The distribution of dark matter (theory & observation)

Cold Dark Matter by Cornelia Parker

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With:

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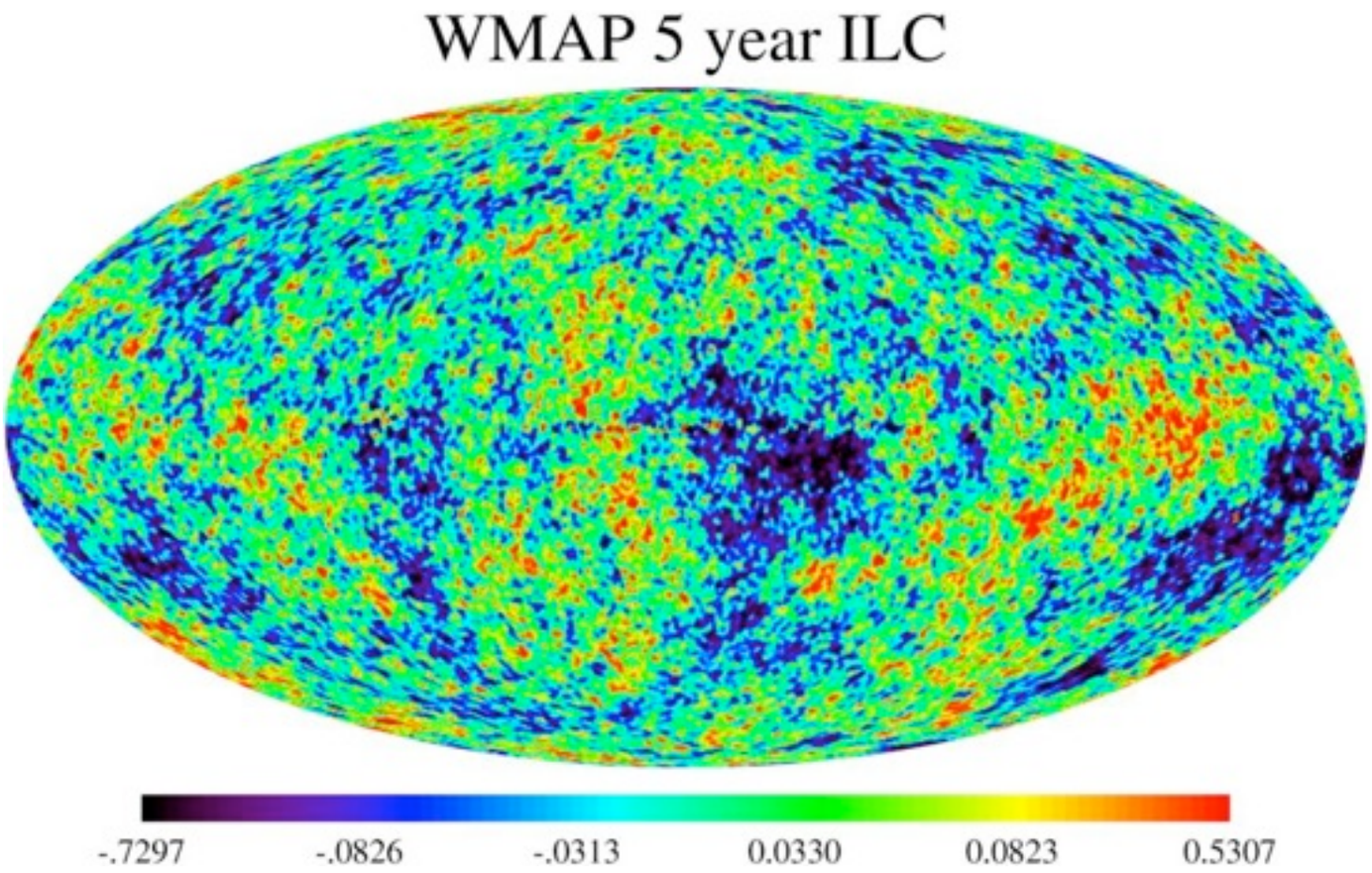
Background | Why study the distribution of dark matter?

1. Calculate the expected distribution of DM in the Universe (assuming something about DM).

2. Compare with observations ⇒ constrain DM properties.

3. Knowledge of the local/nearby DM distribution is important for direct/indirect DM particle detection.

Background | The standard cosmological model LCDM



WMAP team; Hu 2002

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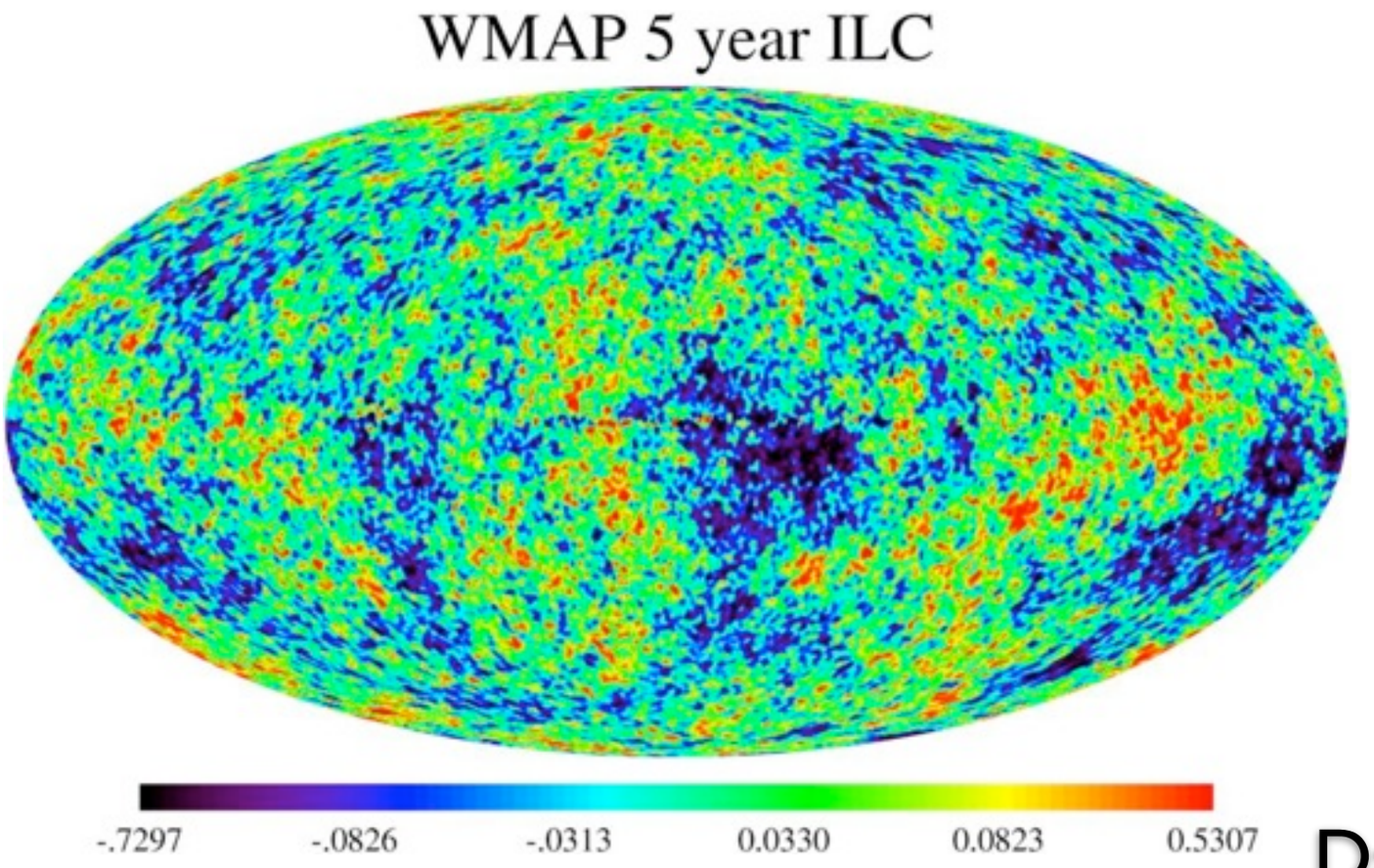
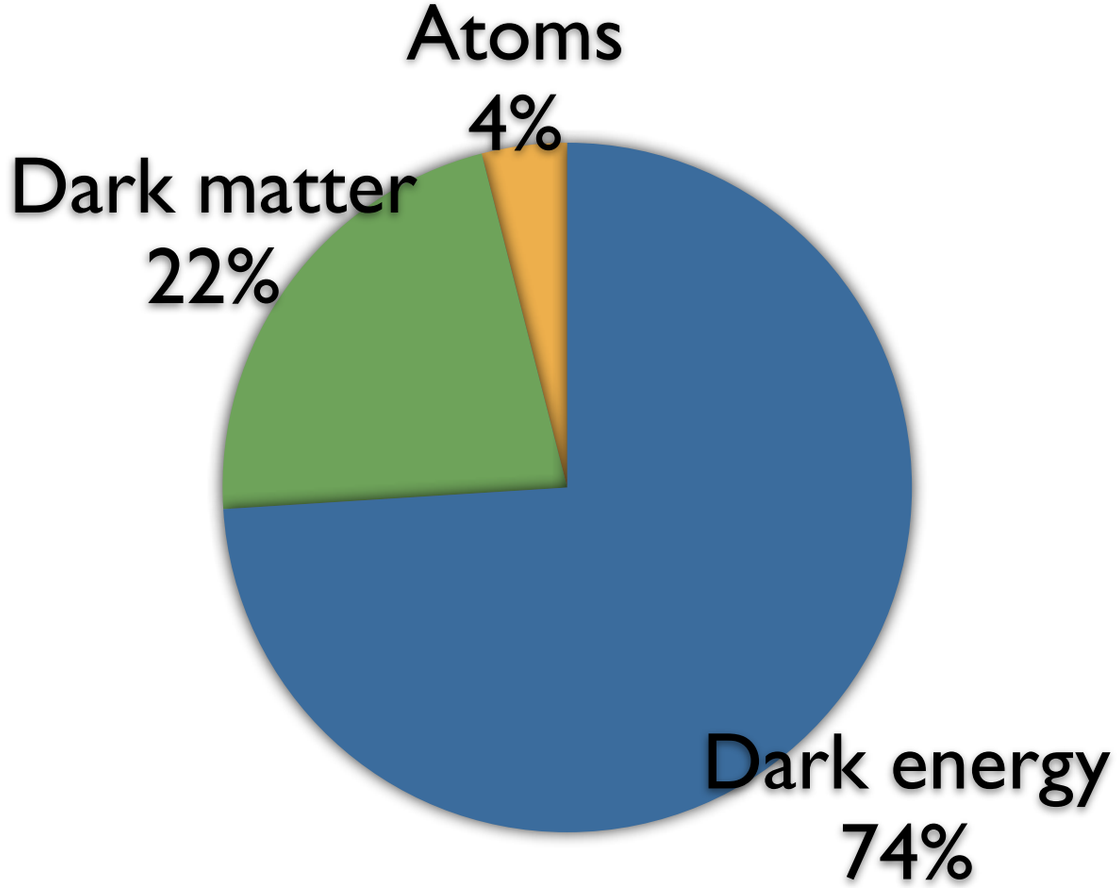




WMAP team; Hu 2002

Z=36.4

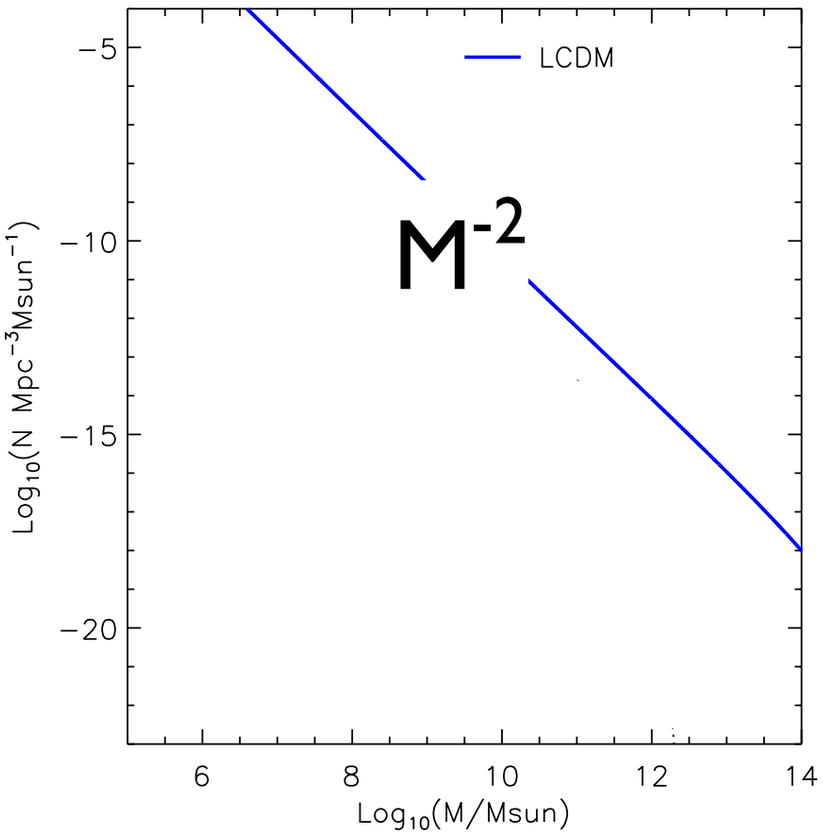
1. Theory | Calculating the dark matter distribution

Doug Potter 2006

‘Dark Matter only’ simulations; LCDM

1. Theory | Calculating the dark matter distribution

1. Halo mass function



Zemp et al. 2009; Vogelsberger et al. 2009

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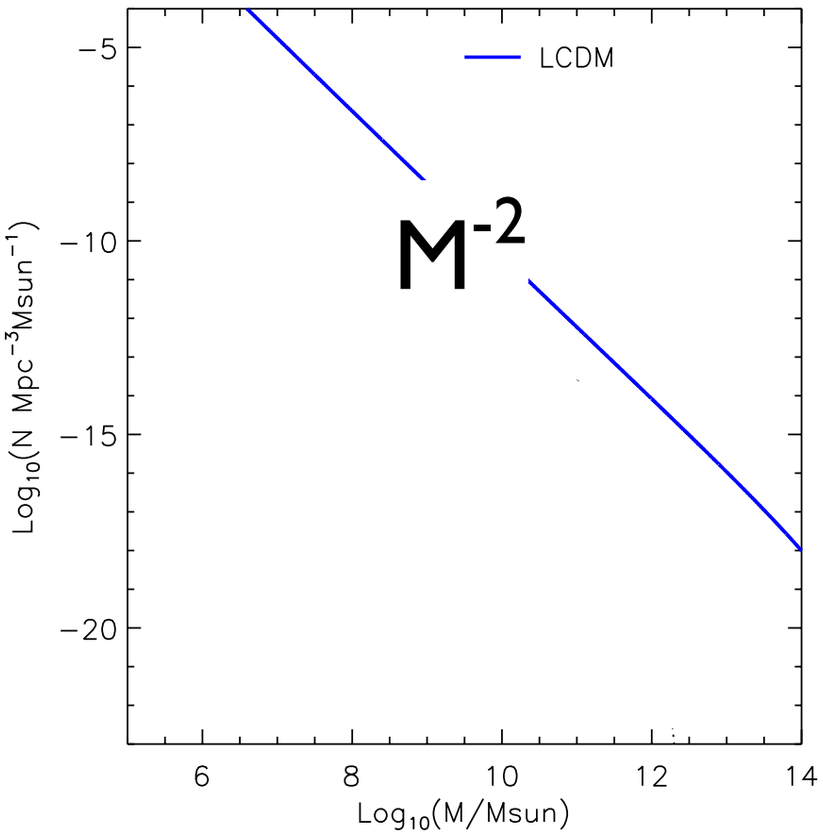
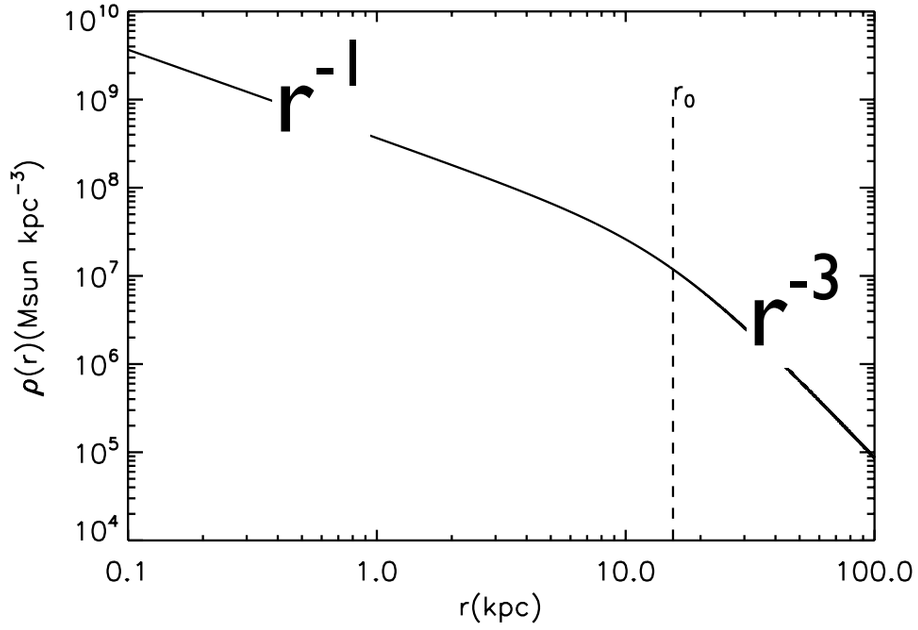


2. 'Universal' density profile



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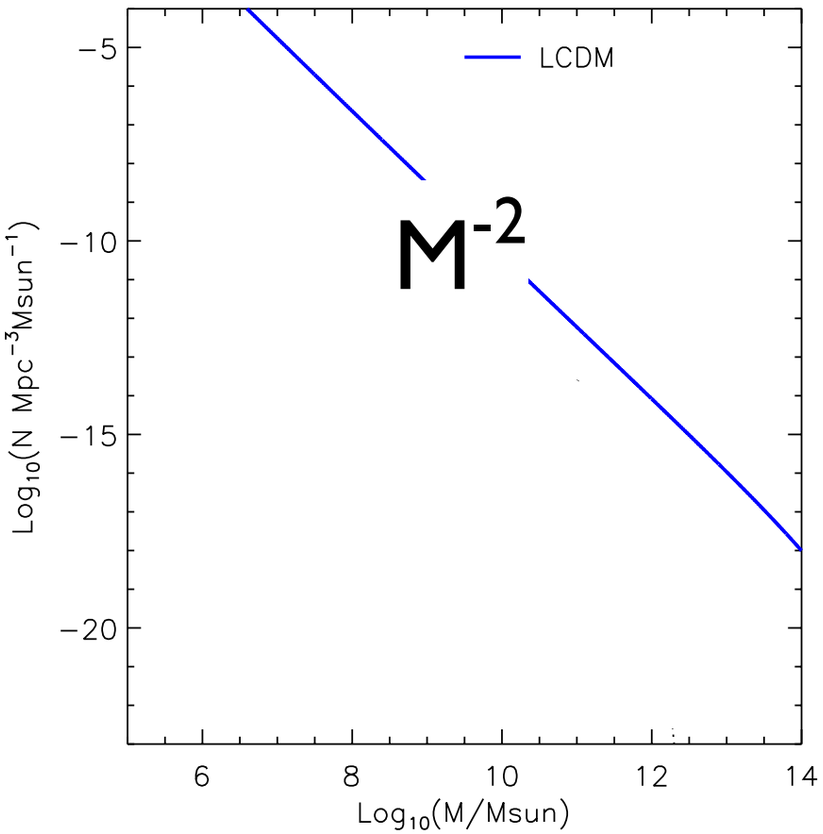

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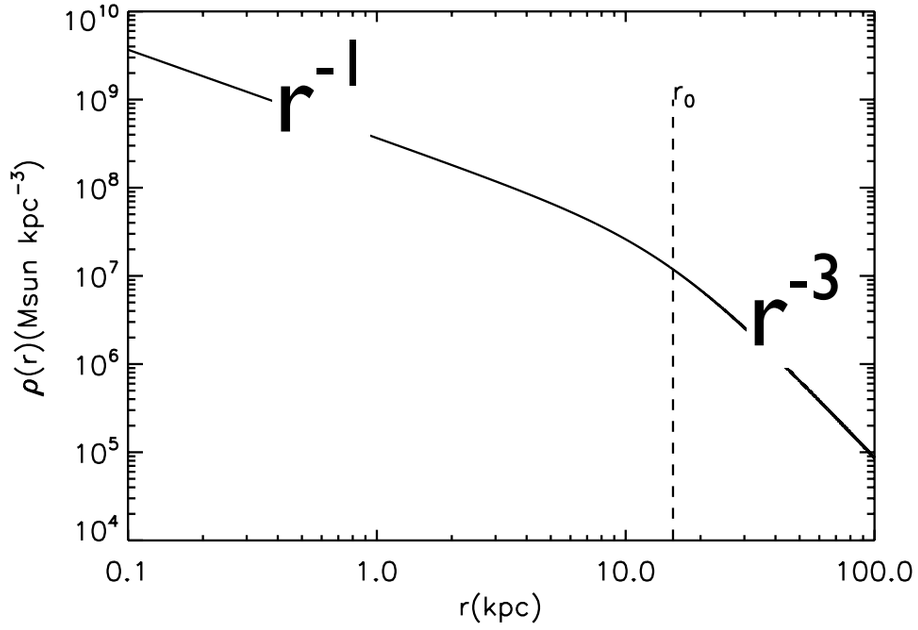
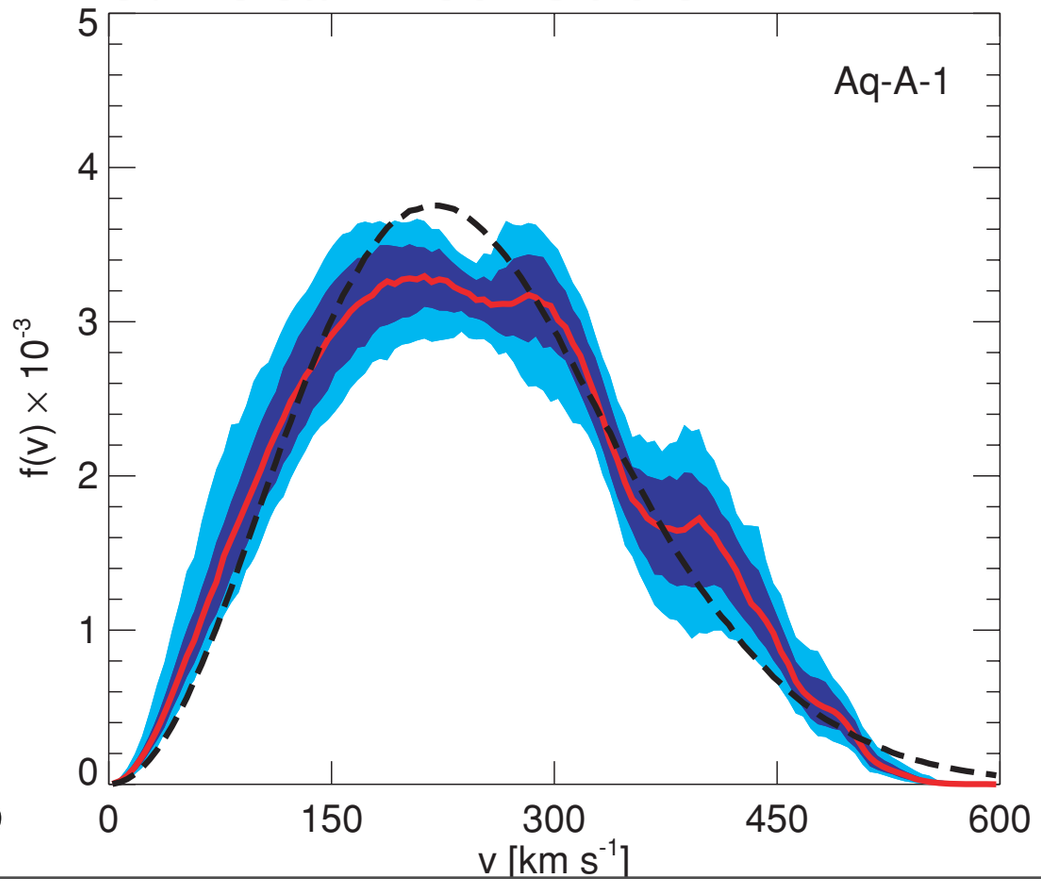


3. Local distribution



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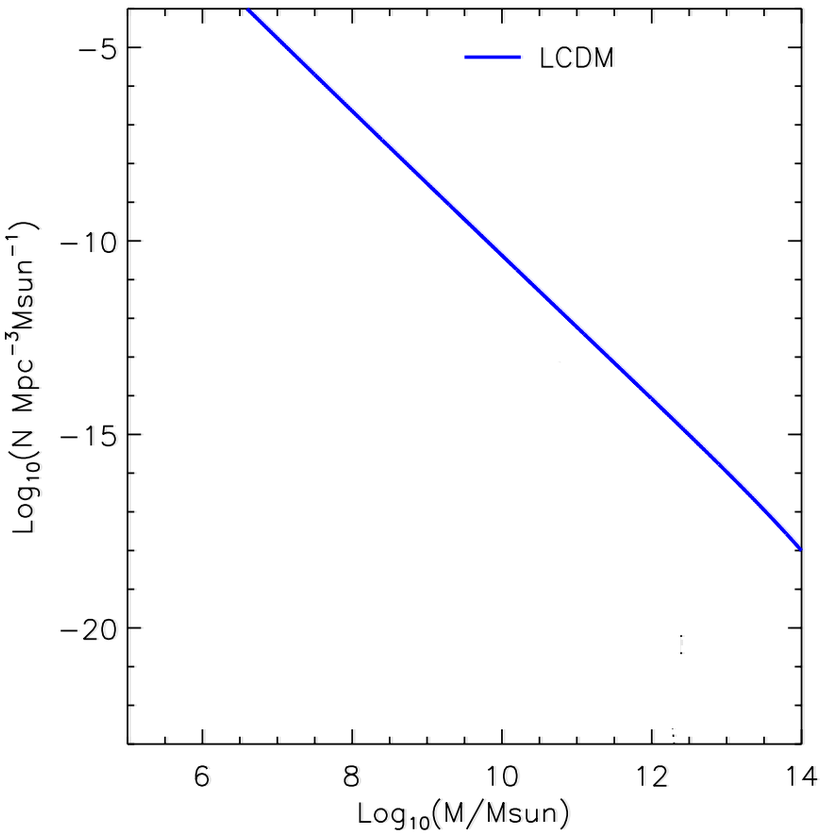

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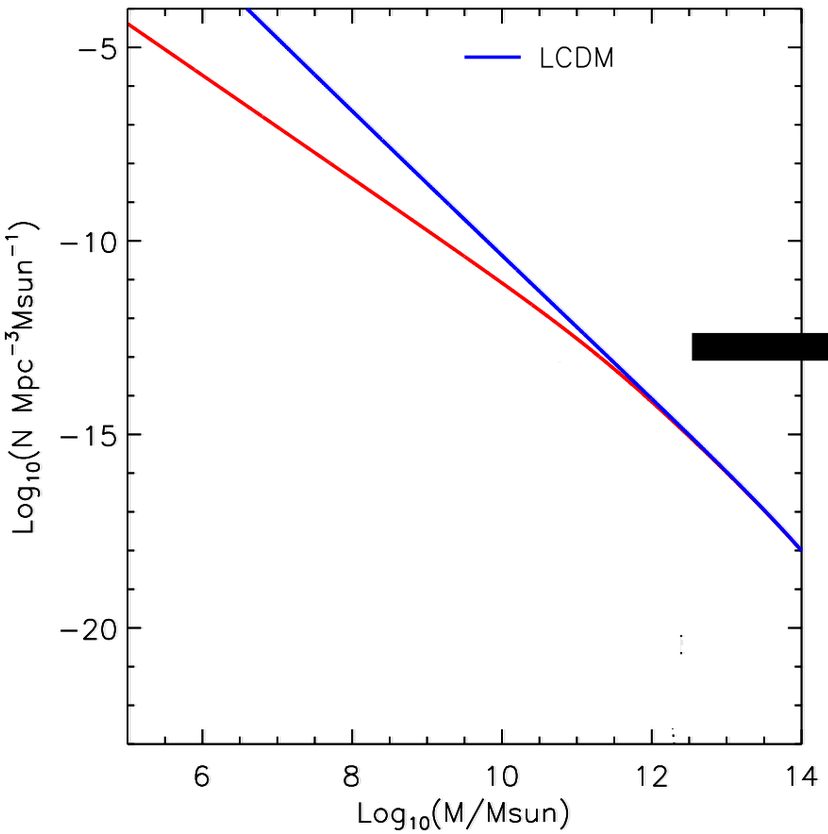

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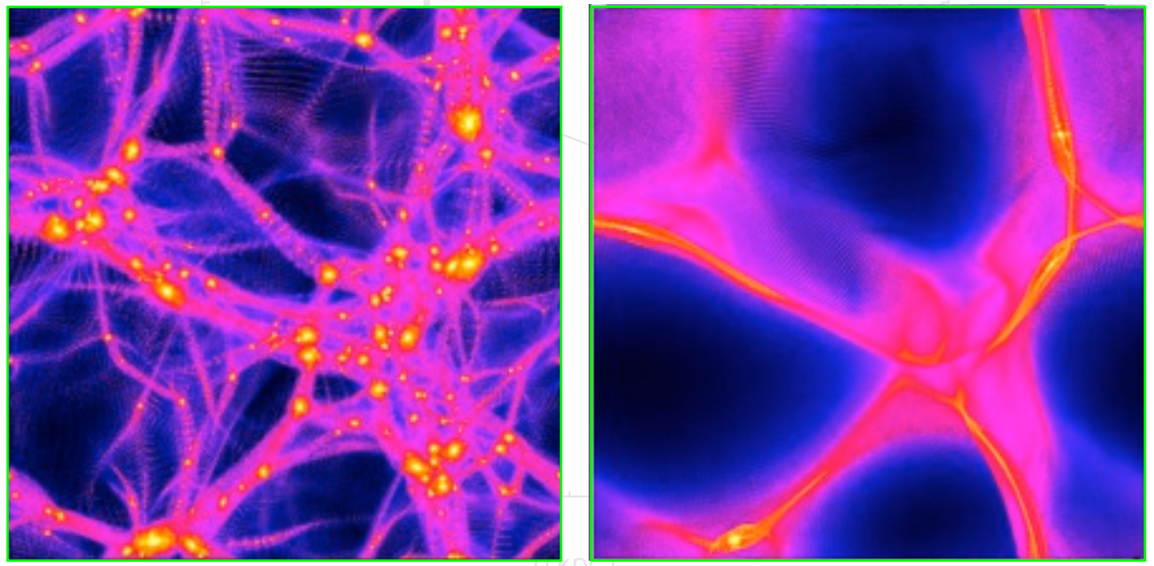
WDM



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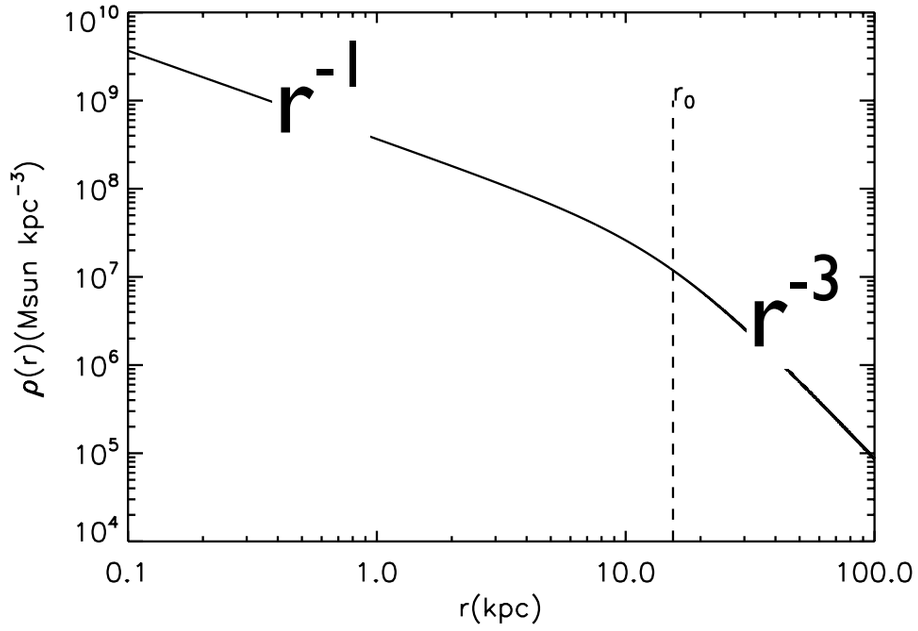

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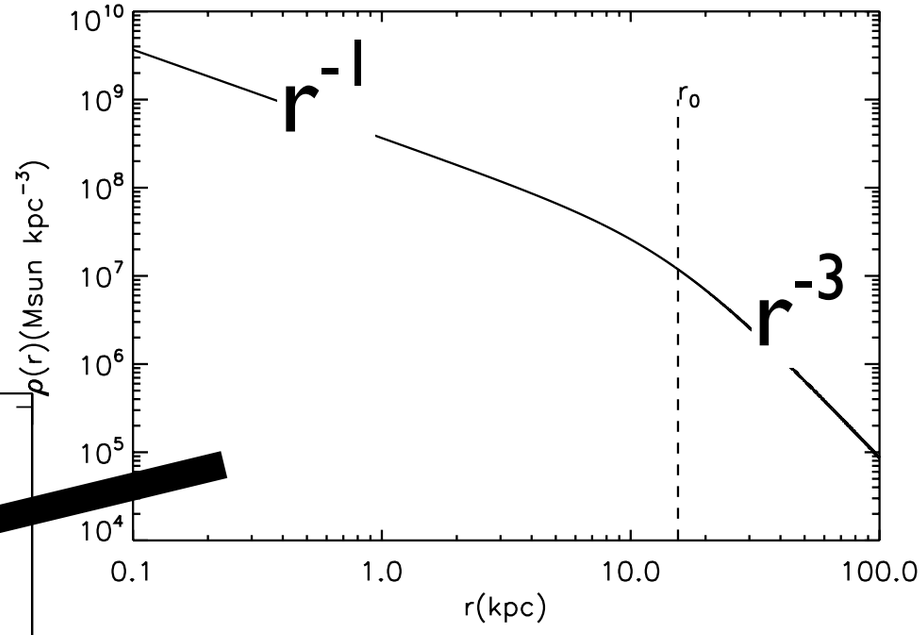
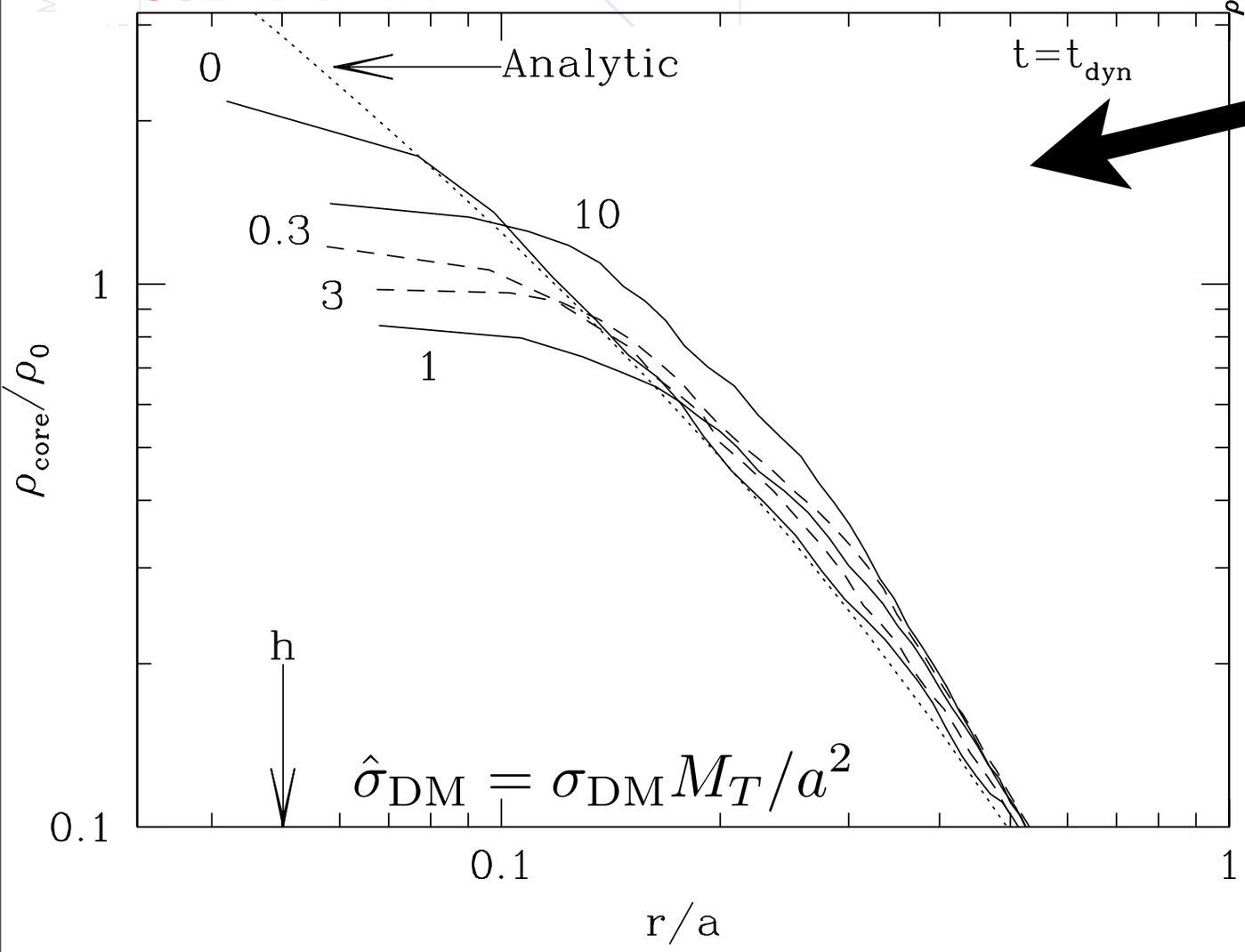


SIDM Kochanek & White 2000



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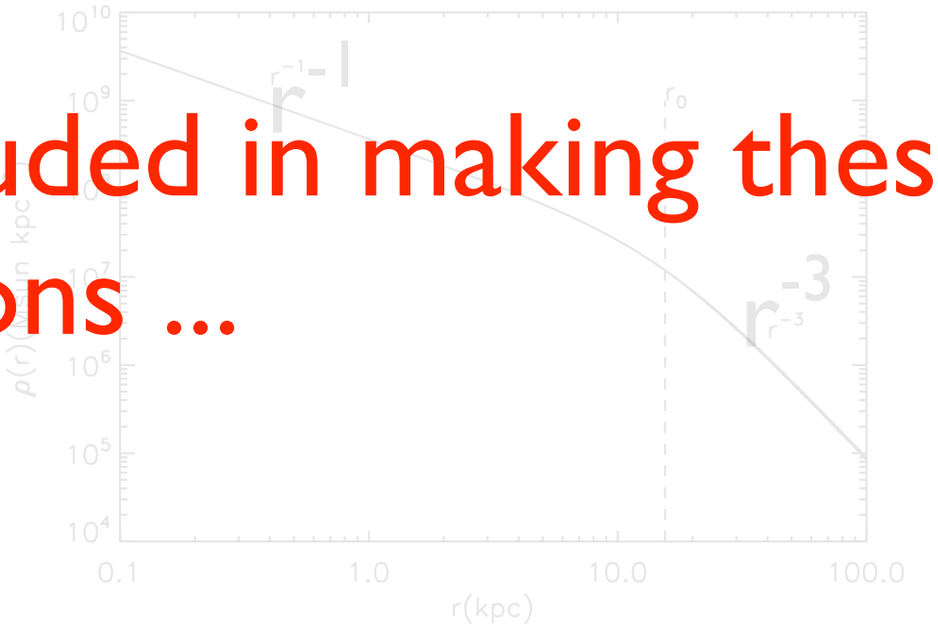

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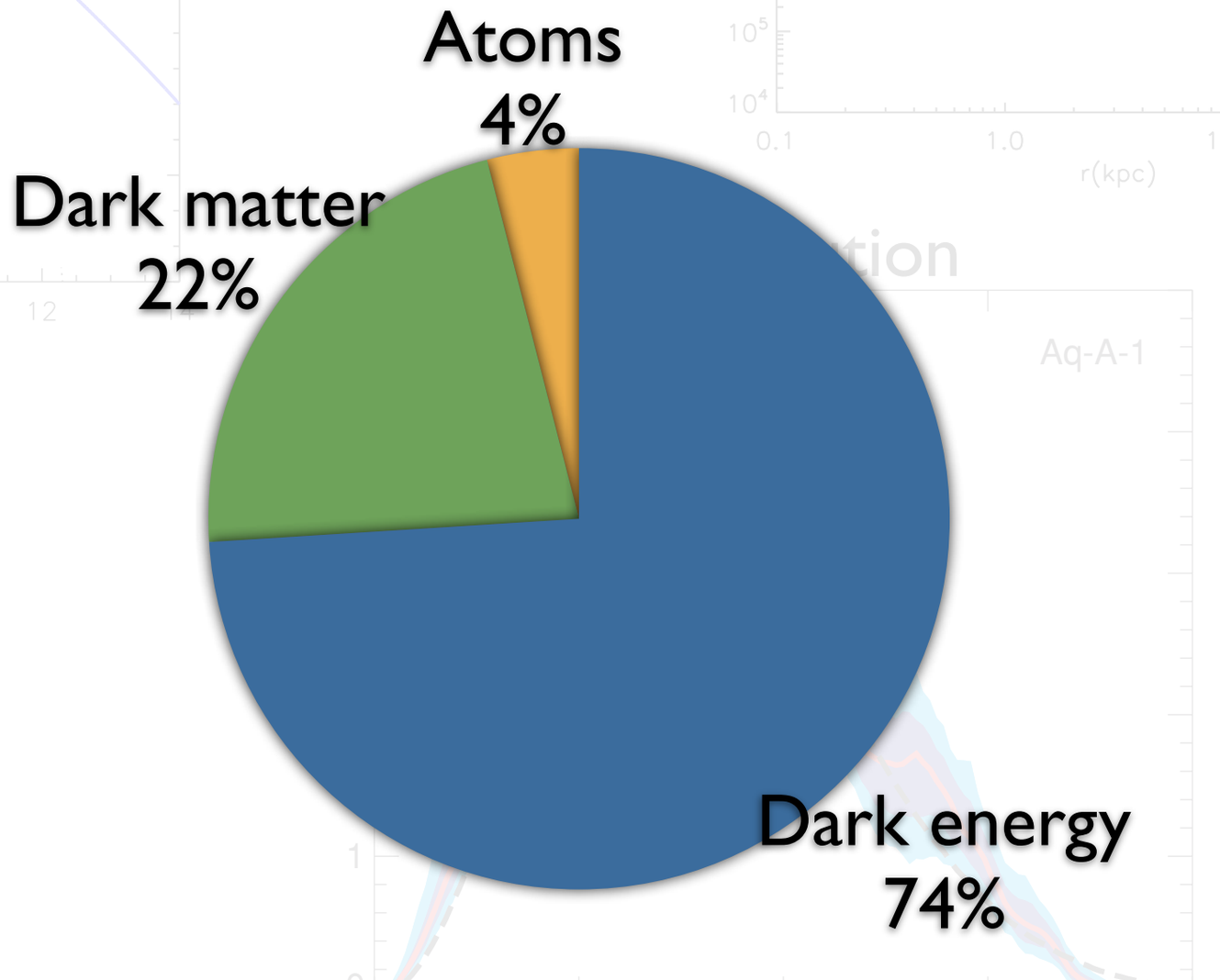

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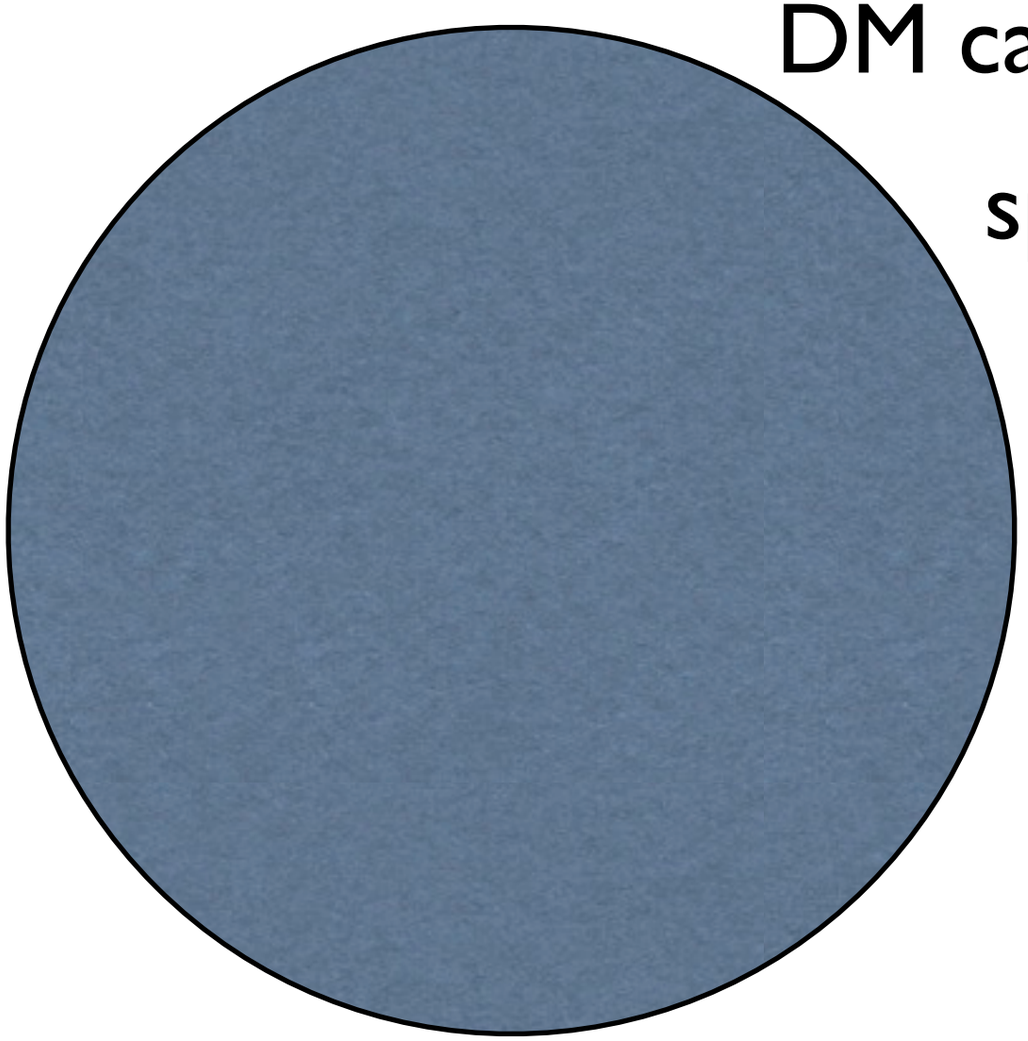

DM cannot radiate ⇒ roughly spherical structures

Navarro et al. 1996; Read & Gilmore 2005; Mashchenko et al. 2008; Governato et al. 2010; Pontzen & Gov. 2011 ...

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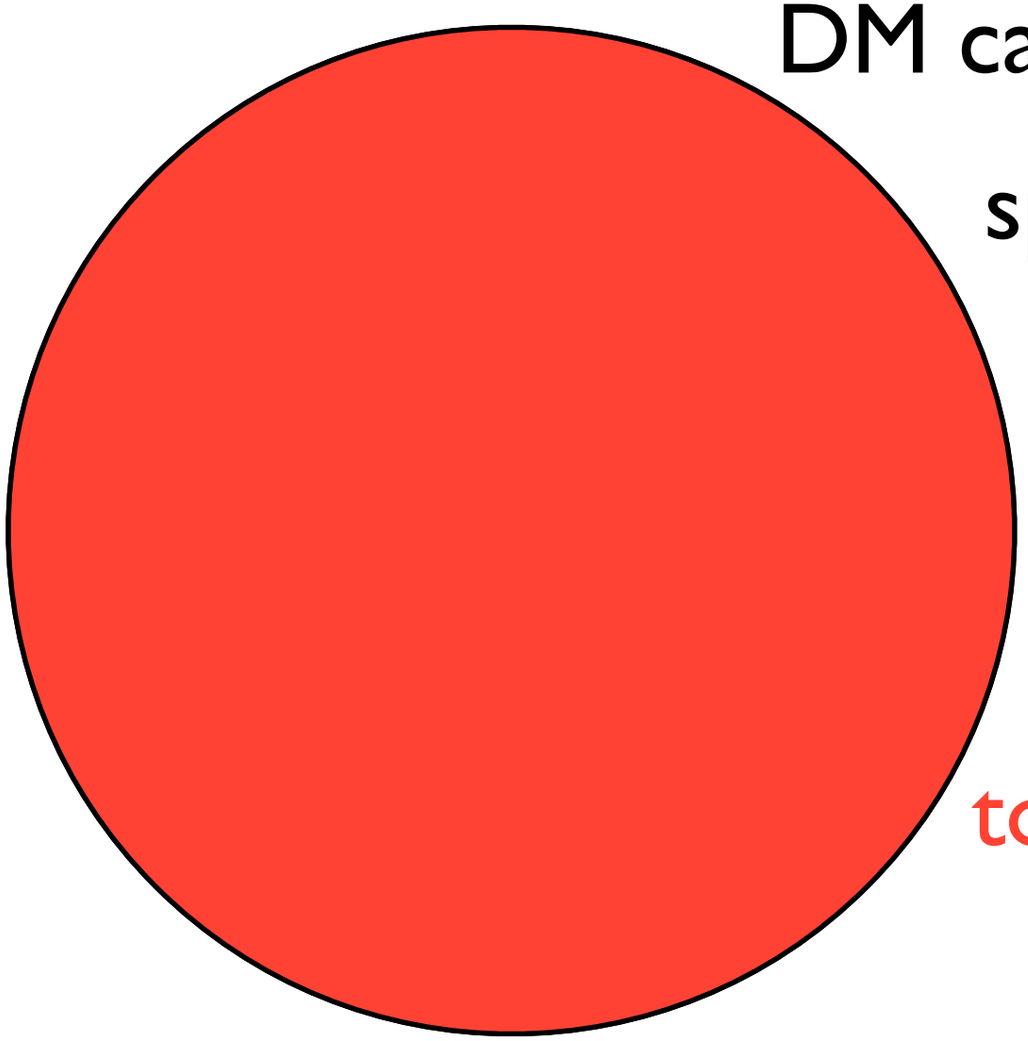

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Baryons radiate ⇒ collapse to smaller and smaller scales

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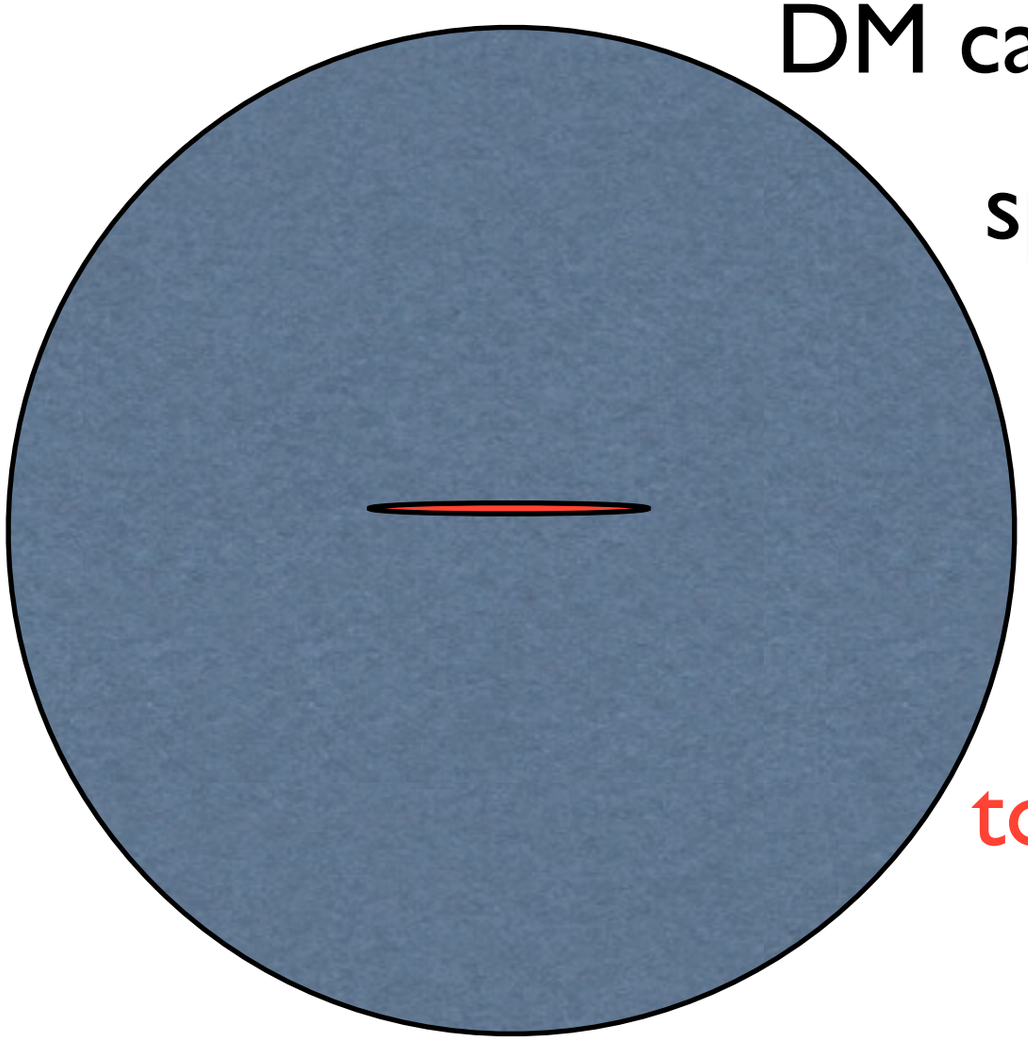

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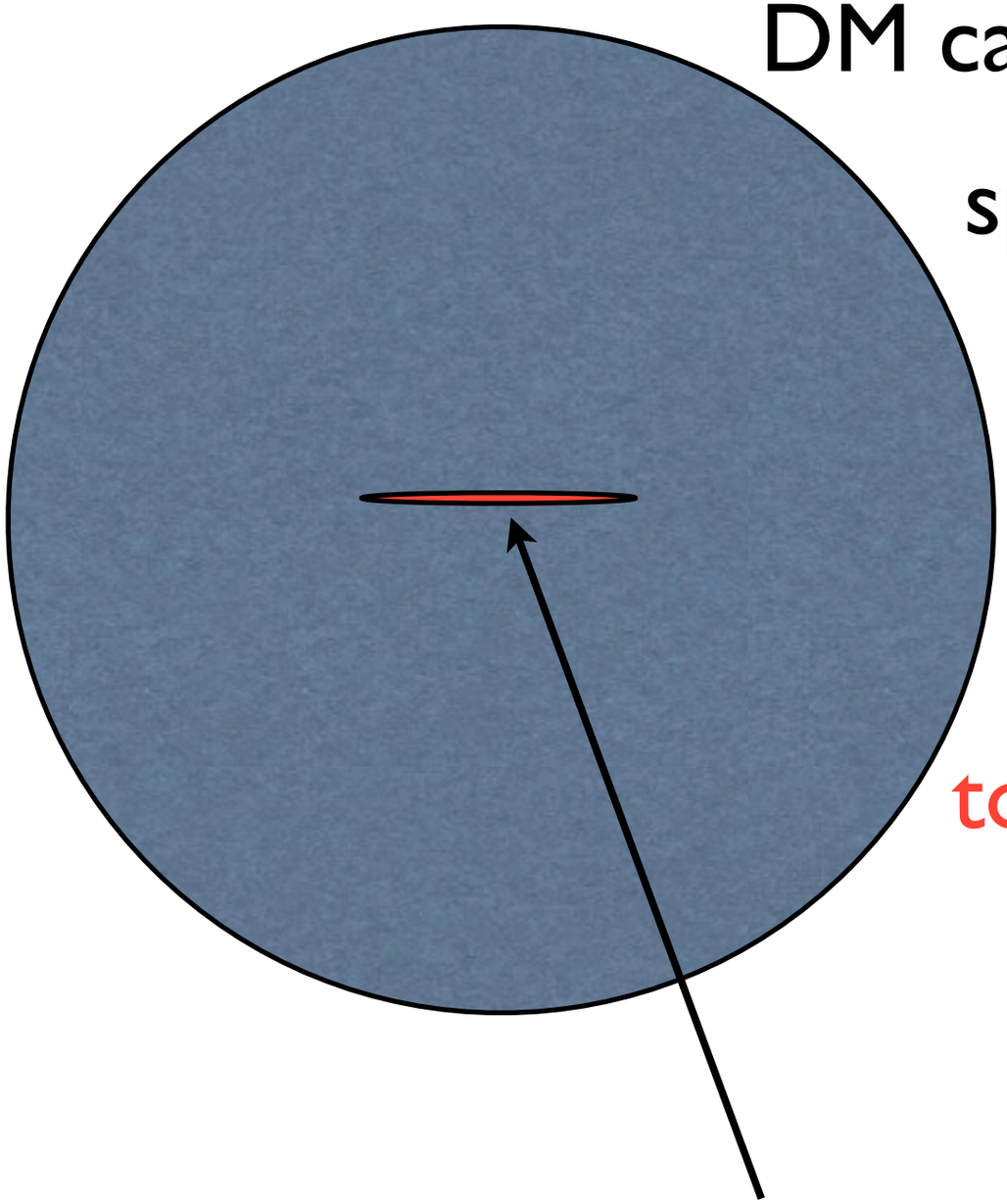

DM cannot radiate ⇒ roughly spherical structures

Baryons radiate ⇒ collapse to smaller and smaller scales

Baryons can dominate the gravitational potential in galaxies

Navarro et al. 1996; Read & Gilmore 2005; Mashchenko et al. 2008; Governato et al. 2010; Pontzen & Gov. 2011 ...

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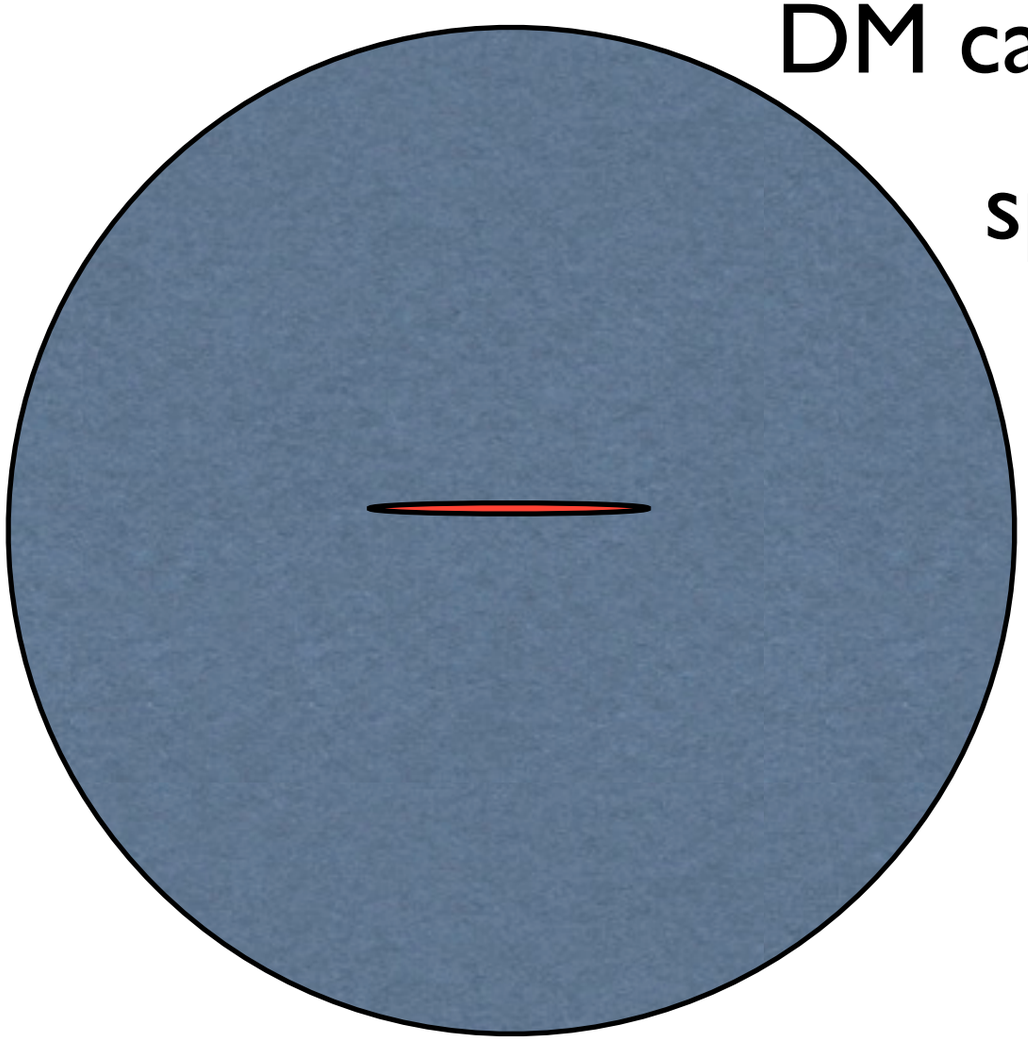

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Baryons can also be heated by Supernovae explosions etc. ⇒ baryons escape the smallest galaxies

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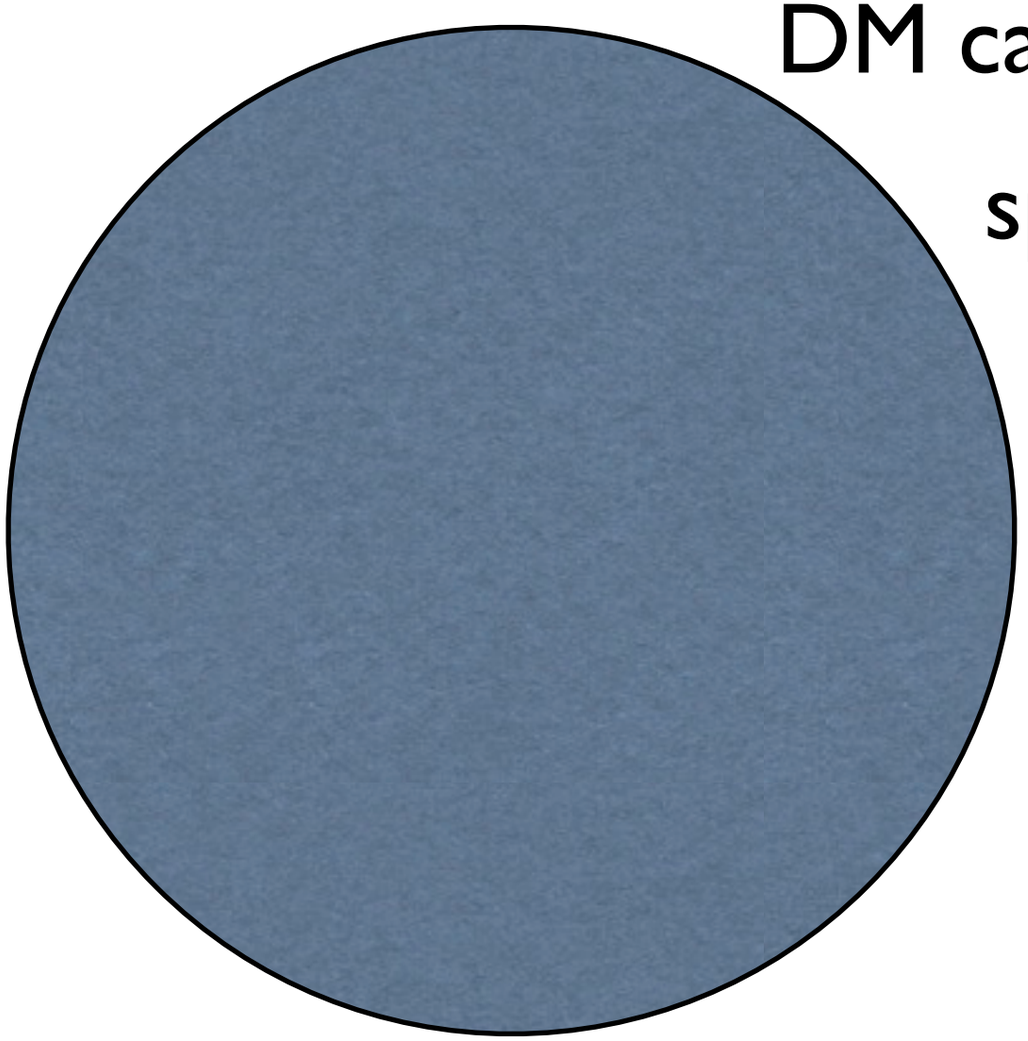

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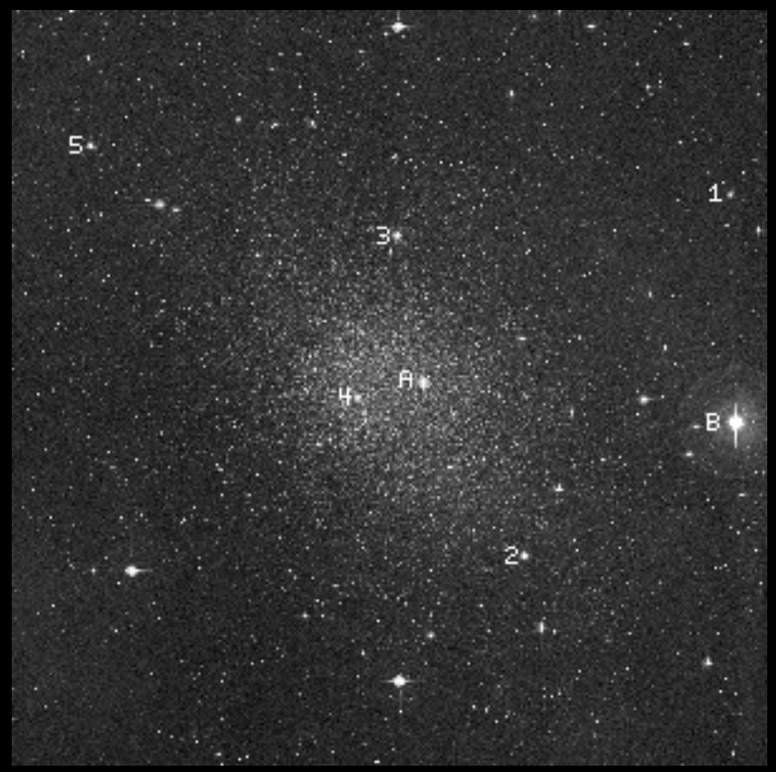

Fornax dwarf

Steger, Read et al. in prep.

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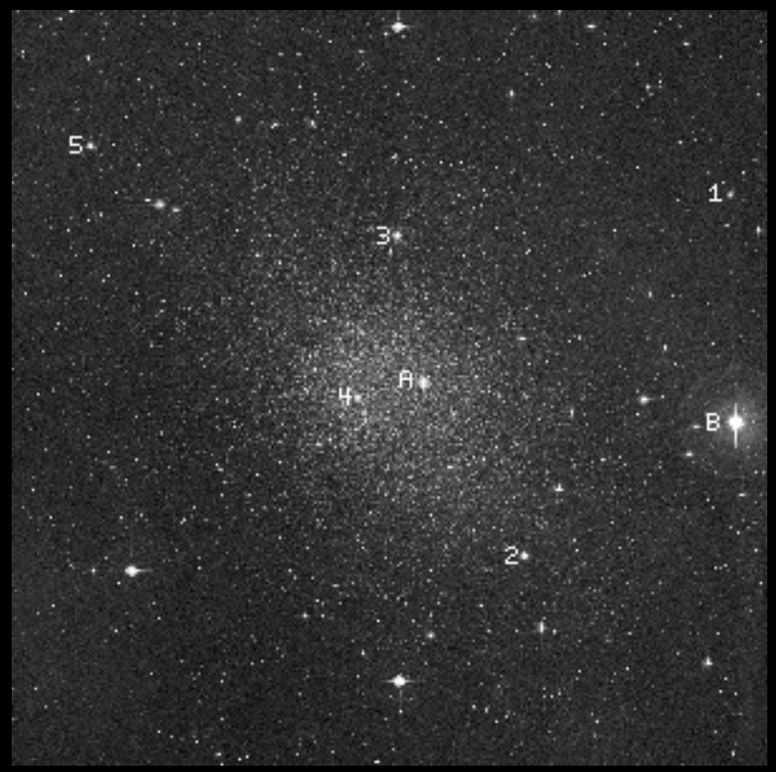

Fornax dwarf

- Smallest known galaxies.
- Nearby ⇒ resolve individual stars.
- Very DM dominated ⇒ natural DM lab.
- Potential target for DM annihilation.

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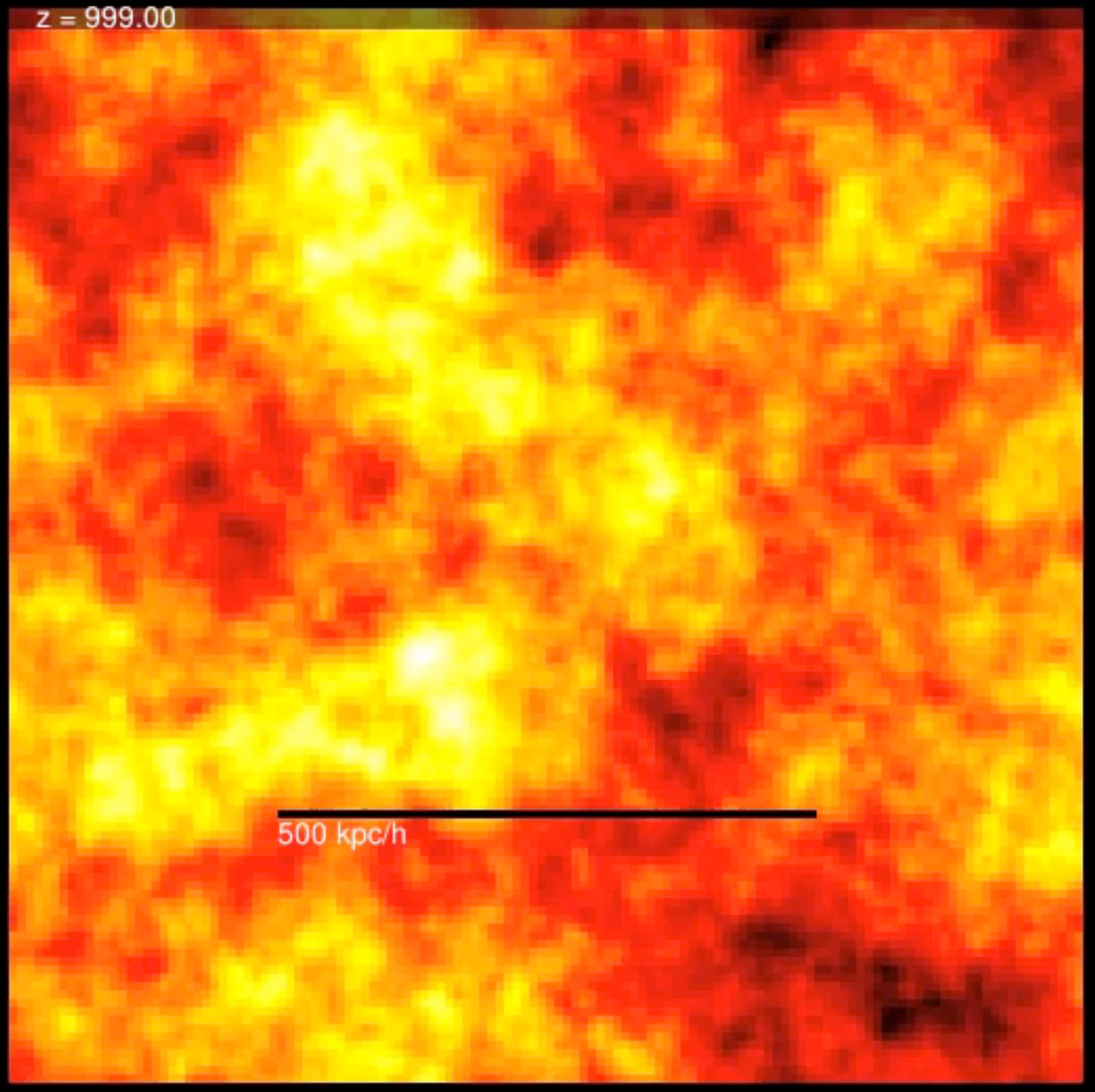

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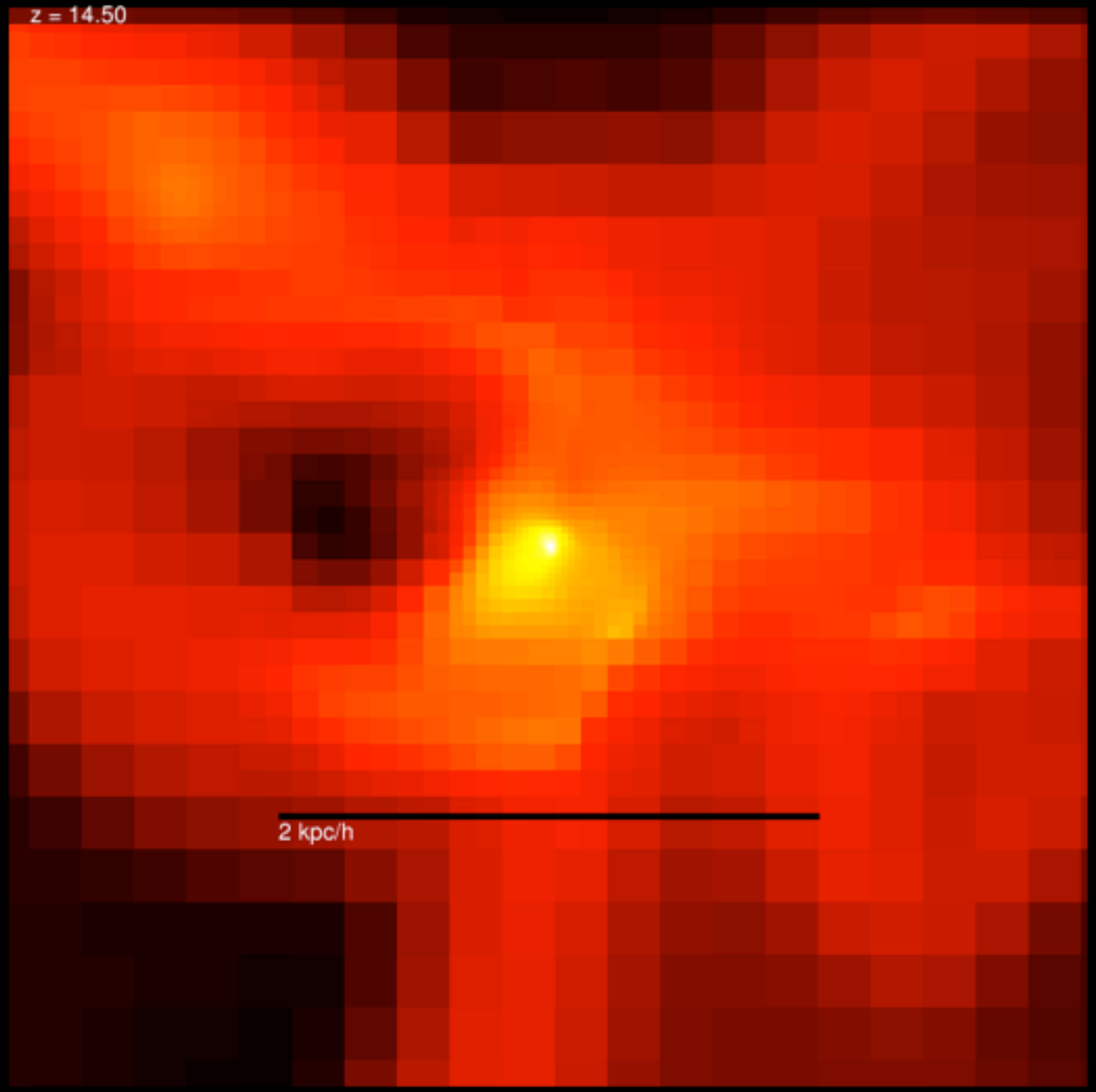

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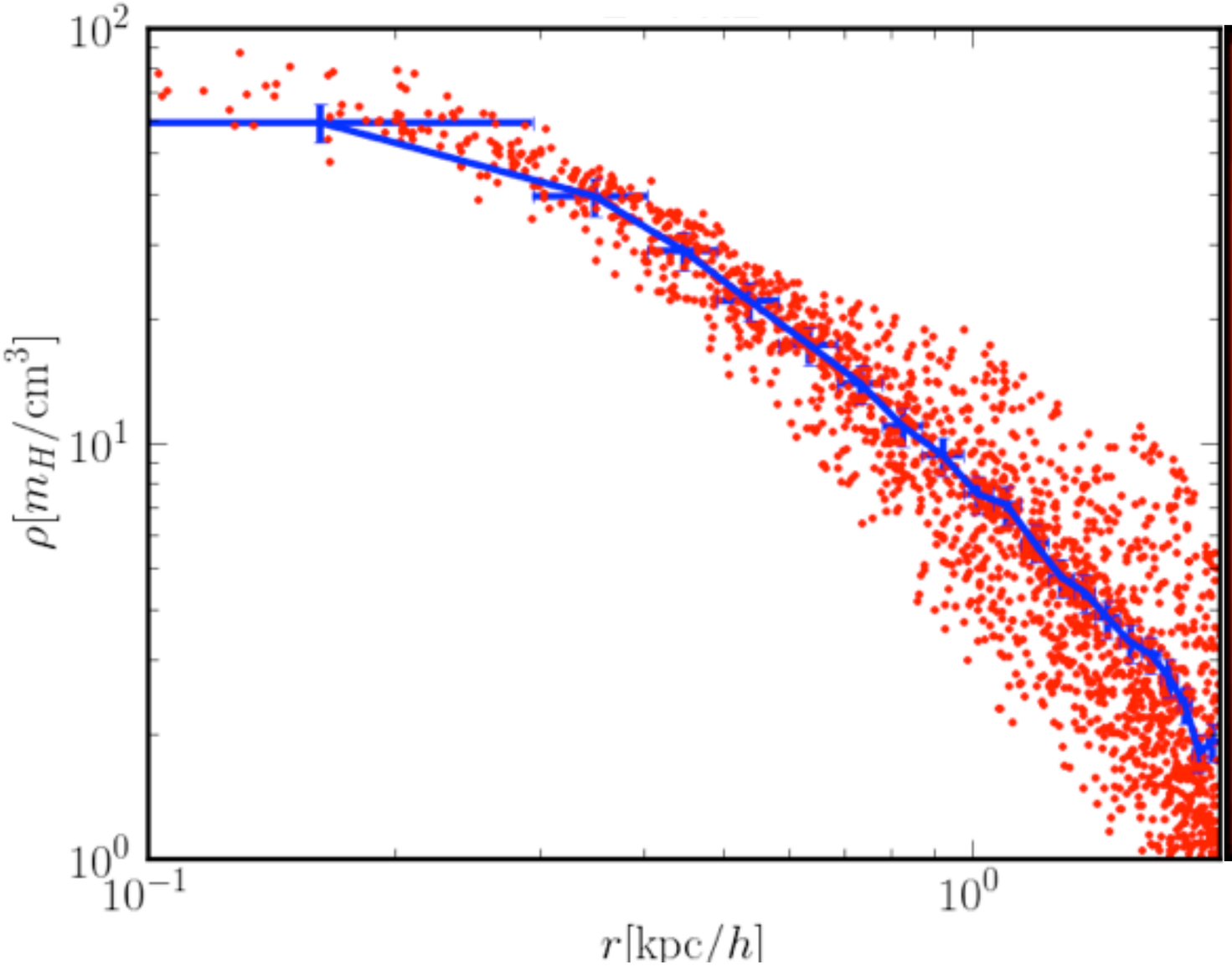
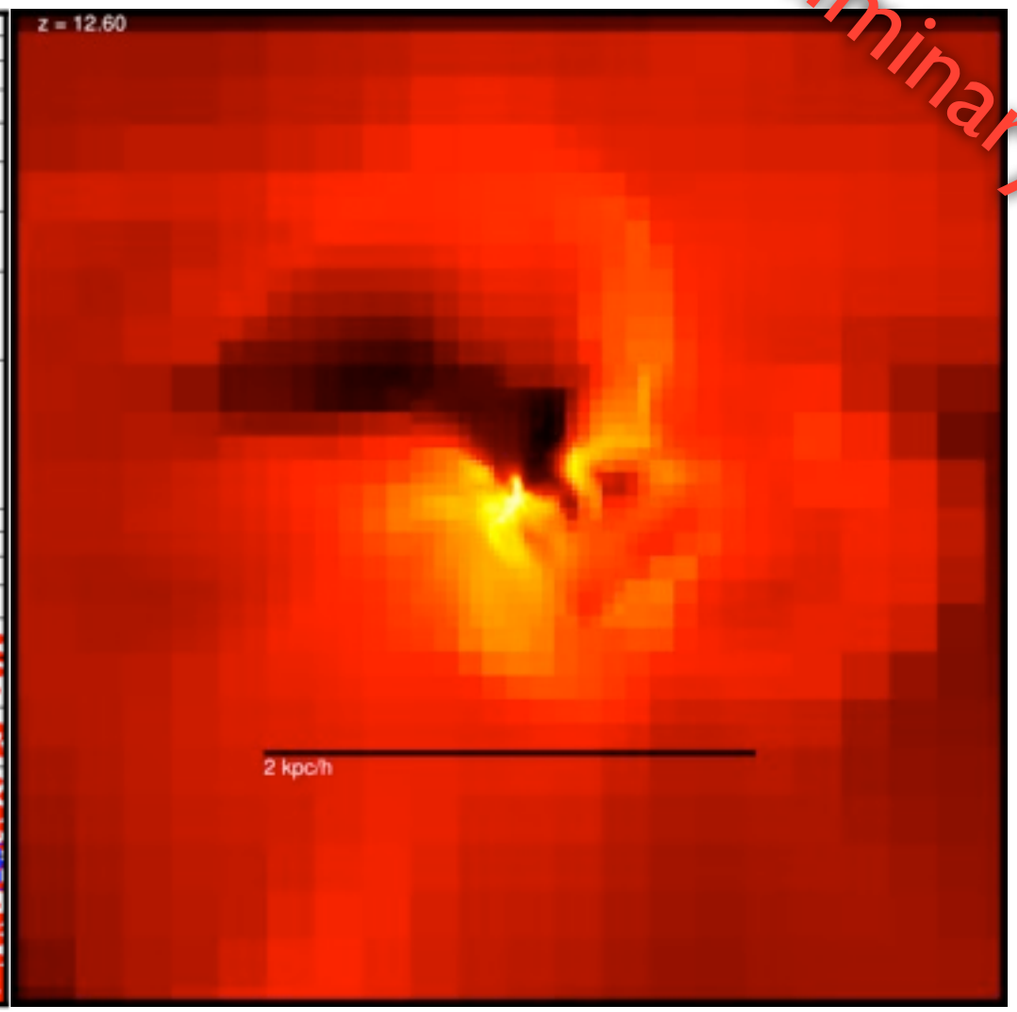
z = 12.6

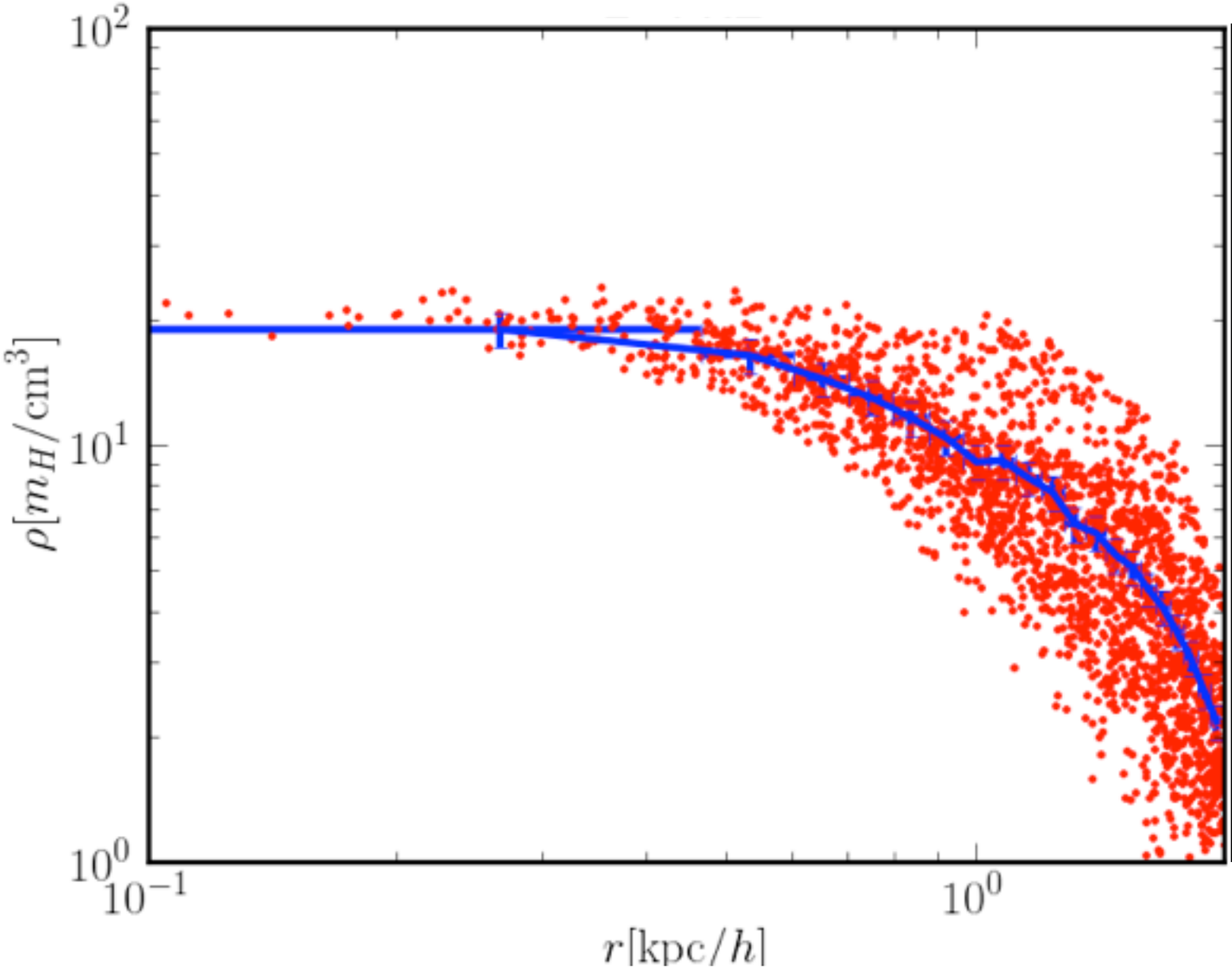


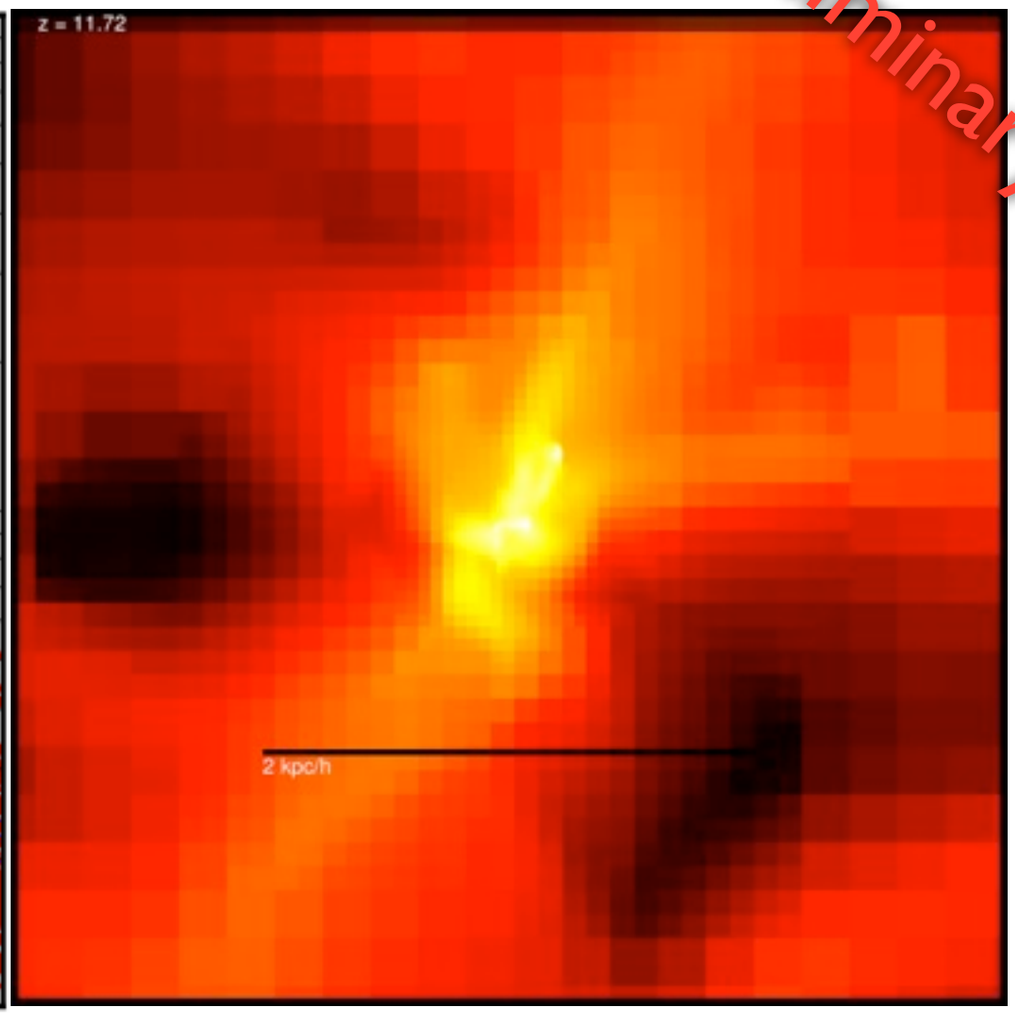


Preliminary!

1. Theory | The importance of baryons: feedback in dwarfs

z = 11.72





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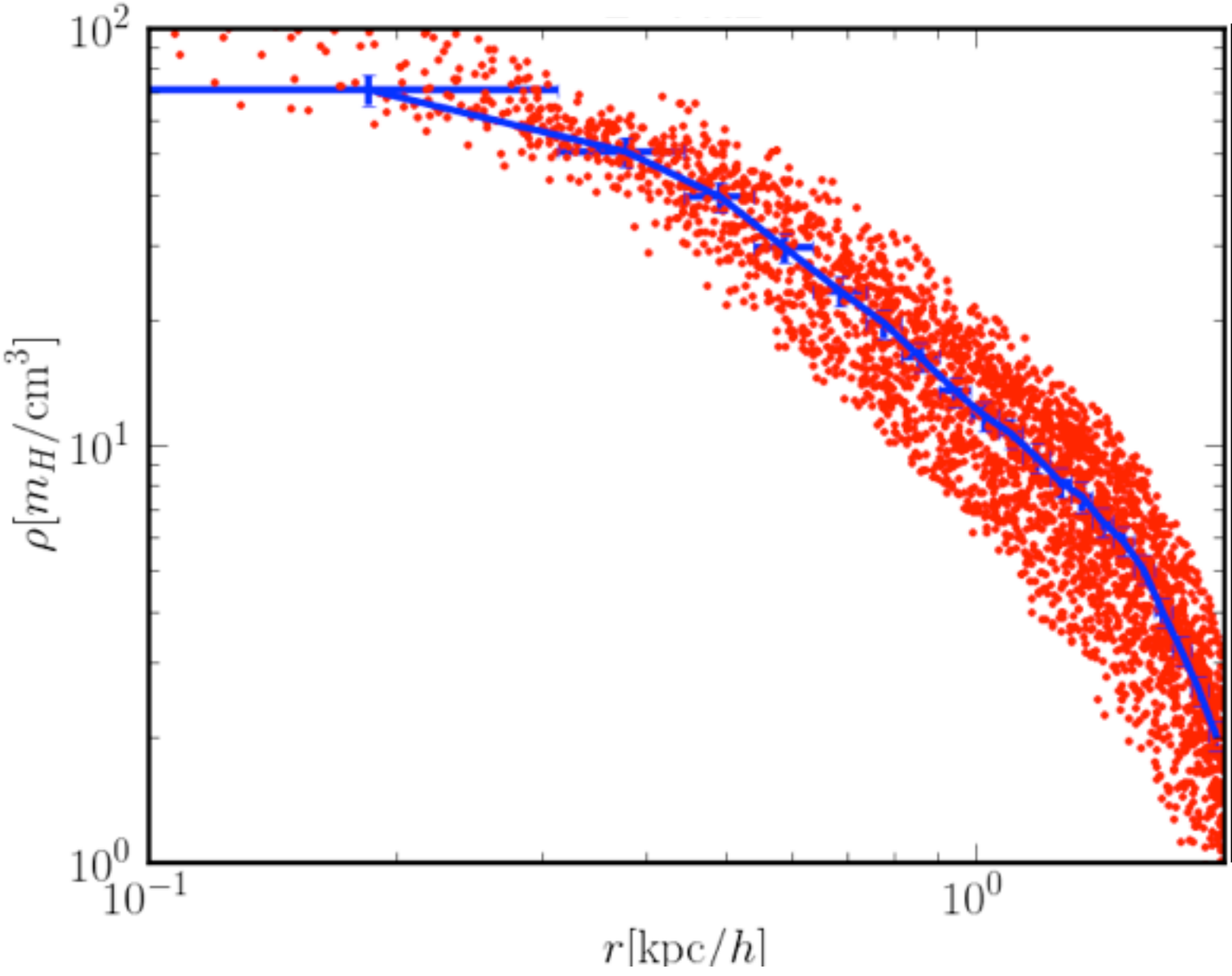
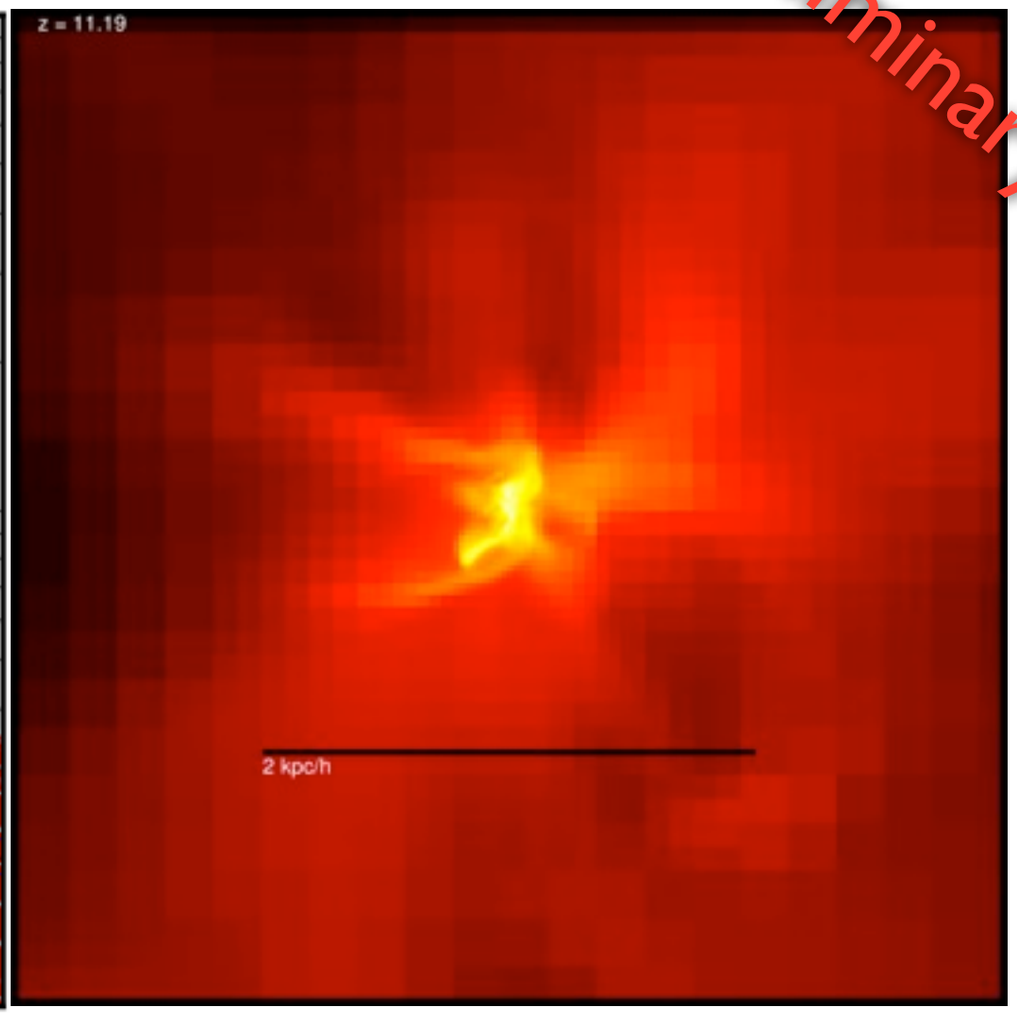
z = 11.19





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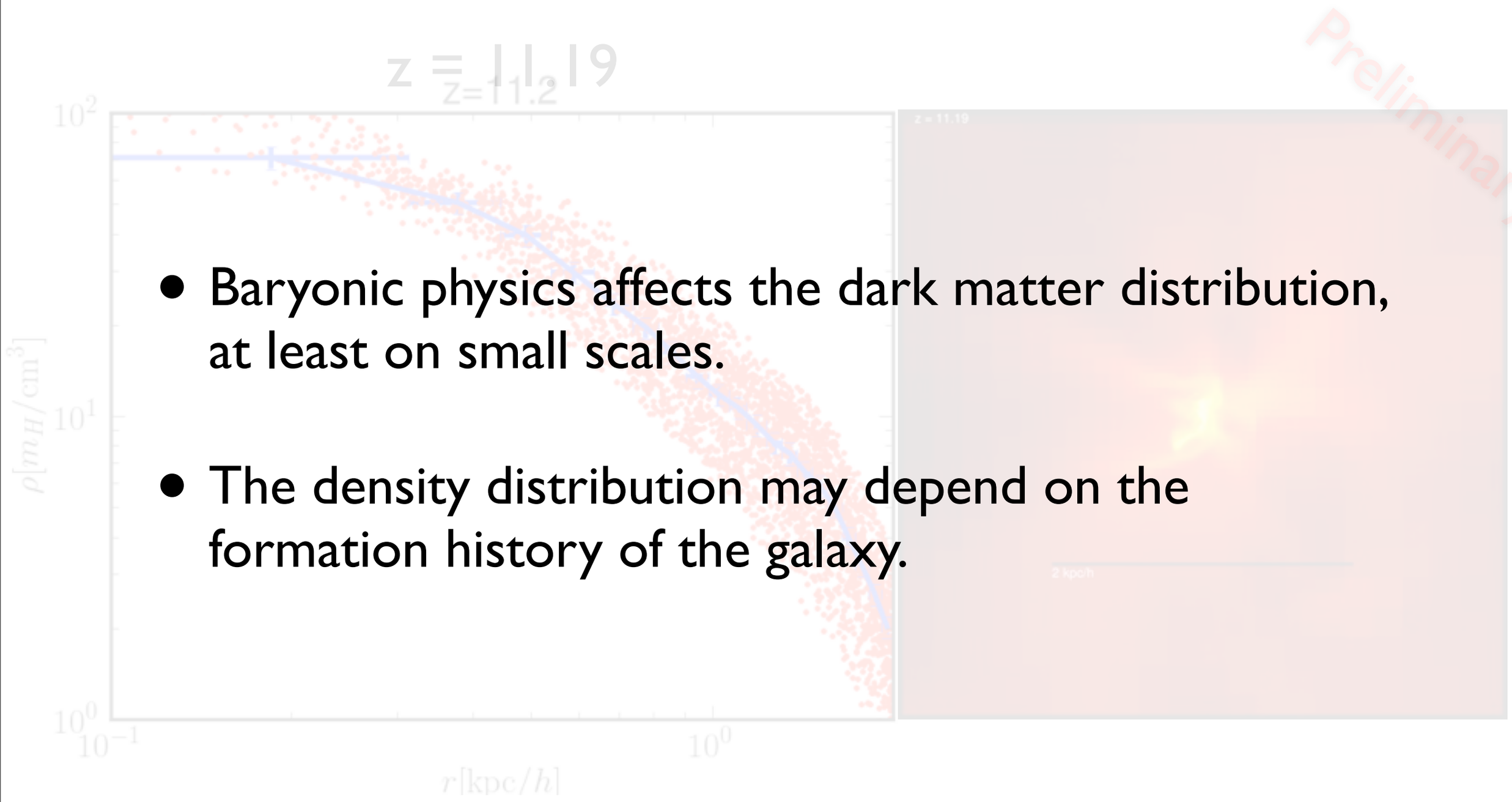

- Baryonic physics affects the dark matter distribution, at least on small scales.
- The density distribution may depend on the formation history of the galaxy.

1. Theory | The importance of baryons: feedback in dwarfs

Lake 1989; Read 2008/9; Purcell 2009; Ling 2010

Z=36.4

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stars & dark matter

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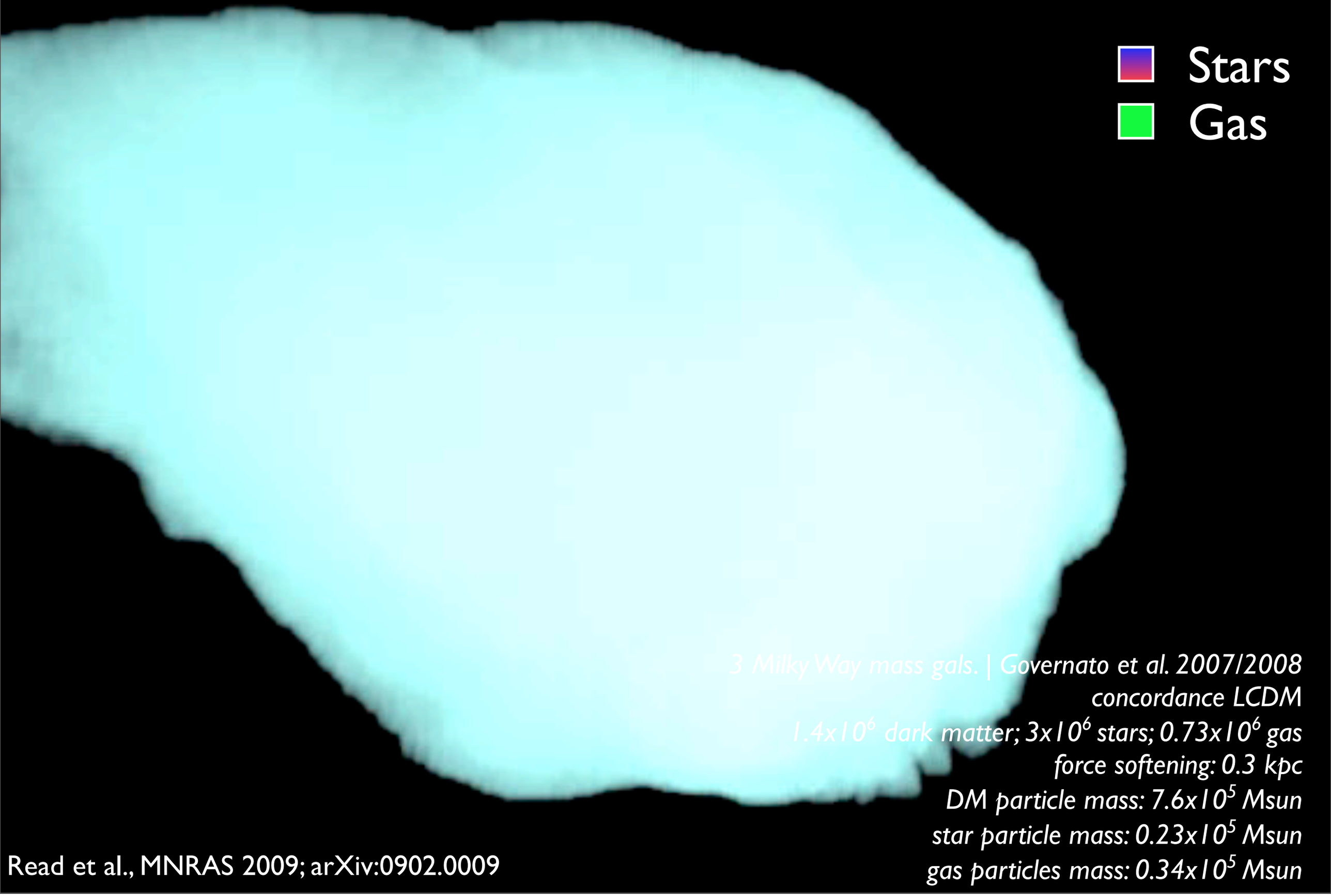

Read et al., MNRAS 2009; arXiv:0902.0009

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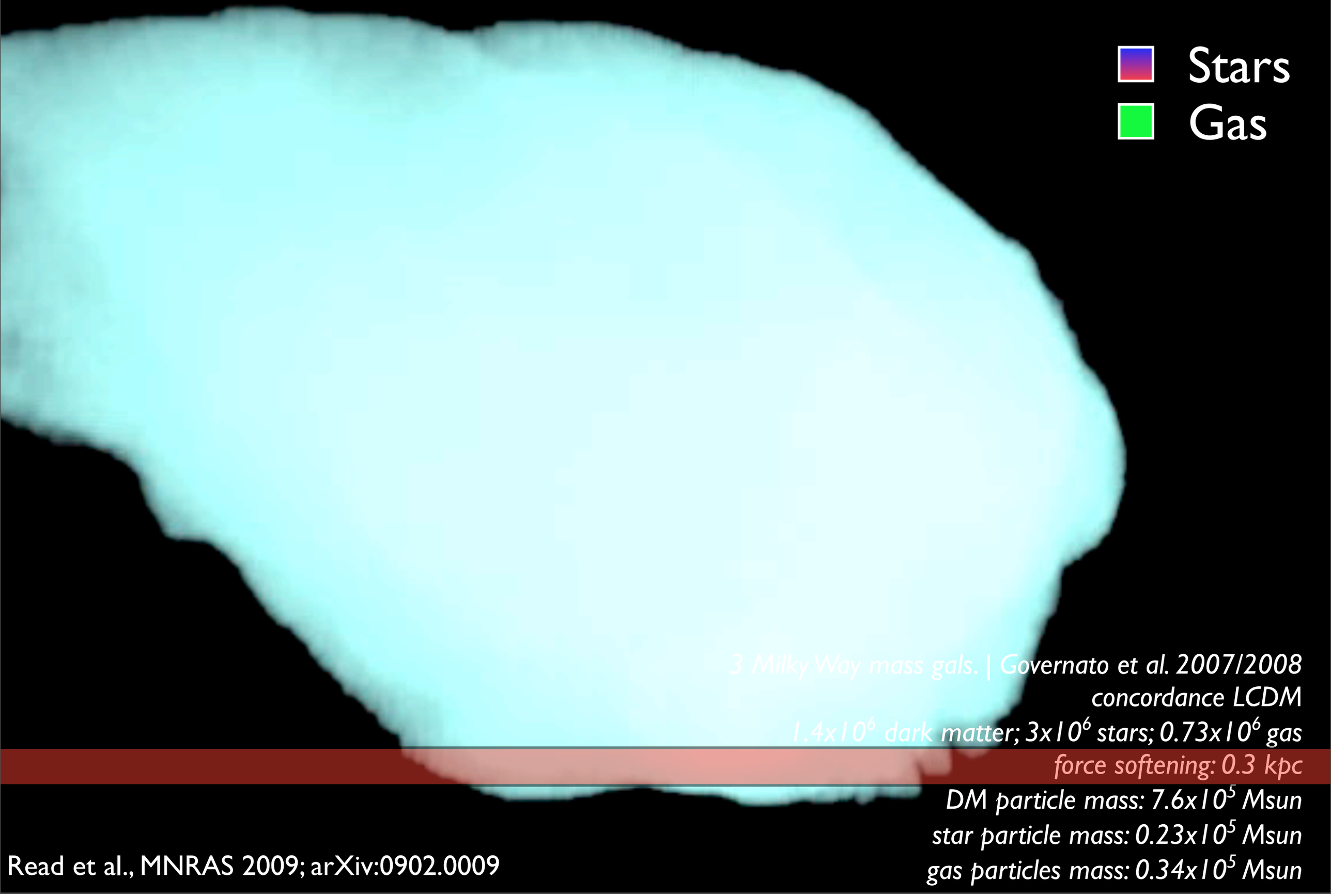

3 Milky Way mass gals. | Governato et al. 2007/2008
concordance LCDM
$1.4x10^6$ dark matter; $3x10^6$ stars; $0.73x10^6$ gas
force softening: 0.3 kpc
DM particle mass: $7.6x10^5$ Msun
star particle mass: $0.23x10^5$ Msun
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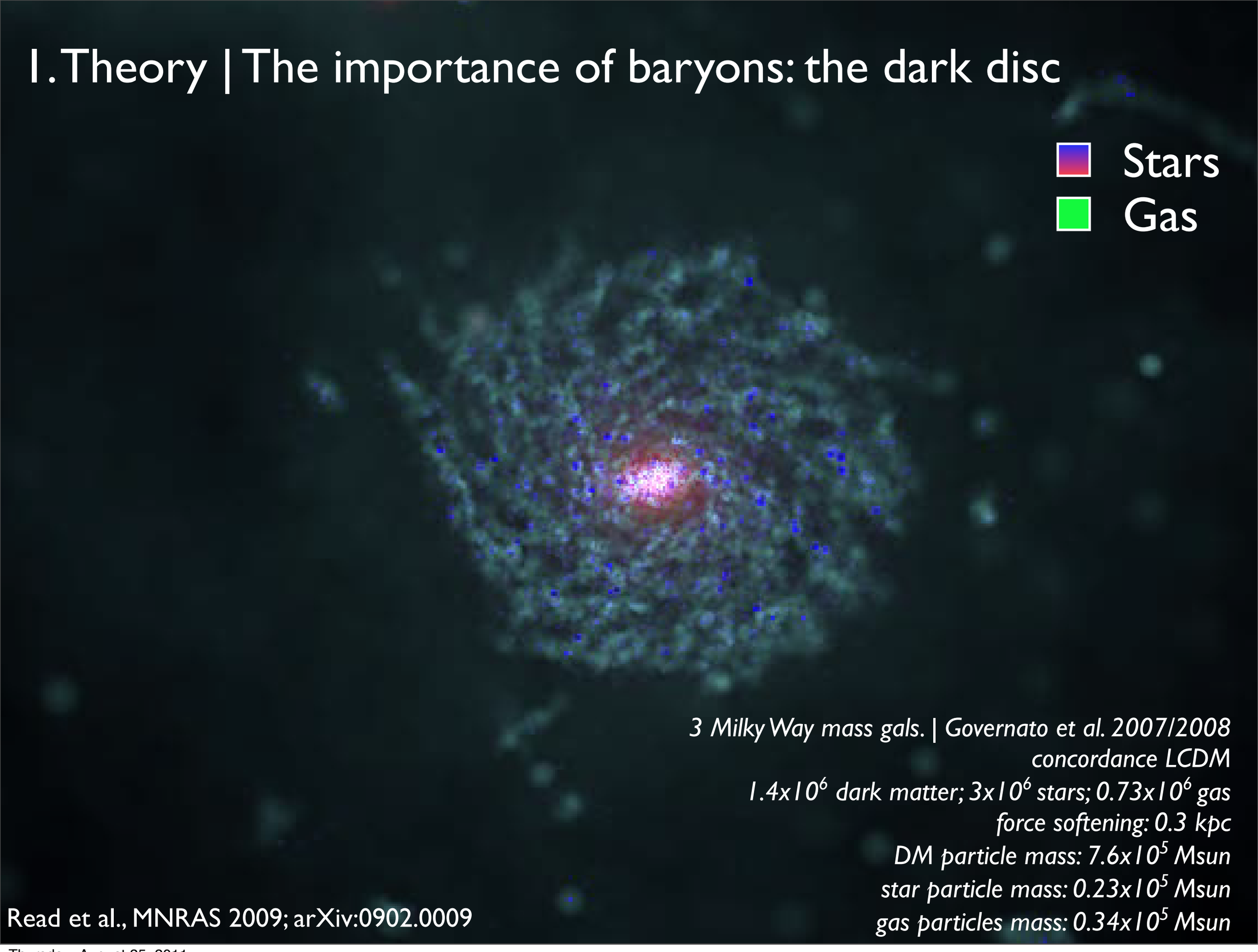

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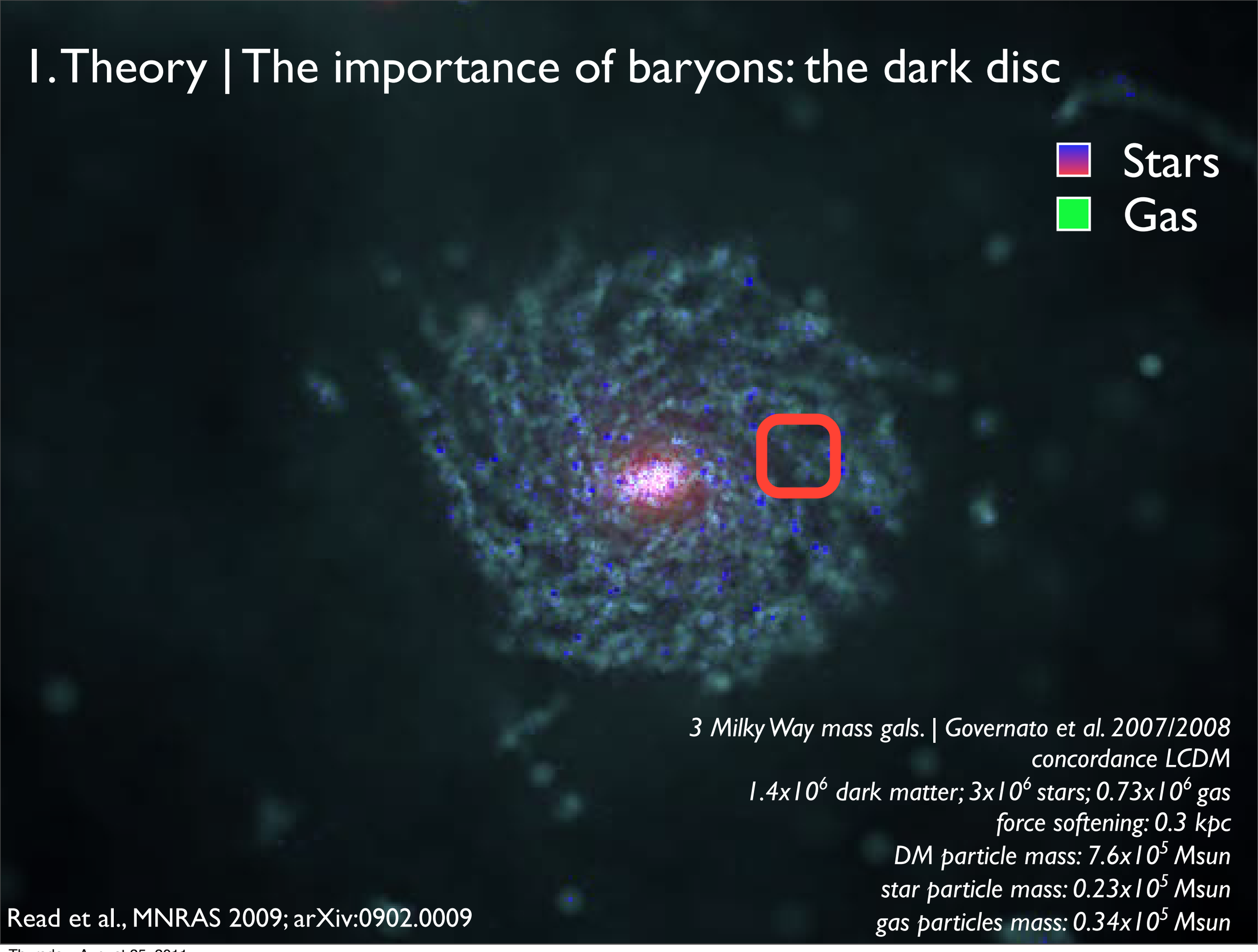

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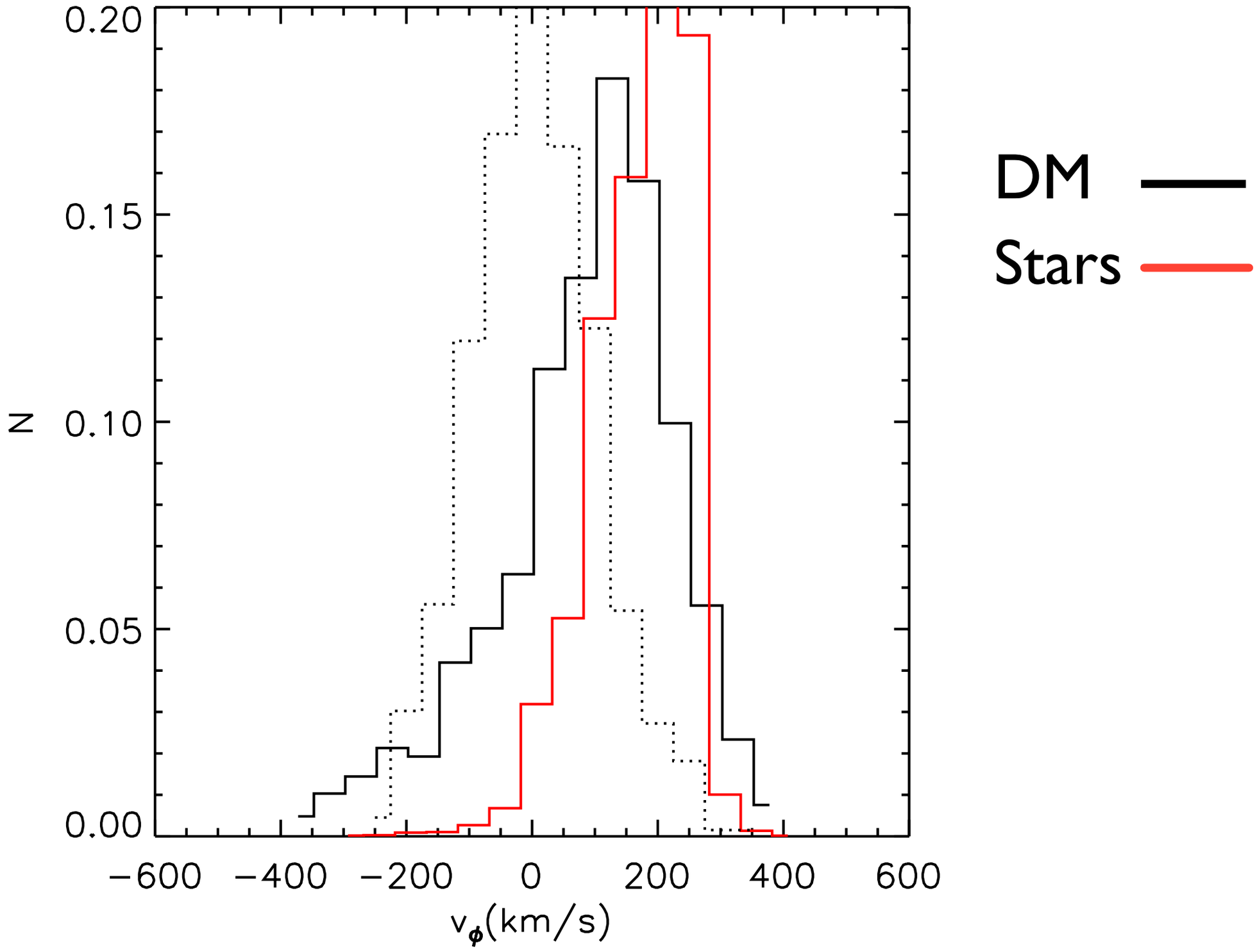

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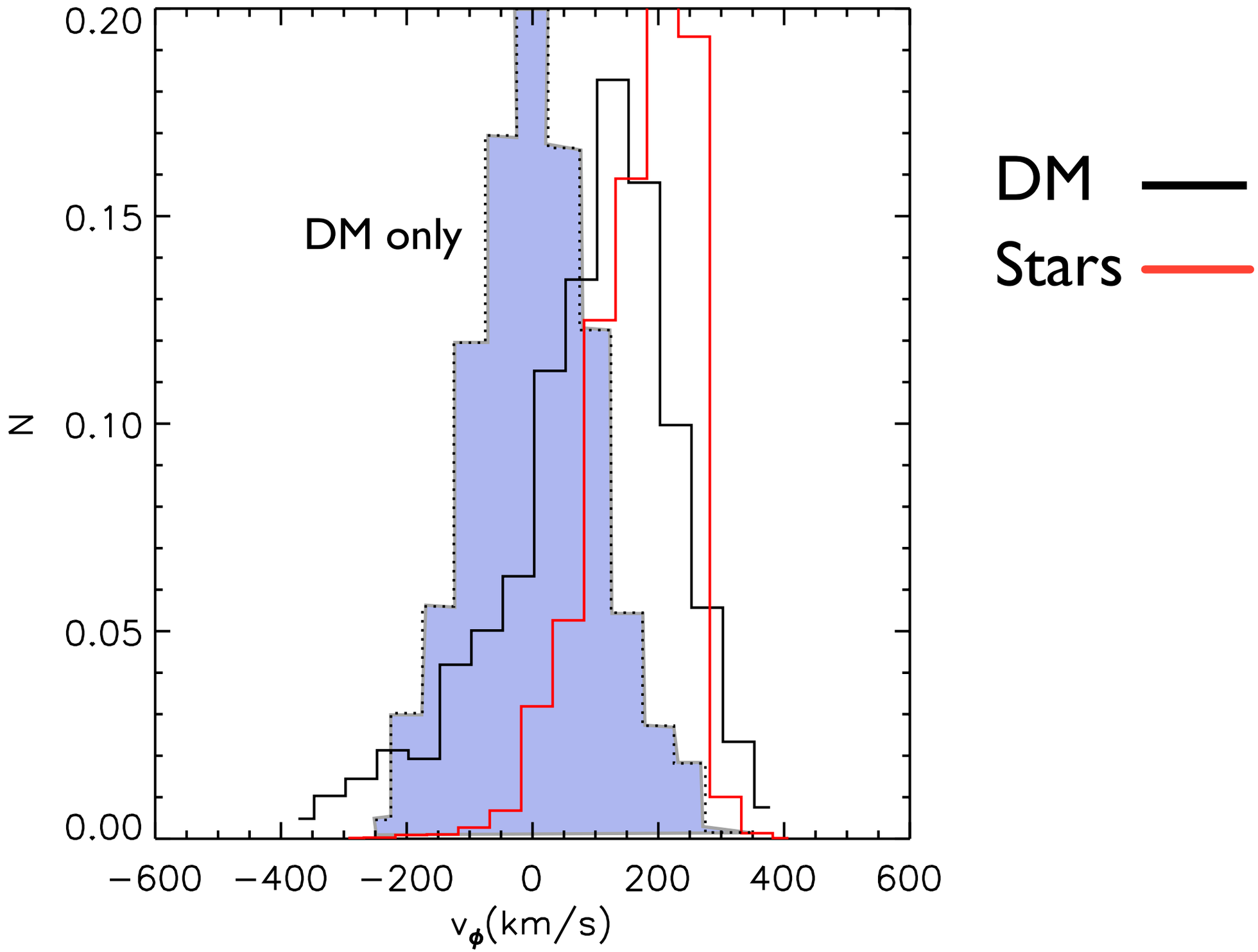

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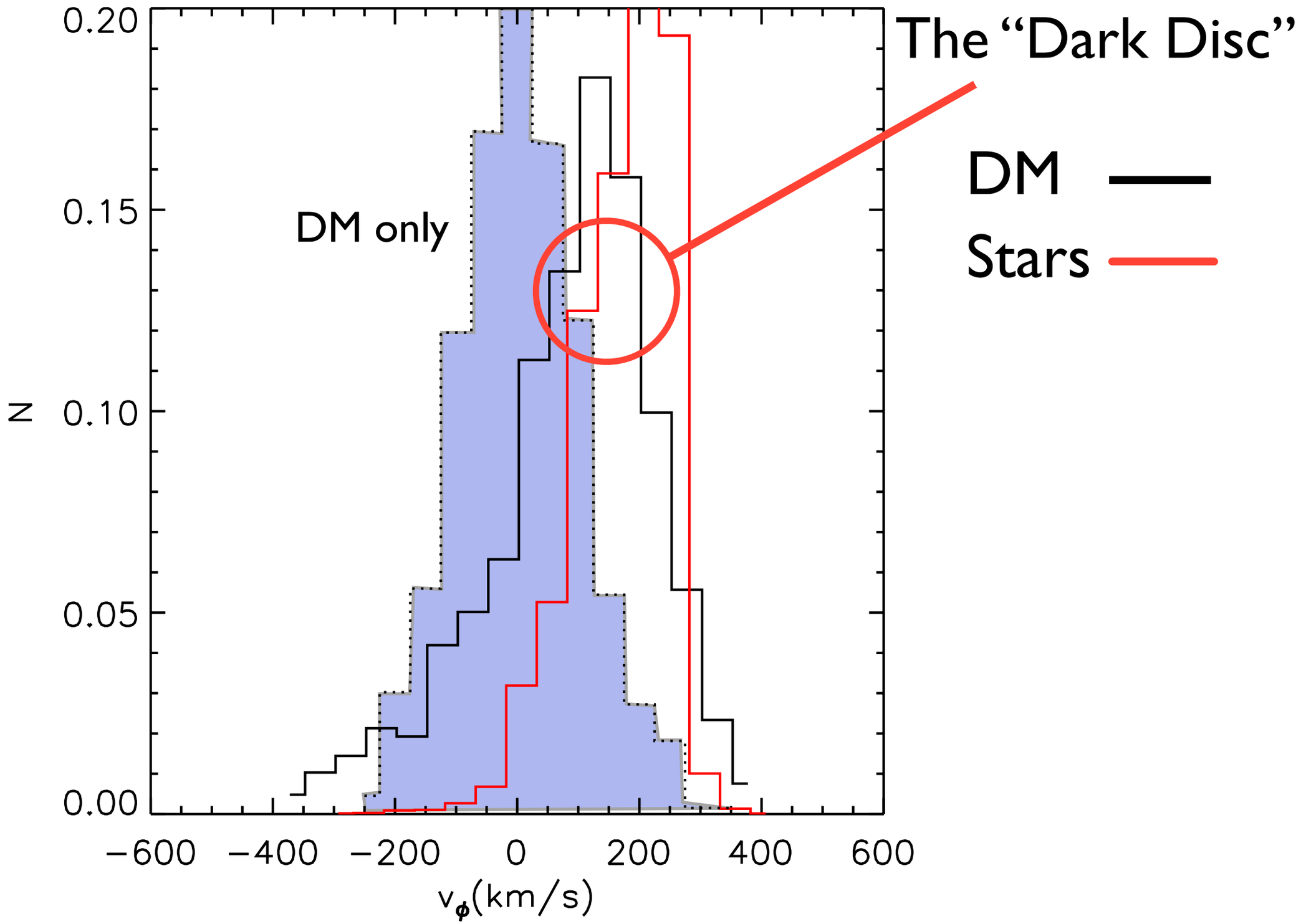

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$\rho_{dd} = 0.25\text{-}1.5\rho_{shm}$; $v_{lag} = 0\text{-}150$km/s; $\sigma = 50\text{-}90$km/s

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

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

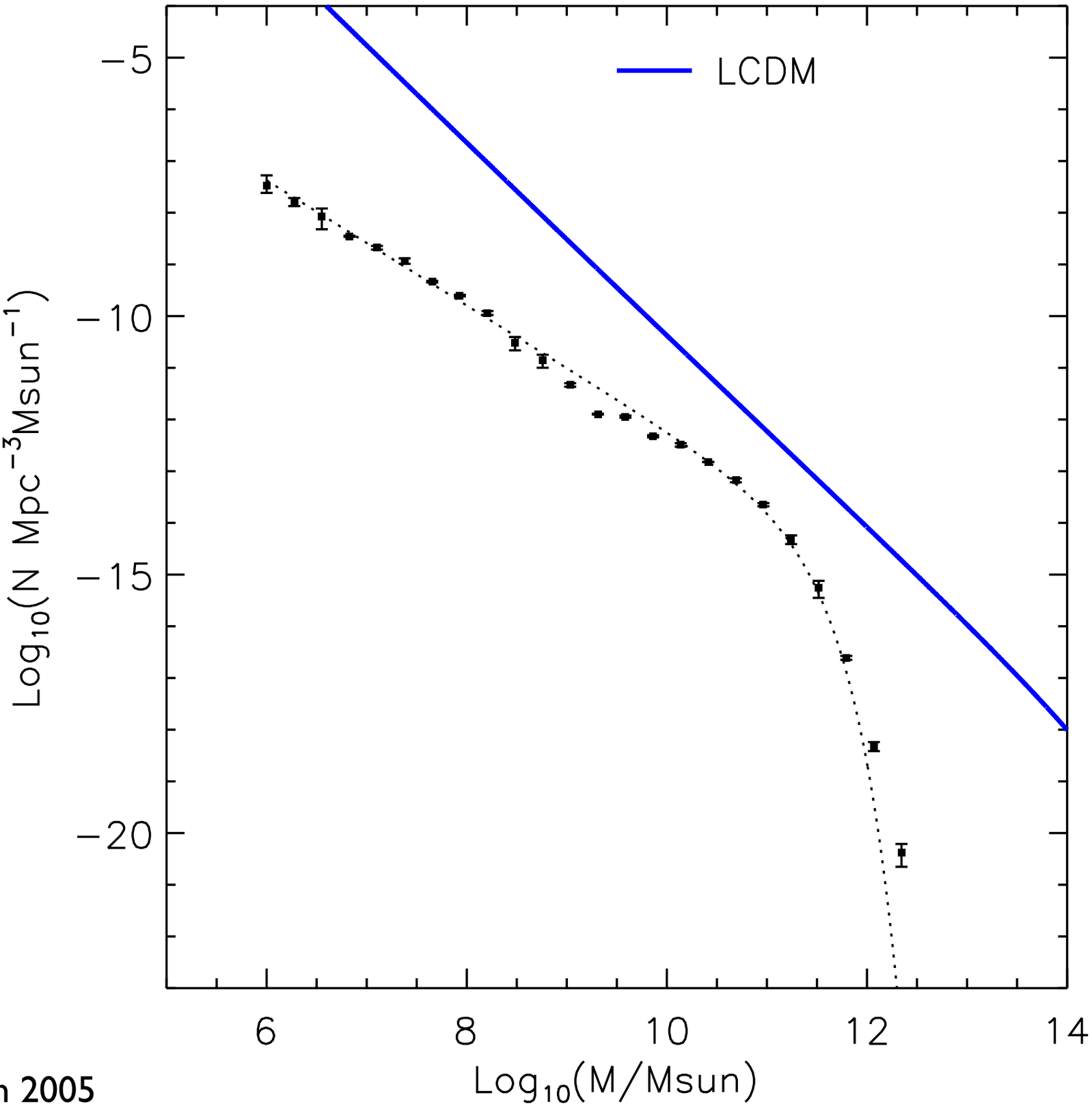
- Boosts the direct detection signal at low recoil energy by a factor ~3 in the 5-20keV range.

- 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.

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

2. Observations | The halo mass function



Read & Trentham 2005

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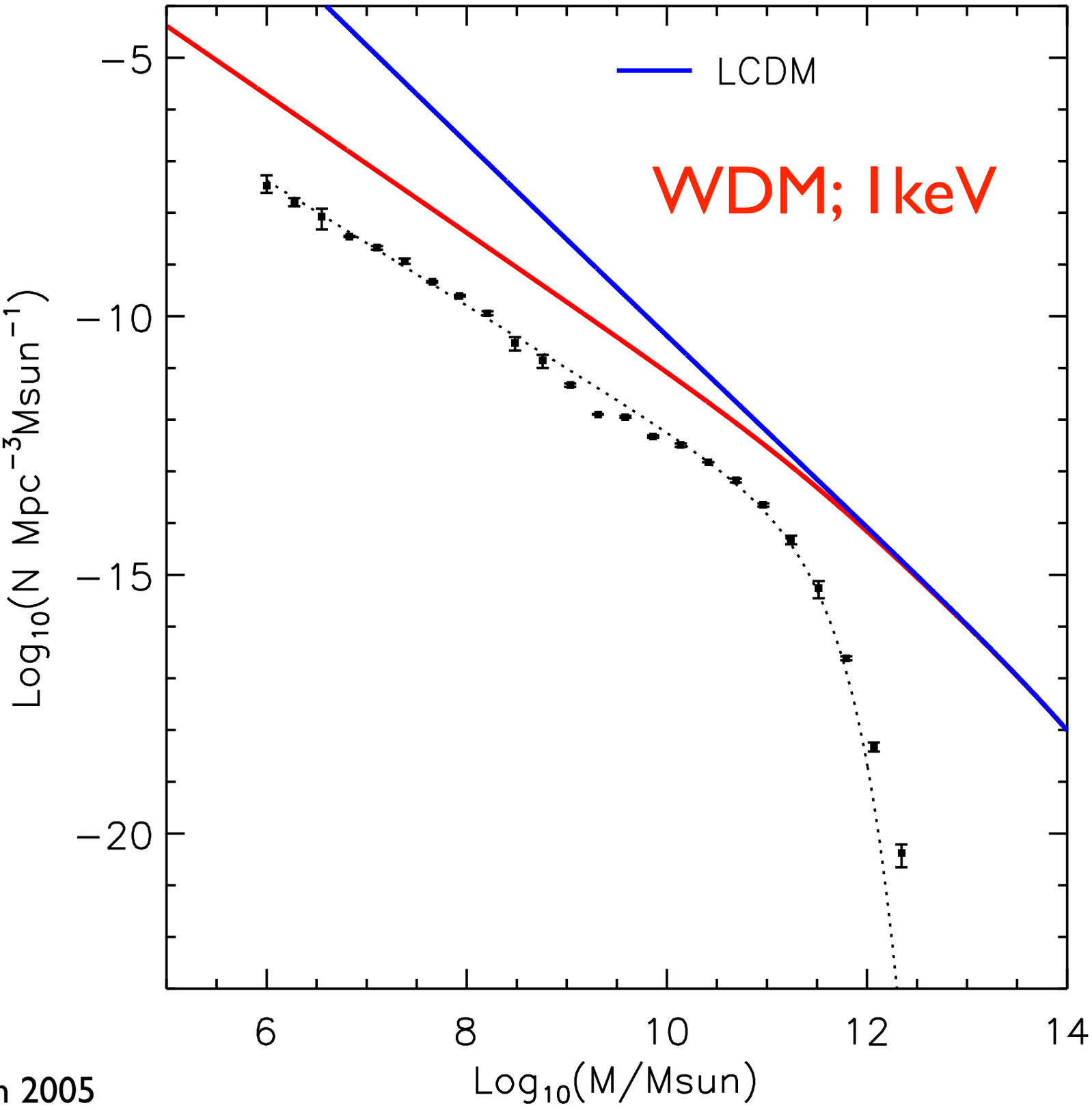

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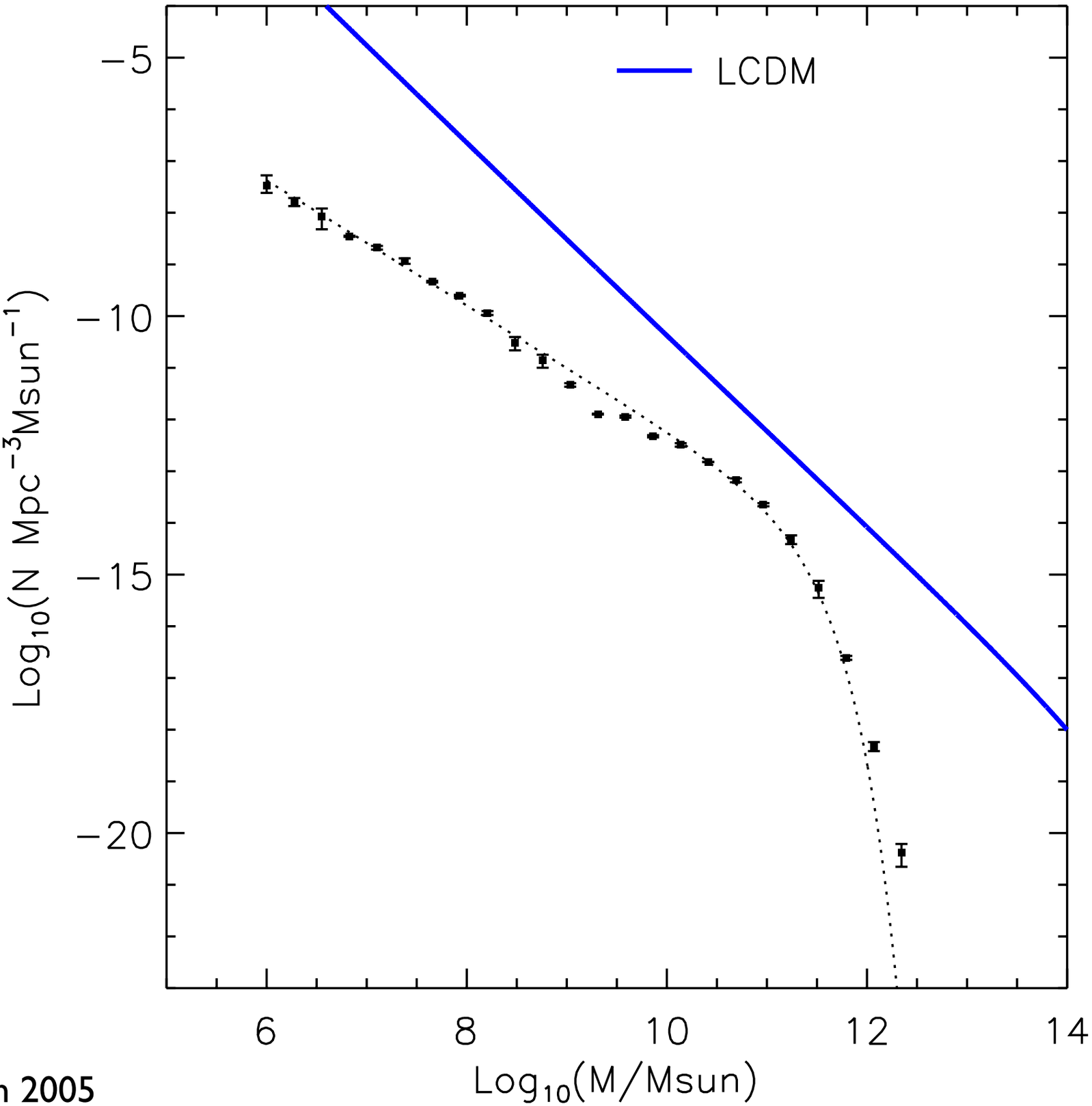
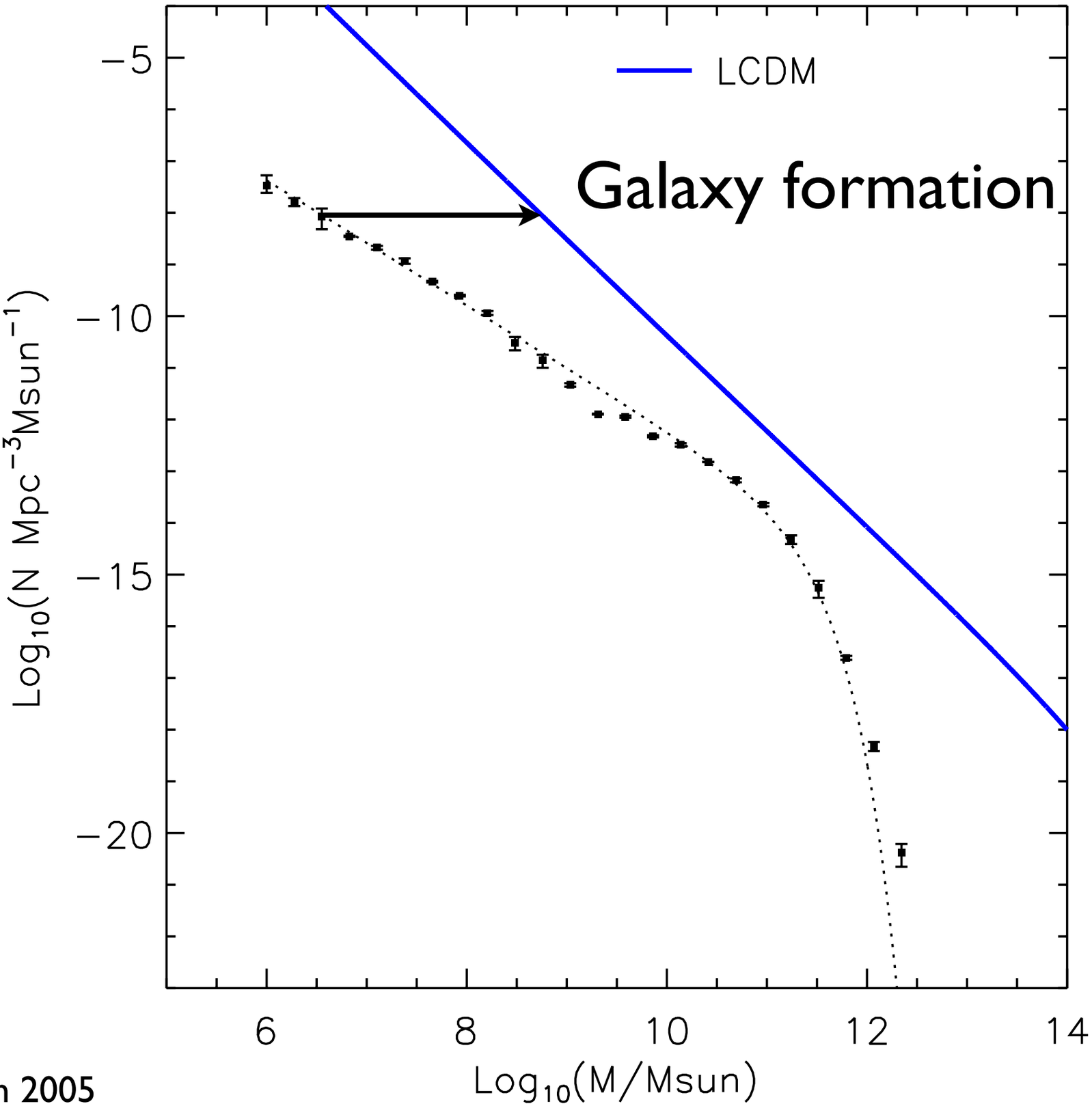


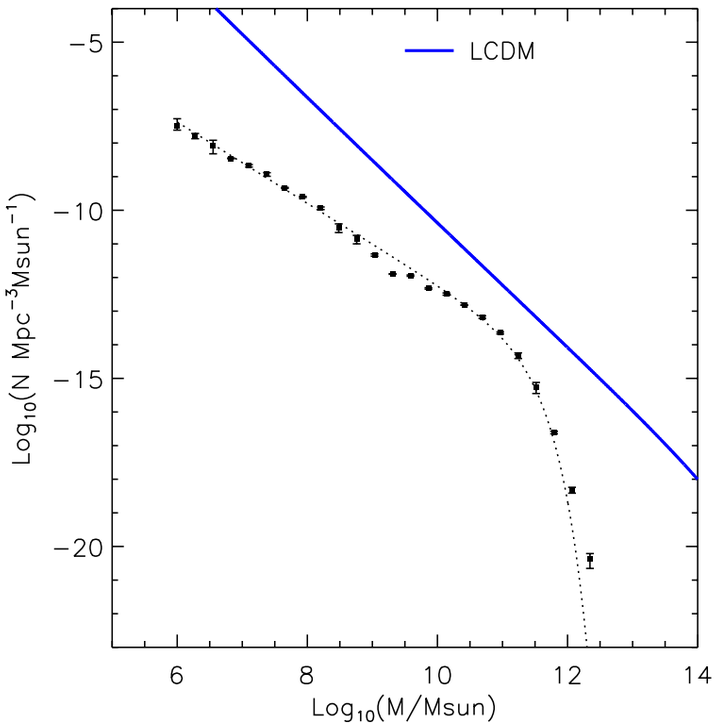
Read & Trentham 2005

2. Observations | The halo mass function

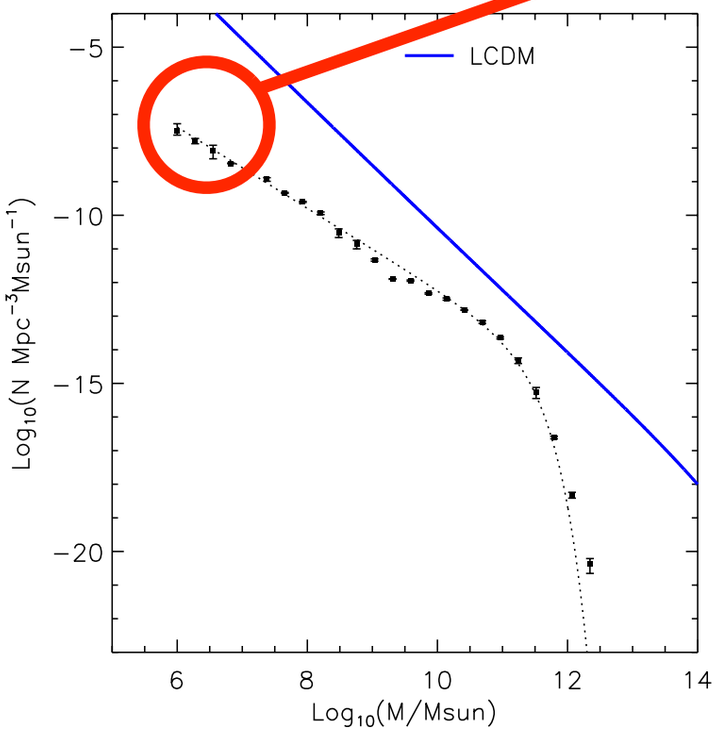


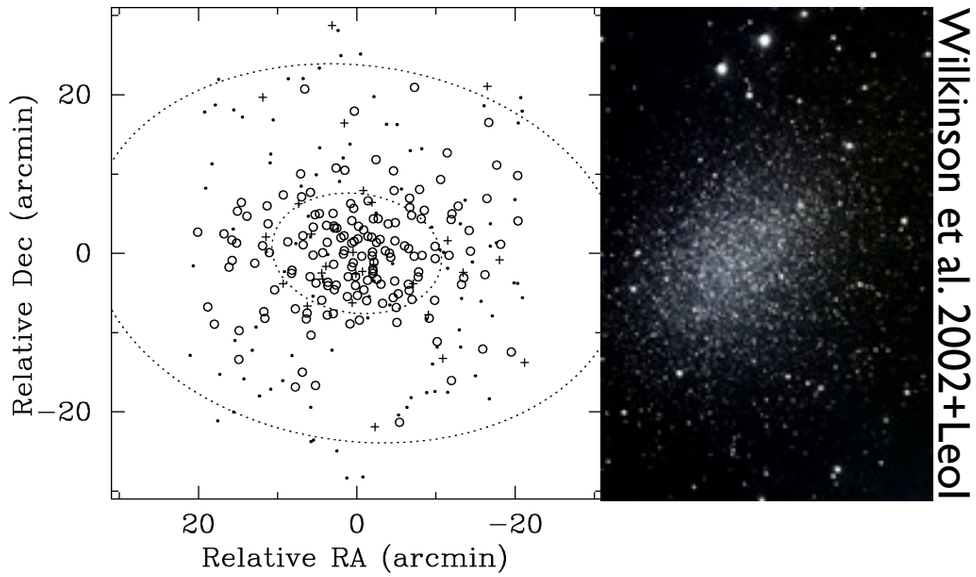
Read & Trentham 2005

2. Observations | Measuring the halo density profile

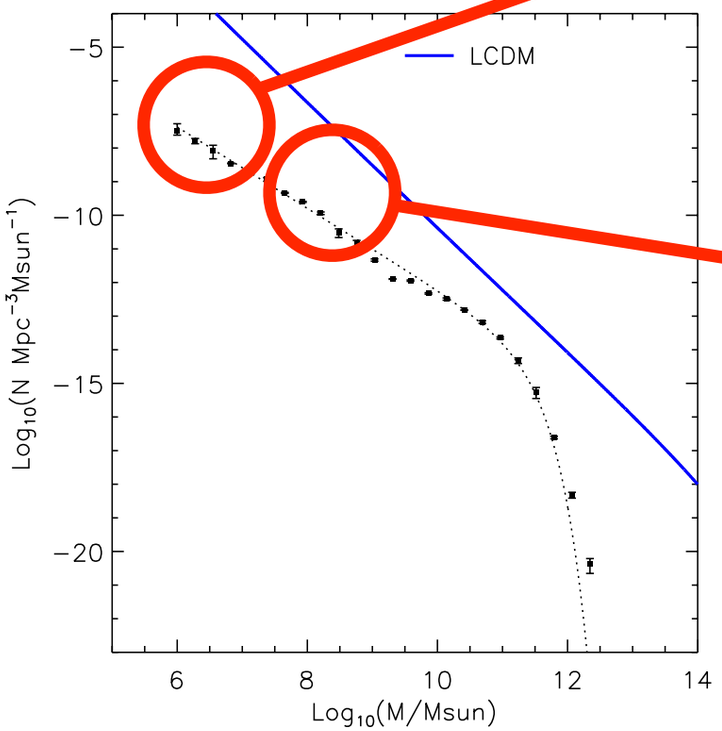


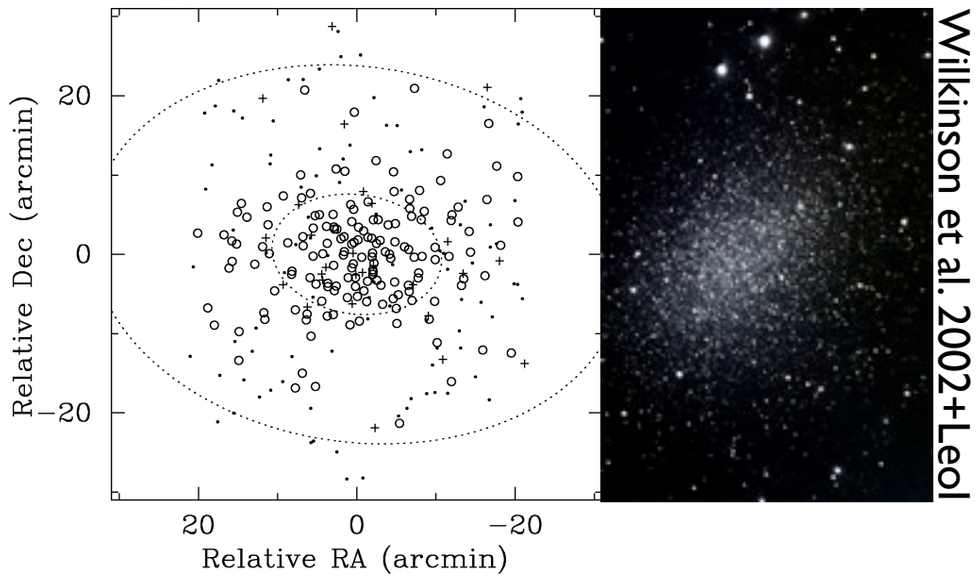
2. Observations | Measuring the halo density profile



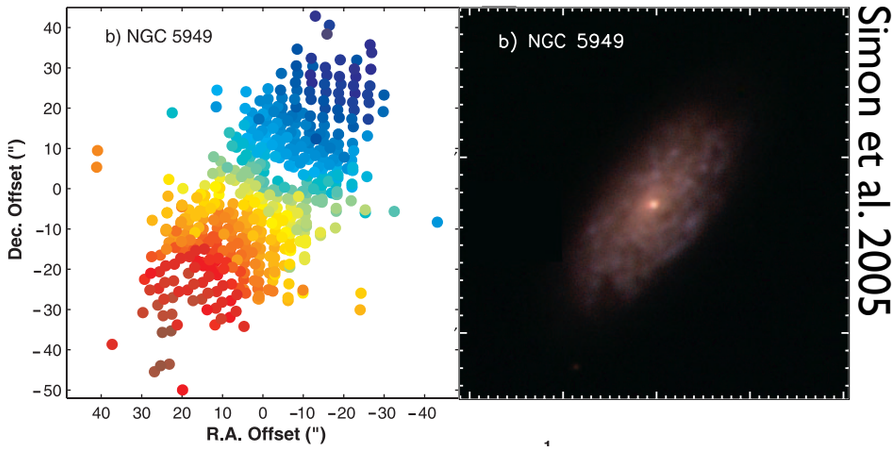


2. Observations | Measuring the halo density profile



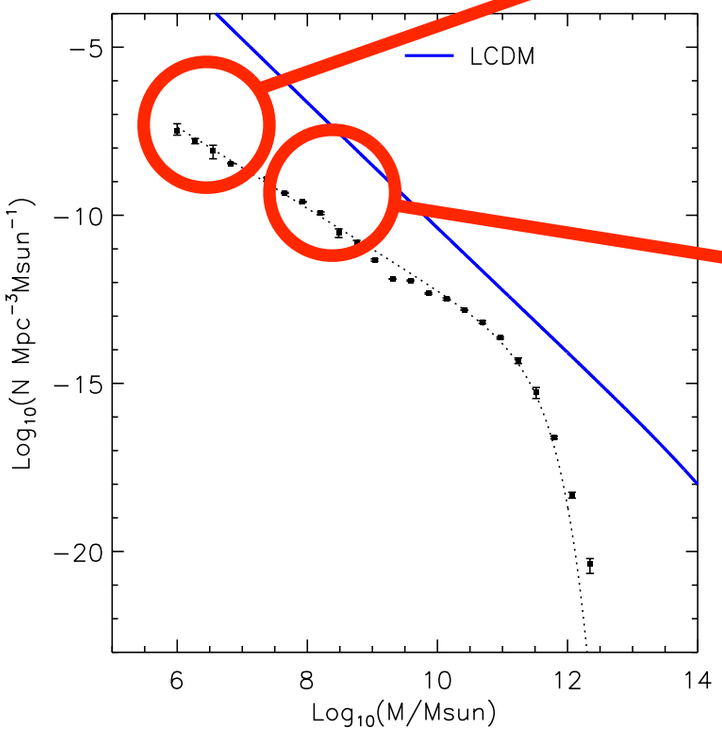


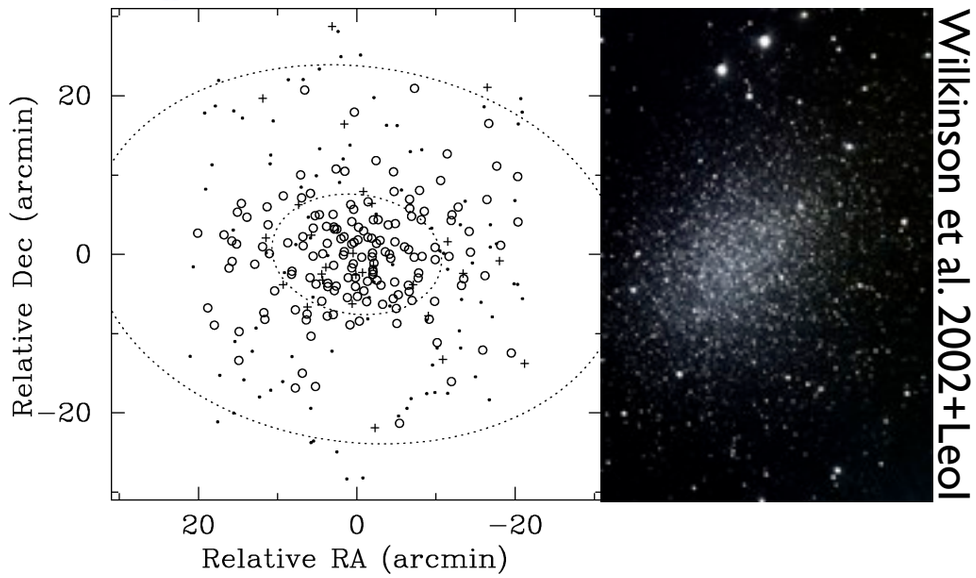
Wilkinson et al. 2002+Leol



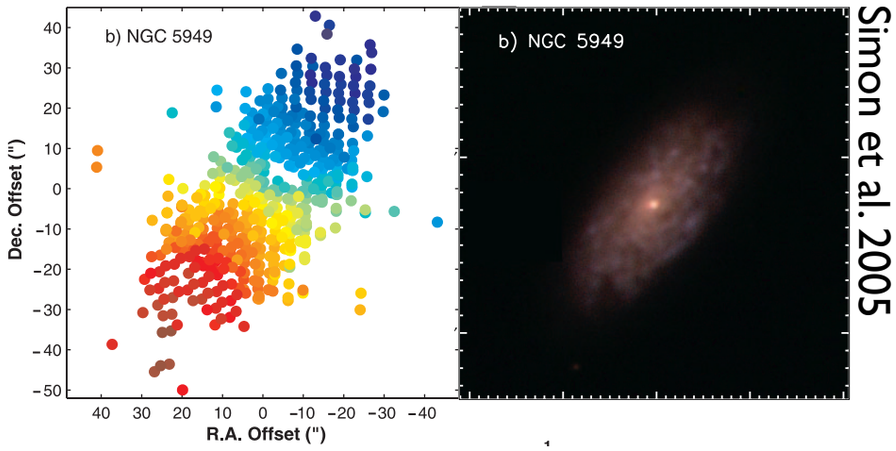
Simon et al. 2005

2. Observations | Measuring the halo density profile





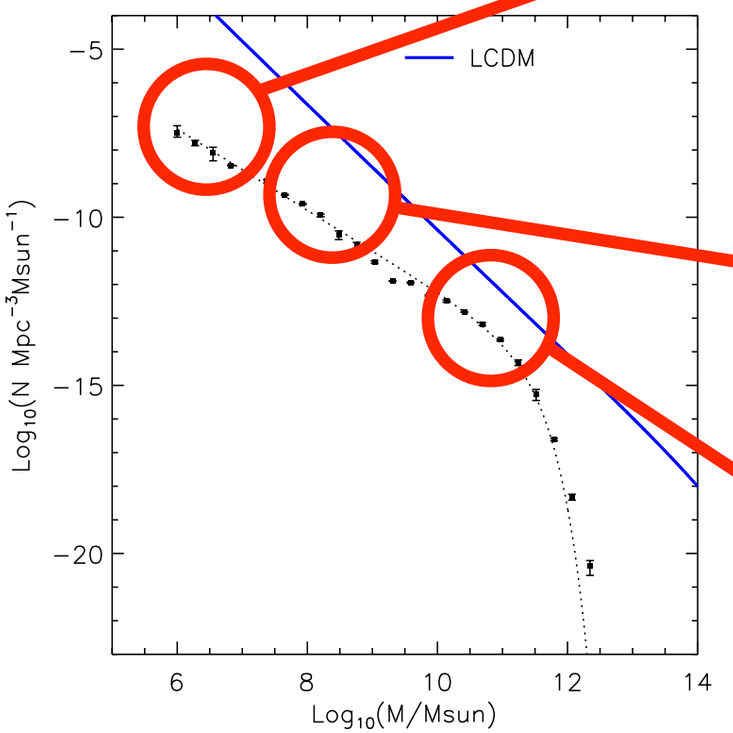
Wilkinson et al. 2002+Leol

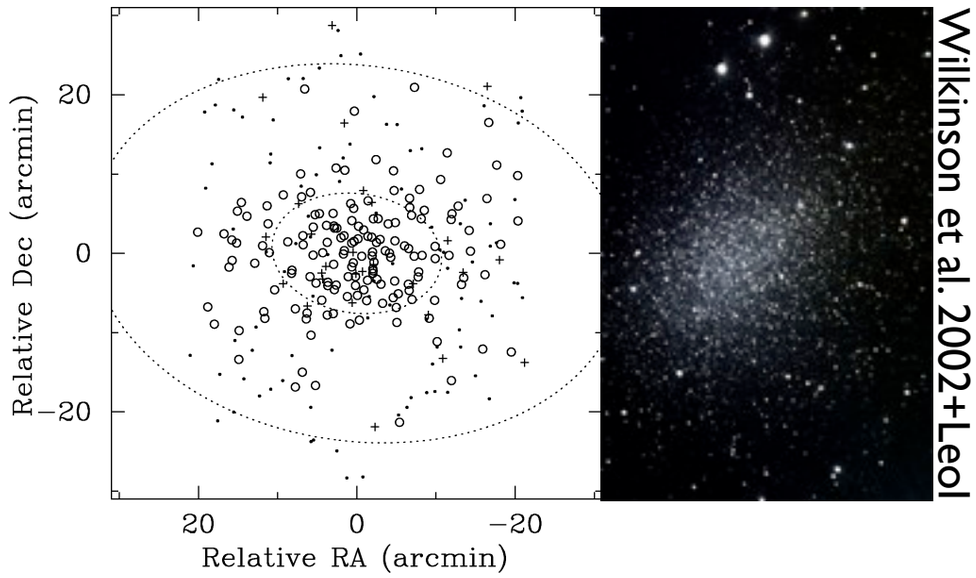


Simon et al. 2005

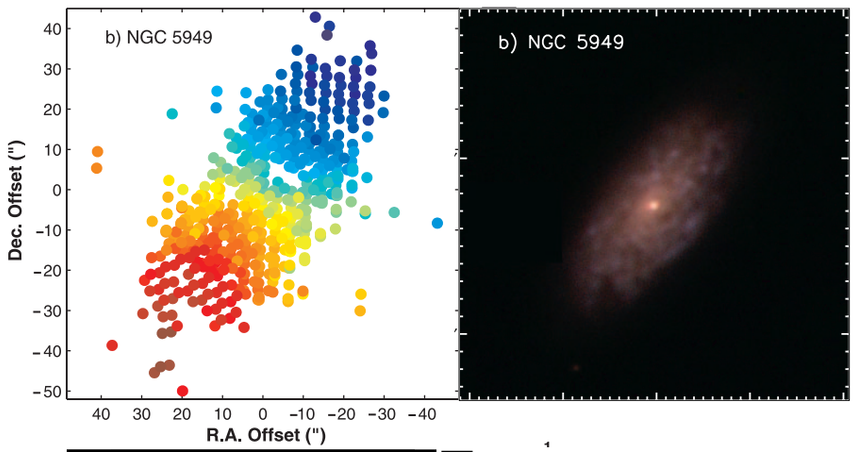
Dynamics

2. Observations | Measuring the halo density profile

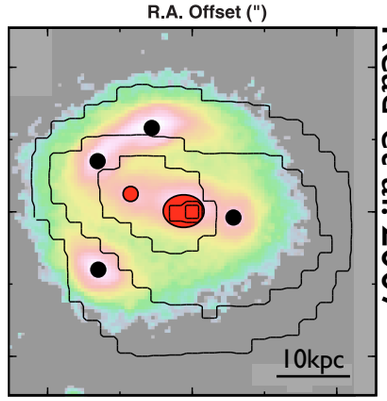




Wilkinson et al. 2002+Leol



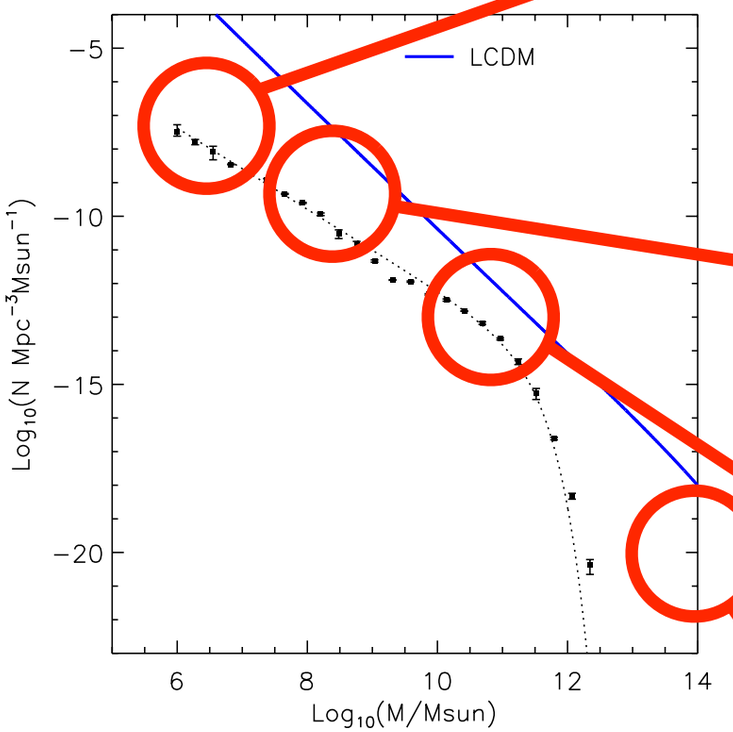
Simon et al. 2005

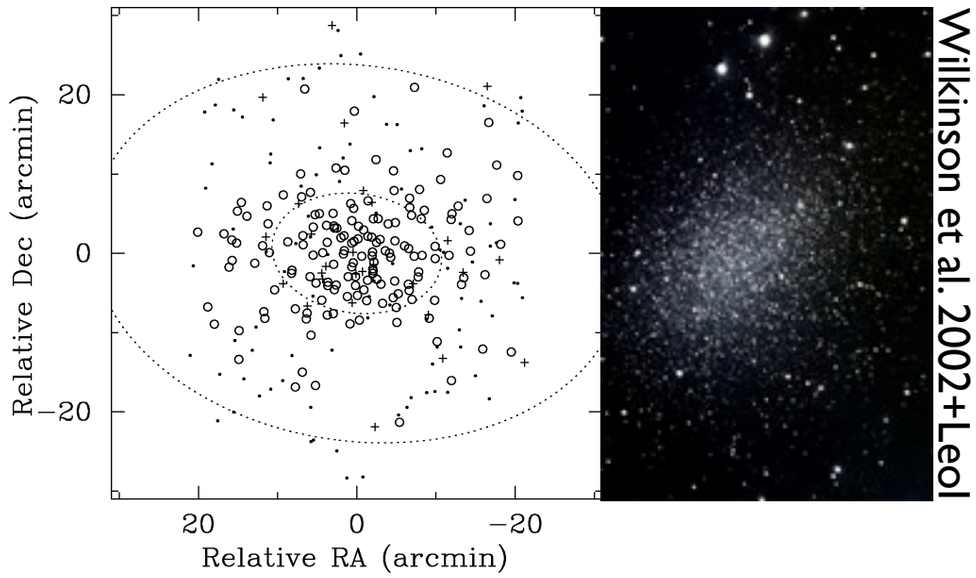


Read et al. 2007

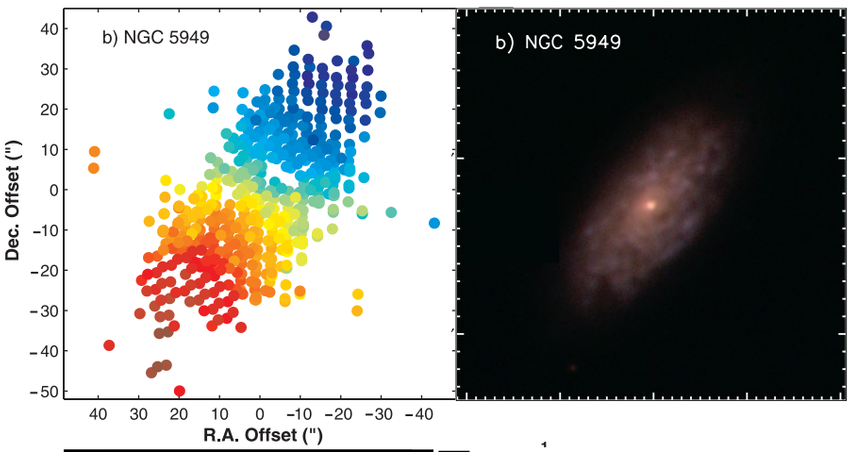
Dynamics

2. Observations | Measuring the halo density profile

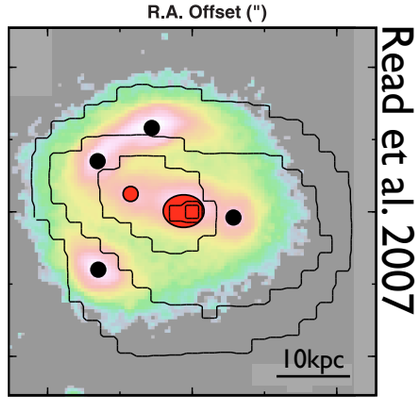




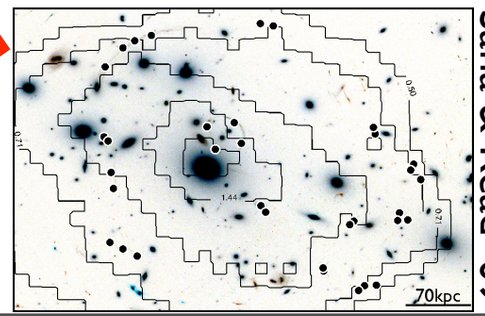
Wilkinson et al. 2002+Leol



Simon et al. 2005



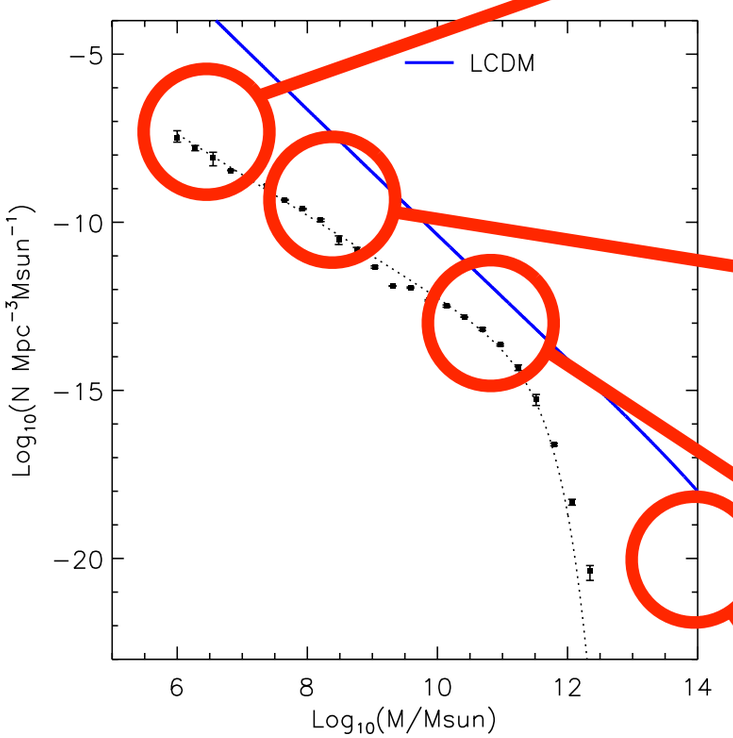
Read et al. 2007

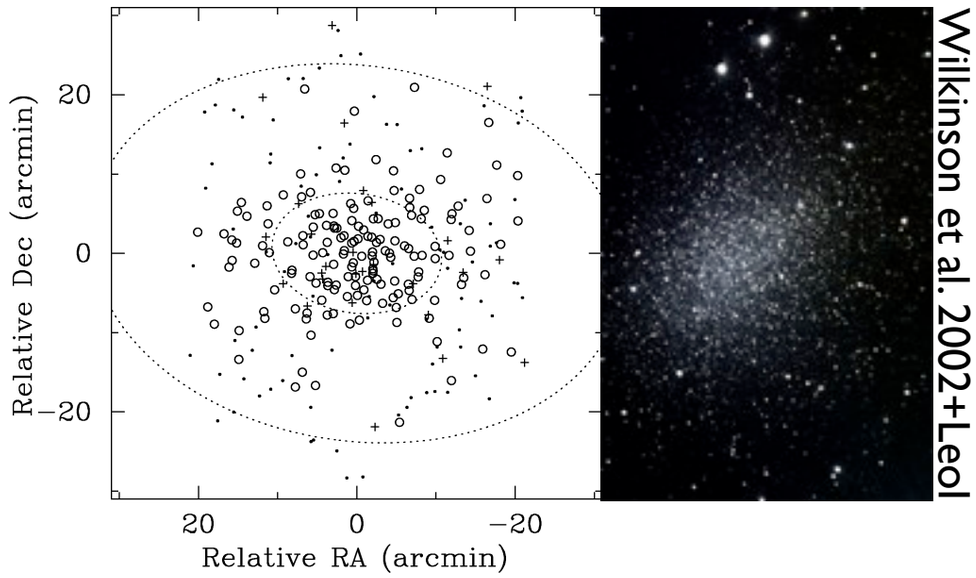


Saha & Read '09

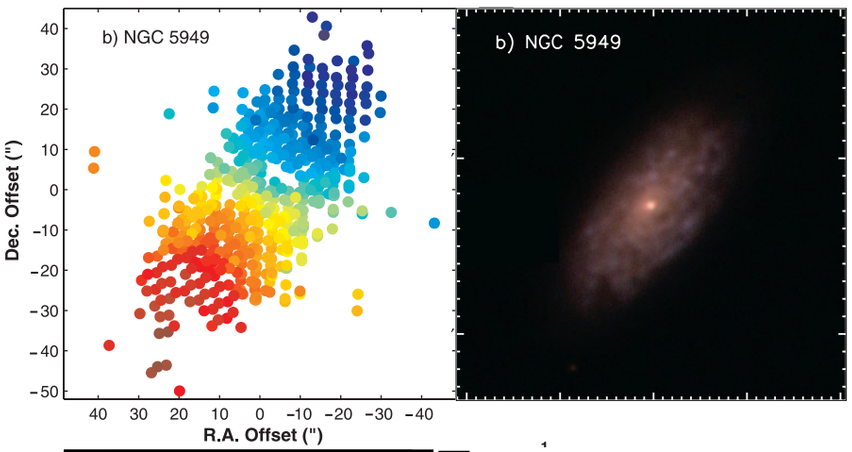
Dynamics

2. Observations | Measuring the halo density profile

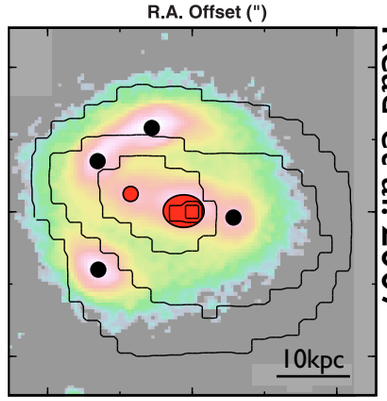




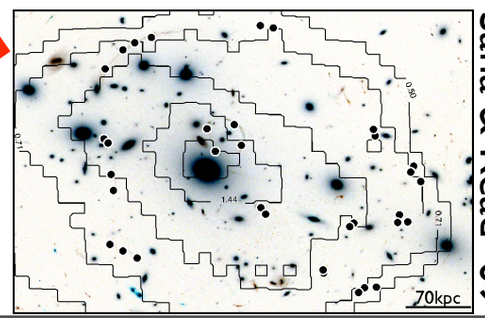
Wilkinson et al. 2002+Leol



Simon et al. 2005



Read et al. 2007

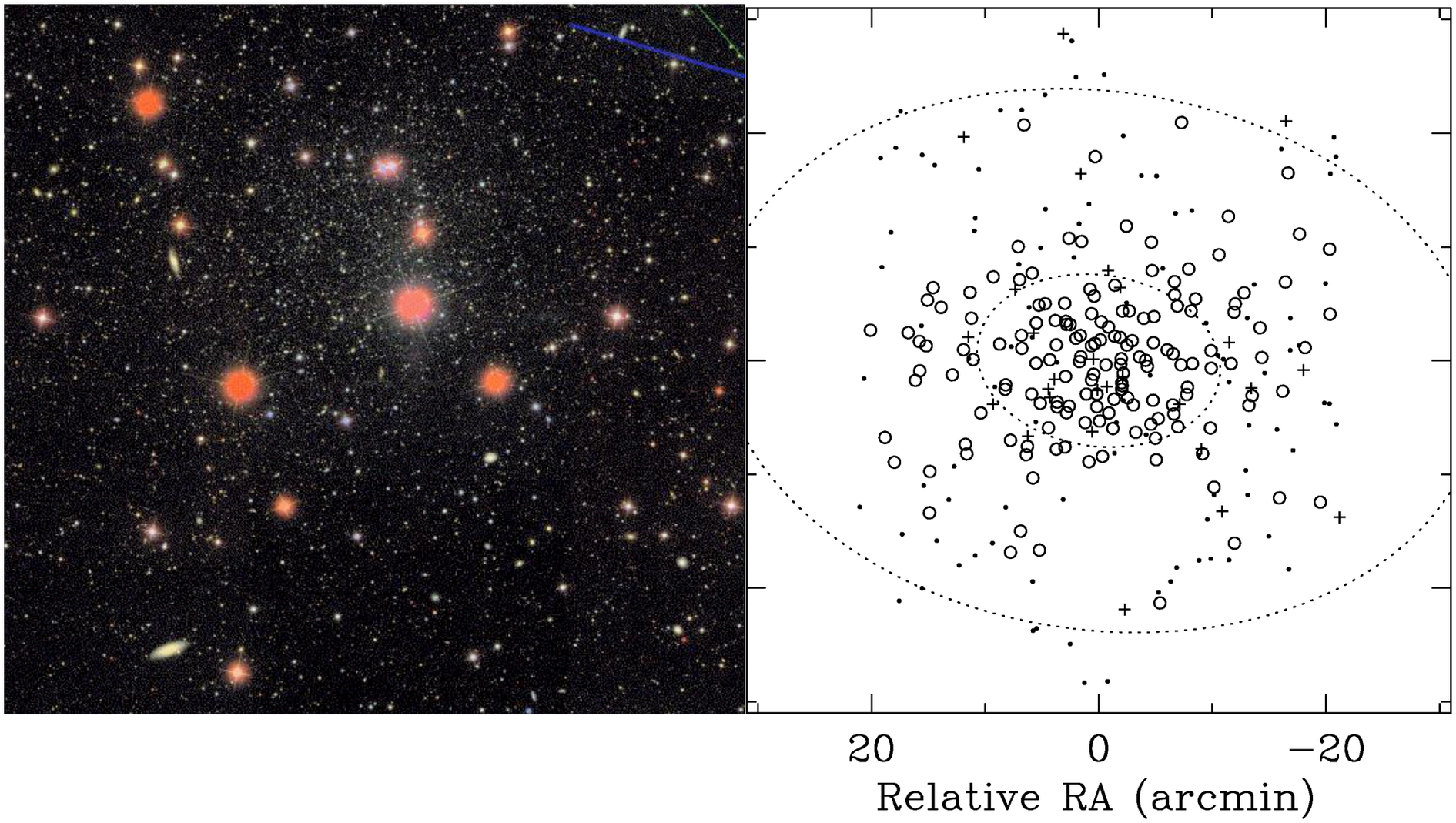


Saha & Read '09

Dynamics

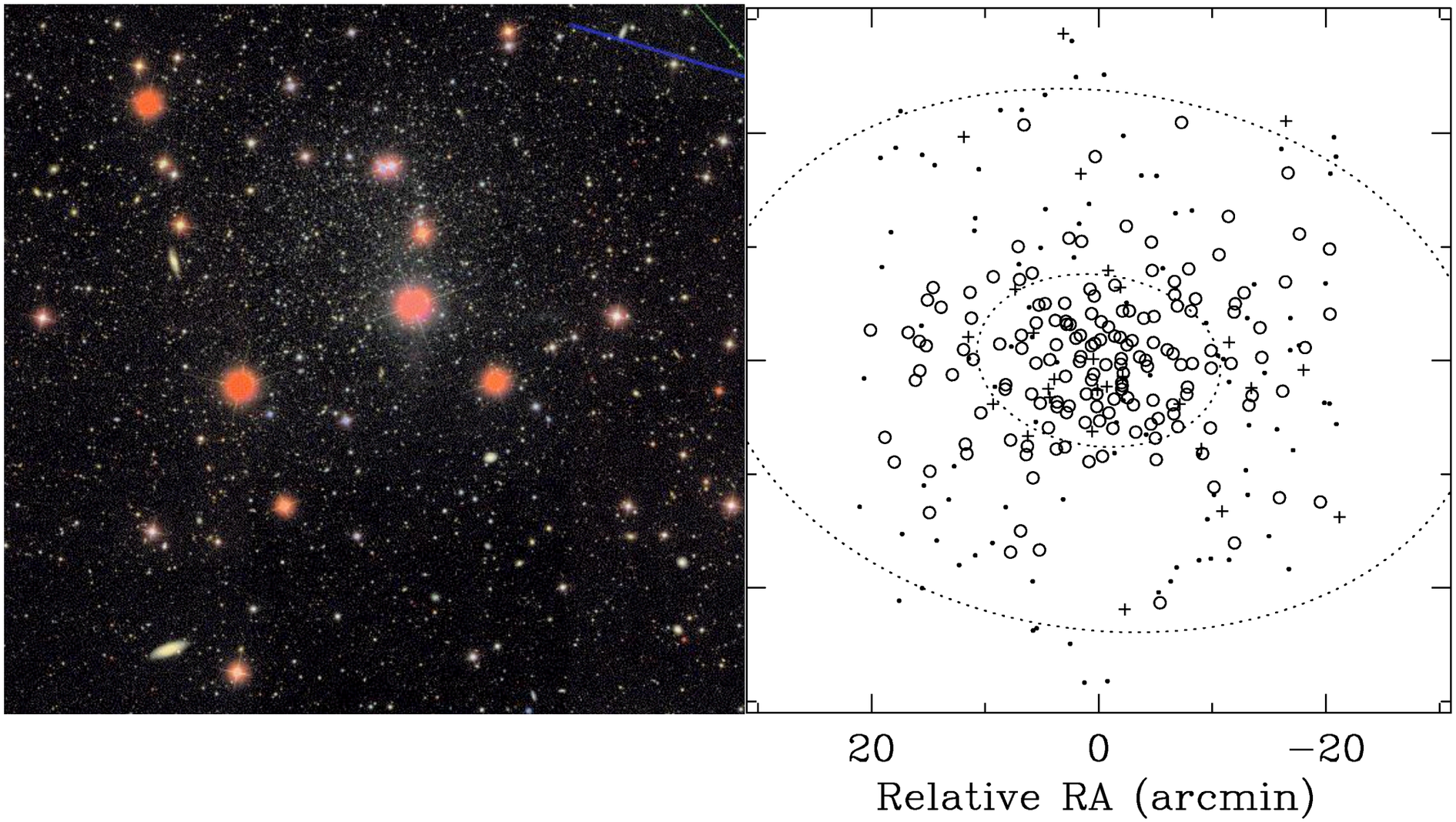
Lensing

2. Observations | The halo density profile: dwarfs



Wilkinson et al. in prep. 2011

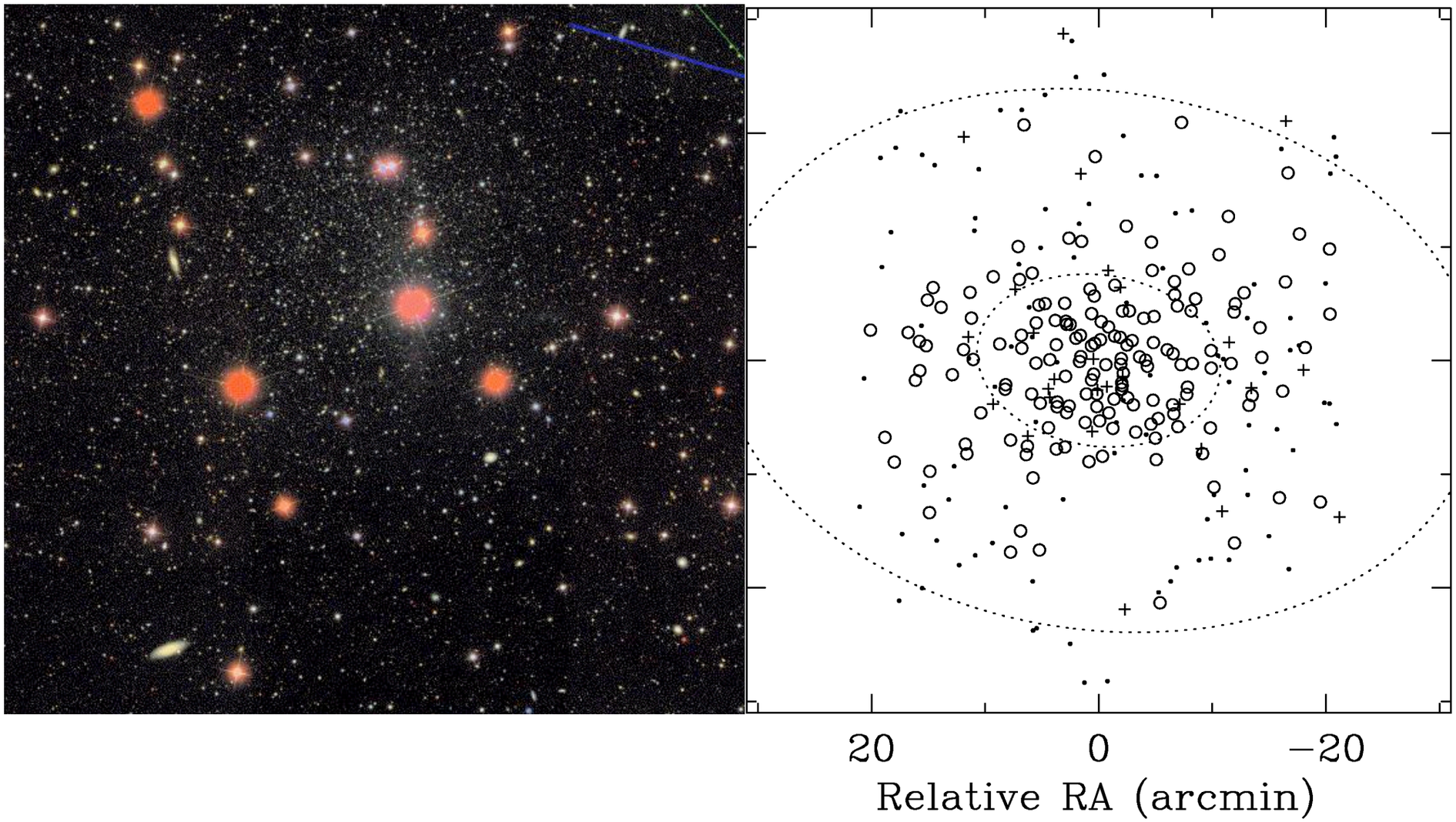
2. Observations | The halo density profile: dwarfs



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

Wilkinson et al. in prep. 2011

2. Observations | The halo density profile: dwarfs

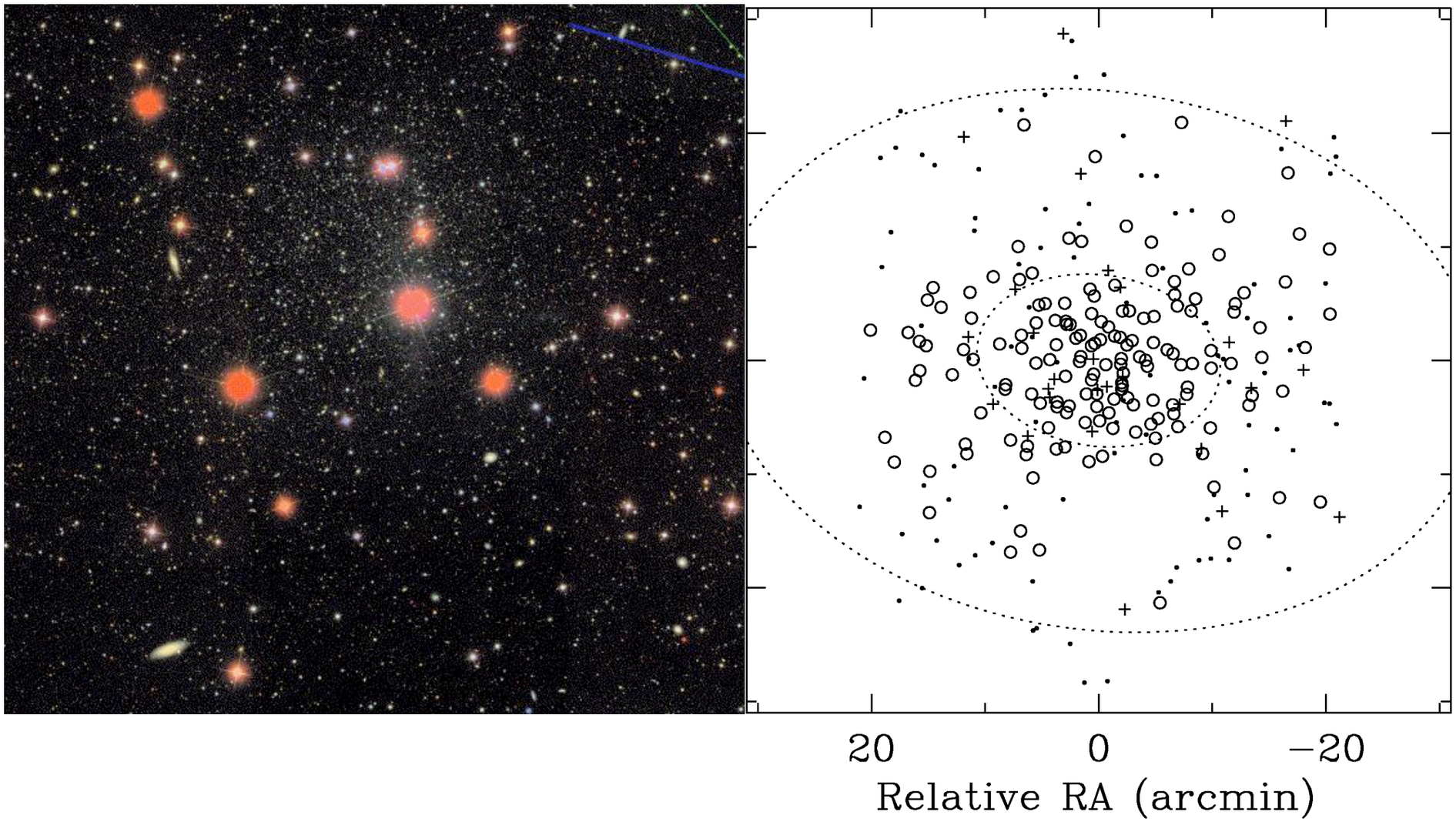


$$\frac{df}{dt} = 0 = \frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi \cdot \frac{\partial f}{\partial \mathbf{v}}$$

Steady state

Wilkinson et al. in prep. 2011

2. Observations | The halo density profile: dwarfs



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

Steady state

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

Wilkinson et al. in prep. 2011

2. Observations | The halo density profile: dwarfs

- Integrate out velocity ⇒ Jeans equations

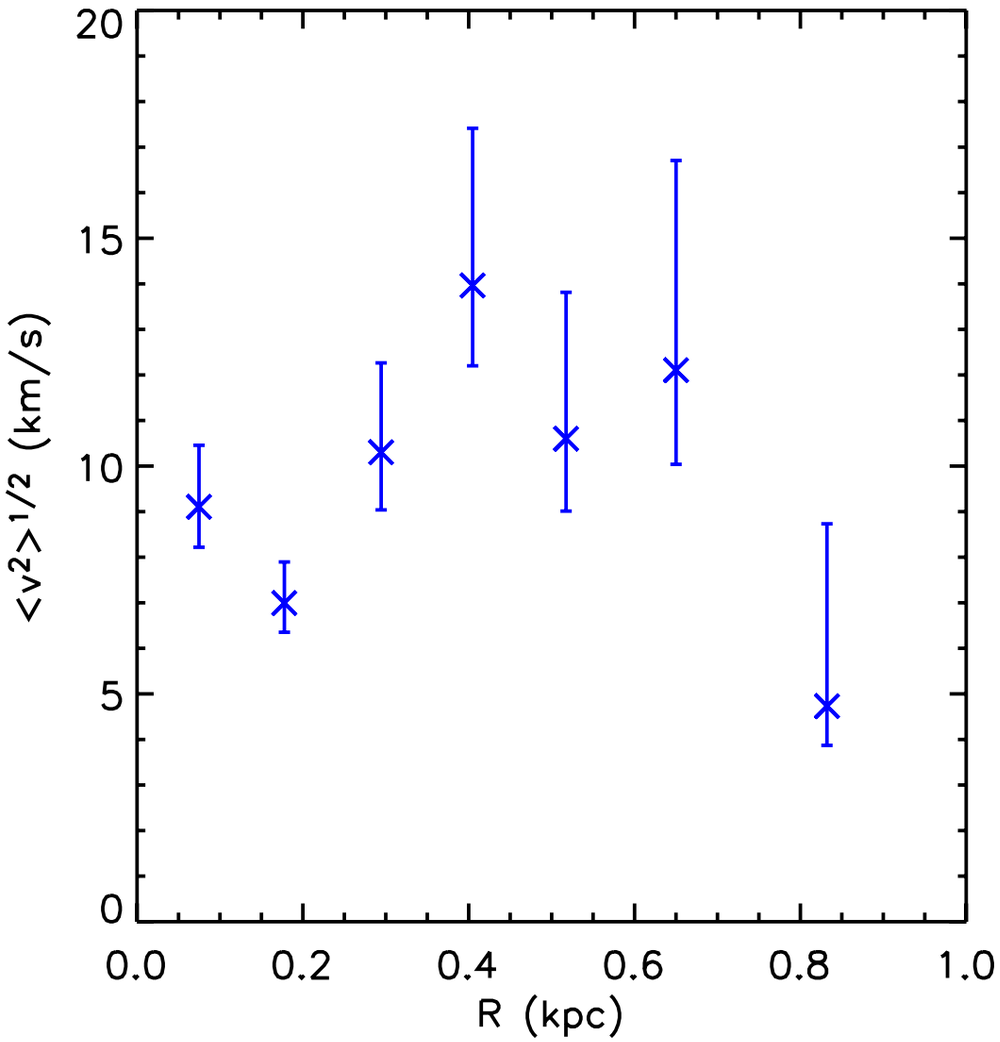
- Assume spherical symmetry

- Bin the data ...

Wilkinson et al. in prep. 2011

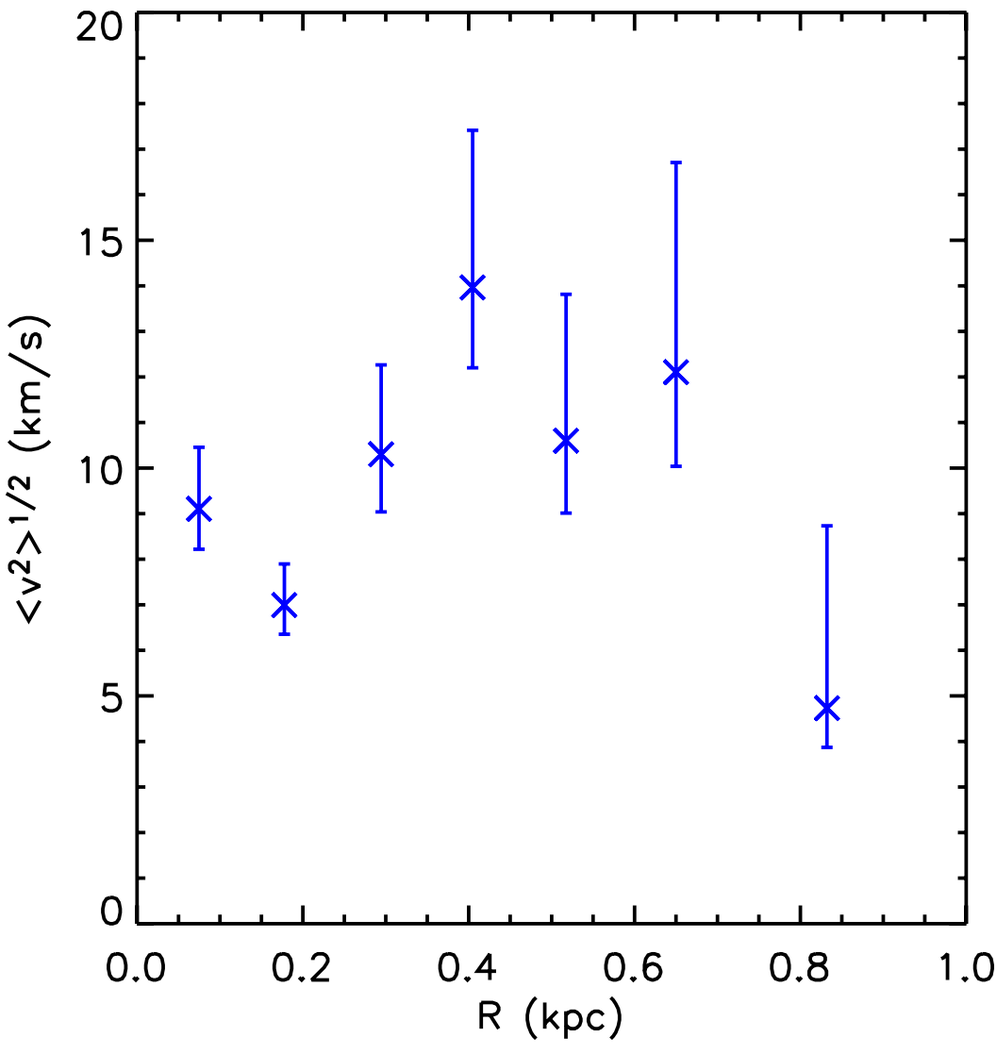
$f(\mathbf{r}, \mathbf{v})$

2. Observations | The halo density profile: dwarfs



See also: Evans, An & Walker 2009; Wilkinson et al. 2004; f(r) is integrating factor that depends only on β(r)

2. Observations | The halo density profile: dwarfs

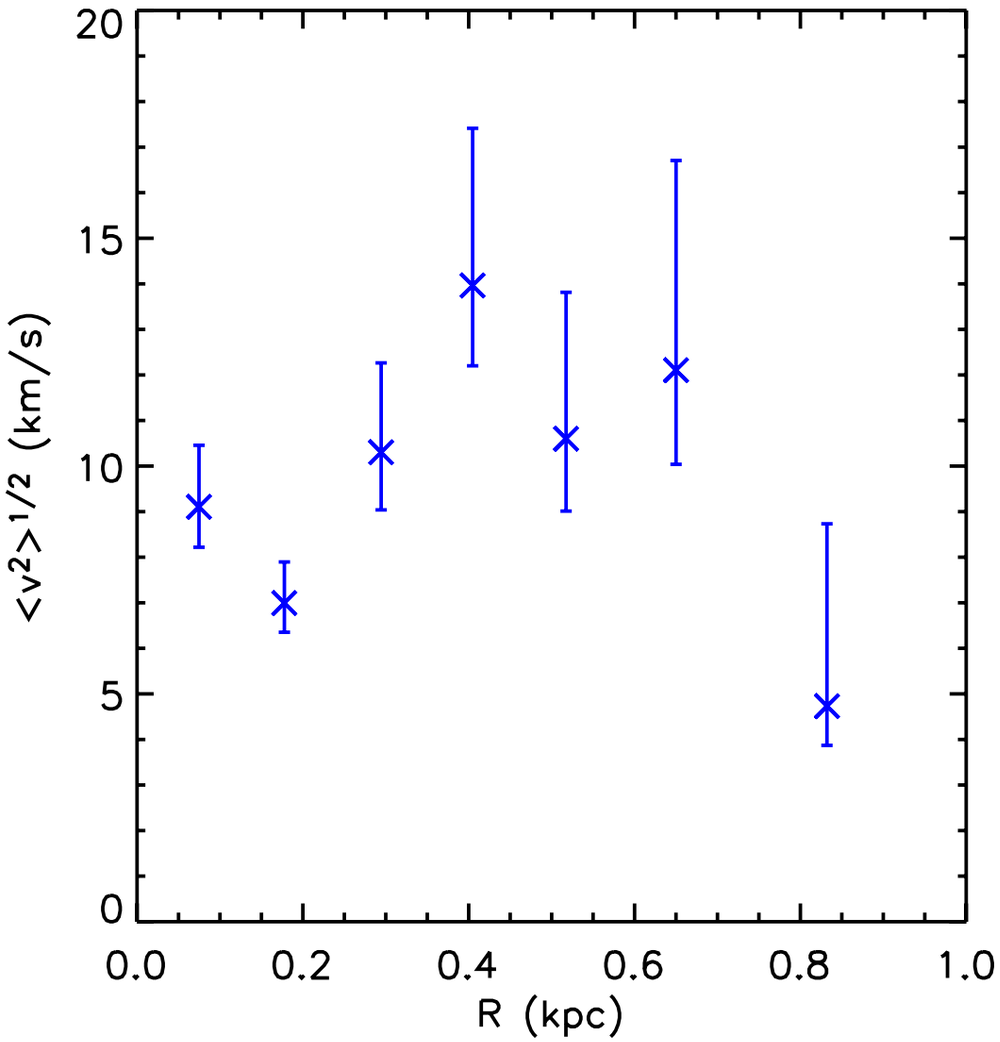


$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty dr\, \nu(r) f(r) \frac{GM(r)}{r}$$

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

See also: Evans, An & Walker 2009; Wilkinson et al. 2004; f(r) is integrating factor that depends only on β(r)

2. Observations | The halo density profile: dwarfs



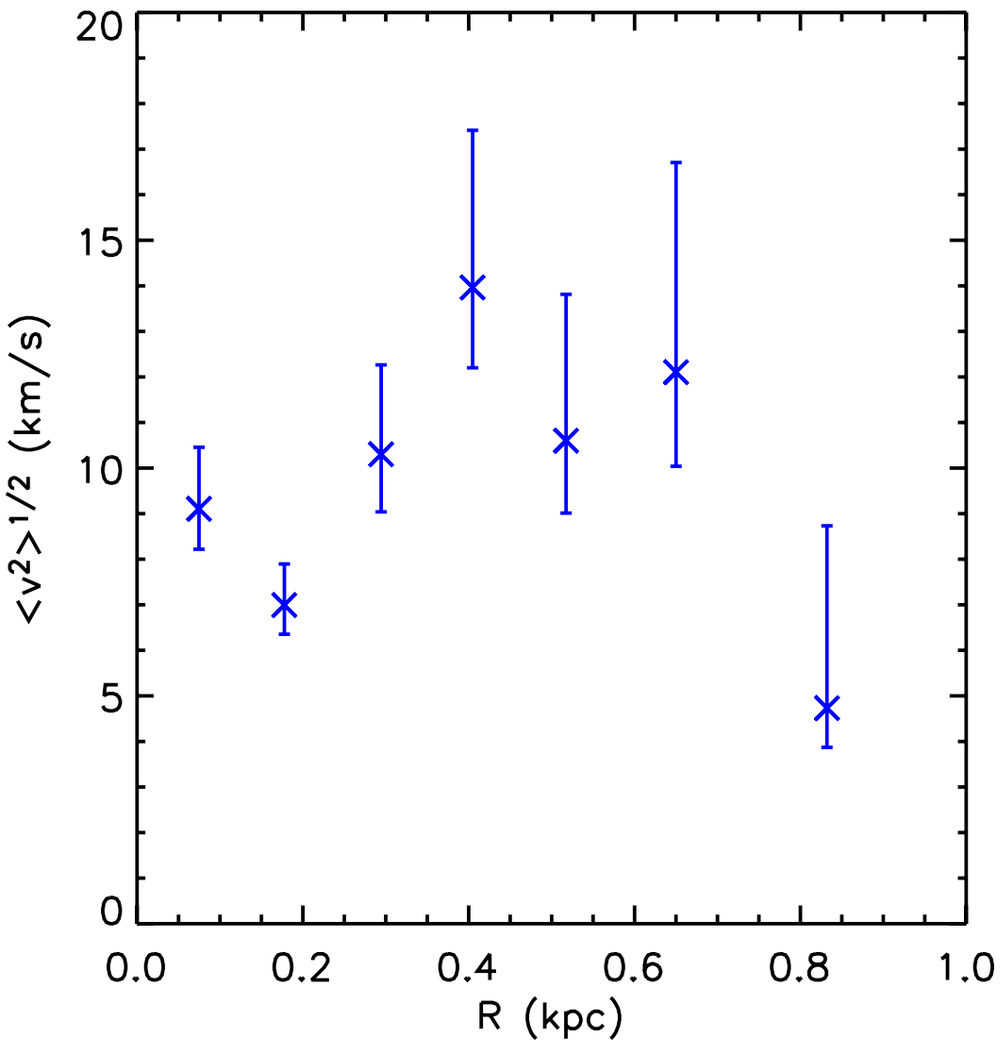
$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty dr\, \nu(r) f(r) \frac{GM(r)}{r}$$

Light distribution

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

See also: Evans, An & Walker 2009; Wilkinson et al. 2004; f(r) is integrating factor that depends only on β(r)

2. Observations | The halo density profile: dwarfs



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

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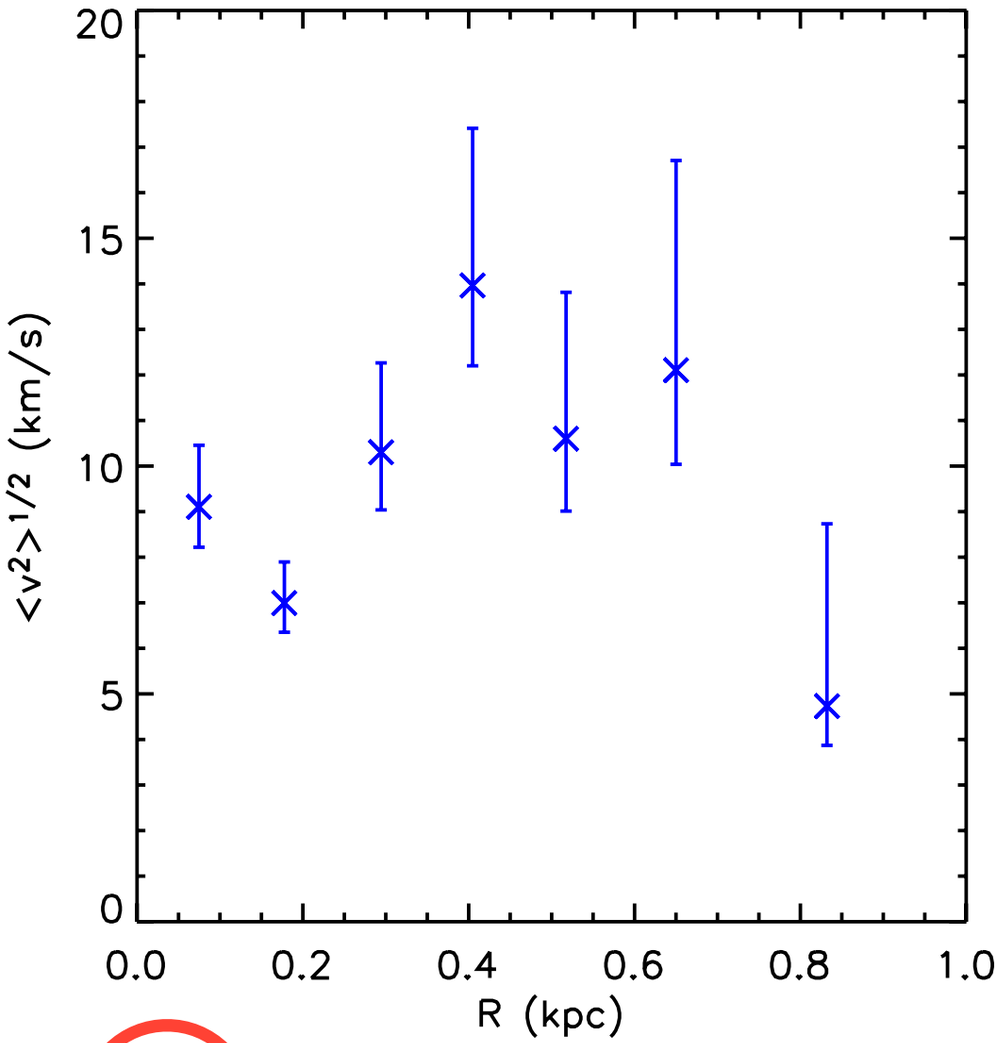
2. Observations | The halo density profile: dwarfs



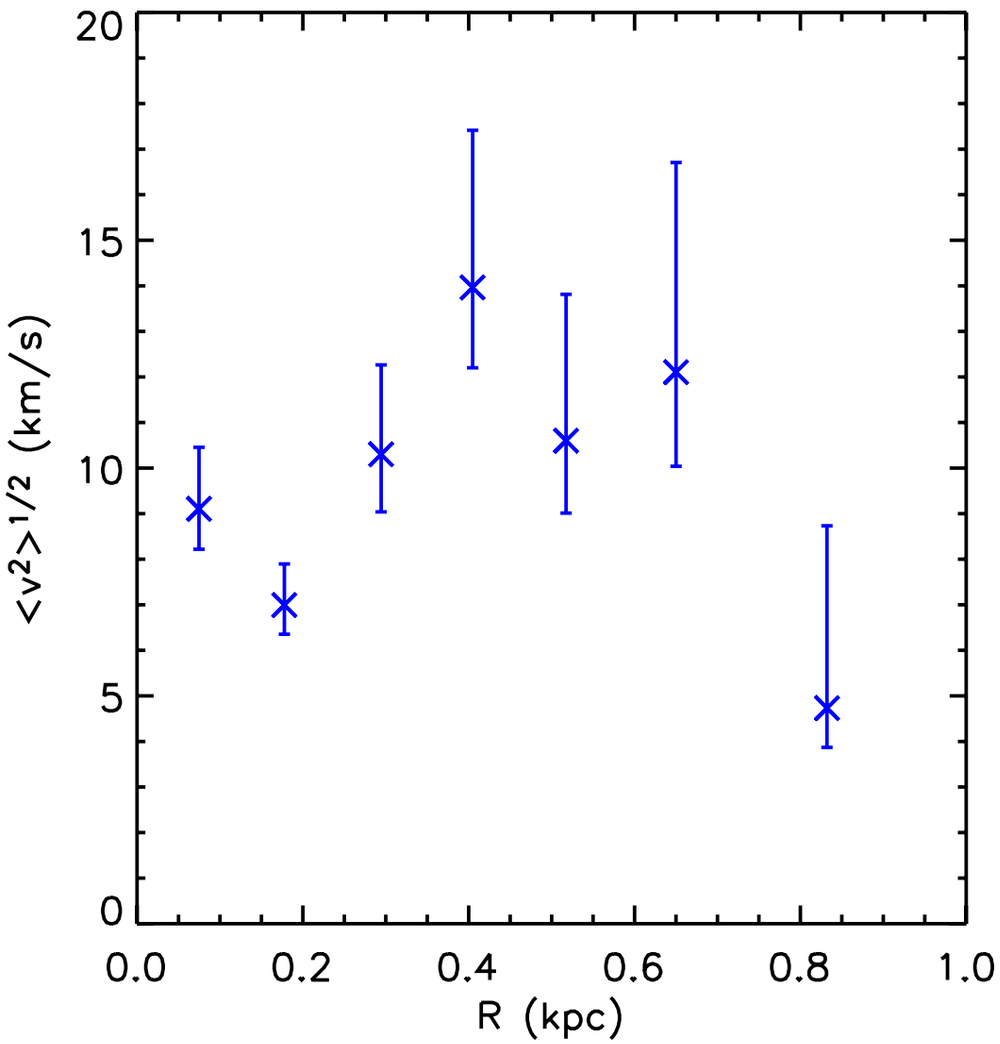
$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty dr\, \nu(r) f(r) \frac{GM(r)}{r}$$

Mass distribution

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

See also: Evans, An & Walker 2009; Wilkinson et al. 2004; f(r) is integrating factor that depends only on β(r)

2. Observations | The halo density profile: dwarfs



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

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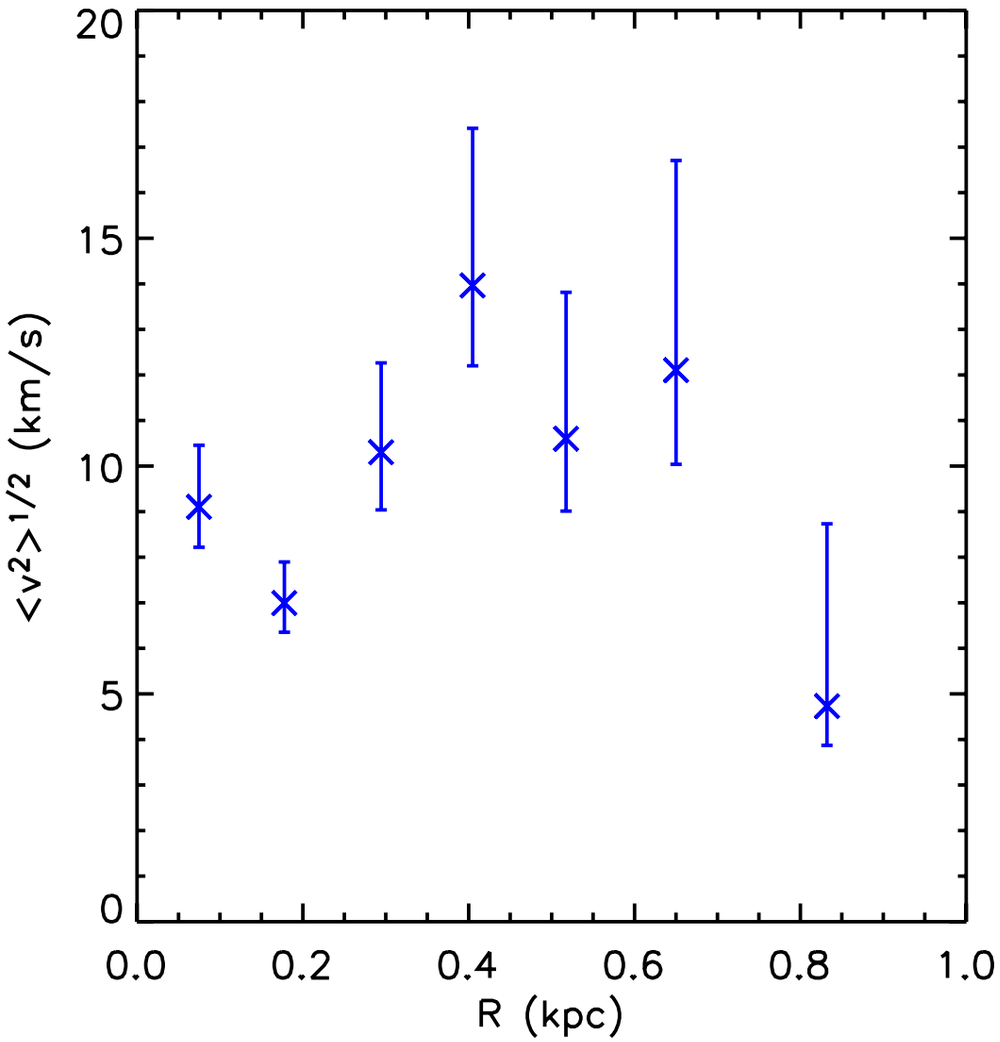
See also: Evans, An & Walker 2009; Wilkinson et al. 2004; f(r) is integrating factor that depends only on β(r)

2. Observations | The halo density profile: dwarfs



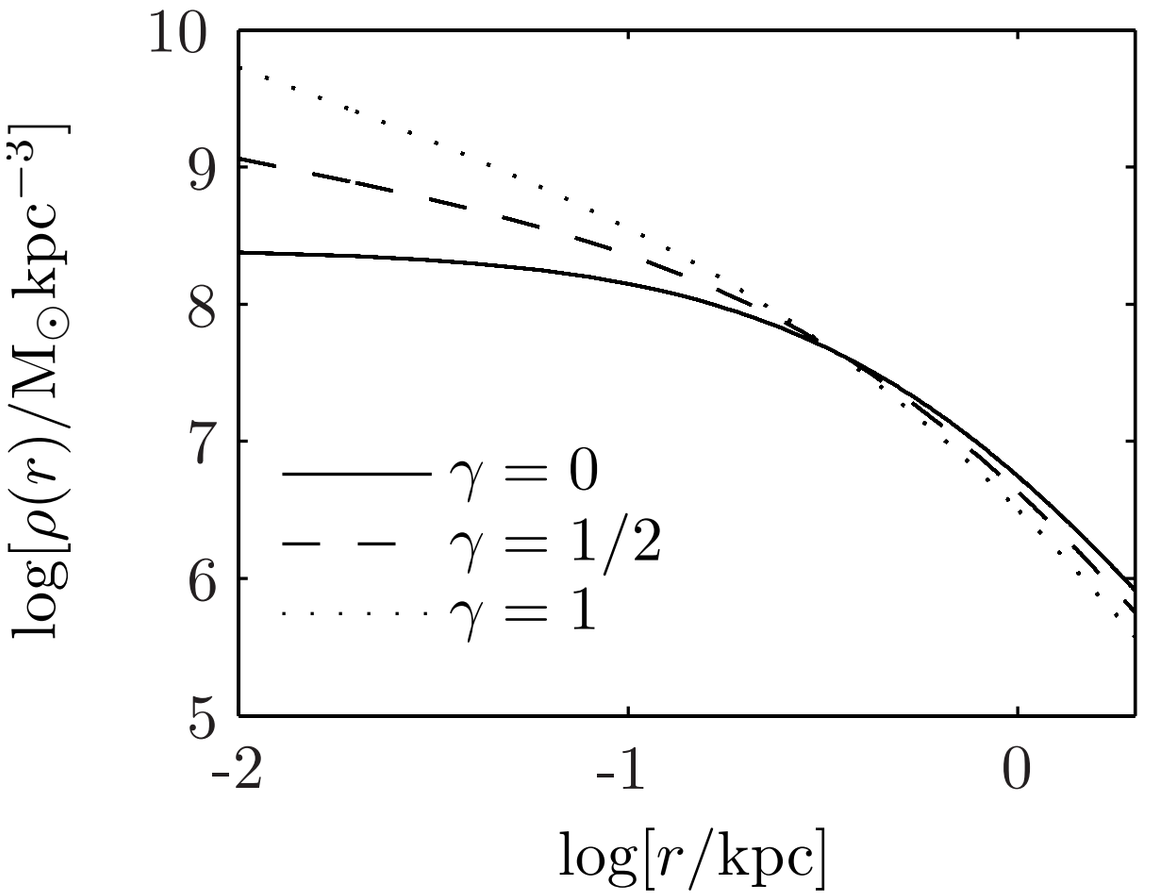
$$\sigma_P^2(R) = \frac{2}{I(R)} \int_R^\infty dr\, \nu(r) f(r) \frac{GM(r)}{r}$$

Velocity anisotropy

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

See also: Evans, An & Walker 2009; Wilkinson et al. 2004; f(r) is integrating factor that depends only on β(r)

2. Observations | The halo density profile: dwarfs



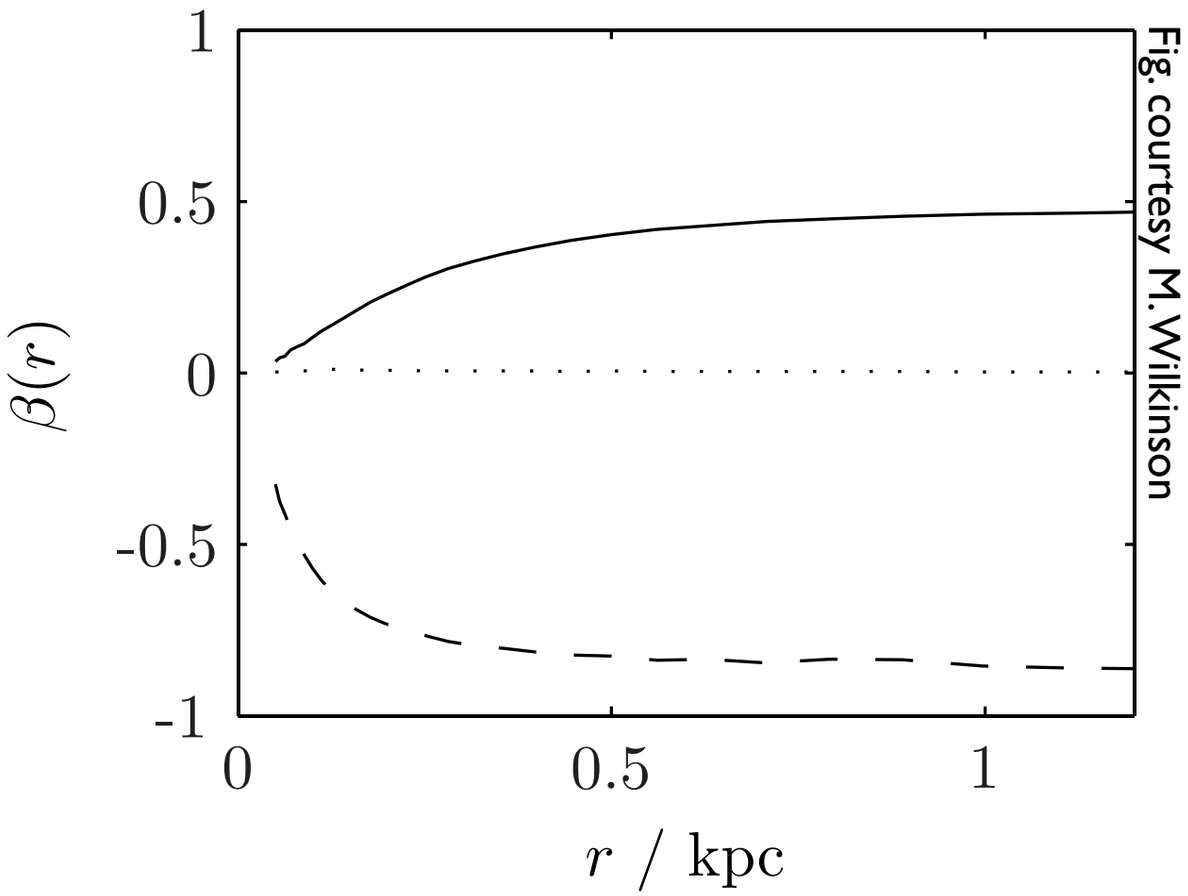


Fig. courtesy M.Wilkinson

Wilkinson et al. in prep. 2011

2. Observations | The halo density profile: dwarfs

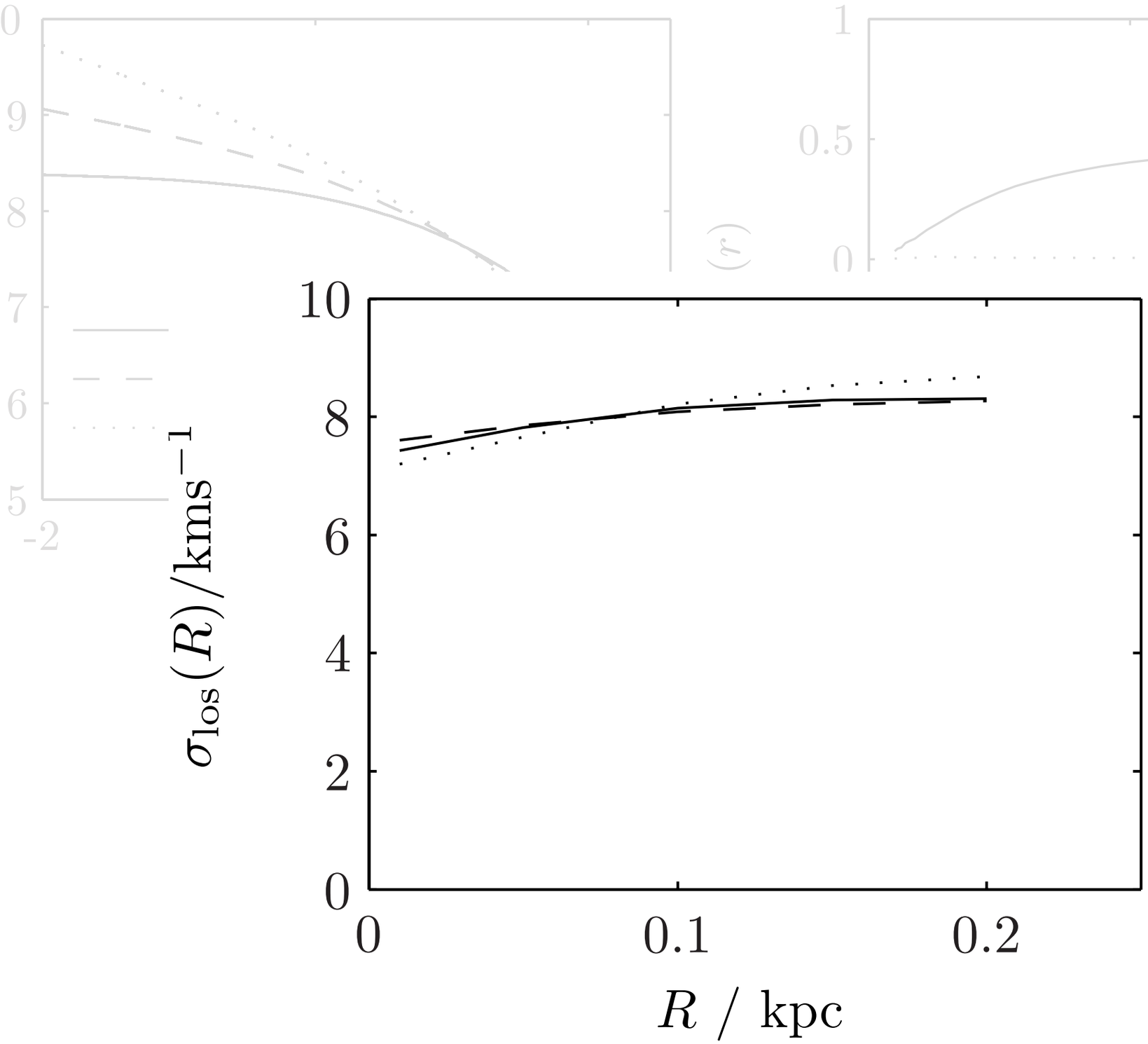
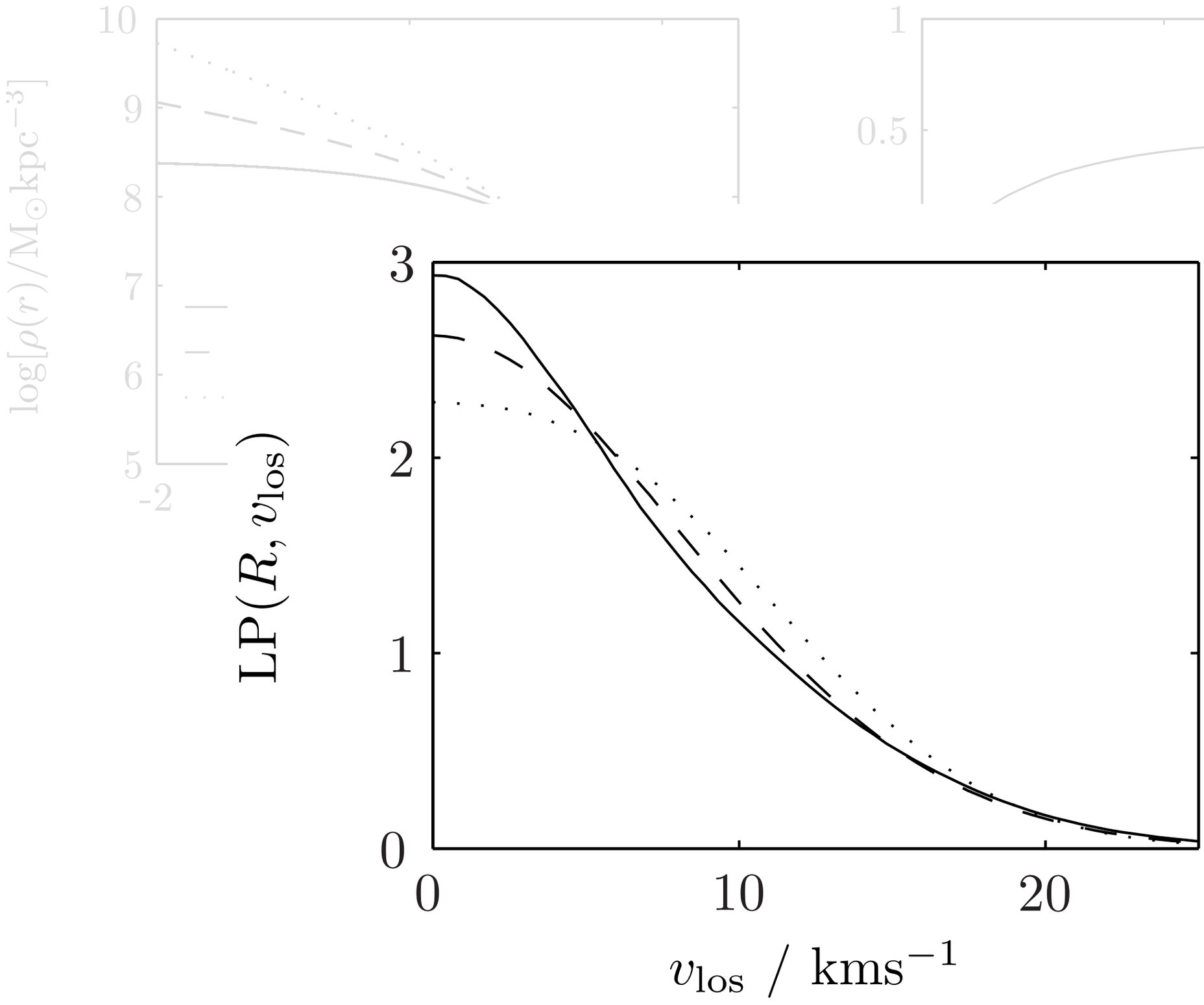


Fig. courtesy M.Wilkinson

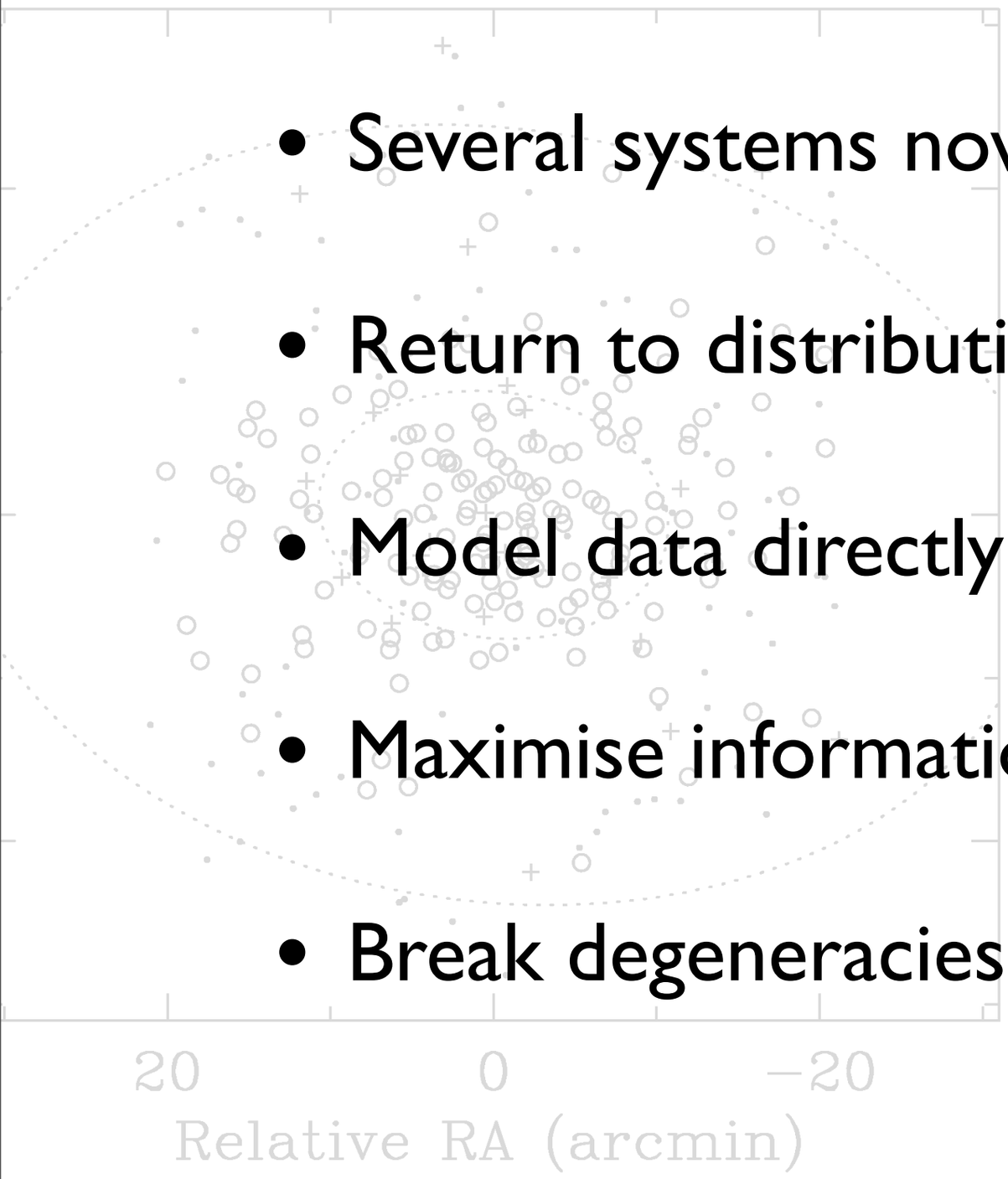
Wilkinson et al. in prep. 2011

2. Observations | The halo density profile: dwarfs



Wilkinson et al. in prep. 2011

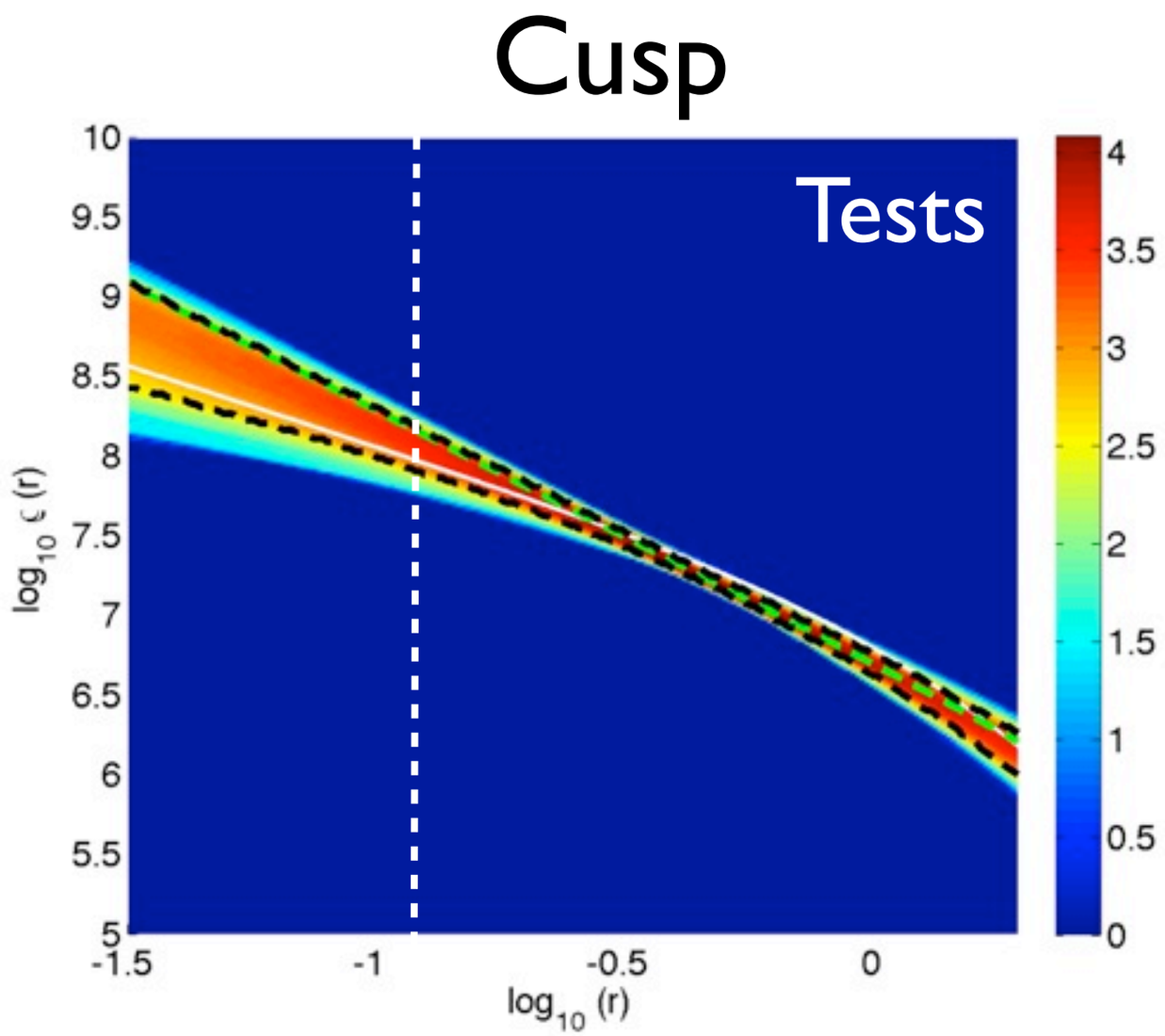
2. Observations | The halo density profile: dwarfs

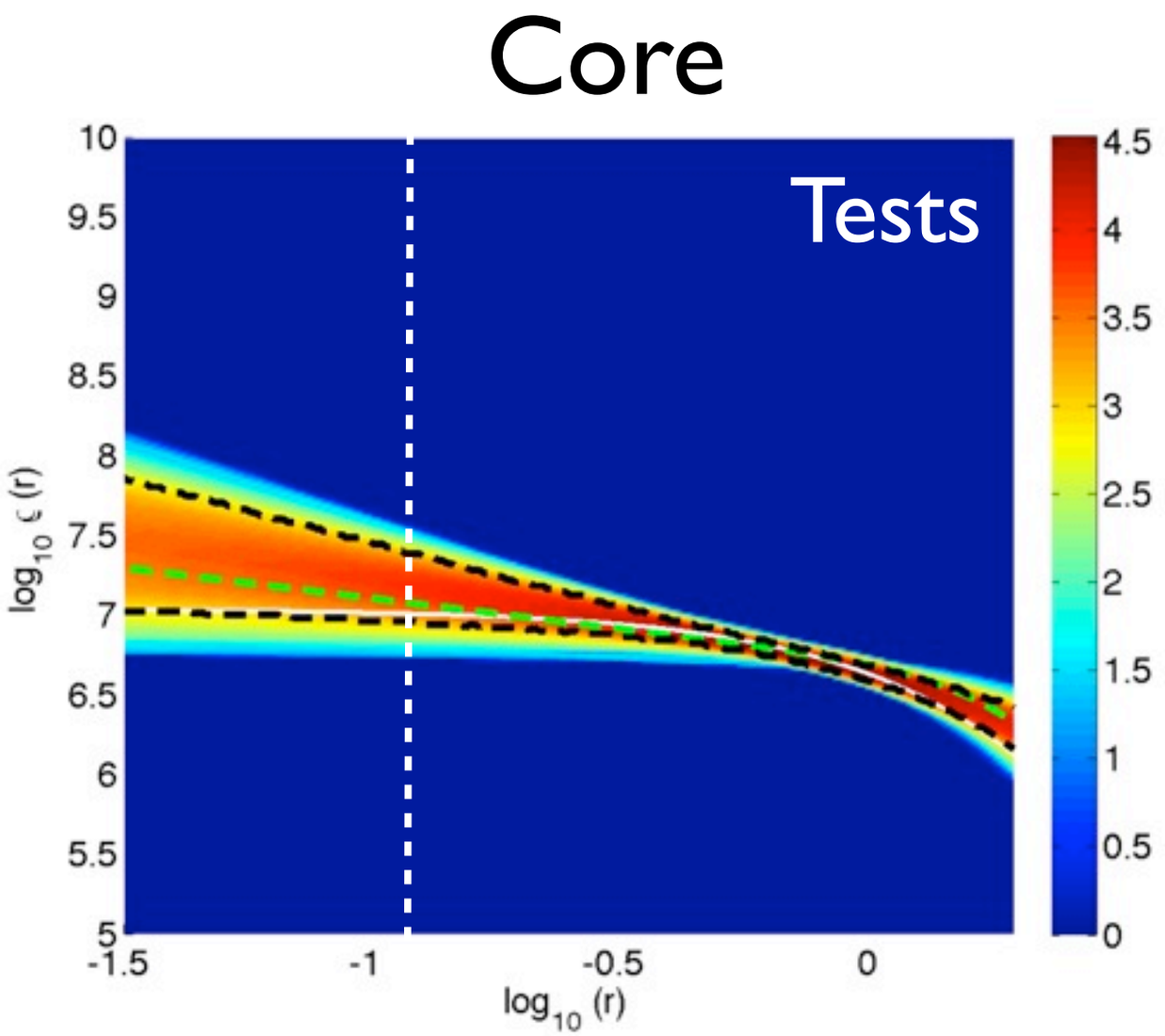


- Several systems now with 1000s of velocities
- Return to distribution function modelling
- Model data directly (no binning)
- Maximise information in the data
- Break degeneracies!

Wilkinson et al. in prep. 2011

2. Observations | The halo density profile: dwarfs



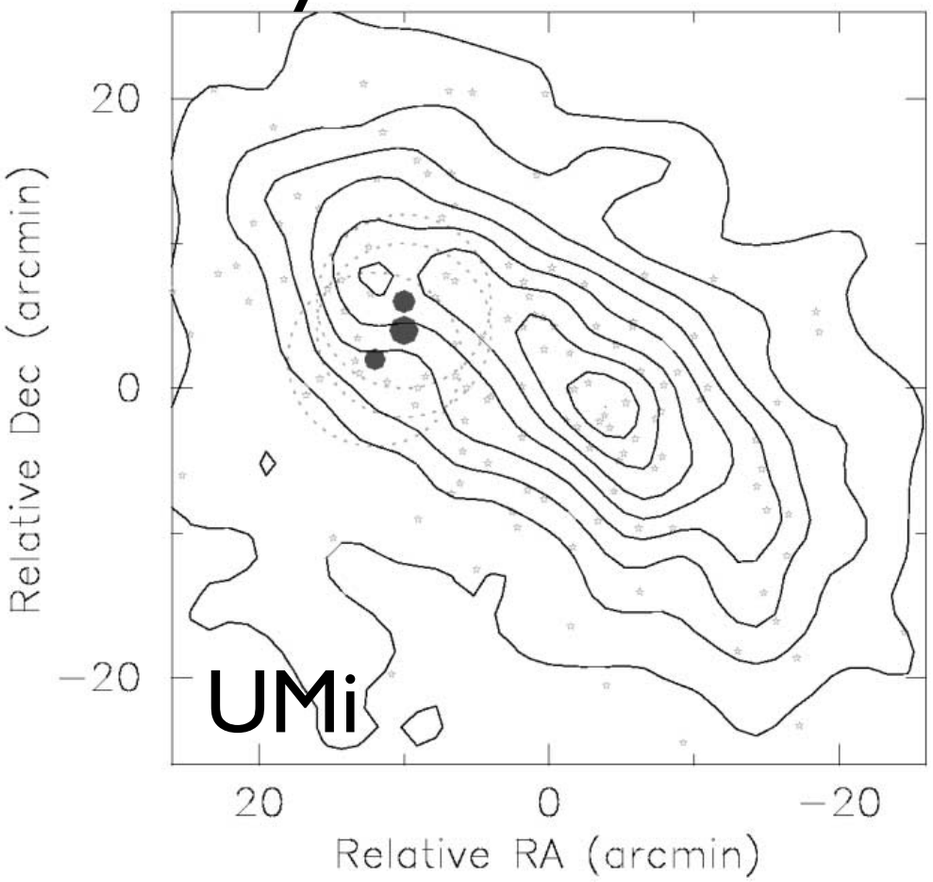


Wilkinson et al. in prep. 2011

2. Observations | The halo density profile: dwarfs

Hints of dark matter cores ...

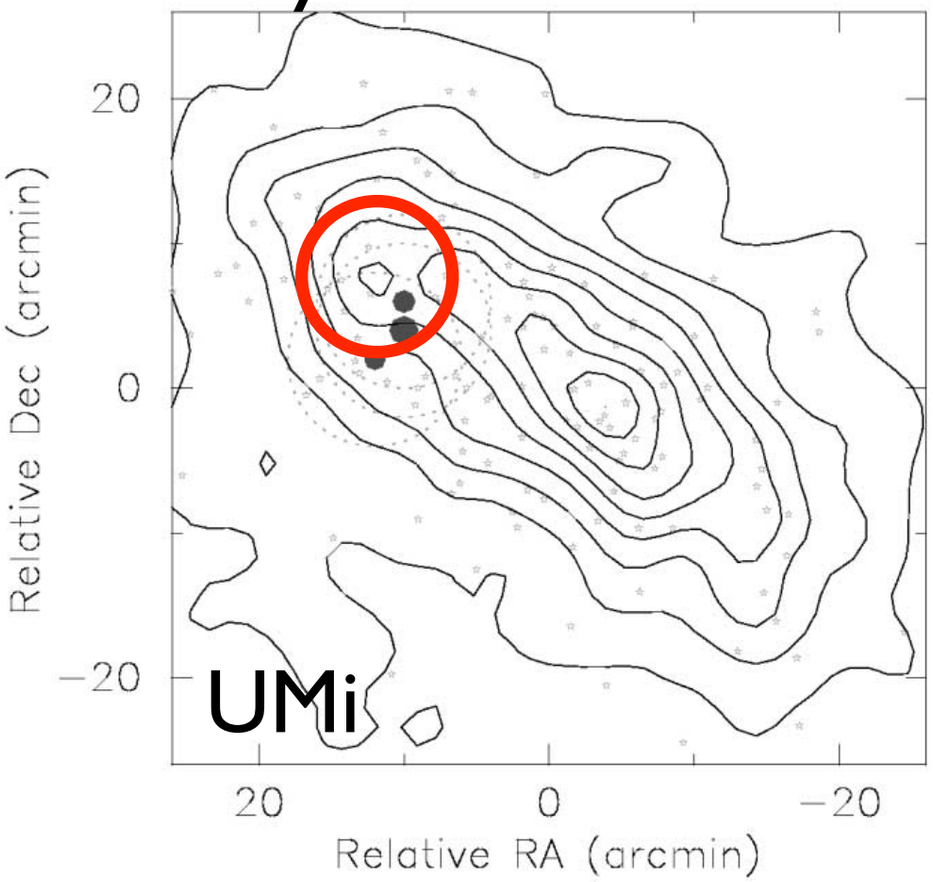
Kleyna et al. 2003



2. Observations | The halo density profile: dwarfs

Hints of dark matter cores ...

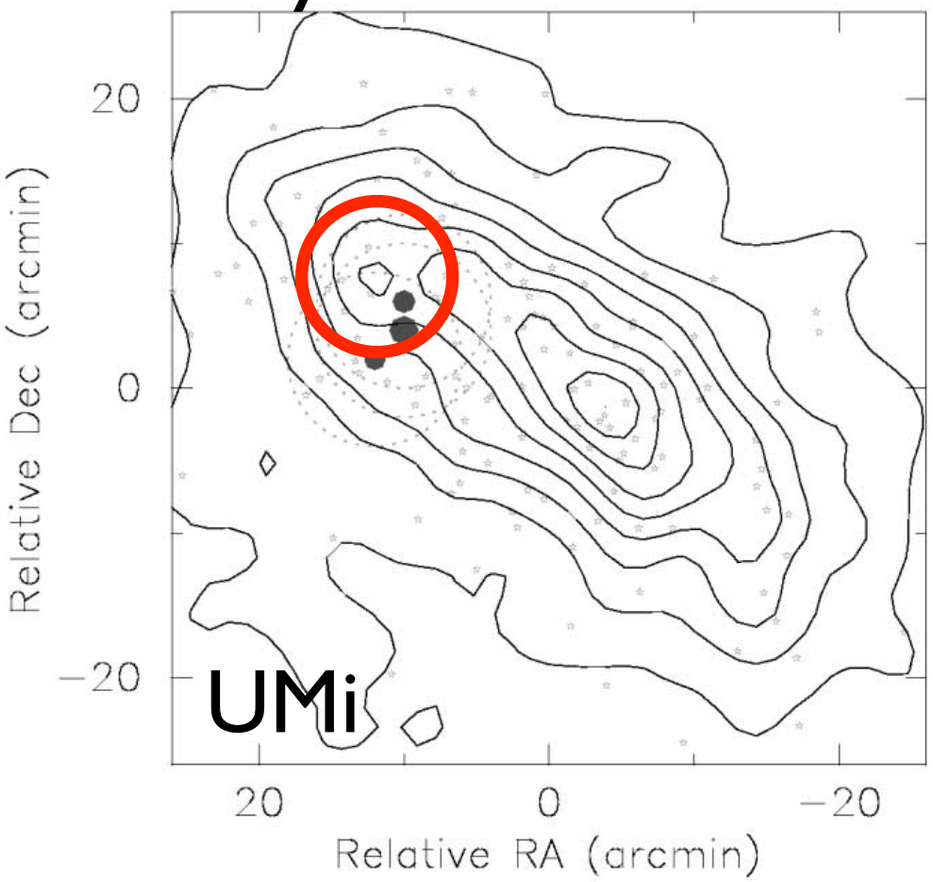
Kleyna et al. 2003



2. Observations | The halo density profile: dwarfs

Hints of dark matter cores ...

Kleyna et al. 2003

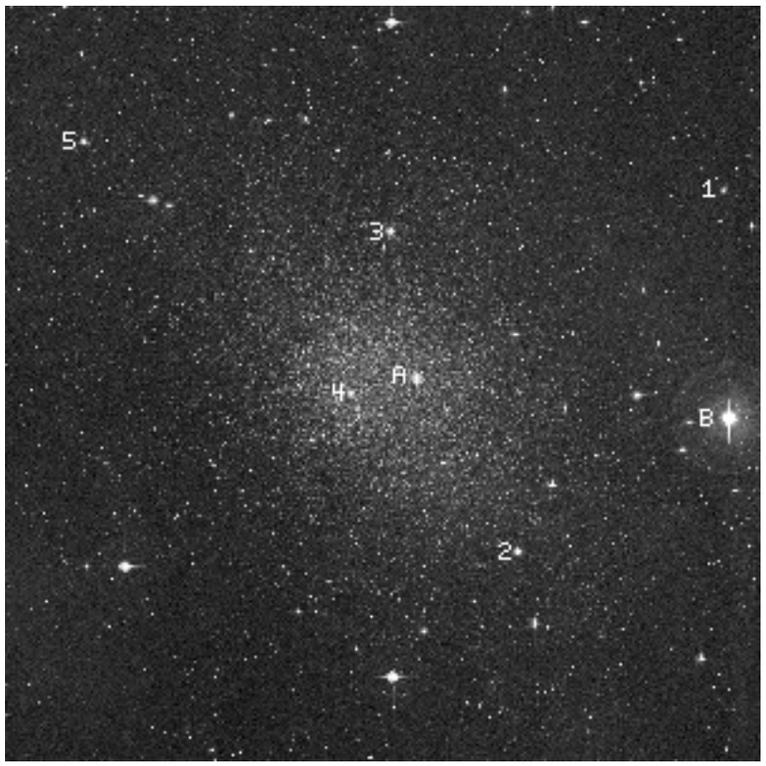


$$\Omega^2 = \frac{GM(r)}{r^3}$$

2. Observations | The halo density profile: dwarfs

Hints of dark matter cores ...

Goerdt et al. 2006



2. Observations | The halo density profile: dwarfs

Hints of dark matter cores ...

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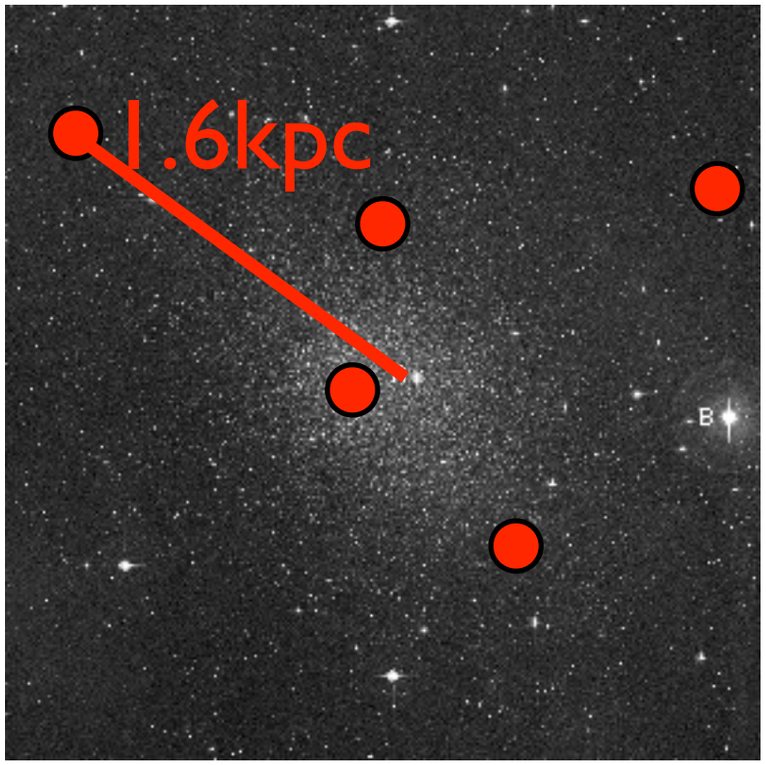
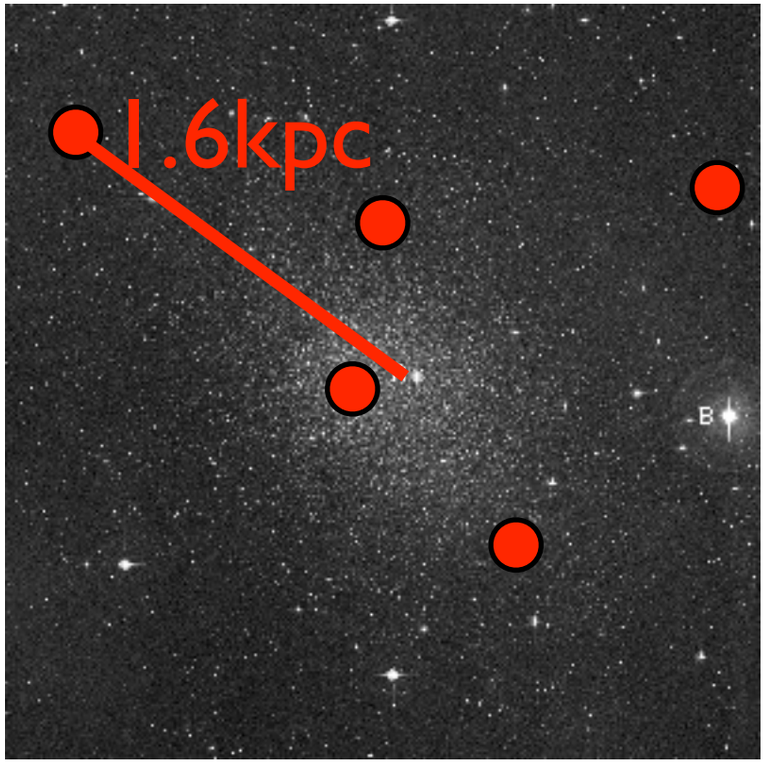


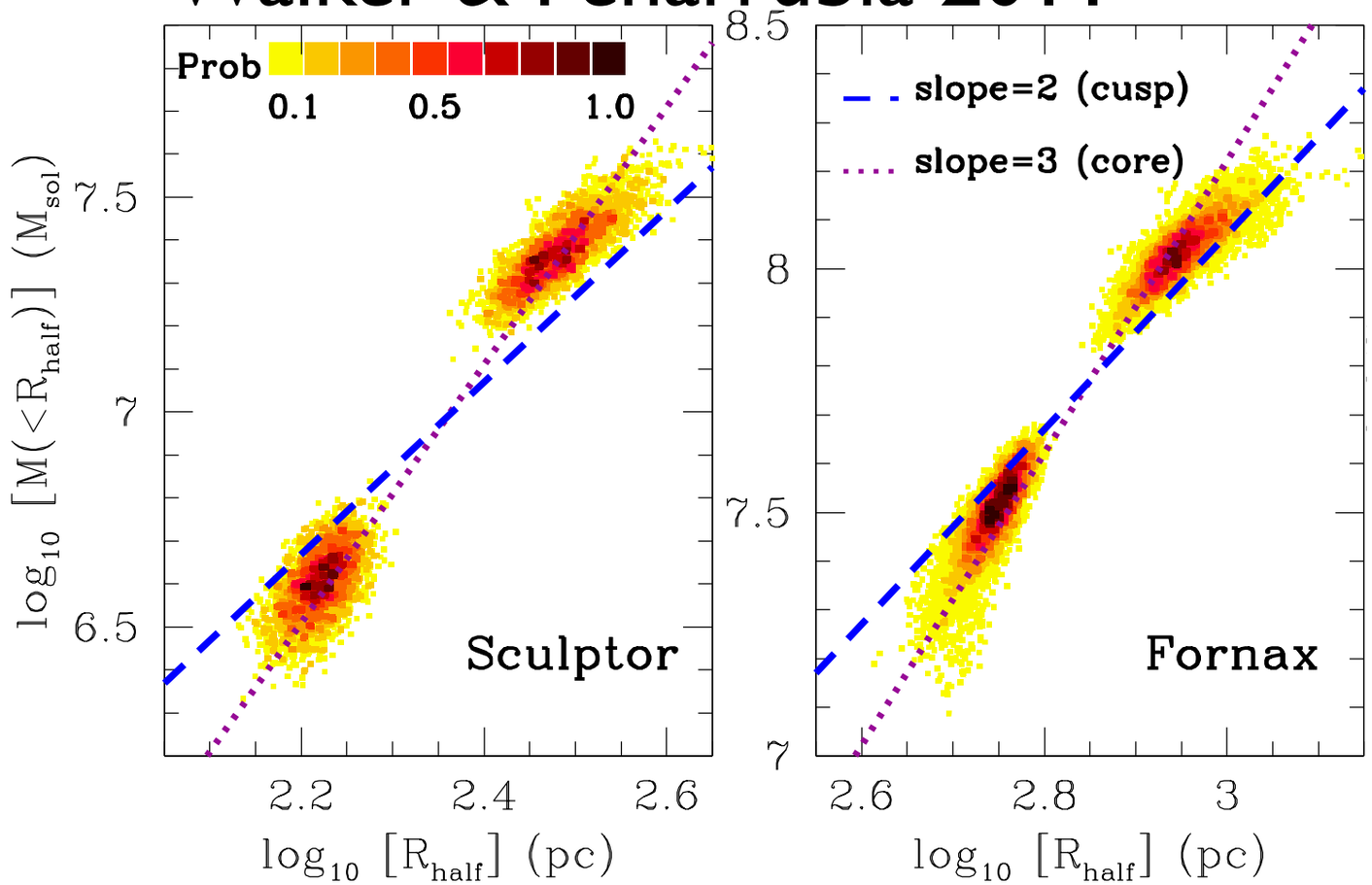
2. Observations | The halo density profile: dwarfs

Hints of dark matter cores ...

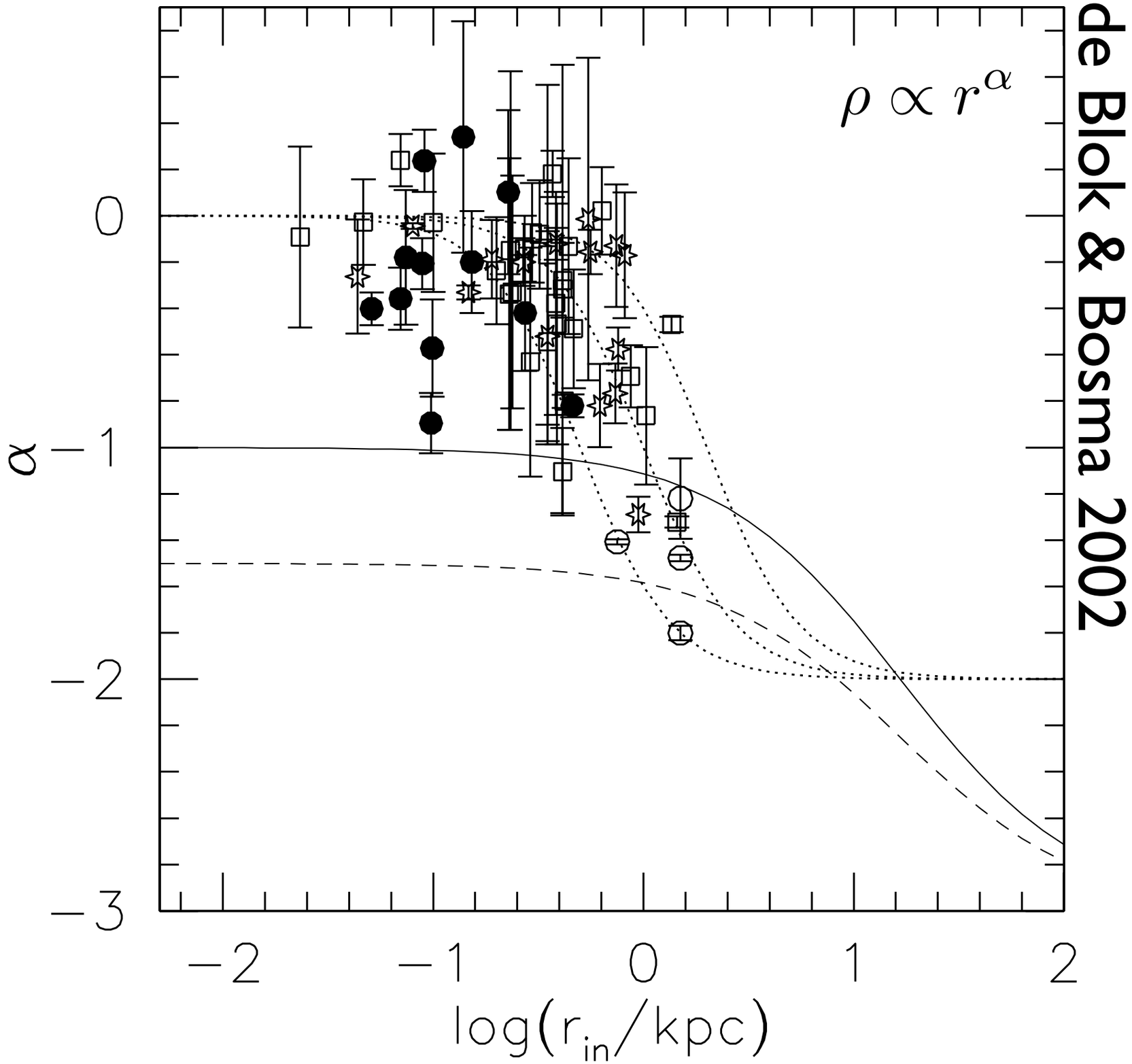
Goerdt et al. 2006



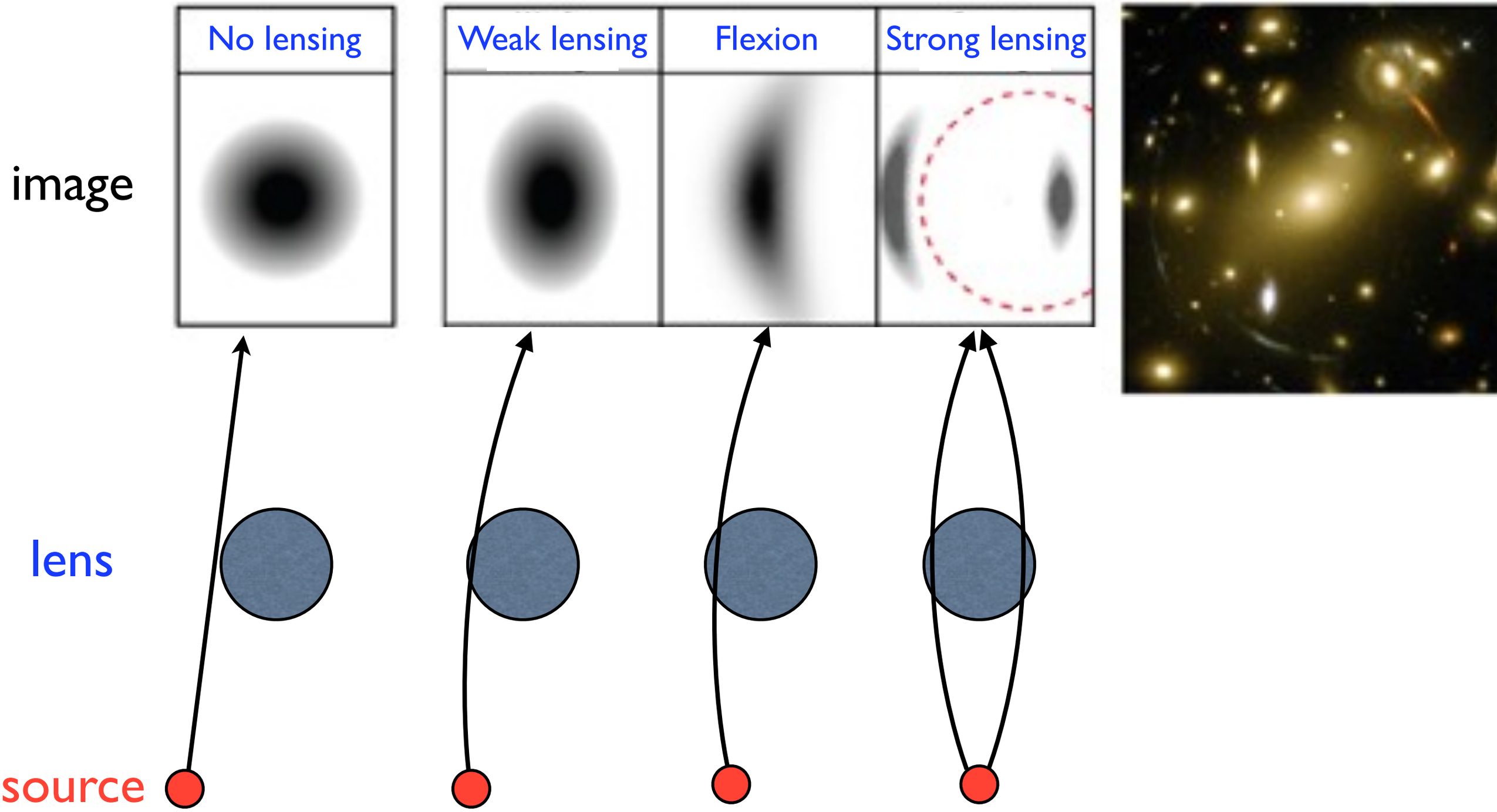
Walker & Peñarrubia 2011



2. Observations | The halo density profile: 'LSB' galaxies



2. Observations | The halo density profile: galaxies/clusters



Adam Amara; Credit for Abell 1669: NASA, ESA, and Johan Richard (Caltech, USA)

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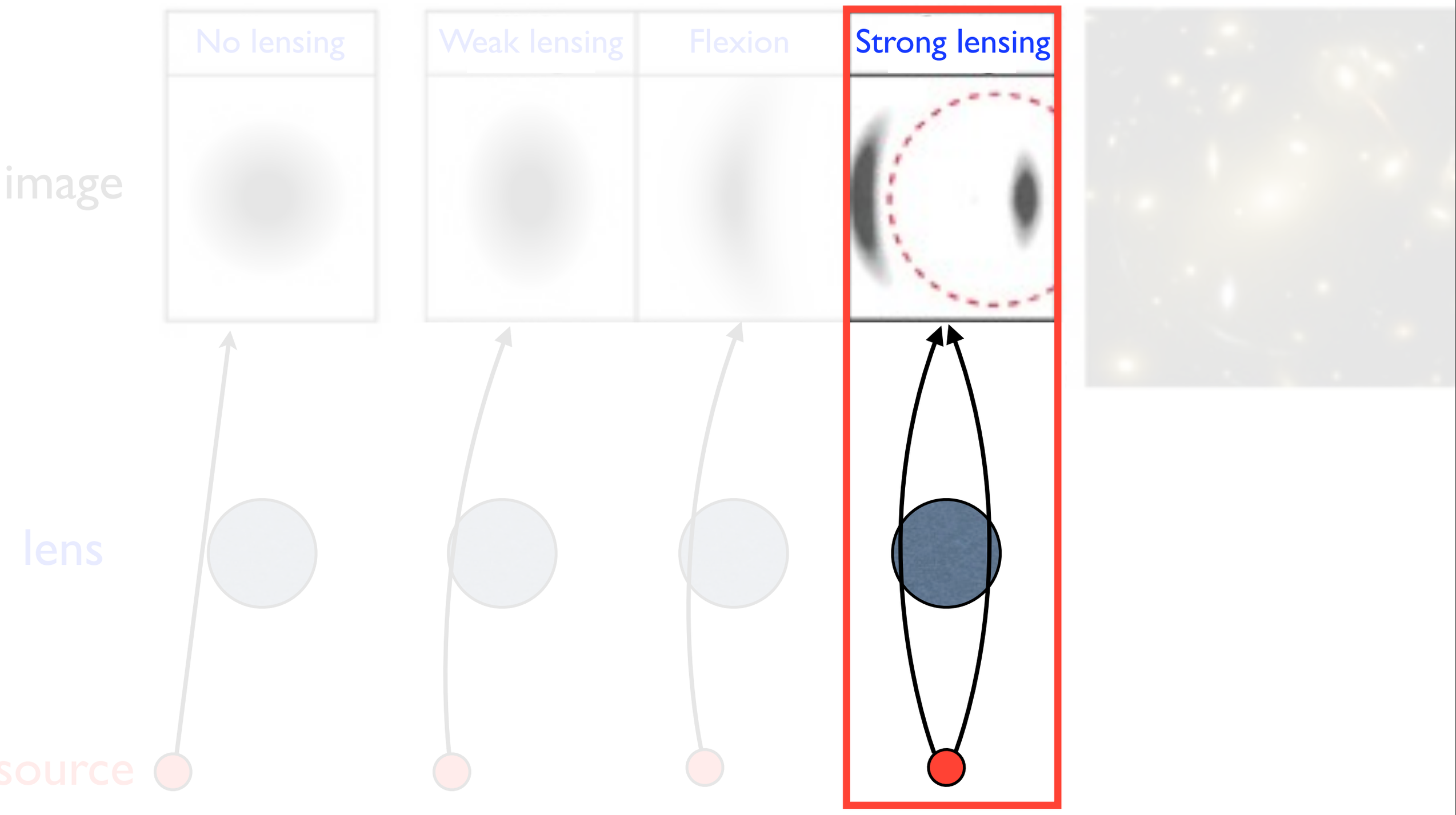

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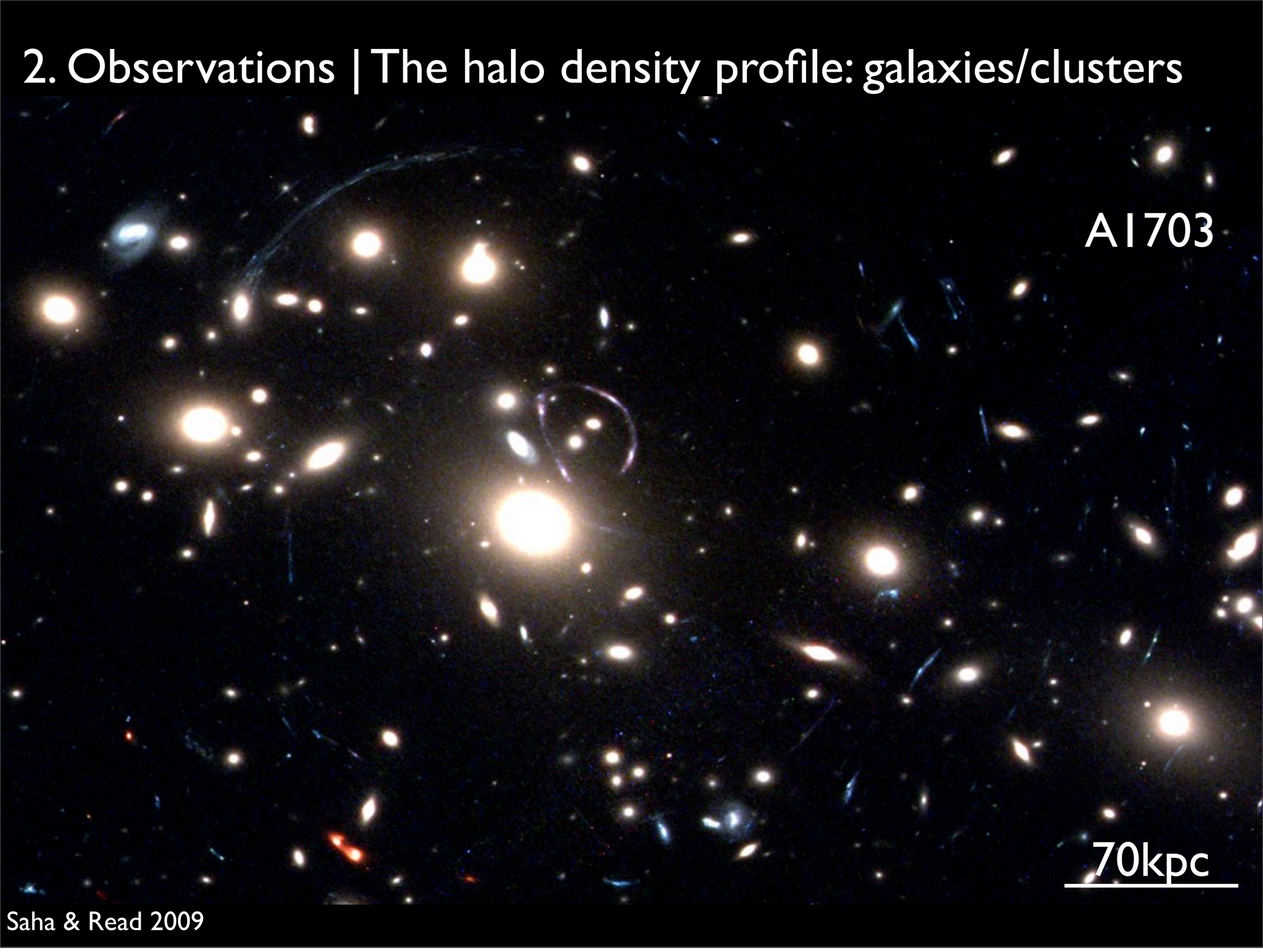
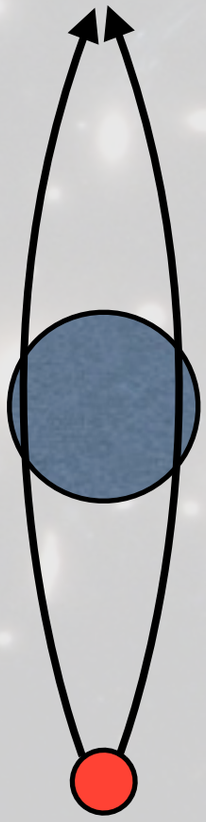


Saha & Read 2009

2. Observations | The halo density profile: galaxies/clusters

Lensing degeneracies ...

A1703



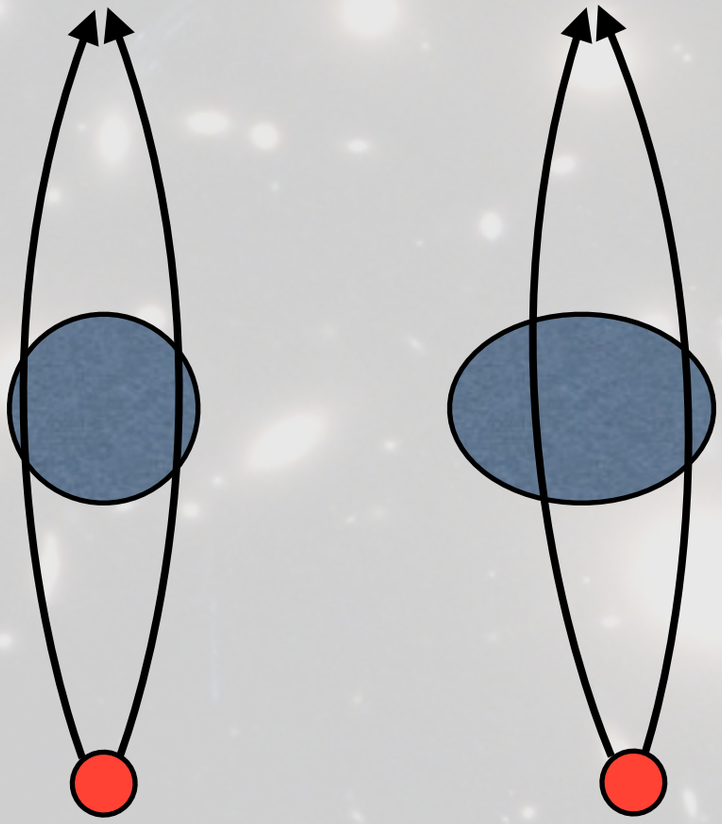
70kpc

Saha & Read 2009

2. Observations | The halo density profile: galaxies/clusters

Lensing degeneracies ...

A1703



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Saha & Read 2009

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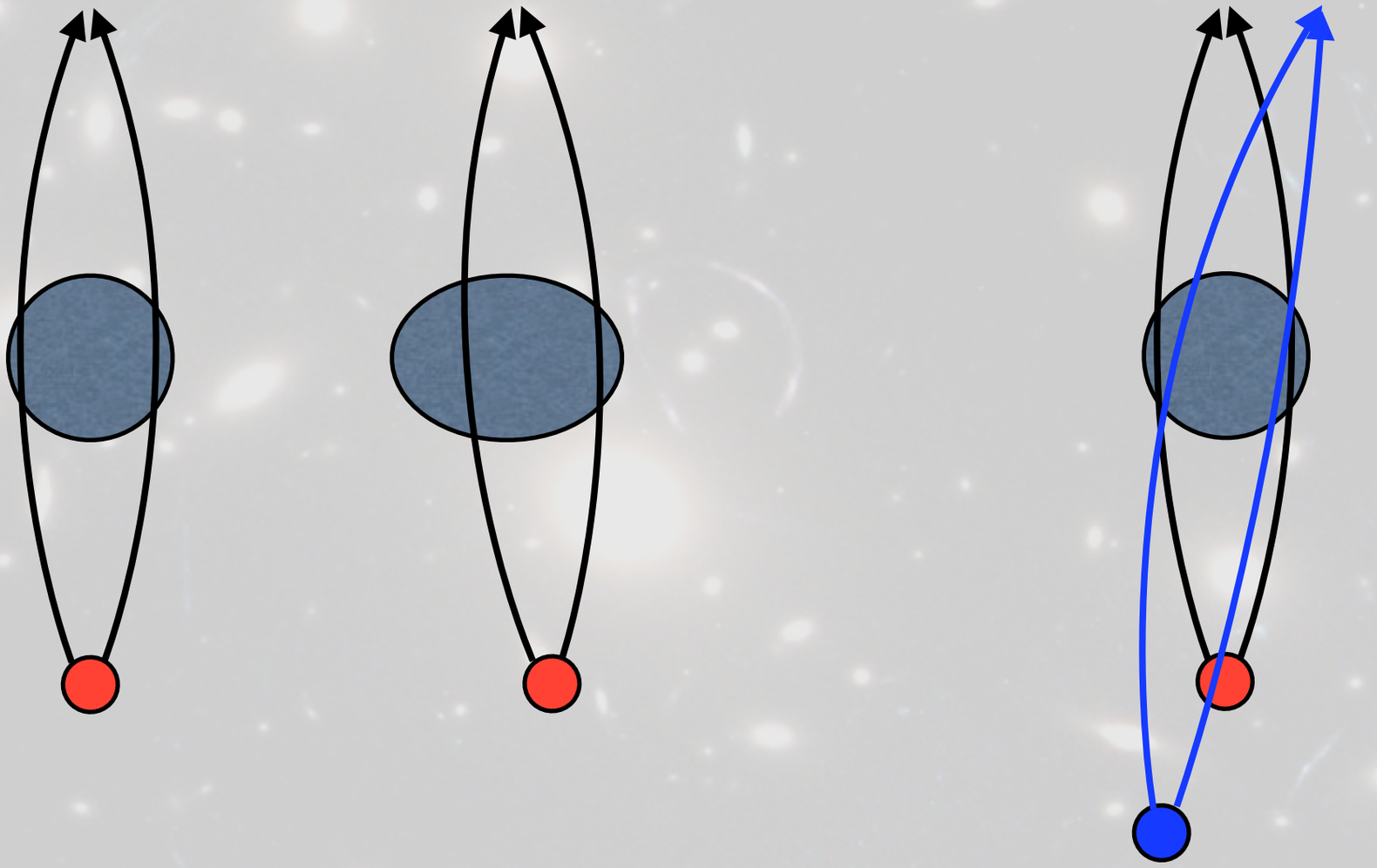

Saha & Read 2009

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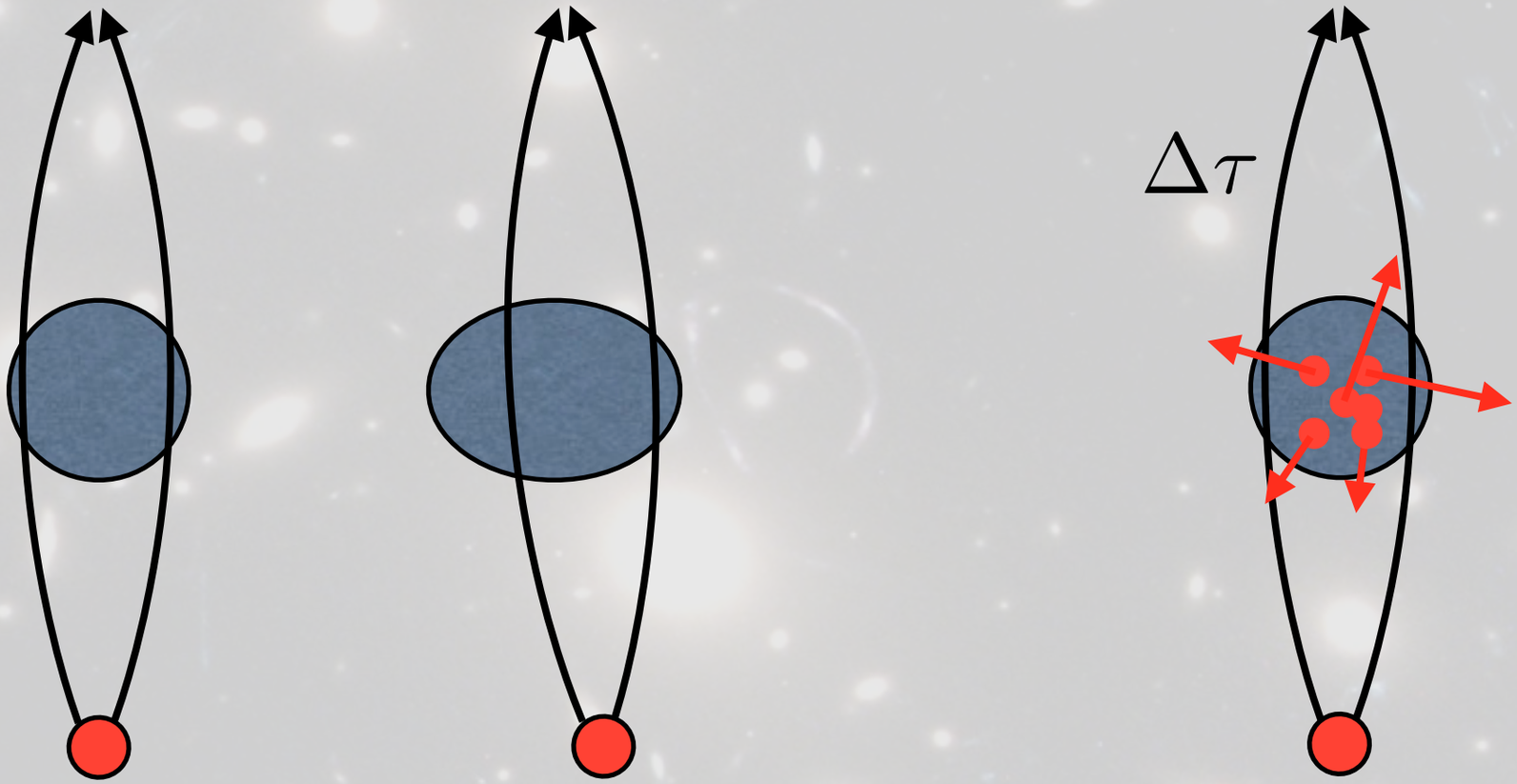

Galaxies

70kpc

Saha & Read 2009

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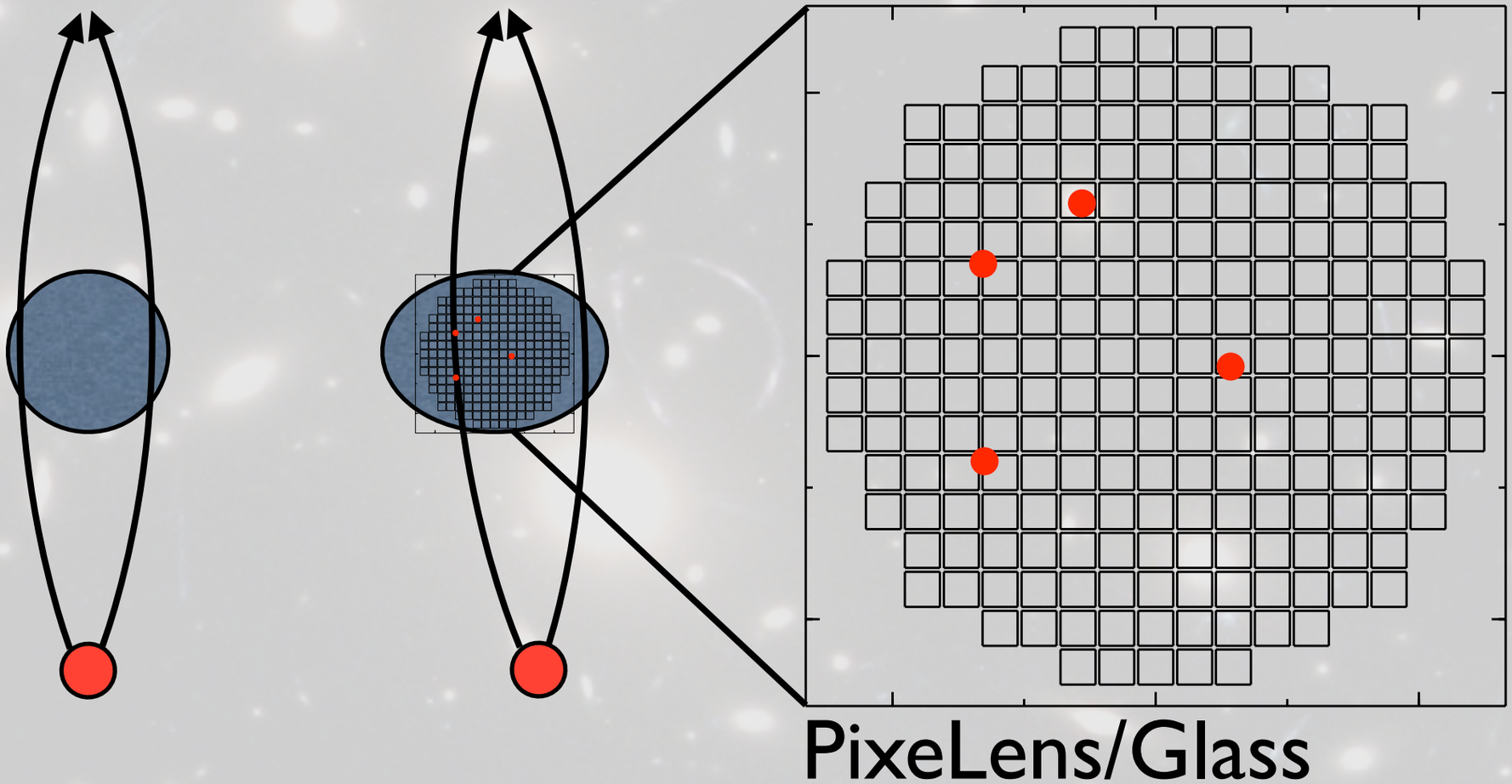

Saha & Read 2009

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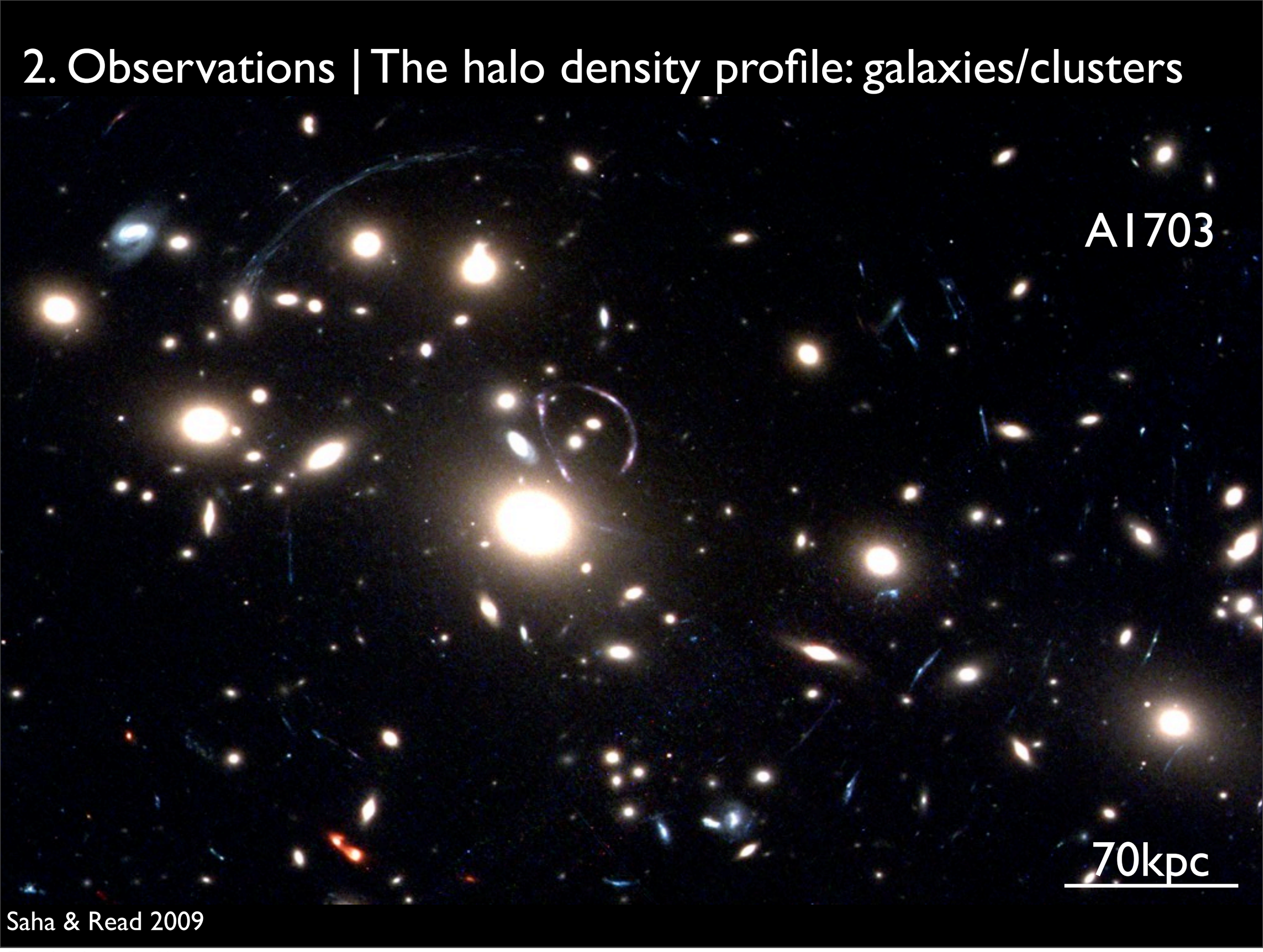

Saha & Read 2009

2. Observations | The halo density profile: galaxies/clusters

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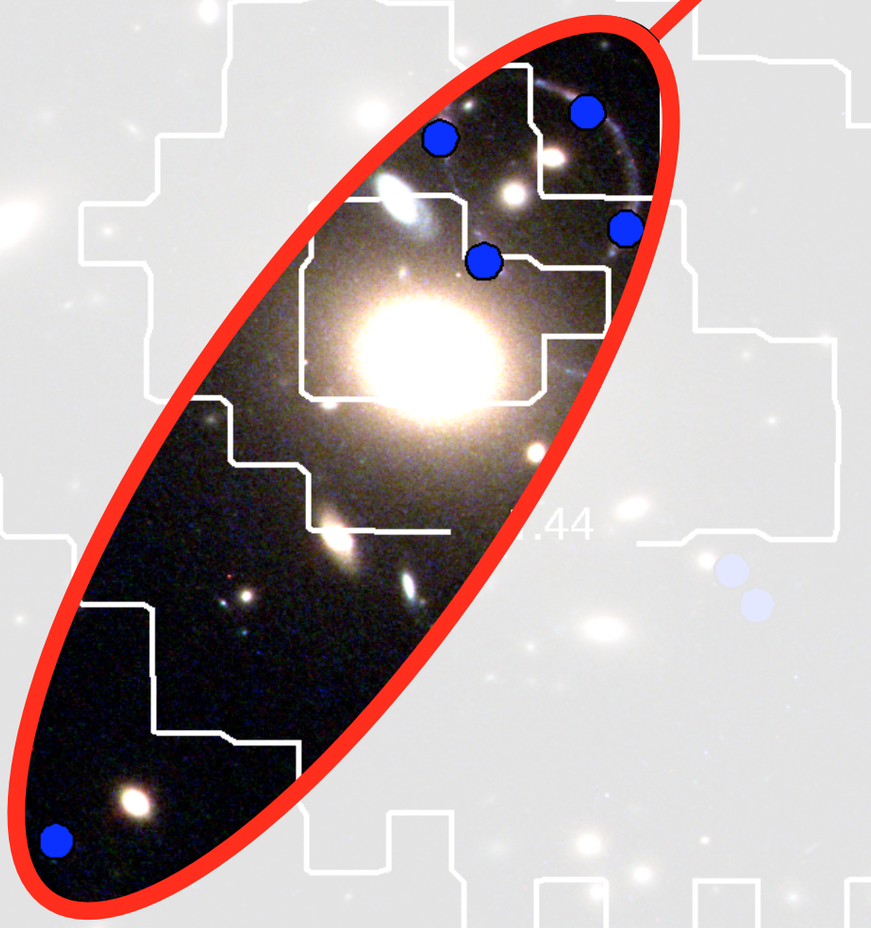
Quint at z=0.88; all others are at z=2.2-3 (the cluster is at z=0.28 ~1Gpc away)



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Saha & Read 2009

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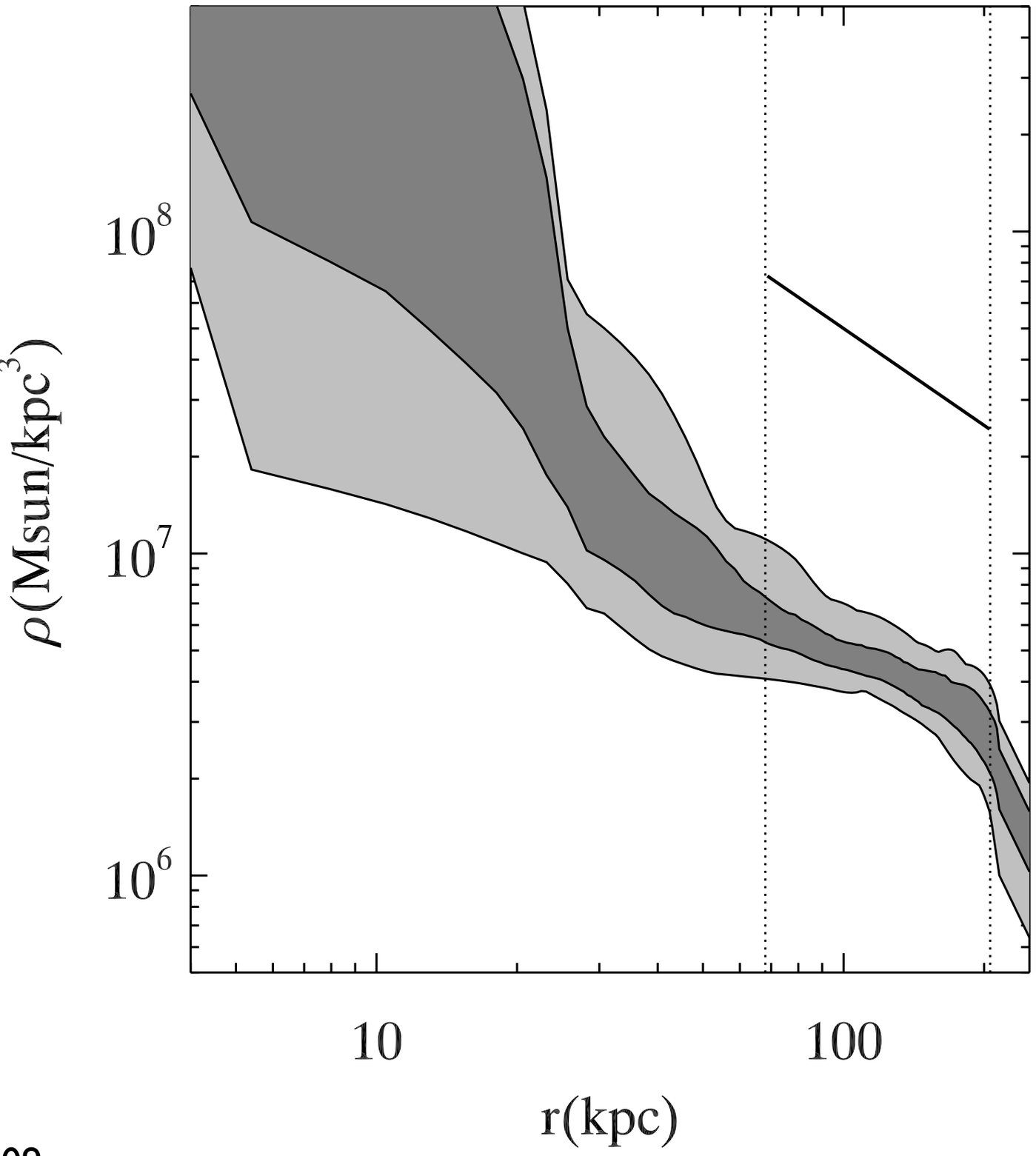

A1703; no quint

Saha & Read 2009

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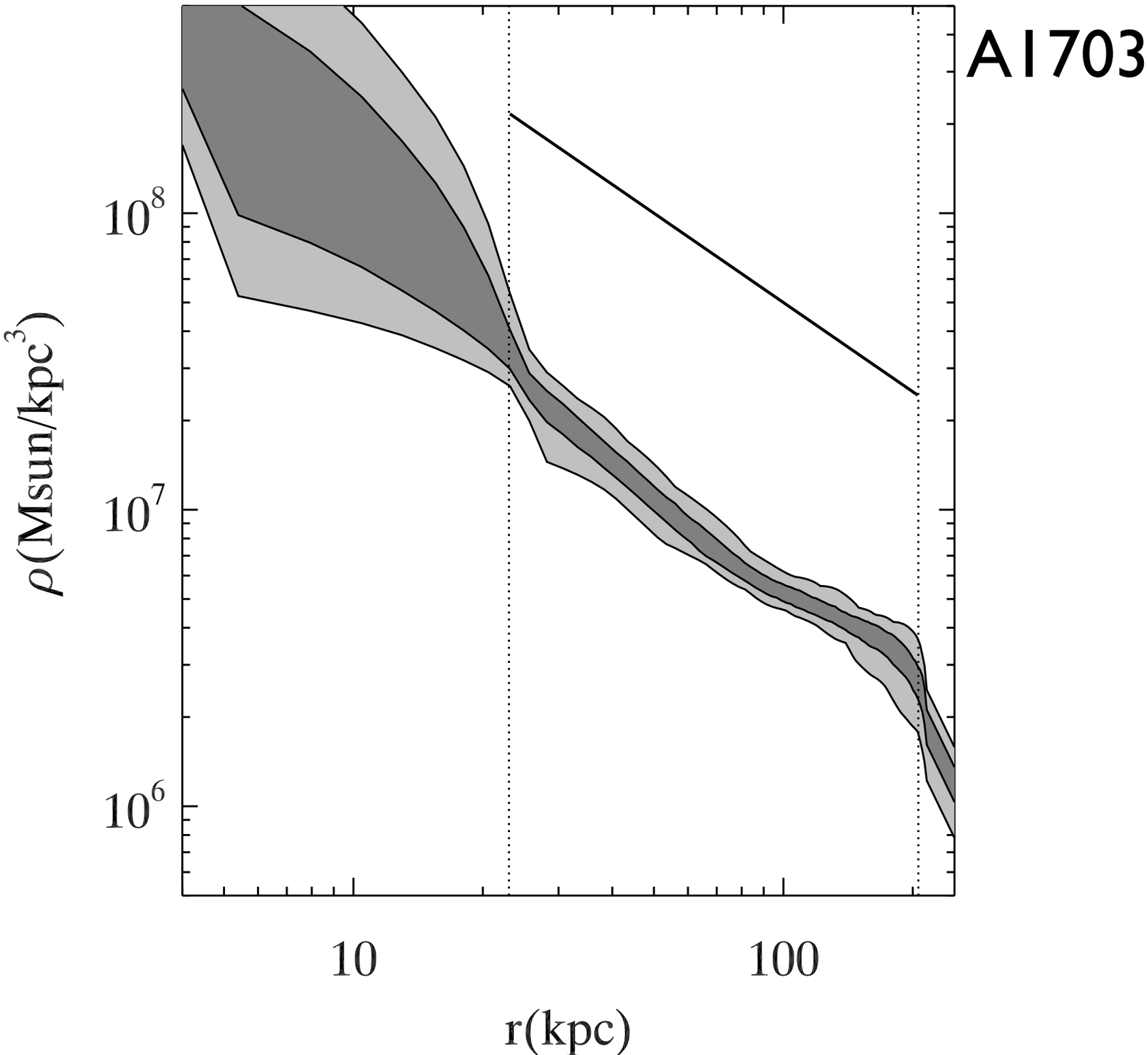

Saha & Read 2009

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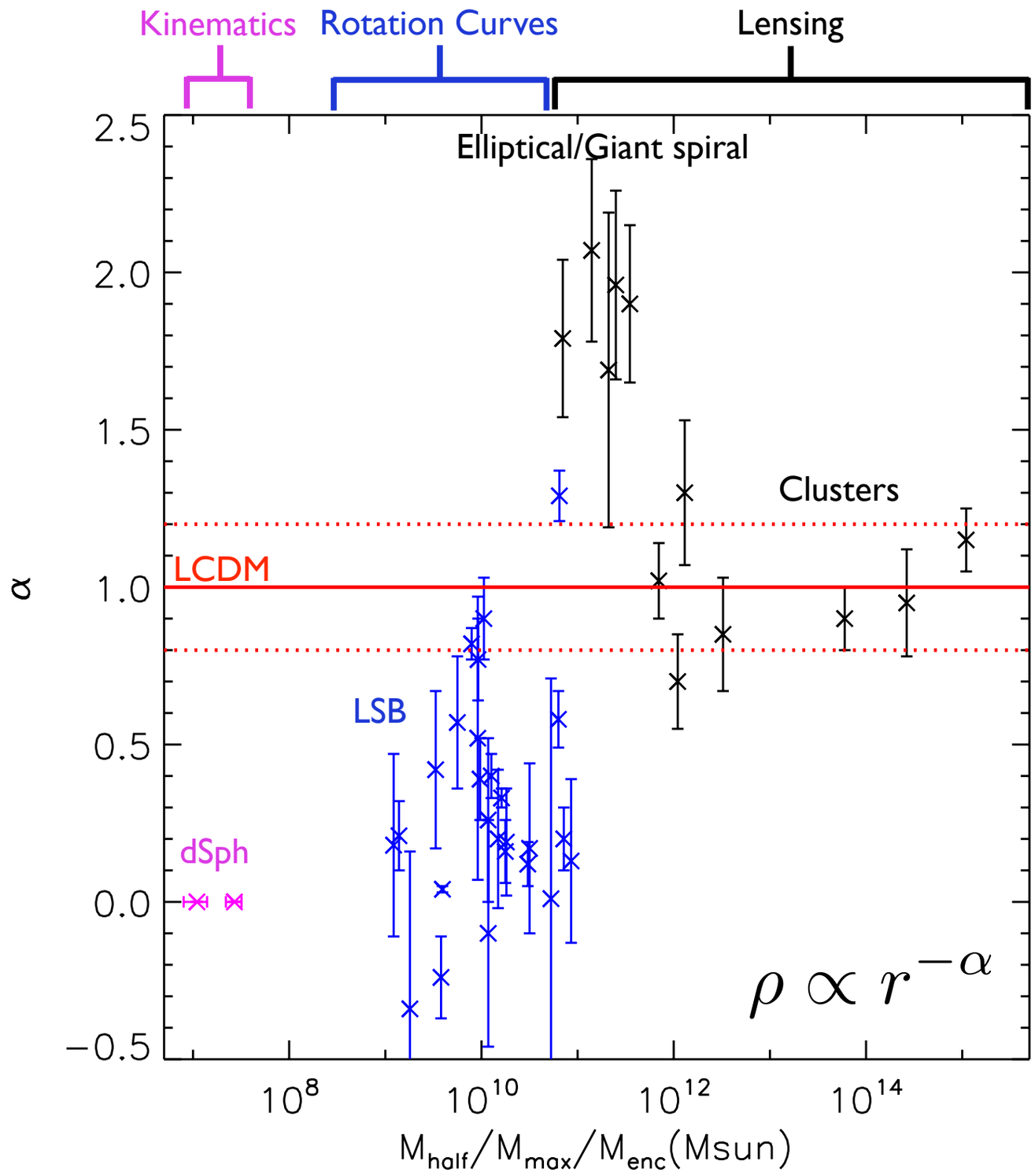

Read, Coles & Saha, 2007/09/ongoing

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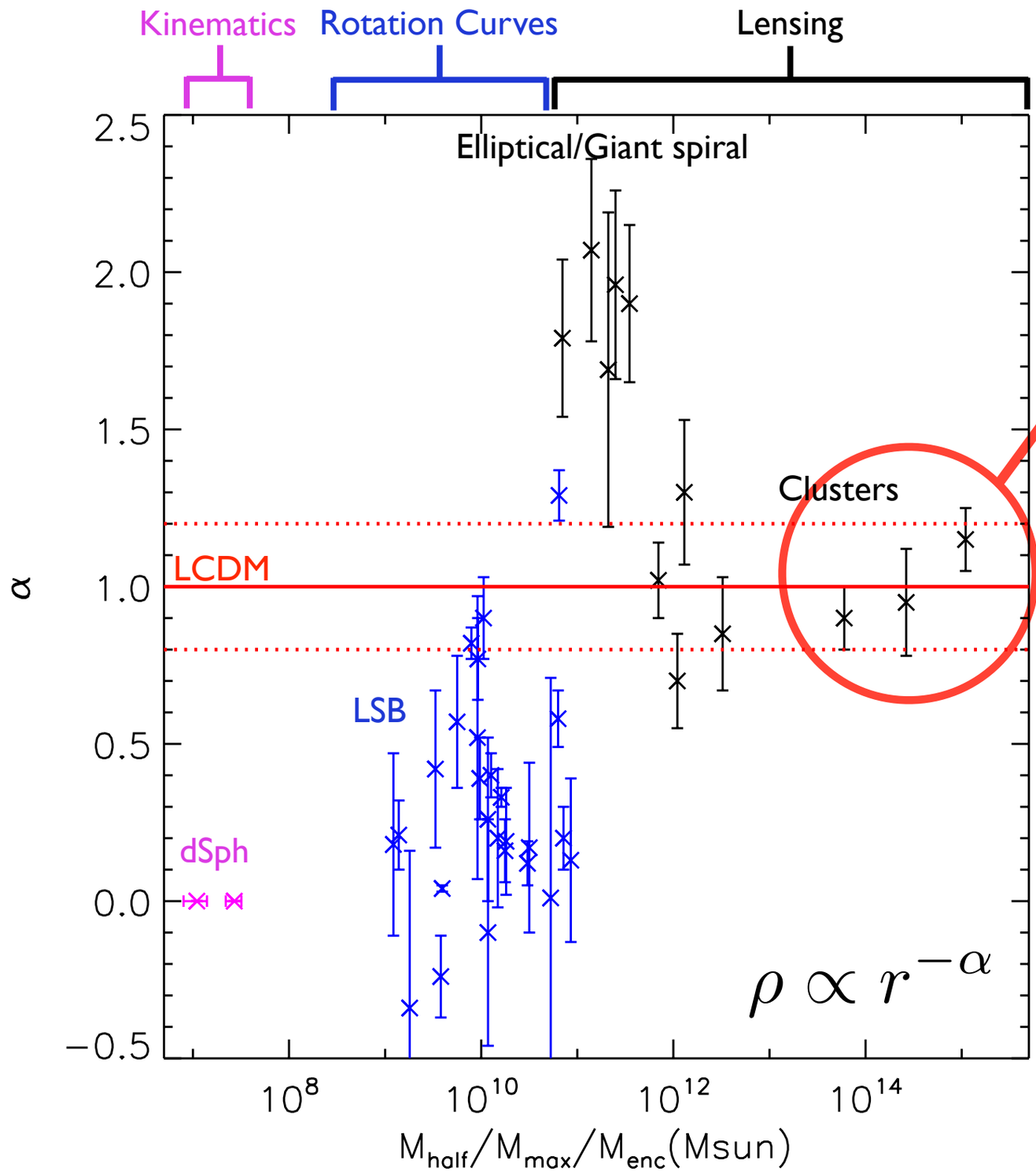

Excellent agreement with cold dark matter simulations

Read, Coles & Saha, 2007/09/ongoing

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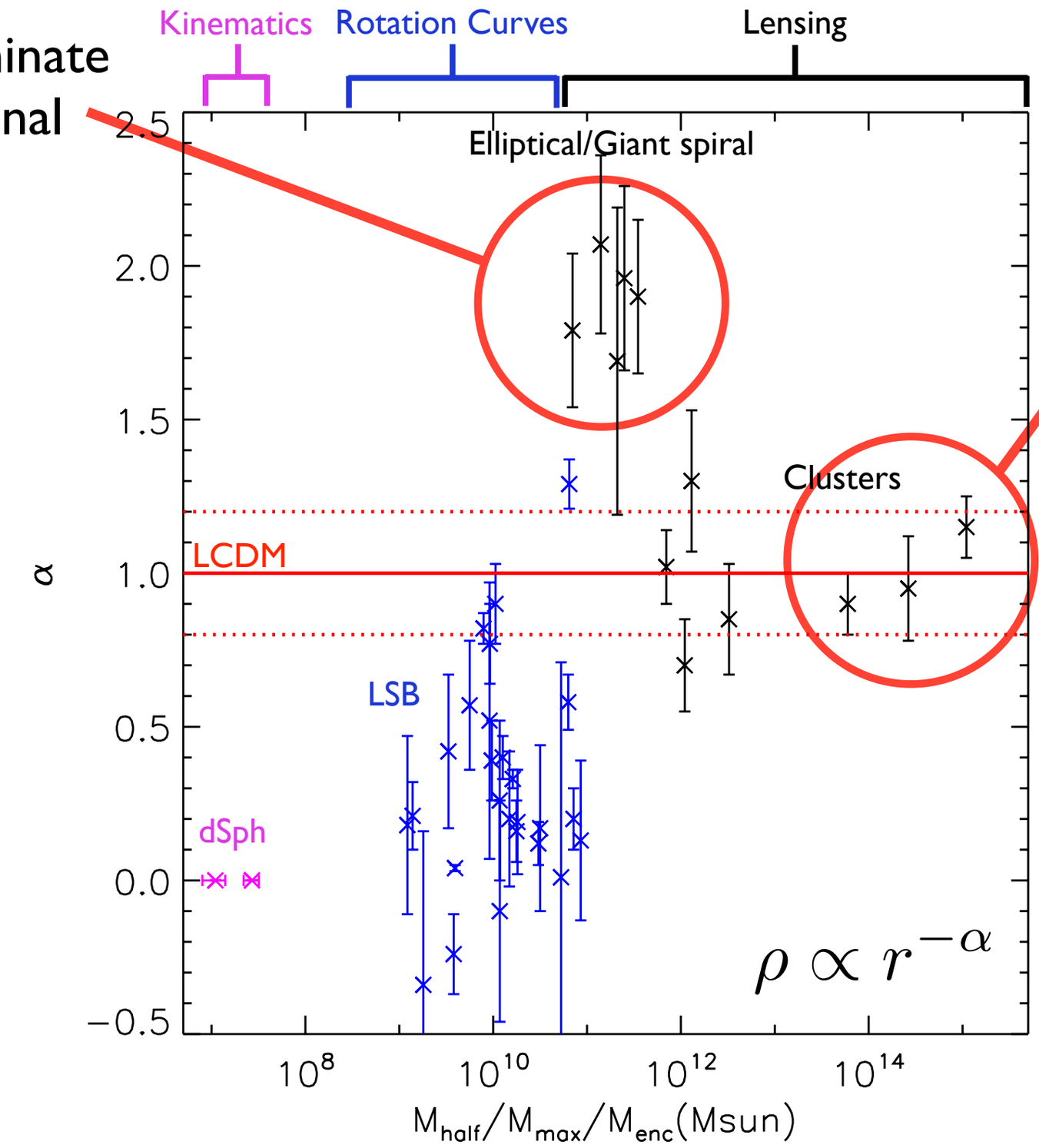
Baryons dominate the gravitational potential



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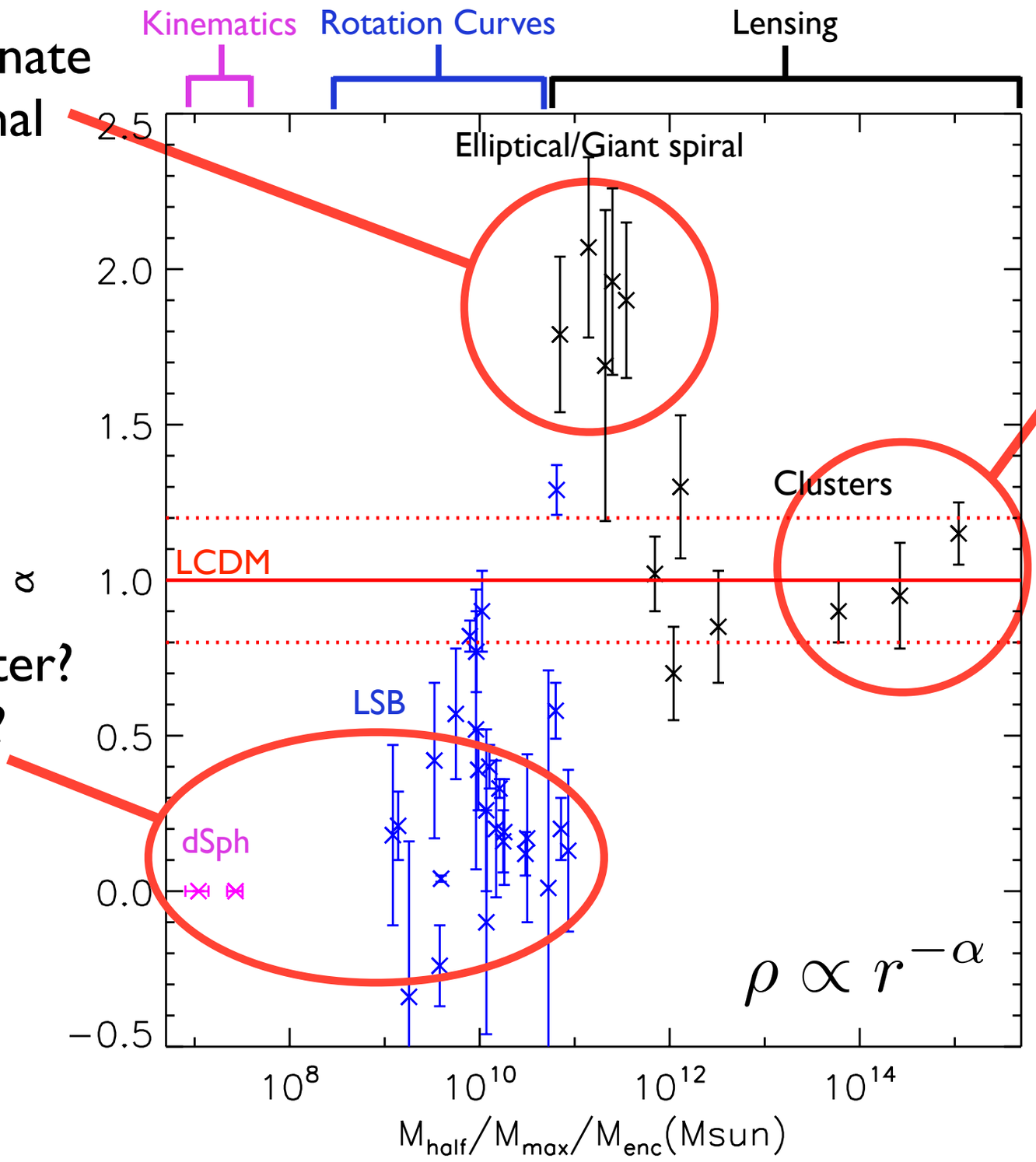

Excellent agreement with cold dark matter simulations

Exotic dark matter?
Baryonic effects?

Read, Coles & Saha, 2007/09/ongoing

3. Hunting for DM | The importance of astrophysics

Direct detection:

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

Particle physics | Astrophysics

3. Hunting for DM | The importance of astrophysics

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Need simulations [see previous]

Particle physics | Astrophysics

3. Hunting for DM | The importance of astrophysics

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But can measure this!

Need simulations [see previous]

Particle physics | Astrophysics

3. Hunting for DM | The importance of astrophysics

Direct detection:

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

Particle physics | Astrophysics

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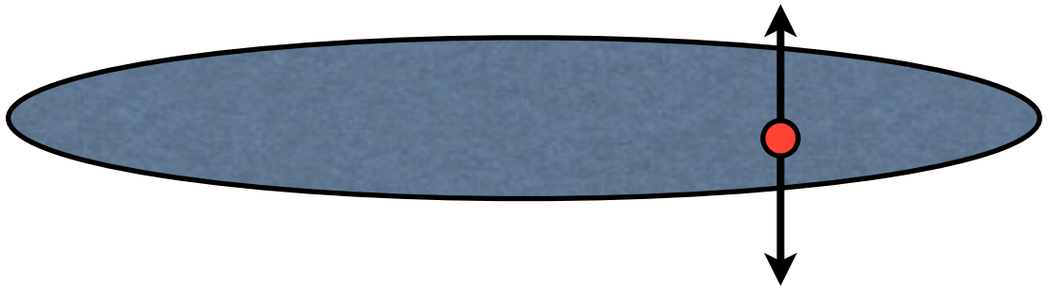
Indirect detection:

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \frac{\langle \sigma_{\rm ann} v \rangle}{2 m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \int_{\Delta\Omega} \int \rho_{\rm DM}^2 \, dl \, d\Omega$$

Particle physics | Astrophysics

3. Hunting for DM | The local dark matter distribution

1. Local measure:

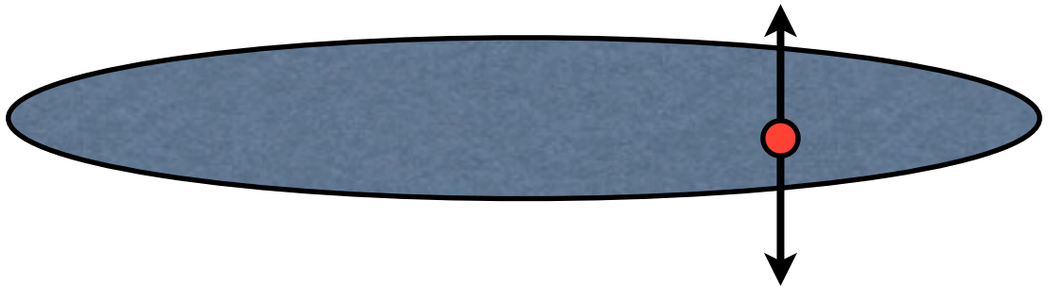


$\rho_{\rm dm}$

Garbari, Read & Lake 2011, MNRAS accepted ... and see Silvia's talk!

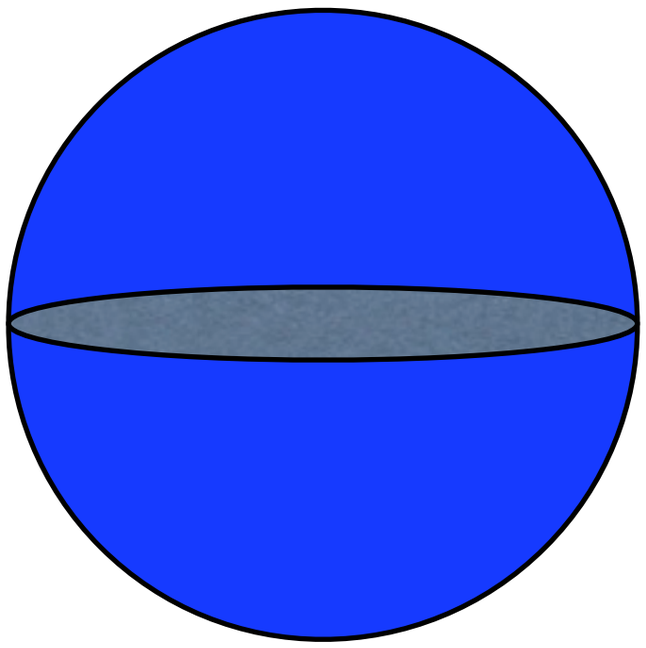
3. Hunting for DM | The local dark matter distribution

1. Local measure:



$\rho_{\rm dm}$

2. Global measure: $v^2 \sim GM(r)/r$



$\rho_{\rm dm,ext}$

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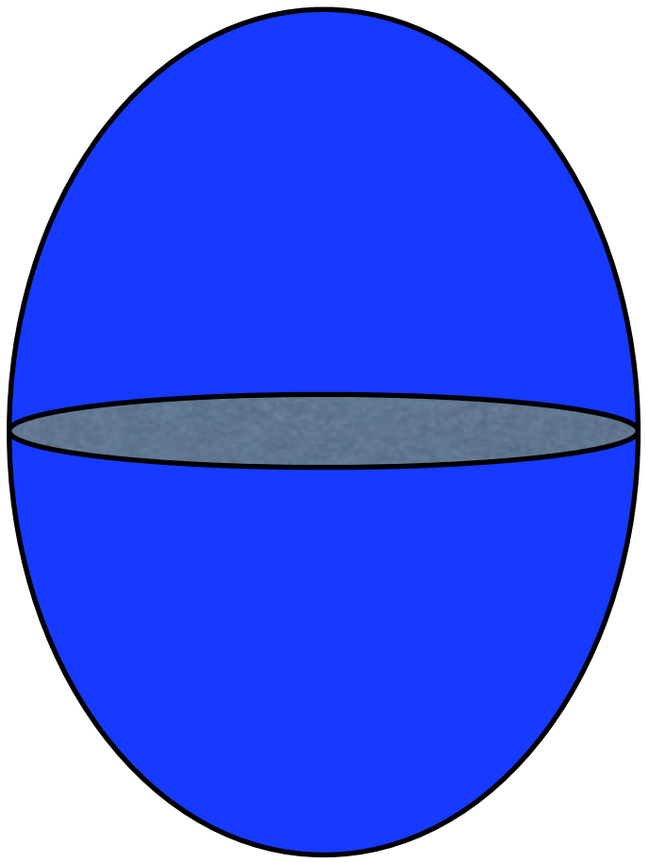
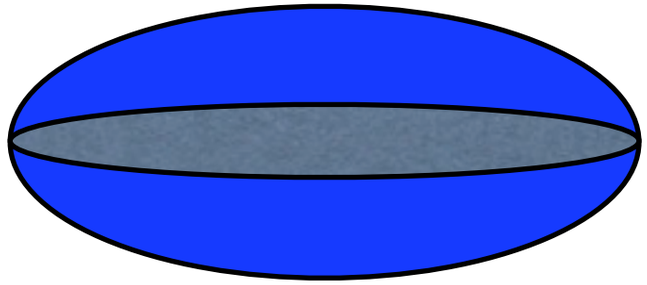
3. Hunting for DM | The local dark matter distribution

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



Prolate

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



Oblate/dark disc

Garbari, Read & Lake 2011, MNRAS accepted ... and see Silvia's talk!

3. Hunting for DM | The local dark matter distribution

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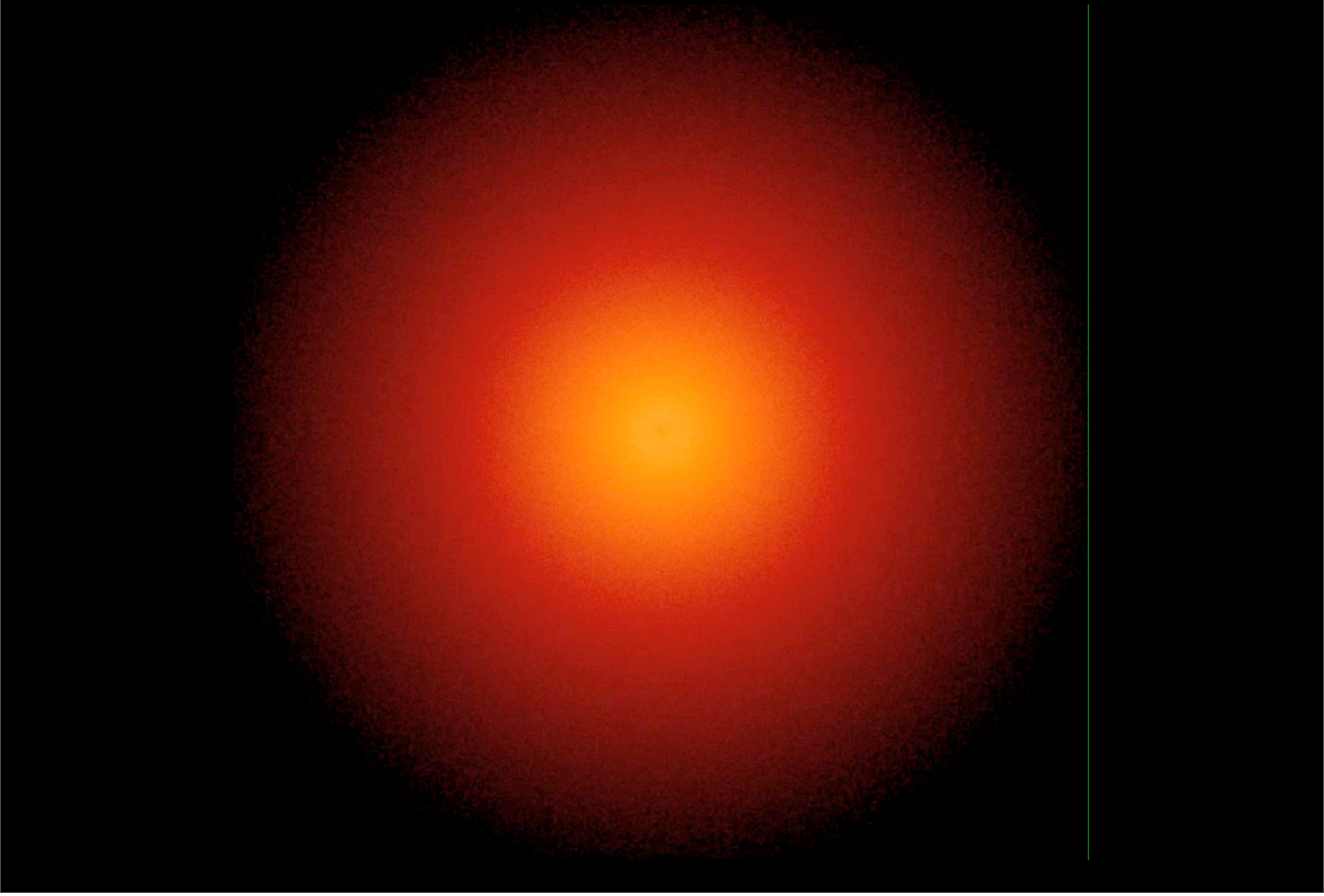

3. Hunting for DM | The local dark matter distribution

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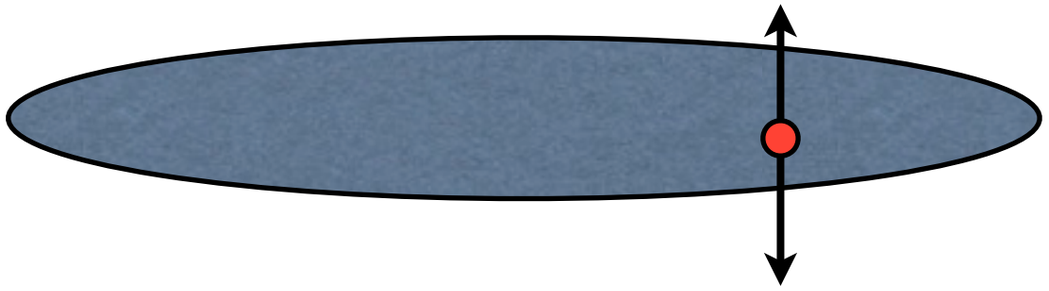
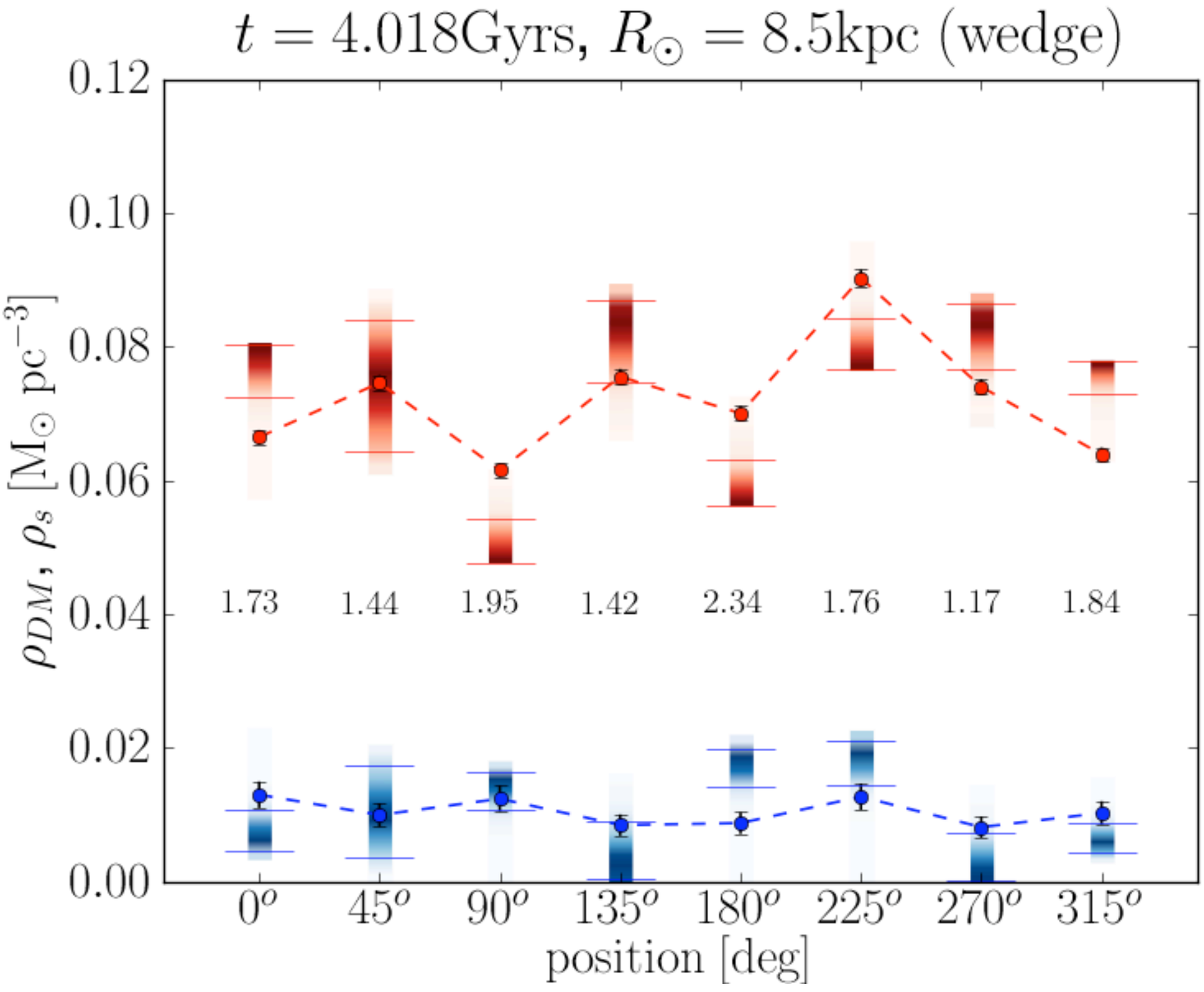
The catch-22:



Need to sample above the plane to see the DM

Garbari, Read & Lake 2011, MNRAS accepted ... and see Silvia's talk!

3. Hunting for DM | The local dark matter distribution



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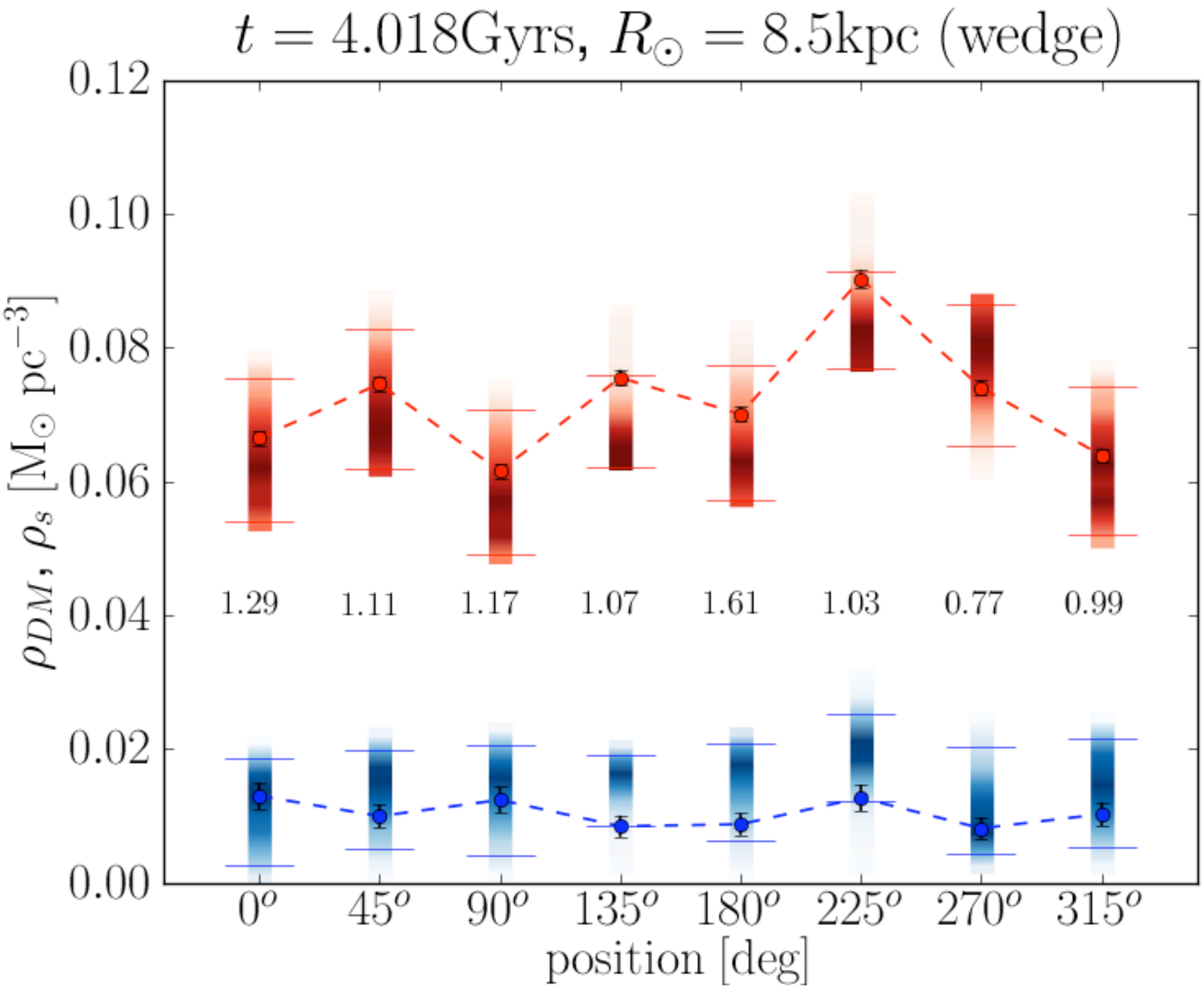

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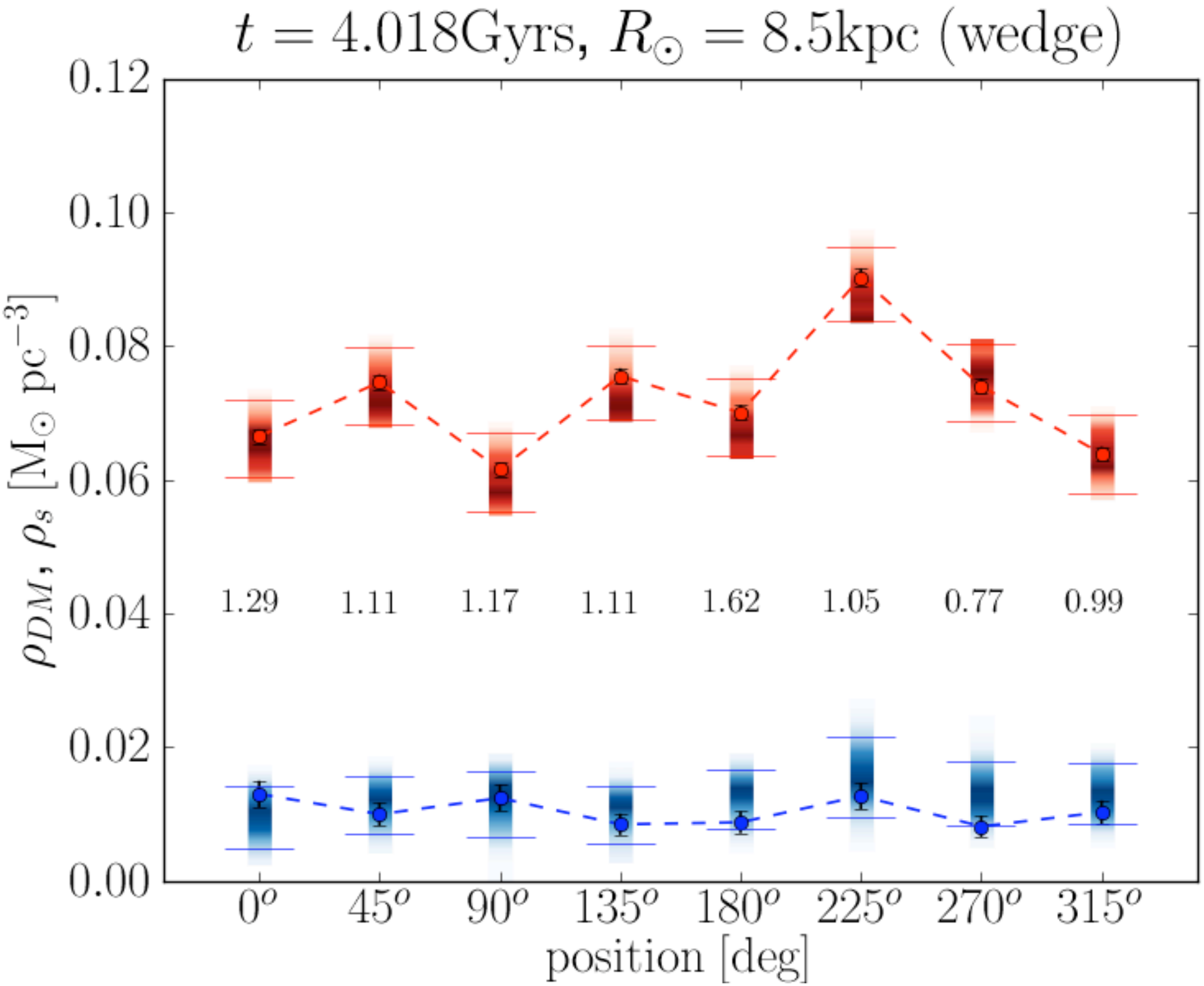

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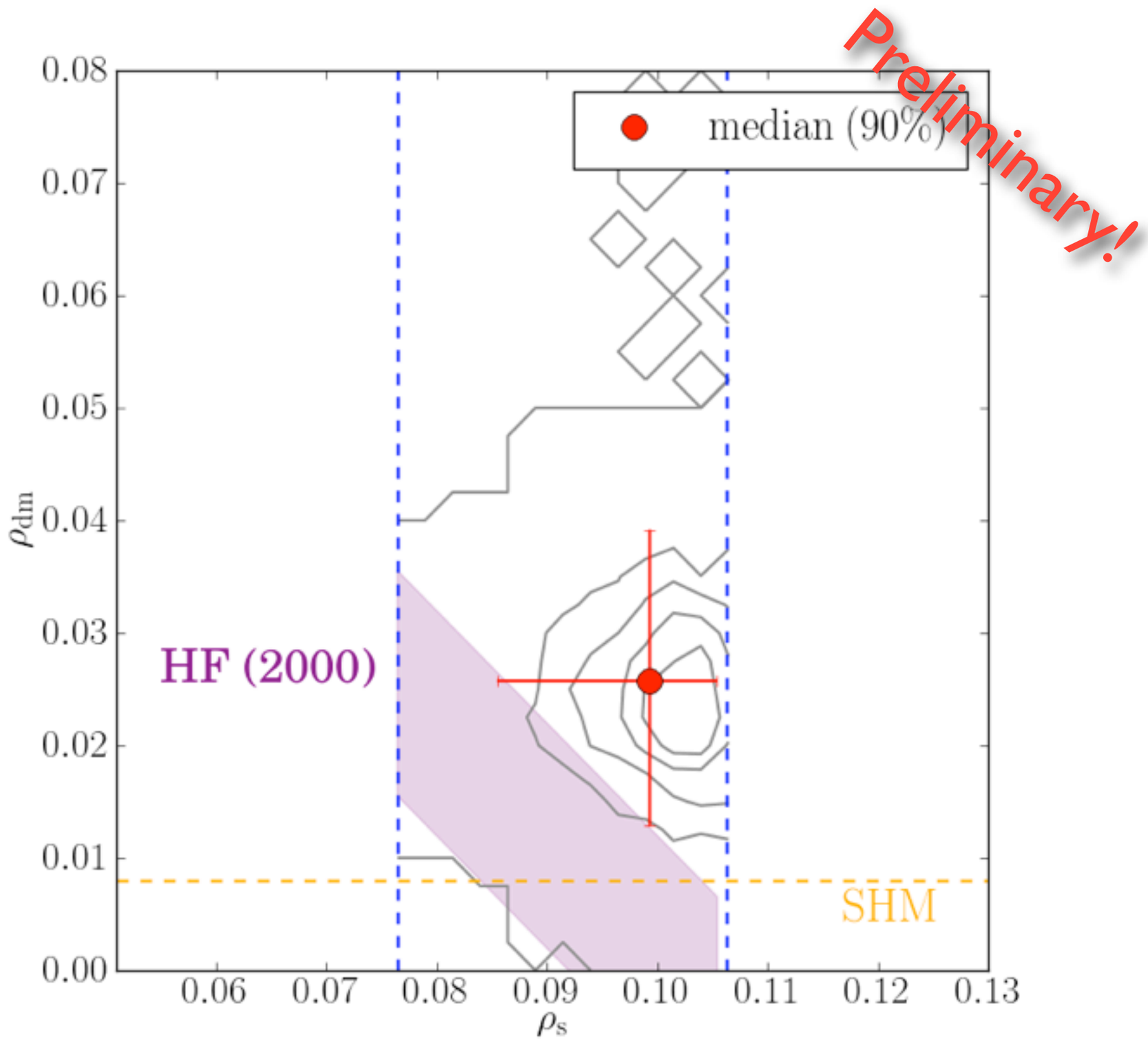

Garbari, Liu, Read & Lake in prep. ... and see Silvia's talk!

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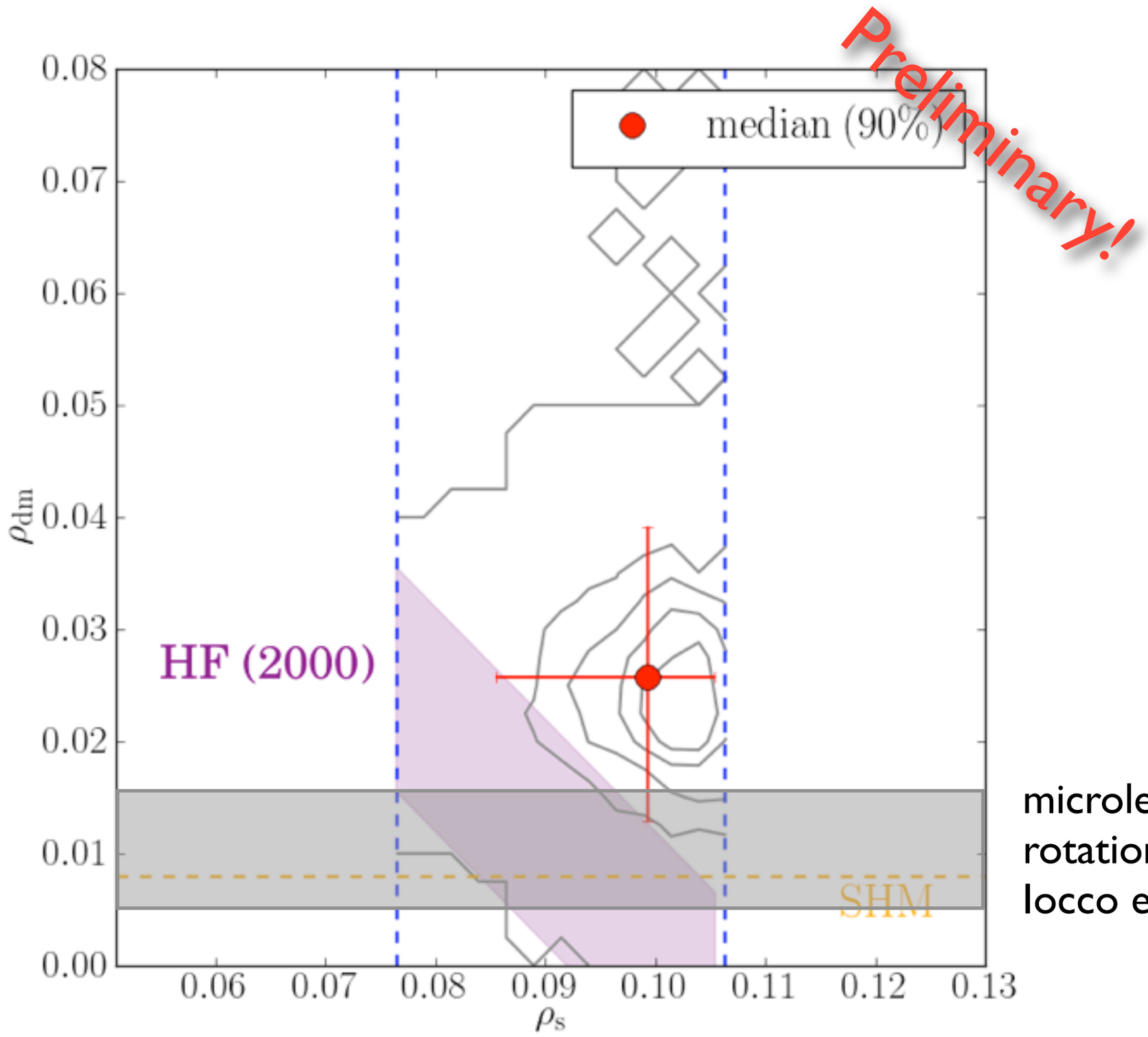

microlensing +
rotation curve
Iocco et al. 2011

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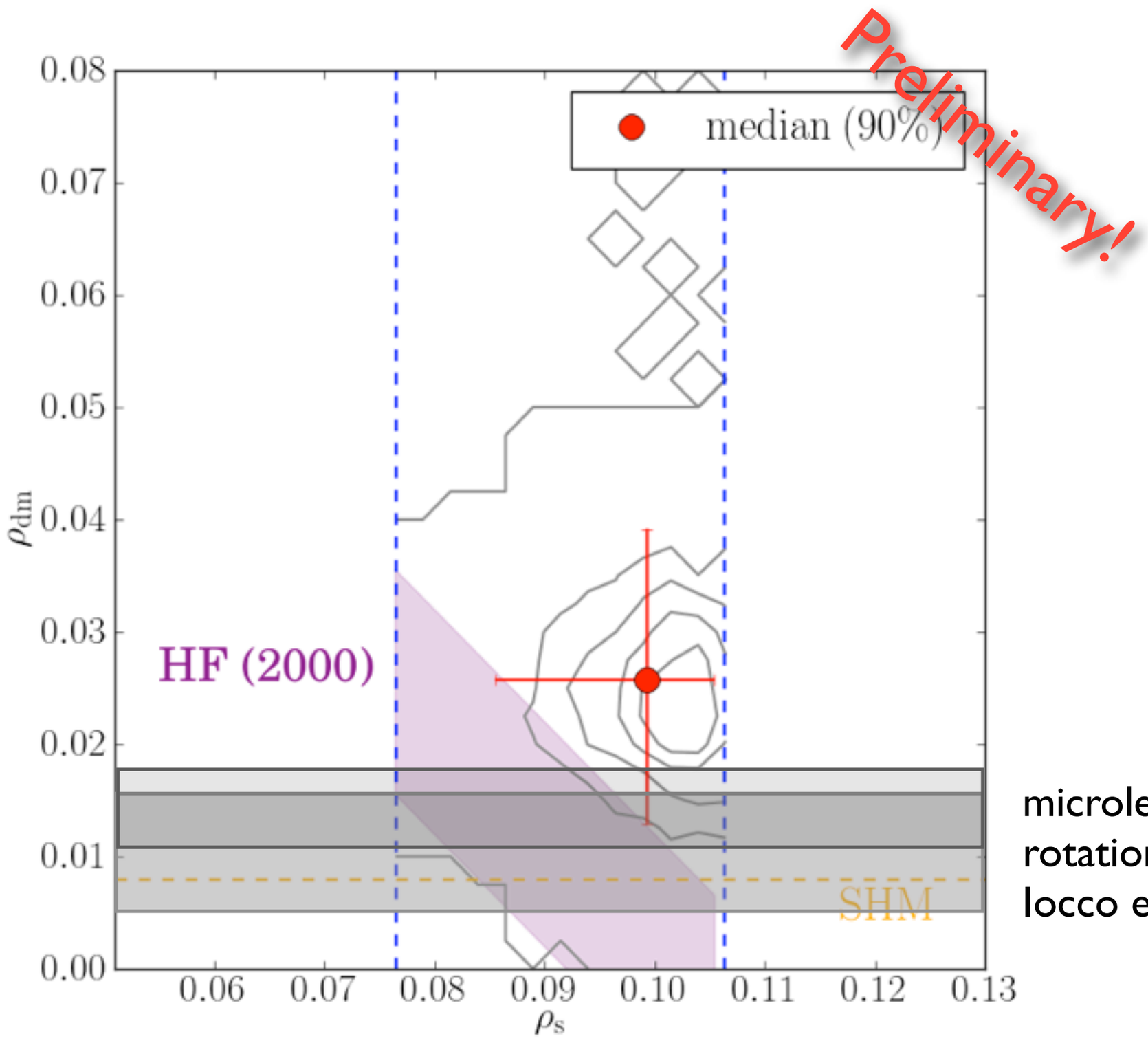

q=0.8
Iocco &
Pato

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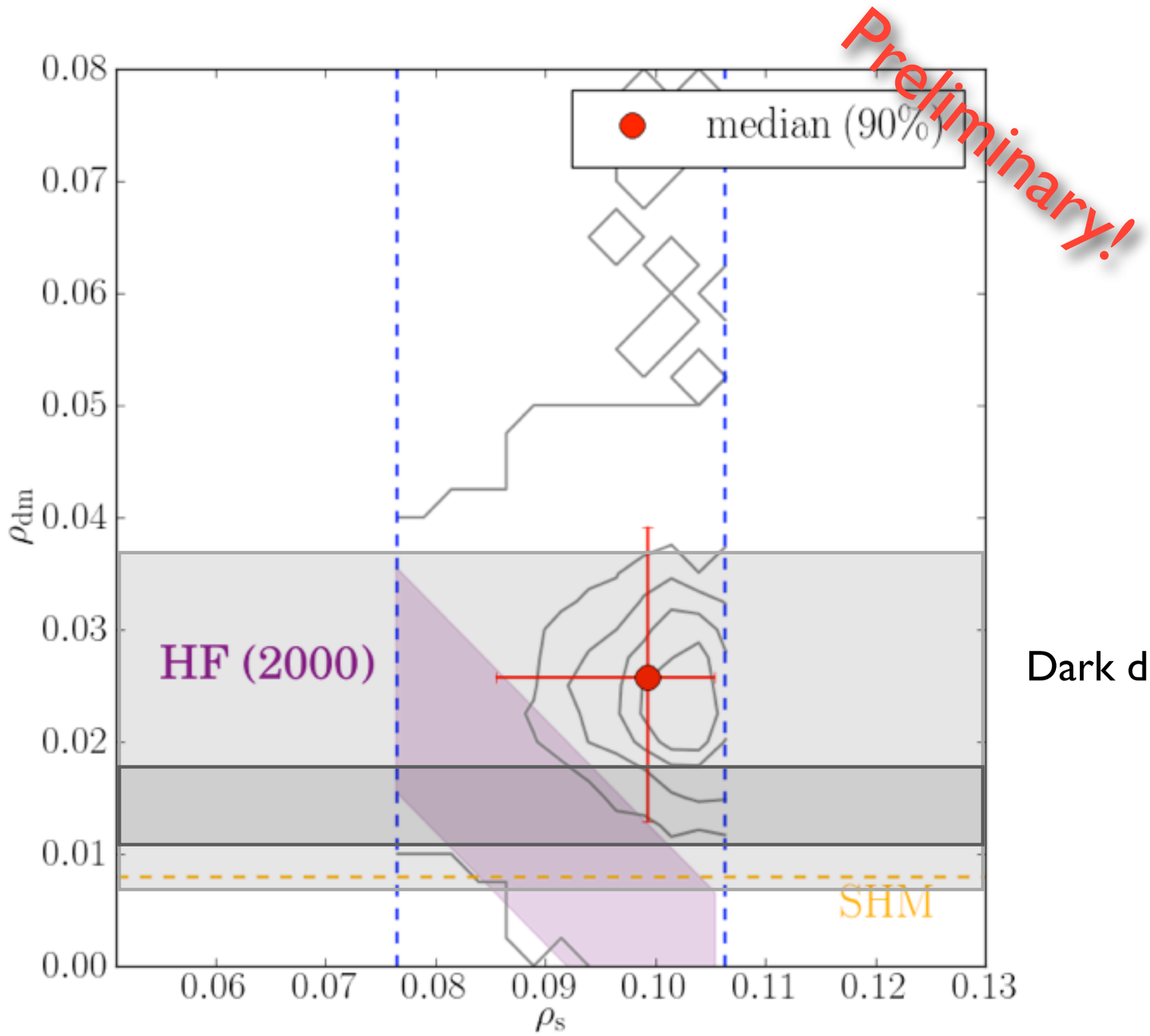


q=0.8
Iocco &
Pato

Dark disc

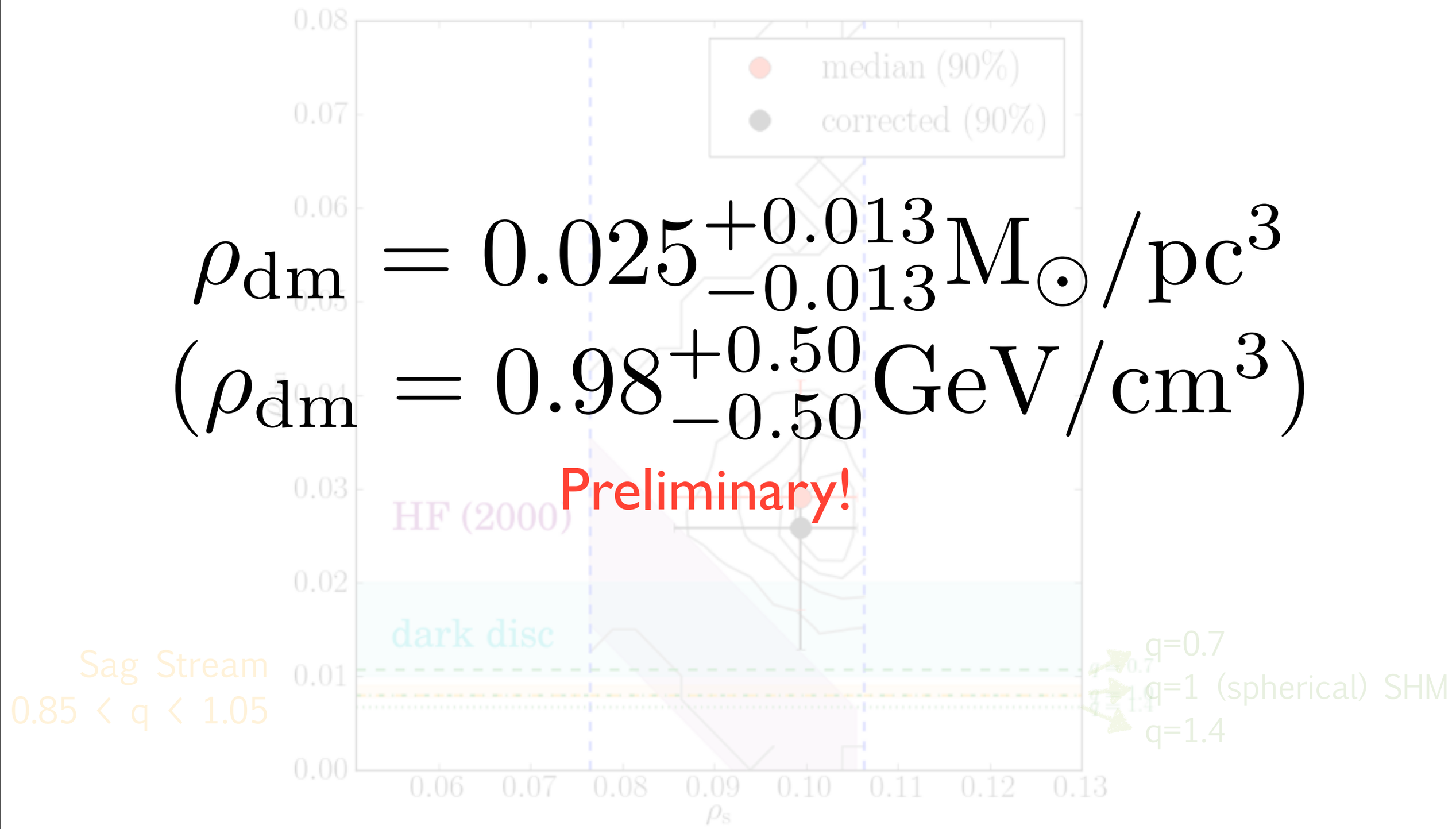
Garbari, Liu, Read & Lake in prep. ... and see Silvia's talk!

3. Hunting for DM | The local dark matter distribution

$$\rho_{\rm dm} = 0.025^{+0.013}_{-0.013} {\rm M}_\odot/{\rm pc}^3$$

$$(\rho_{\rm dm} = 0.98^{+0.50}_{-0.50} {\rm GeV/cm}^3)$$

Preliminary!



Garbari, Liu, Read & Lake in prep. ... and see Silvia's talk!

3. Hunting for DM | Annihilation signals: where to look

The 'Classical' dwarfs...

$$J = \int_{\Delta\Omega} \int \rho^2_{\rm DM}(l, \Omega)\, dl d\Omega.$$

$$\Delta\Omega = 2\pi \cdot (1 - \cos(\alpha_{\rm int}))$$

Lake 1990

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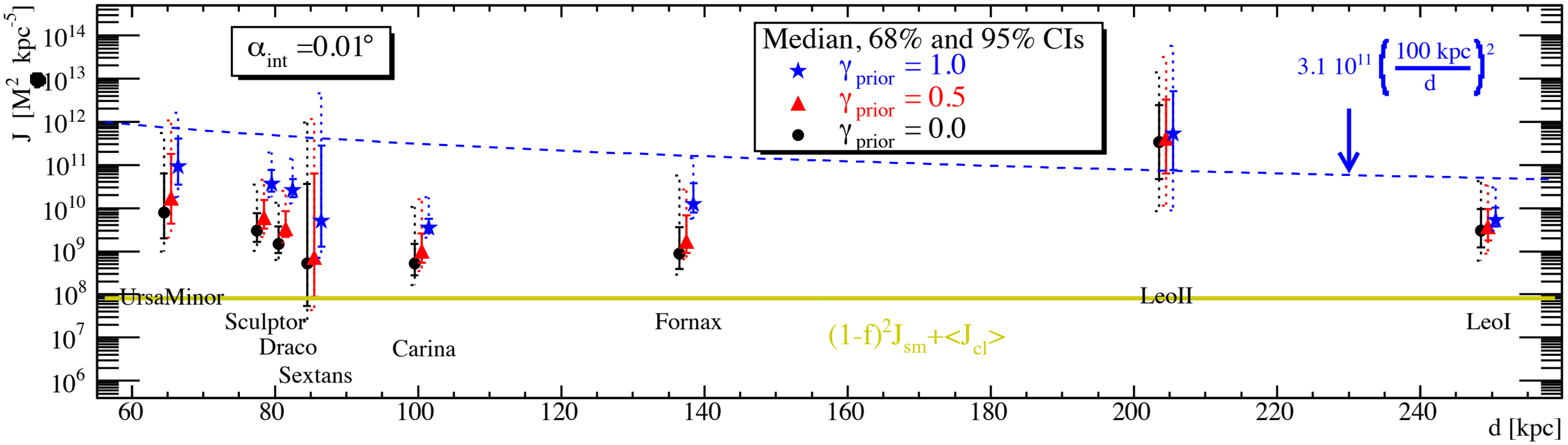

Charbonnier, A.; Combet, C.; Daniel, M.; Funk, S.; Hinton, J. A.; Maurin, D.; Power, C.; Read, J. I.; Sarkar, S.; Walker, M. G.; Wilkinson, M. I.; Walker et al. 2011

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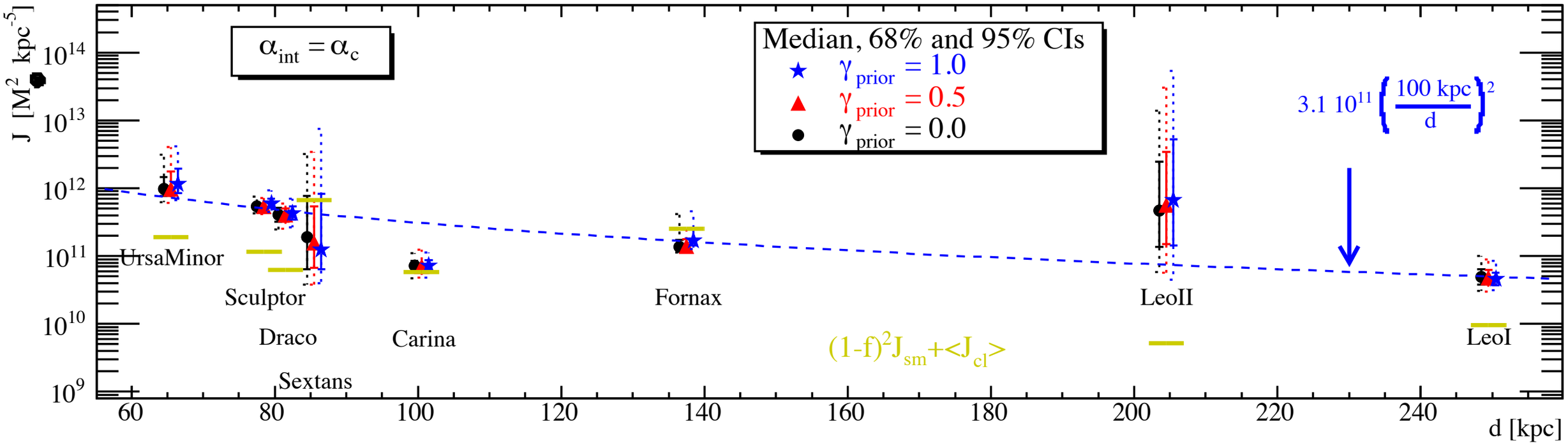

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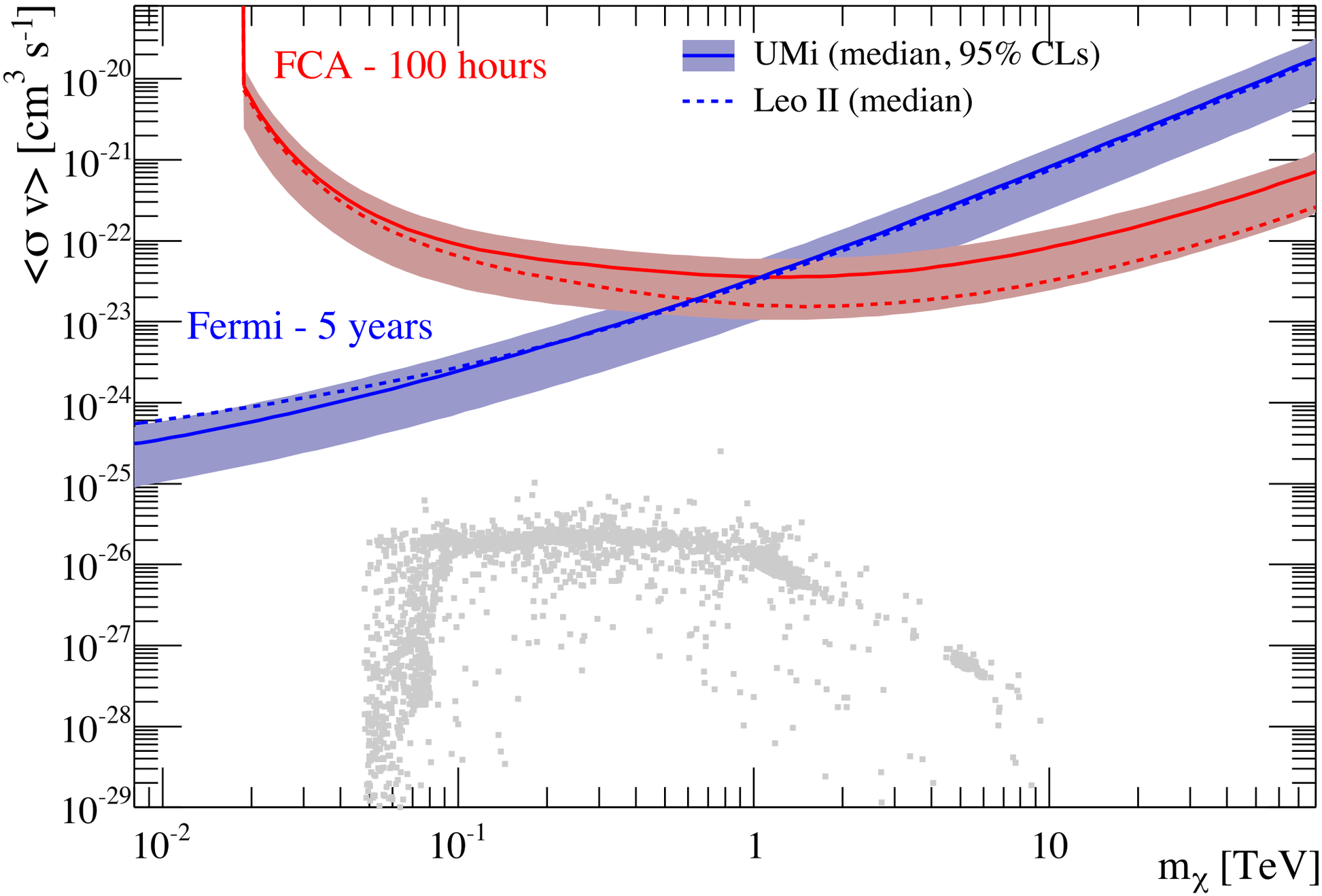
3. Hunting for DM | Annihilation signals: where to look

The bottom line ...



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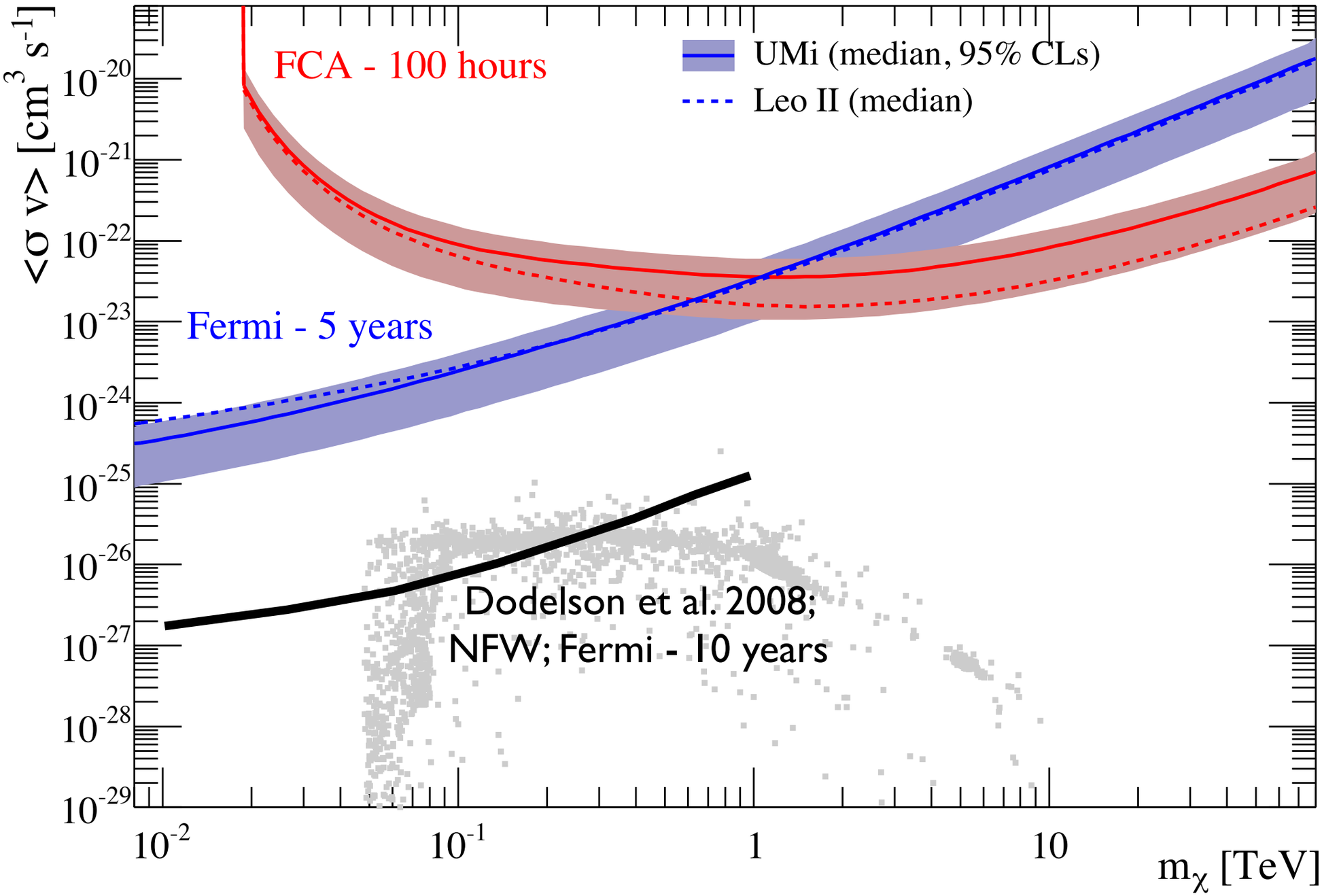

Charbonnier, A.; Combet, C.; Daniel, M.; Funk, S.; Hinton, J. A.; Maurin, D.; Power, C.; Read, J. I.; Sarkar, S.; Walker, M. G.; Wilkinson, M. I. 2011

Conclusions

- On galaxy cluster scales dark matter is cold and seemingly 'vanilla'.

- On LSB galaxy scales and below 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. Improved simulations that successfully model hydrodynamic processes are vital to make further progress.

- Baryons are also important for estimating the local dark matter distribution. Including them leads to the expectation that our Galaxy has a dark matter disc.

- We have recently revisited the local dark matter density, finding: $\rho_{DM} = 0.98 \pm 0.5$ GeV/cm^3. This may be at tension with simple extrapolations from the Milky Way rotation curve.

- The Galactic centre is really the only game in town for annihilation signals for current/planned instruments [unless Sommerfeld ...].