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The gravitational wave and radio signals of ultralight dark matter

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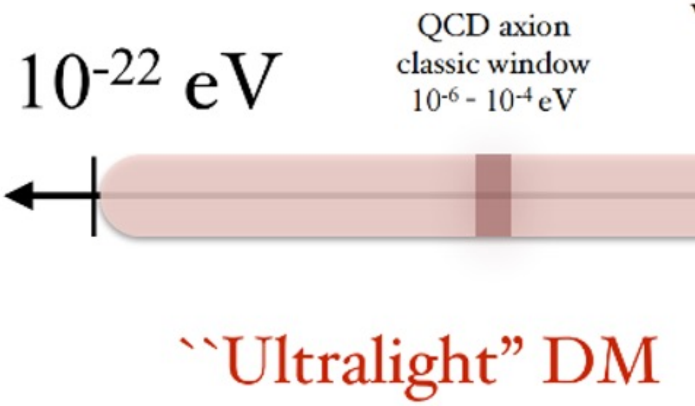
https://fapenghuang.github.io/group/

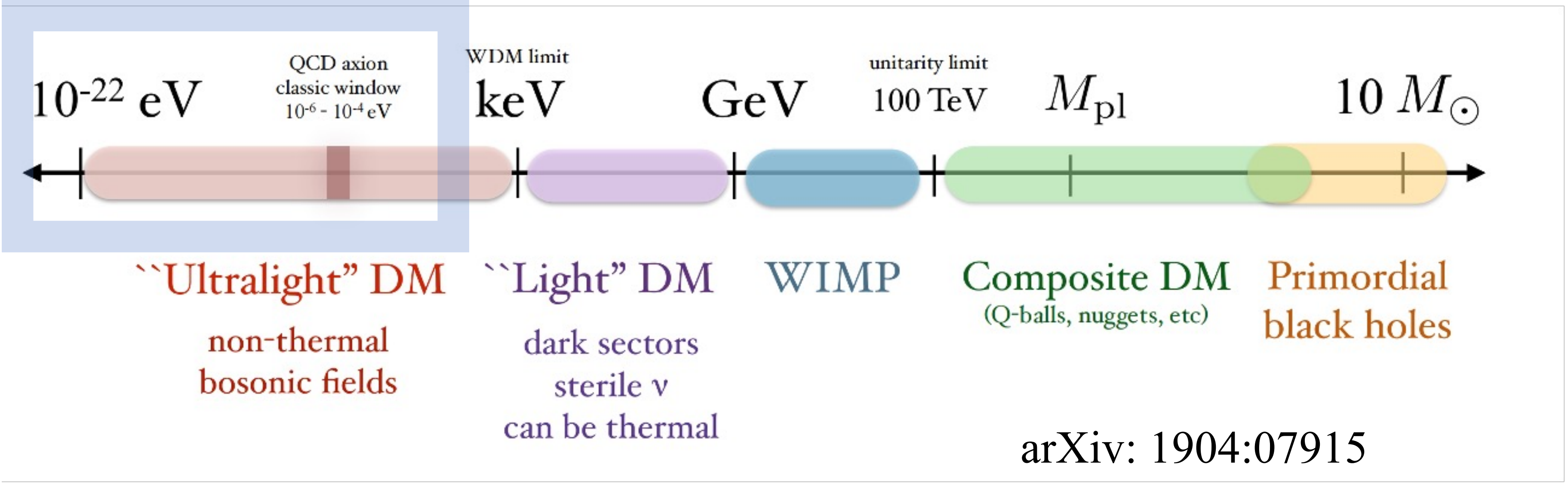
ICHEP 2024@Prague, 2024.07.20

Outline

1. Ultralight axion dark matter (DM) & Gravitational wave (GW)
2. μeV axion DM: radio signals
3. $10^{-17} - 10^{-12}$ eV axion DM: GW and pulsar timing measurement (focus)
4. 10^{-21}eV fuzzy axion DM: GW (focus)
5. Summary and outlook



What is the microscopic nature of DM?



How to detect DM?

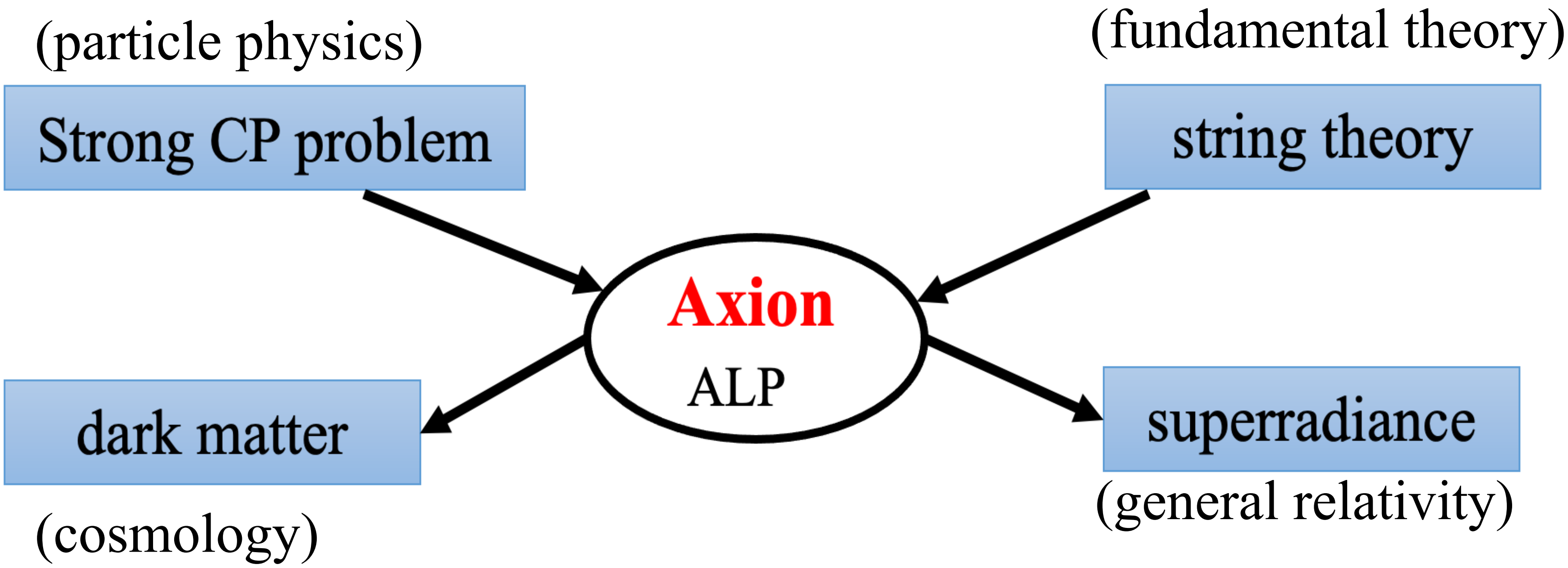
This situation may point us towards ultralight or heavy DM with new approaches, such as

radio telescope (SKA/FAST…)

& GW detector (LISA/TianQin/Taiji…)

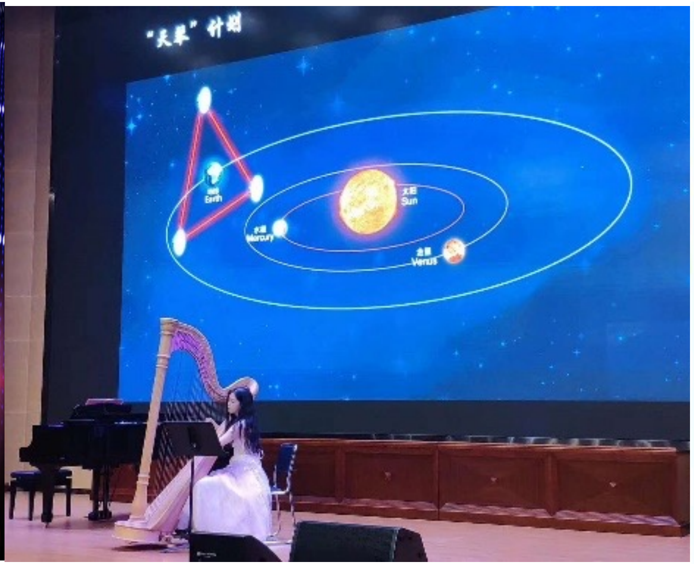
Axion particle cosmology

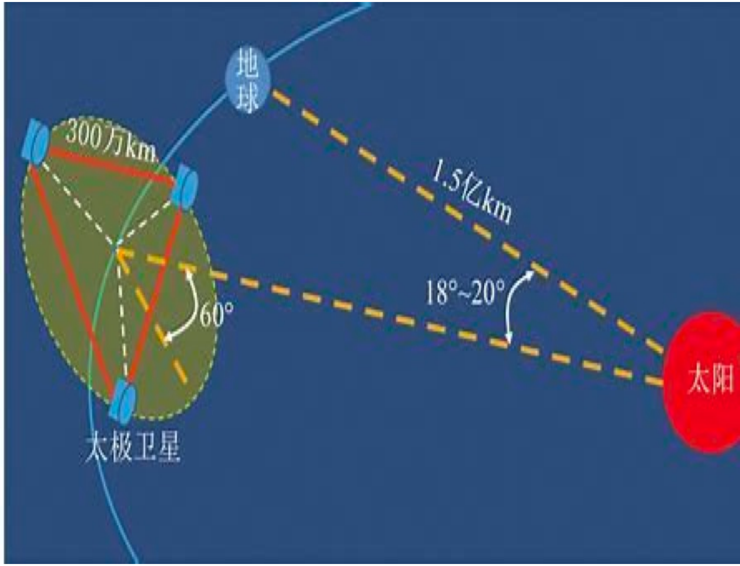
Ultralight axion is a promising DM candidate.



GW experiments

LISA/TianQin/Taiji ~2034



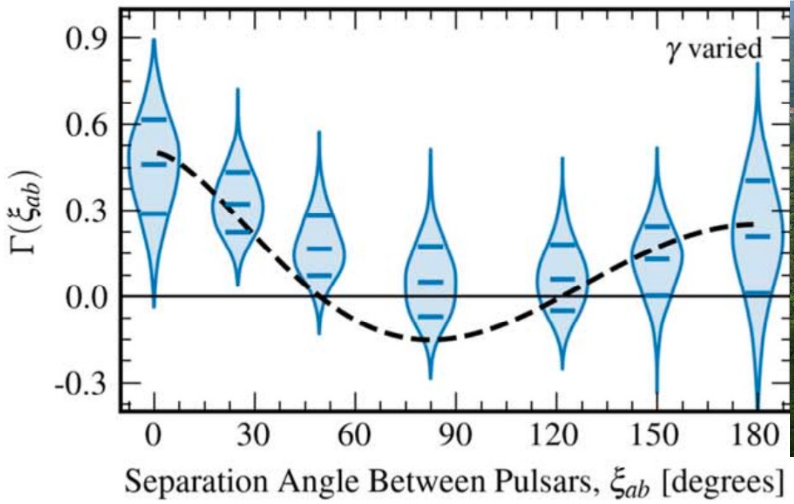


"天琴"

"Harpe in space"

Radio telescope and pulsar timing array

2023 June 29th: NANOGrav, EPTA, InPTA, Parkes PTA, CPTA



Hellings-Downs correlation curve
First observation of stochastic GW

FAST

SKA

High sensitivity sub μJy

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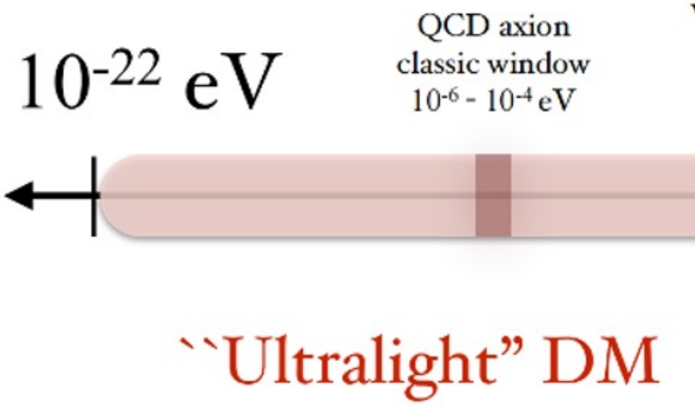
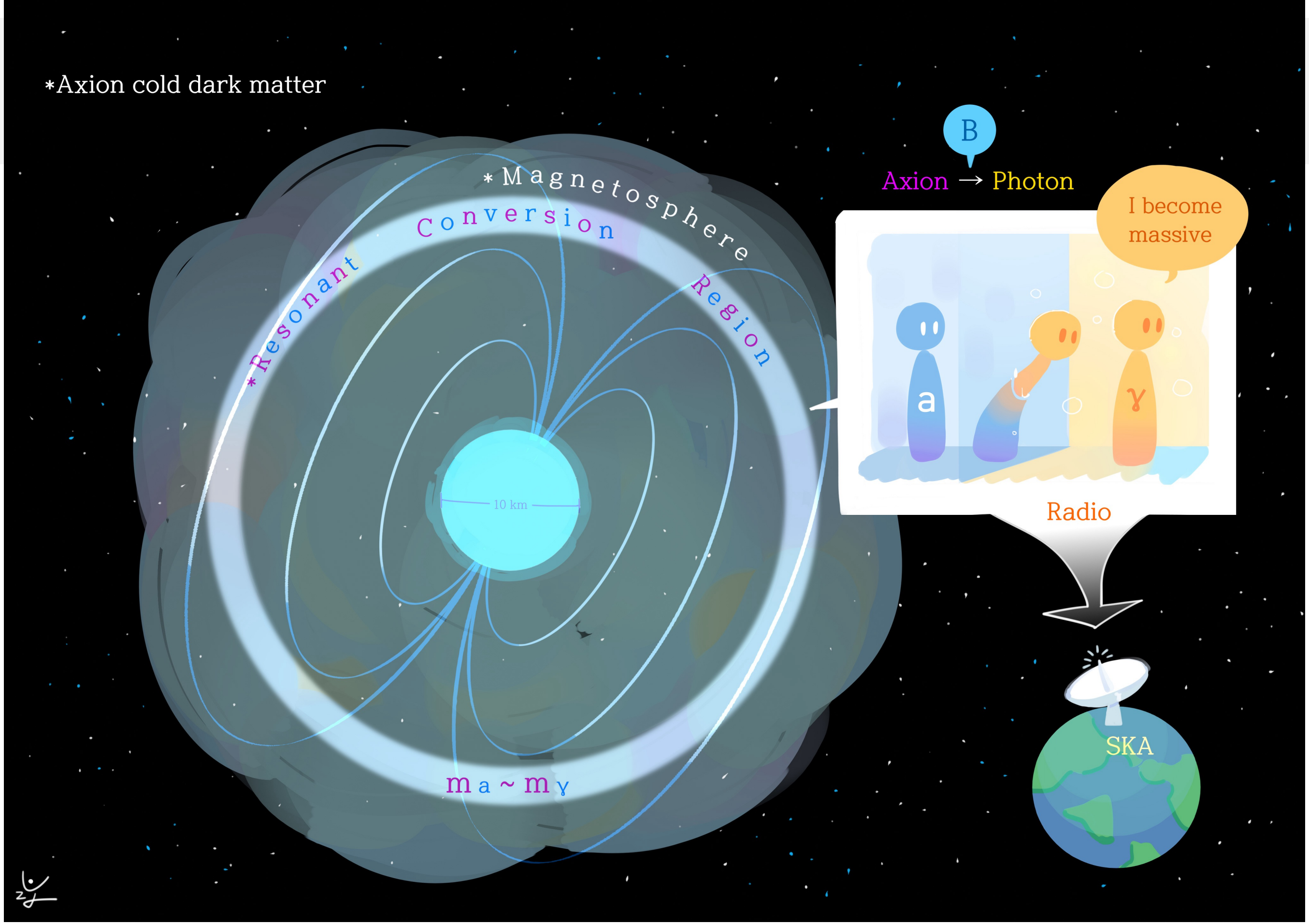


μeV axion DM: radio signals



FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

Axion-photon conversion

$$L_{\rm int} = \frac{1}{4} g \tilde{F}^{\mu\nu} F_{\mu\nu} a = -g\mathbf{E}\cdot\mathbf{B} a,$$

Massive Photon: In the magnetosphere of the neutron star, photon obtains effective mass in the plasma.

$$m_\gamma^2 = \omega_{plasma}^2 = 4\pi\alpha \frac{n_e}{m_e}$$

$$B(r) = B_0 \left(\frac{r}{r_0}\right)^{-3} \qquad n_e(r) = n_e^{\rm GJ}(r) = 7\times 10^{-2} \frac{1 s}{P} \frac{B(r)}{1\ \rm G} \frac{1}{\rm cm^3}$$

Thus, the photon mass is location dependent, and within some region

Line-like radio signal for axion

$$\nu_{\rm peak} \approx \frac{m_a}{2\pi} \approx 240 \frac{m_a}{\mu eV} \mathrm{MHz}$$

1 GHz ~ 4 μeV

FAST: 70MHz–3GHz, SKA: 50MHz–14GHz, GBT:0.3–100GHz

Radio telescopes can probe axion mass of 0.2–400 μeV

Signal: For a trial parameter set, S_γ ~0.51 μJy.

Sensitivity: $S_{\rm min} \sim 0.48 \mu Jy$ for the SKA1

$S_{min} \sim 0.016 \mu Jy$ for SKA2 with 100 hours observation time.

SKA-like experiment can probe the axion DM and the axion mass which corresponds to peak frequency.

Working in progress on more delicate study.

New approach to explore axion DM

FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001, arXiv:1803.08230, Cited by 104 times

- Promising approaches at SKA&FAST, more and more nice works
- more details see the timely new review papers

✓ Physics Briefing Book :
Input for the European Strategy for Particle Physics Update 2020, [arXiv:1910.11775]

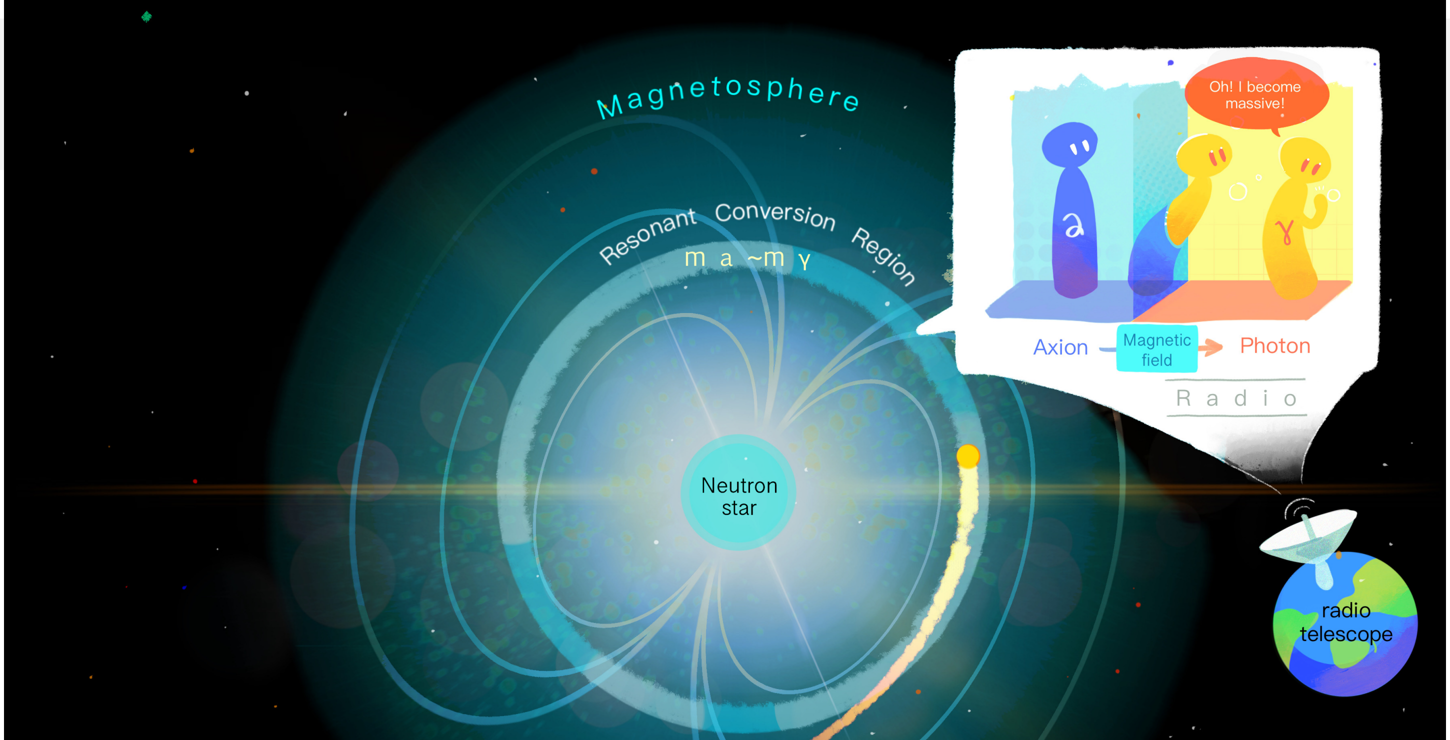
✓ 2021 white paper by EuCAPT [arXiv:2110.10074]

✓ Pierre Sikivie, Rev.Mod.Phys.93(2021)1,015004

✓ 2022 Snowmass papers: [arXiv:2203.06380, arXiv: 2203.07984]

✓ Phys. Rept. 1052(2024)1-48

✓ Science Advances Volume 8, Issue 8



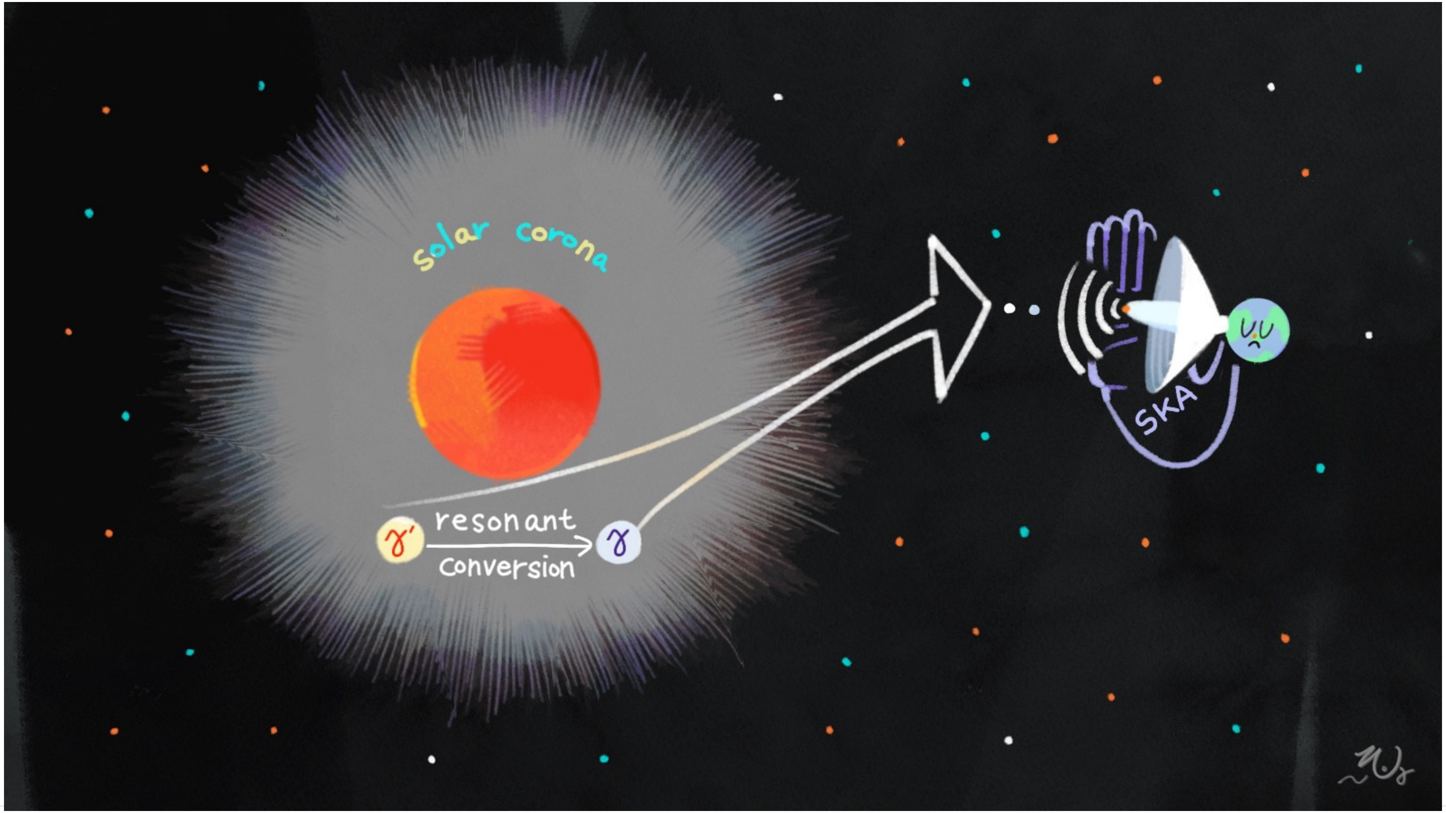
Generalize to axion star

Axions could condense to axion star and resonantly convert to FRBs.

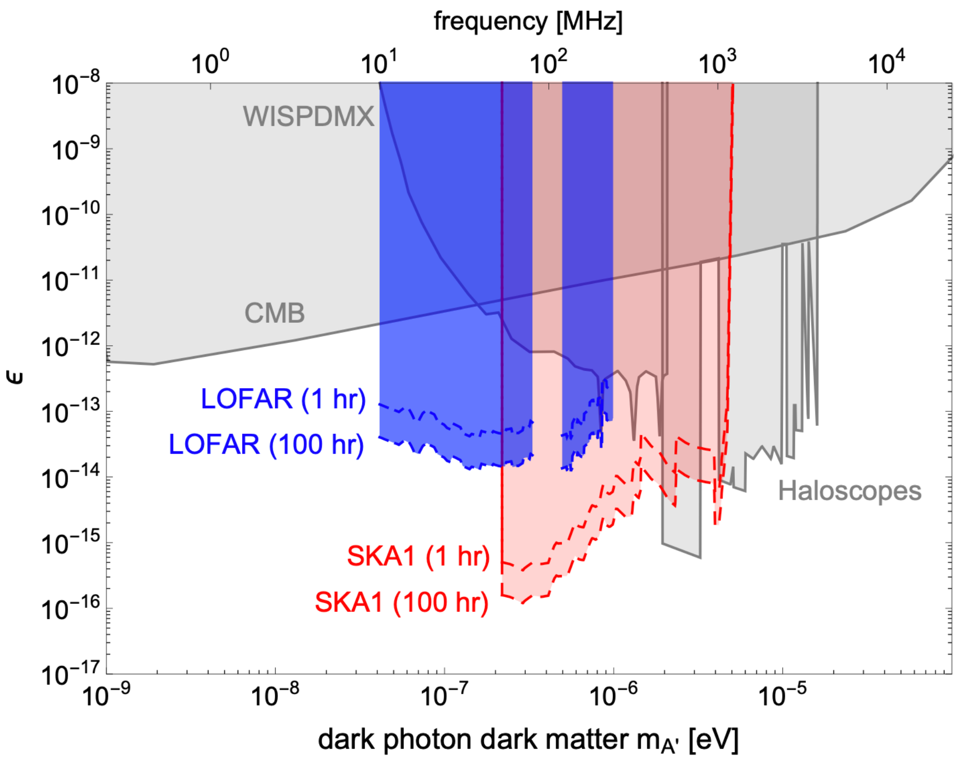
James Buckley, Bhupal Dev, Francesc Ferrer, FPH, *Phys.Rev.D* 103 (2021) 4, 043015

Generalize to dark photon DM case

Haipeng An, FPH, Jia Liu, Wei Xue, Phy. Rev. Lett.126, 181102 (2021)



Generalize to dark photon DM case



Haipeng An, FPH, Jia Liu, Wei Xue, Phy. Rev. Lett.126, 181102 (2021)

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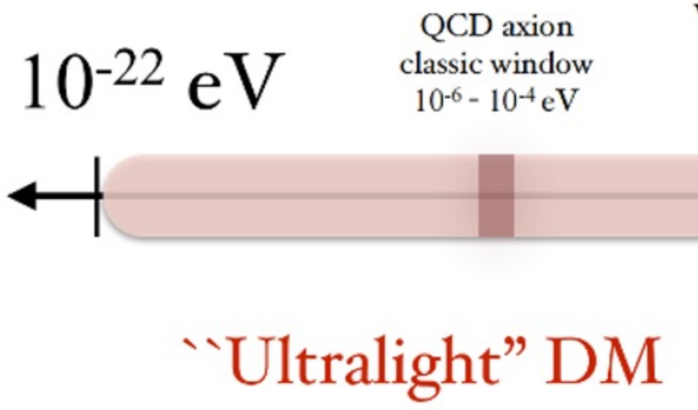
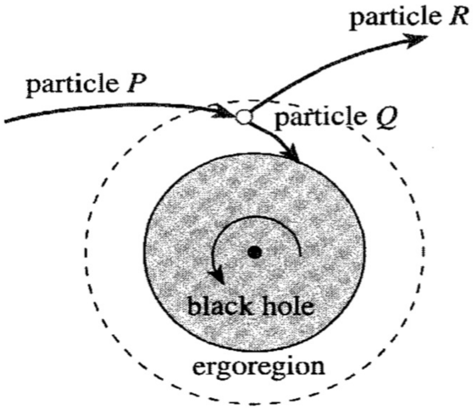


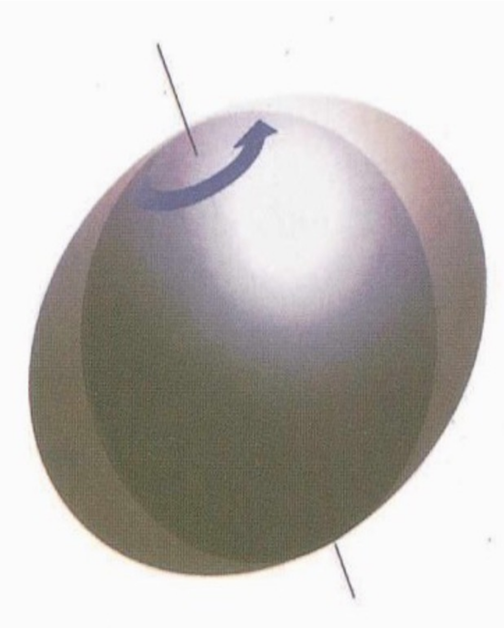
What is superradiance?

When Klein (-Gordon) meets Kerr——superradiance



$$\Delta \frac{d}{dr}\left(\Delta \frac{dR}{dr}\right) + \left[\omega^2\left(r^2+a^2\right)^2 - 4aMrm\omega + a^2m^2 - \Delta\left(m_a^2 r^2 + a^2\omega^2 + \lambda\right)\right] R = 0$$

Penrose '69 '71
Zel'dovich '72
Starobinsky '73



S. Hawking

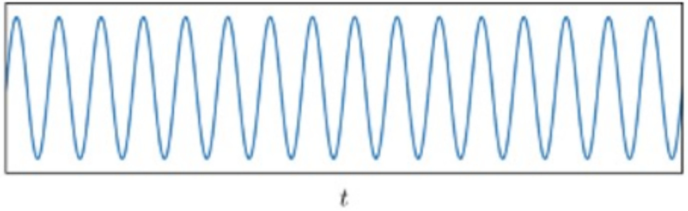
Exponential growth solution of Klein-Gordon equation due to the boundary condition at the horizon of Kerr BH. Ultralight axion can form axion cloud around rotating BH， Gravitational atom (GA).

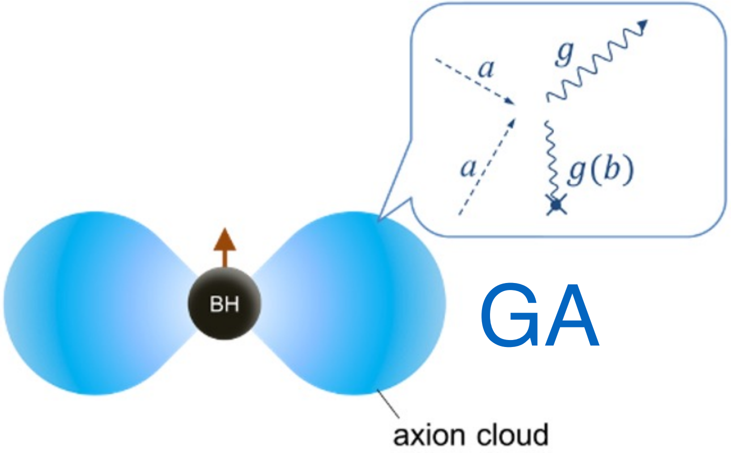
GW of ultralight DM from black hole

Axions can annihilate to GW

A. Arvanitaki and S. Dubovsky, Phys. Rev. D 83, 044026 (2011)
R. Brito, V. Cardoso and P. Pani, Class. Quant. Grav. 32, no.13, 134001 (2015)
H. Yoshino and H. Kodama, PTEP 2014, 043E02 (2014)

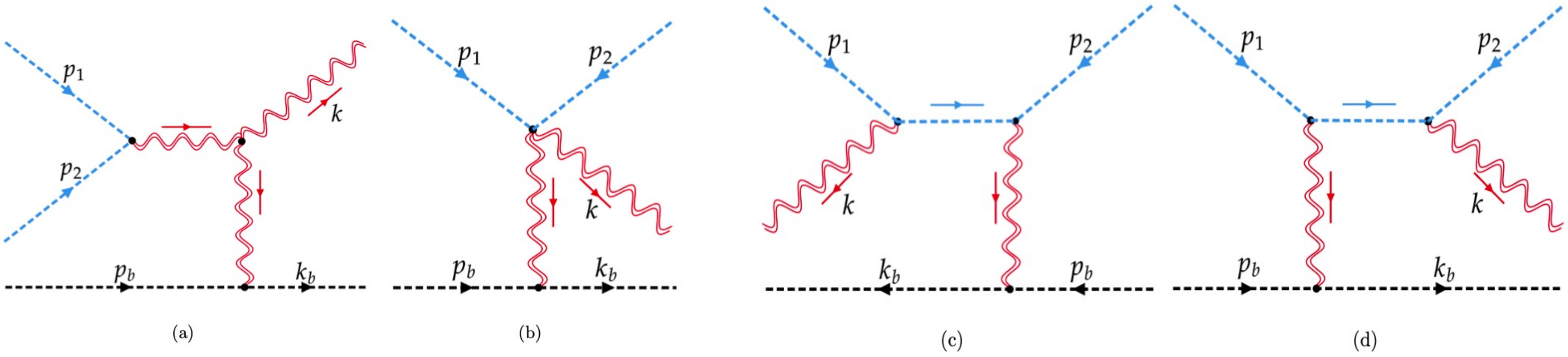
Jing Yang, **FPH**, Phys.Rev.D 108 (2023) 10, 103002



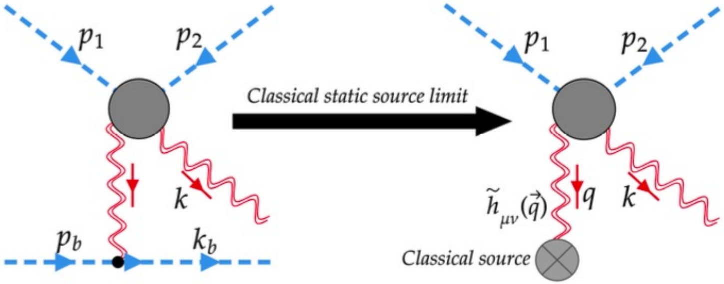


GA

Microscopic physics

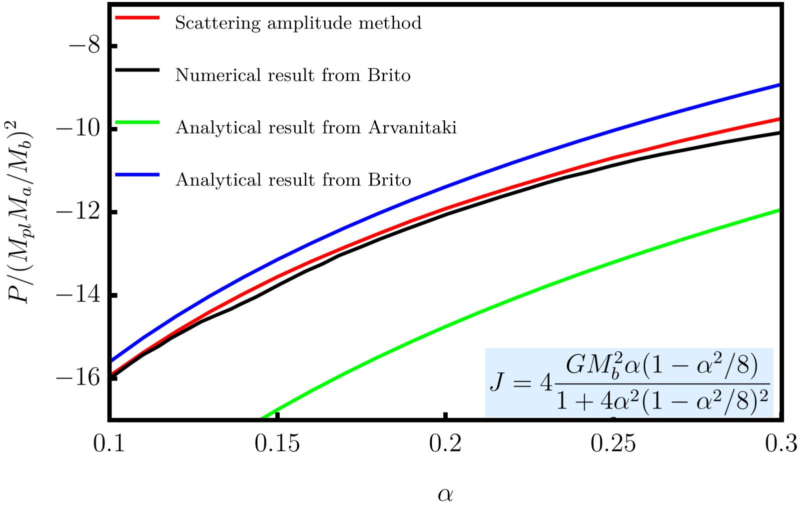


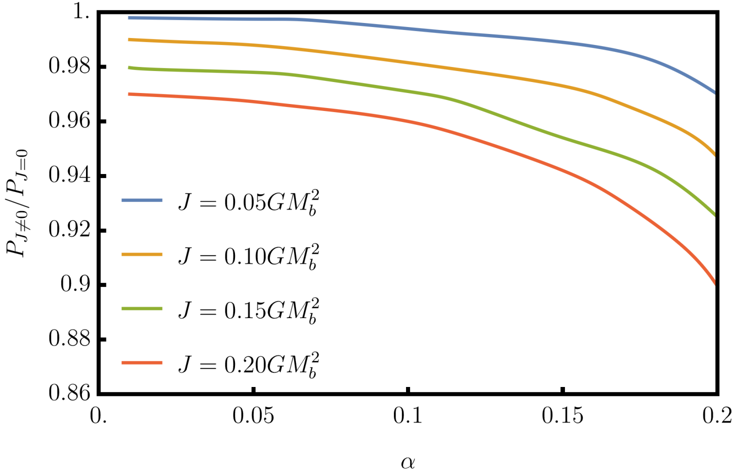
$$M(\boldsymbol{p_b}, \boldsymbol{p_1}, \boldsymbol{p_2} \to \boldsymbol{k}, \boldsymbol{k_b})$$



Jing Yang, FPH,
Phys.Rev.D 108 (2023) 10, 103002

GW radiation from axion annihilation





Jing Yang, FPH,
Phys.Rev.D 108 (2023) 10, 103002

$\alpha = GM_b m_a \quad M_b = 100M_{sun} \quad M_a = M_{sun}$

- ✓ monochromatic GW signal $\omega_{\rm ann} \sim 2\ m_a$
- ✓ gradually depletion of axion cloud (DC) and reduce GA mass

GW radiation from axion annihilation

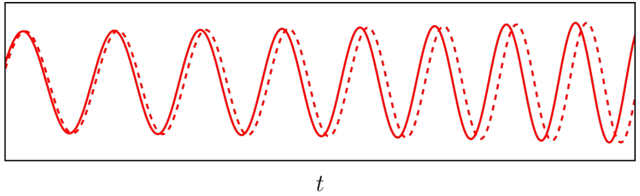
- ✓ Simple and straightforward.
- ✓ Easy to include Kerr metric effects.
- ✓ Microscopic physics is intuitive.
- ✓ It is clearly and simple to demonstrate the analytic approximation formulae.

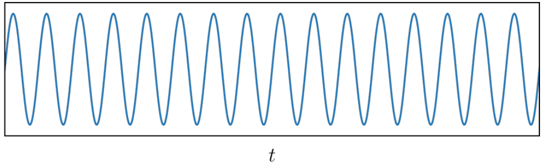
$$
\begin{aligned}
P = & \frac{(M_a/\mathrm{GeV})^2\alpha^{14}}{(M_b/\mathrm{GeV})^6(2+\alpha^2)^{11}(4+\alpha^2)^4}\Big[(M_b/\mathrm{GeV})^4(9.671\times 10^{41}+5.577\times 10^{42}\alpha^2 \\
+ & \ 1.474\times 10^{43}\alpha^4+2.361\times 10^{43}\alpha^6)+J(M_b/\mathrm{GeV})^2\alpha(-3.839\times 10^{80} \\
- & \ -2.111\times 10^{81}\alpha^2-5.329\times 10^{81}\alpha^4-8.165\times 10^{81}\alpha^8)+J^2\alpha^2(3.809\times 10^{118} \\
+ & \ 2.184\times 10^{119}\alpha^2+5.799\times 10^{119}\alpha^4+9.450\times 10^{119}\alpha^6)\Big]\ \mathrm{GeV}^2.
\end{aligned}
$$

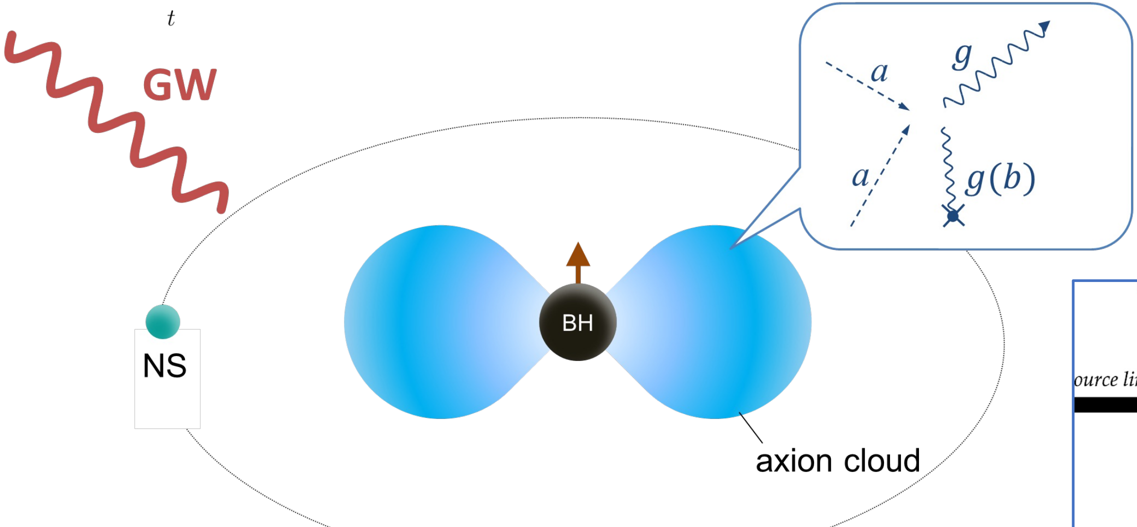
Important for the GW and axion search. More precise calculations and more broad applications are working in progress.

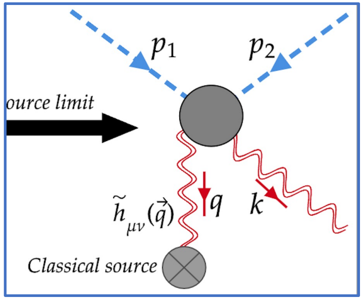
Jing Yang, FPH,
Phys.Rev.D 108 (2023) 10, 103002

Imprints of axions on GW









Ning Xie, FPH, SCPMA Vol.66, No.1(2024)

Imprints of axions on GW

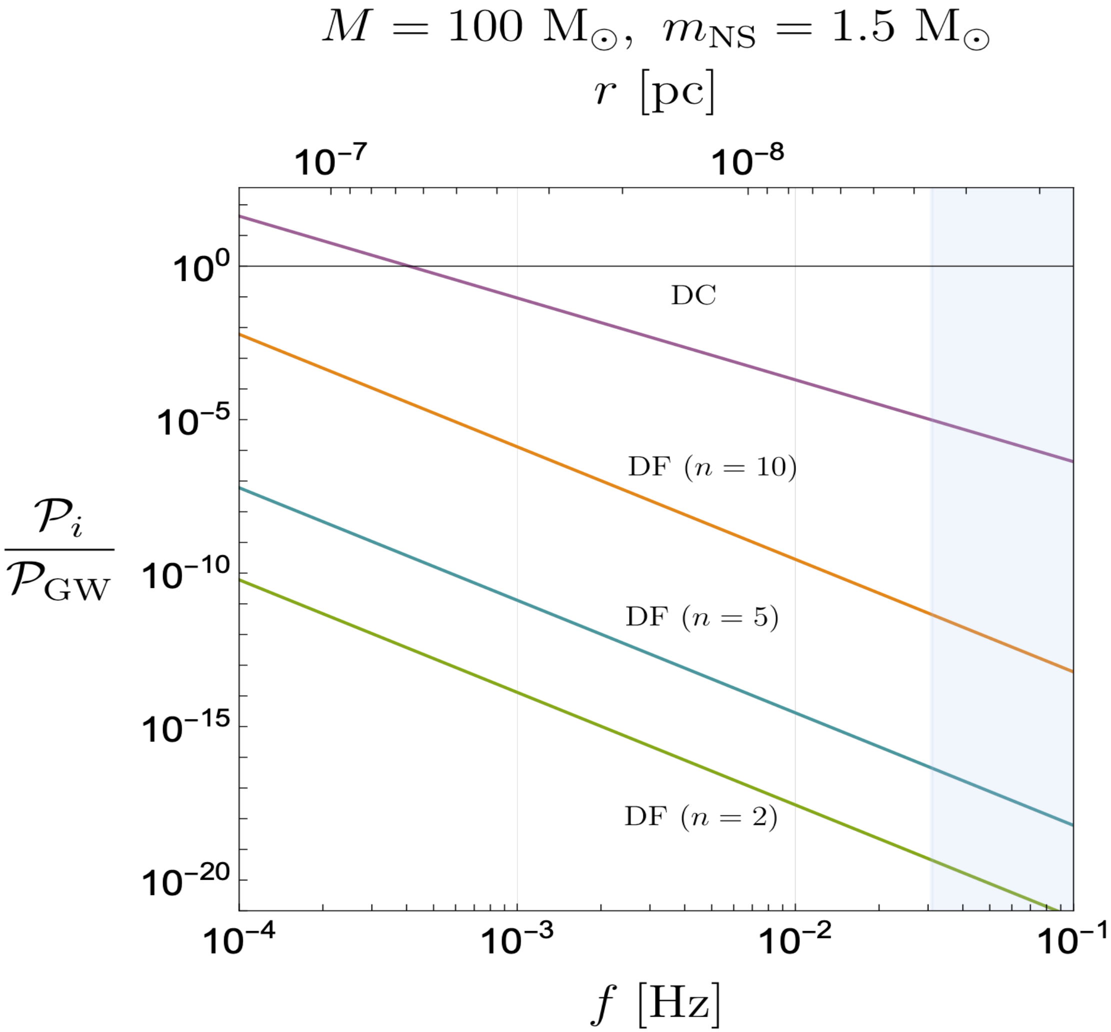
Without ultralight axions $-\frac{\mathrm{d}E_0}{\mathrm{d}t} = \mathcal{P}_{\mathrm{GW}}$ $\mathcal{P}_{\mathrm{GW}} = \frac{32}{5}\mu^2 r^4 \omega^6$

With ultralight axions

$$-\frac{dE}{dt} = (\mathcal{P}_{\mathrm{GW}} + \mathcal{P}_{\mathrm{DC}} + \mathcal{P}_{\mathrm{DF}} + \mathcal{P}_{\mathrm{DR}})$$

dynamical friction (DF), depletion of axion cloud (DC), dipole radiation(DR)

Ning Xie, FPH, SCPMA Vol.66, No.1(2024)



$M = 100\ \mathrm{M}_\odot,\ m_{\mathrm{NS}} = 1.5\ \mathrm{M}_\odot$
r [pc]
10^{-7}
10^{-8}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
$\frac{\mathcal{P}_i}{\mathcal{P}_{\mathrm{GW}}}$
DC
DF ($n = 10$)
DF ($n = 5$)
DF ($n = 2$)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
f [Hz]

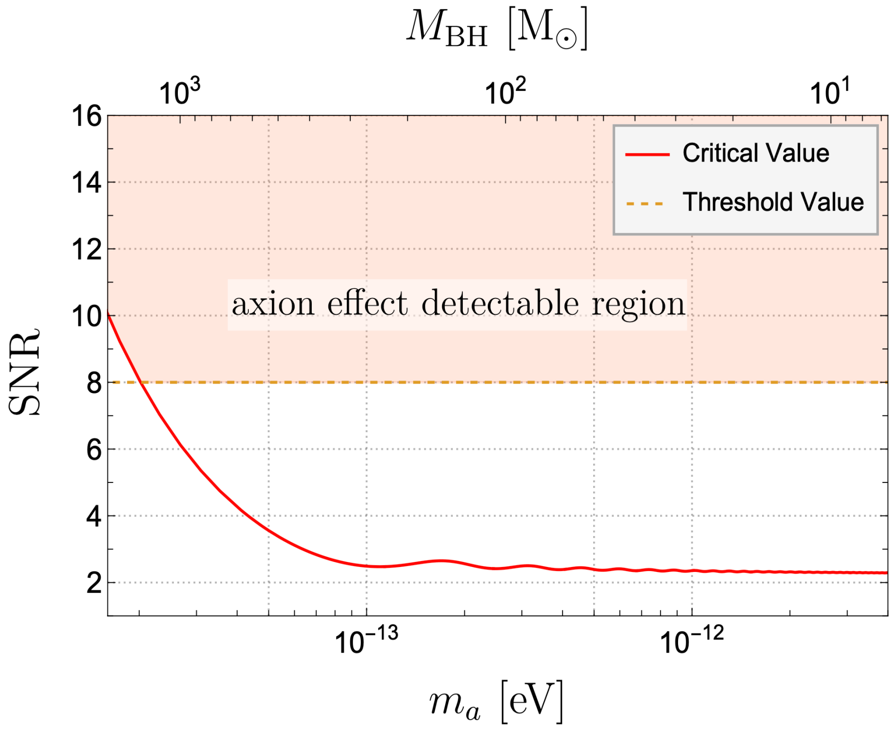
Imprints of axions on GW

$$\frac{\mathrm{d}r}{\mathrm{d}t} = \left(-\frac{M m_{\mathrm{NS}}}{2r^2}\right)^{-1} (\mathcal{P}_{\mathrm{GW}} + \mathcal{P}_{\mathrm{DC}} + \mathcal{P}_{\mathrm{DF}} + \mathcal{P}_{\mathrm{DR}})$$

$$\Delta\phi \sim 15\pi \left(\frac{m_a}{10^{-12}\ \mathrm{eV}}\right) \left(\frac{f_T}{10^{-2}\ \mathrm{Hz}}\right) \left(\frac{T}{5\ \mathrm{yrs}}\right)^2$$

Ning Xie, FPH, SCPMA Vol.66, No.1(2024)

Complementary search: GW+PTA



Axions modify the rate of binary period change

$$\Delta\dot{P} = \left|\dot{P} - \dot{P}_{\rm vac}\right| \approx 10^{-12}\ {\rm s/s}$$

Future Pulsar timing measurement precision, such as SKA

$$10^{-15}\ {\rm s/s}$$

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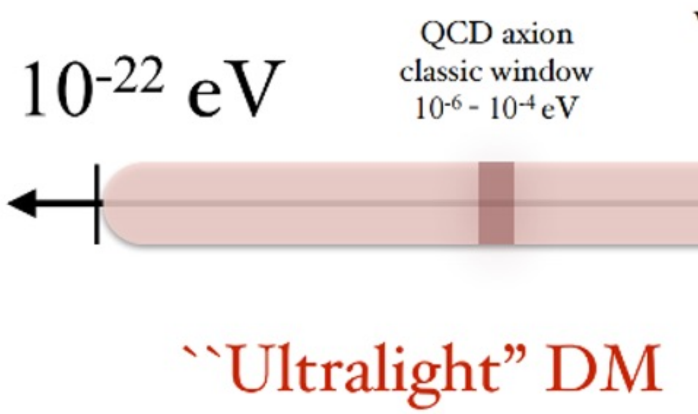
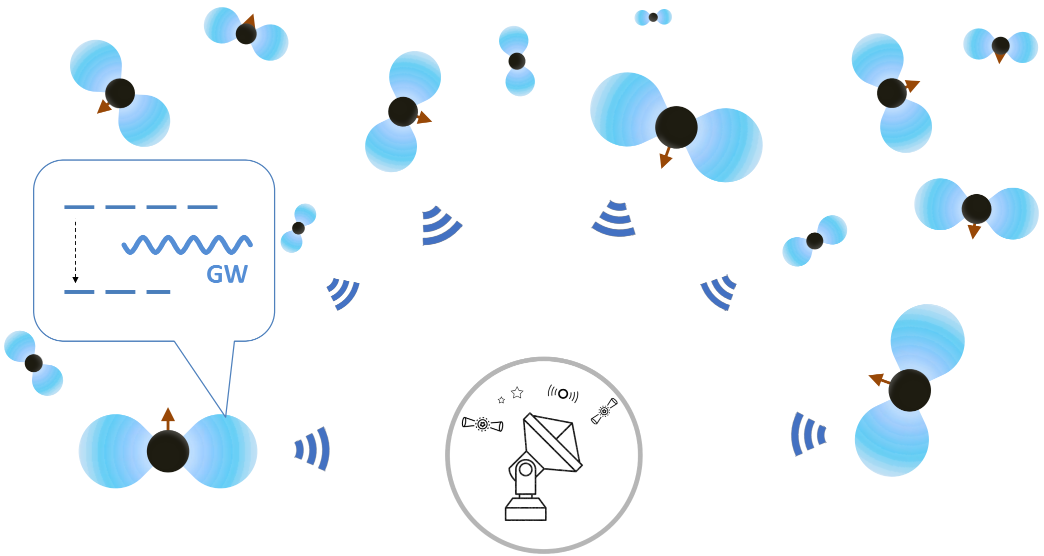


Fuzzy axion (DM) particles

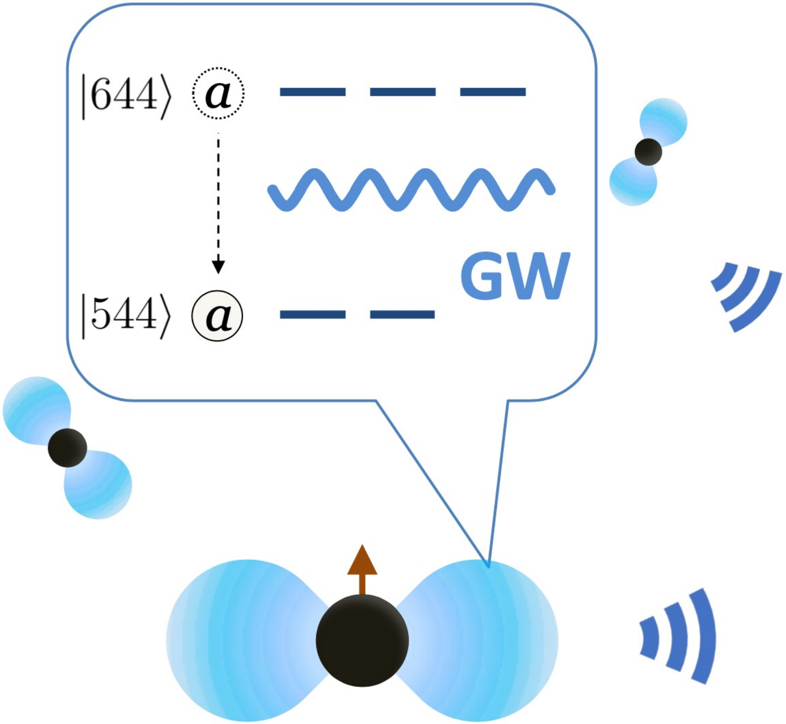


The cosmic populated SMBHs dressed with axion cloud as a natural source of nano-Hertz GW. The energy level transition process can radiate GWs continuously, which naturally fall in nano-Hertz frequency band.

Consequently, the PTA could detect this new source which provides a new approach to probe ultralight axion DM and isolated BHs.

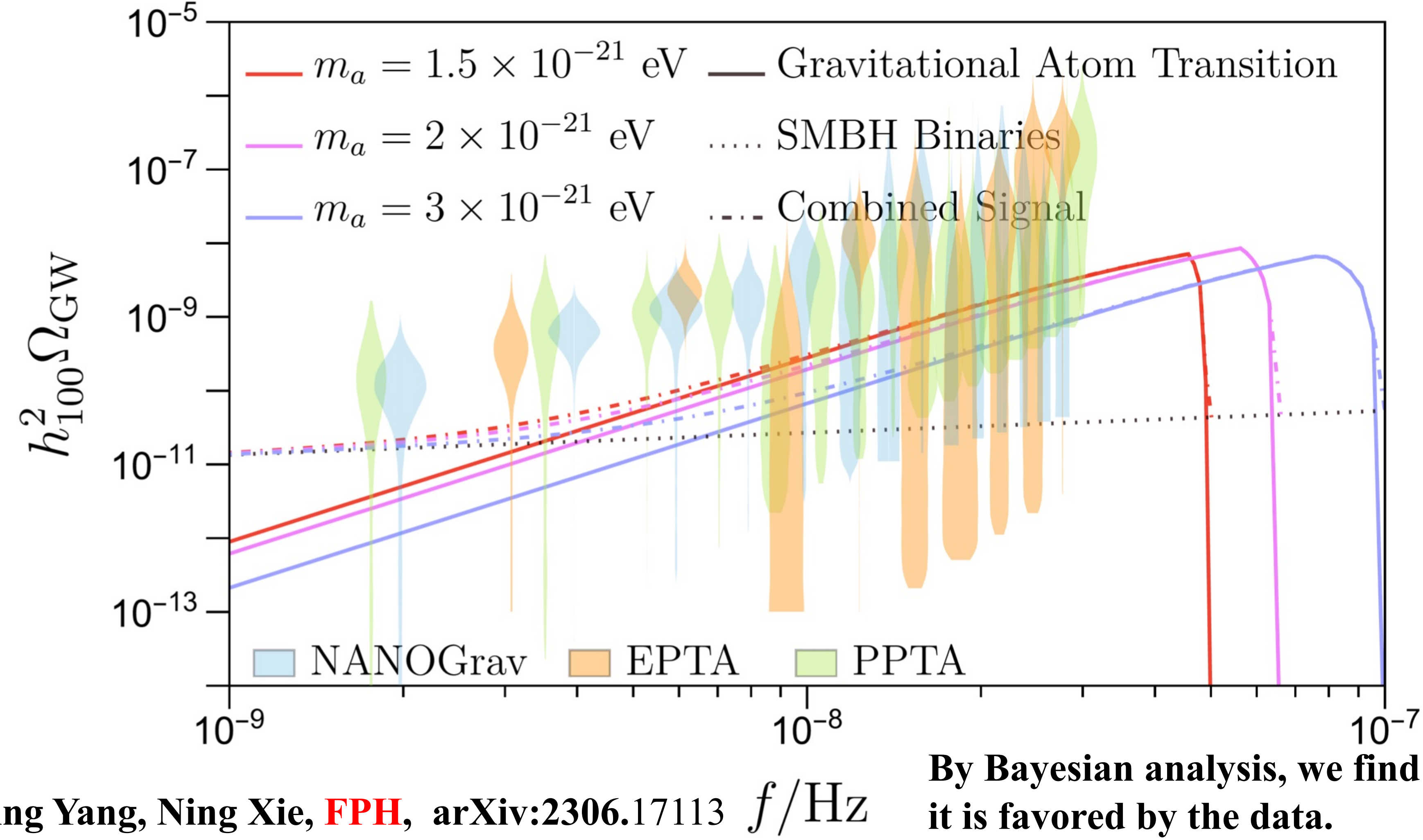
Jing Yang, Ning Xie,
FPH, arXiv:2306.17113

Fuzzy axion (DM) particles



$$\Delta\omega = \frac{11}{1800}\alpha^2 m_a$$

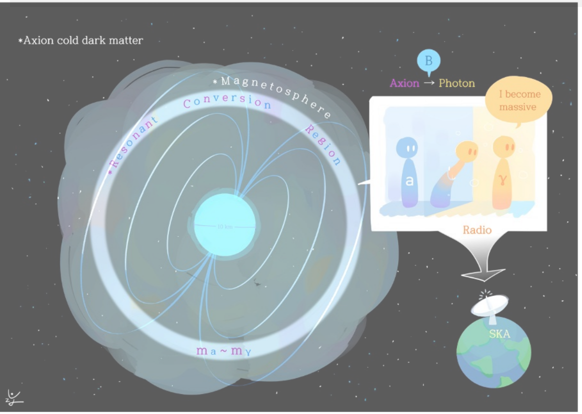
$$P = -\frac{dE}{dt} = \frac{dN_5(t)}{dt}\Delta\omega$$

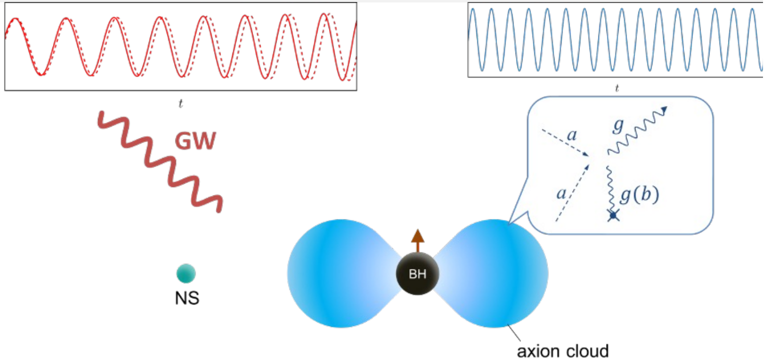


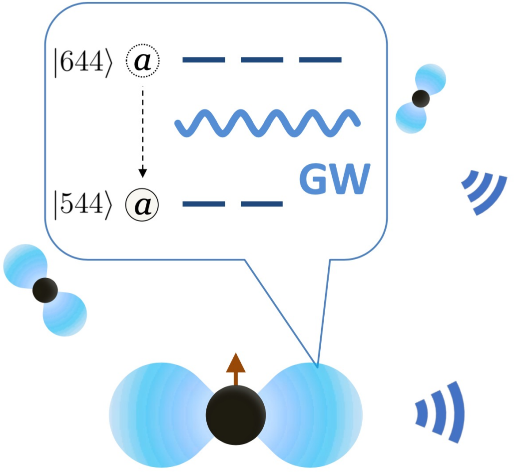
Jing Yang, Ning Xie, FPH, arXiv:2306.17113

By Bayesian analysis, we find it is favored by the data.

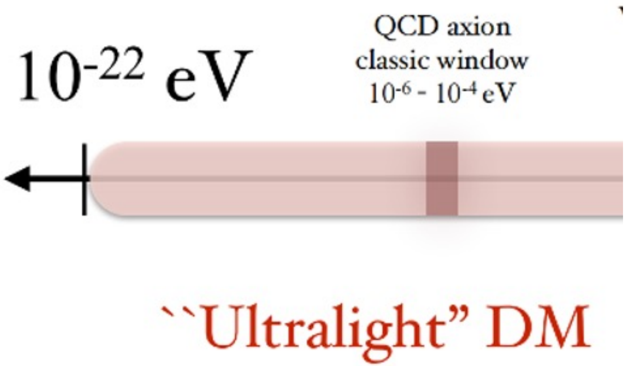
5. Summary and outlook







GW and radio telescopes might provide new approaches to explore ultralight DM with multi-messenger and multi-band.



Thanks!

Comments and collaborations are welcome!

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