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

ApJ accepted
arXiv:1108.5384

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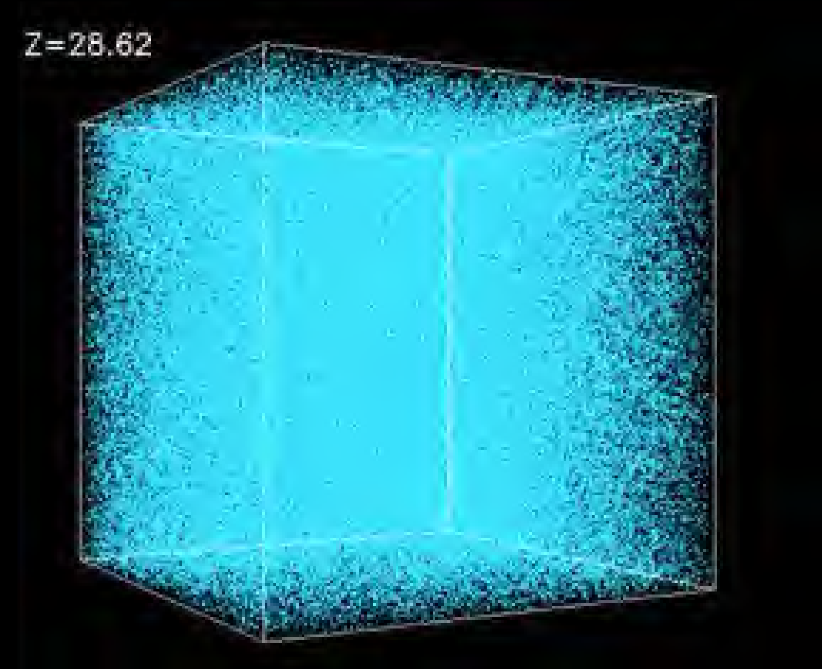
NAOC Colloquium
Beijing, 15. February 2012

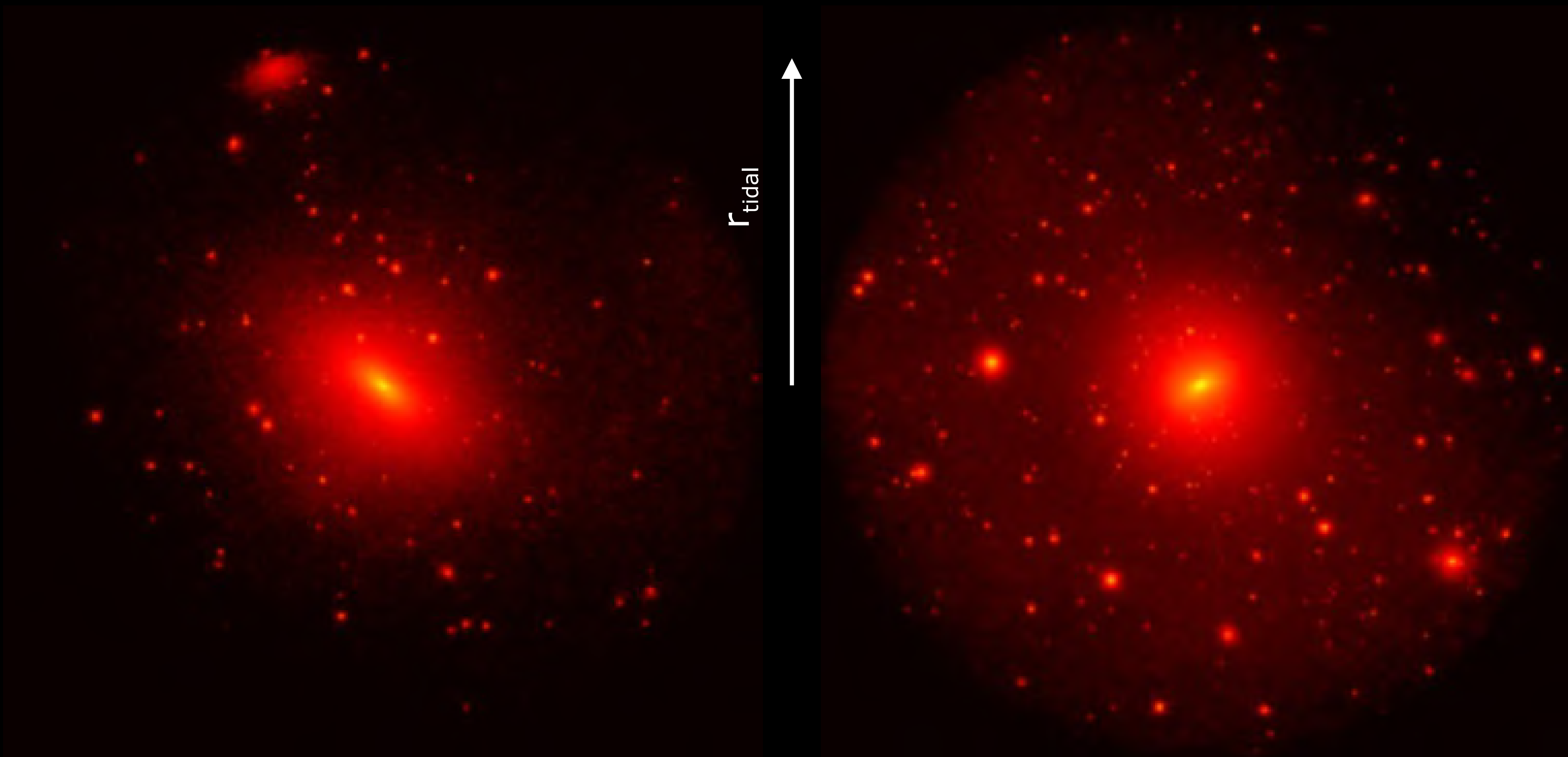


cosmicweb.uchicago.edu

Dark Matter Halo (GHALO)

Stadel et al., MNRAS, 2009, 398, L21

Sub^{n}haloes in Via Lactea II

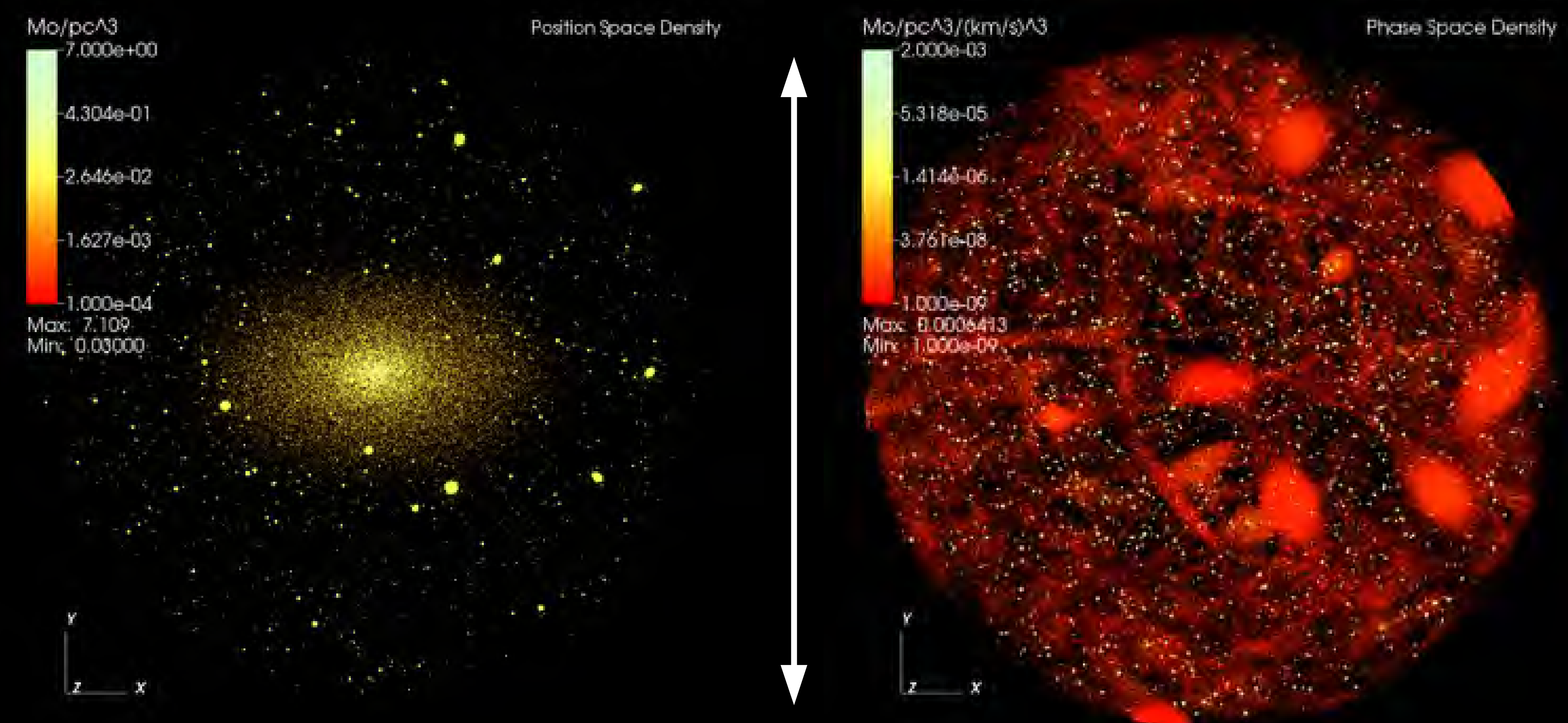


M_{tidal} = 1.97 × 10^9 Mo

M_{tidal} = 5.09 × 10^9 Mo

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

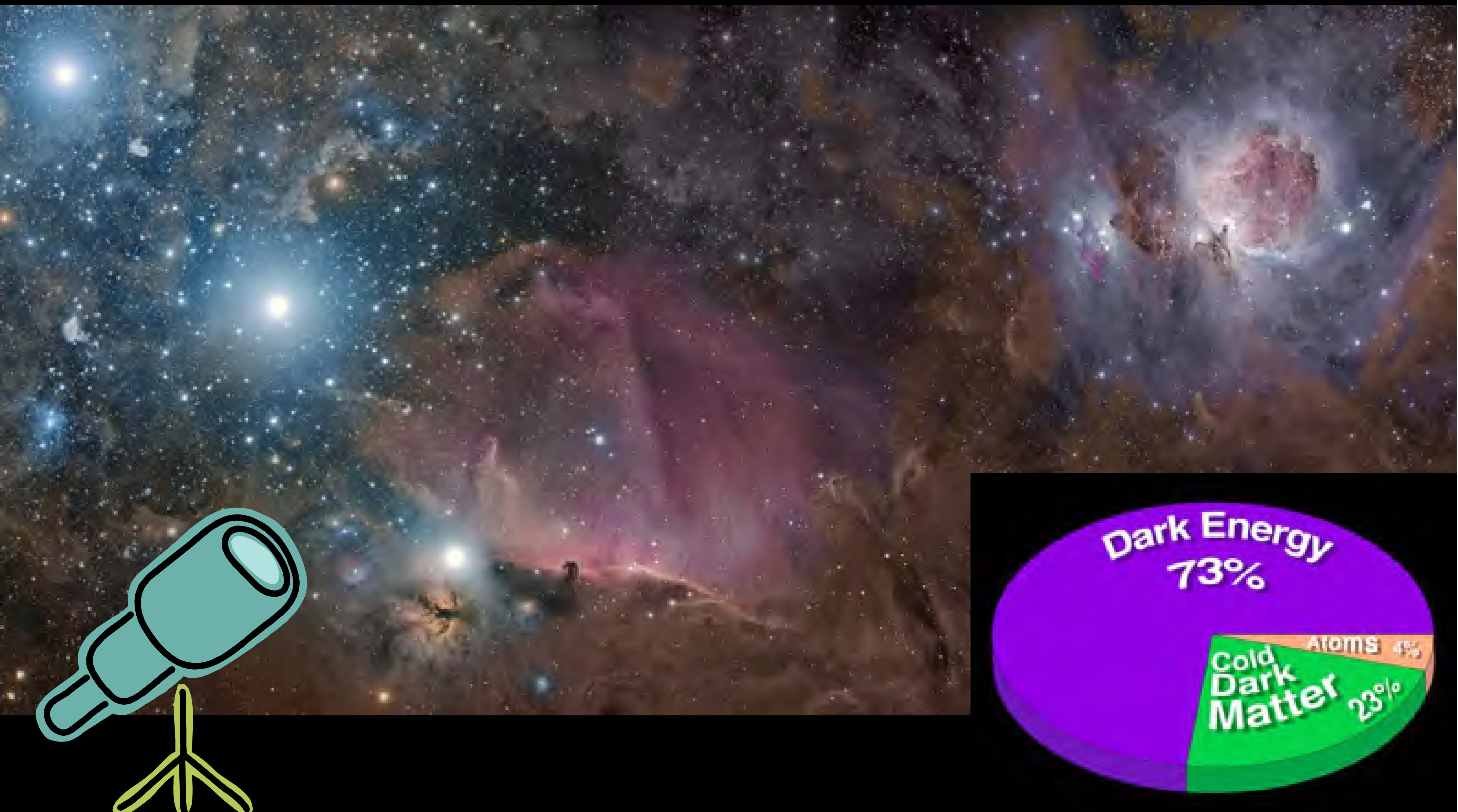
Position vs. Phase Space



100 kpc

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

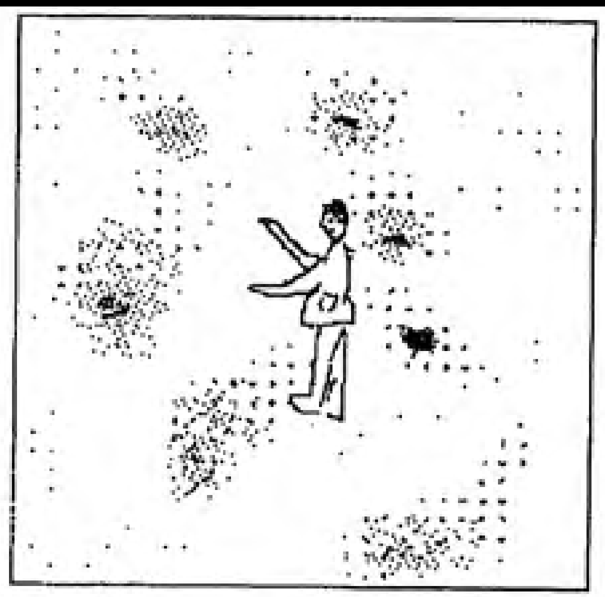


Figure 4. Expert guiding evolution of gas in an N-body code

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

Kennicutt-Schmidt Relation

$$\Sigma_{\mathrm{SFR}} \propto \Sigma^{n}_{\mathrm{HI+H_2}}$$

star formation rate surface density

neutral hydrogen surface density

$$n \approx 1.4$$

$$\Sigma_{\mathrm{HI+H_2}} = \Sigma_{\mathrm{HI}} + \Sigma_{\mathrm{H_2}}$$

atomic hydrogen

molecular hydrogen

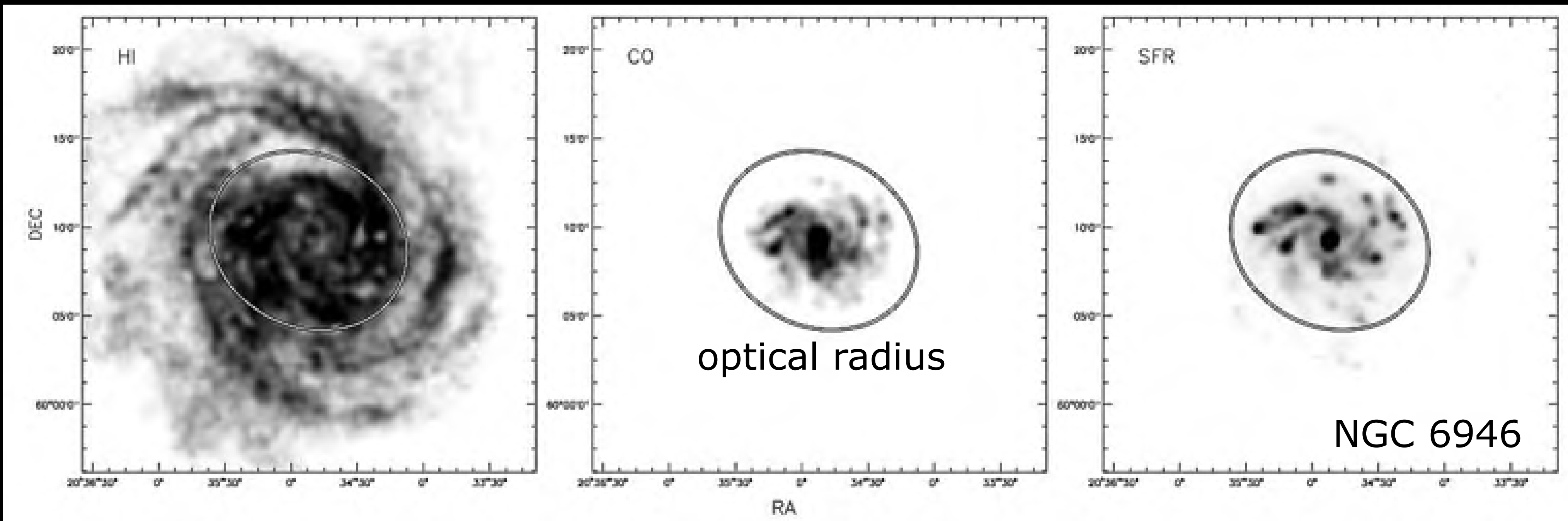
Kennicutt, ApJ, 1998, 498, 541
Schmidt, ApJ, 1959, 129, 243

General Star Formation Recipe

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

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

Where do Stars form?

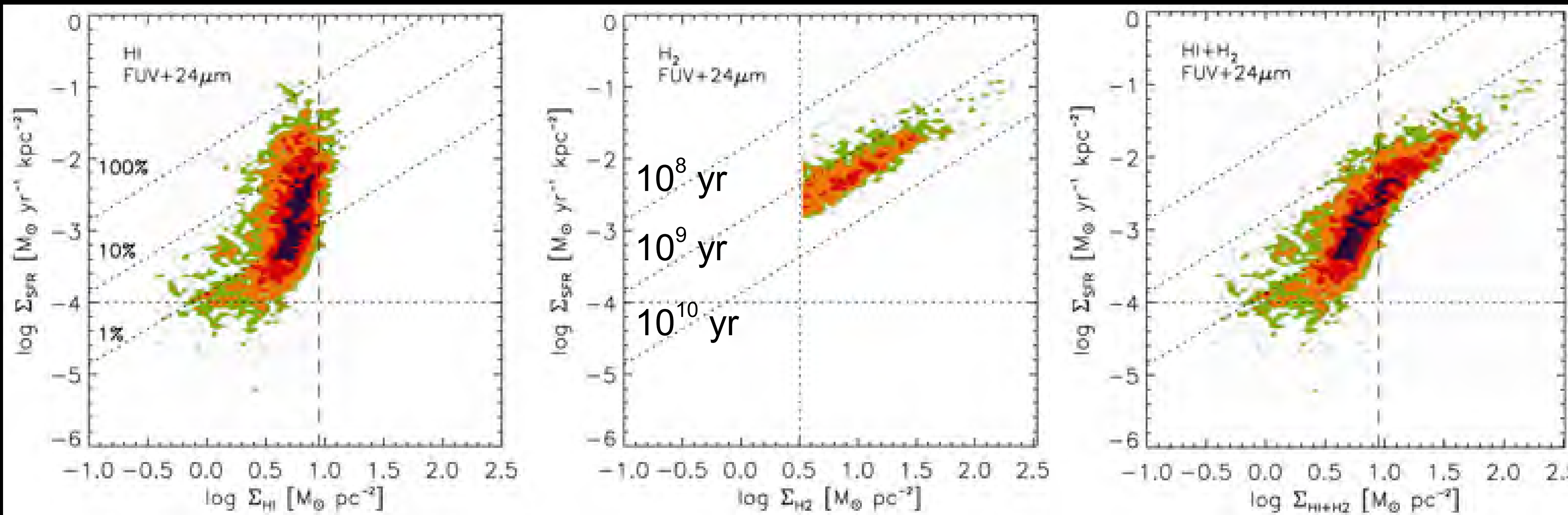


HI CO SFR

Almost all star formation happens within the optical radius

Bigiel et al., AJ, 2008, 136, 2846

What is the best Correlation?

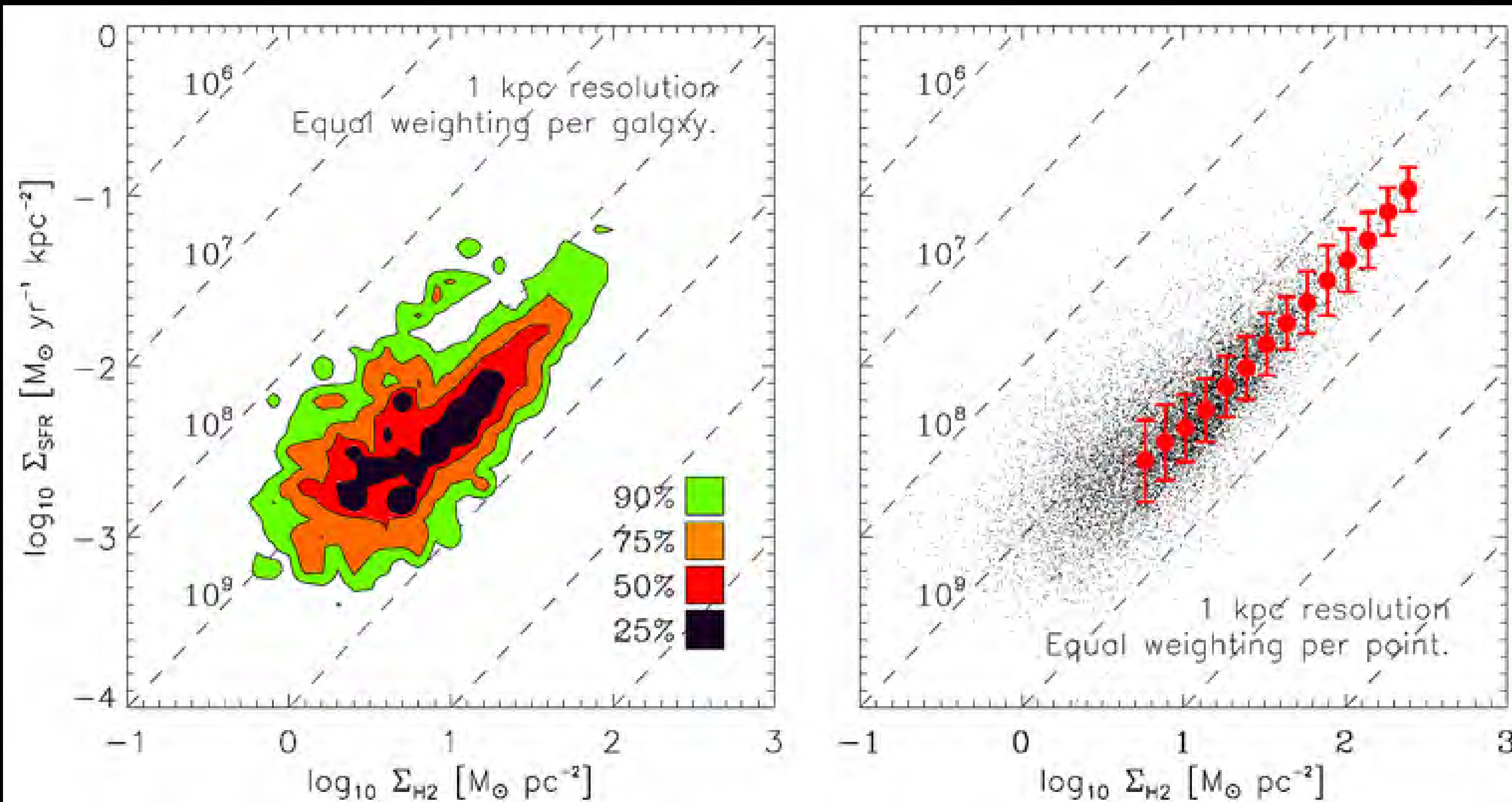


HI | H_2 | $HI+H_2$

$$\Sigma_{\rm SFR} = 10^{-2.1\pm0.2}\Sigma_{\rm H_2}^{1.0\pm0.2}$$

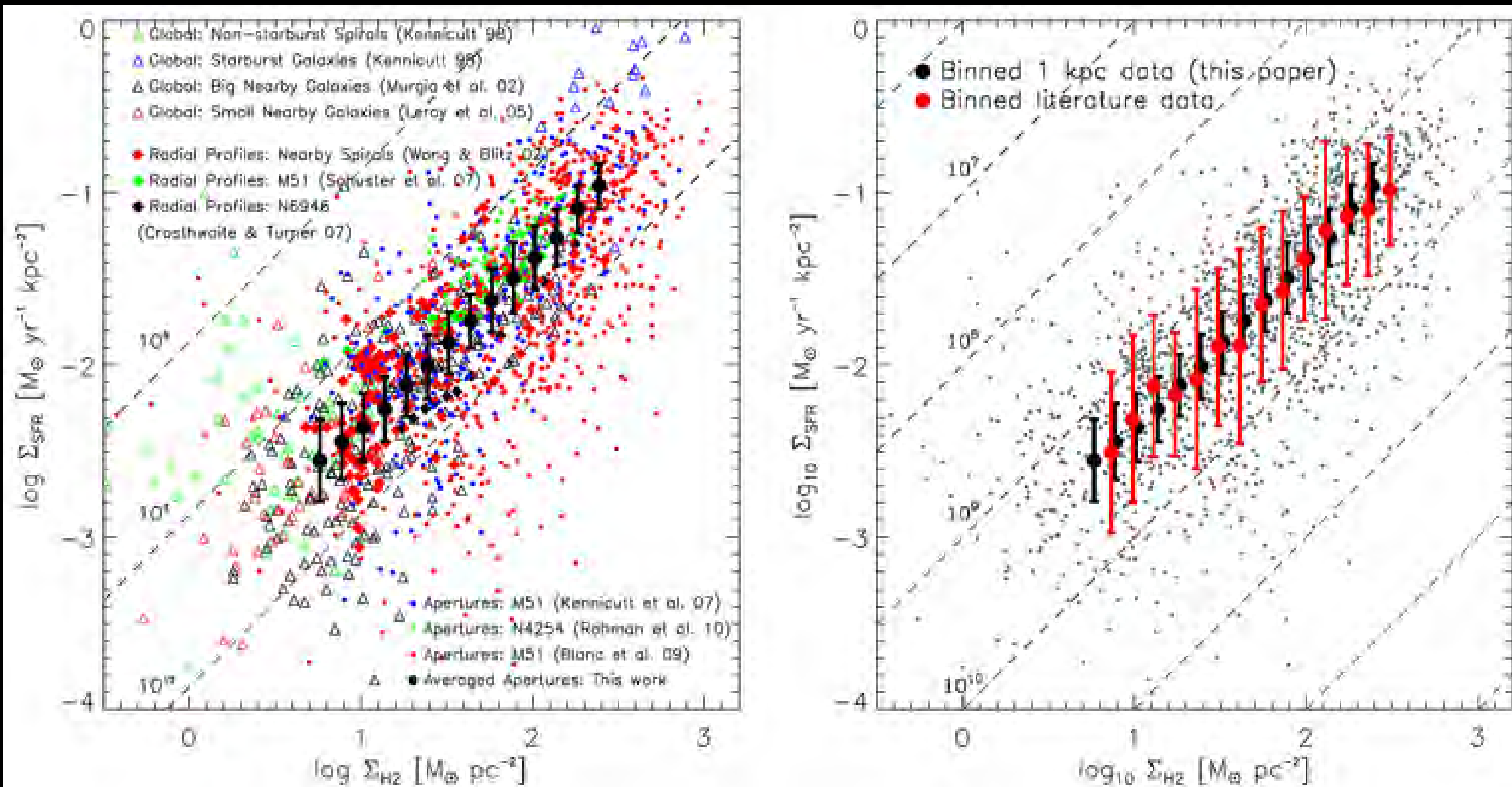
Bigiel et al., AJ, 2008, 136, 2846

Σ_{SFR} - Σ_{H2} Correlation



Bigiel et al., ApJL, 2011, 730, L13

Literature Compilation



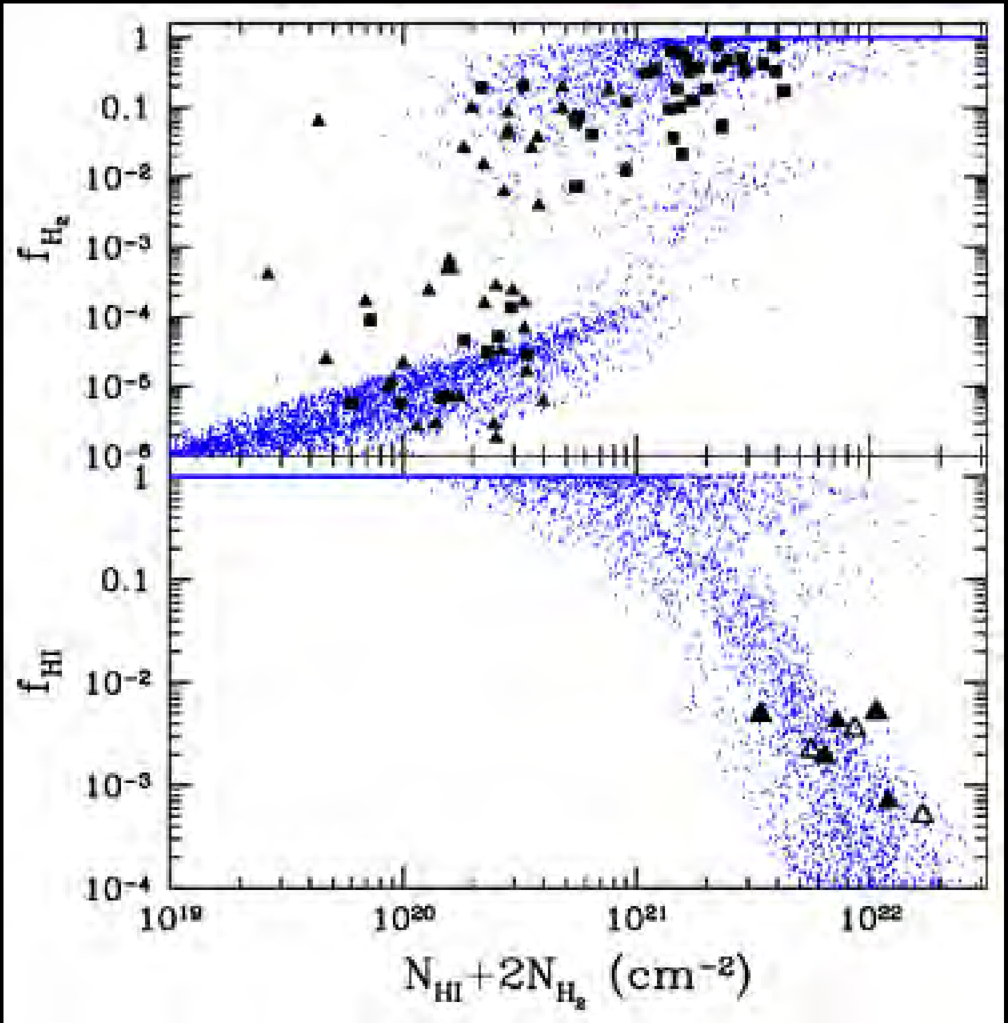
Bigiel et al., ApJL, 2011, 730, L13

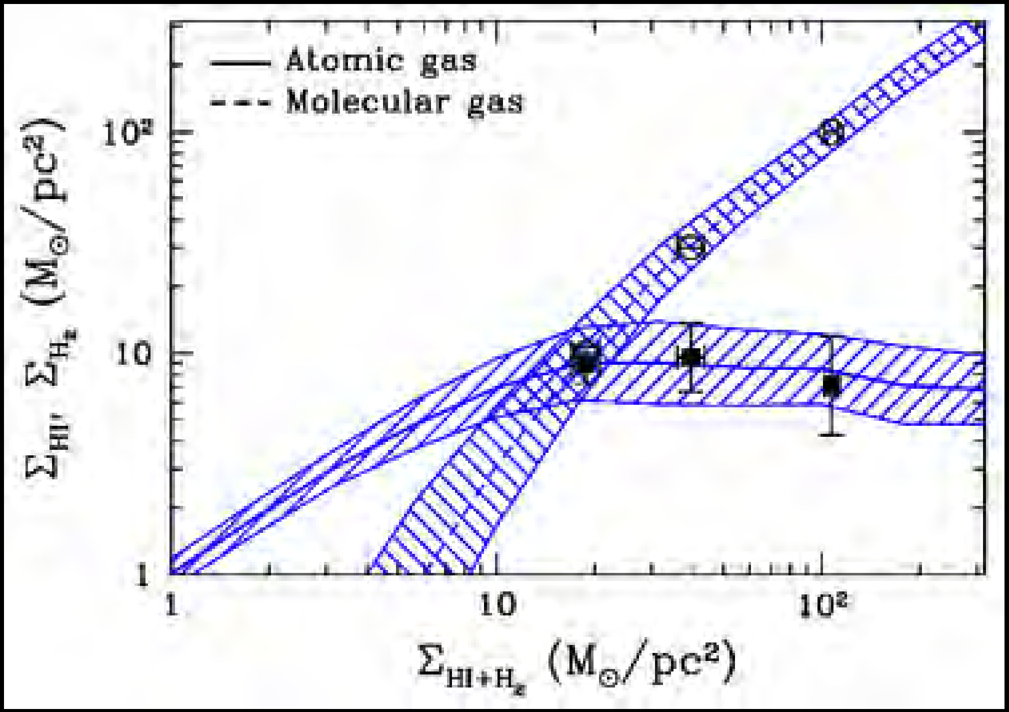
H_2 Formation Model

- Formation of H_2 on dust
- Shielding by dust and H_2
- Requires radiative transfer to get local UV flux
- Requires chemical network $\Rightarrow$ HI, HII, HeI, HeII, HeIII, H_2
- Phenomenological model calibrated by observations

Gnedin & Kravtsov, ApJ, 2011, 728, 88

Model Calibration





Gnedin & Kravtsov, ApJ, 2011, 728, 88

Molecular Star Formation Recipe

$$\dot{\rho}_* = \epsilon_{\rm ff} \frac{\rho_{\rm H_2}}{\tau_{\rm sf}}$$

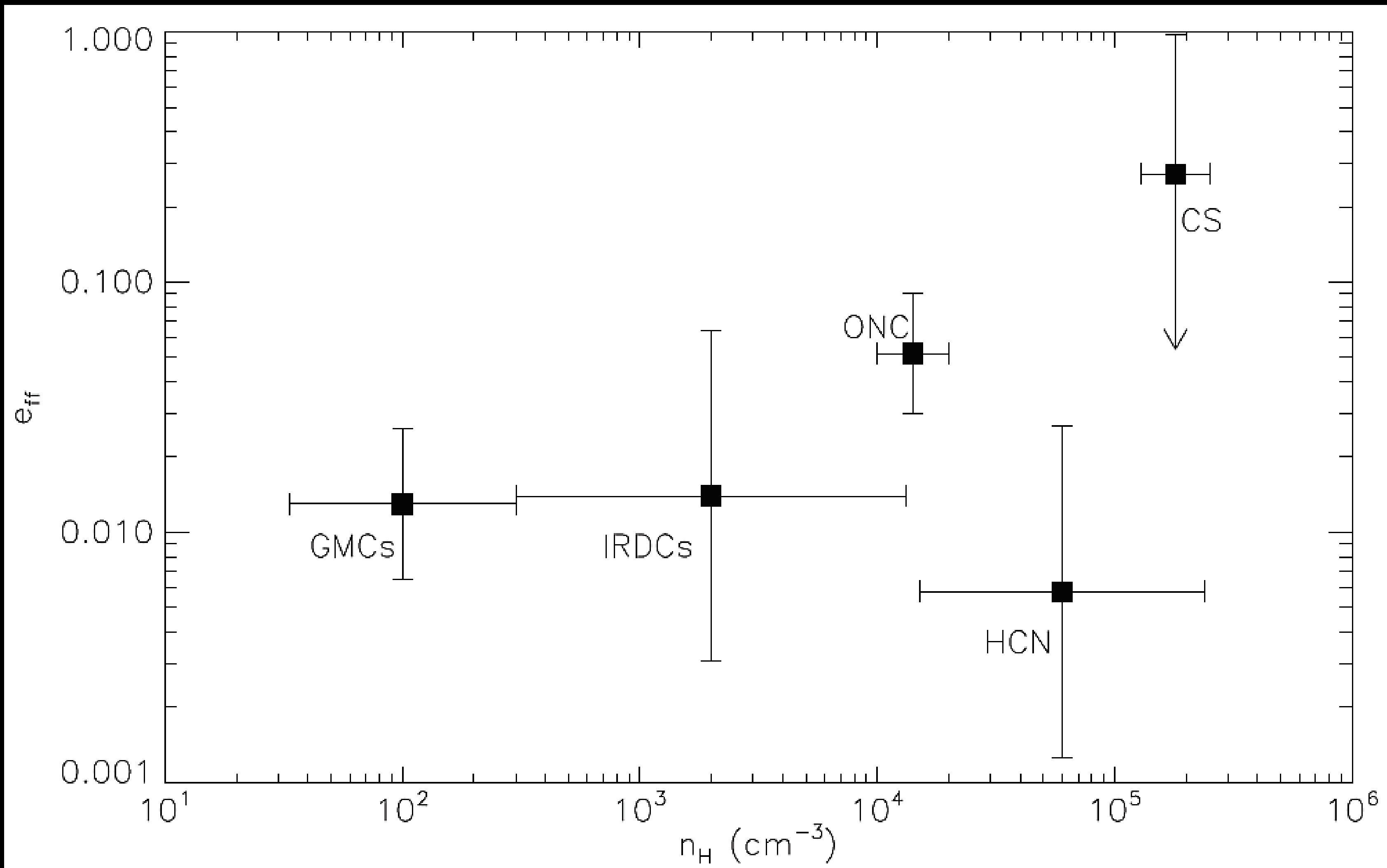
$$\tau_{\rm sf} = \min(\tau_{\rm ff}(\rho_{\rm gas}), \tau_{\rm ff}(\rho_{\rm ff,min}))$$

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

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

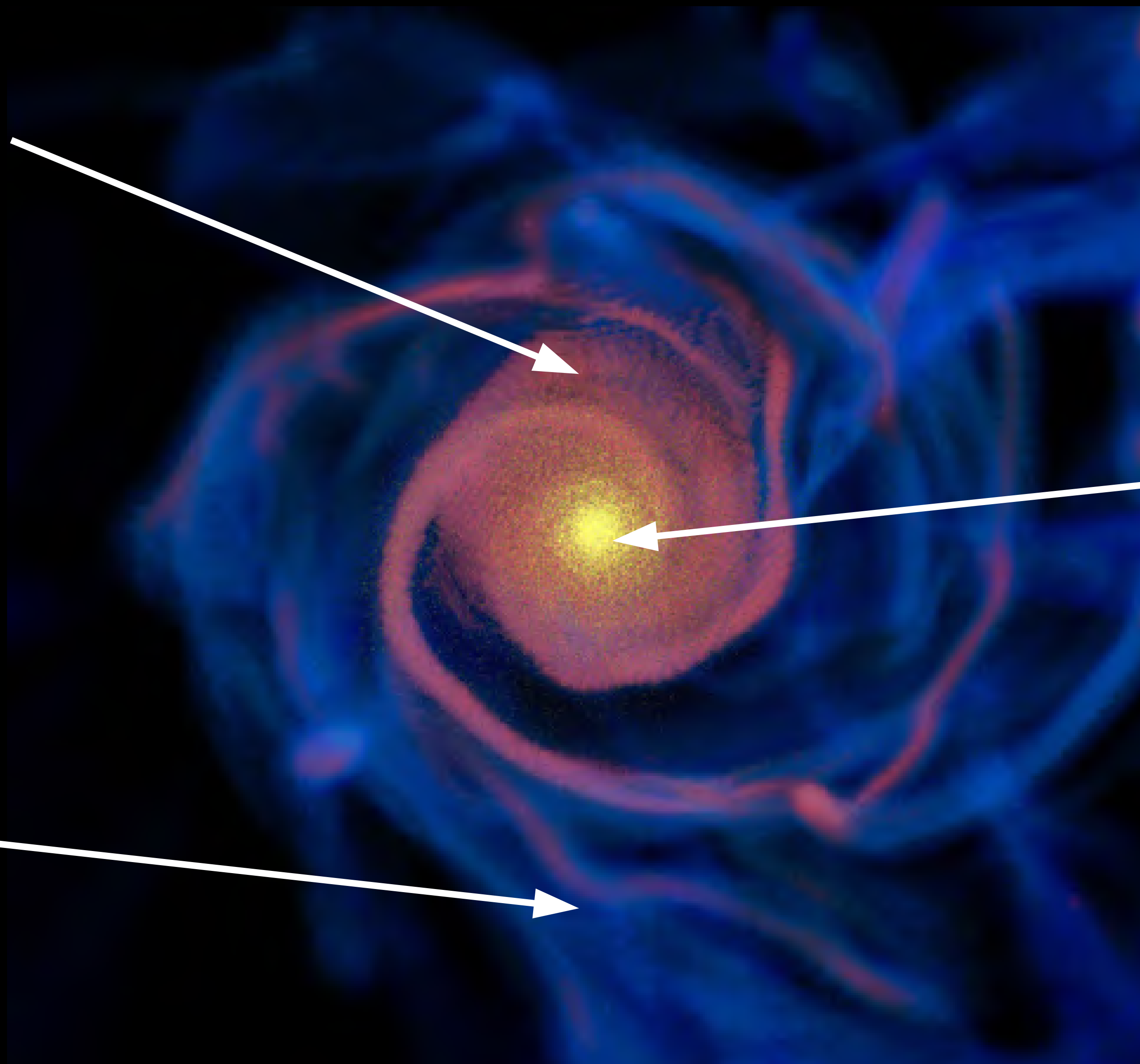
Gnedin et al., ApJ, 2009, 697, 55
Gnedin & Kravtsov, ApJ, 2011, 728, 88

Star Formation Efficiency



Krumholz, Star Formation in Molecular Clouds, 2011

Disc Galaxy



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

Resolution

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

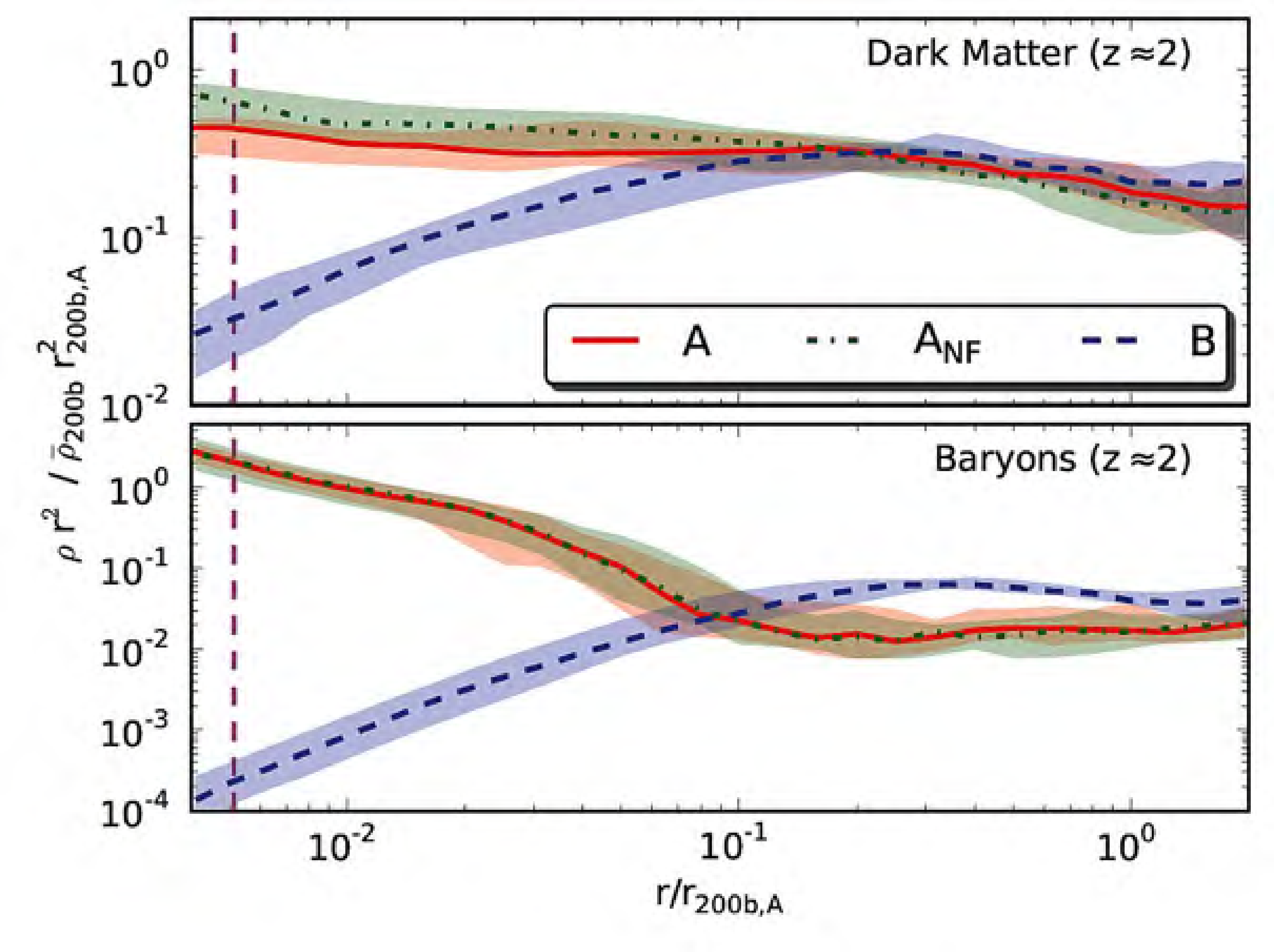
Median Properties

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

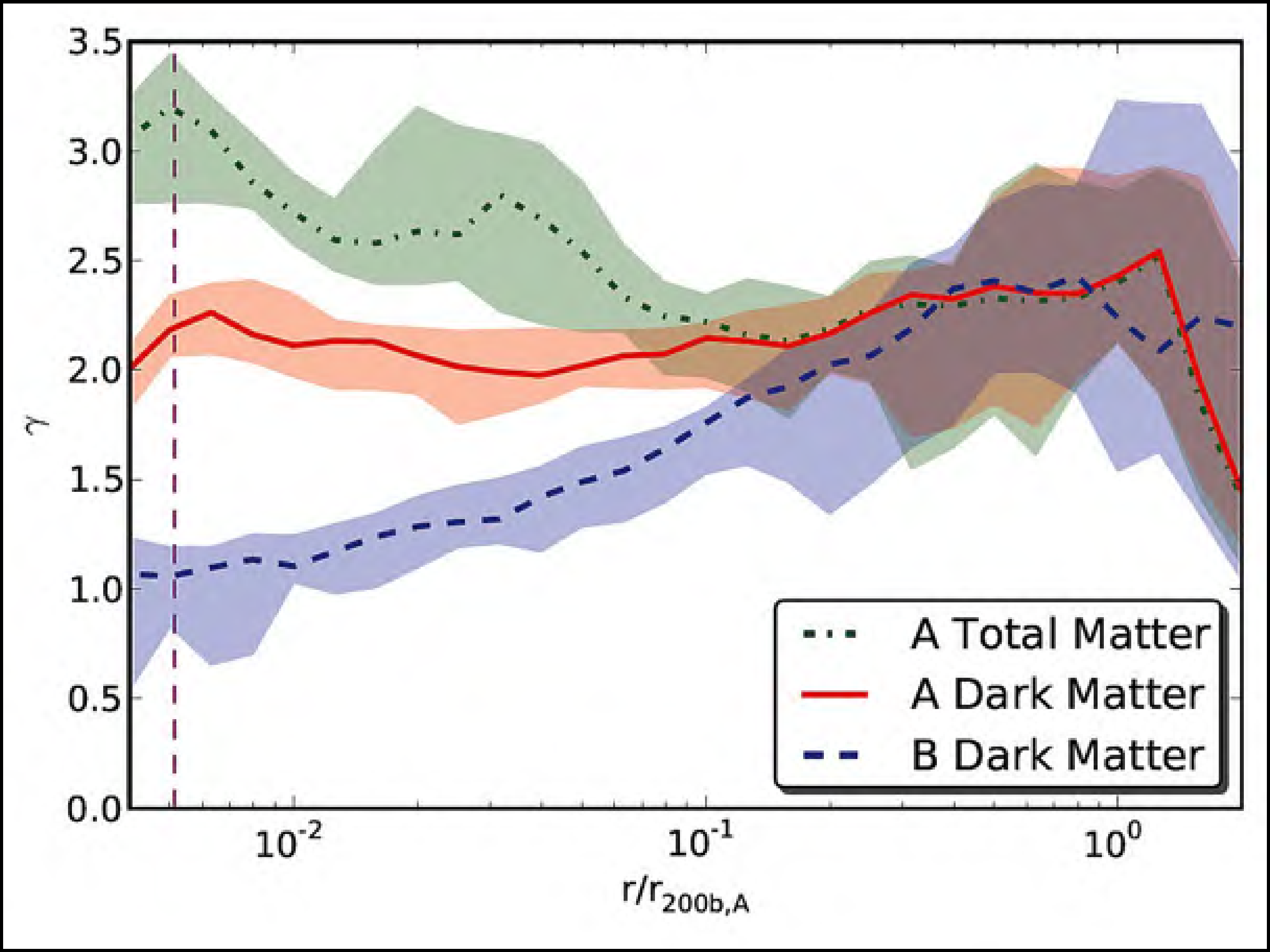
$$\Rightarrow \frac{M_{200b}}{4\pi r_{200b}^3/3} = 200\rho_b$$

- 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

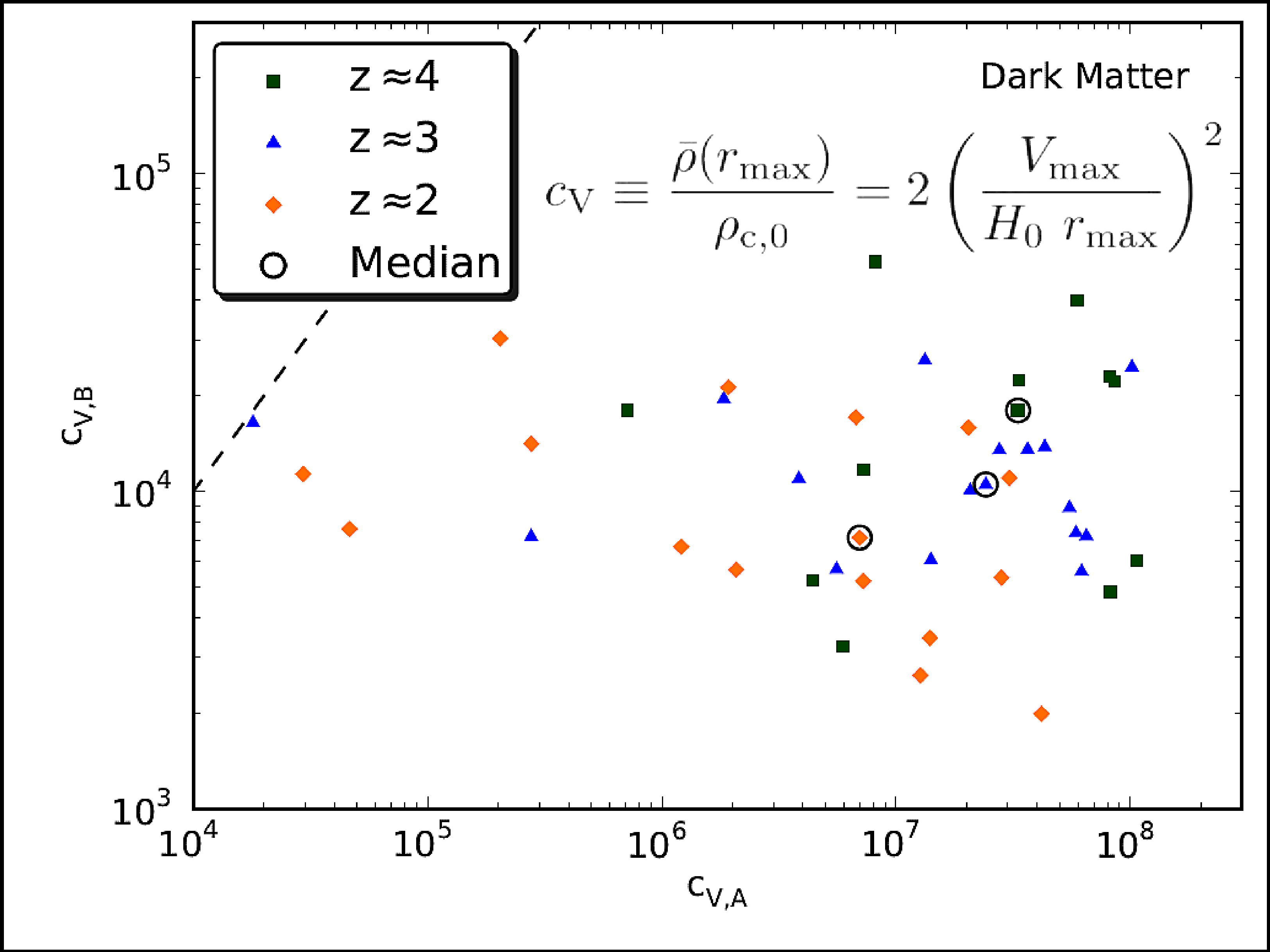
Mass Density



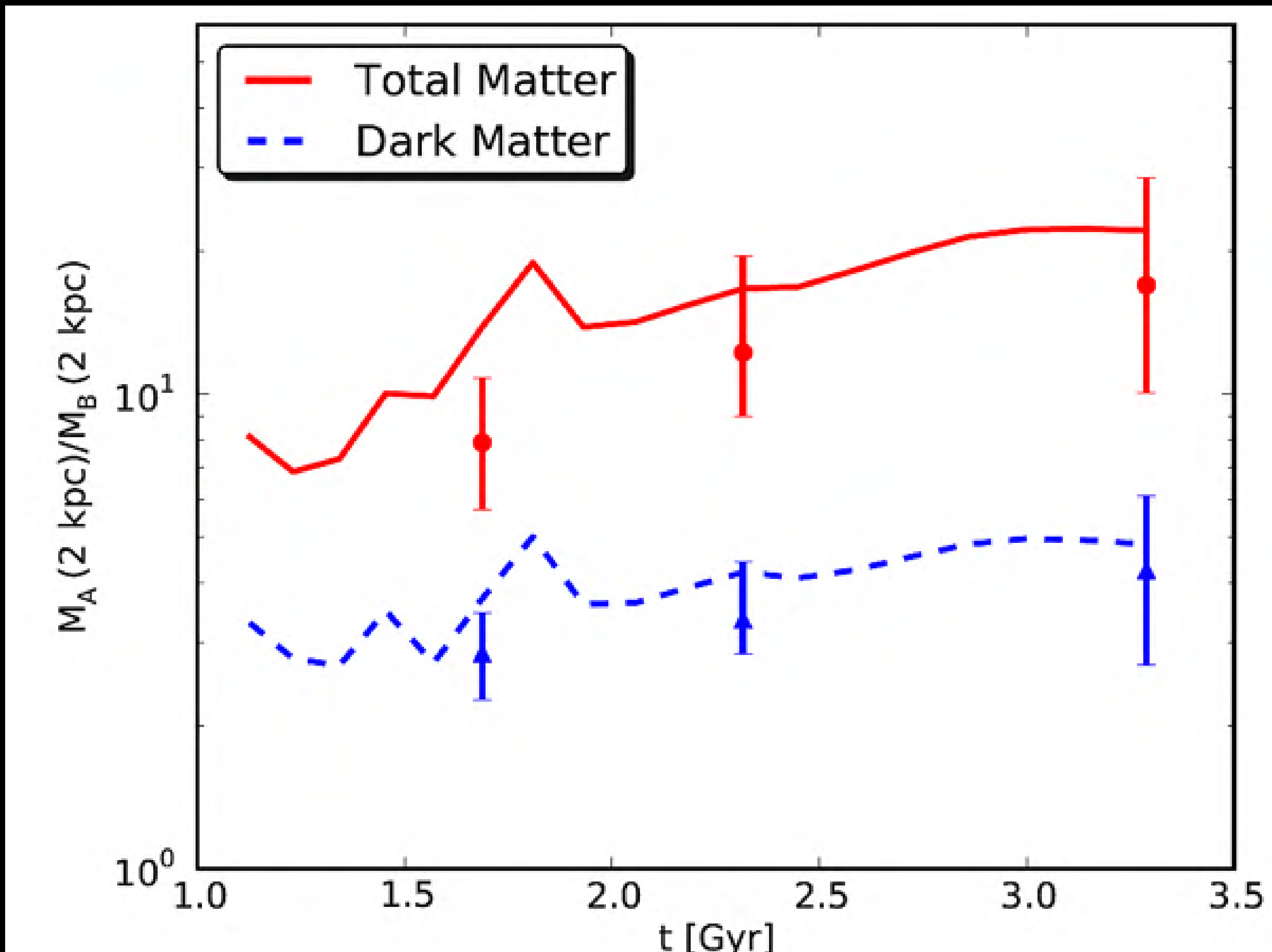
Mass Density Slope



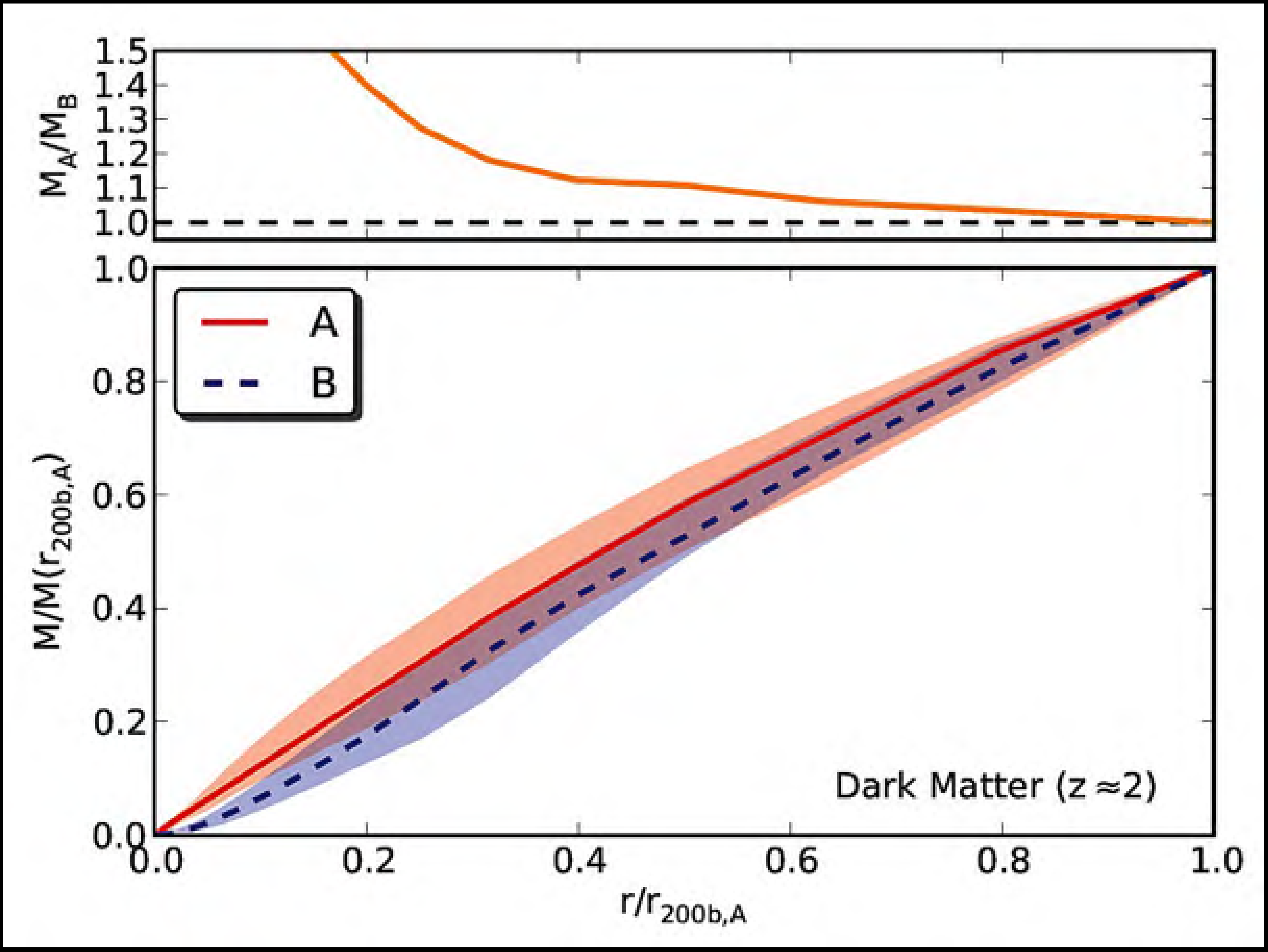
Concentration



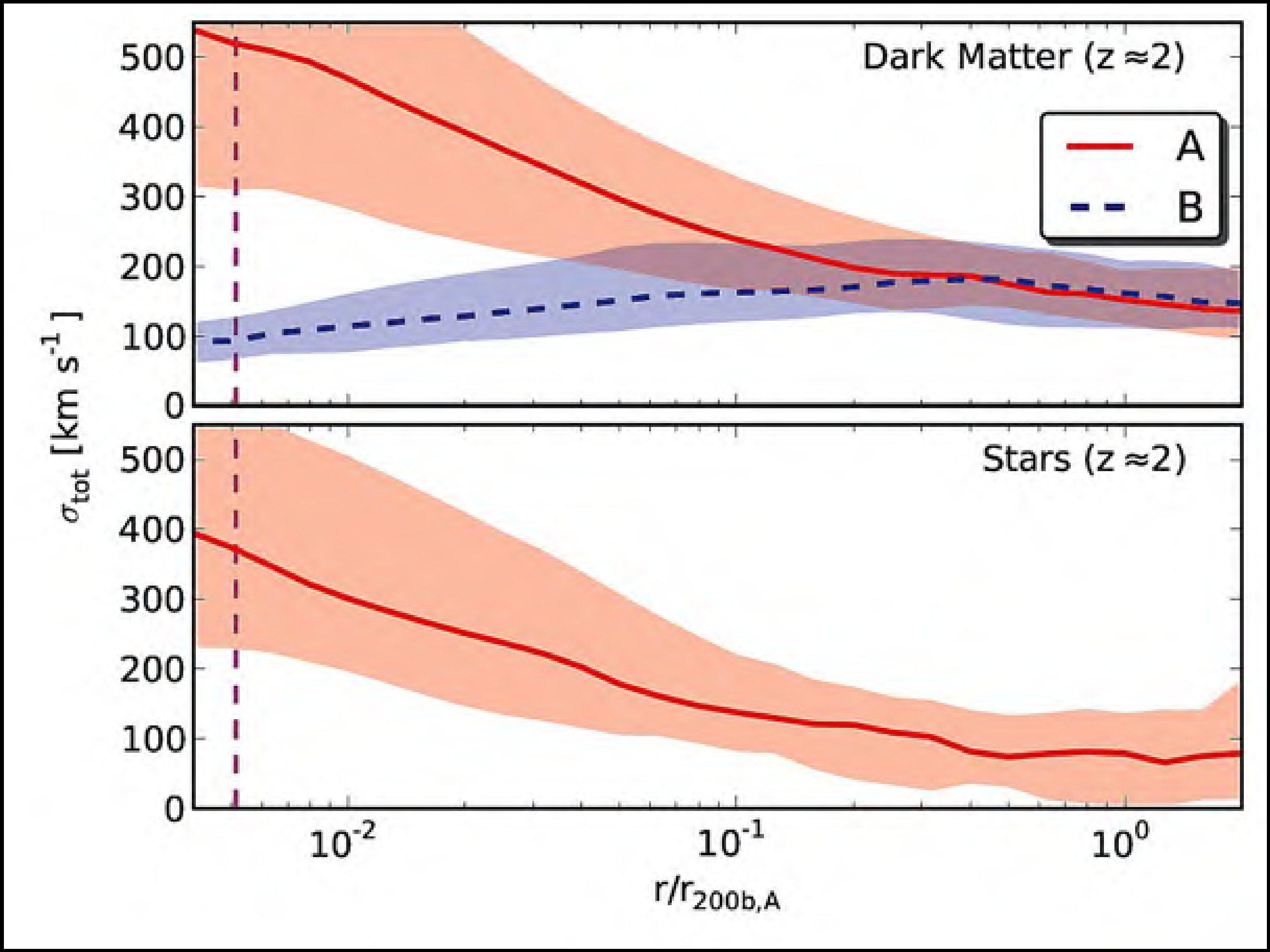
Enclosed Mass



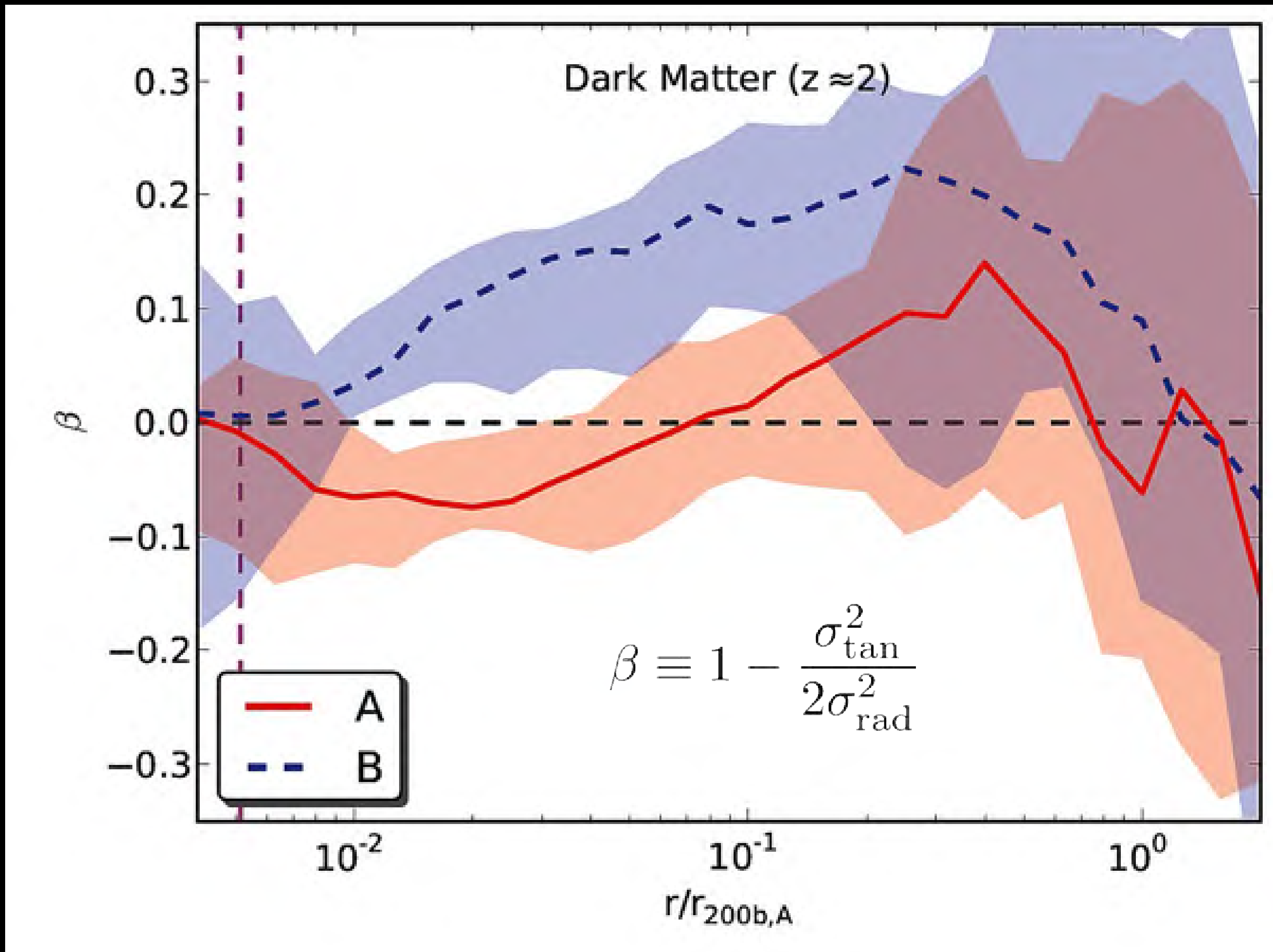
Halo Contraction



Velocity Dispersion

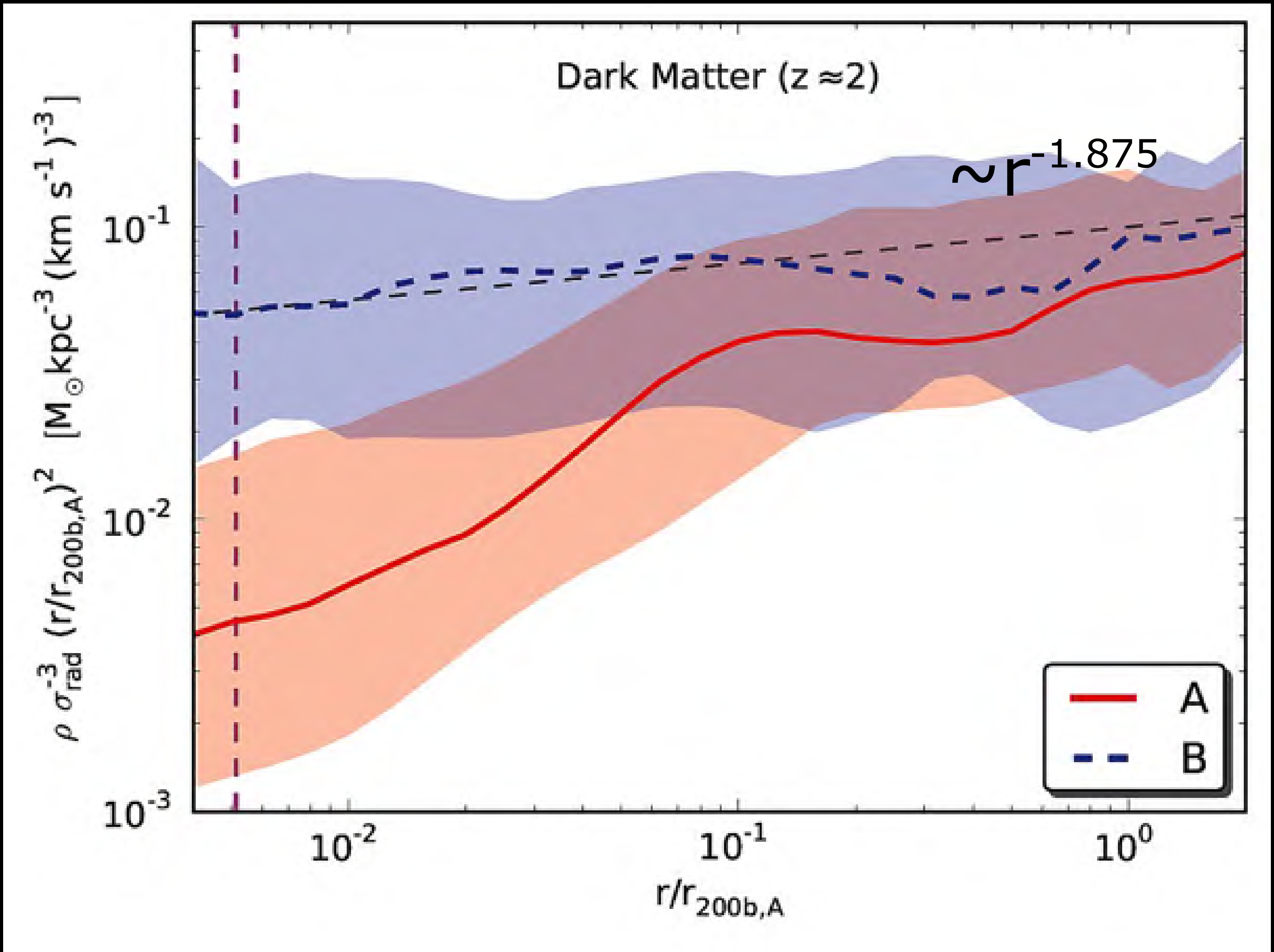


Anisotropy



Dark Matter (z ≈2)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
β
10^{-2}
10^{-1}
10^{0}
$r/r_{200b,A}$
$\beta \equiv 1 - \frac{\sigma_{\tan}^2}{2\sigma_{\rm rad}^2}$
A
B

Pseudo Phase-Space Density



Shape Determination

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

Summation over particles in shells!
Iteration ⇒ 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

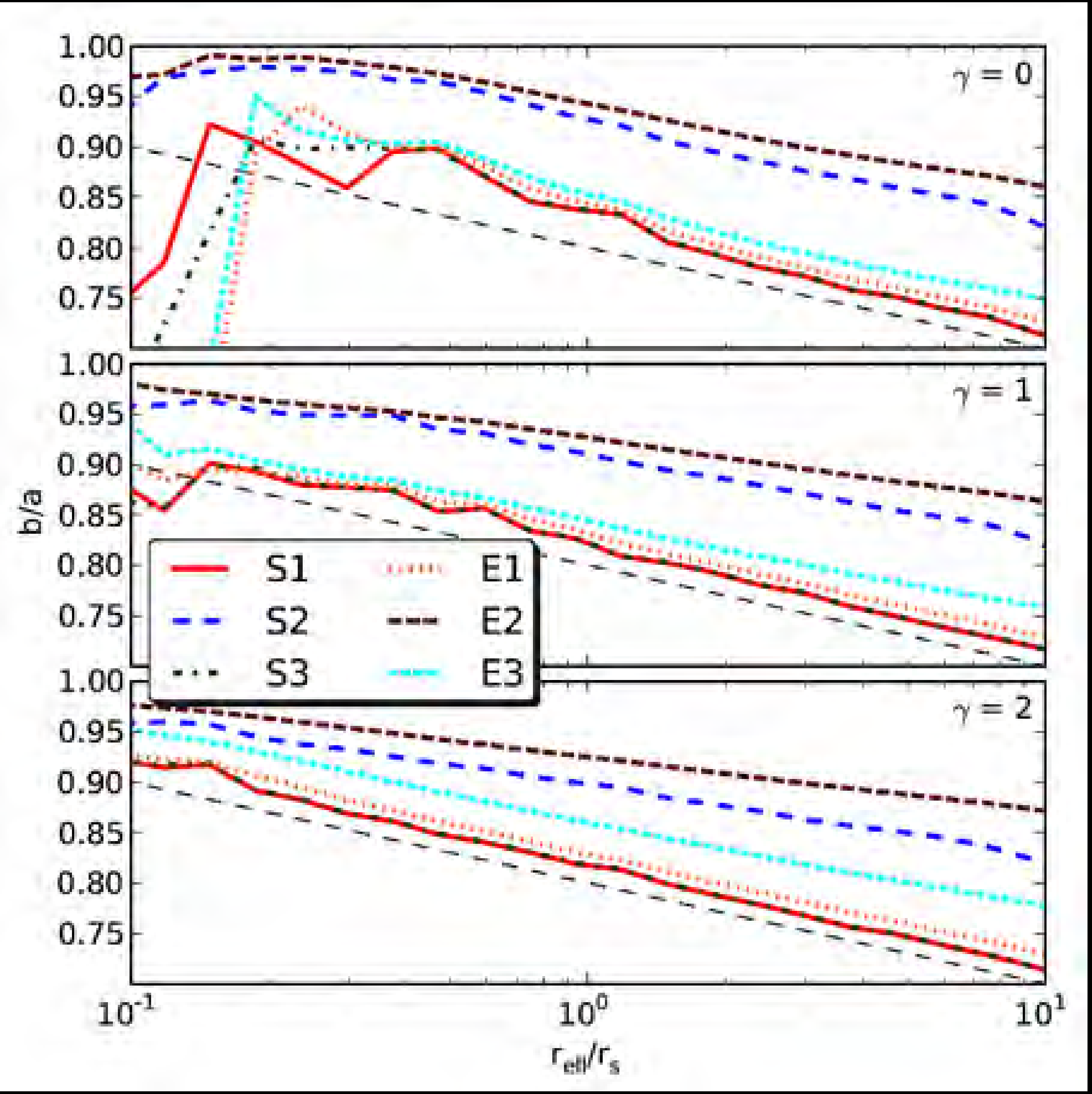
Shape Determination Methods

$$S = \frac{\int_V \rho(\boldsymbol{r}) w(\boldsymbol{r}) \boldsymbol{r}\boldsymbol{r}^T \mathrm{d}V}{\int_V \rho(\boldsymbol{r}) \mathrm{d}V}$$

Method	$w(\boldsymbol{r})$	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

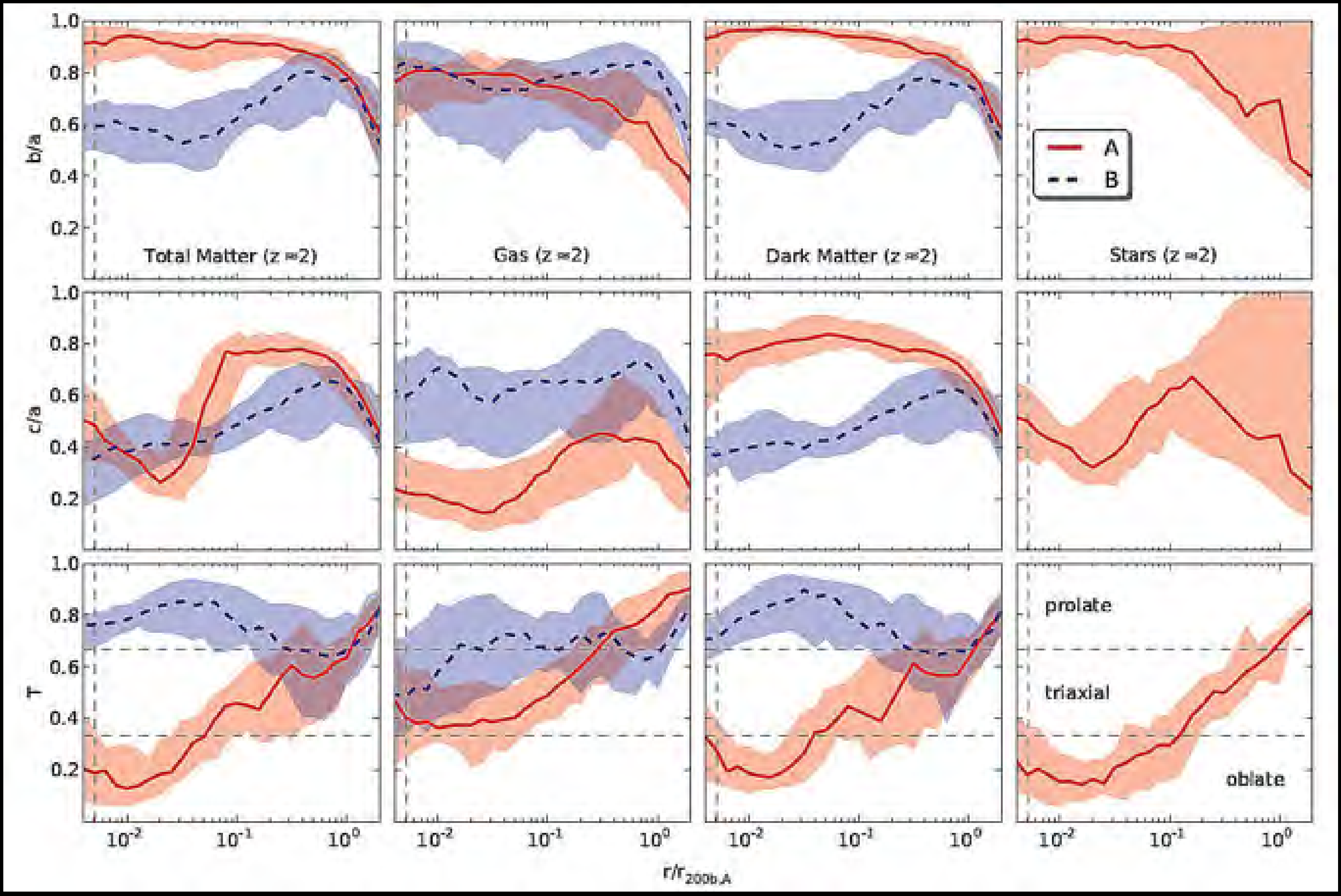
Zemp et al., ApJS, 2011, 197, 30

Shape Determination Bias

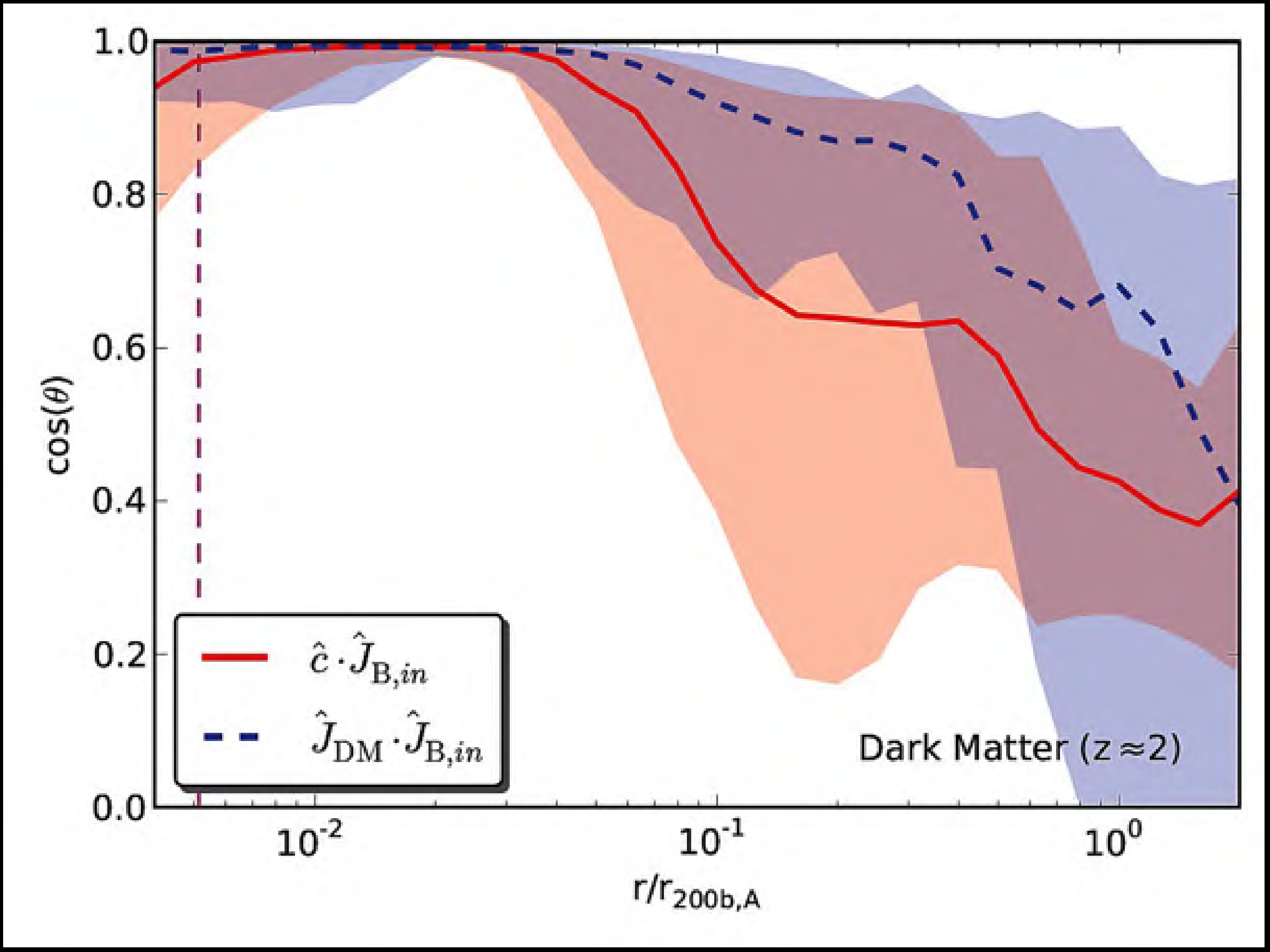


Zemp et al., ApJS, 2011, 197, 30

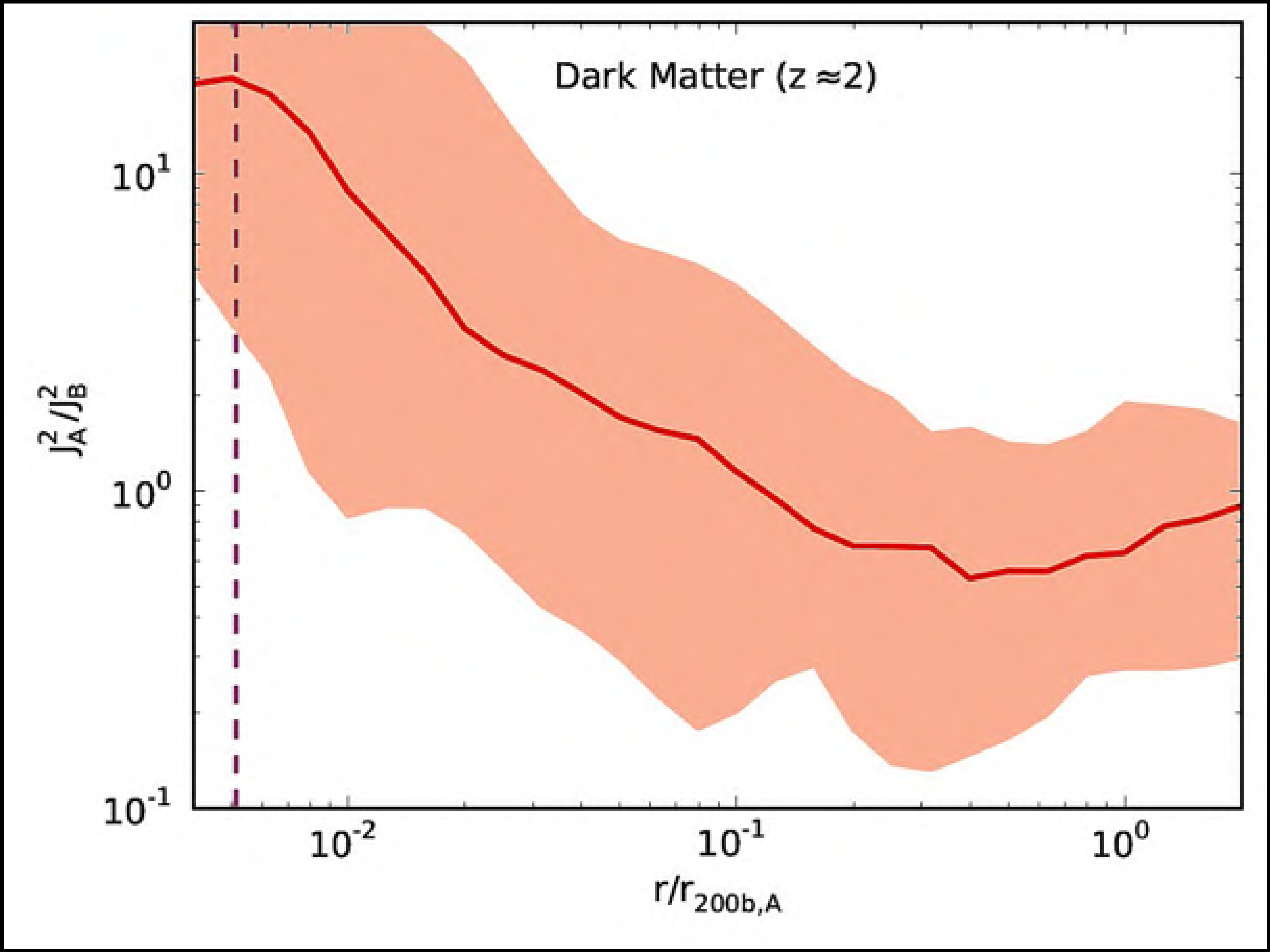
Shape


b/a
c/a
T
Total Matter (z ≈2)
Gas (z ≈2)
Dark Matter (z ≈2)
Stars (z ≈2)
A
B
prolate
triaxial
oblate
r/r200b,A

Twisting of the Halo



Angular Momentum Transfer



Summary

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