Dark Matter Cosmology

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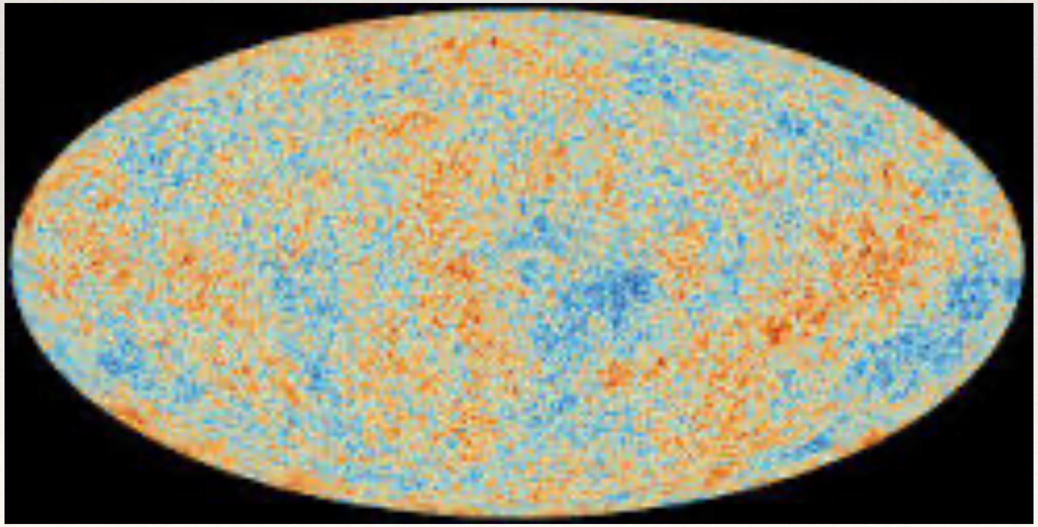
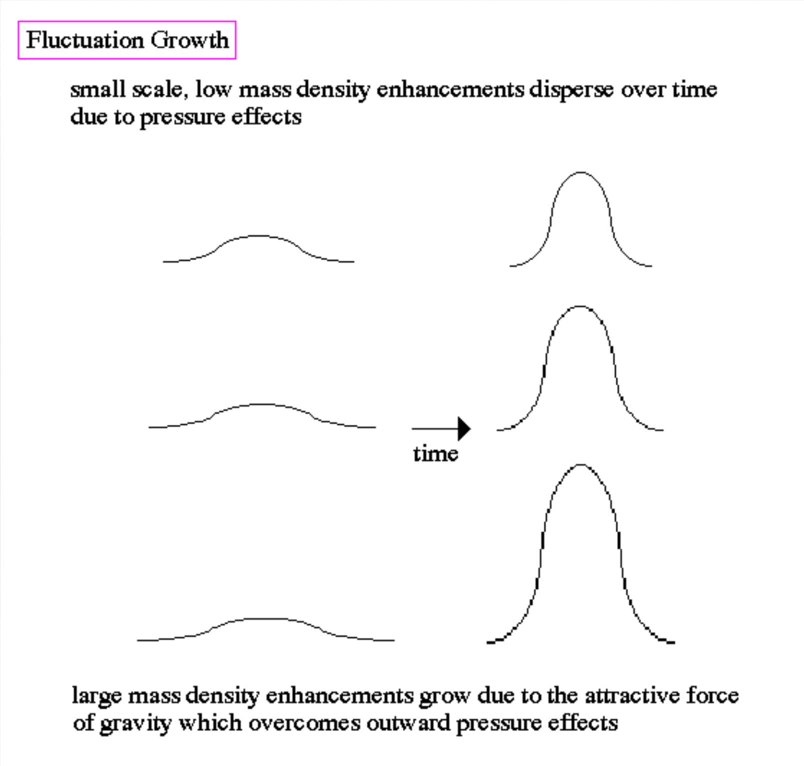
- Course webpage: https://blackboard.cuhk.edu.hk

- The role of dark matter in shaping the universe

Cosmological structure formation

- At about 100k years old (CMB)
- The Universe is relatively uniform
- But gravity starts to work





Hierarchical Structure formation

- There are random density fluctuations in the Universe.
- Overdensity
  - $\delta = \frac{\rho}{\bar{\rho}} - 1$
- *Only when the universe becomes matter dominates (expansion rate slows down), that over density can grow
- Dark Matter density grows first
- Baryon grow started later, because of photon-electron-proton is a strongly interacting plasma
  - Baryon growth starts after photon decoupling
- The dark matter halo produces a potential well for brayon to fall into.

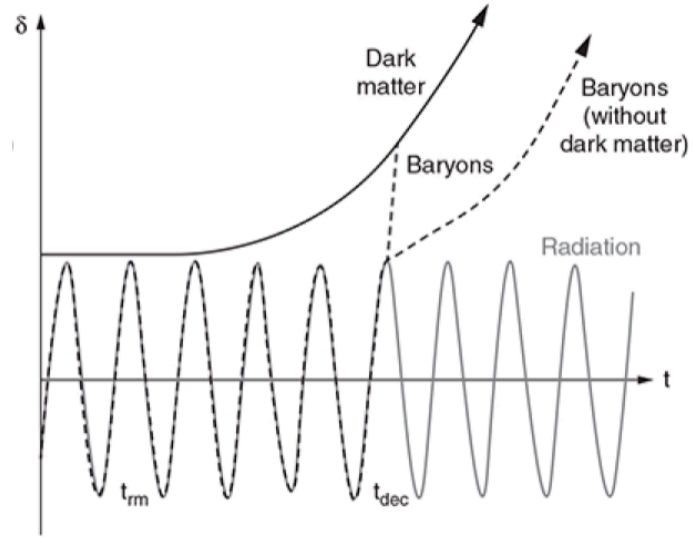


Figure 11.4 A highly schematic drawing of how density fluctuations in different components of the universe evolve with time.

z = 3400: Radiation-Matter transition
z = 1360: Recombination
When
z = 1100: photon decoupling

Hierarchical Structure formation

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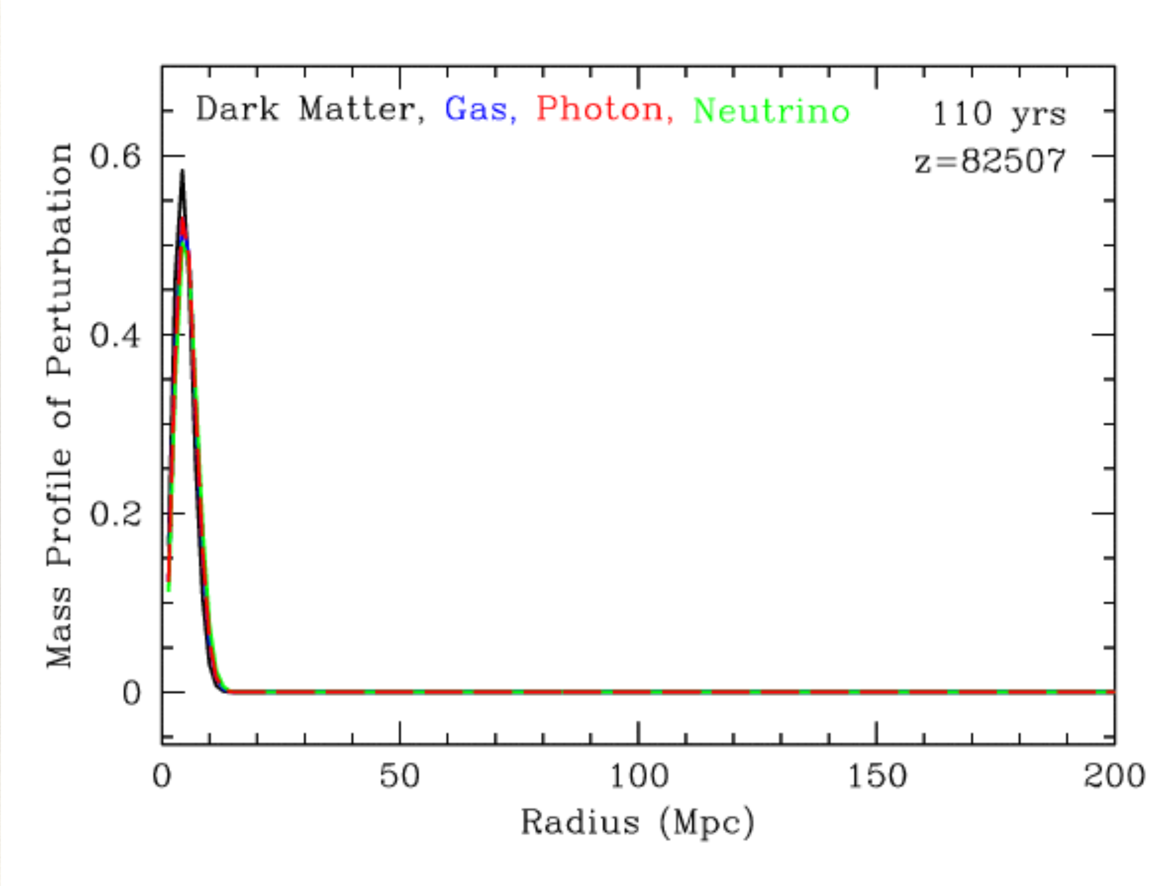


Baryon Acoustic Oscillation Peak

- Due to the two peaks in the previous page, it is more likely to find two pairs of galaxy separated by this distance.
- BAO peak
- This is a "standard ruler", sensitivity to cosmology!

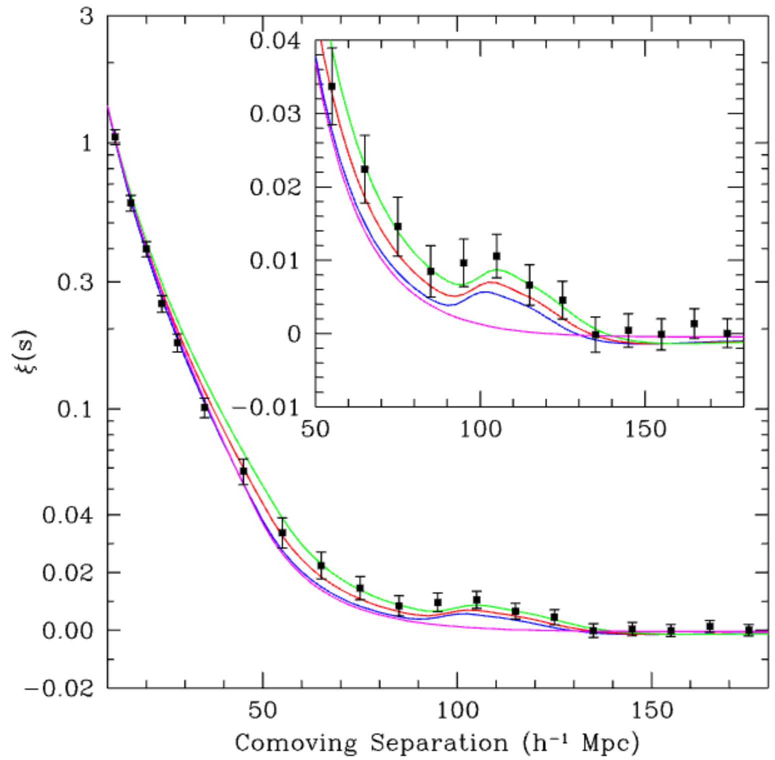
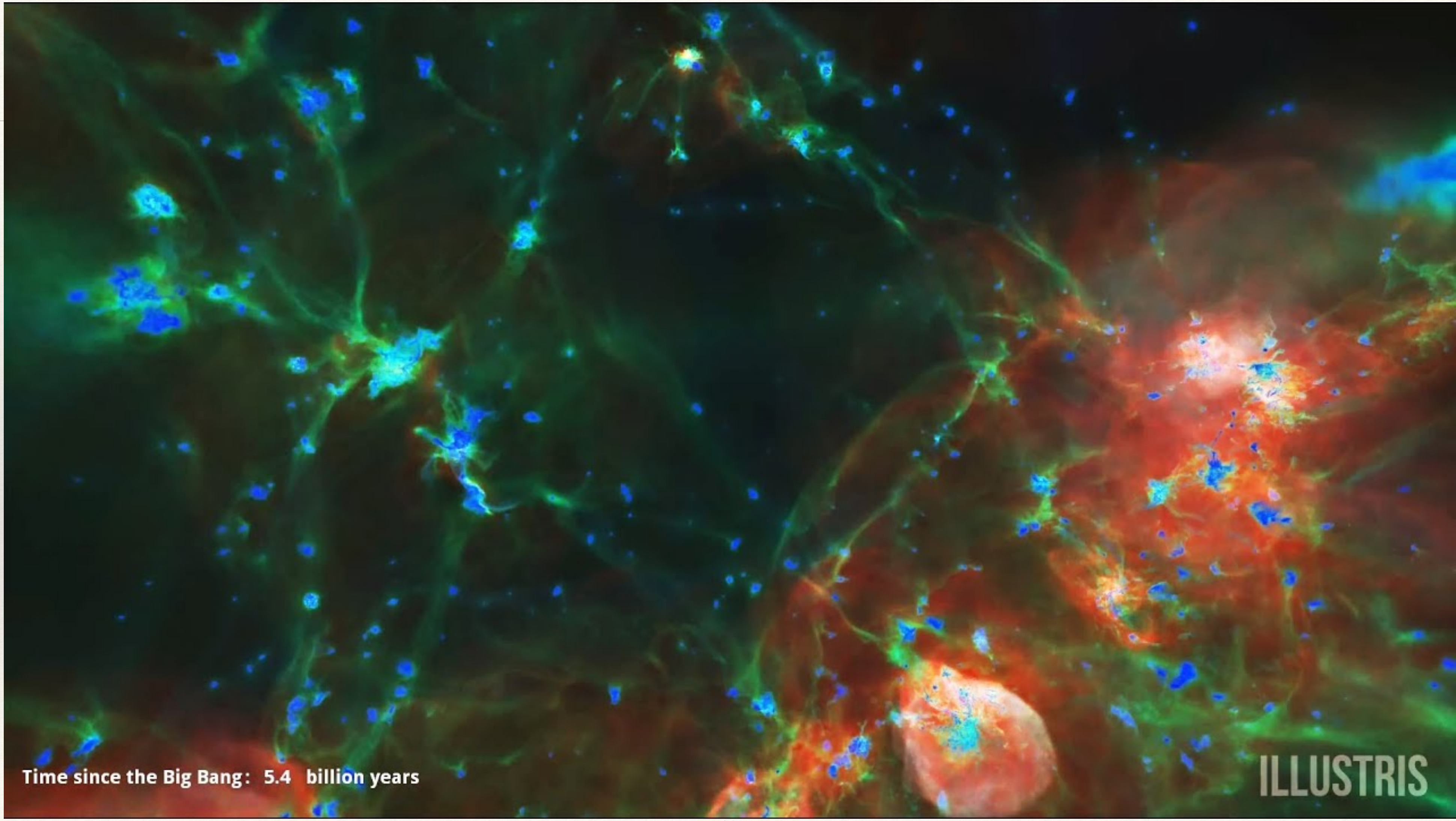
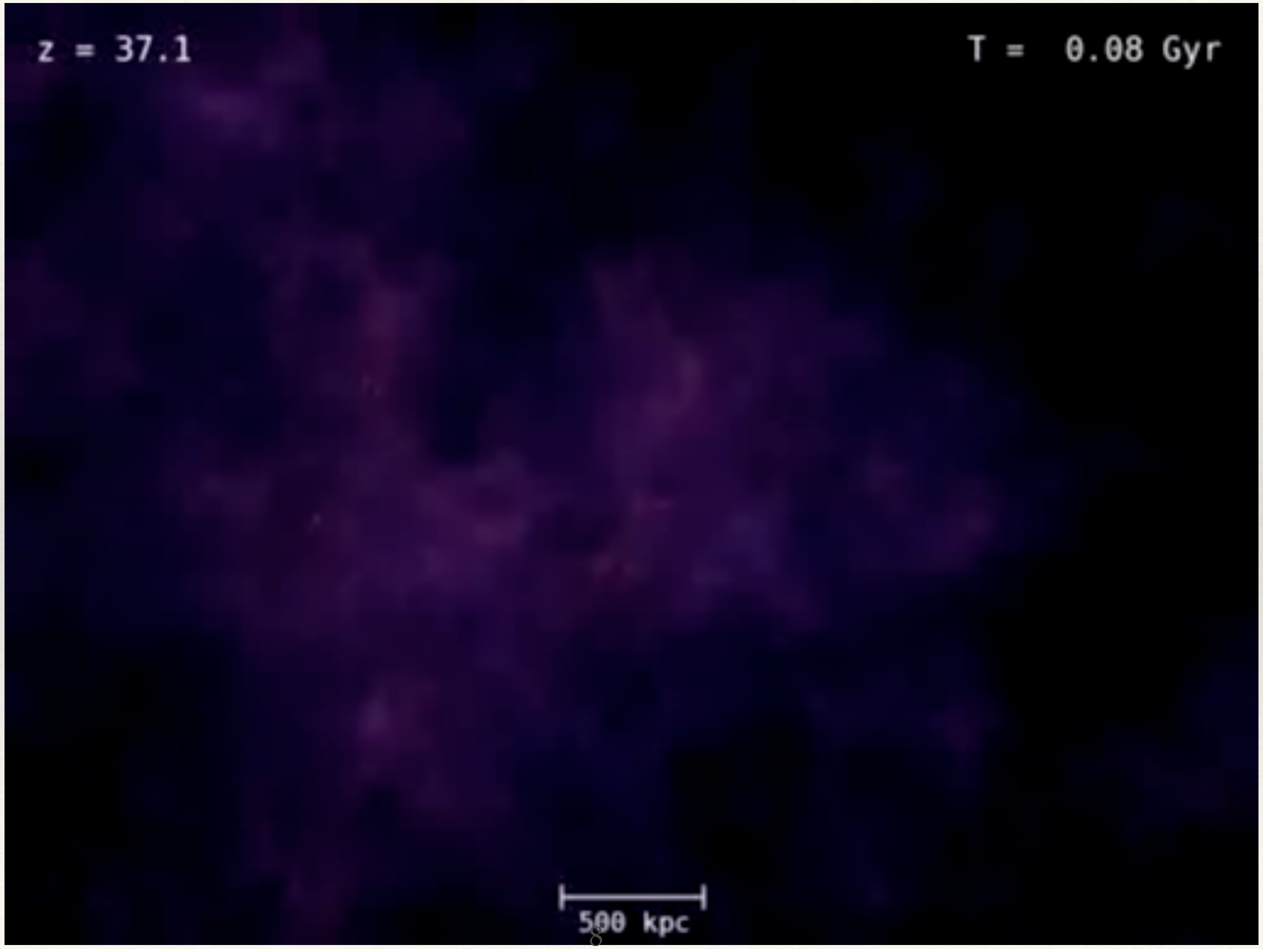


FIG. 2.— The large-scale redshift-space correlation function of the SDSS LRG sample. The error bars are from the diagonal elements of the mock-catalog covariance matrix; however, the points are correlated. Note that the vertical axis mixes logarithmic and linear scalings. The inset shows an expanded view with a linear vertical axis. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. It is interesting to note that although the data appears higher than the models, the covariance between the points is soft as regards overall shifts in $\xi(s)$. Subtracting 0.002 from $\xi(s)$ at all scales makes the plot look cosmetically perfect, but changes the best-fit χ^2 by only 1.3. The bump at $100h^{-1}$ Mpc scale, on the other hand, is statistically significant.

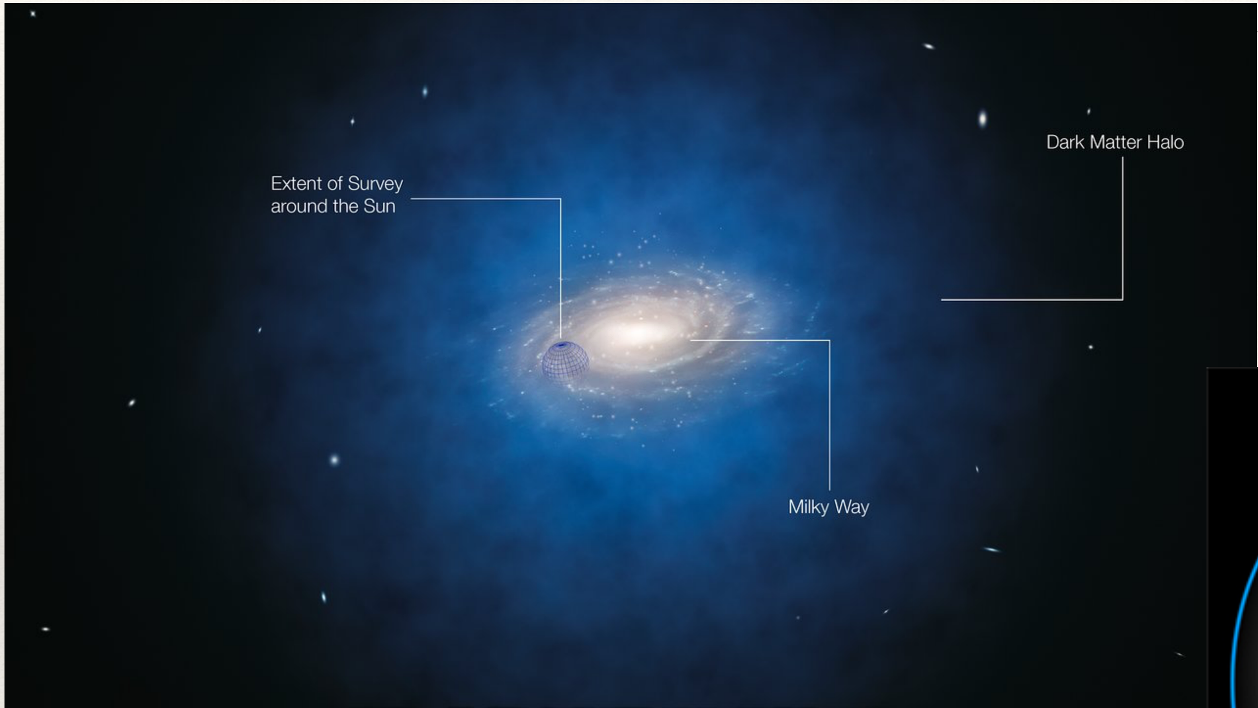

Time since the Big Bang: 5.4 billion years
ILLUSTRIS

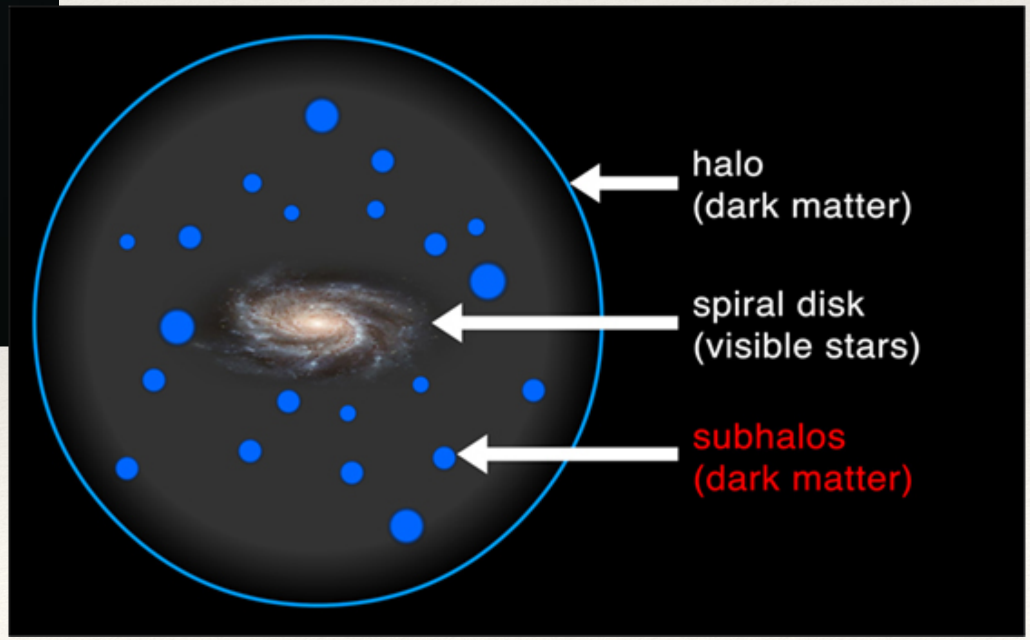
Dark Matter form halos

- Via Lactea Project



We live in a dark matter halo





Milky Way dark matter halo

- Expected to mostly spherical symmetric

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

- e.g., the NFW profile
- Normalized to solar neighbourhood
- $\rho_\chi \sim 0.3\ \mathrm{GeV/cm^3}$

A Universal Density Profile from Hierarchical Clustering

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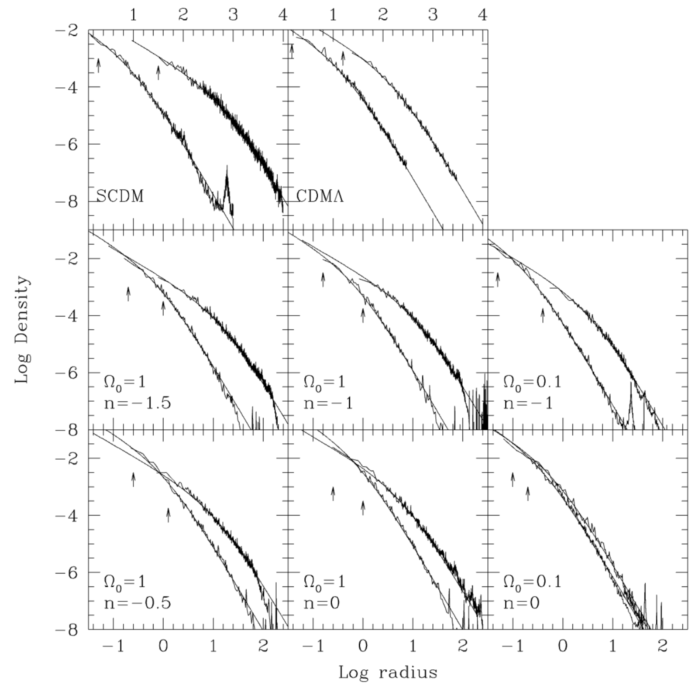

Fig. 2.— Density profiles of one of the most and one of the least massive halos in each series. In each panel the low-mass system is represented by the leftmost curve. In the SCDM and CDMΛ models radii are given in kpc (scale at the top) and densities are in units of $10^{10} M_\odot/\mathrm{kpc}^3$. In all other panels units are arbitrary. The density parameter, Ω_0, and the value of the spectral index, n is given in each panel. Solid lines are fits to the density profiles using eq. (1). The arrows indicate the value of the gravitational softening. The virial radius of each system is in all cases two orders of magnitude larger than the gravitational softening.

Milky Way dark matter halo

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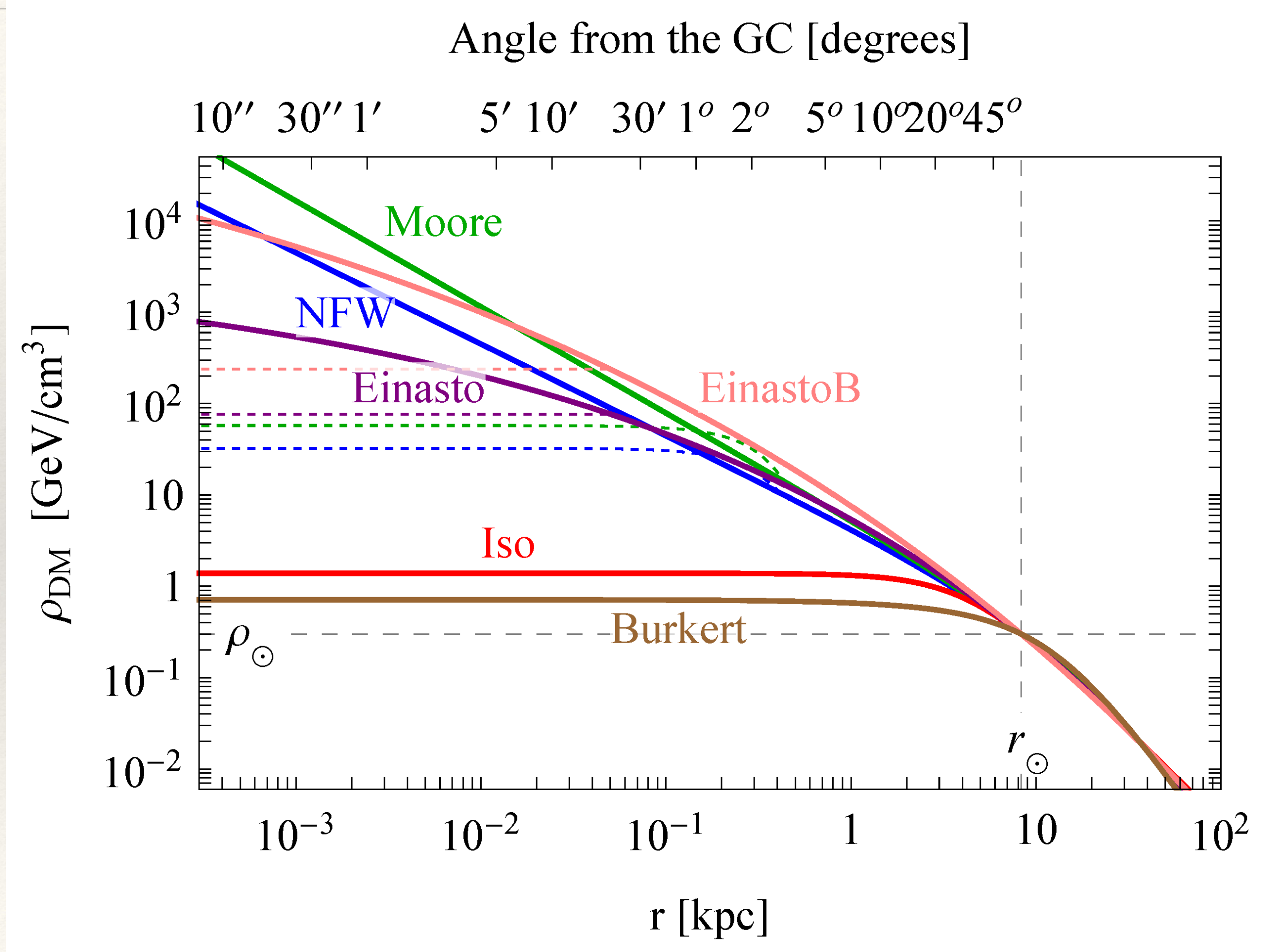
$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s}\left(1 + \frac{r}{R_s}\right)^2}$$

- e.g., the NFW profile
- Normalized to solar neighbourhood
- $\rho_\chi \sim 0.3\ \mathrm{GeV/cm^3}$

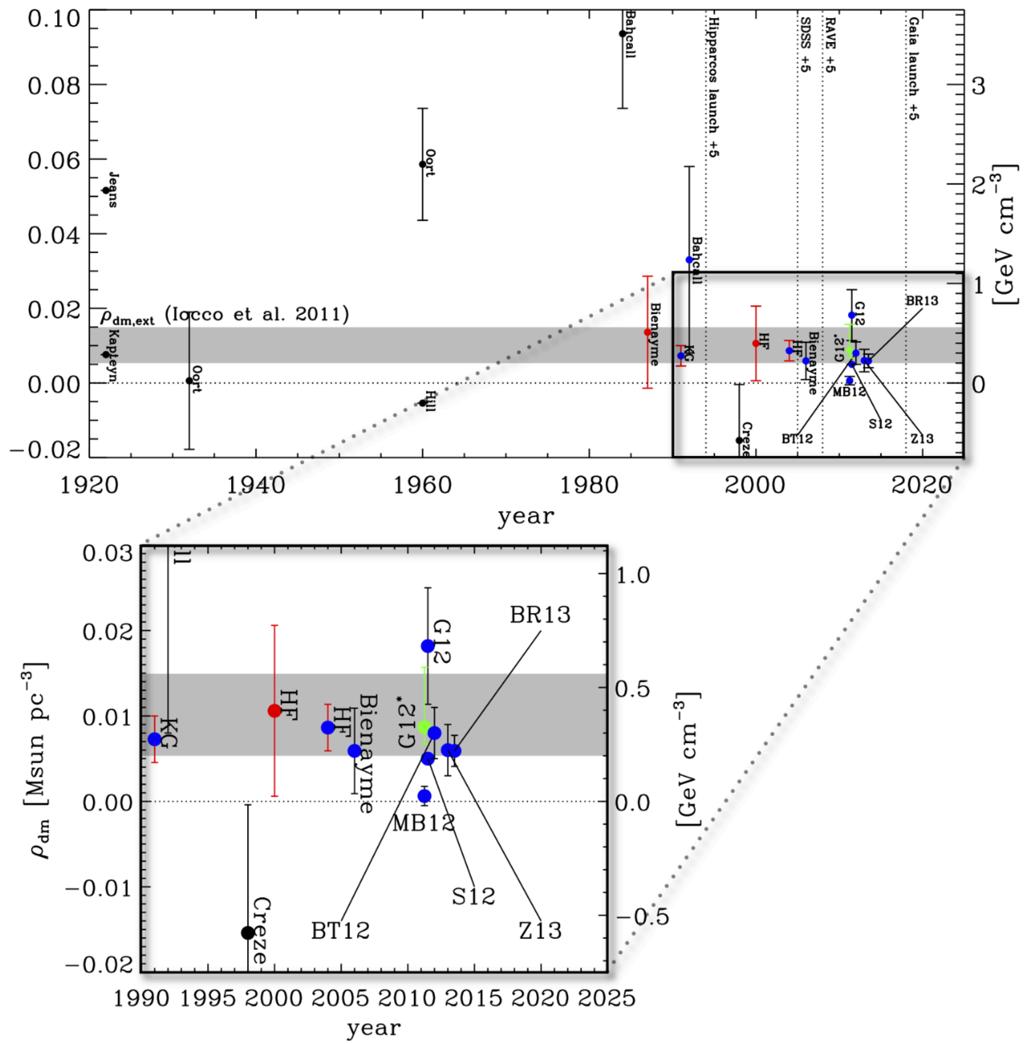
- However, significant uncertainties in the inner part of the galaxy
  - Less sensitivity to dark matter mass, as gravity dominated by Baryons.

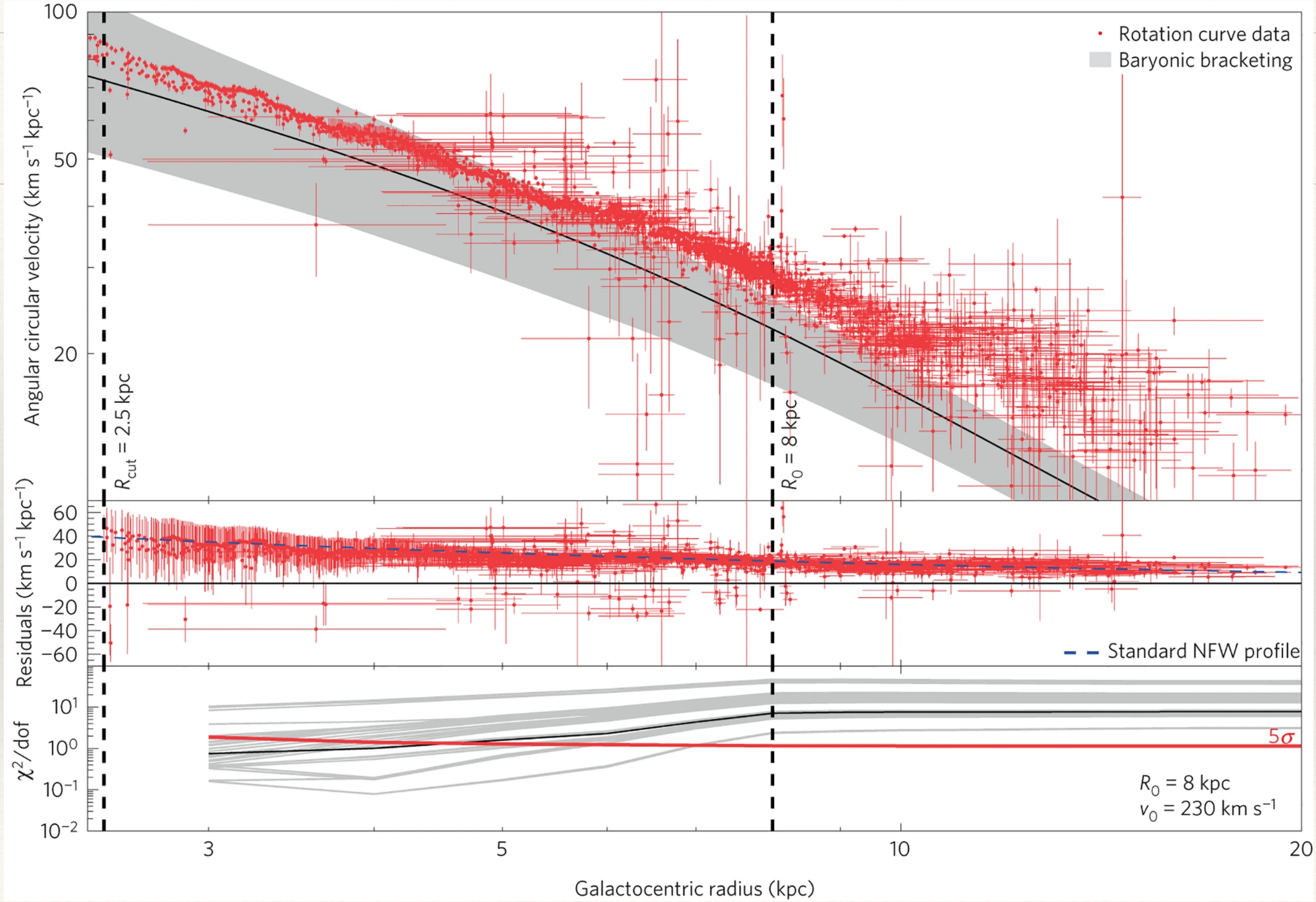


Local Dark Matter density

- Galaxy Scales
  - Galaxy Rotation Curve
    - Assume the shape of the DM halo
  - Local stellar dynamics
    - Measure the speed of the nearby stars
  - As we measure more stars, the two approaches can be considered together
  - About 0.3 GeV/cc

https://arxiv.org/pdf/1404.1938

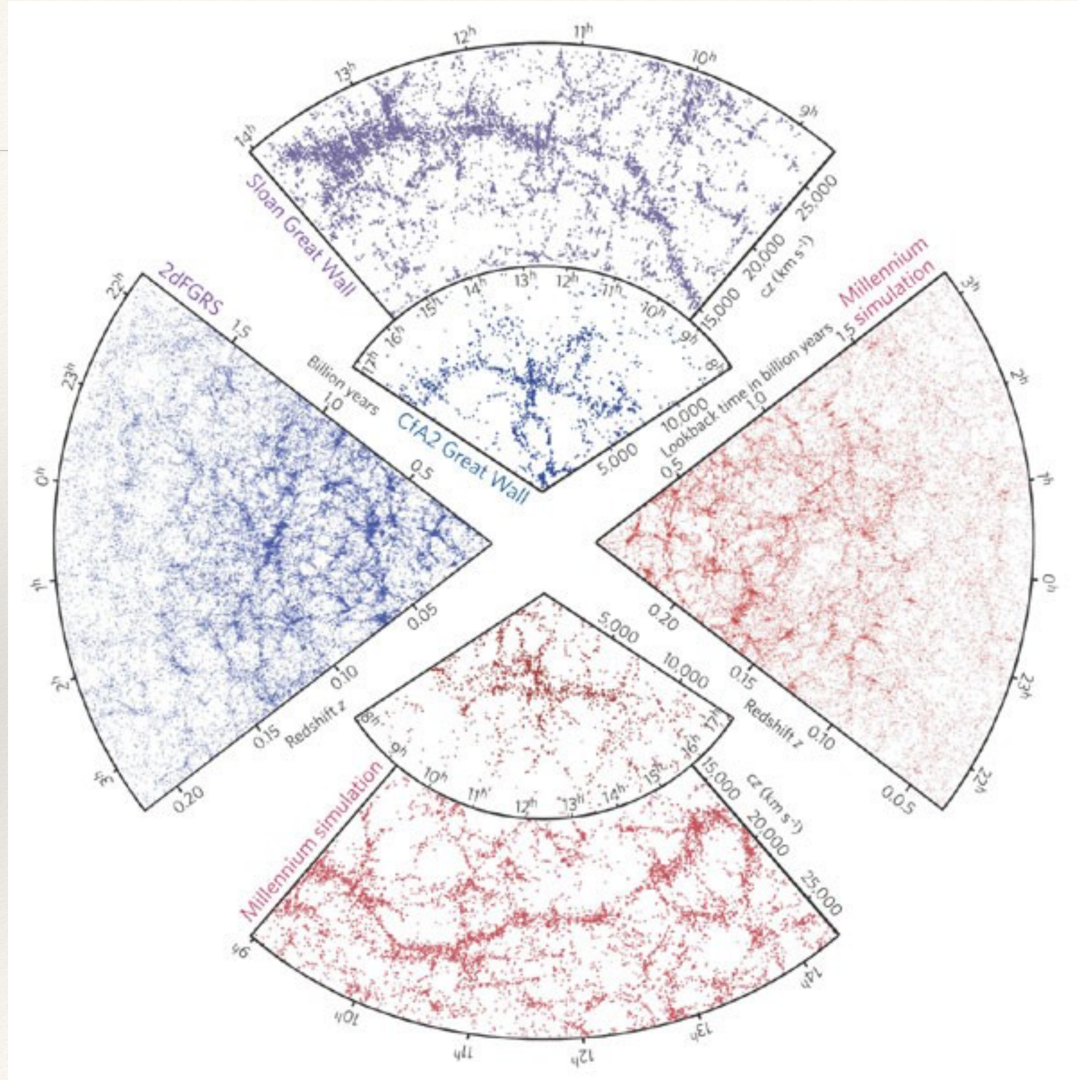




Rotation curve data
Baryonic bracketing
Angular circular velocity (km s^{-1} kpc^{-1})
100
50
20
R_{cut} = 2.5 kpc
R_0 = 8 kpc
Residuals (km s^{-1} kpc^{-1})
60
40
20
0
−20
−40
−60
Standard NFW profile
χ^2/dof
10^1
10^0
10^{-1}
10^{-2}
5σ
R_0 = 8 kpc
v_0 = 230 km s^{-1}
3
5
10
20
Galactocentric radius (kpc)

ΛCDM

- Cold Dark Matter + Cosmological constant
- Extremely successful at large scales
- What does it mean by COLD?



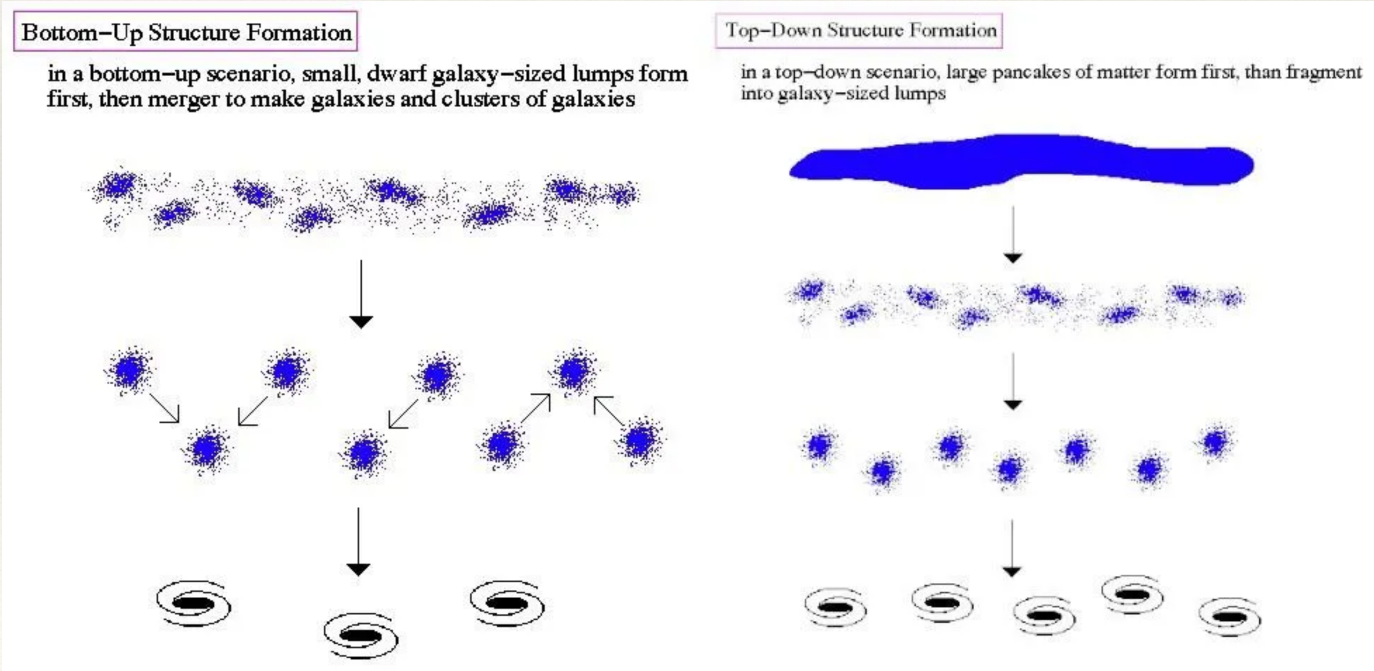
Cold dark matter

- Cold vs Hot dark matter
- Neutrinos are the original DM candidates

- $\Omega_\nu = \frac{m_\nu n_\nu}{\rho_{cr}} \Rightarrow \Omega_\nu h^2 = \frac{m_\nu}{94\text{eV}}$

- It would mean that neutrino dark matter are somewhat relativistic after recombination
- Their speed prevents them to form structures

- Instead structures from in a top-down scenario, and make more smaller objects via fragmentation.
- This means younger objects are smaller.
- This, and the distributions of the structures contradicts data.



https://arxiv.org/pdf/1707.04256

Small-Scale Challenges to the ΛCDM Paradigm

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- Small scale dark matter problems (It is an evolving problem)
  - Warm Dark matter
  - SIDM
  - Wave dark matter
- Dissipative dark matter

ROBUST PREDICTIONS FROM CDM-ONLY SIMULATIONS

A defining characteristic of CDM-based hierarchical structure formation is that the smallest scales collapse first – a fact that arises directly from the shape of the power spectrum (Figure 1) and that lies at the heart of many robust predictions for the counts and structure of dark matter halos today. As discussed below, baryonic processes can alter these predictions to various degrees, but pure dark matter simulations have provided a well-defined set of basic predictions used to benchmark the theory.

The dark matter profiles of individual halos are cuspy and dense [Figure 3]

The density profiles of individual ΛCDM halos increase steadily towards small radii, with an overall normalization and detailed shape that reflects the halo's mass assembly. At fixed mass, early-forming halos tend to be denser than later-forming halos. As with the mass function, both the shape *and* normalization of dark matter halo density structure is predicted by ΛCDM, with a well-quantified prediction for the scatter in halo concentration at fixed mass.

There are many more small halos than large ones [Figure 4]

The comoving number density of dark matter halos rises steeply towards small masses, $dn/dM \propto M^{\alpha}$ with $\alpha \simeq -1.9$. At large halo masses, counts fall off exponentially above the mass scale that is just going non-linear today. Importantly, both the shape and normalization of the mass function is robustly predicted by the theory.

Substructure is abundant and almost self-similar [Figure 5]

Dark matter halos are filled with substructure, with a mass function that rises as $dN/dm \propto m^{\alpha_s}$ with $\alpha_s \simeq -1.8$ down to the low-mass free-streaming scale ($m \ll 1M_{\odot}$ for canonical models). Substructure reflects the high-density cores of smaller merging halos that survive the hierarchical assembly process. Substructure counts are nearly self-similar with host mass, with the most massive subhalos seen at $m_{\rm max} \sim 0.2 M_{\rm host}$.

THREE CHALLENGES TO BASIC ΛCDM PREDICTIONS

There are three classic problems associated with the small-scale predictions for dark matter in the ΛCDM framework. Other anomalies exist, including some that we discuss in this review, but these three are important because 1) they concern basic predictions about dark matter that are fundamental to the hierarchical nature of the theory; and 2) they have received significant attention in the literature.

Missing Satellites and Dwarfs [Figures 4–8]

The observed stellar mass functions of field galaxies and satellite galaxies in the Local Group is much flatter at low masses than predicted dark matter halo mass functions: $dn/dM_\star \propto M_\star^{\alpha_g}$ with $\alpha_g \simeq -1.5$ (vs. $\alpha \simeq -1.9$ for dark matter). The issue is most acute for Galactic satellites, where completeness issues are less of a concern. There are only ~ 50 known galaxies with $M_\star > 300 M_\odot$ within 300 kpc of the Milky Way compared to as many as ~ 1000 dark subhalos (with $M_{\rm sub} > 10^7 M_\odot$) that could conceivably host galaxies. One solution to this problem is to posit that galaxy formation becomes increasingly inefficient as the halo mass drops. The smallest dark matter halos have simply failed to form stars altogether.

Low-density Cores vs. High-density Cusps [Figure 9]

The central regions of dark-matter dominated galaxies as inferred from rotation curves tend to be both less dense (in normalization) and less cuspy (in inferred density profile slope) than predicted for standard ΛCDM halos (such as those plotted in Figure 3). An important question is whether baryonic feedback alters the structure of dark matter halos.

Too-Big-to-Fail [Figure 10]

The local universe contains too few galaxies with central densities indicative of $M_{\rm vir} \simeq 10^{10} M_\odot$ halos. Halos of this mass are generally believed to be too massive to have failed to form stars, so the fact that they are missing is hard to understand. The stellar mass associated with this halo mass scale ($M_\star \simeq 10^6 M_\odot$, Figure 6) may be too small for baryonic processes to alter their halo structure (see Figure 13).

- Missing Satellite Problem

- Many sub halos in dark matter simulations
- Only a few satellite galaxies are observed.

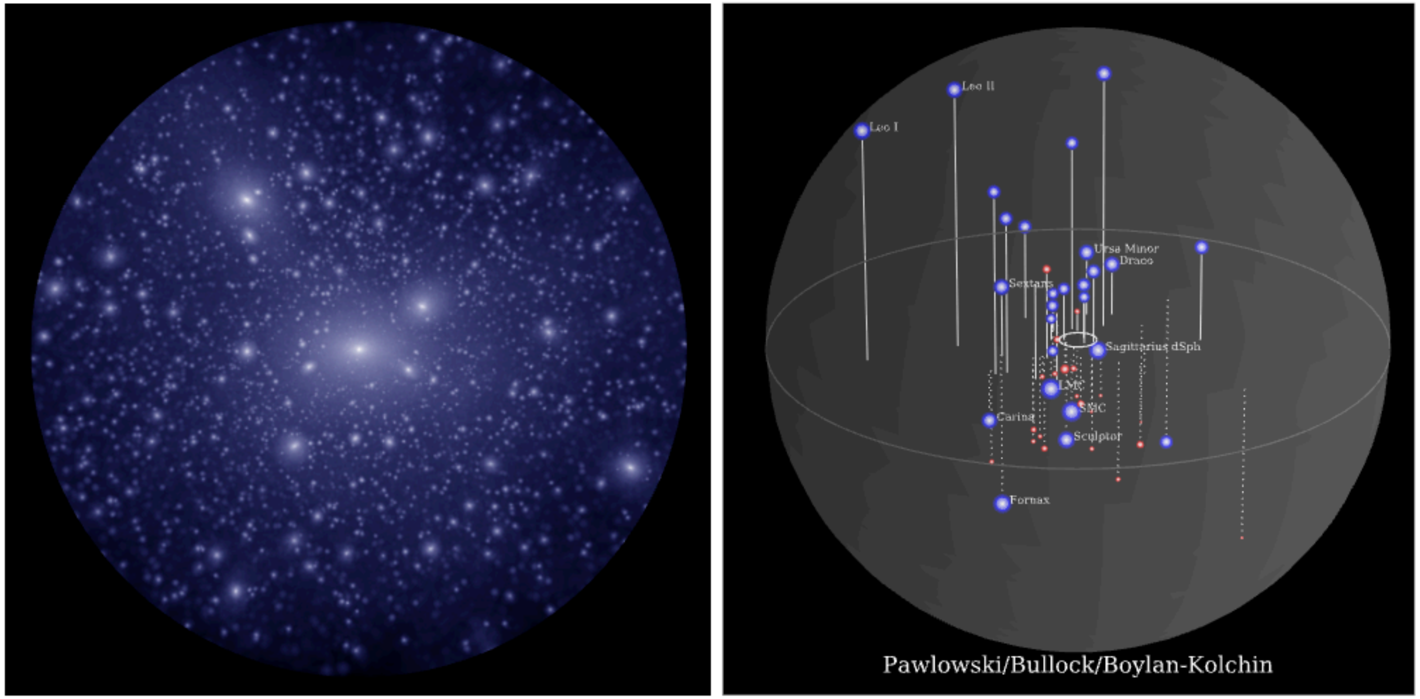

Figure 7

The Missing Satellites Problem: Predicted ΛCDM substructure (left) vs. known Milky Way satellites (right). The image on the left shows the ΛCDM dark matter distribution within a sphere of radius 250 kpc around the center of a Milky-Way size dark matter halo (simulation by V. Robles and T. Kelley in collaboration with the authors). The image on the right (by M. Pawlowski in collaboration with the authors) shows the current census of Milky Way satellite galaxies, with galaxies discovered since 2015 in red. The Galactic disk is represented by a circle of radius 15 kpc at the center and the outer sphere has a radius of 250 kpc. The 11 brightest (classical) Milky Way satellites are labeled by name. Sizes of the symbols are not to scale but are rather proportional to the log of each satellite galaxy's stellar mass. Currently, there are ~ 50 satellite galaxies of the Milky Way compared to thousands of predicted subhalos with $M_{\rm peak} \gtrsim 10^7\, M_\odot$.

- Cusp-core problem

- NFW profile is "cuspy"
- r^{-1} or steeper in the inner halo

- Data seems to suggest more cored like density profiles

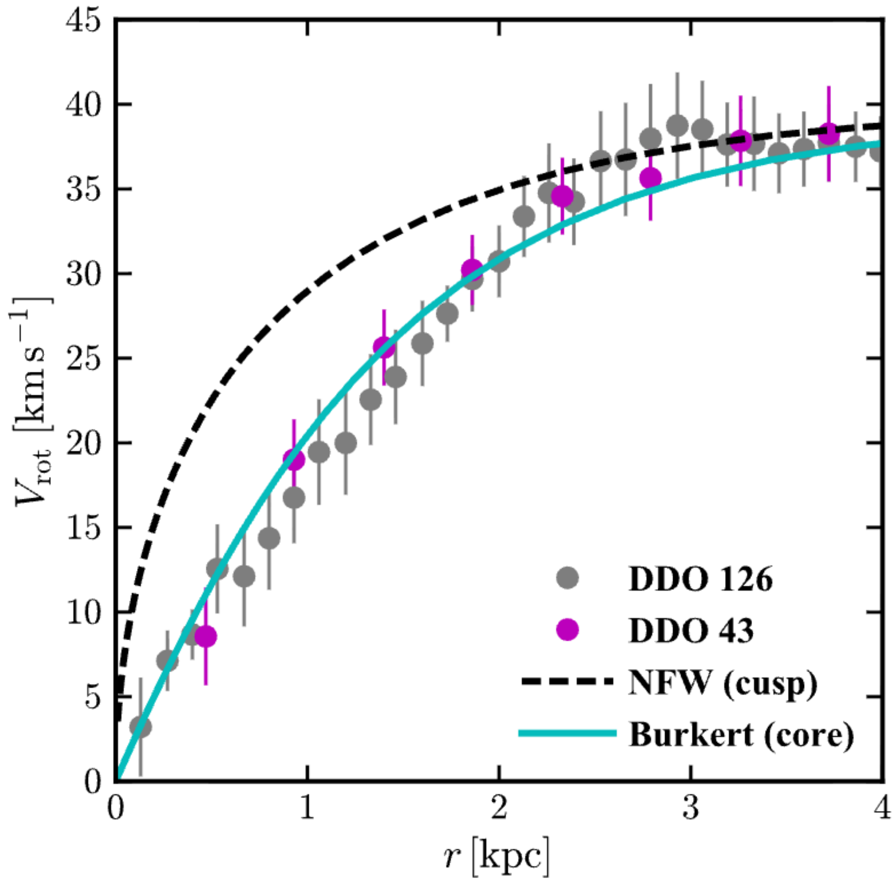

Figure 9

The Cusp-Core problem. The dashed line shows the naive ΛCDM expectation (NFW, from dark-matter-only simulations) for a typical rotation curve of a $V_{\rm max} \approx 40\,{\rm km\,s^{-1}}$ galaxy. This rotation curve rises quickly, reflecting a central density profile that rises as a cusp with $\rho \propto 1/r$. The data points show the rotation curves of two example galaxies of this size from the LITTLE THINGS survey (Oh et al. 2015)), which are more slowly rising and better fit by a density profile with a constant density core (Burkert 1995, cyan line).

- Too big to fail problem
- (A halo-galaxy matching problem)

- Simulated sub halo are heavy
- Observed halos that hosted the satellites are lighter

- Same problems are also observed in field dwarfs (Not satellites)

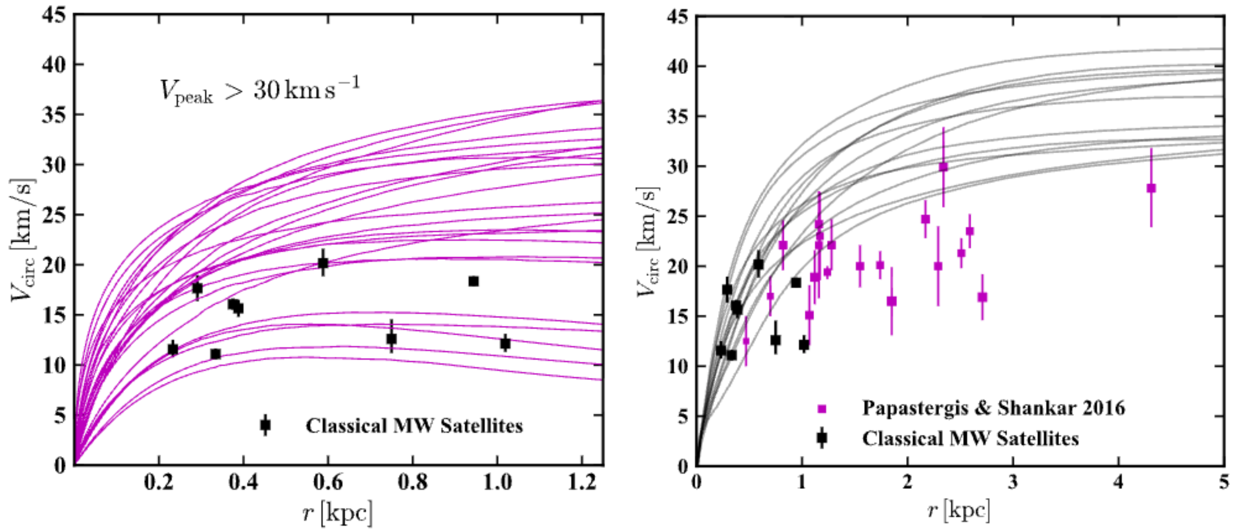

Figure 10

The Too-Big-to-Fail Problem. *Left:* Data points show the circular velocities of classical Milky Way satellite galaxies with $M_\star \simeq 10^{5-7} M_\odot$ measured at their half-light radii $r_{1/2}$. The magenta lines show the circular velocity curves of subhalos from one of the (dark matter only) Aquarius simulations. These are specifically the subhalos of a Milky Way-size host that have peak maximum circular velocities $V_{\rm max} > 30\,{\rm km\,s^{-1}}$ at some point in their histories. Halos that are this massive are likely resistant to strong star formation suppression by reionization and thus naively too big to have failed to form stars (modified from Boylan-Kolchin, Bullock & Kaplinghat 2012). The existence of a large population of such satellites with greater central masses than any of the Milky Way's dwarf spheroidals is the original Too-Big-to-Fail problem. *Right:* The same problem – a mismatch between central masses of simulated dark matter systems and observed galaxies – persists for field dwarfs (magenta points), indicating it is not a satellite-specific process (modified from Papastergis & Ponomareva 2017). The field galaxies shown all have stellar masses in the range $5.75 \leq \log_{10}(M_\star/M_\odot) \leq 7.5$. The gray curves are predictions for ΛCDM halos from the fully self-consistent hydrodynamic simulations of Fitts et al. (2016) that span the same stellar mass range in the simulations as the observed galaxies.

Too many satellite problems?

Letter to the Editor

A too-many dwarf galaxy satellites problem in the M 83 group

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Received tba; accepted tba

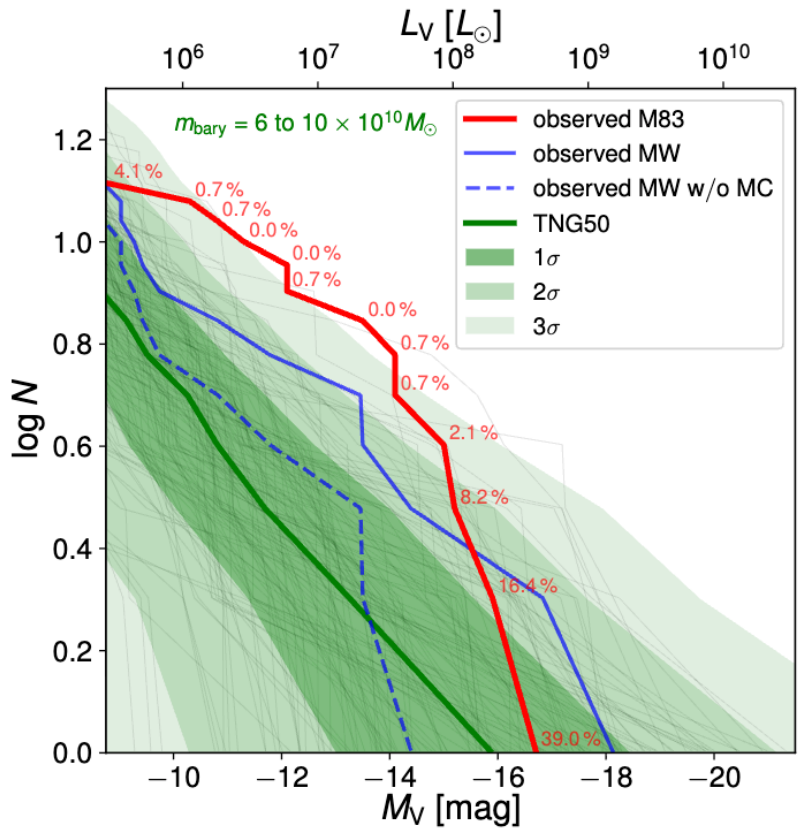


Fig. 3. The observed luminosity function of M 83 (red line) compared to its Illustris-TNG50 analogs, with each analog corresponding to a gray line. The 1, 2, and 3σ confidence intervals are indicated with the green areas. The red numbers indicate the percentage of analogs having more satellites than the observed one at given step. Also shown is the Milky Way luminosity function (blue) including (straight) and excluding (dashed) the rare Magellanic Clouds (MC). While the Milky Way luminosity function without the MC is consistent with expectations from Illustris-TNG50, the M 83 luminosity function deviates by more than 3σ.

Small Scale Challenges

- The Baryon problems
- It is difficult to take into account all kinds of baryon effects
  - Star formation Supernova feedback (gas/cosmic rays/gravity)
  - Galaxy formation
  - Halo disruption by tidal effects
  - Etc……
- Dark Matter problem?
- Could the small scale problems related to physics of dark matter
- (MOND people would say CDM works well in large scales, but opposite for MOND)

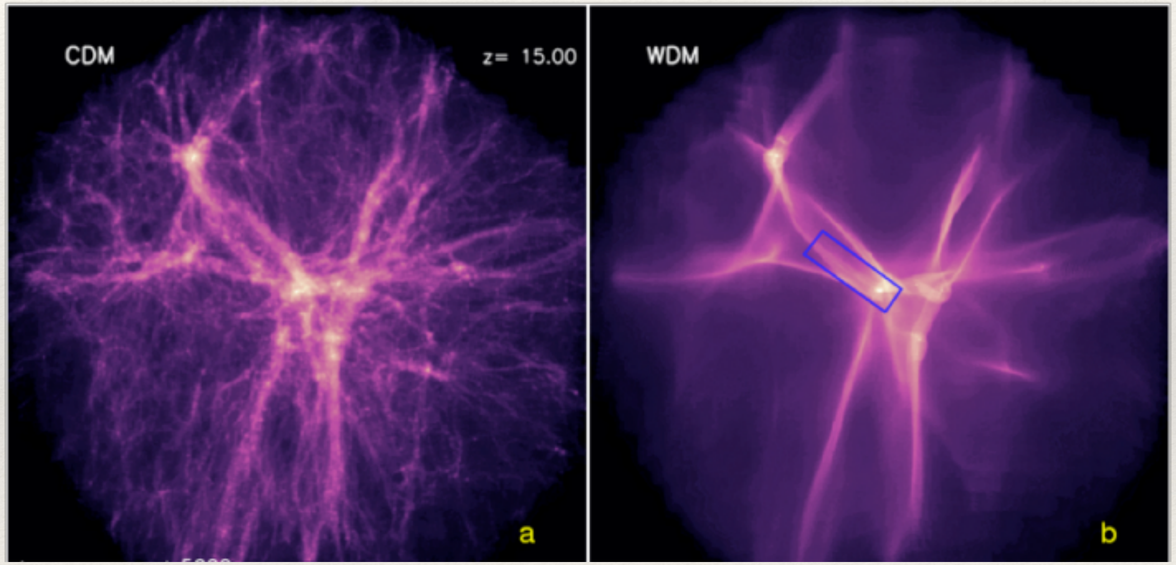
- Some dark matter solutions/ideas that focus on effects on structures

- Warm Dark Matter
- Decaying dark matter
- Self-interacting dark matter
- Wave dark matter
- Double disk dark matter

Warm dark matter

- Dark Matter cannot be hot, but maybe it is warm?

- Warm = dark matter has non-negligible velocity dispersion after matter-radiation equality (The time when structure formation begins)
- Fast moving particles has long ”free steaming length”
  - Halos with size smaller than free streaming scale cannot collapse to halos



- If dark matter is “thermal”
  - Thermal = coupled to the Universe thermally in the early universe
  - Warm dark matter ~ keV

Structure formation with suppressed small-scale perturbations

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- Density perturbation is represented by “powers” (Fourier space)
- WDM suppress small scale power, or, large k

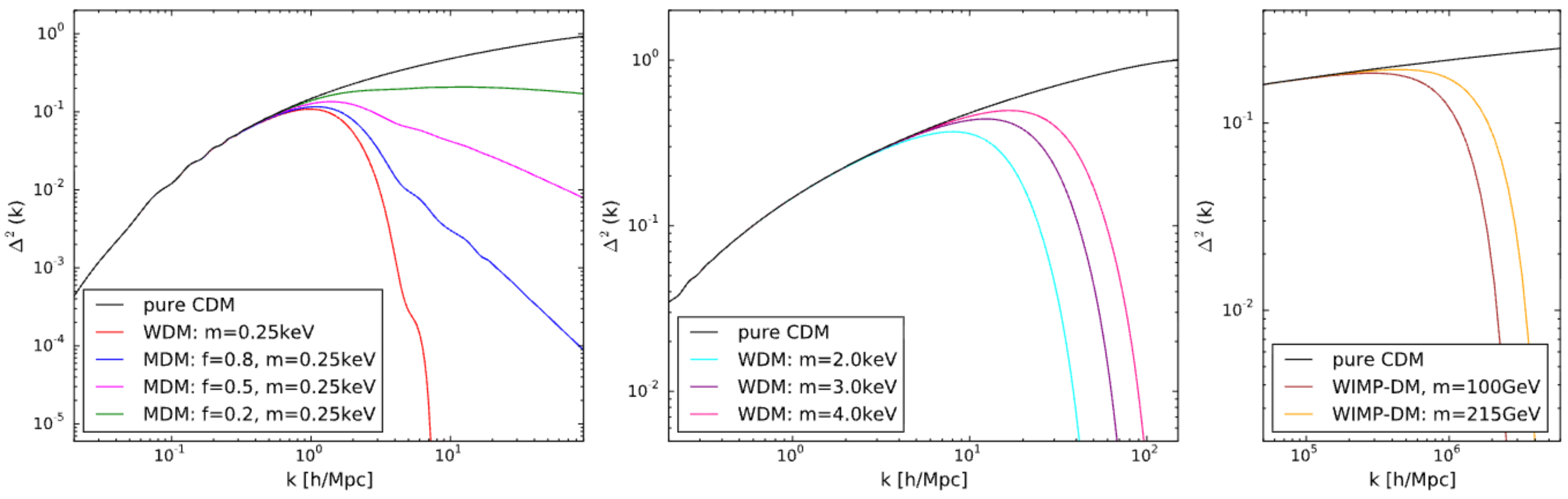

Figure 1. Linear dimensionless power spectrum $\Delta(k) = k^3 P_\chi(k)/2\pi^2$ of the dark matter scenarios (χ) investigated in this paper. Left: CDM (black), WDM (red) and various MDM models (blue, magenta, green) at redshift 50. Middle: CDM (black) and different WDM models (cyan, purple, pink) at redshift 100. Right: pure CDM (black) and two WIMP-DM scenarios (brown, orange) at redshift 300.

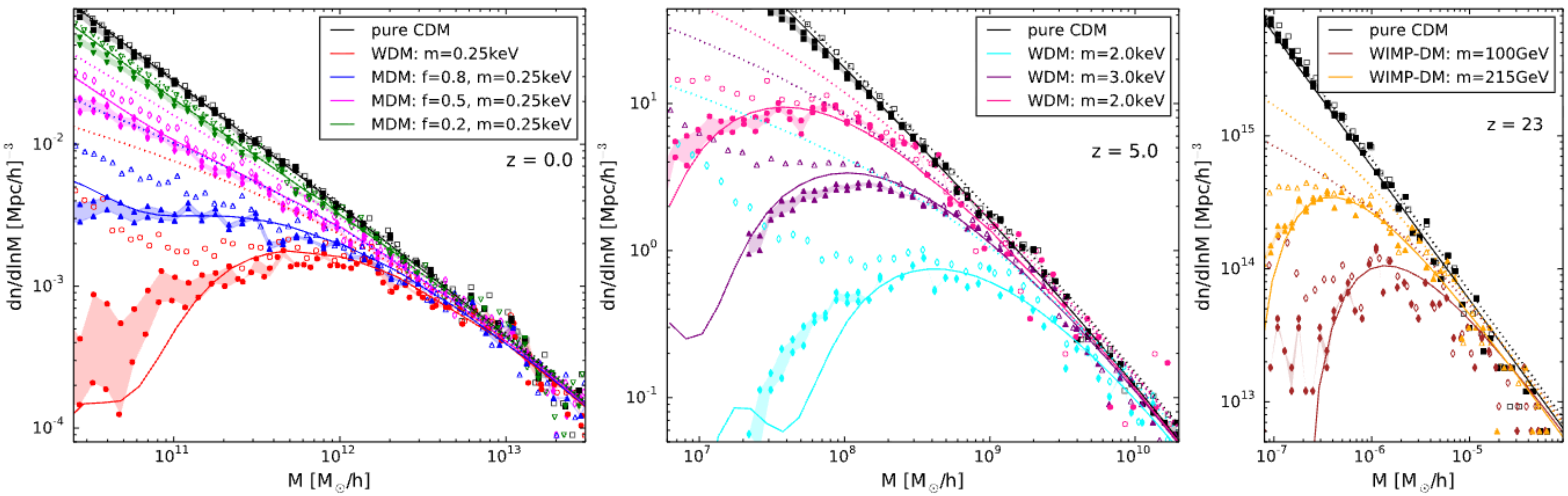

Figure 4. Halo mass functions for various DM models. Left: CDM (black), WDM (red), and MDM (blue, magenta, green) at redshift zero. Middle: CDM (black) and WDM (cyan, purple, pink) at redshift 5. Right: pure CDM (black) and WIMP DM (brown, orange) at redshift 23. The colour-shaded regions account for the uncertainty due to the removal procedure of artefacts (see text). Solid lines represent the sharp-k model, dotted lines the standard Sheth-Tormen mass function.

Decaying Dark Matter

- What if dark matter decay some time between CMB and now?

- Imagine this
- $\chi_1 \rightarrow \chi_2 + \gamma$
- The new dark matter χ_2 will gain a kick (velocity)
- This again surpasses small scale structure formation

Cosmological Structure Formation in Decaying Dark Matter Models

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Abstract. The standard cold dark matter (CDM) model predicts too many and too dense small structures. We consider an alternative model that the dark matter undergoes two-body decays with cosmological lifetime τ into only one type of massive daughters with non-relativistic recoil velocity V_k. This decaying dark matter model (DDM) can suppress the structure formation below its free-streaming scale at time scale comparable to τ. Comparing with warm dark matter (WDM), DDM can better reduce the small structures while being consistent with high redshfit observations. We study the cosmological structure formation in DDM by performing self-consistent N-body simulations and point out that cosmological simulations are necessary to understand the DDM structures especially on non-linear scales. We propose empirical fitting functions for the DDM suppression of the mass function and the concentration-mass relation, which depend on the decay parameters lifetime τ, recoil velocity V_k and redshift. The fitting functions lead to accurate reconstruction of the the non-linear power transfer function of DDM to CDM in the framework of halo model. Using these results, we set constraints on the DDM parameter space by demanding that DDM does not induce larger suppression than the Lyman-α constrained WDM models. We further generalize and constrain the DDM models to initial conditions with non-trivial mother fractions and show that the halo model predictions are still valid after considering a global decayed fraction. Finally, we point out that the DDM is unlikely to resolve the disagreement on cluster numbers between the Planck primary CMB prediction and the Sunyaev-Zeldovich (SZ) effect number count for $\tau \sim H_0^{-1}$.

- What if dark matter decay some time between CMB and now?

- Imagine this
- $\chi_1 \to \chi_2 + \gamma$
- The new dark matter χ_2 will gain a kick (velocity)
- This again surpasses small scale structure formation

Contrary to the short-lifetime decay, we consider non-relativistic decays with long lifetime ($\tau \gtrsim H_0^{-1}$). We will show that such models are completely different from the WDM model. To be more explicit, we consider models in which the mother particle undergoes two-body decay with just one type of massive daughters, where the only two possibilities are

$$ddm \to dm + l \tag{1.1}$$

and

$$ddm \to dm + dm. \tag{1.2}$$

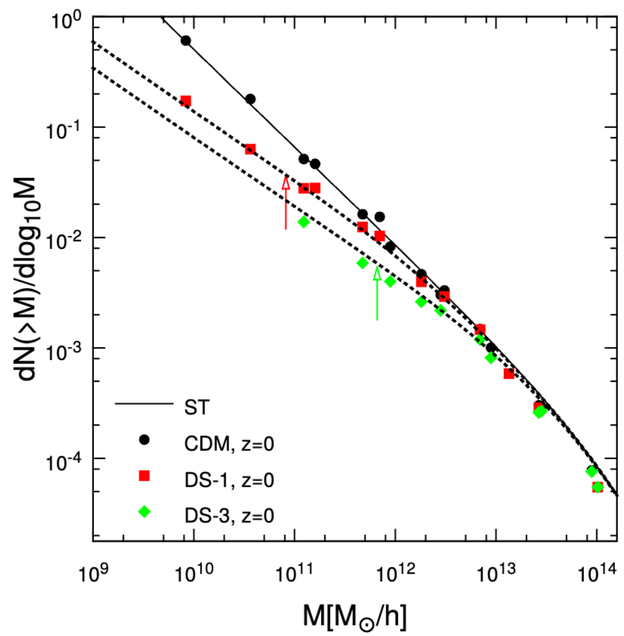
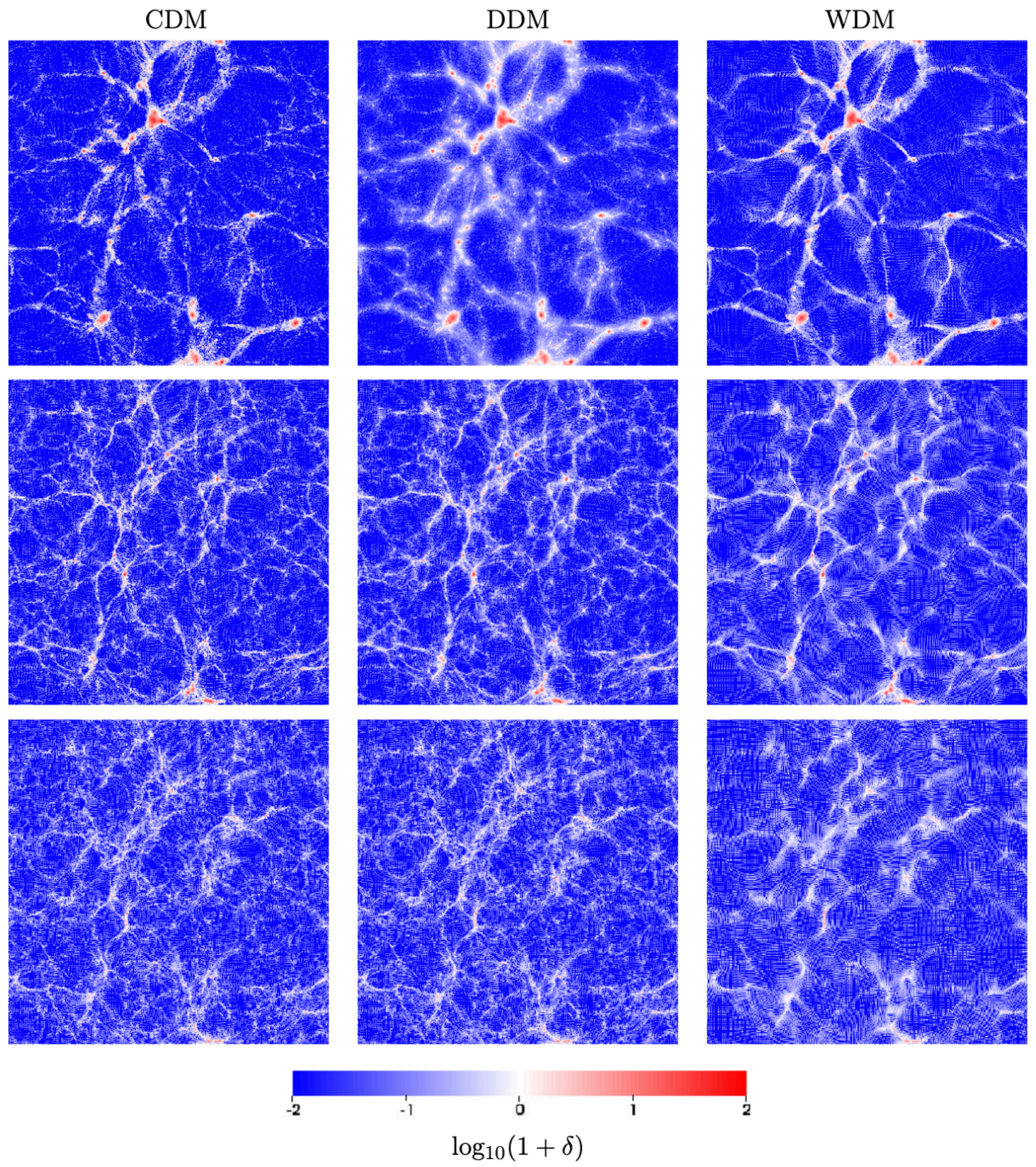


Figure 6. The mass functions of the ST formalism (solid line) and measurements from CDM (round black points) and two DDM simulations (square and diamond points). The CDM data points are measured in simulation boxes of 100, 50 and 20 Mpc/h, while data points of DS-1 and DS-3 are obtained by combing the two simulation boxes in Table 1. The dashed lines are following the best fit of Eq. (4.17) with the arrows pointing to the cutoff mass indicated in Peter et al. [31] for the two sets of decay parameters.



Self Interacting Dark Matter SIDM

- We know that dark matter cannot interacting strong with matter
  - (Will talk about this later)
- But, can it interact with themselves?

- One place to look at this is at the Bullet Cluster

Observational evidence for selfinteracting cold dark matter

David N. Spergel (Princeton U.), Paul J. Steinhardt (Princeton U.)

Sep, 1999

4 pages

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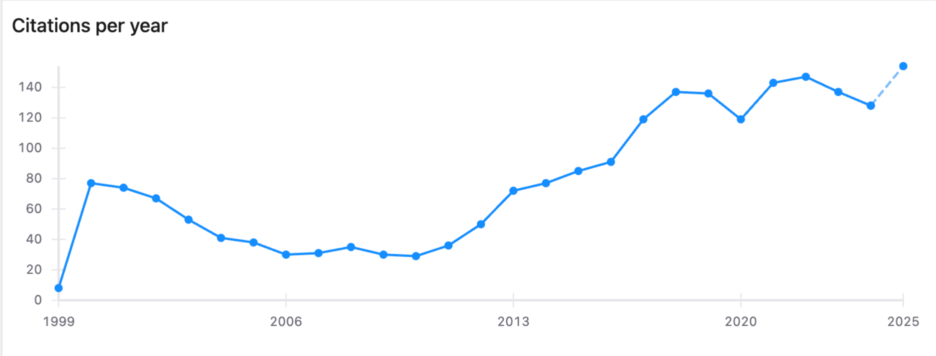
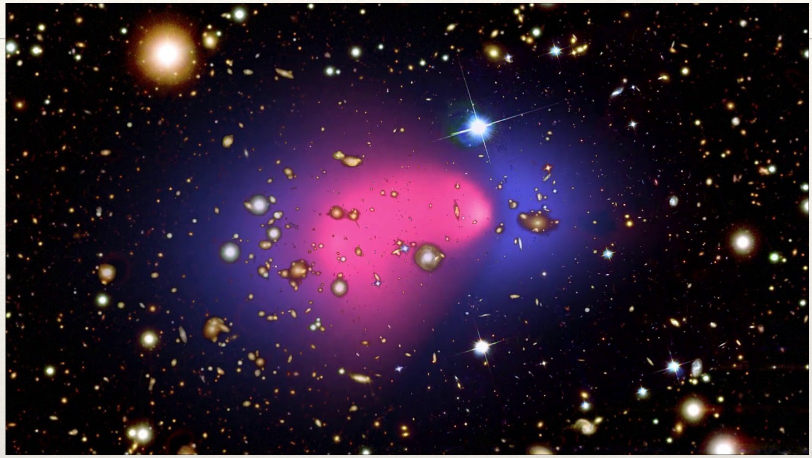
pdf cite claim reference search 2,144 citations



- There are 3 things in the Bullet Cluster simulation
- Blue: gravitational lensing
  - Total matter
- Red: x-ray
  - Baryons, hot gas, dominates baryon mass
- Galaxies
  - Baryons, but subdominant. “Collisionless”
- The fact that dark matter traces galaxies, means that cannot be very very strongly self interacting!

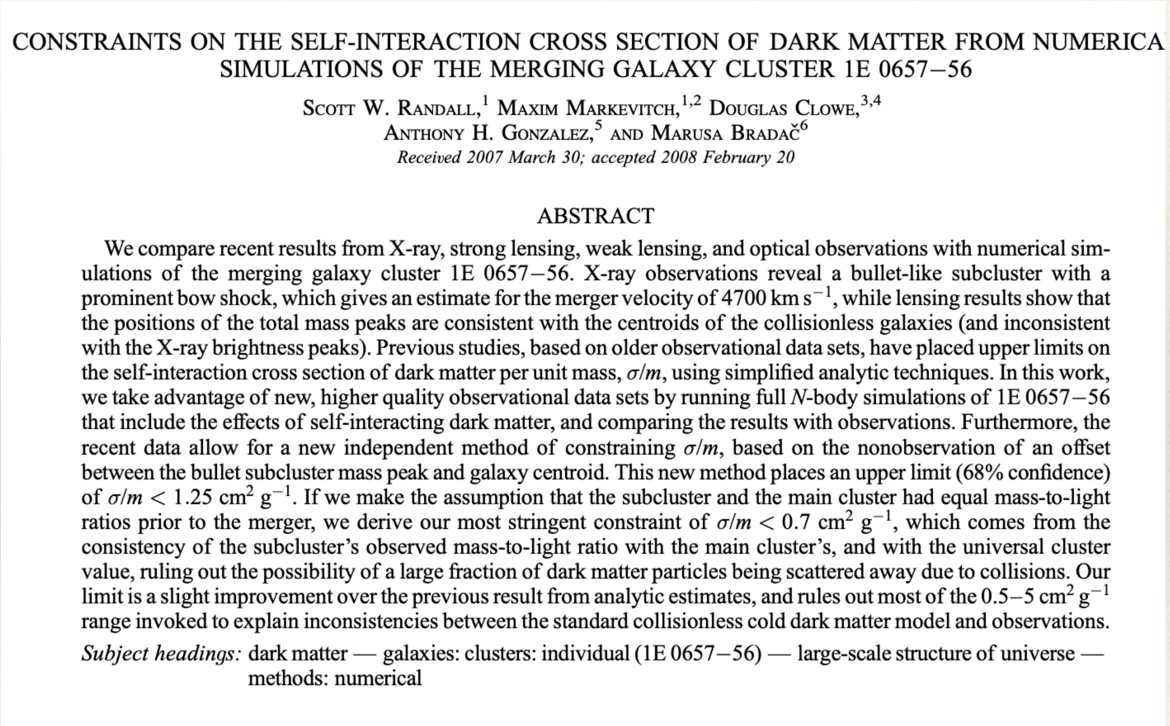


- Rate of interaction
- $\Gamma \sim n_1 n_2 \sigma v_{rel}$
- $n_2 = \rho / m_\chi$
- We only know the mass densities, and thus the constraints are expressed in σ / m

Self Interacting Dark Matter SIDM

- We know that dark matter cannot interacting strong with matter
  - (Will talk about this later)
- But, can it interact with themselves?

- One place to look at this is at the Bullet Cluster



CONSTRAINTS ON THE SELF-INTERACTION CROSS SECTION OF DARK MATTER FROM NUMERICA
SIMULATIONS OF THE MERGING GALAXY CLUSTER 1E 0657−56

Scott W. Randall,[1] Maxim Markevitch,[1,2] Douglas Clowe,[3,4]
Anthony H. Gonzalez,[5] and Marusa Bradač[6]

Received 2007 March 30; accepted 2008 February 20

ABSTRACT

We compare recent results from X-ray, strong lensing, weak lensing, and optical observations with numerical simulations of the merging galaxy cluster 1E 0657−56. X-ray observations reveal a bullet-like subcluster with a prominent bow shock, which gives an estimate for the merger velocity of 4700 km s^{-1}, while lensing results show that the positions of the total mass peaks are consistent with the centroids of the collisionless galaxies (and inconsistent with the X-ray brightness peaks). Previous studies, based on older observational data sets, have placed upper limits on the self-interaction cross section of dark matter per unit mass, σ/m, using simplified analytic techniques. In this work, we take advantage of new, higher quality observational data sets by running full N-body simulations of 1E 0657−56 that include the effects of self-interacting dark matter, and comparing the results with observations. Furthermore, the recent data allow for a new independent method of constraining σ/m, based on the nonobservation of an offset between the bullet subcluster mass peak and galaxy centroid. This new method places an upper limit (68% confidence) of $\sigma/m < 1.25$ cm^2 g^{-1}. If we make the assumption that the subcluster and the main cluster had equal mass-to-light ratios prior to the merger, we derive our most stringent constraint of $\sigma/m < 0.7$ cm^2 g^{-1}, which comes from the consistency of the subcluster's observed mass-to-light ratio with the main cluster's, and with the universal cluster value, ruling out the possibility of a large fraction of dark matter particles being scattered away due to collisions. Our limit is a slight improvement over the previous result from analytic estimates, and rules out most of the 0.5–5 cm^2 g^{-1} range invoked to explain inconsistencies between the standard collisionless cold dark matter model and observations.

Subject headings: dark matter — galaxies: clusters: individual (1E 0657−56) — large-scale structure of universe — methods: numerical

Self Interacting Dark Matter SIDM

- We know that dark matter cannot interacting strong with matter
  - (Will talk about this later)
- But, can it interact with themselves?
- One place to look at this is at the Bullet Cluster
- But……, people argue about it

What does the Bullet Cluster tell us about self-interacting dark matter?

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sets than more observationally-motivated methods such as parametric fits to the projected density or reduced gravitational shear. This suggests that the $\sigma/m < 1.25\,\mathrm{cm^2\,g^{-1}}$ constraint placed on the cross-section for DM scattering by R08 is strongly overstated. In fact, for our fiducial model of the Bullet Cluster with $\sigma/m = 2\,\mathrm{cm^2\,g^{-1}}$, the DM–galaxy offset at the time of the observed Bullet Cluster is $\sim 20\,\mathrm{kpc}$, which is allowed by the $25 \pm 29\,\mathrm{kpc}$ observed offset used by R08 to place their constraint. We produce more robust results by fitting parametric models to the haloes – which can be done observationally (Smith et al. 2005; Richard et al.

Self Interacting Dark Matter SIDM

- But!!! If there are SIDM satisfying bullet cluster could affect dark matter structures too!

- SIDM kicks in when there are high dark matter density

- Solves core cusp problem by pushing dark matter out of high density regions.

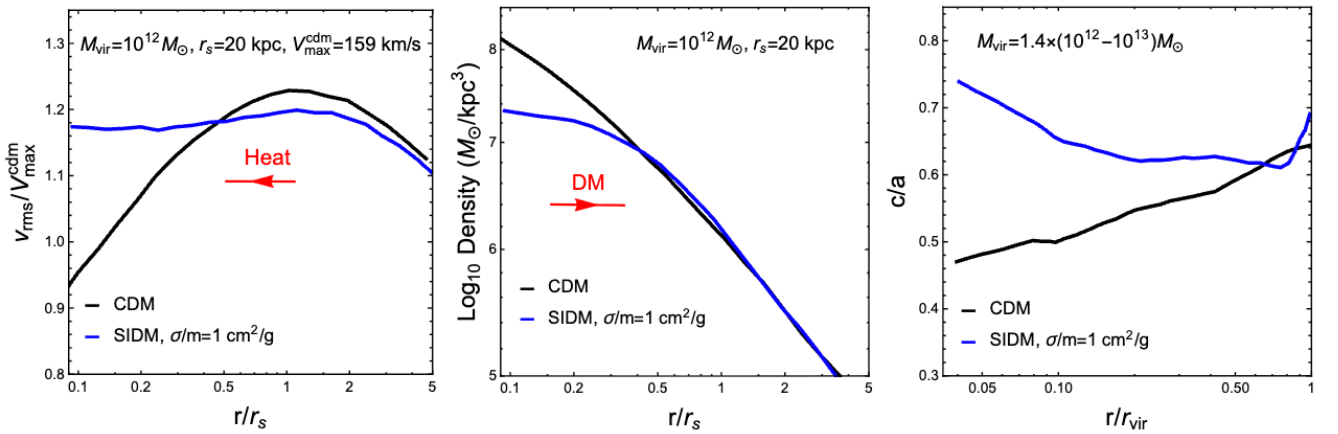

FIG. 2: *Left: Density profiles (left), dispersion profiles (center), and median halo shapes (right) for SIDM with* $\sigma/m = 1\ \mathrm{cm}^2/\mathrm{g}$ *and its CDM counterpart. DM self-interactions cause heat transfer from the hot outer region to the cold inner region of a CDM halo and kinetically thermalize the inner halo, leading to a shallower density profile and a more spherical halo shape. Simulation data from Ref. [94, 95].*

PRL 116, 041302 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Dark Matter Halos as Particle Colliders: Unified Solution to Small-Scale Structure Puzzles from Dwarfs to Clusters

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(Received 25 August 2015; published 28 January 2016)

Astrophysical observations spanning dwarf galaxies to galaxy clusters indicate that dark matter (DM) halos are less dense in their central regions compared to expectations from collisionless DM *N*-body simulations. Using detailed fits to DM halos of galaxies and clusters, we show that self-interacting DM (SIDM) may provide a consistent solution to the DM deficit problem across all scales, even though individual systems exhibit a wide diversity in halo properties. Since the characteristic velocity of DM particles varies across these systems, we are able to measure the self-interaction cross section as a function of kinetic energy and thereby deduce the SIDM particle physics model parameters. Our results prefer a mildly velocity-dependent cross section, from $\sigma/m \approx 2$ cm^2/g on galaxy scales to $\sigma/m \approx 0.1$ cm^2/g on cluster scales, consistent with the upper limits from merging clusters. Our results dramatically improve the constraints on SIDM models and may allow the masses of both DM and dark mediator particles to be measured even if the dark sector is completely hidden from the standard model, which we illustrate for the dark photon model.

DOI: 10.1103/PhysRevLett.116.041302

- We can also play around models of interactions
  - Hard sphere scattering
  - Long-range interactions (like EM)

- Could better fit data at different scales

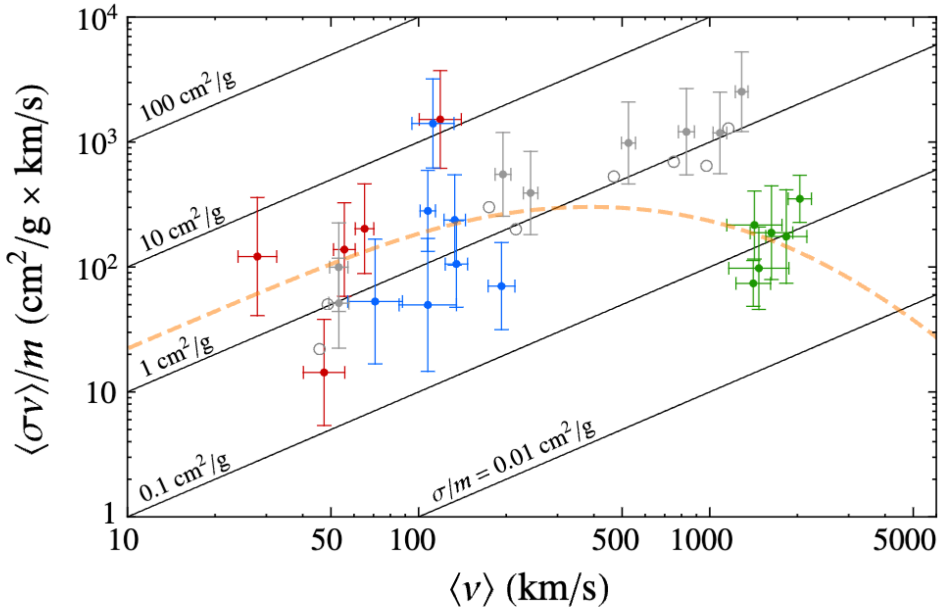

FIG. 1. Self-interaction cross section measured from astrophysical data, given as the velocity-weighted cross section per unit mass as a function of mean collision velocity. Data include dwarfs (red), LSB galaxies (blue), and clusters (green), as well as halos from SIDM *N*-body simulations with $\sigma/m = 1$ cm^2/g (gray). Diagonal lines are contours of constant σ/m and the dashed curve is the velocity-dependent cross section from our best-fit dark photon model (Sec. V).

Wave dark matter

- Or Fuzzy dark matter

- If dark matter is very light, their Compton wavelength becomes macroscopic.
  - Structure formation suppressed below the Compton scales
  - Interferences between waves

Cold and fuzzy dark matter

Wayne Hu (Princeton, Inst. Advanced Study), Rennan Barkana (Princeton, Inst. Advanced Study), Andrei Gruzinov (Princeton, Inst. Advanced Study)
Mar, 2000

4 pages
Published in: *Phys.Rev.Lett.* 85 (2000) 1158-1161
e-Print: astro-ph/0003365 [astro-ph]
DOI: 10.1103/PhysRevLett.85.1158
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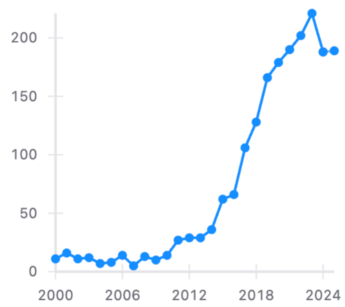

Abstract: (arXiv)
Cold dark matter (CDM) models predict small-scale structure in excess of observations of the cores and abundance of dwarf galaxies. These problems might be solved, and the virtues of CDM models retained, even without postulating {\it ad hoc} dark matter particle or field interactions, if the dark matter is composed of ultra-light scalar particles (m ~ 10^{-22}eV), initially in a (cold) Bose-Einstein condensate, similar to axion dark matter models. The wave properties of the dark matter stabilize gravitational collapse providing halo cores and sharply suppressing small-scale linear power.

- Interference patterns may show up in structures

PHYSICAL REVIEW LETTERS **123**, 141301 (2019)

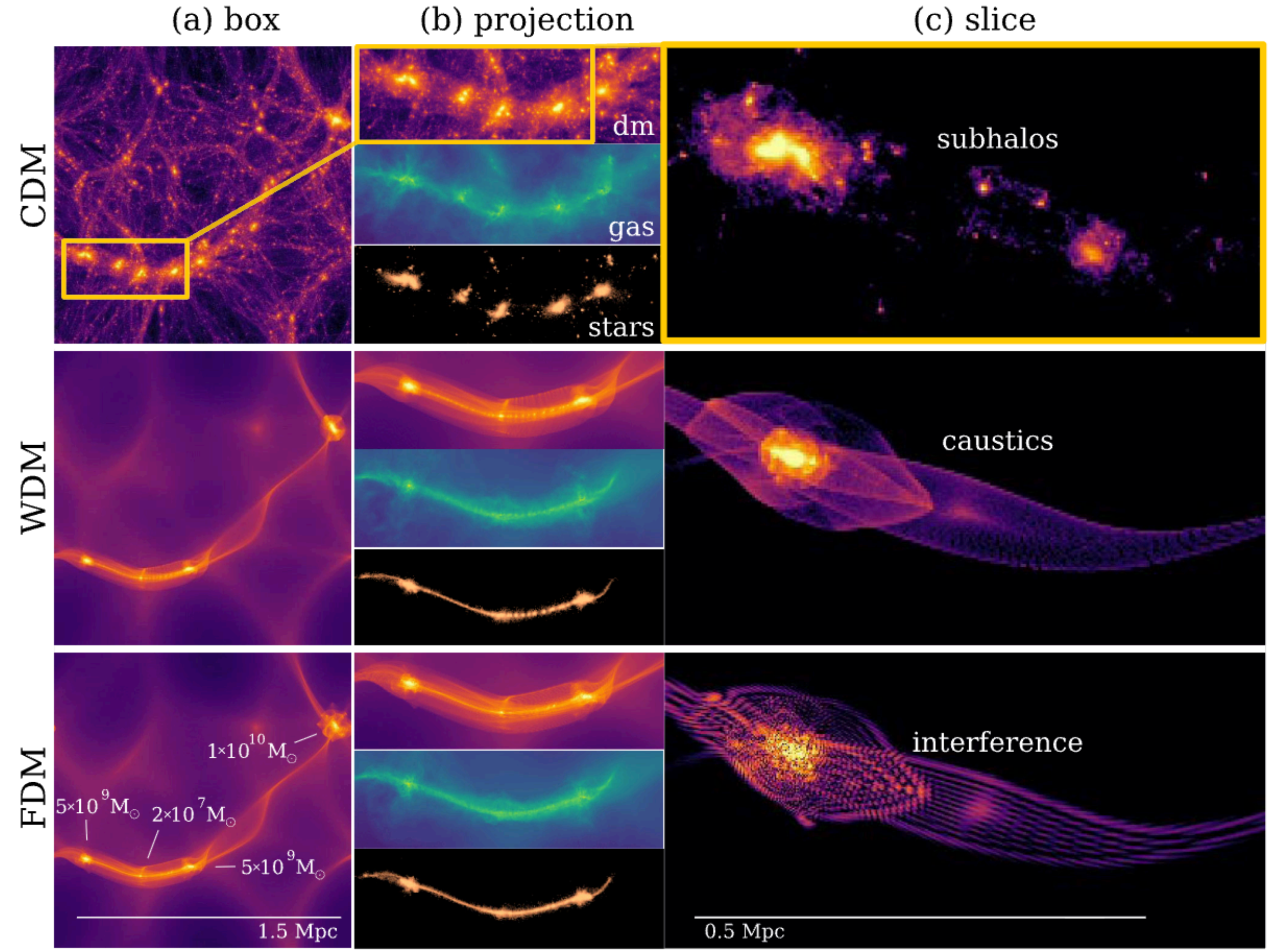

FIG. 1. Anatomy of a cosmic filament. We show, for CDM, WDM, and FDM cosmologies, (a) the projected dark matter distribution in the simulation domain at redshift $z = 5.5$, (b) projections of dark matter, gas, and stars in a filament, and (c) slices of the dark matter through a filament. In CDM the dark matter fragments into subhalos on all scales. WDM exhibits rich caustic structures. FDM has interference patterns at the scales of the de Broglie wavelength, which regularize caustic singularities. These differences in small-scale structure will help constrain the elusive nature of dark matter.

Tremaine

- If dark matter are fermions, they satisfy the Fermi-Dirac Statistics.

Dynamical Role of Light Neutral Leptons in Cosmology

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and

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(Received 31 May 1978)

Using the Vlasov equation, we show that massive galactic halos cannot be composed of stable neutral leptons of mass $\lesssim 1$ MeV. Since most of the mass in clusters of galaxies probably consists of stripped halos, we conclude that the "missing mass" in clusters does not consist of leptons of mass $\lesssim 1$ MeV (e.g., muon or electron neutrinos). Lee and Weinberg's hypothetical heavy leptons (mass ≈ 1 GeV) are not ruled out by this argument.

- Upper limits of amount of dark matter particles given a velocity distribution

- Observed low-mass halos can be used to set constraints on lower limits of Fermion dark matter
  - Modern limit is about 1keV

A lower bound on the mass of Dark Matter particles

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- Fuzzy dark matter must be Bosons
  - They could accumulate in the core of the galaxy and form a condensate
  - Soliton core
    - Some tried to invoke the soliton core to solve the core-cusp problem.

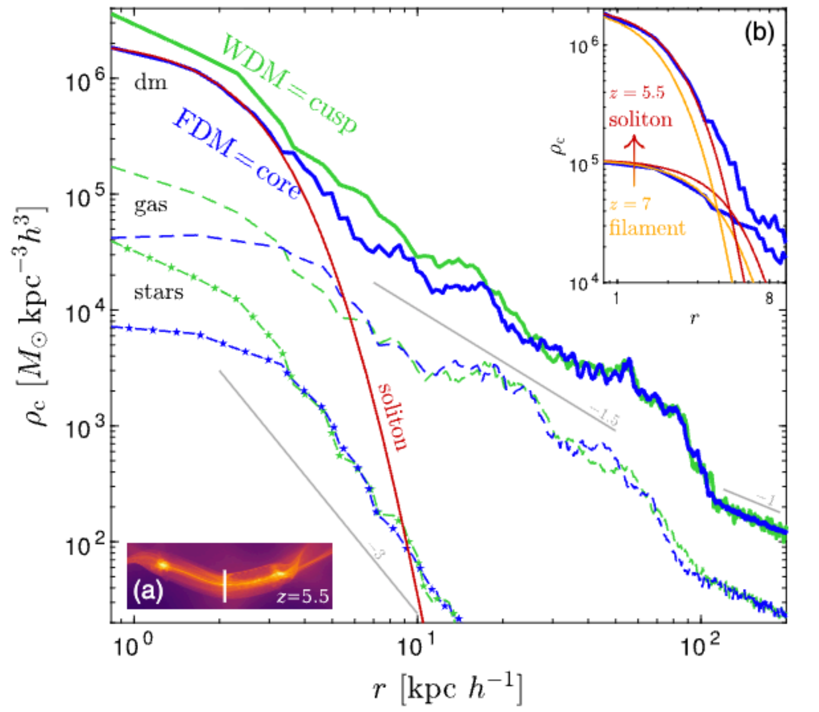

FIG. 2. The structure of FDM filaments: collapse of a cylindrical filament to a spherical soliton. FDM (blue) radial profiles [dark matter (dash); gas (double dash); stars (dash star)] are shown through a cross section of a filament at $z = 5.5$ [shown in inset (a)]. (b) The dark matter filament has previously ($z = 7$) gone unstable from a cylindrical solution and formed a soliton core [the yellow (red) lines are cylindrical (spherical) profiles of Eq. (3)]. Gas traces the dark matter on all scales, while stars form steeper profiles in the filament "spine," but are still cored in the center. In contrast, WDM (green) exhibits cuspy profiles. In CDM (not shown), the filament fragments into multiple subhalos, so the cross section profile is ill defined. Characteristic power law dependencies are shown with gray lines.

Double Disk Dark Matter

- Dark Matter could have several components.
- One of them could be dissipative
- (All of dark matter cannot not be dissipative as baryons)

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PDF

Dark-Disk Universe

JiJi Fan, Andrey Katz, Lisa Randall, and Matthew Reece

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Phys. Rev. Lett. **110**, 211302 – **Published 23 May, 2013**

DOI: https://doi.org/10.1103/PhysRevLett.110.211302

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Abstract

We point out that current constraints on dark matter imply only that the majority of dark matter is cold and collisionless. A subdominant fraction of dark matter could have much stronger interactions. In particular, it could interact in a manner that dissipates energy, thereby cooling into a rotationally supported disk, much as baryons do. We call this proposed new dark matter component double-disk dark matter (DDDM). We argue that DDDM could constitute a fraction of all matter roughly as large as the fraction in baryons, and that it could be detected through its gravitational effects on the motion of stars in galaxies, for example. Furthermore, if DDDM can annihilate to gamma rays, it would give rise to an indirect detection signal distributed across the sky that differs dramatically from that predicted for ordinary dark matter. DDDM and more general partially interacting dark matter scenarios provide a large unexplored space of testable new physics ideas.

Double Disk Dark Matter

- Dark Matter could have several components.
- One of them could be dissipative
- (All of dark matter cannot not be dissipative as baryons)

A Large mass hierarchy from a small extra dimension #1

Lisa Randall (Princeton U. and MIT), Raman Sundrum (Boston U.) (May 4, 1999)

Published in: *Phys.Rev.Lett.* 83 (1999) 3370-3373 • e-Print: hep-ph/9905221 [hep-ph]

pdf DOI cite claim reference search 10,493 citations

An Alternative to compactification #2

Lisa Randall (Princeton U. and MIT, LNS), Raman Sundrum (Boston U.) (Jun, 1999)

Published in: *Phys.Rev.Lett.* 83 (1999) 4690-4693 • e-Print: hep-th/9906064 [hep-th]

pdf DOI cite claim reference search 7,922 citations

News | Published: 07 March 2014

Did dark matter kill the dinosaurs?

Elizabeth Gibney

Nature (2014) | Cite this article

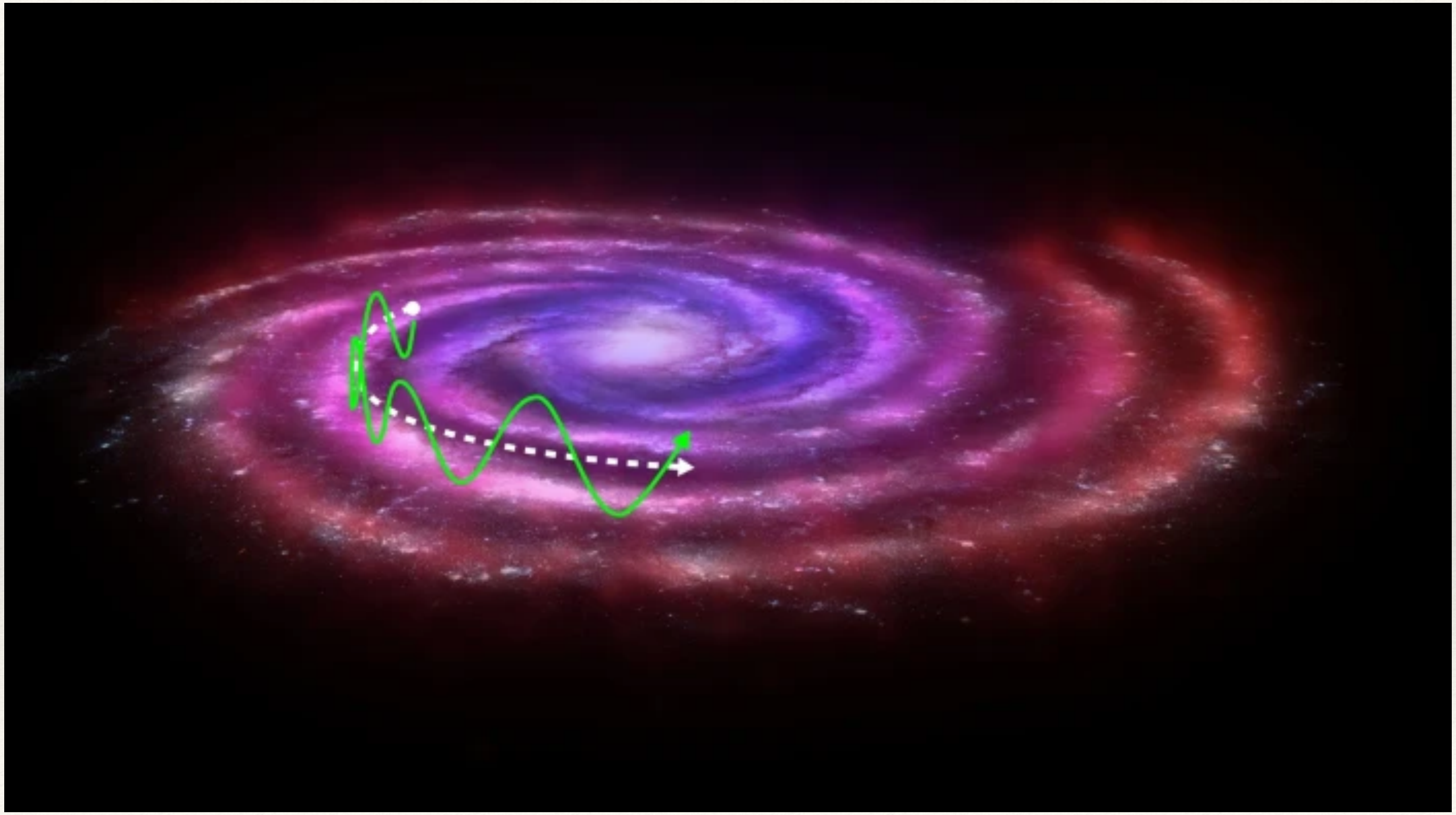
1489 Accesses | **1** Citations | **339** Altmetric | Metrics

The Solar System's periodic passage through a 'dark disk' on the galactic plane could trigger comet bombardments that would cause mass extinctions.

Mass extinctions such as the one that wiped out the dinosaurs seem to happen with regularity, pointing to possible cosmic causes. Credit: Mark Stevenson/Stocktrek Images/Corbis

A thin disk of dark matter running through the Galaxy might be behind the large meteorite strikes that are thought to be responsible for some of Earth's mass extinctions, including that of the dinosaurs, two theoretical physicists have proposed.

- The thin disk could give the additional gravitational pull that perturbs the astroids/comets, and enhances the chance of extinction events (like dinosaurs)



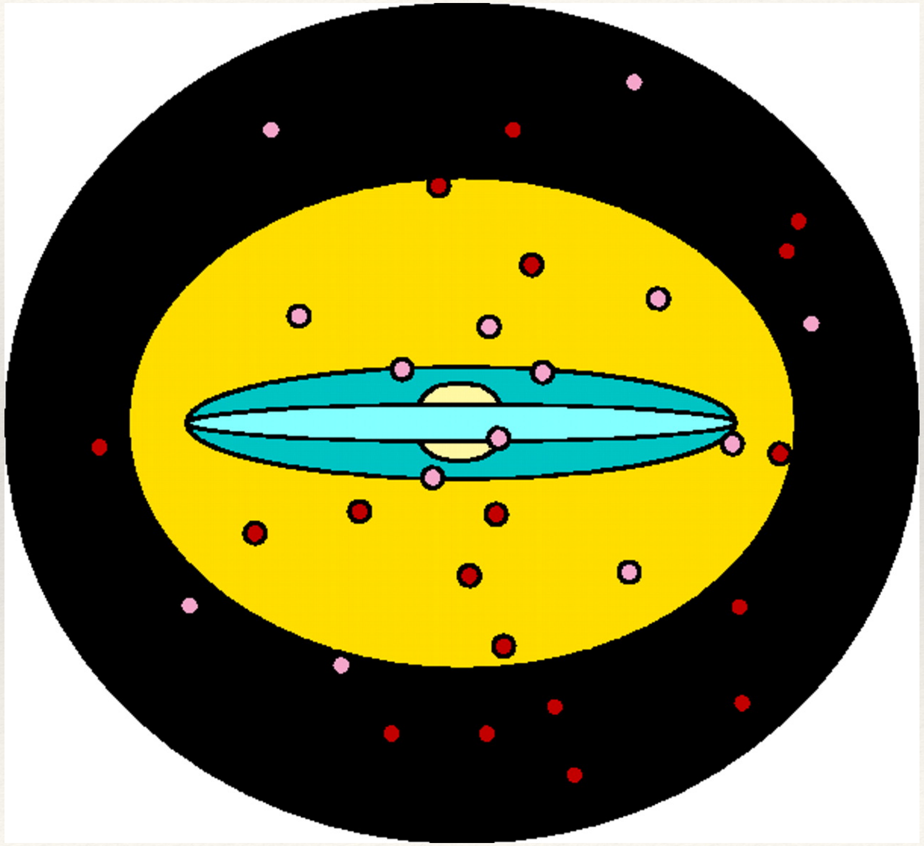
Dark matter is usually thought to be very weakly interacting and thus unable to settle into such a disk. But the authors suggest that a small fraction of dark matter could behave very differently. Last year, they developed a theory of 'dissipative dark matter' in an attempt to explain dark-matter-like signals from the Galaxy's centre seen by the Fermi Gamma-ray Space Telescope[8]. Their model yields a dark disk about 35 light years (10 parsecs) thick, with a density of about 1 solar mass per square light year (10 solar masses per square parsec) — dense enough to trigger periodic comet showers.

Evidence for a 35-million-year cycle, based on the record of impact craters, is itself “sketchy”, says Randall. Fluctuations in the crater record mean that searches for periodicity are always likely to throw up some correlations, she says. So she and Reece flipped the problem around and predicted what the period would be, on the basis of their model. “If you then find a match it has much more statistical significance than it would otherwise,” she says.

They compared their model, using a 35-million year cycle, with the record of craters more than 20 kilometres wide and created in the past 250 million years. Compared to random comet bombardments, their model had a likelihood ratio of 3, meaning it agreed with the observed crater dates three times better than a random rate.

Dark Matter cannot be too dissipative

- All of dark matter cannot not be dissipative
- dissipative = loss energy in the system after interactions
- Example of dissipation:
  - Baryons lose energy through radiation after self interactions
  - That is why we have baryons more concentrated in galaxies
  - Baryons also need to further collapse to form stars
  - Baryons also rotate faster, following the initial angular momentum
- From rotation curve, we know that dark matter is extended in the form of a halo
- So, they cannot be as dissipative as baryons



Summary of dark matter on structures

- ΛCDM is very successful in describing large scale structures. Potential problems are
  - Hubble tension
  - Nature of dark energy
  - Small scale structure anomalies
    - Anomalies if they cant be explained by Baryon physics
- Because dark matter plays an important role in structure formation, particle properties of dark matter could affect small scale structure formation
  - Warm dark matter (suppresses small halo formation below free streaming scale)
  - Decaying dark matter (dark matter gain velocity through a heavier DM decaying into a lighter DM)
  - Self interacting dark matter (large dark matter self interactions could flatten the density cores)
  - Wave dark matter (ultra-light dark matter erase structures small than the Compton scale)
  - Double disk dark matter (A small part of dark matter could collapse like baryons and have observable effects)