Unveiling Dark Matter through Gravitational Waves

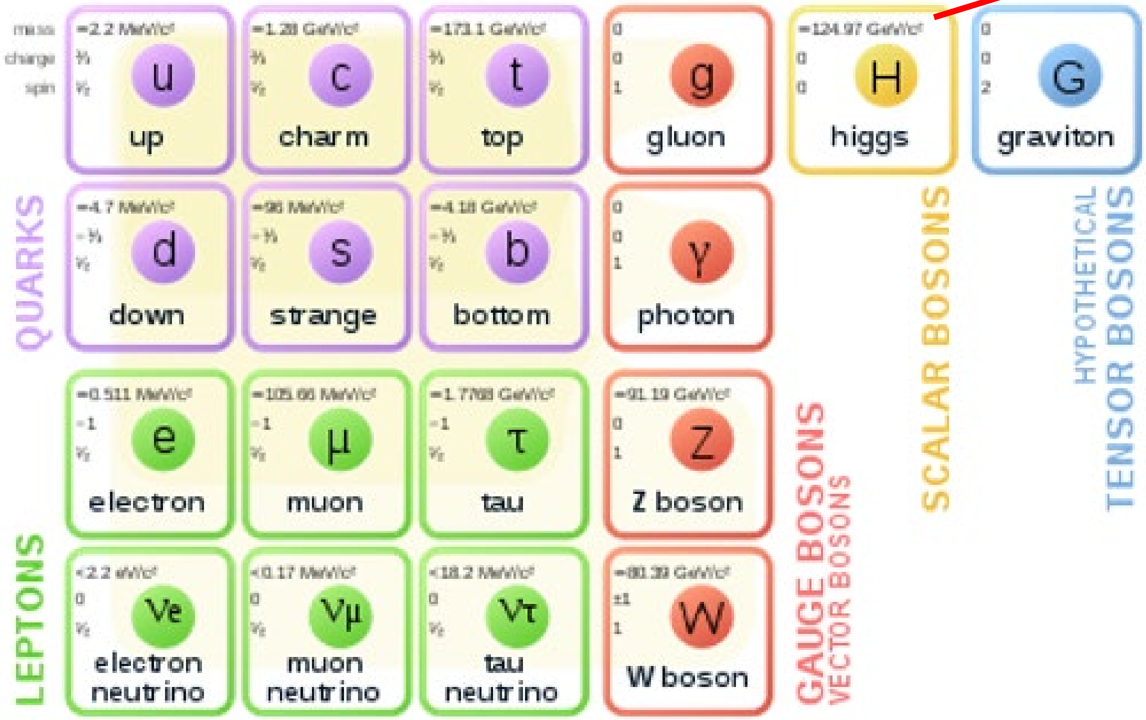
Yue Zhao

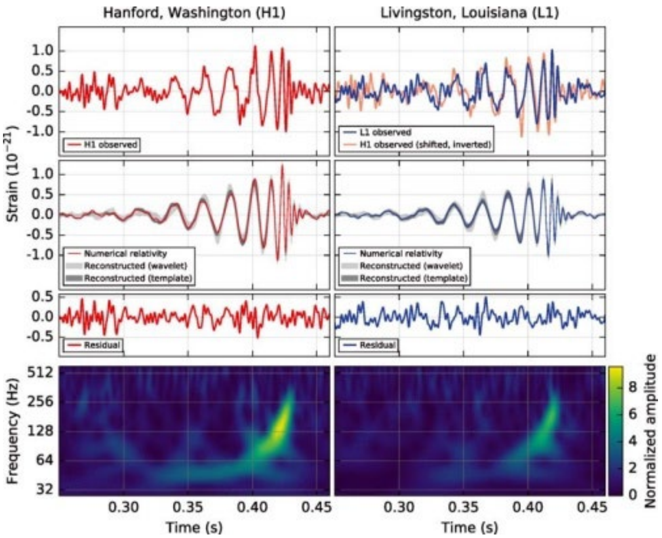
University of Utah

Particle Theory/DUSC seminar

INT workshop

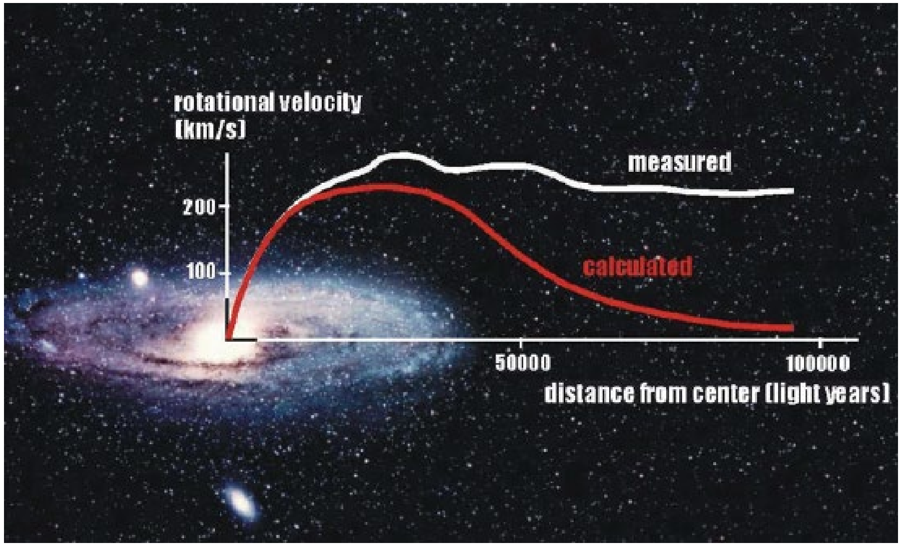
Current Status of Particle Physics:

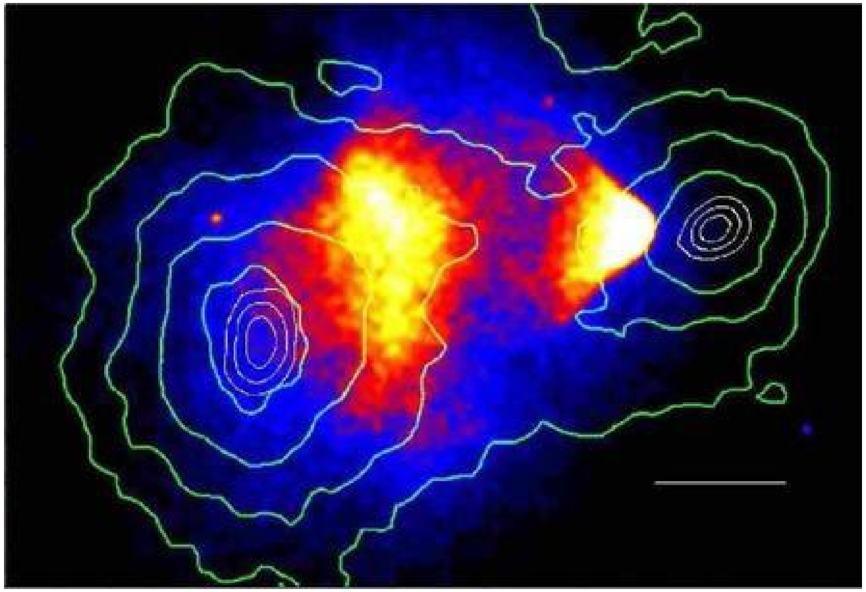


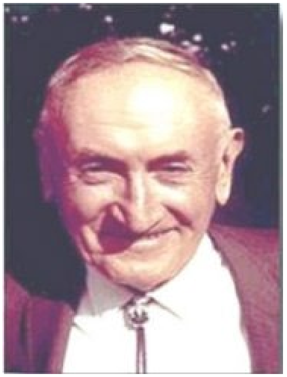


+ anything else?

Dark Matter Overview:

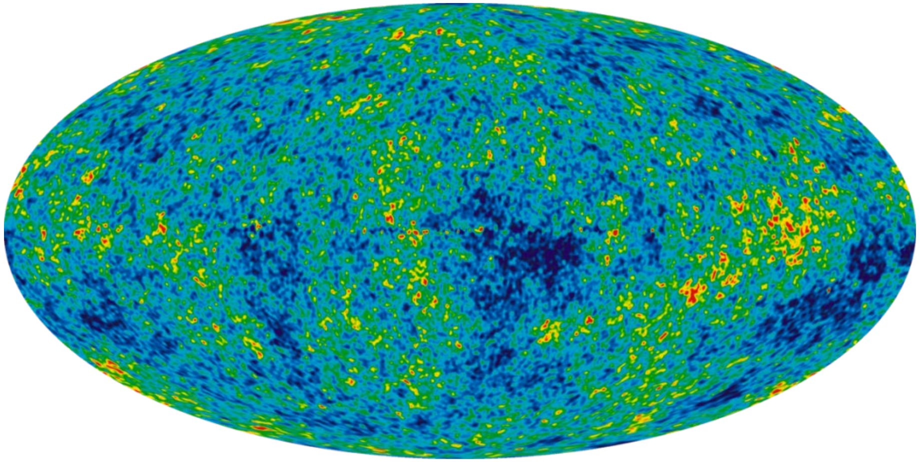






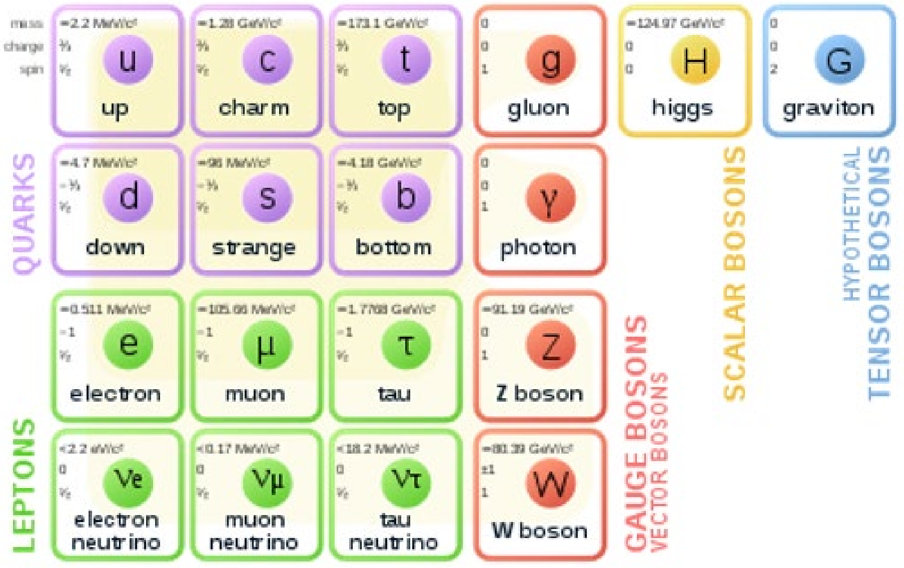
Fritz Zwicky

Vera Rubin



What Do We Know About Dark Matter?

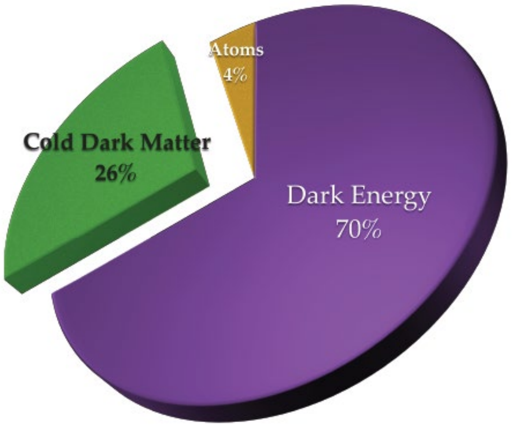
Particle Standard Model works extremely well in short distance, but fails miserably at cosmological scale!

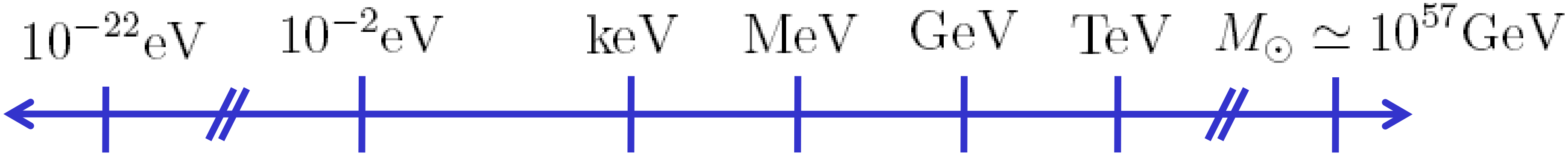


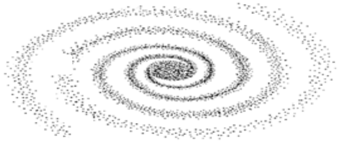

DARK MATTER ?

DARK MATTER is the name given to material in the Universe that does not emit or reflect light but is necessary to explain observed gravitational effects in galaxies and stars. Dark matter, along with dark energy, totals 96% of the Universe, yet it remains a mystery as to what exactly it is.

Acrylic felt, wool felt, and fleece with gravel fill for maximum mass. Packaged in a black opaque bag designed for concealing contents.

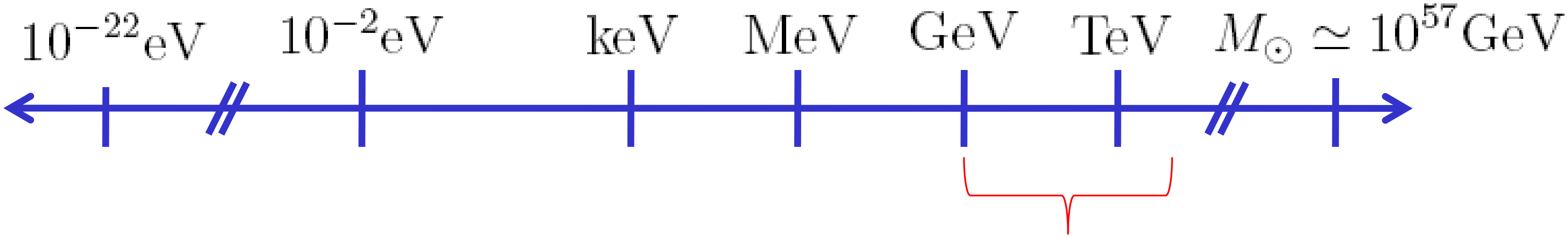




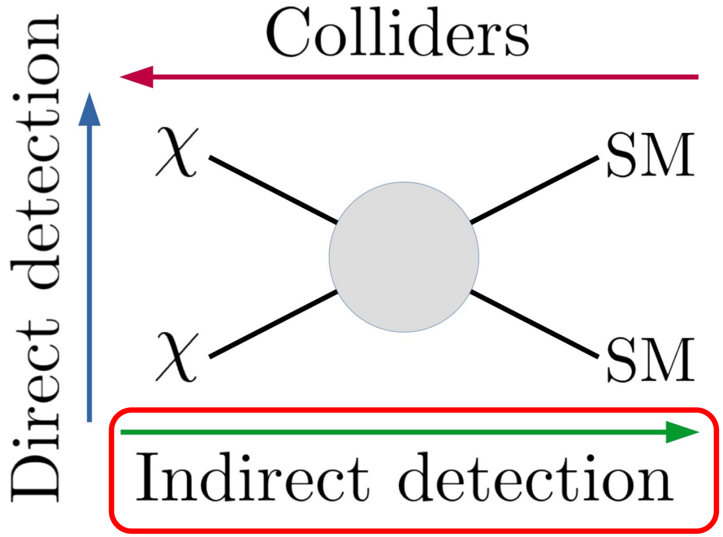


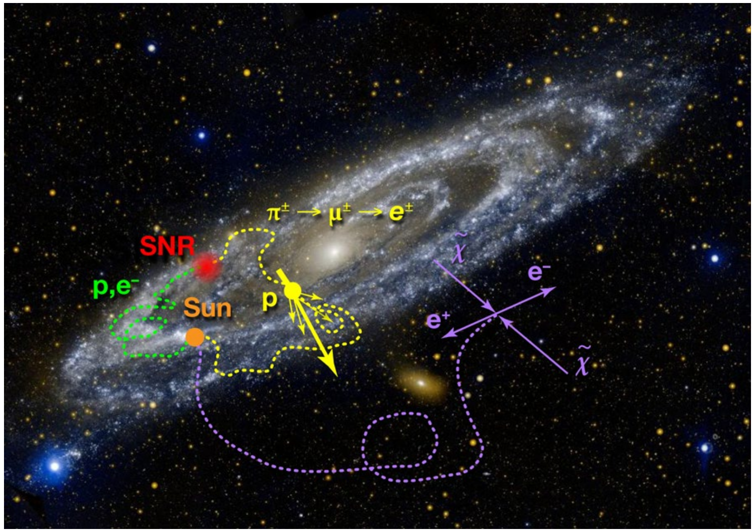
possible dark matter mass range
(Almost 100 orders of magnitude!!!)

A GeV excess at the Galactic Center:



Well motivated.
Correct relic abundance.
Searched for decades.





A GeV excess at the Galactic Center:

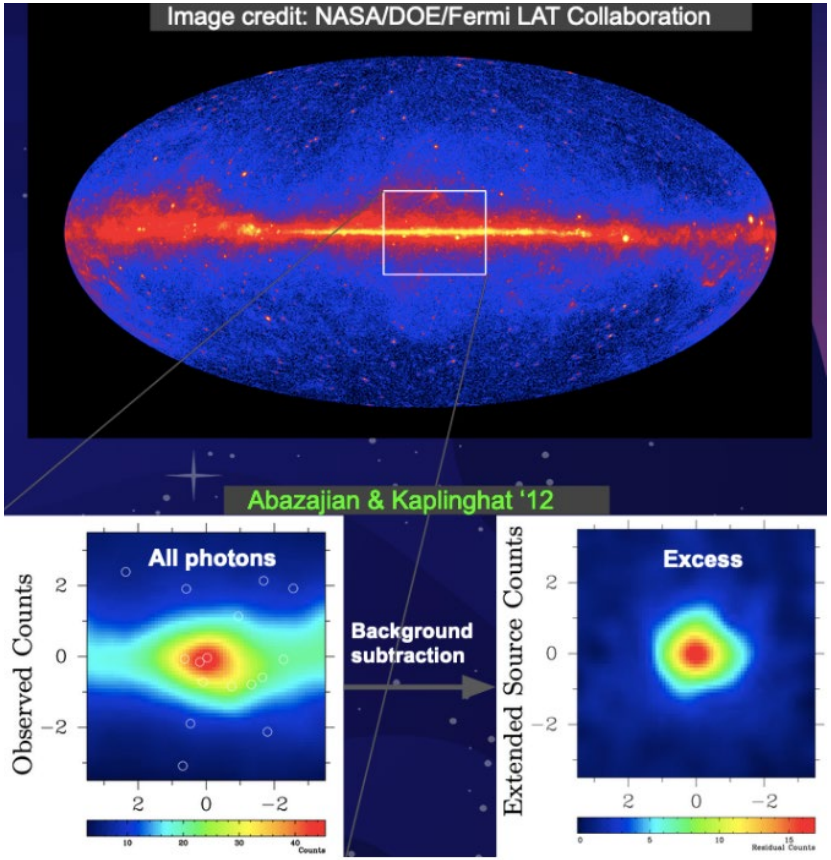
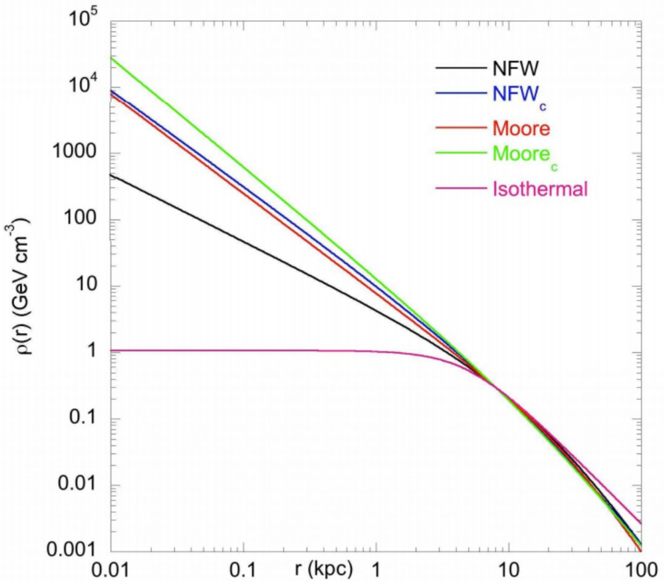


Image credit: NASA/DOE/Fermi LAT Collaboration

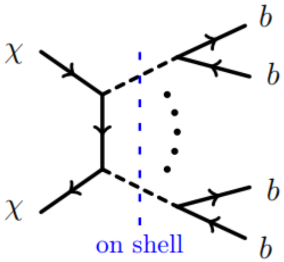
Abazajian & Kaplinghat '12

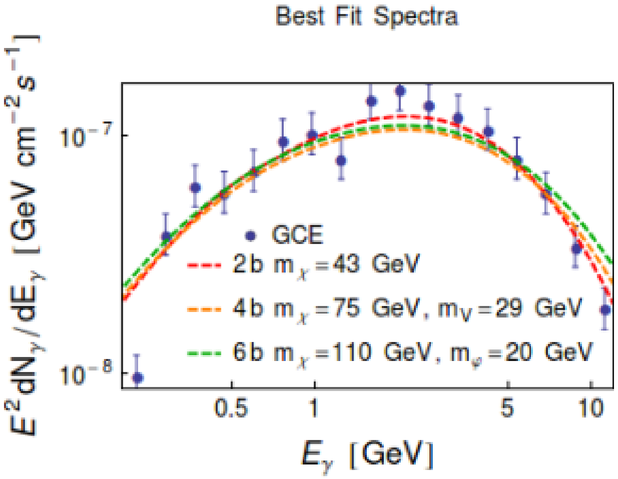


fermi

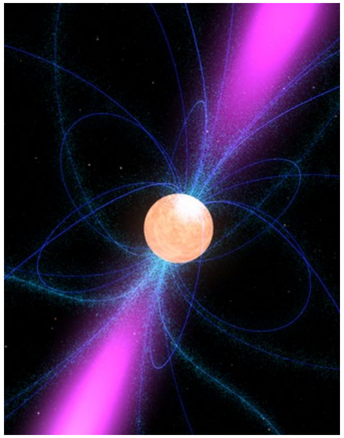
Gamma-ray
Space Telescope

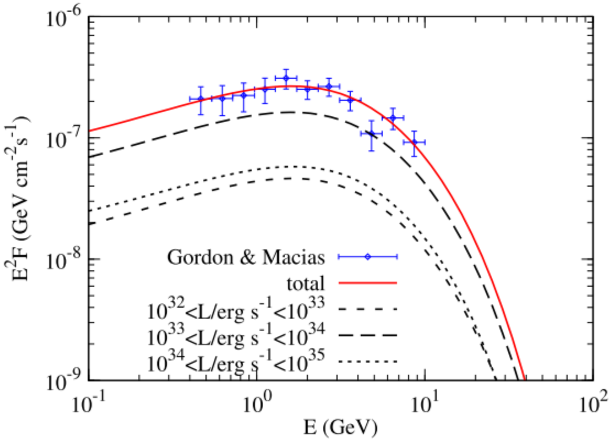
Two explanations:





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

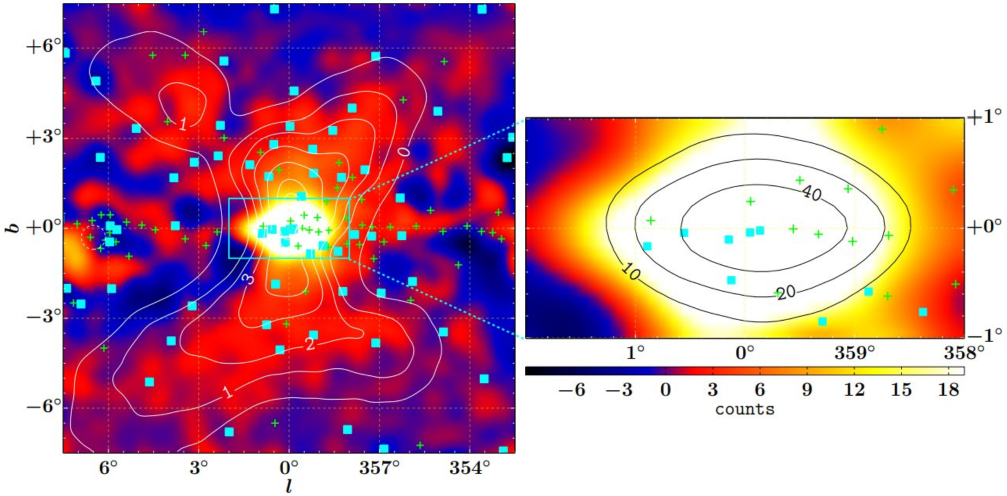




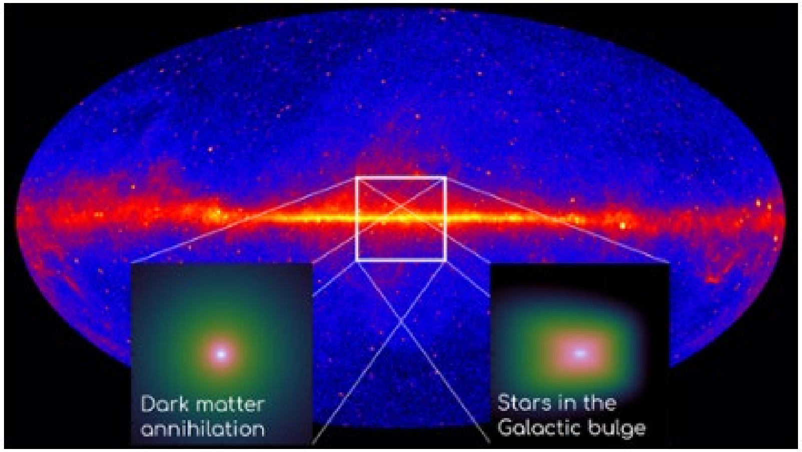
Yuan, et. al.
JHEAp 3 (2014) 1

Efforts to distinguish these two explanations:

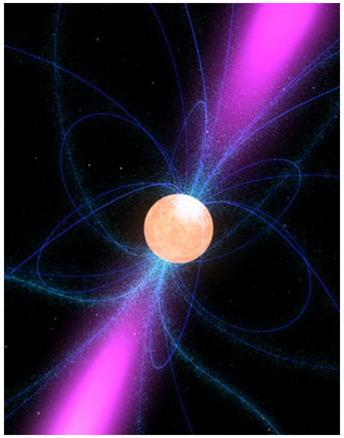
- Smoothness: Point Source v.s. Smeared Distribution

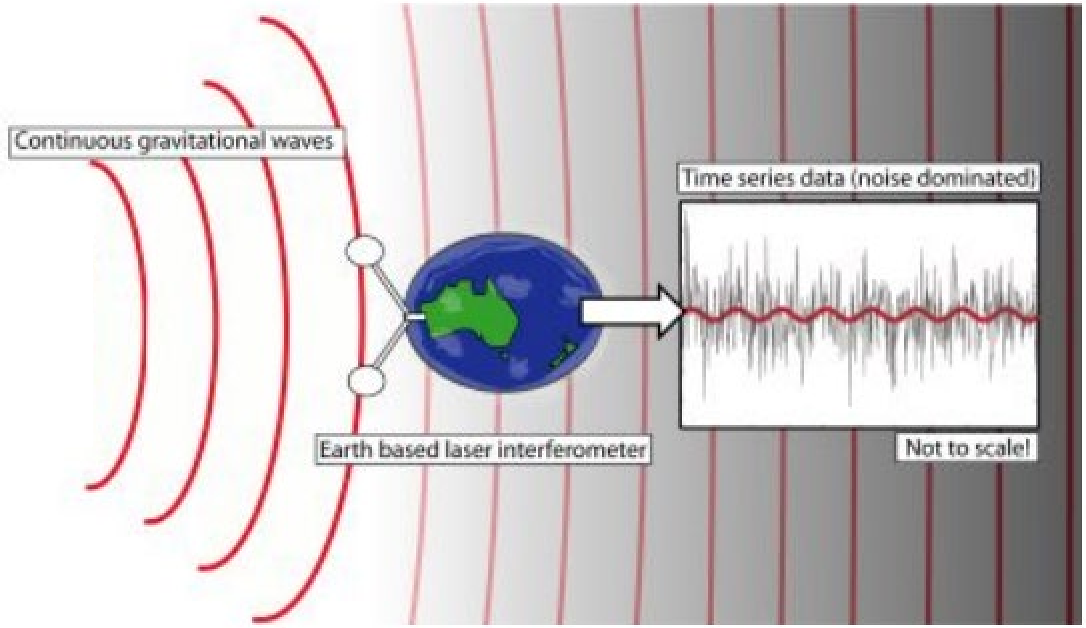


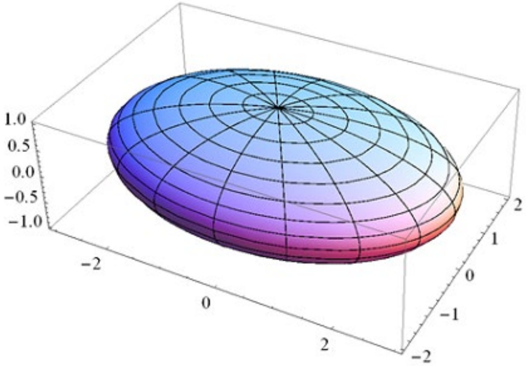
- Morphology: Spherical v.s. Bulge-like



GW channel can be useful:







principal moments of inertia

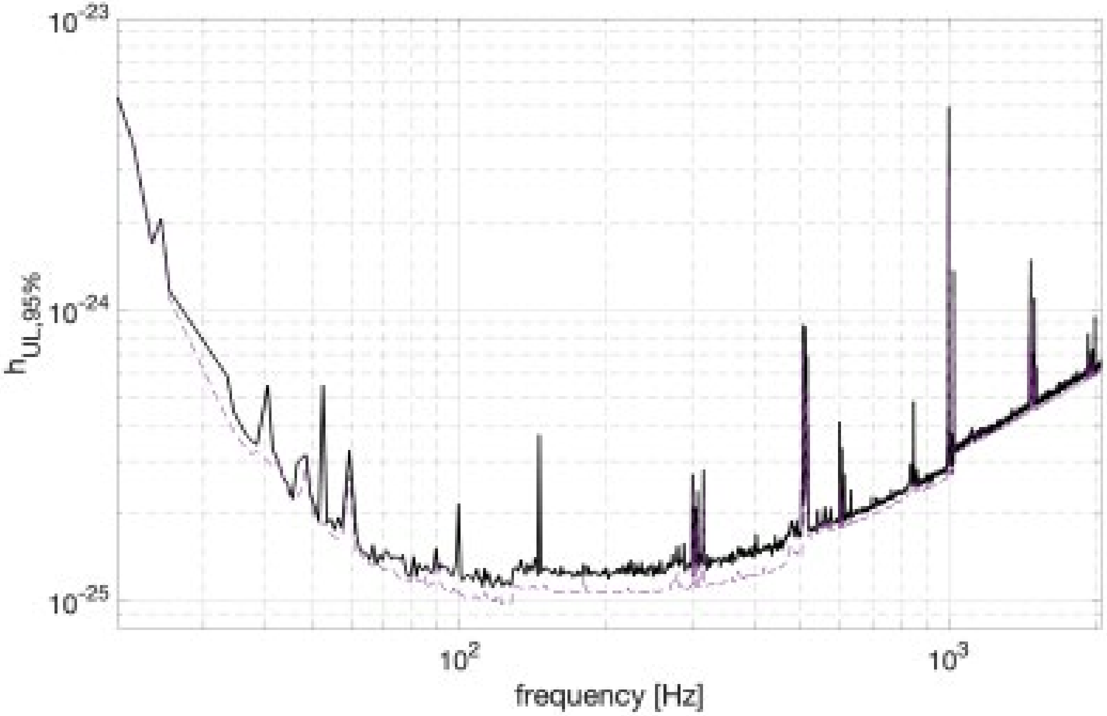
ellipticity

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

residual crustal deformation
non-axisymmetric distribution of magnetic field
Modern Physics Letters A 32, 39, 1730035 (2017)

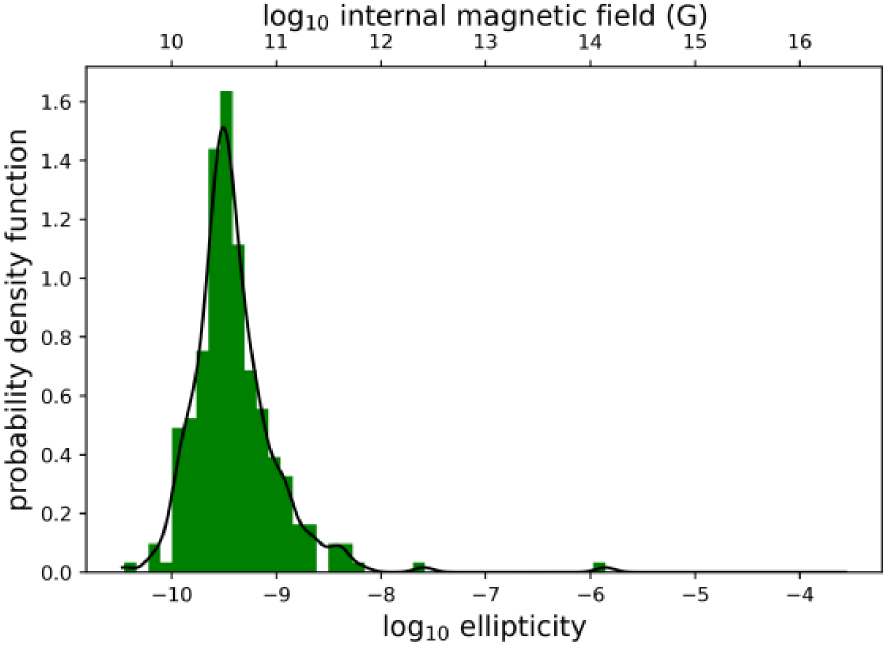
Existing search:

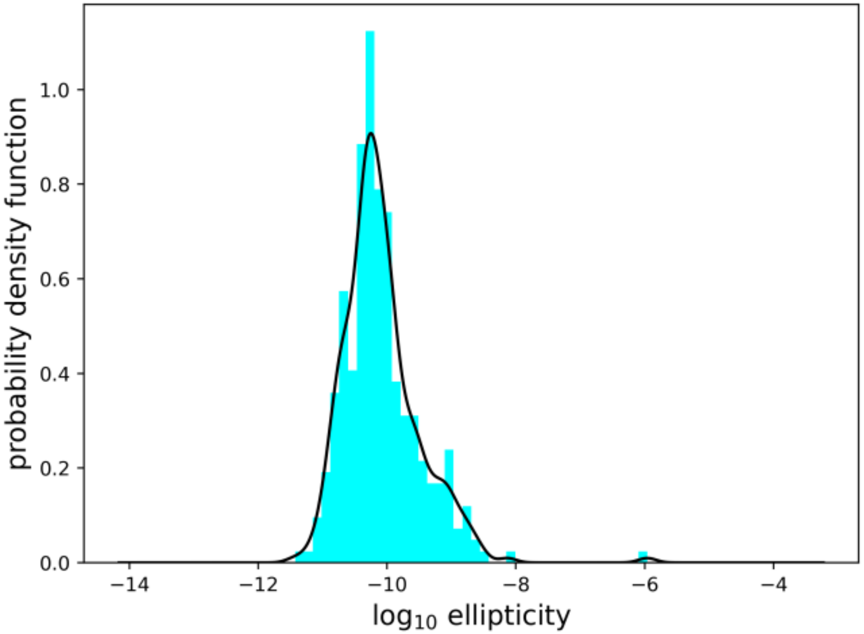
The LVK collaboration
Phys. Rev. D 106, 102008
All-sky pulsar search



Ellipticity distribution:

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





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

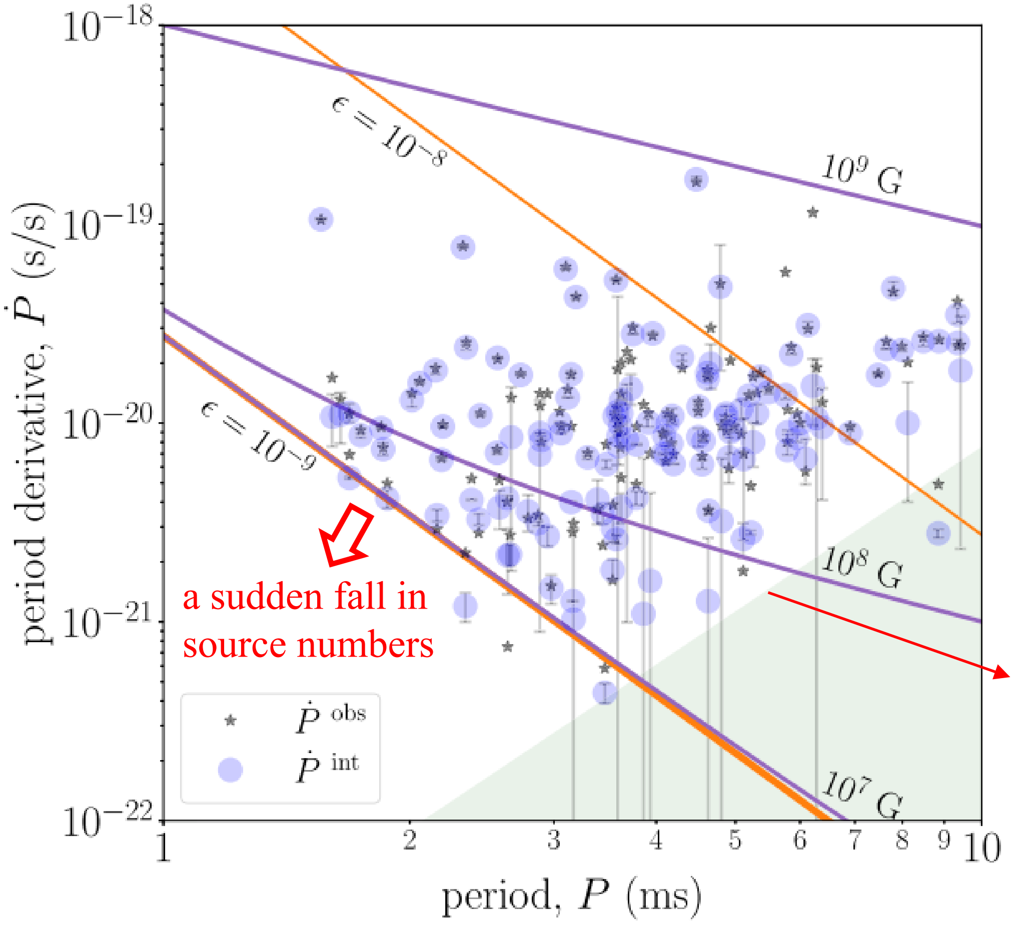
$$B_{\mathrm{int}} = 150 B_{\mathrm{ext}}$$

GW radiation accounts for 1% rotational energy loss.

ATNF pulsar catalogue

Evidence for a Minimum Ellipticity in Millisecond Pulsars

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

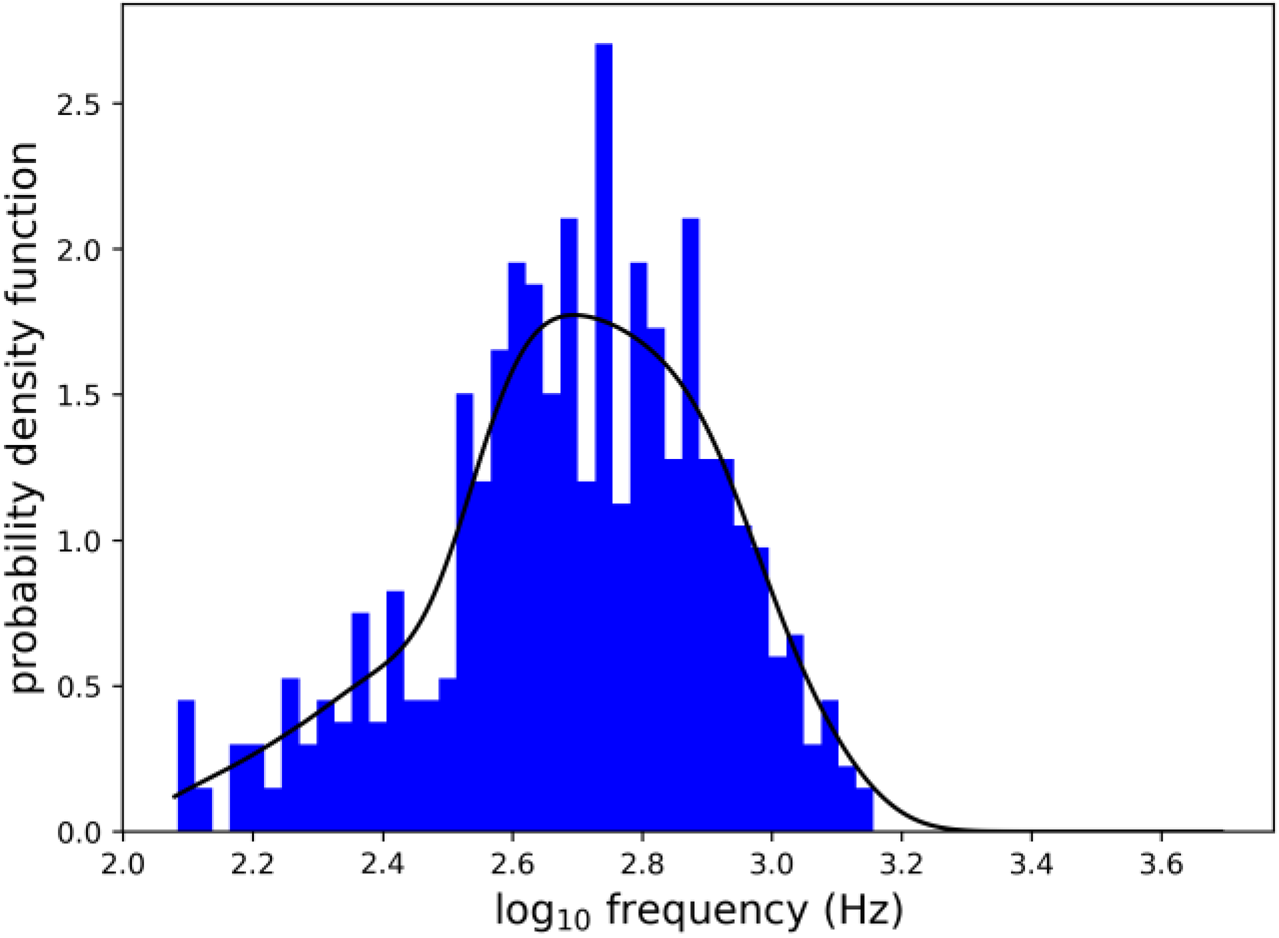


a sudden fall in source numbers

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

Frequency distribution:

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

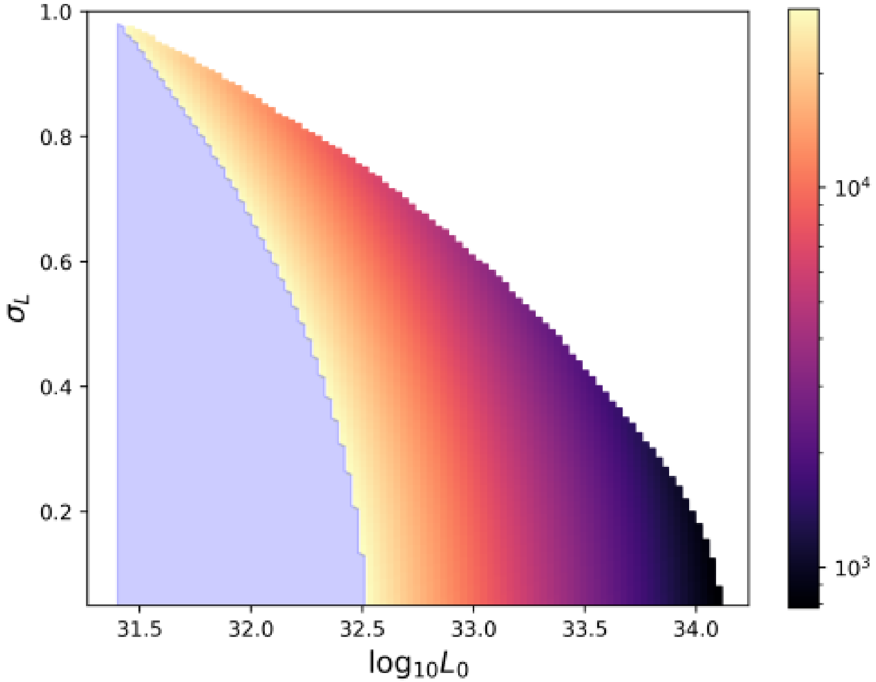


ATNF pulsar catalogue

WIMP DM:

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

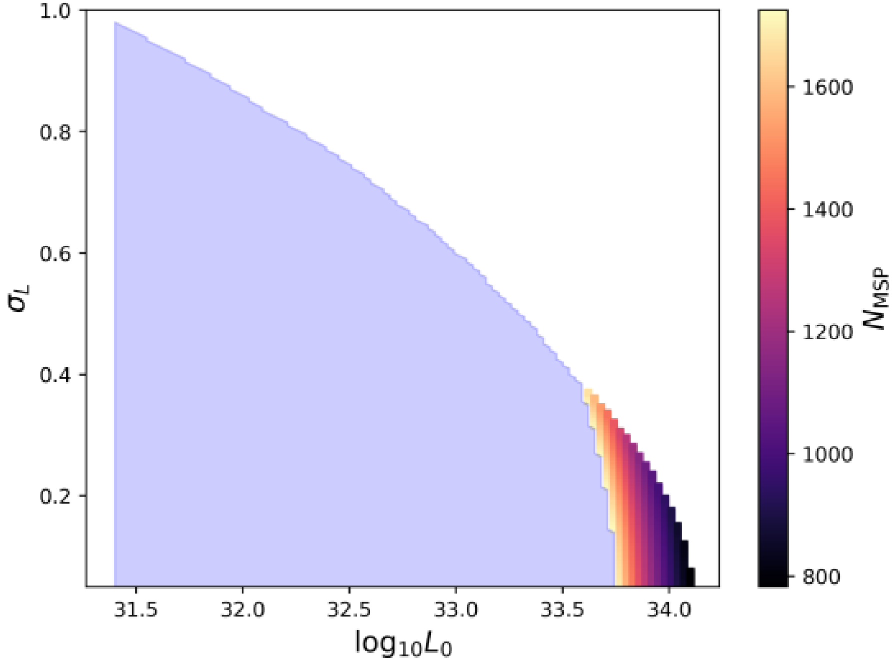
$$\frac{dP(L)}{dL} = \frac{\log_{10} e}{\sigma_L \sqrt{2\pi} L} \exp\left(-\frac{\log_{10}^2(L/L_0)}{2\sigma_L^2}\right)$$



1% energy loss through GW

$d = 8$ kpc

$I_{zz} = 10^{38}$kg·m^2



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

$I_{zz} = 5 \times 10^{38}$kg·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)

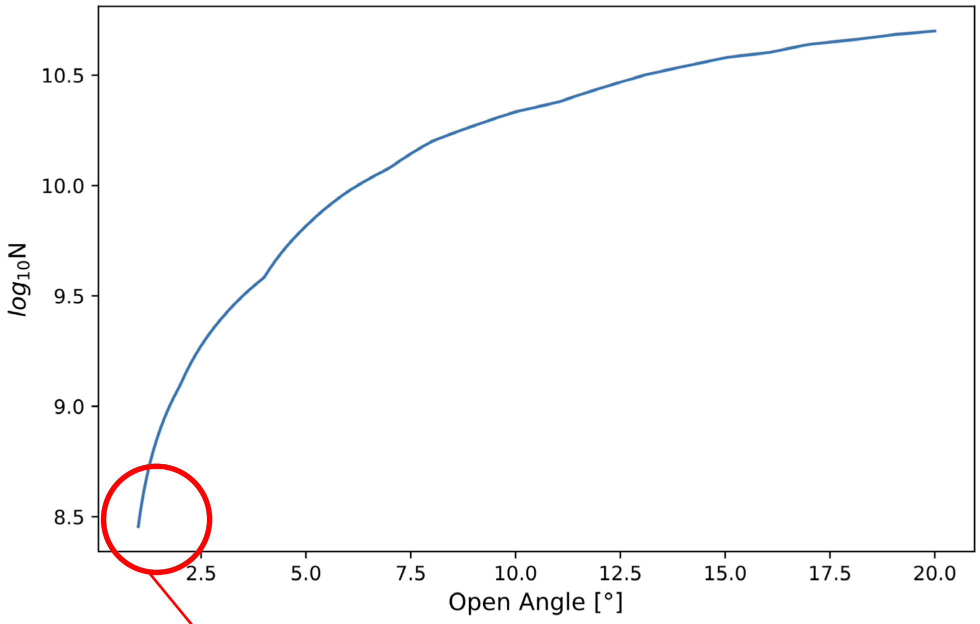
We need to find the middle point for the GeV excess.

~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:



Only covered 1% of the potential MSPs.

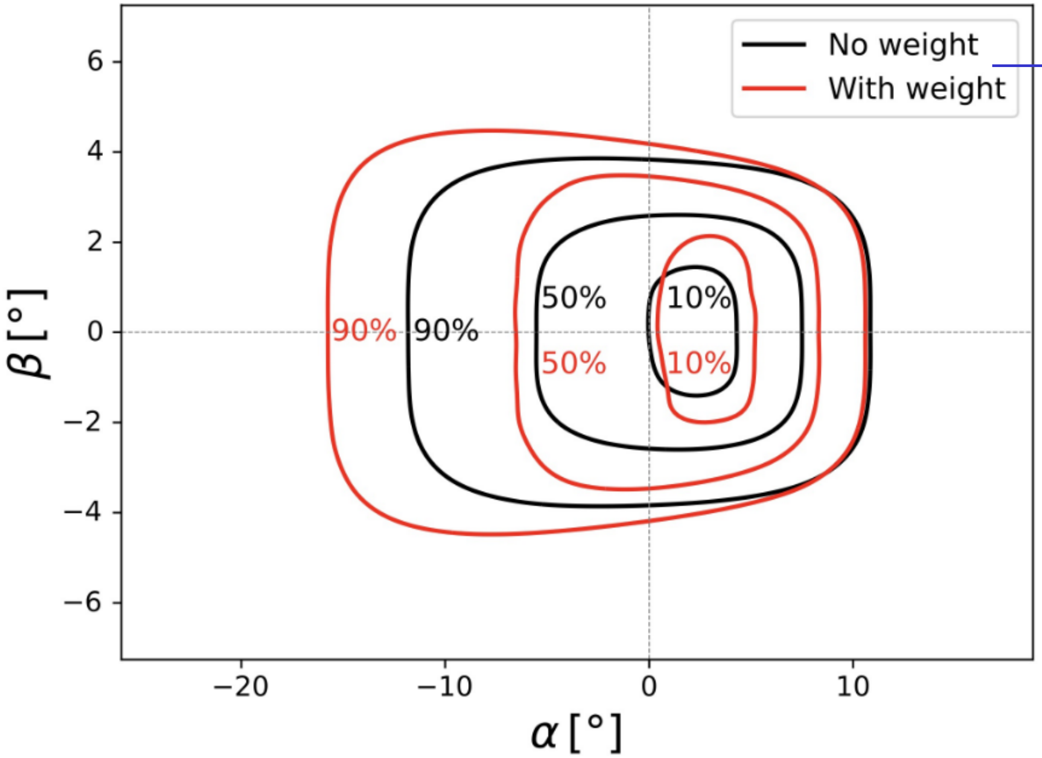
$$n_B(x,y,z) = n_{B0} \exp\left(-r_s^2/2\right)$$

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

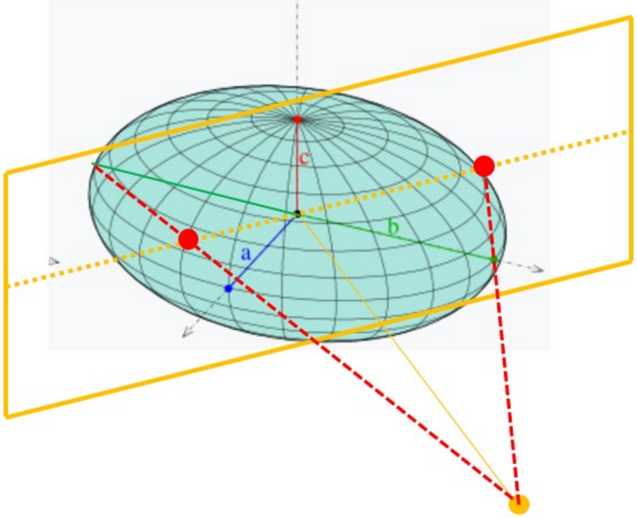
with $x_0 = 1.59$ kpc, $y_0 = 0.424$ kpc, and $z_0 = 0.424$ kpc.

Future Improvement:

Projected MSP distribution



Weighting by 1/r^2



Future Improvement:

Optimize the search strategy:

Current searches:

All-sky: Not focused on the galactic center

Galactic center search: ~ 1 degree by 1 degree

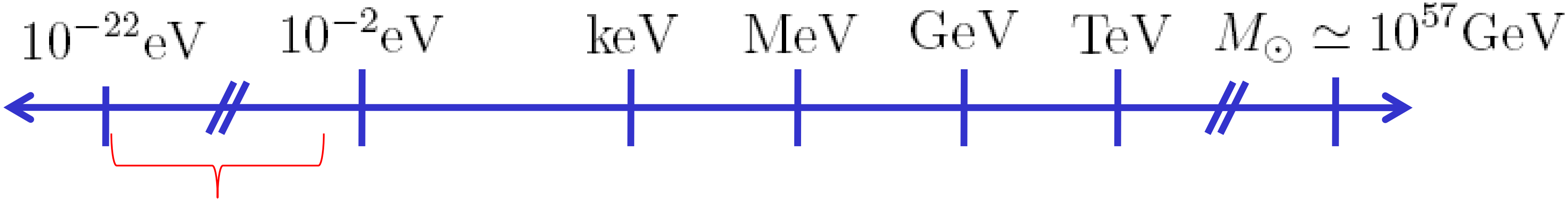
We need to find the middle point for the GeV excess.

~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

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

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

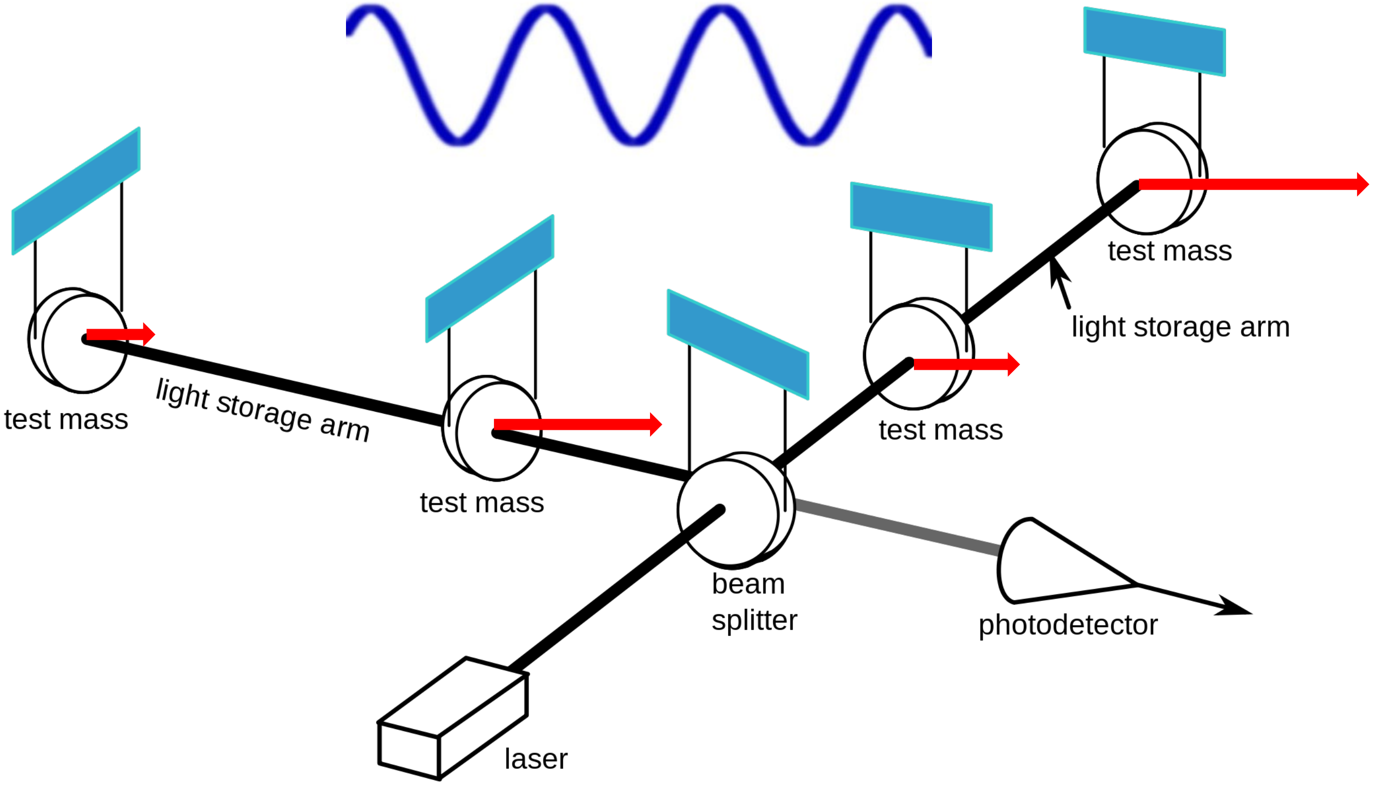
Ordinary materials carry huge dark charges, and thus feel a force by dark photon field!

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



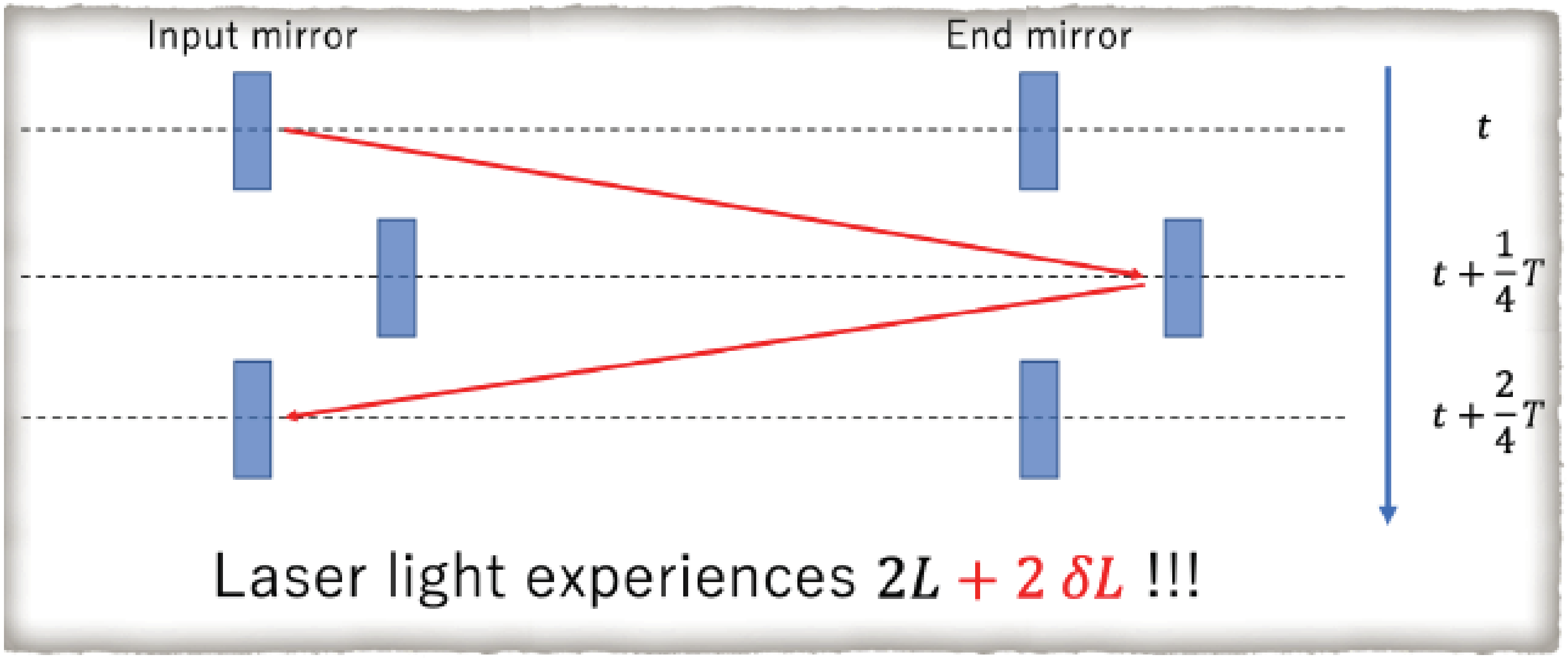
Dark photon dark matter moves mirrors. ⇨ Change photon propagation time between mirrors. ⇨ interferometer pattern

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



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

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.

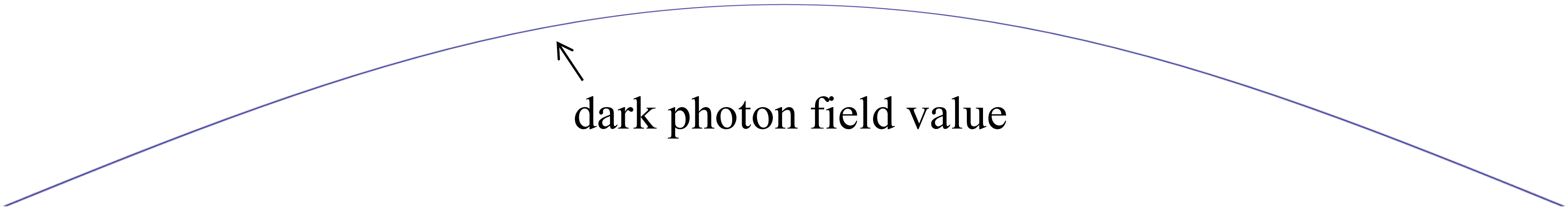
- very long coherent distance

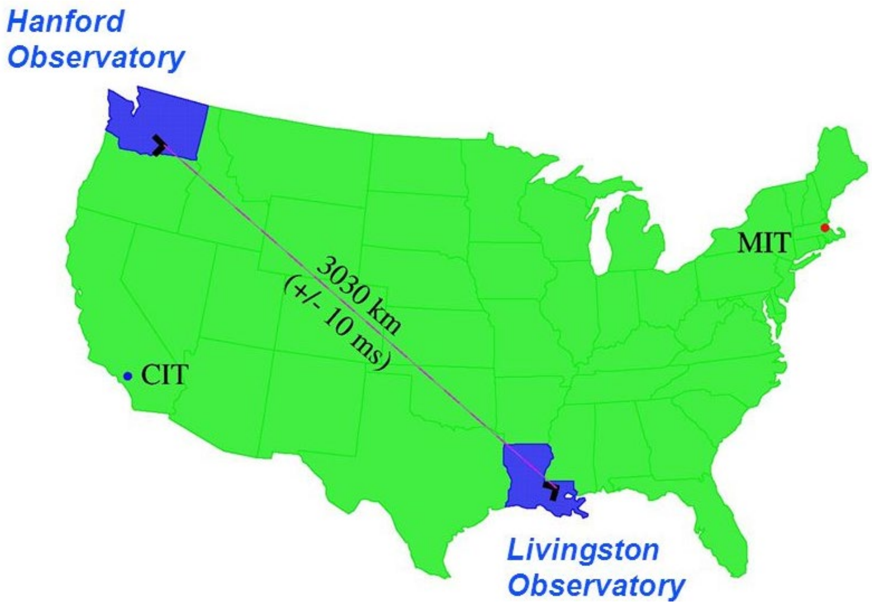
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

⇨ 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.

Search based on SGWB method:

Signal-to-Noise-Ratio can be calculated as:

$$S = < s_1, s_2 > \equiv \int_{-T/2}^{T/2} s_1(t) s_2(t) dt.$$

overlap function
describe the correlation among sites

observation time of an experiment, O(yr)

$$S = \frac{\boxed{T}}{2} \int df \, \boxed{\gamma(|f|)} \, S_{GW}(|f|) \, \boxed{\tilde{Q}(f),}$$

$$N^2 = \frac{T}{4} \int df \, \boxed{P_1(|f|)} \, |\tilde{Q}(f)|^2 \; P_2(|f|).$$

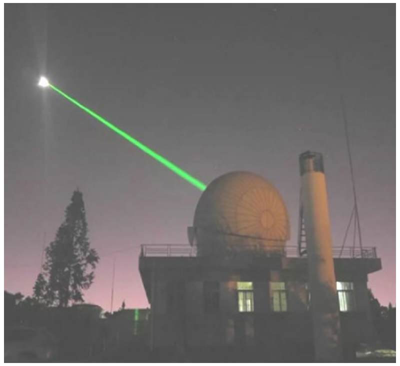
optimal filter function
maximize SNR

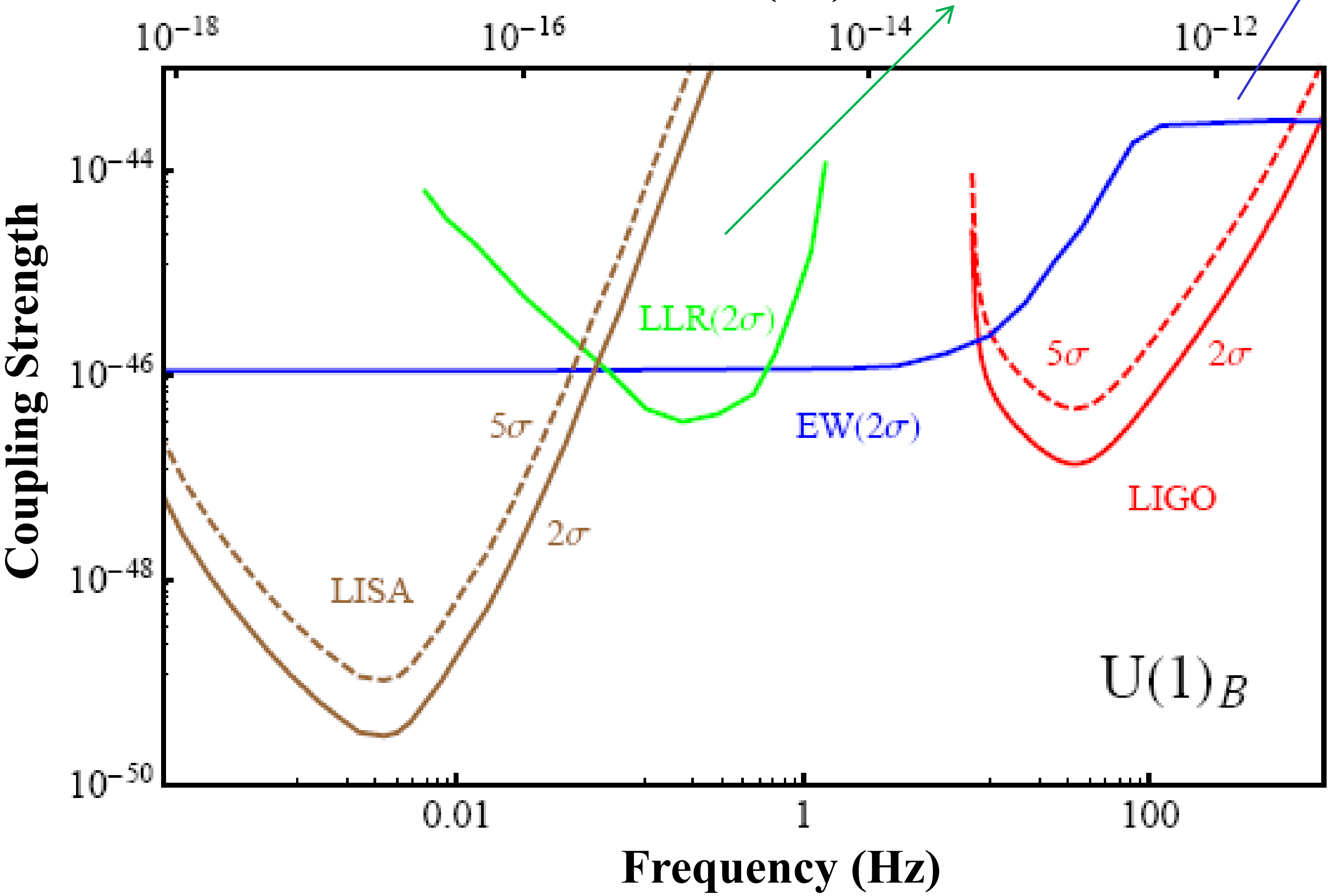
one-sided strain noise power spectra

Sensitivity Plot:

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

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





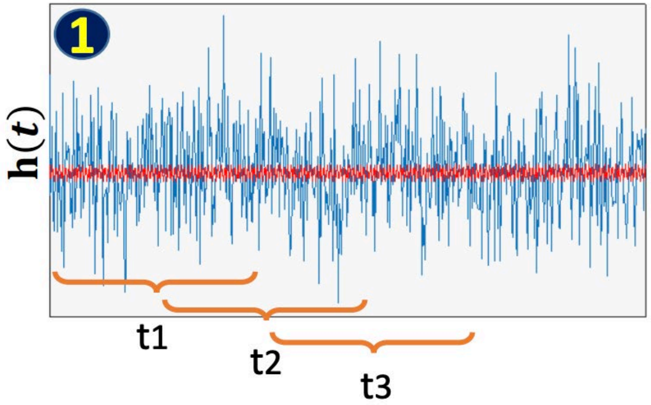
(Eöt-Wash web)

Loránd Eötvös

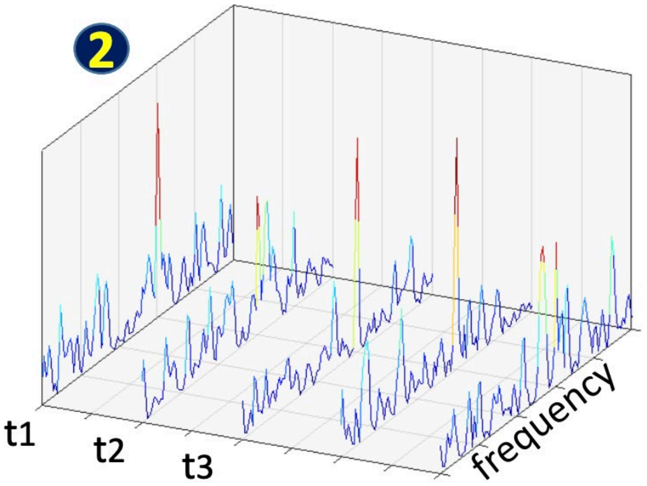
→ Eöt-Wash

design sensitivities, 2 yrs

Search based on CW method:



Take Fourier transforms of length $T_{\mathrm{FFT}} \sim T_{\mathrm{coh}}$ and combine the power in each FFT without phase information

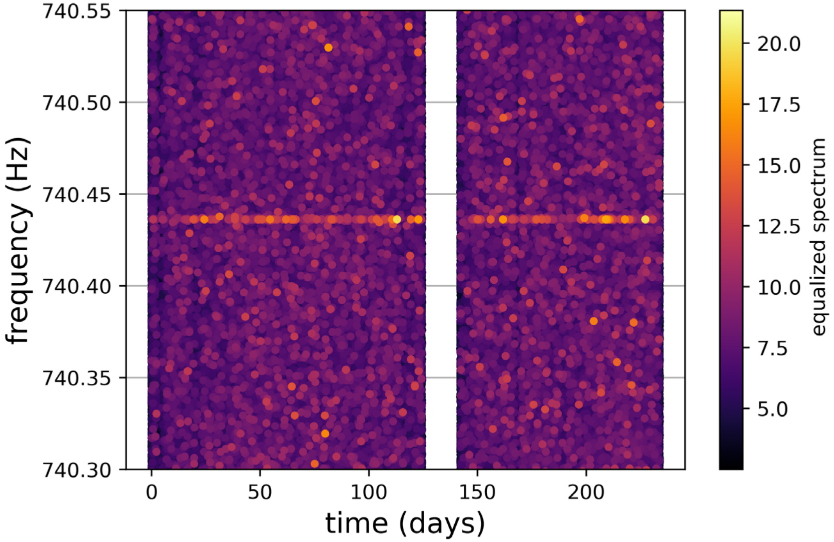


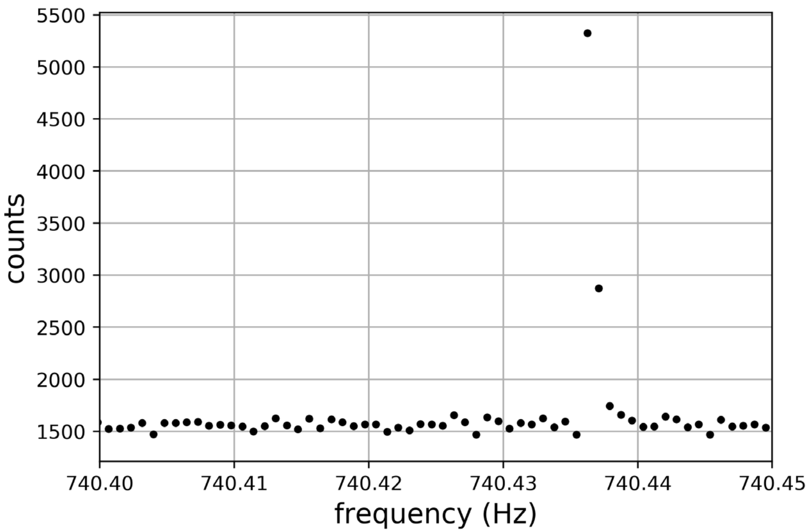
Candidates are considered in coincidence if they are within one frequency bin of each other, and if the critical ratio CR>5

$$CR = \frac{y-\mu}{\sigma}$$

Search based on CW method:

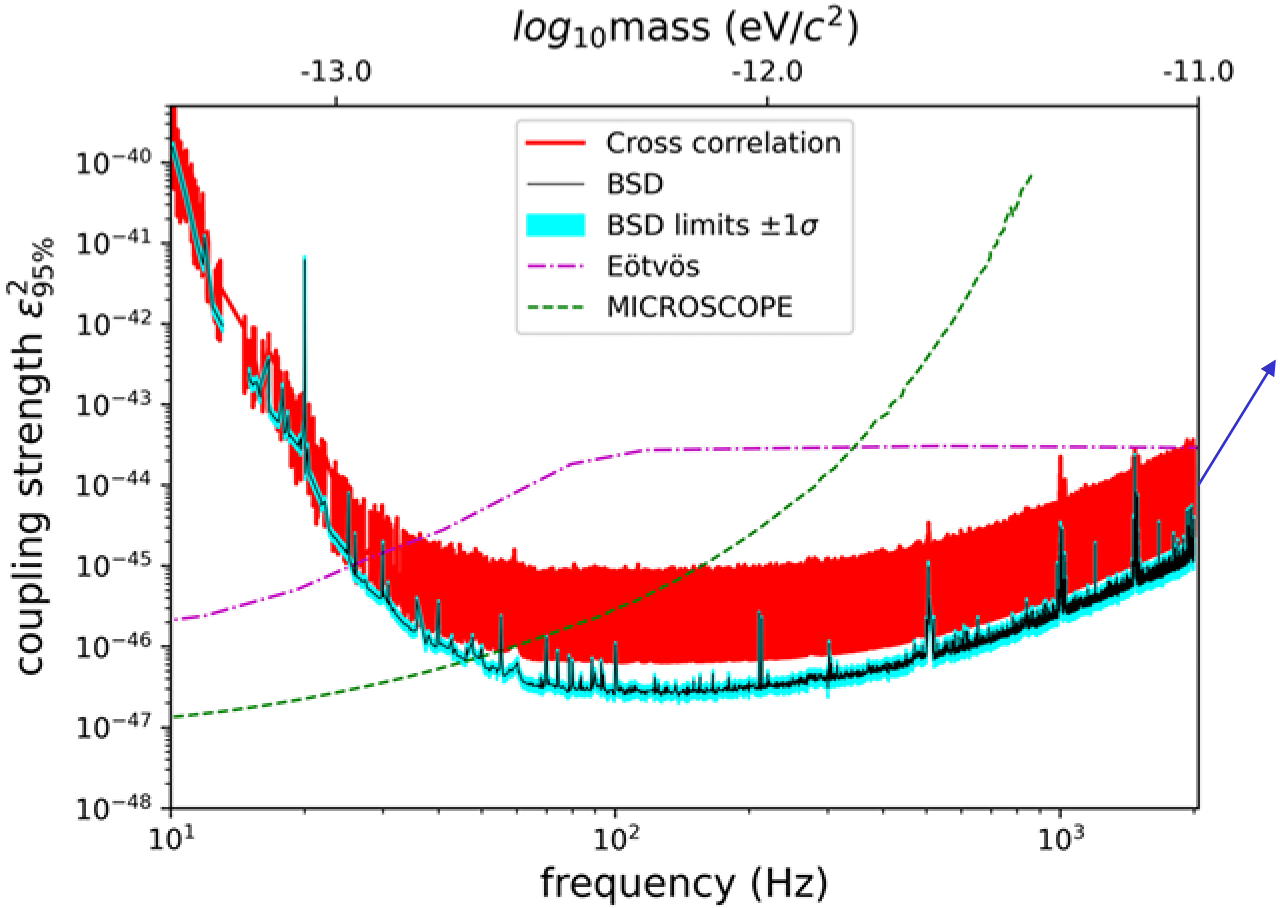
Simulated signal shown here





Determine time/frequency points above a certain power threshold and histogram on frequency axis

O3 Result:

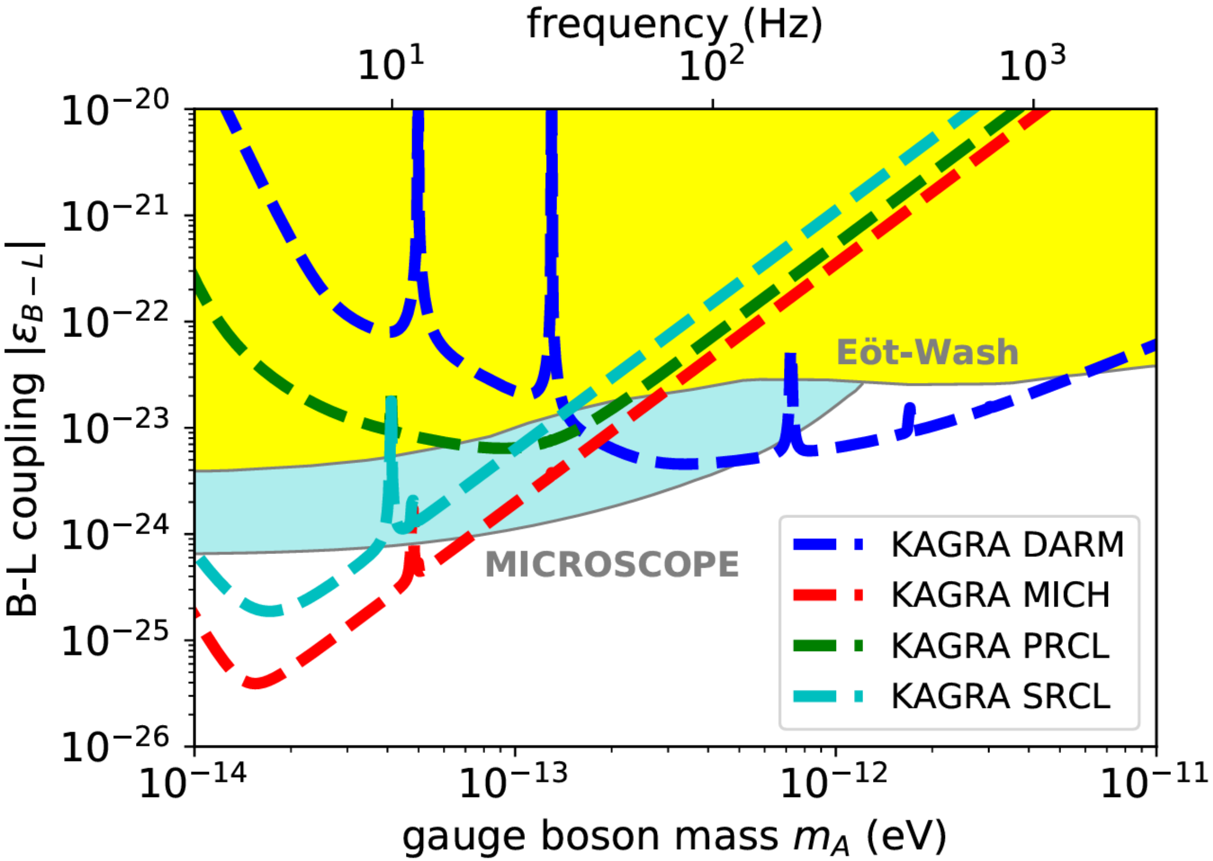


Cross correlation is weaker because Livingston and Hanford are almost anti-aligned.

It will be improved when more detectors join the network.

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

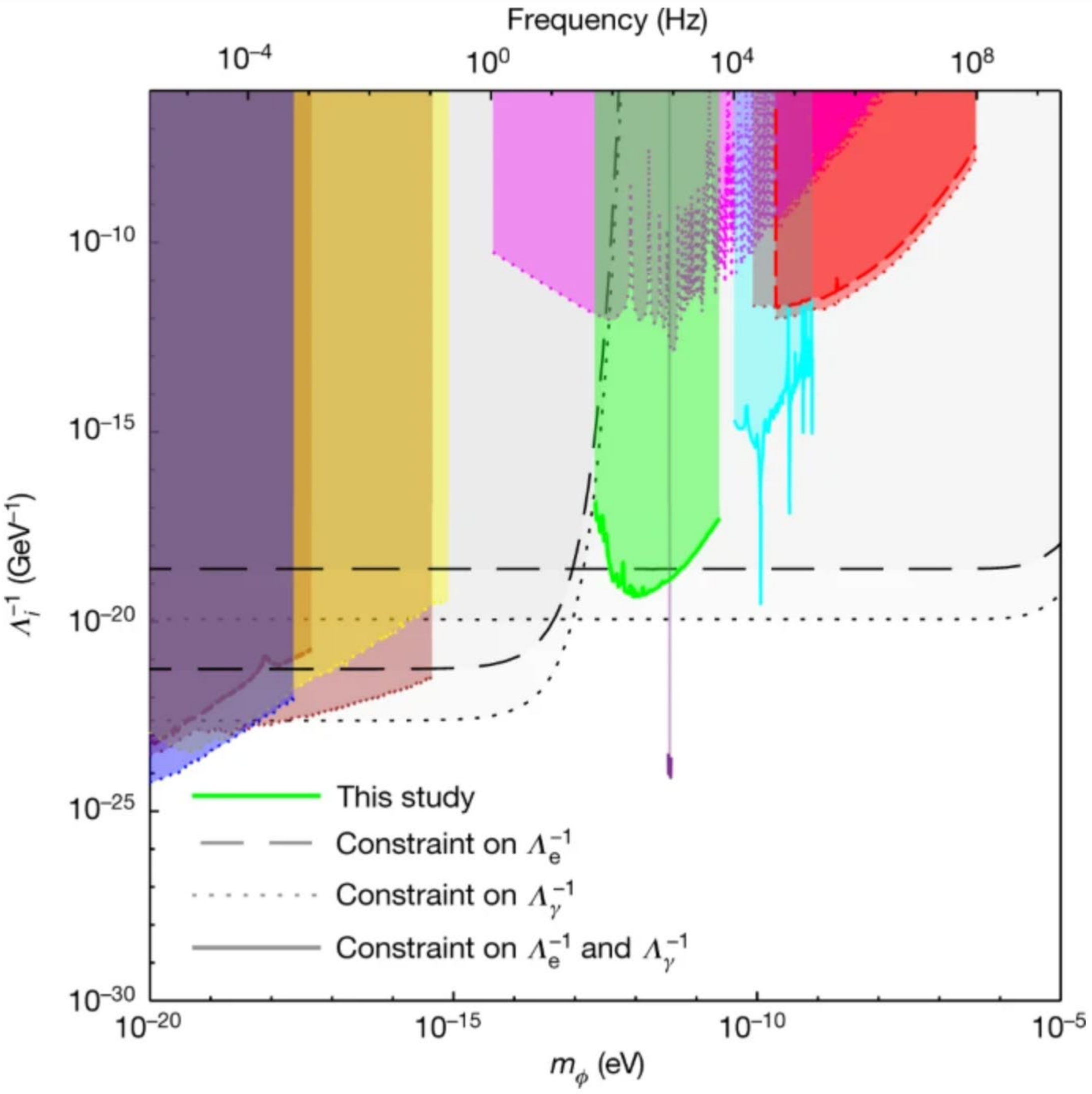
KAGRA is special:



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:

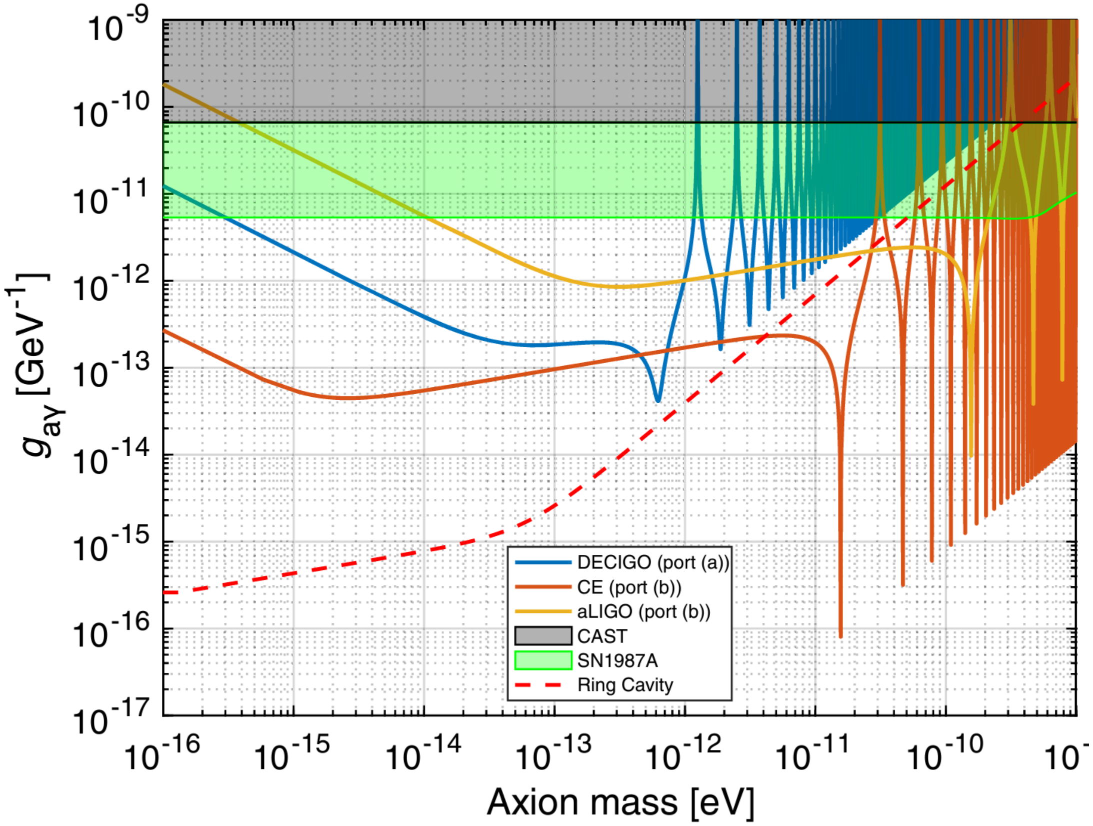


Sander M. Vermeulen et. al.
GEO 600
Nature 600, 424–428 (2021)

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

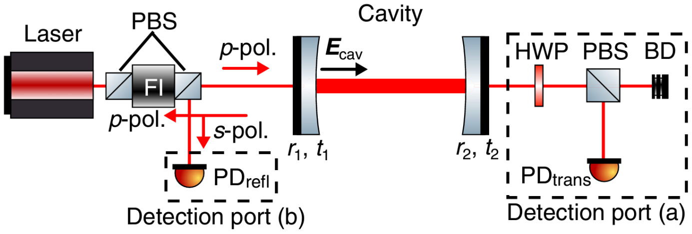
$$\delta(L_x - L_y) \approx \left(\frac{1}{\Lambda_\gamma}+\frac{1}{\Lambda_{\rm e}}\right)\left(\frac{nl\hbar\sqrt{2\rho_{\rm local}}}{m_\varphi {\rm c}}\right)\cos(\omega_{\rm obs} t)$$

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.