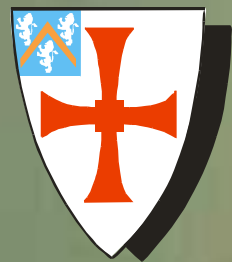


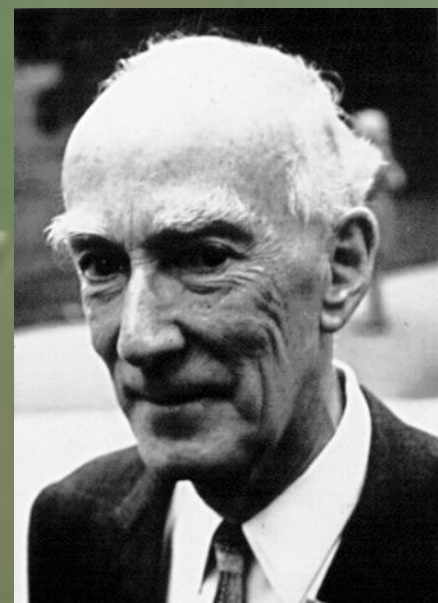


Jan Oort
(1990 – 1992)



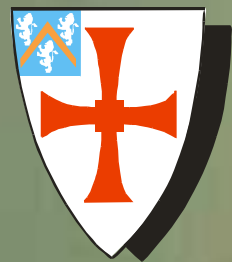


The vicissitudes of the cold dark matter model of cosmogony



Carlos S. Frenk
Institute for Computational Cosmology,
Durham





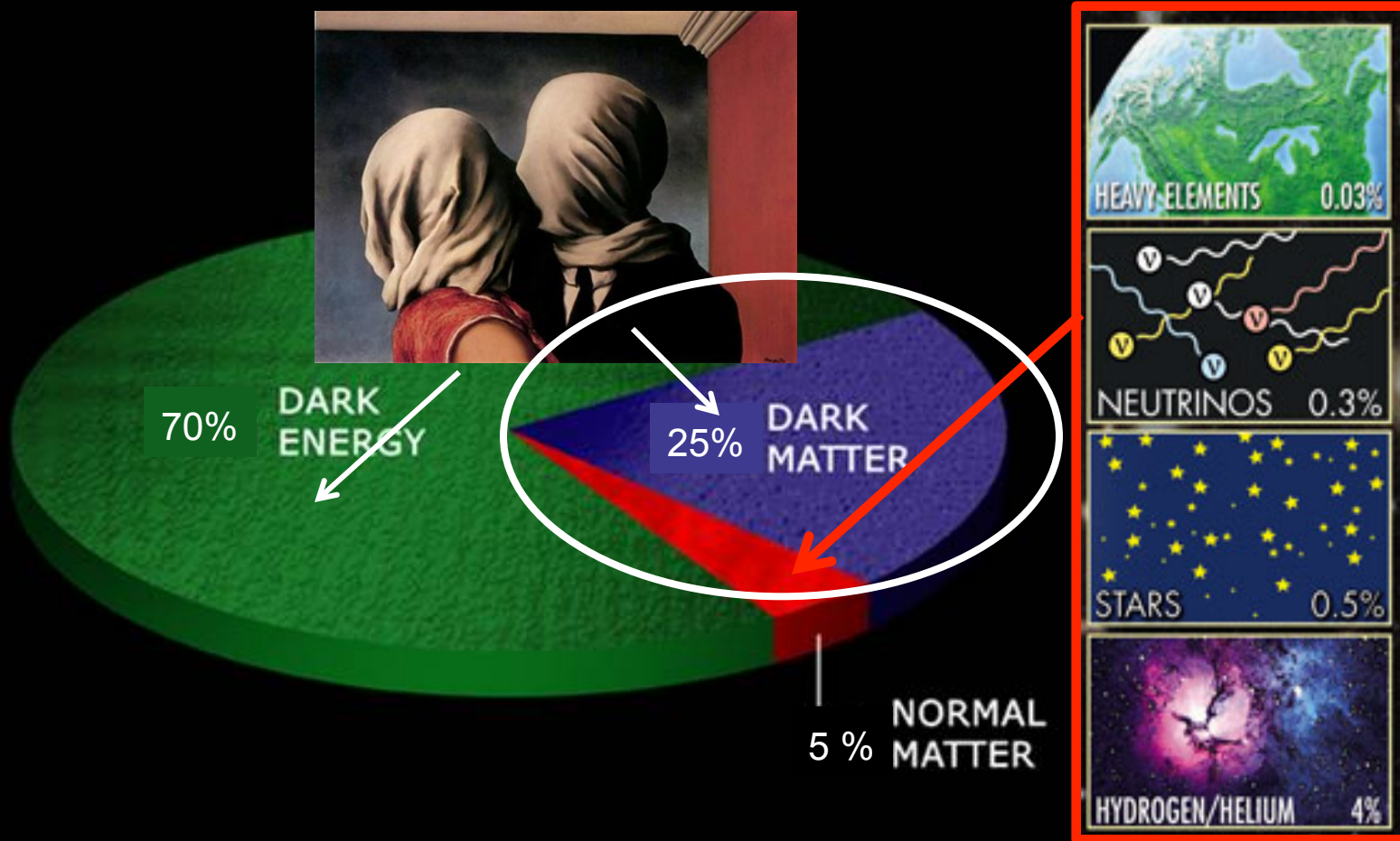
III. Cosmology in our backyard: challenges to the standard model

Carlos S. Frenk
Institute for Computational Cosmology,
Durham





The content of our universe



Non-baryonic dark matter candidates

Type example mass

hot	neutrino	a few eV
warm	sterile ν	keV-MeV
cold	axion neutralino	10^{-5}eV- $>100\text{ GeV}$



Relic abundance of WIMPS

Decoupling occurs when

$$\Gamma < H$$

We have that

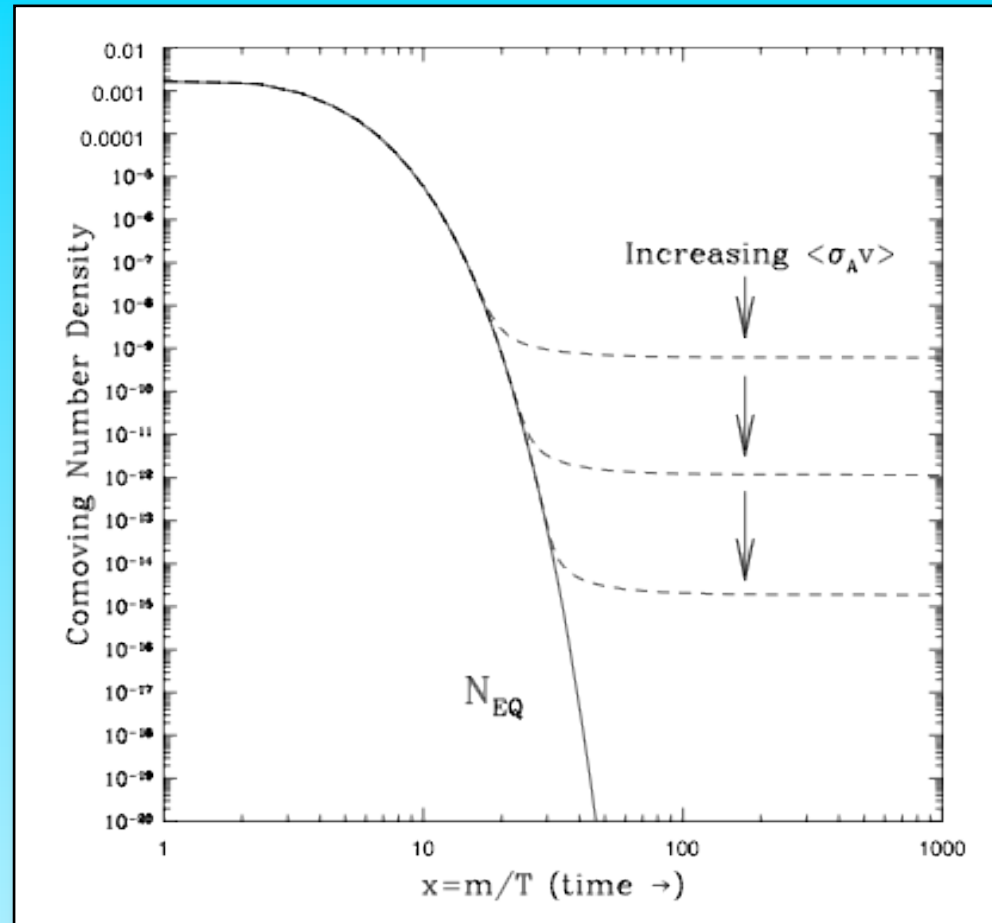
$$\Gamma = \langle \sigma_{\text{ann}} v \rangle n_\chi$$

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

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

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

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

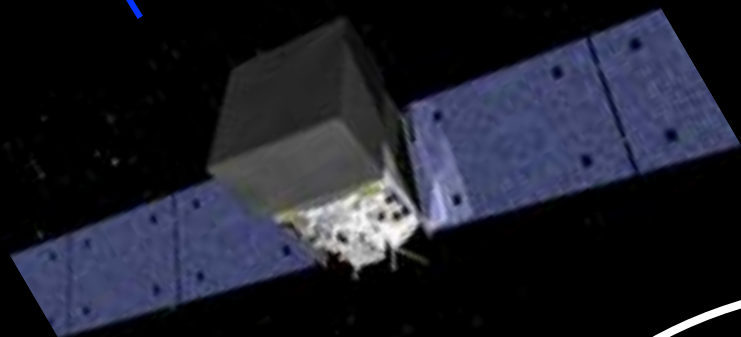


$$\langle \sigma_{\text{ann}} v \rangle \simeq \langle \sigma_{\text{ann}} v \rangle_{\text{WIMP}} \simeq 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \Rightarrow \Omega_\chi h^2 \simeq 0.1$$

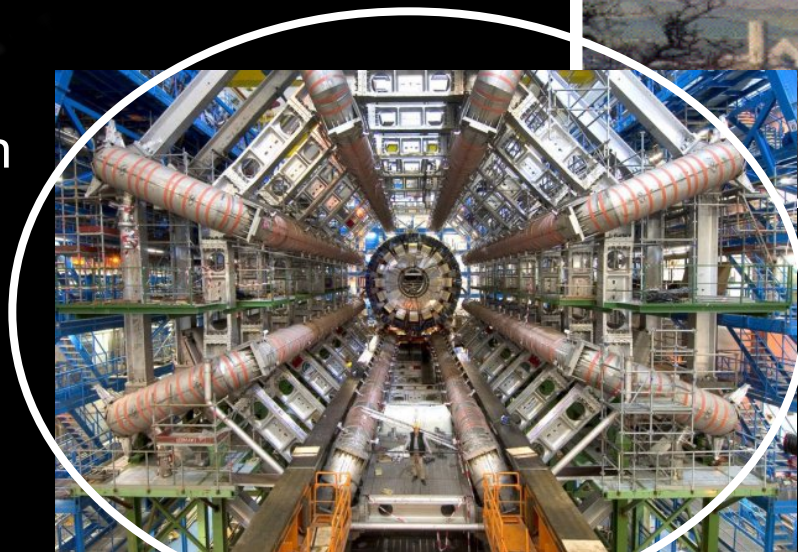
SUSY cold dark matter

Dark matter discovery possible in several ways

Fermi

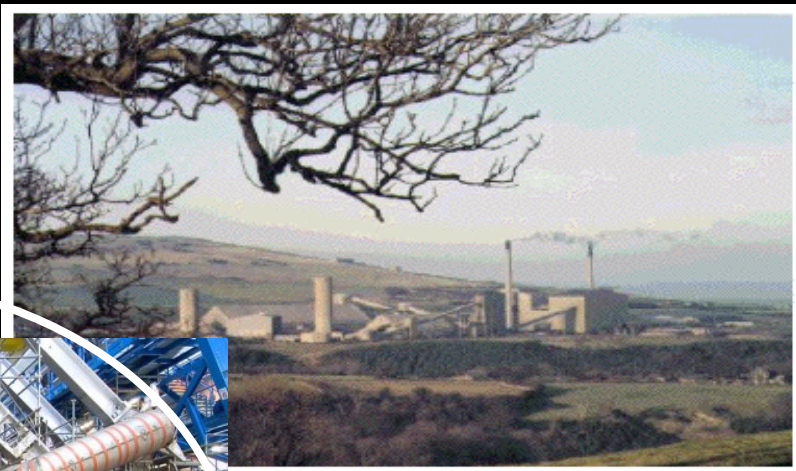


Annihilation radiation



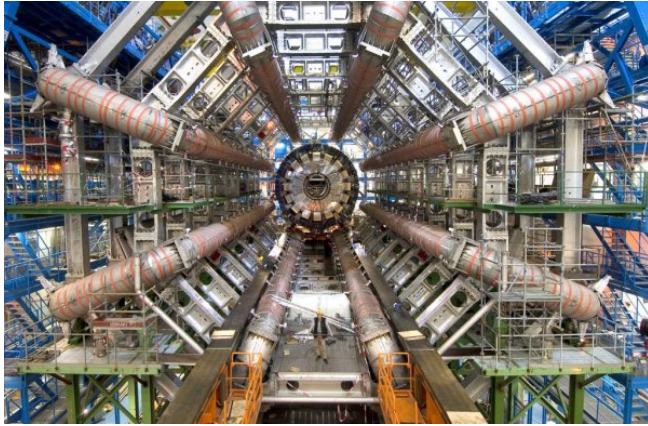
Evidence for SUSY

Direct detection



UK DM search
(Boulby mine)

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



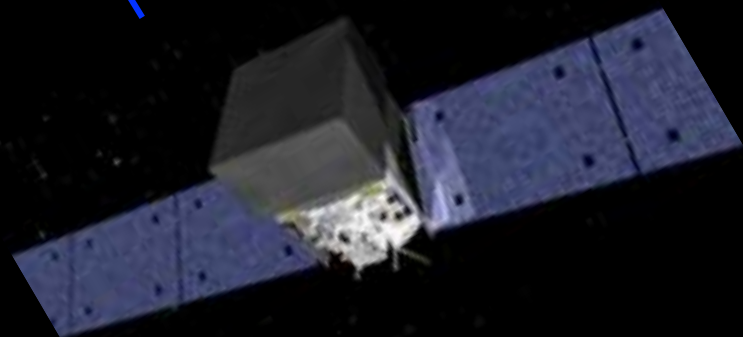
When you are handsome - what difference
does it make that the ski poles are too short
Jan Stenmark

Adapted from Joachim Edsjo

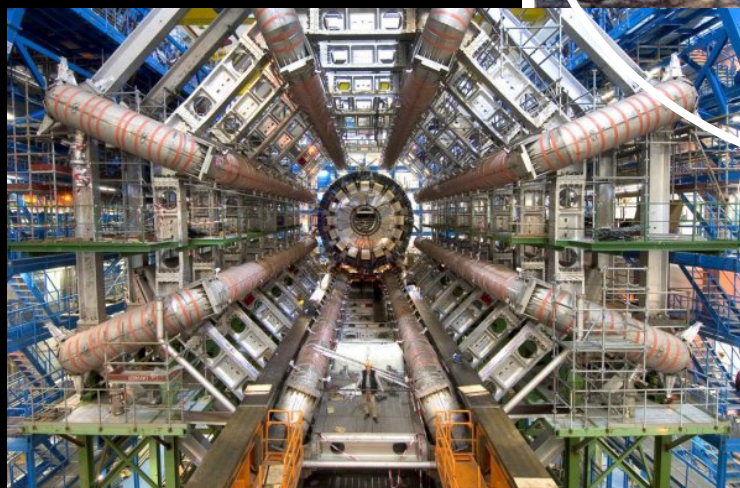
SUSY cold dark matter

Dark matter discovery possible in several ways

Fermi



Annihilation radiation



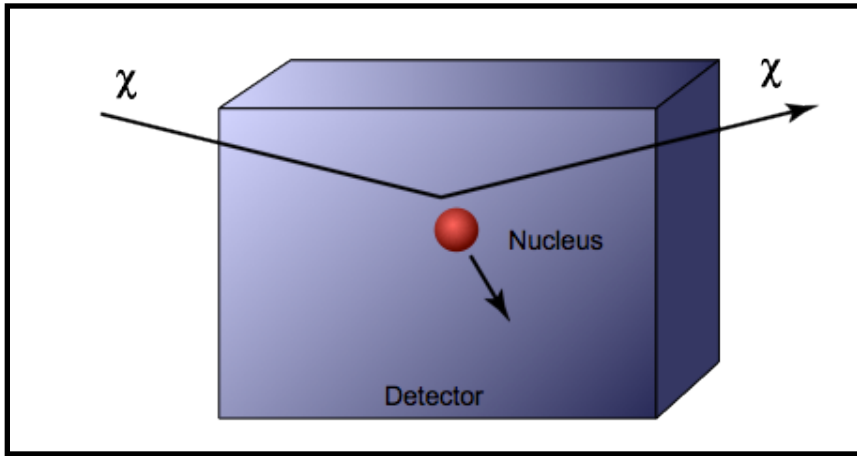
Evidence for SUSY

Direct detection

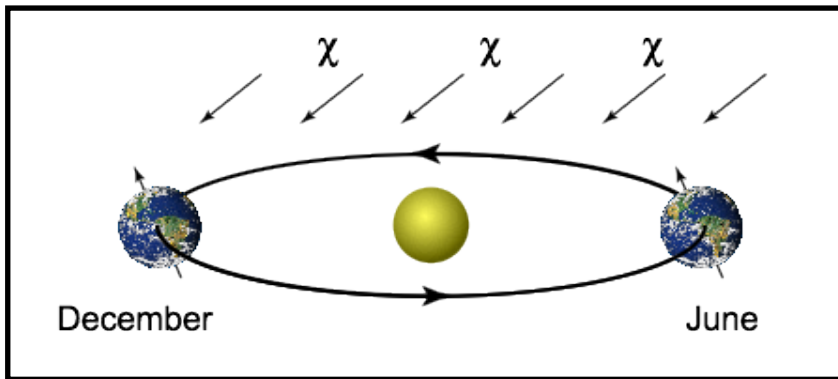


UK DM search
(Boulby mine)

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...

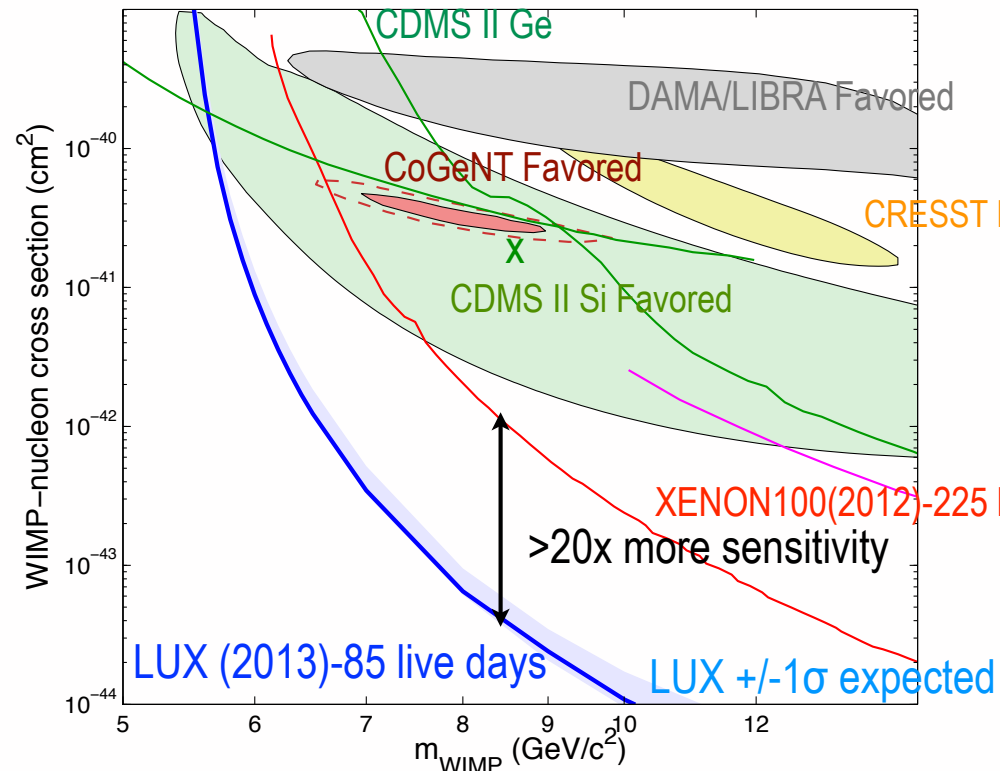
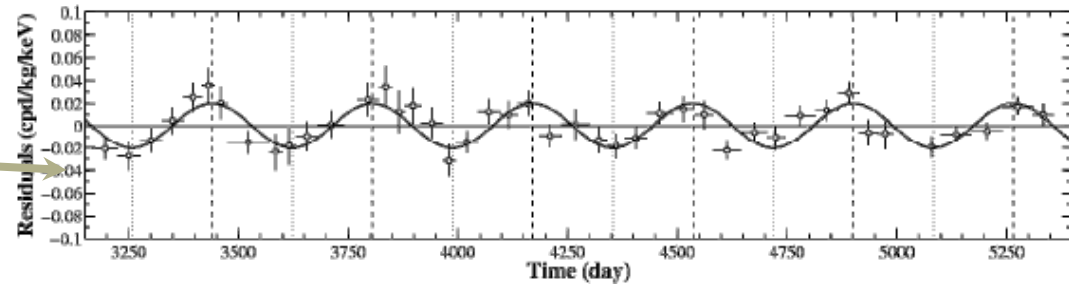


- Search for an annual modulation due to the Earth's motion in the halo

Adapted from Joachim Edsjo

Direct detection: conflicting experiments

DAMA/Libra sees modulation
signal at 8.9σ



Caveat: standard astrophysical model

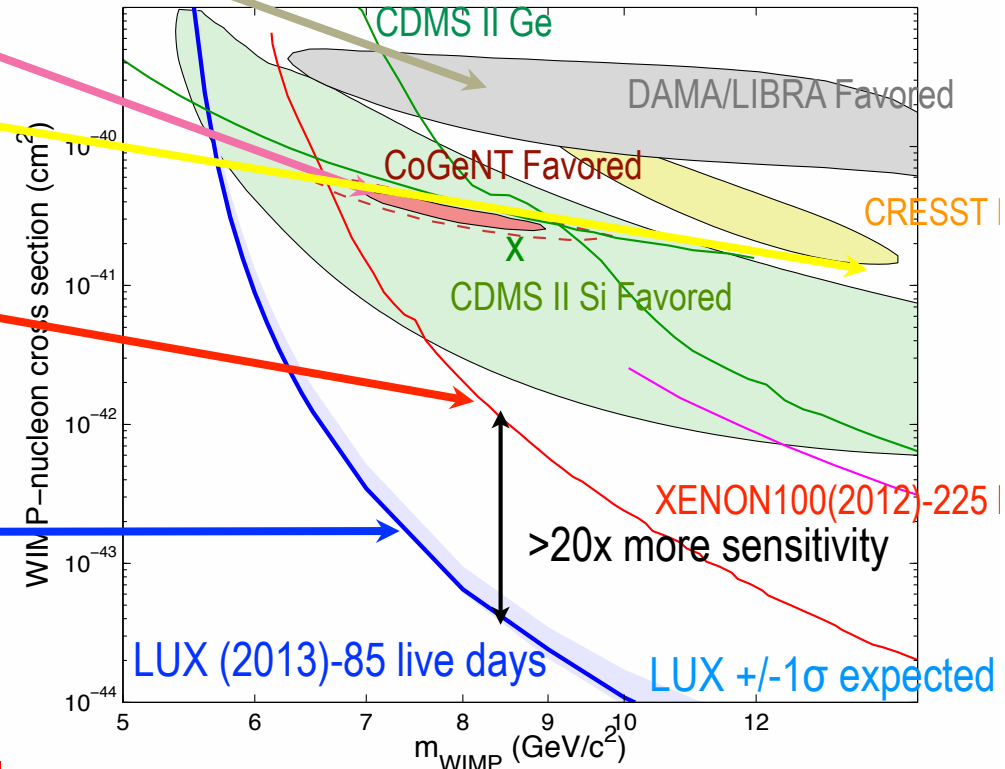
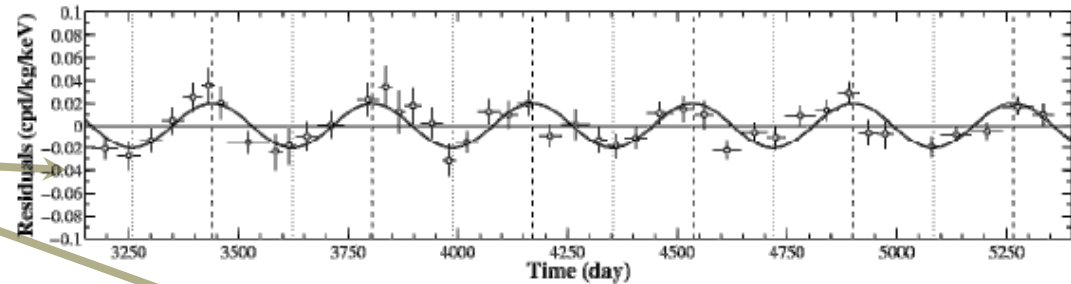
Direct detection: conflicting experiments

DAMA/Libra sees modulation
signal at 8.9σ

CoGeNT sees excess events
as does CRESST-II

but XENON100 excludes
them all

as does LUX



Caveat: standard astrophysical model

Direct detection: halo velocity distribution

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Astrophysics: $\rho_0, f(v)$;

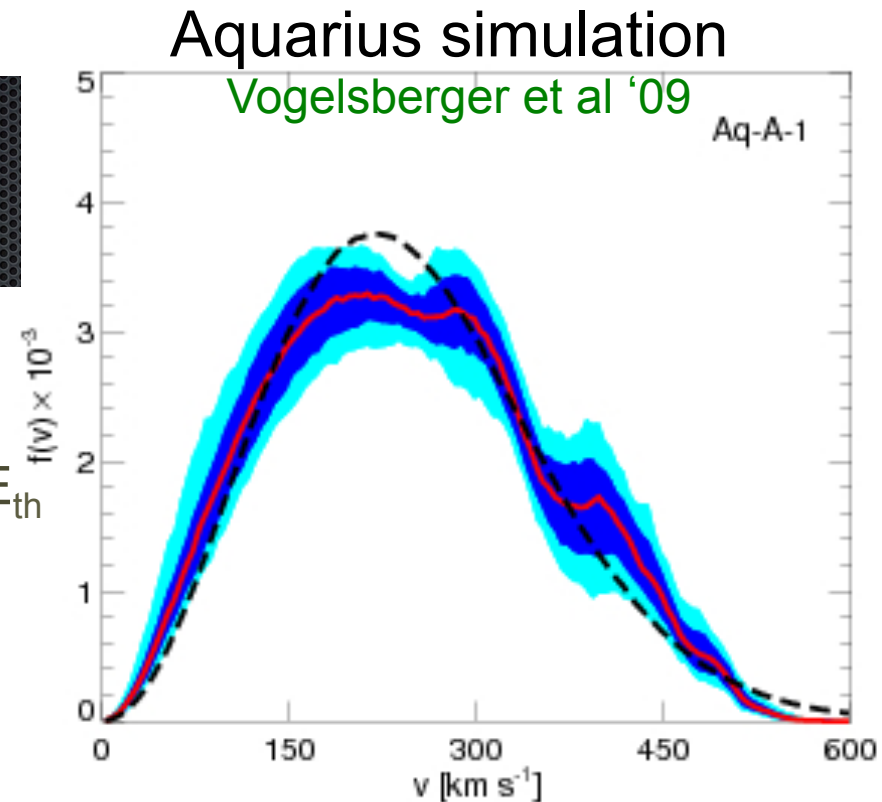
Particle phys: $m_W, d\sigma/dE_R$, Detector: N_N, E_{th}

Direct detection: halo velocity distribution

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Astrophysics: $\rho_0, f(v)$;

Particle phys: $m_W, d\sigma/dE_R$, Detector: N_N, E_{th}

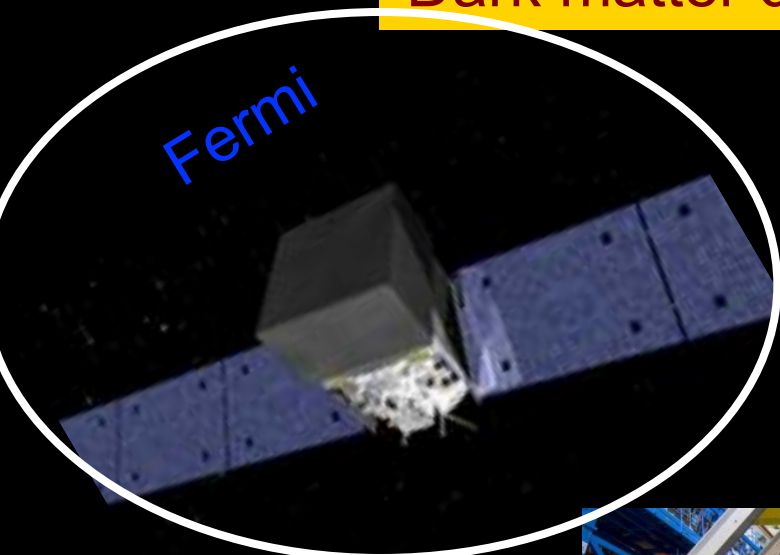


Experiments assume “standard halo model” → Gaussian vel distr

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

SUSY cold dark matter

Dark matter discovery possible in several ways

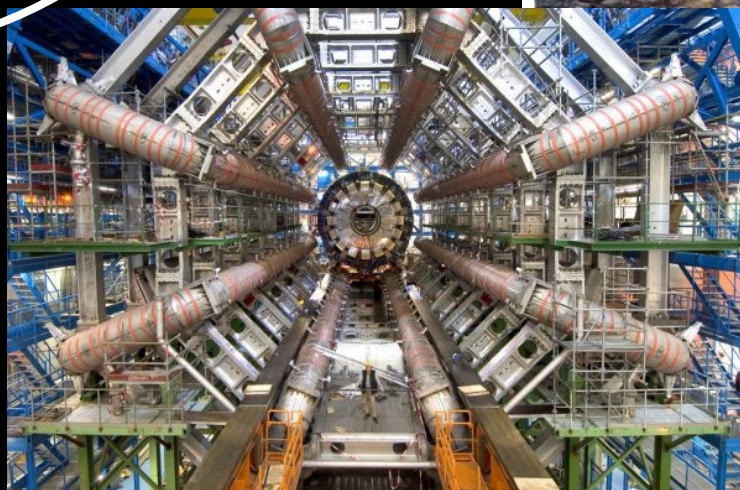


Annihilation radiation

Direct detection



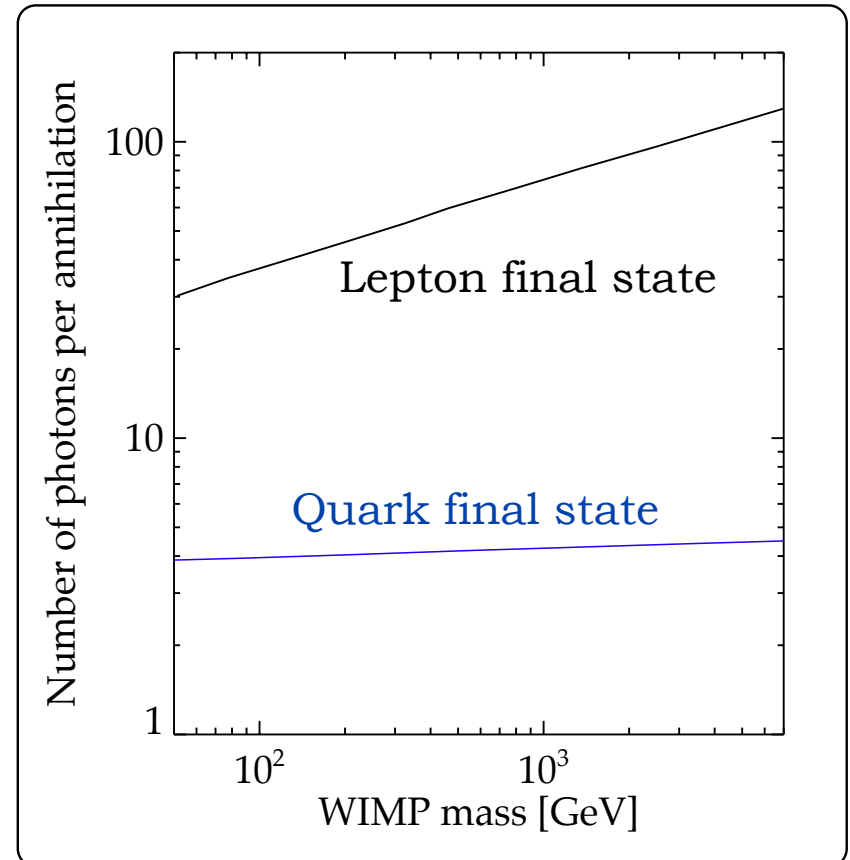
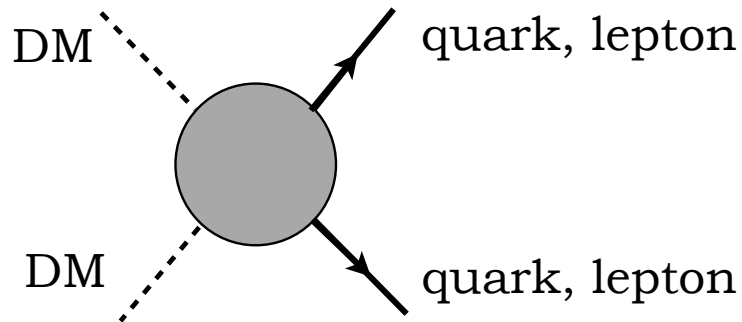
UK DM search
(Boulby mine)



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:

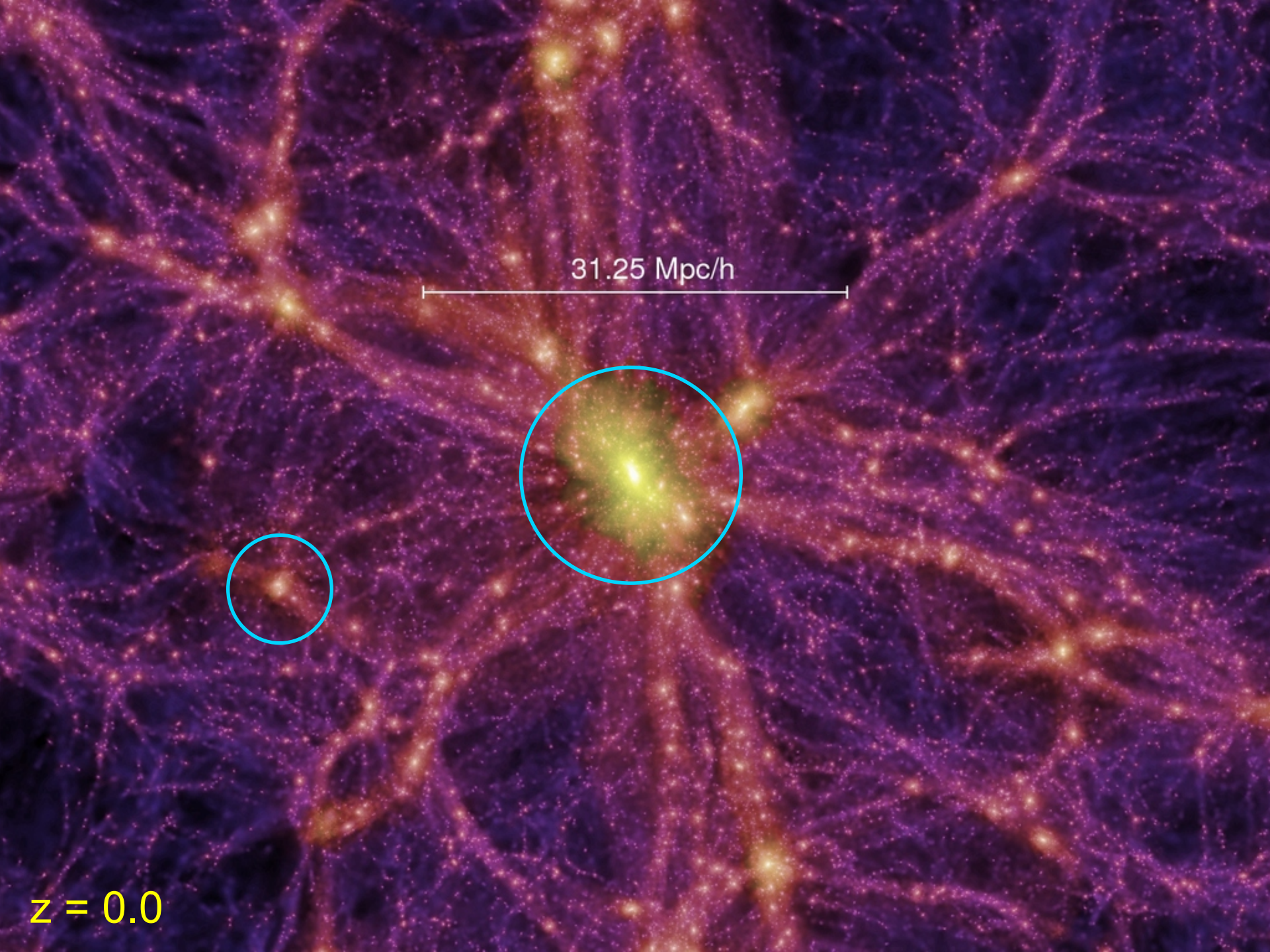
$$I(x) = \frac{1}{8\pi} \sum_f \frac{dN_f}{dE} \langle \sigma_f v \rangle \int_{los} \left(\frac{\rho_\chi}{M_\chi} \right)^2 dl$$

↑ **cross-section** (particle physics) ↓ **halo density at x** (astrophysics)

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

⇒ Theoretical expectation requires knowing **$\rho(x)$**

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

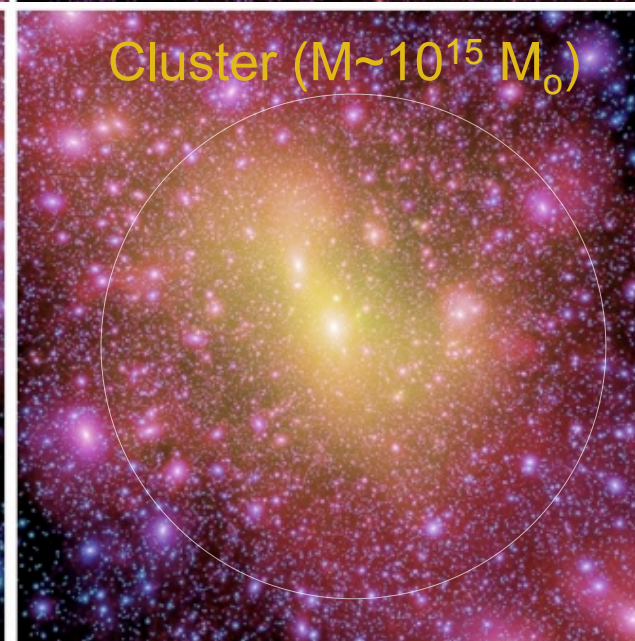
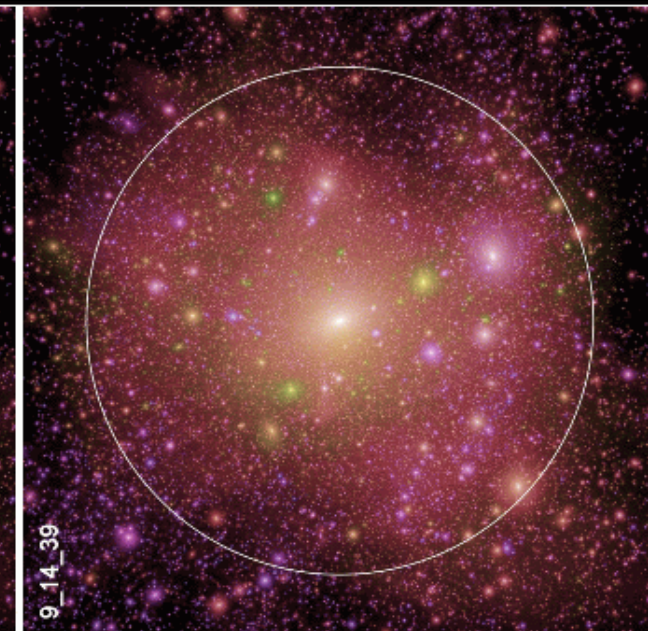
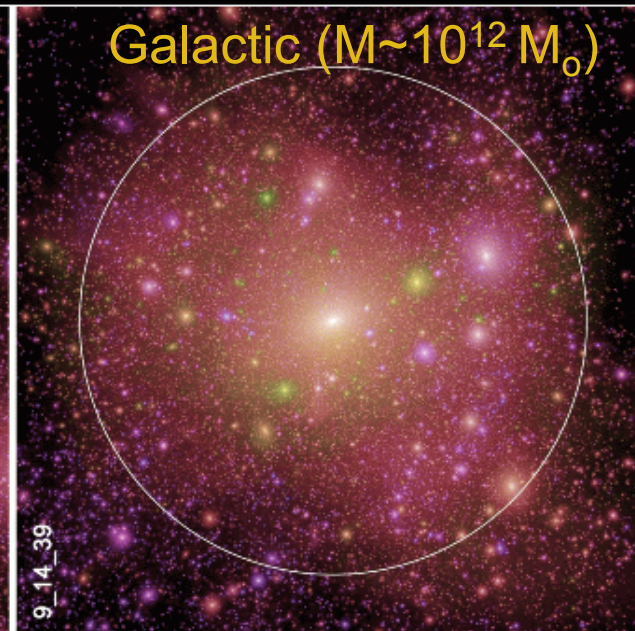
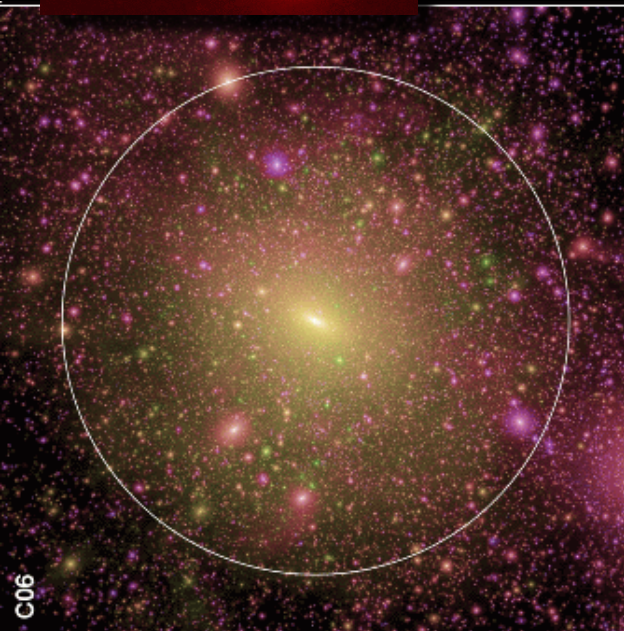


31.25 Mpc/h

$z = 0.0$

VIRG

Aquarius (galactic) & Phoenix (cluster) halos



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



Halo density profiles

NFW:

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

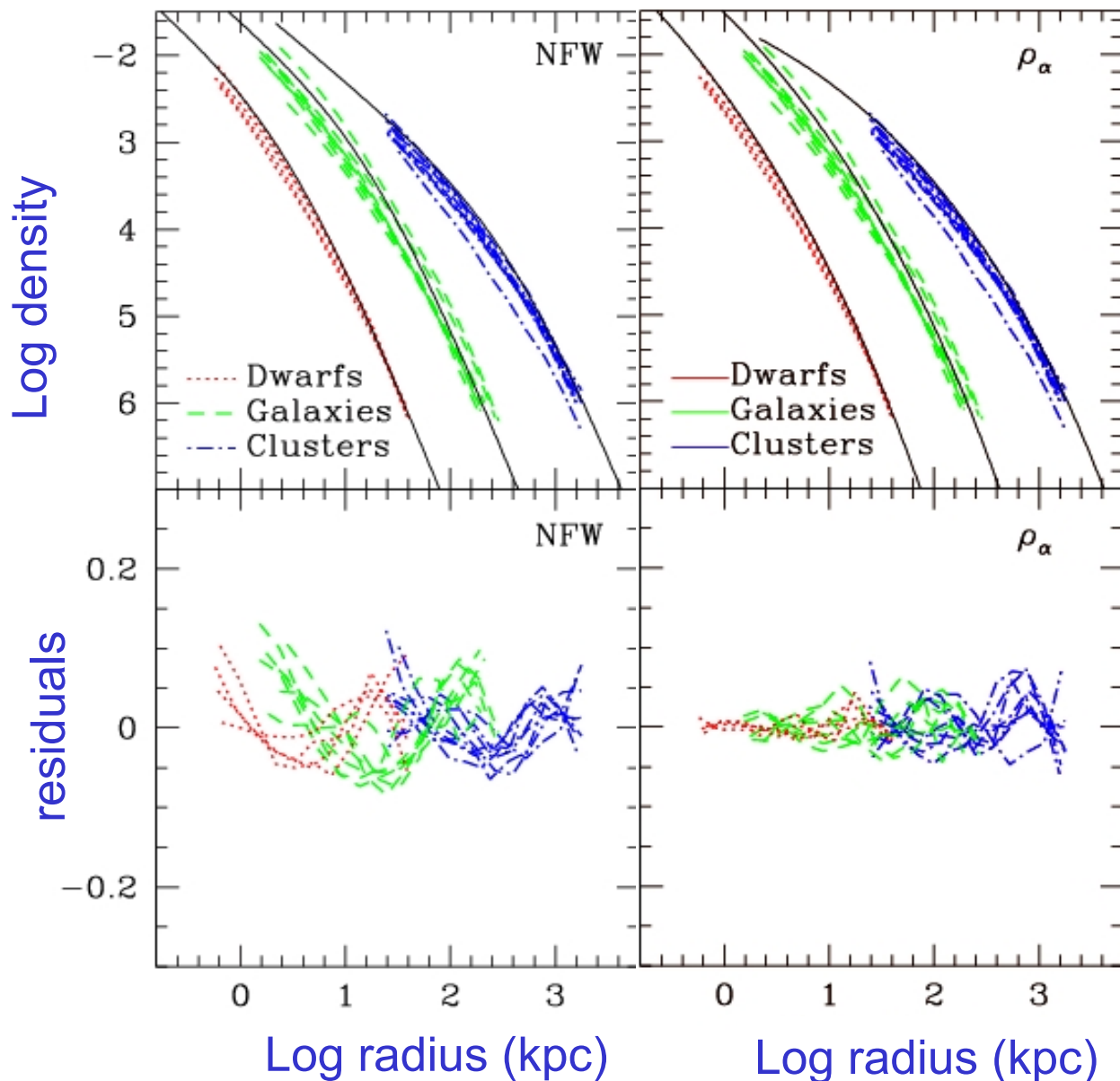
Einasto:

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

Has extra param: α

(similar to stellar
distribution in ellipticals
- Einasto)

Navarro et al 04



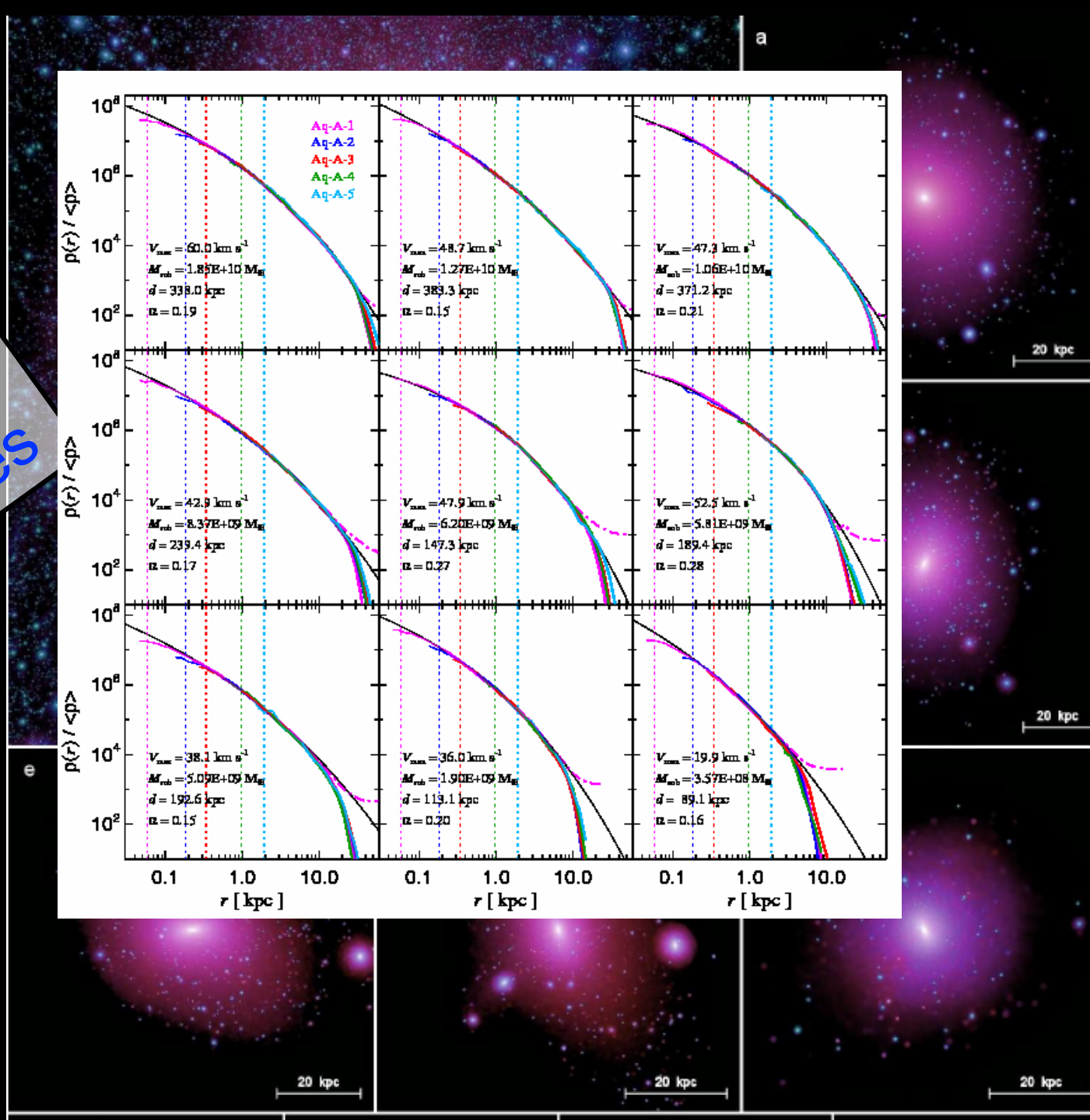
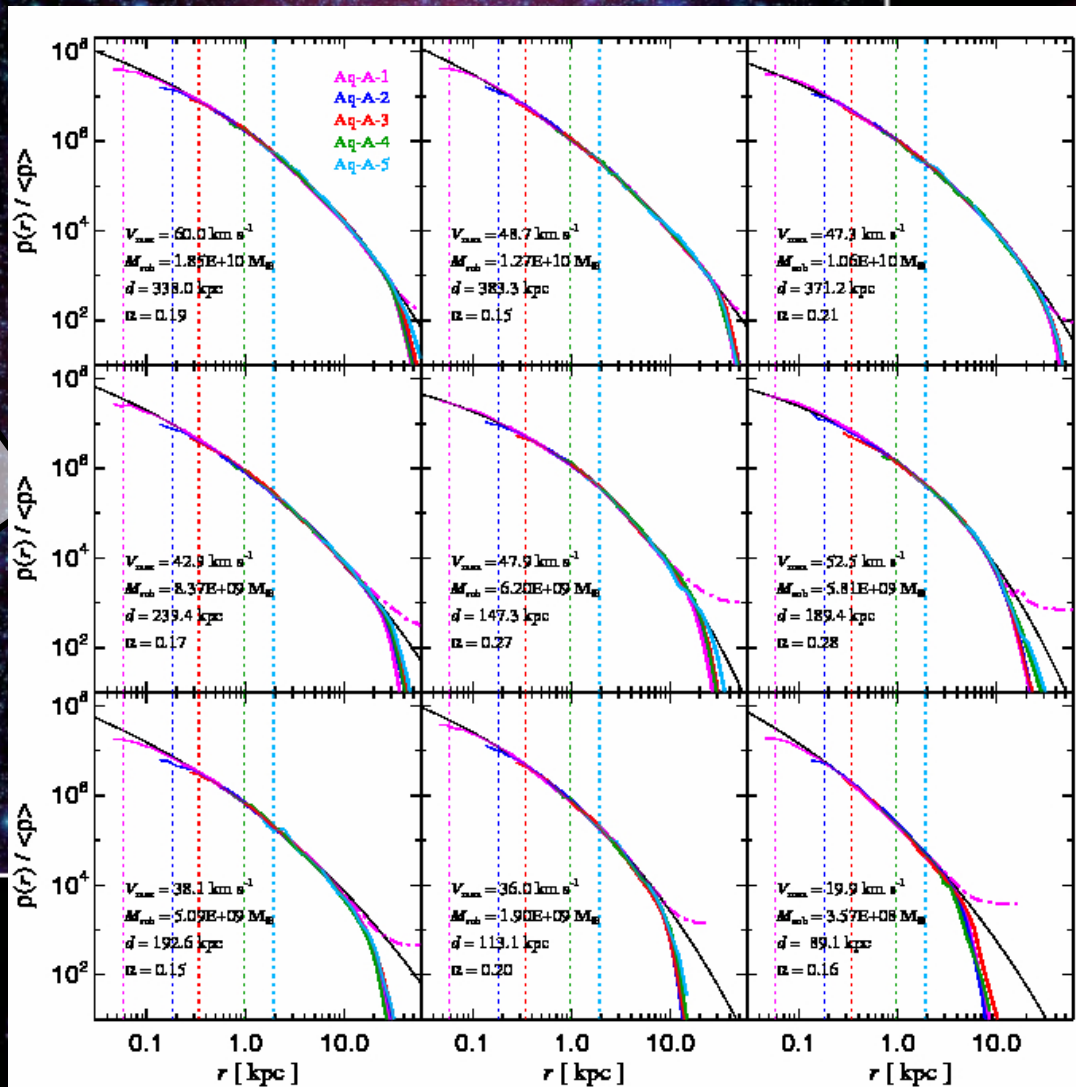


VIRGO

CDM subhalos
also have
cuspy profiles

Aquarius

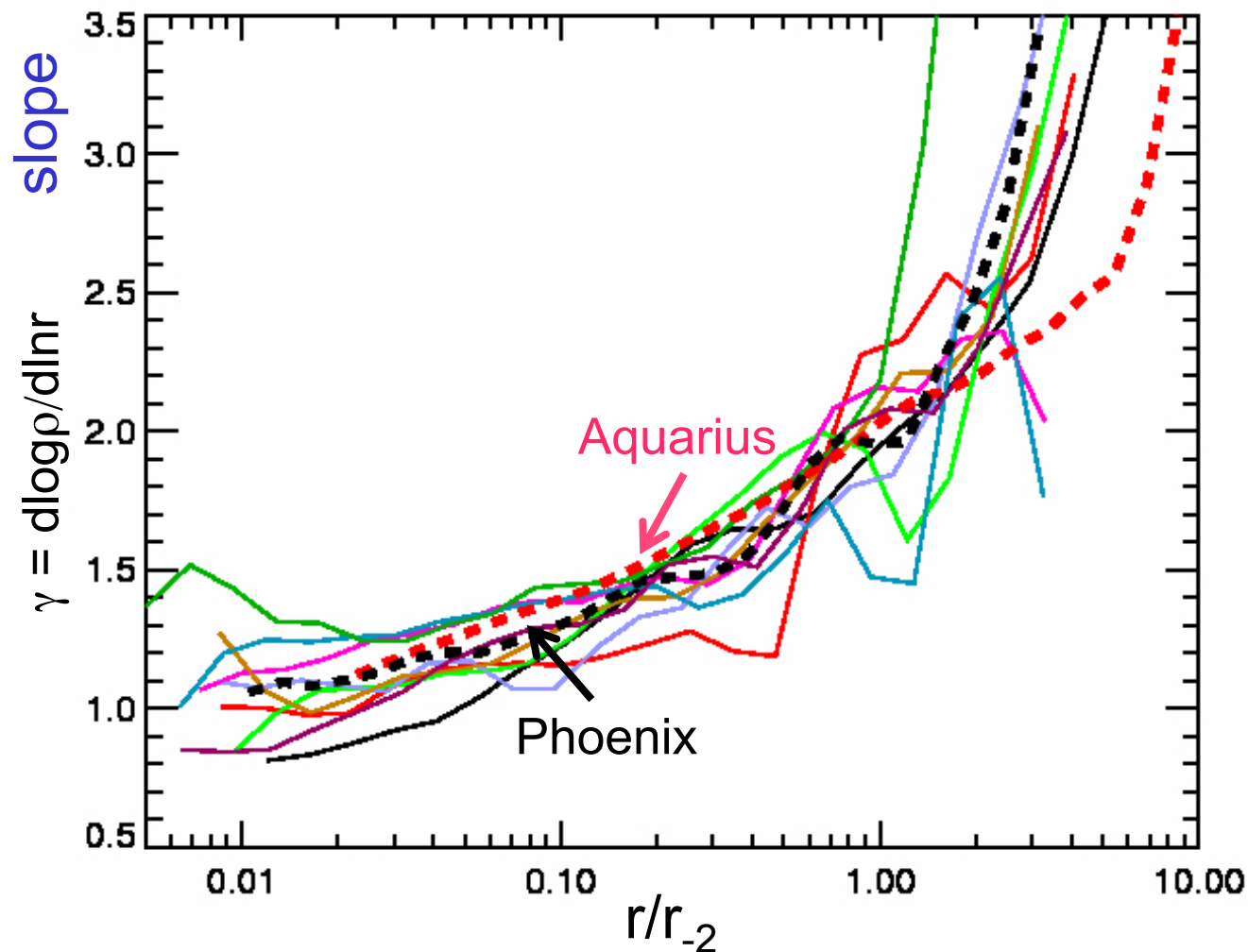
Springel et al '08



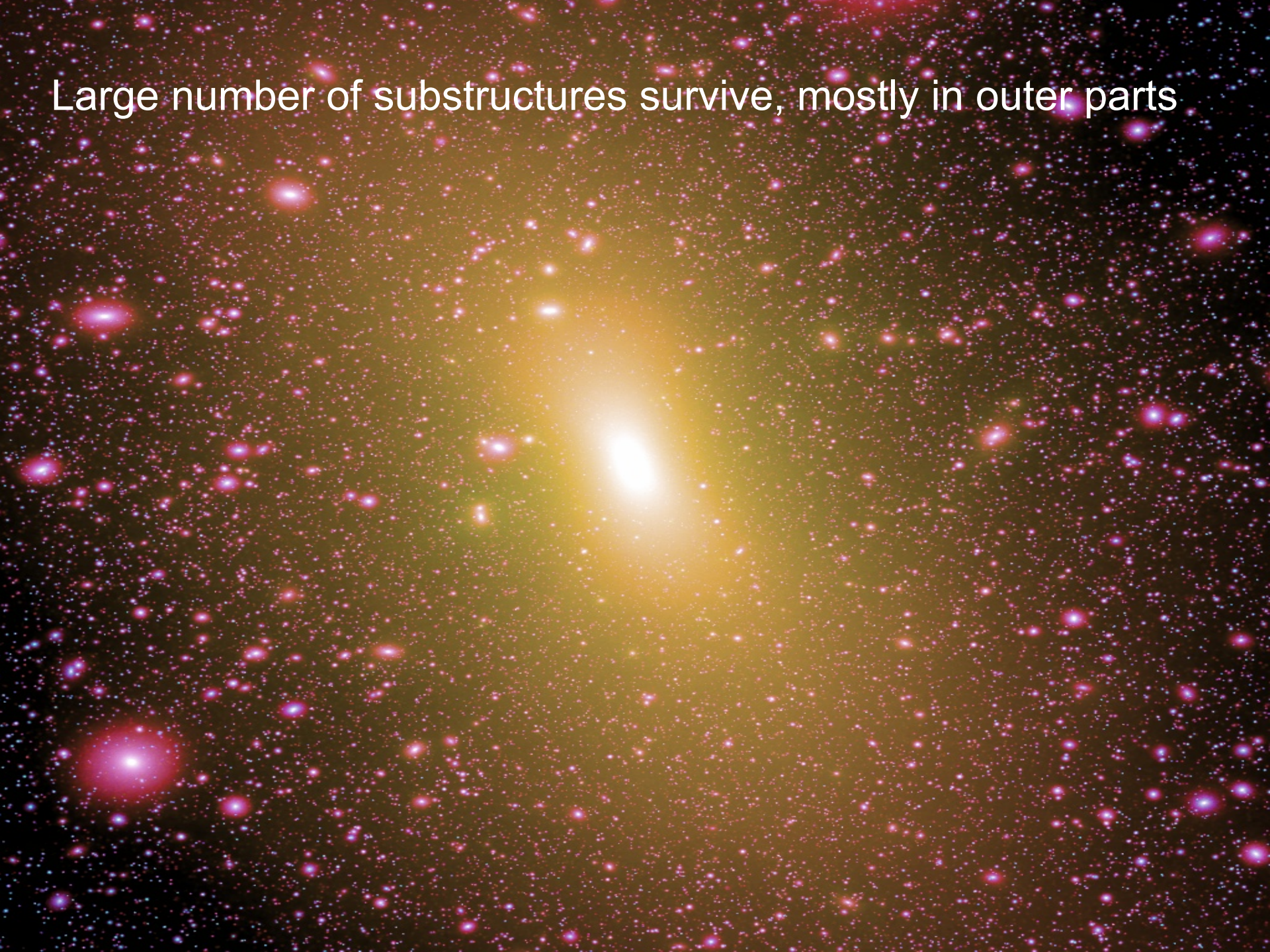
The structure of the cusp

Scatter in the
inner slope

Asymptotic slope ≤ 1

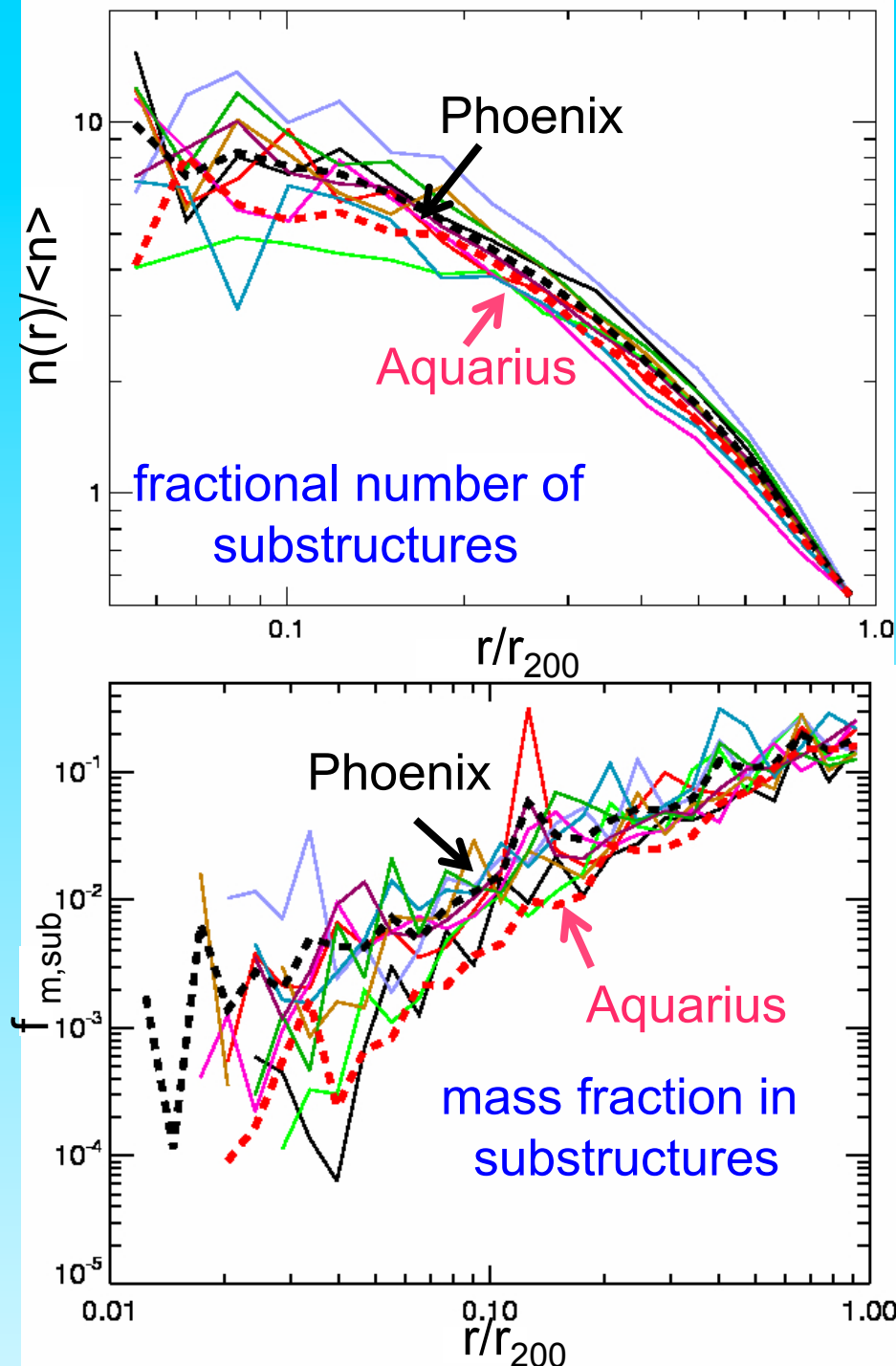


Large number of substructures survive, mostly in outer parts



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

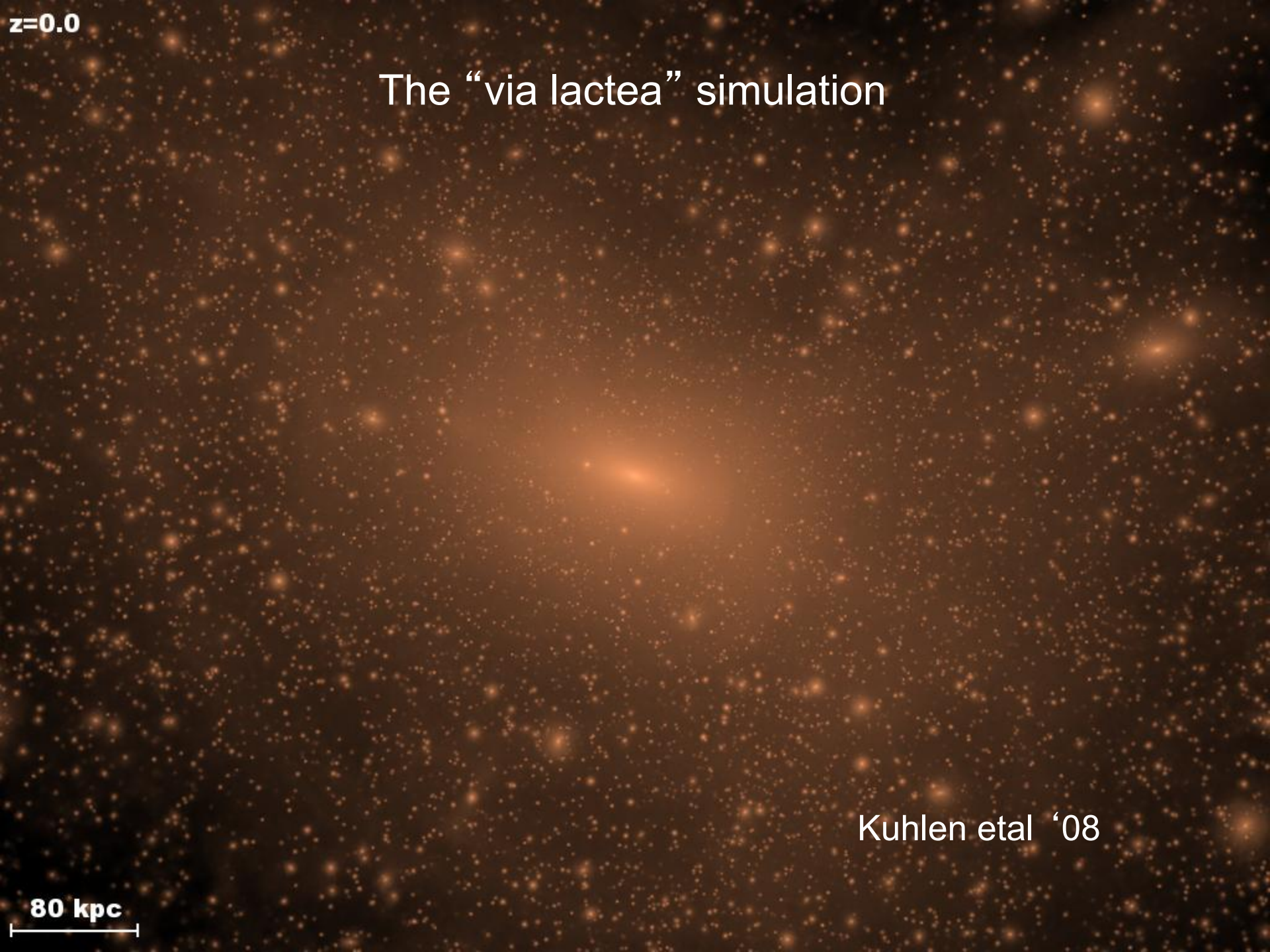


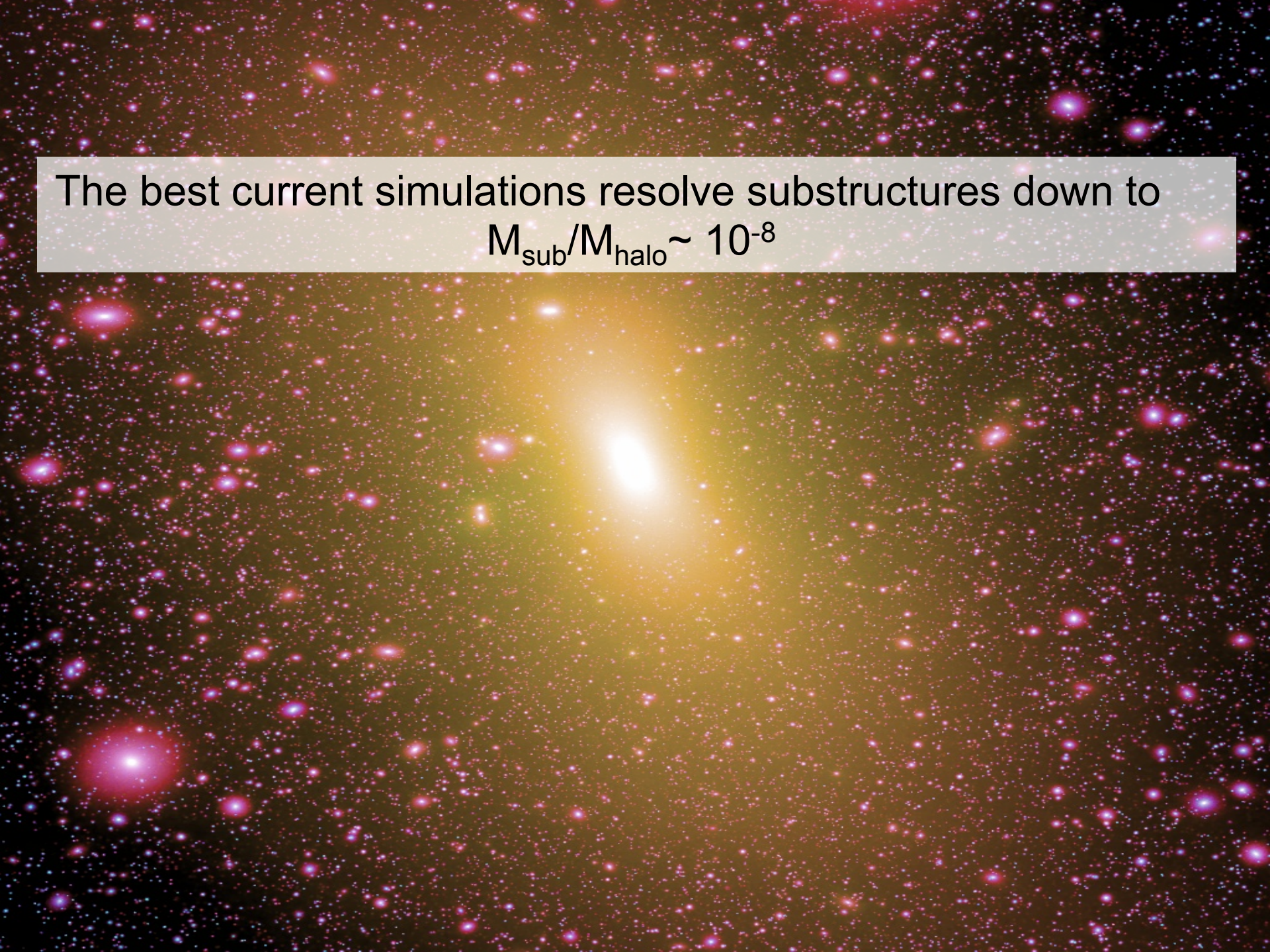
$z=0.0$

The “via lactea” simulation

Kuhlen etal '08

80 kpc



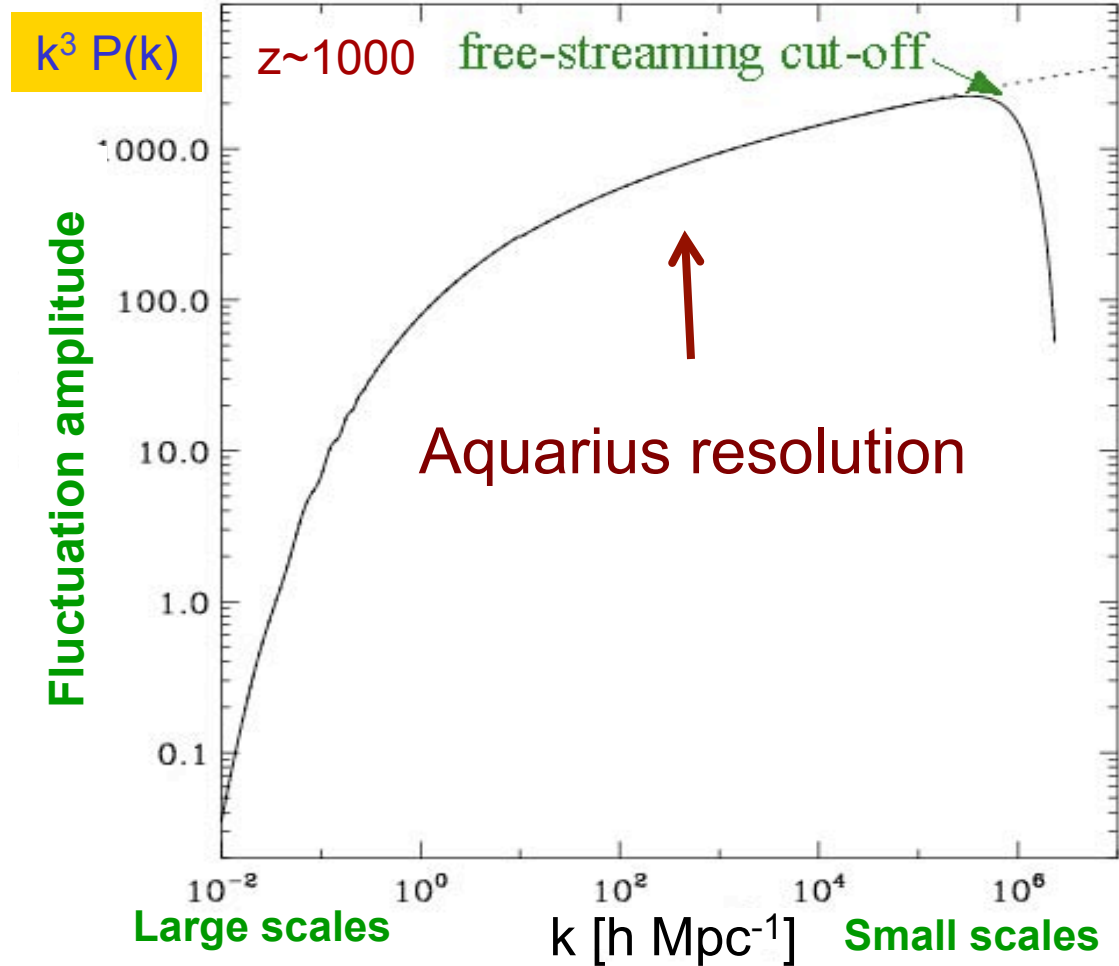
The background of the slide is a deep space image showing a vast field of galaxies. A prominent, bright yellowish-white galaxy cluster is centered in the lower half of the frame, emitting a strong glow. The surrounding space is filled with numerous smaller, distant galaxies in various colors, including red, blue, and white, scattered across a 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





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

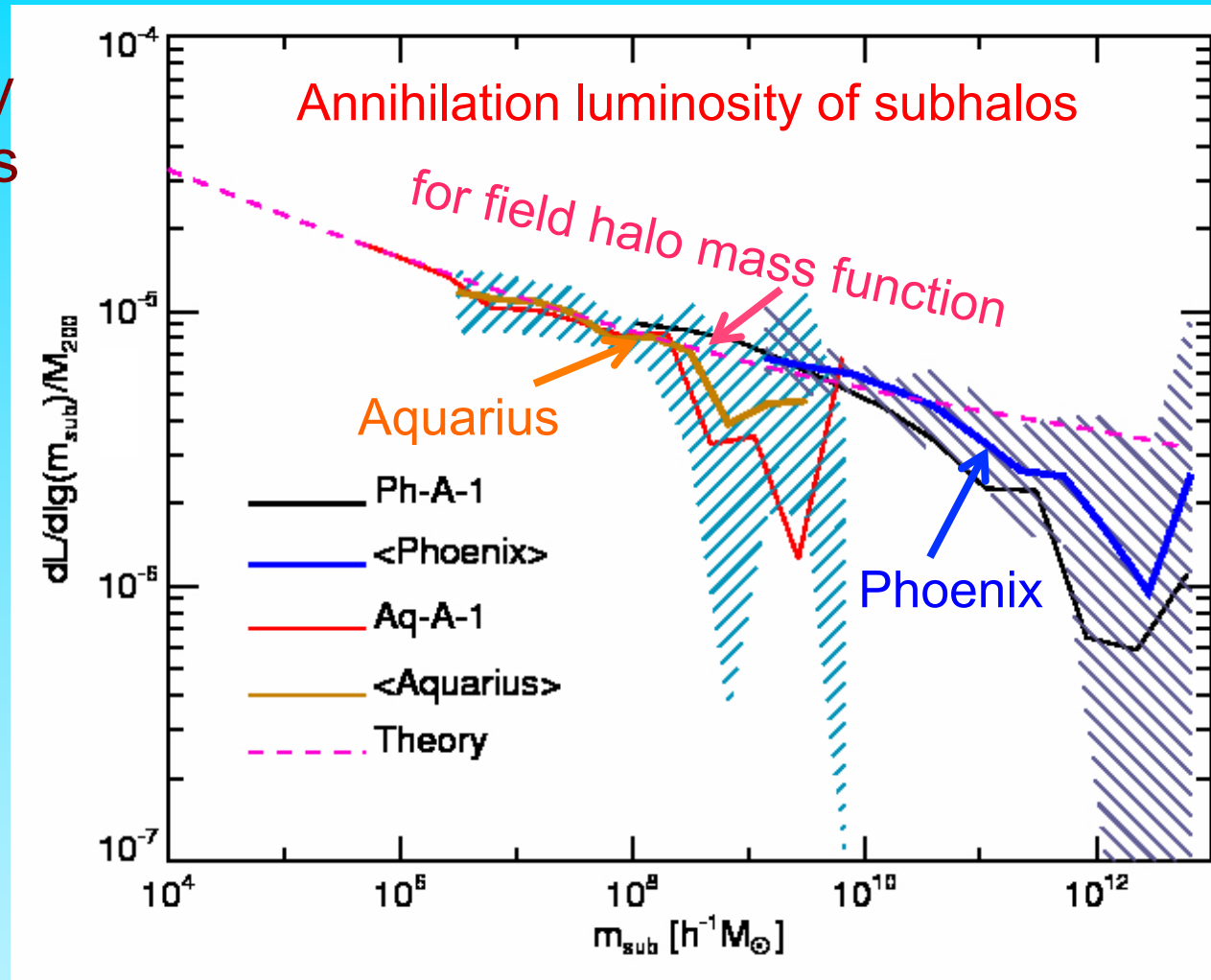
Need to extrapolate to Earth mass
→ gravitational physics

Extrapolation to Earth mass

Annihilation luminosity of subs. per unit mass

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

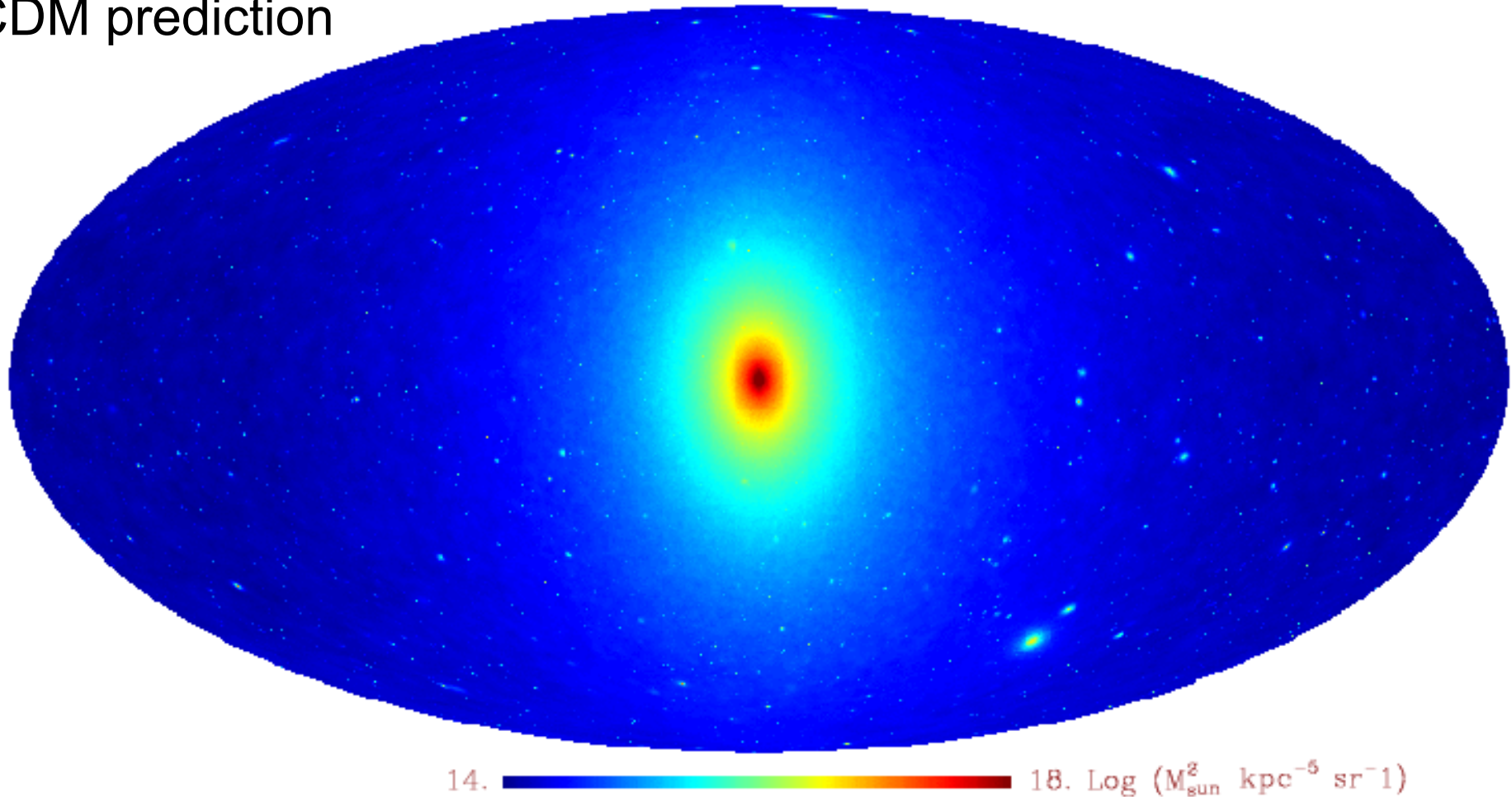
Extrapolate using halo mass function (x1.5) + mass-concentration reln



The Milky Way seen in annihilation radiation

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

CDM prediction

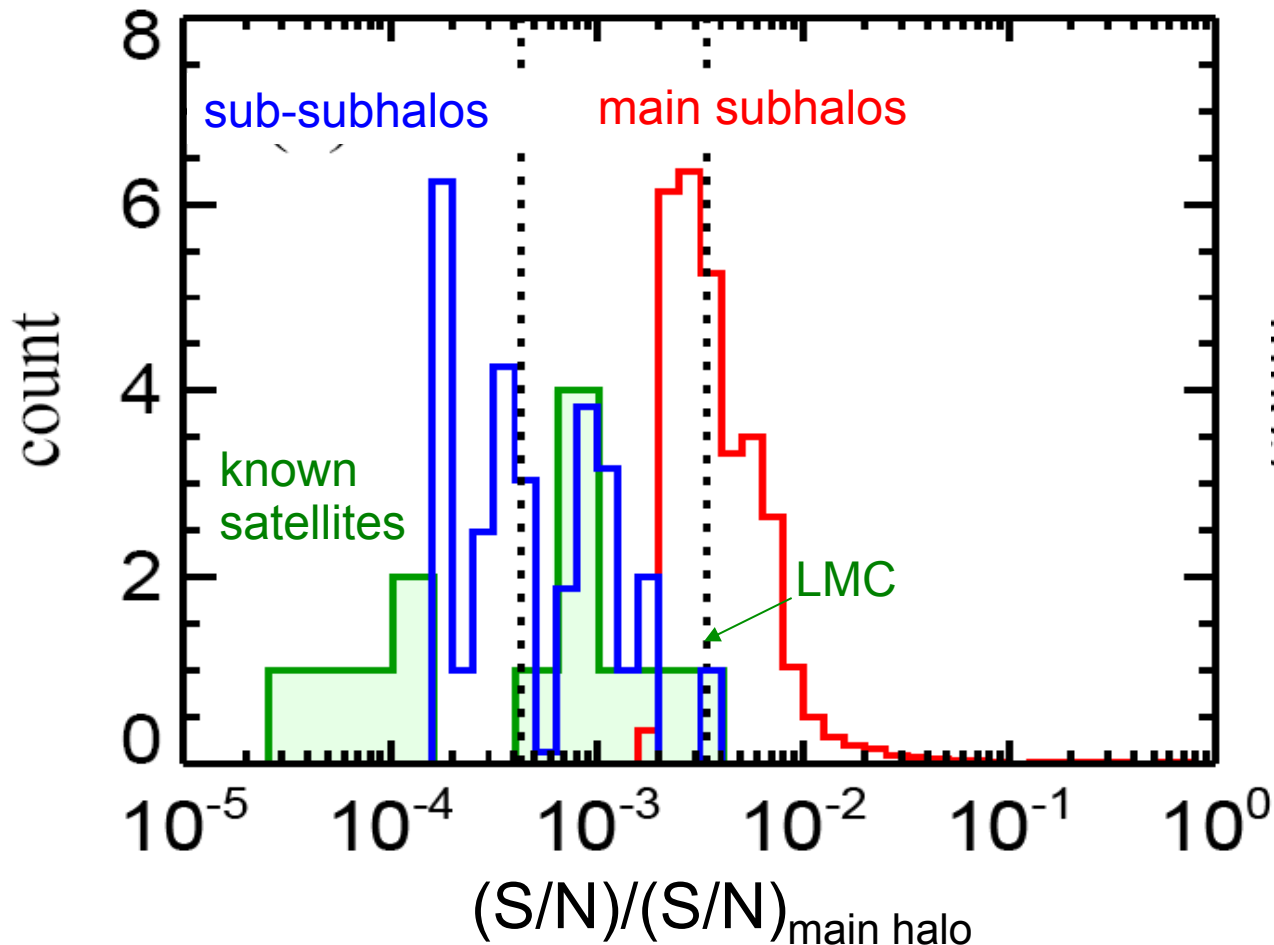


A blueprint for detecting halo CDM

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

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



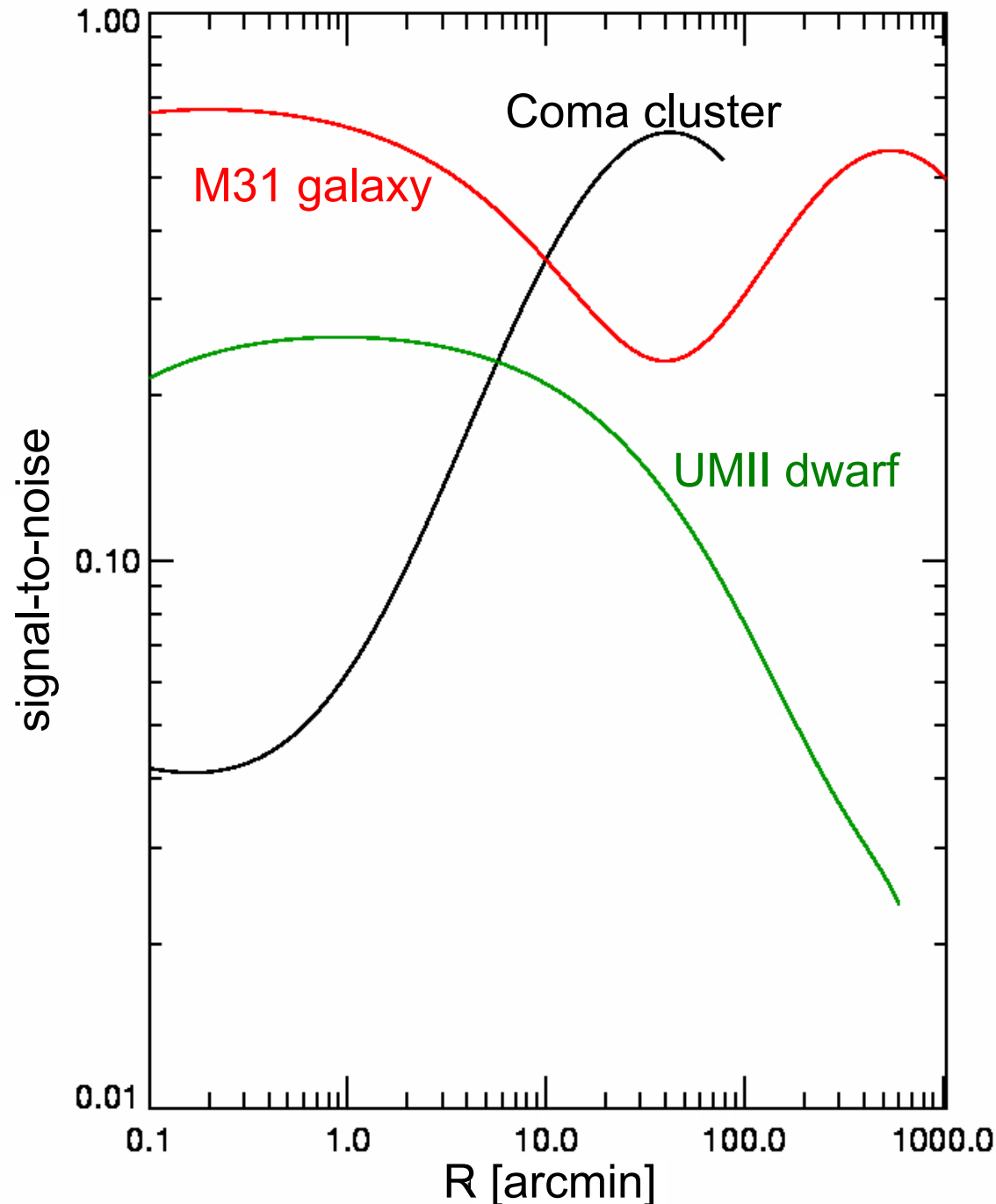
-0.50  2.0 *Log(Intensity)*

Annihilation radiation

Signal-to-noise

larger S/N in clusters
than in MW dwarfs

Gao, Frenk, Jenkins,
Springel & White '11

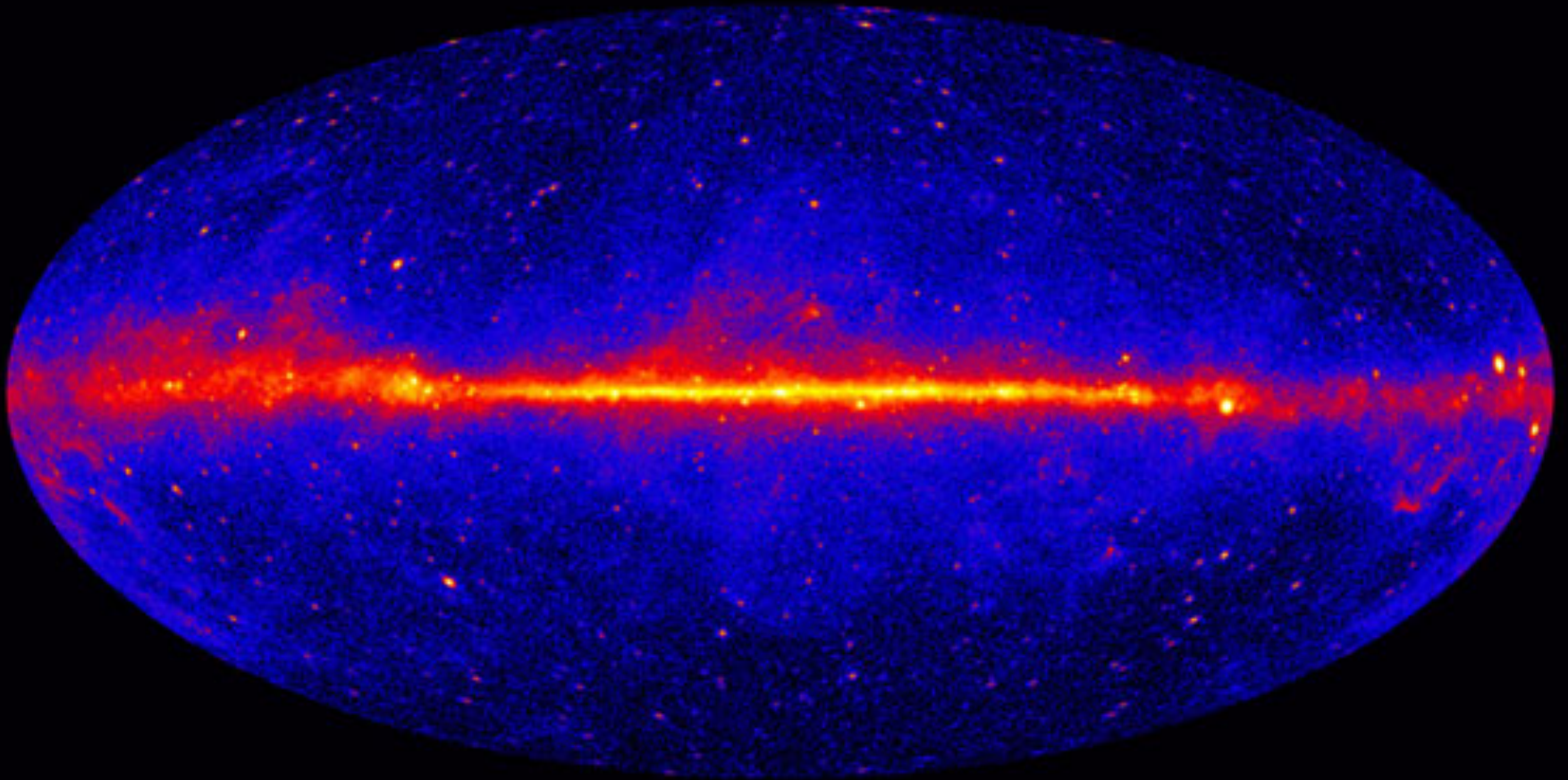


- Galaxy clusters offer the best prospect for detecting dark matter annihilation radiation



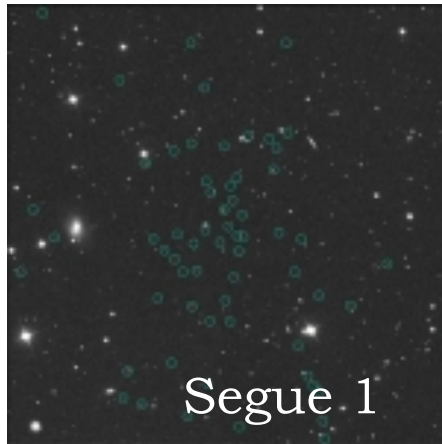


Fermi 3-year all sky map



MW satellites: no Fermi detection

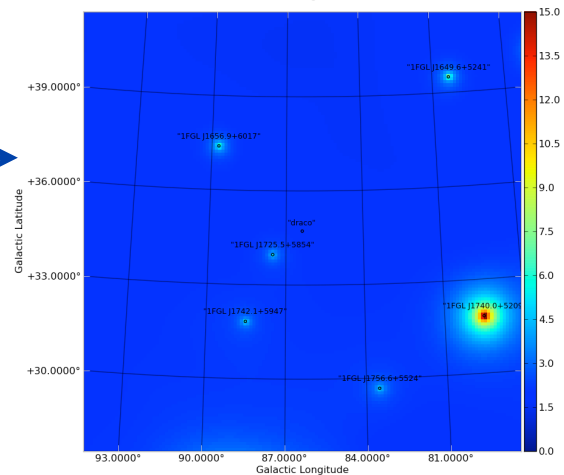
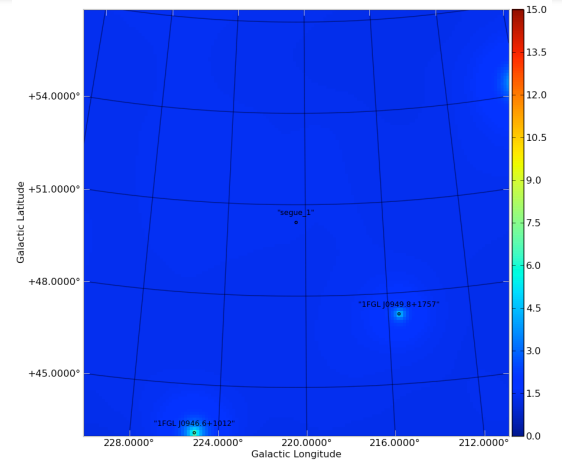
Satellite galaxies in visible light and gamma-rays



Visible
Light

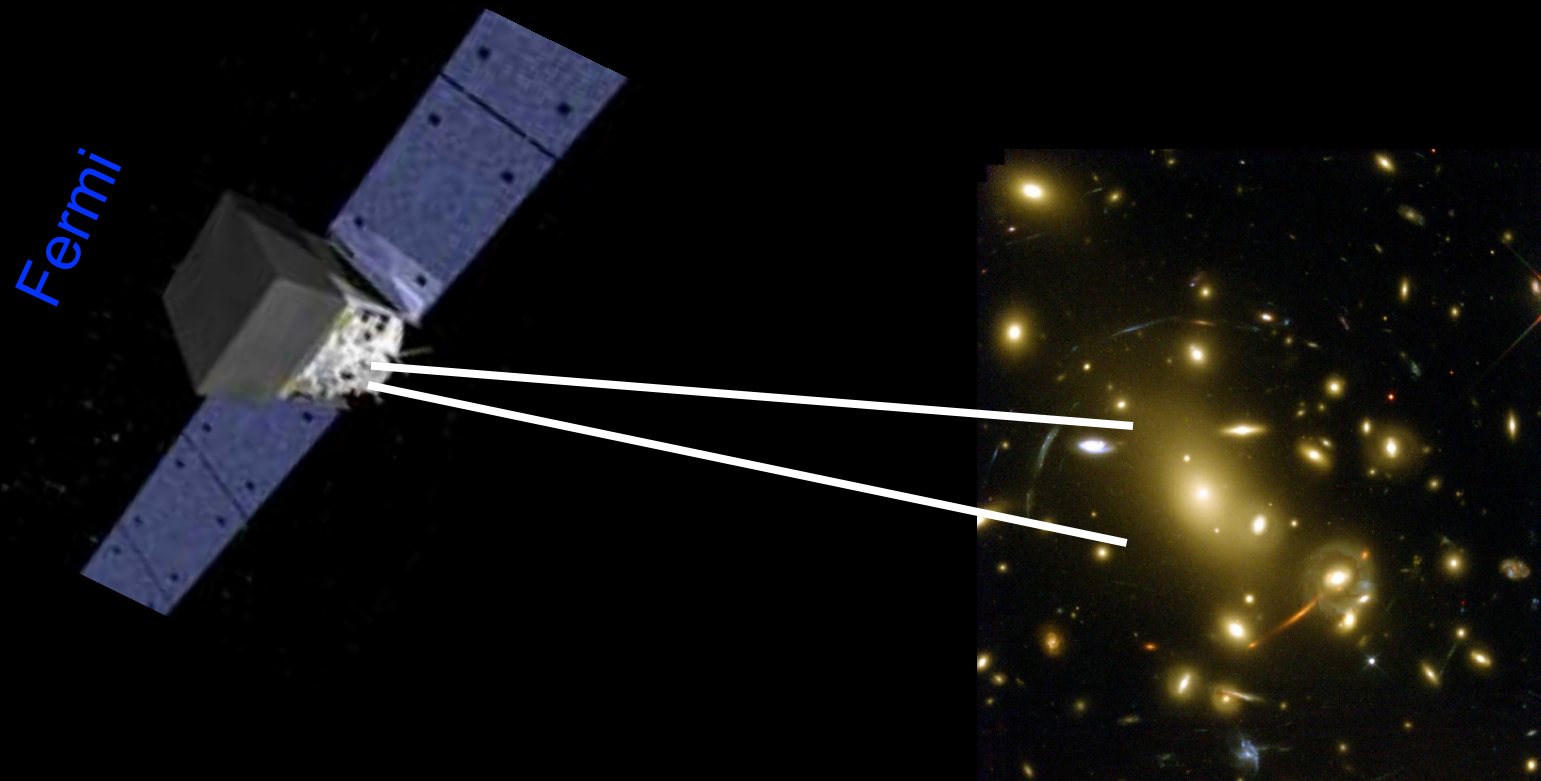


Gamma-
rays





Galaxy clusters in Fermi



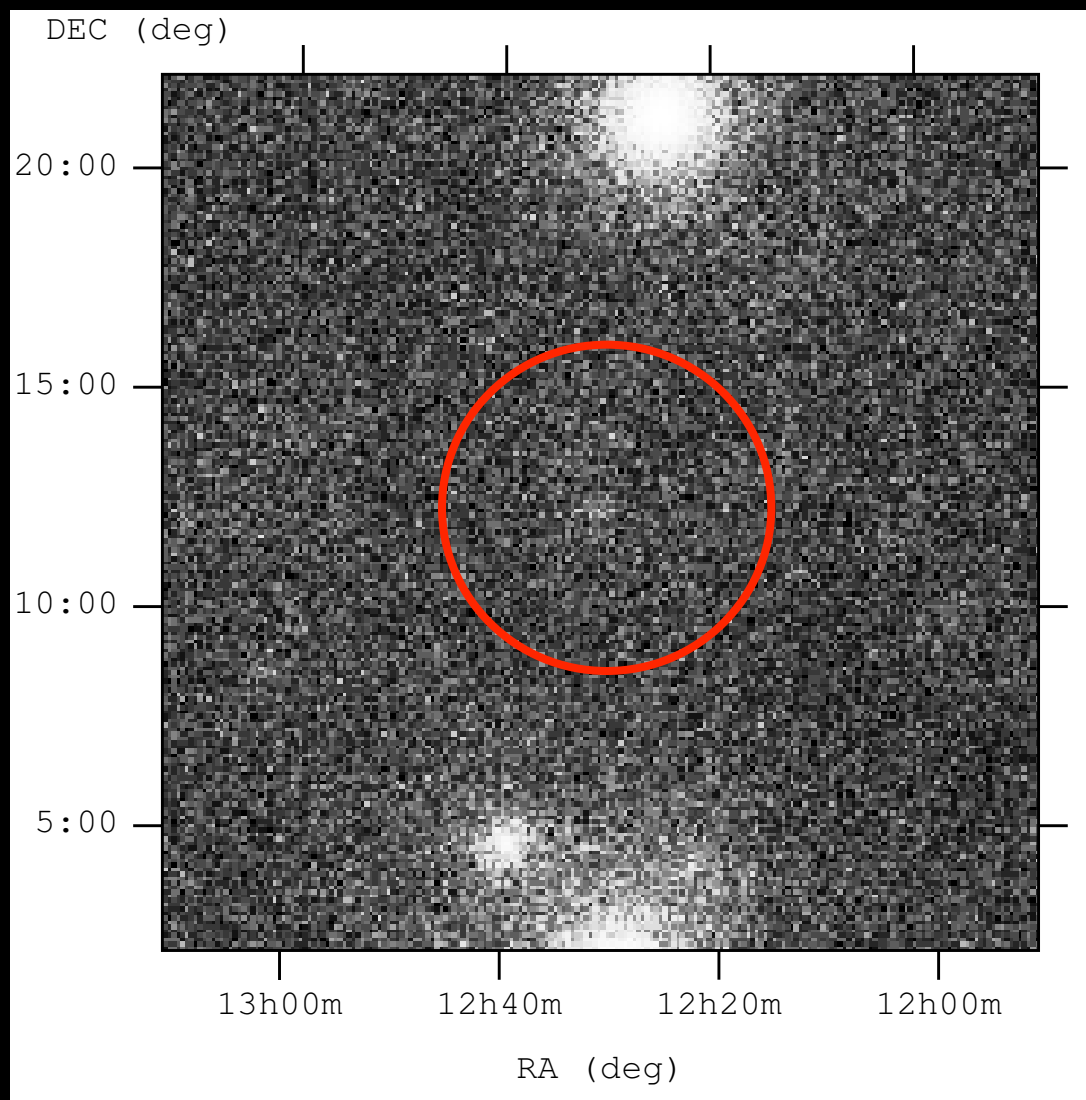


The Virgo cluster in Fermi

Fermi-LAT image

100MeV – 100 GeV

3-year data



Han, Frenk, Eke, Gao, White '12

Upper limits on x-section

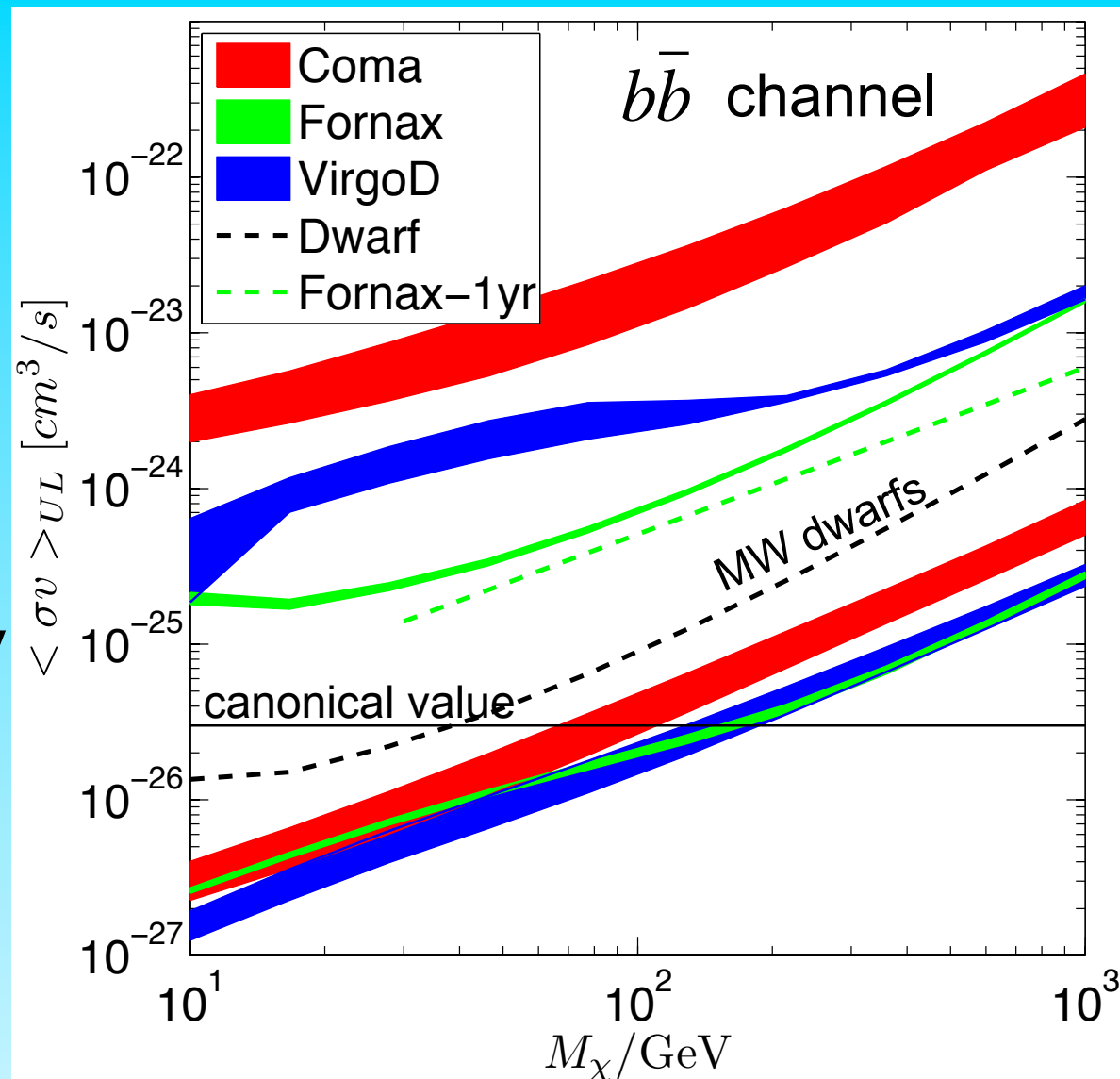
Bands = uncertainty
in CR

Canonical x-section:

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

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

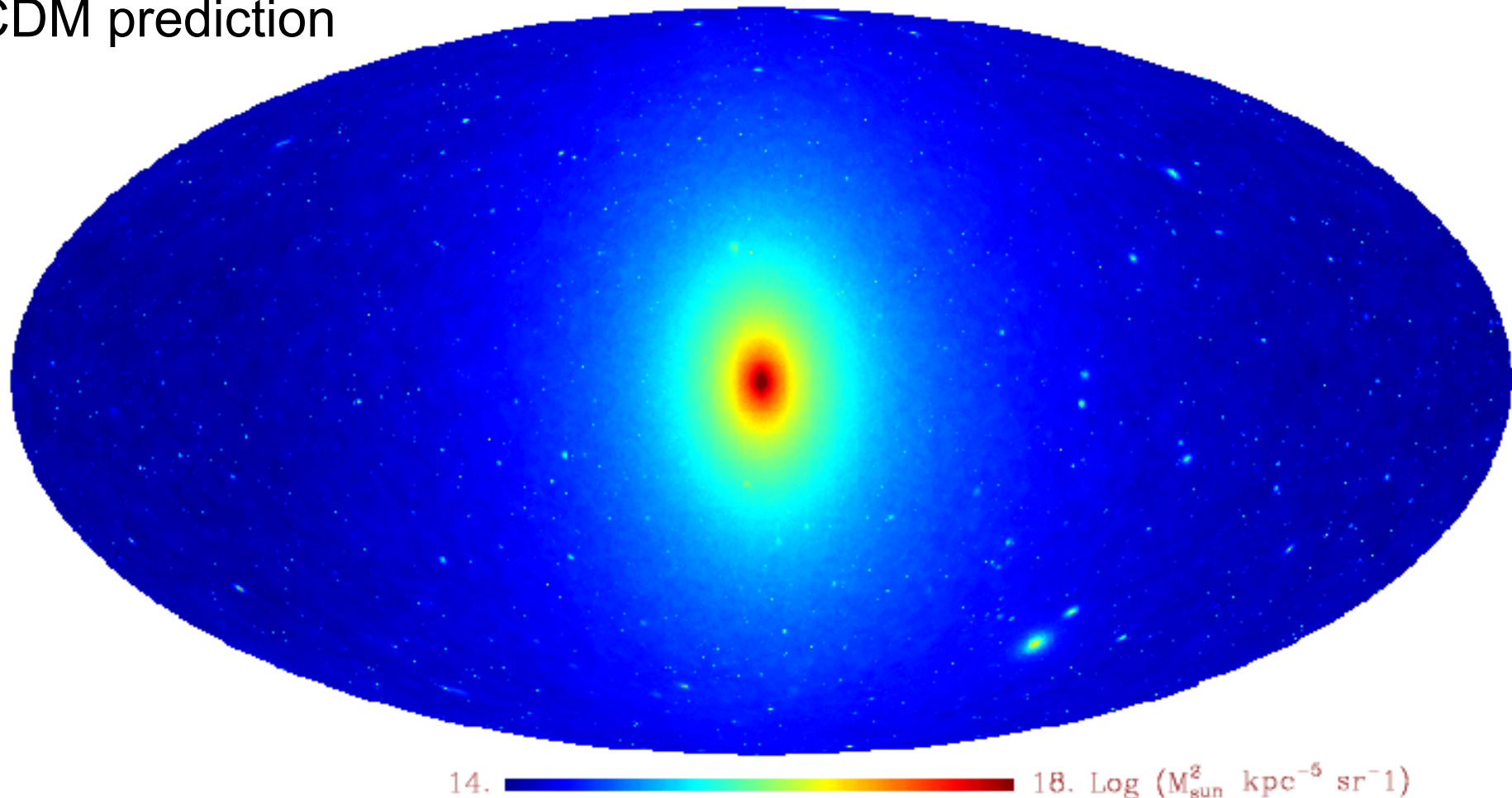
(for $M_{\text{cut}} = 10^{-6} M_{\odot}$)



The Milky Way seen in annihilation radiation

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

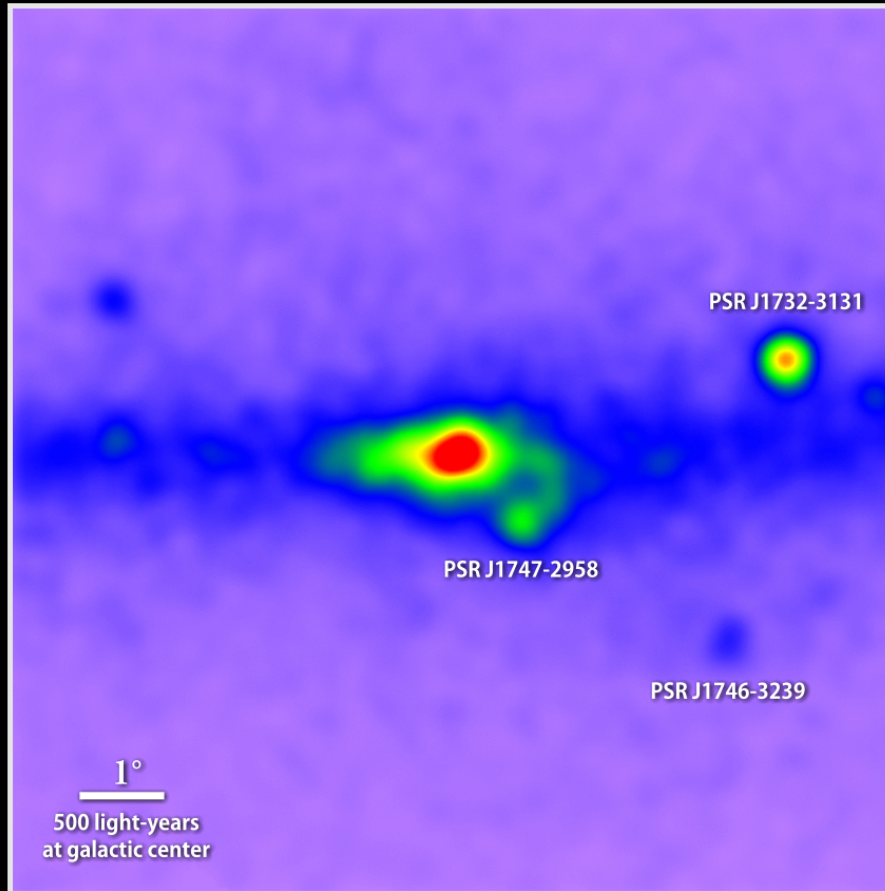
CDM prediction



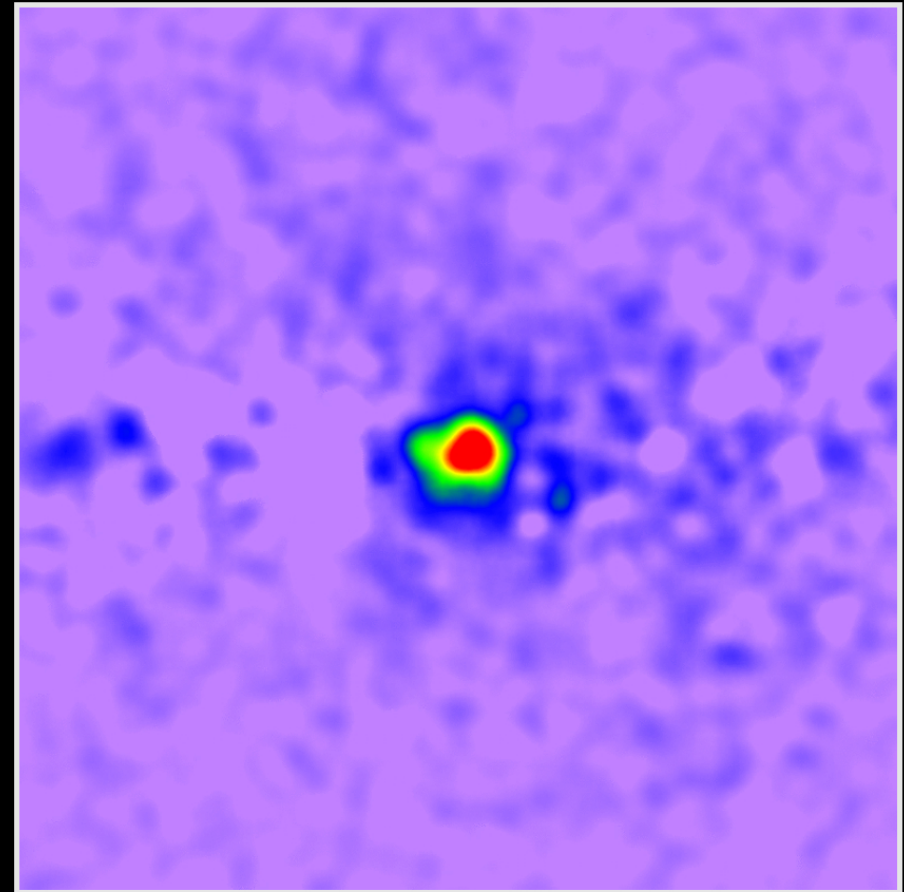
The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,¹ Douglas P. Finkbeiner,^{1,2} Dan Hooper,^{3,4} Tim Linden,⁵
Stephen K. N. Portillo,² Nicholas L. Rodd,⁶ and Tracy R. Slatyer^{6,7}

Uncovering a gamma-ray excess at the galactic center

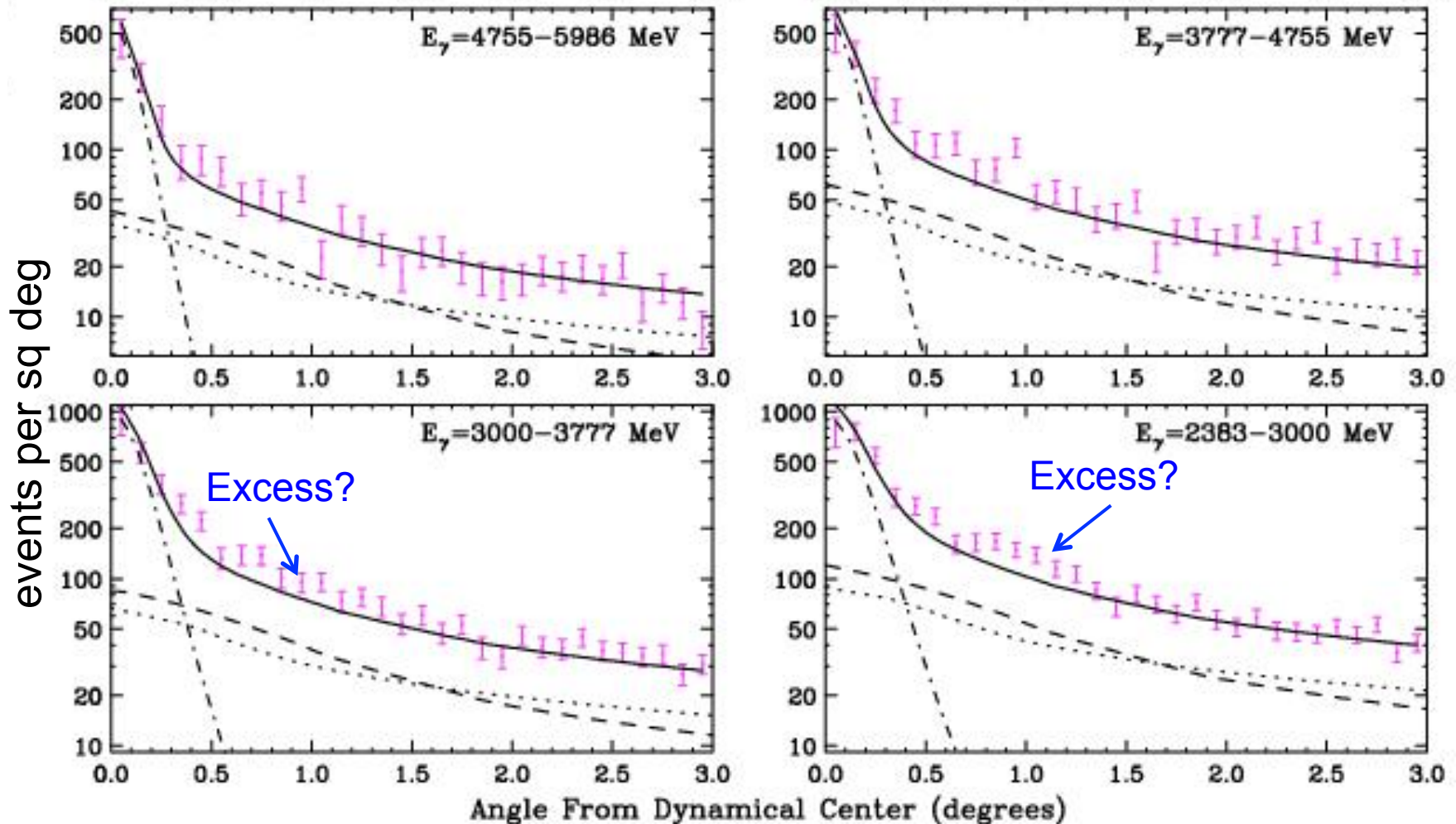


Unprocessed map of 1.0 to 3.16 GeV gamma rays



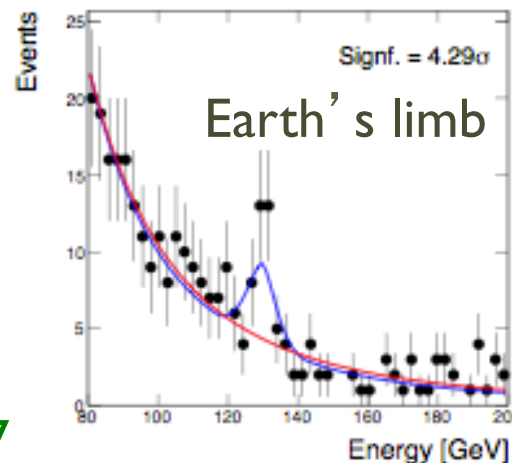
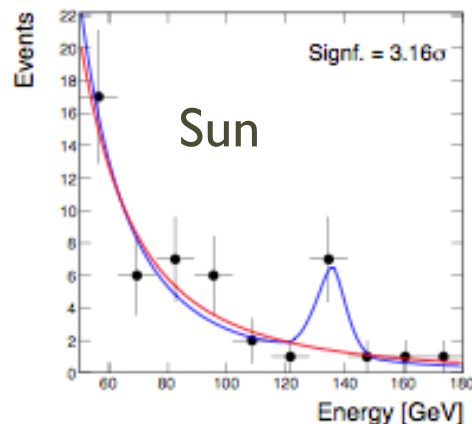
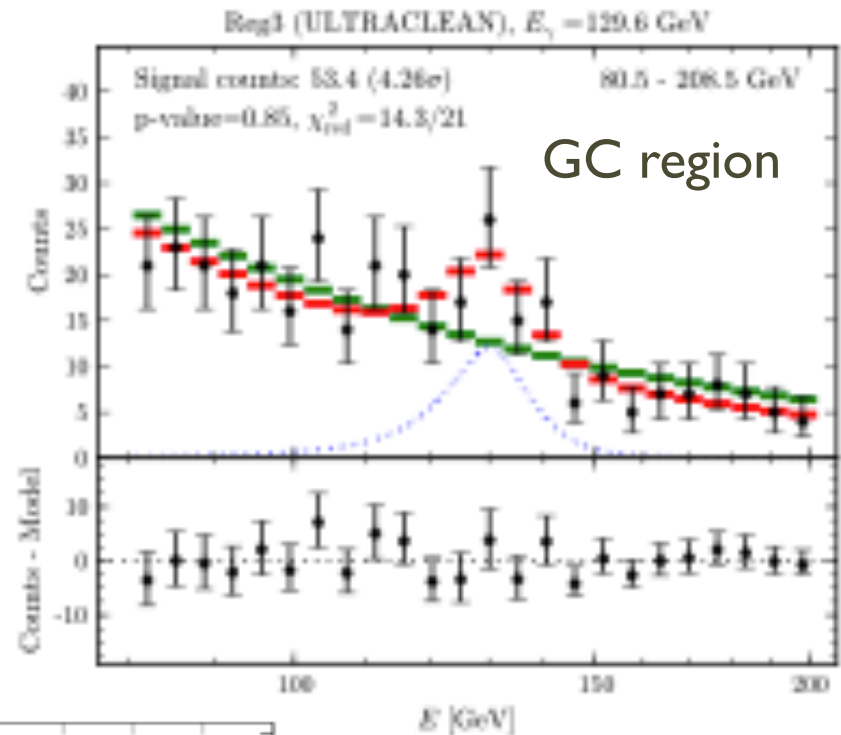
Known sources removed

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)



Weniger, arXiv:1204.2797

Is the line real?

Whiteson, arXiv:1302.0427

From Joachim Edsjo

Conclusions so far

Direct detection

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

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
 - 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

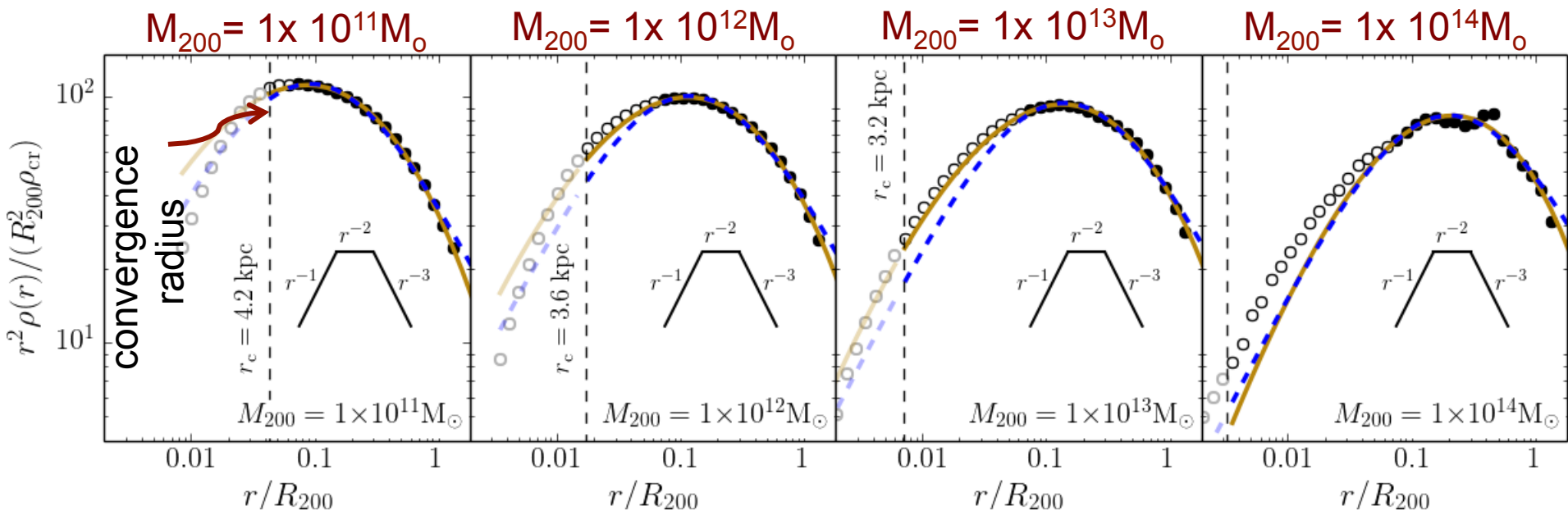
Does nature have them?

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

Best places to look: $\left\{ \begin{array}{l} \text{Clusters (good diagnostics)} \\ \text{Dwarf gals (high M/L)} \end{array} \right.$

Baryon effects on dark matter halos

Eagle simulations: dark matter-only run



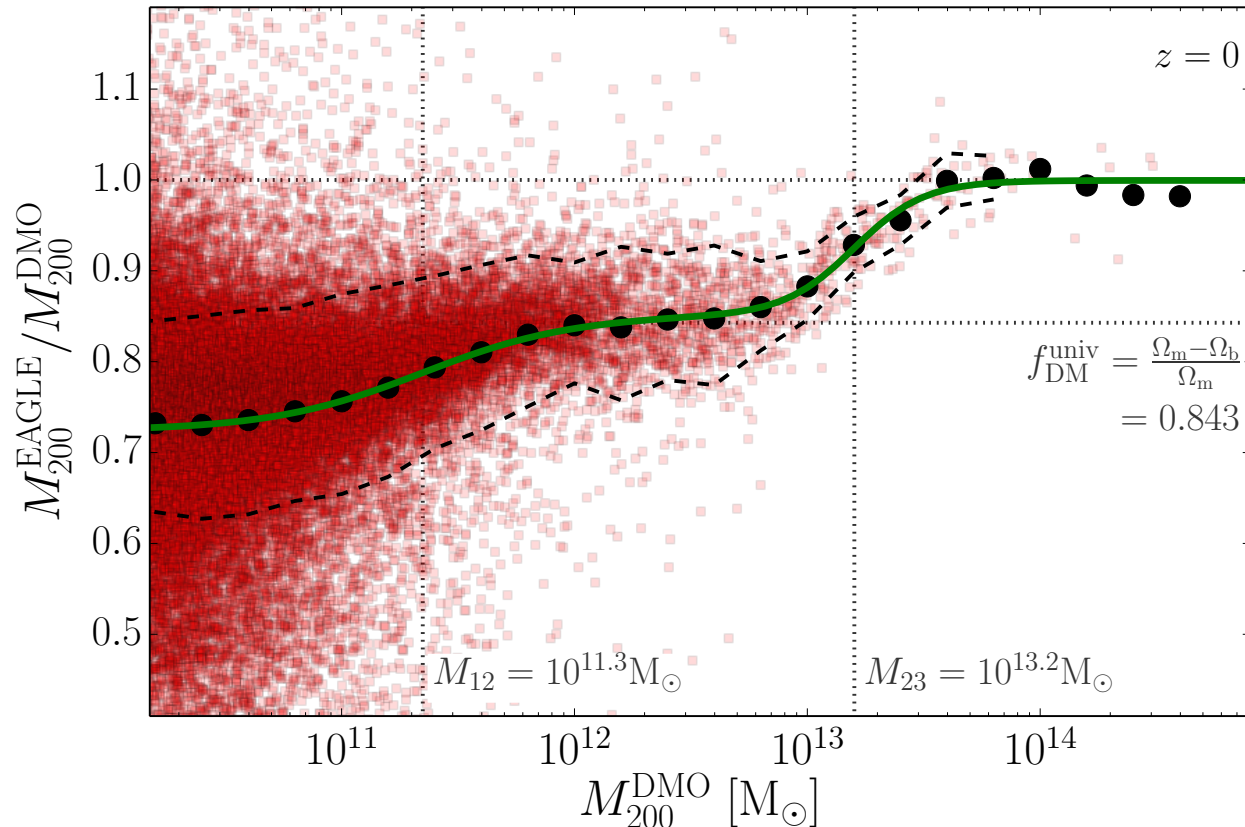
Halos in DM-only run well fit by NFW or Einasto profiles

Schaller, Frenk et al. '15a

Baryon effects on dark matter halos

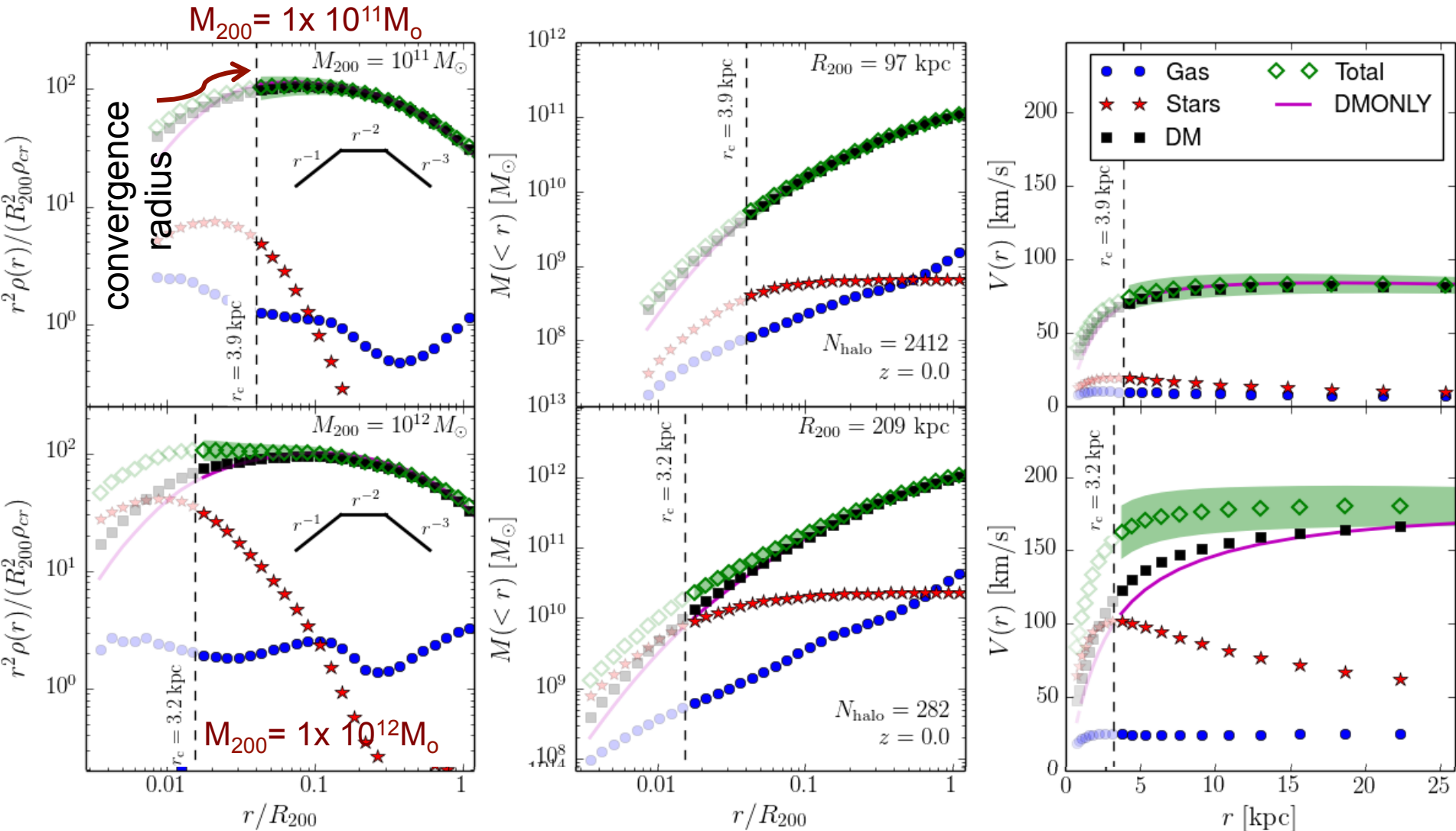
Baryon effects
reduce the mass of
halos of $M < 3 \times 10^{13} M_{\odot}$
by up to 30%

SN winds expel gas
at high z and this
reduces mass and
halo growth rate

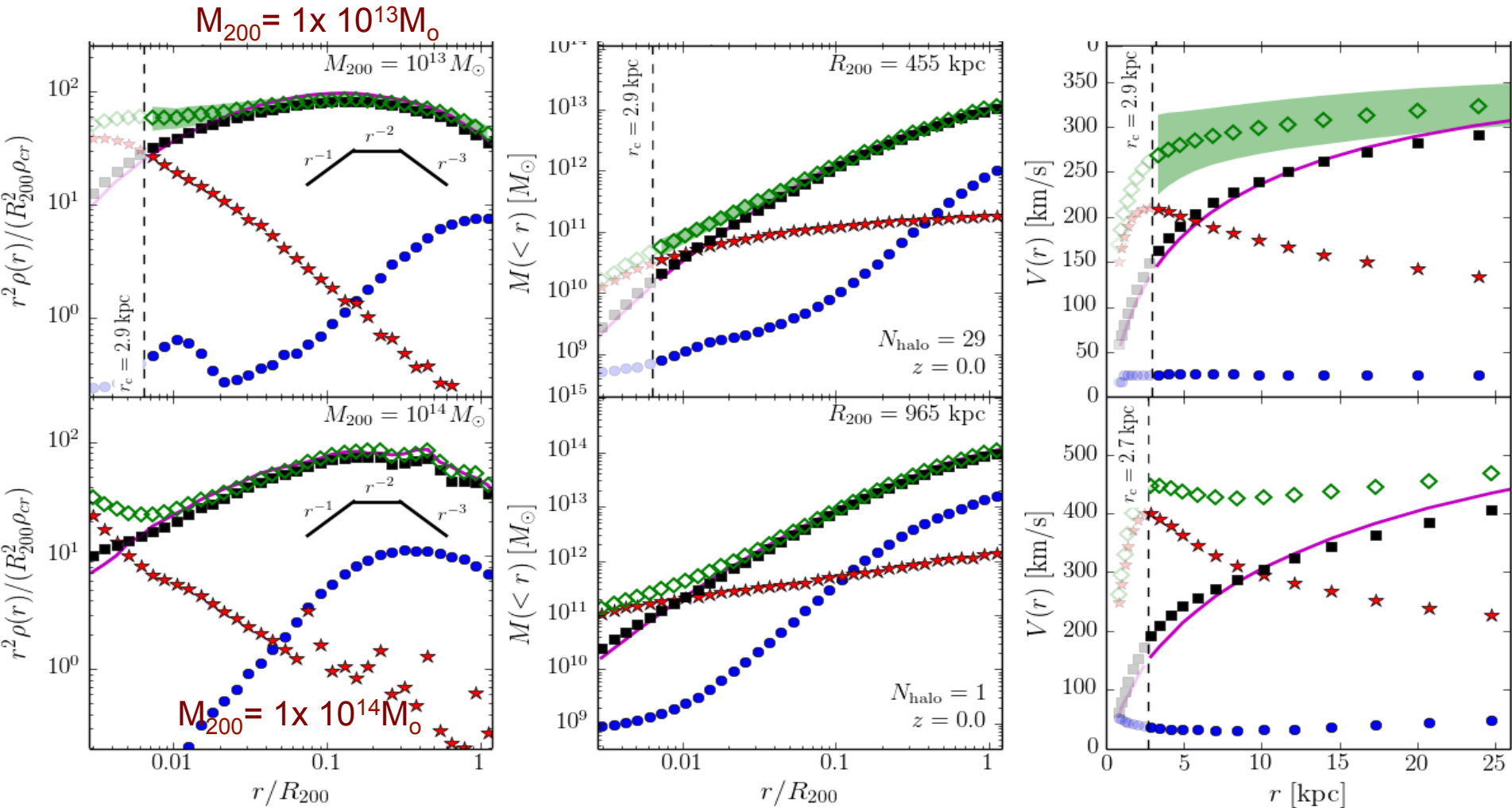


Schaller, Frenk et al. '15a

Baryon effects on dark matter halos

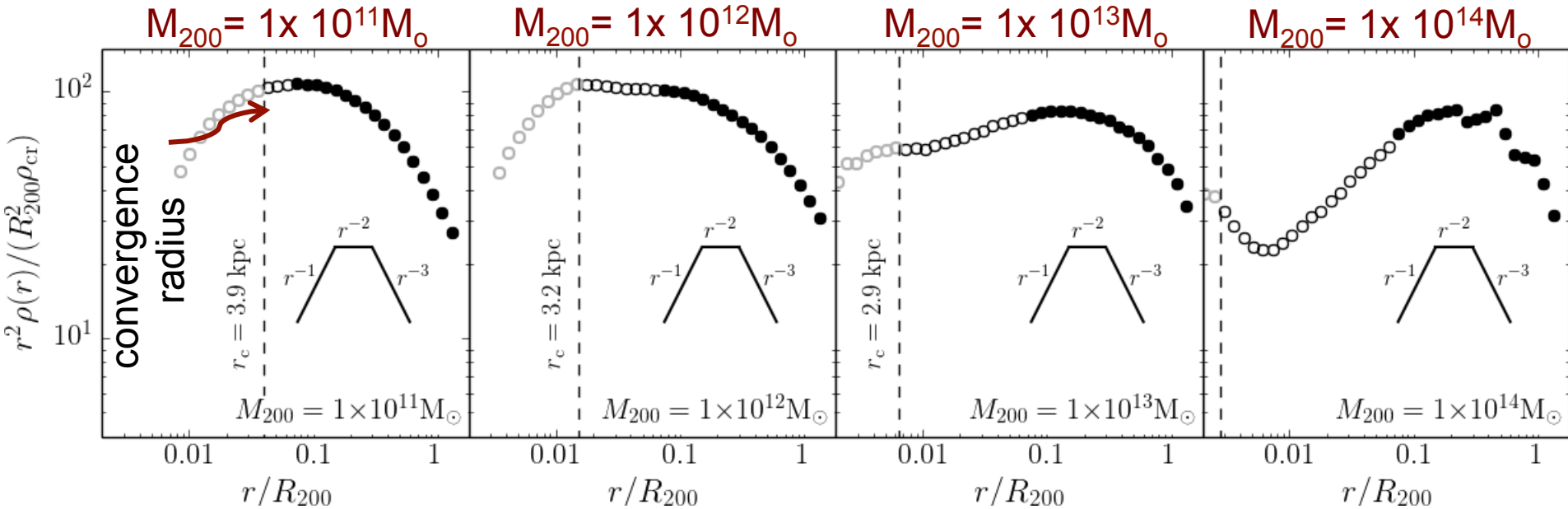


Baryon effects on dark matter halos



Baryon effects on dark matter halos

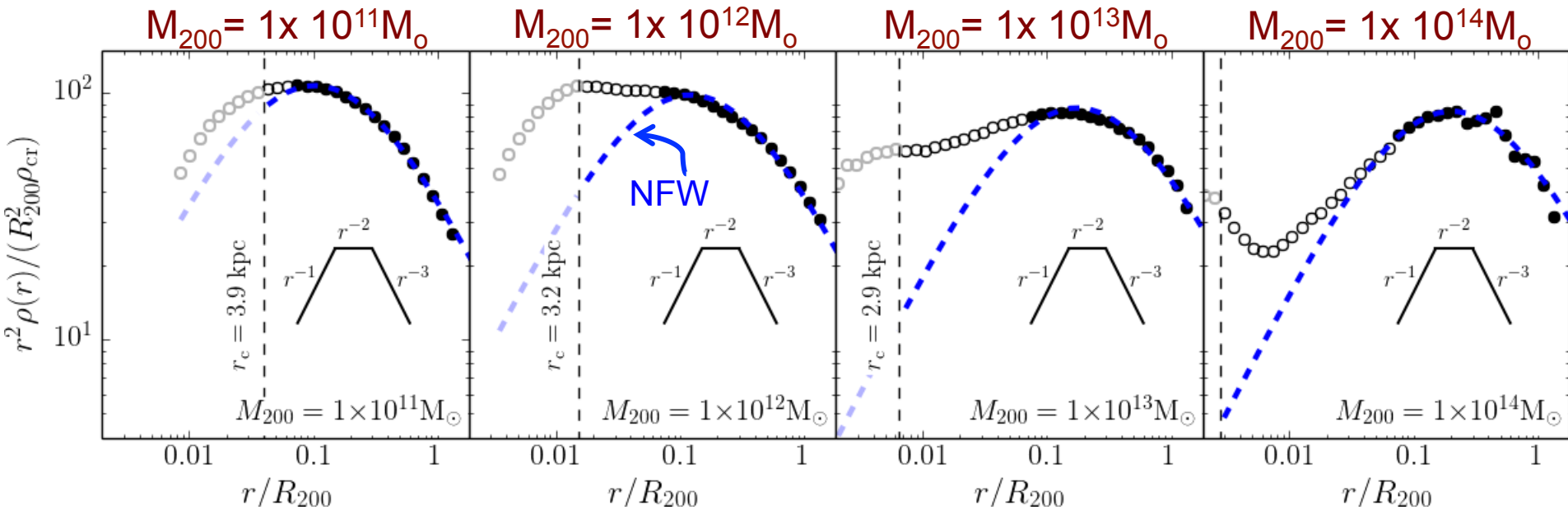
Eagle simulations: total matter profiles



Filled circles $r > 0.05 R_{200}$

Baryon effects on dark matter halos

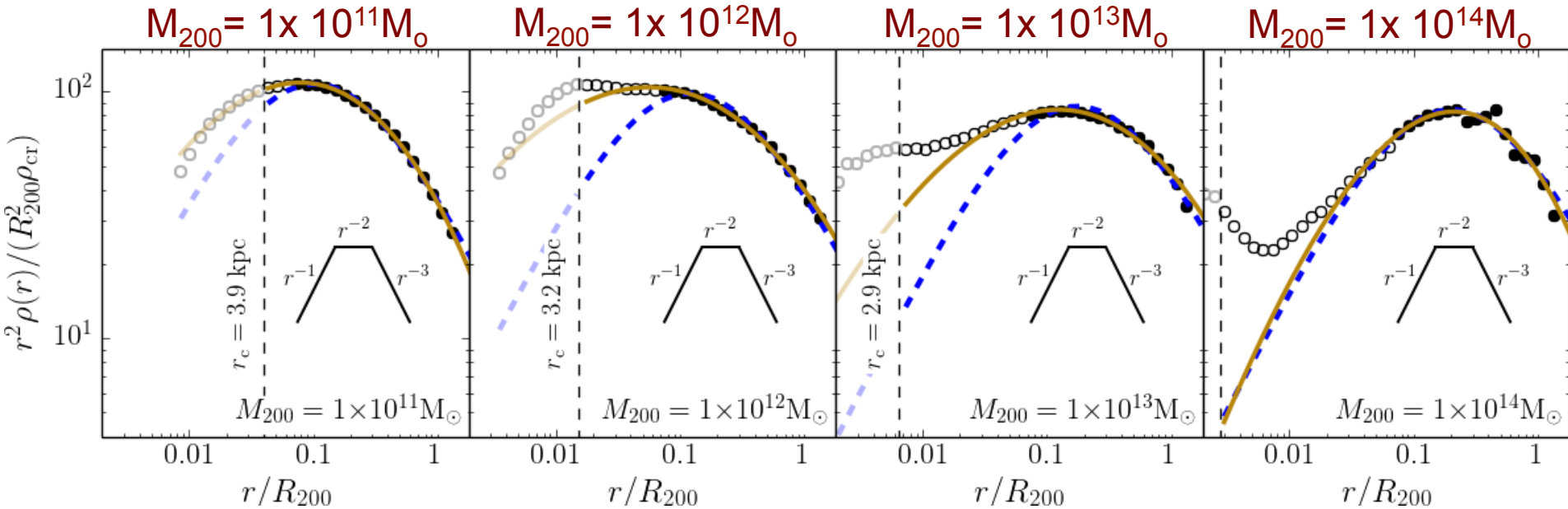
Eagle simulations: total matter profiles



NFW is only good fit in outer parts: baryons have caused contraction of halo in inner parts

Baryon effects on dark matter halos

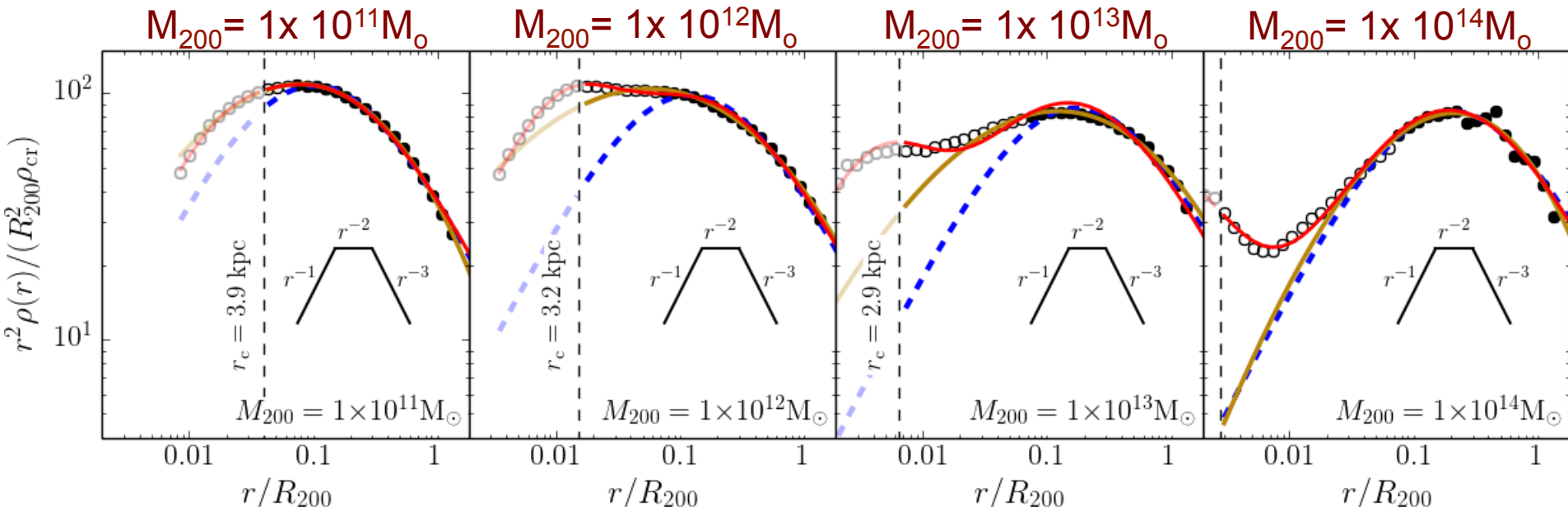
Eagle simulations: total matter profiles



The same is true for Einasto profile

Baryon effects on dark matter halos

Eagle simulations: total matter profiles

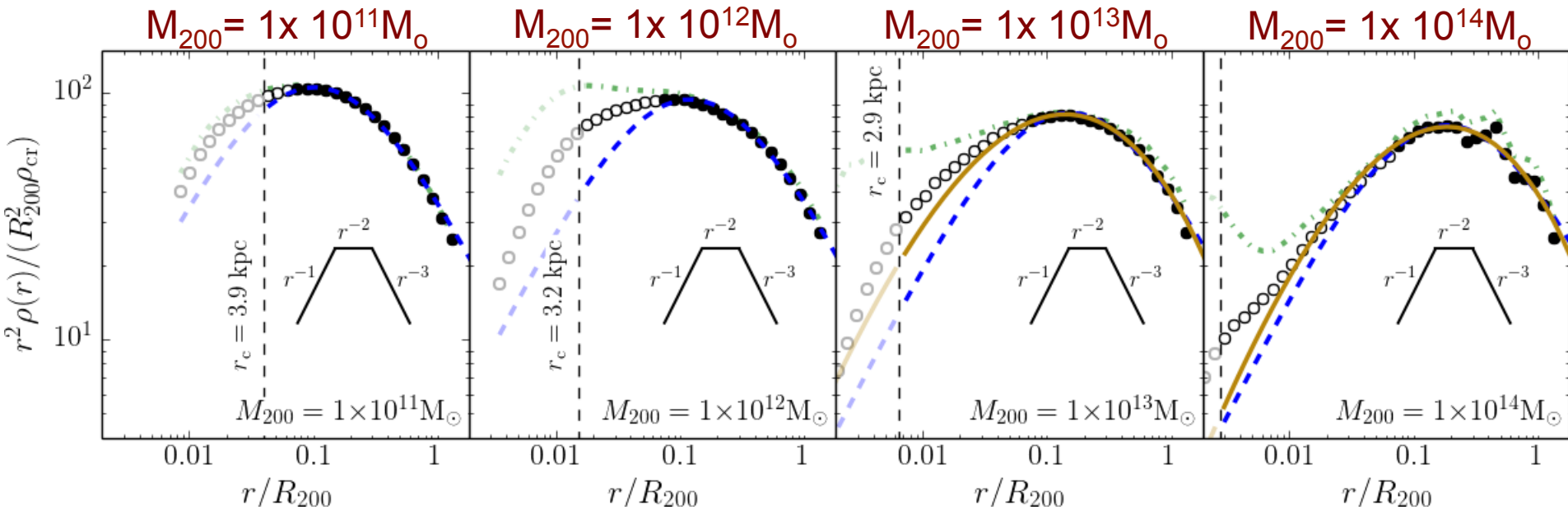


Total matter profile fit by:

$$\frac{\rho(r)}{\rho_{\text{cr}}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2} + \frac{\delta_i}{(r/r_i)(1+(r/r_i)^2)}$$

Baryon effects on dark matter halos

Eagle simulations: DARK MATTER HALO profiles



NFW or Einasto are reasonable fit to DM halo profile except near centre where effects of halo contraction are visible

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?

Cluster profiles can be probed with:

- X-ray emission
- Gravitational lensing

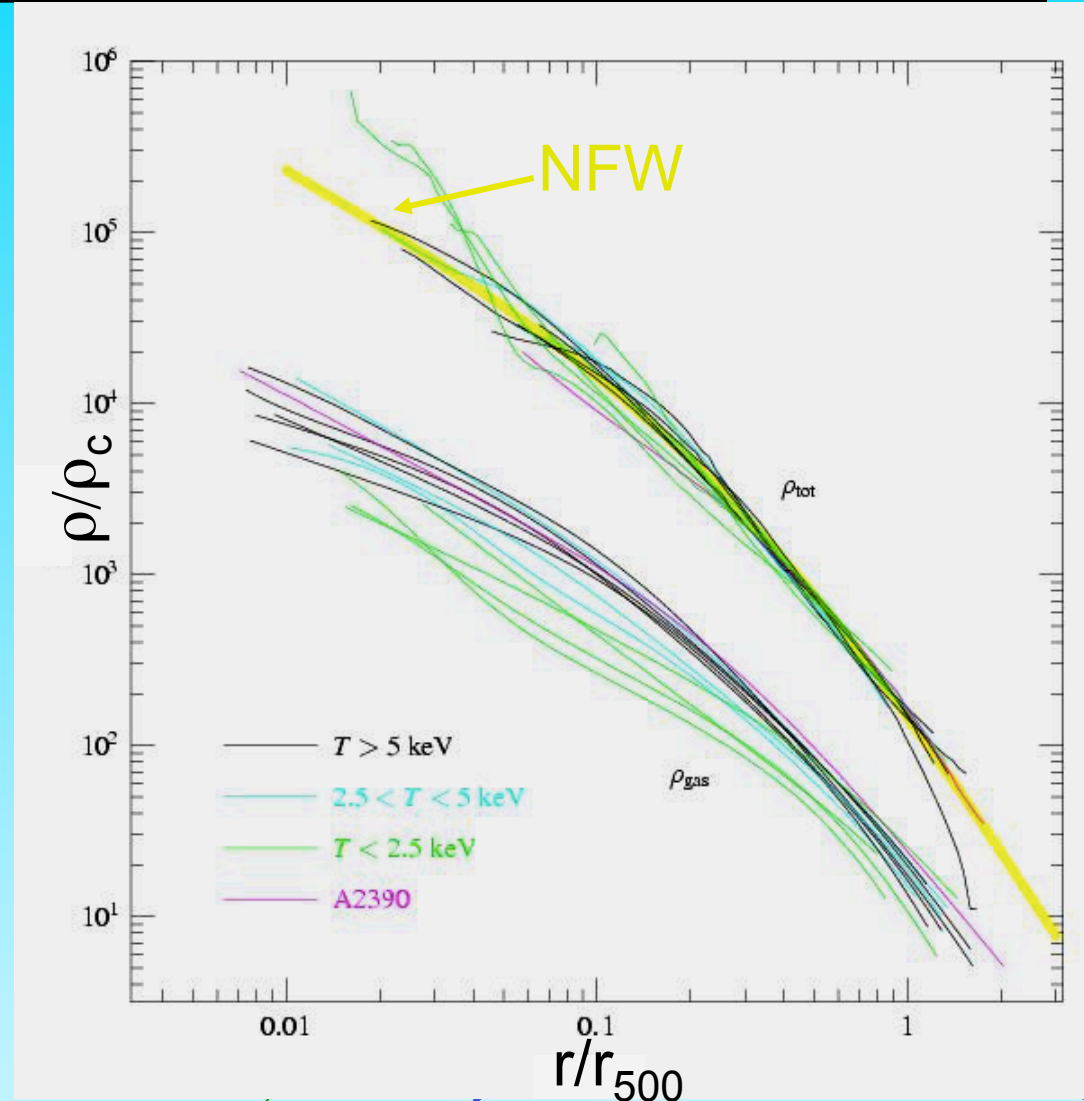
The central density profile of galaxy cluster dark halos

X-ray data

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

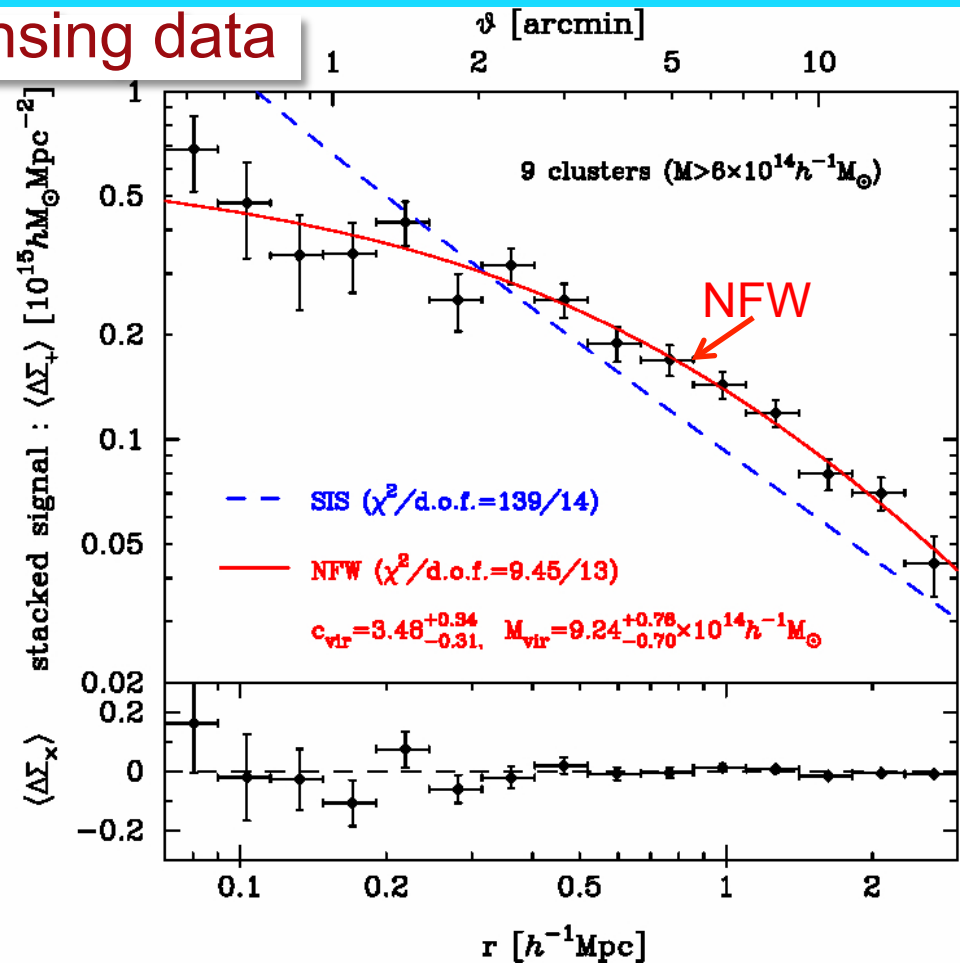
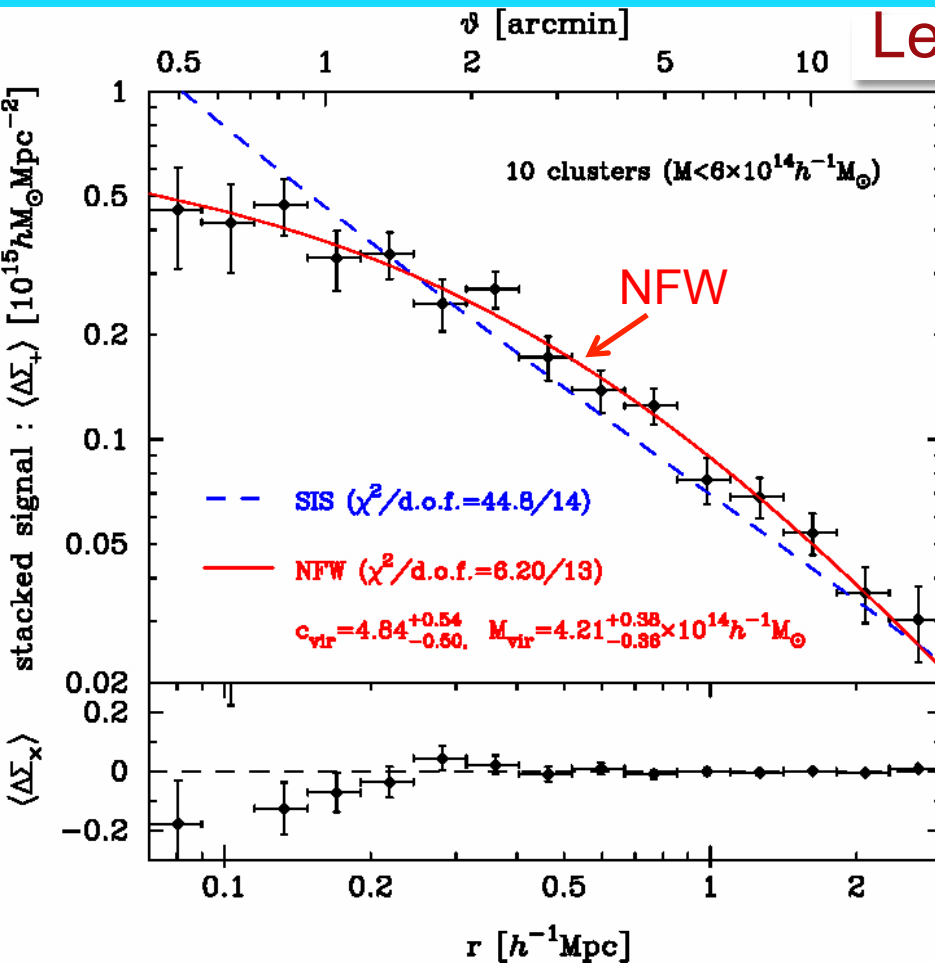


Excellent agreement with CDM halo predictions



The density profile of galaxy cluster dark halos

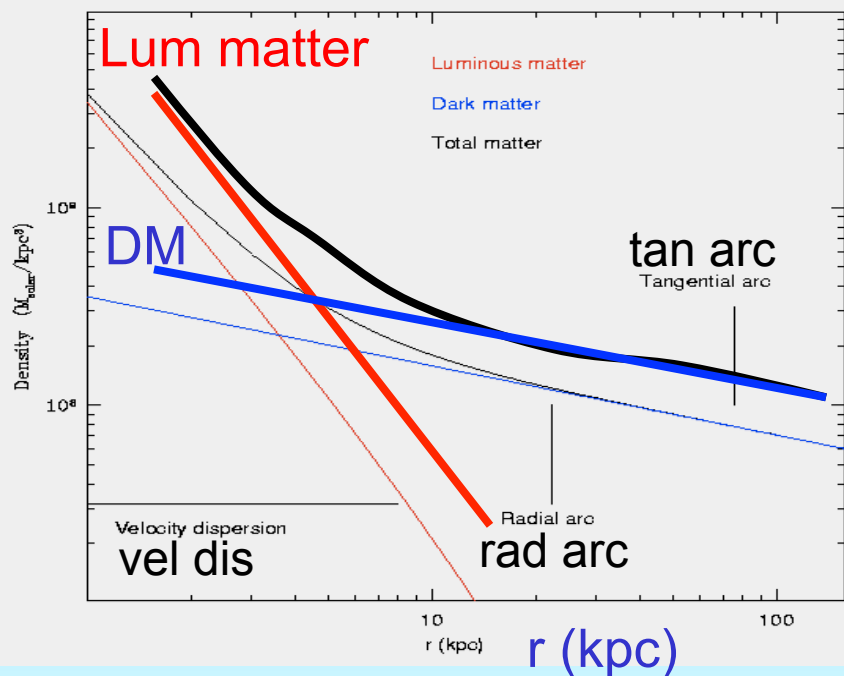
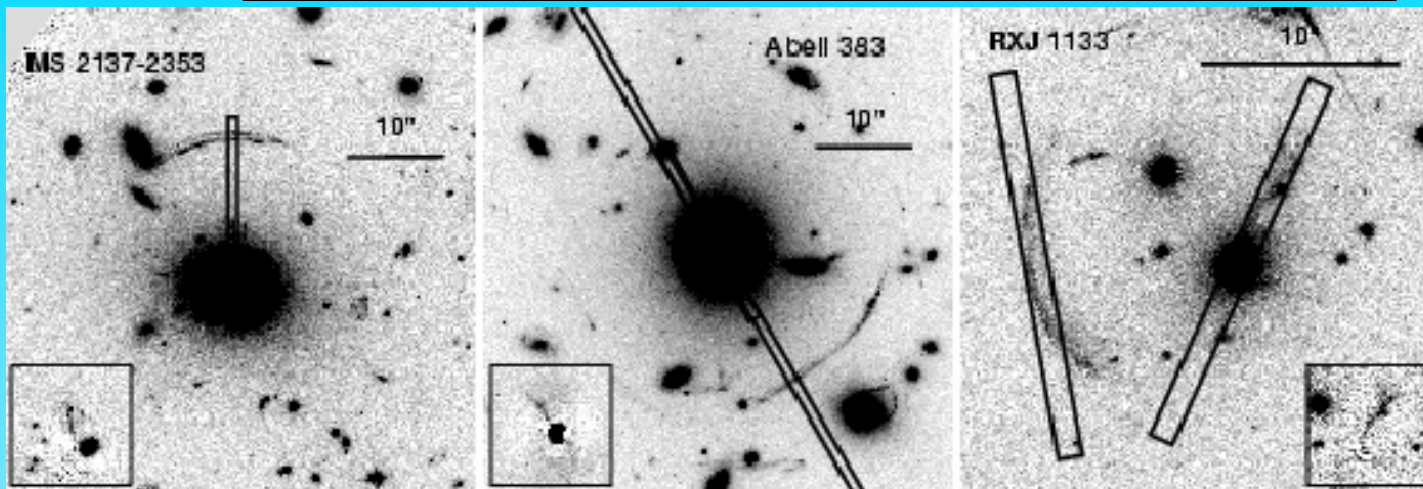
Lensing data



Okabe et al '10

Mass profile in cluster cores from strong lensing

Sand et al 04



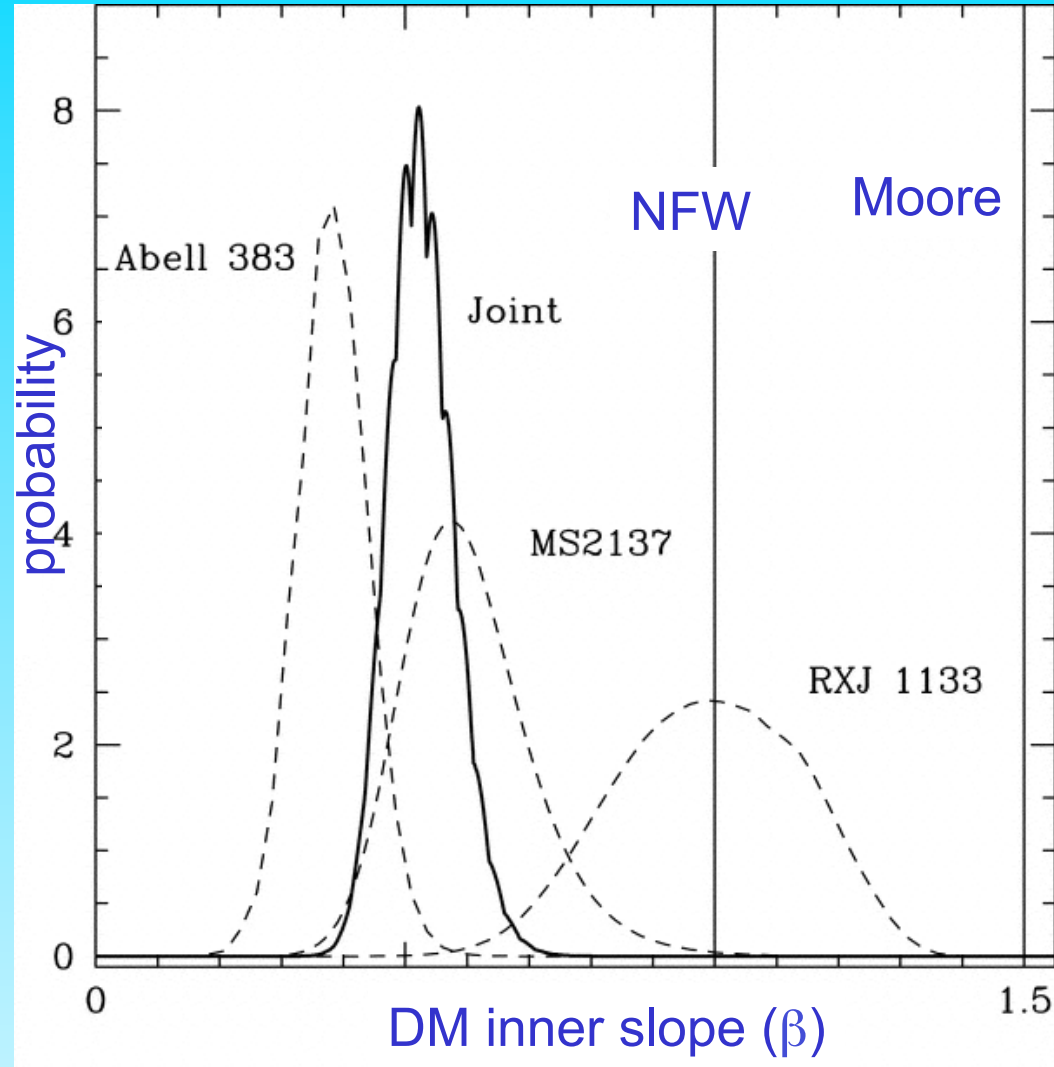
- Assume spherical symmetry
- Model potential as power-law DM + galaxy with constant M/L
- Constrain inner slope of DM profile using tangential arc, radial arc and velocity dispersion profile

Mass profile in cluster cores from strong lensing

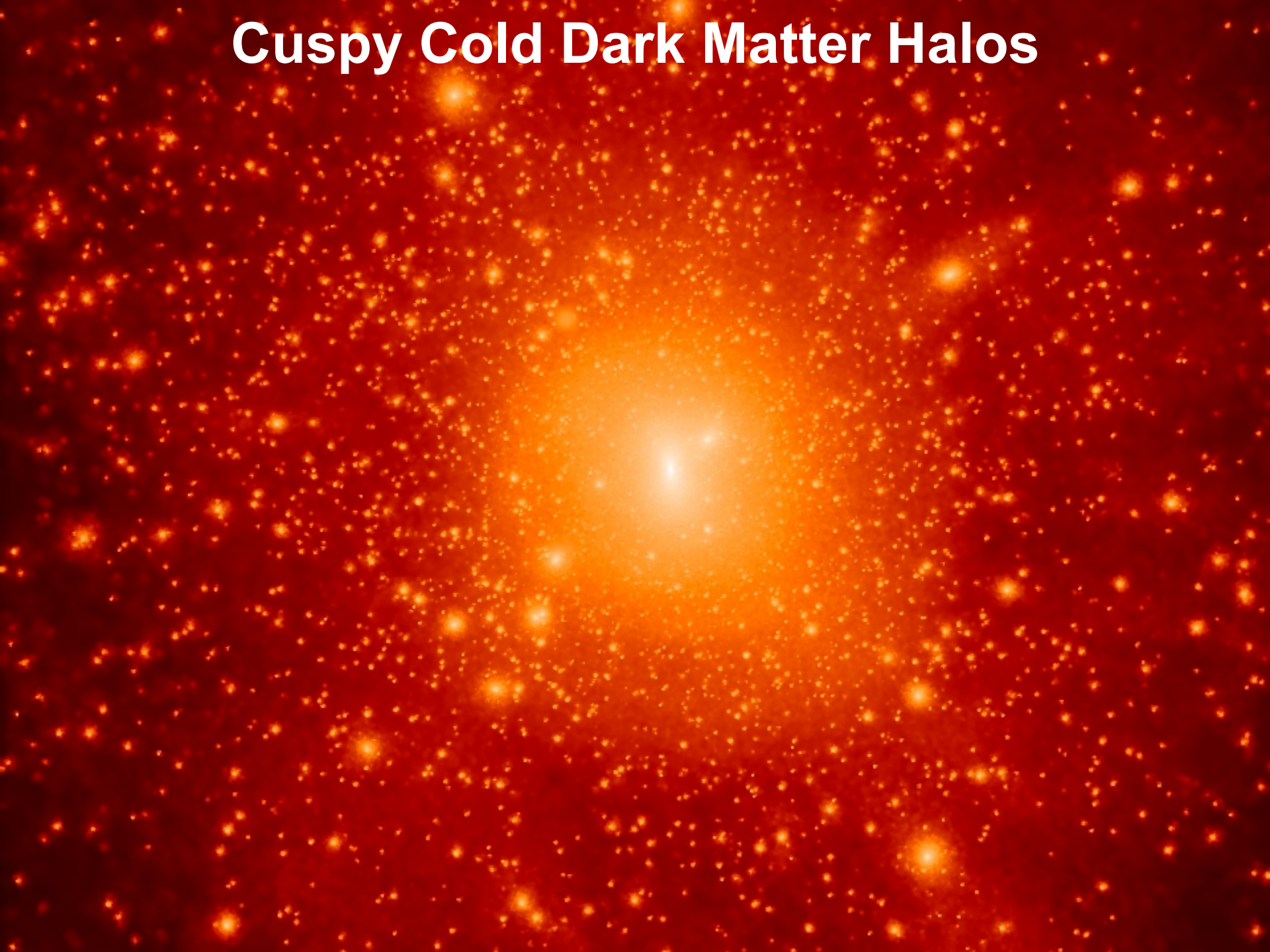
$$\rho(r) \propto r^{-\beta} (r_s + r)^{\beta-3}$$

$\beta=1$ for NFW

Sand et al 04



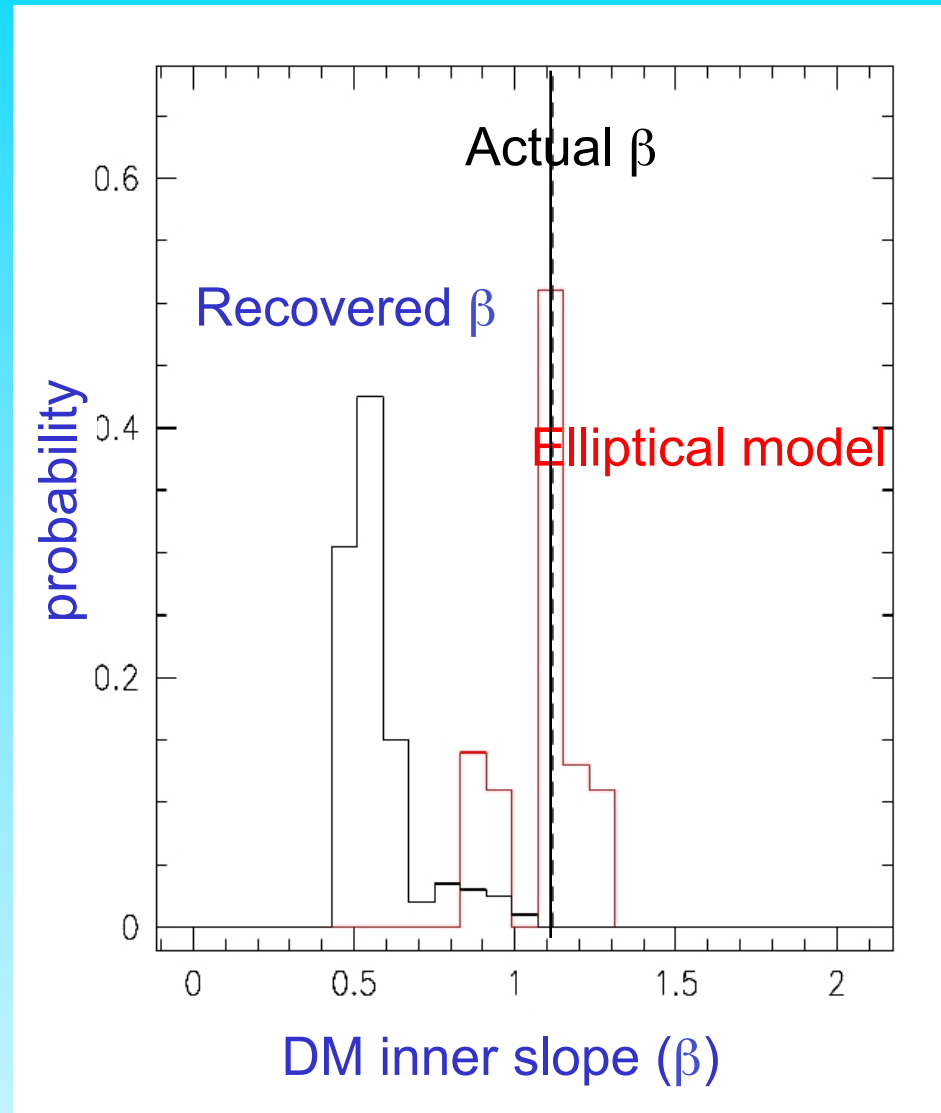
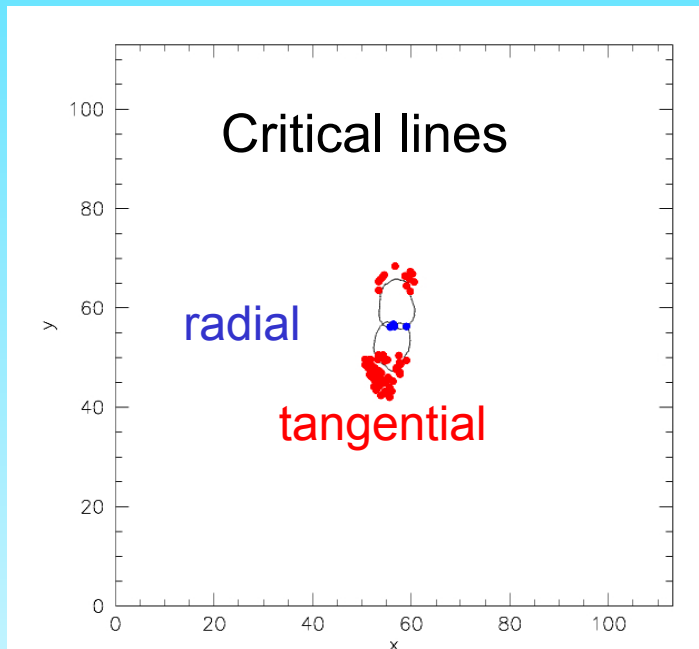
Cuspy Cold Dark Matter Halos



Mass profile in cluster cores from strong lensing

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

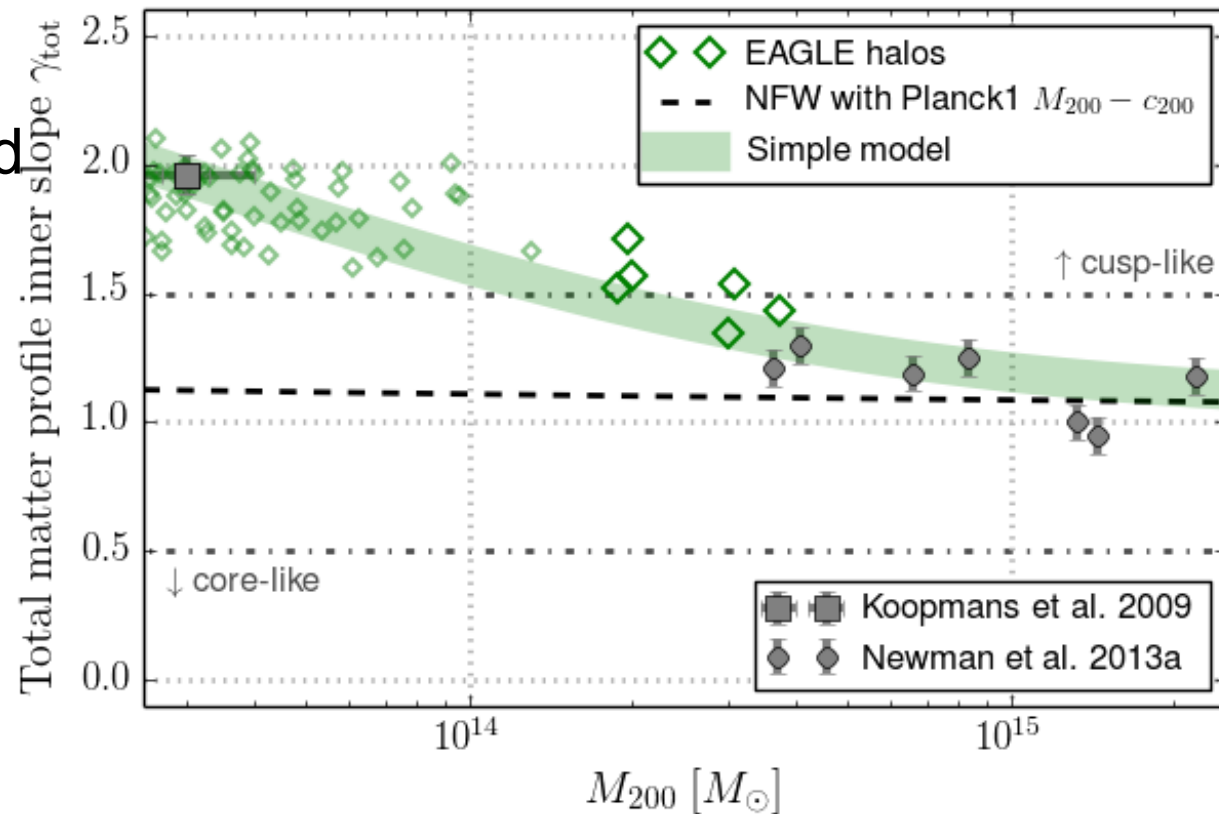
Reason: Sand et al assume
 spherical symmetry



The density profile of galaxy cluster dark halos

Measured slope of TOTAL matter profile

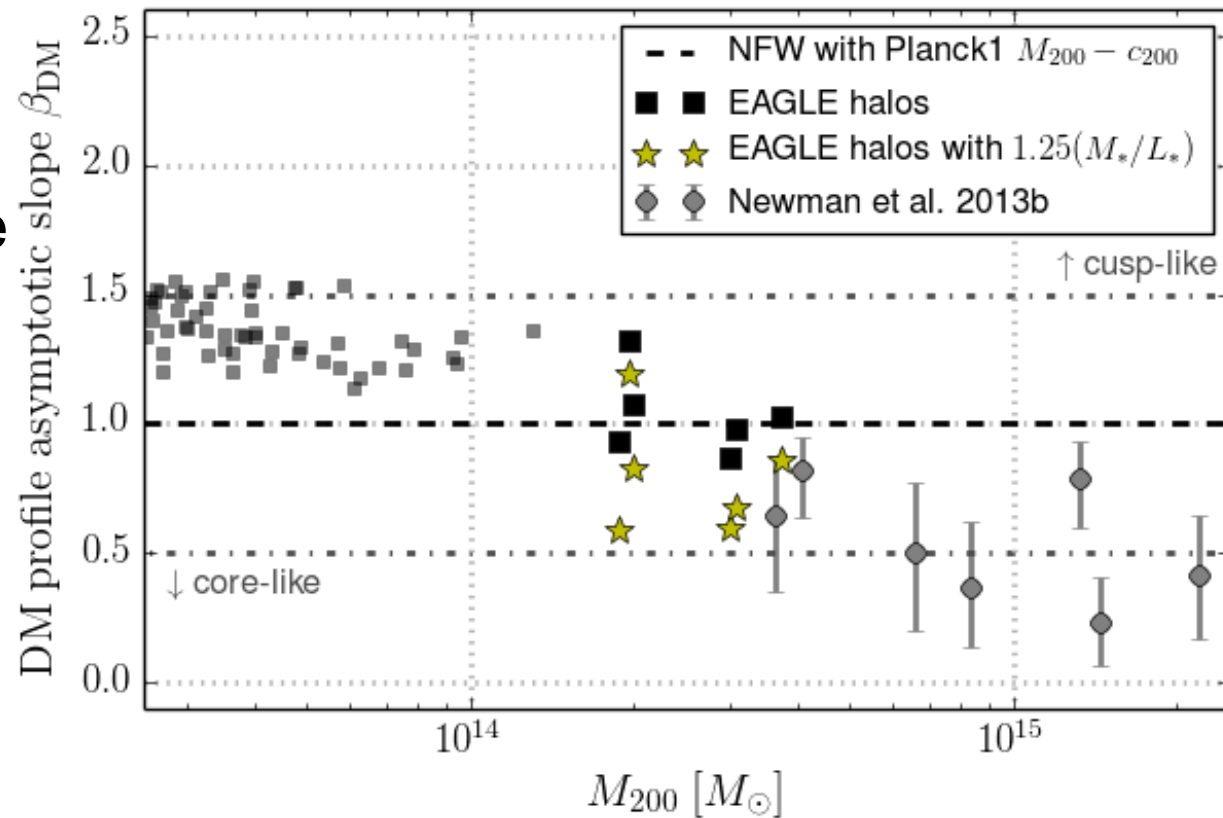
Sims agree w. measured slope of **total matter** profile for clusters of $M \sim (10^{13} - 10^{15}) M_{\odot}$



The density profile of galaxy cluster dark halos

Inferred slope of DM halo matter profile

But NOT w. inferred slope of **DM halo** profile for clusters of $M \sim (10^{13} - 10^{15}) M_{\odot}$



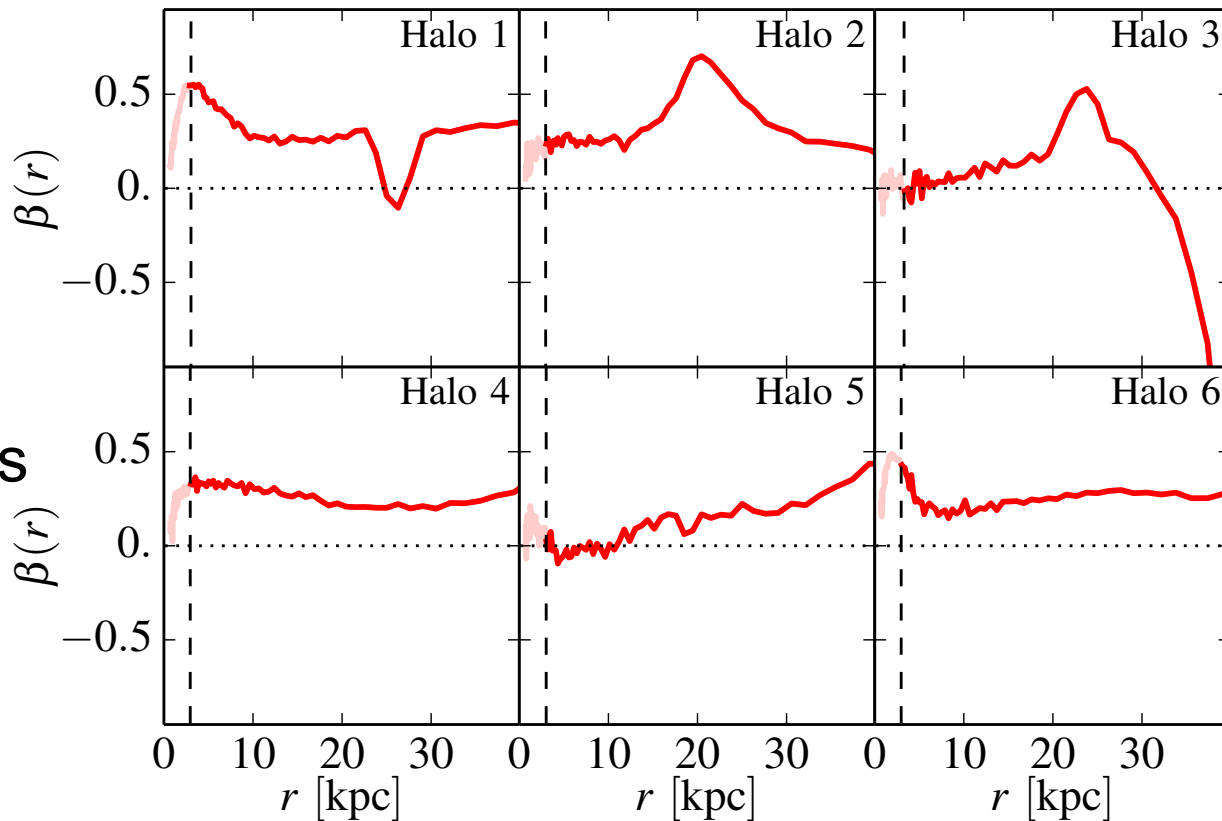
The density profile of galaxy cluster dark halos

Stellar anisotropy parameter

Newman et al.
assumed isotropic
orbits for stars in BCG.

Stars in simulations do
NOT have isotropic orbits

This may explain
discrepancy!





How about on dwarf galaxy scales?



Dwarf galaxies around the Milky Way

Many claims that dwarf spheroidal satellites have density cores

e.g. Gilmore et al. '07, Kuzio de Naray '08 and many more



Fornax



Sculptor



Leo I

© Anglo-Australian Observatory



Carina

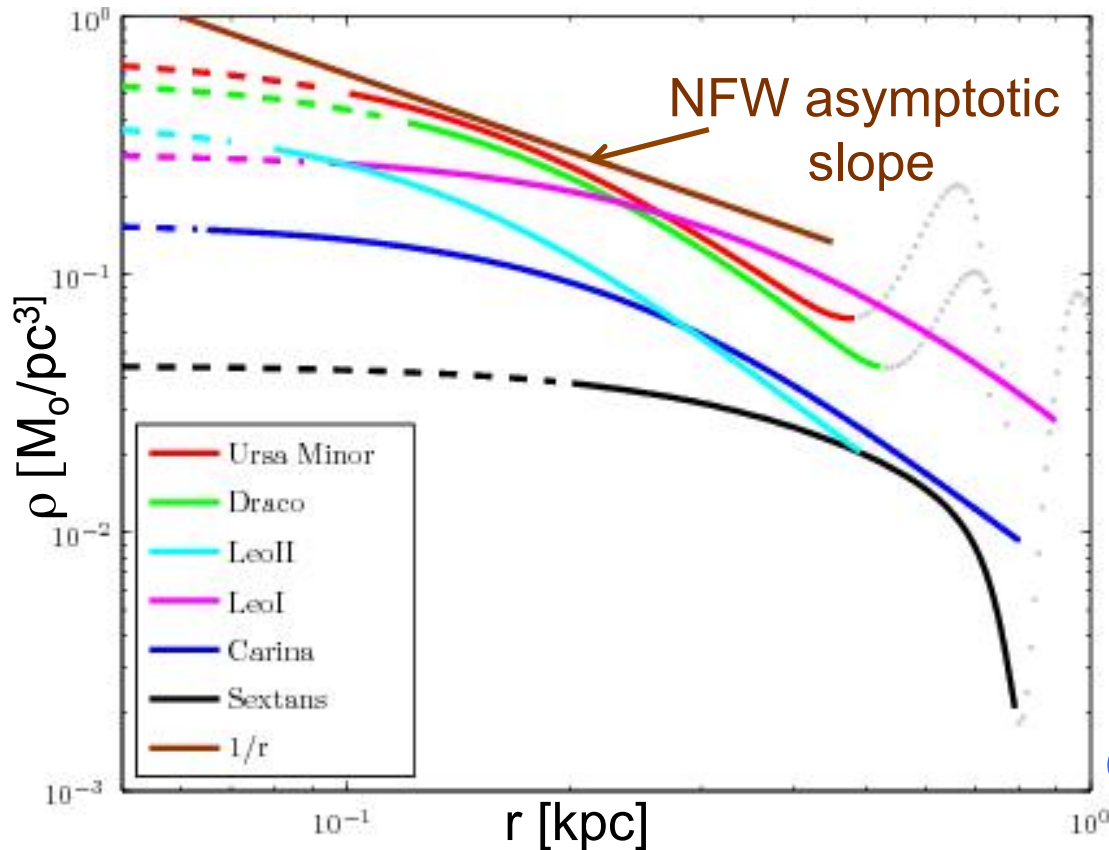


Sextans



Sagittarius

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...”

Fits assuming NFW →

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

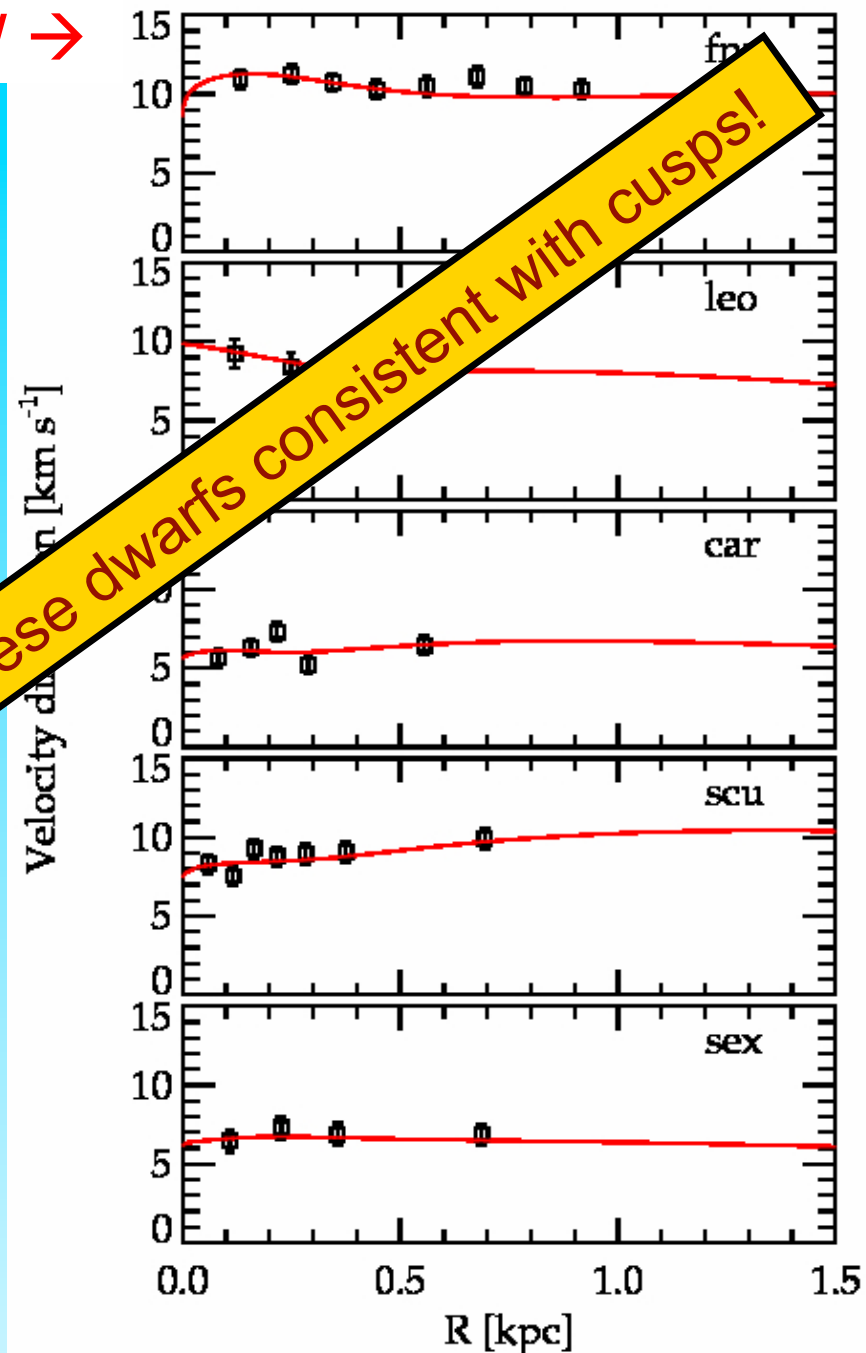
Cuspy!

vel. an...

- Assume isotropic
- Solve for
- Compare with observed $\sigma_r(r)$
- "best fit" subhalo

Photometric and kinematical data for these dwarfs consistent with cusps!

Strigari, Frenk & White '10





Dwarf galaxies around the Milky Way

Fornax

Sculptor

Leo I

© Anglo-Australian Observatory

Carina

Sextans

Sagittarius

The DM halo of the Sculptor dwarf

Sculptor has two stellar pops:

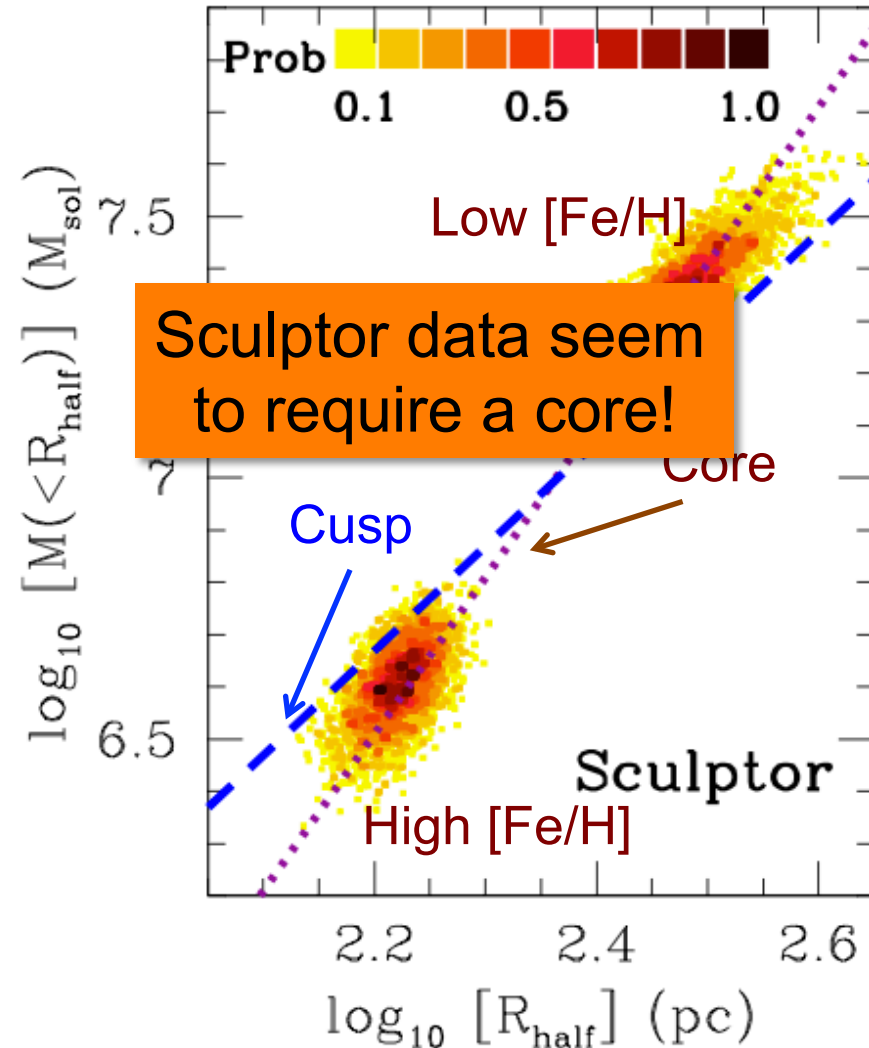
(i) centrally concentrated, high [Fe/H]

(ii) extended, low [Fe/H]

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

Walker '10; Wolf et al '10 →

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



The DM halo of the Sculptor dwarf

Strigari, Frenk & White '14

Distribution function analysis of 2 metallicity pop. data of Battaglia et al.

Assume pops in equil. in NFW halo: $\rho(r) = \frac{\rho_s}{x(1+x)^2}$

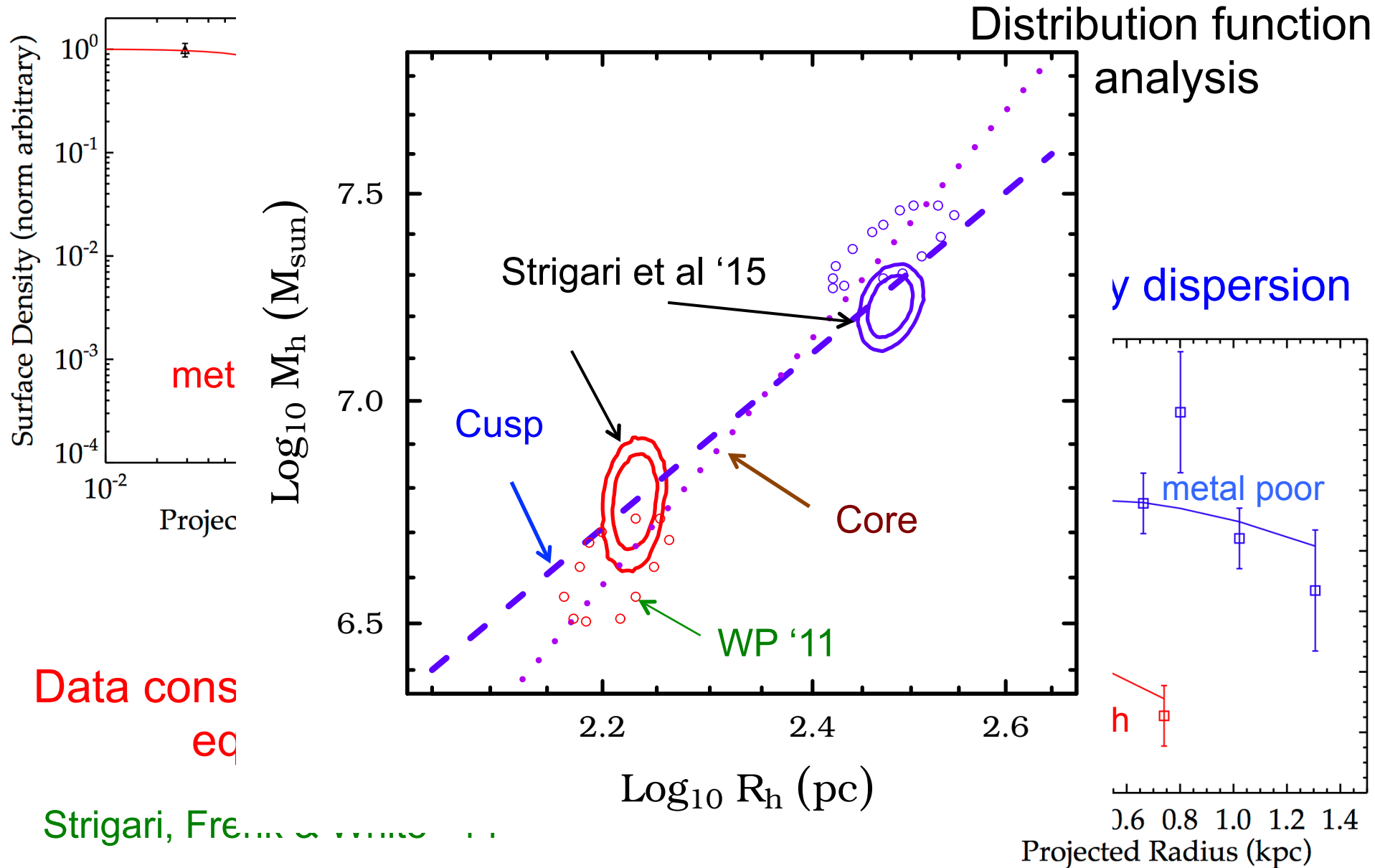
For each population: $f(E, J) = g(J)h(E),$

Parametrize: $g(J) = \left[\left(\frac{J}{J_\beta} \right)^{\frac{b_0}{\alpha}} + \left(\frac{J}{J_\beta} \right)^{\frac{b_1}{\alpha}} \right]^\alpha$

$$h(E) = \begin{cases} N E^a (E^q + E_c^q)^{d/q} (\Phi_{lim} - E)^e & \text{for } E < \Phi_{lim} \\ 0 & \text{for } E \geq \Phi_{lim}, \end{cases}$$

Find best-fit parameters using MCMC

The DM halo of the Sculptor dwarf





Cores or cusps in the dwarf sph. satellites of the MW?

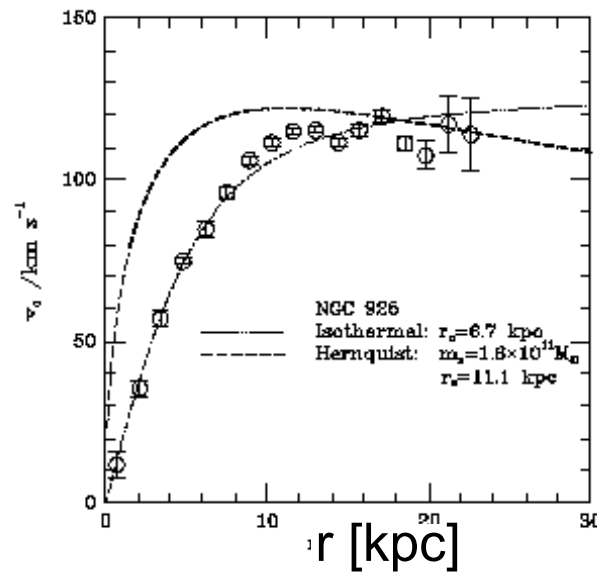
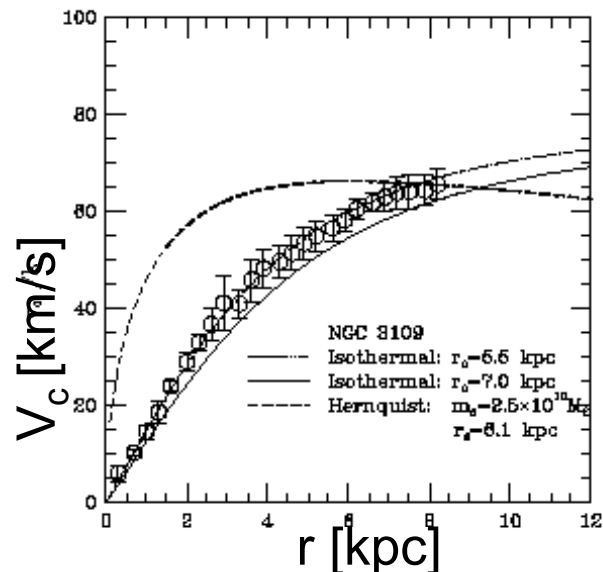
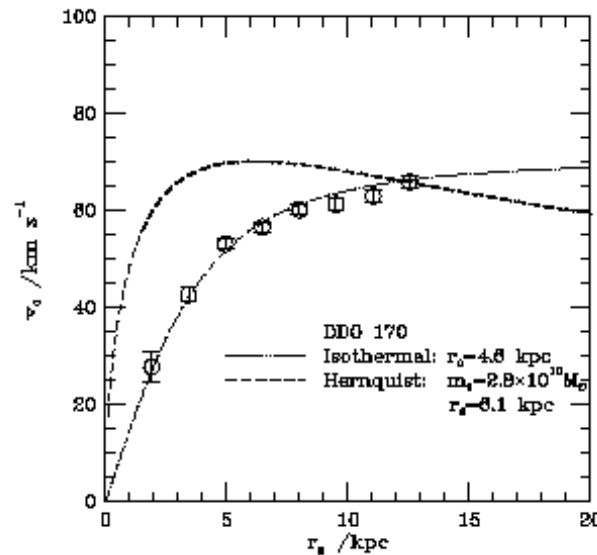
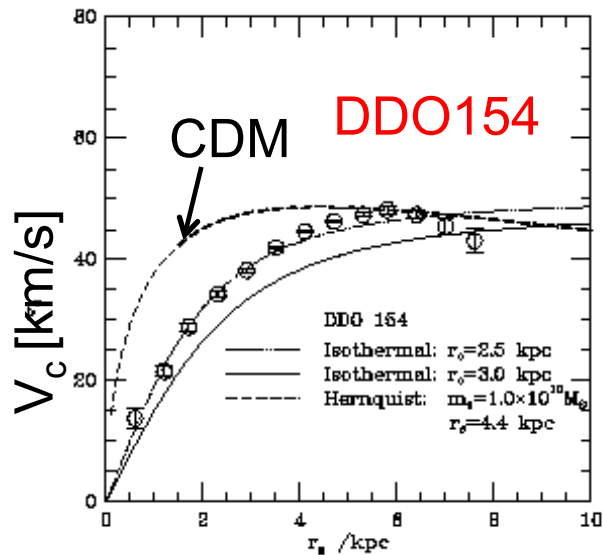
When sufficiently general models are considered, even best data cannot distinguish cores from NFW cusps

Cores in field dwarf galaxies

Moore '94

H α rotation curves

→ core radii



The cores of dwarf galaxy haloes

Julio F. Navarro,^{1,2★} Vincent R. Eke² and Carlos S. Frenk²

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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 gas cool and condense to the galactic centre

→ gas self-gravitating
→ star formation/burst

Rapid ejection of gas during starburst → a core in the halo dark matter density profile

Navarro, Eke, Frenk '96

Governato et al. '12

Pontzen & Governato '12

Brooks et al. '12

Navarro, Eke, Frenk '96

The cores of dwarf galaxy haloes L75

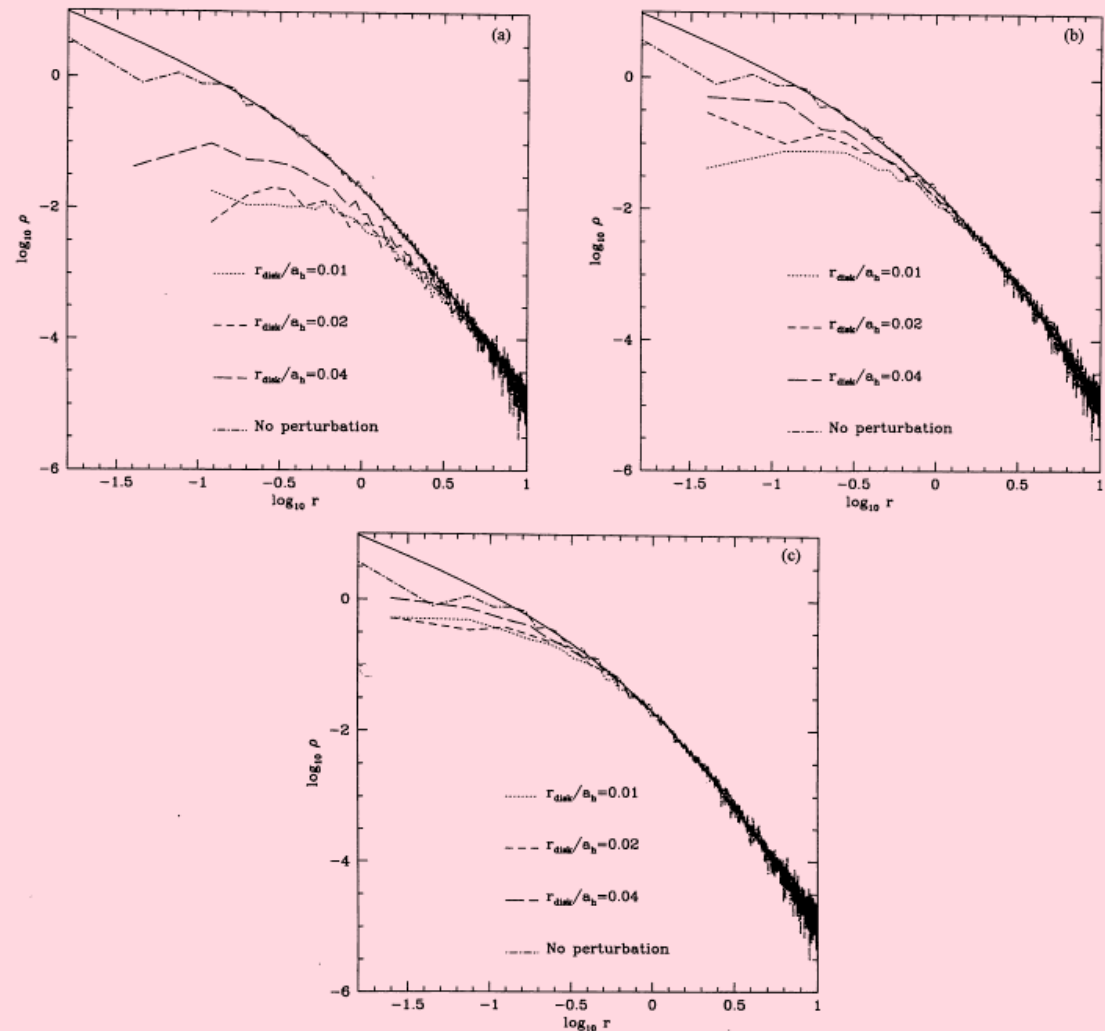
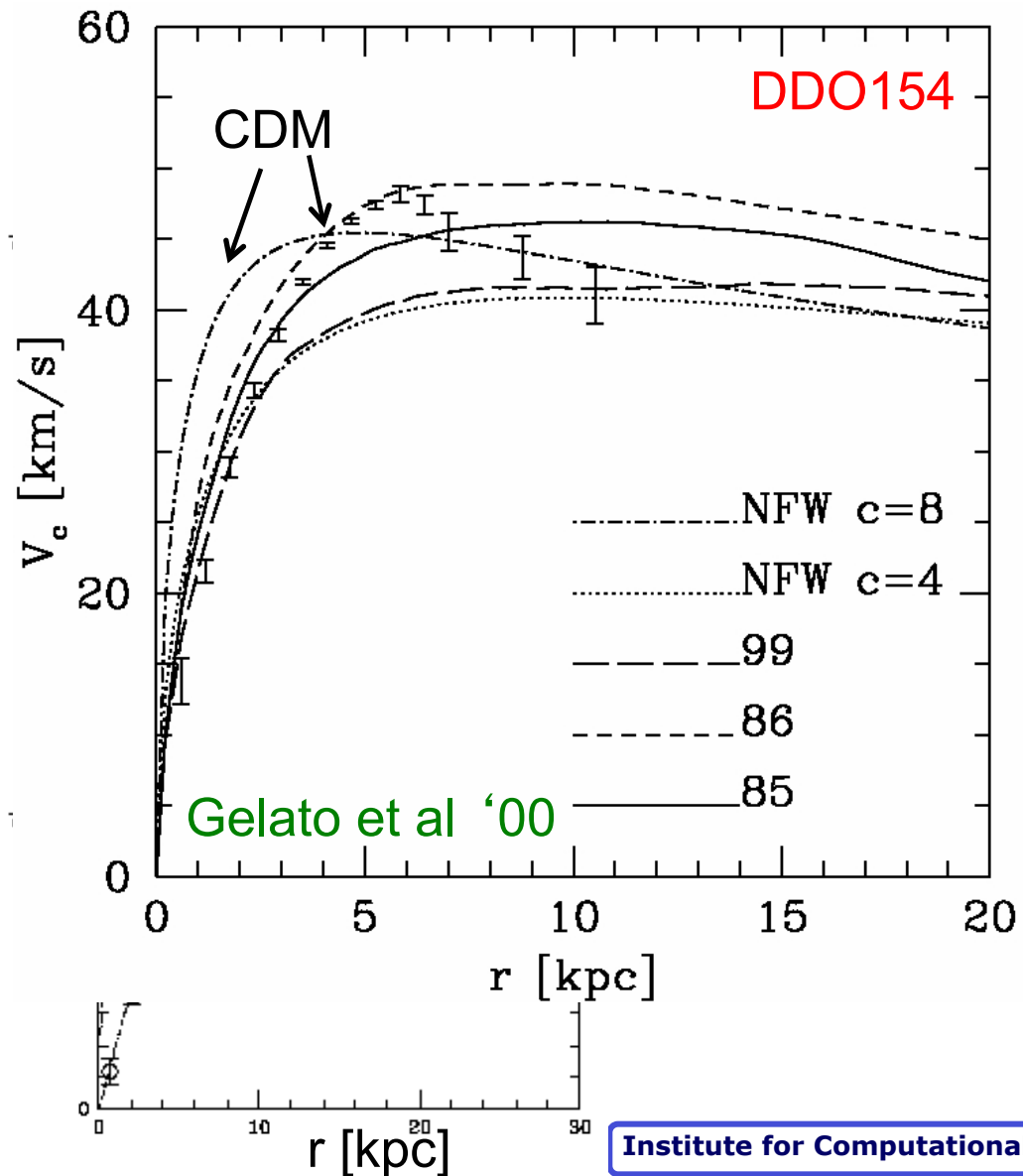
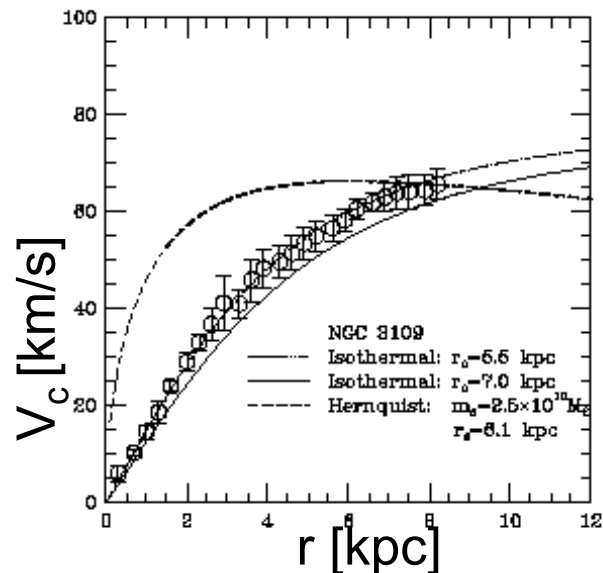
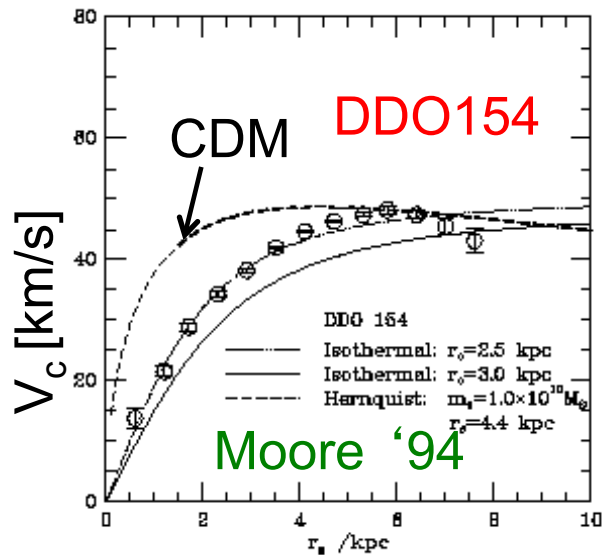


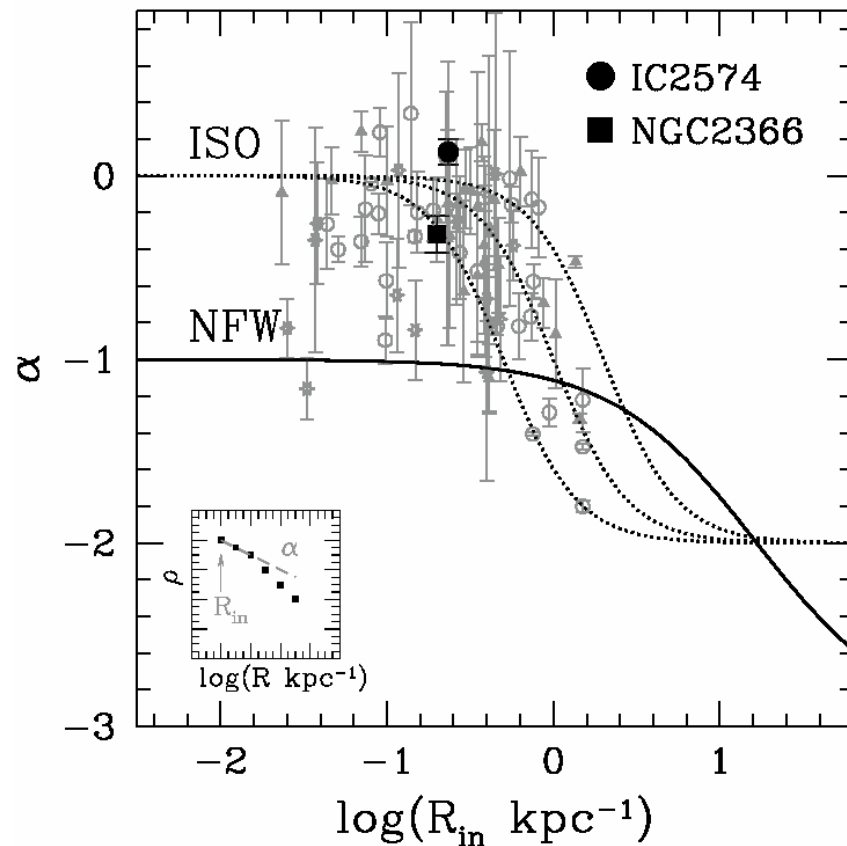
Figure 3. Equilibrium density profiles of haloes after removal of the disc. The solid line is the original Hernquist profile, common to all cases. The dot-dashed line is the equilibrium profile of the 10 000-particle realization of the Hernquist model run in isolation at $t=200$. (a) $M_{\text{disc}}=0.2$.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

Cores in dwarf galaxies



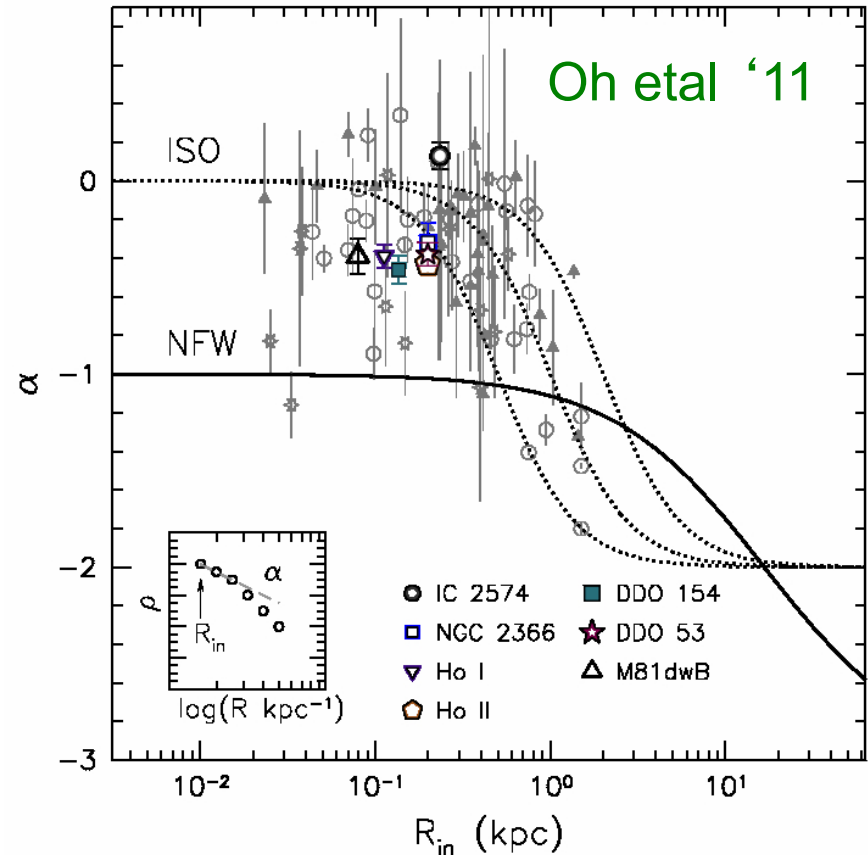
THINGS HI rotn curves of dwarfs

Oh et al '08



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

Oh et al '11



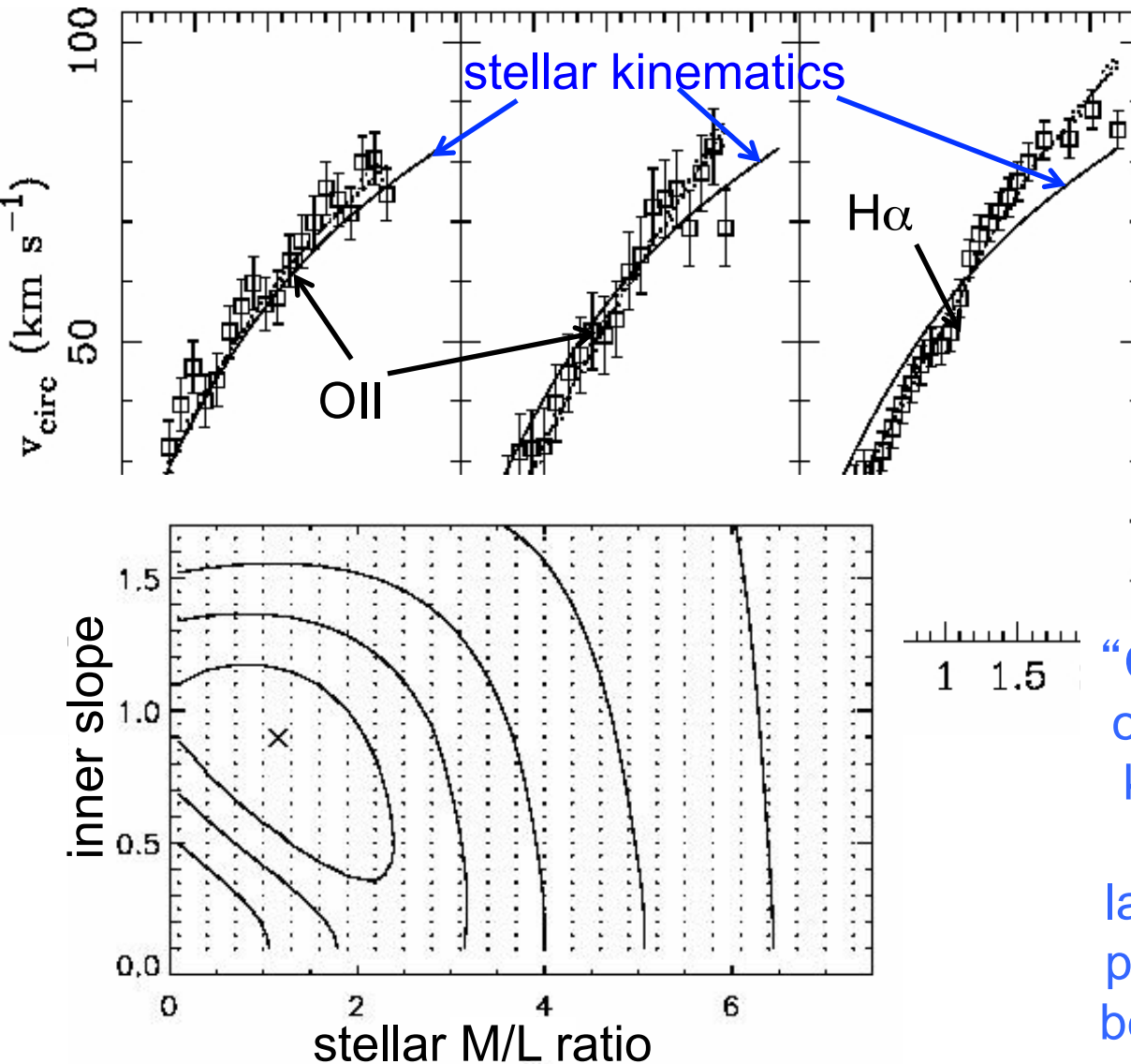
“We find discrepancies between the derived dark matter distributions ... and those of CDM simulations, even after corrections for non-circular motions ...”



University of Durham

The rotation curve of dwarf NGC 2976

Adams et al '13

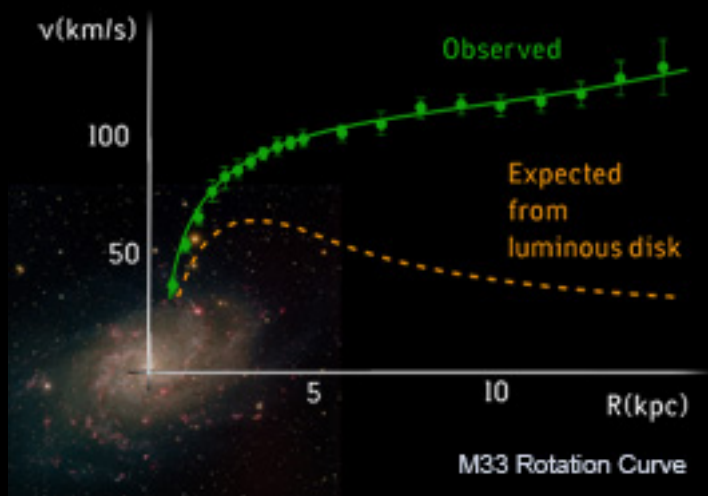
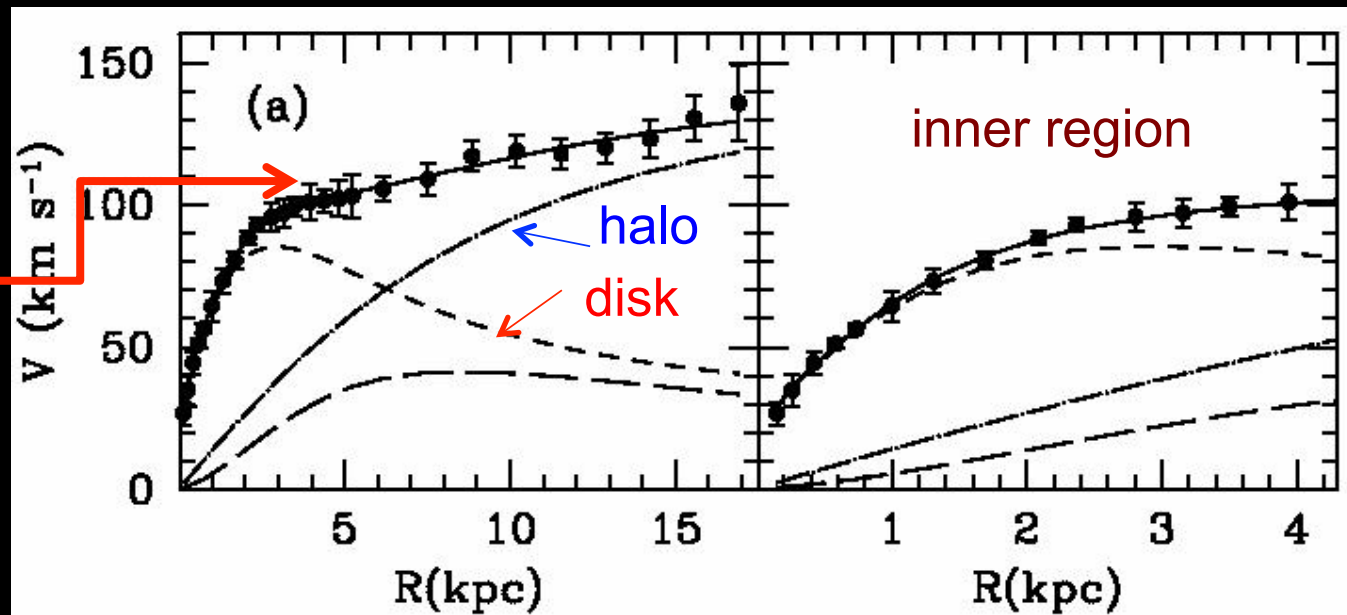


“This difference is likely due to the gas disk not meeting the assumptions that underlie the analysis such as no pressure support, a constant kinematic axis, and planar orbits.”

“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)



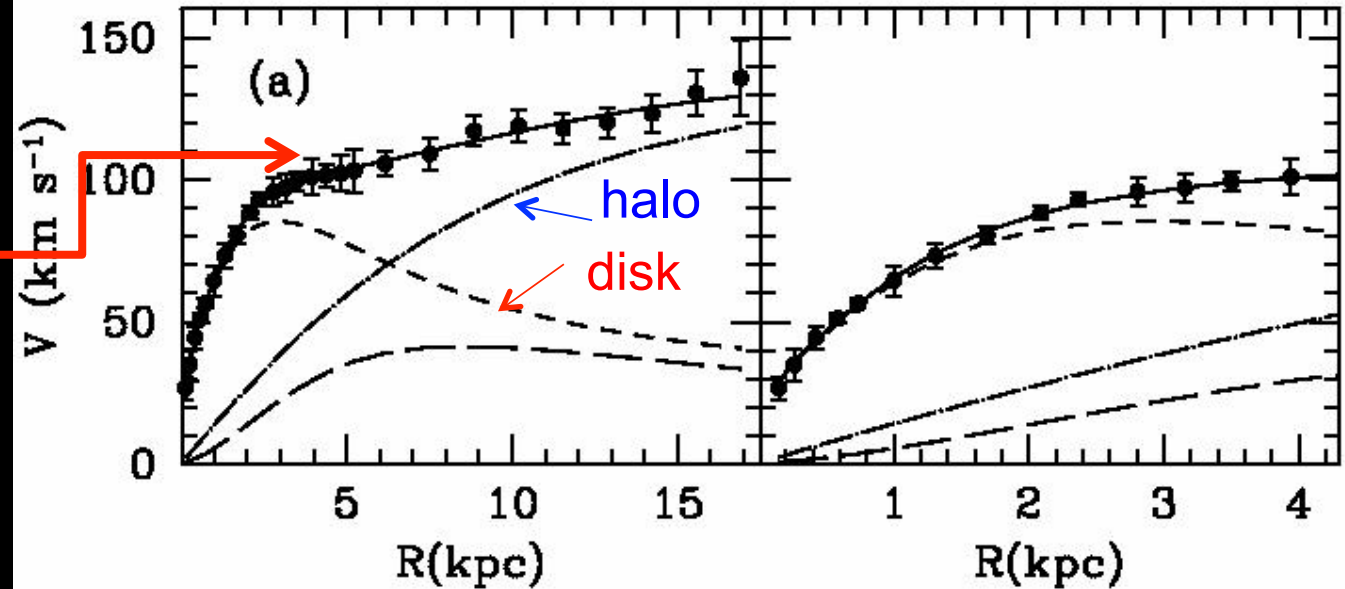
100pc – 17kpc
(dynamic range of 200)

Corbelli '03

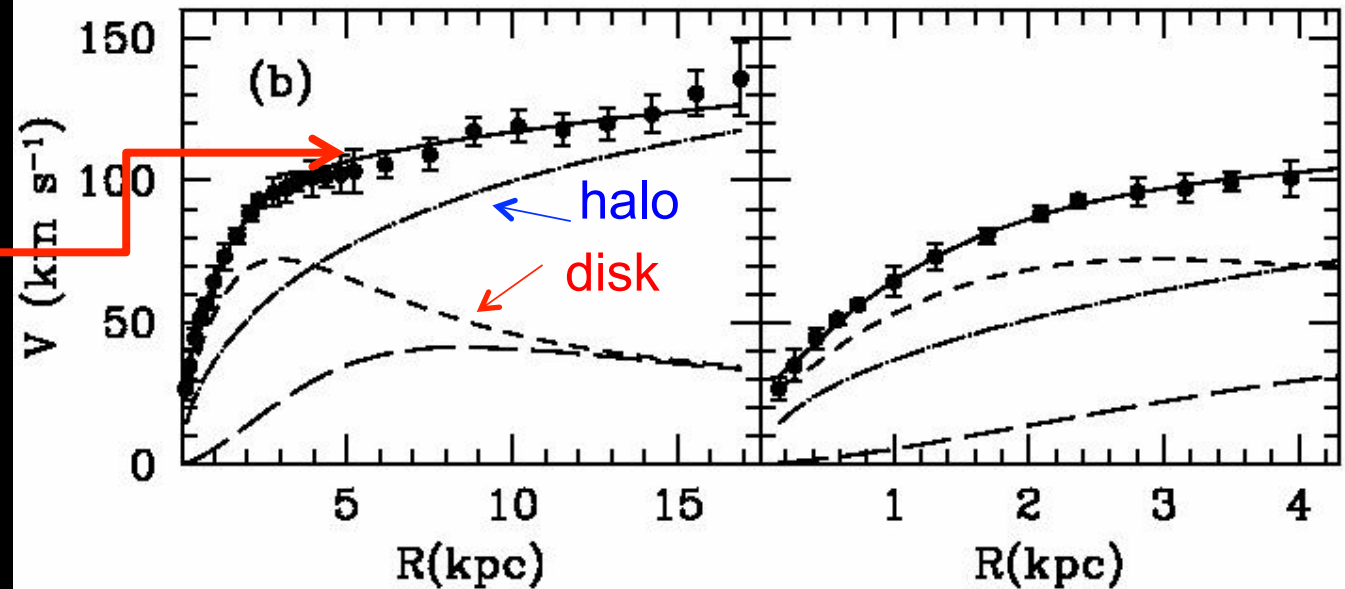


The rotation curve of M33

halo with a core
(Burkert)



NFW halo



Corbelli '03

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

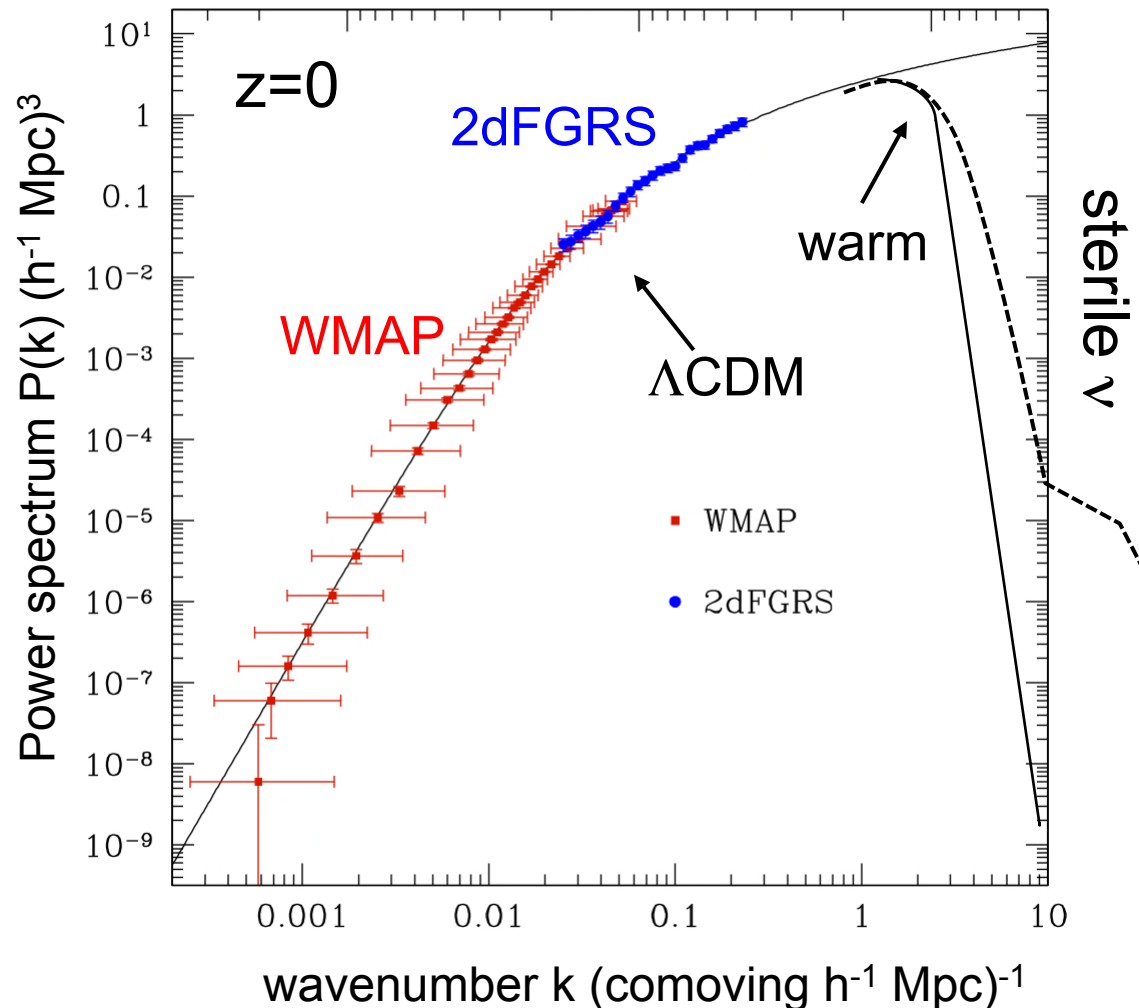
$$m_{\text{CDM}} \sim 100 \text{ GeV}$$

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

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

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

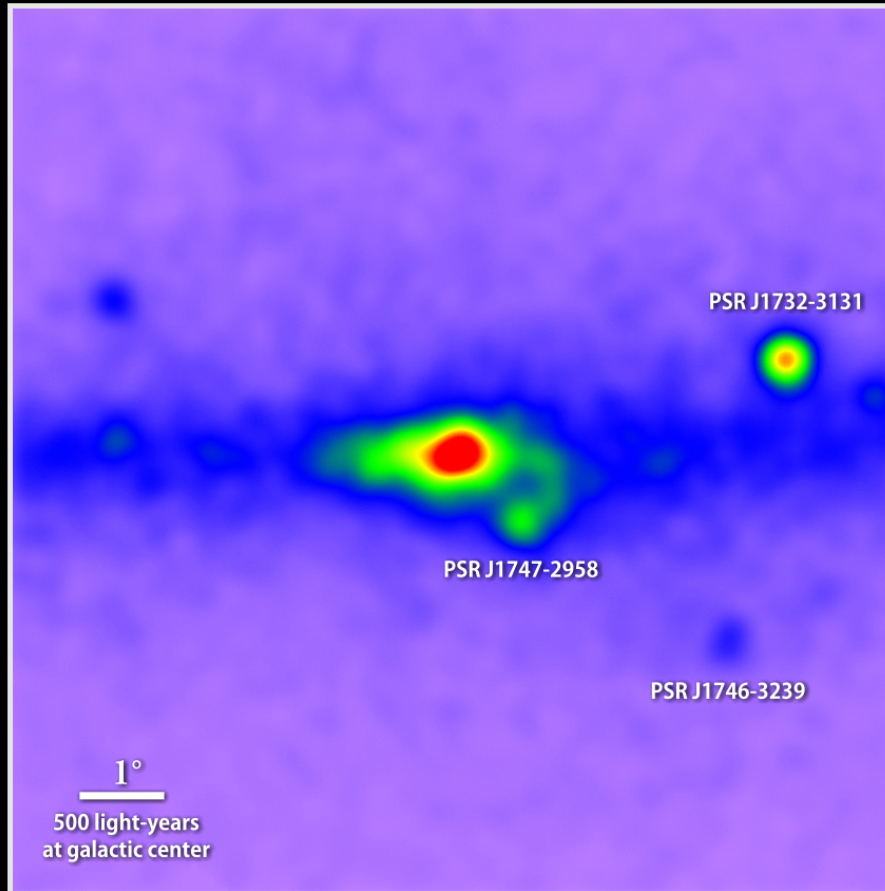
Log $k^3 P(k)$ wavelength k^{-1} (comoving h^{-1} Mpc)



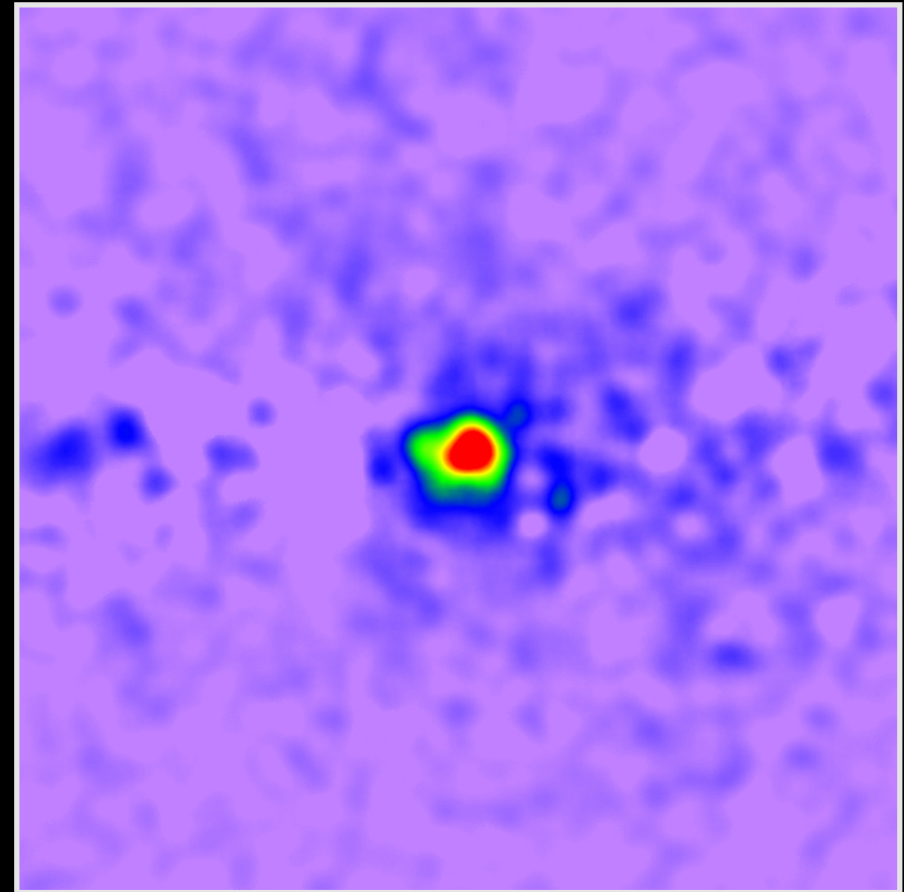
The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter

Tansu Daylan,¹ Douglas P. Finkbeiner,^{1,2} Dan Hooper,^{3,4} Tim Linden,⁵
Stephen K. N. Portillo,² Nicholas L. Rodd,⁶ and Tracy R. Slatyer^{6,7}

Uncovering a gamma-ray excess at the galactic center



Unprocessed map of 1.0 to 3.16 GeV gamma rays



Known sources removed

A. Boyarsky¹, O. Ruchayskiy², D. Iakubovskiy^{3,4} and J. Franse^{1,5}

¹Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands

²Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

³Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine

⁴National University “Kyiv-Mohyla Academy”, Skovorody Str. 2, 04070, Kyiv, Ukraine

⁵Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands

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Preprint typeset using L^AT_EX

arXiv:1402.4119v1 [astro-ph.CO] 17 Feb 2014

DETECTION OF AN U.

ESRA BULBUL^{1,2}, M

¹ Har

We detect a weak
spectrum of 73 ξ

independently show the presence of the line at consistent energies. When the full sample is divided into three subsamples (Perseus, Centaurus+Ophiuchus+Coma, and all others), the line is seen at $> 3\sigma$ statistical significance in all three independent MOS spectra and the PN “all others” spectrum. The line is also detected at the same energy in the *Chandra* ACIS-S and ACIS-I spectra of the Perseus cluster, with a flux consistent with *XMM-Newton* (however, it is not seen in the ACIS-I spectrum of Virgo). The line is present even if we allow maximum freedom for all the known thermal emission lines. However, it is very weak (with an equivalent width in the full sample of only ~ 1 eV) and located within 50–110 eV of several known faint lines; the detection is at the limit of the current instrument capabilities and subject to significant modeling uncertainties. On the origin of this line, we argue that there should be no atomic transitions in thermal plasma at this energy. An intriguing possibility is the decay of sterile neutrino, a long-sought dark matter particle candidate. Assuming that all dark matter is in sterile neutrinos with $m_s = 2E = 7.1$ keV, our detection in the full sample corresponds to a neutrino decay mixing angle $\sin^2(2\theta) \approx 7 \times 10^{-11}$, below the previous upper limits. However, based



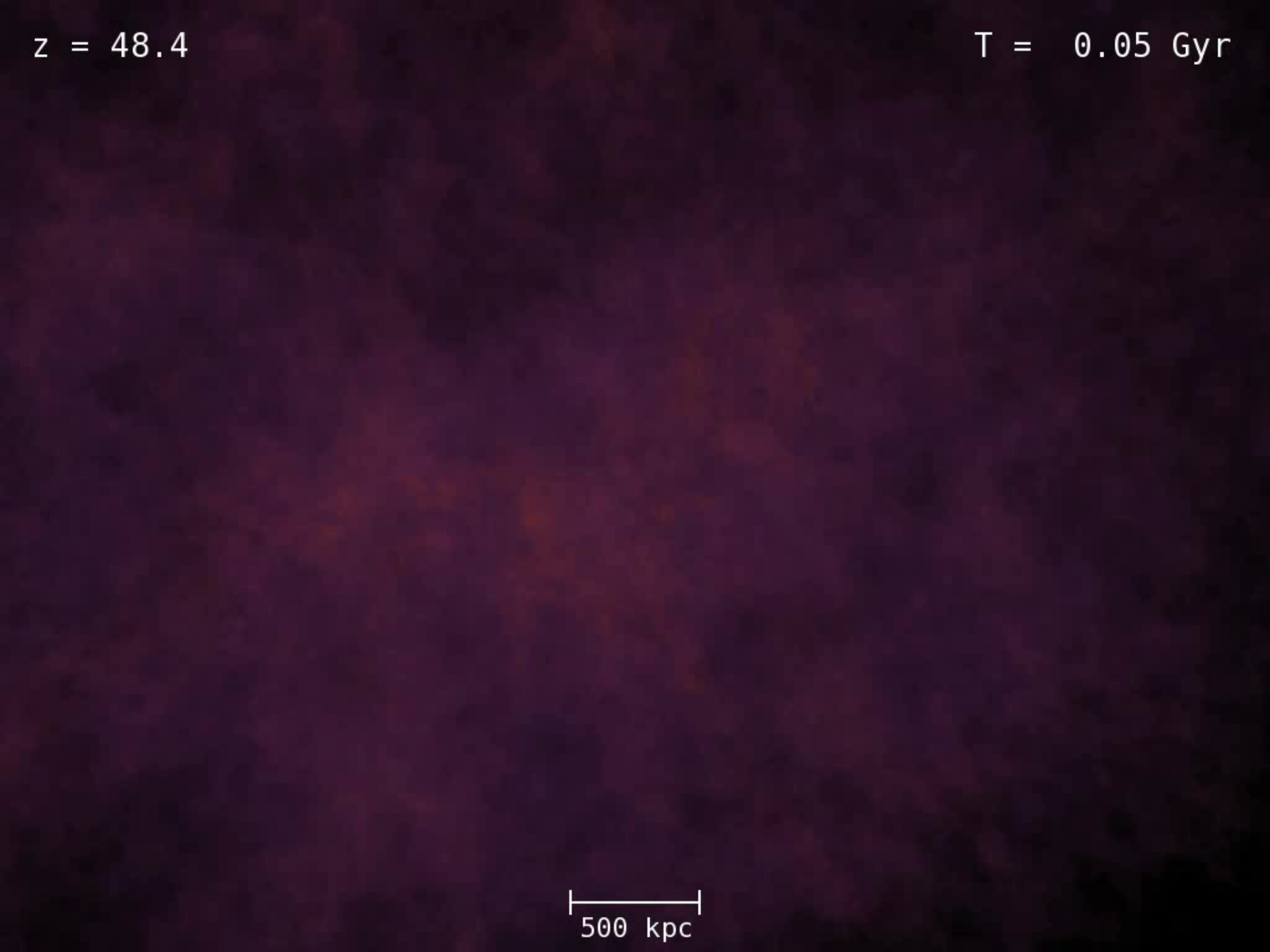
Astrophysical key to identity of dark matter:

→ Subgalactic scales
(strongly non-linear)

$z = 48.4$

$T = 0.05 \text{ Gyr}$

500 kpc

The image shows a dark, grainy field of purple and magenta, representing a simulated galaxy at a very early stage. The texture is noisy and pixelated, typical of early-stage cosmological simulations. A scale bar at the bottom center consists of a horizontal line with vertical ticks at each end, labeled "500 kpc".



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

Four problems on small scales

Traditionally ascribed to CDM:

1. The “core-cusp” problem
2. The “missing satellites” problem
3. The “too-big-to-fail” problem
4. The “satellite disk” problem

Can these help distinguish between CDM & WDM?



The core-cusp problem

cold dark matter

warm dark matter

“Core-cusp” problem:

CDM & WDM halos & subhalos have **cuspy** profiles

BUT: kinematical data “show” that the dwarf satellites of the Milky Way have **cores**



Dark matter subhalos in CDM



The Milky way has only about 25 satellites

BUT: CDM halos have a very large number of subhalos

Why are most subhalos dark?



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

$$V_{\max} = \max V_c$$

The satellites of the MW

Dark matter subhalos in CDM

“Too-big-to-fail” problem:

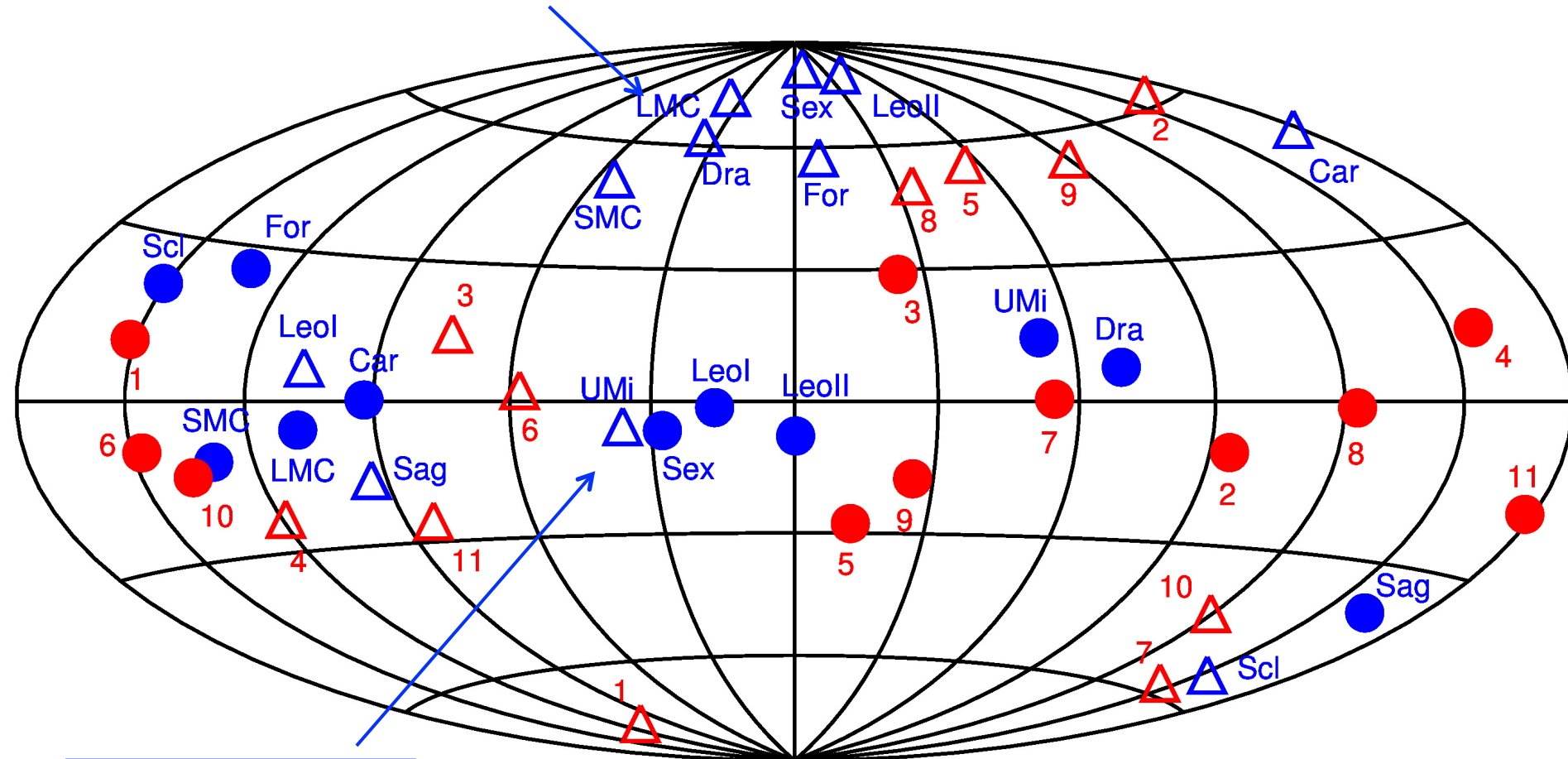
Milky way has only 3 satellites with $V_{\text{max}} > 30$ km/s

BUT: CDM has ~ 10 subhalos with $V_{\text{max}} > 30$ km/s

Why did these not make a galaxy?

The “satellite disk” problem

Direction of ang. mom. Milky Way



MW satellites

Lynden-Bell '76

Four problems on small scales

Traditionally ascribed to CDM:

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Four problems on small scales

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Can these help distinguish between CDM & WDM?



The core-cusp problem

cold dark matter

warm dark matter

No real evidence for cores
at least in the dwarf satellites of the Milky Way

Lovell, Eke, Frenk, Gao, Jenkins, Theuns '12

Four problems on small scales

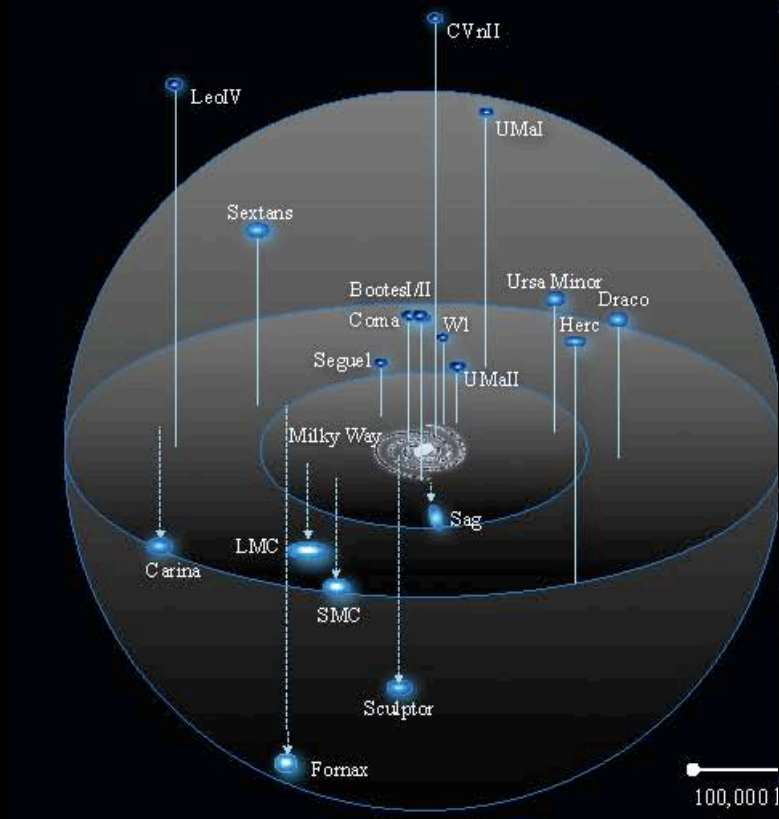
Traditionally ascribed to CDM:

1. The “core-cusp” problem
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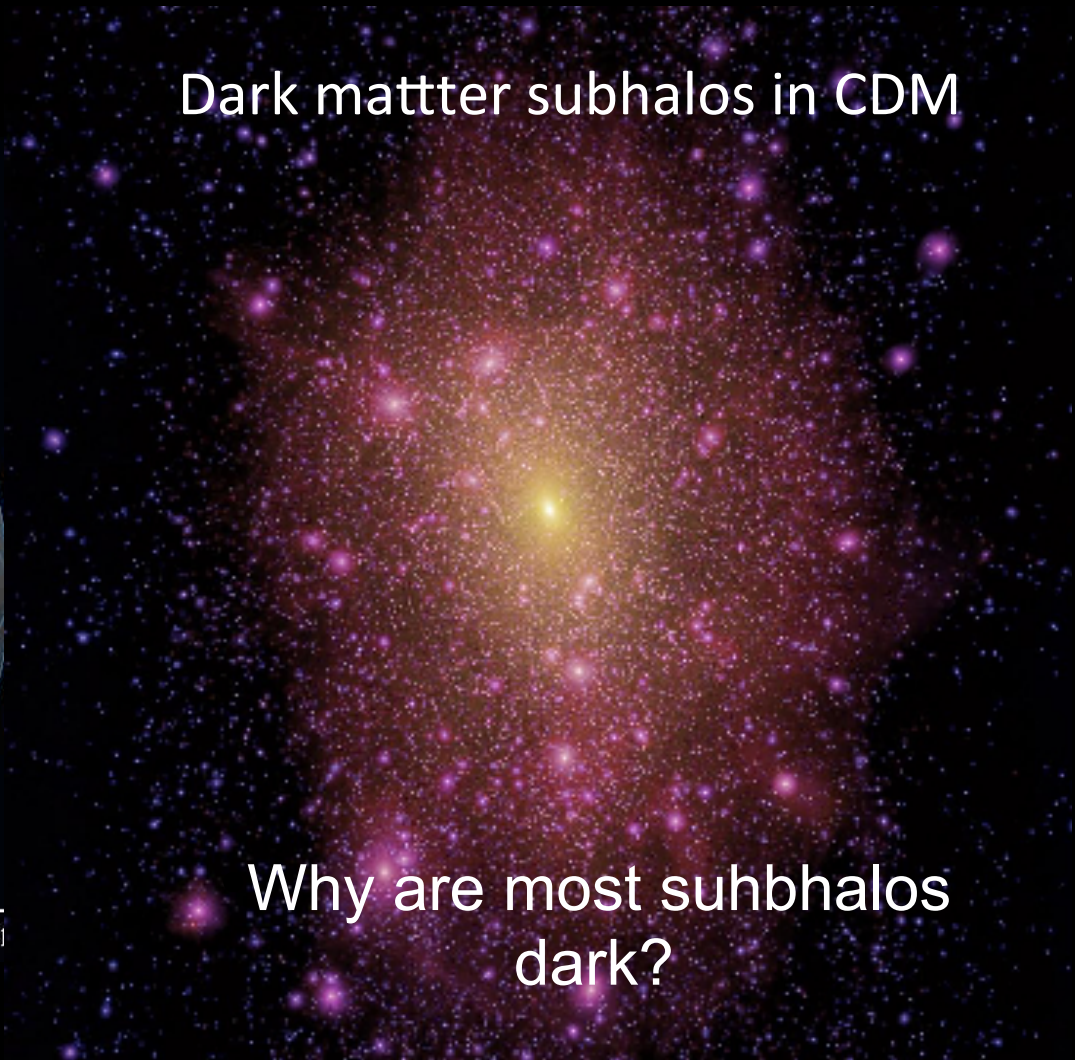
Can these help distinguish between CDM & WDM?

The “missing satellites” problem in CDM

The satellites of the MW



Dark matter subhalos in CDM



Why are most subhalos dark?

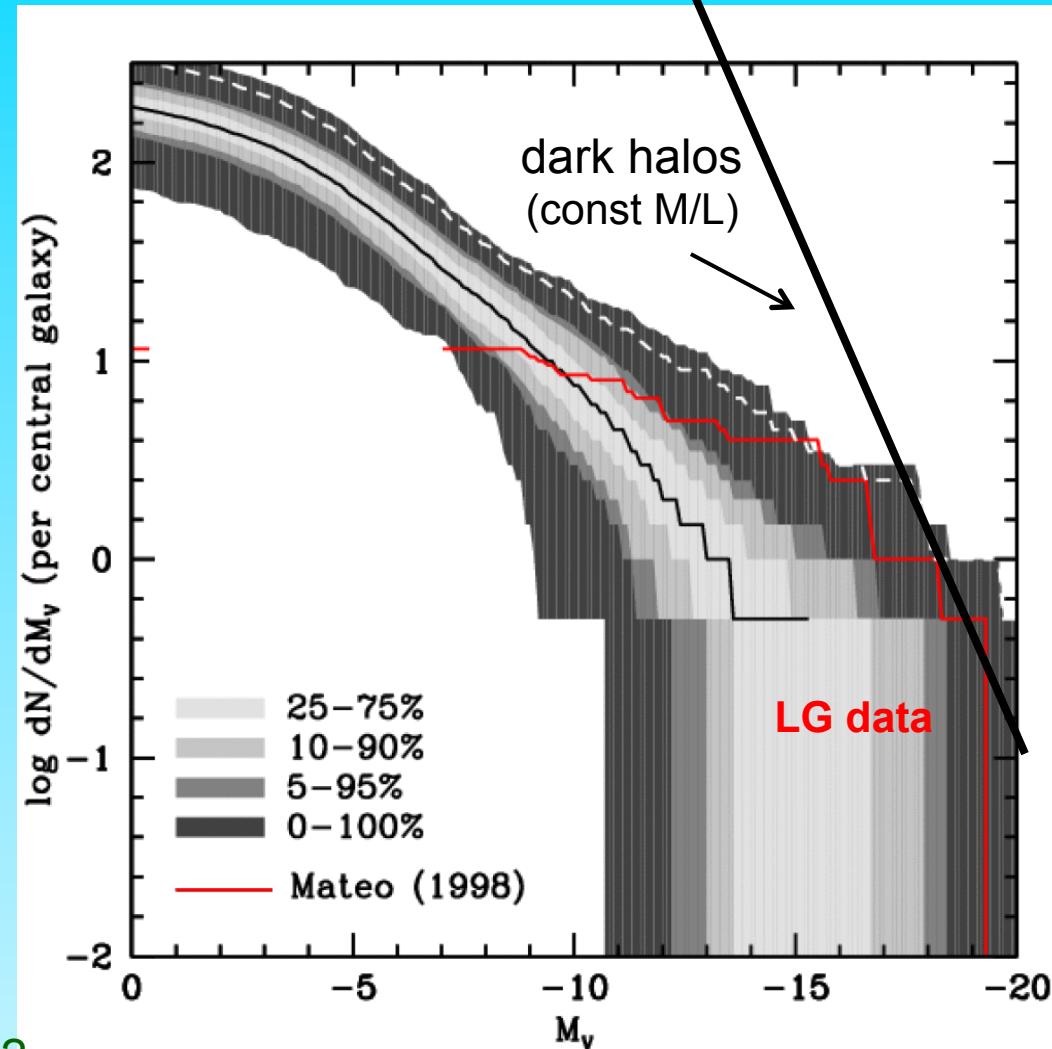
Making a galaxy in a small halo is hard because:

- Reionization heats gas above T_{vir} , preventing it from cooling and forming stars in small halos
- Supernovae feedback expels residual gas

Most subhalos never make a galaxy!

Luminosity Function of Local Group Satellites

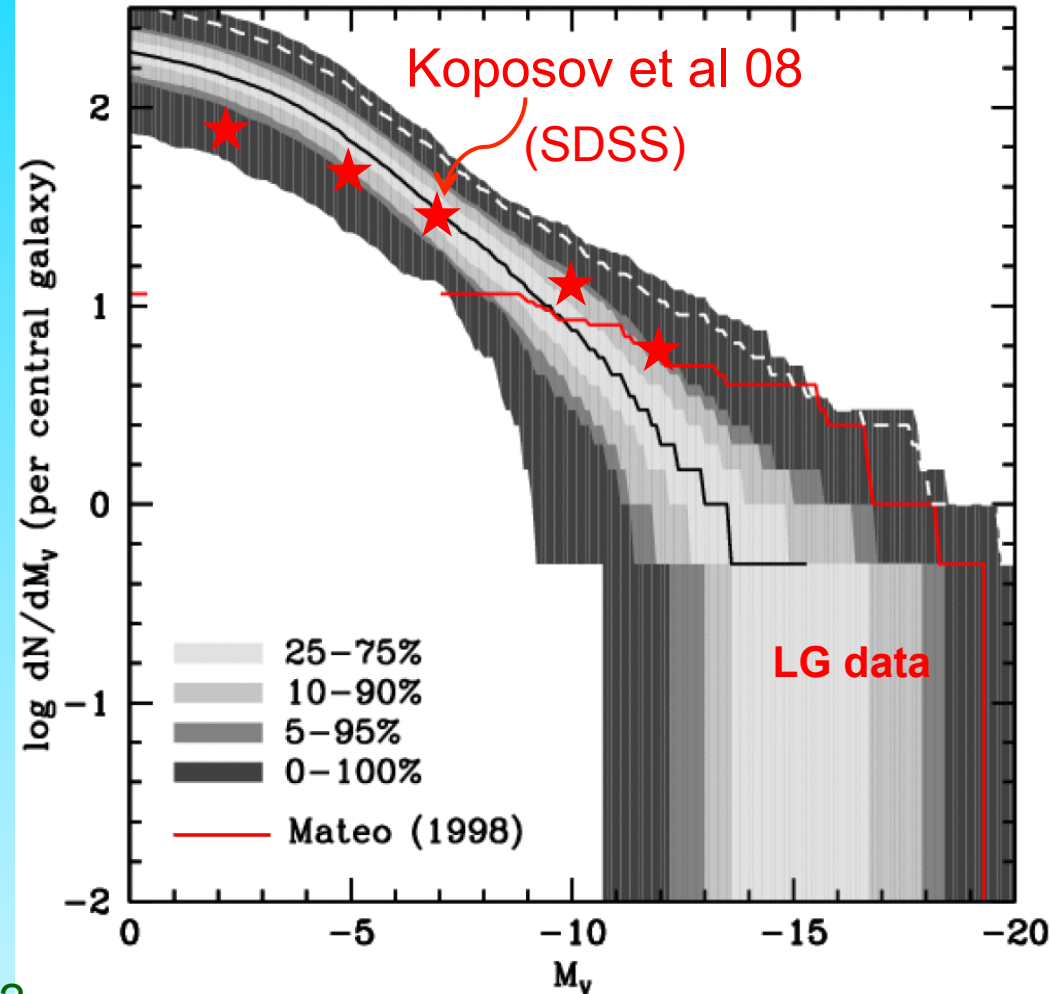
- Median model → correct abund. of sats brighter than $M_V = -9$ and $V_{\text{cir}} > 12$ km/s
- Model predicts many, as yet undiscovered, faint satellites
- LMC/SMC should be rare (~2% of cases)



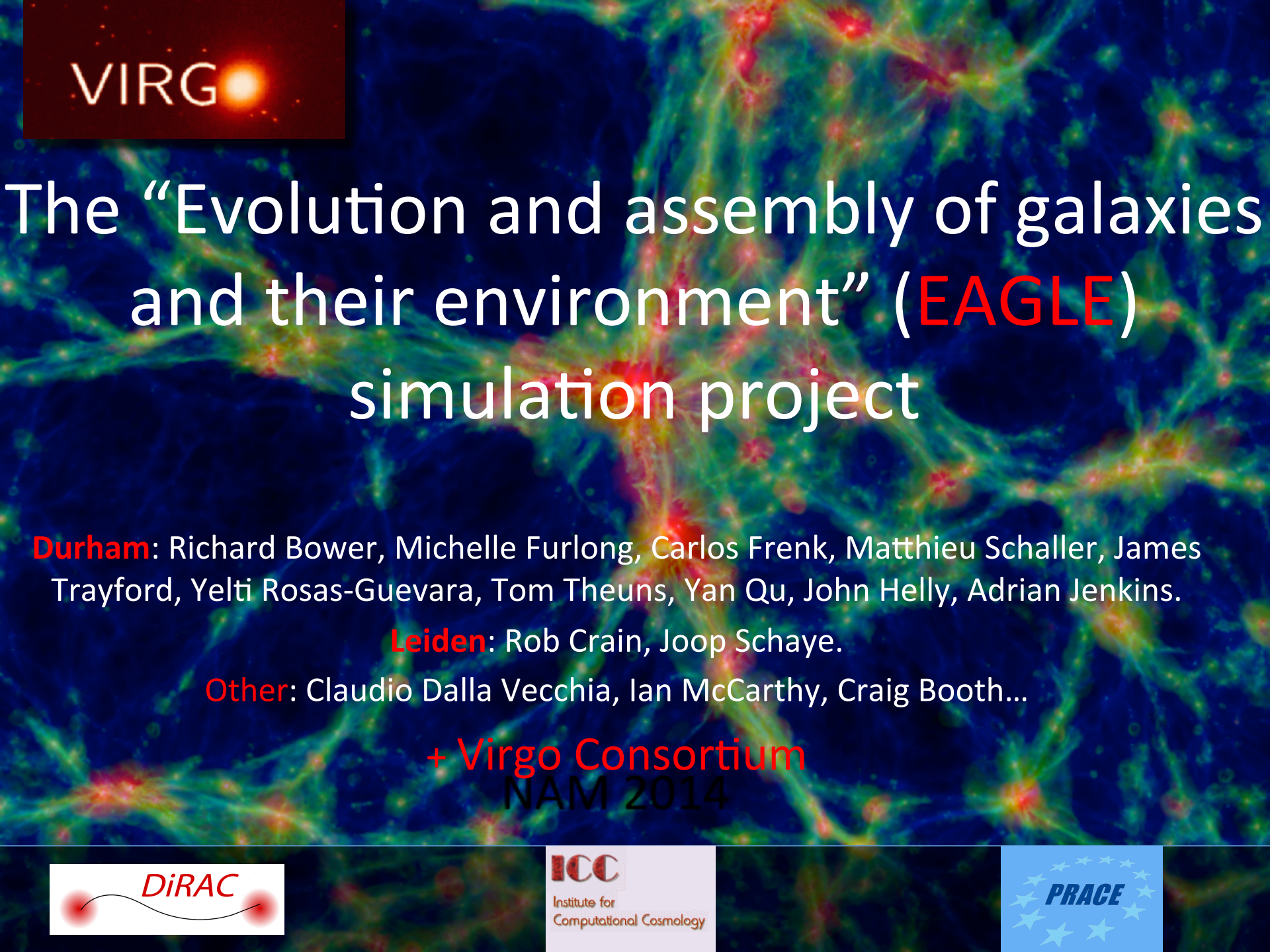
Benson, Frenk, Lacey, Baugh & Cole '02
(see also Kauffman et al '93, Bullock et al '01)

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)



VIRGO

The “Evolution and assembly of galaxies and their environment” (**EAGLE**) simulation project

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth...

+ **Virgo Consortium**
NAM 2014

DiRAC

ICC

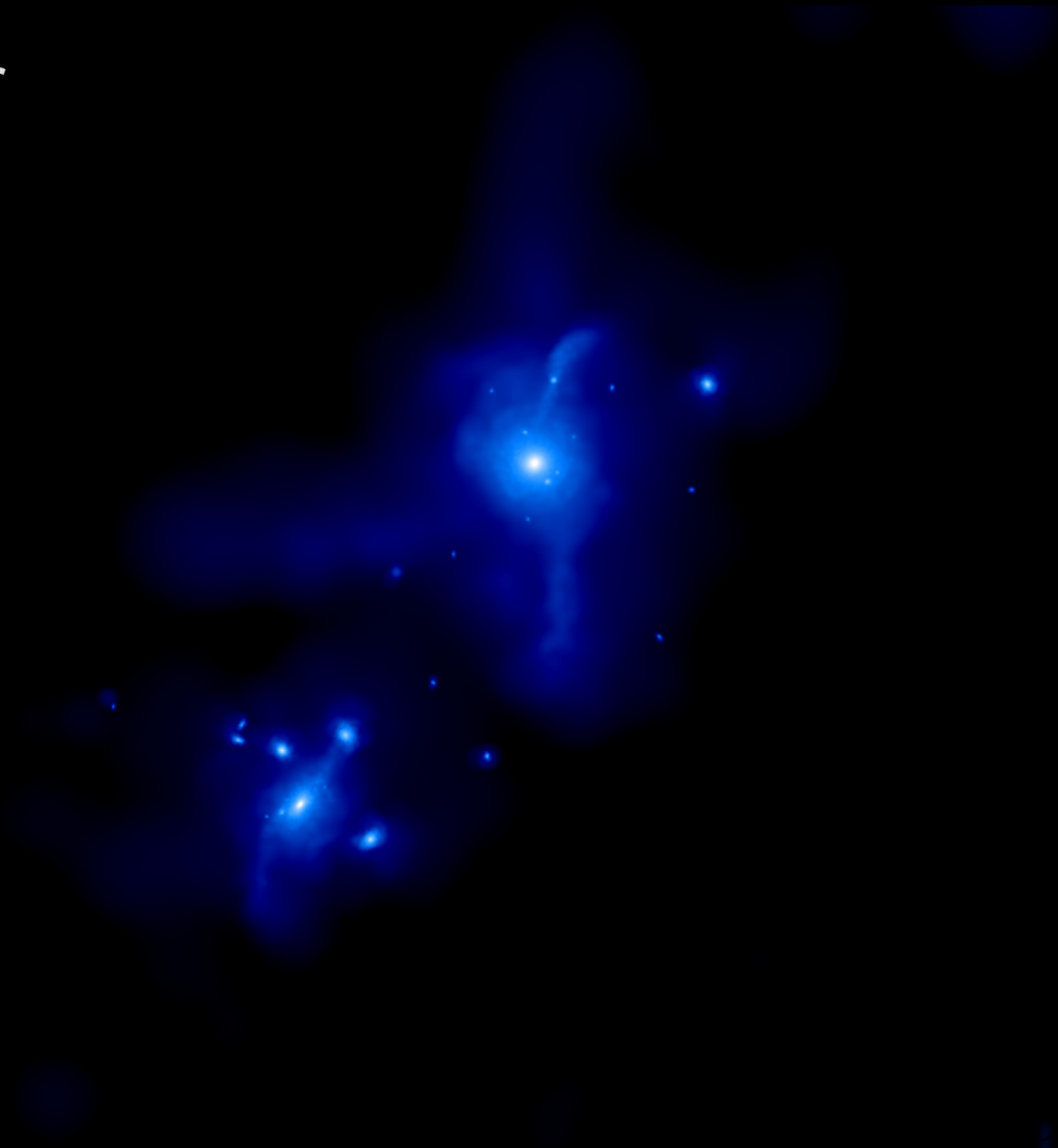
Institute for
Computational Cosmology

PRACE

EAGLE full hydro Local Group simulations

Dark Matter

Gas



VIRG

EAGLE full
hydro
simulations

Local Group

Sawala et al '14

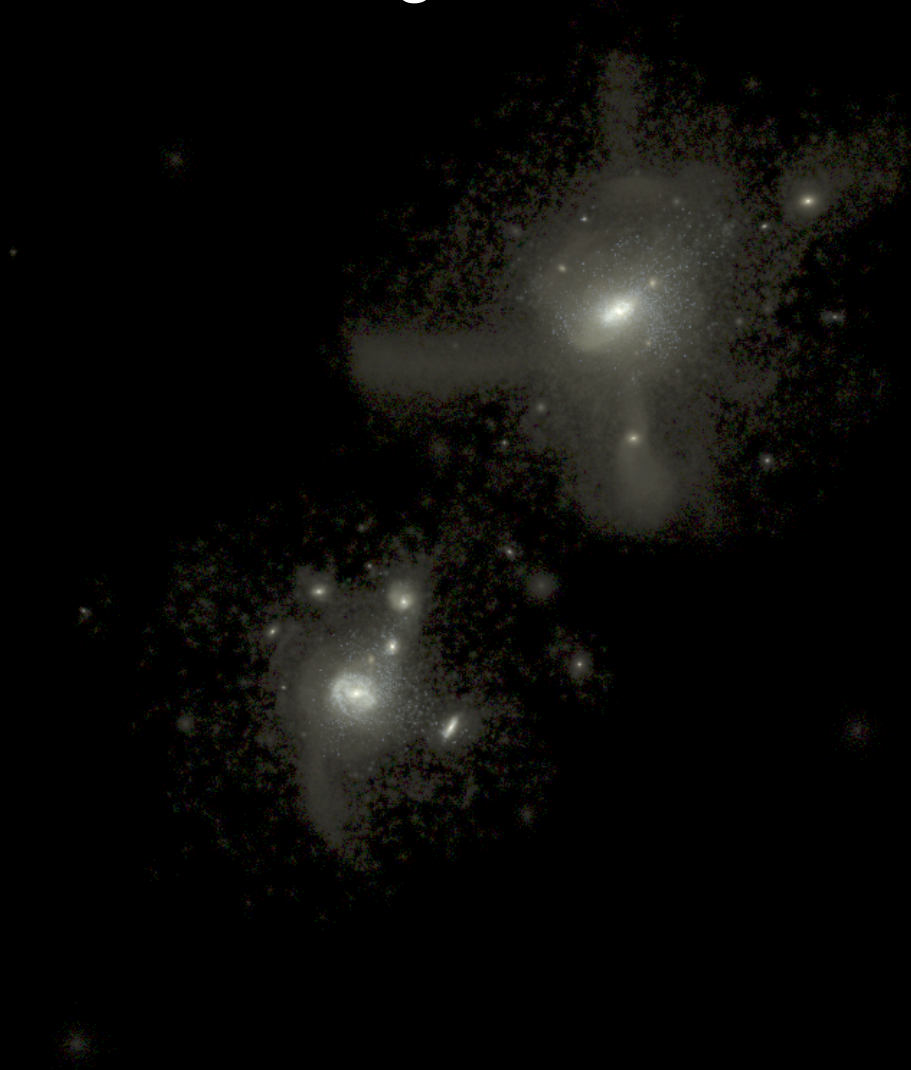


VIRG

Far fewer satellite galaxies than CDM halos

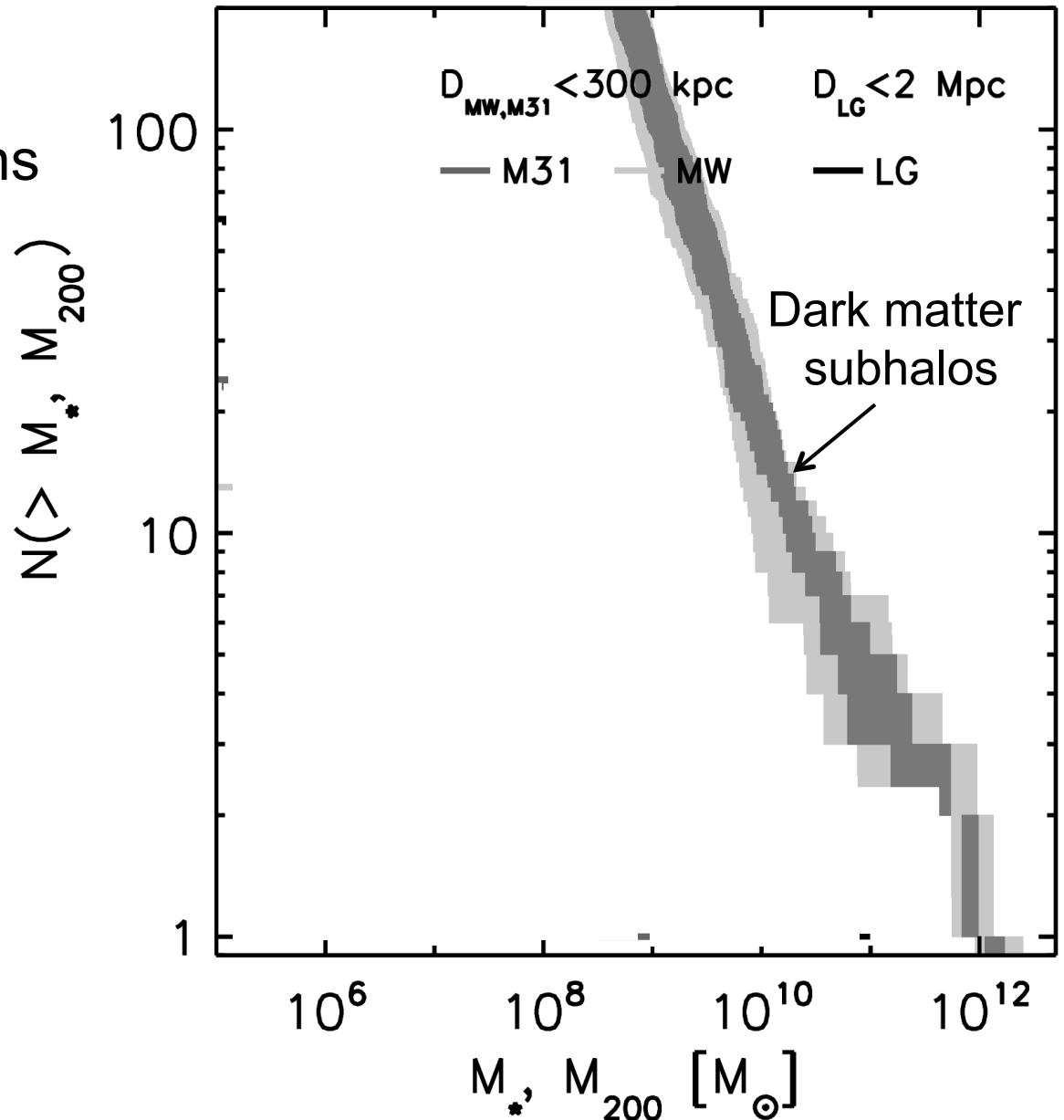
EAGLE full
hydro
simulations

Local Group

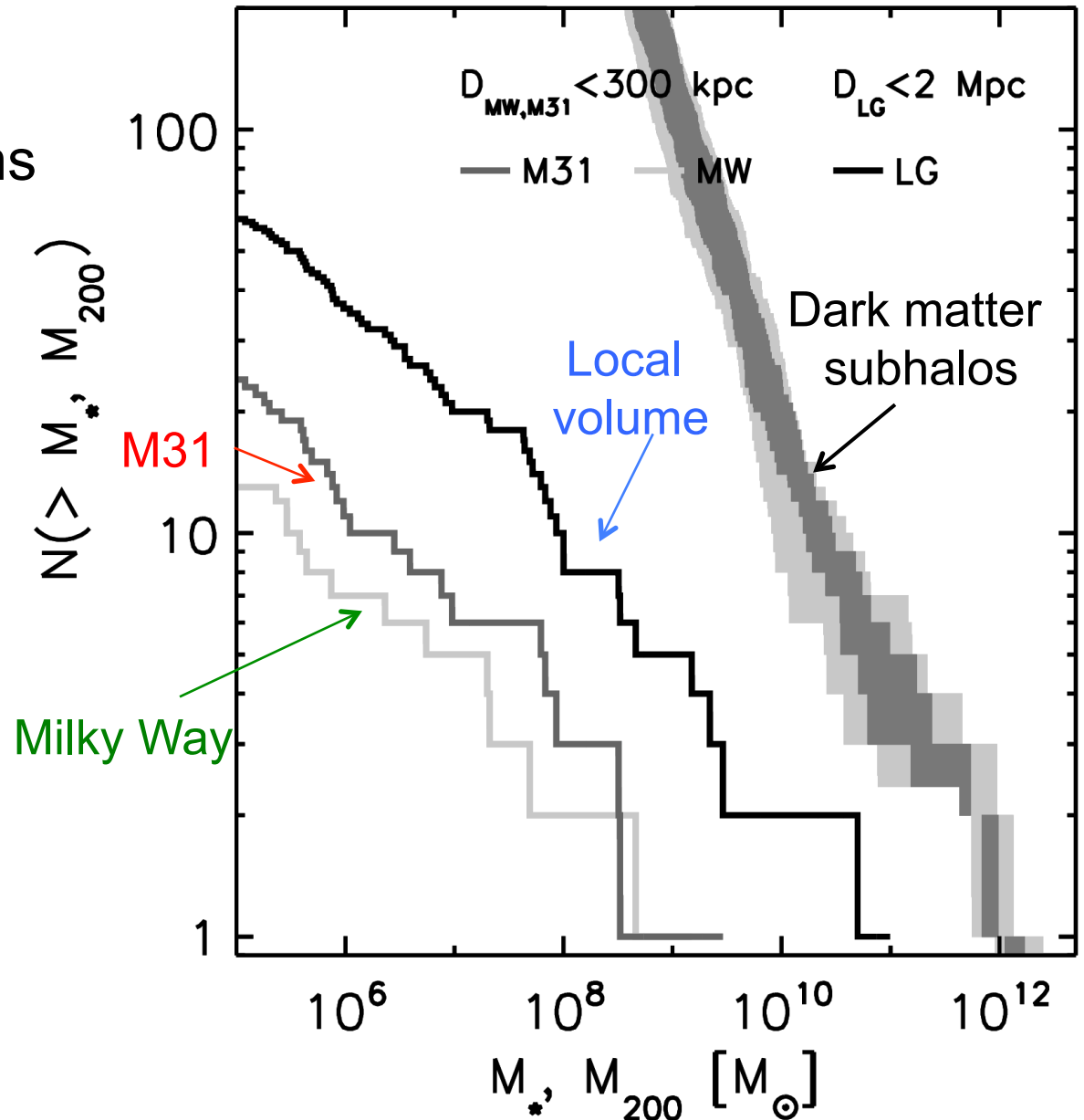


Sawala et al '14

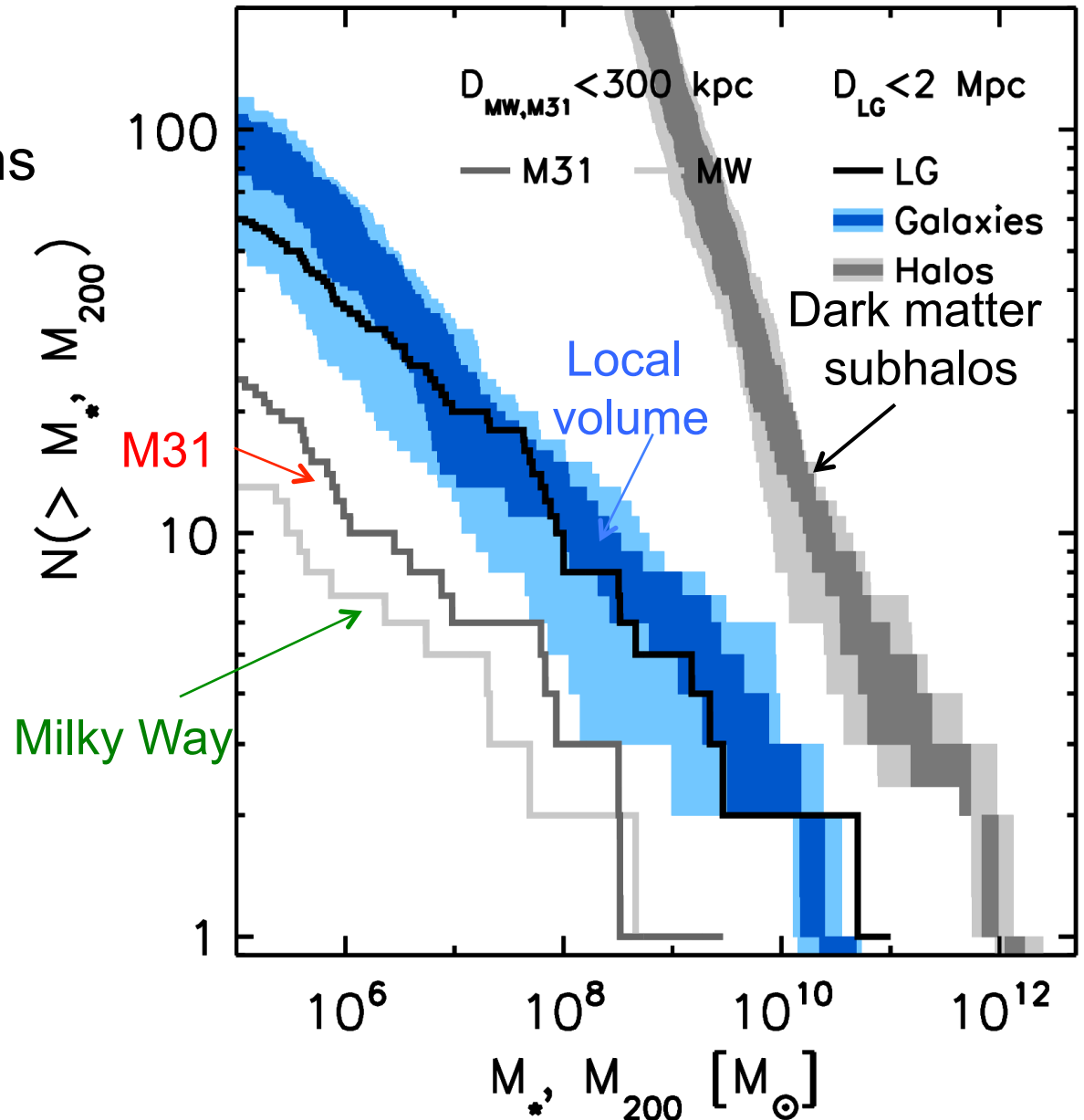
Subhalo mass functions



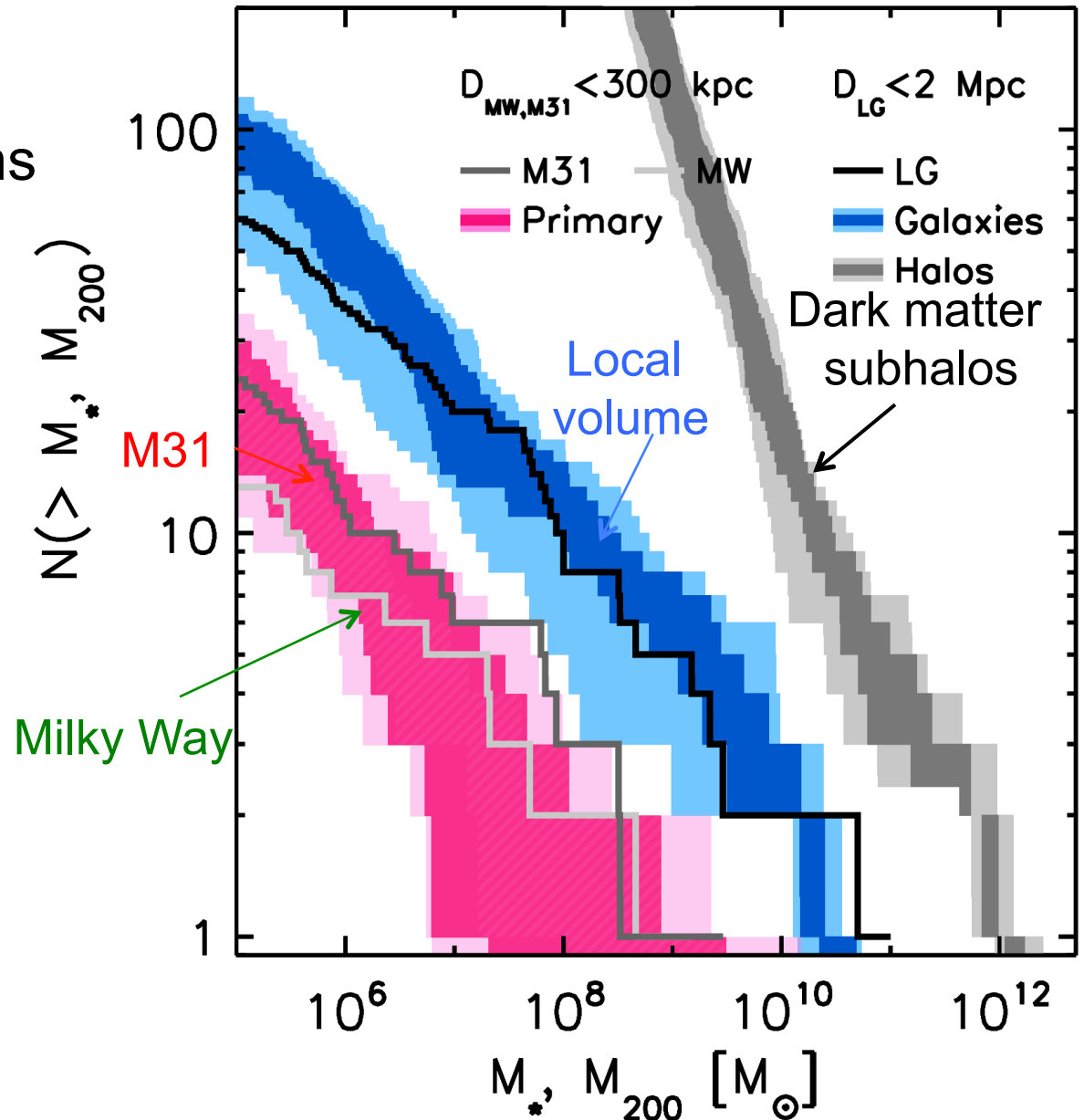
Stellar mass functions



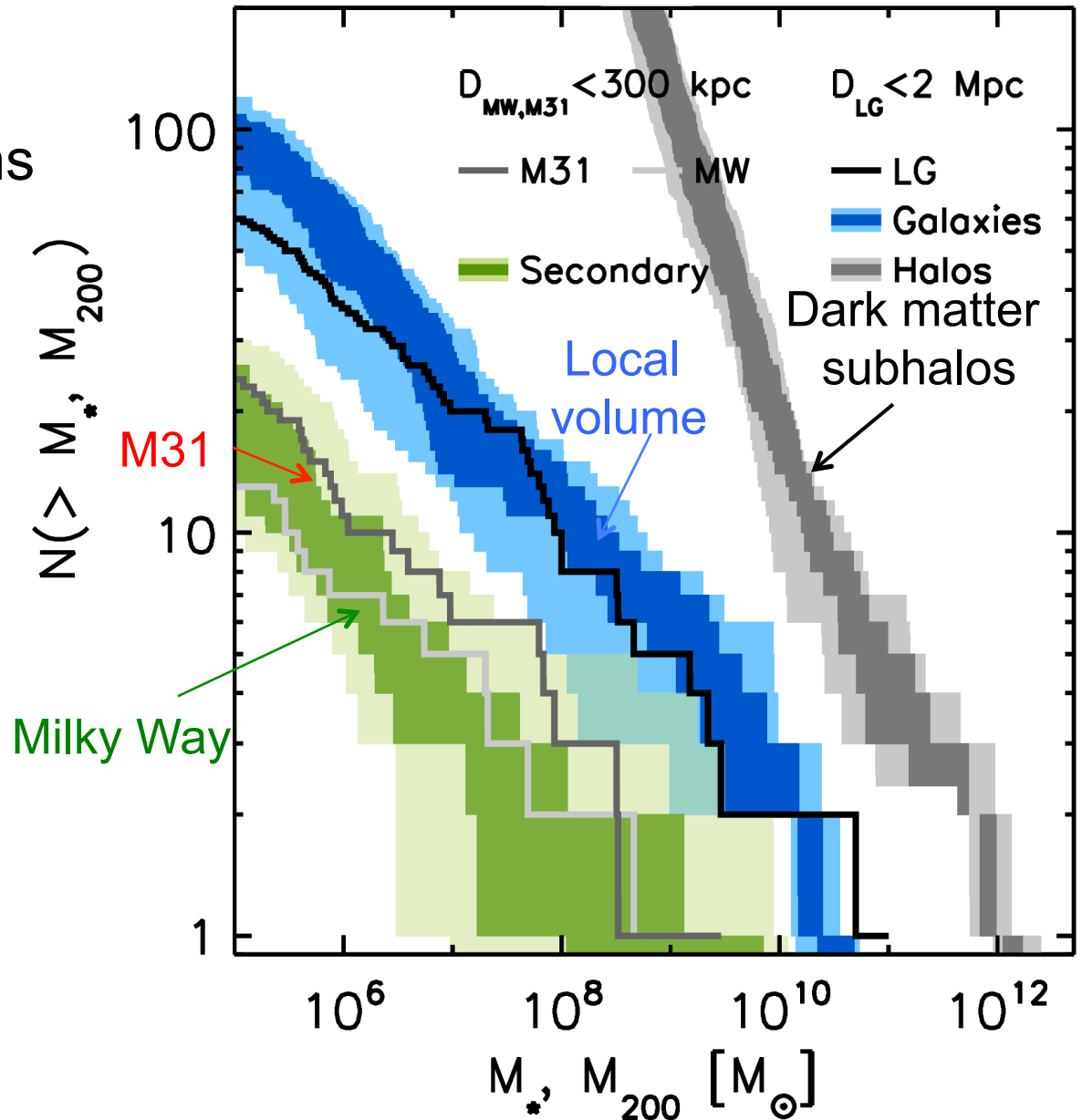
Stellar mass functions



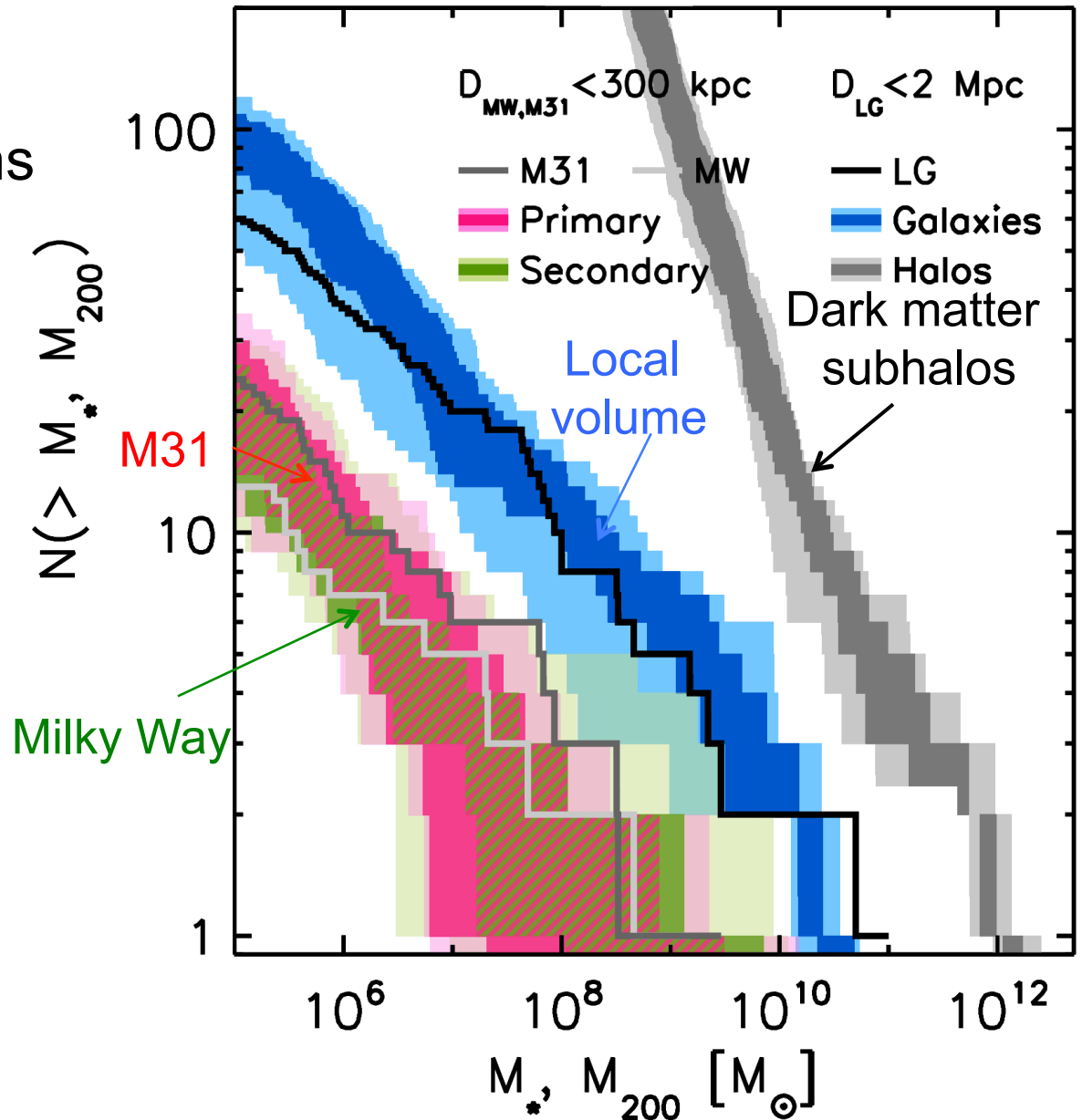
Stellar mass functions



Stellar mass functions



Stellar mass functions





Is there a “satellite problem” in CDM?

No, when galaxy formation is taken into account!



Is there a “satellite problem” in WDM?

Potentially!



Warm DM: different ν mass

$z=3$

WDM

2.3 keV

2.0 keV

1.6 keV

1.4 keV

CDM

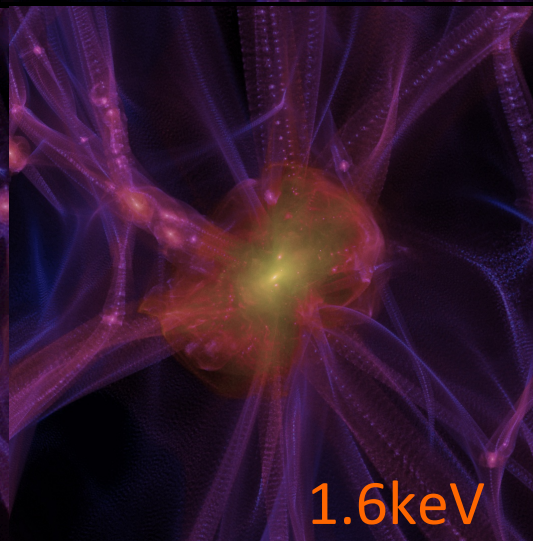
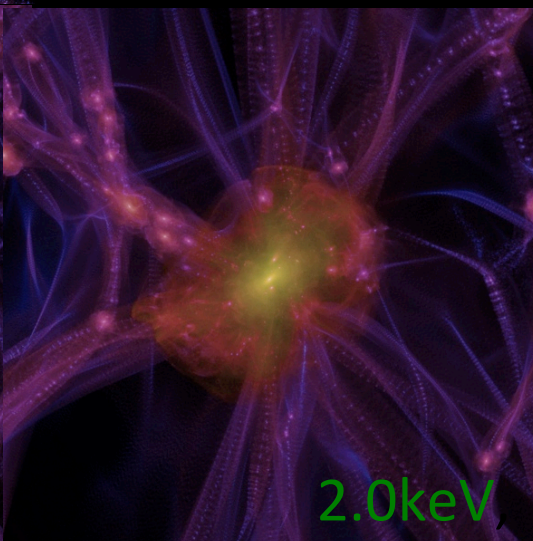
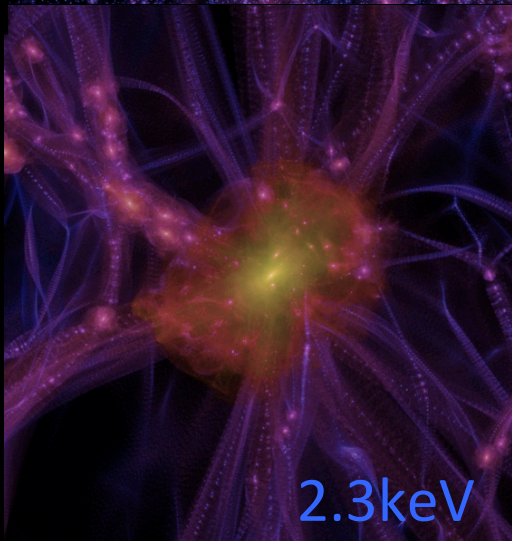
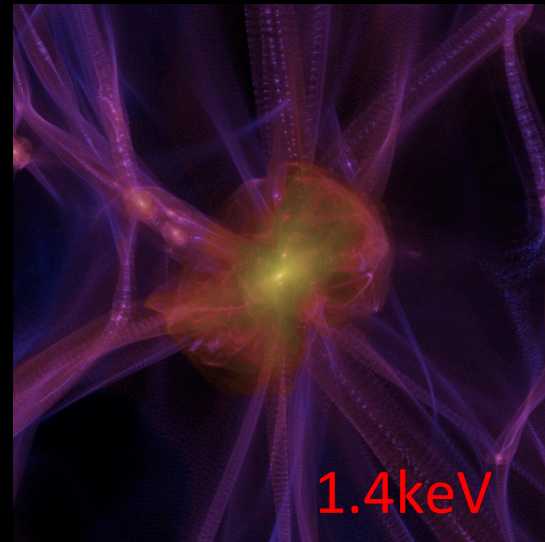
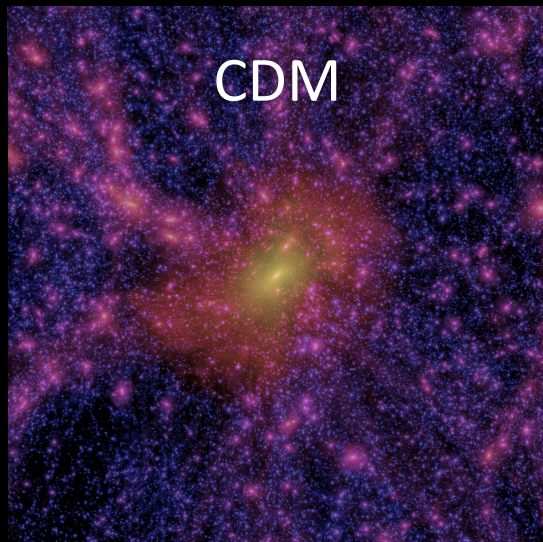
WDM

1.4keV

2.3keV

2.0keV

1.6keV

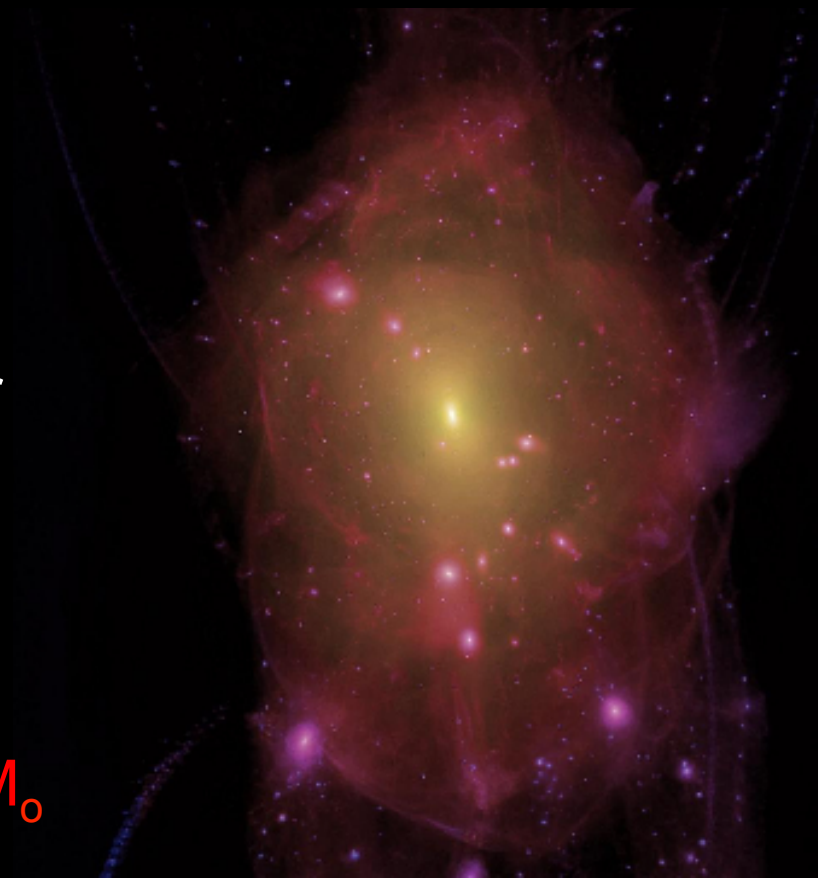


Tests of the nature of the DM

warm dark matter

If the halo mass is too small and/or the WDM particle mass is too small, there will not be enough subhalos to account for the observed satellites!

- lower limit on $m_{\text{wdm}} > 3 \text{ keV}$
- lower limit $M_{\text{halo}} > 1.1 \times 10^{12} M_{\odot}$



Kennedy, Cole & Frenk '13

Four problems on small scales

Traditionally ascribed to CDM:

1. The “core-cusp” problem
2. The “missing satellites” problem
3. The “too-big-to-fail” problem
4. The “satellite disk” problem

Can these help distinguish between CDM & WDM?



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

$$V_{\max} = \max V_c$$

The satellites of the MW



CDM has ~ 10 subhalos with $V_{\text{max}} > 30$ km/s

MW has only 3 satellites
with $V_{\text{max}} > 30$ km/s
(LMC, SMC, Sgr)

Why did these not make a galaxy?

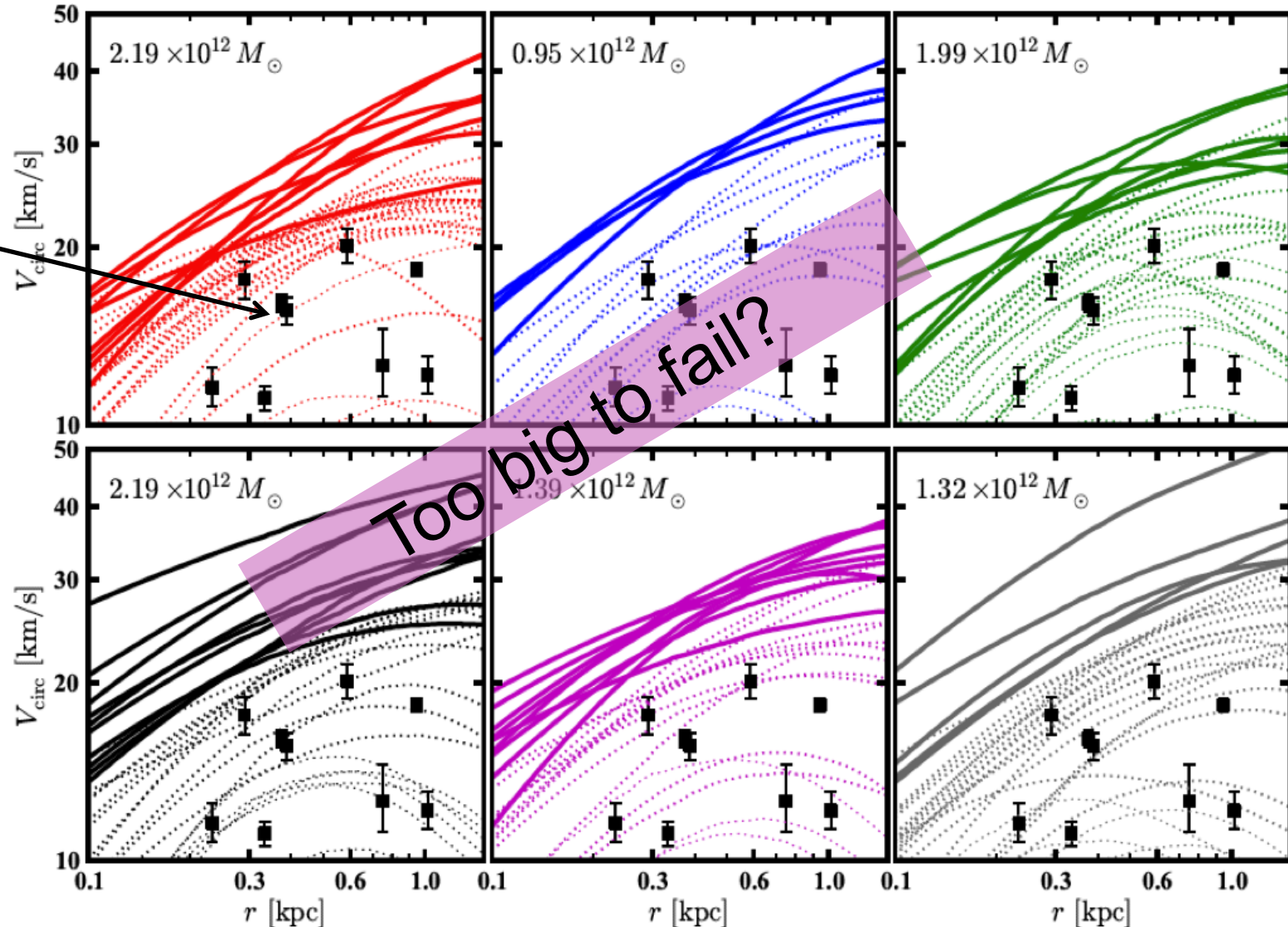
Rotation curves of Aquarius subhalos

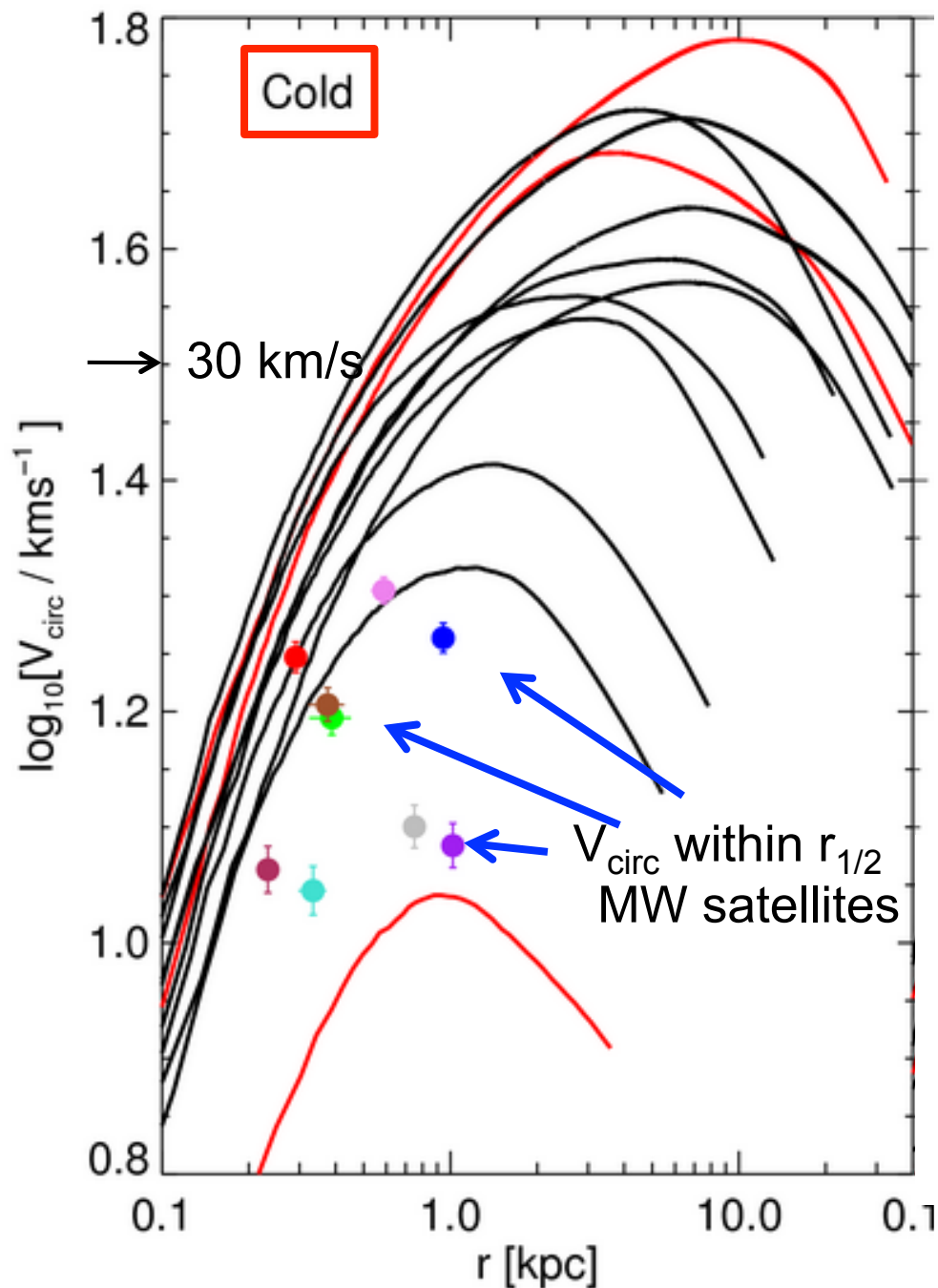
Boylan-Kolchin et al. '11

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

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

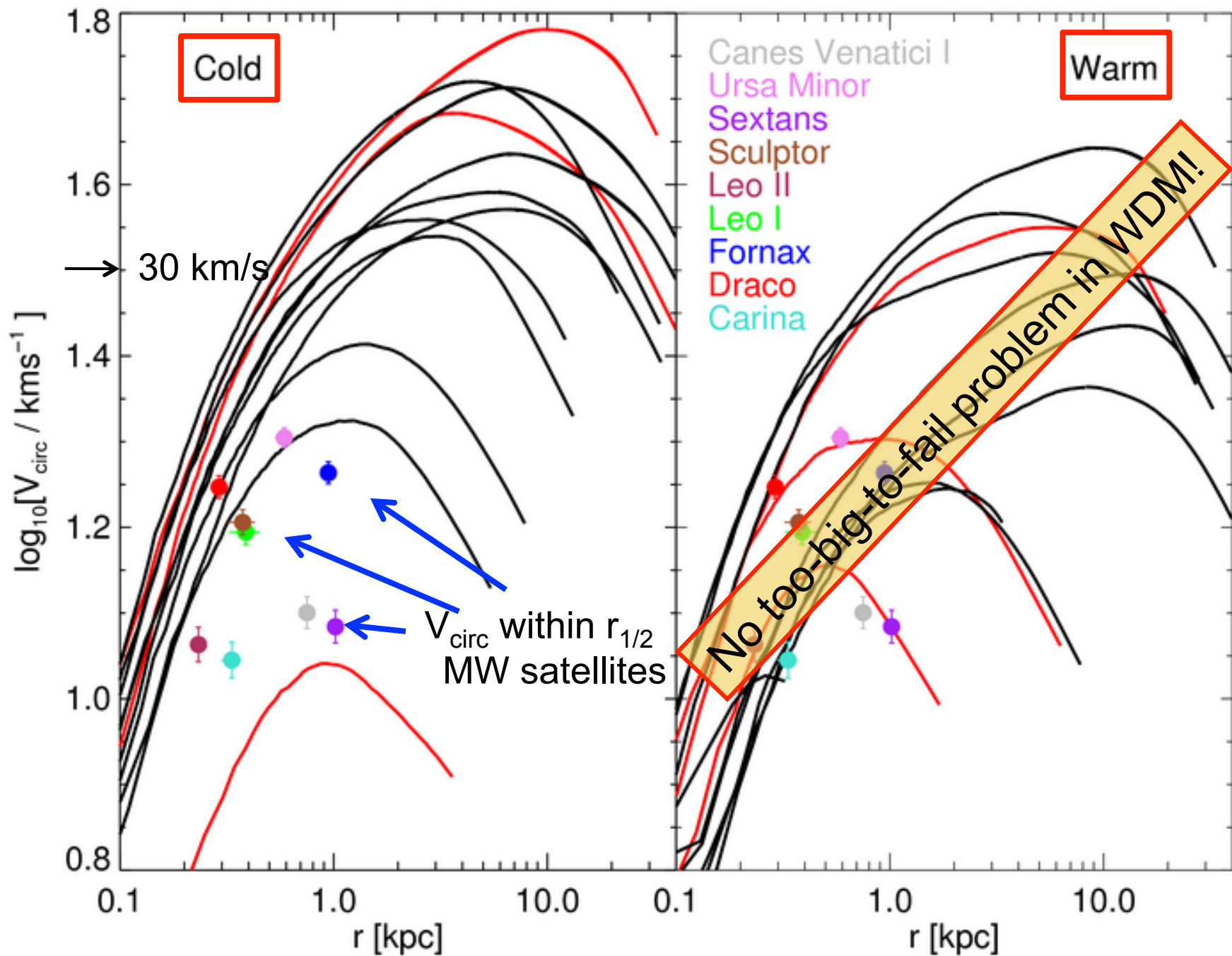
Excludes
LMC, SMC,
Sagittarius





$$V(r)_c = \sqrt{\frac{GM(r)}{r}}$$

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



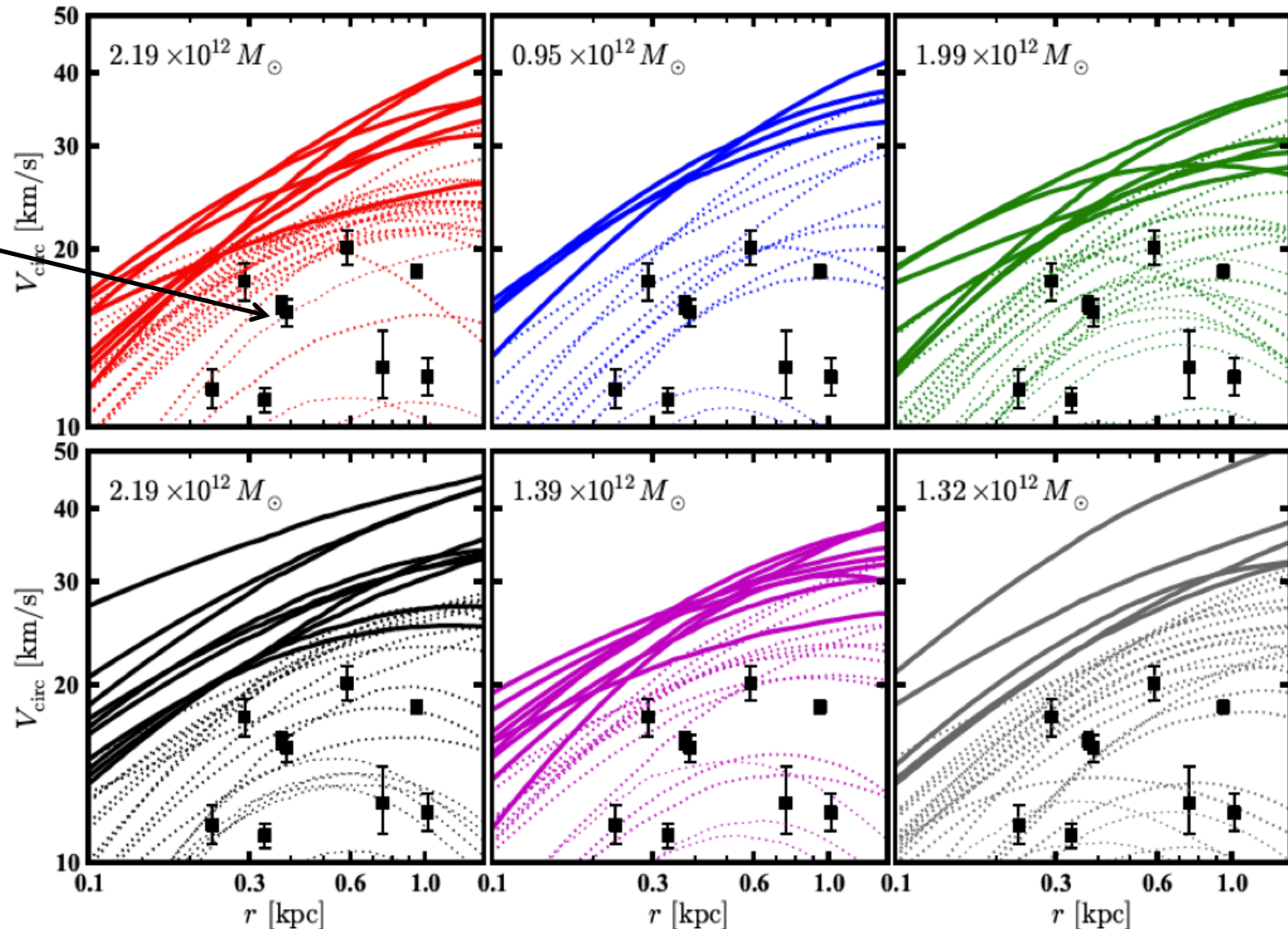
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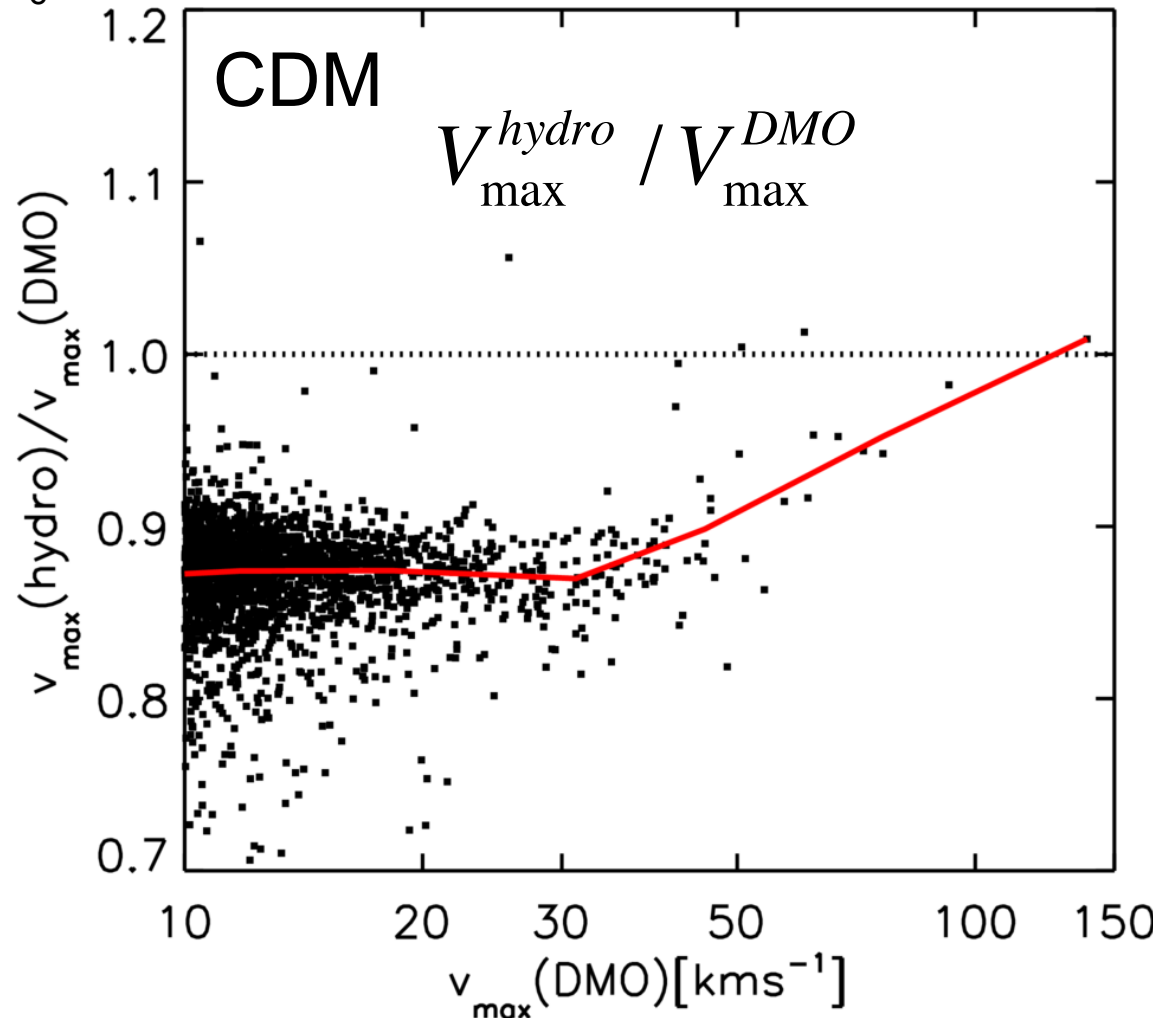
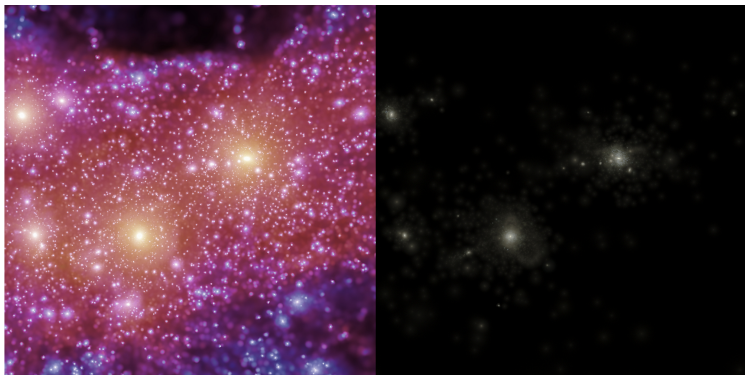


To-big-to-fail in CDM: baryon effects

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

Reduction in $V_{\max}$ due to SN feedback:

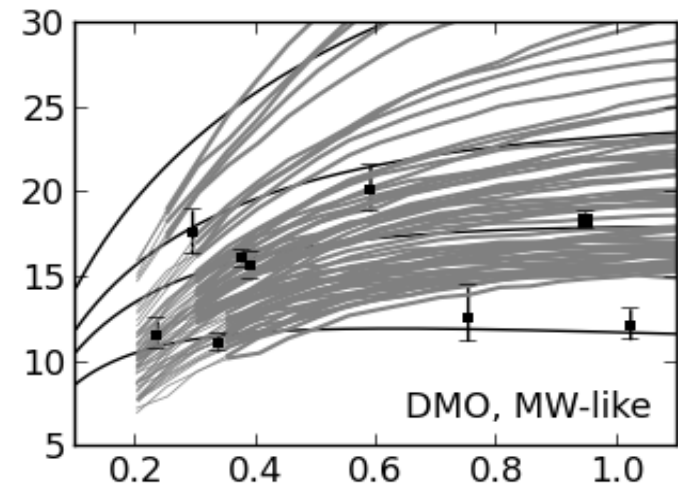
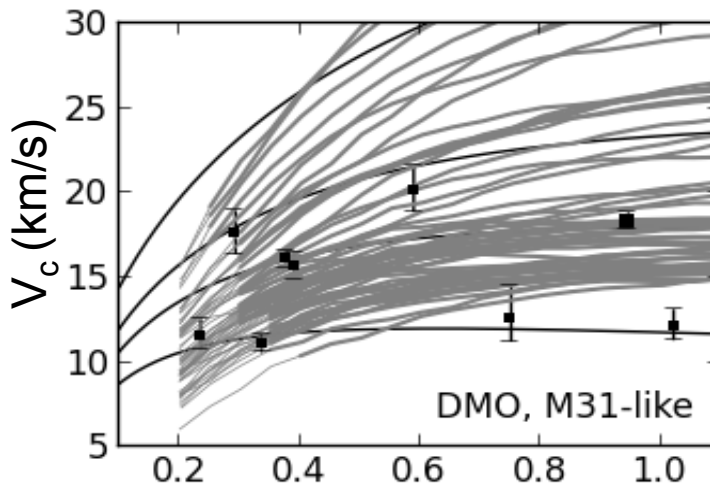
→ Lowers halo mass & thus halo growth rate



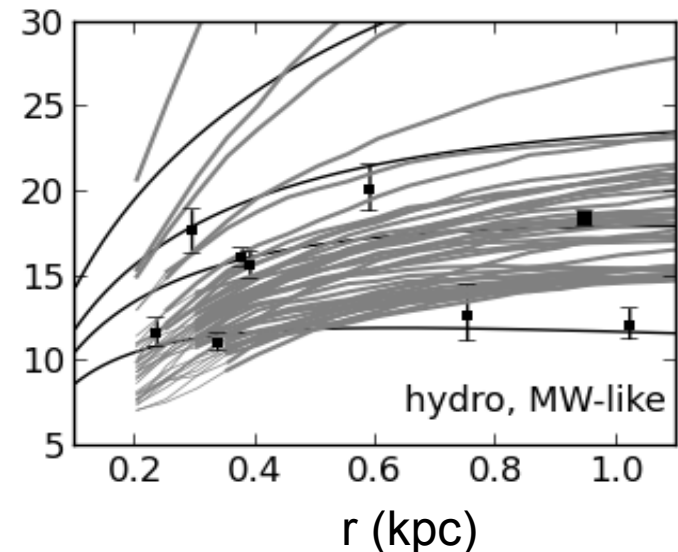
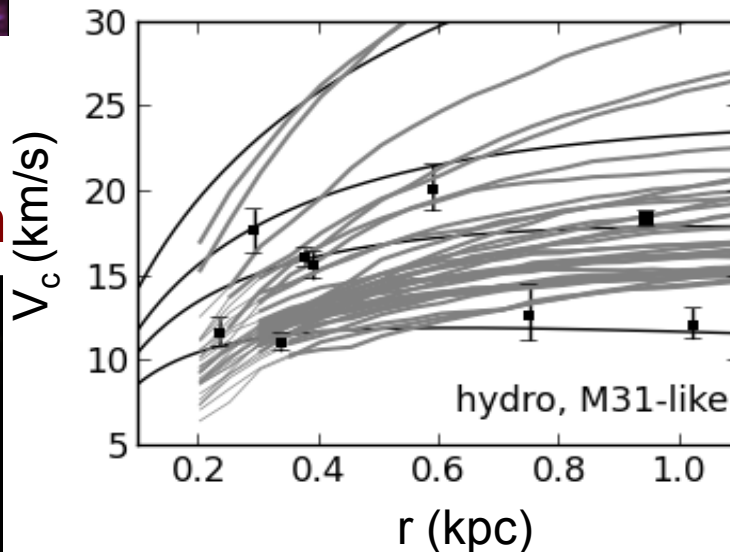
Sawala et al. '13, '14

Too-big-to-fail: the baryon bailout

DM-only
simulation



Gas
simulation

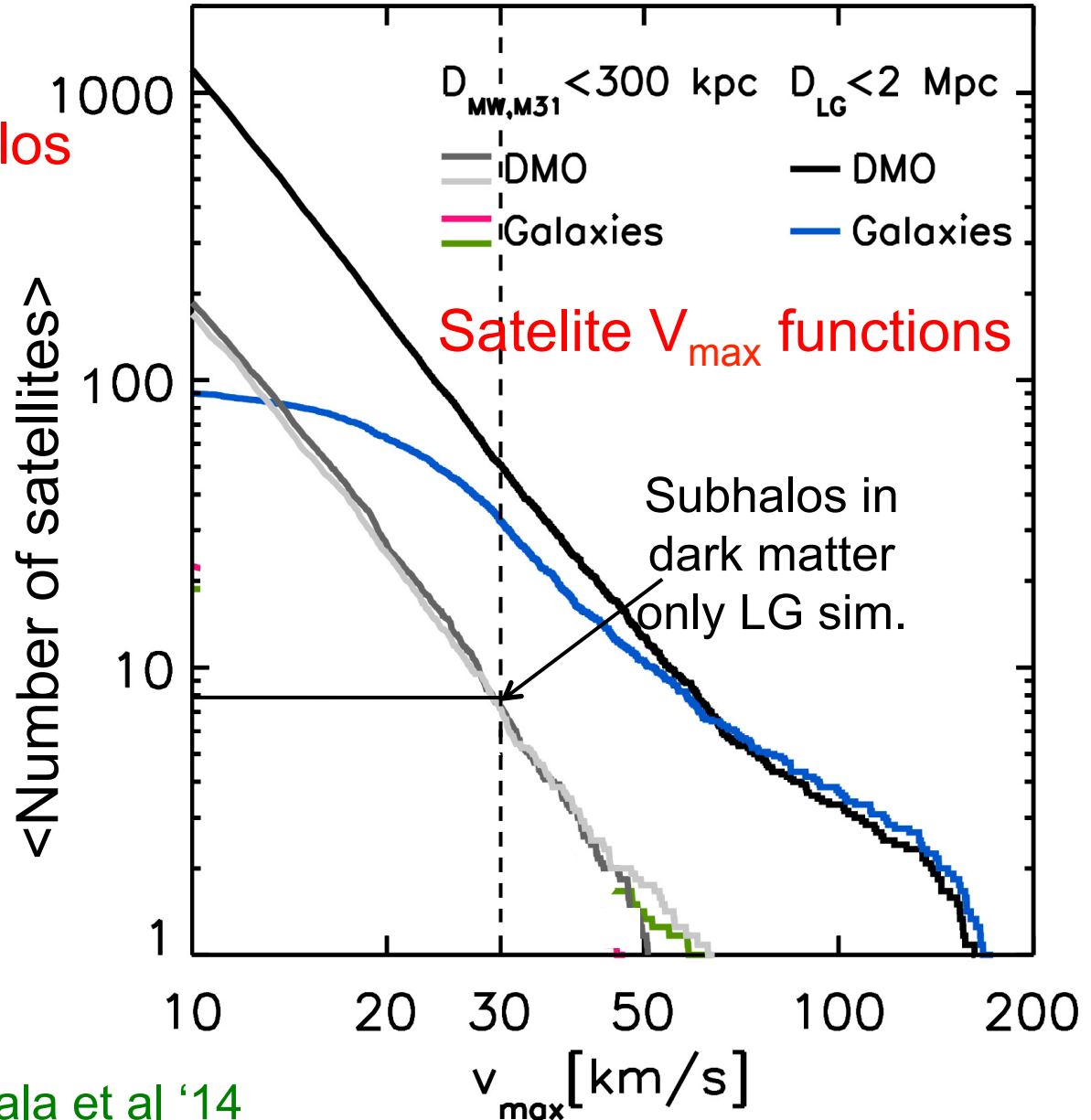


Number of subhalos of given $V_{\max}$ is greatly reduced in gas simulations

Sawala et al. '14

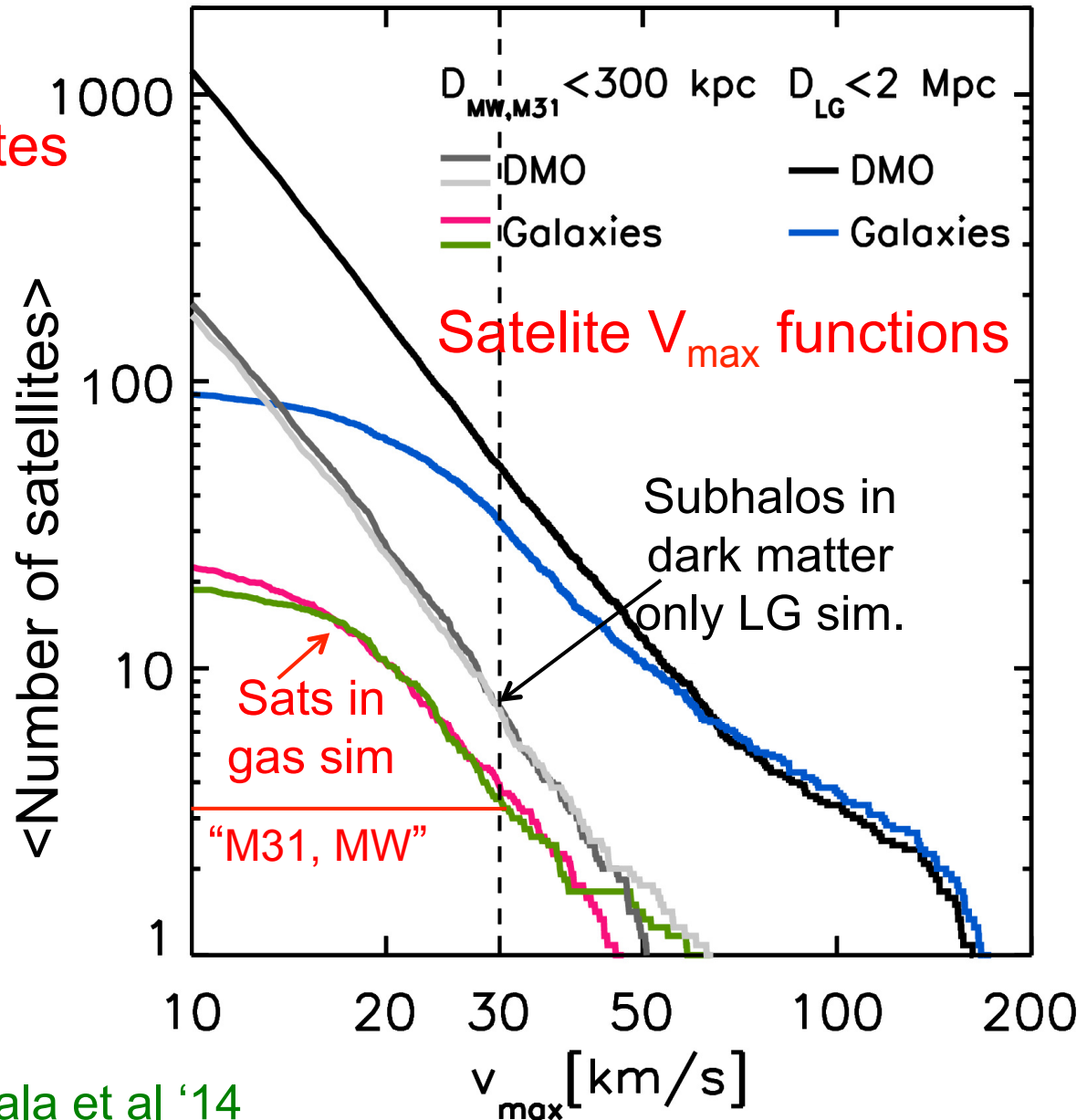
Too-big-to-fail: the baryon bailout

DM only sims $\rightarrow$ **~ 10 halos**
with $V_{\max} > 30$ km/s



Too-big-to-fail: the baryon bailout

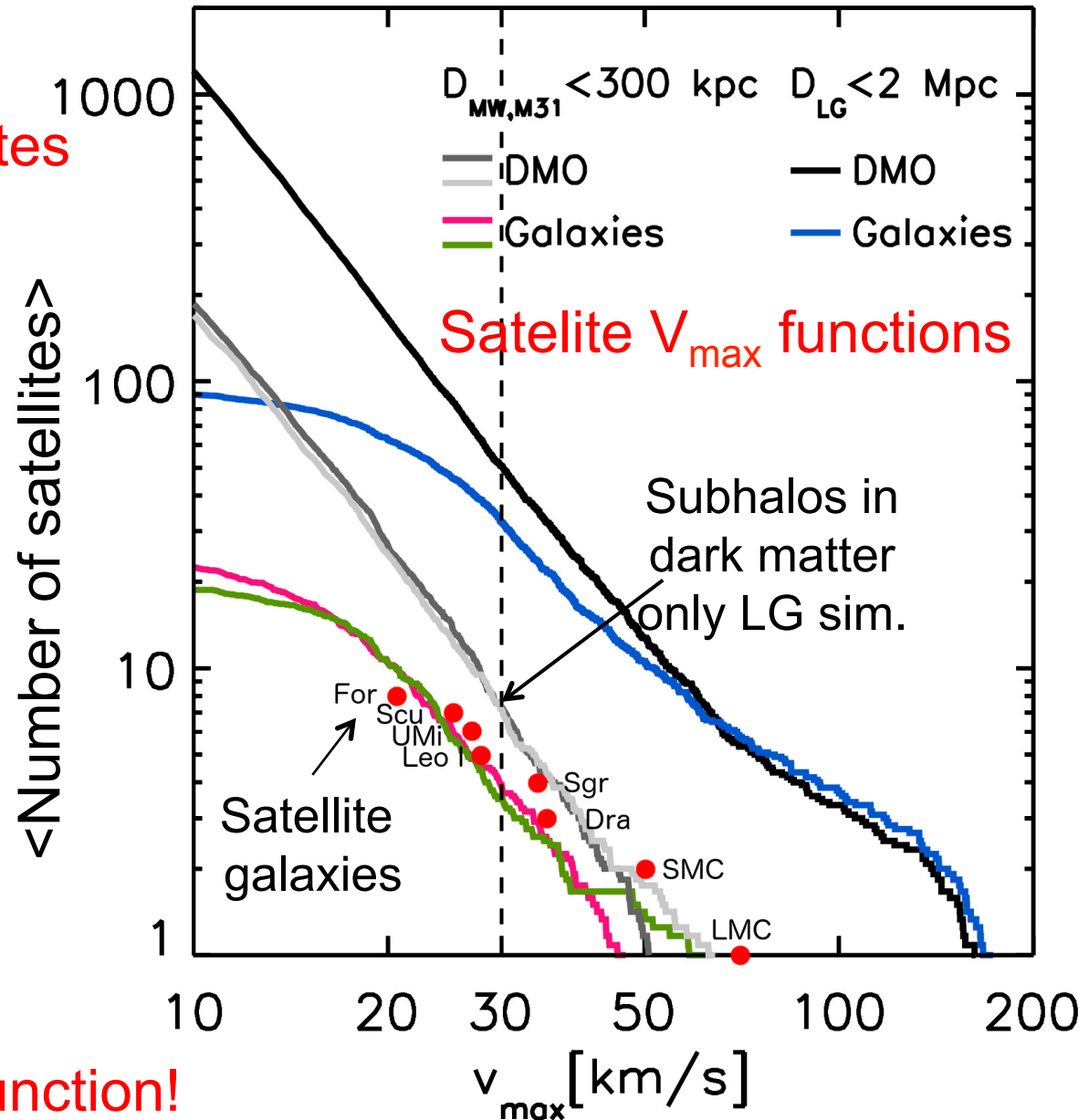
Hydro sims $\rightarrow$ **~3 satellites**
with $V_{\max} > 30$ km/s



Sawala et al '14

Too-big-to-fail: the baryon bailout

Hydro sims $\rightarrow$ **~ 3 satellites**
with $V_{\max} > 30$ km/s



. and with correct $V_{\max}$ function!

Four problems on small scales

Traditionally ascribed to CDM:

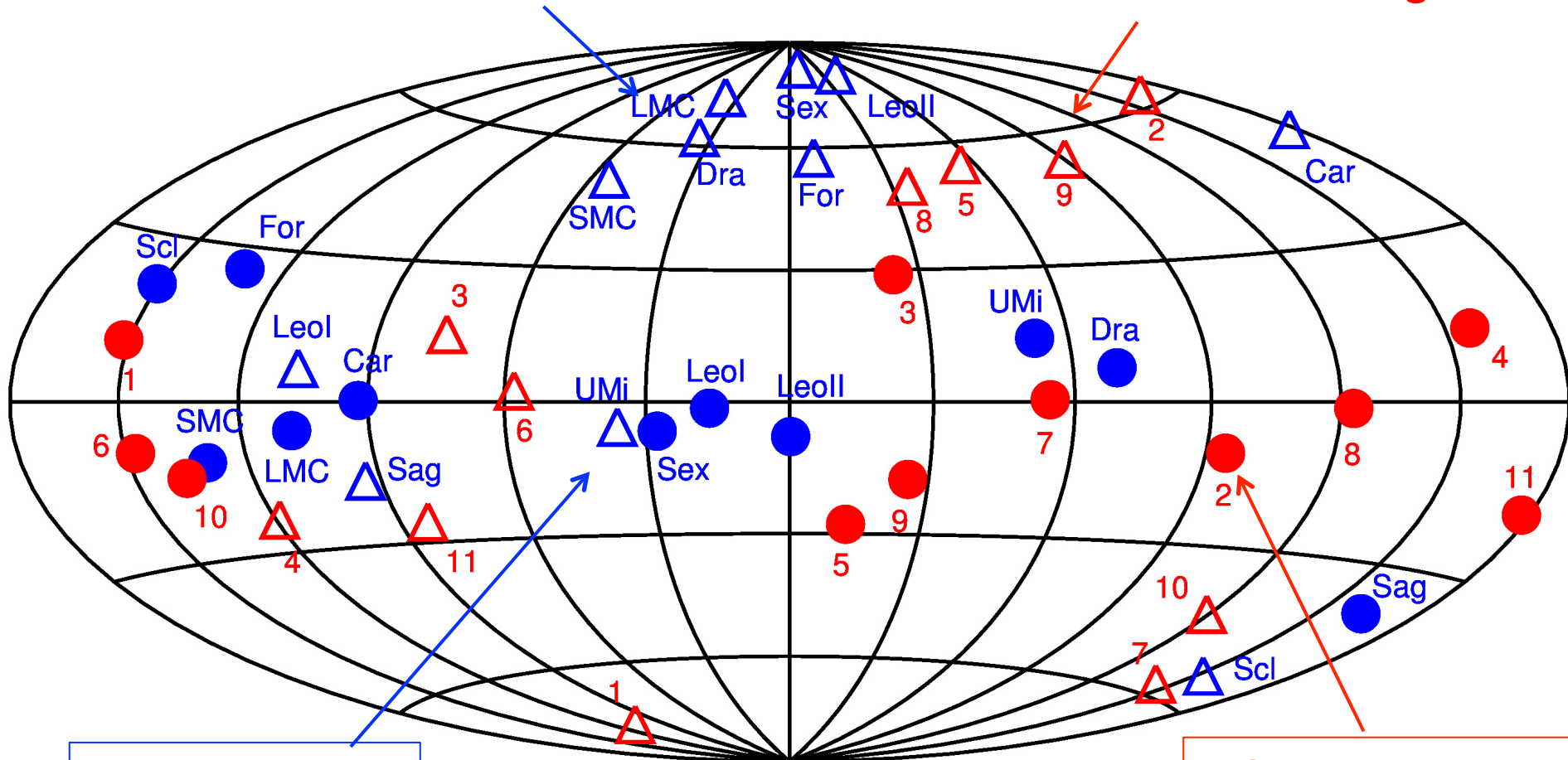
1. The “core-cusp” problem
2. The “missing satellites” problem
3. The “too-big-to-fail” problem
4. The “satellite disk” problem

Can these help distinguish between CDM & WDM?

The “satellite disk” problem

Direction of ang. mom.

Direction of ang. mom.

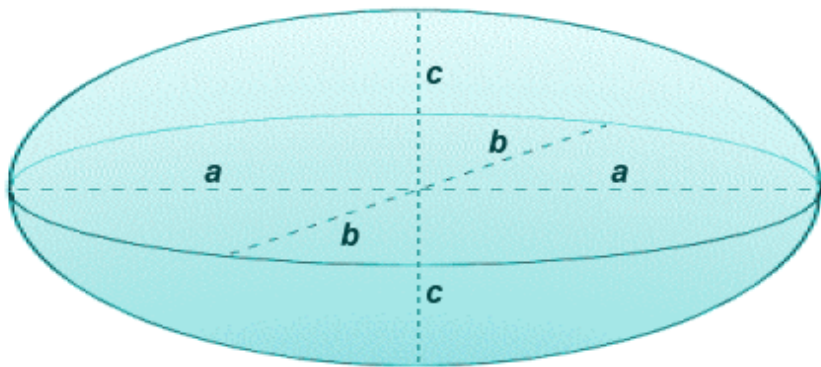


MW satellites

LG simulations

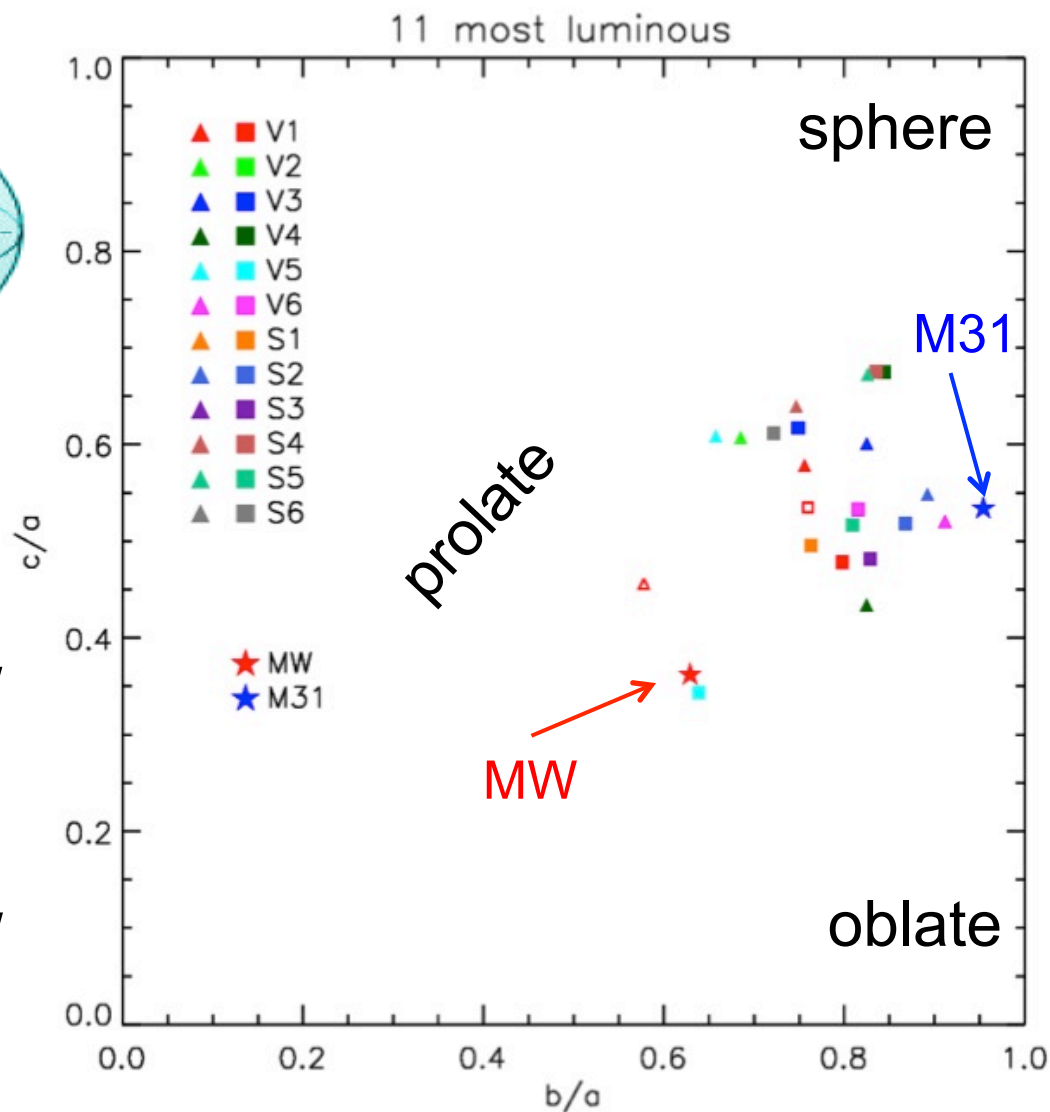
Lynden-Bell '76

The “satellite disk” problem



11 brightest satellites in MW
make up a “great pancake”

1/12 LG simulations $\cong$ MW





Conclusions

- 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**

Four “problems” on small scales:

1. Core-cusp: **Not** a problem? (Baryon effects?)
2. Abundance of sats: **CDM** OK; **WDM** OK if $m_{\text{WDM}} > 3\text{ KeV}$
3. Too-big-to-fail: **CDM**, **WDM** OK
4. Disk of satellites: **CDM**, **WDM** OK