Gravitational wave signals of ultralight axion dark matter

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

Ning Xie, FPH, arXiv:2207.11145 and work in progress
Jing Yang, FPH, arXiv:2306.12375

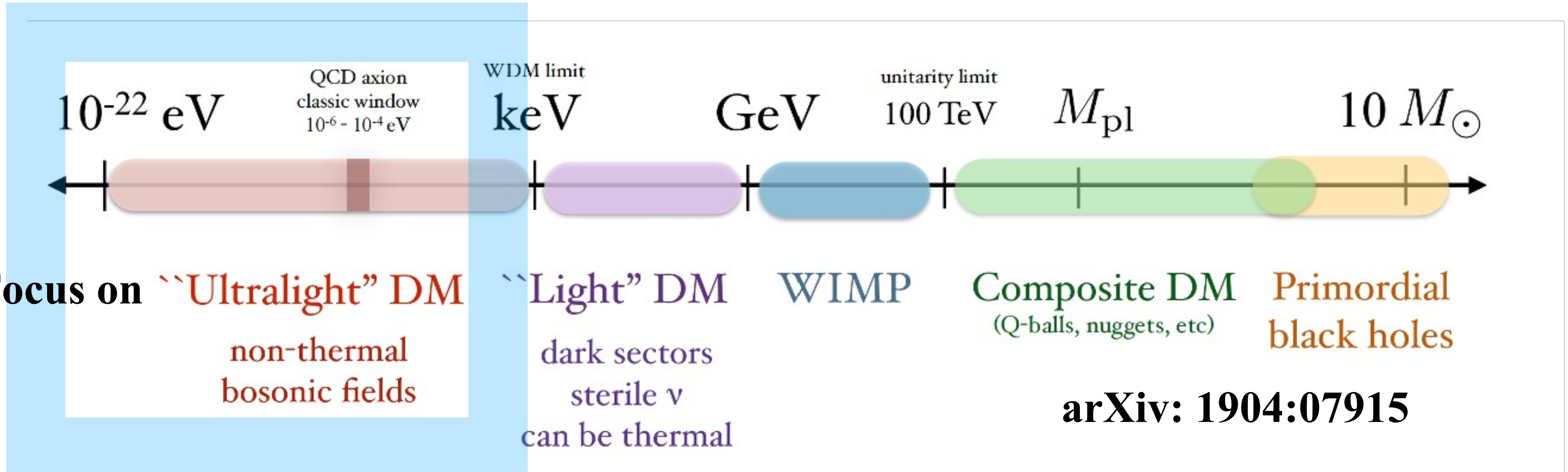
PASCOS2023@UCI, Irvine, USA, 2023.06.26

What is DM?

What is the microscopic nature of DM?

No expected signals at LHC and DM direct search.

Focus on



arXiv: 1904:07915

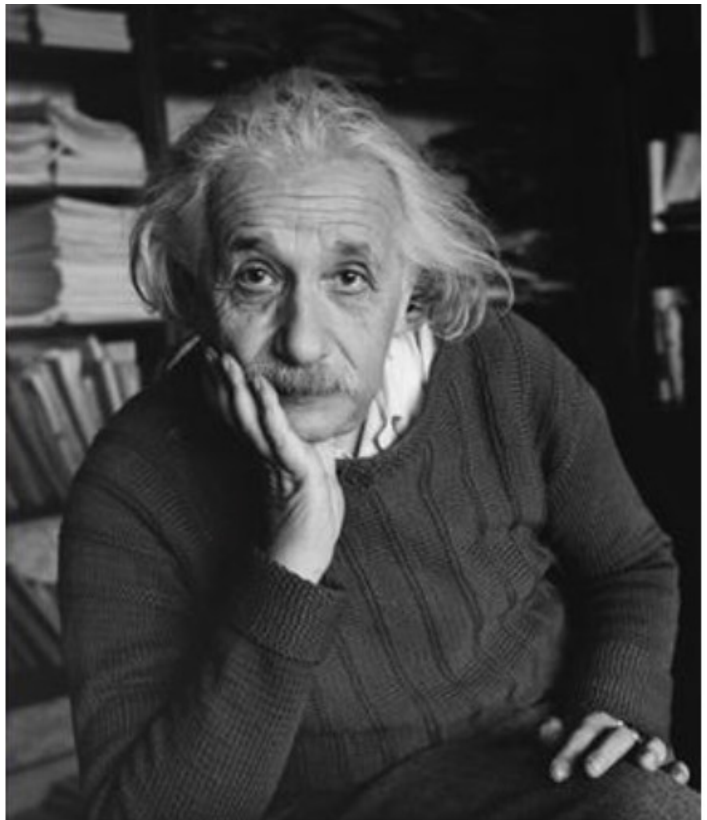
How to detect DM?

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

radio telescope (SKA/FAST…)

& GW detector (LISA/TianQin/Taiji…)

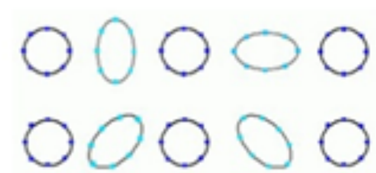
What is GW?

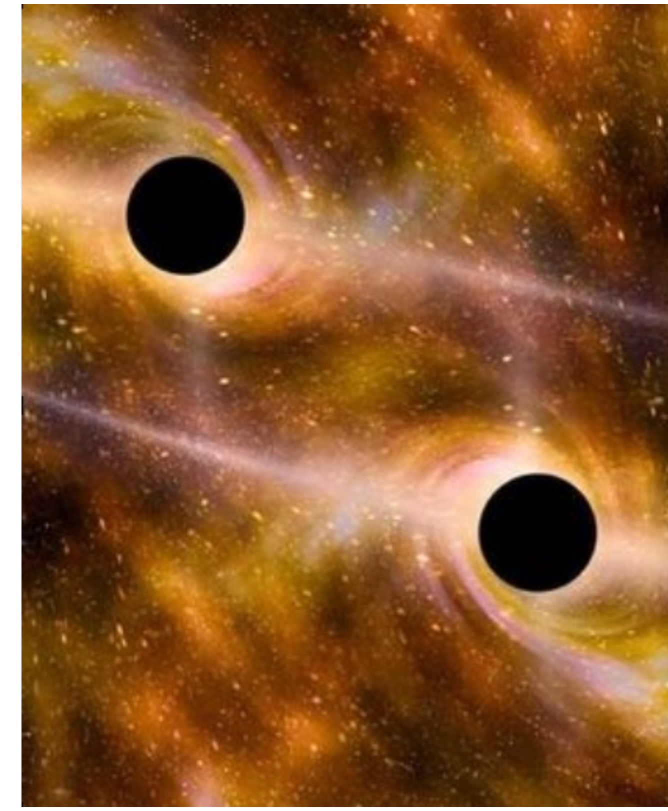


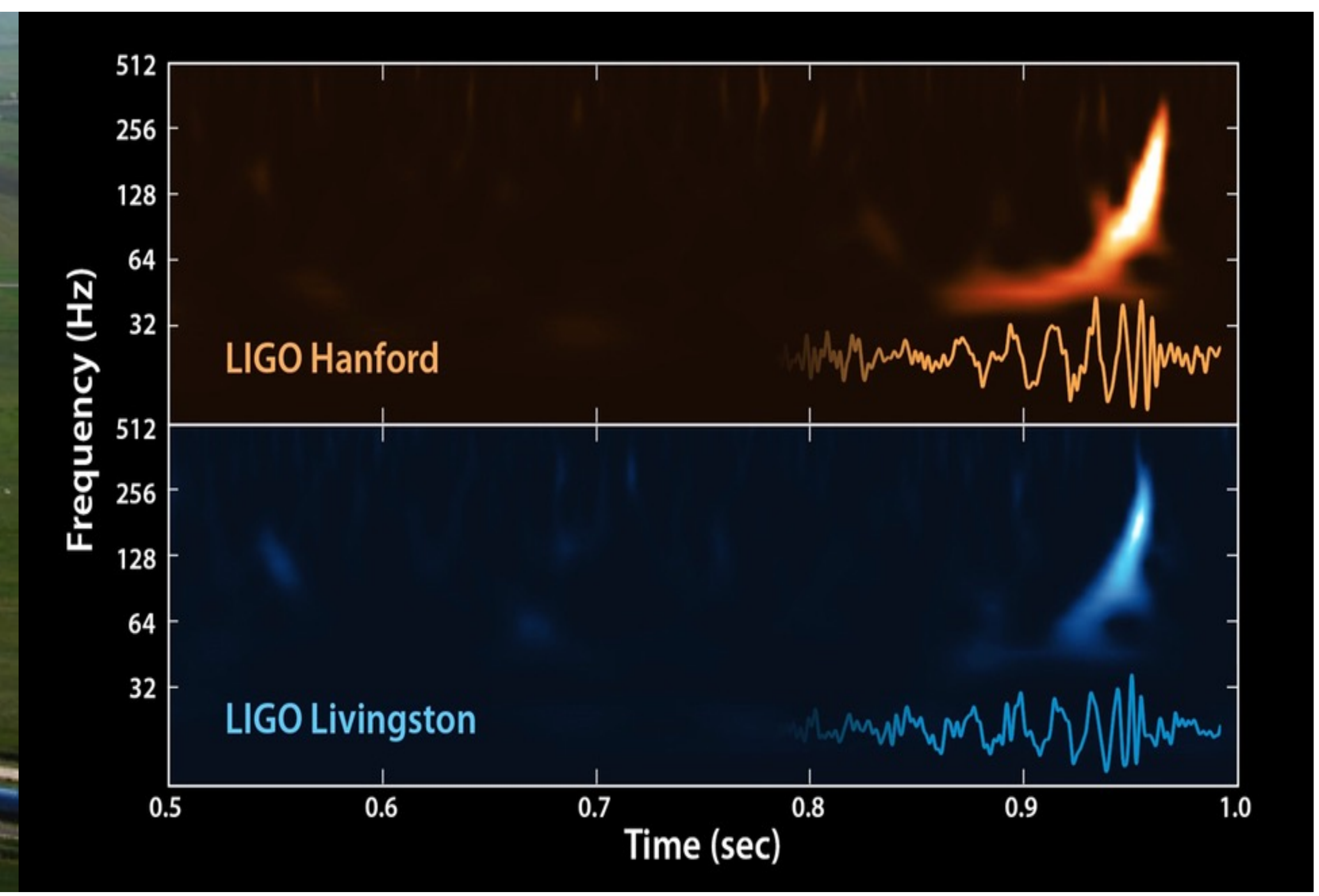
General relativity

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$h_{ij} \simeq \frac{2G}{c^4 r} \ddot{Q}_{ij}^{TT}(t - r/c)$$







The quadruple nature of GW !

EM wave radiation

$$\ddot{\boldsymbol{d}} = e\ddot{\boldsymbol{x}}$$

$$L_{\text{electric quadrupole}} = \frac{1}{20}\dddot{Q}^2 \equiv \frac{1}{20}\dddot{Q}_{jk}\dddot{Q}_{jk}$$

$$Q_{jk} \equiv \sum_A e_A\left(x_{Aj}x_{Ak} - \frac{1}{3}\delta_{jk}{r_A}^2\right)$$

GW radiation

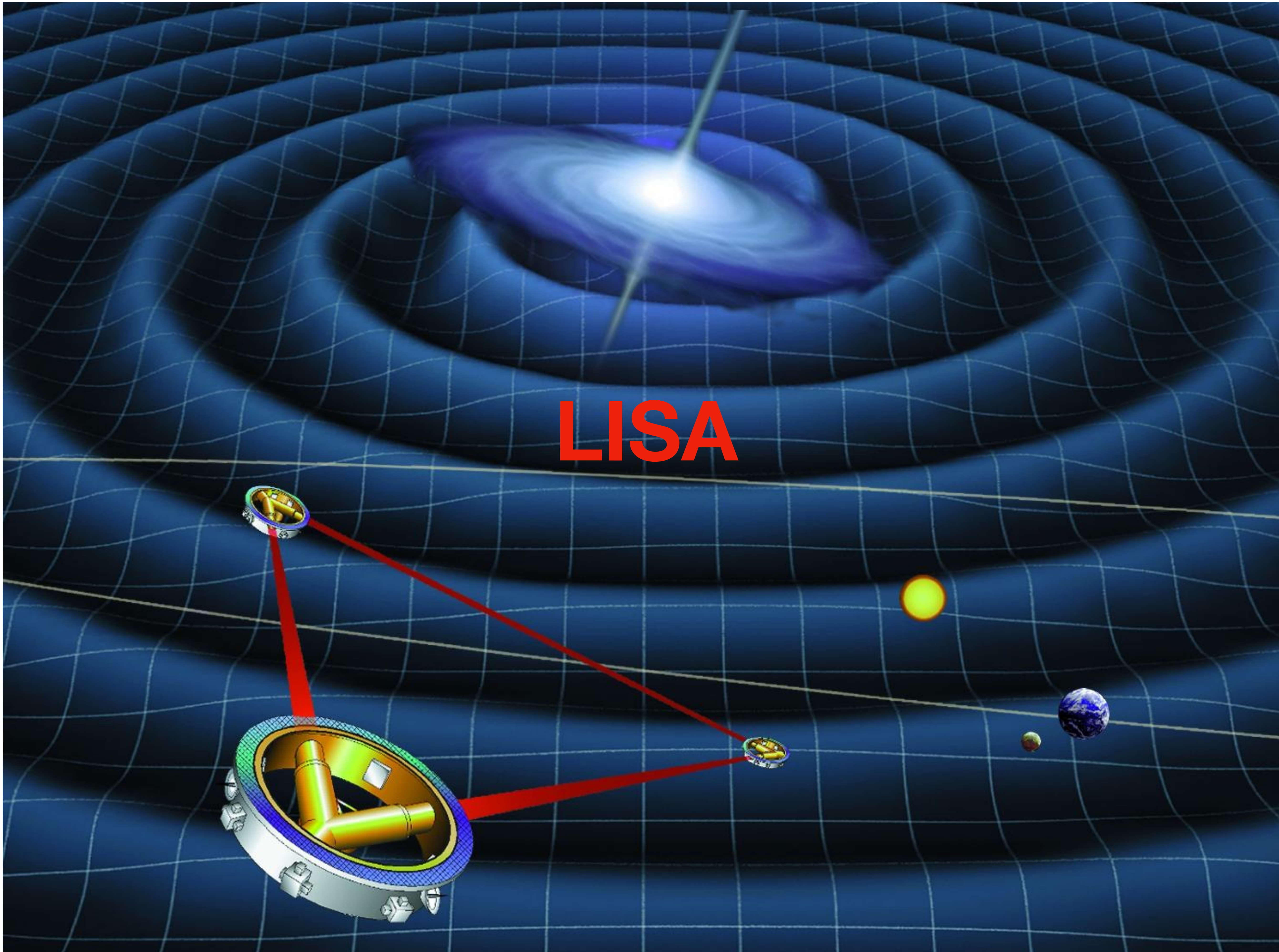
$$\ddot{\boldsymbol{d}} = \sum_{\text{particles } A} m_A\ddot{\boldsymbol{x}}_A = \dot{\boldsymbol{p}} = 0$$

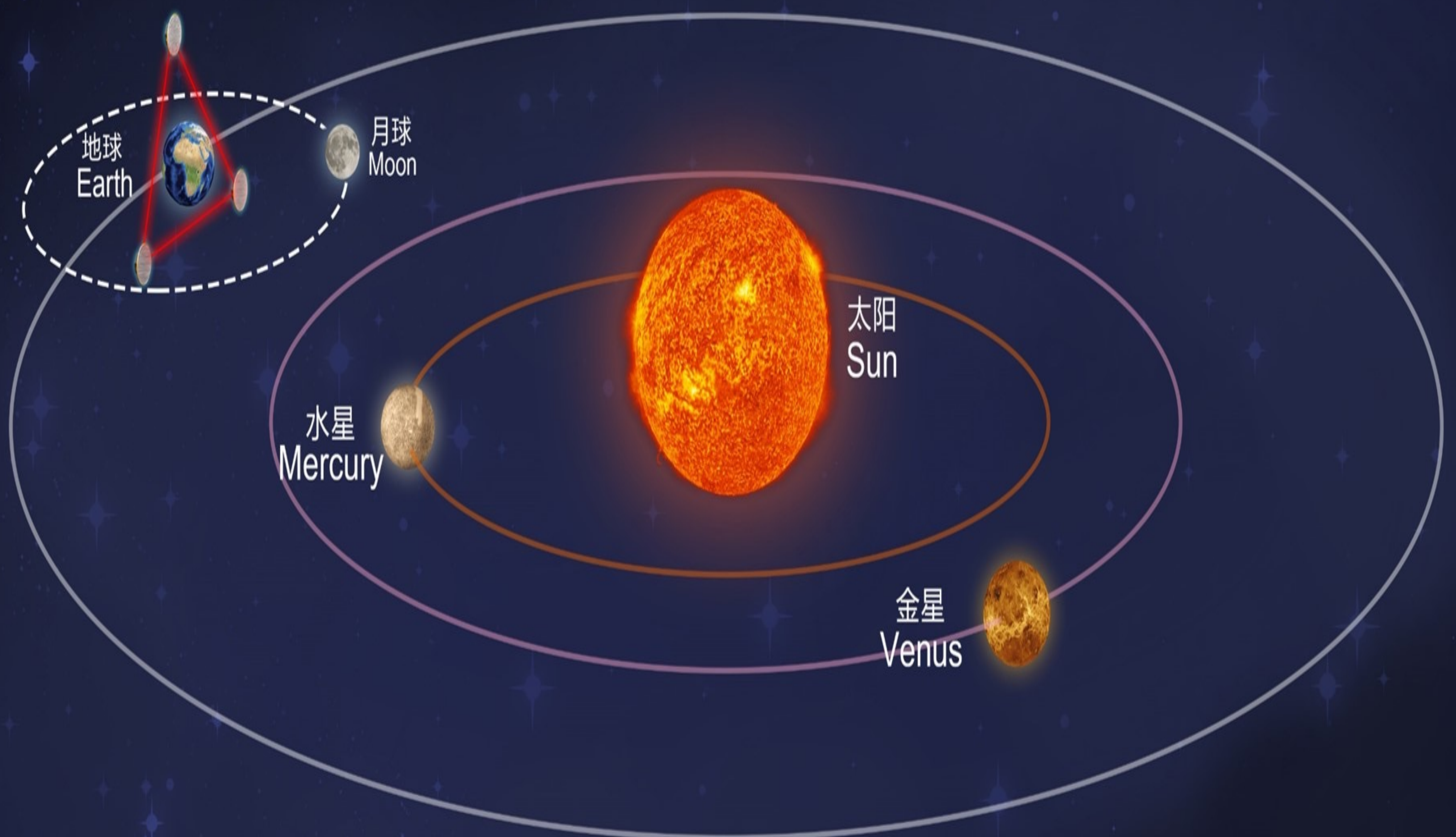
momentum conservation

$$L_{\text{mass quadrupole}} = \frac{1}{5}\langle\dddot{I\!\!\!-}^2\rangle \equiv \frac{1}{5}\langle\dddot{I\!\!\!-}_{jk}\dddot{I\!\!\!-}_{jk}\rangle$$

$$I\!\!\!-_{jk} \equiv \sum_A m_A\left(x_{Aj}x_{Ak} - \frac{1}{3}\delta_{jk}{r_A}^2\right)$$

credit: MTW


LISA



TianQin

Radio telescope and pulsar timing array

The Square Kilometre Array (SKA)

BigAnnouncement June 29th

NANOGrav, EPTAGW, InPTA, Parkes PTA, CPTA

High sensitivity sub μJy

credit: SKA website

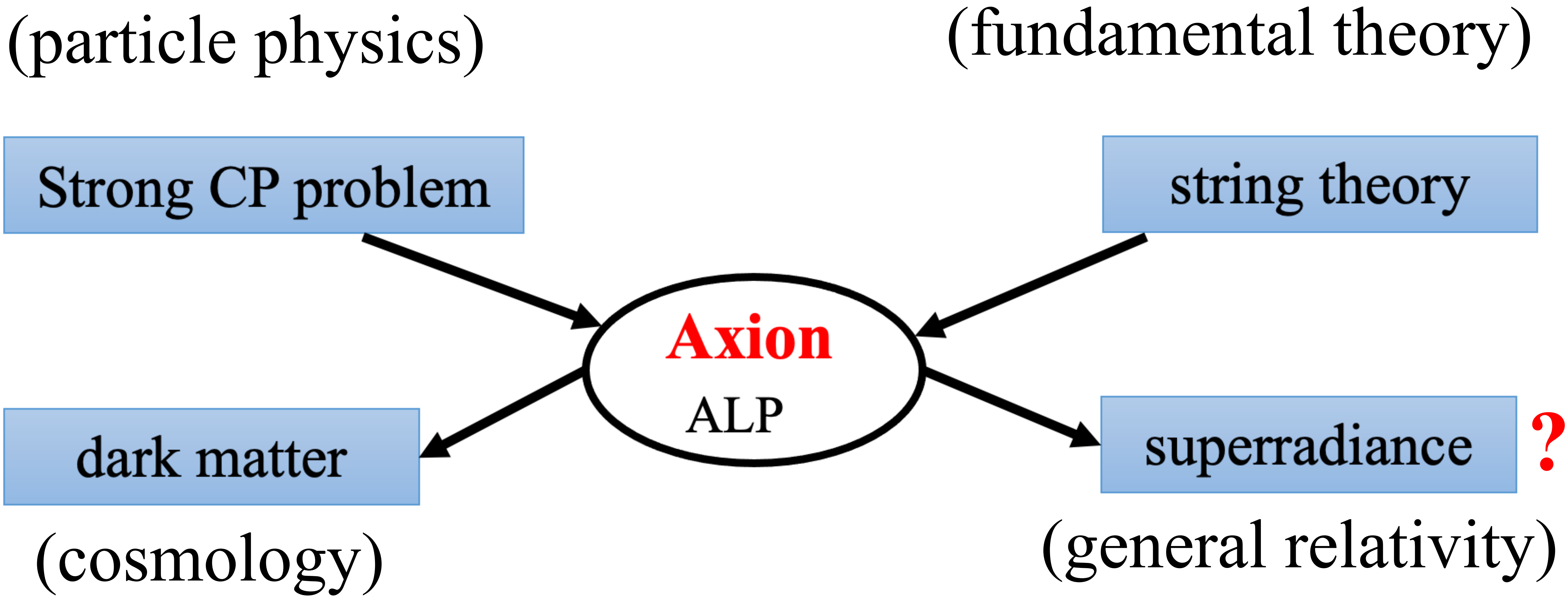
The Five-hundred-meter Aperture Spherical radio Telescope (FAST)

From 25 Sep. 2016

Credit:FAST website

Ultralight axion DM

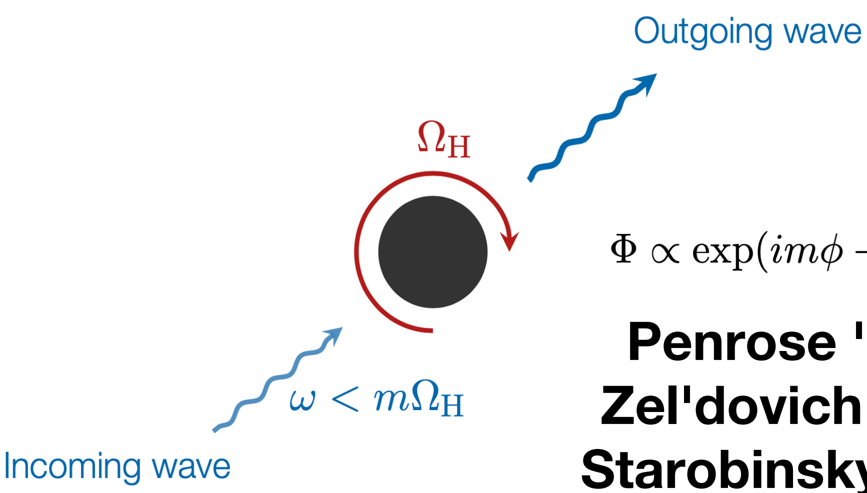
Ultralight axion is a promising DM candidate.



What is superradiance?

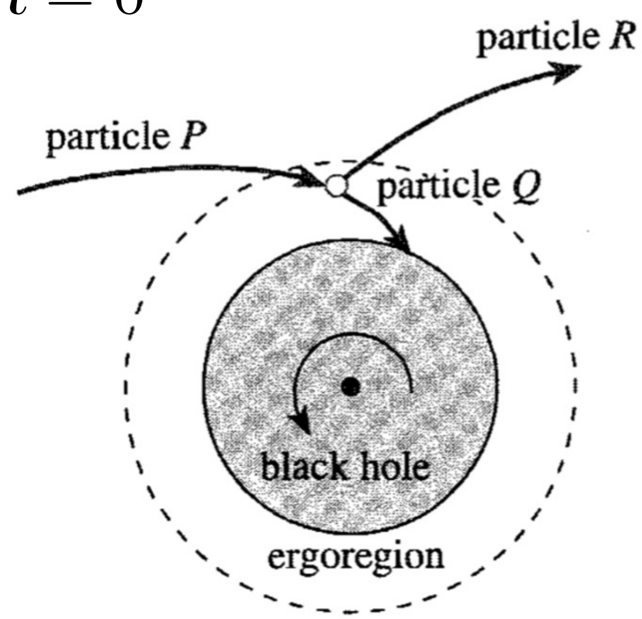
When Klein meets Kerr——superradiance

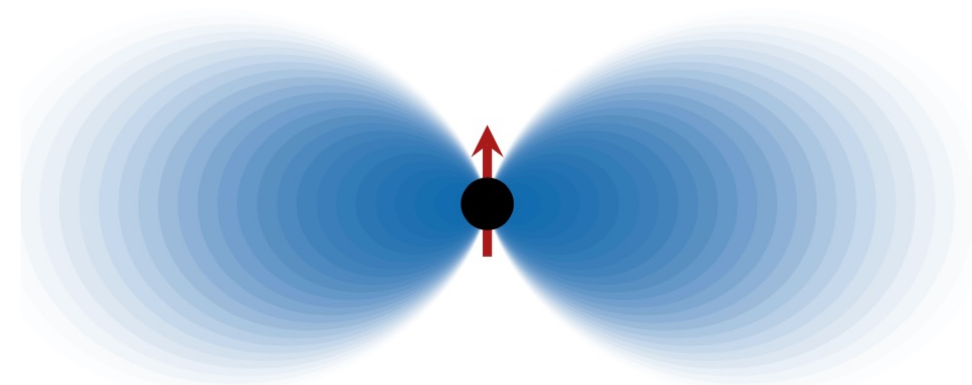
$$\Delta \frac{d}{dr}\left(\Delta \frac{dR}{dr}\right) + \left[\omega^2\left(r^2+a^2\right)^2 - 4aMrm\omega + a^2m^2 - \Delta\left(m_a^2 r^2 + a^2\omega^2 + \lambda\right)\right] R = 0$$



$\Phi \propto \exp(im\phi - i\omega t)$

Penrose '71
Zel'dovich '72
Starobinsky '73





Exponential growth solution of Klein-Gordon equation due to the boundary condition at the horizon of Kerr BH.

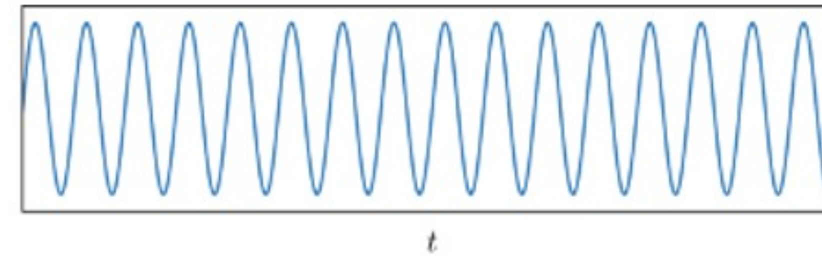
Ultralight axion can form axion cloud around rotating BH.

Resemble hydrogen atom, gravitational atom

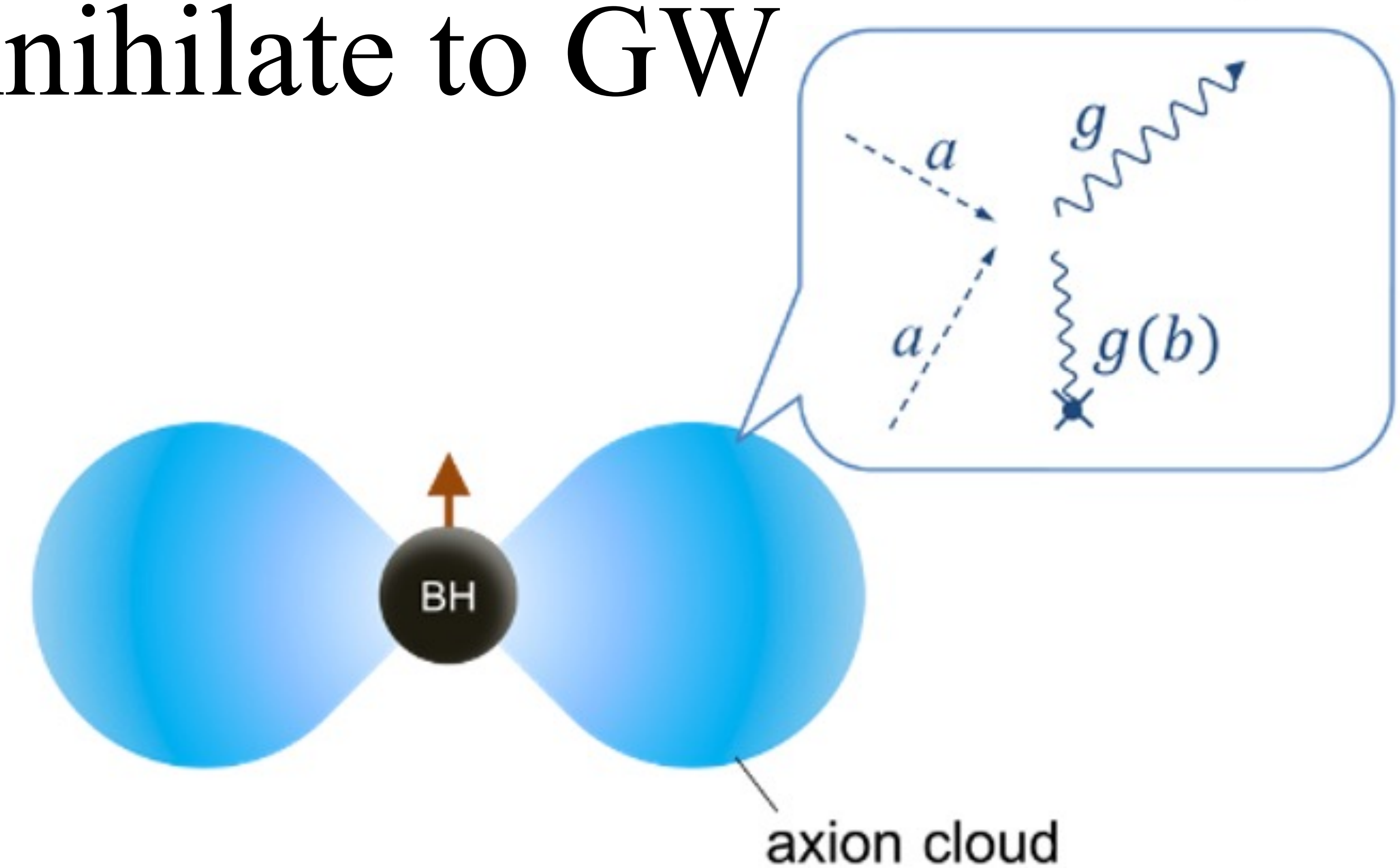
$$\alpha = M_{BH} m_a < 1$$

Credit: Baumann

GW of ultralight DM from black hole



Axions can annihilate to GW



gravitational atom

Jing Yang, **FPH**, arXiv:2306.12375

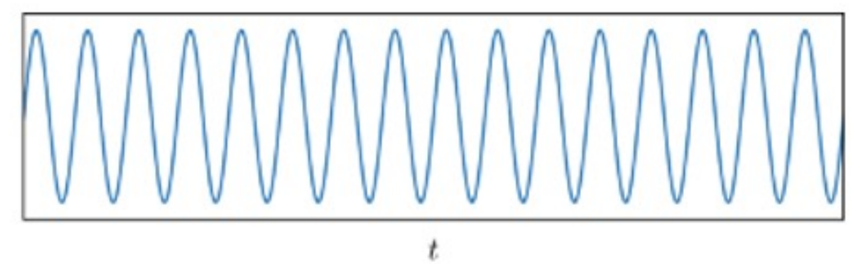
Ning Xie, **FPH**, arXiv:2207.11145 and work in progress

GW of ultralight DM from black hole

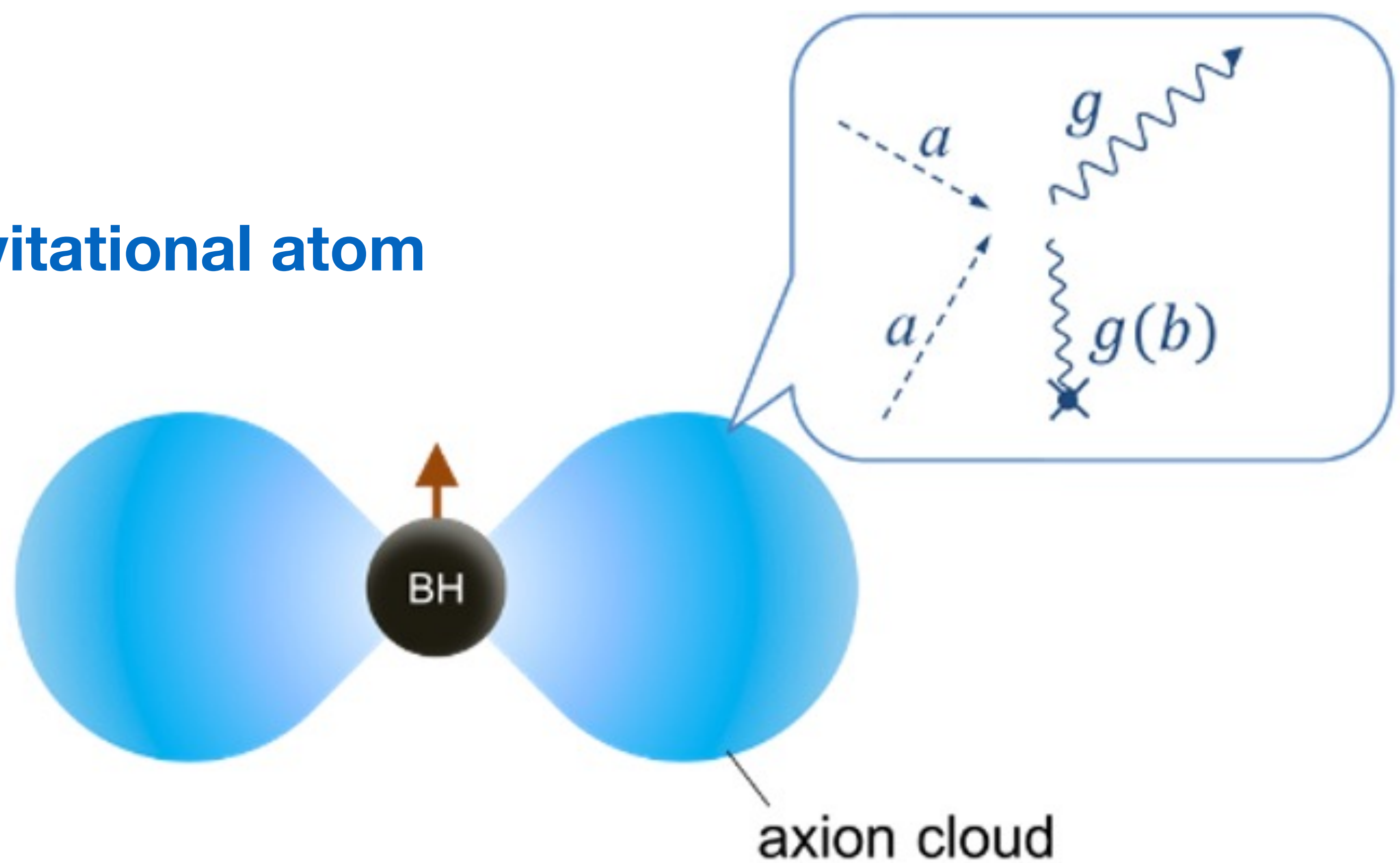
Axions can annihilate to GW

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)

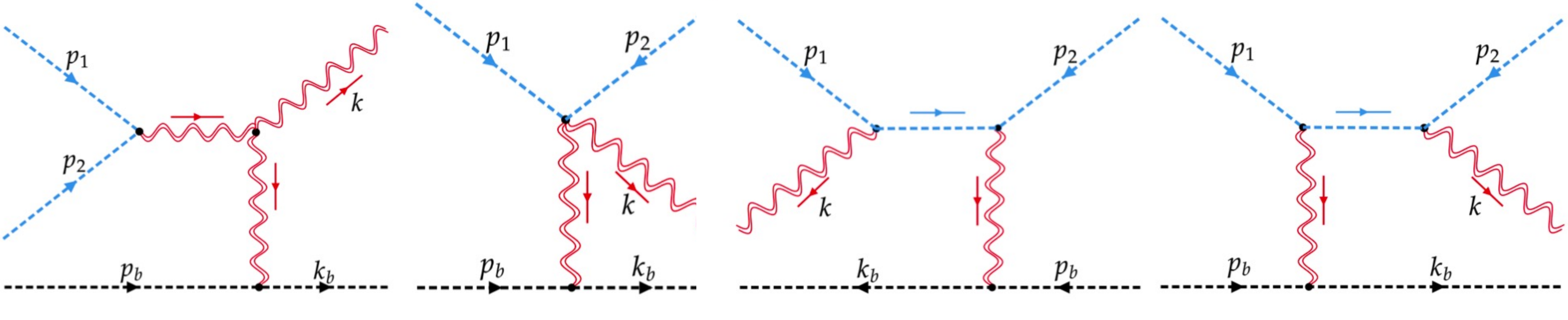
Jing Yang, **FPH**, arXiv:2306.12375



gravitational atom

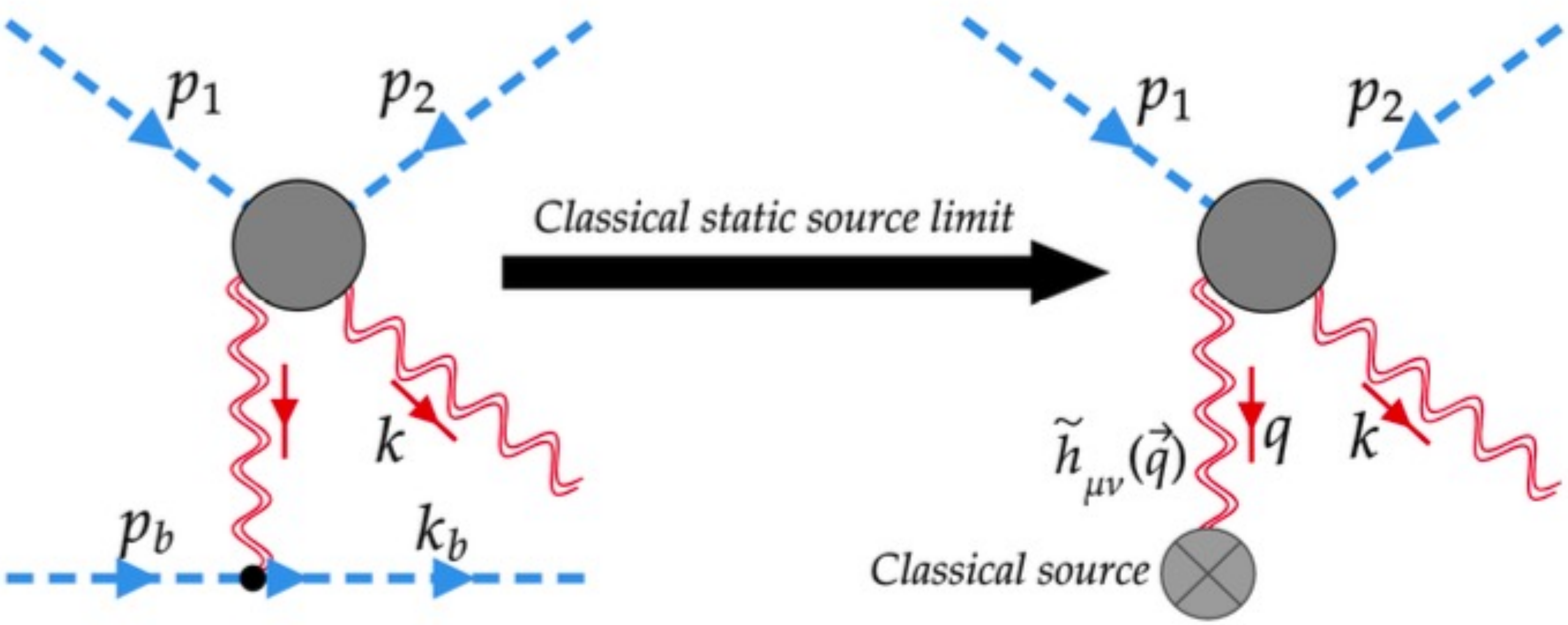


Microscopic physics



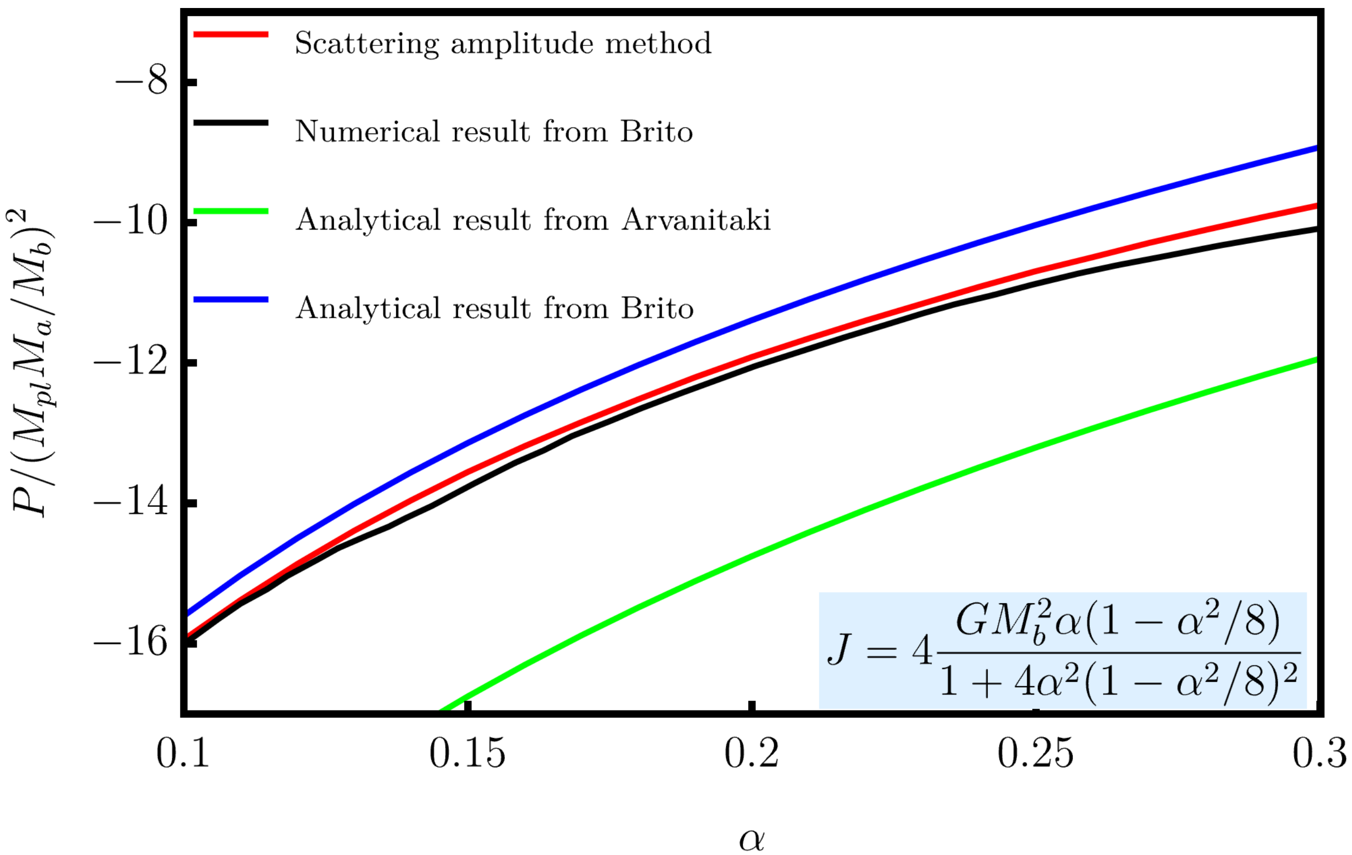
(a) (b) (c) (d)

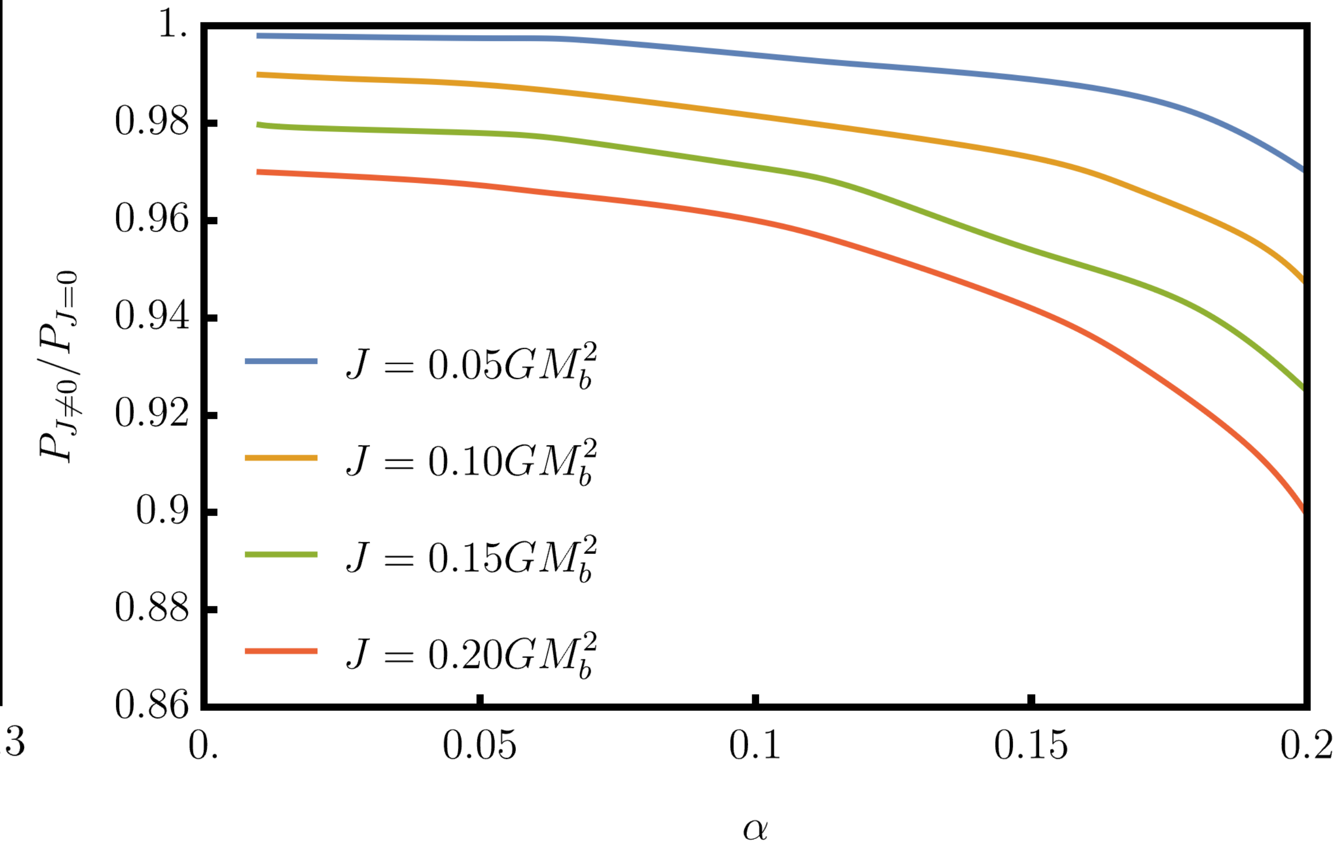
$$M(\boldsymbol{p_b}, \boldsymbol{p_1}, \boldsymbol{p_2} \to \boldsymbol{k}, \boldsymbol{k_b})$$



Jing Yang, **FPH**, arXiv:2306.12375

GW radiation power from axion annihilation



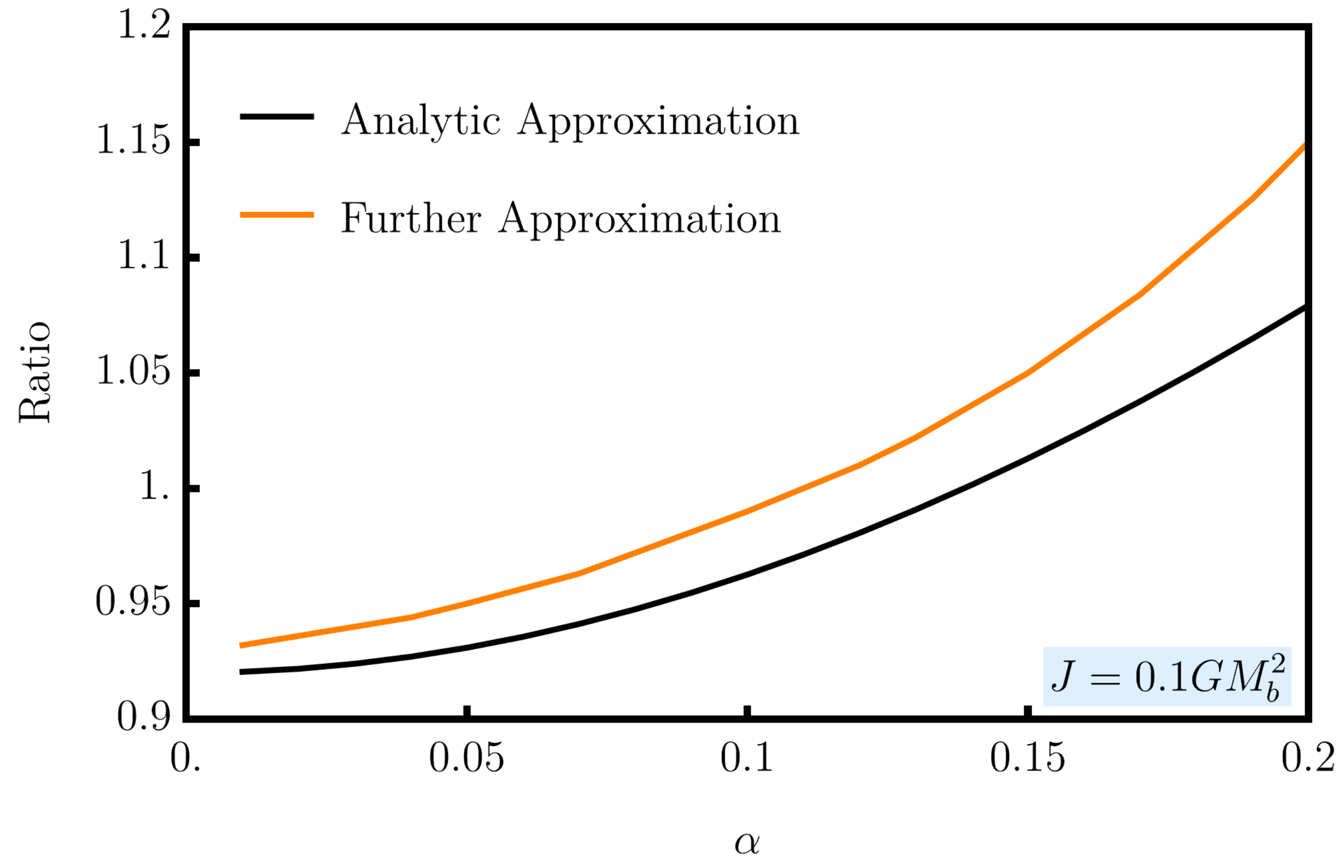


$\alpha = GM_b m_a \quad M_b = 100M_{sun} \quad M_a = M_{sun}$

Jing Yang, **FPH**, arXiv:2306.12375

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

GW radiation power from axion annihilation



Jing Yang, **FPH**, arXiv:2306.12375

$$P = \frac{(M_a/\mathrm{GeV})^2\alpha^{14}}{(M_b/\mathrm{GeV})^6(2+\alpha^2)^{11}(4+\alpha^2)^4}\Big[(M_b/\mathrm{GeV})^4(9.671\times10^{41}+5.577\times10^{42}\alpha^2$$
$$+\ 1.474\times10^{43}\alpha^4+2.361\times10^{43}\alpha^6)+J(M_b/\mathrm{GeV})^2\alpha(-3.839\times10^{80}$$
$$-\ -2.111\times10^{81}\alpha^2-5.329\times10^{81}\alpha^4-8.165\times10^{81}\alpha^8)+J^2\alpha^2(3.809\times10^{118}$$
$$+\ 2.184\times10^{119}\alpha^2+5.799\times10^{119}\alpha^4+9.450\times10^{119}\alpha^6)\Big]\ \mathrm{GeV}^2.$$

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

Advantage for scattering amplitude method

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

We have cross-checked numerical results from the traditional method which is important for the GW and axion search. More precise calculations and more broad applications are working in progress.

Jing Yang, **FPH**, arXiv:2306.12375

Multi-messenger from NS-BH binary

Imprints of ultralight axions on the GW of compact binary

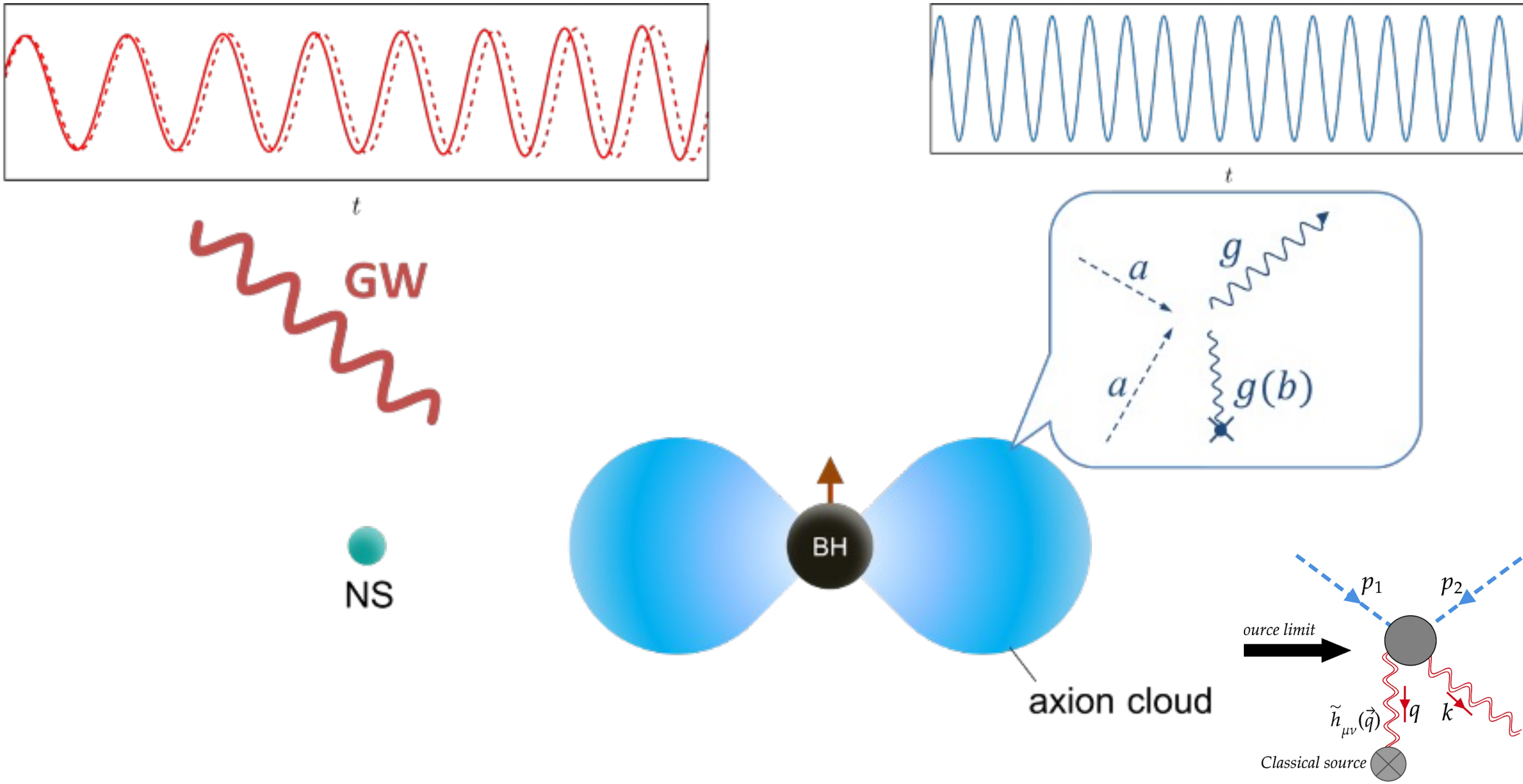
Ultralight DM could potential modify the GW waveform of compact binary

Inspiral: dynamical friction, superradiance, dipole radiation…

Ning Xie, FPH, arXiv:2207.11145 and work in progress

Merge: modify the equation of state of the quark/gluon plasma in neutron state, tidal effects

Imprints of ultralight axions on the GW of compact binary



Ning Xie, FPH, arXiv:2207.11145 and work in progress

Imprints of ultralight axions on the GW of compact binary

Without ultralight axions

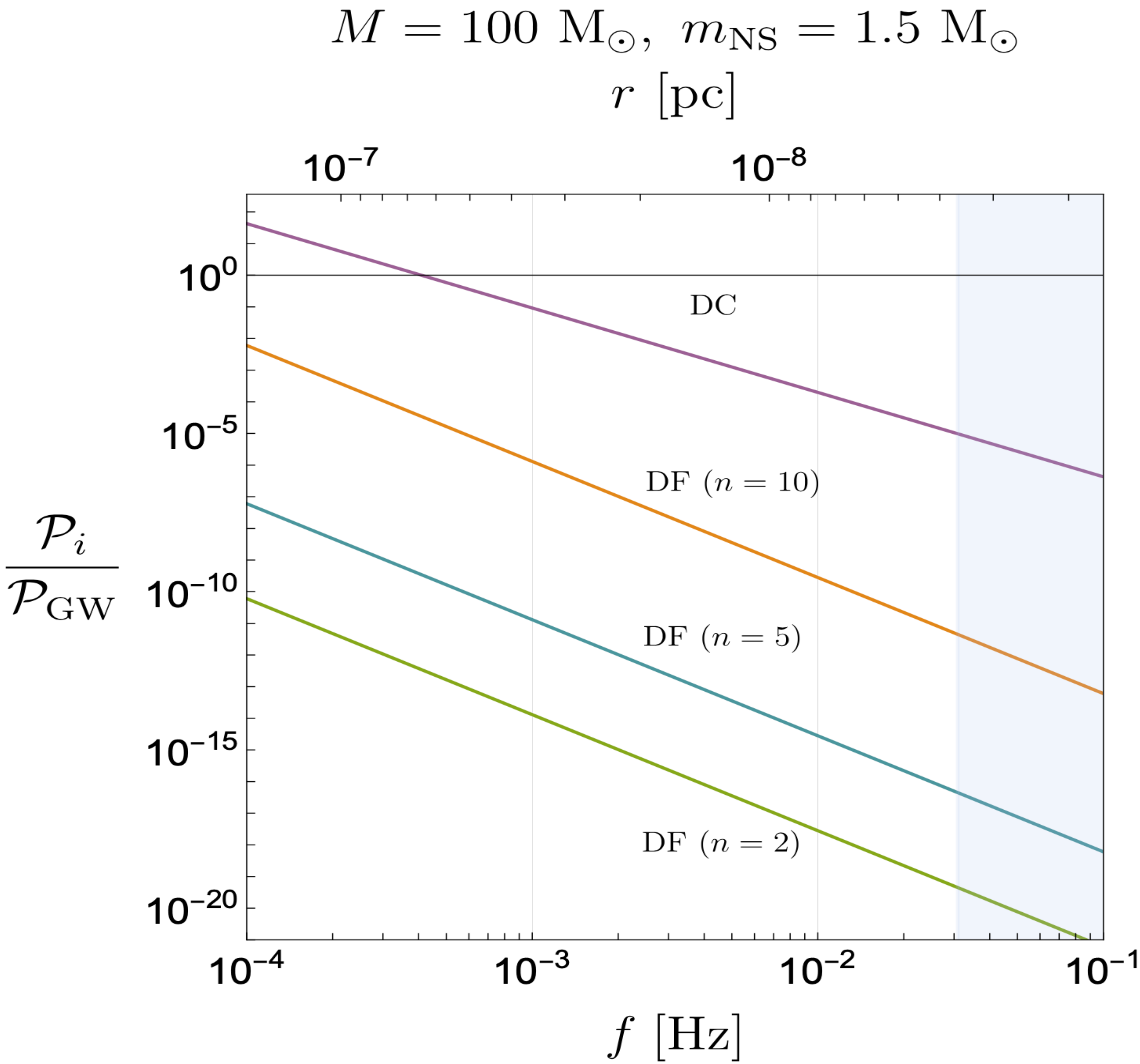
$$-\frac{\mathrm{d}E_0}{\mathrm{d}t} = \mathcal{P}_{\mathrm{GW}} \qquad \mathcal{P}_{\mathrm{GW}} = \frac{32}{5}\mu^2 r^4 \omega^6$$

With ultralight axions

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

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

Ning Xie, FPH, arXiv:2207.11145



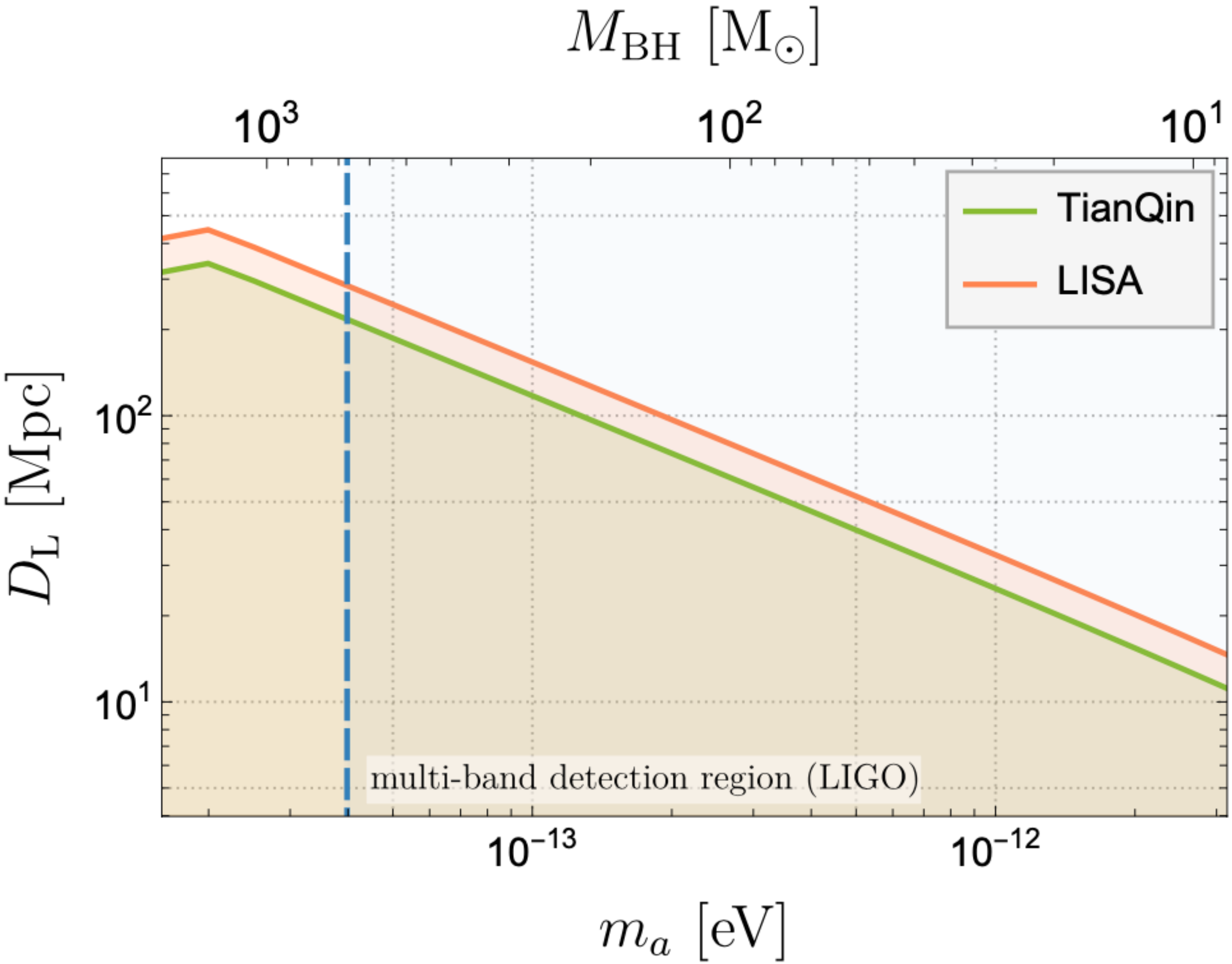
dynamical friction (DF), depletion of axion cloud (DC), dipole radiation(DR)

Imprints of ultralight axions on the GW of compact binary: phase shift of the waveform

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

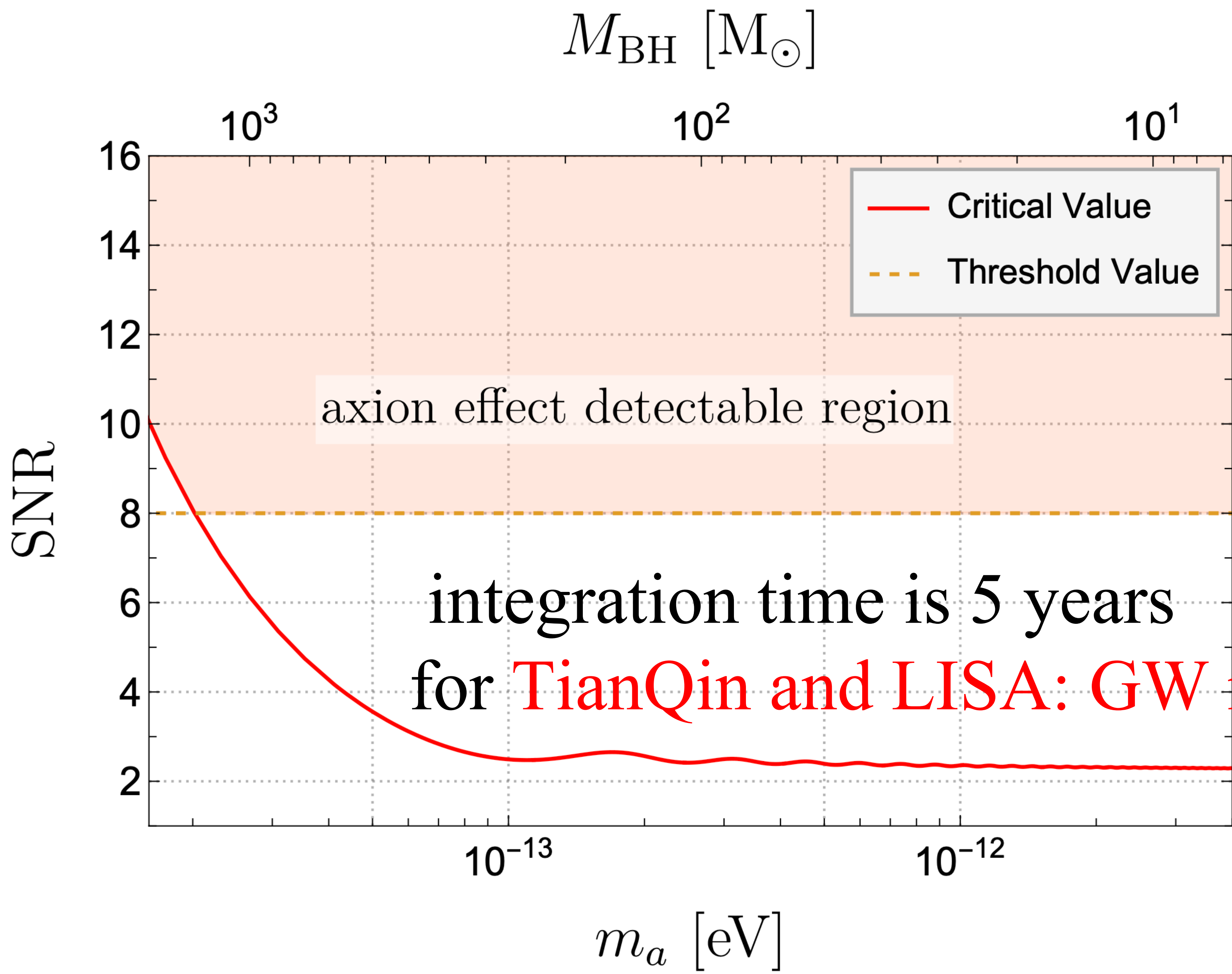
$$\Delta\phi \sim 15\pi \left(\frac{m_a}{10^{-12}\ \mathrm{eV}}\right) \left(\frac{f_T}{10^{-2}\ \mathrm{Hz}}\right) \left(\frac{T}{5\ \mathrm{yrs}}\right)^2$$

Ning Xie, FPH, arXiv:2207.11145



$M_{\rm BH}$ [$M_\odot$]
10^3
10^2
10^1
TianQin
LISA
$D_{\rm L}$ [Mpc]
10^2
10^1
multi-band detection region (LIGO)
10^{-13}
10^{-12}
m_a [eV]

Complementary search: GW+PTA



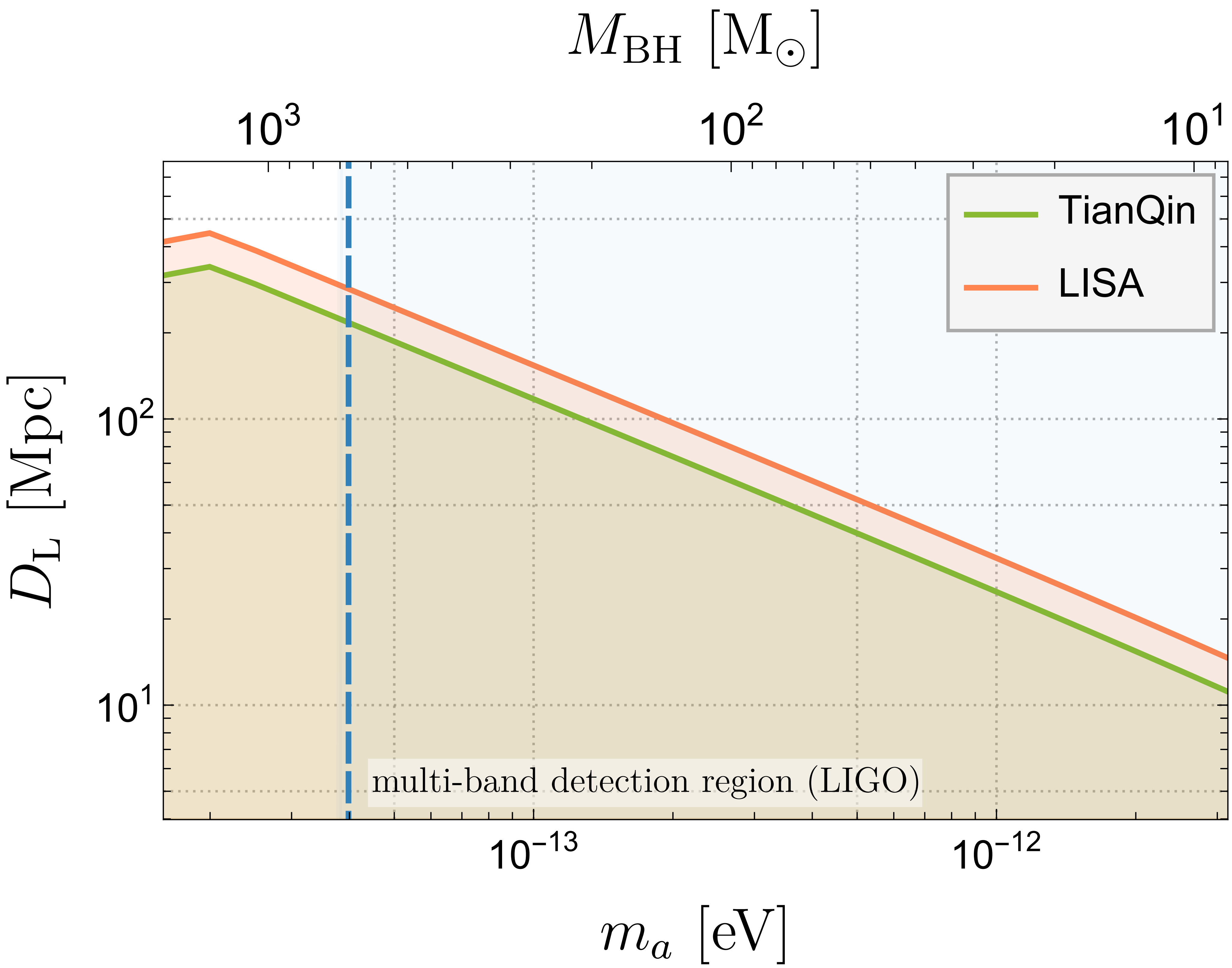
integration time is 5 years
for TianQin and LISA: GW measurement

Axions modify the rate of
period change

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

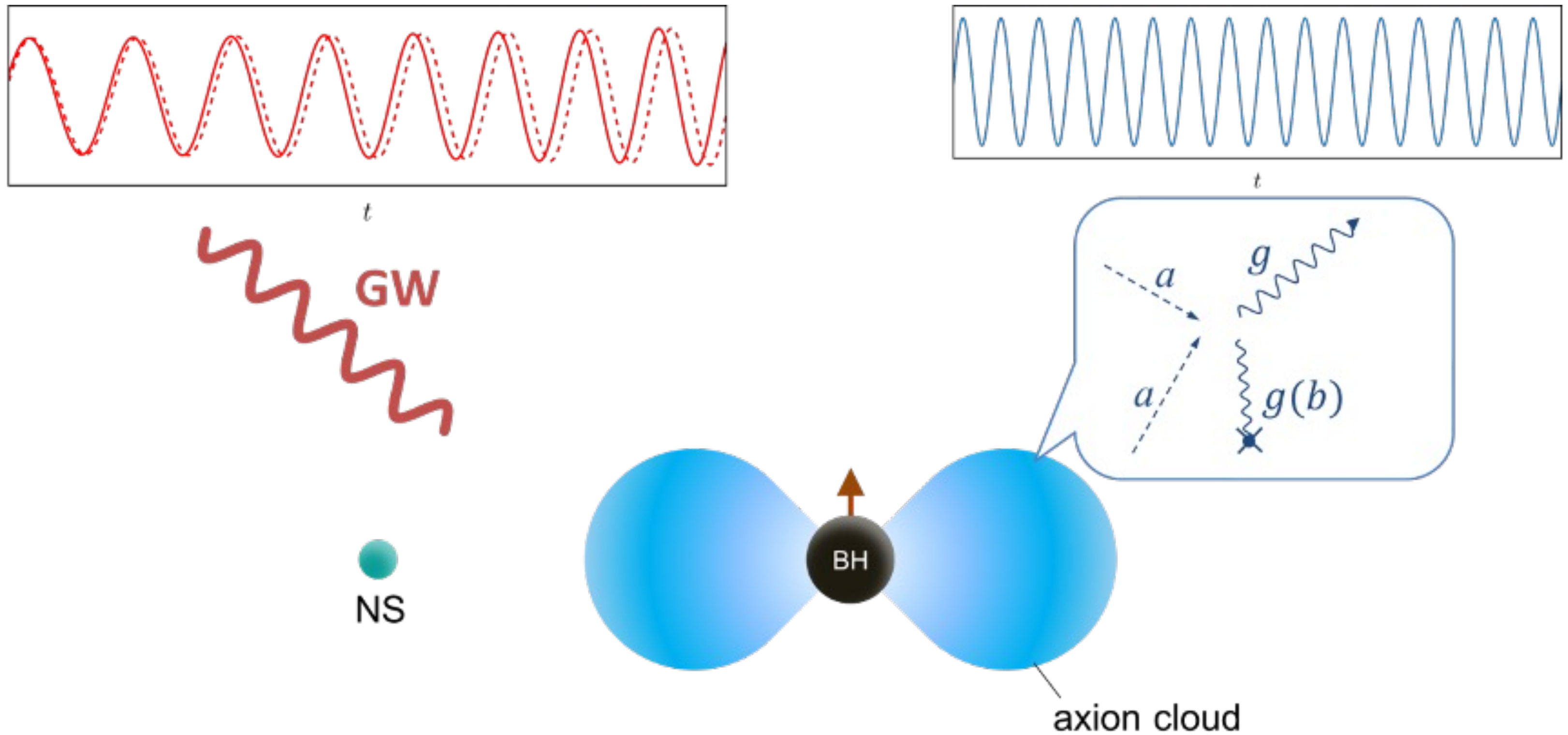
Future Pulsar timing measurement precision， such as SKA

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



$M_{\rm BH}$ [M$_\odot$]
10^3
10^2
10^1
TianQin
LISA
$D_{\rm L}$ [Mpc]
10^2
10^1
multi-band detection region (LIGO)
10^{-13}
10^{-12}
m_a [eV]

Summary and outlook



GW **and radio** **from black hole and neutron star might provide new approaches to explore ultralight axion: multi-messenger and multi-band.**

Thanks for your attention

Comments & collaborations are welcome **huangfp8@sysu.edu.cn**

Backup slides

I. Radio signals of DM from neutron star

We firstly study using SKA-like experiments to explore resonant conversion of axion cold DM to radio signal from magnetized sources, such as neutron star/magnetar/pulsar.

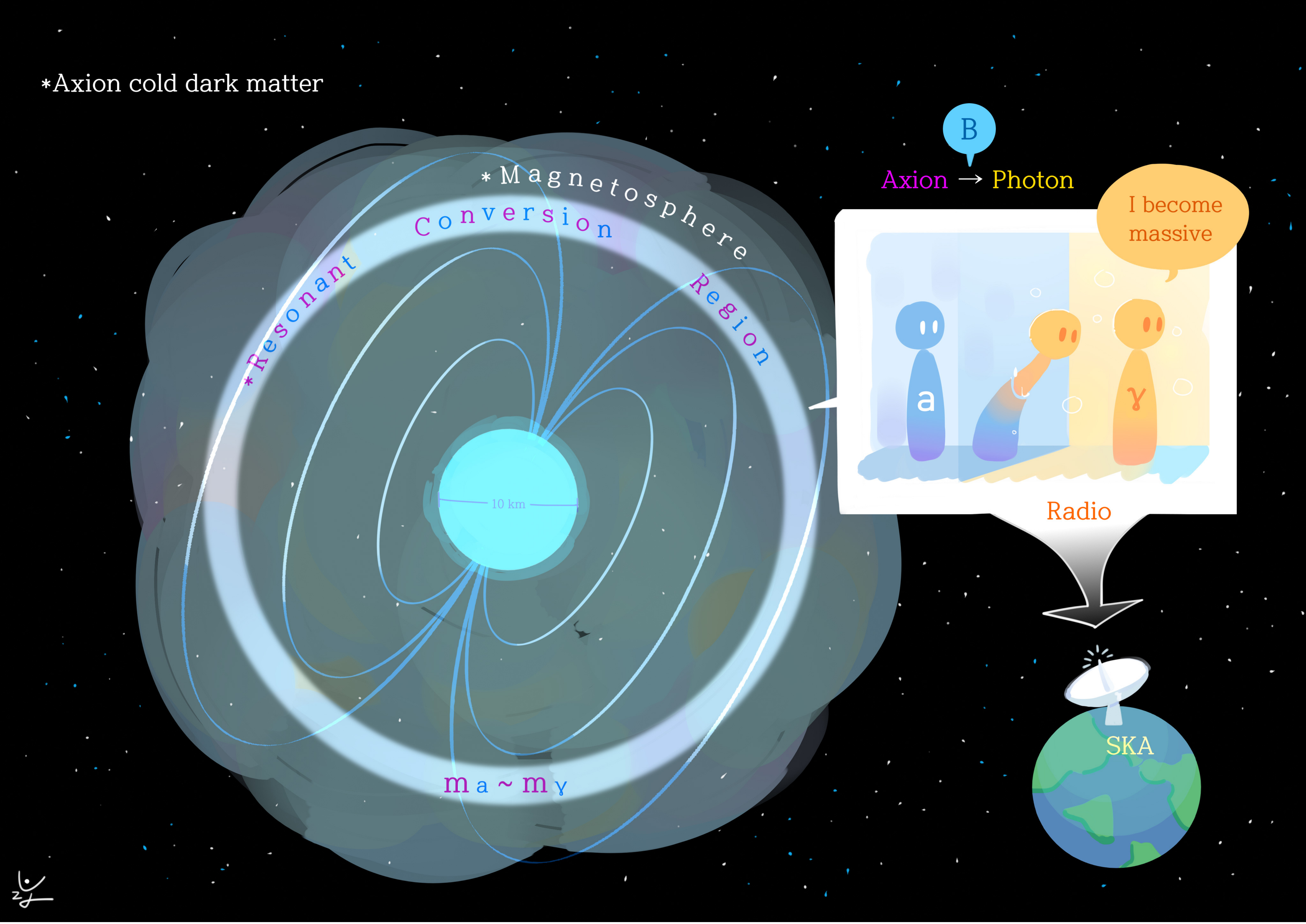
FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001, arXiv:1803.08230

Three key points:

- **Cold DM: non-relativistic axion or ALP**

- **Neutron star/pulsar/magnetar has the strongest position-dependent magnetic field**

- **Neutron star is covered by magnetosphere and photon becomes massive therein**



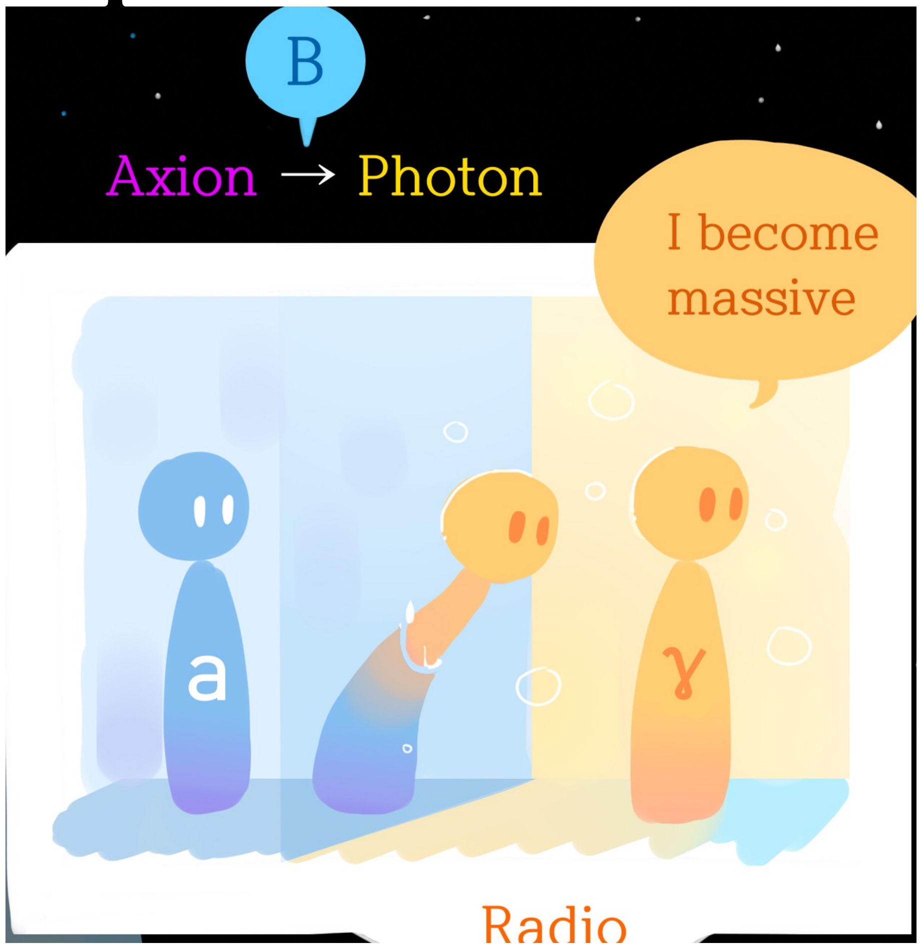
FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

Axion-photon conversion in the magnetosphere

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

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

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



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

$$B(r) = B_0 \left(\frac{r}{r_0}\right)^{-3}$$

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

$$m_\gamma^2(r_{\rm res}) = m_a^2$$

- G. Raffelt and L. Stodolsky, Phys. Rev. D 37, 1237 (1988)

The Adiabatic Resonant Conversion OF AXIONS INTO PHOTONS

Like MSW effects

$$\left[\omega^2 + \partial_z^2 + \begin{pmatrix} -m_\gamma^2 & gB\omega \\ gB\omega & -m_a^2 \end{pmatrix}\right]\begin{pmatrix} \gamma \\ a \end{pmatrix} = 0,$$

$$\sin 2\tilde{\theta} = \frac{2gB\omega}{\sqrt{4g^2B^2\omega^2 + (m_\gamma^2 - m_a^2)^2}} \qquad m_\gamma^2(r_{\rm res}) = m_a^2$$

within resonance region, the conversion rate is greatly enhanced due to resonant effects.

The adiabatic resonant conversion requires the resonance region is valid inside the resonance width.

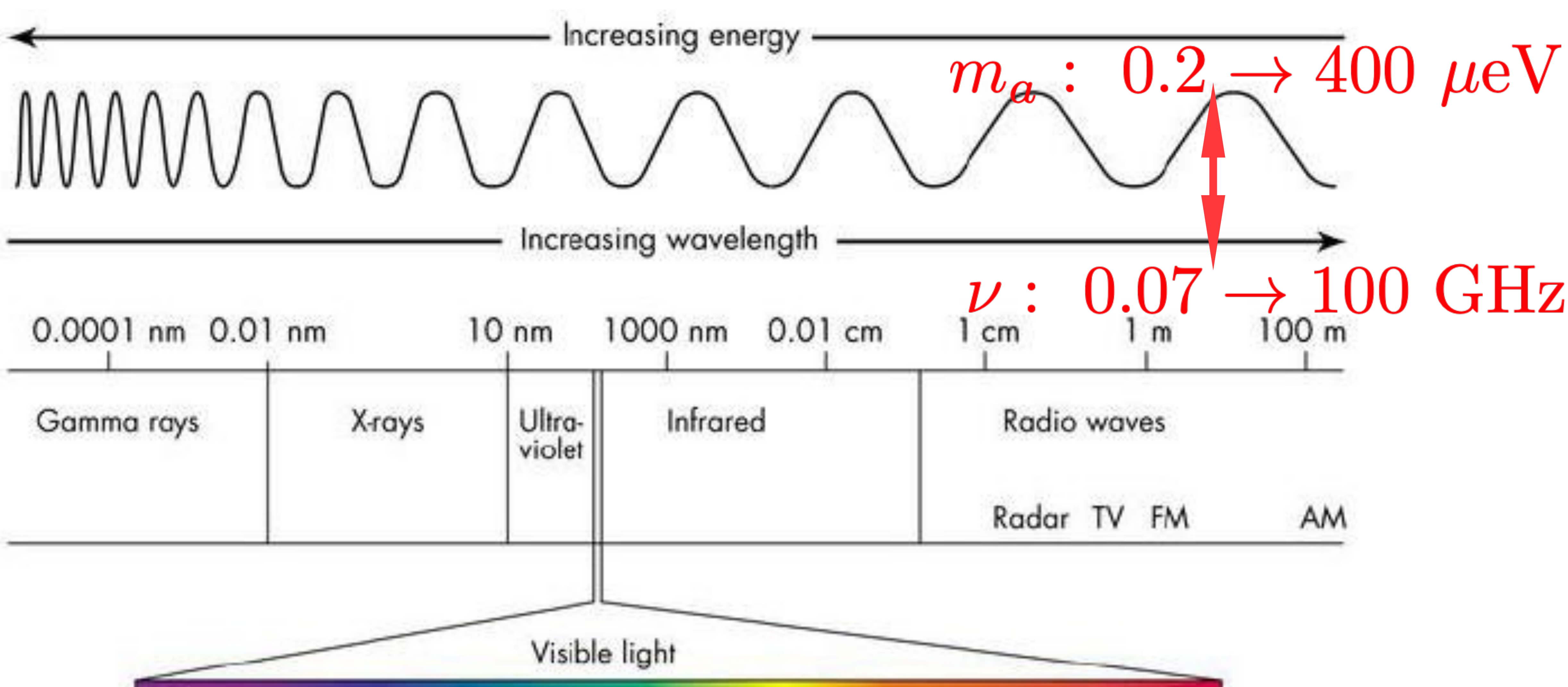
Radio Signal

Line-like radio signal for non-relativistic axion:

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

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



Radio Signal

Signal: For a trial parameter set, $B_0 = 10^{15}$ G, $m_a = 50\ \mu$eV
$P = 10$ s, $g = 5 \times 10^{-11}$ GeV^{-1}, $r_0 = 10$ km, $M = 1.5 M_{sun}$, $d = 1$kpc

$S_\gamma \sim 0.51\ \mu$Jy.

Sensitivity: $S_{min} \sim 0.48 \mu Jy$ 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.

Comments on the radio probe of axion DM

1. **Astrophysical uncertainty: magnetic field distribution, DM density distribution, the velocity dispersion, the plasma effects…**

   working in progress to extract DM density by TianQin/LISA

2. **There are more and more detailed studies after our simple estimation on the radio signal:**

arXiv:1804.03145 They consider more details and extremely high dark matter density around the neutron star, thus the signal is more stronger.

arXiv:1811.01020 by Benjamin R. Safdi, Zhiquan Sun, Alexander Y. Chen

arXiv:1905.04686,They consider multi-messenger of axion DM detection. Namely, using LISA to detect the DM density around the neutron star, which can determine the radio strength detected by SKA.

Precise study see arXiv:2104.08290

***Xiao-Jun Bi, et. al. Phys.Rev.D* 104 (2021) 10, 103015，*Phys.Rev.D* 103 (2021) 11, 115021**

New approaches

FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001, arXiv:1803.08230, Cited by 82 times

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

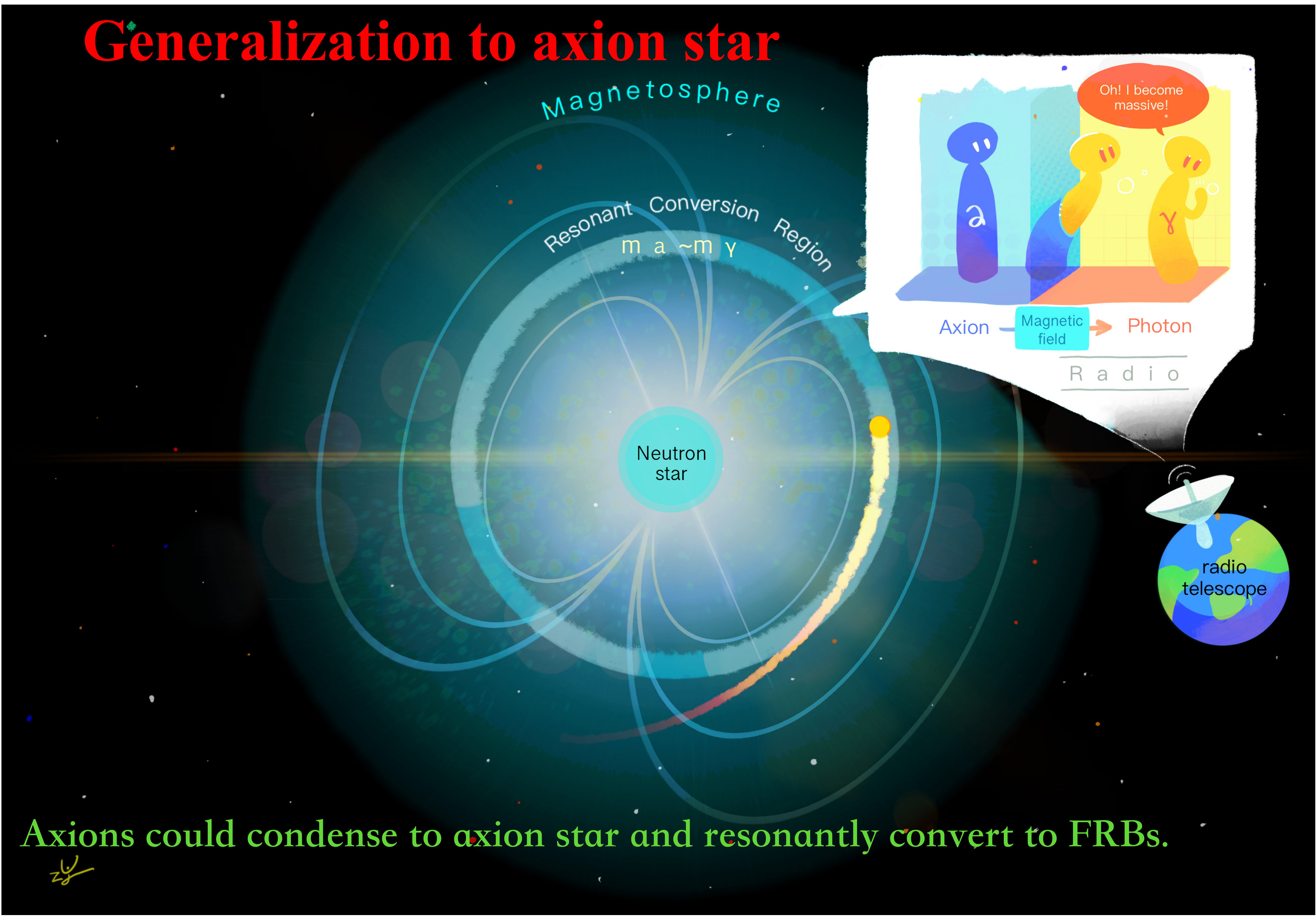
✓ **Physics Briefing Book :**
Input for the European Strategy for Particle Physics Update 2020, [arXiv:1910.11775]

✓ **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]**

Generalization to axion star

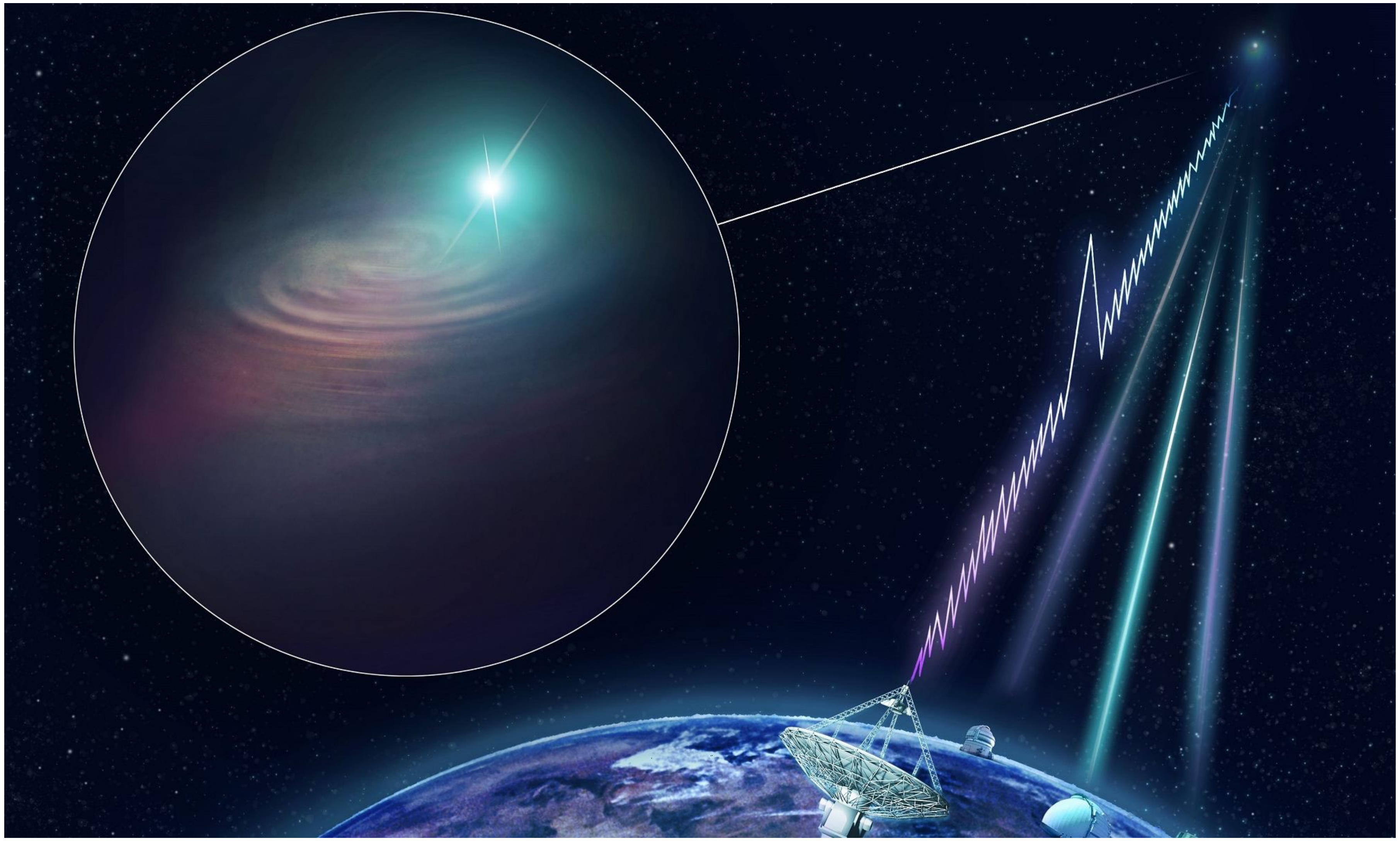


Axions could condense to axion star and resonantly convert to FRBs.

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

Mysterious Fast Radio Bursts (FRBs)

Recently, FRBs become the most mysterious phenomenon in astrophysics and cosmology (D. Thornton, et al., (2013) Science, 341, 53). **FRBs are intense, transient radio signals with large dispersion measure. However, their origin and physical nature are still obscure.**



$\mathcal{O}(0.1)$ to $\mathcal{O}(100)$ Jy

$\mathcal{O}(10^{38})$ to $\mathcal{O}(10^{40})$ erg

Duration: milliseconds

$$0.1 \lesssim z \lesssim 2.2$$

Focus on FRBs events with from 800 MHz to 1.4 GHz by Parkes, ASKAP, and UTMOST.

Credit: Universe Today

Generalize to dark photon DM case

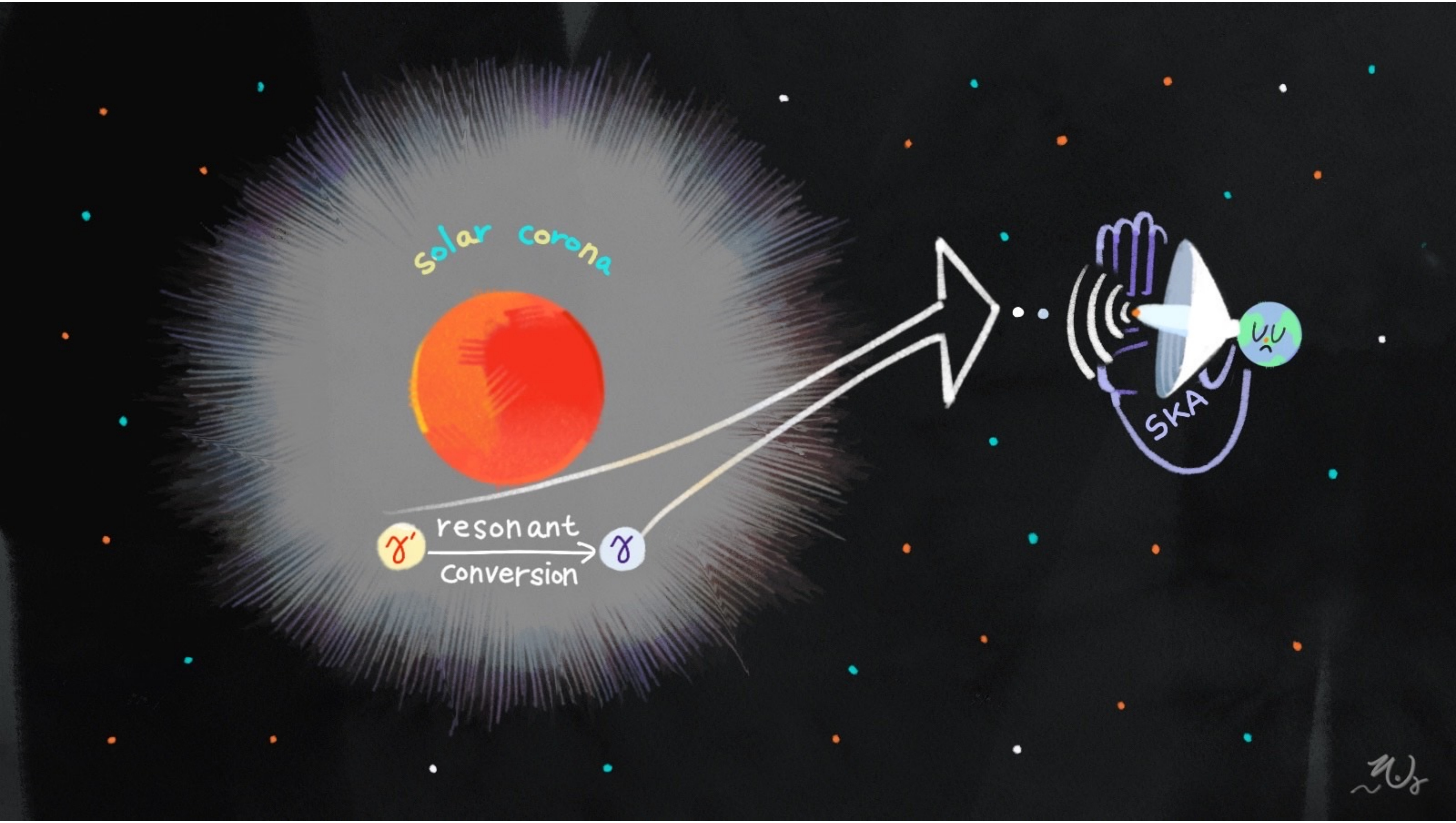
Recently, people realize light dark photon can be a promising DM candidate.

P. W. Graham, J. Mardon, and S. Rajendran, Phys. Rev. D 93, 103520 (2016).
A.J. Long and L.-T. Wang, Phys. Rev. D 99, 063529 (2019)
B. G. Alonso-Álvarez, T. Hugle, and J. Jaeckel, J. Cosmol. Astropart. Phys. 02 (2020) 014.
C. K. Nakayama, J. Cosmol. Astropart. Phys. 10 (2019) 019.
P. Agrawal, N. Kitajima, M. Reece, T. Sekiguchi, and F. Takahashi, Phys. Lett. B 801, 135136 (2020).
R. T. Co, A. Pierce, Z. Zhang, and Y. Zhao, Phys. Rev. D 99, 075002 (2019).
D. Y. Nakai, R. Namba, and Z. Wang, J. High Energy Phys. 12 (2020) 170

We study how to detect light dark photon DM by radio telescope, following the same idea as the axion DM case.

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu - \frac{1}{2}\epsilon F_{\mu\nu}F'^{\mu\nu}$$

Resonant conversion process



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

The sensitivity reach

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