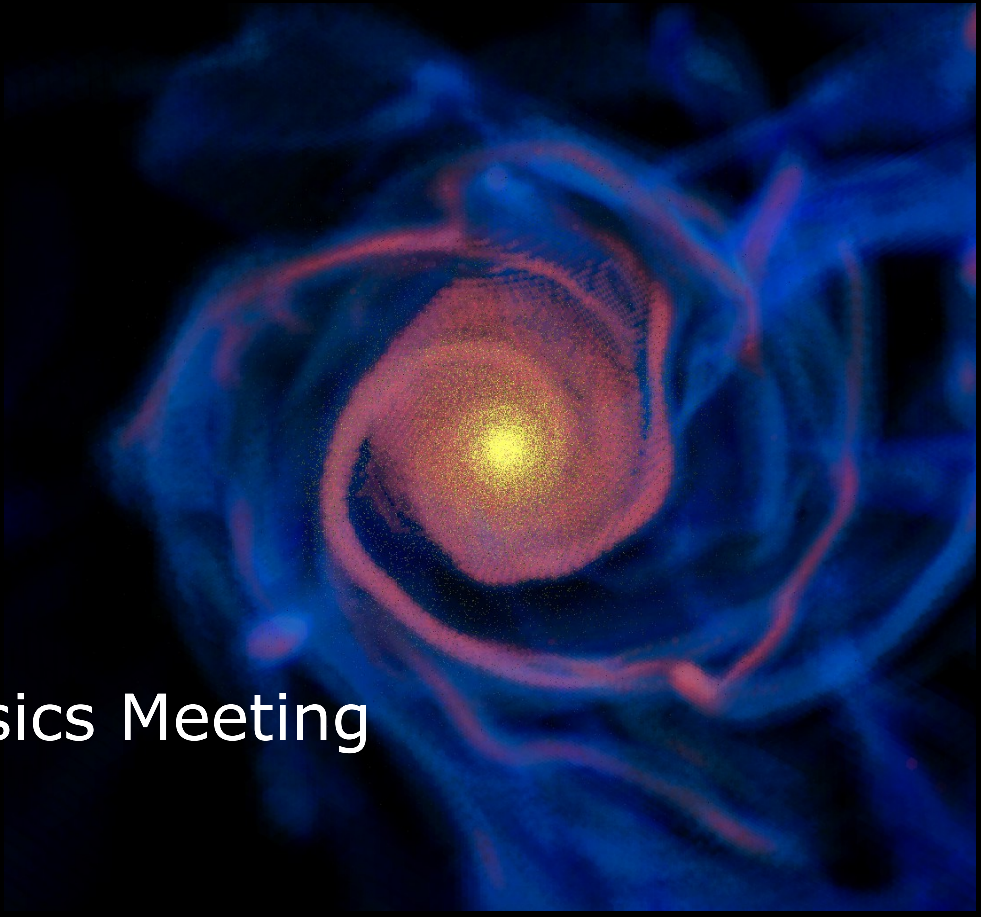
Molecular Hydrogen based Star Formation



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A Long, Long Time Ago…

However if we knew the true functional form of $\mathcal{R}$ 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 $\mathcal{R} = C\,\rho^2$.

Lynden-Bell, On why we need a good theory of star formation, 1977, 75, 291

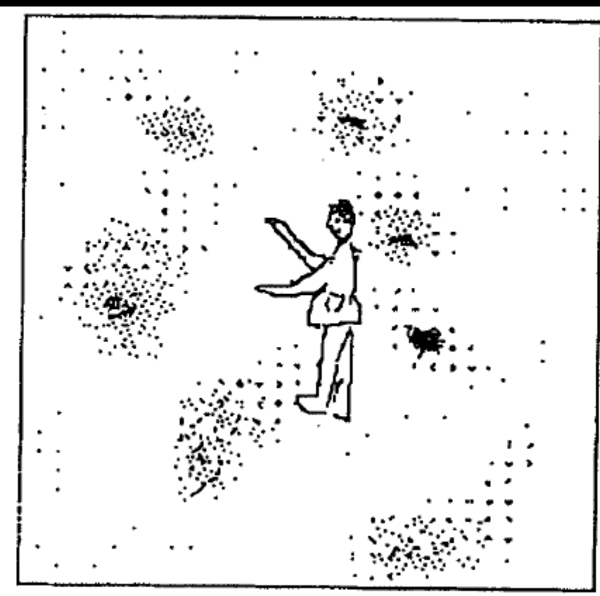


Figure 4. Expert guiding evolution of gas in an N-body code

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

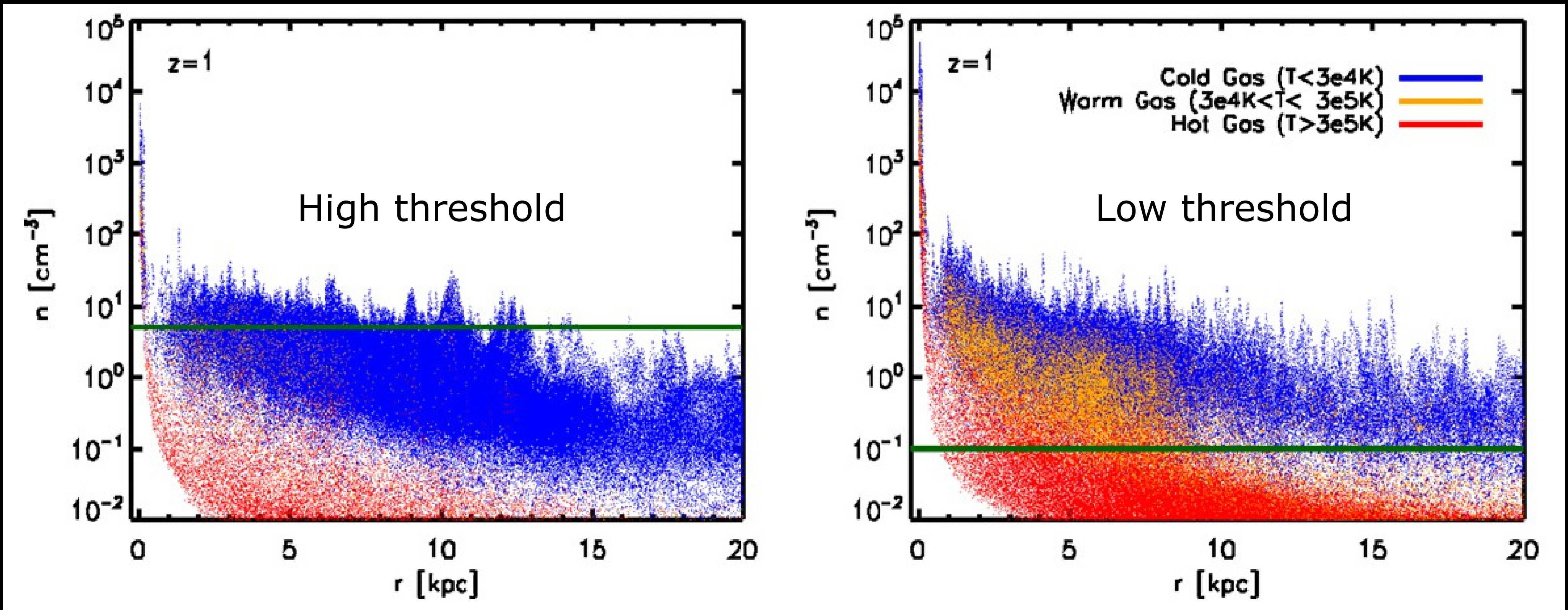
Kennicutt, ApJ, 1998, 498, 541
Schmidt, ApJ, 1959, 129, 243

General Star Formation Recipe

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

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

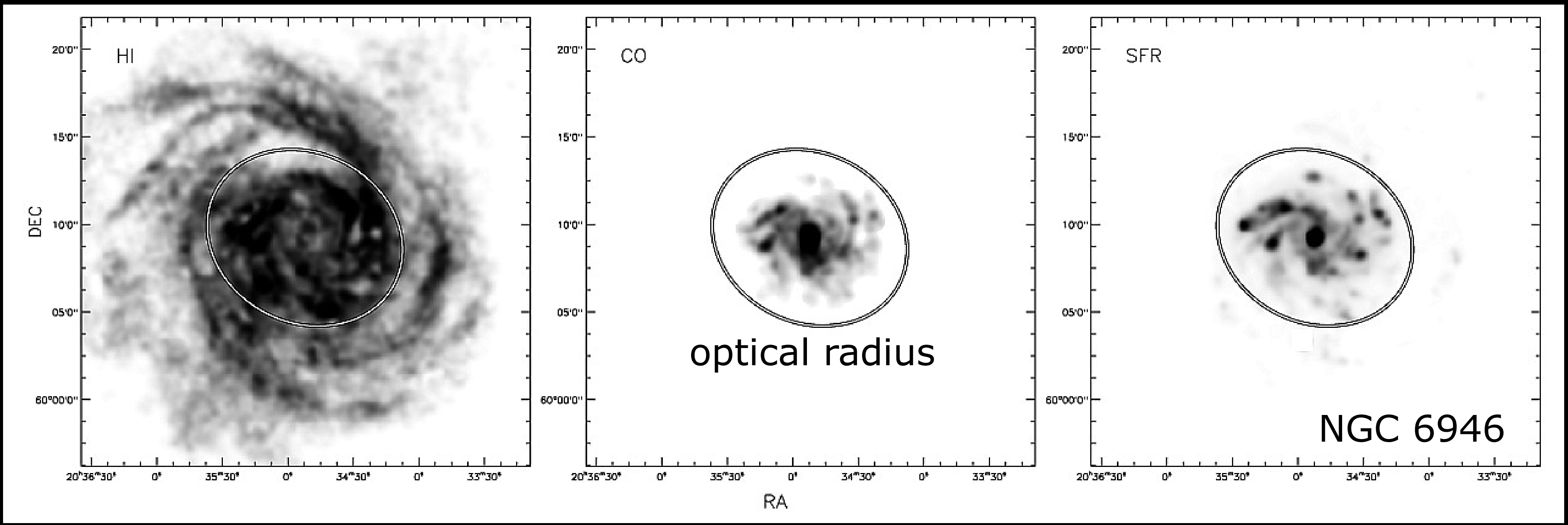
Fine-Tuning ⇒ Convergence?



The state of the gas is very sensitive to the (numerical) star formation density threshold!

Guedes et al., ApJ, 2011, 742, 76

Where do Stars form?

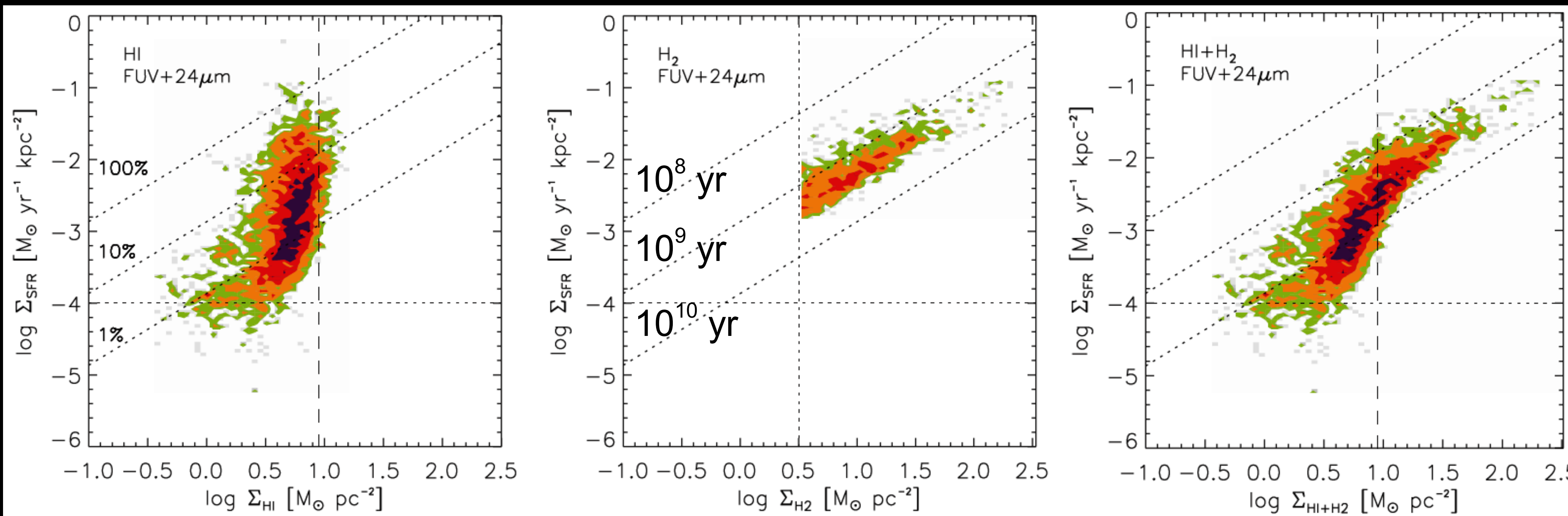


HI CO SFR

Almost all star formation happens within the optical radius

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

What is the best Correlation?

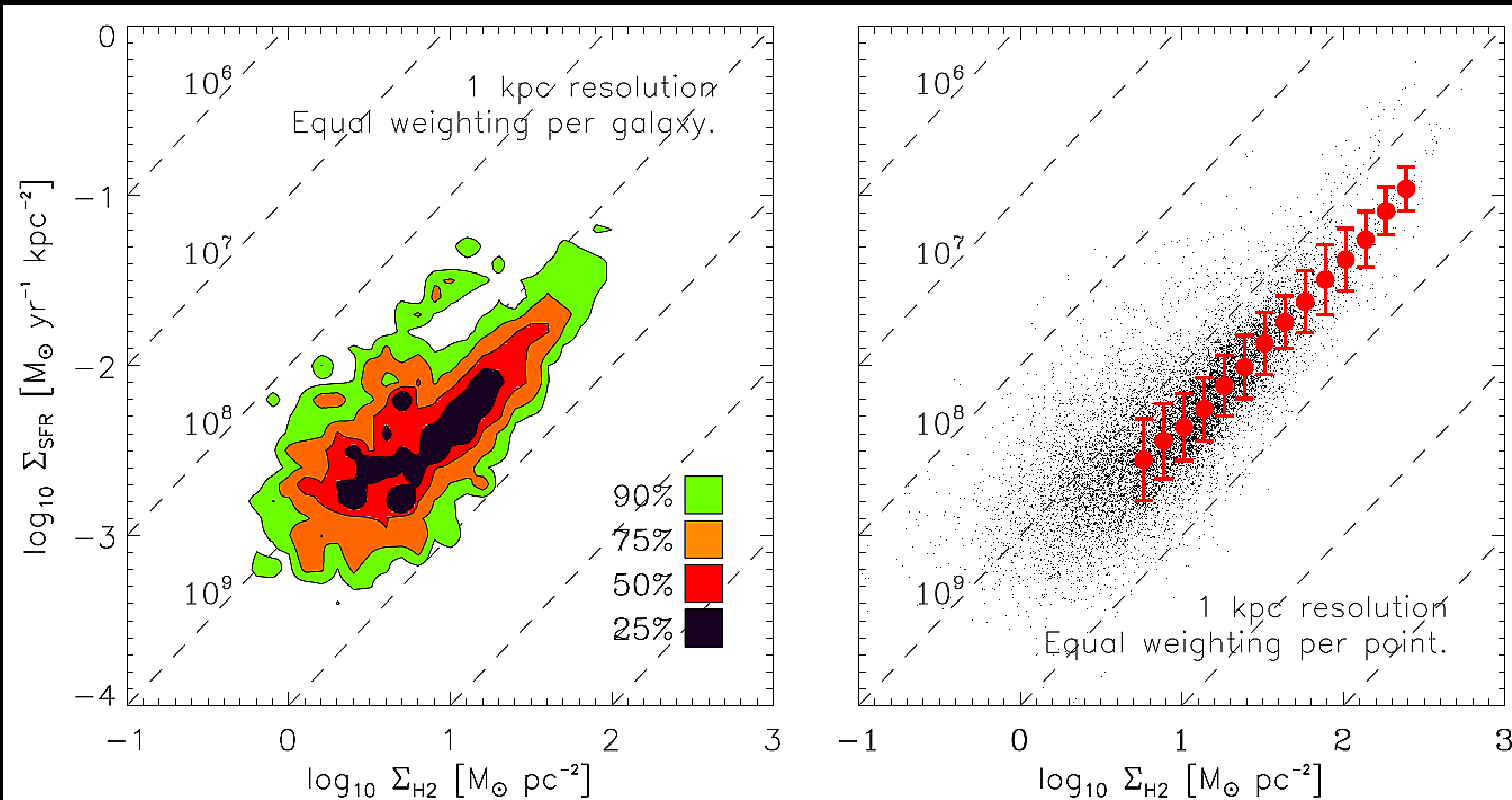


HI | H_2 | $HI+H_2$

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

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

Σ_{SFR} - Σ_{H2} Correlation



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

First take-home Message

- The star formation rate surface density correlates best with the surface density of molecular hydrogen

$$\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{H_2}}$$

- This can be used in simulations in order to implement an observationally motivated star formation prescription
  $\Rightarrow$ no numerical threshold parameters!

H_2 Formation Model in ART

- 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

Molecular Star Formation Recipe

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

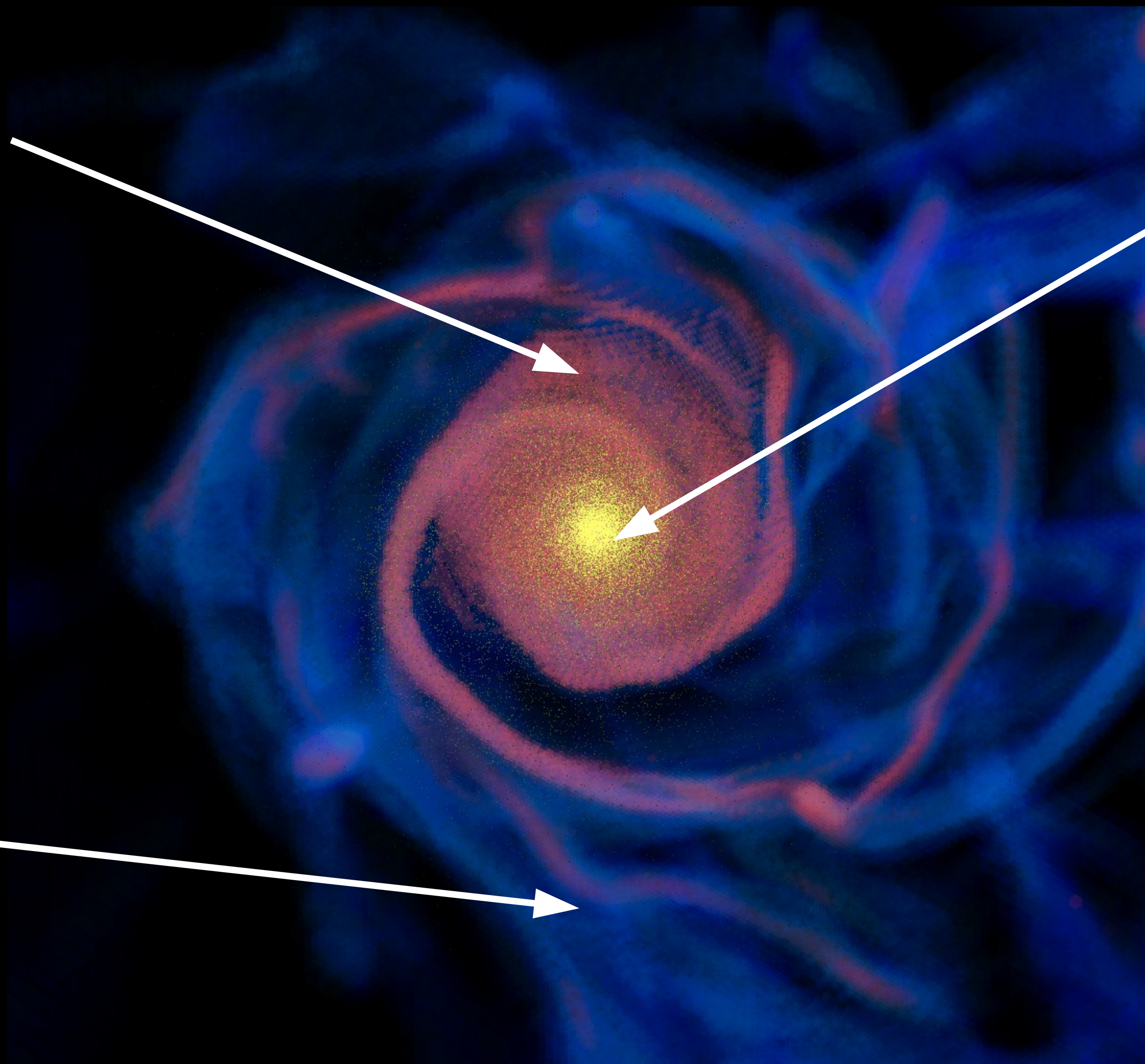
$$\tau_{\rm sf} = \min(\tau_{\rm ff}(\rho_{\rm gas}), \tau_{\rm ff}(\rho_{\rm ff,min}))$$

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

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

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

Disc Galaxy



molecular Hydrogen with 50-10^4 amu cm$^{-3$}
stars
neutral gas
z=3
≈14 kpc
Zemp et al., ApJ, 2012, 748, 54

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

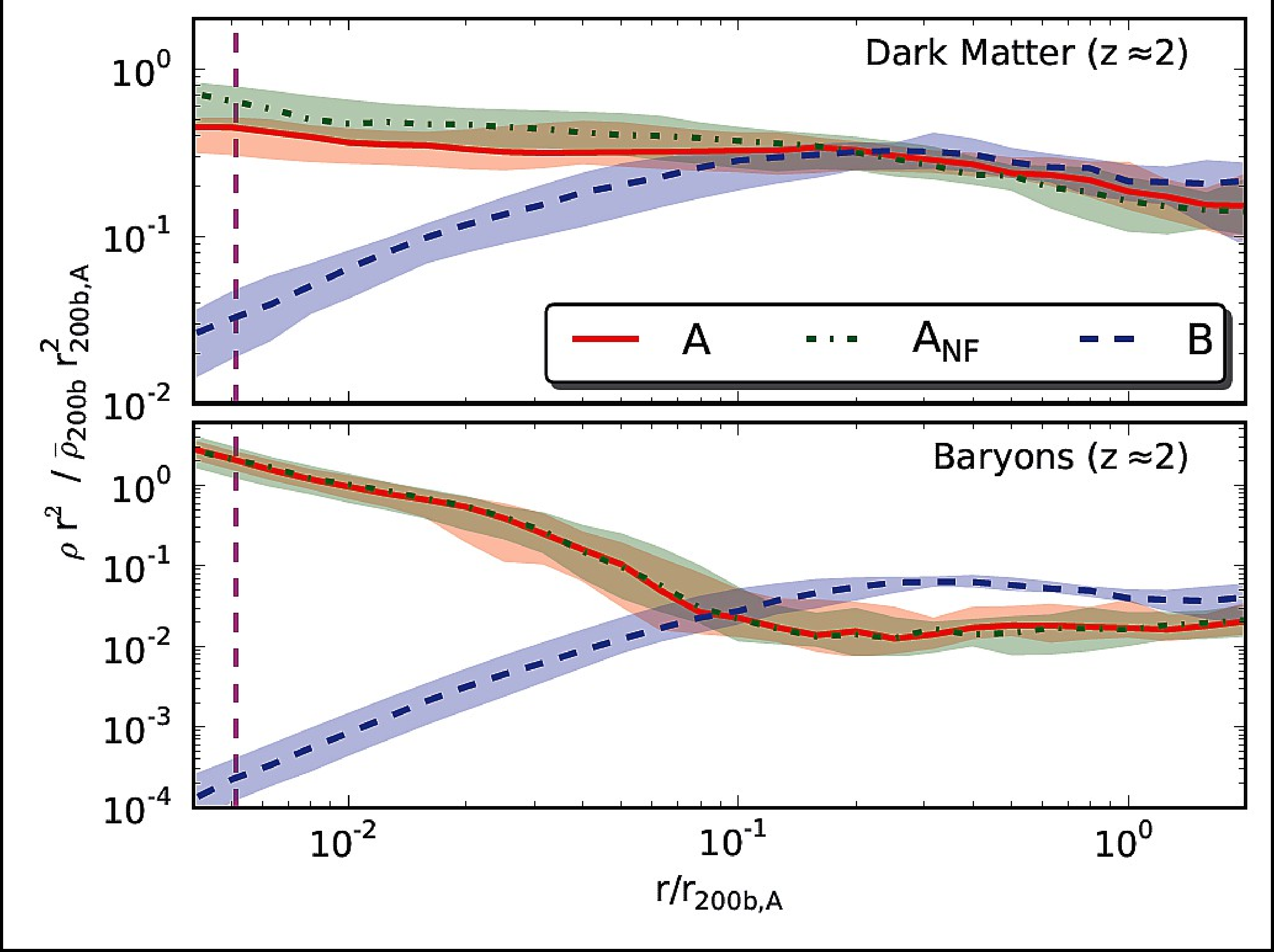
Simulation Setup

- 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: $\delta_{DC,0} = 0.571$
- Refined 7 objects at $z = 0$ with mass $\approx 10^{12}\ M_{solar}$

Resolution

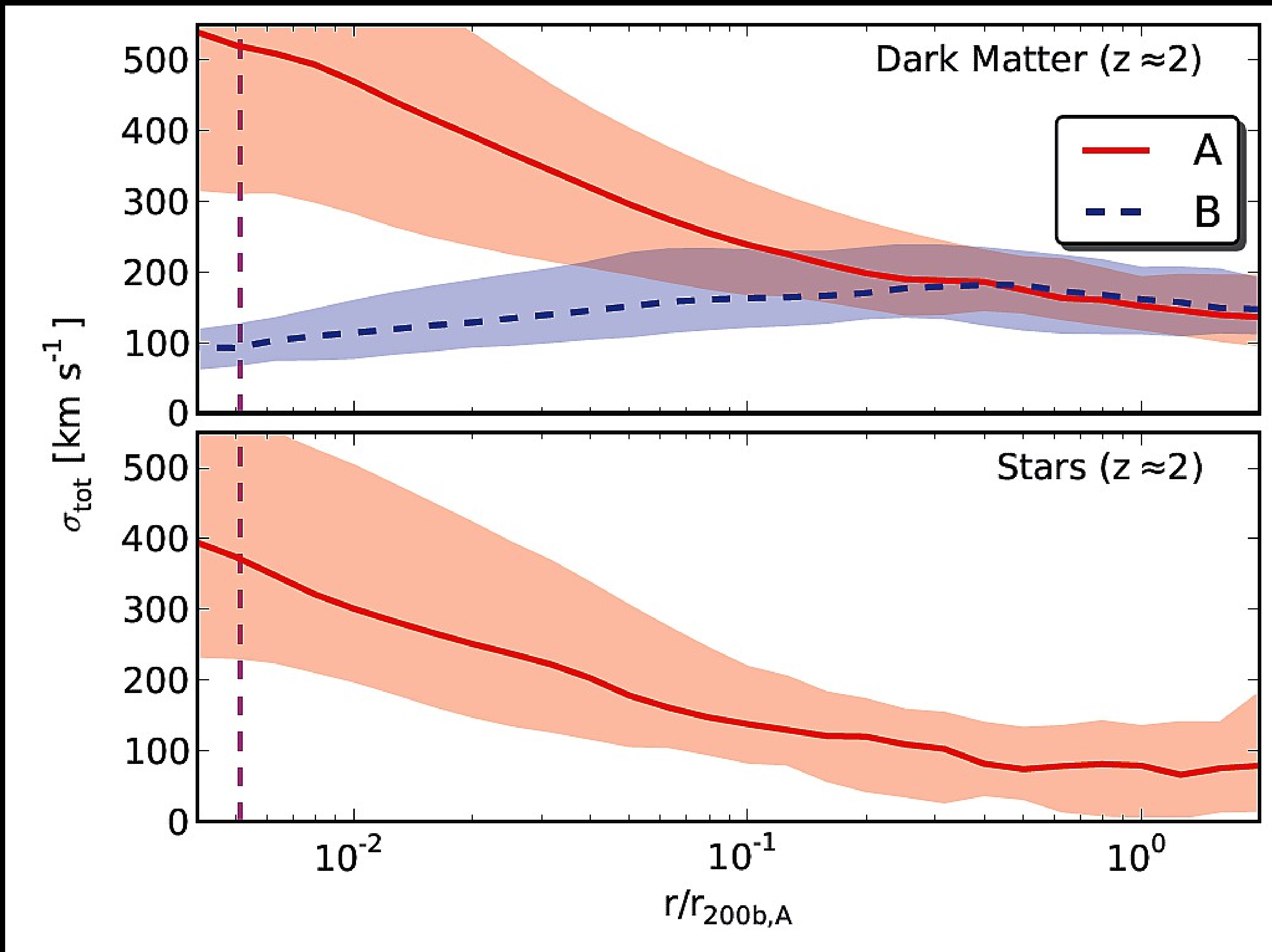
- Adaptive mesh refinement
  $\Rightarrow$ base grid: $(2^8)^3 = 256^3$
  $\Rightarrow$ dark matter: $(2^{11})^3 = 2048^3$
  $\Rightarrow$ gas: $(2^{17})^3 = 131072^3$
- Smallest mesh size: L_9 = 280 pc (comoving)
  $\Rightarrow$ Resolution: 4 L_9 = 1.12 kpc (comoving)
- Number of particles / cells:
  $\Rightarrow$ dark matter: 2.89×10^8 / $1.81\times10^5\ M_{solar}$
  $\Rightarrow$ gas: 3.89×10^8 (at $z = 2$)
- Data size $\Rightarrow$ 1 snapshot ca. 45 GB

Mass Density



Zemp et al., ApJ, 2012, 748, 54

Velocity Dispersion



Zemp et al., ApJ, 2012, 748, 54

Summary

- Simulations with an observationally motivated star formation prescription based on molecular hydrogen
$\Rightarrow$ no numerical threshold parameters!
- Baryons can greatly affect the overall structure of the matter distribution
$\Rightarrow$ contraction, velocity dispersion, angular momentum, anisotropy, shape, orientation
- Still major uncertainties in the modelling of baryons (i.e. feedback and star formation)