

# Dark Matter

## Evidence, Theory, Detection

Shrihari Gopalakrishna

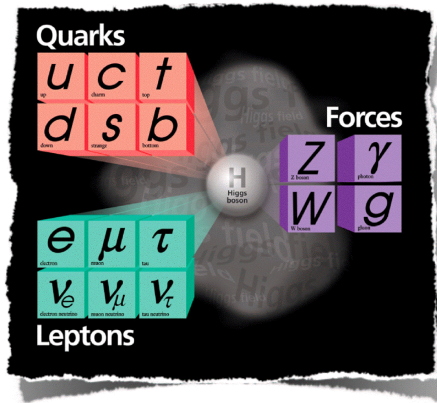
The Institute of Mathematical Sciences (IMSc), Chennai



IMSc Open Day  
Aug 2024

- 1 Dark Matter Evidence
  - Galaxy Rotation Curve
- 2 Particle Dark Matter
- 3 Dark Matter Detection
  - Direct detection
  - Indirect detection
  - Collider detection

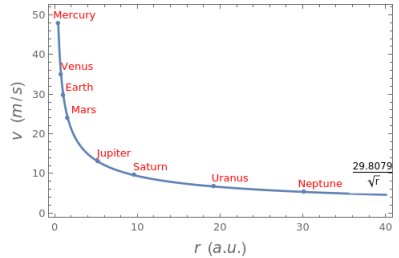
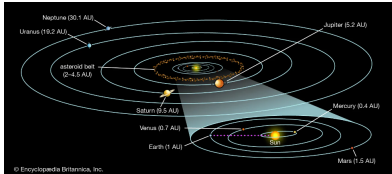
# The Standard Model of Particle Physics: Visible Matter



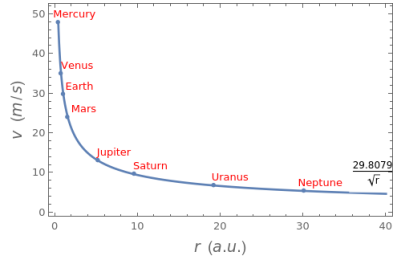
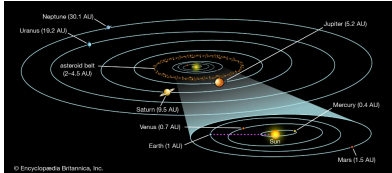
[Fermilab Visual Media]



# Evidence for sun: planets Rotation Curve



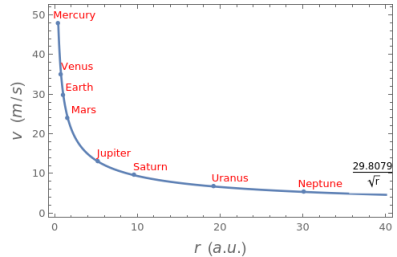
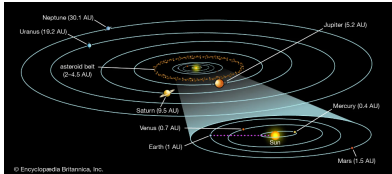
# Evidence for sun: planets Rotation Curve



$$F_{Centrifugal} = F_{Gravity} ; \quad \frac{mv^2}{r} = G \frac{mM}{r^2} \quad \Rightarrow \quad v = \sqrt{\frac{GM}{r}}$$



# Evidence for sun: planets Rotation Curve

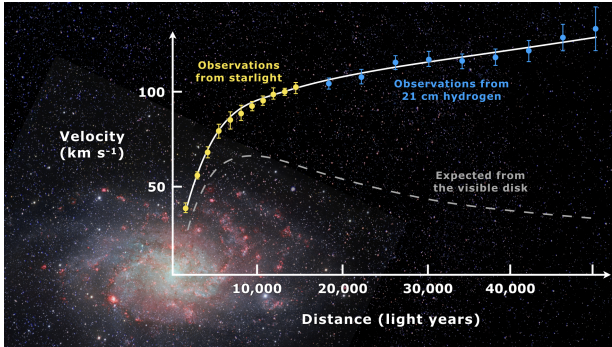


$$F_{\text{Centrifugal}} = F_{\text{Gravity}} ; \quad \frac{mv^2}{r} = G \frac{mM}{r^2} \quad \Rightarrow \quad v = \sqrt{\frac{GM}{r}}$$

$$\text{Sun @ center} \quad \Rightarrow \quad \frac{v_{\text{Earth}}}{v_{\text{Jupiter}}} = \sqrt{\frac{r_{\text{Jupiter}}}{r_{\text{Earth}}}} ; \quad \frac{29.8}{13.1} = \sqrt{\frac{5.2}{1}}$$



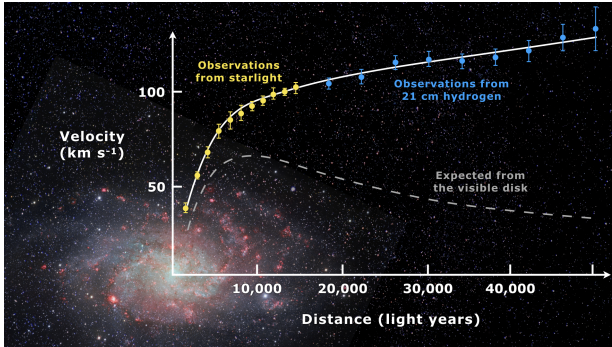
# M33 (Triangulum) Galaxy Rotation Curve



[Image: Mario De Leo, Wikipedia]



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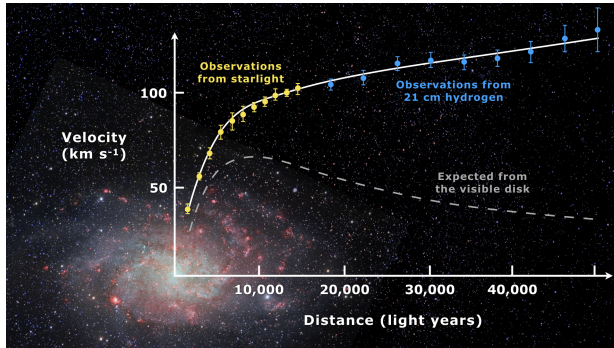


[Image: Mario De Leo, Wikipedia]

$$\frac{mv^2}{r} = G \frac{mM(r)}{r^2} ; M(r) = 4\pi \int_0^r dr' r'^2 \rho(r') \implies v = \sqrt{\frac{GM(r)}{r}}$$



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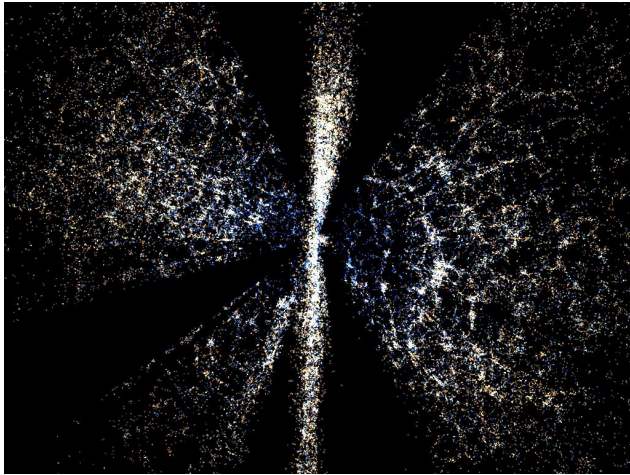
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Eg:  $v \rightarrow \text{constant}$  for  $\rho(r) \rightarrow 1/r^2$  (dark matter!)



# Structure formation

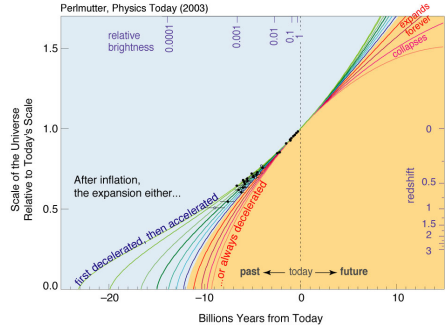
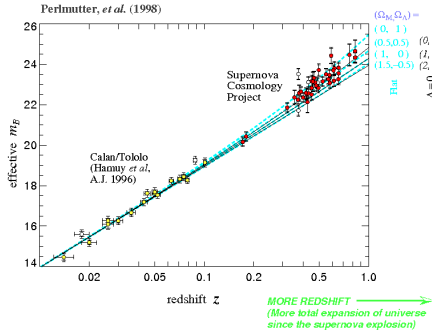
- 2dF, SDSS, BOSS, DES



[SDSS]



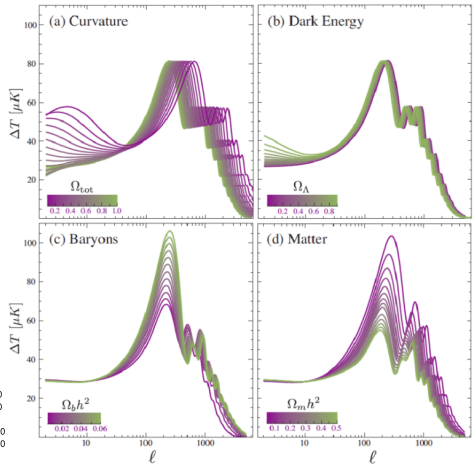
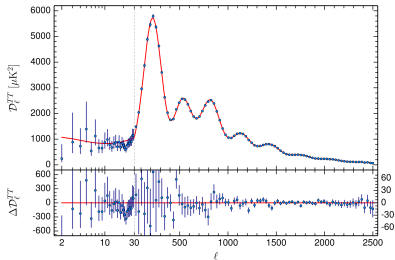
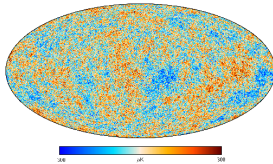
# Supernova Cosmology Project



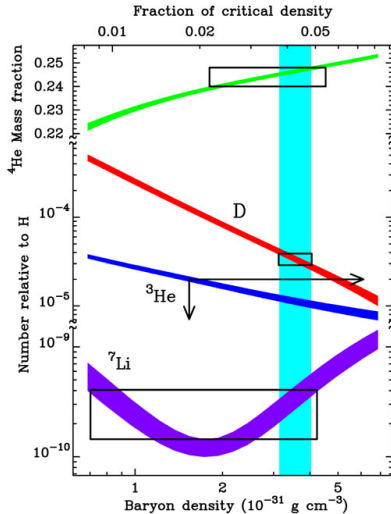


# Cosmic Microwave Background (CMB)

- COBE, WMAP, Planck



# Big-Bang Nucleosynthesis (BBN)

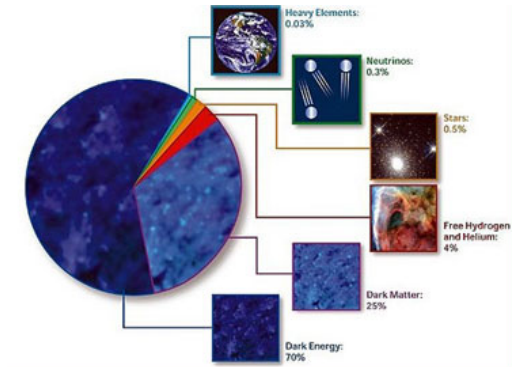
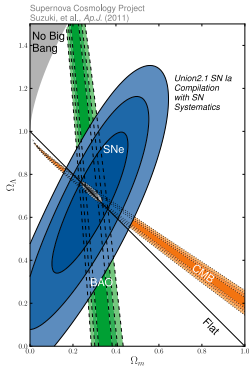


Note: Planck 2015  
 $\Omega_b h^2 = 0.02226 \pm 0.00023$

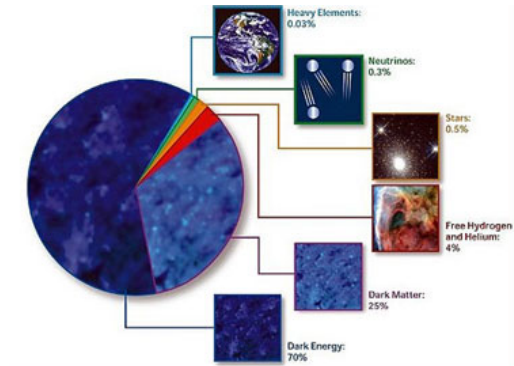
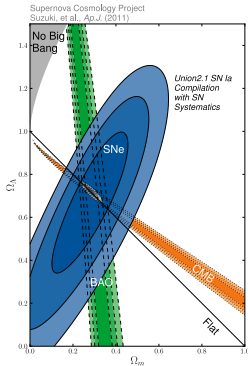
[Tytler et al., 2000]



# Inference



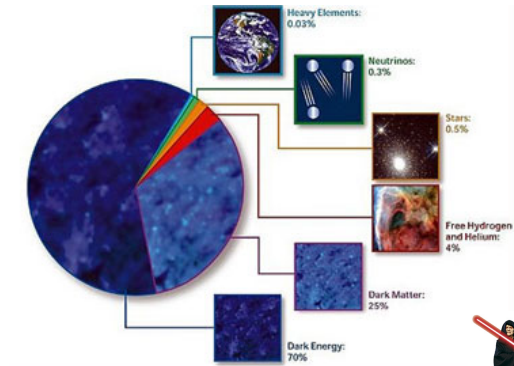
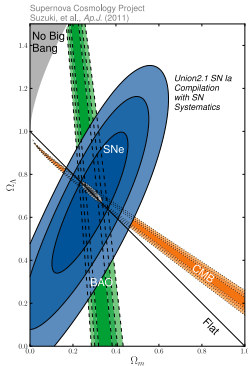
# Inference



- Flat on large scales
- Expansion is **Accelerating**
- **95%** is unknown **dark matter + dark energy**
  - What is it??



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The DARK SIDE rules!



# What is the dark matter?

- Dark Matter (DM)
  - Astrophysical objects? (Disfavoured)
    - MAssive Compact Halo Objects (MACHO) or Black Holes or . . .
  - Particle dark matter? (Favored)
    - Hot or Warm or **Cold Dark Matter (CDM)**
- Requirements for particle DM
  - Must be long lived (stable?)
  - Must be neutral charge
- Can we detect DM in some experiment?



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# Dark Matter Detection

- Direct Detection
  - DM directly interacts with a detector
- Indirect Detection
  - Look for indirect emissions from DM
- Collider Detection
  - DM escapes as missing momentum at colliders



# DAMA

- DAMA, Gran Sasso, Italy. Detection claimed!!



NaI scintillators



# CDMS

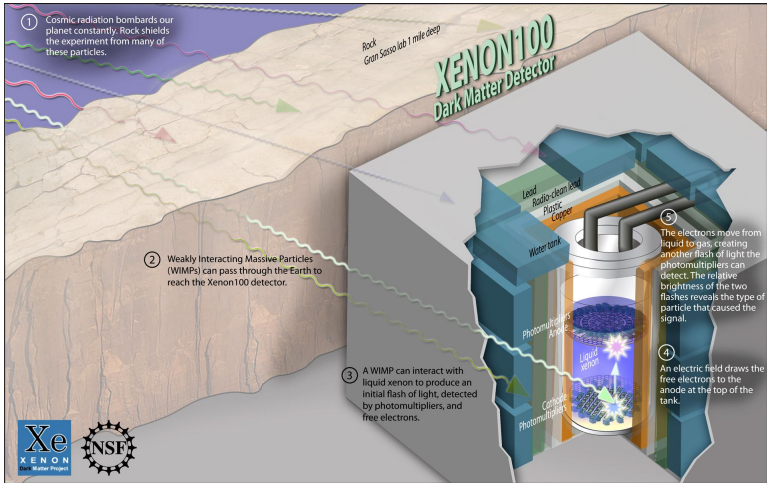
- Cryogenic Dark Matter Search (CDMS), Soudan Mine, USA



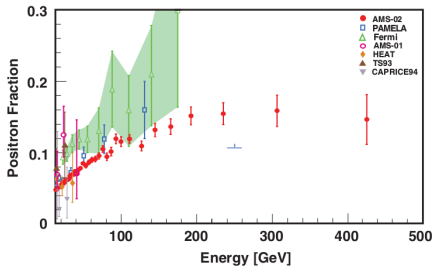
Ge detector



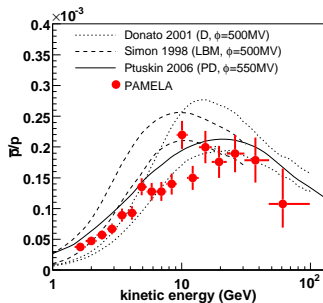
# XENON 100 Detector



# $e^+$ , $\bar{p}$ data



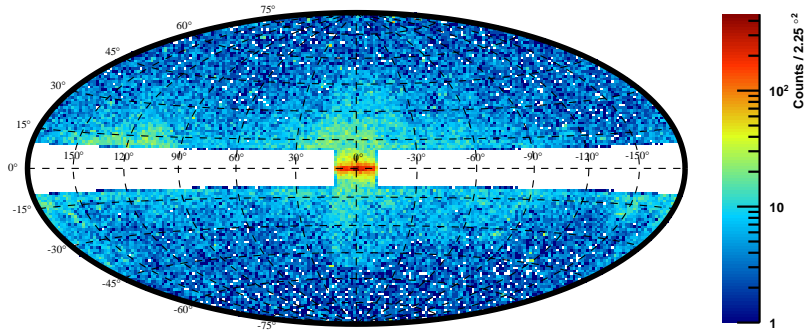
AMS02  $e^+$  [PRL113, 2014]



PAMELA  $\bar{p}$  [Nature 09]

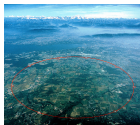


# Fermi LAT $\gamma$



# DM at Colliders I

- CERN Large Hadron Collider (LHC):

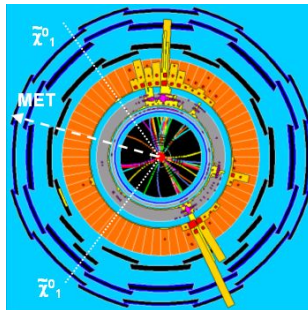
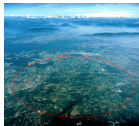


- ATLAS, CMS



# DM at Colliders I

- CERN Large Hadron Collider (LHC): ATLAS, CMS



# Summary

- Strong evidence for Dark Matter
  - But what is it?
    - Many Candidates
  - Vigorous search underway - Direct, Indirect, Collider
    - Exciting times! We might discover DM particle soon

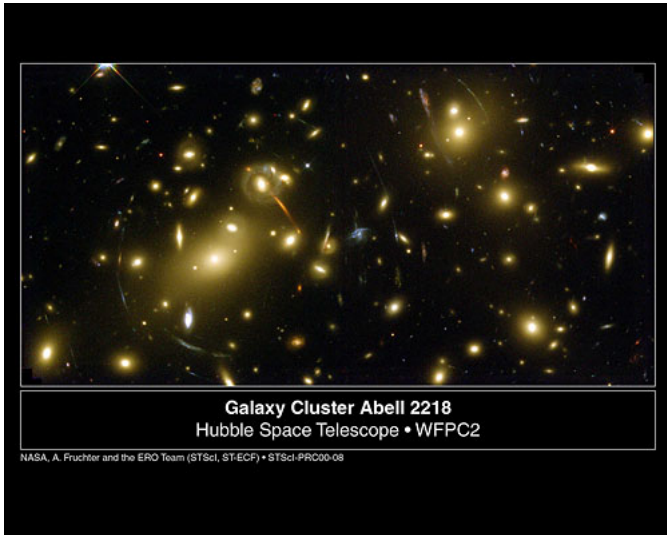


# Backup Slides

Backup Slides



# Gravitational Lensing



# The expanding universe



- Vesto Slipher : measured **Red-shift** (Doppler shift) of galaxies (1917)  $z = \frac{\lambda_{obs} - \lambda_{emit}}{\lambda_{emit}}$

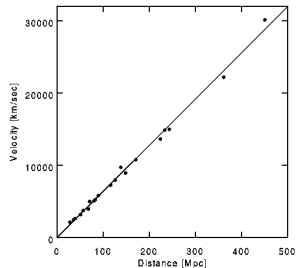
- Georges Lemaitre : Universe is expanding (1927)

- Edwin Hubble

$$v = H_0 d \quad (H_0 : \text{Hubble constant}) \quad (1929)$$

$$H_0 = 67.8 \pm 0.9 \text{ km s}^{-1} \text{ Mpc}^{-1} \quad [\text{Planck 2015}]$$

- $z = \frac{1-a}{a}$  in FLRW cosmology



[Riess, Press and Kirshner (1996)]



# The Standard Model (SM) of Particle Physics

**FERMIONS** matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ lightest neutrino*	$(0-0.13)\times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_\mu$ middle neutrino*	$(0.009-0.13)\times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_\tau$ heaviest neutrino*	$(0.04-0.14)\times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

**BOSONS** force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge	Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0	<b>g</b> gluon	0	0
<b>W<sup>-</sup></b>	80.39	-1	<b>Higgs Boson spin = 0</b>		
<b>W<sup>+</sup></b>	80.39	+1	Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>Z<sup>0</sup></b>	91.188	0	<b>H</b> Higgs	126	0

**Properties of the Interactions**  
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two quarks separated by the specified distance.

Property	Gravitational Interaction	Weak Interaction	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass - Energy	Flavor	Electric Charge	Color Charge
Particles experiencing	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	<b>W<sup>+</sup> W<sup>-</sup> Z<sup>0</sup></b>	$\gamma$	Gluons
Strength at:	$10^{-41}$	0.8	1	25
$3 \times 10^{-17}$ m	$10^{-41}$	$10^{-4}$	1	80

[particleadventure.org]

Units: Mass & Energy in **GeV** ( $E = mc^2$ , set  $c = 1$ ) ( $1\text{GeV} = 10^9 \text{eV}$ )

