Introduction to dark matter

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

- 4.0
    - Early evidence of dark matter
    - Modern “evidence”
- 4.1
    - Impact of dark matter on cosmology
    - ΛCDM model
- 4.2, 4.3
- Dark Matter detection status

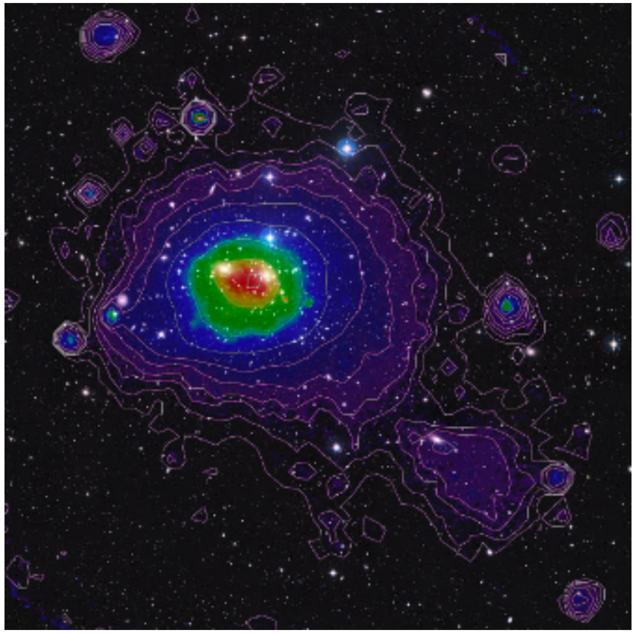
Some early evidence of dark matter

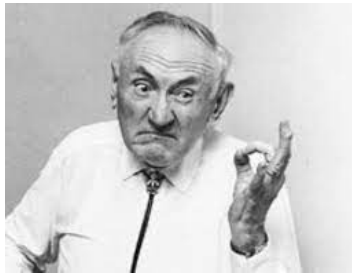
Galaxy Clusters

- Coma Cluster

- Visible Mass
  - Galaxies ~$10^{13} M_\odot$
  - X-ray ~ $10^{14} M_\odot$

- •ΔV ~ 1000 km/s
- •R ~ 9 light years
- •$\langle v^2 \rangle \sim \dfrac{GM}{R}$
- Total gravitational mass $M \sim 10^{15} M_\odot$





~1930 Zwicky
Coma Cluster

Velocity ~ Gravitational mass >> Observable mass

Die Rotverschiebung von extragalaktischen Nebeln

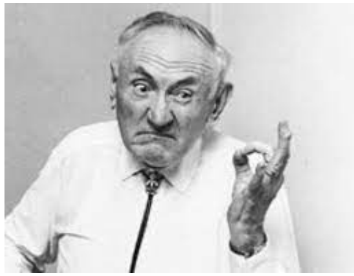
von **F. Zwicky.**

(16. II. 33.)

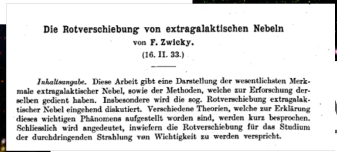
Inhaltsangabe. Diese Arbeit gibt eine Darstellung der wesentlichsten Merkmale extragalaktischer Nebel, sowie der Methoden, welche zur Erforschung derselben gedient haben. Insbesondere wird die sog. Rotverschiebung extragalaktischer Nebel eingehend diskutiert. Verschiedene Theorien, welche zur Erklärung dieses wichtigen Phänomens aufgestellt worden sind, werden kurz besprochen. Schliesslich wird angedeutet, inwiefern die Rotverschiebung für das Studium der durchdringenden Strahlung von Wichtigkeit zu werden verspricht.

Galaxy Clusters

- Cluster Scales
  - Cluster velocity disperson
  - Bullet Cluster



~1930 Zwicky
Coma Cluster



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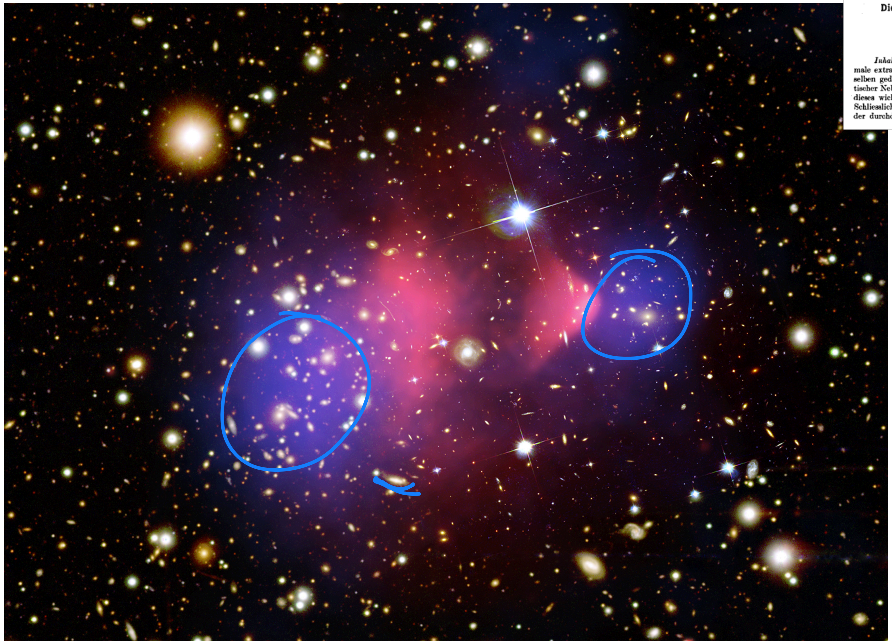
y ~ Gravitational mass >> Observable mass

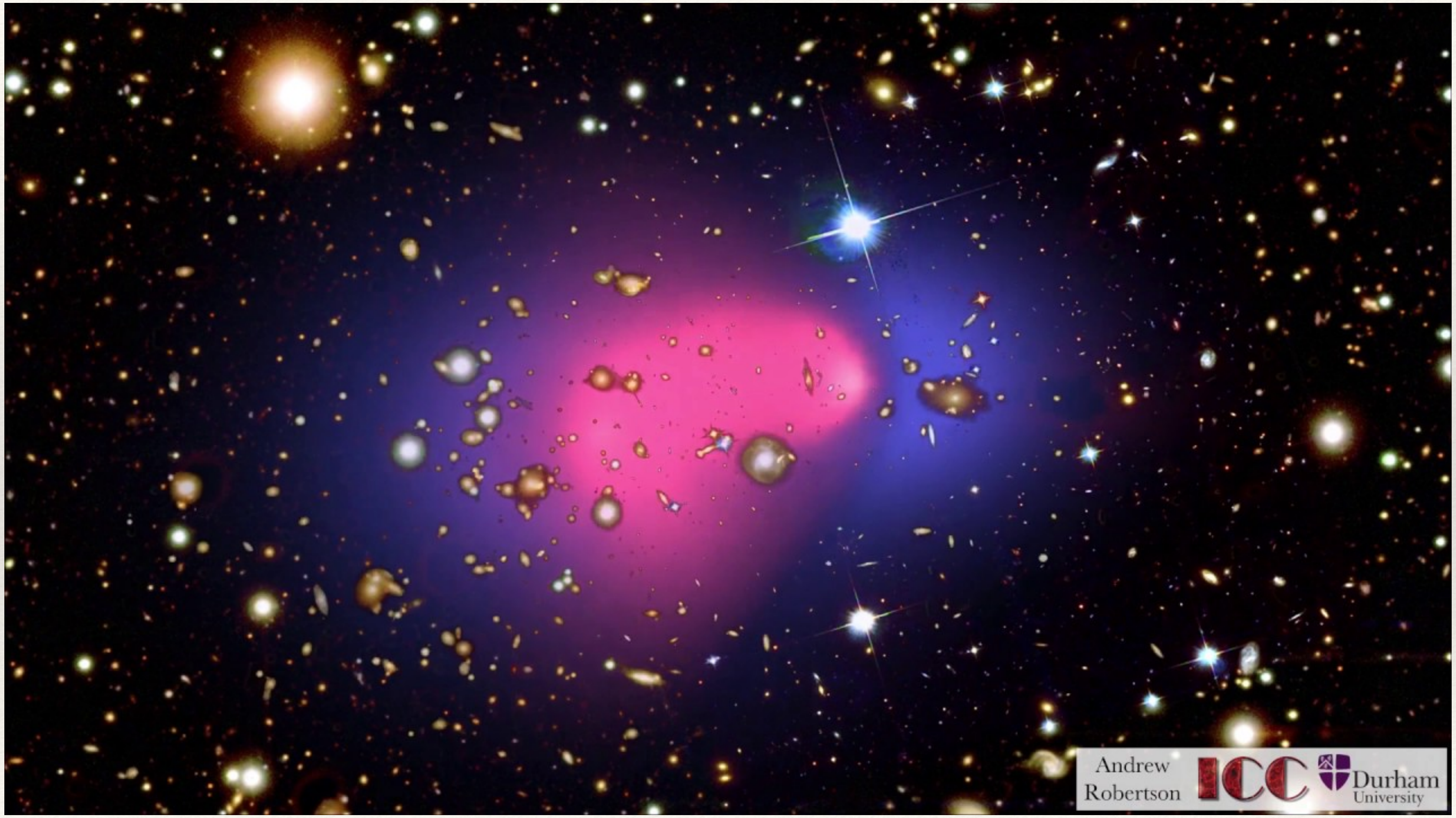


Gravitational mass from gravitational lensing(blue)
Baryonic mass form X-ray (red)

==> Missing mass -> “collisionless Dark Matter”

Bullet Cluster

- Hot gas
  - Dominant baryons
  - Traced by X-ray
- Total mass
  - Traced by gravitational lensing
- Clear separation
- If it is a gravity problem
  - Hard to explain the asymmetry



Rotation Curves

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

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Received 1969 July 7; revised 1969 August 21

ABSTRACT

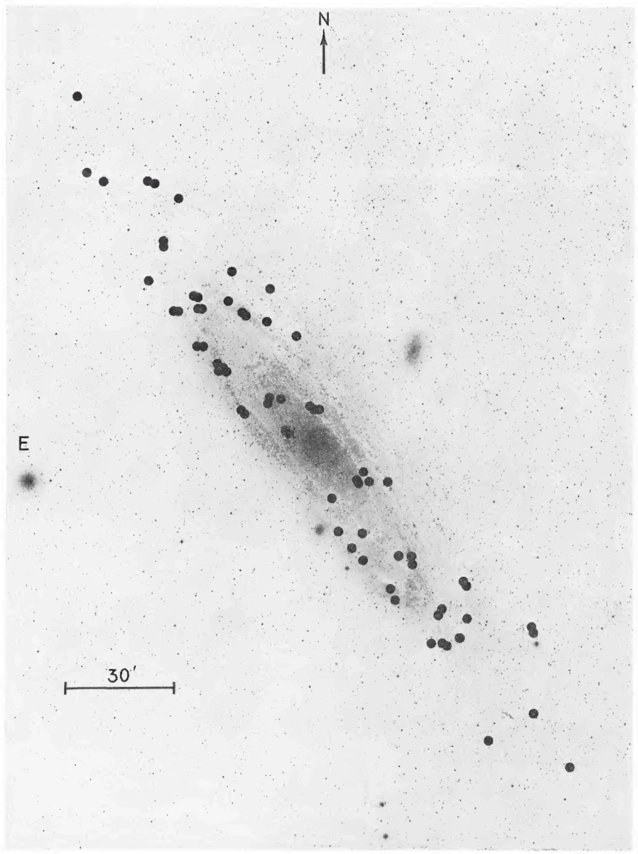

FIG. 1.—Identification chart for emission regions in M31 for which velocities have been obtained. Palomar 48-inch Schmidt ultraviolet photograph, 103aO plate + UG 1 filter, courtesy of Dr. S. van den Bergh.

RUBIN AND FORD (*see* page 380)

Rotation Curves

4852 *A. Afruni, G. Pezzulli and F. Fraternali*

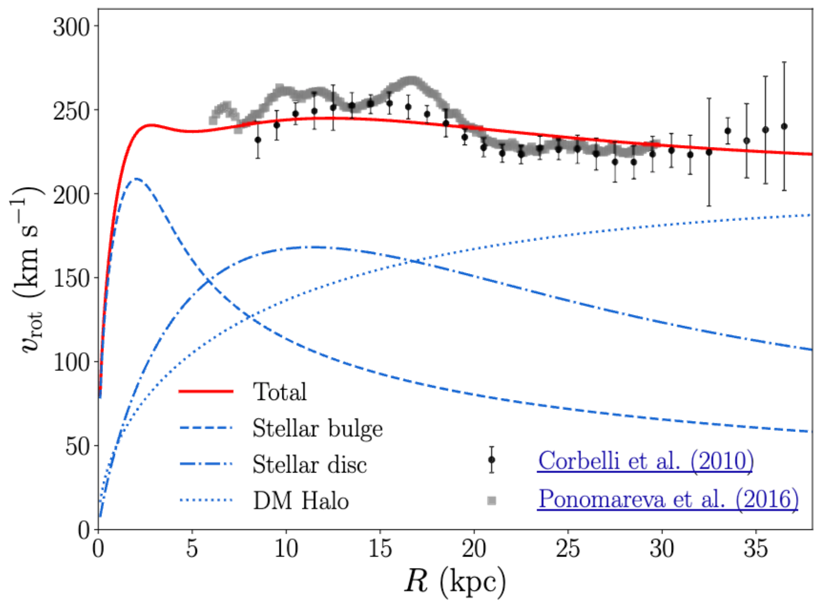

Figure 2. Rotation curve decomposition of M31 adopted in this work. The data points come from H I 21 cm emission and are taken from Corbelli et al. (2010) and Ponomareva et al. (2016). The red curve shows the total circular speed predicted by our model, fairly in agreement with the observations. The total circular speed is given by the sum of three different components: a stellar bulge (dashed curve), a stellar disc (dot–dashed curve), and an NFW DM halo (dotted curve) (see Section 3.1).

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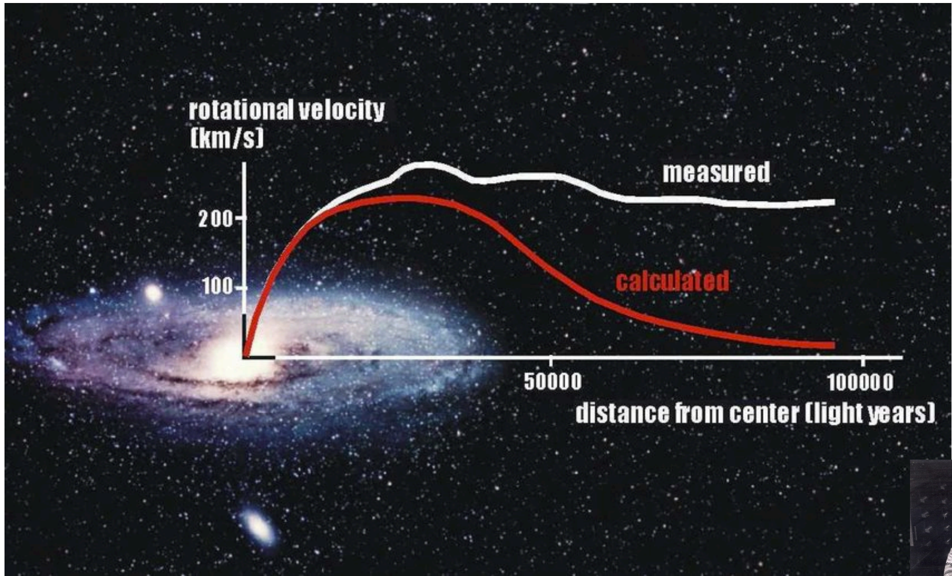

~1970 Rubin, Galaxy Rotation curves
Unobserved mass contributes to gravity

The Dark Matter problem

- There seems to be a mismatch between observations of matter, versus their expected gravitational effect.
- 1. There are more matter than we can see
  - Particle dark matter solution
    - We will focus on this
- 2. (Option 2) The theory of gravity is wrong
  - Modified gravity solution.

Modified Newtonian Dynamics (MOND):
Observational Phenomenology and Relativistic Extensions

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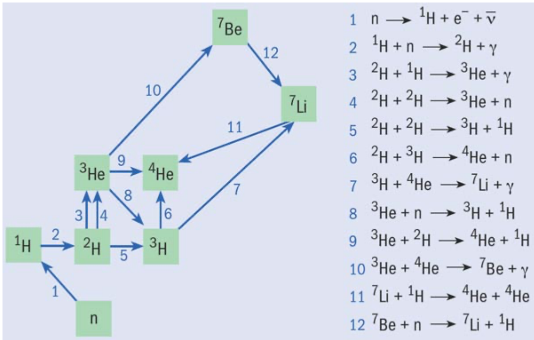
Abstract

A wealth of astronomical data indicate the presence of mass discrepancies in the Universe. The motions observed in a variety of classes of extragalactic systems exceed what can be explained by the mass visible in stars and gas. Either (i) there is a vast amount of unseen mass in some novel form – dark matter – or (ii) the data indicate a breakdown of our understanding of dynamics on the relevant scales, or (iii) both. Here, we first review a few outstanding challenges for the dark matter interpretation of mass discrepancies in galaxies, purely based on observations and independently of any alternative theoretical framework. We then show that many of these puzzling observations are predicted by one single relation – Milgrom's law – involving an acceleration constant a_0 (or a characteristic surface density $\Sigma_\dagger = a_0/G$) on the order of the square-root of the cosmological constant in natural units. This relation can at present most easily be interpreted as the effect of a single universal force law resulting from a modification of Newtonian dynamics (MOND) on galactic scales. We exhaustively review the current observational successes and problems of this alternative paradigm at all astrophysical scales, and summarize the various theoretical attempts (TeVeS, GEA, BIMOND, and others) made to effectively embed this modification of Newtonian dynamics within a relativistic theory of gravity.

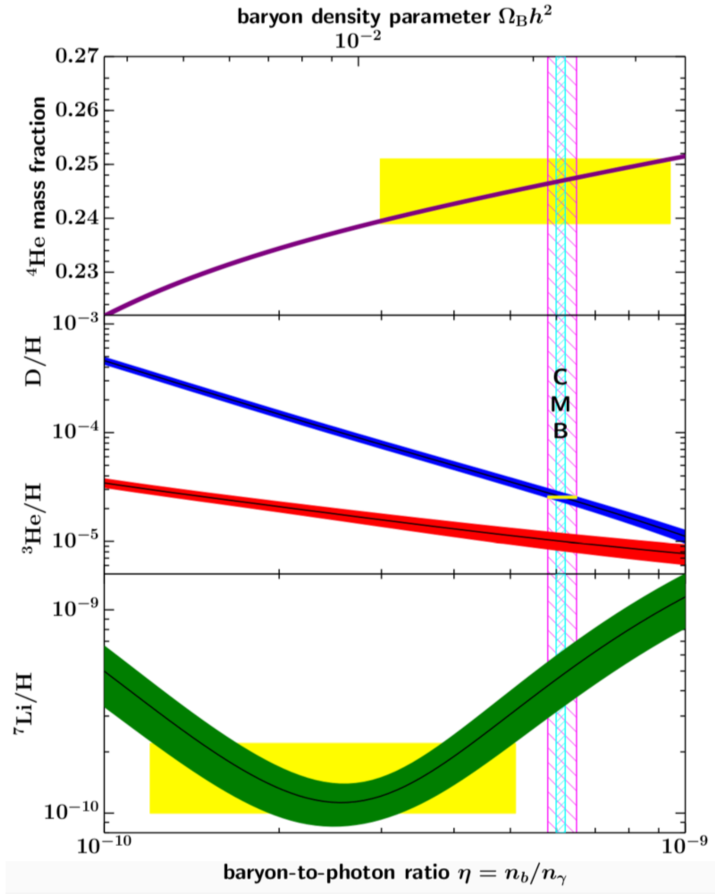
Precision data about dark matter

Big Bang Nucleosynthesis

- The prediction of BBN only depends on 1 parameter.



- The Baryon to Photon ratio.
- By measuring different elements.



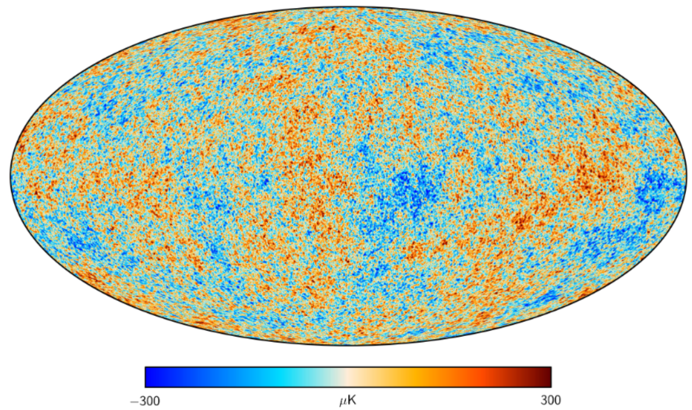
- $\eta \simeq 6 \times 10^{-10}$
- $n_\gamma \sim 400$ /cc
- $\rho_b \simeq m_p \times \eta \times n_\gamma = 2.4 \times 10^{-7}$ GeV/cc
- $\rho_{cr} \simeq 1.05h^2 \times 10^{-5}\,\mathrm{GeVcm}^{-3}$

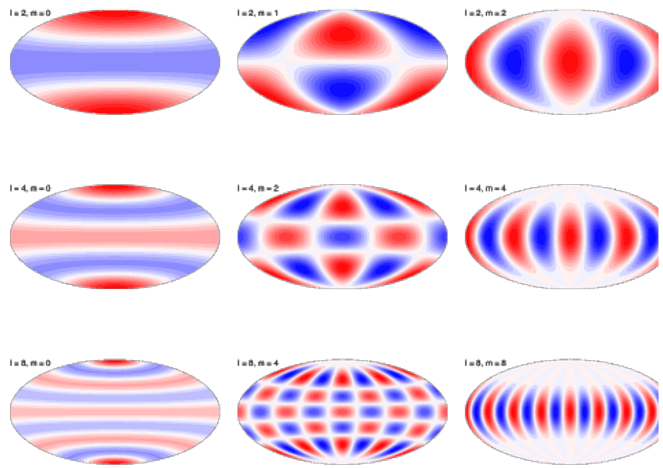
- $\Omega_b \sim 0.05$
- From Supernova cosmology, we already know that
- Ω_Λ~ 0.7, Ω_M~ 0.7
- Baryons are insufficient to explain

CMB Anisotropy

- The CMB is very smooth, but not exactly.
- There are 10^{-5} relative fluctuations
- Can do a spherical harmonic decomposition, which reveal the “power” at characteristic angular scales
  - Similar to 1-D Fourier transform

FLUCTUATIONS IN THE COSMIC MICROWAVE BACKGROUND

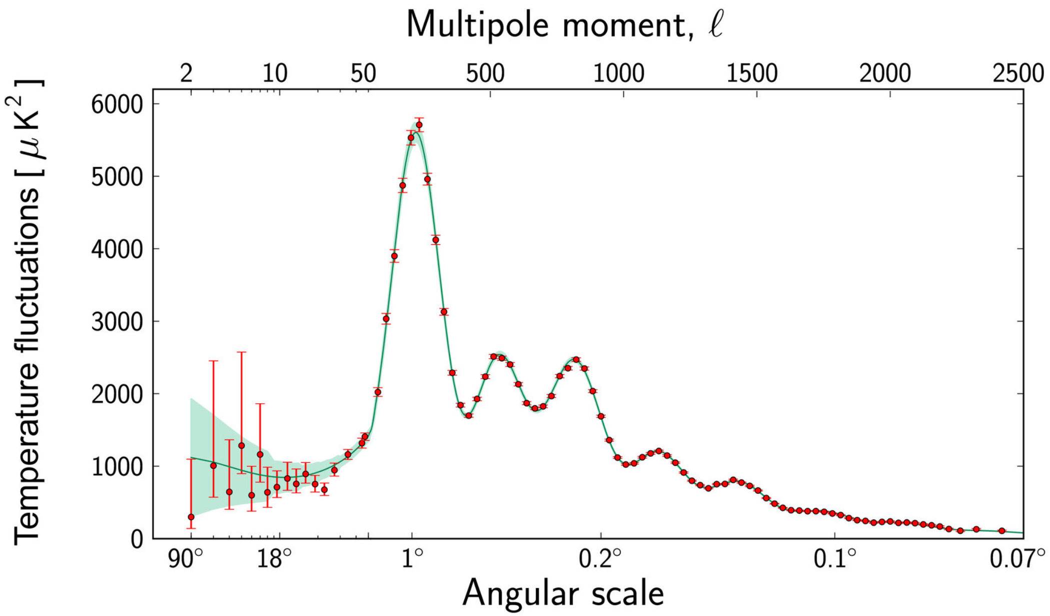




CMB Anisotropy

$$\theta \sim \frac{180°}{\ell}$$

- The CMB is very smooth, but not exactly.
- There are 10^{-5} relative fluctuations
- Can do a spherical harmonic decomposition, which reveal the “power” at characteristic angular scales
    - Similar to 1-D Fourier transform
- Extremely good fit to the data



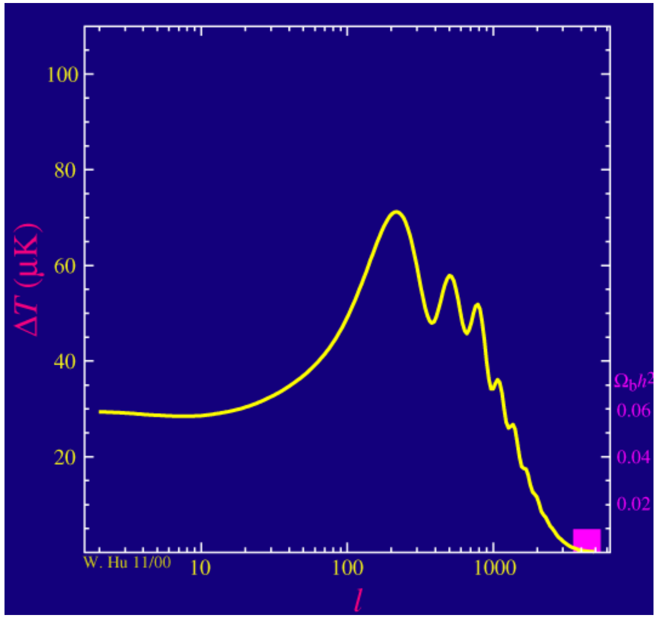
CMB Anisotropy

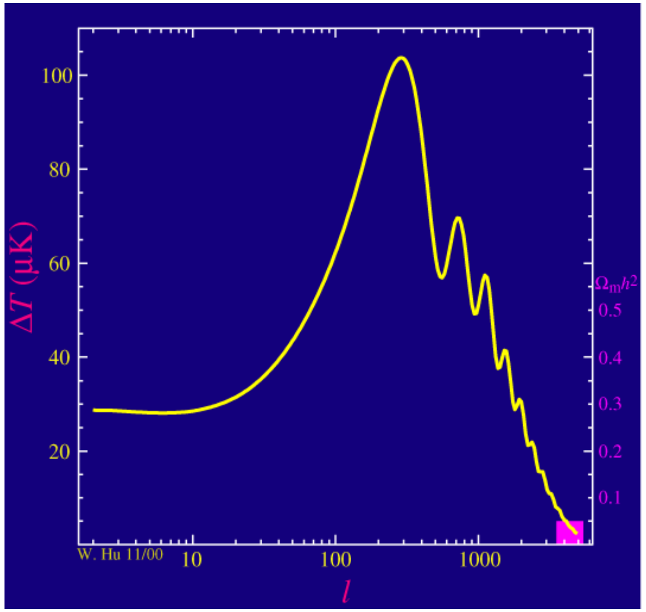
COSMIC BACKGROUND RADIATION ANISOTROPIES IN UNIVERSES DOMINATED BY NONBARYONIC DARK MATTER

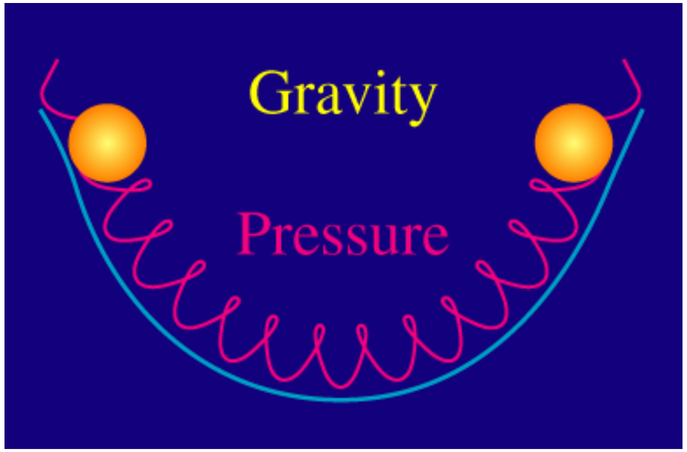
J. R. BOND[1,2] AND G. EFSTATHIOU[2,3]

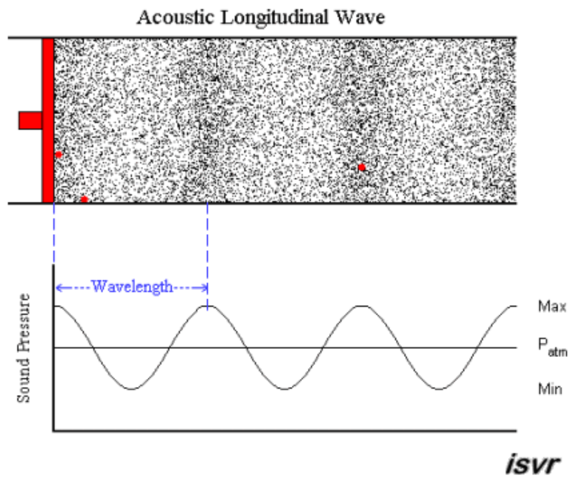
Received 1984 June 4; accepted 1984 July 17

- Dark Matter + Baryon contributes to gravity
- Baryon contributes to pressure of the gas



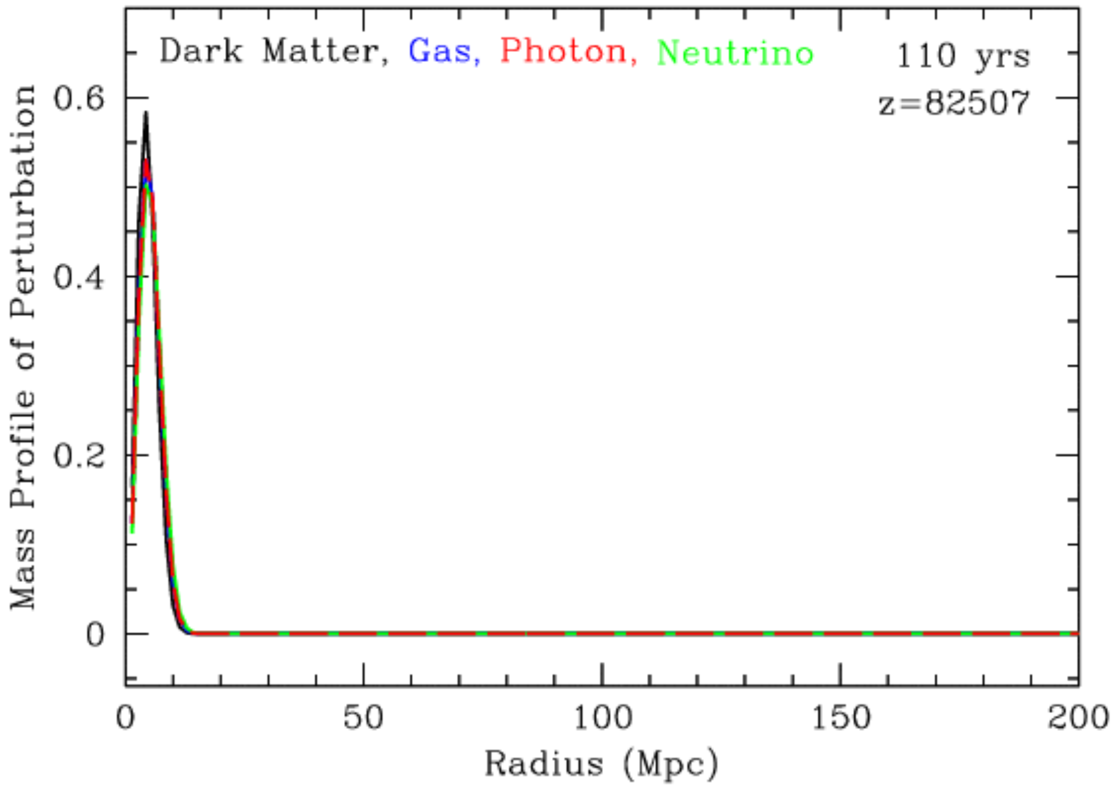






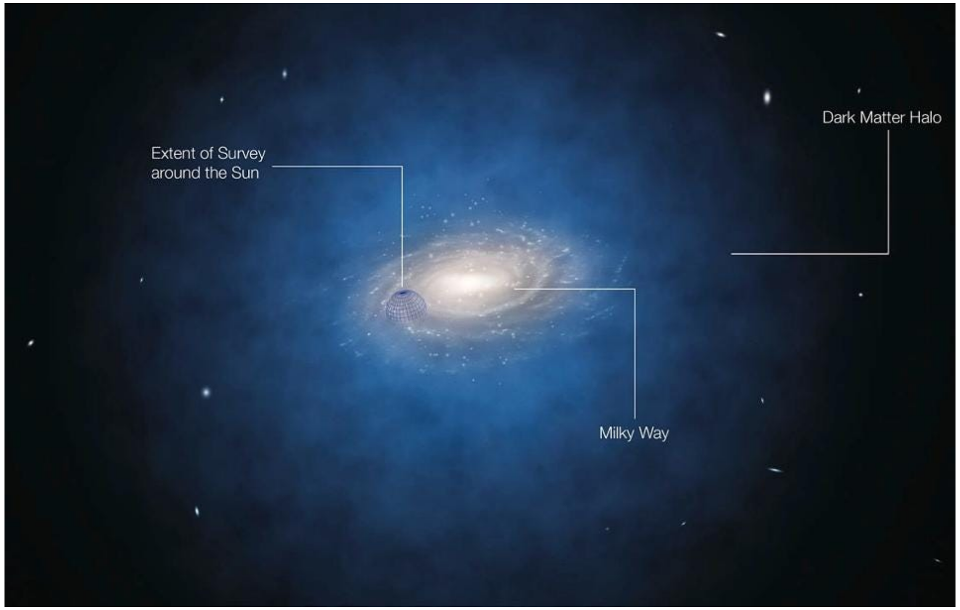
CMB Anisotropy

- The Origin of cosmological structures
  - Galaxies
  - Galaxy clusters
  - Cosmological bound structures

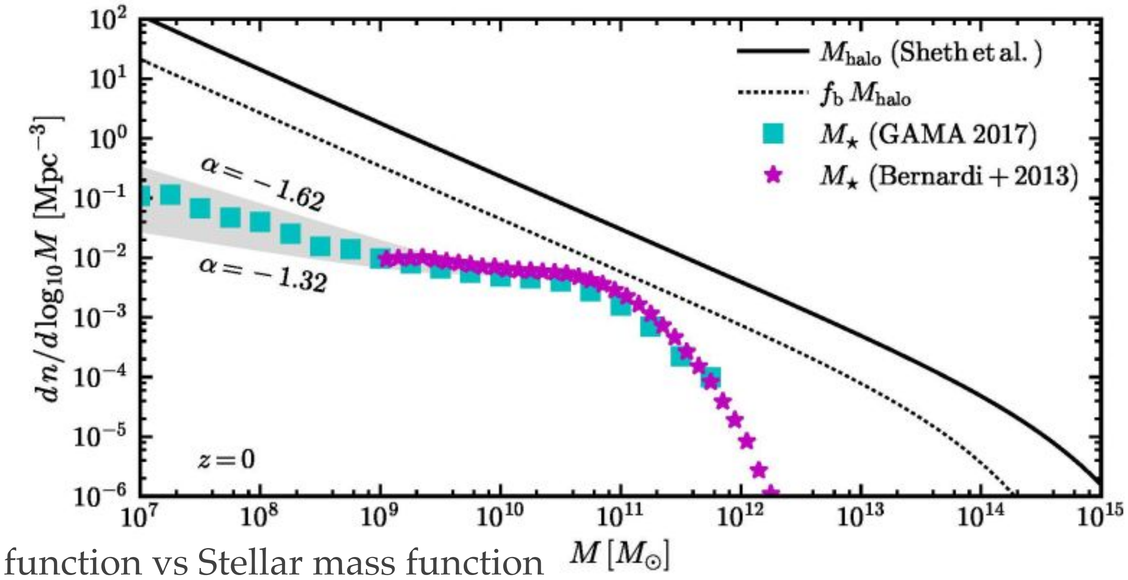


Dark Matter halo

- We expect all galaxies to sit inside a dark matter halo



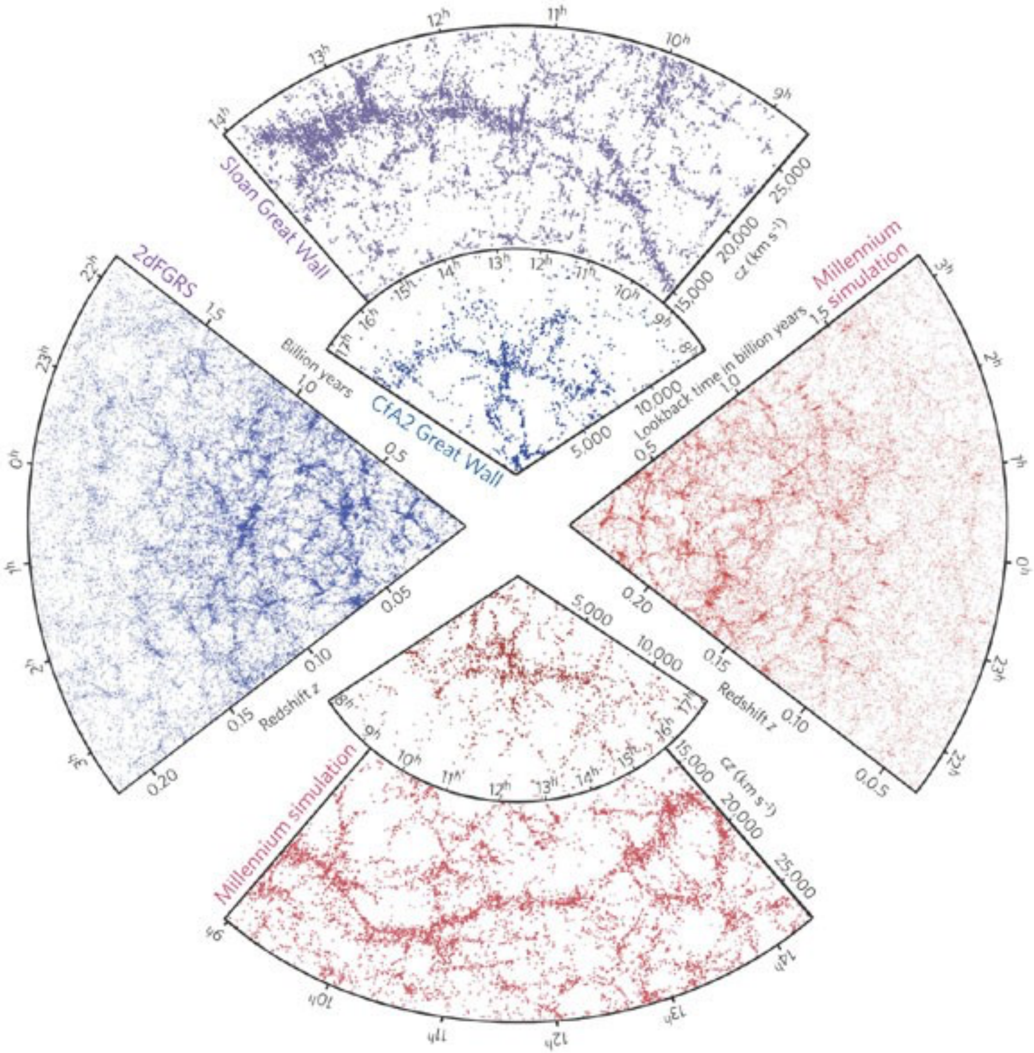
- In galaxies clusters
  - A big halo
- In satellites galaxies
  - A small halo (sub halo)



Halo mass function vs Stellar mass function

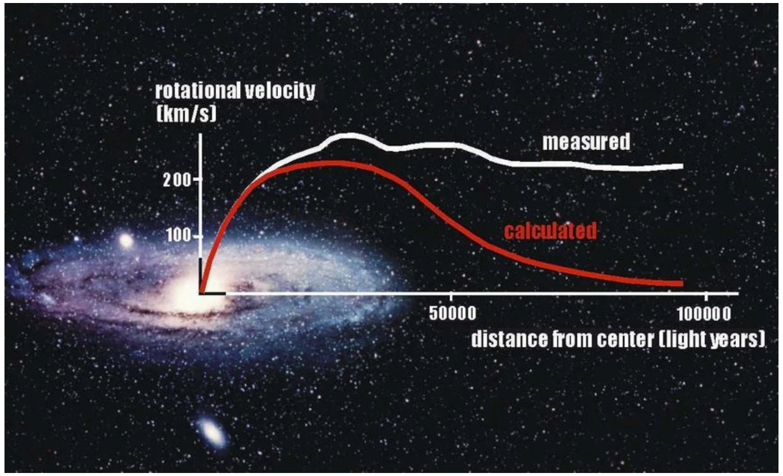
Large Scale Structures

- The distribution of galaxies
- Simulation vs observation.
- Dark Matter simulation seems works well!



Local scale

- Galaxy Scales
    - Galaxy Rotation Curve
    - Local stellar dynamics



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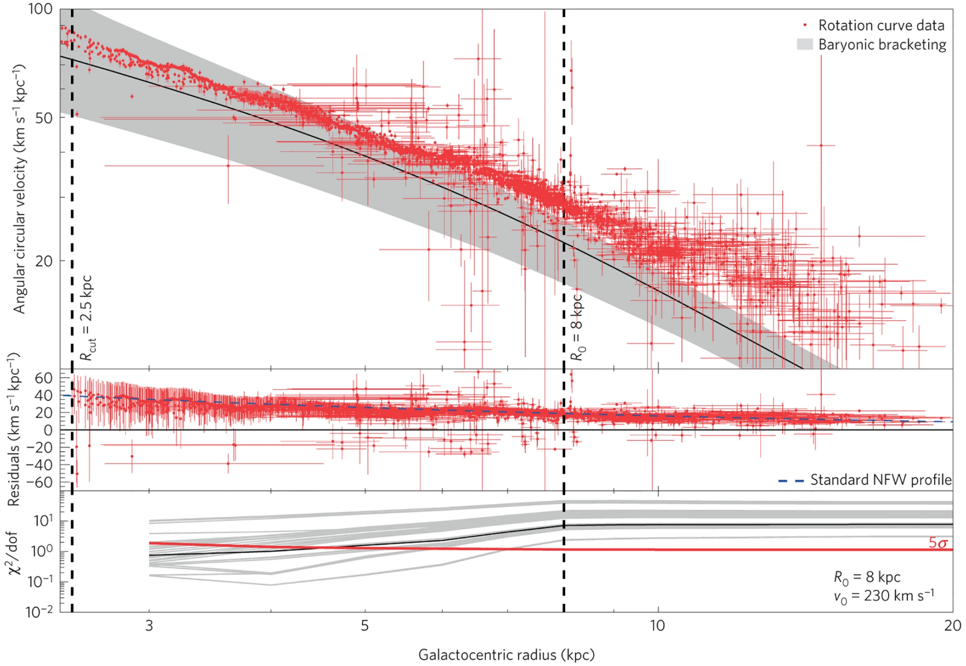


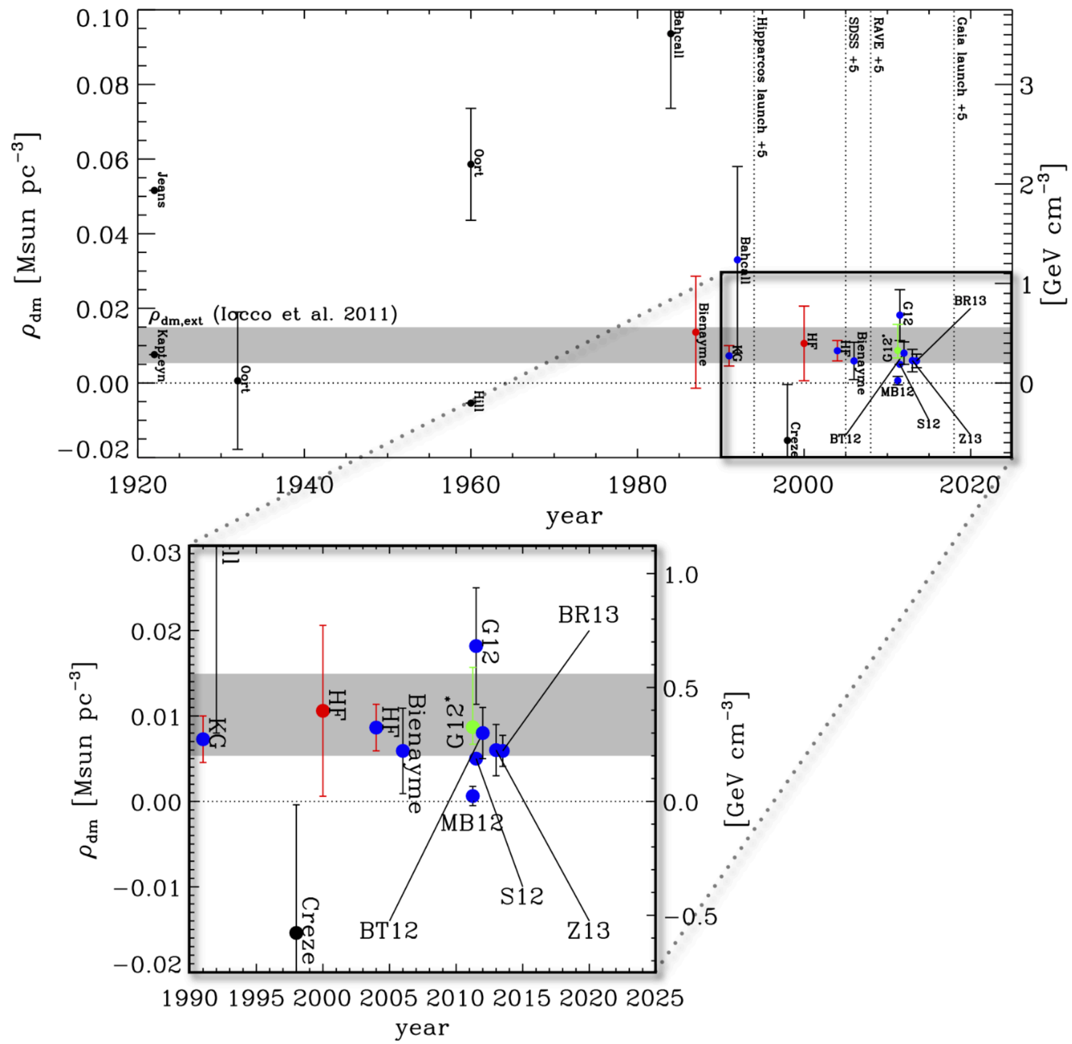
Local stellar dynamics required extra mass
=> $\rho_\chi \simeq 0.3\,\mathrm{GeV cm^{-3}}$
https://arxiv.org/abs/1502.03821

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

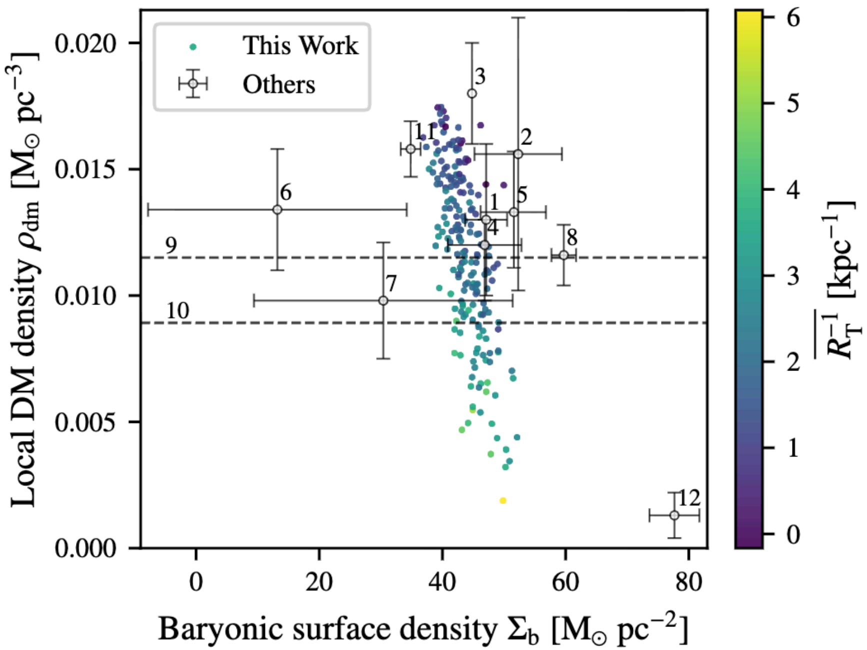
https://arxiv.org/pdf/1404.1938



Local Dark Matter density

https://arxiv.org/pdf/2506.02956

Local dark matter density from Gaia DR3 K-dwarfs using Gaussian processes

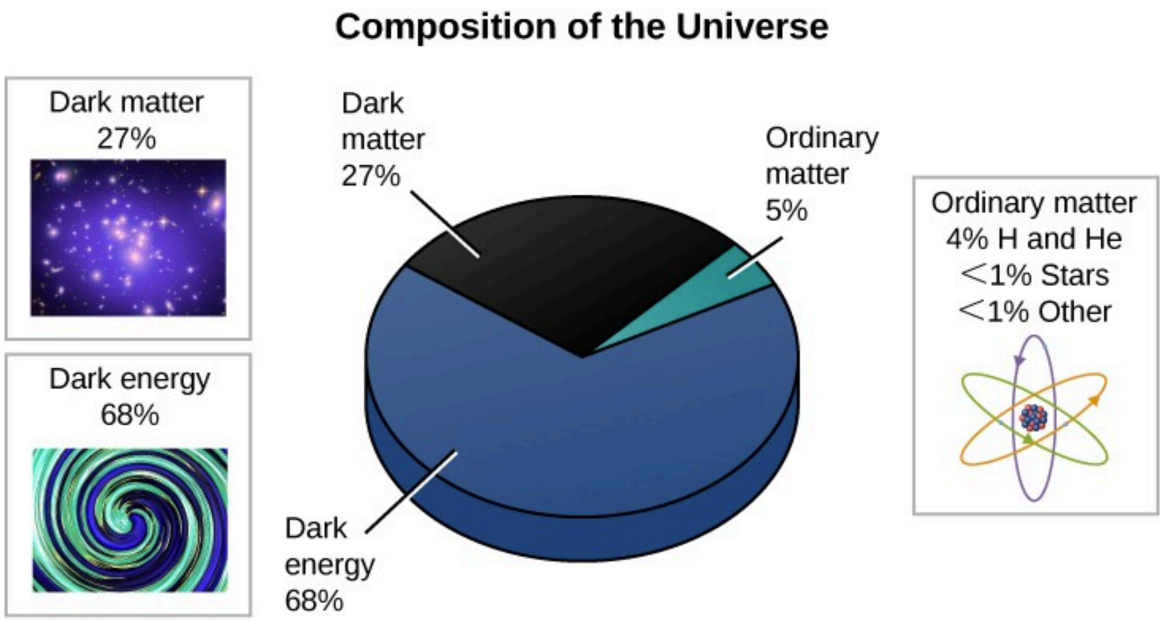


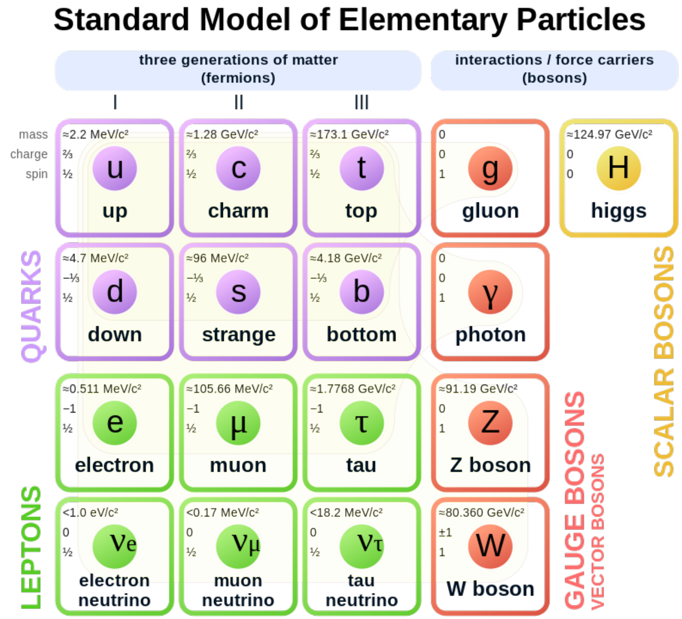
Label	Reference	Description	Sampling	$\rho_{\rm dm}$ [$M_\odot$ pc^{-3}]	$\rho_{\rm dm}$ [GeV cm^{-3}]
a) Local measures ($\rho_{\rm dm}$)					
Kapteyn	Kapteyn (1922)	–	–	0.0076	0.285
Jeans	Jeans (1922)	–	–	0.051	1.935
Oort	Oort (1932)	–	–	0.0006 ± 0.0184	0.0225 ± 0.69
Hill	Hill (1960)	–	–	-0.0054	-0.202
Oort	Oort (1960)	–	–	0.0586 ± 0.015	2.2 ± 0.56
Bahcall	Bahcall (1984a)	–	–	0.033 ± 0.025	1.24 ± 0.94
Bienayme†	Bienayme et al. (1987)	–	–	0.006 ± 0.005	0.22 ± 0.187
KG†	Kuijken & Gilmore (1991)	–	–	0.0072 ± 0.0027	0.27 ± 0.102
Bahcall	Bahcall et al. (1992)	–	–	0.033 ± 0.025	1.24 ± 0.94
Creze	Creze et al. (1998)	–	–	-0.015 ± 0.015	-0.58 ± 0.56
HF†	Holmberg & Flynn (2000b)	–	–	0.011 ± 0.01	0.4 ± 0.375
HF†	Holmberg & Flynn (2004)	–	–	0.0086 ± 0.0027	0.324 ± 0.1
Bienayme	Bienaymé et al. (2006)	–	–	0.0059 ± 0.005	0.51 ± 0.56
Latest measurements					
MB12	Moni Bidin et al. (2012)	CSF	412	0.00062 ± 0.001 [0 ± 0.001]	0.023 ± 0.042 [0 ± 0.042]
BT12	Bovy & Tremaine (2012)	CSF	412	0.008 ± 0.003	0.3 ± 0.11
G12	Garbari et al. (2012)	VC	2×10^3	$0.022^{+0.015}_{-0.013}$	$0.85^{+0.57}_{-0.5}$
G12*	Garbari et al. (2012)	VC + Σ_b	2×10^3	$0.0087^{+0.007}_{-0.002}$	$0.33^{+0.26}_{-0.075}$
S12	Smith et al. (2012)	CSF	10^4	0.005 [no error] [0.015]	0.19 [0.57]
Z13	Zhang et al. (2013)	CSF	10^4	0.0065 ± 0.0023	0.25 ± 0.09
BR13	Bovy & Rix (2013)	CSF + MAP	10^4	0.006 ± 0.0018 [0.008 ± 0.0025]	0.22 ± 0.07 [0.3 ± 0.094]
b) Global measures assuming spherical symmetry ($\rho_{\rm dm,ext}$)					
S10	Salucci et al. (2010)	NP	–	0.011 ± 0.004	0.43 ± 0.15
CU10	Catena & Ullio (2010)	NFW; SP	–	0.0103 ± 0.00072	0.385 ± 0.027
WB10	Weber & de Boer (2010)	NFW/ISO; WP	–	0.005 - 0.01	0.2 - 0.4
I11	Iocco et al. (2011)	gNFW; WP; ML	–	0.005 - 0.015	0.2 - 0.56
M11	McMillan (2011)	NFW; SP	–	0.011 ± 0.0011	0.4 ± 0.04

https://arxiv.org/pdf/1404.1938

The ΛCDM model

- ~70% dark energy/cosmological constant
- ~30% Matter
    - ~25% Dark Matter
    - No particles in the Standard Model of particle physics can explain DM
    - New (Particle) Physics!
- Maybe gravity theory is wrong?
    - MOND, etc





Cosmic neutrino background

- $T_\nu = (\frac{4}{11})^{\frac{1}{3}} T_\gamma \simeq 1.9K$

- Current neutrino number density, per flavor

- $n_\nu = \frac{3}{4}\frac{4}{11} n_\gamma \simeq 112\,\mathrm{cm}^{-3}$

- Energy density

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

Status of Dark Matter Research

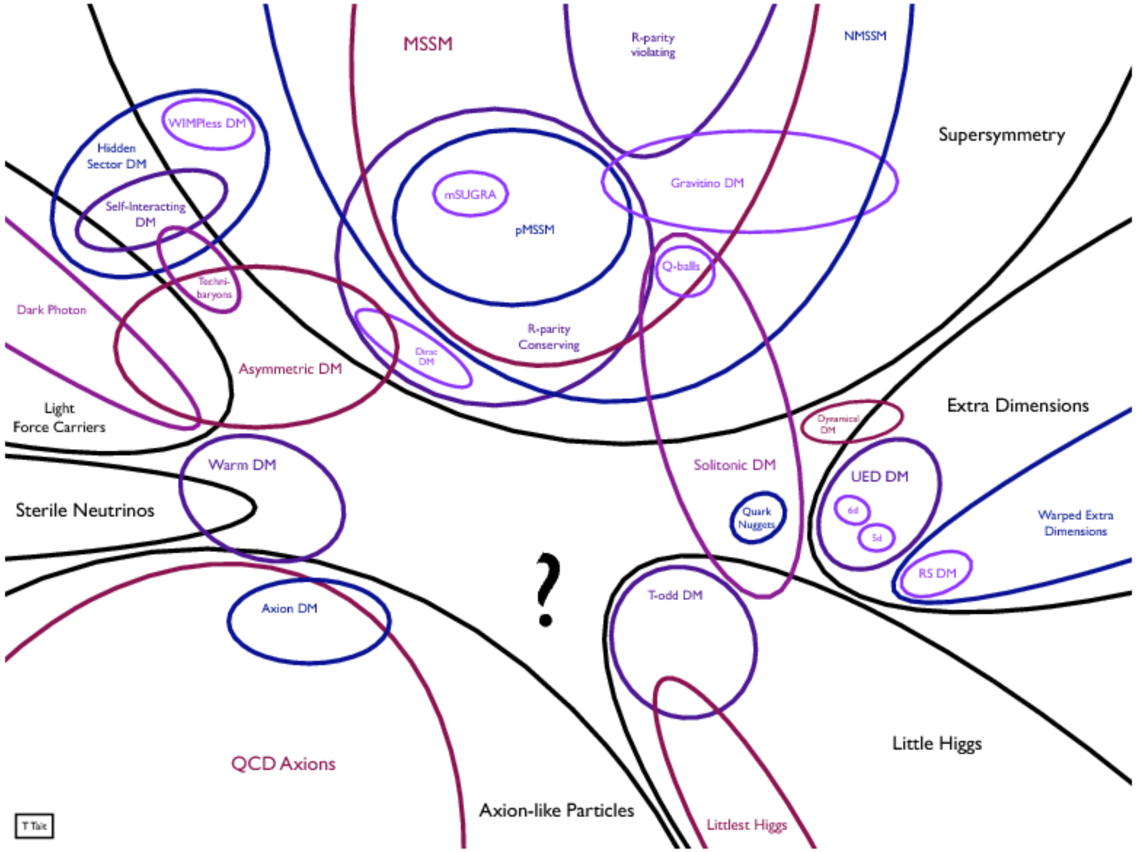
- We know surprisingly a lot about dark matter
  - All from gravity
- How much (mass density) DM are there
- Where are they
- They need to be "cold"*
- They cannot interact with themselves too strongly, or dissipate*

- Other than that, we dont know anything about the identity of dark matter!
  - No Mass, spin, interactions, etc
- What is a good dark matter candidate:
- How the DM is produced with the right abundance?
  - Where does it come from
- How to test the DM model
  - Falsifiability
- Must satisfy the observation constraints
- Connect to other problems?
  - Is it related to dark energy?
  - Can it help unify the forces?
  - Can it help explain neutrino mass?
  - ……

What is dark matter

- The biggest problem of dark matter "identification problem"

- Too many dark matter candidates.



Too many candidates for particle dark matter!