Gravitational Waves for New Physics

Yue Zhao

University of Utah → HKUST

~~Gravitational Waves~~ for ~~New Physics~~

second half

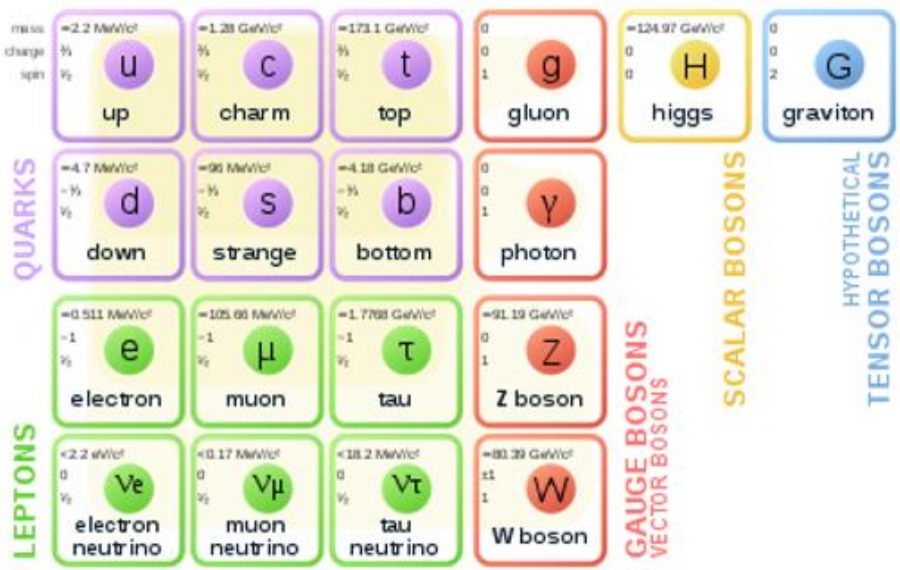
first half

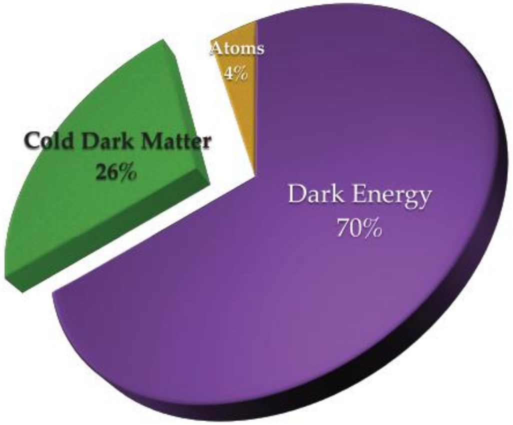
Yue Zhao

University of Utah → HKUST

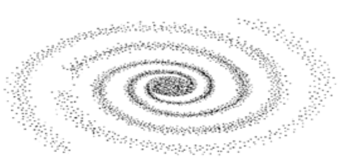
What Do We Know About Dark Matter?

Particle Standard Model works extremely well in short distance, but fails miserably at cosmological scale!



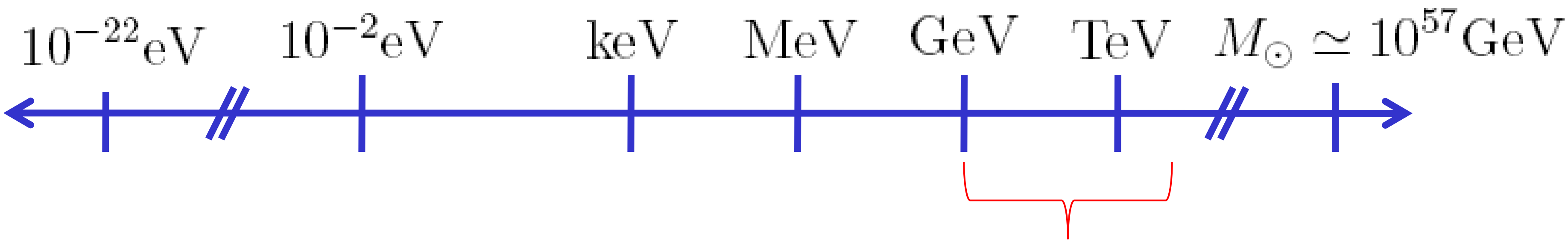


$10^{-22}\mathrm{eV}$ $10^{-2}\mathrm{eV}$ keV MeV GeV TeV $M_{\odot} \simeq 10^{57}\mathrm{GeV}$

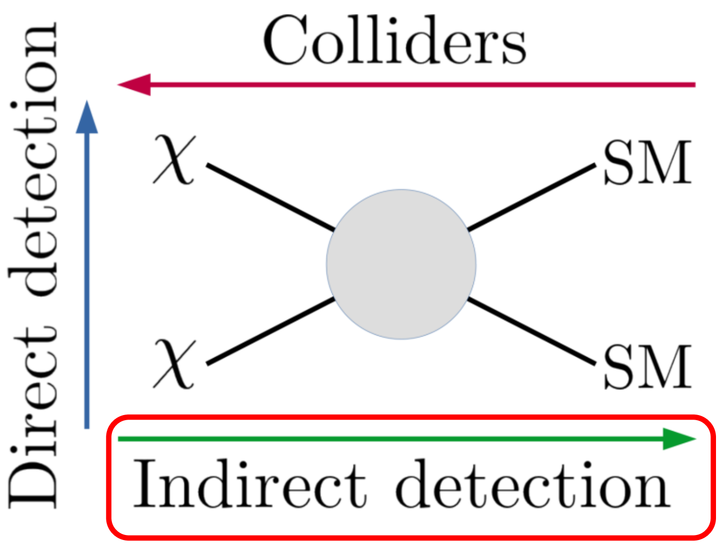


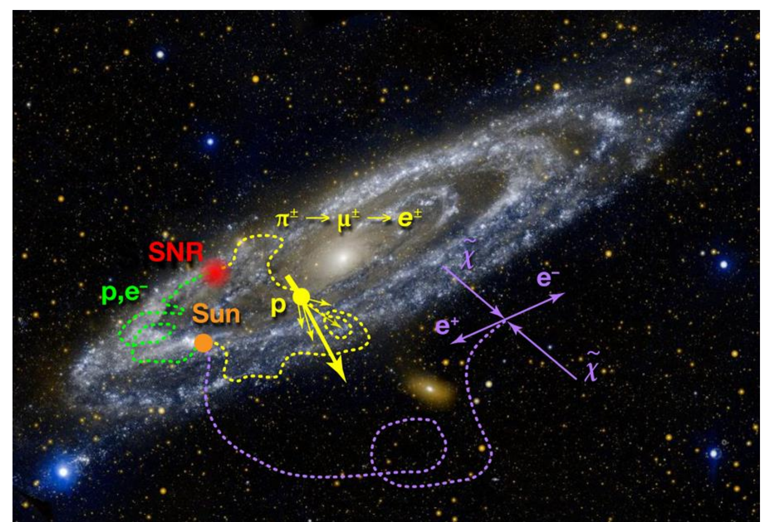
possible dark matter mass range
(Almost 100 orders of magnitude!!!)

A GeV excess at the Galactic Center:

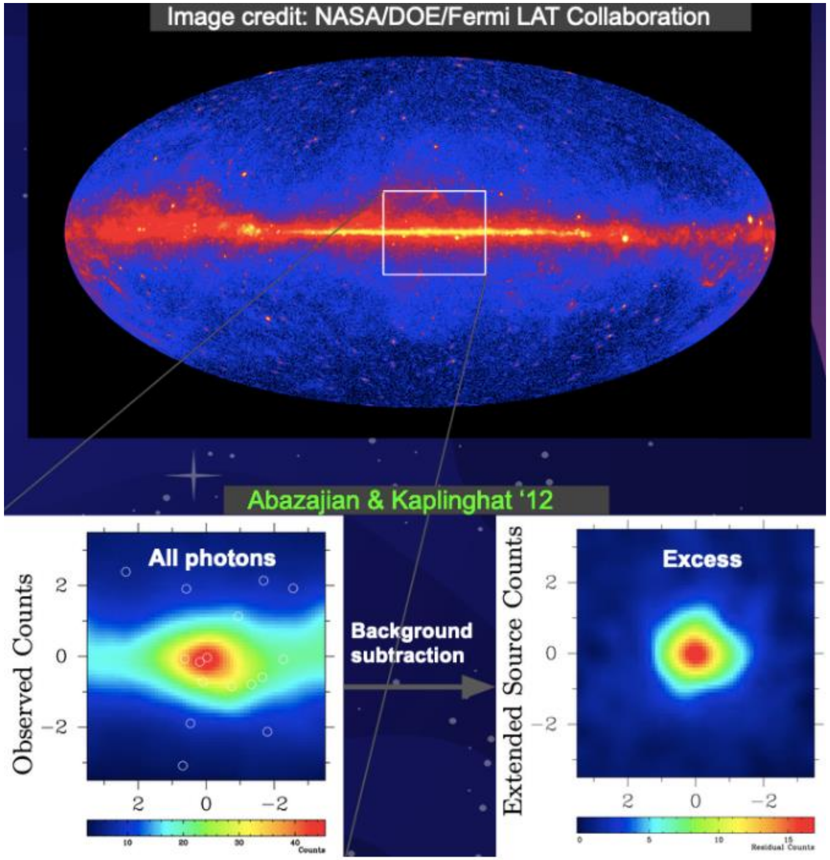


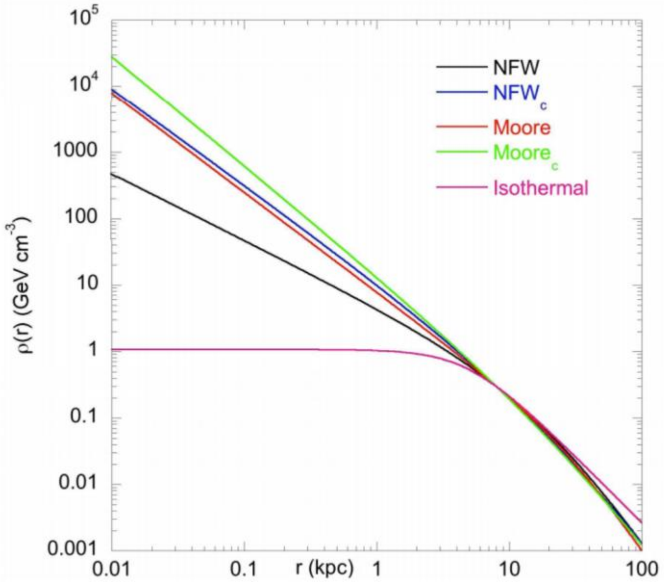
Well motivated.
Correct relic abundance.
Searched for decades.





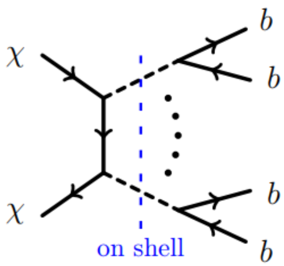
A GeV excess at the Galactic Center:

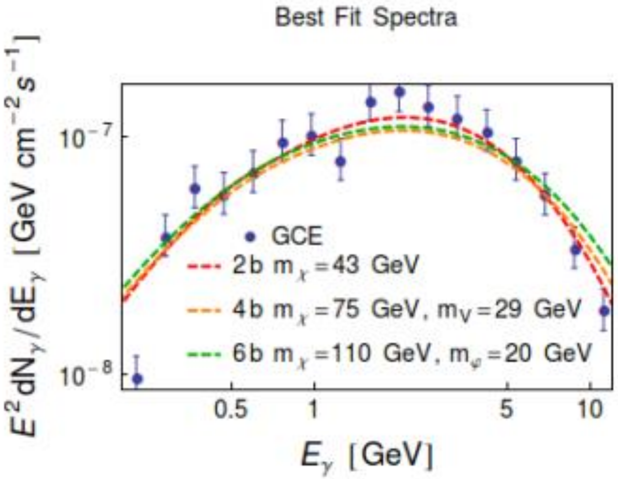


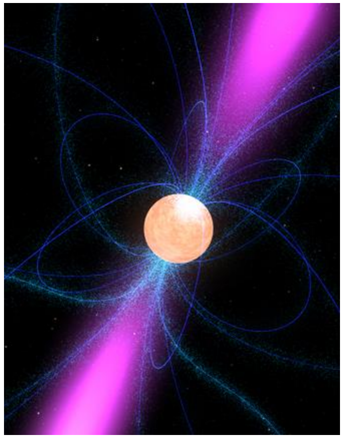


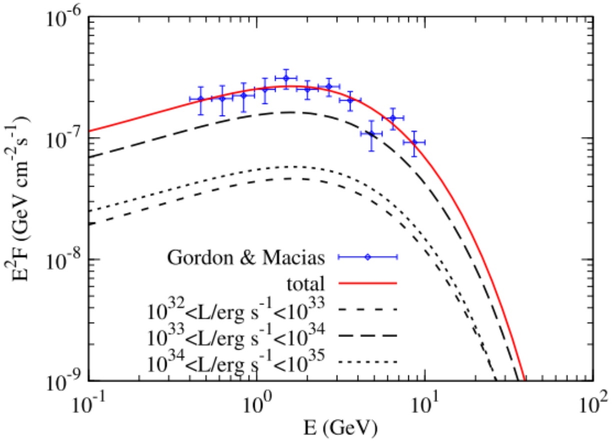
Gamma-ray Space Telescope

Two explanations:







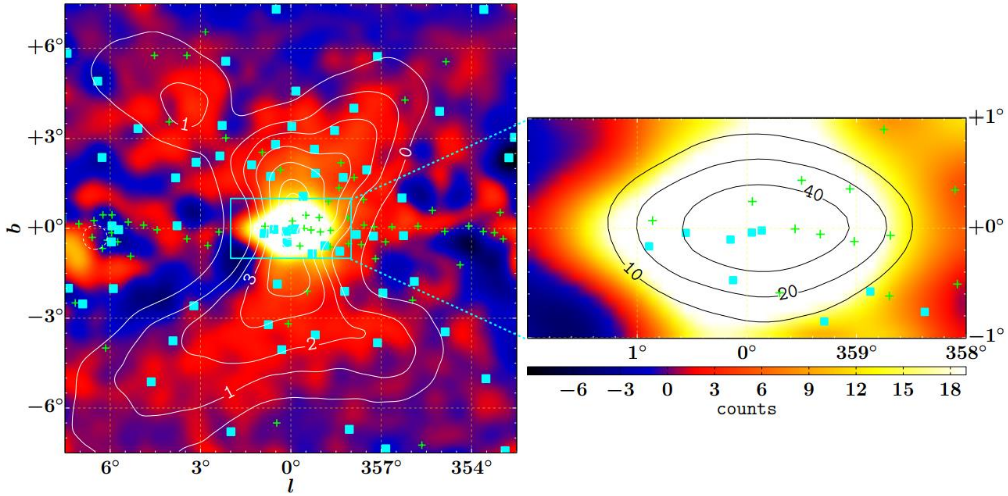


Abdullah, et. al.
Phys. Rev. D 90, 035004 (2014)

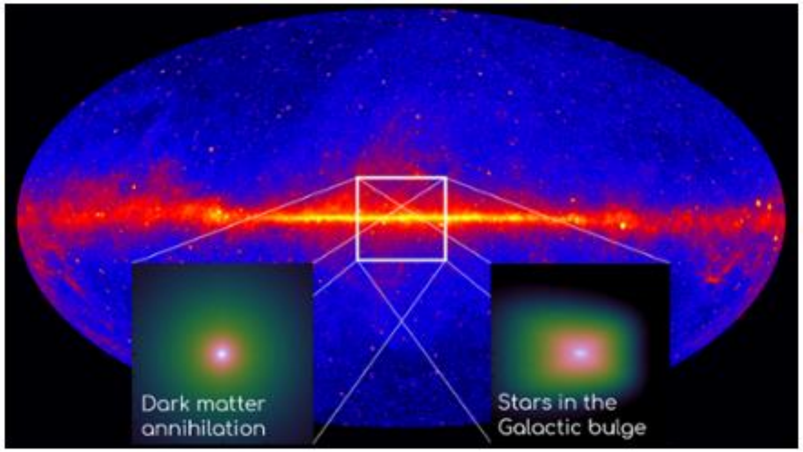
Yuan, et. al.
JHEAp 3 (2014) 1

Efforts to distinguish these two explanations:

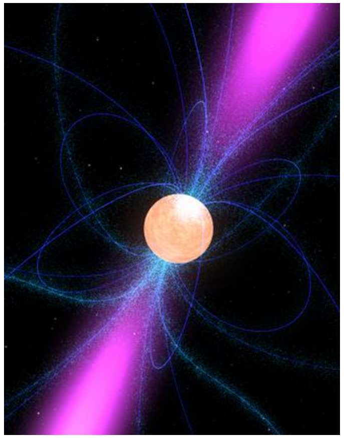
- Smoothness: Point Source v.s. Smeared Distribution

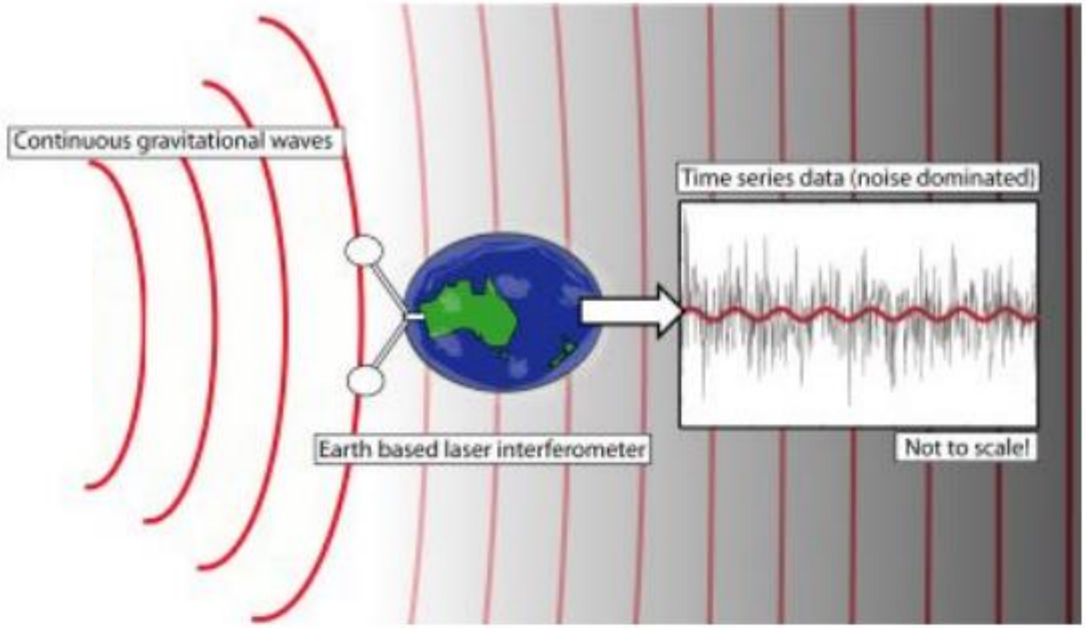


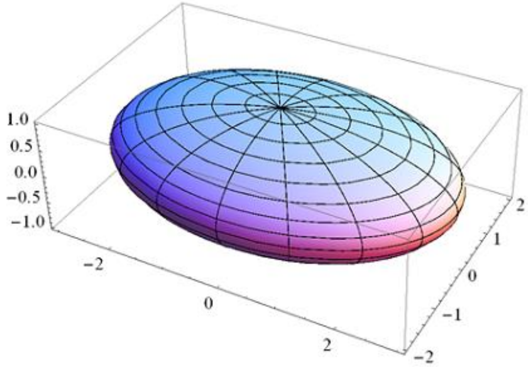
- Morphology: Spherical v.s. Bulge-like



GW channel can be useful:







principal moments of inertia

ellipticity

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} \epsilon f_{\rm rot}^2}{d}$$

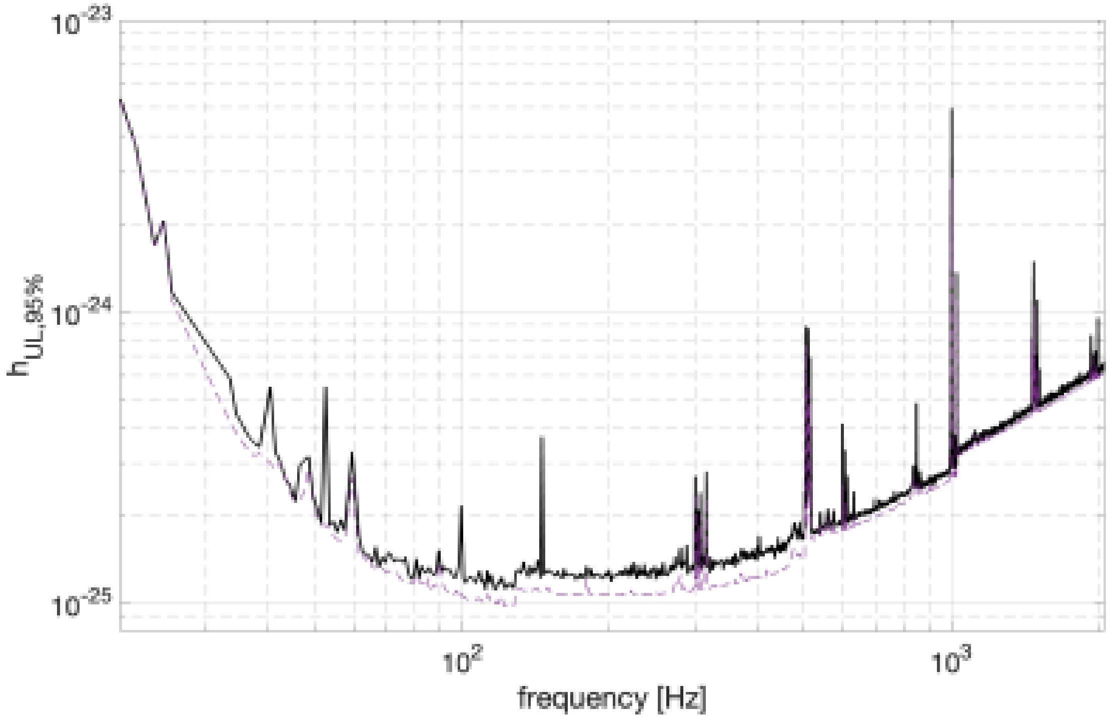
residual crustal deformation

non-axisymmetric distribution of magnetic field

Modern Physics Letters A 32, 39, 1730035 (2017)

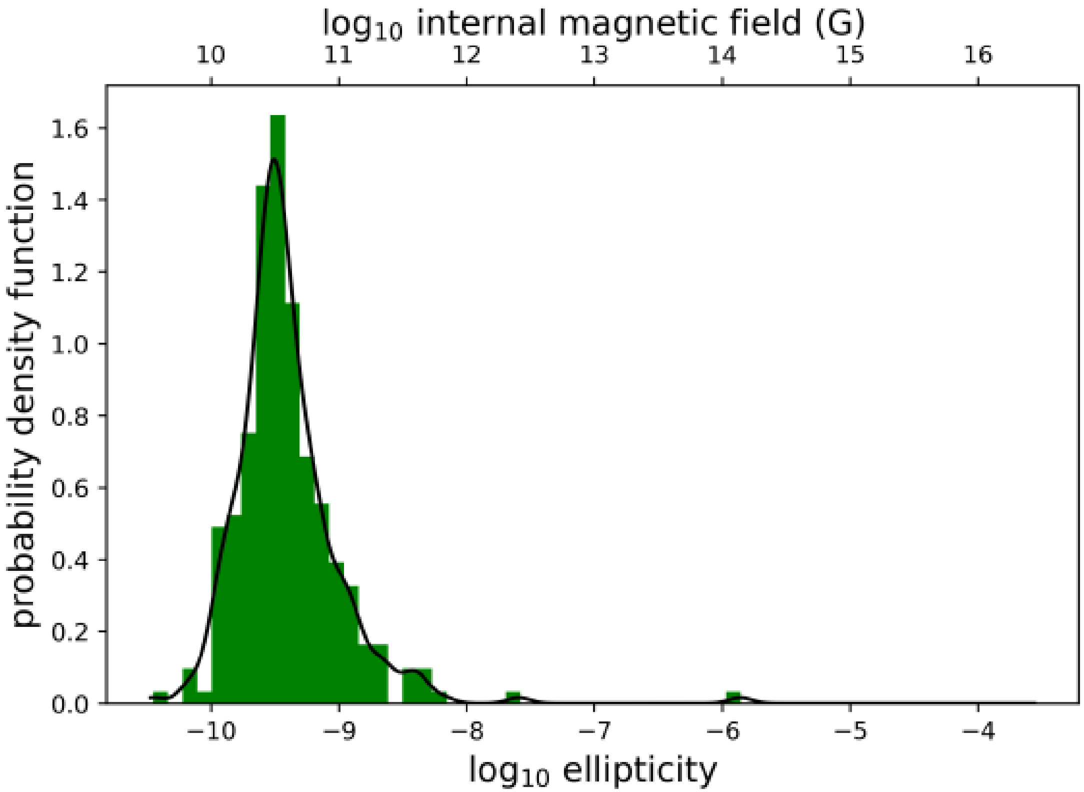
Existing search:

The LVK collaboration
Phys. Rev. D 106, 102008
All-sky pulsar search



Ellipticity distribution:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} \epsilon f_{\rm rot}^2}{d}$$



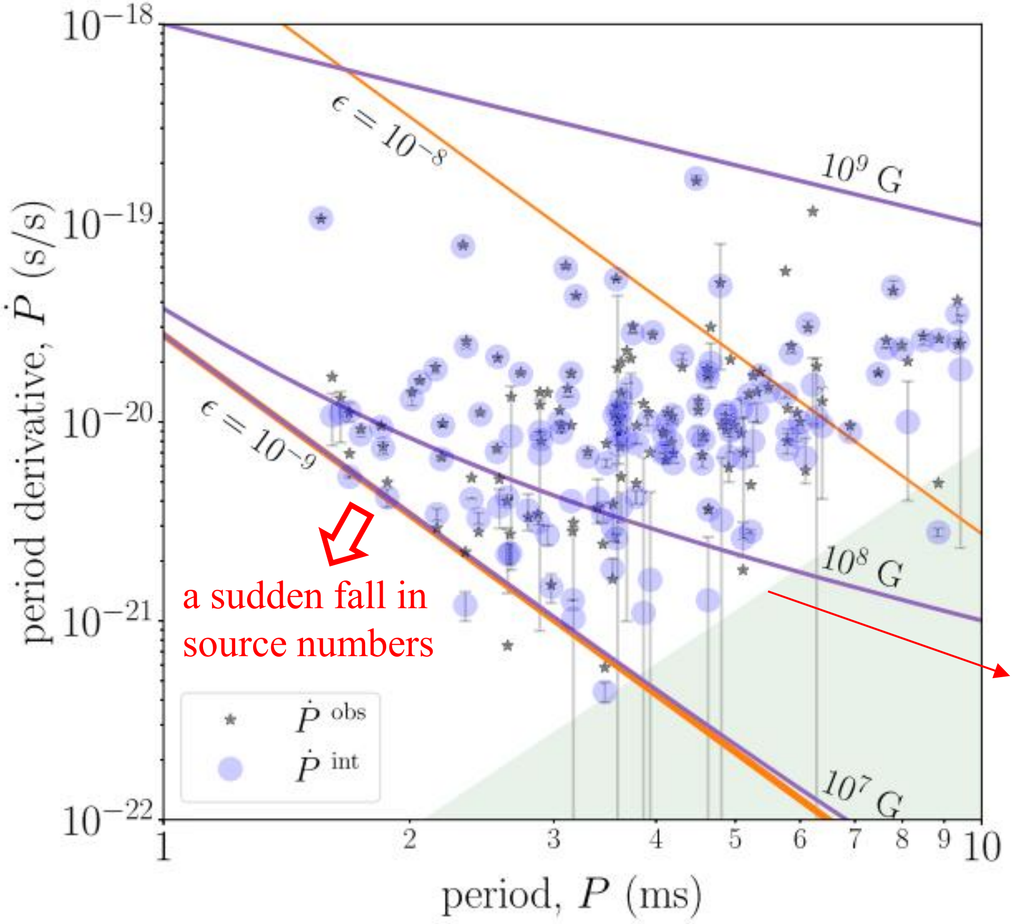
$$\epsilon \approx 10^{-8} \left(\frac{B_{\rm int}}{10^{12}\,{\rm Gs}} \right)$$

$$B_{\rm int} = 150 B_{\rm ext}$$

ATNF pulsar catalogue

Evidence for a Minimum Ellipticity in Millisecond Pulsars

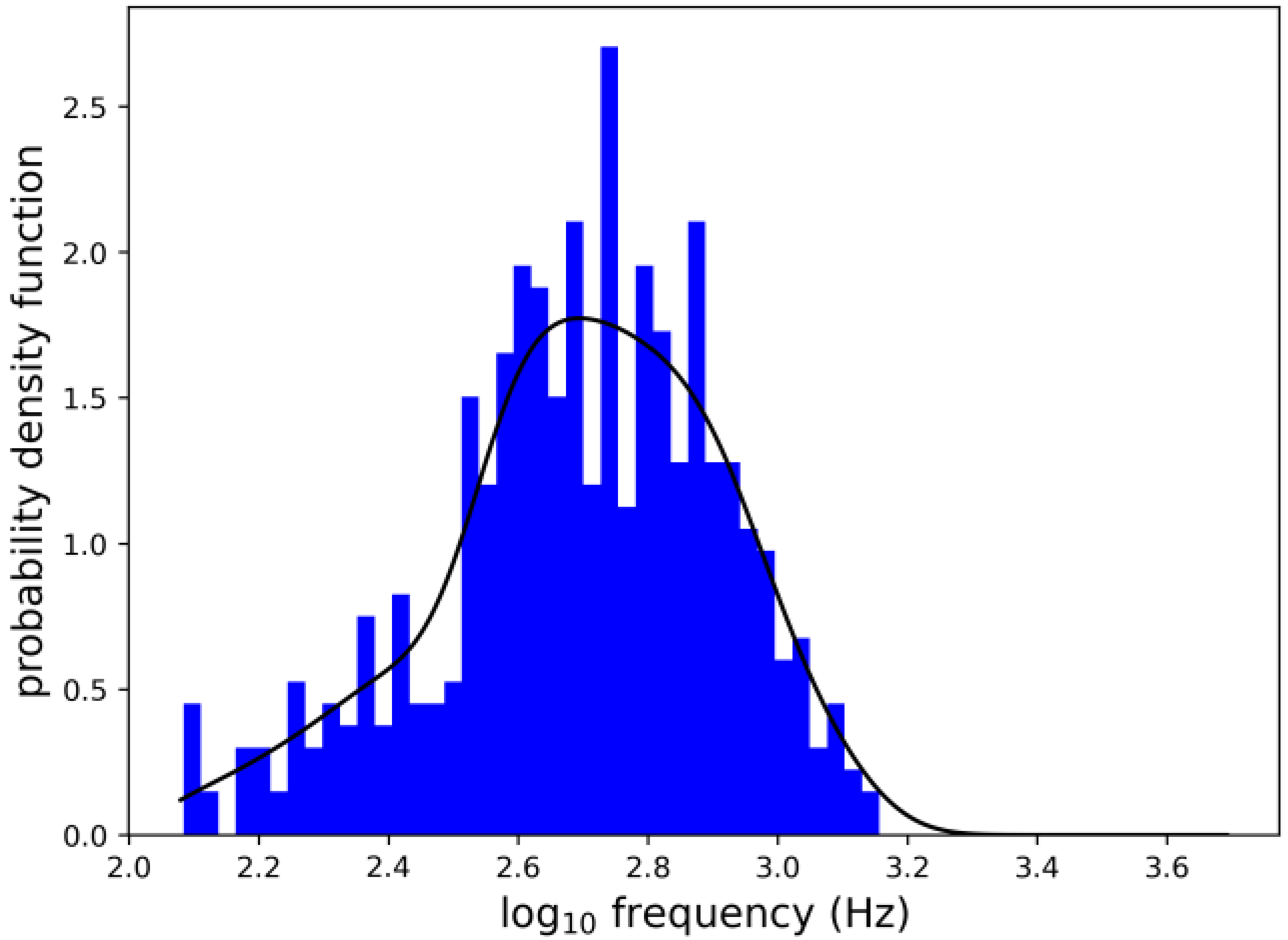
Astrophys.J.Lett. 863 (2018) 2, L40



the "death line" below which neutron stars are not observable as pulsars

Frequency distribution:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz}\epsilon f_{\rm rot}^2}{d}$$

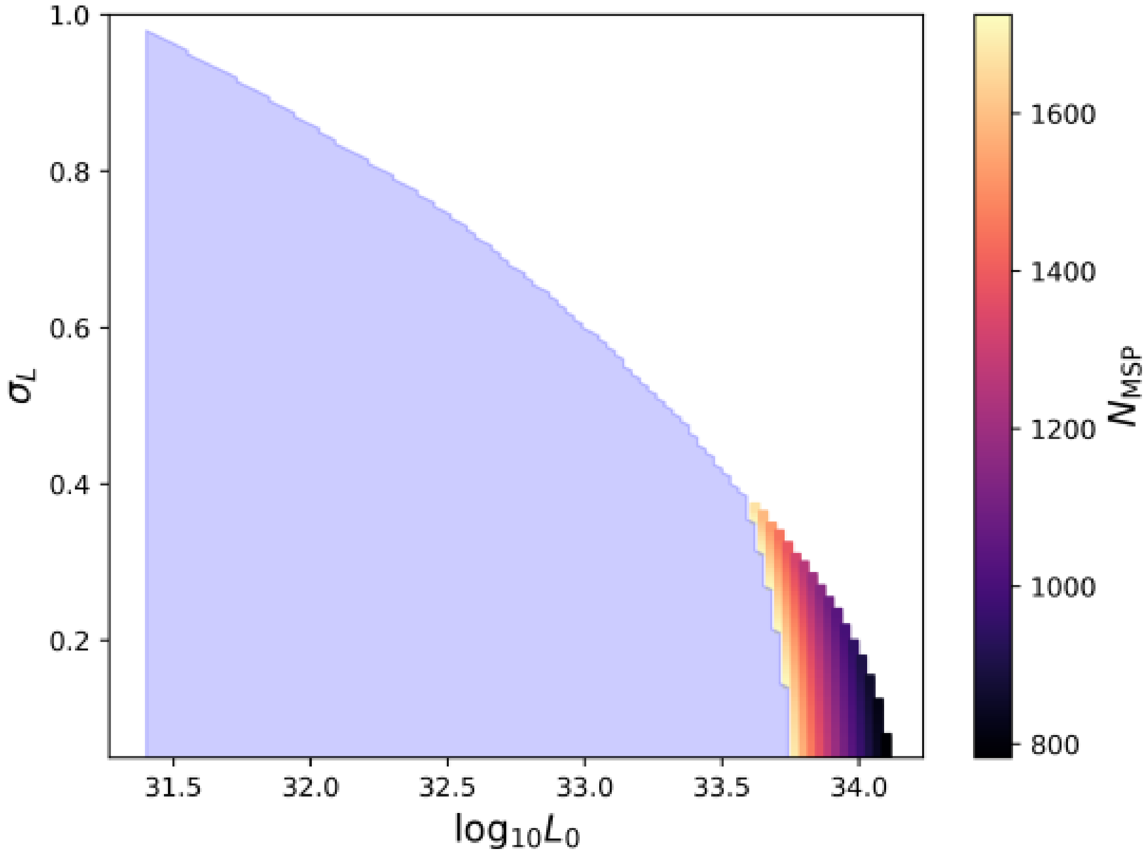


ATNF pulsar catalogue

WIMP DM:

Andrew Miller, Y.Z.
Phys.Rev.Lett. 131 (2023) 8, 081401

$$\frac{dP(L)}{dL} = \frac{\log_{10} e}{\sigma_L \sqrt{2\pi} L} \exp\left(-\frac{\log_{10}^2(L/L_0)}{2\sigma_L^2}\right)$$



$$B_{\rm int} = 150 B_{\rm ext};\ d = 8\ {\rm kpc}.$$

$$I_{zz} = 5 \times 10^{38} {\rm kg \cdot m^2}$$

Future Improvement:

Current results are based on the all-sky pulsar search:

Not focused on the galactic center

For CW search with almost fixed frequency, angular resolution can be excellent due to Earth motion!

$$\delta\theta = \frac{c/v_{earth}}{f \times T_{coh}}$$

Existing galactic center search: Phys. Rev. D 106, 042003

~ 1 degree by 1 degree (@1kHz)

We need to find the middle point for the GeV excess.

~10 degree by 10 degree

Future Improvement:

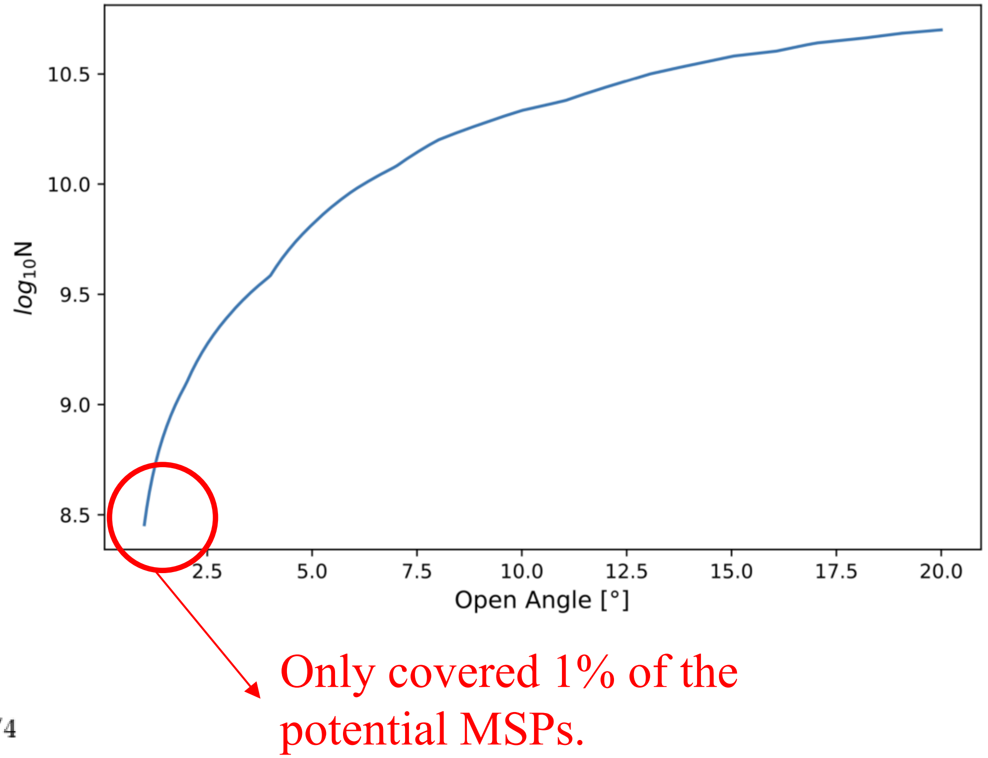
We can estimate the MSP distribution assuming it traces that of stars in the bulge.

The density of stars in the bulge can be modeled as a triaxial Gaussian profile:

$$n_B(x, y, z) = n_{B0} \exp\left(-r_s^2/2\right)$$

$$r_s = \left(\left[(x/x_0)^2 + (y/y_0)^2\right]^2 + (z/z_0)^4\right)^{1/4}$$

with $x_0 = 1.59$ kpc, $y_0 = 0.424$ kpc, and $z_0 = 0.424$ kpc.



Future Improvement:

Optimize the search strategy:

Current searches:

All-sky: Not focused on the galactic center

Galactic center search: ~ 1 degree by 1 degree

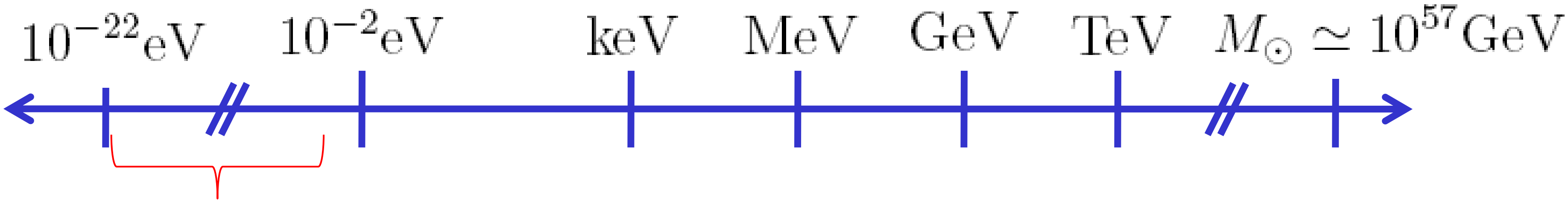
We need to find the middle point for the GeV excess.

~10 degree by 10 degree

Complementarity between CW search vs Stochastic search:

If none of the MSP is bright enough to be identified individually, we can look for the broad band incoherent SGWB.

Ultra-light DM:



a natural prediction of many string-inspired models

Bosonic DM with gigantic occupation number

⇨ Background Field (axion / **dark photon** / dilaton)

Ultra-light DM – Dark Photon

Standard Model gauge group

dark gauge group

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$$

Gauge bosons: gluon, W/Z, photon

Additional U(1) gauge groups naturally appear in many UV models.

Its gauge boson is the **dark photon**.

$U(1)_B$ proton + neutron

$U(1)_{B-L}$ proton + neutron – electron

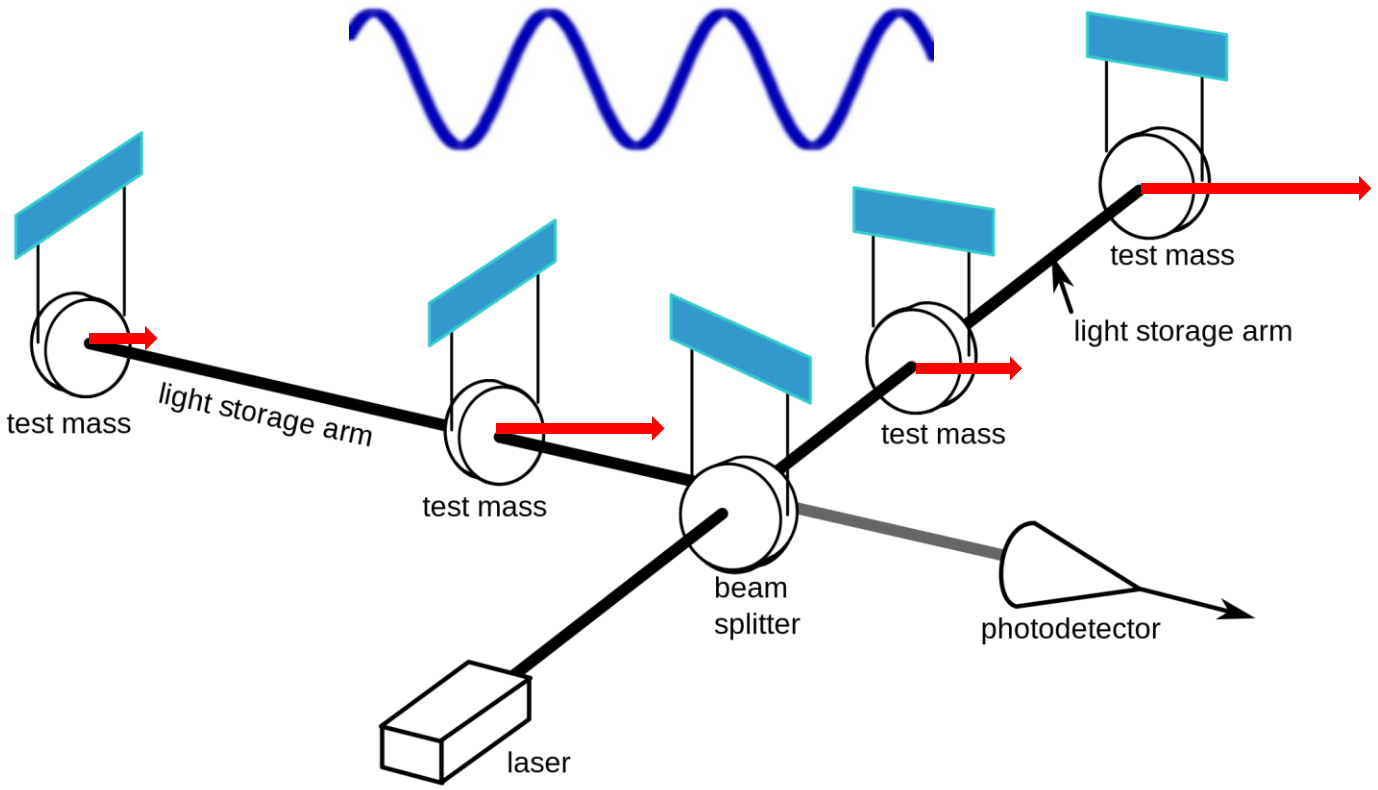
Ordinary materials carry huge dark charges, and thus feel a force by dark photon field!

Ultra-light dark photon can be a good candidate of cold dark matter!

Ultra-light DM – General Picture:

LVK: advanced Michelson–Morley interferometers

Ultra-light DM: coherent state ⇨ background classical radio wave



Dark photon dark matter moves mirrors. ⇨ Change photon propagation time between mirrors. ⇨ interferometer pattern

Properties of DPDM Signals:

Signal:

- almost monochromatic

$$f \simeq \frac{m_A}{2\pi}$$

- very long coherence time

$$\Delta f / f = v_{vir}^2 \simeq 10^{-6}$$

DM velocity dispersion. Determined by gravitational potential of our galaxy.

⇨ A bump hunting search in frequency space.

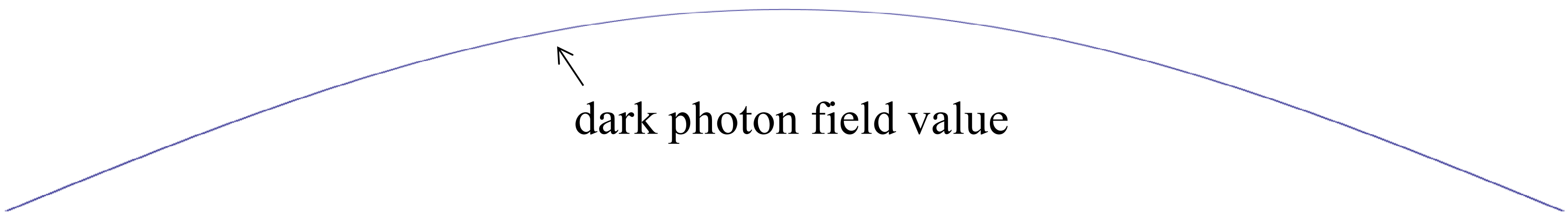
- very long coherent distance

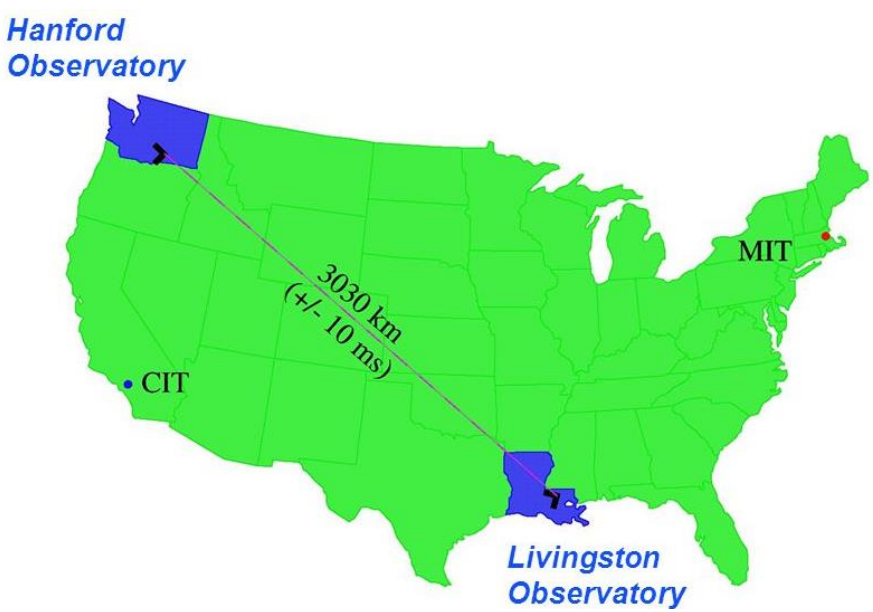
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f}\right)$$

⇨ Propagation and polarization directions remain constant approximately.

Ultra-light DM – Dark Photon Induced Displacement:

Correlation between two sites is important to reduce background!



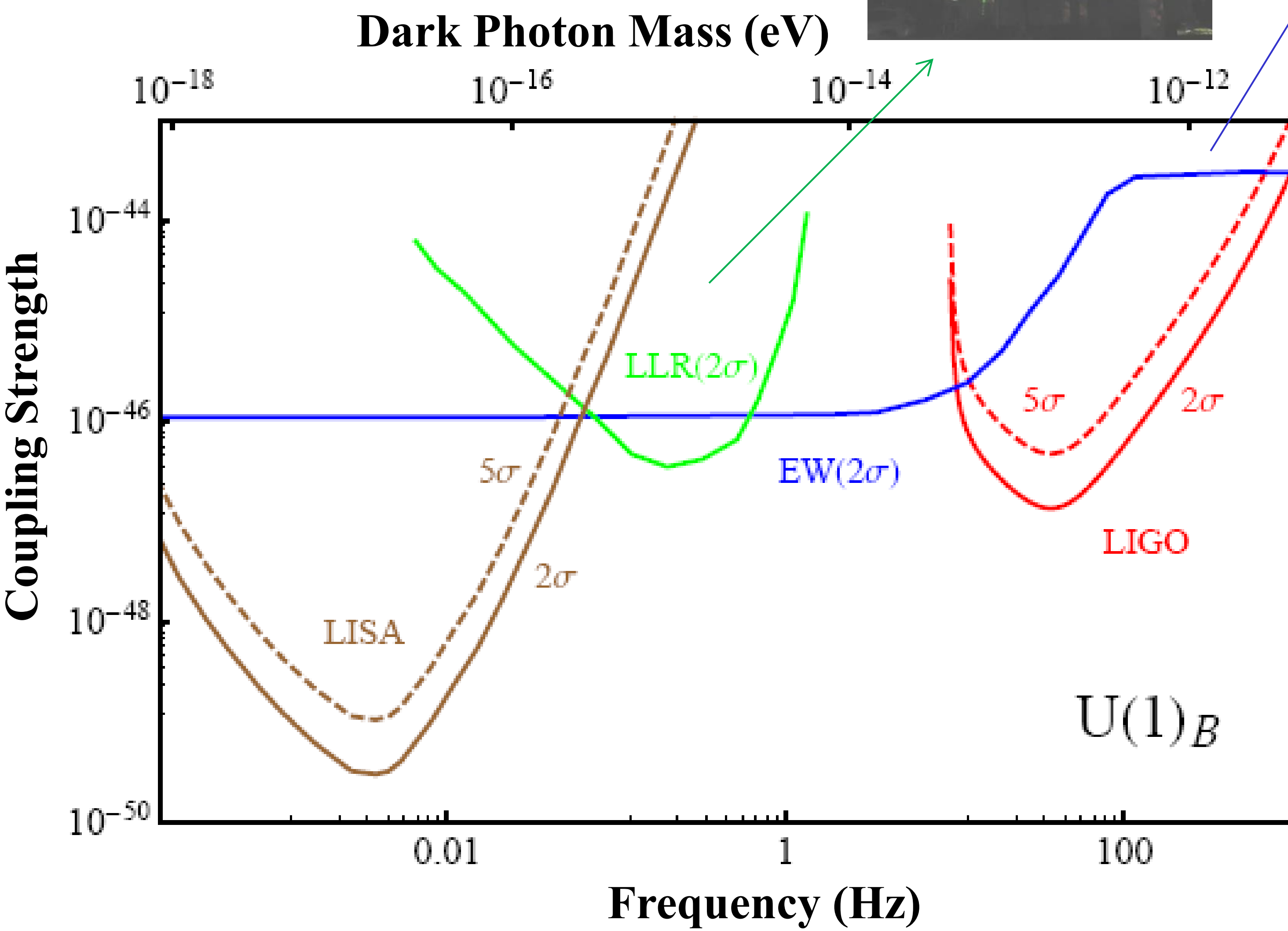


Due to long coherence length, signal is almost the same for both sites.

Sensitivity Plot:

A. Pierce, K. Riles, Y.Z.

Phys.Rev.Lett. 121 (2018) 6, 061102



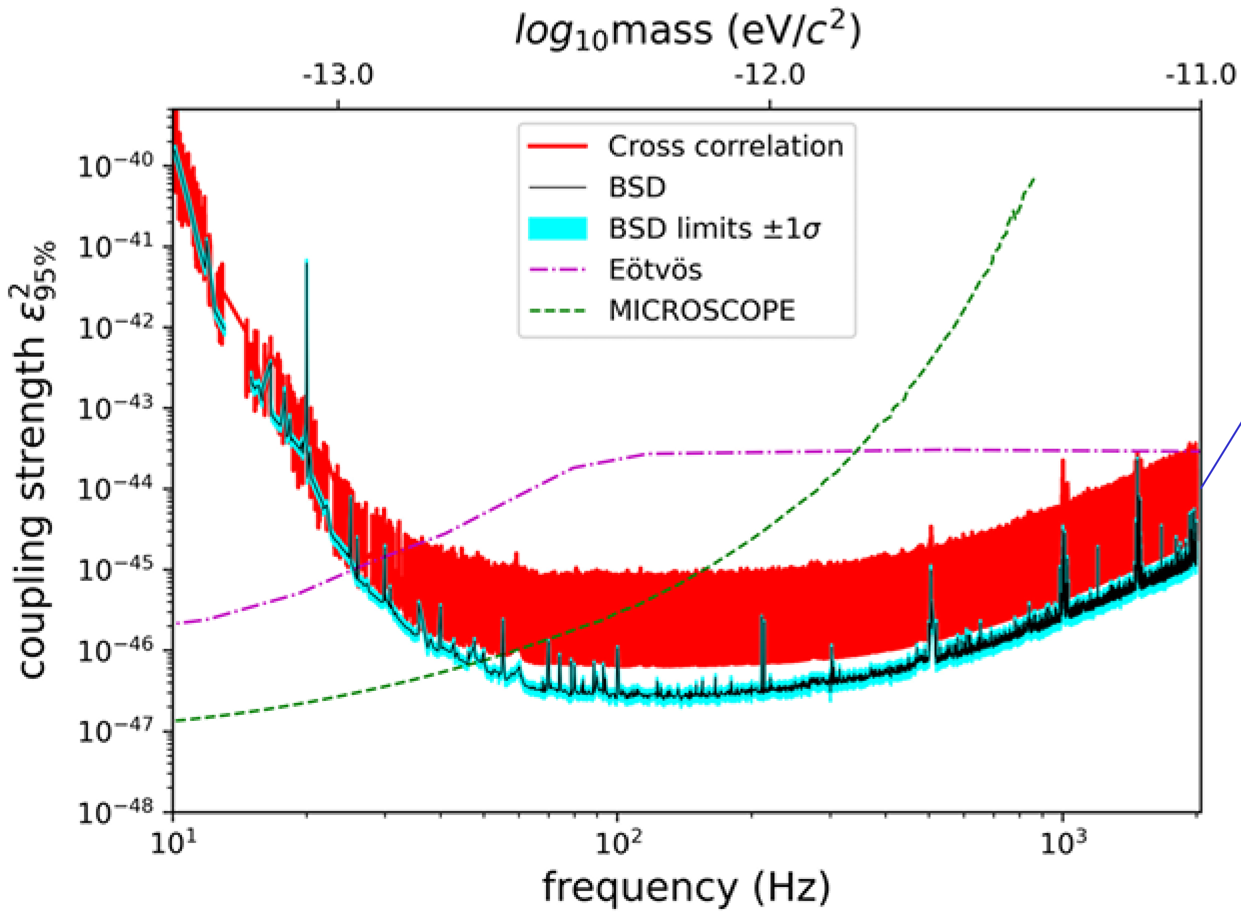
(Eöt-Wash web)

Loránd Eötvös

→ Eöt-Wash

design sensitivities, 2 yrs

O3 Result:

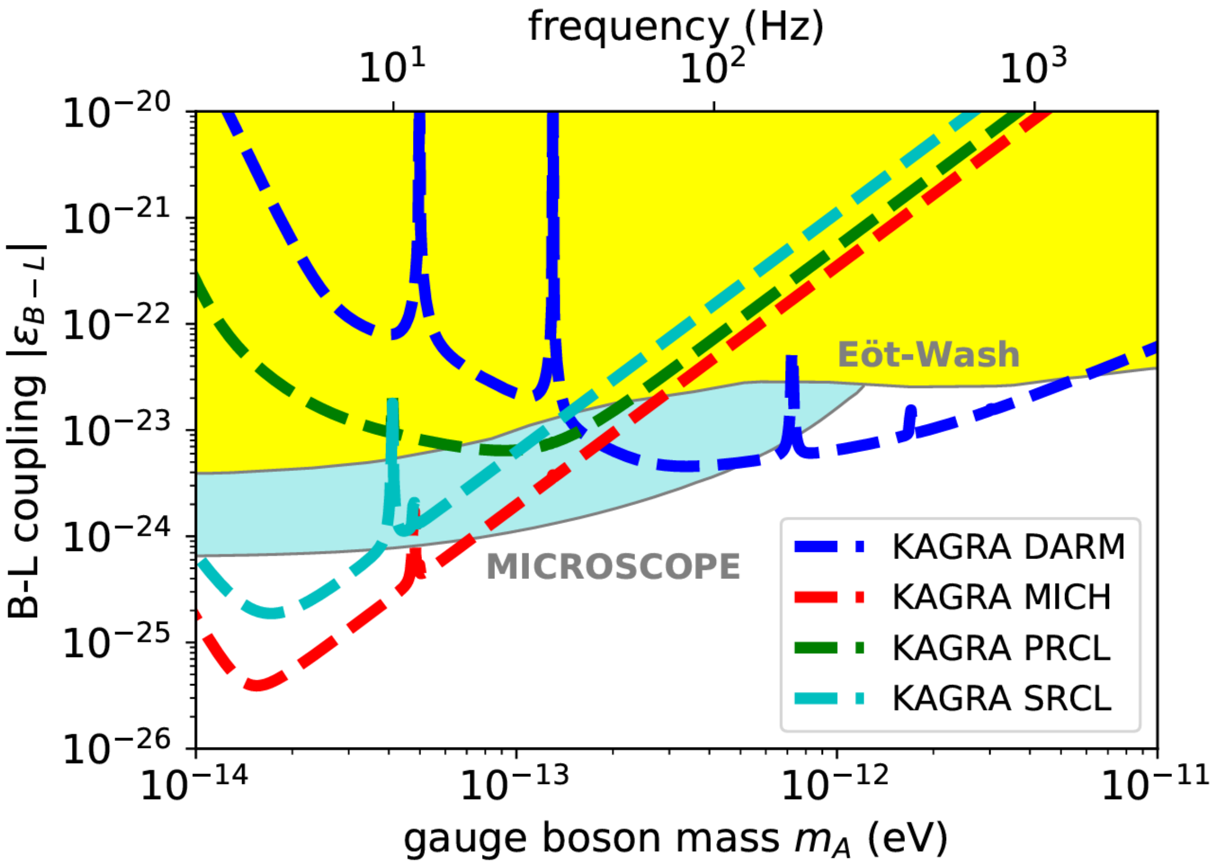


Cross correlation is weaker because Livingston and Hanford are almost anti-aligned.

It will be improved when more detectors join the network.

LIGO-Virgo-KAGRA Collaboration
Phys. Rev. D 105, 063030, 2022

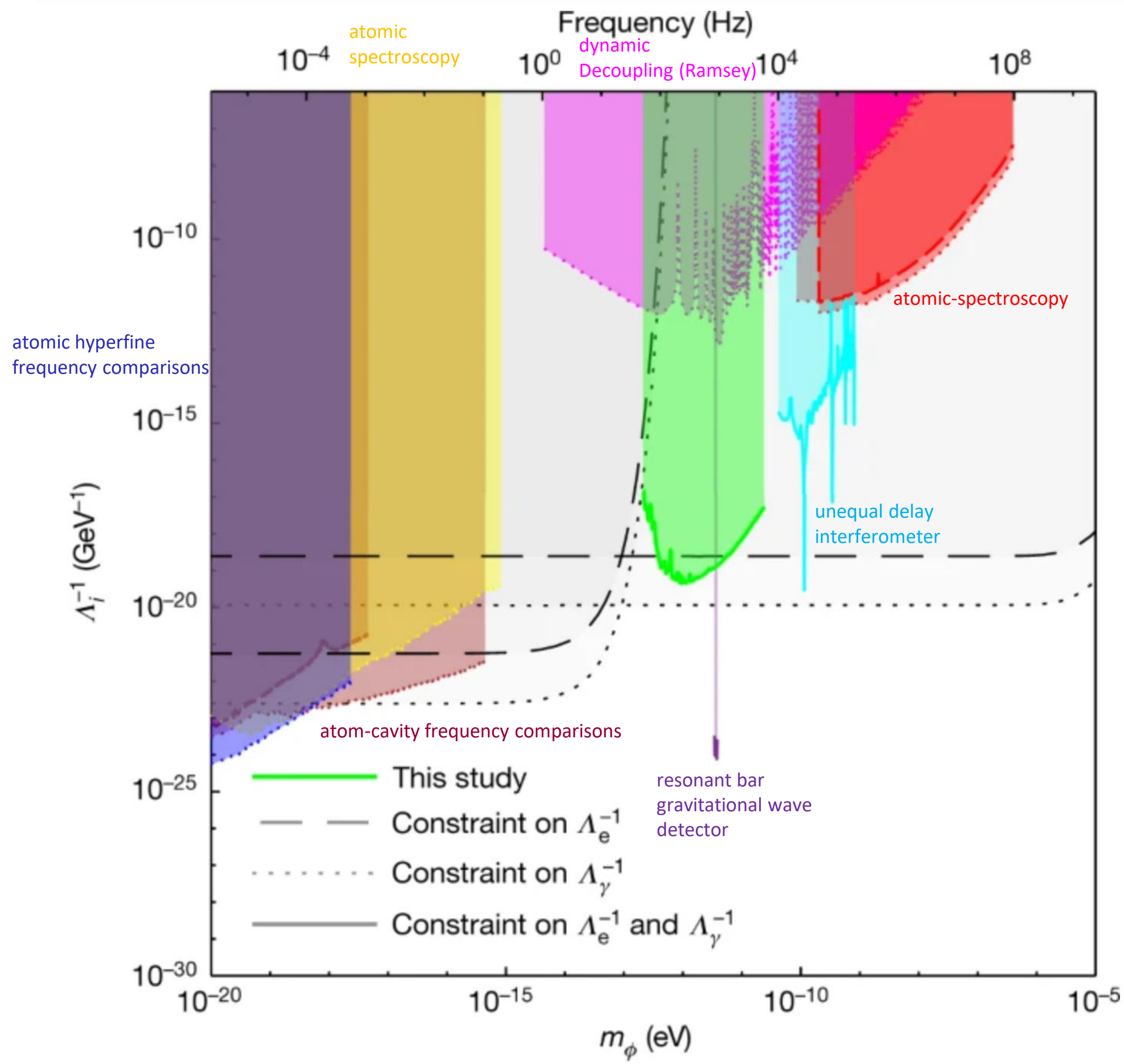
KAGRA is special:



differential arm length (DARM)
differential Michelson interferometer length (MICH)
power recycling cavity length (PRCL)
signal recycling cavity length (SRCL)

auxiliary parts consist of sapphire test masses and fused silica auxiliary mirrors

Dilaton Dark matter:

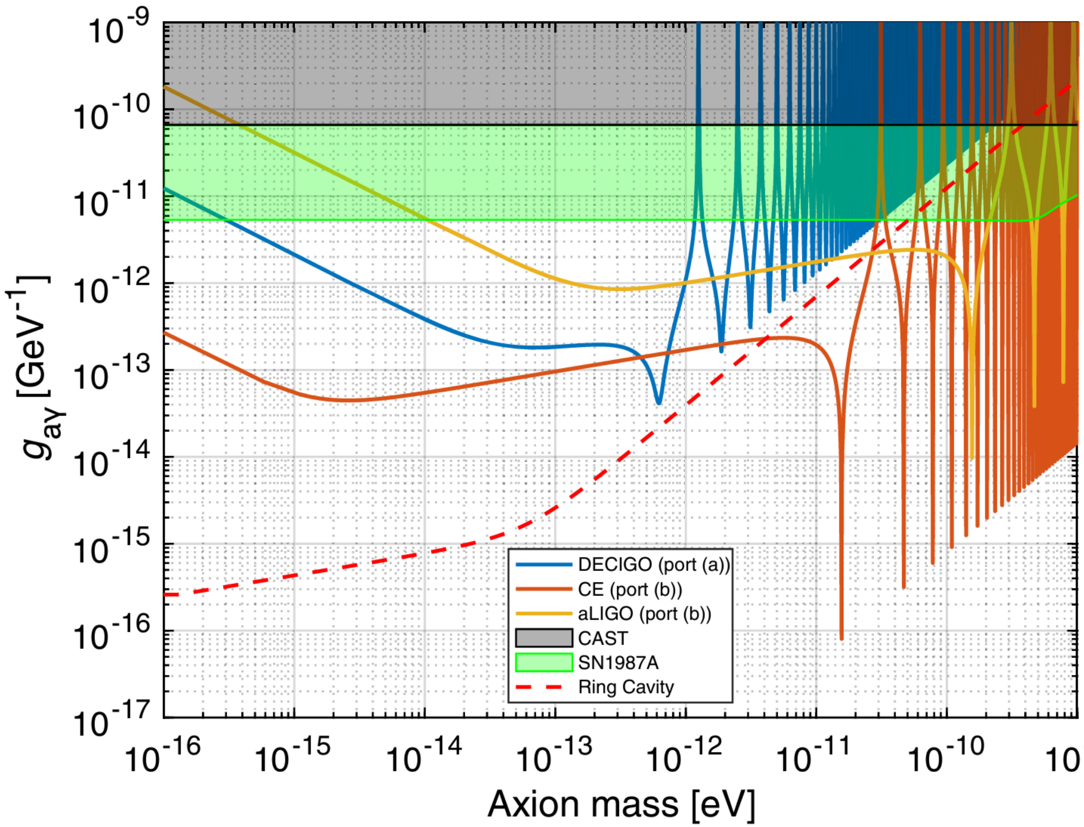


Sander M. Vermeulen et. al.
GEO 600
Nature 600, 424–428 (2021)

$$\mathcal{L}_{\text{int}} \supset \frac{\varphi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\varphi}{\Lambda_e} m_e \bar{\psi}_e \psi_e,$$

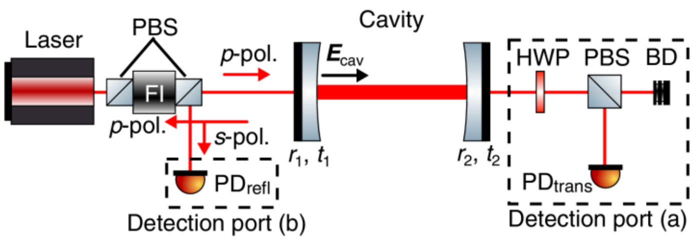
$$\delta(L_x - L_y) \approx \left(\frac{1}{\Lambda_\gamma} + \frac{1}{\Lambda_e}\right)\left(\frac{nl\hbar\sqrt{2\rho_{\text{local}}}}{m_\varphi c}\right)\cos(\omega_{\text{obs}} t)$$

Axion Dark matter:



Some extra components for polarization measurements need to be added to the existing GW detectors.

KAGRA may do it.



Koji Nagano et. al.
Phys. Rev. Lett. 123, 111301

Conclusion

GW detection opens new windows to search for new physics!

The MSP hypothesis at the galactic center has been tested.
Future improvements will be implemented.

Dark matter direct detection can be performed.
Similar analysis will be carried out for other DM candidates.

Nice complementarity:

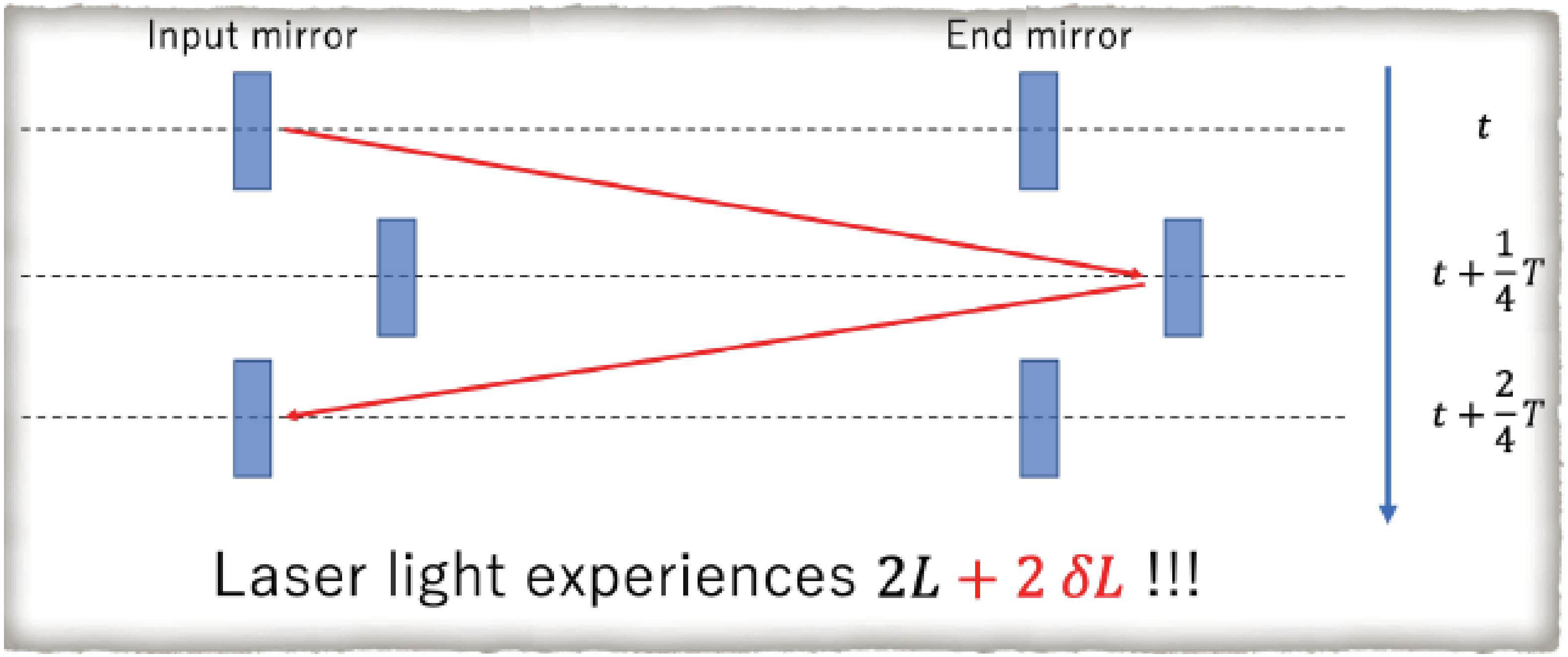
GW physics and particle physics.
CW method and SGWB method.

Ultra-light DM – General Picture:

A common motion of mirrors can also induce observable signals!

⇨ due to finite photon traveling time

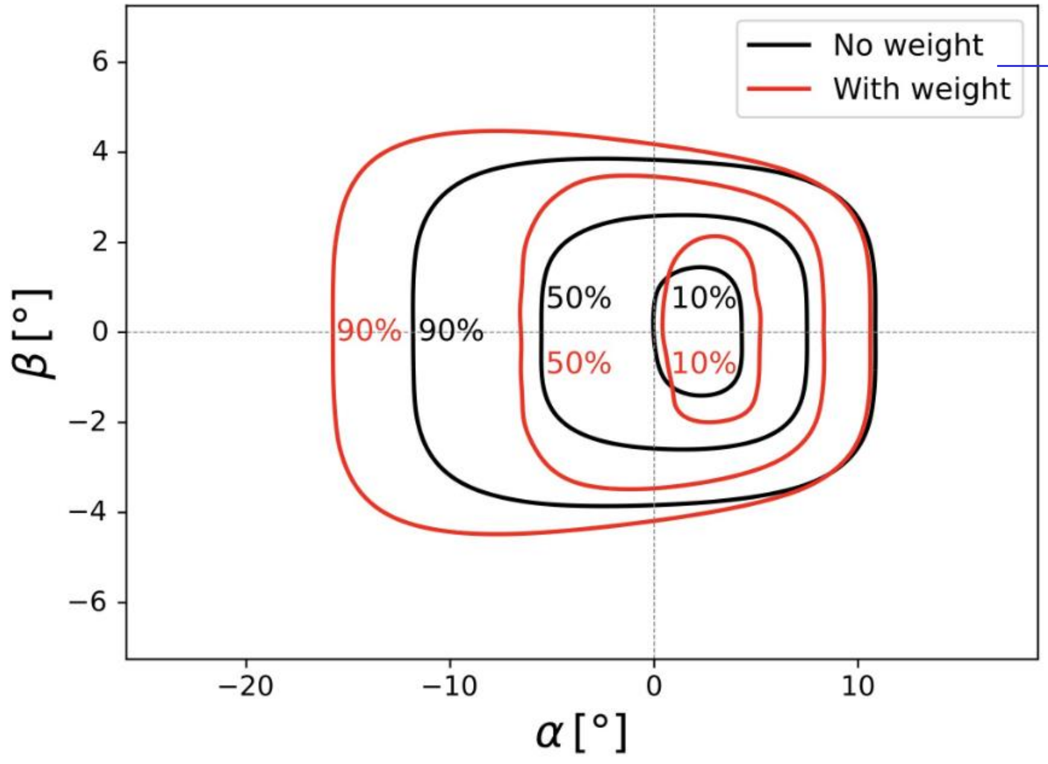
S. Morisaki, T. Fujita, Y. Michimura, H. Nakatsuka, I. Obata
Phys.Rev.D 103 (2021) 5, L051702



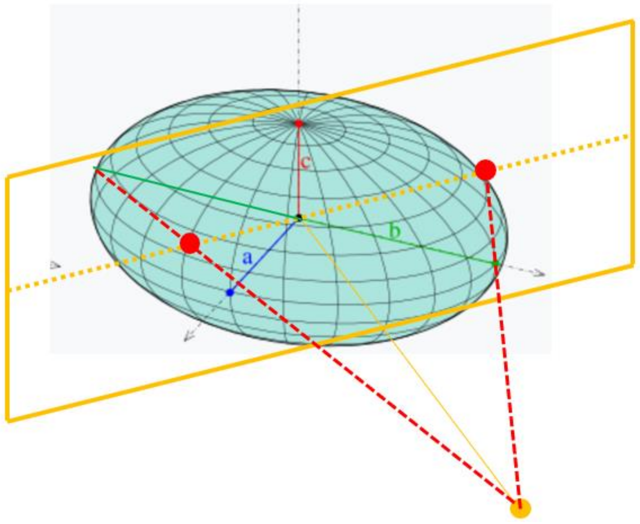
$$\sqrt{\langle h_C^2 \rangle} = \frac{\sqrt{3}}{2} \sqrt{\langle h_D^2 \rangle} \frac{2\pi f_0 L}{v_0}$$

Future Improvement:

Projected MSP distribution



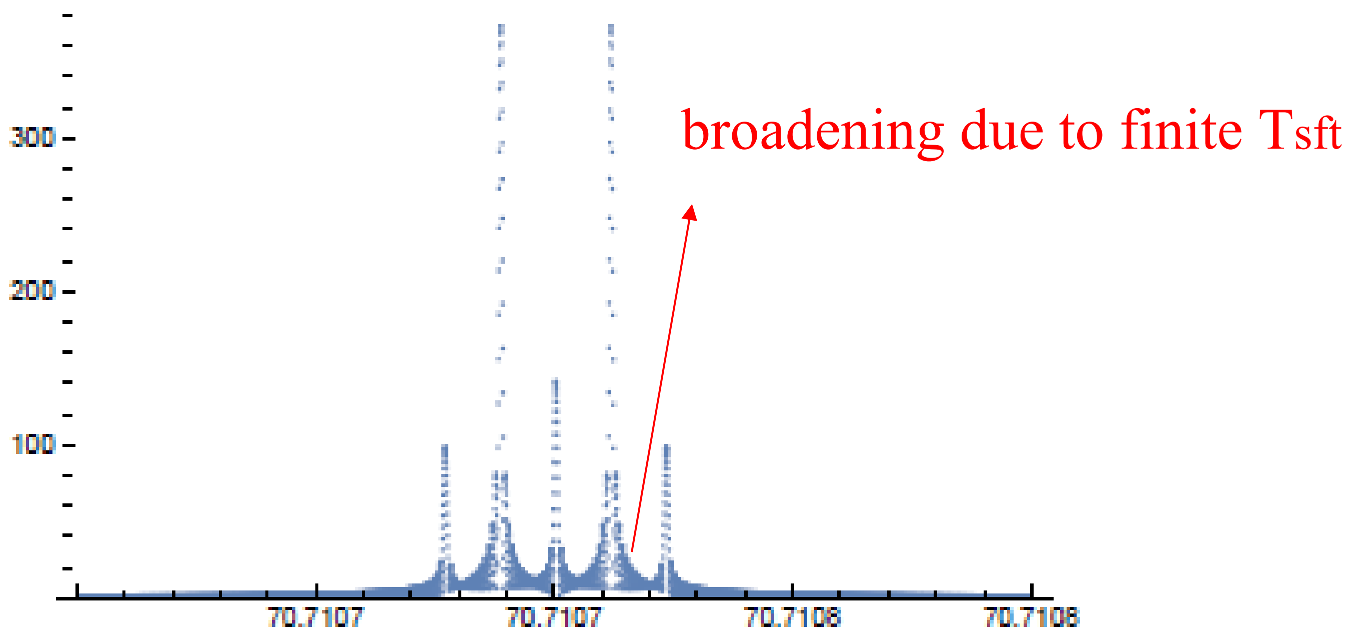
Weighting by 1/r^2



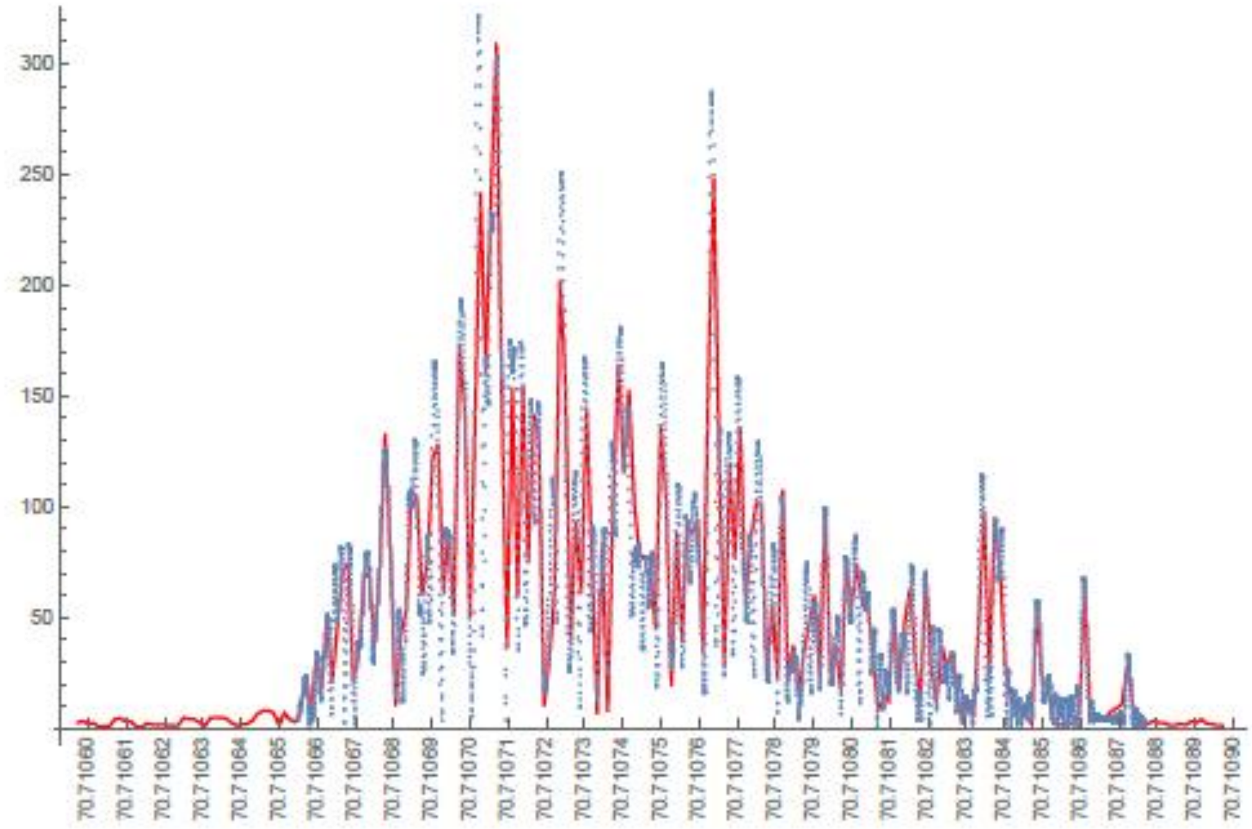
Earth Rotation Effects:

$$R_L \approx -\sum_{i=1}^{n} \frac{\cos(\omega_i t + \Phi_i)}{\omega_i^2} \Big(C^i_{2,1} \cos(2\omega_E t) +$$

$$C^i_{2,2} \sin(2\omega_E t) + C^i_{1,1} \cos(\omega_E t) + C^i_{1,2} \sin(\omega_E t) + C^i_0 \Big)$$



Fine structure of the signal:



Analytic understanding matches very well with numerical result!