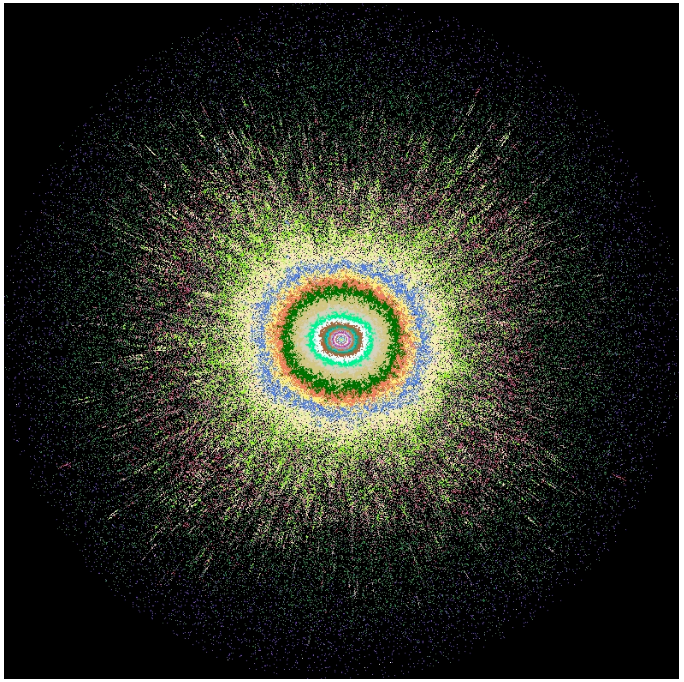
Why cosmological dark matter structures look the way they do

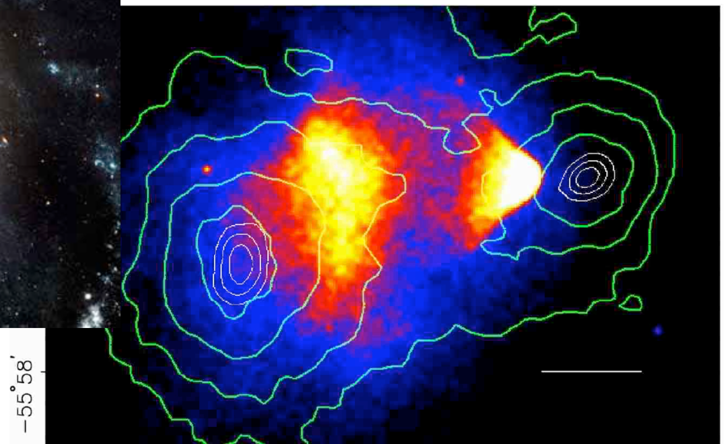


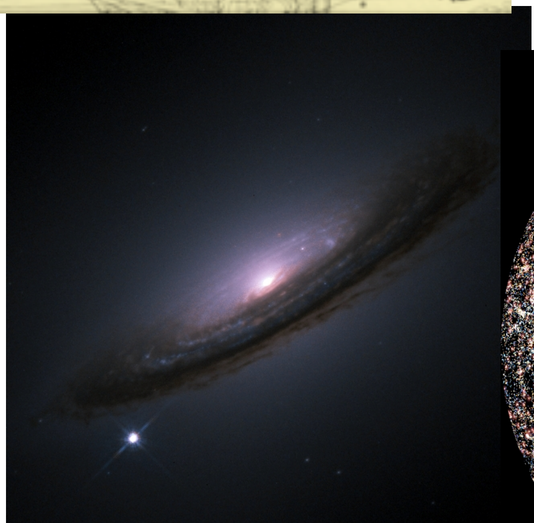
Steen H. Hansen,
Dark Cosmology Centre,
Niels Bohr Institute, Copenhagen

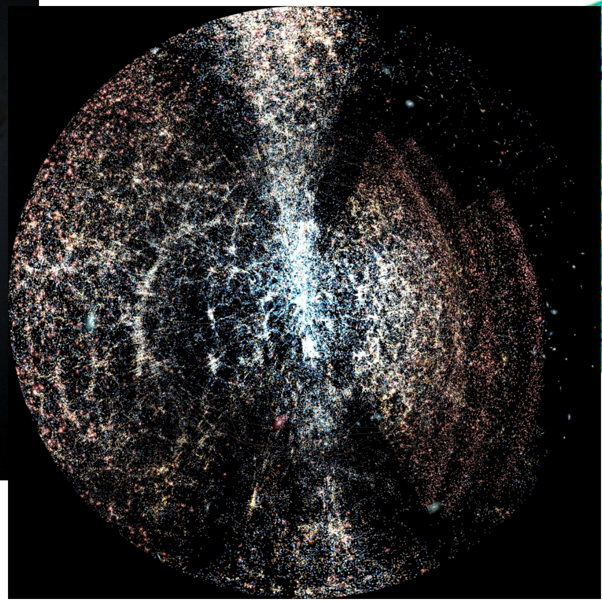
Heidelberg, November, 2009

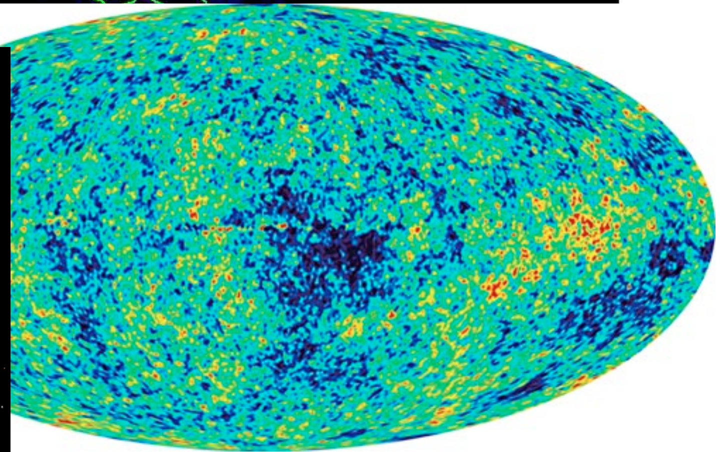
Dark Cosmology Centre

Dark matter observations









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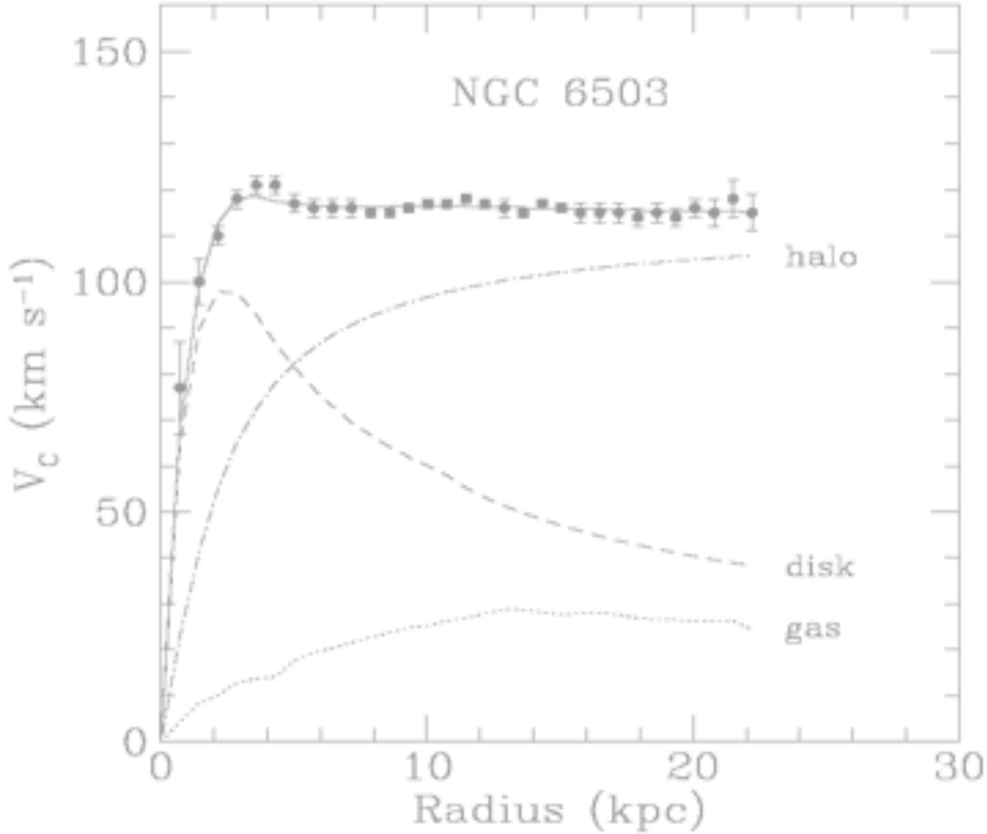
Galaxy rotation curves



$$V \sim \sqrt{\frac{GM(r)}{r}}$$

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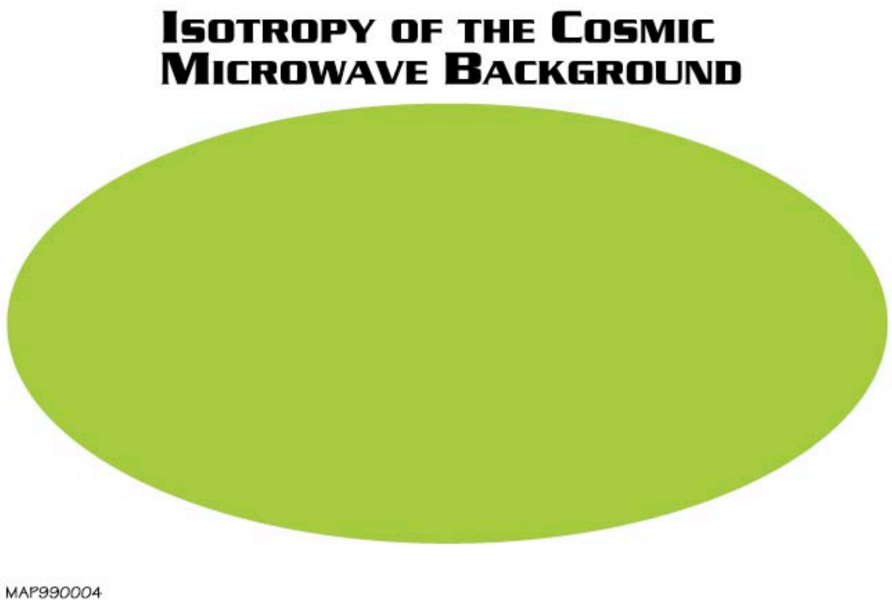
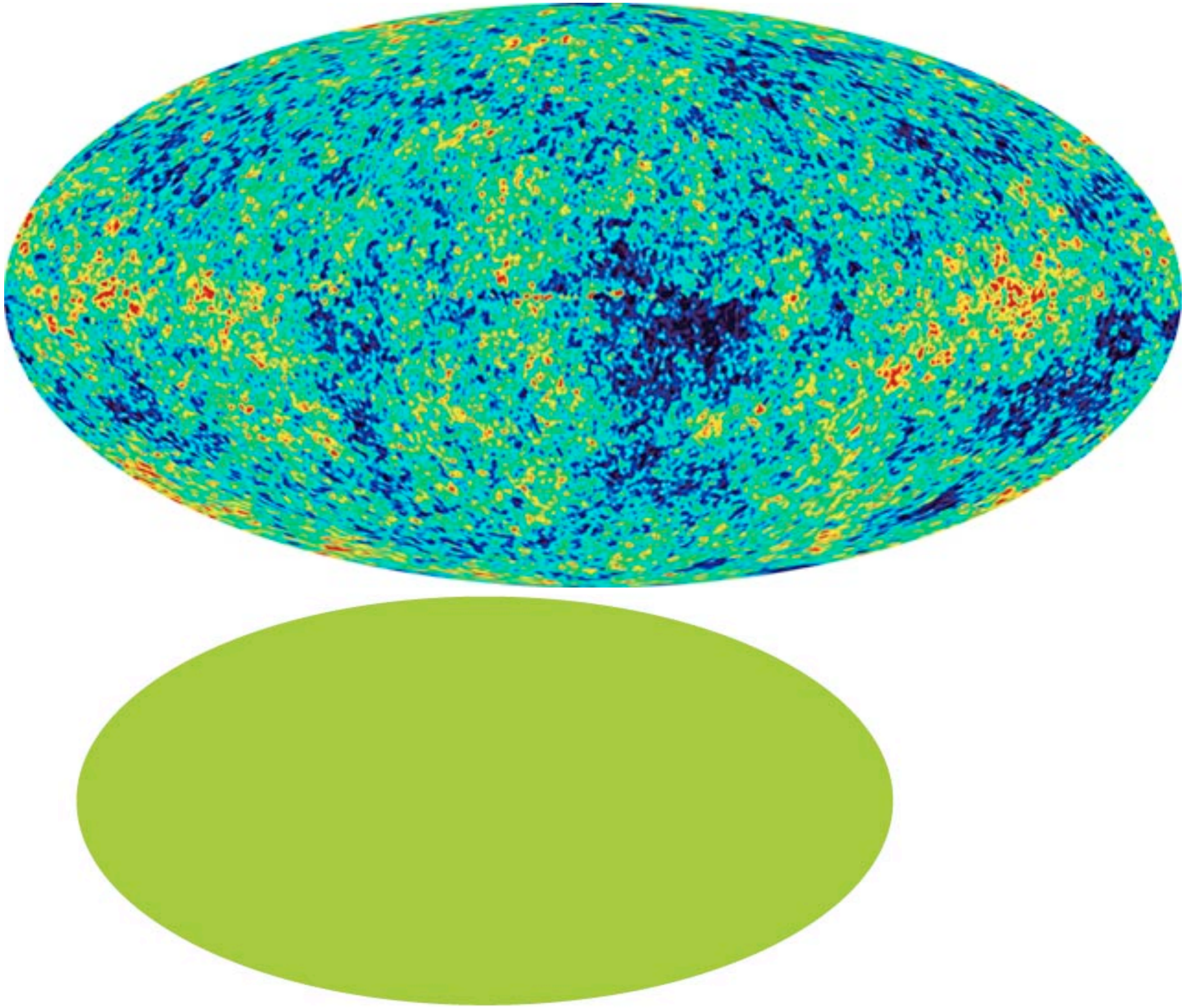
Cosmic background radiation



Cosmic background radiation



MAP990004

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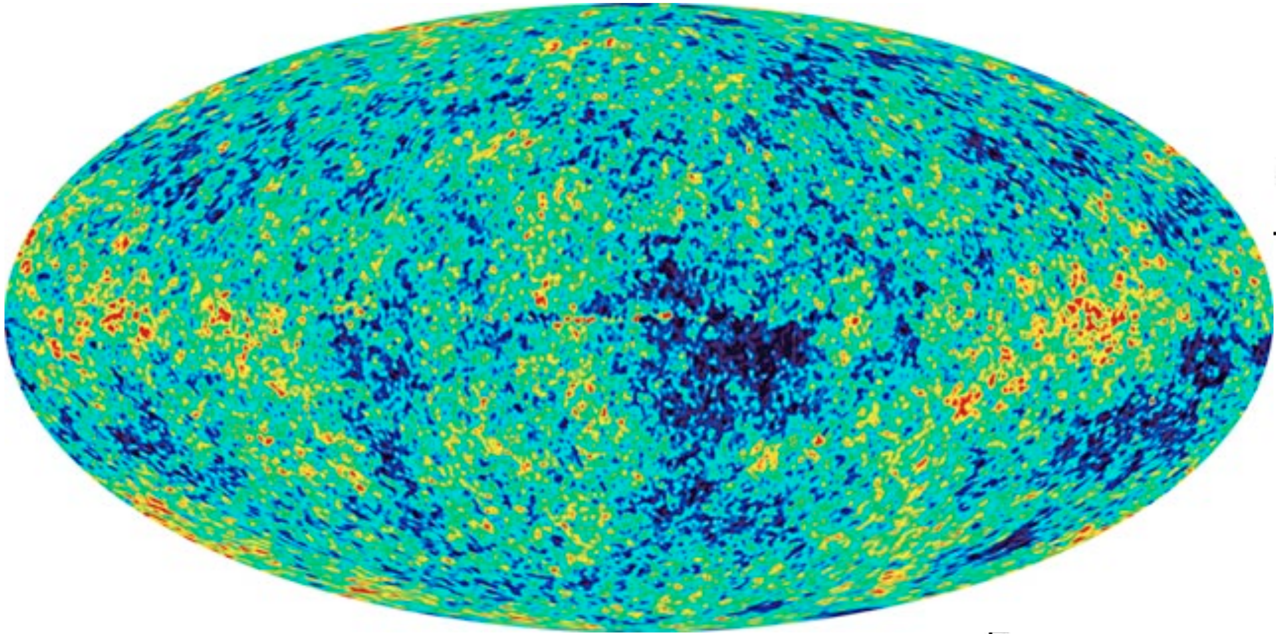
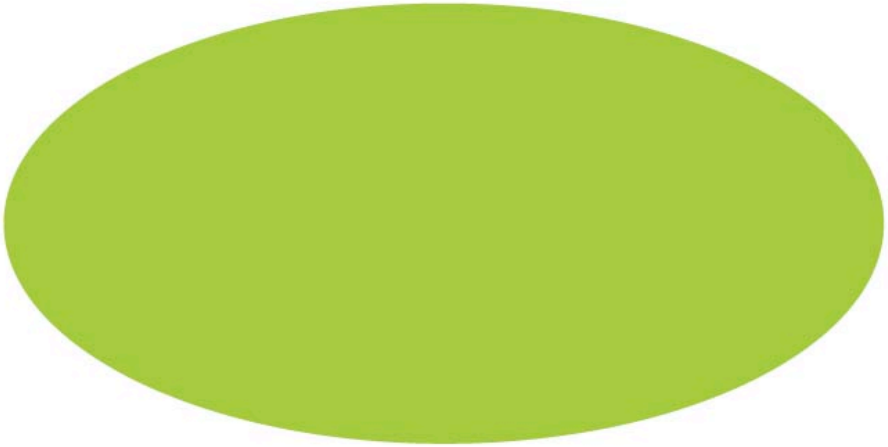
Cosmic background radiation





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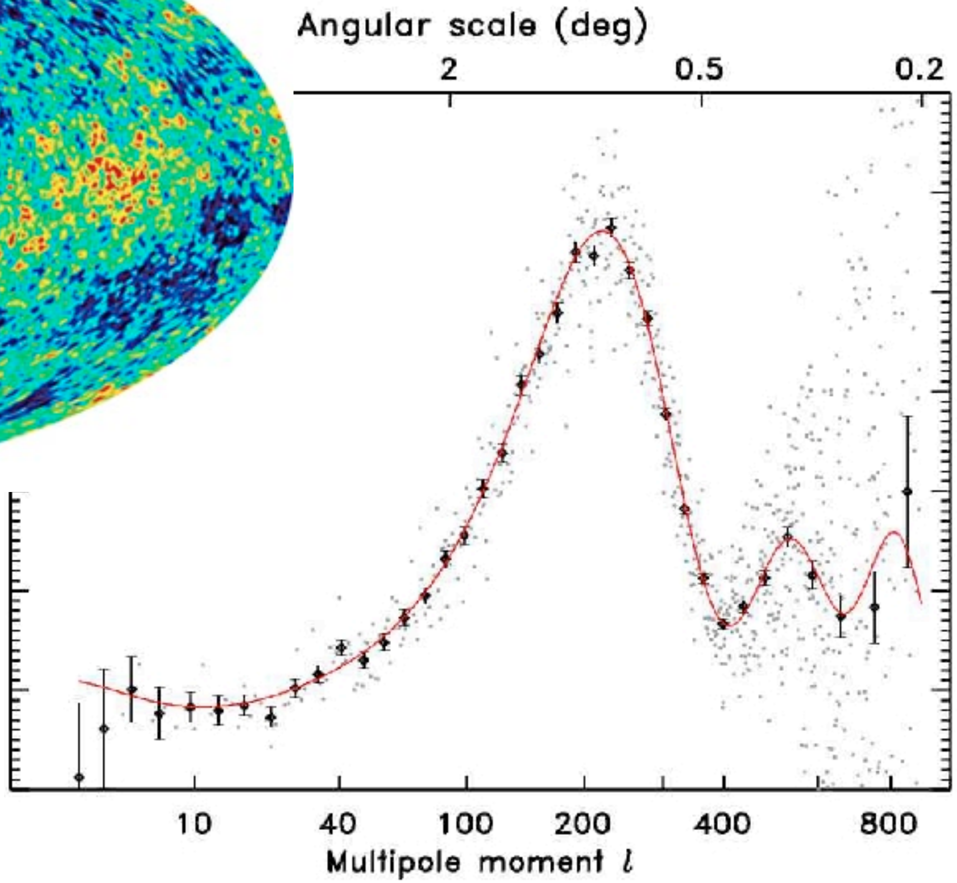

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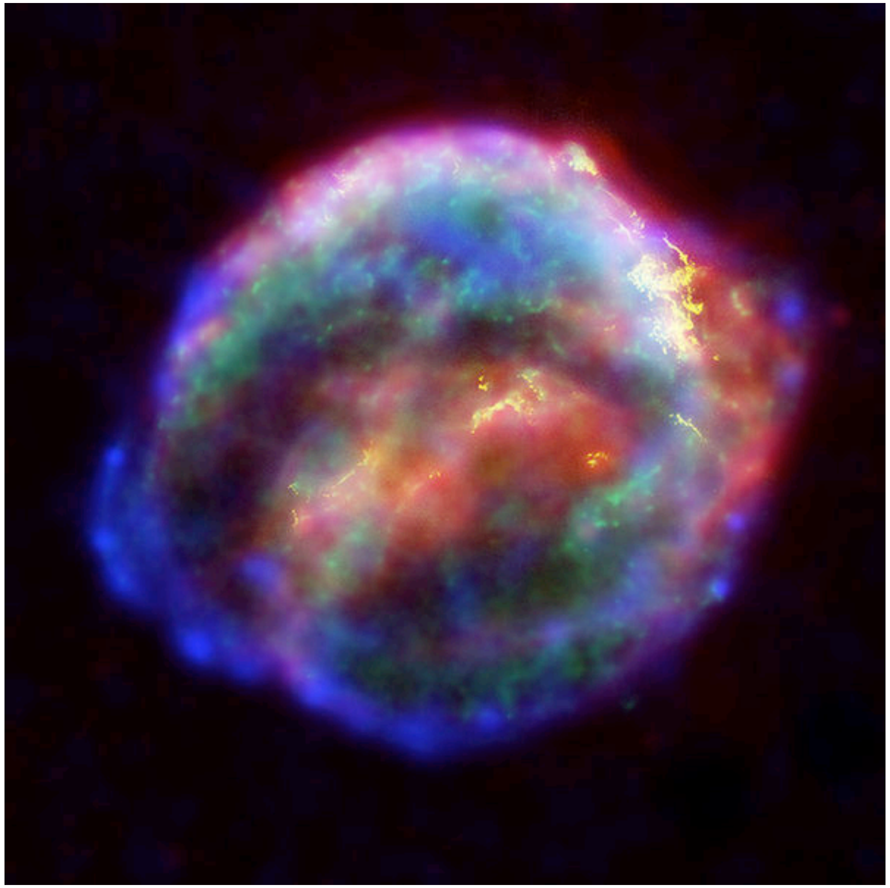
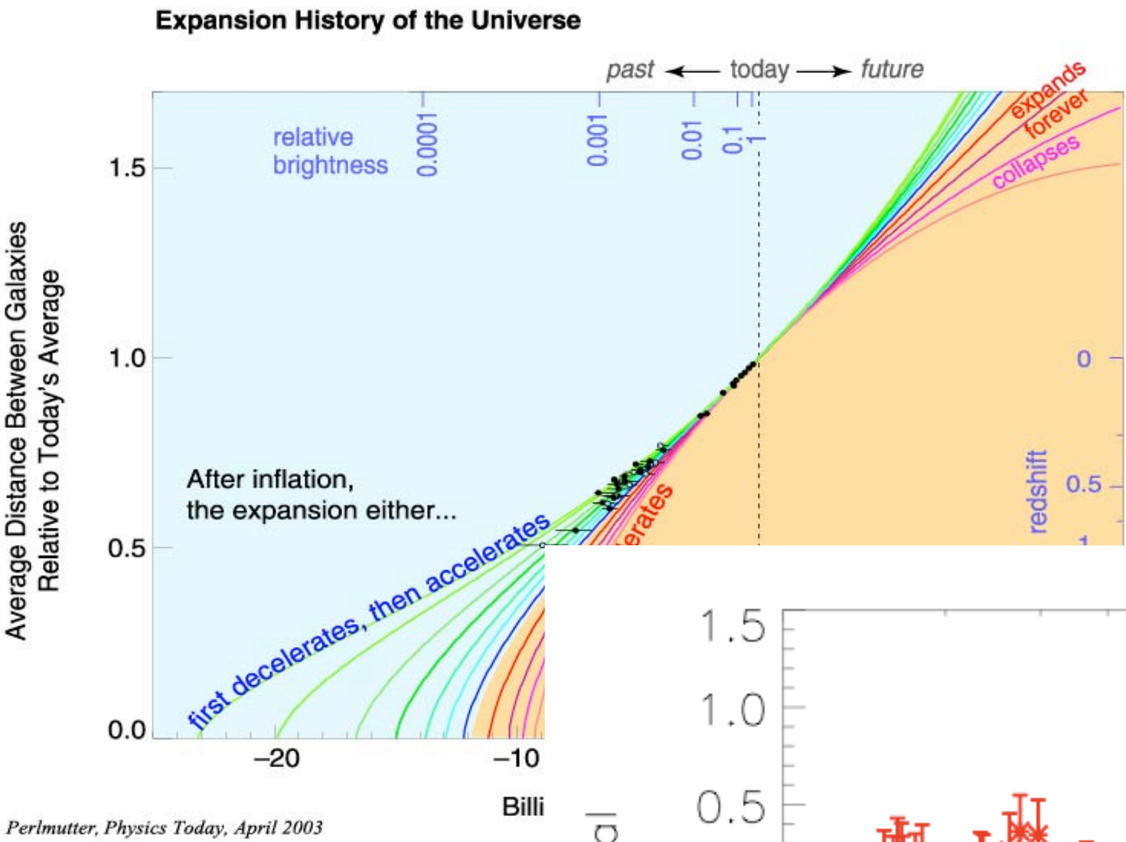
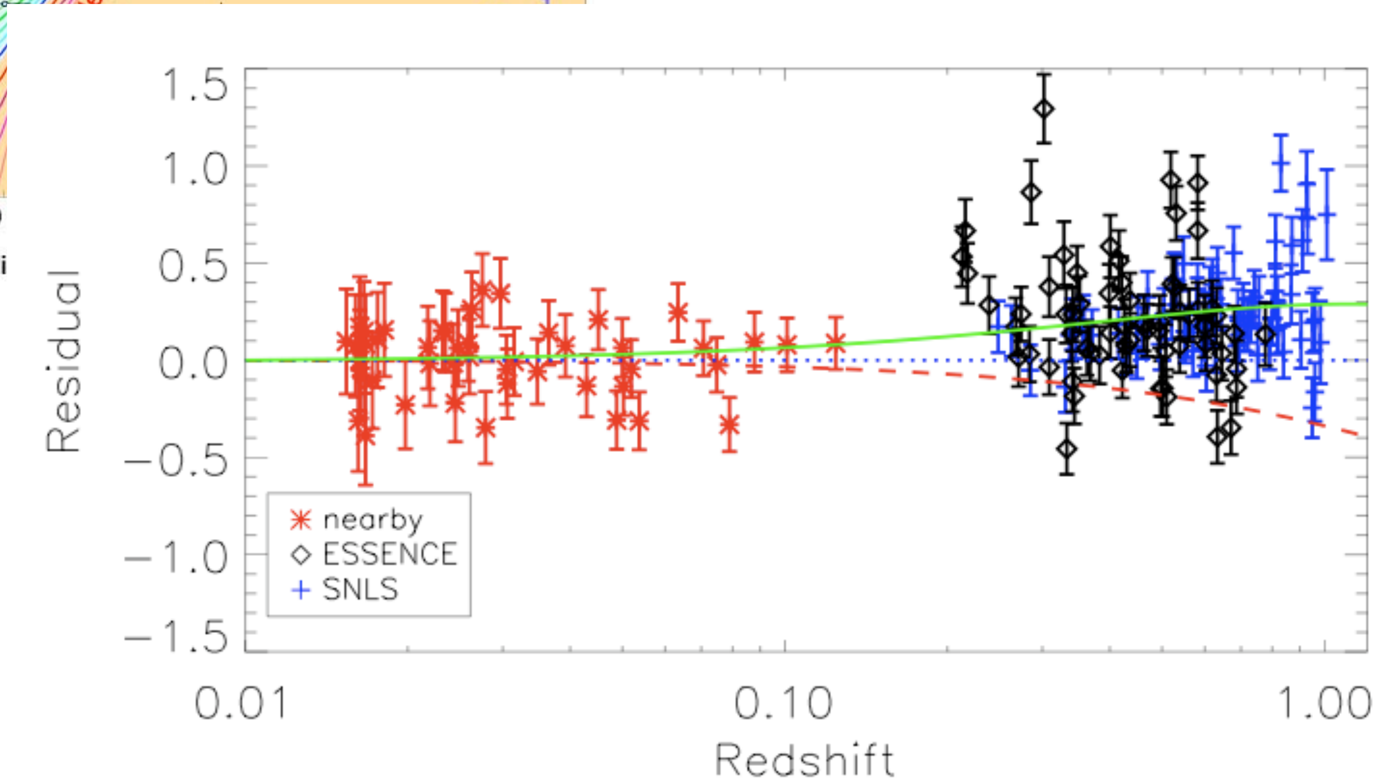
Super novae





Perlmutter, Physics Today, April 2003

Super novae



The conclusion from CMB, SN, LSS,...

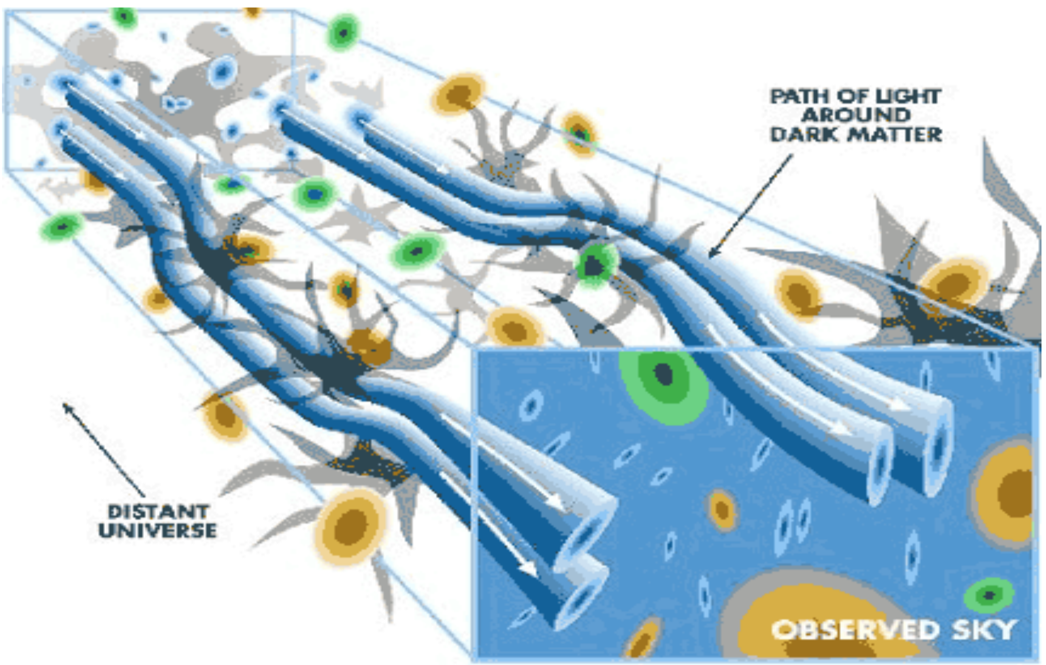
3 possibilities

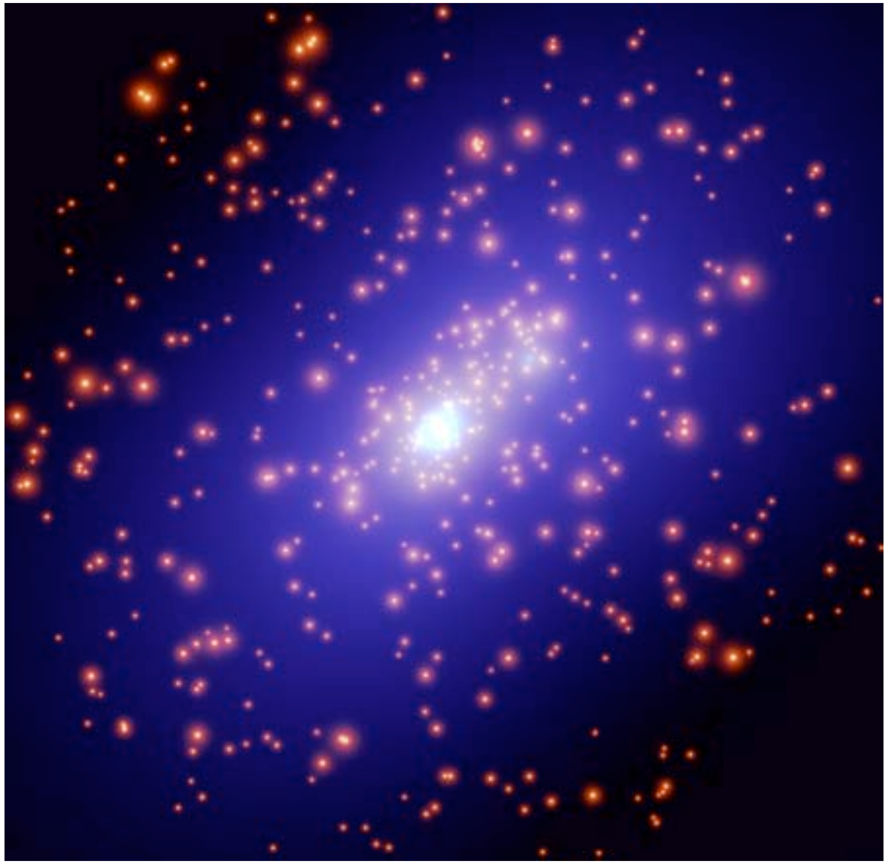
1. all these independent observations are incorrect

2. gravitation behaves weird, and hence our interpretations are incorrect

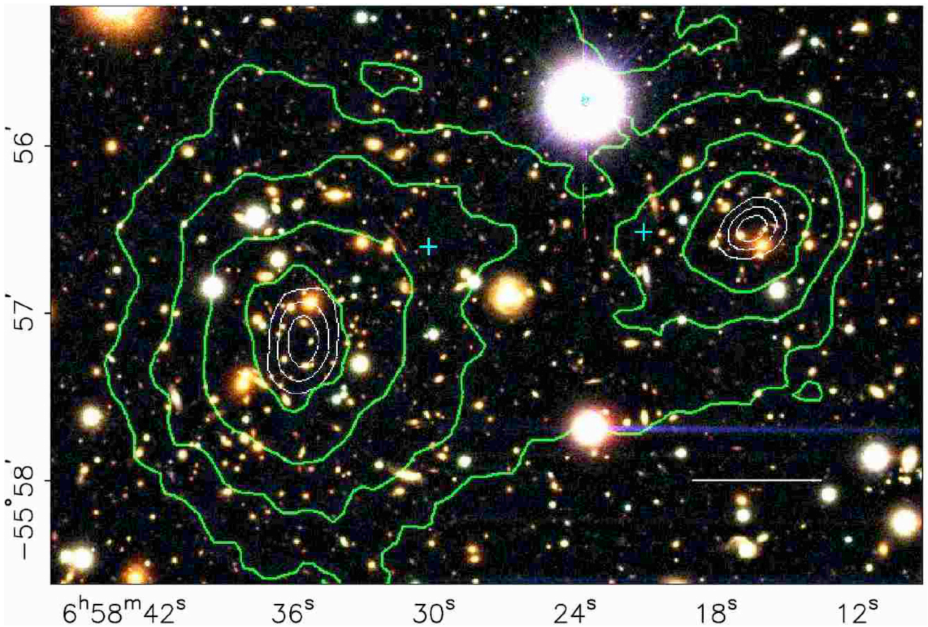
3. there are vast amounts of dark matter on all scales, from dwarf galaxies, over galaxies and clusters, to the entire universe

Lensing


PATH OF LIGHT
AROUND
DARK MATTER
DISTANT
UNIVERSE
OBSERVED SKY

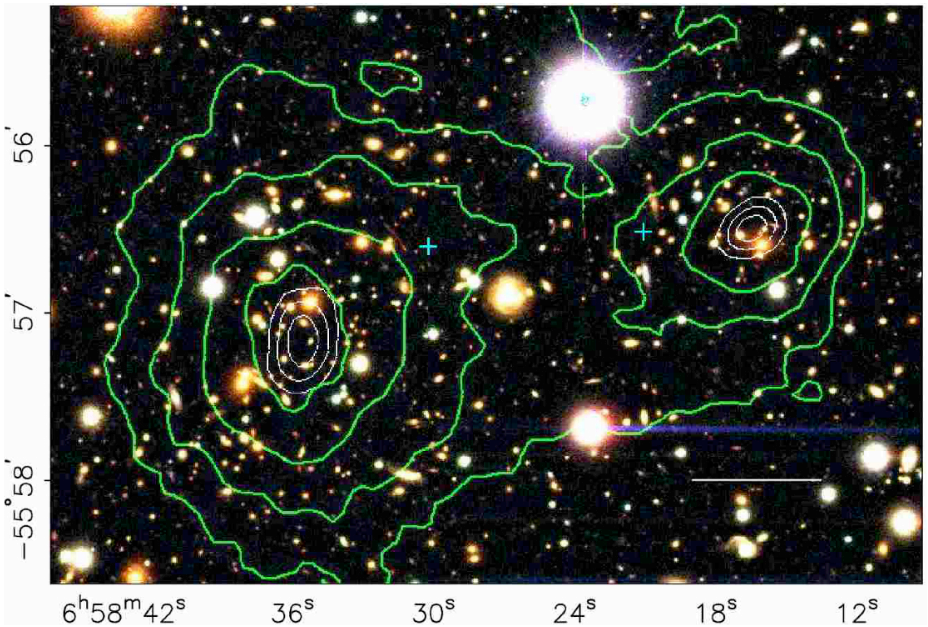


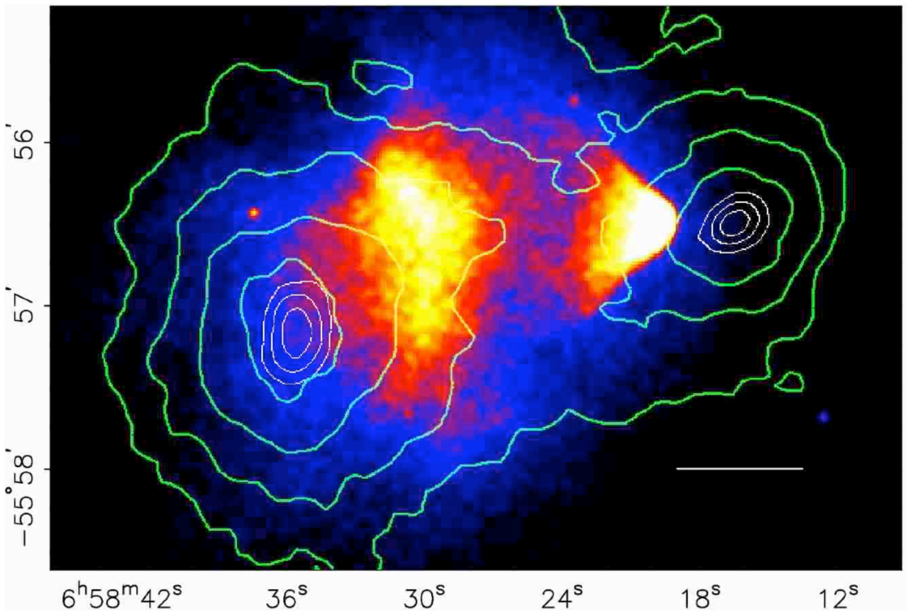
A galaxy cluster seen through lensing



Clowe et al. 2006

A galaxy cluster seen through lensing and x-ray observation





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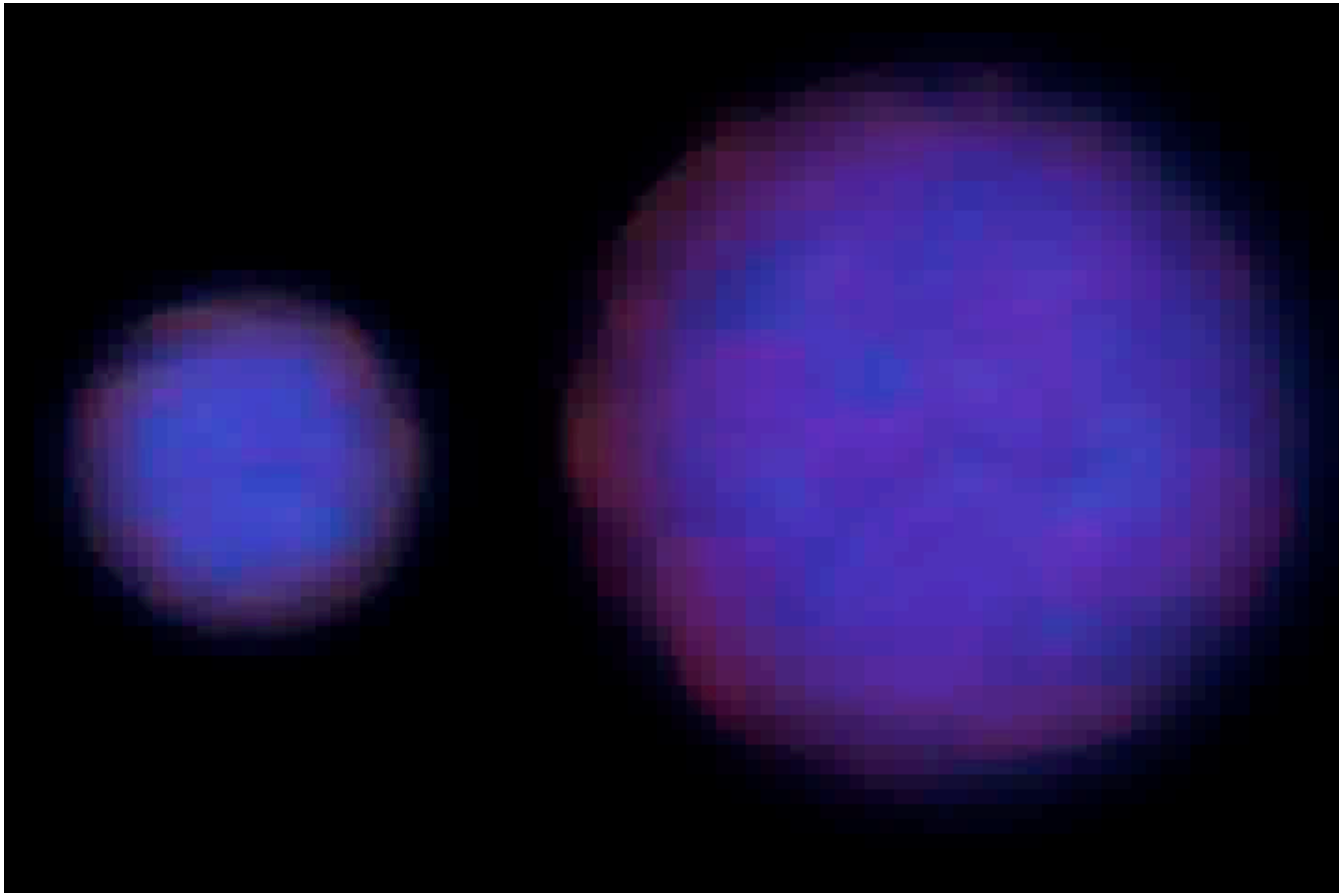
Collision between clusters



2 ~~3~~ possibilities

1. all these independent observations are incorrect

2. ~~gravitation behaves weird, and hence our interpretations are incorrect~~

3. there are vast amounts of dark matter on all scales, from dwarf galaxies, over galaxies and clusters, to the entire universe

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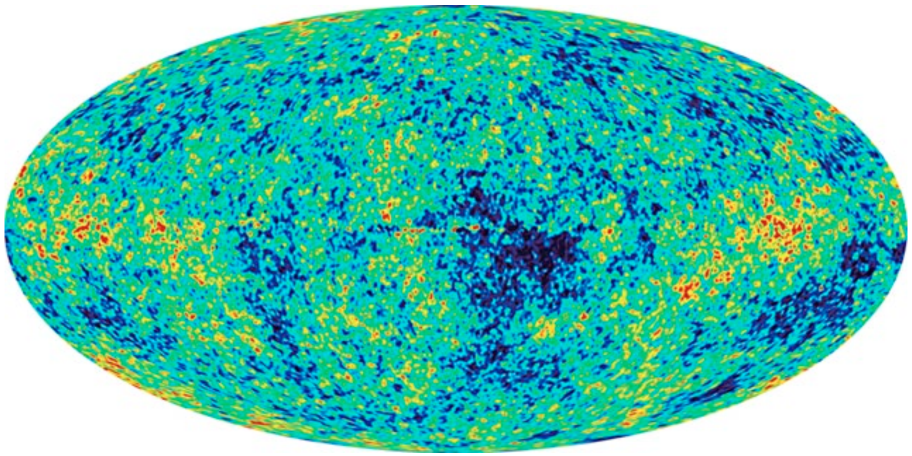
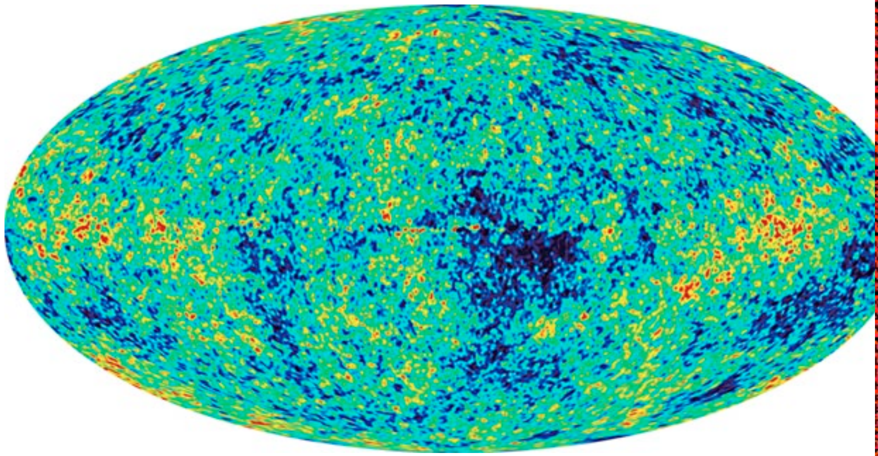
Dark matter profiles

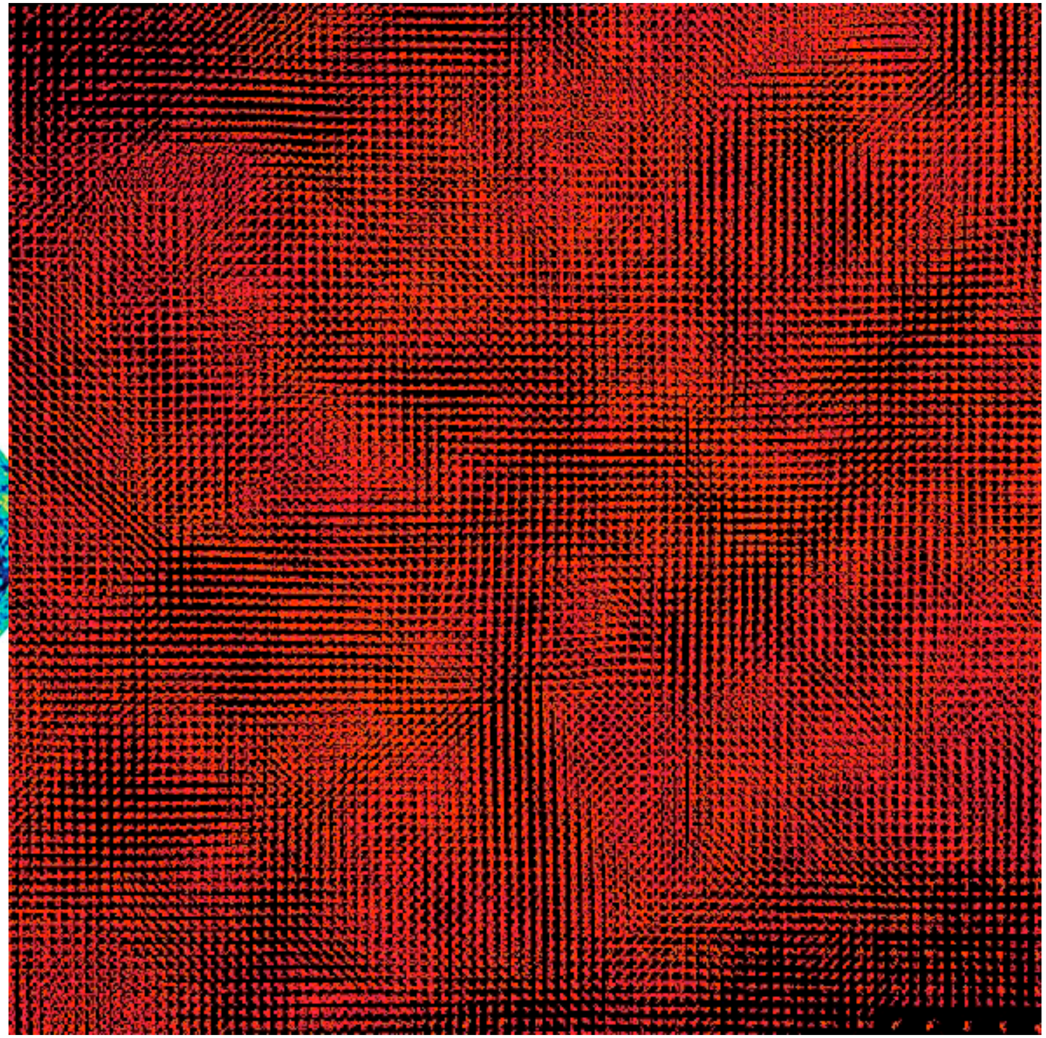
Numerical simulations



Initial conditions known from observations

Numerical simulations





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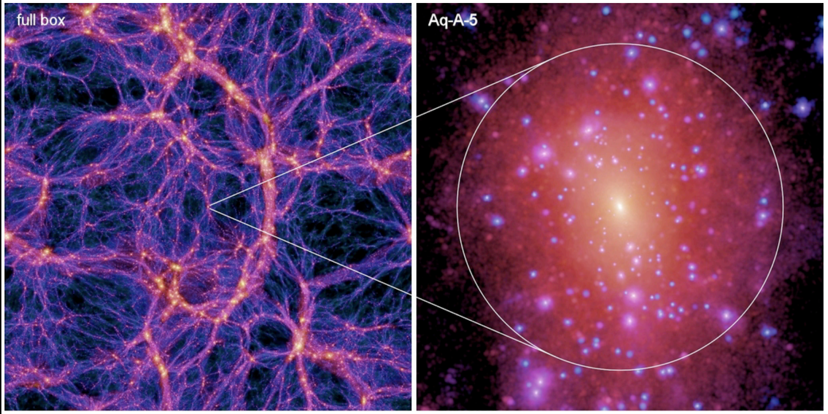
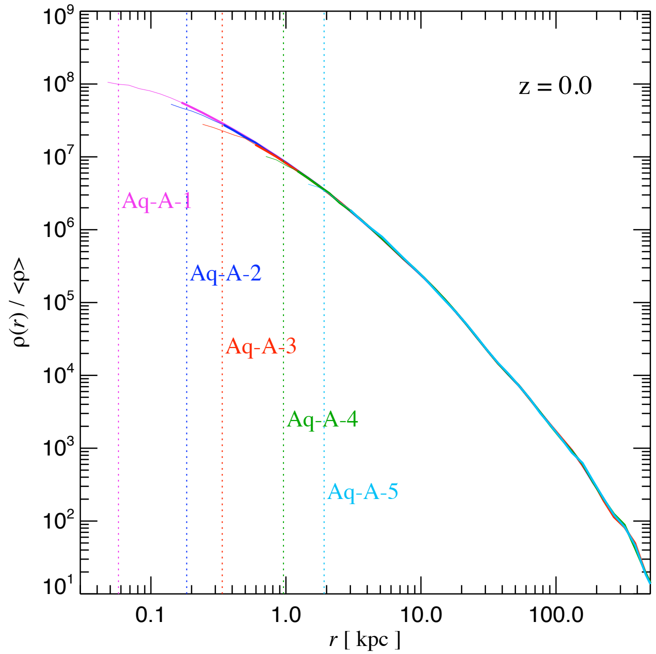
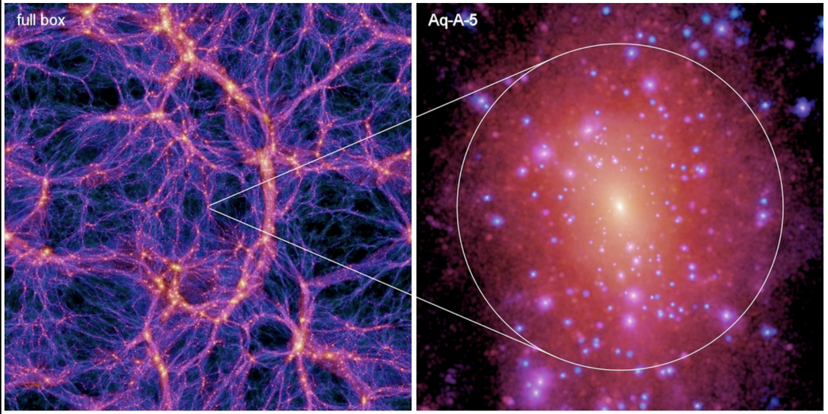
Simulated density profiles

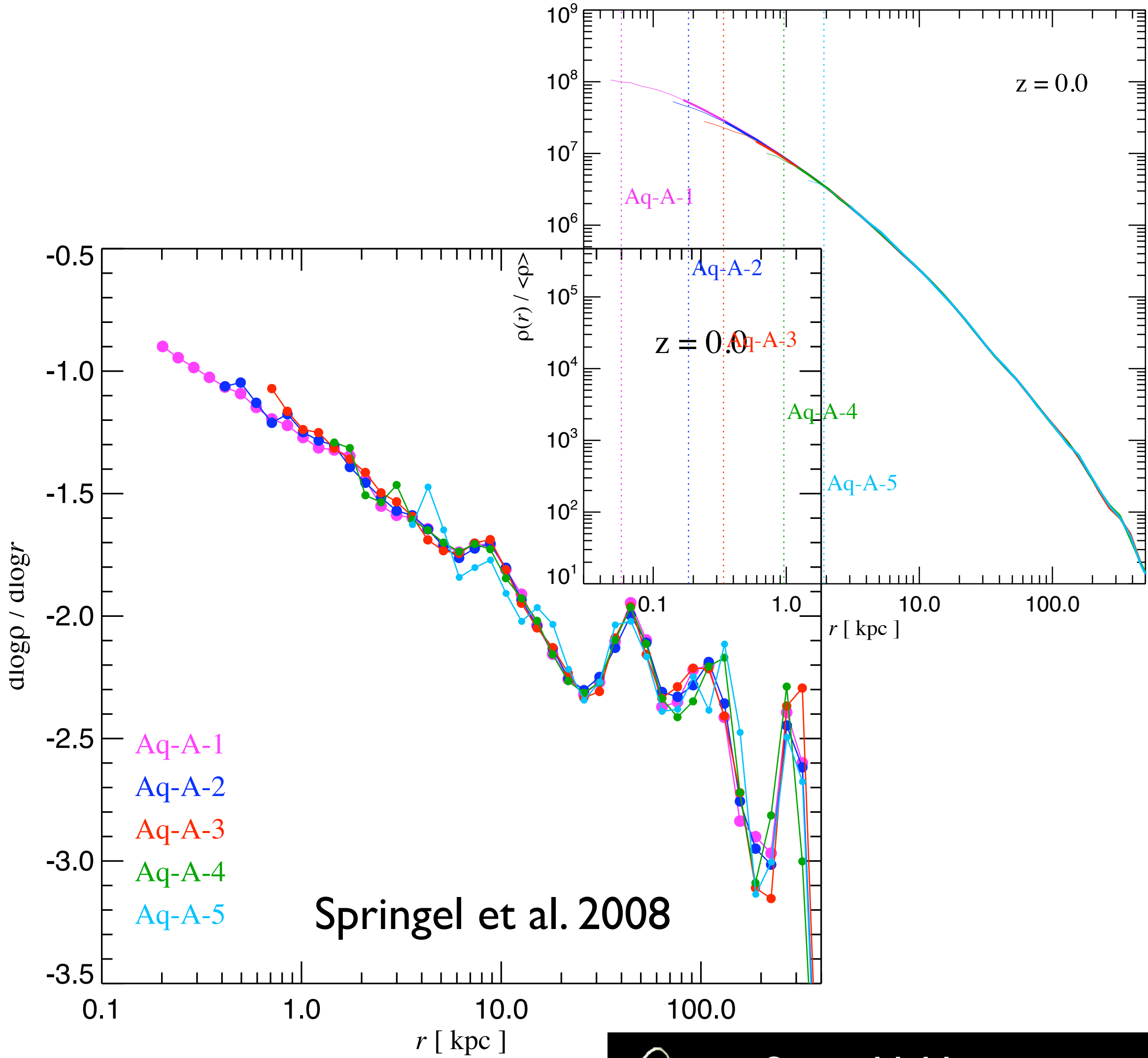




Springel et al. 2008

Simulated density profiles





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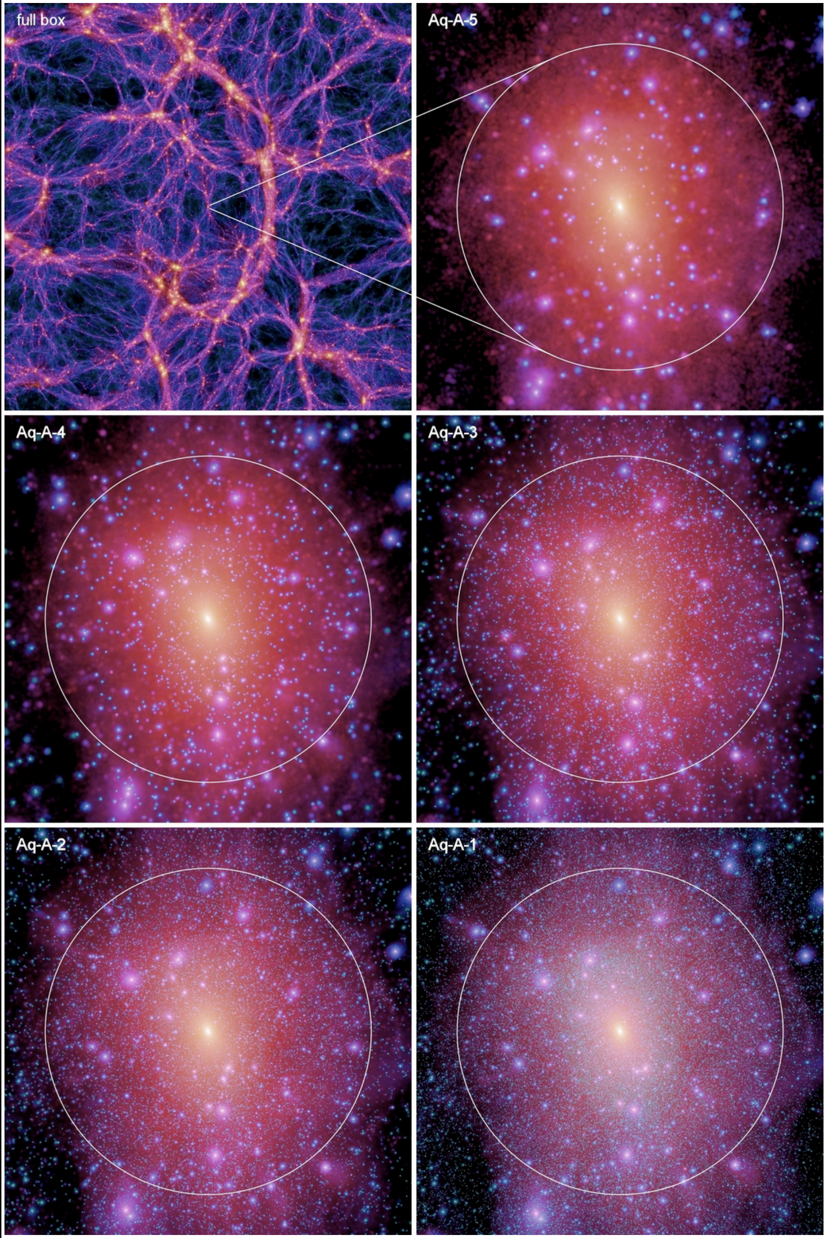
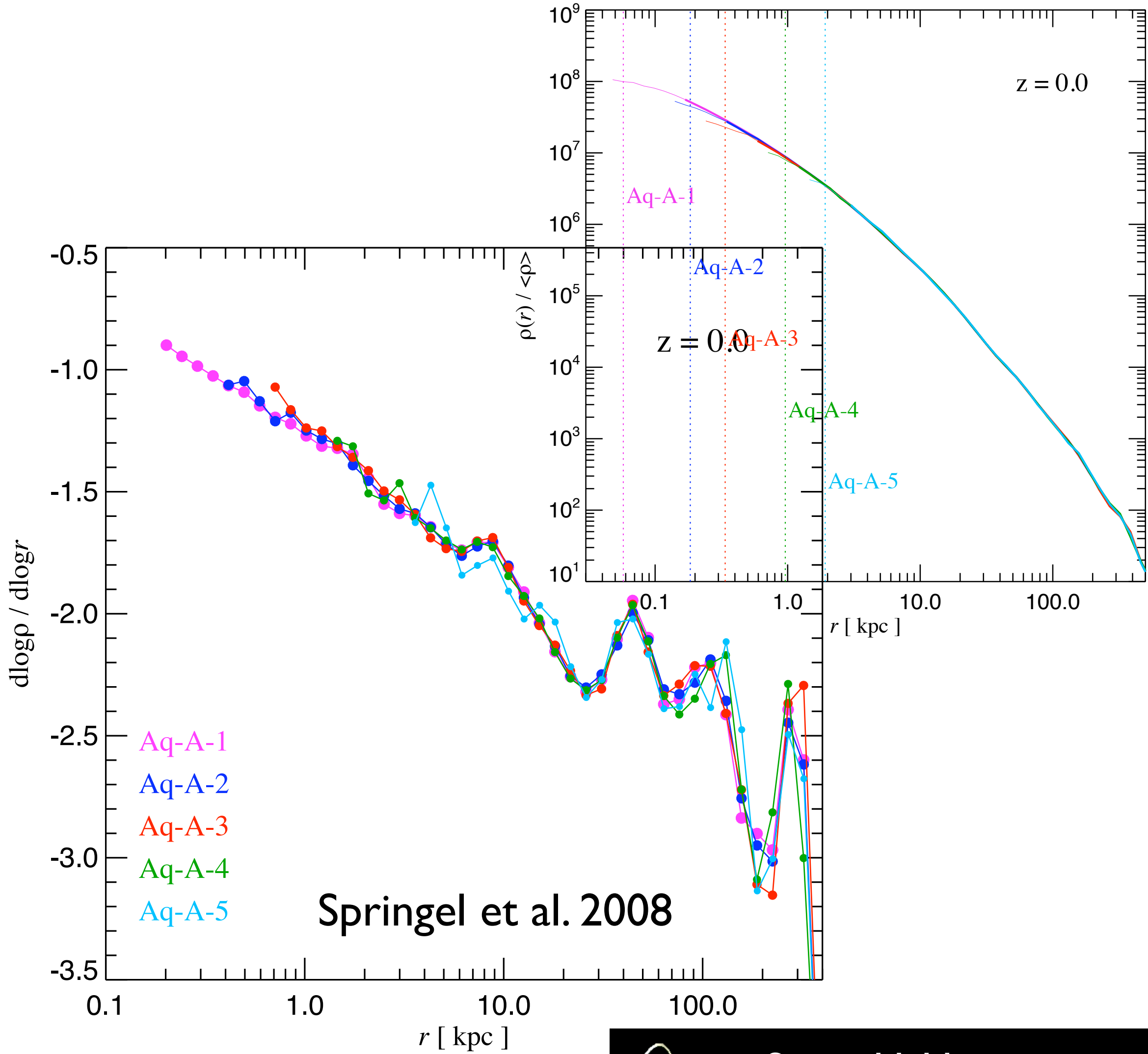
Simulated density profiles





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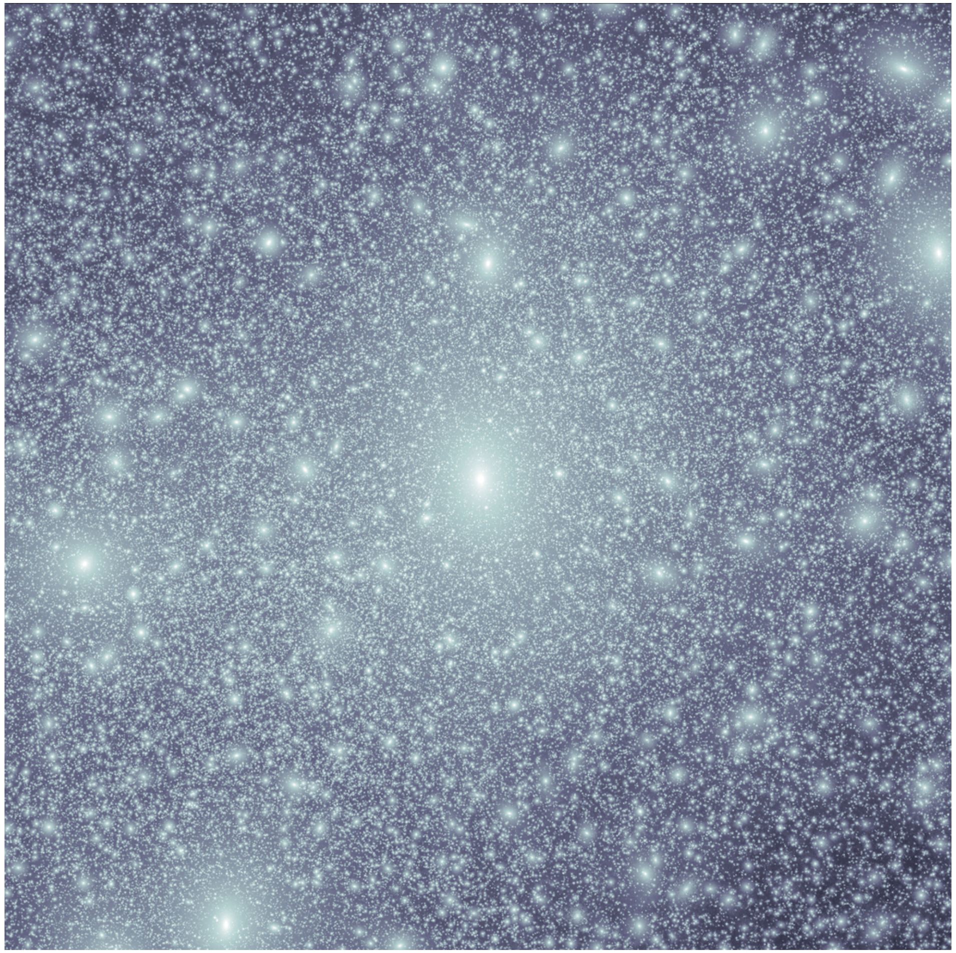
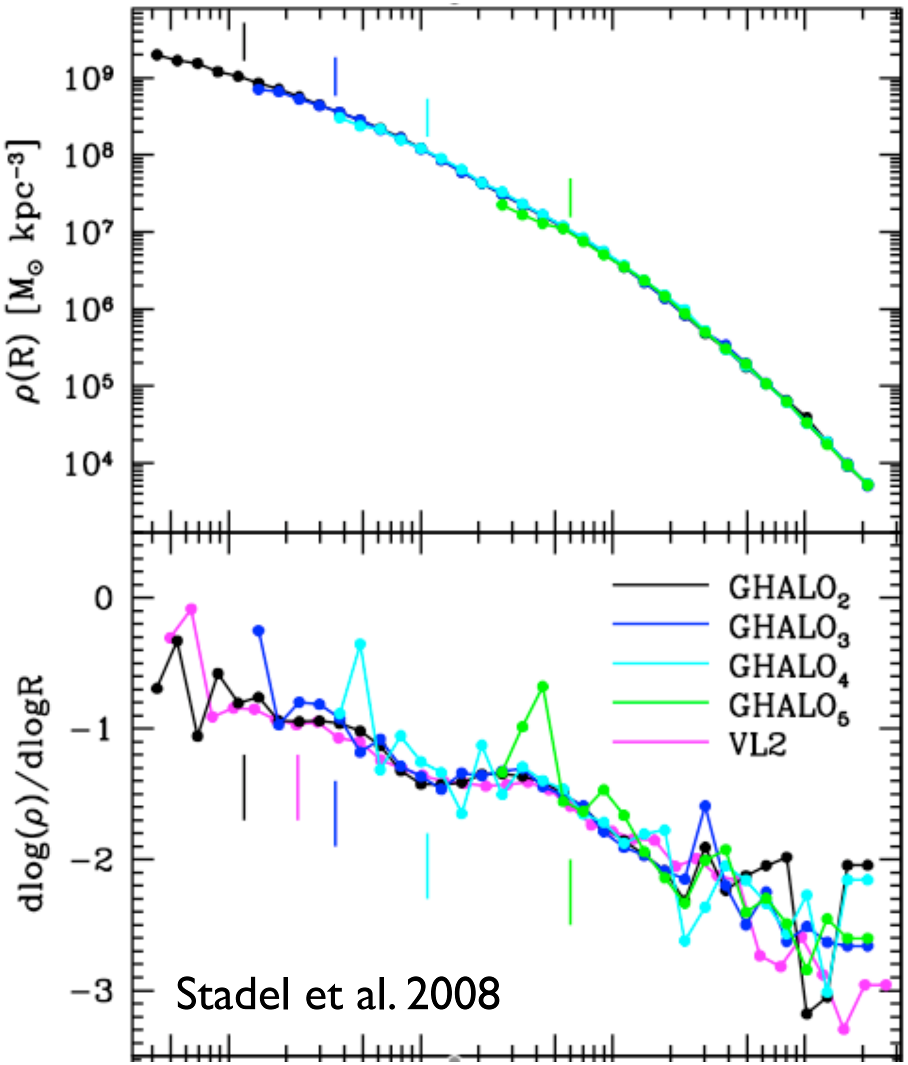
Simulated density profiles





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Observed density profile

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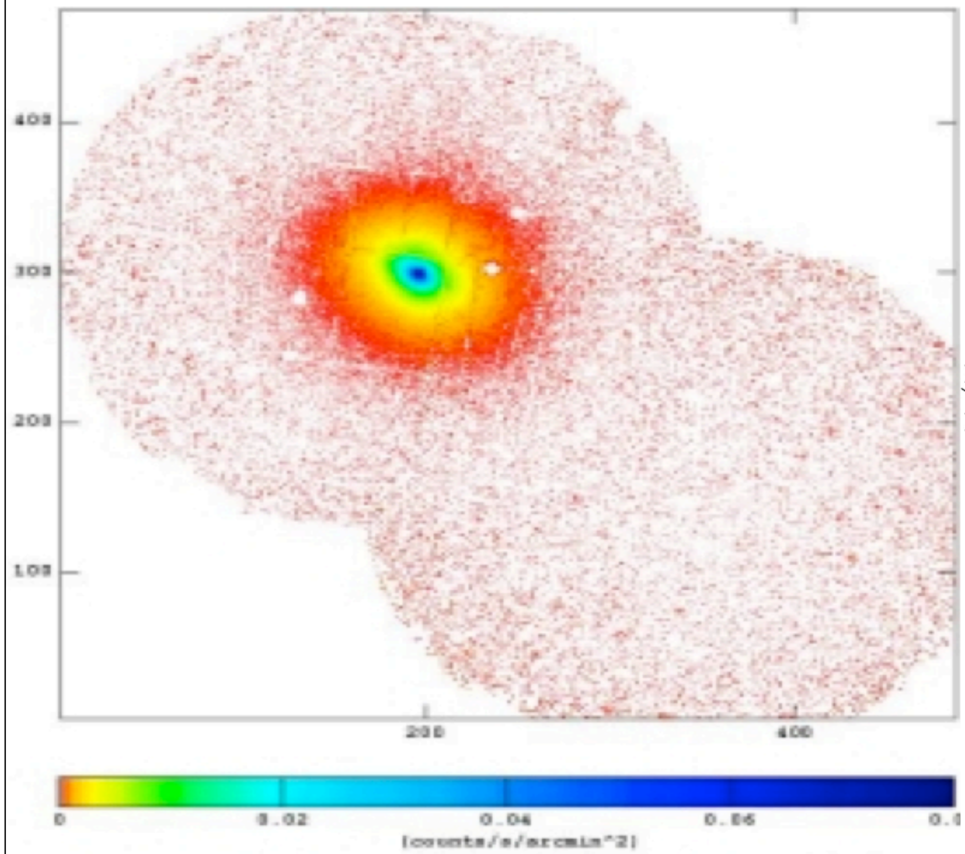
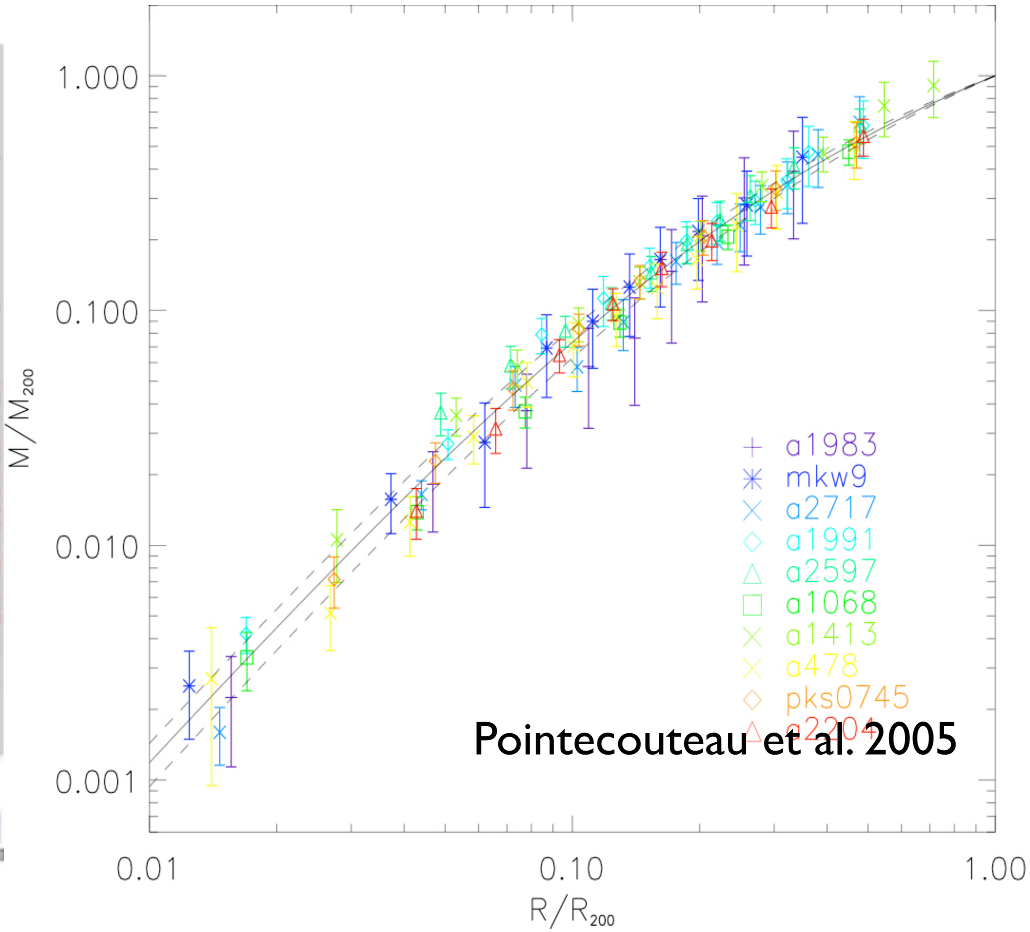
Observed density profile

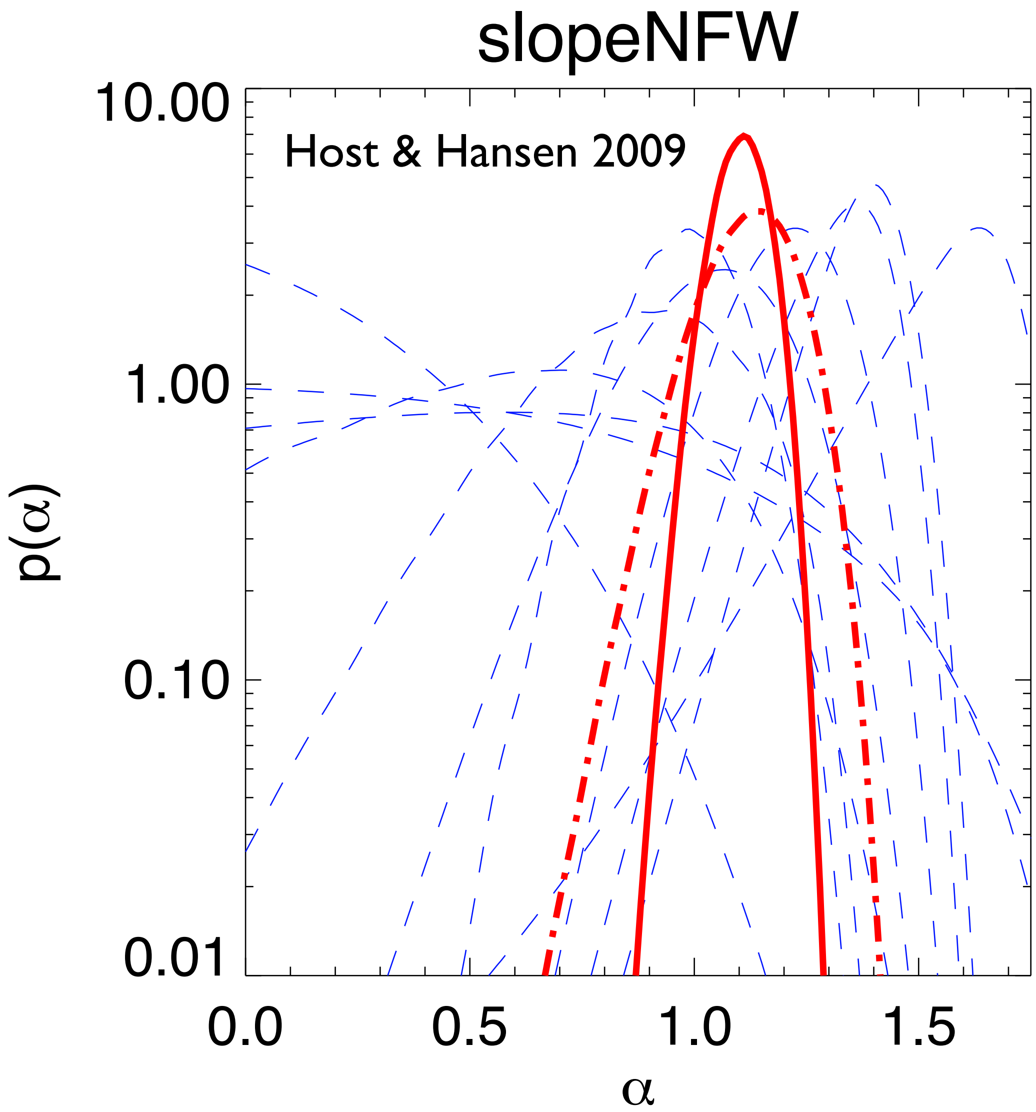
X-ray observations





Pointecouteau et al. 2005

Observed density profile



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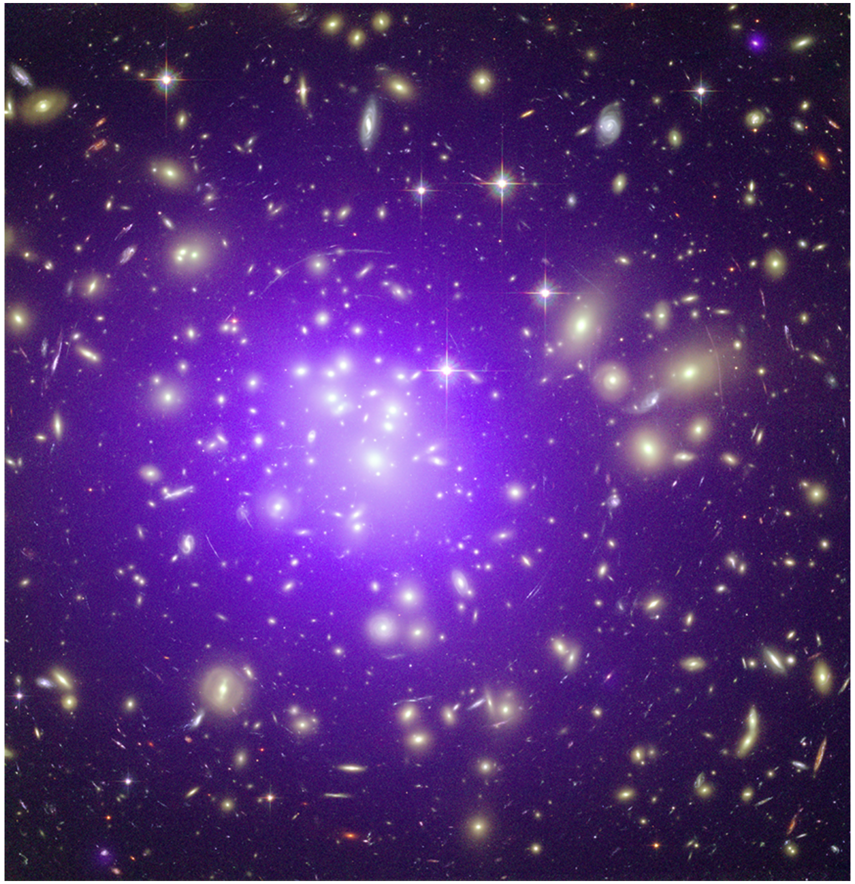
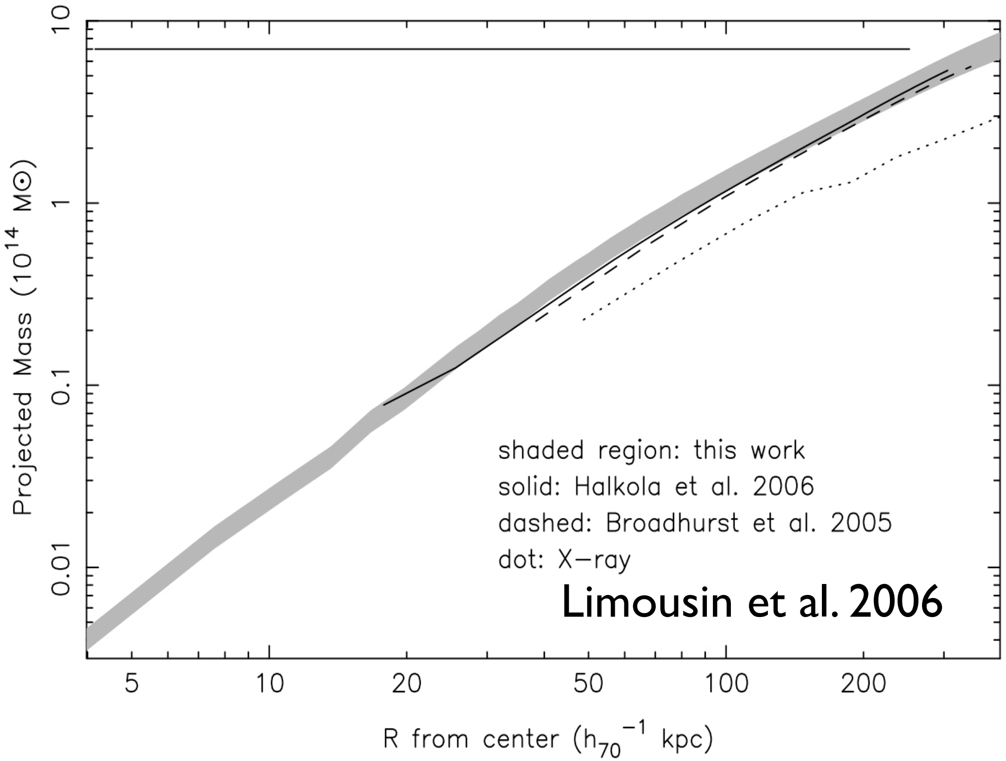
Observed density profile

Lensing observations





Limousin et al. 2006

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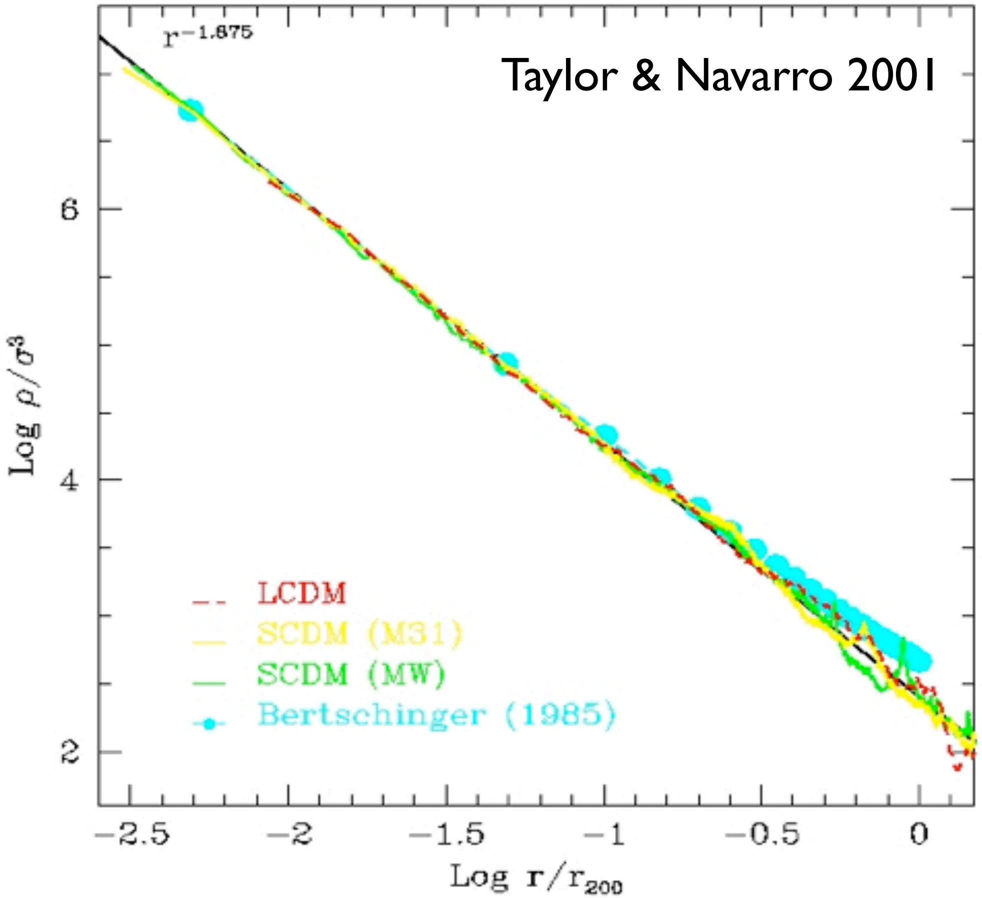
Theoretical density profiles

Jeans equation (dark matter)

$$\frac{GM_{\rm tot}}{r} = -\sigma_r^2 \left(\frac{d{\rm ln}\sigma_r^2}{d{\rm ln}r} + \frac{d{\rm ln}\rho}{d{\rm ln}r} + 2\beta \right)$$

...pretty hard to solve (impossible?)

Theoretical density profiles

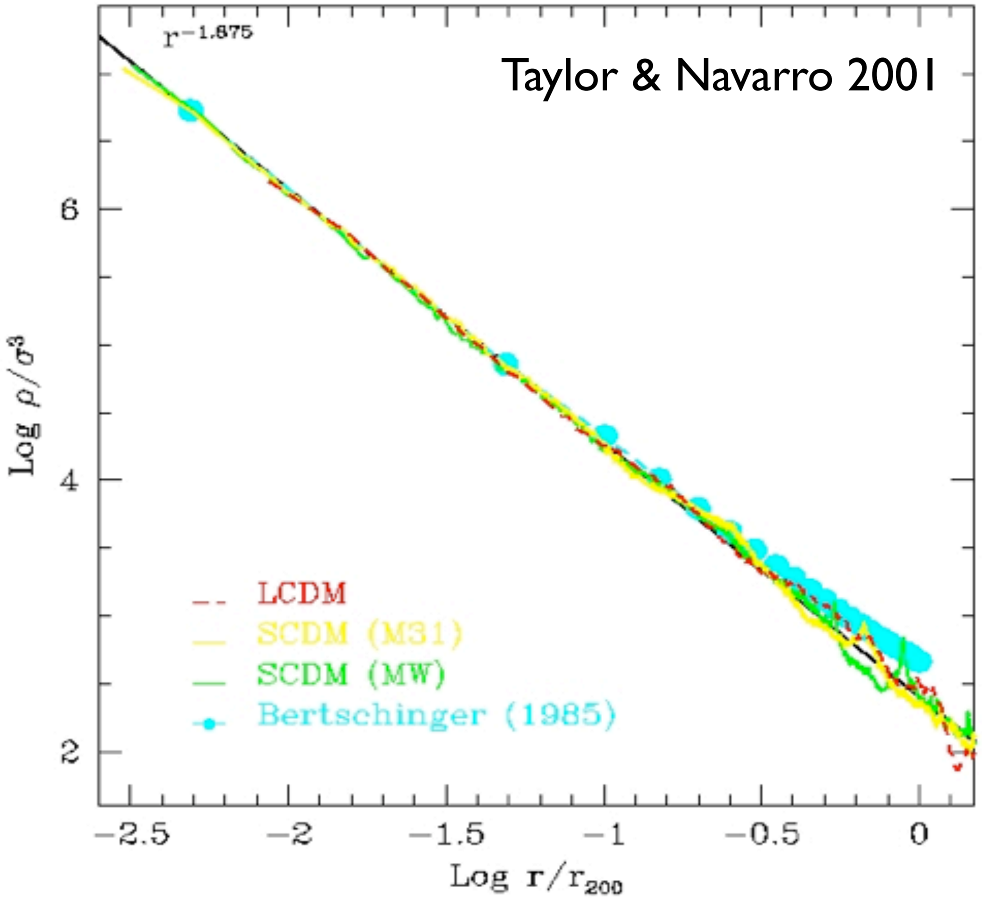


Assumption

Phase-space density = power law in radius

$$\rho/\sigma_r^3 \sim r^{-\alpha}$$

Theoretical density profiles



Assumption

Phase-space density = power law in radius

$$\rho/\sigma_r^3 \sim r^{-\alpha}$$

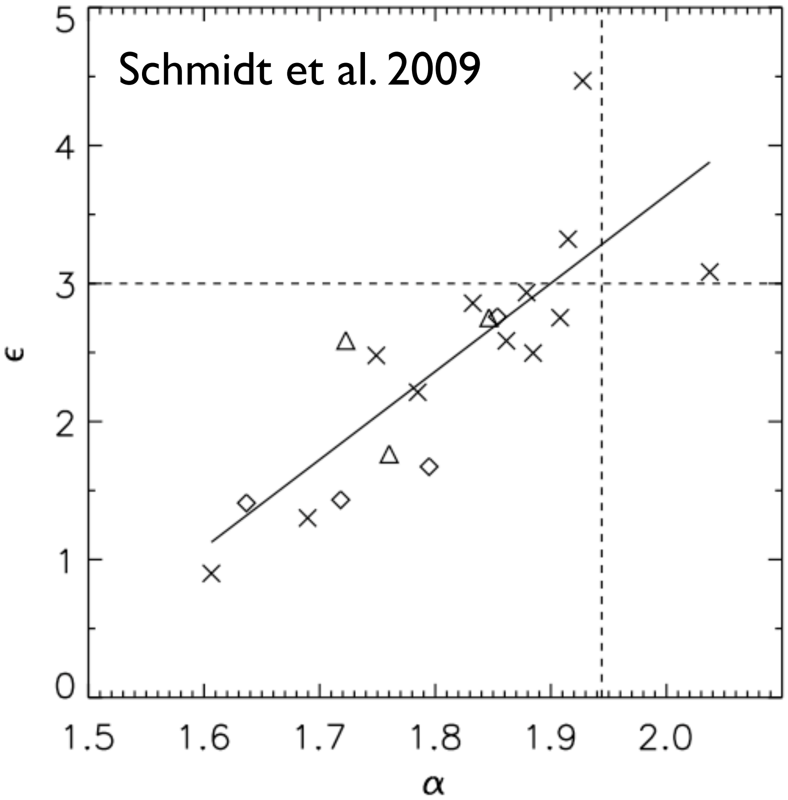
Solution to Jeans equation

$$\rho(r) = \frac{1}{r^{7/9}(1 + r^{4/9})^6}$$

Hansen 2004
Austin et al. 2005
Dehnen & McLaughlin 2005

Theoretical density profiles

The phase-space density argument does unfortunately not work, because different structures are fit with different forms



$$\rho/\sigma_d^\epsilon \sim r^{-\alpha}$$

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Theoretical density profiles

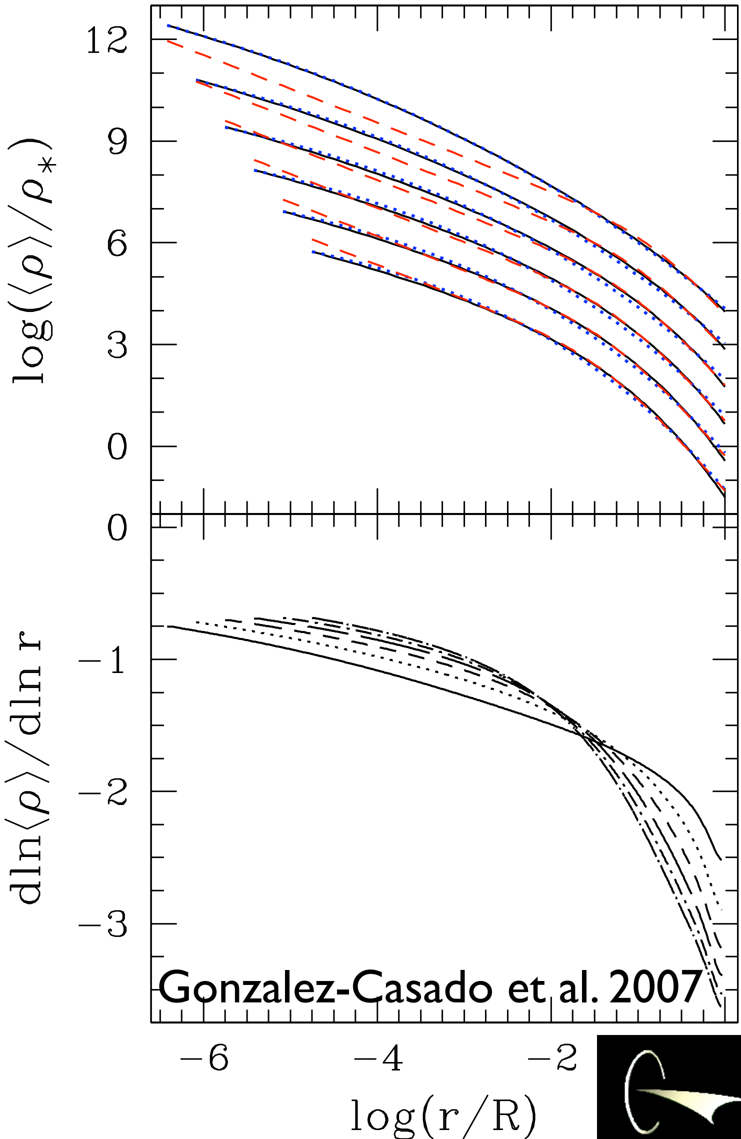
The Barcelona model:

Completely analytical

Accretion driven structure formation

Sersic profiles seem to fit surprisingly well

Manrique et al, 2003
Salvador-Sole et al. 2009



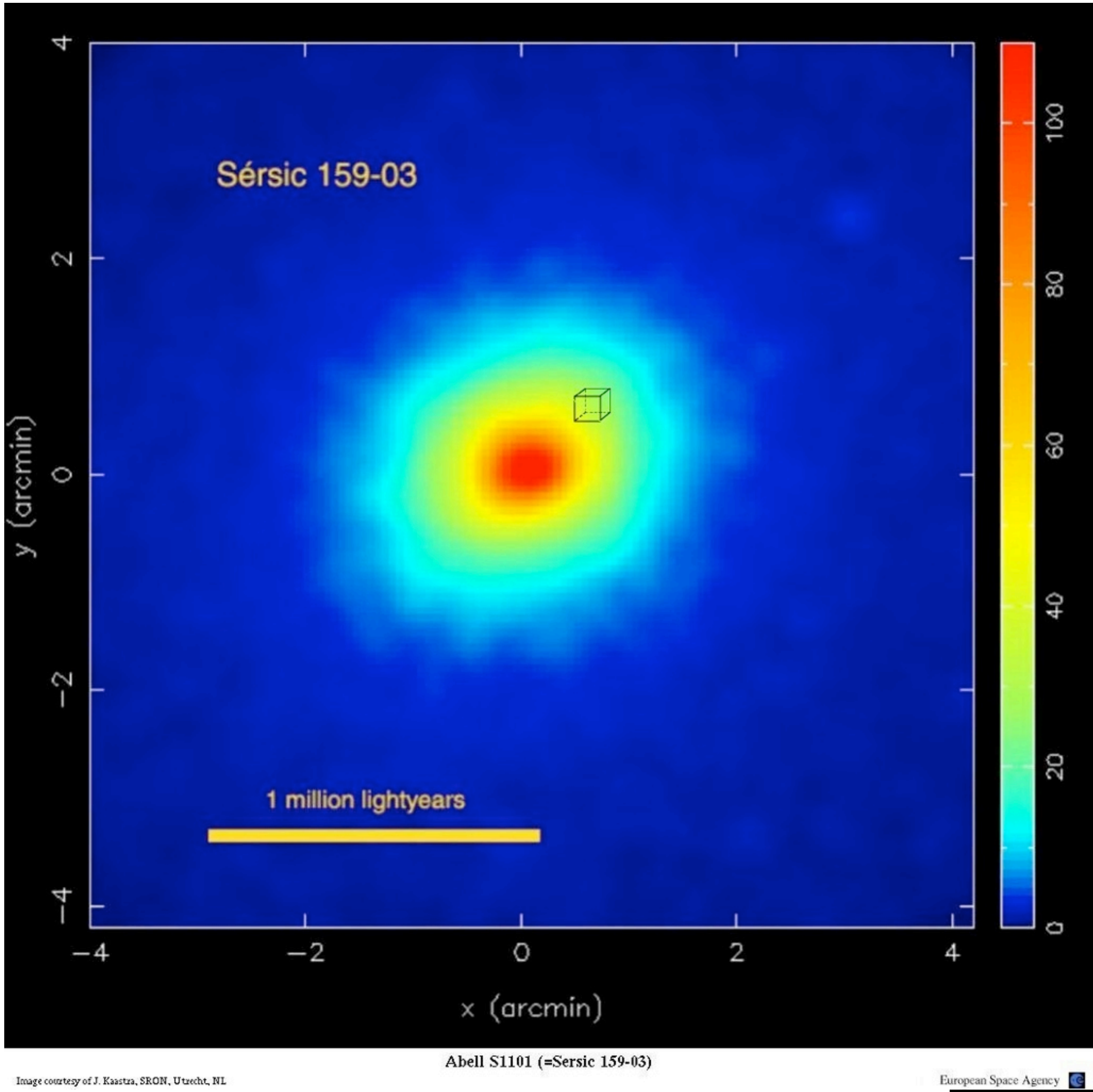
Summarizing the density profiles

1) Good agreement between DM numerical simulations and observations on cluster scale

2) Surely gas physics is crucial on small scale
(but no disagreement between DM sim. and obs.)

3) Theory:
Phase-space argument not supported by numerical simulations.
Barcelona model appears impressively strong

and now something completely new...



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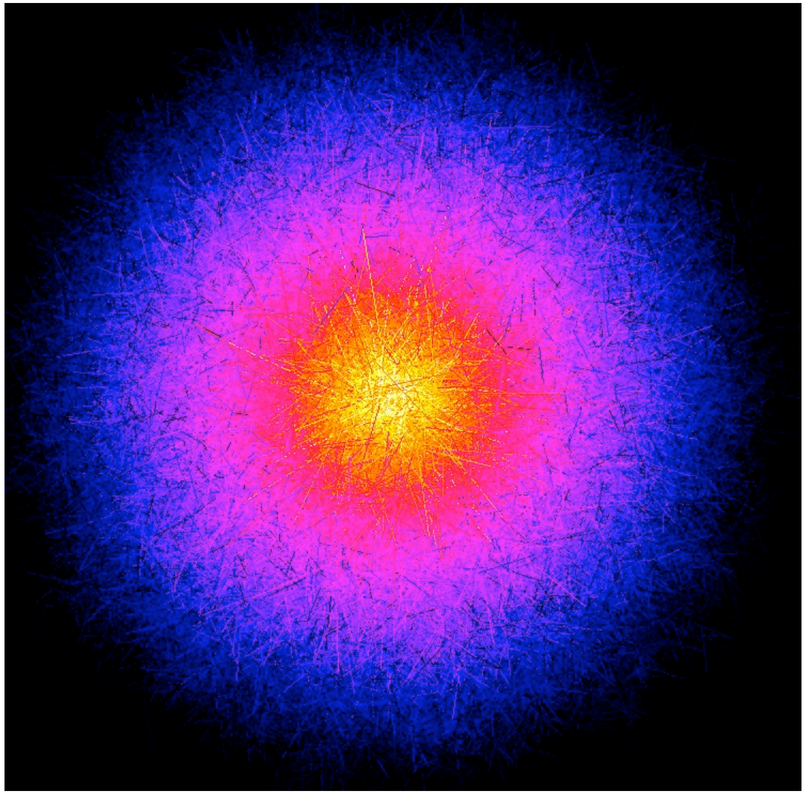
Velocity anisotropy profiles

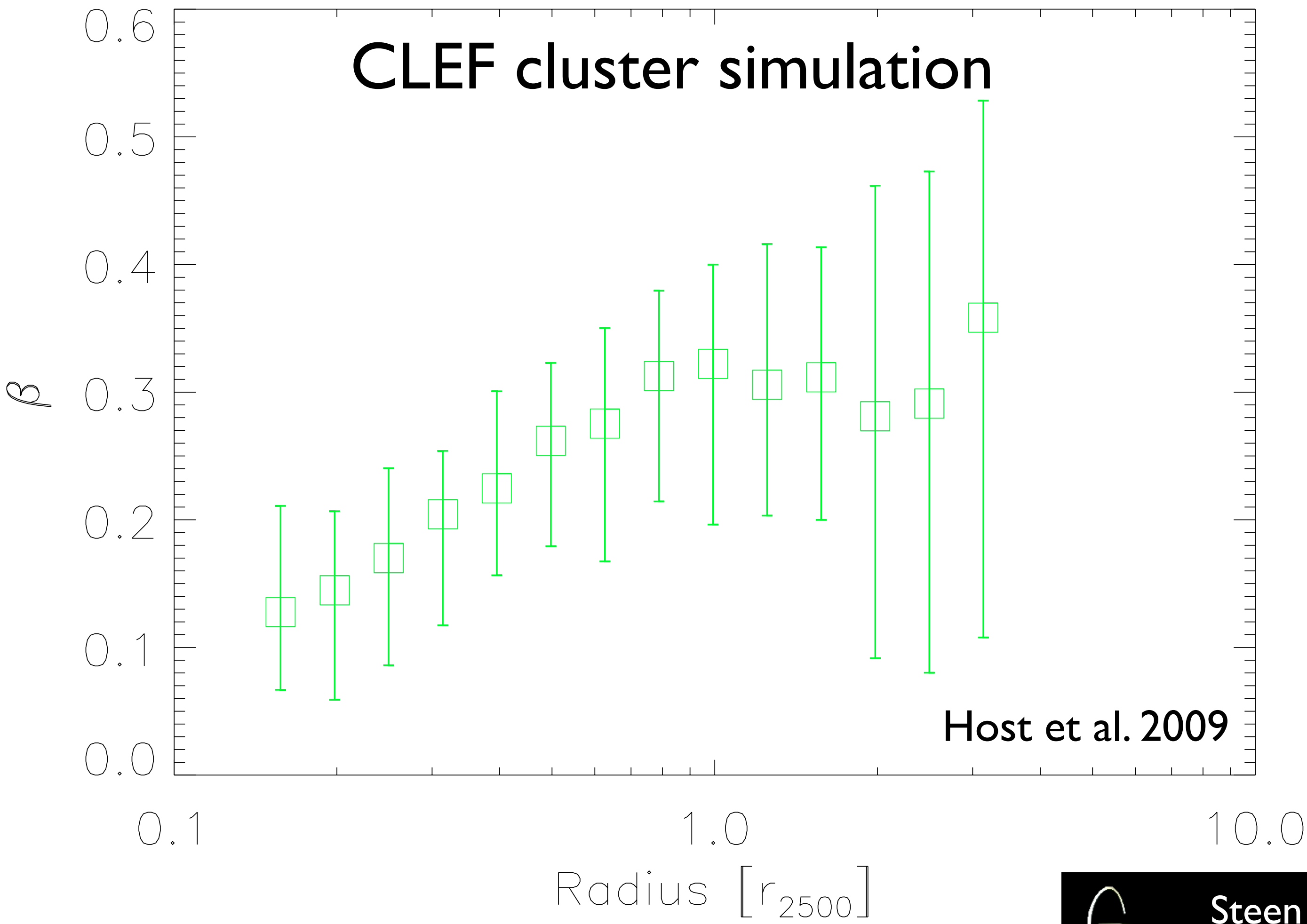
Velocity anisotropy =
different "temperature"
in different directions

$$\beta = 1 - \frac{\sigma^2_{\rm tan}}{\sigma^2_{\rm rad}}$$



Must be zero for a gas

Simulated velocity anisotropy



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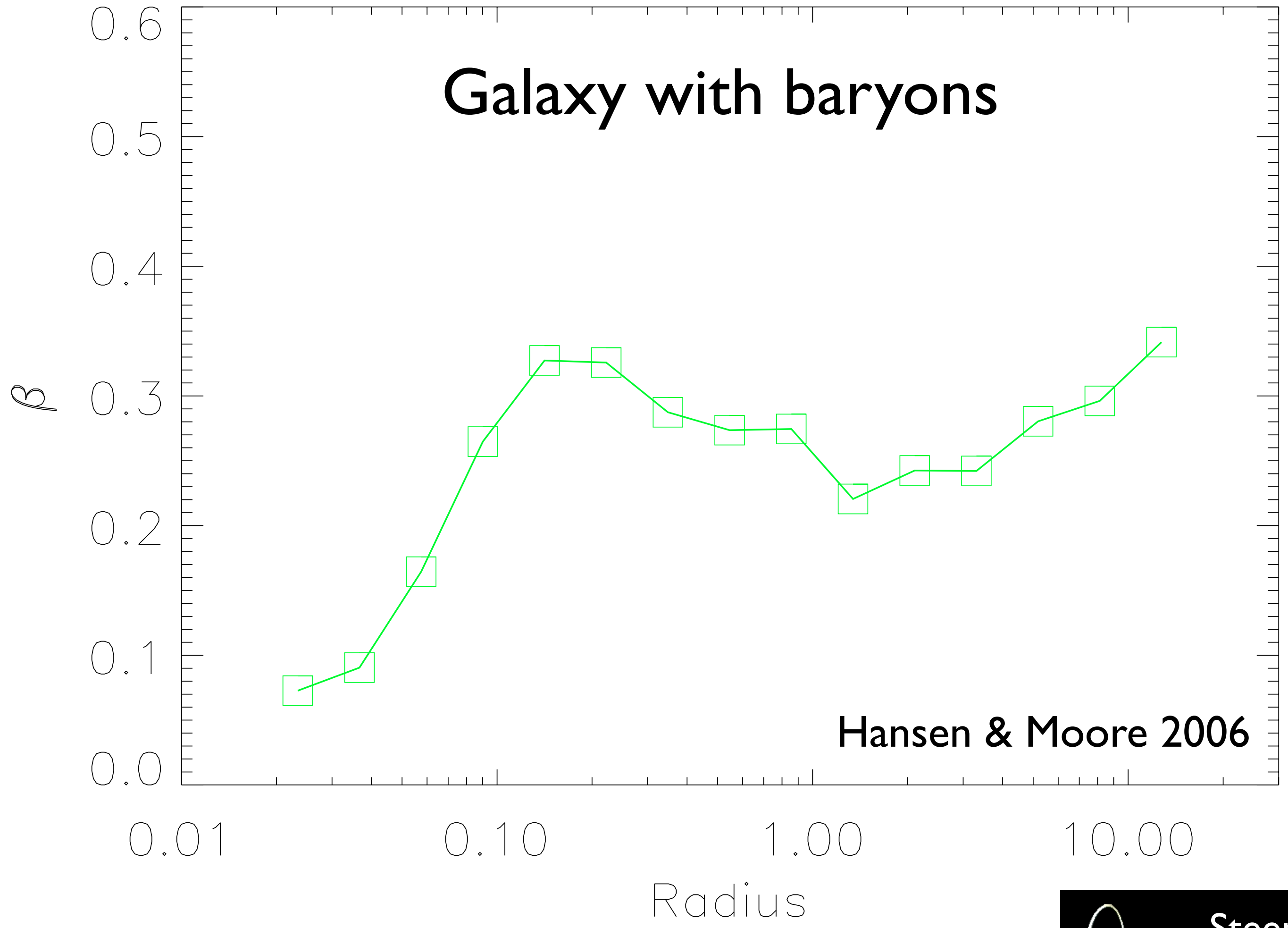
Simulated velocity anisotropy



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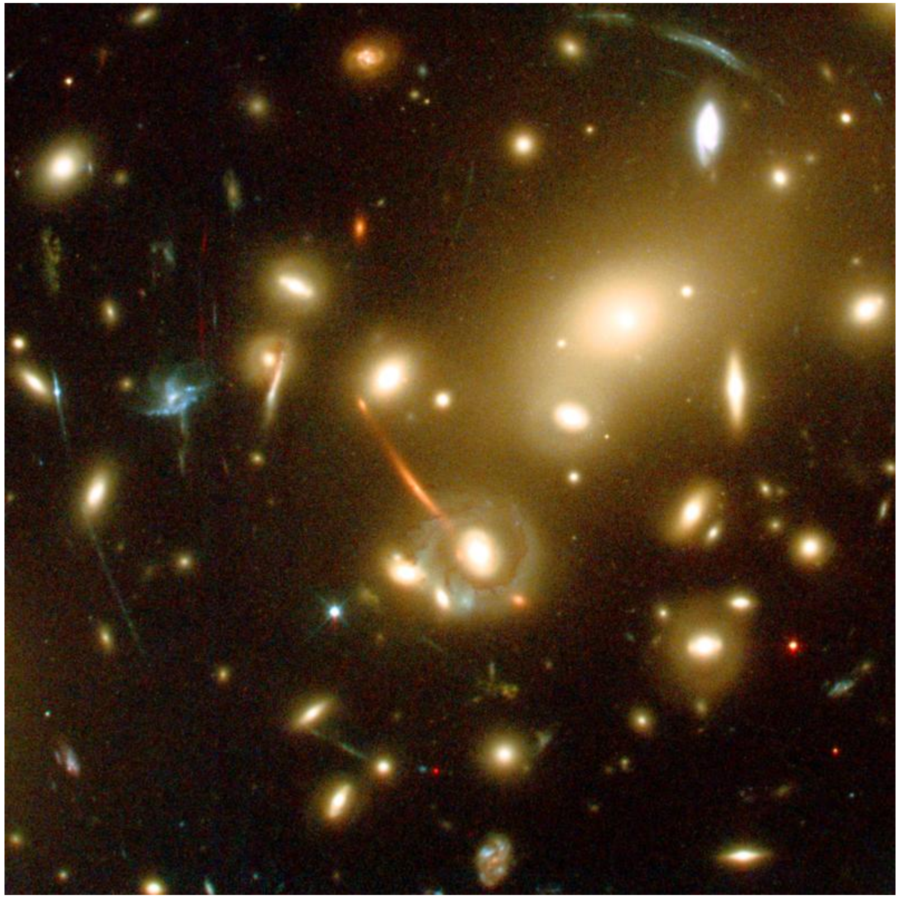
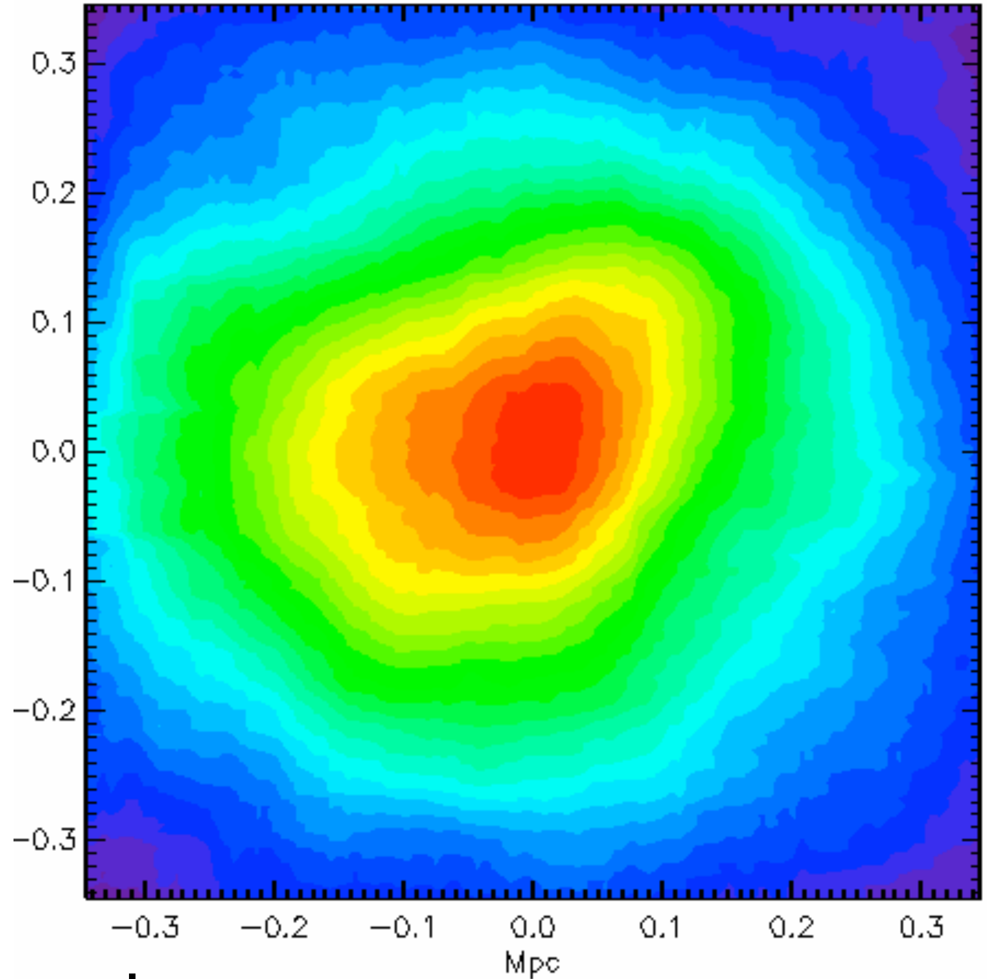
Observed velocity anisotropy





Consider an equilibrated galaxy cluster

Observed velocity anisotropy

Hydrostatic equilibrium (gas)

$$\frac{GM_{\rm tot}}{r} = -\frac{k_B T}{\mu m_p}\left(\frac{d{\rm ln}T}{d{\rm ln}r} + \frac{d{\rm ln}n_e}{d{\rm ln}r}\right)$$

Jeans equation (dark matter)

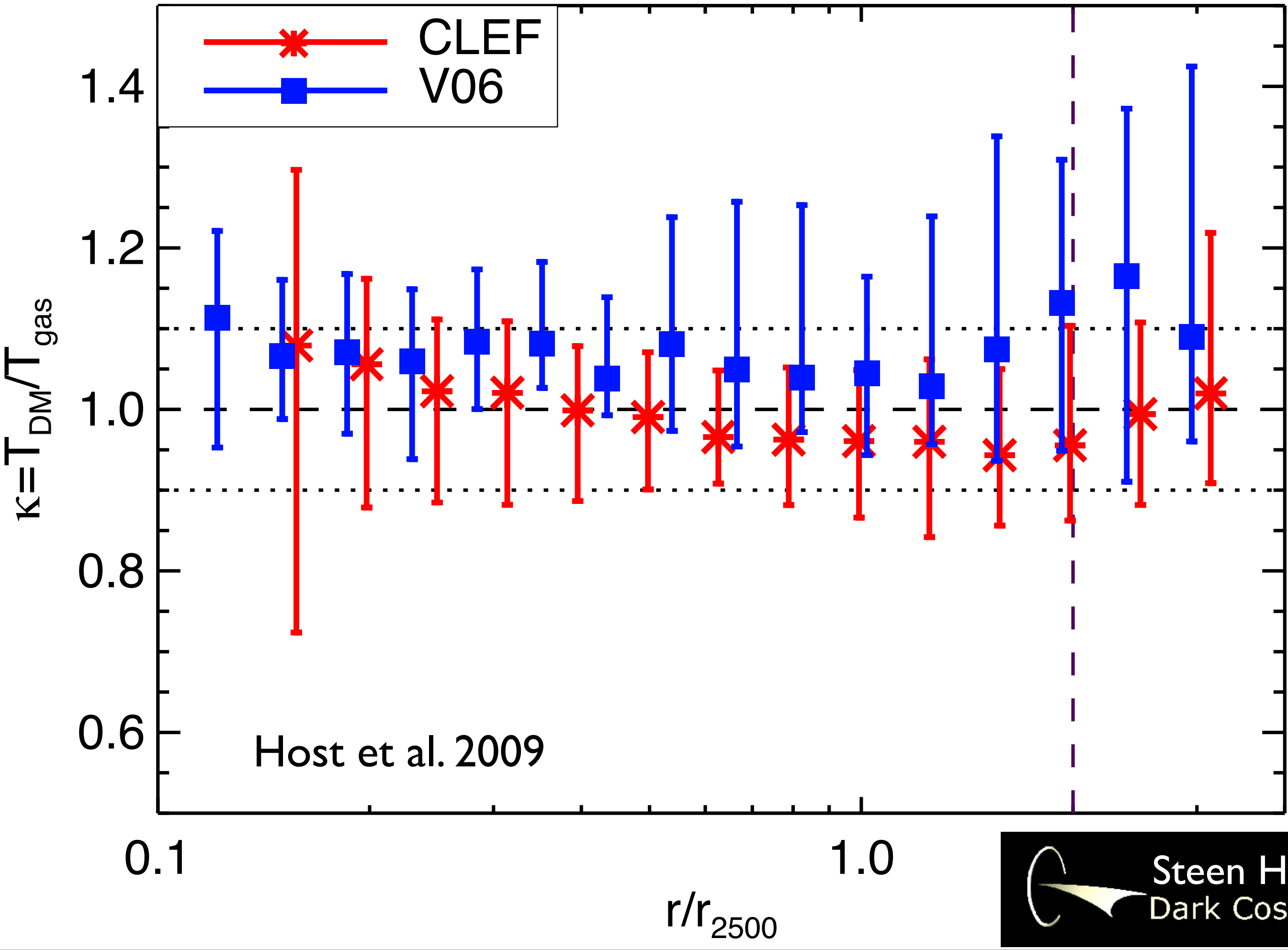
$$\frac{GM_{\rm tot}}{r} = -\sigma_r^2\left(\frac{d{\rm ln}\sigma_r^2}{d{\rm ln}r} + \frac{d{\rm ln}\rho}{d{\rm ln}r} + 2\beta\right)$$

If $\frac{T}{\sigma_{\rm tot}^2} \approx 1$, then we can solve for β

Hansen & Piffaretti 2007

Observed velocity anisotropy

We have to make **one** assumption



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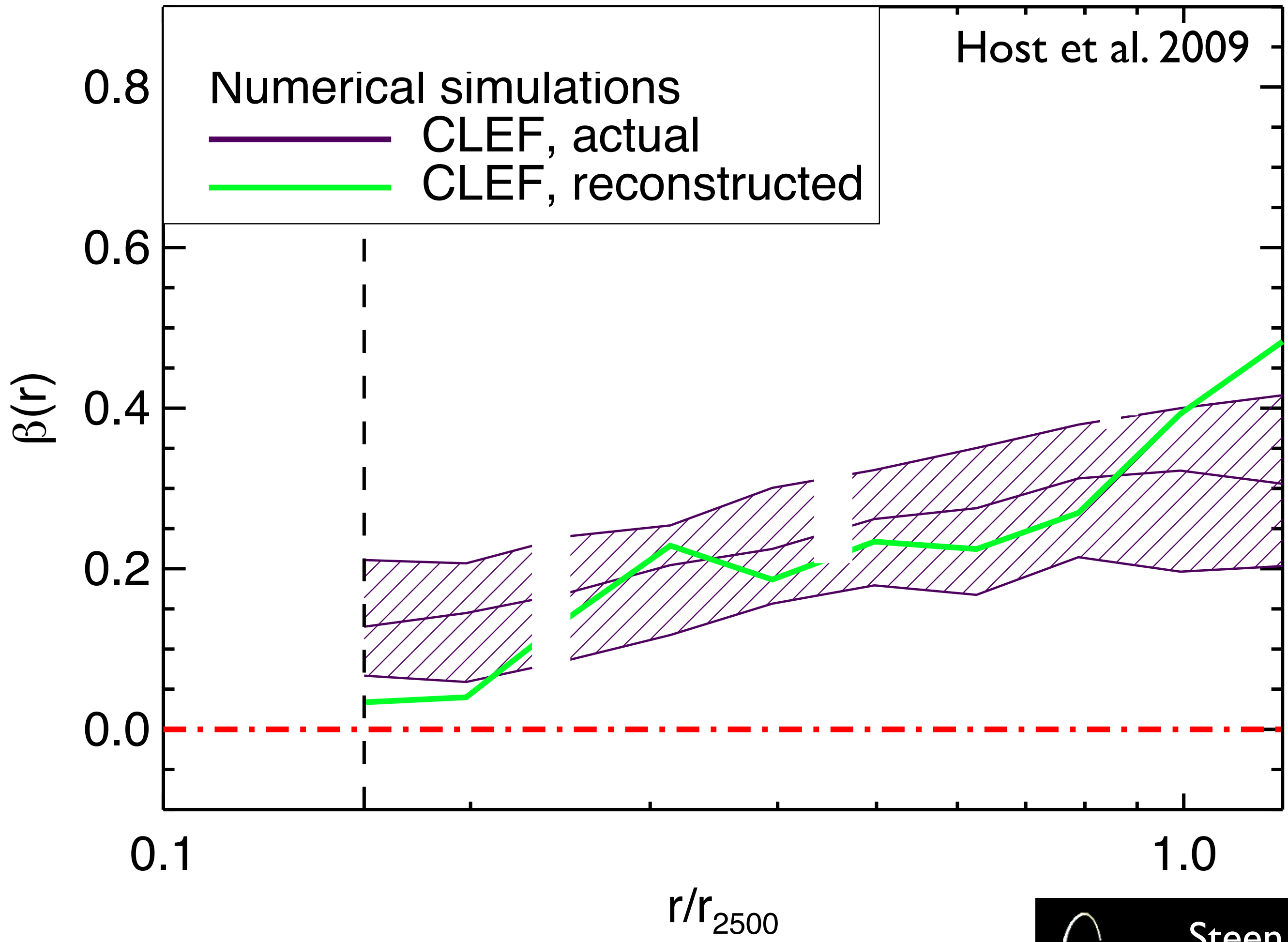
Observed velocity anisotropy



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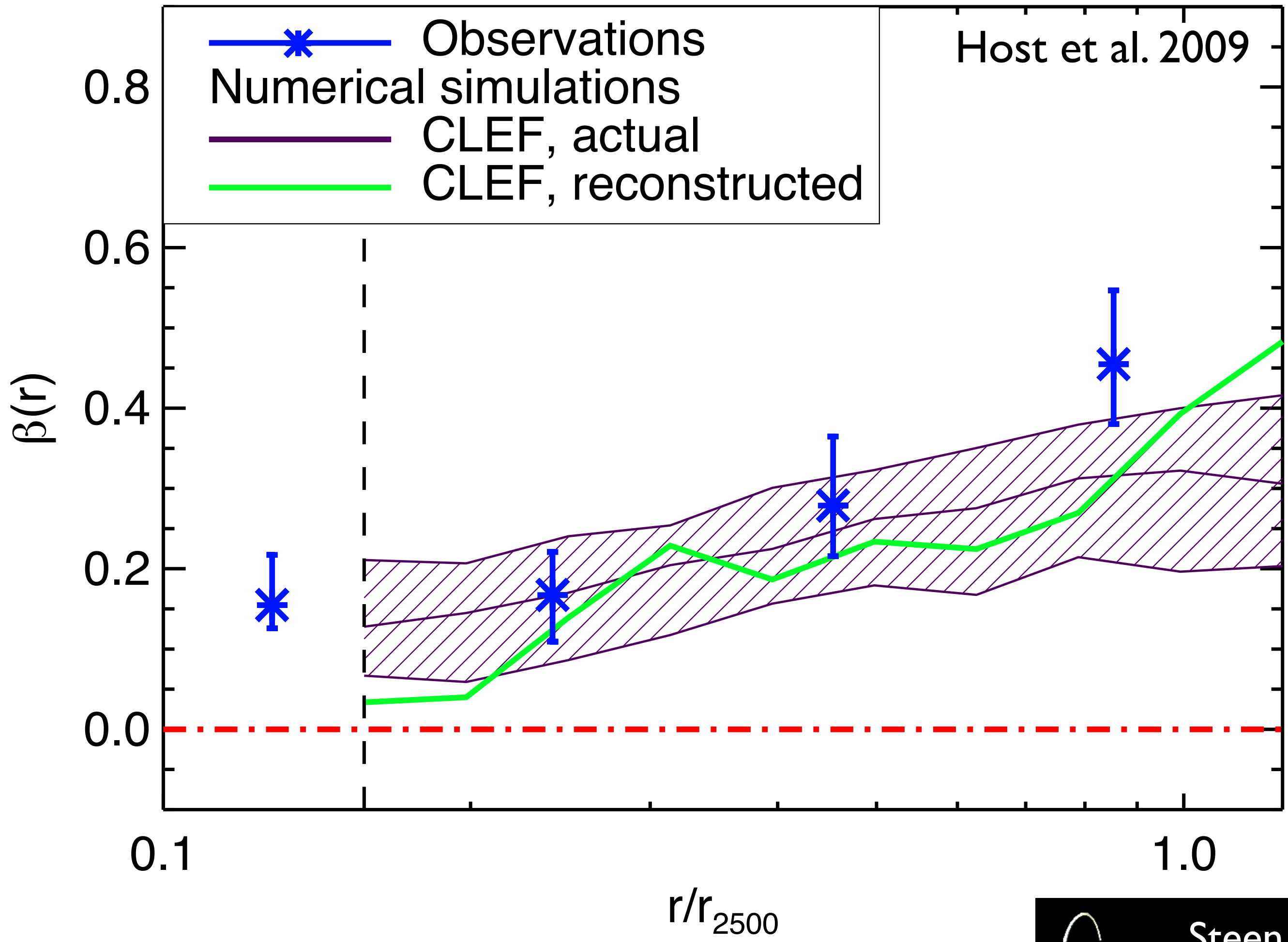
Observed velocity anisotropy

The observed galaxy clusters



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So, that means...

Dark matter structures do not achieve equilibrium through collisions (as normal particles do)

This gives an upper limit on the DM-DM scattering cross section

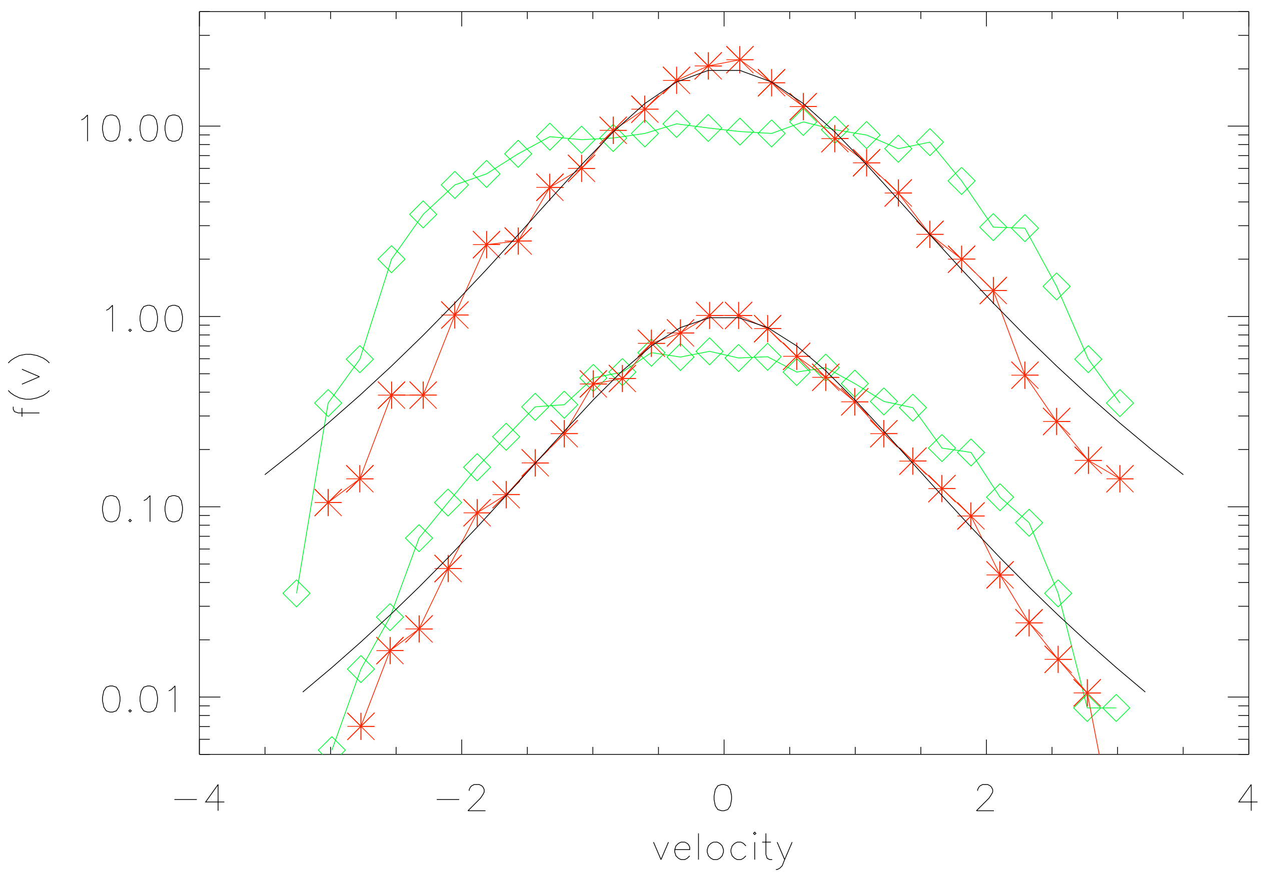
Dark matter behaves fundamentally different from baryons

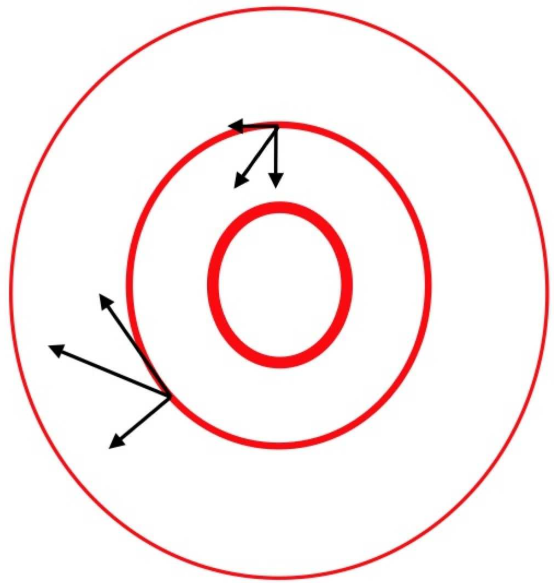
Where should we go from here?

- The density is an integrated quantity
  $\rho(r) = \int f(v,r)\, d^3v$
- the velocity anisotropy is an integrated quantity
  $\sigma^2(r) = \int v^2 f(v,r)\, d^3v$
- so, how about trying to understand f(v,r)

Theoretical velocity anisotropy

The velocity distribution function is exp(-v^2/T) for a normal gas, but what about **collisionless** dark matter?





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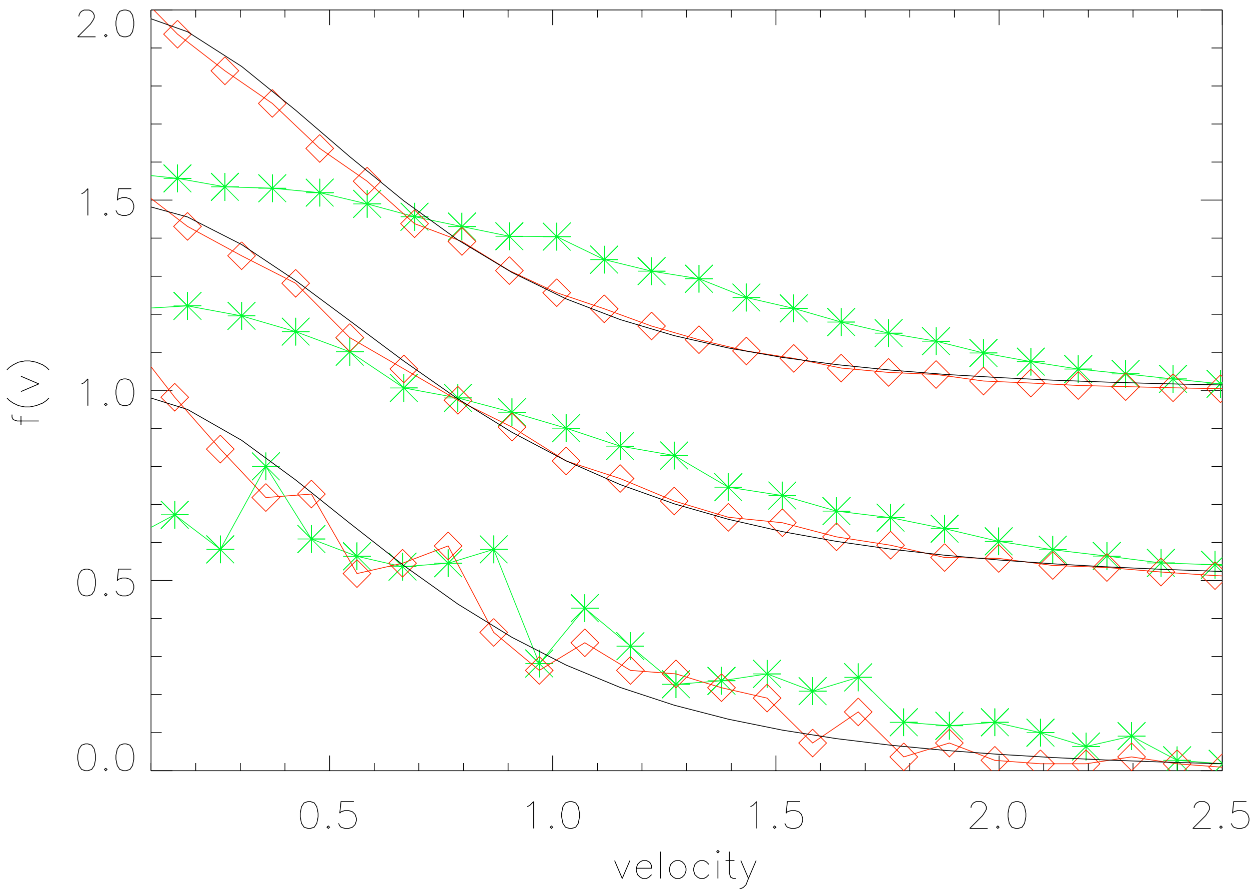
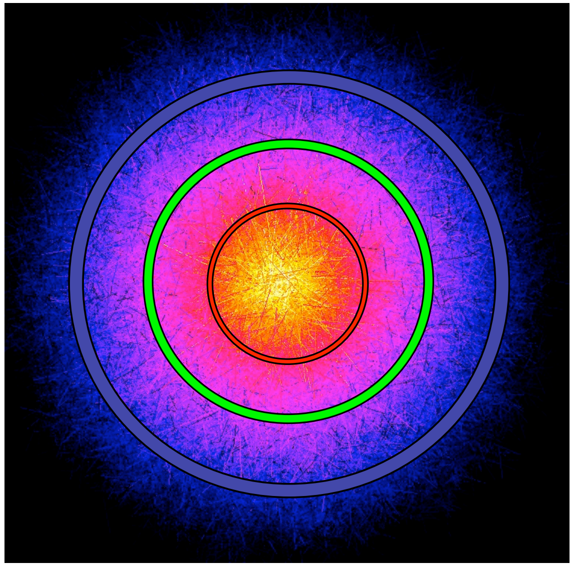
We (almost) know the tangential distribution function





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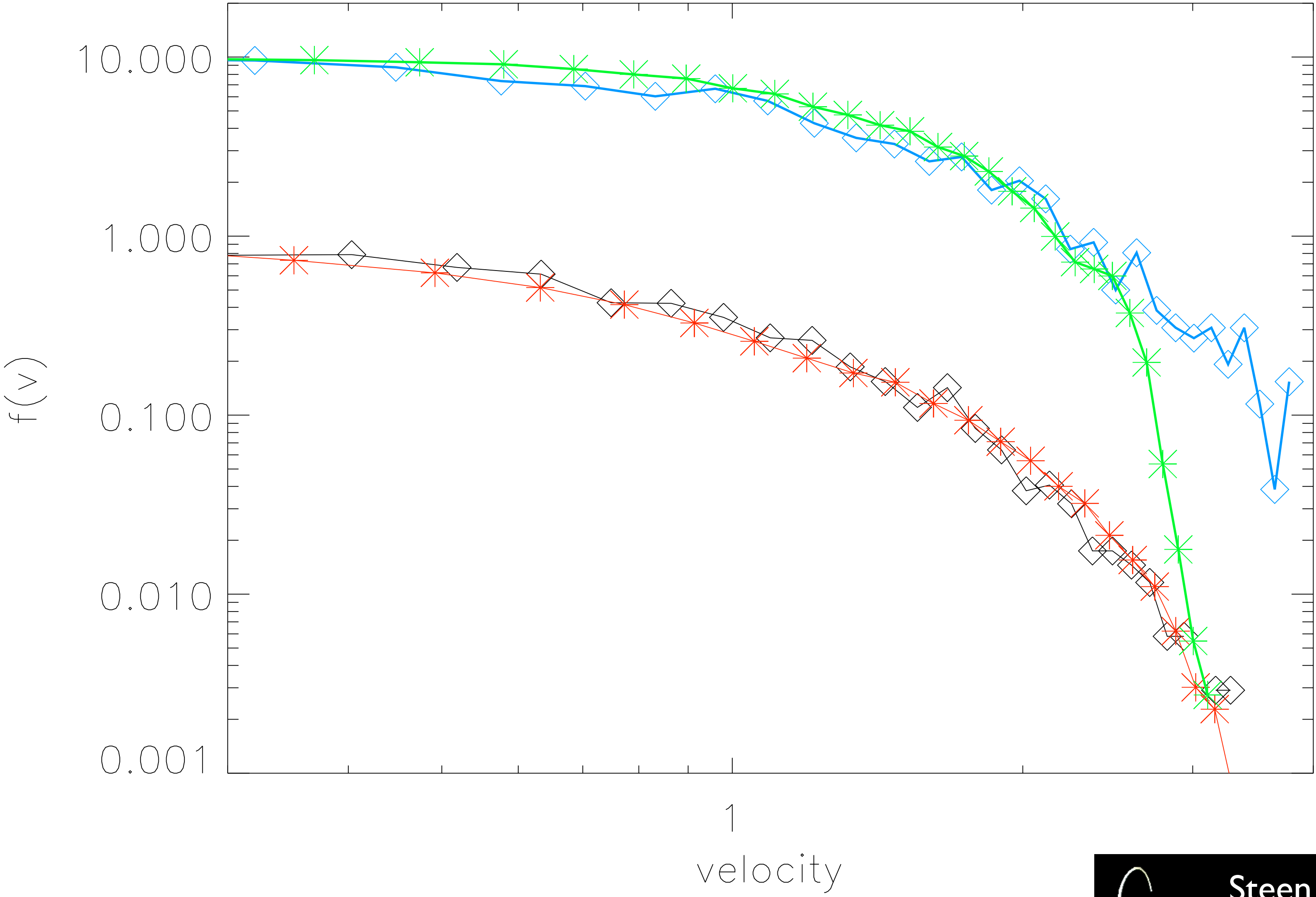
We (almost) know the radial distribution function



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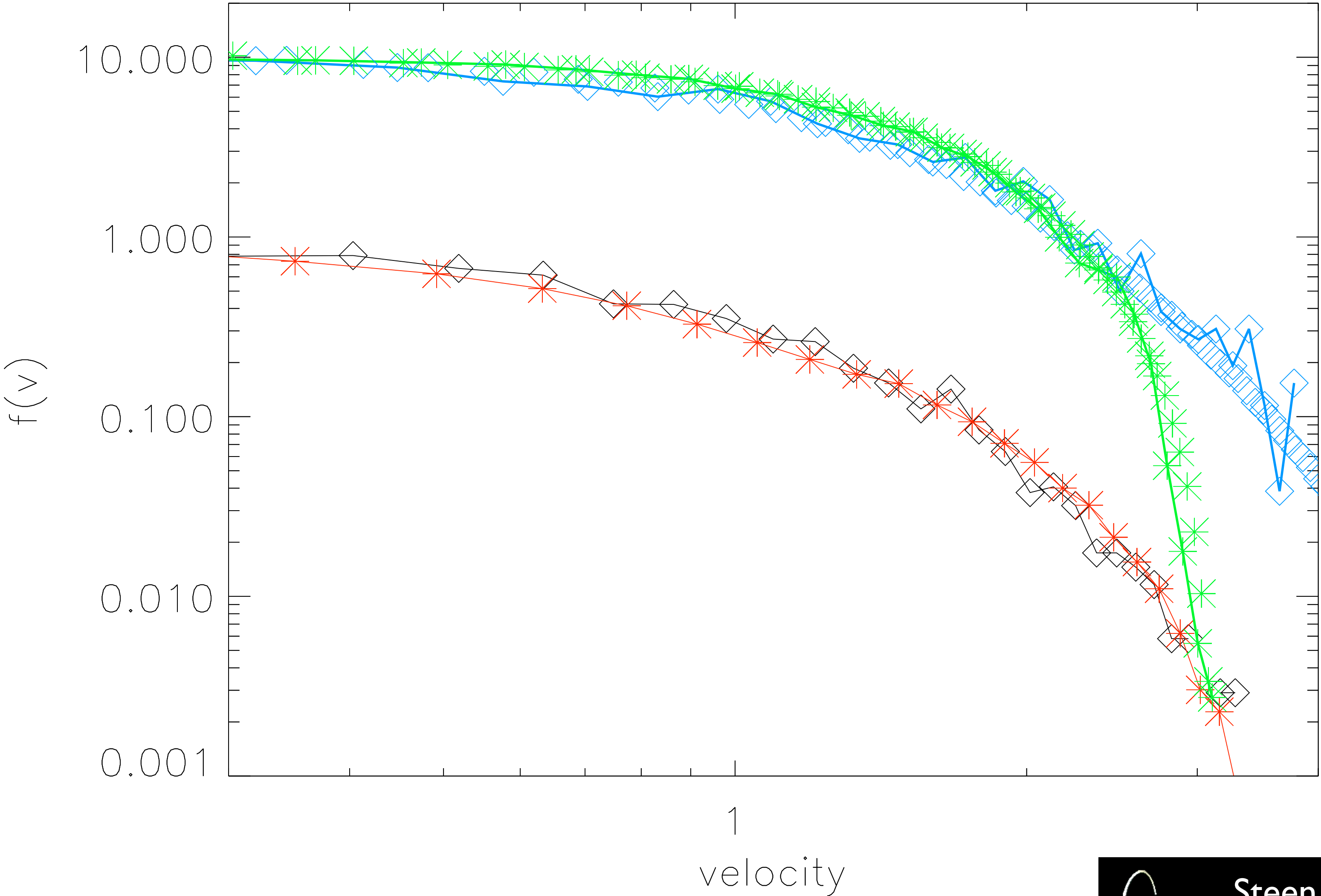
We (almost) know the radial distribution function



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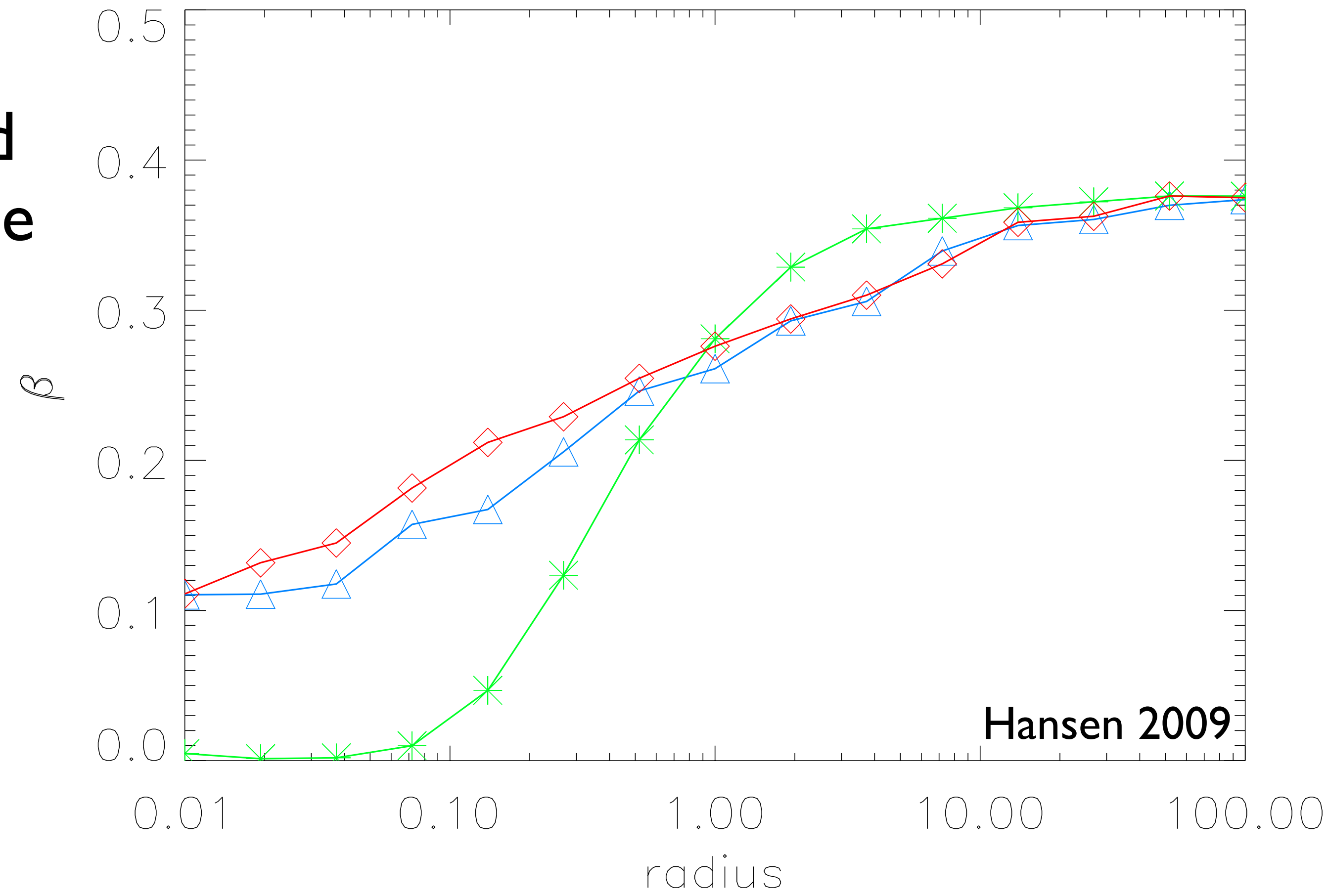
Theoretical velocity anisotropy

Analytically derived
from "first" principle

$\beta(r)$ depends
only on $\rho(r)$



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Theoretical velocity anisotropy

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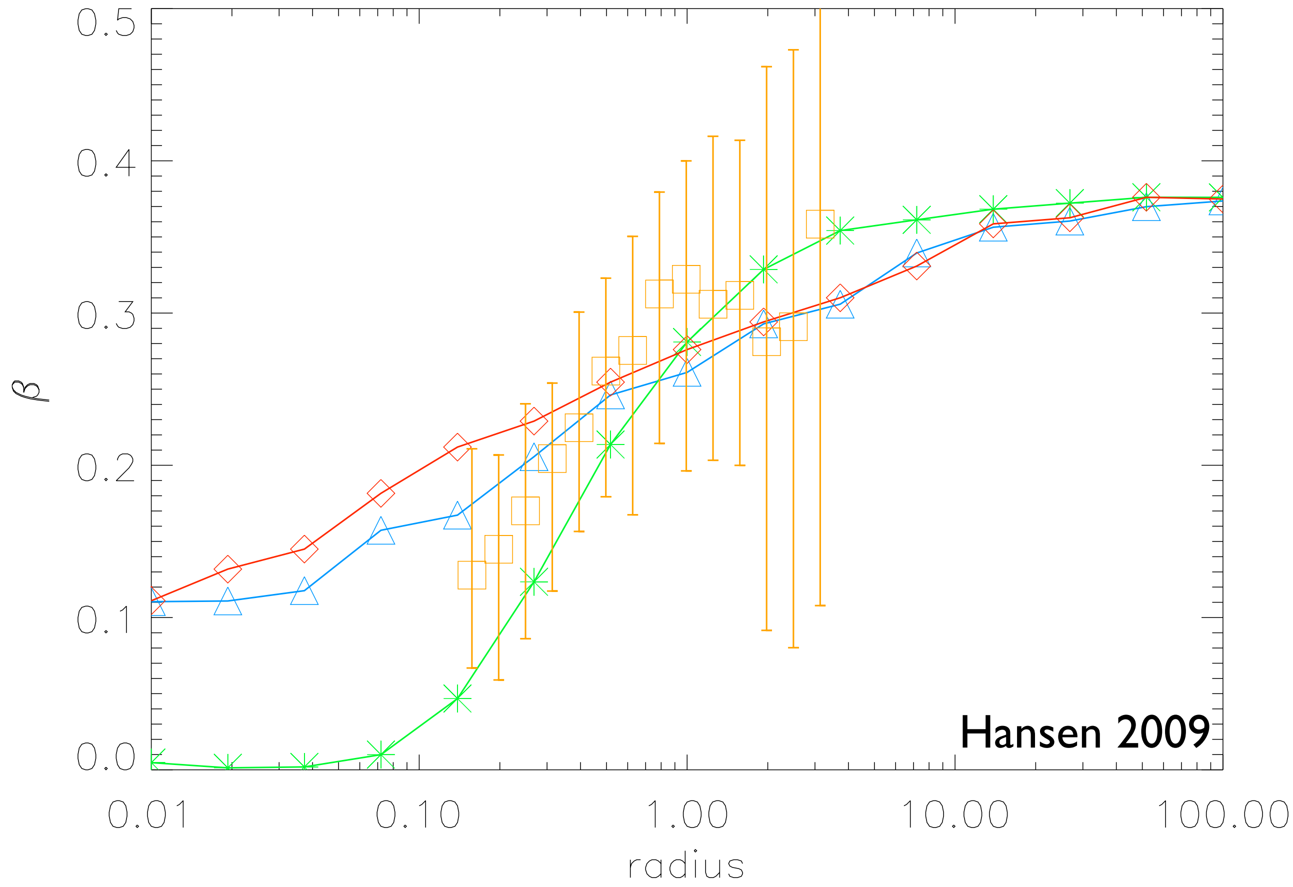

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Summarizing the velocity anisotropy

1) Numerical **simulations** show radial variation from about 0 (inner) to about 0.5 (outer)

2) First ever **observations** of this dynamical aspect confirm the predicted behavior

3) The **analytically** derived velocity anisotropy confirms the magnitude and radial variation

4) If this derivation is correct, then the velocity anisotropy is a function only of the density profile. This implies that we can close the Jeans equation

Conclusions

We have impressive agreement between numerical simulations, observations and theory concerning the large dark matter structures

Conclusions

We have impressive agreement between numerical simulations, observations and theory concerning the large dark matter structures

Thank you

Steen H. Hansen
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