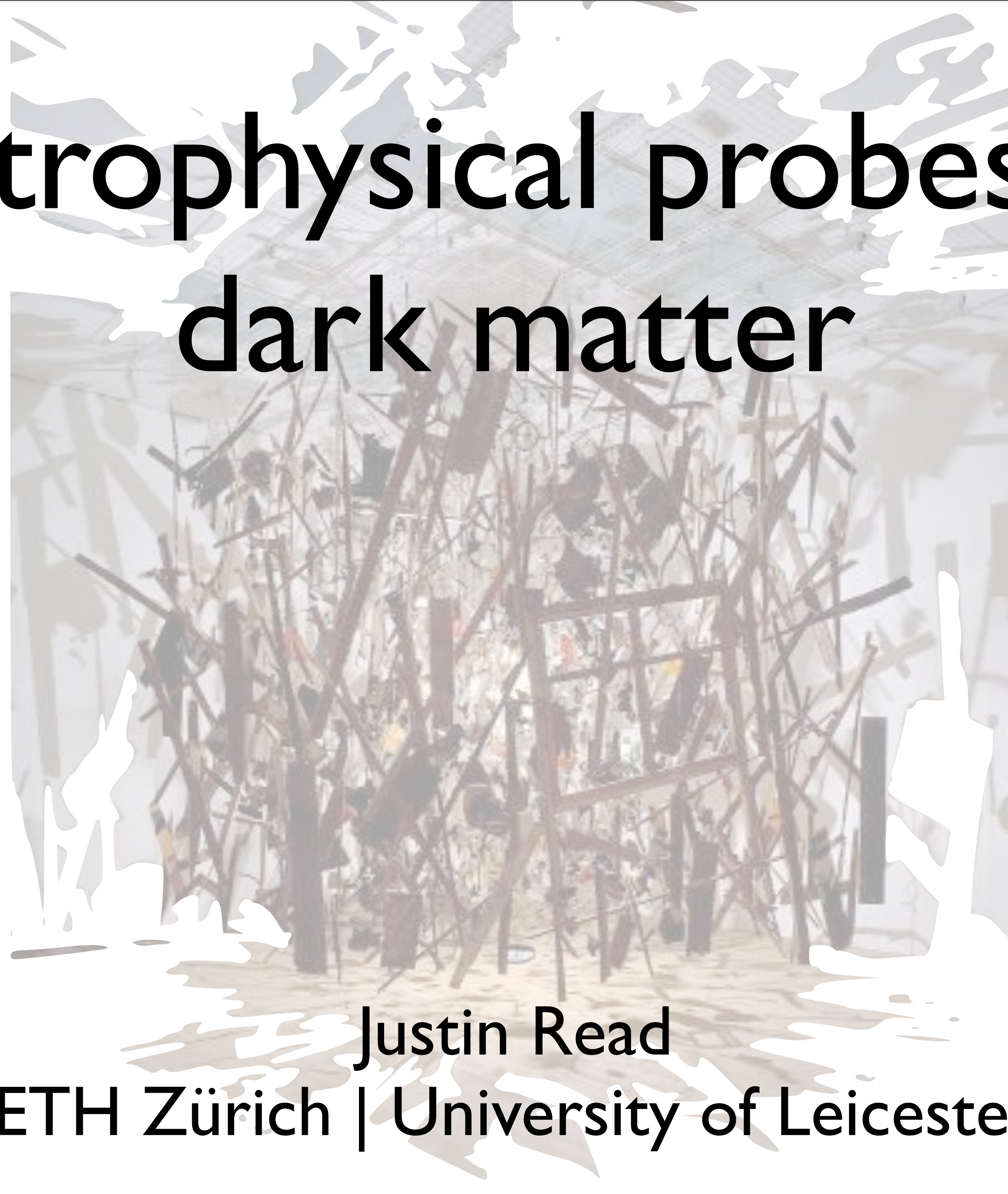
Astrophysical probes of dark matter

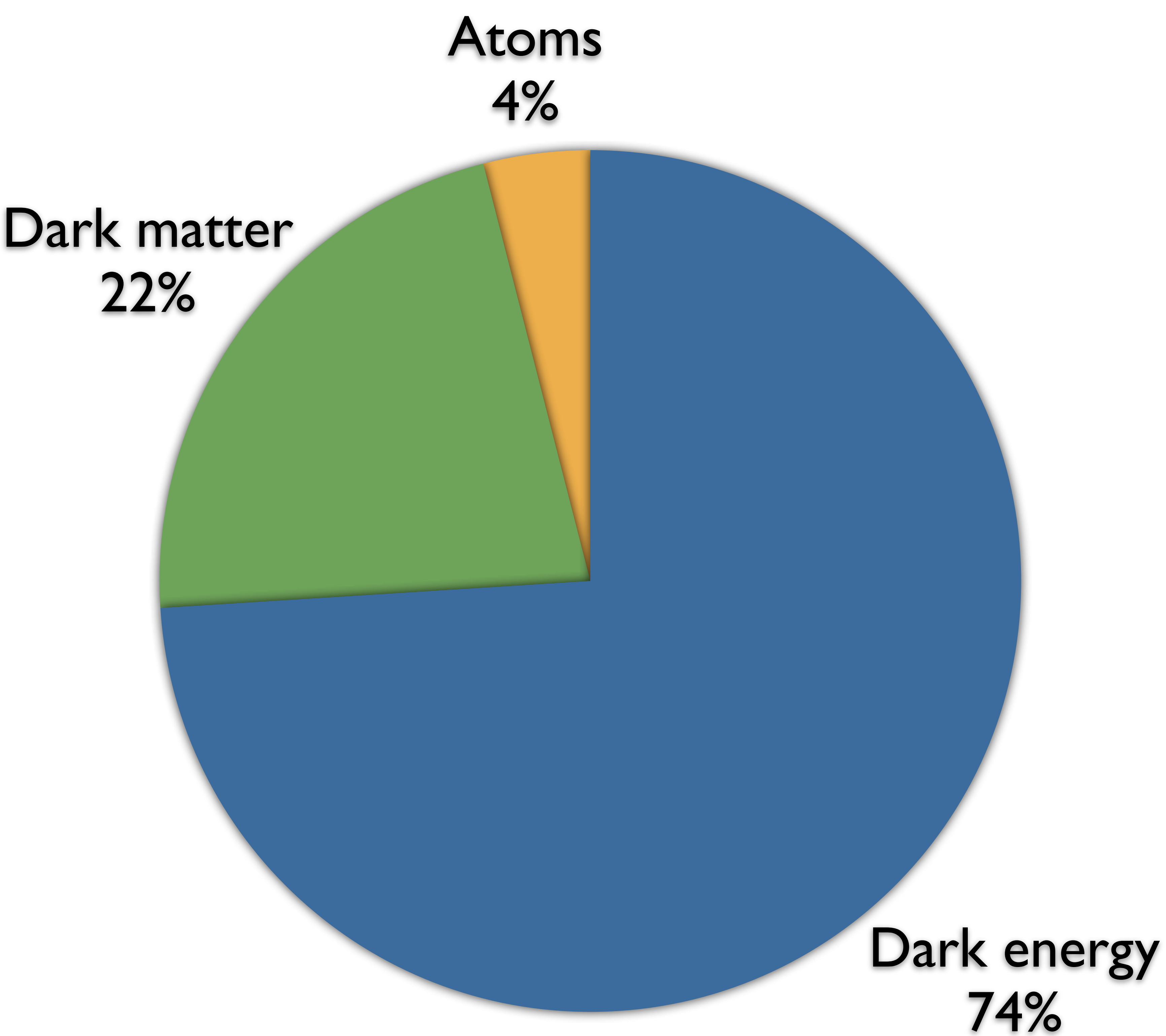


Cold Dark Matter by Cornelia Parker

Justin Read
ETH Zürich | University of Leicester

With:
Silvia Garbari, Alex Hobbs, David Cole, Walter Dehnen, Mark Wilkinson, George Lake, Lucio Mayer, Fabio Governato, Alyson Brooks, Romain Teyssier, Prasenjit Saha, Jonathan Coles

Background | The standard cosmological model LCDM



WMAP team; e.g. Dunkley et al. 2009

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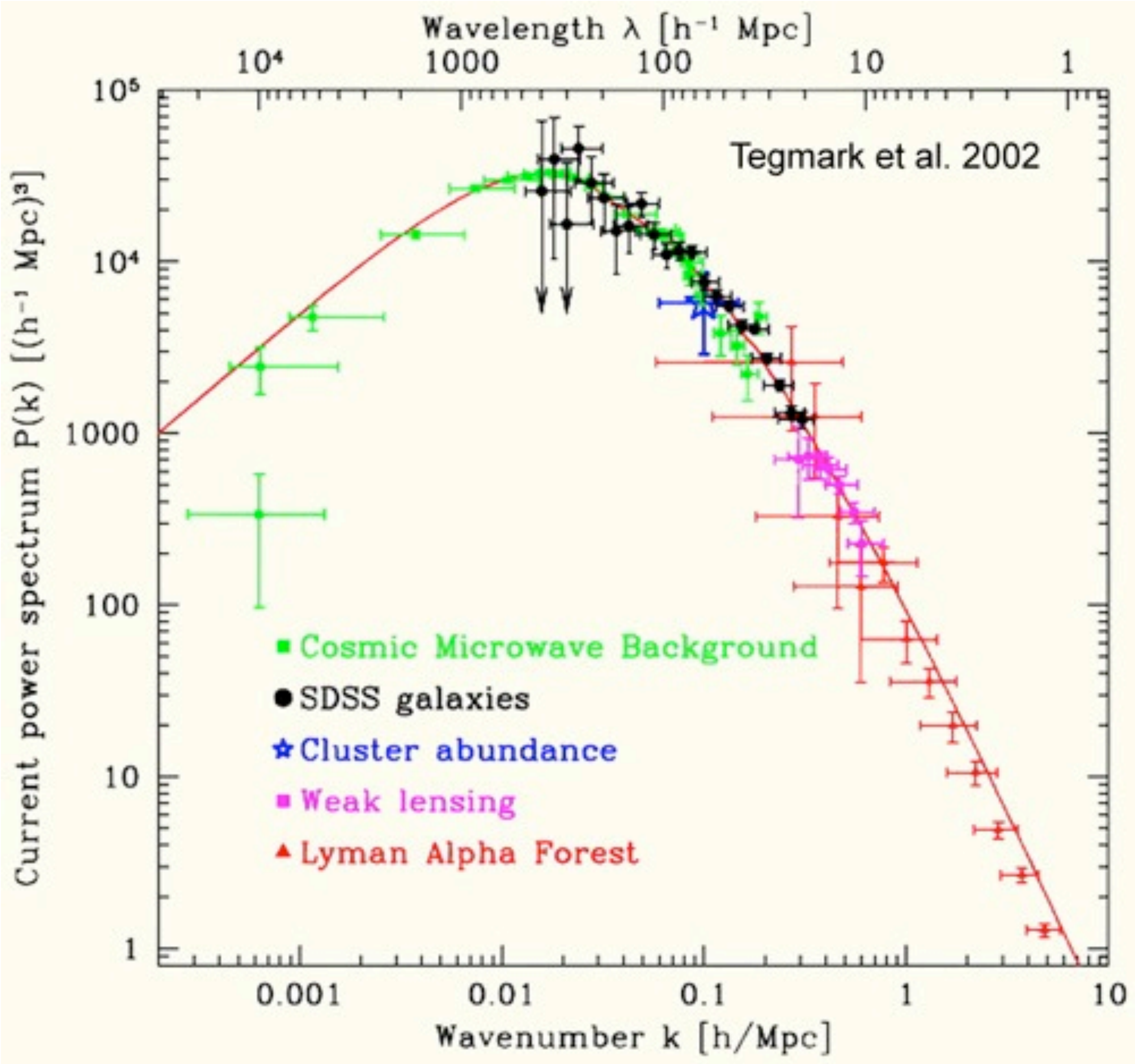


WMAP team; e.g. Dunkley et al. 2009

Probing dark matter models | Two approaches

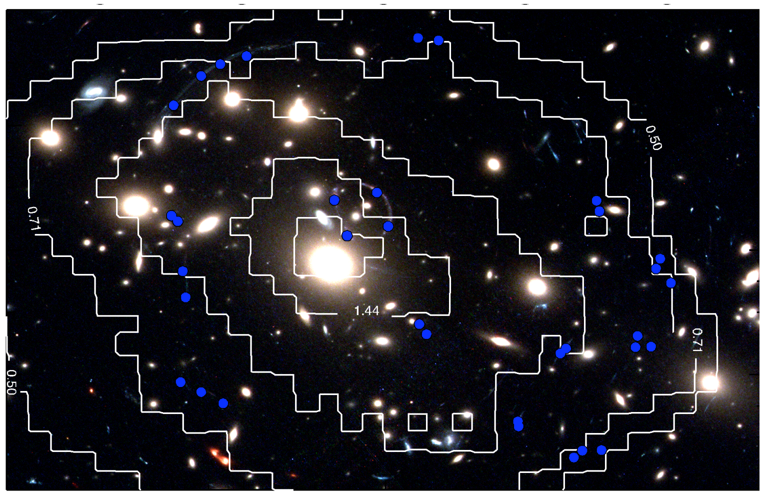
1. Gravity as a dark matter probe

Probing dark matter models | Two approaches

1. Gravity as a dark matter probe

Theory

Compare

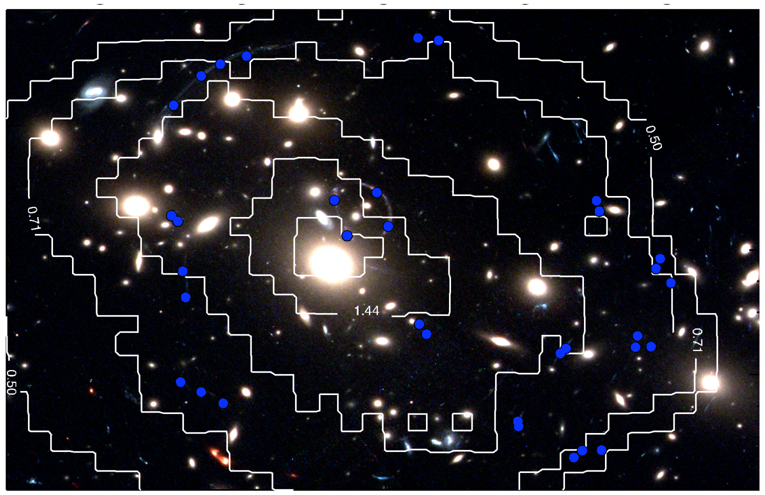


Observation

Probing dark matter models | Two approaches

1. Gravity as a dark matter probe

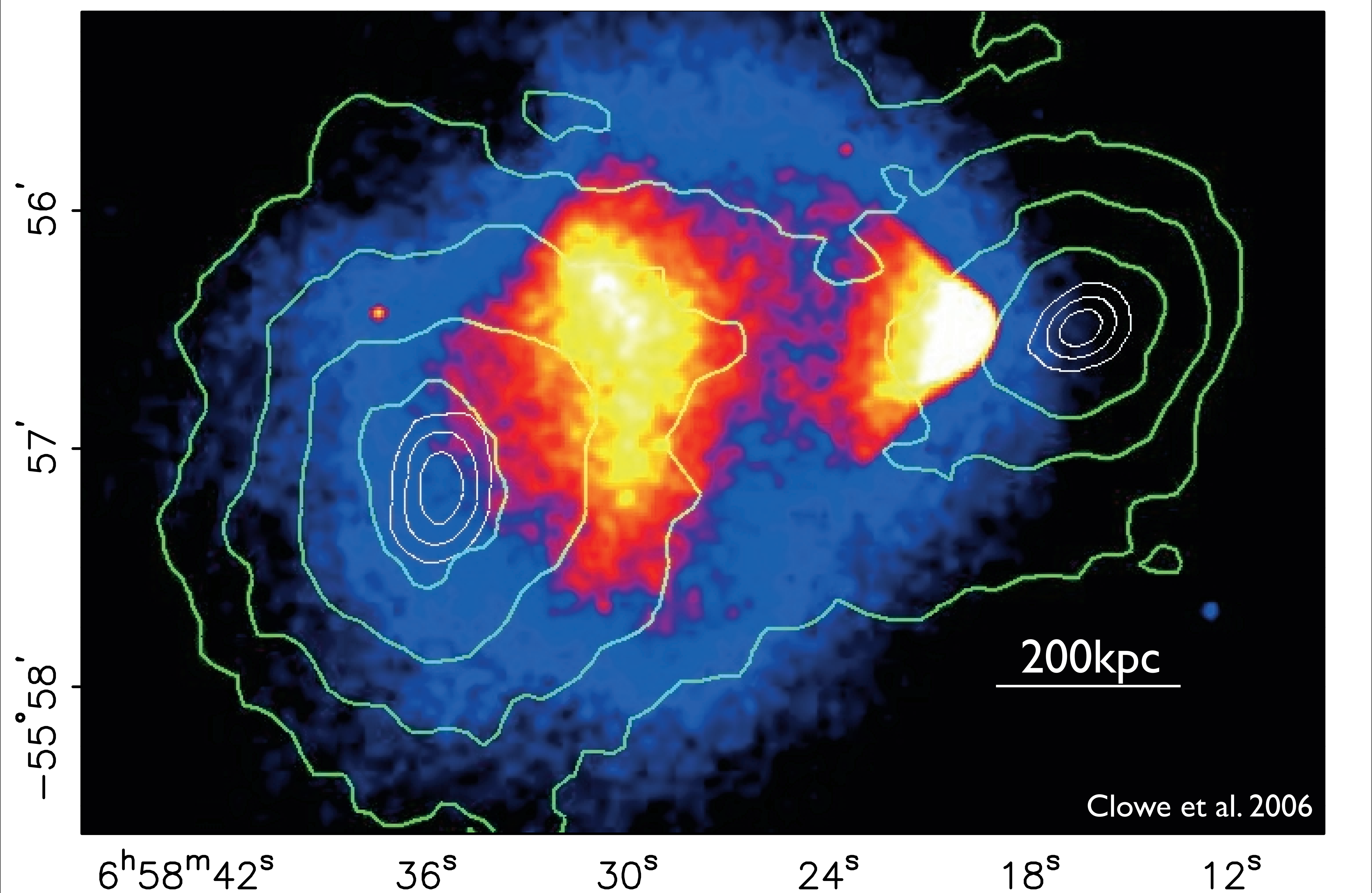
Compare



Theory

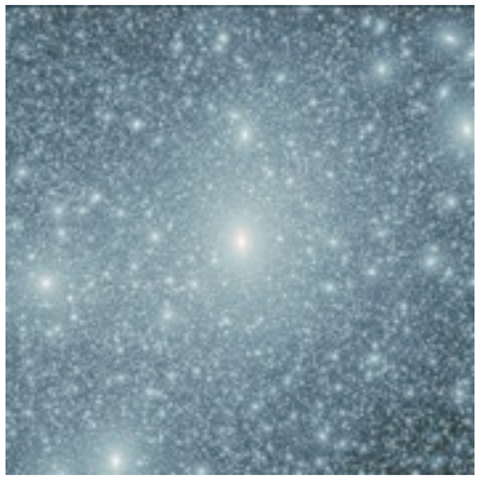
Observation

2. Dark matter as a particle


56'
57'
−55°58'
6h58m42s
36s
30s
24s
18s
12s
200kpc
Clowe et al. 2006

Probing dark matter models | Two approaches

1. Gravity as a dark matter probe



Theory

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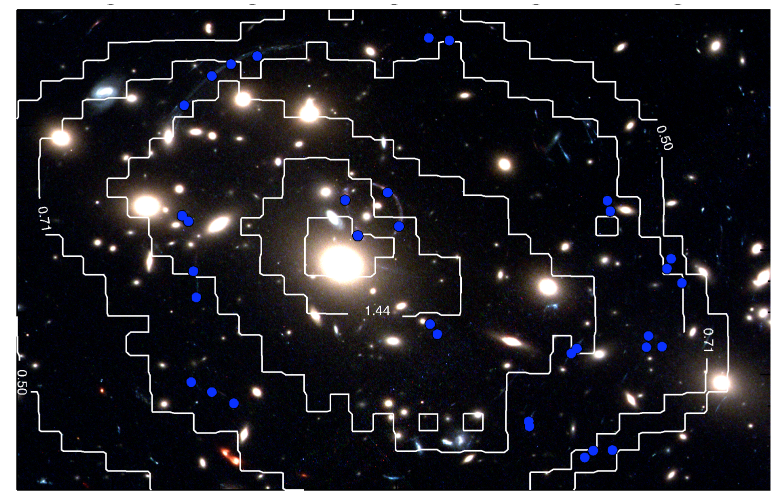

Observation

2. Dark matter as a particle

Probing dark matter models | Two approaches

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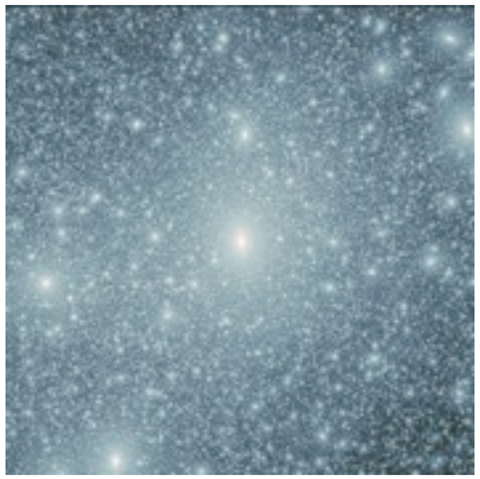

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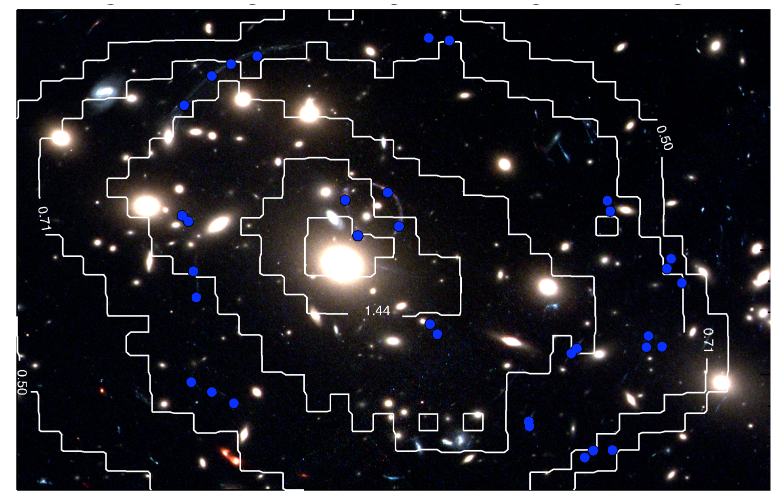

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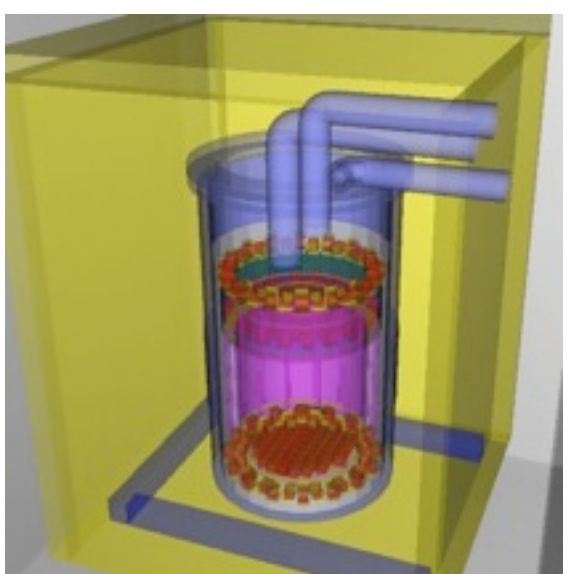


Detect

Create

Background | Talk outline

1. Theory. How to calculate the DM distribution (for an assumed DM fluid)

2. Observations. What can we measure? What do we learn?

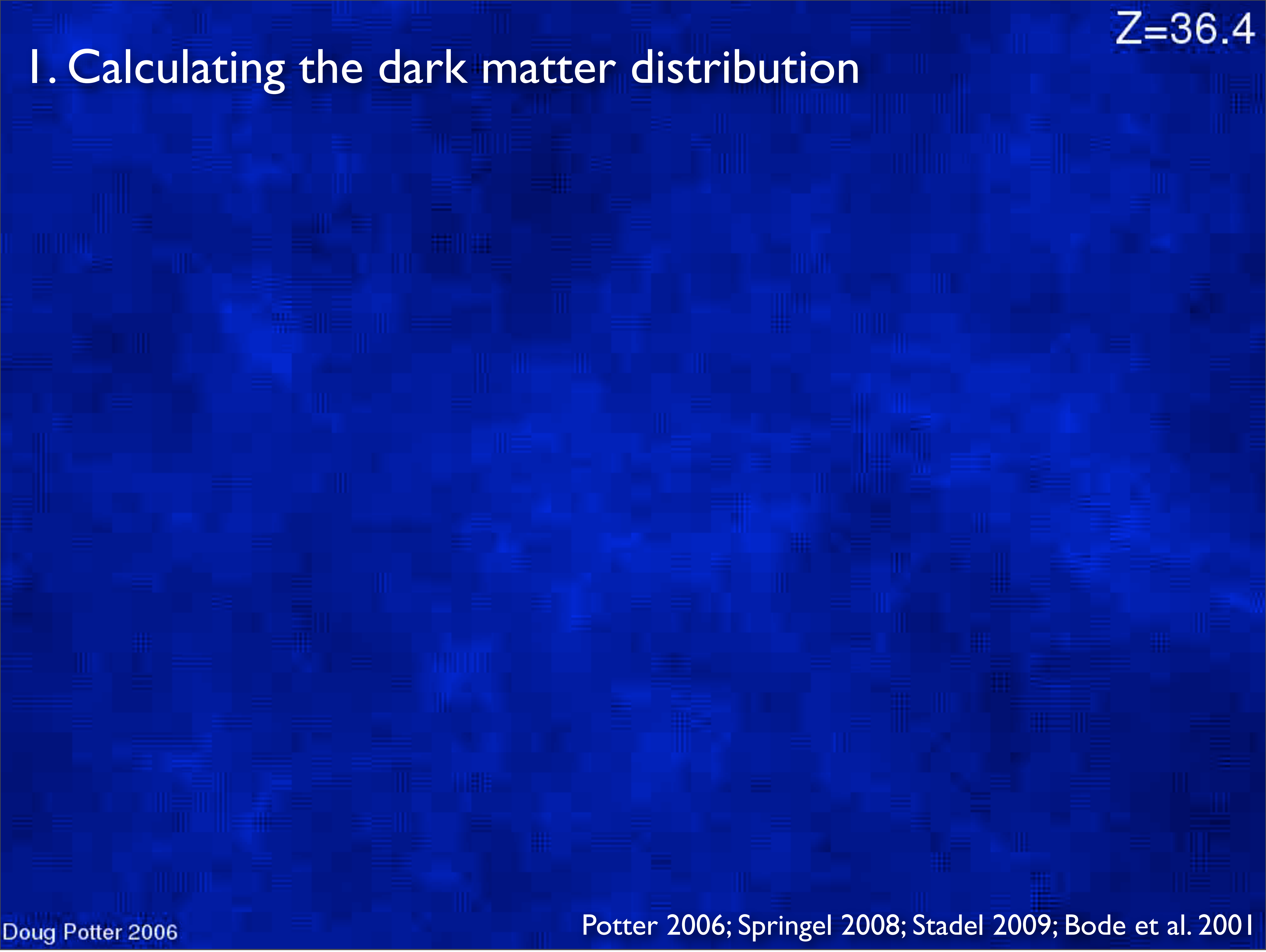
3. Direct/indirect probes of particle dark matter. Measuring the local dark matter distribution

4. Conclusions / Future prospects

1. Calculating the dark matter distribution

Potter 2006; Springel 2008; Stadel 2009; Bode et al. 2001

1. Calculating the dark matter distribution



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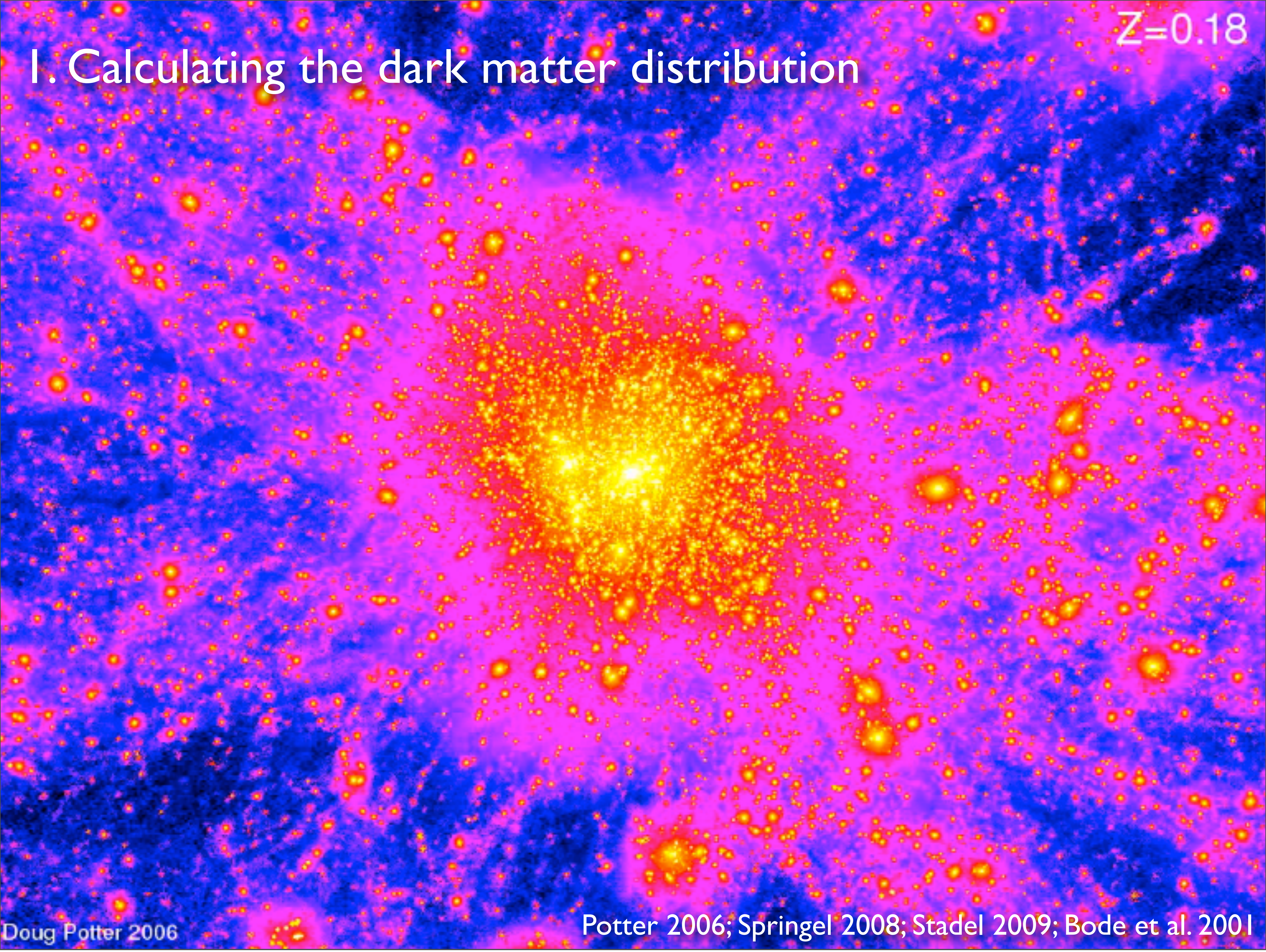

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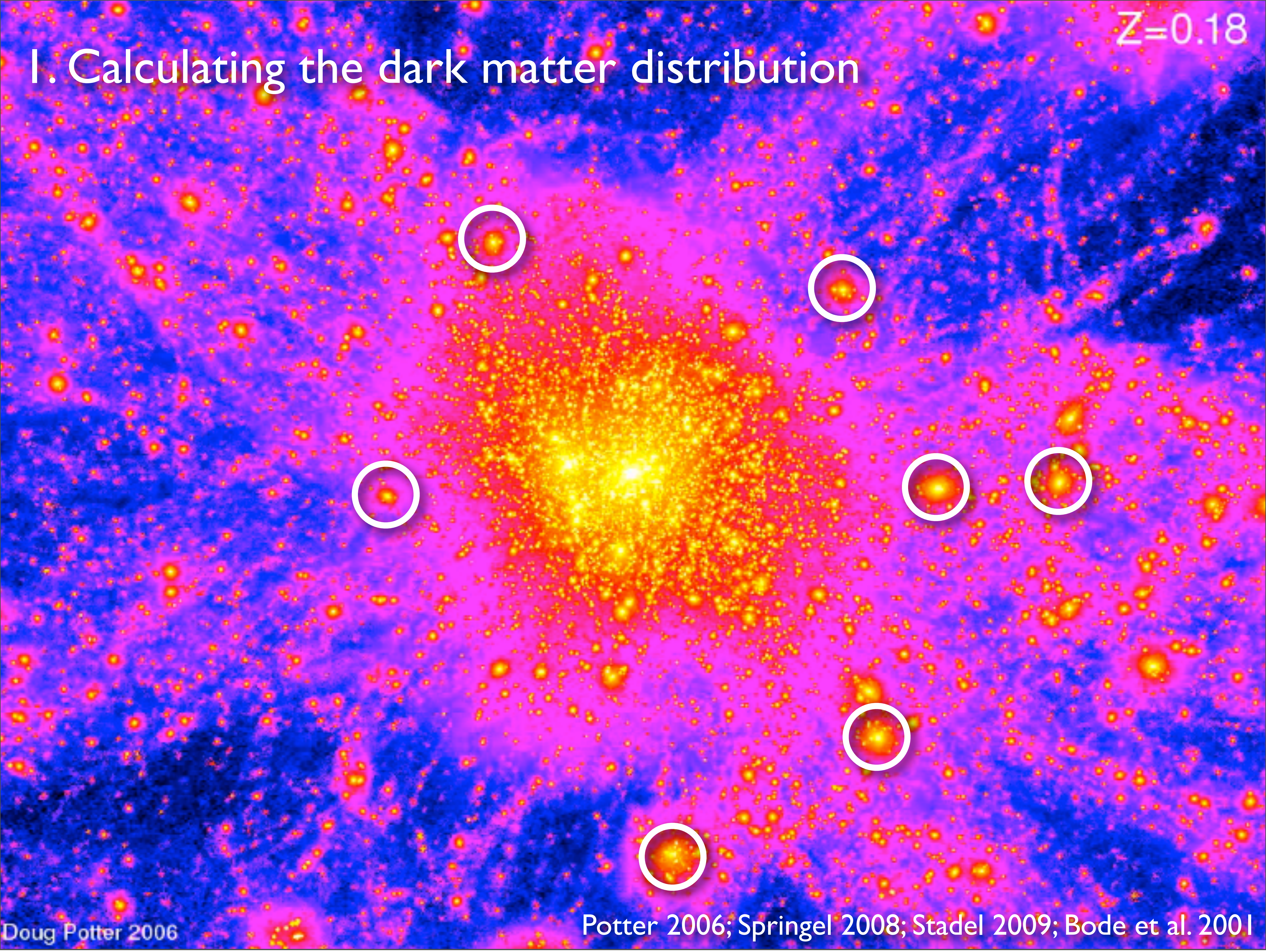

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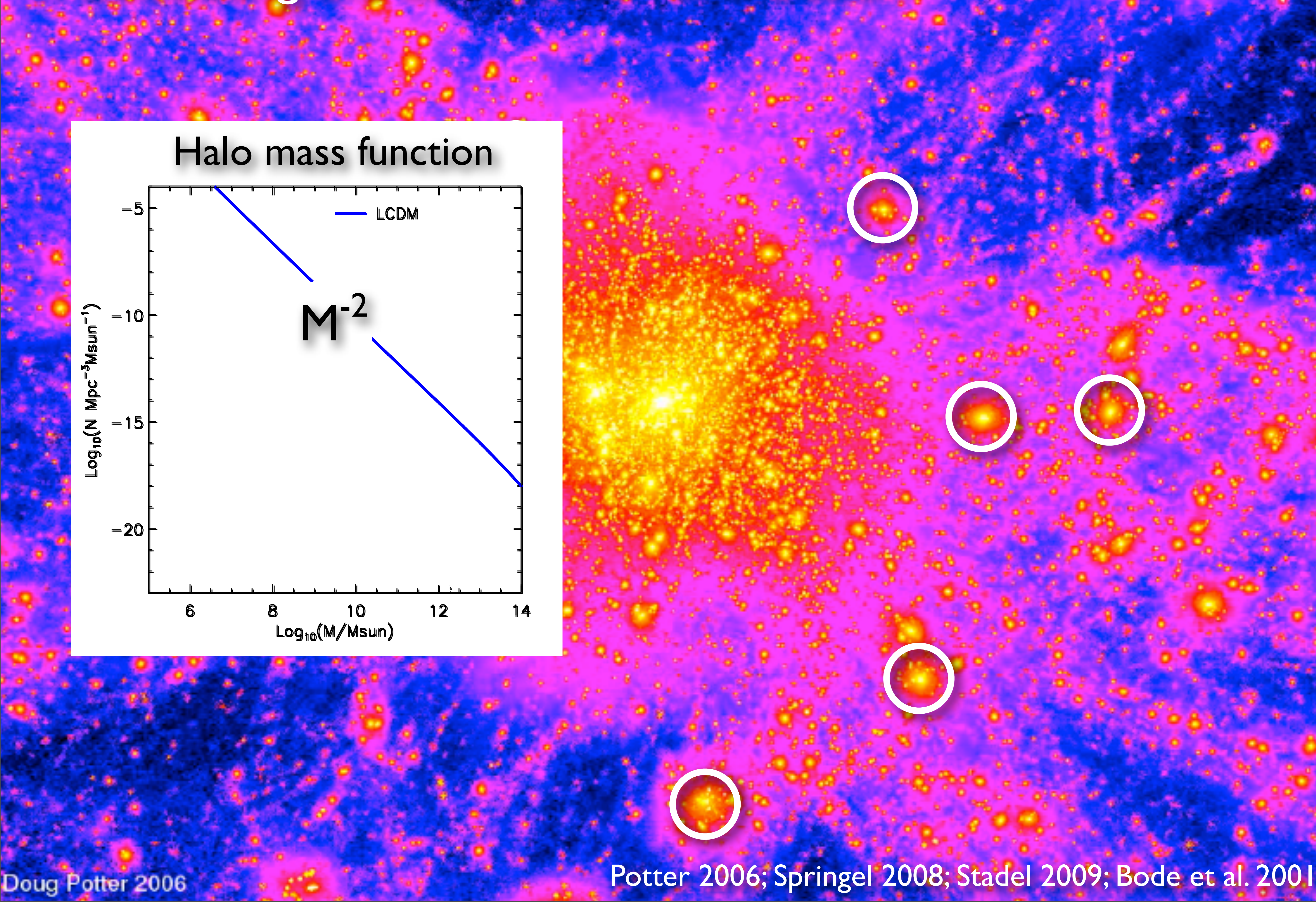

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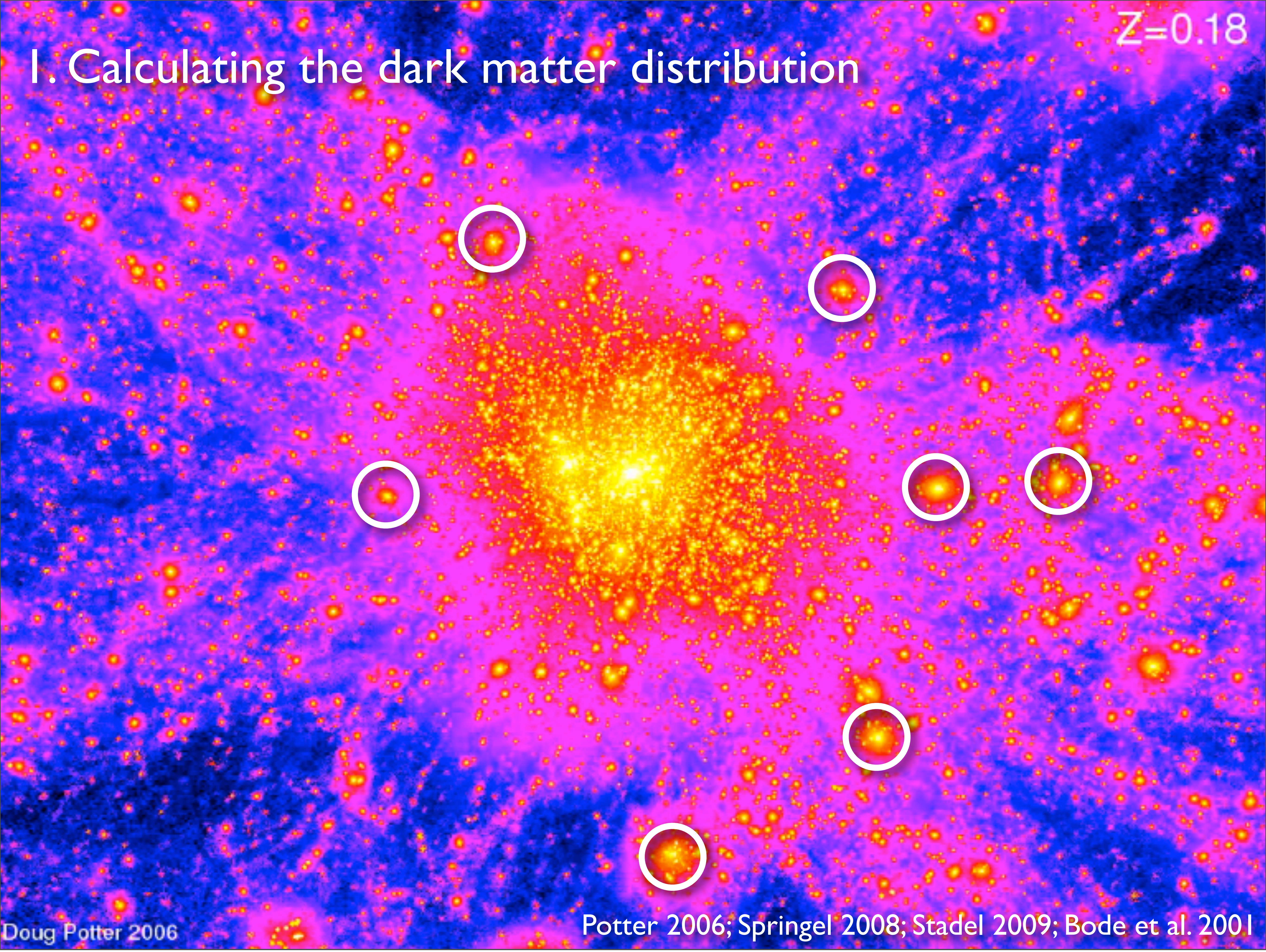
1. Calculating the dark matter distribution
Z=0.18
Doug Potter 2006
Potter 2006; Springel 2008; Stadel 2009; Bode et al. 2001

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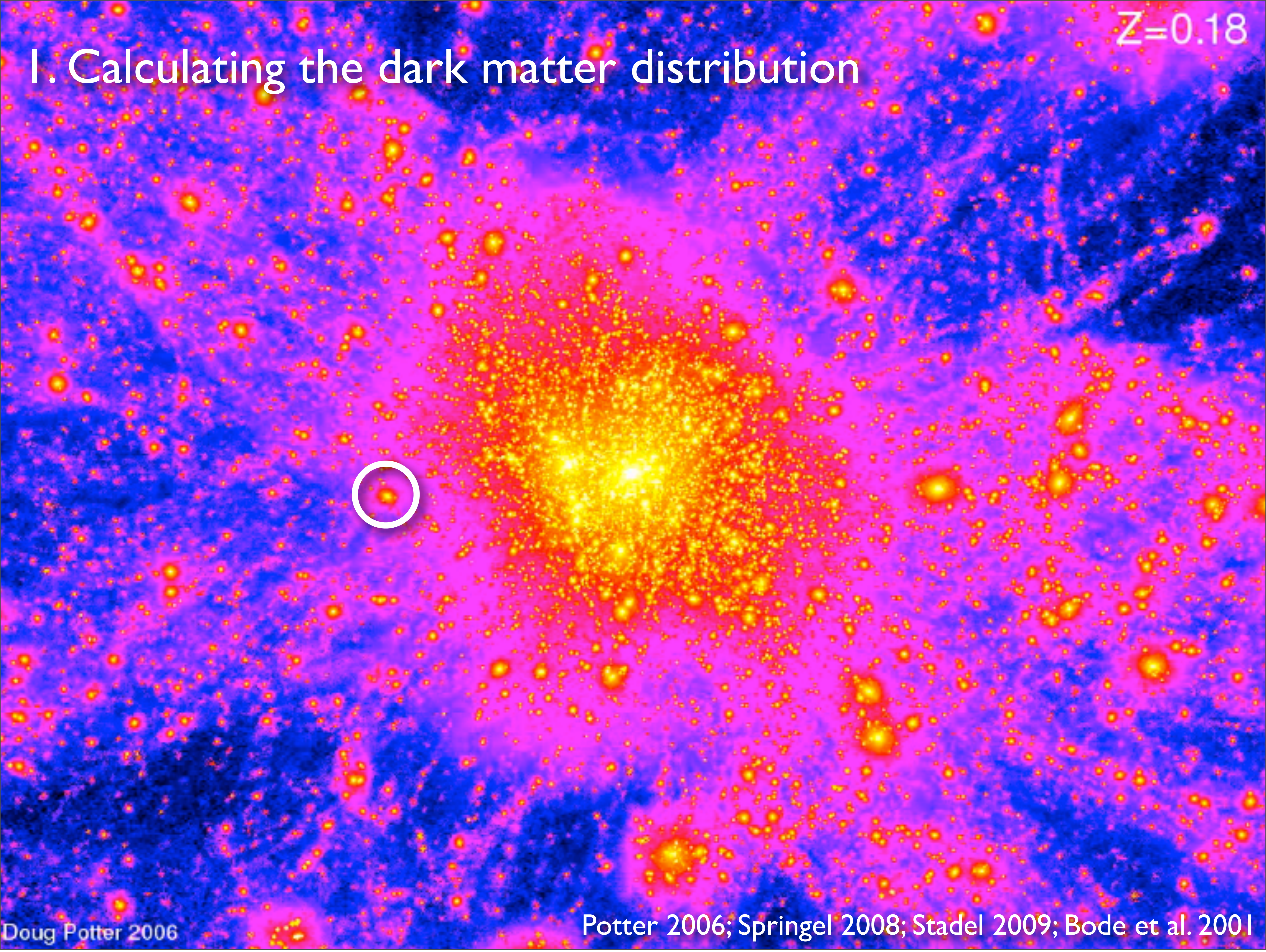

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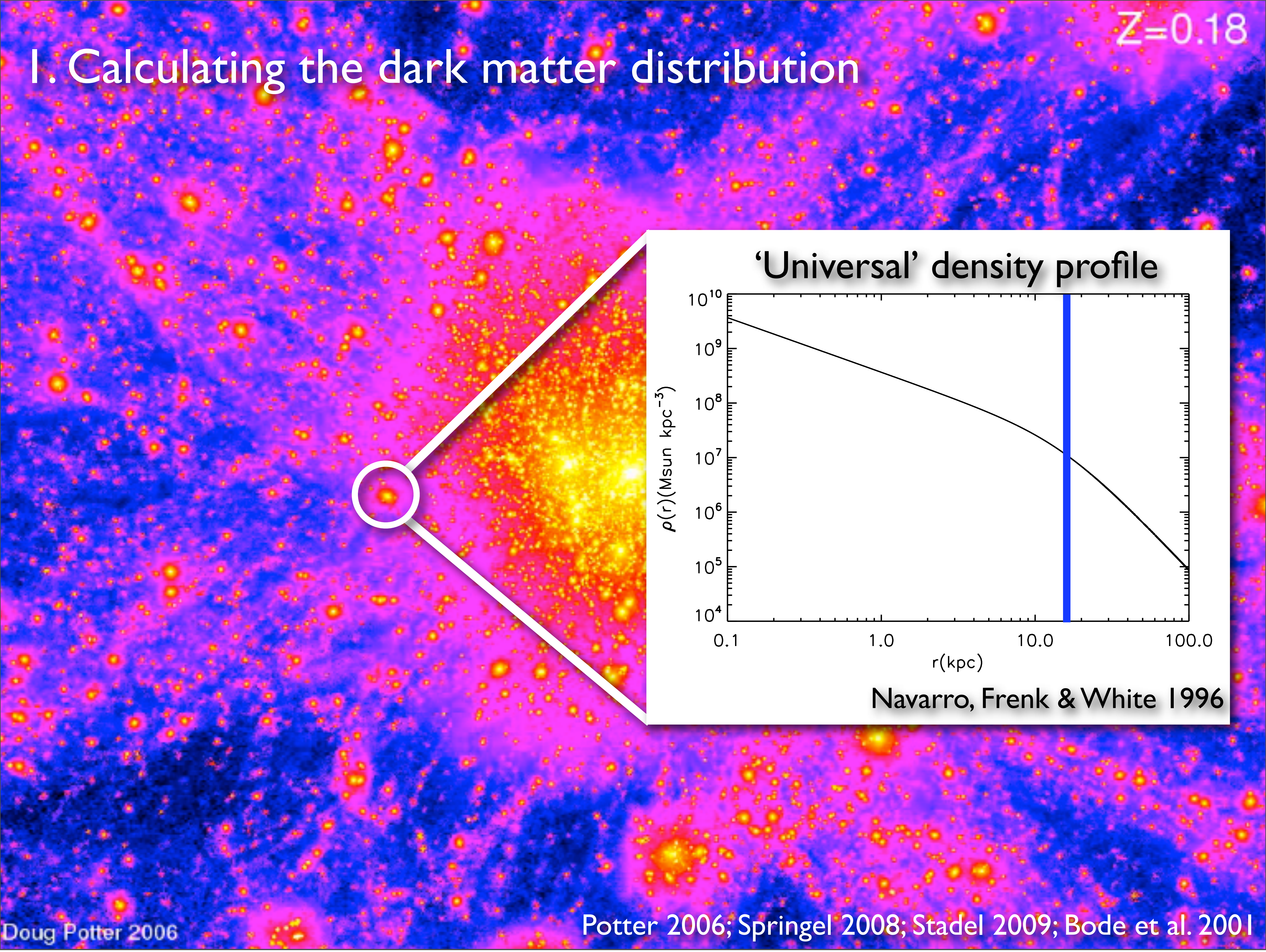

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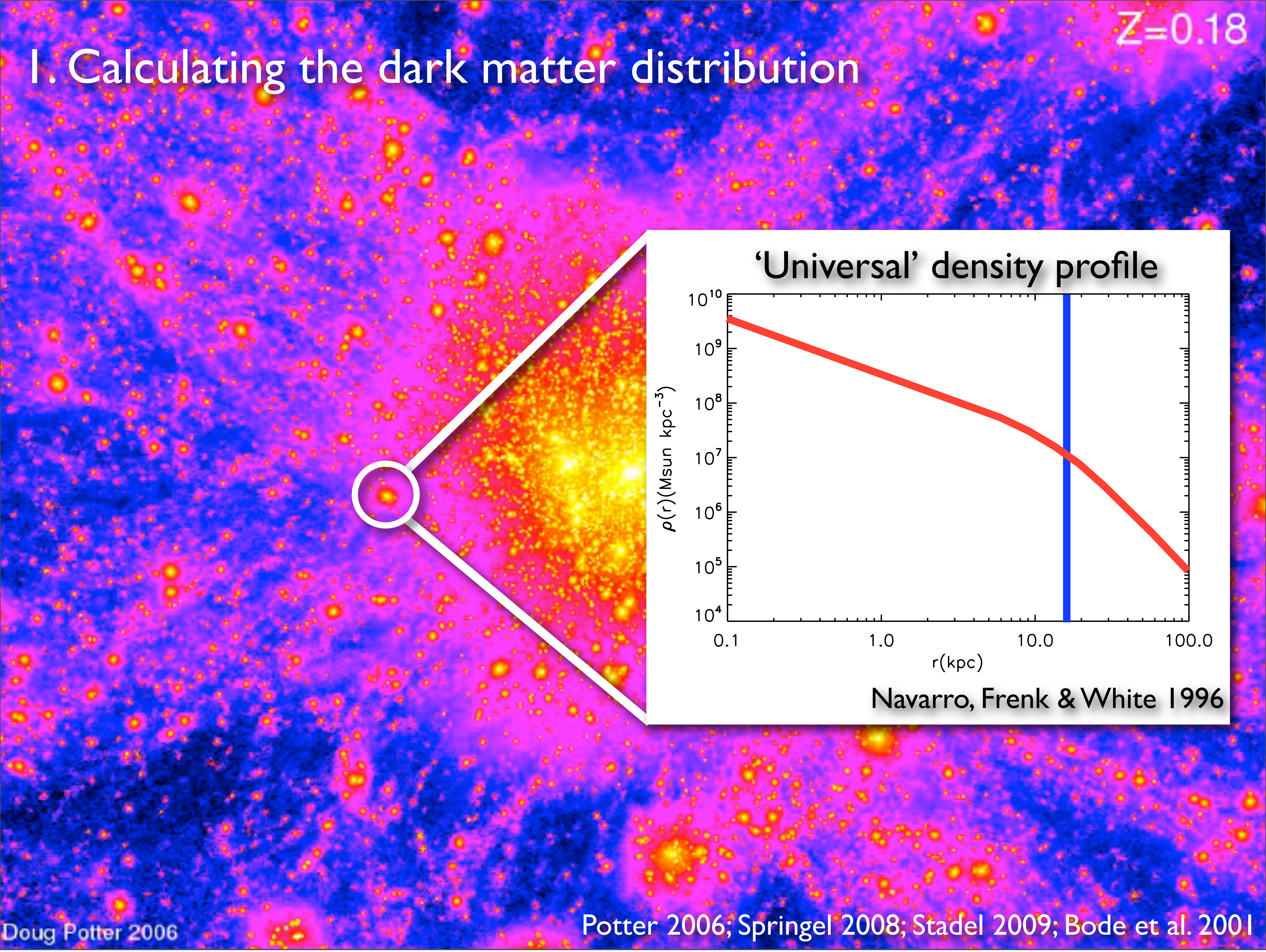
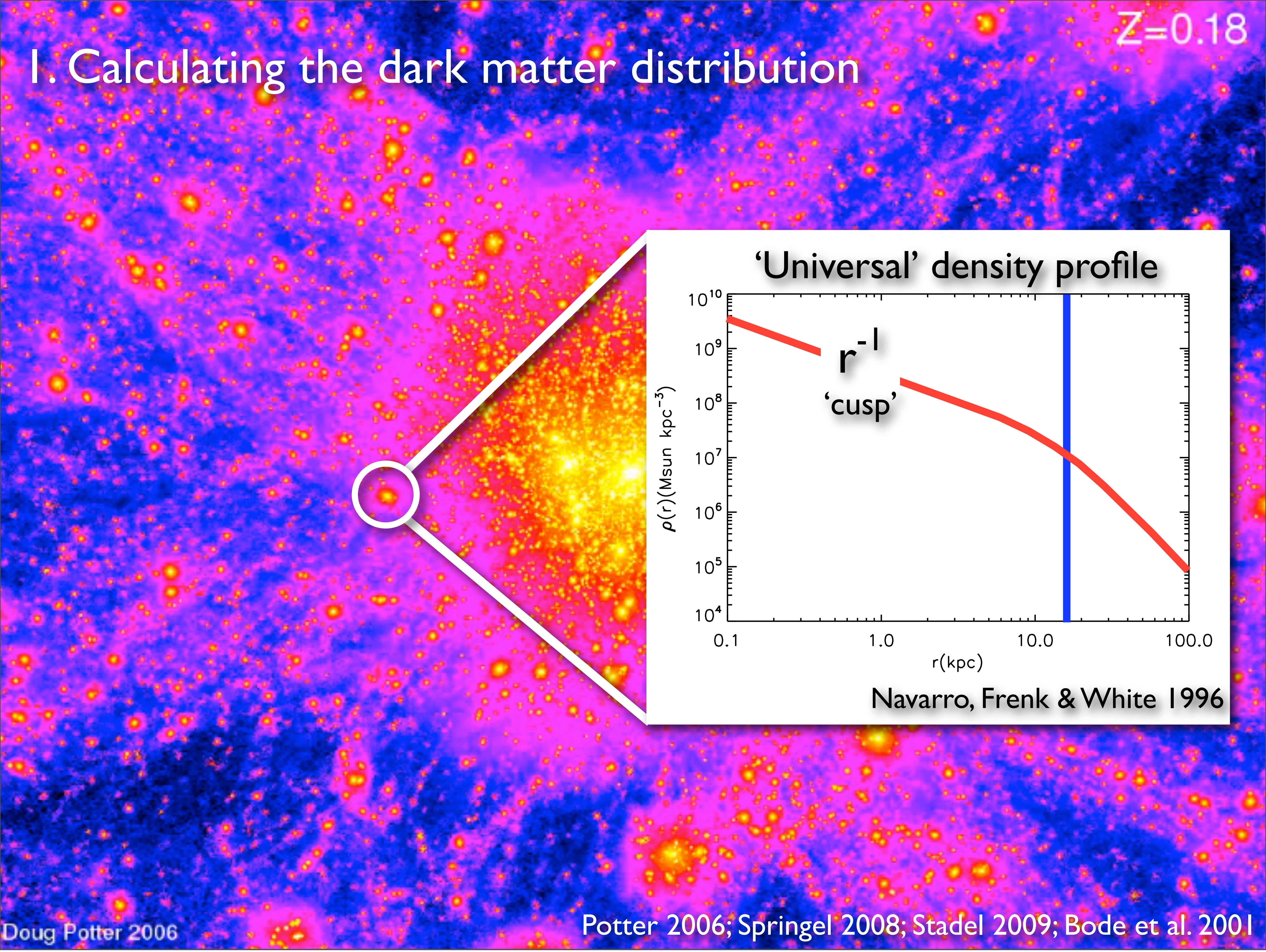
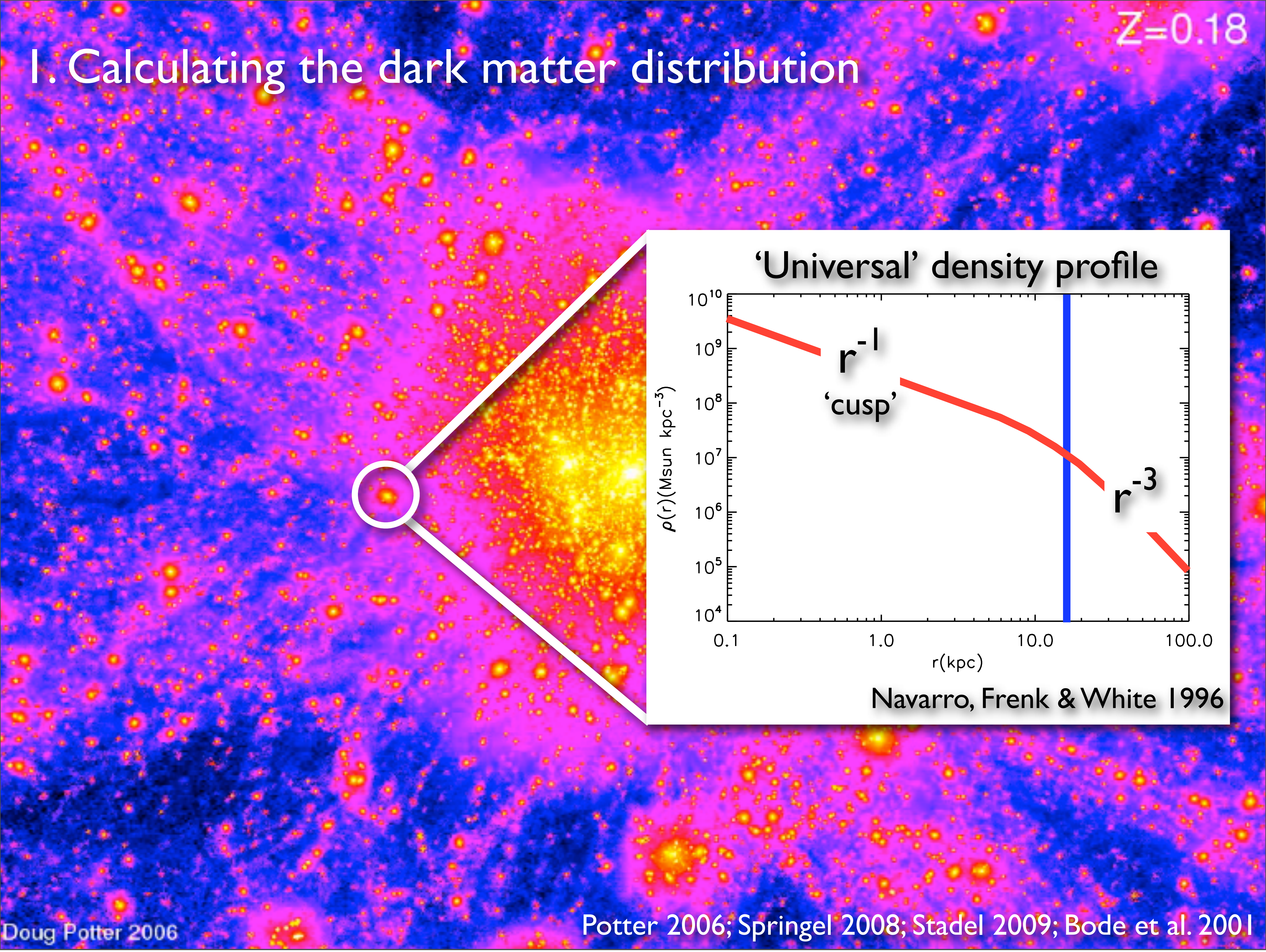



Z=0.18
1. Calculating the dark matter distribution
'Universal' density profile
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
$\rho(r)$(Msun kpc^{-3})
r^{-1}
'cusp'
0.1
1.0
10.0
100.0
r(kpc)
Navarro, Frenk & White 1996
Doug Potter 2006
Potter 2006; Springel 2008; Stadel 2009; Bode et al. 2001



Tuesday, April 3, 2012

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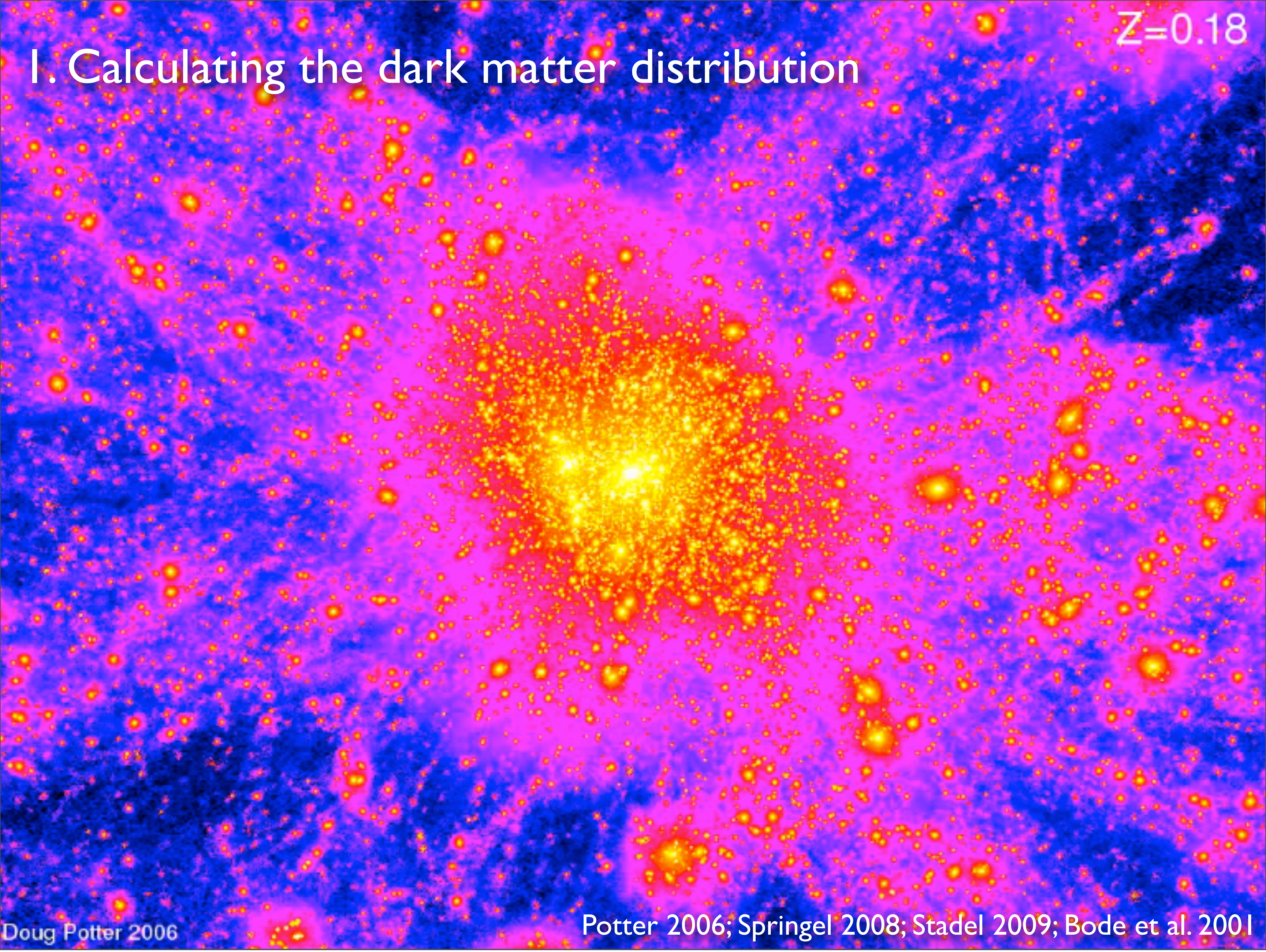

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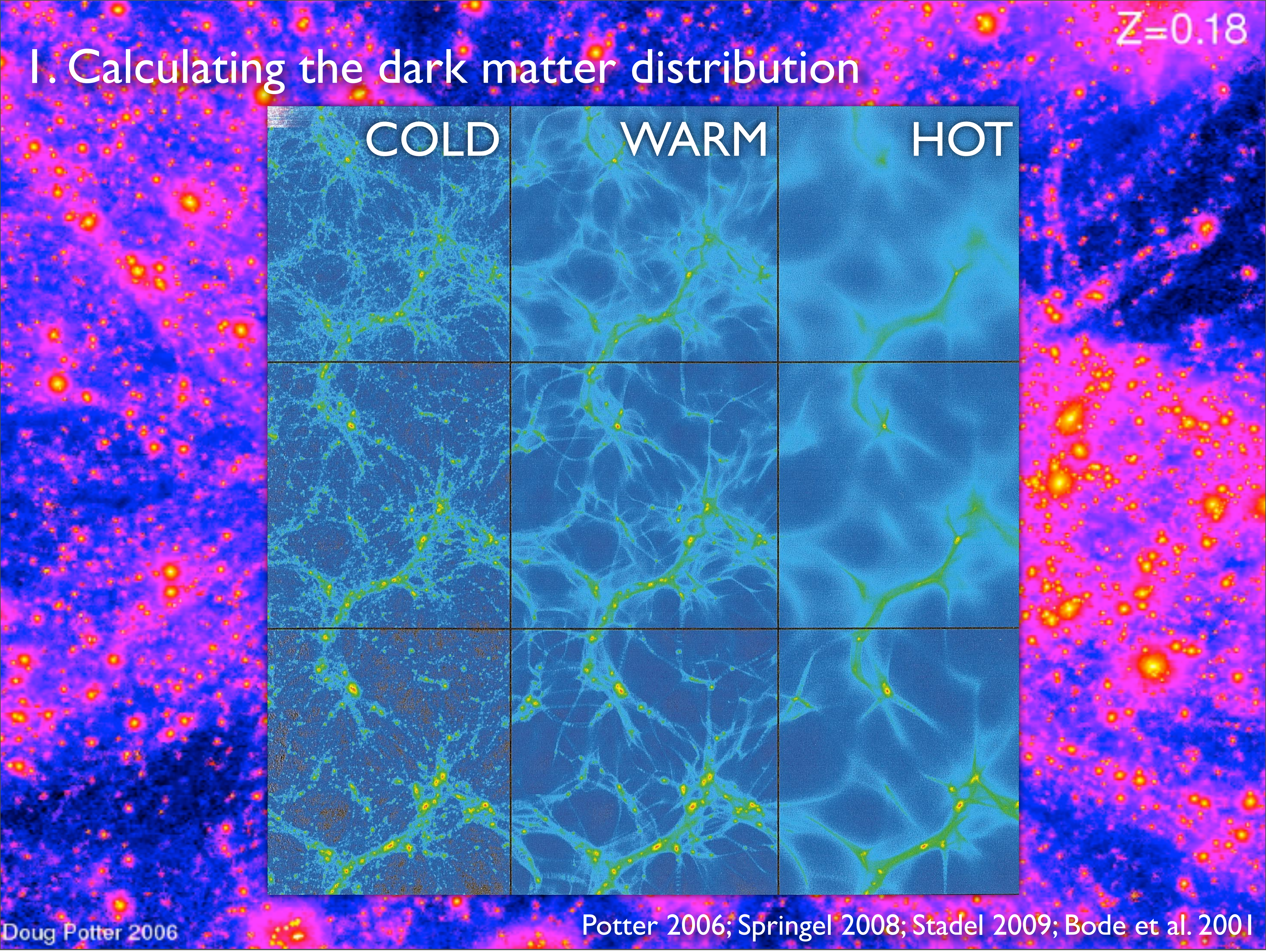
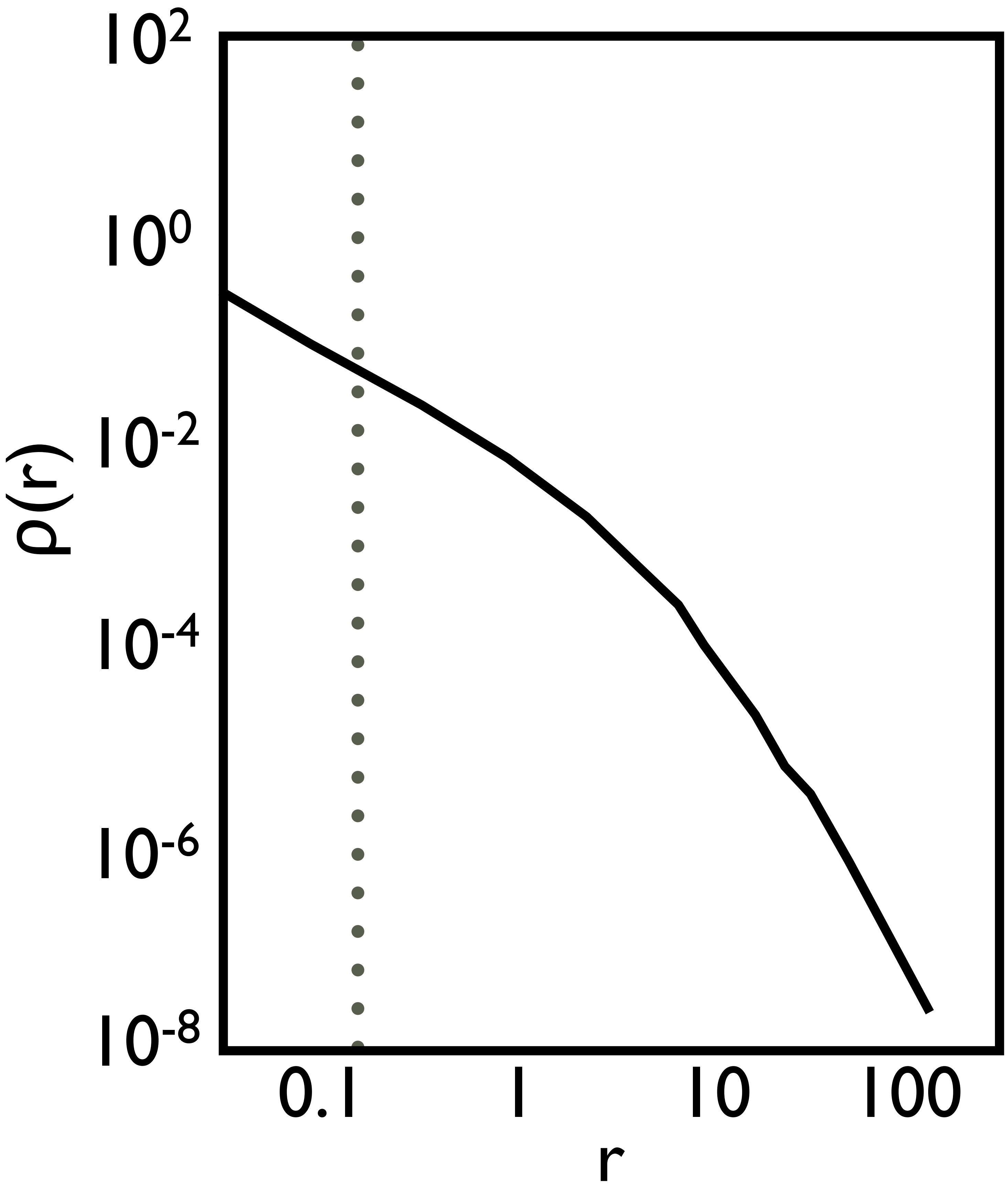
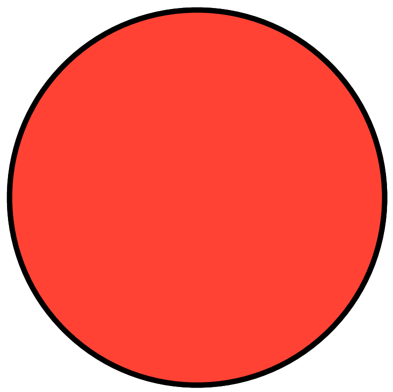


Potter 2006; Springel 2008; Stadel 2009; Bode et al. 2001

1. Calculating the DM dist. | The importance of baryons





Read & Gilmore 2005; Navarro et al. 1996

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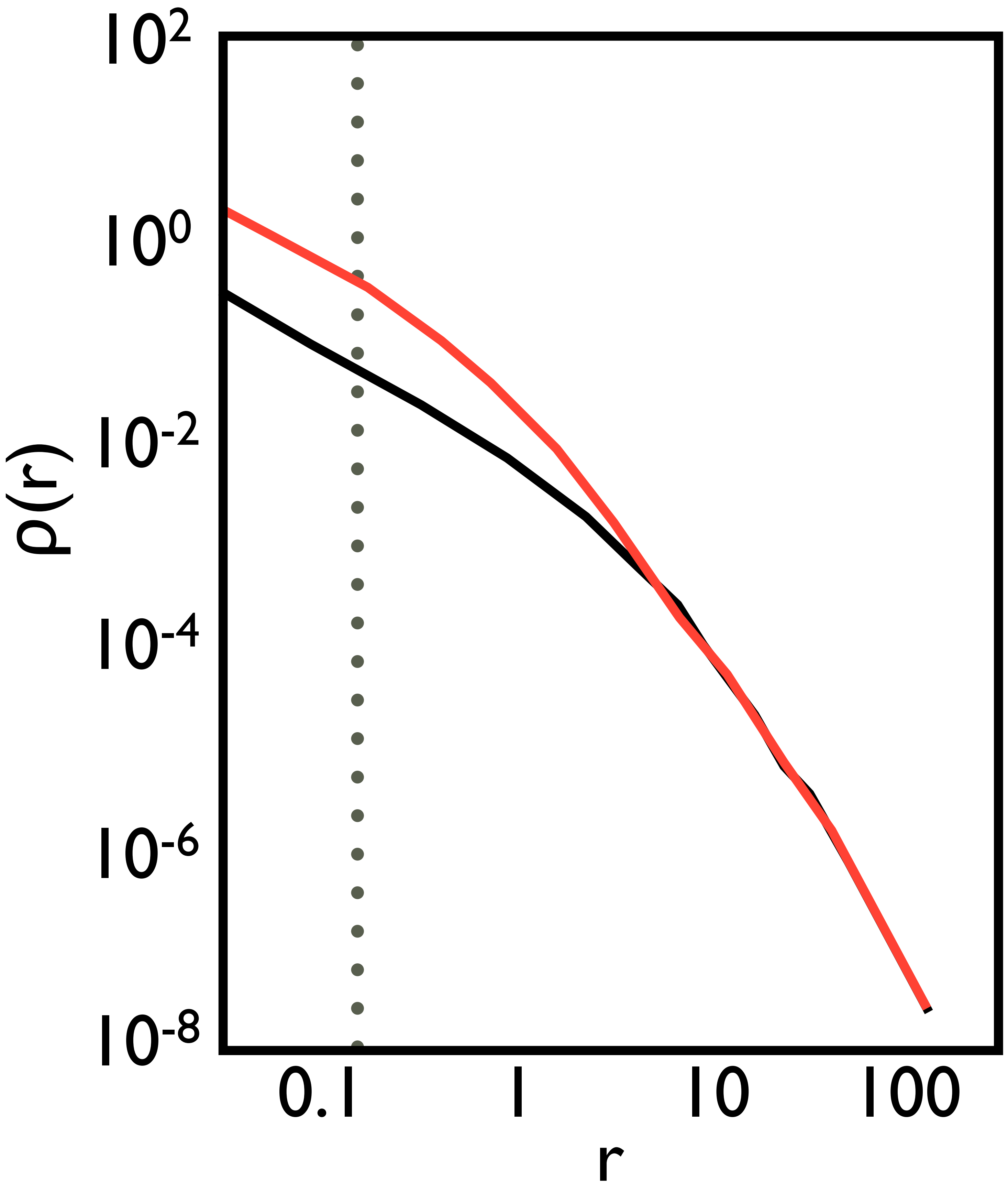

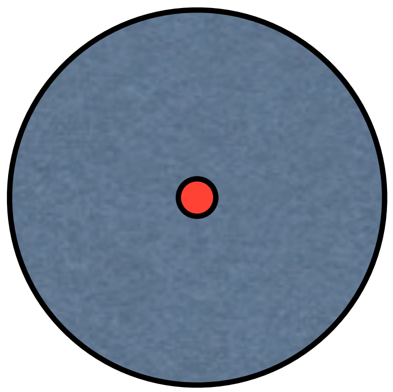

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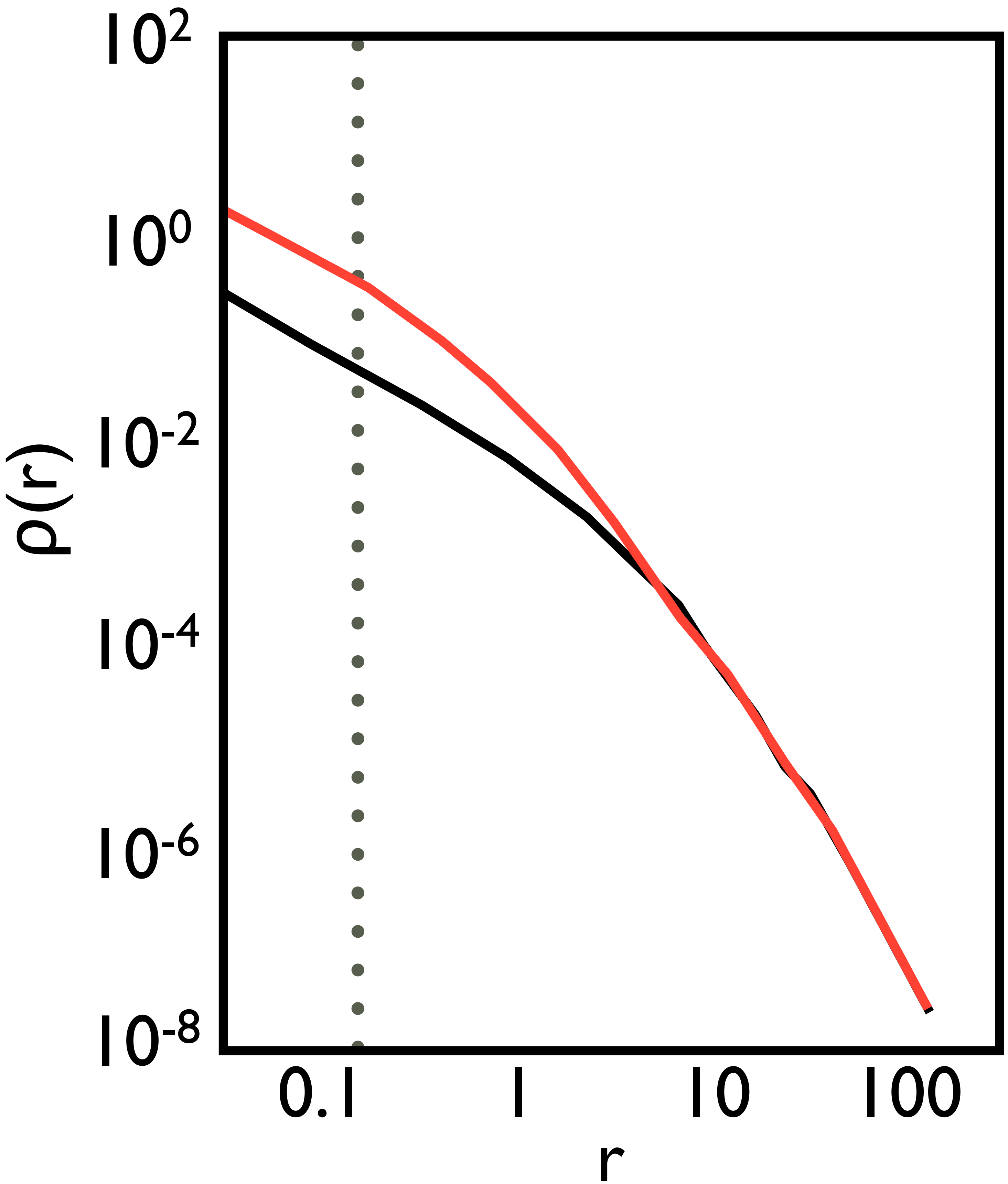

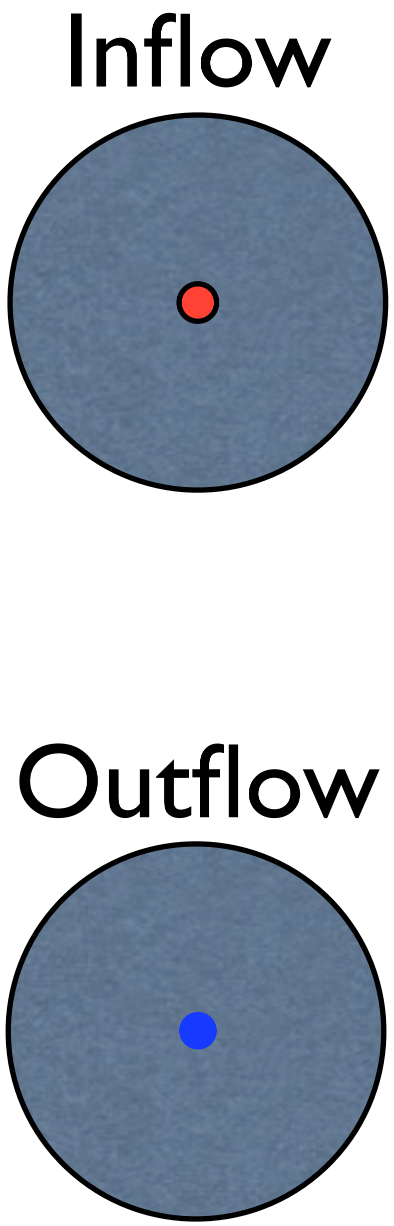

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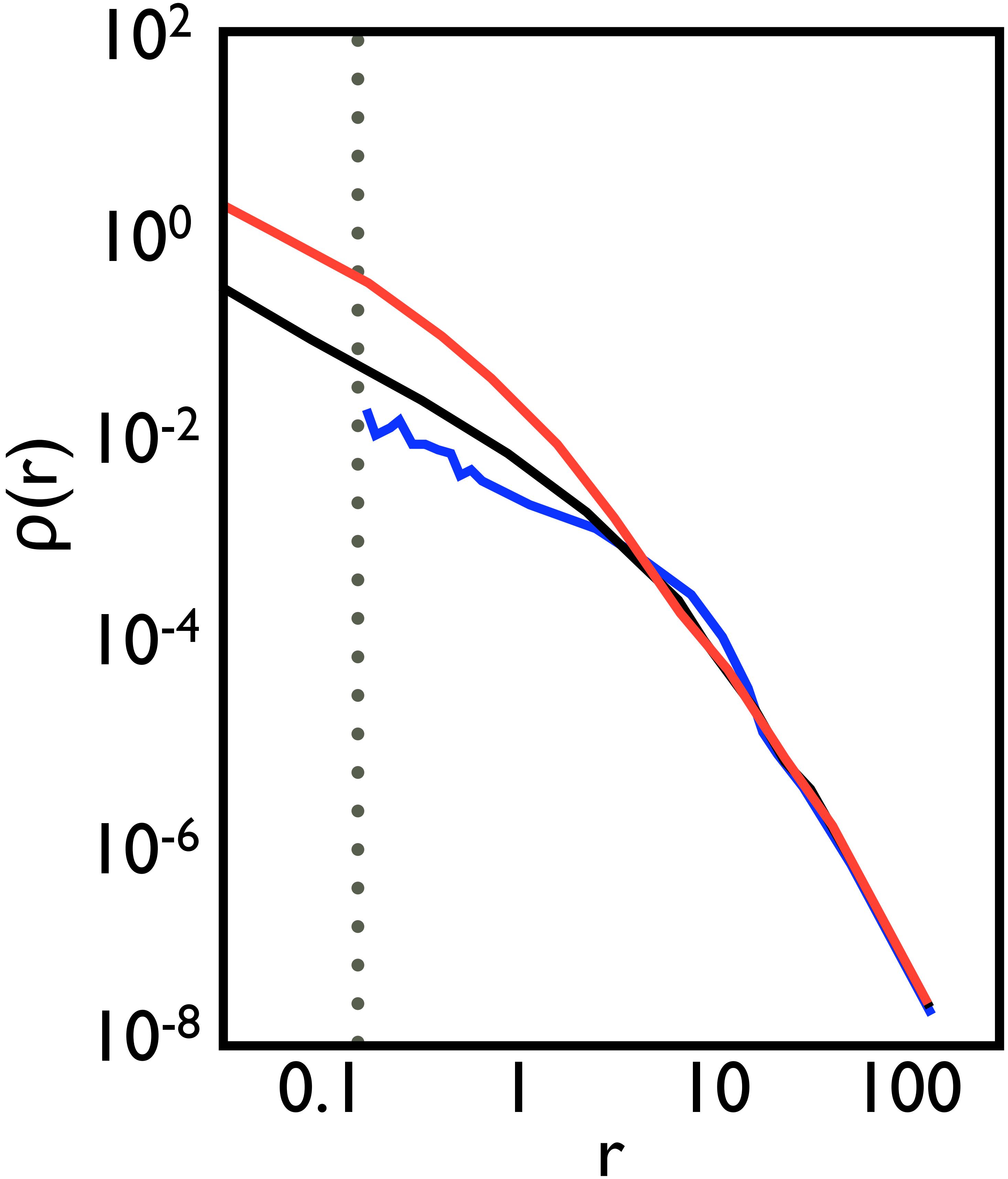

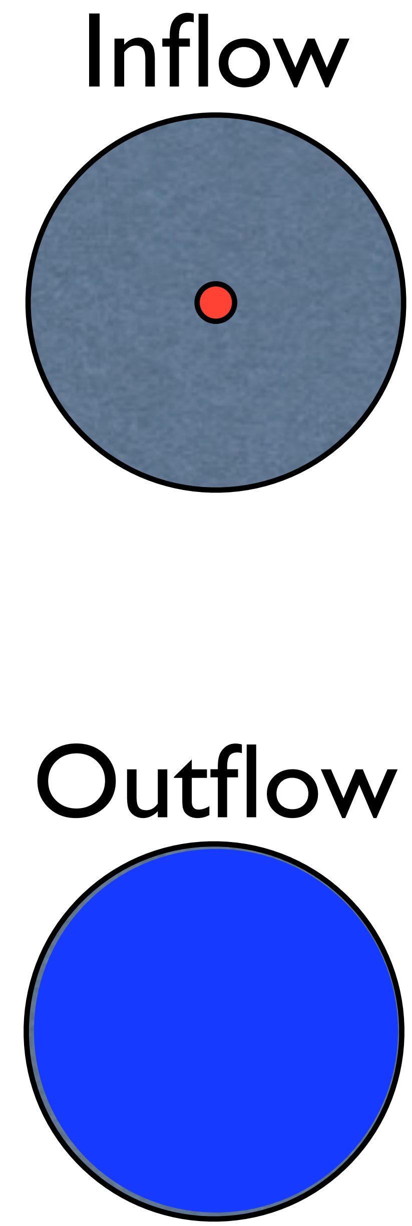

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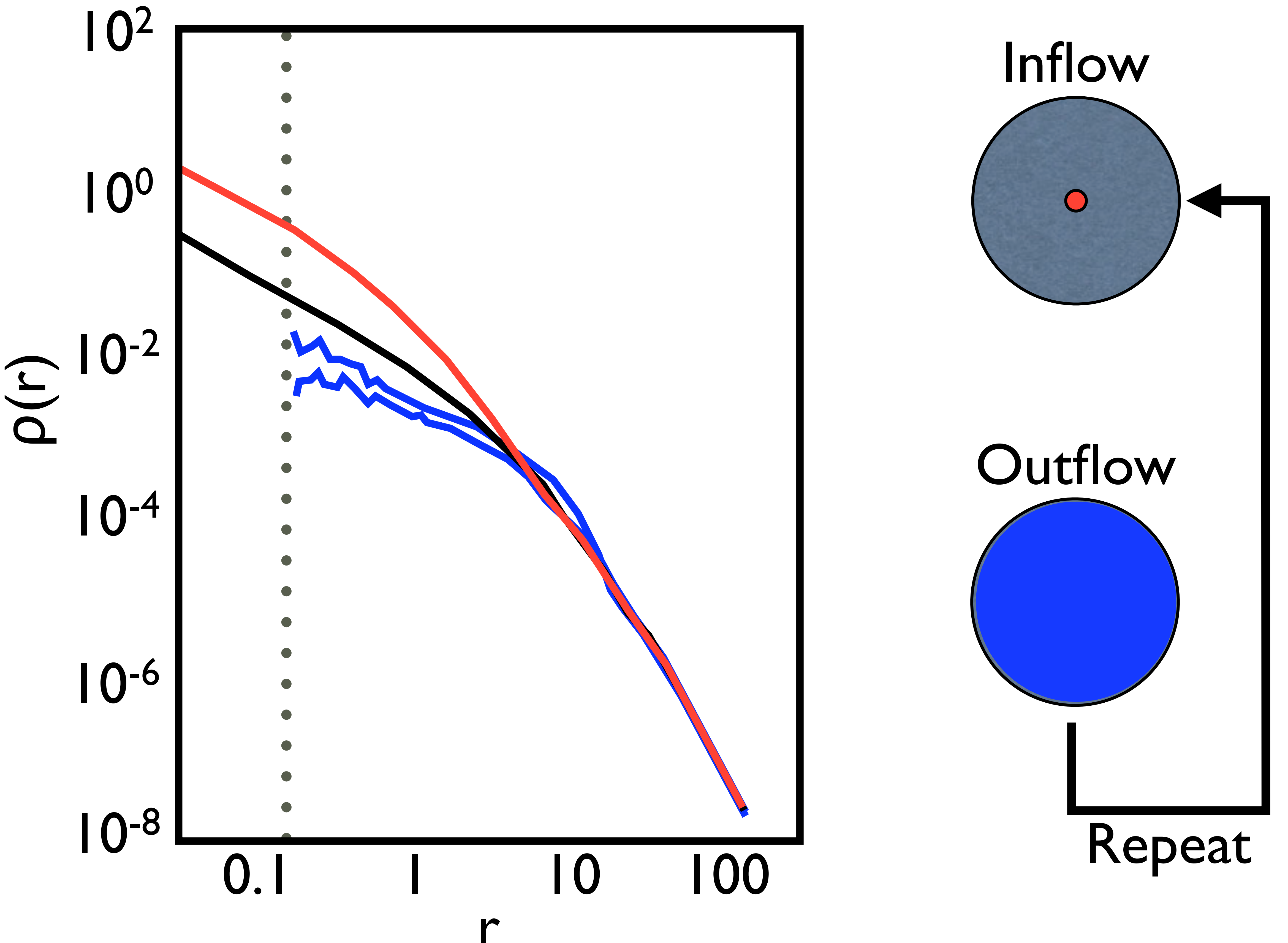

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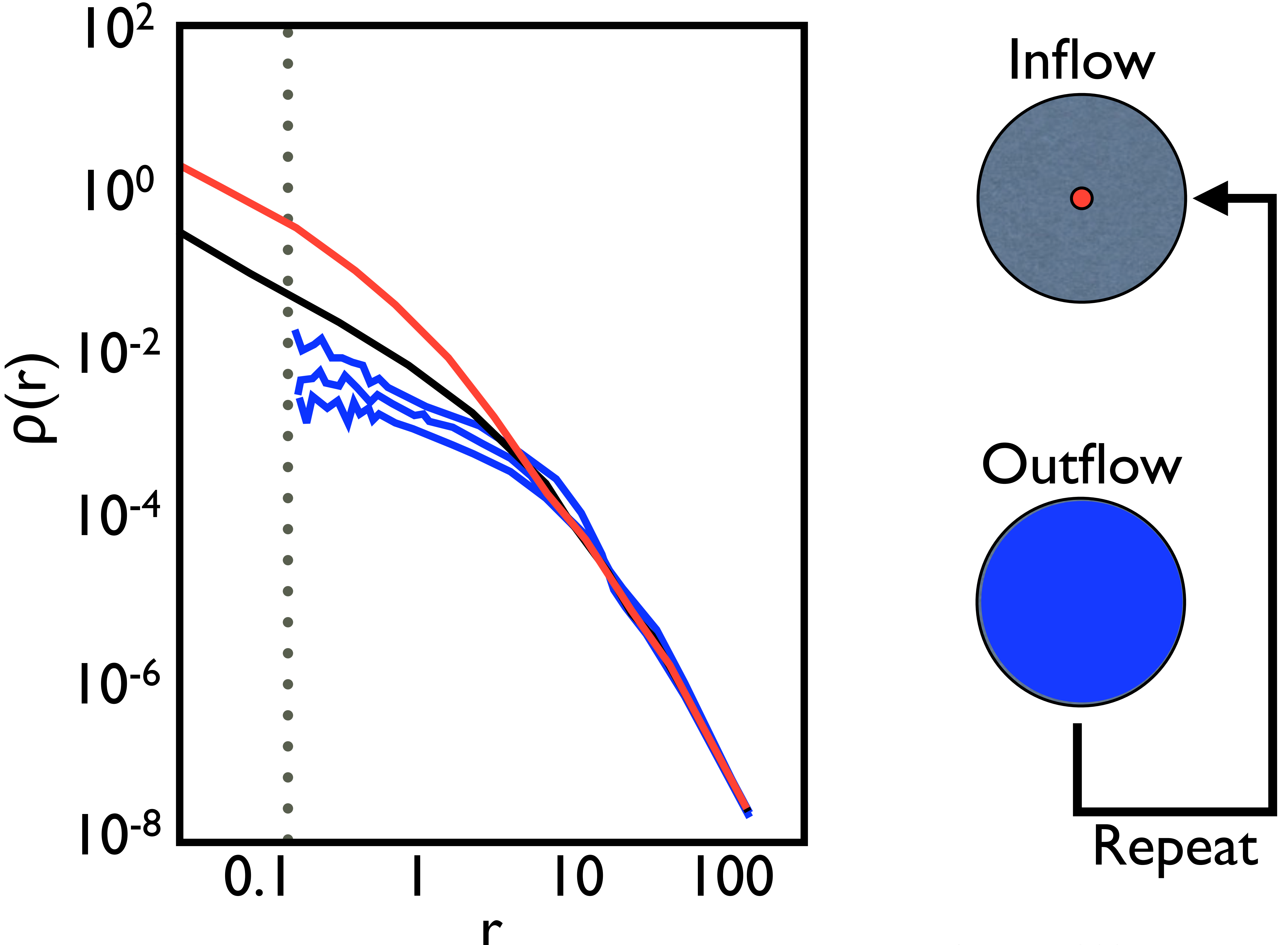

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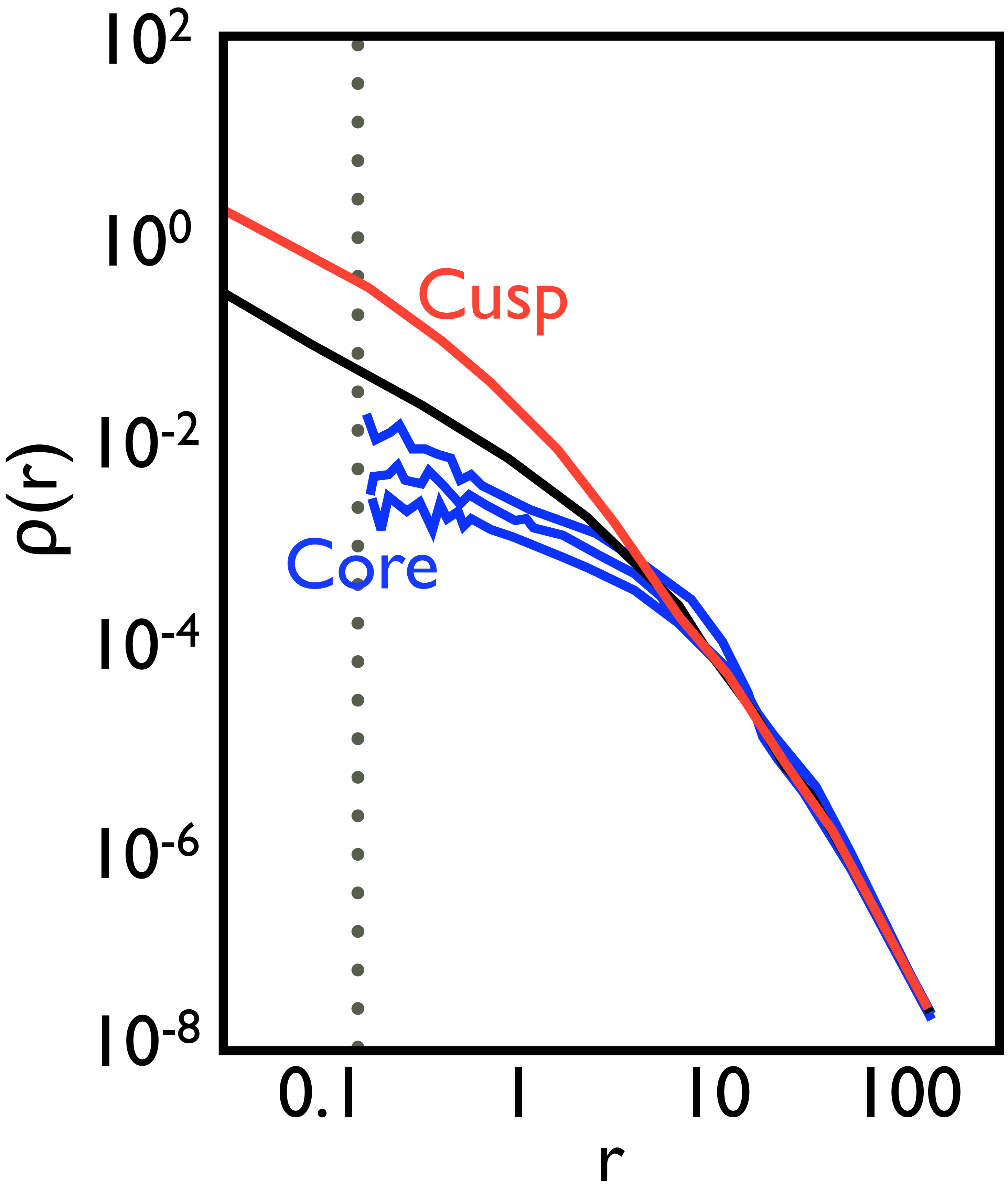

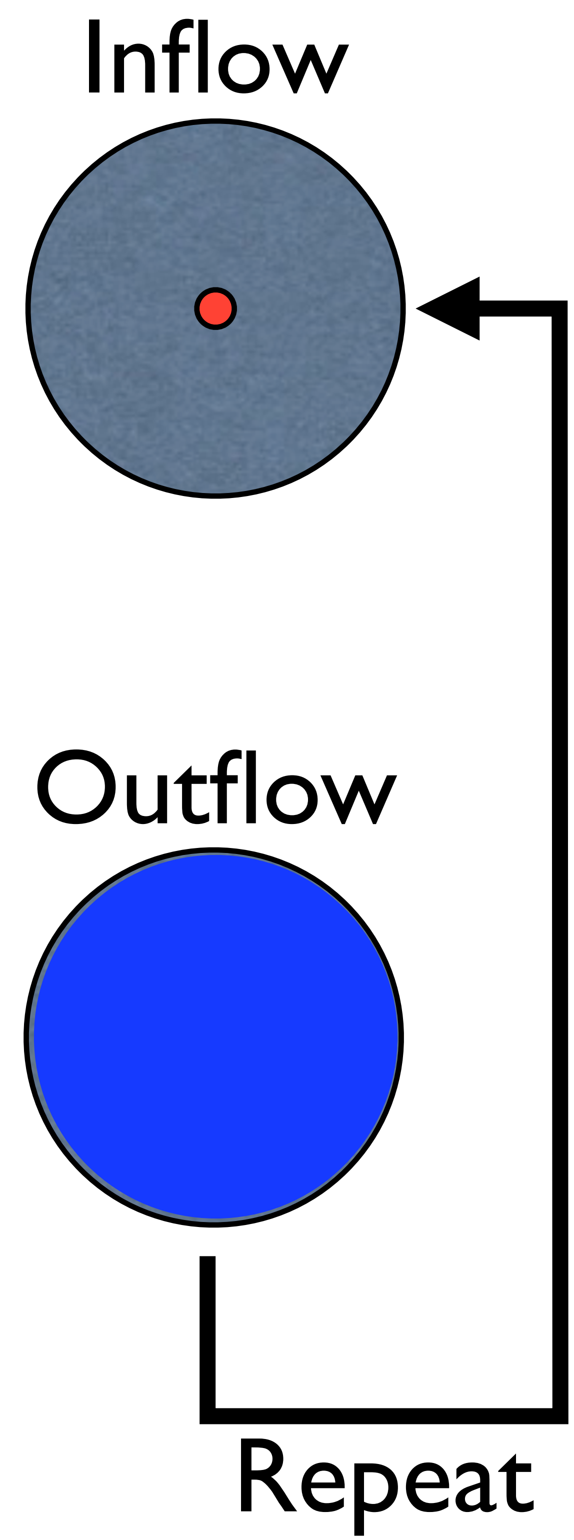

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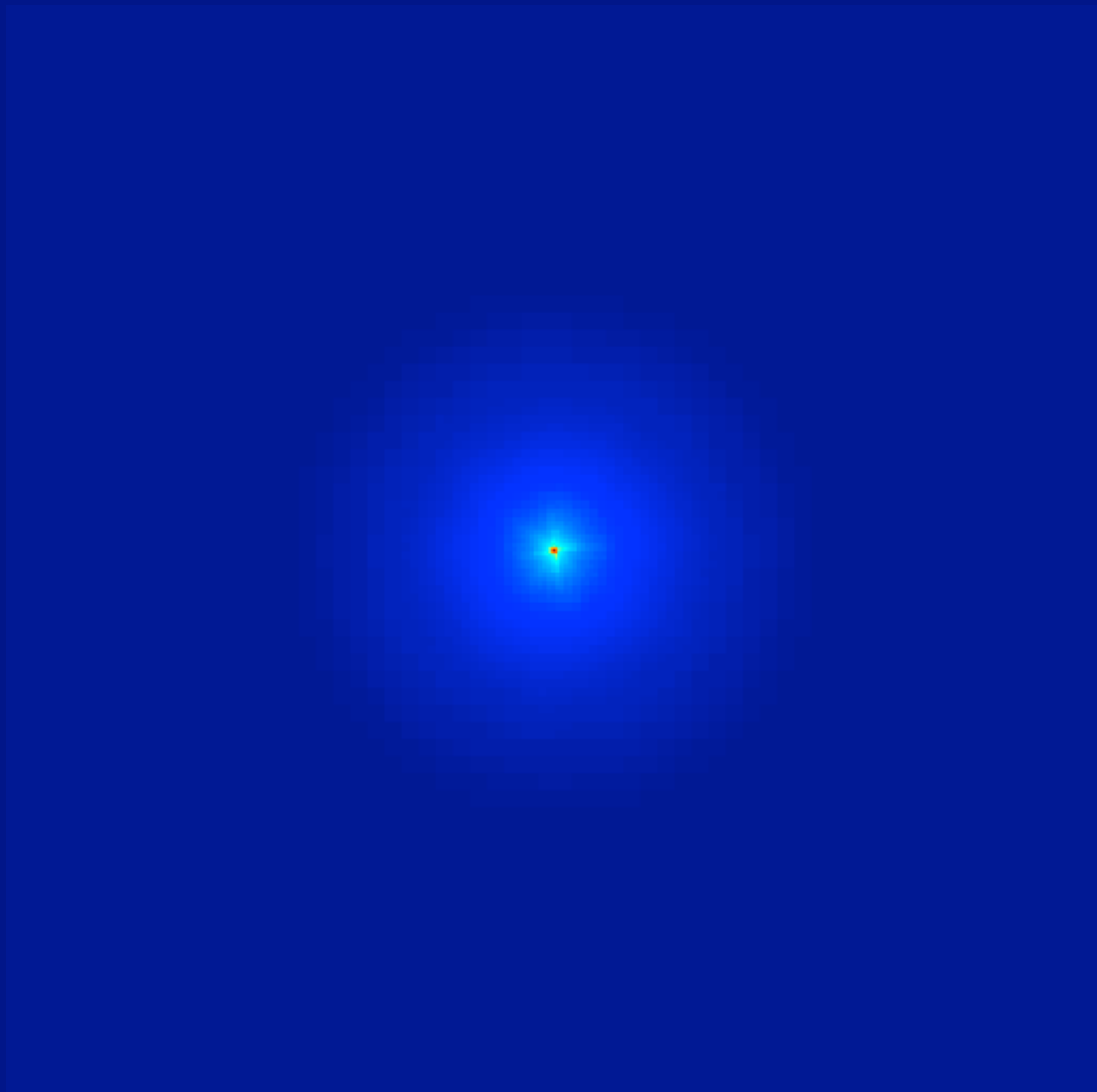

Teyssier, Pontzen, Dubois & Read in prep. 2012

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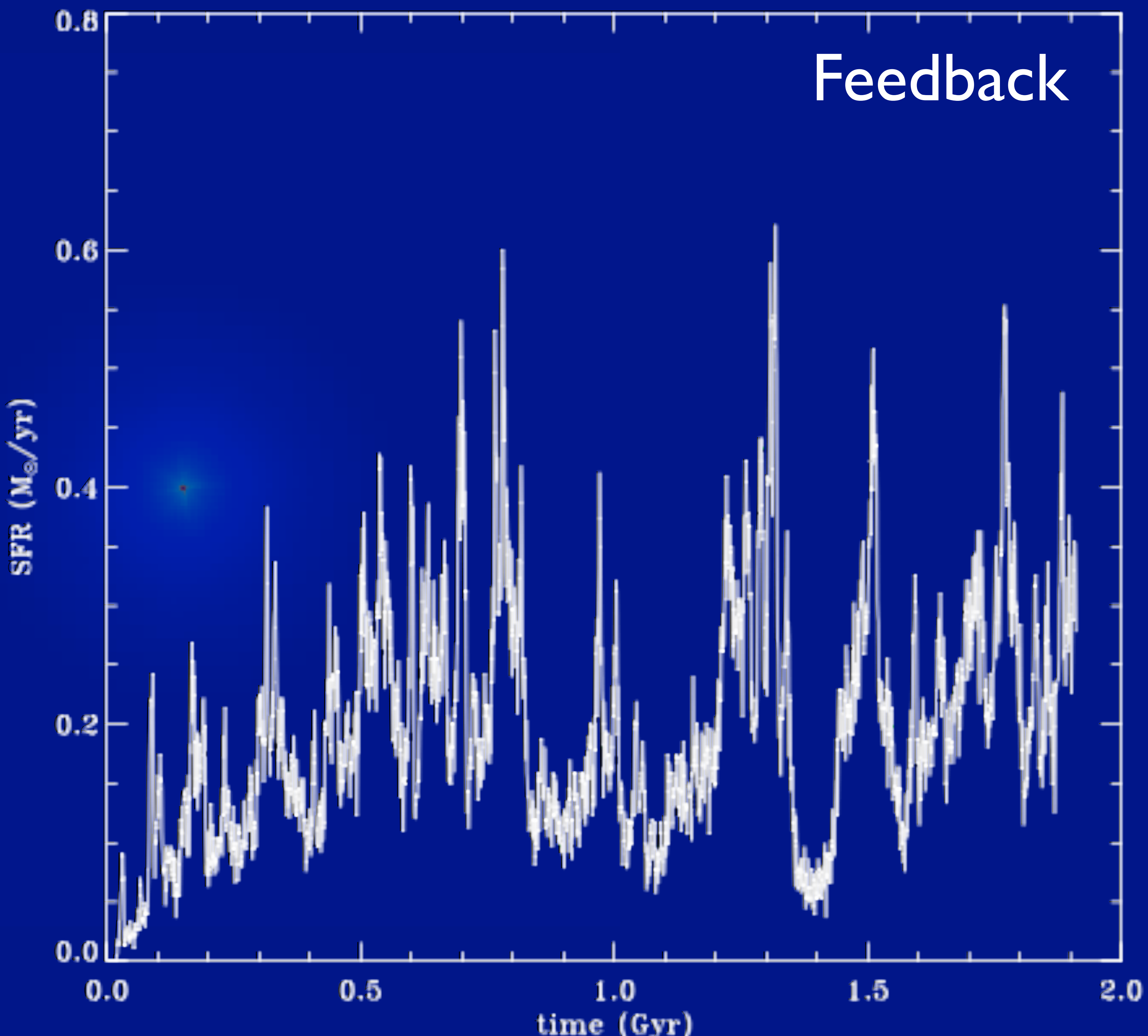

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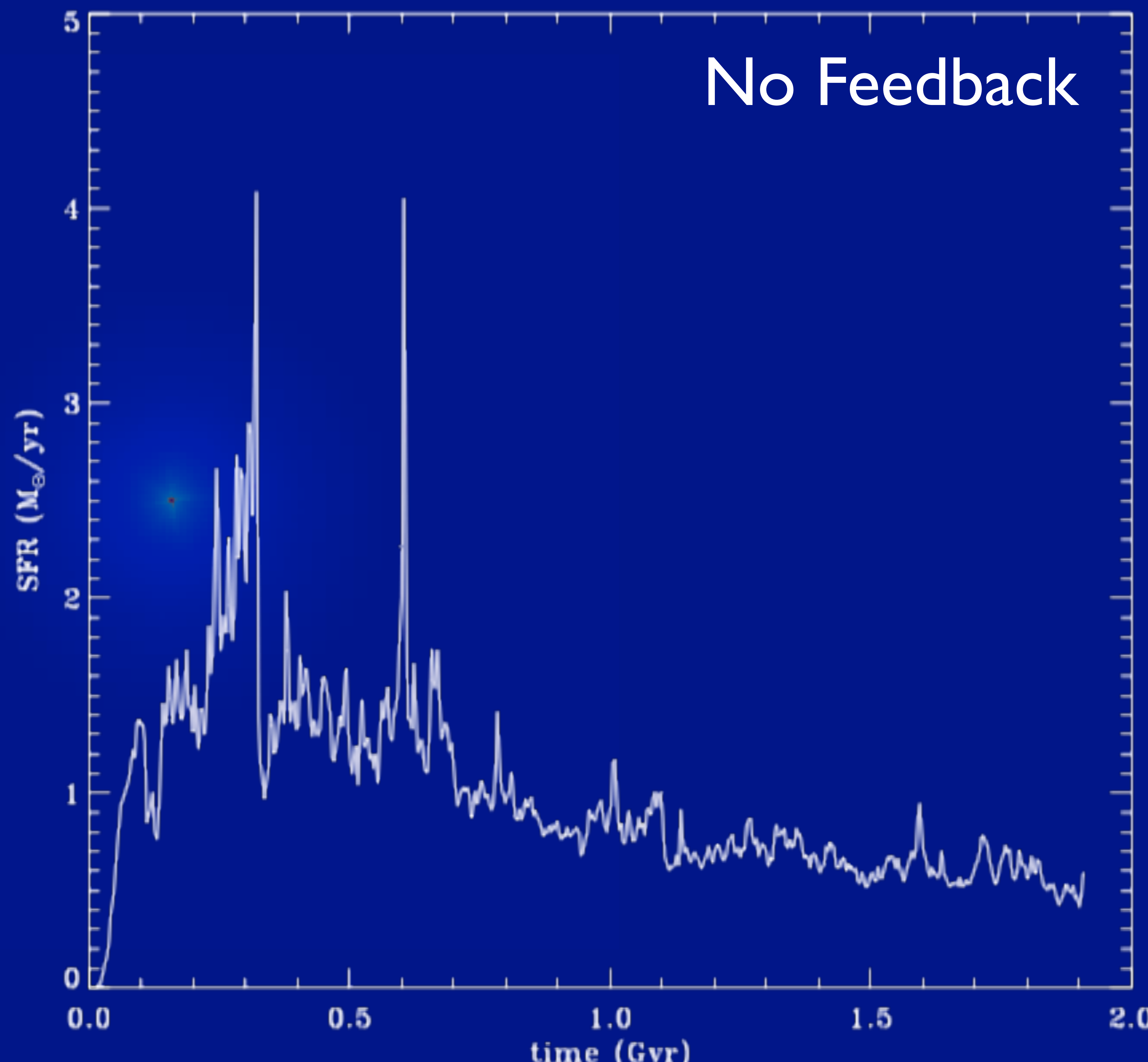

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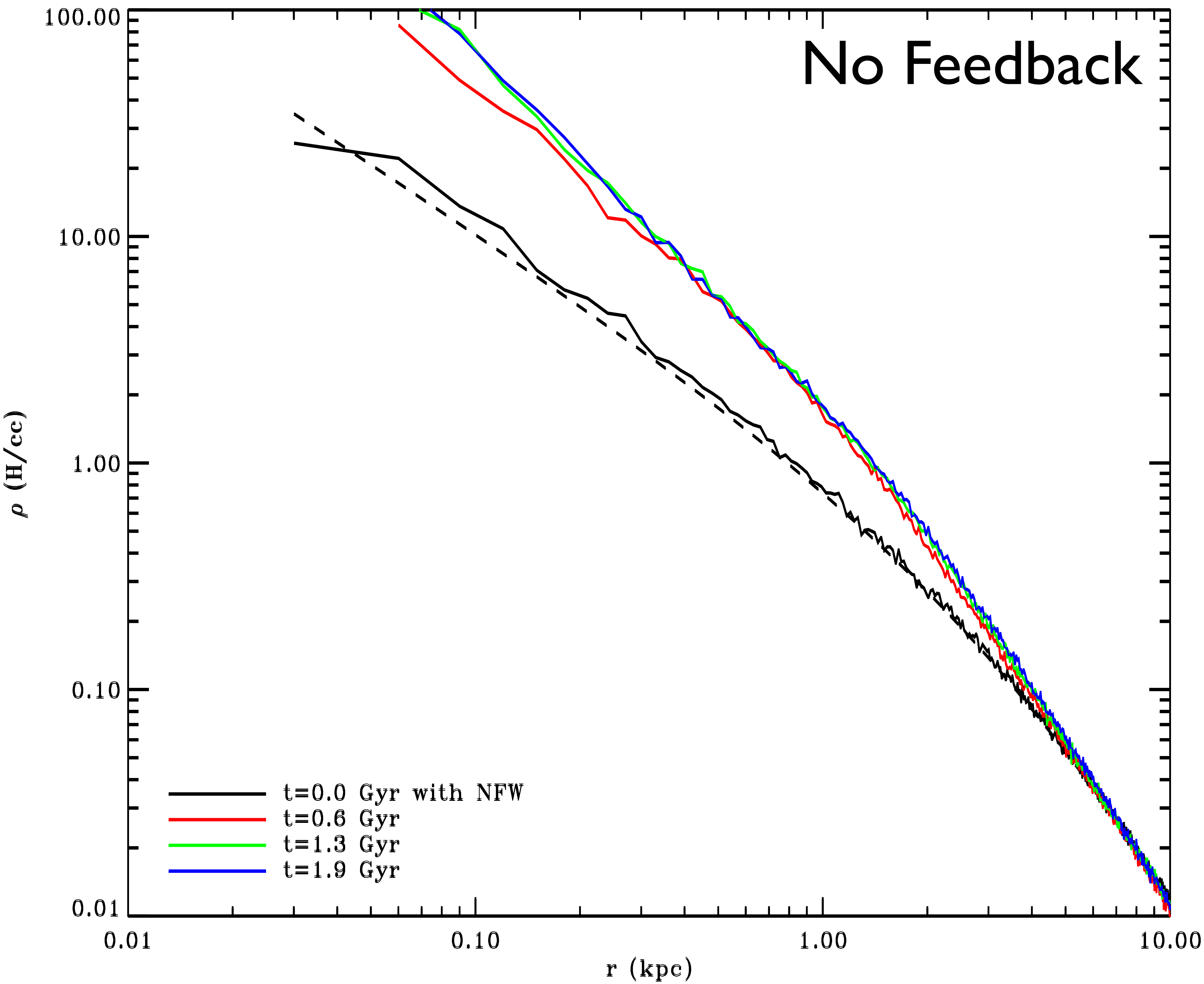

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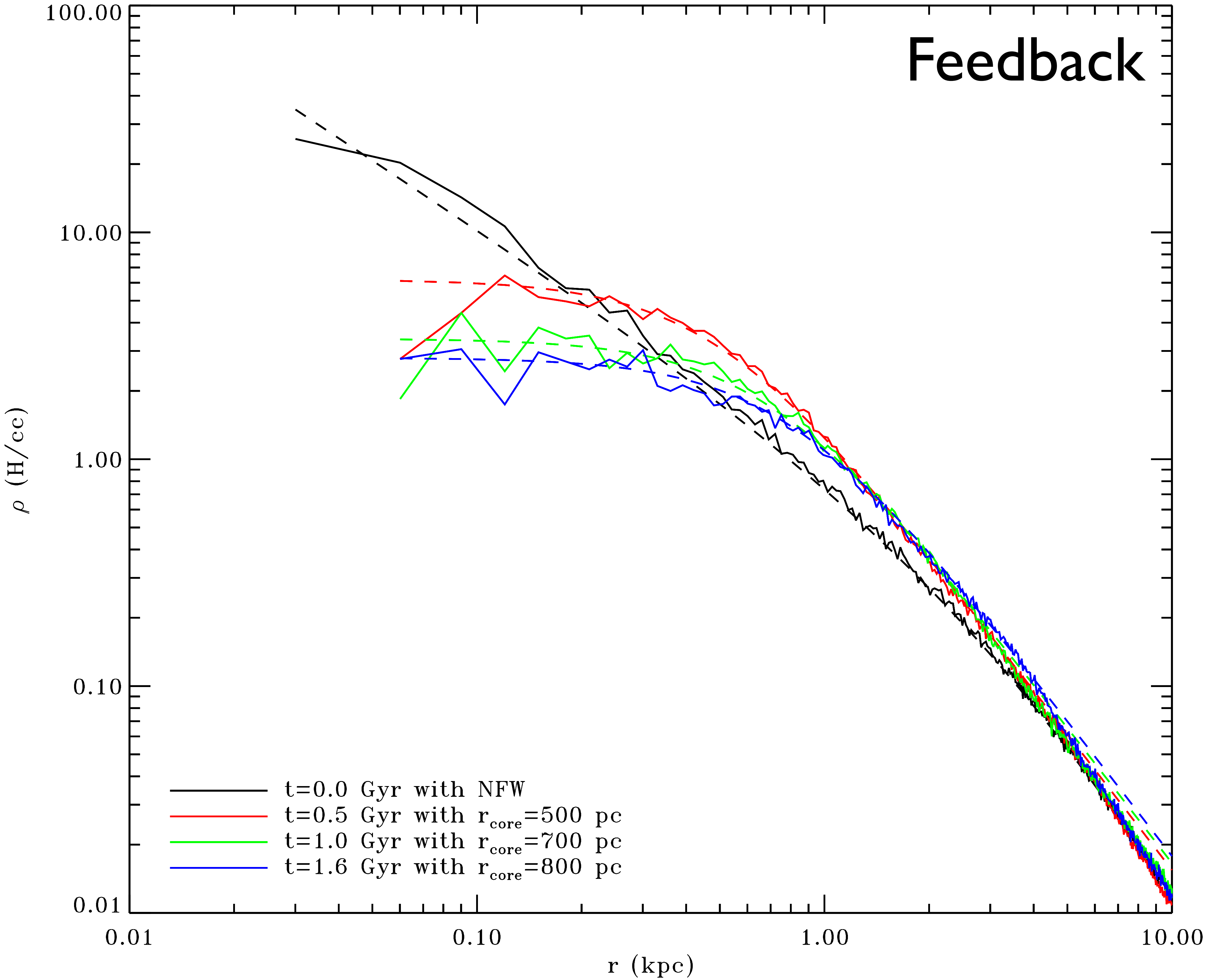

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1. Calculating the DM dist. | The importance of baryons

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Lake 1989; Read et al. 2008/9

Z=36.4

1. Calculating the DM dist. | The importance of baryons

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Lake 1989; Read et al. 2008/9

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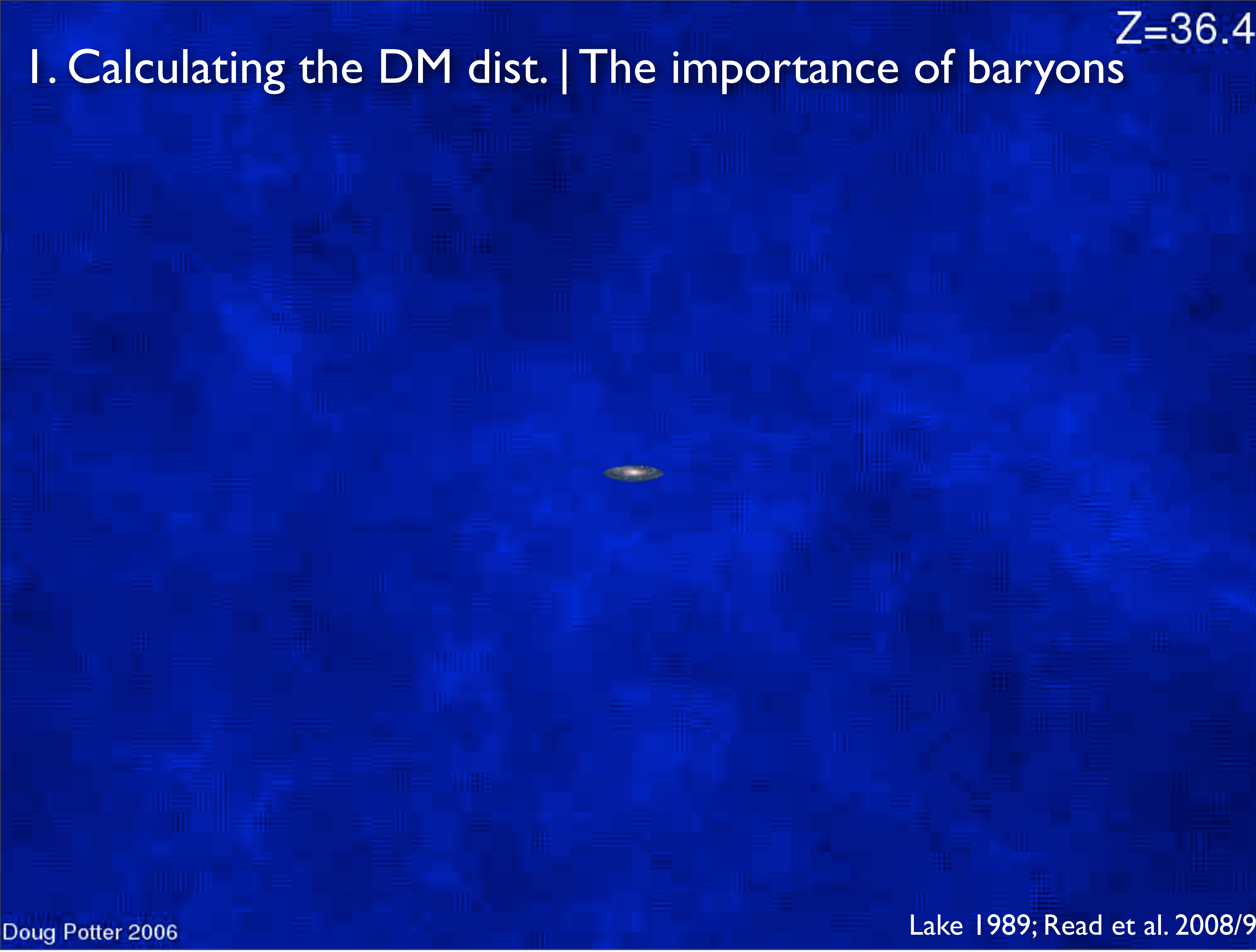

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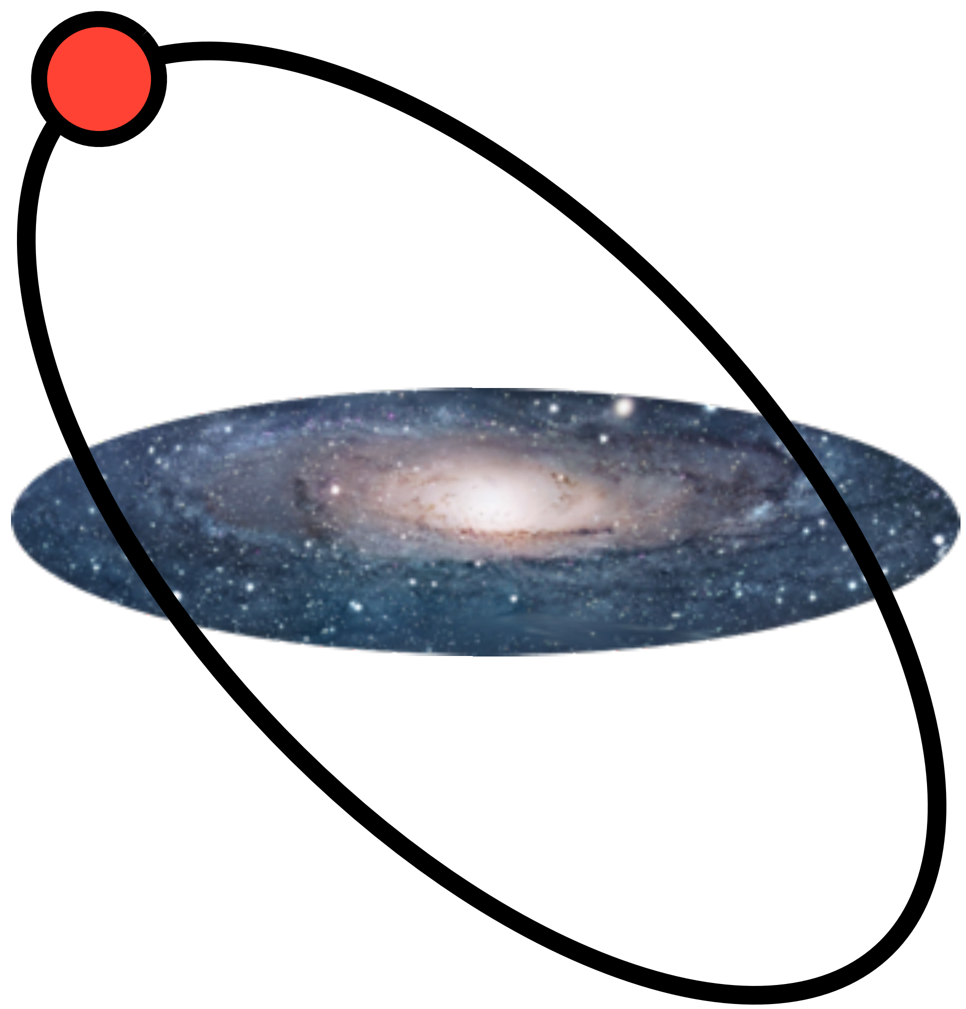

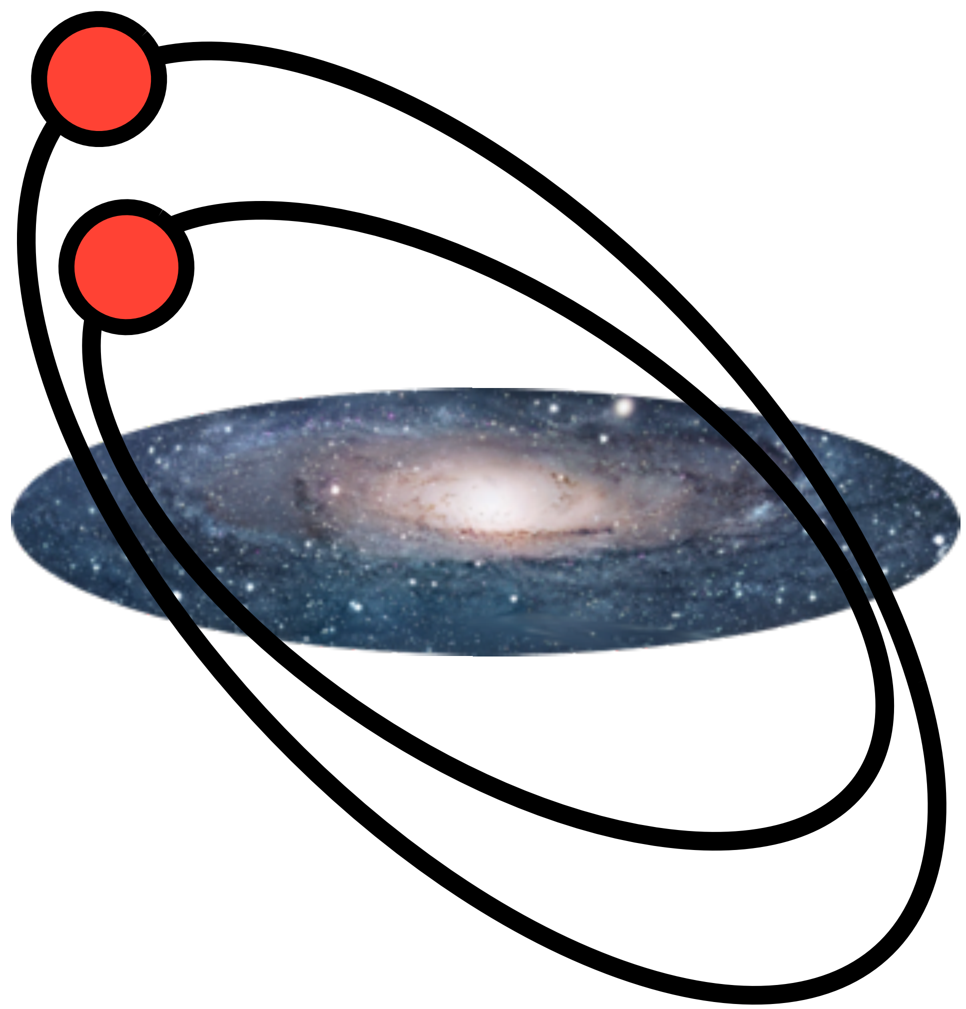

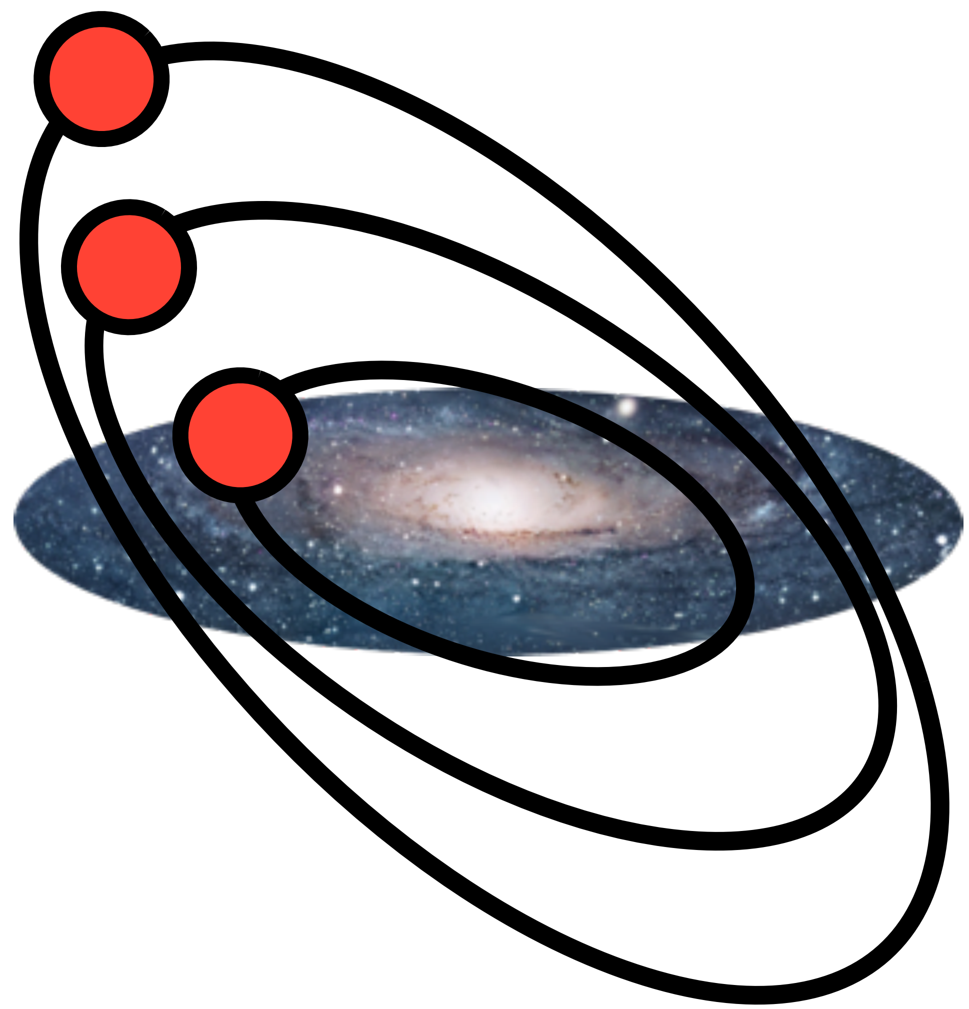

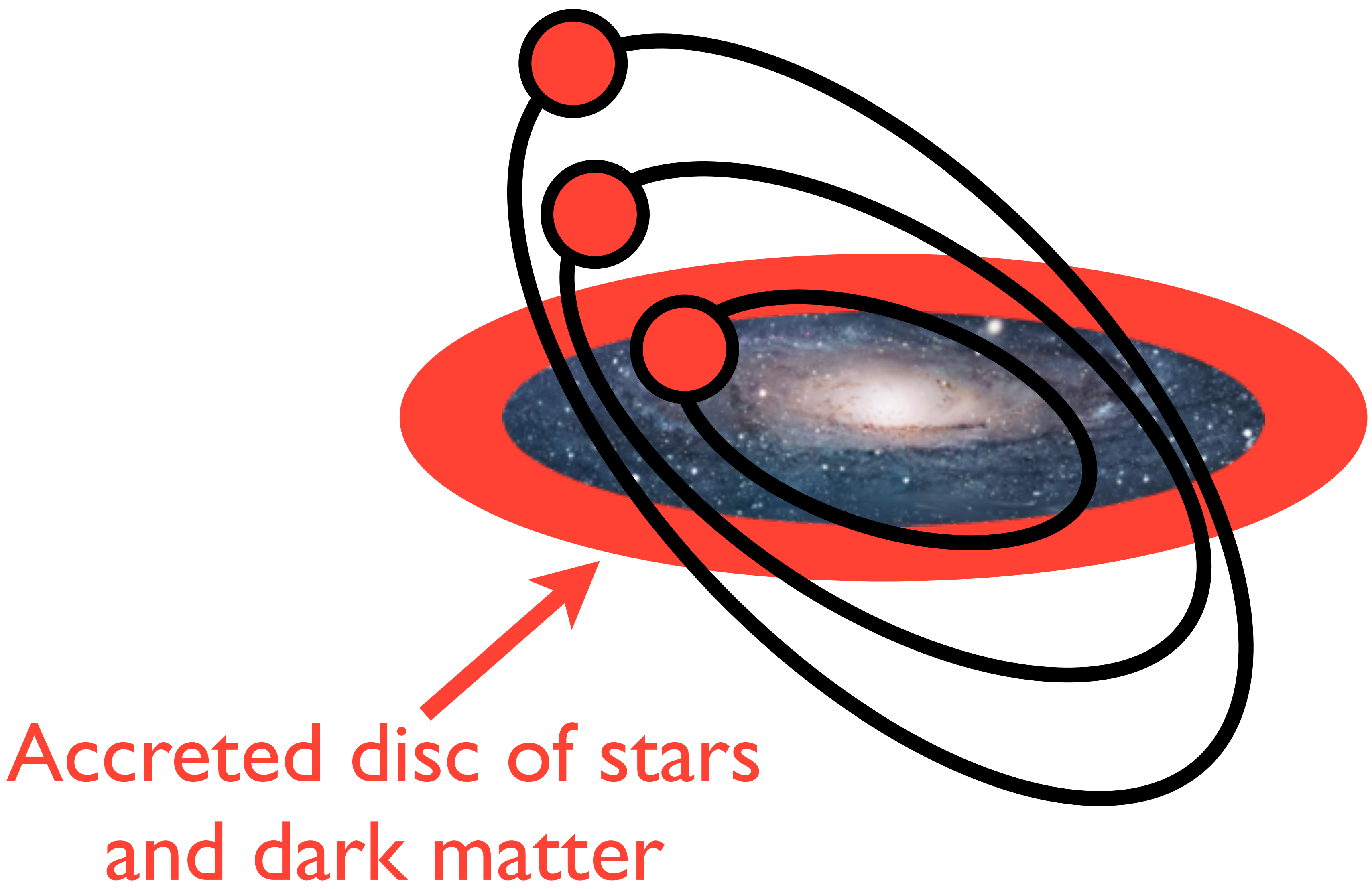
Accreted disc of stars
and dark matter

1. Calculating the DM dist. | The importance of baryons

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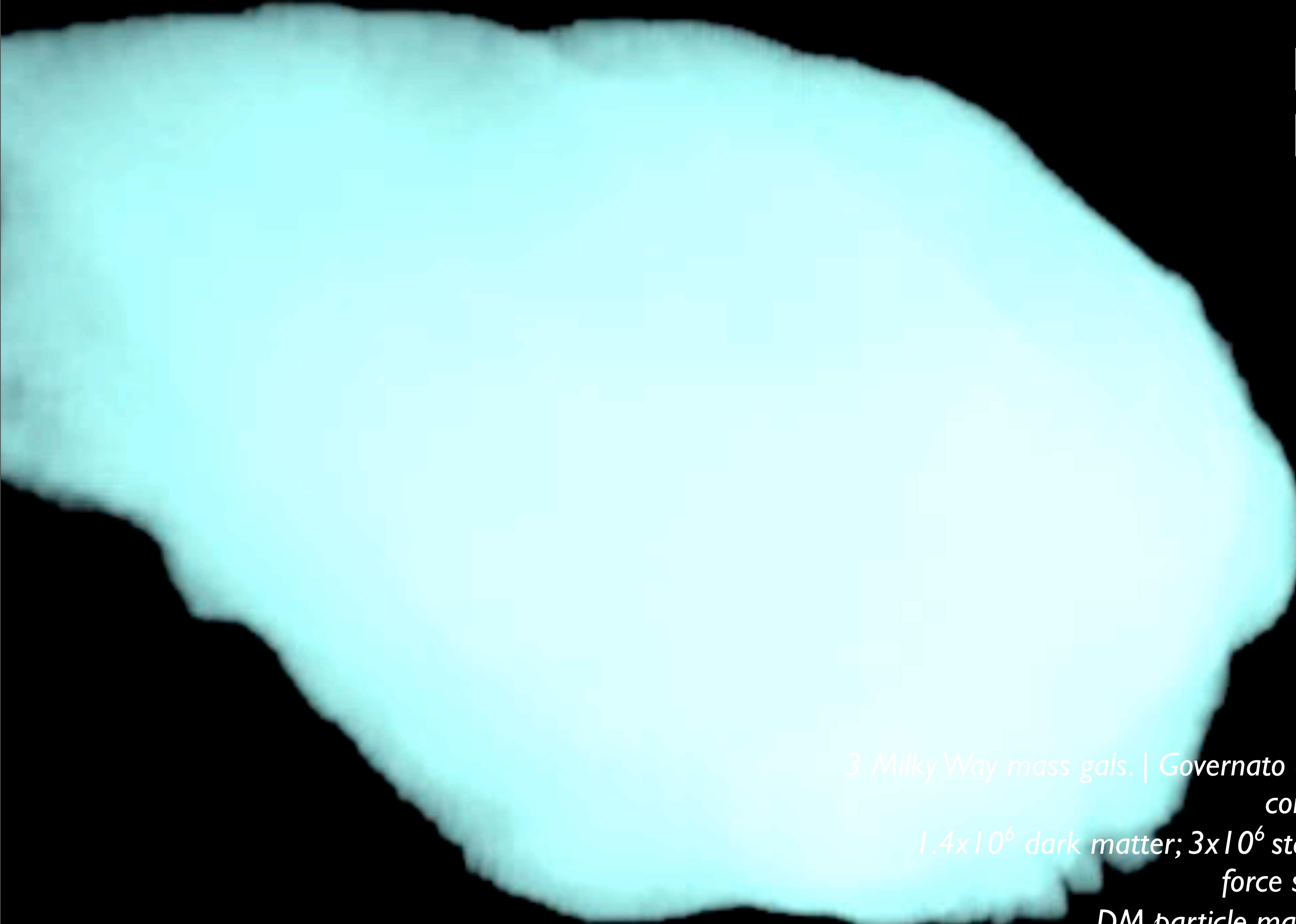


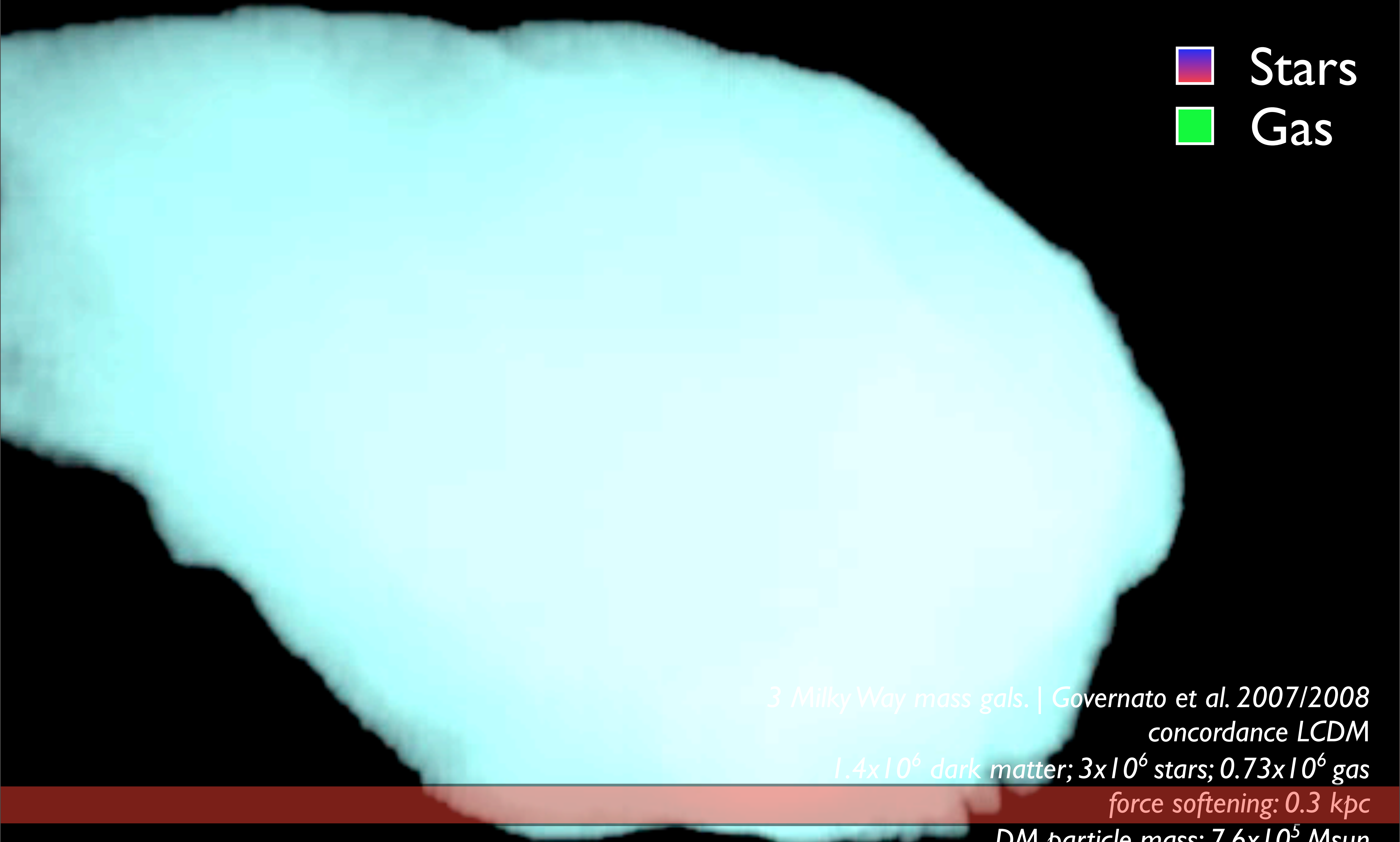
Stars

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

I. Calculating the DM dist. | The importance of baryons



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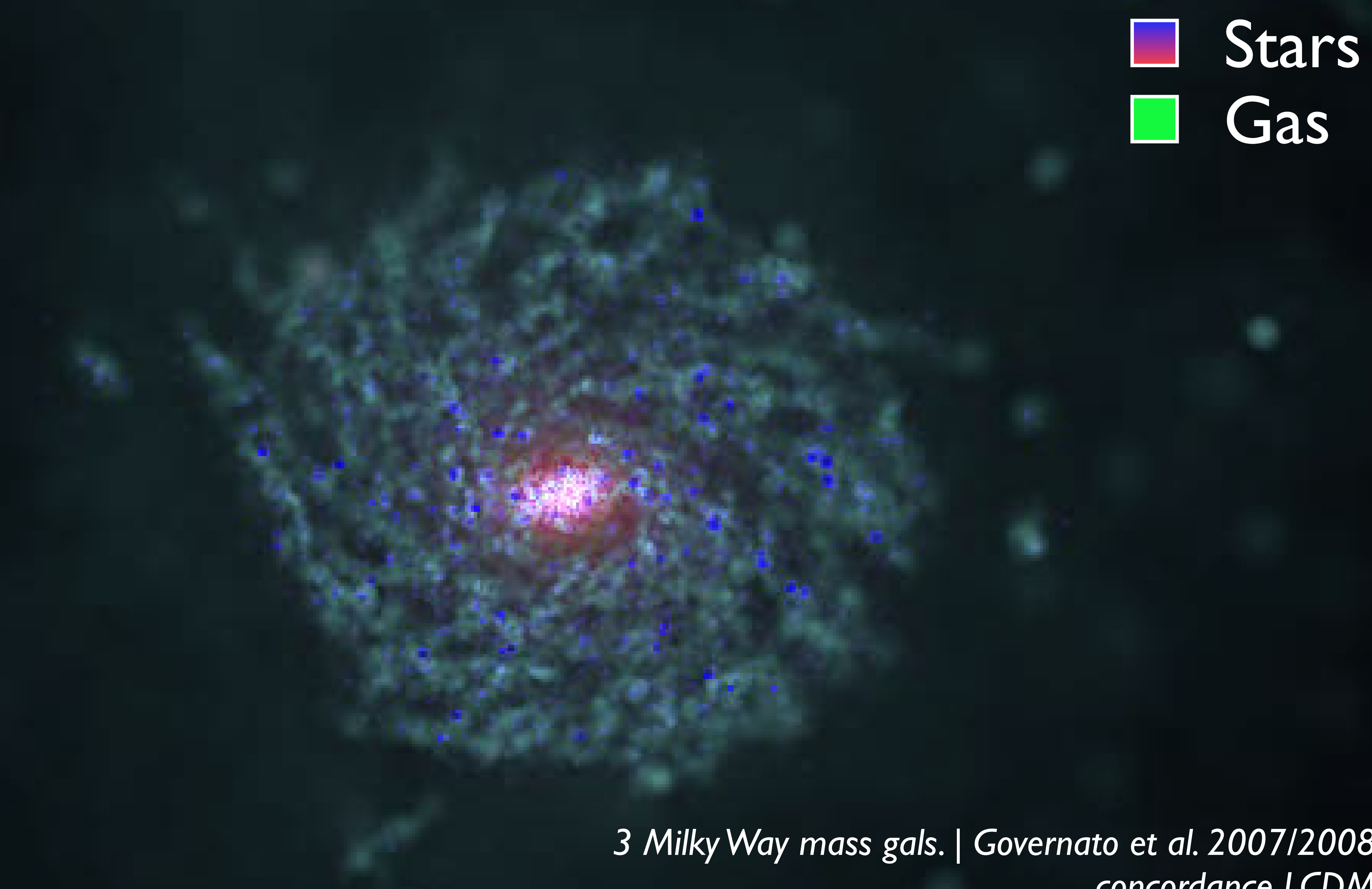

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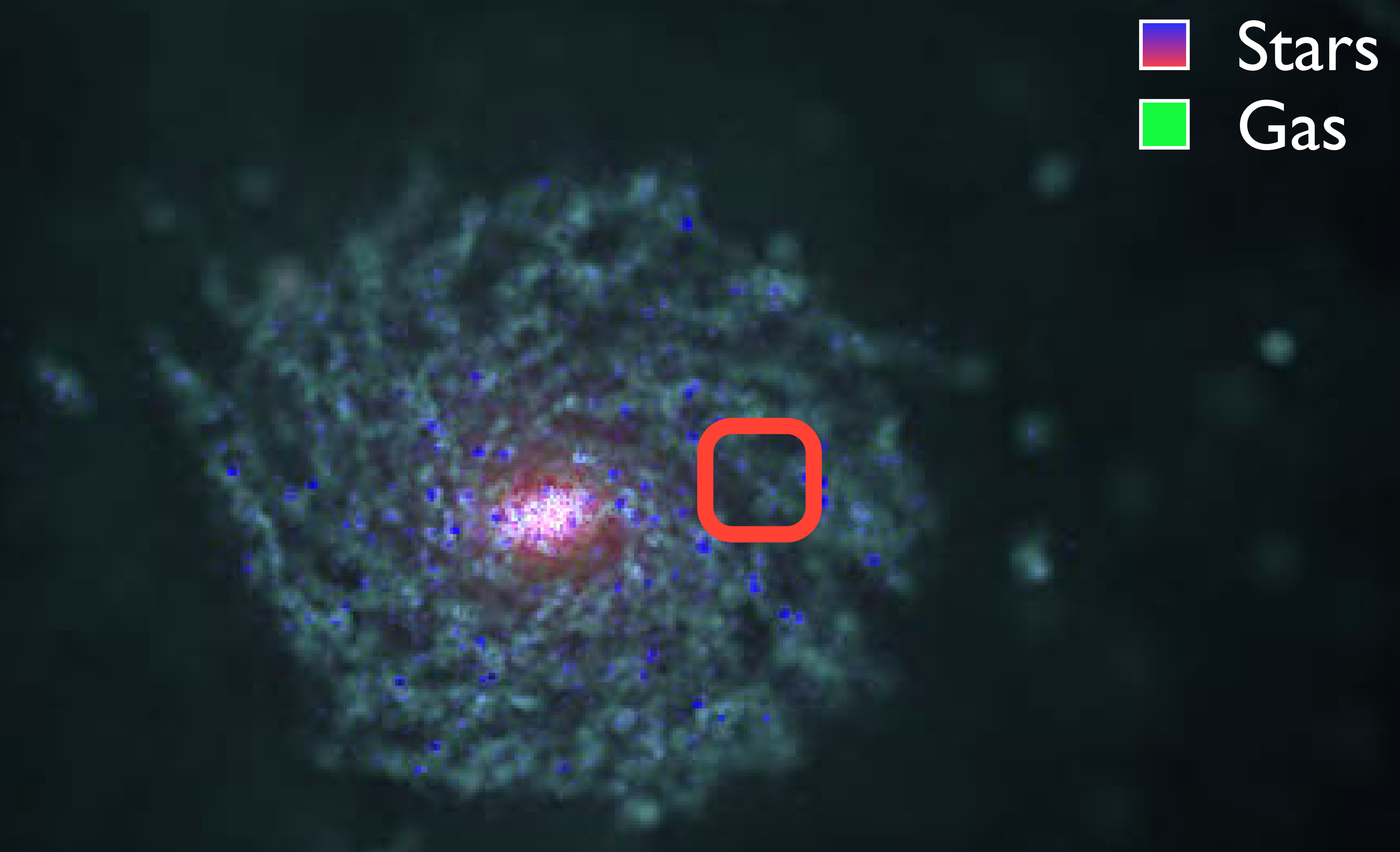

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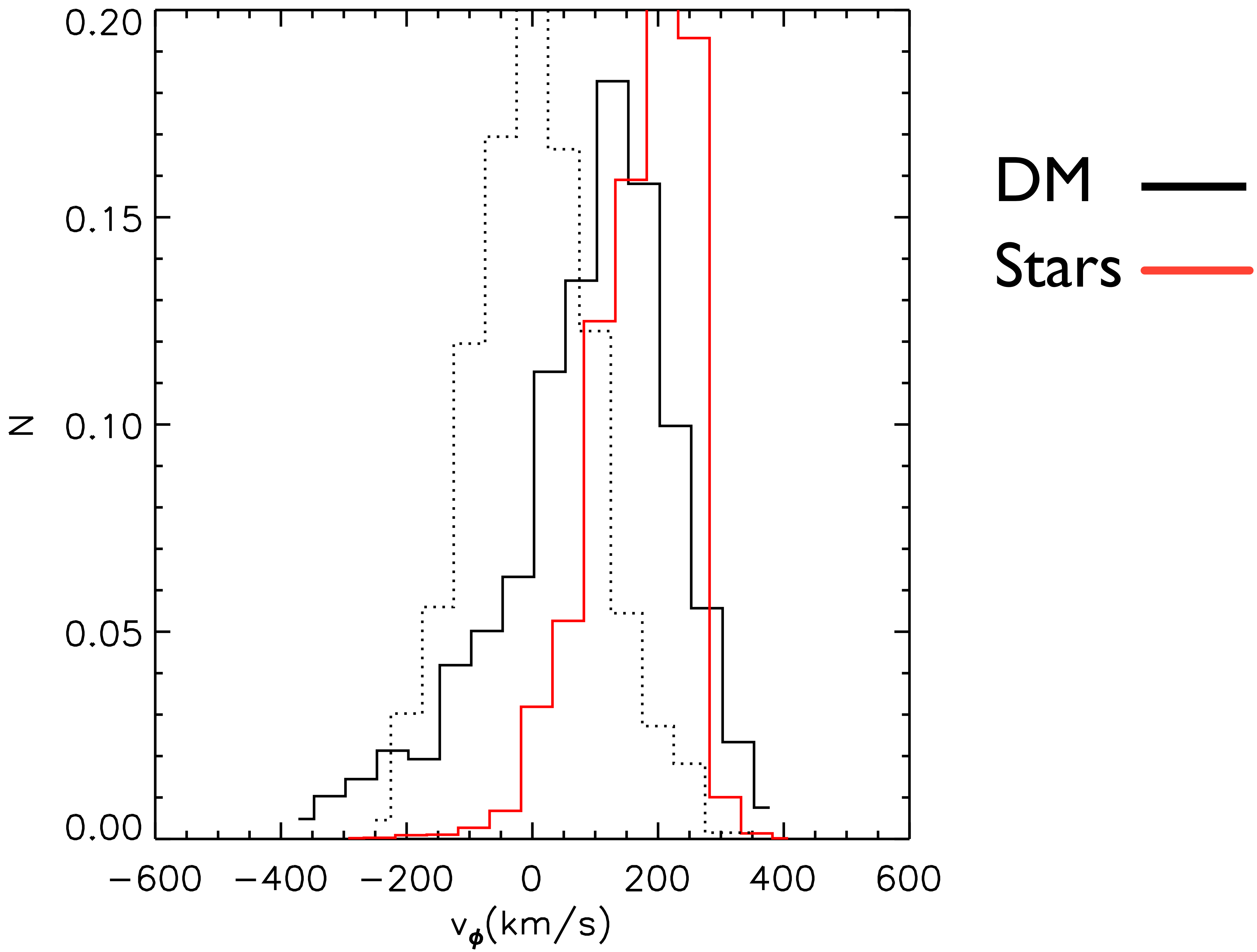

Read et al., 2008/9; Bruch et al. 2009a/b.

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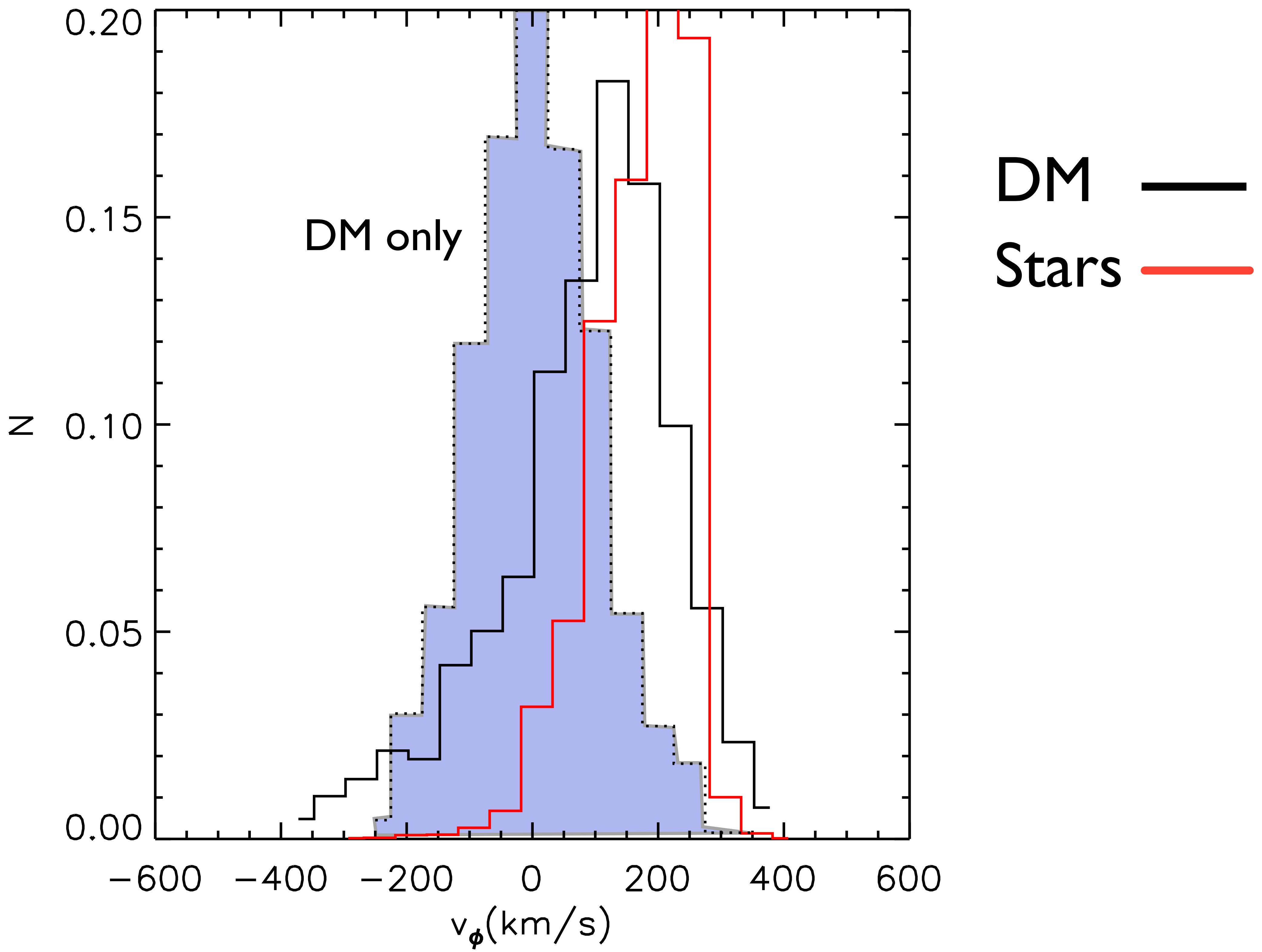

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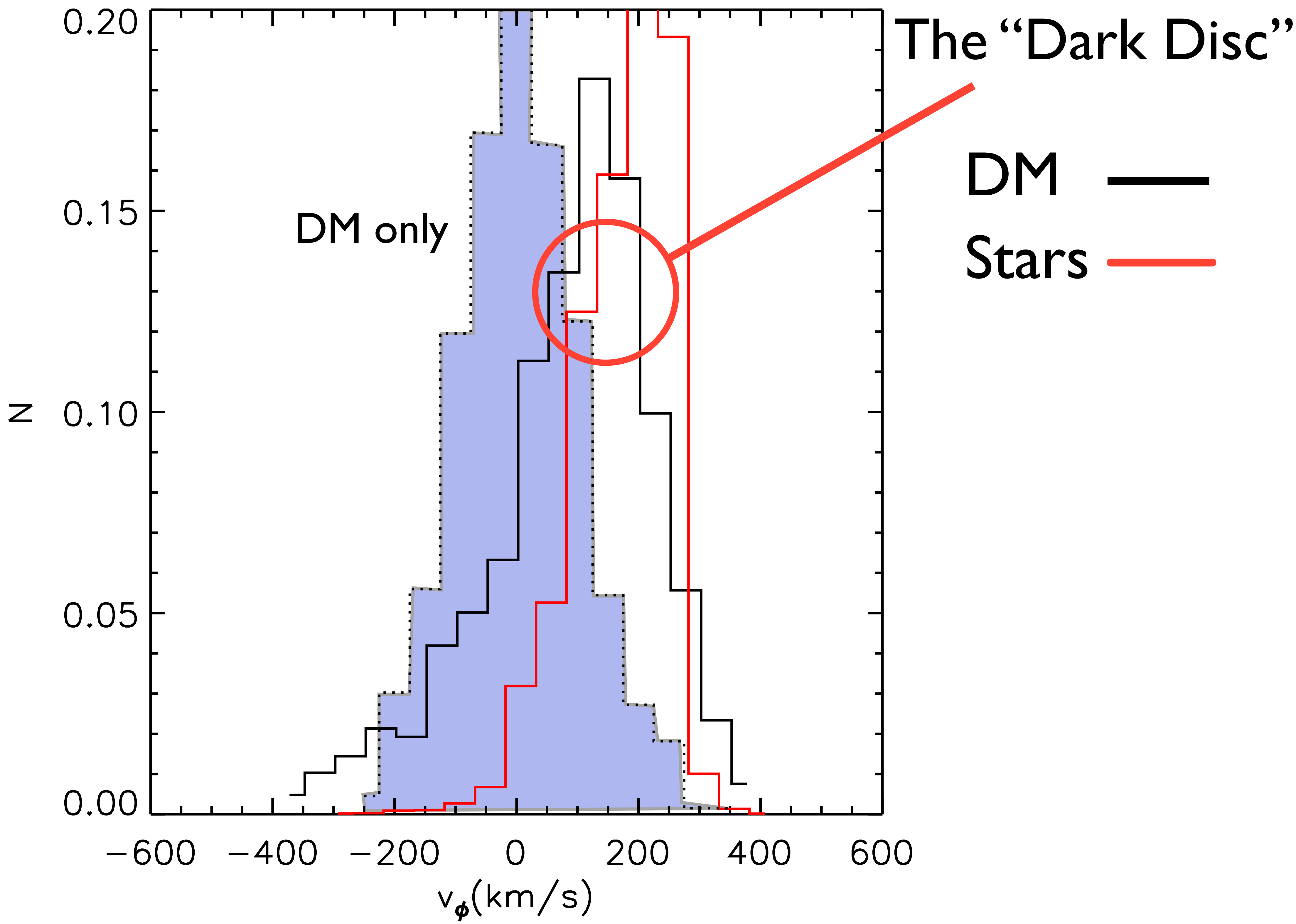

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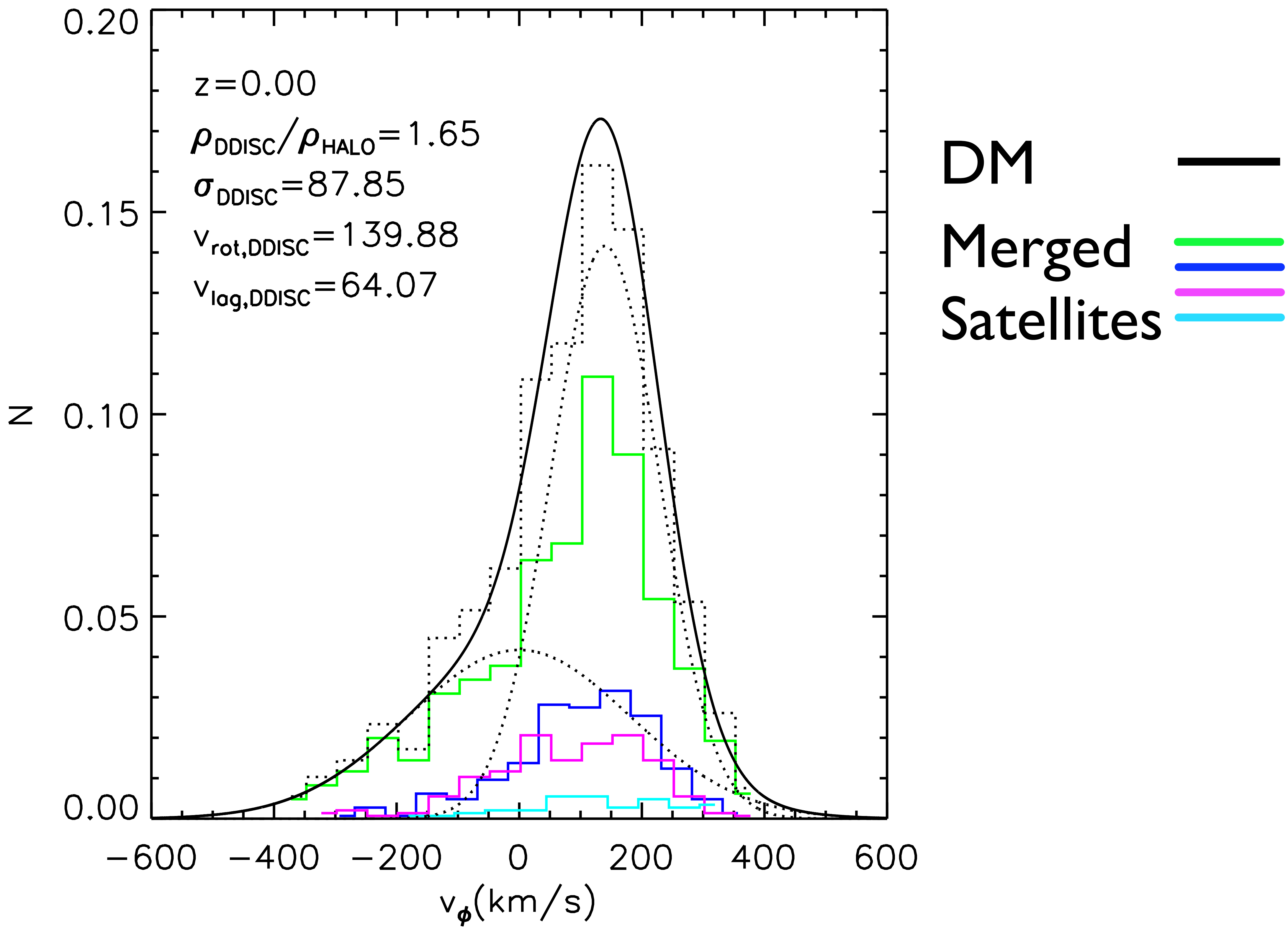

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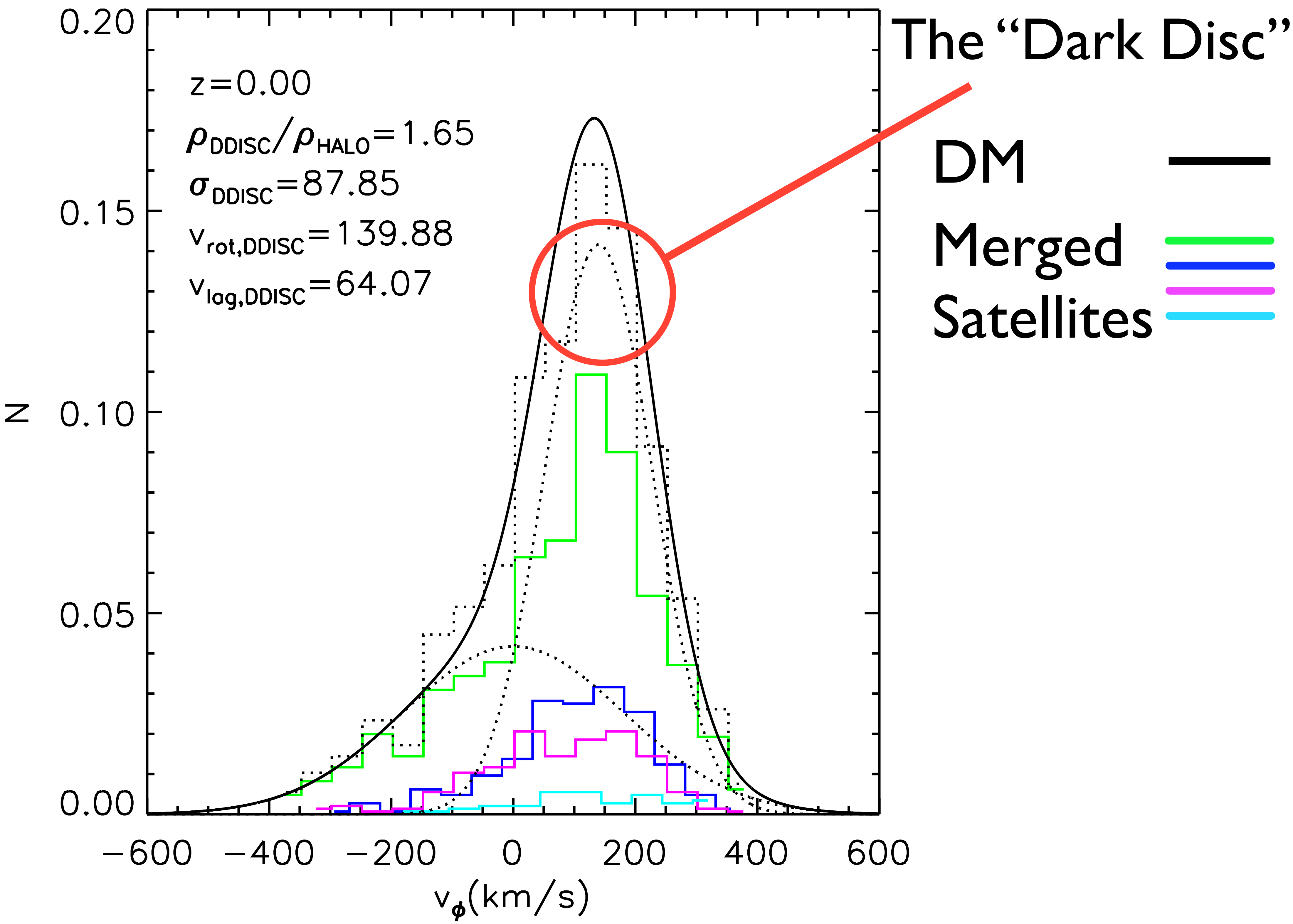

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$\rho_{dd} = 0.25\text{-}1.5\rho_{shm}$; $v_{lag} = 0\text{-}150$km/s; $\sigma = 50\text{-}90$km/s

Read et al., 2008/9; Bruch et al. 2009a/b.

1. Calculating the DM dist. | The importance of baryons

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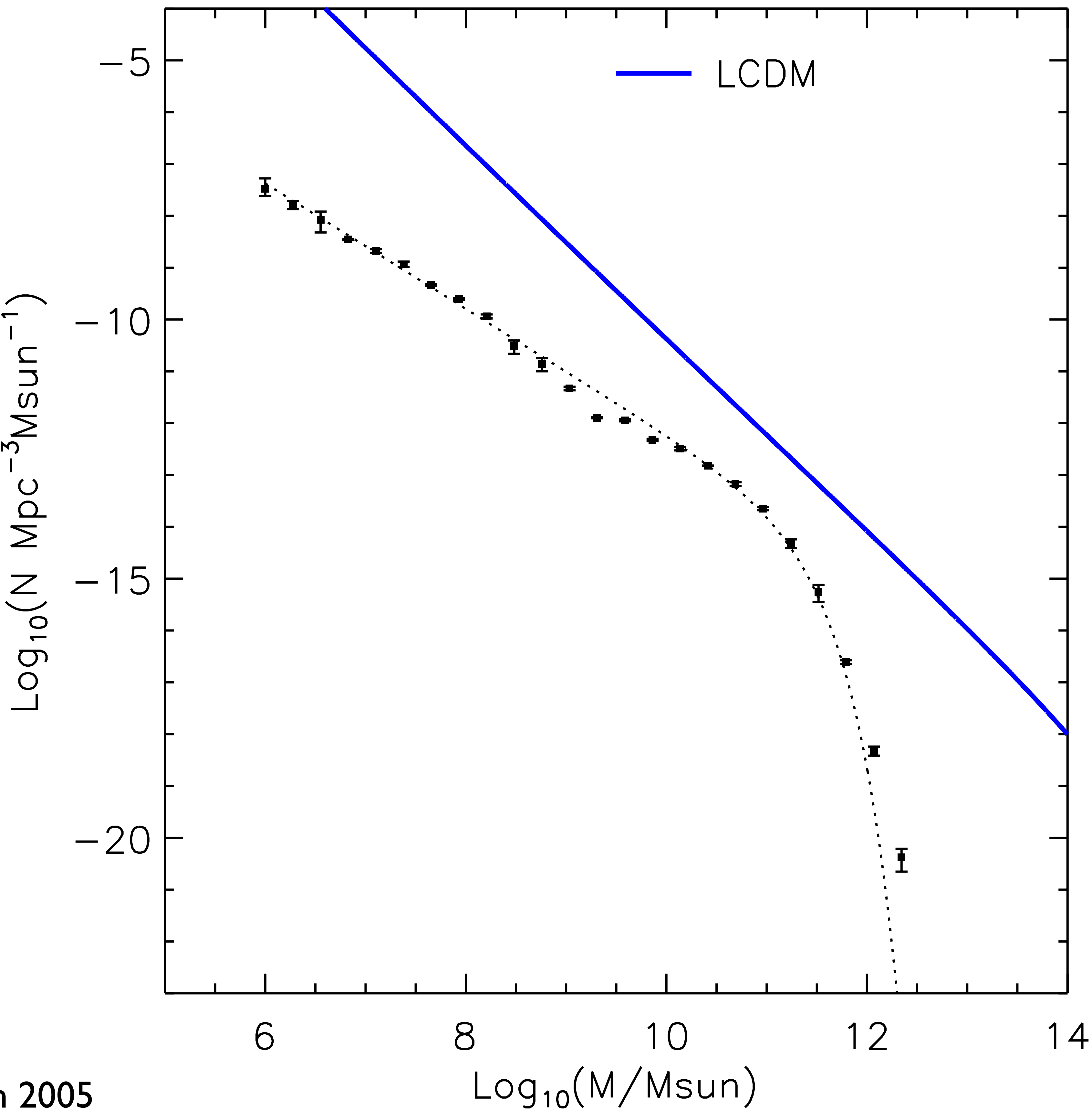
- Boosts the direct detection signal at low recoil energy by a factor ~3 in the 5-20keV range.
- Shifts the phase of the annual modulation signal allowing the WIMP mass to be determined.
- Significantly boosts WIMP capture in the Sun and Earth by factors of ~10 and ~1000, respectively.

Read et al., 2008/9; Bruch et al. 2009a/b.

2. Gravity as a DM probe | The mass function



Read & Trentham 2005

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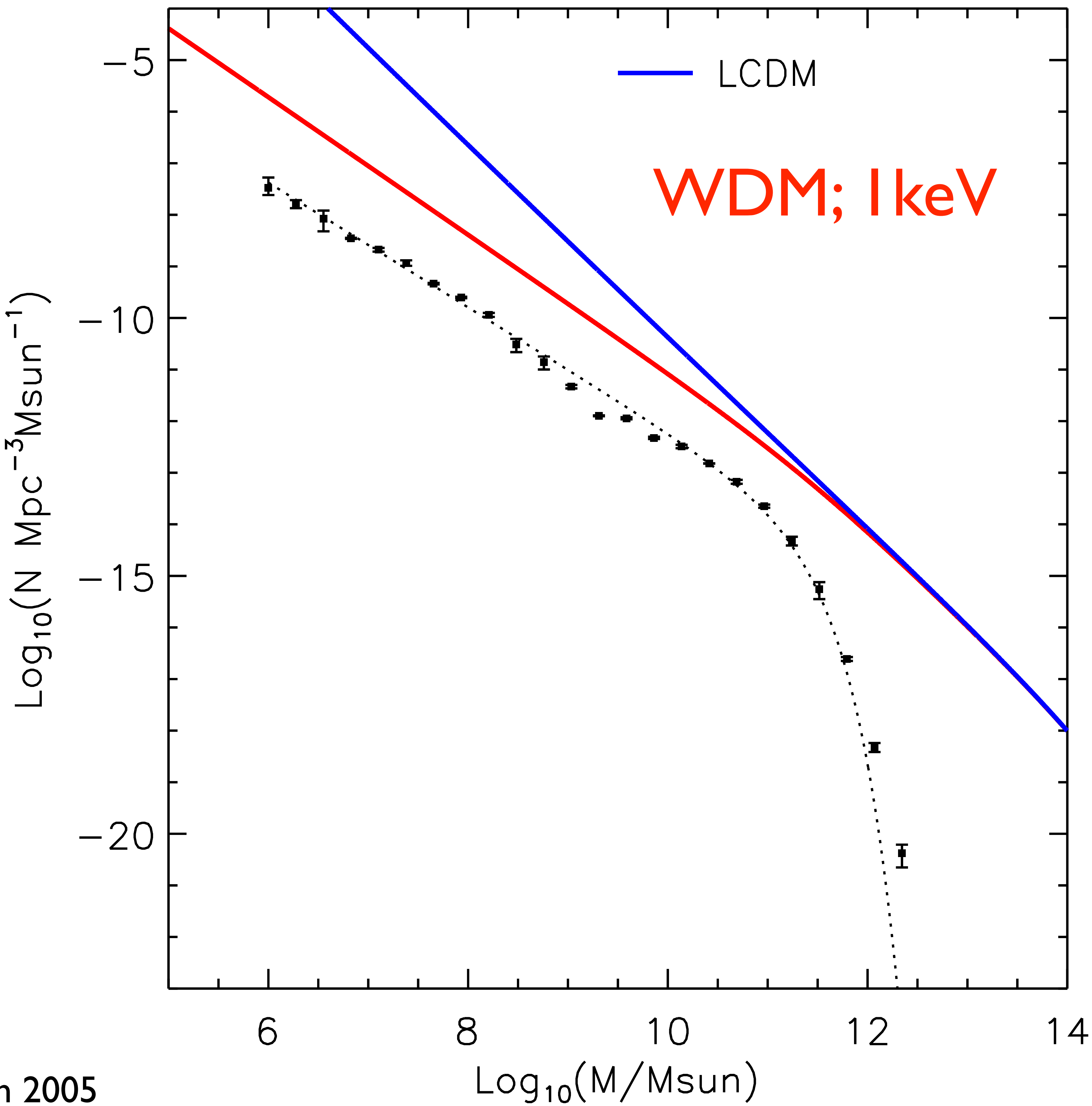

Read & Trentham 2005

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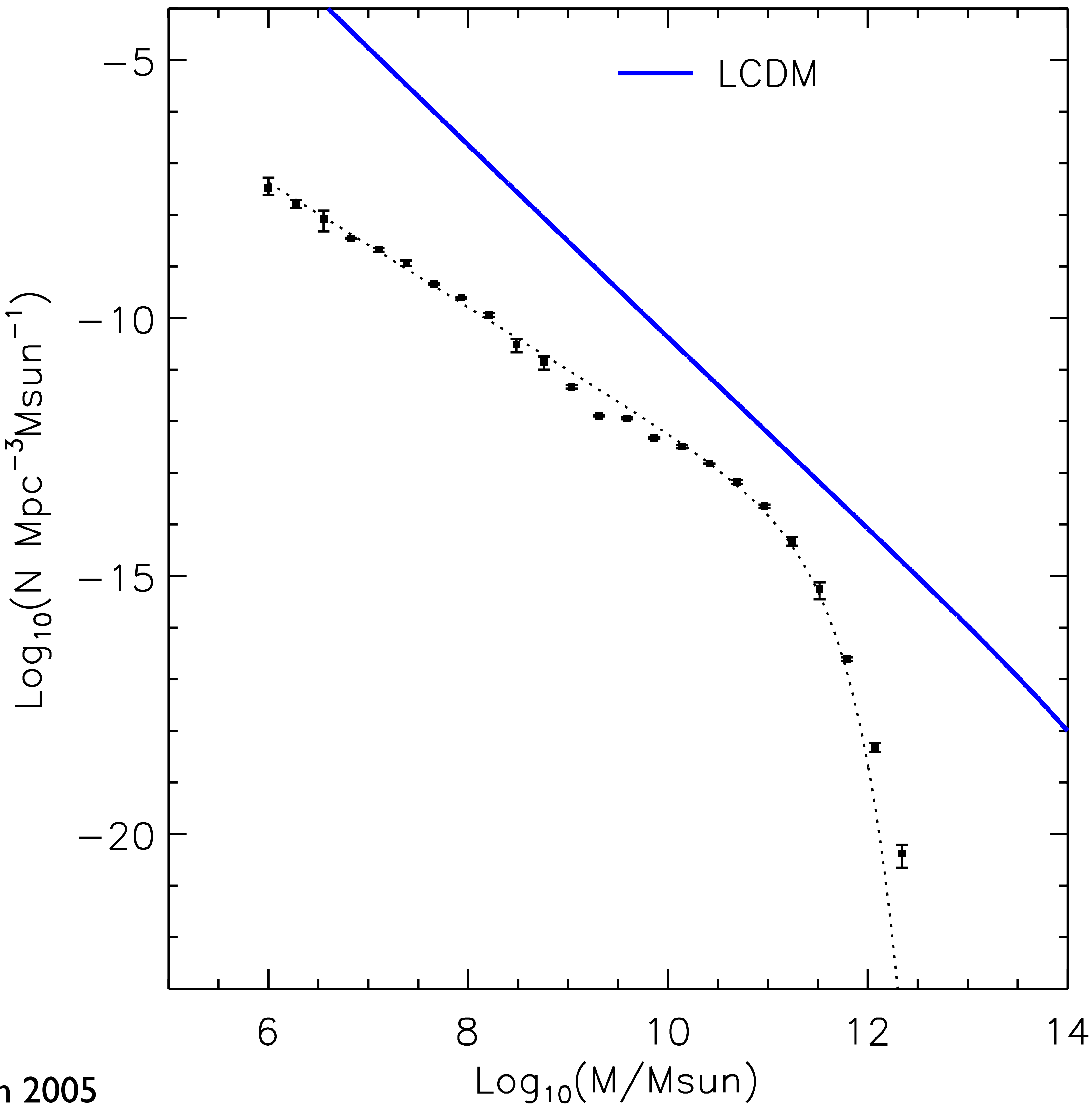

Read & Trentham 2005

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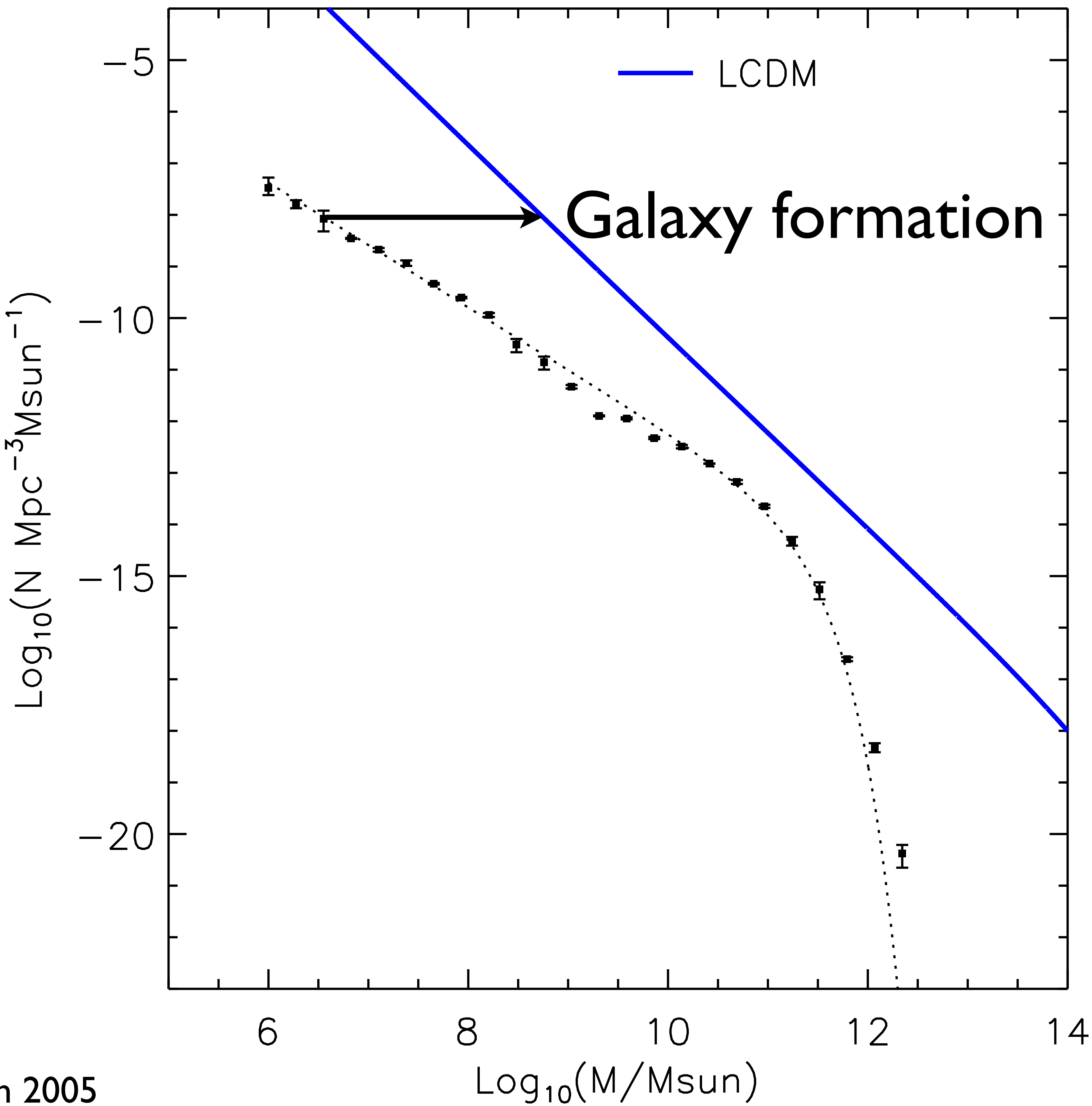
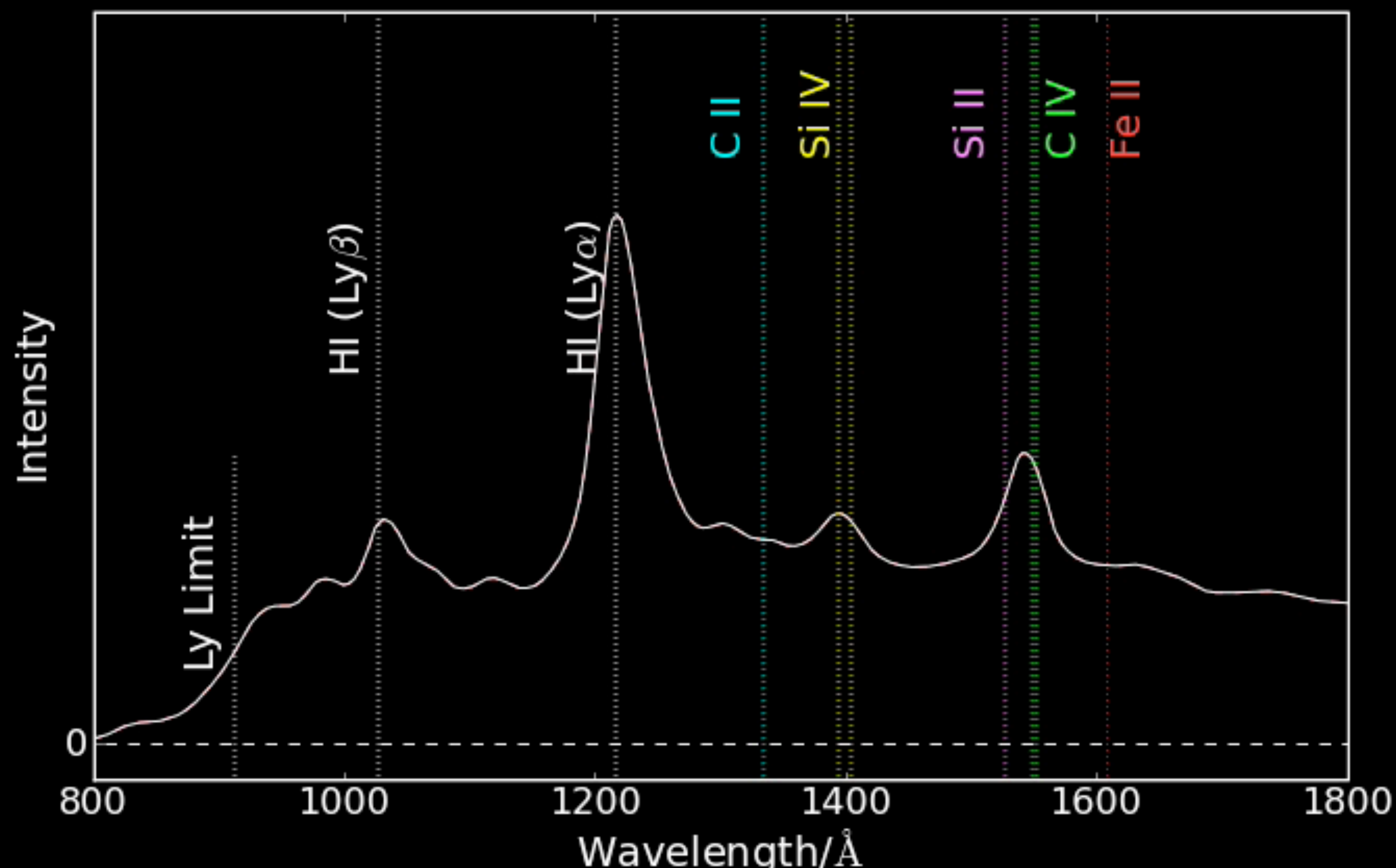


Read & Trentham 2005

2. Gravity as a DM probe | Quasar absorption

Movie by Andrew Pontzen

2. Gravity as a DM probe | Quasar absorption



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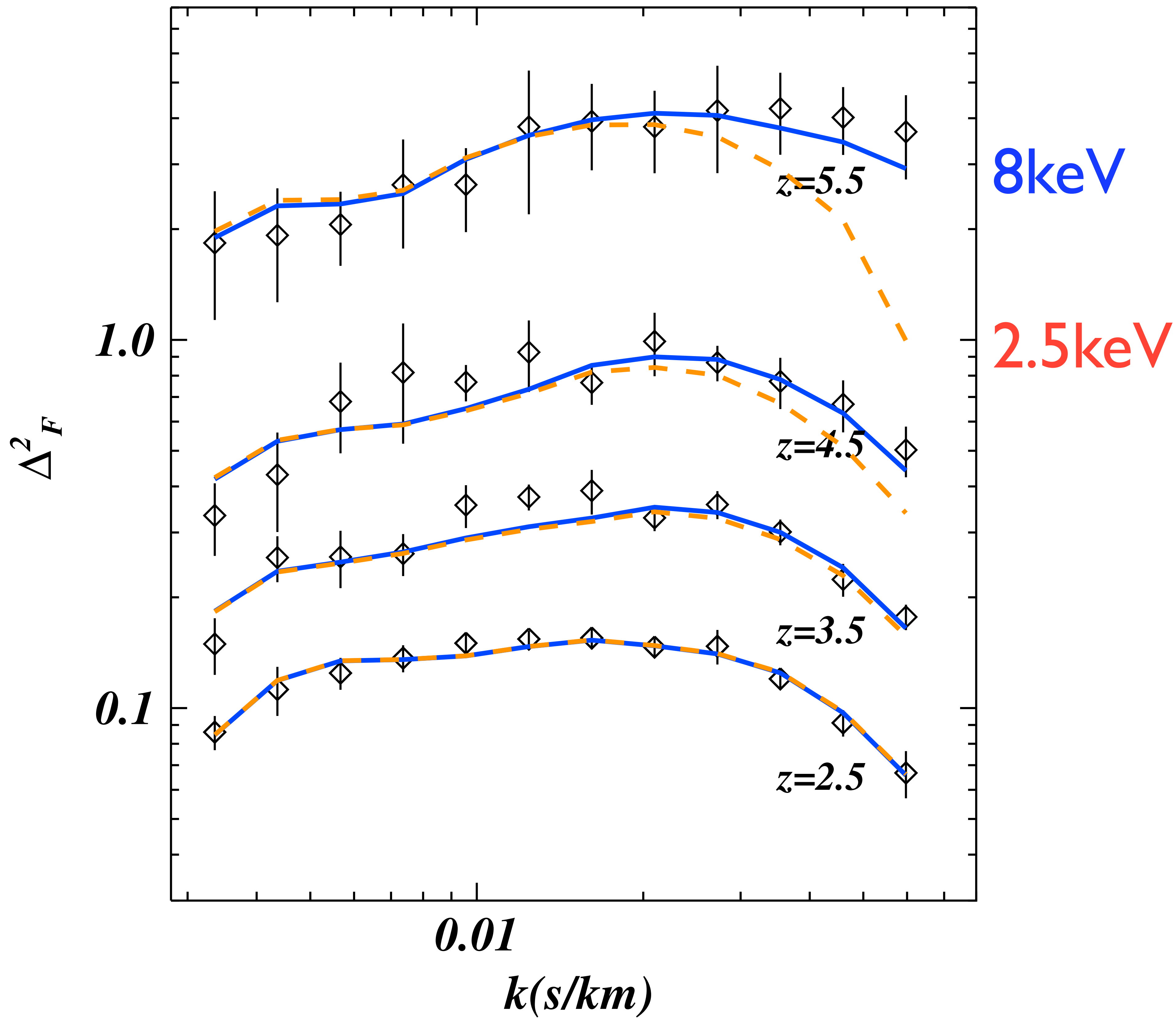
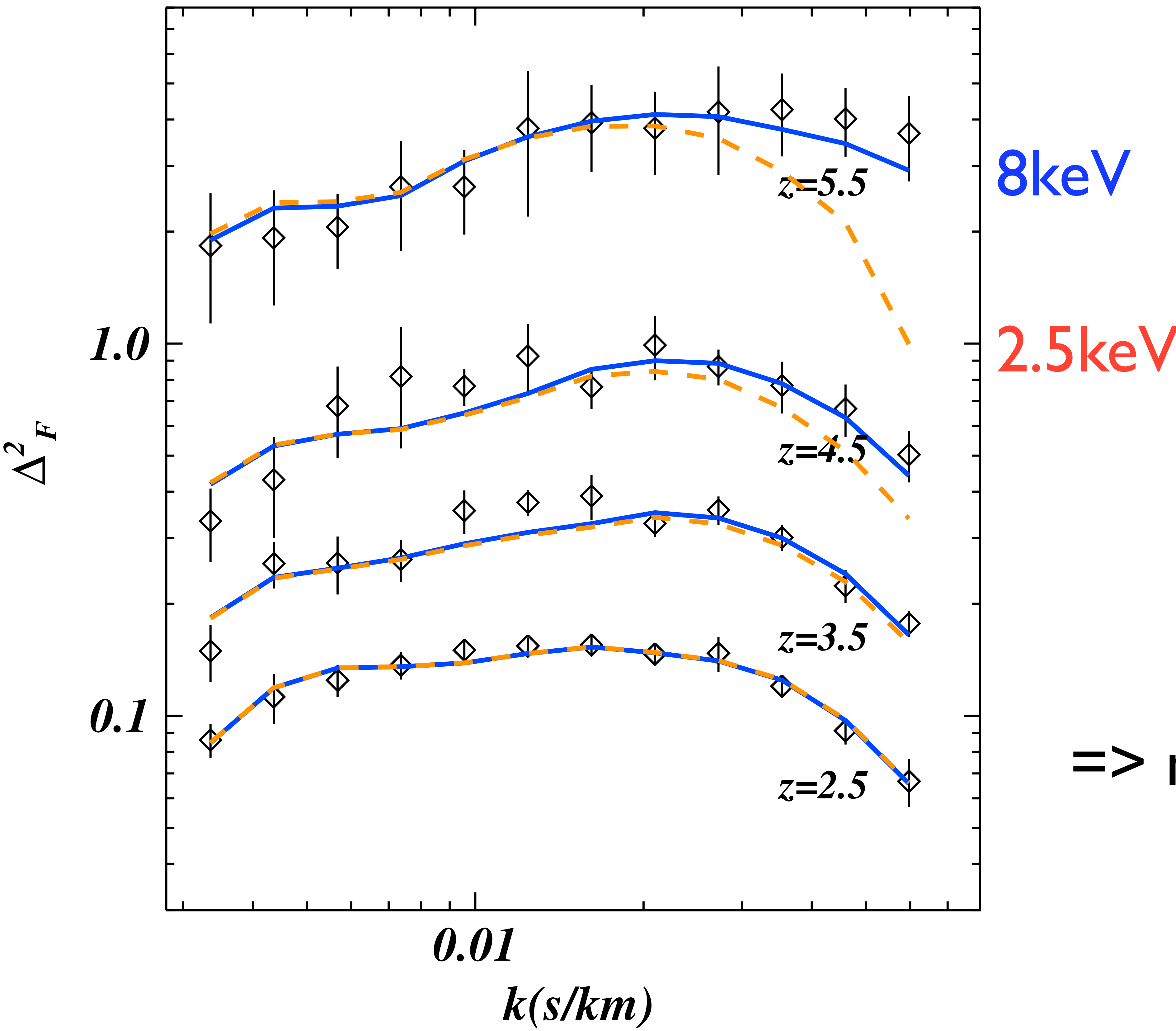


Viel et al. 2008

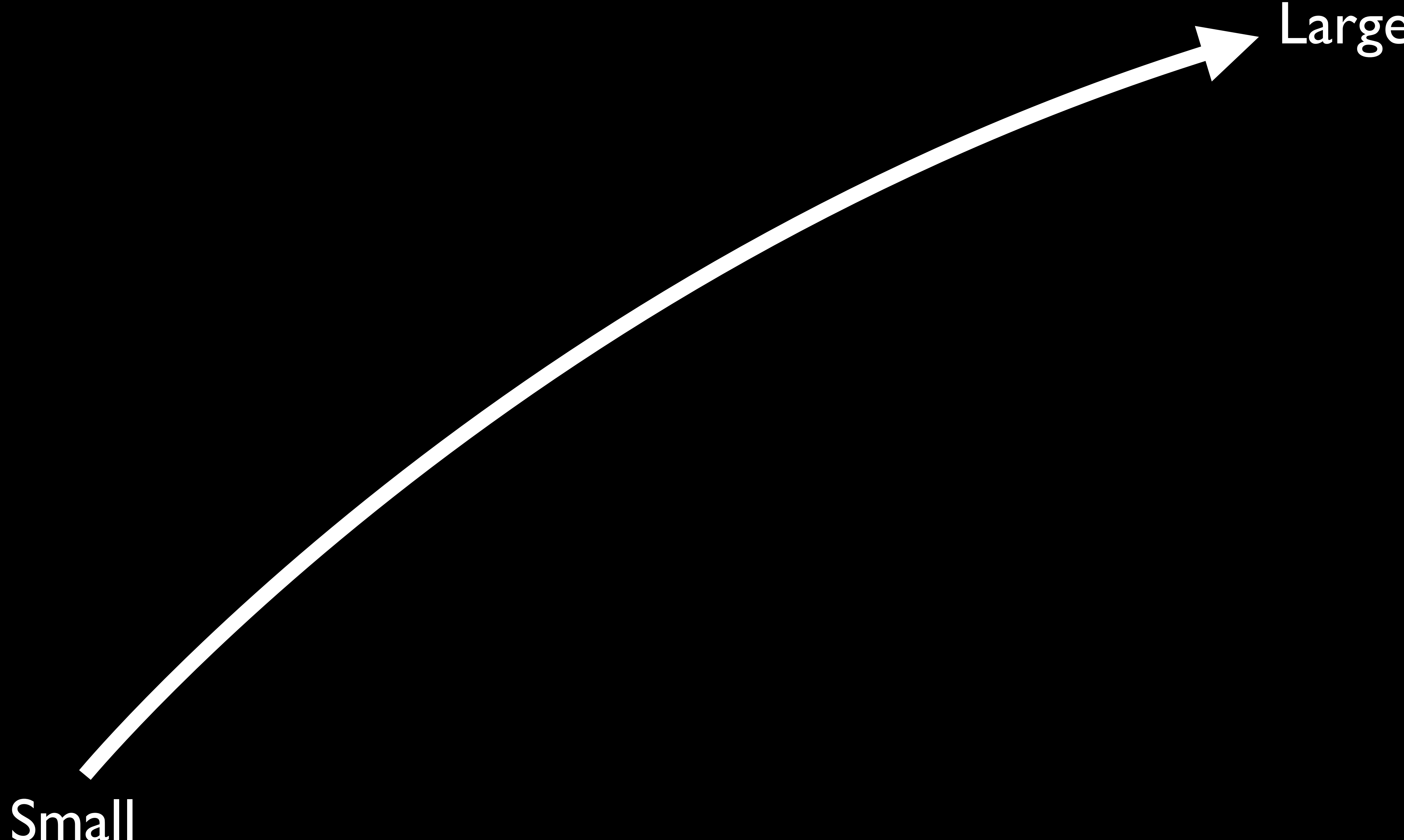
2. Gravity as a DM probe | Quasar absorption



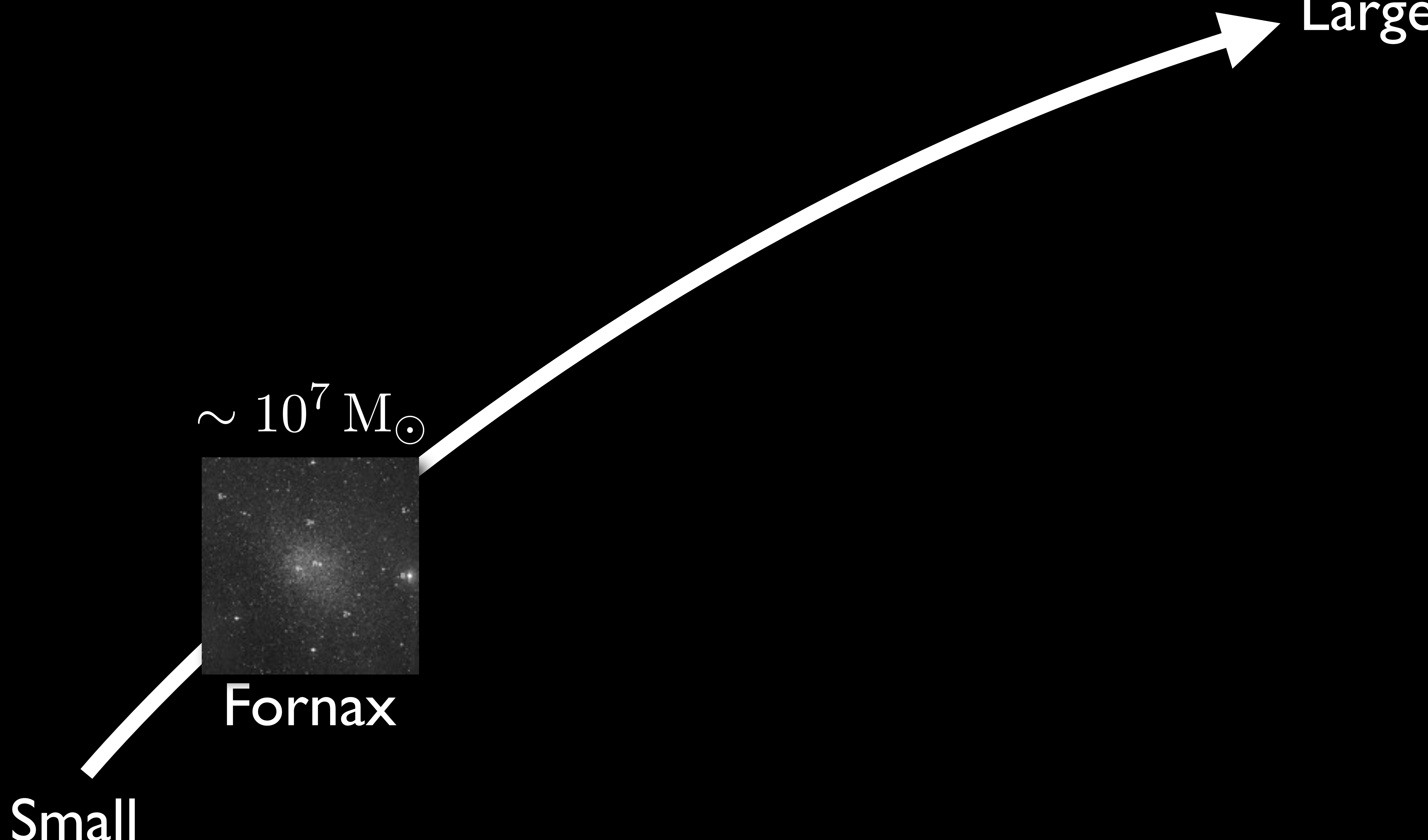
=> m_{WDM} > 4keV

Viel et al. 2008

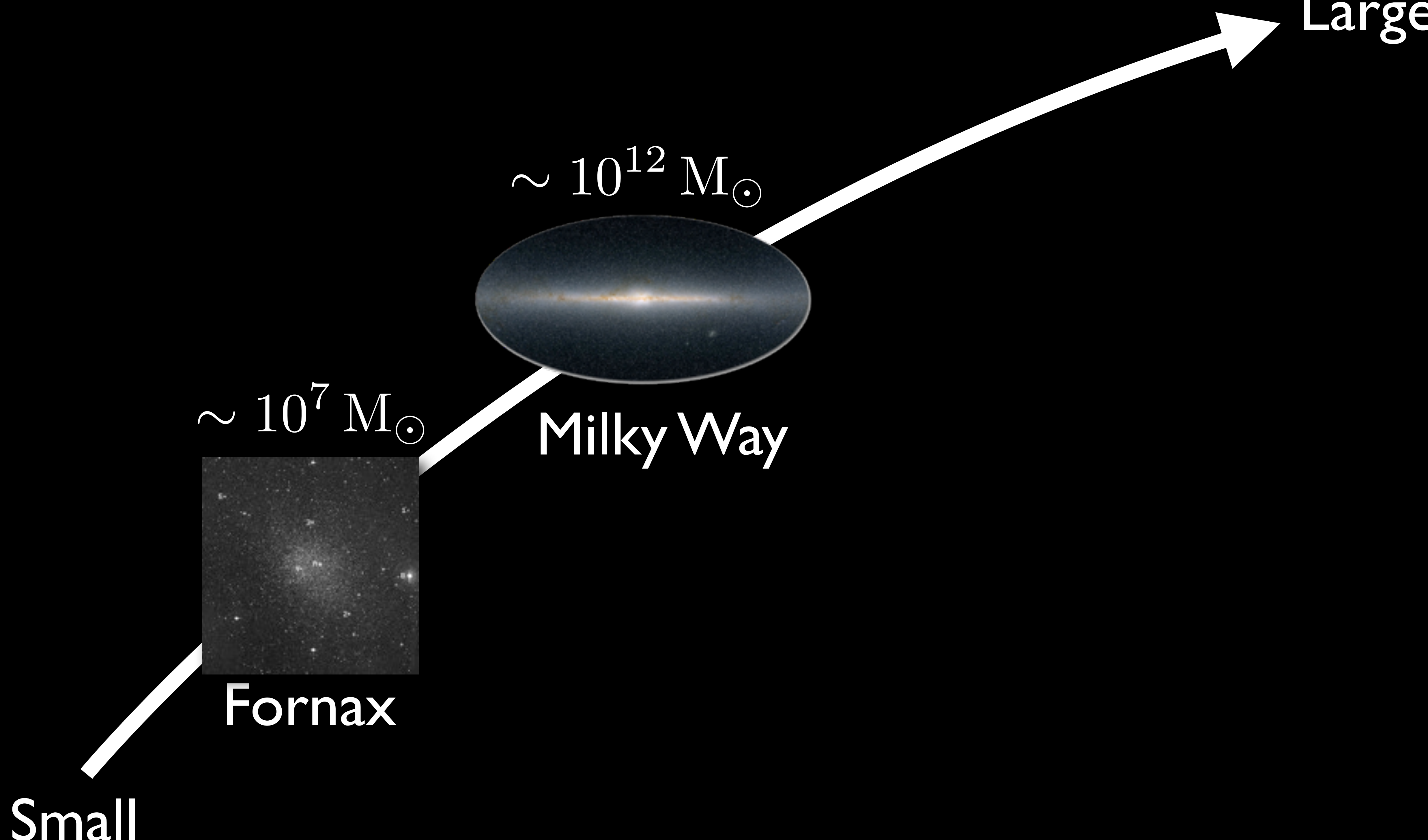
2. Gravity as a DM probe | Observations



2. Gravity as a DM probe | Observations



2. Gravity as a DM probe | Observations



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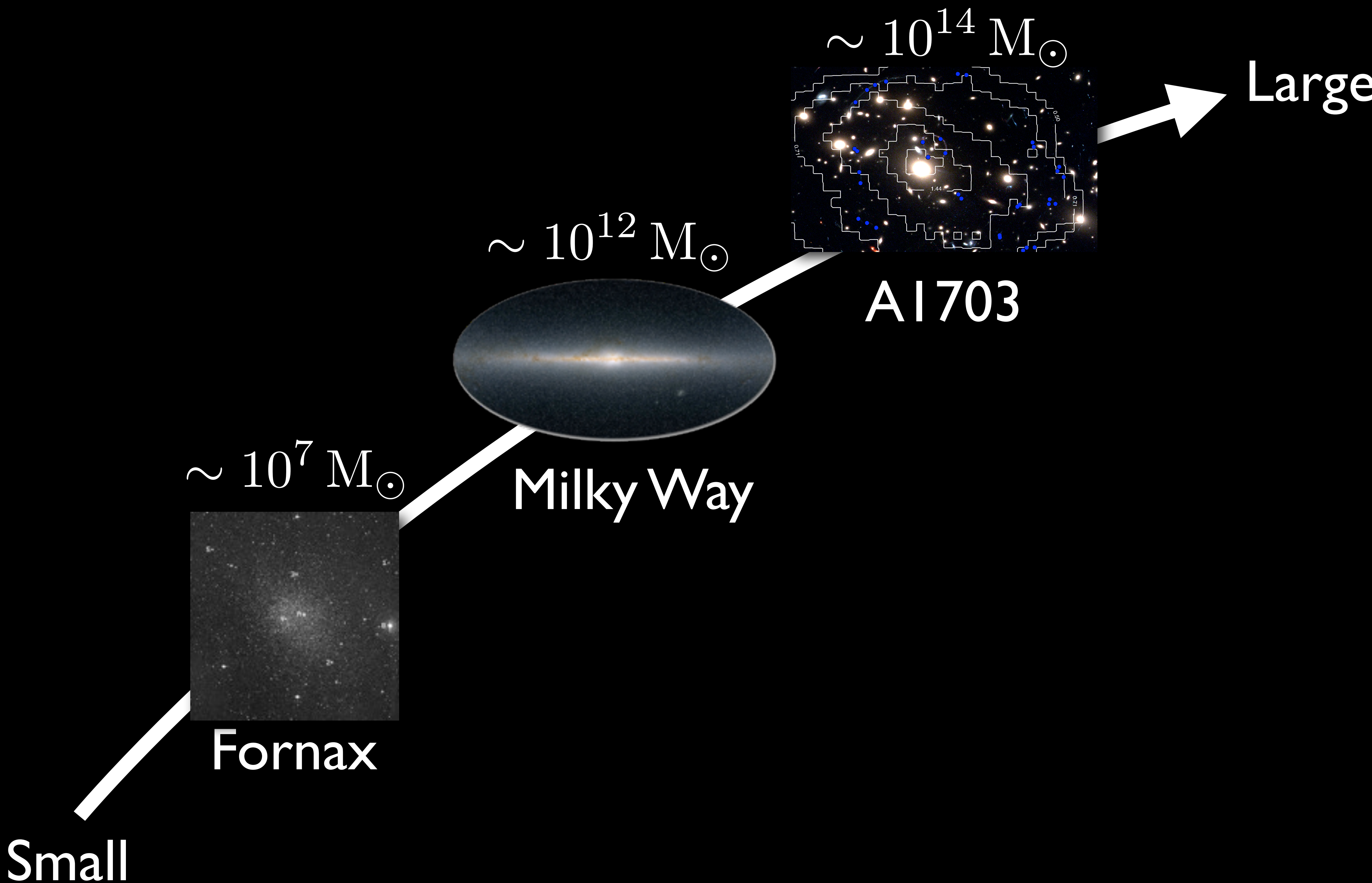

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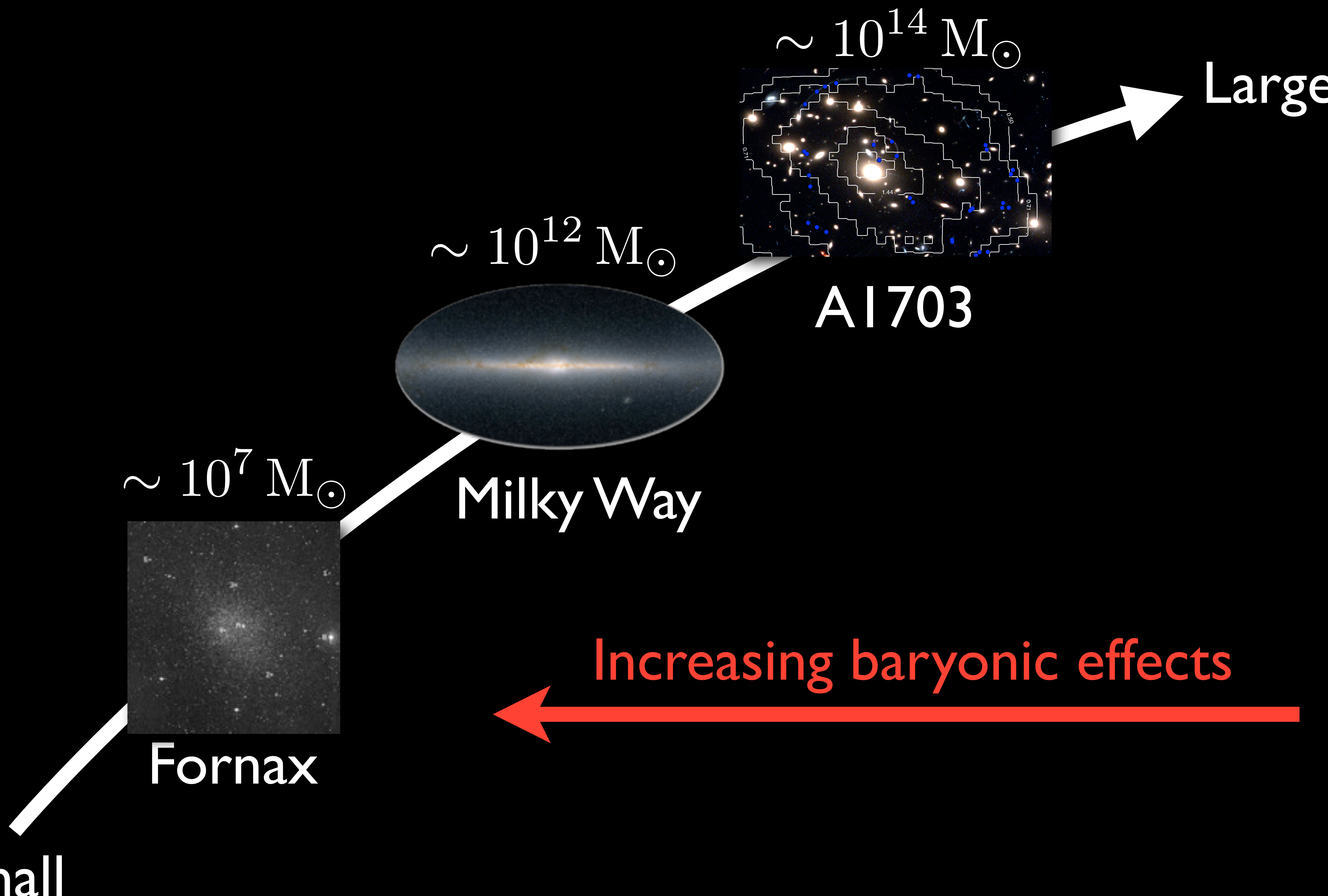
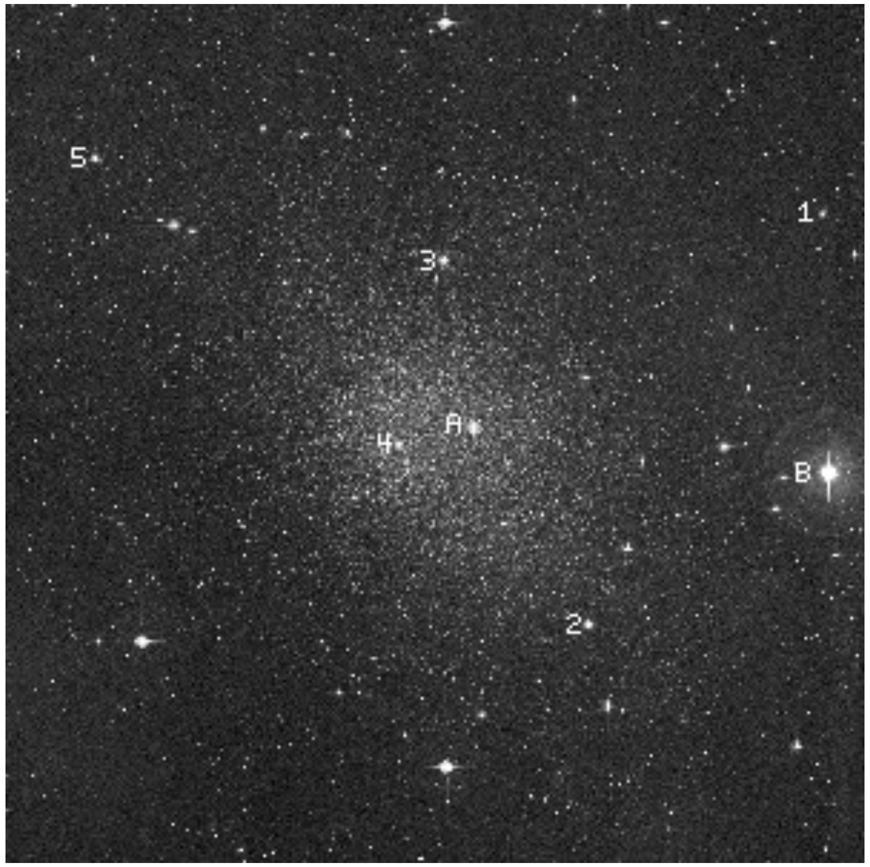


2. Gravity as a DM probe | Observations



Fornax

Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

2. Gravity as a DM probe | Observations

$$\frac{df}{dt} = 0 = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi \cdot \frac{\partial f}{\partial \mathbf{v}}$$

Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

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$$\frac{df}{dt} = 0 = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi \cdot \frac{\partial f}{\partial \mathbf{v}}$$

Steady state

Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

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$$\frac{df}{dt} = 0 = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi \cdot \frac{\partial f}{\partial \mathbf{v}}$$

Steady state

But! hard to measure $f(\mathbf{r}, \mathbf{v})$

Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

2. Gravity as a DM probe | Observations

$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty dr\; \nu(r) f(r)\, \frac{GM(r)}{r}$$

$$\times \int_R^r dw\; \frac{w}{f(w)\sqrt{w^2 - R^2}} \left[1 - \beta(w)\, \frac{R^2}{w^2}\right]$$

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Light distribution

Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

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Light distribution

Mass distribution

Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

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Light distribution

Mass distribution

Velocity anisotropy

Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

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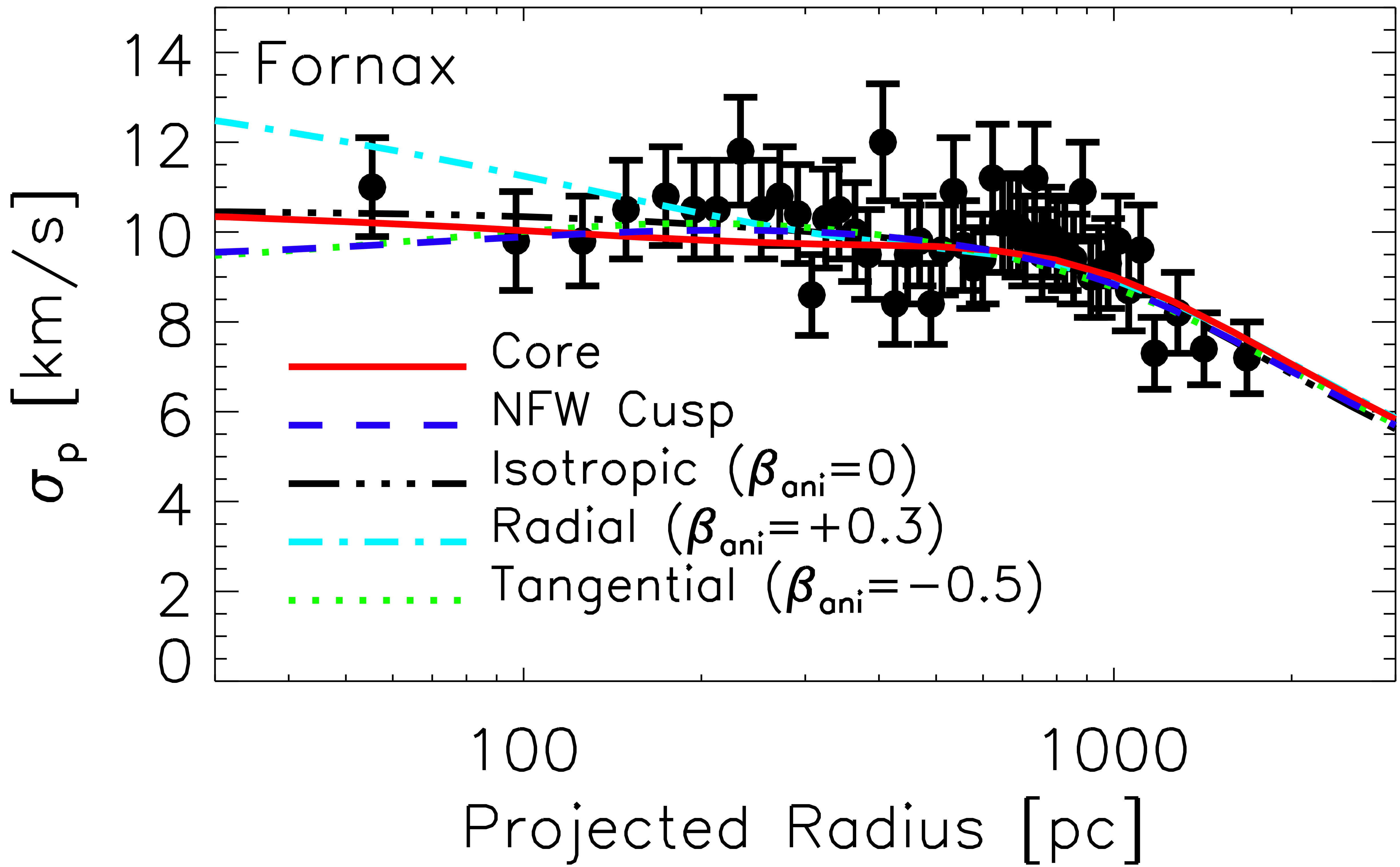

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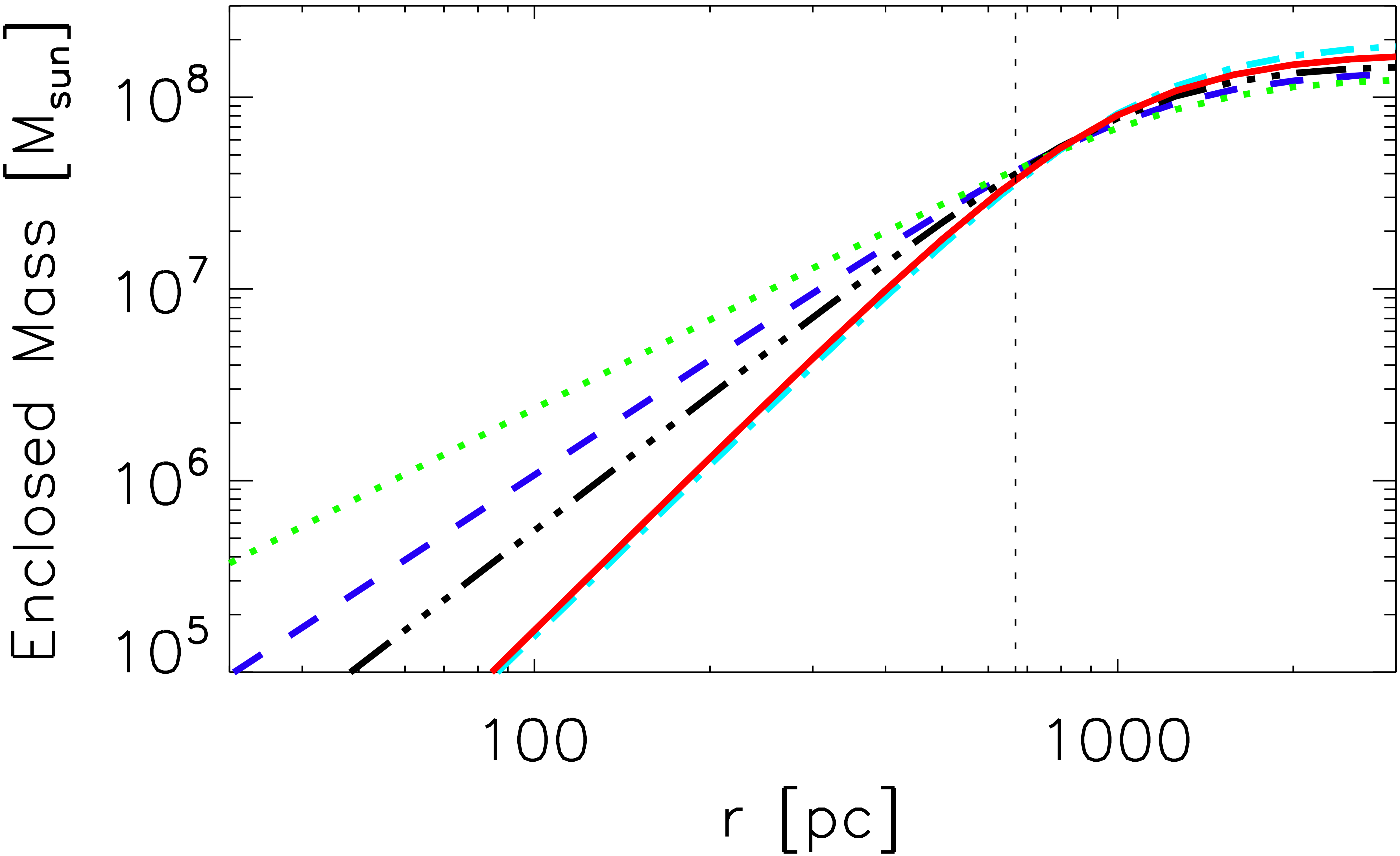

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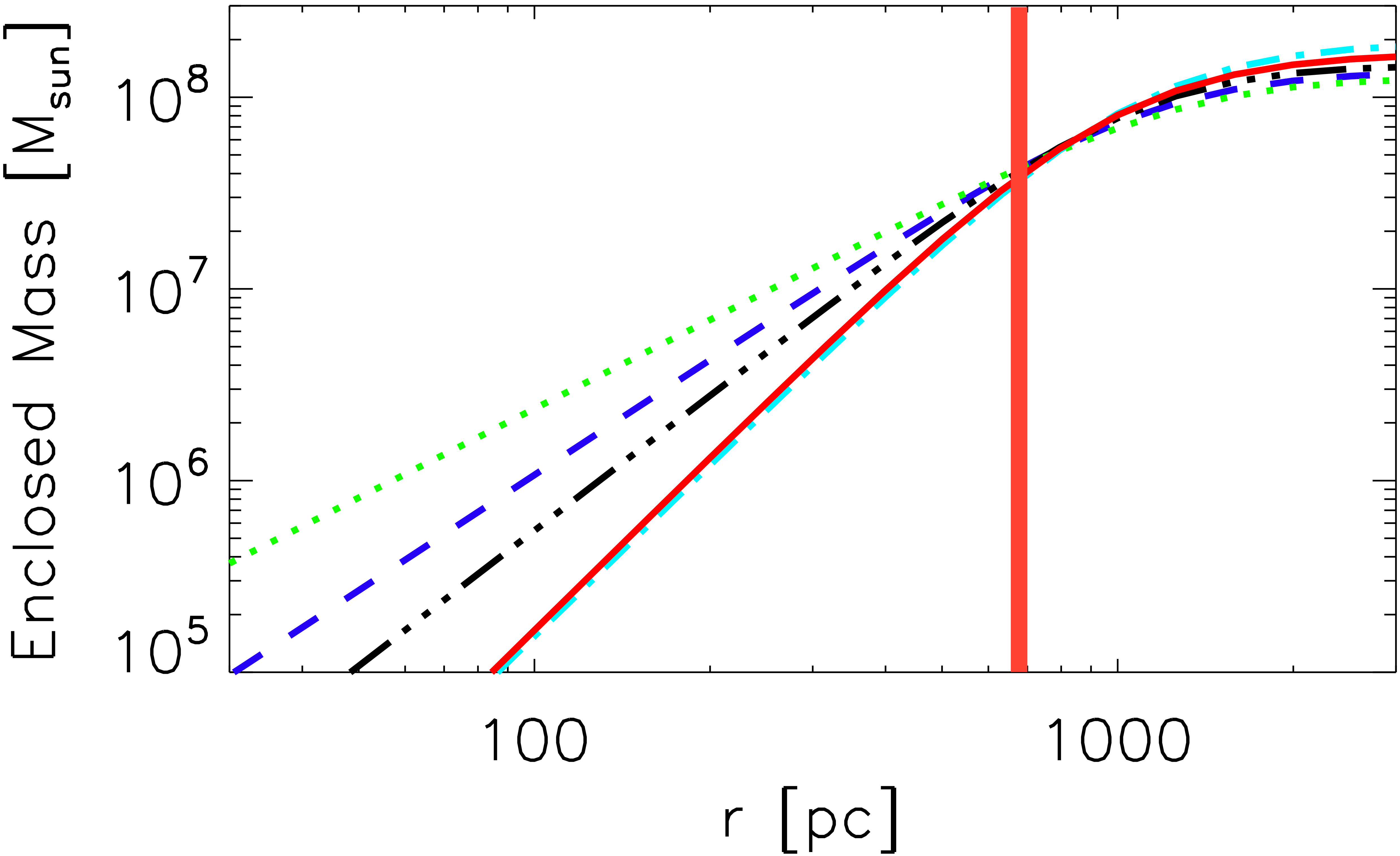

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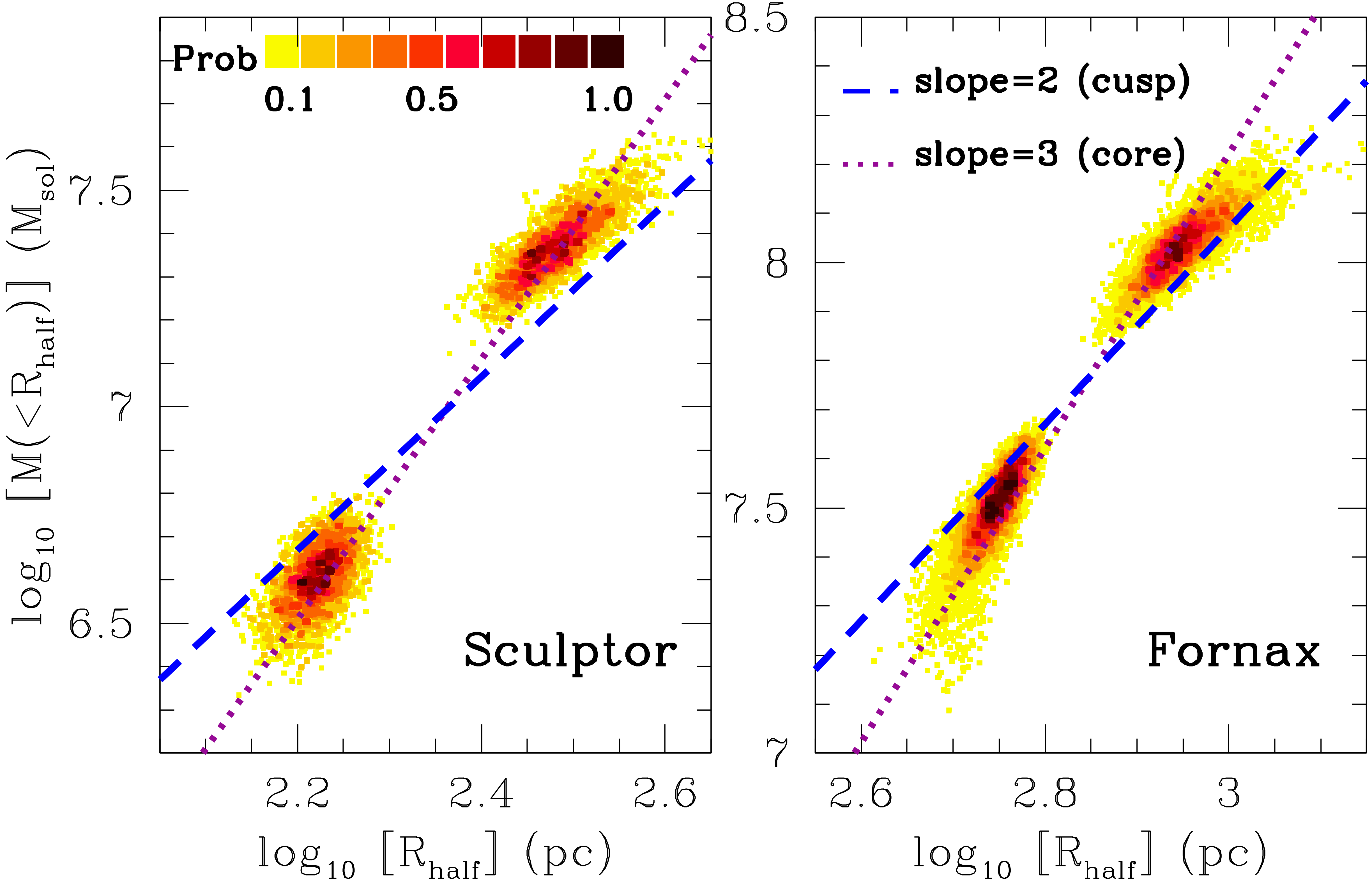

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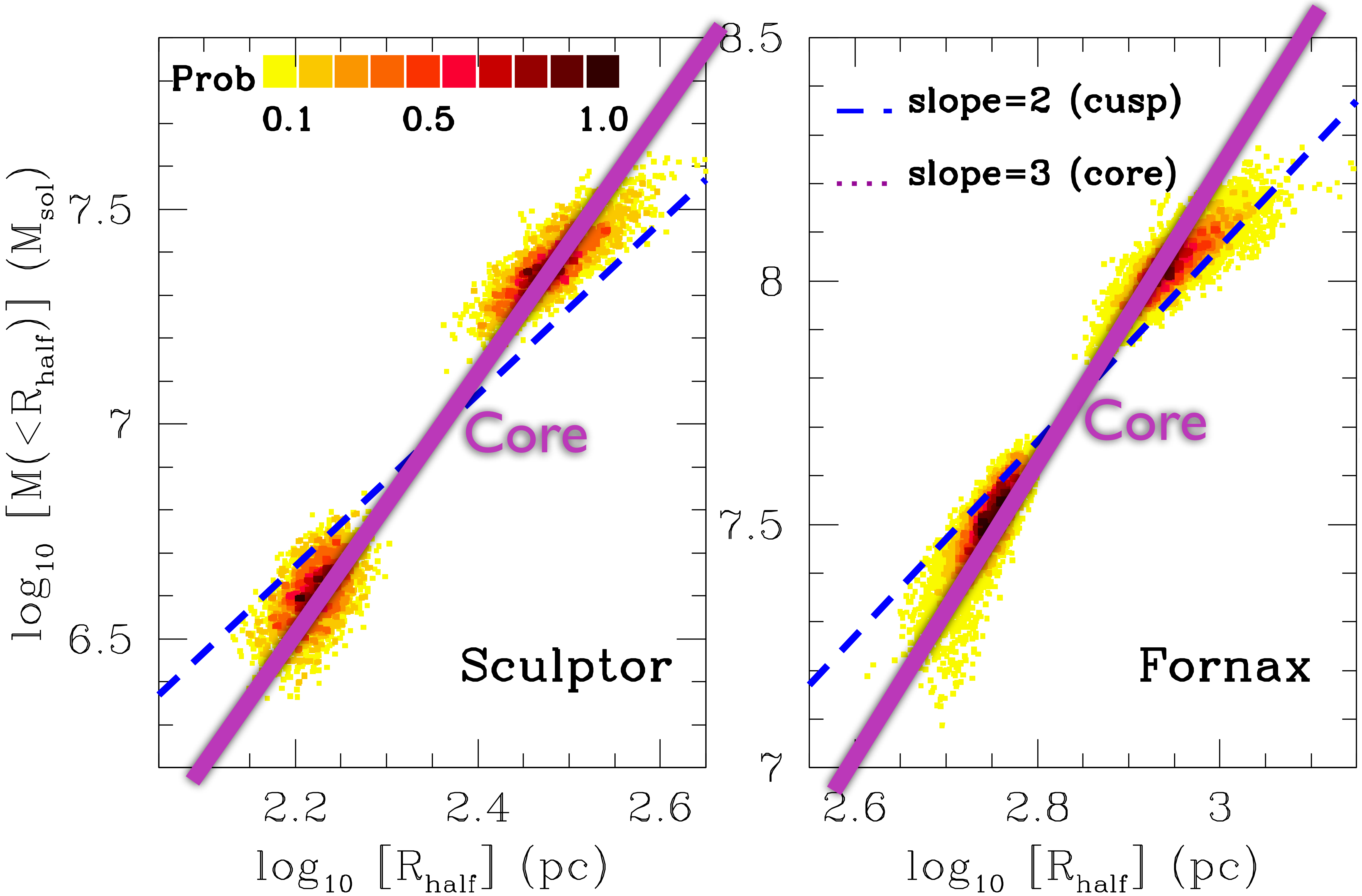


Battaglia et al. 2008; Walker & Penarrubia 2012; Amorisco & Evans 2012

2. Gravity as a DM probe | Observations

Saha, Read & Williams 2006; Saha & Read 2009; and see Limousin et al. 2008

2. Gravity as a DM probe | Observations

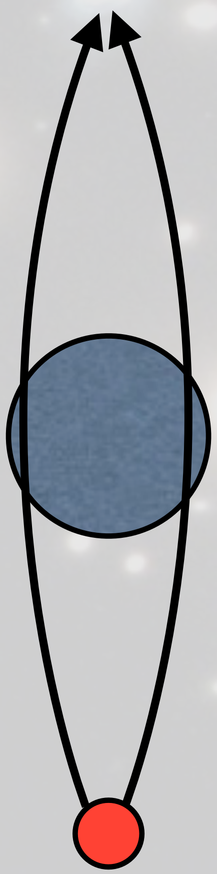
Lensing degeneracies ...

Saha & Read 2009

2. Gravity as a DM probe | Observations

Lensing degeneracies ...

A1703



$$\theta_E^2 = \frac{D_{LS}}{D_S D_L}\frac{4GM}{c^2}$$

70kpc

Saha & Read 2009

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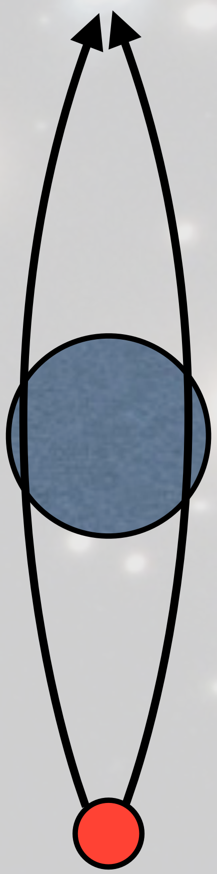
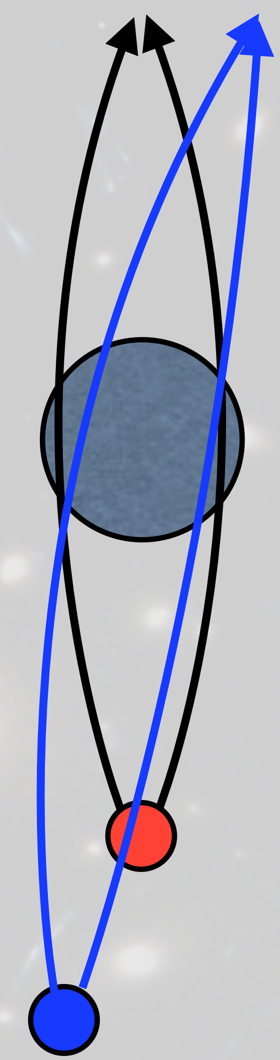
Lensing degeneracies ...



$$\theta_E^2 = \frac{D_{LS}}{D_S D_L}\frac{4GM}{c^2}$$



Saha & Read 2009

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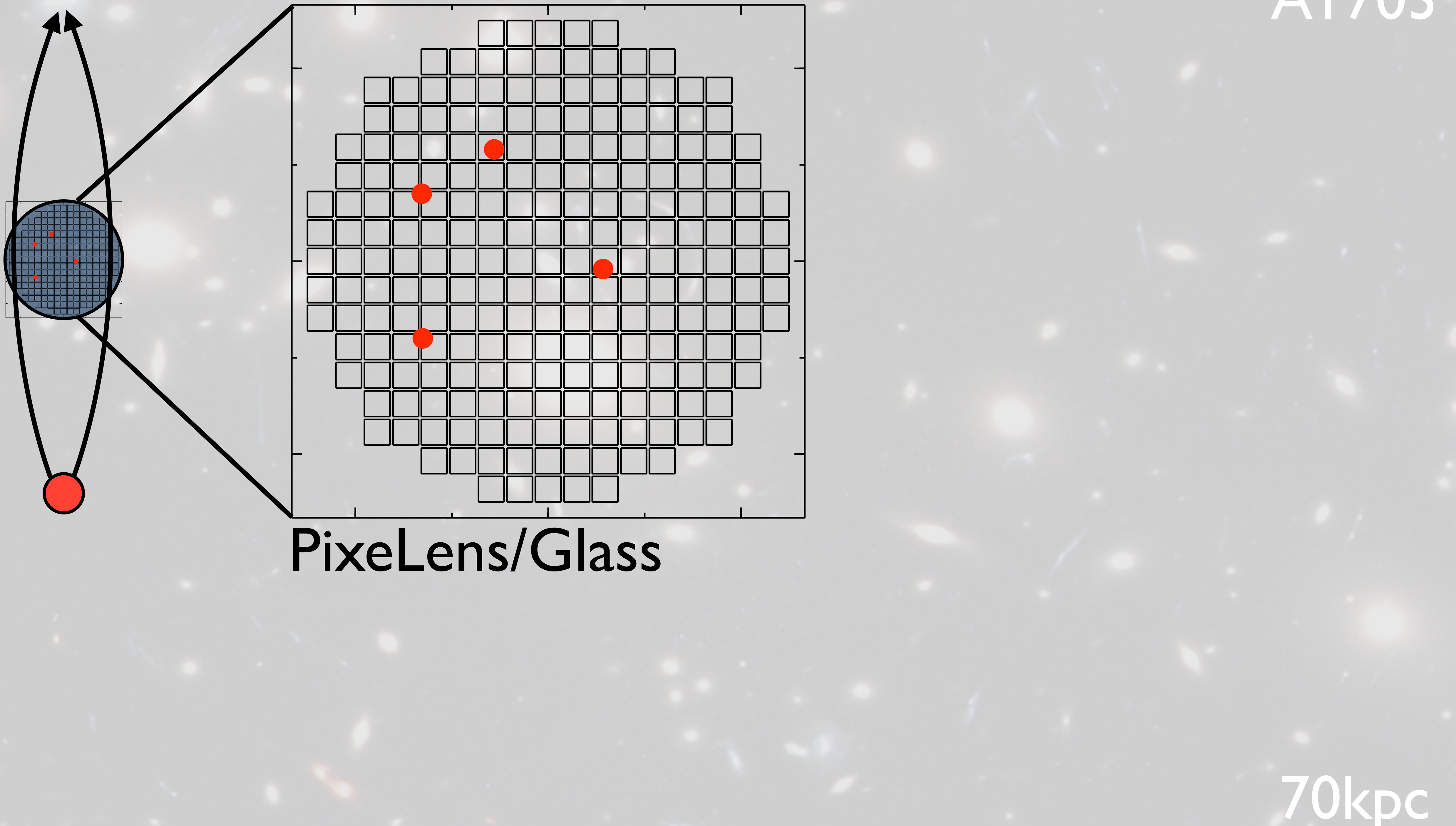

Saha & Read 2009

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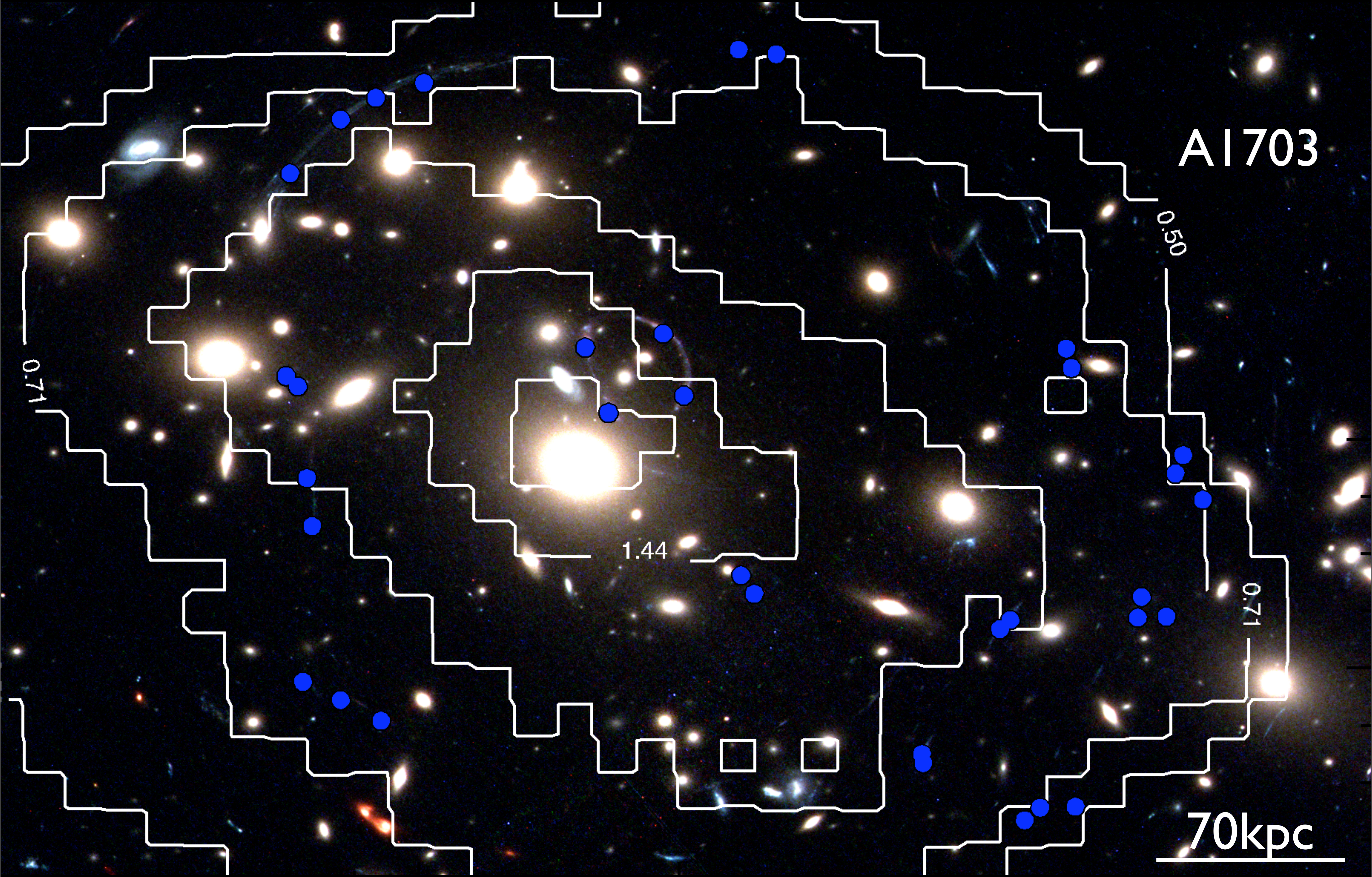

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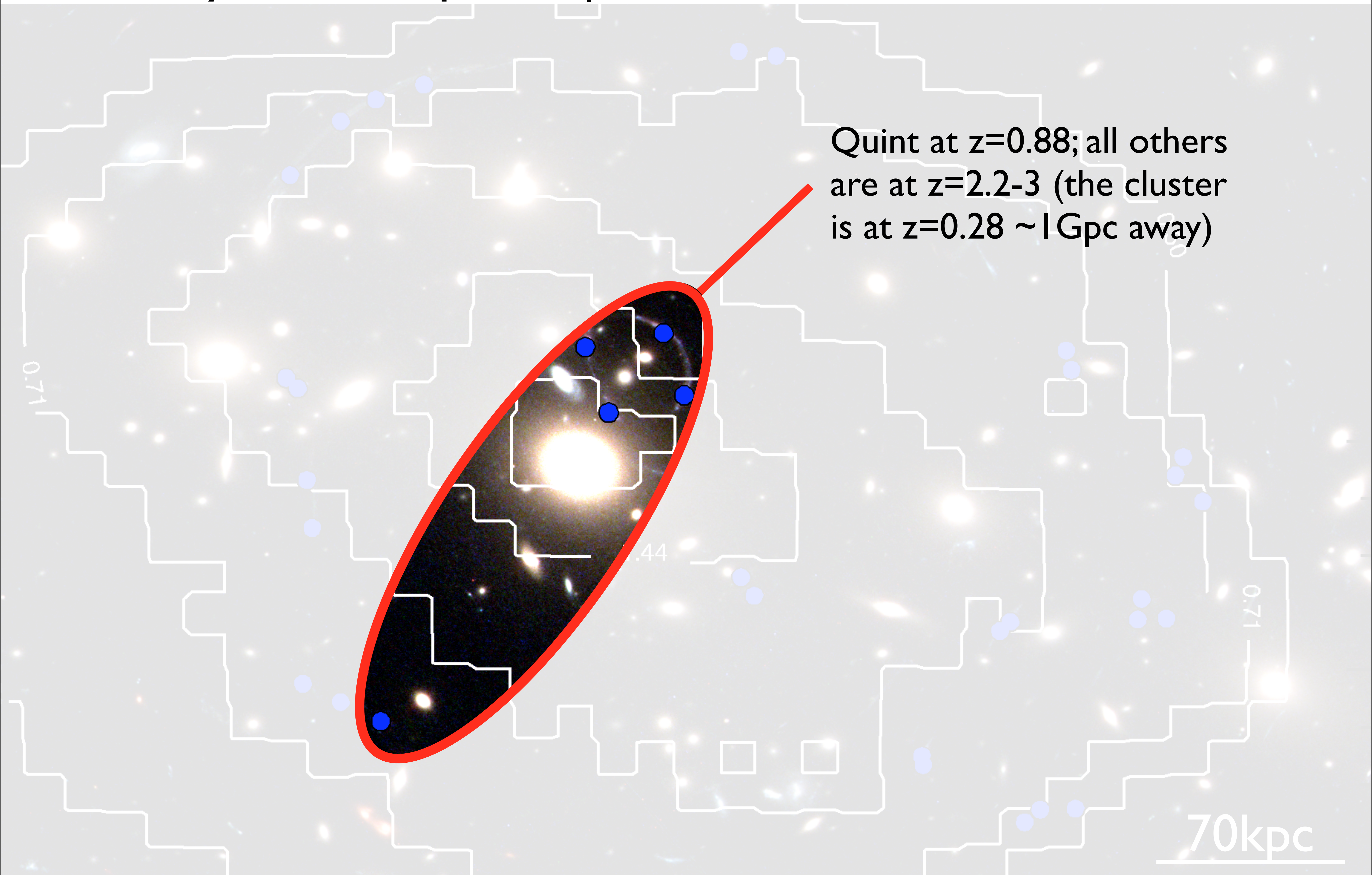

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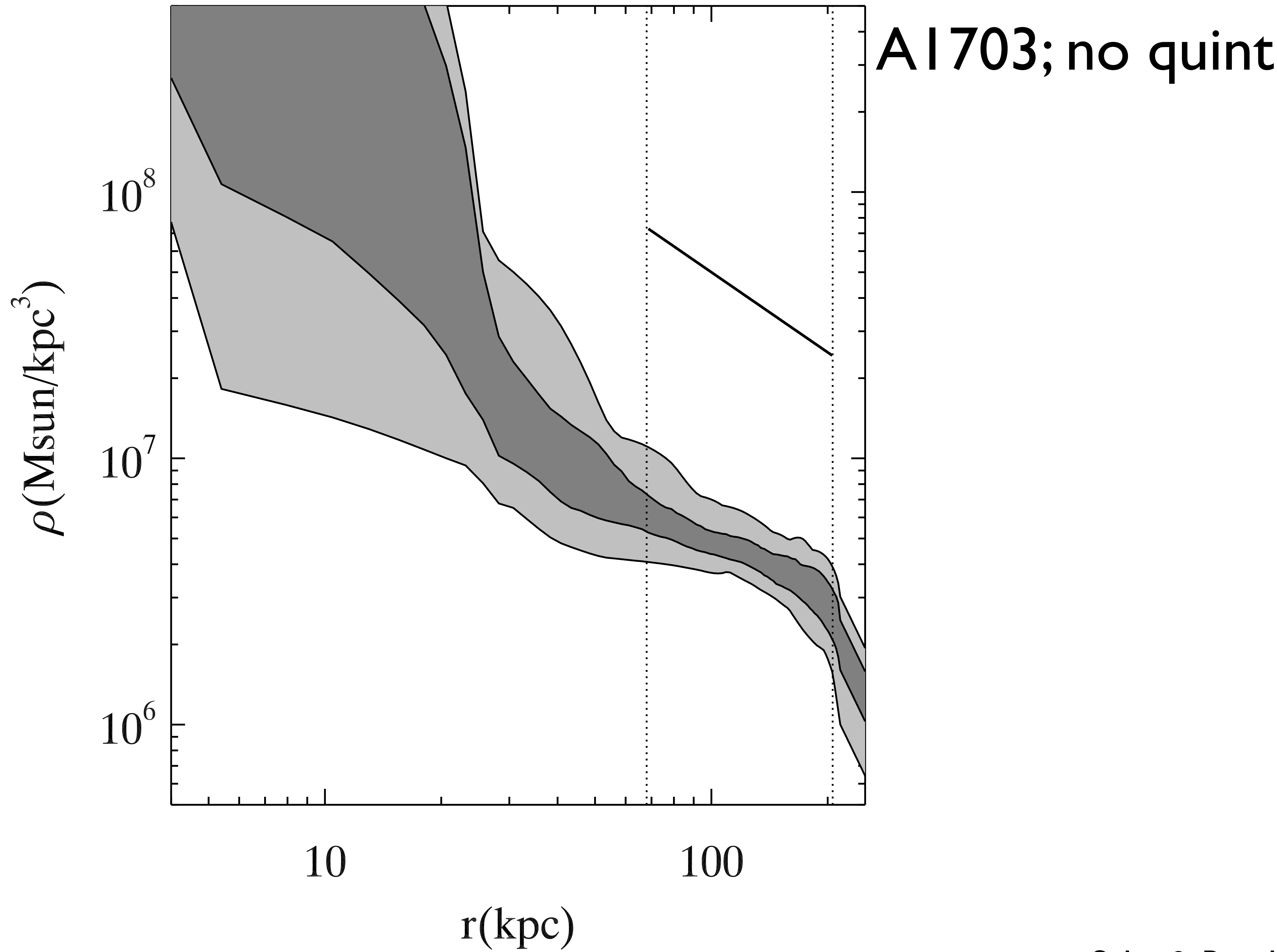

Saha & Read 2009

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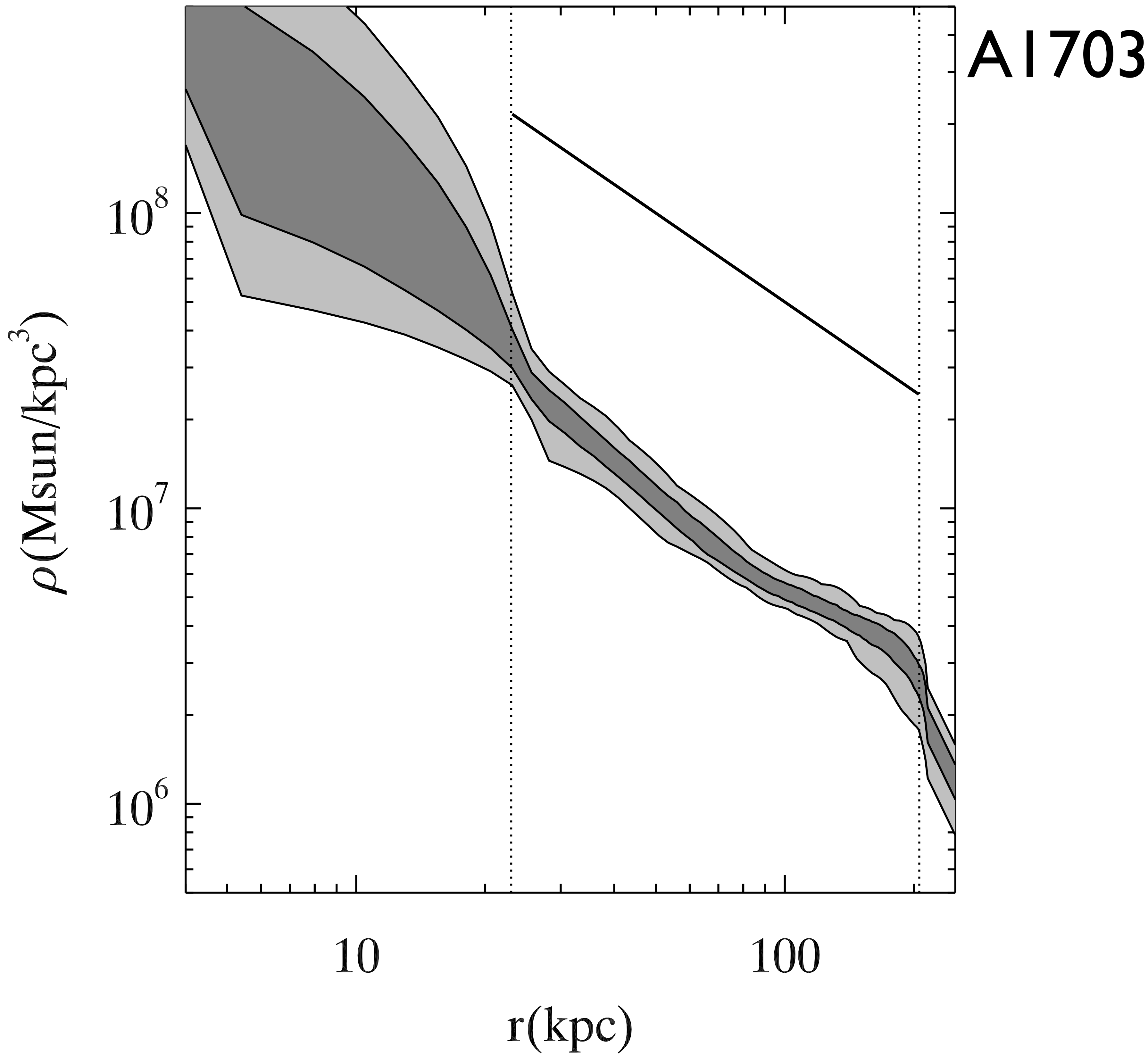

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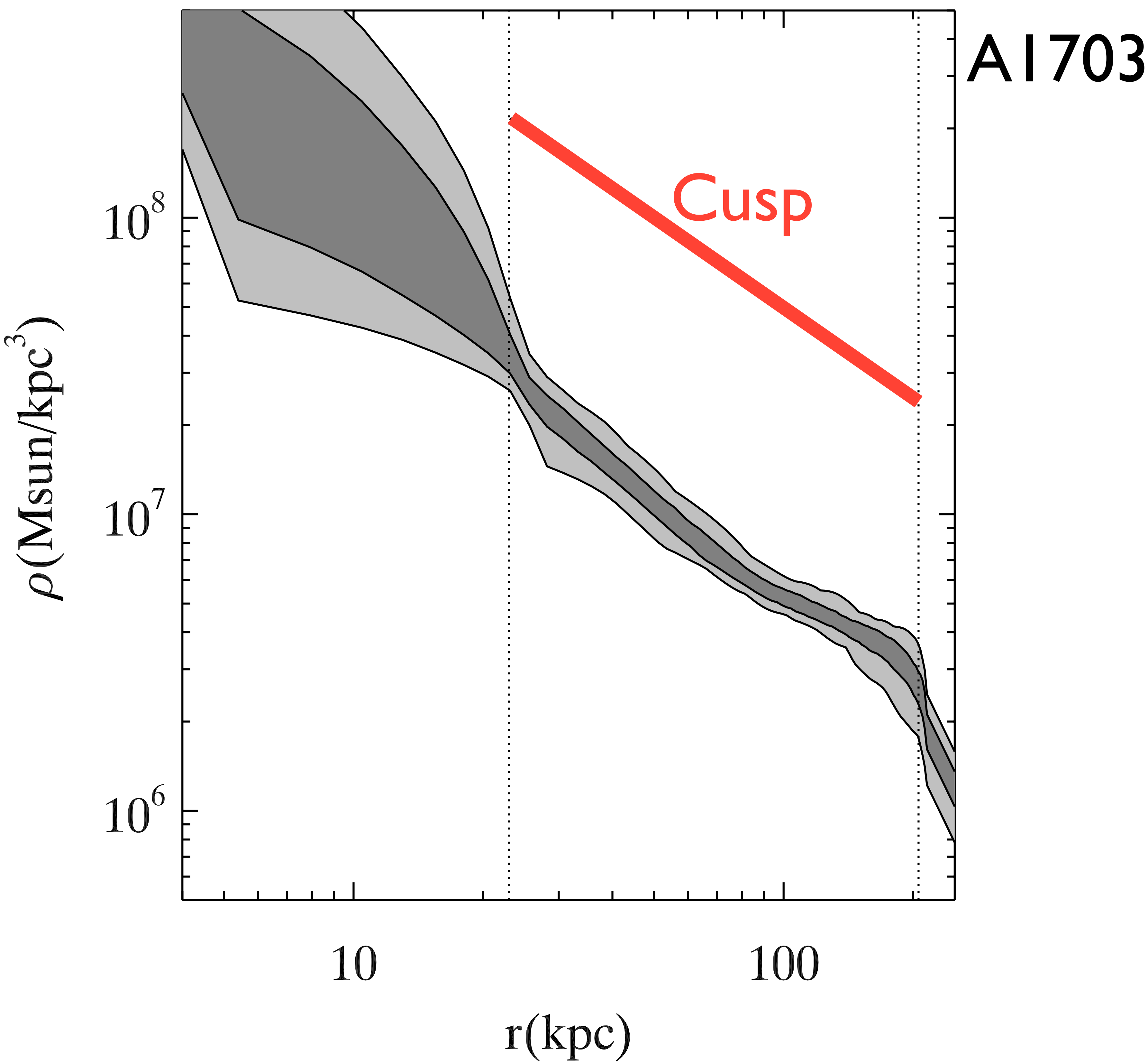

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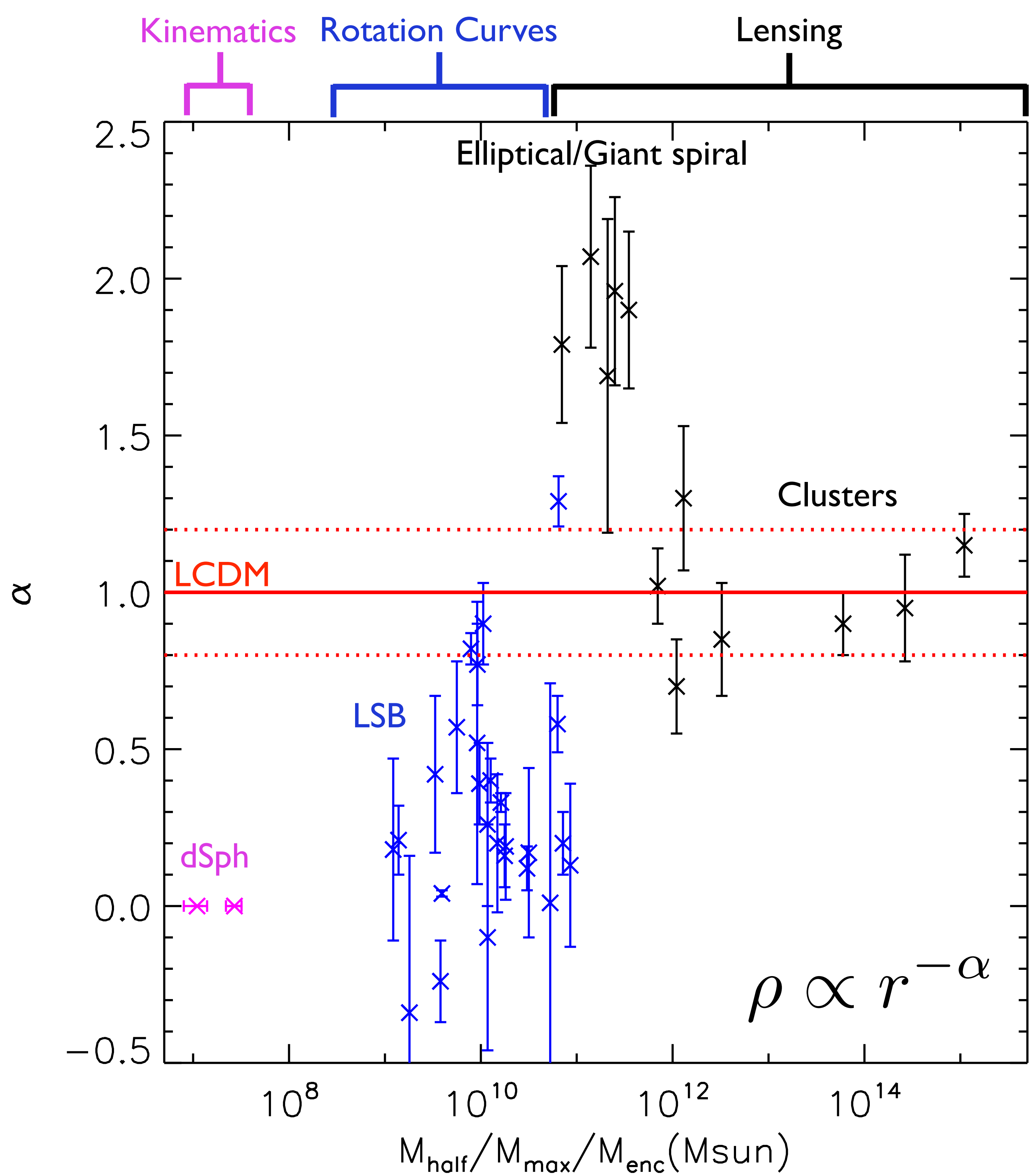

Read, Coles & Saha, 2007/09/ongoing

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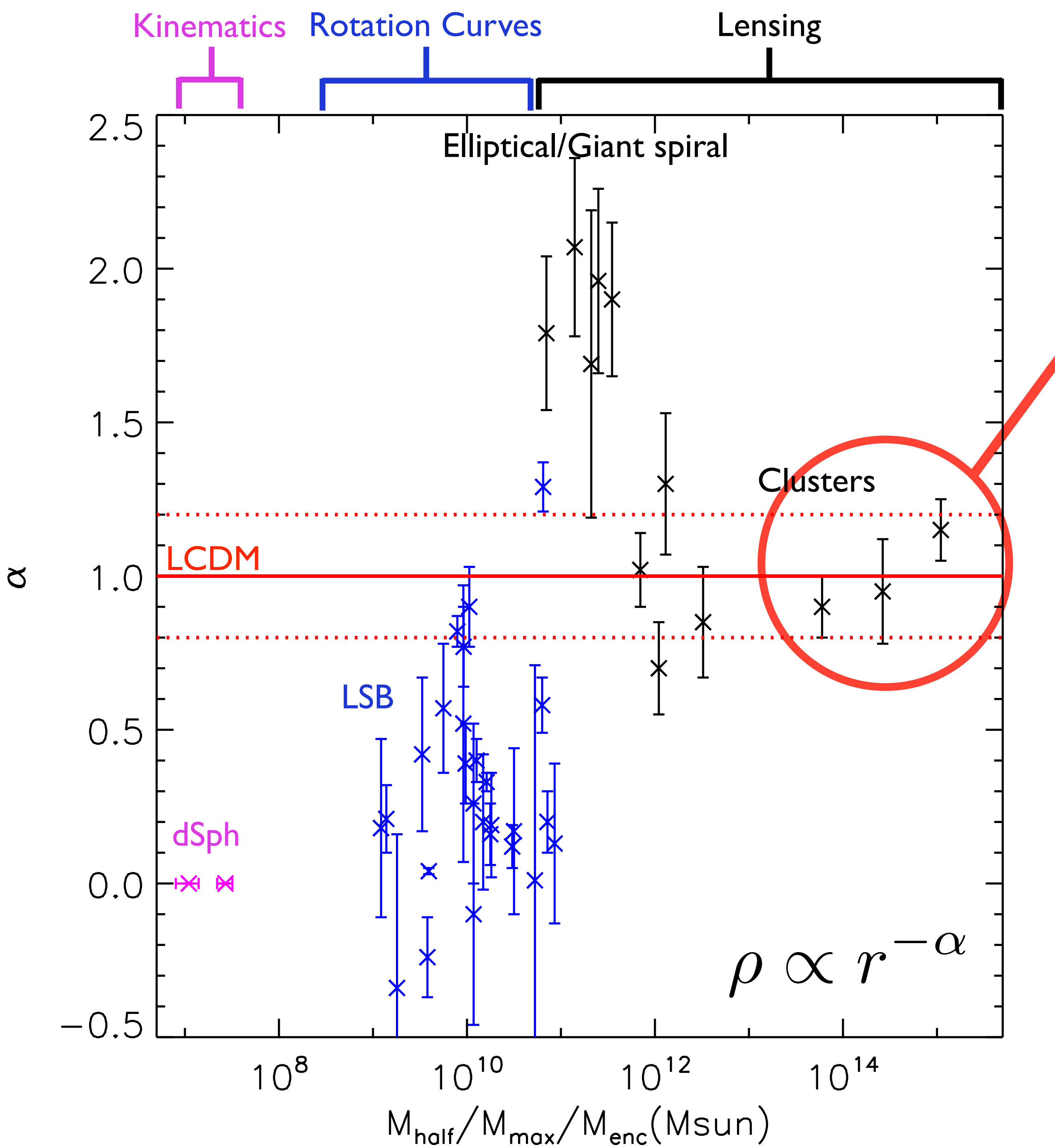

Excellent agreement with cold dark matter simulations

Read, Coles & Saha, 2007/09/ongoing

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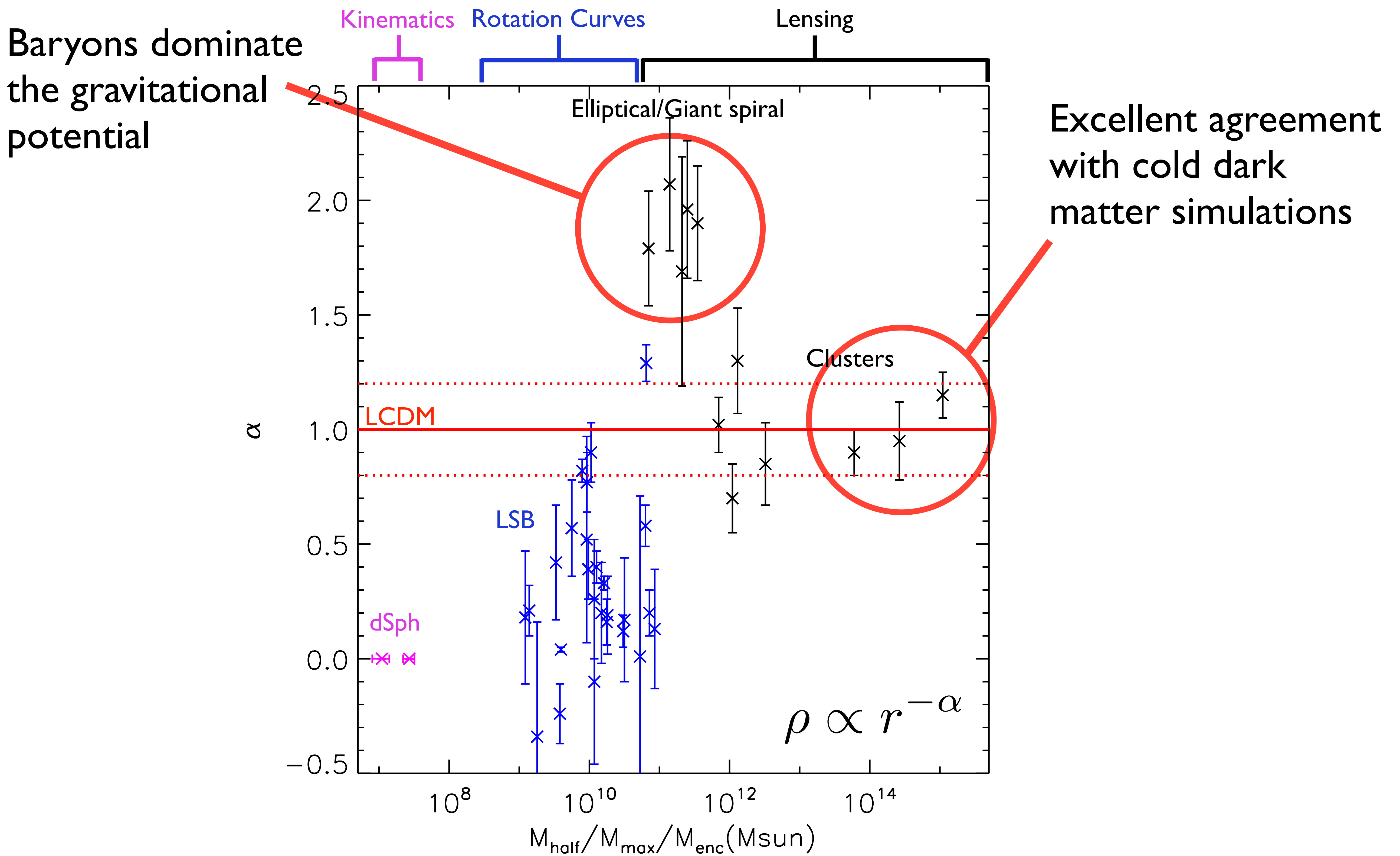


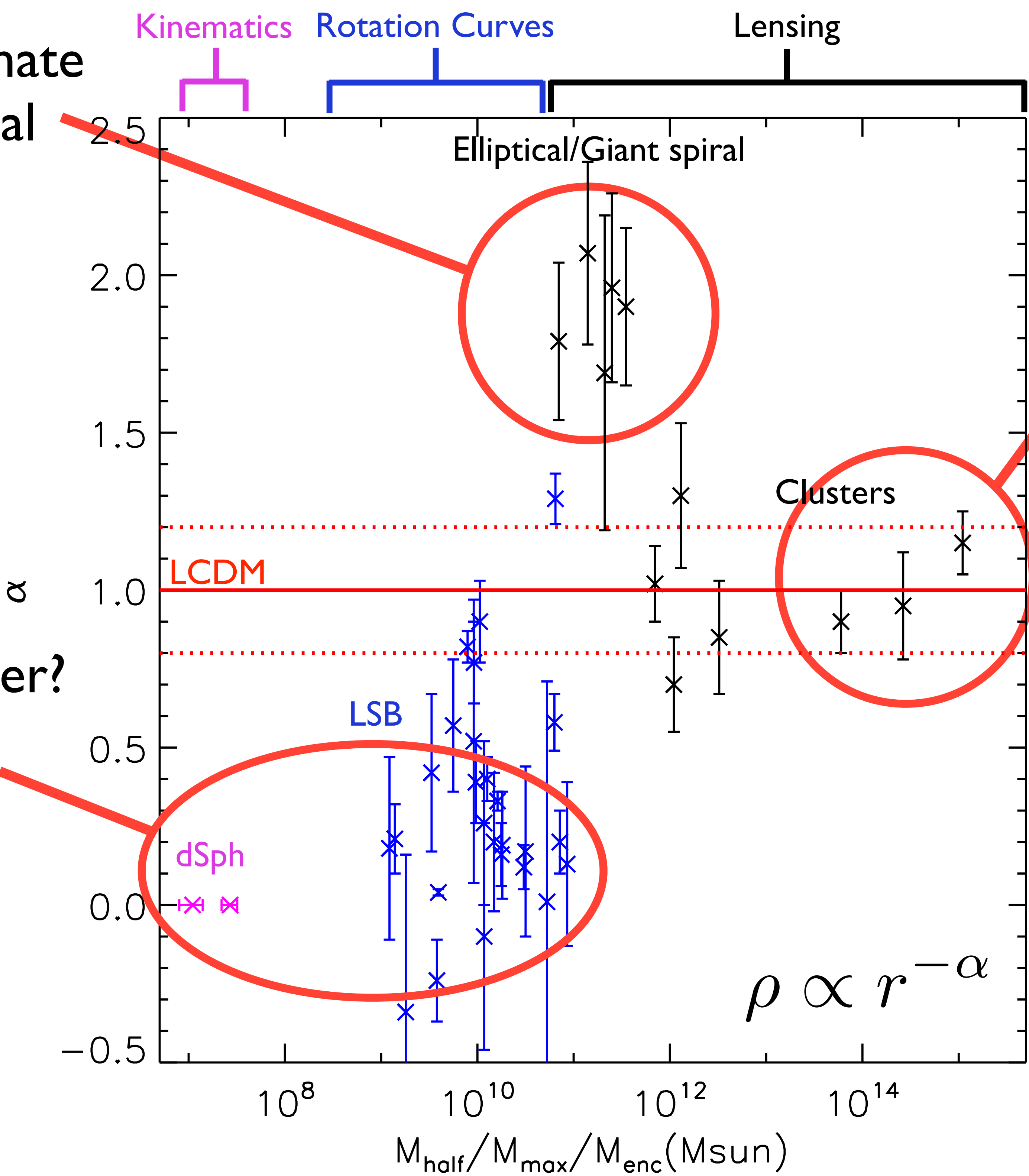
Read, Coles & Saha, 2007/09/ongoing

2. Gravity as a DM probe | Observations

Baryons dominate the gravitational potential

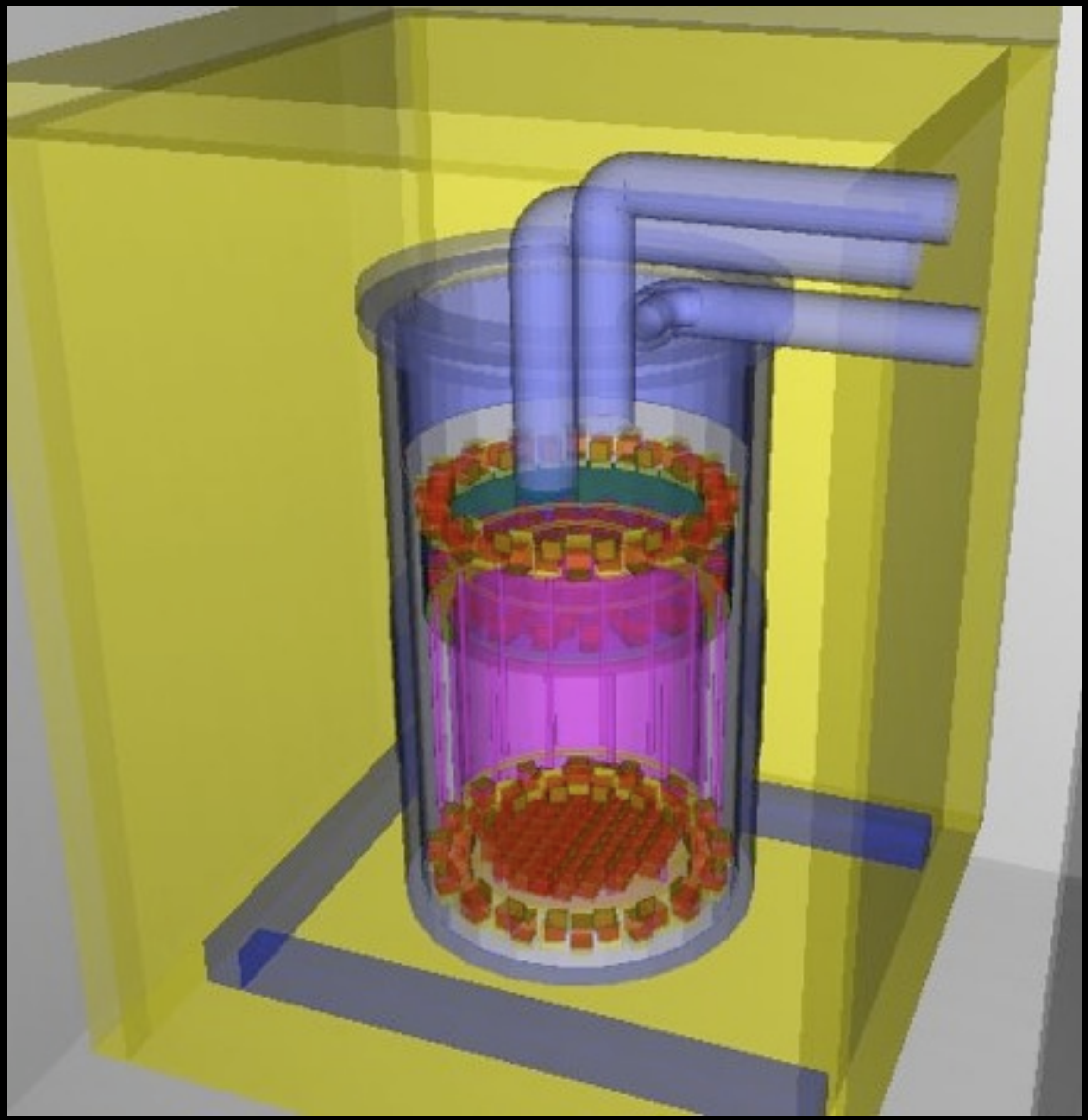
Excellent agreement with cold dark matter simulations

Exotic dark matter? Baryonic effects?



Read, Coles & Saha, 2007/09/ongoing

3. Detecting DM particles | ‘Direct’ detection

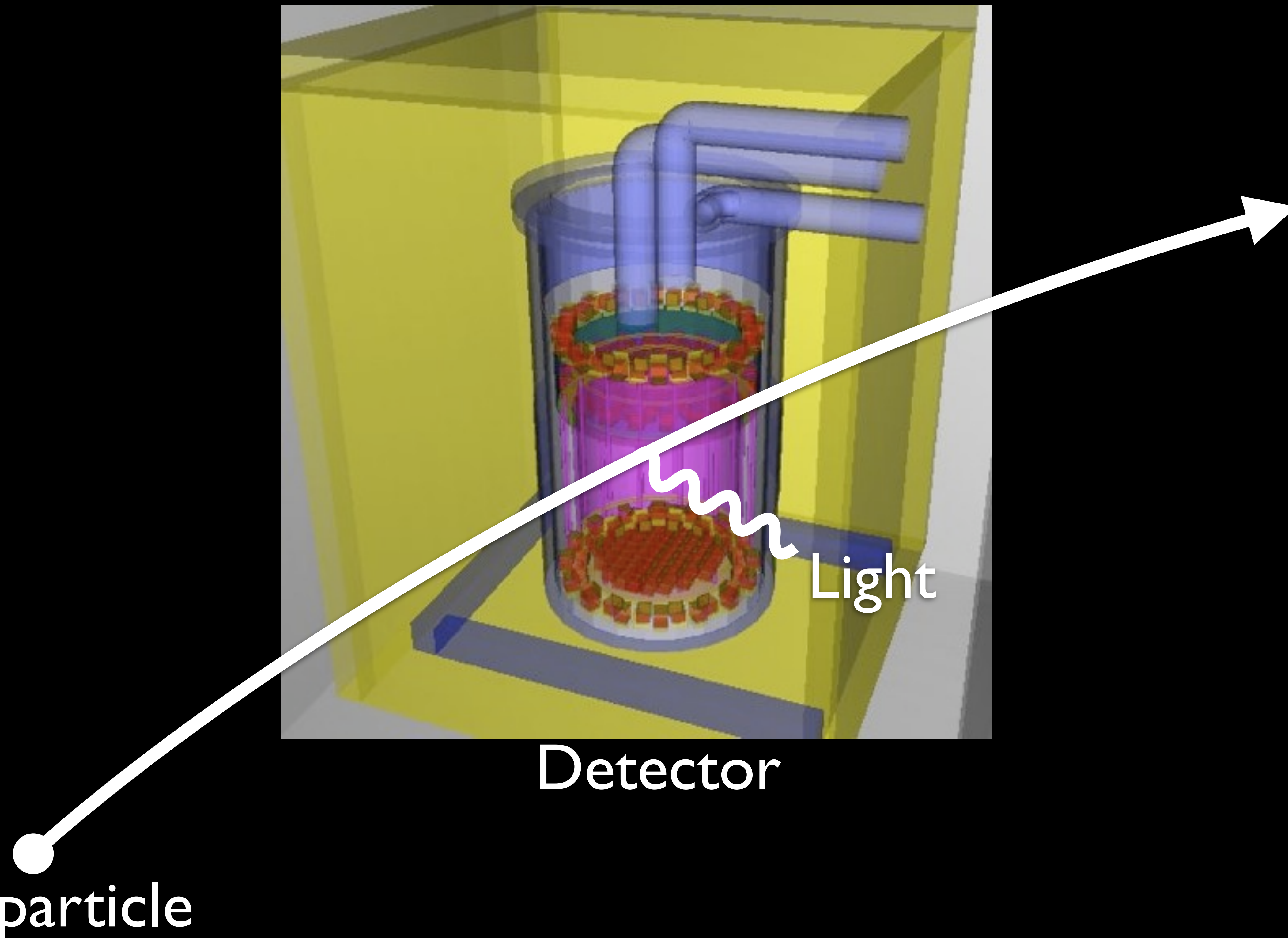


Detector

DM particle

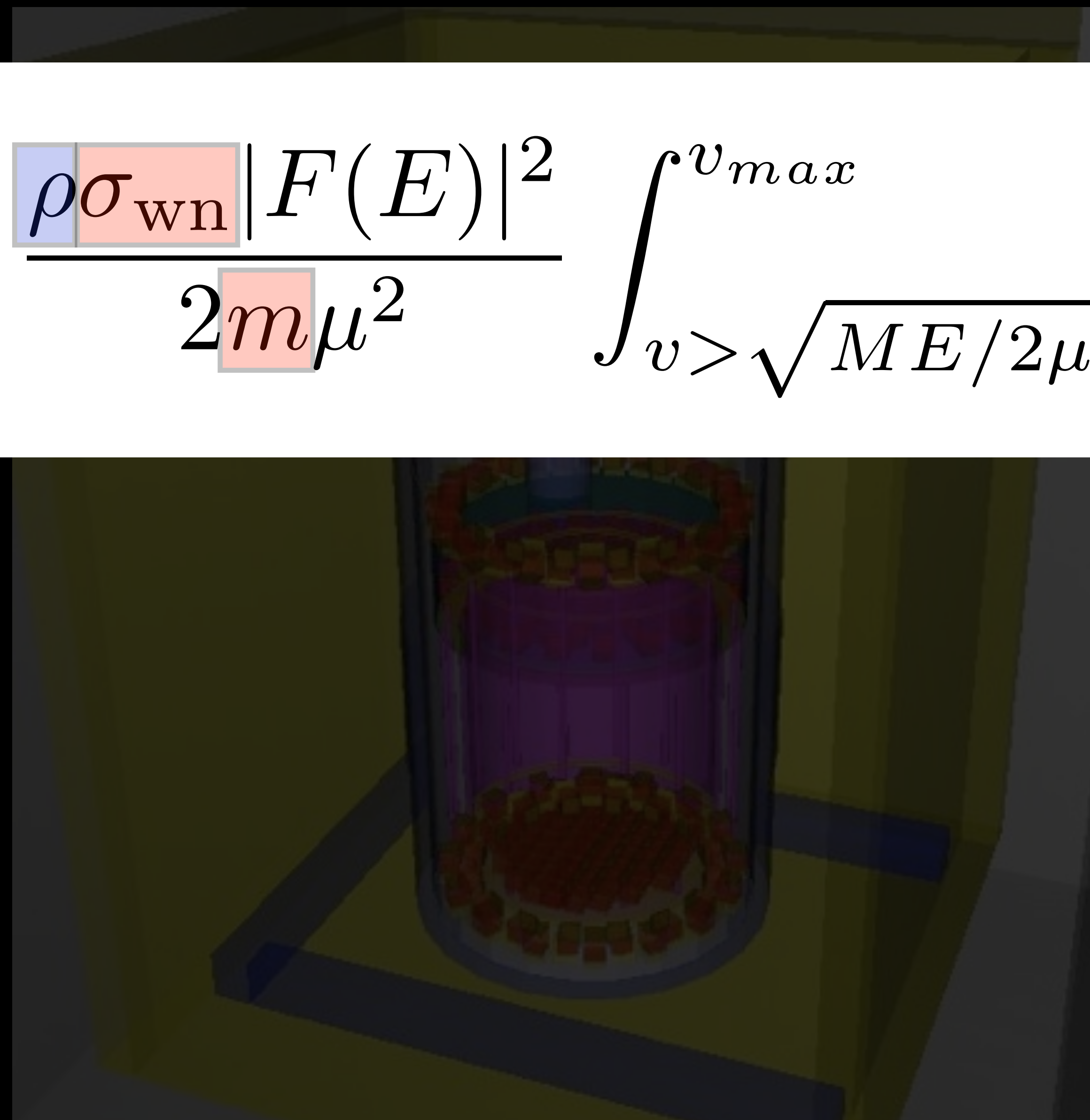
Garbari, Read & Lake 2011

3. Detecting DM particles | 'Direct' detection



Garbari, Read & Lake 2011

3. Detecting DM particles | 'Direct' detection



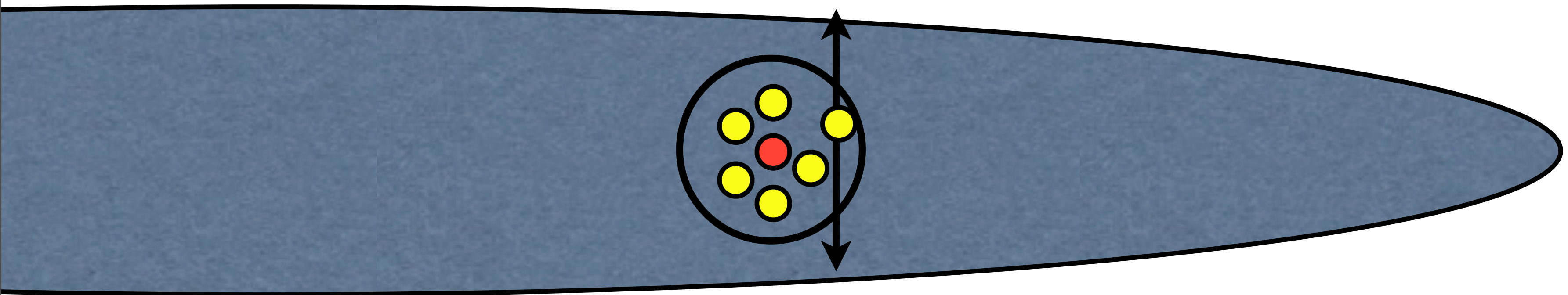
$$\frac{dR}{dE} = \frac{\rho\sigma_{\mathrm{wn}}|F(E)|^2}{2m\mu^2}\int_{v>\sqrt{ME/2\mu^2}}^{v_{max}}\frac{f(\mathbf{v},t)}{v}d^3v$$

Particle | Astro

Garbari, Read & Lake 2011

3. Detecting DM particles | The local DM density

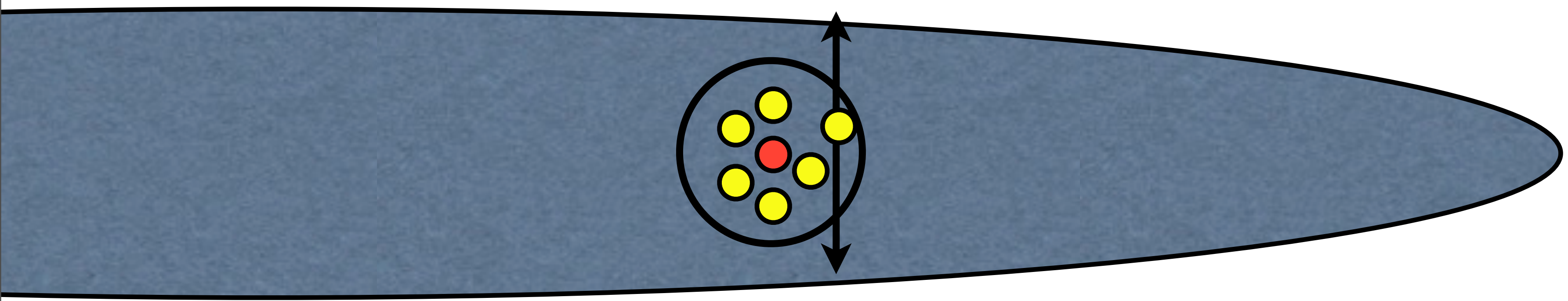
1. Local measure:



$\rho_{\rm dm}$

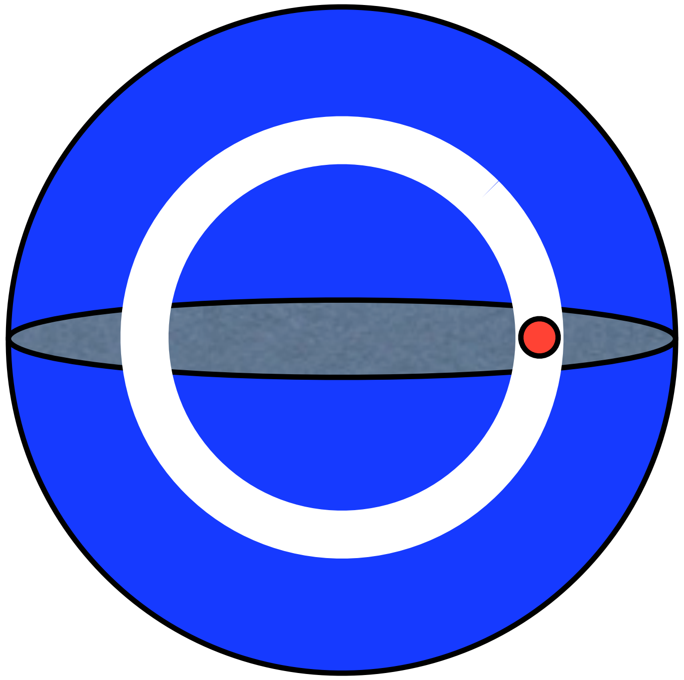
3. Detecting DM particles | The local DM density

1. Local measure:



$\rho_{\rm dm}$

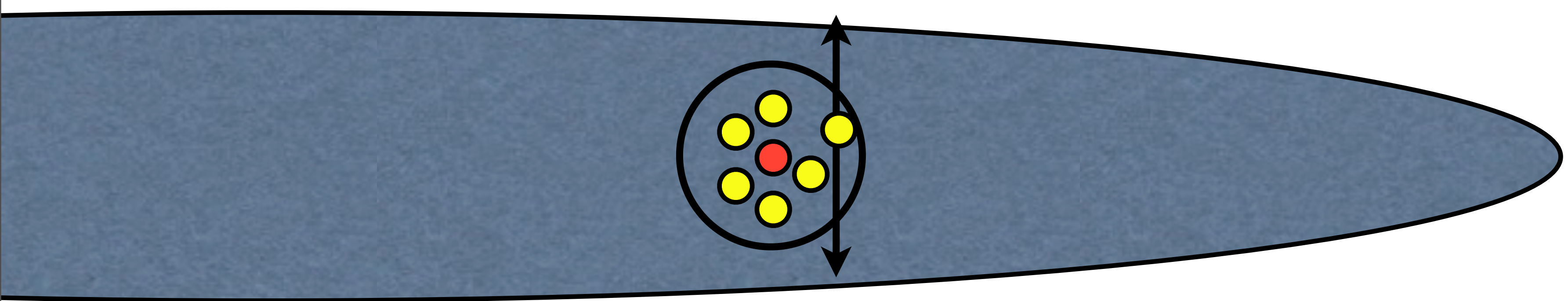
2. Global measure:



$\rho_{\rm dm,ext}$

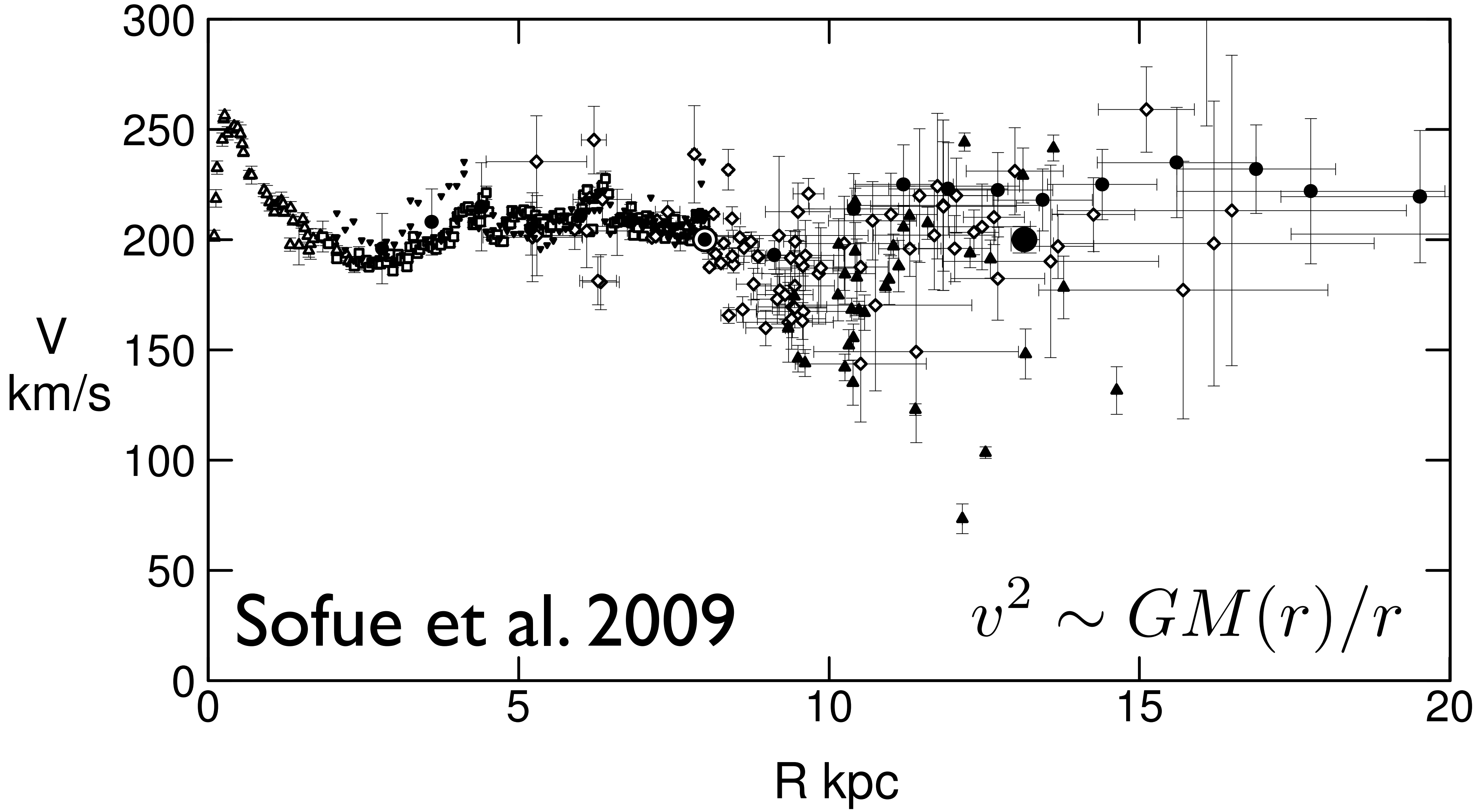
3. Detecting DM particles | The local DM density

1. Local measure:



$\rho_{\rm dm}$

2. Glc



3. Detecting DM particles | The local DM density

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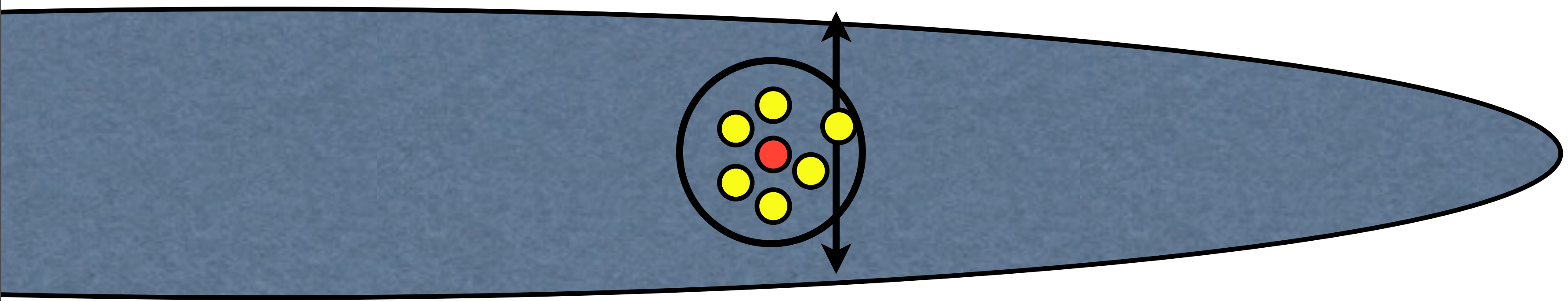
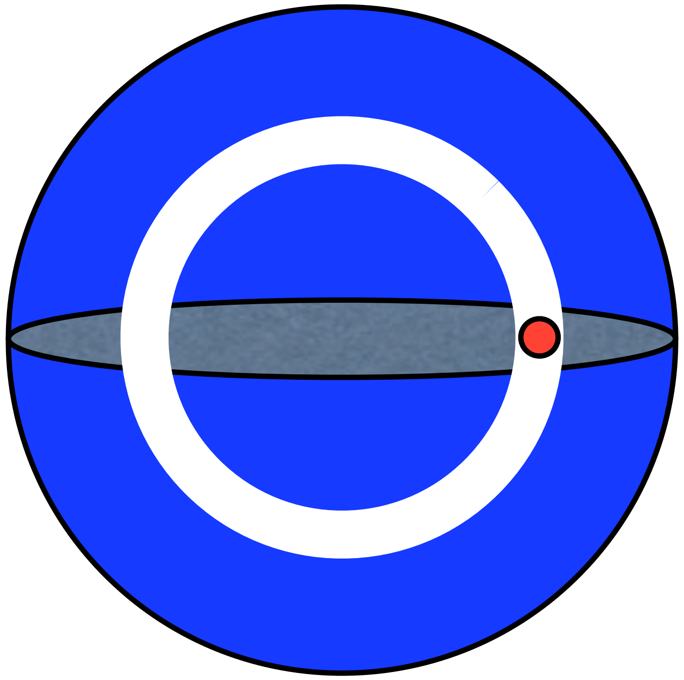


$\rho_{\rm dm}$

2. Global measure:



$\rho_{\rm dm,ext}$

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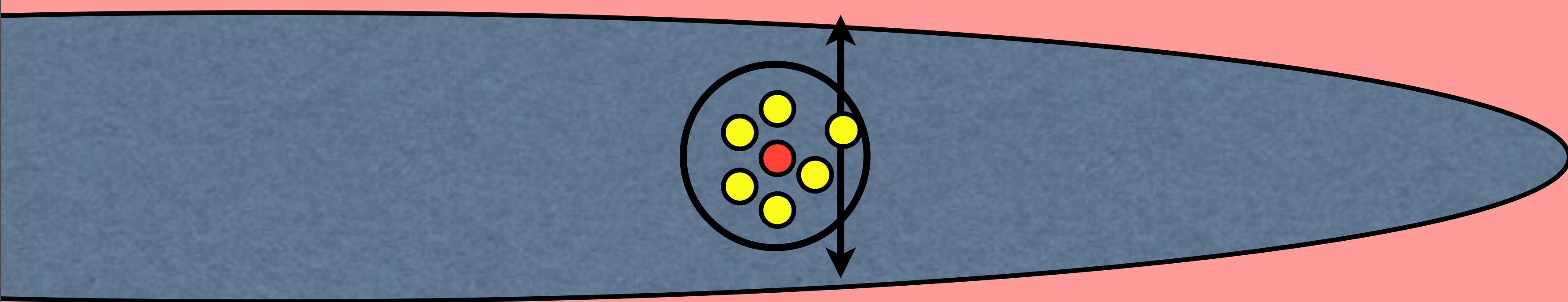
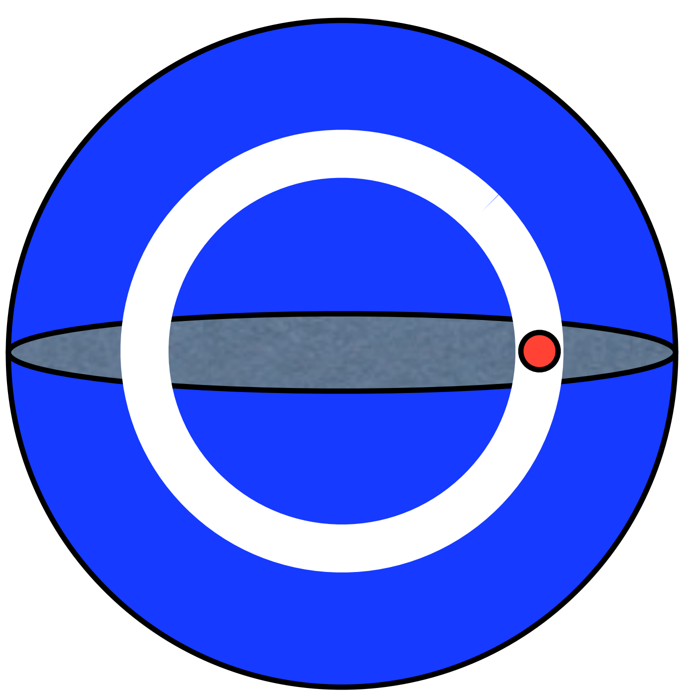


$\rho_{\rm dm}$

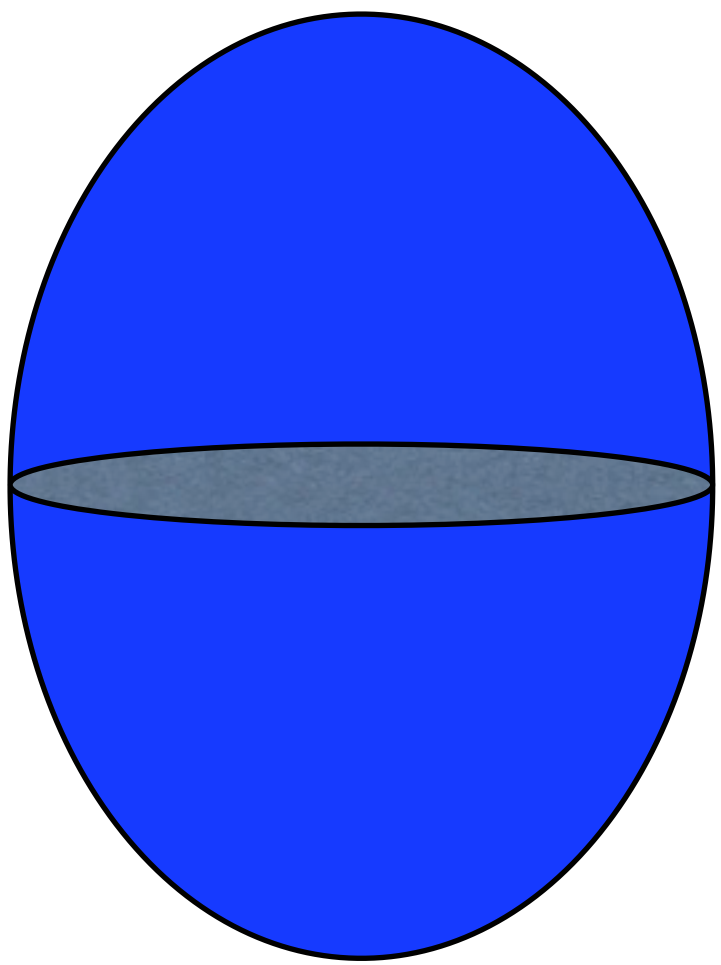
2. Global measure:



$\rho_{\rm dm,ext}$

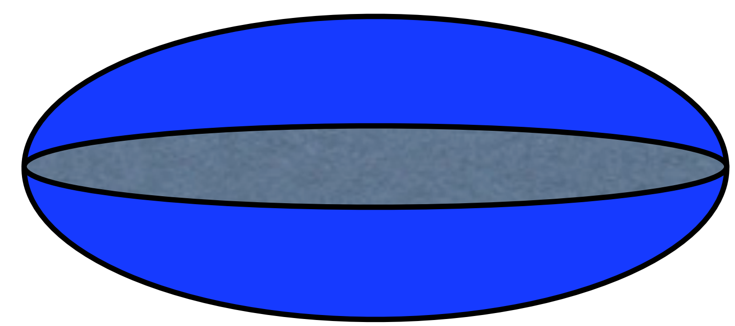
3. Detecting DM particles | The local DM density

$$\rho_{\rm dm} < \rho_{\rm dm,ext}$$



Prolate

$$\rho_{\rm dm} > \rho_{\rm dm,ext}$$



Oblate/dark disc

Our Minimal Assumption (MA) method:

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

$$\frac{\nu_i(z_*)}{\nu_i(0)} = \frac{\overline{v_{z,i}^2}(0)}{\overline{v_{z,i}^2}(z_*)} \exp\left(-\int_0^{z_*} \frac{1}{\overline{v_{z,i}^2}(z)} \frac{d\Phi}{dz} dz\right)$$

Assumes only:

- Equilibrium
- 'Tilt' term in Jeans equation small

All other uncertainties MCMC marginalised

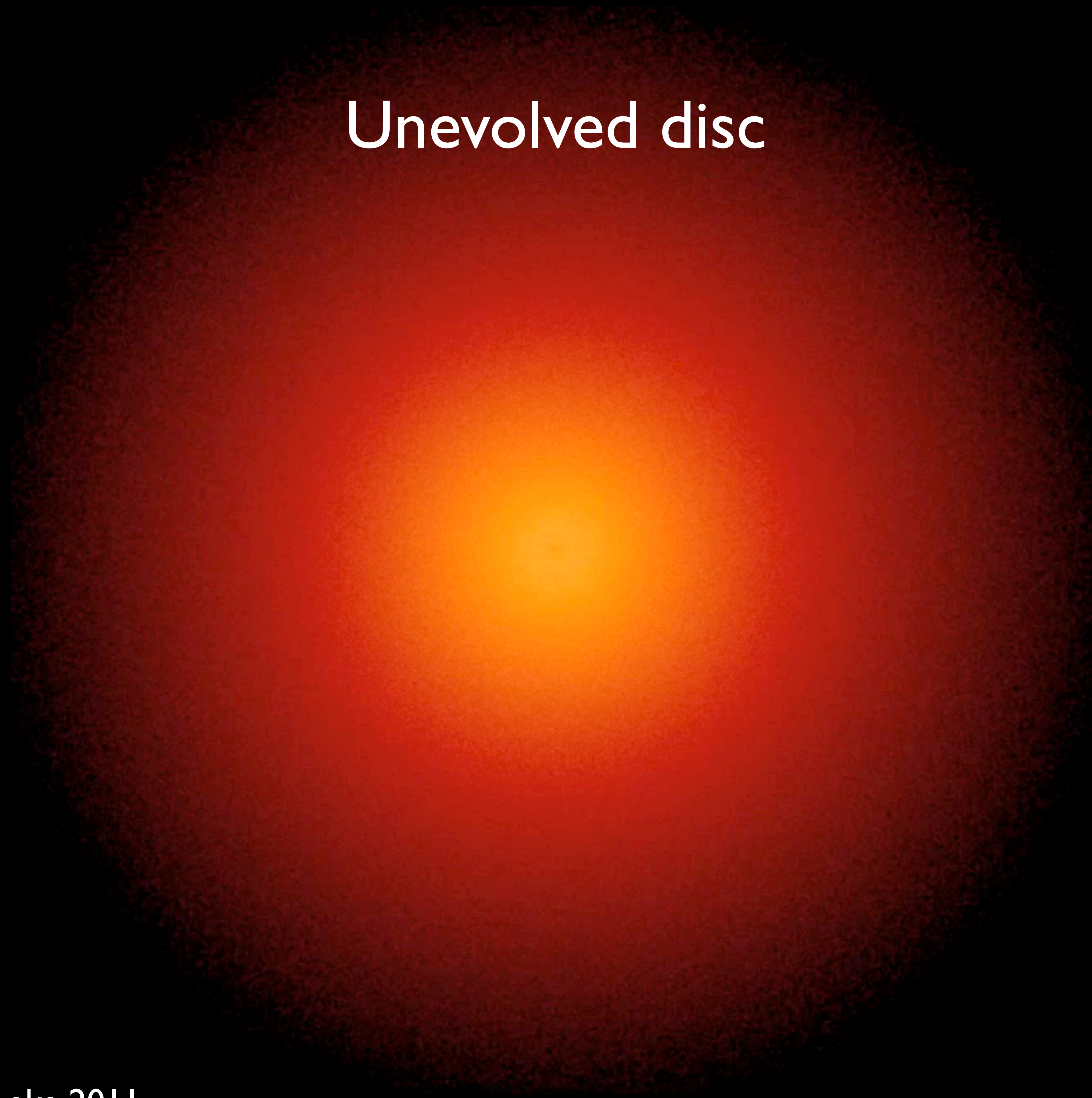
Development of Bahcall (1989)

Garbari, Read & Lake 2011

3. Detecting DM particles | The local DM density

Garbari, Read & Lake 2011

3. Detecting DM particles | The local DM density



Garbari, Read & Lake 2011

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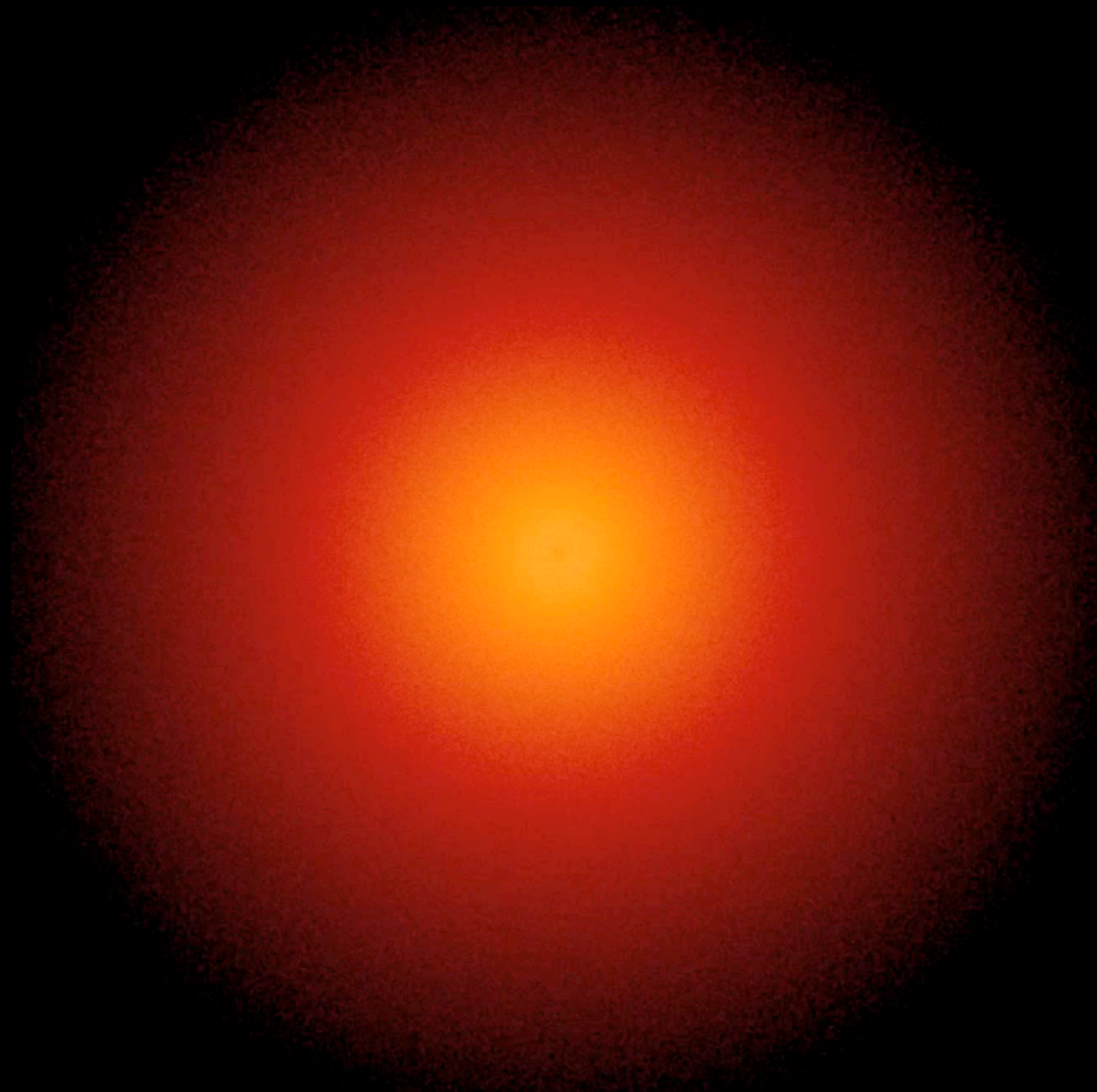

Garbari, Read & Lake 2011

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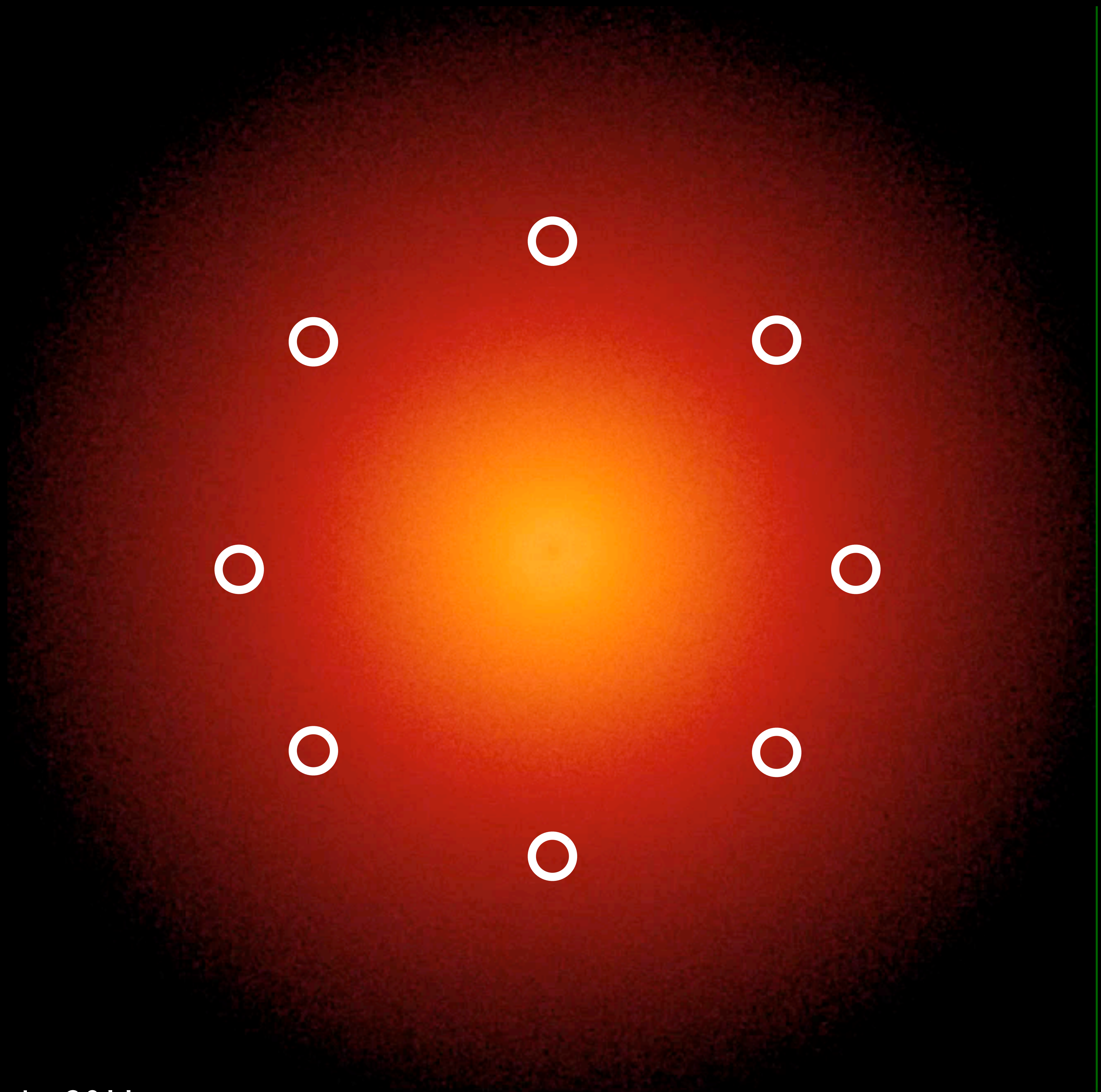

Garbari, Read & Lake 2011

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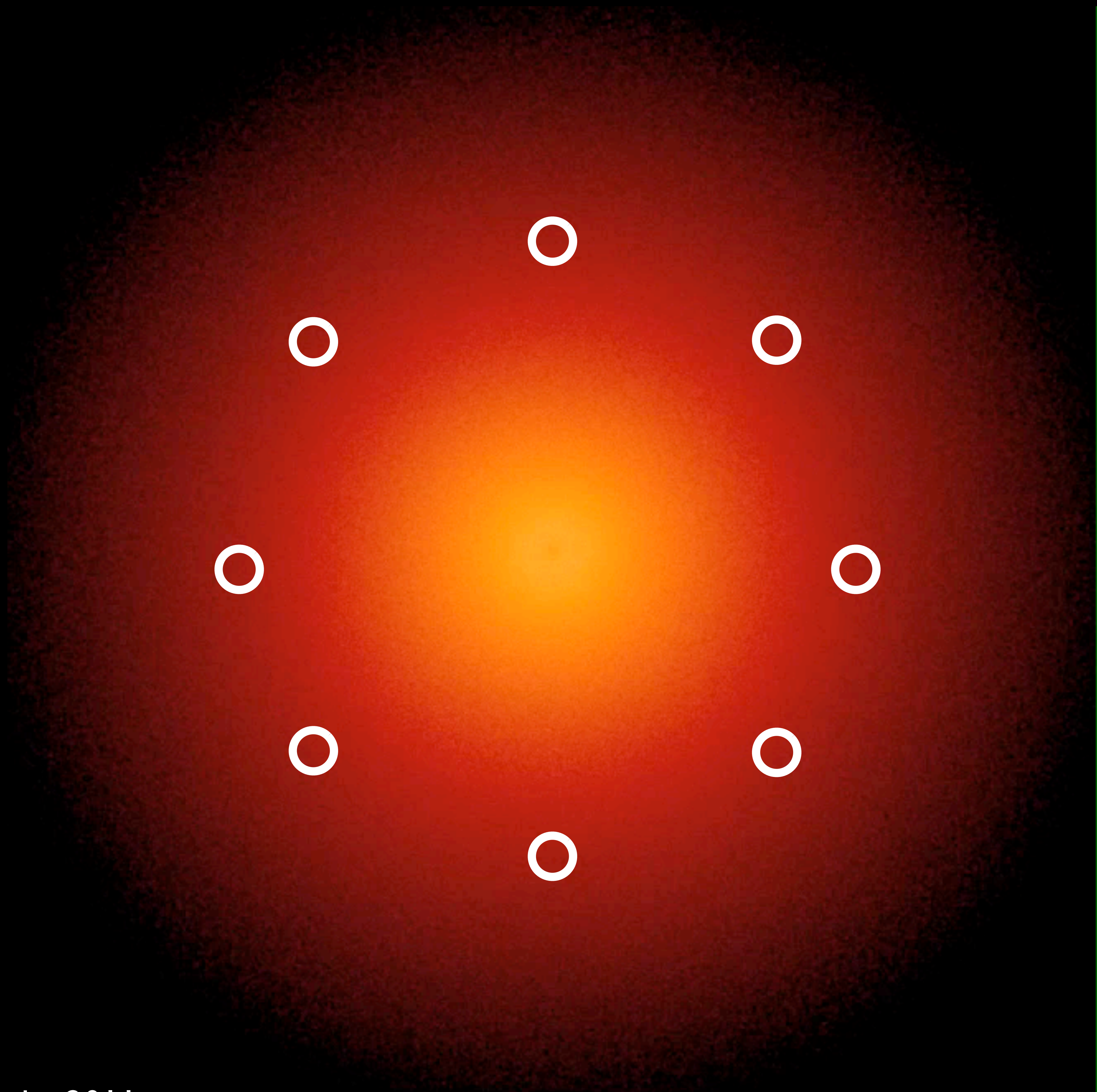

Garbari, Read & Lake 2011

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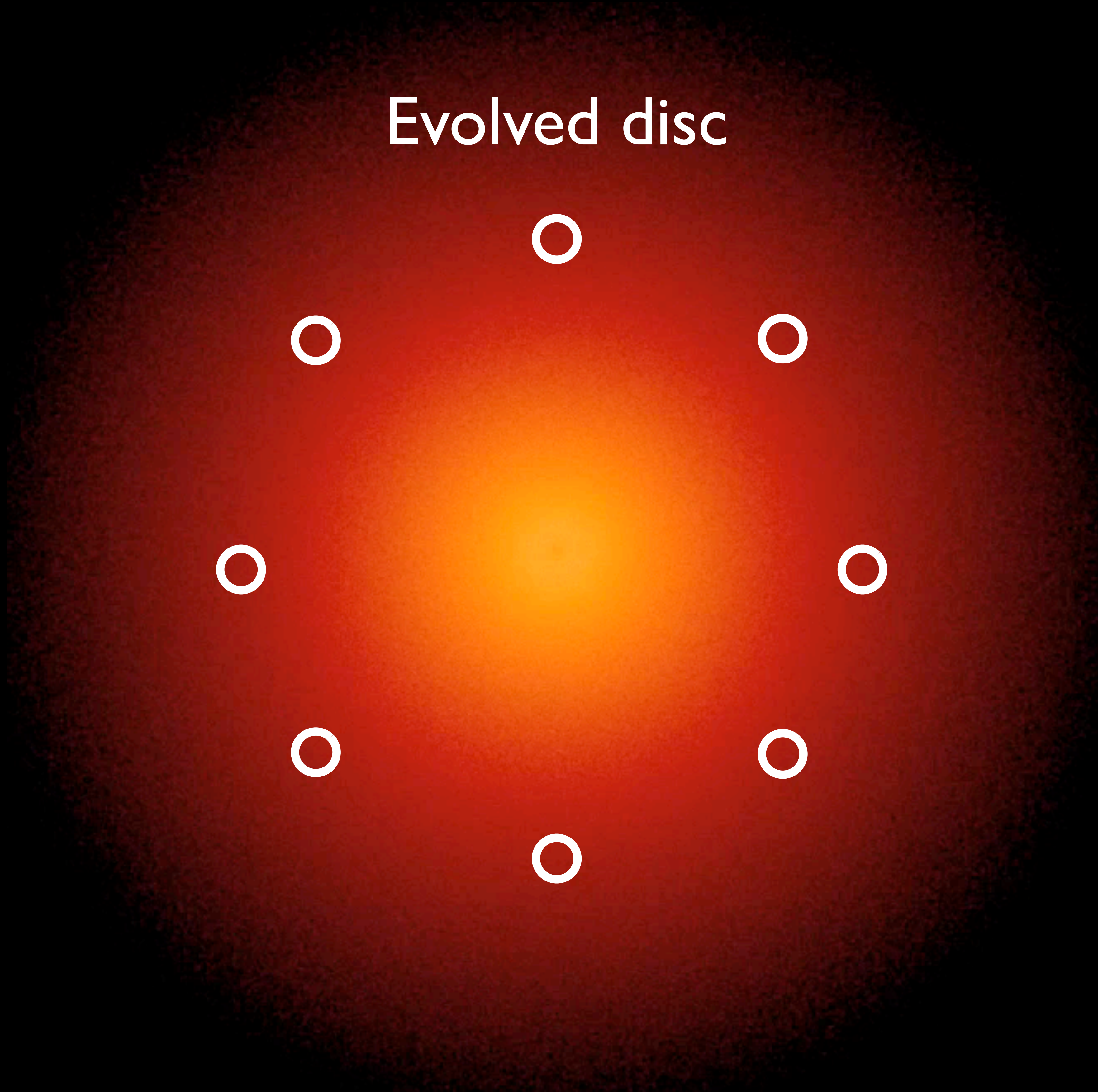

Garbari, Read & Lake 2011

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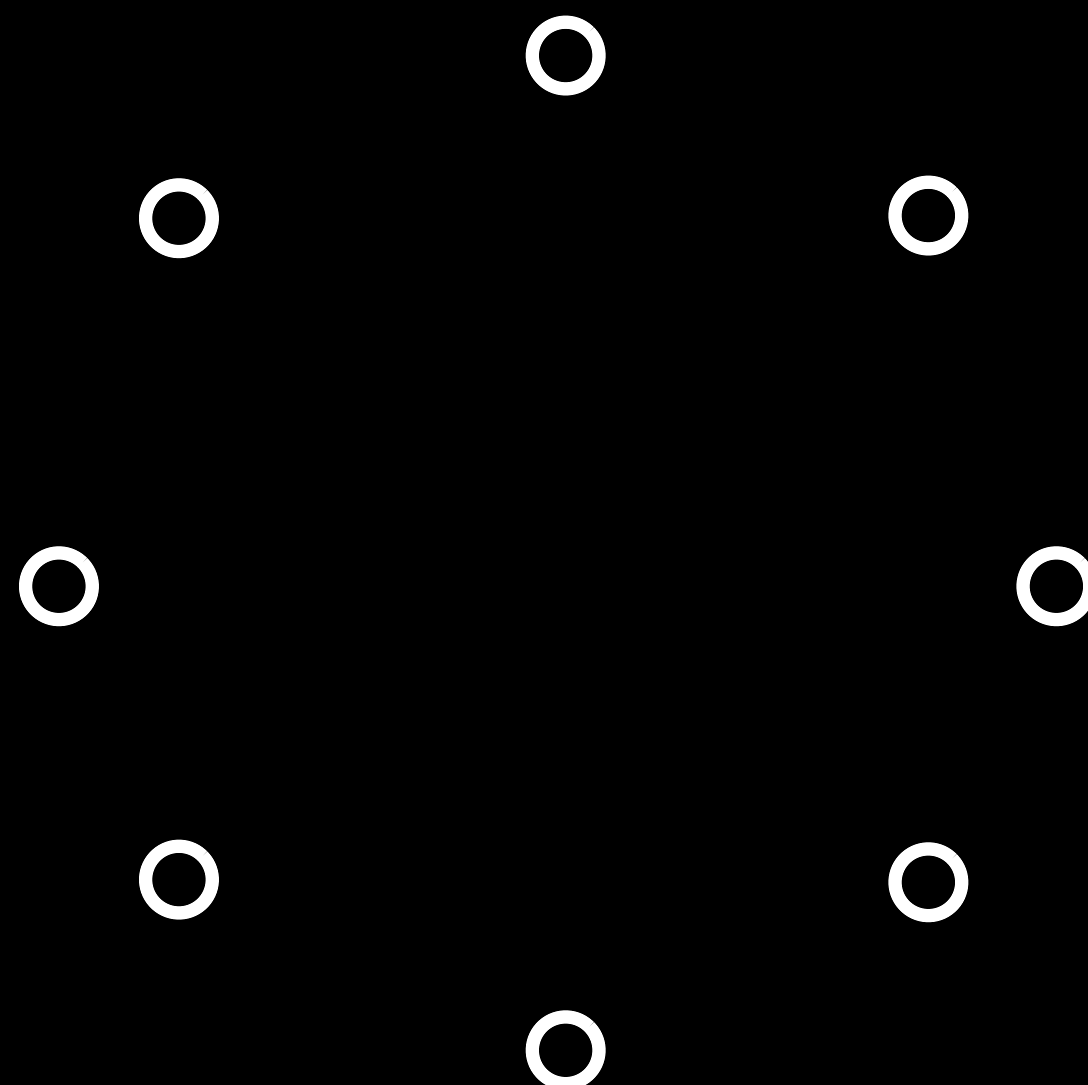

Garbari, Read & Lake 2011

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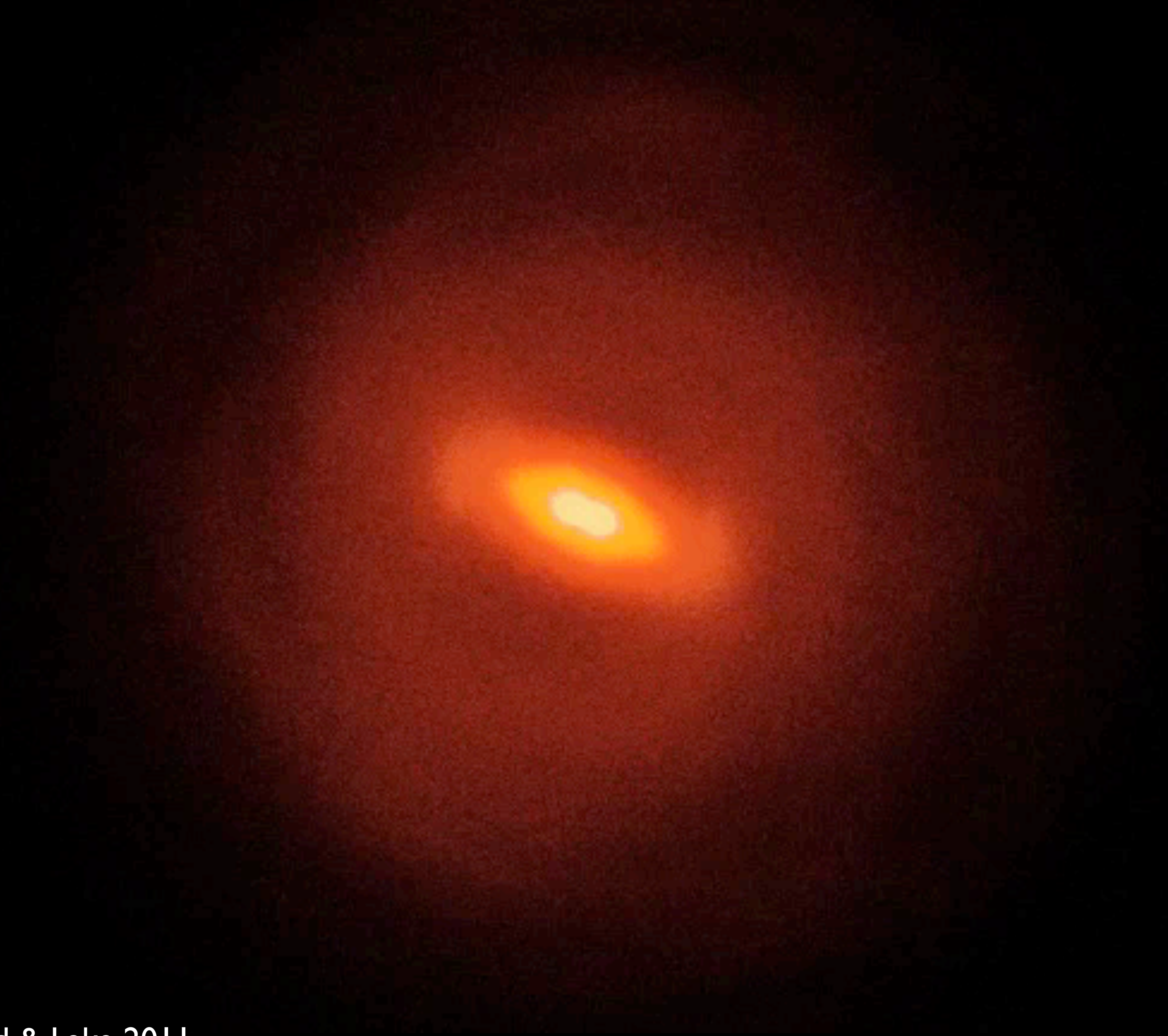


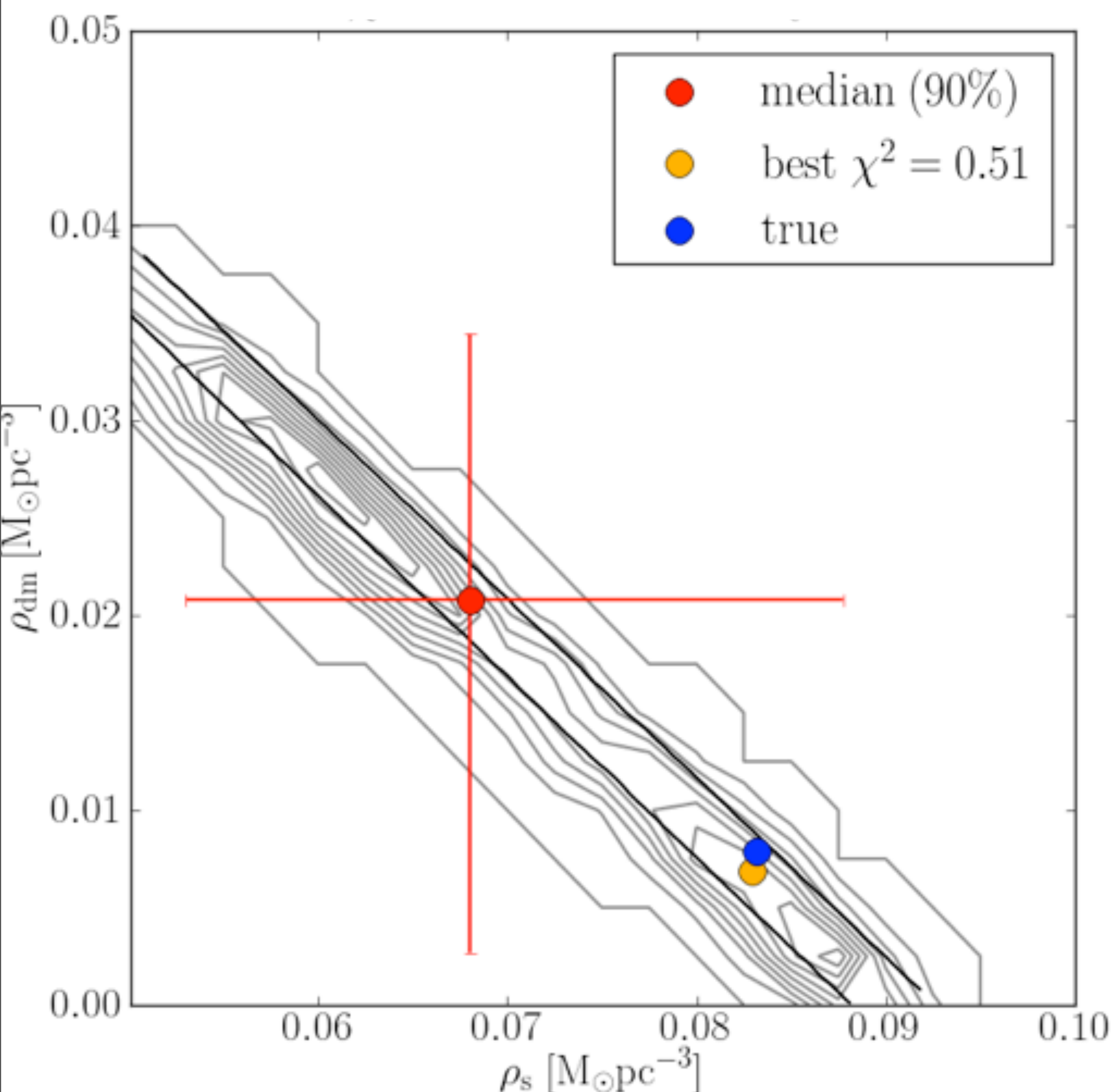
Garbari, Read & Lake 2011

3. Detecting DM particles | The local DM density

Garbari, Read & Lake 2011

3. Detecting DM particles | The local DM density

Unevolved disc

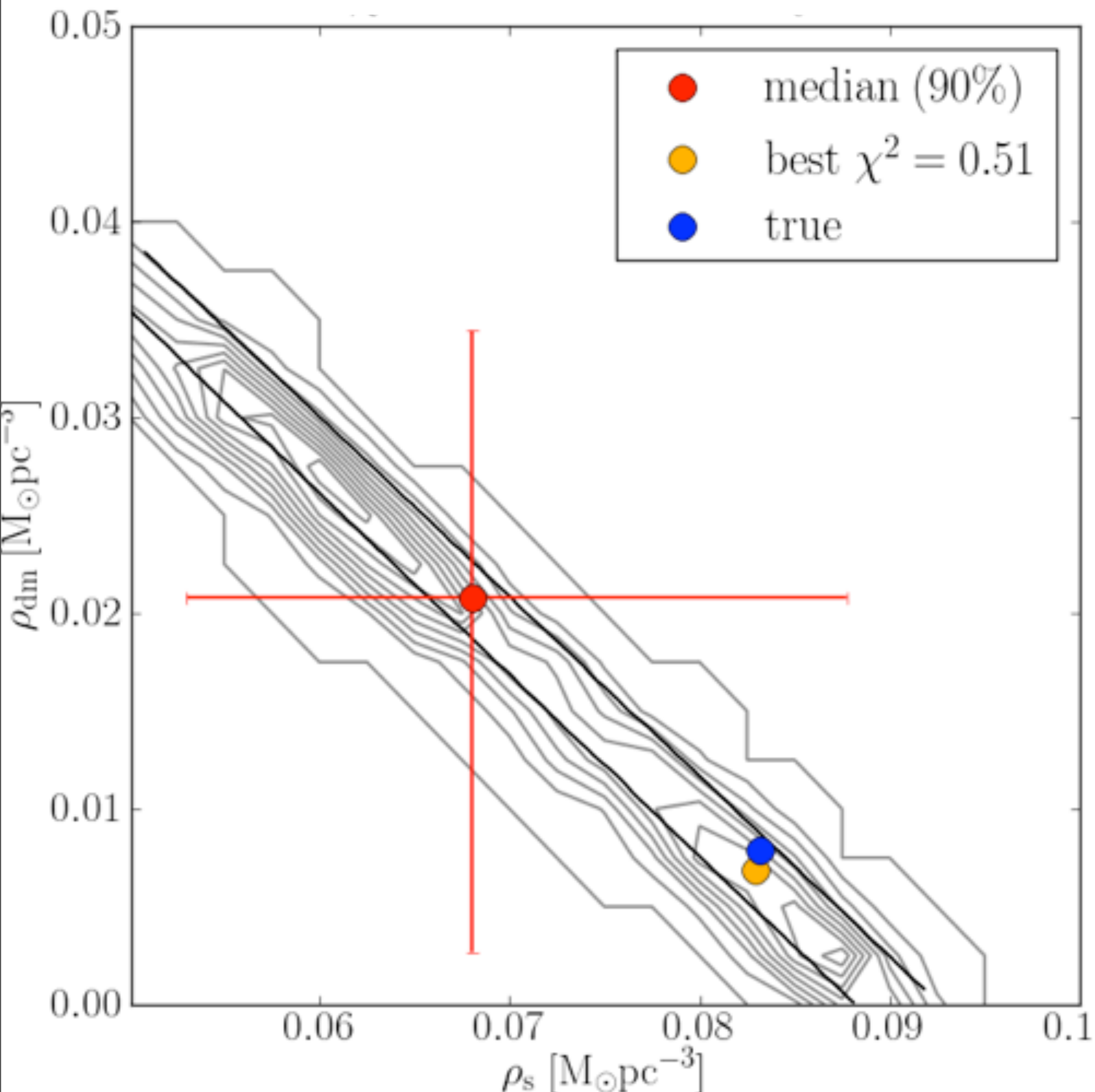


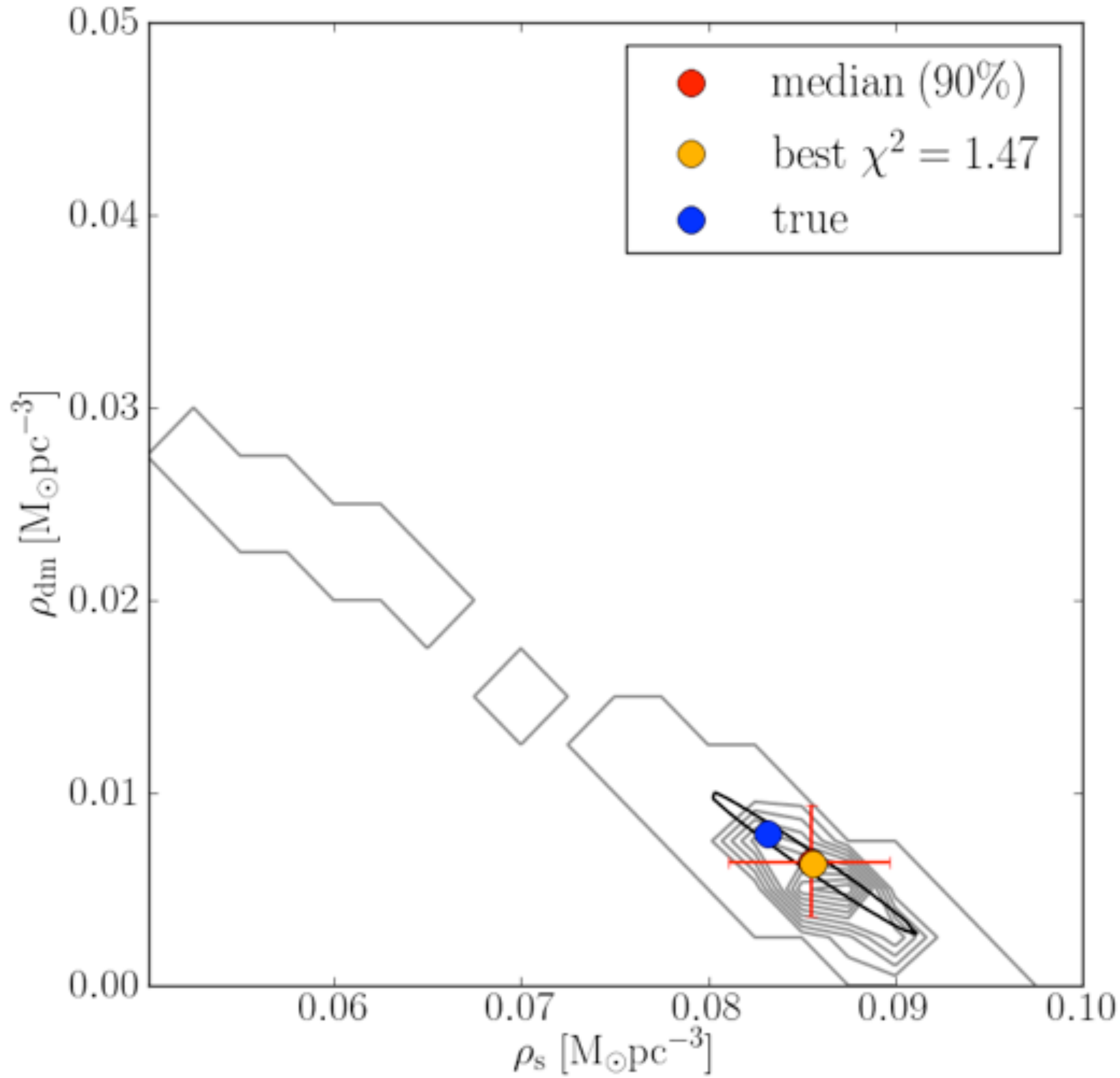
z=0.25kpc

Garbari, Read & Lake 2011

3. Detecting DM particles | The local DM density

Unevolved disc





z=0.25kpc

z=0.75kpc

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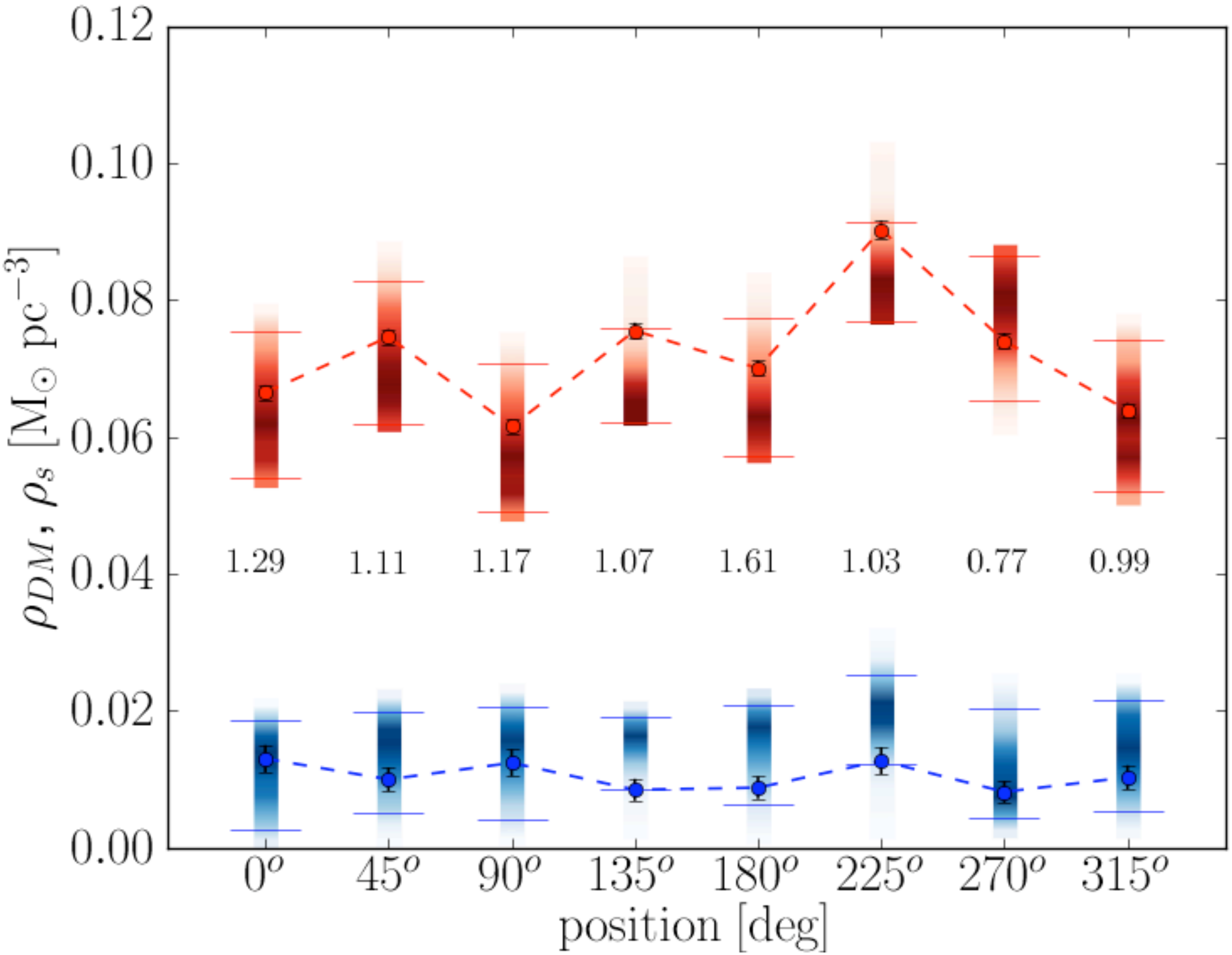
3. Detecting DM particles | The local DM density

Evolved disc; MA method

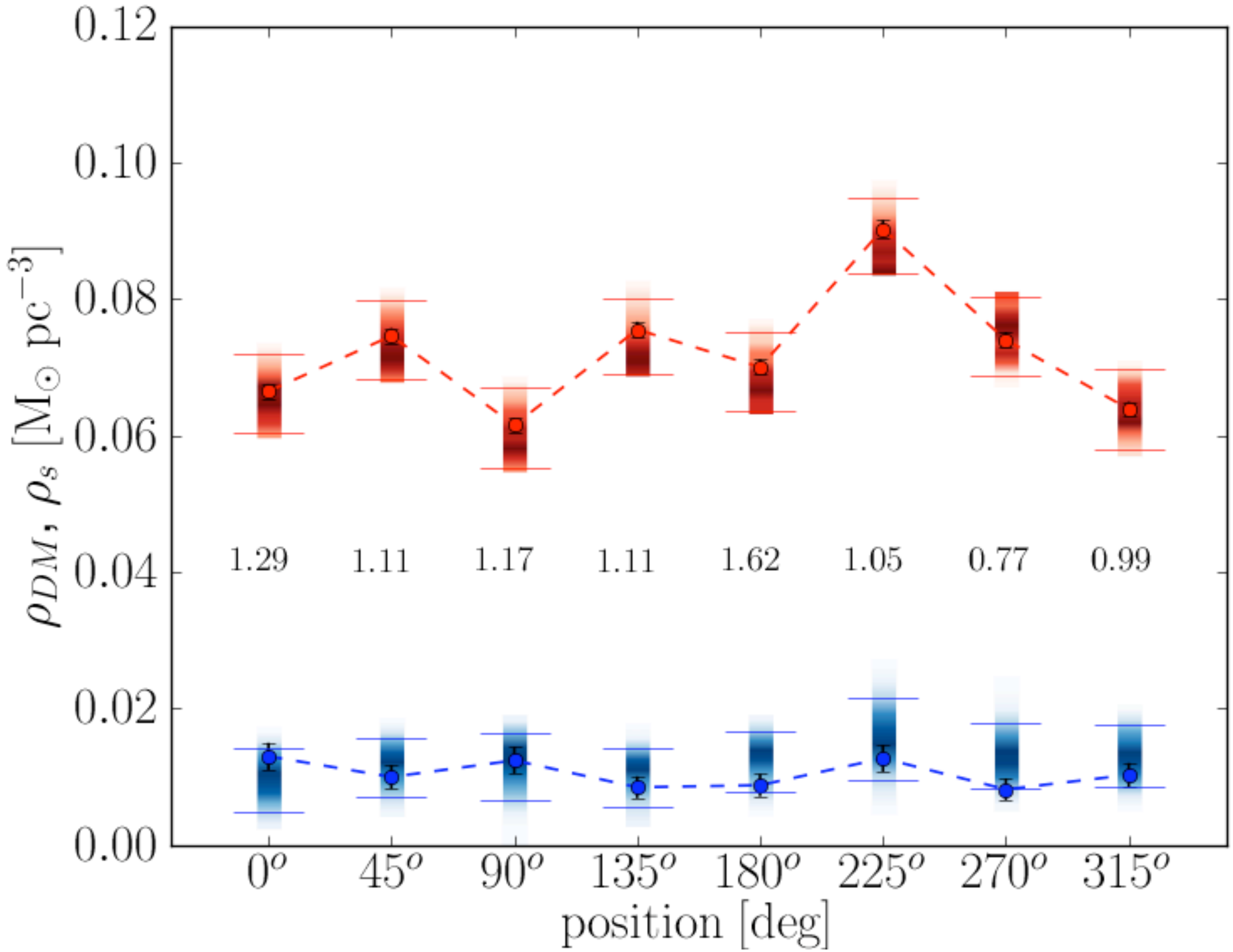


Garbari, Read & Lake 2011

$$\Delta\rho_s = \pm 0.014 M_\odot/pc^3$$

3. Detecting DM particles | The local DM density

Evolved disc; MA method



Garbari, Read & Lake 2011

$$\Delta\rho_s = \pm 0.007 M_\odot/pc^3$$

3. Detecting DM particles | The local DM density

Garbari, Liu, Read & Lake 2012, in prep.

3. Detecting DM particles | The local DM density

1. Need a (good) mass model

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3. Detecting DM particles | The local DM density

1. Need a (good) mass model

Visible Mass Model by Flynn et al 2006

Component	$\nu_{i,0}(0)$ [M⊙/pc^3]	$\overline{v_{z,i}^2}(0)$ [km/s]
H_2^*	0.021	4.0 ± 1.0
HI(1)*	0.016	7.0 ± 1.0
HI(2)*	0.012	9.0 ± 1.0
Warm gas*	0.0009	40.0 ± 1.0
Giants	0.0006	20.0 ± 2.0
$M_V < 2.5$	0.0031	7.5 ± 2.0
$2.5 < M_V < 3.0$	0.0015	10.5 ± 2.0
$3.0 < M_V < 4.0$	0.0020	14.0 ± 2.0
$4.0 < M_V < 5.0$	0.0022	18.0 ± 2.0
$5.0 < M_V < 8.0$	0.007	18.5 ± 2.0
$M_V > 8.0$	0.0135	18.5 ± 2.0
White dwarfs	0.006	20.0 ± 5.0
Brown dwarfs	0.002	20.0 ± 5.0
Thick disc	0.0035	37.0 ± 5.0
Stellar halo	0.0001	100.0 ± 10.0

density errors:
Stars: 10-20%;
Gas*: 50%

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3. Detecting DM particles | The local DM density

2. Need a good tracer

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3. Detecting DM particles | The local DM density

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- Well mixed => equilibrium
- Well populated => good statistics (at high z!)
- Volume complete
- Velocity data (v_z)
- Good distances

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3. Detecting DM particles | The local DM density

2. Need a good tracer

- Well mixed => equilibrium
- Well populated => good statistics (at high z!)
- Volume complete
- Velocity data (v_z)
- Good distances

=> K dwarfs (c.f. Kuijken & Gilmore 1989-91)

- 2016 K dwarf stars; photometry in B and V bands
- 580 K dwarfs with radial velocities

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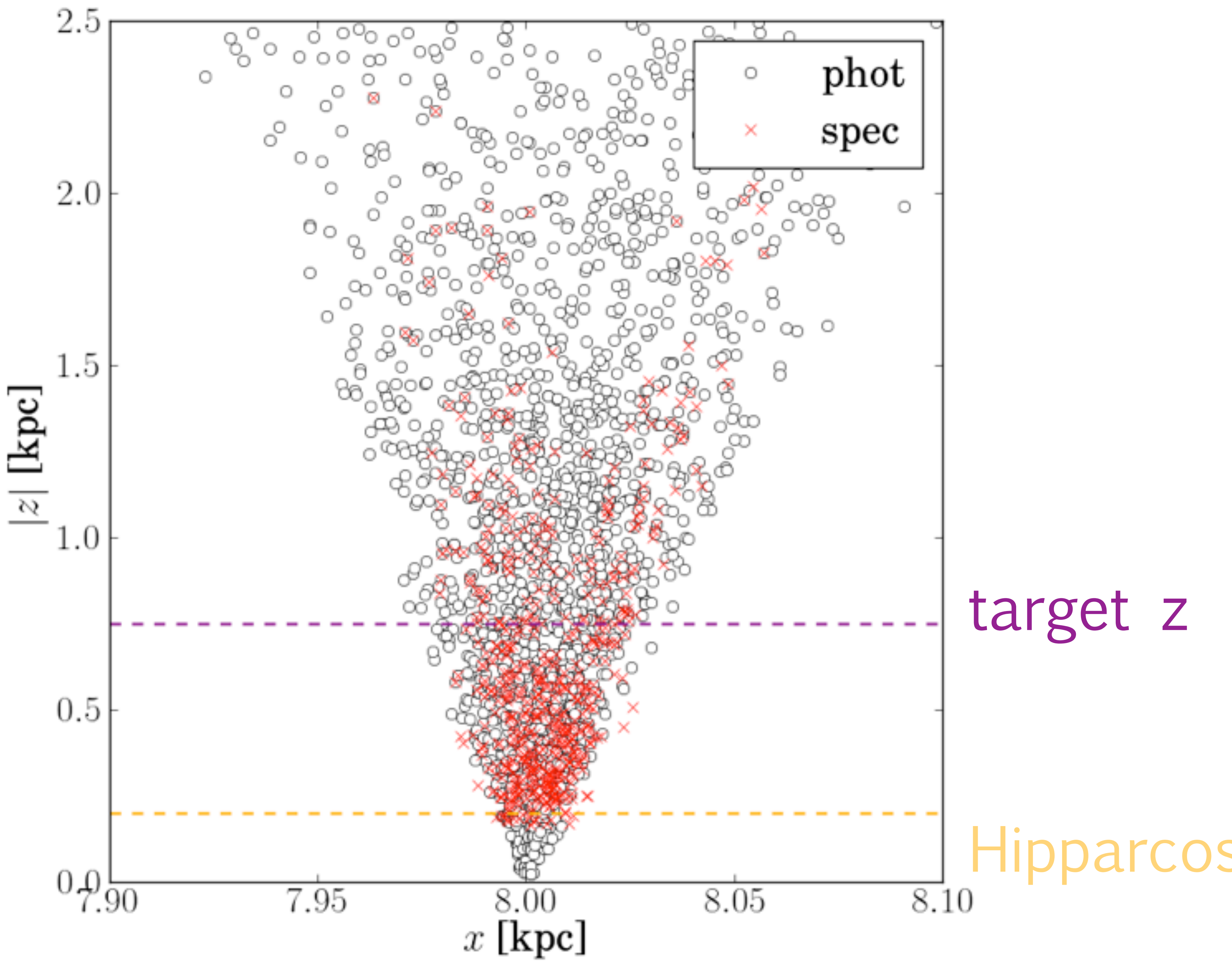
3. Detecting DM particles | The local DM density



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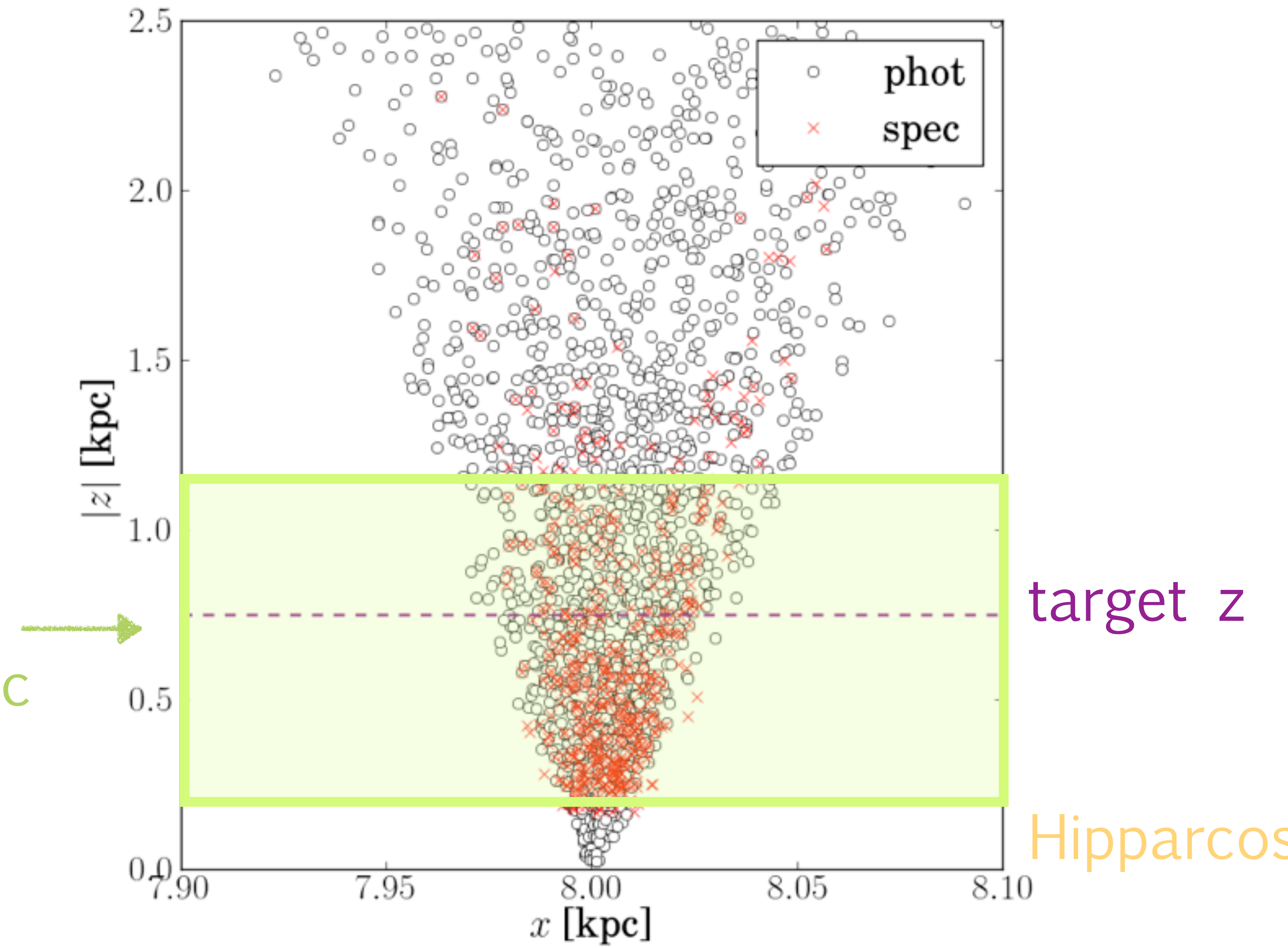
3. Detecting DM particles | The local DM density

Volume complete photometric sample



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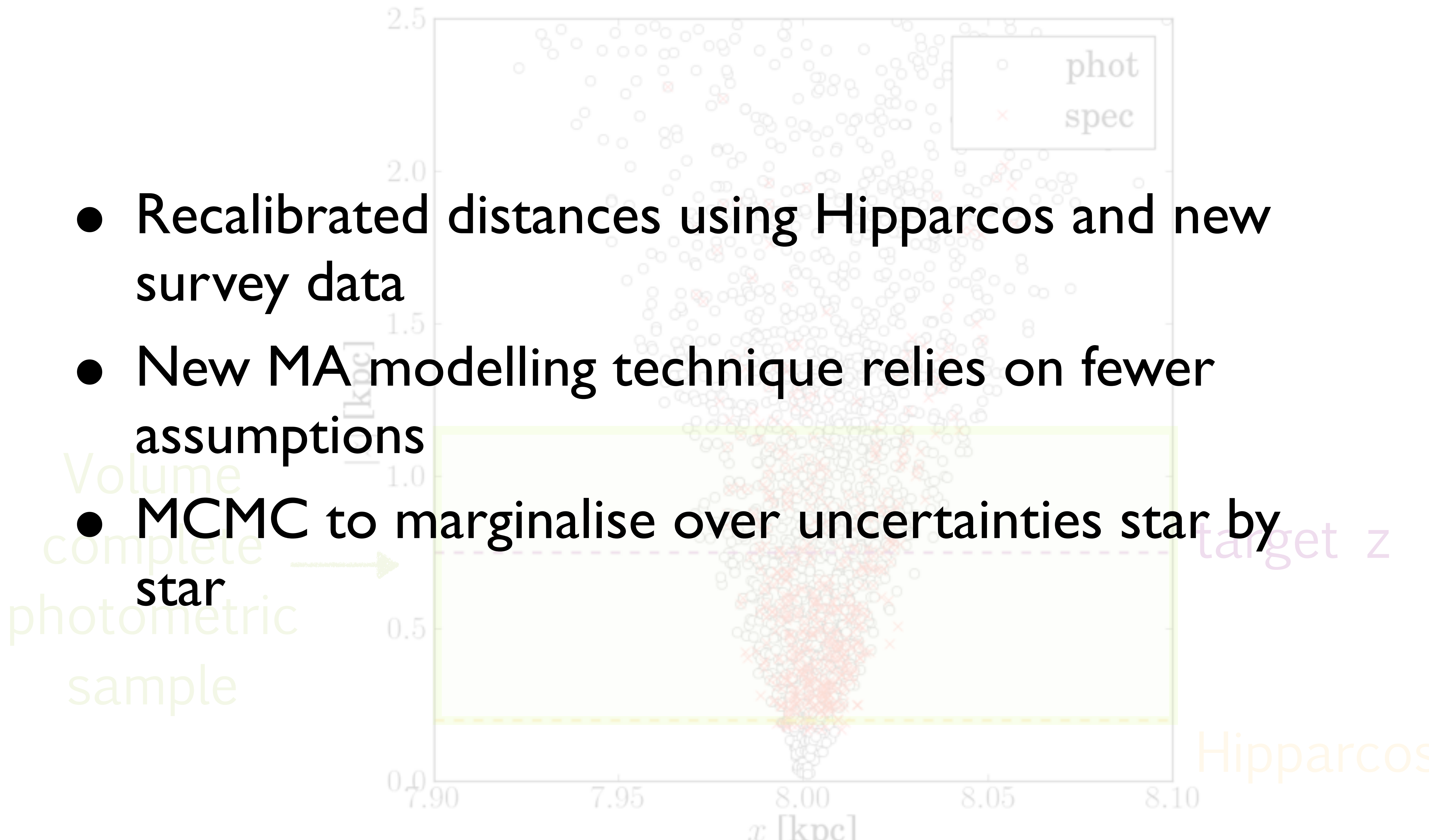
3. Detecting DM particles | The local DM density



- Recalibrated distances using Hipparcos and new survey data
- New MA modelling technique relies on fewer assumptions
- MCMC to marginalise over uncertainties star by star

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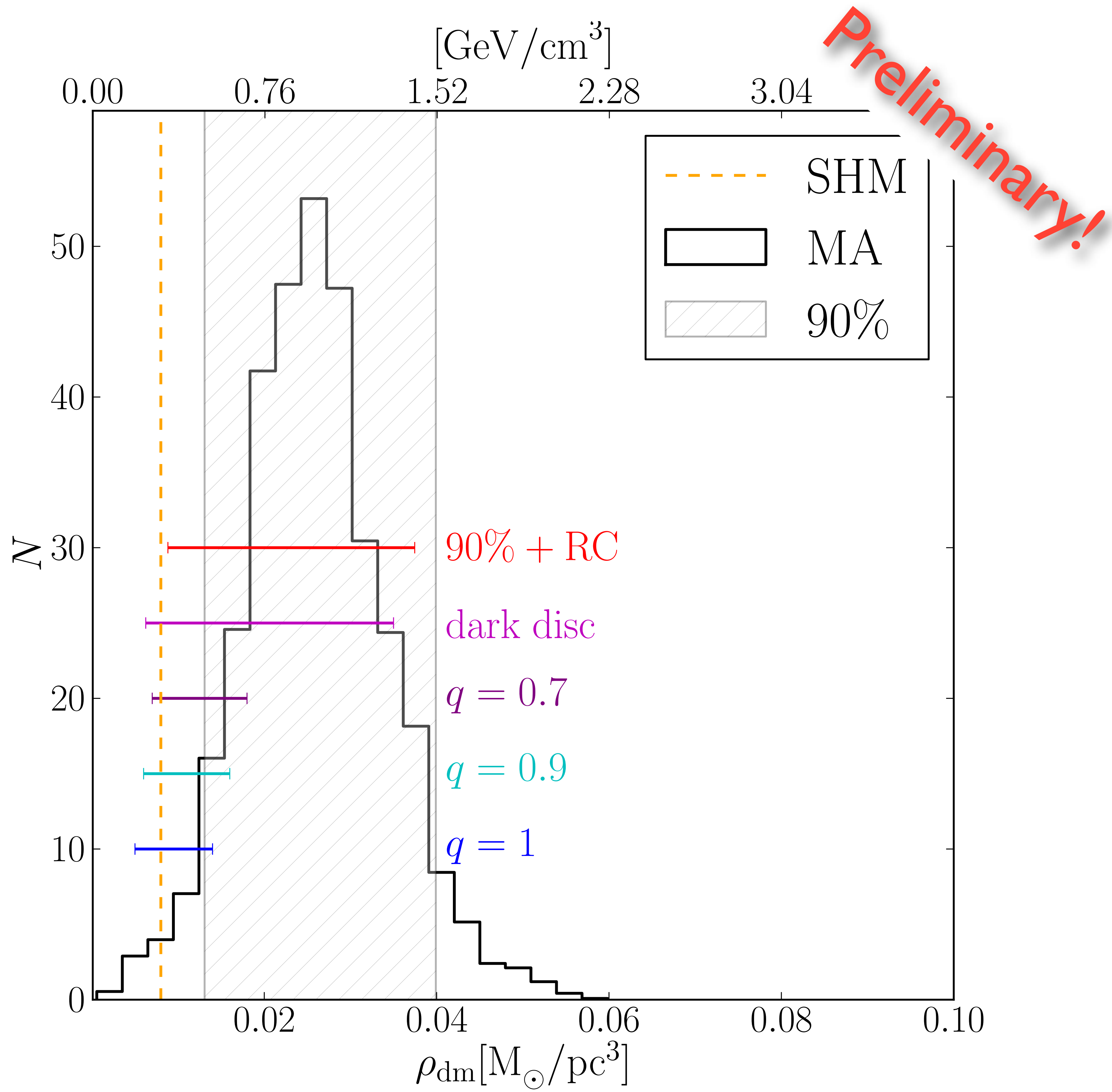
3. Detecting DM particles | The local DM density



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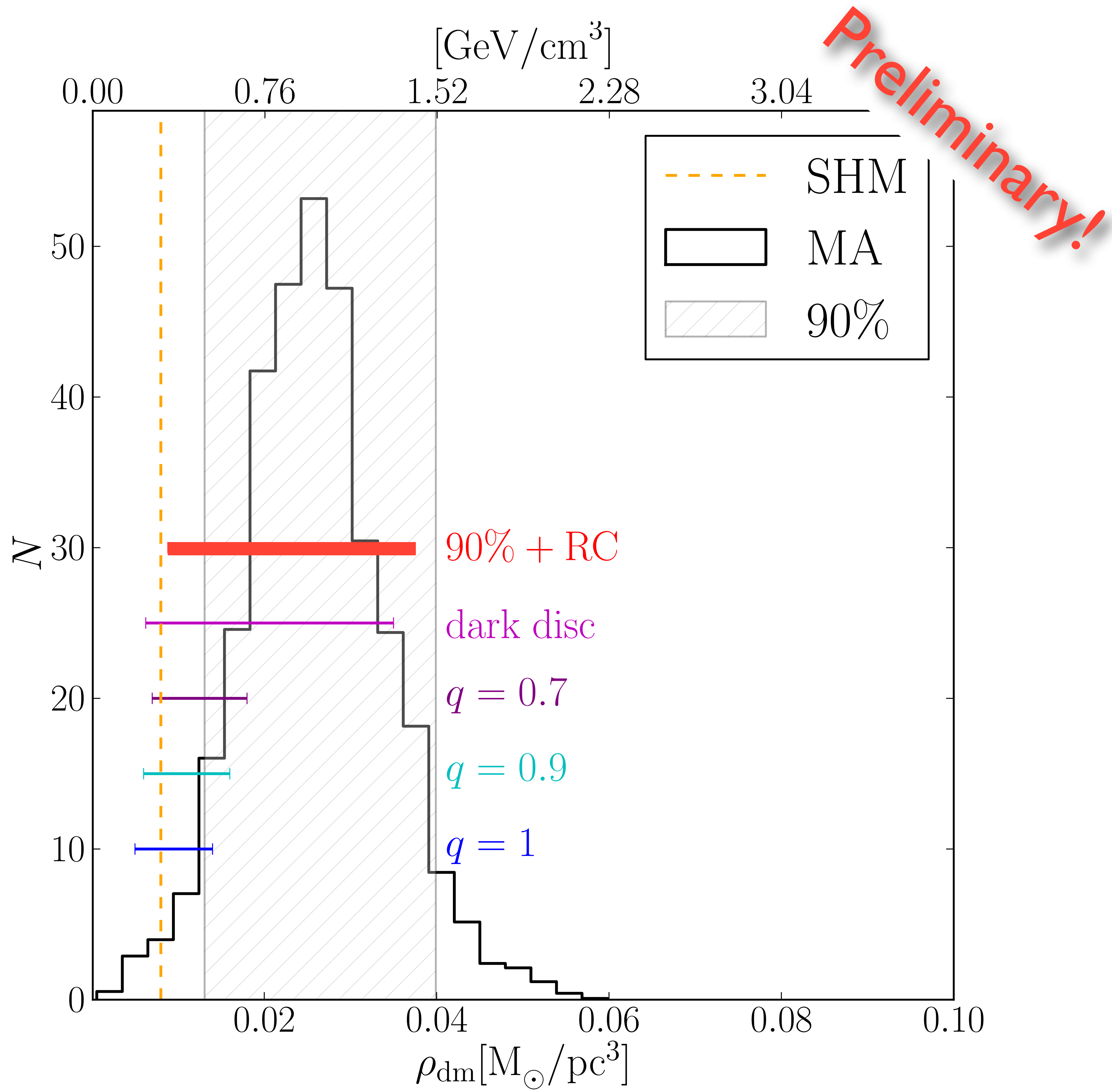

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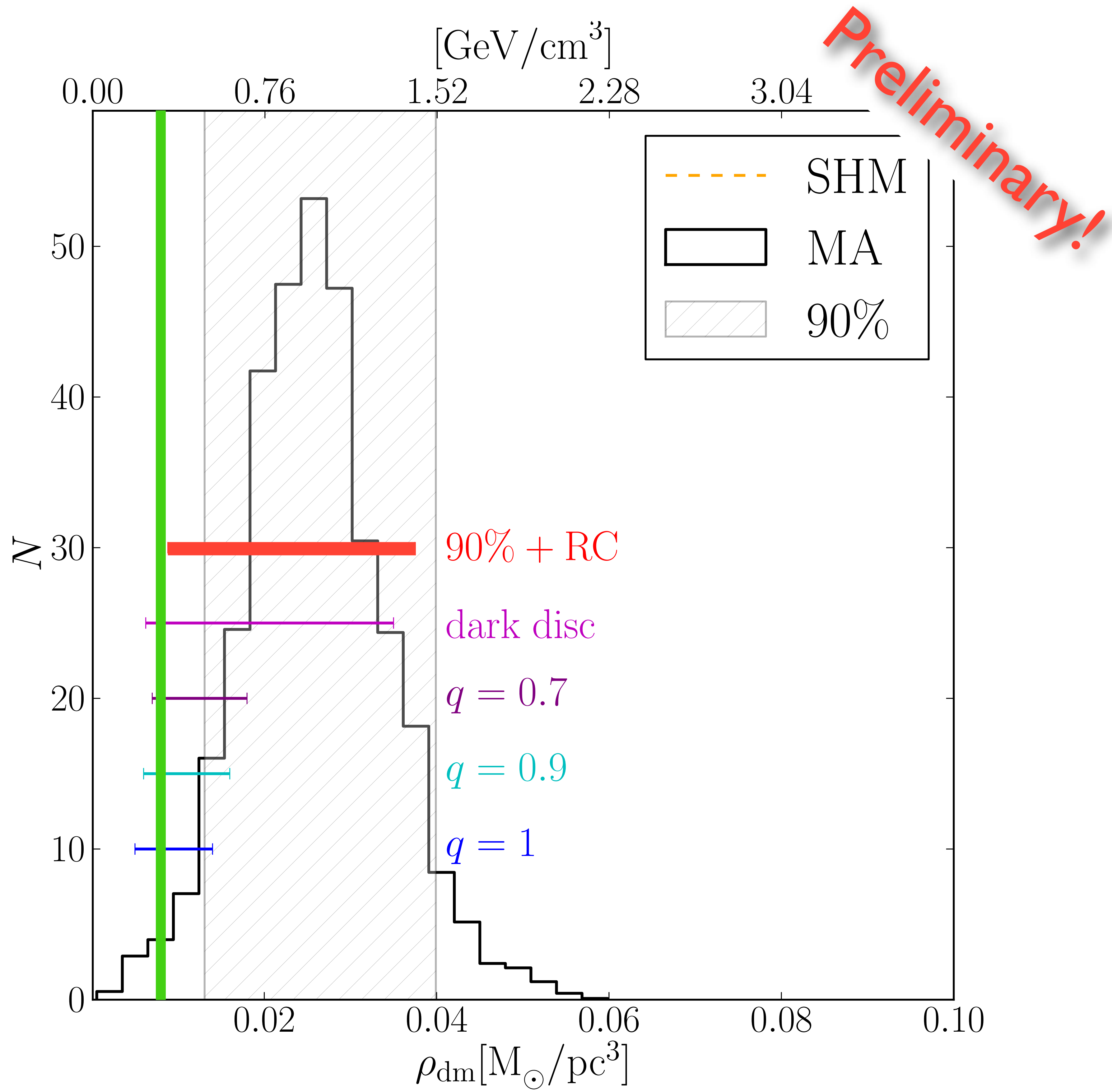

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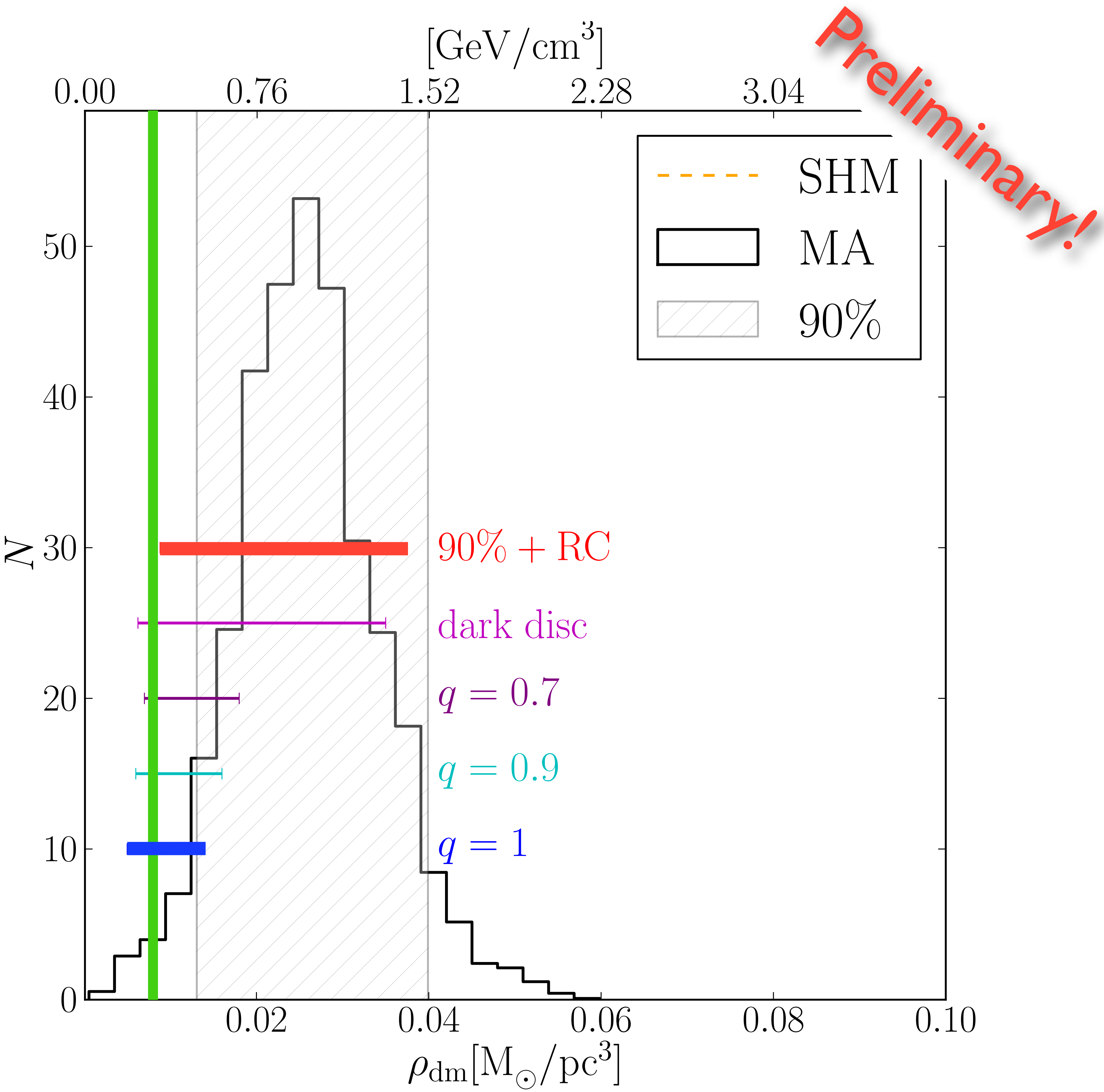

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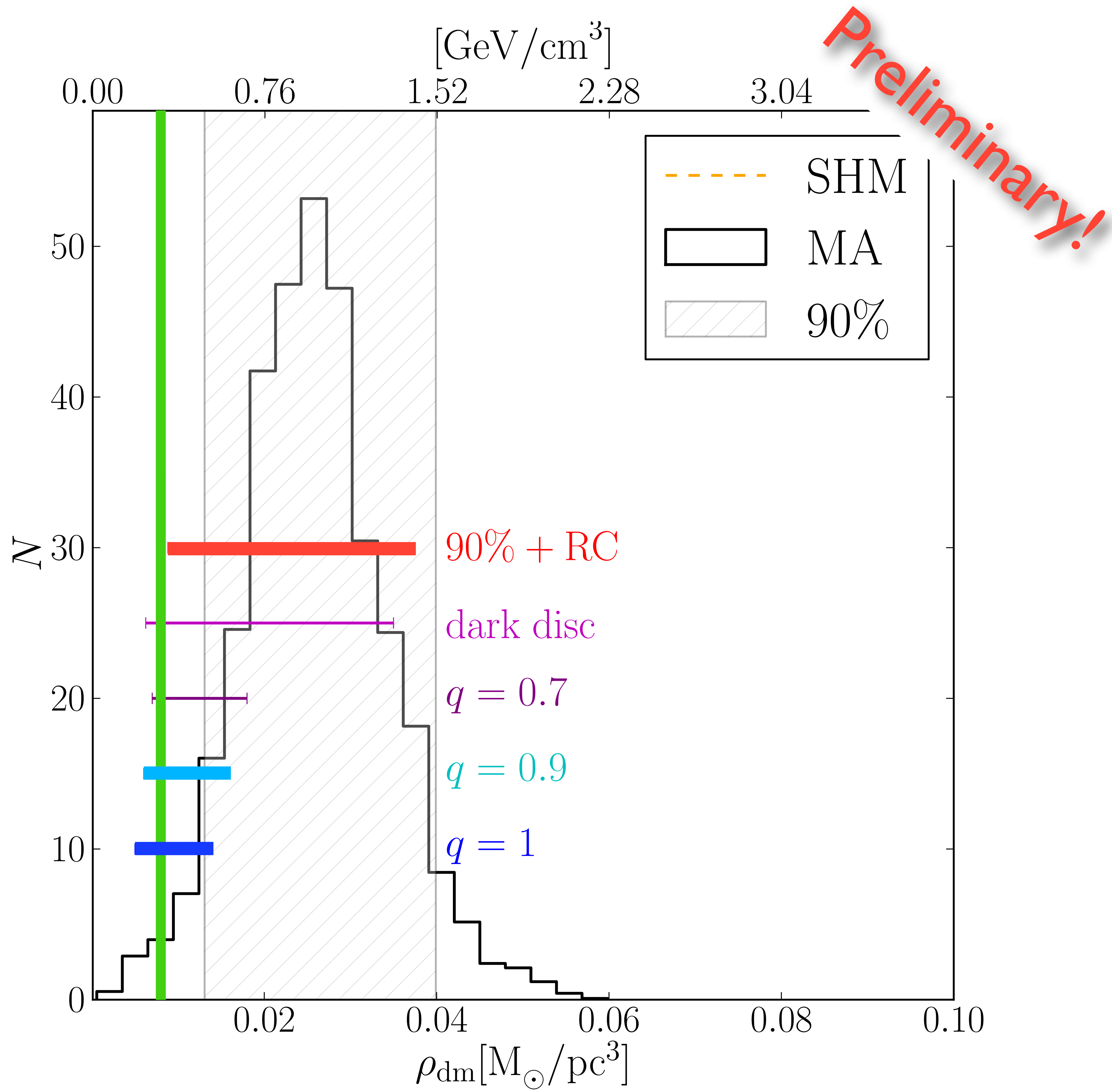

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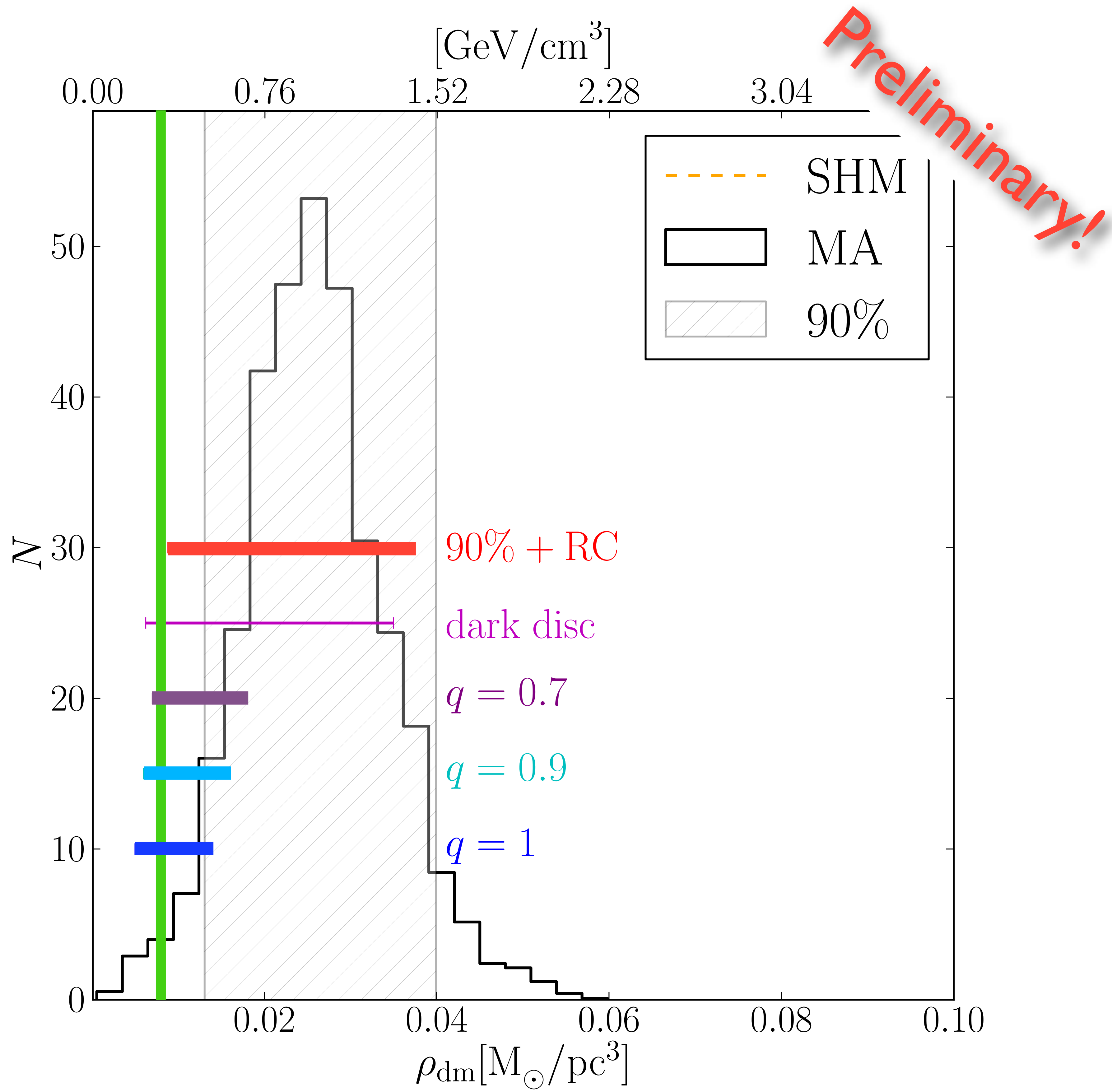

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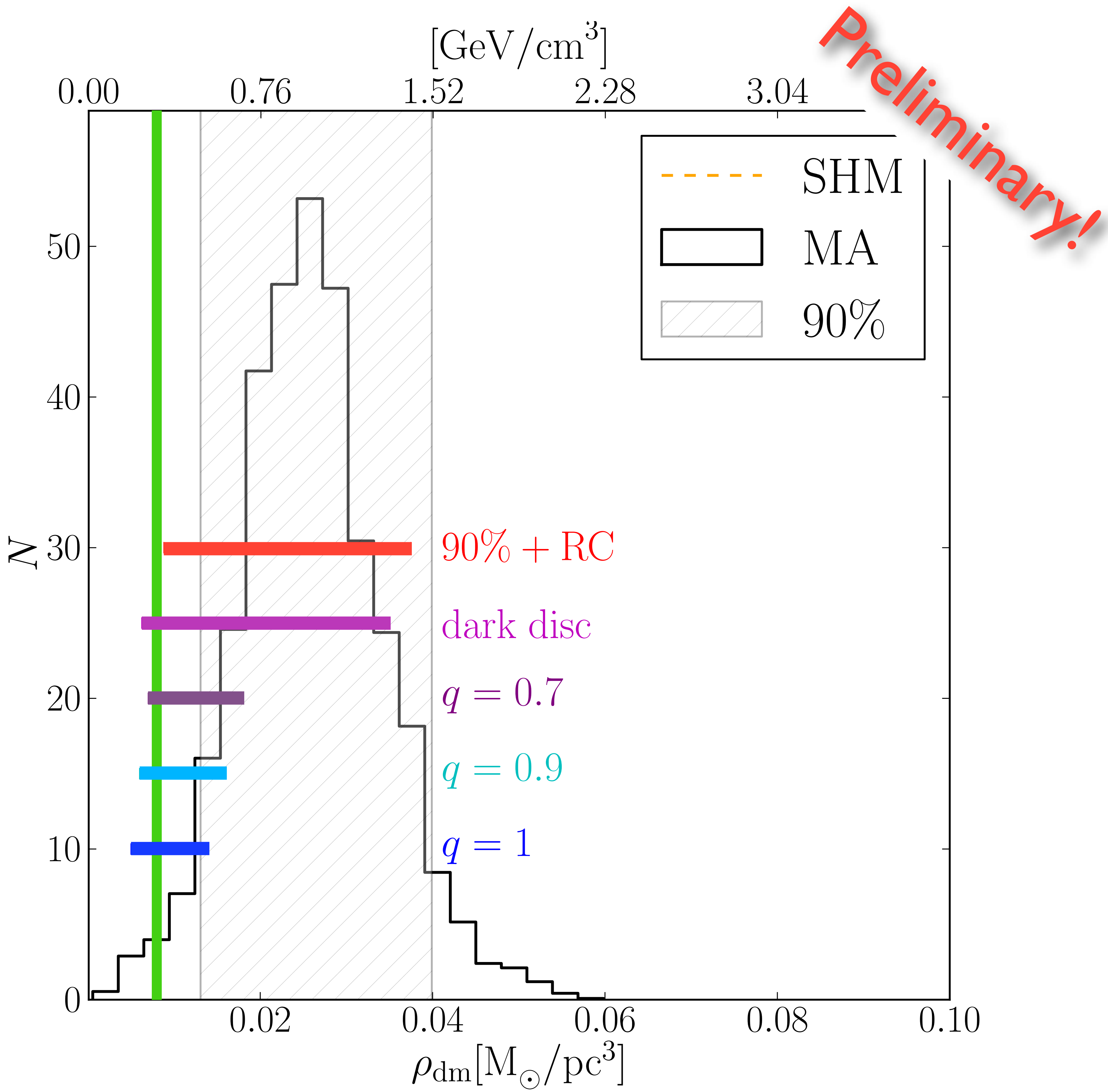

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3. Detecting DM particles | The local DM density

$$\rho_{\rm dm} = 0.022^{+0.015}_{-0.013}\,{\rm M}_\odot/{\rm pc}^3$$

$$(\rho_{\rm dm} = 0.85^{+0.57}_{-0.50}\,{\rm GeV}/{\rm cm}^3)$$

Preliminary!

Sag Stream
$0.85 < q < 1.05$

q=0.7
q=1 (spherical) SHM
q=1.4

Garbari, Liu, Read & Lake 2012, in prep.

Conclusions

- Down to galaxy cluster scales dark matter is cold and ‘standard’.
- On dwarf galaxy scales there is mounting evidence for dark matter cores. However, these can arise naturally as a consequence of rapid, multiple, gas inflows and outflows driven by mergers and supernovae.
- Baryons also influence the local dark matter distribution. Including them leads to the expectation that our Galaxy has a dark matter disc.
- We have recently measured the local dark matter density, finding: $\rho_{DM} = 0.85 \pm 0.5$ GeV/cm^3. This is at mild tension with simple spherical extrapolations from the Milky Way’s rotation curve.
- Improved modelling of baryonic processes (galaxy formation) are vital for making concrete predictions for the dark matter distribution on small scales. We have a new tool that we are applying to this problem.