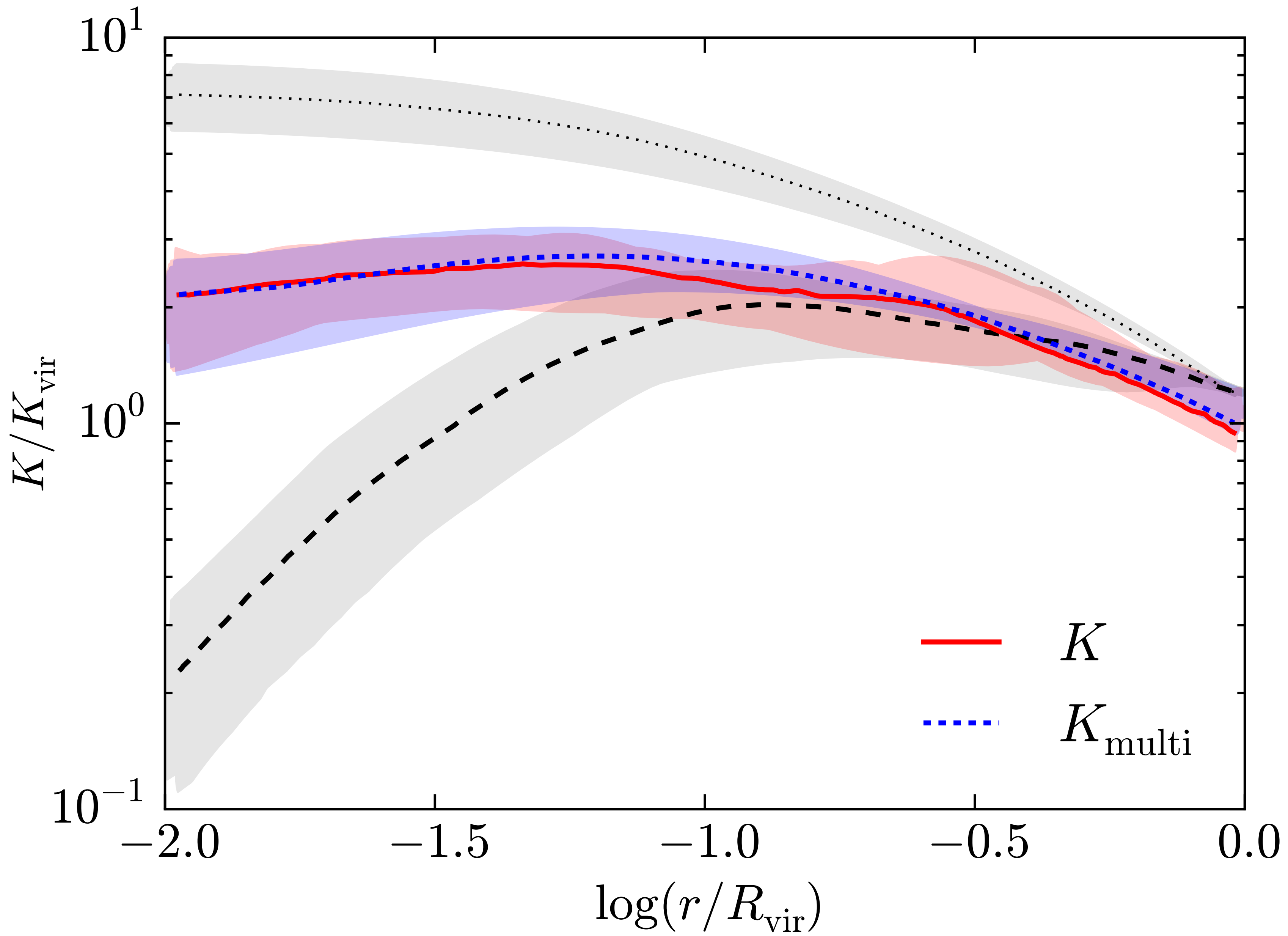


Dekel et al. (2017) parametrization:

- ✦ $\rho(r) \propto \frac{1}{x^a(1+x^{1/2})^{2(3.5-a)}}$ with $x = cr/R_{\rm vir}$
- ✦ Analytical potential ($U_{\rm DM}$)
- ✦ Free inner slope

Freundlich, Dekel, Jiang+ 2019

Parametrization of the local kinetic energy



$$K(r) \propto \Big[\mathscr{B}(4(1-a)-2n, 9+2n, \zeta)\Big]_{\chi}^{1}$$

- ✦ Spherical symmetry and anisotropy
- ✦ Jeans equilibrium
- ✦ Dekel+17 halo

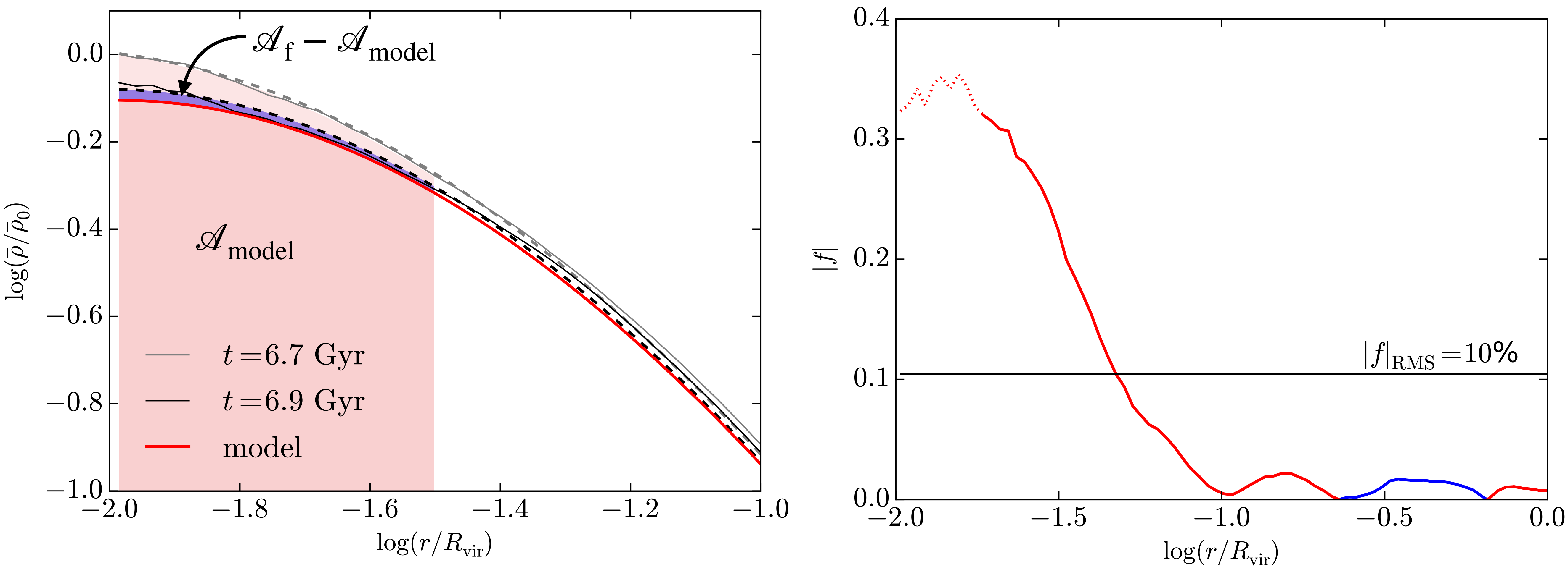
Incomplete beta function:

$$\mathscr{B}(a,b,x) = \int_0^x t^{a-1}(1-t)^{b-1}dt$$

Freundlich, Dekel, Jiang+ 2019

Test with the NIHAO simulations

✦ **33 galaxies with M_{star}=10^7-10^9 M_{sun} at z=0** (specific mass range for core formation, cf. Di Cintio+14, Oh+15, Tollet+16, Dutton+16)



Measuring success:

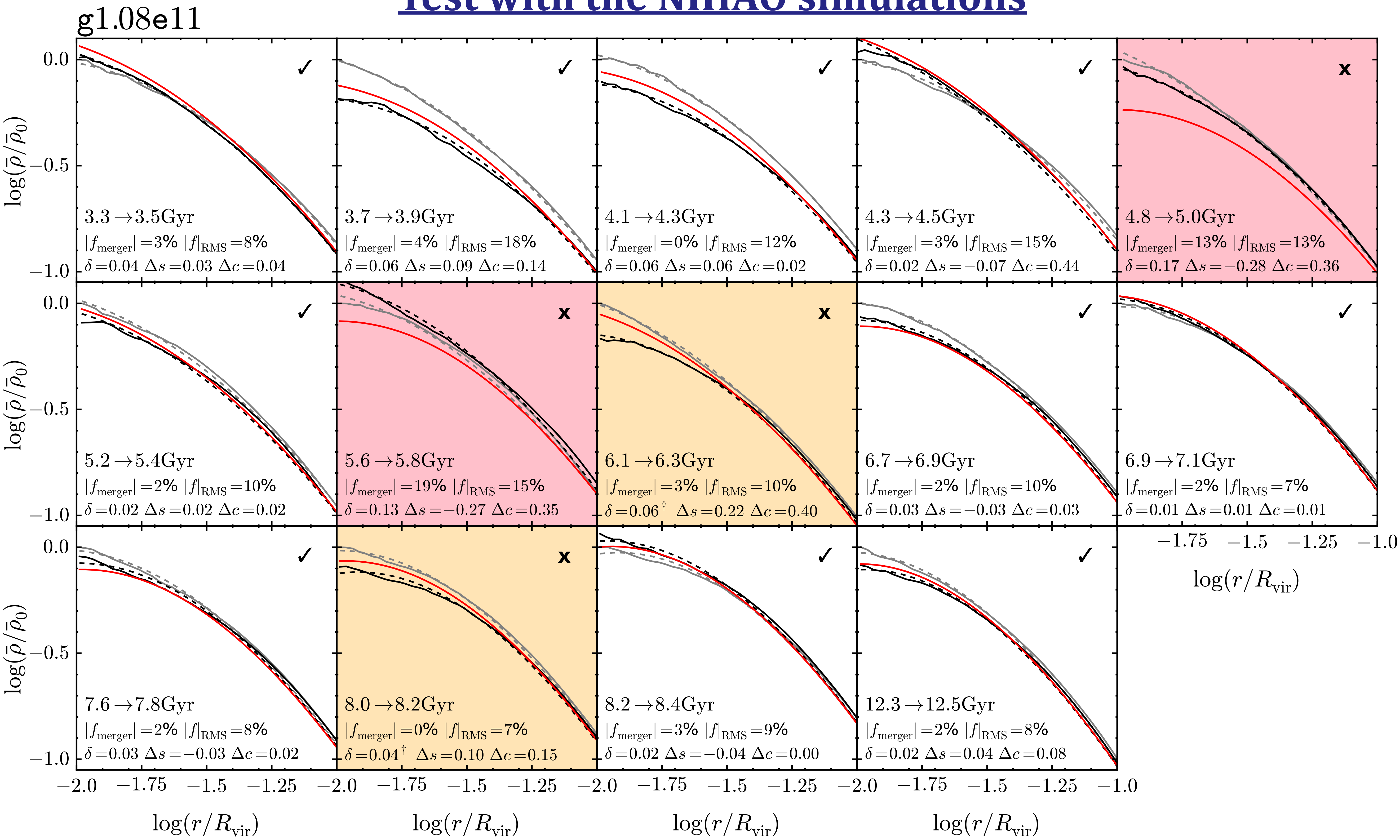
$$\delta = 2\left|\frac{\mathscr{A}_{\rm model} - \mathscr{A}_f}{\mathscr{A}_{\rm model} + \mathscr{A}_f}\right| \quad \text{or} \quad \Delta s = s_{0,\rm model} - s_{0,f} \quad \text{or} \quad \Delta c = \log(c_{\rm max,model}/c_{{\rm max},f})$$

Success criterion with δ:

$(\delta \leq 10\%)$ AND $(\delta \leq \delta_0$ OR $\delta_{\rm sim} \leq 3\%)$

Freundlich, Dekel, Jiang+ 2019

Test with the NIHAO simulations

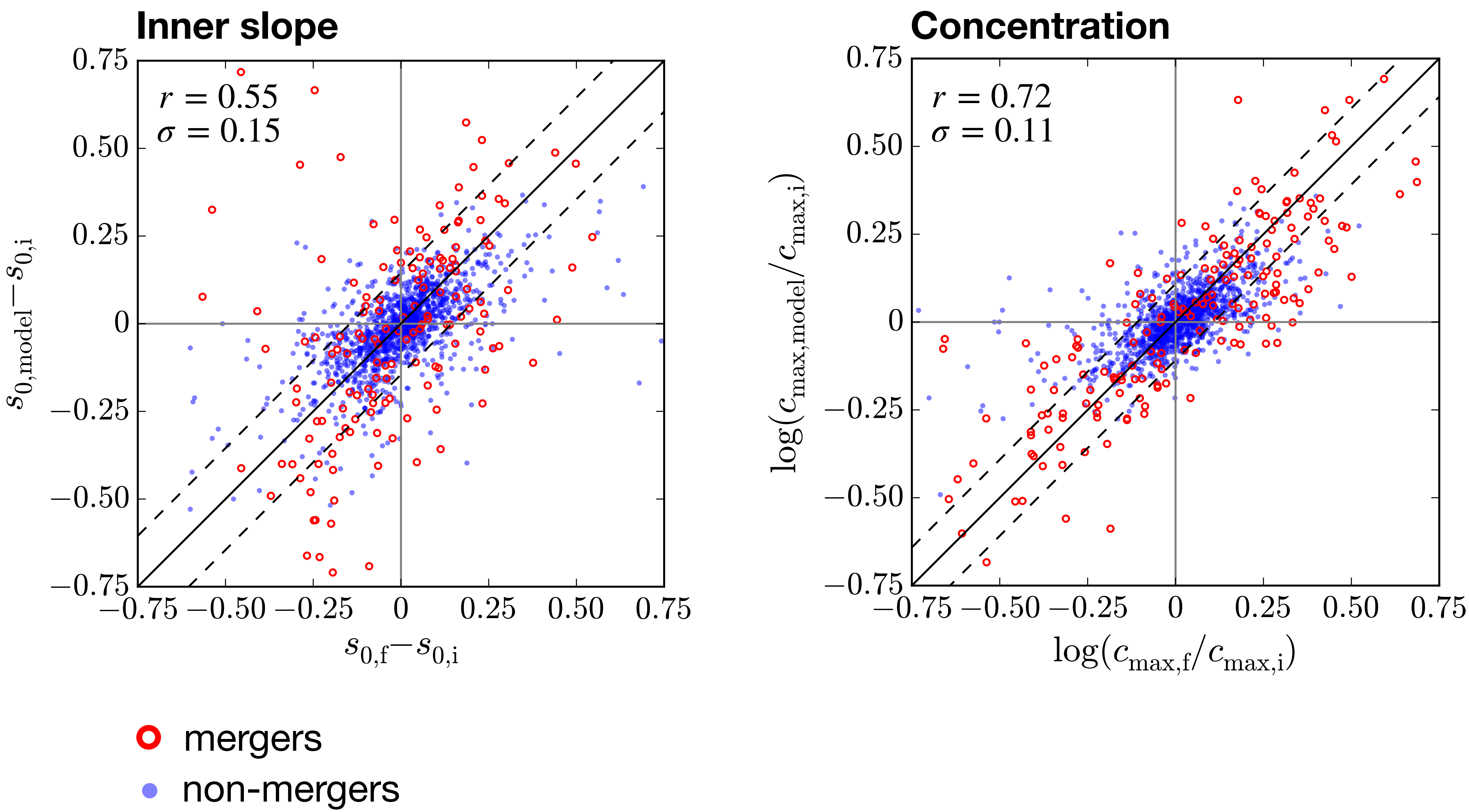


Success rate overall:

- 67% overall
- 74% without mergers
- 66% when $|f|_{\rm RMS} > 7\,\%$
- 81% when $f|_{\rm RMS} < 7\,\%$

Freundlich, Dekel, Jiang+ 2019

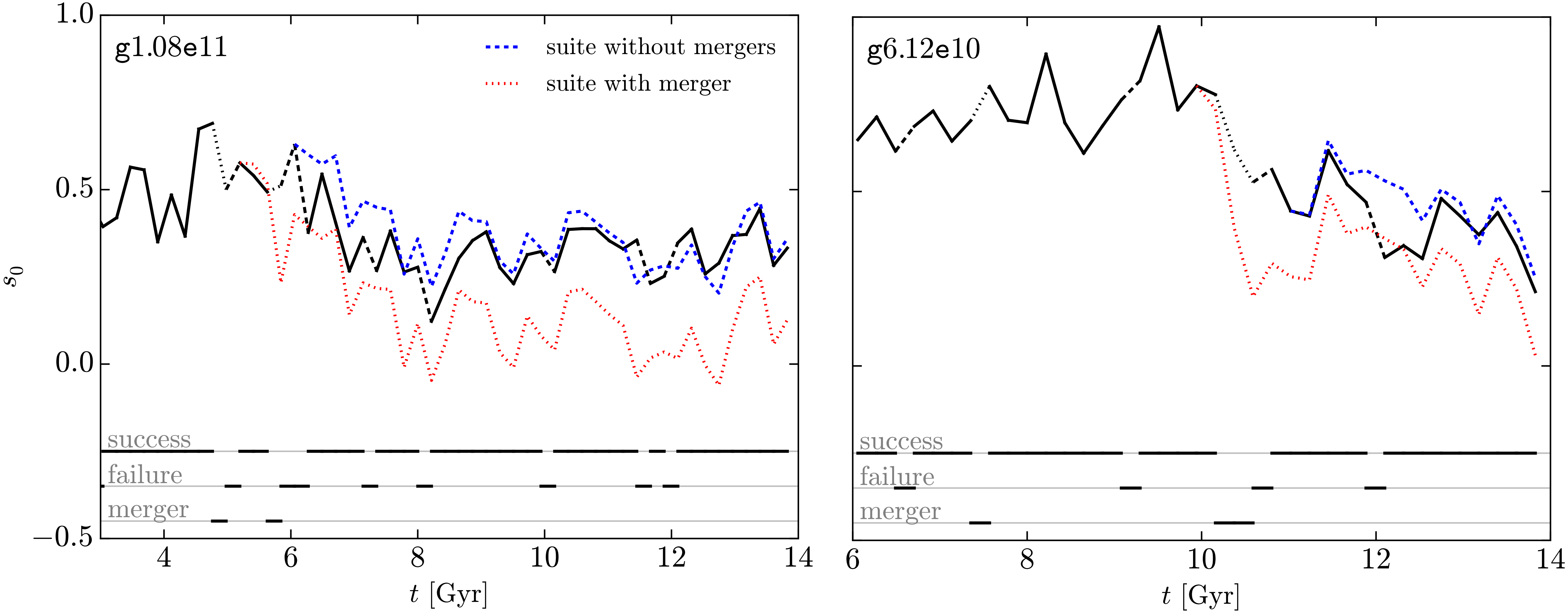
Predicted vs. actual inner slope and concentration



Freundlich, Dekel, Jiang+ 2019

Multiple episodes

- ✦ Mergers are the main cause of failure.
- ✦ Merger-free time steps contribute to ~80% of Σs_0 after 3 Gyr: how successful is the model over multiple episodes?

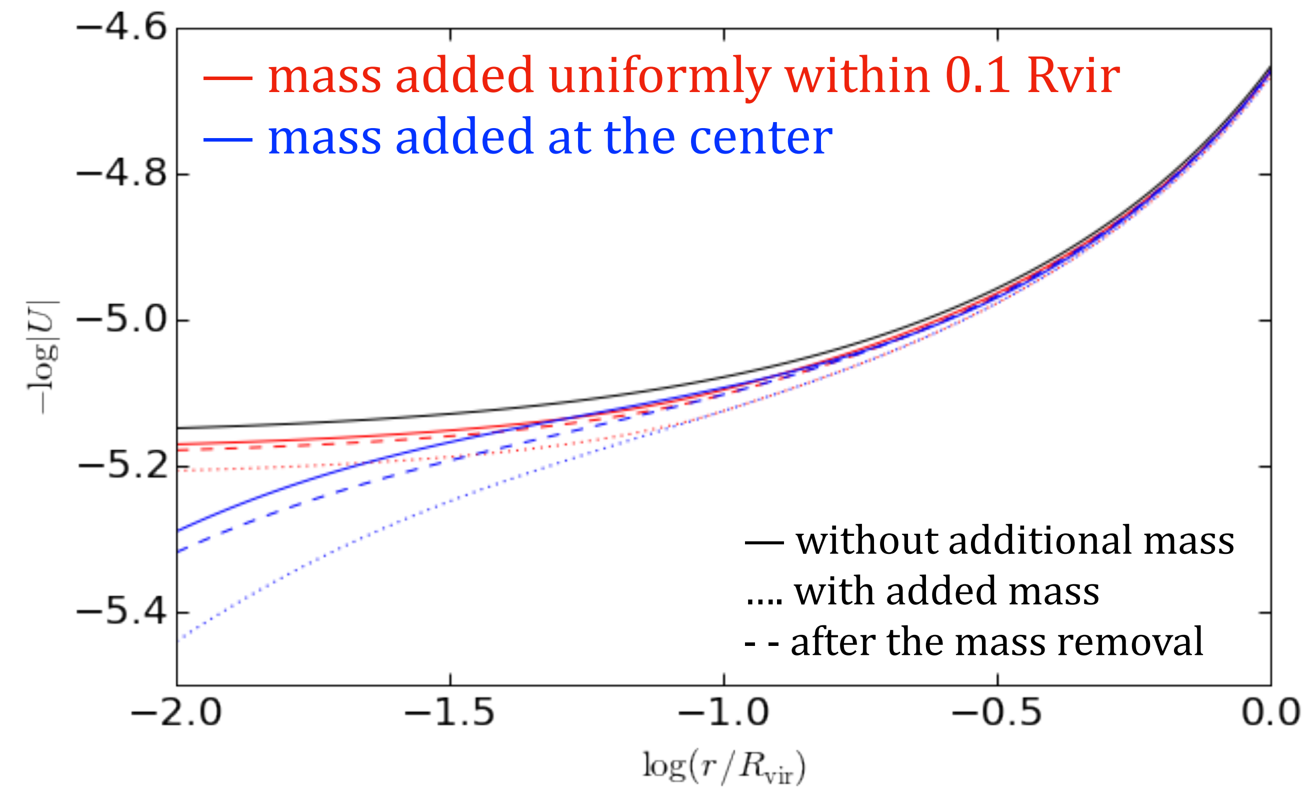


$\delta \lesssim 0.10$ for non-mergers up to N~20, i.e., ~4 Gyr

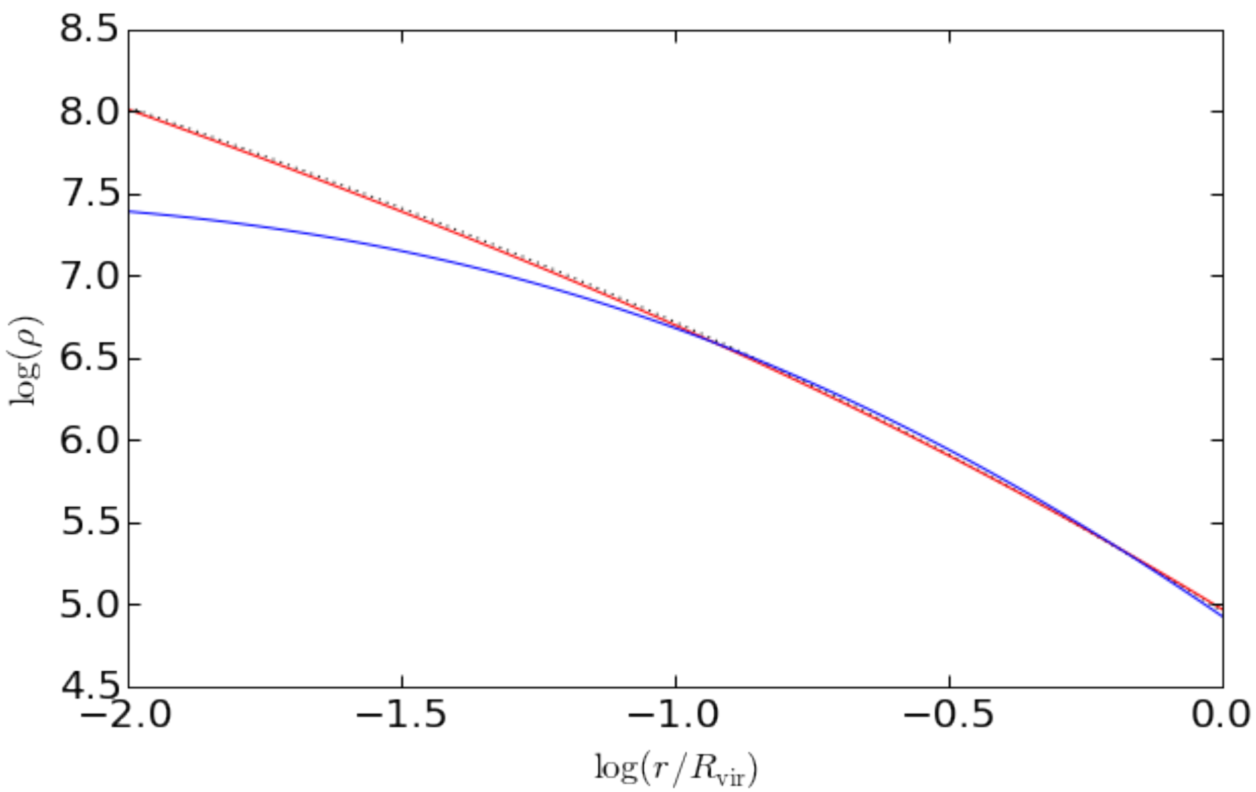
Freundlich, Dekel, Jiang+ 2019

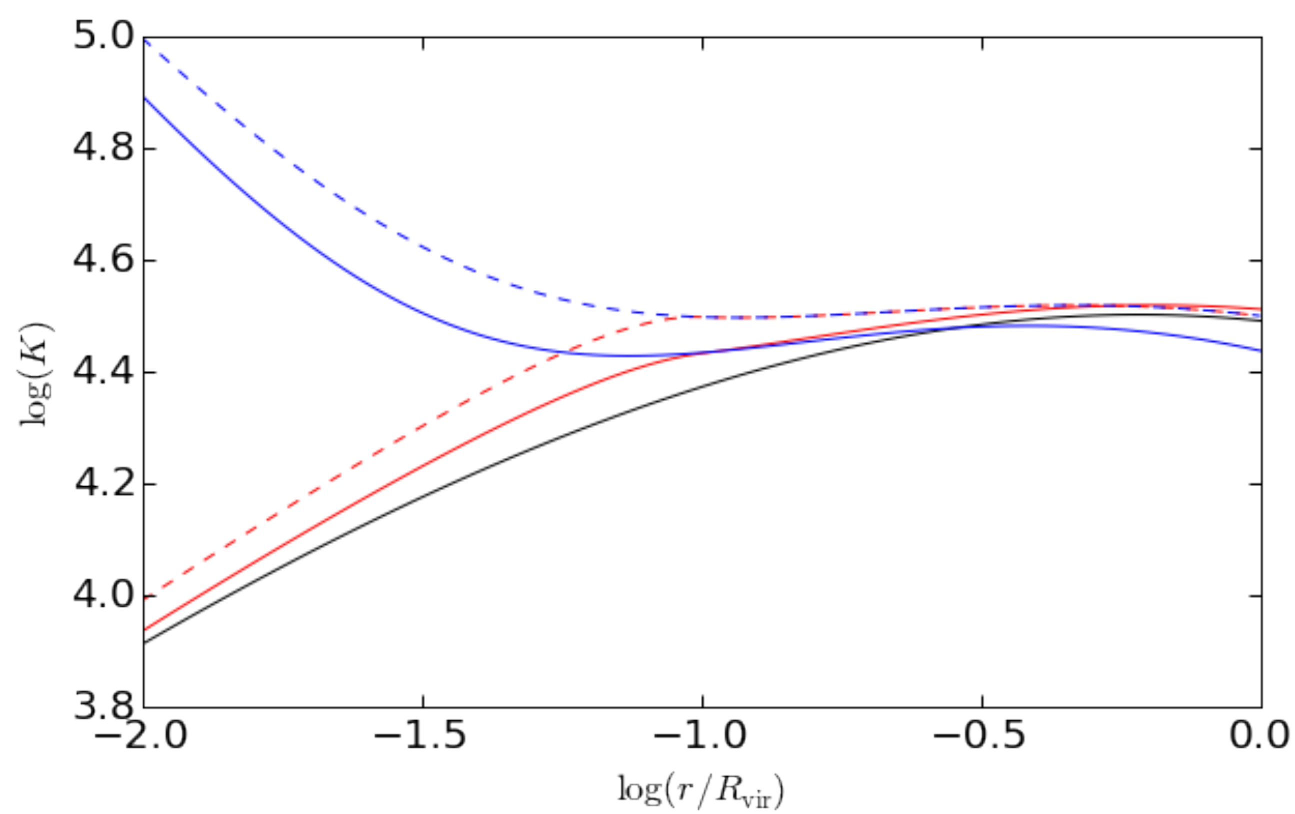
Explaining baryon-dominated galaxies at high-z?

✦ **Massive baryon-dominated galaxies at z=1-2 (Genzel+17, Genzel+in prep.)**
— low DM fraction incompatible with NFW
— fast processes bringing both gas to the center and driving dark matter out?



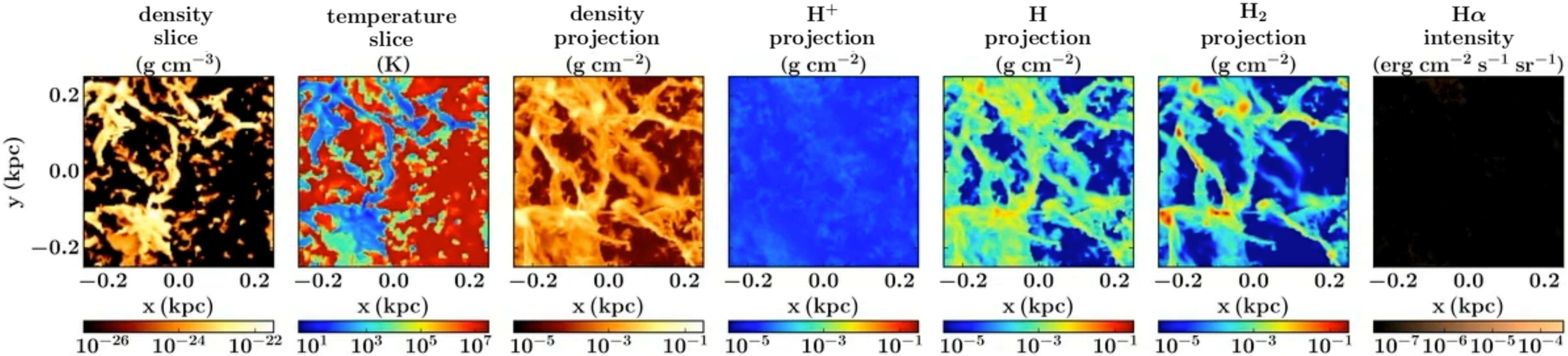
✦ **A possibility: dynamical friction + AGN outflows**
— Dynamical friction 'pre-heats' the halo and make outflows more efficient at expanding the DM
— Test:
- NFW halo of concentration c=5
- 0.03 Mvir added towards the center
- half of it suddenly removed





Core formation from stochastic density fluctuations

✦ **Effects of radiation, stellar winds and supernovae on the interstellar medium (e.g., SILCC Peters+17)**



✦ **Stochastic gas density fluctuations in an unperturbed homogeneous medium**

Fourier decomposition of the density contrast:

$$\delta(\vec{r}) = \frac{V}{(2\pi)^3} \int \delta_{\vec{k}}\, e^{i\vec{k}.\vec{r}}\, d^3\vec{k}$$

Each perturbation $\delta_{\vec{k}}$ induces a **'kick'**

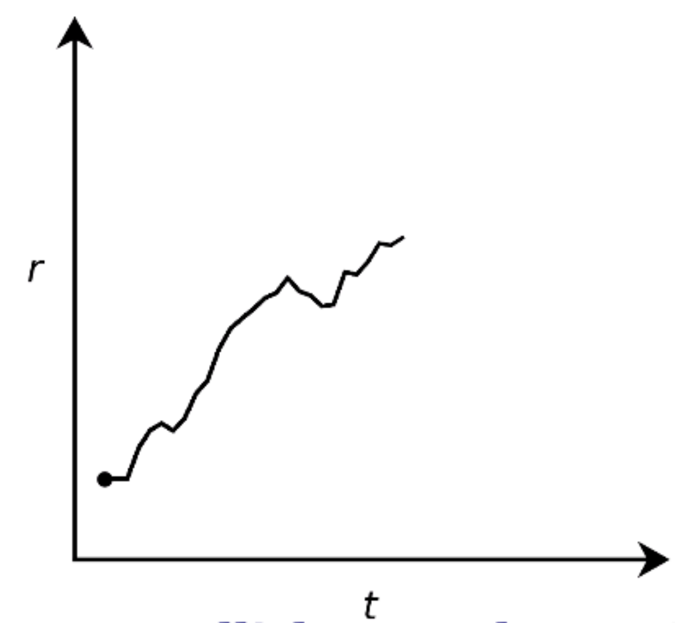
$$\vec{F}_{\vec{k}} = 4\pi i\ G\rho_0\ \vec{k}\ k^{-2}\ \delta_{\vec{k}}$$

Which cumulatively induces the dark matter particles to deviate from their trajectories by

$$\langle \Delta v^2 \rangle = 2 \int_0^T (T-t)\,\langle F(0)F(t)\rangle\ dt.$$

Relaxation time in the diffusion limit $\lambda_{max} \ll R$

$$t_{\rm relax} = \frac{n v_r \langle v \rangle^2}{8\pi (G\rho_0)^2 V \langle |\delta_{k_{\rm min}}|^2 \rangle}$$

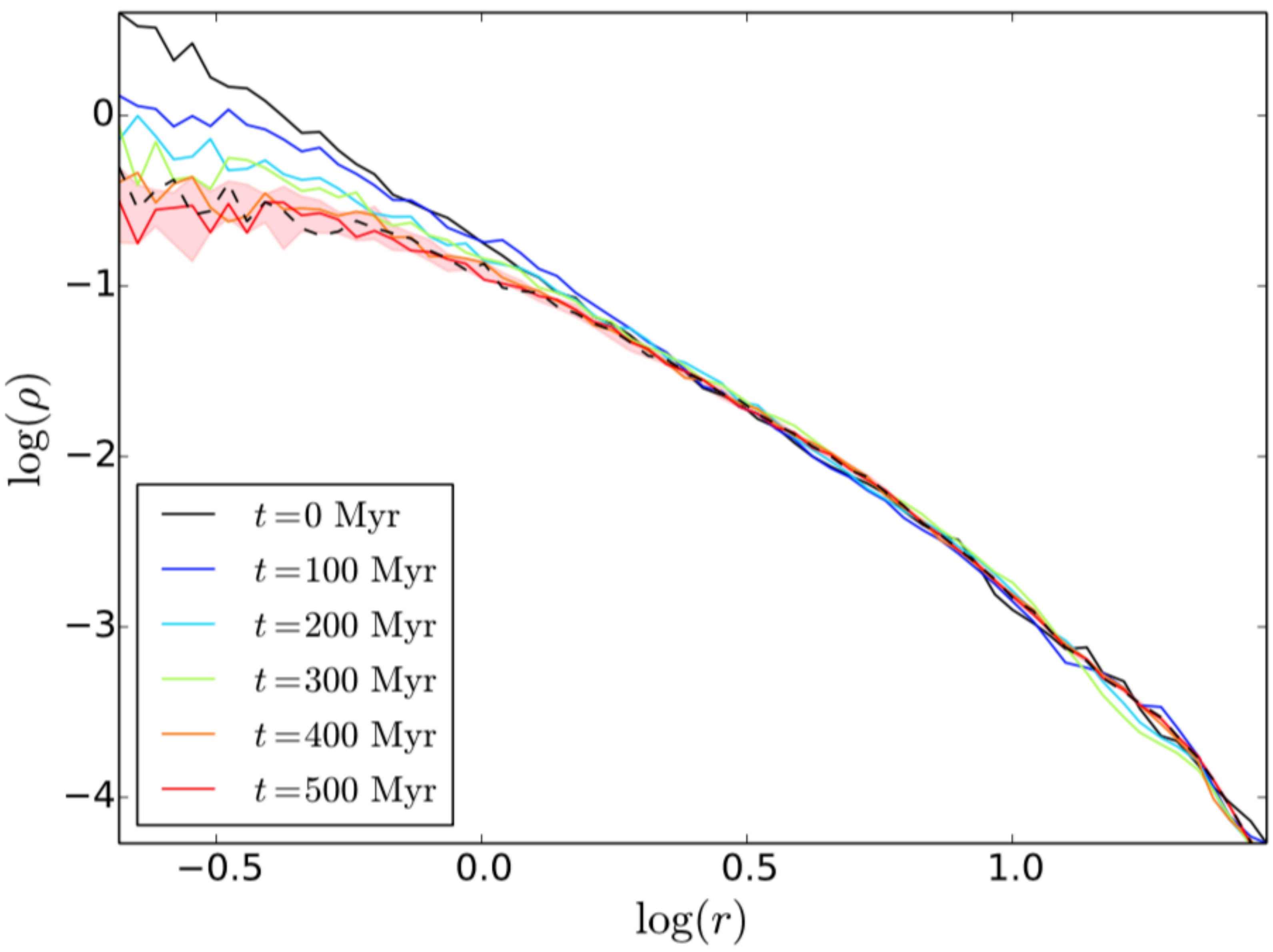


El-Zant, Freundlich & Combes 2016

Numerical test

✦ **Self Consistent Field (SCF) method (Hernquist & Ostriker 1992)**

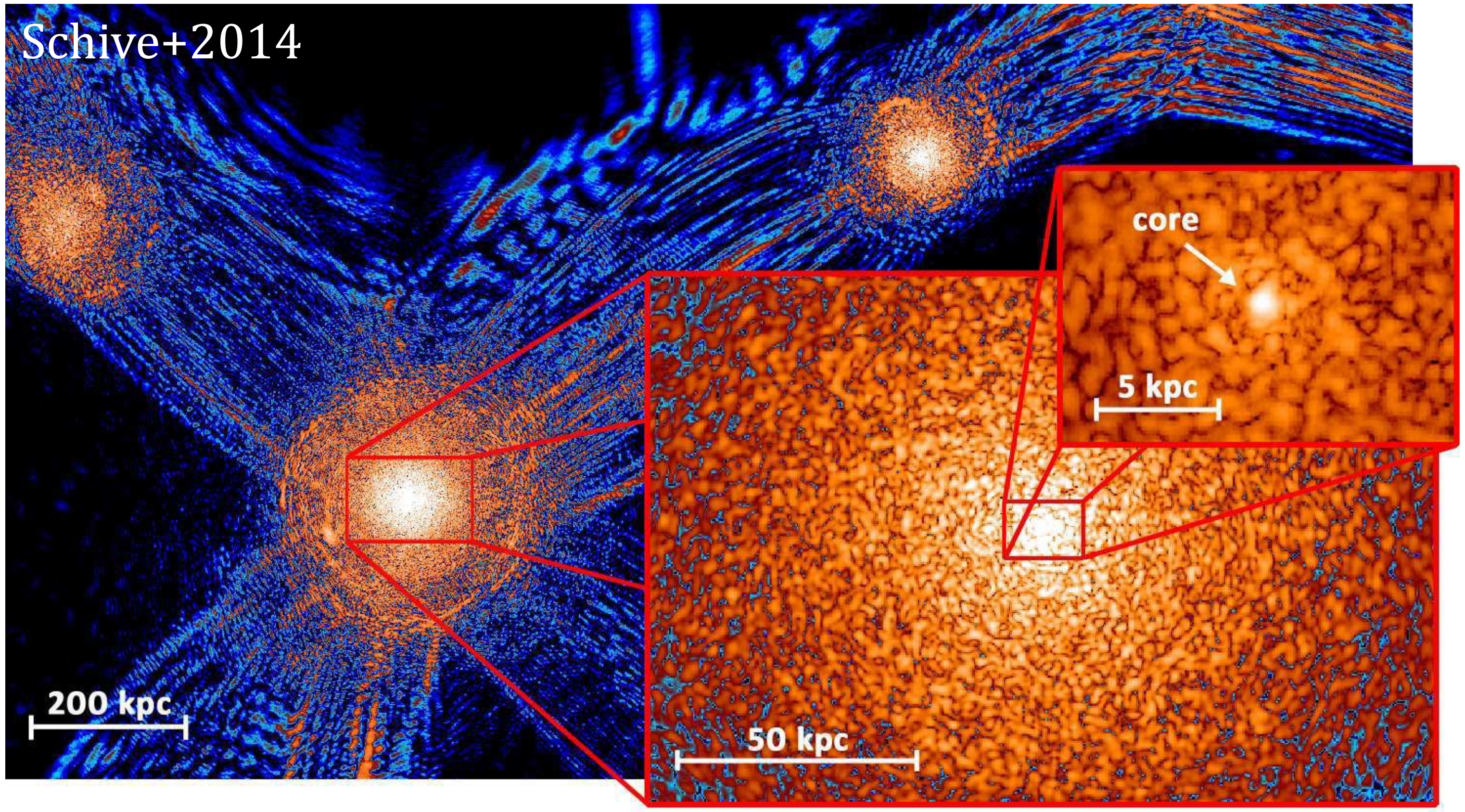
✦ **Fiducial dwarf NFW halo + force resulting from the stochastic density fluctuations**

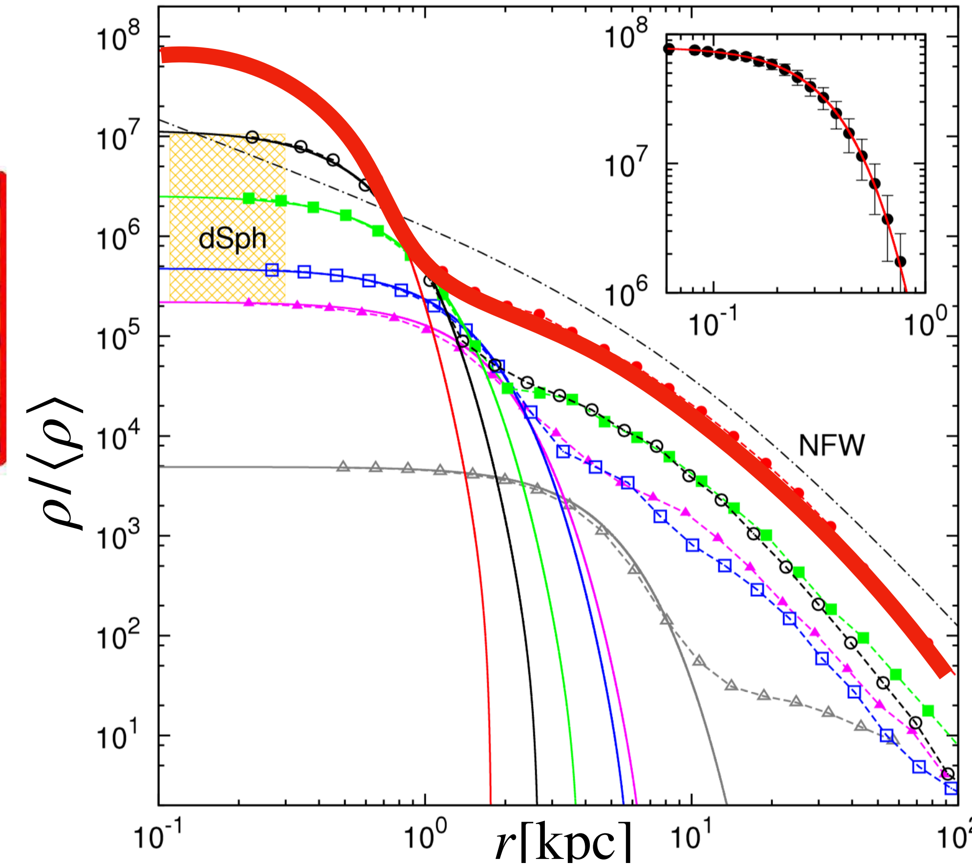


El-Zant, Freundlich & Combes 2016

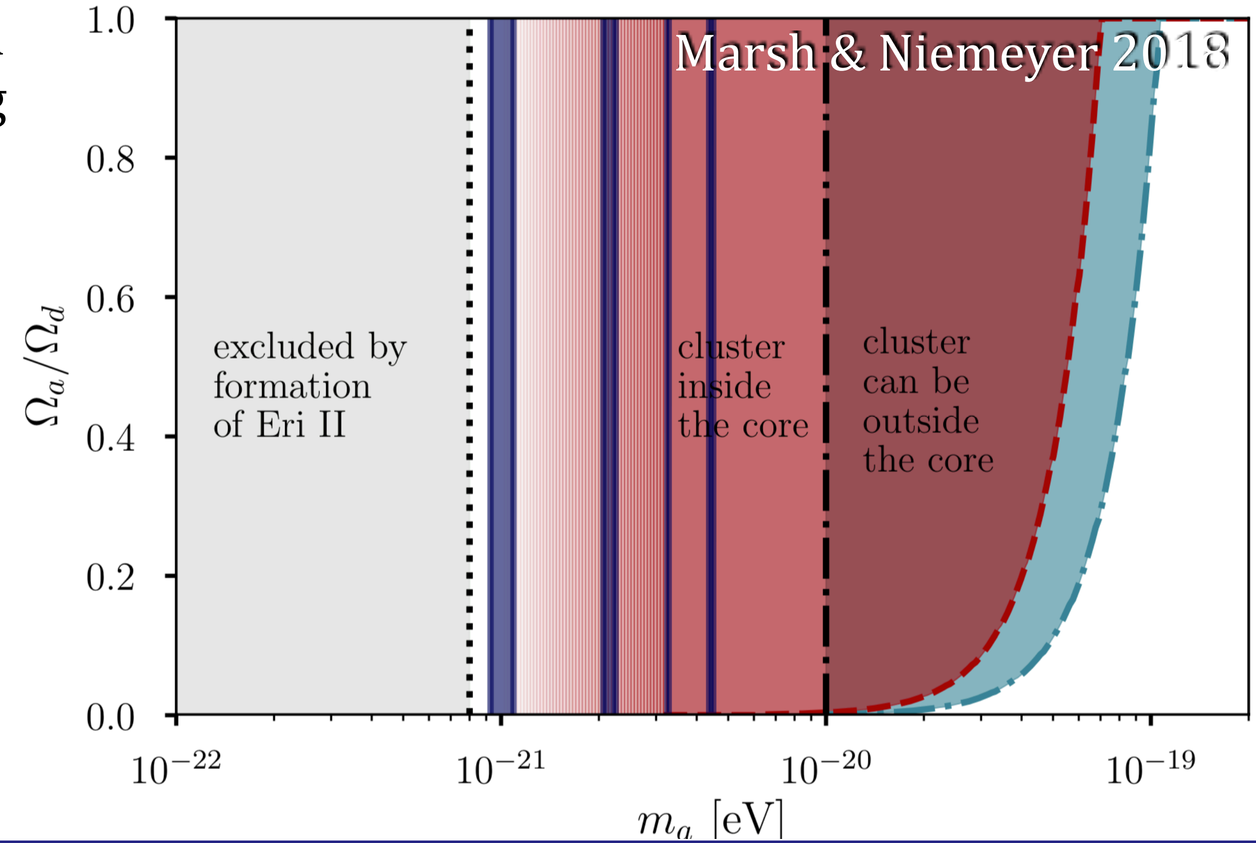
An unexpected application: constraining Fuzzy Dark Matter (FDM)

(a.k.a Ultra Light DM, Scalar Field DM, Wave DM, Bose-Einstein Condensate DM)





- ✦ Constraining the FDM mass from the survival of an old stellar cluster in Eridanus II + heating from fluctuating FDM granules:
  — **Marsh & Niemeyer 2018**
  — **El-Zant, Freundlich, Combes & Hallé 2019**
  — **Hallé, El-Zant, Freundlich & Combes in prep.**
- ✦ **Bar-Or, Fouvry & Tremaine 2018:** Fokker-Planck formalism



Conclusion

Gas and star formation: molecular gas reservoirs across cosmic time

- *The cosmic SFR history is mainly determined by the molecular gas reservoirs.*

✦ **PHIBSS (**Tacconi+2010, 2013, **Freundlich+2013, Genzel+2013)**
— a KS relation at sub galactic scales

✦ **PHIBSS2 (Genzel+2015, Tacconi+2018, Freundlich+2019)**
— Molecular gas fraction and depletion time across the main sequence
— Molecular gas and morphology: uniform star-forming processes in the disk?

Gas and collisionless particles: core formation from outflow episodes

- *Gas outflows resulting from feedback can explain both the formation of dark matter cores and UDGs.*

✦ **Ultra-diffuse galaxies in simulations (Jiang, Dekel, Freundlich+19a,b)**
— Cored dark matter haloes and bursty star formation history in the field
— Tidal puffing-up and ram pressure stripping in groups and clusters

✦ **Core formation from bulk outflow episodes (Freundlich+2019)**
— Prediction of the dark matter density profile evolution
— Test against the NIHAO simulations
— Perspective: controlled experiments

✦ **Core formation from stochastic density fluctuations (El-Zant, Freundlich & Combes 2016)**
— Diffusive model akin to 2-body relaxation
— Test with idealised simulations (SCF method)
— Perspective: input from hydrodynamical simulations
— Unexpected application: FDM 'granule' density fluctuations
(**El-Zant, Freundlich, Combes & Hallé 2019**)

thanks