Astrophysical Probes to New Physics Beyond the Standard Model

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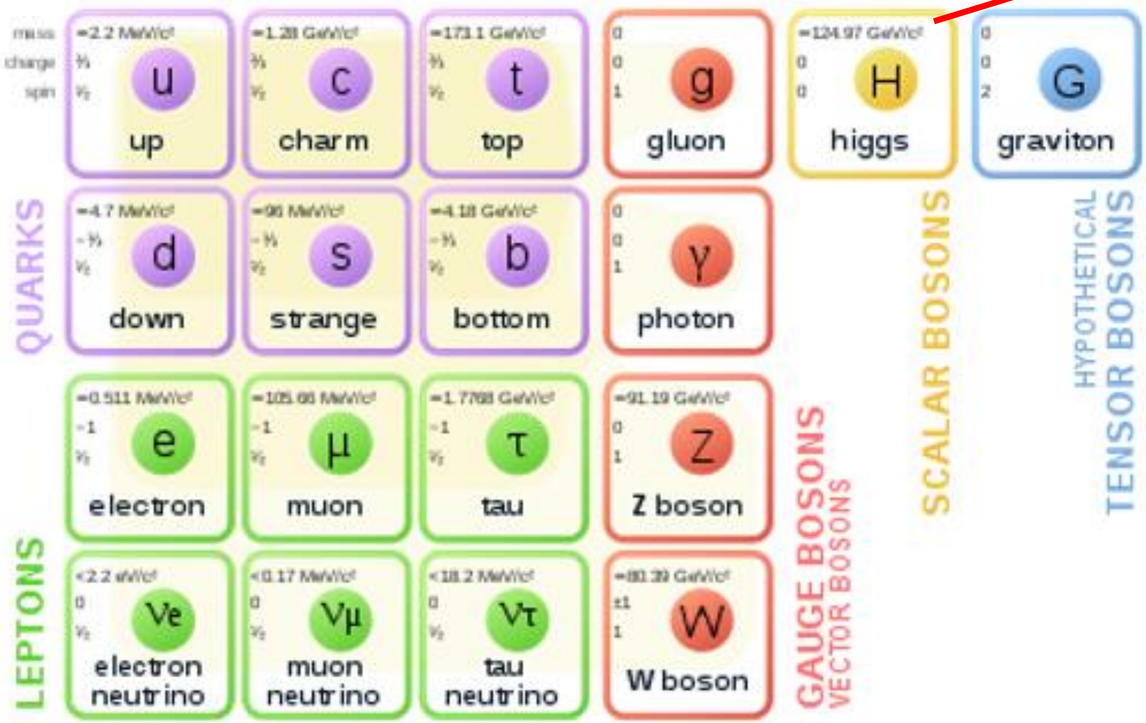
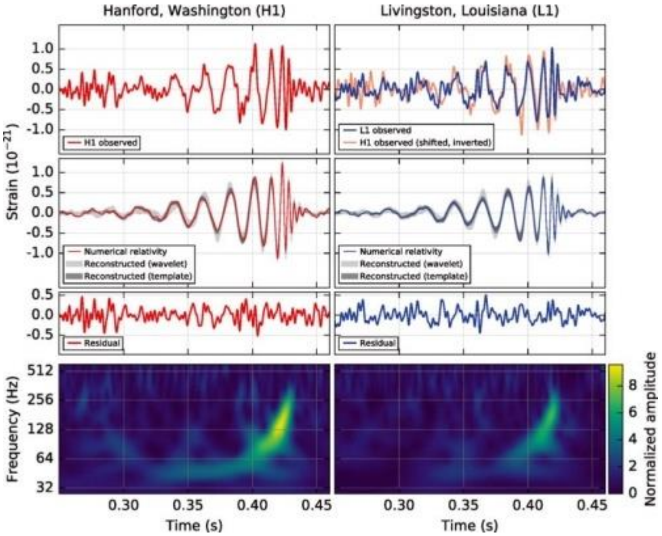
Nature - Commun.Phys. 2 (2019) 155

Current Status of Particle Physics:





+ anything else?

Left-over problems:

- The identity of dark matter
- Gauge hierarchy problem
- Strong CP problem
- The identity of inflaton field
- Baryogenesis
- Cosmological constant

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$\vdots$

Probing New Physics Beyond the Standard Model:

Extend purposes of existing experiments:

Event Horizon Telescope

LIGO/LISA

Pulsar Timing Array

Gaia Satellite

DUNE/MicroBooNE/Super-K/XENON-1T

Propose new experiments:

Mechanical Quantum Sensors

Superconducting Detectors

Dark Matter Radio
Light-Shining-Through-Wall Exp

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Event Horizon Telescope

Yifan Chen, Jing Shu, Xiao Xue,
Qiang Yuan, and Y.Z.
Phys.Rev.Lett. 124 (2020) 6, 061102

Propose new experiments:

- Mechanical Quantum Sensors
- Superconducting Detectors
- Dark Matter Radio
- Light-Shining-Through-Wall Exp

Left-over problems:

- The identity of dark matter → misalignment mechanism
- Gauge hierarchy problem → relaxion
- Strong CP problem → QCD axion
- The identity of inflaton field
- Baryogenesis
- Cosmological constant

} can be related to axion

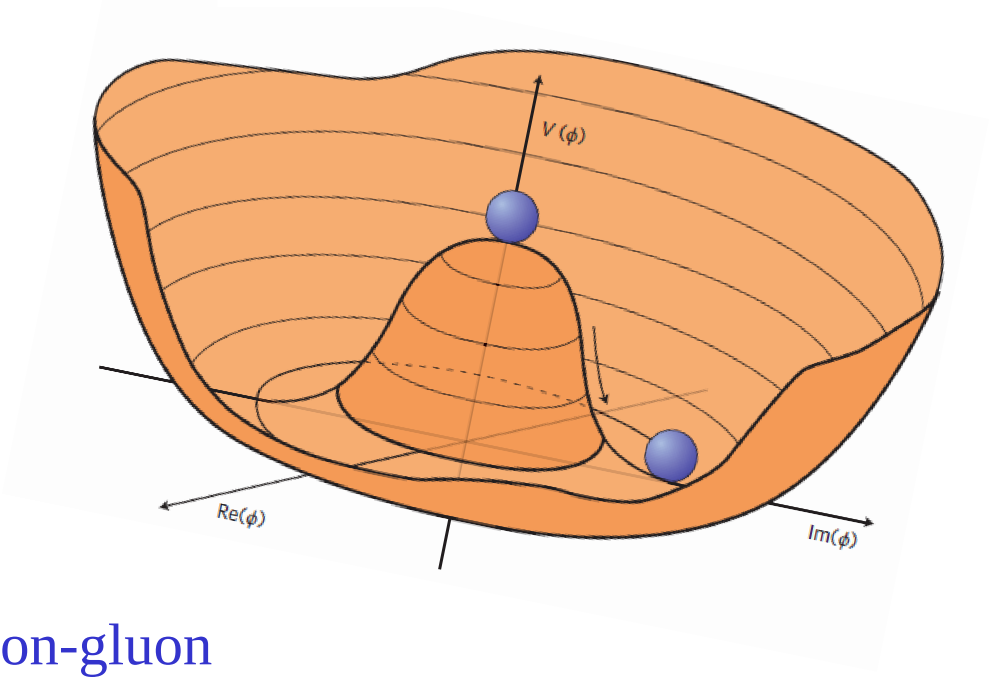
•
•
•

Theory motivations:

Strong CP-problem:

$$\underbrace{(\theta - \mathrm{arg\ det\ M_q})}_{\bar{\theta} < 10^{-10}}\frac{\alpha_s}{8\pi}\mathrm{G}\tilde{\mathrm{G}}$$

Introduce axion field:



Couplings:

axion-gluon-gluon
axion-photon-photon
axion-fermion-fermion

Search strategies:

- axion-gluon-gluon coupling:

  CASPEr (DM)
  QCD phase transition inside neutron stars

- axion-photon-photon coupling:

  ADMX (DM)
  CAST
  ALPS

- axion-fermion-fermion coupling:

  stellar cooling
  absorption in superconductor (DM)

Search strategies:

- axion induced birefringent effect

$$\omega_\pm \simeq k \mp 2g_{a\gamma}(\partial a/\partial t + \partial_z a)$$

different phase velocities for +/- helicities

A linearly polarized photon can be decomposed into the super-position of photons with +/- helicities.

⇨ change of position angle

$$\begin{aligned}\Delta\Theta &= g_{a\gamma}\Delta a(t_{\rm obs}, \mathbf{x}_{\rm obs}; t_{\rm emit}, \mathbf{x}_{\rm emit}) \\ &= g_{a\gamma}\int_{\rm emit}^{\rm obs} ds\; n^\mu\; \partial_\mu a \\ &= g_{a\gamma}[a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})].\end{aligned}$$

Search strategies:

A region with:

a concentration of axion field

axion field is an oscillating background field

+ source for linearly polarized photon

the position angle, at emission, should be stable

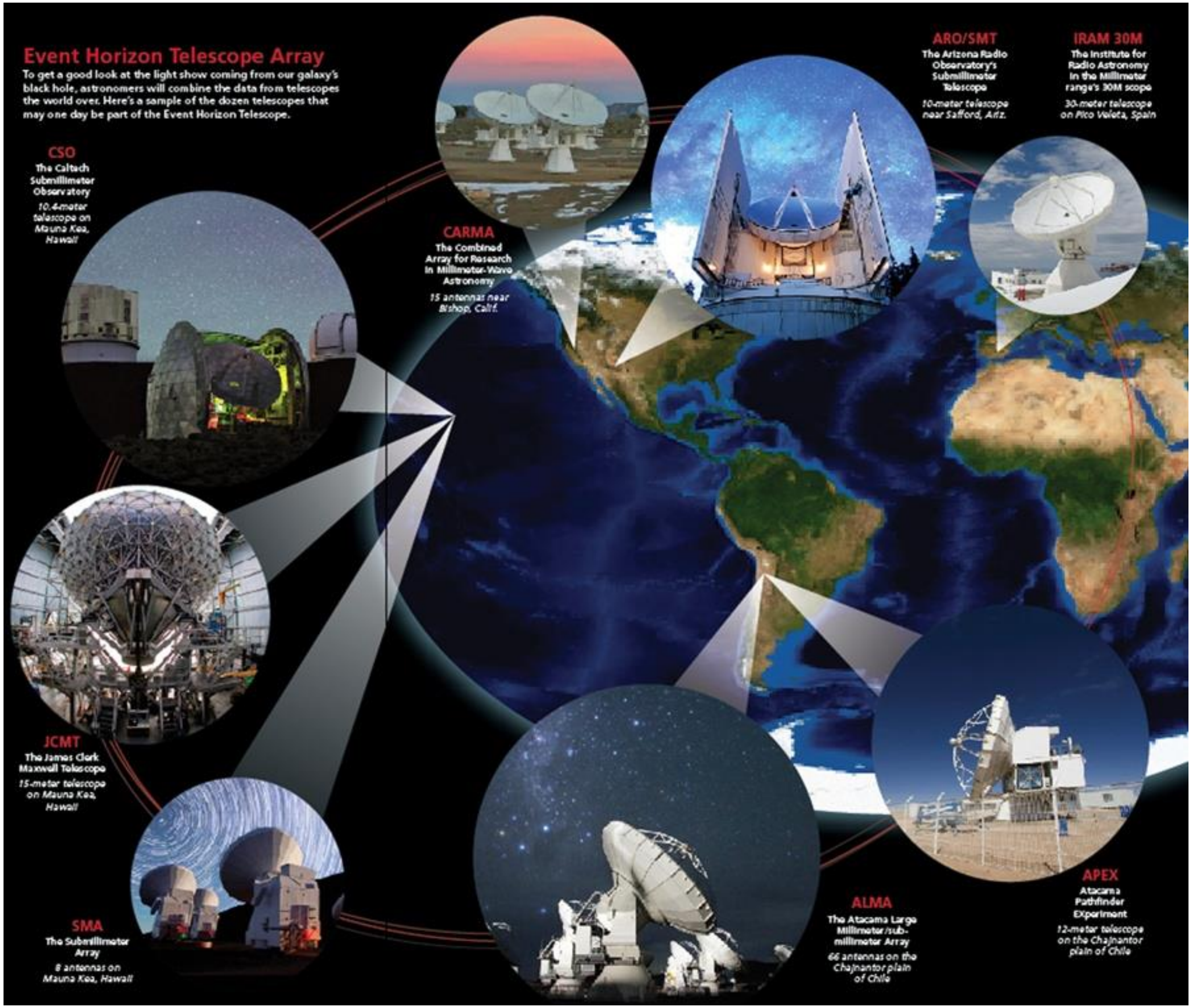
Search for:

- position angle oscillates with time

- study the axion induced position angle change as a function of spatial distribution. (extended light source)

Scenarios: EHT-SMBH

Event Horizon Telescope:



Event Horizon Telescope Array

To get a good look at the light show coming from our galaxy's black hole, astronomers will combine the data from telescopes the world over. Here's a sample of the dozen telescopes that may one day be part of the Event Horizon Telescope.

telescope array at radio frequency around the Earth

Event Horizon Telescope:

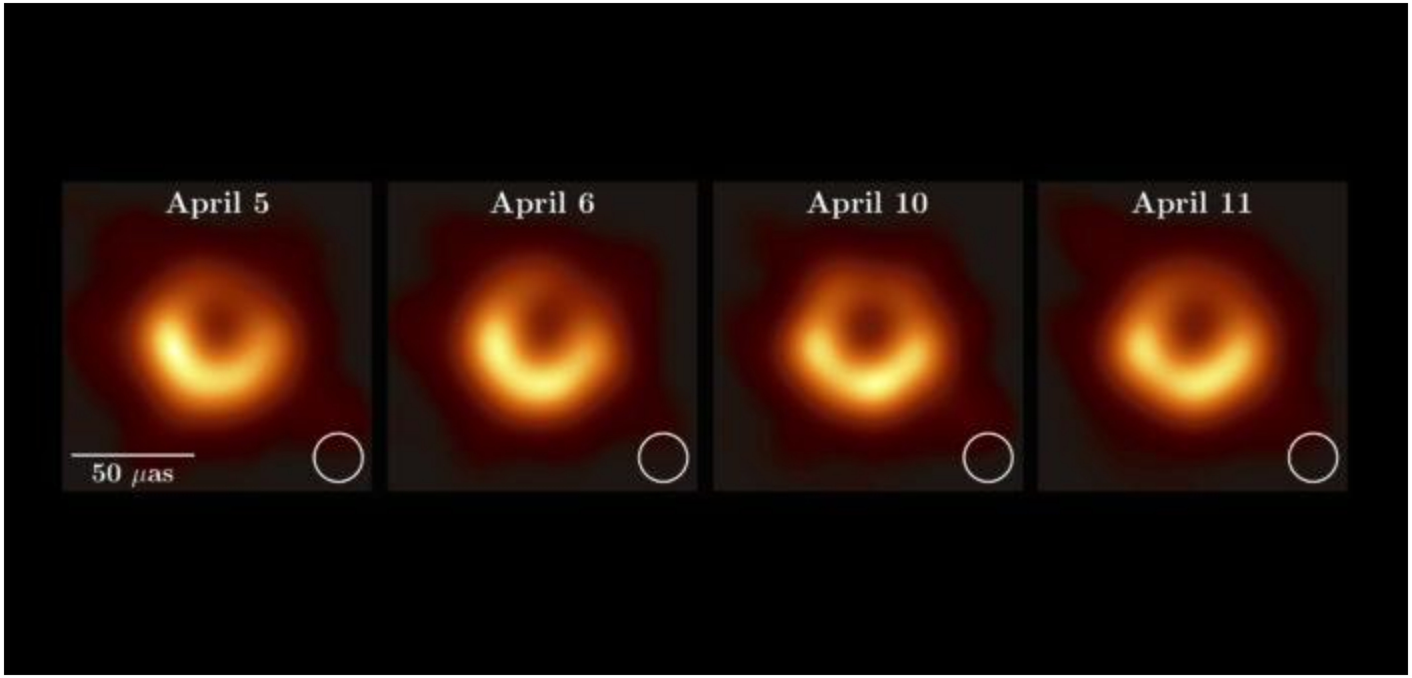


Image of the supermassive black hole at the center of the elliptical galaxy M87, for four different days.

Event Horizon Telescope:

Black holes measured:

M87*:	16 Mpc,	10^9 solar mass
	10^{13} m,	10^{-20} eV
	10^5 s,	spin = 0.9
Sgr A*:	8 kpc,	10^6 solar mass
	10^{10} m,	10^{-17} eV
	100 s,	spin = ?

Excellent angular resolution:

~ 20 micro-as!

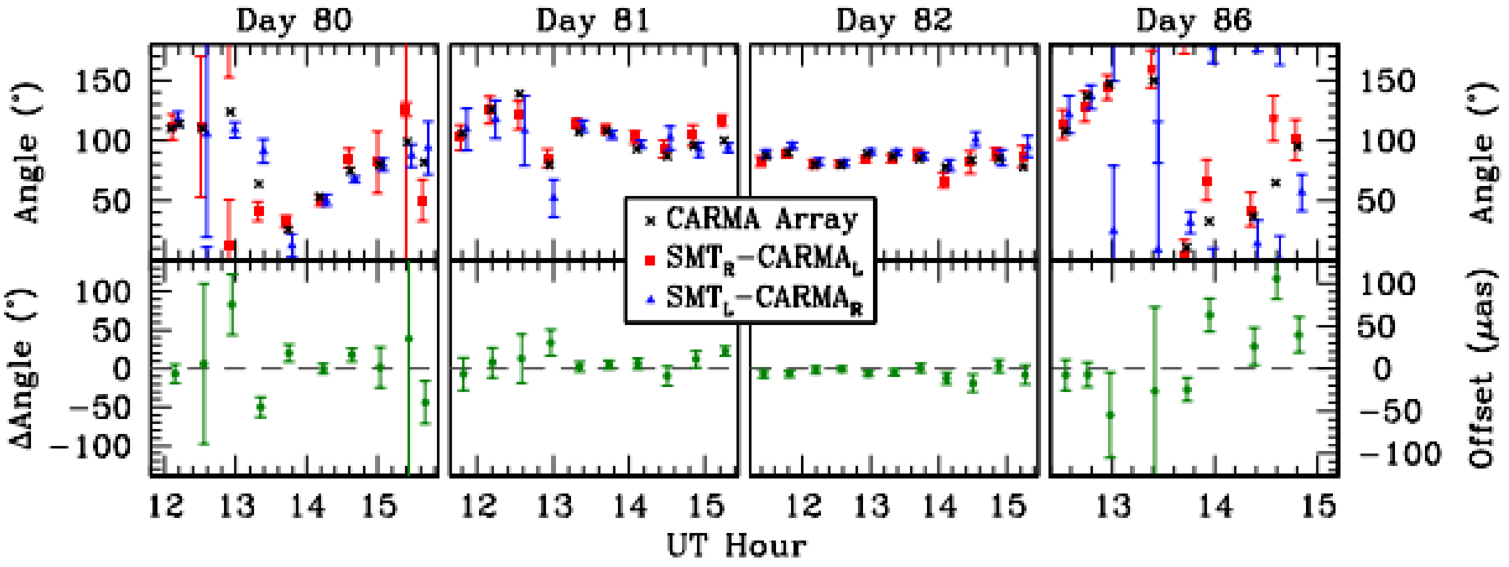
resolve features ~ BH size

Event Horizon Telescope:

Accretion disk around SMBH gives linearly polarized radiation.

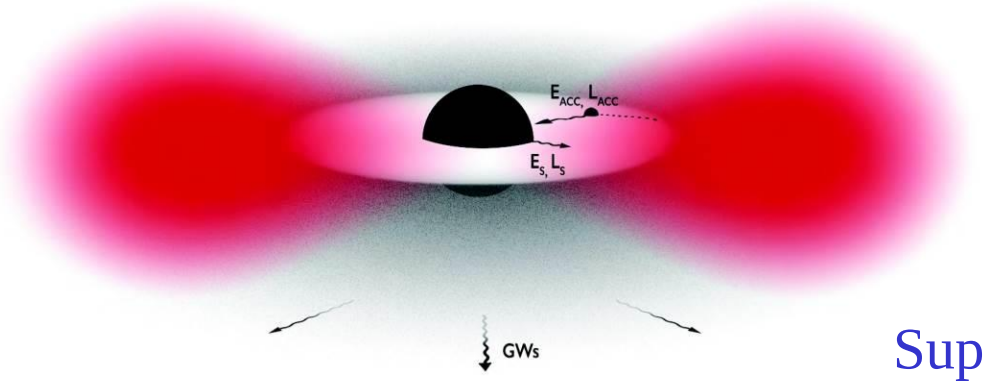
Millimeter wavelength: optimal for the position angle measurement!

measure Sgr A*



A subset of EHT has achieved a precision at 3 degrees!

Black hole superradiance:



© a.s./grit

Superradiance condition

$$\omega < \omega_c = \frac{a_J m}{2r_+}$$

When $\lambda_a \sim GM$:

a rapidly rotating black hole loses:
energy + angular momentum

axion cloud will be produced around BH

Energy in axion cloud can be comparable to BH mass!

Black hole superradiance:

A gravitational bound state between BH and axion cloud.

Very similar to the hydrogen solution:

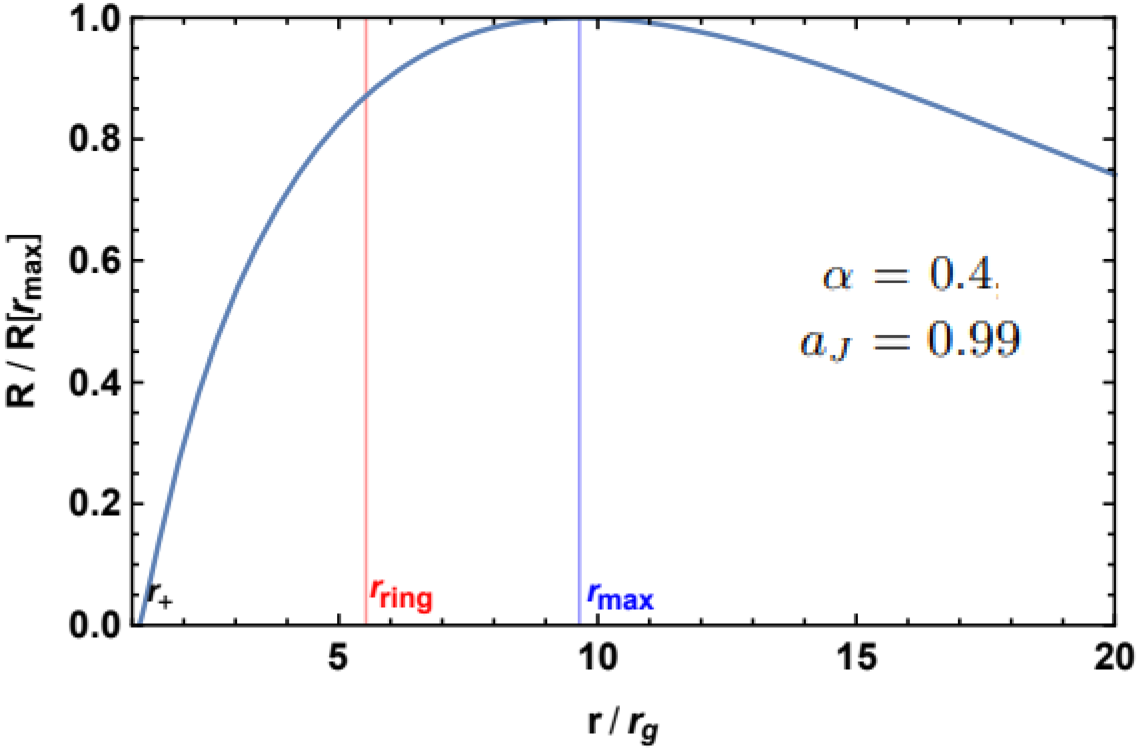
$$a(x^\mu) = e^{-i\omega t}\boxed{e^{im\phi}S_{lm}(\theta)}R_{lm}(r)$$

reduce to Y_{lm} in spherical/non-relativistic limit

Black hole superradiance:

The ring from EHT has a radius comparable to the peaking radius of the axion cloud

$$r_\pm = r_g \left(1 \pm \sqrt{1 - a_J^2}\right)$$



Axion cloud in non-linear region:

axion Lagrangian including self-interaction:

$$S = \int d^4x \sqrt{-g}\left[-\frac{1}{2}(\nabla a)^2 - \mu^2 f_a^2 \left(1 - \cos\frac{a}{f_a}\right)\right]$$

take

$$a = \frac{1}{\sqrt{2\mu}}\left(e^{-i\mu t}\psi + e^{i\mu t}\boxed{\psi^*}\right)$$

slowly varying function

non-relativistic limit:

gravitational potential

$$S_{\mathrm{NR}} = \int d^4x \left(i\psi^*\partial_t\psi - \frac{1}{2\mu}\partial_i\psi\partial_i\psi^* - \boxed{\frac{\alpha}{r}\psi^*\psi} + \boxed{\frac{(\psi^*\psi)^2}{16 f_a^2}}\right)$$

leading self-potential term

Axion cloud in non-linear region:

axion self-interaction becomes important when

gravitational potential ~ self-interaction potential

$$\frac{\alpha}{r} \simeq \frac{\mu a_0^2}{4 f_a^2}$$

two possible consequences:

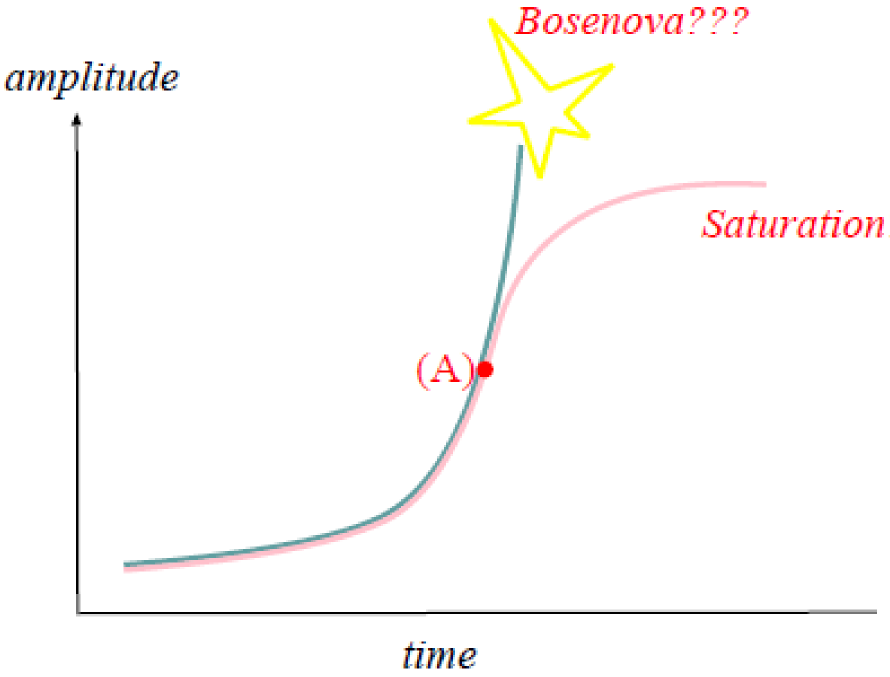
bosenova: a drastic process which explodes away axion cloud

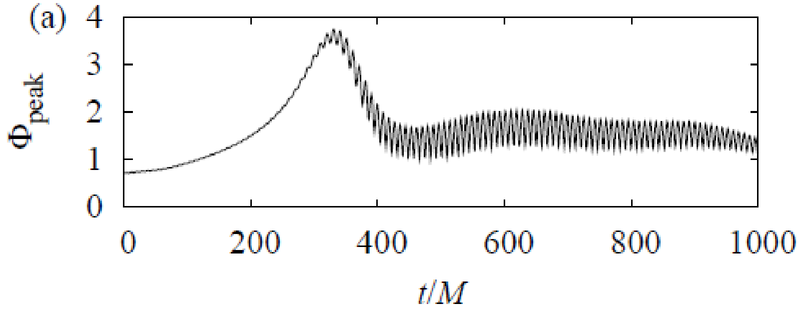
steady axion outflow to infinity

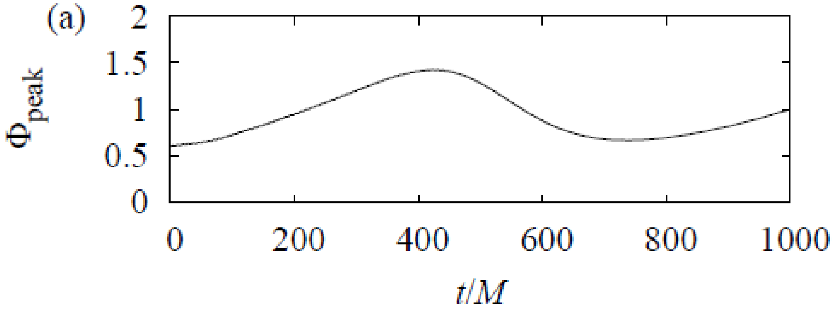
numerical simulation has been performed:

H. Yoshino and H. Kodama, Prog. Theor. Phys. 128, 153 (2012), etc

Axion cloud in non-linear region:







In either scenario, the amplitude of the axion cloud remains O(1) of its maximal value for most of the time

$$\frac{a}{f_a} \sim O(1)$$

Axion cloud induced position angle change:

$$\boxed{b \equiv a_{max}/f_a}$$

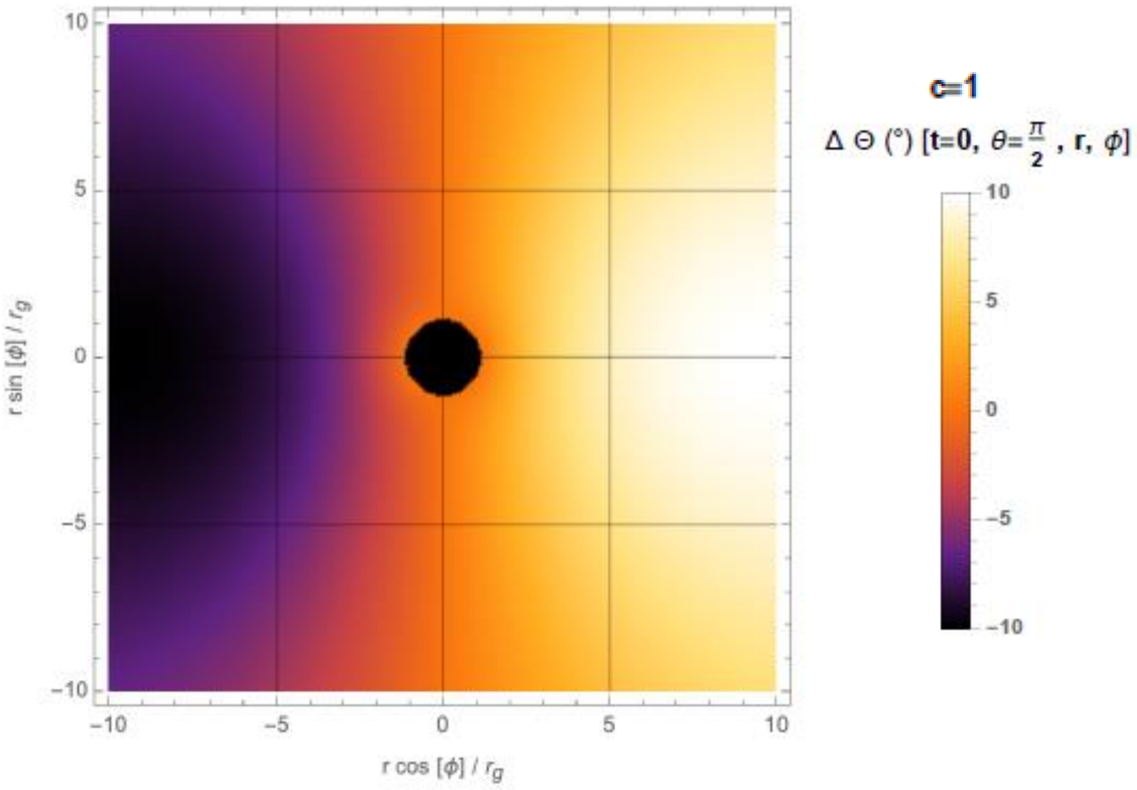
~1 for the parameter space we are interested in

$$\boxed{g_{a\gamma} = \frac{\alpha_{em} N}{4\pi f_a} = \frac{c}{2\pi f_a}}$$

additional loop suppression to translate f_a to axion-photon coupling

$$\Delta\Theta(r_{max}) \simeq -\frac{bc}{2\pi}\cos\left[\mu\, t_{emit} + \beta(|\mathbf{x}_{emit}| = r_{max})\right]$$

Axion cloud induced position angle change:

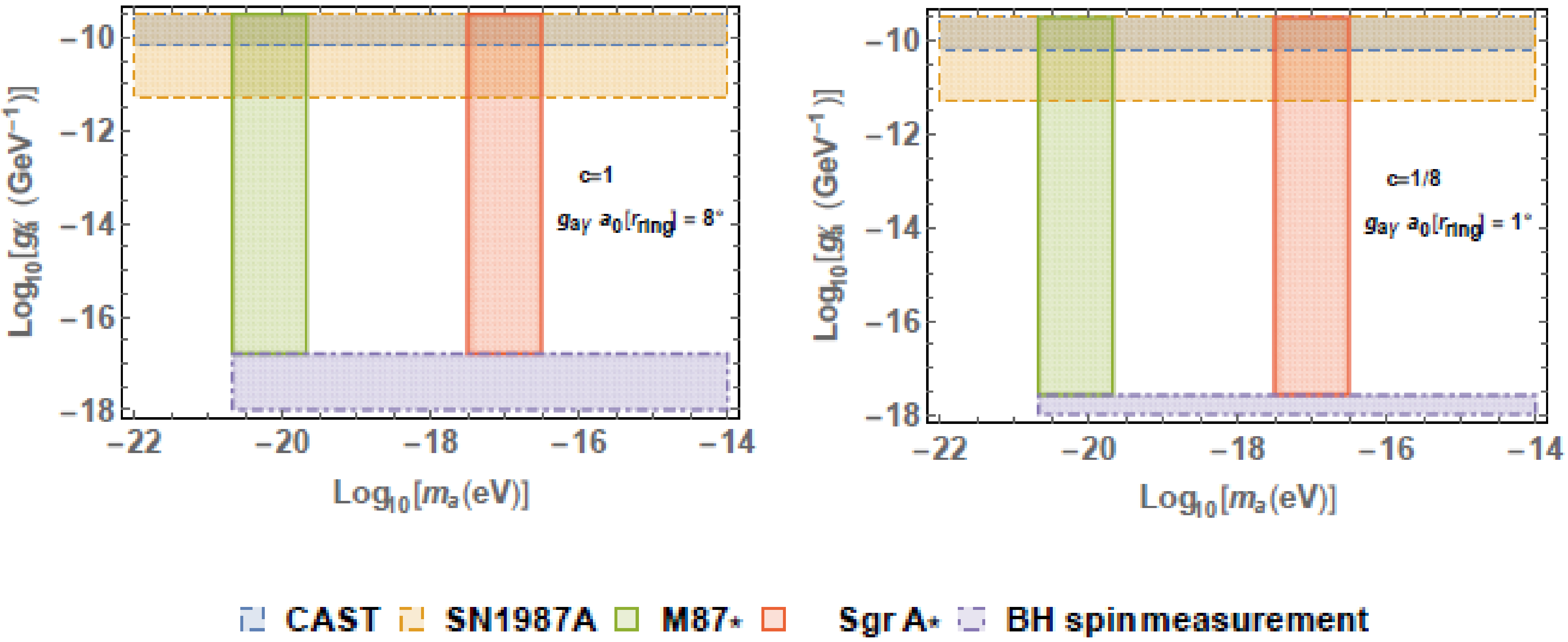


- temporal dependence for a fixed position

- spatial dependence for a fixed time

FIG. 2: $\Delta\Theta(t=0, \theta=\frac{\pi}{2}, r, \phi)$ assuming the rotation axis is towards the observer. The amplitude of oscillation is around 8° at r_{ring} with $l=1, m=1$ state, $\alpha=0.4$, $a_J=0.99$, excluding the region for $r<r_+$. The time evolution is equivalent to the rotation around ϕ.

EHT expected sensitivity:



Probing New Physics Beyond the Standard Model:

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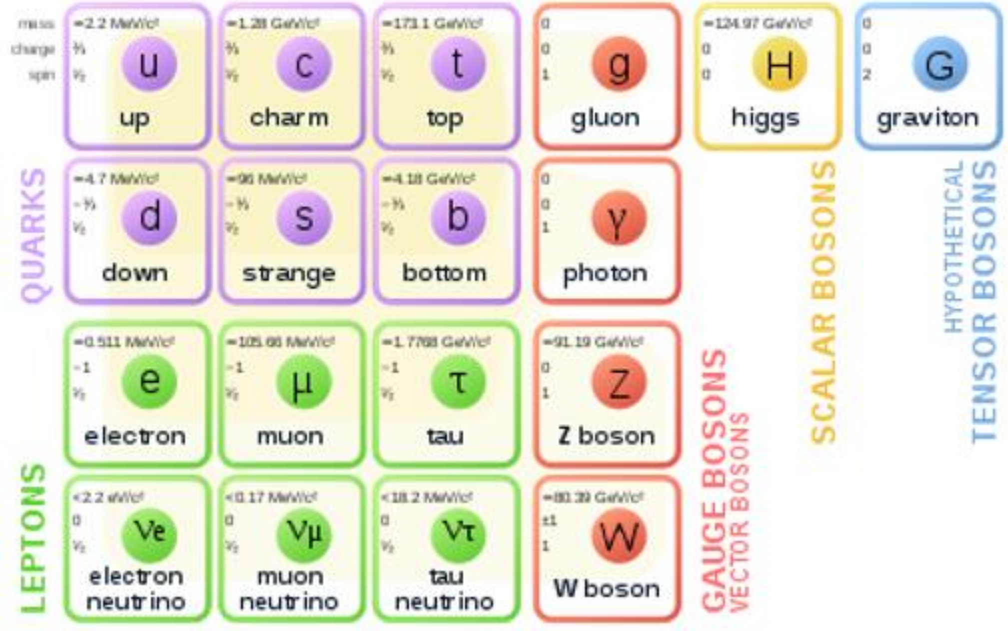
What Do We Know About Dark Matter?

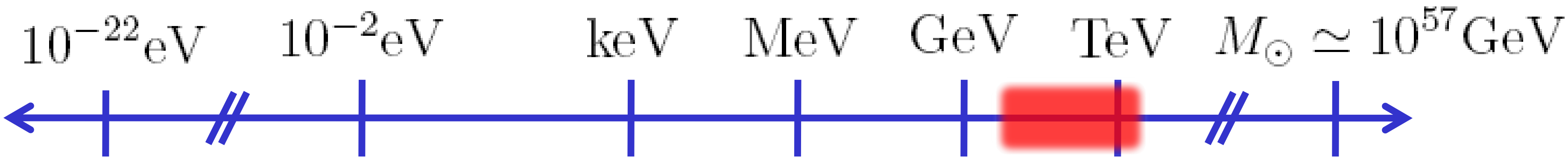
Particle Standard Model works extremely well in short distance, but fails miserably at cosmological scale!

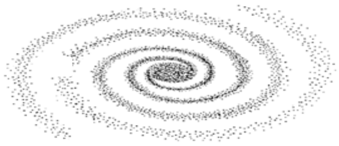


DARK MATTER ?

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.





Weakly Interacting Massive Particles (WIMPs)

The WIMP Miracle ?

Why is O(100) GeV a special scale?

Coincide with electroweak (EW) scale, determined by the Higgs mass.
The fundamental mass scale in the Standard Model!

New physics is highly expected in order to explain the Higgs mass.

Supersymmetry: All particles in SM have their superpartners.
Natural DM candidates: superpartners of W/Z/photon/Higgses

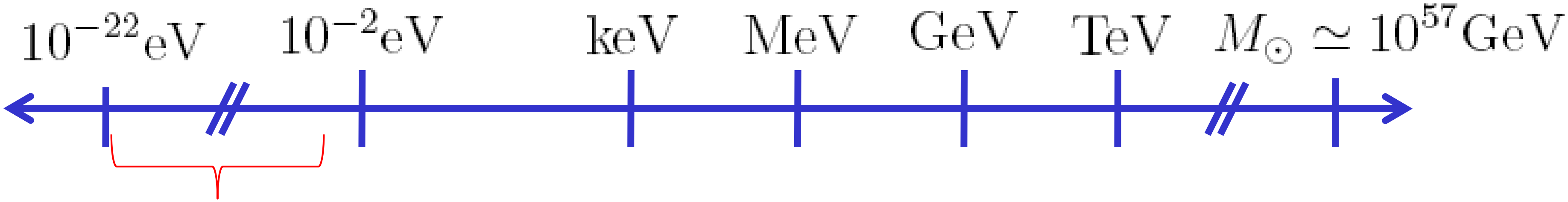
Worldwide efforts are devoted to searching for WIMPs for many decades!

No confirmations on WIMPs yet.
No hints on new physics at the LHC.

⇨ reducing the likelihood of WIMPs

Maybe just around the corner?
Waiting for more data to reach a conclusion.

Ultra-light DM:



a natural prediction of many string-inspired models

Bosonic DM with gigantic occupation number

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

A. Pierce, K. Riles, Y.Z.
Phys.Rev.Lett. 121 (2018) 6, 061102

H. Guo, K. Riles, F. Yang, Y.Z.
Nature - Commun.Phys. 2 (2019) 155

LIGO

⇩

GW detector can
be a multi-purpose
experiment.

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

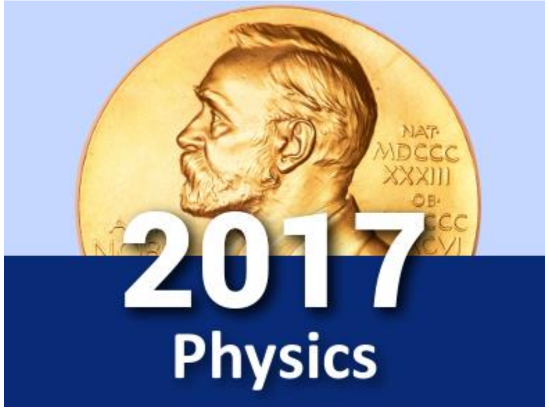
Ordinary materials carry huge dark charges, and thus feel a force by dark photon field!

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

Laser Interferometer Gravitational-Wave Observatory

LIGO (ground-based)

Amazing precision at LIGO:
O(1/1000) the radius of a single proton!

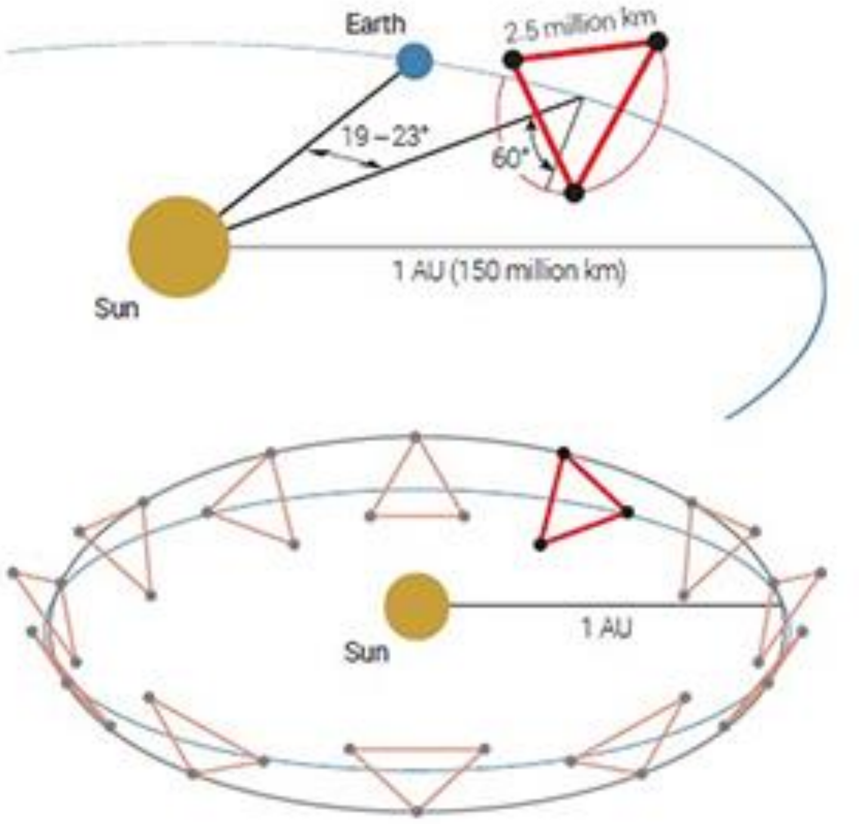


Opened a field:
Gravitational Wave Astronomy

Enrich our understanding on fundamental physics and early cosmology.

Laser Interferometer Space Antenna

LISA (space-based)



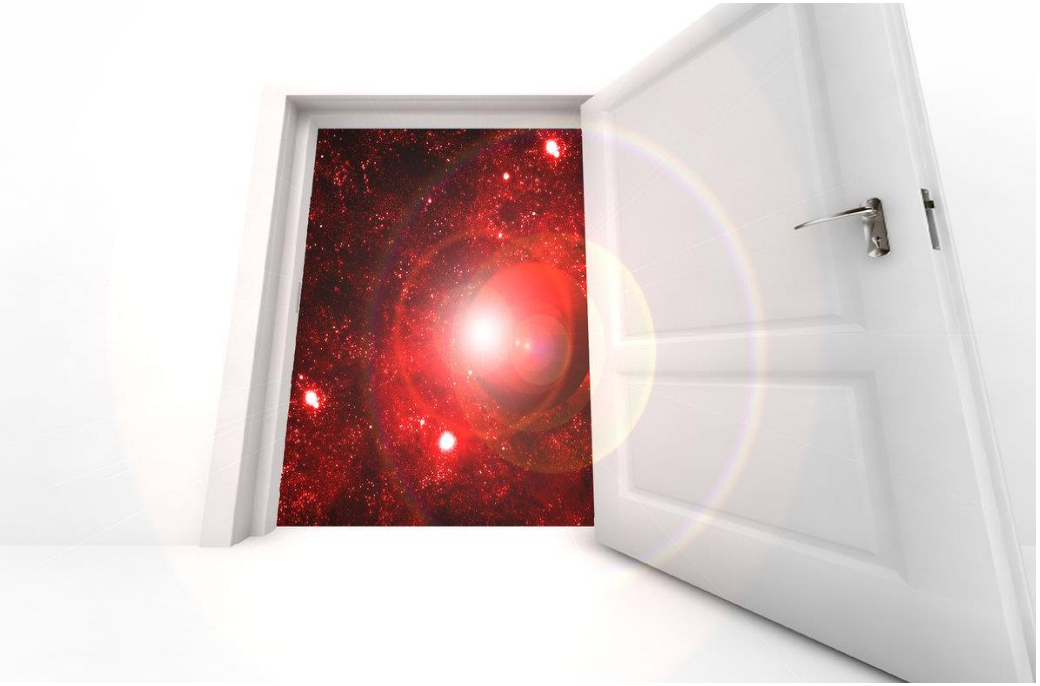
(LISA Mission Consortium)

Recently approved by the European Space Agency.

U.S. (NASA) just rejoined the program.

LISA PathFinder is a great success!

A new field just opened up!



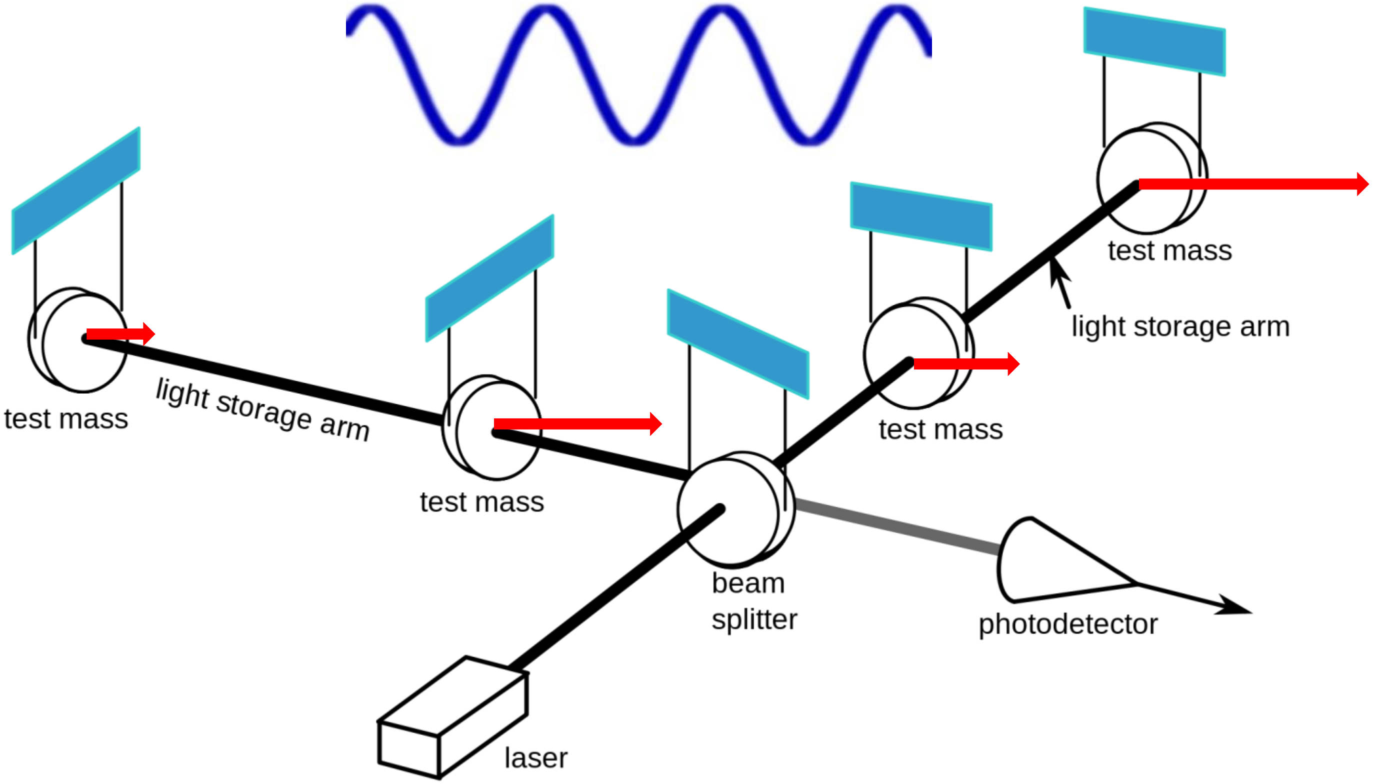
Developments on Gravitational Wave experiments provide a great potential for astrophysics!

High energy physics community should also benefit from this fantastic opportunity.

Ultra-light DM – General Picture:

LIGO/LISA: advanced Michelson–Morley interferometer

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 - Properties of Dark Photon Signals:

Signal:

- almost monochromatic

Frequency is determined by dark photon mass.

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

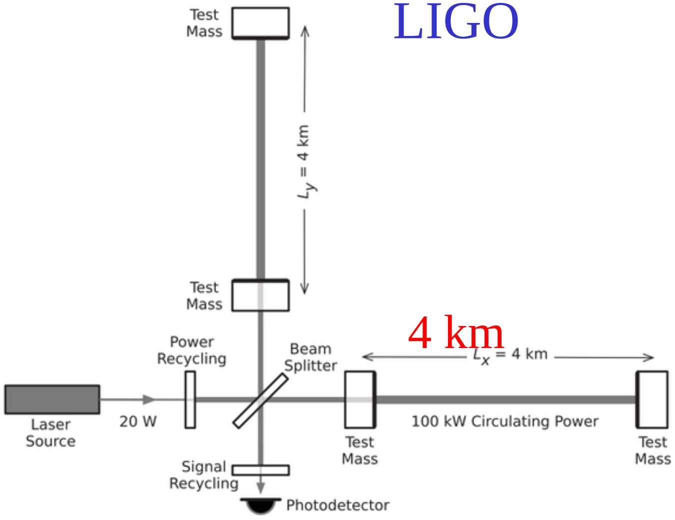
⇨ A bump hunt in frequency space.

Detailed shape of the bump contains information on DM Maxwell–Boltzmann distribution.

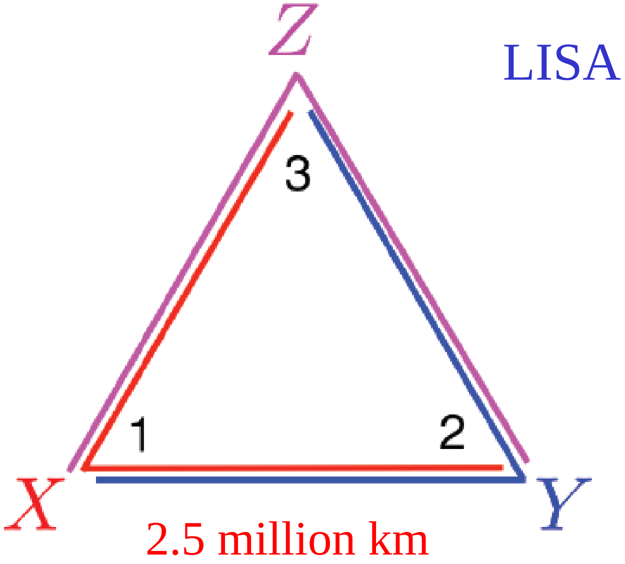
Once measured, the signal provides great details of the local DM properties!

Ultra-light DM – Dark Photon Induced Displacement:

$$\Delta L[t] = (x_1[t] - x_2[t]) - (y_1[t] - y_2[t])$$



LIGO



LISA

$$\frac{1}{2} m_A^2 A_{\mu,0} A_0^{\mu} \simeq 0.4 \ \mathrm{GeV/cm^3}$$ ⇨ field strength of dark photon

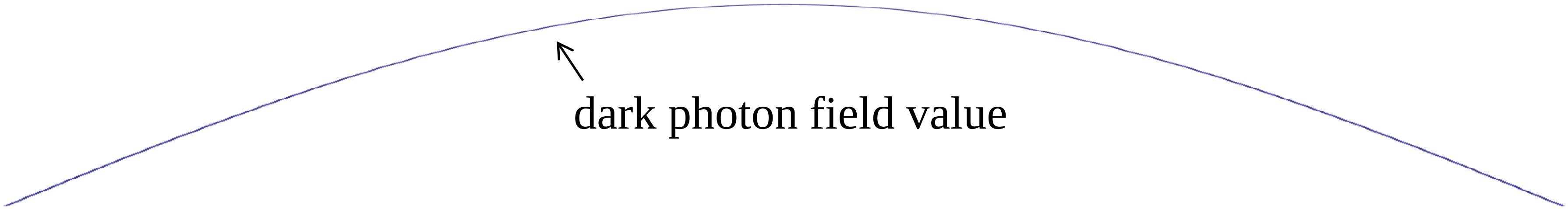
⇨ force on a mirror ⇨ relative change of arm lengths $\sqrt{\langle \Delta L^2 \rangle}$

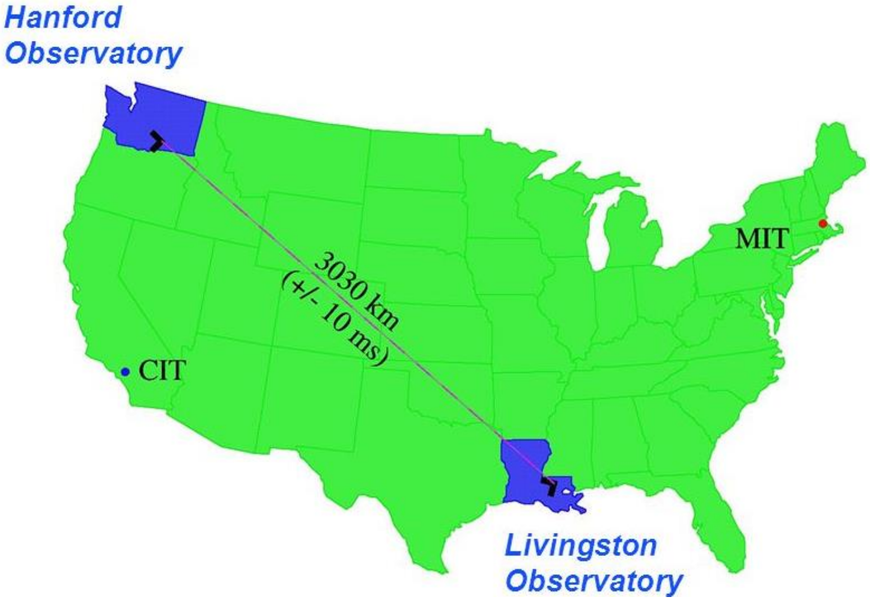
(dark photon mass m_A, coupling constant ε)

$$\sqrt{\langle \Delta L^2 \rangle} \propto \frac{\epsilon}{m_A} v_{vir} L$$

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 to Dark Photon Signal of GW Detectors:

Signal-to-Noise-Ratio is calculated similarly as the stochastic GW search.

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

overlap function
describes the correlation among sites

observation time of an experiment, O(yr)

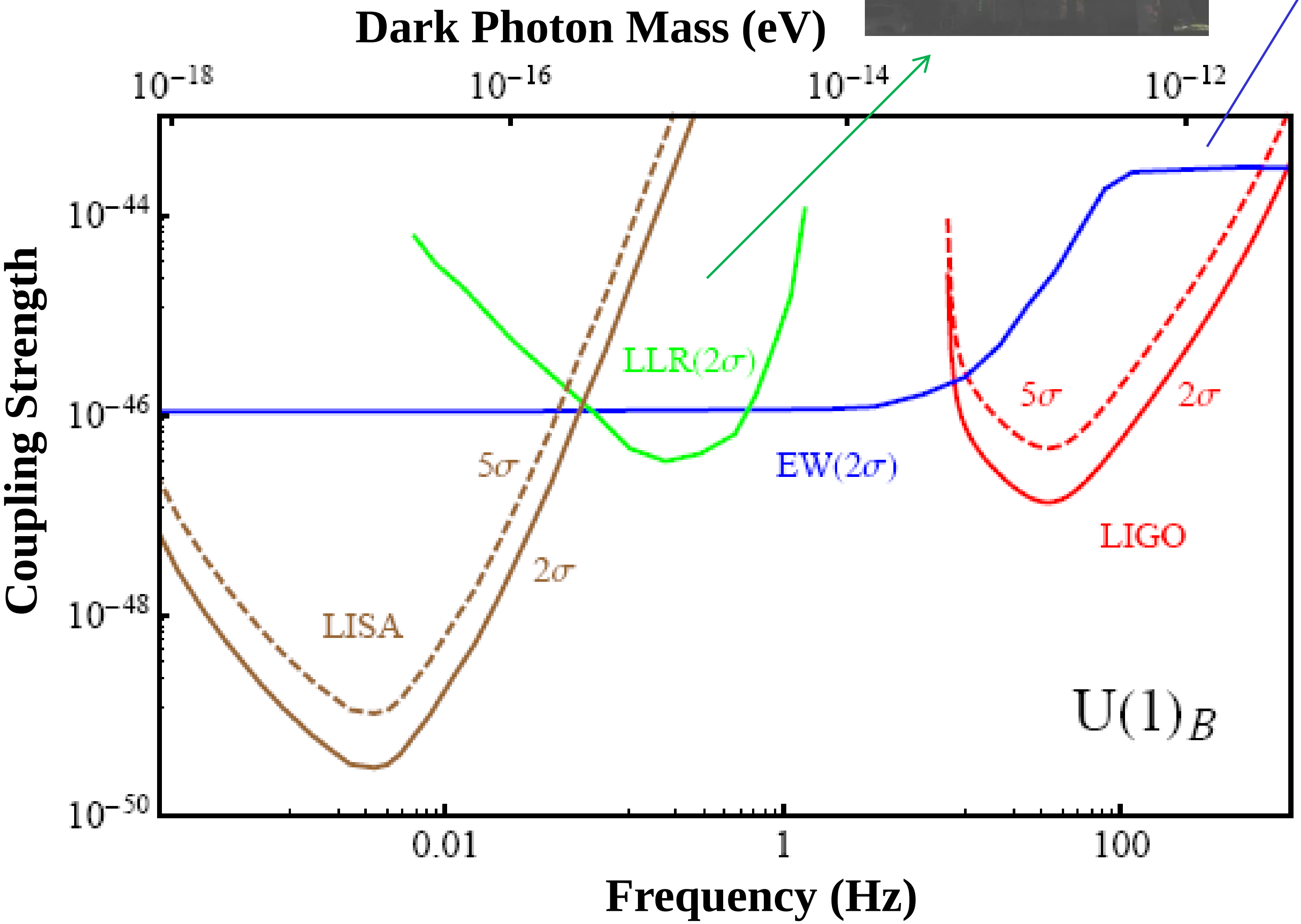
$$\mathrm{SNR} = \frac{2\boxed{\gamma(|f|)}\boxed{\sqrt{T}}}{\sqrt{\boxed{P_1(f)P_2(f)}\Delta f}} \frac{\langle \Delta L^2 \rangle}{L^2}$$

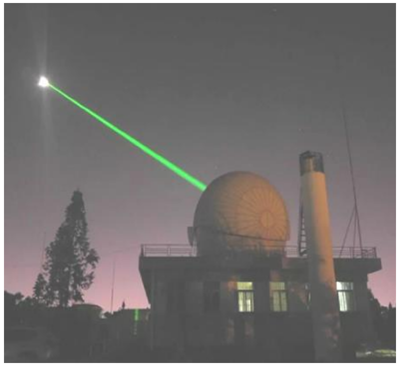
one-sided strain noise power spectra

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

O1 Result:

- Fourier transform: power spectrum in frequency domain
- Remove known noise bins and their neighbor bins
- Within 10-2000 Hz frequency band, require Re[SNR] < -5.8

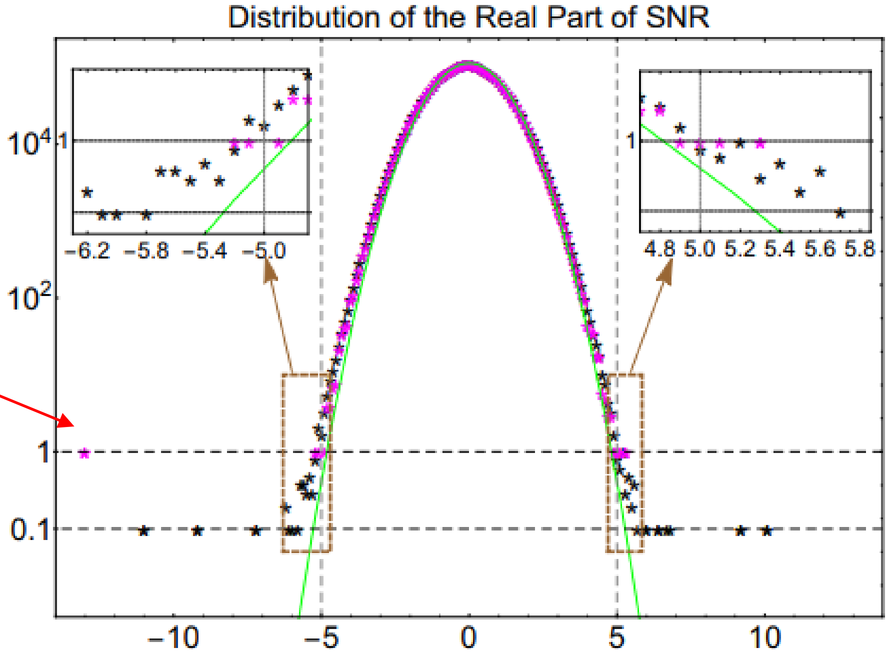
  ~ 1% false alarm probability after including trial factors.

two GW detectors are anti-aligned

- Frequency lags: to deal with non-Gaussian noise

  offset bins (−50, −40, ..., −10, +10, ..., +50)

  Remove single interferometer artifacts and broadband correlated artifacts



H. Guo, K. Riles, F. Yang, Y.Z.

Nature - Commun.Phys. 2 (2019) 155

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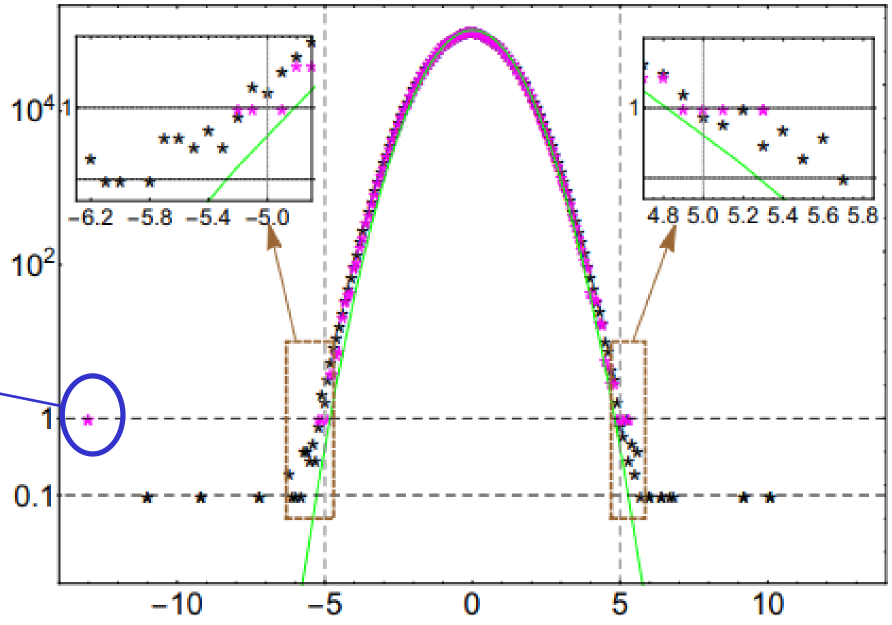
Distribution of the Real Part of SNR



known continuous wave
“hardware injections”
with random phase

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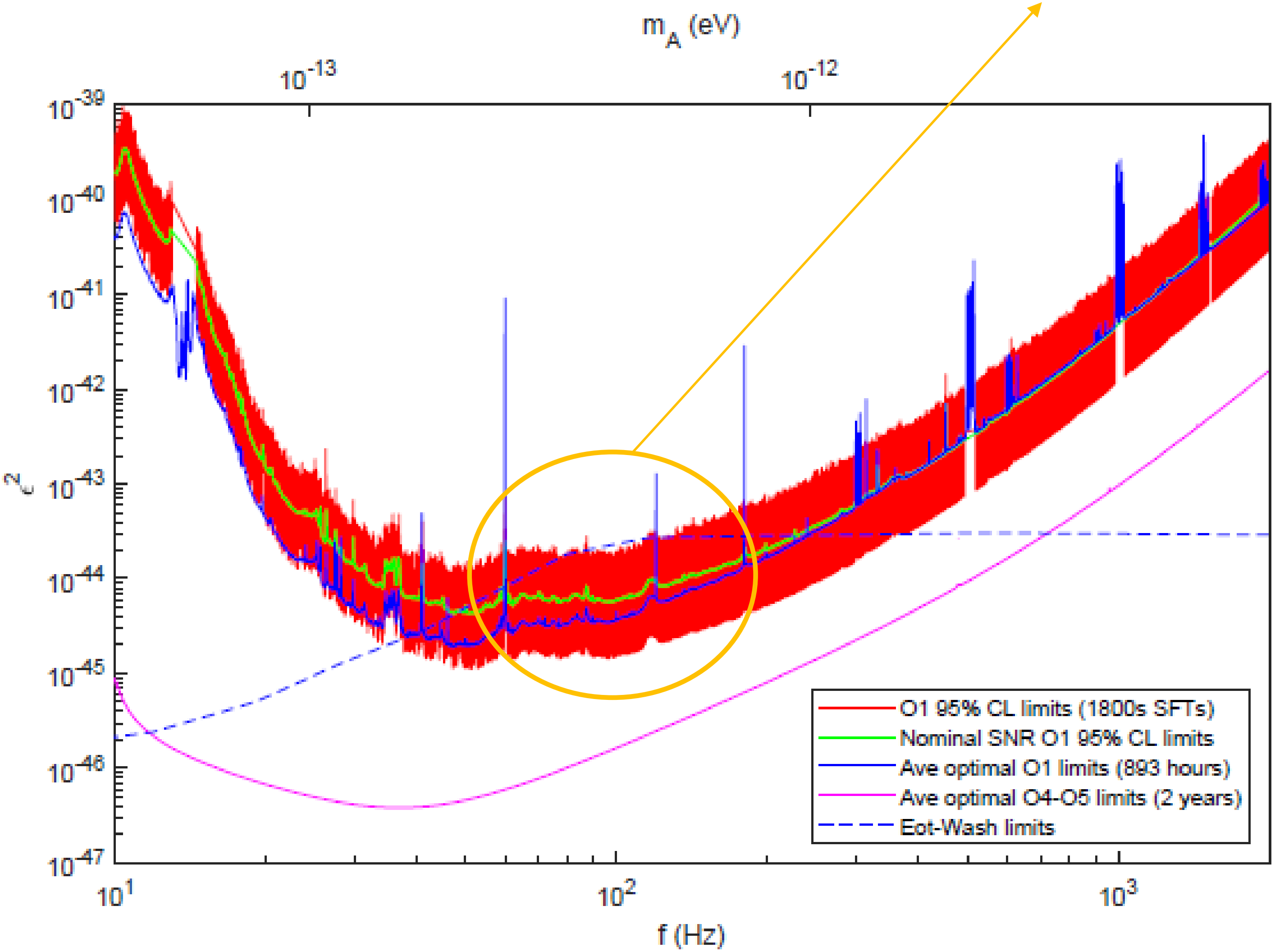
O1 Result:

We set the world record in this mass window!



Conclusion and Overview

- Many reasons to expect new physics beyond the Standard Model!

  DM candidate

  Strong CP problem

  Gauge hierarchy problem

  Cosmological constant problem

- Astrophysical measurements provide powerful probes to new physics!

  Extremal conditions

  Relics from very early time

Conclusion and Overview

- Astro. observations provide powerful probes to look for new physics.

GW experiments (LIGO/LISA)

ultralight: dark photon dark matter

ultraheavy: primordial black holes (Phys.Rev.D 99 (2019) 2, 023001)

cosmic string network

strong first order phase transition at early universe

to appear on today's arxiv

Event Horizon Telescope: axion

actively investigated by the EHT collaboration now

Pulsar Timing Array (Phys.Rev.D 101 (2020) 6, 063012)

Gaia satellite (JCAP 05 (2019) 015)