中山大學天琴中心
TIANQIN CENTER FOR GRAVITATIONAL PHYSICS, SYSU

超轻轴子的引力波信号

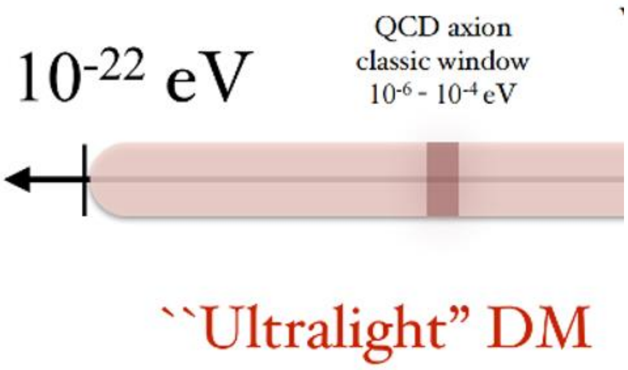
黄发朋 (Fa Peng Huang)
中山大学物理与天文学院

based on recent work with my Ph.D students:
Ning Xie, FPH, arXiv:2503.10347;
FPH, arXiv: 2409.19906
Aidi Yang, FPH, arXiv:2404.18703, JCAP (2025) ;
Jing Yang, Ning Xie, FPH, JCAP 11 (2024) 045;
Ning Xie, FPH, SCPMA Vol.66, No.1(2024).

Axion Dark Matter: Theory and Phenomenology
@山东大学, 青岛, 2025.05.11

Outline

1. Axion and axion dark matter (DM), Gravitational wave (GW)
2. DFSZ axion and its phase transition GW signals
3. μeV axion and radio signals of axion DM (multi-messenger)
4. 10^{-12}-10^{-17} eV axion: GW and pulsar timing measurement
5. 10^{-21} eV fuzzy axion DM GW
6. Summary and outlook

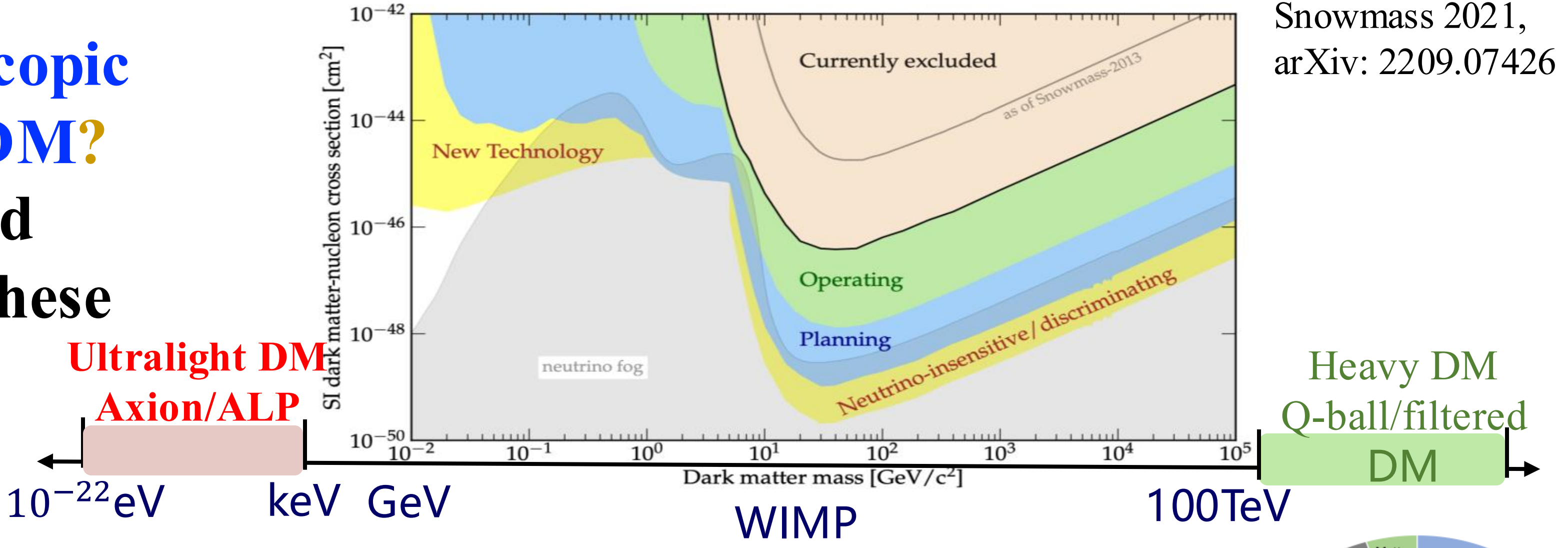


Motivation

What is the microscopic nature of DM?

No expected signals in these region

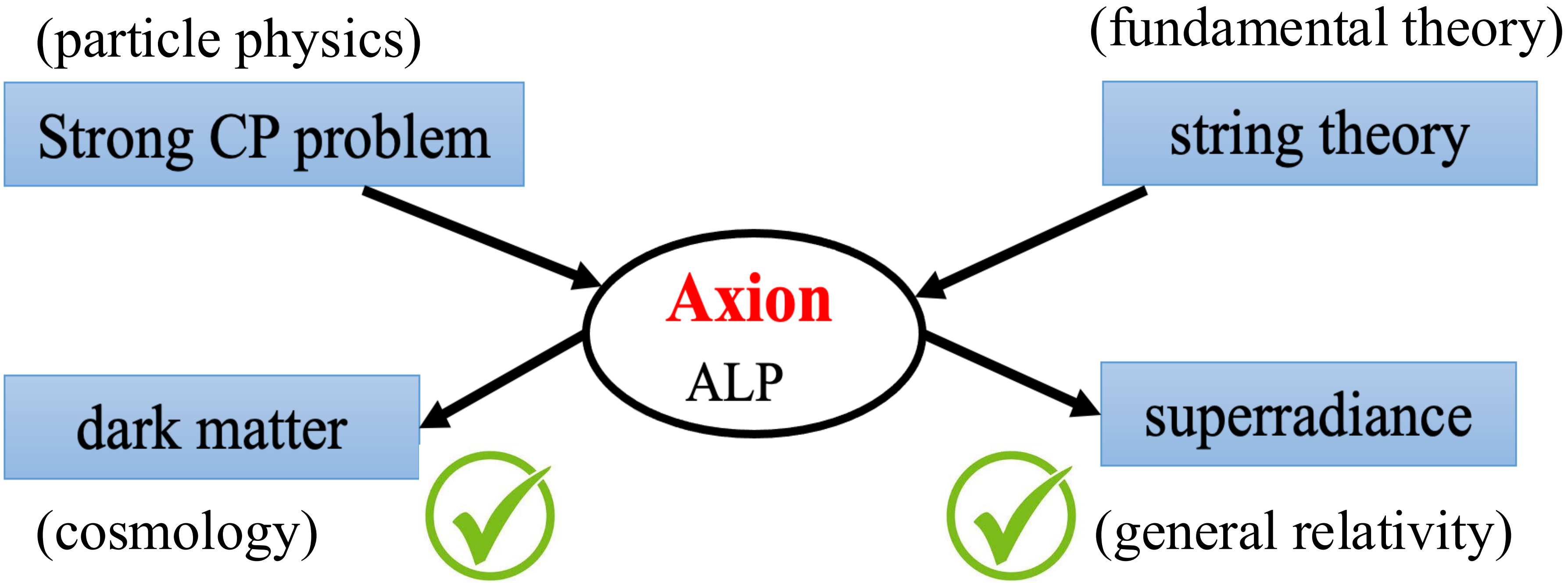
arXiv: 1904:07915
Snowmass 2021,
arXiv: 2209.07426



- **new DM mechanism beyond freeze out: cosmic phase transition**
- **new detection method: GW detector (LISA, TianQin, Taiji, aLIGO, FAST, SKA, NanoGrav, Cosmic Explorer…)**

Axion particle cosmology

Ultralight axion is a promising DM candidate.



GW detection of DM

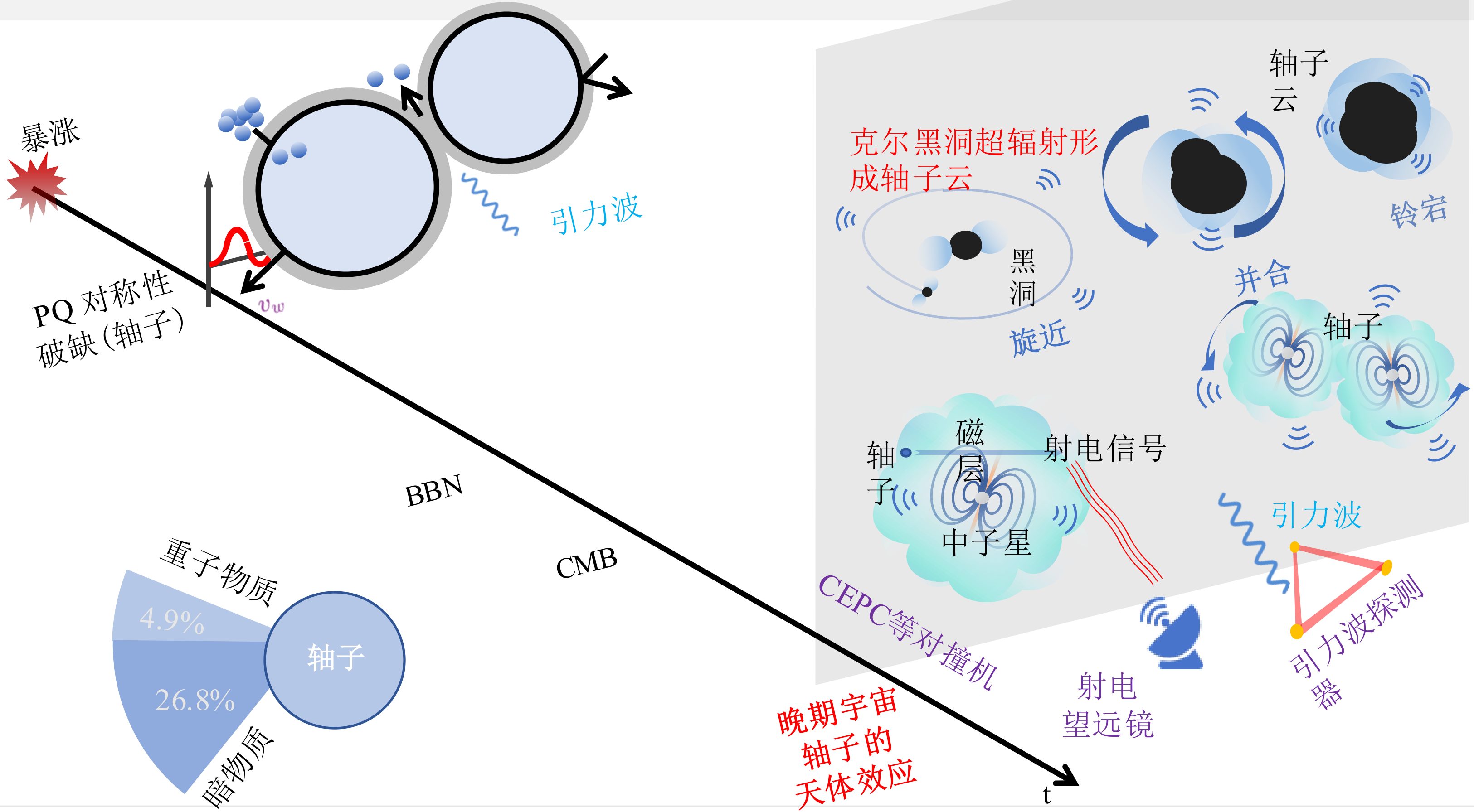
The observation of GW@LIGO initiates a new era of exploring DM and new physics by GW.

[Fundamental Physics and Cosmology with TianQin](), arXiv: [2502.20138]()

J.Jaeckel, V. V. Khoze, M. Spannowsky, Phys.Rev. D94 (2016) no.10, 103519
Zhaofeng Kang,et.al. arXiv:2101.03795, arXiv:2003.02465
Yan Wang, Chong Sheng Li, and **FPH**, arXiv:2012.03920
FPH, Eibun Senaha Phys.Rev. D100 (2019) no.3, 03501
FPH PoS ICHEP2018 (2019) 397
FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028
FPH, Jiang-Hao Yu, Phys.Rev. D98 (2018) no.9, 095022
FPH, Xinmin Zhang, Phys.Lett. B788 (2019) 288-
Haipeng An, et.al, arXiv: 2208.14857, arXiv:2009.12381, arXiv:2201.05171

Credit: Gianfranco Bertone et. al.

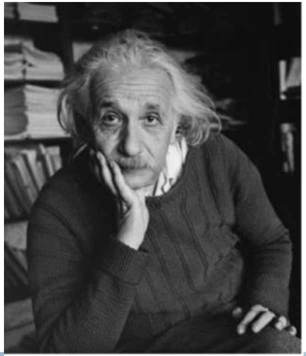
超轻轴子的引力波信号



暴涨
PQ 对称性
破缺 (轴子)
v_w
引力波
BBN
CMB
重子物质
4.9%
26.8%
暗物质
轴子
晚期宇宙
轴子的
天体效应
t
克尔黑洞超辐射形
成轴子云
黑
洞
旋近
轴子
云
铃宕
并合
轴子
轴
子
磁
层
射电信号
中子星
引力波
CEPC等对撞机
射电
望远镜
引力波探测
器

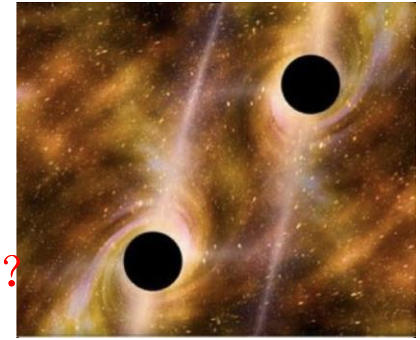
What is GW ?

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



Isolated sources: quadrupole radiation

axion effect?

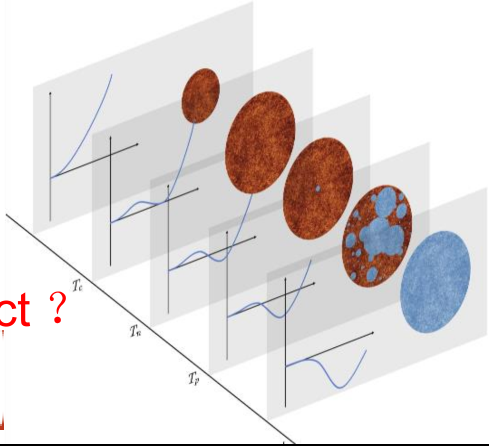


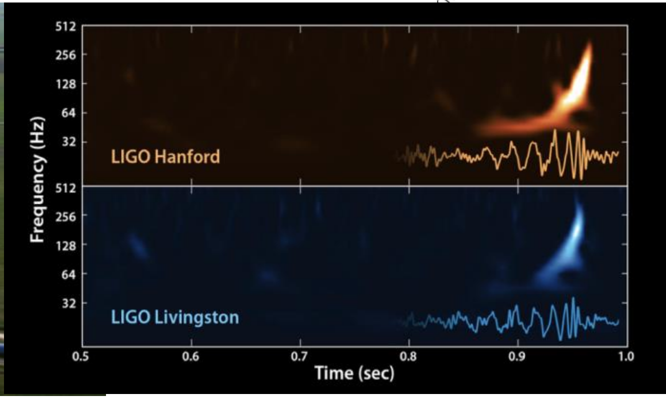
$$h_{ij} \simeq \frac{2G}{c^4 r} \ddot{Q}_{ij}^{TT}(t - r/c)$$

Stochastic sources: anisotropic stress tensor

axion effect ?

$$\Pi_{ij}(\mathbf{x}, t)$$





GW radiation in a nutshell

The quadruple nature of GW !

EM wave radiation

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

GW radiation

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

momentum conservation

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

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

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

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

Cosmological source of GW

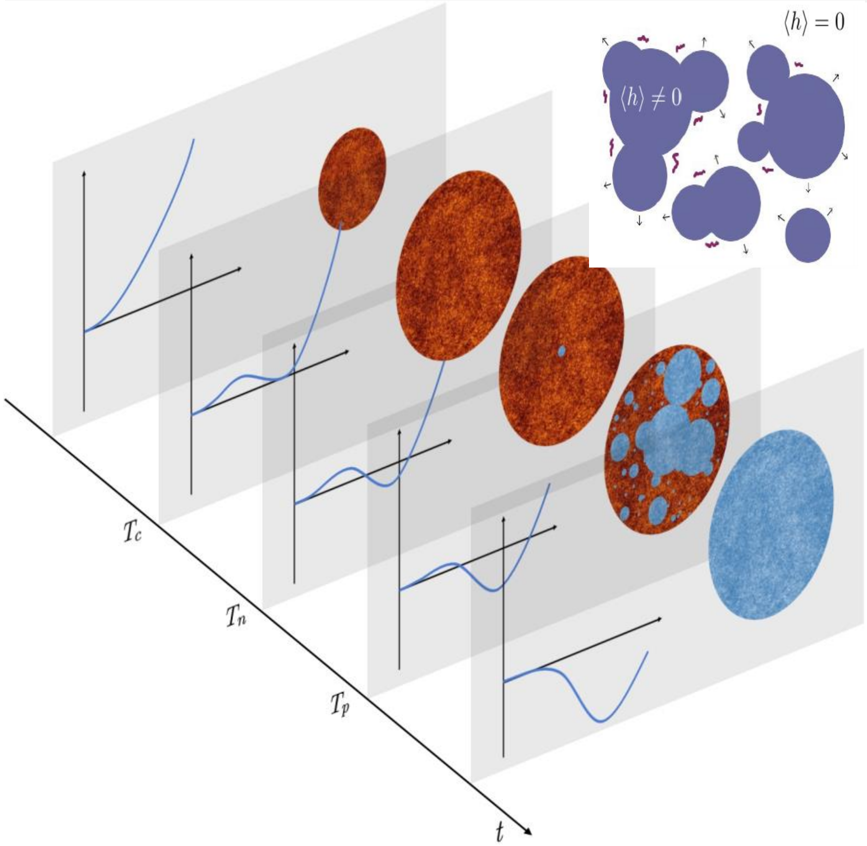
General GW source from the early universe

各向异性
剪切应力张量

$$\ddot{h}_{ij}(\mathbf{x},t) + 3\,H\,\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}h_{ij}(\mathbf{x},t) = 16\pi G\,\Pi_{ij}(\mathbf{x},t)$$

GW sources	Sources of tensor anisotropic stress	General form Π_{ij}
Collisions of bubble walls	scalar field gradients	$[\partial_i\phi\partial_j\phi]^{TT}$
Sound waves and turbulence	bulk fluid motion	$[\gamma^2(\rho+p)v_iv_j]^{TT}$
Primordial magnetic fields	gauge fields	$[-E_iE_j - B_iB_j]^{TT}$
Scalar perturbations	second order scalar perturbations	$\partial_i\Psi, \partial_i\Phi$

Phase transition GW in a nutshell



calculate the finite-temperature effective potential using the thermal field theory: free energy density.

$$V_{\text{eff}}^{(1)}(\bar{\phi}) = \sum_i n_i \Big[\int \frac{d^D p}{(2\pi)^D} \ln\big(p^2 + m_i^2(\bar{\phi})\big) + J_{\text{B,F}}\Big(\frac{m_i^2(\bar{\phi})}{T^2}\Big) \Big]$$

$$S(T) = \int d^4x \left[\frac{1}{2} \left(\frac{\partial \phi}{\partial x} \right)^2 + V_{\text{eff}}(\phi, T) \right]$$

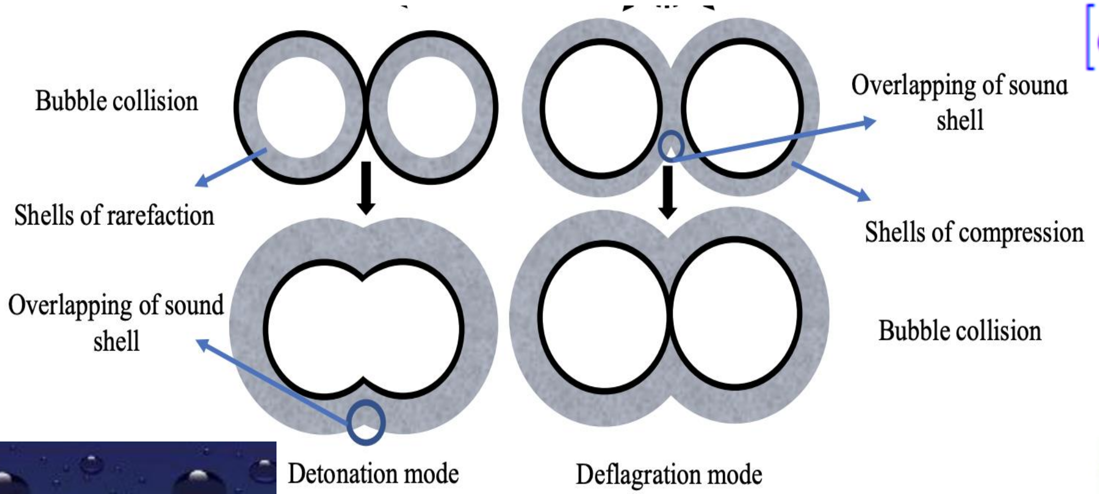
$$\Gamma = \Gamma_0 e^{-S(T)}$$

Strong first-order phase transition (SFOPT)

这世上的热闹，源自隧穿

Xiao Wang, FPH, Xinmin Zhang, JCAP05(2020)045

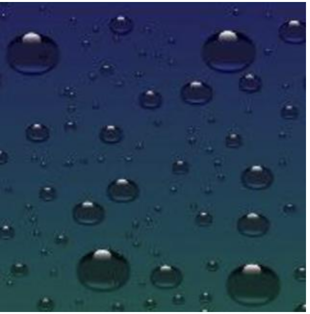
Phase transition GW in a nutshell

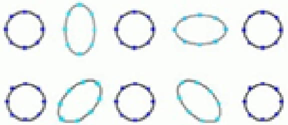


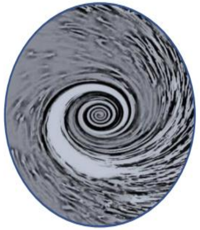
$$[\partial_i \phi \partial_j \phi]^{TT}$$

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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







Turbulence

$$[\gamma^2(\rho + p) v_i v_j]^{TT}$$

E. Witten, Phys. Rev. D 30, 272 (1984)
C. J. Hogan, Phys. Lett. B 133, 172 (1983);
M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994))

EW phase transition GW becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.

Xiao Wang, FPH, Xinmin Zhang, JCAP05(2020)045

Phase transition dynamics

Theory: 相变引力波信号、相变暗物质、早期宇宙电弱重子生成机制**最核心却最难计算**的是泡泡膨胀速度

v_w

Experiment: 实验上最重要的相变参数也是泡泡膨胀速度

Finite-temperature effective potential

$V_{eff}(\phi, T)$ α T_p $R_* H_*$

(1). **Daisy resummation problem:** Pawani scheme vs. Arnold scheme
(2). **Gauge dependence problem:** see Michael J. Ramsey-Musolf's works
(3). **No perturbative calculations: lattice calculations and dim-reduction method: by D. Weir, Michael J. Ramsey-Musolf et.al**

Bubble wall velocity

v_w

Energy budget

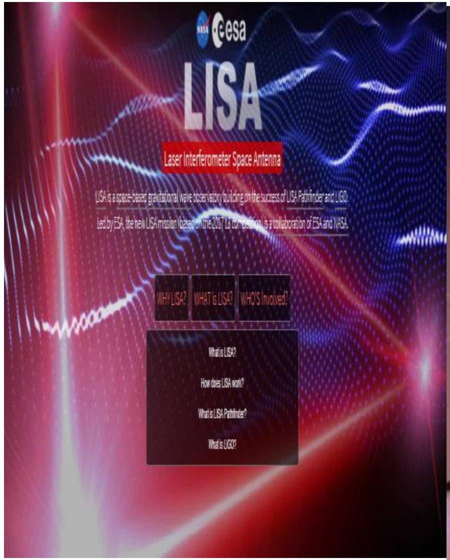
κ

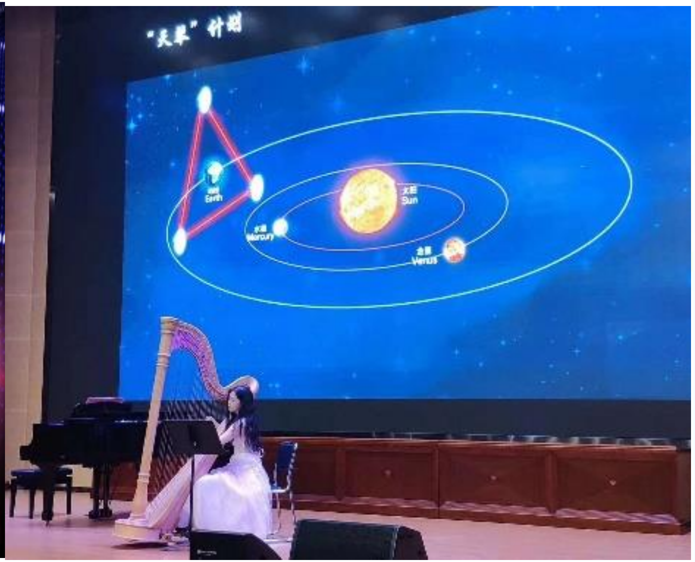
S. Hoche, J. Kozaczuk, A. J. Long, J. Turner and Y. Wang , arXiv:2007.10343,
Avi Friedlander, Ian Banta, James M. Cline, David Tucker-Smith, arXiv:2009.14295v2
Xiao Wang, **FPH,** Xinmin Zhang,arXiv:2011.12903
Siyu Jiang, FPH, xiao wang, Phys.Rev.D 107 (2023) 9, 095005

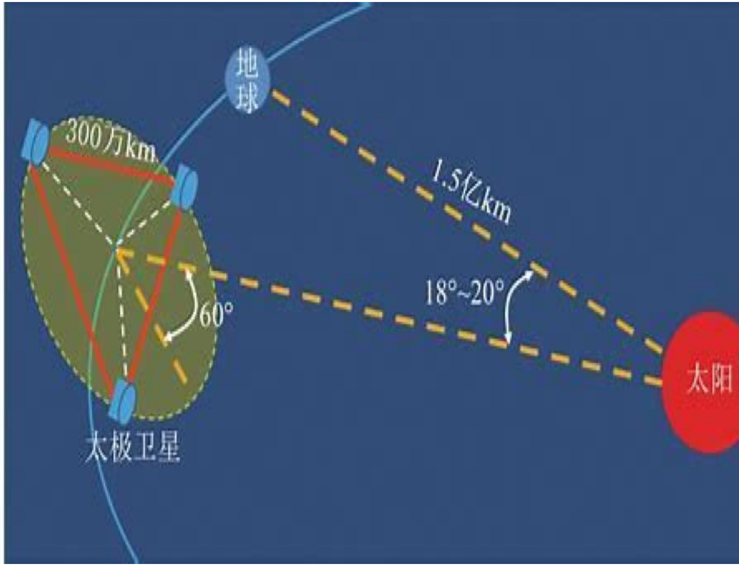
F. Giese, T. Konstandin, K. Schmitz and J. van de Vi ,arXiv:2010.09744
Xiao Wang, **FPH** and Xinmin Zhang, Phys.Rev.D 103 (2021) 10, 103520
Xiao Wang, Chi Tian, **FPH**, JCAP 07 (2023) 006

GW experiments

LISA/TianQin/Taiji ~2034



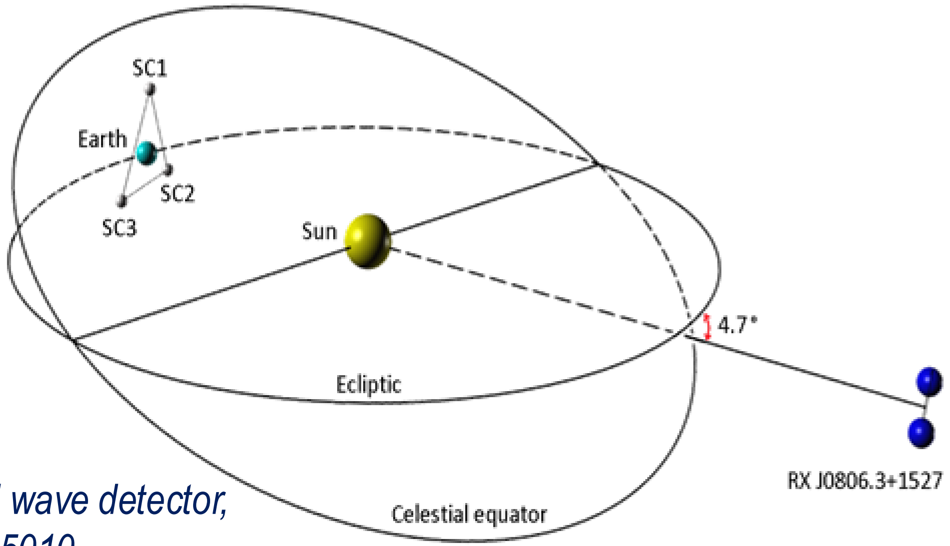




“天琴”
“Harpe in space”

TianQin

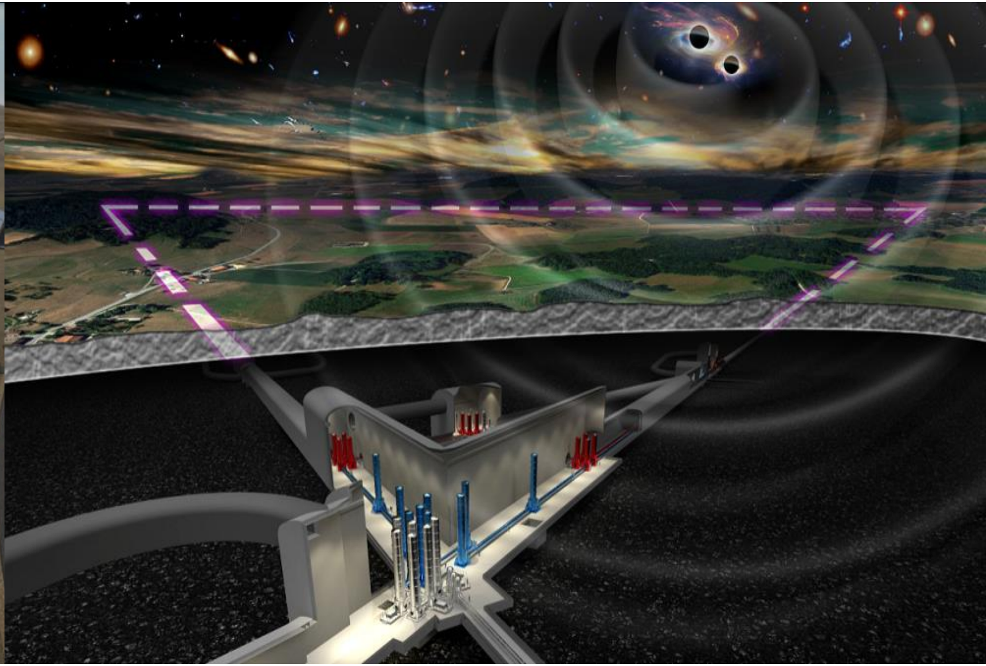
- Expected around 2035
- Geocentric orbit, normal triangle constellation, radius ~10^5km
- Unique frequency band 10^{-4}-1 Hz, easier for deployment, tracking, control, and communication



J. Luo et al. TianQin: a space-borne gravitational wave detector, Class. Quant. Grav. 33 (2016) no.3, 035010.

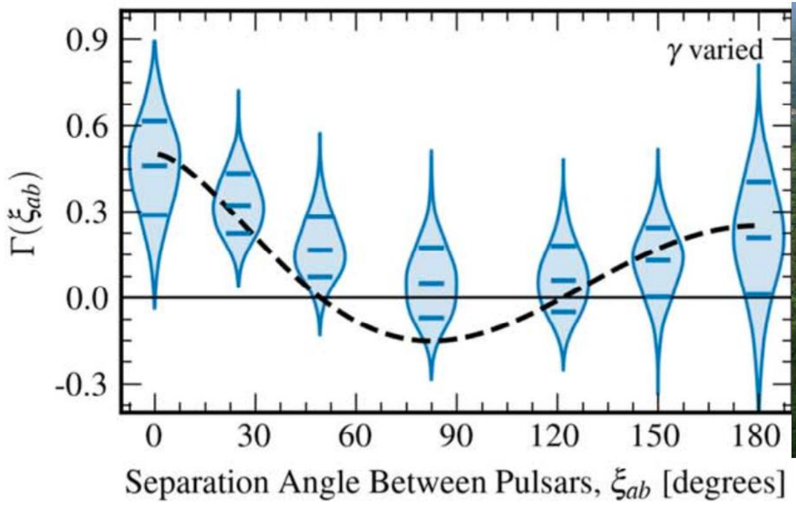
GW experiments

Next generation: Einstein telescope
Cosmic Explorer



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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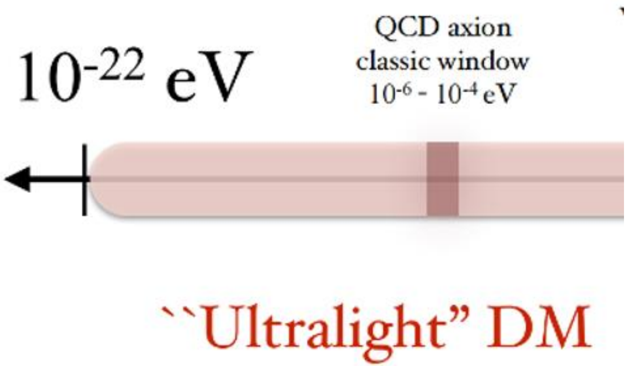
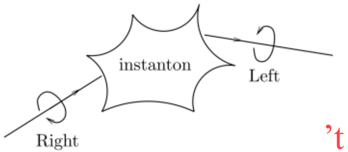


Strong CP problem and QCD axion

Strong CP problem → PQWW → ruled out by

$K^{+} \rightarrow \pi^{+} + \phi$



't Hooft, G. Phys. Rev.Lett. 37, 8 (1976)

PQWW → Invisible axion model

Invisible axion model → DFSZ

Invisible axion model → KSVZ

M. Dine, W. Fischler, and M. Srednicki, Physics letters B 104, 199 (1981).

GW detection of DFSZ axion model

The U(1) Peccei-Quinn symmetry breaking might be a SFOPT process, which could produce detectable phase transition GW.

$$
\begin{aligned}
V_{\text{tree}} = & -\mu_1^2|H_u|^2 - \mu_2^2|H_d|^2 + \lambda_1|H_u|^4 + \lambda_2|H_d|^4 + \lambda_4|H_u^\dagger H_d|^2 \\
& - \mu_3^2|\sigma|^2 + \lambda_3|\sigma|^4 + \lambda_{12}|H_u|^2|H_d|^2 + \lambda_{13}|\sigma|^2|H_u|^2 \\
& + \lambda_{23}|\sigma|^2|H_d|^2 + \left(\lambda_5\sigma^2\tilde{H}_u^\dagger H_d + \text{h.c.}\right),
\end{aligned}
$$

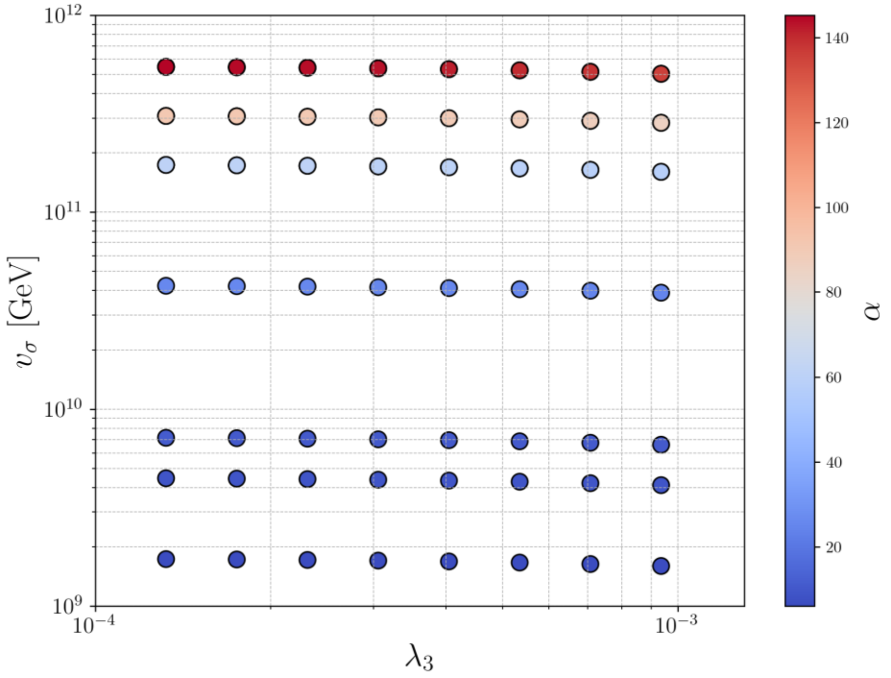
$$
\sigma = \frac{1}{\sqrt{2}}\left(v_\sigma + \sigma^0 + i\eta_\sigma^0\right).
$$

$$
V_{\text{eff}}(\sigma^0, T) \equiv V_{\text{tree}}(\sigma^0) + V_{\text{CW}}(\sigma^0) + V_T(\sigma^0, T),
$$

Aidi Yang, FPH*,
arXiv:2404.18703, JCAP (2025)

GW detection of DFSZ axion model

There exists a substantial parameter space for realizing a SFOPT in the DFSZ model.

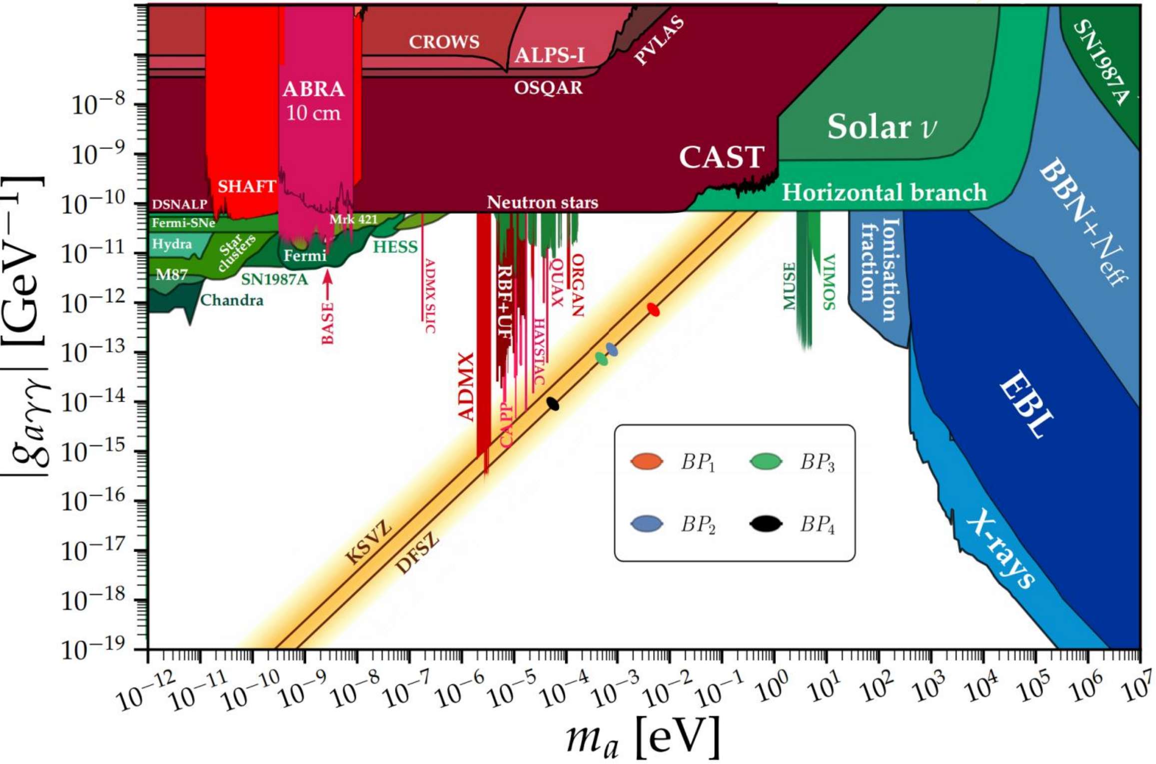


Aidi Yang, FPH*, arXiv:2404.18703, JCAP (2025)

Each point plotted in the figure represents a set of parameters for which a SFOPT occurs. The color of each point in the figure indicates the value of α, with the color bar ranging from blue to red.

Parameter space exploration results of the SFOPT in the DFSZ axion model.

GW detection of DFSZ axion model



Aidi Yang, FPH*, arXiv:2404.18703, JCAP (2025)

All four points fall within the expected yellow region which represents the range of axion masses and coupling constants that have not yet been excluded by ALP-photon coupling experiments.

The m_a and $g_{a\gamma\gamma}$ obtained from all four benchmark points

GW detection of DFSZ axion model

10^{-3}-10^{-5} eV DFSZ axion

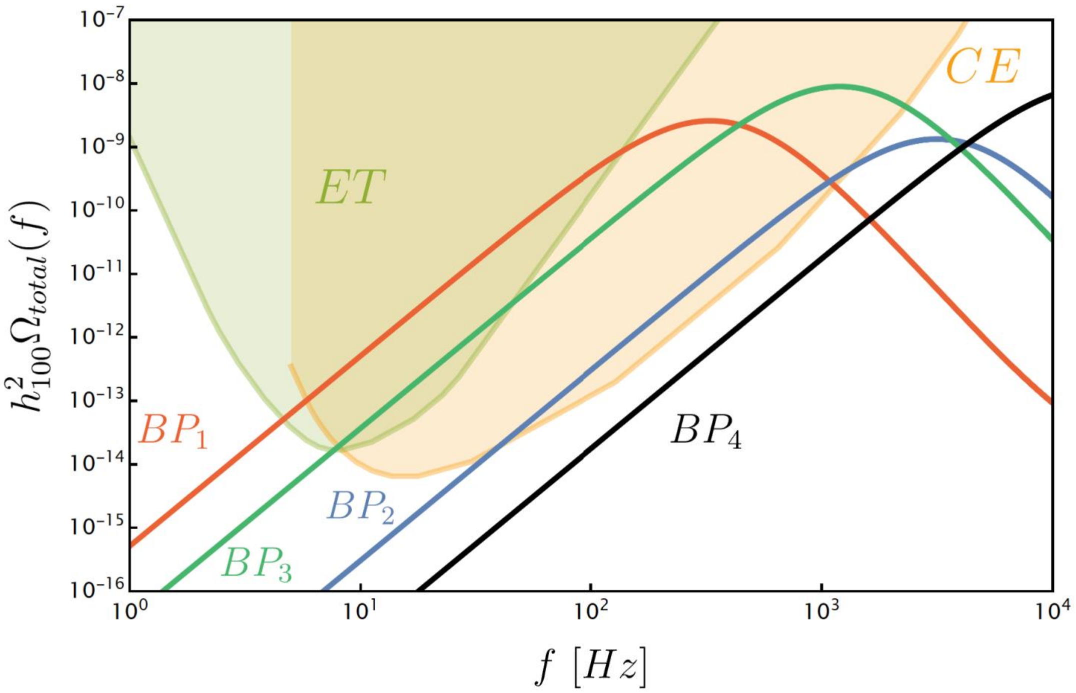
	$f_{\rm PQ}$ [GeV]	m_a [eV]	$g_{a\gamma\gamma}$ [GeV^{-1}]
BP$_1$	1.24×10^9	4.59×10^{-3}	7.01×10^{-13}
BP$_2$	7.01×10^9	8.12×10^{-4}	1.21×10^{-13}
BP$_3$	1.62×10^{10}	3.51×10^{-4}	5.37×10^{-14}
BP$_4$	1.57×10^{11}	3.63×10^{-5}	5.54×10^{-15}

The corresponding m_a and $g_{a\gamma\gamma}$ values.

Aidi Yang, FPH*, arXiv:2404.18703, JCAP

The axion mass and axion-photon coupling constant predicted by the DFSZ model are consistent with current experimental constraints.

GW detection of DFSZ axion model



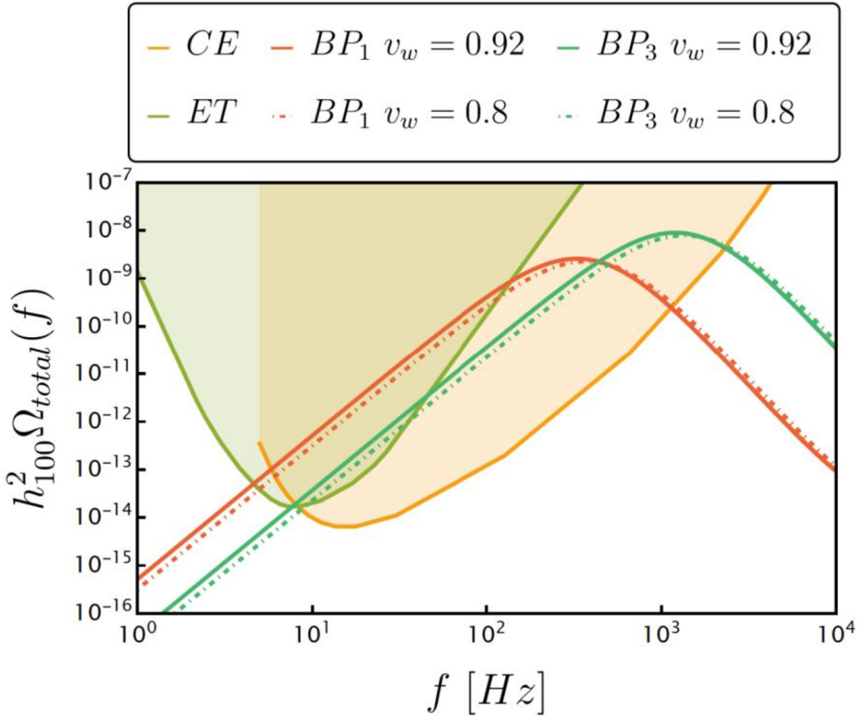
Aidi Yang, FPH*, arXiv:2404.18703,JCAP (2025)

$$\mathrm{SNR_{gw}} = \sqrt{T_t \int_{f_{\min}}^{f_{\max}} df \left(\frac{h^2_{100}\Omega_{\mathrm{gw}}}{h^2_{100}\Omega_{\mathrm{sens}}} \right)^2},$$

SNR： $BP_1(21794.10)$ $BP_2(46.19)$ $BP_3(3964.97)$ $BP_4(0.15)$

The SNR values of BP_1, BP_2, and BP_3 exceed the CE SNR threshold of 8, indicating that they can be detected by the CE detector.

GW detection of DFSZ axion model



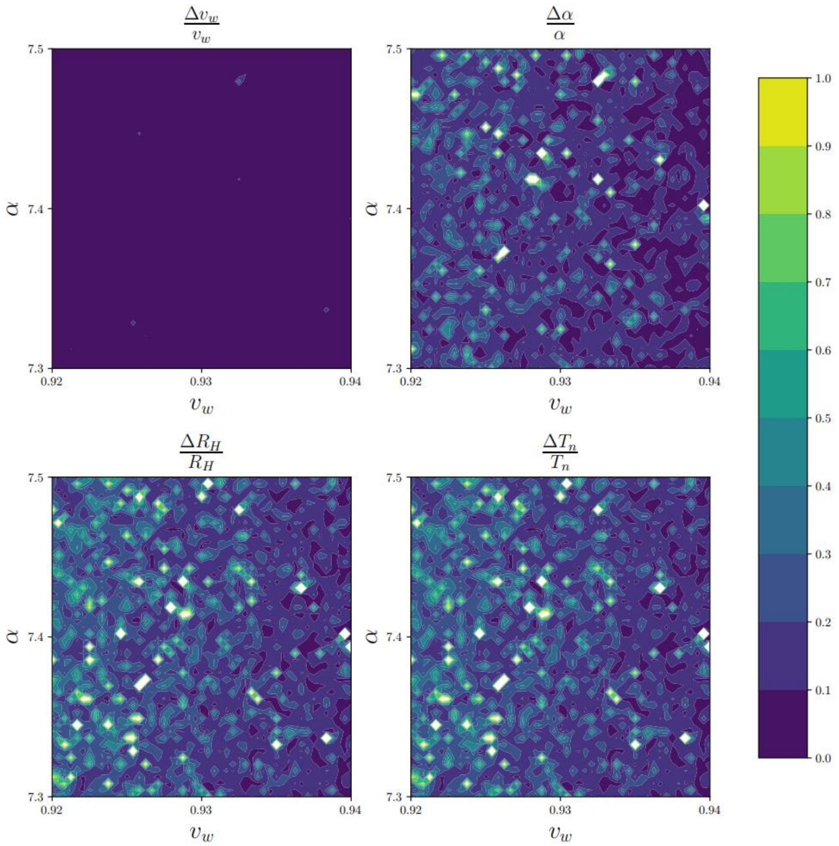
To assess the constraining power of CE on these phase transition parameters more precisely, we need to quantify the uncertainties of each parameter. FM analysis is a powerful statistical tool widely used to estimate the precision with which model parameters can be determined from a given set of observations.

Aidi Yang, FPH*, arXiv:2404.18703,JCAP (2025)

The differences in the frequency and strength of the GW spectra for DFSZ model with v_w=0.92 and v_w=0.8 .

GW detection of DFSZ axion model

Relative uncertainty with phase transition dynamics parameters bubble wall speed v_w, transition strength α, Hubble-scaled mean bubble spacing R_H , and nucleation temperature T_n . From dark blue to light green, the relative uncertainties gradually increase.



By Fisher matrix analysis,
CE will be most sensitive to v_w

实验上最先确定的相变参数将是
泡泡膨胀速度 v_w

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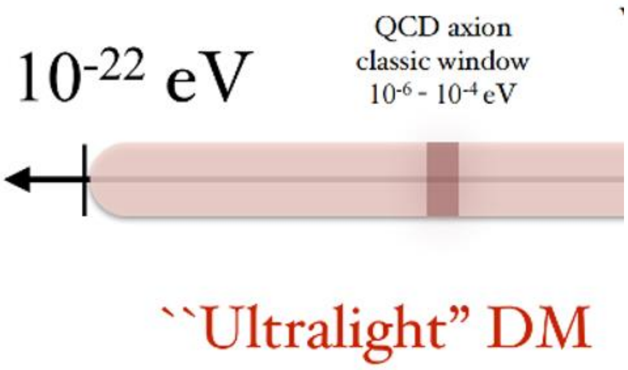
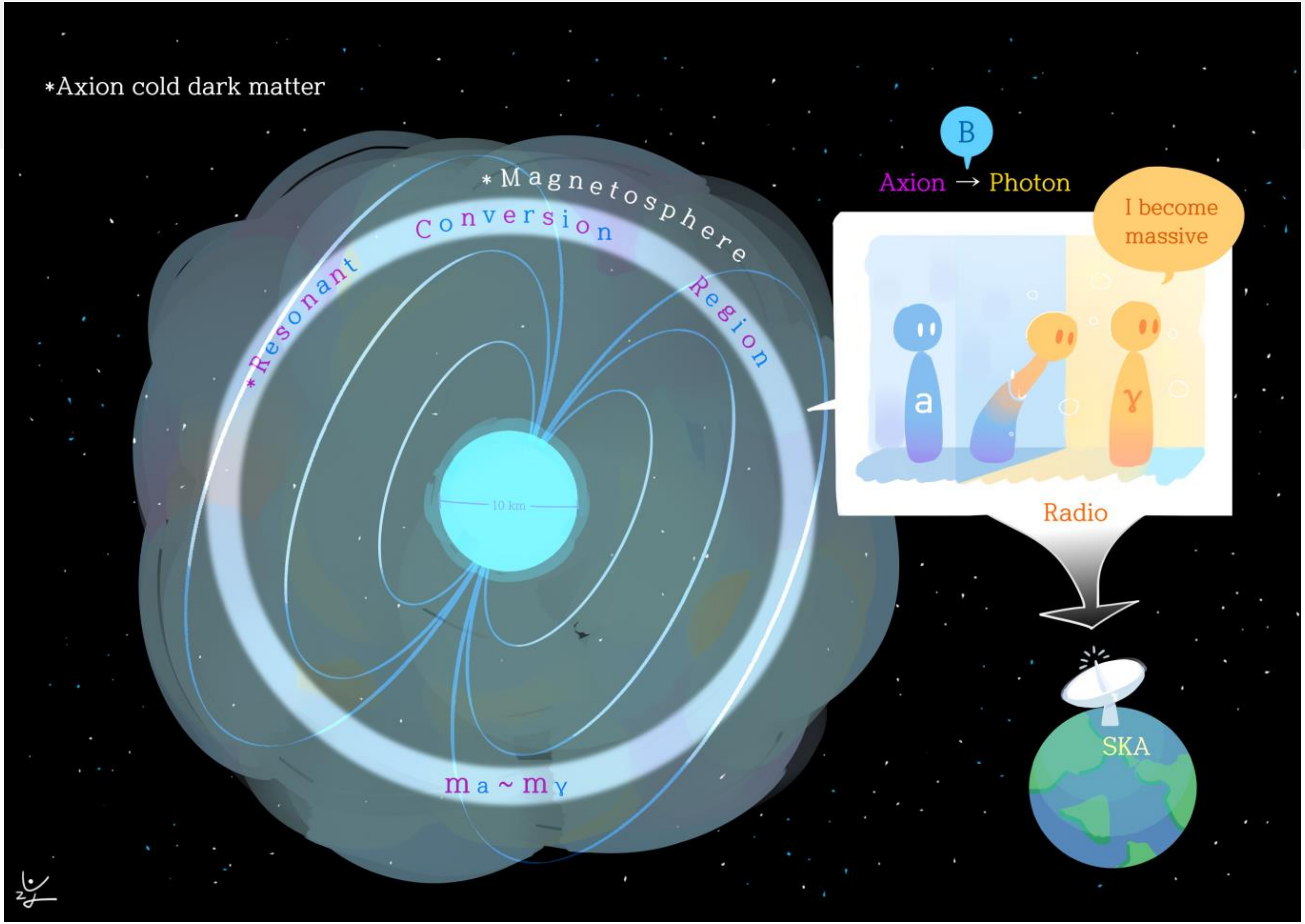




FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

天体磁层中的轴子-光子共振过程

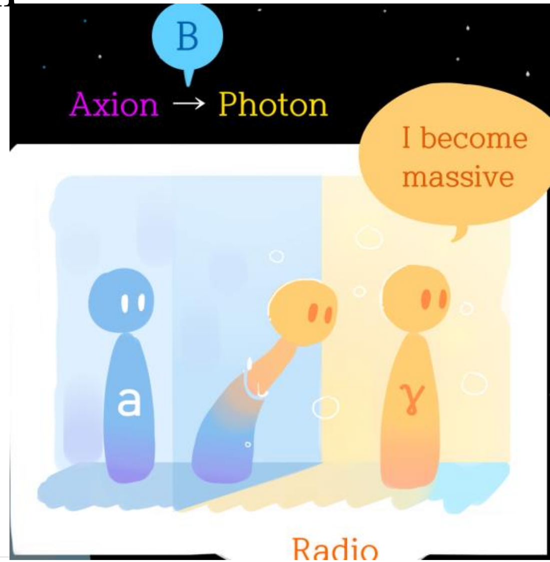
$$L_{\text{int}} = \frac{1}{4} g \tilde{F}^{\mu\nu} F_{\mu\nu} a = -g \mathbf{E} \cdot \mathbf{B} a,$$

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

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

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

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



Line-like radio signal from axion DM

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

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, $S_\gamma \sim 0.51$ 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.

探测暗物质的热门新方法

FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001, arXiv:1803.08230, Cited by 119 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]

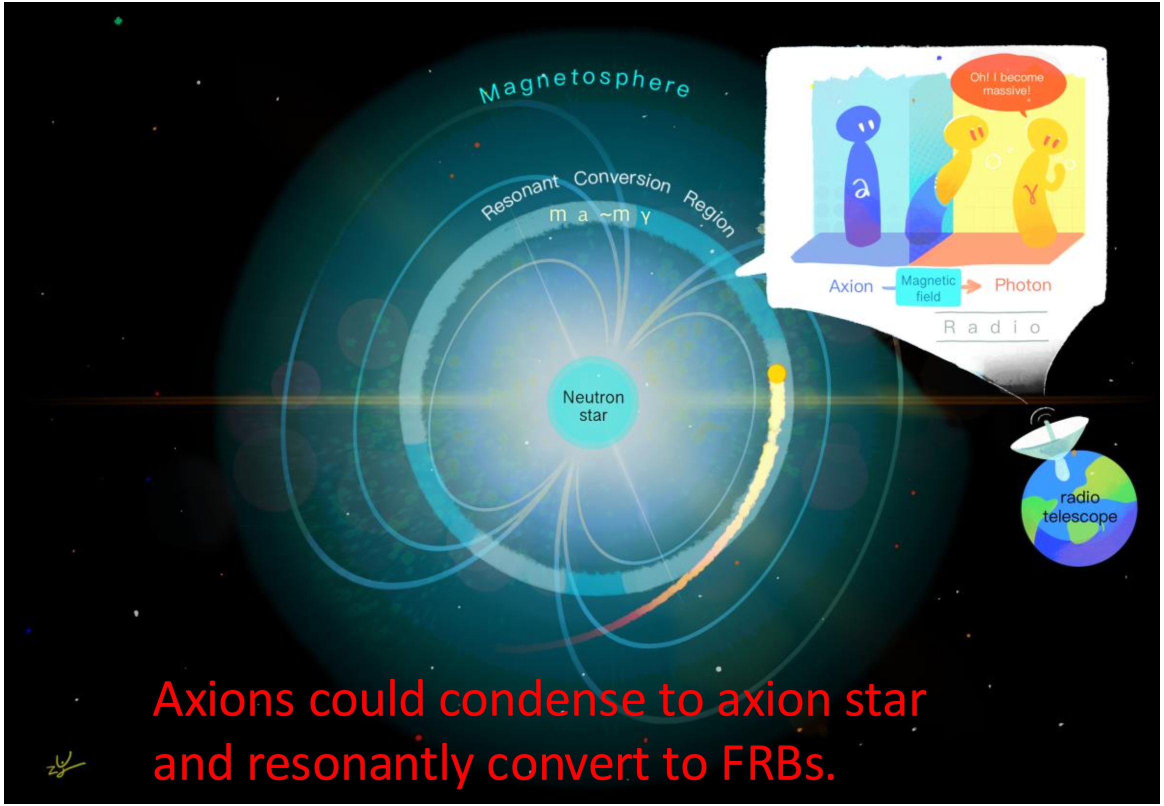
✓ Pierre Sikivie, Rev.Mod.Phys.93(2021)1,015004

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

✓ Phys. Rept. 1052(2024)1-48

✓ Science Advances Volume 8, Issue 8

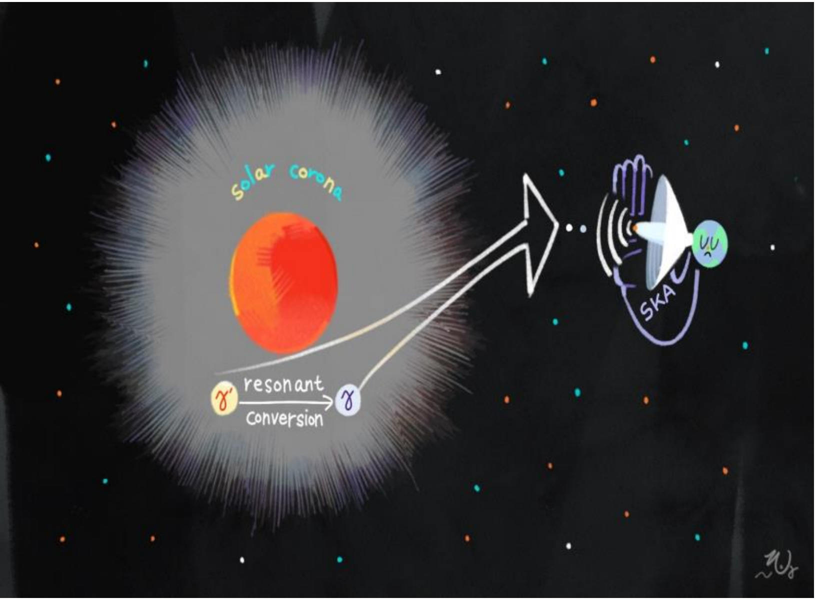
Generalize to axion star/FRBs

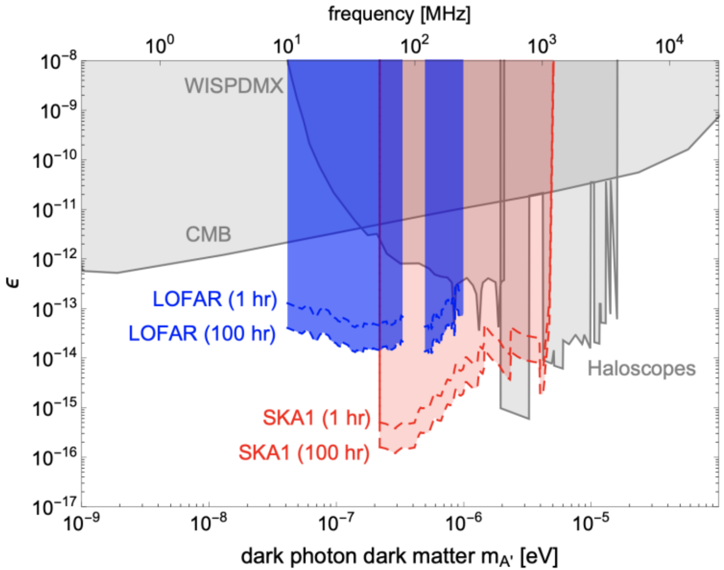


James Buckley, Bhupal Dev, Francesc Ferrer, FPH, *Phys.Rev.D* 103 (2021) 4, 043015

Generalize to dark photon DM case

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

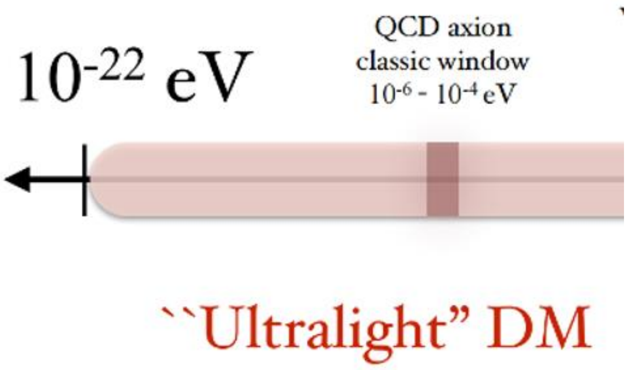




See Jia Liu, Haipeng An's works for further study with real data

Outline

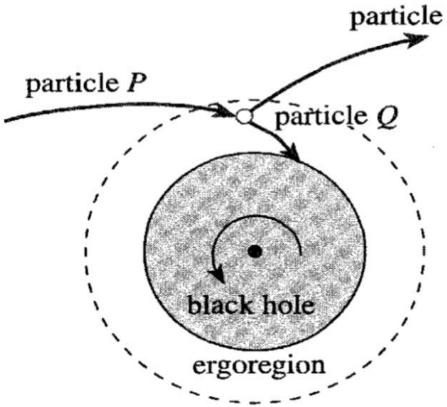
1. Axion and axion dark matter (DM), Gravitational wave (GW)
2. DFSZ axion and its phase transition GW signals
3. μeV axion and radio signals of axion DM (multi-messenger)
4. 10^{-12}-10^{-17} eV axion: GW and pulsar timing measurement
5. 10^{-21} eV fuzzy axion DM GW
6. Summary and outlook



What is superradiance?

When Klein (-Gordon) meets Kerr——superradiance

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



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

物体坍缩形成黑洞后，将最后终结于由克尔解描述的一个稳态。

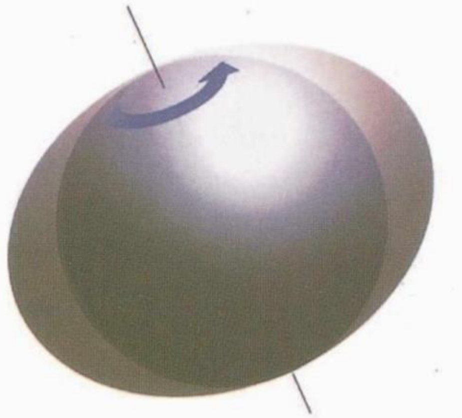


图6.8　当一个“克尔”黑洞的旋转加快时它的赤道附近鼓了出来。而零旋转的黑洞是

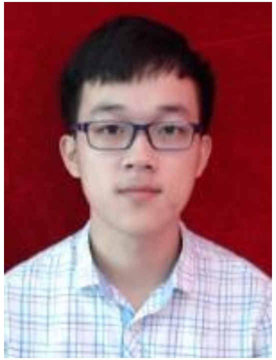
书名：时间简史（插图本）
作者：【英】霍金

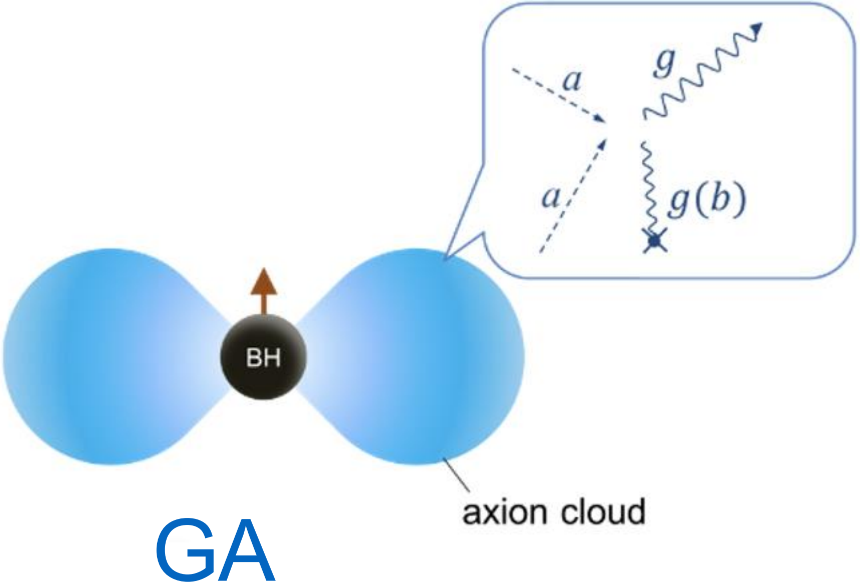
Exponential growth solution of Klein-Gordon equation due to the boundary condition at the horizon of Kerr BH. Ultralight axion can form axion cloud around rotating BH， Gravitational atom (GA).

GW of ultralight DM from black hole:

Gravitational atom from superradiance

1. Axions can annihilate to GW
2. Energy-level transition of GA





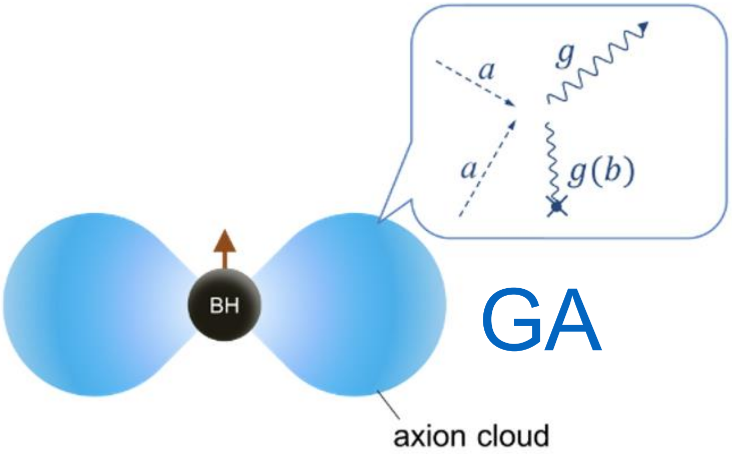
Jing Yang, FPH Phys.Rev.D 108 (2023) 10, 103002
Jing Yang, Ning Xie, FPH **arXiv:2306.**17113
Ning Xie, FPH SCPMA Vol.66, No.1(2024)
Ning Xie, FPH*, arXiv:2503.10347;

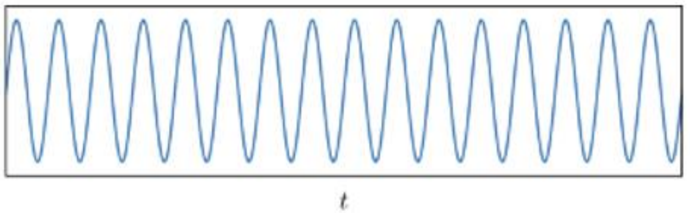
GW of ultralight DM from black hole

Axions can annihilate to GW

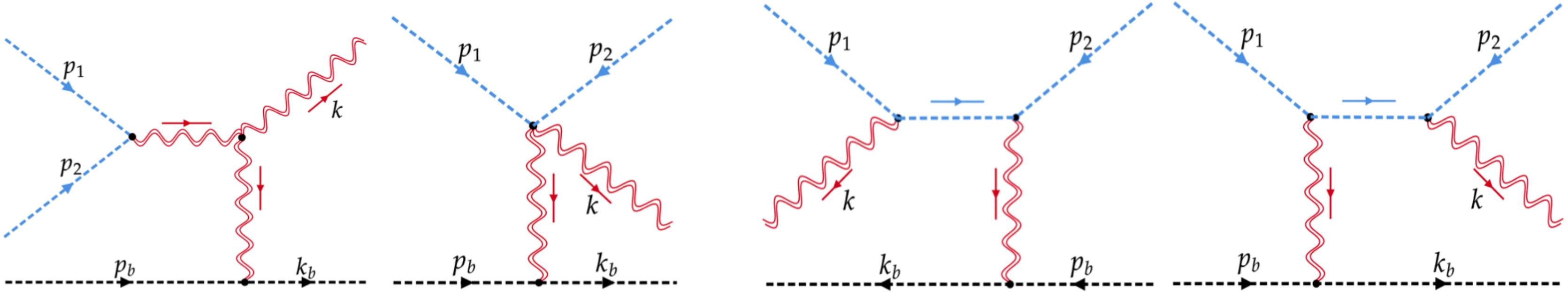
A. Arvanitaki and S. Dubovsky, Phys. Rev. D 83, 044026 (2011)
R. Brito, V. Cardoso and P. Pani, Class. Quant. Grav. 32, no.13, 134001 (2015)
H. Yoshino and H. Kodama, PTEP 2014, 043E02 (2014)

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



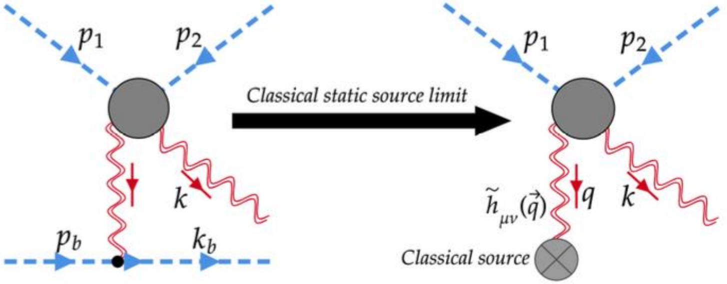


Microscopic physics



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

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



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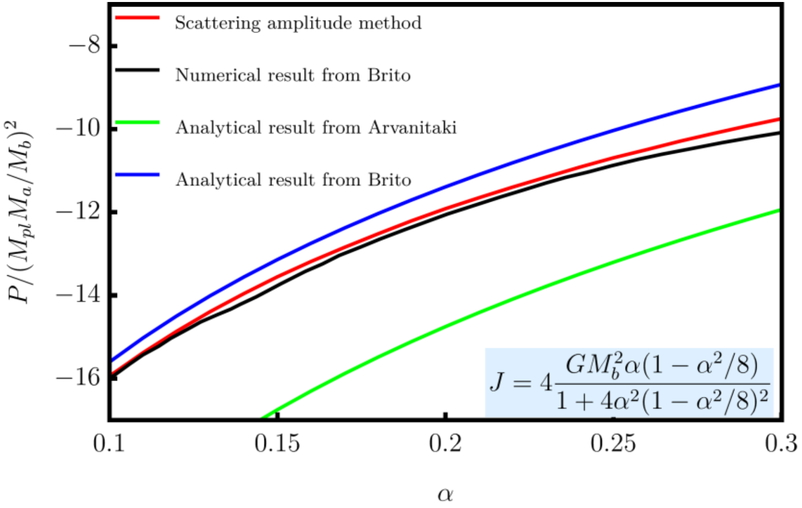
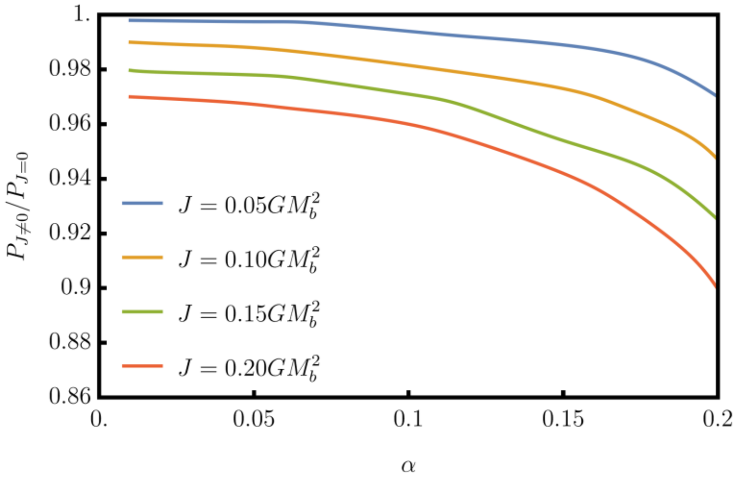
GW radiation from axion annihilation





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

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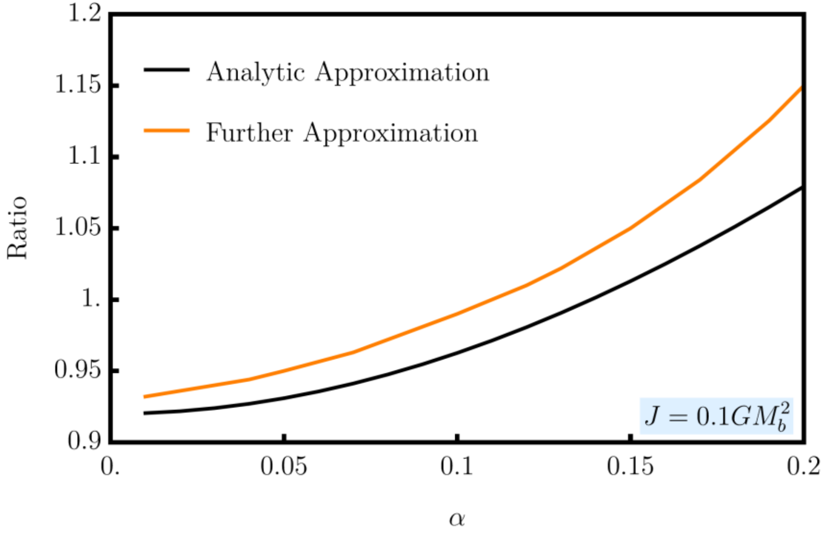
Phys.Rev.D 108 (2023) 10, 103002

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

GW radiation from axion annihilation



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

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

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Phys.Rev.D 108 (2023) 10, 103002

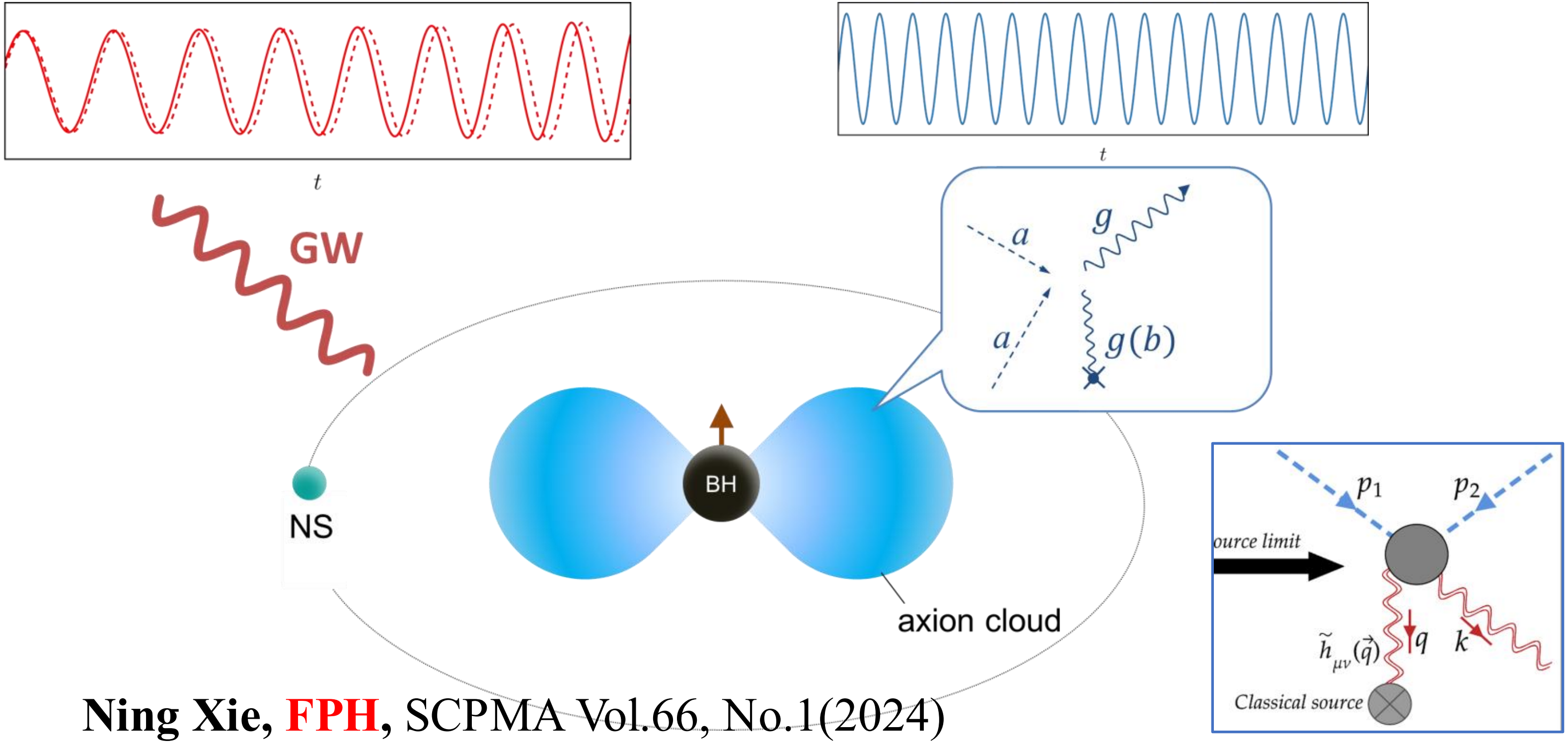
- ✓ monochromatic GW signal $\omega_{ann} \sim 2\ m_a$
- ✓ gradually depletion of axion cloud (DC) and reduce GA mass

Advantages

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

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

Imprints of axions on GW



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

Imprints of axions on GW

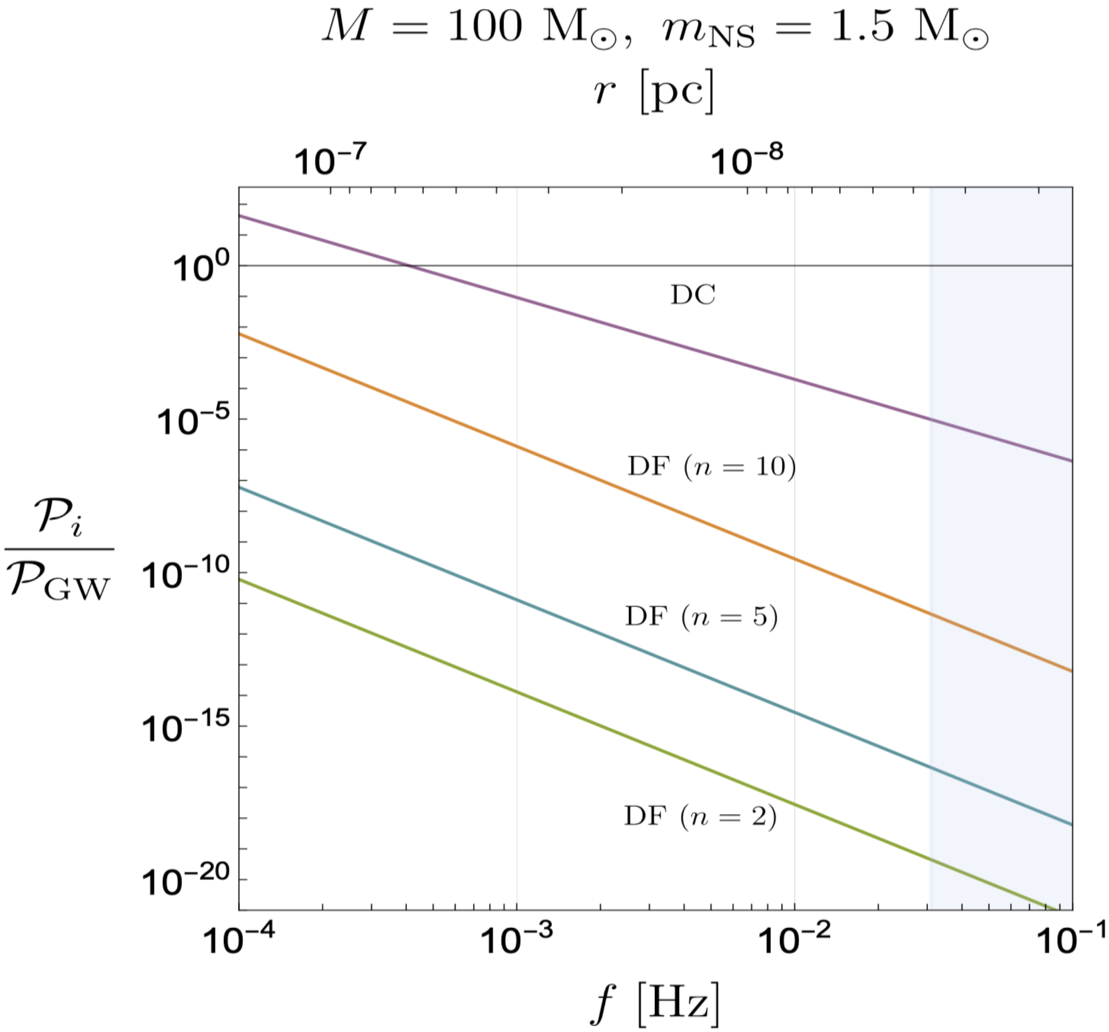
Without ultralight axions $-\frac{\mathrm{d}E_0}{\mathrm{d}t} = \mathcal{P}_{\mathrm{GW}}$ $\mathcal{P}_{\mathrm{GW}} = \frac{32}{5}\mu^2 r^4 \omega^6$

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

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

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

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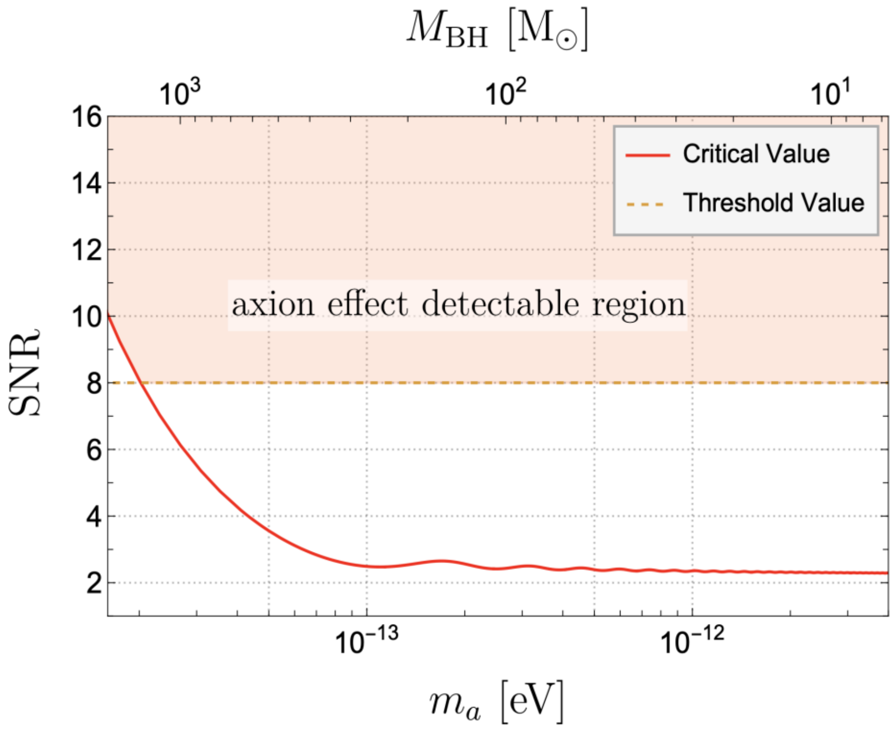
Complementary search: GW+PTA



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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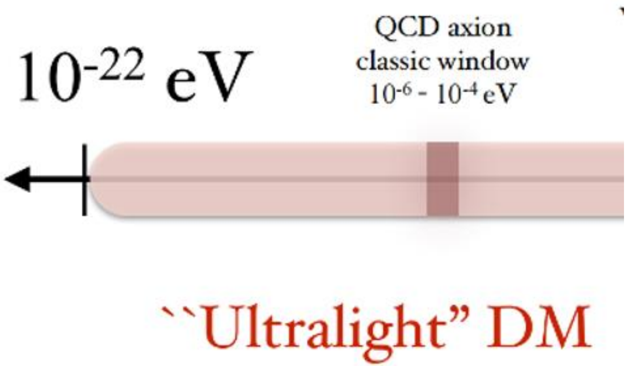
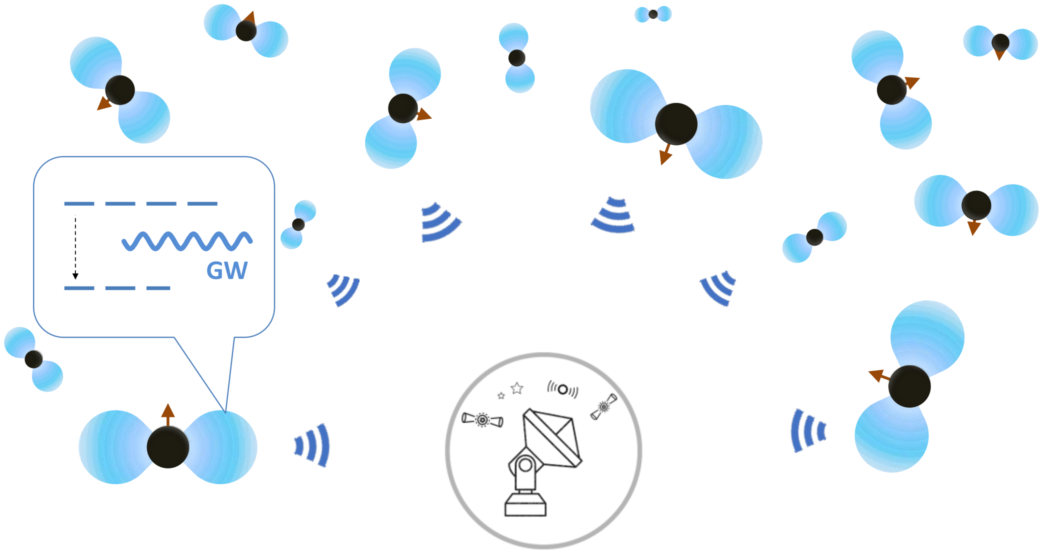


Fuzzy axion (DM) particles



The cosmic populated SMBHs dressed with axion cloud as a natural source of nano-Hertz SGWB. 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.

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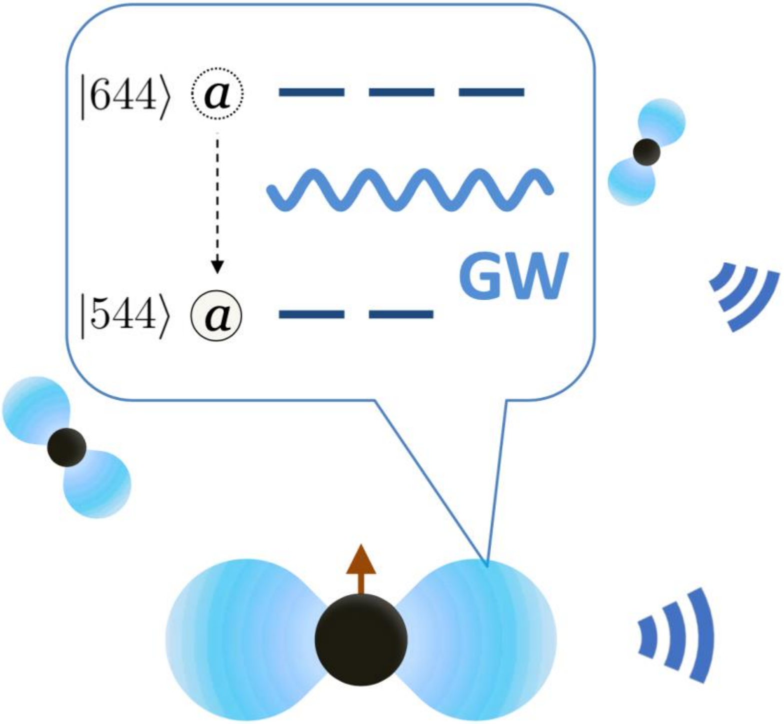
Fuzzy axion (DM) particles



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

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

超轻轴子云的引力波

随机引力波背景

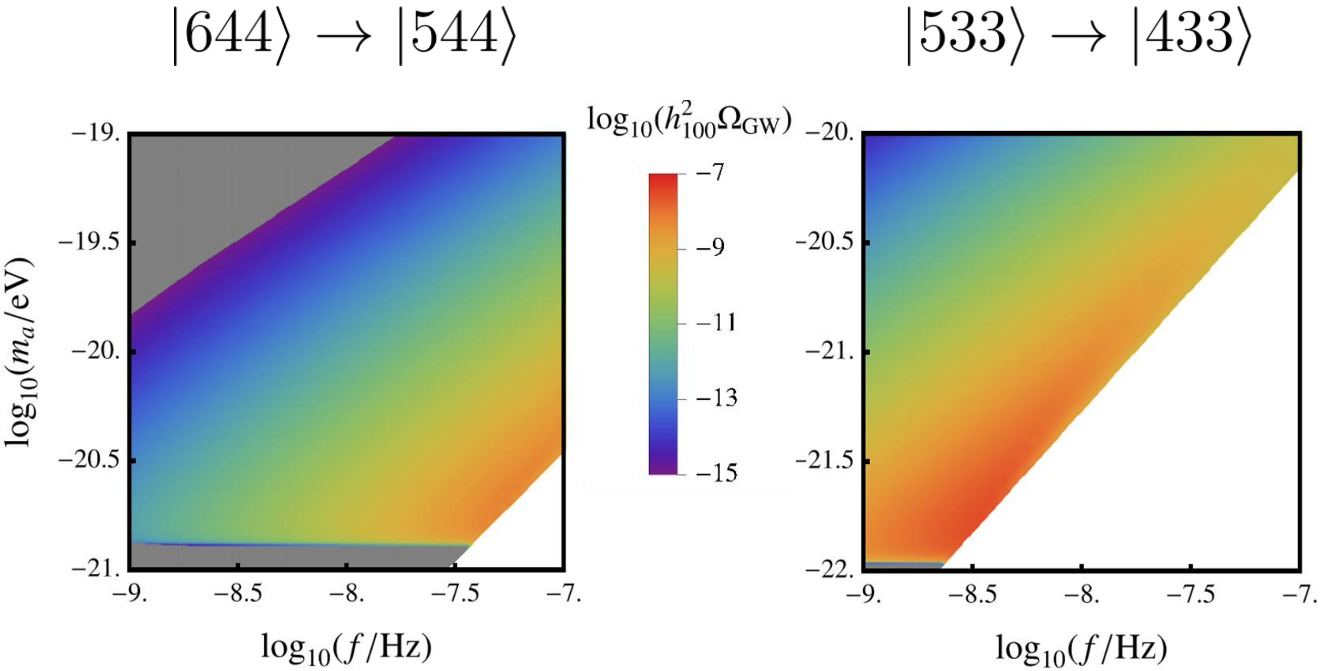
$$\Omega_{\rm gw}(f) = \frac{f}{\rho_c}\int dM dz \frac{dt}{dz}\frac{d\dot{n}}{dM}\frac{dE_s}{df_s},$$

$$dt/dz = \frac{1}{H_0(1+z)\sqrt{\Delta(z)}}$$

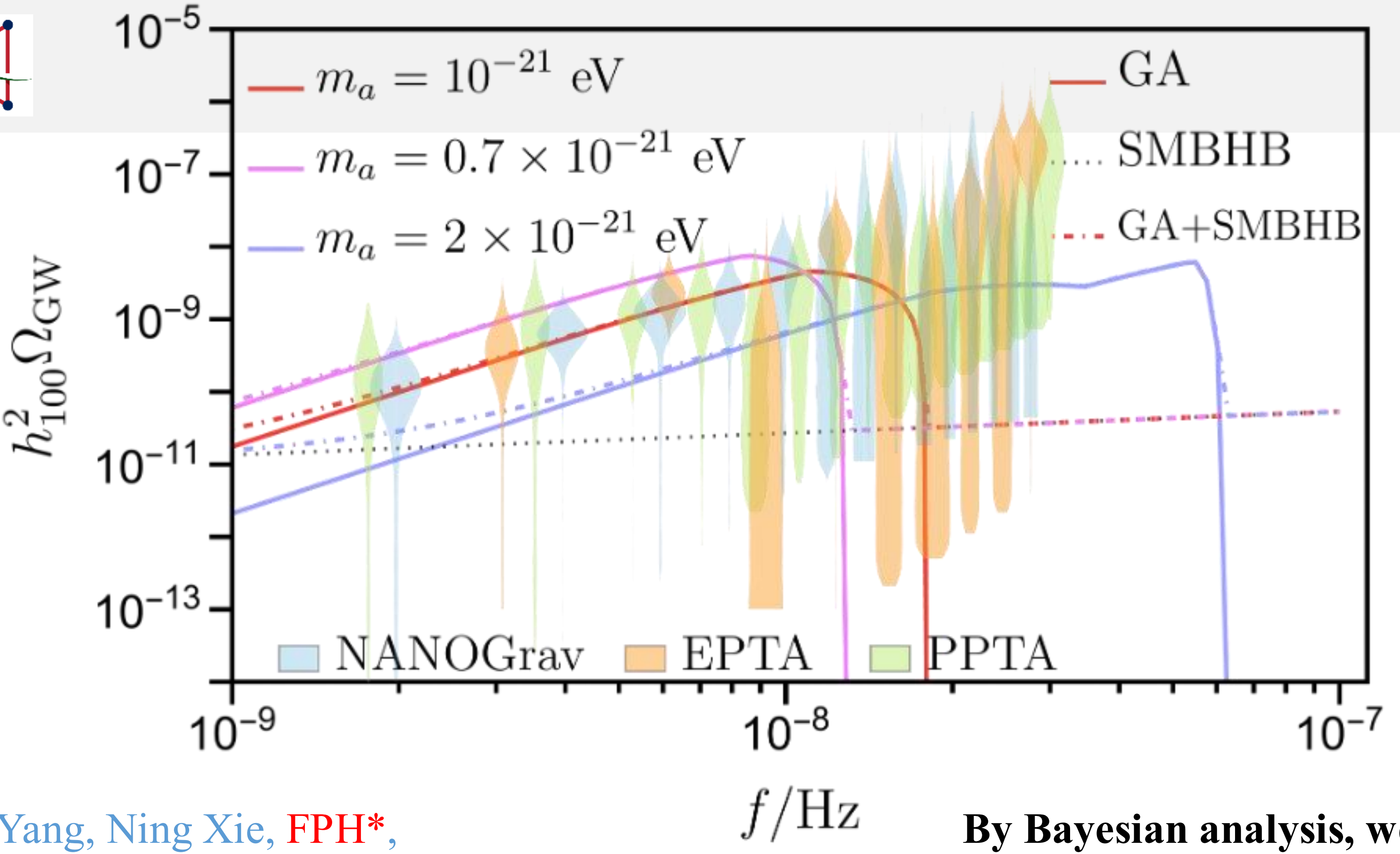
$$d\dot{n}/(dM) = (1/t_0)(dn/dM)$$

$$\frac{dE_s}{df_s} \approx E_{\rm GW}\delta\left(f(1+z) - f_s\right)$$

随机引力波背景



图注：不同超轻轴子质量下随机引力波背景的能量密度



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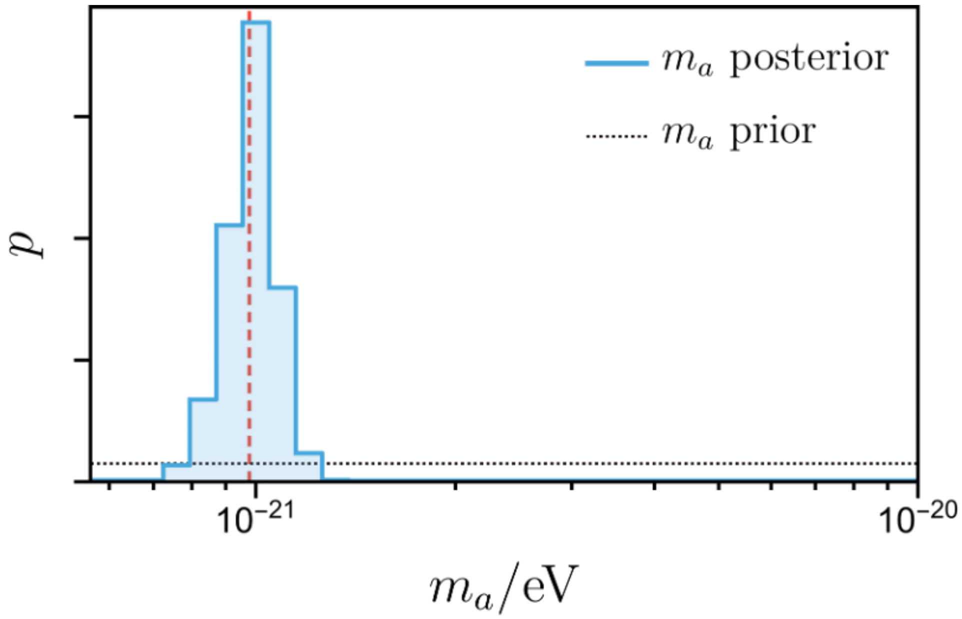
By Bayesian analysis, we find fuzzy DM is favored by the data.

随机引力波背景

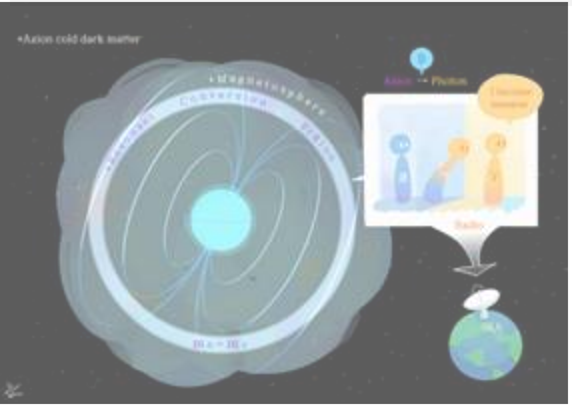
贝叶斯分析

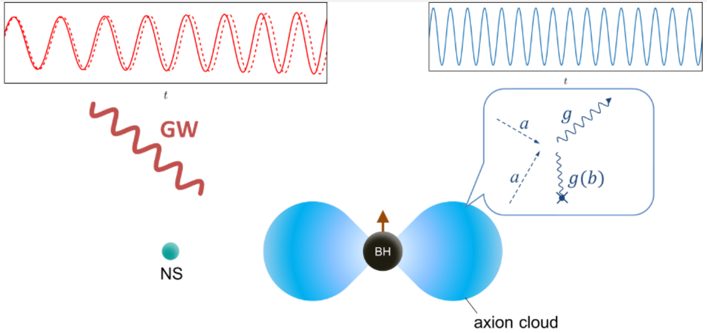


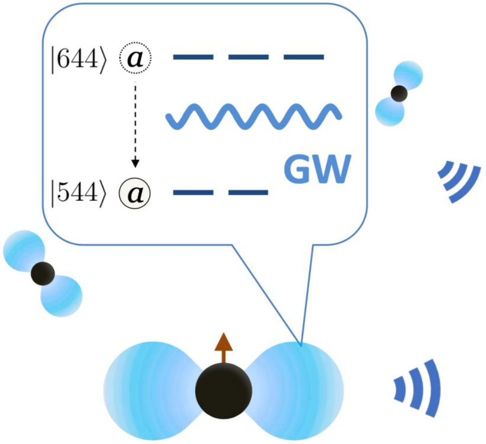
贝叶斯因子
(GA+SMBHB/SMBHB)=7.1

图注：NG15数据给出的超轻轴子质量的后验分布，红色虚线标出了最大概率的质量大小

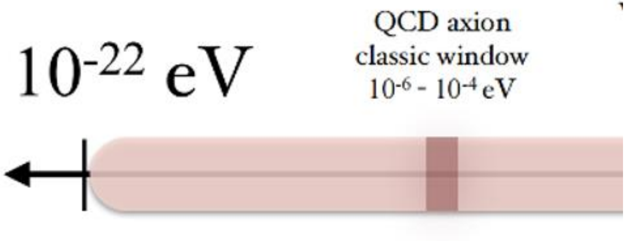
6. Summary and outlook







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



``Ultralight” DM

Thanks！ Comments and collaborations are welcome!

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