

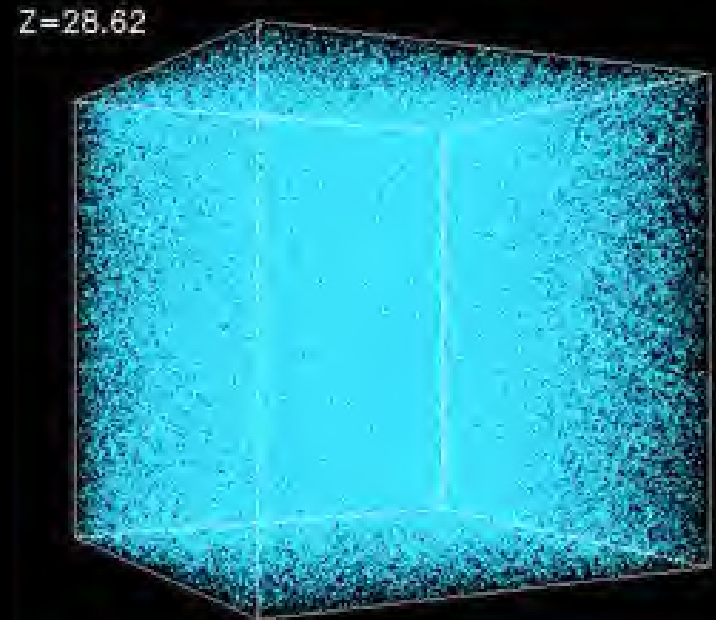
The Impact of Baryon Physics on the Structure of high-redshift Galaxies

ApJ accepted
arXiv:1108.5384

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Beijing, 15. February 2012

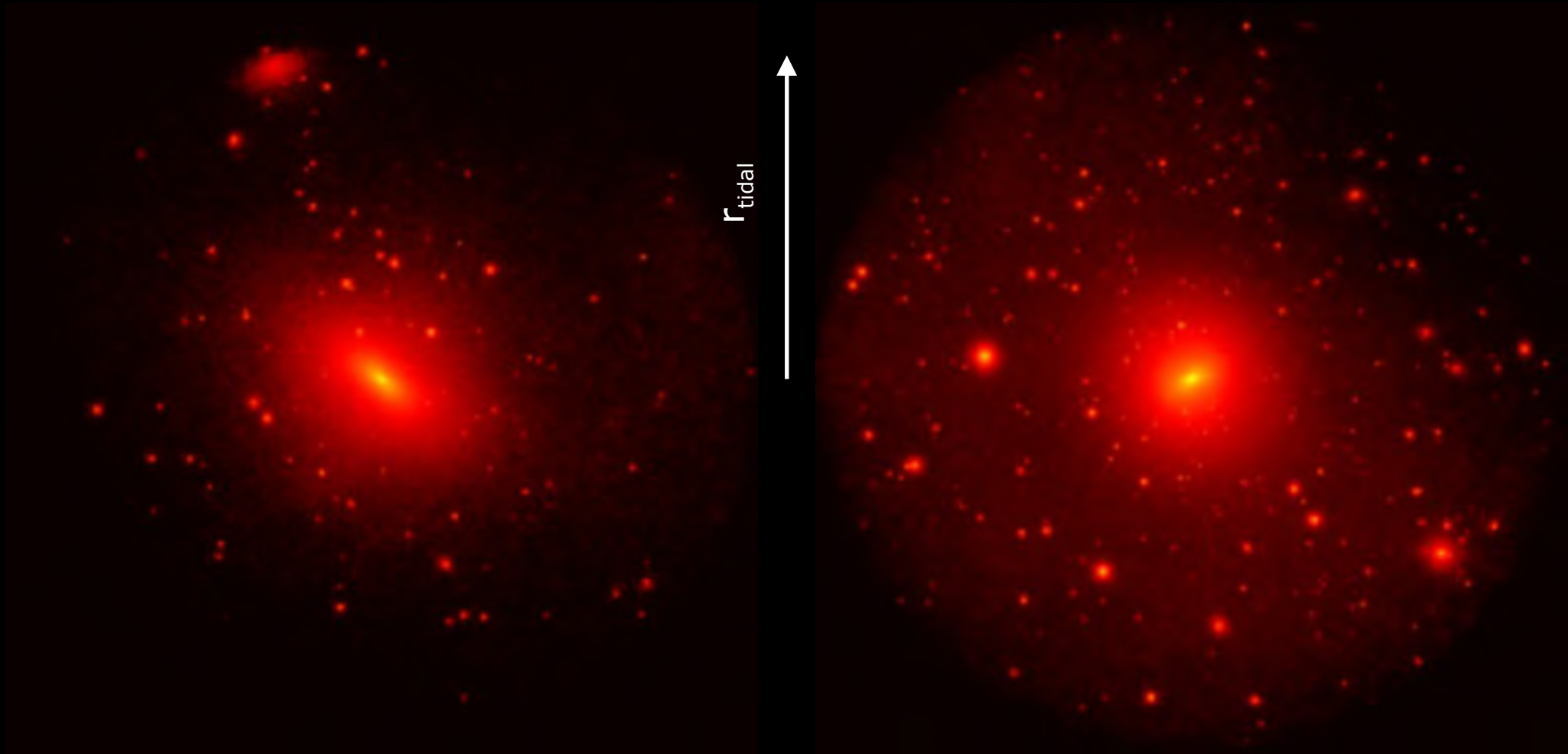


cosmicweb.uchicago.edu

Dark Matter Halo (GHALO)



Subⁿhaloes in Via Lactea II

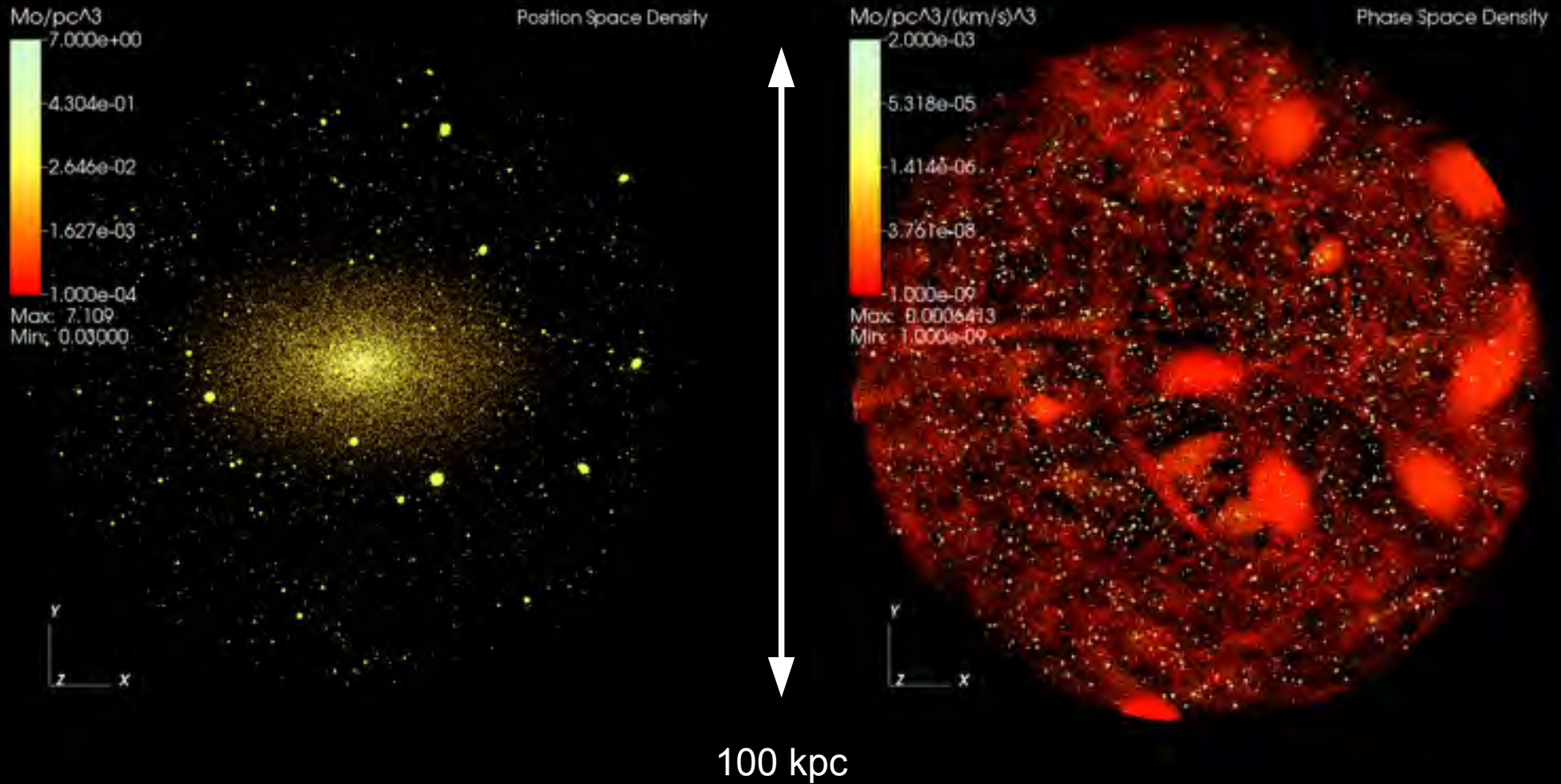


$$M_{\text{tidal}} = 1.97 \times 10^9 \text{ Mo}$$

$$M_{\text{tidal}} = 5.09 \times 10^9 \text{ Mo}$$

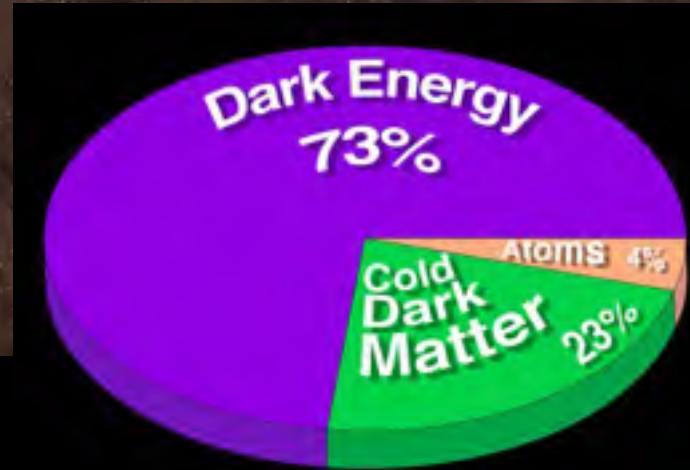
Diemand et al., 2008, Nature, 454, 735

Position vs. Phase Space



Zemp et al., MNRAS, 2009, 394, 641
Zemp, 2009, MPLA, 24, 2291

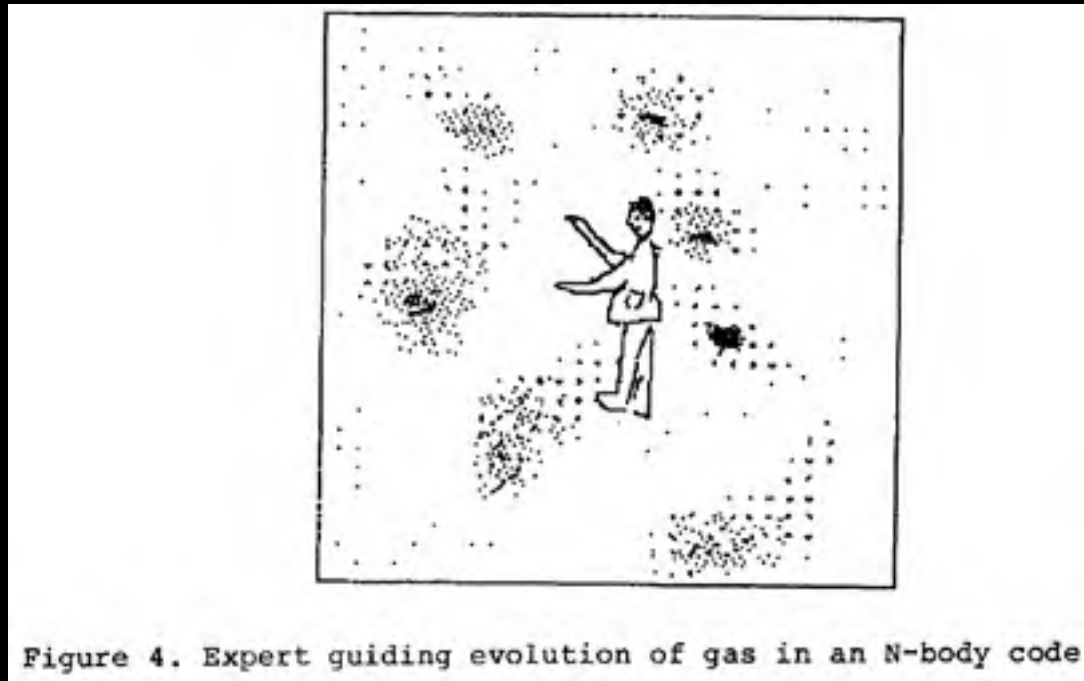
How about the Baryons?



A Long, Long Time Ago...

However if we knew the true functional form of R and offered it to a galaxy builder he would probably tell us "Oh, go and jump in the lake, that's far too complicated". Thus galaxy builders need oversimplified average laws like Schmidt's suggestion $R = C \rho^2$.

Lynden-Bell, Star Formation, 1977, 75, 291



Efstathiou, The Use of Supercomputers in Stellar Dynamics, 1986, 267, 36

Kennicutt-Schmidt Relation

$$\Sigma_{\text{SFR}} \propto \Sigma_{\text{HI}+\text{H}_2}^n$$

star formation rate
surface density

neutral hydrogen
surface density

$$n \approx 1.4$$

$$\Sigma_{\text{HI}+\text{H}_2} = \Sigma_{\text{HI}} + \Sigma_{\text{H}_2}$$

atomic hydrogen molecular hydrogen

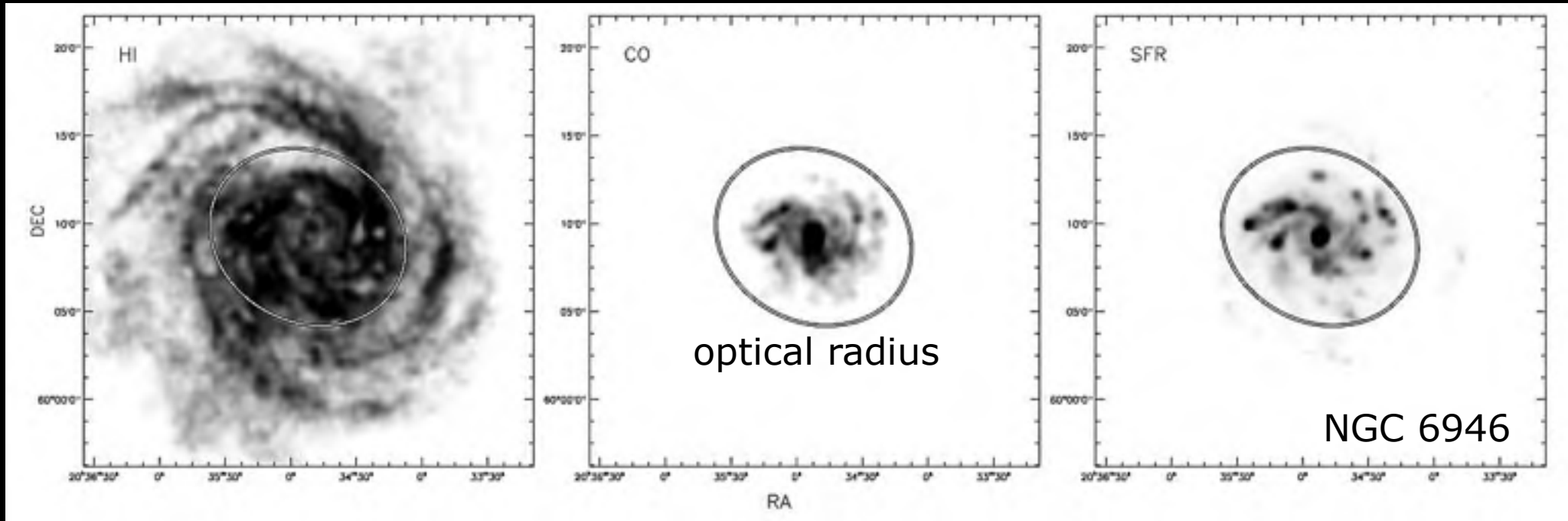
Kennicutt, ApJ, 1998, 498, 541
Schmidt, ApJ, 1959, 129, 243

General Star Formation Recipe

$$\dot{\rho}_* = \epsilon \frac{\rho_{\text{Gas}}}{t_*}$$

Fine-tuning is achieved with thresholds
(e.g. for density and/or temperature)
in order to reproduce the
Kennicutt-Schmidt relation

Where do Stars form?



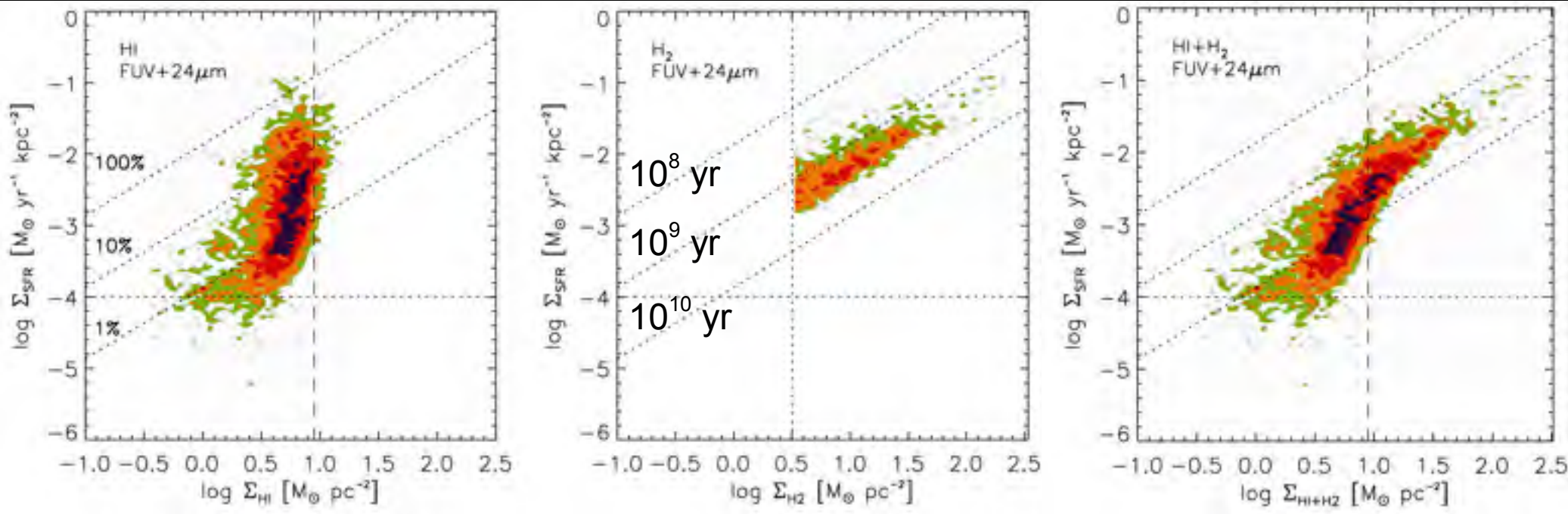
HI

CO

SFR

Almost all star formation happens
within the optical radius

What is the best Correlation?



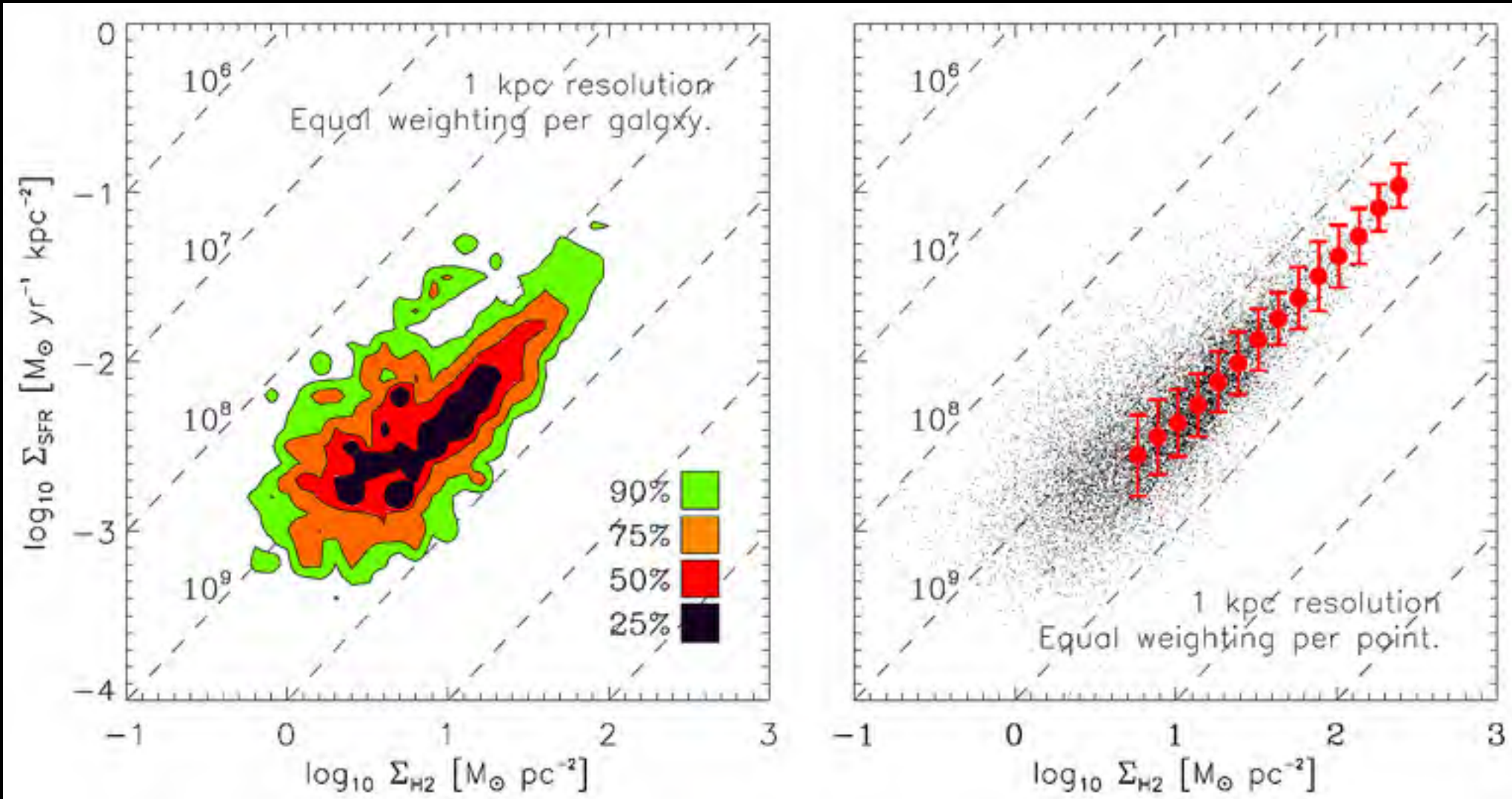
HI

H₂

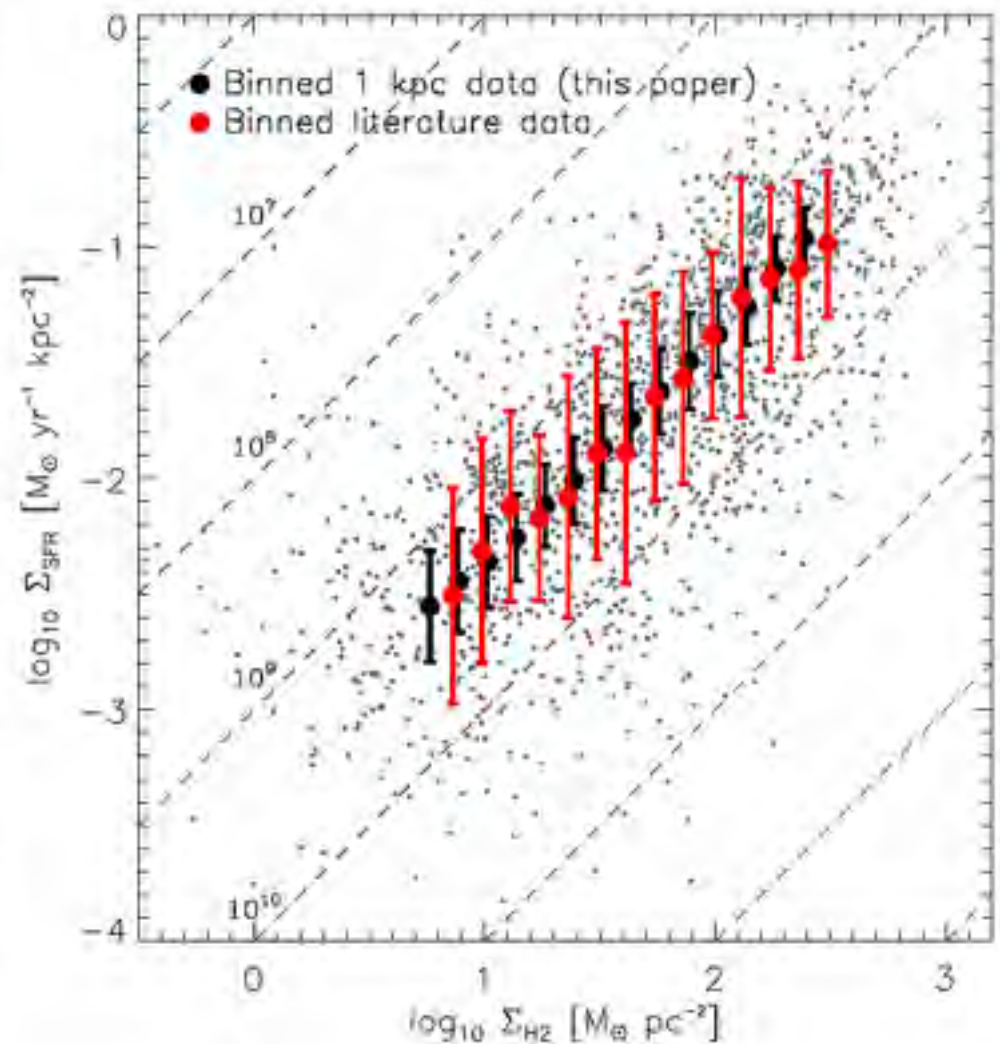
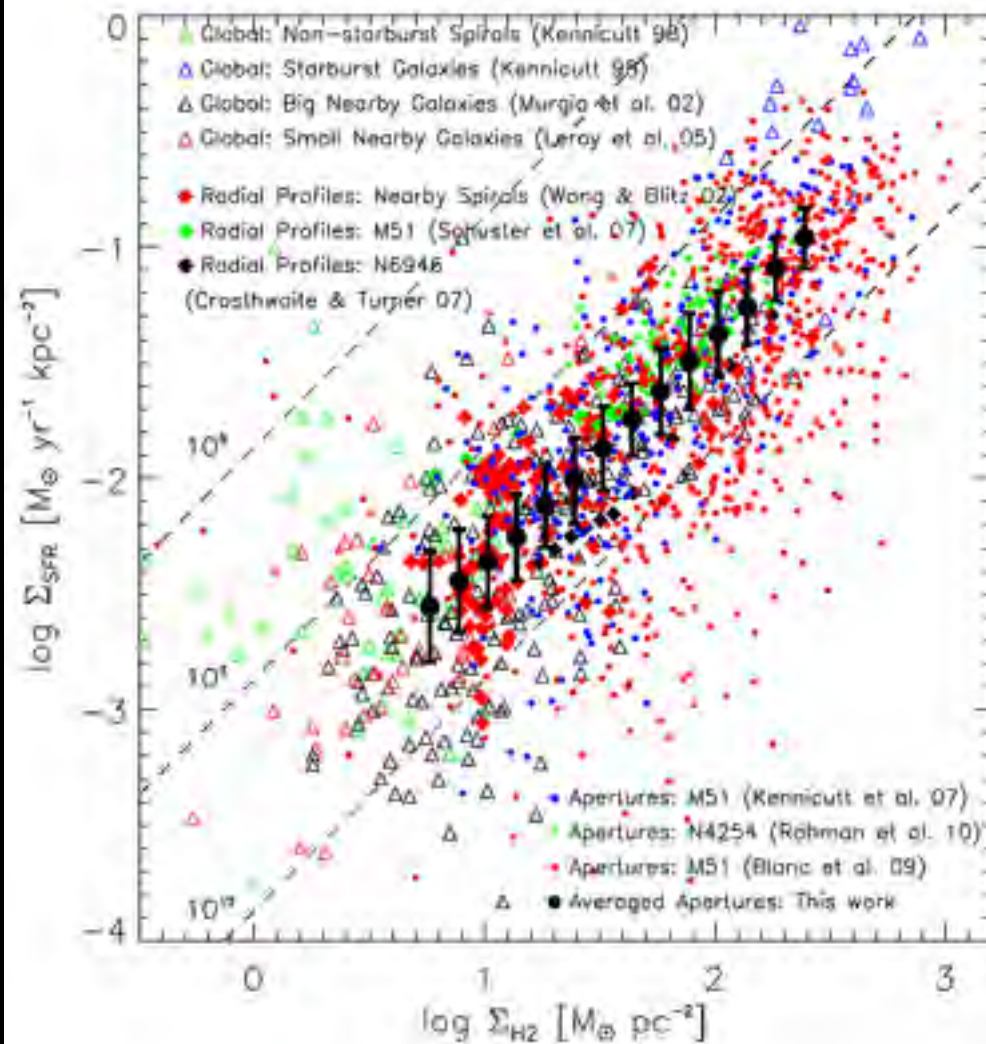
HI+H₂

$$\Sigma_{\text{SFR}} = 10^{-2.1 \pm 0.2} \Sigma_{\text{H}_2}^{1.0 \pm 0.2}$$

$\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$ Correlation



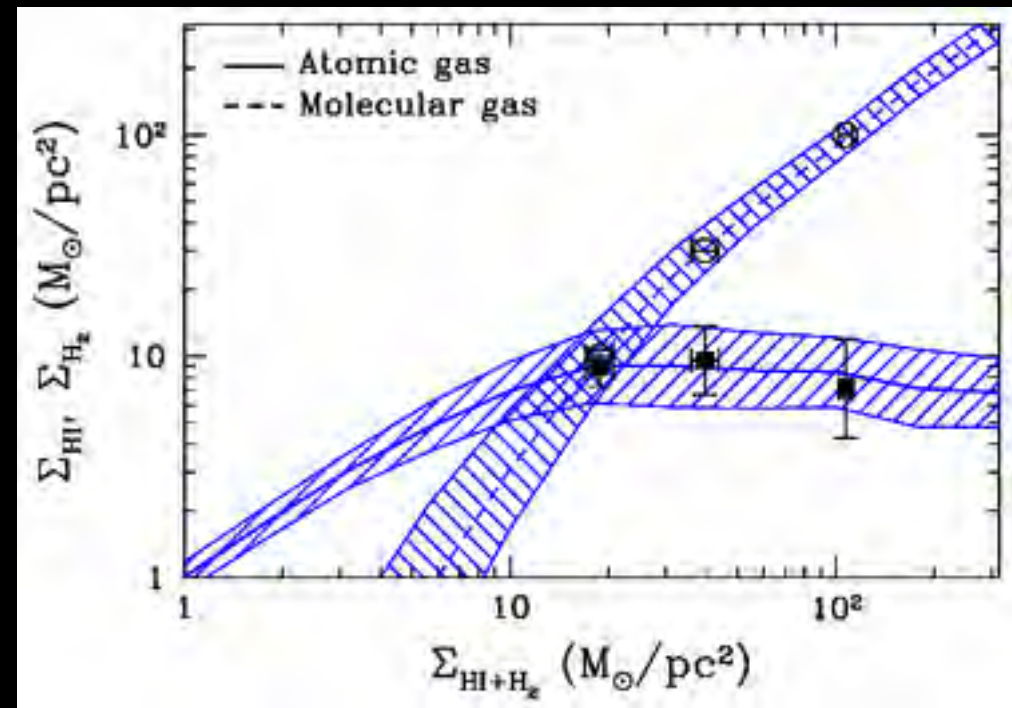
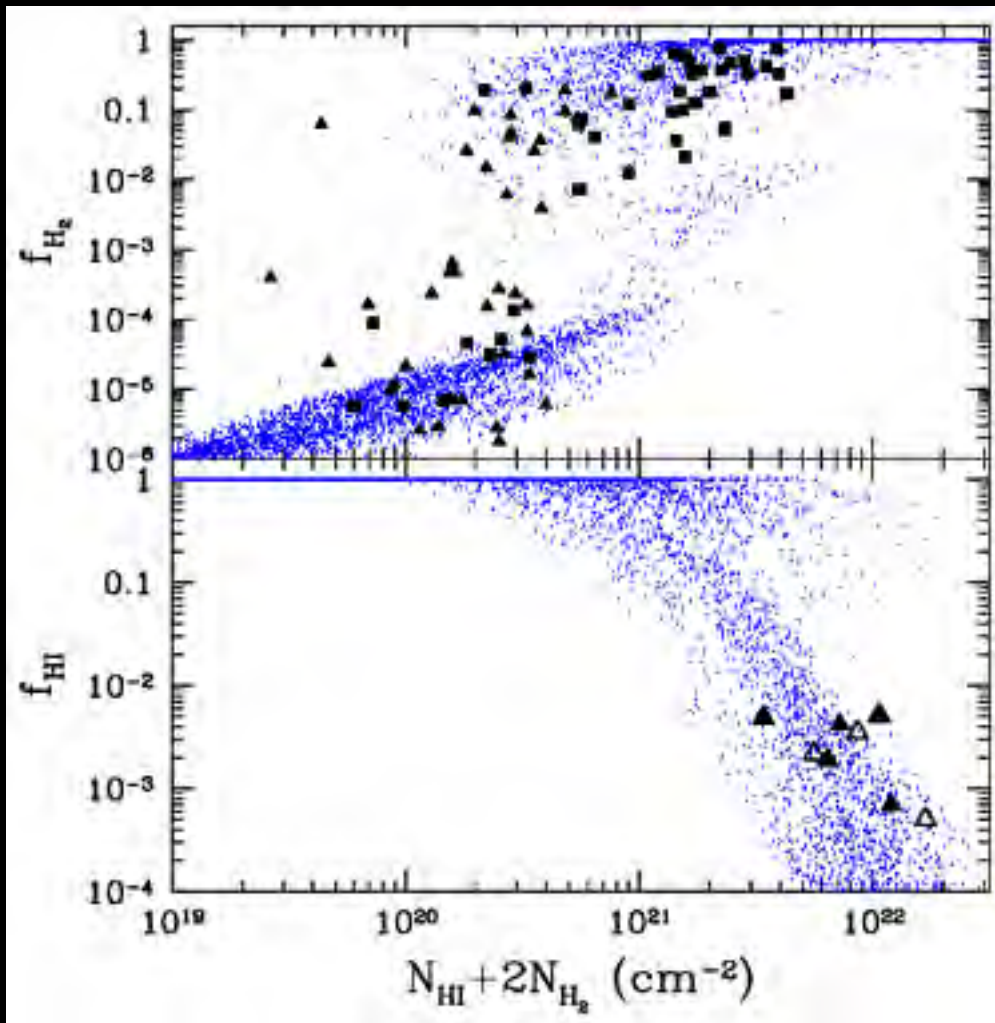
Literature Compilation



H₂ Formation Model

- Formation of H₂ on dust
- Shielding by dust and H₂
- Requires radiative transfer to get local UV flux
- Requires chemical network
⇒ HI, HII, HeI, HeII, HeIII, H₂
- Phenomenological model calibrated by observations

Model Calibration



Molecular Star Formation Recipe

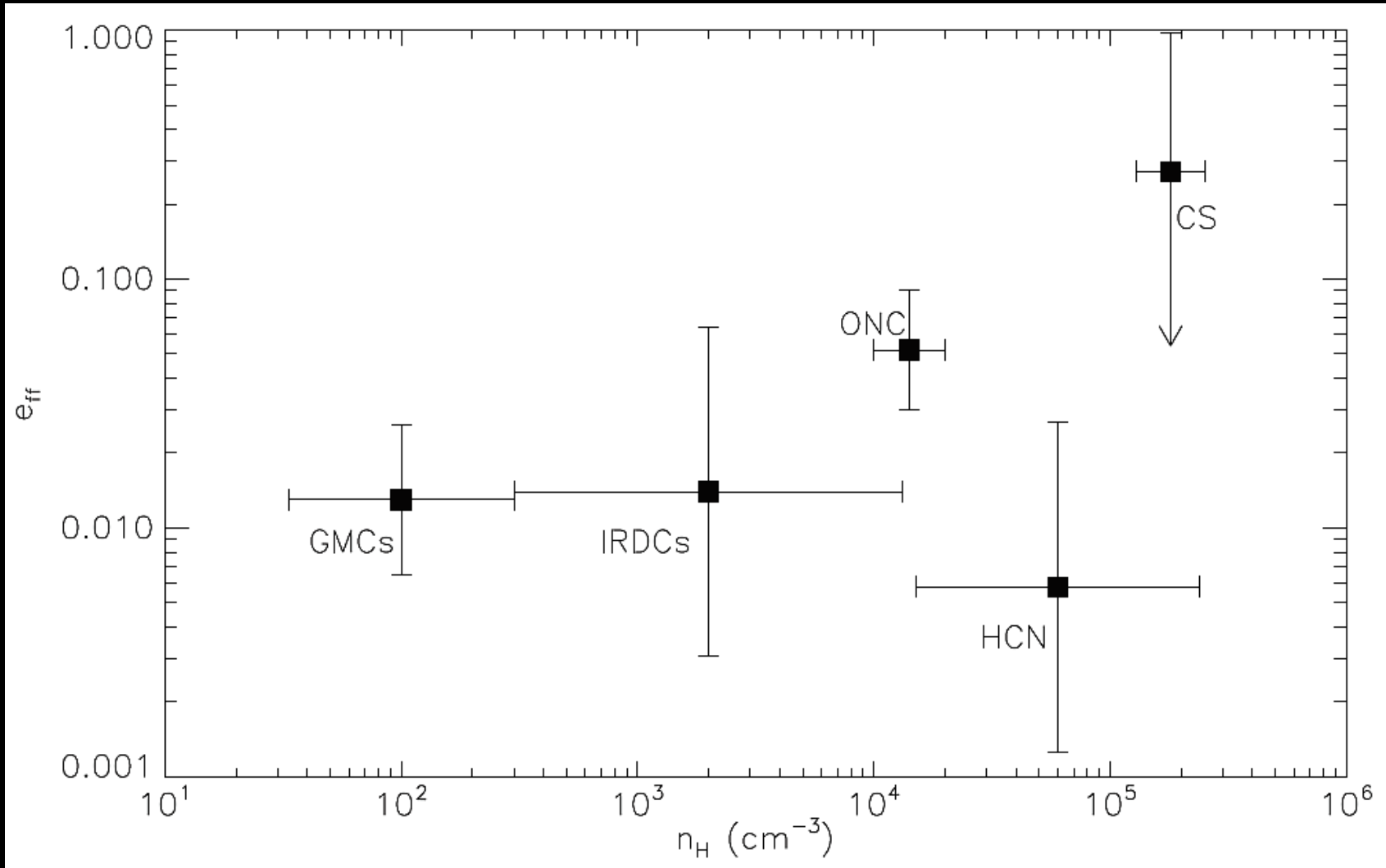
$$\dot{\rho}_* = \epsilon_{\text{ff}} \frac{\rho_{\text{H}_2}}{\tau_{\text{sf}}}$$

$$\tau_{\text{sf}} = \min(\tau_{\text{ff}}(\rho_{\text{gas}}), \tau_{\text{ff}}(\rho_{\text{ff},\text{min}}))$$

$$\tau_{\text{ff}}(\rho) = \sqrt{\frac{3\pi}{32G\rho}}$$

$$\epsilon_{\text{ff}} = 7 \times 10^{-3} \quad \rho_{\text{ff},\text{min}} = 50 \text{ cm}^{-3}$$

Star Formation Efficiency

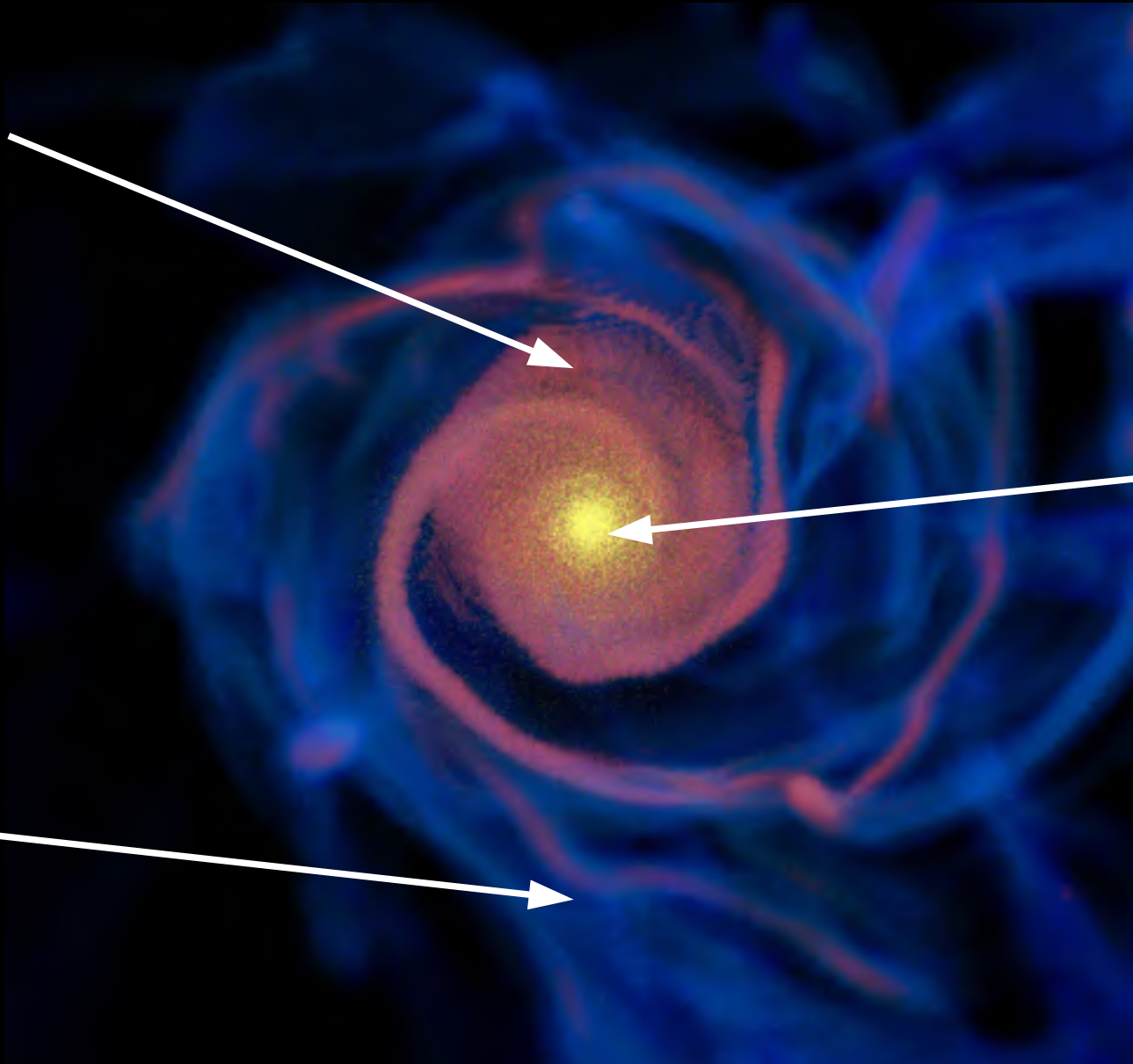


Disc Galaxy



$z=3$

molecular
hydrogen



stars

neutral
gas

ART Code

- Adaptive Refinement Tree (ART)
- 3D radiative transfer of UV
- Non-equilibrium chemical network of hydrogen and helium
- Non-equilibrium cooling and heating rates
- Star formation based on the local molecular hydrogen density
- Supernova metal enrichment and thermal feedback

Simulation Setup

- Cosmology consistent with WMAP 7-yr parameters: $\Omega_{\text{DM},0} = 0.234$, $\Omega_{\text{B},0} = 0.046$, $\Omega_{\Lambda,0} = 0.72$, $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$
- Periodic cosmological volume
 $L_{\text{box}} = 25.6 h^{-1} \text{ Mpc} = 36.6 \text{ Mpc (comoving)}$
- DC mode: $\Delta_{\text{DC},0} = 0.746$
- Refined 7 objects at $z = 0$
with mass $\approx 10^{12} M$

Resolution

- Adaptive mesh refinement
 - ⇒ base grid: $(2^8)^3 = 256^3$
 - ⇒ dark matter: $(2^{11})^3 = 2048^3$
 - ⇒ gas: $(2^{17})^3 = 131072^3$
- Smallest mesh size: $L_9 = 280$ pc (comoving)
 - ⇒ Resolution: $4 L_9 = 1.12$ kpc (comoving)
- Number of particles / cells:
 - ⇒ dark matter: $2.89 \times 10^8 / 1.81 \times 10^5 M$
 - ⇒ gas: 3.89×10^8 (at $z = 2$)
- Data size ⇒ 1 snapshot ca. 45 GB

3 Versions

- A: full physics run with star formation, radiative transfer, cooling, supernova metal enrichment and thermal feedback
- A_{NF} : same as A, but no supernova thermal feedback
- B: adiabatic version, i.e. no star formation and no cooling

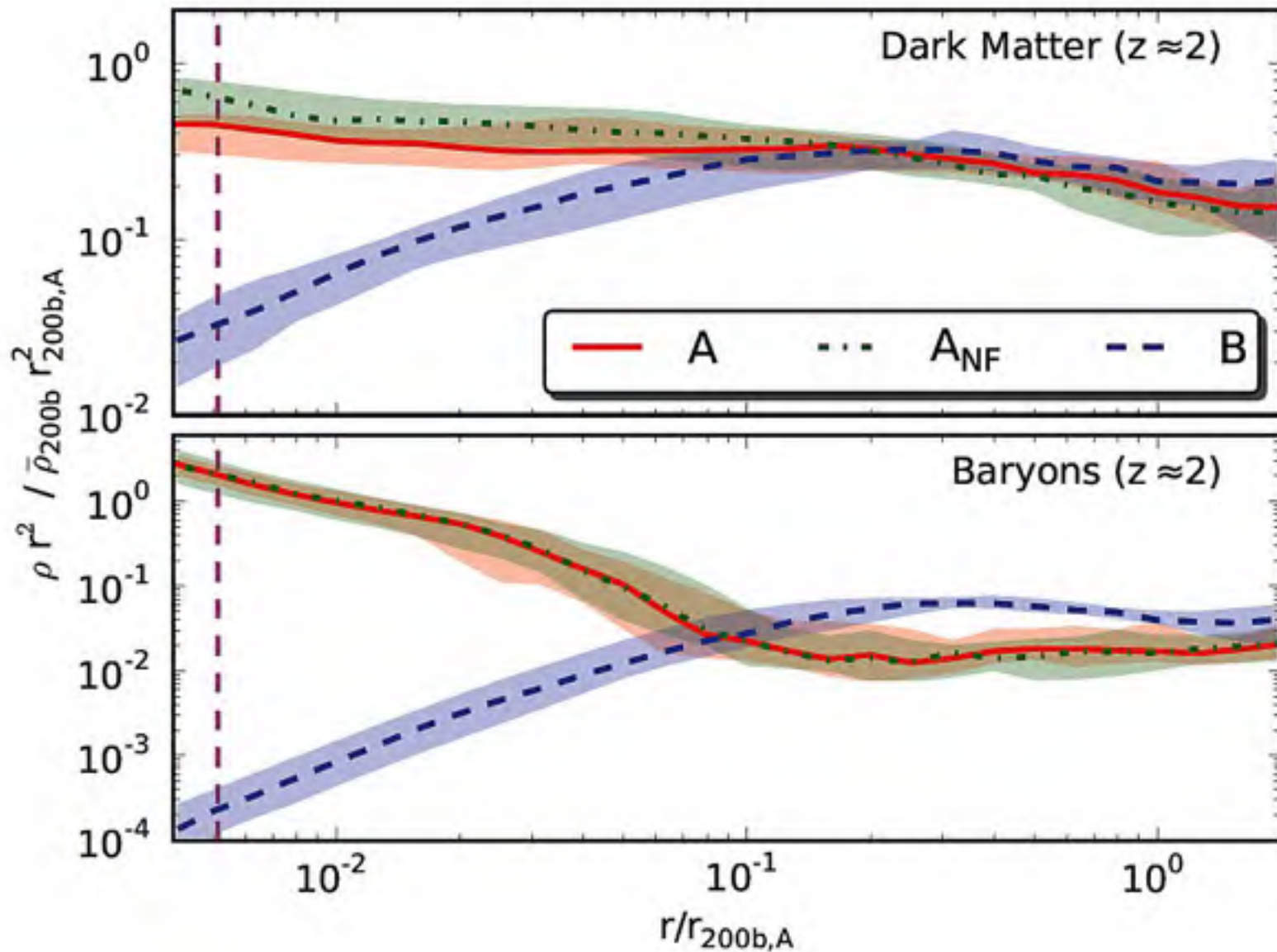
Median Properties

- Most massive haloes at $z = 4, 3$ and 2
- Characteristic scale: r_{200b} and M_{200b}

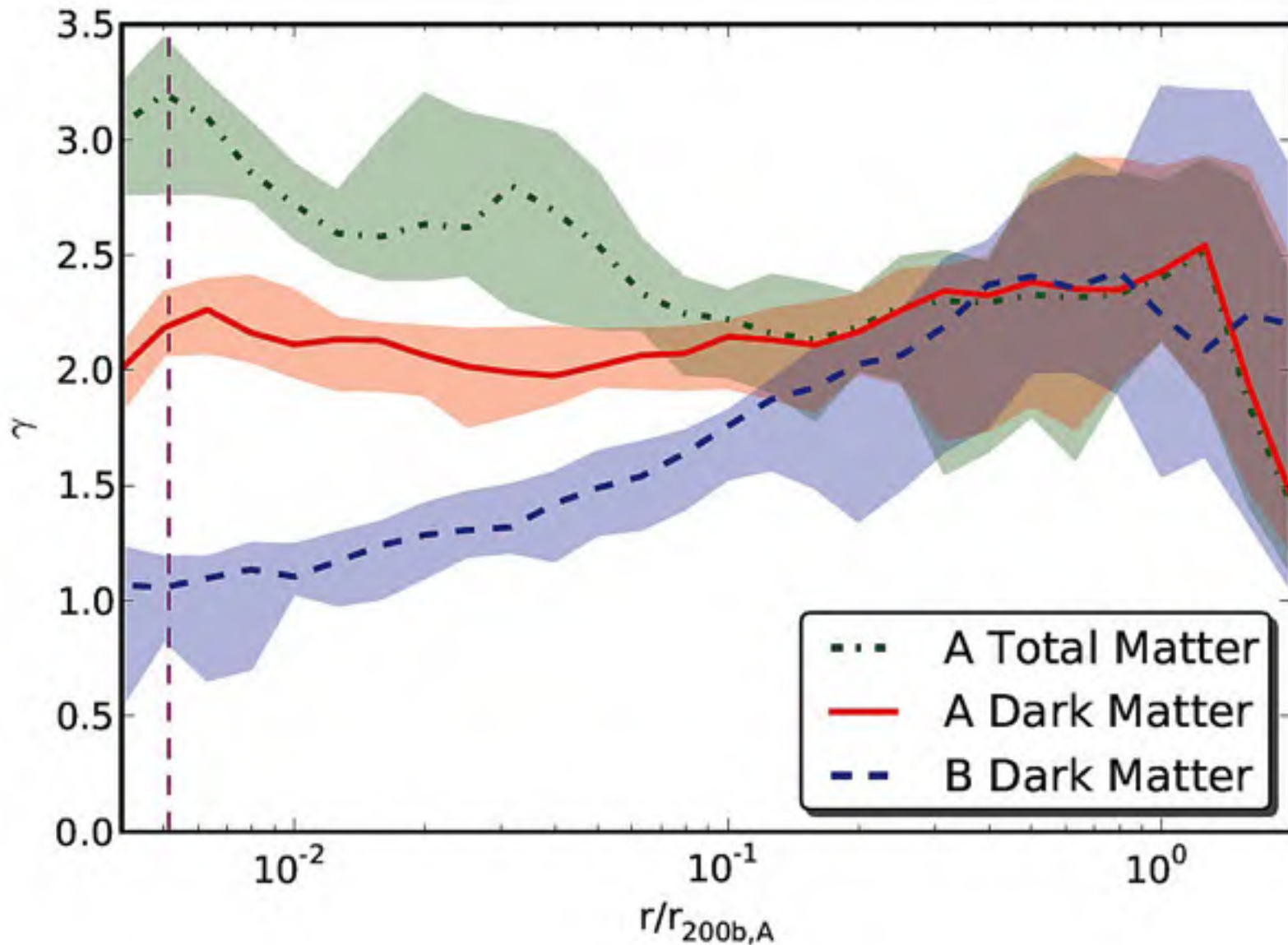
$$\Rightarrow \frac{M_{200b}}{4\pi r_{200b}^3/3} = 200\rho_b$$

- Mass cut: $M_{200b} \geq 10^{11} M$
- Match haloes between different simulations
 $\Rightarrow 12, 16, 16$ objects
- Median mass: $1.7, 2.7, 3.3 \times 10^{11} M$
- Scatter: 15 and 85 percentile

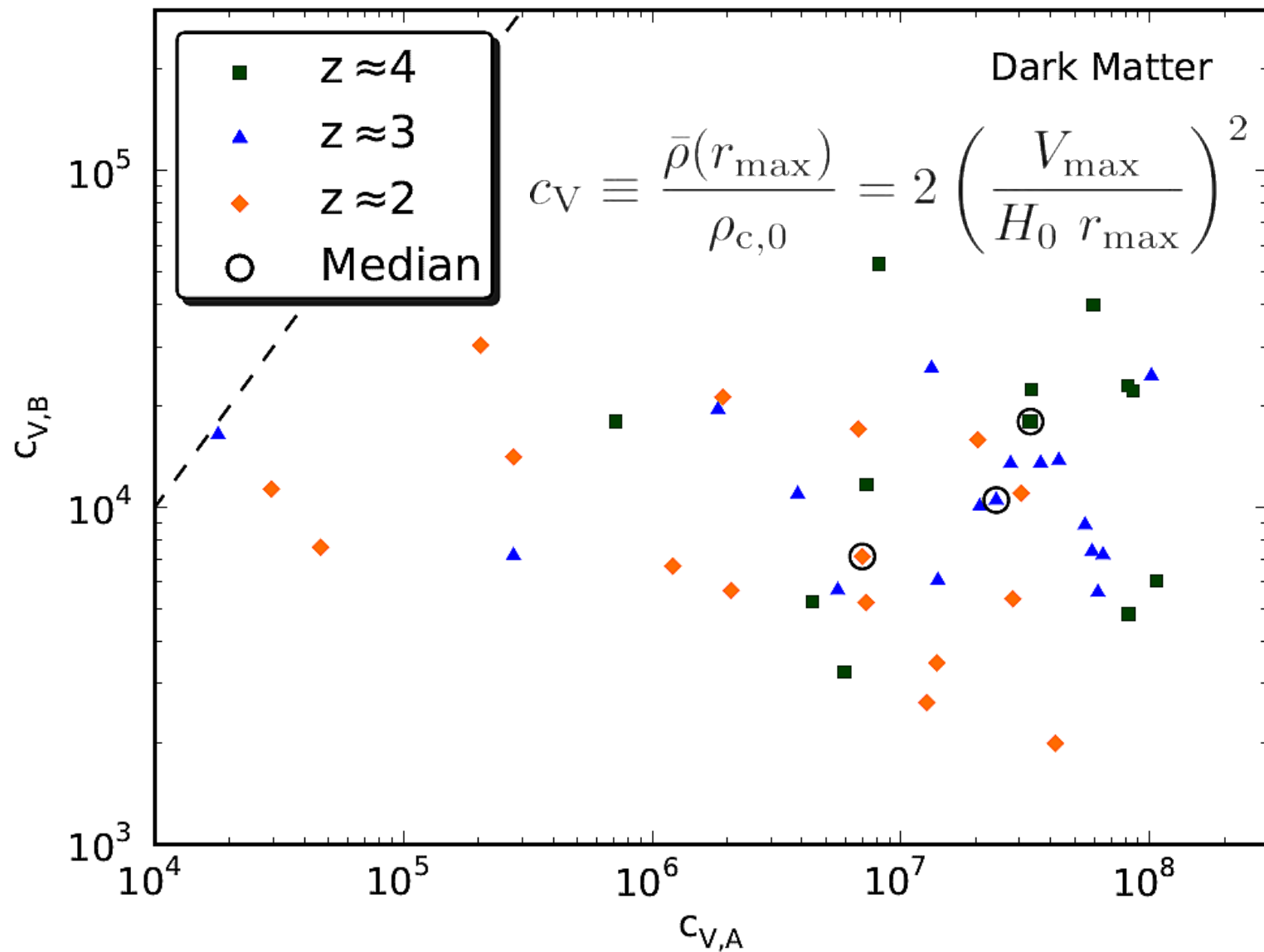
Mass Density



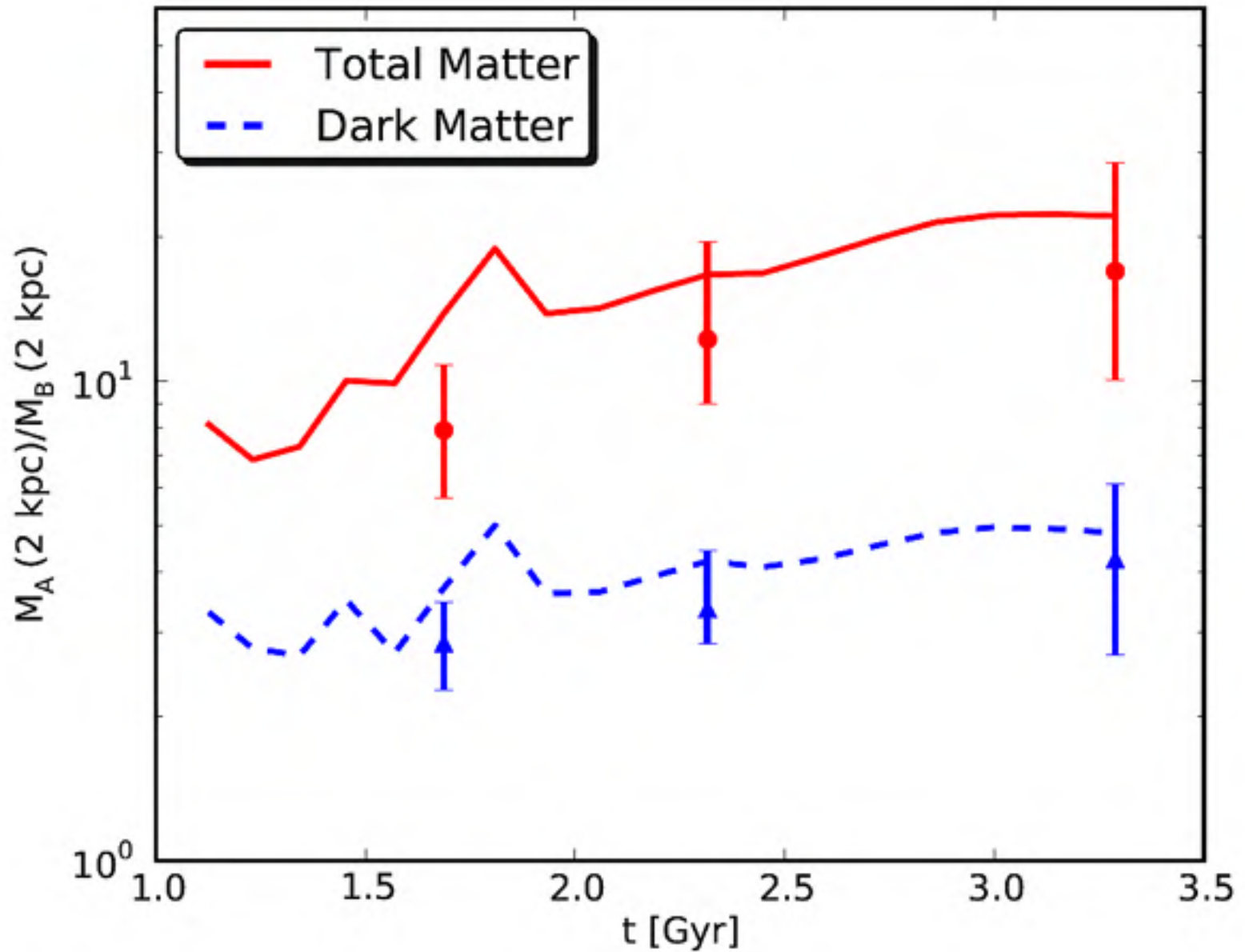
Mass Density Slope



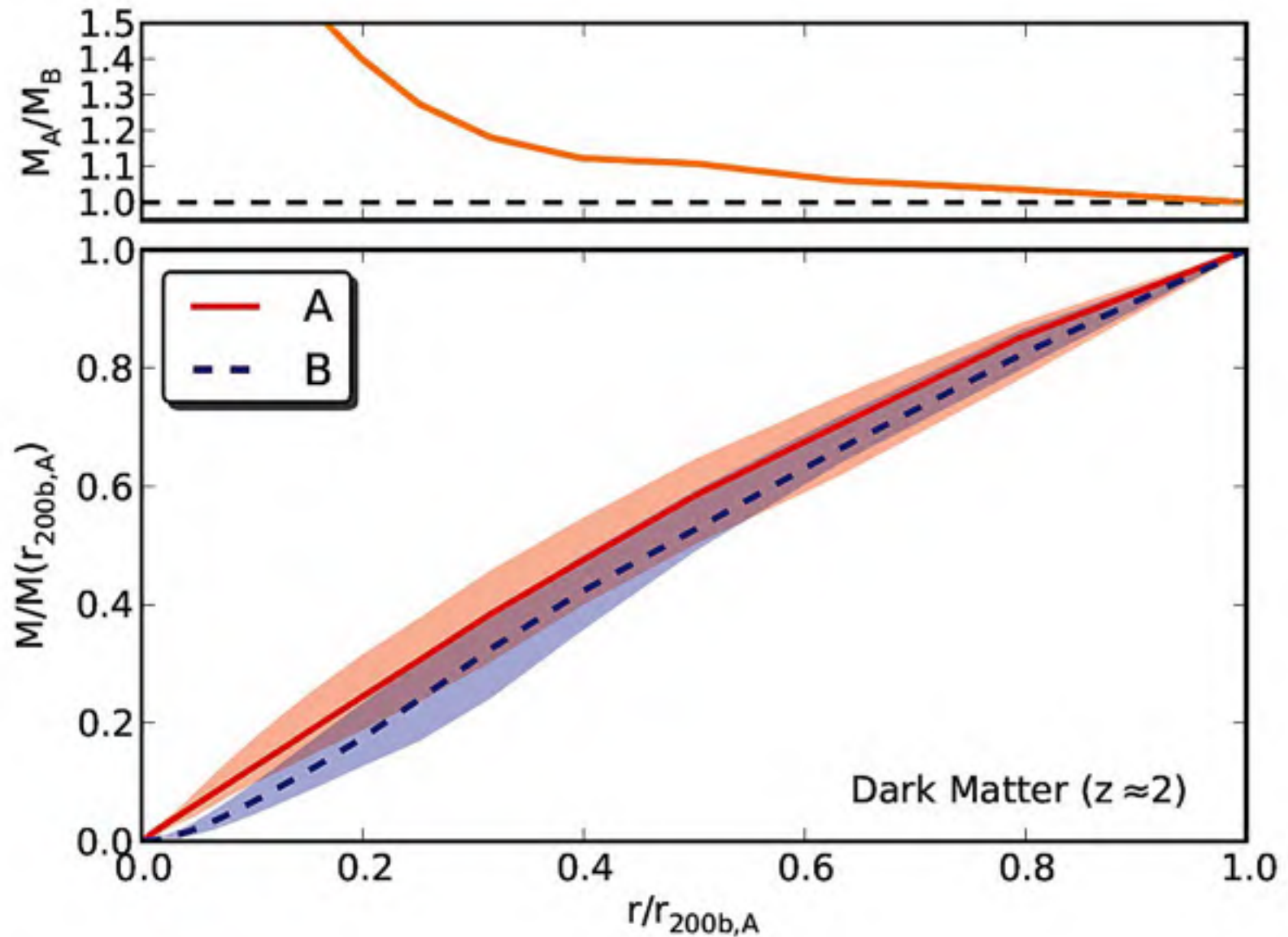
Concentration



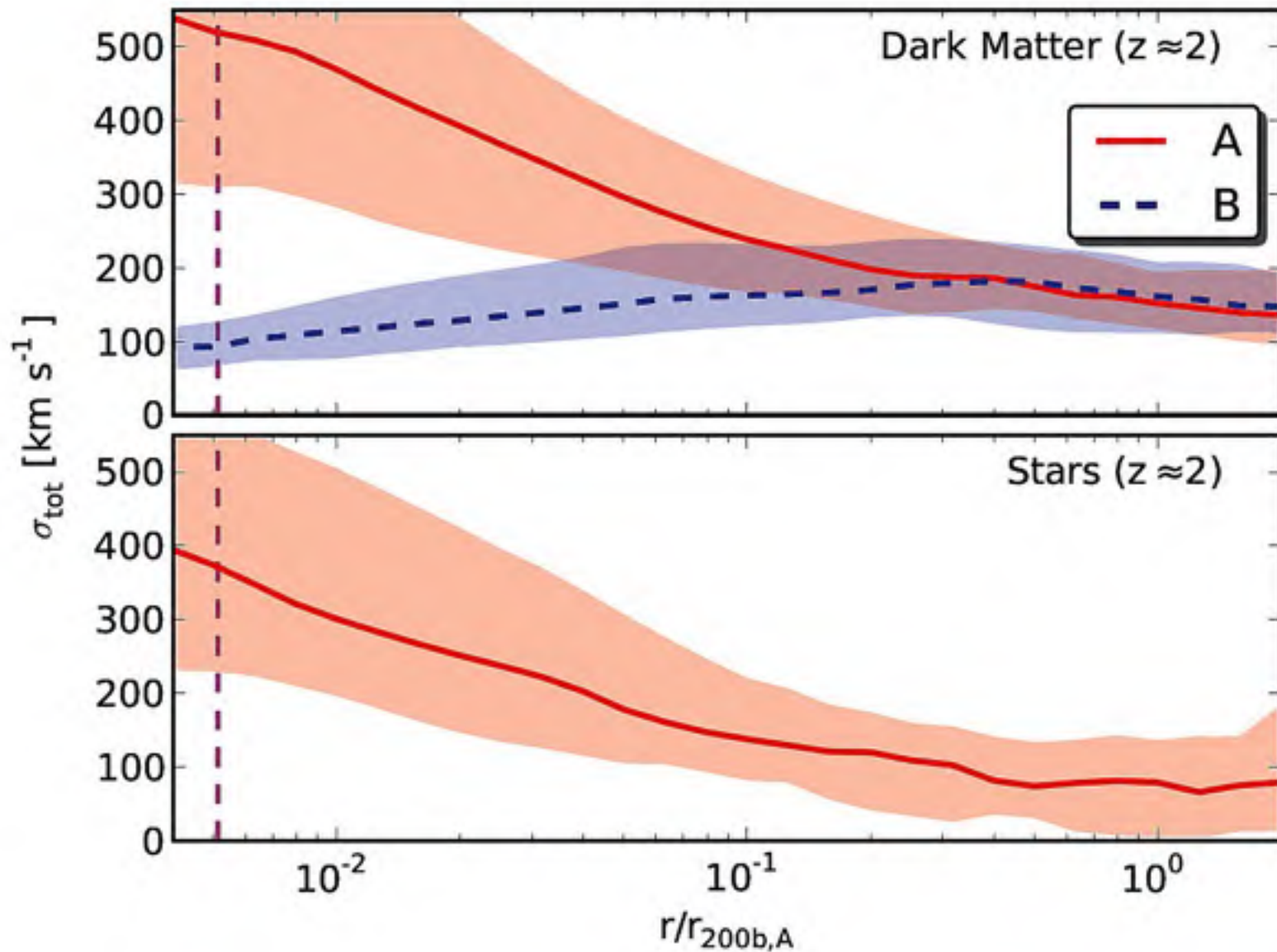
Enclosed Mass



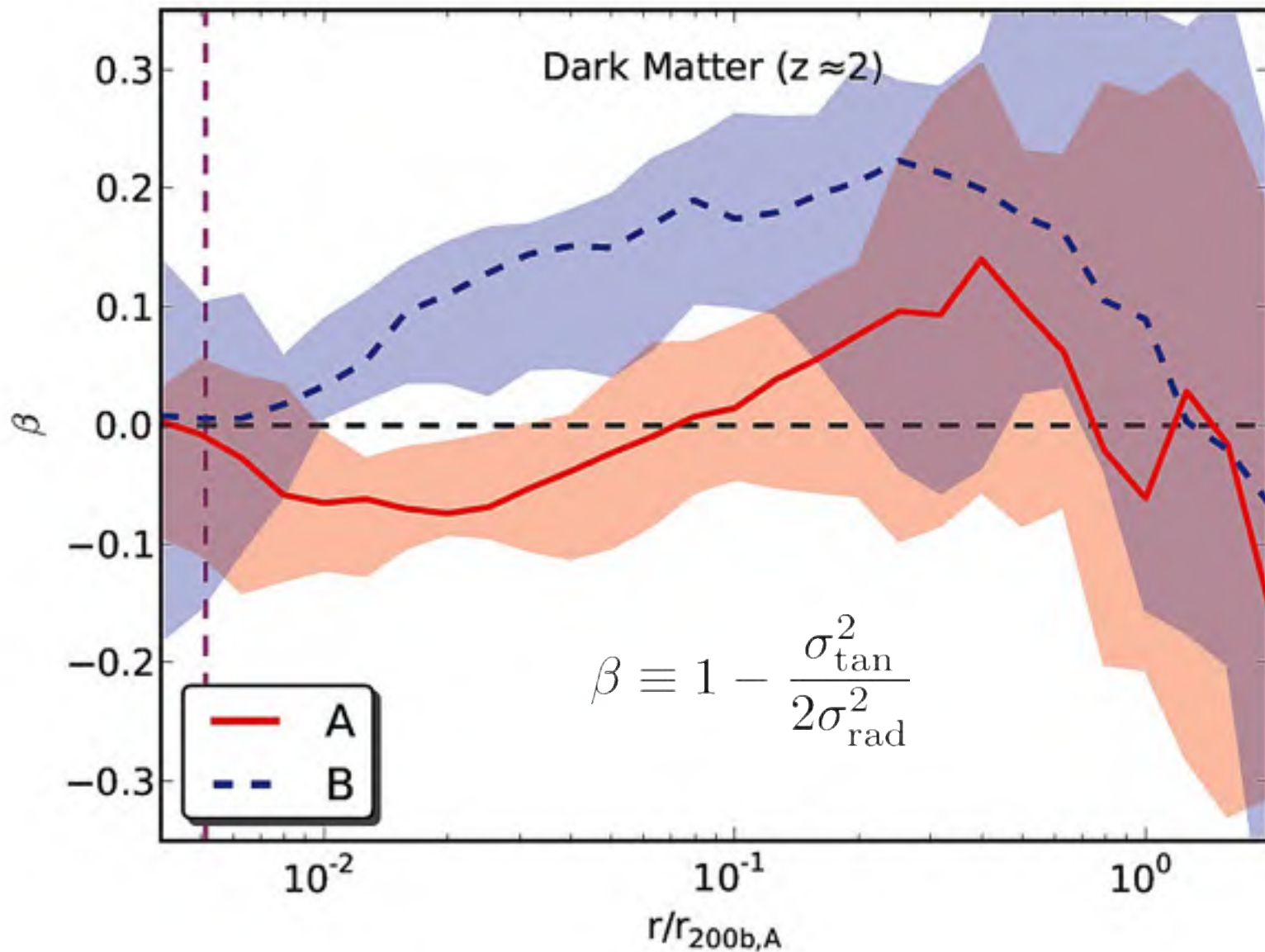
Halo Contraction



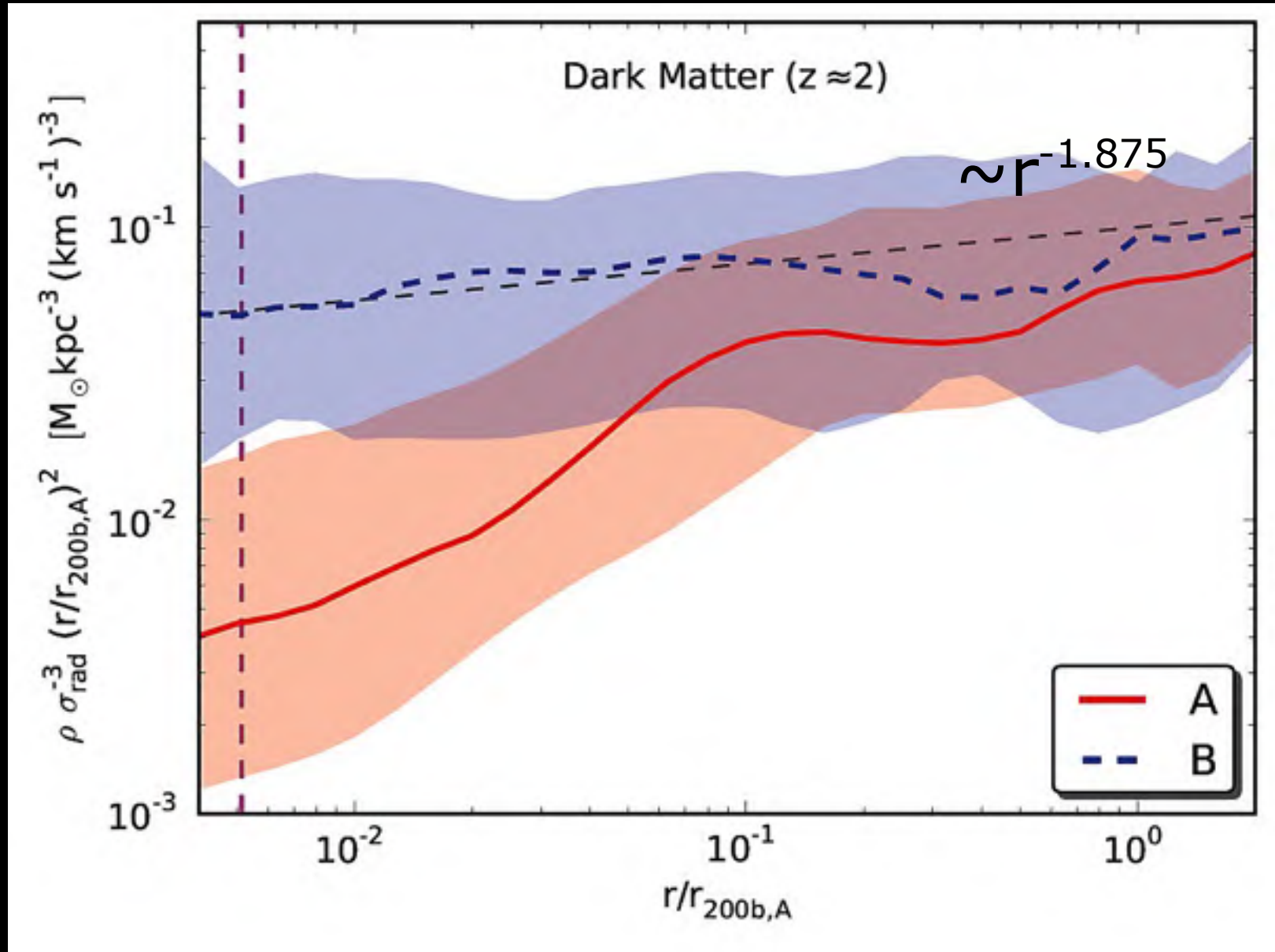
Velocity Dispersion



Anisotropy



Pseudo Phase-Space Density



Shape Determination

$$S_{ij} = \frac{\sum_k m_k (\mathbf{r}_k)_i (\mathbf{r}_k)_j}{\sum_k m_k}$$

Summation over particles in shells!

Iteration \Rightarrow orientation as well as a, b and c

$$T \equiv \frac{1 - (b/a)^2}{1 - (c/a)^2}$$

$1 > T > 2/3$ prolate

$2/3 > T > 1/3$ triaxial

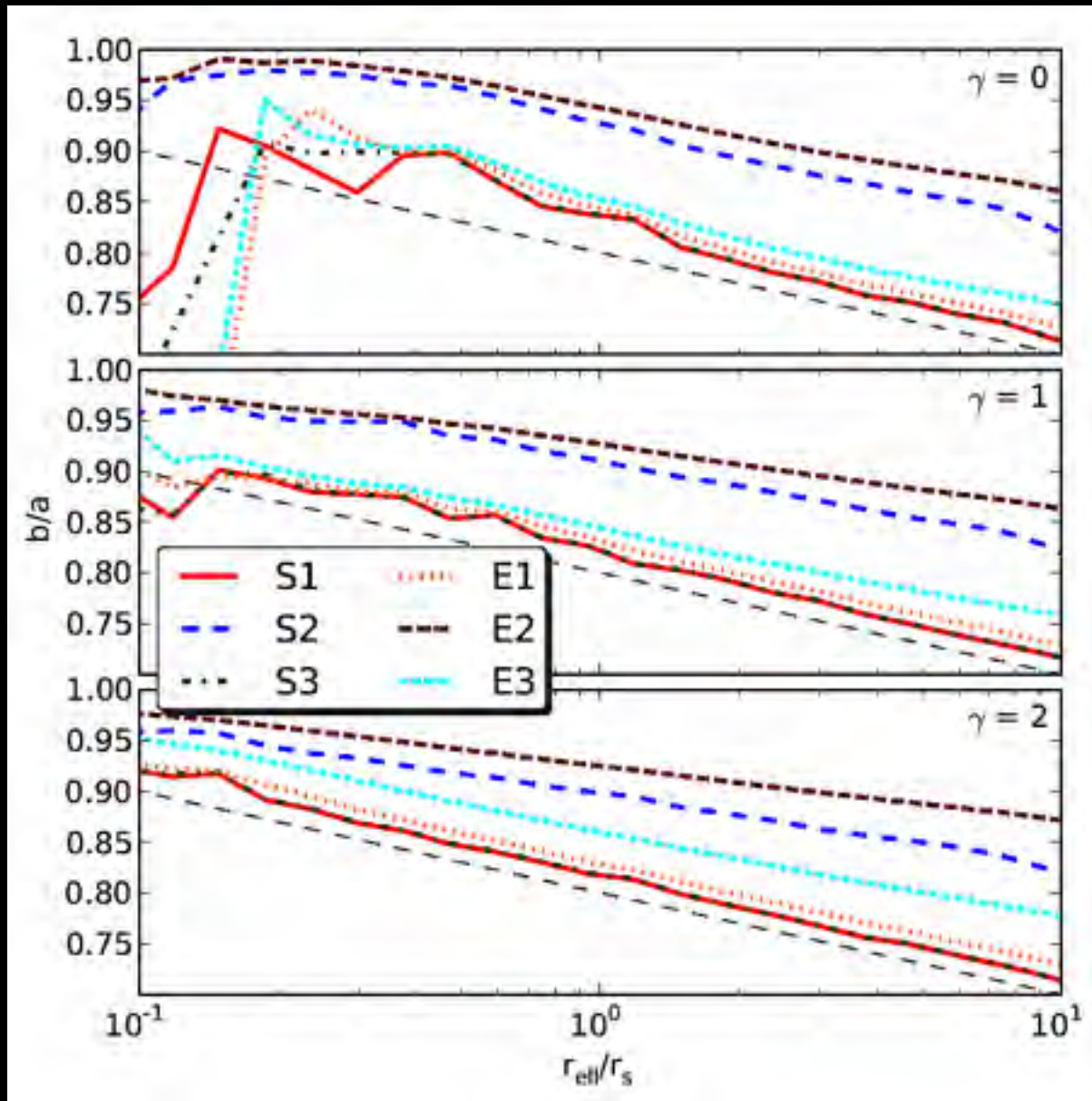
$1/3 > T > 0$ oblate

Shape Determination Methods

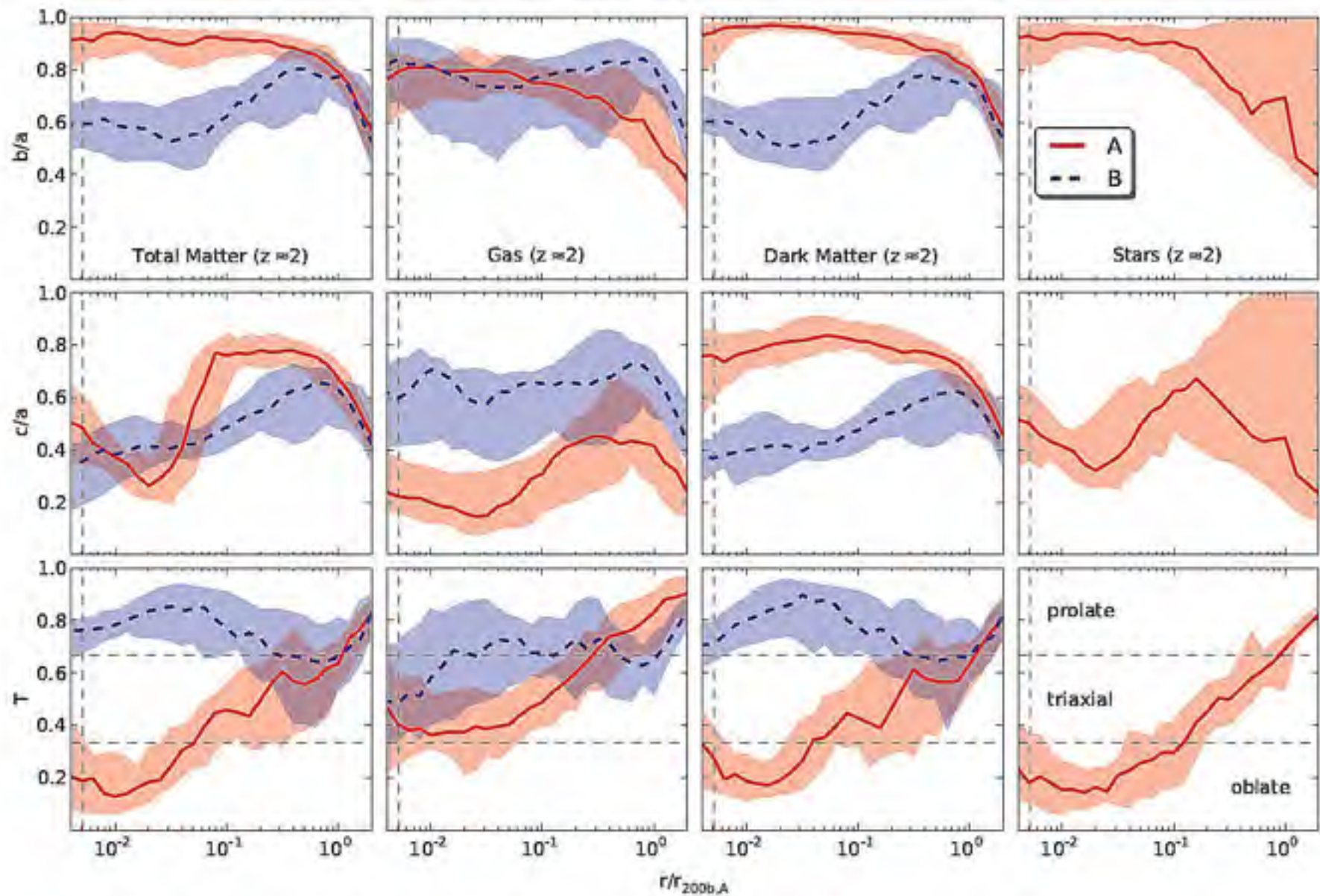
$$\mathbf{S} = \frac{\int_V \rho(\mathbf{r}) w(\mathbf{r}) \mathbf{r} \mathbf{r}^T dV}{\int_V \rho(\mathbf{r}) dV}$$

Method	$w(\mathbf{r})$	V
S1	1	Ellipsoidal shell
S2	r^{-2}	Ellipsoidal shell
S3	r_{ell}^{-2}	Ellipsoidal shell
E1	1	Enclosed ellipsoid
E2	r^{-2}	Enclosed ellipsoid
E3	r_{ell}^{-2}	Enclosed ellipsoid

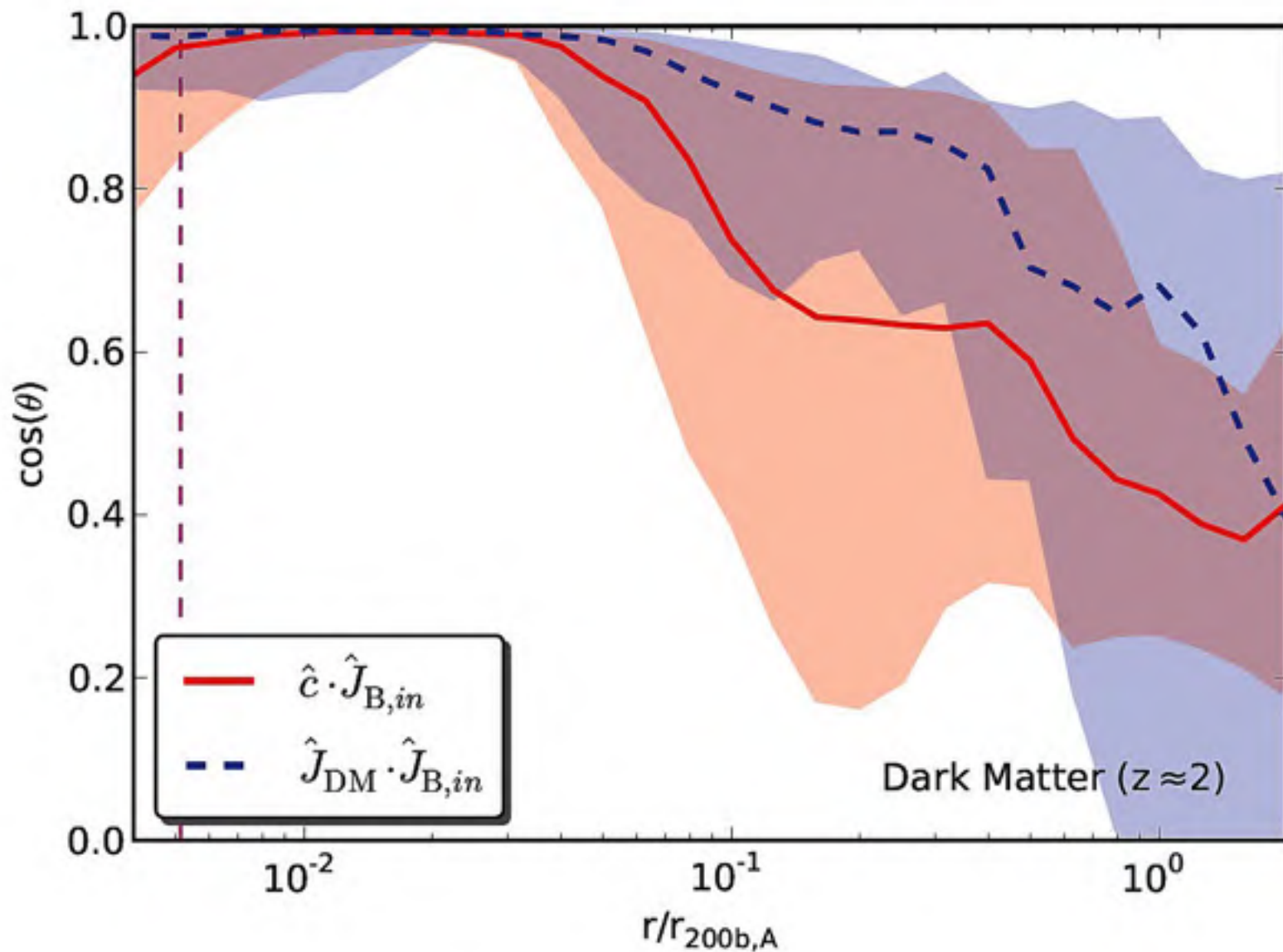
Shape Determination Bias



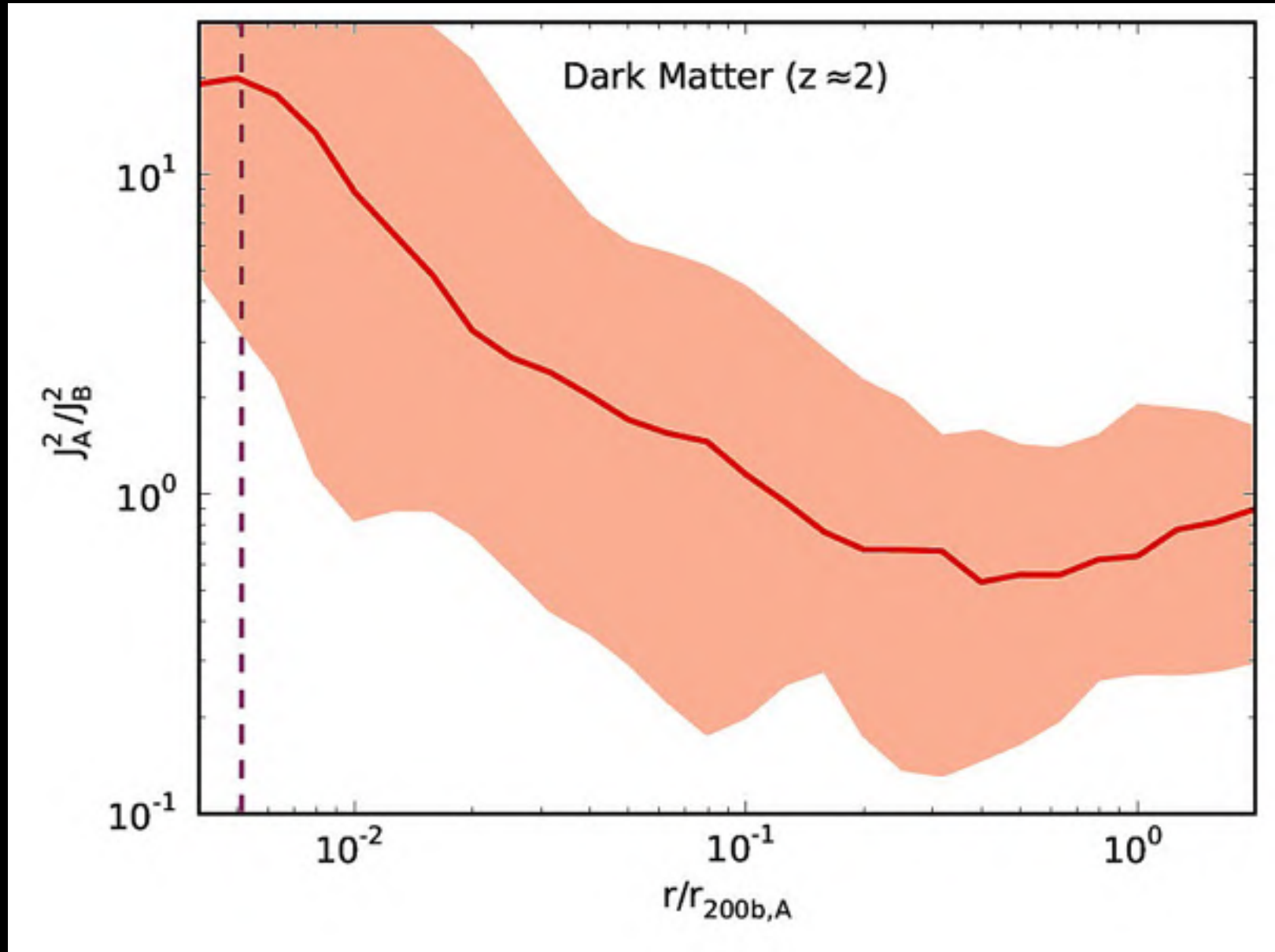
Shape



Twisting of the Halo



Angular Momentum Transfer



Summary

- Set of simulations with an observationally motivated star formation prescription based on molecular hydrogen
- Baryon dissipation
 - ⇒ redistribution of matter and angular momentum
 - ⇒ clear indication for halo contraction
 - ⇒ change in potential affects velocity dispersion, anisotropy, shape, orientation