Phenomenology of primordial black hole from a first order phase transition

Speaker: **Po-Yen Tseng**

(Department of Physics, NTHU)

References:
2305.14399, 2304.10084, 2212.13035, 2209.01552

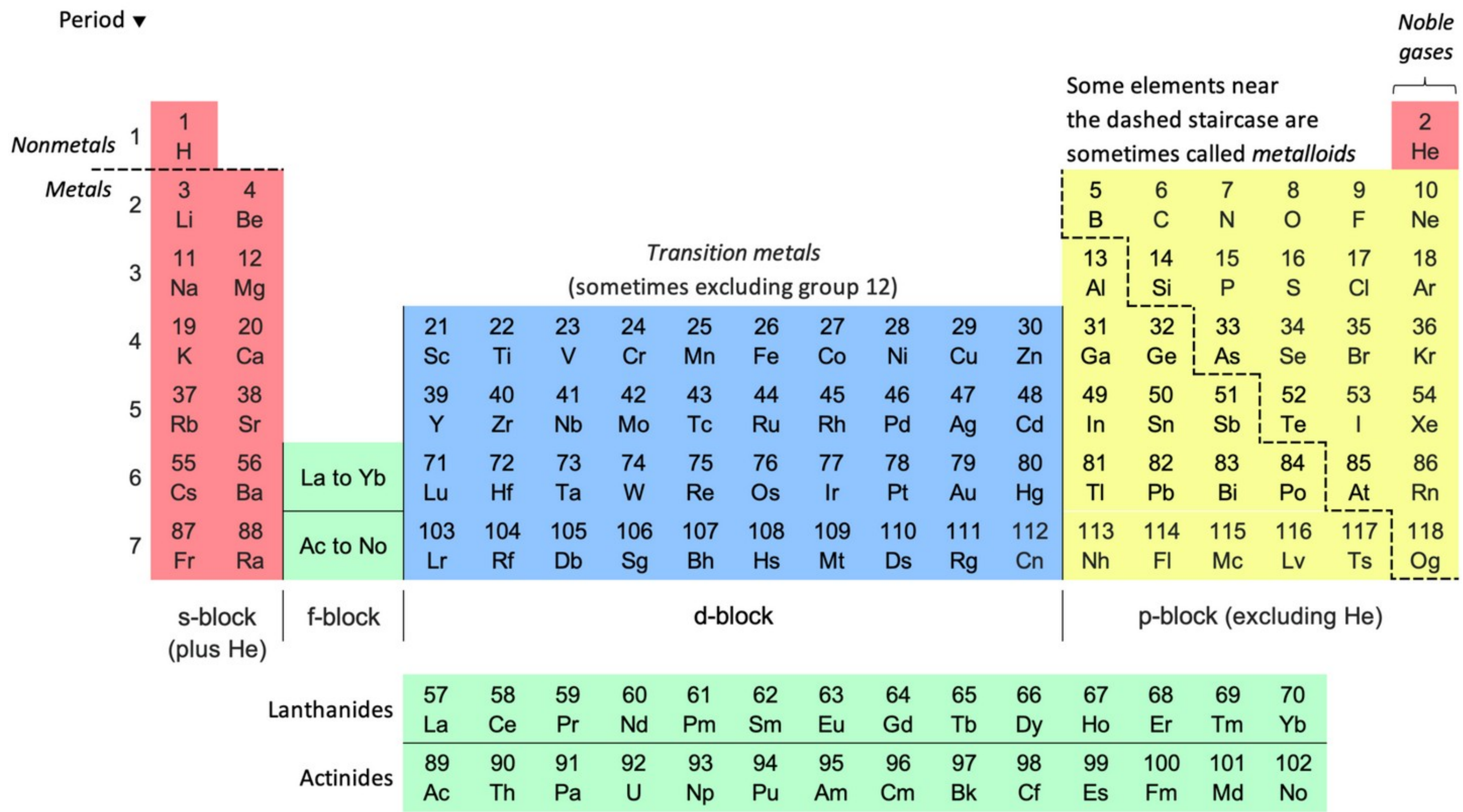
大阪公立大学
Osaka Metropolitan University

國立清華大學
NATIONAL TSING HUA UNIVERSITY

OMU-NTHU Meeting, Feb 6-9 2025

Goal for particle physics

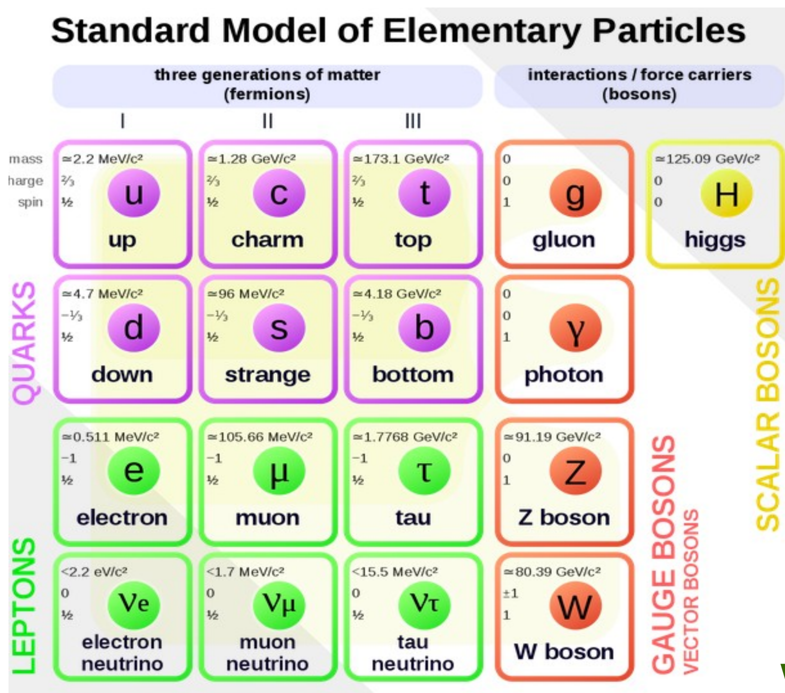
- The periodic table:



Wikipedia: Periodic table

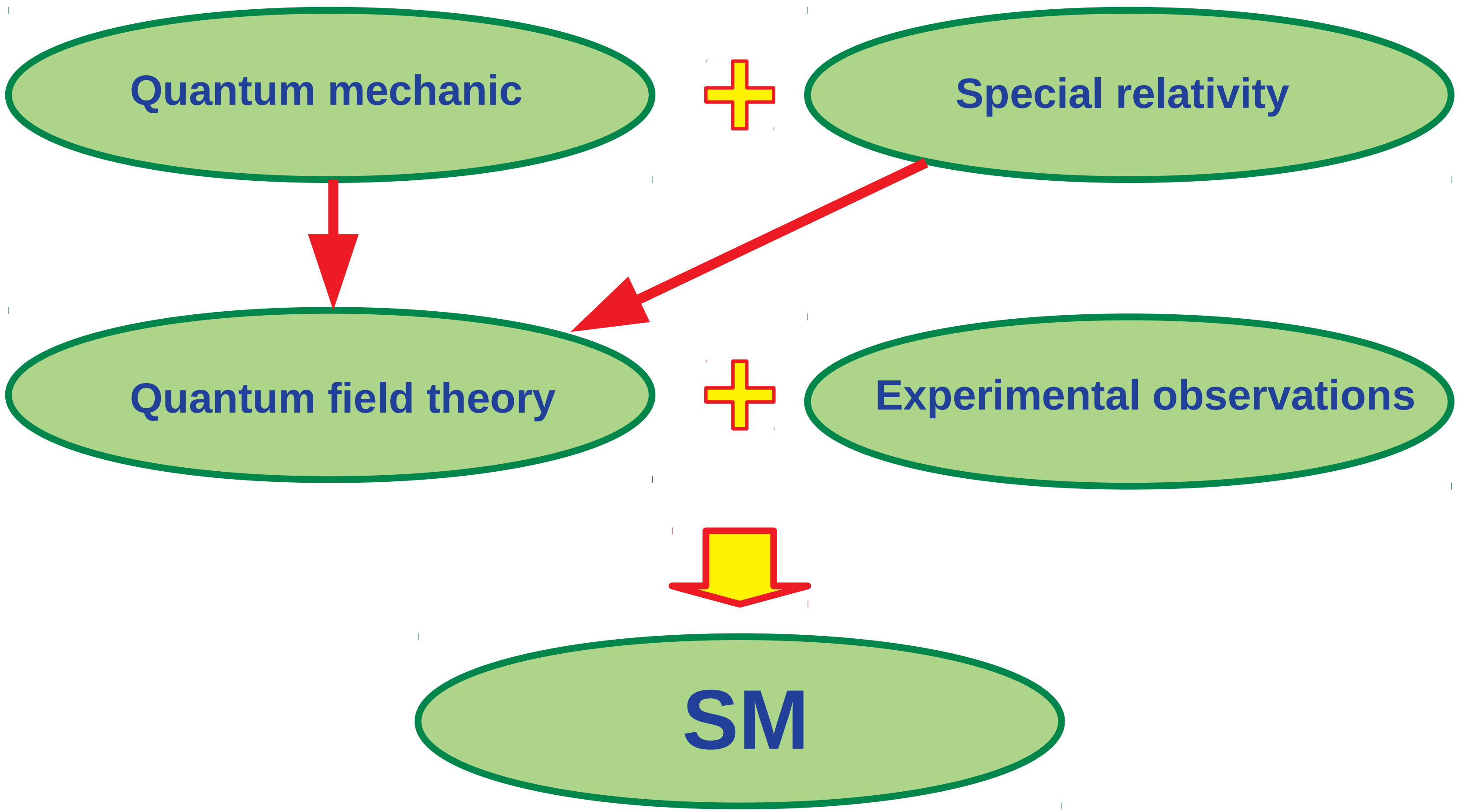
Standard Model (SM)

- (1978-present): SM unifies three of the four fundamental forces (electromagnetic, weak, and strong interactions), and classifies all known elementary particles.



Wikipedia: standard model

Standard Model (SM)



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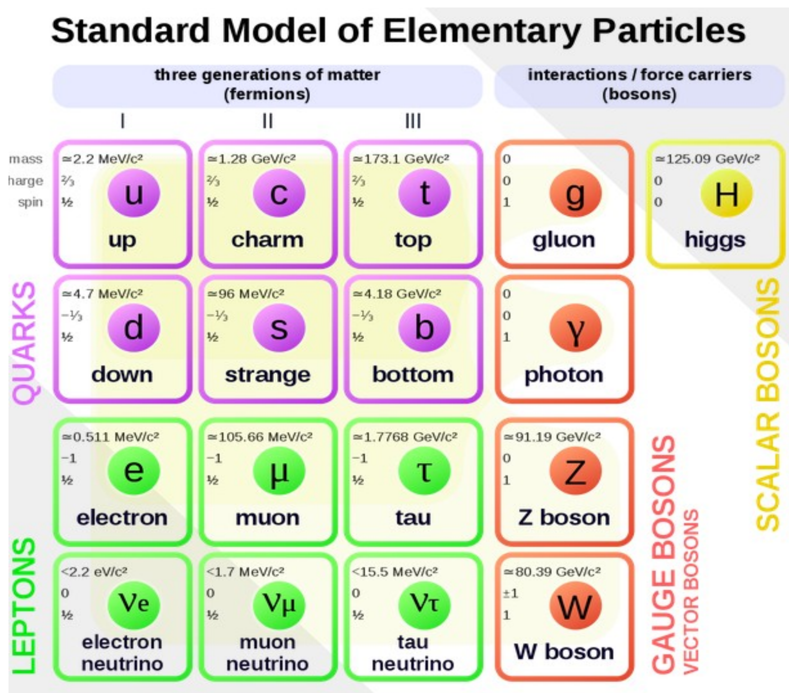
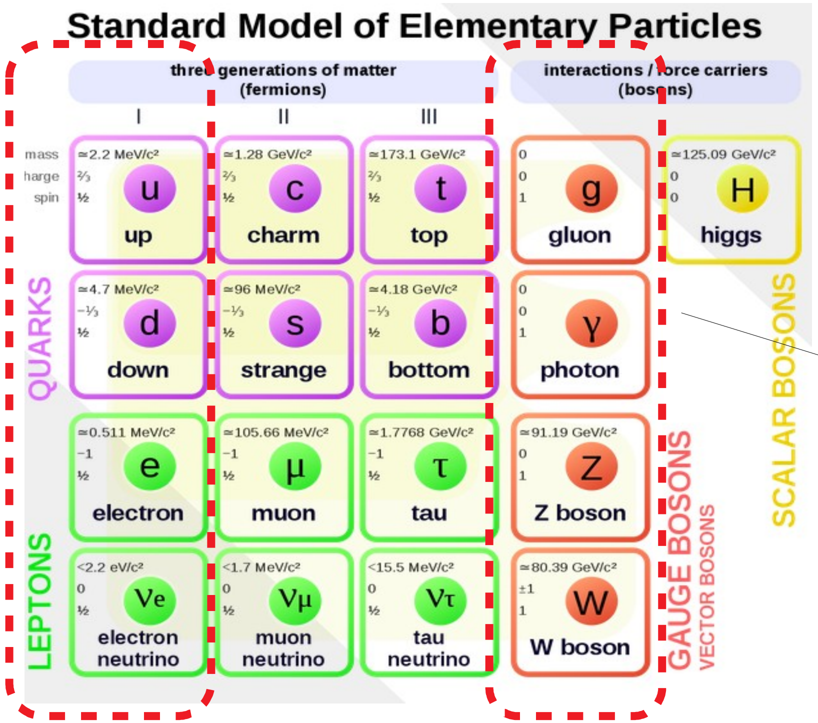


Wikipedia: Standard Model

Standard Model (SM)

- (1978-present): SM unifies three of the four fundamental forces (electromagnetic, weak, and strong interactions), and classifies all known elementary particles.

Building block
for matter



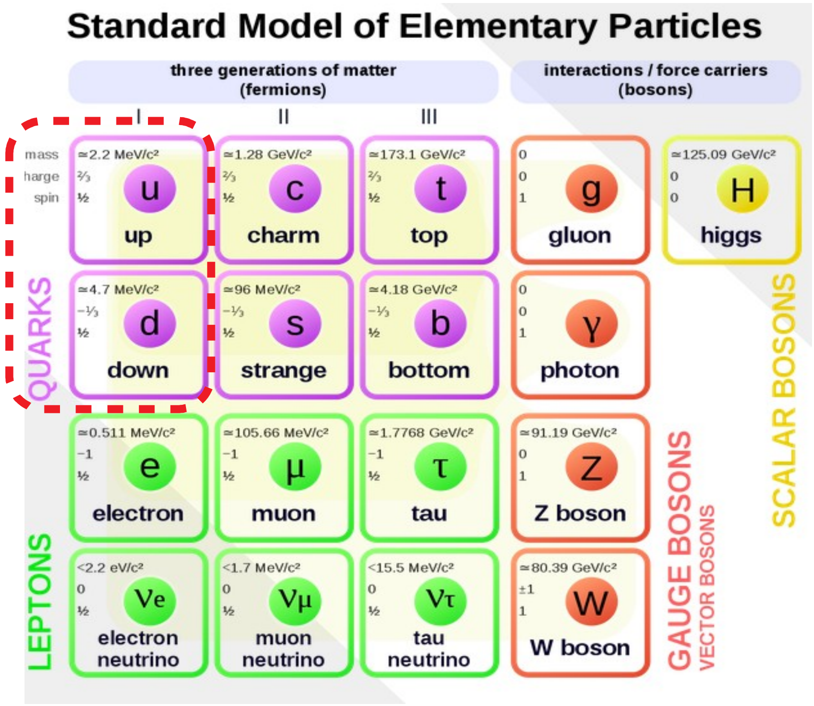
Interactions

Wikipedia: Standard Model

Standard Model (SM)

- (1978-present): SM unifies three of the four fundamental forces (electromagnetic, weak, and strong interactions), and classifies all known elementary particles.

Proton: (uud)
Neutron: (udd)



Wikipedia: Standard Model

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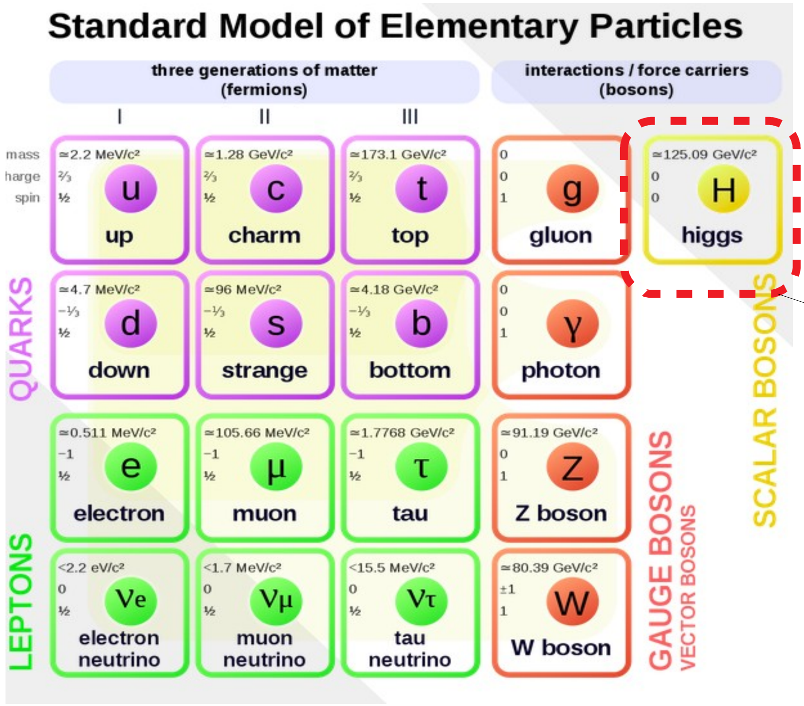


Higgs boson: gives masses to other particles.

Wikipedia: Standard Model

Standard Model (SM)

- (1978-present): SM unifies three of the four fundamental forces (electromagnetic, weak, and strong interactions), and classifies all known elementary particles.
- Lagrangian of SM is invariant under the symmetry transformation:

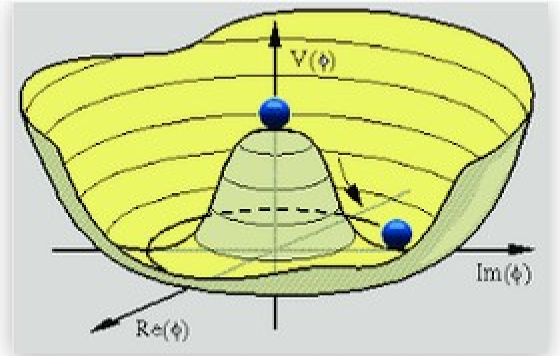
$$\underbrace{SU(3)_c}_{\text{Strong interaction}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{Electroweak interactions}}$$

Strong interaction

Electroweak interactions

Standard Model: Higgs mechanism

- Potential of Higgs field:



Explanation of the Brout-Englert-Higgs (BEH) ...
researchgate.net

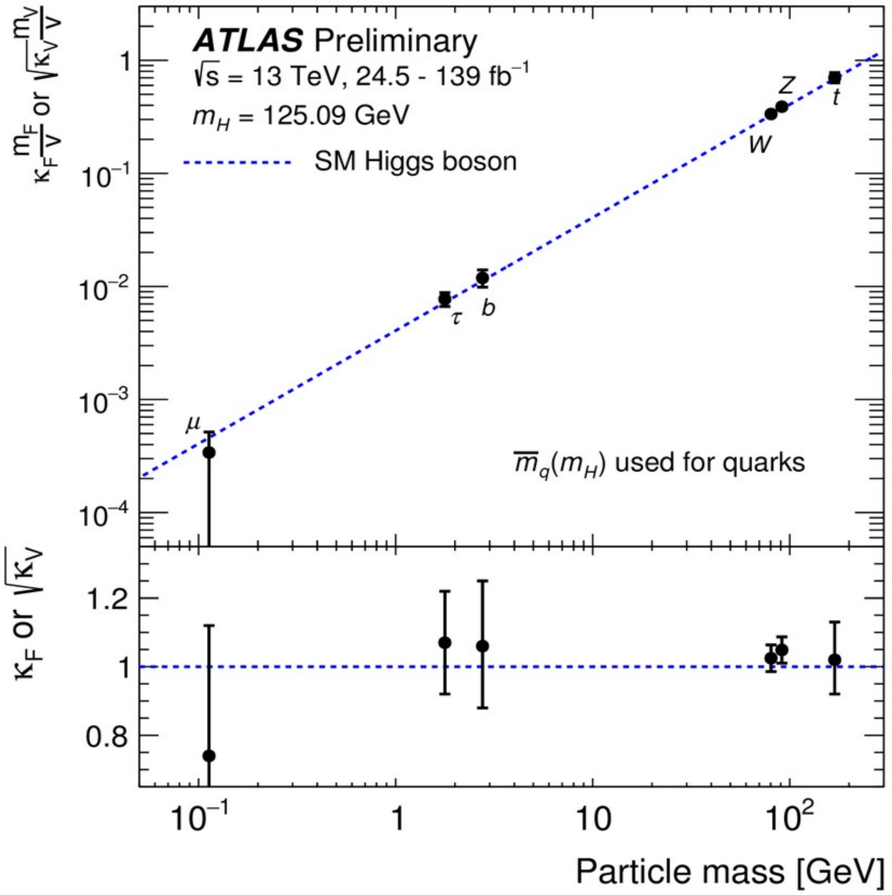
$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

- Minimum of potential: $H \neq 0$

Standard Model (SM)

- Higgs mechanism prediction that **particle's mass *proportional* to its coupling strength with Higgs.**

Heavier particle has stronger interaction with Higgs boson.

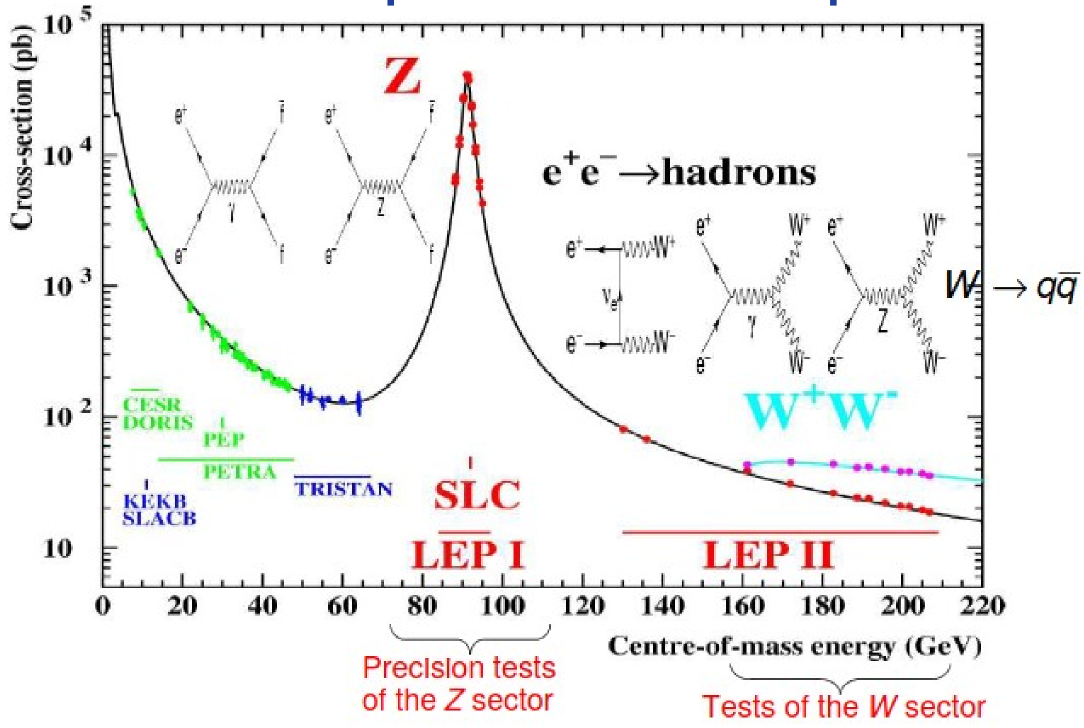


ATLAS Higgs physics group

Success of SM

- Successful theory should be tested by many observations and experiments.

Electron-positron collider experiment

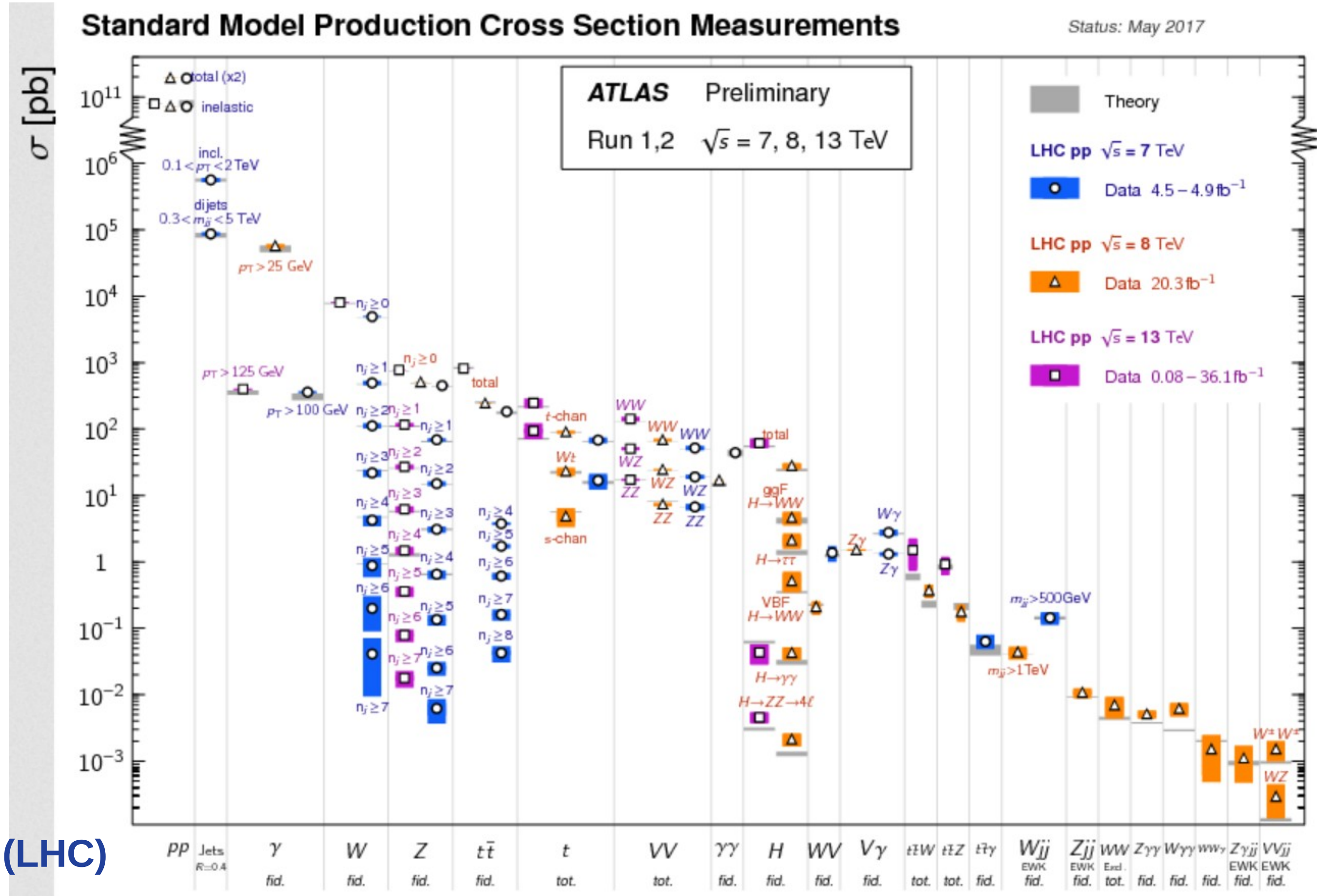


CERN Courier
Revisiting the b revolution – CERN Courier
방문

Success of SM

- Successful theory should be tested by many observations and experiments.

Kretzschmar,Jan, ATLAS,CMS,CERN Document: arXiv:1803.10800

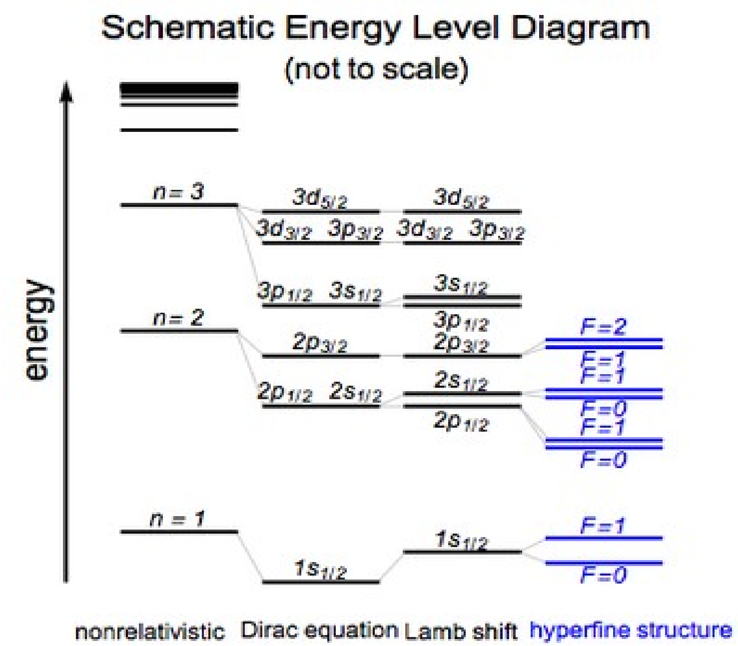


Large Hadron Collider (LHC)

Success of SM

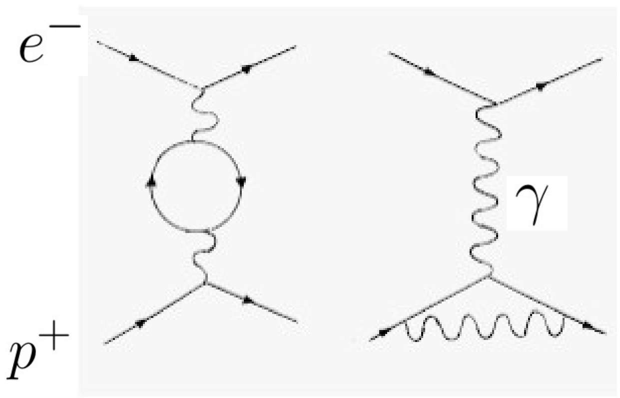
- Successful theory should be tested by many observations and experiments.

Energy spectra of Hydrogen atom:



Wolfram Demonstrations Project
Relativistic Energy Levels for Hydrogen Atom - Wolfram Demonstrations ...

Lamb shift



What exactly are virtual particles, and what p...
reddit.com

Members in our group

- Postdoc:

Jan Tristram Acuna

- PhD:

Yu-Min Yeh

Kuan-Yen Chou

- Master:

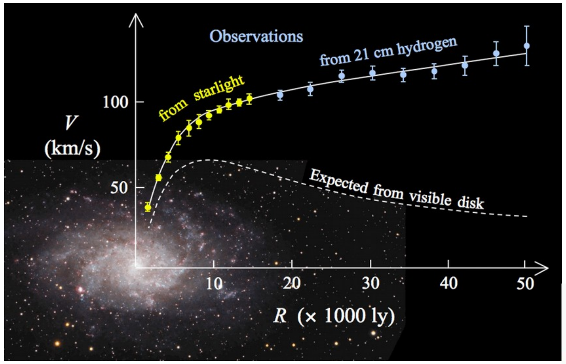
Leah, Ya-Ling Lin

Chang-Yu Dai

Dark Matter (DM):

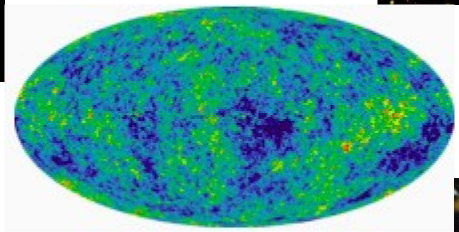
Indirect evidences of DM

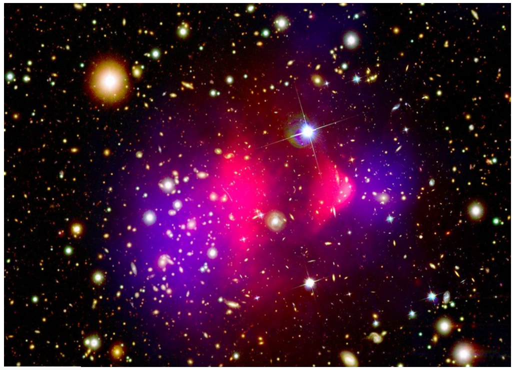
- Dark matter



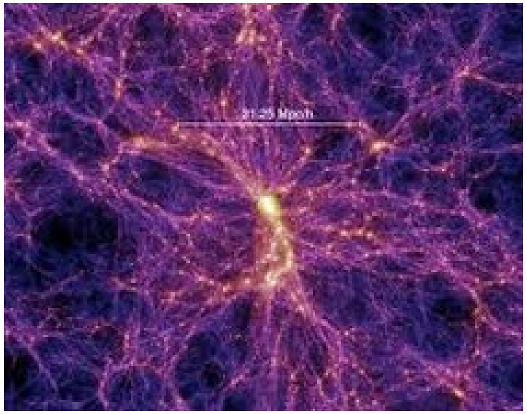
wikipedia.org Extended
rotation curve of M33

CMB





NASA: bullet cluster



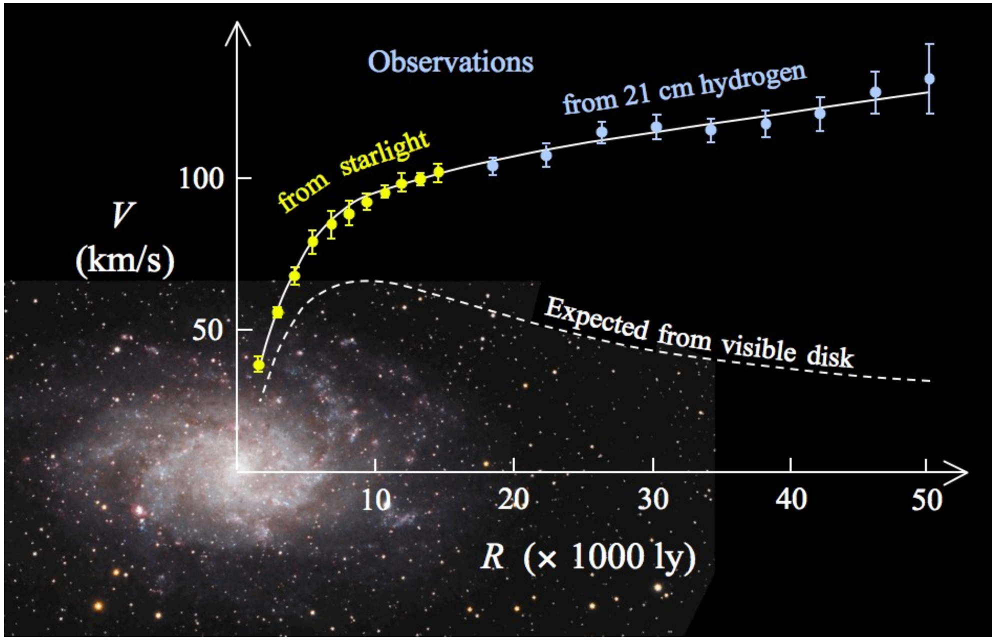
Large scale structure:
astro-ph/0504097

Hubble Space Telescope

Indirect evidences of DM

- Rotational curve of spiral galaxy: gravitational pulling force equals to centrifugal force.
- However, the observed rotational velocity is much faster than expected from visible disk.

$$m\frac{V^2}{r} = \frac{GMm}{r^2}$$

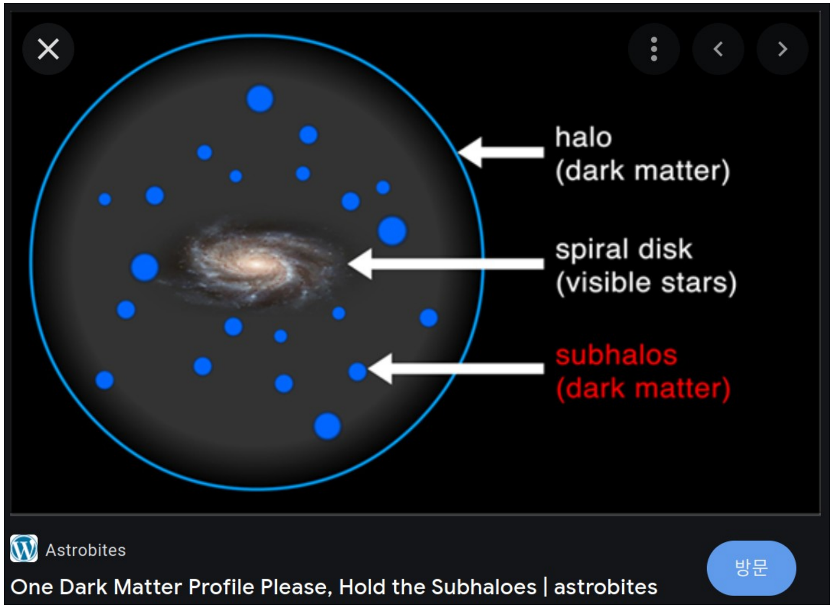


wikipedia.org Extended rotation curve of M33

Indirect evidences of DM

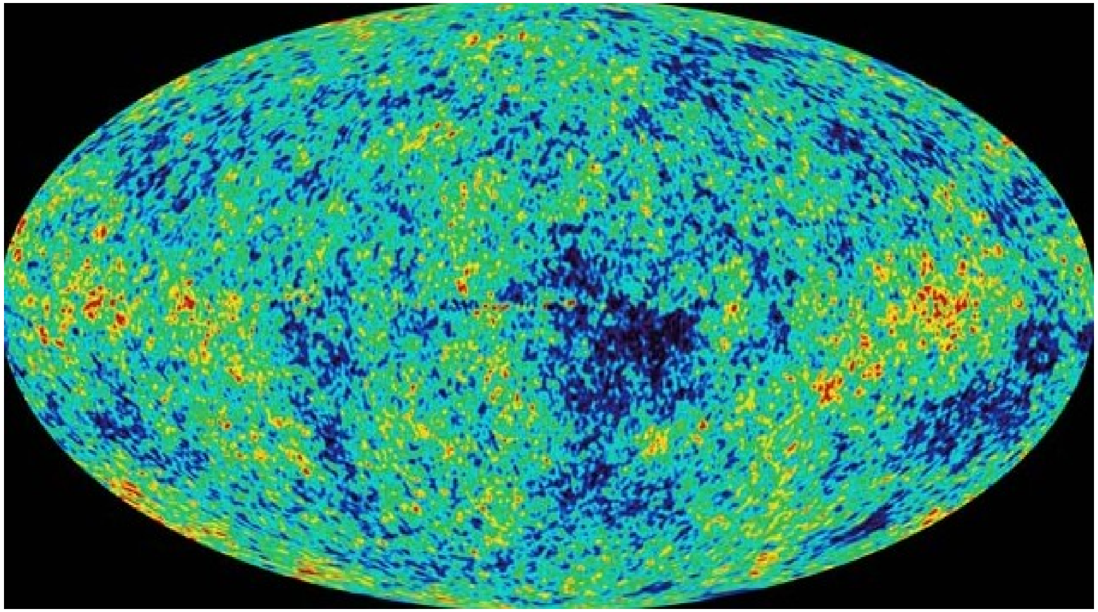
- We believe that the galaxy disk is surrounded by spherical DM halo.
- Total DM mass is 5 times heavier than galaxy disk.

Dark matter do not interact with photon.



Indirect evidences of DM: CMB

- Observation of Cosmic Microwave Background (CMB) by satellite Planck

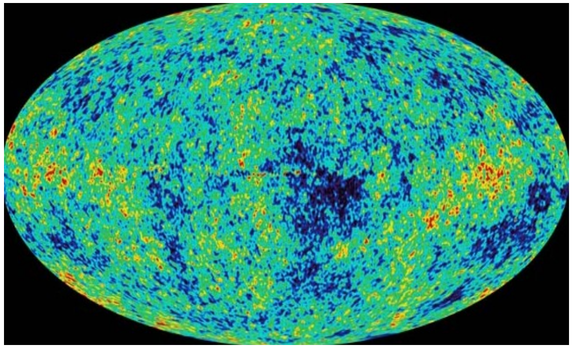


Planck Collaboration

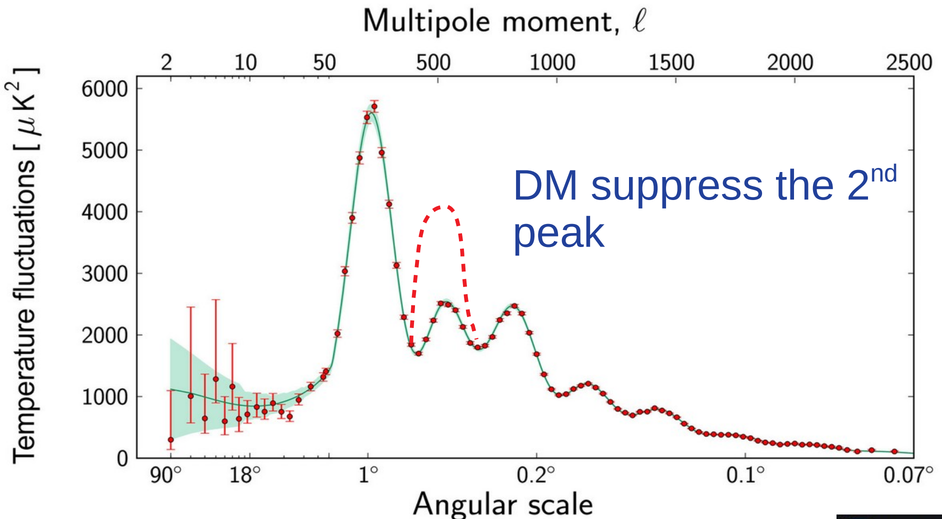
T=2.725 K. Temperature is very uniform universe. The color indicate the temperature fluctuation by 1/10000

Indirect evidences of DM: CMB

- Expand the temperature by spherical harmonic functions:

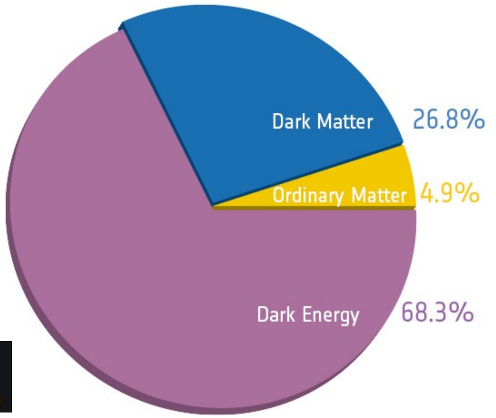


Planck Collaboration



European Space Agency
ESA - Planck Power Spectrum

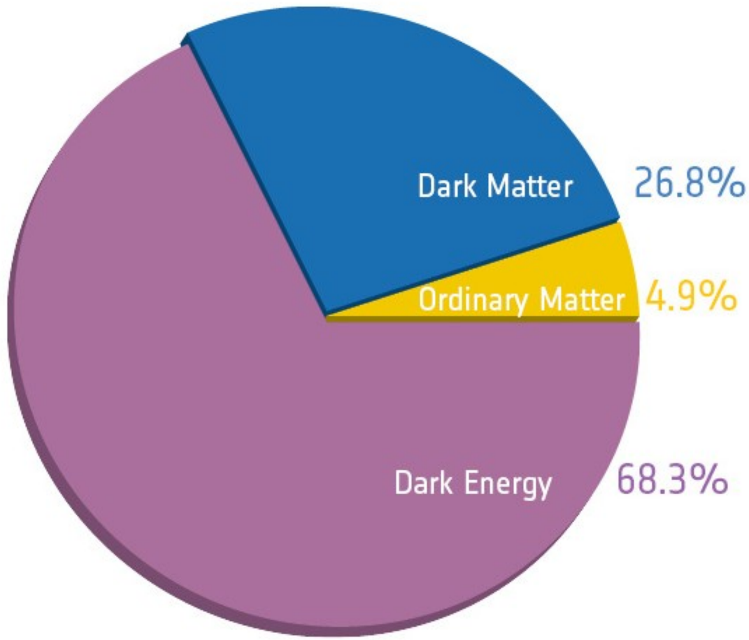
Composition of the Universe



Planck Satellite
Cosmic Microwave Background – Planck Satellite

DM relic abundance

- **Dark matter** *relic abundance* **is about 25% of our Universe. Ordinary matter***(SM particles, baryon, matter interact with photon)* **is about 5%.**



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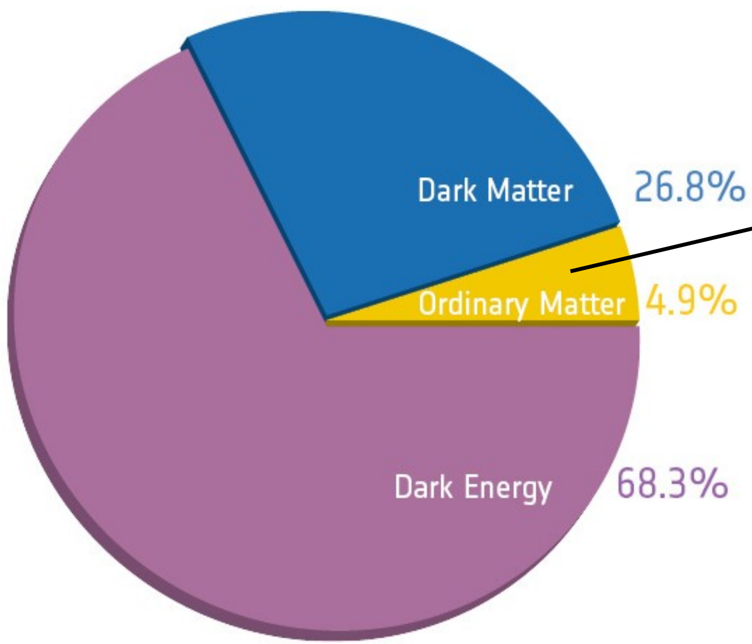
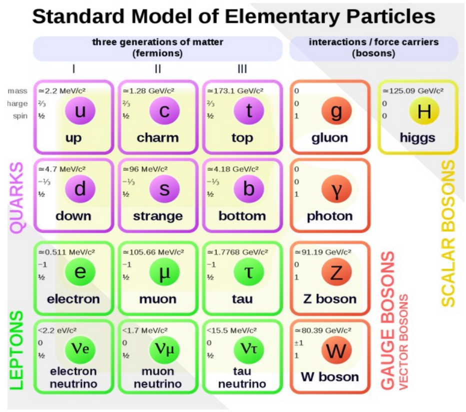


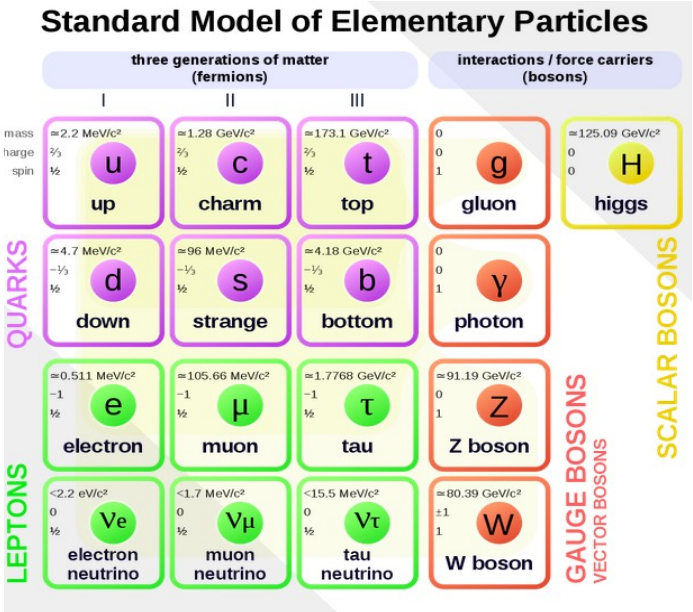


Planck Satellite
Cosmic Microwave Background – Planck Satellite

DM candidates

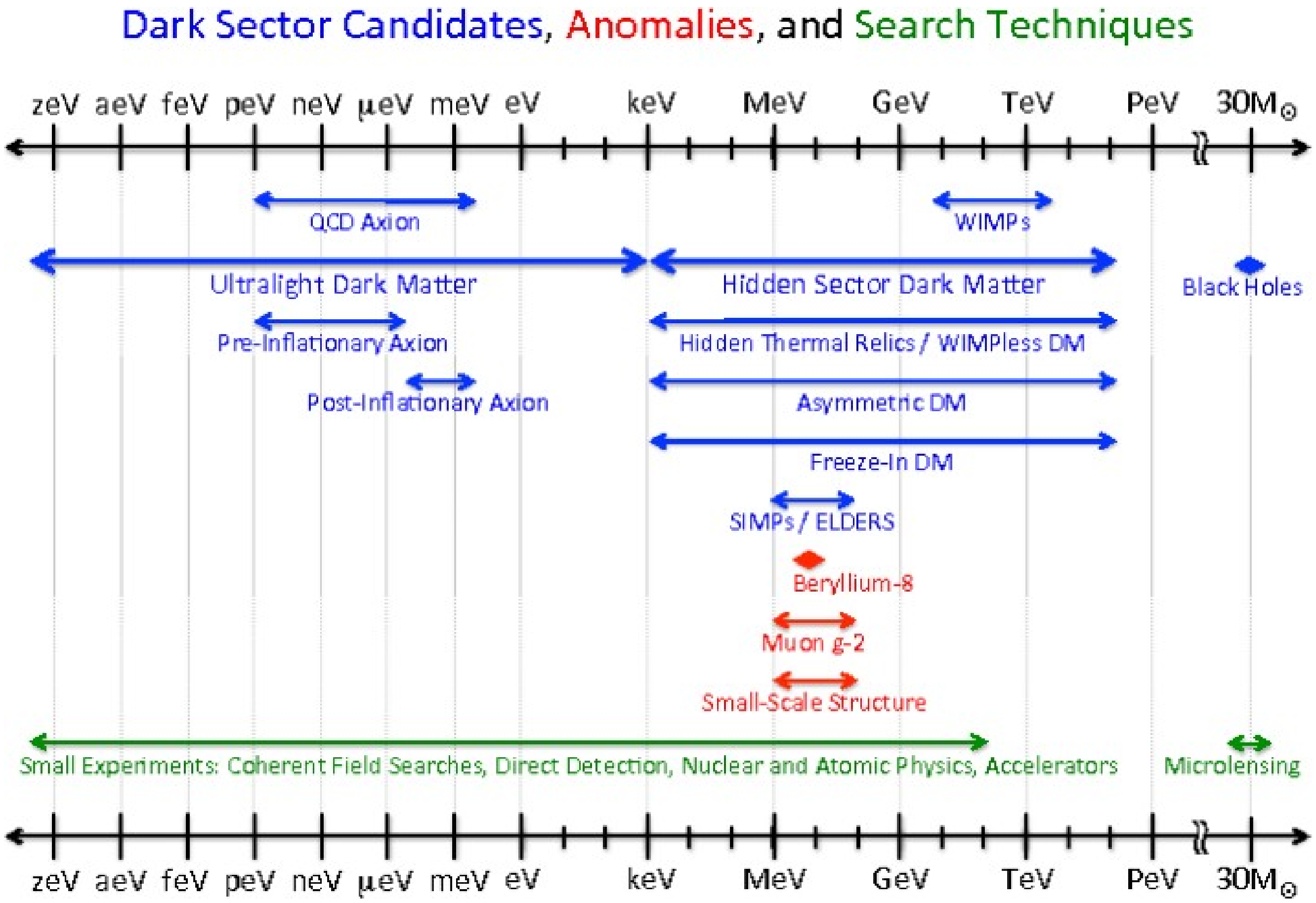
- Properties of **Dark matter:**
- I).Charge neutral.
- II).Lifetime longer than age of Universe.
- III).Non-relativistic.

Neutron decays.
Neutrinos are relativistic.



DM candidates

- DM mass:



CERN document Server: US:Cosmic Visions: New ideas in dark matter 2017

DM candidates

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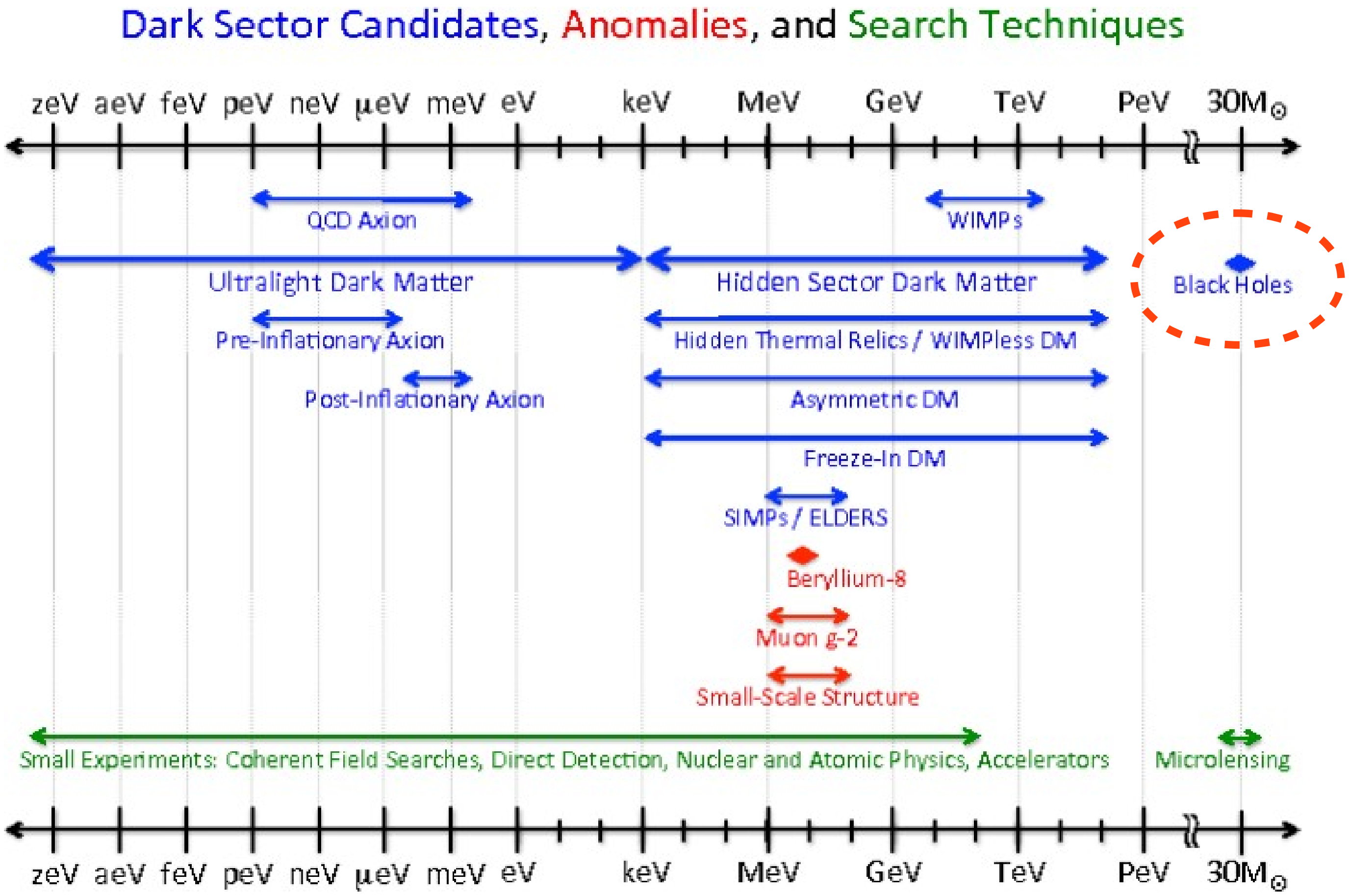


CERN document Server: US:Cosmic Visions: New ideas in dark matter 2017

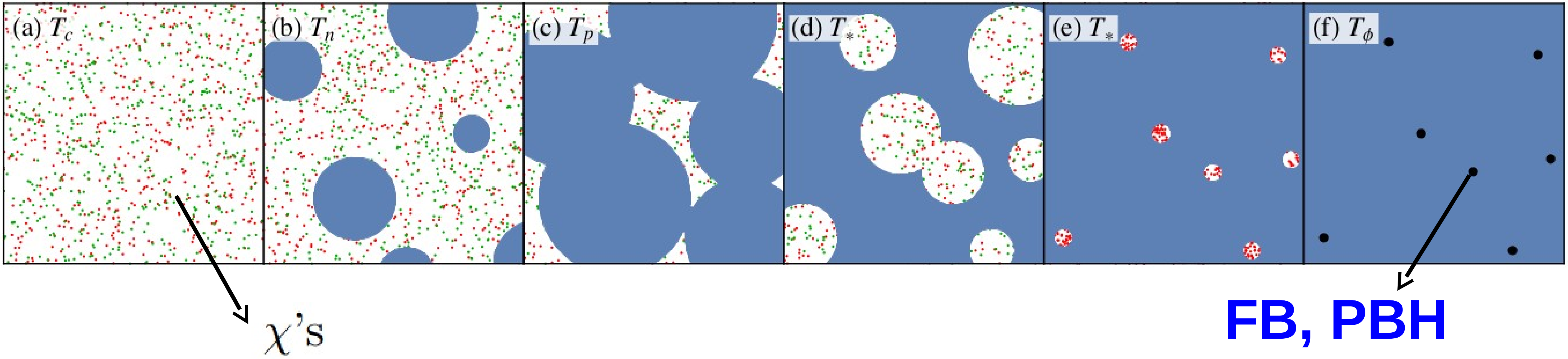
Research topics:

First order phase transition and macroscopic DM

PBHs from FOPT

- Schematic for **PBHs** formation form **FOPT**:

K.Kawana, K.P.Xie: 2106.00111



- The χ's trapped outside the bubble form macroscopic DM (**Fermi Ball** or **PBH**). Consequently, the mass of PBH can be much lighter than the Sun.

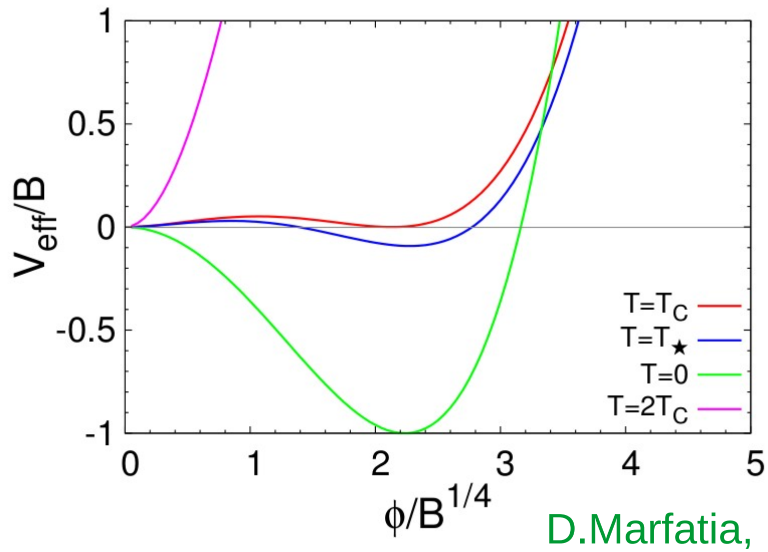
Model framwork

- The origin of DM mass may come from the **spontaneous symmetry breaking** inducing by another scalar.

$$\mathcal{L} \supset \bar{\chi} i \partial\!\!\!/ \chi - g_\chi \phi \bar{\chi} \chi - V_{\rm eff}(\phi, T)$$

$$m_\chi \simeq g_\chi \langle \phi \rangle$$

- We consider **1st order phase transition (FOPT)**.



D.Marfatia, P.Y.Tseng, JHEP 11 (2021) 068

Light PBHs from FOPT

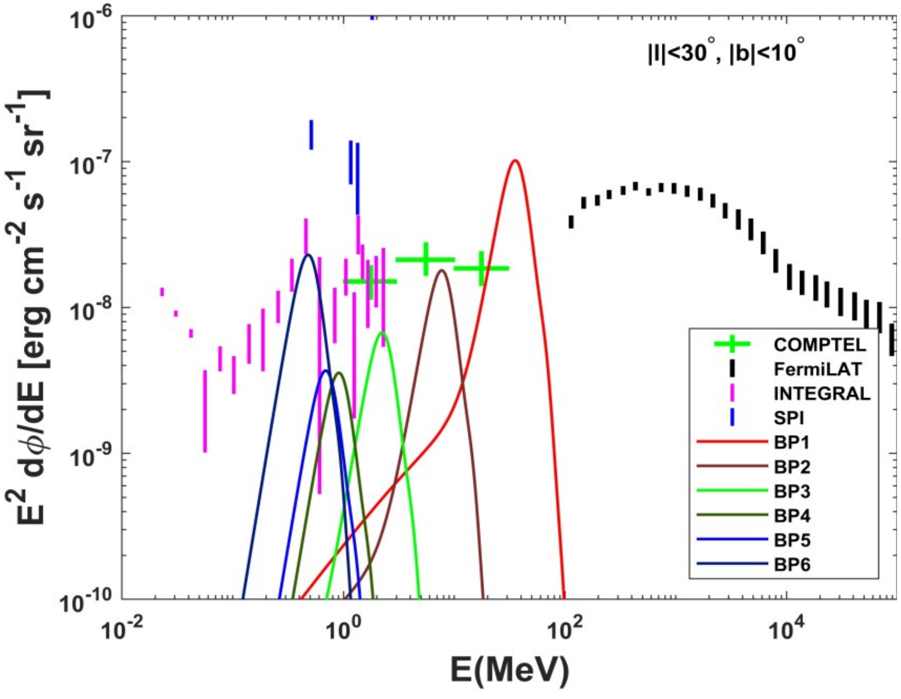
- PBHs with 1E-17 solar mass are produced from MeV energy scale **FOPT**.

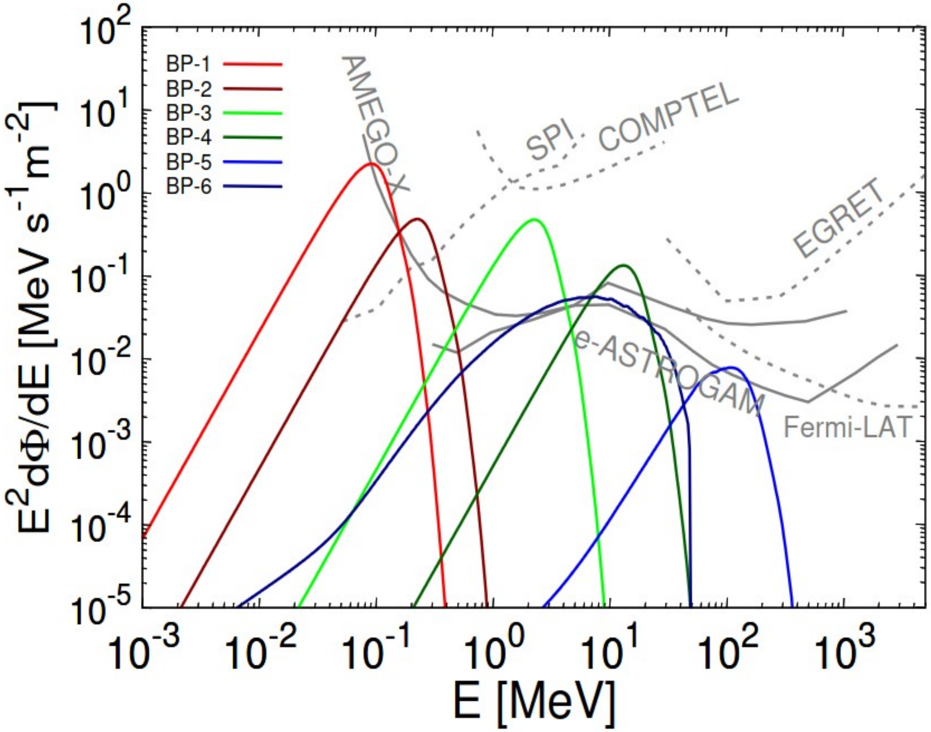
	BP-1	BP-2	BP-3	BP-4	BP-5	BP-6
λ	0.061	0.110	0.195	0.087	0.150	0.158
$B^{1/4}$/MeV	75.14	13.81	1.501	1.261	0.121	2.999
C/MeV	0.249	0.462	0.078	0.052	0.011	0.325
D	0.596	1.458	1.119	0.596	1.418	0.519
g_χ	1.088	1.301	1.011	1.289	0.983	1.228
η_χ	1.03×10^{-9}	1.28×10^{-10}	1.64×10^{-12}	1.21×10^{-15}	2.59×10^{-18}	6.26×10^{-17}
m/MeV	53.41	0.120	0.259	0.394	0.341	1.704
$T_{\mathrm{SM}\star}$/MeV	94.68	14.63	0.895	2.104	0.164	4.774
$T_\star$/MeV	53.16	6.143	0.421	0.868	0.052	2.287
T_f/MeV	59.63	6.888	0.472	1.023	0.068	2.571
T_ϕ/MeV	53.09	6.045	0.415	0.857	0.050	1.950
$S_3(T_\star)/T_\star$	155	159	166	171	180	170
$M_{\mathrm{PBH}}/M_\odot$	2.92×10^{-16}	1.15×10^{-16}	1.19×10^{-17}	1.93×10^{-18}	3.91×10^{-19}	4.23×10^{-20}
Q_{FB}	1.26×10^{42}	4.31×10^{42}	5.96×10^{42}	5.01×10^{41}	7.58×10^{41}	4.18×10^{39}
β'	2.80×10^{-17}	2.54×10^{-19}	7.78×10^{-23}	4.45×10^{-26}	5.75×10^{-30}	8.97×10^{-28}
α	1.48×10^{-2}	7.40×10^{-3}	1.20×10^{-2}	1.12×10^{-2}	1.35×10^{-2}	1.30×10^{-2}
$\beta/H_\star$	4.41×10^{3}	9.36×10^{3}	3.21×10^{4}	3.25×10^{3}	4.94×10^{3}	2.64×10^{3}
v_w	0.904	0.904	0.904	0.930	0.963	0.905
$v_\phi(T_\star)$/MeV	224	23.1	1.426	3.821	0.247	8.157
$dM_{\mathrm{FB}}/dQ_{\mathrm{FB}}$/MeV	258	28.3	1.980	4.264	0.573	10.89
$\Omega_{\mathrm{PBH}}h^2$	0.079	1.12×10^{-3}	1.09×10^{-6}	1.52×10^{-9}	2.15×10^{-13}	6.35×10^{-29}
ΔN_{eff}	0.218	0.126	0.208	0.146	0.147	0.221

D.Marfatia, P.Y.Tseng, JHEP 08 (2022) 001

Gamma-ray from PBH evaporation

- Galactic/Extragalactic gamma-ray spectra and GC 511 keV line from PBH evaporation:

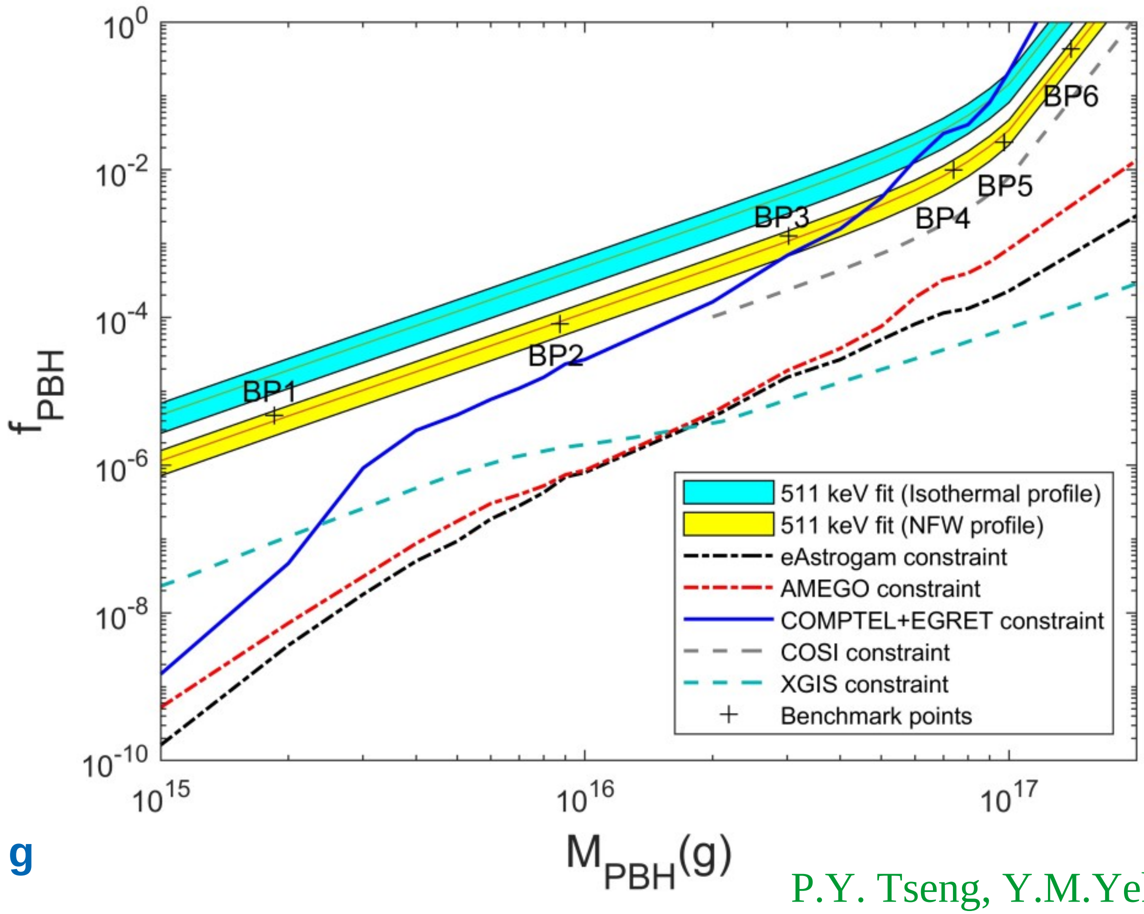




P.Y. Tseng, Y.M.Yeh: JCAP 08 (2023) 035

GC 511 keV gamma-ray and PBH

- Produced black hole mass can be much lighter than our Sun:

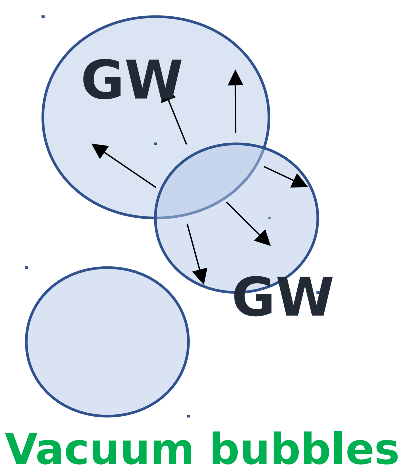


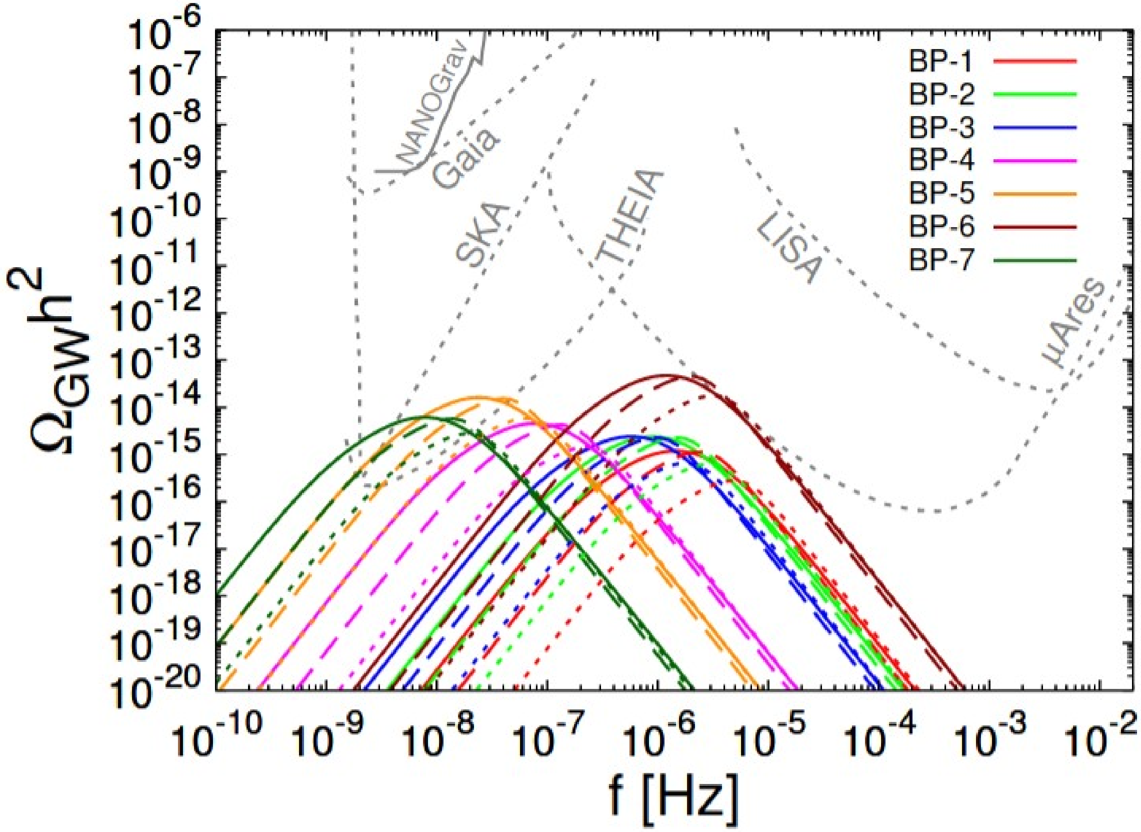
Solar mass=2*10^33 g

P.Y. Tseng, Y.M.Yeh: JCAP 08 (2023) 035

Gravitational wave signals

- GW spectra from the FOPT with bubble size distribution:





D. Marfatia, P.Y. Tseng, Y.M.Yeh: 2407.15419

Axion star and Fast Radio Bursts

Introduction

- **QCD axion**: solve strong CP problem.
- **Axion-like particle (ALP)**: is a psuedoscalar boson, its mass is not linear proportional to the couplings to SM particles.
- **ALP** remains one of the dark matter candidates.
- **ALP** can couple to photons: $g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$

Introduction

- **ALPs** are produced at high occupancy in the early Universe by a misalignment mechanism.
- **ALPs** form the Bose-Einstein condensate (BEC) if they are in thermal equilibrium.
- **ALPs** BEC is driven by attractive gravitational interaction, result in gravitational bound object *axion stars* (or *axion clumps, boson stars*).

Profile of Axion star

- Hamiltonian carries a global U(1) symmetry, which implies the total number of axion is conserved: $N \equiv \int d^3x |\psi|^2$
- We adopt the Gaussian ansatz for spatial wavefunction:

$$\psi_{\rm G}(r;R) = \sqrt{\frac{N}{\pi^{3/2}R^3}} \exp\left(-\frac{r^2}{2R^2}\right), \quad f_{\rm G}(x) = \exp\left(-x^2/2\right).$$

- Minimizing the Hamiltonian:

$$\gamma \equiv \frac{f_a^2}{m_a^2}\lambda$$

$$N = 2.4258 \times 10^{60} \times \alpha \left(\frac{10^{-5}\,{\rm eV}}{m_a}\right)^2 \left(\frac{f_a}{10^{12}\,{\rm GeV}}\right) \left(\frac{0.3}{|\gamma|}\right)^{\frac{1}{2}}$$

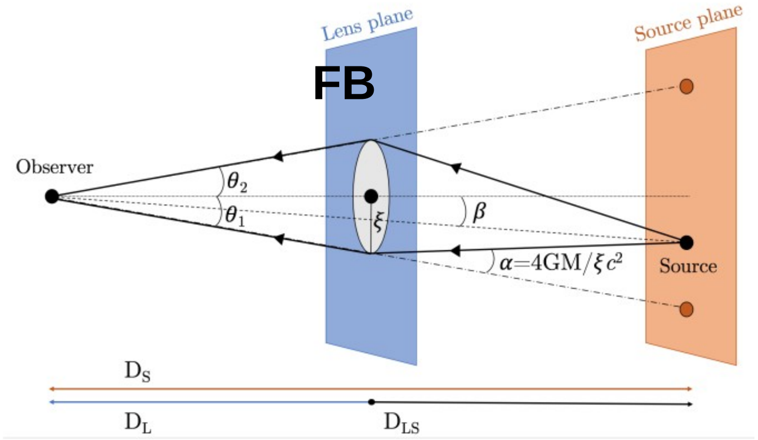
$$R = 2.2830 \times 10^4\,{\rm m} \times \left(\frac{1+\sqrt{1 \mp \alpha^2}}{\alpha}\right) \left(\frac{10^{-5}\,{\rm eV}}{m_a}\right) \left(\frac{10^{12}\,{\rm GeV}}{f_a}\right) \left(\frac{|\gamma|}{0.3}\right)^{\frac{1}{2}}$$

$$M_{\rm AS} = 2.1716 \times 10^{-11} M_\odot \times \alpha \left(\frac{10^{-5}\,{\rm eV}}{m_a}\right) \left(\frac{f_a}{10^{12}\,{\rm GeV}}\right) \left(\frac{0.3}{|\gamma|}\right)^{\frac{1}{2}}.$$

Phys.Rev.D 104 (2021) 12, 123012. [2109.04283]

Microlensing

- These FB mass and radius ranges can induce microlensing effects.



$$\theta_{\rm E} \equiv \sqrt{\frac{4GM}{c^2}\frac{D_{\rm LS}}{D_{\rm L}D_{\rm S}}}$$

$$\mu_{\rm tot} = \frac{u^2+2}{u\sqrt{u^2+4}} \xrightarrow{u=1} 1.34 \,.$$

D.Croon, D. McKeen, N. Raj: 2002.08962

- The separating angle of two images of the background star are too small to be resolved, but we can observe the sudden luminosity enhancement of the star.

Light propagation in axion medium

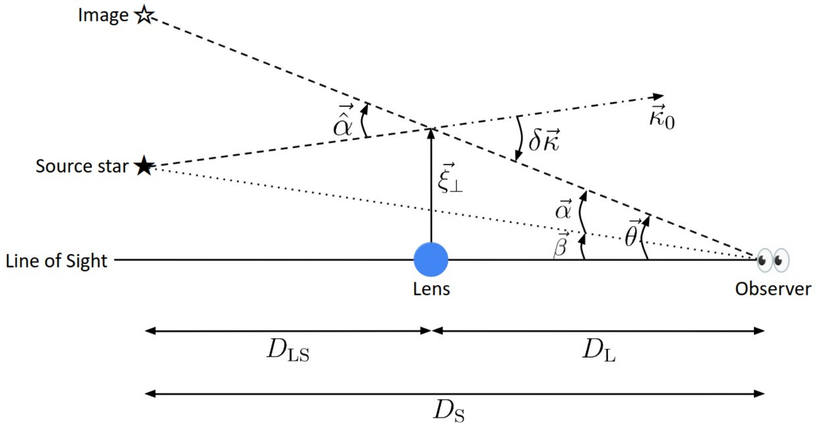
- Deflection angle increases in longer wavelength, i.e lower frequency.

J.T.Acuna, K.Y.Chou, P.Y.Tseng, arXiv:2501.07176

- The change in momentum of propagating photon

$$\left(\frac{\delta\vec{\kappa}}{\kappa_0}\right)_{\text{axion}} \approx \frac{g_{a\gamma\gamma}^2}{8\kappa_0^2}\int_{-\infty}^{\infty} dt'\ \vec{\nabla}_\perp (\partial a)^2$$

$$\left(\frac{\delta\vec{\kappa}}{\kappa_0}\right)_{\text{gravity}} = -2\int_{-\infty}^{\infty} dz\ \vec{\nabla}_\perp \Phi$$



Fast Radio Bursts (FRBs)

- FRBs are short-duration radio transients emitted by extragalactic sources.

Mandana Amiri et al. CHIME/FRB, Astrophys. J. Supp., 257(2):59, 2021.

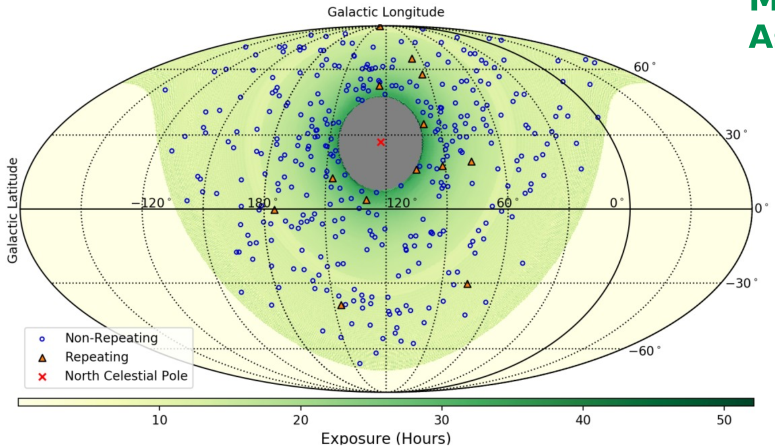


Figure 1.7: Sky map of FRBs detected by CHIME/FRB [34].

- Advantages from FRBs: I) observed in radio frequency, II) short-pulse signature.
- Lens effect increases in low frequency.
- The observation can resolve two images due to time delay.

Fast Radio Bursts (FRBs)

- Signal requirements: I) Magnification ratio between two images < 5, ii) Time difference between two images is longer than microsecond. Julian B. Munoz et al. Phys.Rev.Lett 117 (2016) 9, 091301.

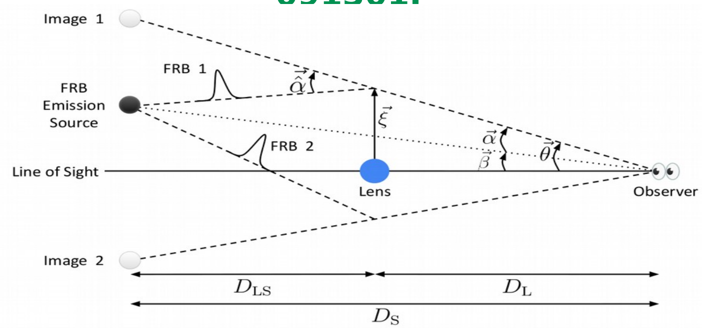


Figure 4.1: Geometrical setup of the FRB lensing event.

K.Y.Chou's thesis

- Signal criteria:

$$\Delta t = |t(\theta_+) - t(\theta_-)|$$

$$R_f \equiv \frac{|\mu(\theta_+)|}{|\mu(\theta_-)|}$$

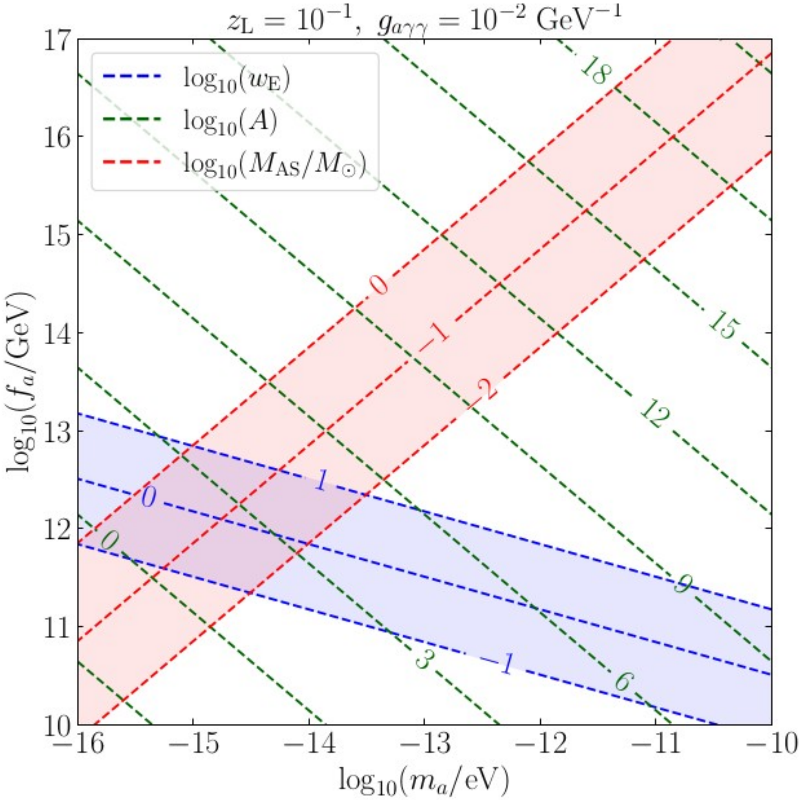
$$\Delta\bar{t} = 1\,\mu\text{s}$$

$$R_{f,\text{max}} = 5$$

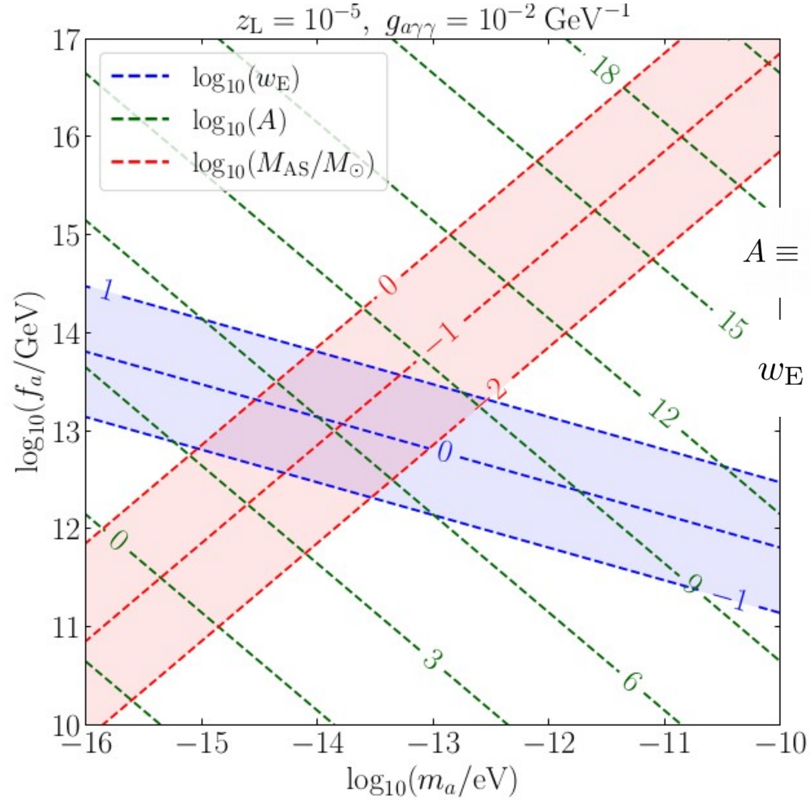
Parameter regine

- Parameter region: gravity and axion-photon lensing are comparable:

Extragalactic AS:



Galactic AS:



$$A \equiv \frac{g_{a\gamma\gamma}^2}{16\pi G_N (\kappa_0 R)^2}$$

$$w_E \equiv \frac{D_L \theta_E}{R}$$

Sensitivities

- Sensitivities:

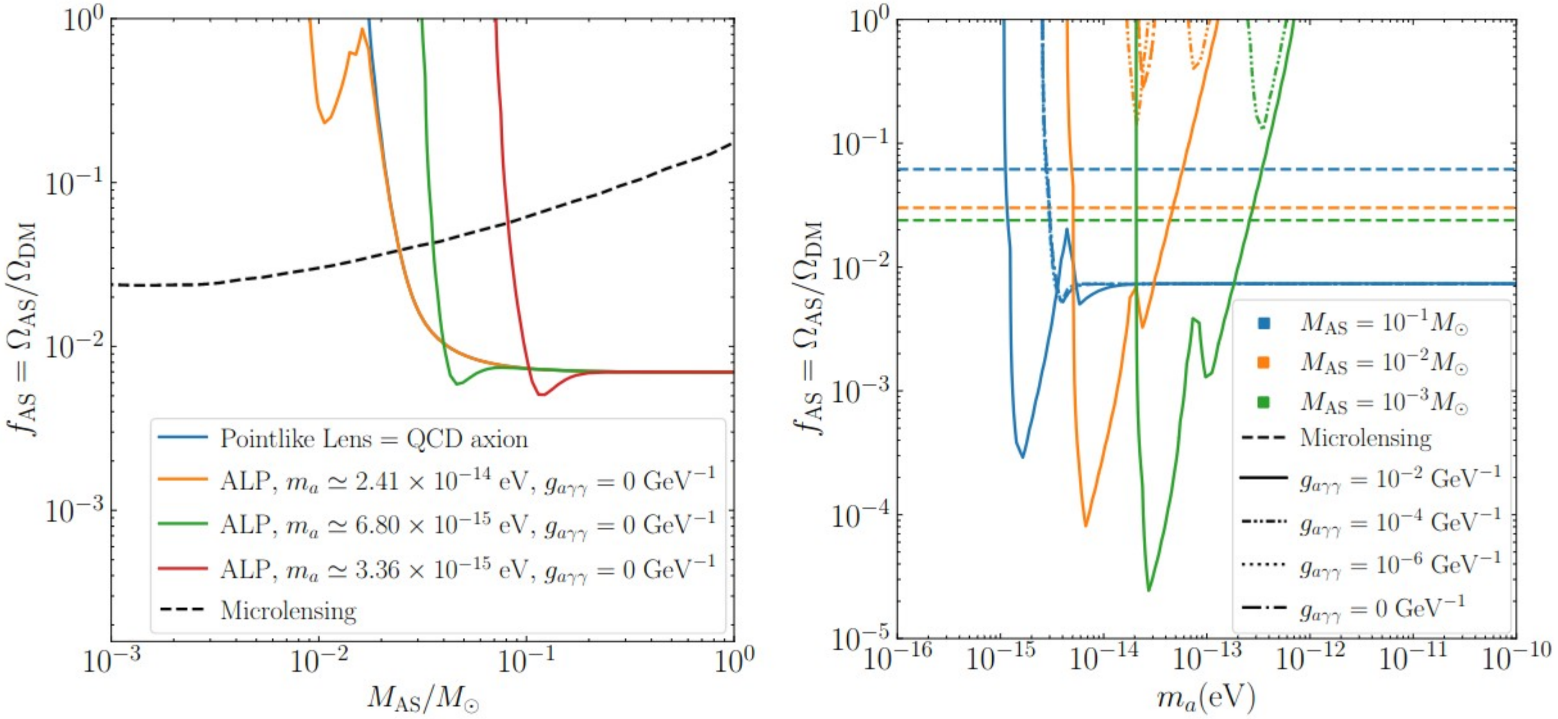


Figure 12: Constraint curves with $N_{obs} = 10^4$ and $\Delta t_{min} = 1\,\mu$s in the f_{AS}-$M_{AS}/M_\odot$ plane and f_{AS}-m_a plane, for the case of axion stars made of QCD axions and ALPs of fixed m_a (left panel) and ALPs (right panel).

J.T.Acuna, K.Y.Chou, P.Y.Tseng, arXiv:2501.07176

Summary

- We investigate the signatures from various DM candidates, including **PBH** and **axion star**.
- Light **PBH** features Hawking evaporation, generating gamma-ray or neutrino (cosmic-ray).
- **FOPT** provides a production mechanism for light **PBH**s and predicts Gravitational Waves.
- For **axion star**, we study the lensing effect induced by gravity and axion-photon couplings, considering signal of FRBs.

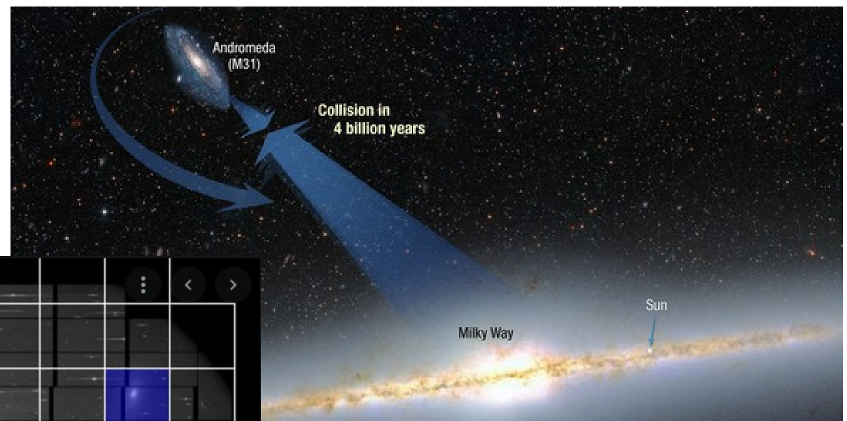
Thank you for your attention!

Back up

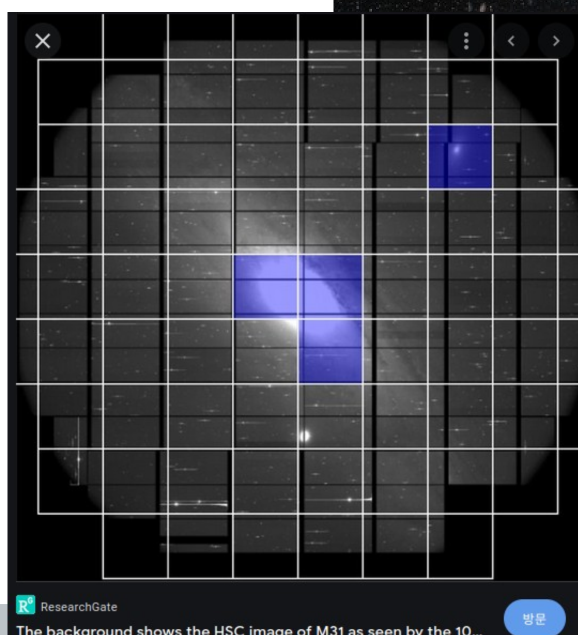
Microlensing

- Astrophysical Sky surveys are ideal for observing microlensing. Ex. Subaru-HSC (observing M31 for 7 hrs).

FB halos surround MW and M31. FBs and stars have relative velocity of 250 km/s.



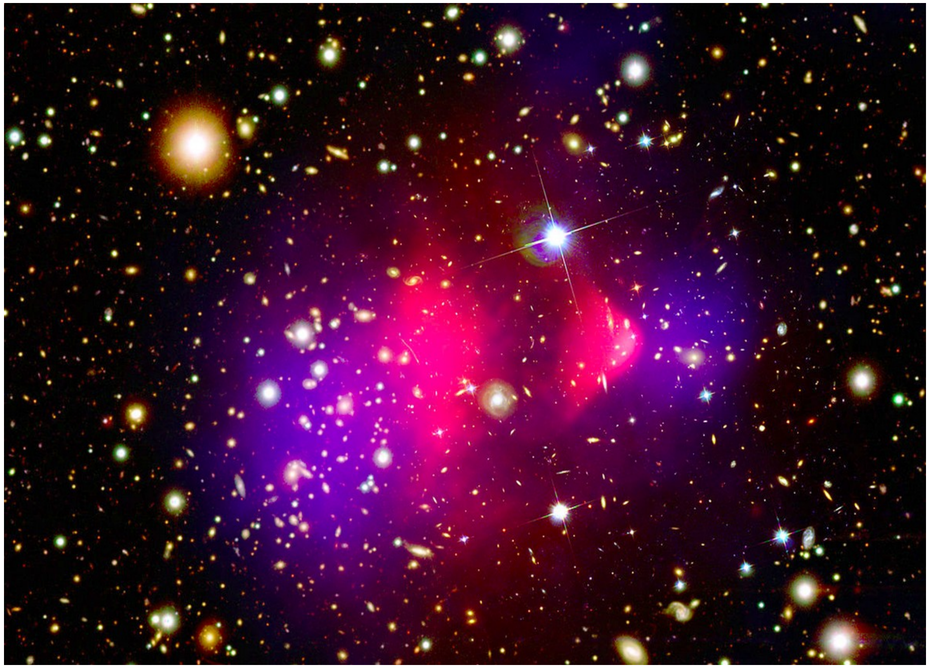
Milky Way Destined for Head-On Collision | NASA



M31 image from Subaru-HSC

Indirect evidences of DM

- Supporting evidence from Bullet cluster: picture of the two galaxies collided and pass through each other.



NASA: bullet cluster

Indirect evidences of DM

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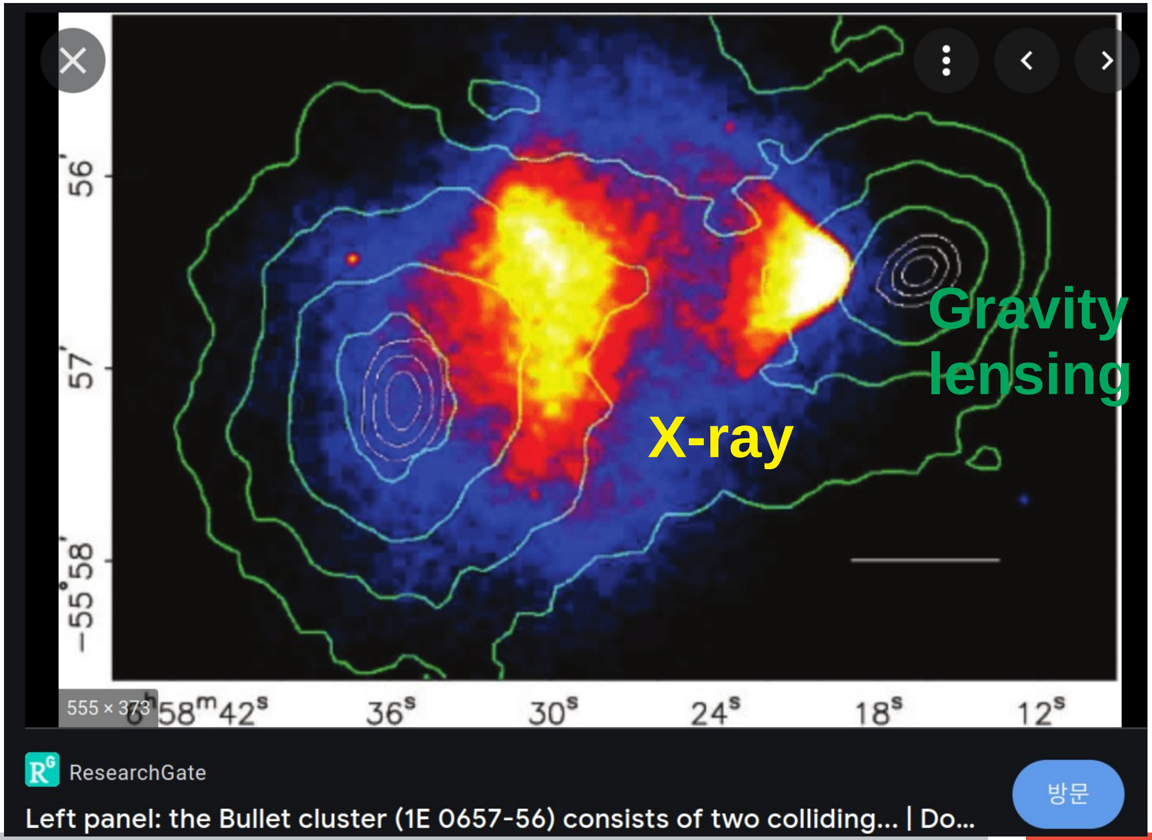

Indirect evidences of DM

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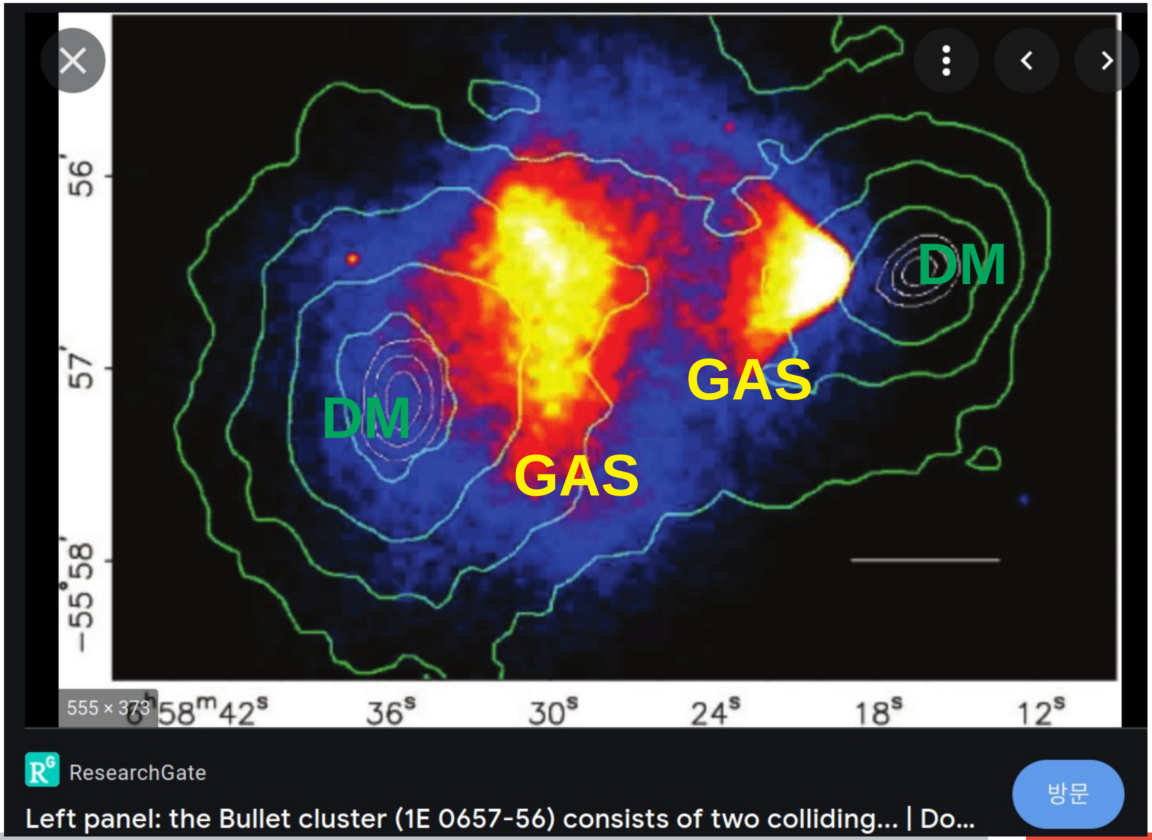
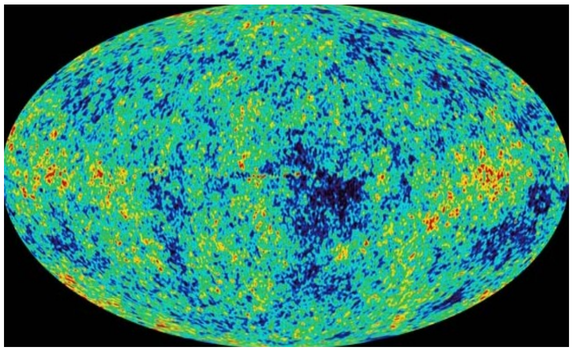
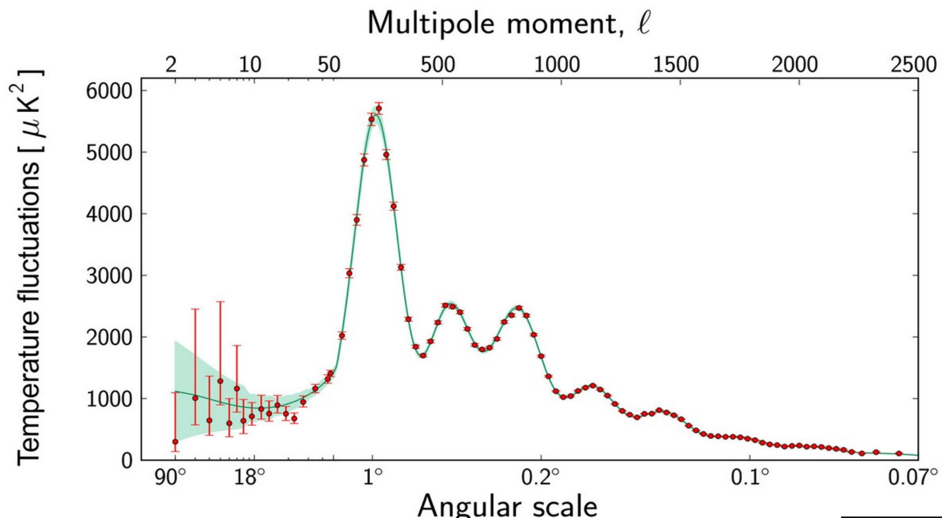


Indirect evidences of DM: CMB

- Expand the temperature by spherical harmonic functions:



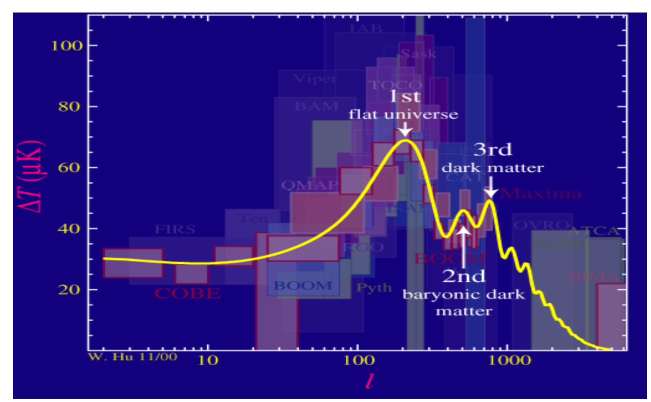
Planck Collaboration



European Space Agency

ESA - Planck Power Spectrum

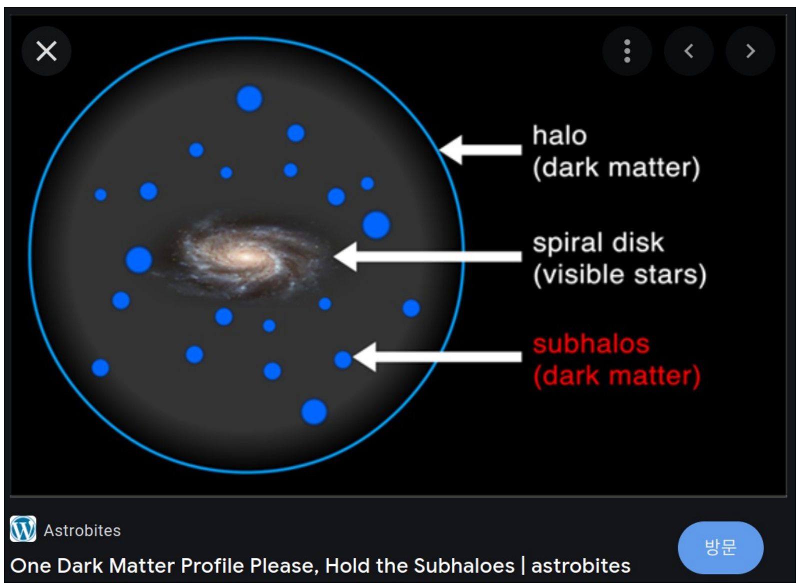
DM provides gravitational force can enhance the 1st and 3rd peaks, but weak the 2nd peak.



DM Search

DM search: direct detection

- DM direct detection.
- We can detect more DM signal in summer than in winter.



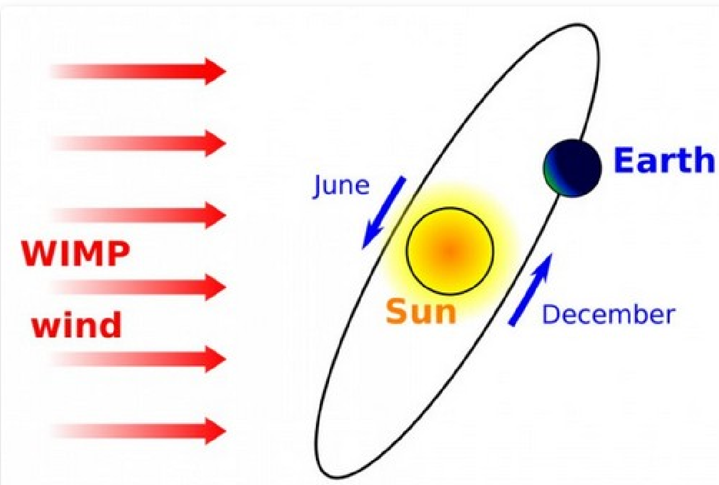


Illustration of the expected "WIMP wind" due to the motion of the Sun relative to the DM halo of the Milky Way. Figure from arXiv:1209.3339

DM search: direct detection

- DM direct detection.
- Experimentalists put a detector underground shielding the background, mostly come from cosmic ray.

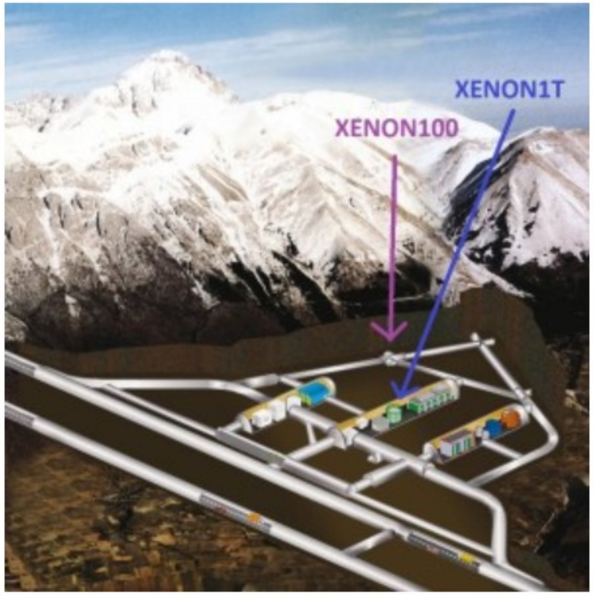
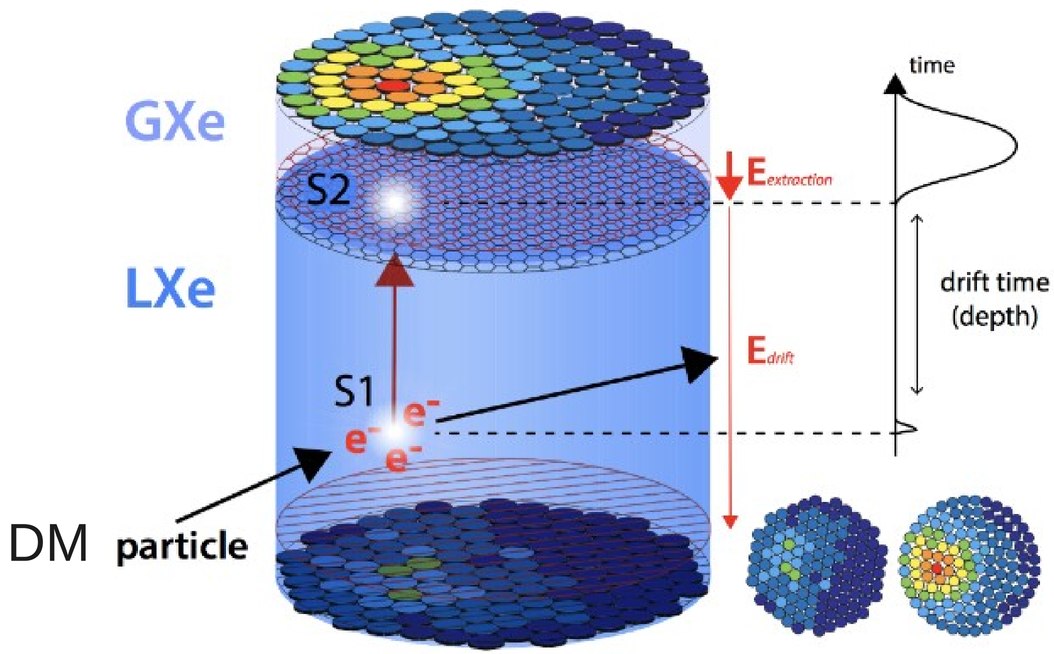


Figure 1: XENON100 and XENON1T Locations at LNGS

DM search: direct detection

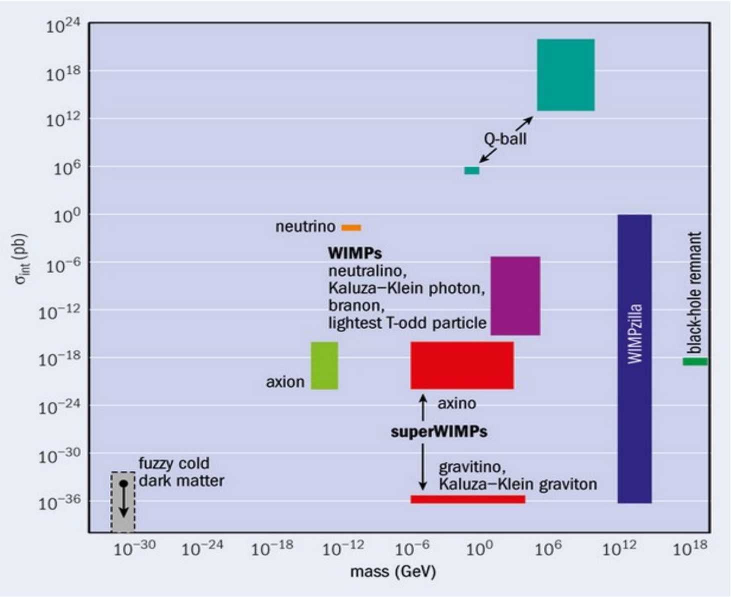
- XENON1T detector:

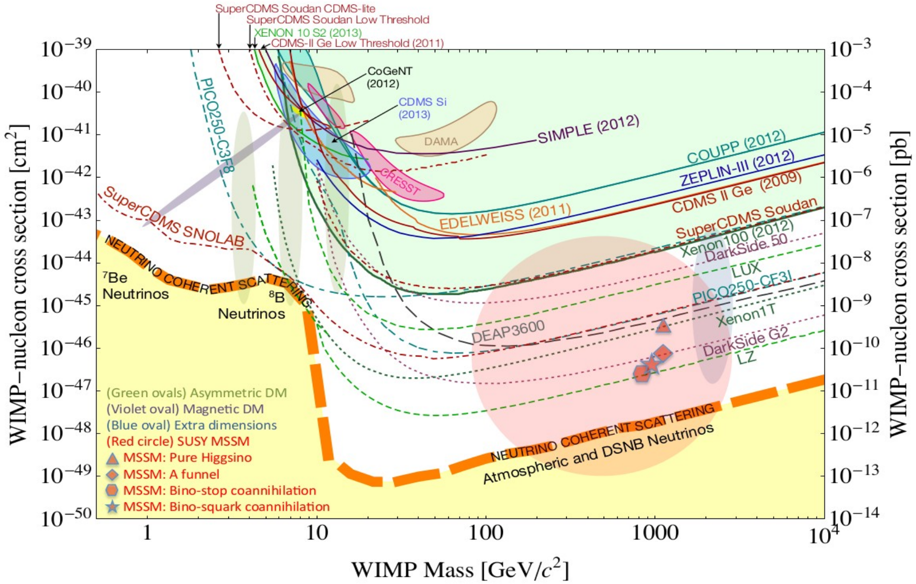


Ni Group at UC San Diego - University of California San Diego
[PDF] Status and Results of the XENON1T Dark Matter Search

DM search: direct detection

- Supersymmetry theory predicts the **WIMP (weakly interactive massive particle)** around O(100) GeV to 1 TeV.
- It is constrained from direct detection searches.





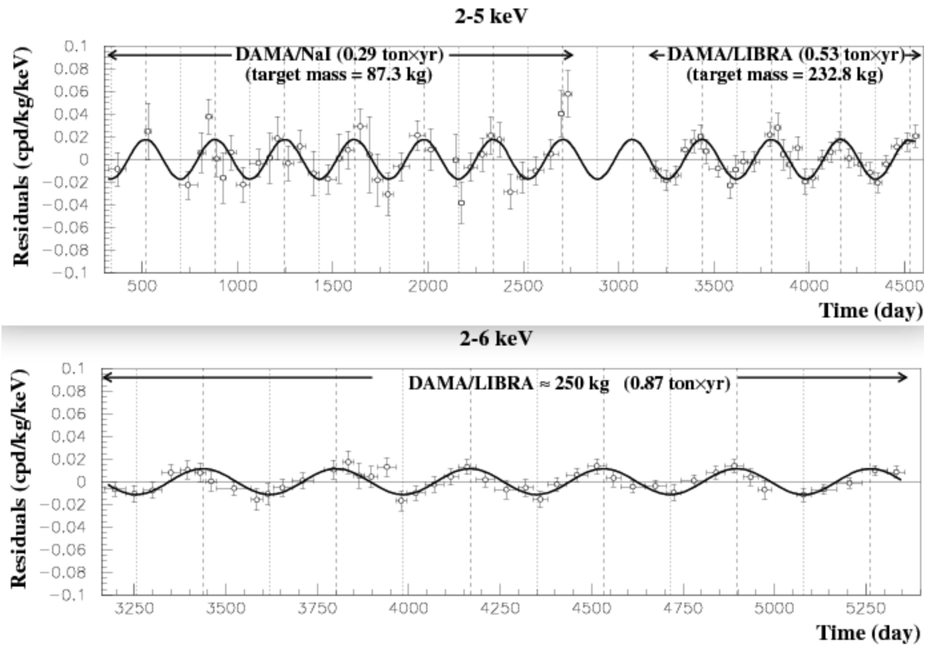
Towards Dark Matter Discovery 2018

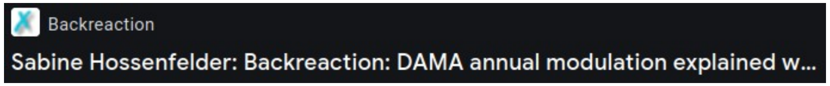
P. Cushman et. al.:1310.8327v2

DM search: direct detection

- DAMA/LIBRA (NaI) annul modulation signal.

But it can be explained without DM. (arXiv:1407.1052)





DAMA/LIBRA: arXiv:0804.2741