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

超轻轴子暗物质的引力波探测
Gravitational wave detection of ultralight axion dark matter

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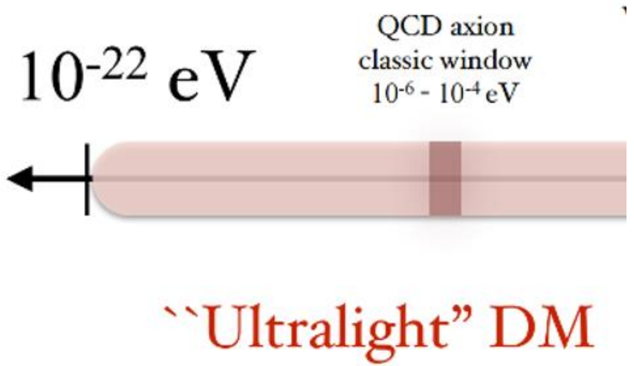
Sun Yat-sen university

Higgs potential 2024@Hefei, 2024.12.22

Outline

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

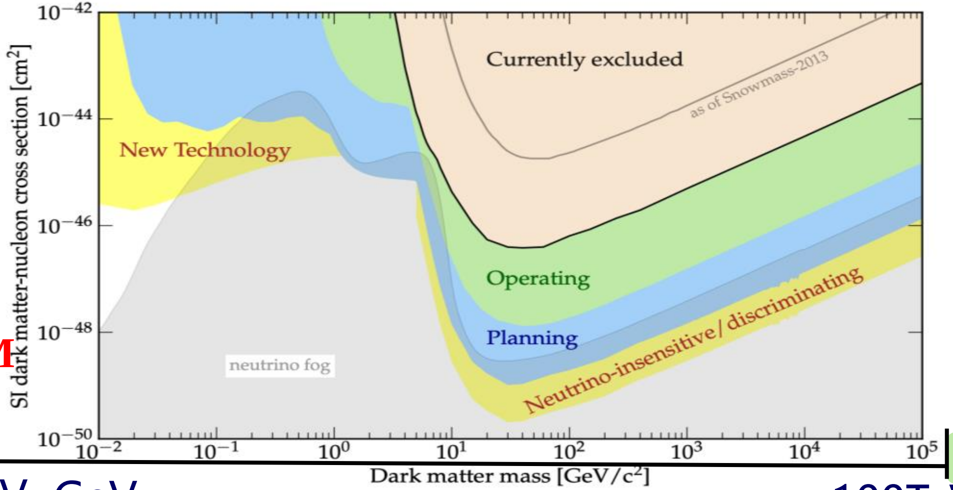


Motivation DM theory and experiments status

arXiv: 1904:07915
Snowmass 2021,
arXiv: 2209.07426

What is the microscopic nature of DM?

No expected signals in these region



Ultralight DM
Axion/ALP

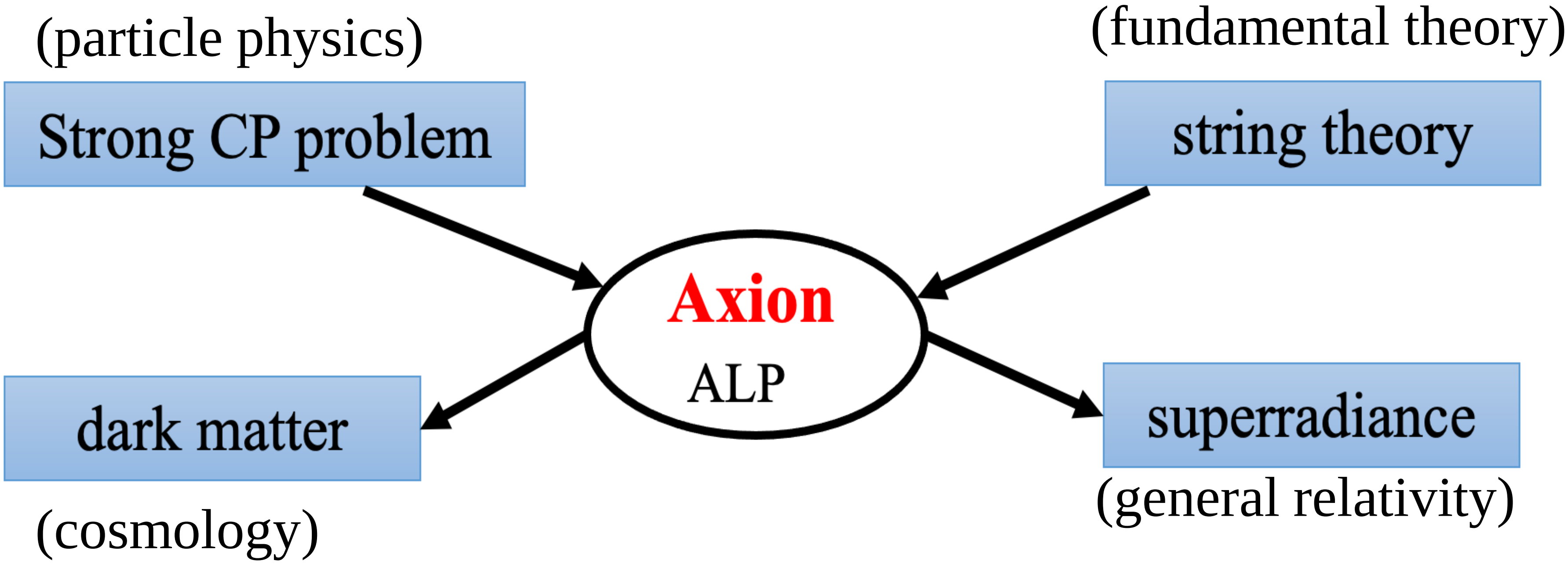
10^{-22}eV keV GeV WIMP 100TeV

Heavy DM
Q-ball/filtered DM

- **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.



Strong CP problem and QCD axion

Why is the CP-violating $\bar{\theta}$ parameter in QCD so small?

The QCD Lagrangian density contains a CP violation term

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta} \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{a\mu\nu}$$

The neutron electric dipole moment with $\bar{\theta}$

$$d_n^{(th)} \simeq 2.4(1.0) \times 10^{-16} \bar{\theta} \text{ e cm}$$

M. Pospelov and A. Ritz, Phys. Rev. Lett. 83, 2526-2529 (1999)

The neutron electric dipole moment

$$|d_n^{(exp)}| < 1.8 \times 10^{-26} \text{ e cm}$$

C. A. Baker, D. D. Doyle, P. Geltenbort, K. Green, M. G. D. van der Grinten, P. G. Harris, P. Iaydjiev, S. N. Ivanov, D. J. R. May and J. M. Pendlebury, et al. Phys. Rev. Lett. 97, 131801 (2006)

$$\bar{\theta} < 10^{-10}$$

Strong CP problem and QCD axion

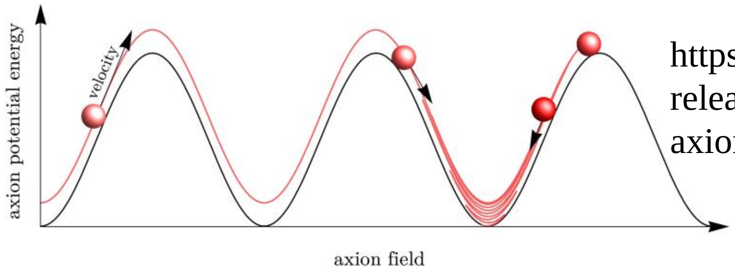
Dynamical solution: U(1) Peccei-Quinn symmetry spontaneously breaking

Promote $\bar{\theta}$ to a dynamical field (=QCD axion)

R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440-1443 (1977)
R. D. Peccei and H. R. Quinn, Phys. Rev. D 16, 1791-1797 (1977)
S. Weinberg, Phys. Rev. Lett. 40, 223-226 (1978) doi:10.1103/PhysRevLett.40.223
F. Wilczek, Phys. Rev. Lett. 40, 279-282 (1978) doi:10.1103/PhysRevLett.40.279

The QCD vacuum energy density is minimized at the CP-conserving point $\bar{\theta} = 0$
C. Vafa and E. Witten, Nucl. Phys. B 234, 173-188 (1984)

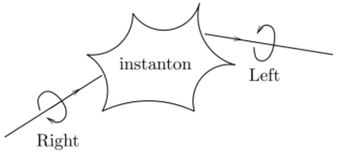
Natural DM candidate through the simple misalignment mechanism, axion cosmic string/domain wall decay



https://www.ias.edu/press-releases/2020/dark-matter-axion-origin

Strong CP problem and QCD axion

Strong CP problem → PQWW → ruled out by $K^{+} \to \pi^{+} + \phi$



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

PQWW → Invisible axion model → DFSZ, KSVZ

DFSZ

$$
\begin{aligned}
V\left(\sigma, H_{\mathrm{u}}, H_{\mathrm{d}}\right) = & \lambda_{\mathrm{u}}\left(\left|H_{\mathrm{u}}\right|^{2}-v_{\mathrm{u}}^{2}\right)^{2}+\lambda_{\mathrm{d}}\left(\left|H_{\mathrm{d}}\right|^{2}-v_{\mathrm{d}}^{2}\right)^{2} \\
& +\lambda\left(|\sigma|^{2}-v_{\sigma}^{2}\right)^{2}+\left(\lambda_{a}\left|H_{\mathrm{u}}\right|^{2}+\lambda_{b}\left|H_{\mathrm{d}}\right|^{2}\right)|\sigma|^{2} \\
& +\lambda_{c}\left(H_{\mathrm{u}}^{i} \epsilon_{ij} H_{\mathrm{d}}^{j} \sigma^{n}+\text{ h.c. }\right)+\lambda_{d}\left|H_{\mathrm{u}}^{i} \epsilon_{ij} H_{\mathrm{d}}^{j}\right|^{2}+\lambda_{e}\left|H_{\mathrm{u}}^{*} H_{\mathrm{d}}\right|^{2}
\end{aligned} \tag{1}
$$

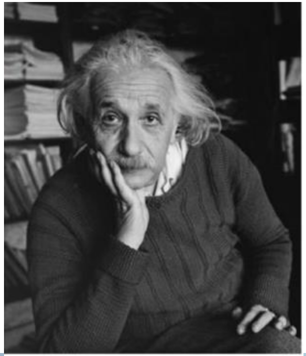
KSVZ

$$
\mathcal{L}_{\mathrm{KSVZ}} \supset \lambda_{K} \sigma Q_{E} Q_{E}^{C}-\lambda\left(|\sigma|^{2}-\frac{f_{a}^{2}}{2}\right)^{2}
$$

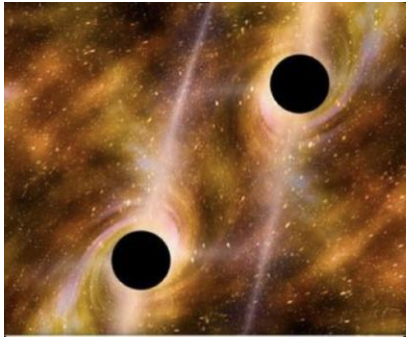
M. Dine, W. Fischler, and M. Srednicki, Physics letters B 104, 199 (1981).

What is GW ?

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



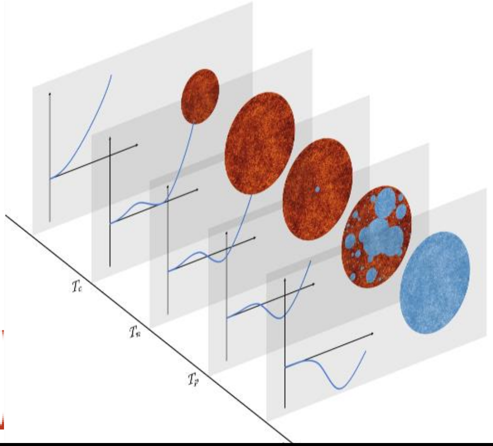
Isolated sources: quadrupole radiation

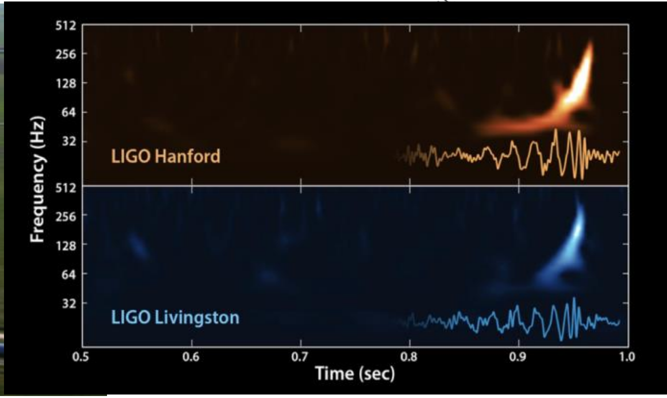


$$h_{ij} \simeq \frac{2G}{c^4 r} \ddot{Q}_{ij}^{TT}(t - r/c)$$

Stochastic sources: anisotropic stress tensor

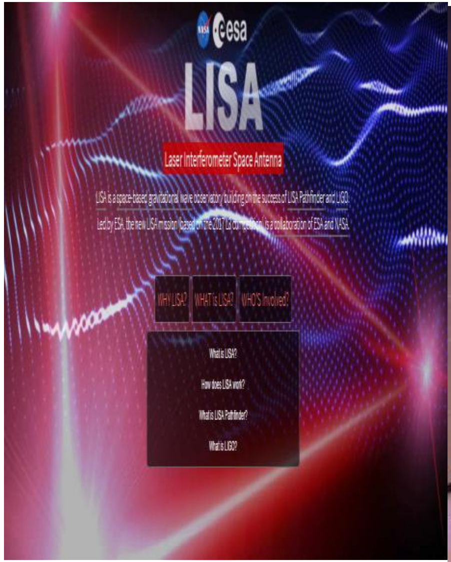
$$\Pi_{ij}(\mathbf{x}, t)$$

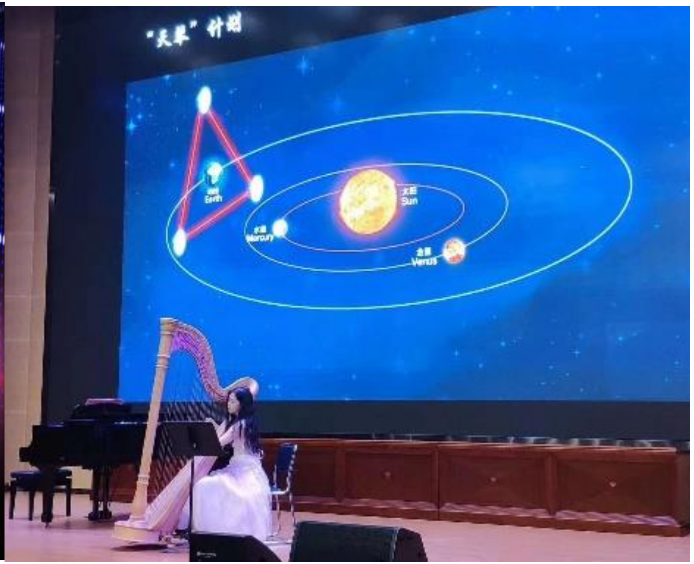


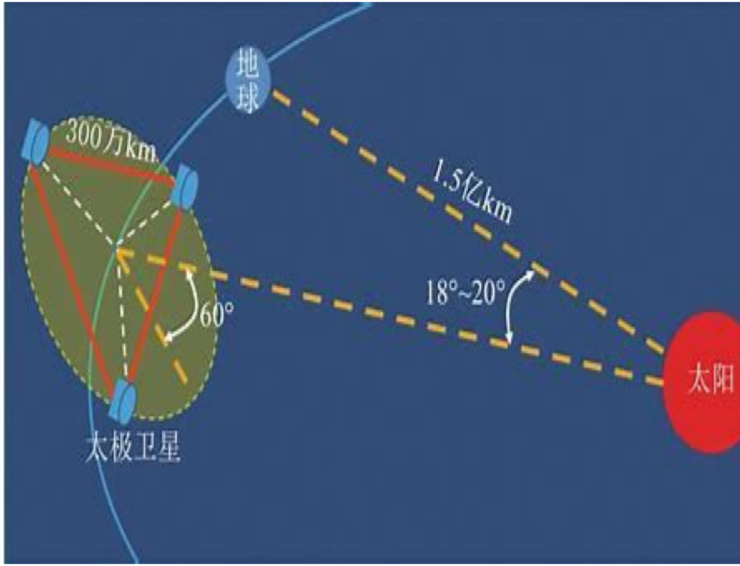


GW experiments

LISA/TianQin/Taiji ~2034





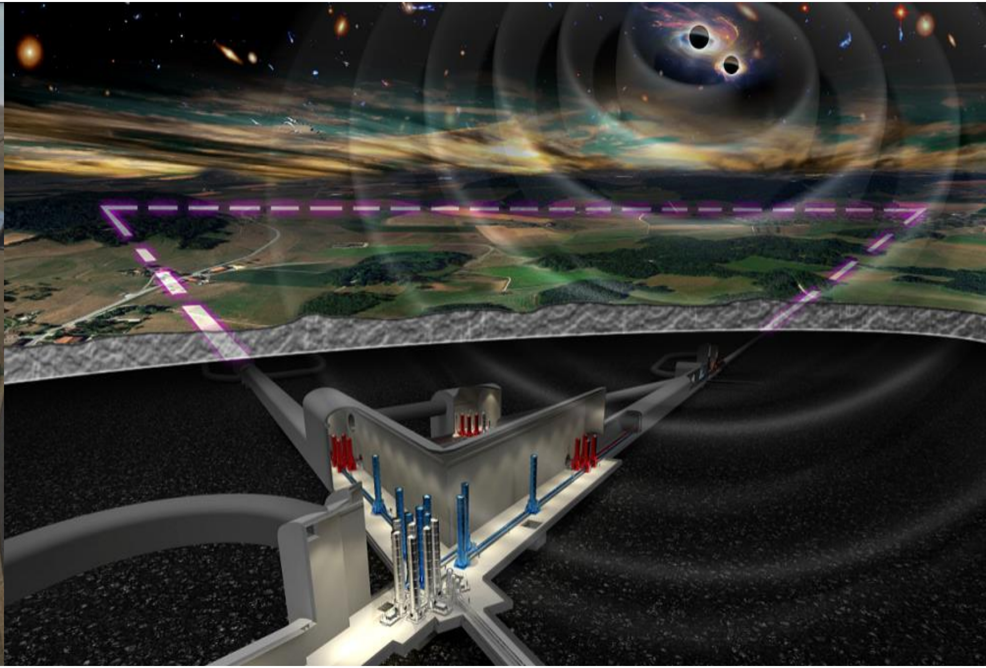


“天琴”

“Harpe in space”

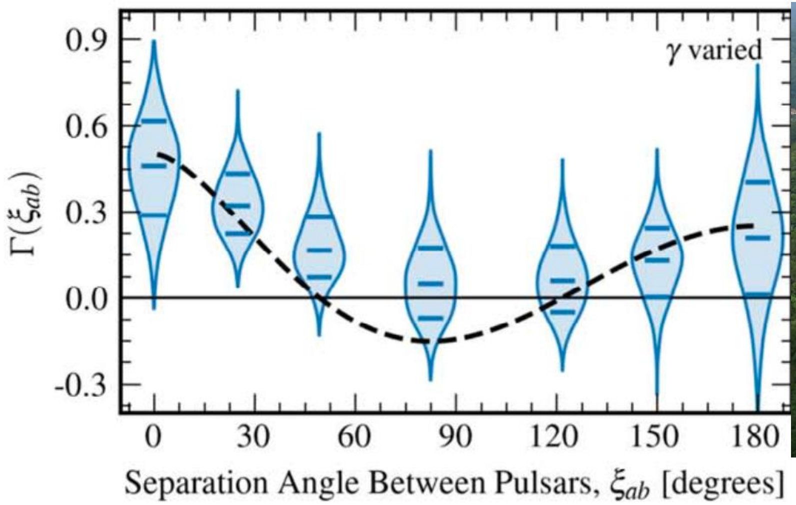
GW experiments

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

DM and GW

- ➢ The observation of GW@LIGO initiates a new era of exploring DM by GW.
- ➢ DM can trigger a SFOPT in the early universe and detectable GW signals.
- ➢ SFOPT could provide a new approach for DM production.

Credit: Gianfranco Bertone et. al.

General GW in the early universe

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

各向异性
剪切应力张量

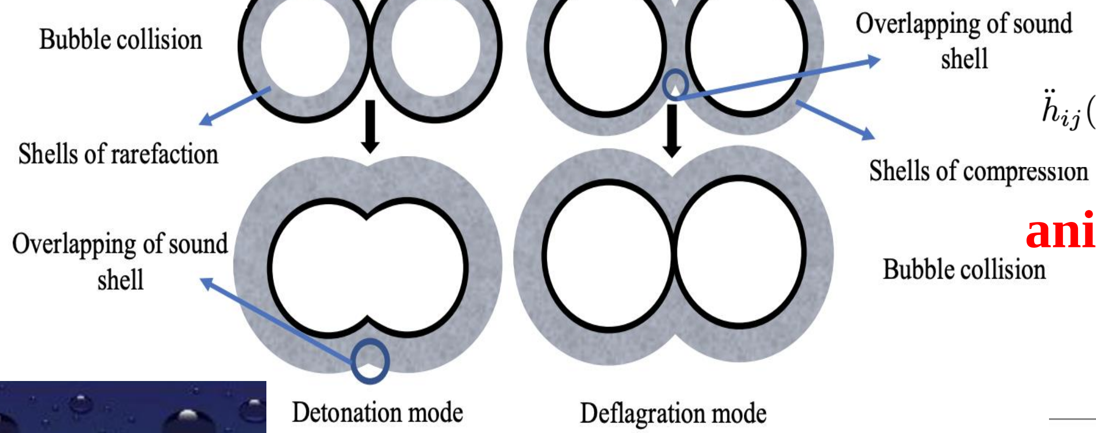
- ✓ phase transition:TeV physics (focus)
- ✓ cosmic defects: cosmic string, domain wall…

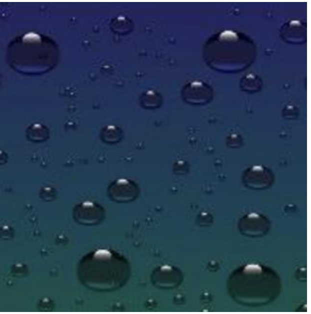
Possible sources of tensor anisotropic stress in the early universe

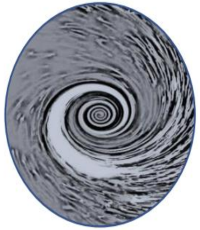
- Scalar field gradients $\Pi_{ij} \sim [\partial_i\phi\partial_j\phi]^{TT}$ eg. Collisions of bubble walls, cosmic string
- Bulk fluid motion $\Pi_{ij} \sim [\gamma^2(\rho+p)v_iv_j]^{TT}$ eg. Sound waves and turbulence in the fluid
- Gauge fields $\Pi_{ij} \sim [-E_iE_j - B_iB_j]^{TT}$ eg. Primordial magnetic fields (MHD turbulence)
- Second order scalar perturbations, Π_{ij} from a combination of $\partial_i\Psi, \partial_i\Phi$
- … arXiv:1801.04268

Phase transition GW in a nutshell

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







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

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

anisotropic stress tenor: source of GW

General form Π_{ij}
$[\partial_i\phi\partial_j\phi]^{TT}$
$[\gamma^2(\rho+p)v_iv_j]^{TT}$
$[-E_iE_j - B_iB_j]^{TT}$
$\partial_i\Psi, \partial_i\Phi$

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

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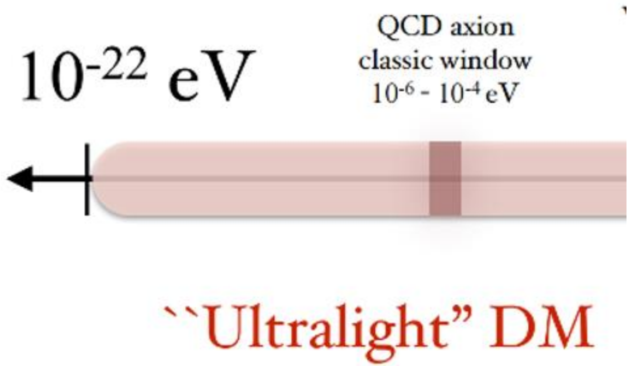


GW detection of DFSZ axion models

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

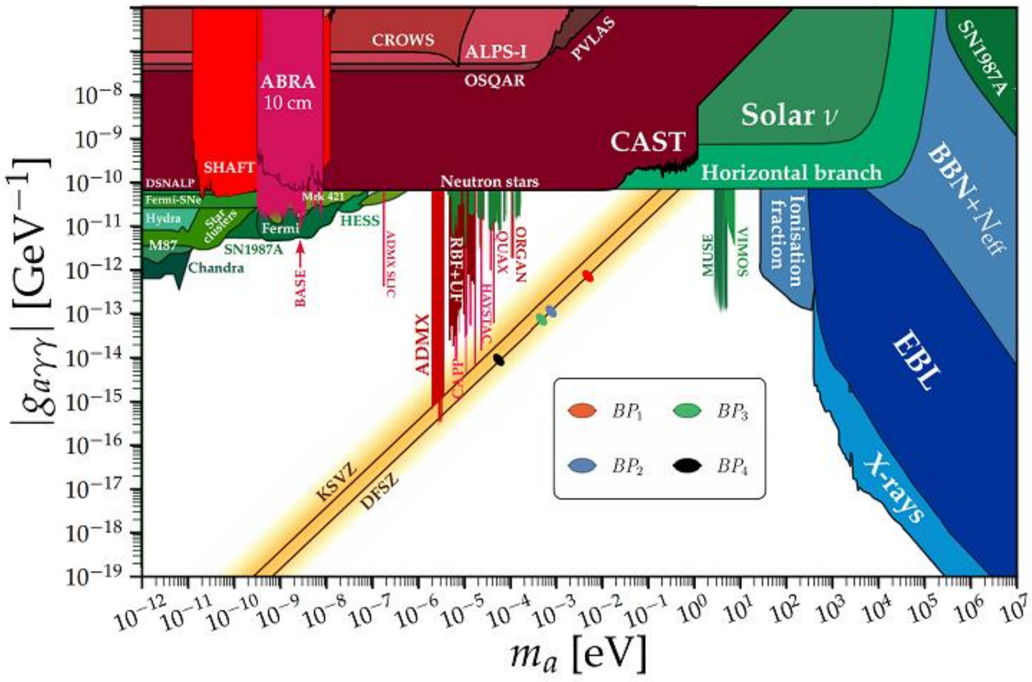
$$
\begin{aligned}
V_{\text{tree}}^{DFSZ} = & -\mu_1^2|H_u|^2 - \mu_2^2|H_d|^2 + \lambda_1|H_u|^4 + \lambda_2|H_d|^4 + \lambda_4|H_u^\dagger H_d|^2 \\
& - \mu_3^2|\sigma|^2 + \lambda_3|\sigma|^4 + \lambda_{12}|H_u|^2|H_d|^2 + \lambda_{13}|\sigma|^2|H_u|^2 \\
& + \lambda_{23}|\sigma|^2|H_d|^2 + \left(\lambda_5\sigma^2\tilde{H}_u^\dagger H_d + \text{h.c.}\right)
\end{aligned} \quad (1)
$$

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

$$
V_{\text{eff}}\left(v_\sigma, T\right) \equiv V_{\text{tree}}\left(v_\sigma\right) + V_{\text{CW}}(v_\sigma) + V_{\text{T}}(v_\sigma, T)
$$

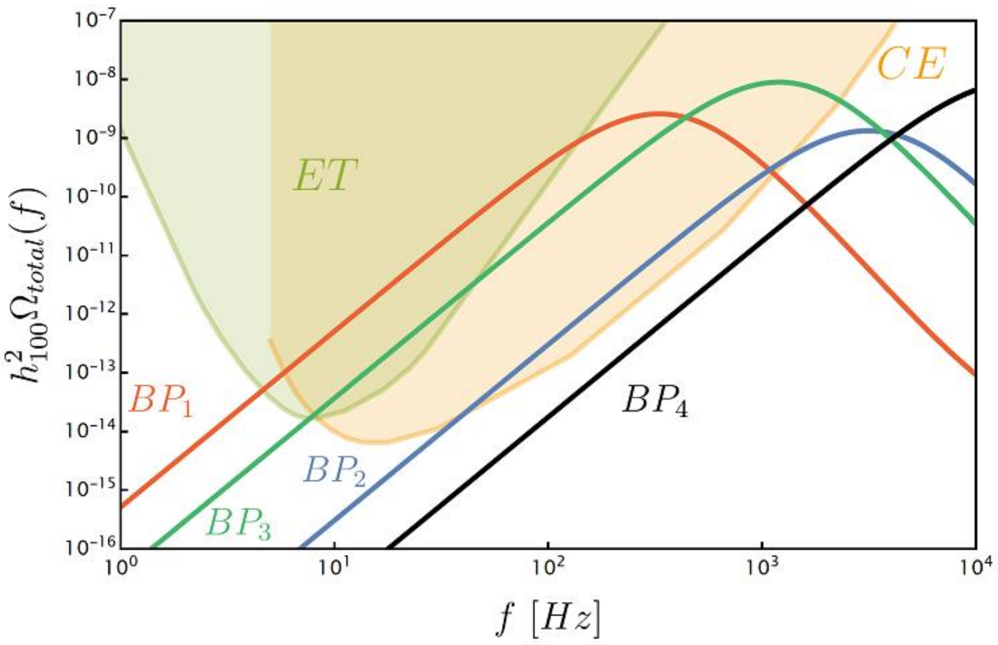
arXiv: 2404.18703, Aidi Yang, FPH

GW detection of DFSZ axion models



arXiv: 2404.18703, Aidi Yang, FPH

GW detection of DFSZ axion models



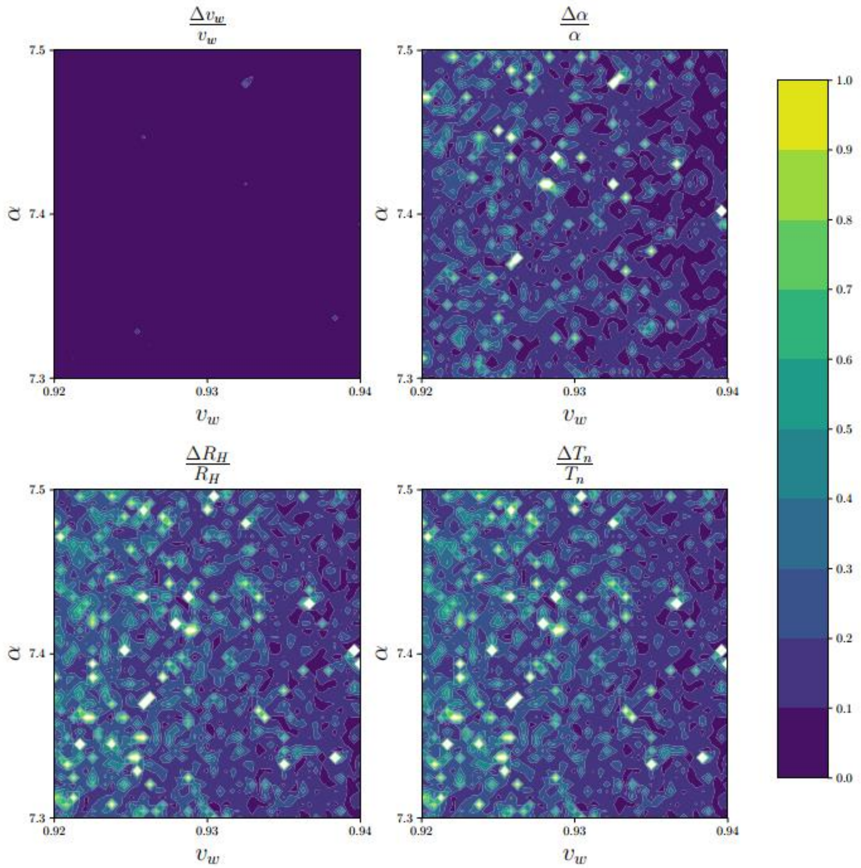
$$SNR_{\rm gw} = \sqrt{T_t \int_{f_{\rm min}}^{f_{\rm max}} df \left(\frac{h^2_{100}\Omega_{\rm GW}}{h^2_{100}\Omega_{\rm sens}}\right)^2}$$

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 models

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

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.



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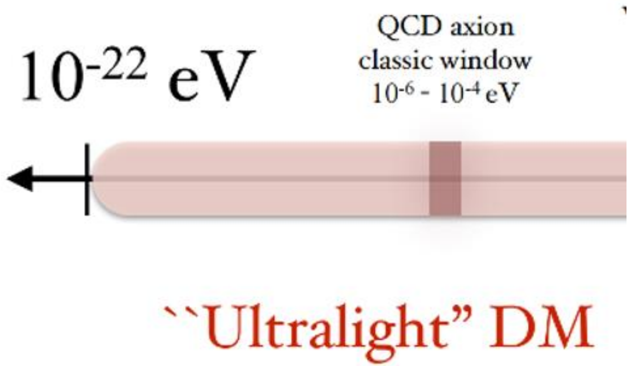
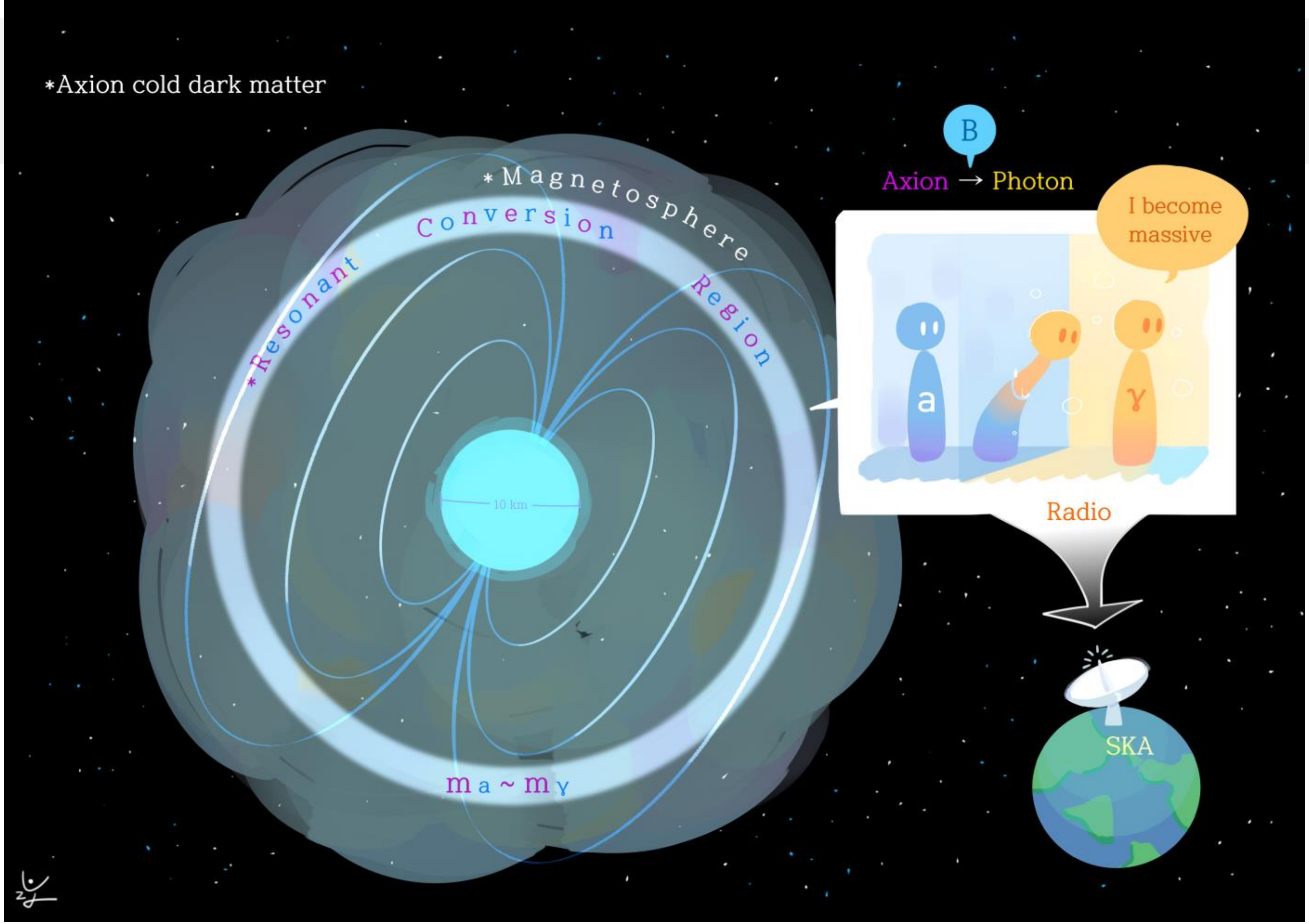




FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

Axion-photon conversion in magnetosphere

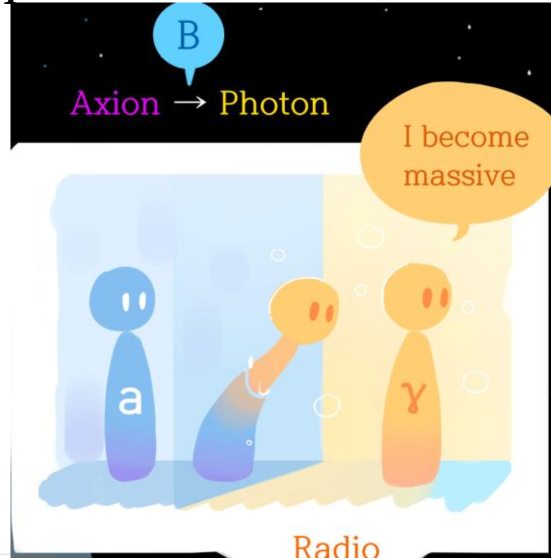
$$L_{\text{int}} = \frac{1}{4} g \tilde{F}^{\mu\nu} F_{\mu\nu} a = -g \mathbf{E} \cdot \mathbf{B} a,$$

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 for axion DM

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

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

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.

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 113 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]

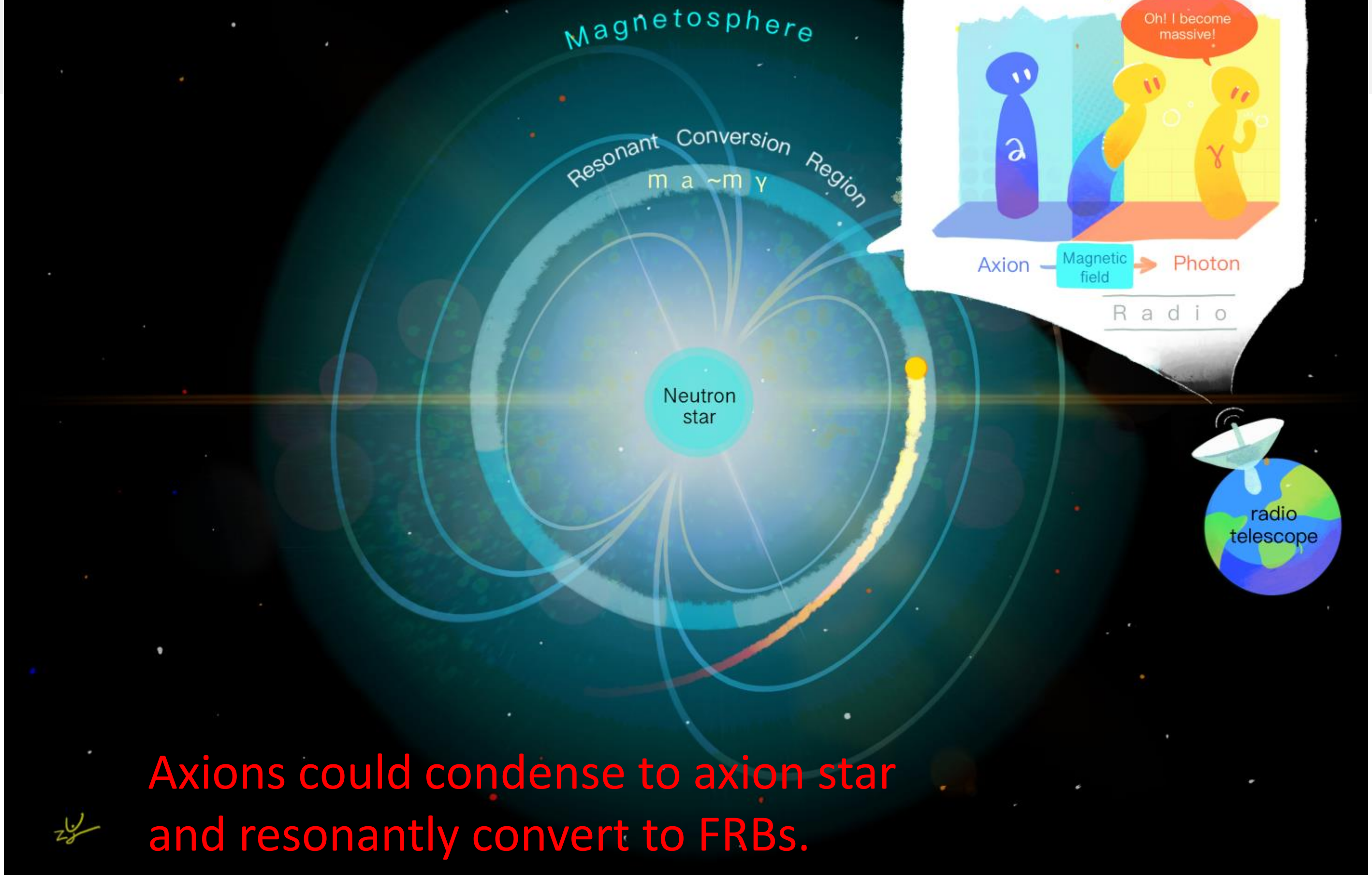
✓ Pierre Sikivie, Rev.Mod.Phys.93(2021)1,015004

✓ 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

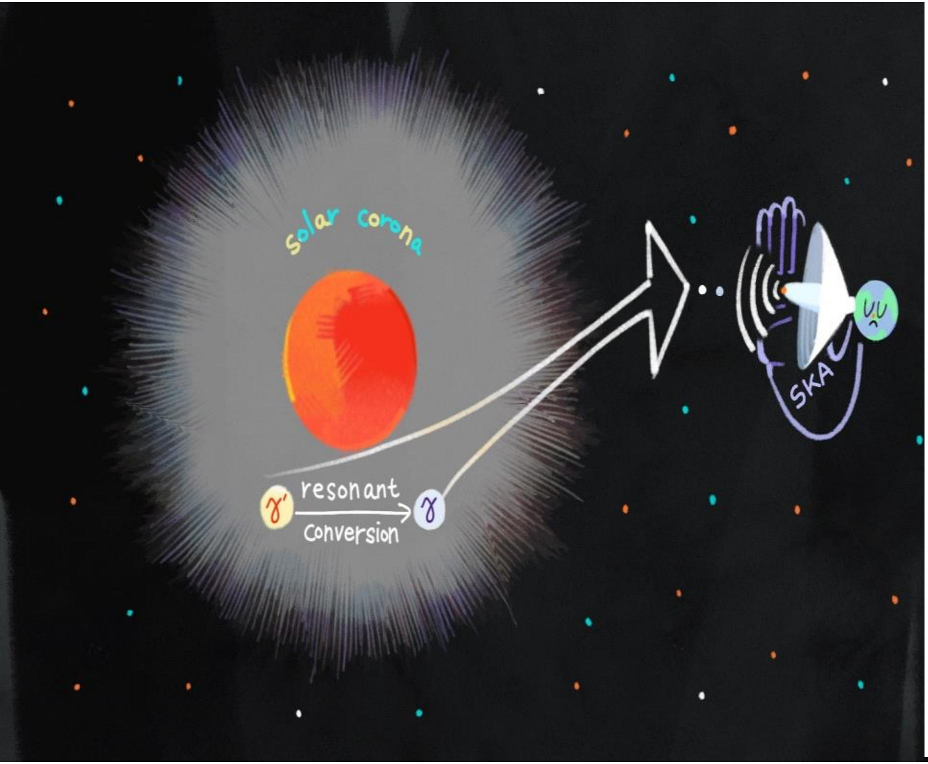


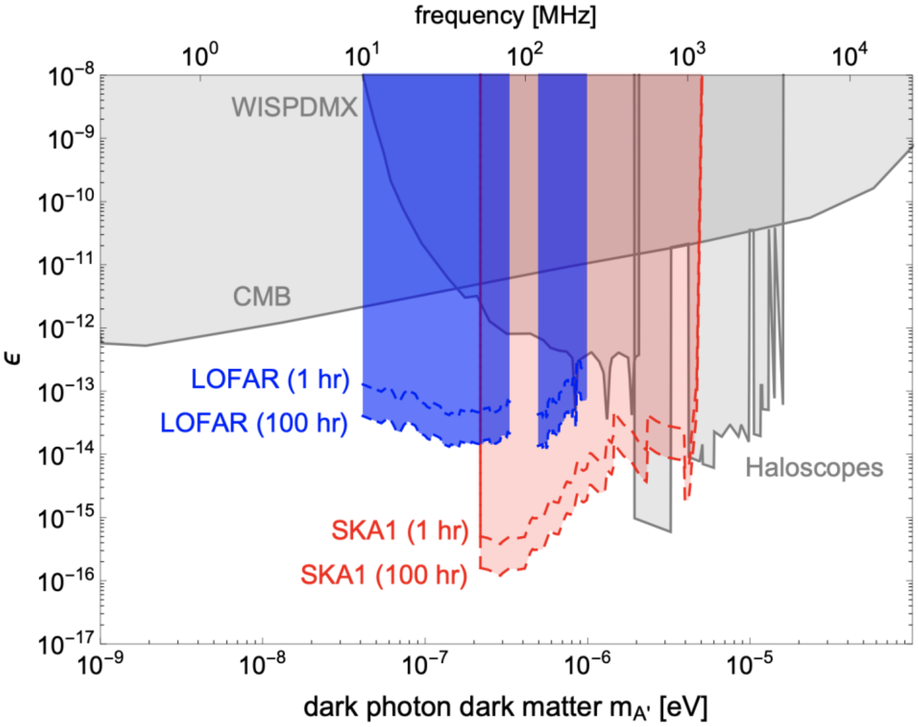
Axions could condense to axion star and resonantly convert to FRBs.

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)





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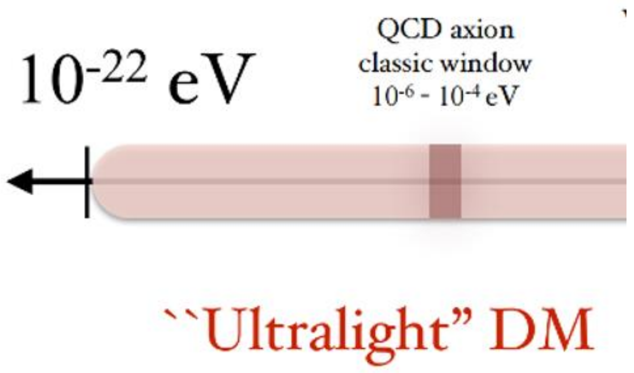
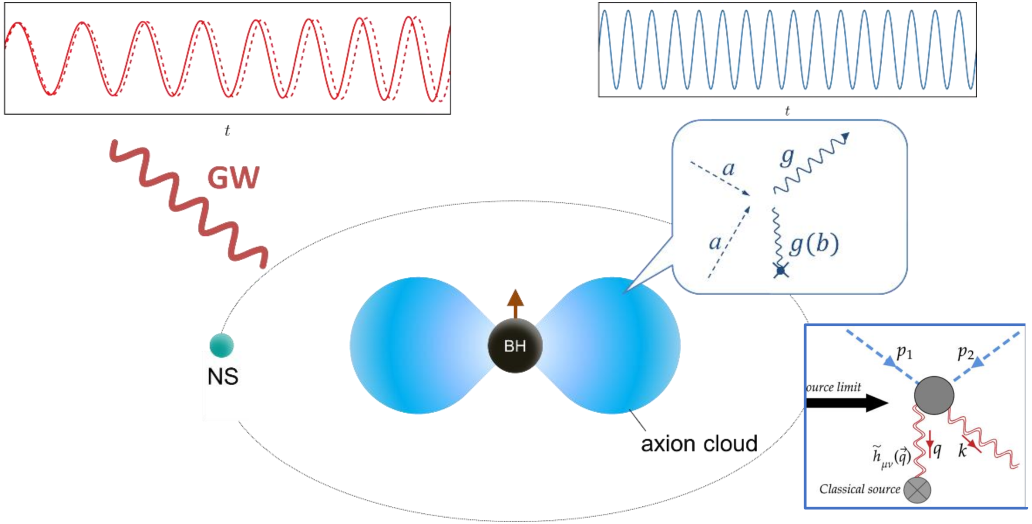
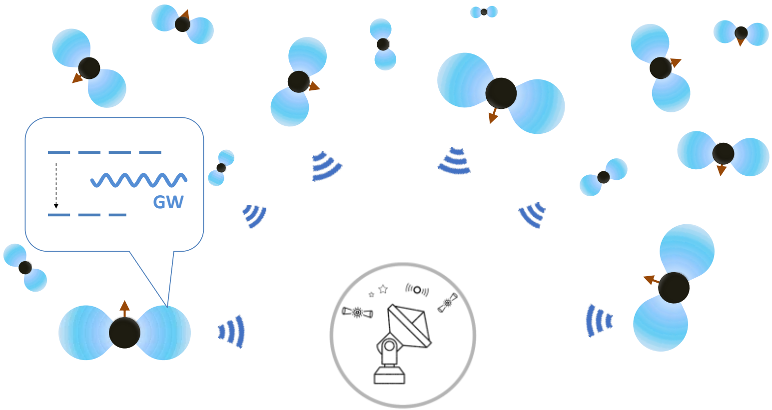


GW signals of ultralight axion DM





Jing Yang, Ning Xie, FPH arXiv:2306.17113, JCAP 11 (2024) 045

arXiv:2404.18703Aidi Yang, FPH

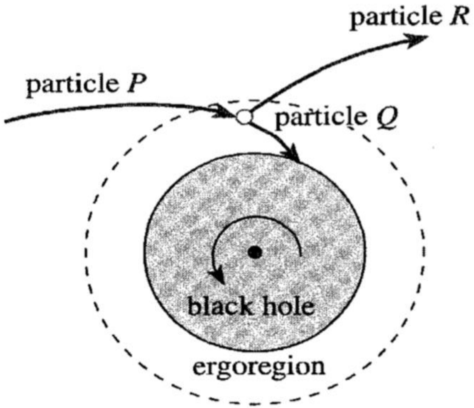
Ning Xie, FPH, SCPMA Vol.66, No.1(2024);

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

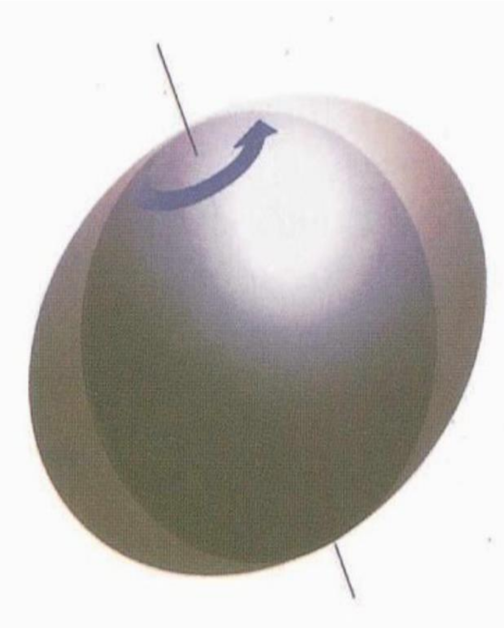
What is superradiance?

When Klein (-Gordon) meets Kerr——superradiance

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



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



S. Hawking

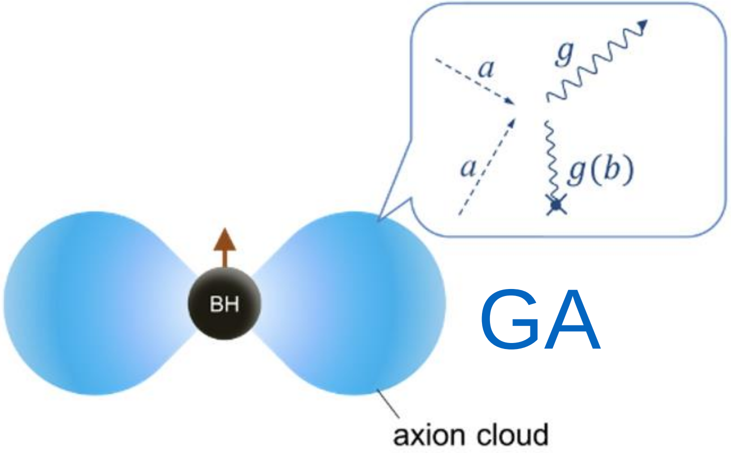
Exponential growth solution of Klein-Gordon equation due to the boundary condition at the horizon of Kerr BH. Ultralight axion can form axion cloud around rotating BH， Gravitational atom (GA).

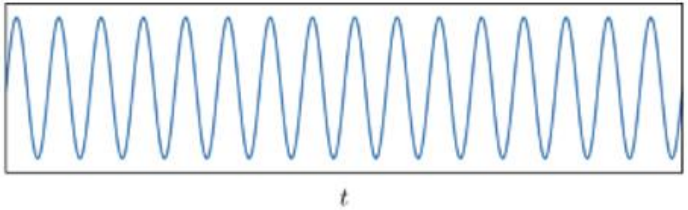
GW of ultralight DM from black hole

Axions can annihilate to GW

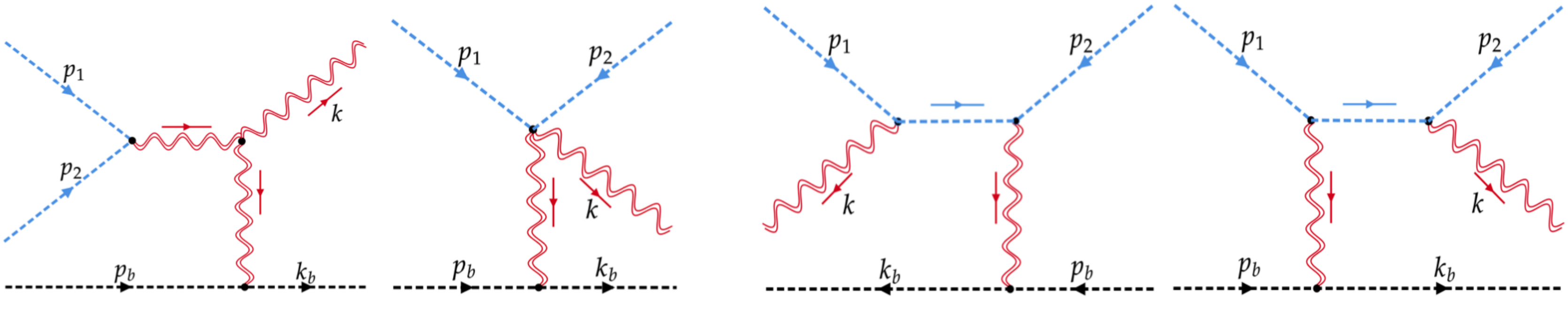
A. Arvanitaki and S. Dubovsky, Phys. Rev. D 83, 044026 (2011)
R. Brito, V. Cardoso and P. Pani, Class. Quant. Grav. 32, no.13, 134001 (2015)
H. Yoshino and H. Kodama, PTEP 2014, 043E02 (2014)

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



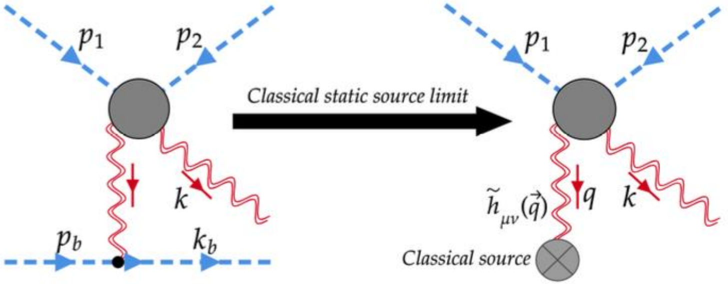


Microscopic physics



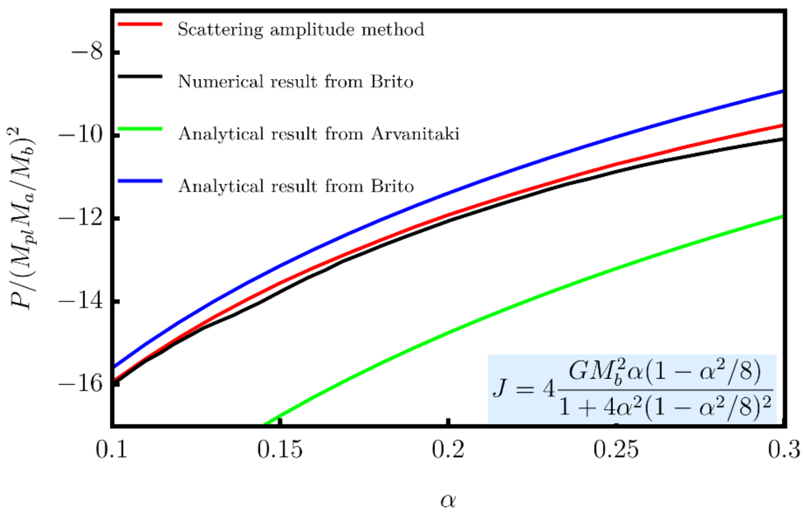
(a) (b) (c) (d)

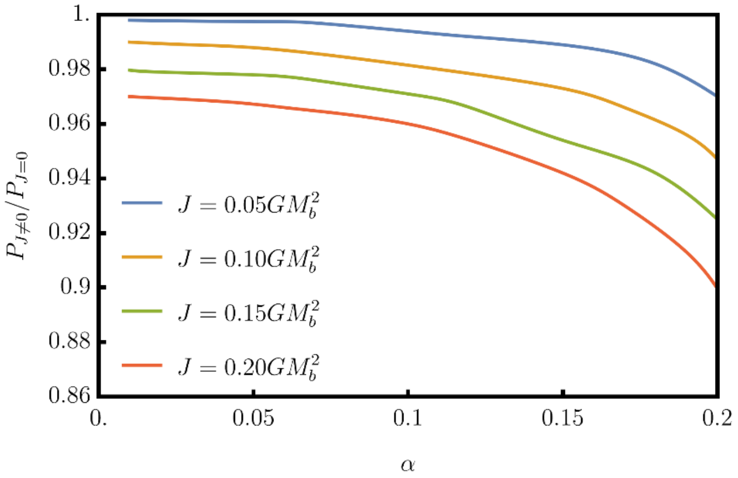
$$M(\boldsymbol{p_b}, \boldsymbol{p_1}, \boldsymbol{p_2} \to \boldsymbol{k}, \boldsymbol{k_b})$$



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

GW radiation from axion annihilation





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

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

✓ 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

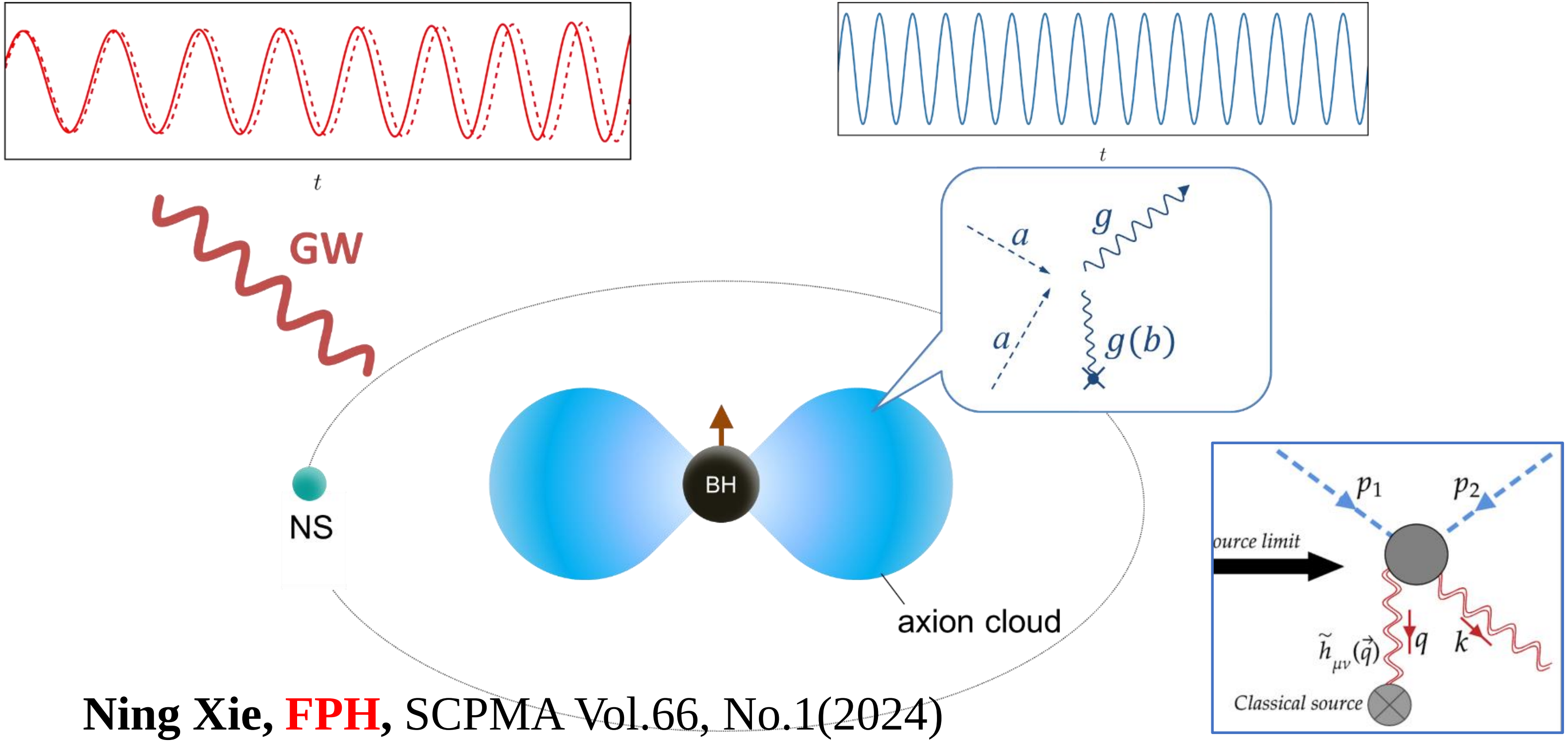
- ✓ Simple and straightforward.
- ✓ Easy to include Kerr metric effects.
- ✓ Microscopic physics is intuitive.
- ✓ It is clearly and simple to demonstrate the analytic approximation formulae.

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

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

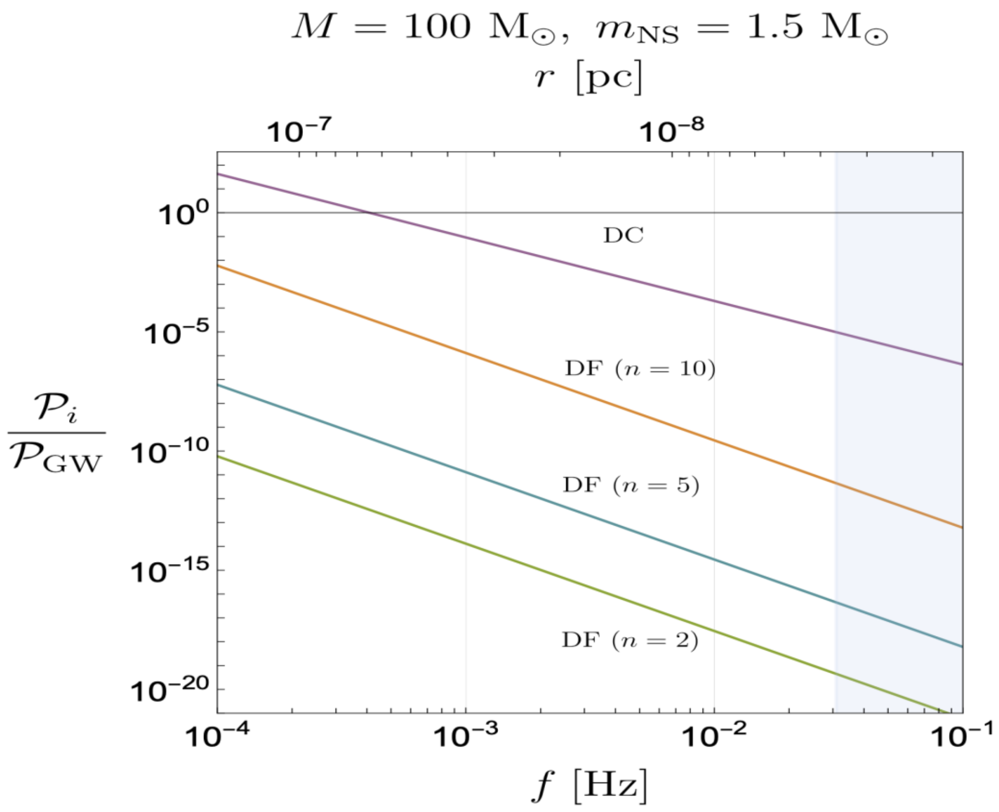
With ultralight axions

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

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

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

Imprints of axions on GW



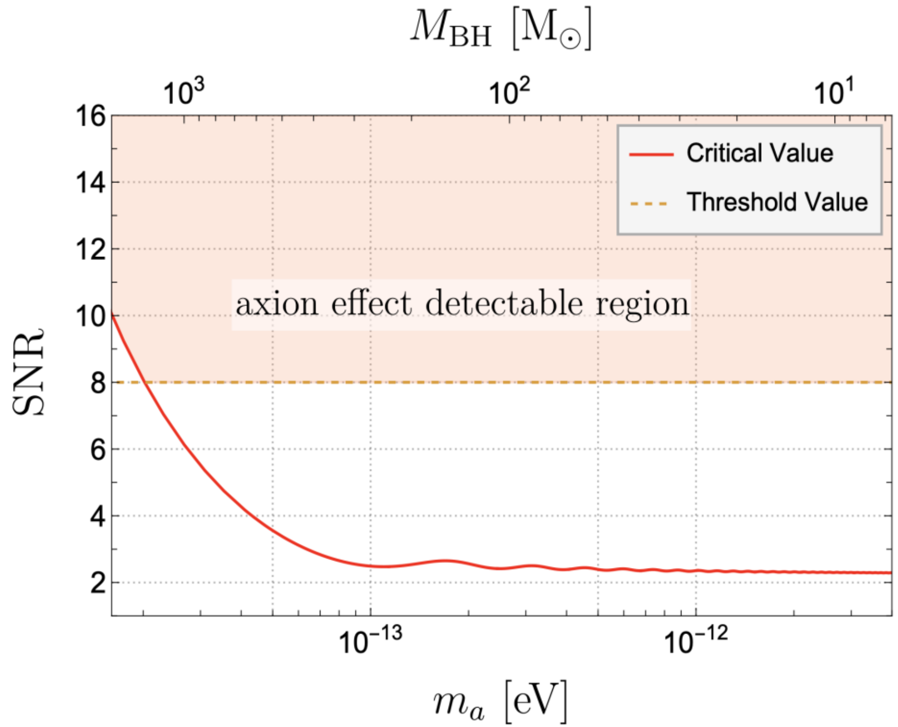
Imprints of axions on GW

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

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

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

Complementary search: GW+PTA



Axions modify the rate of binary period change

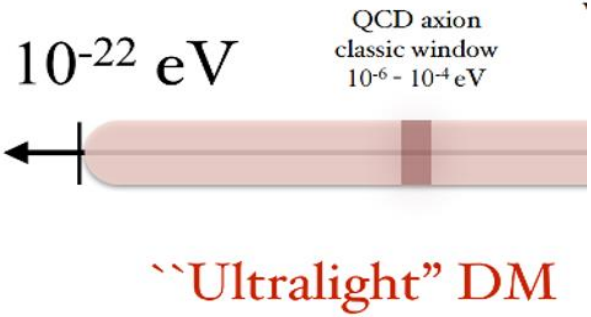
$$\Delta\dot{P} = \left|\dot{P} - \dot{P}_{\rm vac}\right| \approx 10^{-12}\ {\rm s/s}$$

Future Pulsar timing measurement precision, such as SKA

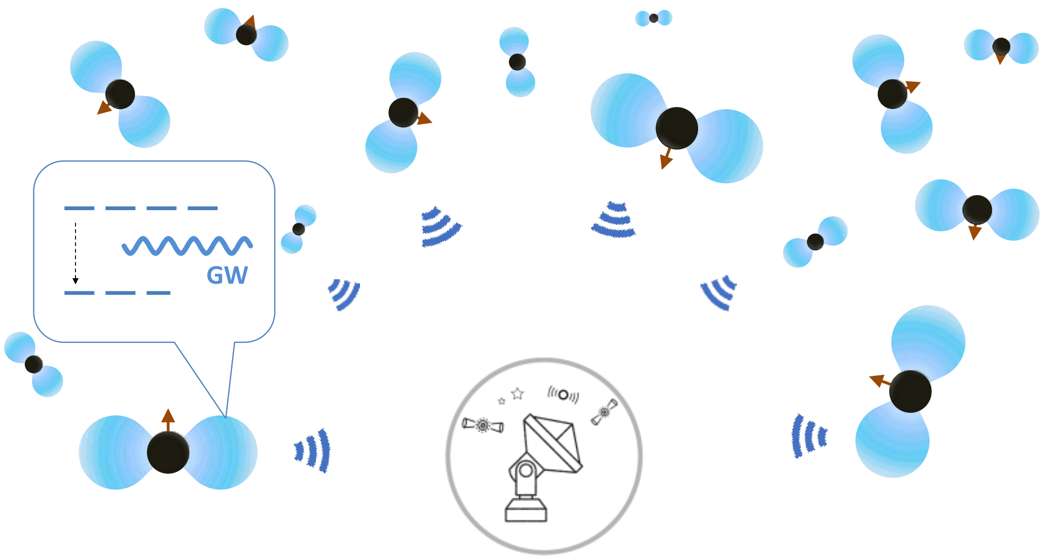
$$10^{-15}\ {\rm s/s}$$

Outline

1. Axion and axion dark matter (DM), Gravitational wave (GW)
2. 0.1 eV DFSZ axion and its phase transition GW signals
3. μeV axion and radio signals of axion DM
4. 10^(-12)-10^(-17)eV axion: GW and pulsar timing measurement
5. 10^(-21)eV fuzzy axion DM GW
6. Summary and outlook



Fuzzy axion (DM) particles

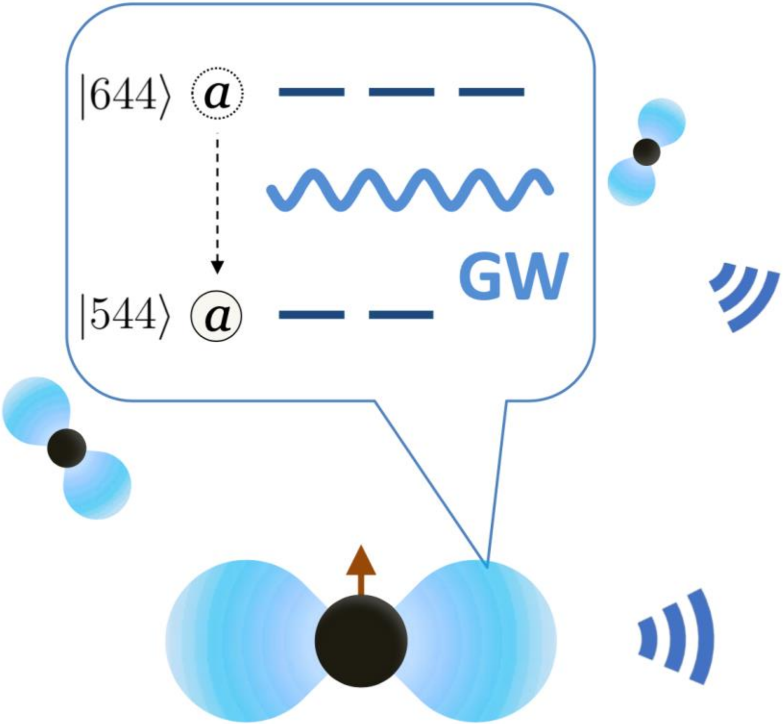


The cosmic populated SMBHs dressed with axion cloud as a natural source of nano-Hertz GW. The energy level transition process can radiate GWs continuously, which naturally fall in nano-Hertz frequency band.

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, **JCAP 11 (2024) 045**

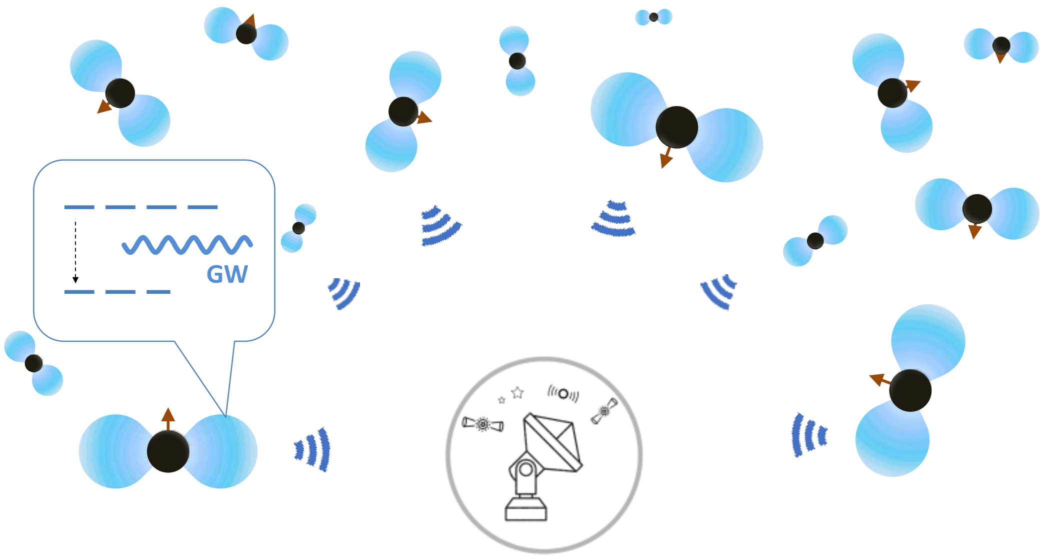
Fuzzy axion (DM) particles



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

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

Fuzzy axion (DM) particles



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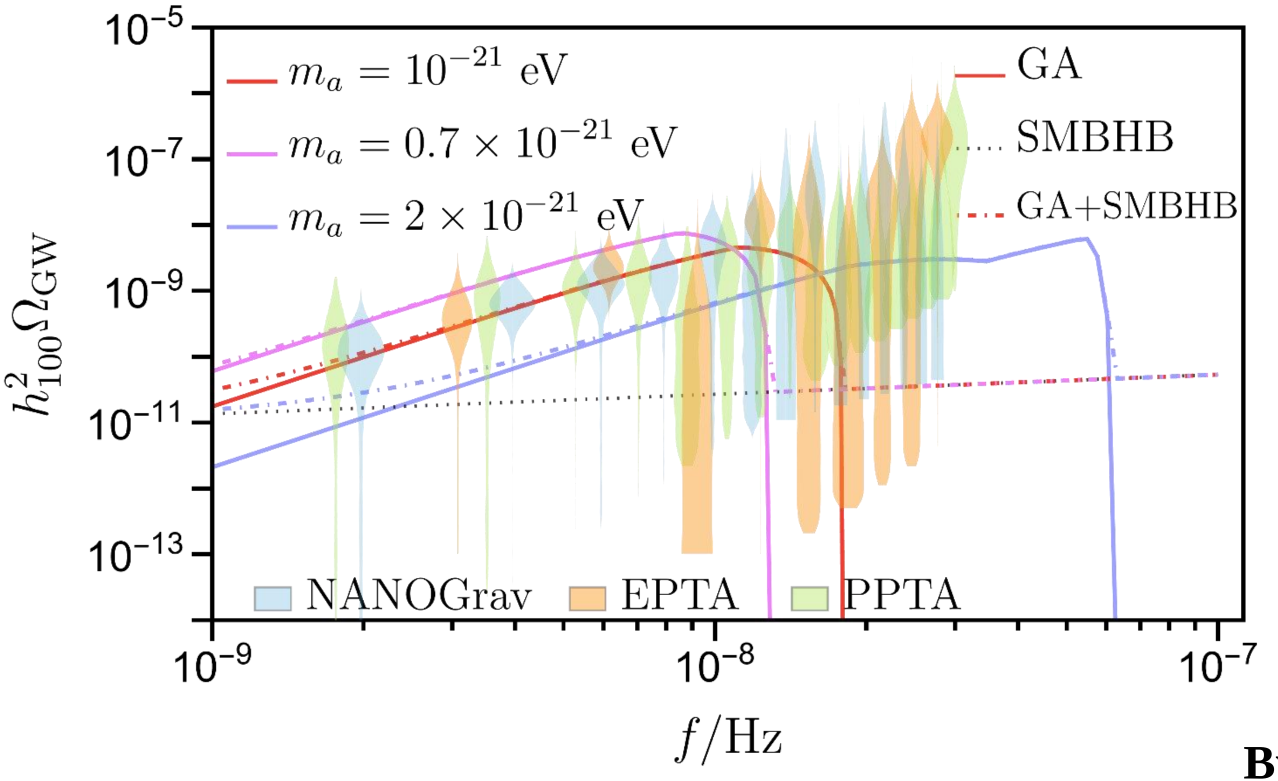
Jing Yang, Ning Xie,
FPH, arXiv:2306.17113,
JCAP 11 (2024) 045

Fuzzy axion (DM) particles



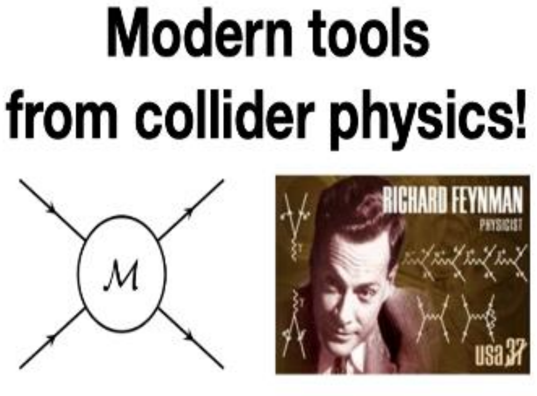
Jing Yang, Ning Xie, FPH, arXiv:2306.17113, JCAP 11 (2024) 045

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

State of the art: GW precise calculation

Scattering amplitude method in GW precise calculations.

See Zvi Bern's recent works

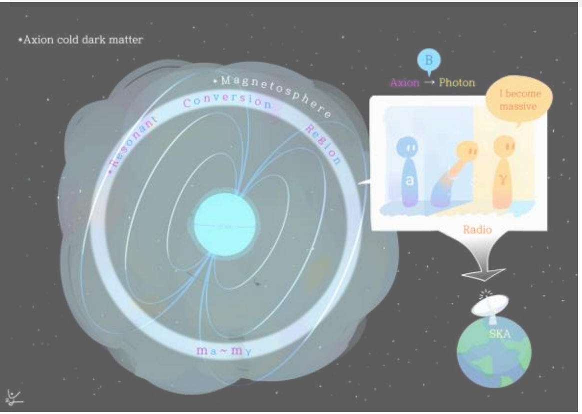


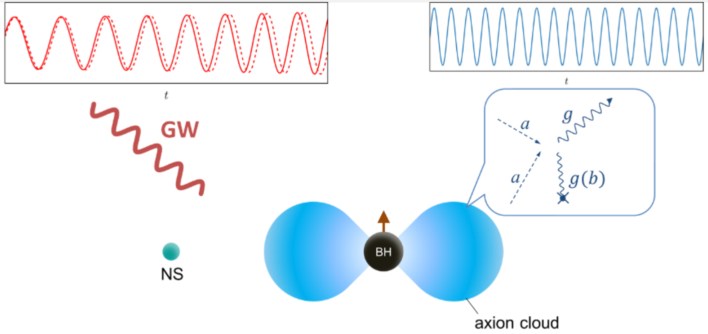
Towards accurate calculations of GW power spectrum from new physics models: non-linear evolution (turbulence, shocks) not well understood; P.Auclair, C.Caprini, D.Cutting, M.Hindmarsh, K.Rummukainen, D.A.Steer and D.J.Weir, [arXiv:2205.02588]
J.Dahl, M.Hindmarsh, K.Rummukainen and D.J.Weir, [arXiv:2112.12013].

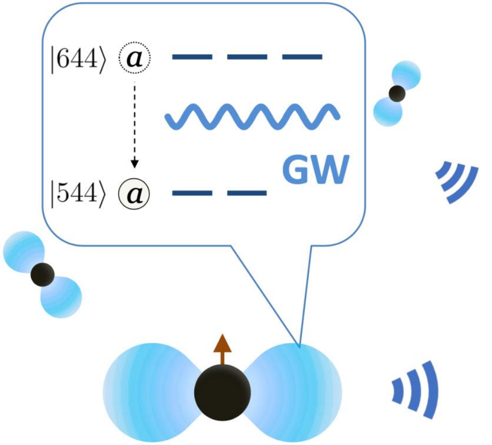
EW baryogenesis with high bubble wall velocity

See James Cline and Hindmarsh's recent works

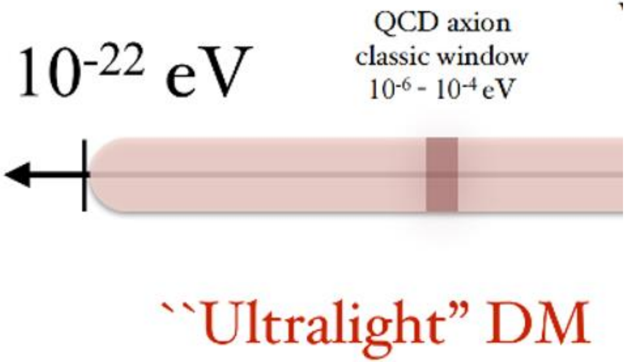
6.Summary and outlook







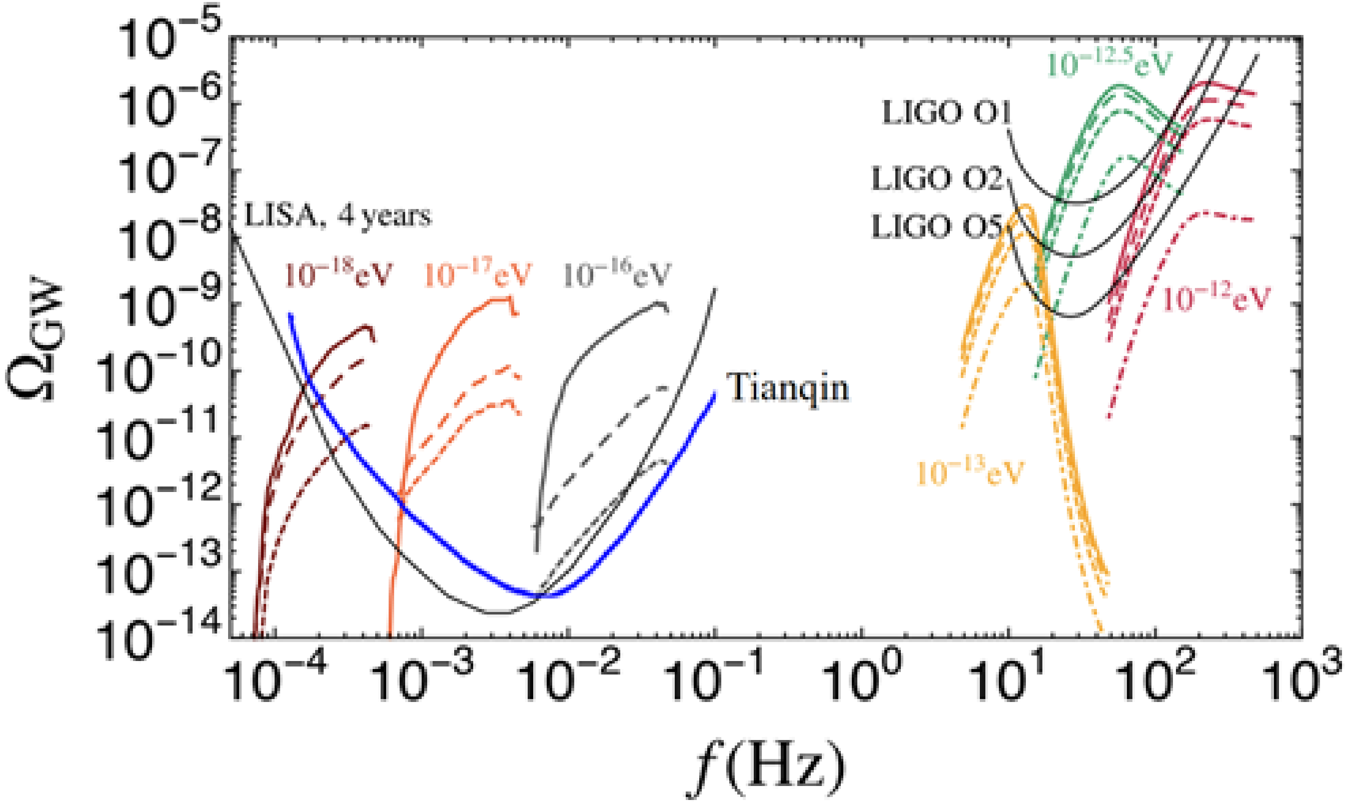
GW and radio telescope might provide new approaches to explore DM: multi-messenger and multi-band.



Thanks! Comments and collaborations are welcome!

Email:huangfp8@sysu.edu.cn

Backup slides: Axion cloud annilating to GW



Phase transition dynamics and heavy DM

Theory: The most important and difficult phase transition parameter for GW, dynamical DM, baryogenesis is bubble wall velocity v_w

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
this talk v_w

Energy budget
κ

Experiment: GW experiment is most sensitive to bubble wall velocity v_w

arXiv: 2404.18703
Aidi Yang, **FPH**

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
,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

Bubble wall is essential (like a filter)

The most essential parameter for phase transition GW, phase transition DM, baryogenesis v_w

GW detection favor lager v_w
EW baryogenesis favor smaller v_w
Dynamical DM is sensitive to v_w

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
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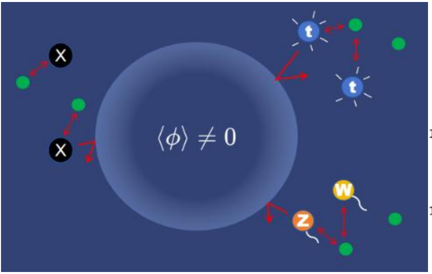
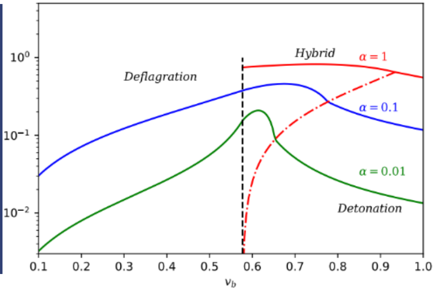
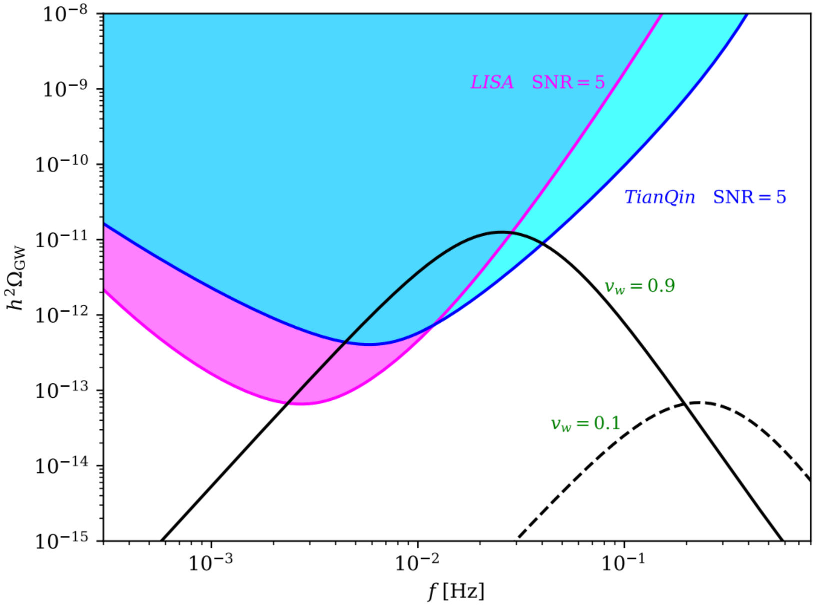






$$\rho_{DM}^4 v_w^{3/4} = 73.5(2\eta_B s_0)^3 \lambda_S \sigma^4 \Gamma^{3/4}$$

FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028;

Case I:DM induced SFOPT (wall velocity)

Inert Doublet Models (example)

$$V_0 = M_D^2 D^\dagger D + \lambda_D (D^\dagger D)^2 + \lambda_3 \Phi^\dagger \Phi D^\dagger D + \lambda_4 |\Phi^\dagger D|^2 + (\lambda_5/2)[(\Phi^\dagger D)^2 + h.c.],$$

mixed singlet-doublet model

$$V_0 = \frac{1}{2} M_S^2 S^2 + M_D^2 H_2^\dagger H_2 + \frac{1}{2}\lambda_S S^2 |\Phi|^2 + \lambda_3 \Phi^\dagger \Phi H_2^\dagger H_2 + \lambda_4 |\Phi^\dagger H_2|^2 + \frac{\lambda_5}{2}[(\Phi^\dagger H_2)^2 + \mathrm{H.c.}] + A[S\Phi H_2^\dagger + \mathrm{H.c.}].$$

mixed singlet-triplet model

$$V_0 = \frac{1}{2} M_S^2 S^2 + M_\Sigma^2 \mathrm{Tr}(H_3^2) + \kappa_\Sigma \Phi^\dagger \Phi \mathrm{Tr}(H_3^2) + \frac{\kappa}{2} |\Phi|^2 S^2 + \xi S \Phi^\dagger H_3 \Phi.$$

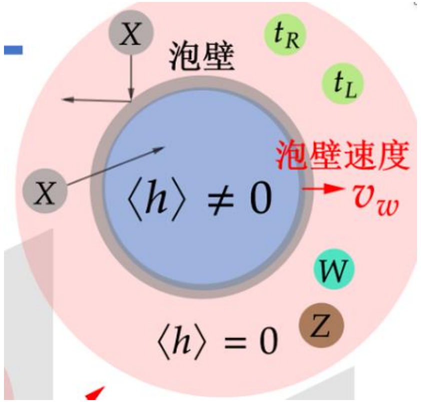
provide natural DM candidate

produce SFOPT and phase transition GW

FPH, Jiang-Hao Yu, Phys.Rev. D98 (2018) no.9, 095022

Yan Wang, Chong Sheng Li, and **FPH**, *Phys.Rev.D* 104 (2021) 5, 053004;

How to calculate wall velocity?



基于有效势，通过能动张量守恒得到早期宇宙plasma中的希格斯场运动方程

$$(1-v_w^2)h'' + \sum_i \frac{dm_i^2}{dh}\int \frac{d^3p}{(2\pi)^3 2E_i}\delta f_i(x,p) + \frac{\partial V_{\rm eff}(h,T)}{\partial h} = 0$$

求解玻尔兹曼方程得到粒子偏离热平衡的扰动分布

$$\frac{d}{dt}(f_i^{\rm eq}+\delta f_i) = \left(\left(v_w + \frac{p_z}{E}\right)\frac{\partial}{\partial z} - \frac{(m_i^2)'}{2E}\frac{\partial}{\partial p_z}\right)(f_i^{\rm eq}+\delta f_i) = -C[(f_i^{\rm eq}+\delta f_i)]$$

用量子场论的方法计算 碰撞项C

计算粒子在泡壁处的散射

采用合理的flow ansatz以及truncation scheme，求解扰动的演化方程组

δf_i

将扰动代入运动方程，数值求解提取出泡壁速度和泡壁厚度 v_w, L_w
进一步可讨论相变动力学暗物质、电弱重子生成和相变引力波信号

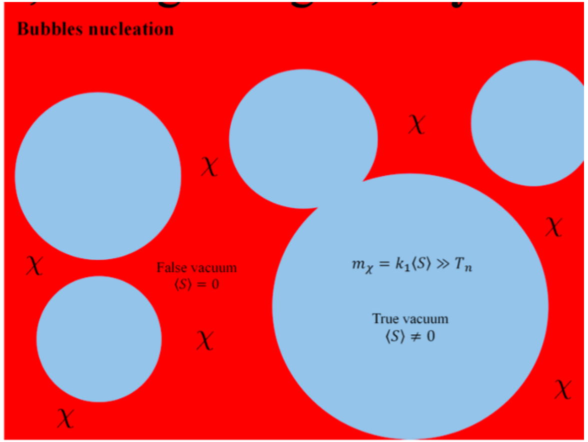
Siyu Jiang, **FPH**, Xiao Wang,
Phys.Rev.D 107 (2023) no.9, 095005

Case II: anti-filtered Q-ball DM

DM

FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028;

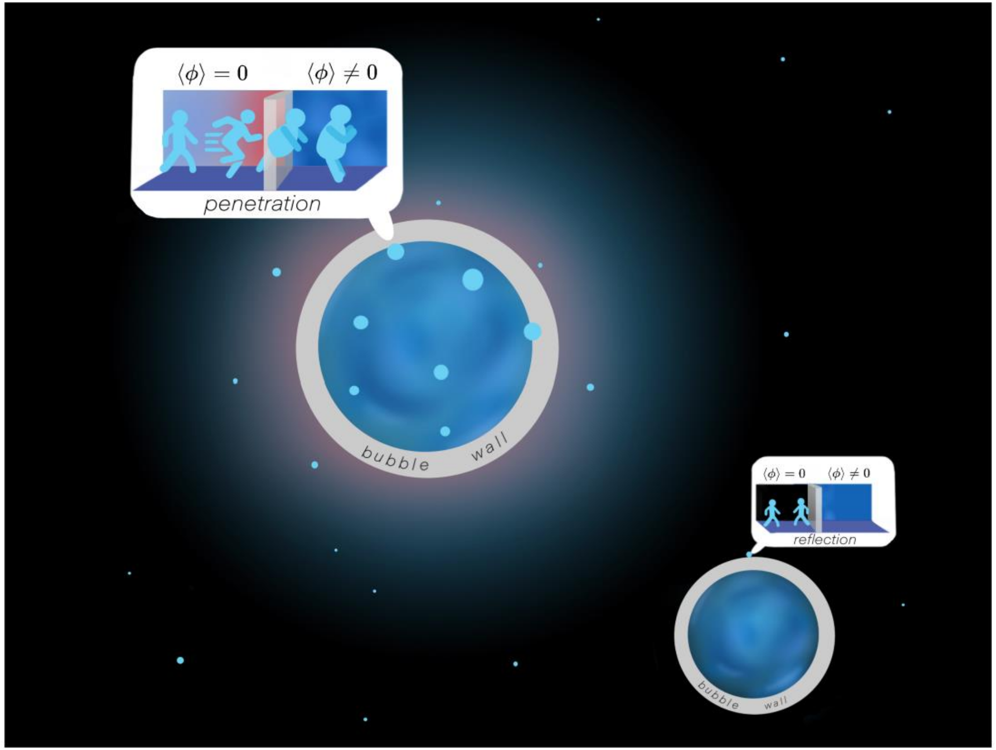
Gauged Q-ball dark matter through a cosmological first-order phase transition, Siyu Jiang, FPH, Pyungwon Ko, arXiv:2404.16509, JHEP 07 (2024) 053



Case III: filtered DM

DM

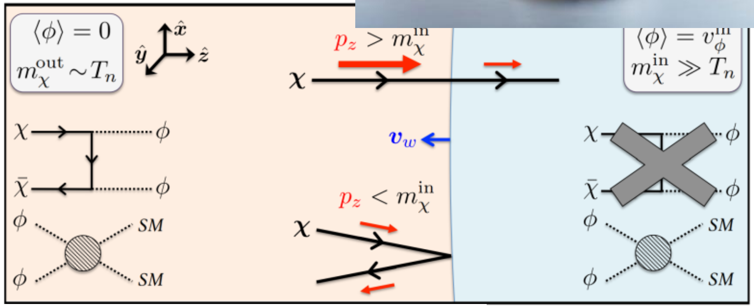
Bubble wall dynamics plays an essential role in the filtered DM mechanism.



Siyu Jiang, FPH, Chong Sheng Li,
Phys.Rev.D 108 (2023) 6, 063508

Case III: filtered DM

In recent years, this dynamical DM formed by phase transition has became a new idea and attracted more and more attentions. Namely, bubble in SFOPT can be the "filter" to packet the needed heavy DM.



$$\Omega_{\rm DM}h^2 \approx 0.17\left(\frac{T_n}{\rm TeV}\right)\left(\frac{m_\chi^\infty}{30T_n}\right)^{-\frac{5}{2}}\exp\left(-\frac{m_\chi^\infty}{30T_n}\right)$$

FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028
arXiv:1912.04238, Dongjin Chway, Tae Hyun Jung, Chang Sub Shin
arXiv:1912.02830, Phys.Rev.Lett. 125 (2020) 15, 151102 , Michael J. Baker, Joachim Kopp,and Andrew J. Long
arXiv:2012.15113, Wei Chao, Xiu-Fei Li, Lei Wang
arXiv:2101.05721, Aleksandr Azatov, Miguel Vanvlasselaer, Wen Yin
arXiv:2103.09827, Pouya Asadi , Eric D. Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, J. Smirnov
arXiv:2103.09822, Pouya Asadi , Eric D. Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, J. Smirnov
arXiv:2008.04430 Jeong-Pyong Hong， Sunghoon Jung, Ke-pan Xie
Haipeng An, et.al, arXiv: 2208.14857
Siyu Jiang, FPH, Chong Sheng Li, arXiv:2305.02218
more and more new works…