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New dark matter production mechanism and the gravitational wave signals

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Sun Yat-sen University, TianQin center

based on our recent work

Dayun Qiu, Siyu Jiang, FPH, arXiv: 2508.04314

Siyu Jiang, FPH, JCAP06 (2025) 023

Siyu Jiang, FPH, Pyungwon Ko, JHEP 07 (2024) 053

Siyu Jiang, Aidi Yang, Jiucheng Ma, FPH
Class.Quant.Grav. 41 (2024) 6, 065009

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

The XIX International Conference on Topics in Astroparticle and Underground Physics (TAUP2025)@Xichang, 2025.08.28

Outline

1. **Motivation for new dark matter (DM) mechanism**
2. **pNGB DM from Primordial black hole (PBH) radiation and superradiance with its gravitational wave (GW) signals**
3. **DM from first-order phase transition (FOPT) and GW**

   Case I: Q-ball and gauged Q-ball DM

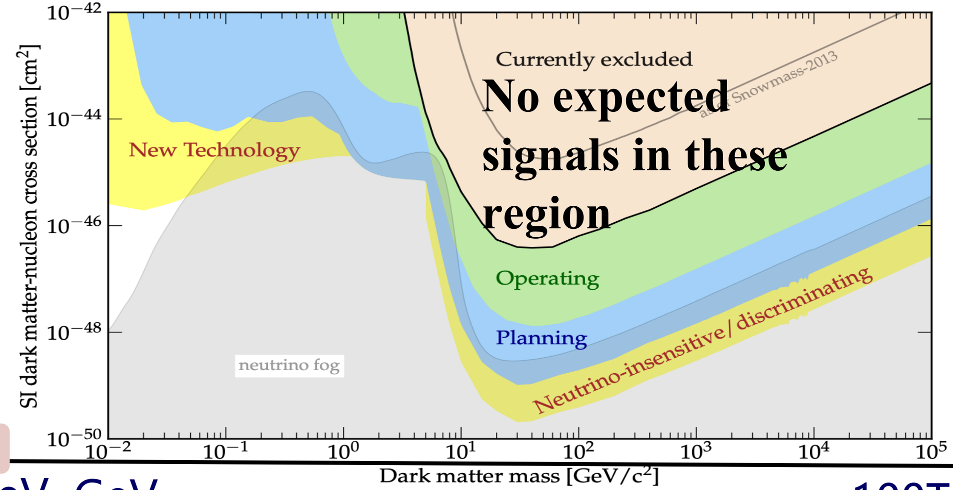
   Case II: filtered DM
4. **Summary and outlook**

Motivation DM theory and experiments status

arXiv: 1904:07915
Snowmass 2021,
arXiv: 2209.07426

What is the microscopic nature of DM?

How DM relic density is produced?



Ultralight DM: Axion/ALP

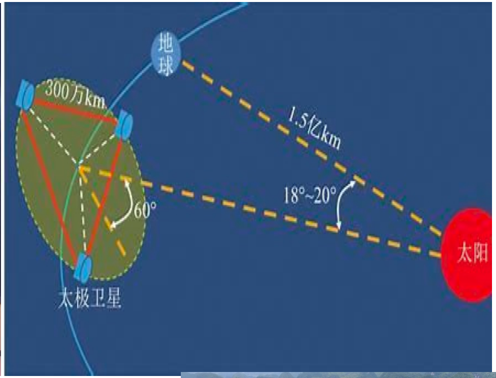
Heavy DM:Q-ball/filtered/ PBH (radiation, superradiance)

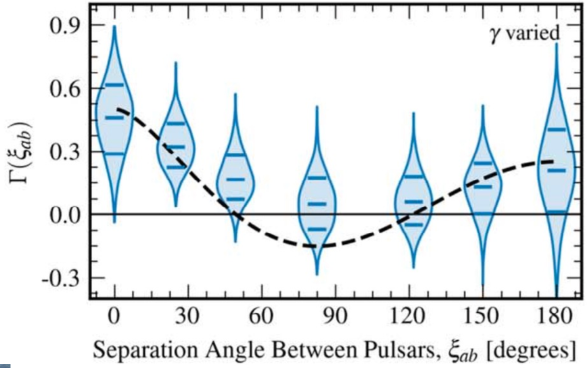
10^{-22}eV keV GeV WIMP 100TeV

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

GW experiments

LISA/TianQin/Taiji ~2034





"TianQin"
"Harpe in space"

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

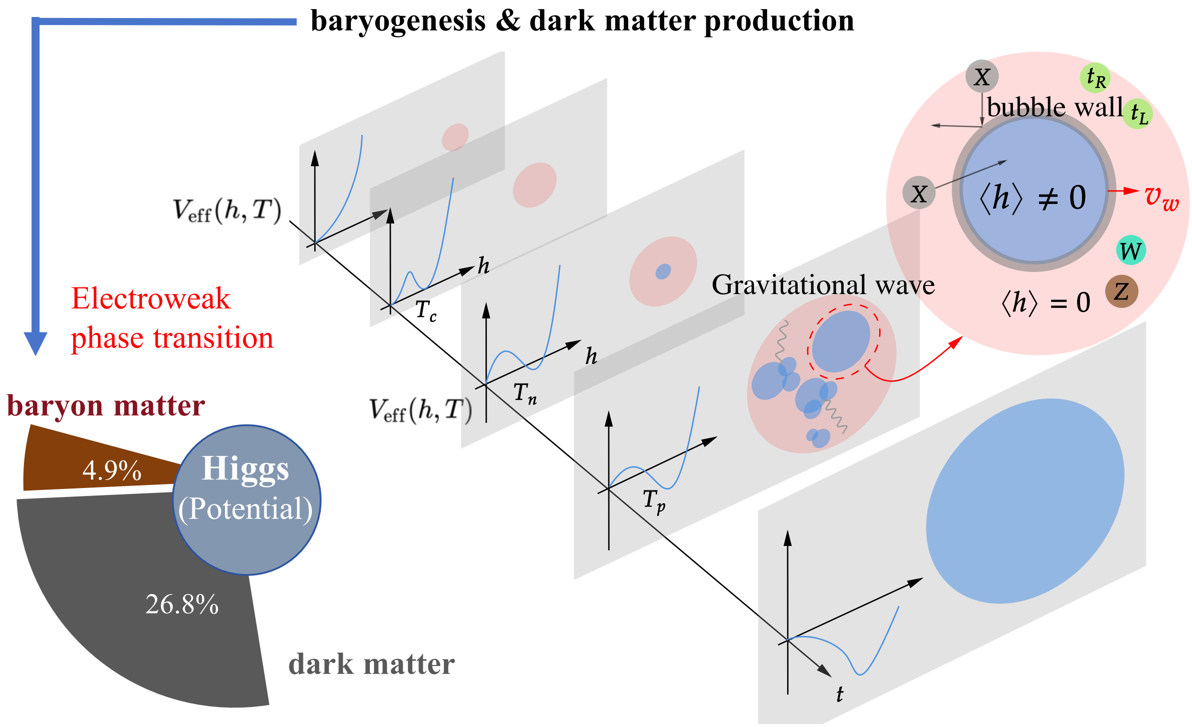
FAST

SKA

Motivation DM in post-Higgs and GW Era

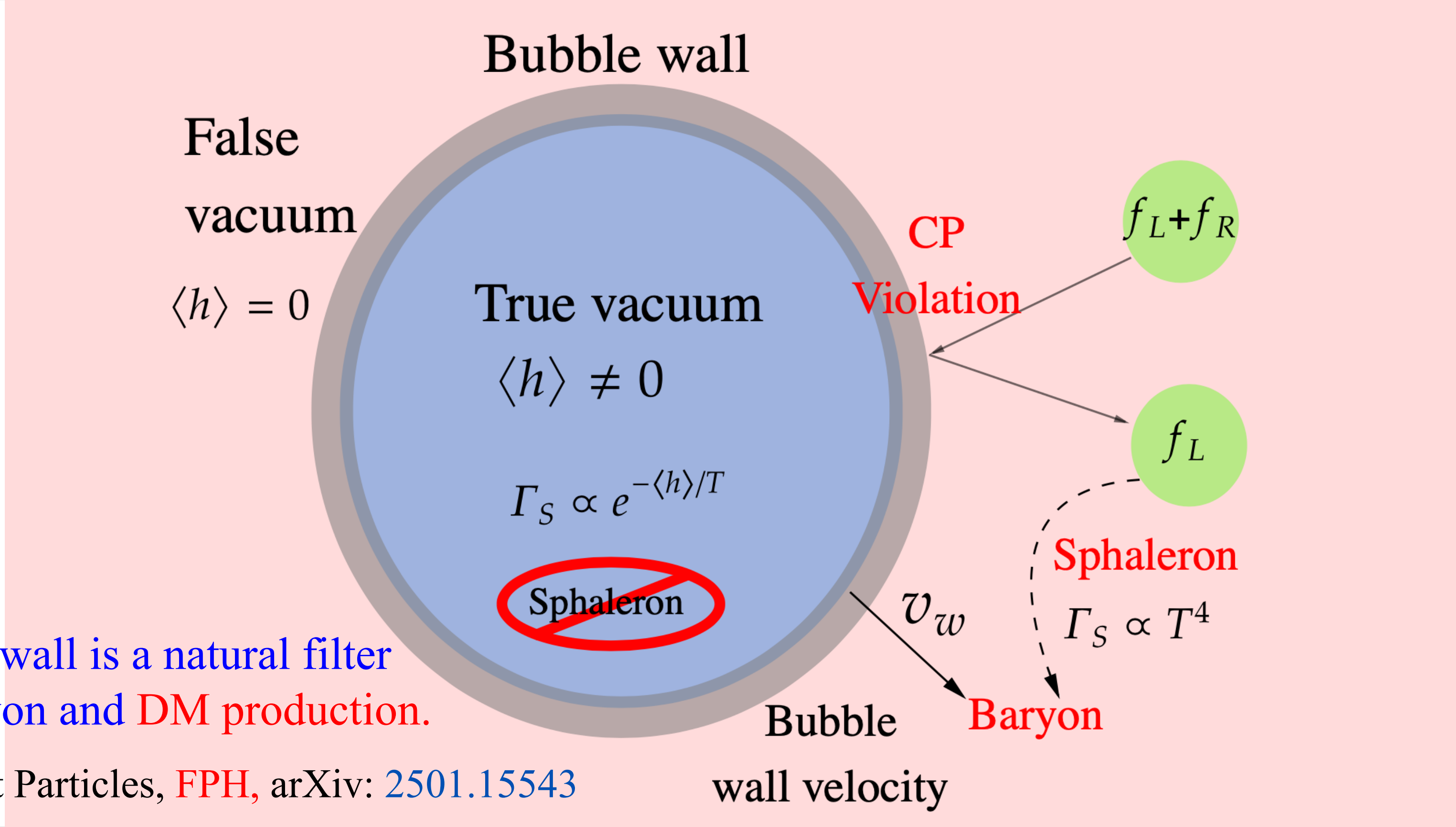
The observation of Higgs@LHC and GW@LIGO initiates new era of exploring DM by GW.

FOPT by Higgs could provide a new approach for DM production.



The First Particles, FPH, arXiv: 2501.15543

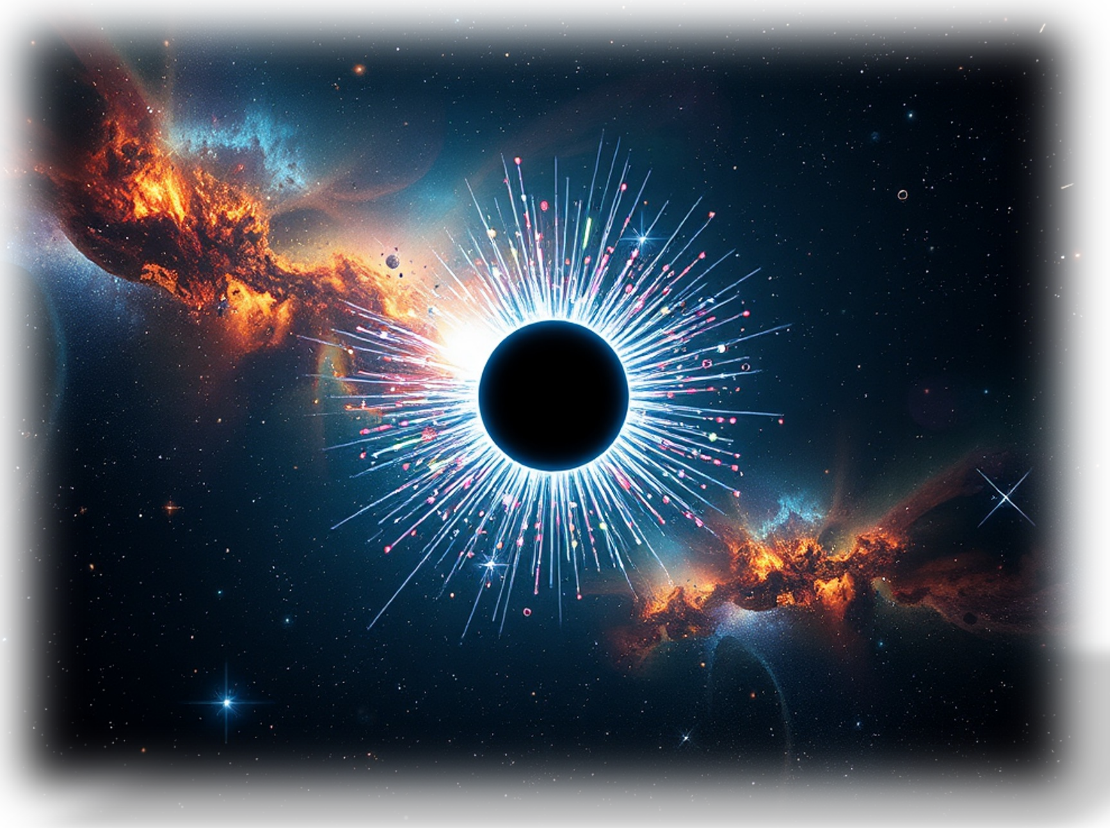
DM from cosmic phase transition



Bubble wall is a natural filter for baryon and DM production.

The First Particles, FPH, arXiv: 2501.15543

DM from PBH radiation/superradiance



PBH can be the particle factory in the early universe.

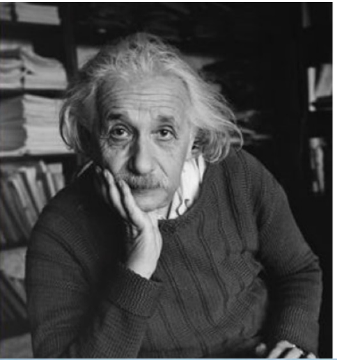
(Kerr) PHB can produce SM particles and DM through (superradiance) Hawking radiation.

Gravitational interaction is universal.

S.W. Hawking, Black hole explosions, Nature 248 (1974) 30
S.W. Hawking, Particle Creation by Black Holes, Commun. Math. Phys. 43 (1975) 199

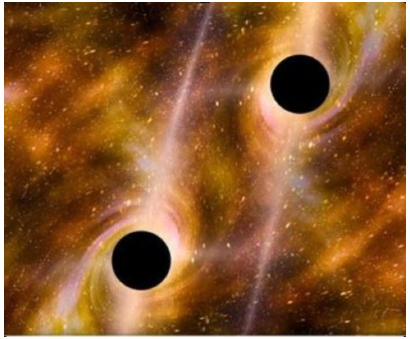
What is GW ?

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



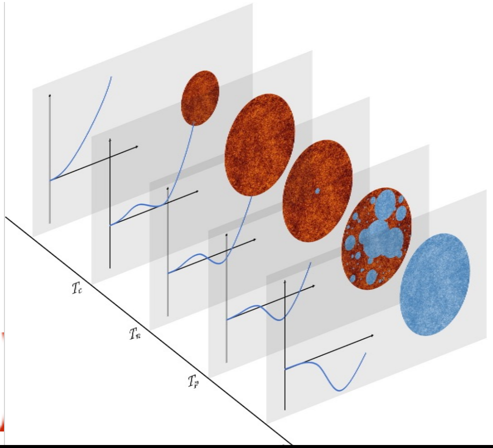
Isolated sources: quadrupole radiation

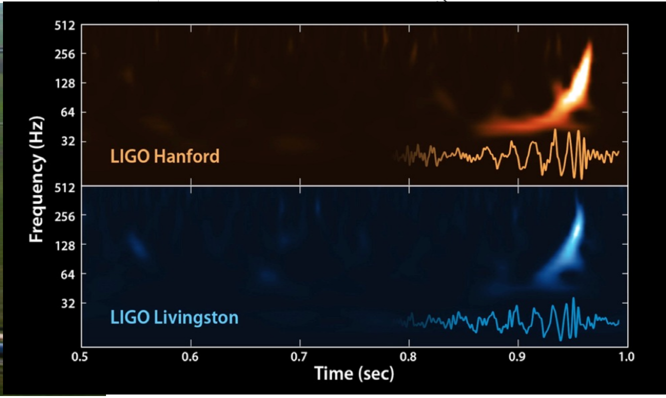
$$h_{ij} \simeq \frac{2G}{c^4 r} \ddot{Q}^{TT}_{ij}(t - r/c)$$



Stochastic sources: anisotropic stress tensor

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





General GW in the early universe

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

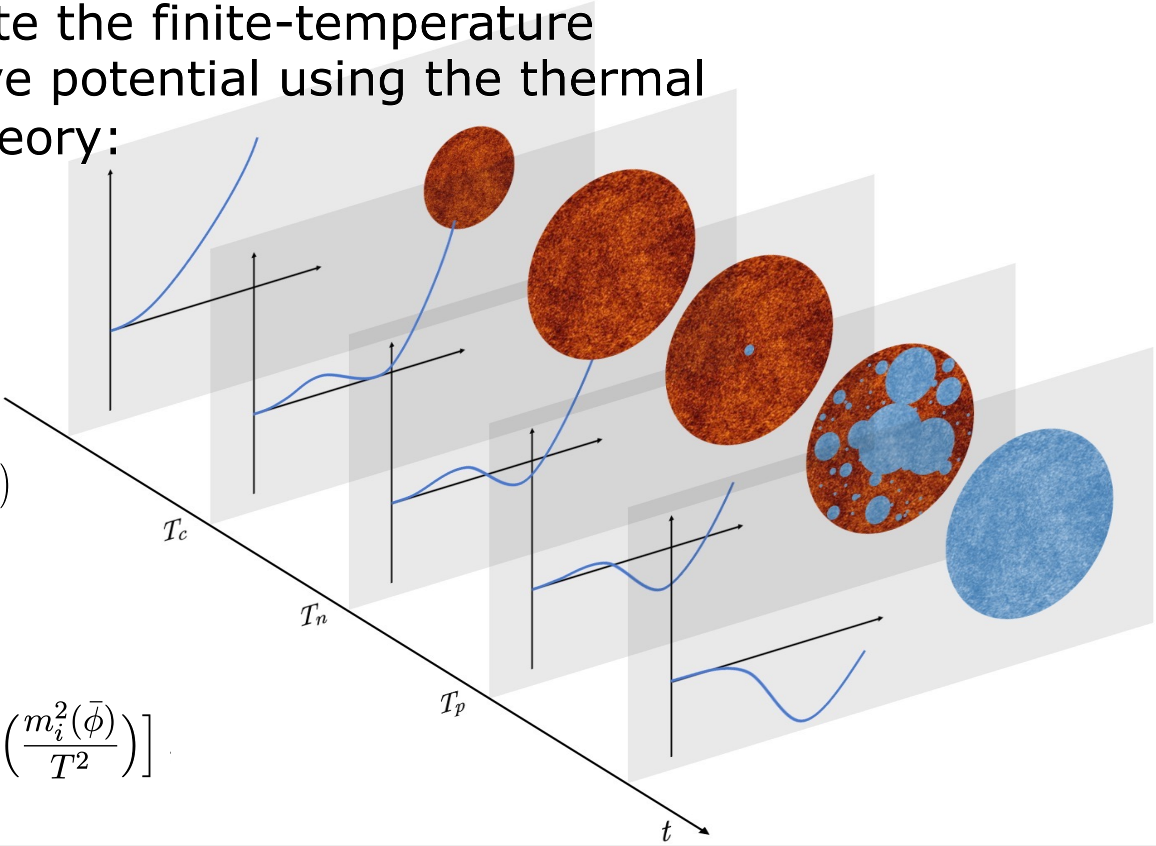
- ✓ phase transition:TeV physics (focus)
- ✓ cosmic defects: cosmic string, domain wall…

Possible sources of tensor anisotropic stress in the early universe

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

Phase transition in a nutshell

calculate the finite-temperature effective potential using the thermal field theory:



这世上的热闹，源自隧穿

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

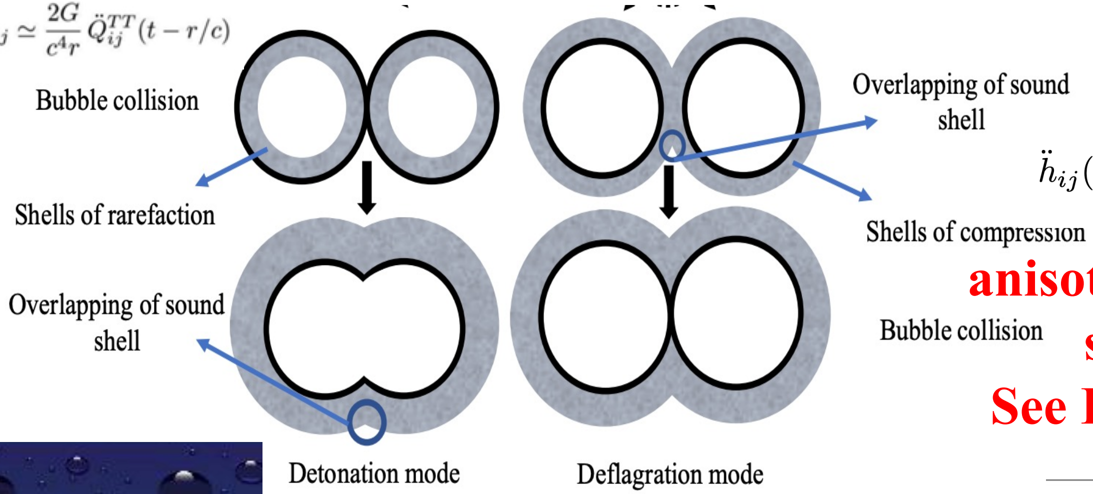
$$S(T) = \int d^4x \left[\frac{1}{2} \left(\frac{\partial \phi}{\partial x} \right)^2 + V_{\text{eff}}\left(\phi, T\right) \right]$$

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

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

Phase transition GW in a nutshell

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

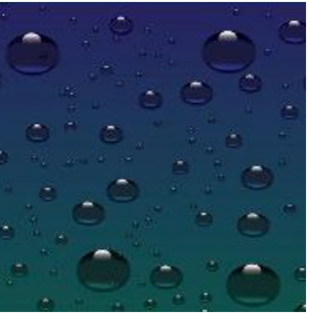


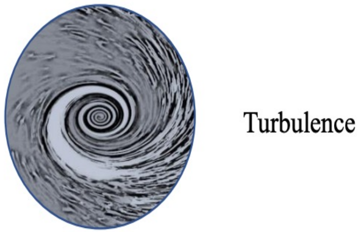
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

anisotropic stress tenor: source of GW

See Haipeng An's talk





General form Π_{ij}
$[\partial_i \phi \partial_j \phi]^{TT}$
$[\gamma^2 (\rho + p) v_i v_j]^{TT}$
$[-E_i E_j - B_i B_j]^{TT}$
$\partial_i \Psi, \partial_i \Phi$

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

Phase transition dynamics

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,JCAP 2025**

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…

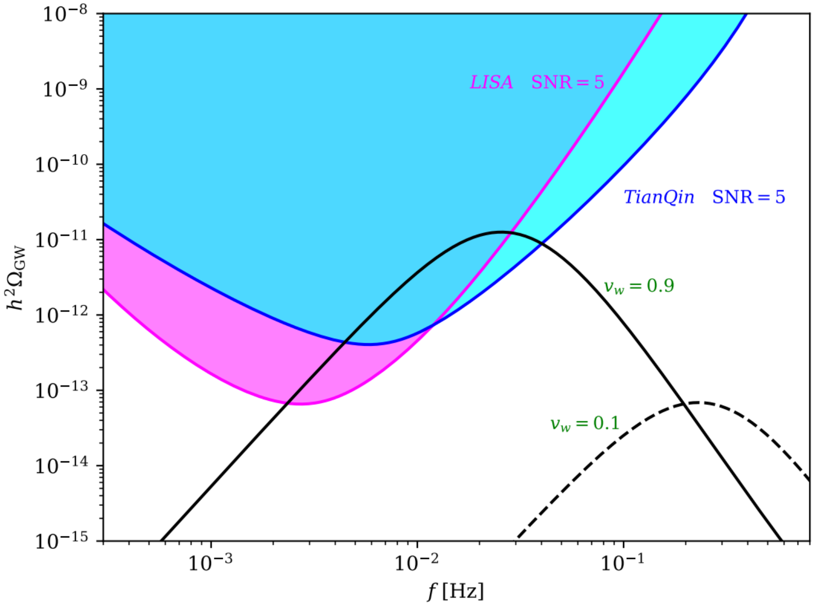
F. Giese, T. Konstandin, K. Schmitz and J. van de Vis, arXiv:2010.09744
Xiao Wang, **FPH** and Xinmin Zhang, Phys.Rev.D 103 (2021) 10, 103520
Xiao Wang, Chi Tian, **FPH**, JCAP 07 (2023) 006

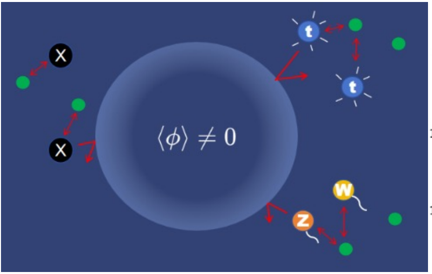
Bubble wall is essential (like a filter)

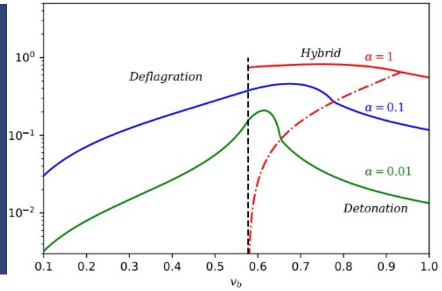
The most essential parameter for phase transition GW, phase transition DM, baryogenesis v_w

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
Xiao Wang, **FPH,** Xinmin Zhang,arXiv:2011.12903
Siyu Jiang, **FPH**, xiao wang, Phys.Rev.D 107 (2023) 9, 095005







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

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

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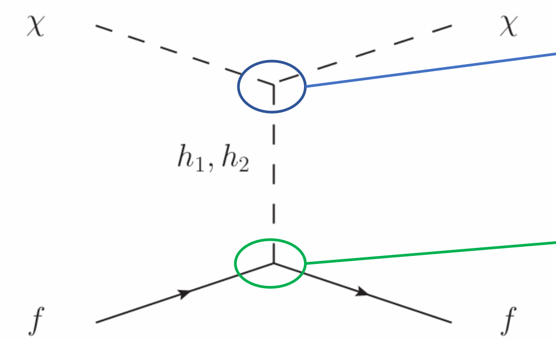
4. Summary and outlook

Pseudo-Goldstone DM

In many well-motivated new physics models, the pseudo-Nambu-Goldstone boson (pNGB) from U(1) symmetry breaking emerges as a promising DM candidate.

Meanwhile, pNGB DM candidate naturally suppress the direct detection signals!



$$\mathcal{L} \supset \frac{v_s}{2}\chi^2 \left(\kappa_{\chi\chi h_1}\, h_1 + \kappa_{\chi\chi h_2}\, h_2\right)$$

$$\kappa_{\chi\chi h_1} = +\, m_{h_1}^2/v_s^2\ \sin\theta\,,$$
$$\kappa_{\chi\chi h_2} = -\, m_{h_2}^2/v_s^2\ \cos\theta\,,$$

$$\mathcal{L} \supset -(h_1\cos\theta + h_2\sin\theta)\sum_f \frac{m_f}{v}\bar{f}f\,.$$

$$\mathcal{A}_{dd}(t) \propto \sin\theta\cos\theta\left(\frac{m_{h_2}^2}{t-m_{h_2}^2} - \frac{m_{h_1}^2}{t-m_{h_1}^2}\right) \simeq \sin\theta\cos\theta\,\frac{t\,(m_{h_2}^2 - m_{h_1}^2)}{m_{h_1}^2\, m_{h_2}^2} \simeq 0$$

Phys.Rev.Letts.119.191801

$$t \simeq 0.$$

pNGB DM

Minimal Pseudo-Goldstone DM model

$$V(H,S) = -\frac{\mu_H^2}{2}|H|^2 + \frac{\lambda_H}{2}|H|^4 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_S}{2}|S|^4 + \lambda_{HS}|H|^2|S|^2 - \frac{m^2}{4}(S^2 + S^{*2})$$

Explicit symmetry breaking term to give DM mass

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = \frac{v_s + s}{\sqrt{2}} e^{i\chi/v_s}$$

pNGB coupling is small due to the suppression of high symmetry-breaking scale, then how to produce enough DM relic density?

CP symmetry $S \to S^*$.

$\chi \to -\chi$

DM candidate

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$

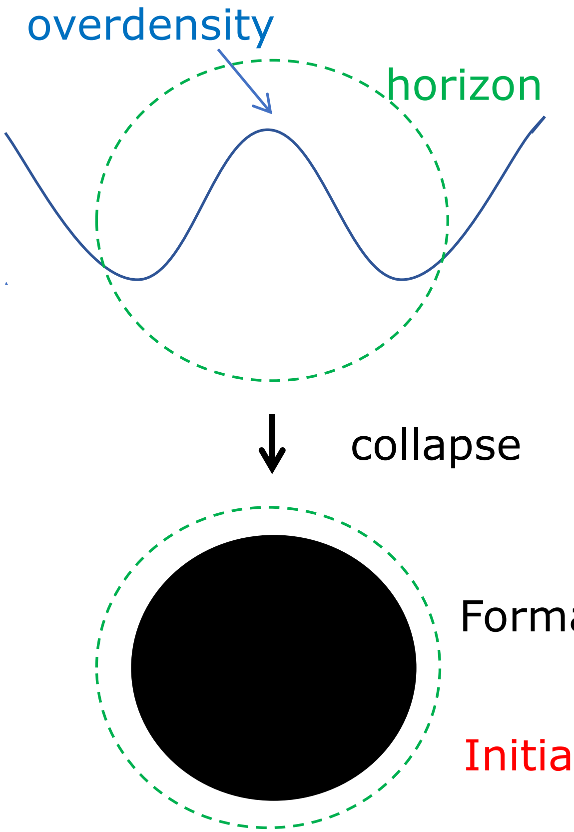
$$m_{h_1}^2 = \frac{1}{2}\left[\lambda_H v^2 + \lambda_S v_s^2 - \sqrt{(\lambda_S v_s^2 - \lambda_H v^2)^2 + 4\lambda_{HS}^2 v^2 v_s^2}\right],$$

$$m_{h_2}^2 = \frac{1}{2}\left[\lambda_H v^2 + \lambda_S v_s^2 + \sqrt{(\lambda_S v_s^2 - \lambda_H v^2)^2 + 4\lambda_{HS}^2 v^2 v_s^2}\right],$$

$$\tan 2\alpha = \frac{2\lambda_{HS} v v_s}{\lambda_S v_s^2 - \lambda_H v^2}$$

$v \ll v_s$ mixing can be ignored

Basic properties of PBH



Initial PHB mass

$$M_{\rm in} \equiv M_{\rm PBH}\left(T_{\rm in}\right) = \frac{4\pi}{3}\gamma \frac{\rho_R\left(T_{\rm in}\right)}{H^3\left(T_{\rm in}\right)}$$

Plank limit

$$H(T_{\rm in}) \leq 5 \times 10^{13}\ {\rm GeV}$$

$$\longrightarrow \quad M_{\rm in} \geq 0.5\ {\rm g}.$$

Hubble rate

$$H = \sqrt{\frac{8\pi}{3}\frac{\rho_R}{M_{\rm Pl}^2}} = \sqrt{\frac{4\pi^3 g_\star}{45}}\frac{T^2}{M_{\rm Pl}}$$

Formation temperature of PHB

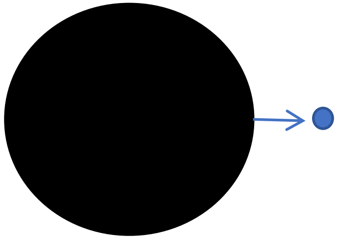
$$T_{\rm in} = \frac{1}{2}\left(\frac{5}{g_* \pi^3}\right)^{1/4}\left(\frac{3\gamma M_{\rm Pl}^3}{M_{\rm in}}\right)^{1/2}$$

Initial energy fraction of PBH

$$\beta \equiv \frac{\rho_{\rm PBH}\left(T_{\rm in}\right)}{\rho_R\left(T_{\rm in}\right)} = \frac{n_{\rm PBH}\left(T_{\rm in}\right) M_{\rm in}}{\rho_R\left(T_{\rm in}\right)}$$

pNGB from PBH

PBH can radiate particles lighter than the Hawking temperature.



$$T_{\rm PBH} = \frac{M_{\rm Pl}^2}{4\pi M_{\rm PBH}} f(a_\star) = \frac{M_{\rm Pl}^2}{4\pi M_{\rm PBH}} \frac{\sqrt{1-a_\star}}{1+\sqrt{1-a_\star}}$$

$$a_\star \equiv J M_{\rm Pl}^2 / M_{\rm PBH}^2$$

$$\Gamma_{{\rm PBH}\to i} \equiv \frac{dN_i}{dt} = \frac{27 g_i M_{\rm Pl}^2}{1024\pi^4 M_{\rm PBH}} \begin{cases} 2\zeta(3), & \text{Bosons} \\ \frac{3}{2}\zeta(3), & \text{Fermions} \end{cases}$$

Particle spectrum from Hawking radiation

absorption cross section

$$\frac{{\rm d}^2 N_i}{{\rm d}p{\rm d}t} = \frac{g_i}{2\pi^2} \sum_{l=s_i}^{\infty} \sum_{m=-l}^{l} \frac{\sigma_{s_i}^{lm}\left(M_{\rm PBH}, p, a_\star\right)}{\exp\left[\left(E_i(p) - m\Omega\right)/T_{\rm PBH}\right] - (-1)^{2s_i}} \frac{p^3}{E_i(p)} \qquad E_i(p) = \sqrt{p^2 + m_i^2}$$

horizon angular velocity

$$\Omega = \left(a_\star M_{\rm Pl}^2 / \left(2 M_{\rm PBH}\right)\right)\left(1/\left(1+\sqrt{1-a_\star^2}\right)\right)$$

Schwarzschild PBH

geometric limit

$$\frac{dM_{\rm PBH}}{dt} = -\varepsilon\left(M_{\rm PBH}\right)\frac{M_{\rm Pl}^4}{M_{\rm PBH}^2} \approx -\frac{27}{4}\frac{g_{*\rm PBH}}{30720\pi}\frac{M_{\rm Pl}^4}{M_{\rm PBH}^2}$$

$$M_{\rm PBH}(t) = M_{\rm in}\left(1-\frac{t-t_{\rm in}}{\tau}\right)^{1/3}$$

Lifetime of PBH

$$\tau = \frac{40960\pi}{27 g_{*\rm PBH}}\frac{M_{\rm in}^3}{M_{\rm Pl}^4}$$

$\beta < \beta_c$ If the universe were always radiation dominated

$$H(\tau) = 1/(2\tau) \qquad H = \sqrt{\frac{8\pi}{3}\frac{\rho_R}{M_{\rm Pl}^2}} \qquad T_{\rm evap} \simeq \frac{9}{128}\left(\frac{1}{5 g_* \pi^5}\right)^{1/4}\left(\frac{g_{*\rm PBH} M_{\rm Pl}^5}{2 M_{\rm in}^3}\right)^{1/2}$$

$\beta > \beta_c$ Since BHs evolve as matter, if they dominate universe before fully decaying

$$H(\tau) = 2/(3\tau) \qquad H = \sqrt{\frac{8\pi}{3}\frac{M_{\rm in} n_{\rm PBH}(T_{\rm in}) T_{\rm evap}^3/T_{\rm in}^3}{M_{\rm Pl}^2}}$$

$$\beta_c \equiv T_{\rm evap}/T_{\rm in}$$

$$T_{\rm evap}|_{\rm PBHdom} \simeq \frac{9}{256}\left(\frac{g_{*\rm PBH}^2}{2\beta}\right)^{1/3}\left(\frac{1}{5^5\pi^{17}g_*^3}\right)^{1/12}\left(\frac{M_{\rm Pl}^{17}}{3\gamma M_{\rm in}^{11}}\right)^{1/6}$$

Schwarzschild PBH

If particle mass is smaller than initial Hawking temperature: $M_i < \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$

$$N_i = \int_0^{M_{\rm in}} \frac{1}{\varepsilon\left(M_{\rm PBH}\right)} \frac{M_{\rm PBH}^2}{M_{\rm Pl}^4} \frac{27 g_i \zeta(3) M_{\rm Pl}^2}{512\pi^4 M_{\rm PBH}} dM_{\rm PBH} = \frac{120\zeta(3)}{\pi^3} \frac{g_i}{g_{*\rm PBH}} \left(\frac{M_{\rm in}}{M_{\rm Pl}}\right)^2$$

If particle mass is heavier than the initial temperature, PBHs firstly radiate other lighter particles and then the temperature increases:

$$N_i = \int_0^{\frac{M_{\rm Pl}^2}{8\pi M_i}} \frac{1}{\varepsilon\left(M_{\rm PBH}\right)} \frac{M_{\rm PBH}^2}{M_{\rm Pl}^4} \frac{27 g_i \zeta(3) M_{\rm Pl}^2}{512\pi^4 M_{\rm PBH}} dM_{\rm PBH} = \frac{15\zeta(3)}{8\pi^5} \frac{g_i}{g_{*\rm PBH}} \left(\frac{M_{\rm Pl}}{M_i}\right)^2$$

If the PBHs dominate the Universe before evaporation, the radiation into SM particles will reheat the Universe and dilute the final DM relic.

$$\frac{\pi^2}{30} g_* T_{\rm evap}^4 + M_{\rm in} \frac{n_{\rm PBH}\left(T_{\rm in}\right)}{s\left(T_{\rm in}\right)} s\left(T_{\rm evap}\right) = \frac{\pi^2}{30} g_* \tilde{T}_{\rm evap}^4 \longrightarrow Y_i \equiv \frac{N_i n_{\rm PBH}\left(T_{\rm evap}\right)}{s\left(T_{\rm evap}\right)} \frac{s\left(T_{\rm evap}\right)}{s(\tilde{T}_{\rm evap})}$$

Schwarzschild PBH

DM relic density

$$\Omega_{\rm DM} = \frac{\rho_{\rm DM}}{\rho_c} = \frac{M_{\rm DM}}{\rho_c}\frac{n_{\rm DM}}{s}(t_0)s_0 = \frac{M_{\rm DM}}{\rho_c}Y_{\rm DM}s_0$$

$\beta < \beta_c$

$$\Omega_{\rm DM} \simeq 1.61 \times 10^8 \beta \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm in}}{M_{\rm Pl}}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} < \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

$$\simeq 2.55 \times 10^5 \beta \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm Pl}^7}{M_{\rm in}^3 M_{\rm DM}^4}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} > \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

$\beta > \beta_c$

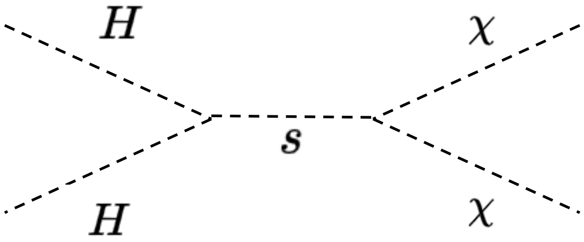
$$\Omega_{\rm DM} \simeq 6.46 \times 10^7 \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{*\rm PBH}}{115}\right)^{1/2}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm Pl}}{M_{\rm in}}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} < \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

$$\simeq 1.02 \times 10^5 \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{*\rm PBH}}{115}\right)^{1/2}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm Pl}^9}{M_{\rm in}^5 M_{\rm DM}^4}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} > \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

N.B. If PBHs dominate the energy density of the early Universe before they evaporate, the relic density is independent of β.

UV freeze-in

UV freeze-in

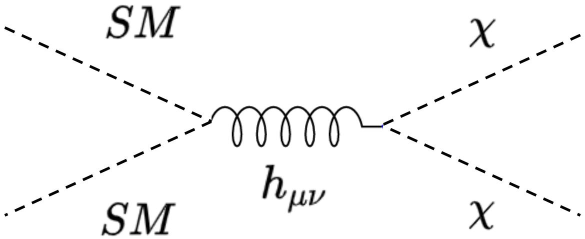


$$\frac{dY_\chi^{\rm FI}(x)}{dz} = \frac{2}{s(z)H(z)z}\gamma_{\chi\chi\to H^\dagger H}$$

$$\gamma_{\chi\chi\to H^\dagger H} \equiv \frac{g_H}{2!2!}\frac{T\lambda_{HS}^2}{2^9\pi^5}\int_{4M_\chi^2}^{\infty} ds\sqrt{s-4M_\chi^2}K_1(\sqrt{s}/T)\frac{s^2}{(s-M_s^2)^2}$$

$$\Omega_\chi^{\rm FI} = 3.34\times 10^{22}\lambda_{HS}^2\left(\frac{100}{g_s}\right)\left(\frac{100}{g_*}\right)^{1/2}\left(\frac{T_{\rm reh}}{M_s}\right)^4\left(\frac{M_\chi}{T_{\rm reh}}\right)$$

Gravitational freeze-in



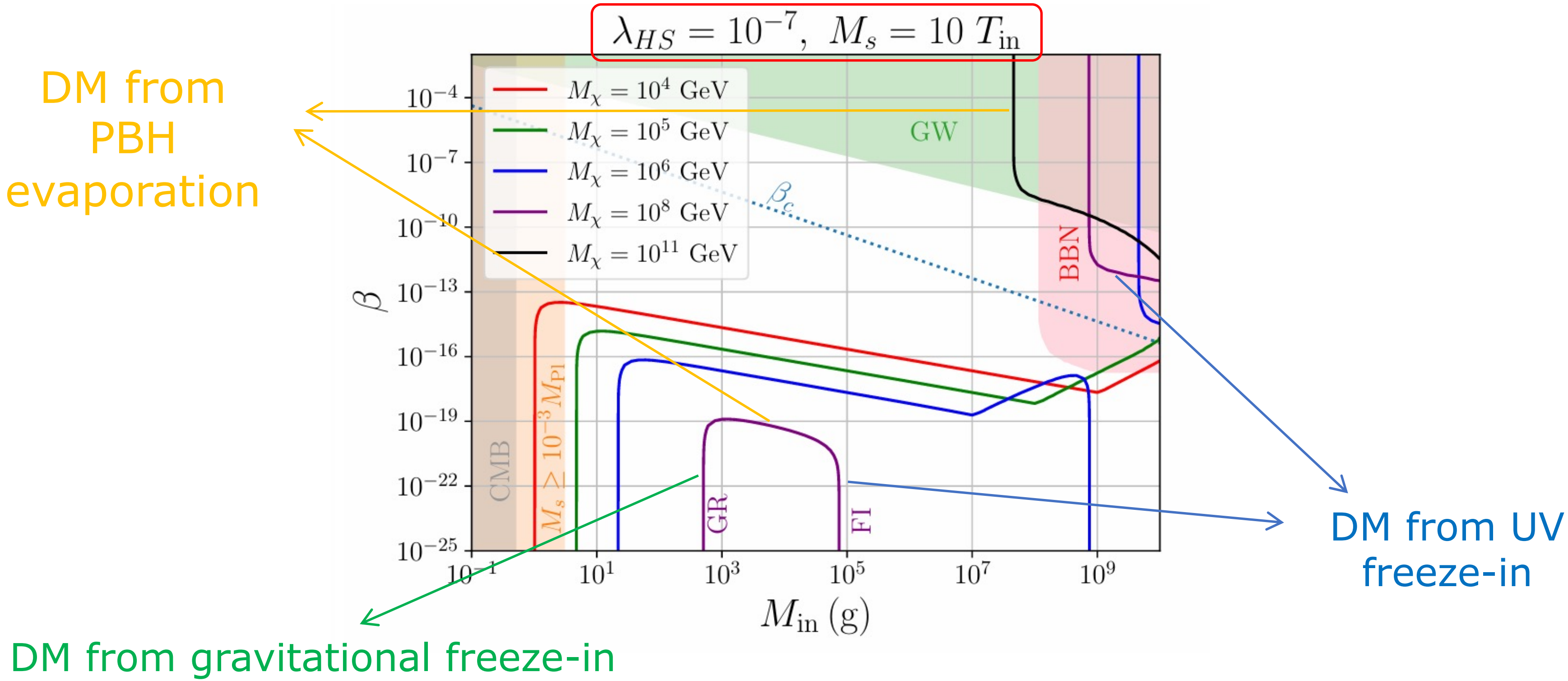
Phys.Lett.B 774 (2017) 676-681; Phys.Rev.D 97 (2018) 11, 115020; Phys.Rev.D 105 (2022) 7, 075005

$$\frac{dY_\chi^{\rm GR}(x)}{dz} = \frac{2}{s(z)H(z)z}\gamma_g$$

$$\gamma_g = 64\pi^2\delta\frac{T^8}{M_{\rm Pl}^4} \qquad \delta = \frac{3997\pi^3}{41472000}$$

$$Y_\chi^{\rm GR} = \frac{720\delta}{\pi^2 g_{*s}}\sqrt{\frac{5\pi}{g_*}}\left(\frac{T_{\rm in}}{M_{\rm Pl}}\right)^3\frac{s\,(T_{\rm evap})}{s(\tilde{T}_{\rm evap})}\times\begin{cases}1, & M_\chi \ll T_{\rm in}\\ \left(\frac{T_{\rm in}}{M_\chi}\right)^4, & M_\chi \gg T_{\rm in}\end{cases}$$

Schwarzschild PBH: superheavy DM



Siyu Jiang, FPH*, arXiv:2503.14332, JCAP06 (2025) 023

Kerr PBH： superheavy DM

Since the DM is pseudo-Goldstone boson， it can also be produced by superradiance process of Kerr BH.

The superradiance is efficient when the Compton length of the DM particle is comparable with the gravitational radius of Kerr BH.

The superradiant rate can be given approximately and analytically

$$\Gamma_{\rm SR} = \frac{M_\chi}{24}\left(\frac{M_{\rm PBH}M_\chi}{M_{\rm Pl}^2}\right)^8 (a_\star - 2M_\chi r_+)$$

The event horizon

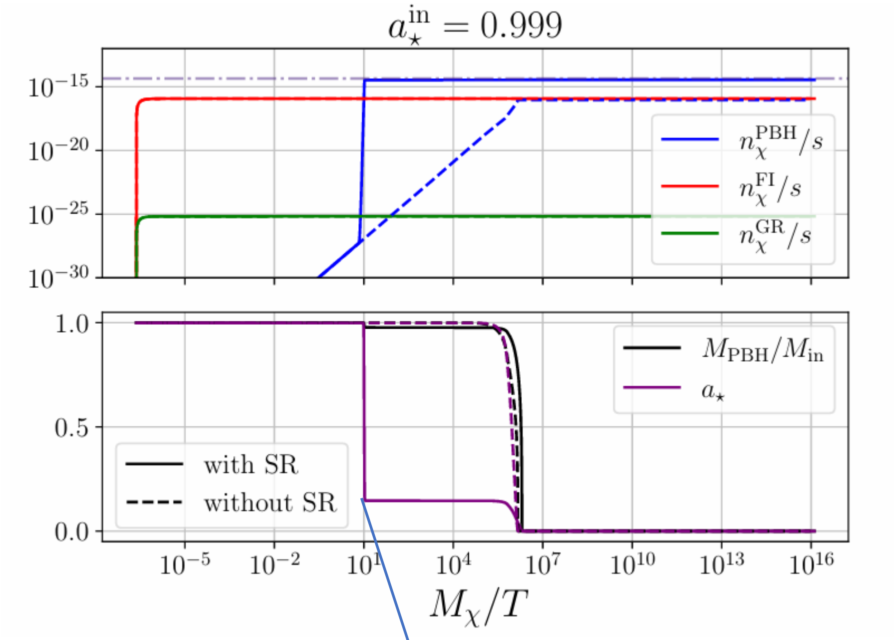
$$r_+ = r_g(1+\sqrt{1-a_\star^2})$$

Or more accurately by solving the Teukolsky equation numerically

$$\frac{1}{\sin\theta}\partial_\theta\left(\sin\theta\,\partial_\theta S\right) + \left[a_\star^2 r_g^2\left(\omega^2-\mu^2\right)\cos^2\theta - \frac{m^2}{\sin^2\theta} + \lambda\right] S = 0\,,$$

$$\Delta\partial_r\left(\partial_r R\right) - \Delta\left[\mu^2 r^2 + a_\star^2 r_g^2\omega^2 - 2\omega\, m\, a_\star r_g\, r + \left(\omega\left(r^2+a_\star^2 r_g^2\right) - m\, a_\star r_g\right)^2 + \lambda\right] R = 0$$

Kerr PBH： superheavy DM



$$Ha\frac{dN_\chi^{\rm SR}}{da} = \Gamma_{\rm SR} N_\chi^{\rm SR},$$

$$Ha\frac{dM_{\rm PBH}}{da} = -\varepsilon(M_{\rm PBH}, a_\star)\frac{M_{\rm Pl}^4}{M_{\rm PBH}^2} - M_\chi \Gamma_{\rm SR} N_\chi^{\rm SR},$$

$$Ha\frac{da_\star}{da} = -a_\star[\gamma(M_{\rm PBH}, a_\star) - 2\varepsilon(M_{\rm PBH}, a_\star)]\frac{M_{\rm Pl}^4}{M_{\rm PBH}^3} - \left[\sqrt{2} - 2\alpha a_\star\right]\Gamma_{\rm SR} N_\chi^{\rm SR}\frac{M_{\rm Pl}^2}{M_{\rm PBH}^2},$$

$$Ha\frac{dN_\chi^{\rm PBH}}{da} = \frac{\varrho_{\rm PBH}}{M_{\rm PBH}}\left[\Gamma_{\rm PBH\to\chi} + \Gamma_{\rm SR} N_\chi^{\rm SR}\right],$$

$$Ha\frac{dN_\chi^{\rm FI}}{da} = 2a^3\gamma_{\chi\chi\to H^\dagger H}, \quad Ha\frac{dN_\chi^{\rm GR}}{da} = 2a^3\gamma_g$$

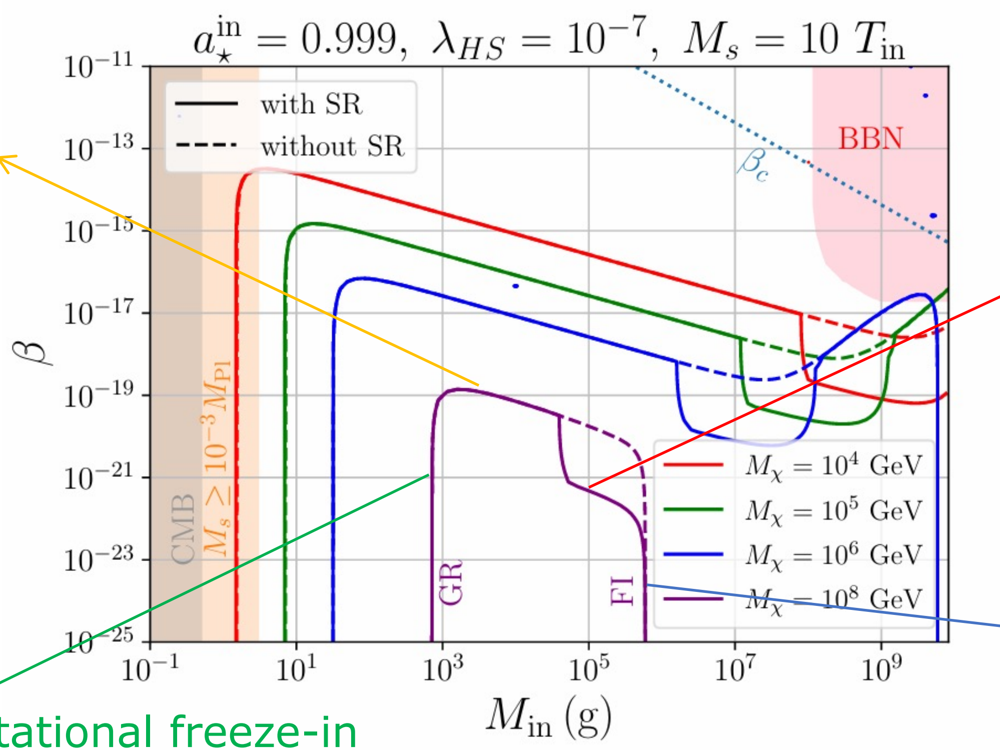
Superradiance reduces the BH angular momentum before the Hawking radiation, DM is mainly produced by superradiance.

Solve by using ULYSSES (2301.05722)

Kerr PBH： superheavy DM

DM from PBH evaporation

DM from superradiance

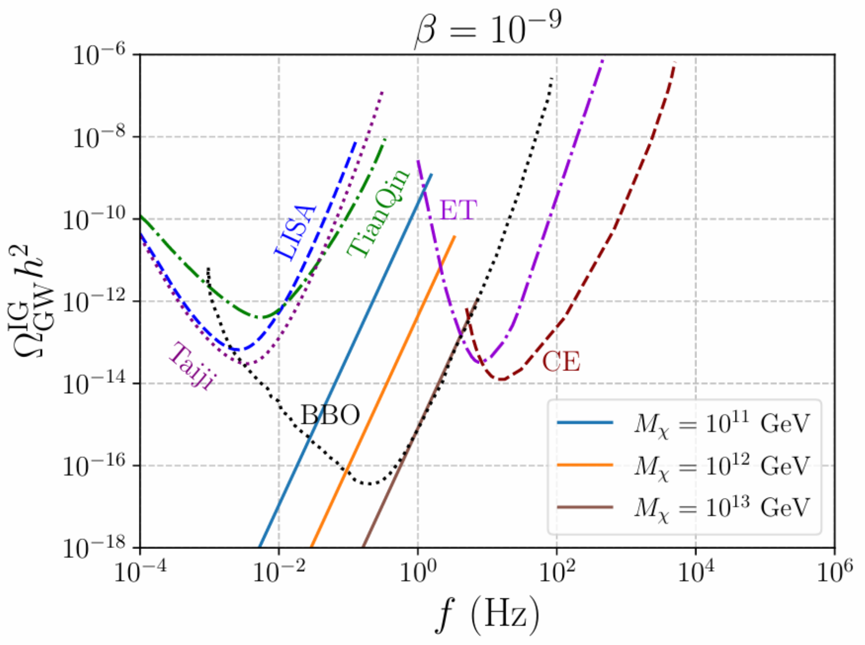


DM from UV freeze-in

DM from gravitational freeze-in

Siyu Jiang, FPH*, arXiv:2503.14332, JCAP06 (2025) 023

Induced GW from superheavy DM



When the PBHs begin to dominate the energy density of the Universe, the inhomogeneous distribution of PBHs leads to curvature perturbations. Subsequently, at second order, these perturbations can generate GWs.

$$f_p^{\rm IG} \simeq 1.7\times 10^3\ {\rm Hz}\left(\frac{M_{\rm in}}{10^4\ {\rm g}}\right)^{-5/6}$$

$$\simeq 0.33\ {\rm Hz}\left(\frac{M_\chi}{10^9\ {\rm GeV}}\right)^{1/3}$$

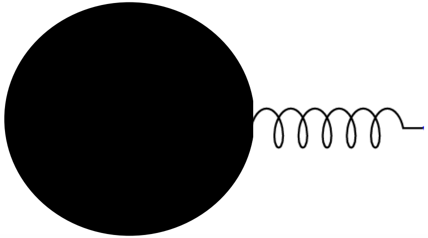
$$\Omega_p^{\rm IG} h^2 \simeq 9\times 10^{-7}\left(\frac{\beta}{10^{-8}}\right)^{16/3}\left(\frac{M_{\rm in}}{10^7\ {\rm g}}\right)^{34/9}$$

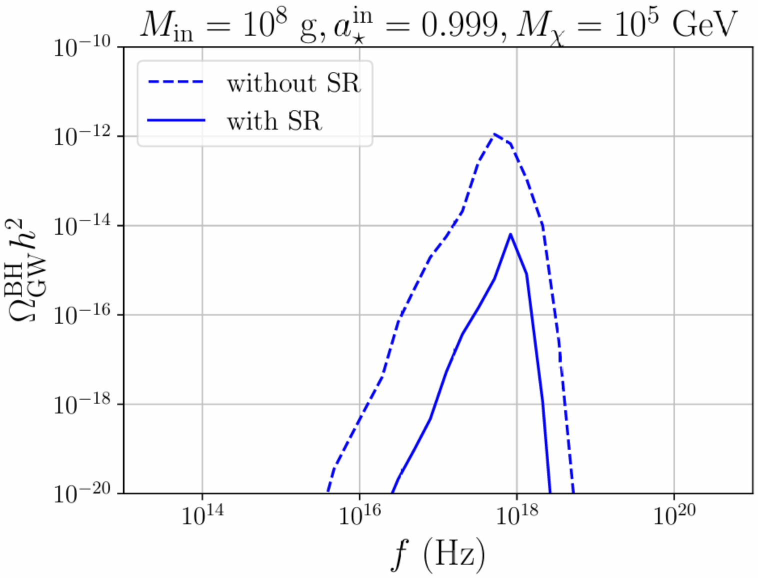
$$\Omega_{\rm GW}^{\rm IG} h^2 \simeq \Omega_p^{\rm IG} h^2 \left(\frac{f}{f_p^{\rm IG}}\right)^{11/3}\Theta\left(f_p^{\rm IG} - f\right)$$

Siyu Jiang, FPH*, arXiv:2503.14332, JCAP06 (2025) 023

JCAP 04 (2021) 062; JCAP 03 (2021) 053; JHEP 03 (2023) 127

GW from Hawking radiation





$$\frac{d\rho_{\rm GW}}{dtdp} = n_{\rm PBH}(t)p\frac{dN_{\rm grav}}{dtdp}$$

↓

public code BlackHawk

$$\frac{d\rho_{\rm GW,0}}{d\ln p_0} = 2\times 10^{32}\beta M_{\rm in}^{-3/2} p_0^4 \int_{\frac{a_0}{a_{\rm evap}}}^{\frac{a_0}{a_{\rm in}}} dx \frac{\sigma_{s_i}^{lm}}{\exp\left[\left(xp_0 - m\Omega\right)/T_{\rm PBH}\right] - 1}$$

$$\Omega_{\rm GW}^{\rm BH} h^2 = \frac{h^2}{\rho_c}\frac{d\rho_{\rm GW,0}}{d\ln p_0}$$

Outline

1. **Motivation for new dark matter (DM) mechanism**
2. **pNGB DM from Primordial black hole (PBH) radiation and superradiance with its gravitational wave (GW) signals**
3. **DM from first-order phase transition (FOPT) and GW**
   - **Case I: Q-ball and gauged Q-ball DM**
   - **Case II: filtered DM**
4. **Summary and outlook**

Heavy DM from cosmic phase transition

Renaissance of quark nugget DM idea by E. Witten.

Recently, dynamical DM formed by phase transition has became a new idea for heavy. Bubble wall in FOPT can be the “filter” to obtain the needed heavy DM when avoiding the unitarity constraints.

FOPT in the early universe	Coffee making process
Bubble wall	filter
Case I:(gauged) Q-ball DM	Large coffee beans
Case II: filtered DM	Coffee
Phase transition GW	Aroma

E. Krylov, A. Levin, V. Rubakov, Phys.Rev.D 87 (2013) 8, 083528
FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028
arXiv:1912.04238, Dongjin Chway, Tae Hyun Jung, Chang Sub Shin
Phys.Rev.Lett. 125 (2020) 15, 151102 , M. J. Baker, J. Kopp,and A. J. Long
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
Siyu Jiang, FPH, Chong Sheng Li, arXiv:2305.02218
Siyu Jiang, FPH, Pyungwon Ko, arXiv:2404.16509
more than 100 papers in recent 5 years

Case I: Q-ball DM　　What is Q-ball?

PHYSICS REPORTS (Review Section of Physics Letters) 221, Nos. 5 & 6 (1992) 251–350. North-Holland　PHYSICS REPORTS

Nontopological solitons*

T.D. Lee
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and

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Received May 1992; editor: D.N. Schramm

Nuclear Physics B262 (1985) 263–283

Q-BALLS*

Sidney COLEMAN

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Q-ball is the most typical non-topological soliton, initially proposed by Prof. Tsung-Dao Lee and Sidney Coleman. In quantum field theory, a spherically symmetric extended body that forms a non-topological soliton structure with a conserved global quantum number Q is called a Q-ball.

$$\phi = (\phi_R + i\phi_I)/\sqrt{2} \qquad Q = \int j^0 dx = \int \left(\phi_I \dot{\phi}_R - \phi_R \dot{\phi}_I\right) dx. \qquad \delta(E - \omega Q) = 0$$

↓

$$E = \int \left\{ \frac{1}{2}\left[\dot{\phi}_R^2 + \dot{\phi}_I^2 + (\nabla\phi_R)^2 + (\nabla\phi_I)^2\right] + U\left[\frac{1}{2}\left(\phi_R^2 + \phi_I^2\right)\right]\right\} dx \qquad \phi = f(r)e^{-i\omega t}$$

Q-ball production mechanism

Q-ball production：

(1) produce the charge asymmetry (i.e. locally produce lots of particles with the same charge to form Q-ball)

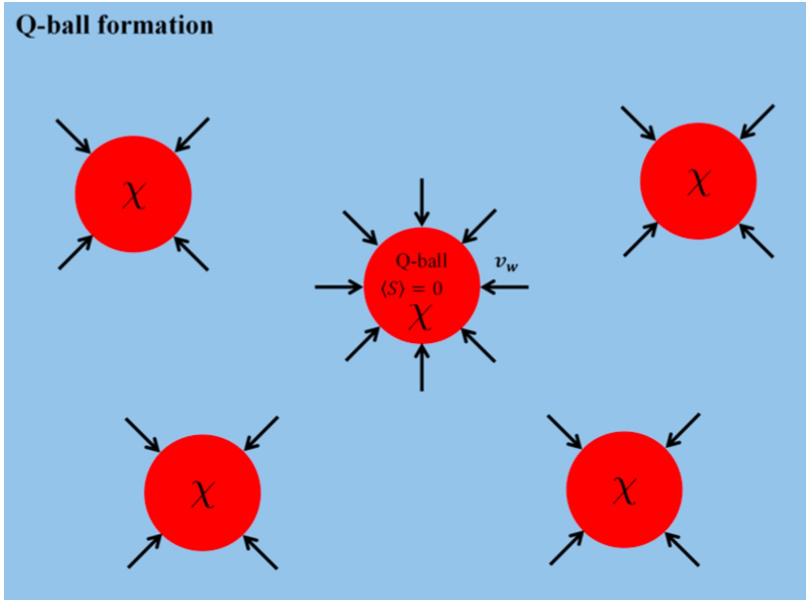
(2) and packet the same sign charge in the small size after overcoming the Coulomb repulsive interaction.

1. Supersymmetry？ Affleck-Dine mechanism.

We do not observe the supersymmetry until now!

2. Q-ball formation based on FOPT.

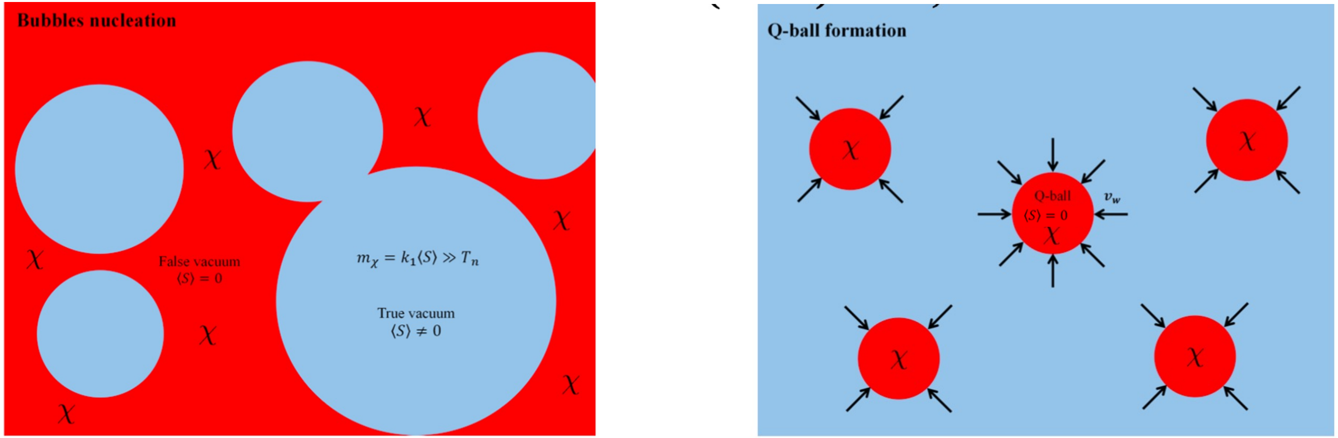
This talk



Case I: Q-ball DM

Global Q-ball DM: The cosmic phase transition with Q-balls production can explain baryogenesis and DM simultaneously.

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



(a) Bubble nucleation: χ particles trapped in the false vacuum due to Boltzmann suppression

(b) Q-ball formation: After the formation of Q-balls, they should be squeezed by the true vacuum

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

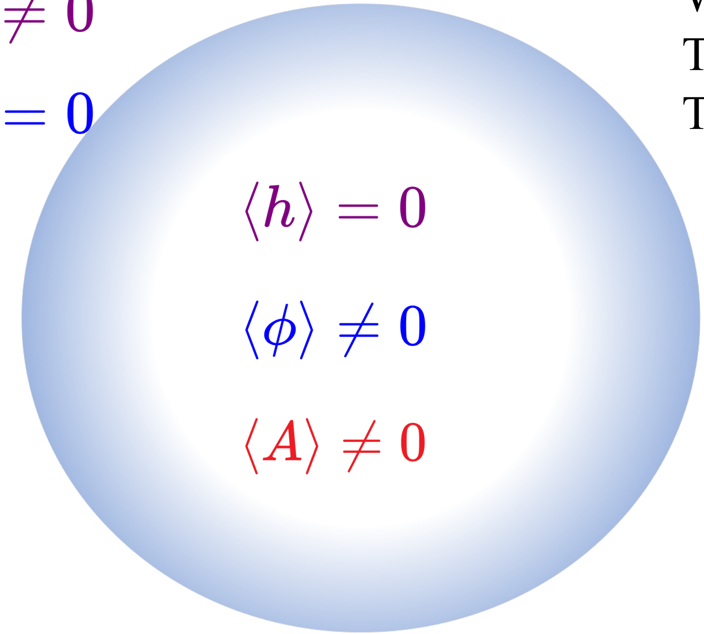
New DM production scenario by the bubbles.
The global Q-ball model proposed by T.D. Lee

Friedberg-Lee-Sirlin model
R. Friedberg, T.D. Lee and A. Sirlin.
Rev. D 13 (1976) 2739

Case I: Gauged Q-ball DM

$\langle h \rangle \neq 0$

$\langle \phi \rangle = 0$



When the conserved U(1) symmetry is local,
This introduces an extra gauge field A.
The minimal model achieving

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} - V(\phi, h)$$

$$V(\phi, h) = \frac{\lambda_{\phi h}}{2} h^2 |\phi|^2 + \frac{\lambda_h}{4}\left(h^2 - v_0^2\right)^2$$

Interestingly, this portal coupling also naturally induces a strong FOPT.

$$J_\mu = i\left(\phi^\dagger \overleftrightarrow{\partial}_\mu \phi + 2i\tilde{g}\tilde{A}_\mu |\phi|^2\right) \qquad Q = \int d^3x J^0$$

Conserved charge

Siyu Jiang, FPH, Pyungwon Ko, JHEP 07 (2024) 053

Gauged Q-ball

$$\mathcal{L} = \left(D_\mu\phi\right)^\dagger\left(D^\mu\phi\right) + \frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} - V(\phi,h) \qquad V(\phi,h) = \frac{\lambda_{\phi h}}{2}h^2|\phi|^2 + \frac{\lambda_h}{4}\left(h^2 - v_0^2\right)^2$$

$$\tilde{A}_t(r) = v_0\frac{\tilde{g}}{\sqrt{2\lambda_h}}\mathcal{A}(\rho), \quad \phi(t,r) = \frac{v_0}{\sqrt{2}}\Phi(\rho)e^{-i\omega t}, \quad h(r) = v_0\mathcal{H}(\rho)$$

Friedberg-**Lee**-Sirli-Maxwell model

$$\frac{1}{\rho^2}\partial_\rho\left(\rho^2\partial_\rho\mathcal{A}\right) + (\nu - \alpha^2\mathcal{A})\Phi^2 = 0\,,$$

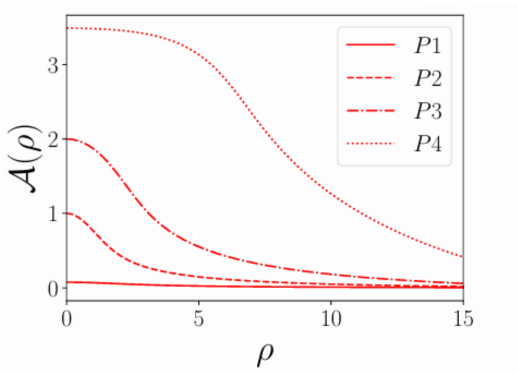
$$\alpha \equiv \frac{|\tilde{g}|}{\sqrt{2\lambda_h}}, k \equiv \frac{\sqrt{\lambda_{\phi h}}}{2\sqrt{\lambda_h}} = \frac{m_\phi}{m_h}$$

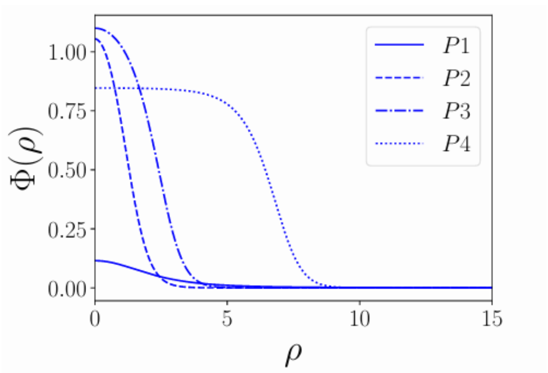
$$\frac{1}{\rho^2}\partial_\rho\left(\rho^2\partial_\rho\Phi\right) + \left[(\nu - \alpha^2\mathcal{A})^2 - k^2\mathcal{H}^2\right]\Phi = 0\,,$$

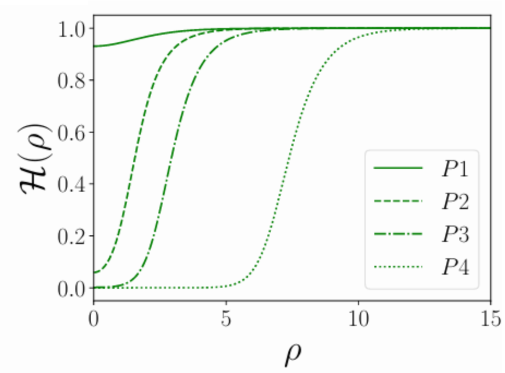
$$\nu \equiv \frac{\omega}{\sqrt{2\lambda_h}v_0}$$

relaxation method

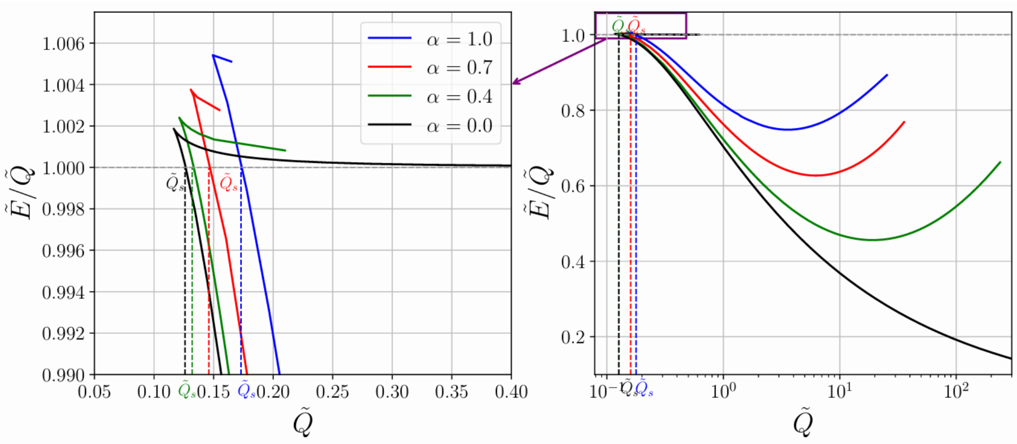
$$\frac{1}{\rho^2}\partial_\rho\left(\rho^2\partial_\rho\mathcal{H}\right) - k^2\mathcal{H}\Phi^2 - \frac{1}{2}\mathcal{H}\left(\mathcal{H}^2 - 1\right) = 0\,.$$







Gauged Q-ball stability

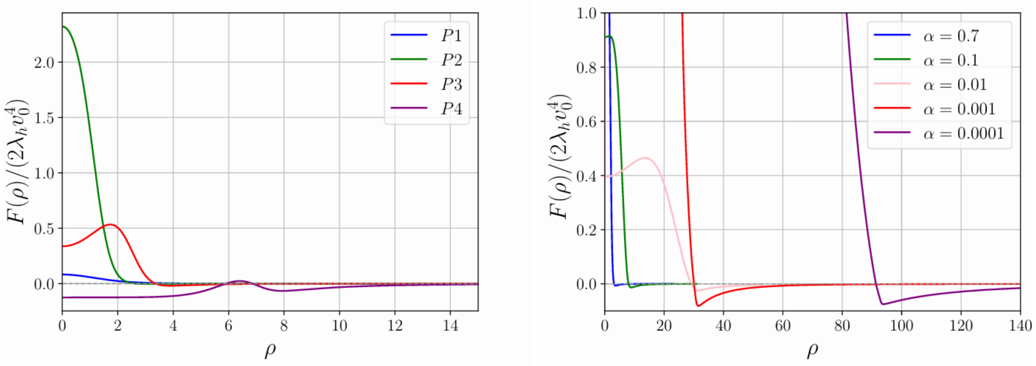


Quantum stability

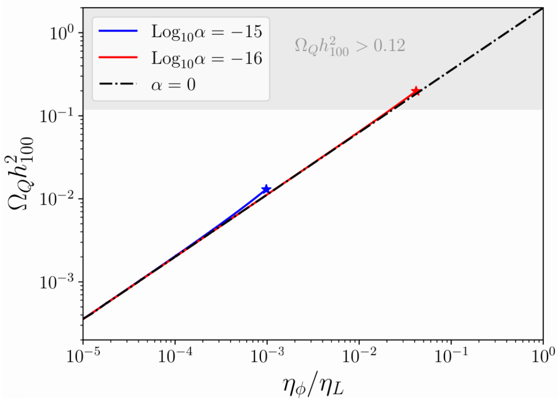
$$E < m_\phi Q \quad \text{or} \quad \tilde{E}/\tilde{Q} < 1$$

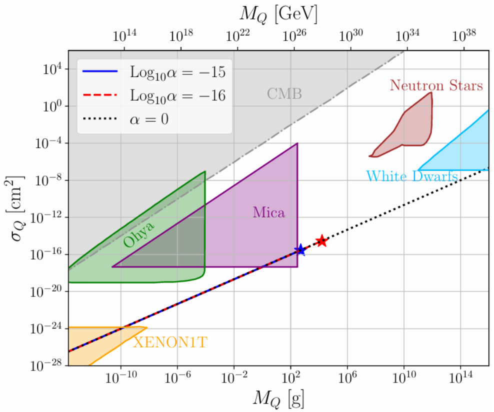
Stress stability

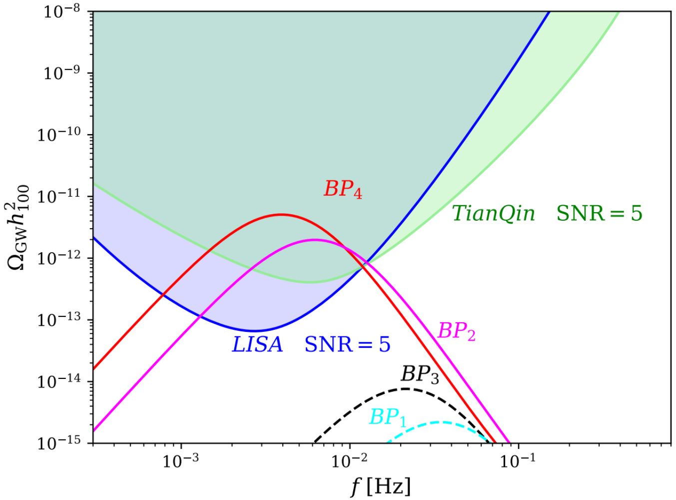
$$F(r) = \frac{2}{3}s(r) + p(r) > 0$$



Gauged Q-ball DM from a FOPT







$$\Omega_Q h^2_{100} \simeq 2.81 \times \left(\frac{s_0 h^2_{100}}{\rho_c}\right)\left(\frac{\Gamma(T_\star)}{v_w}\right)^{3/16} s_\star^{-1/4}(F_\phi^{\rm trap}\eta_\phi)^{3/4}\lambda_h^{1/4} v_0 \left(1 + \frac{108^{1/4}\tilde{g}^2 F_\phi^{\rm trap}\eta_\phi s_\star v_w^{3/4}}{5.4\pi^{7/4}\Gamma(T_\star)^{3/4}}\right)$$

	$\lambda_{\phi h}$	T_p [GeV]	α_p	β/H_p	v_w	$F_\phi^{\rm trap}$	η_ϕ/η_L	$\delta\sigma_{Zh}$	GW
BP_1	6.8	69.8	0.12	540	0.1	0.932	0.48	-0.36%	● (cyan)
BP_2	6.8	70.4	0.12	578	0.6	0.805	3.0	-0.36%	● (magenta)
BP_3	7.0	63.0	0.15	372	0.1	0.965	3.4	-0.37%	● (black)
BP_4	7.0	63.9	0.15	403	0.6	0.858	20.8	-0.37%	● (red)

F_ϕ^{trap}: The fraction of particles trapped into the false vacuum. It is determined by the phase transition dynamics.

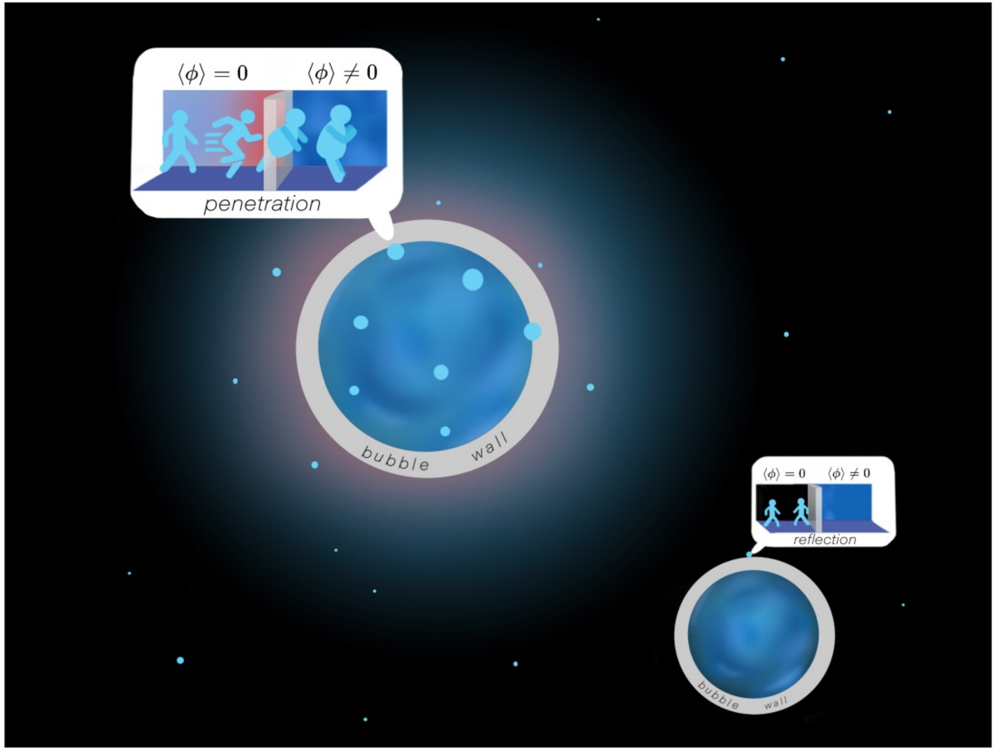
Siyu Jiang, FPH, Pyungwon Ko, JHEP 07 (2024) 053

Case II: filtered DM from a FOPT

DM

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

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

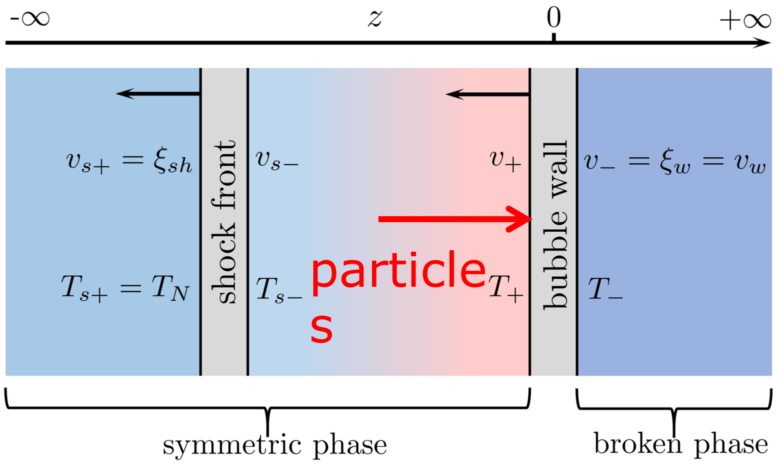


Case II: filtered DM

Original work:

$$\tilde{v}_{\rm pl} = v_w, \quad T = T' = T_n$$

Phys.Rev.Lett. 125 (2020) 15, 151102 , M. J. Baker, J. Kopp, and A. J. Long



$$\tilde{v}_{\rm pl} = \tilde{v}_+, \quad T = T_+, \quad T' = T_- \qquad \text{(this work with hydrodynamic effects)} .$$

$$J_w^{\rm in} = \frac{g_\chi}{(2\pi)^2}\int_0^{-1} d\cos\theta\cos\theta \int_{-\frac{m_\chi^{\rm in}}{\cos\theta}}^{\infty} dp \frac{p^2}{e^{\tilde{\gamma}_+(1+\tilde{v}_+\cos\theta)p/T_+}} = \frac{g_\chi T_+^3\left(1+\tilde{\gamma}_+ m_\chi^{\rm in}(1-\tilde{v}_+)/T_+\right)}{4\pi^2\tilde{\gamma}_+^3(1-\tilde{v}_+)^2} e^{-\tilde{\gamma}_+ m_\chi^{\rm in}(1-\tilde{v}_+)/T_+} .$$

$$n_\chi^{\rm in} = \frac{J_w^{\rm in}}{\gamma_w v_w} \qquad \Omega_{\rm DM}^{\rm (hy)} h^2 = \frac{m_\chi^{\rm in}(n_\chi^{\rm in}+n_{\bar{\chi}}^{\rm in})}{\rho_c/h^2}\frac{g_{\star 0}T_0^3}{g_\star(T_-)\,T_-^3} \simeq 6.29\times 10^8 \frac{m_\chi^{\rm in}}{\rm GeV}\frac{(n_\chi^{\rm in}+n_{\bar{\chi}}^{\rm in})}{g_\star(T_-)\,T_-^3}$$

Case II: filtered DM

$$T_\phi^{\mu\nu} = \partial^\mu\phi\partial^\nu\phi - g^{\mu\nu}\left[\frac{1}{2}(\partial\phi)^2 - V_{T=0}(\phi)\right]$$

Energy-momentum tensor of scalar field

$$T_{\rm pl}^{\mu\nu} = \sum_i \int \frac{d^3k}{(2\pi)^3 E_i} k^\mu k^\nu f_i^{\rm eq}(k)$$

Energy-momentum tensor of fluid

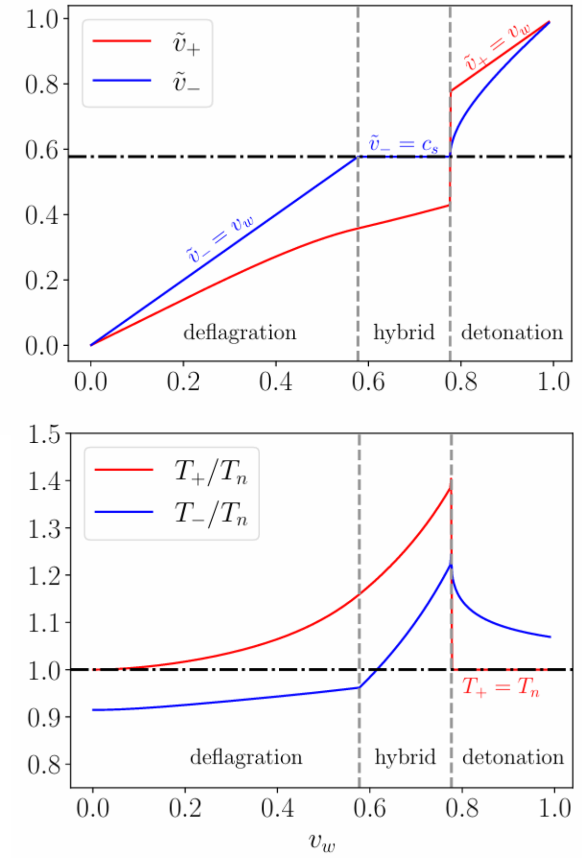
$$T_{\rm fl}^{\mu\nu} = T_\phi^{\mu\nu} + T_{\rm pl}^{\mu\nu} = \omega u^\mu u^\nu - p g^{\mu\nu}$$

Energy-momentum conservation

$$\omega_+\tilde{v}_+^2\tilde{\gamma}_+^2 + p_+ = \omega_-\tilde{v}_-^2\tilde{\gamma}_-^2 + p_-, \quad \omega_+\tilde{v}_+\tilde{\gamma}_+^2 = \omega_-\tilde{v}_-\tilde{\gamma}_-^2$$

$$\alpha_+ \equiv \epsilon/\left(a_+T_+^4\right) \qquad r_\omega = \omega_+/\omega_- = (a_+T_+^4)/(a_-T_-^4)$$

$$\nabla_\mu T^{\mu\nu} = 0 \quad \longleftrightarrow \quad j\frac{v}{\xi} = \gamma^2(1-v\xi)\left[\frac{\mu^2}{c_s^2} - 1\right]\partial_\xi v, \qquad \frac{\partial_\xi \omega}{\omega} = \left(1 + \frac{1}{c_s^2}\right)\gamma^2 \mu \partial_\xi v \,.$$



Case II: filtered DM

Boltzmann equation

$$\mathbf{L}[f_\chi] = \mathbf{C}[f_\chi]$$

$$f_\chi = \mathcal{A}(z,p_z)\, f^{\rm eq}_{\chi,+} = \mathcal{A}(z,p_z) \exp\left(-\frac{\tilde{\gamma}_+(E-\tilde{v}_+p_z)}{T_+}\right)$$

$$\mathbf{L}[f_\chi] = \frac{p_z}{E}\frac{\partial f_\chi}{\partial z} - \frac{m_\chi}{E}\frac{\partial m_\chi}{\partial z}\frac{\partial f_\chi}{\partial p_z} \qquad m_\chi(z) \equiv \frac{m_\chi^{\rm in}(\phi_-)}{2}\left(1+\tanh\frac{2z}{L_w}\right)$$

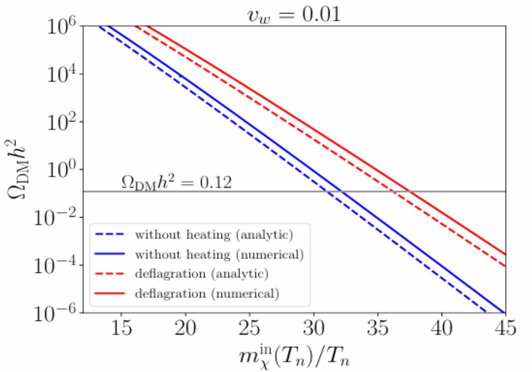
$$g_\chi \int \frac{dp_x dp_y}{(2\pi)^2}\mathbf{L}[f_\chi] \approx \left[\left(\frac{p_z}{m_\chi}\frac{\partial}{\partial z} - \left(\frac{\partial m_\chi}{\partial z}\right)\frac{\partial}{\partial p_z} - \left(\frac{\partial m_\chi}{\partial z}\right)\frac{\tilde{\gamma}_+\tilde{v}_+}{T_+}\right)\mathcal{A}(z,p_z)\right]\frac{g_\chi m_\chi T_+}{2\pi\tilde{\gamma}_+}e^{\tilde{\gamma}_+\left(\tilde{v}_+p_z-\sqrt{m_\chi^2+p_z^2}\right)/T_+}$$

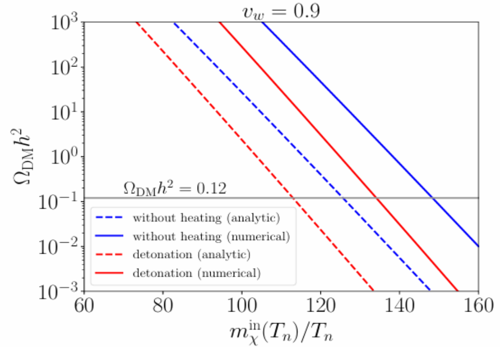
including$\chi\bar{\chi} \leftrightarrow \phi\phi, \chi\phi \leftrightarrow \chi\phi, \chi\chi \leftrightarrow \chi\chi, \chi\bar{\chi} \leftrightarrow \chi\bar{\chi}, \dots$

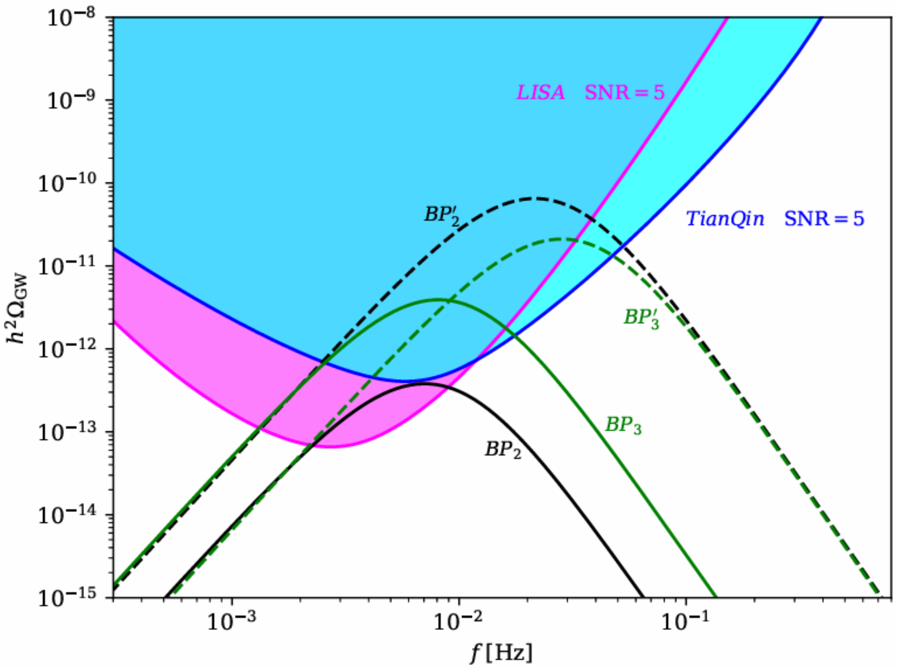
$$\begin{aligned} g_\chi \int \frac{dp_x dp_y}{(2\pi)^2}\mathbf{C}[f_\chi] &= -g_\chi g_{\bar{\chi}} \int \frac{dp_x dp_y}{(2\pi)^2 2E_p^{\mathcal{P}}} d\Pi_{q^{\mathcal{P}}} 4F\sigma_{\chi\bar{\chi}\to\phi\phi}\left[f_{\chi_p} f^{\rm eq}_{\bar{\chi}_q,+} - f^{\rm eq}_{\chi_p} f^{\rm eq}_{\bar{\chi}_q}\right] \\ &= -g_\chi g_{\bar{\chi}} \int \frac{dp_x dp_y}{(2\pi)^2 2E_p^{\mathcal{P}}} d\Pi_{q^{\mathcal{P}}} 4F\sigma_{\chi\bar{\chi}\to\phi\phi}\left[\mathcal{A} f^{\rm eq}_{\chi_p,+} f^{\rm eq}_{\bar{\chi}_q,+} - f^{\rm eq}_{\chi_p} f^{\rm eq}_{\bar{\chi}_q}\right] \\ &\equiv \Gamma_{\rm P}(z,p_z)\mathcal{A}(z,p_z) - \Gamma_{\rm I}(z,p_z)\ , \end{aligned}$$

Case II: filtered DM

$$n_\chi^{\rm in} = \frac{T_+}{\gamma_w \tilde{\gamma}_+} \int_0^\infty \frac{dp_z}{(2\pi)^2} \mathcal{A}(z \gg L_w, p_z) \exp\left[\tilde{\gamma}_+ \left(\tilde{v}_+ p_z - \sqrt{p_z^2 + (m_\chi^{\rm in})^2}\right) / T_+\right] \left(\sqrt{p_z^2 + (m_\chi^{\rm in})^2} + \frac{T_+}{\tilde{\gamma}_+}\right)$$



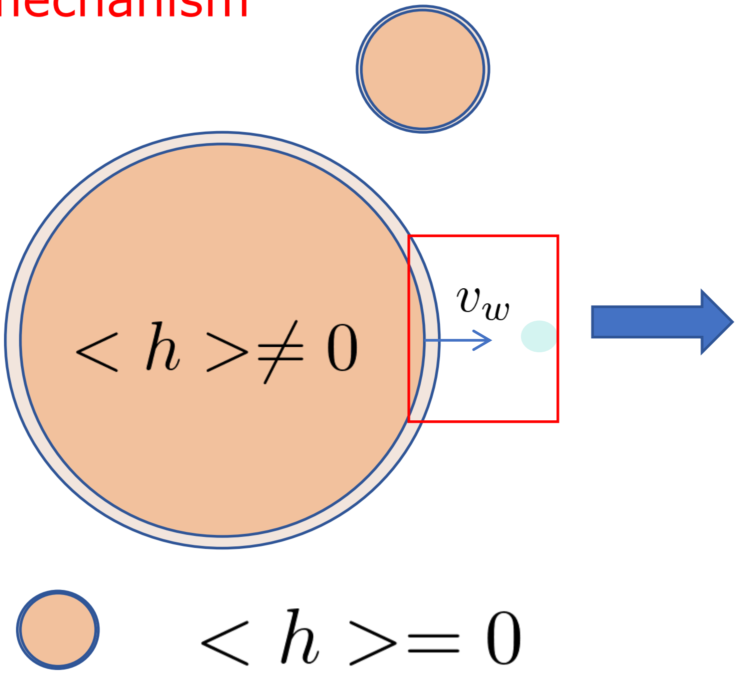


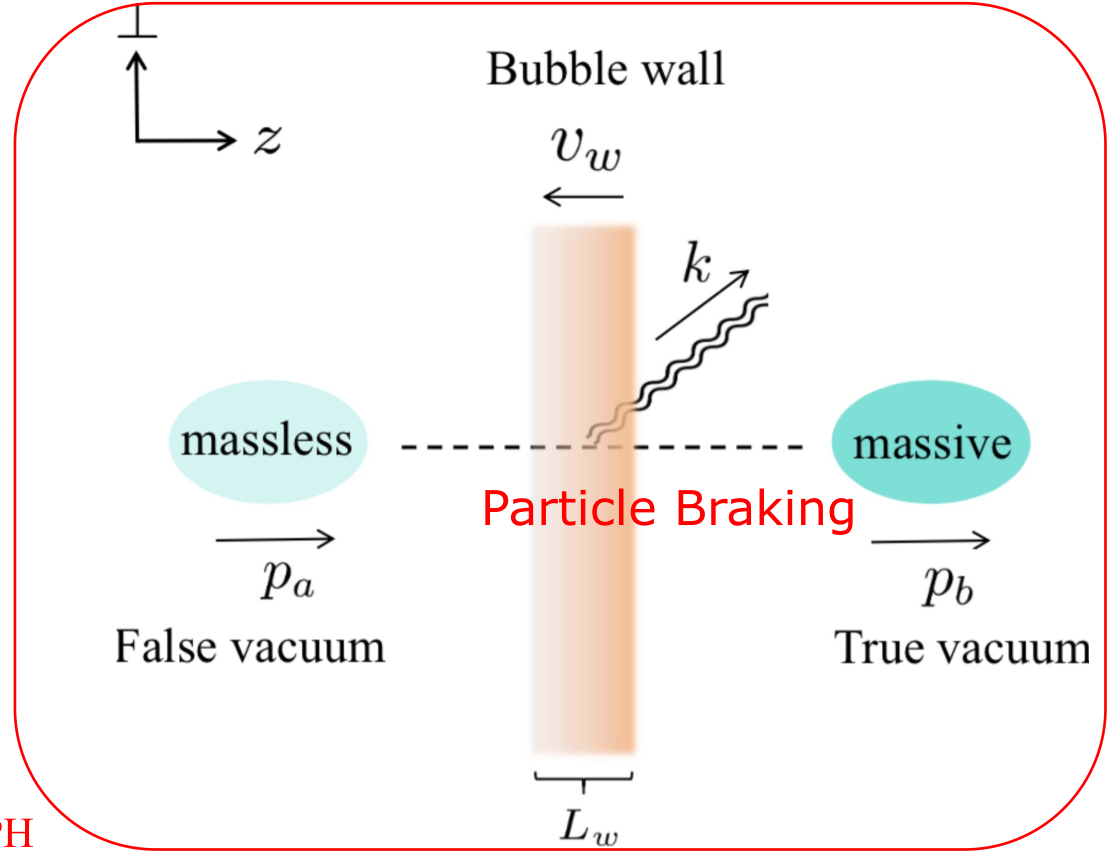


The missing GW source ?

Braking GW from phase transition

New phase transition GW mechanism





arXiv: 2508.04314, Dayun Qiu, Siyu Jiang, FPH

Bremsstrahlung probability

Now, we can calculate the interaction matrix element.

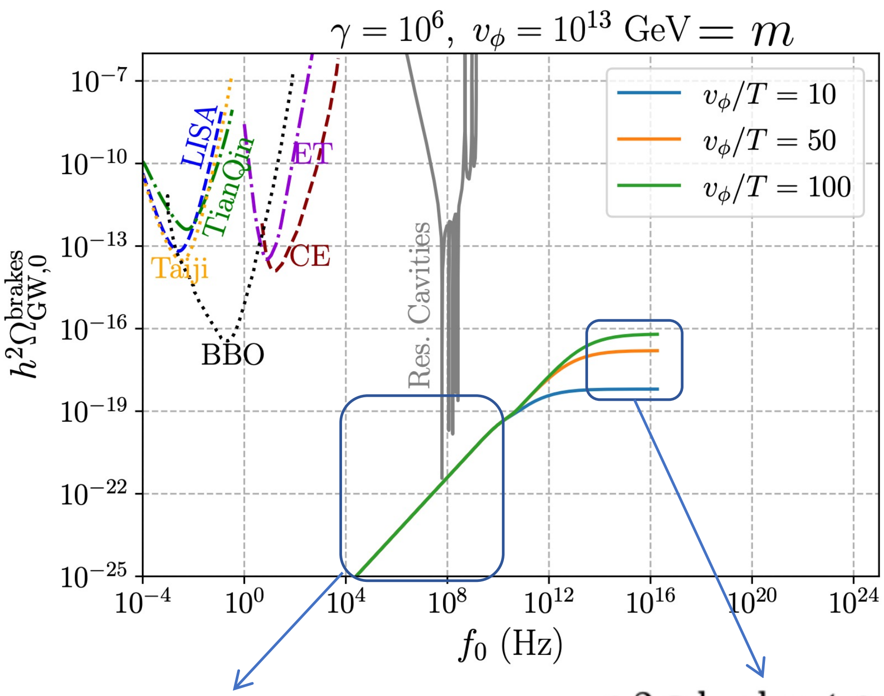
Feynman amplitude

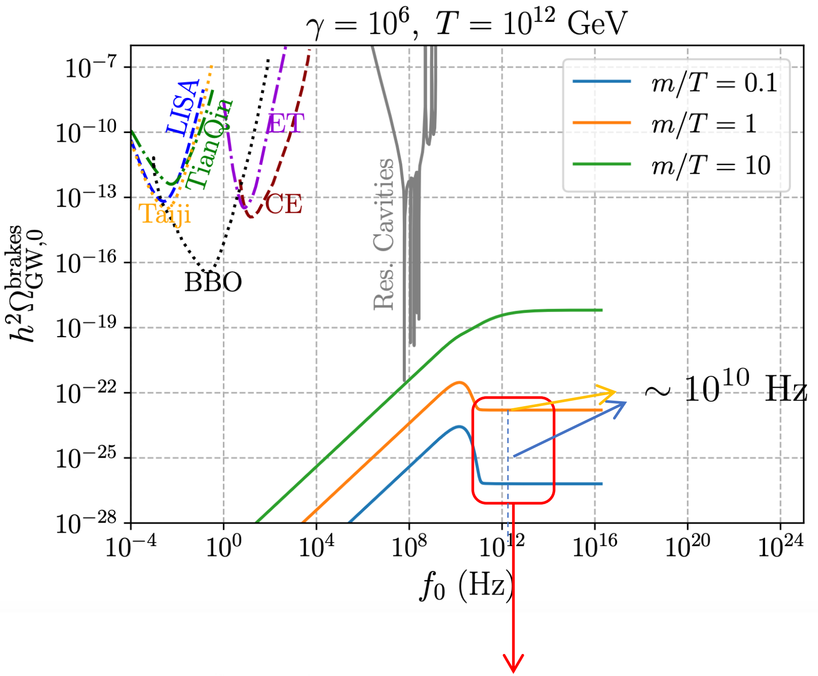
$$
\begin{aligned}
\langle \vec{p}_b^{\,I,\text{out}}, \vec{k} | \mathcal{T} | \vec{p}_a^{\,R} \rangle &= \int \mathrm{d}^4x \, \langle \vec{p}_b^{\,I,\text{out}}, \vec{k} | \mathcal{H}_{\text{int}} | \vec{p}_a^{\,R} \rangle \\
&= \int \mathrm{d}z \int \frac{\mathrm{d}^3 p_a'}{(2\pi)^3} \int \frac{\mathrm{d}^3 p_b'}{(2\pi)^3} \int \frac{\mathrm{d}^3 k'}{(2\pi)^3} \boxed{V^\dagger(z)} \chi_R(z, p_a'^z) \zeta_I^*(z, p_b'^z) \chi^*(z, k'^z) \\
&\quad \times (2\pi)^3 \delta(E_a' - E_b' - E_k') \delta^{(2)}(\vec{p}'_{a,\perp} - \vec{p}'_{b,\perp} - \vec{k}'_\perp) \langle \vec{p}_b^{\,I,\text{out}}, \vec{k} | a_k^\dagger a_{I,b}^\dagger a_{R,a} | \vec{p}_a^{\,R} \rangle \\
&= (2\pi)^3 \delta\left(\sum E\right) \delta^{(2)}\left(\sum \vec{p}_\perp\right) \mathcal{M}_I ,
\end{aligned}
$$

$$
\mathcal{M}_I = \int_{-\infty}^{+\infty} \mathrm{d}z \, V^\dagger(z) \chi_R(z, p_a^z) \zeta_I^*(z, p_b^z) \chi^*(z, k^z).
$$

GW spectrum

arXiv: 2508.04314, Dayun Qiu, Siyu Jiang, FPH





$h^2\Omega_{\mathrm{GW},0}^{\mathrm{brakes}}(f_0) \propto m^2 f_0,\quad h^2\Omega_{\mathrm{GW},0}^{\mathrm{brakes}}(f_{\mathrm{peak}}) \propto m^4/T^2.\quad$ when $T \gtrsim m$,

collinear gravitons　non-collinear gravitons　double-peaked structure

GW spectrum recap

The GW power spectrum exhibits two distinct behaviors across different frequency regimes.

arXiv: 2508.04314, Dayun Qiu, Siyu Jiang, FPH

- In the low-frequency regime, the spectrum scales linearly with frequency and is proportional to the square of the mass, primarily sourced from ultra-collinear radiation emitted as particles traverse the bubble wall.

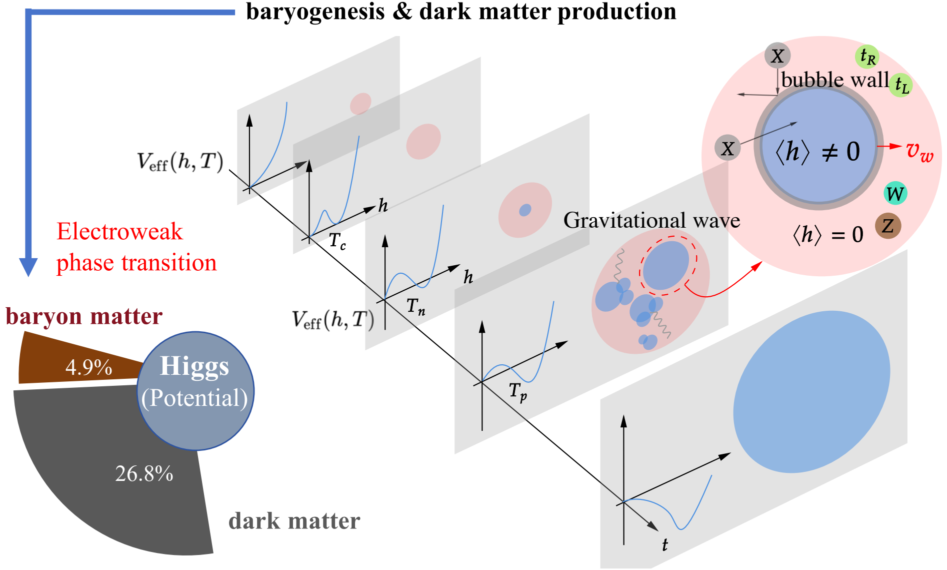
- In contrast, the high-frequency regime displays an approximately flat spectrum up to a cutoff frequency and the amplitude scales with the fourth power of the mass, dominated by non-collinear gravitons.

proportional to the Lorentz factor of the bubble wall

These distinct behaviors may help to more directly to extract the new particle information.

Summary and outlook

- **Explore new mechanisms to produce heavy DM beyond thermal freeze out.**
- **Cosmic phase transition and PBH can naturally produce heavy DM.**
- **The associated GW provides new approaches to explore DM.**



Thanks! Comments and collaborations are welcome!

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