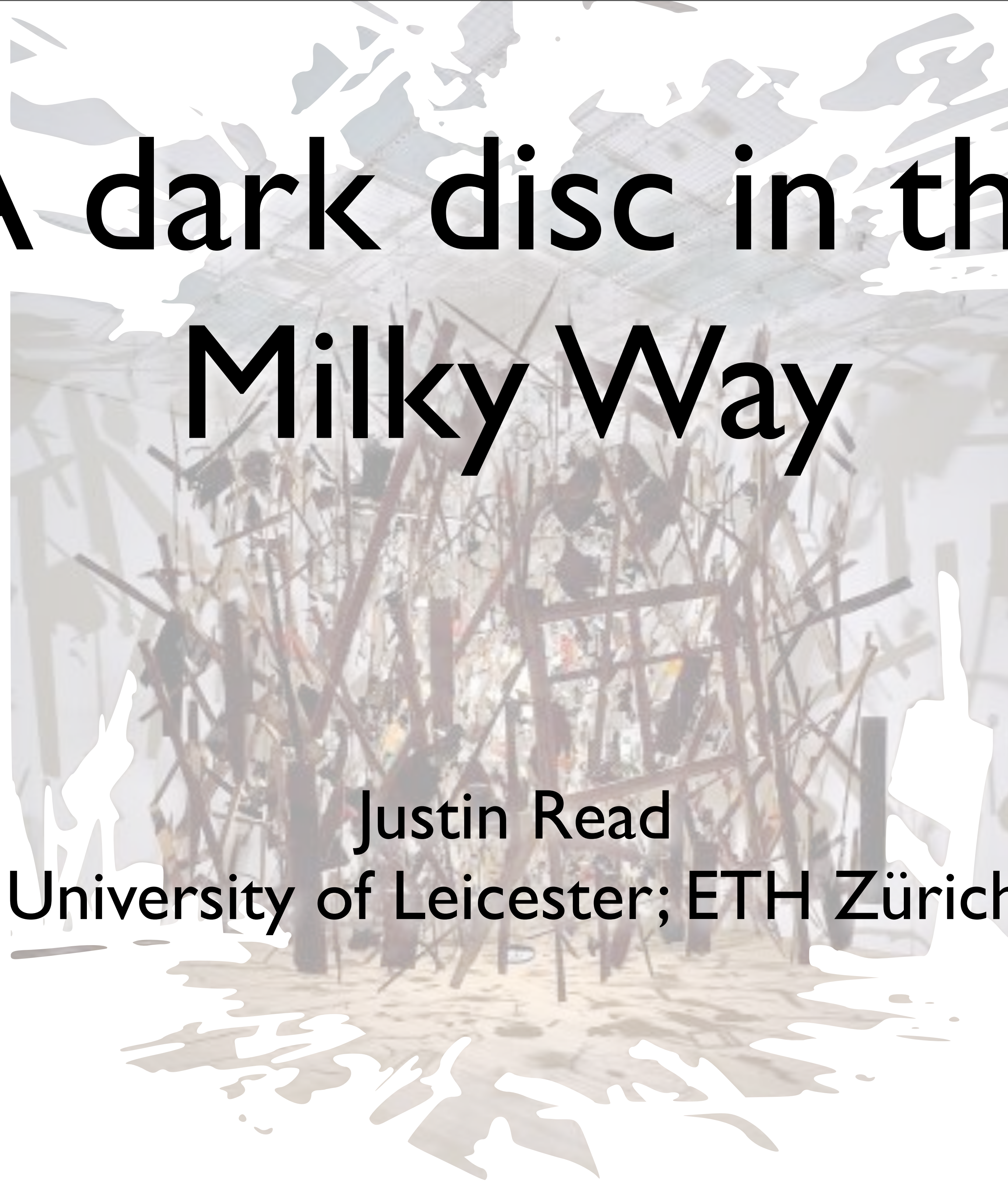


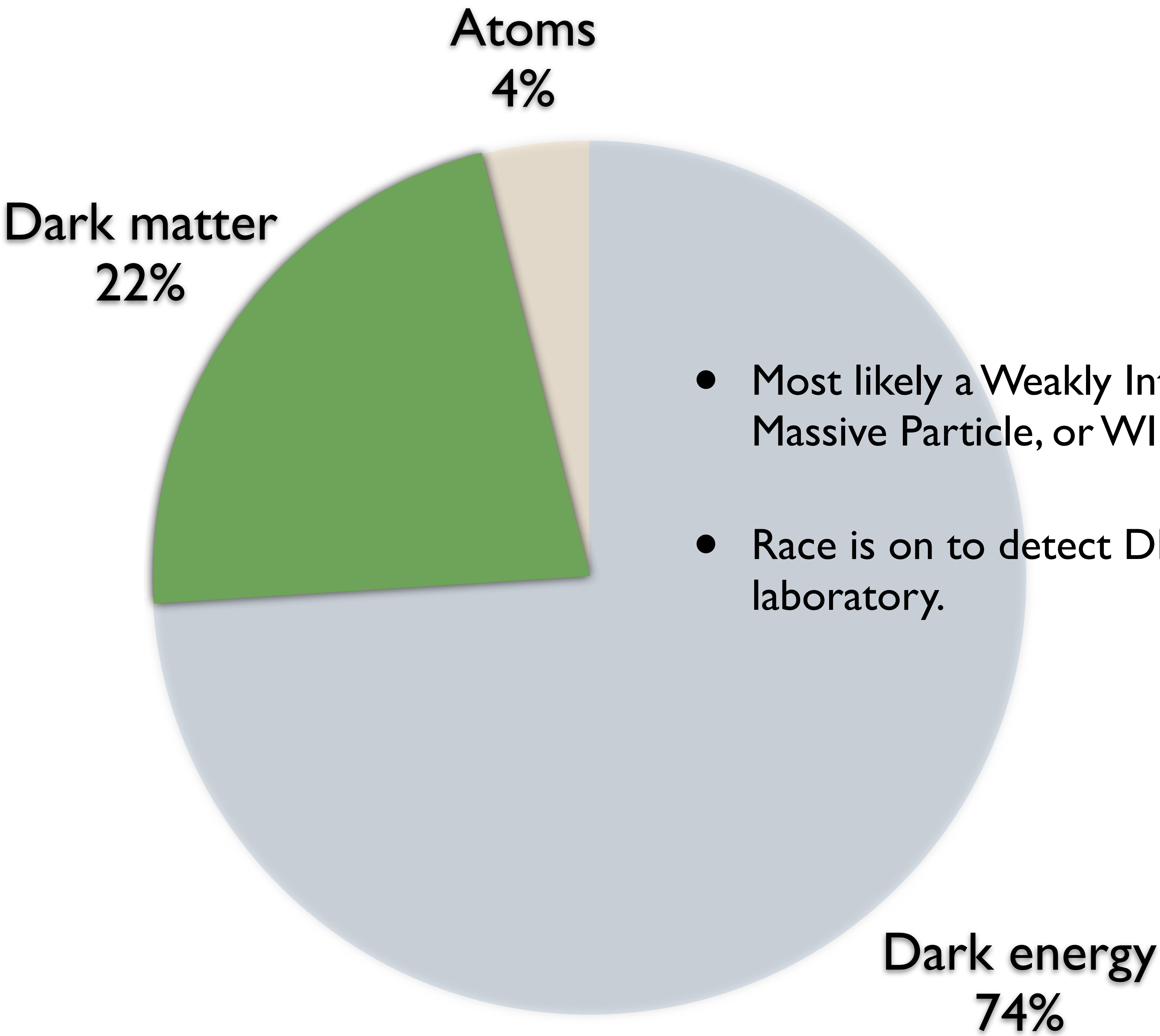
Cold Dark Matter by Cornelia Parker

A dark disc in the Milky Way

Justin Read
University of Leicester; ETH Zürich

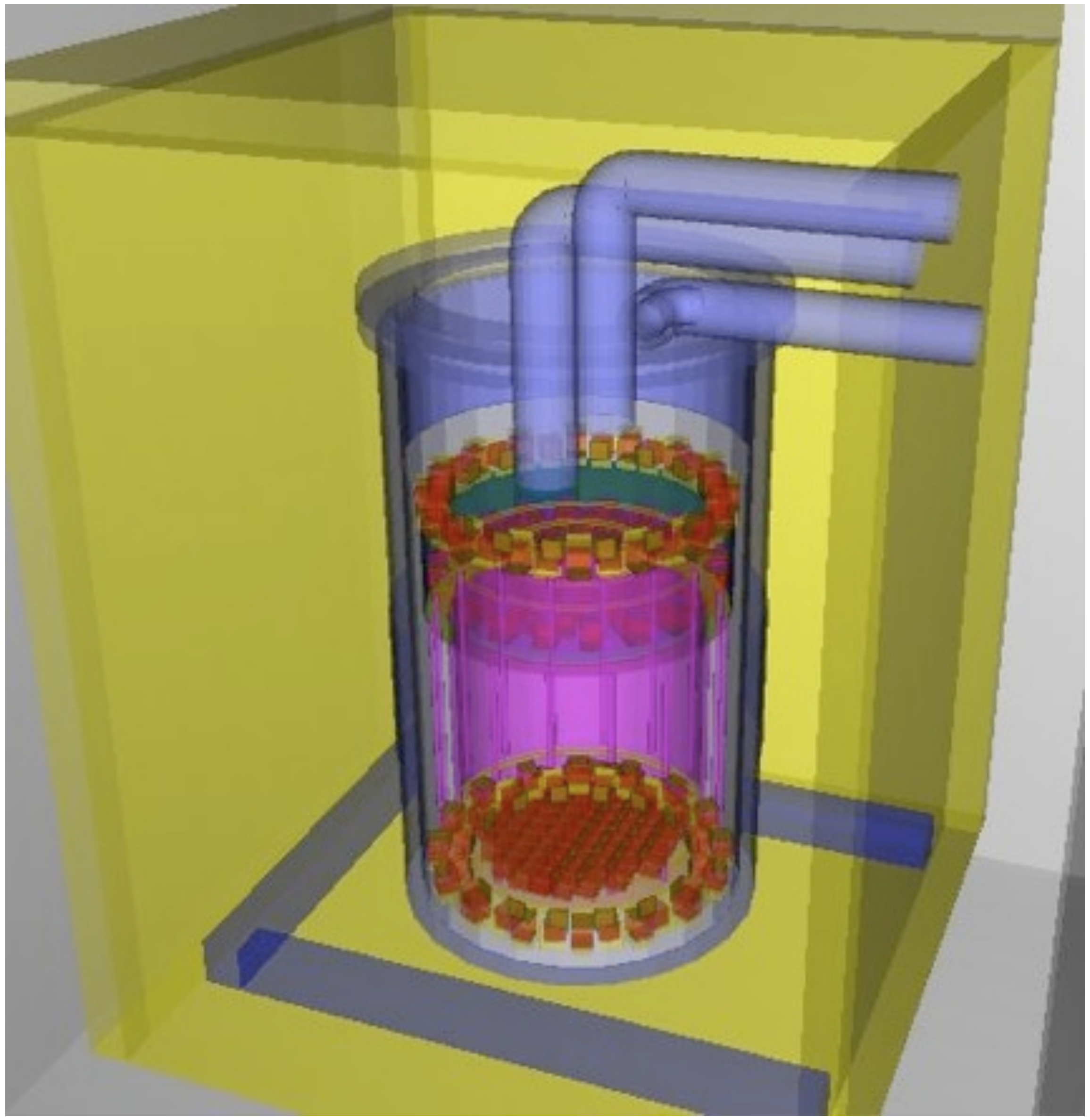
With:
George Lake, Victor Debattista, Oscar Agertz, Tobias Bruch, Lucio Mayer, Fabio Governato, Alyson Brooks, Silvia Garbari, Hanni Lux

Background | The standard cosmological model LCDM



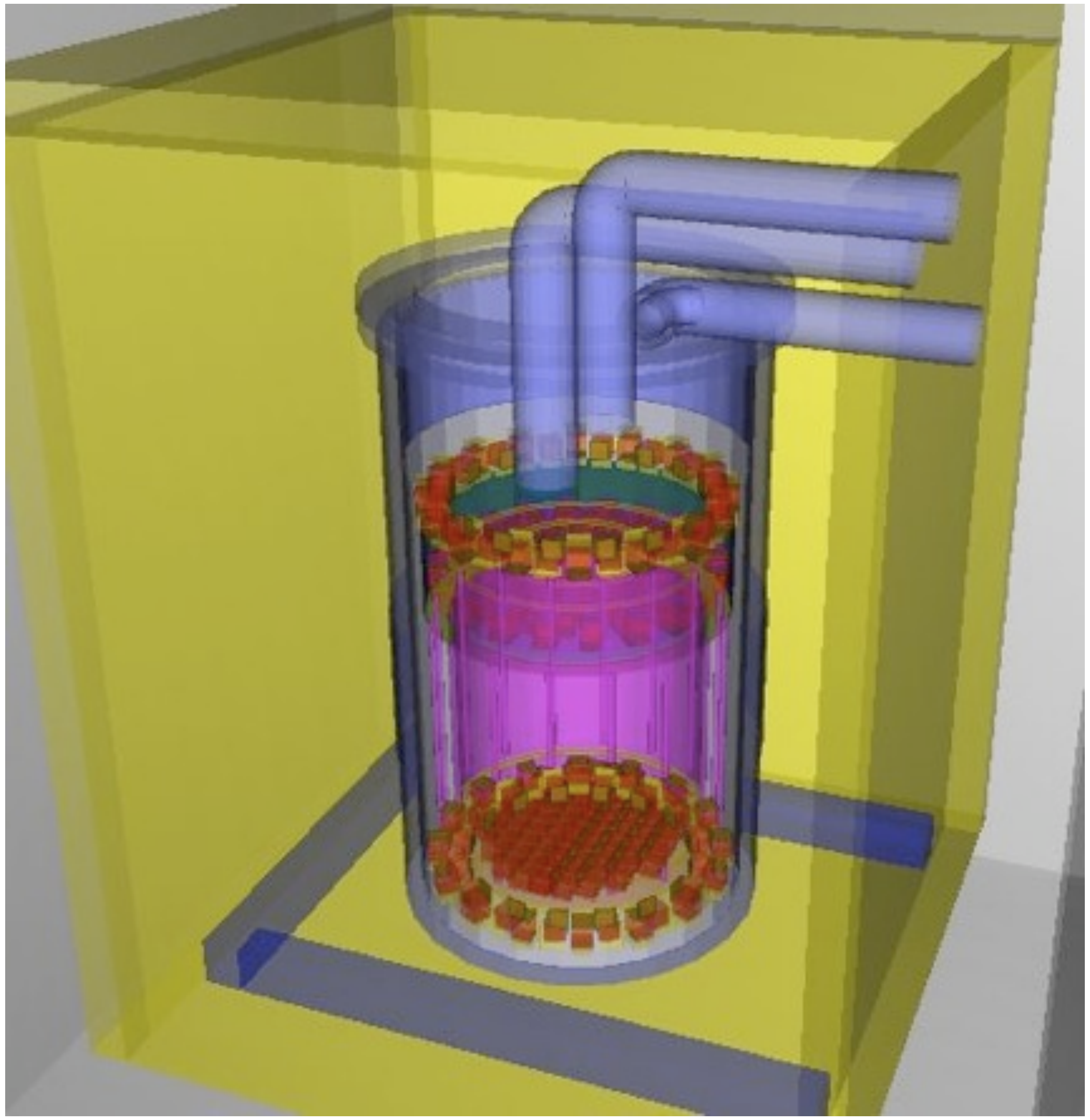
- Most likely a Weakly Interacting Massive Particle, or WIMP.
- Race is on to detect DM in the laboratory.

Background | Hunting for dark matter



- Big tub of inert material
- Deep underground
- Wait for rare event
- Need to know very local phase space distribution

Background | Hunting for dark matter



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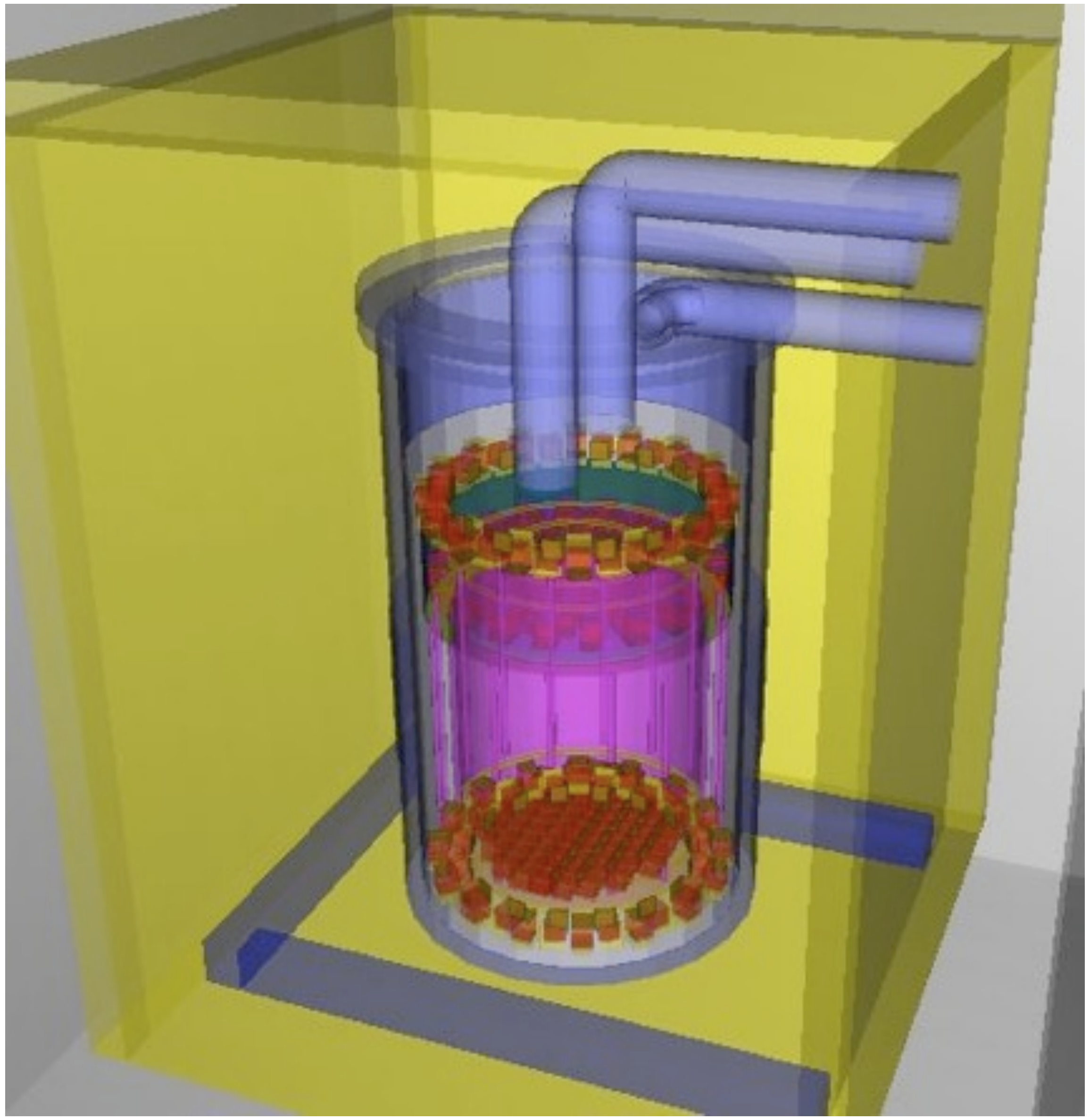
$$\frac{dR}{dE} = \frac{\rho\sigma_{\rm wn}|F(E)|^2}{2m\mu^2}\int_{v>\sqrt{ME/2\mu^2}}^{v_{max}} \frac{f(\mathbf{v},t)}{v} d^3v$$

Background | Hunting for dark matter



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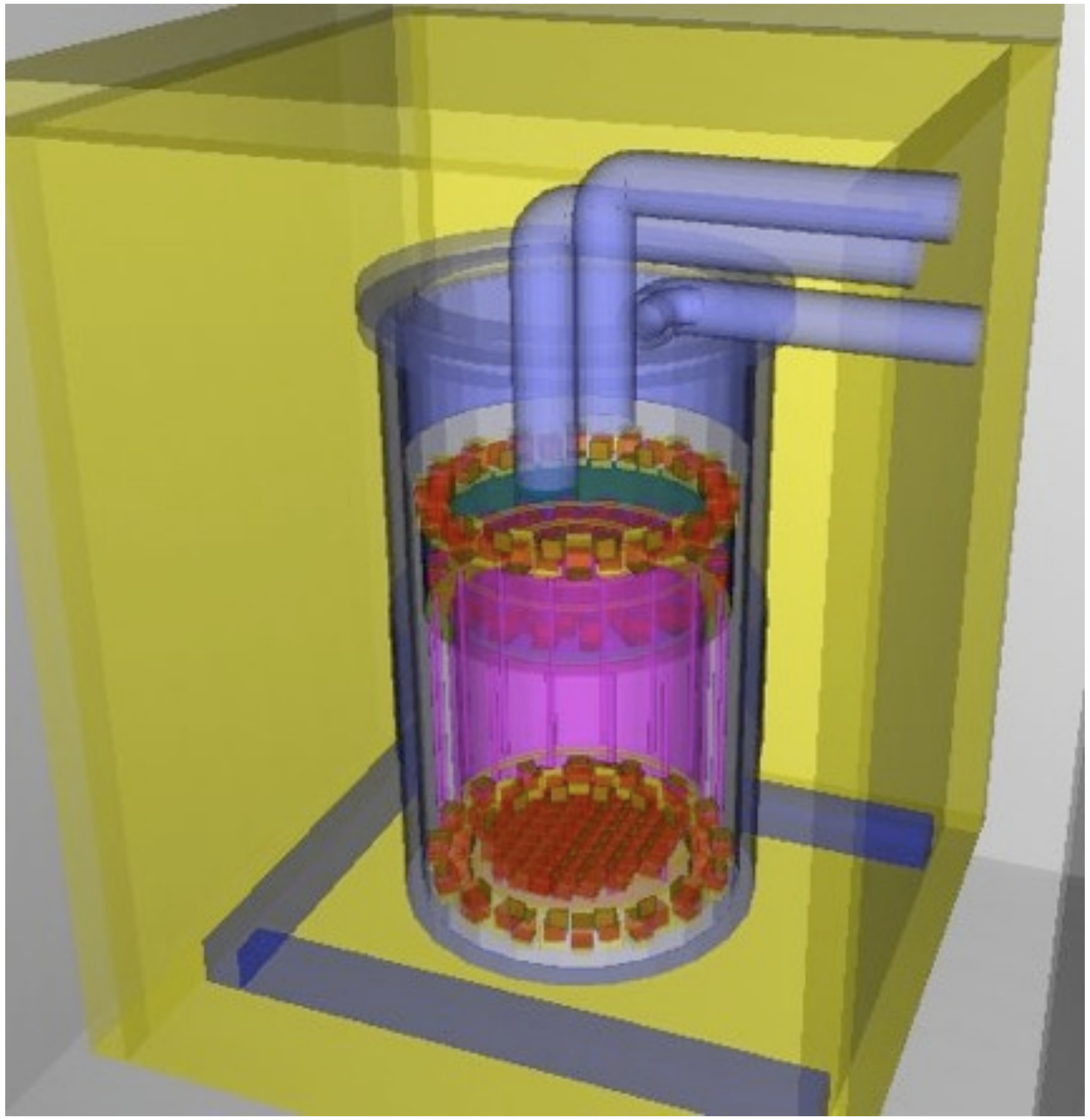
Particle physics

Background | Hunting for dark matter



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Particle physics | Astrophysics

Measuring ρ_{dm} local | Basic equations

Silvia Garbari, Read & Lake 2010; in prep.

& see *Conf. Proc. arXiv:1001.1038*

Measuring ρ_{dm} local | Basic equations

$$\frac{1}{R}\frac{\partial}{\partial R}\left(R\nu_i\overline{v_R v_z}\right) + \frac{\partial}{\partial z}\left(\nu_i\overline{v_z^2}\right) + \nu_i\frac{\partial\Phi}{\partial z} = 0$$

Measuring ρ_{dm} local | Basic equations

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$$h \ll R_d$$

Measuring ρ$_{dm}$ local | Basic equations

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$h \ll R_d$

$\overline{v_z^2} \sim \text{const.}$

$$\overline{v_{z,i}^2}\frac{\partial\nu_i}{\partial z} + \nu_i\frac{\partial\Phi}{\partial z} = 0$$

Measuring ρ_{dm} local | Basic equations

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$$\nu_i = \nu_{0,i}\exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right)$$

Measuring ρ_{dm} local | Basic equations

Tracer population:

$$\nu_i = \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v^2_{z,i}}}\right)$$

Poisson => matter density:

$$\begin{aligned}4\pi G\rho &= \frac{\partial^2\Phi}{\partial z^2} + \frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial\Phi}{\partial R}\right) \\ &= \frac{\partial^2\Phi}{\partial z^2} + \frac{1}{R}\frac{\partial V_c^2(R)}{\partial R}\end{aligned}$$

Measuring ρ_{dm} local | Basic equations

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$V_c^2 \sim \mathrm{const.}$

Measuring ρ_{dm} local | Basic equations

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$$4\pi G\left(\rho_{\rm disc} + \rho_{\rm dm}\right) = \frac{\partial^2 \Phi}{\partial z^2}$$

Measuring ρ_{dm} local | Basic equations

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$$\rho_{\rm disc}(z) = \sum_i^N \nu_{i,0} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right)$$

Measuring ρ$_{dm}$ local | Basic equations

Tracer population:

$$\nu_i = \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right)$$

Poisson => matter density:

$$4\pi G\left(\rho_{\rm disc} + \rho_{\rm dm}\right) = \frac{\partial^2 \Phi}{\partial z^2}$$

$$r_h \gg R_d$$

$$\rho_{\rm disc}(z) = \sum_i^N \nu_{i,0} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right)$$

$$\rho_{\rm dm} \sim {\rm const.}$$

Measuring ρ_{dm} local | Basic equations

$$\frac{\partial^2 \Phi}{\partial z^2} - 4\pi G \sum_i \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right) - 4\pi G \rho_{\mathrm{dm}} = 0$$

Measuring ρ_{dm} local | Basic equations

$$\frac{\partial^2 \Phi}{\partial z^2} - 4\pi G \sum_i \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right) - 4\pi G \rho_{\mathrm{dm}} = 0$$

Guess/Measure

Measuring ρ_{dm} local | Basic equations

$$\frac{\partial^2\Phi}{\partial z^2} - 4\pi G \sum_i \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right) - 4\pi G \rho_{\mathrm{dm}} = 0$$

Guess/Measure

Guess

Measuring ρ_{dm} local | Basic equations

$$\frac{\partial^2\Phi}{\partial z^2} - 4\pi G \sum_i \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right) - 4\pi G \rho_{\mathrm{dm}} = 0$$

Solve

Guess/Measure

Guess

Measuring ρ$_{\rm dm}$ local | Basic equations

$$\frac{\partial^2\Phi}{\partial z^2} - 4\pi G\sum_i \nu_{0,i}\exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right) - 4\pi G\rho_{\rm dm} = 0$$

Solve

Guess/Measure

Guess

$$f = f(E_z);\, \Phi(0) = 0$$

$$\nu_i(z) = 2\int_{\sqrt{2\Phi}}^{\infty} dv_z \frac{v_z f(v_z)}{\sqrt{v_z^2 - 2\Phi}}$$

Measuring ρ_{dm} local | Basic equations

$$\frac{\partial^2 \Phi}{\partial z^2} - 4\pi G \sum_i \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right) - 4\pi G \rho_{\mathrm{dm}} = 0$$

Solve

Guess/Measure

Guess

$$f = f(E_z); \Phi(0) = 0$$

$$\nu_i(z) = 2\int_{\sqrt{2\Phi}}^{\infty} dv_z \frac{v_z \boxed{f(v_z)}}{\sqrt{v_z^2 - 2\Phi}}$$

Measure

Measuring ρ_{dm} local | Basic equations

$$\frac{\partial^2\Phi}{\partial z^2} - 4\pi G \sum_i \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v^2_{z,i}}}\right) - 4\pi G \rho_{\rm dm} = 0$$

Solve Guess/Measure Guess

$$f = f(E_z);\, \Phi(0) = 0$$

Compare with obs.

$$\boxed{\nu_i(z)} = 2\int_{\sqrt{2\Phi}}^{\infty} dv_z \frac{v_z \boxed{f(v_z)}}{\sqrt{v_z^2 - 2\Phi}}$$ Measure

$$\Rightarrow \chi^2$$

Measuring ρ_{dm} local | Basic equations

$$\frac{\partial^2\Phi}{\partial z^2} - 4\pi G \sum_i \nu_{0,i} \exp\left(-\frac{\Phi(z)}{\overline{v_{z,i}^2}}\right) - 4\pi G \rho_{\mathrm{dm}} = 0$$

Solve

Guess/Measure

Guess

$$f = f(E_z); \Phi(0) = 0$$

Compare with obs.

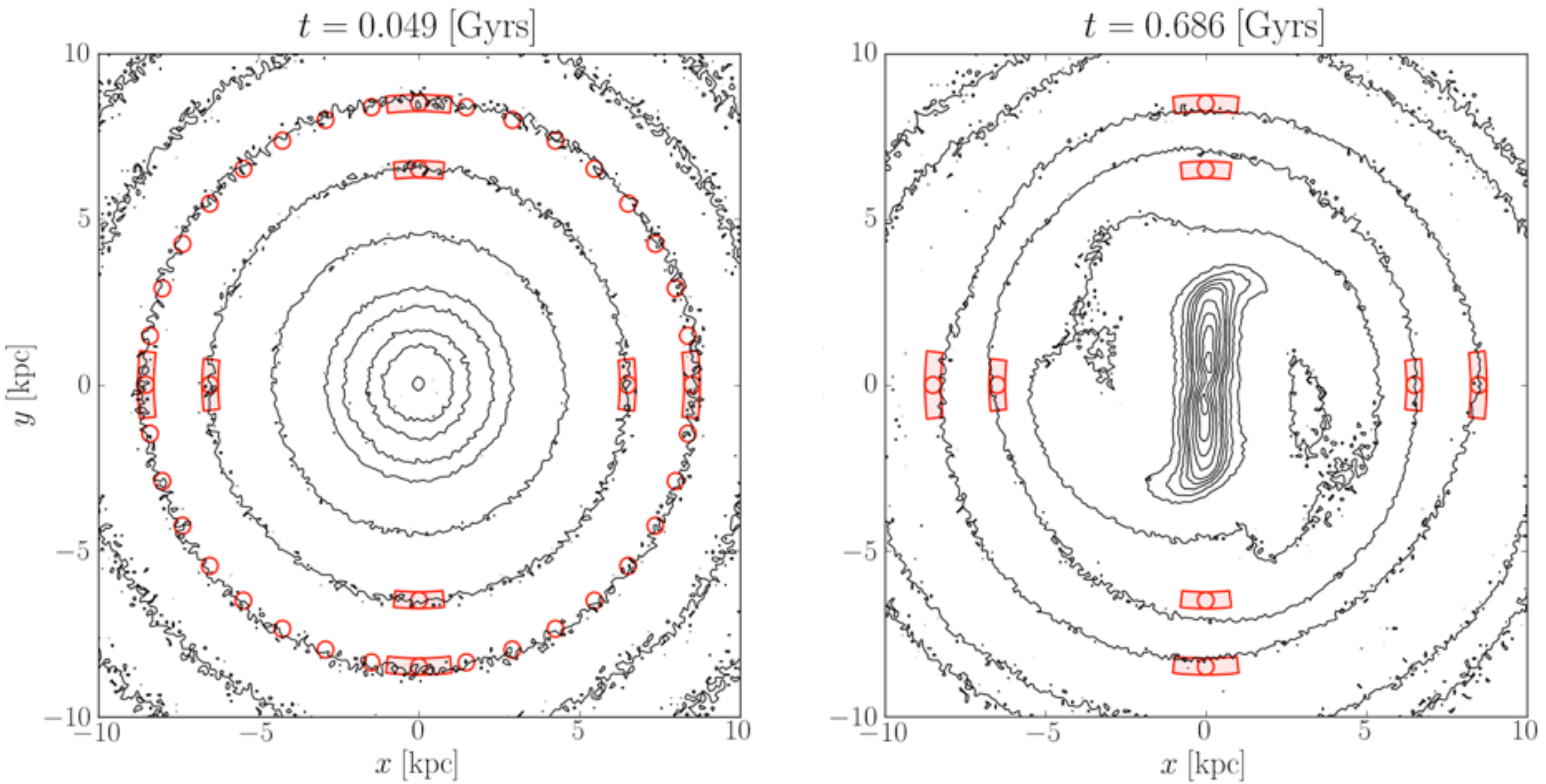
$$\nu_i(z) = 2\int_{\sqrt{2\Phi}}^{\infty} dv_z \frac{v_z f(v_z)}{\sqrt{v_z^2 - 2\Phi}}$$

Measure

$\Rightarrow \chi^2$

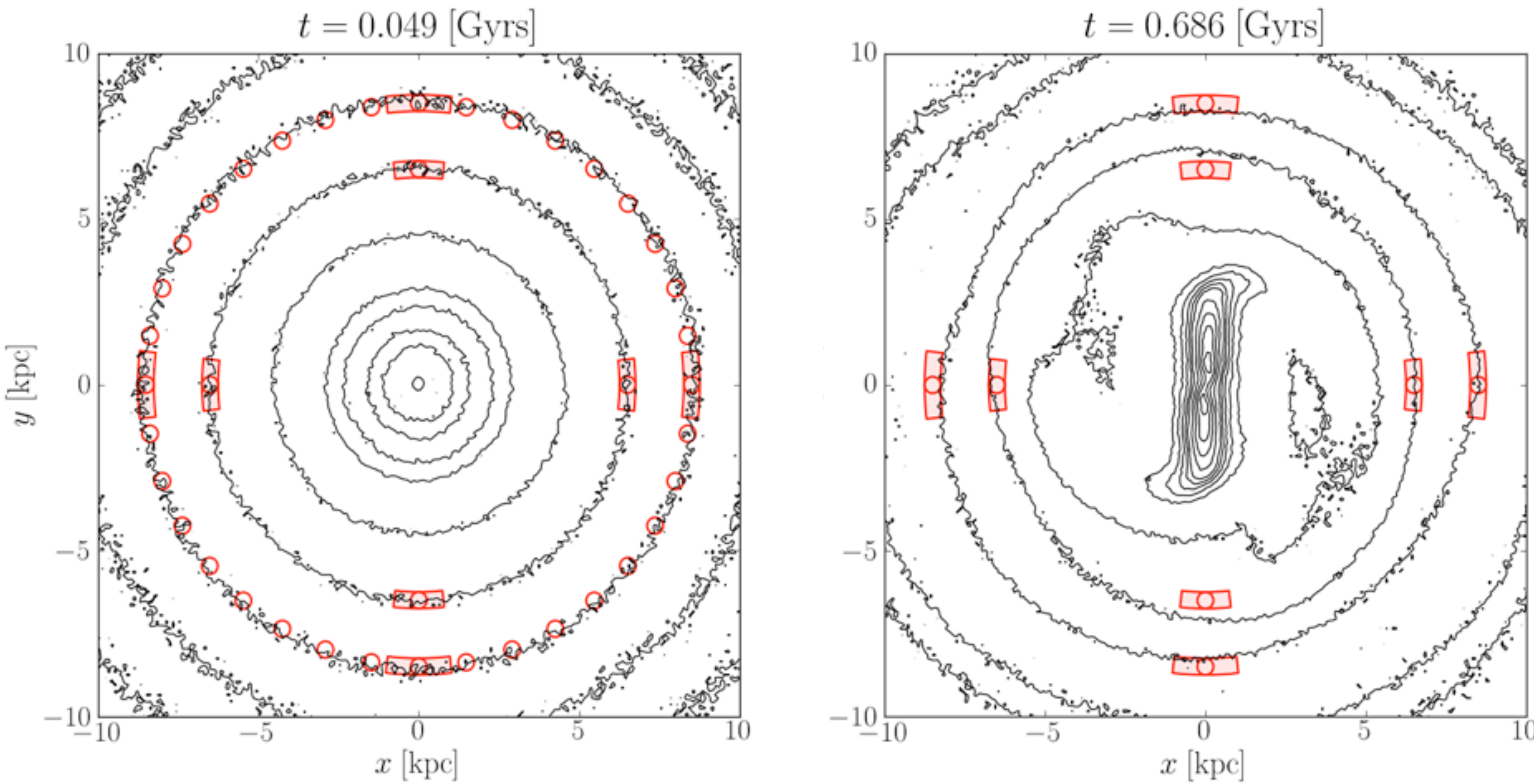
... & use MCMC

Measuring ρ_{dm} local | Testing the method



	N $[10^6]$	M $[10^{10} M_\odot]$	ε [kpc]	$r_{1/2}$ [kpc]	$z_{1/2}$ [kpc]
Disc	30	5.30	0.015	4.99	0.17
Halo	15	45.40	0.045	-	-
Bulge	0.5	0.83	0.012	-	-

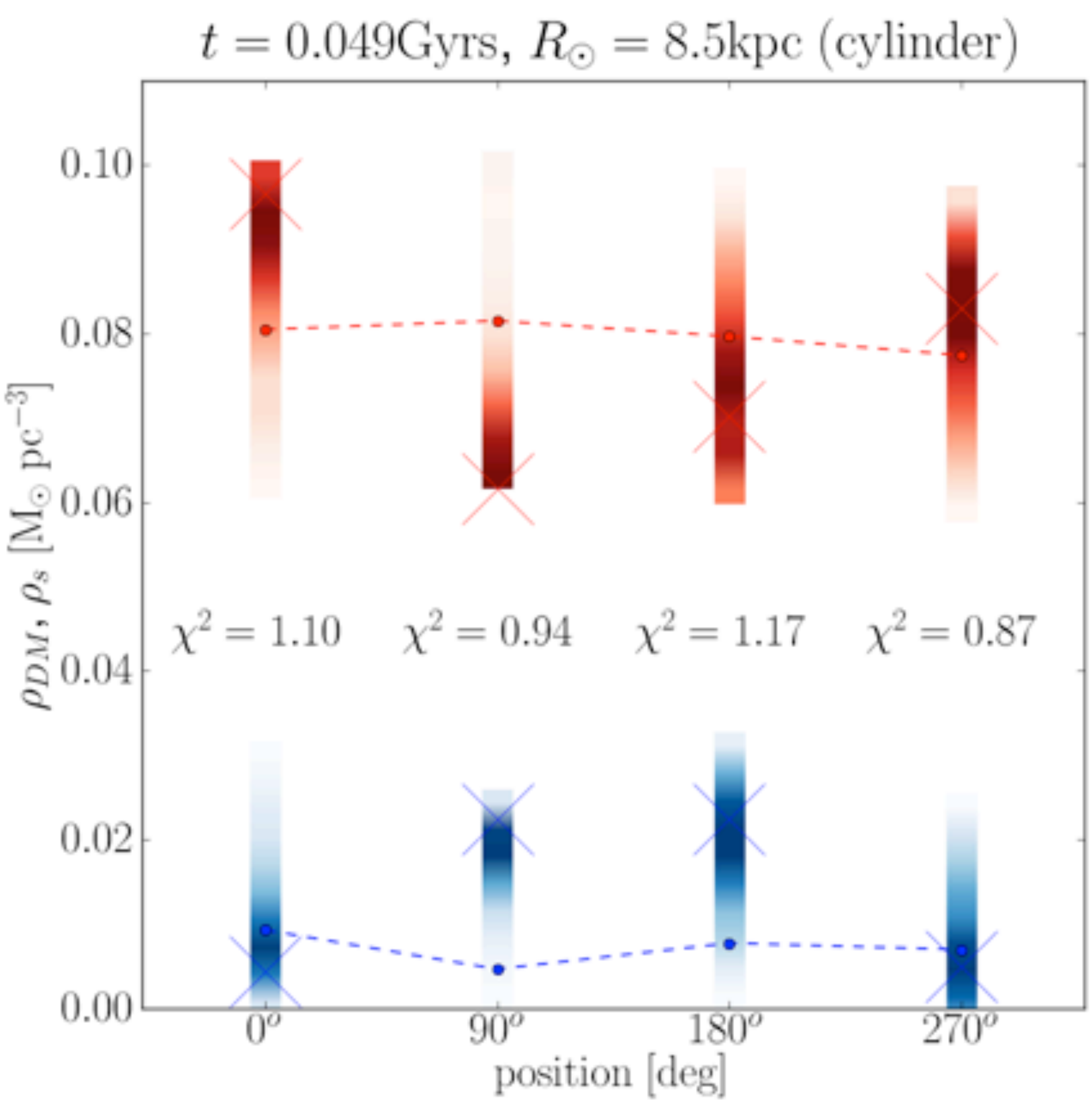
Measuring ρ_{dm} local | Testing the method



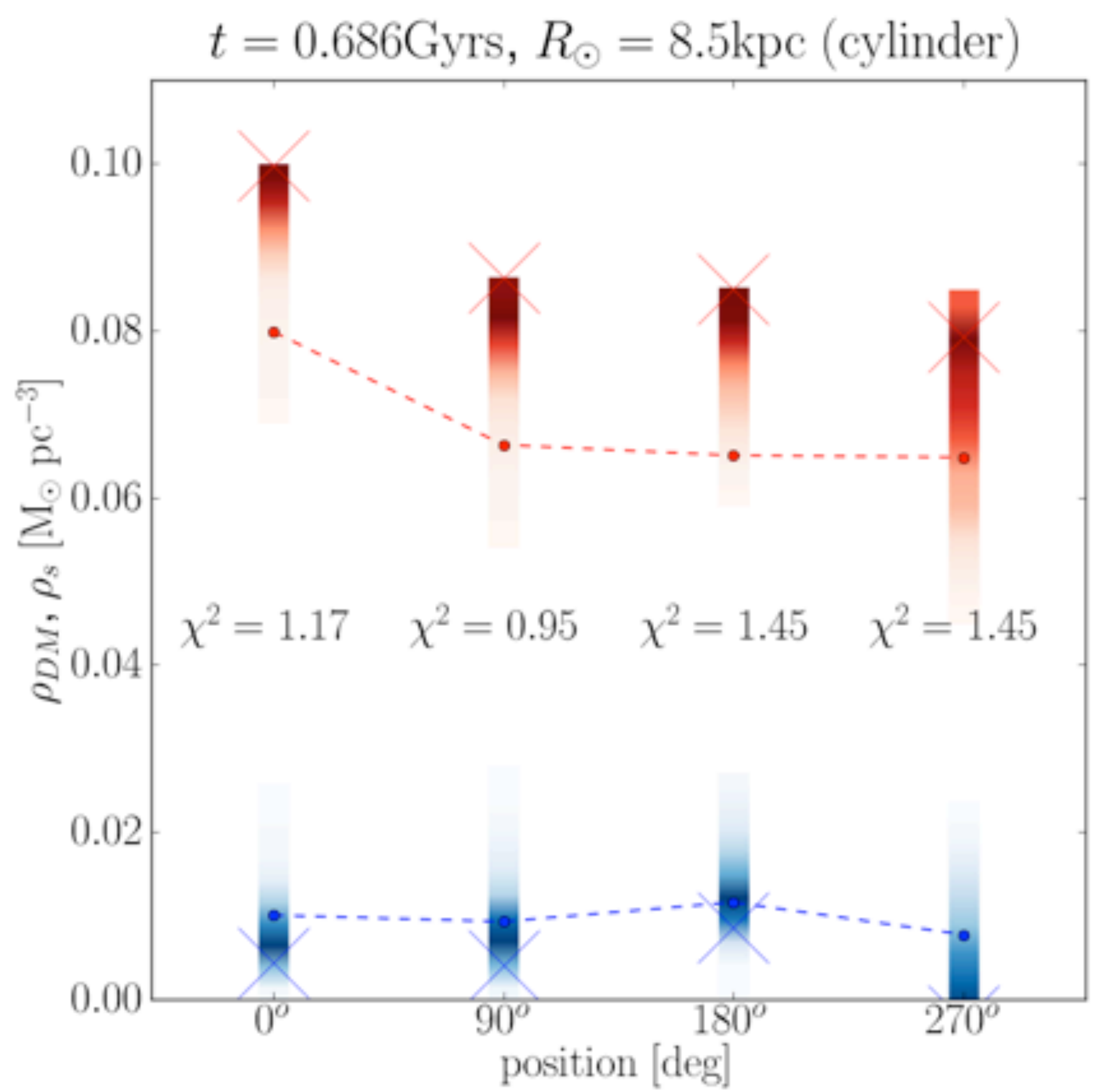
unevolved

evolved

Measuring ρ_{dm} local | Testing the method; current sampling

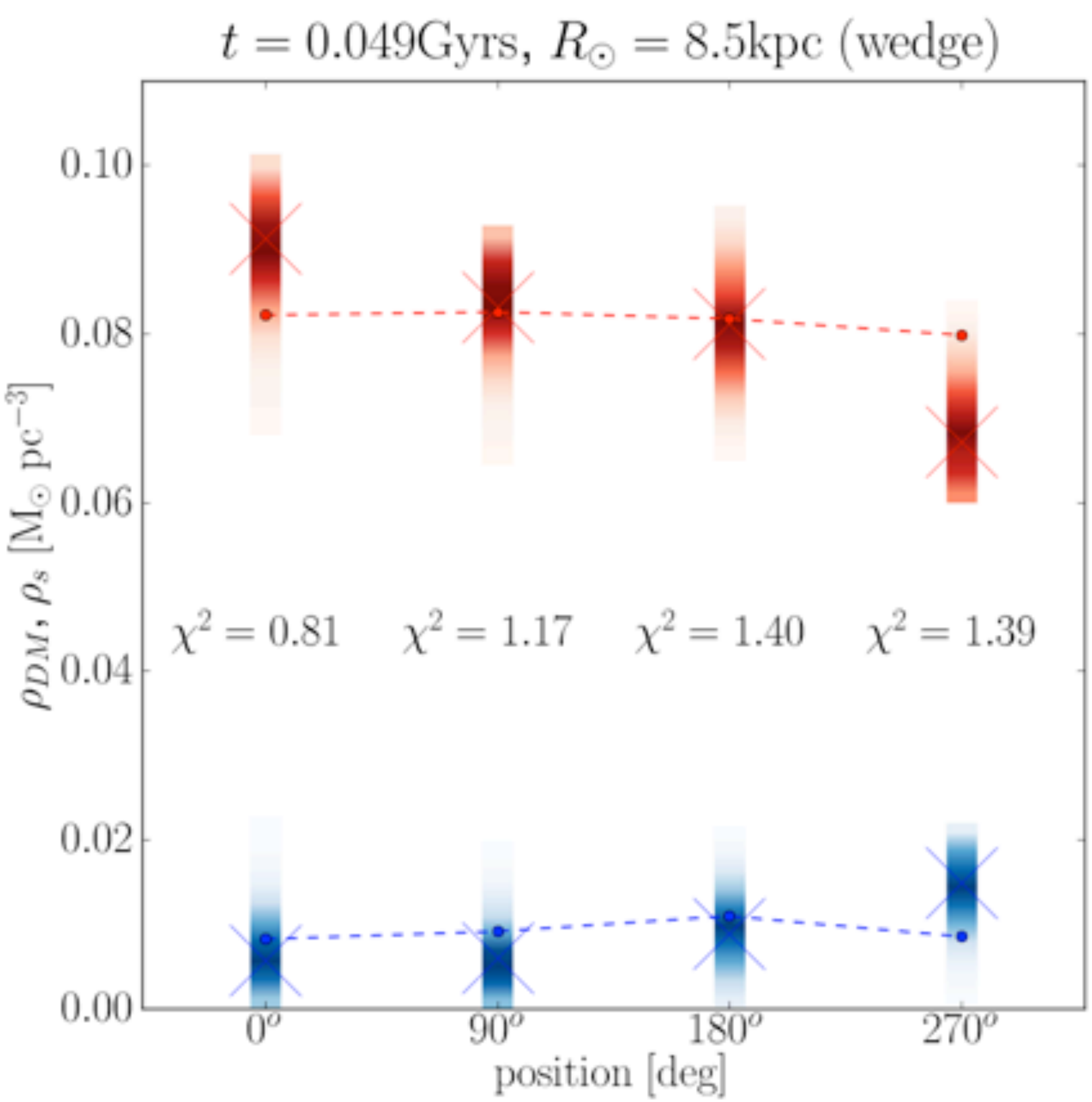


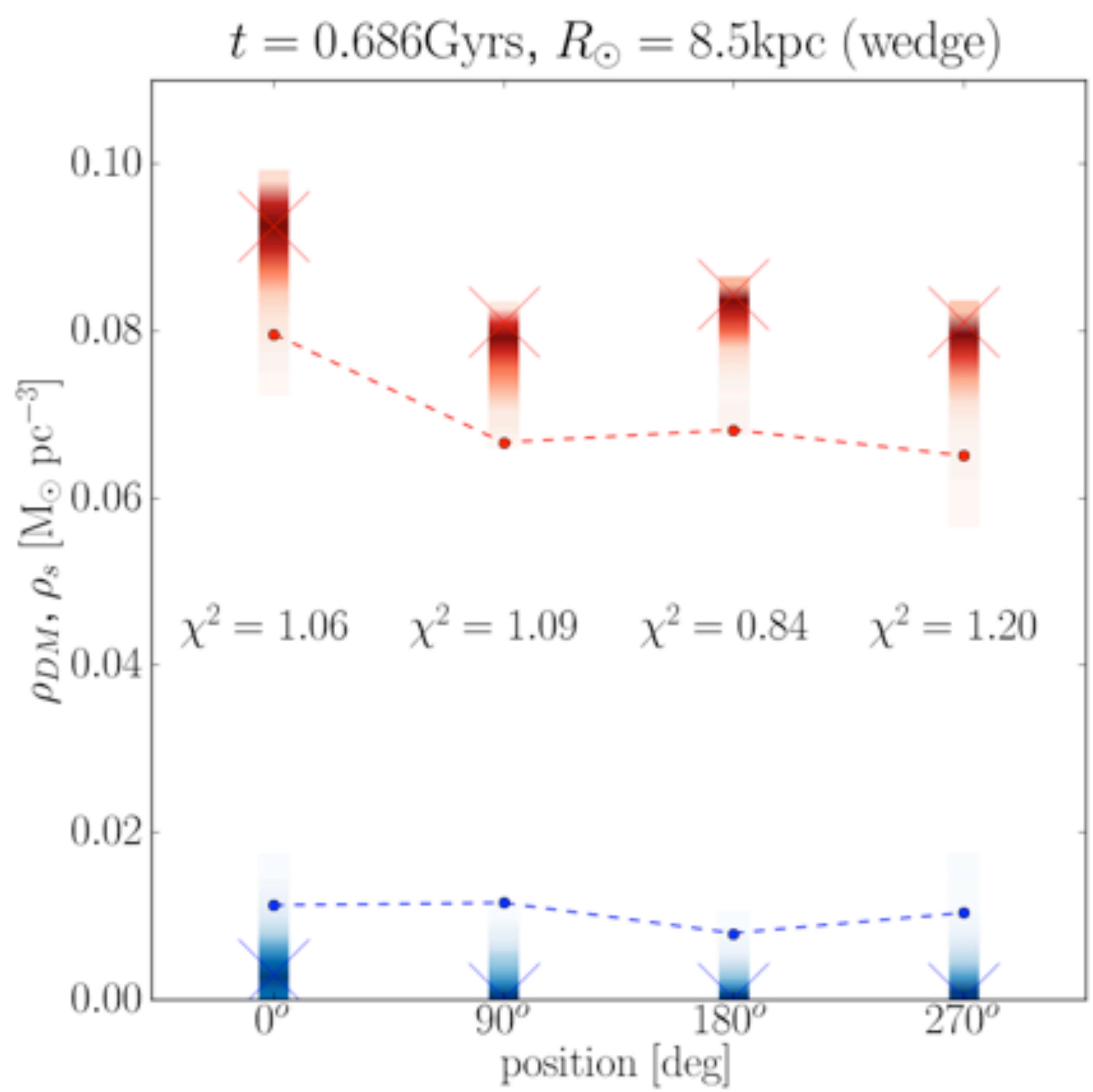
unevolved



evolved

Measuring ρ_{dm} local | Testing the method; future sampling





unevolved

evolved

Measuring ρ_{dm} local | Application to real data

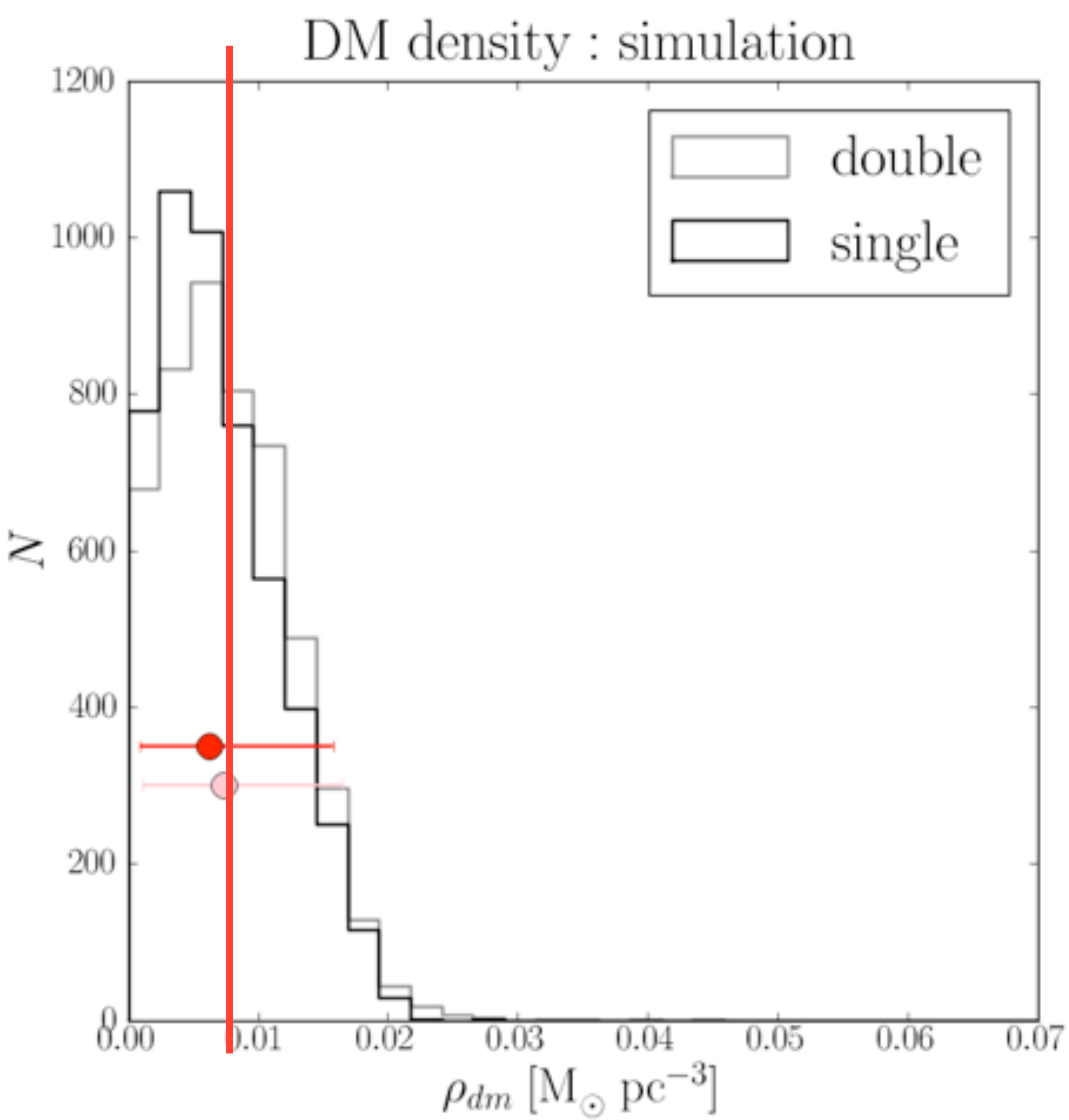
Additional complications ...

- Tracers are magnitude limited, not volume limited
- Velocity distribution comes from same star type as tracer density distribution; but not same stars
- Multiple mass components in the disc
- Measurement errors

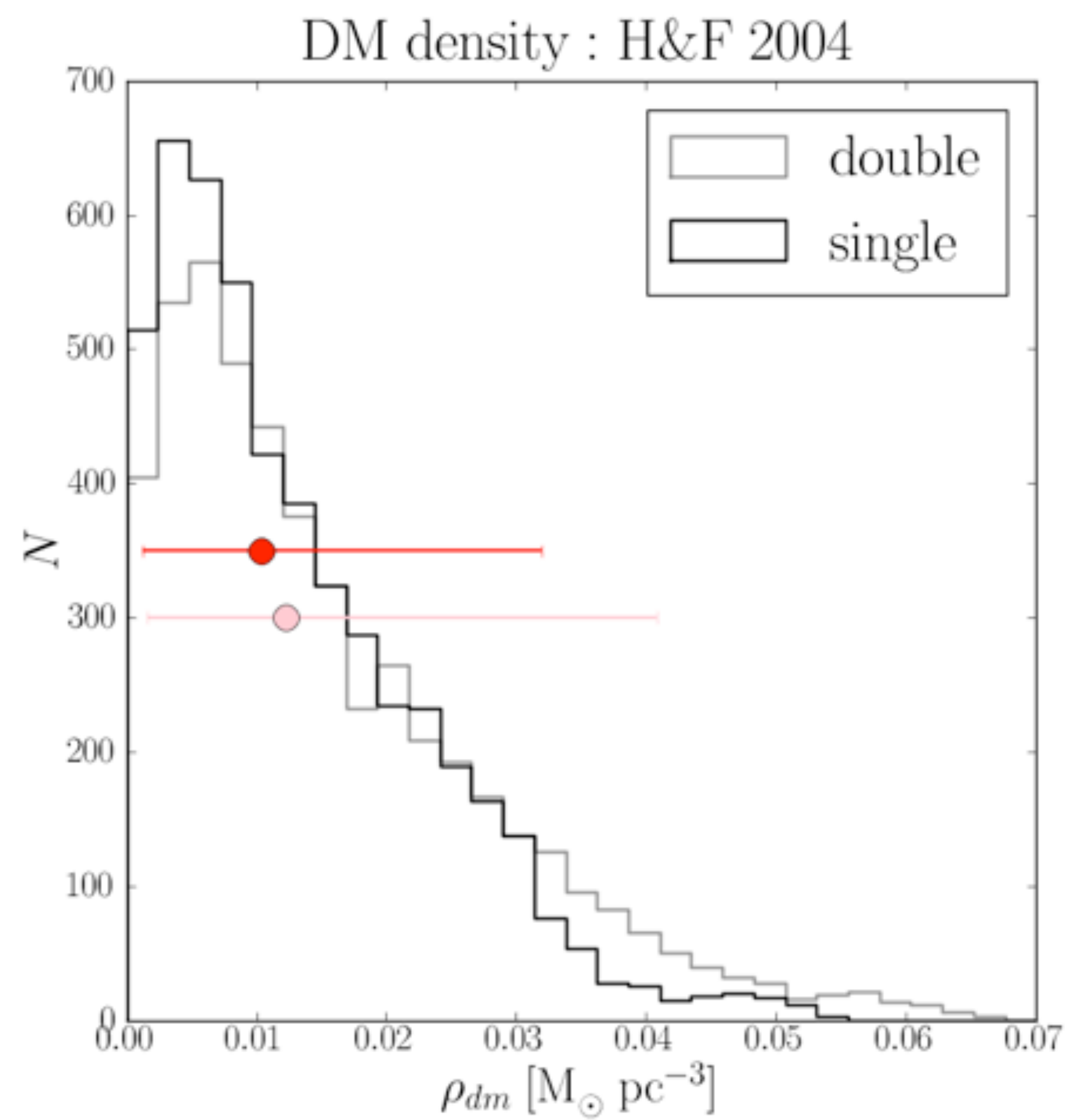
=> Marginalise over all of these in the MCMC!

Measuring ρ_{dm} local | Application to real data

PRELIMINARY!! Results ...



simulation

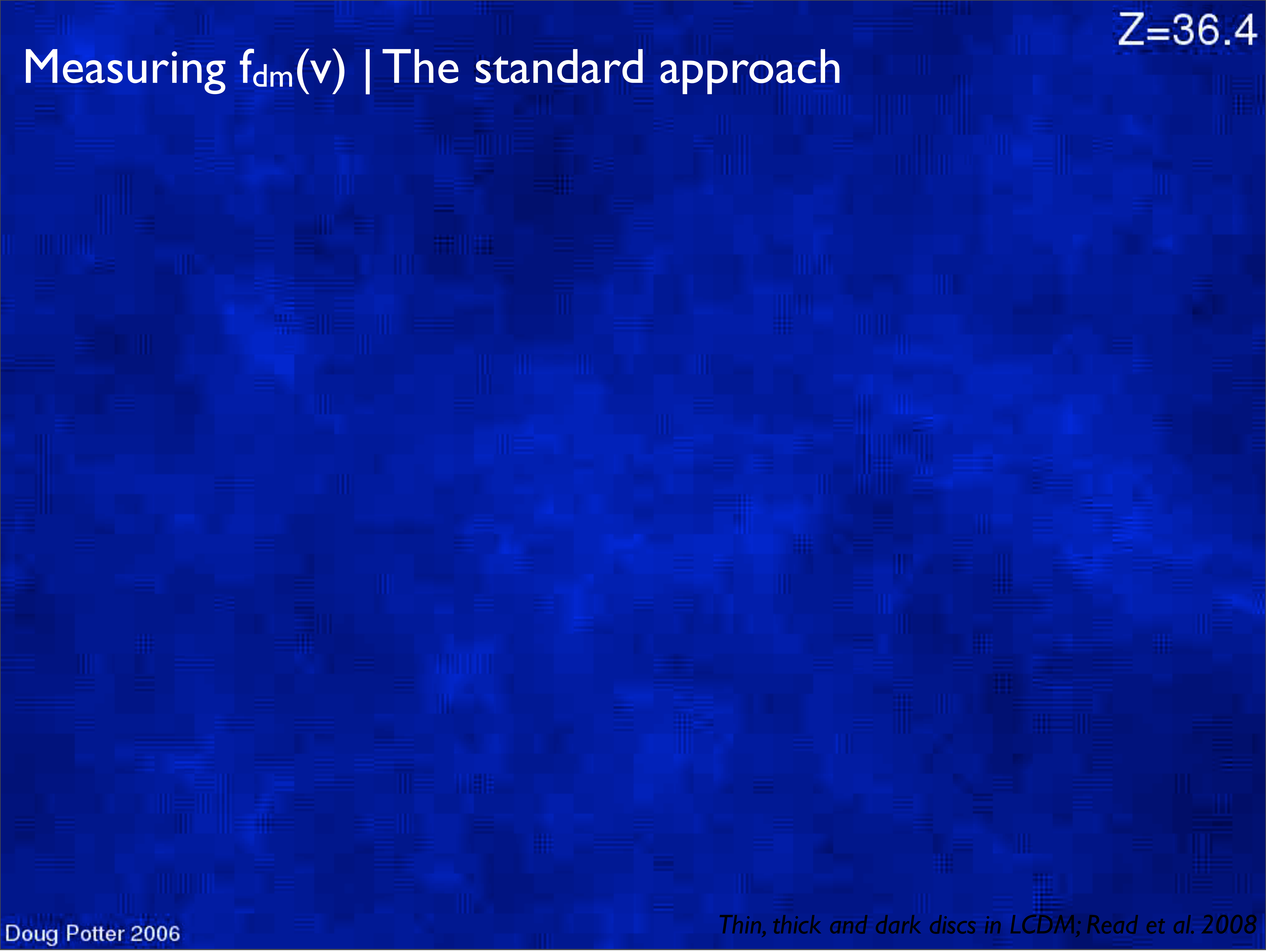


real data

Measuring $f_{dm}(v)$ | The standard approach

Thin, thick and dark discs in LCDM; Read et al. 2008

Measuring $f_{dm}(v)$ | The standard approach



Thin, thick and dark discs in LCDM; Read et al. 2008

Z=0.18

Measuring $f_{dm}(v)$ | The standard halo model (SHM)

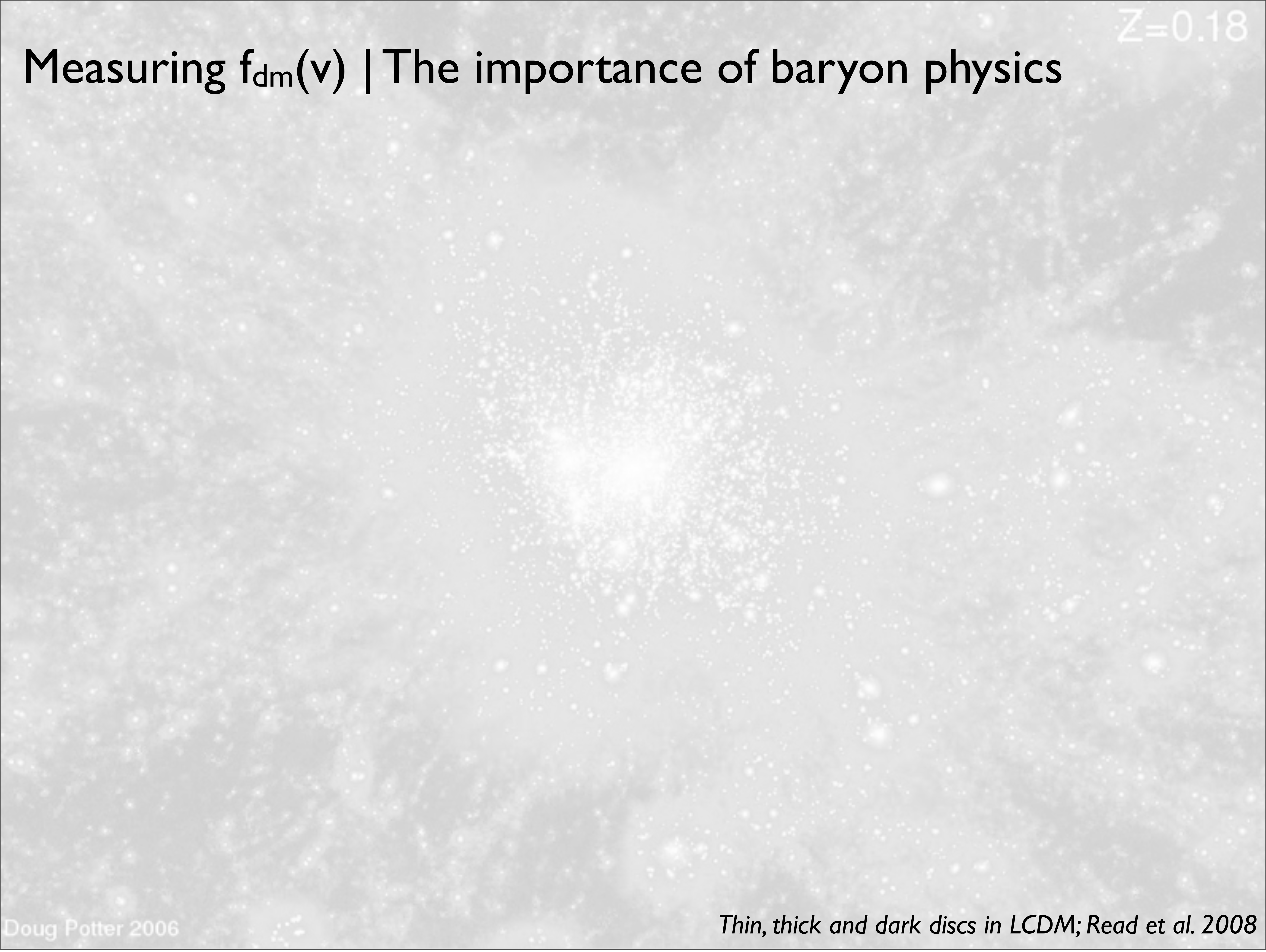
Isotropic Gaussian in the Galactic frame:

$$f(v) \propto \exp\left(-\frac{v^2}{2\sigma^2}\right)$$

Doug Potter 2006

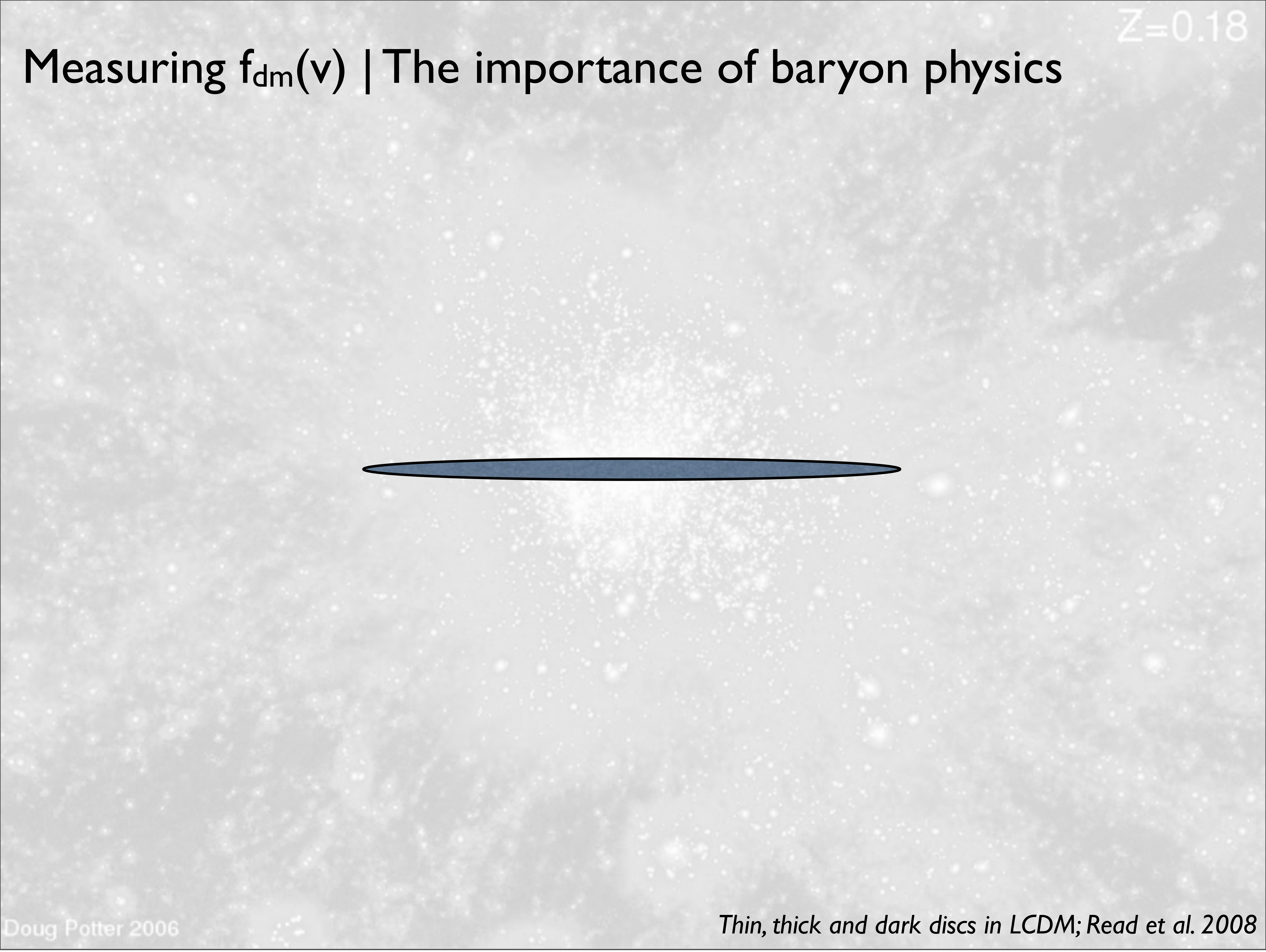
Thin, thick and dark discs in LCDM; Read et al. 2008

Measuring $f_{dm}(v)$ | The importance of baryon physics



Thin, thick and dark discs in LCDM; Read et al. 2008

Measuring $f_{dm}(v)$ | The importance of baryon physics



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Measuring $f_{dm}(v)$ | The importance of baryon physics

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Measuring $f_{dm}(v)$ | The importance of baryon physics

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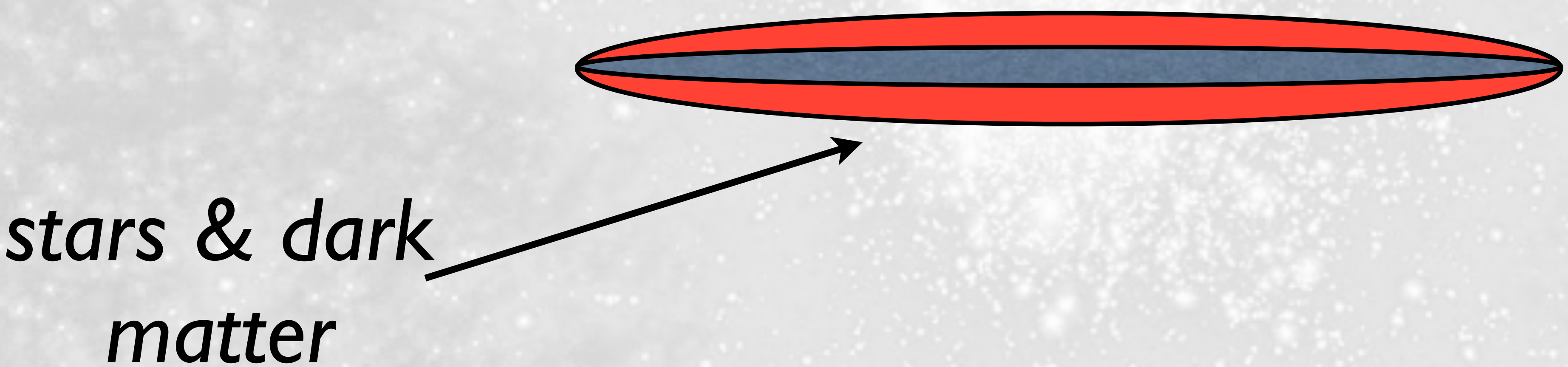
Measuring $f_{dm}(v)$ | The importance of baryon physics



Doug Potter 2006

Thin, thick and dark discs in LCDM; Read et al. 2008

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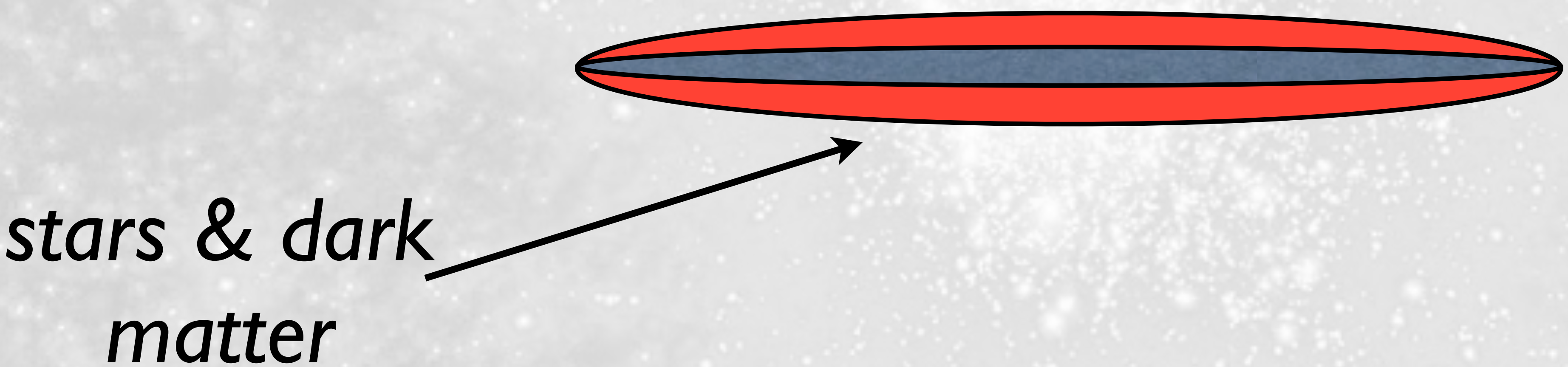
Measuring $f_{dm}(v)$ | The importance of baryon physics

Dynamical friction plane dragging



Doug Potter 2006

Thin, thick and dark discs in LCDM; Read et al. 2008

Measuring $f_{dm}(v)$ | A simulator's wish list

- Resolve star formation in molecular clouds (~10pc)
- Full cosmological box to z=0 (~50Mpc)
- Cooling physics & non-equilibrium chemistry
- Feedback from supernovae & ionising radiation

=> Spatial dynamic range of 5×10^6

=> Temporal dynamic range of 5000

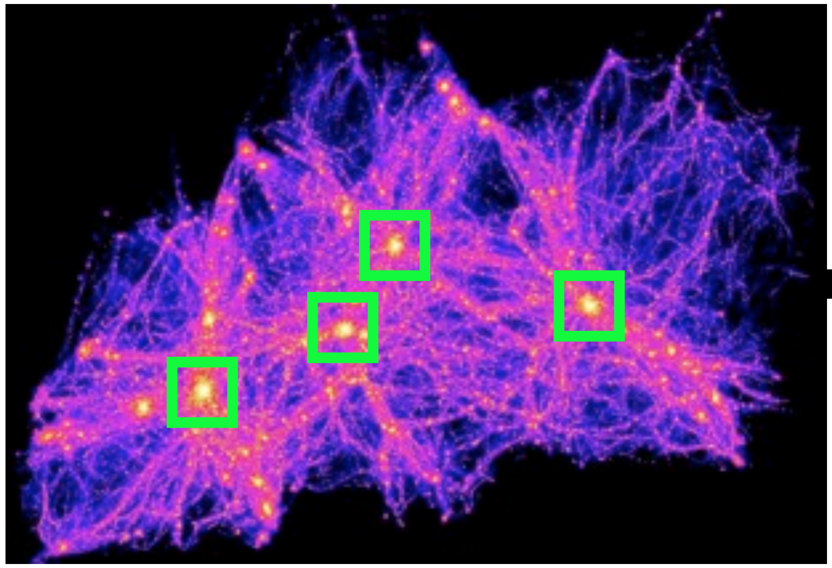
=> $O(10^9)$ particles

Measuring $f_{dm}(v)$ | A first approach

Read et al., MNRAS 2008; arXiv:0803.2714

Measuring $f_{dm}(v)$ | A first approach

a)



Diemand et al. 2005

Number/mass/orbits of LCDM mergers

Read et al., MNRAS 2008; arXiv:0803.2714

Measuring $f_{dm}(v)$ | A first approach

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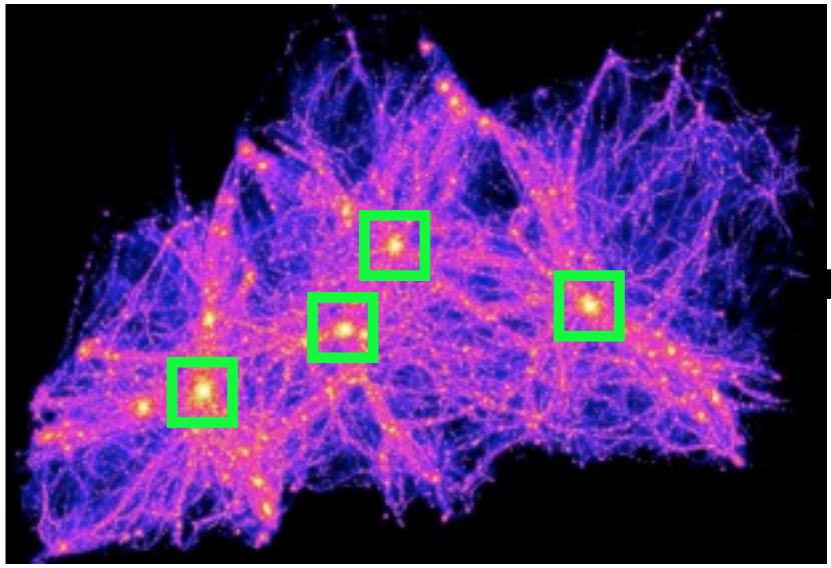
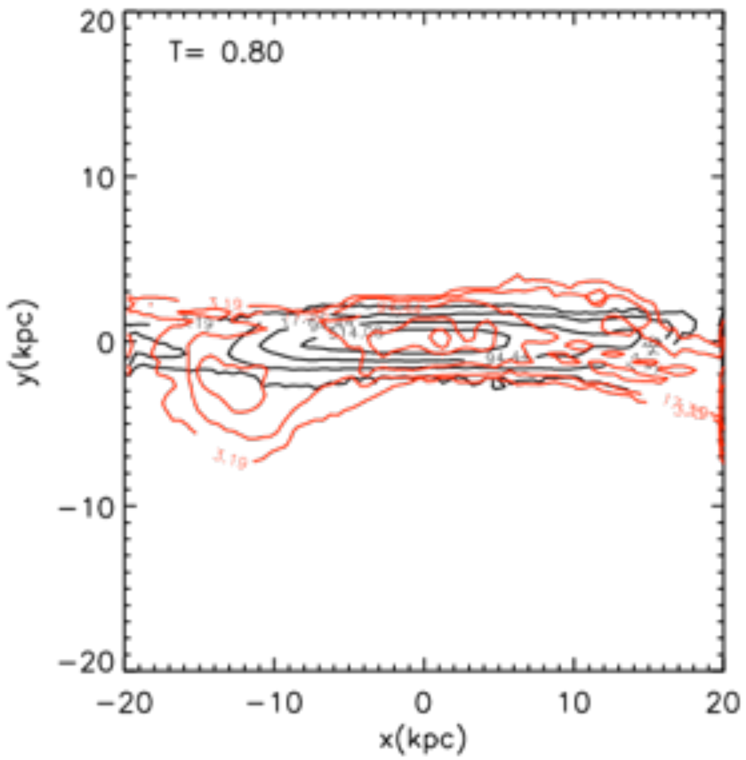


Diemand et al. 2005

Number/mass/orbits of LCDM mergers

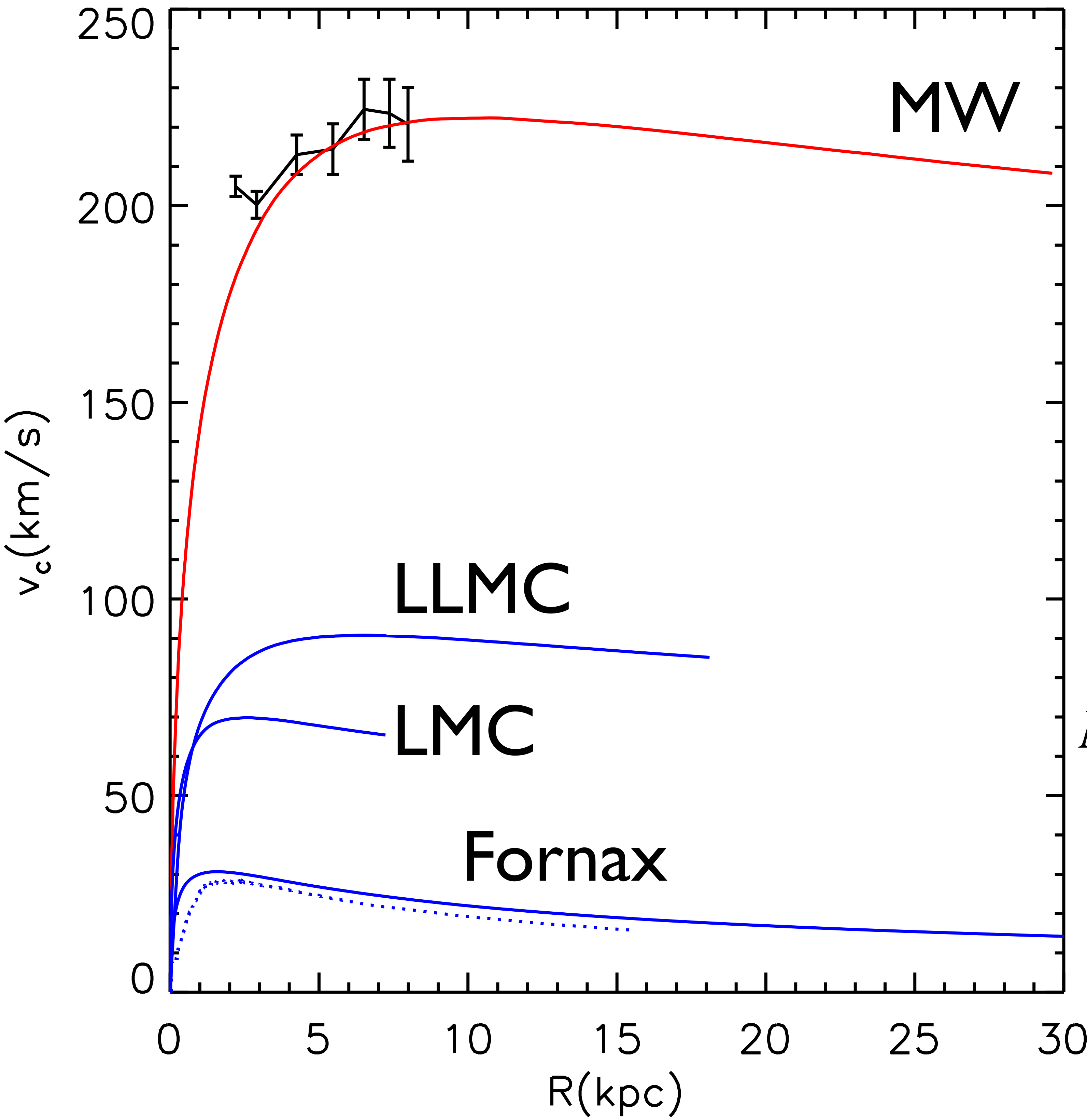
b)



Effect of dissipationless LCDM disc mergers

Read et al., MNRAS 2008; arXiv:0803.2714

Approach I | Initial conditions

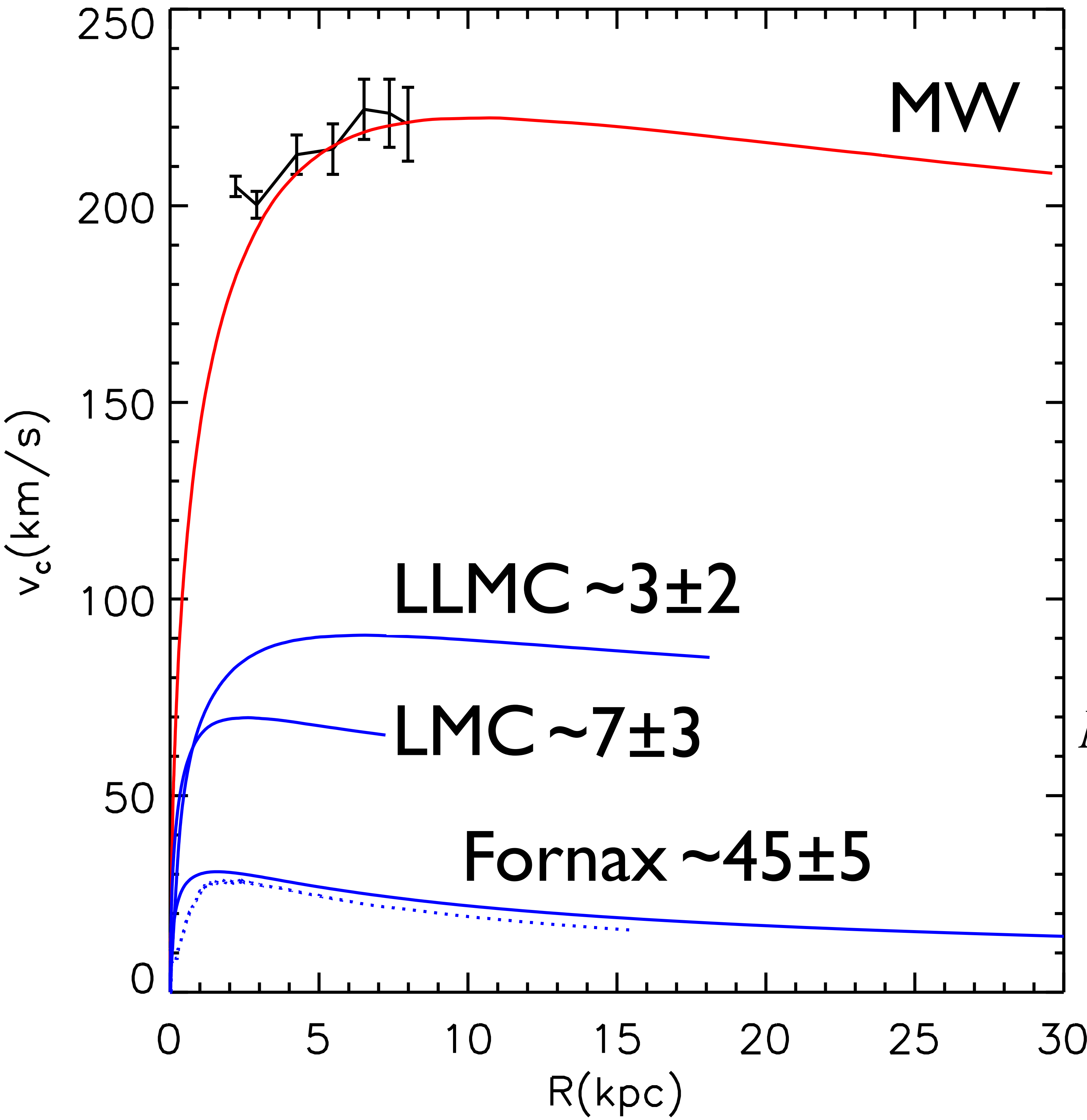


$$N_* = 7.5 \times 10^5; \varepsilon_* = 0.06\,\mathrm{kpc}$$
$$N_{dm} = 2 \times 10^6; \varepsilon_{dm} = 0.1\,\mathrm{kpc}$$

$$N_* = 7.5 \times 10^5; \varepsilon_* = 0.01\,\mathrm{kpc}$$
$$N_{dm} = 2 \times 10^6; \varepsilon_{dm} = 0.03\,\mathrm{kpc}$$

Read et al., MNRAS 2008; arXiv:0803.2714

Approach I | Initial conditions



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Read et al., MNRAS 2008; arXiv:0803.2714

Approach I | A dark matter disc in the Milky Way

In situ stars; accreted stars

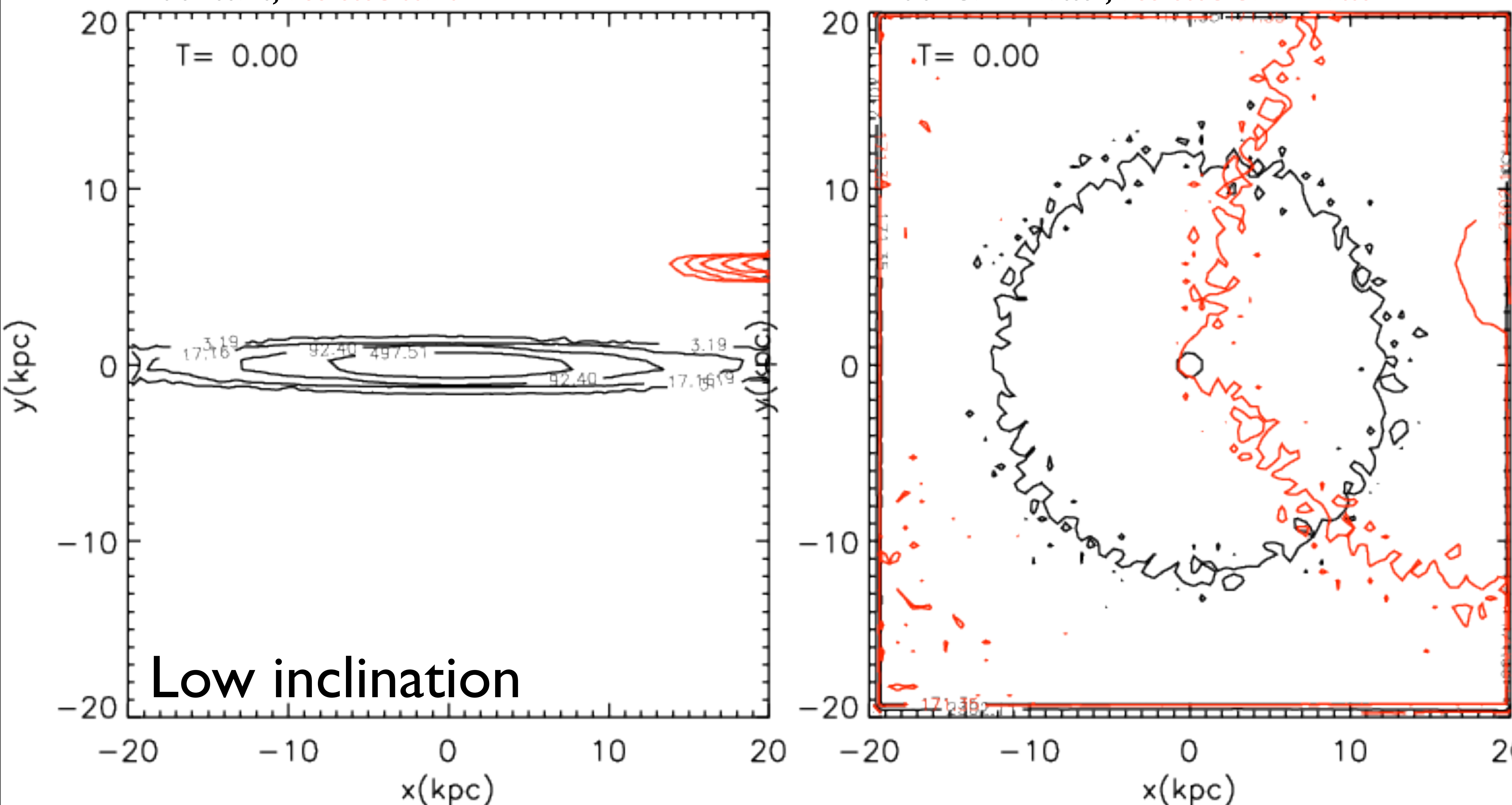
In situ dark matter; accreted dark matter

Low inclination

Read et al., MNRAS 2008; arXiv:0803.2714; and see also Villalobos & Helmi 2008 (VH08)

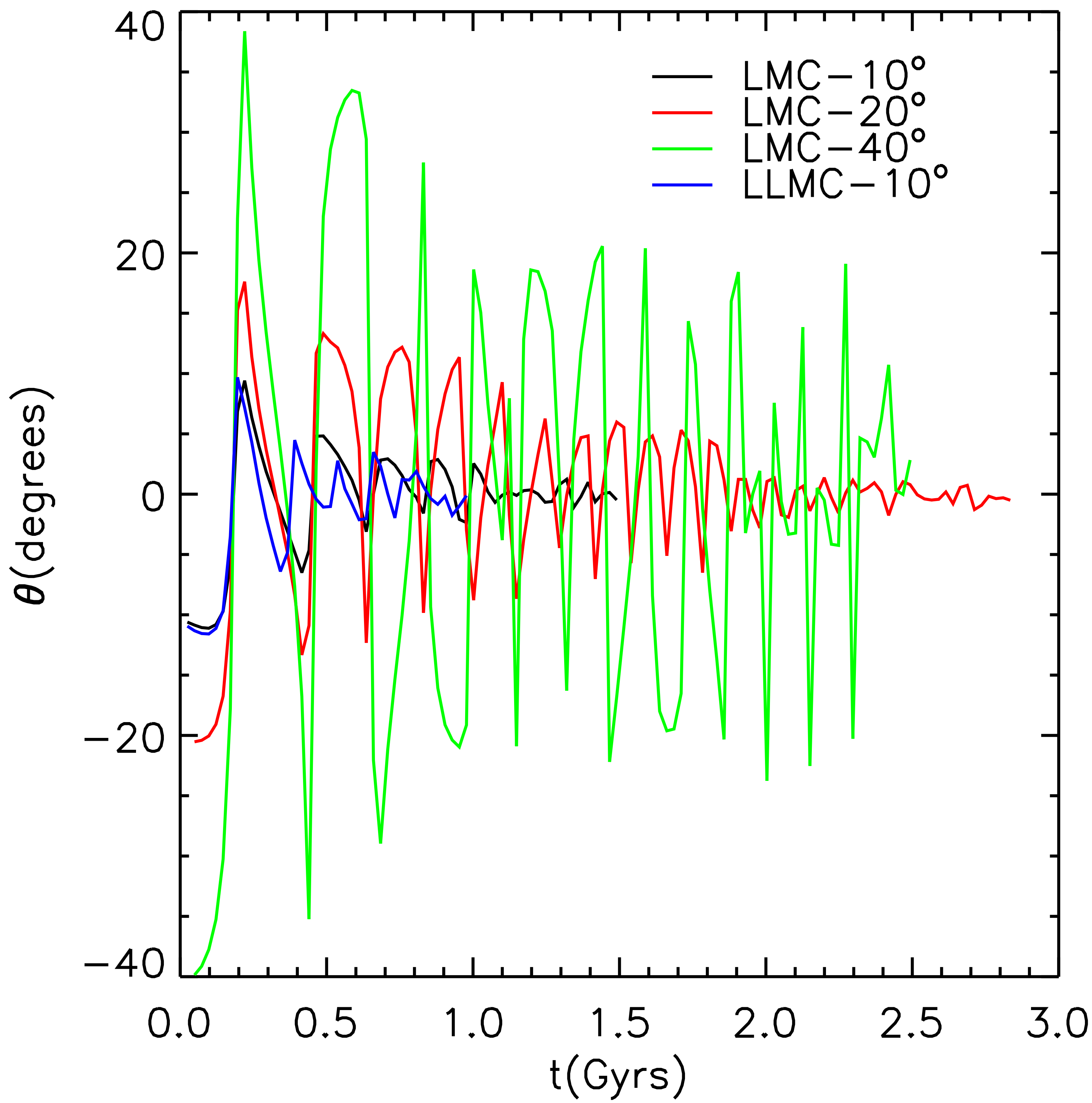
Approach I | A dark matter disc in the Milky Way

In situ stars; accreted stars *In situ dark matter; accreted dark matter*



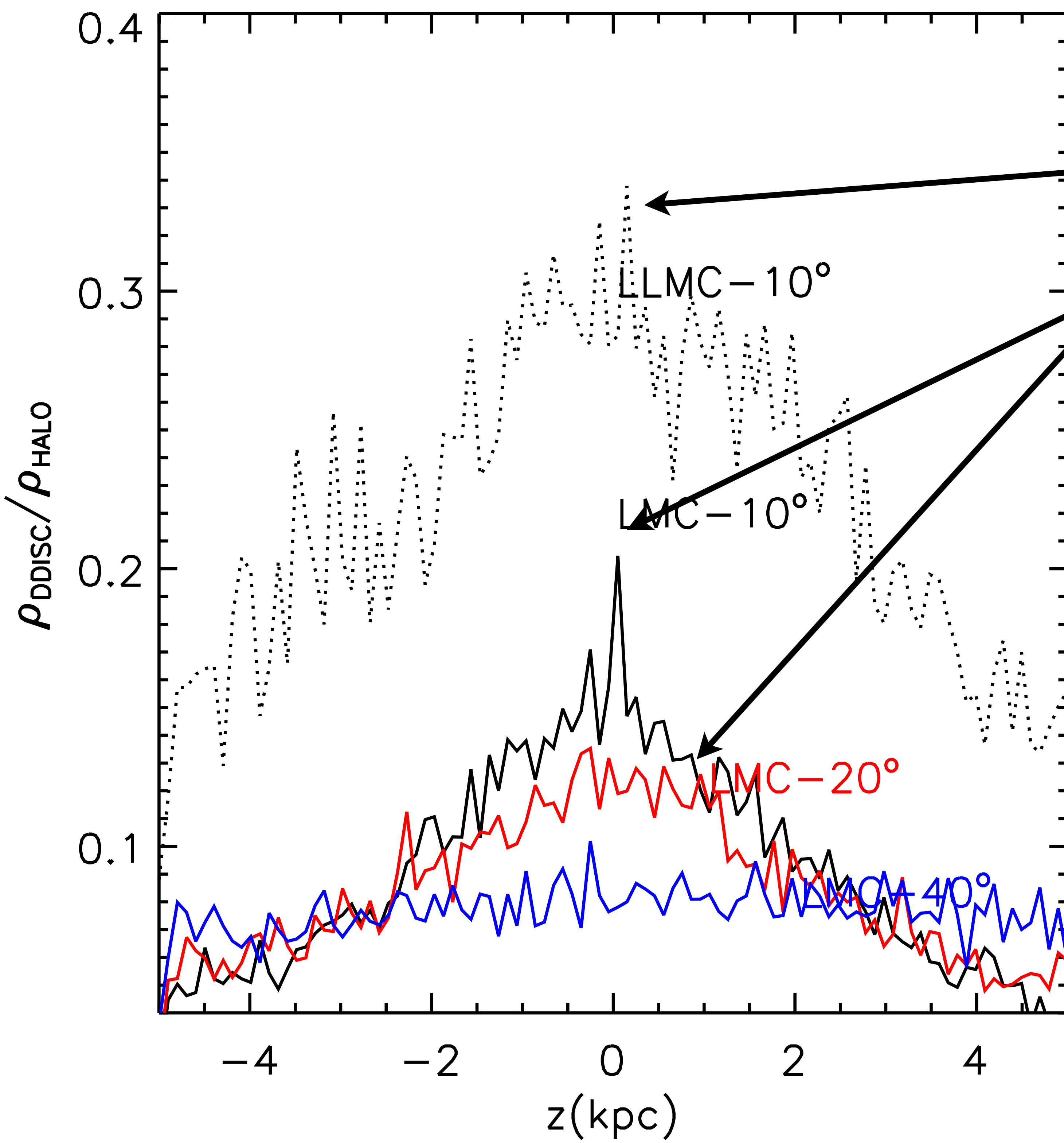
Read et al., MNRAS 2008; arXiv:0803.2714; and see also Villalobos & Helmi 2008 (VH08)

Approach I | Disc-plane dragging



Read et al., MNRAS 2008; arXiv:0803.2714

Approach I | Quantifying the dark disc



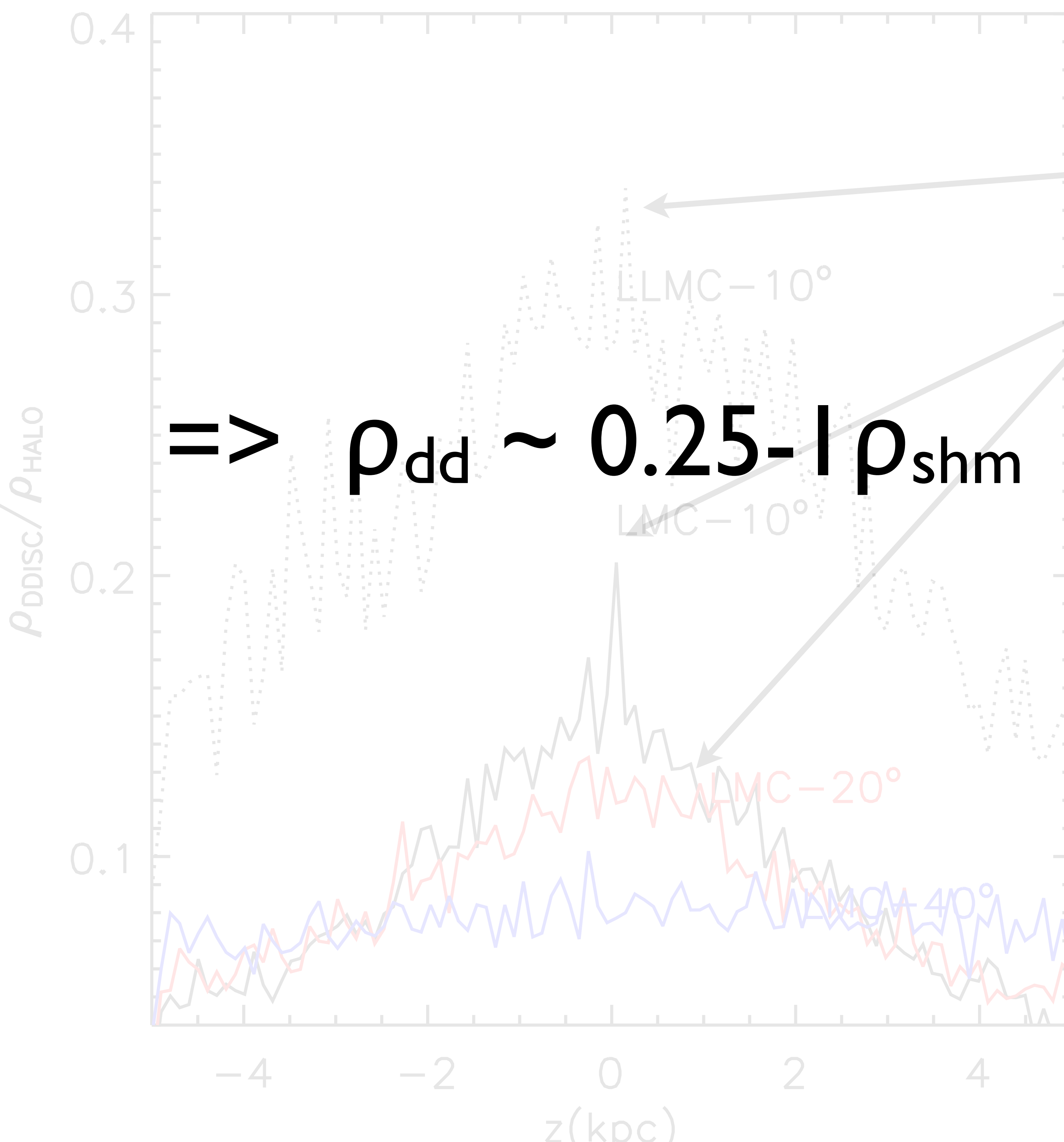
For <20^0:

0-1 > 80 km/s

2-3 > 60km/s

Read et al., MNRAS 2008; arXiv:0803.2714

Approach 1 | Quantifying the dark disc



For <20^0:

0-1 > 80 km/s

2-3 > 60km/s

=> $\rho_{dd} \sim 0.25\text{-}1\,\rho_{shm}$

Read et al., MNRAS 2008; arXiv:0803.2714

Approach II | Cosmological hydrodynamical simulations

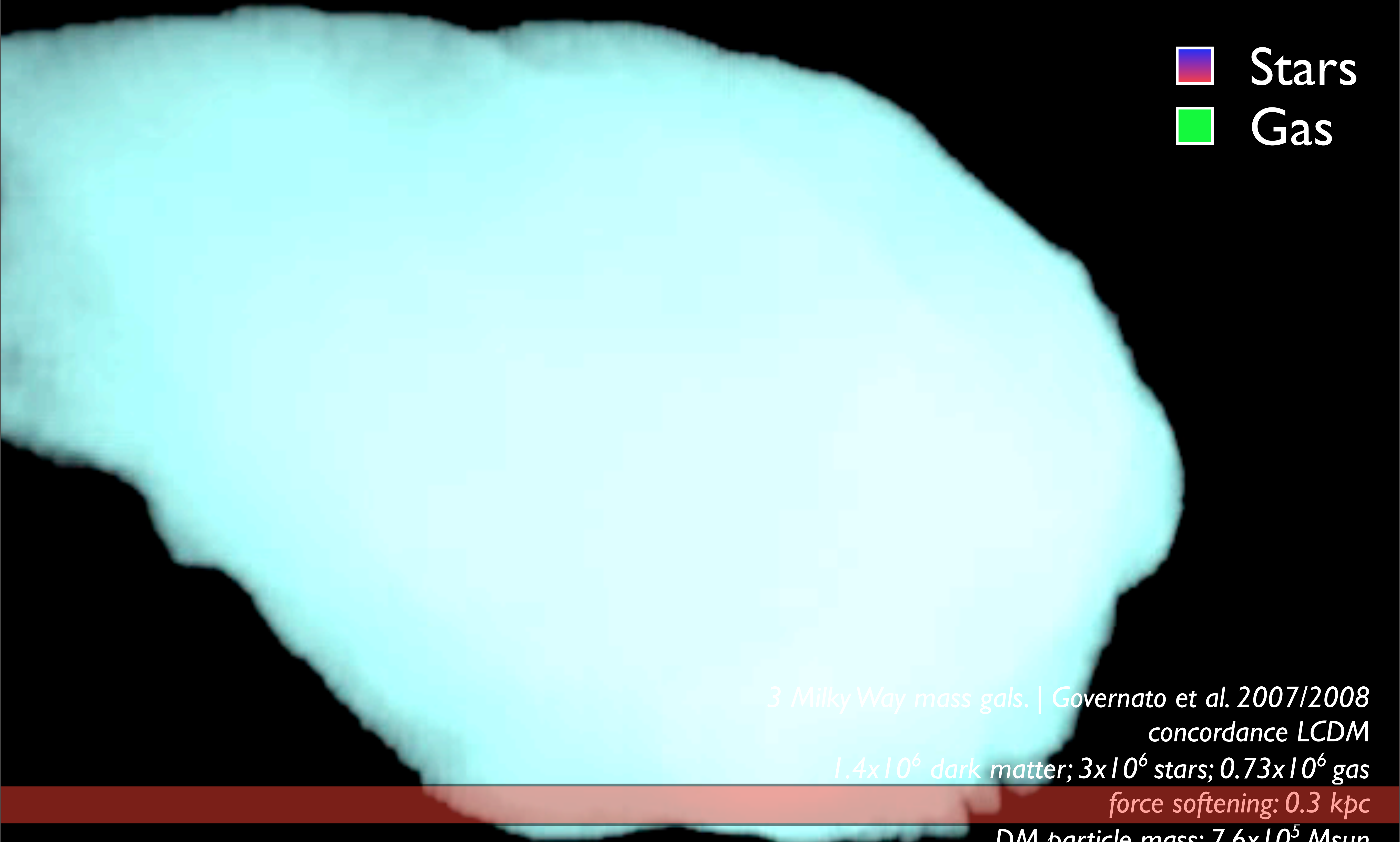
Stars

Gas

3 Milky Way mass gals. | Governato et al. 2007/2008
concordance LCDM
1.4×10^6 dark matter; 3×10^6 stars; 0.73×10^6 gas
force softening: 0.3 kpc
DM particle mass: 7.6×10^5 Msun
star particle mass: 0.23×10^5 Msun
gas particles mass: 0.34×10^5 Msun

Read et al., MNRAS 2009; arXiv:0902.0009

Approach II | Cosmological hydrodynamical simulations



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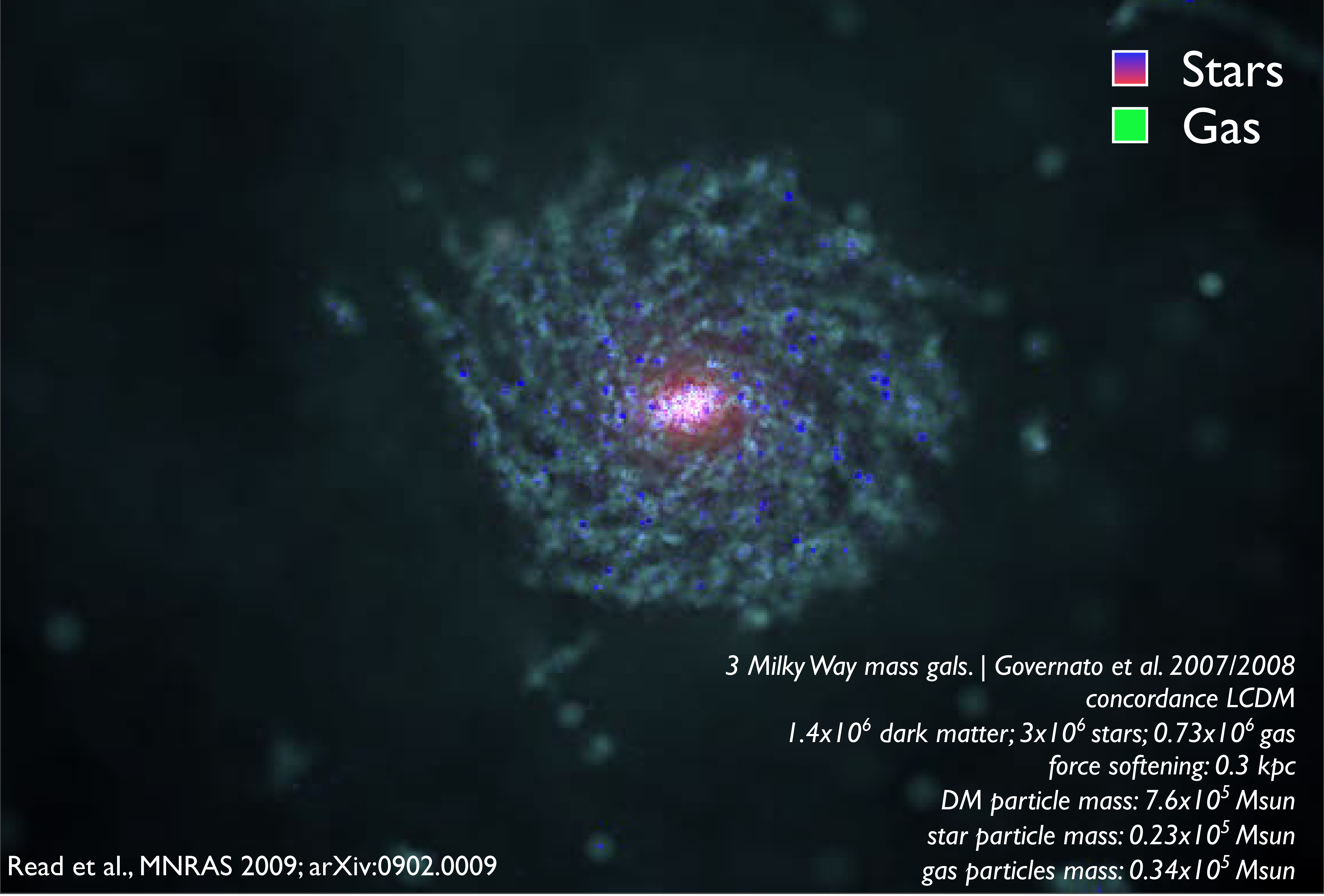

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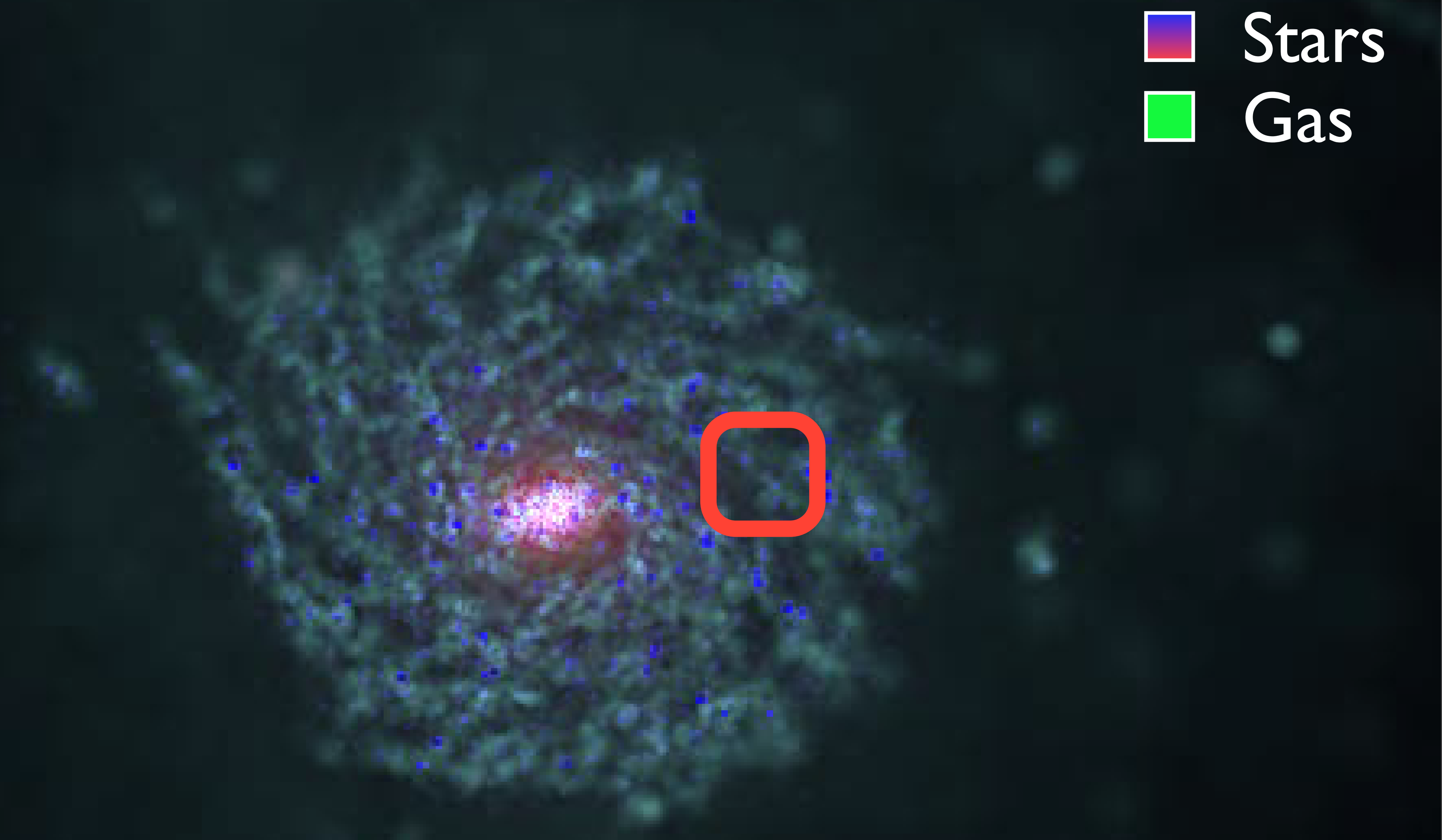
Read et al., MNRAS 2009; arXiv:0902.0009

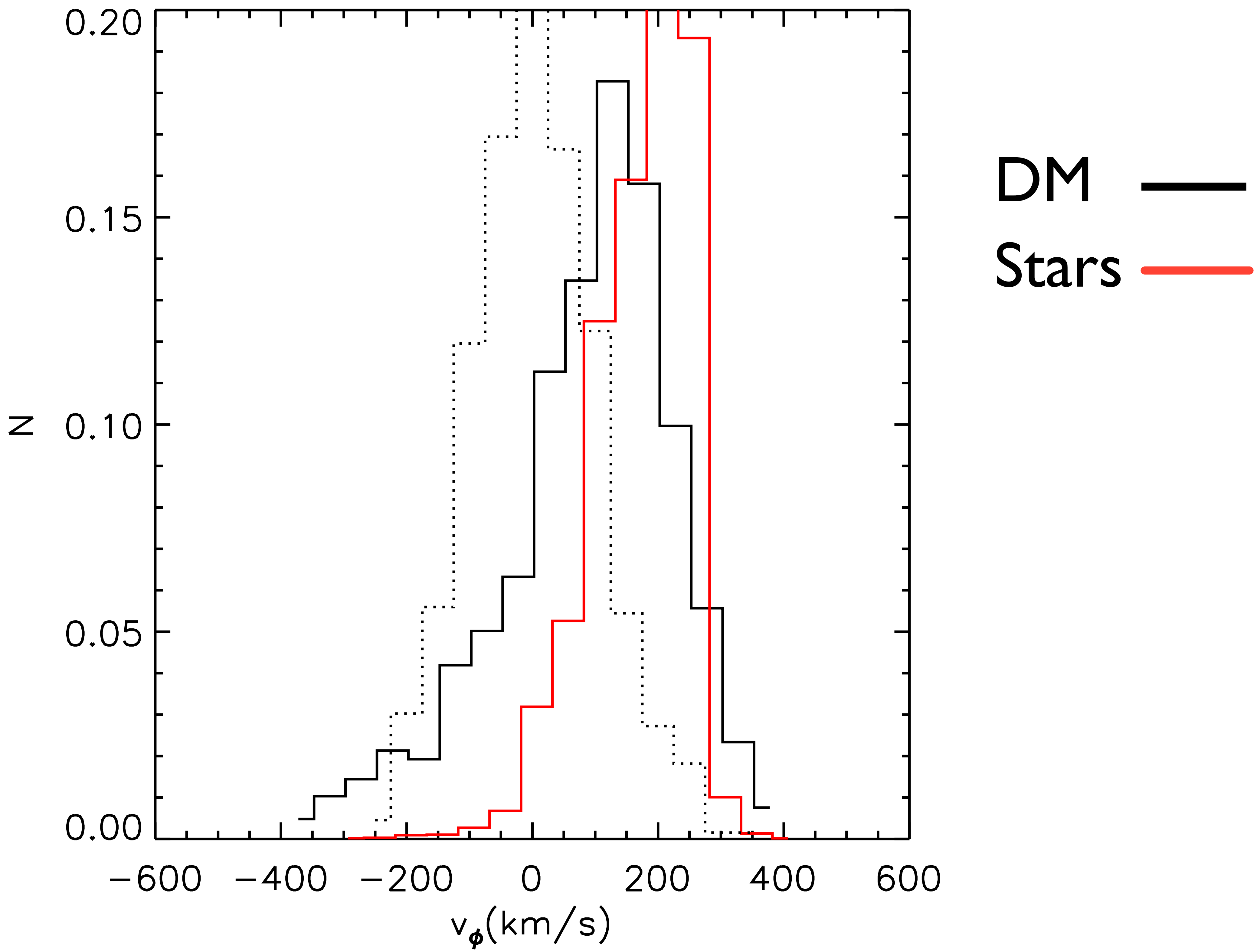
Approach II | Cosmological hydrodynamical simulations



3 Milky Way mass gals. | Governato et al. 2007/2008
concordance LCDM
1.4×10^6 dark matter; 3×10^6 stars; 0.73×10^6 gas
force softening: 0.3 kpc
DM particle mass: 7.6×10^5 Msun
star particle mass: 0.23×10^5 Msun
gas particles mass: 0.34×10^5 Msun

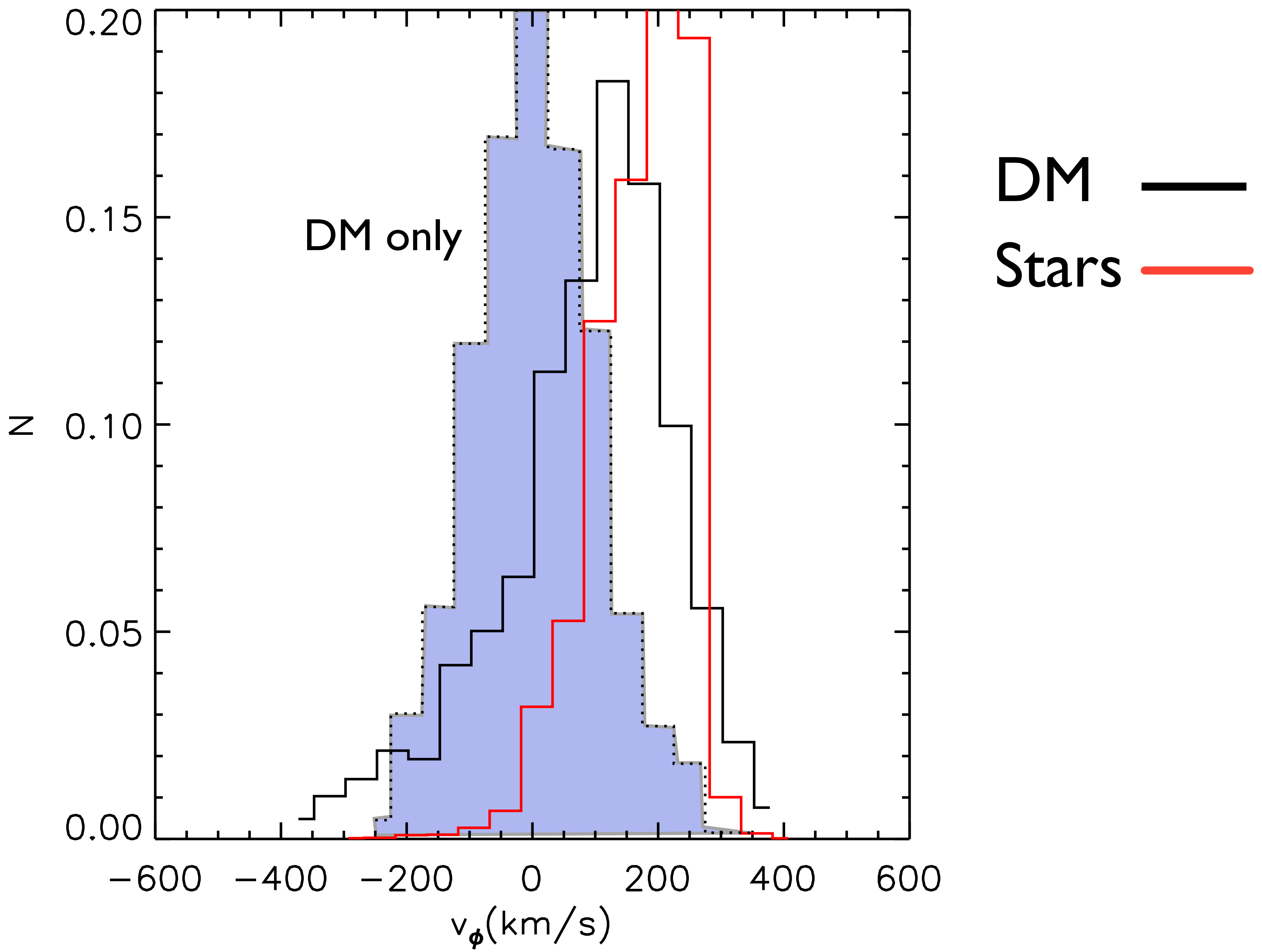
Read et al., MNRAS 2009; arXiv:0902.0009

Approach II | A disc of dark matter again!



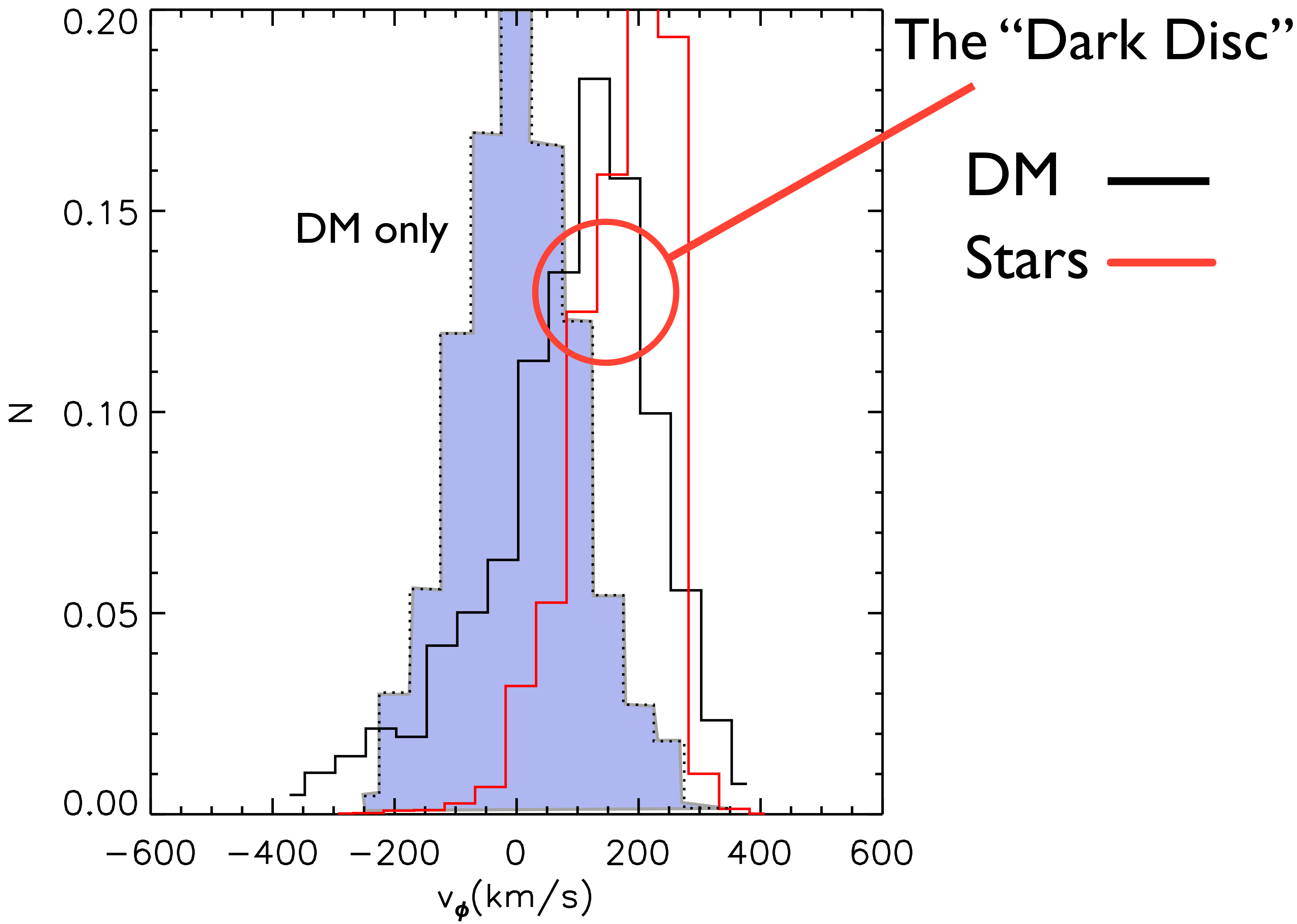
Read et al., MNRAS 2009; arXiv:0902.0009

Approach II | A disc of dark matter again!



Read et al., MNRAS 2009; arXiv:0902.0009

Approach II | A disc of dark matter again!



Read et al., MNRAS 2009; arXiv:0902.0009

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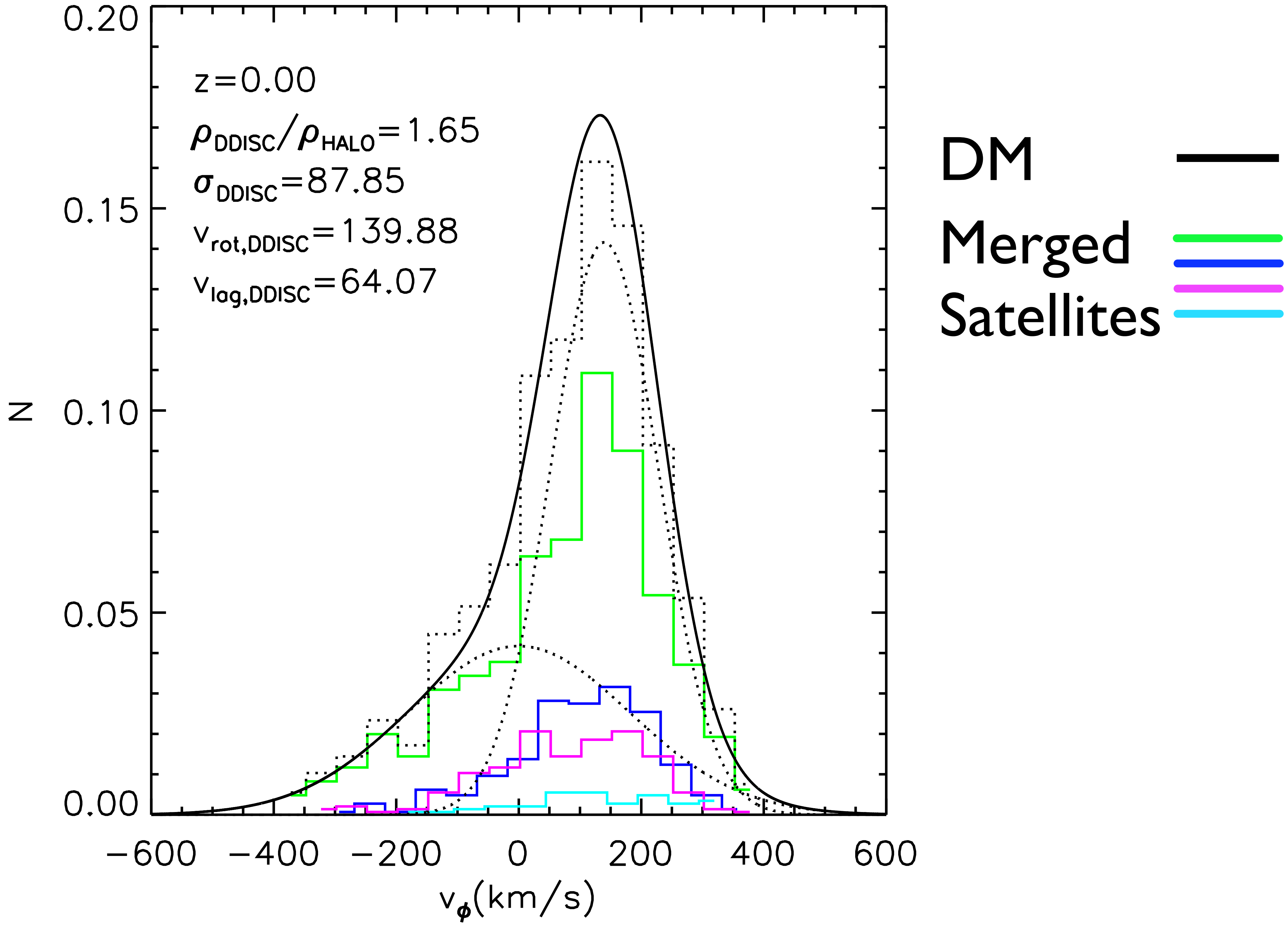

Read et al., MNRAS 2009; arXiv:0902.0009

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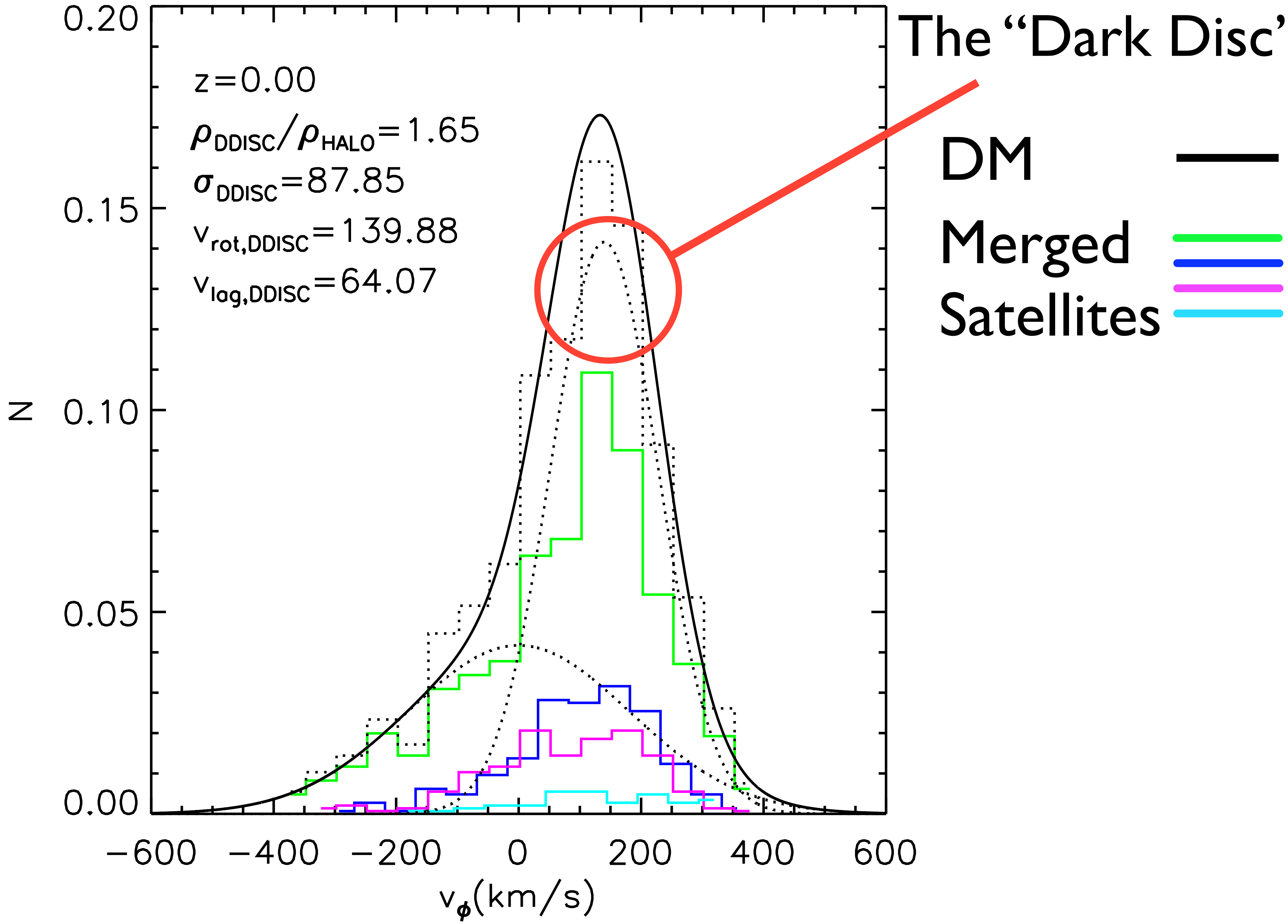

Read et al., MNRAS 2009; arXiv:0902.0009

Summary | Dark disc properties

ρ_{dd}/ρ_{shm} = 0.25-1.5 ; v_{dd} = 0-150km/s ; σ_{dd} = 50-90km/s

=> ~Isotropic rotating double Gaussian in the Galactic frame:

$$f(v_\phi) = \rho_{\rm dm}\left[(1-\frac{\rho_{\rm dd}}{\rho_{\rm shm}})\exp\left(-\frac{v_\phi^2}{2\sigma^2}\right) + \frac{\rho_{\rm dd}}{\rho_{\rm shm}}\exp\left(-\frac{(v_\phi - v_{\rm dd})^2}{2\sigma_{\rm dd}^2}\right)\right]$$

Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896; Bruch, Peter, Read, Baudis & Lake, 2009; arXiv:0902.4001

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Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896; Bruch, Peter, Read, Baudis & Lake, 2009; arXiv:0902.4001

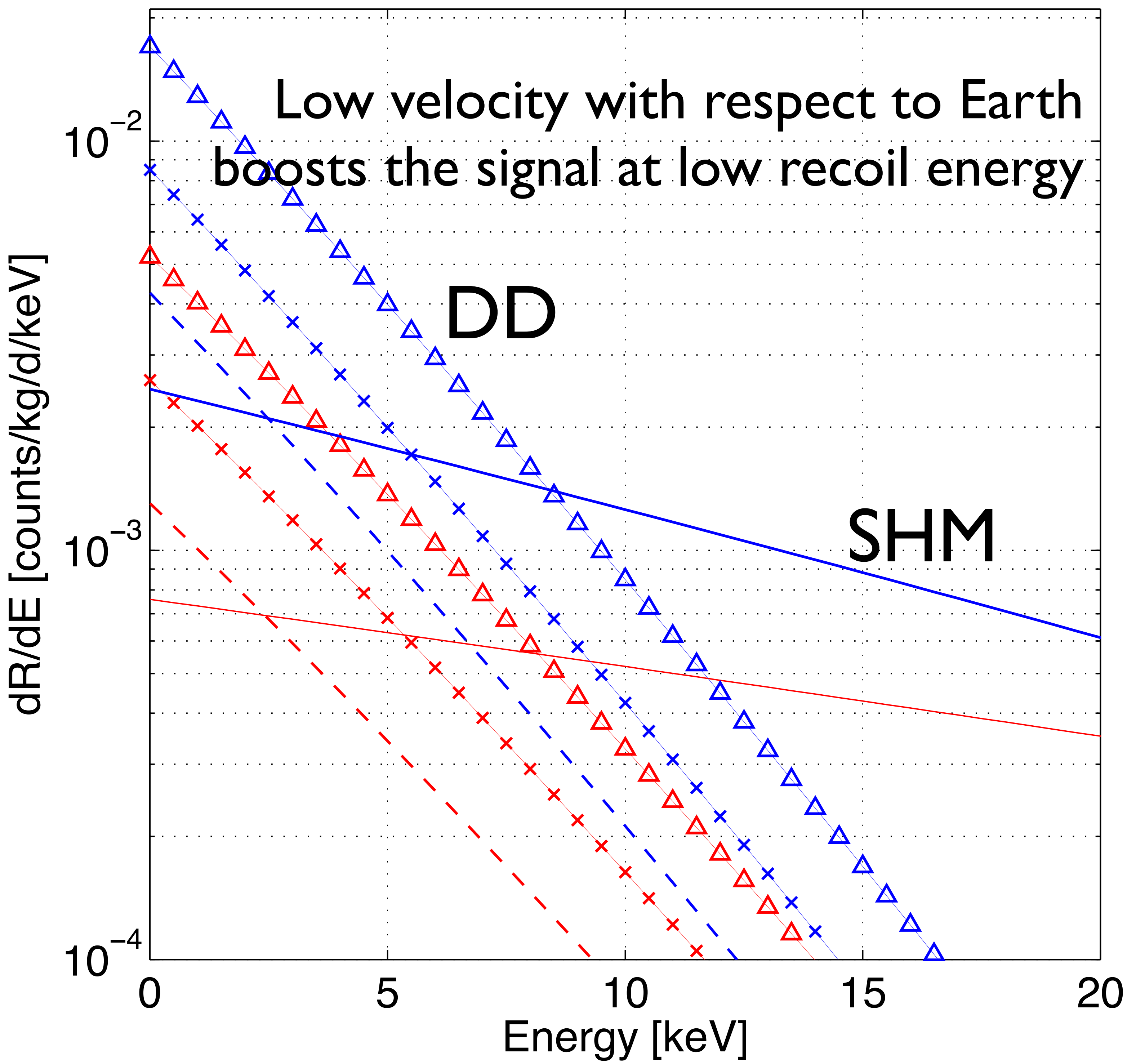
Summary | Dark disc implications

$\rho_{dd} = 0.25\text{-}1.5\rho_{shm}$; $v_{lag} = 0\text{-}150$km/s ; $\sigma = 50\text{-}90$km/s

- Boosts the direct detection signal at low recoil energy by a factor ~3 in the 5-20keV range,
- Shifts the phase of the annual modulation signal allowing the WIMP mass to be determined,
- Significantly boosts WIMP capture in the Sun and Earth by factors of ~10 and ~1000, respectively,
- Increases the possibility of detecting dark matter in the near future.

Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896; Bruch, Peter, Read, Baudis & Lake, 2009; arXiv:0902.4001

Dark disc implications | Direct dark matter detection



Xe; Ge

100GeV

10^{-8}pb

ρ_{dd}/ρ_{shm}

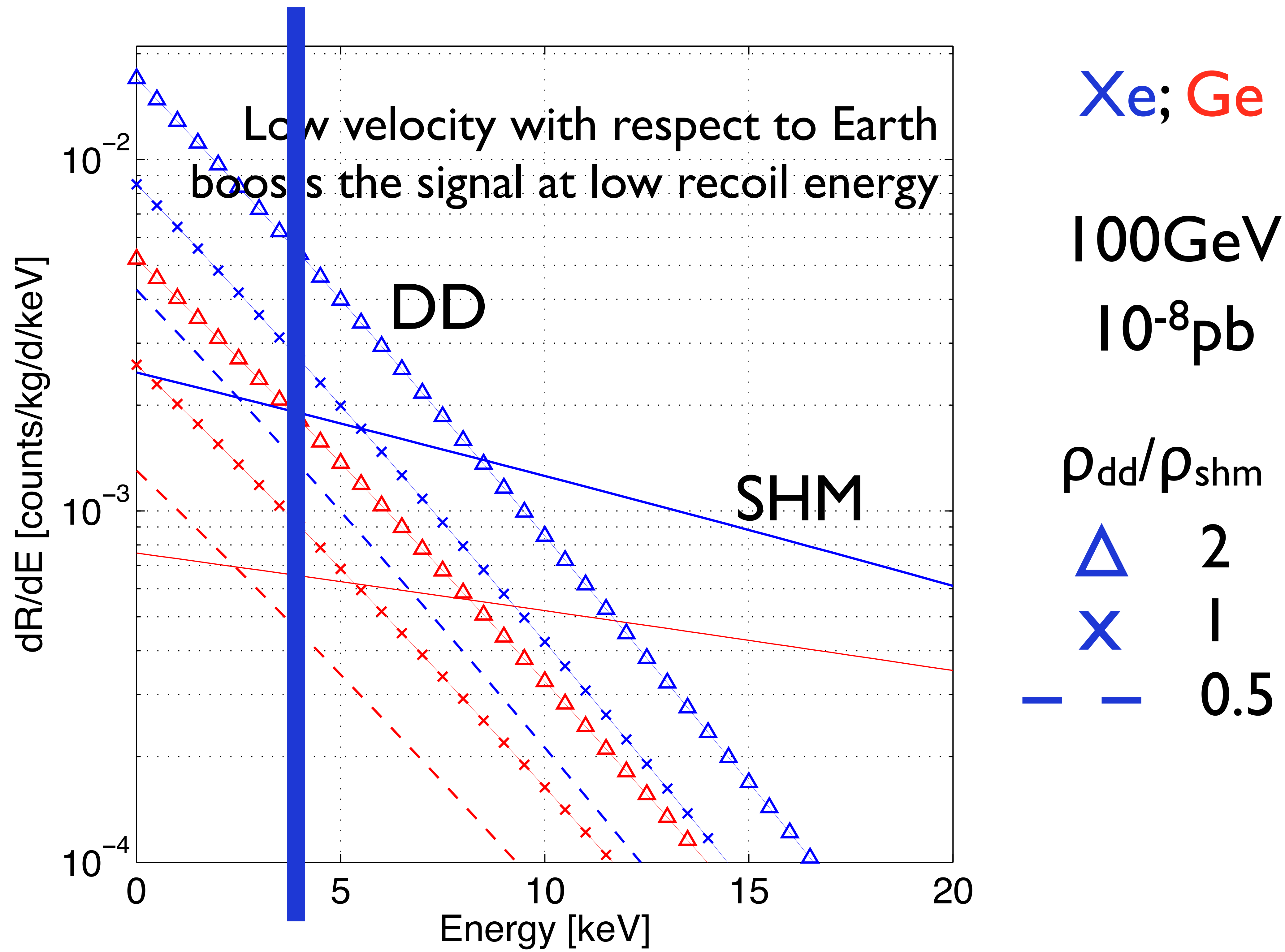
△ 2

× 1

– – 0.5

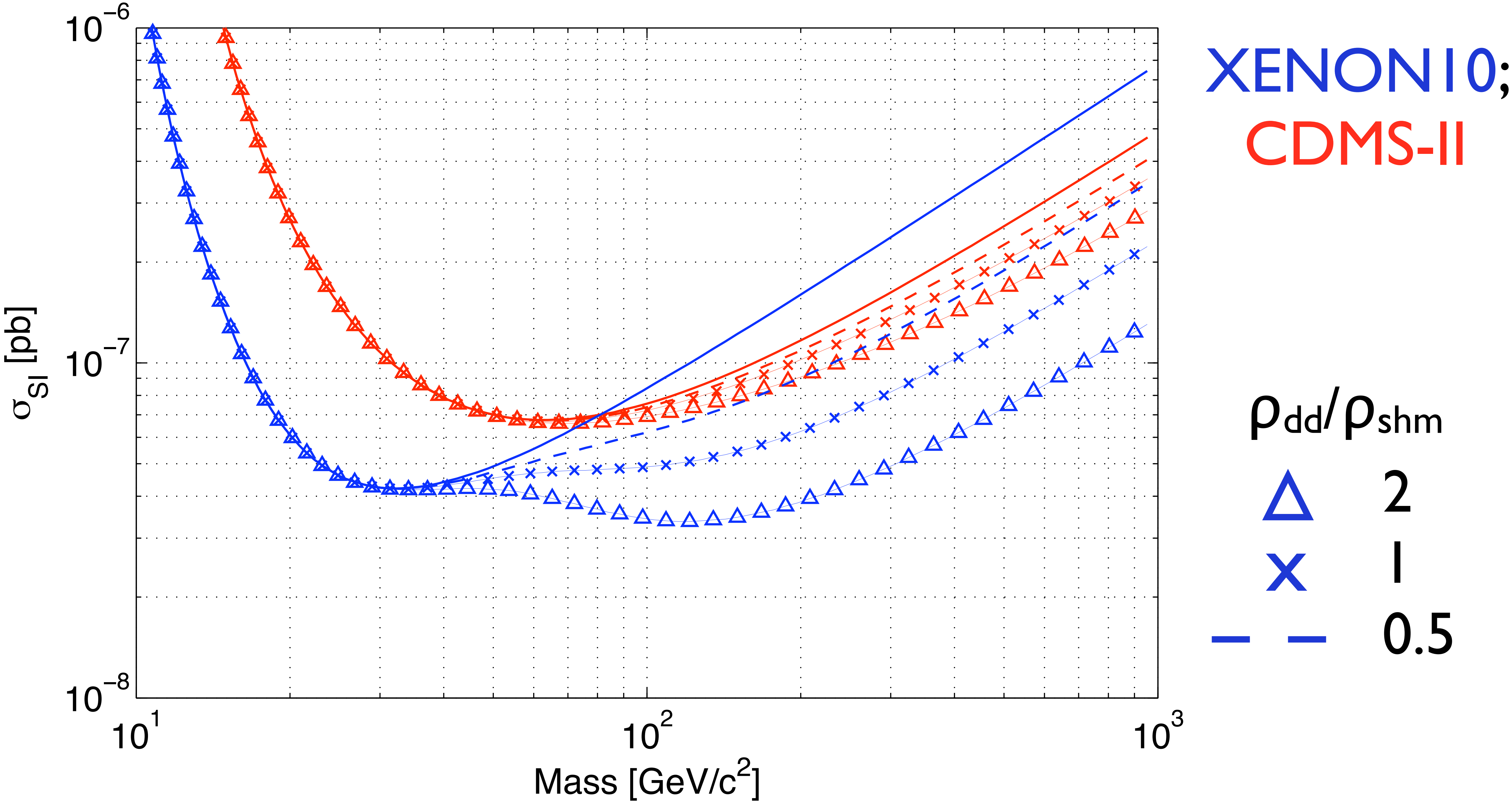
Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896

Dark disc implications | Direct dark matter detection



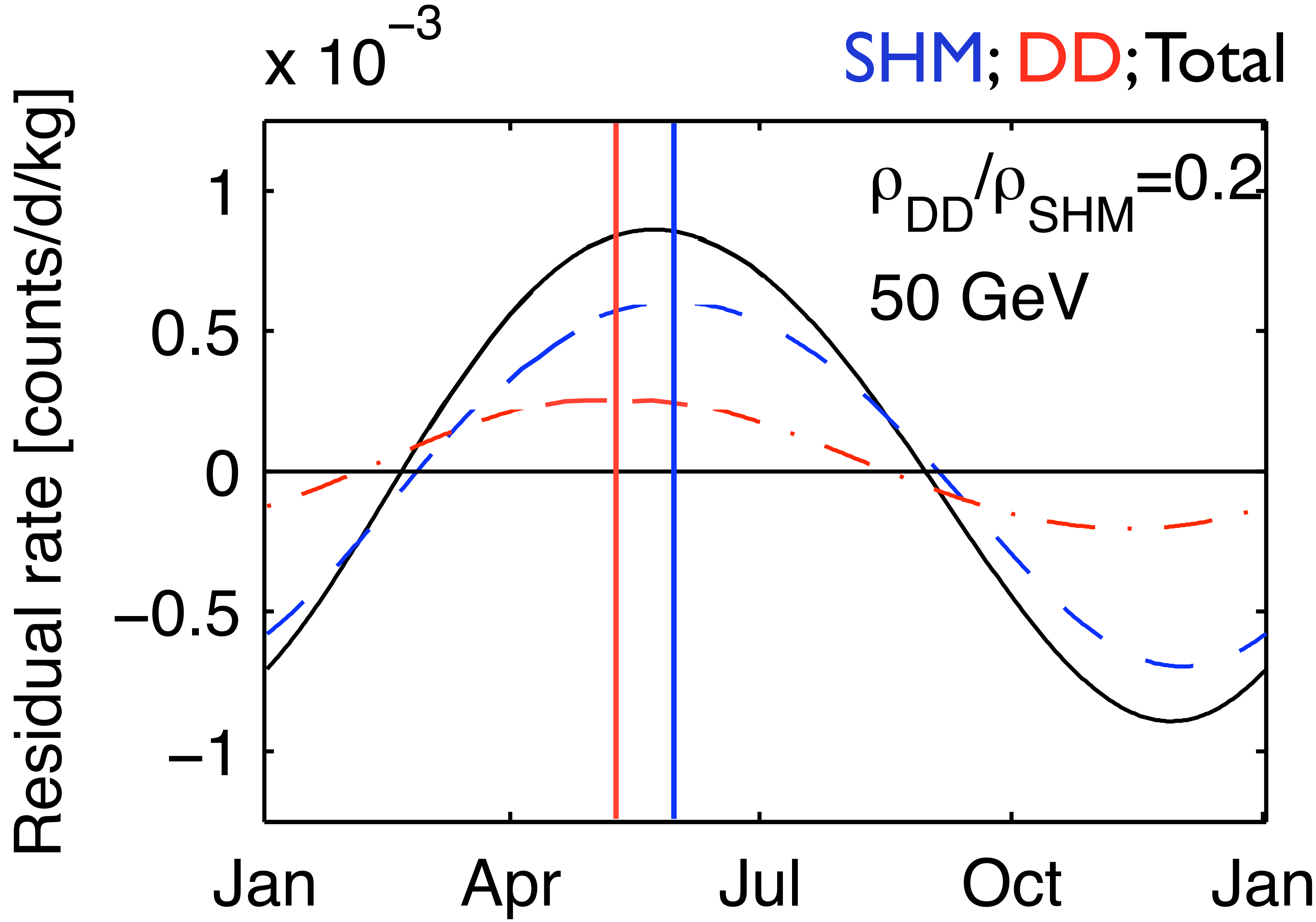
Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896

Dark disc implications | Direct dark matter detection



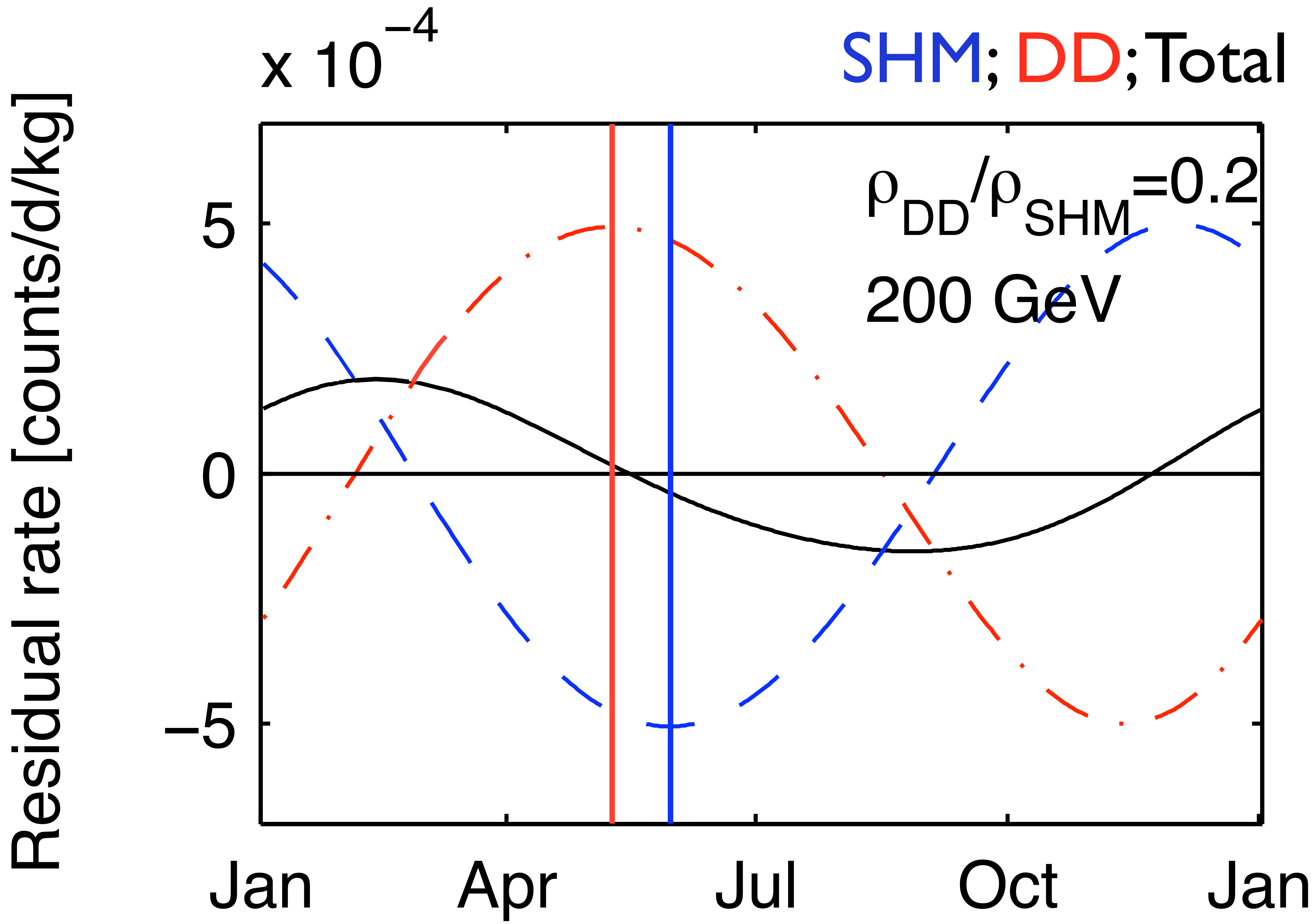
Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896

Dark disc implications | Annual modulation signal



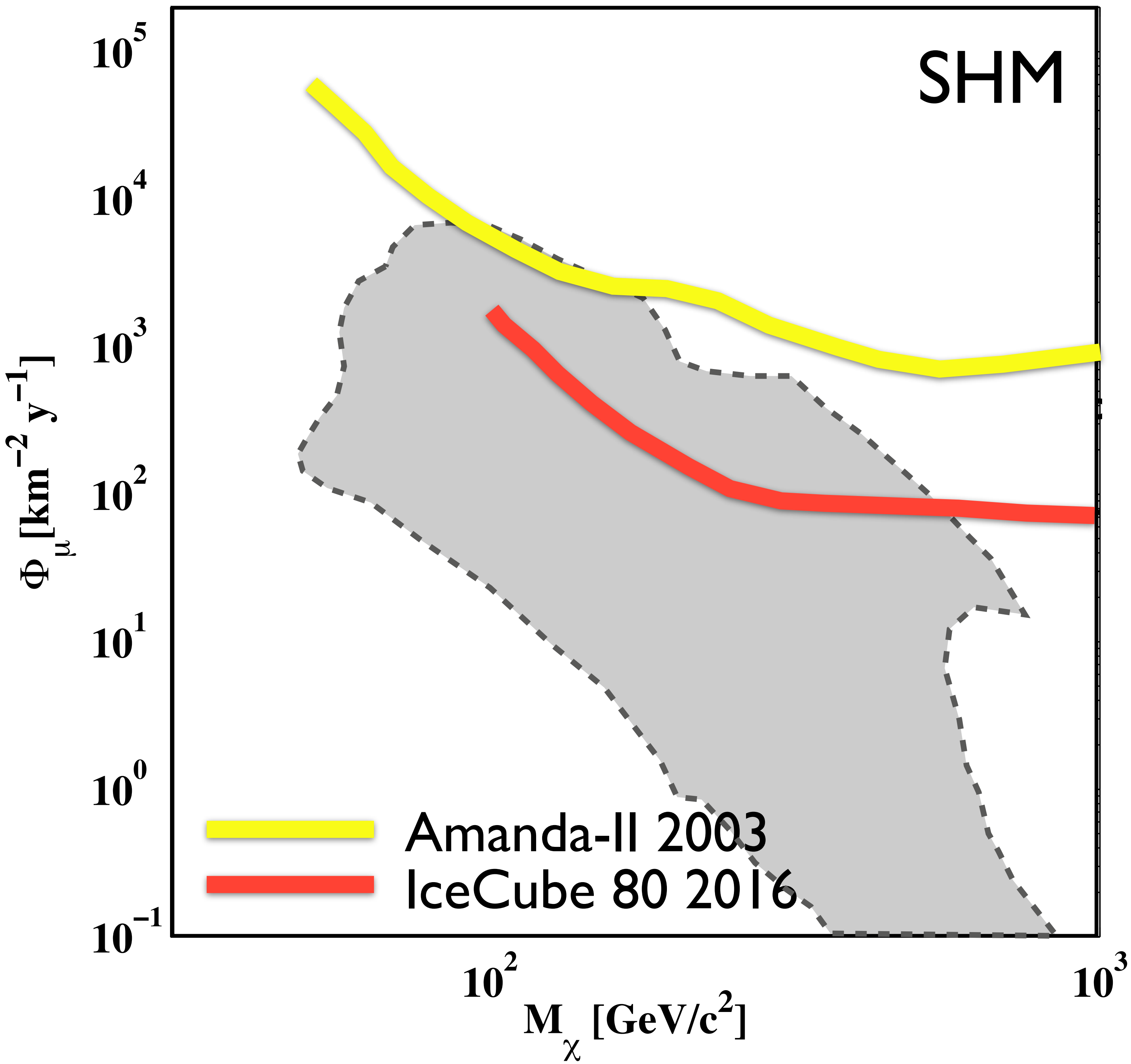
Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896

Dark disc implications | Annual modulation signal



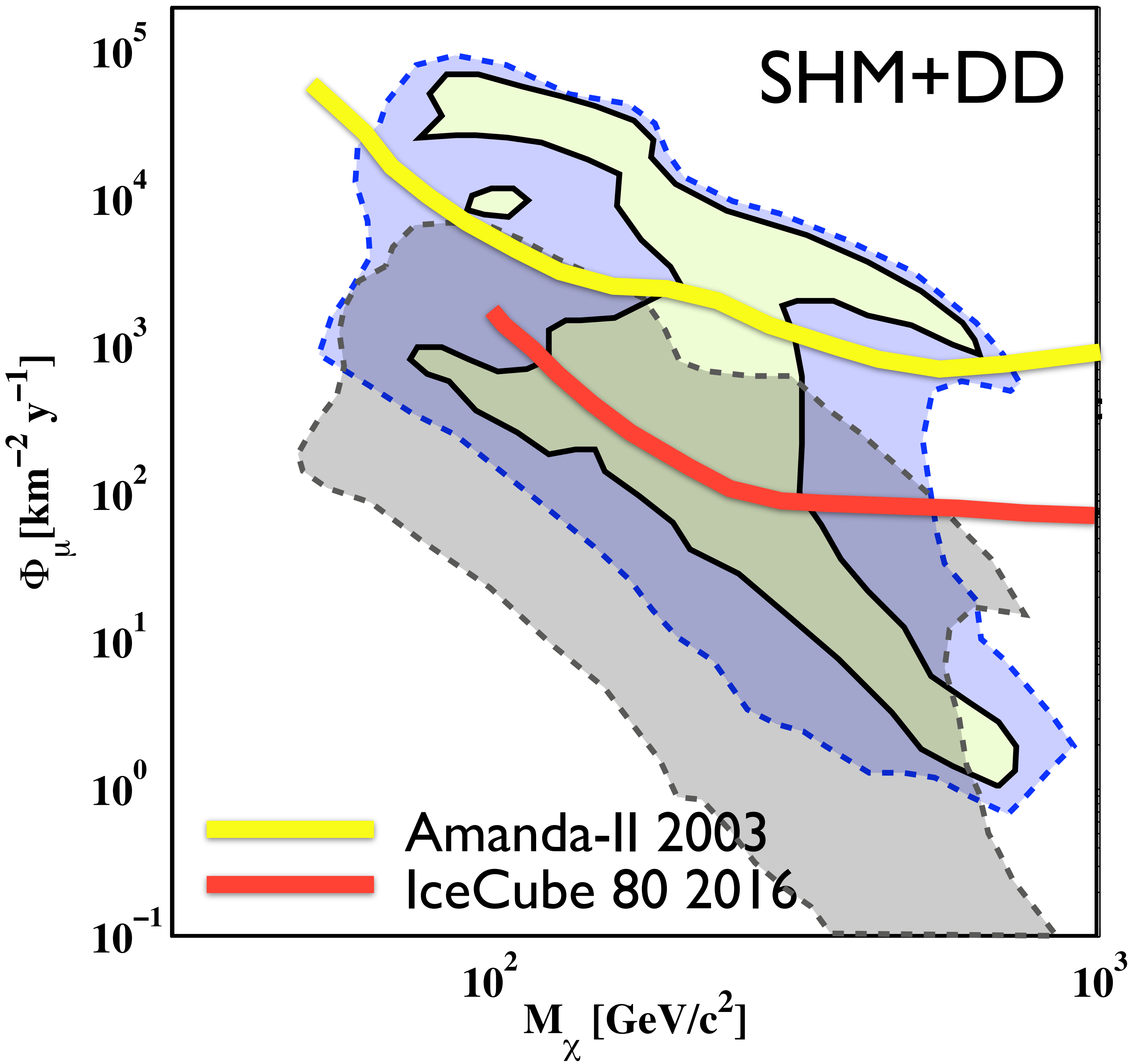
Bruch, Read, Baudis & Lake, 2009; arXiv:0804.2896

Dark disc implications | Sun dark matter capture



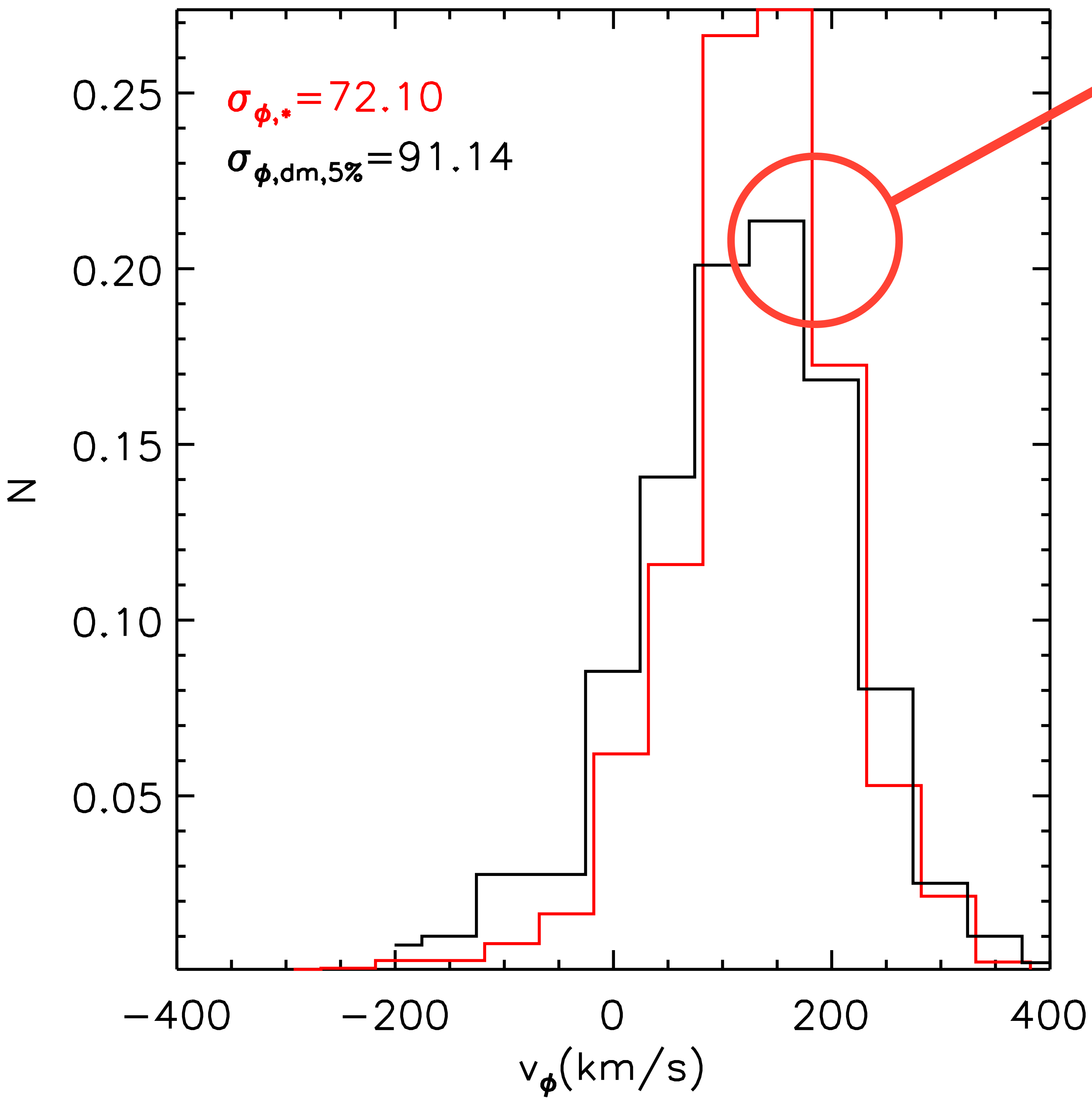
Bruch, Peter, Read, Baudis & Lake, 2009; arXiv:0902.4001

Dark disc implications | Sun dark matter capture



Bruch, Read et al., 2008/9

Detecting dark/accreted discs | Hunting for accreted stars



Dark disc velocity distribution matches the accreted stars

Read et al., MNRAS 2009; arXiv:0902.0009

Detecting dark/accreted discs | Hunting for accreted stars

- C. Liu et al. 2010 (in prep.): evidence for accreted stars above the Milky Way disc plane?
- Klement et al. 2009: streams in the Solar neighbourhood with disc-like kinematics - an accreted disc(s)?
- Carollo et al. 2010: 'metal weak' thick disc - an accreted disc?

- Could one or all of these be the 'smoking gun' for a dark disc?

Conclusions

- The race is on to detect WIMPs in the laboratory. For this we need to know the local dark matter density ρ_{dm} and velocity distribution f_{dm}.
- Using kinematics of Solar Neigh. stars, we obtain a [preliminary] estimate of ρ_{dm}
- To measure f_{dm}, we require numerical simulations. These must include baryonic physics. Doing so leads to a disc of dark matter in our Galaxy.
- The dark disc: boosts the direct detection signal at low recoil energy by a factor ~3 in the 5-20keV range; shifts the phase of the annual modulation signal allowing the WIMP mass to be determined; and boosts WIMP capture in the Sun and Earth by factors of ~10 and ~1000, respectively.
- We find tentative evidence for several accreted discs of stars in the Milky Way. This is the smoking gun for a dark disc.