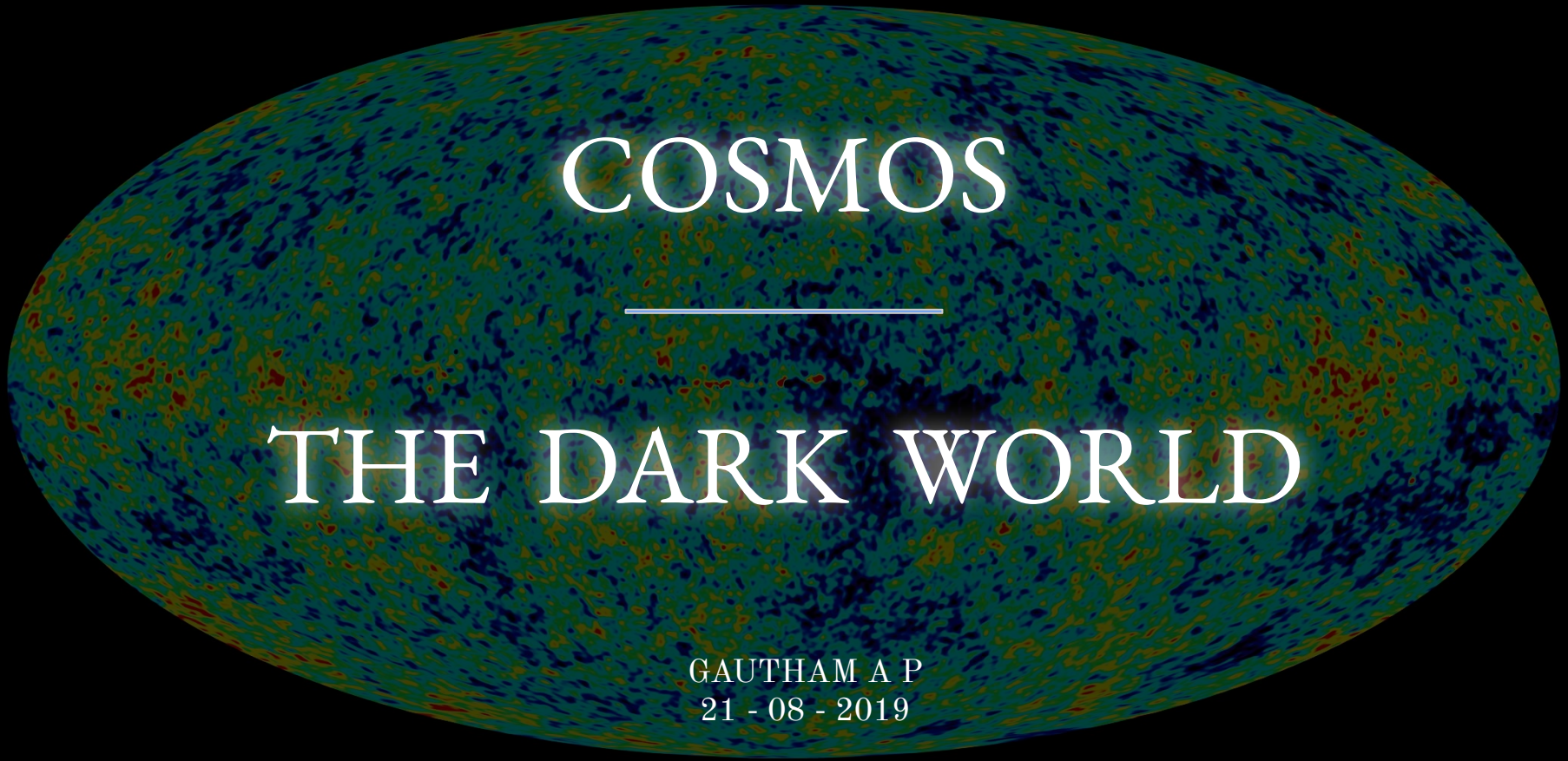


COSMOS

THE DARK WORLD

GAUTHAM A P

21 - 08 - 2019

Cosmology

IS NOT

Astro(physics/nomy)

Cosmology

IS NOT

Astro(physics/nomy)

Cosmology

IS NOT

Astro(physics/nomy)

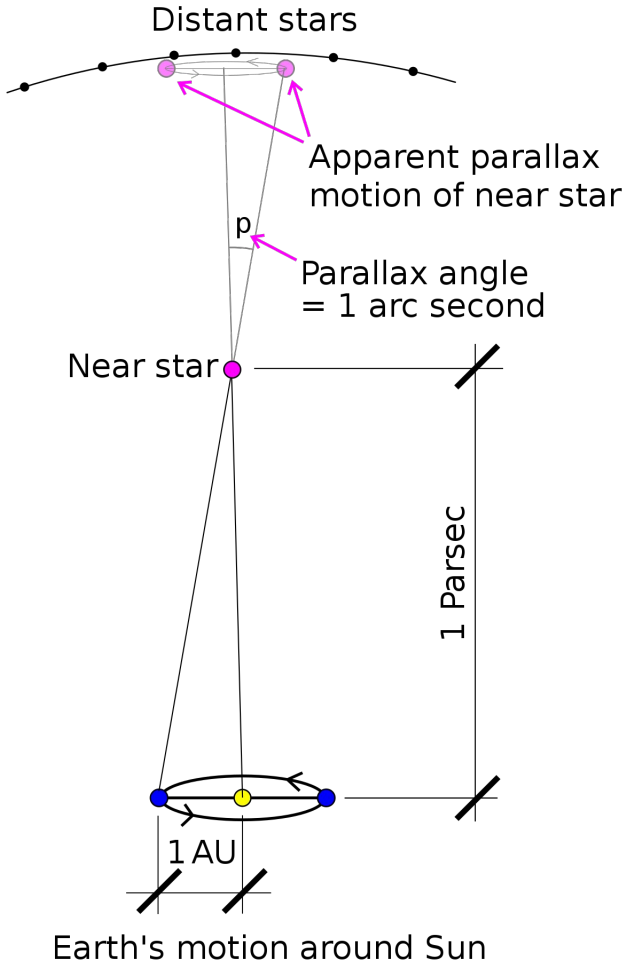
DARK ENERGY ≠ DARK MATTER

PARSEC -

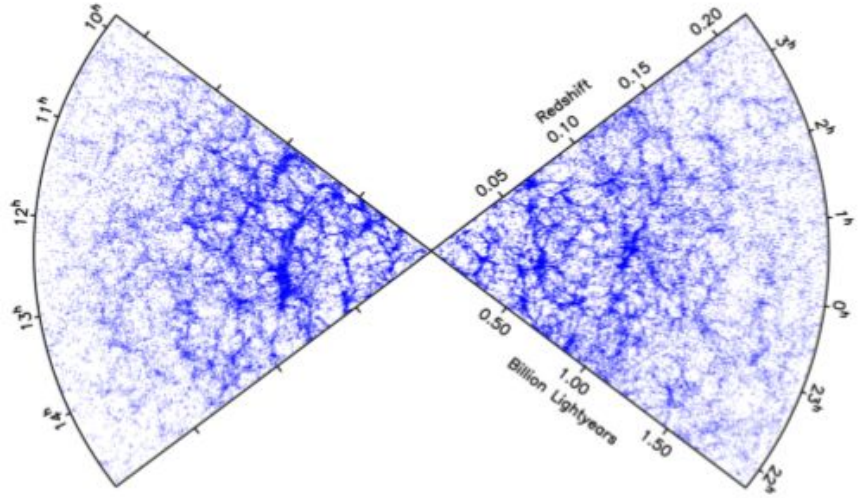
A measure of distance
It is a convenient unit to represent the scales in Cosmology

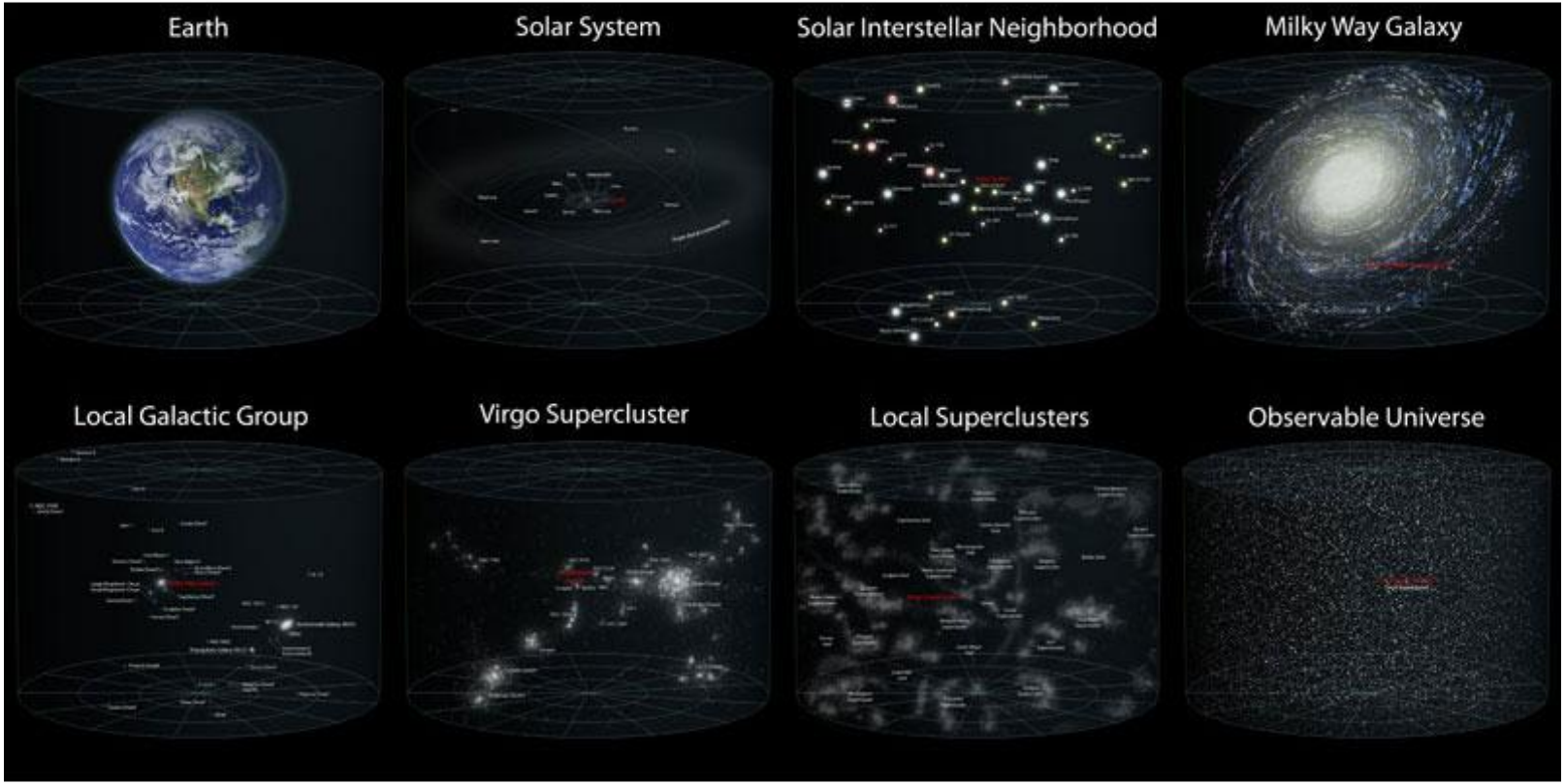
1 parsec = 3.26 Light years

1 parsec ~ 10^{16} m



- Cosmology deals with Universe at large while Astro deals with substructures within it
- For example: Astrophysics usually deals with Planets, Stars up until Clusters of Galaxies
- Cosmology starts only at these scales of several MPc

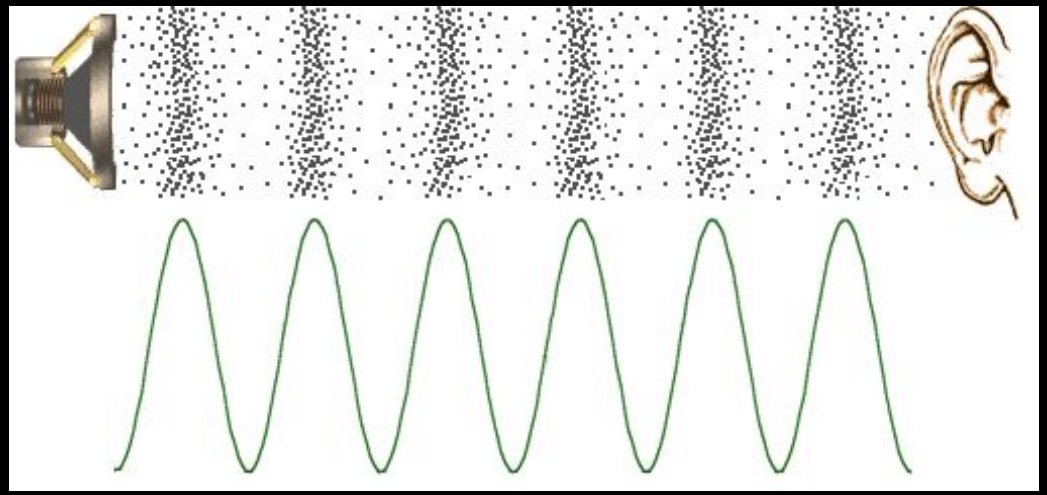


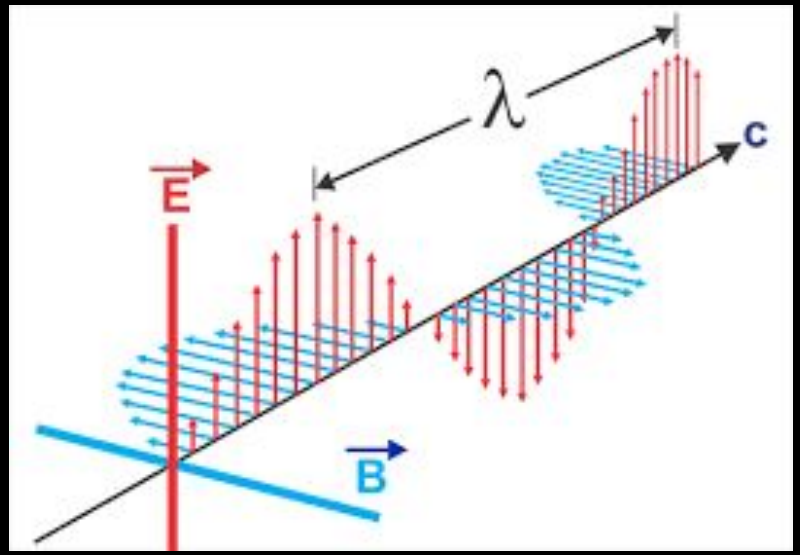

Earth
Solar System
Solar Interstellar Neighborhood
Milky Way Galaxy
Local Galactic Group
Virgo Supercluster
Local Superclusters
Observable Universe

Thor: The Dark World !!

(The obvious inspiration!!)

Fight for (A)Ether




λ
c
E
B

??

- MICHELSON-MORLEY EXPERIMENT
- Essentially measured change in velocity of light due to relative movement of medium of transmission
- Resulted in a NULL result
- Did not disprove Ether! But told that speed of light is constant implying SR
- Other conclusion can be that there is no Ether wind!

MICHELSON MORLEY EXPERIMENT - 1887 (And other similar experiments)

Special Relativity (1905) and General Relativity (1915)

General Theory of Relativity -

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

METRIC

- Metric, in simple terms, is a way to measure distance
- $g_{\mu\nu}$ is the metric tensor and $ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$ is the “distance”
- Distance in a simple 2d metric space -

$$ds^2 = dx^2 + dy^2$$

- Distance on a surface of 4 sphere -

$$ds^2 = \frac{1}{1-\frac{r^2}{R^2}}dr^2 + r^2(d\theta^2 + sin^2(\theta)d\phi^2)$$

FLRW UNIVERSE

One of the solutions to Einstein's equations was discovered by Alexander Friedmann in 1922 but it remained unknown

In 1927, Georges Lemaître arrived at the same result independently

In 1930s Robertson and Walker rigorously proved that this is the only solution "applicable" to our universe (only if we apply certain principles to our universe)

Hence the name FLRW universe

FLRW UNIVERSE

FLRW : Friedmann–Lemaître–Robertson–Walker

This describes a dynamic universe which may expanding, contracting etc

Assumption(?!) : Homogeneous and Isotropic universe

Homogeneous - Translation Invariance
Isotropic - Spherical symmetry

FLRW METRIC

$$ds^2 = -c^2dt^2 + a(t)^2\left[\frac{1}{1-kr^2}dr^2 + r^2(d\theta^2 + sin^2(\theta)d\phi^2)\right]$$

$k = 0$, Flat universe
$= +1$, Closed unive
$= -1$, Open univers

On solving Einstein's equations in this universe (a.k.a our universe) we get :

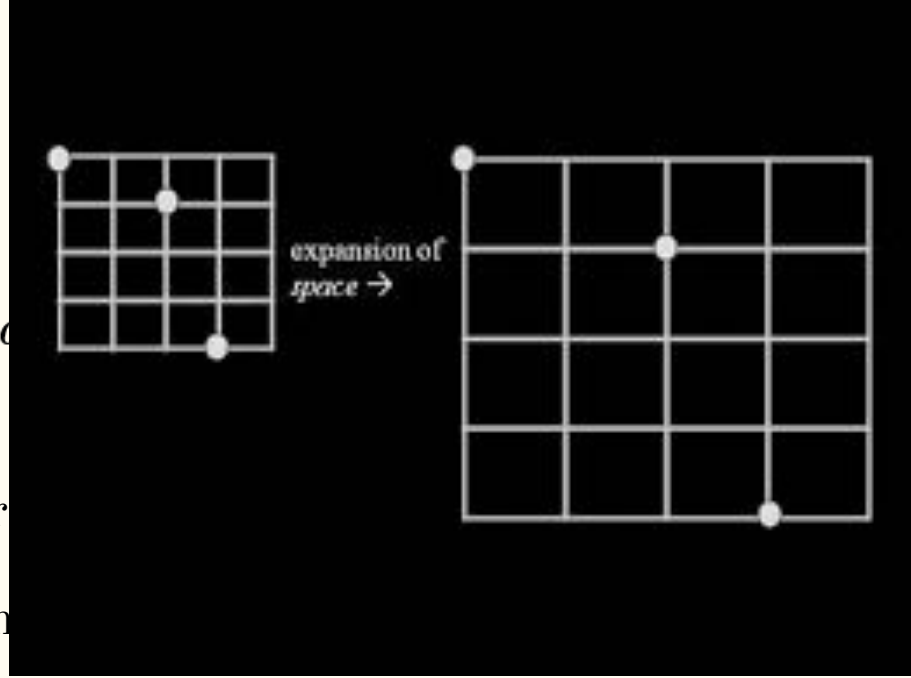
Friedmann Equations - (H is the hubble's constant)

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \qquad H = \frac{\dot{a}}{a}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

FLRW METRIC

$$ds^2 = -c^2dt^2 + a(t)^2\left[\frac{1}{1-kr^2}dr^2 + r^2(d$$



On solving Einstein's equations in this univer

Friedmann Equations - (H is the hubble's con

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \qquad H = \frac{\dot{a}}{a}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

FLRW METRIC

$$ds^2 = -c^2dt^2 + a(t)^2\left[\frac{1}{1-kr^2}dr^2 + r^2(d\theta^2 + sin^2(\theta)d\phi^2)\right]$$

$k = 0$, Flat universe
$= +1$, Closed unive
$= -1$, Open univers

On solving Einstein's equations in this universe (a.k.a our universe) we get :

Friedmann Equations - (H is the hubble's constant)

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \qquad H = \frac{\dot{a}}{a}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$$

Cosmological Constant and Einstein's "Greatest Blunder"(??!)

Einstein's equations for Gravity suggested an expanding universe

But Einstein wanted to achieve a static universe and thus introduced a cosmological constant

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \boxed{- \Lambda g_{\mu\nu}}$$

FLRW METRIC (revisited) -

The new Friedmann Equations are -

$$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} + \frac{\Lambda}{3} \qquad H = \frac{\dot{a}}{a}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda}{3}$$

Static solution -

To get a static solution we set **H** and **ä** to zero. This gives -

$$\Lambda = 4\pi G\rho$$

However this solution is unstable

After Hubble's observation (in 1929) of expanding universe this term was dropped .....

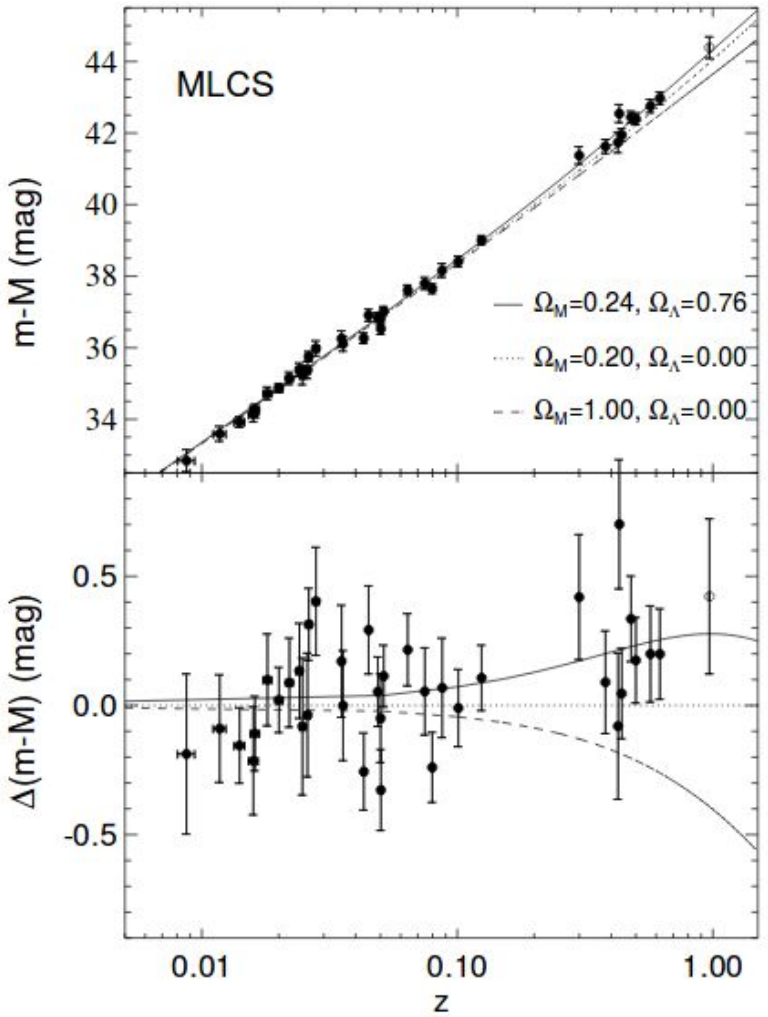
UNTIL 1998 !!!!!

COSMOLOGICAL CONSTANT RETURNS !

Measuring Hubble's constant, H, using SNIa suggested accelerated expansion of the universe

Negative Pressure ! $p_\Lambda = -\rho_\Lambda c^2$

SO - What the hell is this Dark Energy?



Headache of the order of 10^{123} !!!

The problem of negative pressure has a readymade solution in QFT with observational evidence !!

Casimir Effect !

Vacuum Energy !!

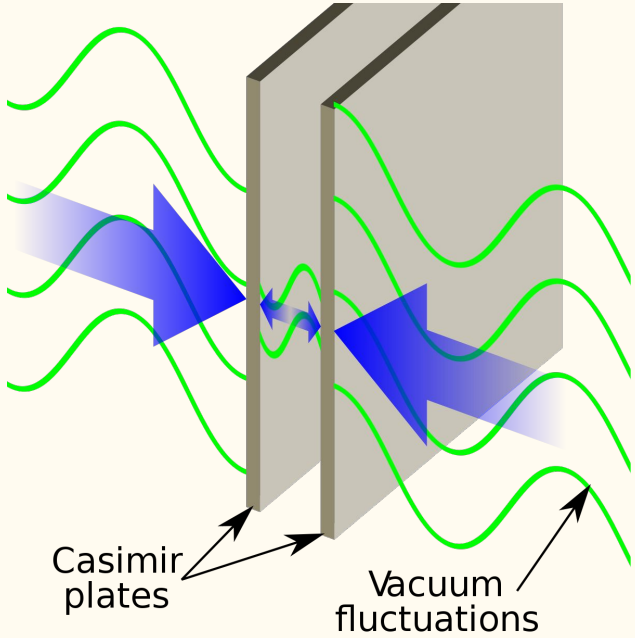
BUT .....

A simple order of magnitude estimate gives -

$$\rho_\Lambda(theory) \sim \frac{c^5}{hG^2} \sim 10^{96}\, kg/m^3$$

$$\rho_\Lambda(measured) \sim 0.7\rho_{crit} \sim 10^{-27}\, kg/m^3$$

$$\Rightarrow \Delta \sim 10^{123}$$



$$\sum n = -\frac{1}{12}$$

2nd story!

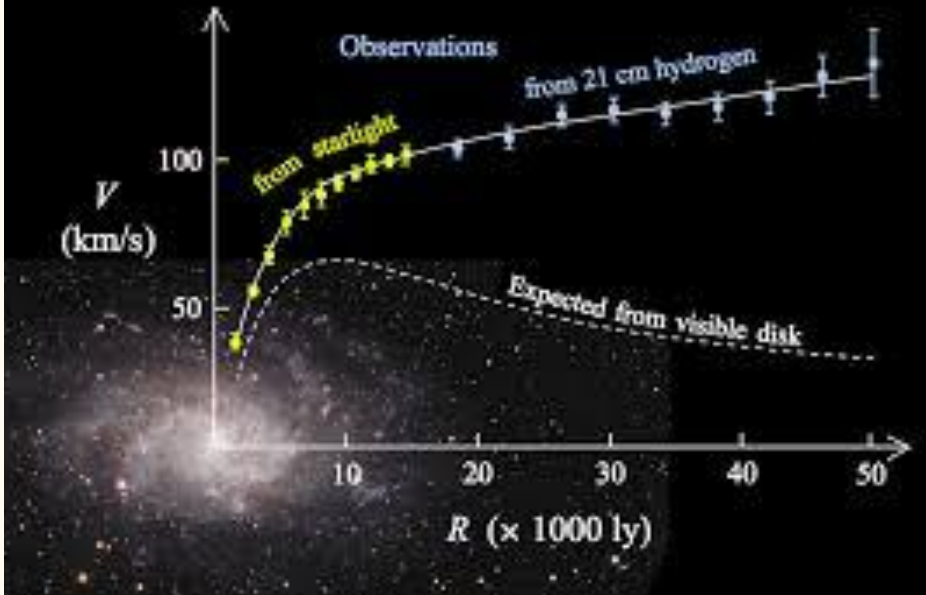
DARK MATTER
Galaxy rotation curves

From Newton's laws :

$$v \sim \sqrt{\frac{GM_r}{r}}$$

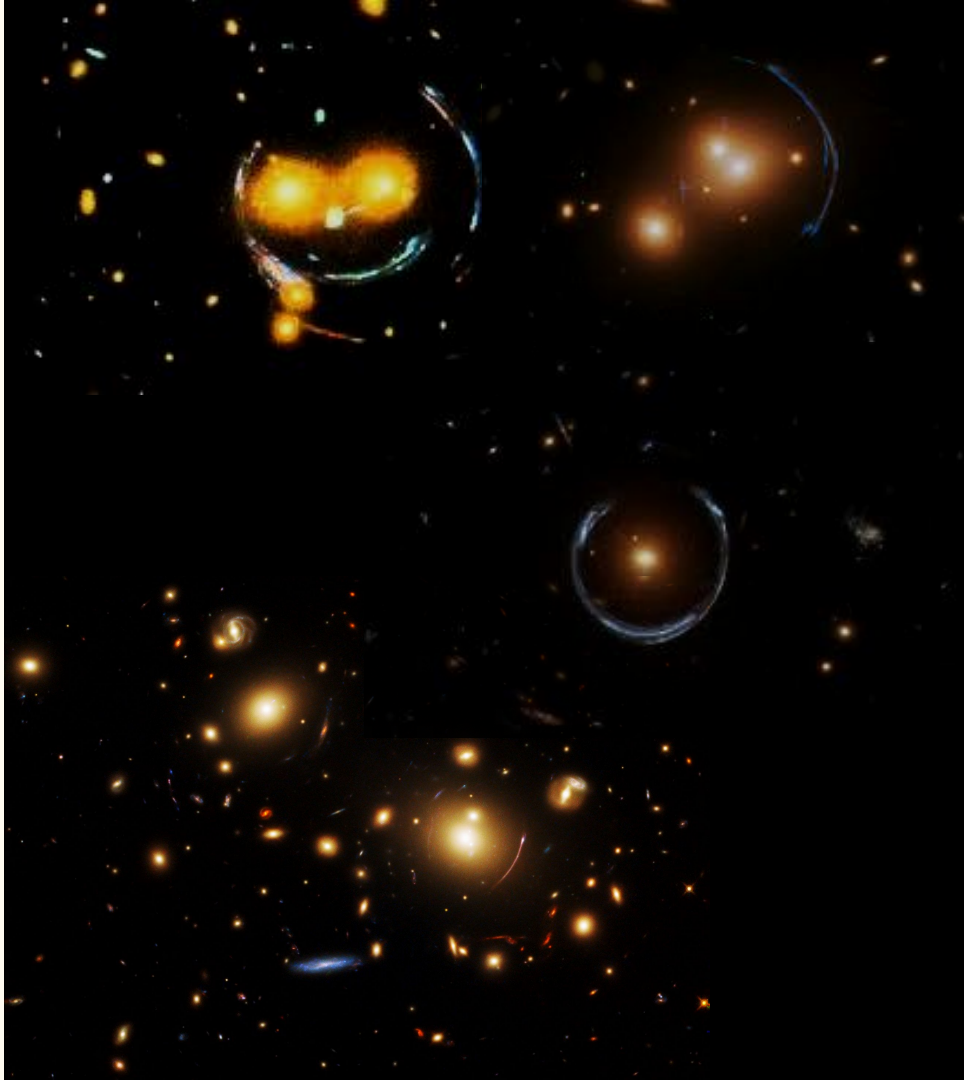
$$\Rightarrow \text{if } r < R : v \sim r\sqrt{G\rho}$$

$$\text{if } r > R : v \sim \sqrt{\frac{GM_{tot}}{r}}$$



Gravitational lensing

Excess lensing than expected!



MOND

- Modified Newtonian Dynamics is a proposed modification to Newton's Laws to explain previous phenomenons
- Suggests that at low acceleration Newton's law is modified but holds at high acceleration

For very small acceleration -

$$F_N = m\frac{a^2}{a_0}$$

$$\Rightarrow v^4 \sim GMa_0$$

Thus it explains constancy in Galaxy rotation curves
However, other observational and theoretical problems remain

Death of MOND(?!)

Galaxies with Matter agreeing exactly with it's luminosity profile have been discovered

- DF2 and DF4 -

Since MOND would be applicable for all galaxies we expect modifications as usual. However in DF2,DF4 we see no such modifications. This essentially ends the run of MOND as a candidate to all such weird phenomenon!

(Un)Natural solution!

A new form of matter which interacts only Gravitationally is proposed!

Dark Matter is proposed as a solution

They are supposed to interact only gravitationally

The observations suggest this would constitute upto 25% of total mass density in the universe (compared to 5% of usual matter)

Any other proofs for their existence ?

Cosmic Microwave Background (CMB)

CMB data suggests 70% Dark Energy and 30% Matter
But we expect only 5% of this to be normal matter

Electrons and Protons interact(exchange momenta) and constitute Baryon Fluid

Photons interact with charged particles via Thomson scattering and give Photon-Baryon Fluid

The oscillating Photon-Baryon fluid interaction dominates expansion until around T~3000K (a~1e-3)

At this point, the Photons decouple and start free streaming. These photons are called CMB

The evolution of CMB is affected by Gravitational potential wells created Dark Matter. Thus CMB can be used to probe properties of Dark Matter

Cold Dark Matter(CDM)

Cold ≡ Non-Relativistic

i.e Rest Mass > Kinetic Energy

Dark Matter are proposed to explain Galaxy Rotation Curves at distances larger than the size of Galaxy

This suggests a Dark Matter halo much bigger than radius of galaxy

To sustain the halo, Dark Matter has to be have low kinetic energy or else they'll free stream (eventually)

Hence the Cold Dark Matter!

Candidates for Dark Matter

Beyond Standard Model particles (BSM)!

Might suggest existence of new physics [SUSY, Effective Field Theories]

Several candidates have been proposed :

Known Physics -

- Neutrinos
- MaCHO

Unknown Physics -

- WIMP
- SuSy
- Axion

All proposed particles interact non-gravitationally too !!!

Else there is no way we can hope to detect them

DM from known Physics

[Meh!]
These definitely contribute to DM density. But how much?

Neutrinos - Neutrinos are very weakly interacting low mass particles. Very abundant and very weakly interacting and are an ideal candidate. But they are very light (m~0.12eV) and they are Warm. So this cannot explain all of the DM

MaCHO - Massive Compact Halo Objects are non-luminous massive objects such as Black Holes, Neutron Stars etc (almost star planets like Jupiter too!). However, this cannot explain everything as CMB suggests a need for larger amount non-Baryonic DM

DM from unknown Physics

[YAY !!]
Not a single detection until but still our best bet!

WIMP - Weakly Interacting Massive Particle is a proposed “particle” to explain DM. They are supposed to be massive (m > few MeV at least) and interact Gravitationally as well as via some other force weakly

SuSy - Several WIMP particles are proposed such as Neutralino, Gravitino !!!

Axions - They are proposed to solve CP problem (charge-parity symmetry not being broken) in Quantum ChromoDynamics. Very exciting candidate because of its stability and possibilities of solving other issues.


My work and experience
in BSM dark matter

Milli-Charged Dark Matter -

In 2018, EDGES (Experiment to Detect the Global EoR Signature) result suggested that Baryons had cooled significantly at early times(z~17)

To explain this cooling, direct interaction between Baryons and Dark Matter was proposed

Leading idea was Milli-Charged Dark Matter particles interacting with Baryons (via Colomb scattering) and cooling them

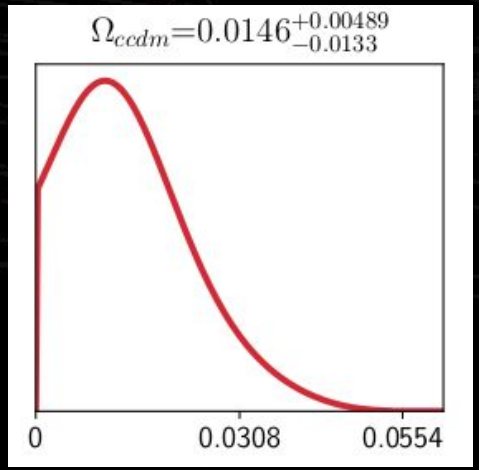
Such a particle would have -

$$M > 10\text{MeV and } q < 10^{-5}e$$

To study this, we model a fraction of Dark Matter to be charged and try to evolve this system. The final effects on CMB are matched with experimental data.

The current results are positive! It suggests that there can be almost 5% such Dark Matter.

But that does not mean they exist! Only that they cannot be ruled by CMB data!



This work was started as a part of internship under Prof.Shiv Sethi in Raman Research Institue, Bangalore (RRI)

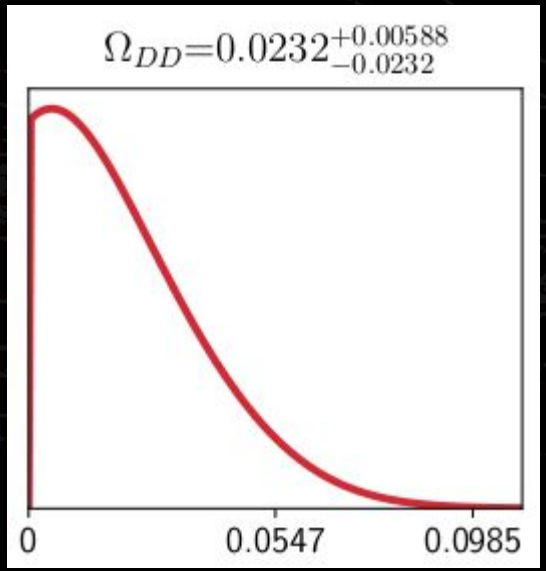
An early result (This is slightly incorrect with new modifications. However those modifications will only increase the fraction!)

Dark Matter atoms with itself and other Baryons -

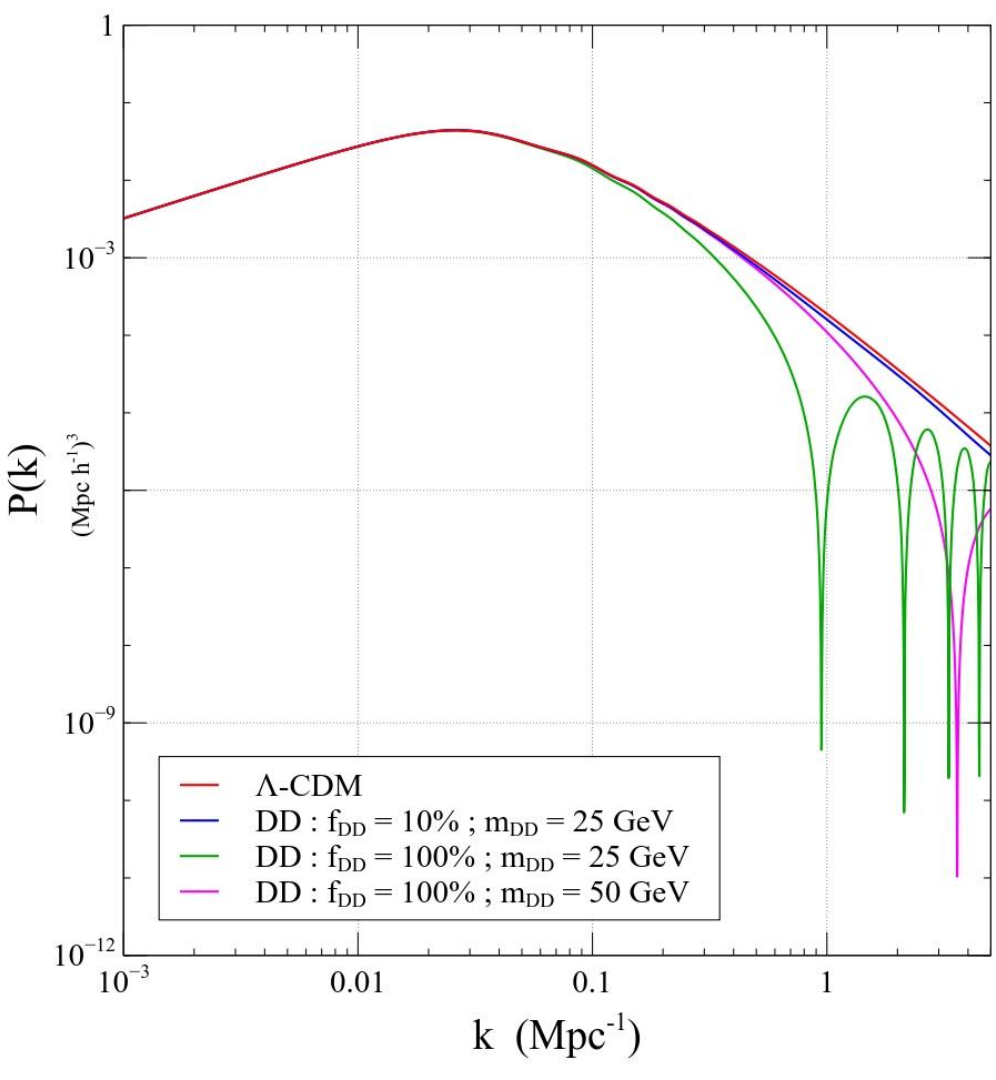
We hypothesize BSM negatively charged DM particles which can form atoms with Baryons

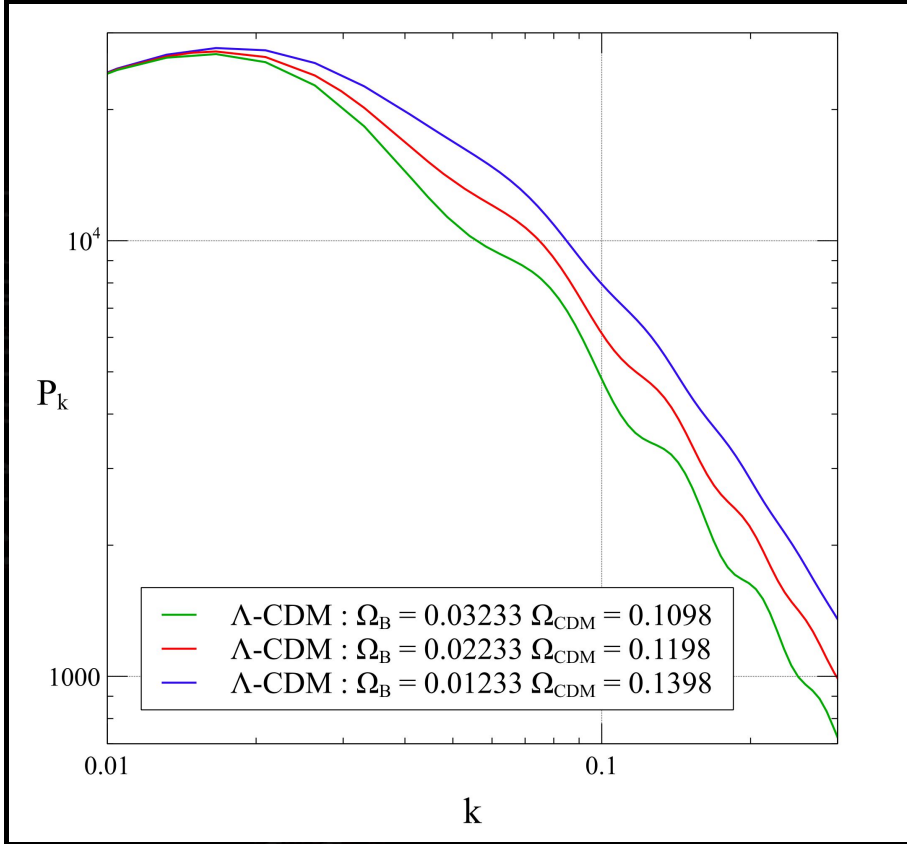
Such atoms would interact with other Baryons as well and leave an imprint on CMB

Again, current results do not rule them out based on CMB data!!



This work was started as a part of internship under Prof.Shiv Sethi in Raman Research Institue, Bangalore (RRI)


P(k)
(Mpc h^{-1})^3
k (Mpc^{-1})
Λ-CDM
DD : f_{DD} = 10% ; m_{DD} = 25 GeV
DD : f_{DD} = 100% ; m_{DD} = 25 GeV
DD : f_{DD} = 100% ; m_{DD} = 50 GeV


P_k
k
Λ-CDM : Ω_B = 0.03233 Ω_{CDM} = 0.1098
Λ-CDM : Ω_B = 0.02233 Ω_{CDM} = 0.1198
Λ-CDM : Ω_B = 0.01233 Ω_{CDM} = 0.1398

Axionic Dark Matter -

Axions were proposed in 1977 to solve CP problem in QCD

They are similar to π^0 meson (a known standard model particle) . These mesons can undergo Primakoff & Inverse Primakoff process i.e they can mix into Photons in the presence of magnetic field.

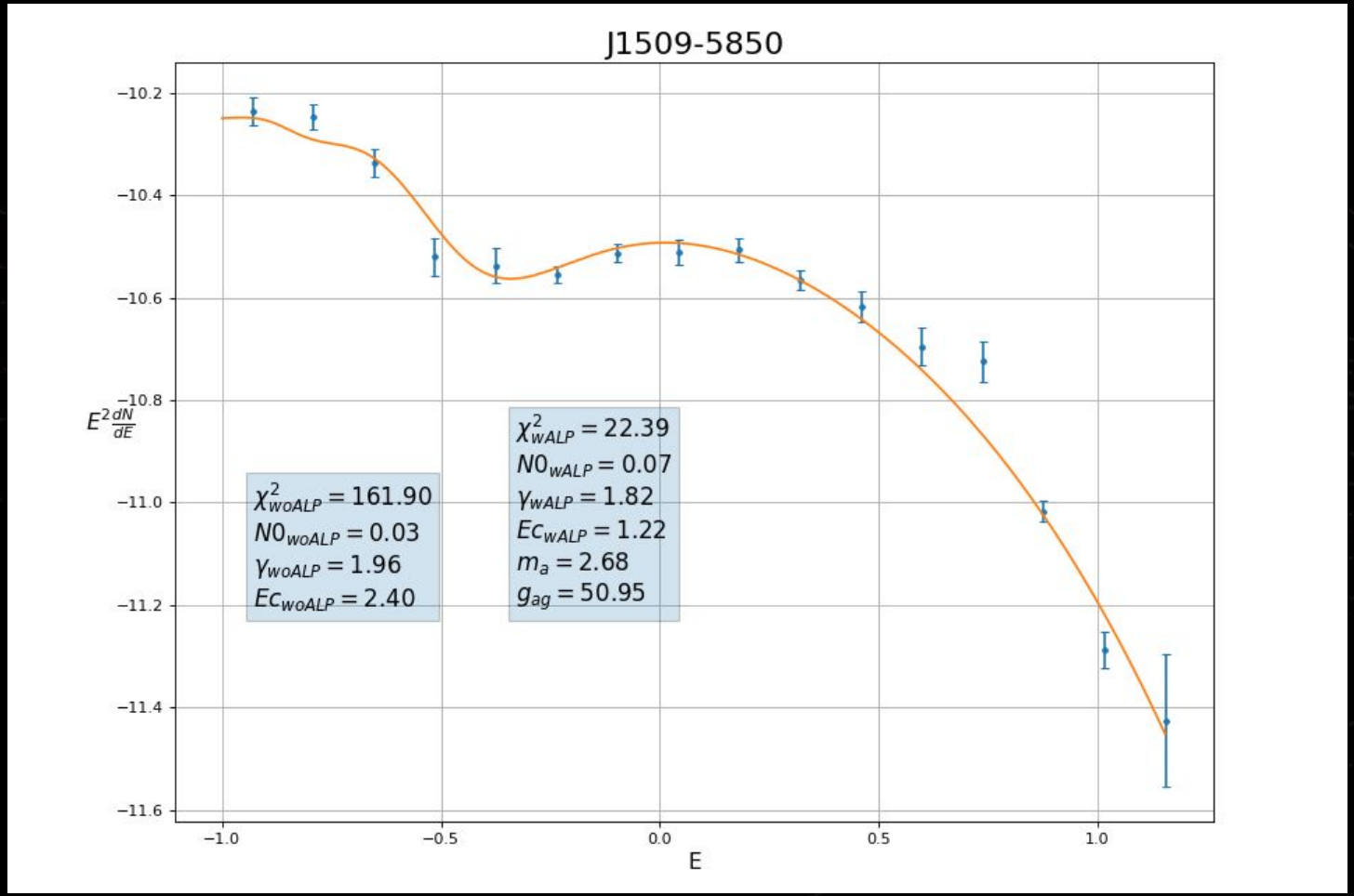
Thus Axions too are expected to mix with Photons in presence of magnetic field.

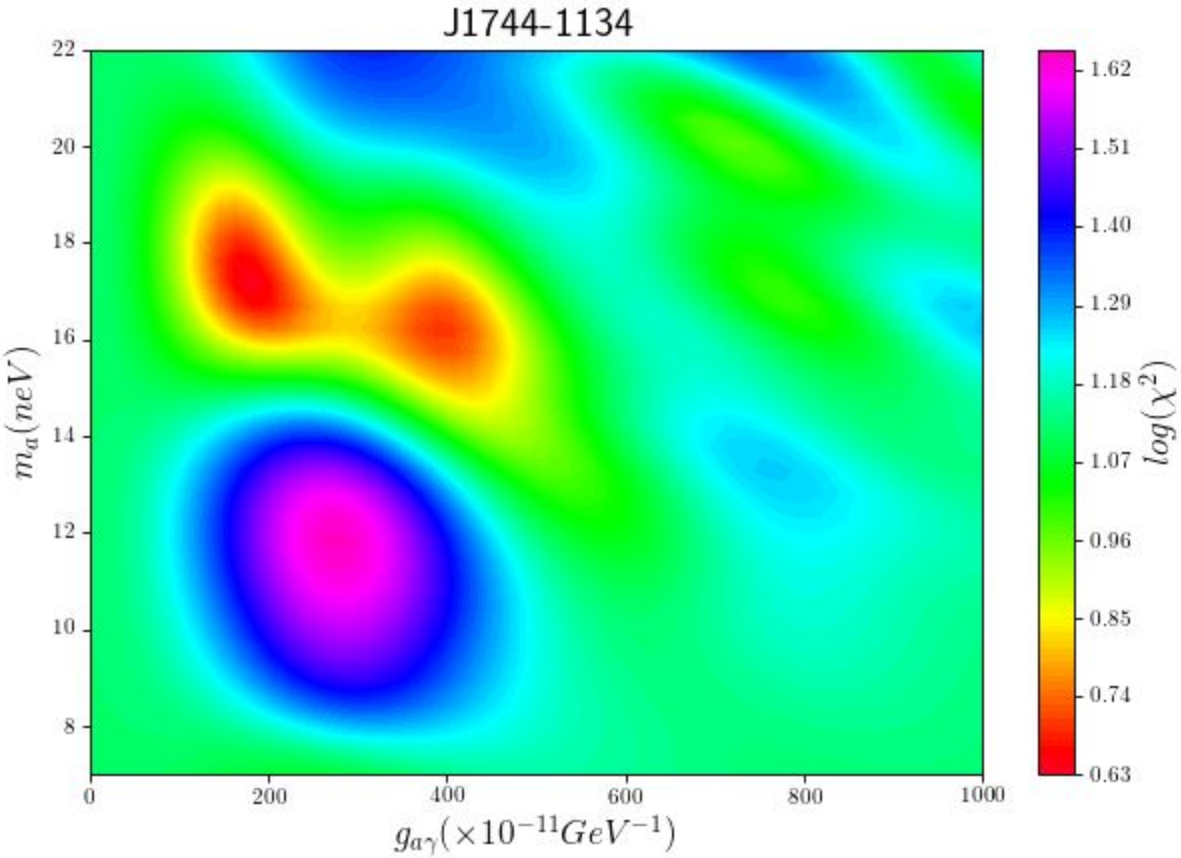
This mixing shows oscillatory behaviour and can modulate Gamma-ray spectra from Pulsars

We try to study these modulations and try to fit or Axion model to Pulsar data.

Once again, Axions seem to explain quite a bit of modulations and do their job well! Hence cannot be ruled out!

This work was started as a part of internship under Dr.Francesca Calore in Laboratoire d'Annecy-le-Vieux de Physique Théorique (LAPTh), Annecy, France


J1509-5850
$E^2\frac{dN}{dE}$
E
−10.2
−10.4
−10.6
−10.8
−11.0
−11.2
−11.4
−11.6
−1.0
−0.5
0.0
0.5
1.0
$\chi^2_{woALP} = 161.90$
$N0_{woALP} = 0.03$
$\gamma_{woALP} = 1.96$
$Ec_{woALP} = 2.40$
$\chi^2_{wALP} = 22.39$
$N0_{wALP} = 0.07$
$\gamma_{wALP} = 1.82$
$Ec_{wALP} = 1.22$
$m_a = 2.68$
$g_{ag} = 50.95$


J1744-1134
22
20
18
16
14
12
10
8
$m_a(n\epsilon V)$
0
200
400
600
800
1000
$g_{a\gamma}(\times 10^{-11} GeV^{-1})$
1.62
1.51
1.40
1.29
1.18
1.07
0.96
0.85
0.74
0.63
$log(\chi^2)$

Dark Matter Detection

Indirect detection - Dark Matter Self-Annihilation, Dark Matter decay etc

Detection in colliders - For example in case Dark Matter particles are produced in colliders we may not detect them due to weak interactions. This might show up as missing energy as hence an indirect detection.

Direct detection - WIMPs may interact with normal matter and we try to detect this.

Because interaction is weak, this is an unlikely event and hence hard to detect.

One such experiment is XENON1T

It uses 3.2 Tons(!!!) of Xenon as target and hopes to find an interaction !

Dark Matter Detection

Indirec

Self-Ann

Detecti

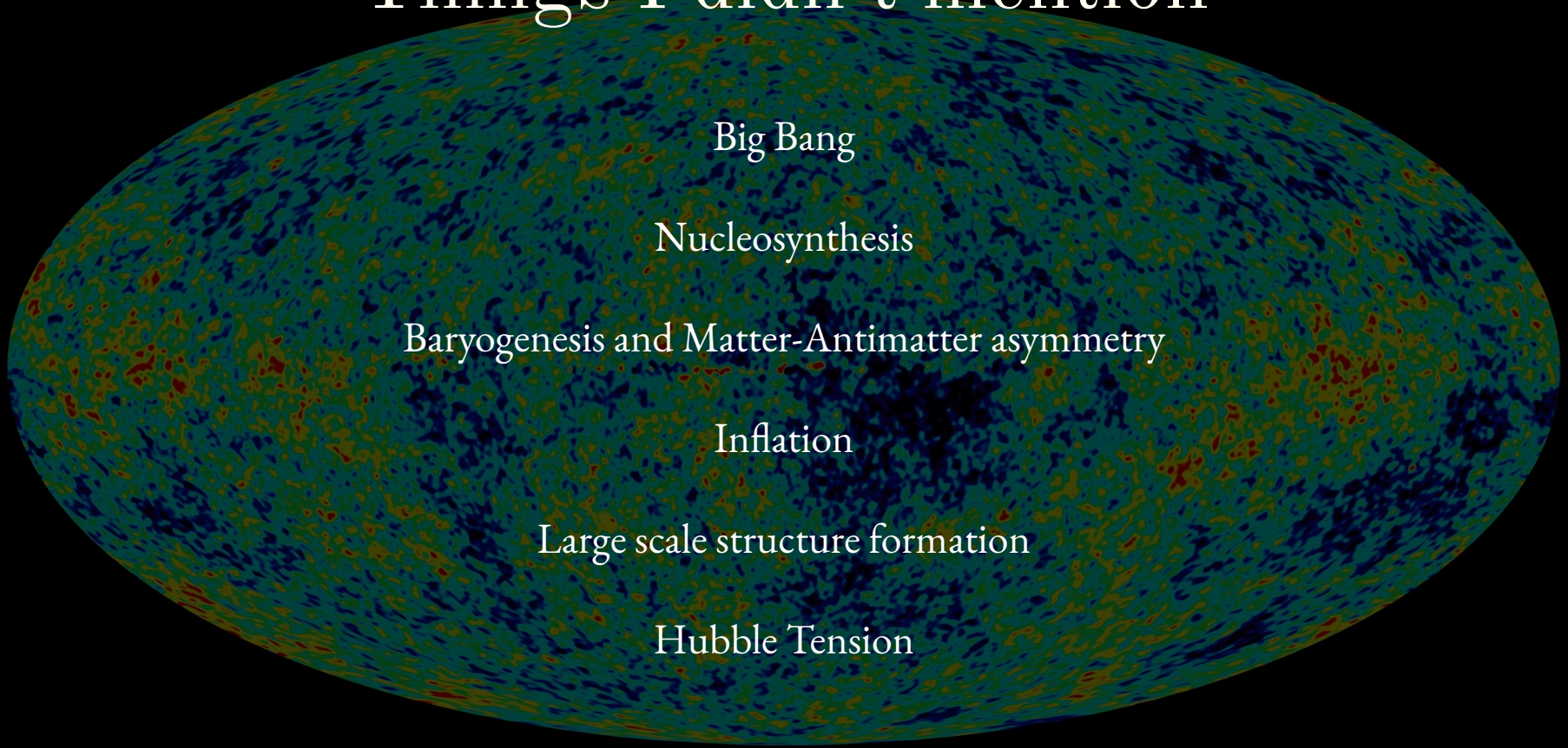
example i
produced
them due
might sho
an indire

th

likely

nd

Things I didn't mention



Big Bang

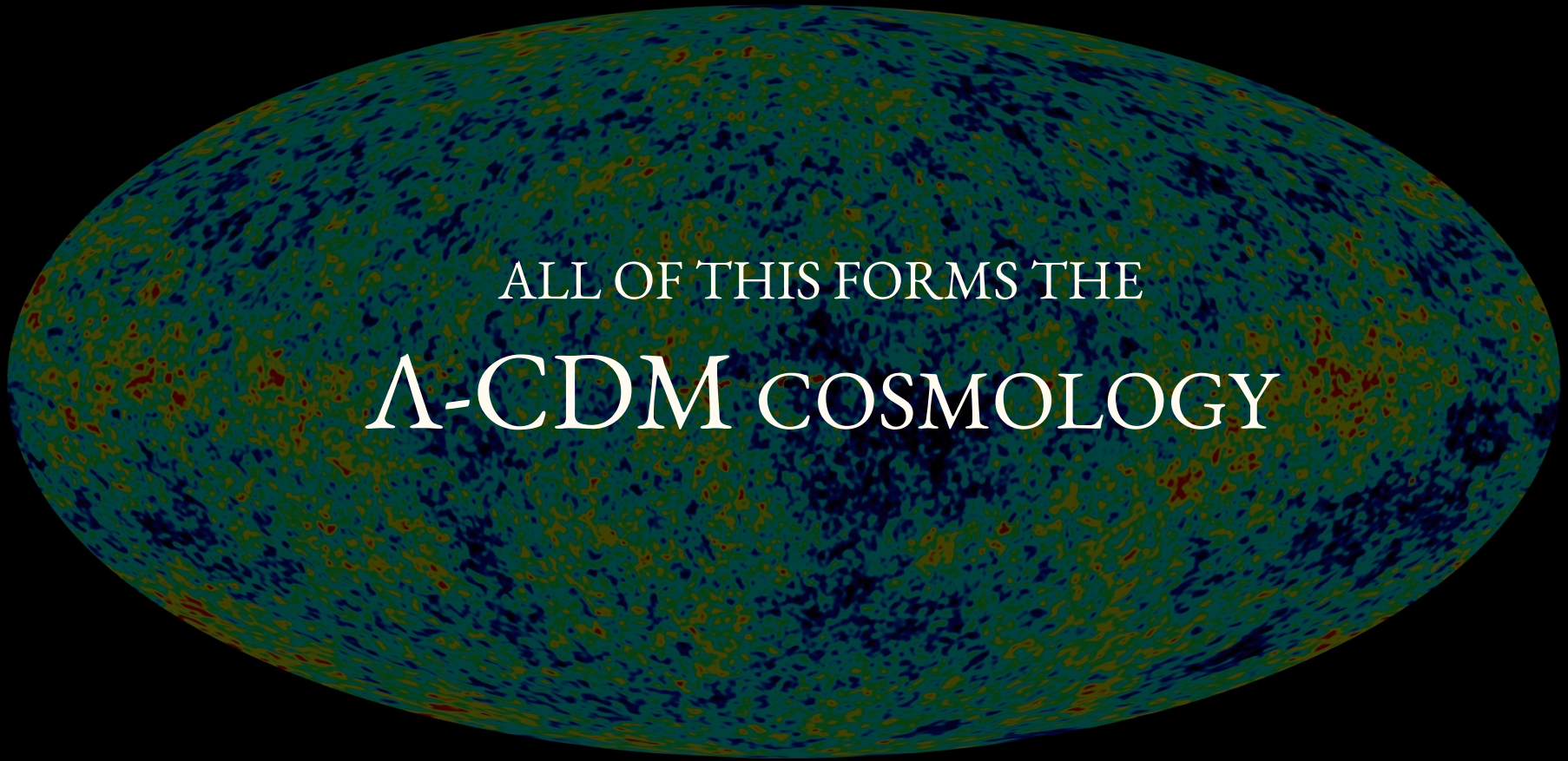
Nucleosynthesis

Baryogenesis and Matter-Antimatter asymmetry

Inflation

Large scale structure formation

Hubble Tension


ALL OF THIS FORMS THE
Λ-CDM COSMOLOGY