



Ludwig Franz Benedict Biermann

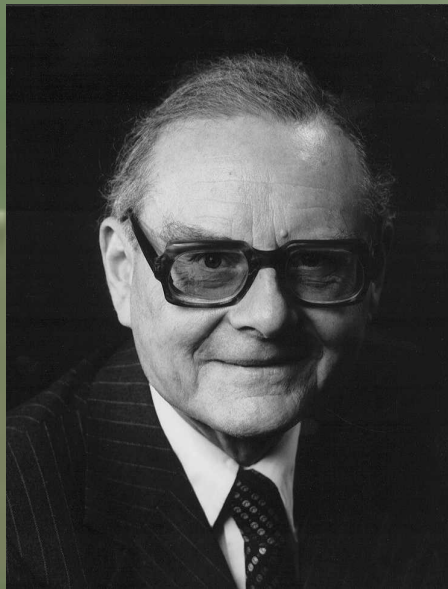
• (1907 – 1986)



Founding director Max Planck Institute for Astrophysics (1958)



The vicissitudes of the cold dark matter model of cosmogony



Carlos S. Frenk
Institute for Computational Cosmology,
Durham





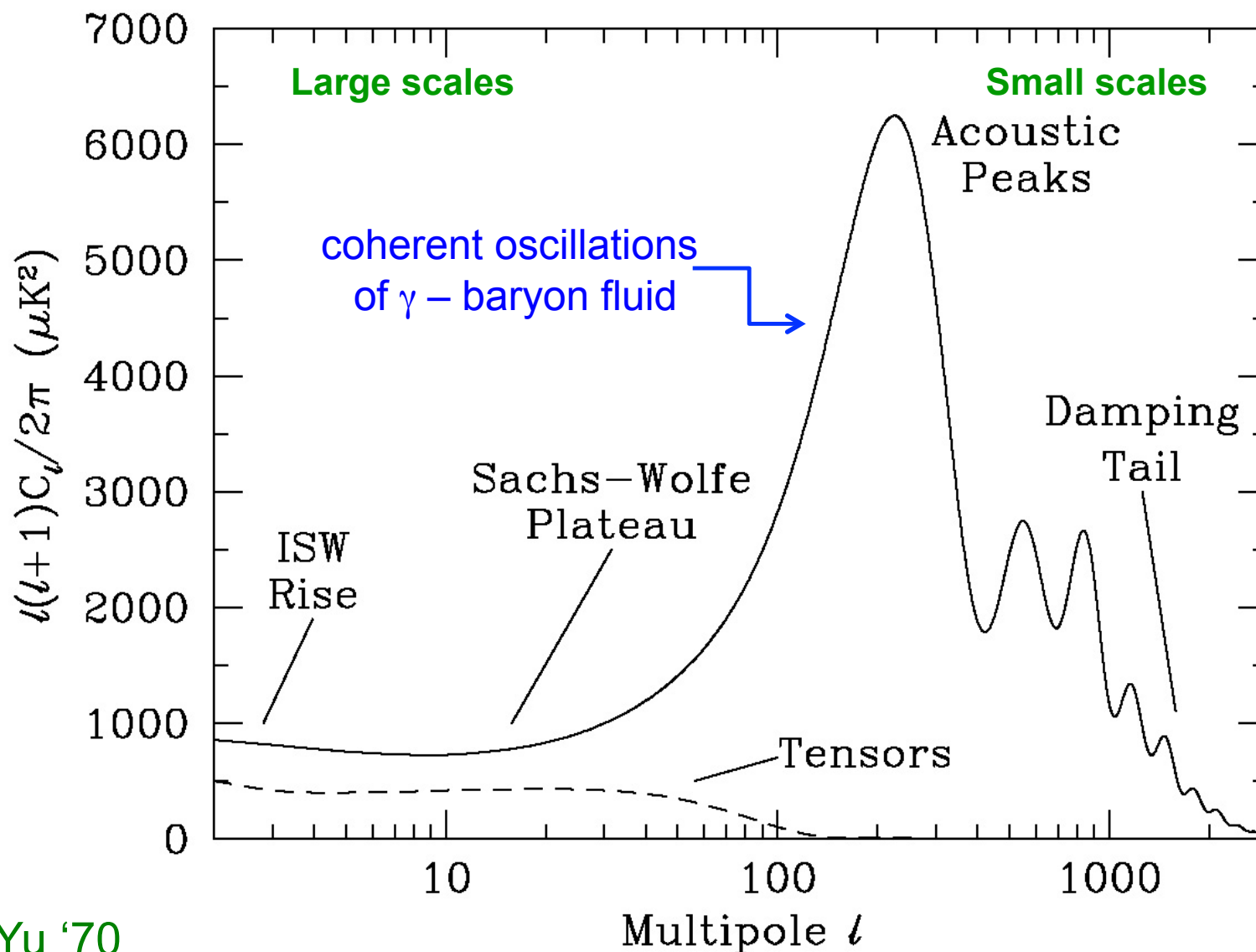
Decoding the identity of the dark matter from Milky Way data

Carlos S. Frenk
Institute for Computational Cosmology,
Durham



Temperature anisotropies in CMB

2D power spectrum



Peebles & Yu '70

Peebles '82, Bond & Efstathiou '84

Institute for Computational Cosmology

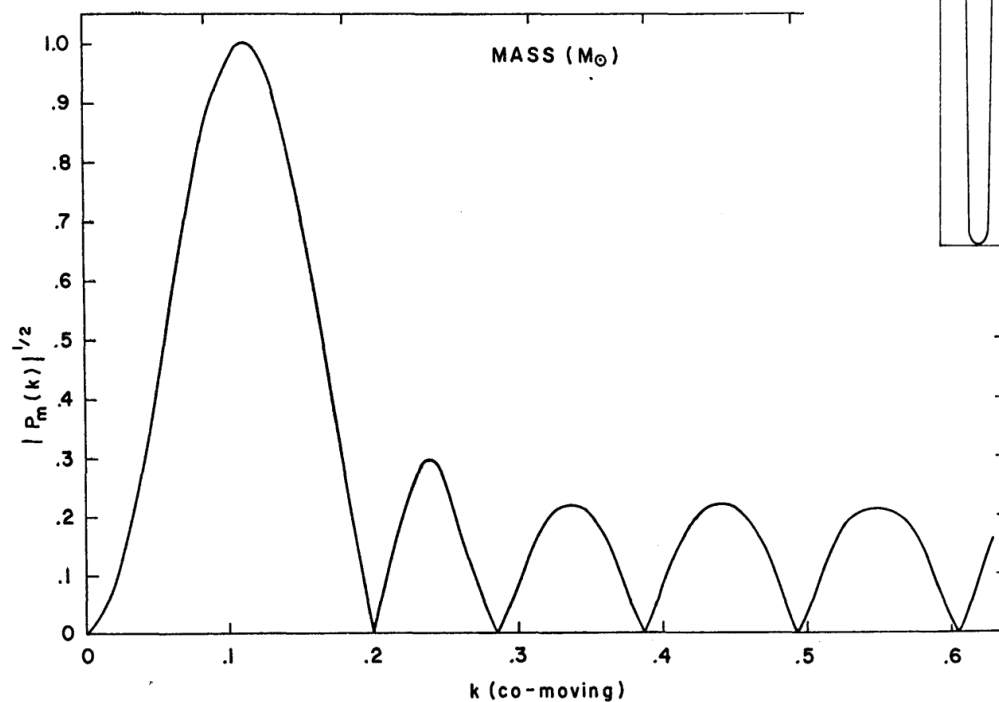


University of Durham

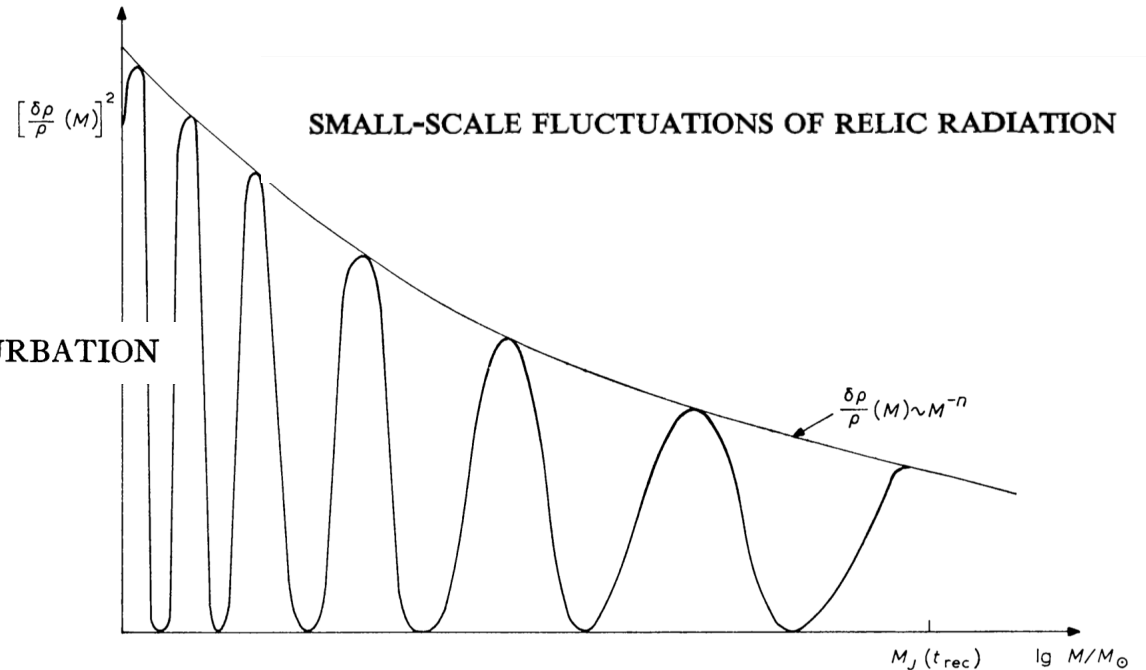
Temperature anisotropies in CMB

No. 3, 1970

PRIMEVAL ADIABATIC PERTURBATION



Peebles & Yu '70

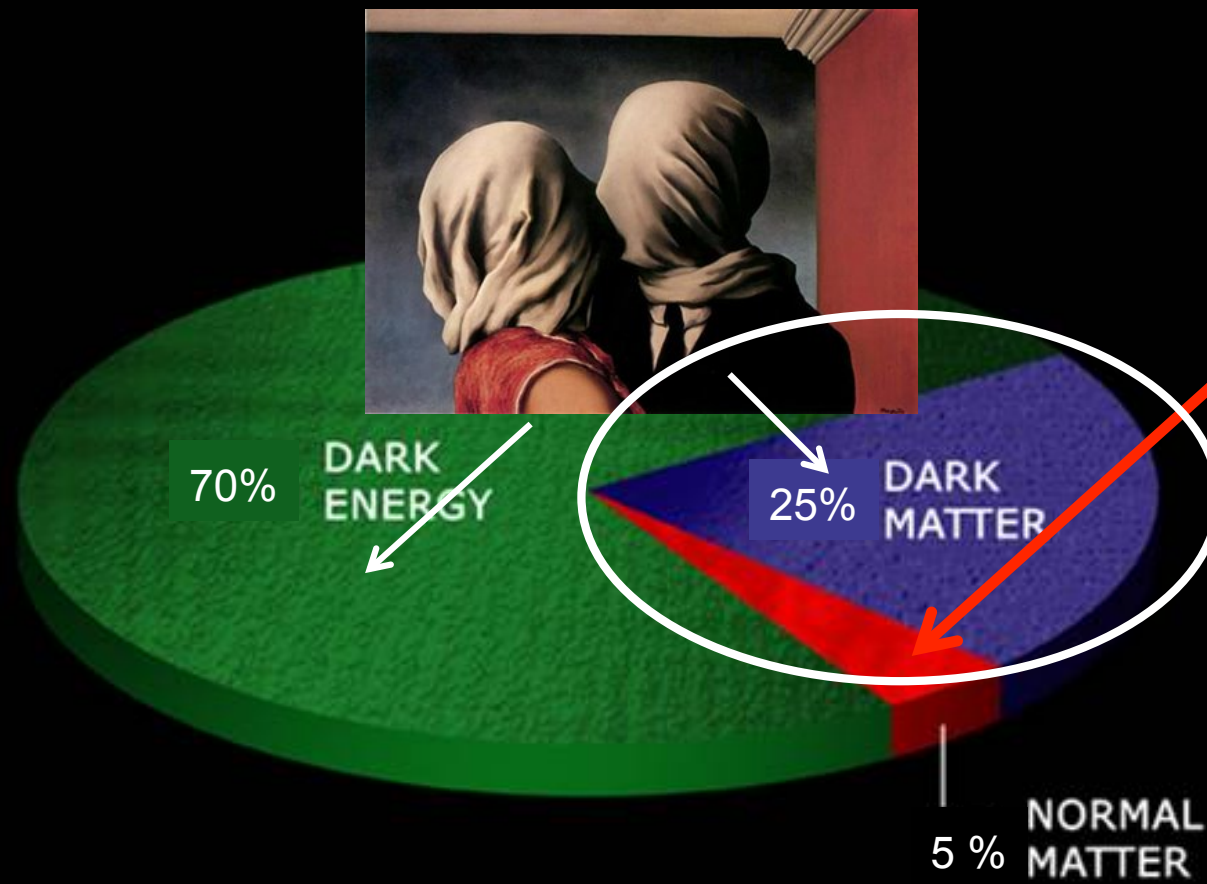


Sunyaev & Zel'dovich '70



ICC

The content of our universe



Non-baryonic dark matter candidates

Type	example	mass
hot	neutrino	a few eV
warm	sterile neutrino majoron; KeVin	keV-MeV
cold	axion neutralino, WIMPS	$10^{-5}\text{eV} - 100 \text{ GeV}$

Relic abundance of WIMPS

Decoupling occurs when

$$\Gamma < H$$

We have that

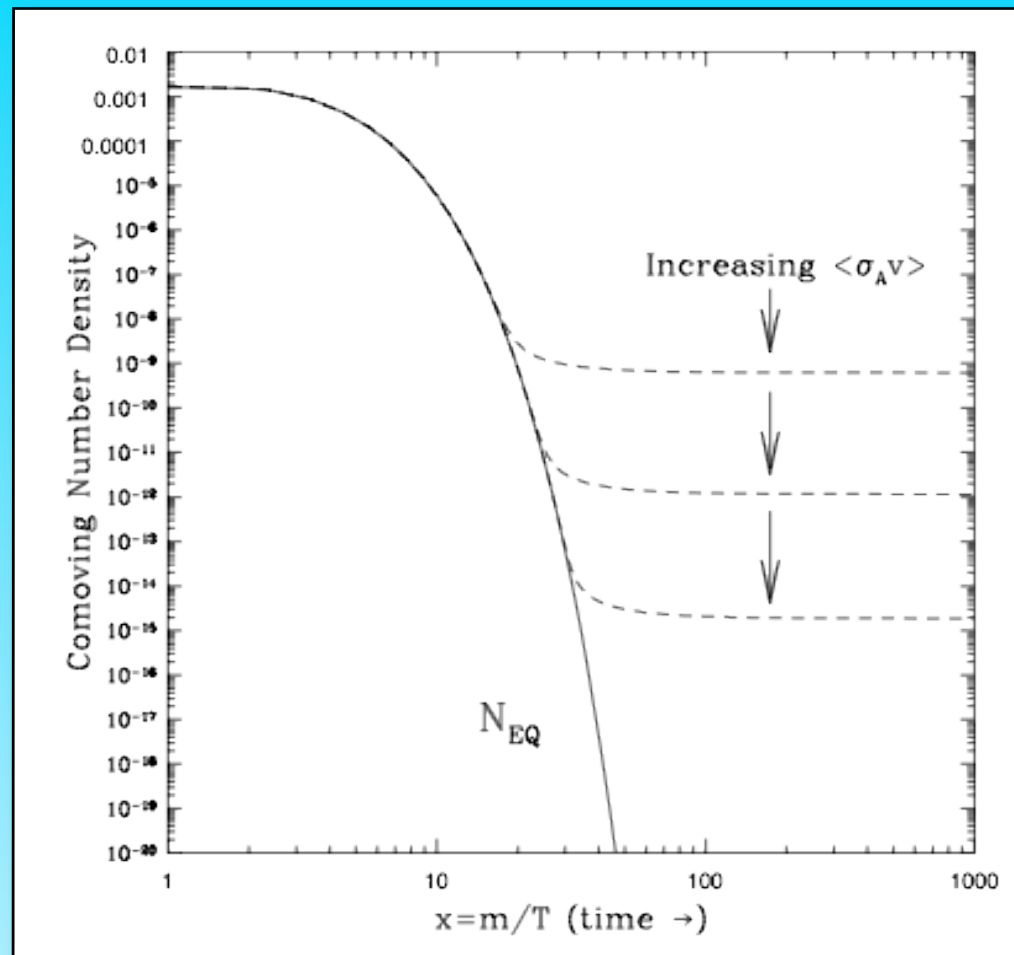
$$\Gamma = \langle \sigma_{\text{ann}} v \rangle n_\chi$$

$$n_\chi^{\text{eq}} = g_\chi \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-m_\chi/T}$$

$$H(T) = 1.66 g_*^{1/2} \frac{T^2}{m_{\text{Planck}}}$$

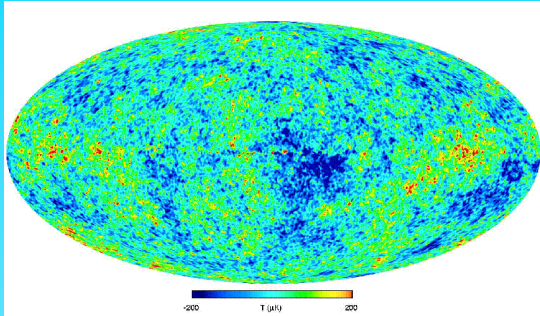
$$\Gamma \simeq H \quad \Rightarrow \quad T_f \simeq \frac{m_\chi}{20}$$

$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$

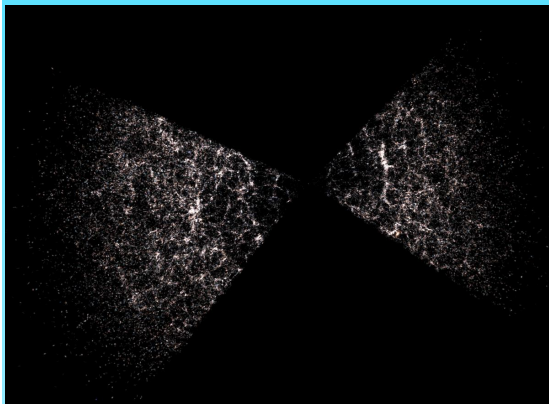


$$\langle \sigma_{\text{ann}} v \rangle \simeq \langle \sigma_{\text{ann}} v \rangle_{\text{WIMP}} \simeq 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \quad \Rightarrow \quad \Omega_\chi h^2 \simeq 0.1$$

The cosmic power spectrum: from the CMB to the 2dFGRS



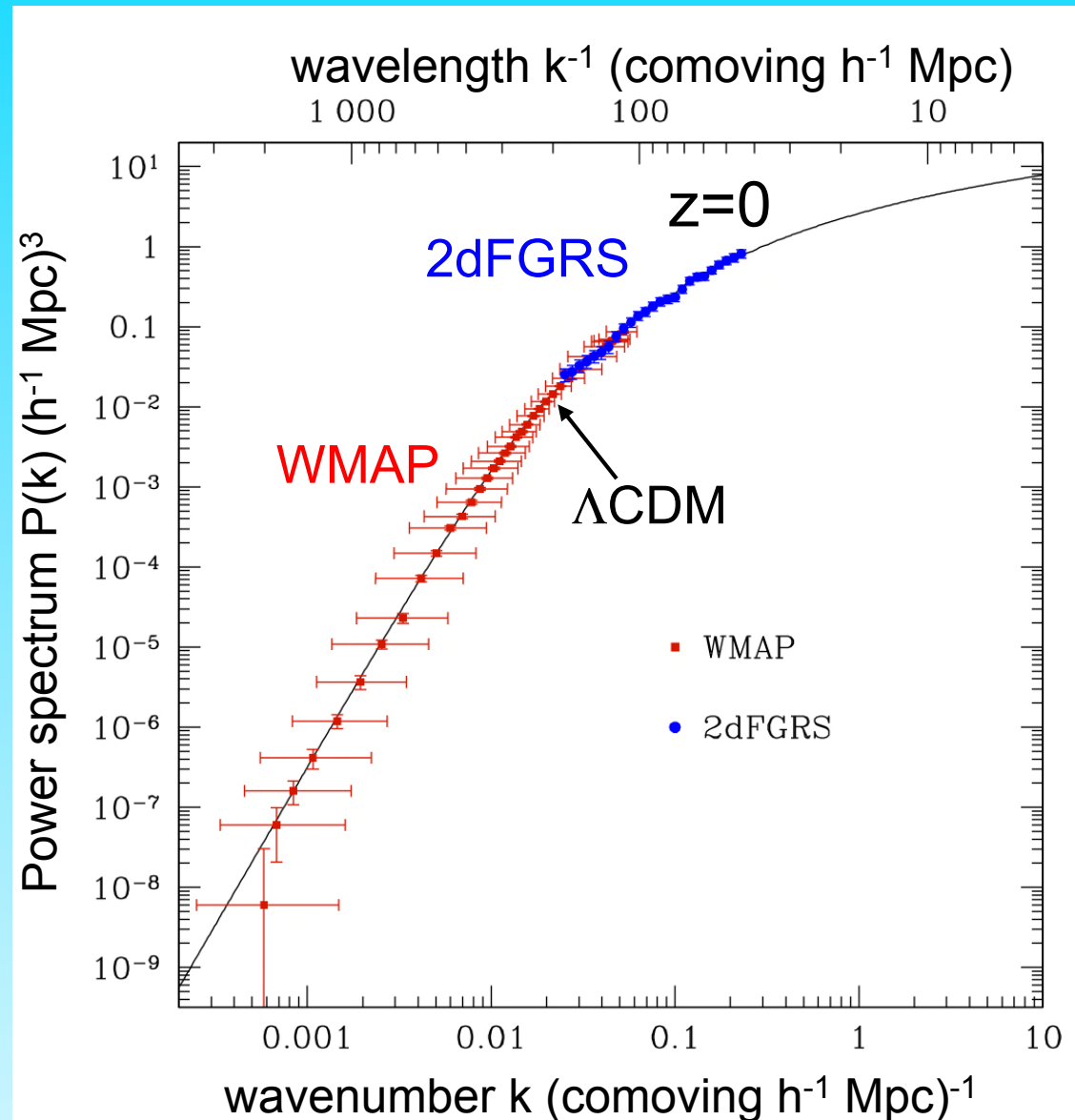
$z \sim 1000$



$z \sim 0$

⇒ Λ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

Sanchez et al 06





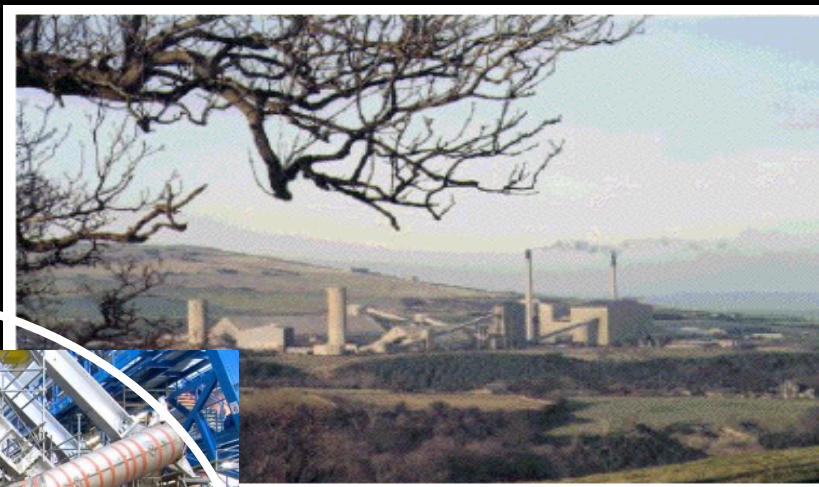
SUSY cold dark matter

Dark matter discovery possible in several ways

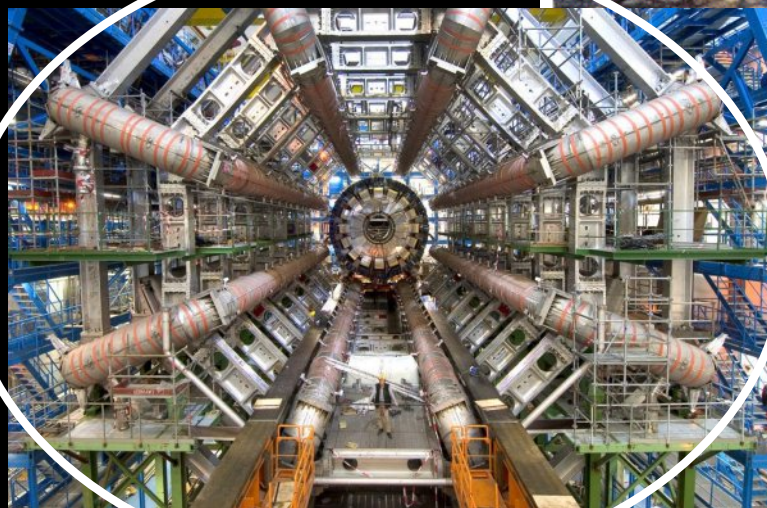
Fermi

Annihilation radiation

Direct detection

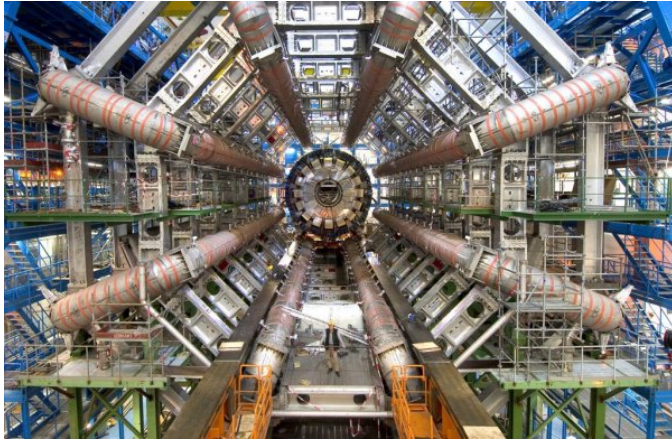


UK DM search
(Boulby mine)



Evidence for SUSY

WIMP example: lightest particle in e.g. Minimal Supersymmetric Standard Model (MSSM)



No missing energy events →
no evidence for SUSY (yet)

Higgs discovery →

✓ – predicted by SUSY

✗ – mass rules out MSSM



When you are handsome - what difference
does it make that the ski poles are too short

Jan Stenmark

Adapted from Joachim Edsjo



SUSY cold dark matter

Dark matter discovery possible in several ways

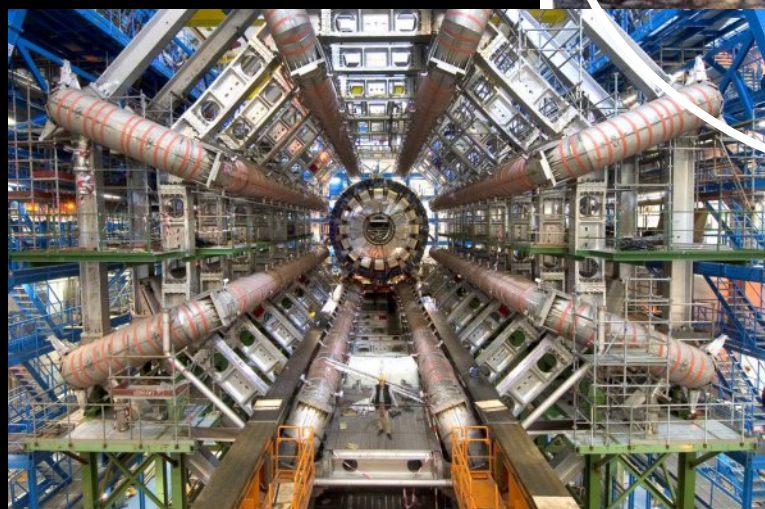
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Annihilation radiation

Direct detection

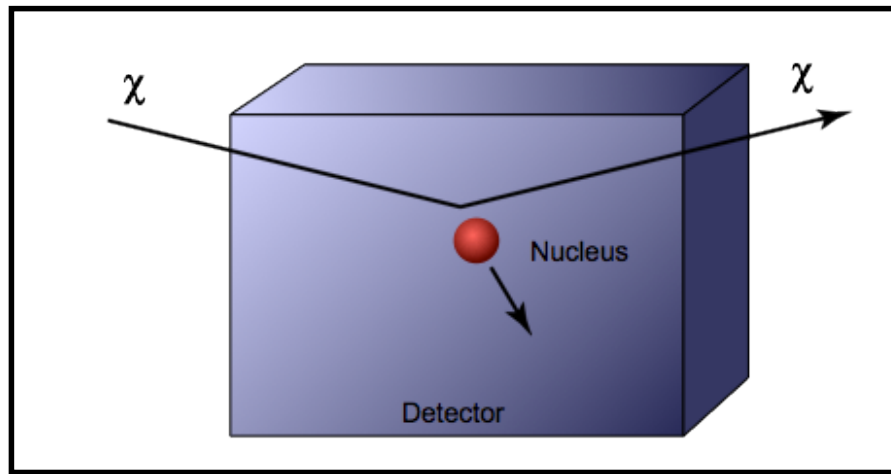


UK DM search
(Boulby mine)

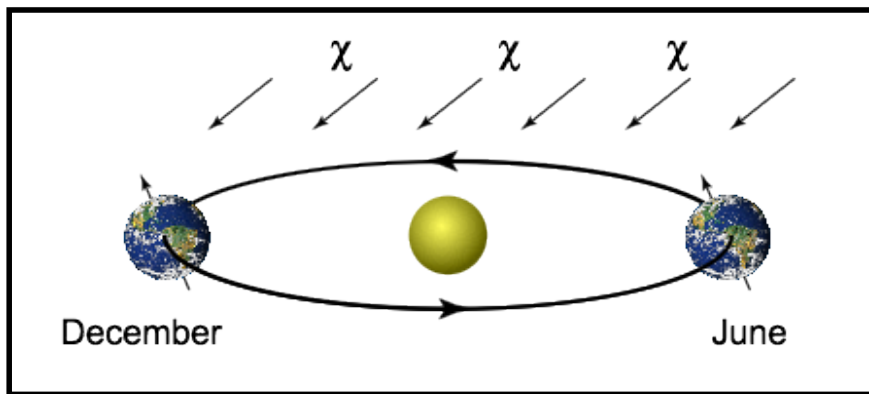


Evidence for SUSY

Direct detection of WIMPS



- $\text{WIMP} + \text{nucleus} \rightarrow \text{WIMP} + \text{nucleus}$
- Measure recoil energy ($\sim 10\text{KeV}$)
- Suppress background enough to be sensitive to a signal, or...

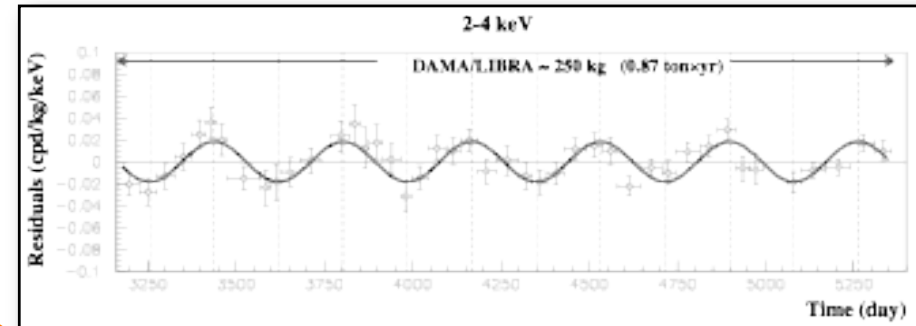


- Search for an annual modulation due to the Earth's motion in the halo

Adapted from Joachim Edsjo

Direct detection: conflicting experiments

DAMA/Libra sees modulation
signal at 8.9σ

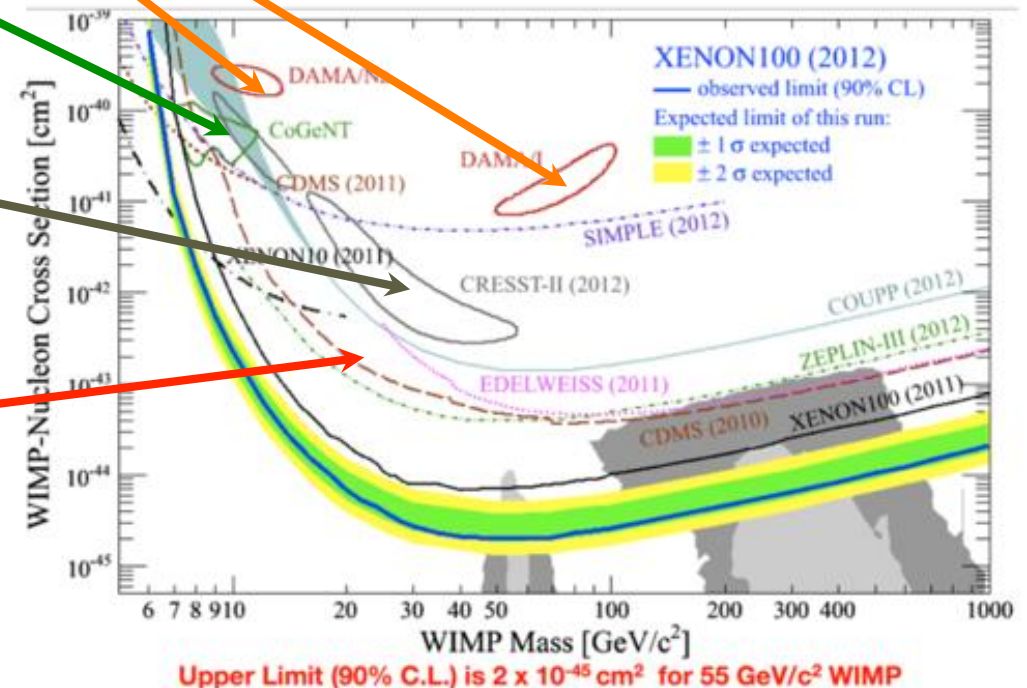


CoGeNT sees excess events
(less now than earlier)

as does CRESST-II

but XENON100 excludes
them all

XENON100: New Spin-Independent Results

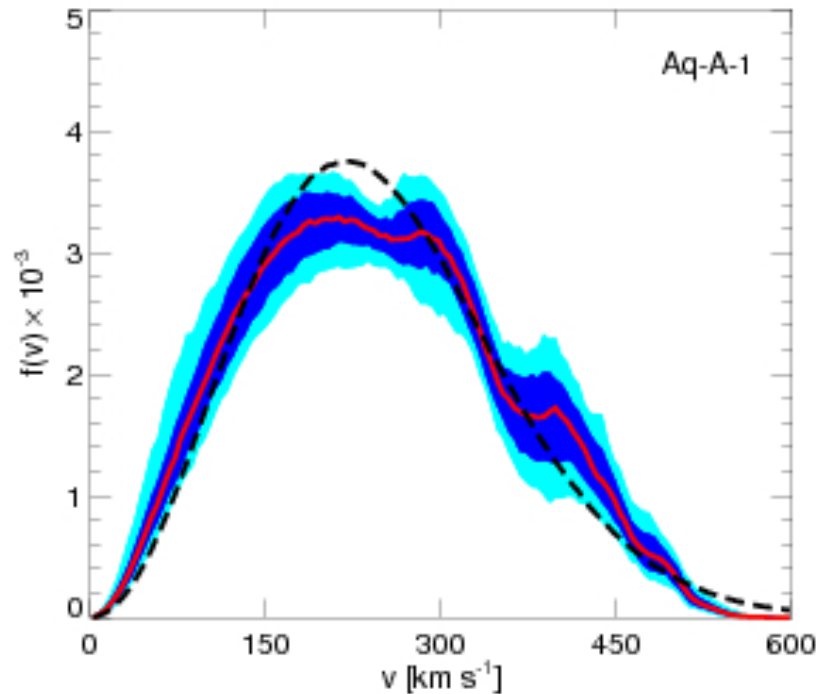


Caveat: standard astrophysical model

Direct detection: halo velocity distribution

Aquarius simulation

Vogelsberger et al '09



Experiments assume “standard halo mode” → Gaussian vel distr

Simulations → fewer particles in tail of distribution;
smooth fall off to escape vel.



SUSY cold dark matter

Dark matter discovery possible in several ways

Fermi

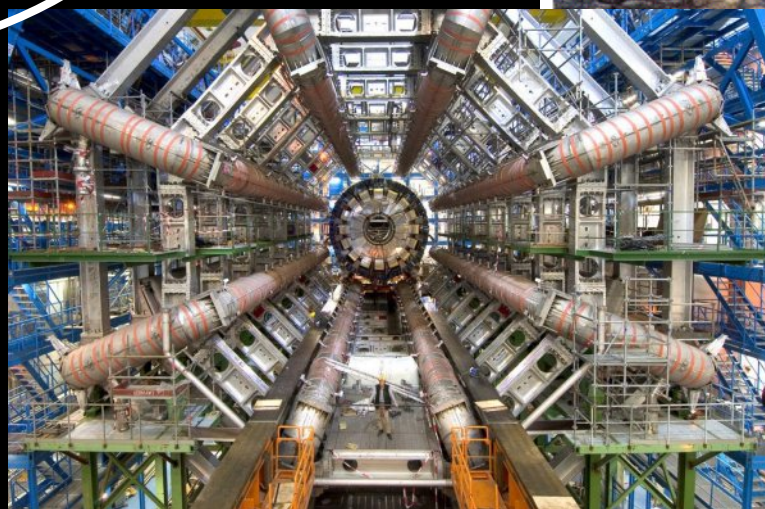


Annihilation radiation

Direct detection



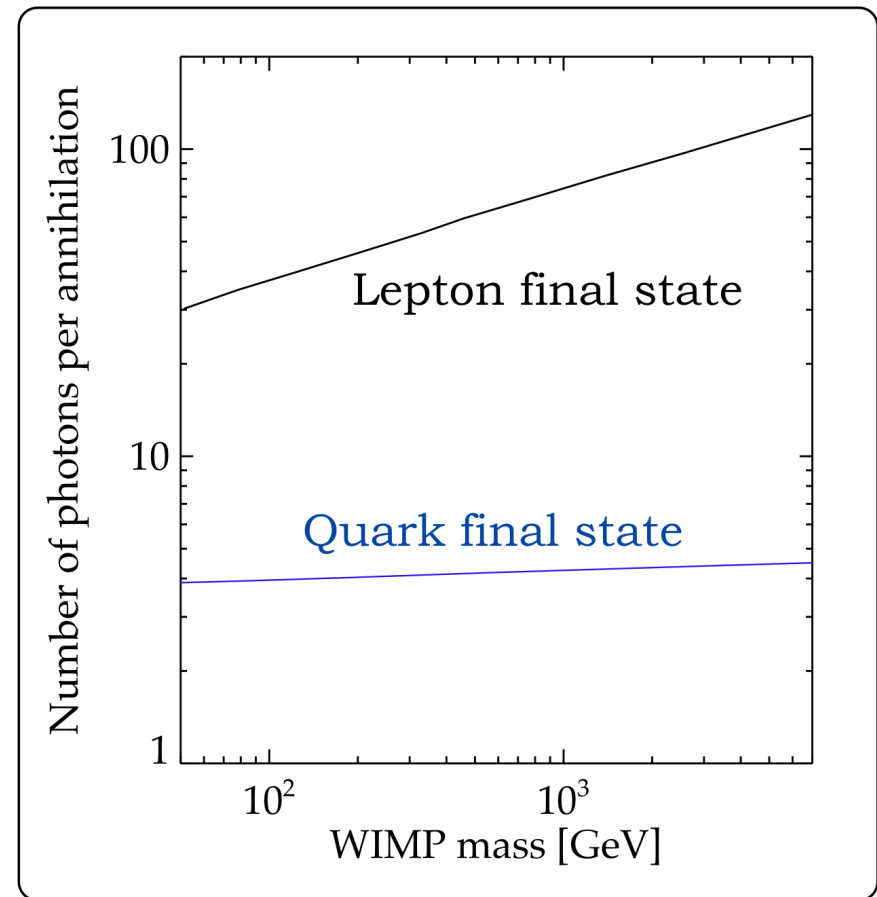
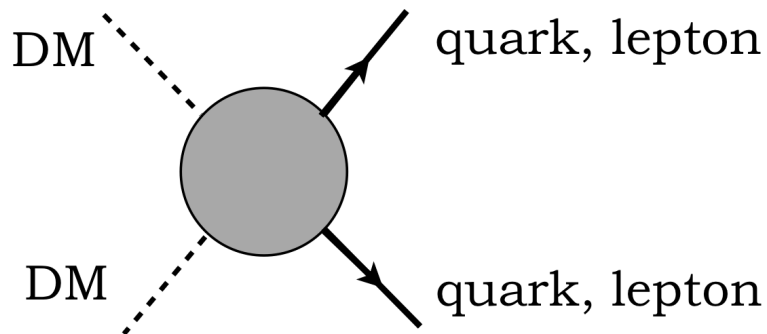
UK DM search
(Boulby mine)



Evidence for SUSY

Indirect dark matter detection

Supersymmetric particles are Majorana particles → **annihilate** into Standard Model particles (including γ -rays)



Dark matter annihilation

Neutral annihilation products

100 GeV mass WIMPS photons in
 γ – ray band 10MeV – 10 GeV

$$\chi\chi \rightarrow \gamma, \nu$$



Charged annihilation products

$$\chi\chi \rightarrow \bar{p}, \bar{D}, e^+$$

- Diffusion zone



Adapted from Joachim Edsjo

Indirect CDM detection through annihilation radiation

Supersymmetric particles are Majorana particles → **annihilate** into Standard Model particles (including **γ -rays**)

Intensity of annihilation radiation at x is:

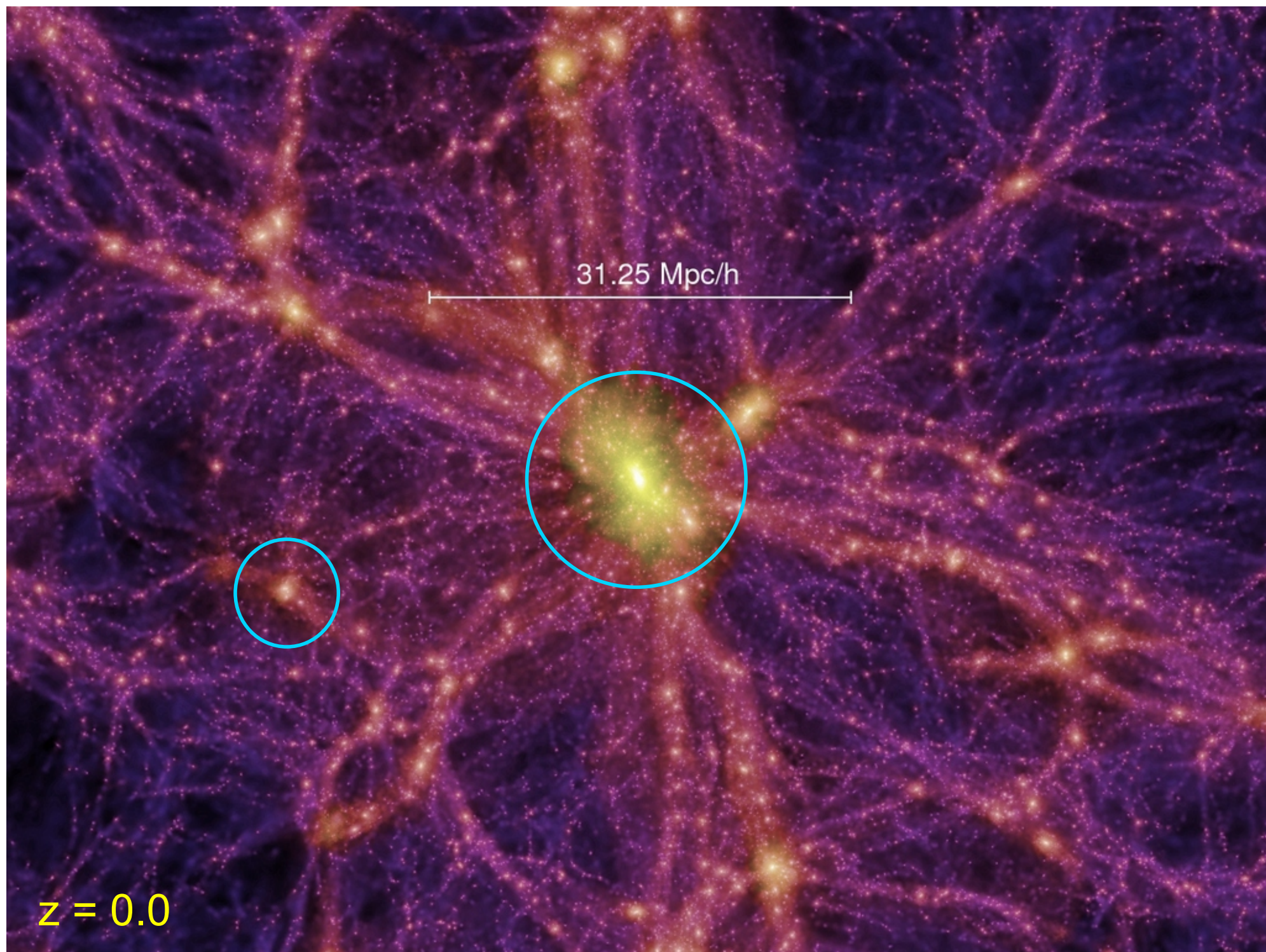
$$I(x) = \frac{1}{8\pi} \sum_f \frac{dN_f}{dE} \langle \sigma_f v \rangle \int_{los} \left(\frac{\rho_\chi}{M_\chi} \right)^2 dl$$

↙ halo density at x (astrophysics)
↗ cross-section (particle physics)

$\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ → relic abundance in simple SUSY models

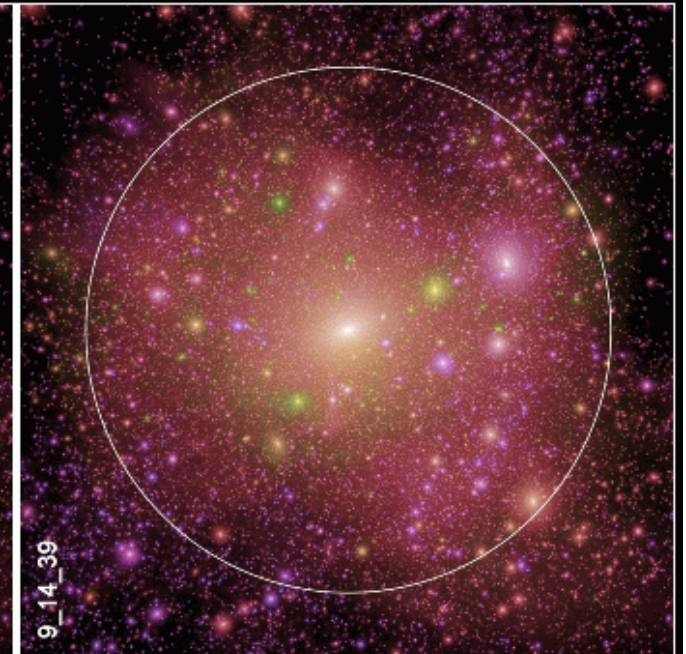
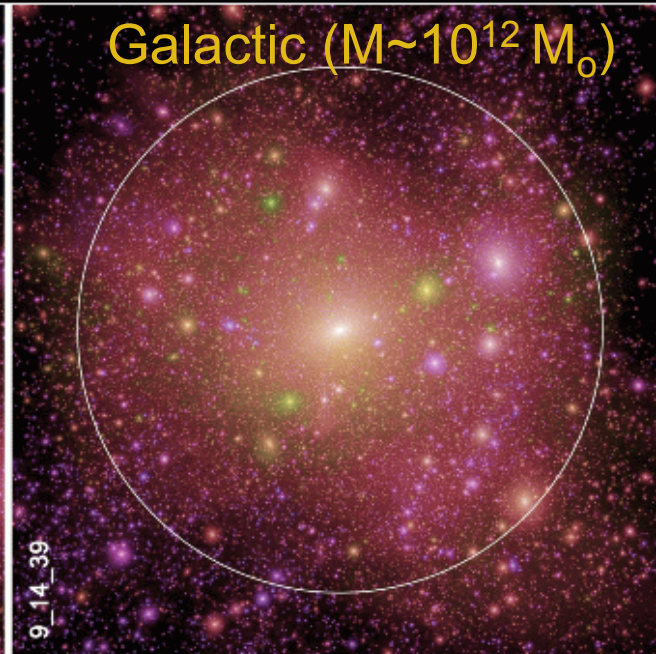
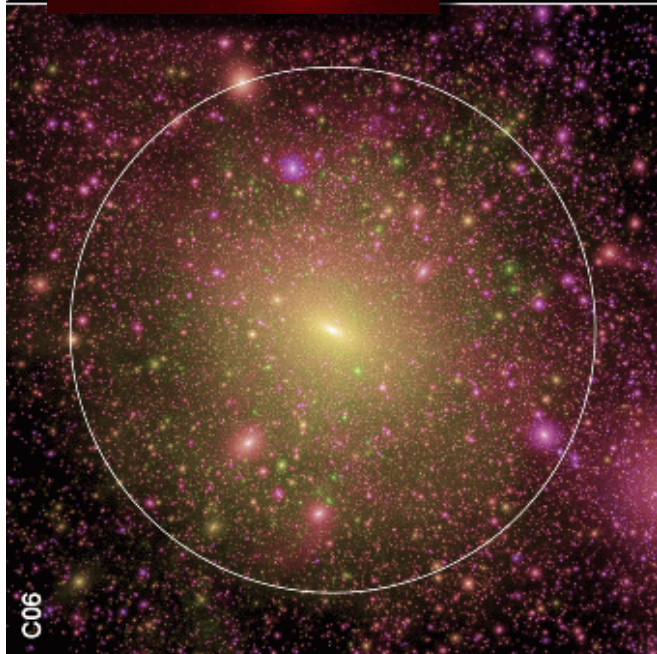
⇒ Theoretical expectation requires knowing $\rho(\mathbf{x})$

⇒ Accurate high resolution **N-body** simulations of **halo** formation from **CDM initial conditions**

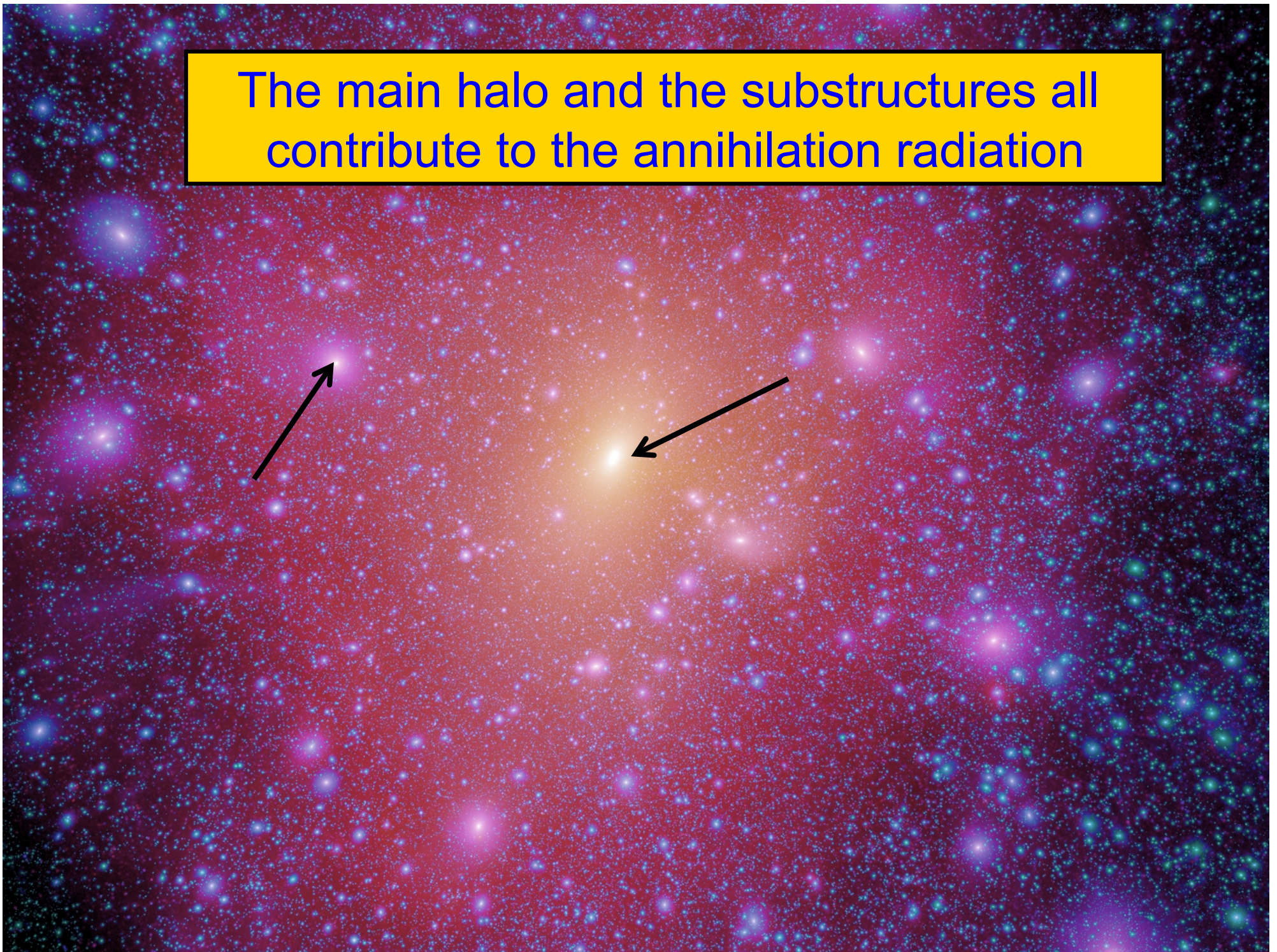


VIRG

Aquarius (galactic) & Phoenix (cluster) halos



The main halo and the substructures all contribute to the annihilation radiation



Halo density profiles

NFW:

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

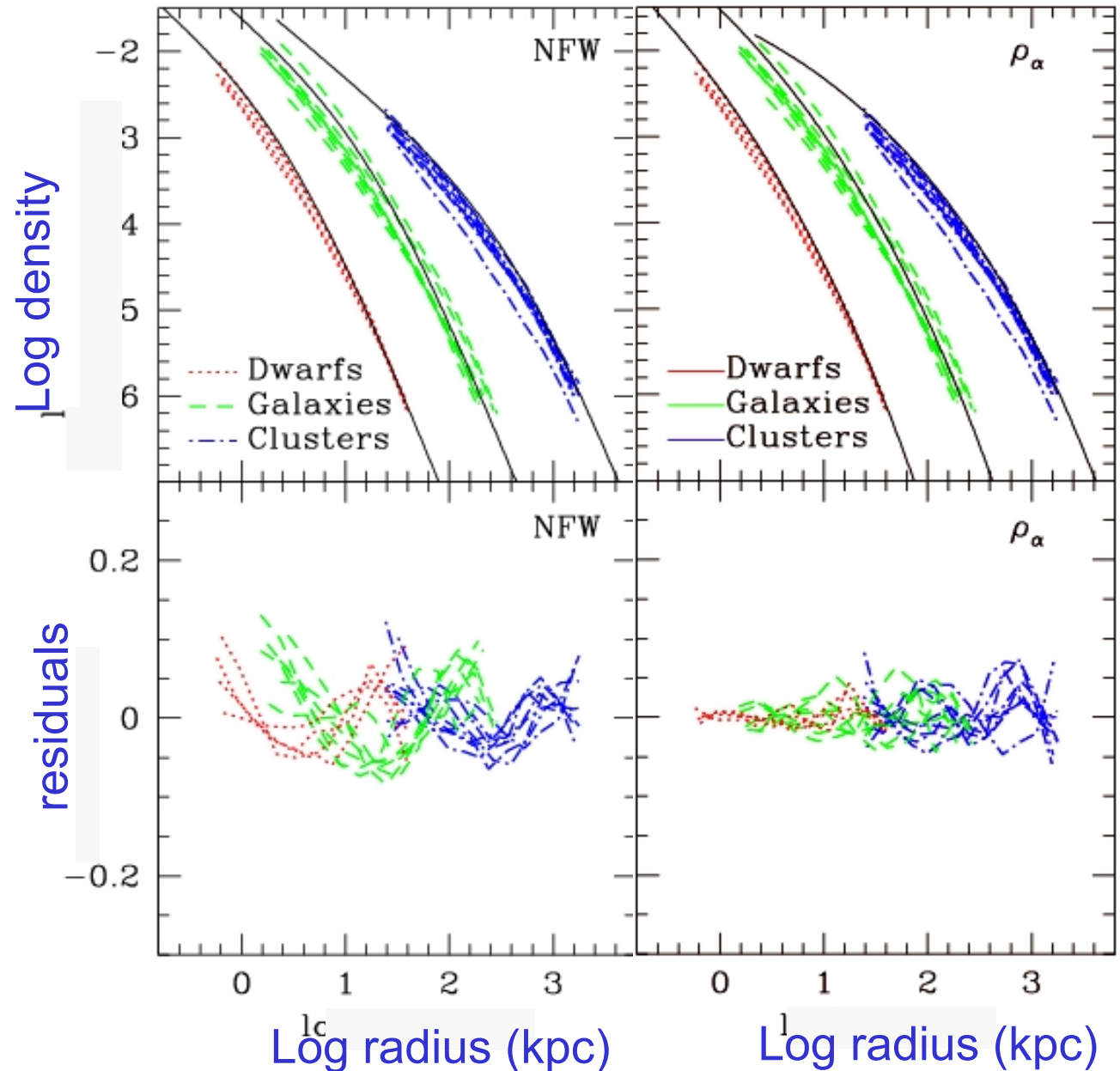
Einasto:

$$\frac{d \log \rho_\alpha}{d \log r} = -2 \left(\frac{r}{r_{-2}} \right)^\alpha$$

Has extra param: α

(similar to stellar
distribution in ellipticals
- Einasto)

Navarro et al 04



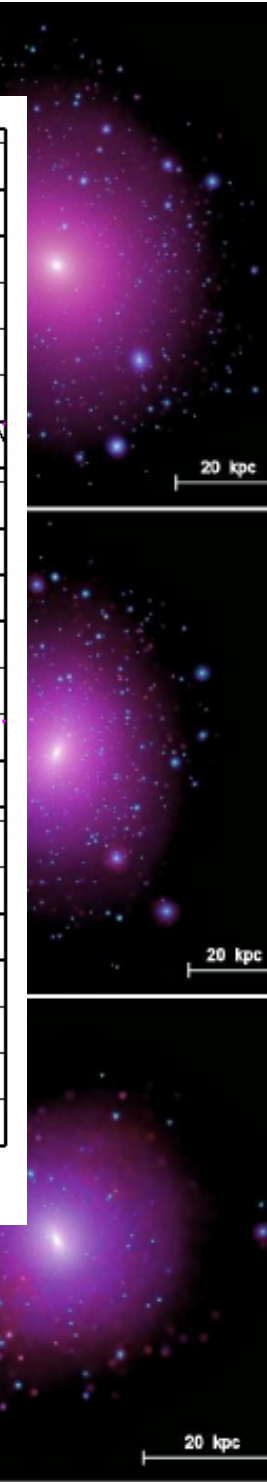
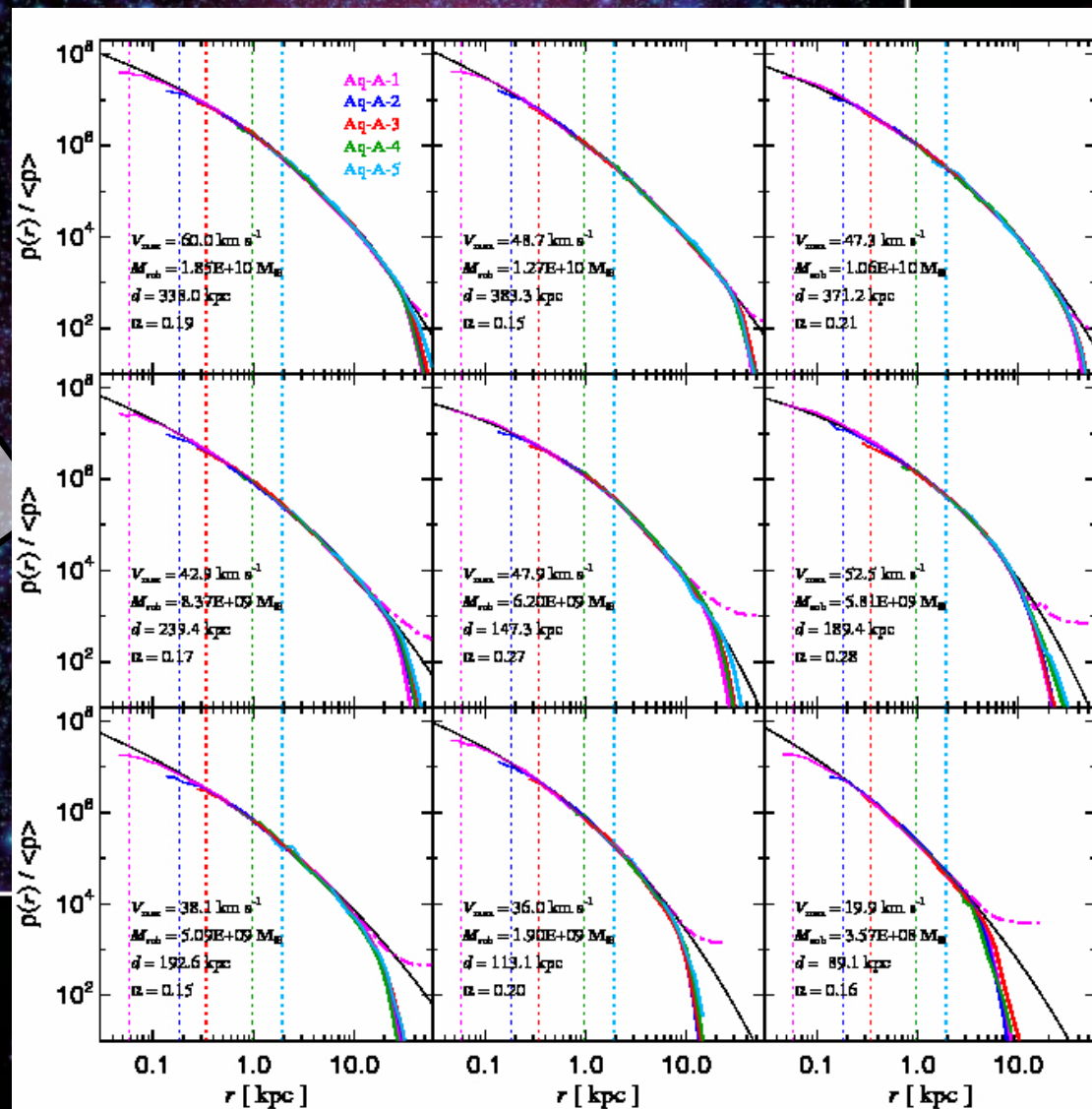


VIRG

CDM subhalos
also have
cuspy profiles

Aquarius

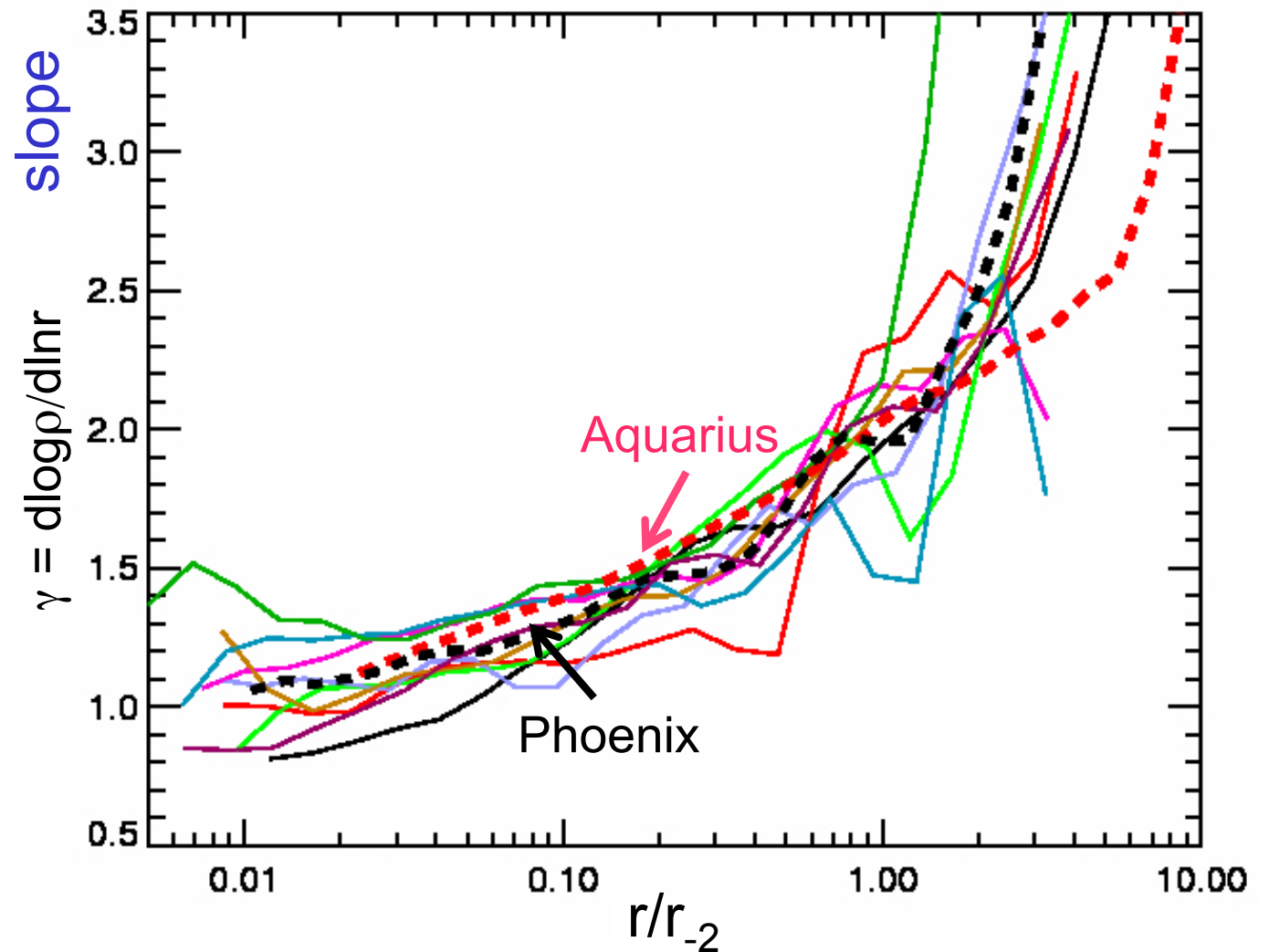
Springel et al '08



The structure of the cusp

Scatter in the
inner slope

Asymptotic slope ≤ 1



Large number of substructures survive, mostly in outer parts

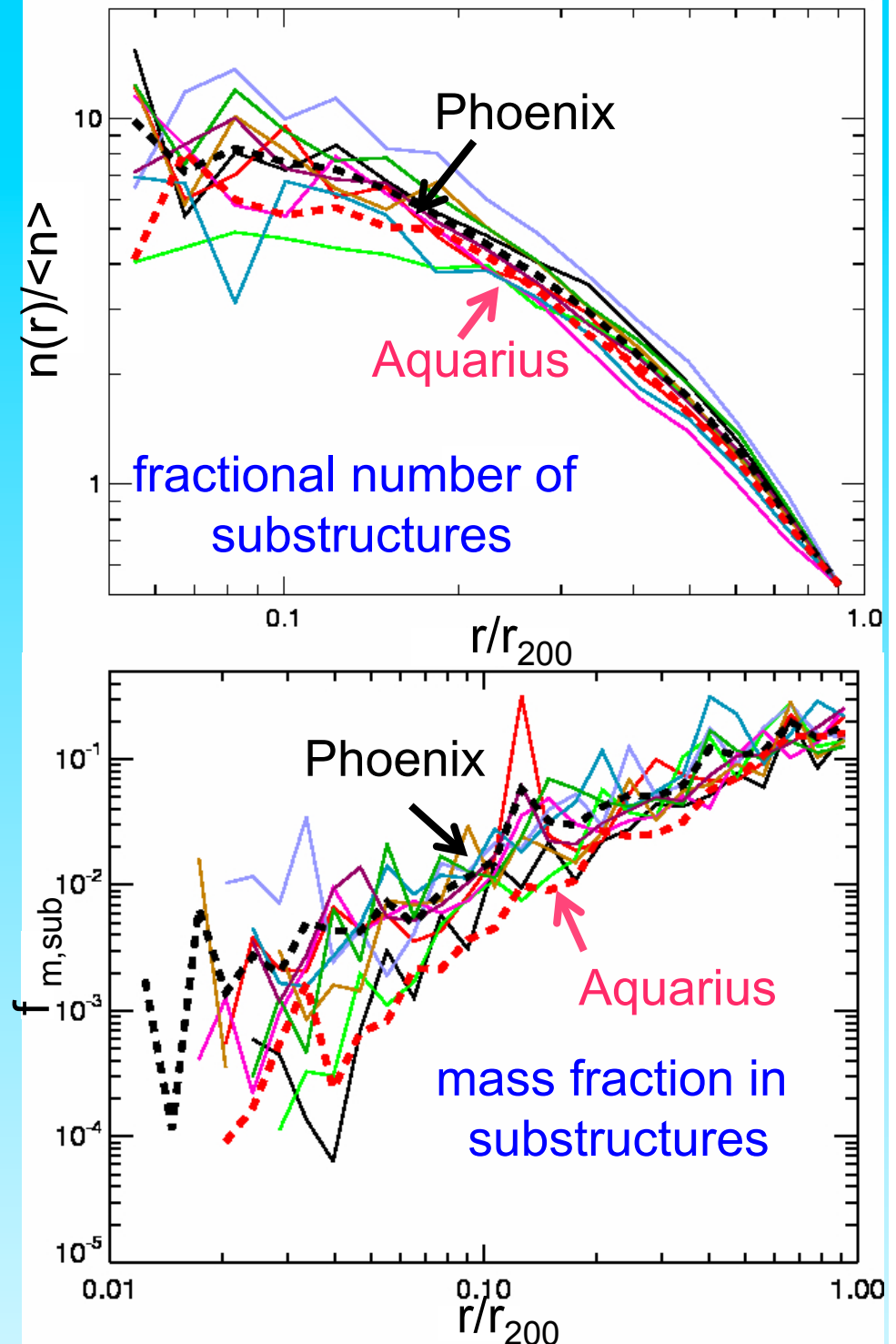


Large number of substructures survive, mostly in outer parts



The subhalo number density profile

- The spatial **distribution** of subhalos (except for the few most massive ones) is **independent** of **mass**
- Most **subhalos** are at **large radii** -- subhalos are more effectively destroyed near the centre
- Most subhalos have completed only **a few orbits**; dynamical friction unimportant below a subhalo mass threshold
- **Total mass fraction** in subs (**$\sim 10\%$**) **similar** in galaxies and clusters except in inner parts



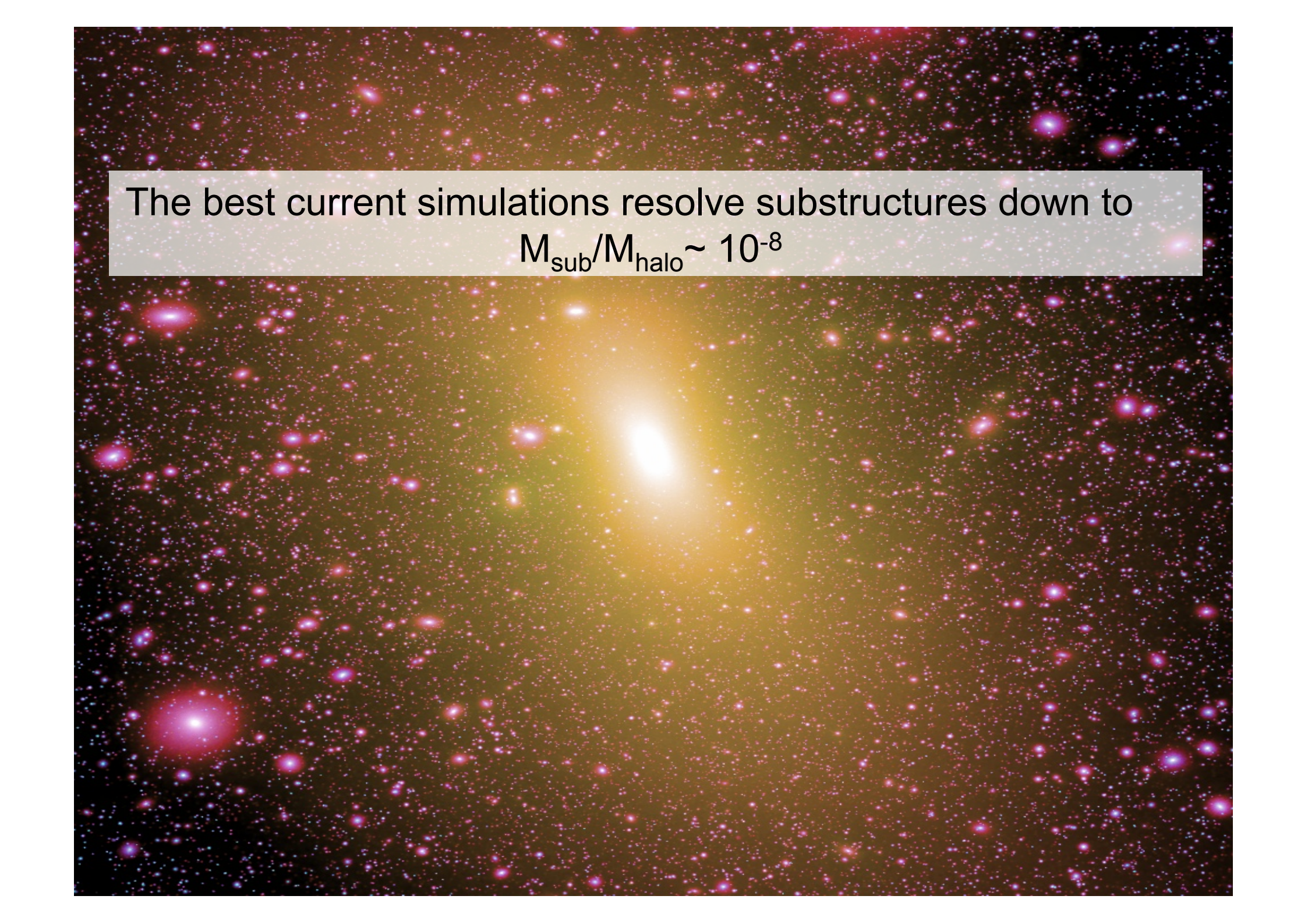
$z=0.0$

The “via lactea” simulation

Kuhlen etal '08

80 kpc



The background of the slide is a deep space image showing a vast field of galaxies. In the center, there is a large, bright, yellowish-white galaxy cluster. Surrounding it and throughout the rest of the image are numerous smaller, distant galaxies, many of which appear as red and purple points of light against the dark cosmic background.

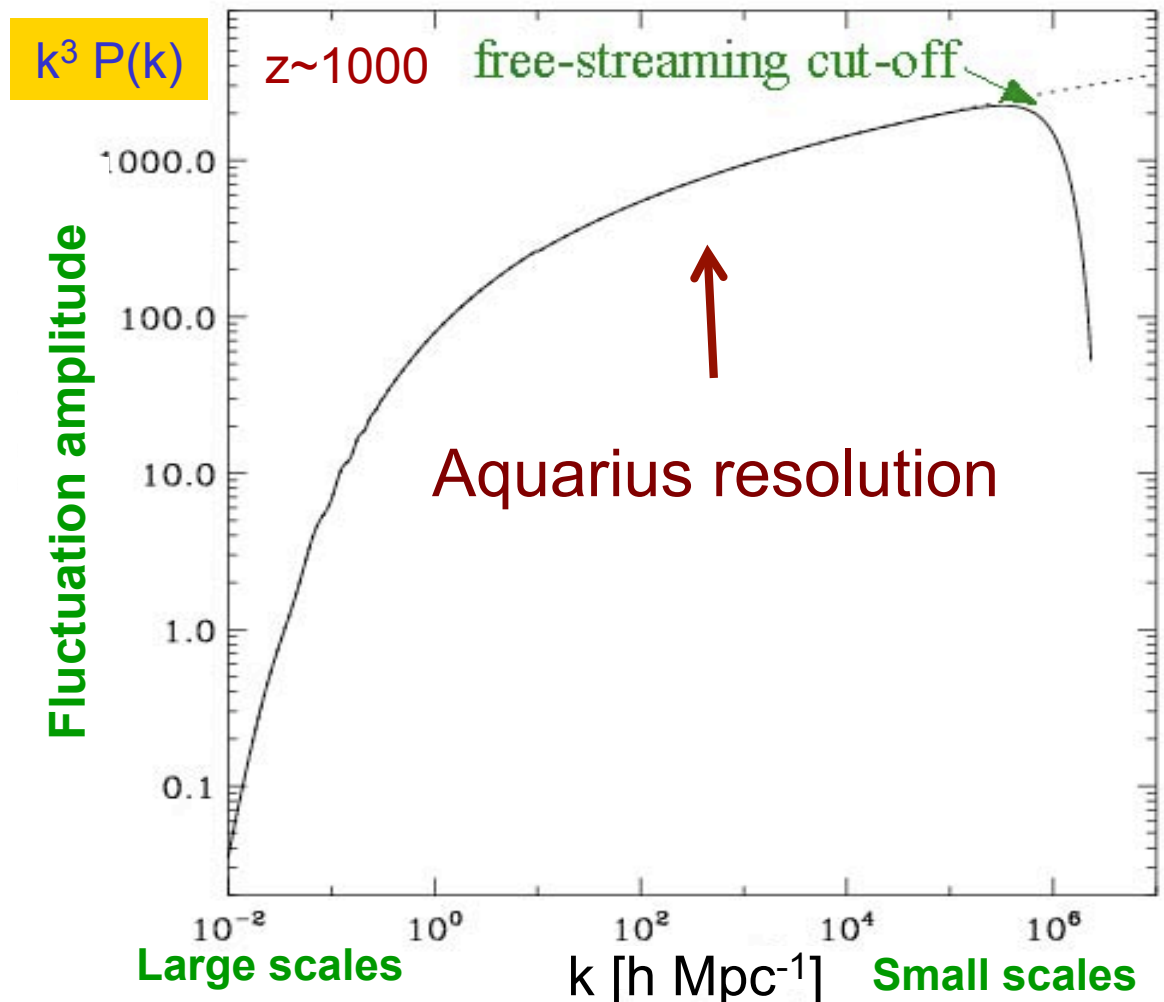
The best current simulations resolve substructures down to

$$M_{\text{sub}}/M_{\text{halo}} \sim 10^{-8}$$

The cold dark matter power spectrum

The linear power spectrum
("power per octave")

Assumes a 100GeV wimp
Green et al '04





$$\text{Intensity} \propto \int \rho^2(\mathbf{x}) \langle \sigma v \rangle dV$$

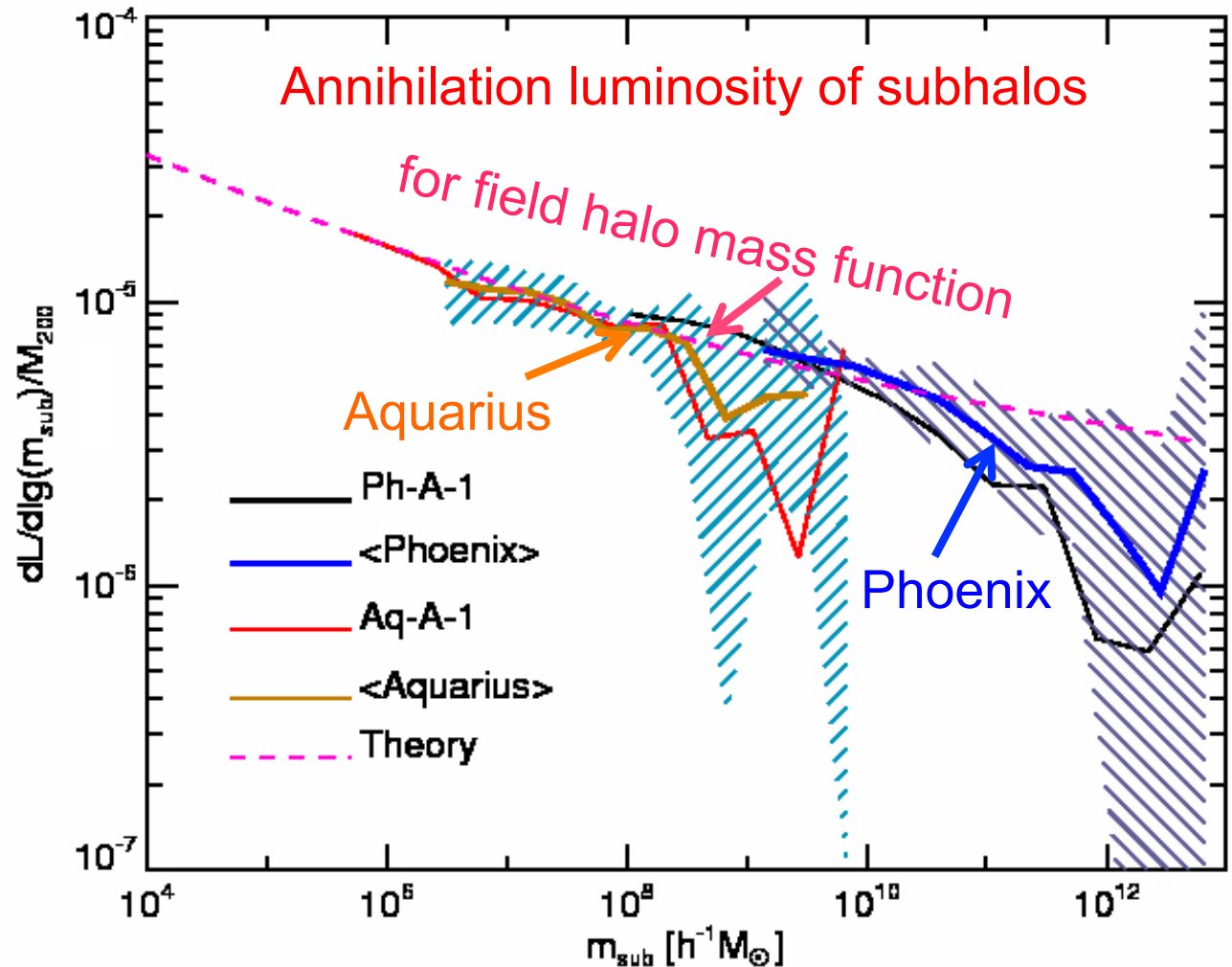
Need to extrapolate to Earth mass
→ gravitational physics

Extrapolation to Earth mass

Annihilation luminosity of subs. per unit mass

Subhalo L (per halo mass) similar to L of field halo mass fn.

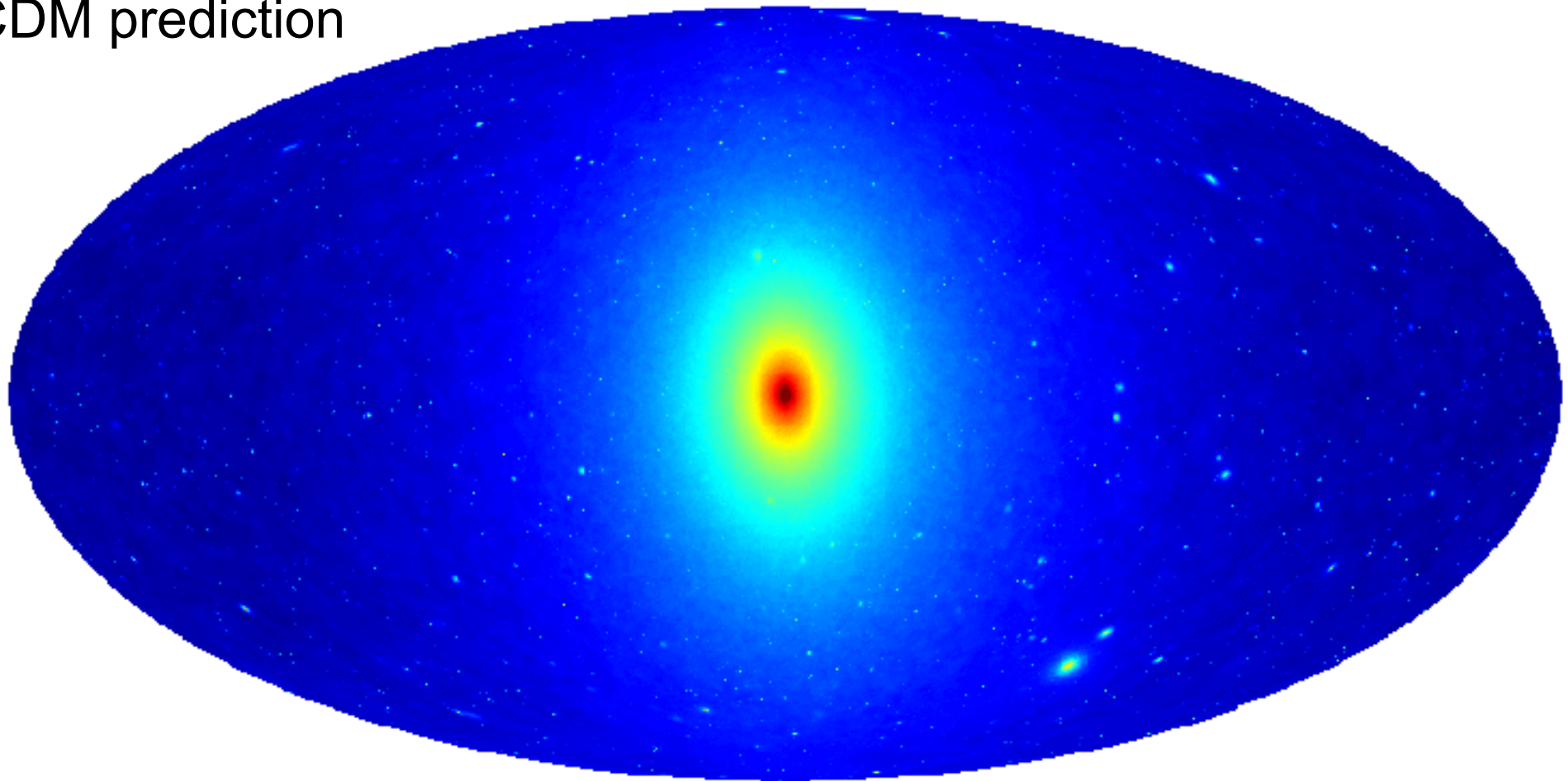
Extrapolate using halo mass function (x1.5) + mass-concentration reln



The Milky Way seen in annihilation radiation

Aquarius simulation: $N_{200} = 1.1 \times 10^9$

CDM prediction



14.  18. $\text{Log} (M_{\text{sun}}^2 \text{ kpc}^{-5} \text{ sr}^{-1})$

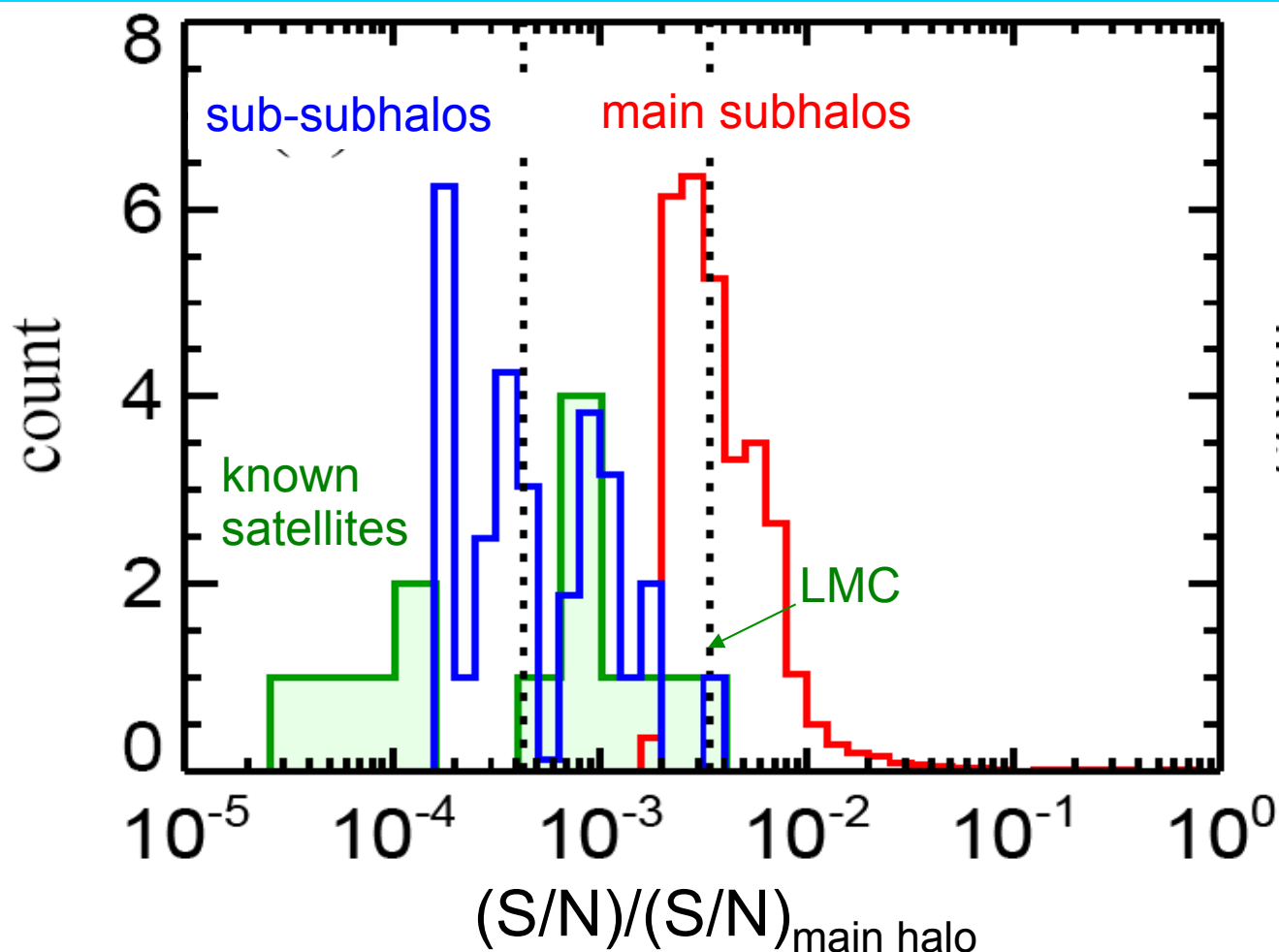
Springel et al. '08

A blueprint for detecting halo CDM

$$S/N = F / (\theta_h^2 + \theta_{\text{psf}}^2)^{1/2}$$

S/N for detecting subhalos in units of that for detecting the main halo.

30 highest S/N objects, assuming use of optimal filters



- Highest S/N subhalos have 1% of S/N of main halo
- Highest S/N subhalos have 10 times S/N of known satellites
- Substructure of subhalos has no influence on detectability

A galaxy cluster seen in annihilation radiation

CDM prediction



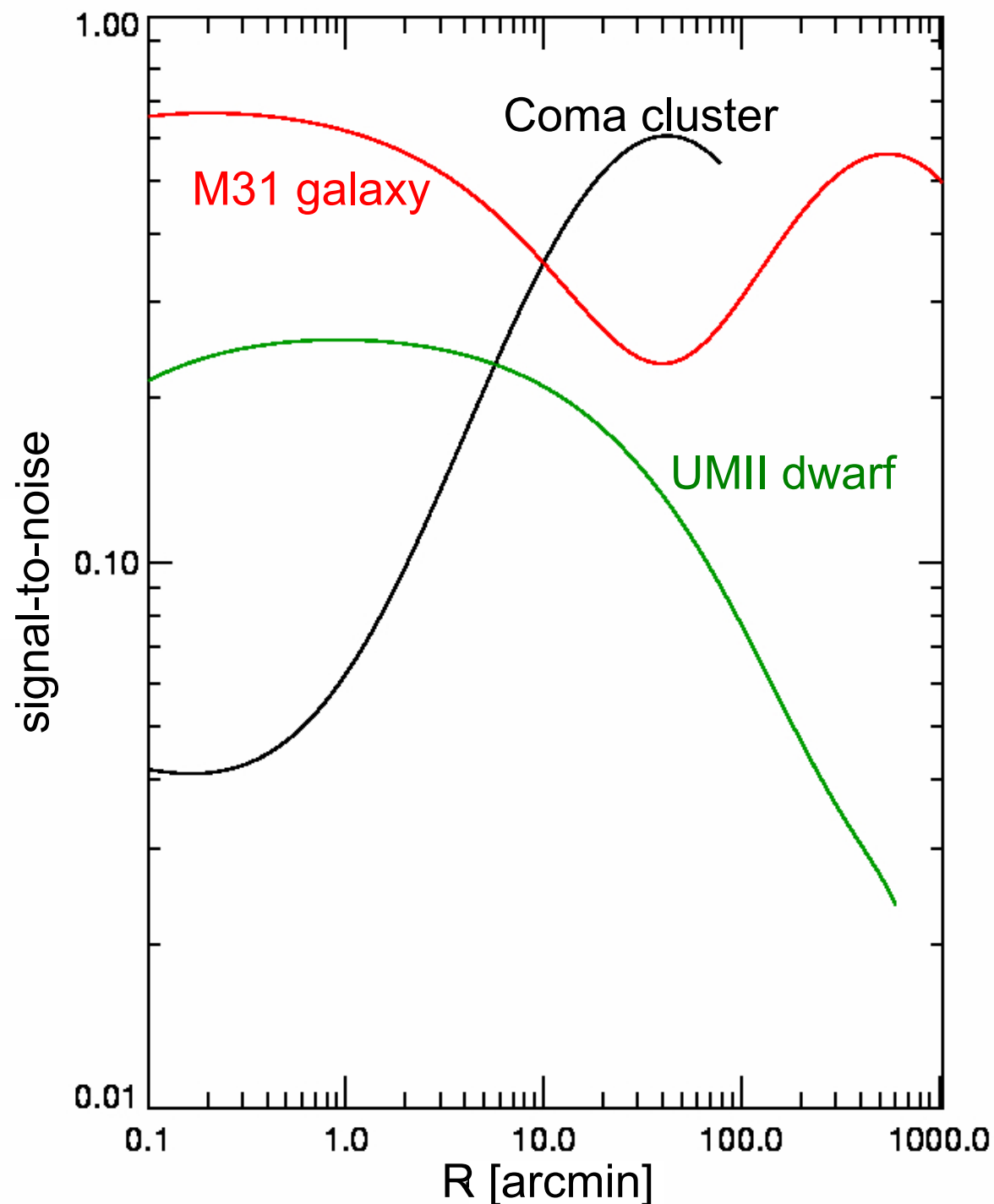
-0.50  2.0 Log(Intensity)

Annihilation radiation

Signal-to-noise

larger S/N in clusters
than in MW dwarfs

Gao, Frenk, Jenkins,
Springel & White '11

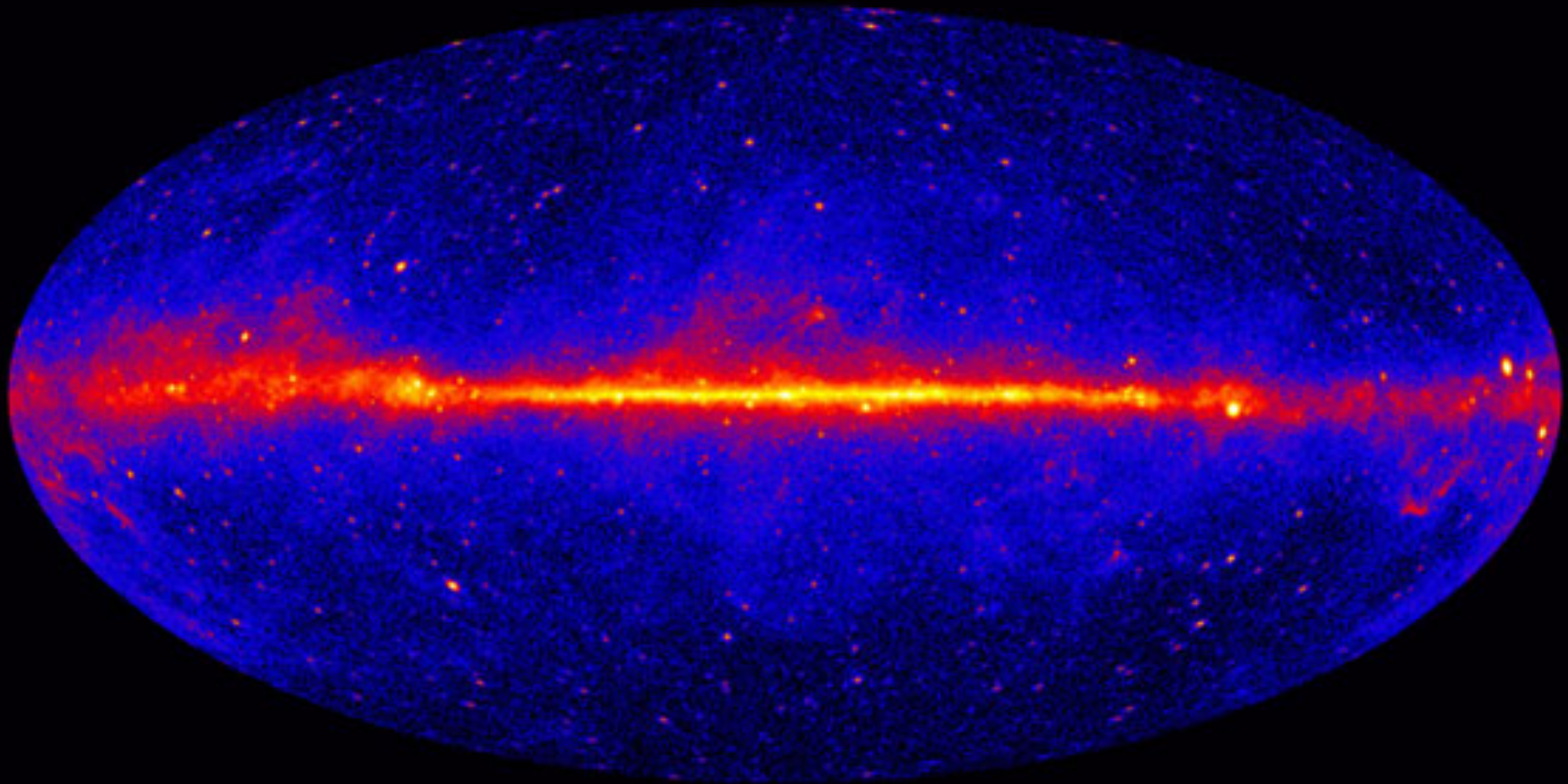


- Galaxy clusters offer the best prospect for detecting dark matter annihilation radiation



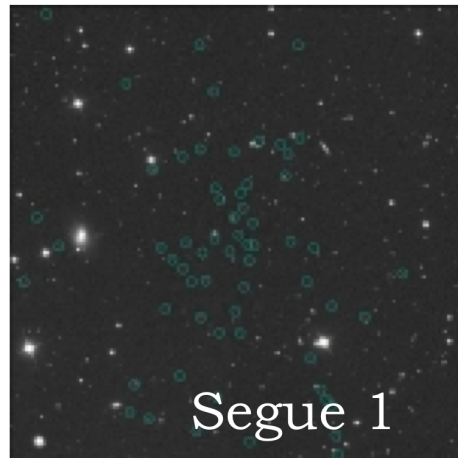


Fermi 3-year all sky map

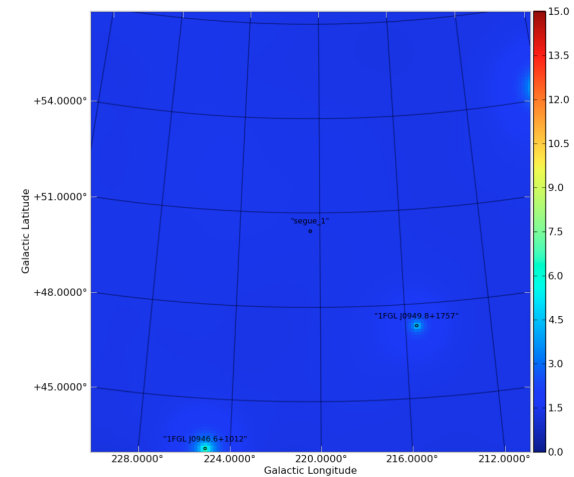


MW satellites: no Fermi detection

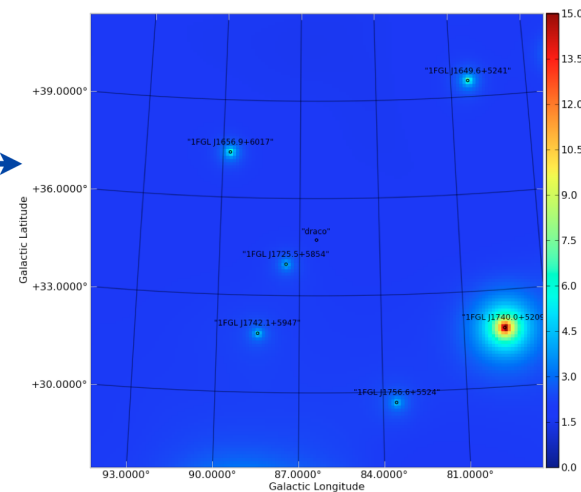
Satellite galaxies in visible light and gamma-rays



Visible
Light

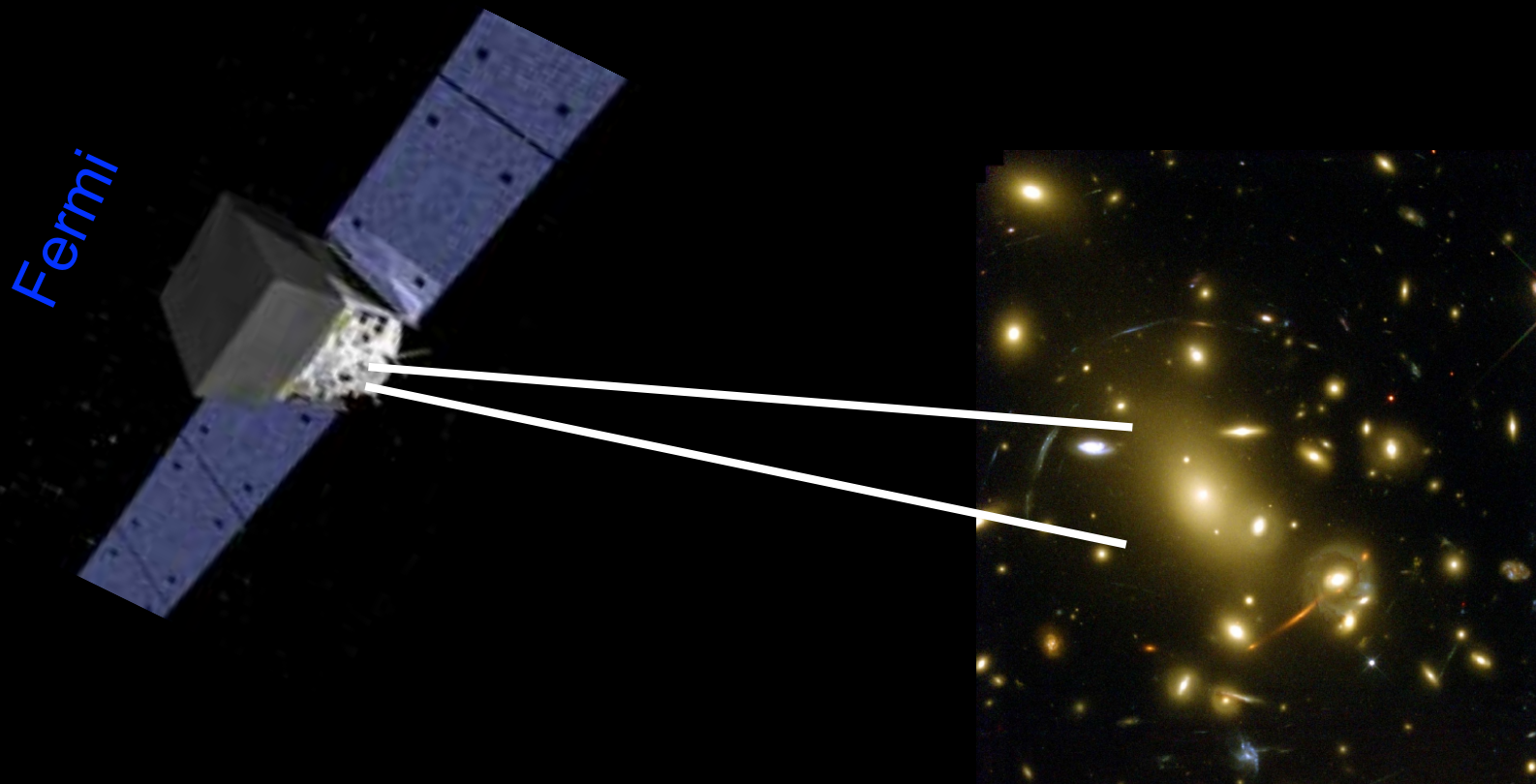


Gamma-
rays





Galaxy clusters in Fermi

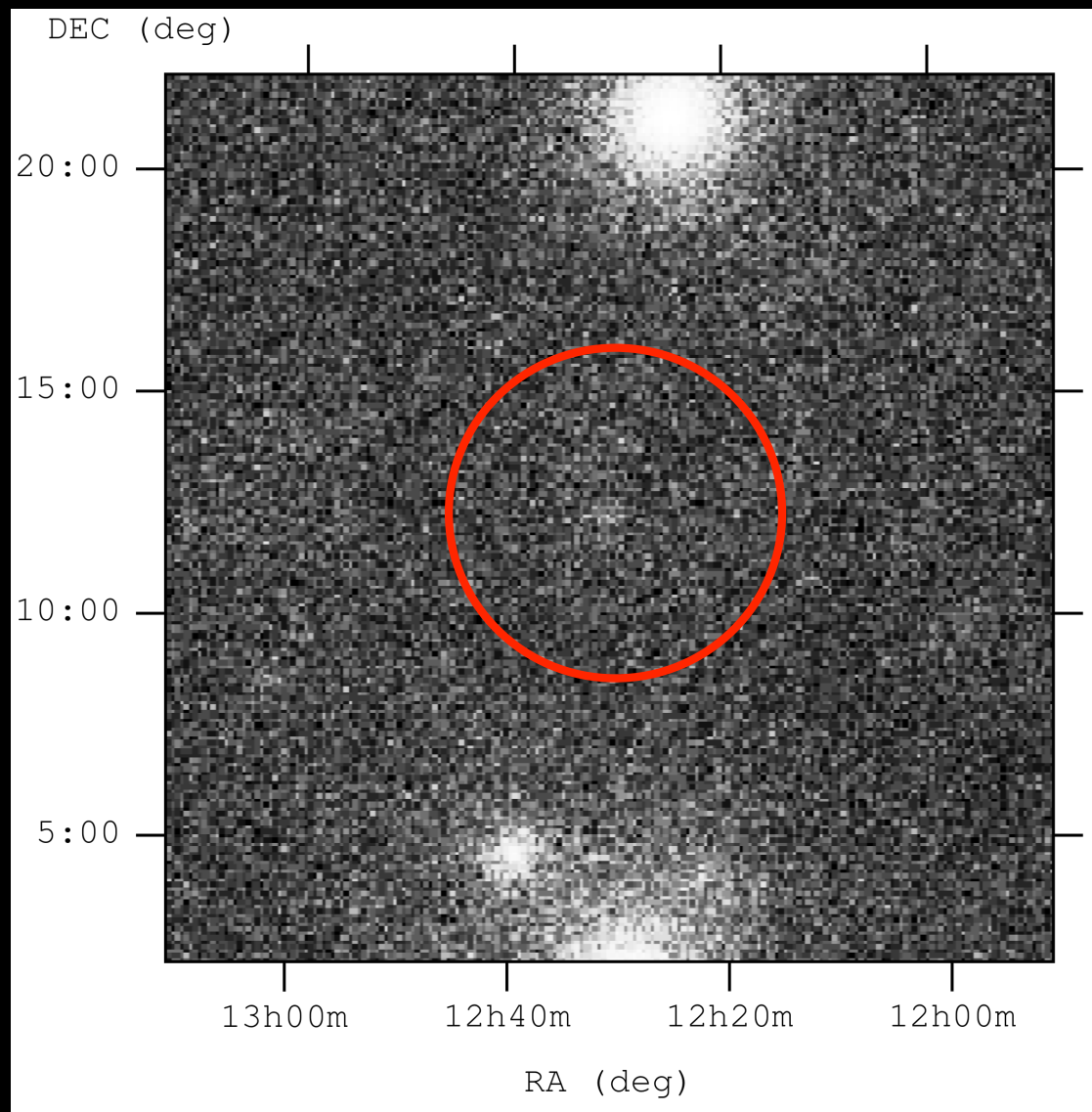




The Virgo cluster in Fermi

Fermi-LAT image
100MeV – 100 GeV

3-year data



Han, Frenk, Eke, Gao, White '12

Upper limits on x-section

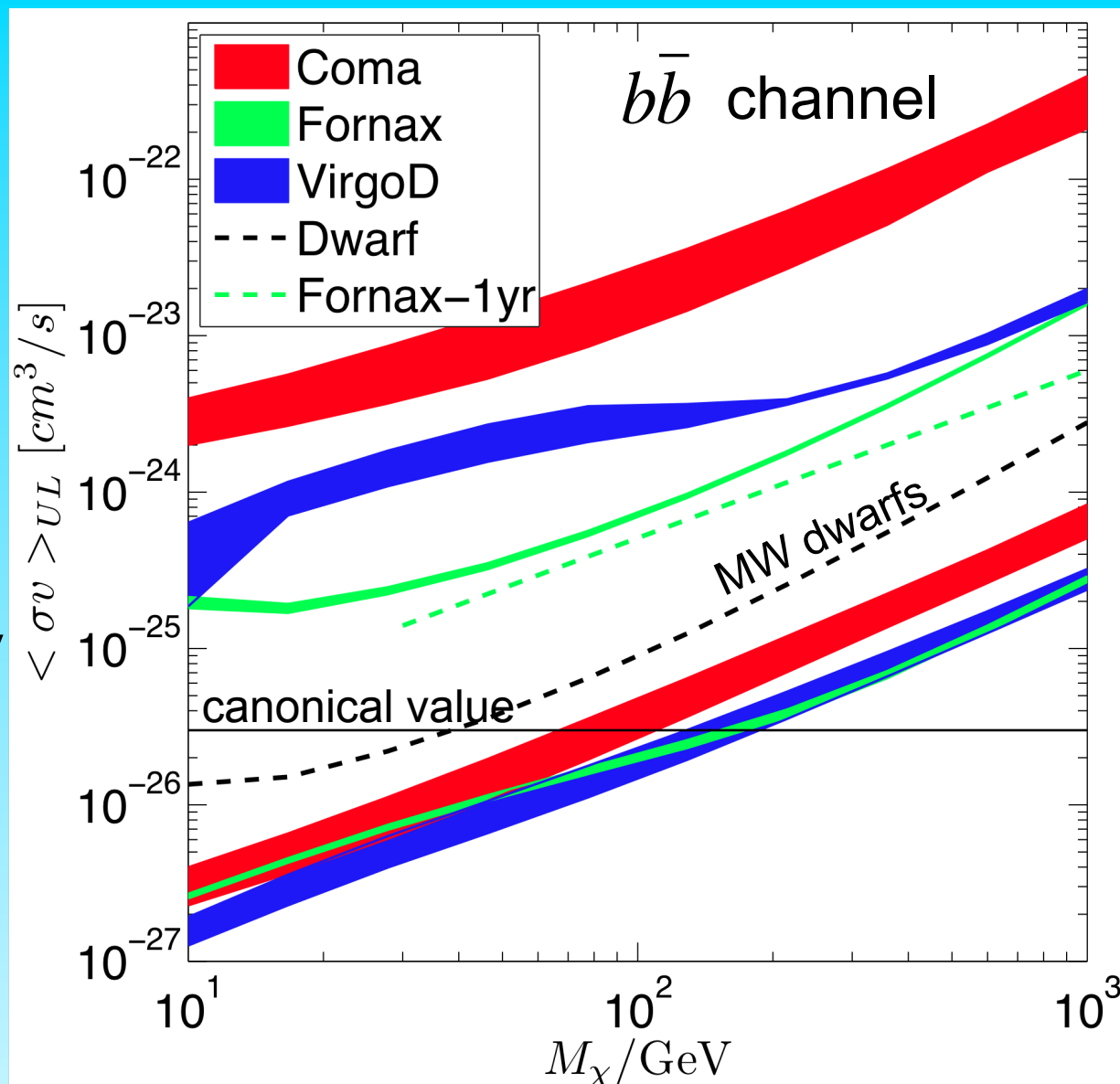
Bands = uncertainty
in CR

Canonical x-section:

$$\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

excluded for $M < 100 \text{ GeV}$

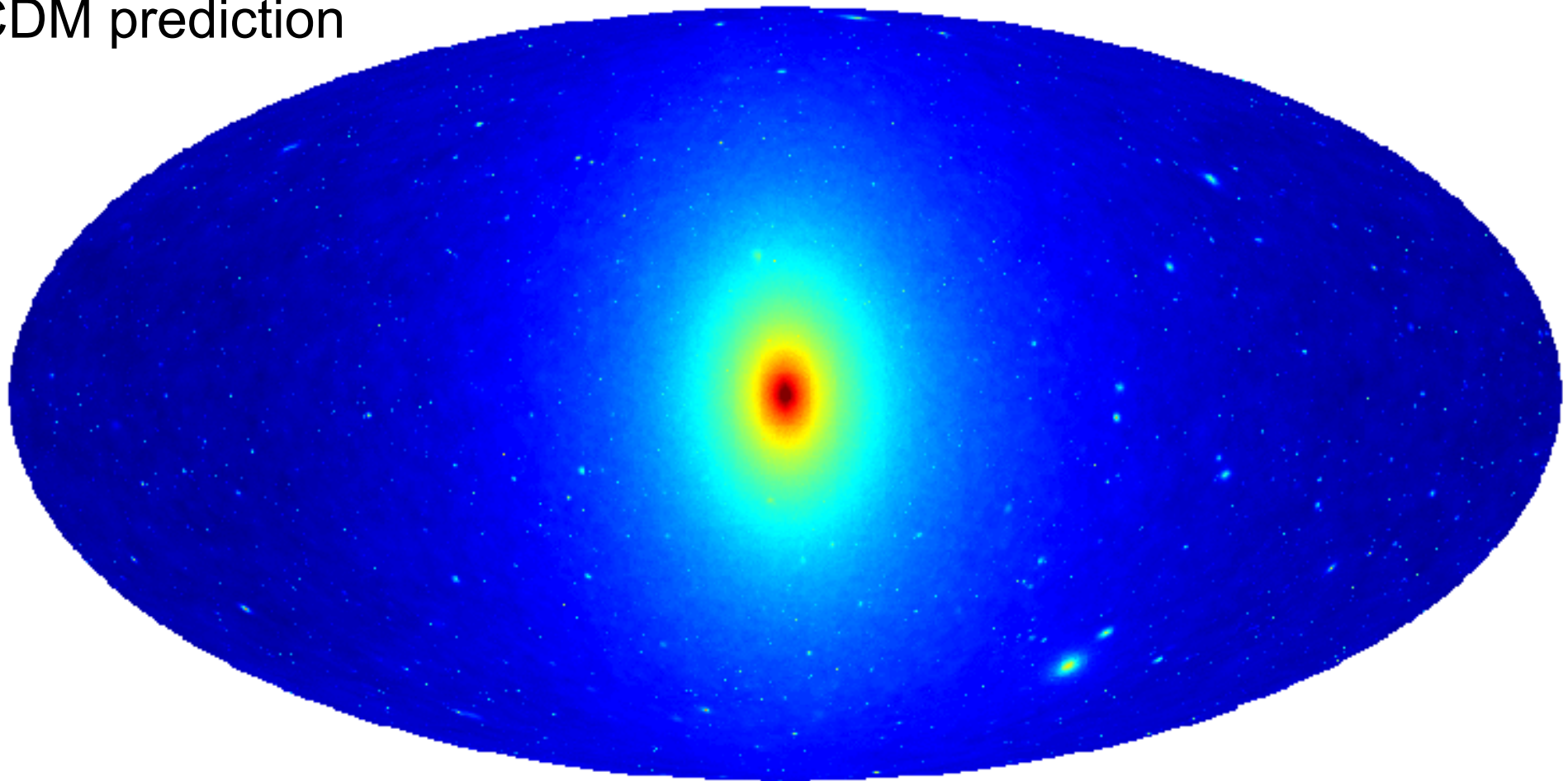
(for $M_{\text{cut}} = 10^{-6} M_{\odot}$)



The Milky Way seen in annihilation radiation

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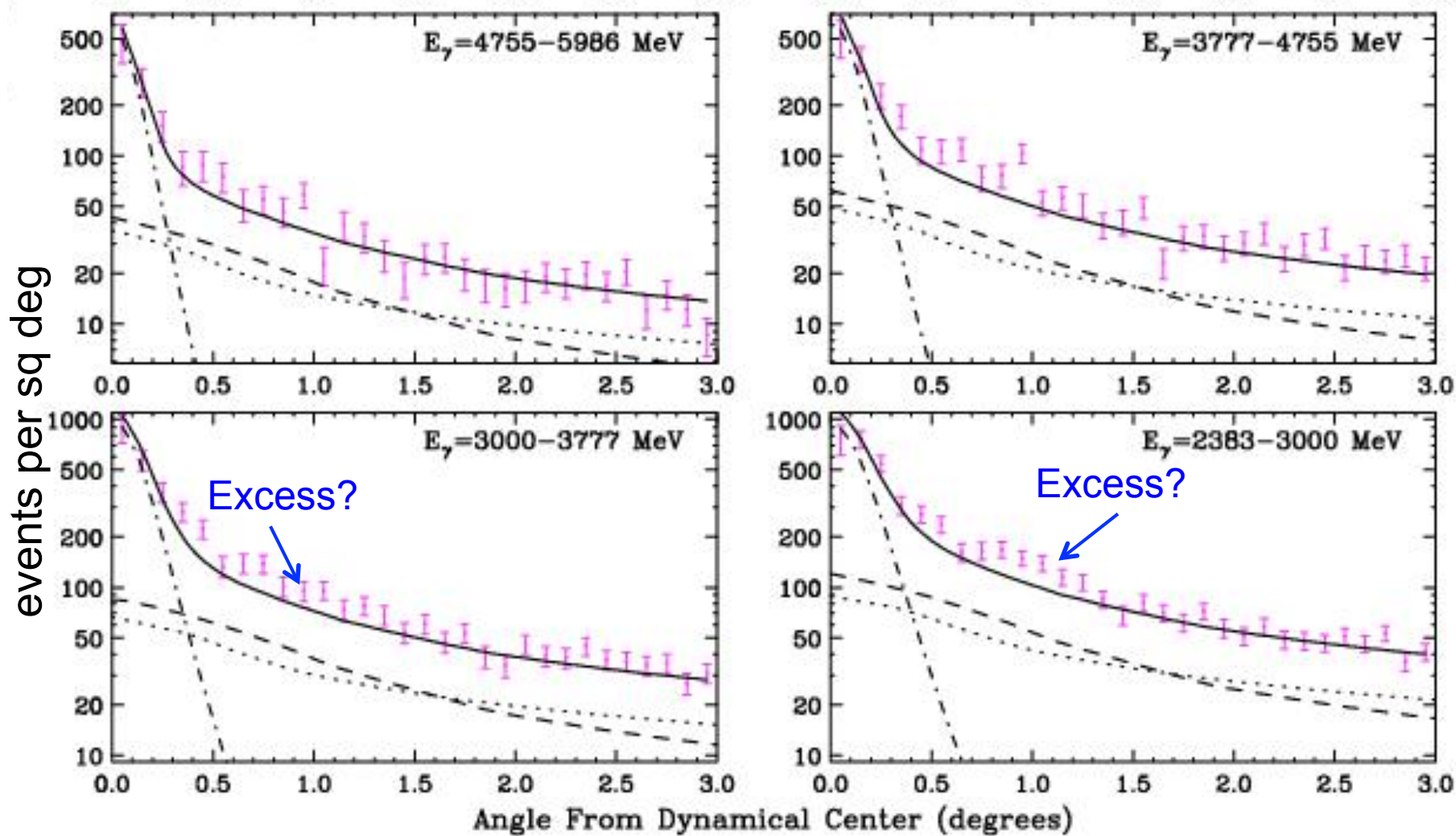
CDM prediction



14.  18. $\text{Log} (M_{\text{sun}}^2 \text{ kpc}^{-5} \text{ sr}^{-1})$

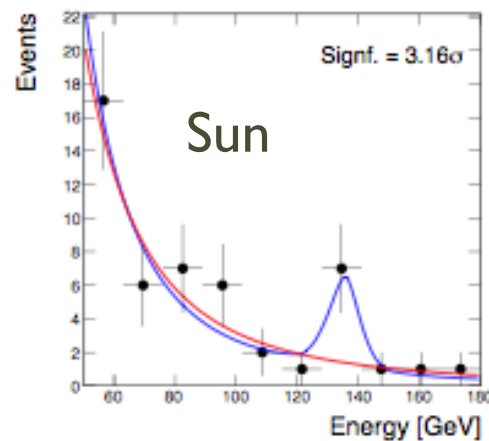
Springel et al. '08

Annihilation radiation from the Galactic Centre?

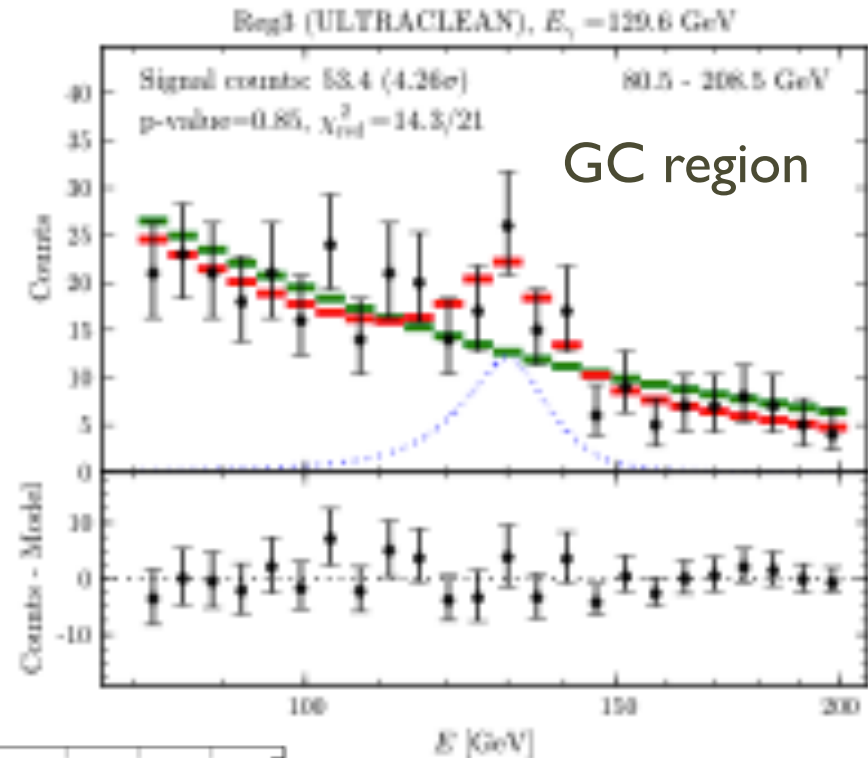
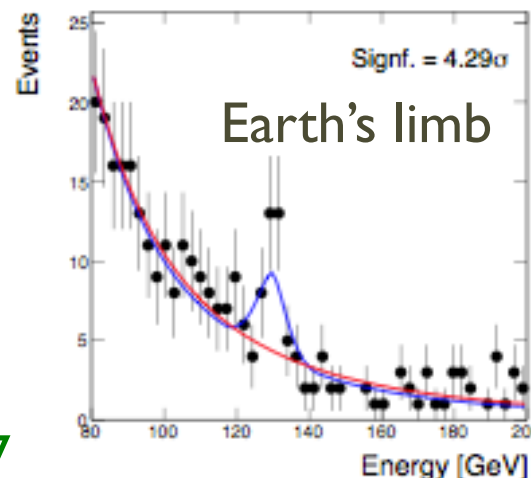


130 (135) GeV line

- Line at around 130 GeV in optimized regions around galactic centre
- Seen also in other areas (unassociated sources, Sun), even where it shouldn't (Earth's limb)



Whiteson, arXiv:1302.0427



Weniger, arXiv:1204.2797

Is the line real?

From Joachim Edsjo

Conclusions so far

Direct detection

- Several claims (DAMA, Cogent, CRESST) some incompatible
- All incompatible with Xenon 100

Annihilation radiation

- In Milky Way:
 - γ -ray flux **dominated** by **central** region
 - **dark substructures** have 10xS/N of known satellites
 - **no** detection from **sats**, but **claims** from **GC (130 GeV line)**
- Emission from clusters is **extended** with **higher S/N** than sats
 - **boost** factor in **clusters** is several **hundred**
 - **no** detection yet

A Cold dark matter universe

N-body simulations show that cold dark matter halos
(from galaxies to clusters) have:

“Cuspy” density profiles

Does nature have them?

Difficult problem: in visible objects halo structure modified by baryons?

Best places to look:

{ Clusters (good diagnostics)
Dwarf gals (high M/L)

A Cold dark matter universe

N-body simulations show that cold dark matter halos
(from galaxies to clusters) have:

“Cuspy” density profiles

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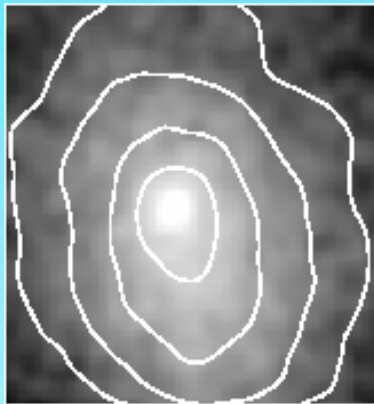
Cluster profiles can be probed with:

- X-ray emission
- Gravitational lensing

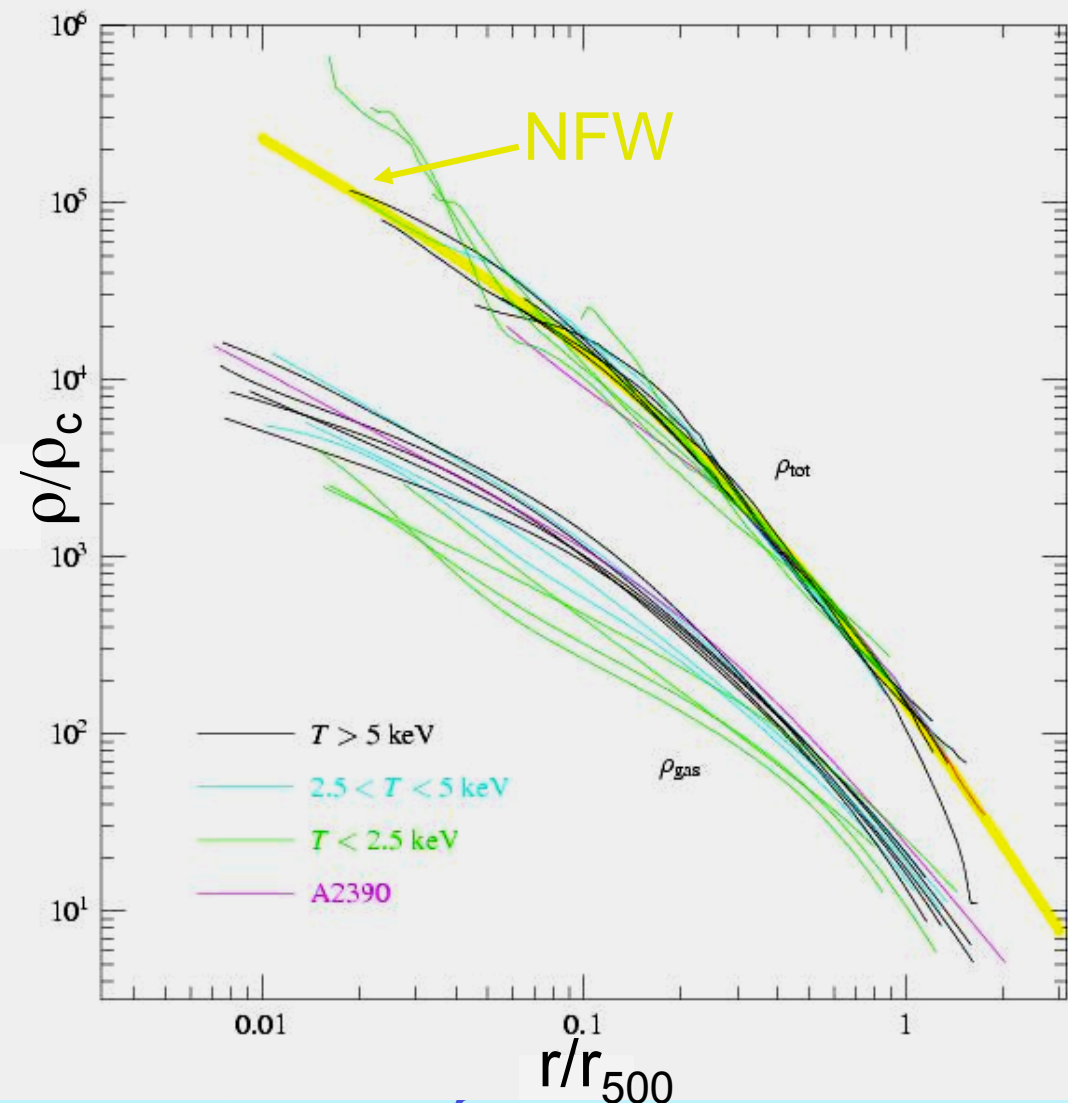
The central density profile of galaxy cluster dark halos

X-ray data

Mass profile of galaxy clusters, from X-ray data & assumption of hydrostatic equilibrium



Excellent agreement with CDM halo predictions

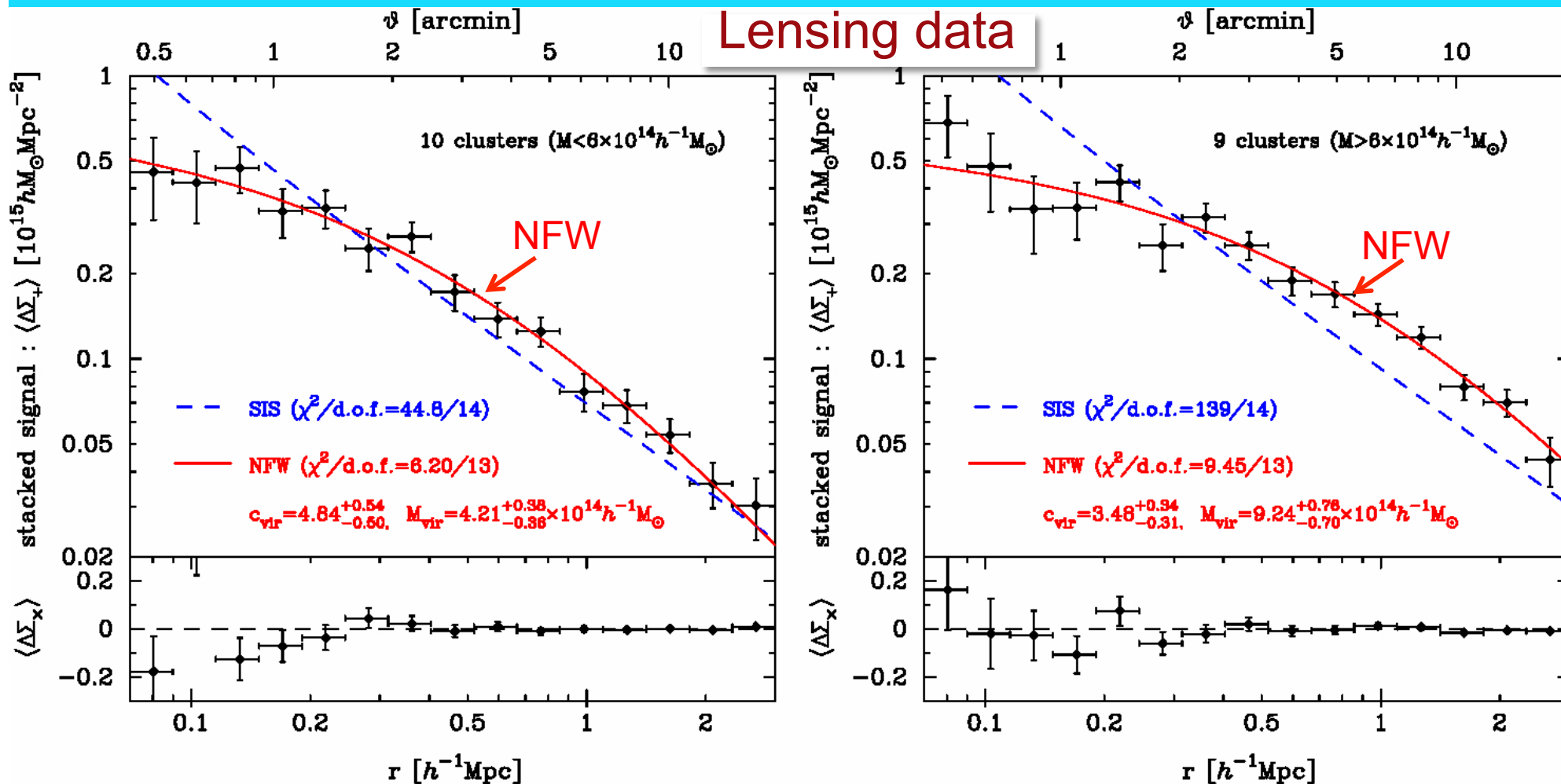


Vikhlinin et al '06

Institute for Computational Cosmology

The density profile of galaxy cluster dark halos

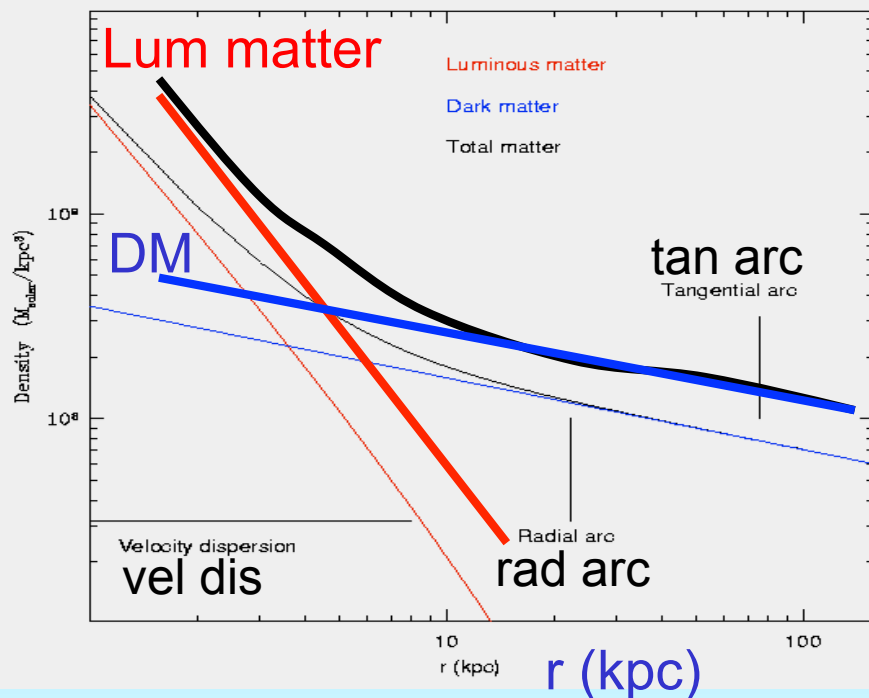
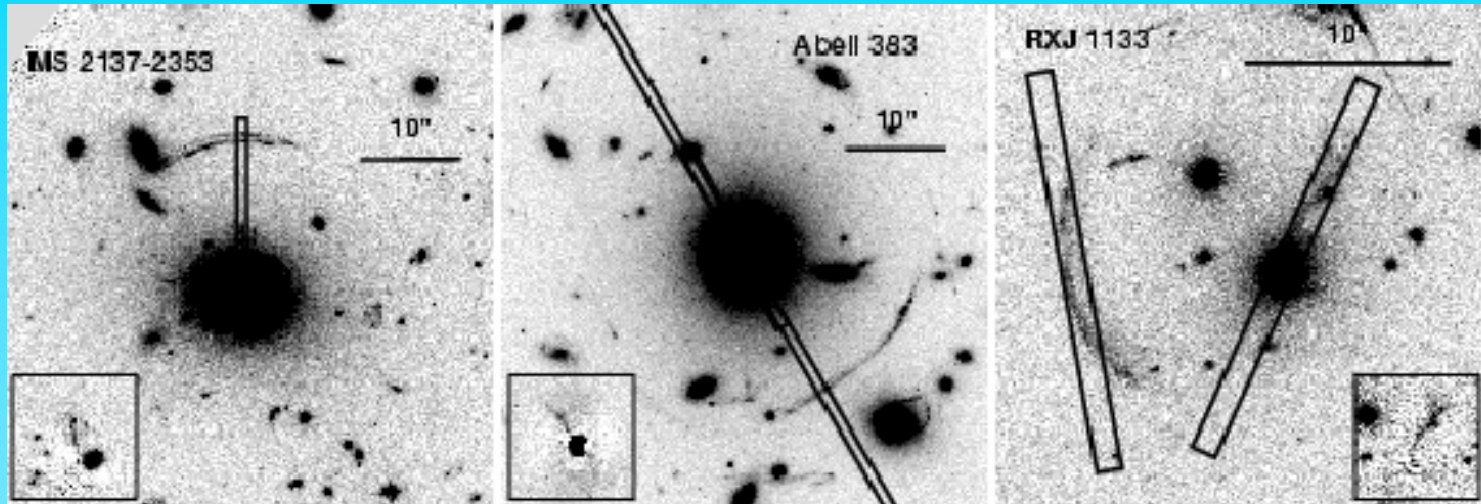
Lensing data



Okabe et al '10

Mass profile in cluster cores from strong lensing

Sand et al 04



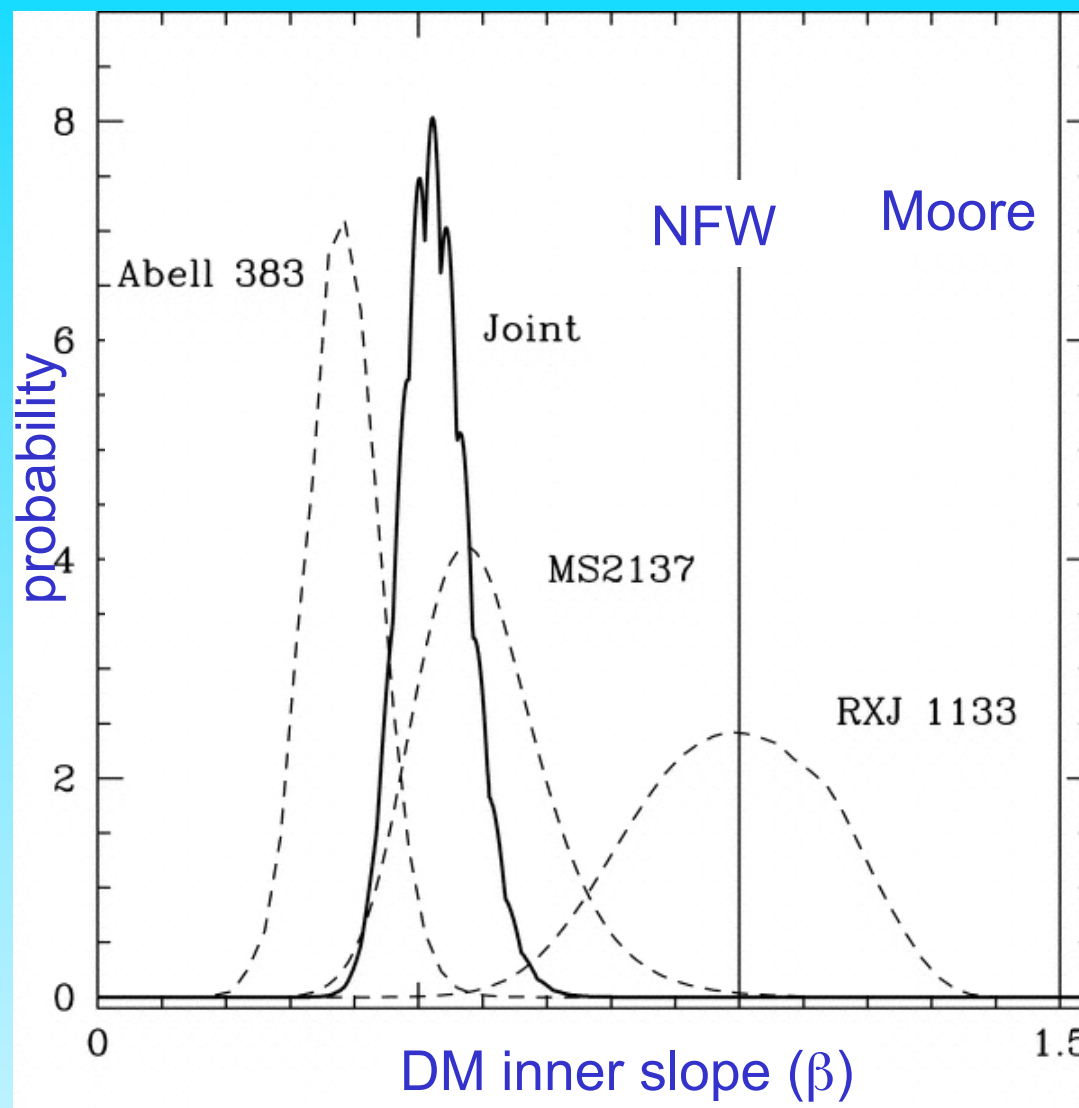
- Assume spherical symmetry
- Model potential as power-law DM + galaxy with constant M/L
- Constrain inner slope of DM profile using tangential arc, radial arc and velocity dispersion profile

Mass profile in cluster cores from strong lensing

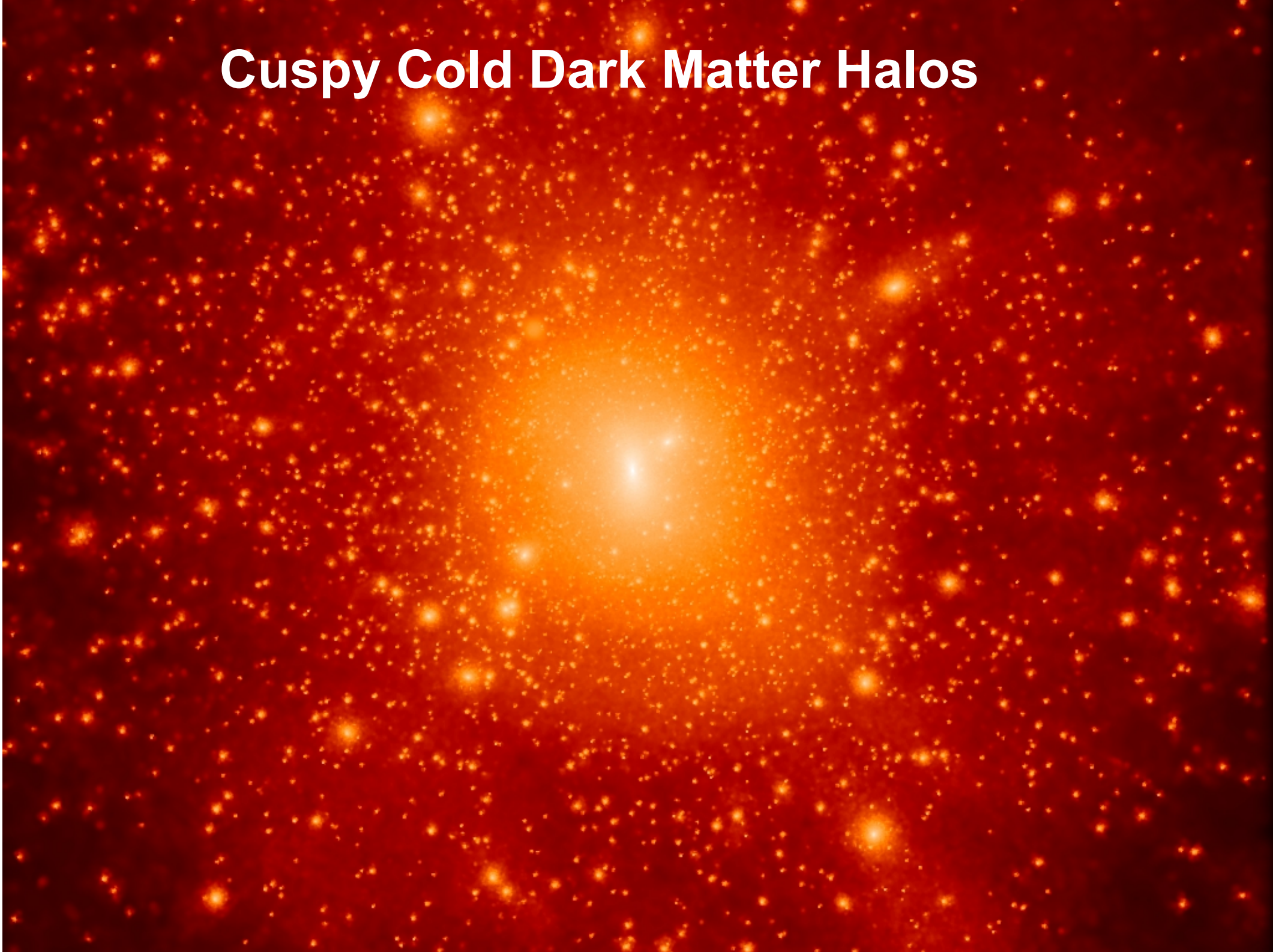
$$\rho(r) \propto r^{-\beta} (r_s + r)^{\beta-3}$$

$\beta=1$ for NFW

Sand etal 04



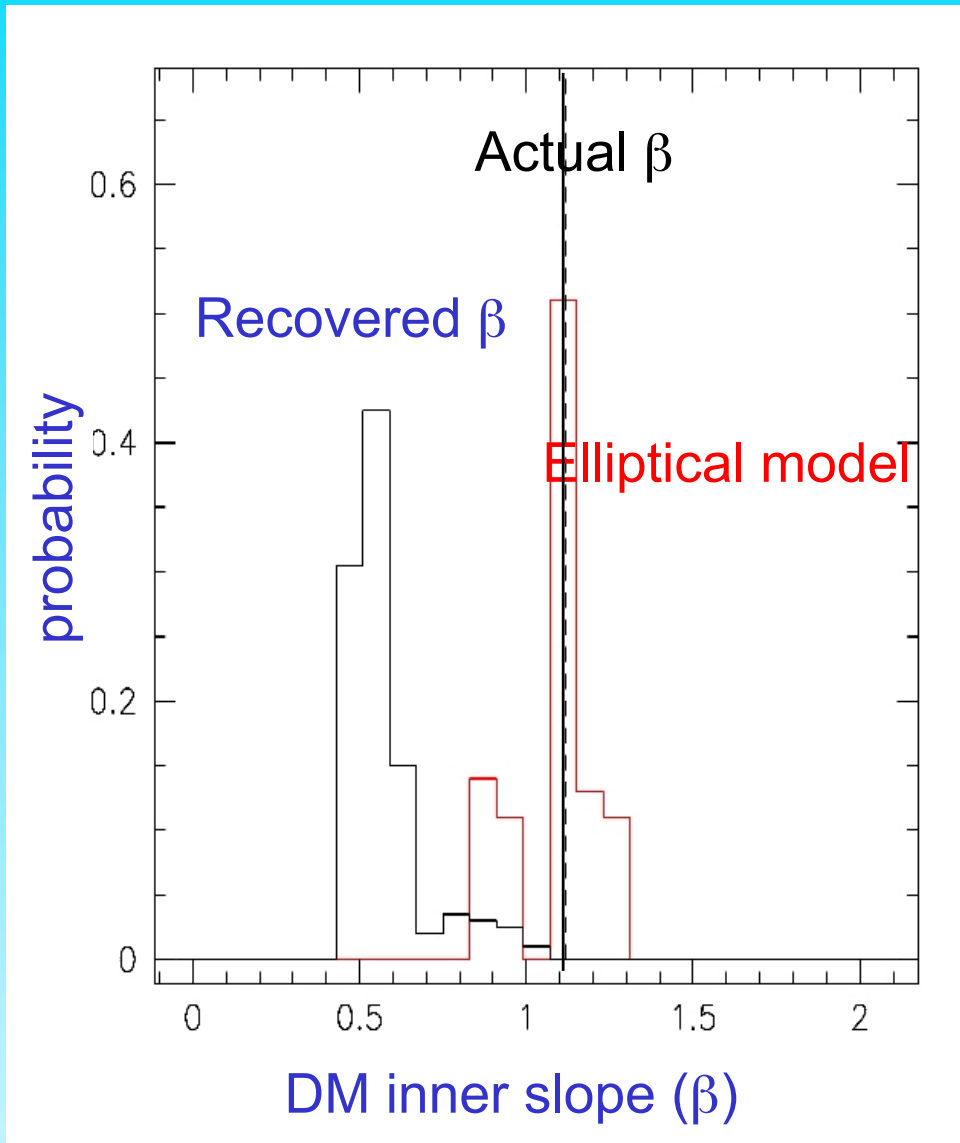
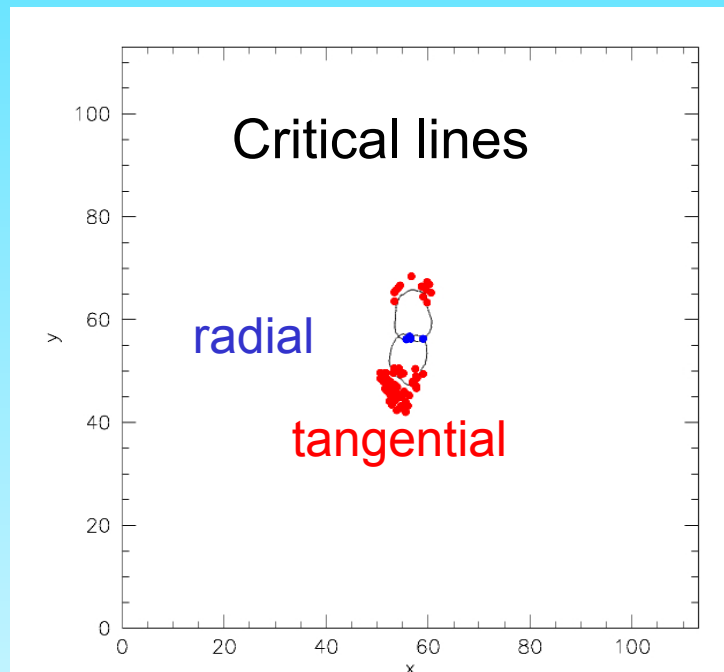
Cuspy Cold Dark Matter Halos



Mass profile in cluster cores from strong lensing

For this simulation, $\beta=1.2$
Sand et al (spherically symm)
analysis returns $\beta \sim 0.5!!!$

Reason: Sand et al assume
spherical symmetry

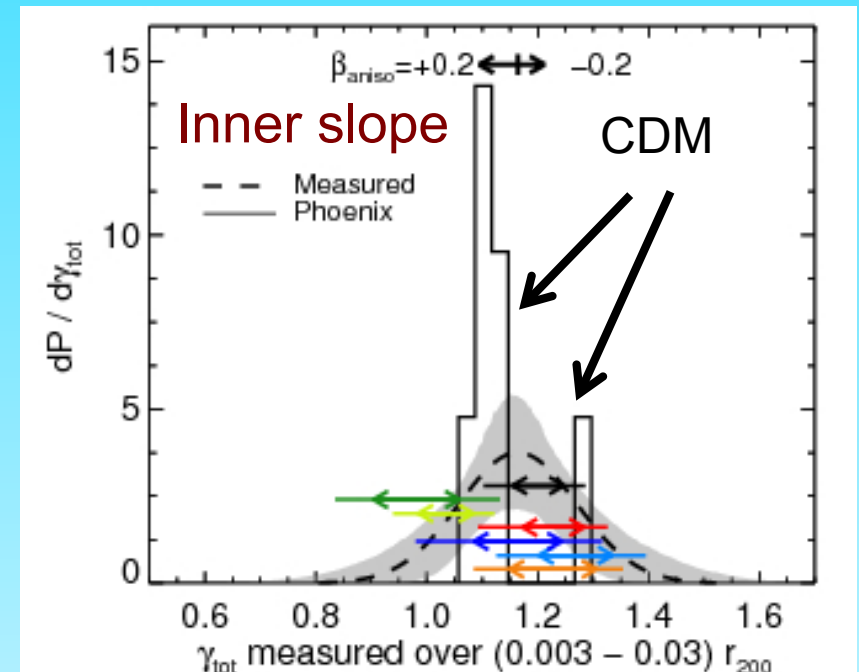
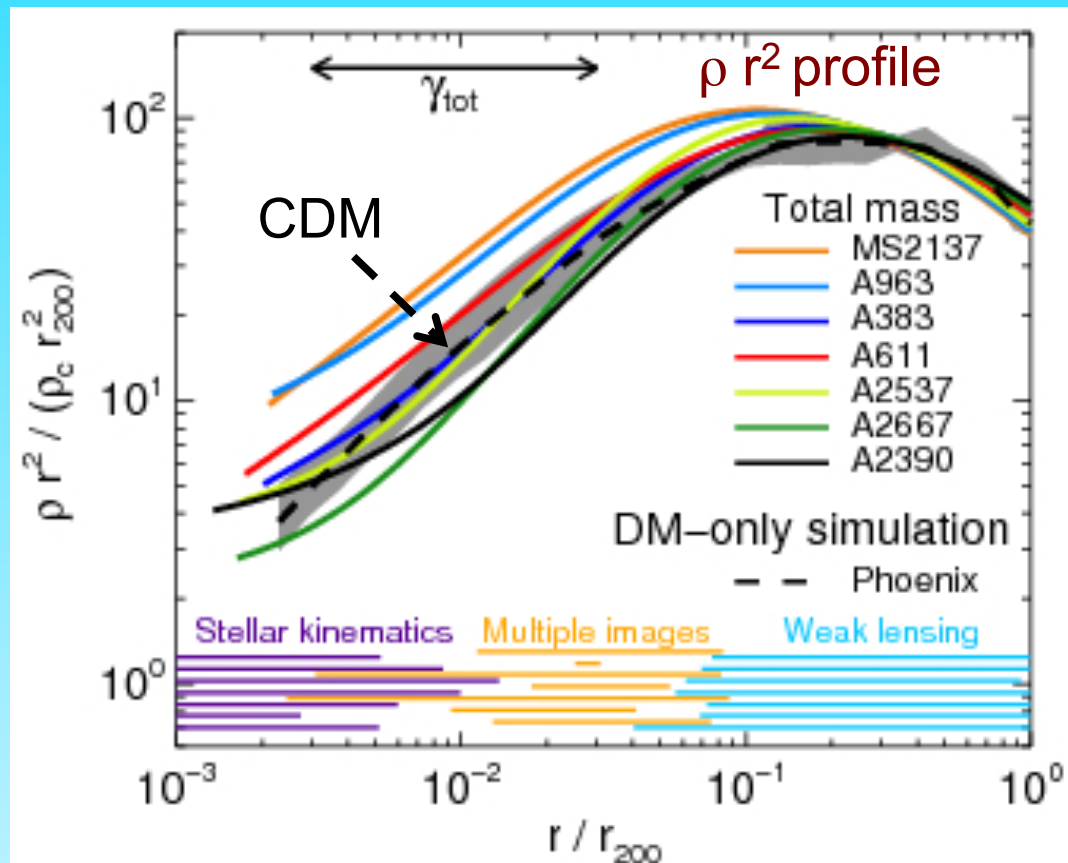


The density profile of galaxy cluster dark halos

7 clusters with strong & weak lensing & resolved stellar kinematics

Compared with CDM Phoenix sims

(Gao et al '12)



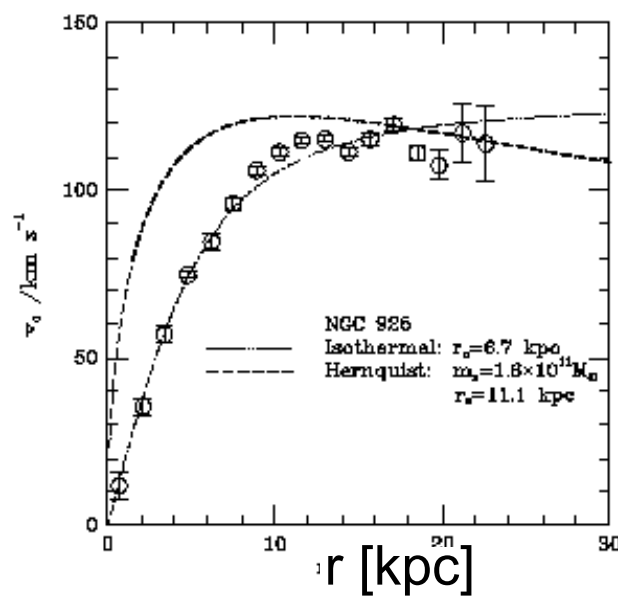
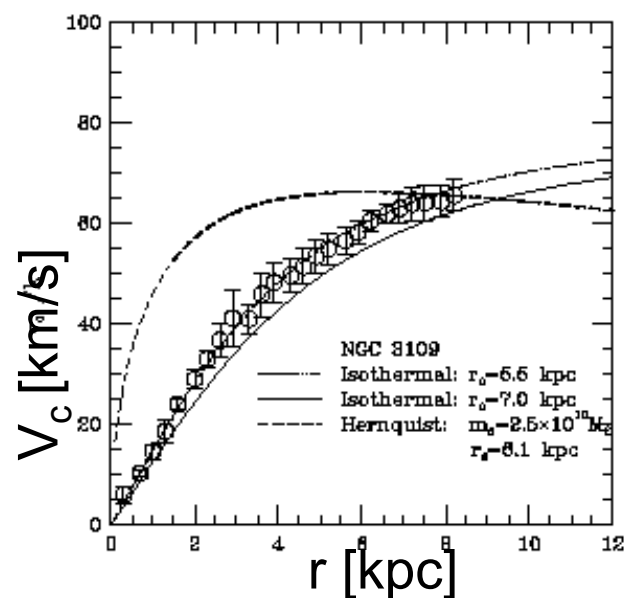
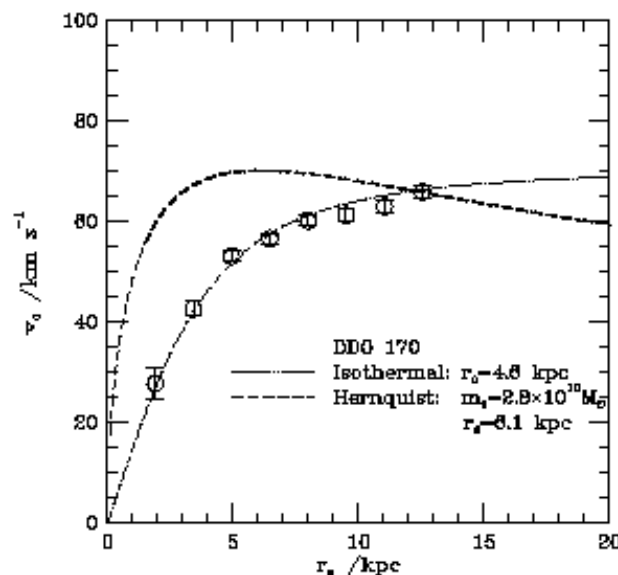
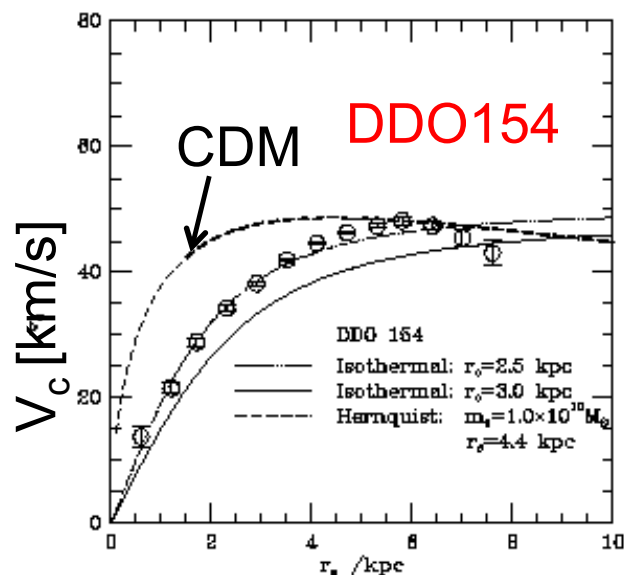
Newman et al '13

Agreement with NFW over 3-3000pc!



How about on dwarf galaxy scales?

Cores in dwarf galaxies



Moore '94

H α rotation curves

→ core radii

The cores of dwarf galaxy haloes

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²*Physics Department, University of Durham, South Road, Durham DH1 3LE*

Accepted 1996 September 2. Received 1996 August 28; in original form 1996 June 26

ABSTRACT

We use N -body simulations to examine the effects of mass outflows on the density profiles of cold dark matter (CDM) haloes surrounding dwarf galaxies. In particular, we investigate the consequences of supernova-driven winds that expel a large fraction of the baryonic component from a dwarf galaxy disc after a vigorous episode of star formation. We show that this sudden loss of mass leads to the formation of a core in the dark matter density profile, although the original halo is modelled by a coreless (Hernquist) profile. The core radius thus created is a sensitive function of the mass and radius of the baryonic disc being blown up. The loss of a disc with mass and size consistent with primordial nucleosynthesis constraints and angular momentum considerations imprints a core radius that is only a small fraction of the original scalelength of the halo. These small perturbations are, however, enough to reconcile the rotation curves of dwarf irregulars with the density profiles of haloes formed in the standard CDM scenario.

Let baryons cool and condense to the galactic centre

Rapid ejection of large fraction of gas during starburst can lead to a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

Governato et al. '12

Pontzen & Governato '12

Brooks et al. '12

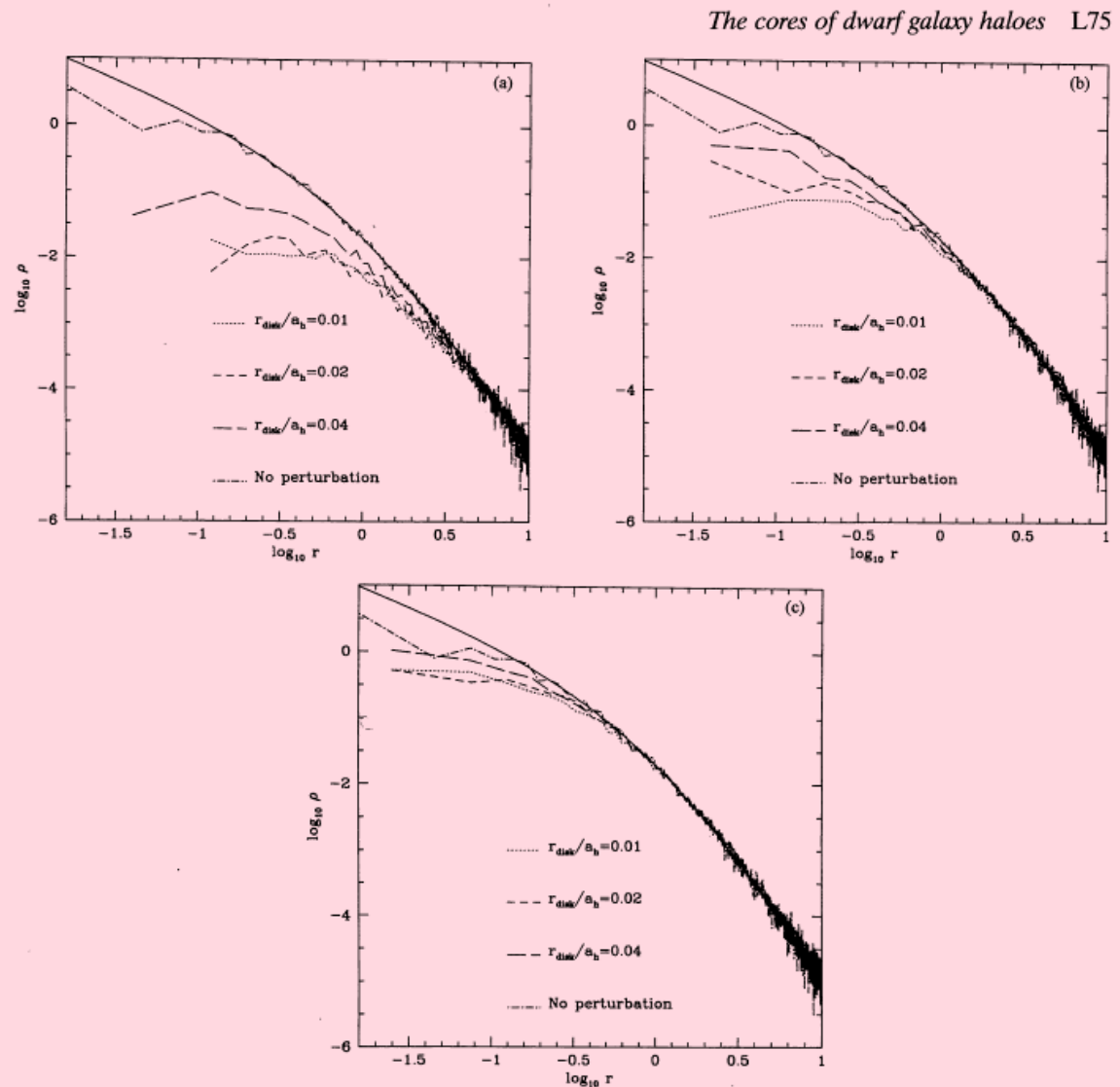
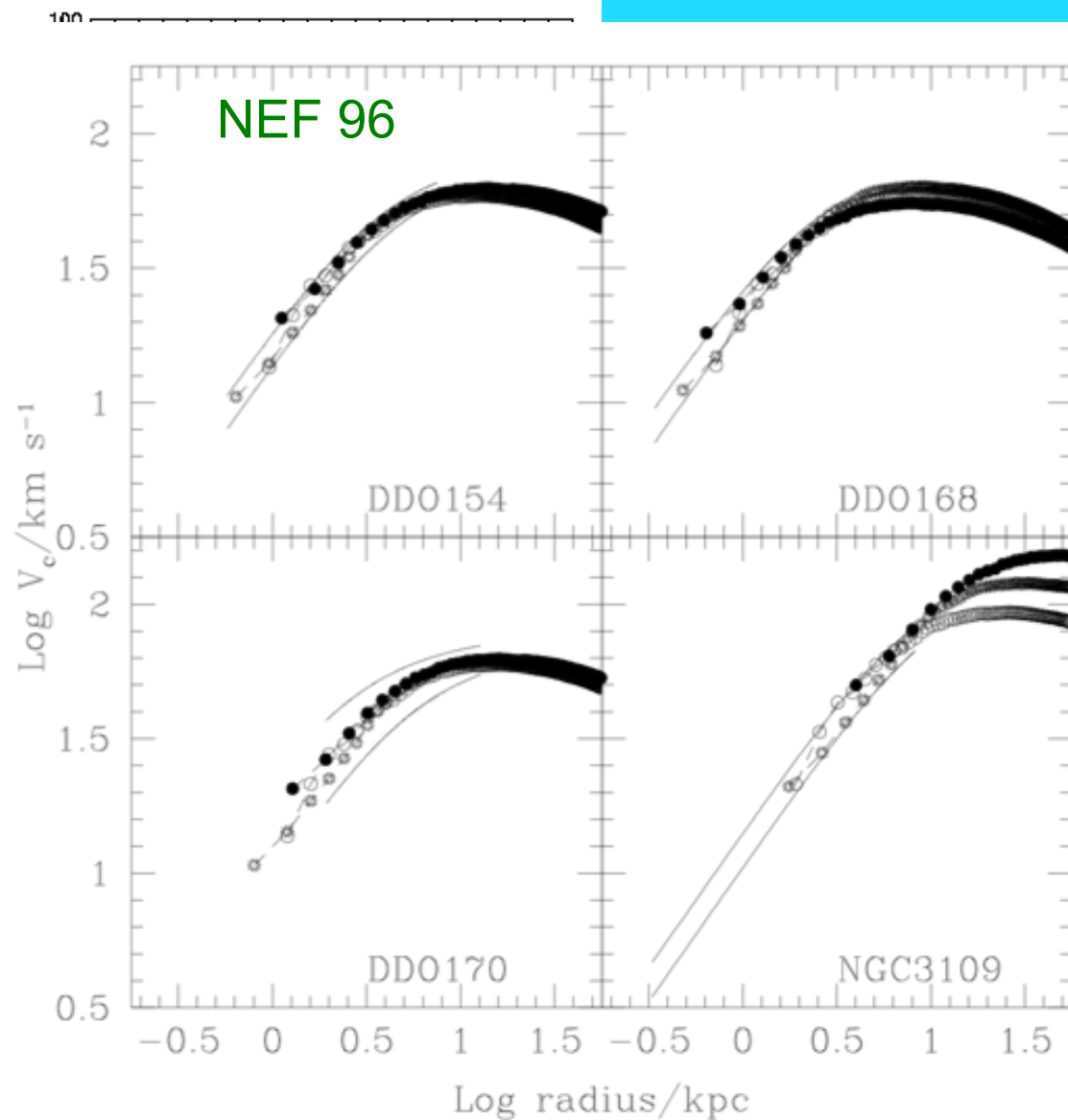
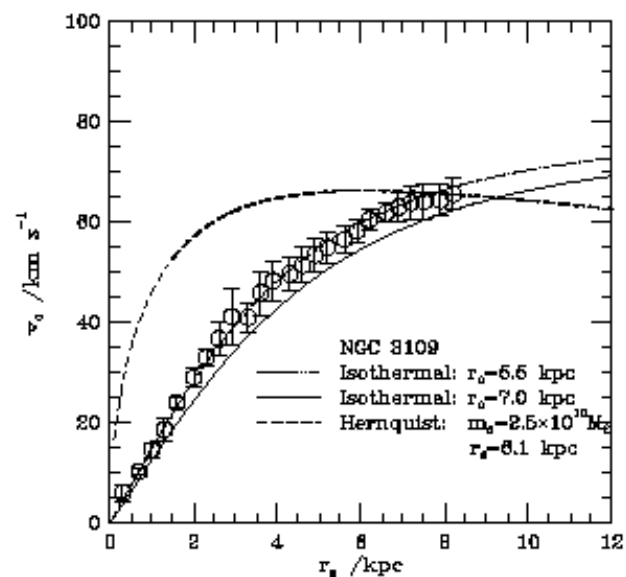
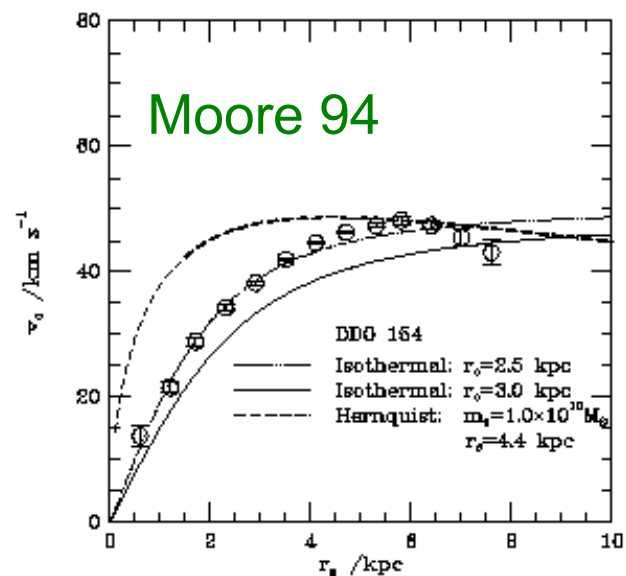


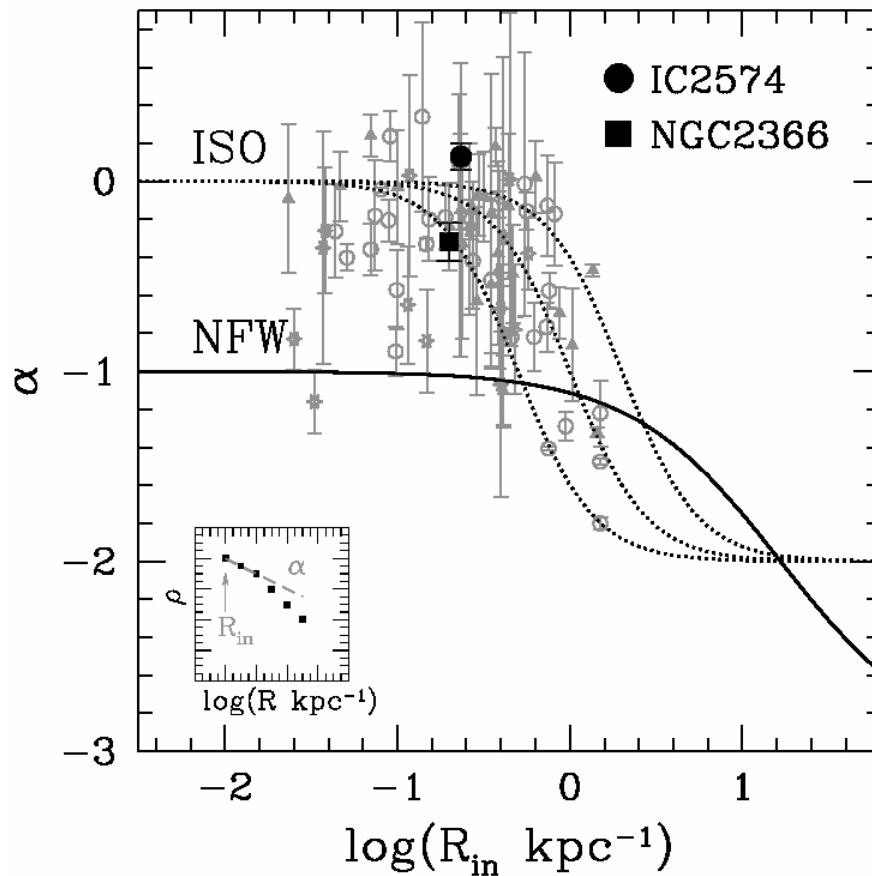
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{\text{disc}}=0.2$. (b) $M_{\text{disc}}=0.1$. (c) $M_{\text{disc}}=0.05$.

Cores in dwarf galaxies

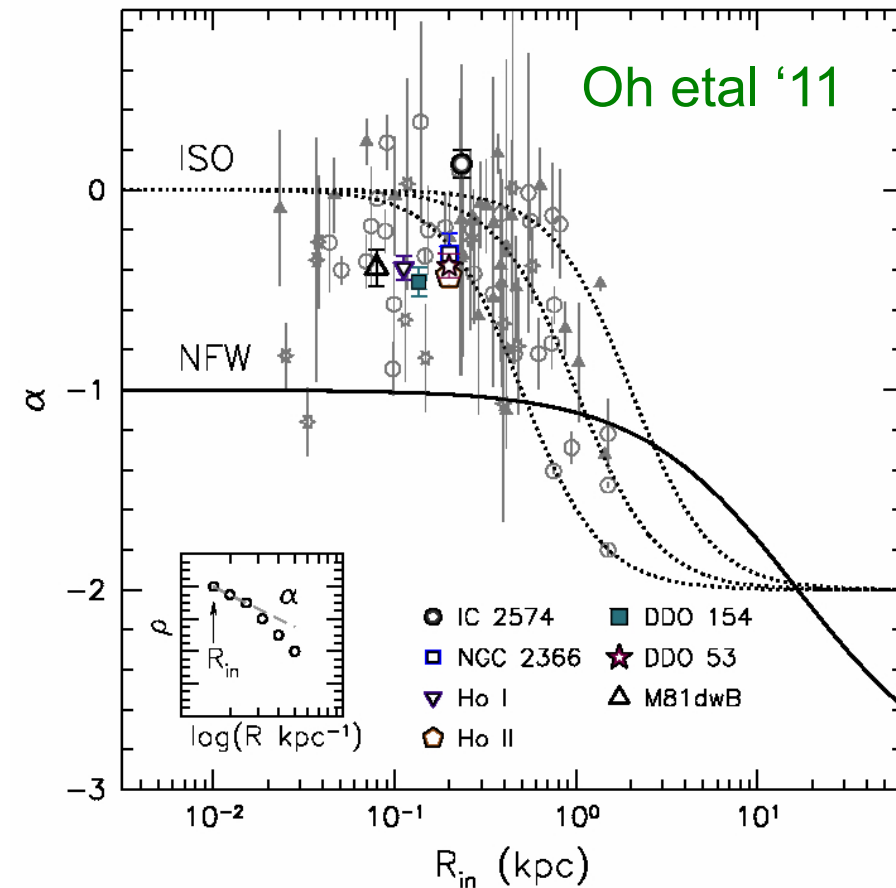


THINGS HI rotn curves of dwarfs

Oh et al '08



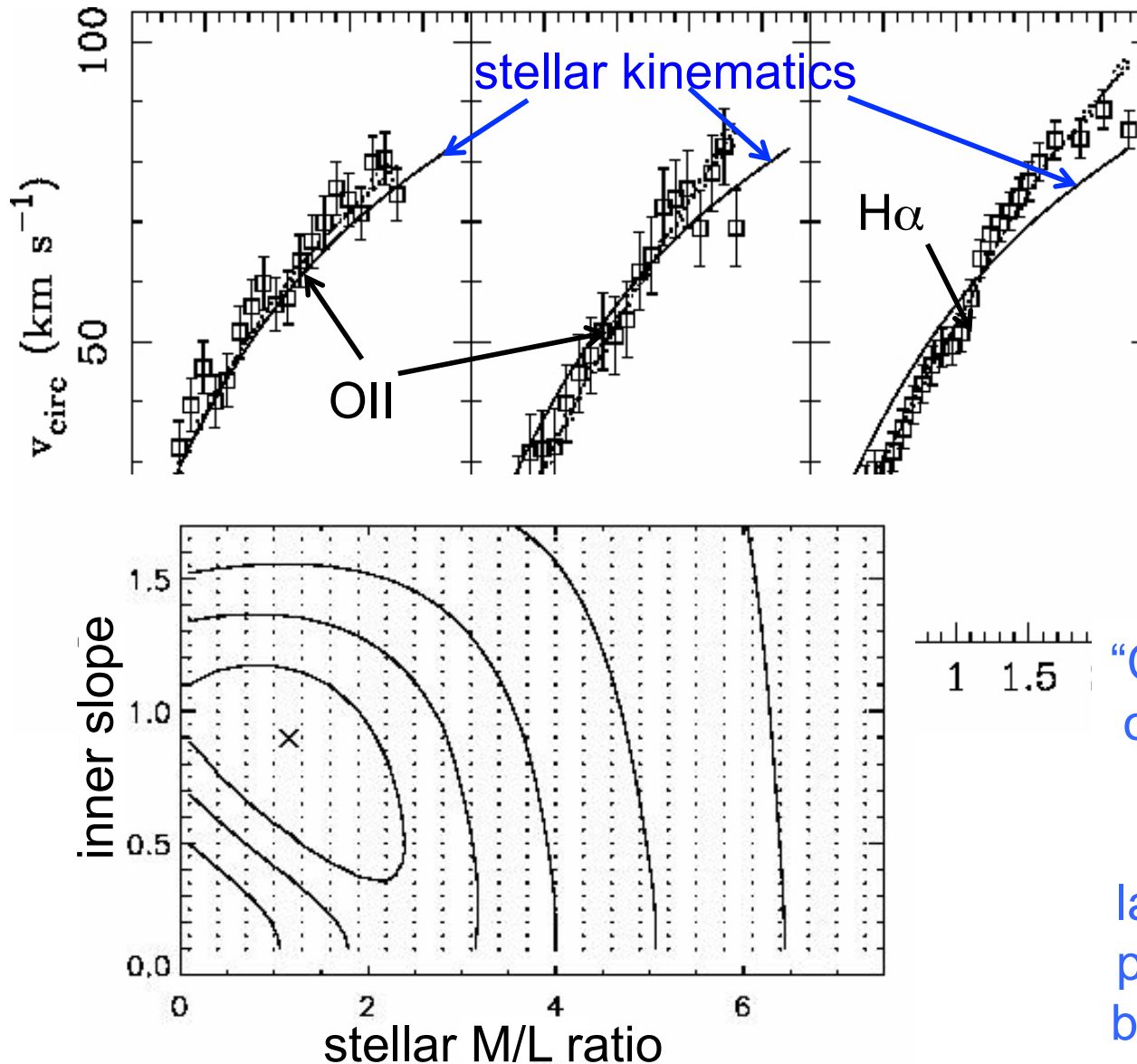
$$\rho(r) \propto r^\alpha (1 + r/r_s)^\beta$$



“We find discrepancies between the derived dark matter distributions ... and those of CDM simulations, even after corrections for non-circular motions ...”

The rotation curve of dwarf NGC 2976

Adams et al '13

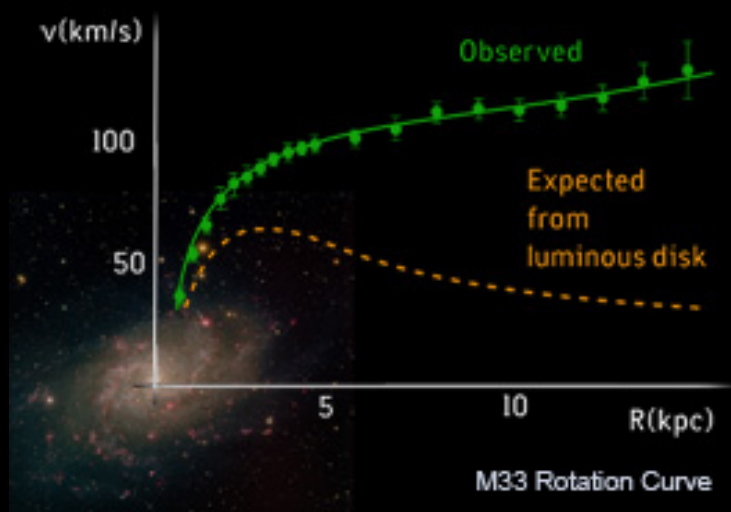
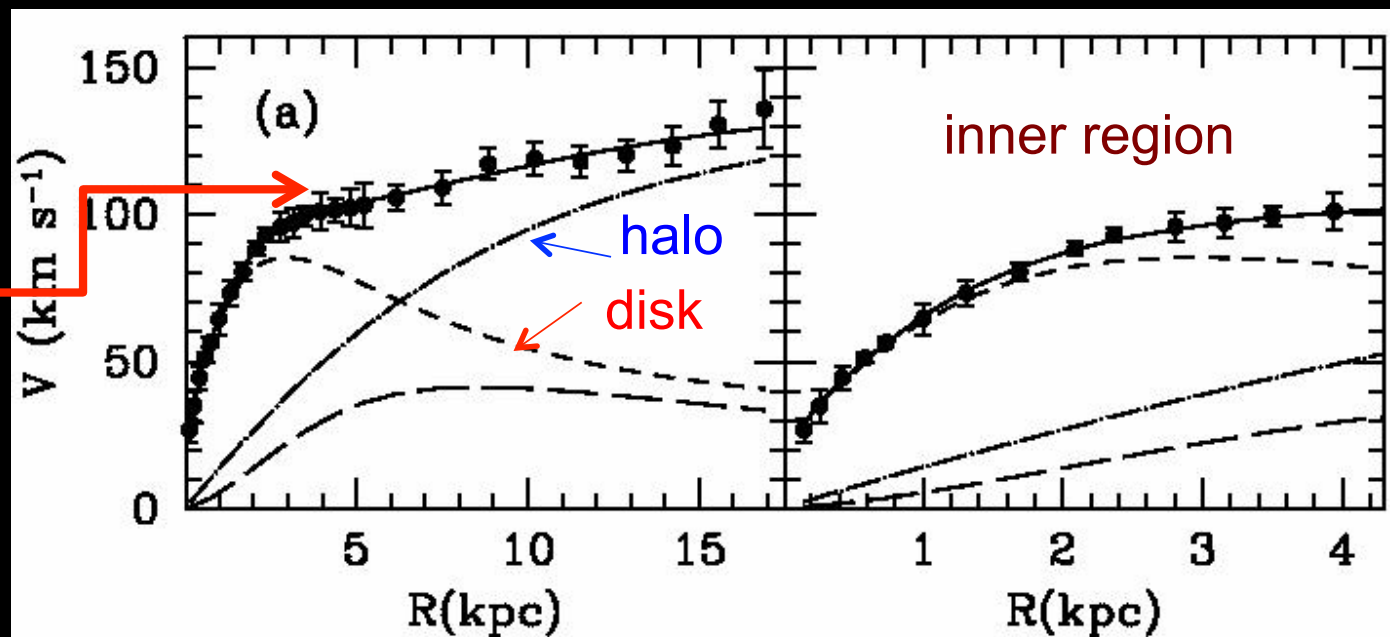


“This difference is likely due to the gas disk not meeting the assumptions that underlie the analysis such as no pressure support, a constant kinematic axis, and planar orbits.”

“Cored dark matter halo fits are only consistent with the stellar kinematics if the stellar mass-to-light ratio is significantly larger than derived from stellar population synthesis, while the best-fitting cuspy model has no such conflict”

The rotation curve of M33

halo with a core
(Burkert)



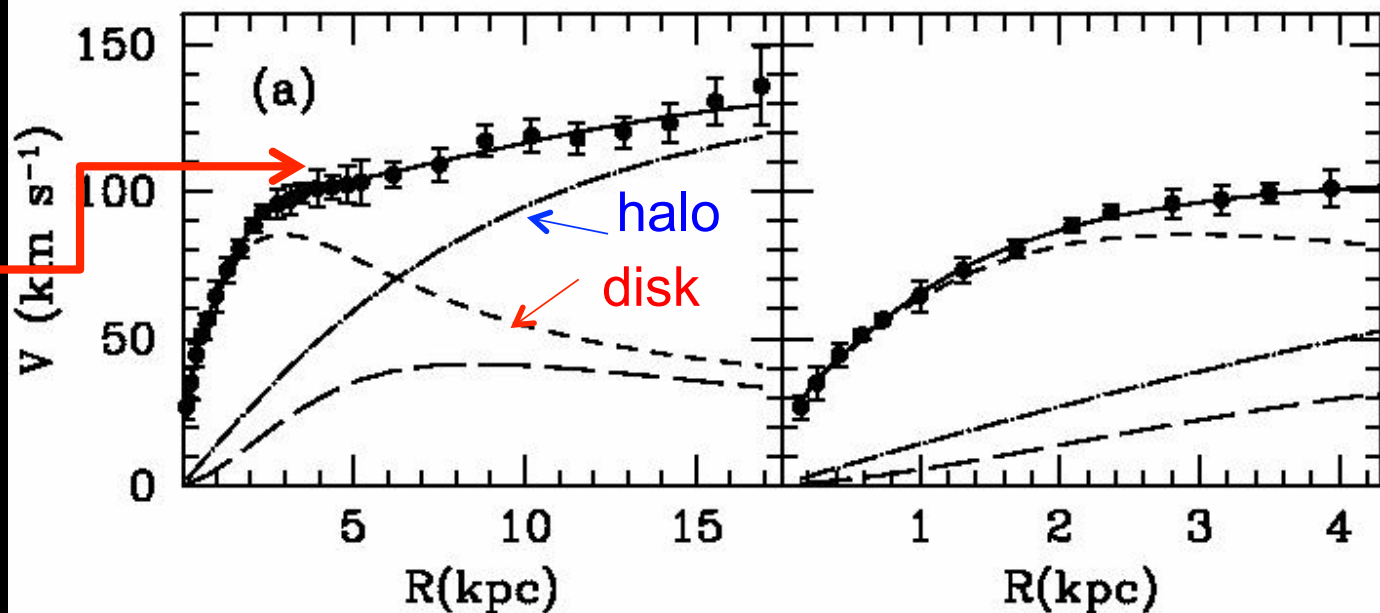
100pc – 17kpc
(dynamic range of 200)

Corbelli '03

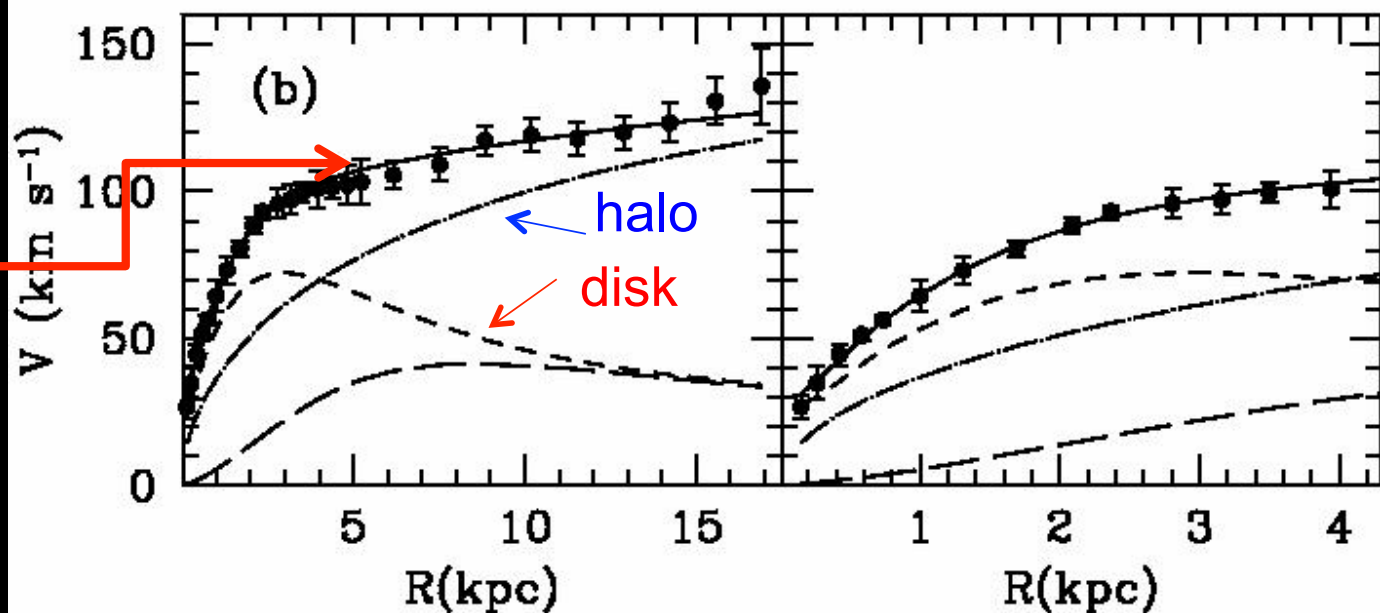


The rotation curve of M33

halo with a core
(Burkert)



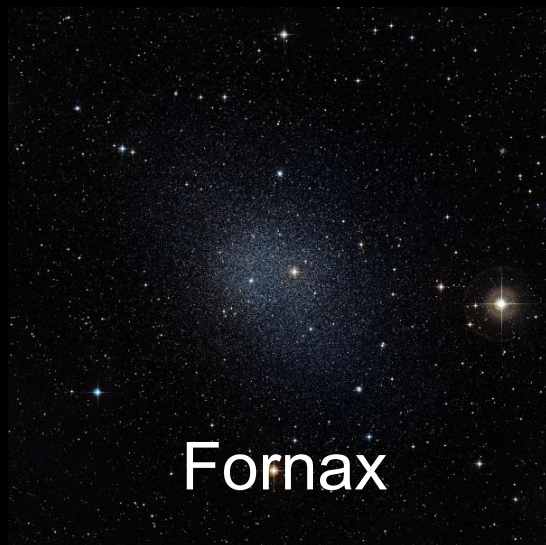
NFW halo



Corbelli '03



Dwarf galaxies around the Milky Way



Fornax



Sculptor



Leo I

© Anglo-Australian Observatory



Sextans



Carina



Sagittarius

The structure of dark matter halos

Dwarf sphs: cores or cusps?

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

stellar density profile

radial velocity dispersion

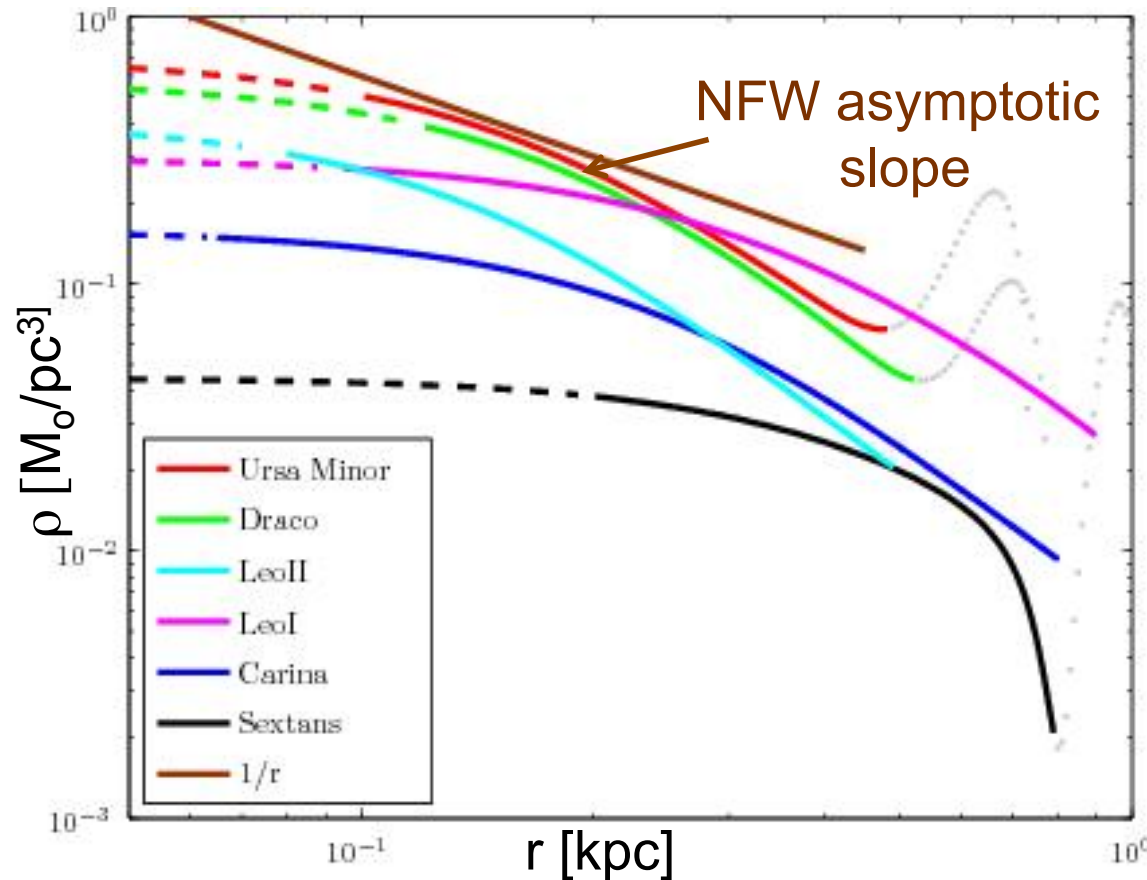
from Aquarius sim

vel. anisotropy

The DM halos of dwarf spheroidals

Gilmore et al '07

Inferred density profiles for 6 dwarf spheroidals



“...dark matter forms cored mass distributions, with a core scale length of greater than about 100pc...”



Dwarf galaxies around the Milky Way

A more rigorous analysis
(Strigari, Frenk & White '10)

Fornax

Sculptor

Leo I

© Anglo-Australian Observatory

Carina

Sextans

Sagittarius

Milky Way Dwarfs

Fit stellar surface density profile
with a 3D profile of the form:

$$\rho_*(r) \propto \frac{1}{x^a (1 + x^b)^{(c-a)/b}}$$

Jeans eqn:

$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

Milky Way Dwarfs

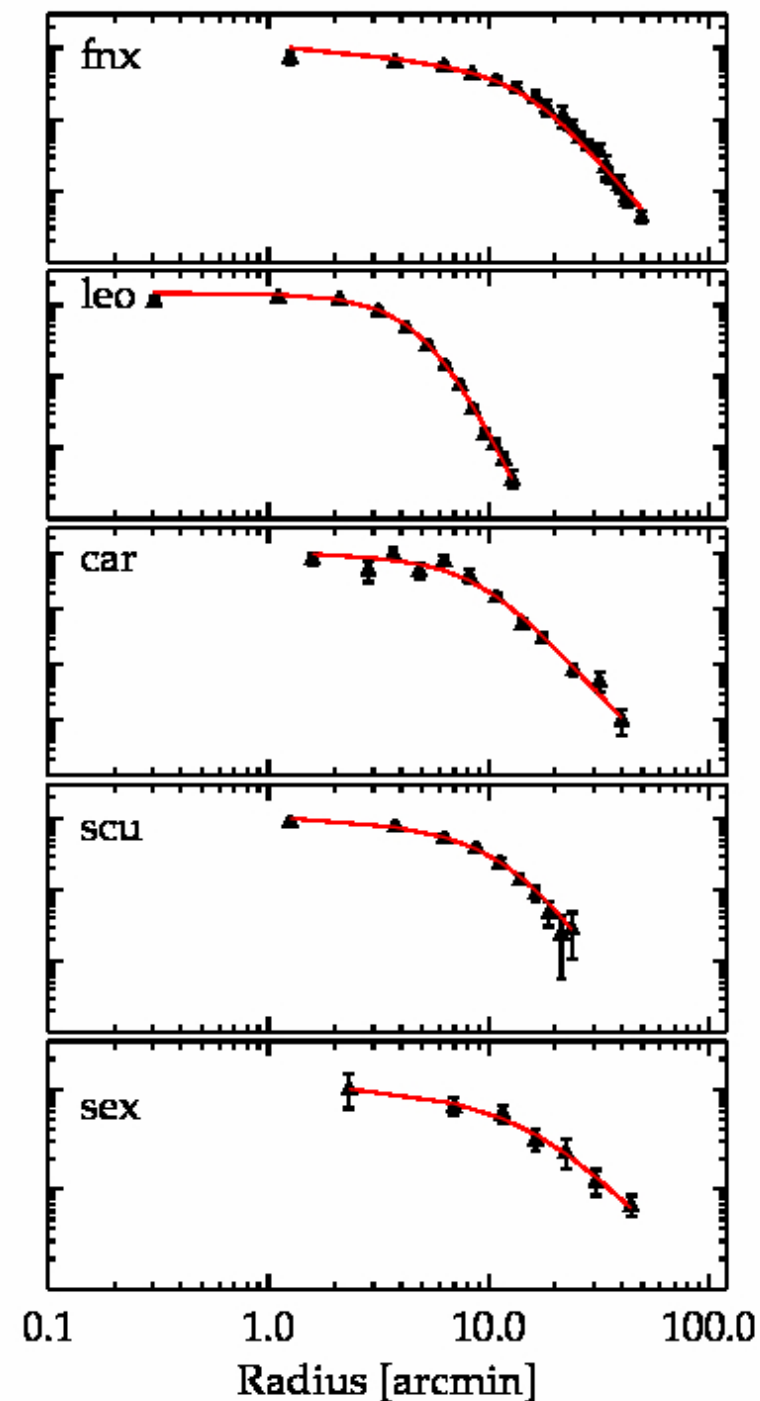
Fit stellar surface density profile with a 3D profile of the form:

$$\rho_*(r) \propto \frac{1}{x^a (1 + x^b)^{(c-a)/b}}$$

Satellite	a	χ^2 /d.o.f.
Fornax	1	1.0
Leo I	0	1.6
Carina	0.5	1.1
Sculptor	0.5	0.4
Sextans	0.5	01

Strigari, Frenk & White '10

Surface Density [Norm. arbitrary]



Dwarf sphs: cores or cusps?

Jeans eqn:

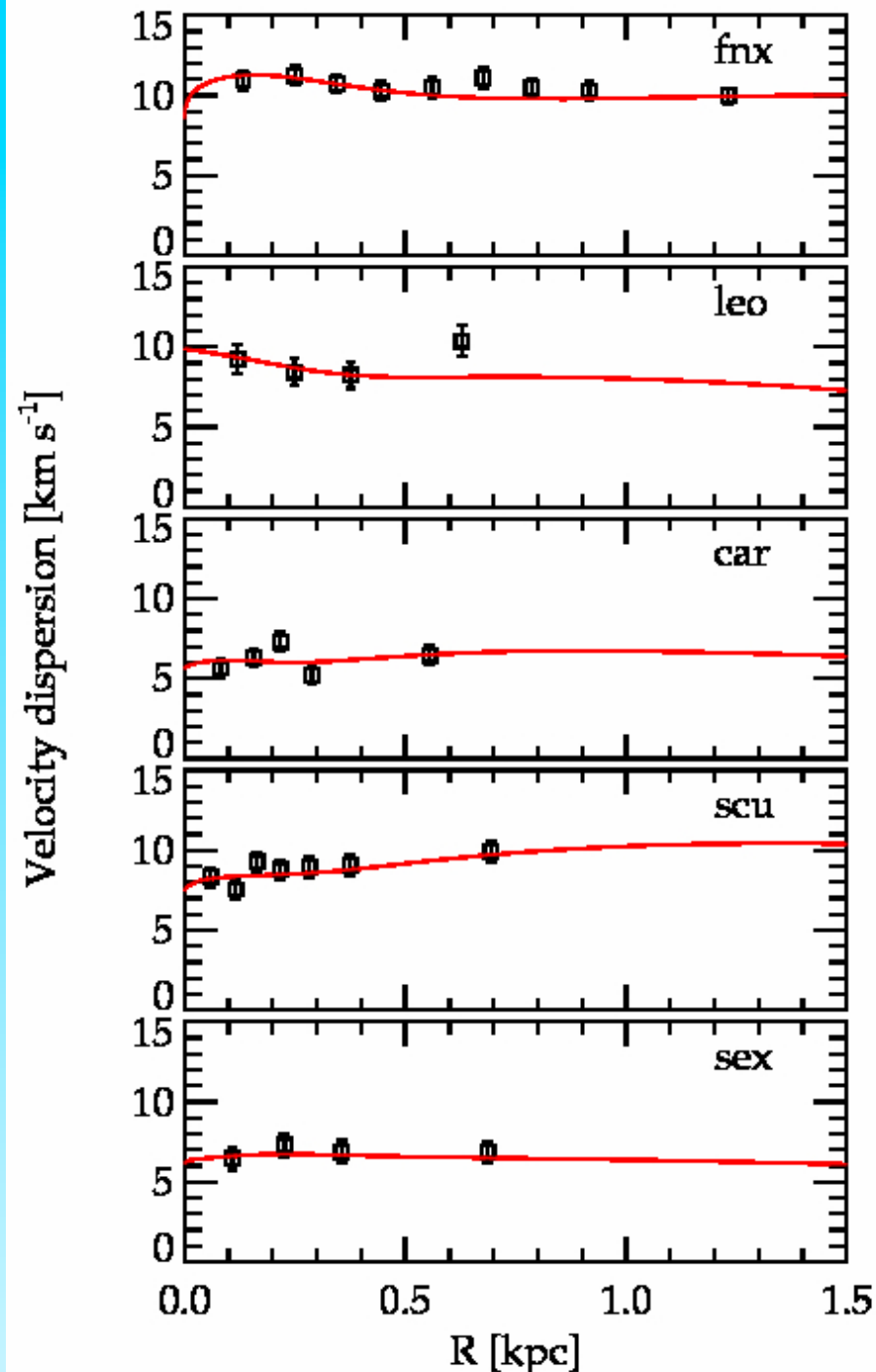
$$\frac{GM(r)}{r} = -\sigma_r^2 \left[\frac{d \ln \rho_*}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

from Aquarius sim

Cuspy!

vel. anisotropy

- Assume isotropic orbits
- Solve for $\sigma_r(r)$
- Compare with observed $\sigma_r(r)$
- Find “best fit” subhalo



Velocity distribution function

For $\beta = 0$, the distr. fn $f(\varepsilon)$ is known

$$f(\varepsilon) = \frac{1}{\sqrt{8\pi^2}} \int_{\varepsilon}^0 \frac{d^2 \rho_*}{d\Psi^2} \frac{d\Psi}{\sqrt{\Psi - \varepsilon}}$$

$$\varepsilon = \Psi(r) + v^2 / 2$$

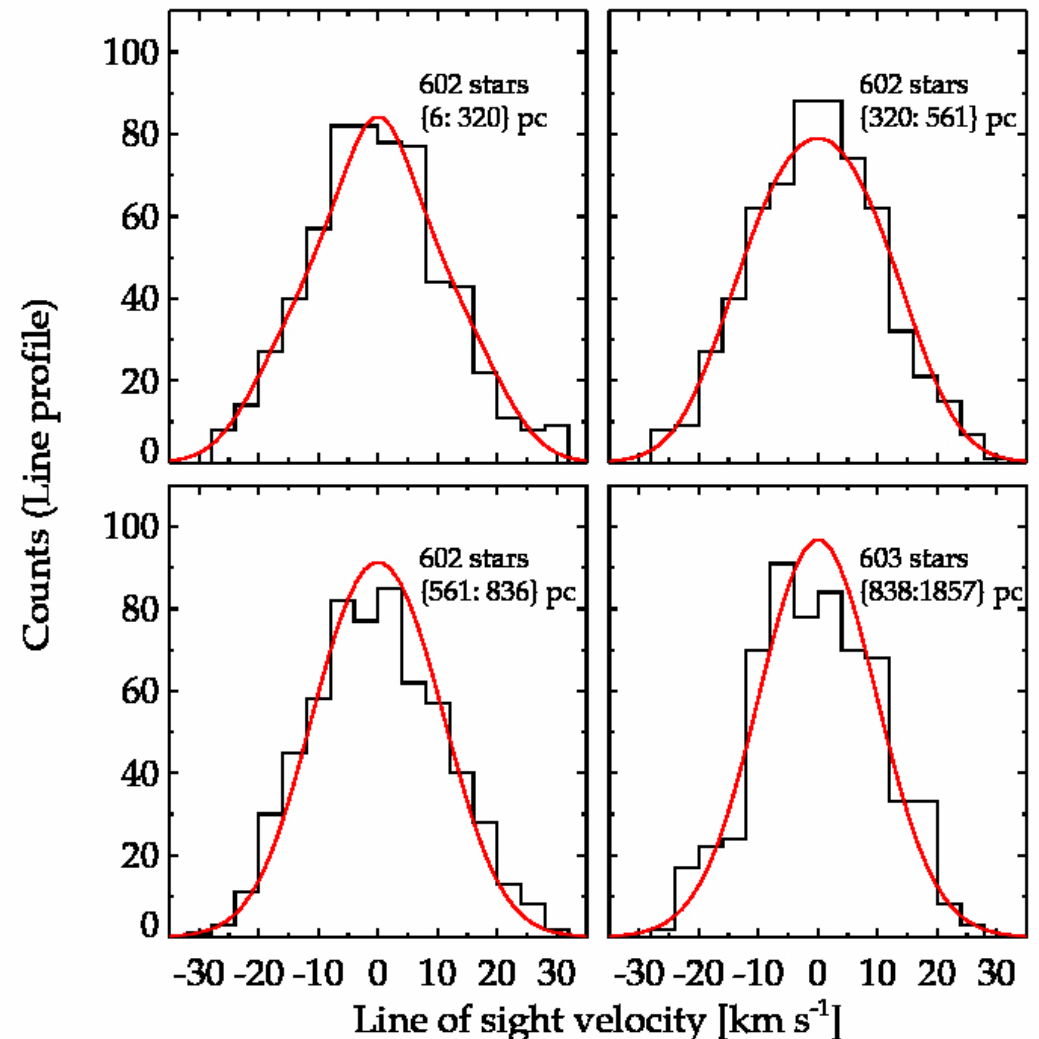
KS rejection probability ($\beta=0$)

Satellite	b1	b2	b3	b4
Fornax	0.95	0.85	.997	0.98
Leo I	0.54	0.48	0.69	.997
Carina	0.49	0.56	0.71	0.66
Sculptor	0.68	0.32	0.38	0.33
Sextans	0.59	0.19	0.97	0.03

Strigari, Frenk & White 2010

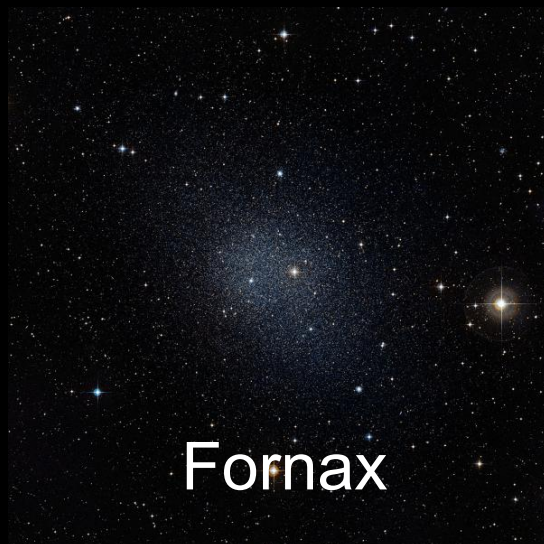
4 radial bins

Fornax

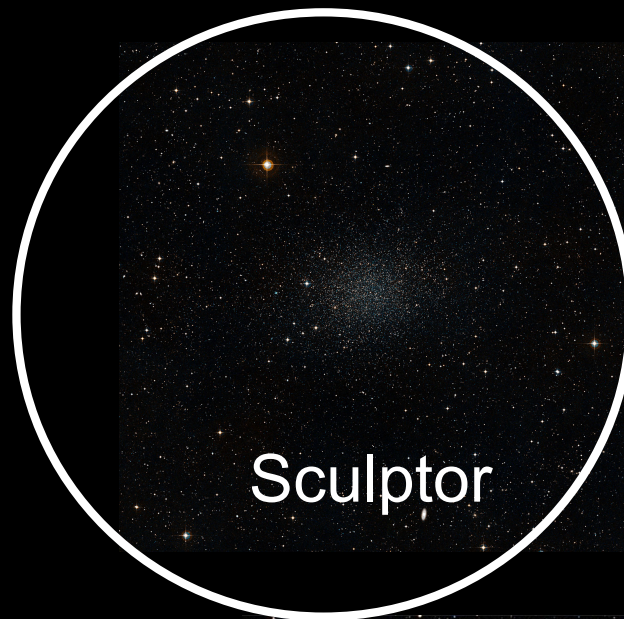




Dwarf galaxies around the Milky Way



Fornax



Sculptor



Leo I

© Anglo-Australian Observatory



Sextans



Carina



Sagittarius

The DM halo of the Sculptor dwarf

Sculptor has two stellar pops:

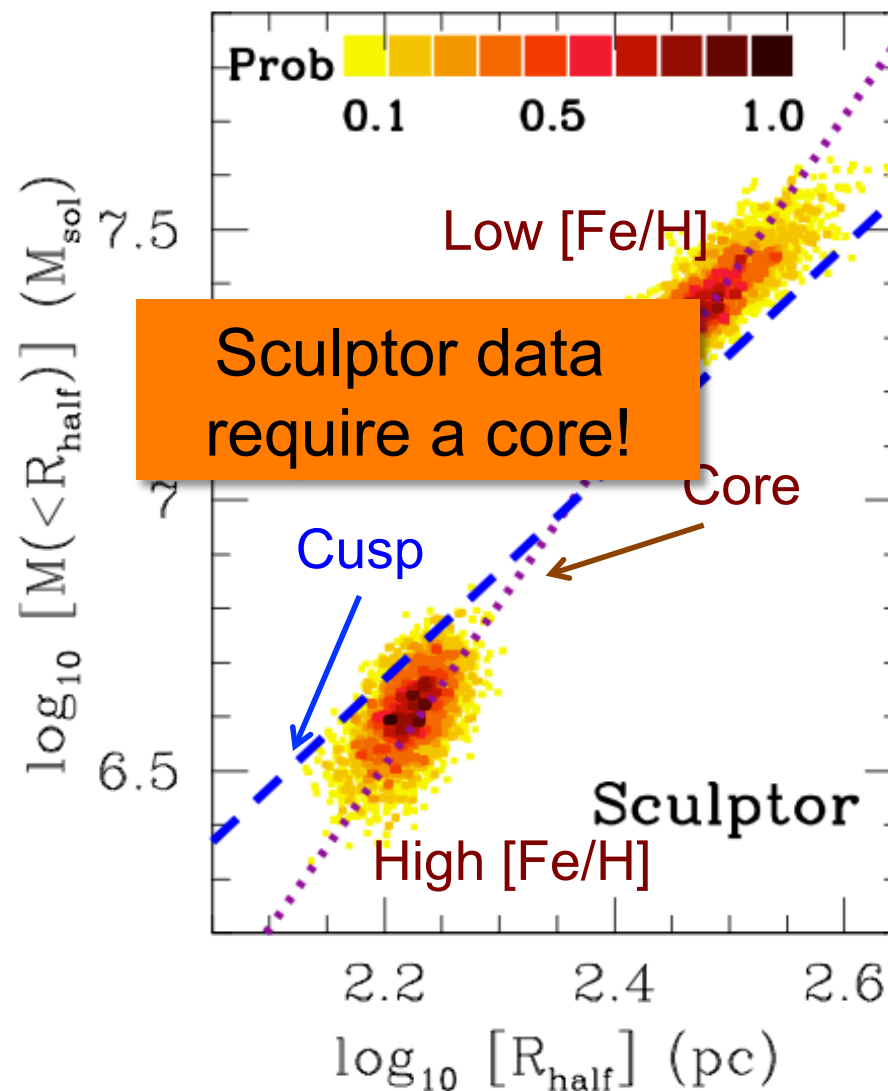
(i) centrally concentrated,
high [Fe/H]

(ii) extended, low [Fe/H]

$$M(< r) = \mu \frac{r < \sigma_{los}^2 >}{G}$$

Wolf et al '10; Walker '10 →

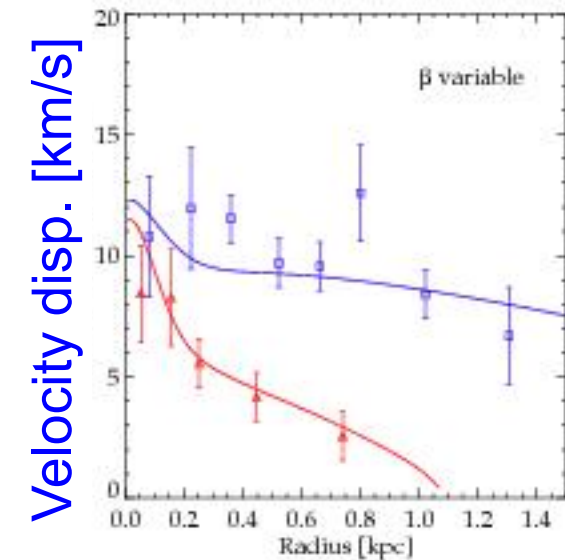
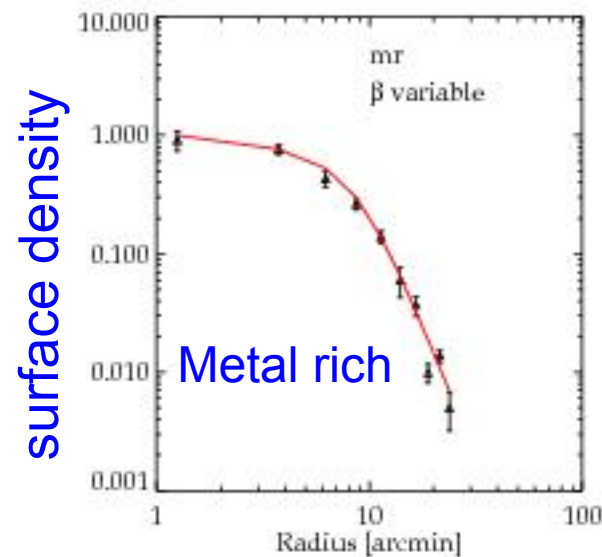
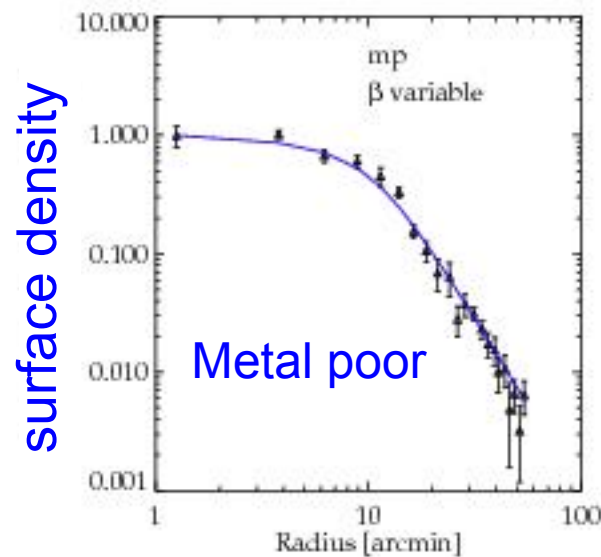
if $r=r_{1/2}$, $\mu=2.5$, independently of
model assumptions!



The DM halo of the Sculptor dwarf

Strigari, Frenk & White '13

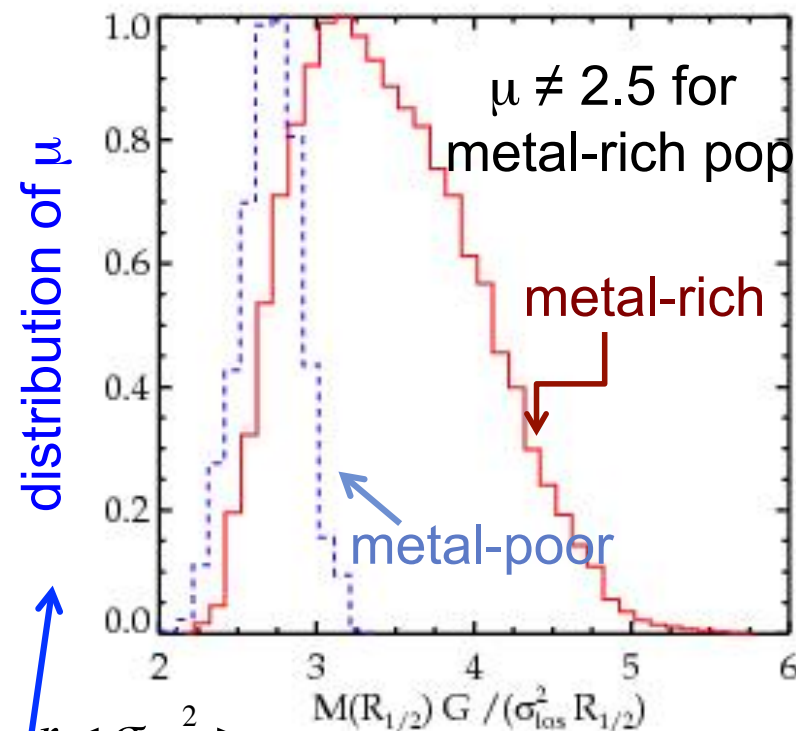
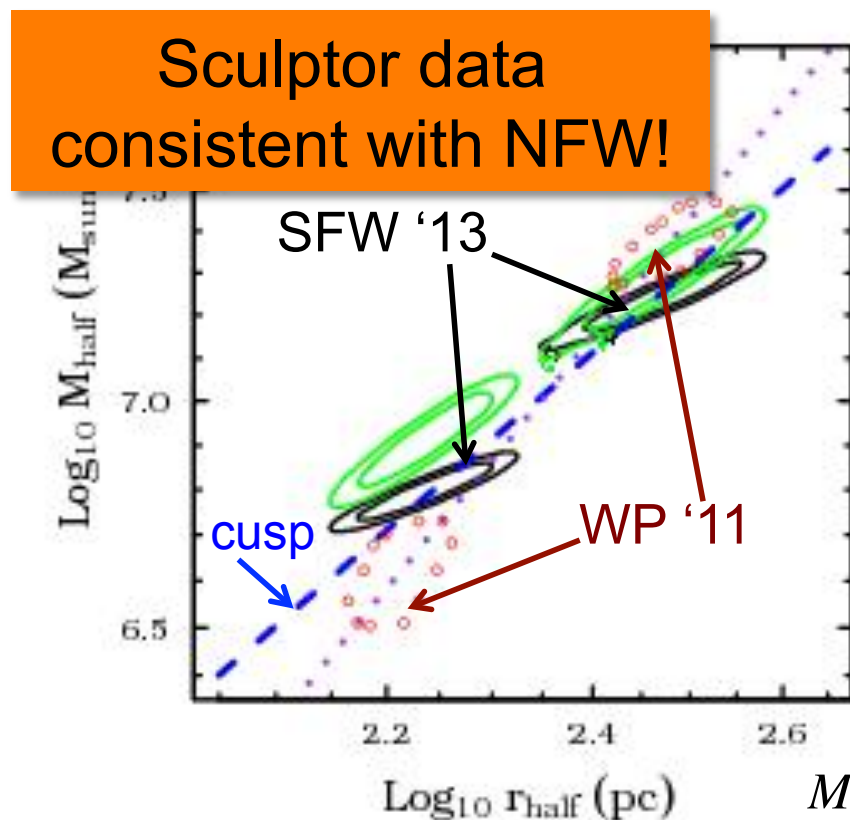
When sufficiently general models for $\rho_*(r)$, $\sigma(r)$ are considered, do Sculptor data require a core or could they be consistent with NFW?



The DM halo of the Sculptor dwarf

Strigari, Frenk & White '13

When sufficiently general models for $\rho_*(r)$, $\sigma(r)$ are considered, are the Sculptor data consistent with NFW?



$$M(< r) = \mu \frac{r < \sigma_{\text{los}}^2 >}{G}$$

A Cold dark matter universe

“Cuspy” density profiles

Does nature have them?

Best places to look:

{ Clusters (good diagnostics)
Dwarf gals (high M/L)

Galaxy clusters: X-ray and lensing data

Evidence seems to favour NFW cusps

Dwarf galaxies: Gas kinematics, stellar kinematics

When sufficiently general models are considered, even best data cannot distinguish cores from NFW cusps

The cosmic power spectrum: from the CMB to the 2dFGRS

Free streaming →

$$\lambda_{\text{cut}} \propto m_x^{-1}$$

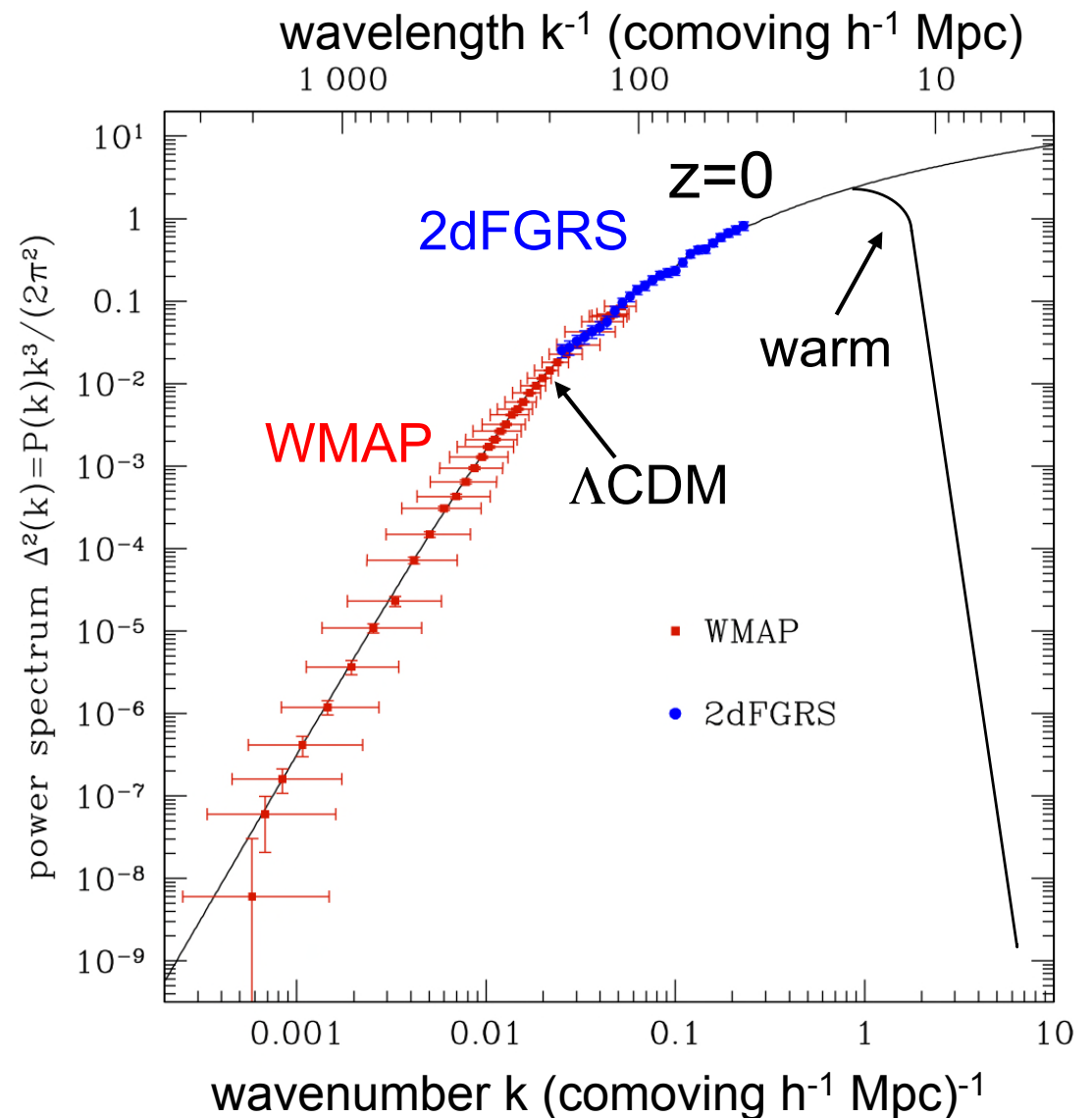
for thermal relic

$$m_{\text{CDM}} \sim 100 \text{ GeV}$$

$$\text{susy}; M_{\text{cut}} \sim 10^{-6} M_{\odot}$$

$$m_{\text{WDM}} \sim \text{few keV}$$

$$\text{sterile } \nu; M_{\text{cut}} \sim 10^9 M_{\odot}$$





The neutrino minimal standard model

Sterile neutrino detection possible

Decay line in X-rays

- Neutrino Minimal Standard Model (ν MSM) proposed to explain neutrino masses (Asaka & Shaposhnikov, '05)
- Adds three **sterile neutrinos** to the SM. The lightest of these would be the **dark matter**



Constellation X





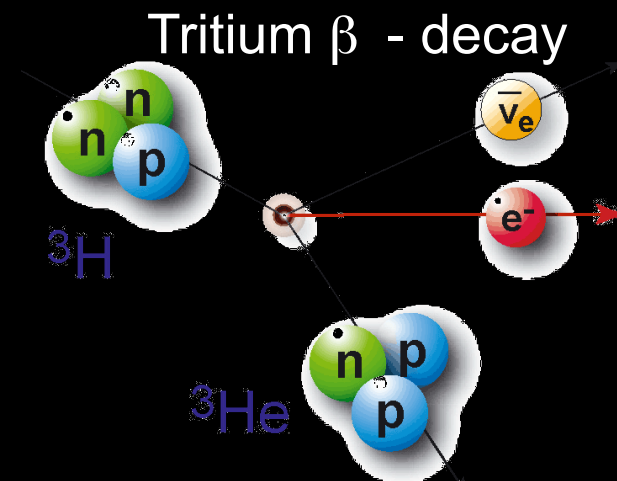
The neutrino minimal standard model

Sterile neutrino detection possible

Decay line in X-rays



Constellation X





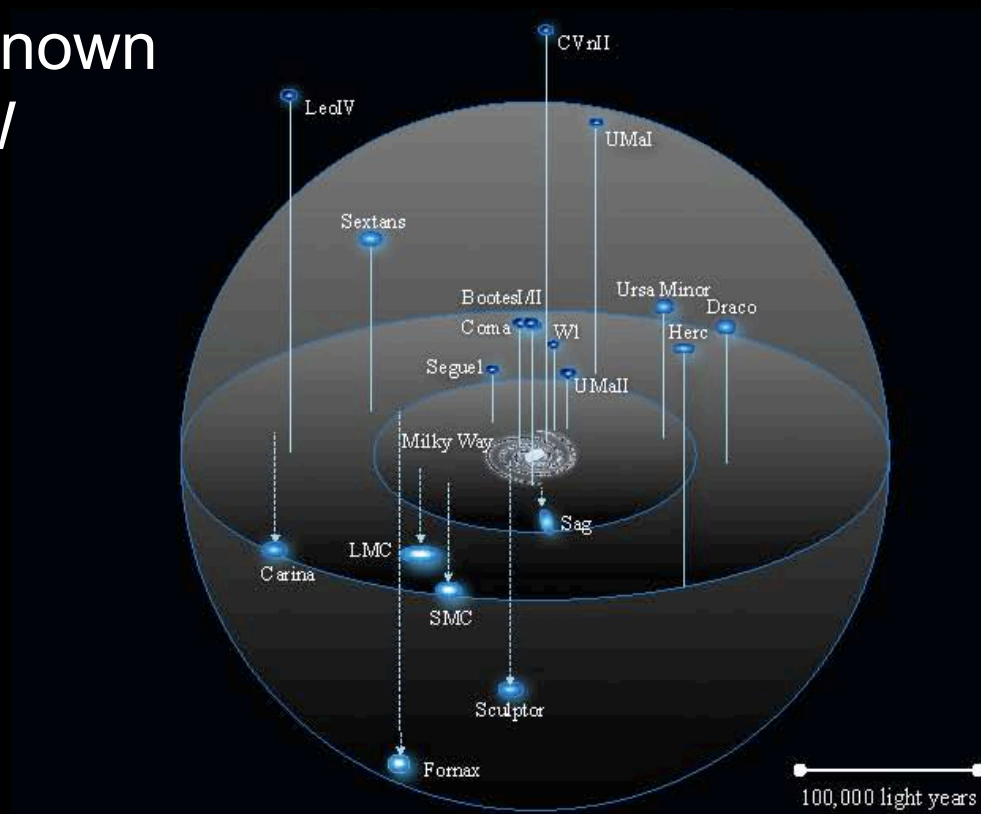
Astrophysical key to identity of dark matter:

→ Subgalactic scales

(strongly non-linear)

The satellites of the Milky Way

~25 satellites known
in the MW

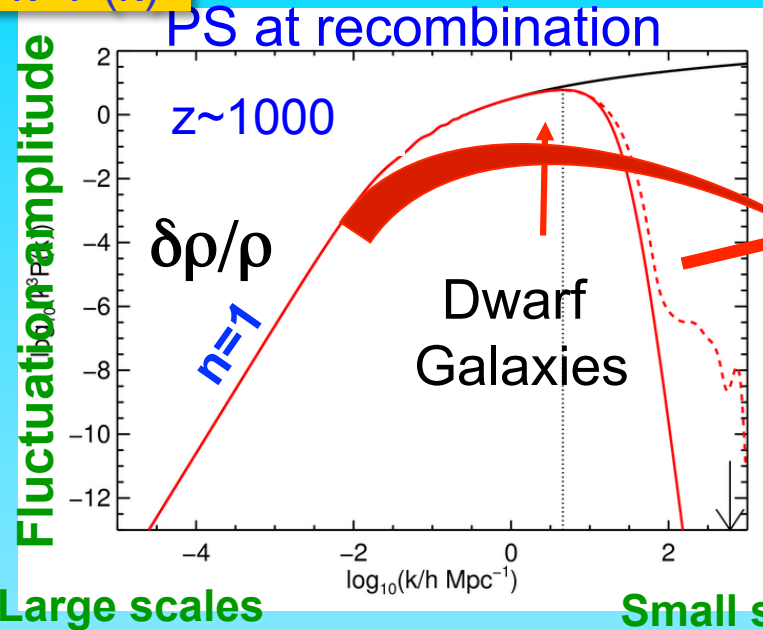




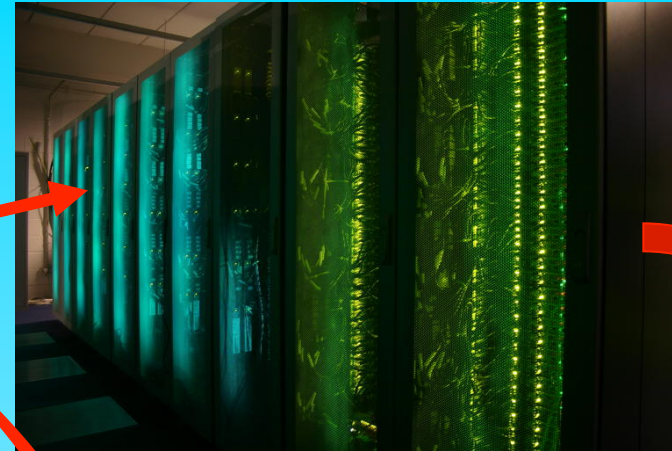
University of Durham

The formation of cosmic structure

$k^3 P(k)$



“Cosmology machine”



$t=380,000$ yrs

$\delta\rho/\rho \sim 10^{-5}$

Simulations

Supercomputer **simulations** are the best technique for calculating how small **primordial perturbations** grow into **galaxies** today



$t=14.1$ billion yrs

$\delta\rho/\rho \sim 1-10^6$

Institute for Computational Cosmology

$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

The image shows a dark, textured field of purple and black, representing a simulated galaxy at a very early stage. The texture is grainy and noisy, with some faint, irregular patterns of slightly lighter purple. In the top left corner, the text 'z = 48.4' is displayed. In the top right corner, the text 'T = 0.05 Gyr' is displayed. At the bottom center, there is a horizontal scale bar with vertical end caps, and the text '500 kpc' is written below it.



Cold Dark Matter

Warm Dark Matter

13.4 billion years ago

cold dark matter

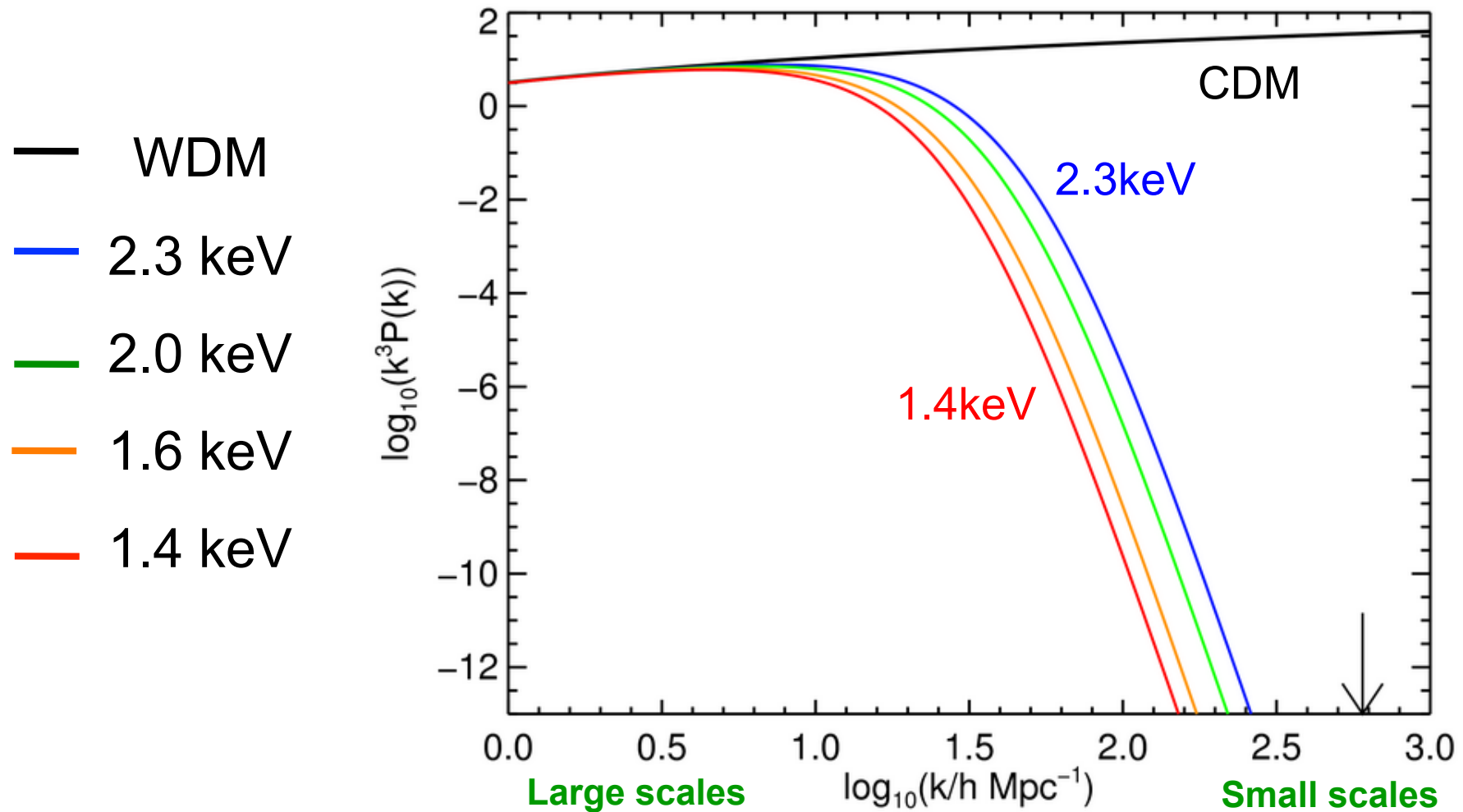
warm dark matter



Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
BoyarSKI & Ruchayskiy '12

Warm DM: different ν mass

The linear power spectrum (“power per octave”)





Warm DM: different ν mass

$z=3$

WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV

CDM

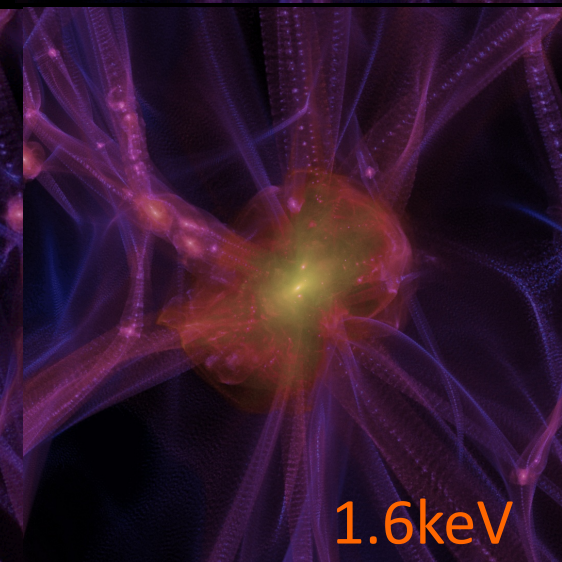
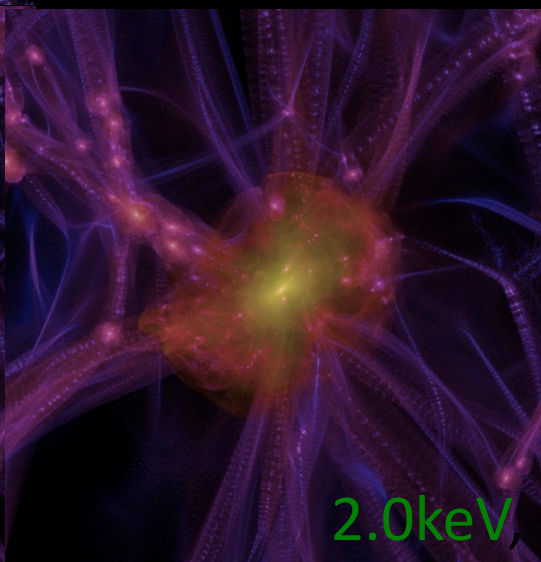
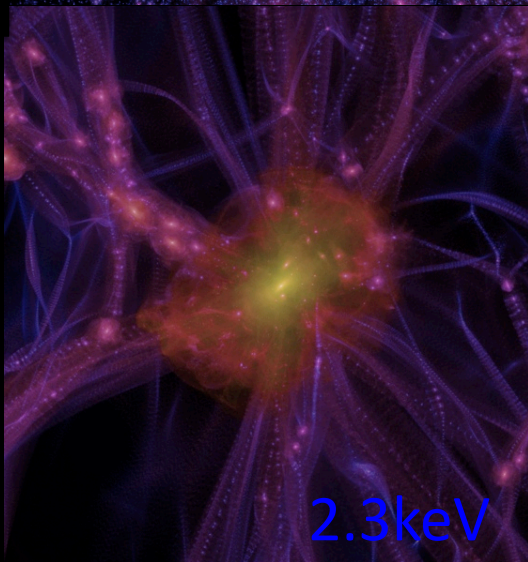
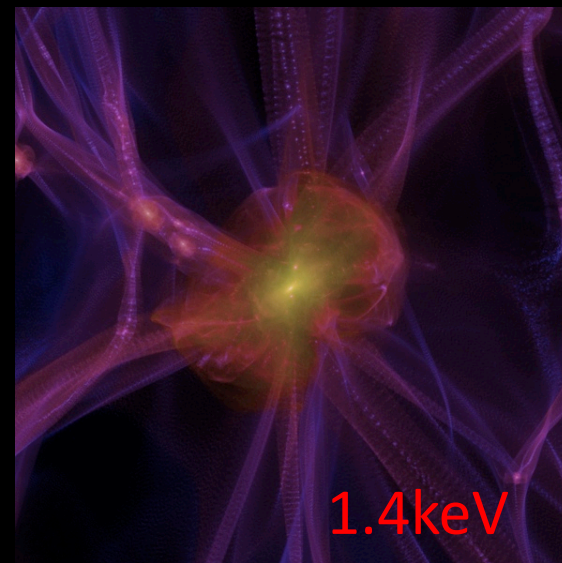
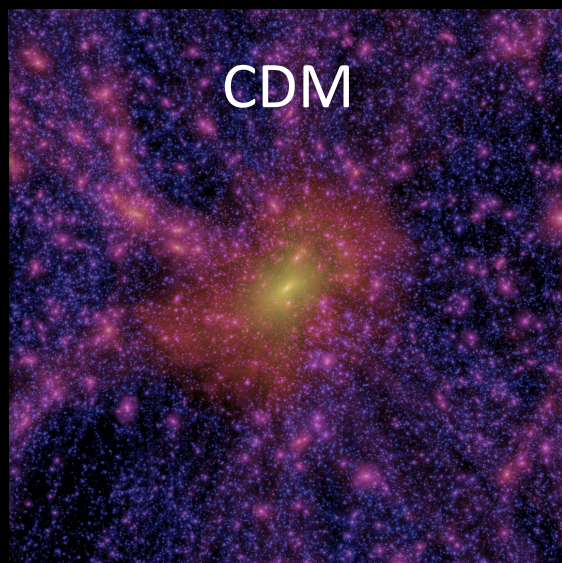
WDM

1.4keV

2.3keV

2.0keV

1.6keV



N-body simulations: CDM vs WDM

Simulations make 2 important predictions on galactic scales:

Cold dark matter

- Large number of self-bound substructures (**10% of mass**) survive
- The main halo and its subhalos have “cuspy” density profiles

Warm dark matter

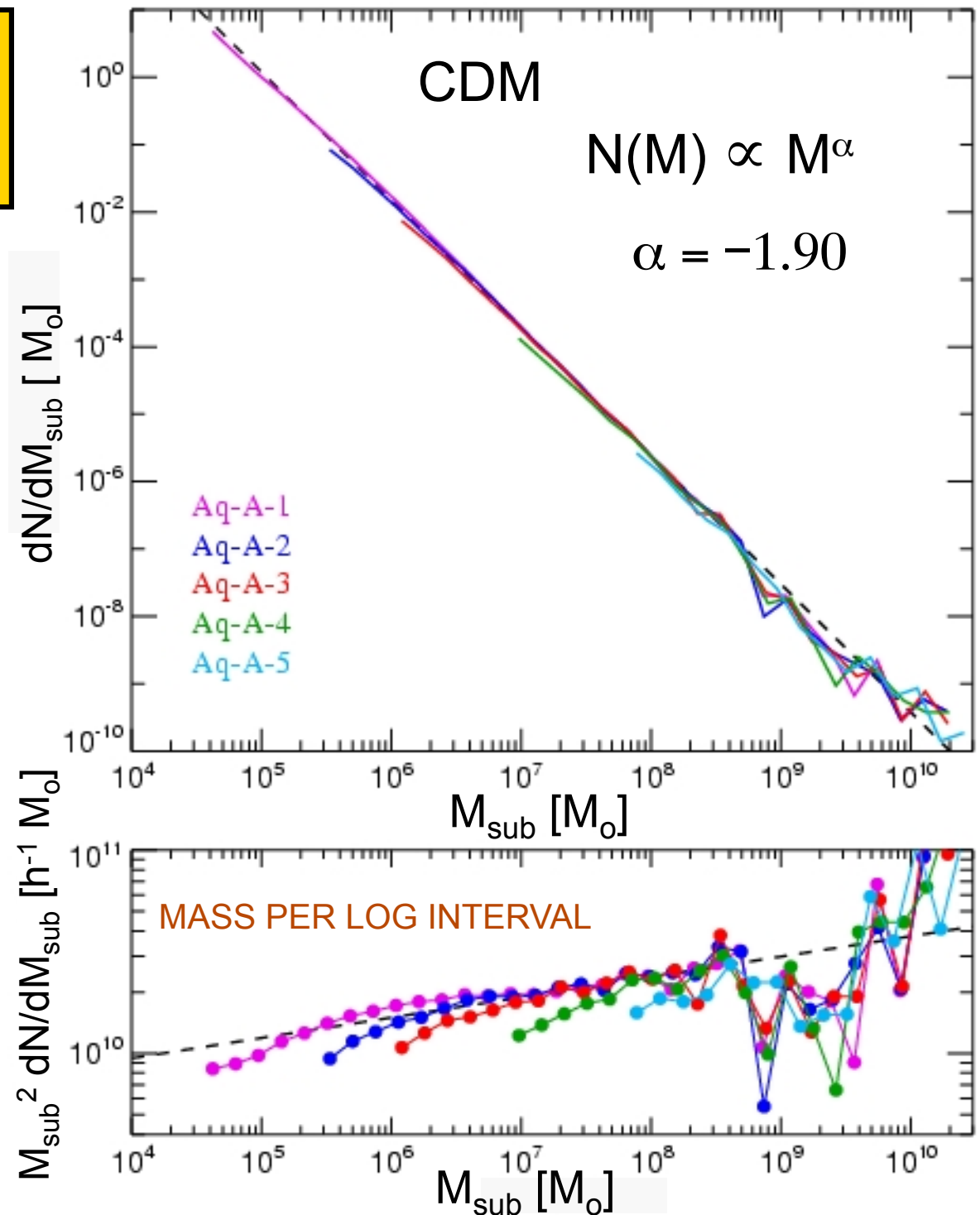
- Far fewer self-bound substructures (**5% of mass**) survive
- Main halo profile identical to CDM; subhalos still “cuspy” but less concentrated than in CDM

The mass function of substructures

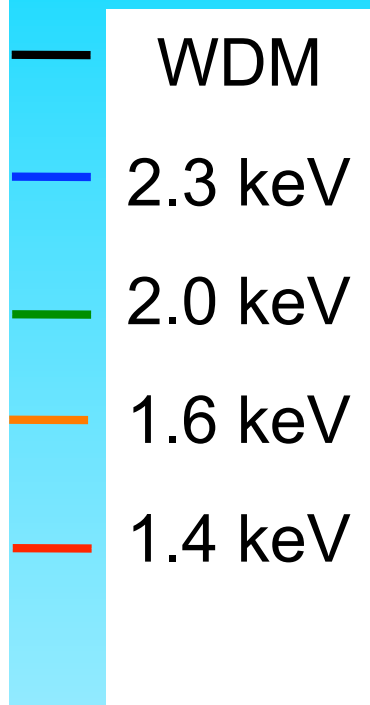
The subhalo mass function is **shallower** than M^2

- **Most** of the substructure **mass** is in the few **most massive** halos
- The total **mass** in substructures **converges** well even for moderate resolution

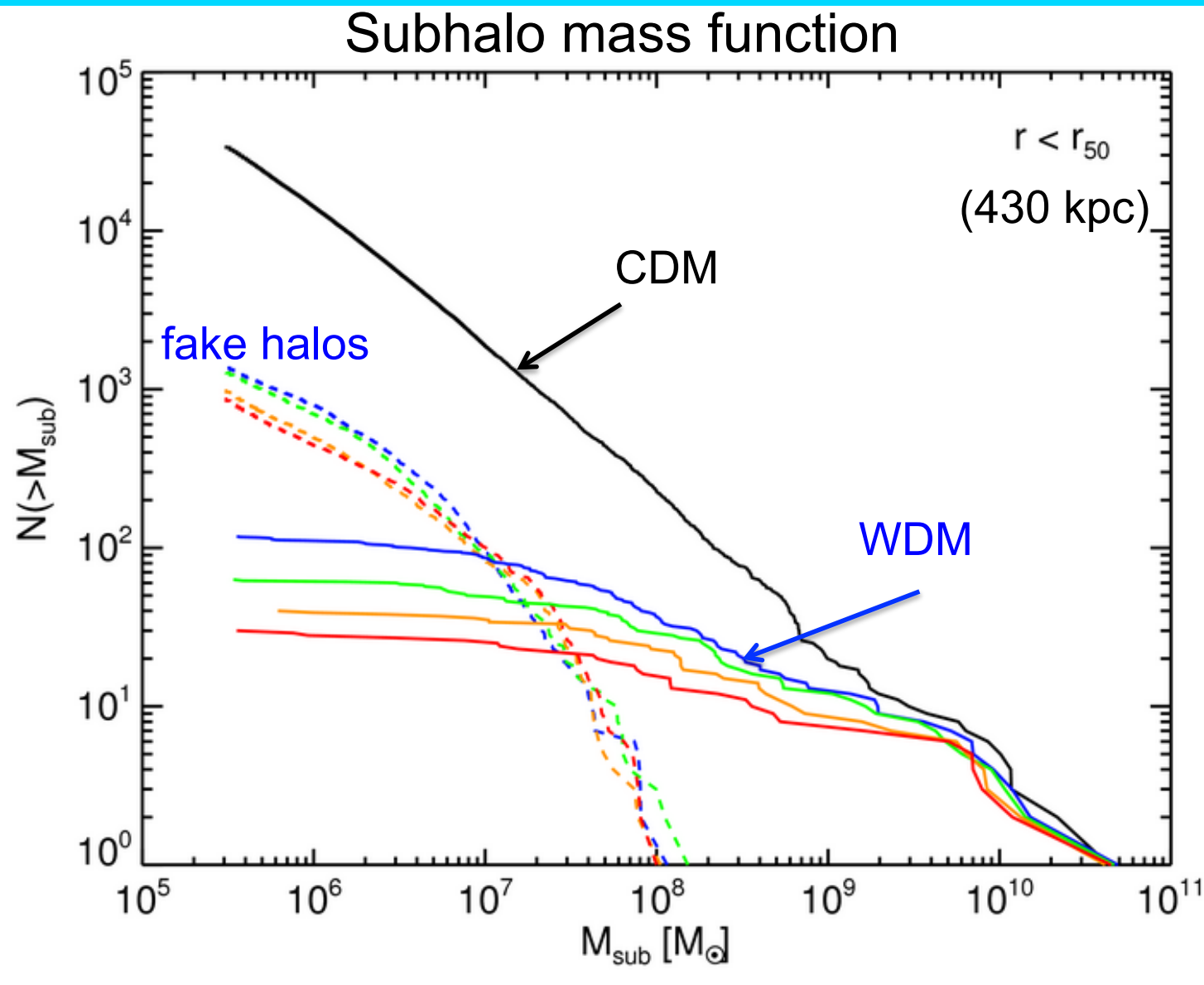
Virgo consortium '08



The mass function of substructures



No of suhalos
 ↗ with m_{WDM}





Subhalo density profiles

CDM & WDM
subhalos have
cuspy profiles

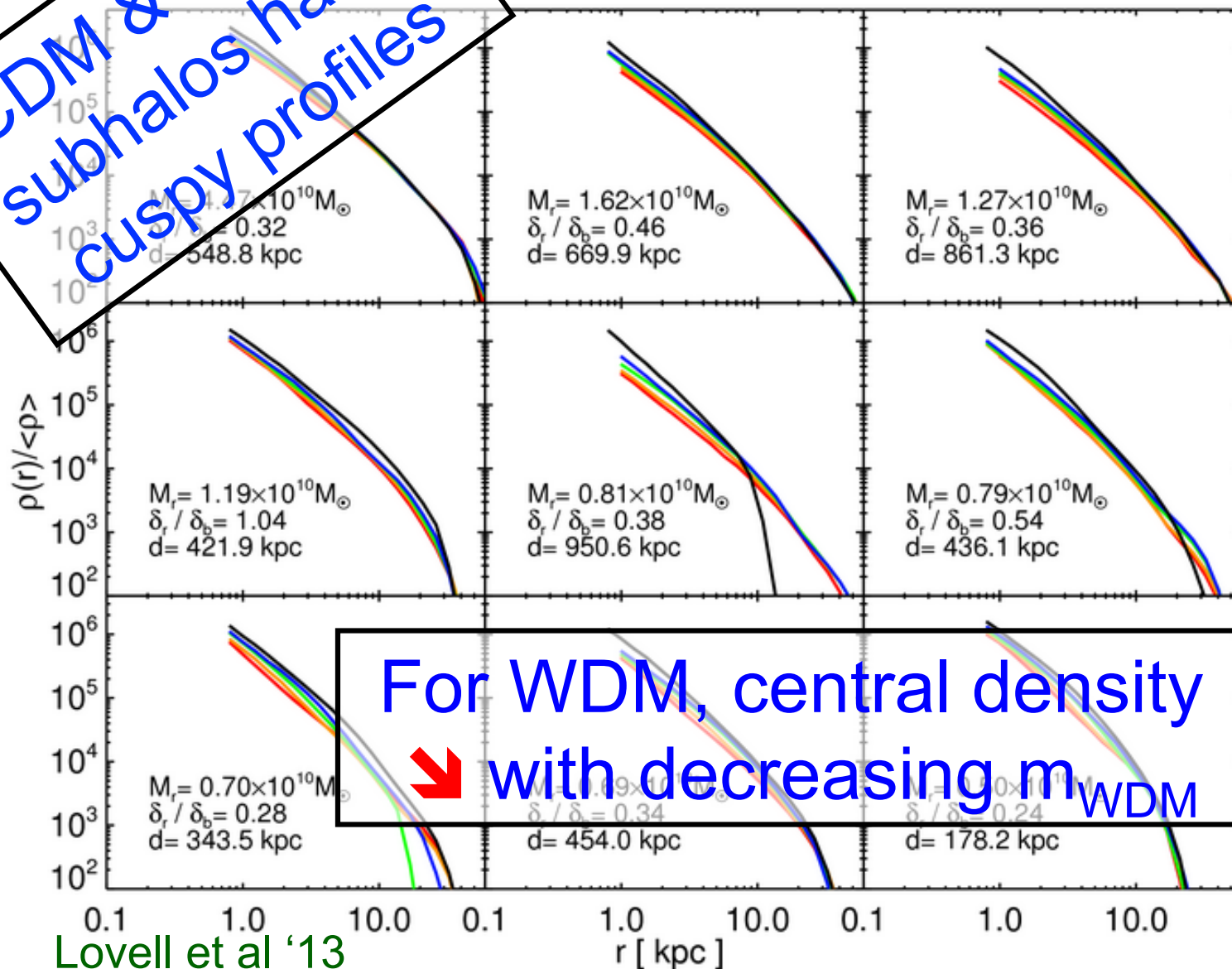
WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV



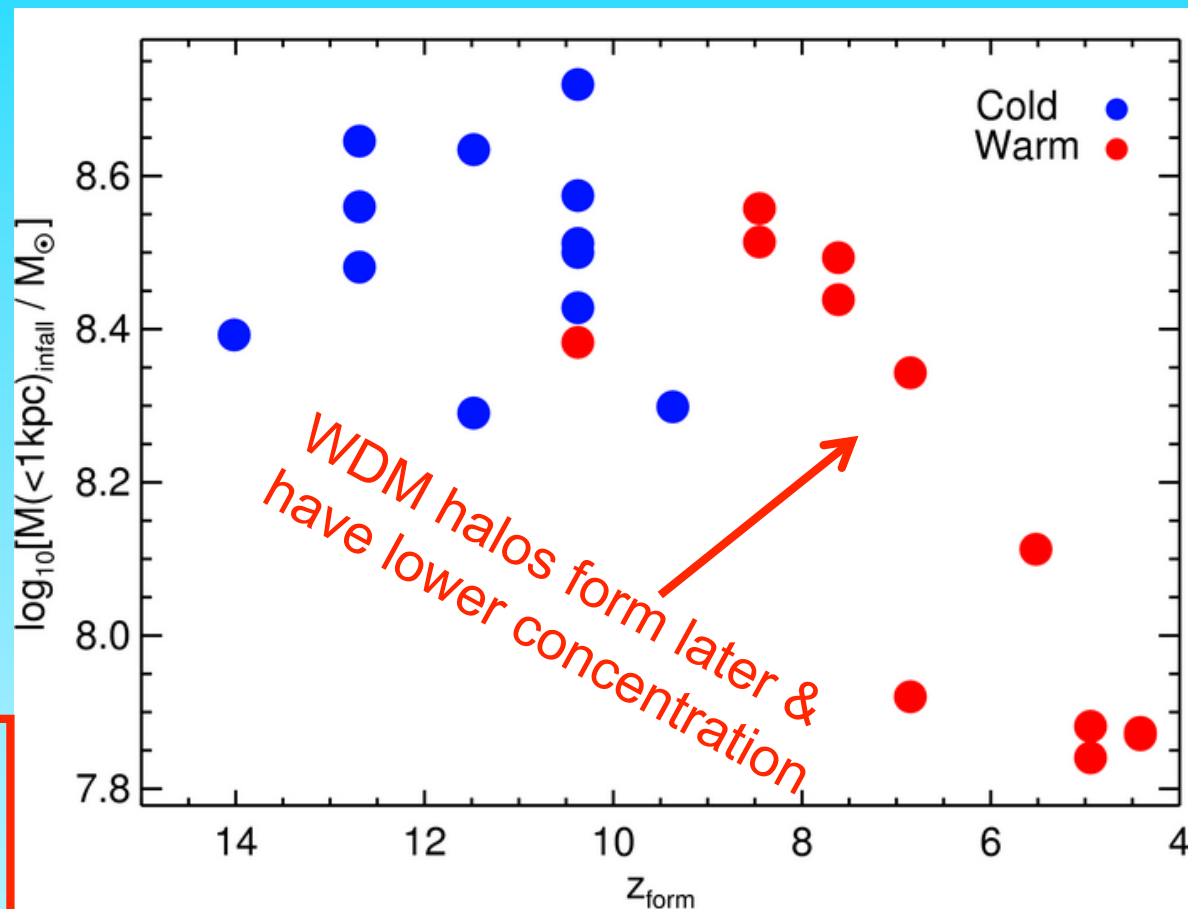
Warm vs cold dark matter subhalos

“Formation redshift” →
 z at which M_{halo} first
 exceeded $M_{\text{infall}}(<1\text{kpc})$

WDM halos form later
 & have lower central
 masses than their
 CDM counterparts!



WDM subhalos are still
 cuspy but are less
 concentrated than CDM
 subhalos



Lovell, Eke, Frenk, Gao, Jenkins et al '11



How can we distinguish between CDM & WDM ?



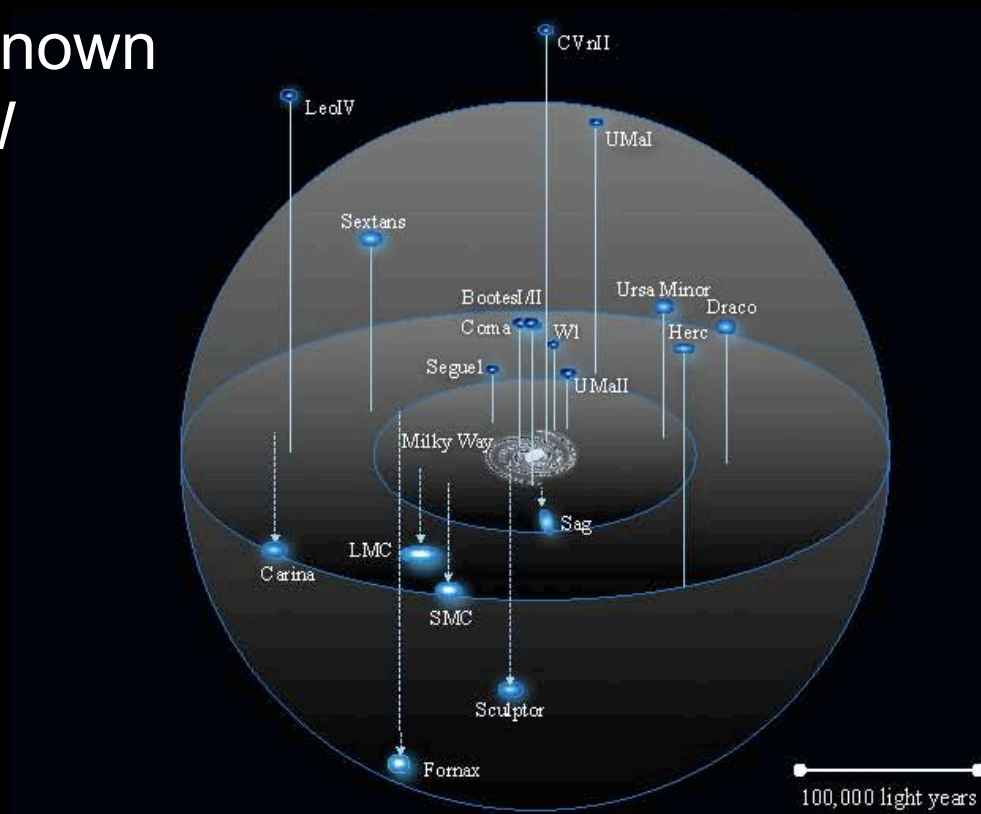
Cosmology on small scales

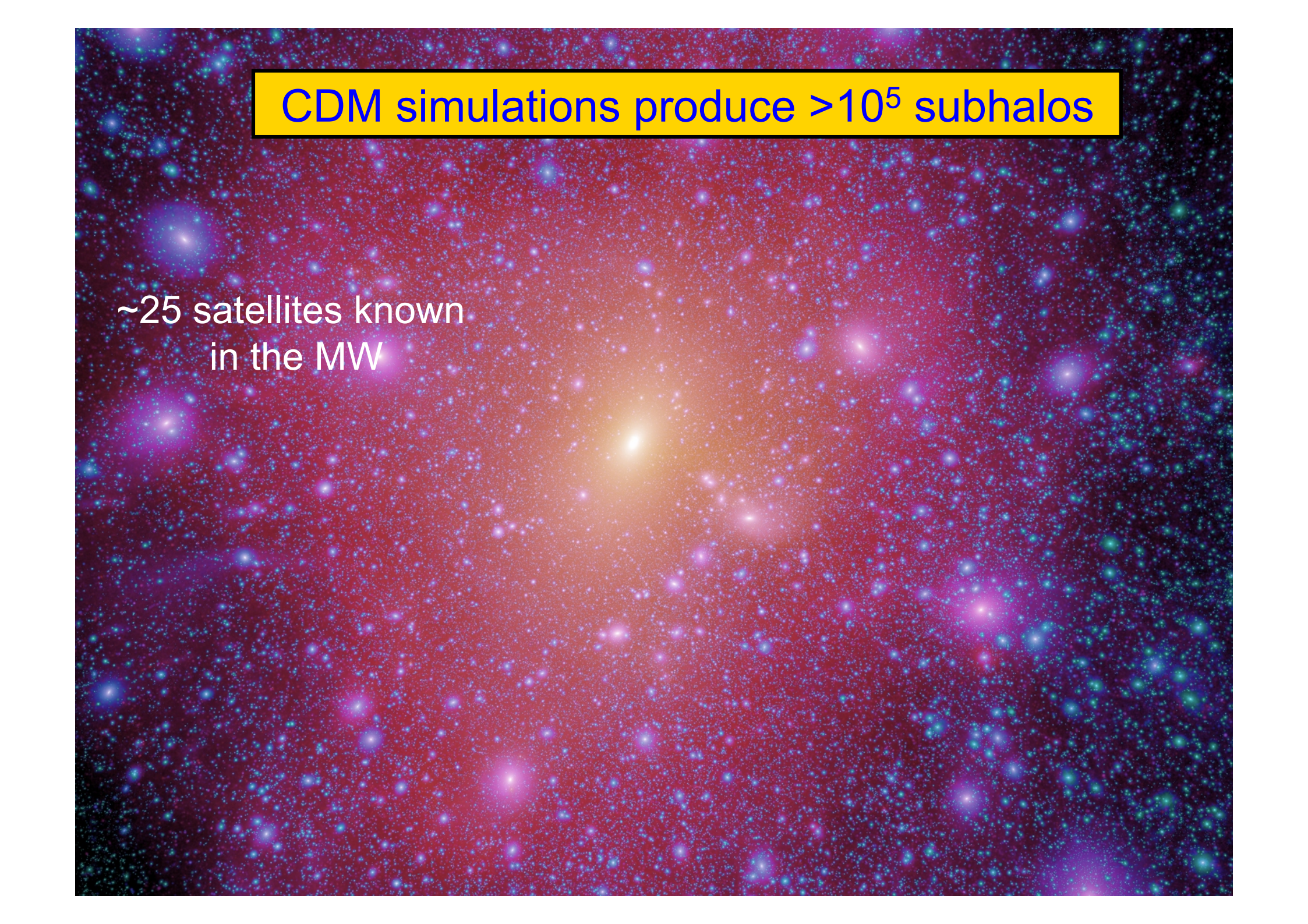
Two “problems” are said to afflict CDM :

- The “satellite problem”
- The “too-big-to-fail” problem

The satellites of the Milky Way

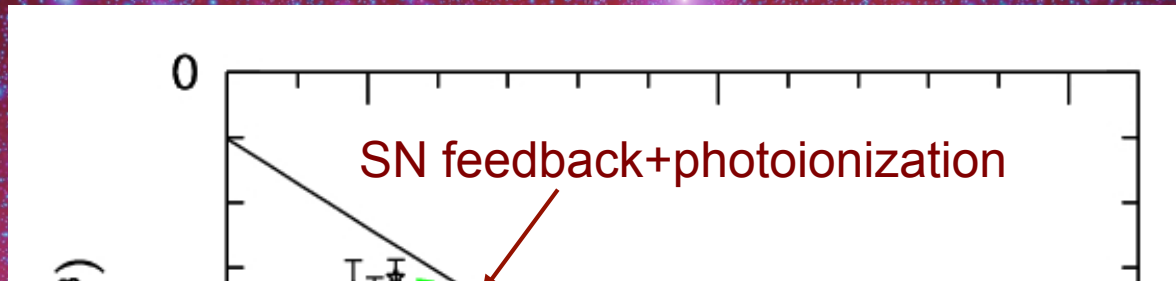
~25 satellites known
in the MW



The background of the slide is a deep space image showing a vast field of galaxies. In the center, there is a bright, dense cluster of galaxies, likely the Coma Cluster, which appears as a glowing yellow and orange core. Surrounding this central cluster are numerous other galaxies, some appearing as distinct blue and white points of light, while others are more diffuse. The overall color palette is dominated by the reds and oranges of the central cluster, contrasting with the cooler blues and whites of the distant galaxies.

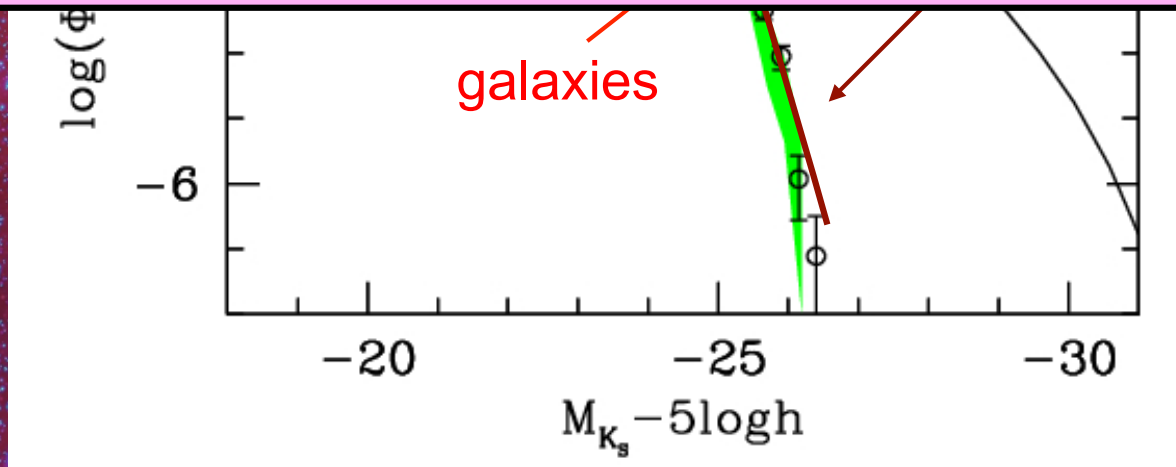
CDM simulations produce $>10^5$ subhalos

~25 satellites known
in the MW



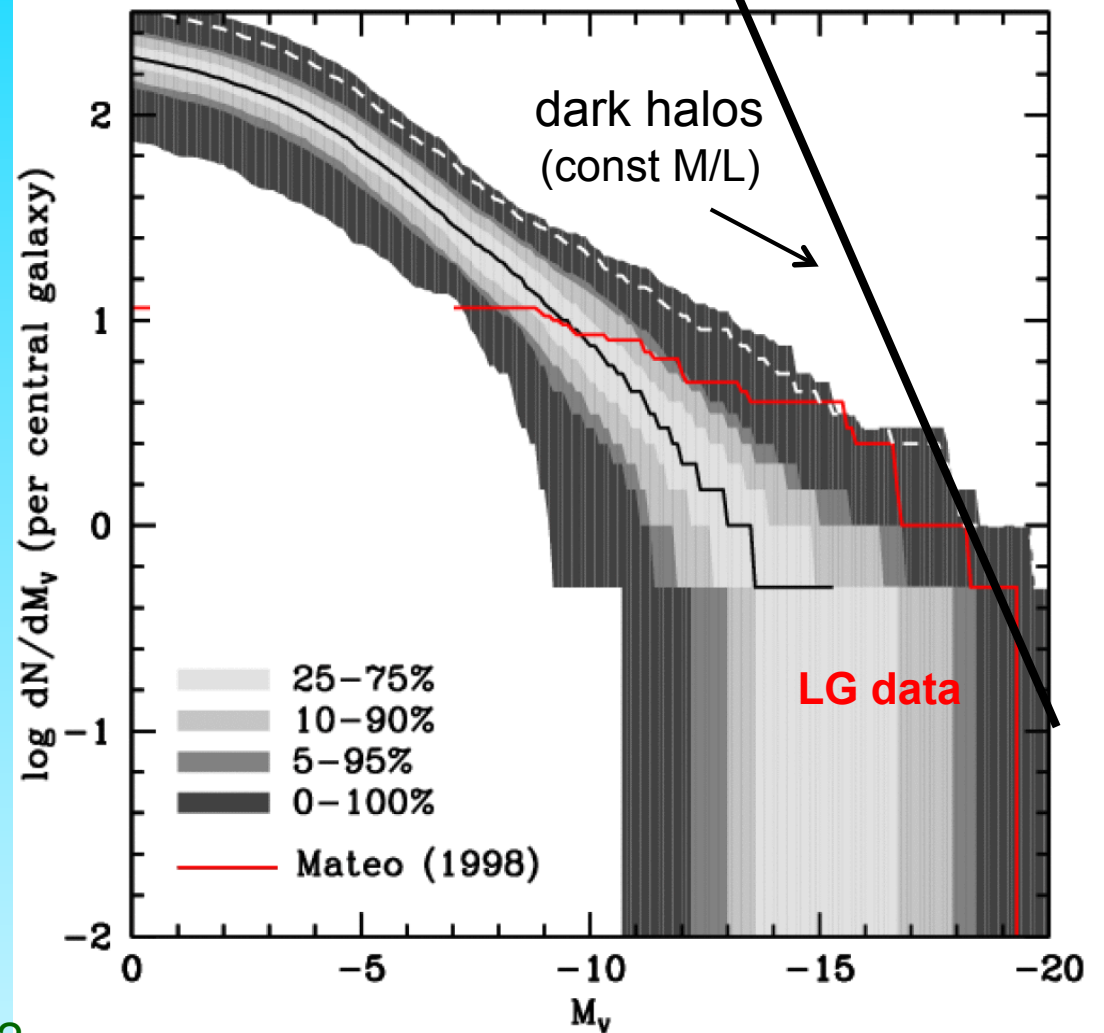
Making a galaxy in a small halo is hard because:

- Early reionization heats gas above T_{vir}
- Supernovae feedback expels gas



Luminosity Function of Local Group Satellites

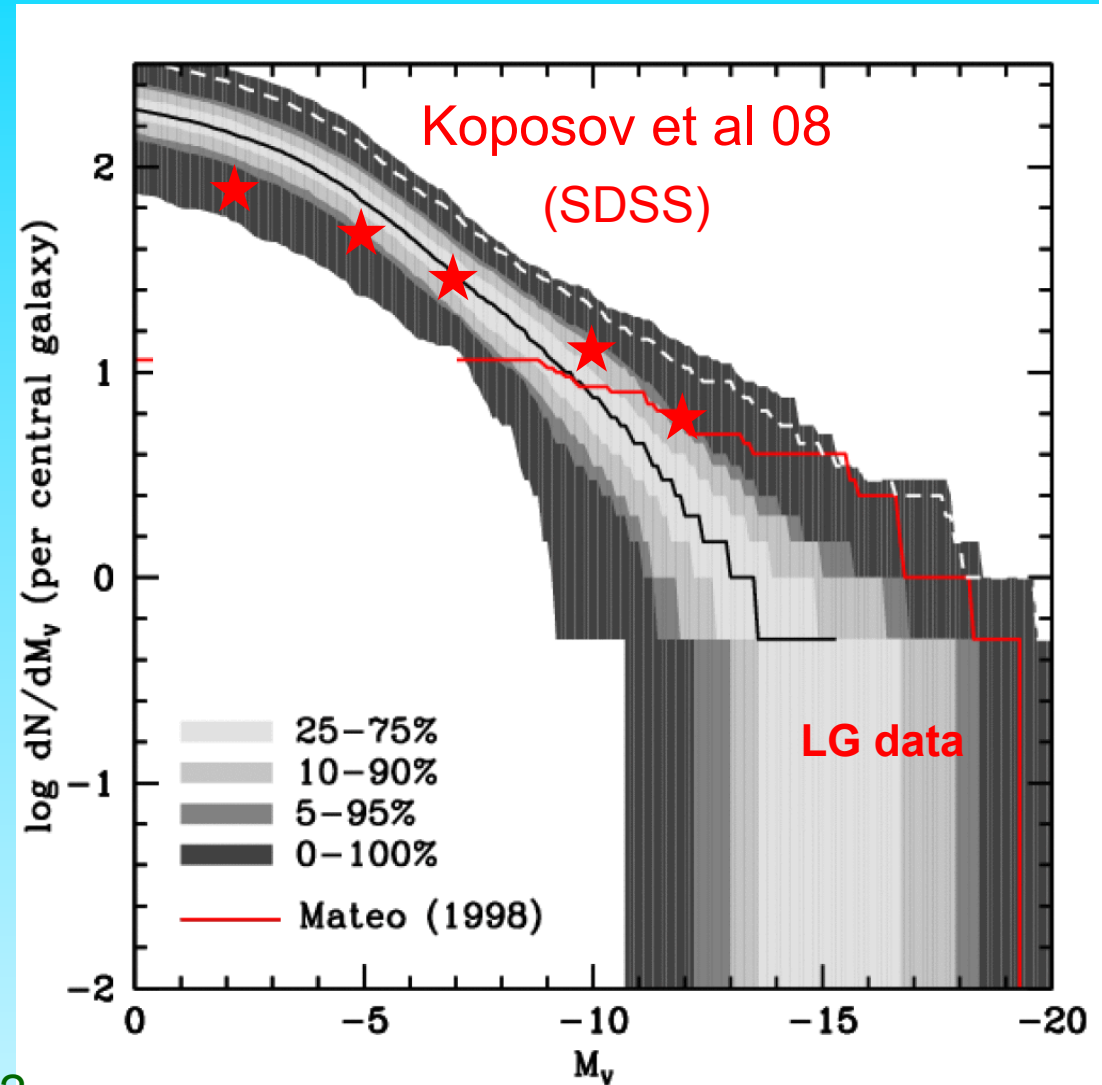
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

Luminosity Function of Local Group Satellites

- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
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Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)



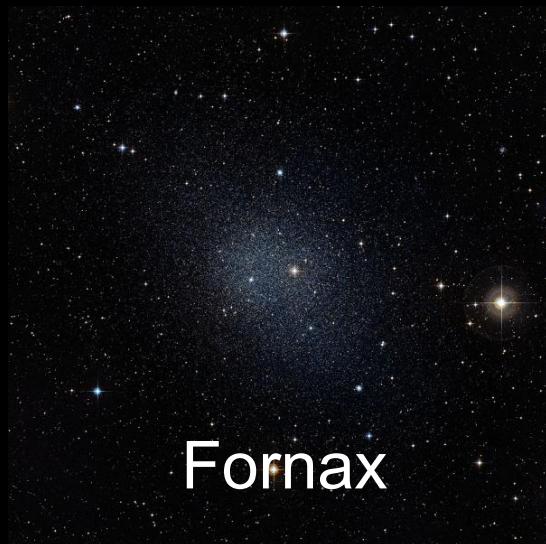
Cosmology on small scales

Two “problems” are said to afflict CDM :

- The “satellite problem”
- The “too-big-to-fail” problem



Dwarf galaxies around the Milky Way



Fornax



Sculptor



Leo I



Sextans



Carina



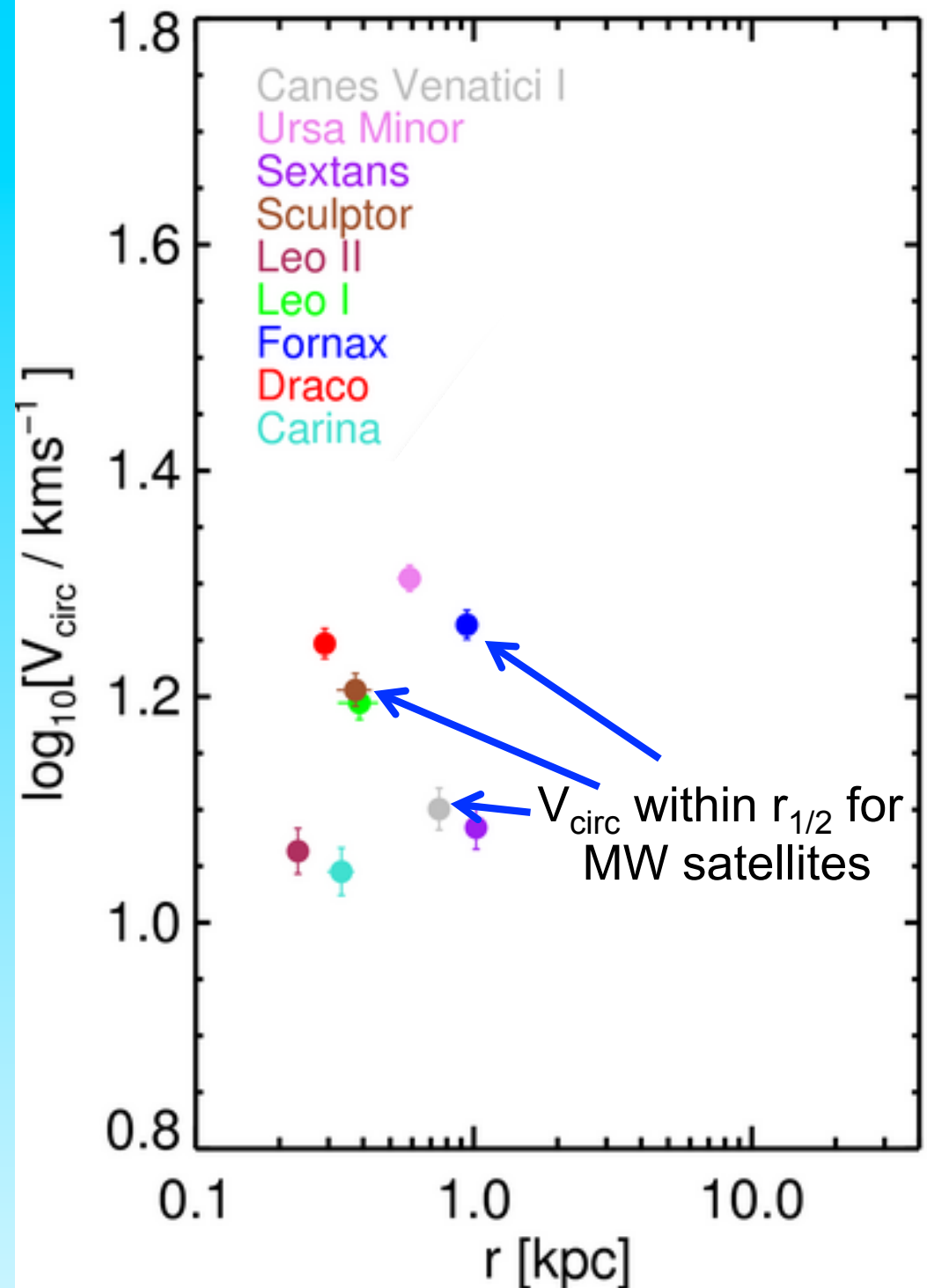
Sagittarius

Kinematical data → mass within half-light radius (Wolf, Walker)

Is CDM compatible w.
luminosity & structure
of observed satellites?

$$V_c = \sqrt{\frac{GM}{r}} \quad V_{\max} = \max V_c$$

Mass within half-light
radius for 9 dwarf
satellites of the Milky Way



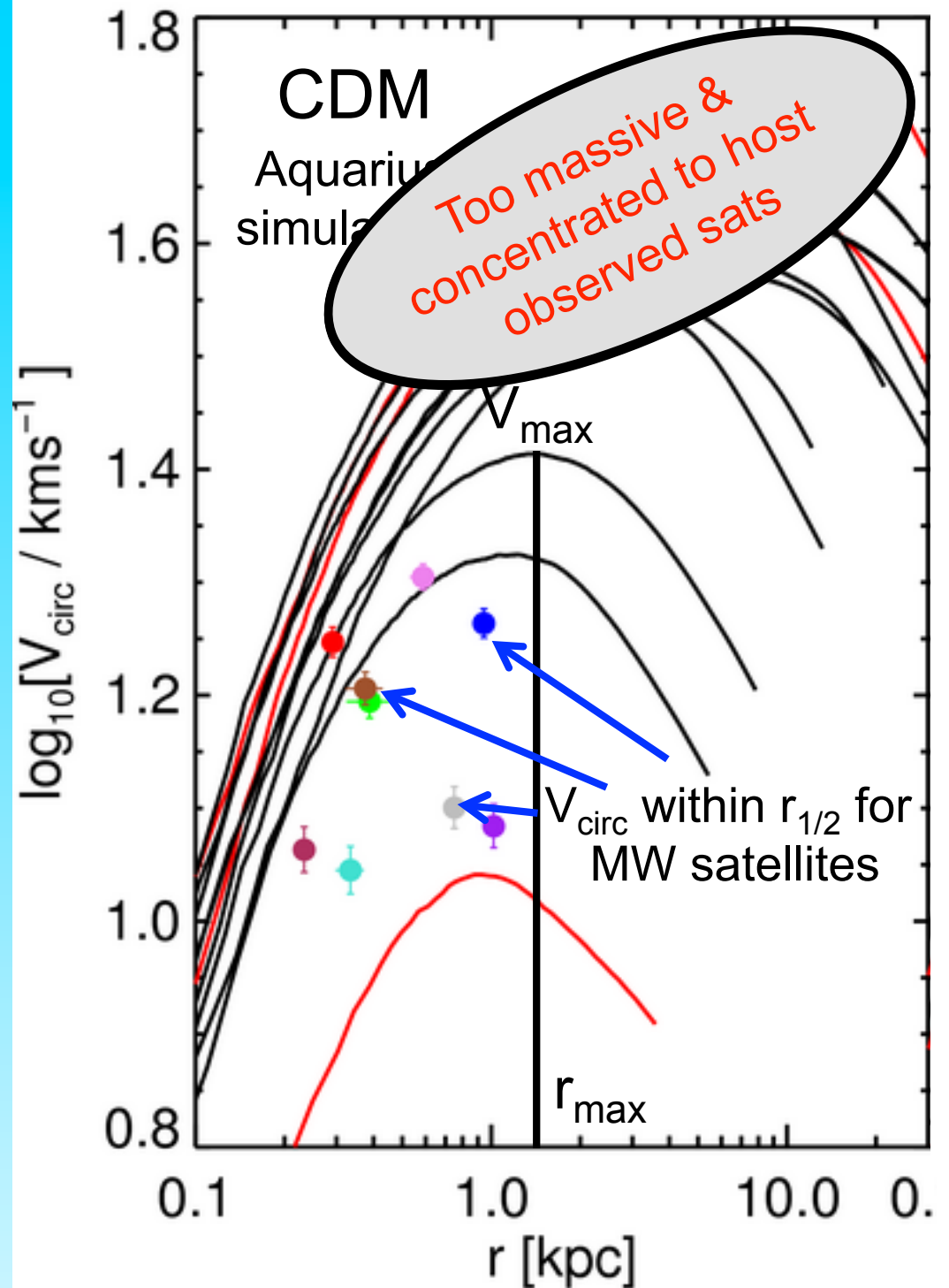
Is CDM compatible w. luminosity & structure of observed satellites?

$$V_c = \sqrt{\frac{GM}{r}} \quad V_{\max} = \max V_c$$

Rotation curves of 12 subhalos with most massive progenitors

Red → 3 halos with most massive progenitors (LMC, SMC, Sagittarius?)

Lovell, Eke, Frenk, Gao et al '11;
see also Boylan-Kolchin et al '11a,b



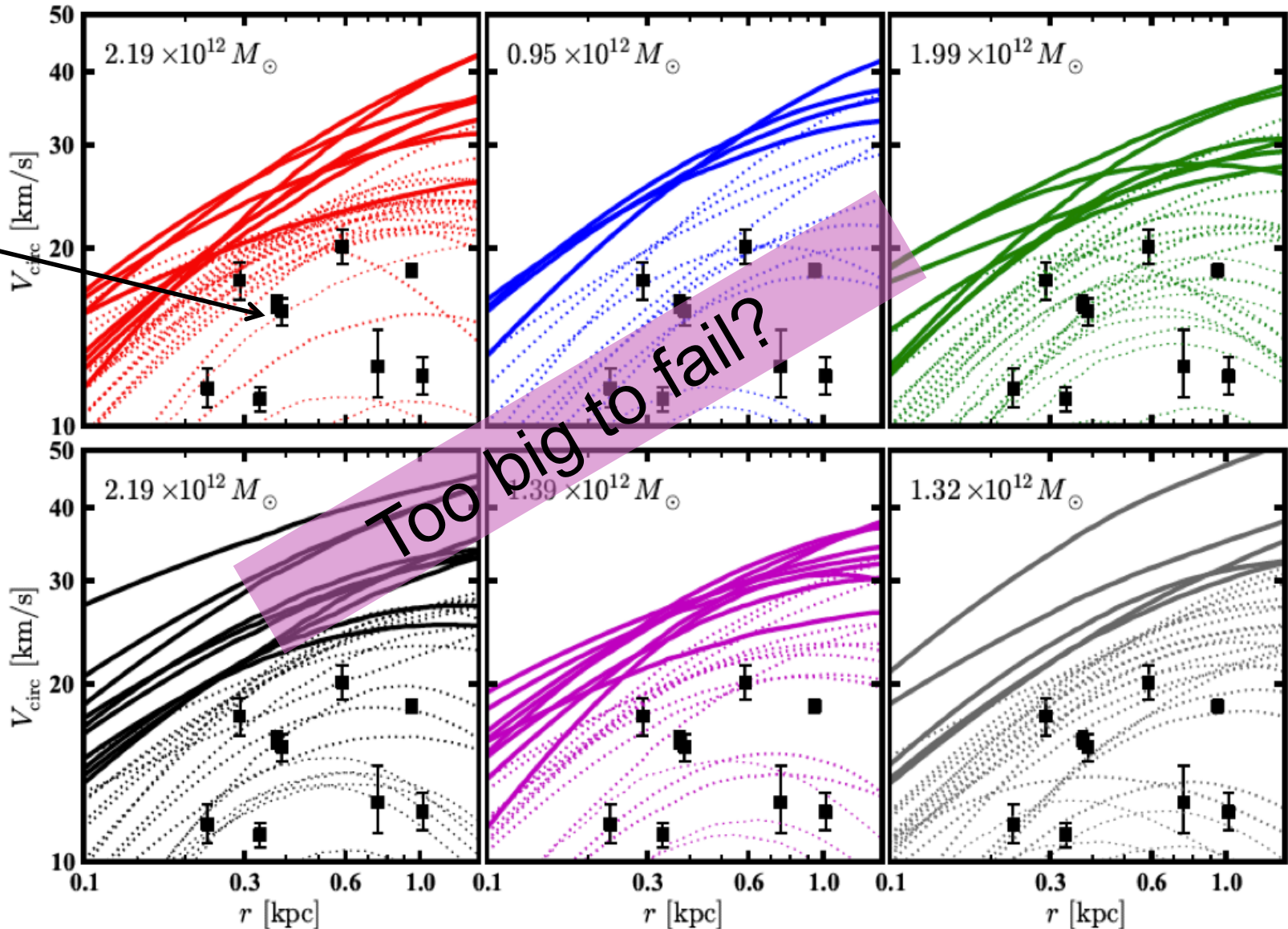
Rotation curves of Aquarius subhalos

Boylan-Kolchin et al. '11

$$V_c = \sqrt{\frac{GM}{r}}$$

9 dwarf
satellites of
Milky Way:
Mass within
half-light
radius

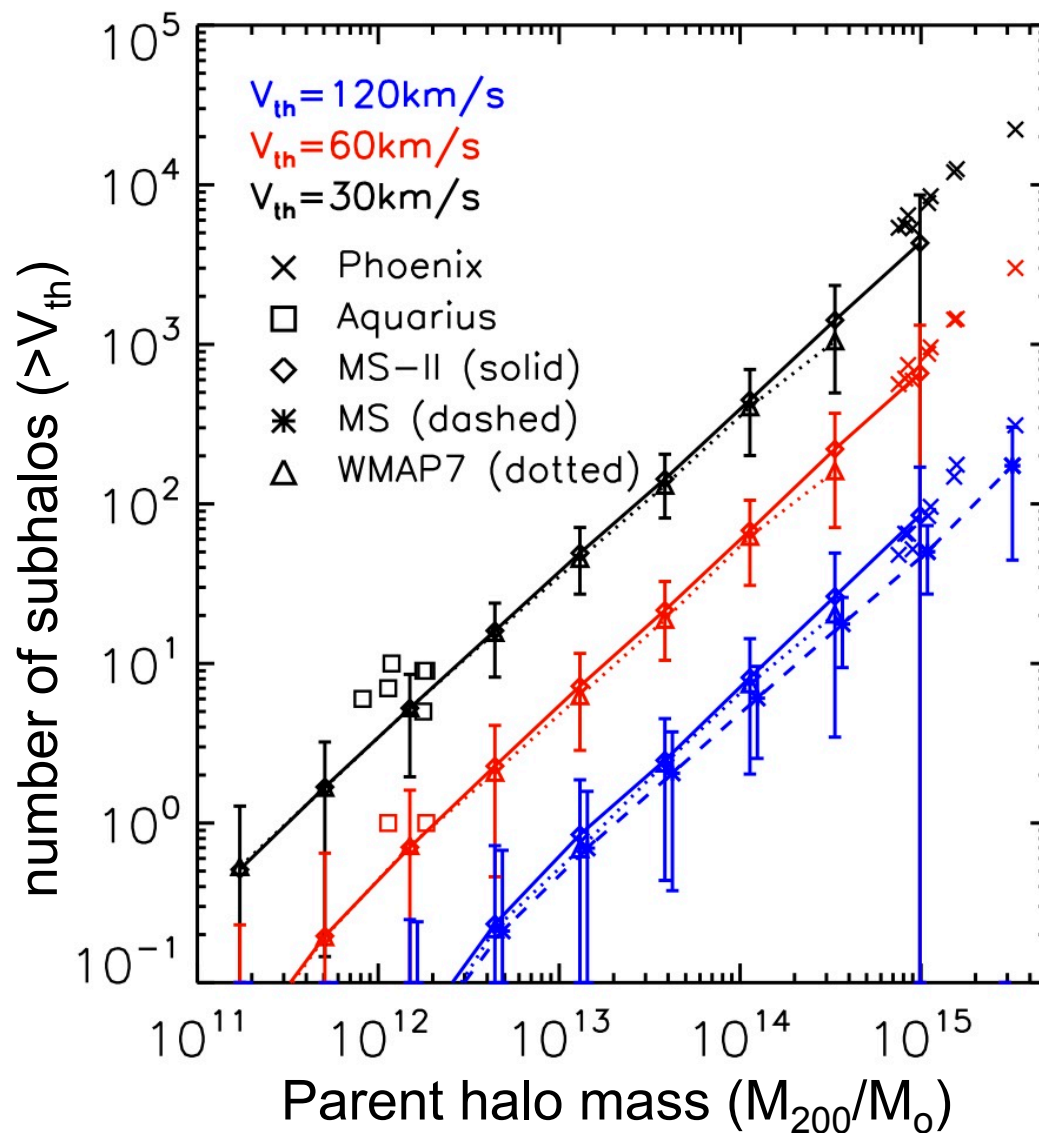
Excludes
LMC, SMC,
Sagittarius



Number of massive subhalos

Number of massive subhalos increases rapidly with halo mass

→ Milky Way halo mass cannot be too large if CDM is right!



Probability of massive subhalos

Probability of having no more than 3 subhalos with $V_{\max} > 30$ km/s

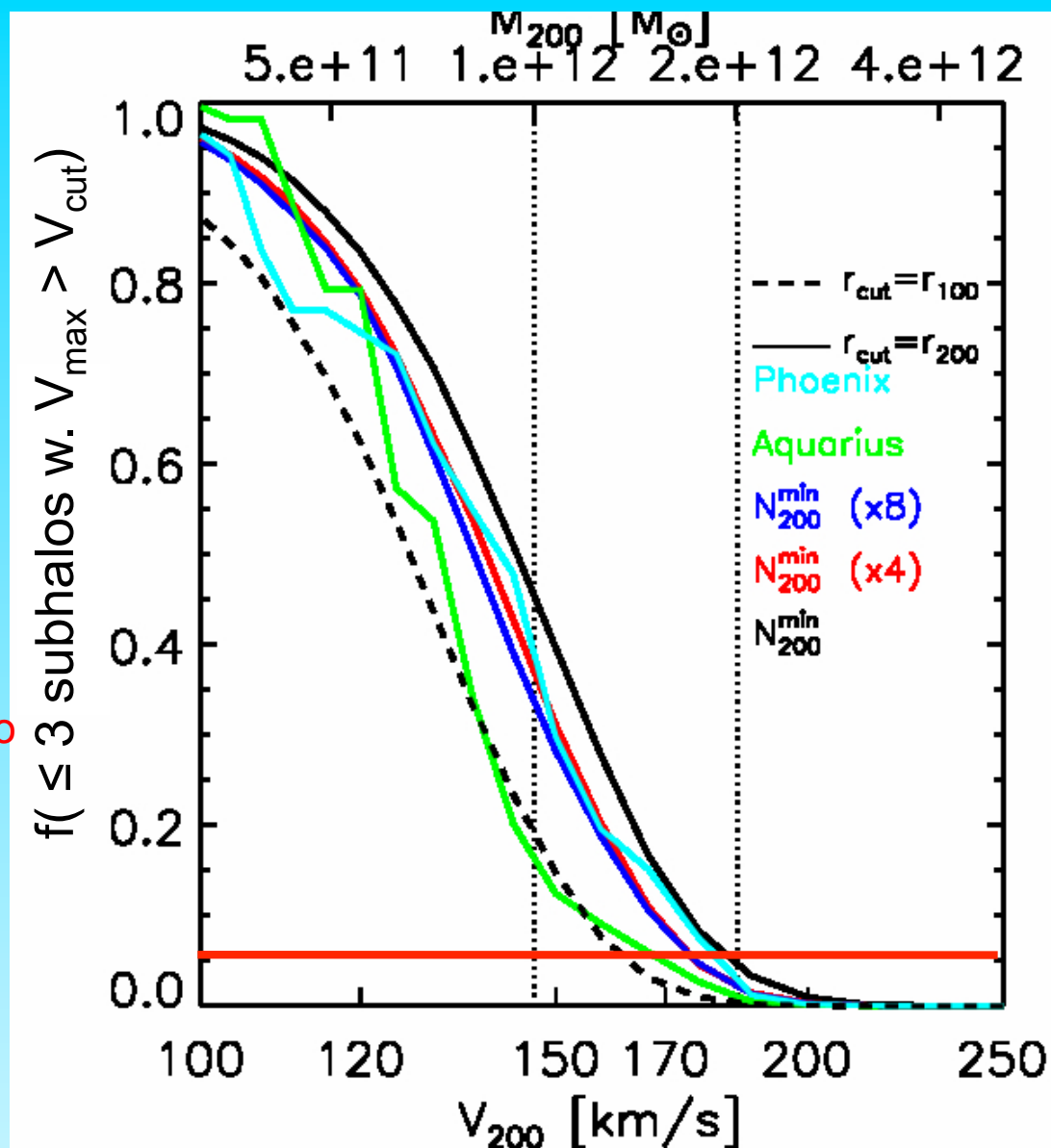
Depends strongly on M_{200} (and V_{cut})

If mass of MW halo $> 2 \times 10^{12} M_{\odot}$
pure CDM is ruled out

CDM requires

$M_{\text{halo}} < 1.5 \times 10^{12} M_{\odot}$ (95% confidence)

Wang, Frenk, Navarro, Gao '12



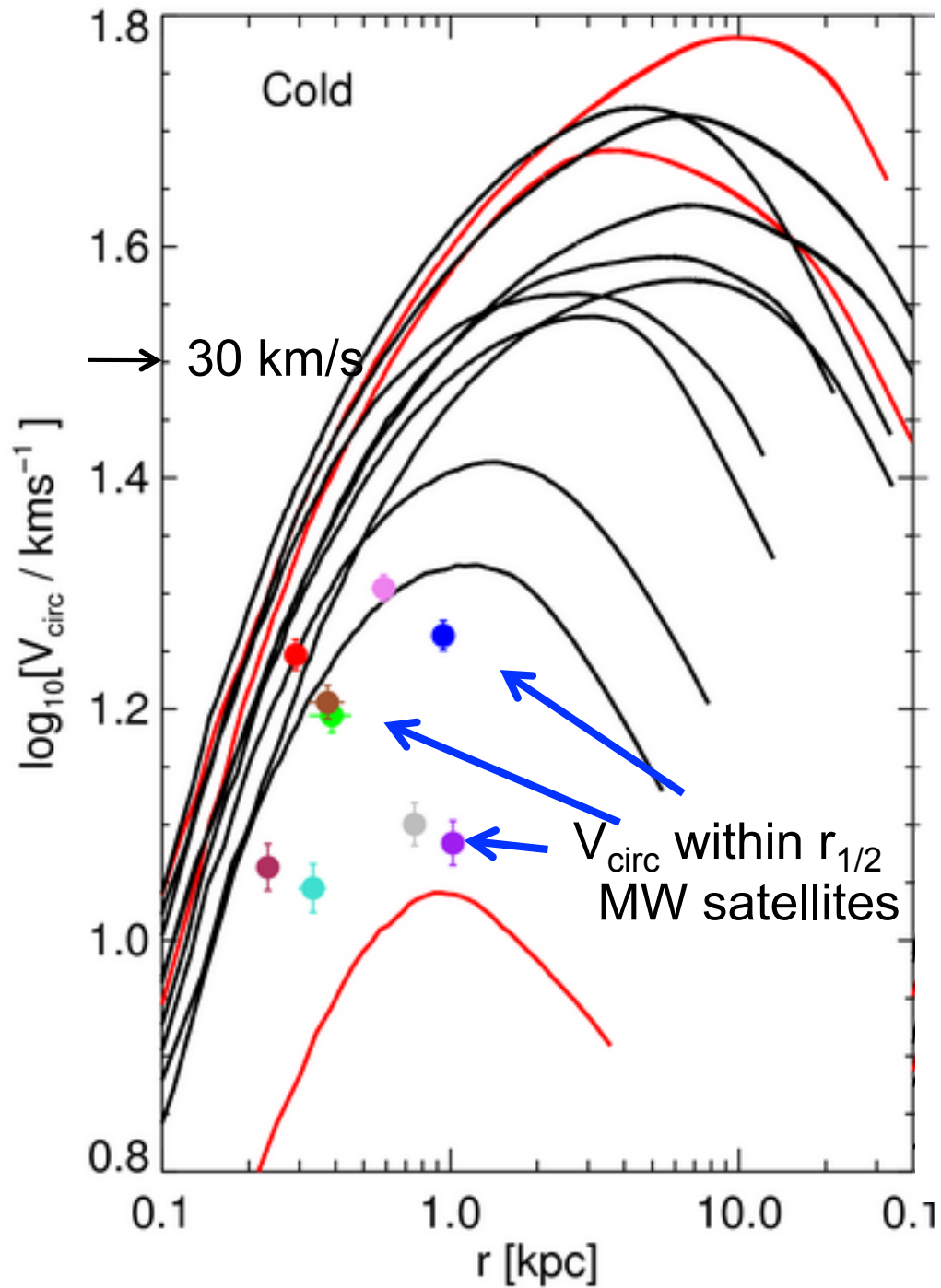


Cosmology on small scales

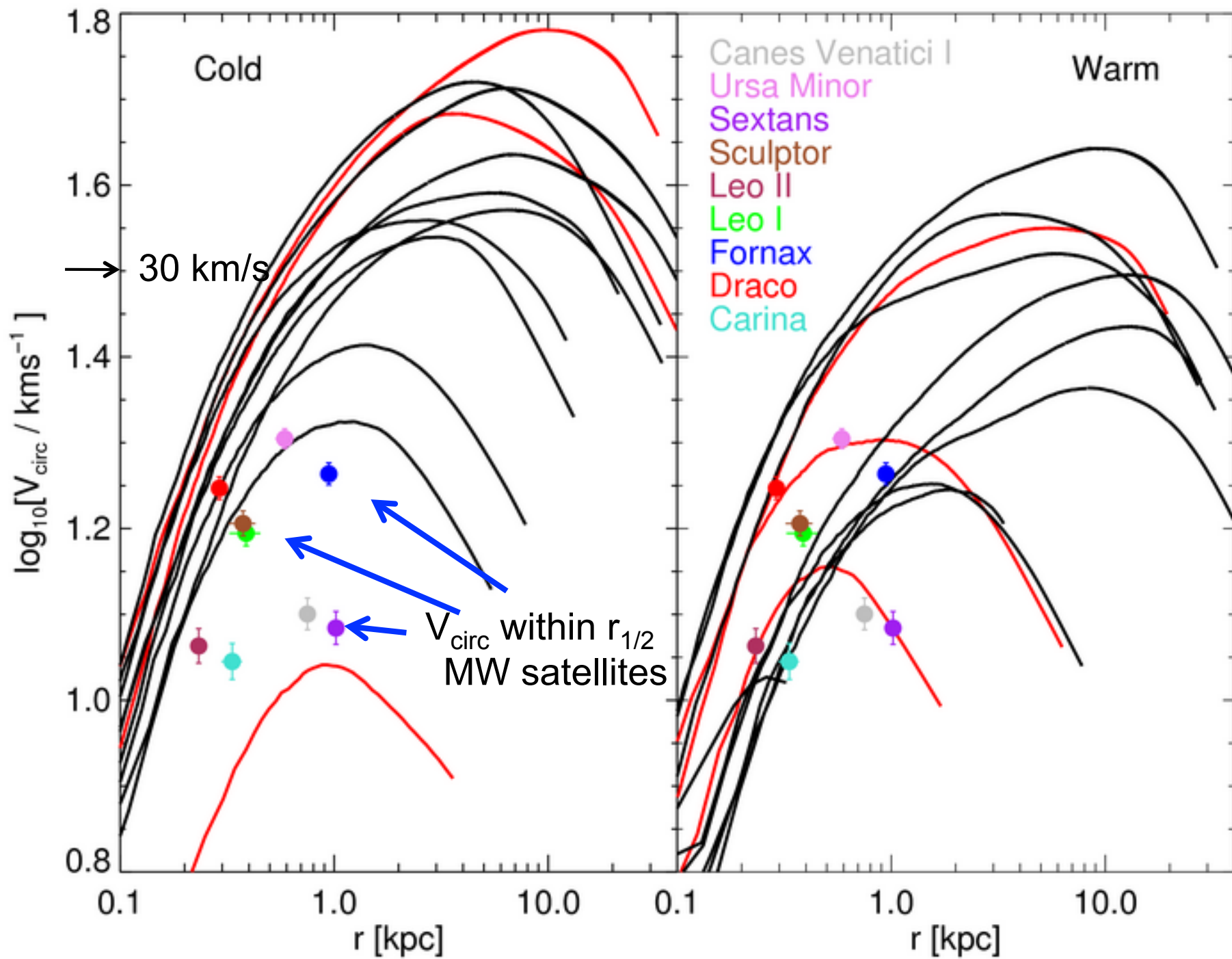
Two “problems” are said to afflict CDM :

- The “satellite problem”
- The “too-big-to-fail” problem

How about WDM?



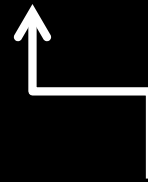
Lovell, Eke, Frenk, Gao,
Jenkins, Wang, White, Theuns,
BoyarSKI & Ruchayskiy '11





Cosmology on small scales

- The “satellite problem”
- The “too-big-to-fail” problem



Not a problem for WDM?



Tests of the nature of the DM

cold dark matter

warm dark matter



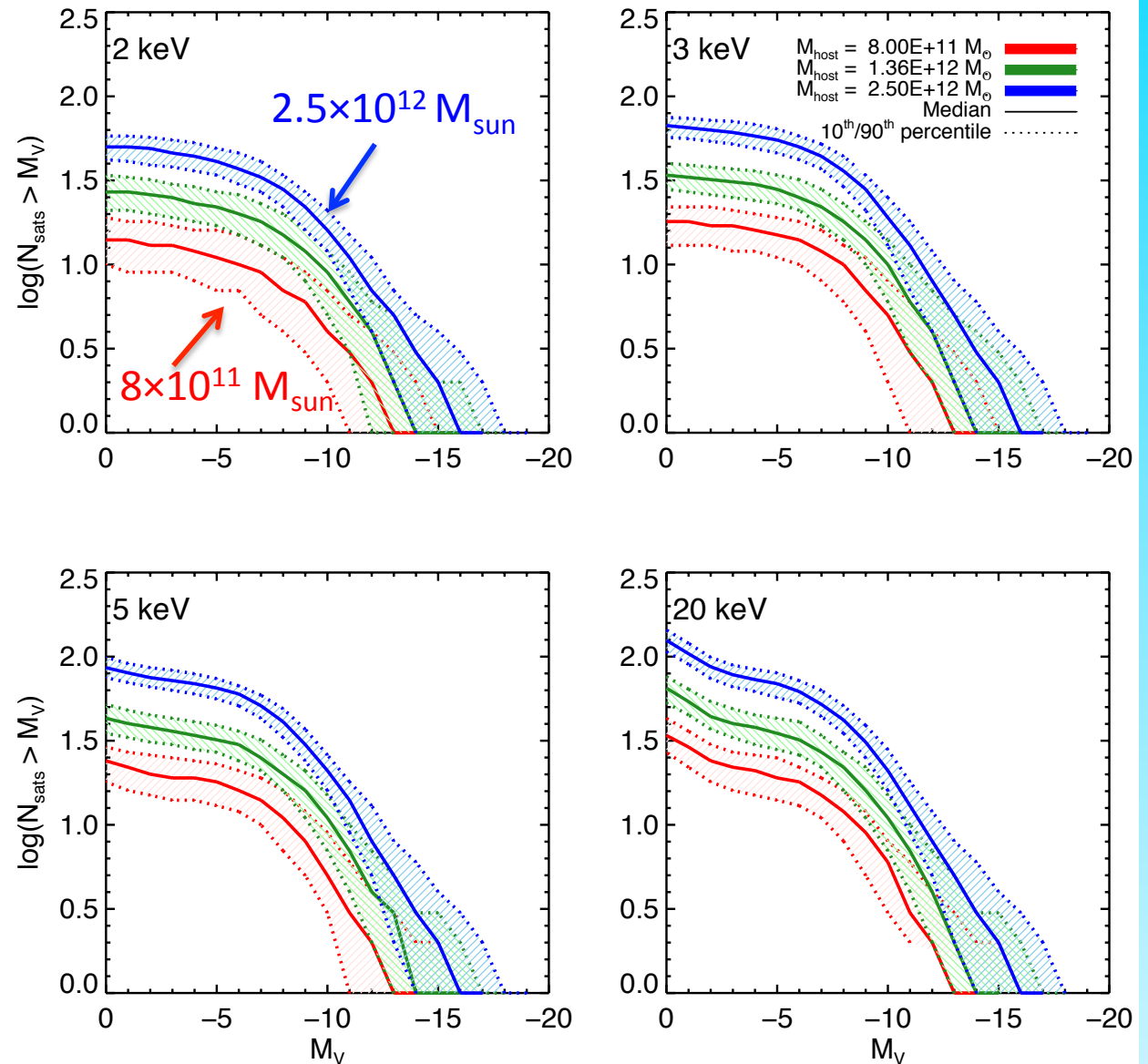
Lovell, Eke, Frenk, Gao, Jenkins, Wang, White, Theuns,
Boyarski & Ruchayskiy '12

Institute for Computational Cosmology

Luminosity Function of Local Group Satellites in WDM

No of sats $\nearrow$ with:

- host halo mass
- WDM particle mass

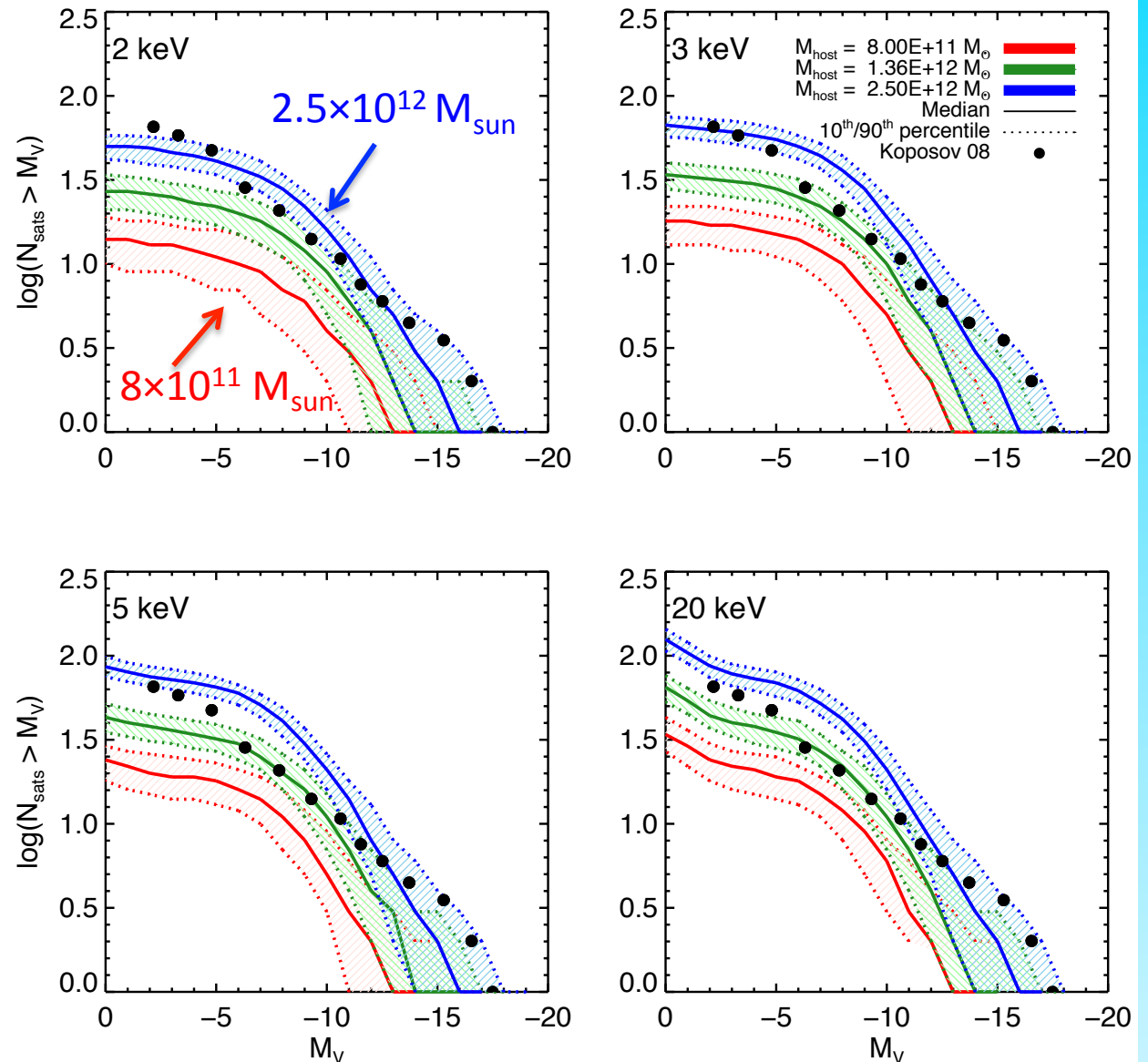


Kennedy, Cole & Frenk '13

Luminosity Function of Local Group Satellites in WDM

No of sats $\nearrow$ with:

- host halo mass
- WDM particle mass



Kennedy, Cole & Frenk '13

Limits on WDM particle mass

For given m_{wdm} model must predict **at least** observed no of sats

→ lower limit on m_{wdm}

Assumptions:

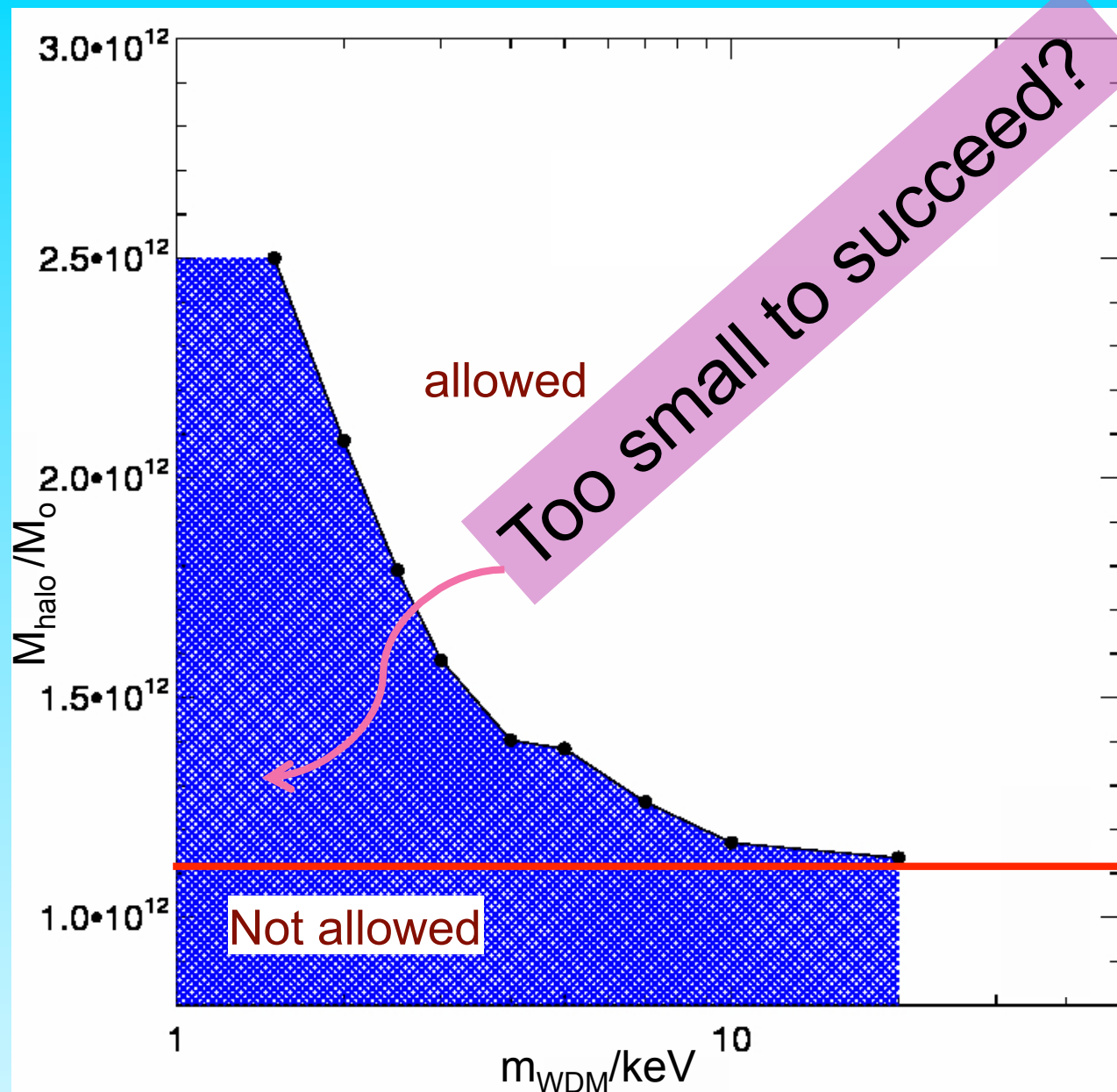
- All classical satellites have been observed
- SDSS (DR5) satellites are isotropically distributed
- Correct SDSS sample for survey area ($f=0.194$), but not for faintness limit (conservative limit)

Limits on WDM particle mass

Minimum halo mass consistent (95%) with observed no. of sats for given m_{WDM}

For standard galaxy formation model, WDM ruled out if $M_{\text{halo}} < 1.1 \times 10^{12} M_{\odot}$

Kennedy, Cole & Frenk '13



Constraints on CDM & WDM from the Milky Way satellites

With our standard assumptions: at 95% confidence

Cold dark matter :

Ruled out unless $M_{\text{halo}} < 1.5 \times 10^{12} M_{\odot}$

(from abundance of massive satellites)

Unless baryon effects are important

Warm dark matter :

Ruled out unless $M_{\text{halo}} > 1.2 \times 10^{12} M_{\odot}$

(from abundance of satellites)

From X-ray decay limit, for resonantly produced sterile vs

→ need $m_{\text{WDM}} < 5\text{keV}$ and $M_{\text{halo}} > 1.4 \times 10^{12} M_{\odot}$

Estimates of the MW halo mass

- Li & White $\rightarrow M_{200} = 2.4 \times 10^{12} M_{\odot}$; $M_{200} > 8 \times 10^{11} M_{\odot}$ at 95% CL
- Guo et al $\rightarrow 8 \times 10^{11} M_{\odot} < M_{200} < 4.7 \times 10^{12} M_{\odot}$
- Deason et al $\rightarrow 5 \times 10^{11} M_{\odot} < M_{150\text{kpc}} < 1 \times 10^{12} M_{\odot}$
- Xue et al $\rightarrow 8 \times 10^{11} M_{\odot} < M_{100} < 1.3 \times 10^{12} M_{\odot}$
- Battaglia et al $\rightarrow 6 \times 10^{11} M_{\odot} < M_{100} < 3 \times 10^{12} M_{\odot}$

Conclusions

- Dark matter has **not** yet been **detected** experimentally
... but there are **hints** ... and the prospects look **promising**
- Evidence favours **cusps** in **clusters**; data **inconclusive** on **dwarfs**
... but **baryon** effects could **reduce** central densities in dwarfs
- Λ CDM great **success** on scales $> 1\text{Mpc}$: CMB, LSS, gal evolution
- But on these scales Λ CDM cannot be distinguished from **WDM**
- The **identity** of the **DM** makes a big difference on **small scales**
- Abundance and kinematics of MW **satellites** set strong constraints
on **nature** of dark matter
... **measuring** mass of **Milky Way halo** may discriminate between
cold and **warm** DM



The discovery of the
dark matter may be
just round the corner

