

Using GW to look for dark matter (in)directly

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Gravitational Wave Probes of Physics Beyond Standard Model

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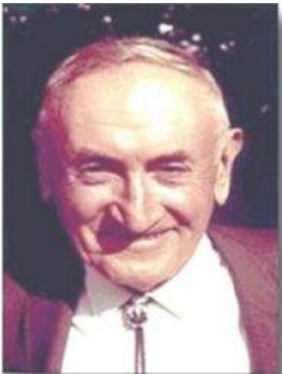
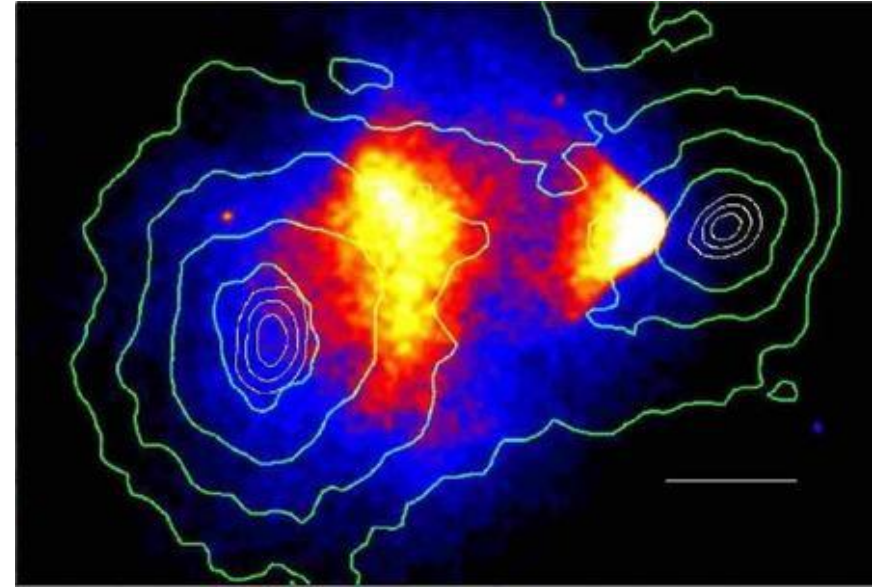
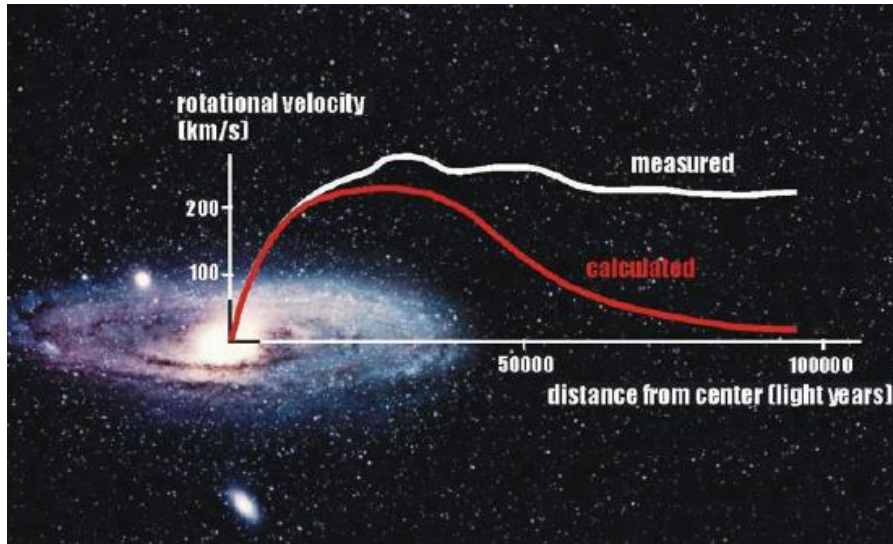
University of Utah

~~Gravitational Wave Probes of Physics Beyond Standard Model~~

second half

first half

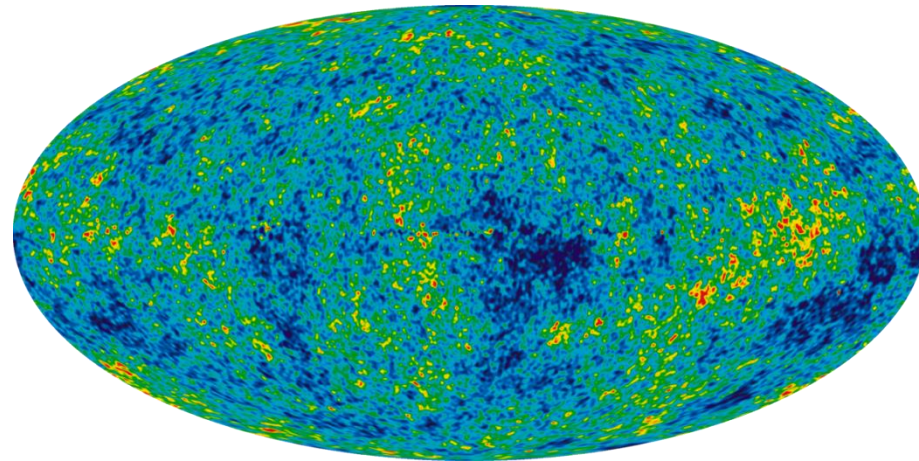
Dark Matter Overview:



Fritz Zwicky



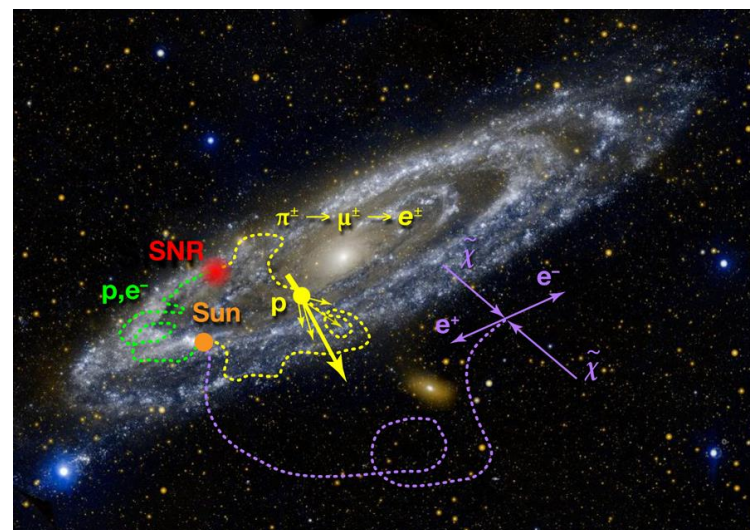
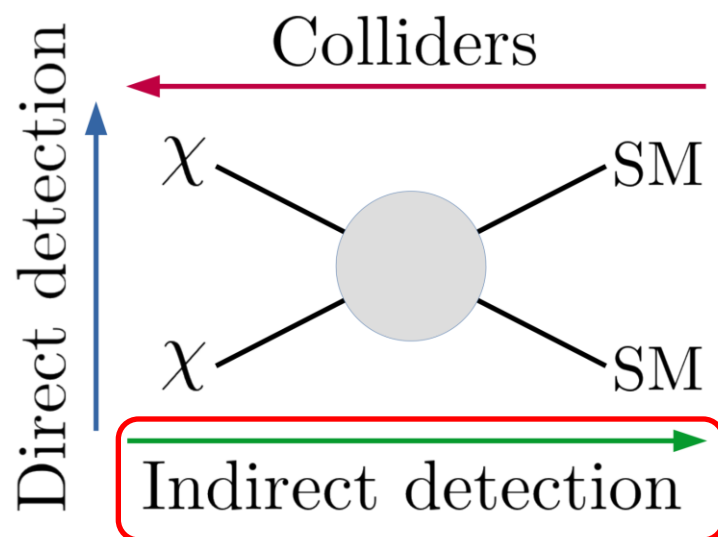
Vera Rubin



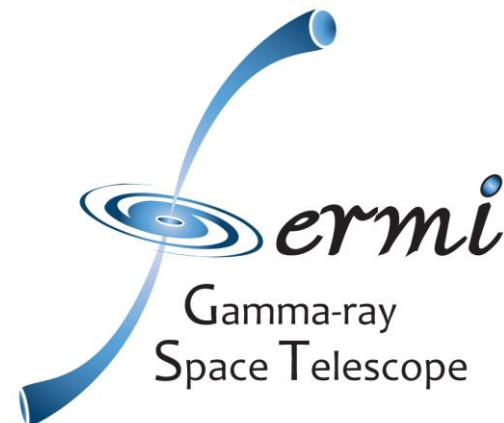
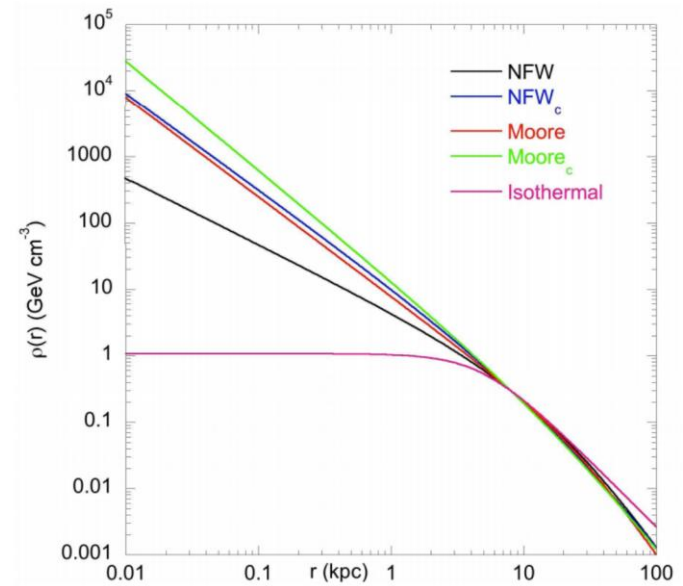
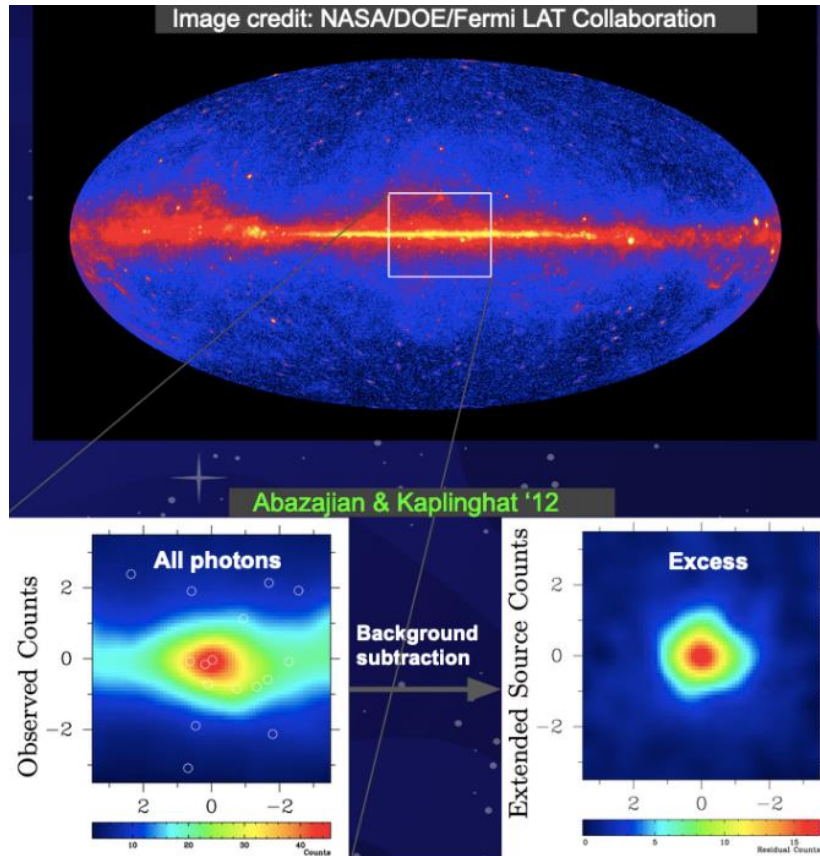
A GeV excess at the Galactic Center:



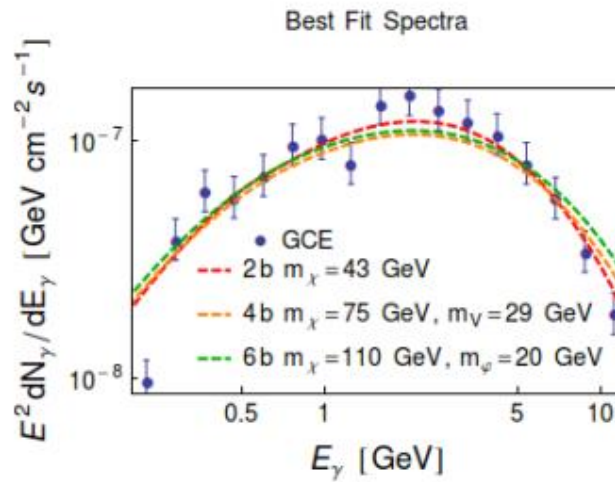
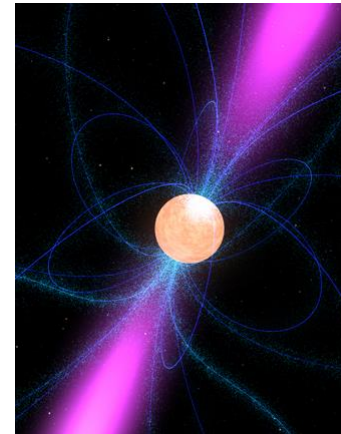
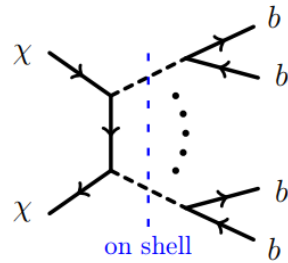
Well motivated.
Correct relic abundance.
Searched for decades.



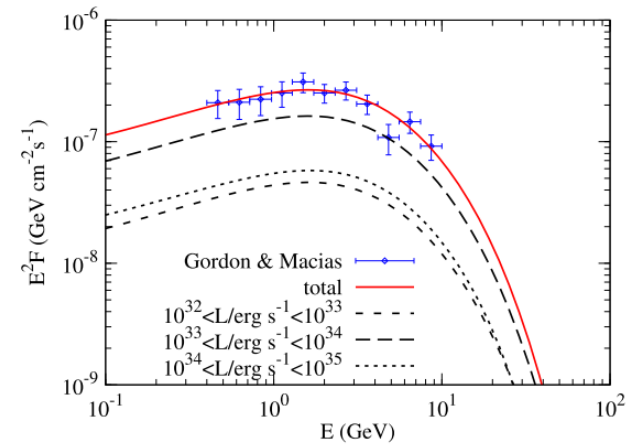
A GeV excess at the Galactic Center:



Two explanations:



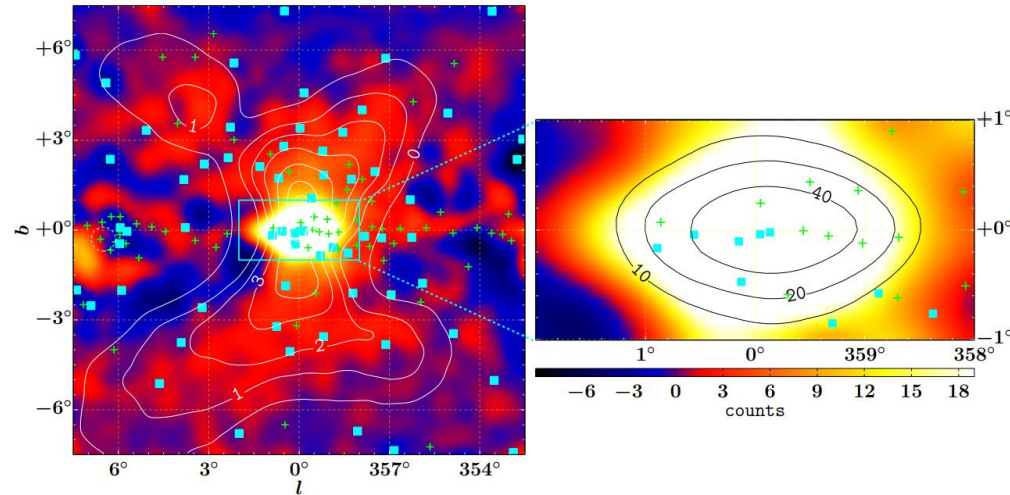
Abdullah, et. al.
Phys. Rev. D 90, 035004 (2014)



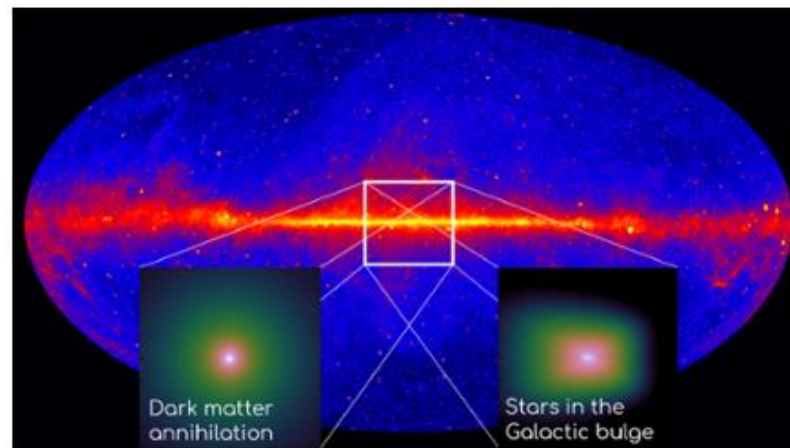
Yuan, et. al.
JHEAp 3 (2014) 1

Efforts to distinguish these two explanations:

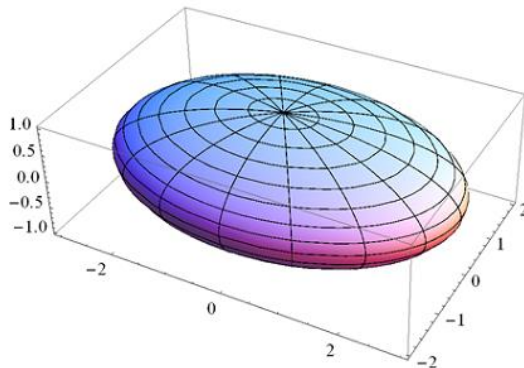
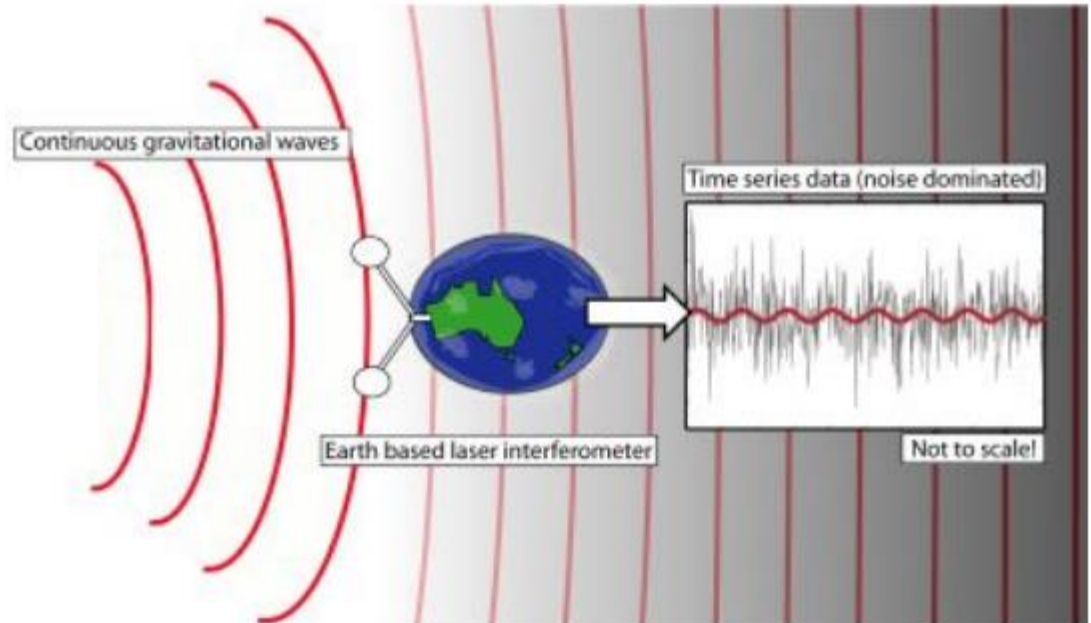
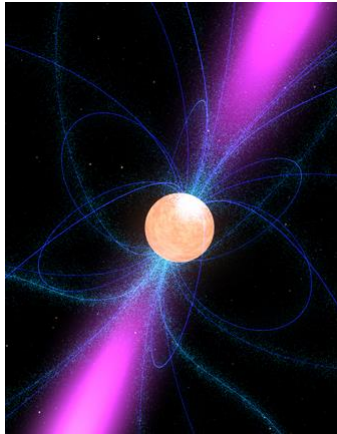
- Smoothness: Point Source v.s. Smeared Distribution



- Morphology: Spherical v.s. Bulge-like



GW channel can be useful:



principal moments of inertia

ellipticity

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

residual crustal deformation

non-axisymmetric distribution of magnetic field

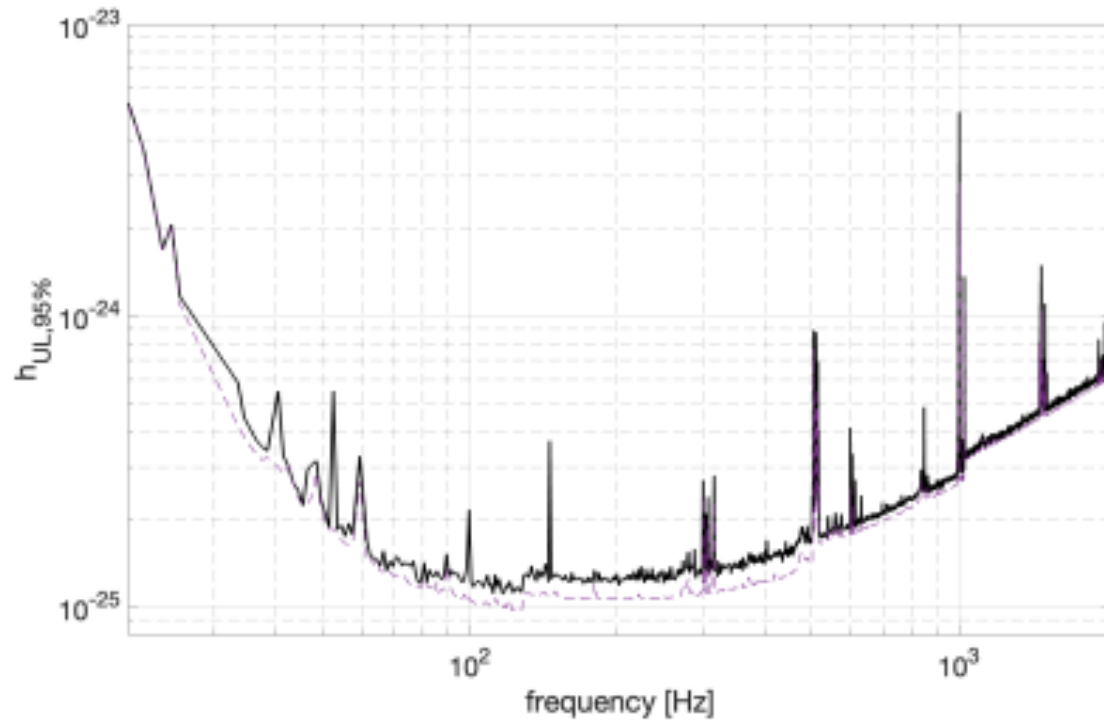
Modern Physics Letters A 32, 39, 1730035 (2017)

Existing search:

The LVK collaboration

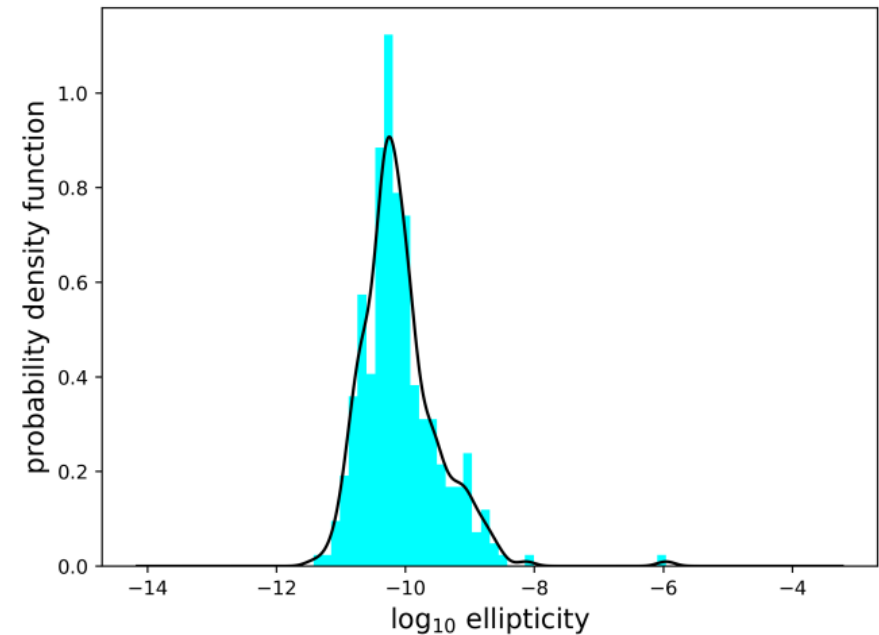
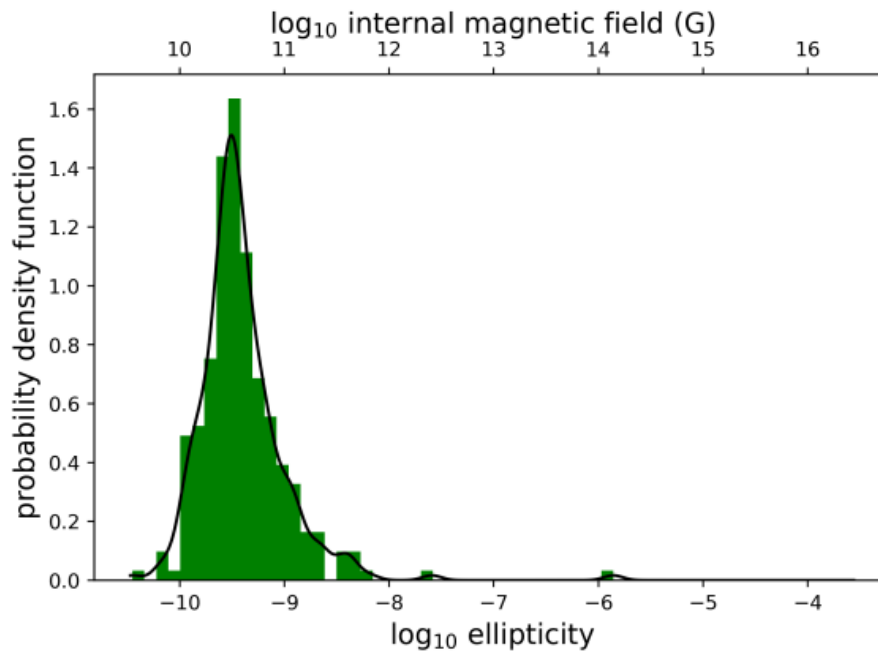
Phys. Rev. D 106, 102008

All-sky pulsar search



Ellipticity distribution:

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



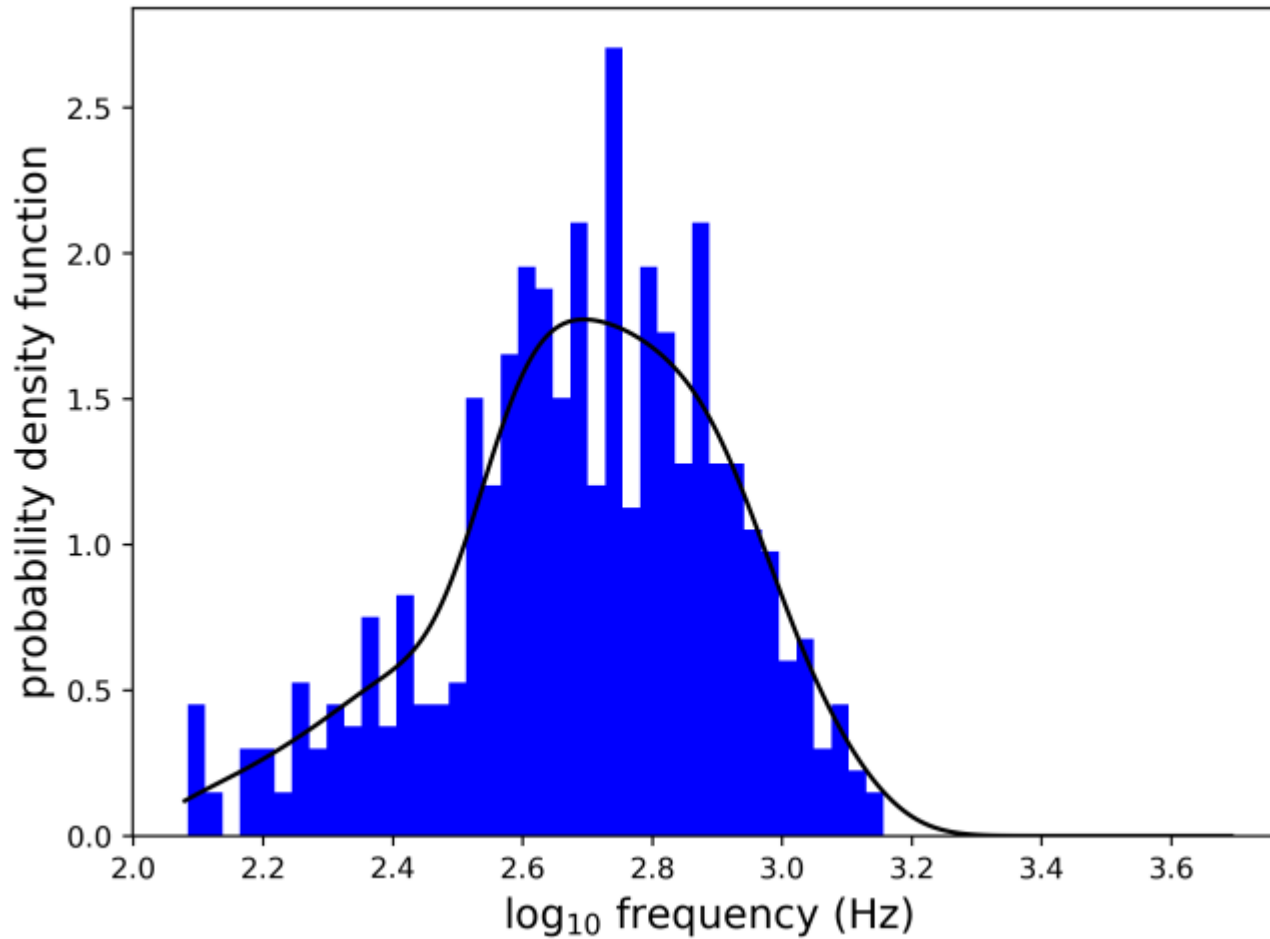
$$\epsilon \approx 10^{-8} \left(\frac{B_{\text{int}}}{10^{12} \text{ Gs}} \right)$$

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

GW radiation accounts for 1% rotational energy loss.

Frequency distribution:

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



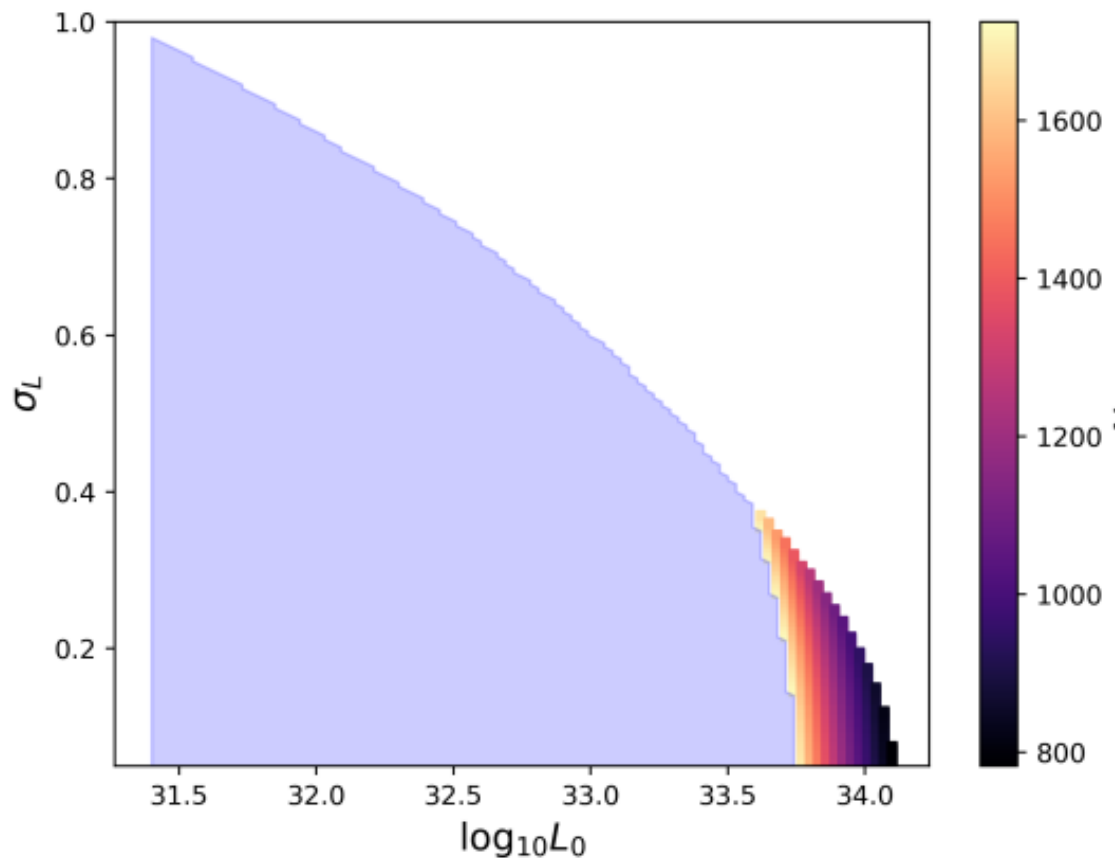
ATNF pulsar catalogue

WIMP DM:

Andrew Miller, Y.Z.

Phys.Rev.Lett. 131 (2023) 8, 081401

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



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

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

Future Improvement:

Optimize the search strategy:

Current searches:

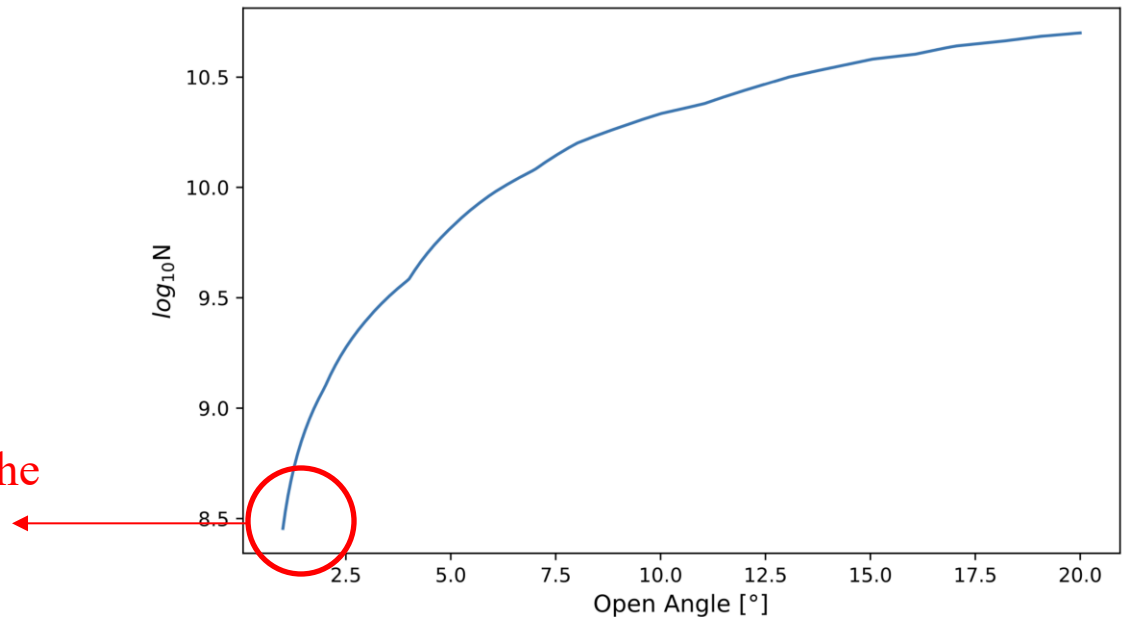
All-sky: Not focused on the galactic center

Galactic center search: ~ 1 degree by 1 degree

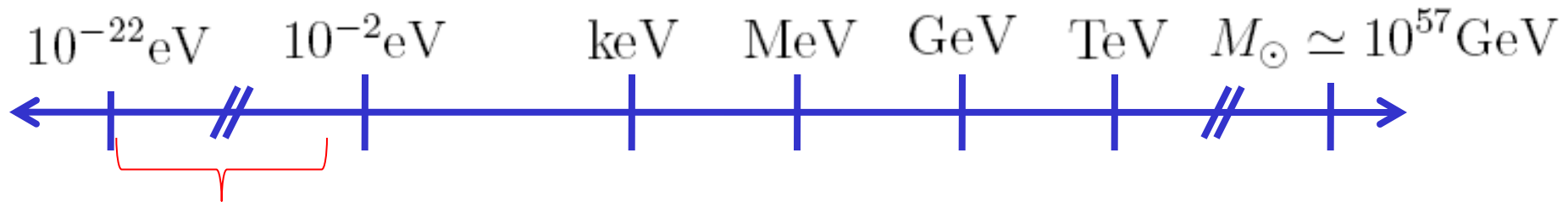
We need to find the middle point for the GeV excess.

~ 10 degree by 10 degree

Only covered 1% of the
potential MSPs.



Ultra-light DM:



a natural prediction of many string-inspired models

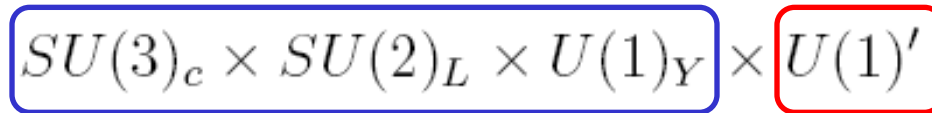
Bosonic DM with gigantic occupation number

⇒ 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

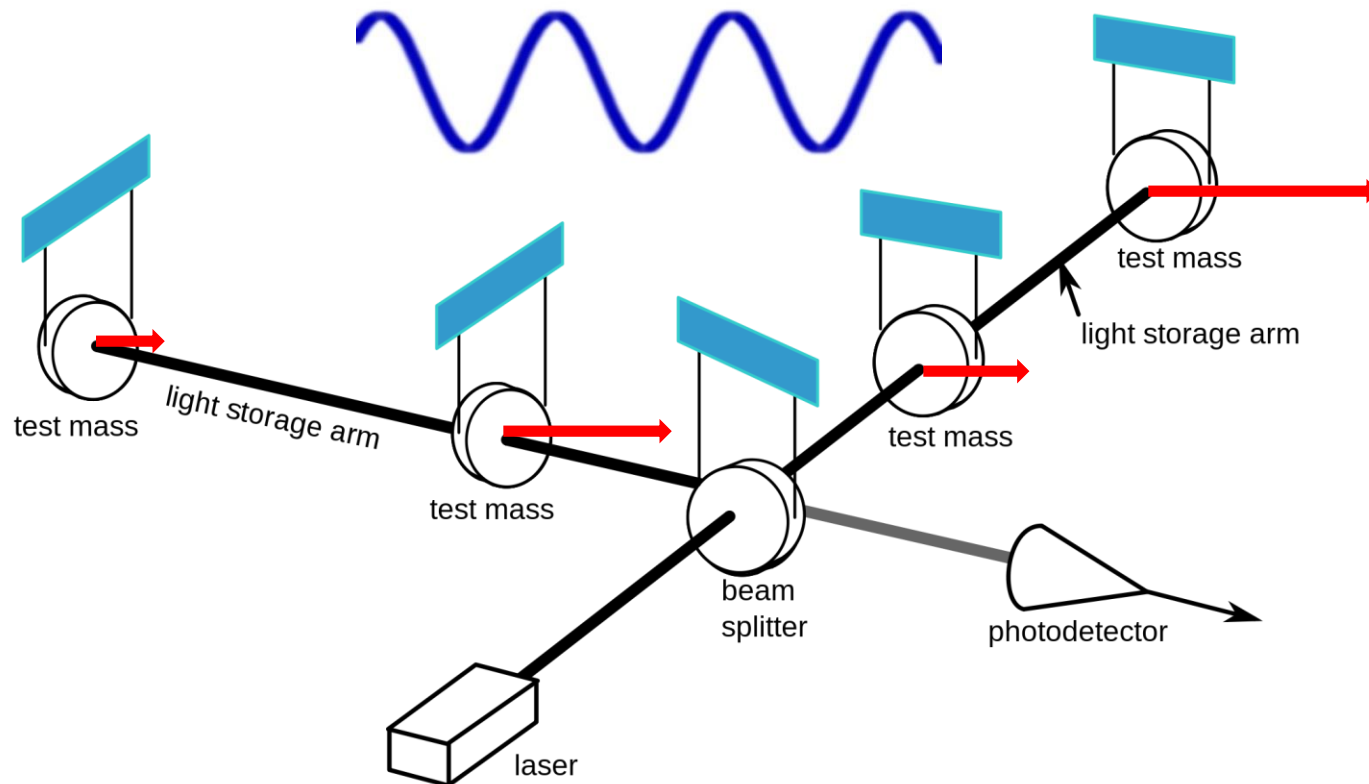
Ordinary materials carry huge dark charges, and thus feel a force by dark photon field!

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 \Rightarrow background classical radio wave



Dark photon dark matter moves mirrors. \Rightarrow Change photon propagation time between mirrors. \Rightarrow 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.

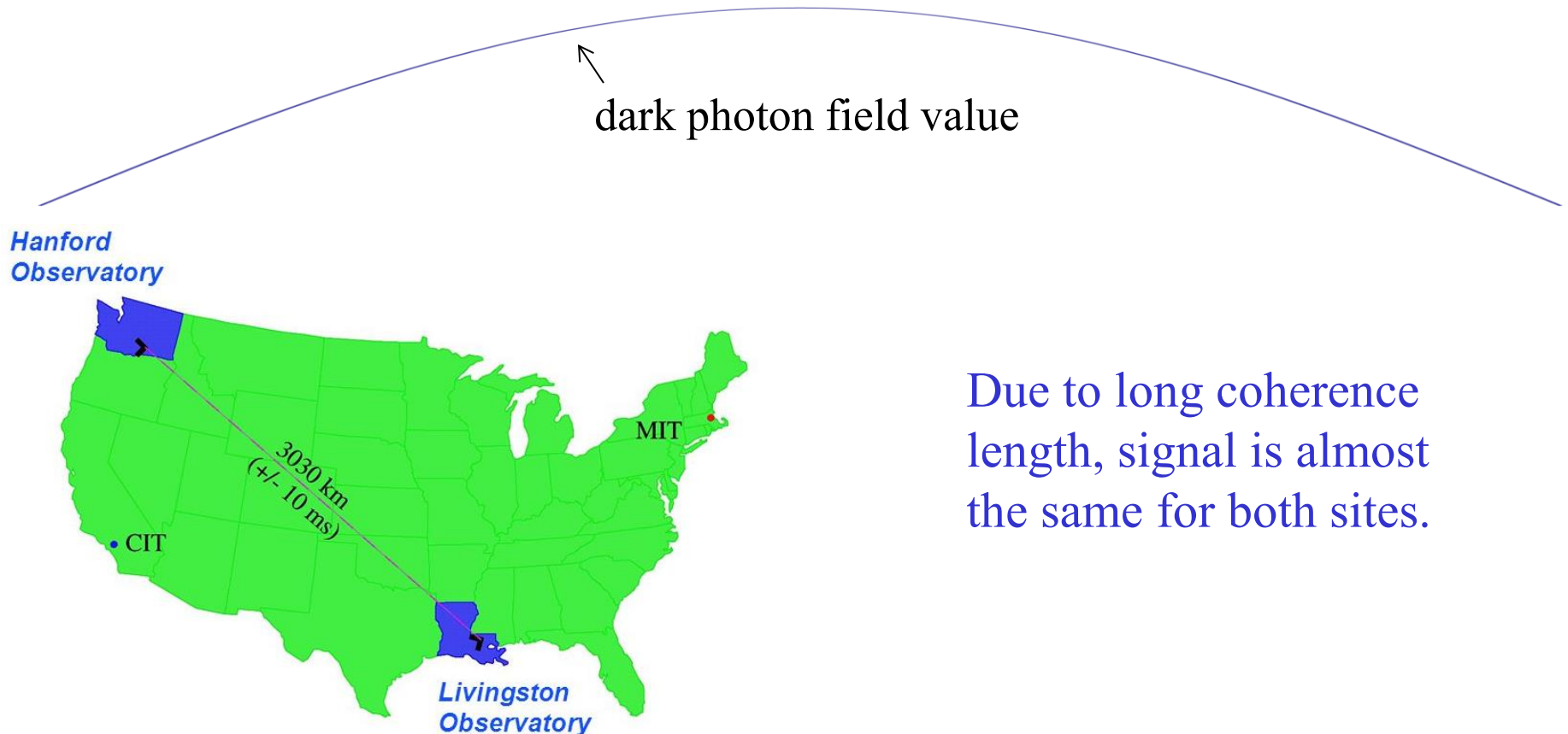
- very long coherent distance

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

⇒ Propagation and polarization directions remain constant approximately.

Ultra-light DM – Dark Photon Induced Displacement:

Correlation between two sites is important to reduce background!



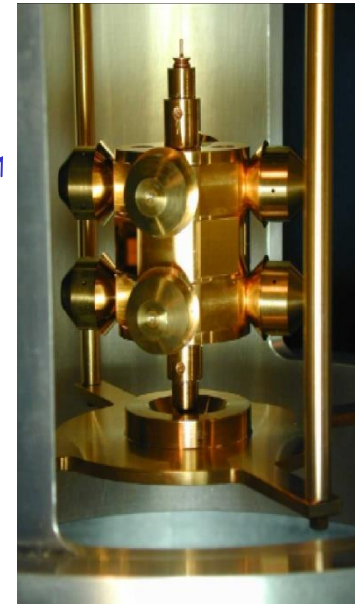
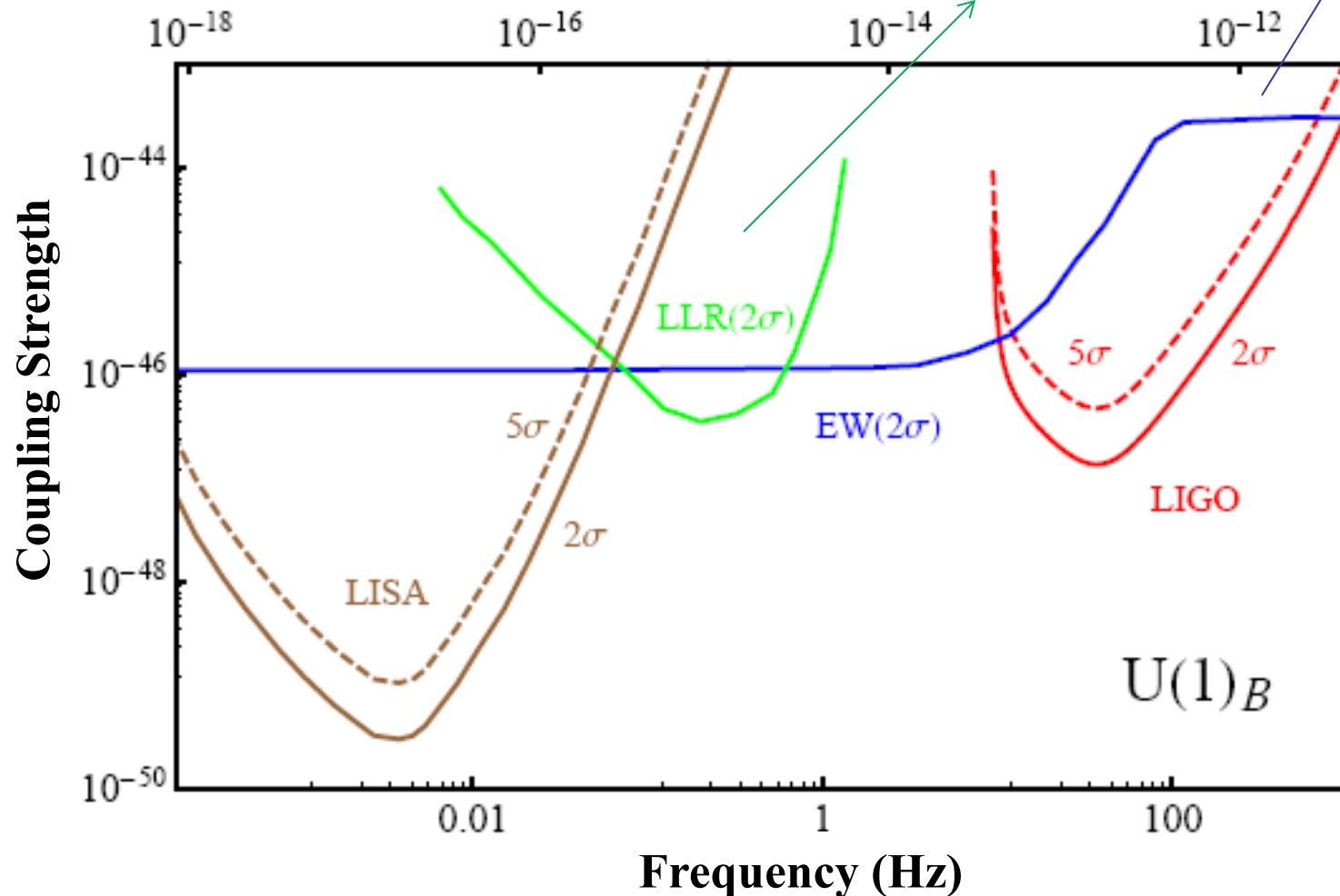
Sensitivity Plot:

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

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



Dark Photon Mass (eV)



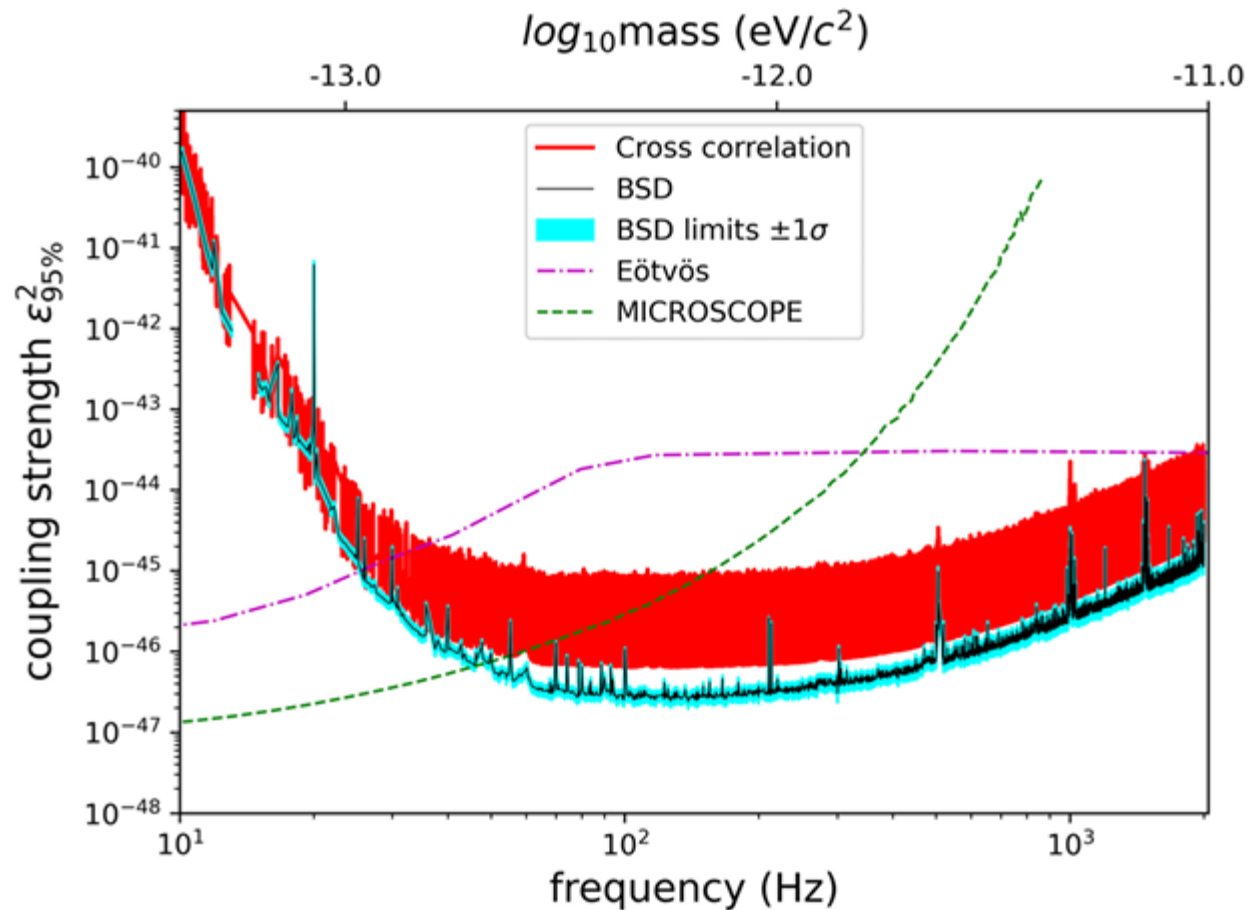
(Eöt-Wash web)

Loránd Eötvös

→ Eöt-Wash

design
sensitivities,
2 yrs

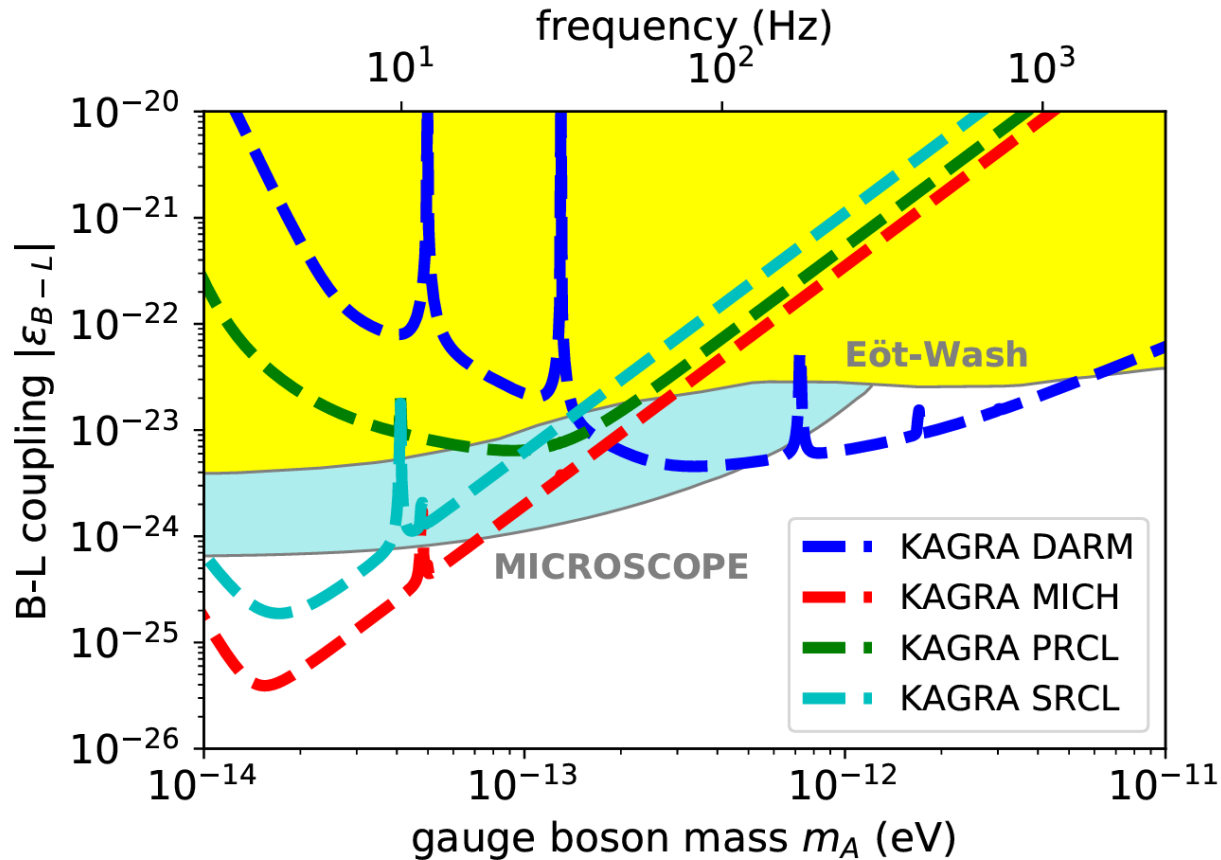
O3 Result:



LIGO-Virgo-KAGRA Collaboration

Phys. Rev. D 105, 063030, 2022

KAGRA is special:



differential arm length (DARM)

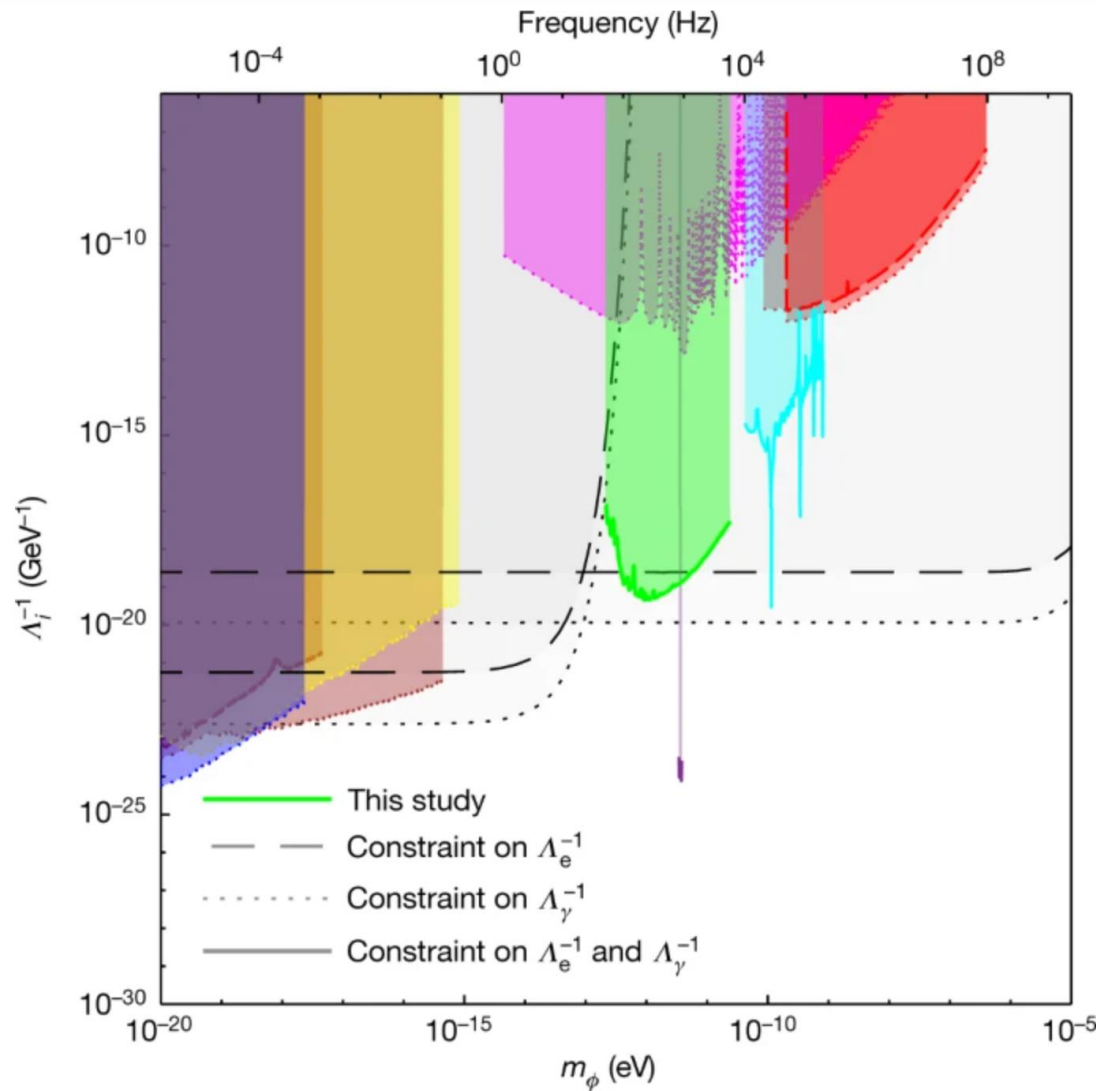
differential Michelson interferometer length (MICH)

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:

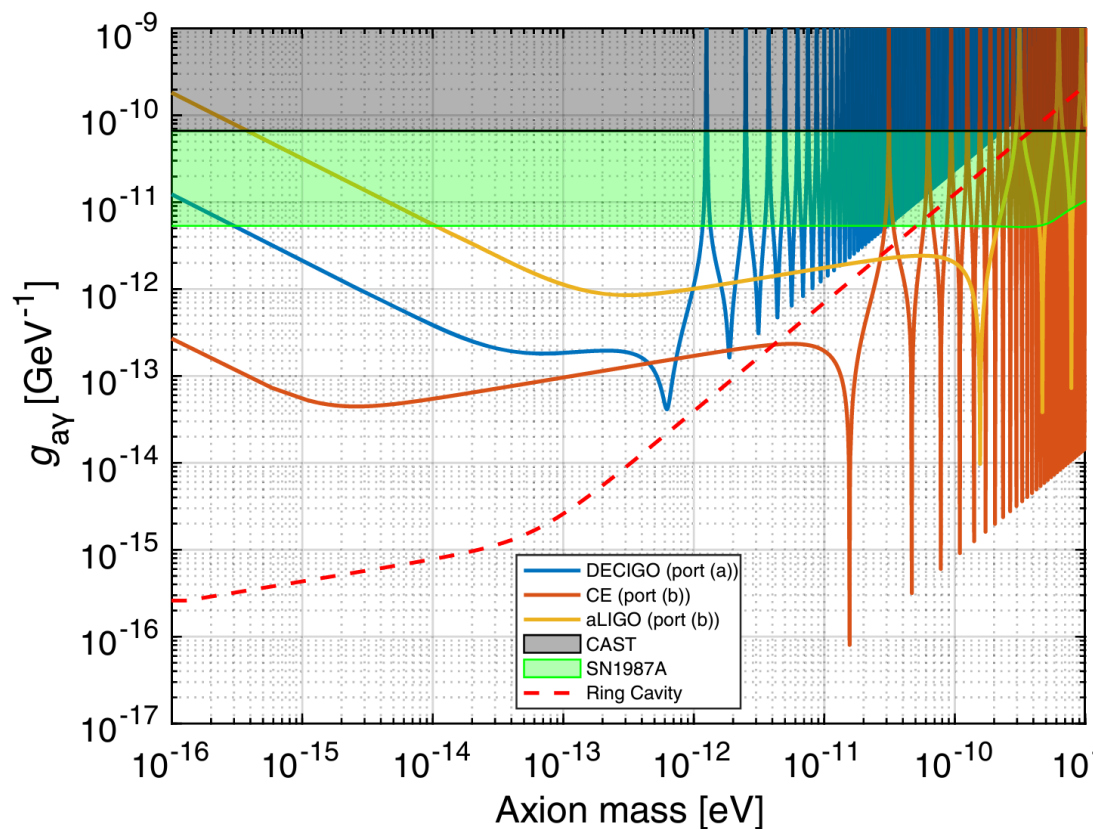


Sander M. Vermeulen et. al.
 GEO 600
 Nature 600, 424–428 (2021)

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

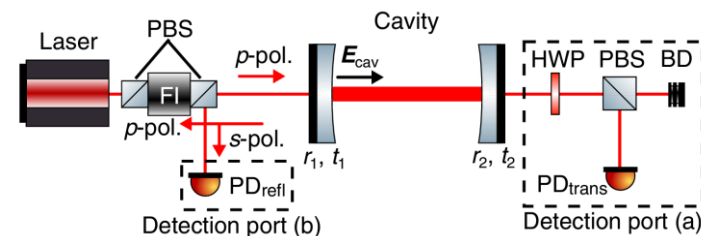
$$\delta(L_x - L_y) \approx \left(\frac{1}{\Lambda_\gamma} + \frac{1}{\Lambda_e} \right) \left(\frac{nl\hbar\sqrt{2\rho_{\text{local}}}}{m_\varphi c} \right) \cos(\omega_{\text{obs}} t)$$

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.

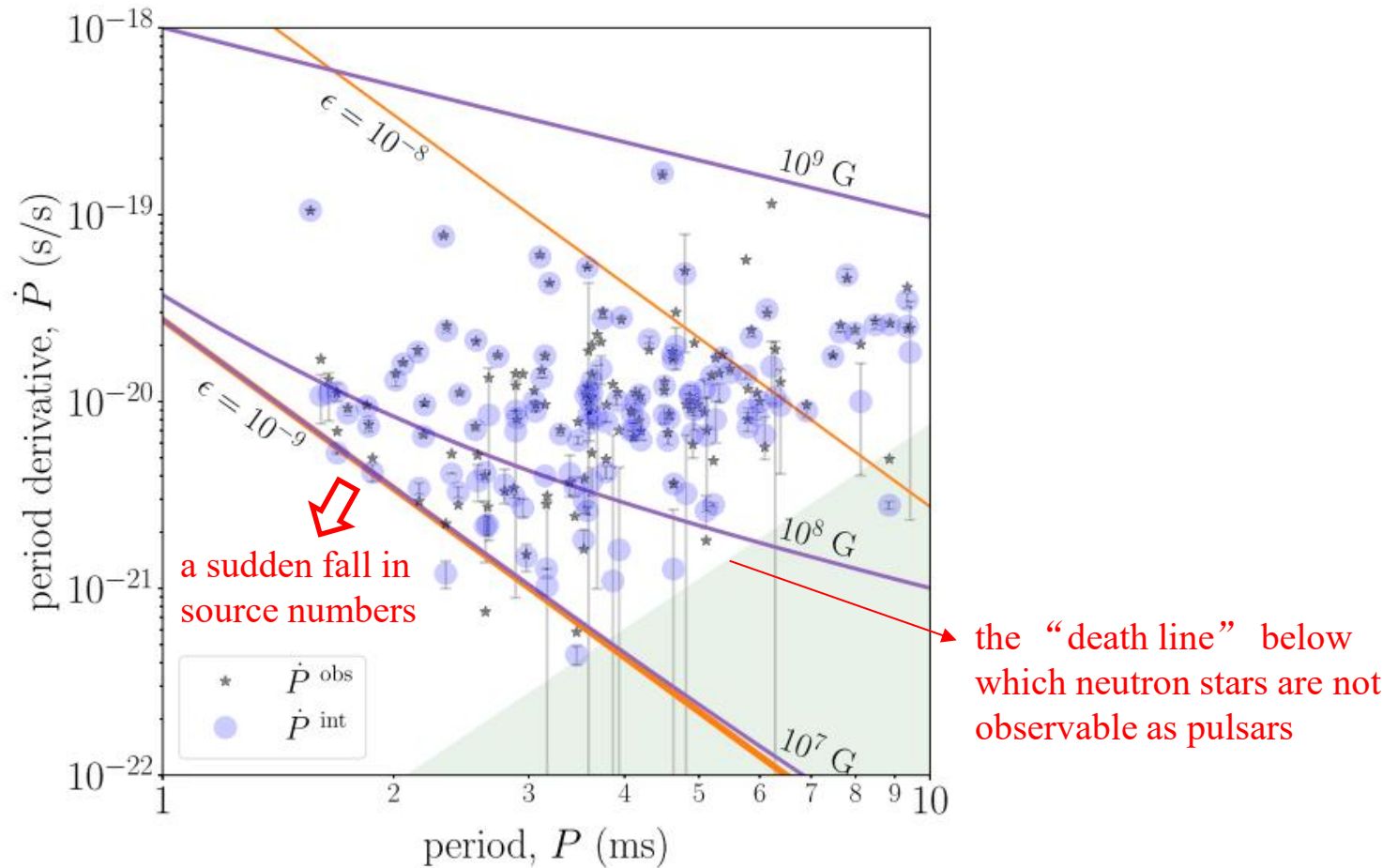
Dark matter direct detection can be performed.
Similar analysis will be carried out for other DM candidates.

Nice complementarity:

GW physics and particle physics

Evidence for a Minimum Ellipticity in Millisecond Pulsars

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



Search based on SGWB method:

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

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

observation time of an experiment, O(yr)

overlap function
describe the correlation among sites

$$S = \frac{T}{2} \int df \gamma(|f|) S_{GW}(|f|) \tilde{Q}(f),$$
$$N^2 = \frac{T}{4} \int df P_1(|f|) |\tilde{Q}(f)|^2 P_2(|f|).$$

one-sided strain noise power spectra

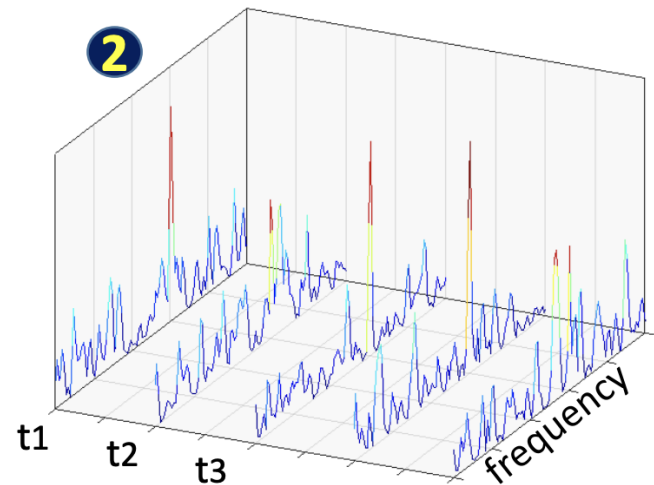
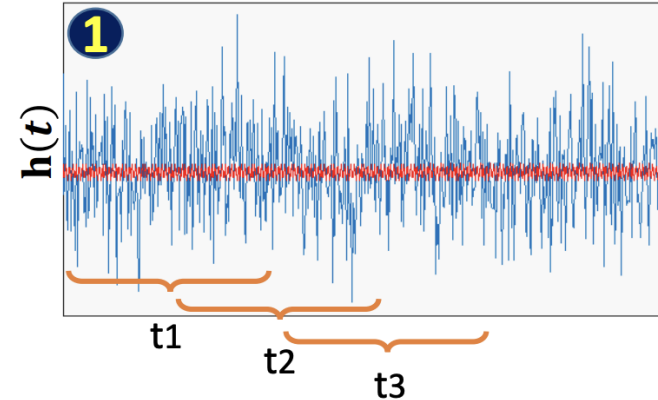
optimal filter function
maximize SNR

Search based on CW method:

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

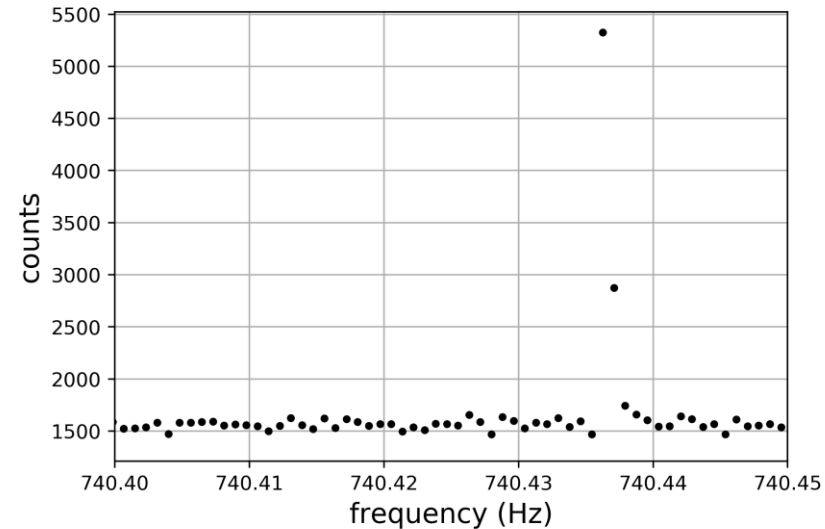
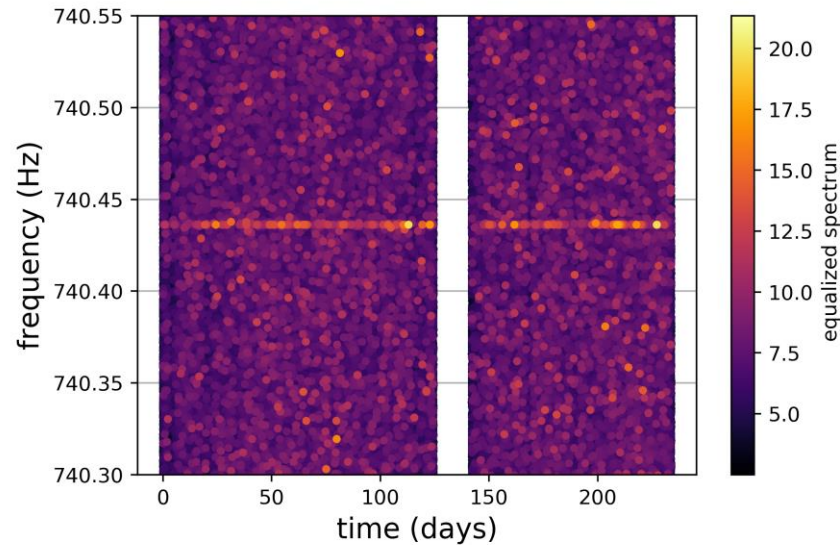
Candidates are considered in **coincidence** if they are within one frequency bin of each other, and if the critical ratio $CR > 5$

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



Search based on CW method:

Simulated signal shown here



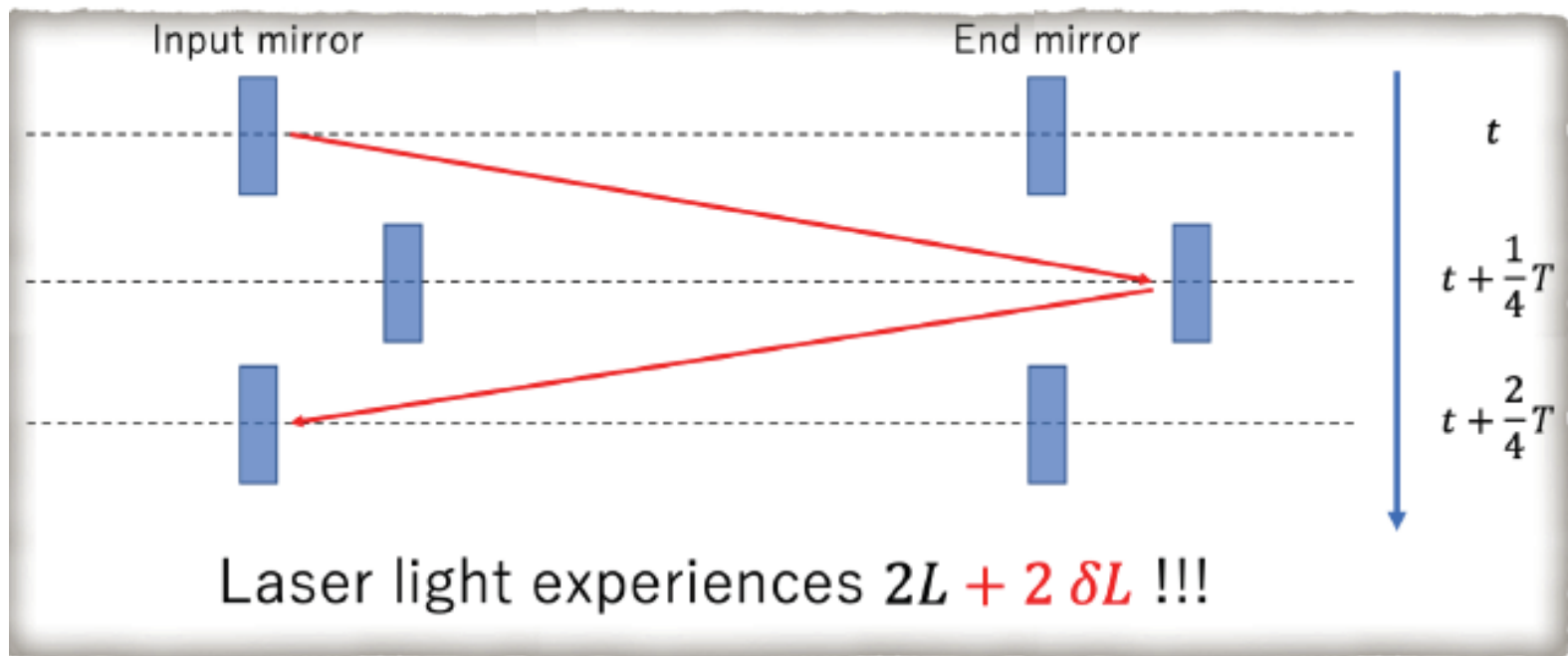
Determine time/frequency points above a certain power threshold and histogram on frequency axis

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:

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:

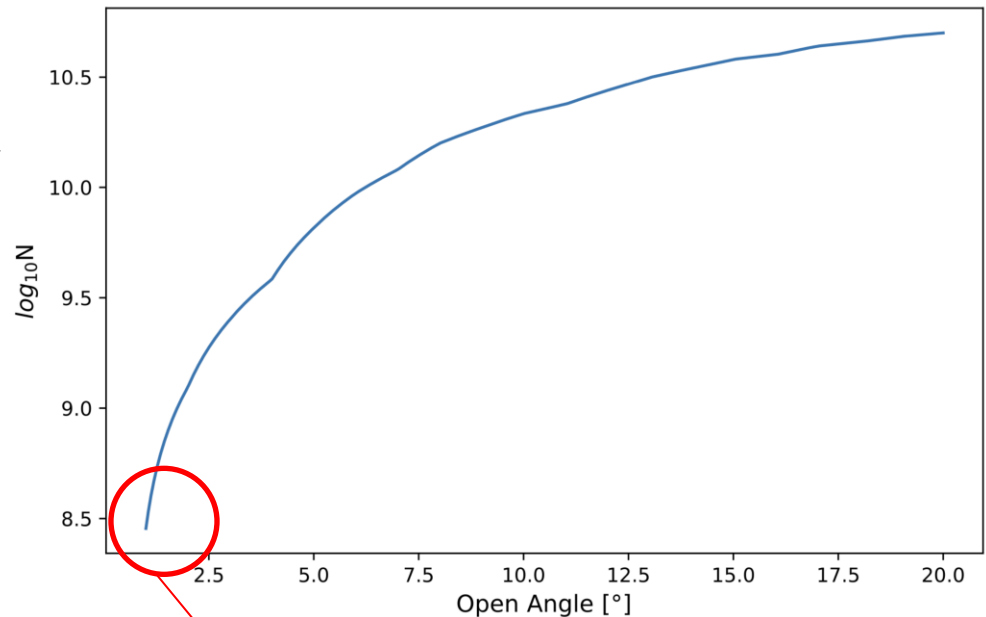
We can estimate the MSP distribution assuming it traces that of stars in the bulge.

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

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

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

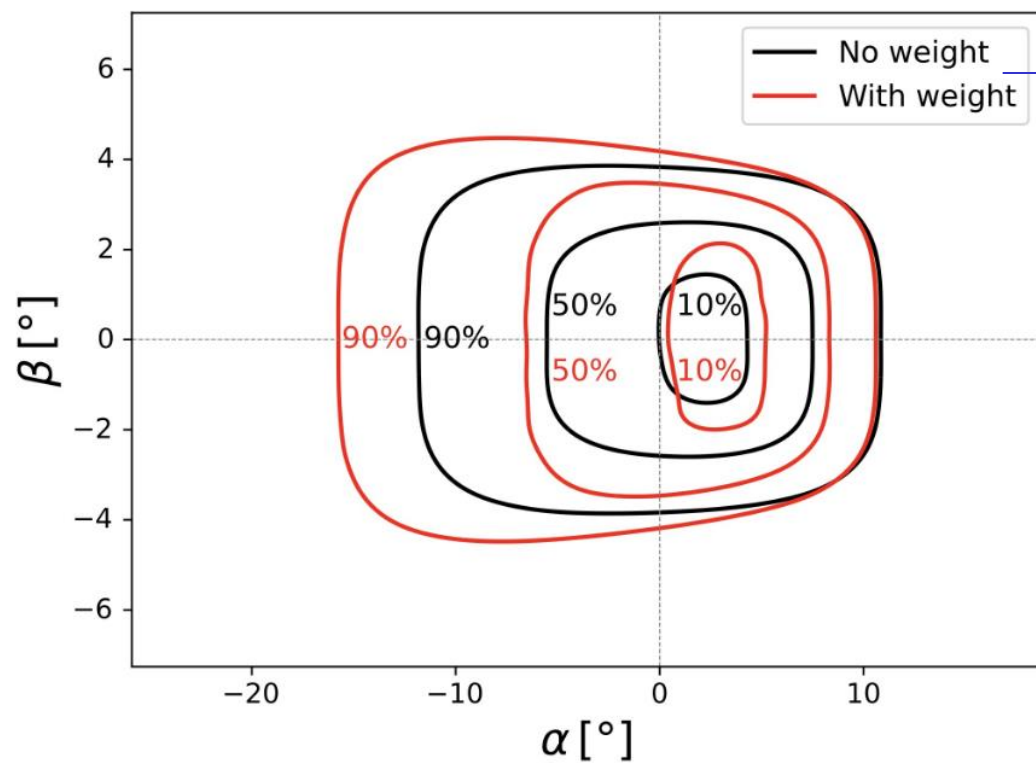
with $x_0 = 1.59$ kpc, $y_0 = 0.424$ kpc, and $z_0 = 0.424$ kpc.



Only covered 1% of the potential MSPs.

Future Improvement:

Projected MSP distribution



Weighting by $1/r^2$

