Astrophysical Probes to the BSM New Physics

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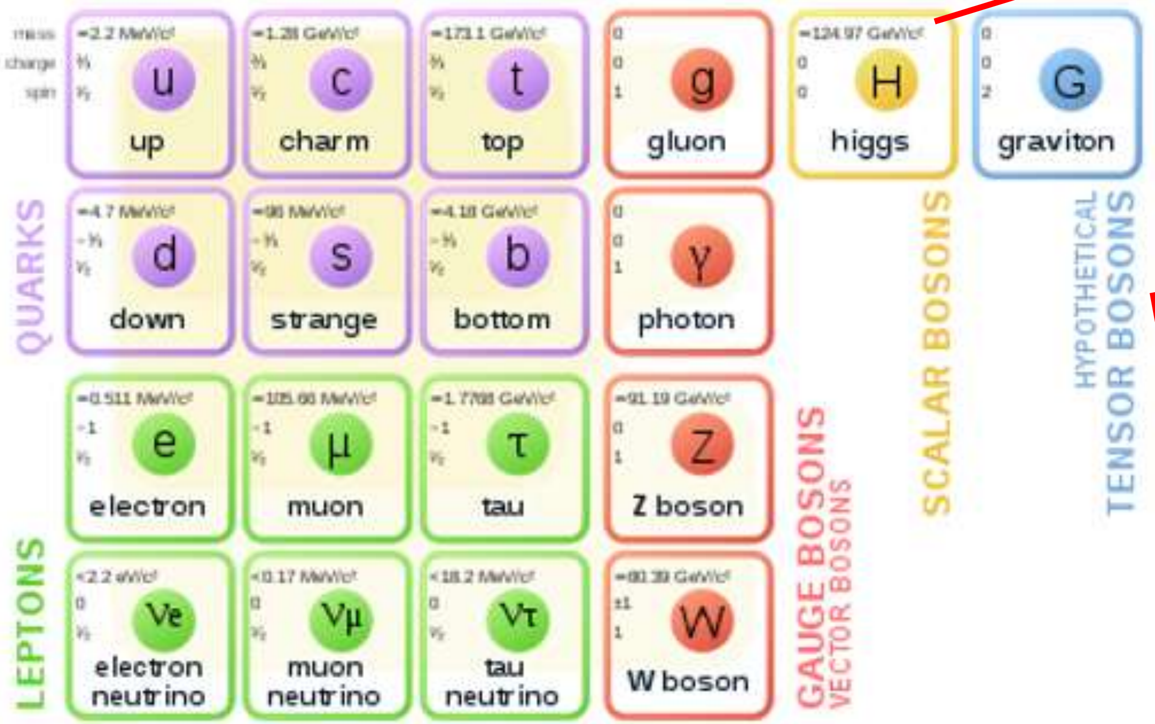
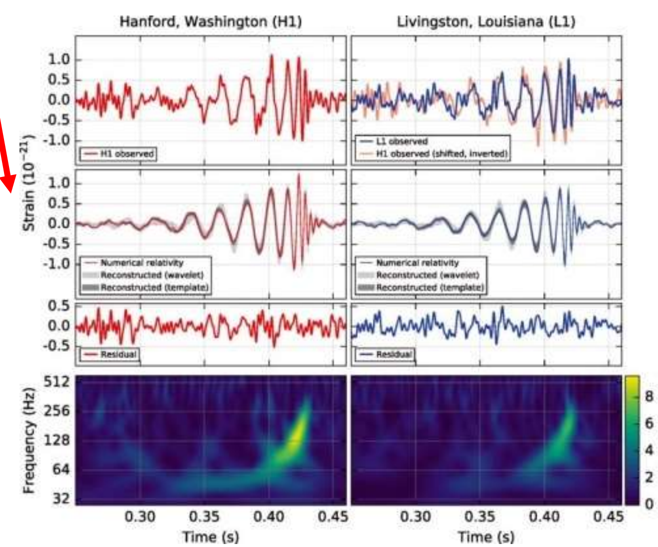
University of Utah

Current Status of Particle Physics:





+ anything else?

Astro environments can provide extreme conditions.

⇨ Ideal labs to search for new physics

Event Horizon Telescope:

Probe the existence of axion clouds by EHT.

Gravitational wave experiments (LVK):

Help to beat the background of WIMP searches.

Left-over problems:

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

⋮

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

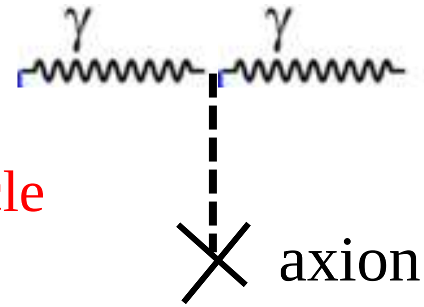
} can be related to axion

⋮

Search strategies:

- axion induced birefringent effect (Harari & Sikivie 92)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\nabla^{\mu}a\nabla_{\mu}a.$$



The condensation of a CP-odd particle distinguishes helicities of a photon

$$\Rightarrow \quad \Box A_{\pm} = \pm 2 i g_{a\gamma}[\partial_z a \dot{A}_{\pm} - \dot{a}\partial_z A_{\pm}]$$

- Only the derivatives on the axion background can change photon’s EoM.
- The modifications are opposite for different helicity.

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

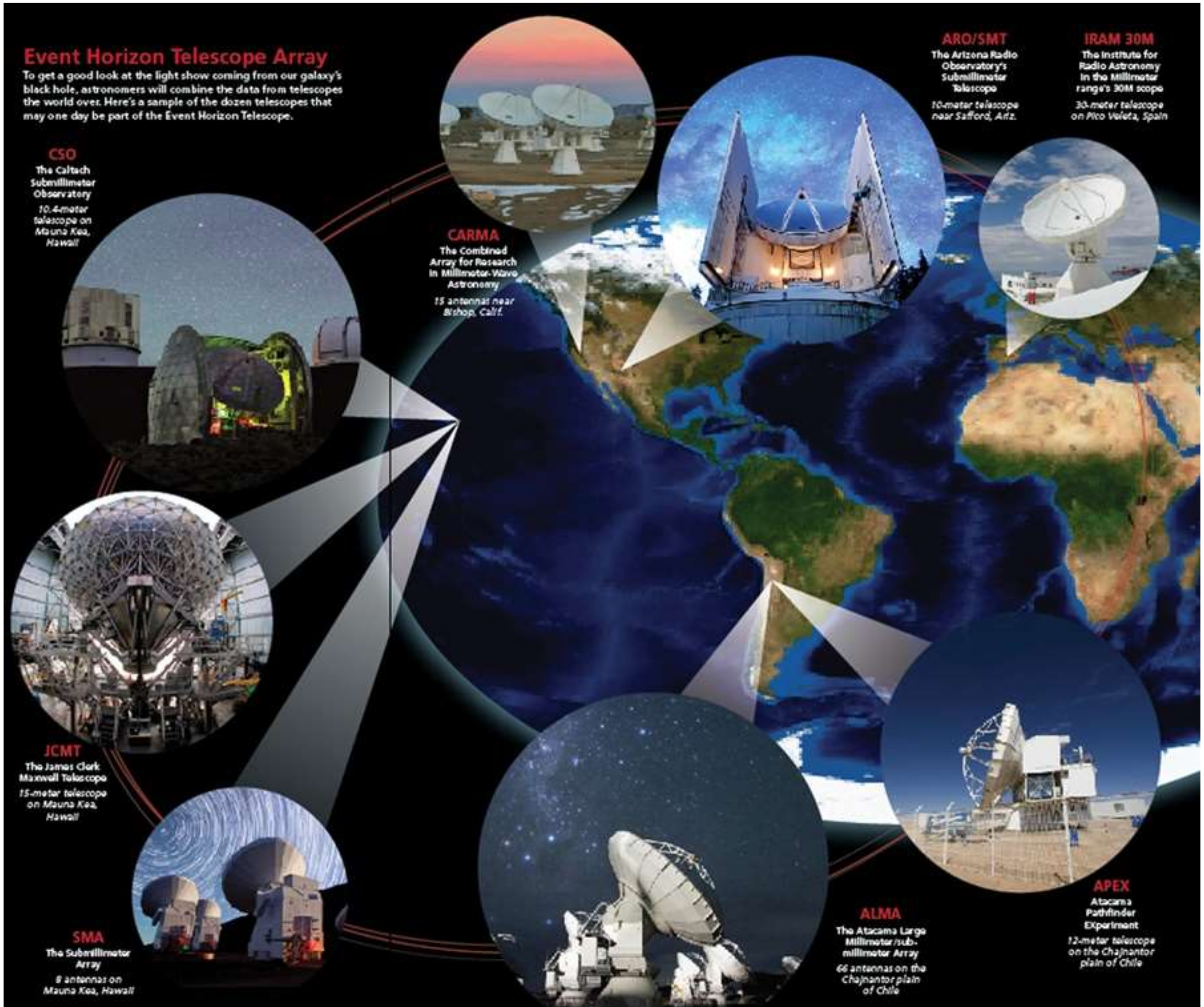
Search for:

- 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:



telescope array at radio frequency around the Earth

Event Horizon Telescope:

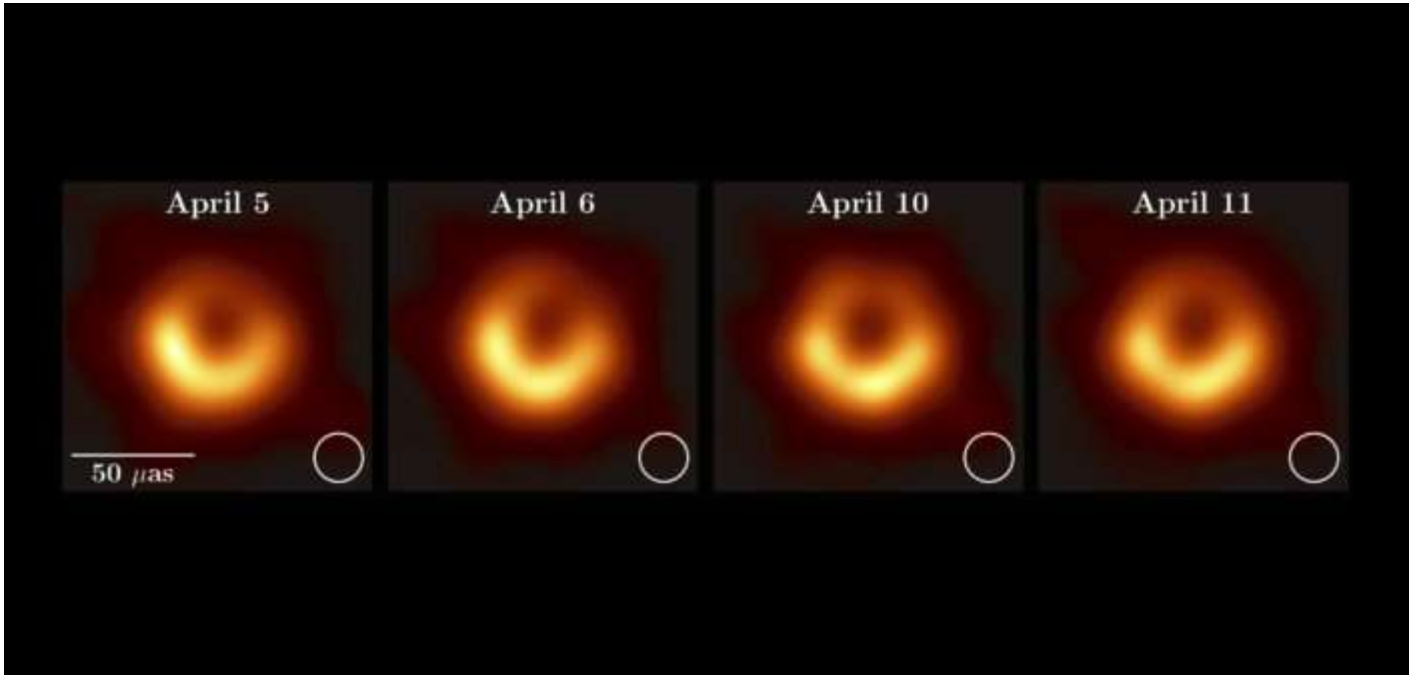
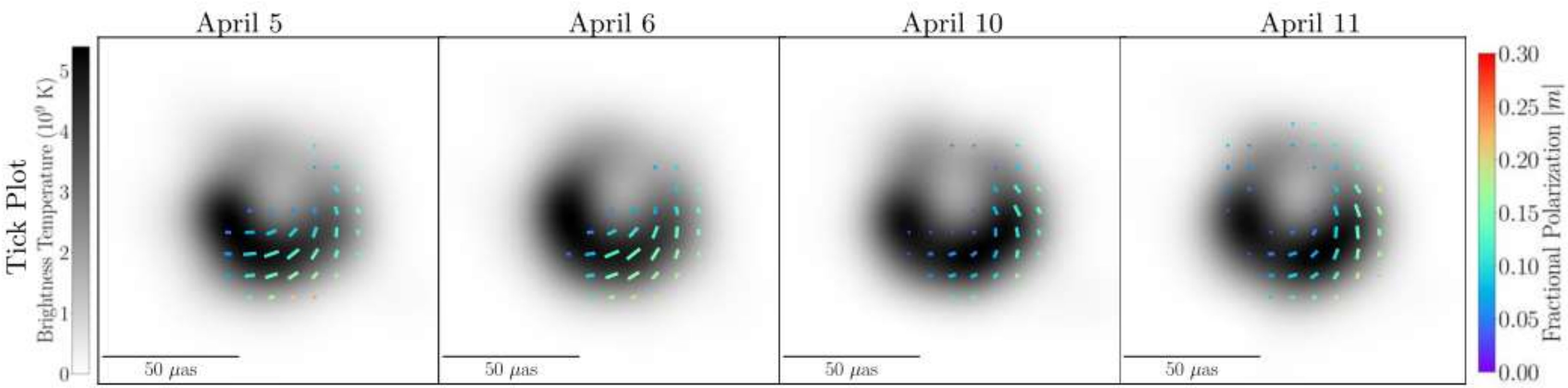
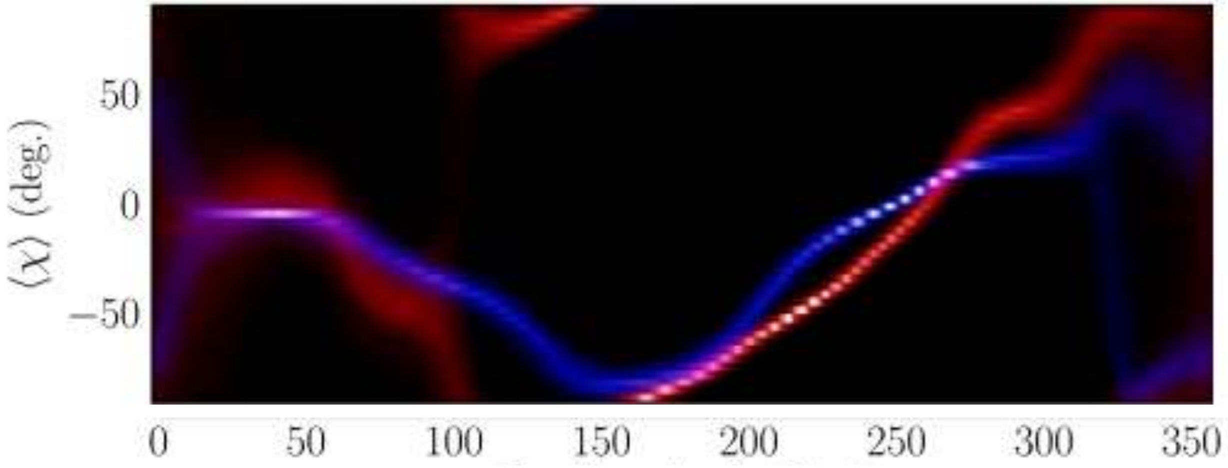


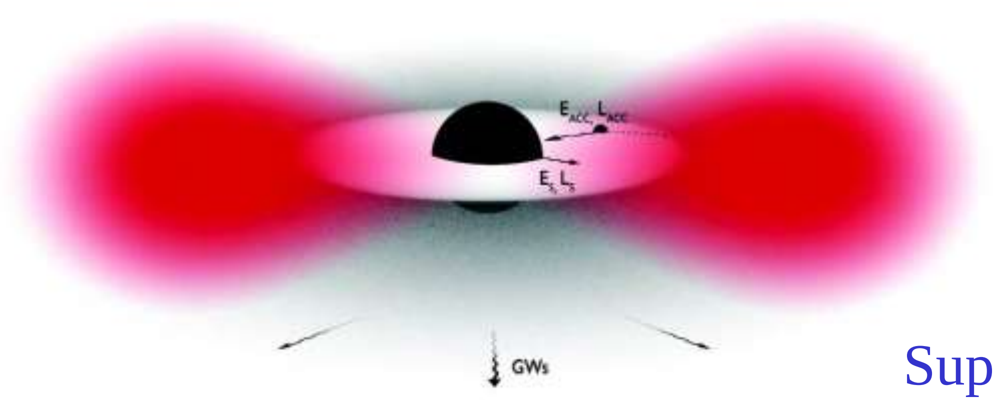
Image of the supermassive black hole at the center of the elliptical galaxy M87, for four different days.

Event Horizon Telescope:





Black hole superradiance:



Superradiance condition

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

When $\lambda_a \sim GM$:

a rapidly rotating black hole loses:
energy + angular momentum

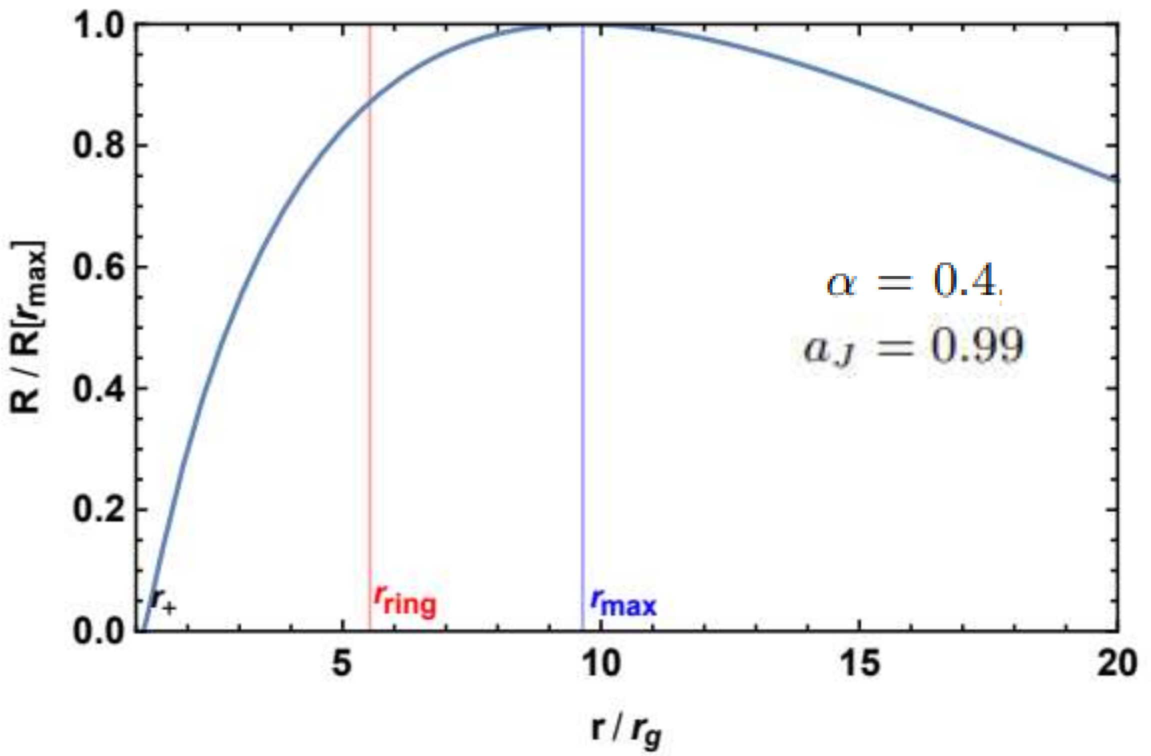
axion cloud will be produced around BH

Energy in axion cloud can be comparable to BH mass!

Black hole superradiance:

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:

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

take

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

slowly varying function

non-relativistic limit:

gravitational potential

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

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:

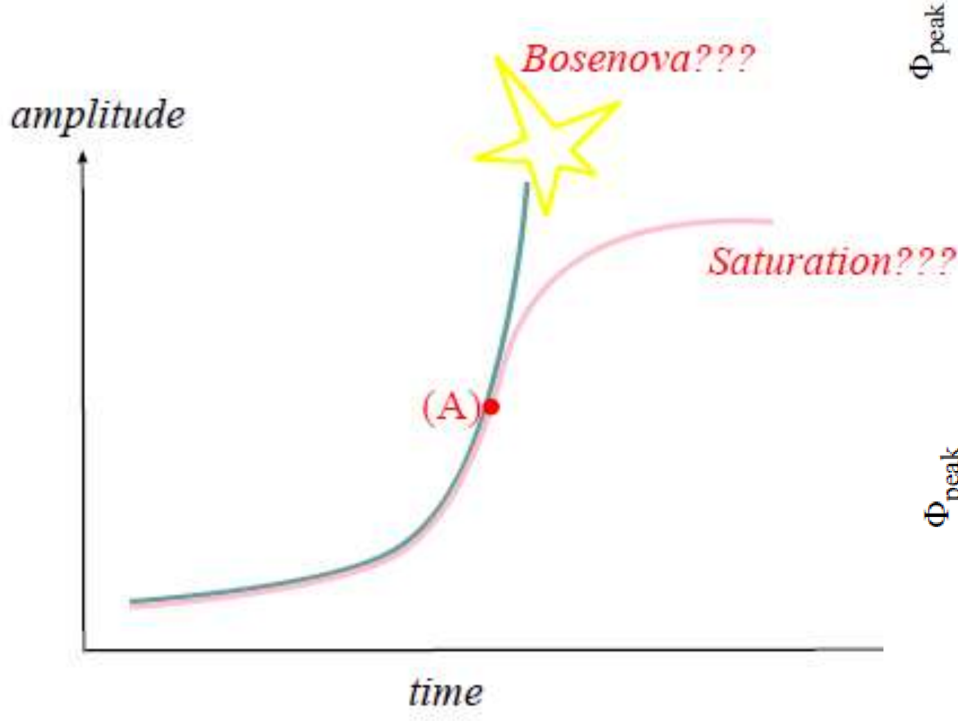
bosenova: a drastic process which explodes away axion cloud

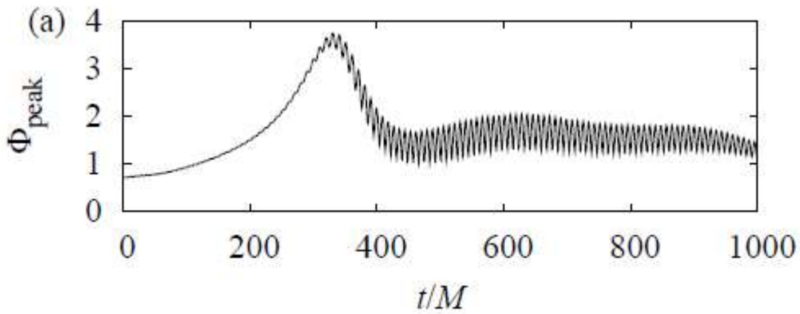
steady axion outflow to infinity

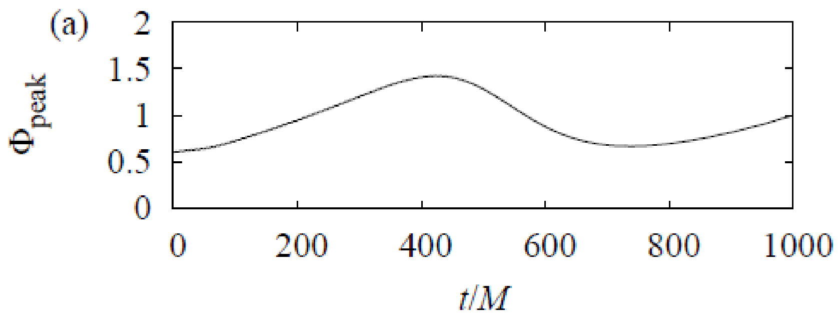
numerical simulation has been performed:

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:

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

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

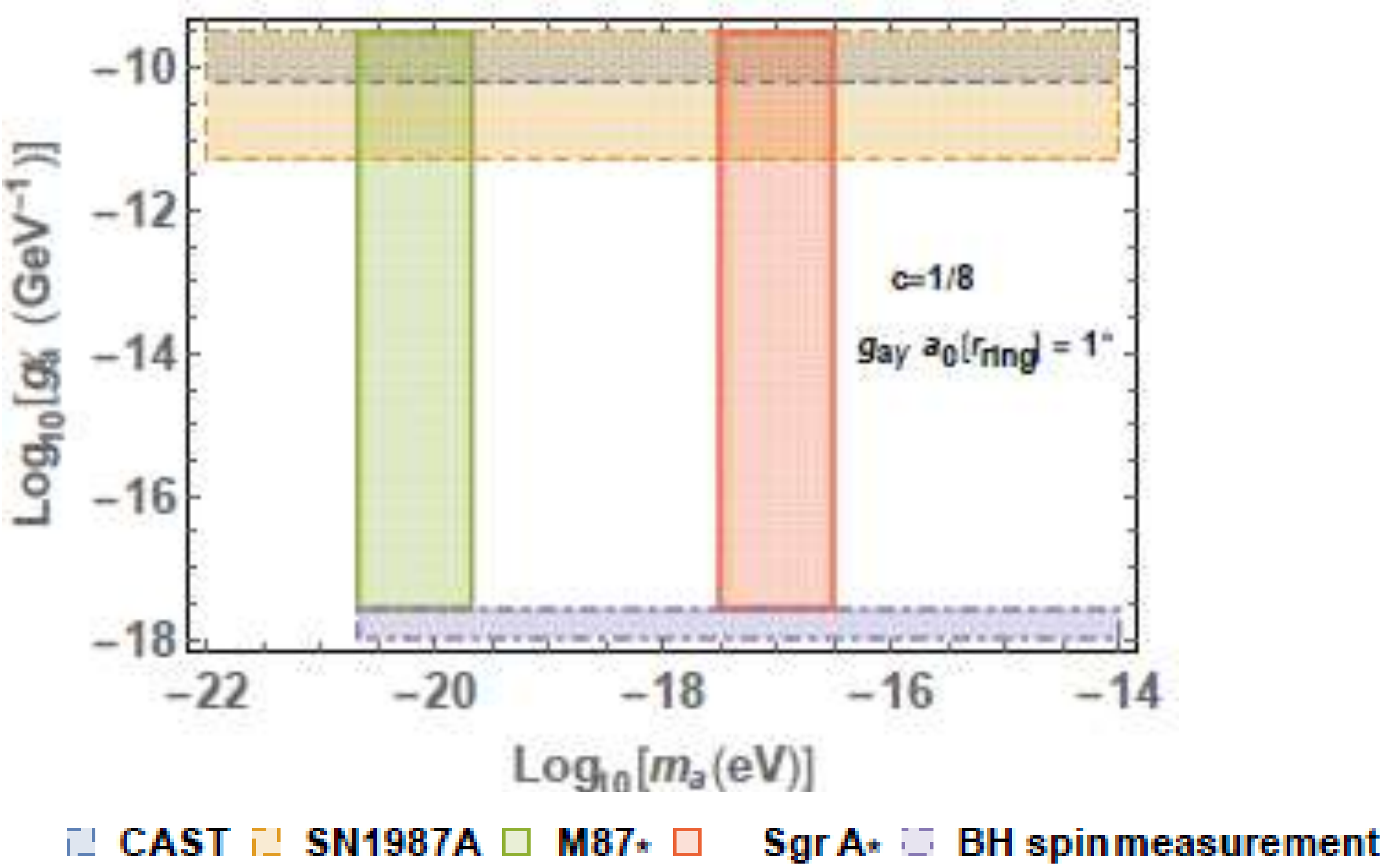
additional loop suppression to
translate f_a to axion-photon coupling

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

EHT expected sensitivity:

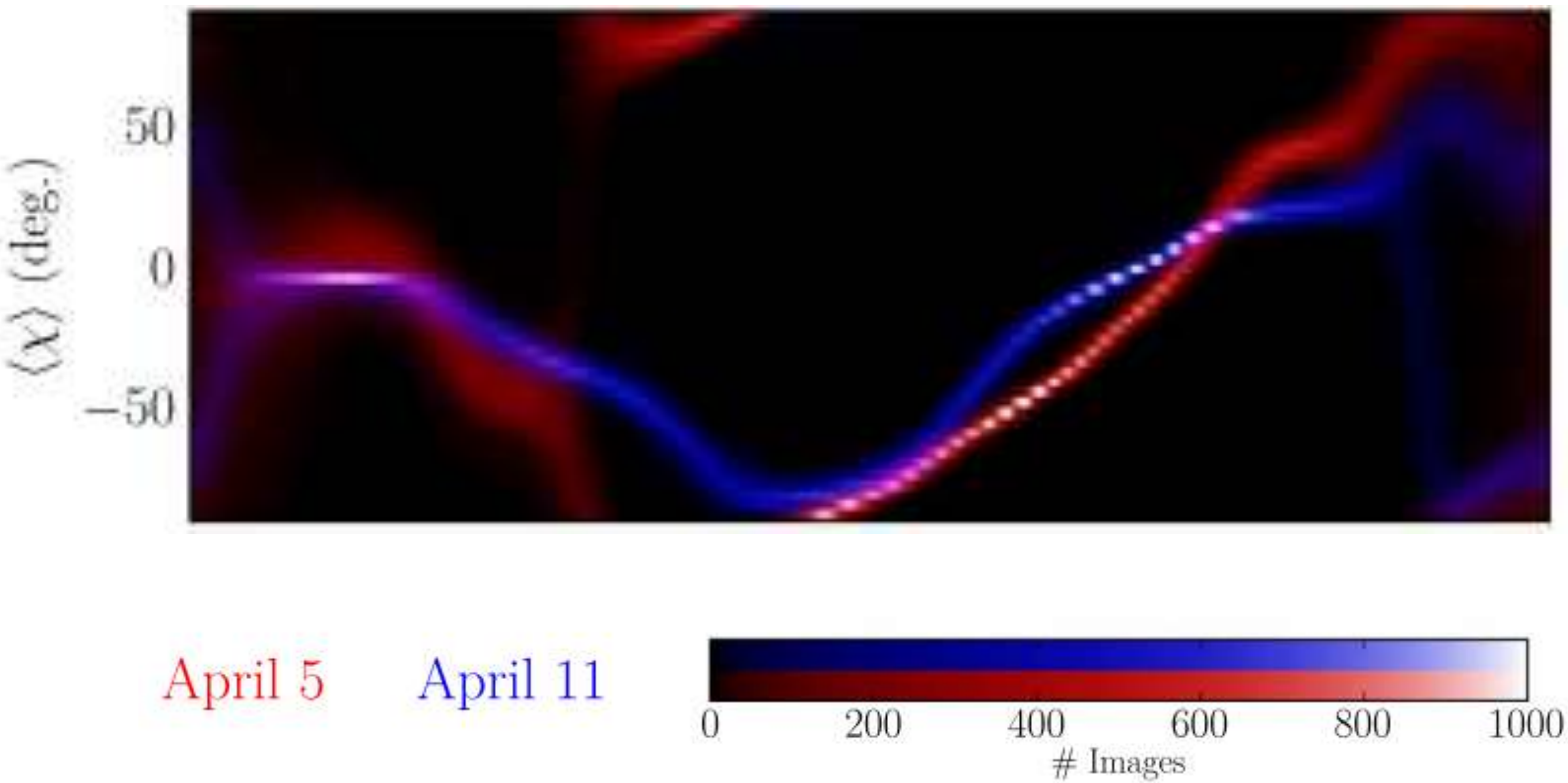
Yifan Chen, Jing Shu, Xiao Xue,
Qiang Yuan, and Y.Z.

Phys.Rev.Lett. 124 (2020) 6, 061102



Event Horizon Telescope Results:

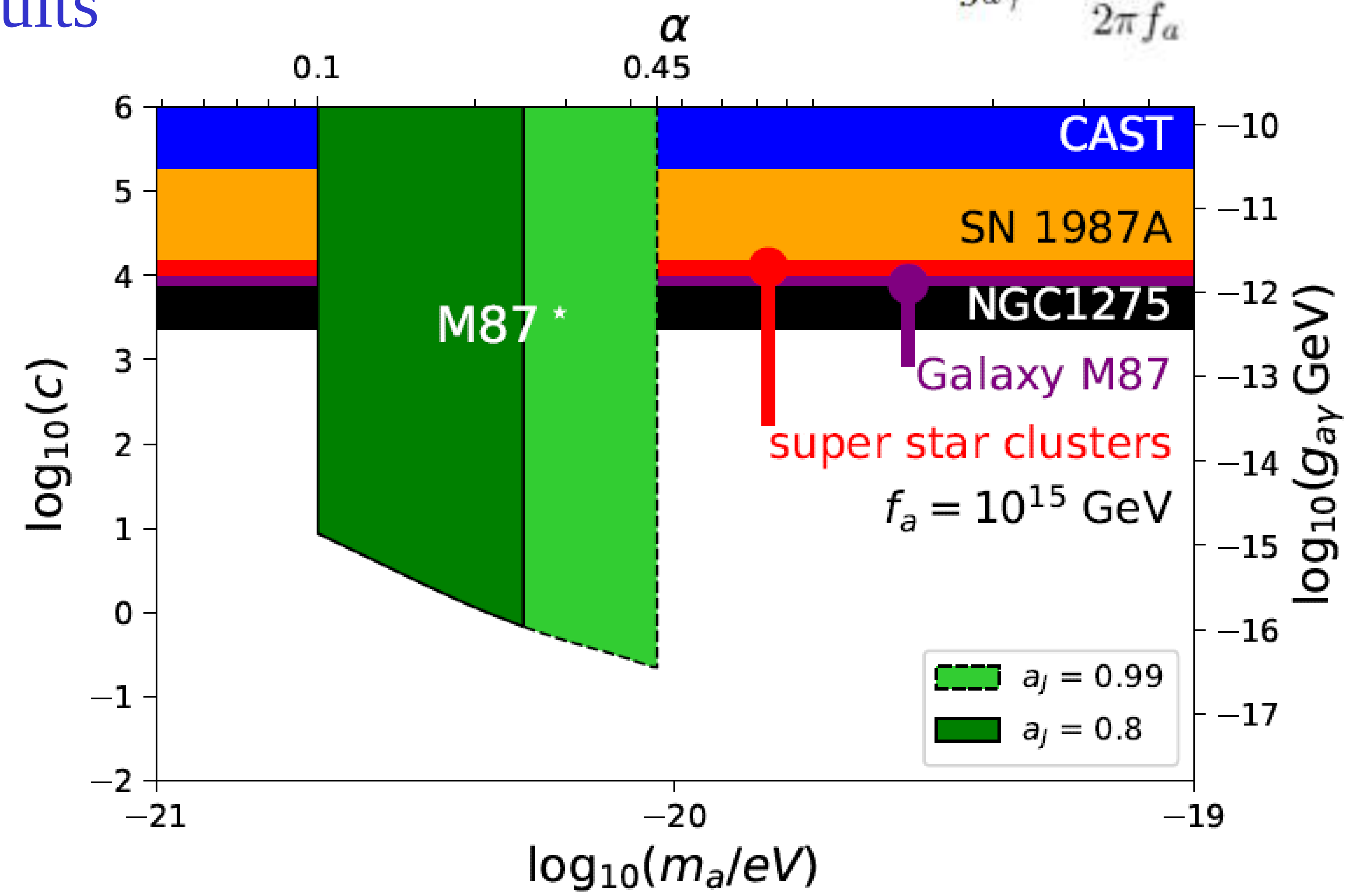
Polsolve method:



Intensity-weighted averages within an angular section of a width of 10°

Results

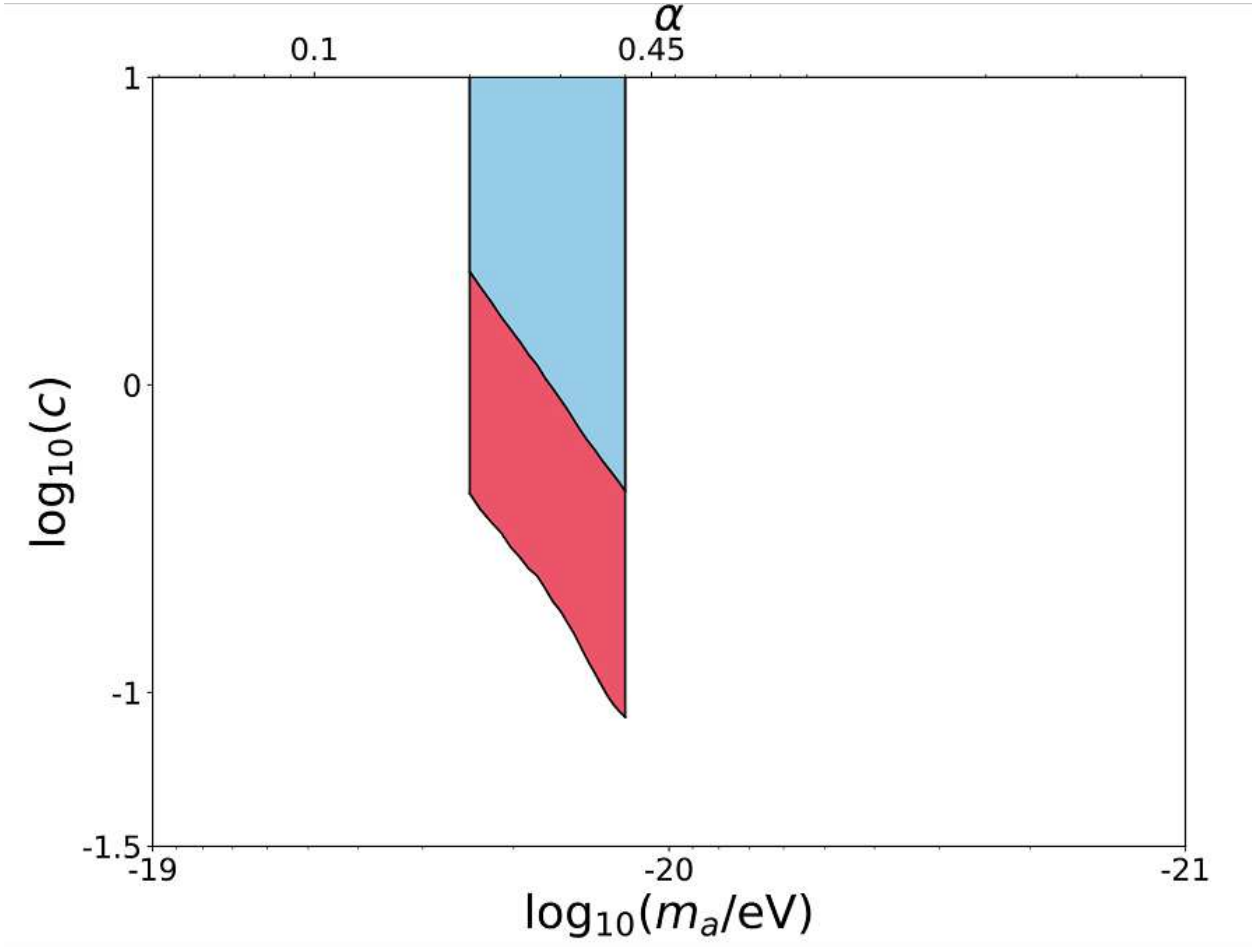
$$g_{a\gamma} = \frac{c}{2\pi f_a}$$



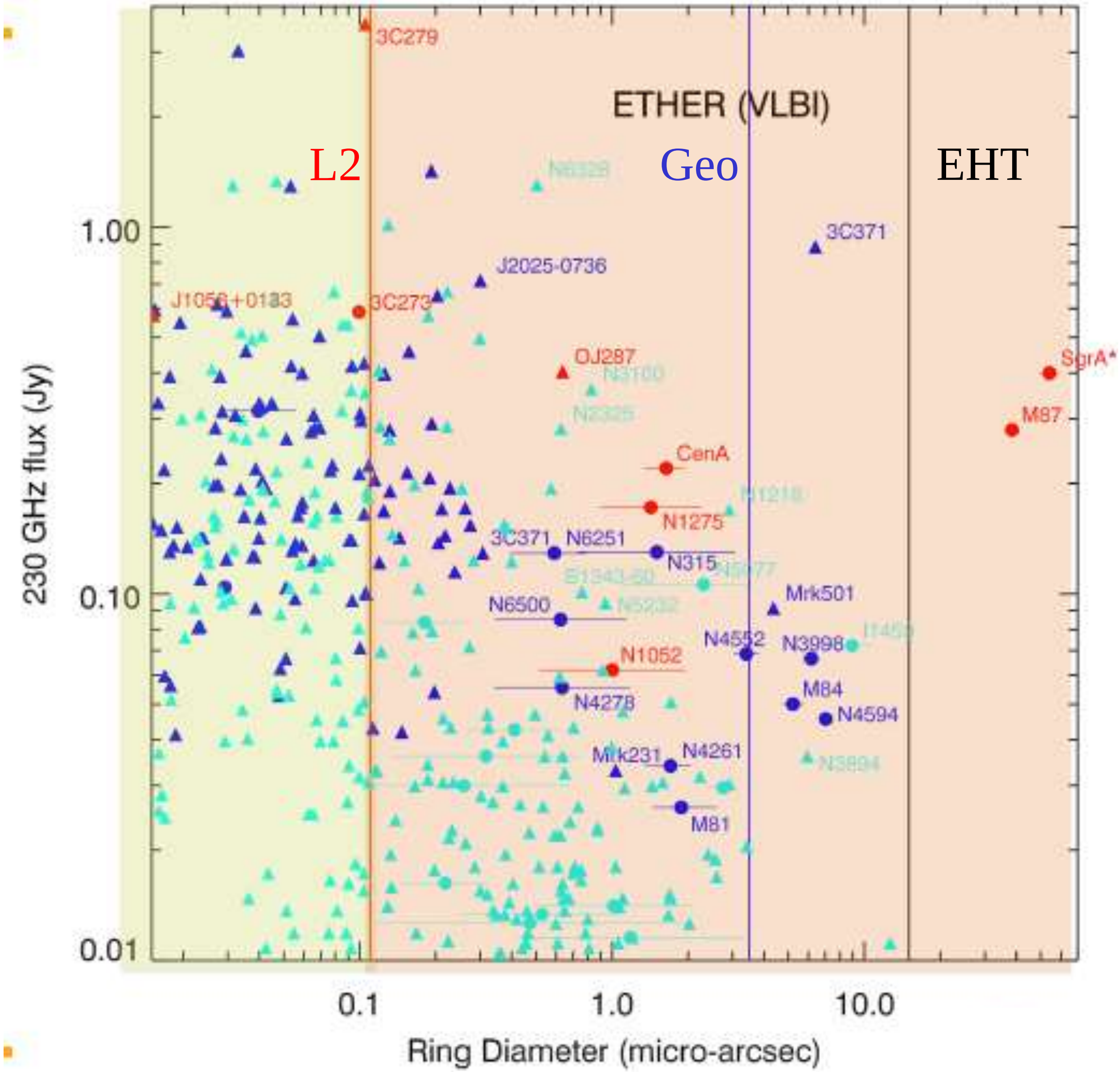
Y. Chen, Y. Liu, R. Lu, Y. Mizuno,
J. Shu, X. Xue, Q. Yuan, Y.Z.
Nature Astron. 6 (2022) 5, 592-598

Results

Preliminary results if the pixel-by-pixel polarization measurement is performed.

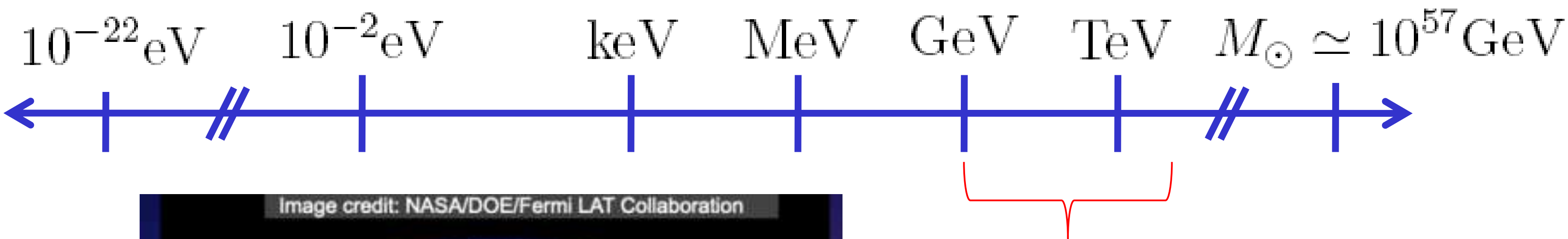


Future

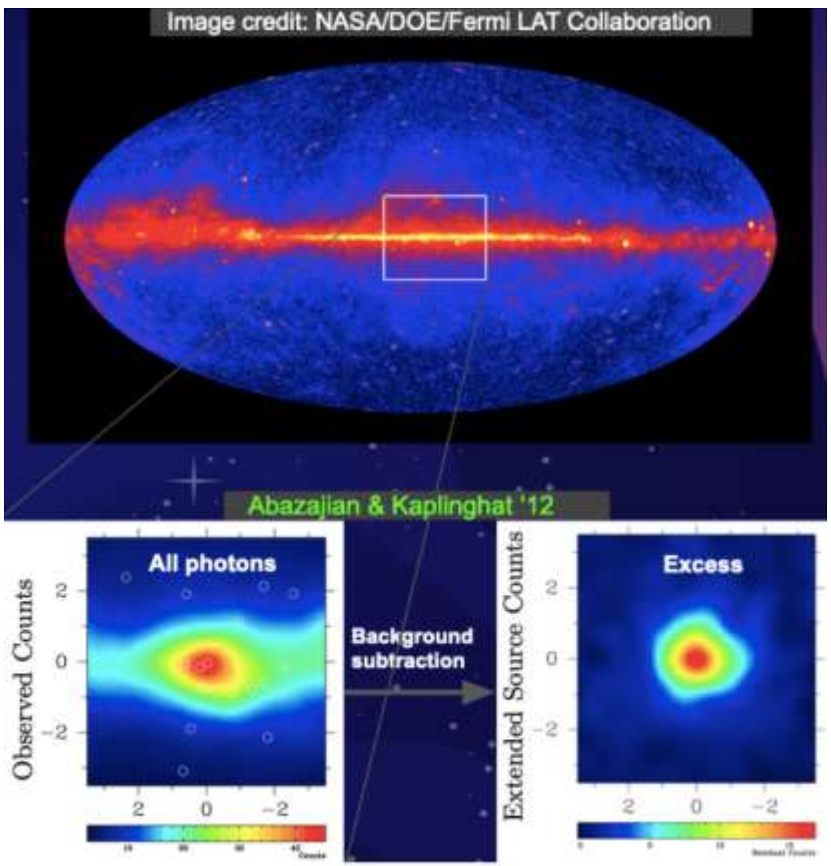


ETHER (VLBI)
L2
Geo
EHT
230 GHz flux (Jy)
Ring Diameter (micro-arcsec)
1.00
0.10
0.01
0.1
1.0
10.0
3C279
3C371
J2025-0736
J1058+0133
3C273
OJ287
SgrA*
M87
CenA
N1275
3C371
N6251
N315
Mrk501
N6500
N4552
N3998
N1052
N4278
M84
N4594
Mrk231
N4261
M81

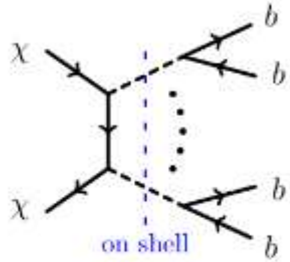
A GeV excess at the Galactic Center:

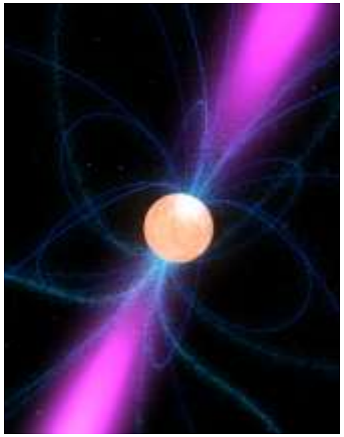


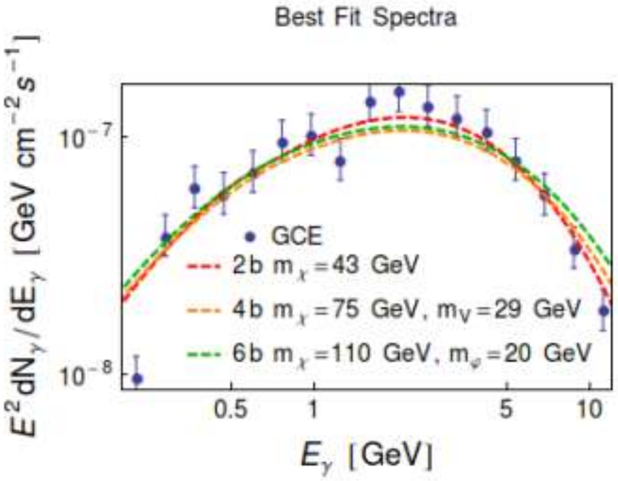
Well motivated.
Correct relic abundance.
Searched for decades.

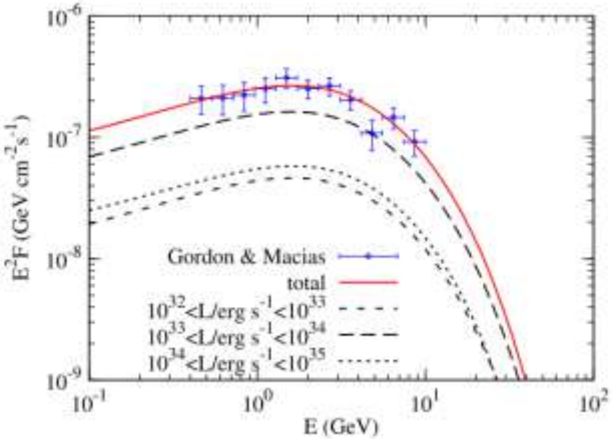


Two explanations:







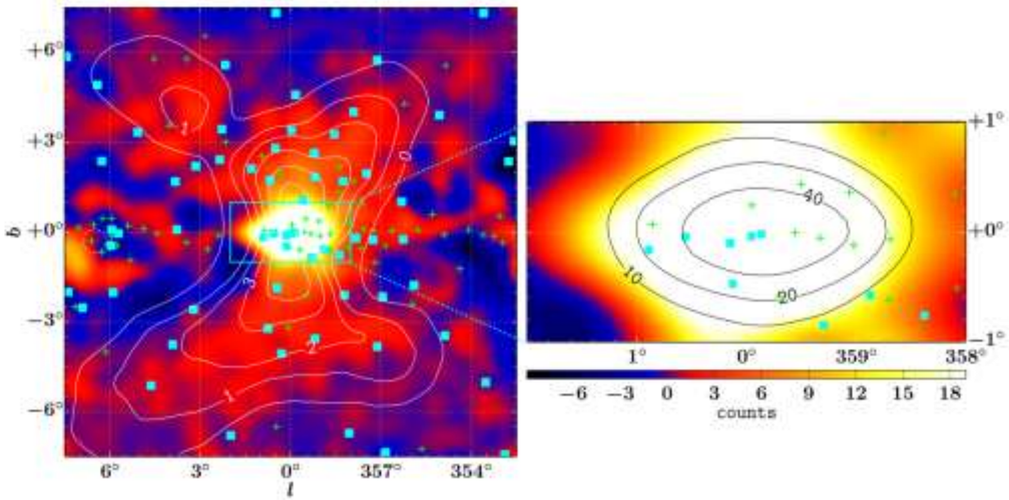


Abdullah, et. al.
Phys. Rev. D 90, 035004 (2014)

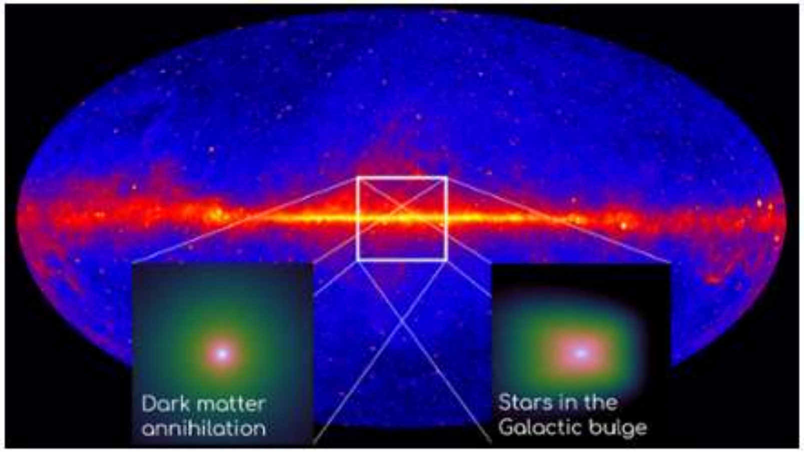
Yuan, et. al.
JHEAp 3 (2014) 1

Efforts to distinguish these two explanations:

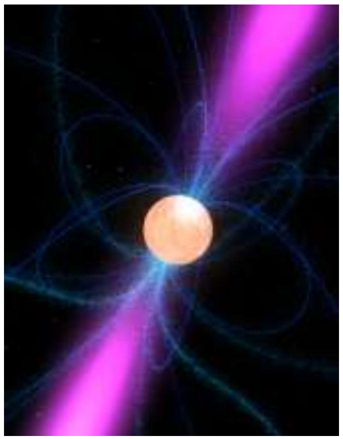
- Smoothness: Point Source v.s. Smeared Distribution

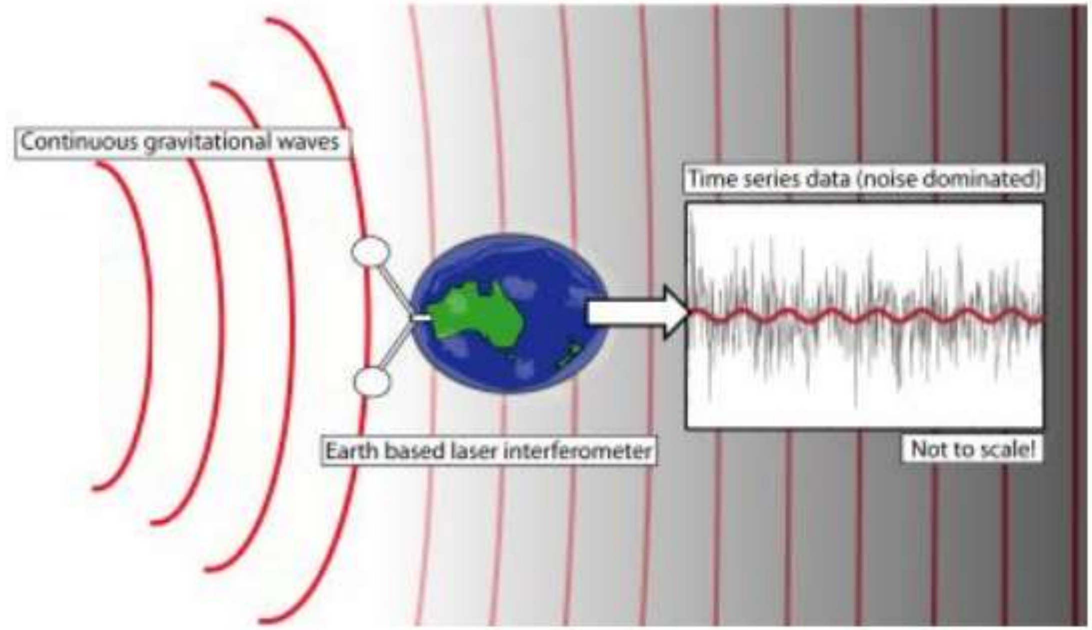


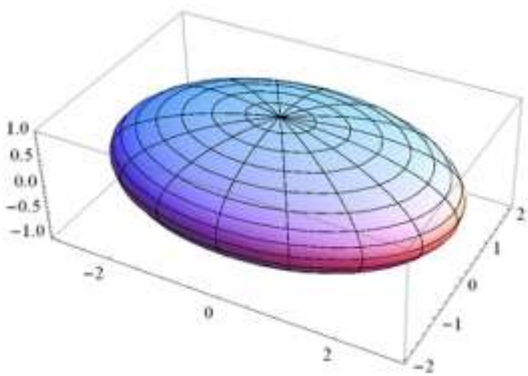
- Morphology: Spherical v.s. Bulge-like



GW channel can be useful:



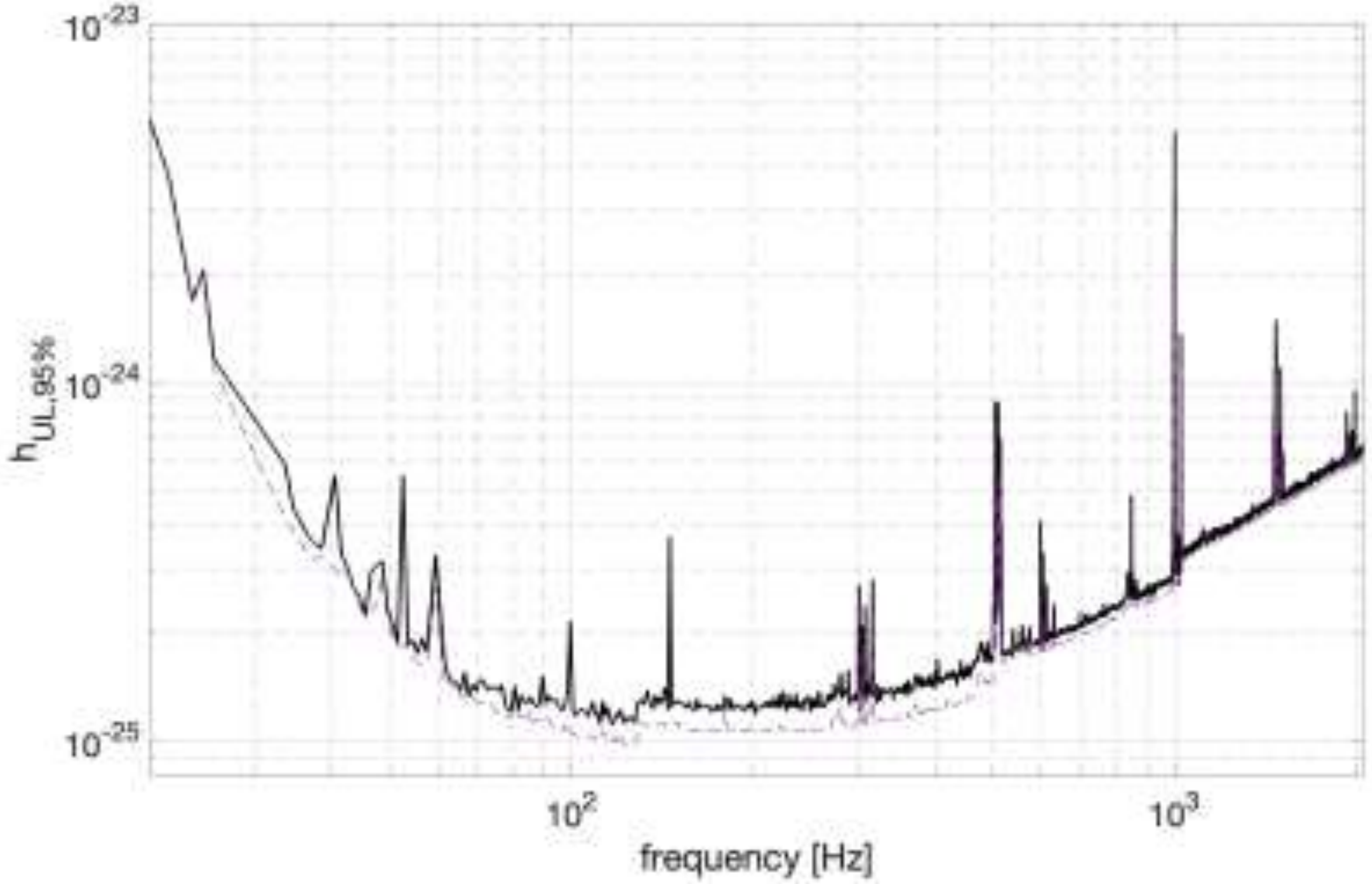




$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} \epsilon f_{\rm rot}^2}{d}$$

WIMP DM:

The LVK collaboration
Phys. Rev. D 106, 102008

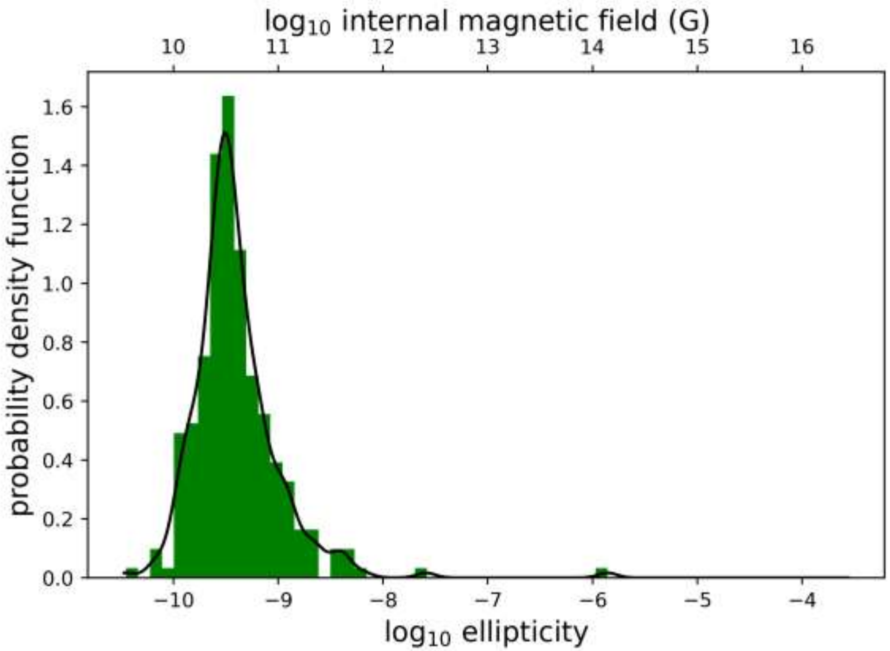


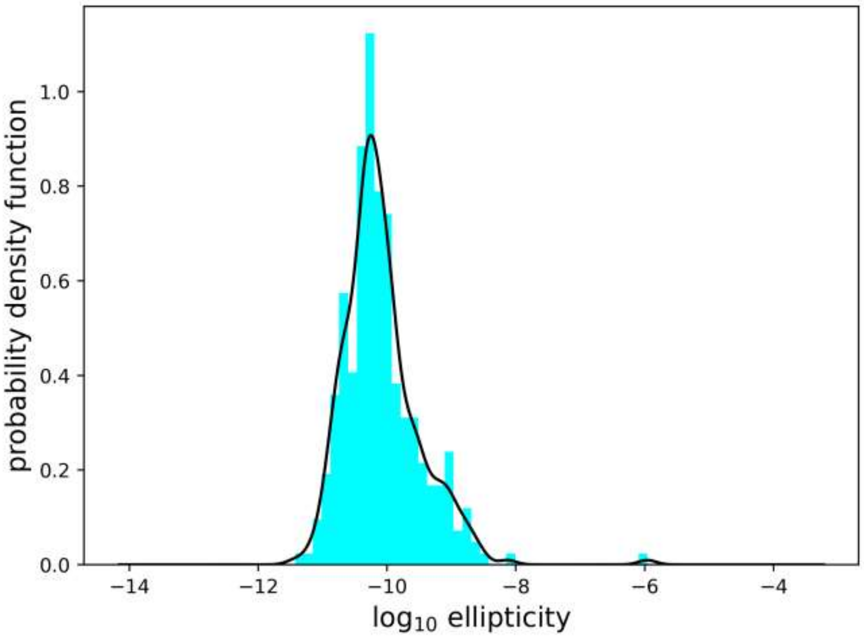
Ellipticity distribution:

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

$$\epsilon \equiv |I_{xx} - I_{yy}|/I_{zz}$$

principal moments of inertia





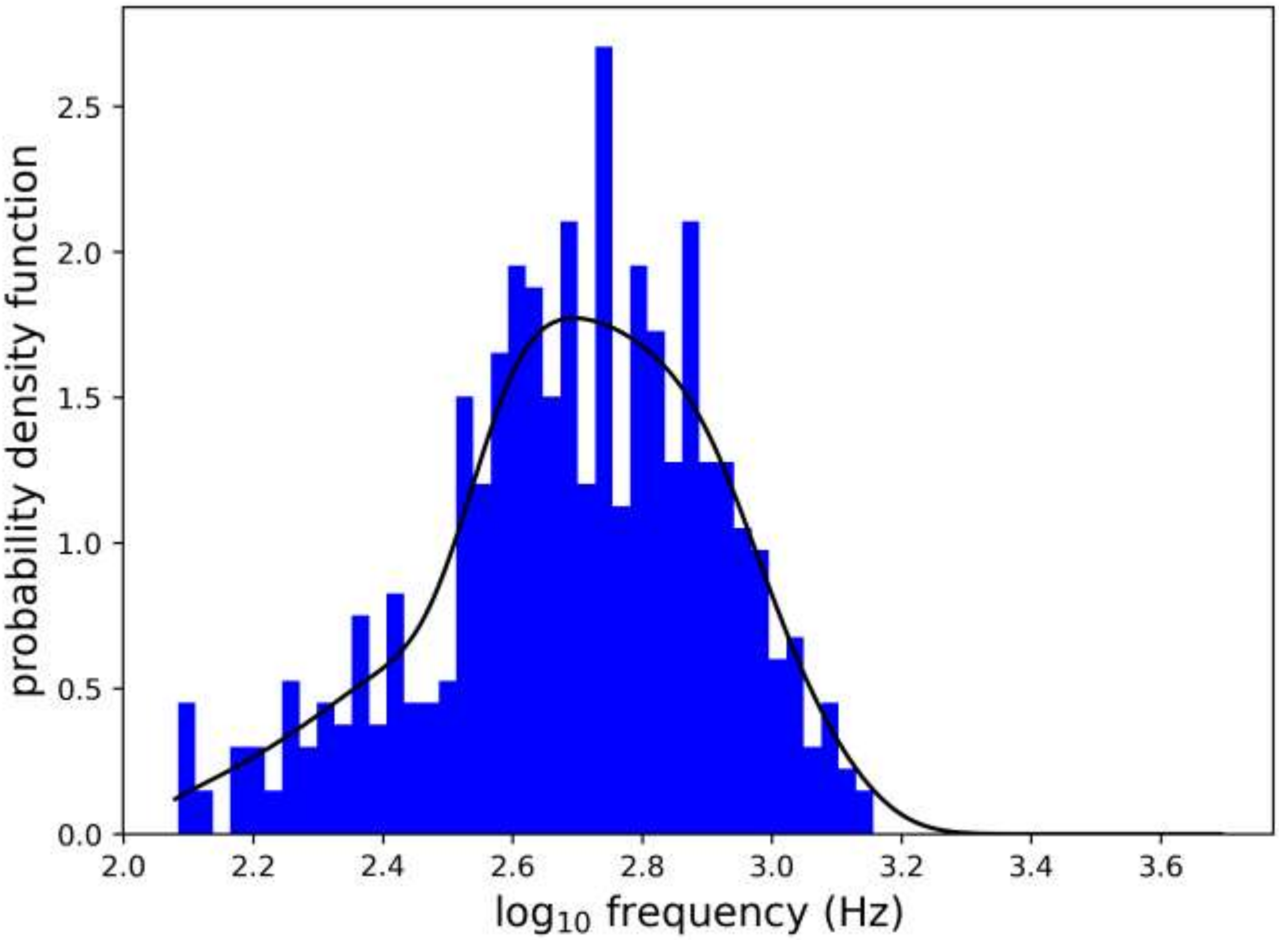
$$\epsilon \approx 10^{-8} \left(\frac{B_{int}}{10^{12}\ \mathrm{Gs}} \right)$$

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

GW radiation accounts for 1% rotational energy loss.

Frequency distribution:

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

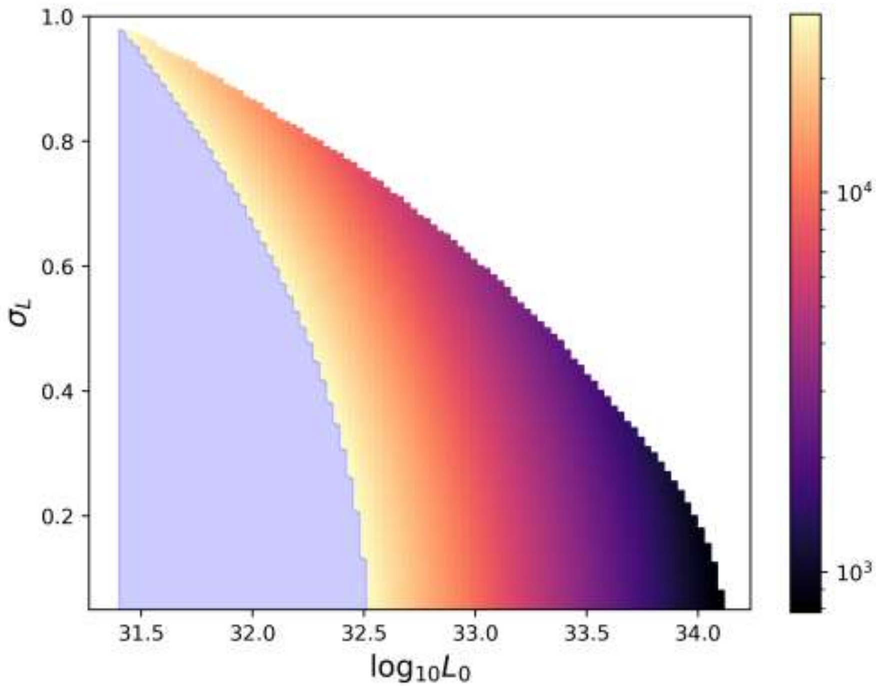


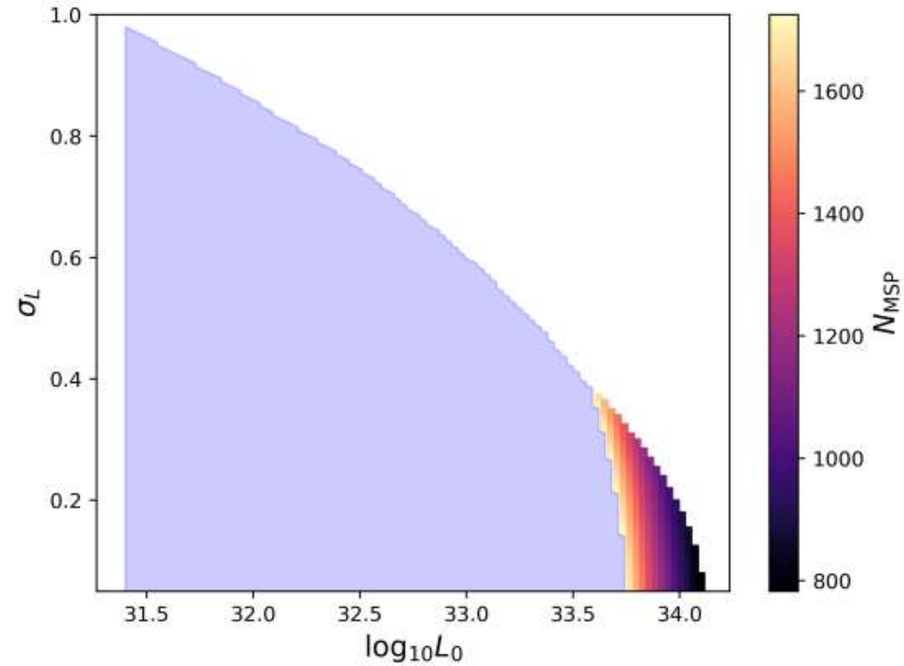
WIMP DM:

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

$$d = 8 \text{ kpc}$$

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

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

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

Conclusion

Astrophysics provides excellent probes to search for New Physics!

EHT:

A dense axion cloud can build up near by SMBHs.

Accretion disk emits linearly polarized photons.

EHT resolves the fine features near SMBHs.

EHT can provide measurements on position angles.

⇨ Probe the existence of axion clouds by EHT.

LVK:

MSPs may explain the GeV excess at GC.

CW is an ideal method to search for these MSPs.

GW and gamma ray will push the boundaries from two ends.

Let’s bring bad luck from particle physics to astronomy!