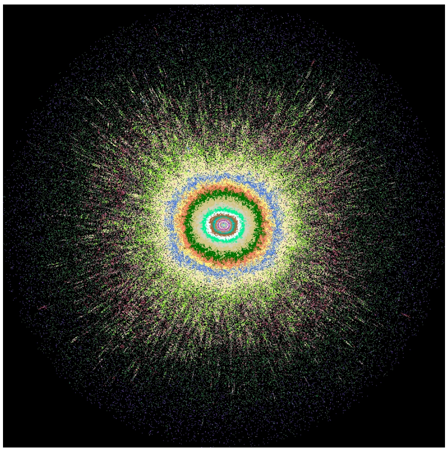
What do cosmological dark matter structures look like, and why



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

Firenze, April, 2010

Dark Cosmology Centre

Dark matter density profiles

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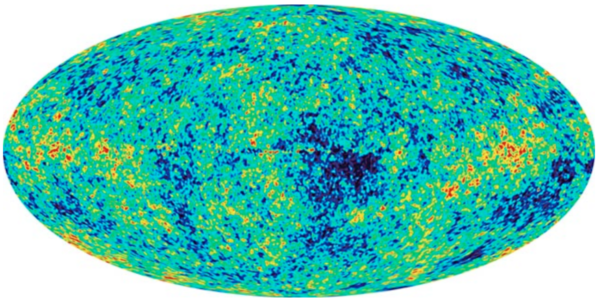
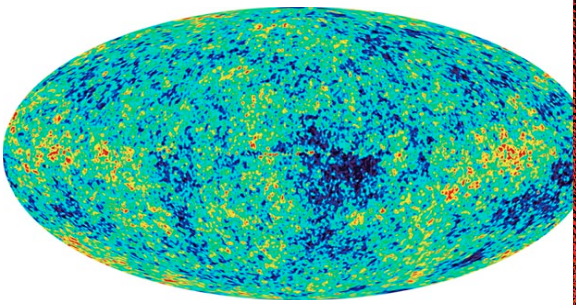
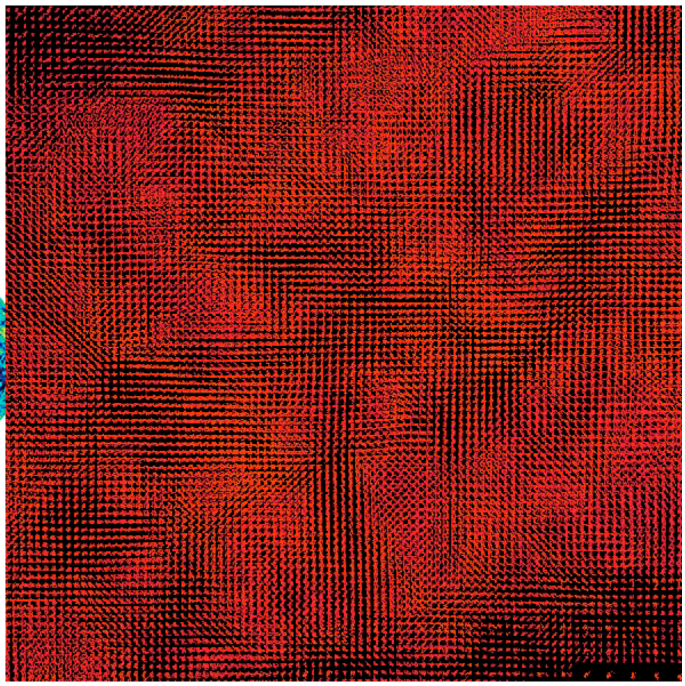
Numerical simulations



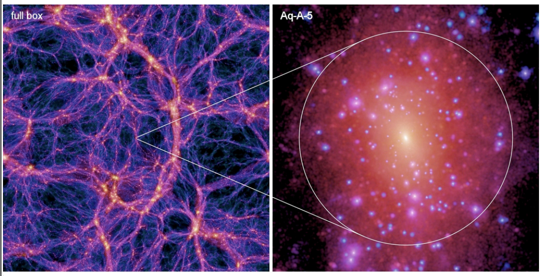
Initial conditions known from observations

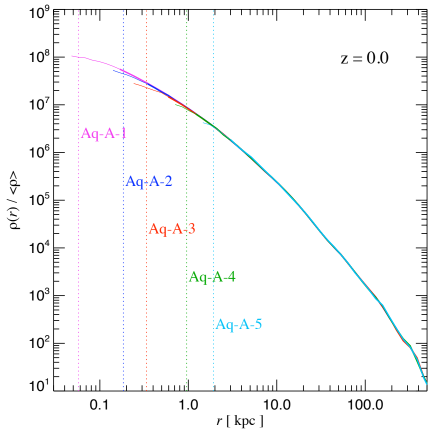
Numerical simulations





Simulated density profiles





Springel et al. 2008

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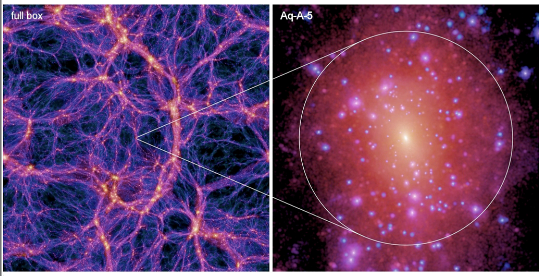
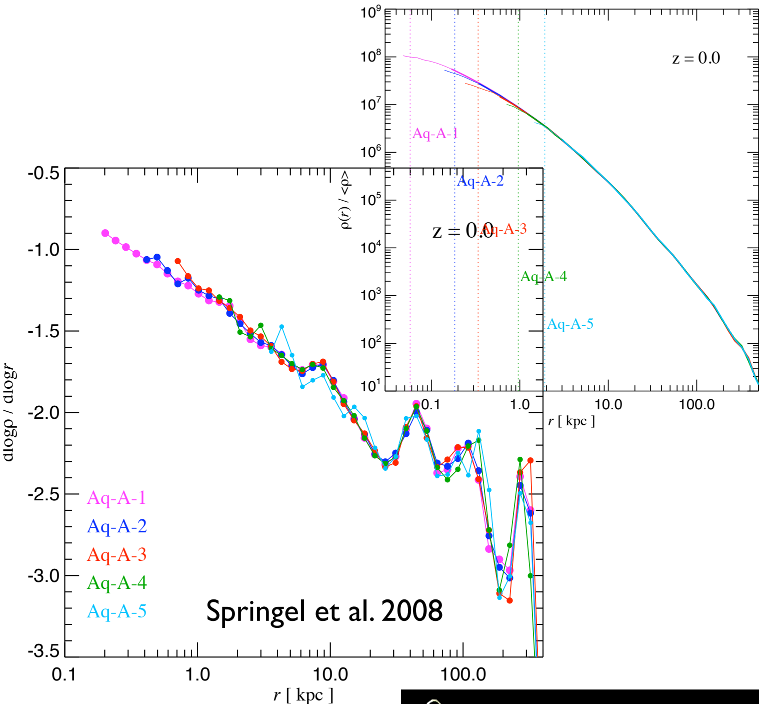
Simulated density profiles





Springel et al. 2008

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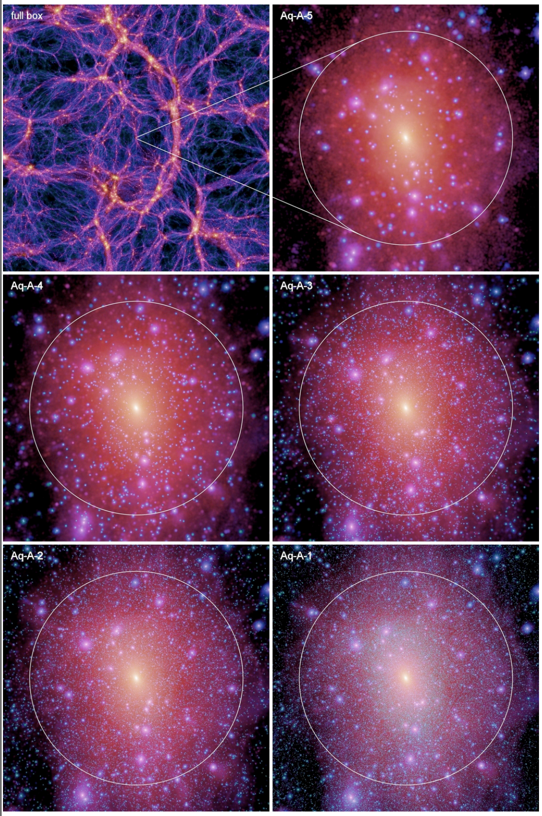
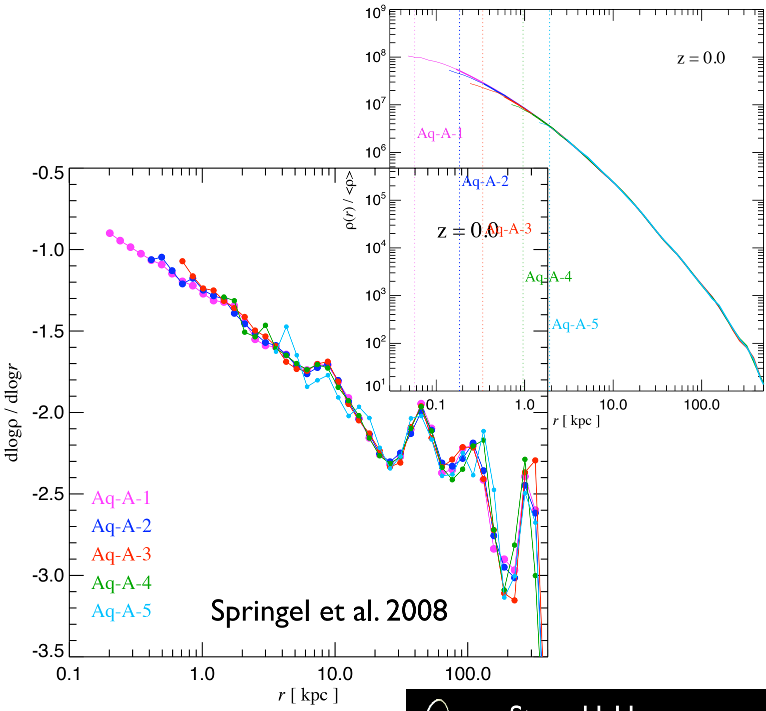
Simulated density profiles





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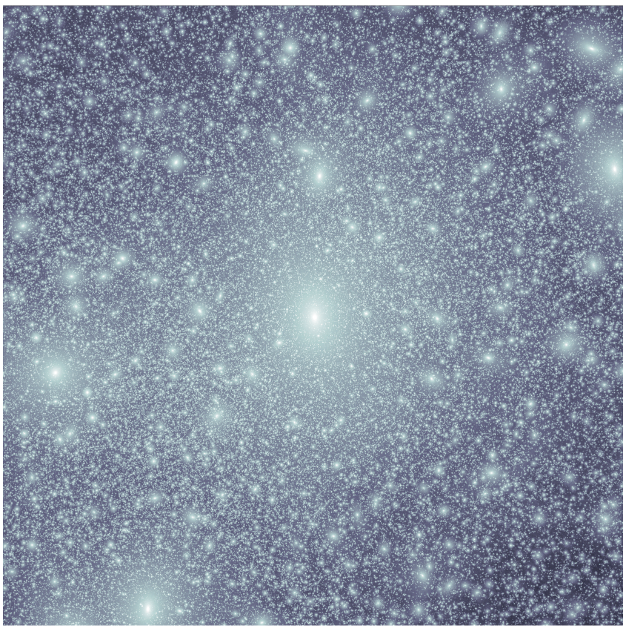
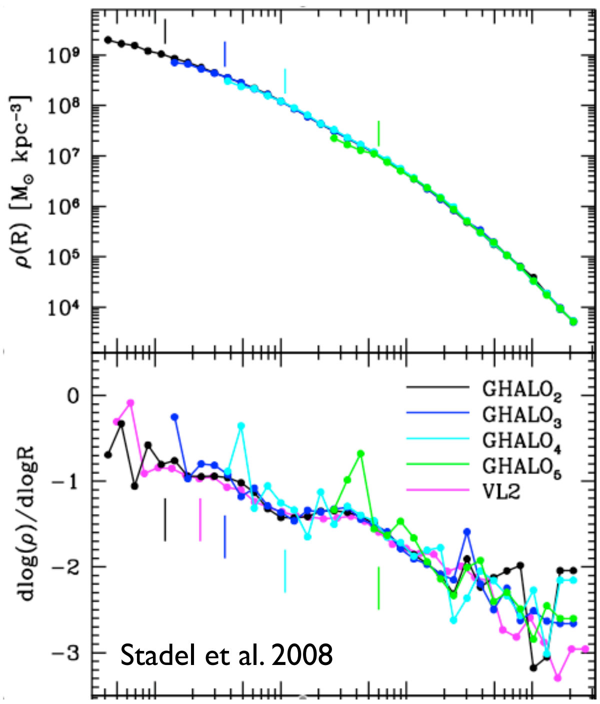
Simulated density profiles





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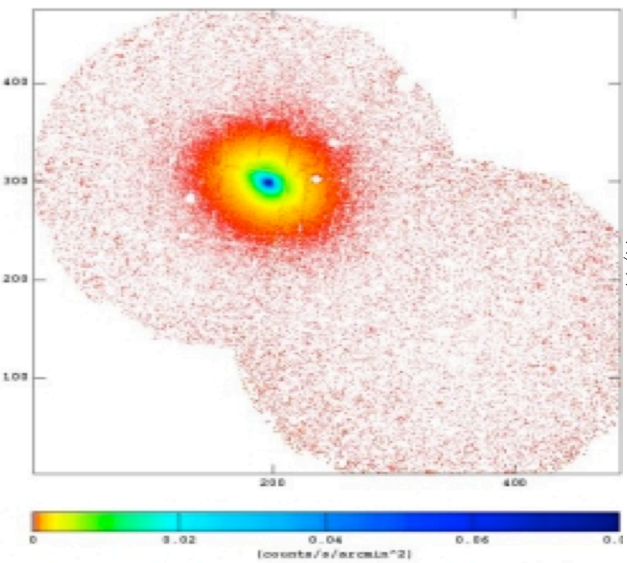
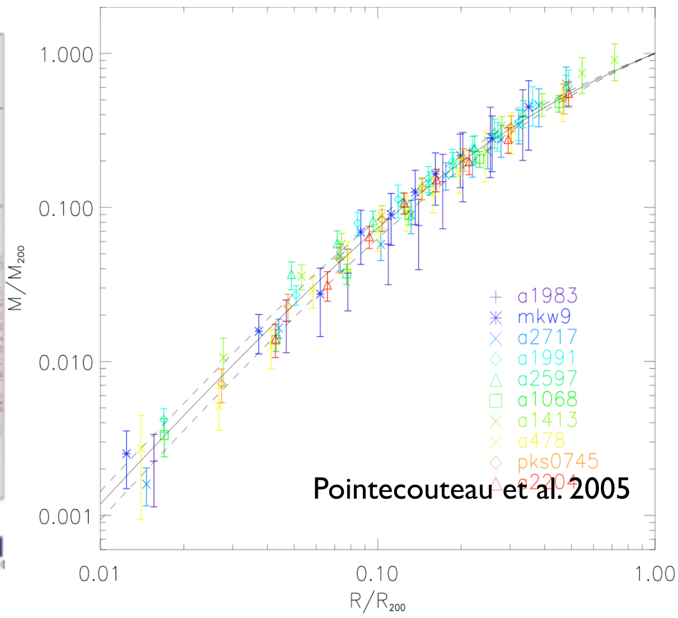
Observed density profile

Observed density profile

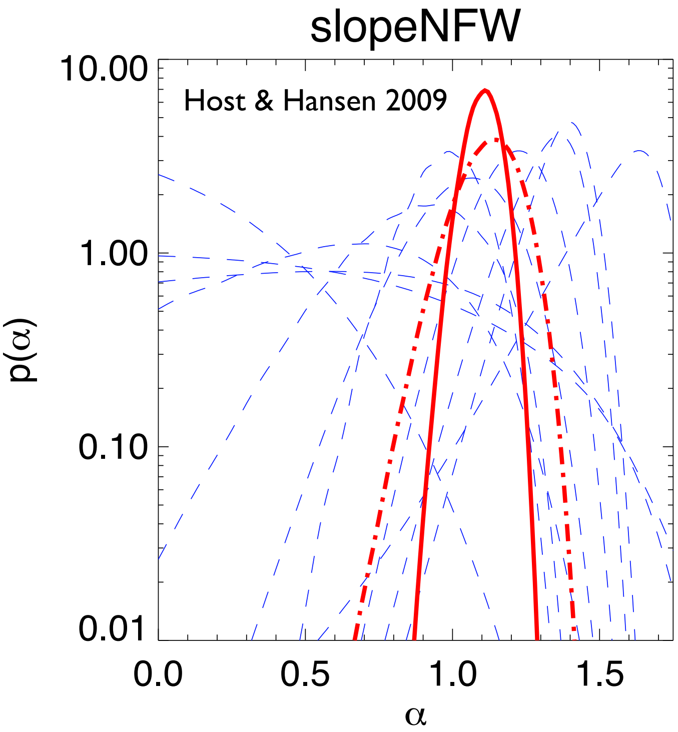
X-ray observations





Pointecouteau et al. 2005

Observed density profile



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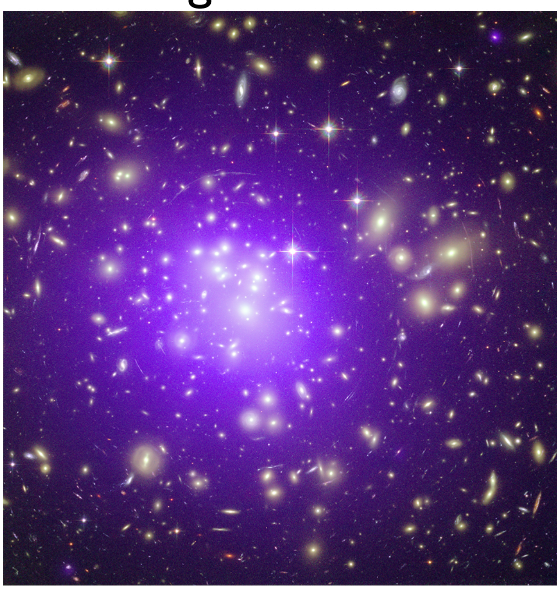
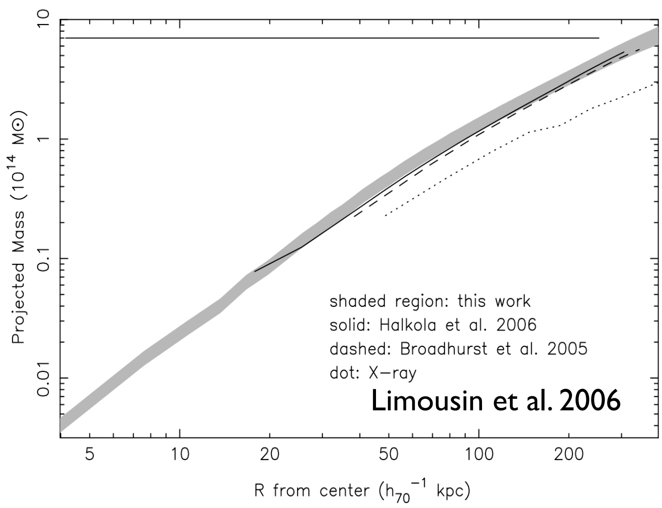
Observed density profile

Lensing observations





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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?)

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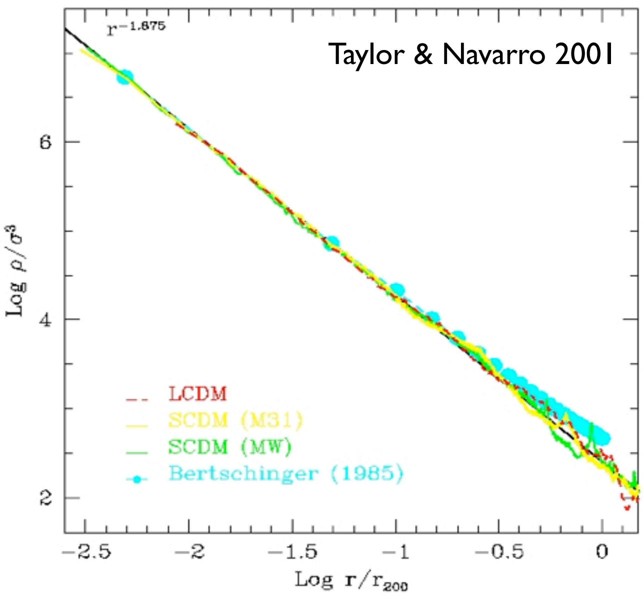
Theoretical density profiles



Assumption
Phase-space density = power law in radius

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

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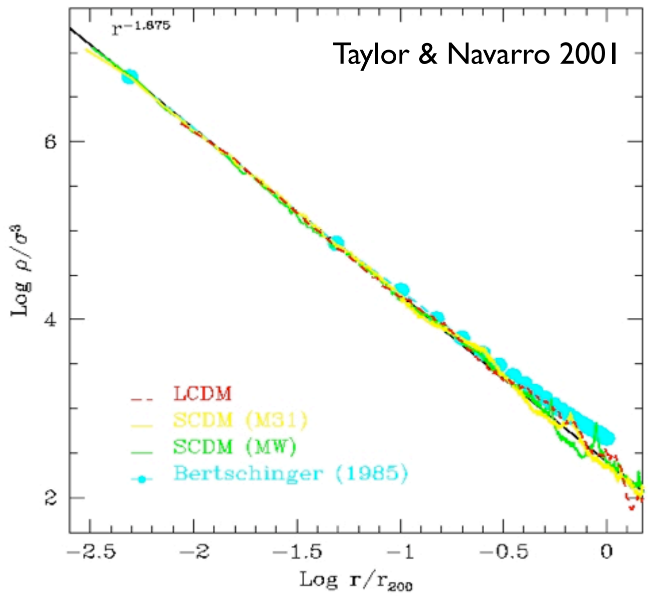
Theoretical density profiles



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

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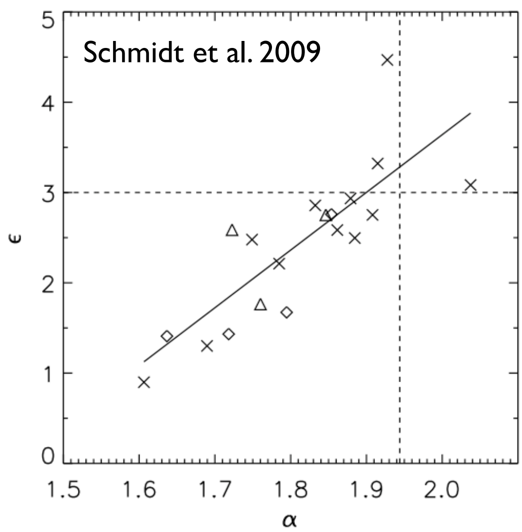
Theoretical density profiles

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

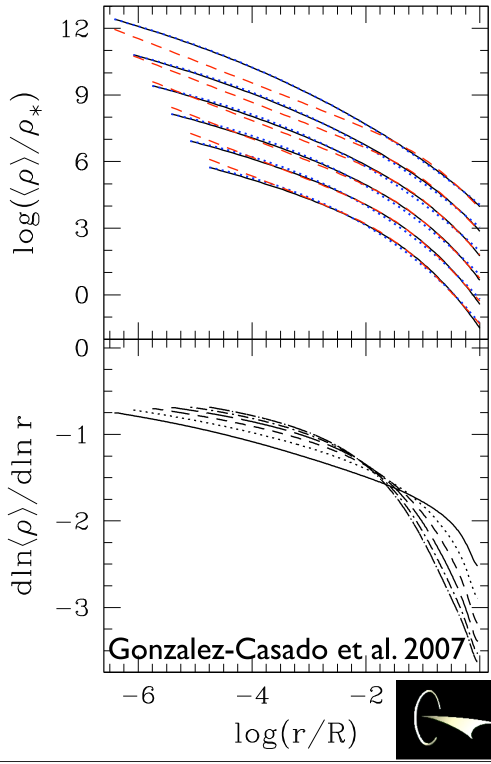
The Barcelona model:

Completely analytical

Accretion driven structure formation

Sersic profiles seem to fit surprisingly well

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



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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

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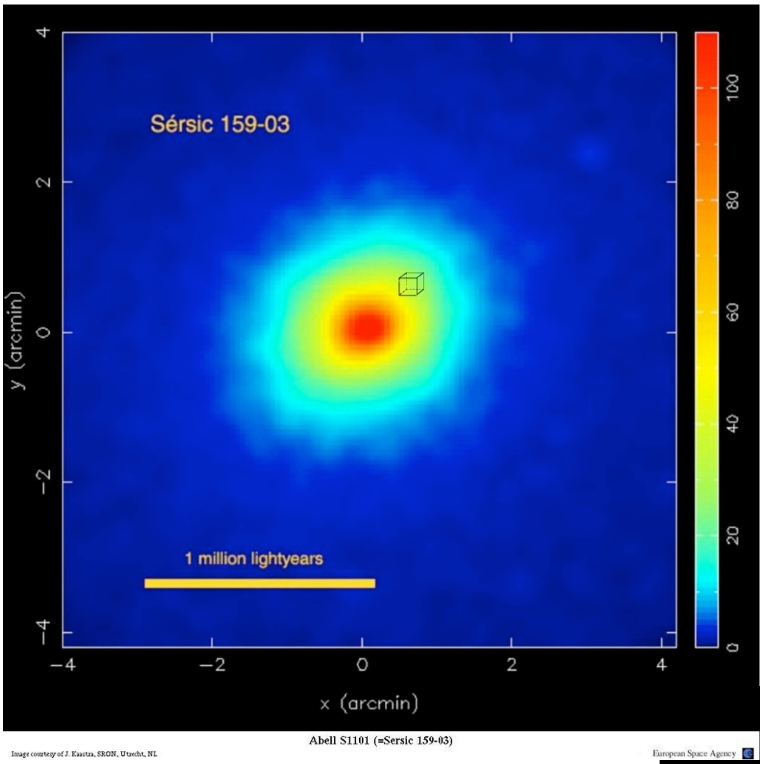
and now something acceptably new...



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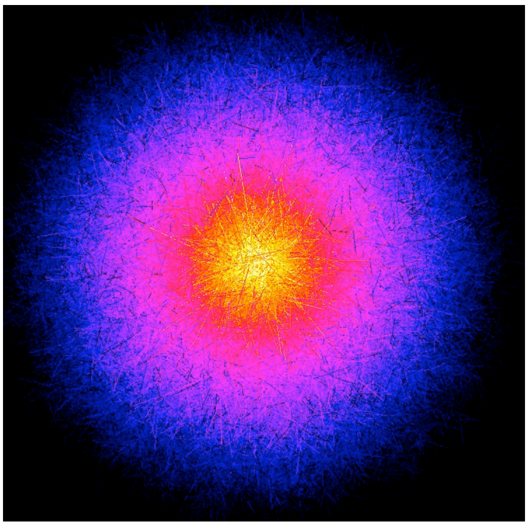
Velocity anisotropy profiles

Velocity anisotropy =
different "temperature"
in different directions

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

Must be zero for a gas



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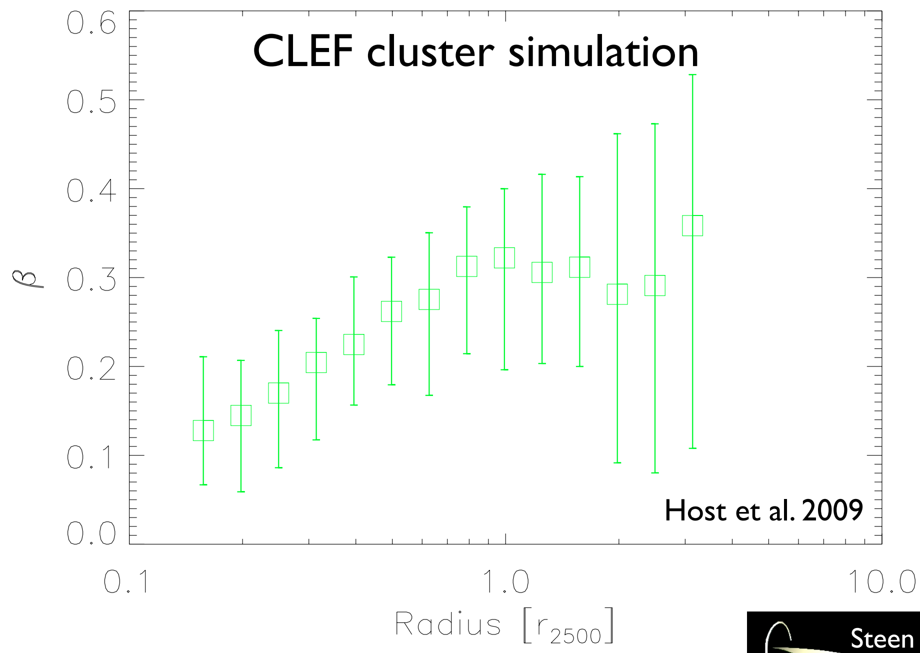
Simulated velocity anisotropy



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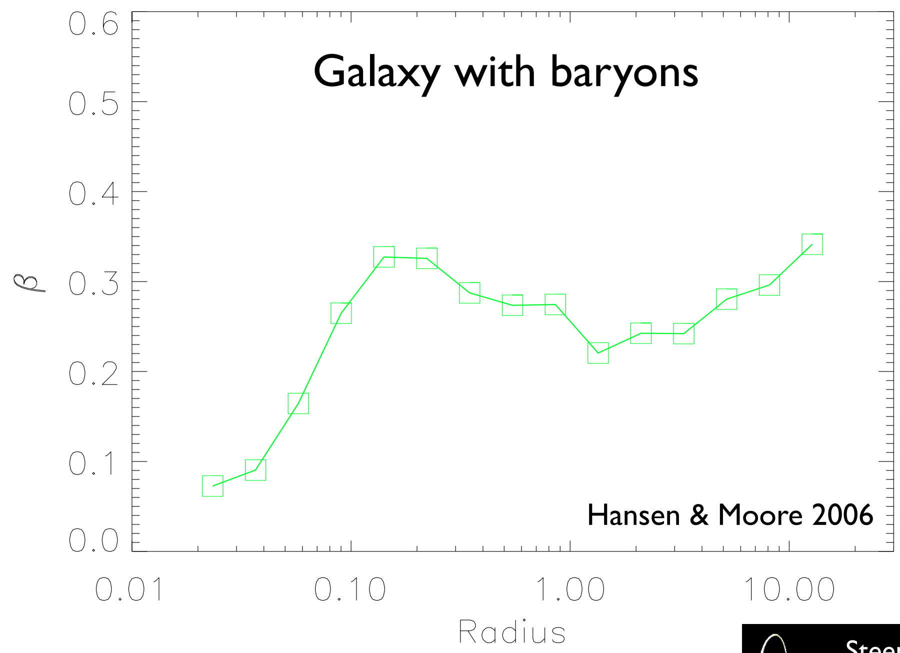
Simulated velocity anisotropy



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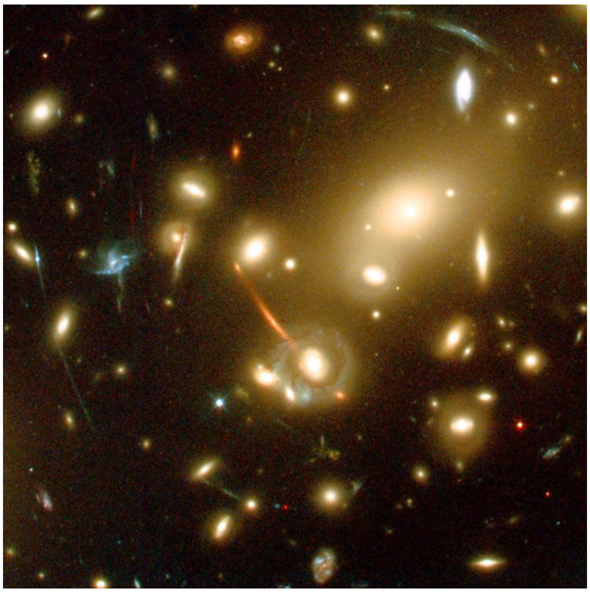
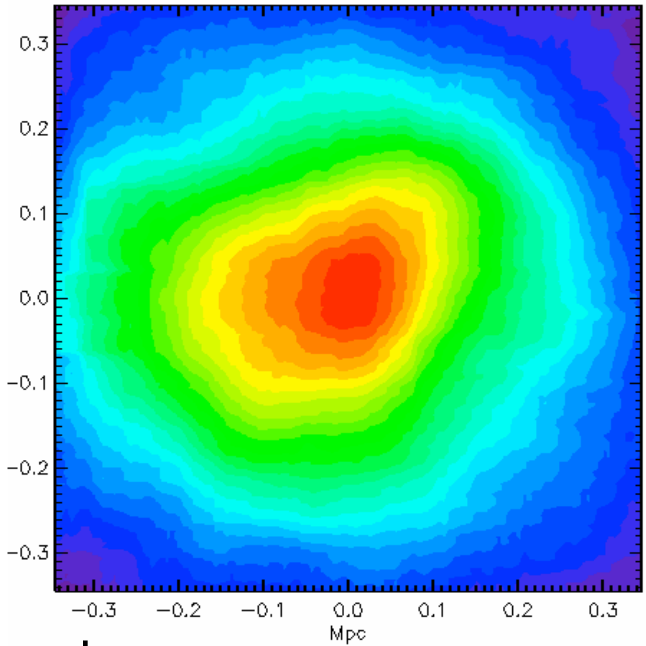
Observed velocity anisotropy





Consider an equilibrated galaxy cluster

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Observed velocity anisotropy

Hydrostatic equilibrium (gas)

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

Jeans equation (dark matter)

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

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

Hansen & Piffaretti 2007

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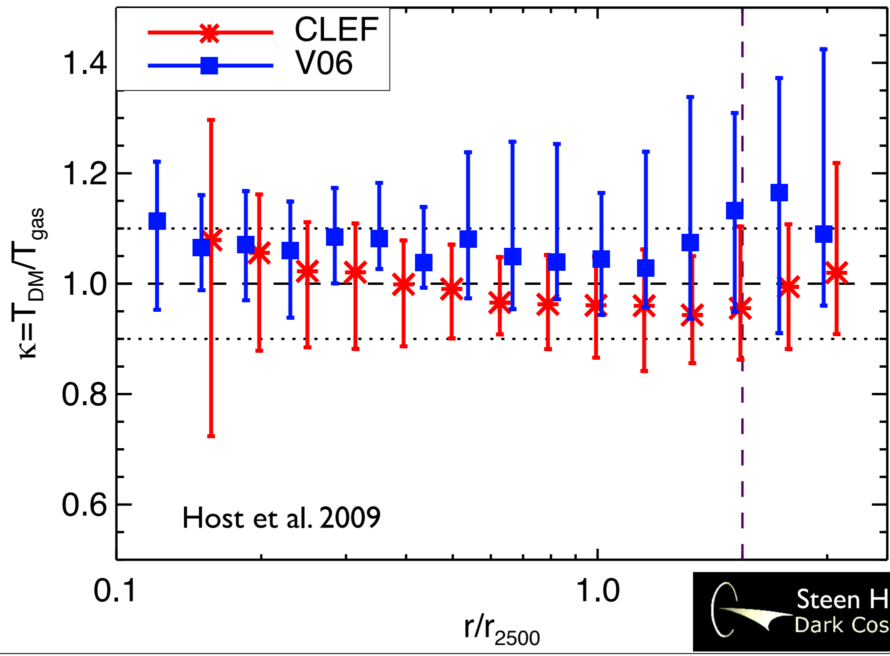
Observed velocity anisotropy

We have to make **one** assumption



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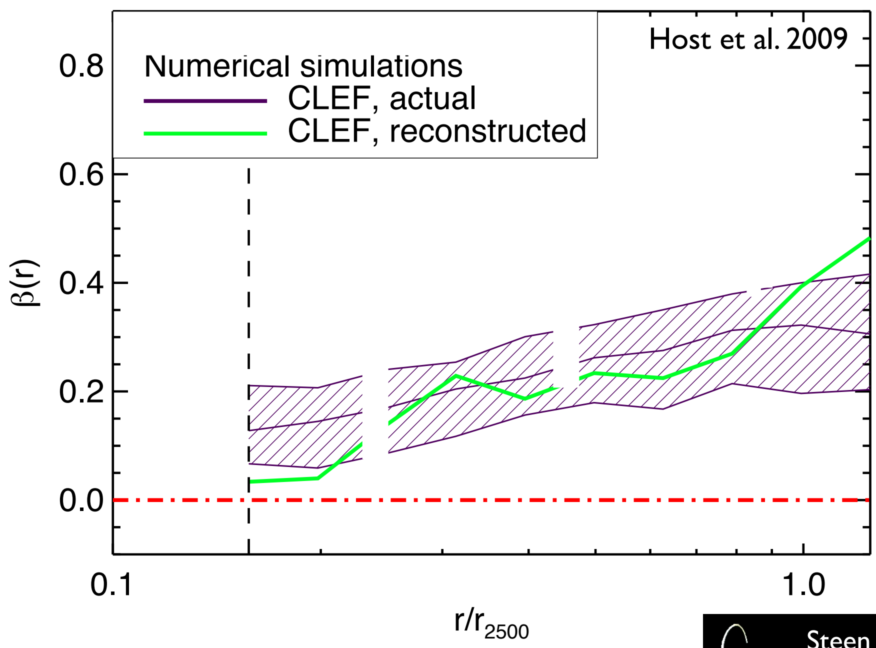
Observed velocity anisotropy



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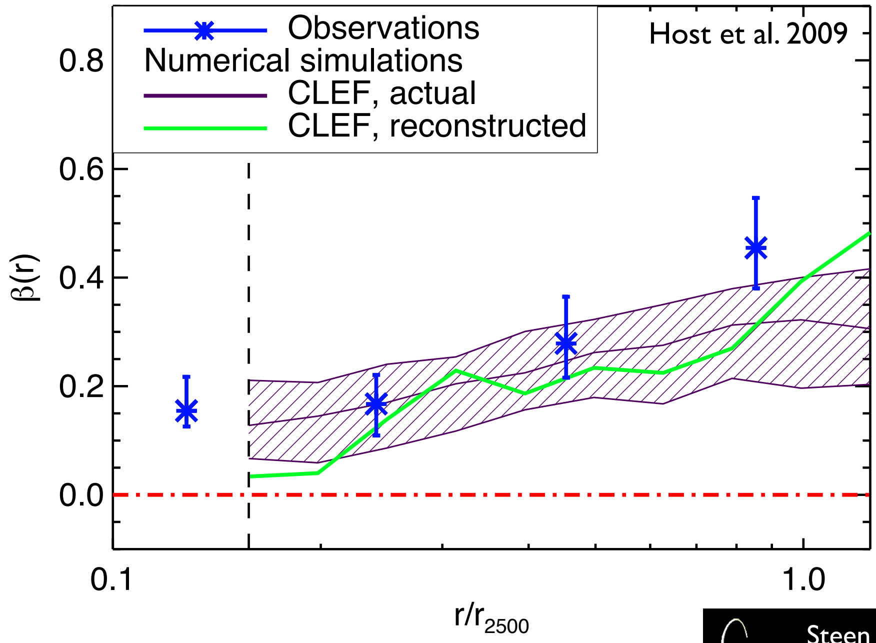
Observed velocity anisotropy

The observed galaxy clusters



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

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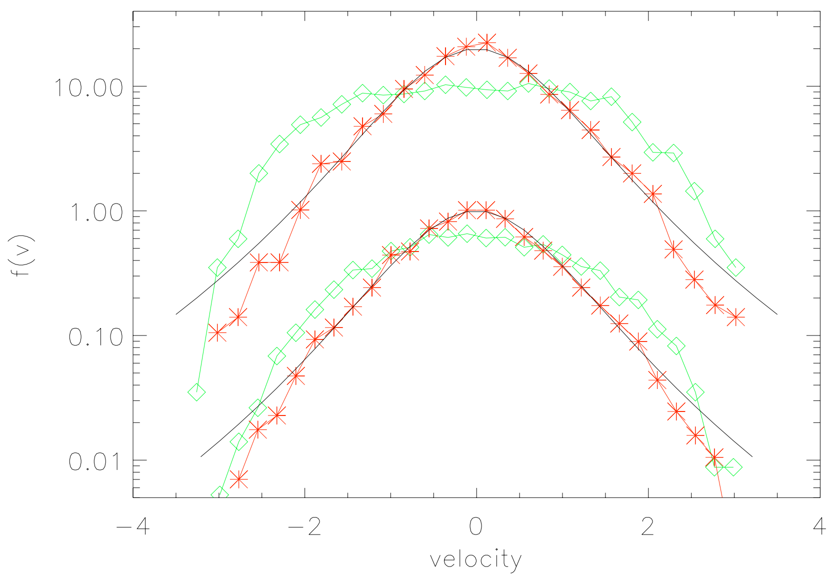
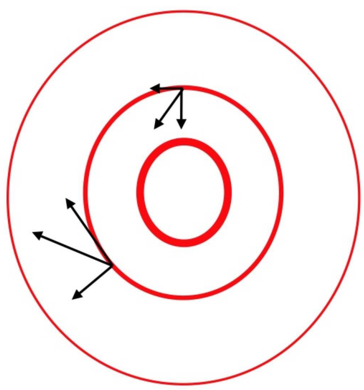
Where should we go from here?

- 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)

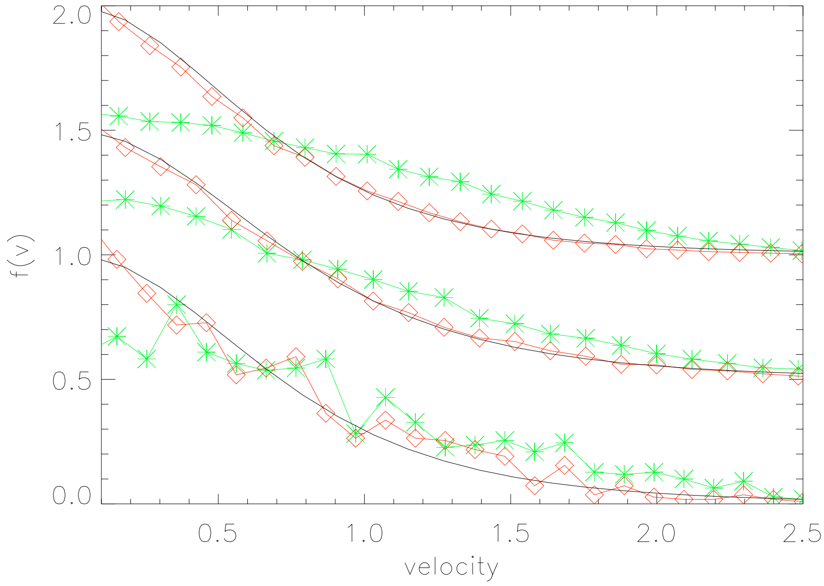
Theoretical velocity anisotropy

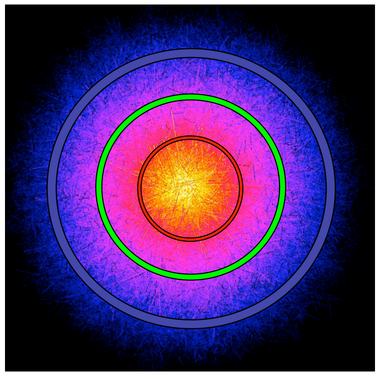
The velocity distribution function is exp(-v^2/T) for a normal gas, but what about **collisionless** dark matter?





We (almost) know the tangential distribution function





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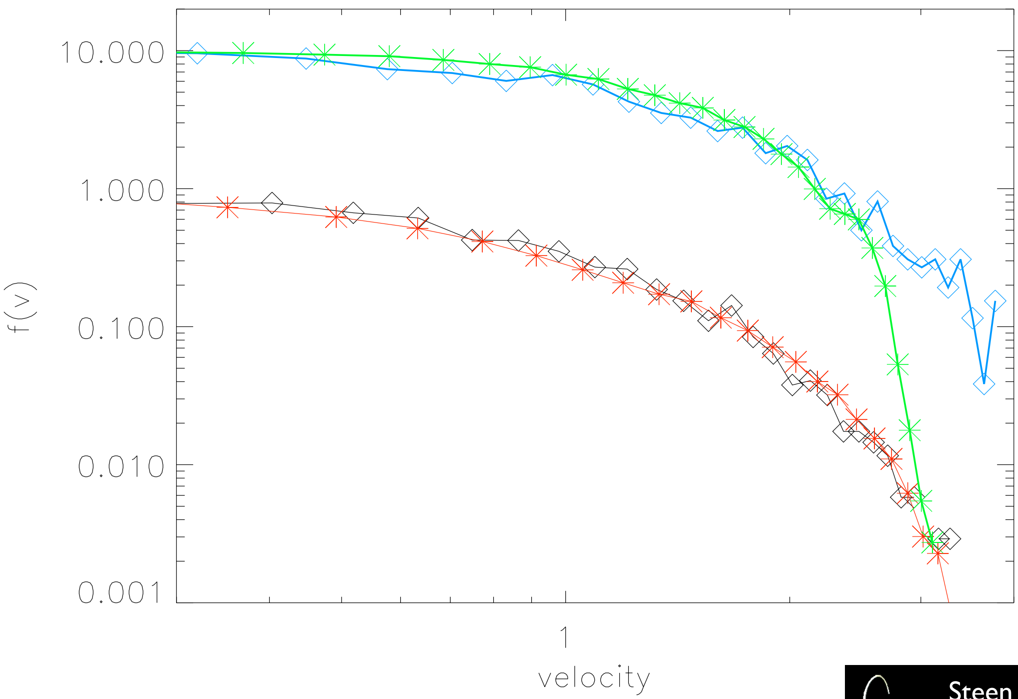
We (almost) know the radial distribution function



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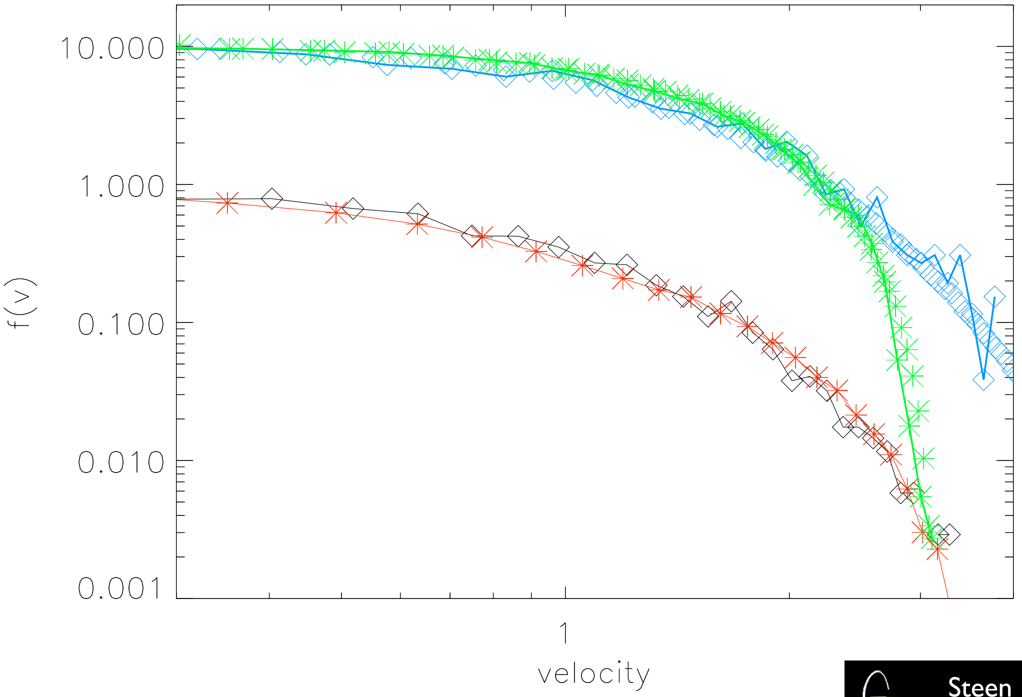
We (almost) know the radial distribution function



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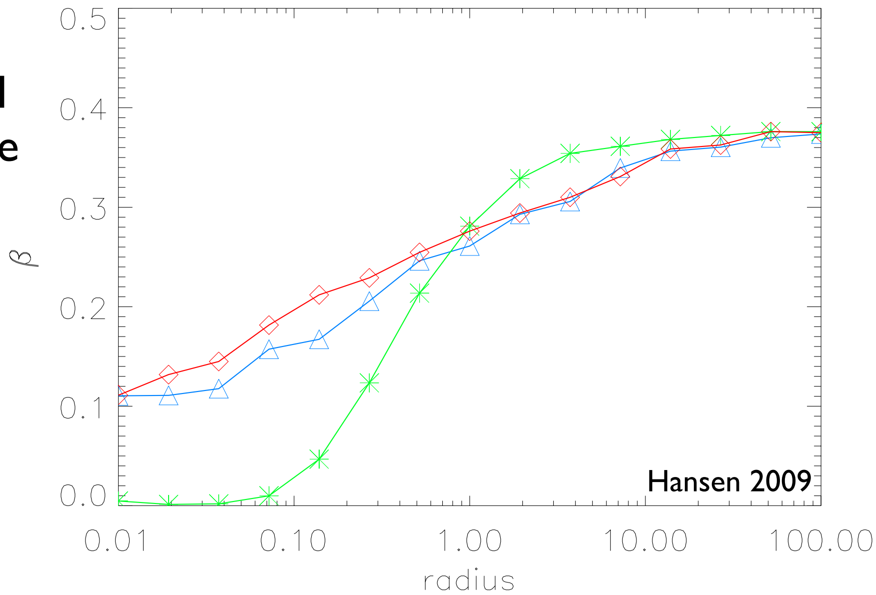
Theoretical velocity anisotropy

Analytically derived from “first” principle

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



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Theoretical velocity anisotropy

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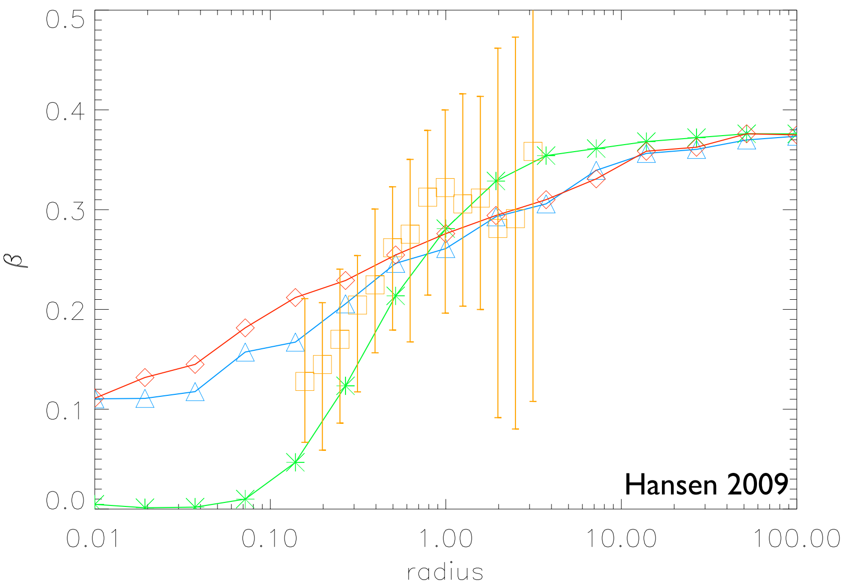

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Theoretical velocity anisotropy

Many people used to think the non-zero velocity anisotropy is simply because the structure is not in equilibrium

if that would be true, then we could never derive it, because beta would depend only on merger history

carefully designed numerical tests demonstrate that beta is more fundamental than just "merger history"

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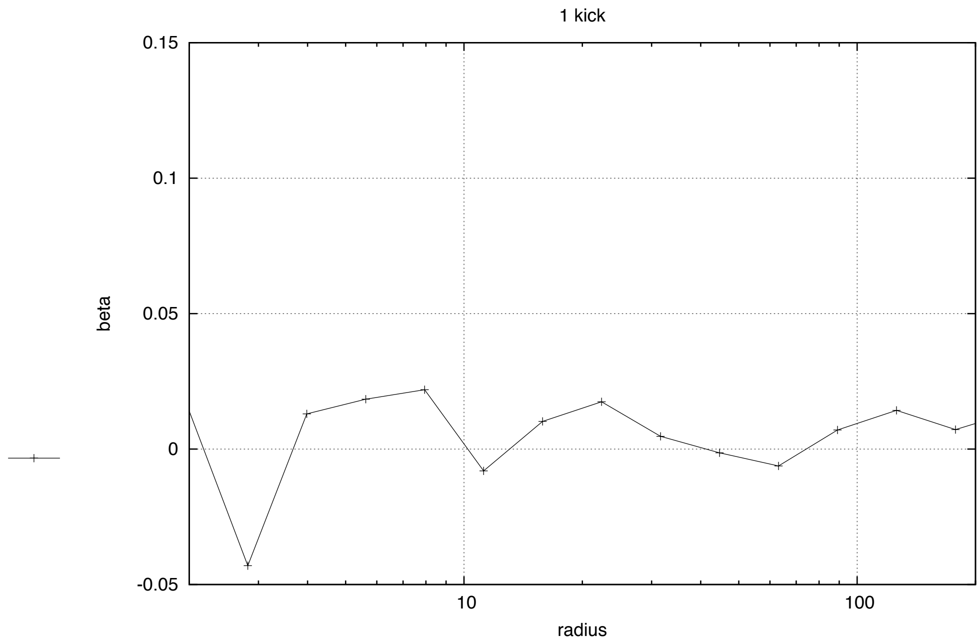
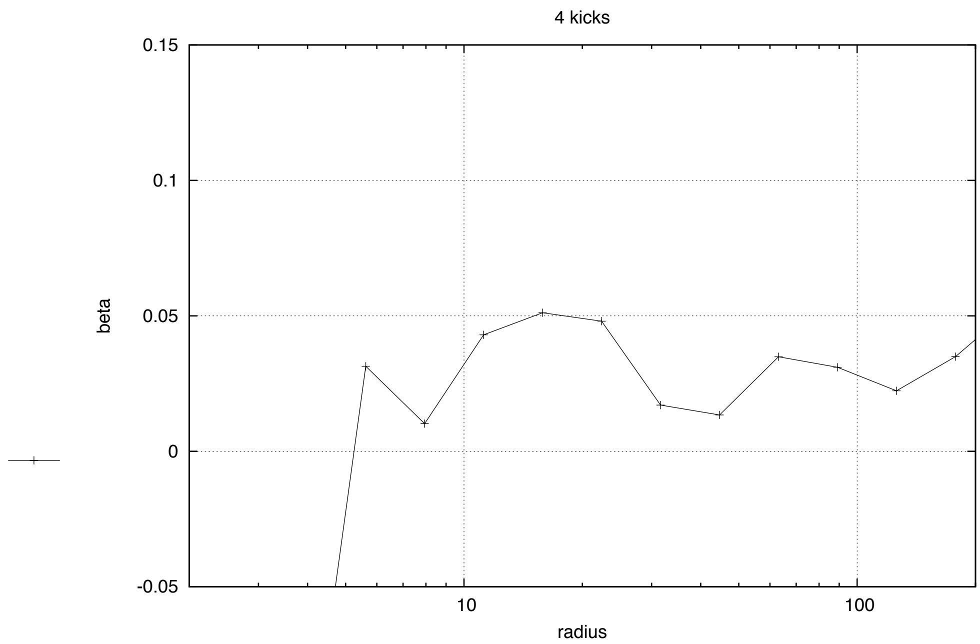
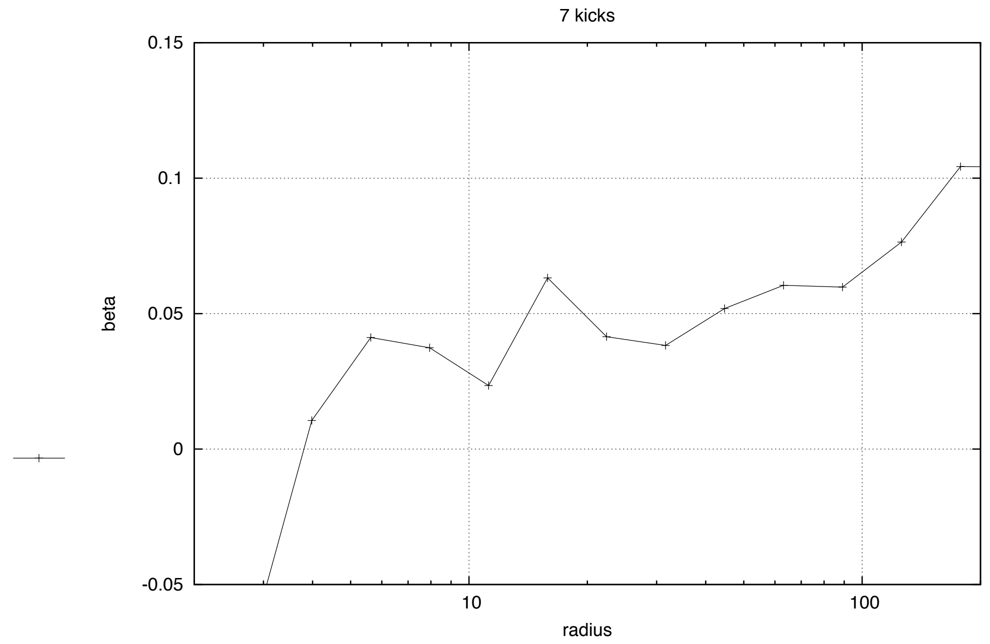
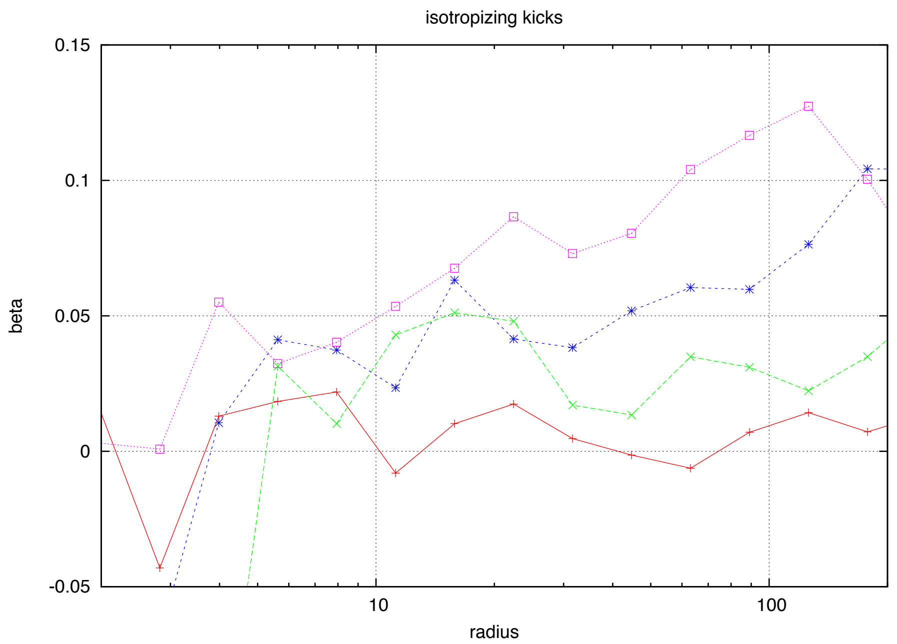

1 kick
0.15
0.1
0.05
0
-0.05
beta
10
100
radius


4 kicks
0.15
0.1
0.05
0
-0.05
beta
10
100
radius


7 kicks
0.15
0.1
0.05
0
-0.05
beta
10
100
radius


isotropizing kicks
0.15
0.1
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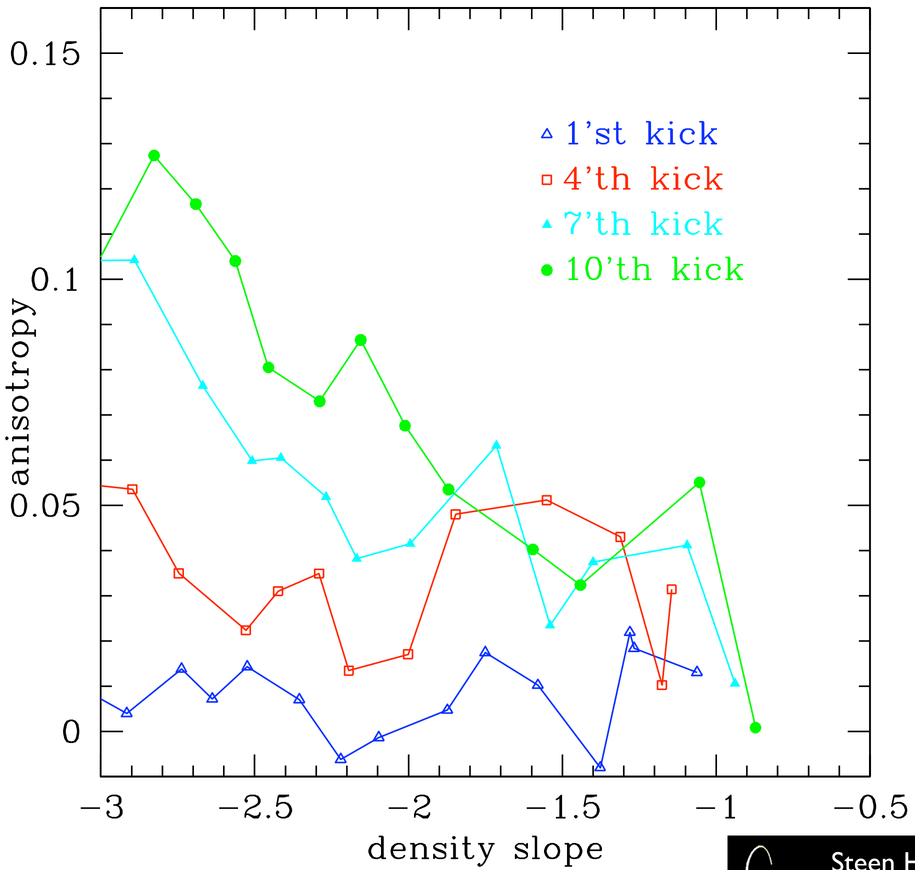
0
-0.05
beta
10
100
radius



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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

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Conclusions

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

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we don’t know why

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we don't know why

Thank you!

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