Dark matter

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1. **Evidence, properties and distribution**

2. WIMPs: production & direct detection

3. Primordial Black Holes

1. Evidence, properties and distribution

Observational evidence + properties

Distribution (on galactic scales)

Modified gravity (very briefly, if time permits)

1. Recommended further reading/viewing

- chapter 2 of ‘Particle dark matter: evidence, candidates & constraints’, Bertone, Hooper & Silk, Phys. Rep. hep-ph/0404175.

- chapter 1 of ‘An introduction to particle dark matter’, Profumo, World Scientific.

- Particle Data Group review of Particle Physics
  - Dark matter, Baudis & Profumo
  - Cosmological parameters, Lahav & Liddle

- Les Houches Dark Matter Summer School 2021: videos and lecture notes
  - ‘Dark matter in astrophysics/cosmology’, Green
  - ‘Dark matter numerical simulations’, Peter

Questions

Questions on things which aren't clear:

during the pauses in the lectures
or (if it's urgent) raise your hand to interrupt

Questions on technical details or extensions:

in person after/between lectures
by email: anne.green@nottingham.ac.uk
or padlet: https://padlet.com/annegreen3/benasquedm

if I think the answer is of broad interest I'll share it on padlet or in a subsequent lecture.

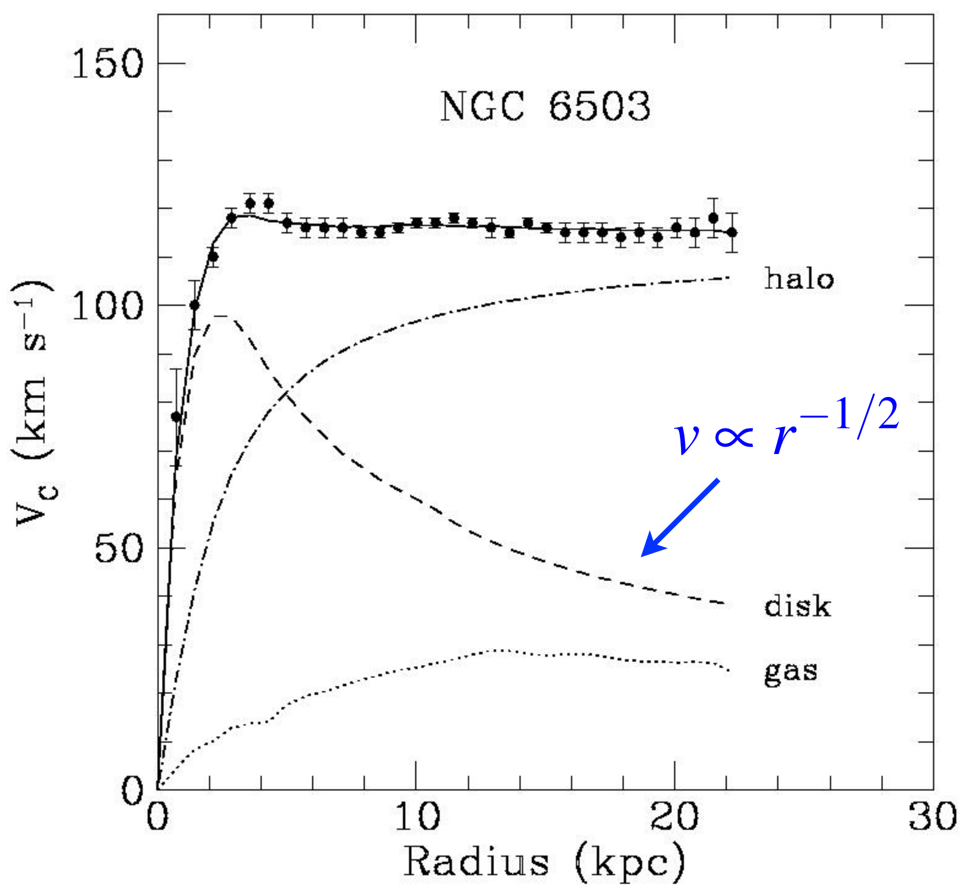
Observational evidence + properties

Rotation curves of spiral galaxies Rubin & Ford; Freeman;…

Using Newton's law of gravity:

$$\frac{v_{rot}^2}{r} = \frac{GM(< r)}{r^2}$$

$M(< r)$ = mass enclosed within a radius r.



Begeman, Broeils & Sanders

$$v_{\rm rot} = \sqrt{\frac{GM(< r)}{r}}$$

Outside of matter distribution:

$M(< r)$ const & $v_{\rm rot} \propto r^{-1/2}$

$$v_{\rm rot} \sim {\rm const} \;\rightarrow\; M(< r) \propto r \;\rightarrow\; \rho(r) \propto r^{-2}$$

(Assuming Newtonian gravity is correct) galaxies are surrounded by extended halos of invisible dark matter.

Galaxy clusters

Contain 100s or 1000s of galaxies plus hot X-ray emitting gas.

Largest gravitational bound objects in Universe, therefore expect that the material they contain is roughly representative of the Universe as a whole.

i) mass from virial theorem Zwicky; Smith

For a self-gravitating system in equilibrium, kinetic energy (T) and potential energy (V) are related by the virial theorem: $2T + V = 0$

$$\rightarrow \quad \frac{M}{L} \sim 400 \frac{M_\odot}{L_\odot}\,, \qquad \equiv \quad \Omega_\mathrm{m} \sim 0.3$$

density parameter: $\Omega_\mathrm{X} \equiv \dfrac{\rho_\mathrm{X}}{\rho_\mathrm{c}}$

critical density
(geometry flat)

ii) baryon fraction from X-ray emitting gas

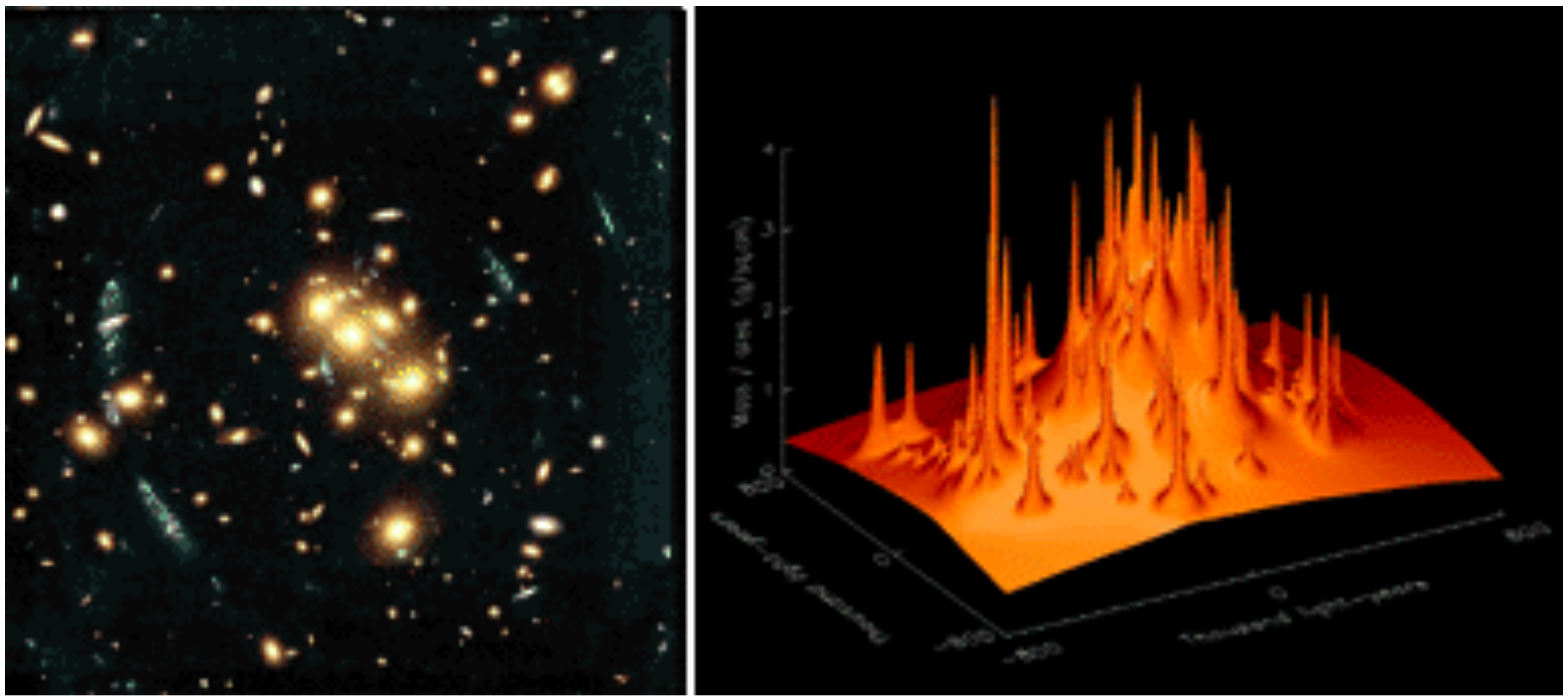
Assuming the gas is spherically symmetric and in hydrostatic equilibrium (so pressure gradient force and gravity balance):

Baryon fraction: $$f_\mathrm{b} = \frac{M_\mathrm{b}}{M_\mathrm{tot}} = \frac{\Omega_\mathrm{b}}{\Omega_\mathrm{m}}$$

$$f_\mathrm{b} = 0.144 \pm 0.005$$ Gonzalez et al.

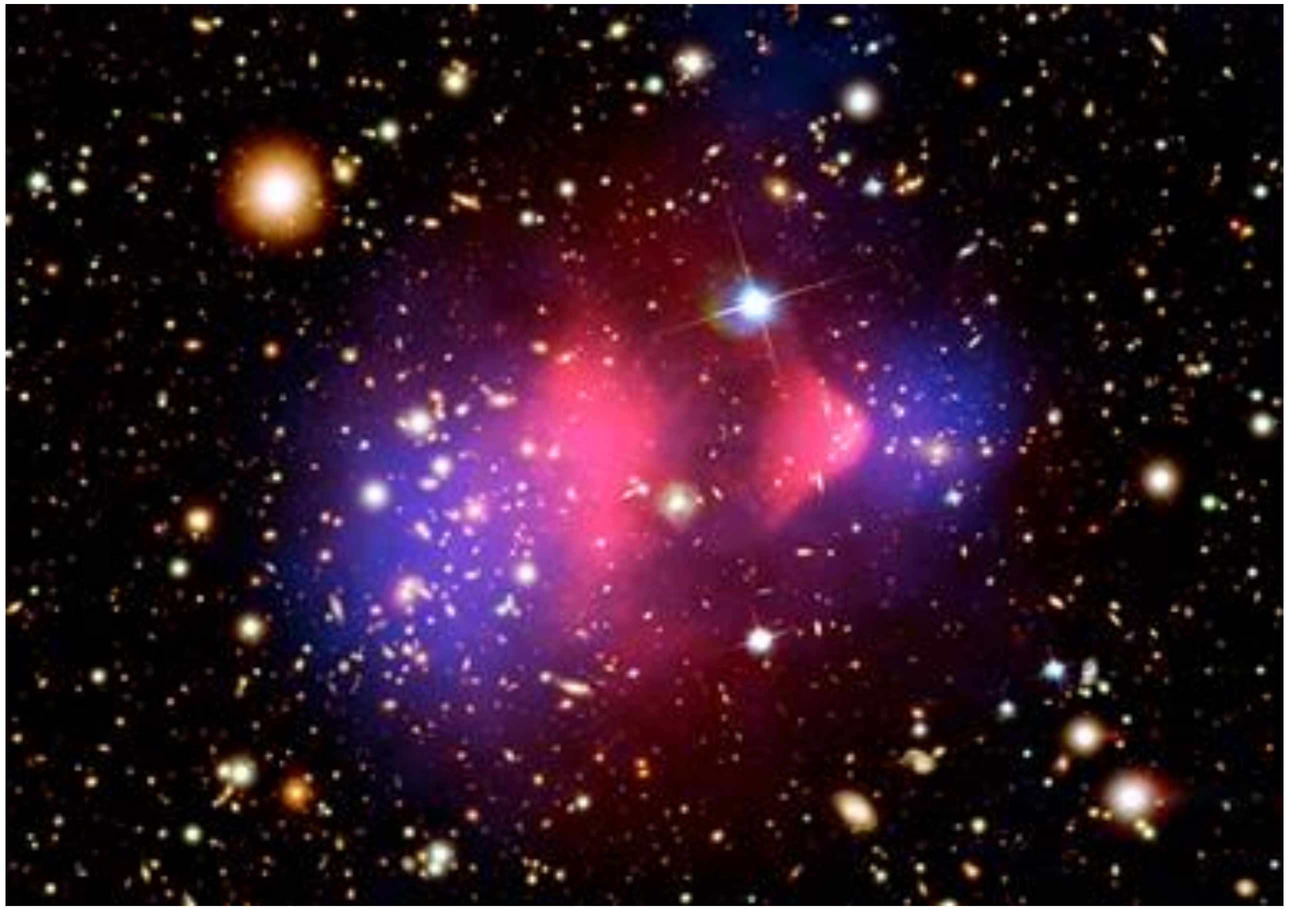
iii) mass distribution from gravitational lensing

Strong lensing of galaxy behind galaxy cluster CL0024+1654:



Tyson, Kochanski & Dell’Antonio

Bullet cluster:

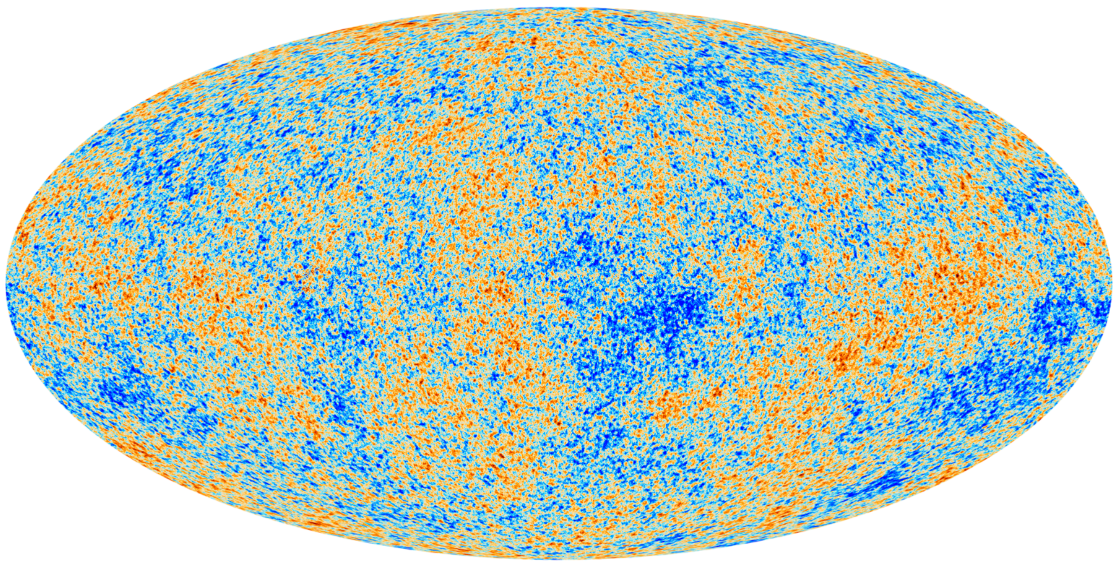


X-ray: NASA/CXC/M.Markevitch et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

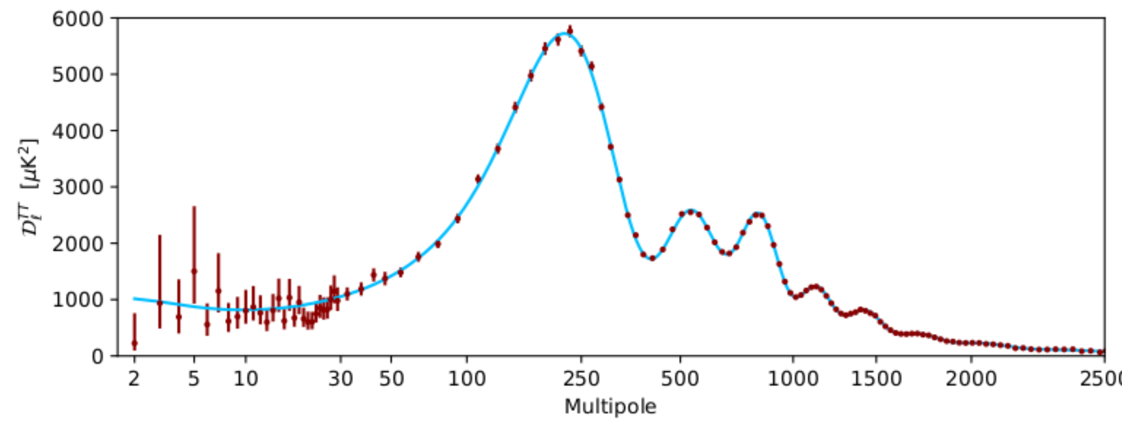
Separation of gravitational potential (reconstructed from weak lensing obs.) and dominant baryonic mass component (hot gas, X-ray emission imaged by Chandra).

→ dark matter

Anisotropies in Cosmic Microwave Background (CMB)



angular power spectrum



Planck 2018

i) total energy density/geometry

From characteristic size of hot & cold spots/positions of peaks in angular power spectrum:

$$\Omega_\mathrm{m} + \Omega_\Lambda - 1 = 0.0106 \pm 0.0065$$

ii) baryon and matter densities

From peak heights:

$$\Omega_\mathrm{b} h^2 = 0.02237 \pm 0.00015$$

$$\Omega_\mathrm{cdm} h^2 = 0.1200 \pm 0.0012$$

cold dark matter

h dimensionless Hubble constant:

$$H_0 = 100h\,\mathrm{km}^{-1}\,\mathrm{s}^{-1}\,\mathrm{Mpc}^{-1}$$

(Big Bang) Nucleosynthesis

Nuclei of the light elements (D, ^{3}He, ^{4}He and Li) synthesised seconds to minutes after the Big Bang.

Abundances depend on the baryon density.

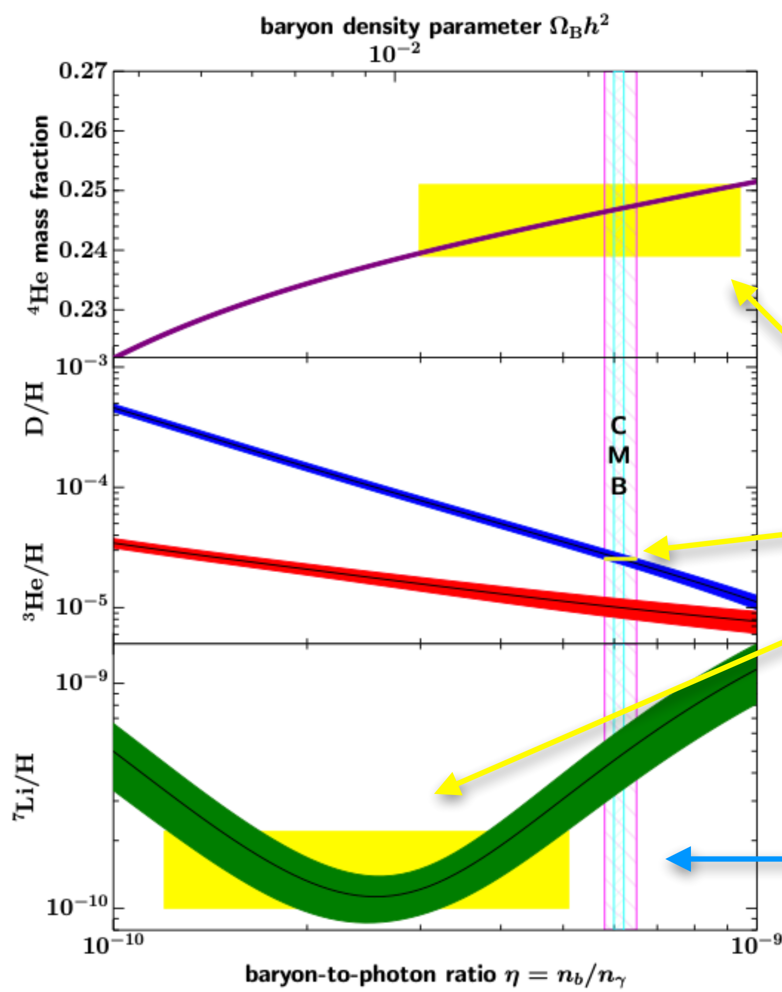
baryon density

^{4}He

D

^{3}He

^{7}Li



baryon-to-photon ratio

Lines: theoretical predictions (thickness of lines denotes nuclear physics uncertainties)

Yellow boxes: observations.

^{4}He emission lines of metal poor galaxies

D absorption of quasar light by primordial gas clouds.

^{7}Li metal poor stars

Blue vertical band: baryon density determined by CMB observations.

Fields, Molaro & Sarkar.

$$0.021 \le \Omega_b h^2 \le 0.024$$

Large scale structure

Typically not as powerful/clean a probe of cosmological parameters alone, as the CMB. However different observables have different degeneracies (combinations of parameters they're insensitive to), so combining data sets can lead to more precise constraints.

e.g. Dark Energy Survey (DES)

Analysis combining
- i) cosmic shear (weak lensing)
- ii) galaxy clustering
- iii) galaxy-galaxy lensing

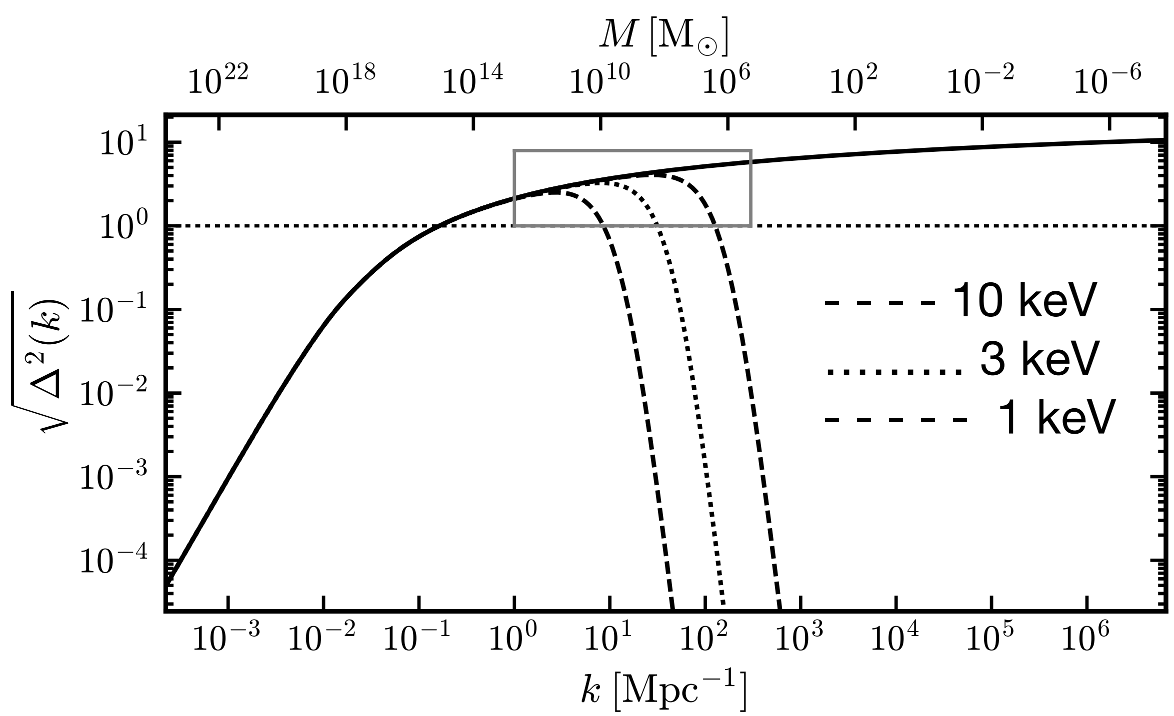
$$\Omega_{\rm m} = 0.34 \pm 0.03$$

Combined with other cosmological datasets (including Planck, BBN, h,):

$$\Omega_{\rm m} = 0.306^{+0.004}_{-0.005}$$

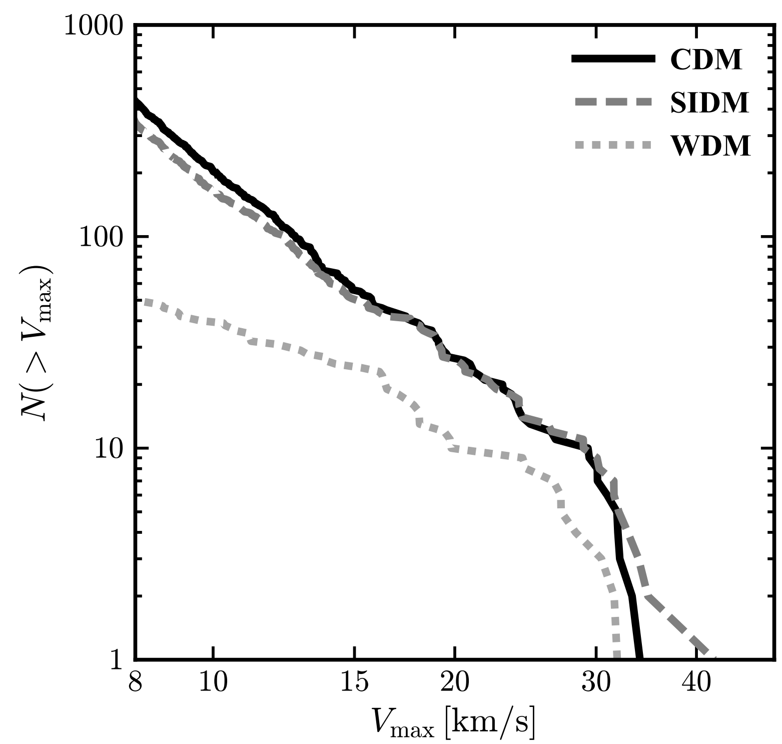
Free-streaming of DM particles erases perturbations, and hence prevents halos forming, on small scales.

amplitude of perturbations



sub-halo 'mass'-function

number v. size



Bullock & Boylan-Kolchin

For warm dark matter (e.g. sterile neutrinos) this occurs on scales that can be probed by e.g. Lyman-alpha forest, observations of Milky Way satellites, gaps in stellar streams, gravitational imaging

for thermal relics: $m_{\mathrm{DM}} > 6\,\mathrm{keV}$ Enzi et al.

Distribution

Why is the dark matter distribution important?

All the observational evidence for dark matter arises from its gravitational effects.

If we want to confirm the existence of dark matter (and the standard cosmological model) and understand its nature we need to detect it.

The signals in DM detection experiments depend on:

Lab based direct detection experiments (see lecture 2 & Javier Redondo axion lectures)

the local (i.e. at Solar radius $r = R_{\odot}$) Milky Way DM density and speed distribution.

$R_{\odot} = (8.178 \pm 0.013 \pm 0.022)\,\mathrm{kpc}$ GRAVITY Collaboration, using orbit of star S2 around Sgr A* (massive BH at MW centre).

Indirect detection via annihilation/decay products (see Francesca Calore lectures)

the DM density distribution: density profile of individual (sub)halos & subhalo mass function, in particular for Milky Way and dwarf galaxies.

Numerical simulations

see Les Houches DM lectures by Annika Peter

In CDM cosmologies structure forms hierarchically: small halos (typically) form first and then larger halos form via mergers and accretion.

Dark matter only simulation of a Milky Way like halo

Aquarius

N-body simulations (e.g. Aquarius): dark matter only

Hydrodynamical simulations (e.g APOSTLE, Auriga, FIRE): include baryons (i.e. stars and gas) using prescriptions for ‘sub-grid’ physics.

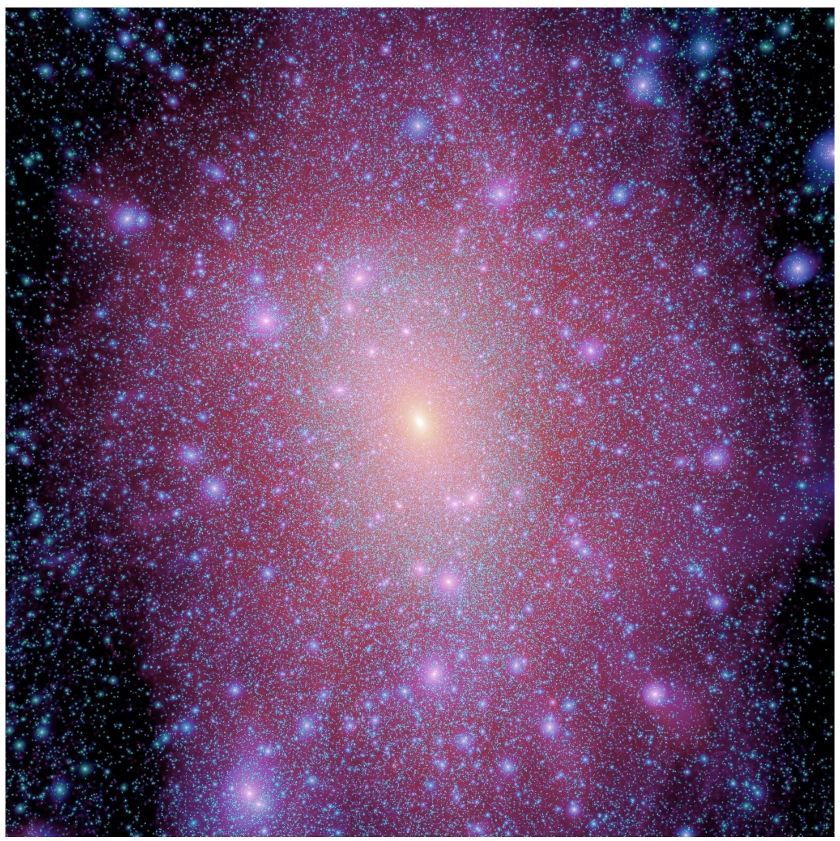
Baryons affect the dark matter distribution by, e.g. :

baryonic contraction: infall of baryons pulls in DM, steepening DM density profile
Blumenthal et al.

stellar feedback: can reduce density in inner regions and form a core

Subhalo mass function

e.g. Aquarius (DM only):

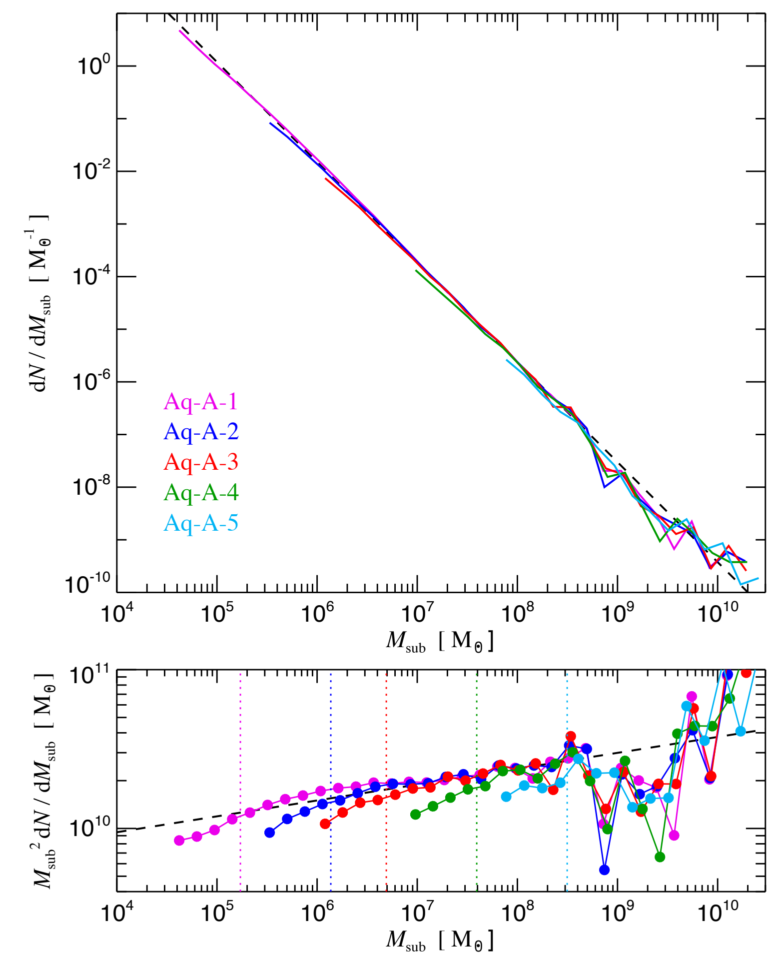


$M/M_\odot$

10^4 10^{10}

$\frac{\mathrm{d}n}{\mathrm{d}M}$

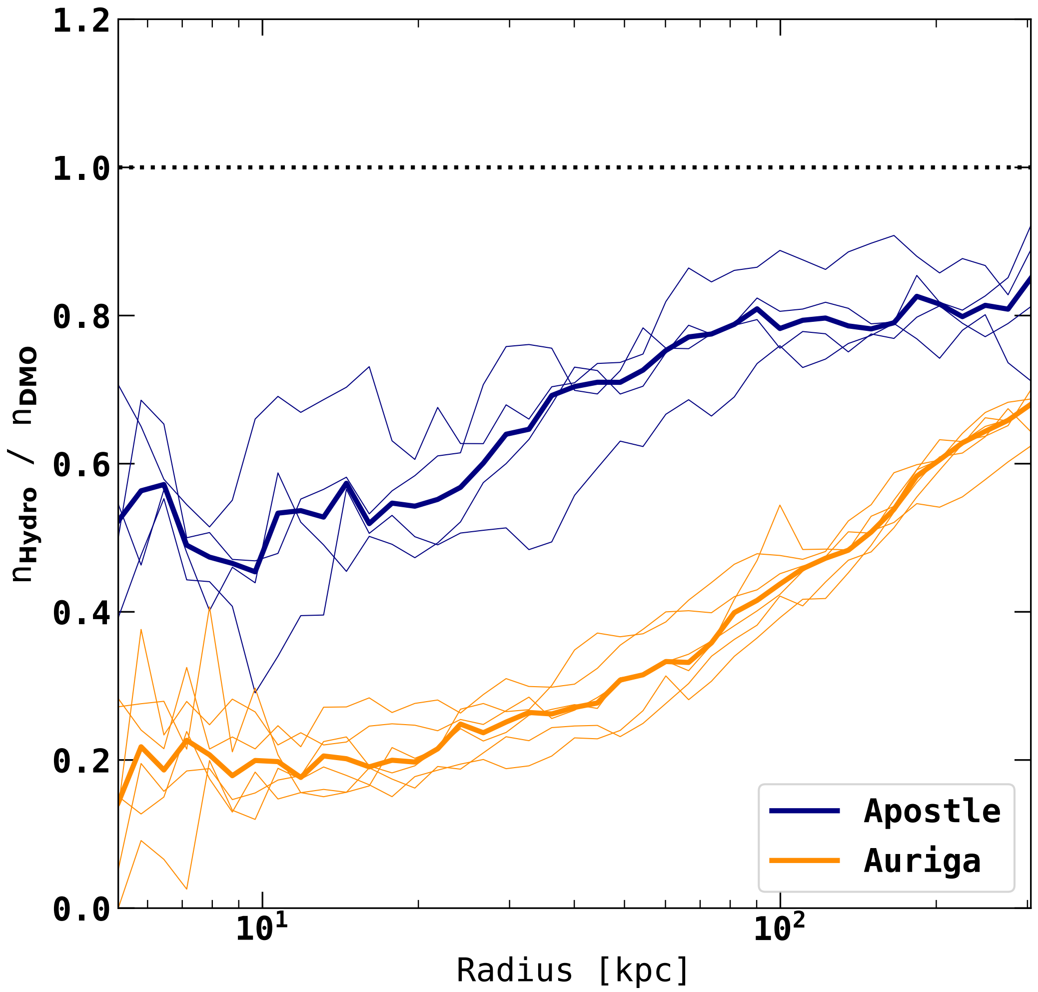
$M^2 \frac{\mathrm{d}n}{\mathrm{d}M}$



subhalo mass function for 5 varying resolution simulations of same halo

mass function: $$\frac{\mathrm{d}n}{\mathrm{d}M} \propto \left(\frac{M}{M_\odot}\right)^{-\alpha} \qquad \alpha = 1.90 \pm 0.03$$

Ratio of the number density of halos with mass $(10^{6.5} - 10^{8.5})M_\odot$ in hydrodynamical (APOSTLE & Auriga) and dark matter only simulations, as a function of radius



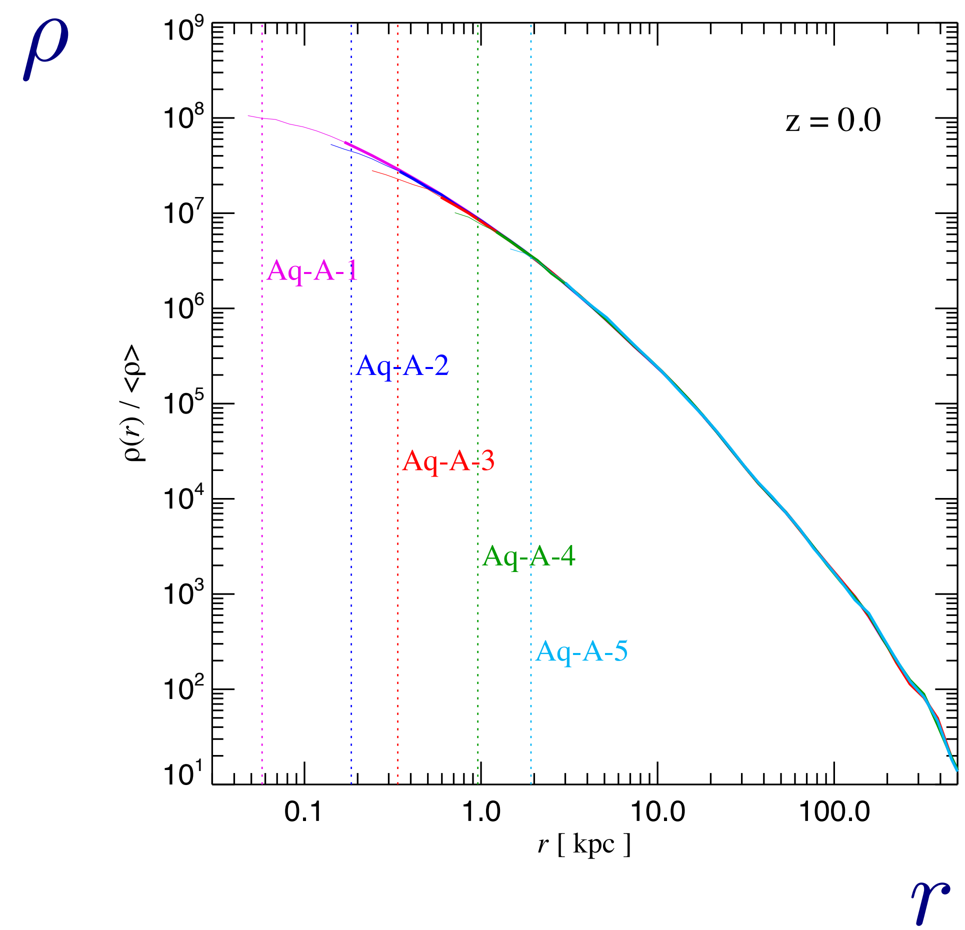
Richings et al.

Fraction of halo in subhalos is smaller in hydrodynamical simulations, and is decreased more at small radii.

Size of reduction depends on how baryonic component is modelled.

Density profile

Aquarius
(dark matter only)



Navarro, Frenk & White (NFW) profile

$r_{\rm s}$ scale radius $\left(\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}\right)_{r=r_{\rm s}} = -2$

$$\rho(r) = \frac{\rho_0}{(r/r_{\rm s})[1+(r/r_{\rm s})]^2}$$

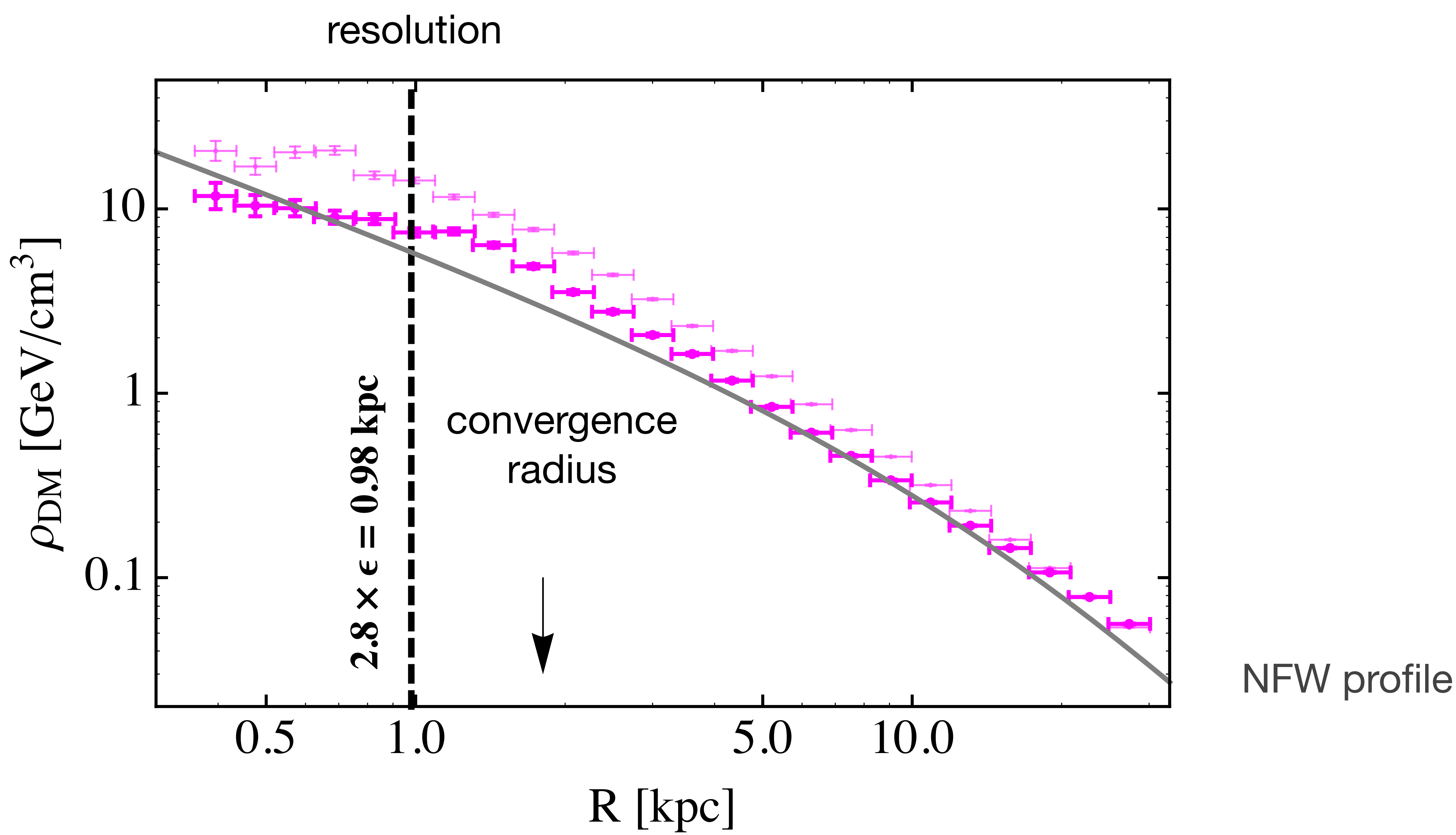
$c = r_{\rm vir}/r_{\rm s}$ concentration

$$\rho(r) \propto r^{-1}\,,\ \text{as } r \to 0\,,\ \rho(r) \propto r^{-3}\,,\ \text{for } r \gg r_{\rm s}$$

c.f. (singular) isothermal sphere: $\rho(r) \propto r^{-2}$ for all r.

EAGLE (hydrodynamical simulations of MW like galaxies, with baryons)

Calore et. al:

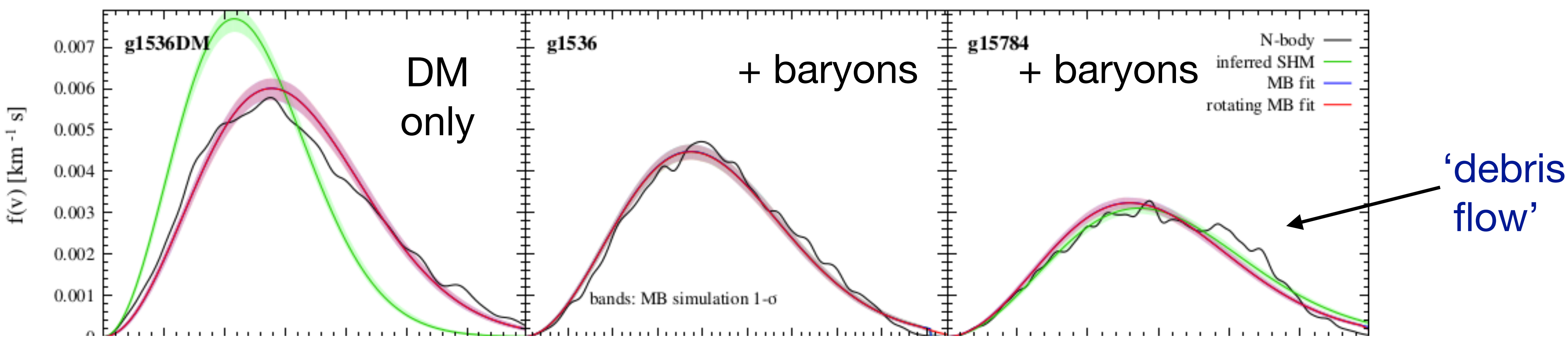


Density profile steeper than NFW for r~(1.5-6) kpc due to baryonic contraction.

Local velocity distribution

Simulations of ‘MW like halos’ with baryons find Maxwellian/gaussian f(v) is a fairly good fit: Bozorgnia et al.; Kelso et al.; Sloane et al.

Kelso et al.:



Standard halo model Maxwellian

Features in tail of dist, ‘debris flows’, incompletely phased mixed material.
Lisanti & Spergel; Kuhlen, Lisanti & Spergel

Observations

Huge progress in understanding the Milky Way in recent years thanks to Gaia.

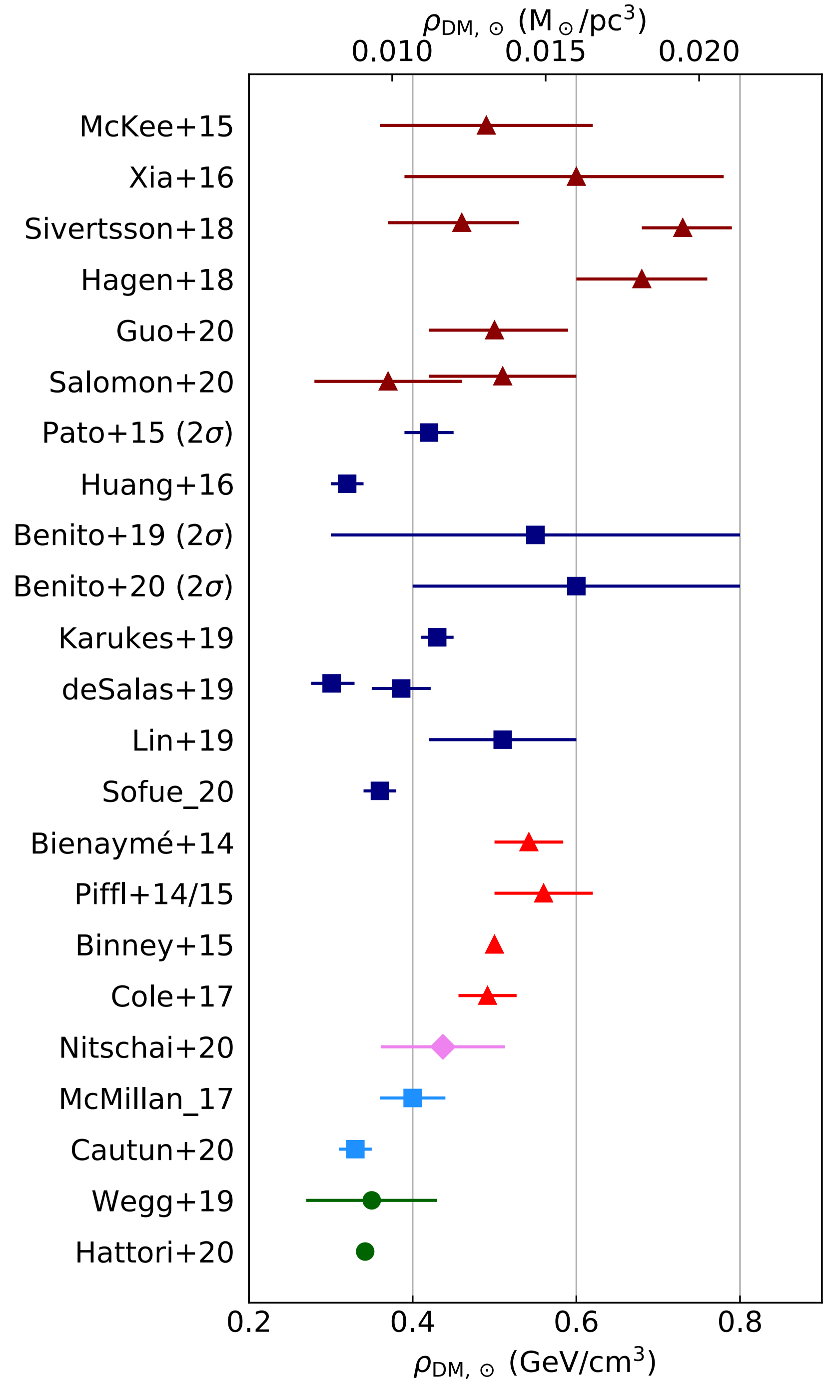
Often combined with info on metallicity, [Fe, H], from spectroscopic surveys
e.g. APOGEE, RAVE, LAMOST.

Need modelling/simulations to interpret observations, and systematic errors are often now comparable or similar to statistical errors.

For more info see Helmi 2020 Annual Reviews article
(or, for implications for DM experiments O'Hare talk slides 1 and 2).

Local density $\rho(R_\odot)$:

Various techniques: local (using kinematics of nearby stars) and global (e.g. mass modelling) see Read's 2014 extensive review and de Salas & Widmark 2020 review:



local stars

rotation curve

mass modelling

Jeans modelling disc stars

circular velocity based mass modelling

halo stars

Local circular speed e.g:

Reid et al. proper motion of Sgr A*:

$$v_c(R_\odot)/R_\odot = (30.3 \pm 0.9)\,\mathrm{km\,s^{-1}\,kpc^{-1}}$$

and using new precise measurement of $R_\odot$ gives

$$v_c(R_\odot) = (248 \pm 7)\,\mathrm{km\,s^{-1}\,kpc^{-1}}$$

Eilers et al. Jeans analysis (taking moment of collision less Boltzmann equations) combing data from Gaia, APOGEE and other sources:

$$v_c(R_\odot) = (229.0 \pm 0.2)\,\mathrm{km\,s^{-1}}$$

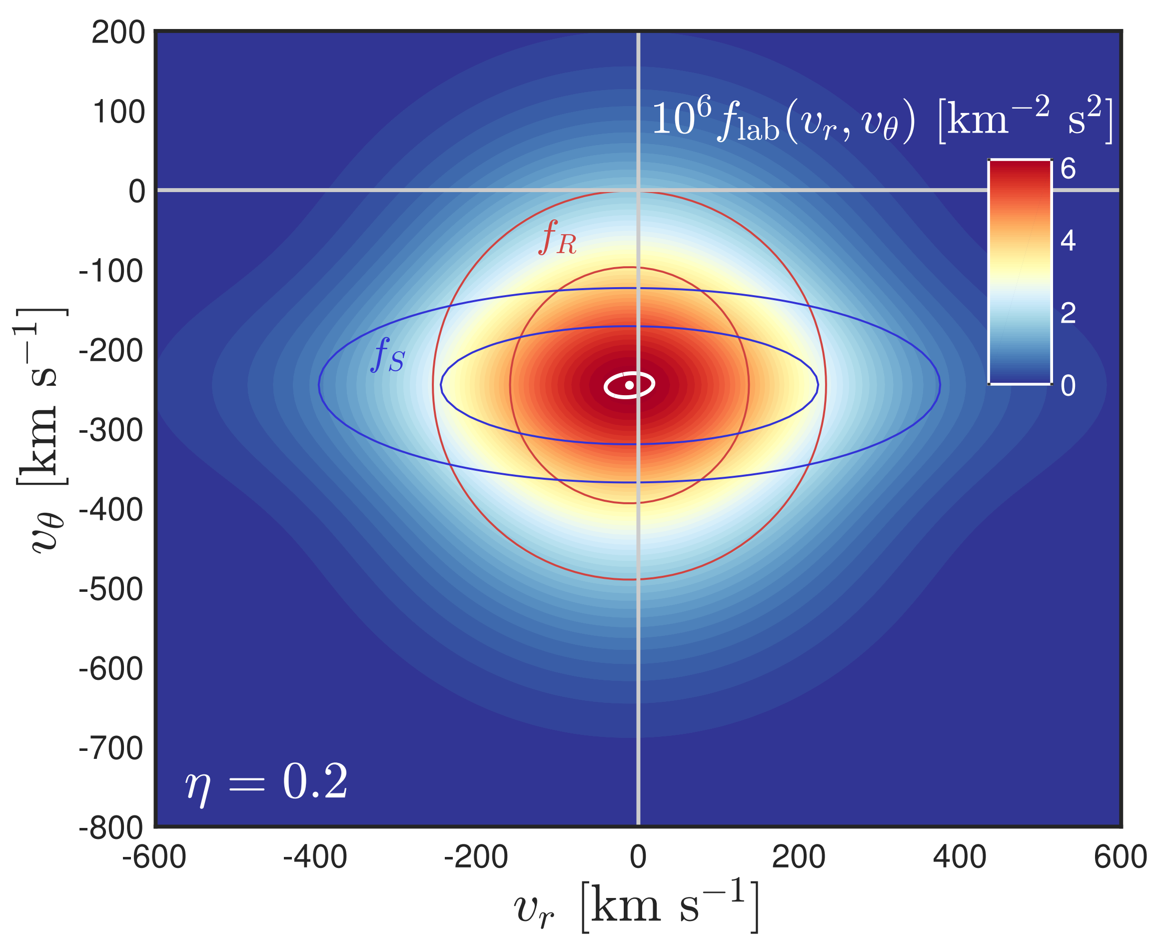
with (2-5)% systematic uncertainty (from e.g. uncertainty in distribution of tracer stars).

Gaia-Enceladus/Sausage

A significant fraction of the halo near the Sun is made up of debris from a major merger with a $\sim 10^{11} M_\odot$ dwarf galaxy (8-10) Gyr ago. Helmi et al.

Stars have radially biased orbits, distribution of v_r is ‘sausage like’. Belokurov et al.

Fraction of local dark matter density it makes up is ~(10-30)% (see e.g. Evans et al., also for effects on WIMP and axion direct detection experiments).



Small scale challenges

See Bullock & Boylan-Kolchin and Annika Peter's Les Houches lectures.

Since 1990s, discrepancies between CDM predictions and observations

Cusp-core: DM only simulations produce halos with cuspy inner density profiles ($\rho(r) \propto r^{-\gamma}$, $\gamma \approx 1$) while galaxies, in particular low mass DM dominated dwarfs, have shallower profiles ($\gamma \sim 0$, core).

Missing satellites: simulated MW-size halos contain ~1000 of dwarf galaxy sized sub-halos, but 'only' ~50 dwarf galaxies have been observed (n.b. observations 'incomplete': not all of the dwarfs that exist have been observed).

'too-big-to-fail': too few medium sized ($M_{\rm dm} \sim 10^{10} \, M_{\odot}$) galaxies observed (and it's harder to explain a deficit of these larger galaxies).

These discrepancies could be resolved by

i) better understanding/modelling of baryonic physics

ii) non-'vanilla' DM (self-interacting, warm, fuzzy,…)

Modified gravity

All the evidence for dark matter to date comes from its gravitational effects.

Could the observations be explained by instead modifying the laws of gravity? Newton's laws have been tested to high accuracy on terrestrial scales, however the laws of gravity could, in principle, be different on astronomical/cosmological scales.

MOND (MOdified Newtonian Dynamics): Milgrom

A phenomenological modification of Newton's laws of gravity for small accelerations, proposed to explain galaxy rotation curves without dark matter.

$$F = m\mu(a/a_0)a$$

$$\mu(x) \to 1 \quad \text{for} \quad x \gg 1$$
$$\mu(x) \to x \quad \text{for} \quad x \ll 1$$

$$a_0 \approx 10^{-10}\,\mathrm{m\,s^{-2}}$$

Also explains some properties of galaxies (Tully-Fisher relationship between baryonic mass and rotation speed). McGaugh

But dark matter still required in galaxy clusters, and can't make predictions for large scale structure or the CMB.

TeVeS (Tensor Vector Scalar): Bekenstein

Relativistic generalisation of MOND.

Can’t fit 3rd peak in CMB temperature angular power spectrum. Skordis et al.

‘Dark matter emulators’ (including TeVeS), where photons/neutrinos & gravitational waves couple to different metrics, ruled out by simultaneous observation of GWs and electromagnetic radiation from GW170817 (coalescence of binary neutron stars). Boran et al.

New relativistic theory for MOND: Skordis & Zlosnik

Has a field that on cosmological scales has same equation of state and sound speed as dark matter.

Reproduces GR for large accelerations, and MOND for small accelerations, consistent with CMB temperature and polarisation angular power spectra and matter power spectrum, reproduces gravitational lensing observations without DM, GWs travel at speed of light.

See: Les Houches DM Summer School lectures by Justin Khoury.
‘Le MOND’ day lecture by Spergel

Summary

A wide range of diverse astronomical and cosmological observations indicate that 85% of the matter in the Universe is **cold**, **non-baryonic**, **dark matter**, which is **stable** on cosmological timescales.

To confirm the existence of dark matter (& the standard cosmological model) and understand its nature we need to detect it. The signals in DM direct and indirect detection experiments depend on how it's distributed:

Simulations:

DM halos have cuspy density profiles and contain substructure (subhalos+streams).

Local velocity distribution is fairly close to Maxwellian + features in high speed tail.

Observations:

Local DM density and circular speed measured to high precision (but systematic errors larger than statistical errors).

Stellar halo contains substructure in spatial & velocity distribution: Gaia Enceladus & streams.

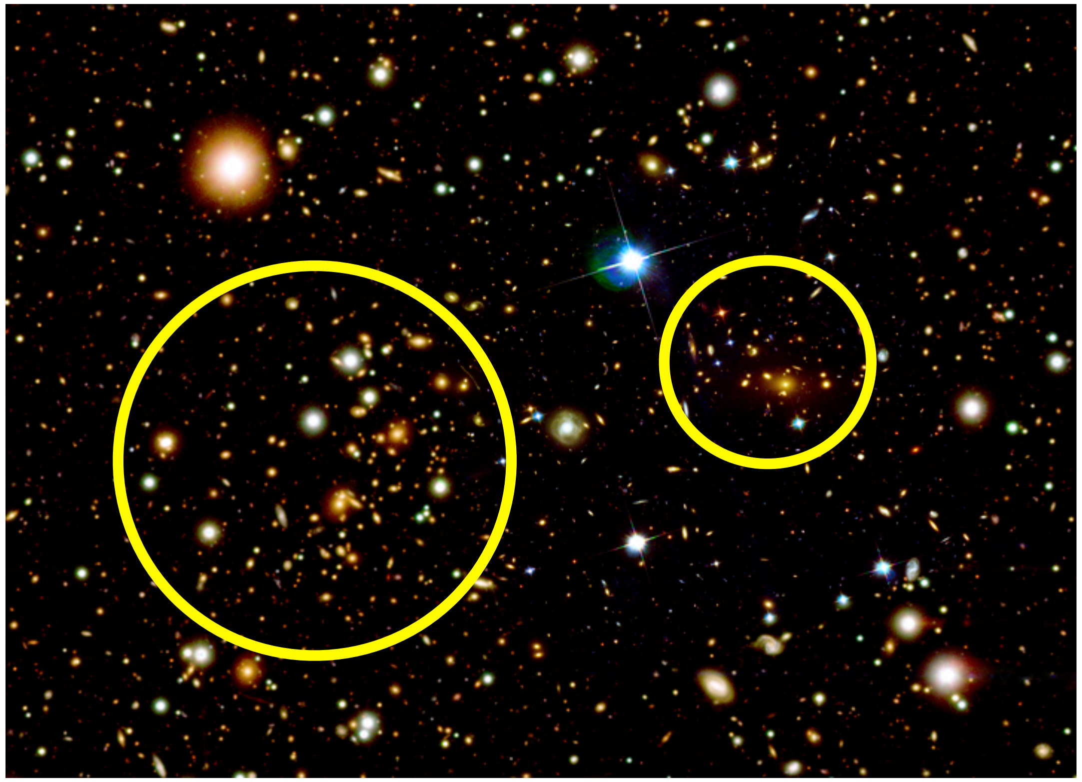
n.b. majority of DM thought to be smoothly distributed.

BACK UP SLIDES

the bullet cluster

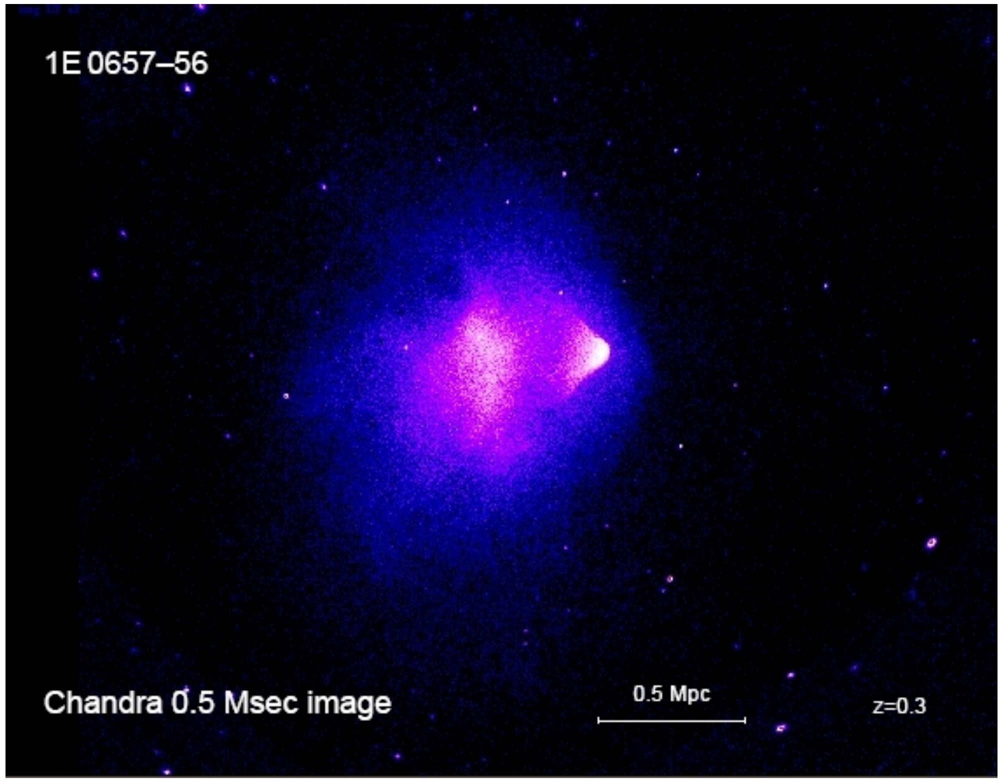
Clowe et al.

optical image

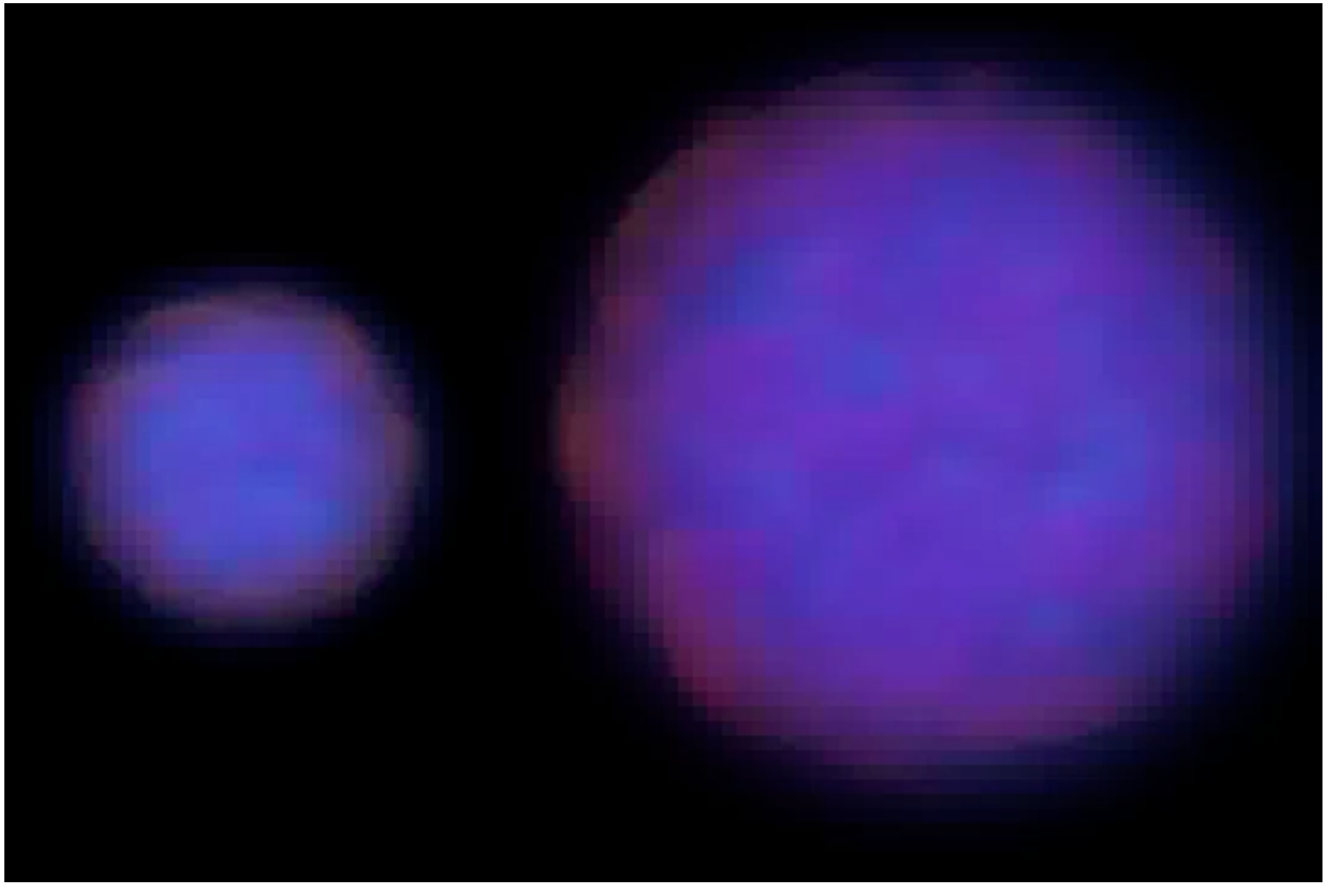


NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

X-ray image

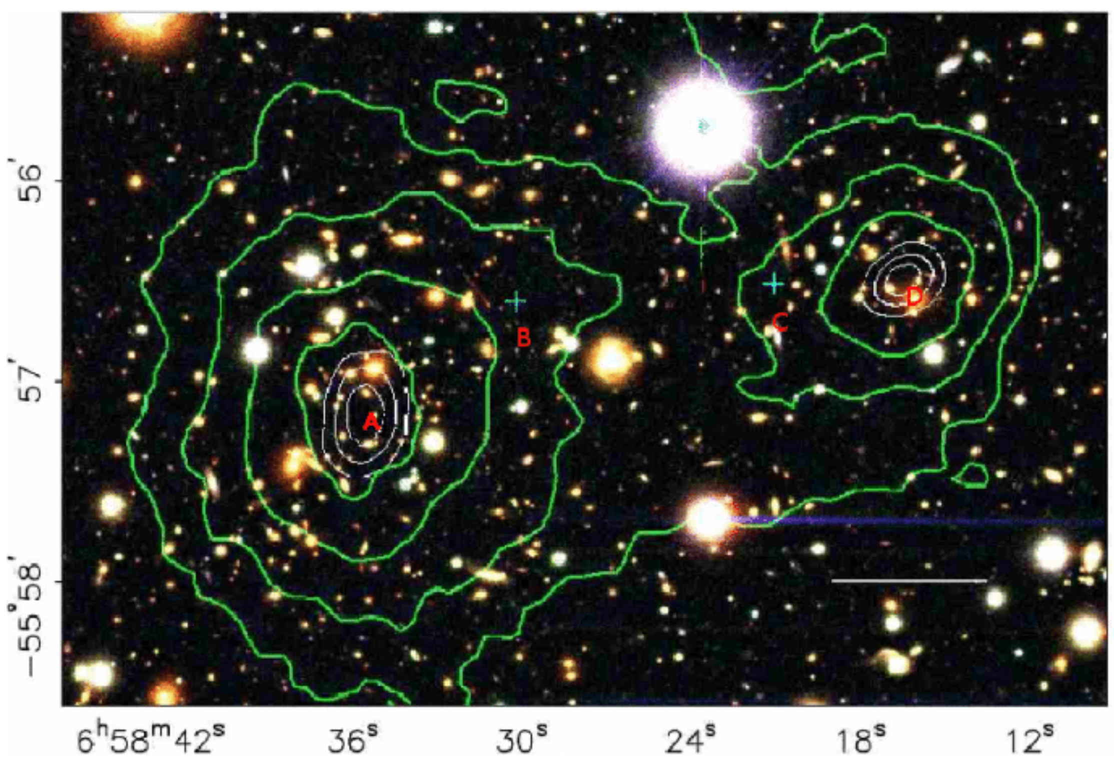


NASA/CXC/M.Markevitch et al.



NASA/CXC/M.Weiss

weak lensing mass contours



NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

composite image

X-ray: NASA/CXC/M.Markevitch et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.
Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Separation of gravitational potential (reconstructed from weak lensing obs.) and dominant baryonic mass component (hot gas, X-ray emission imaged by Chandra).

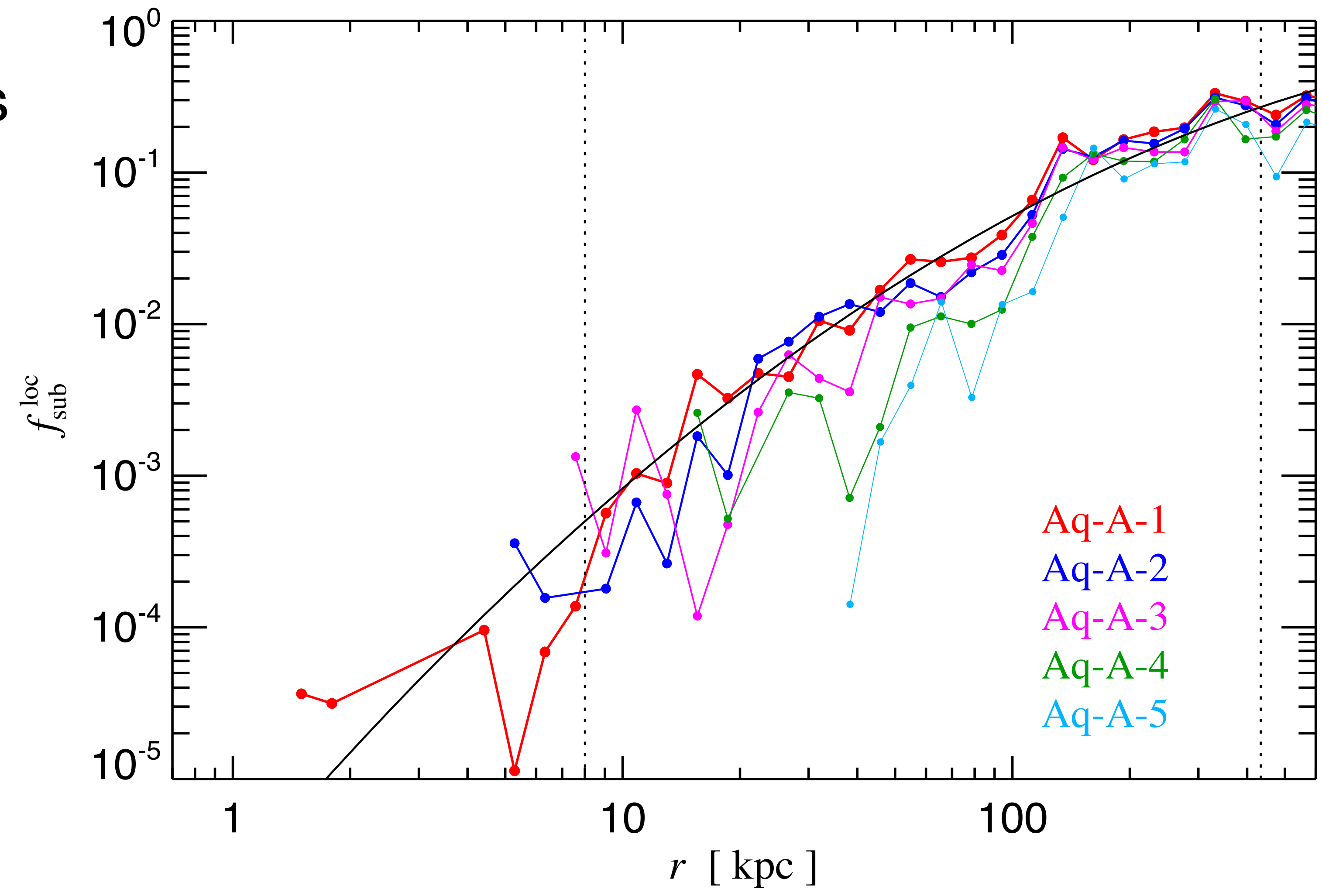
→ dark matter

n.b. lensing analysis assumes GR, however explaining these observations is a big challenge for modified gravity theories.

Subhalo radial distribution

e.g. Aquarius (DM only):

Fraction of local mass in subhalos as a function of radius



~10% of the total mass in DM only simulations is in (resolved) subhalos

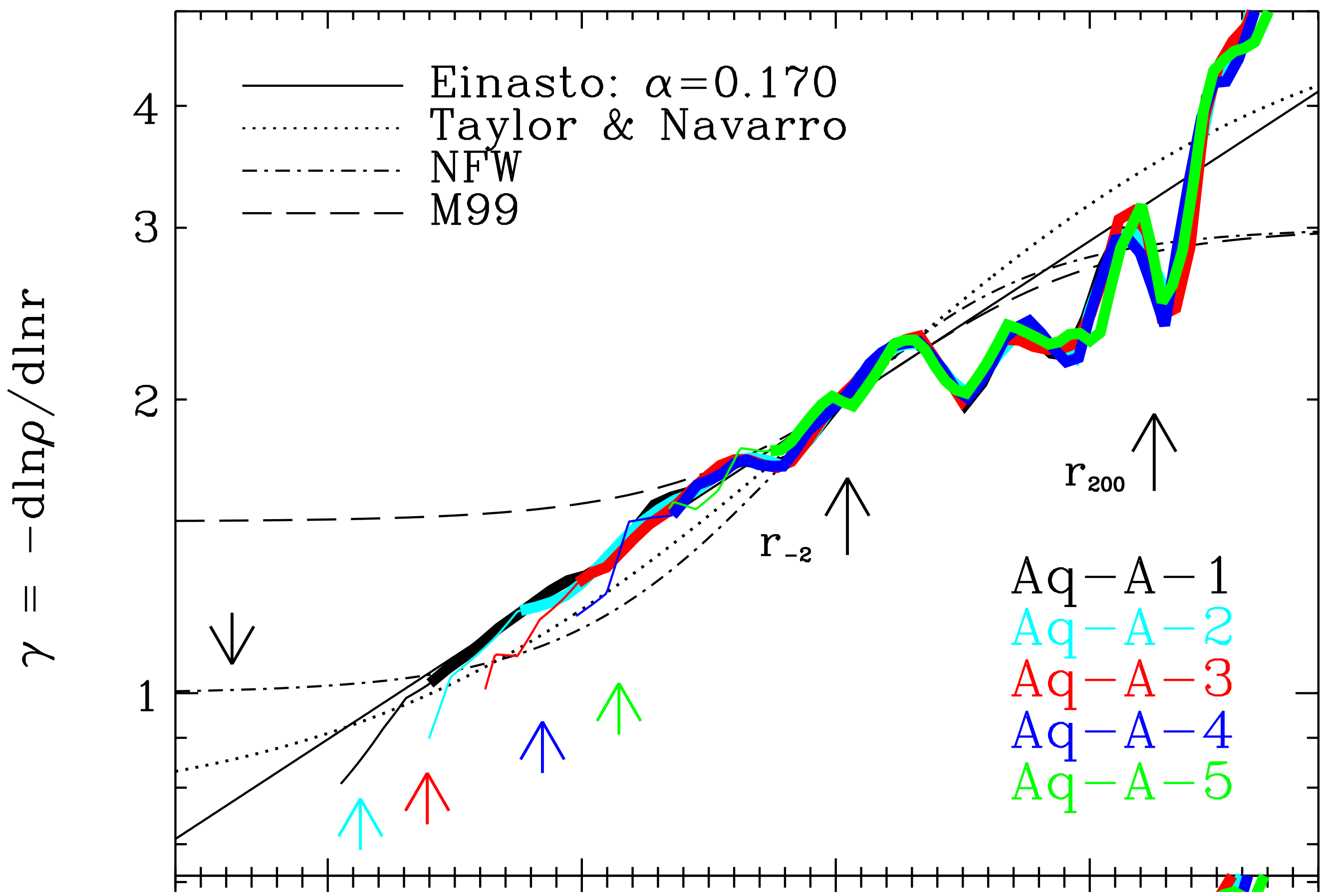
< 0.1% of the mass at the solar radius is in (resolved) subhalos
(less subhalos in inner regions as they're more effectively disrupted there)

How does the density profile behave in $r \to 0$ limit?

Aquarius:

logarithmic slope
of density profile

$$\gamma = -\frac{d \ln \rho}{d \ln r}$$



log r [kpc/h]

_._._._ NFW
$(\gamma \to 1 \text{ as } r \to 0)$

——— Einasto

Einasto profile:

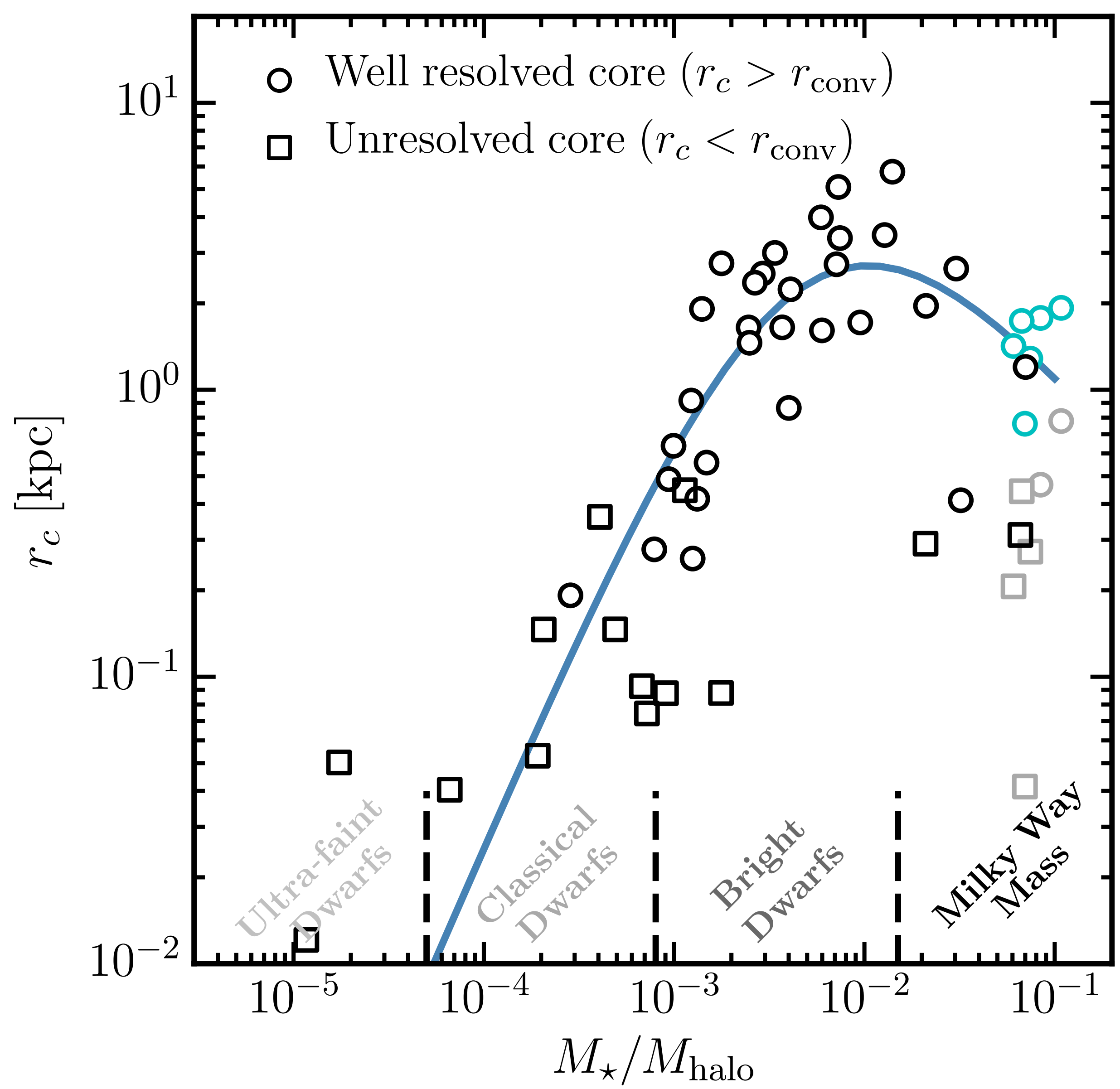
$$\rho(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[(r/r_s)^\alpha - 1\right]\right\}$$

$$\gamma = 2\left(\frac{r}{r_s}\right)^\alpha$$

Stellar feedback is most efficient at producing cores (constant density inner regions) in bright dwarf galaxies with radius r_{core} ~ (1-5) kpc (see Lazar et al. and references therein).

Can get cores in Milky Way sized galaxies with r_{core} ~ (0.5-2) kpc (e.g. Lazar et al. using FIRE-2)

Core formation depends on gas density threshold for star formation.



Lazar et al.

Huge progress in understanding the Milky Way in recent years thanks to Gaia:

ongoing ESA space astrometry mission (2013-2022+?)

positions, parallaxes and proper motions (change in apparent position) of >1 billion stars (~1% of MW)

20 (200) million stars with distances measured to 1 (10)%

40 million stars with tangential velocities measure to $< 0.5\,\mathrm{km\,s^{-1}}$

7 million stars with full 6d phase space coordinates (x, y, z, v_x, v_y, v_z)

Mass modelling: use multiple data sets (e.g. rotation curve, velocity dispersions of halo stars, local surface mass density, total mass…) to constrain a model for the MW (luminous components + halo).

Eilers et al.   Jeans analysis from taking moment of collision less Boltzmann equations (in cylindrical co-cordinates):

$$v_{\rm c}^2(R) = R\frac{\partial \Phi}{\partial R}_{z\approx 0} = \langle v_\phi^2 \rangle - \langle v_R^2 \rangle \left(1 + \frac{\partial \ln \nu}{\partial \ln R} + \frac{\partial \ln \langle v_R^2 \rangle}{\partial \ln R}\right)$$

ν = density of tracer stars.

combing data from Gaia, APOGEE and other sources:

$$v_{\rm c}(R_\odot) = (229.0 \pm 0.2)\,{\rm km\,s^{-1}}$$

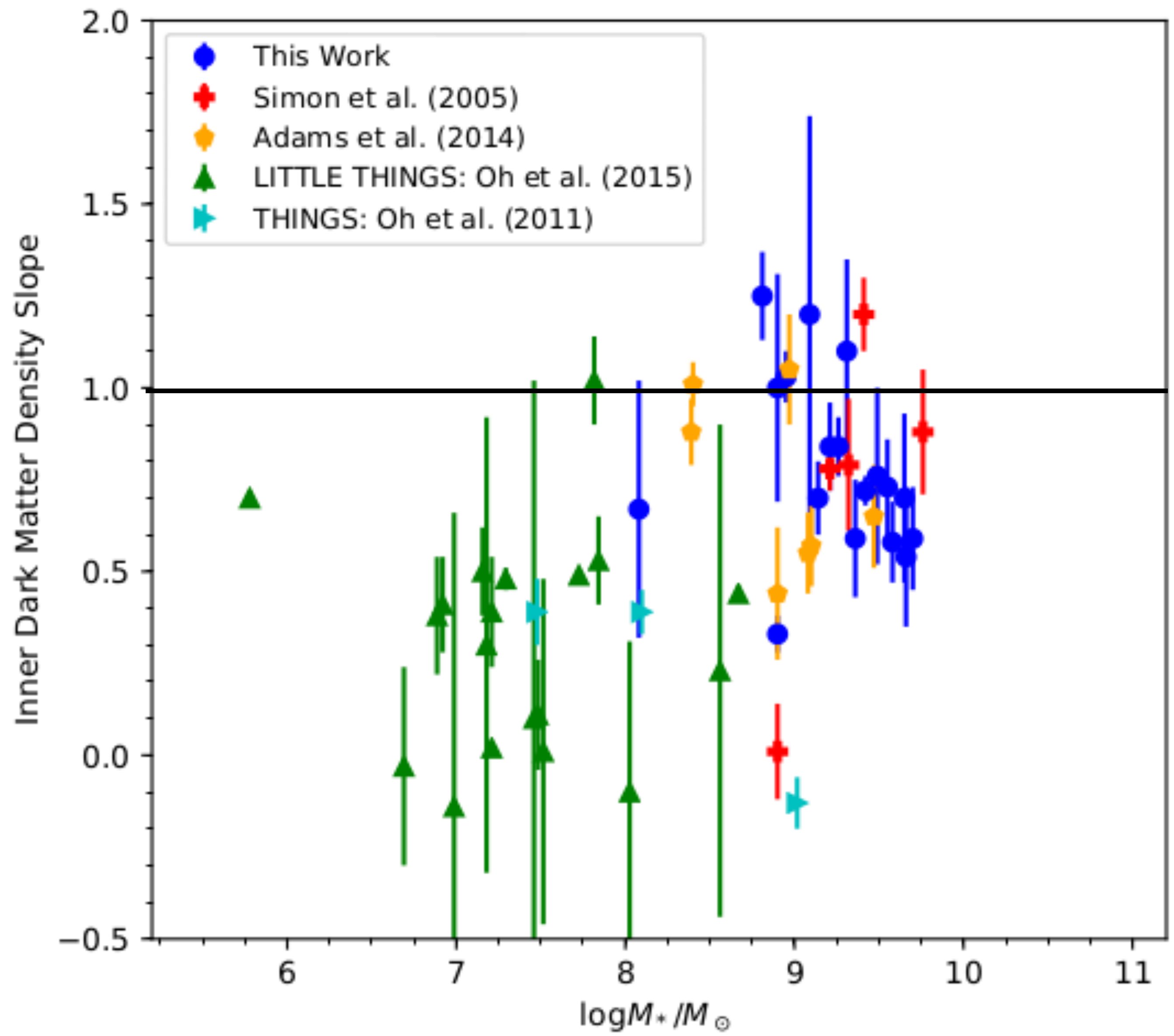
with (2-5)% systematic uncertainty (from e.g. uncertainty in distribution of tracer stars).

dark matter density profile: dwarf galaxies

Compilation of rotation curve measurements of inner slope:
Relatores et al.

$$\gamma = -\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}$$

at $r = 0$



NFW

stellar mass

Local escape speed:

Piffl et al: high velocity stars from the RAVE survey,

assume $f(|\mathbf{v}|) \propto (v_{\rm esc} - |\mathbf{v}|)^k$ in tail of distribution

k in range 2.3 to 3.7 (motivated by numerical simulations)

$$v_{\rm esc}(R_\odot) = 533^{+54}_{-41}\,{\rm km\,s^{-1}}$$

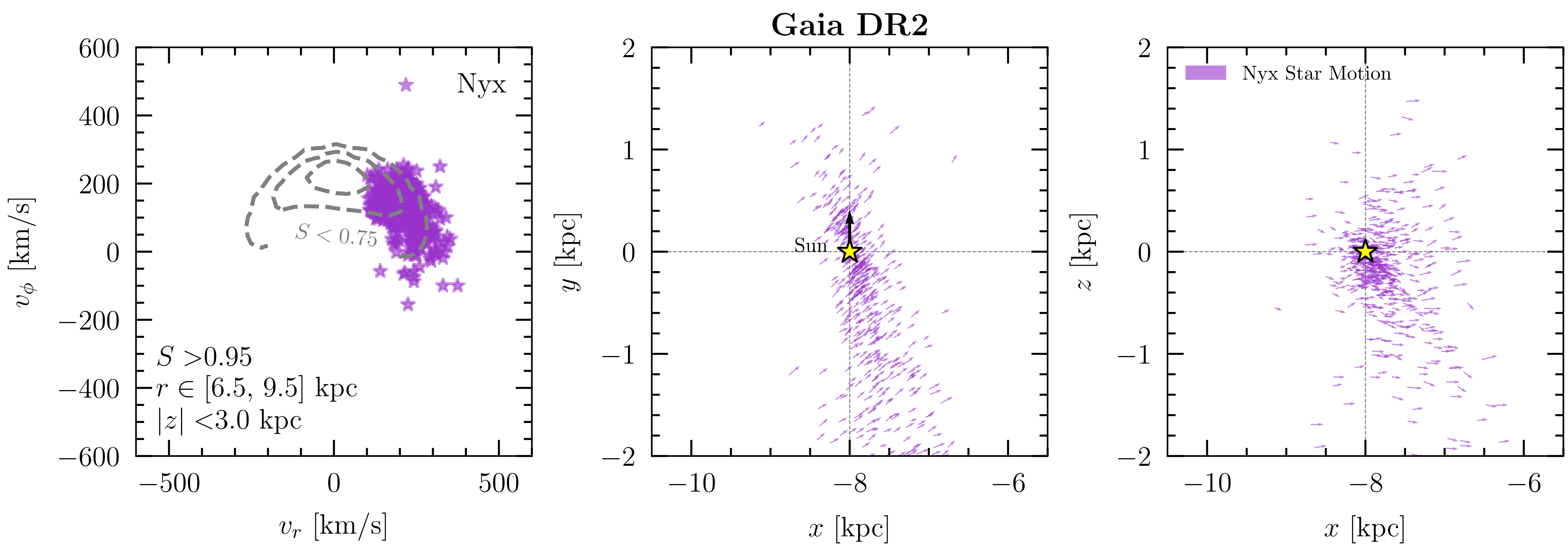
Monari et al. similar approach using Gaia Data Release 2, but without assuming a potential in modelling

$$v_{\rm esc}(R_\odot) = (580 \pm 63)\,{\rm km\,s^{-1}}$$

Tidal streams

Also less extended tidal streams from smaller or more recent mergers.

In the Solar neighbourhood: S1, Helmi streams, Nyx,

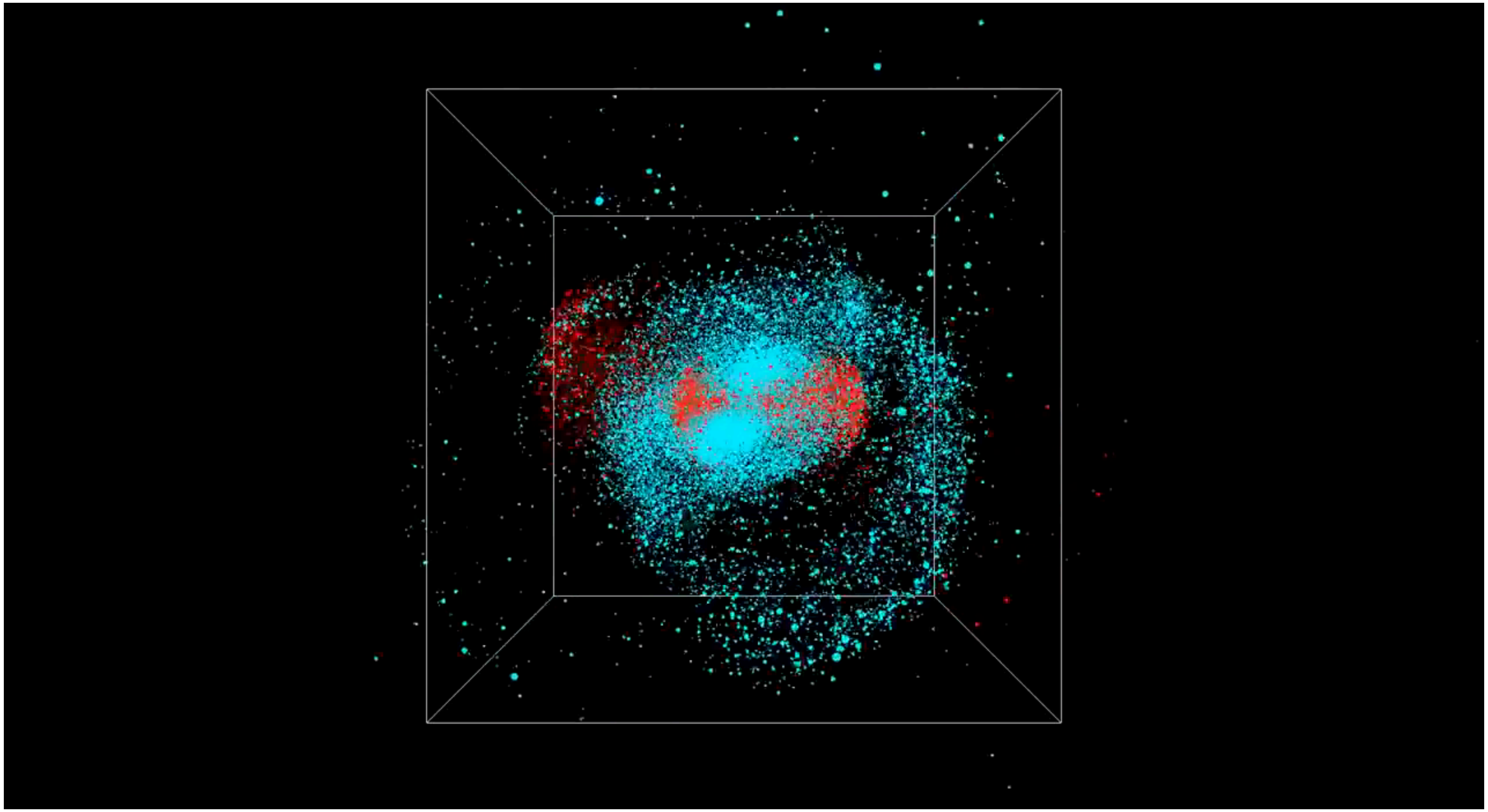


Nyx

More on how tidal streams throughout the MW halo, and also subhalo fraction, can be used to probe the nature of dark matter in section 4

Gaia-Enceladus/Sausage

The aftermath of a major merger with a $\sim 10^{11} M_{\odot}$ dwarf galaxy (8-10) Gyr ago
Helmi et al.



Simulation: Koppelman, Villalobos & Helmi