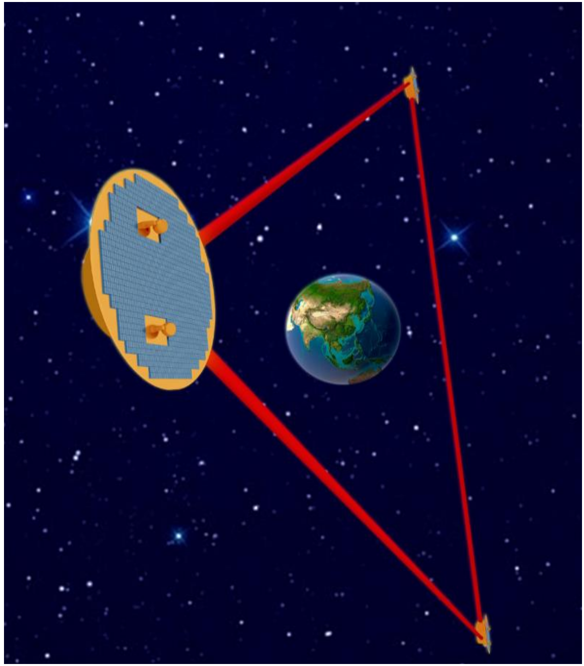
中山大學天琴中心
TIANQIN CENTER FOR GRAVITATIONAL PHYSICS, SYSU

# Fundamental Physics and Cosmology with TianQin


**Fa Peng Huang**

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

Sun Yat-sen University, TianQin center

The Rencontres du Vietnam on Cosmology @ Quy Nhon, Vietnam 2025.08.12

# Outline

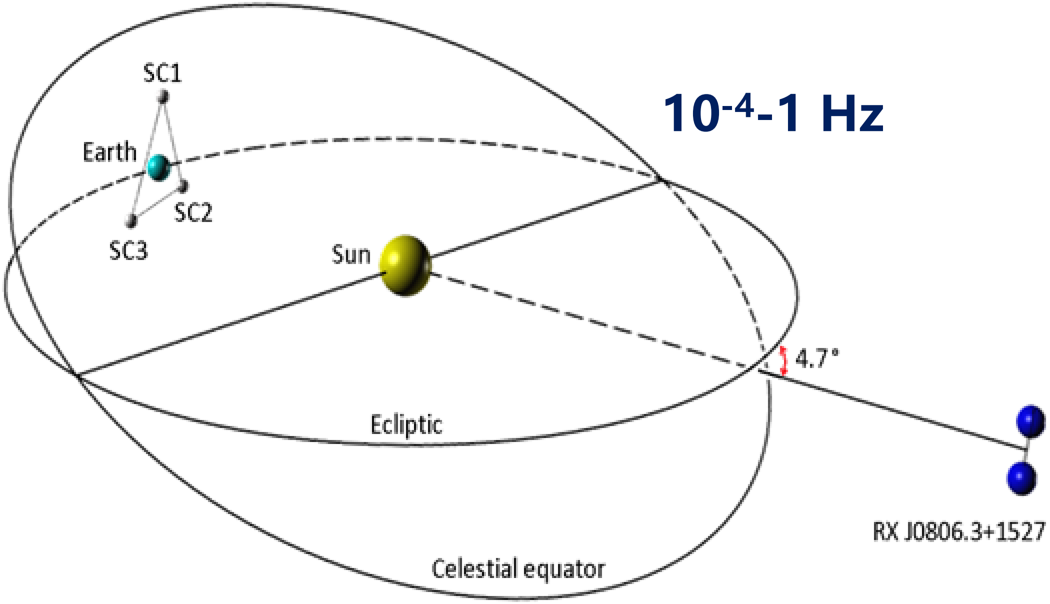
1. TianQin and gravitational wave (GW) in a nutshell
2. Higgs potential, Electroweak (EW) phase transition/baryogenesis at TianQin
3. Dark matter (DM) signals at TianQin (focus)

✓ Ultralight DM

✓ Heavy DM

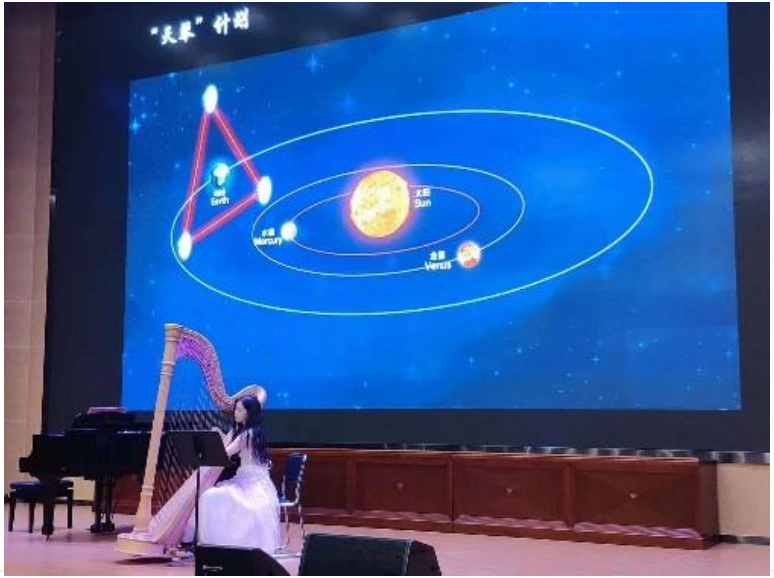
3. Summary and outlook

# What is TianQin ?




**$10^{-4}$-1 Hz**

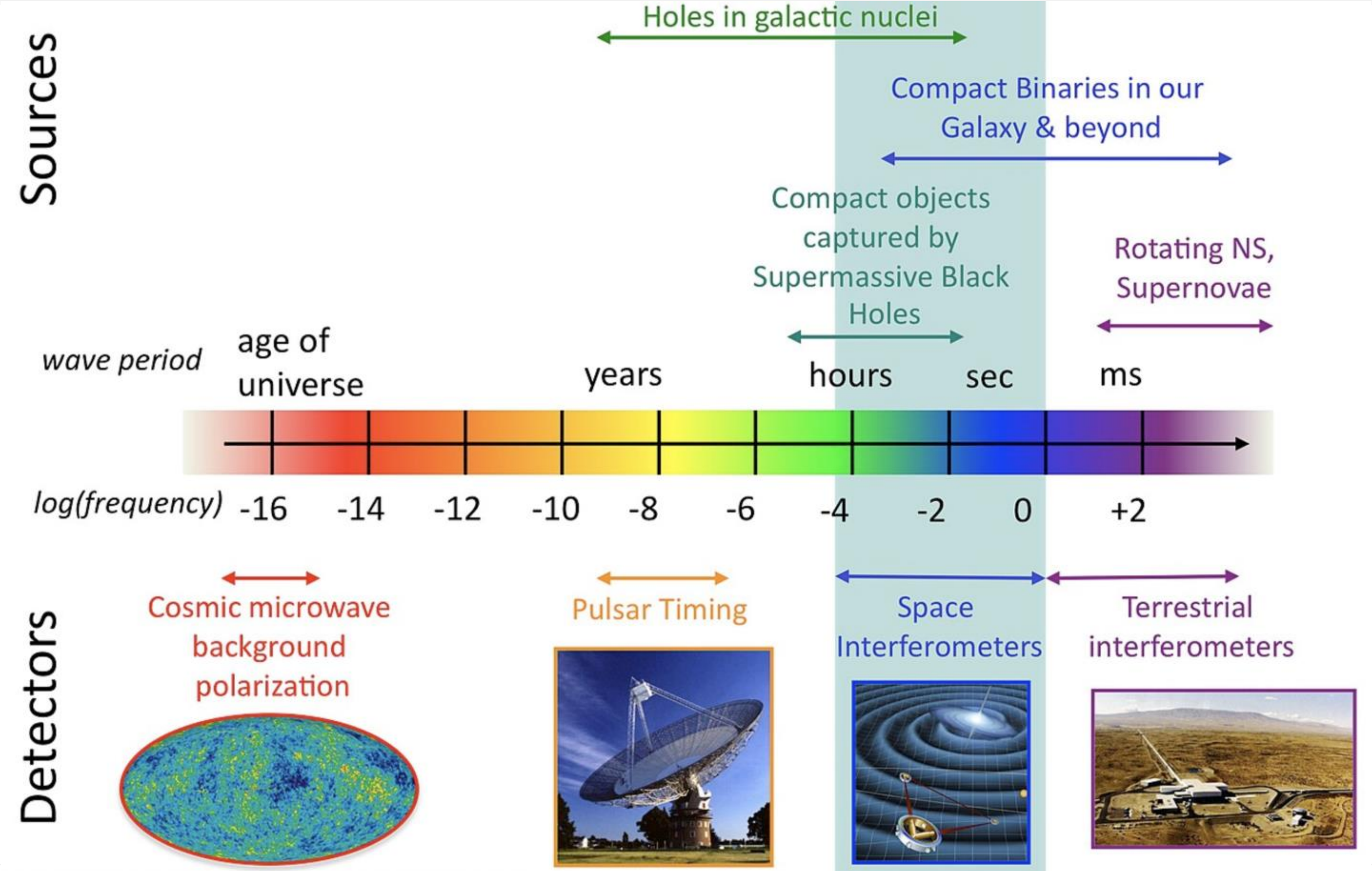
- **Expected in 2035**
- **Geocentric orbit, normal triangle constellation, radius ~$10^5$ km**
- **Unique frequency band, easier for deployment, tracking, control, and communication**



**“天琴”(TianQin)“Harpe in space”**

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

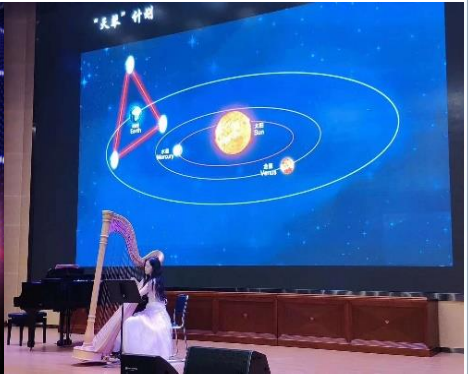
# Why needs TianQin?

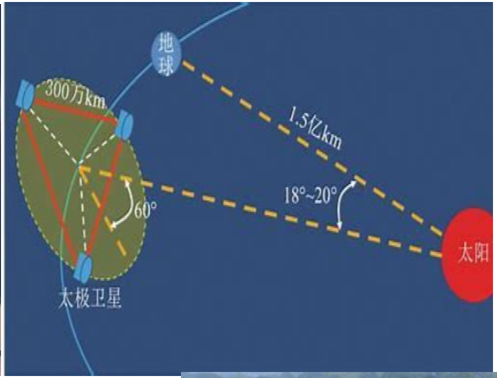


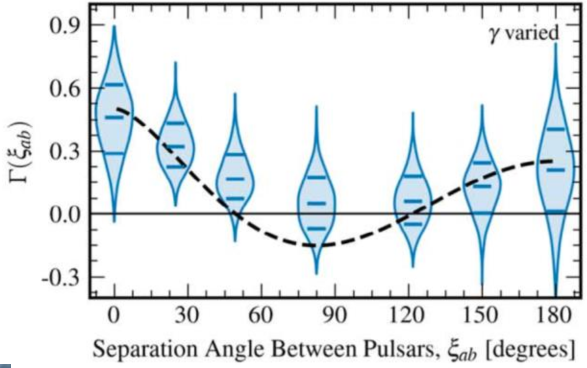

from Wiki

# GW experiments

## LISA/TianQin/Taiji ~2035




“TianQin”

“Harpe in space”

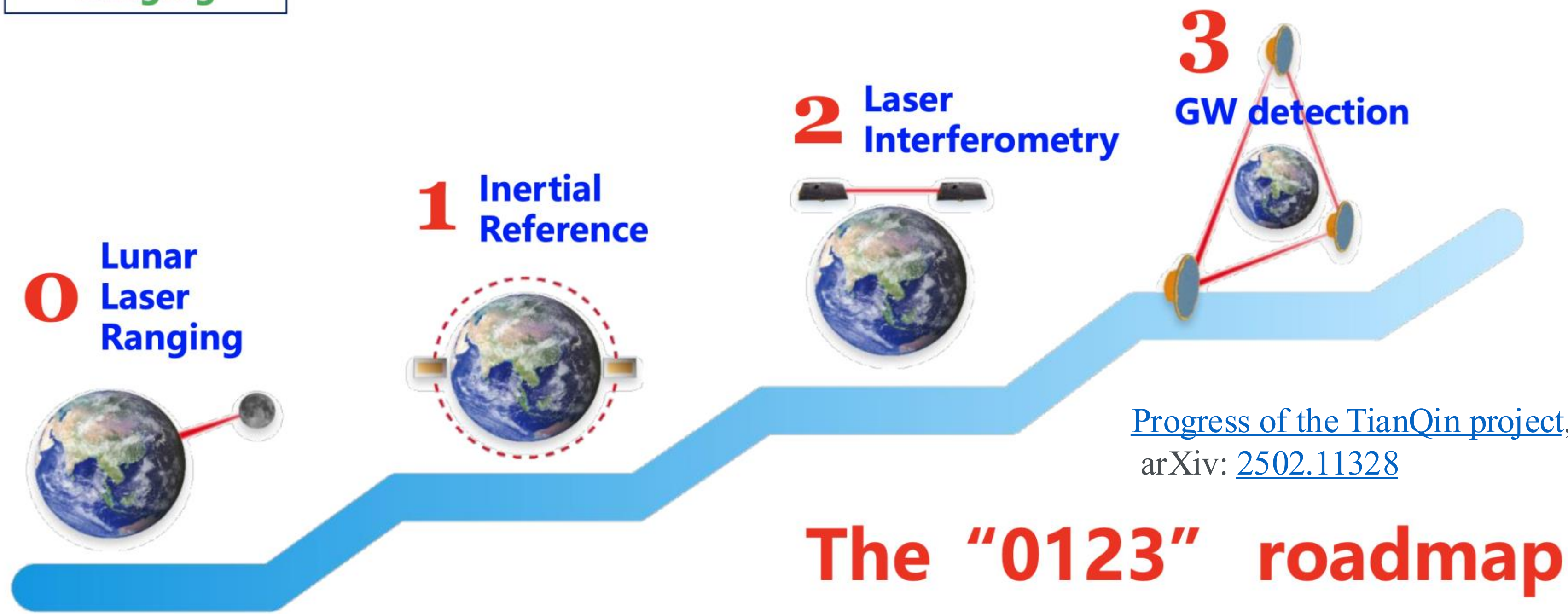
FAST

SKA

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

# Woking toward TianQin-2035

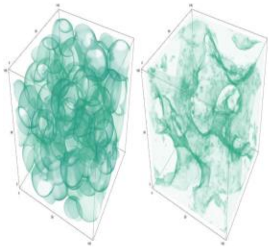
| Lunar Laser Ranging | TianQin 1 | TianQin 2 | TianQin 3 |
|---|---|---|---|




Progress of the TianQin project, arXiv: 2502.11328

# GW science at TianQin

## mHZ GW science @TianQin

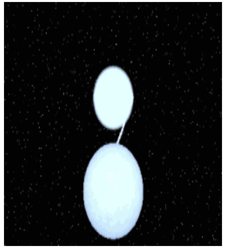


early universe (EW phase transition…)

MBHB

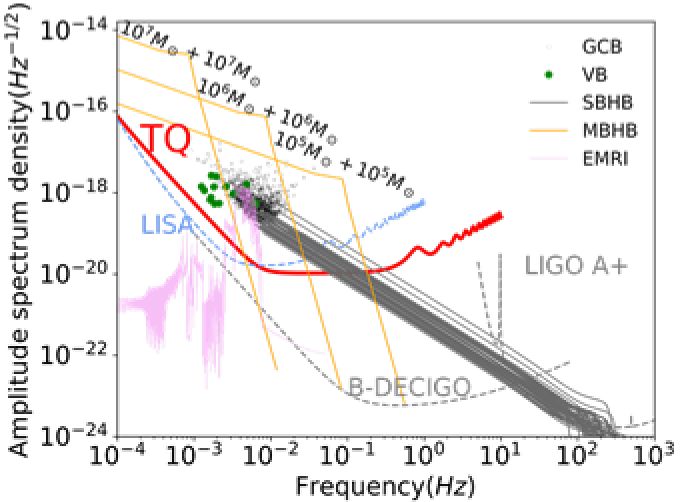
EMRI

SBHB



GCB

- **Astrophysics: Origin and evolution of SMBH**
- **Fundamental physics: gravity theory/model**
- **cosmology: dark matter, EW phase transition…**



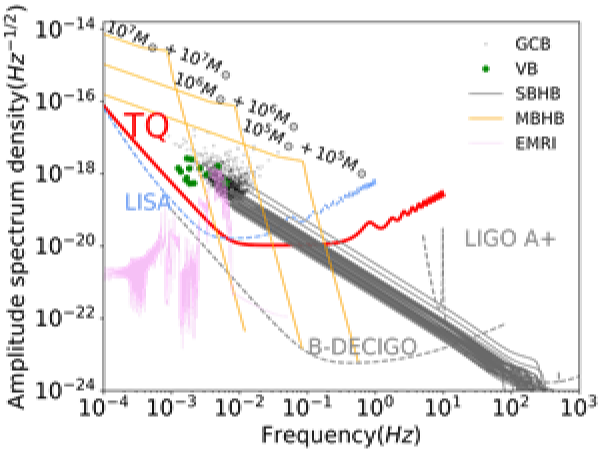

*Acta Scientiarum Naturalium Universitatis Sunyatseni, 2021, 60(1-2): 1-19*

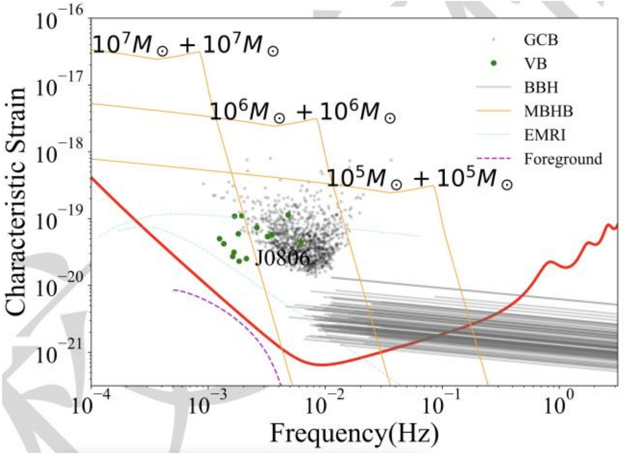
- **Detectable sources (event rates)**
- **SNR**
- **Precision of parameter reconstruction**

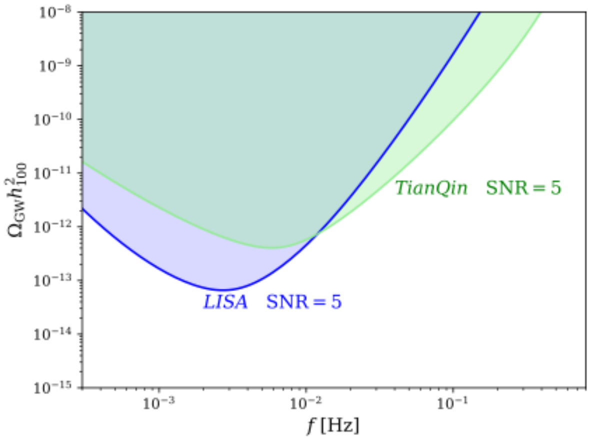
Detectability

# TianQin sensitivity/Detectability

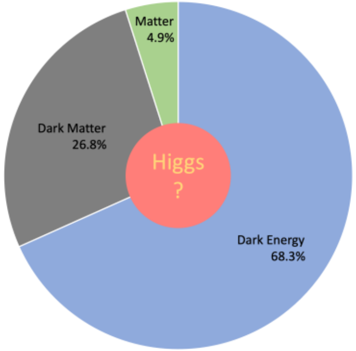
$$\Omega_{\mathrm{gw}}(f) = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f) = \frac{2\pi^2 S_h(f)}{3H_0^2} f^3$$



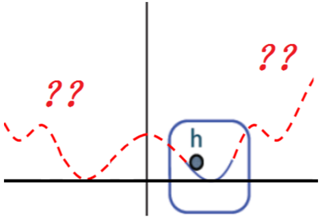
# Particle cosmology at TianQin




Collider signals at loop level@CEPC/LHC

Correlation and complementary test with GW

Higgs physics (potential), Z-pole physics, TeV new physics

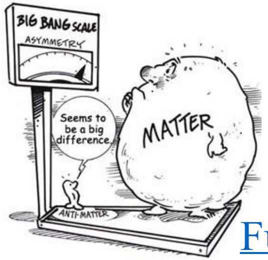


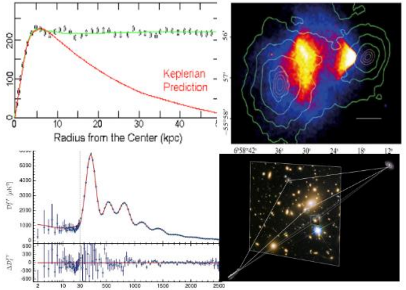

Baryon asymmetry of our Universe (EW baryogenesis)

How to probe? GW@TianQin

cosmic symmetry breaking relics

DM formation mechanism;
New approach to explore DM

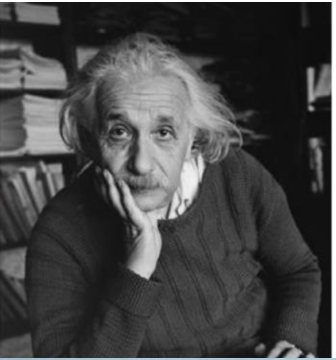



Fundamental Physics and Cosmology with TianQin, arXiv: 2502.20138

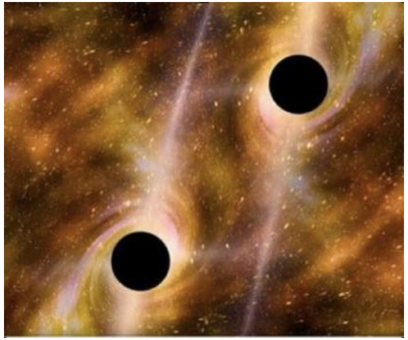
# What is GW ?

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



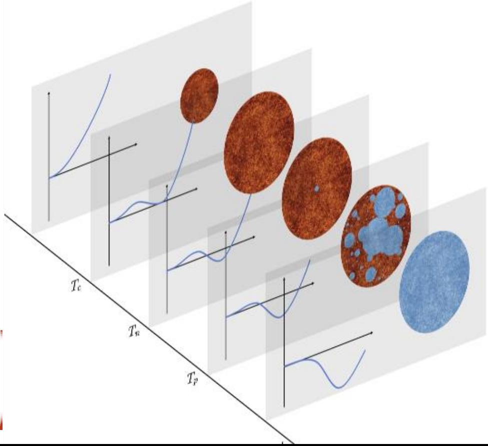
Isolated sources: quadrupole radiation

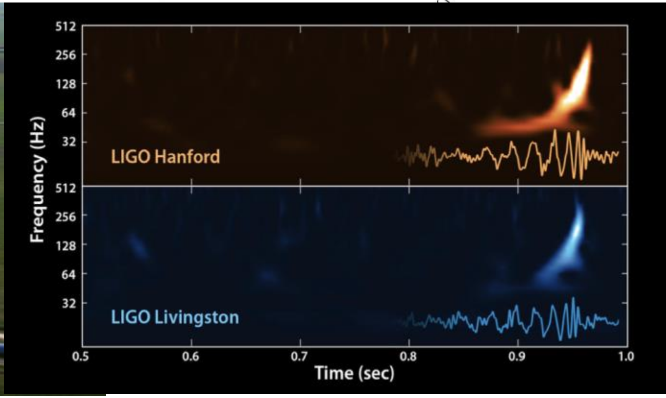
$$h_{ij} \simeq \frac{2G}{c^4 r} \ddot{Q}_{ij}^{TT}(t - r/c)$$



Stochastic sources: anisotropic stress tensor

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





# General GW in the early universe

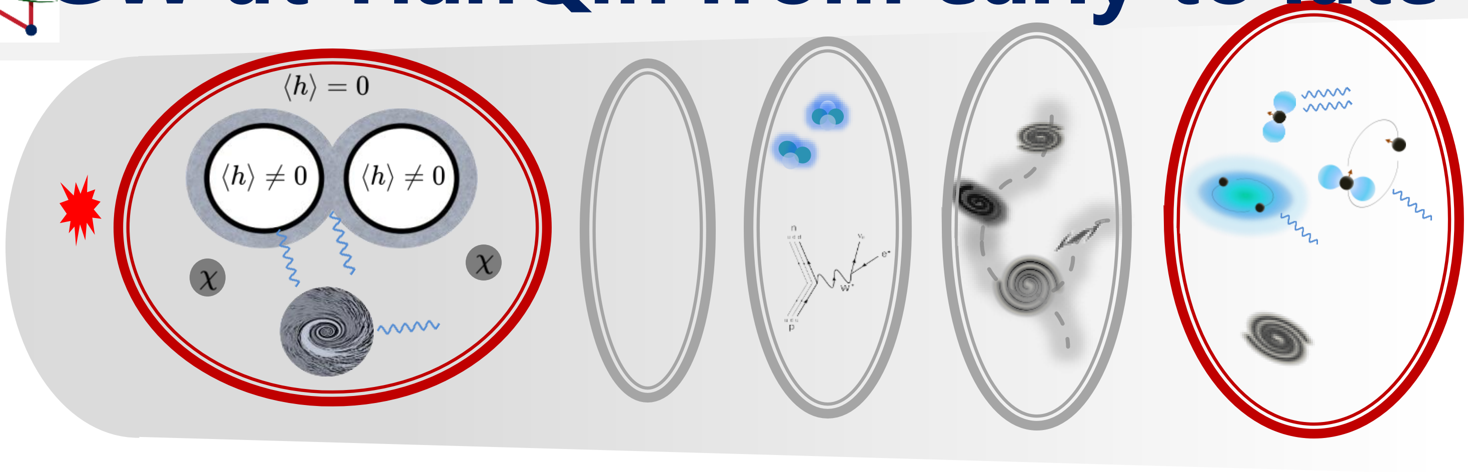
$$\ddot{h}_{ij}(\mathbf{x},t) + 3H\dot{h}_{ij}(\mathbf{x},t) - \frac{\nabla^2}{a^2}h_{ij}(\mathbf{x},t) = 16\pi G\,\Pi_{ij}(\mathbf{x},t)$$

- ✓ 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, $\Pi_{ij}$ from a combination of $\partial_i\Psi, \partial_i\Phi$ — induced GW
- … arXiv:1801.04268

# GW at TianQin from early to late universe




- EW Phase transition GW from EW baryogenesis and DM production induced by Higgs effective potential
- GW from cosmic string
- GW from domain wall
- induced GW
- ….

- various type of astrophysical binaries
- superradiance of axion (DM)
- DM imprints in the waveform of binaries
- ….

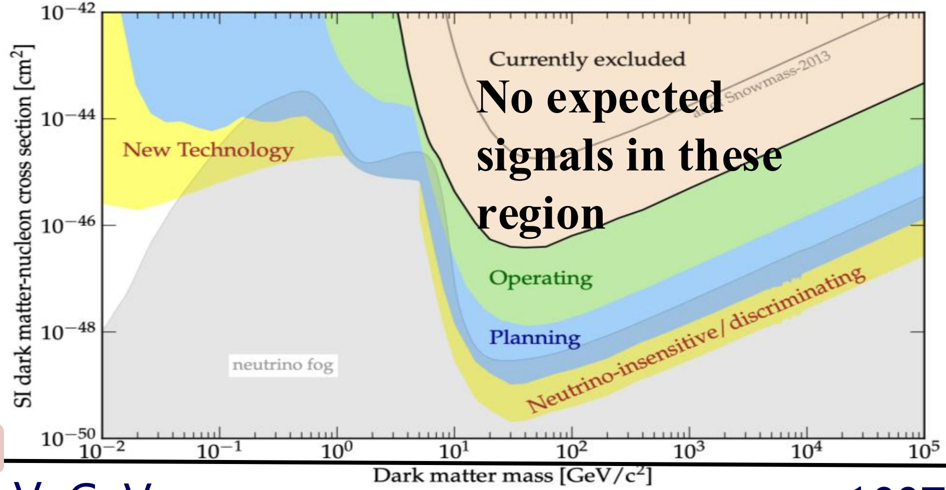
Fundamental Physics and Cosmology with TianQin,arXiv: 2502.20138

# DM search at TianQin

**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

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

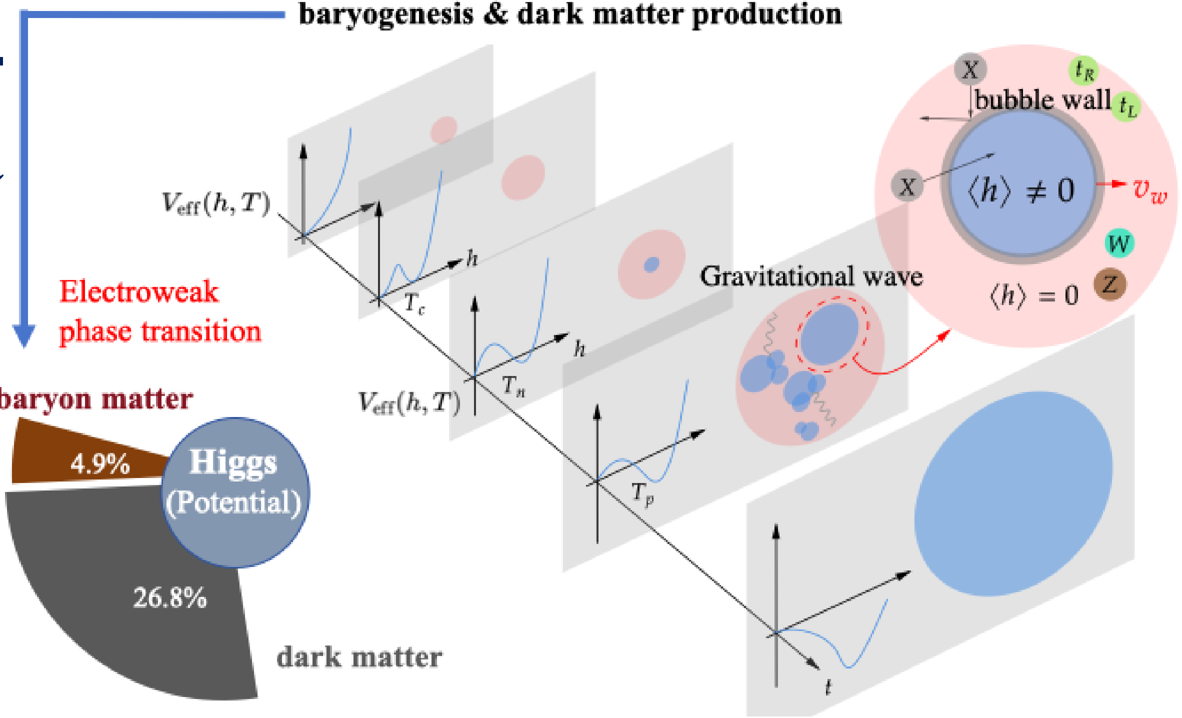
- **new DM mechanism beyond thermal freeze out: cosmic phase transition, Hawking radiation, superradiance…**
- **new detection method: LISA, TianQin, aLIGO, SKA, NanoGrav, Cosmic Explorer, Einstein telescope**

# EW phase transition at TianQin

## Cosmology in post-Higgs and GW Era

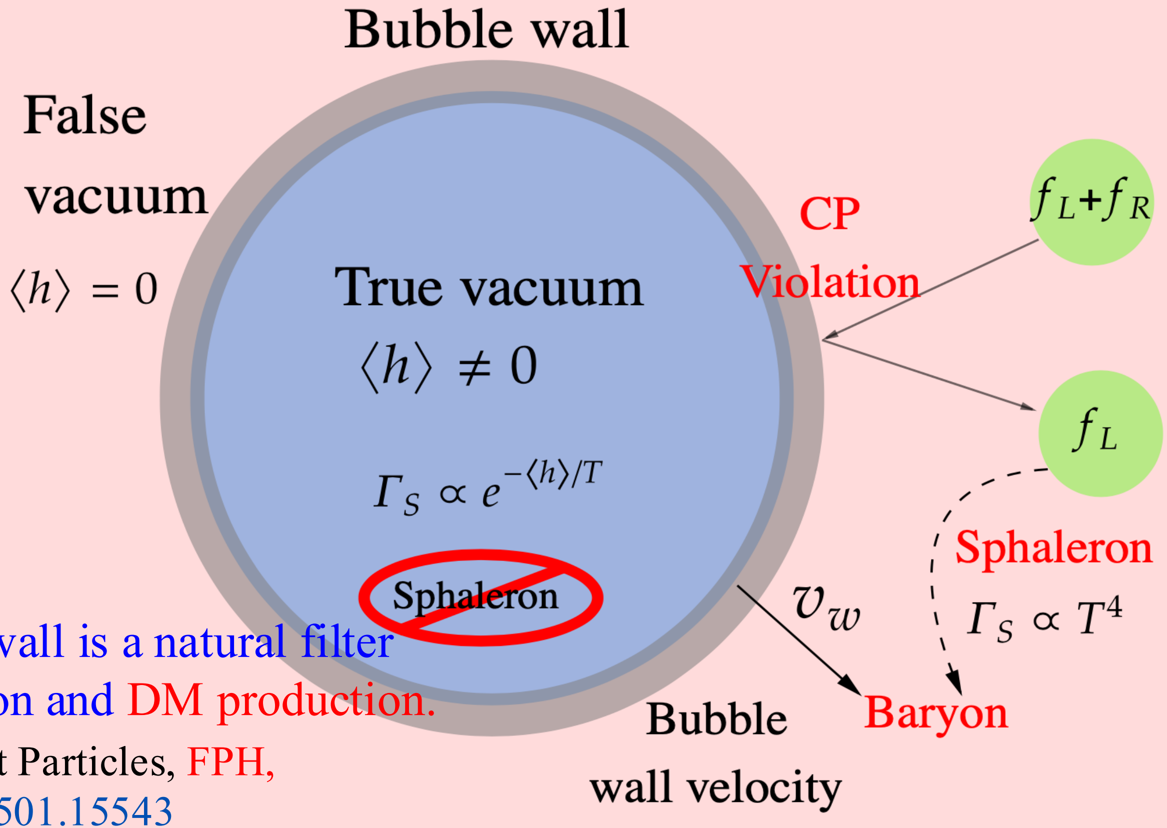
The observation of Higgs@LHC and GW@LIGO initiates a new era of exploring DM and baryogenesis by GW.

First-order phase transition by Higgs could provide a new approach for DM production.




The First Particles, FPH, arXiv: 2501.15543

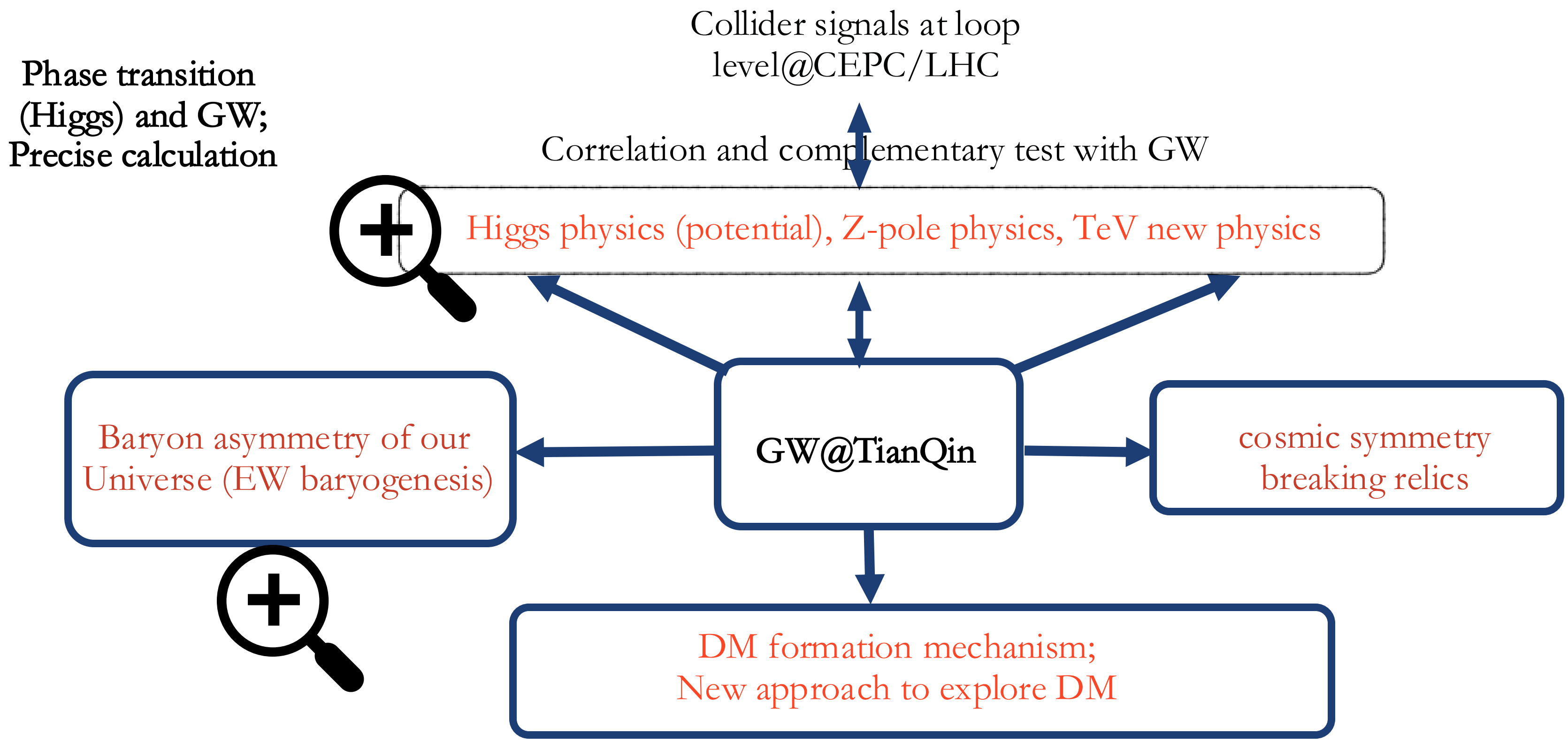
# DM/baryogenesis from phase transition




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

The First Particles, FPH,
arXiv: 2501.15543

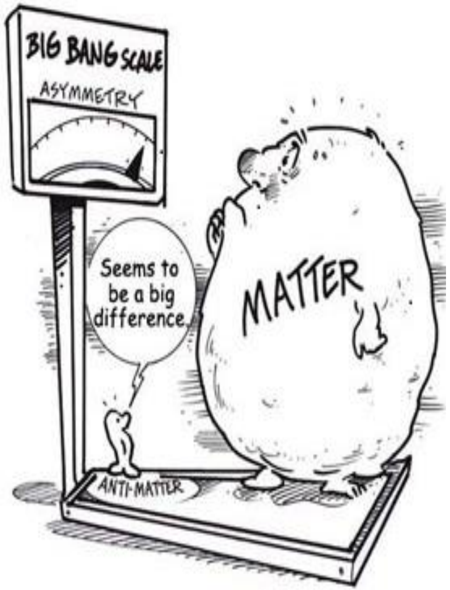
# Particle cosmology at TianQin




Fundamental Physics and Cosmology with TianQin,arXiv: 2502.20138

# EW baryogenesis

**The baryon asymmetry of the universe is a long standing problem.**




$\eta_B = n_B/n_\gamma = 5.8-6.6\times10^{-10}$

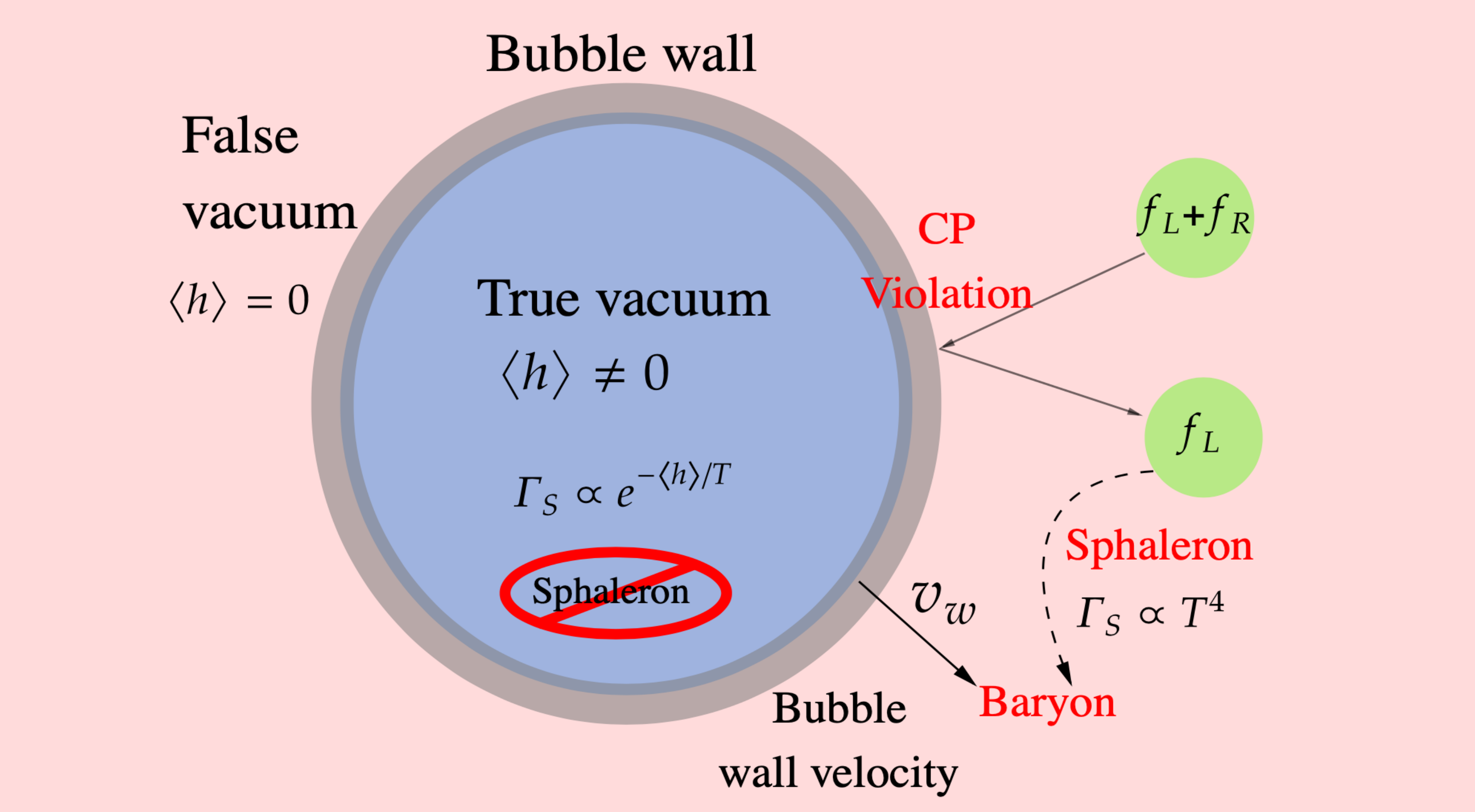
(CMB, BBN)

**After discovery of Higgs @LHC & GW @aLIGO,**
**EW baryogenesis becomes a timely and testable scenario.**

**SM technically has all the 3 elements for baryogenesis (Sakharov conditions)**

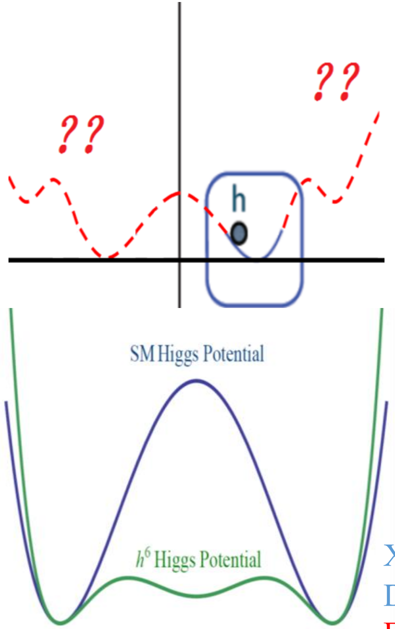
- **B violation from anomaly in B+L current**
- **C and CP-violation: CKM matrix, but too weak, need new CP-violating sources**
- **Departure from thermal equilibrium: first-order phase transition with expanding Higgs bubble wall**

# EW baryogenesis



# Higgs potential

**What is the shape of Higgs potential?**




**Current data tells us nothing but the quadratic oscillation around the VEV 246 GeV with 125 GeV mass.**

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

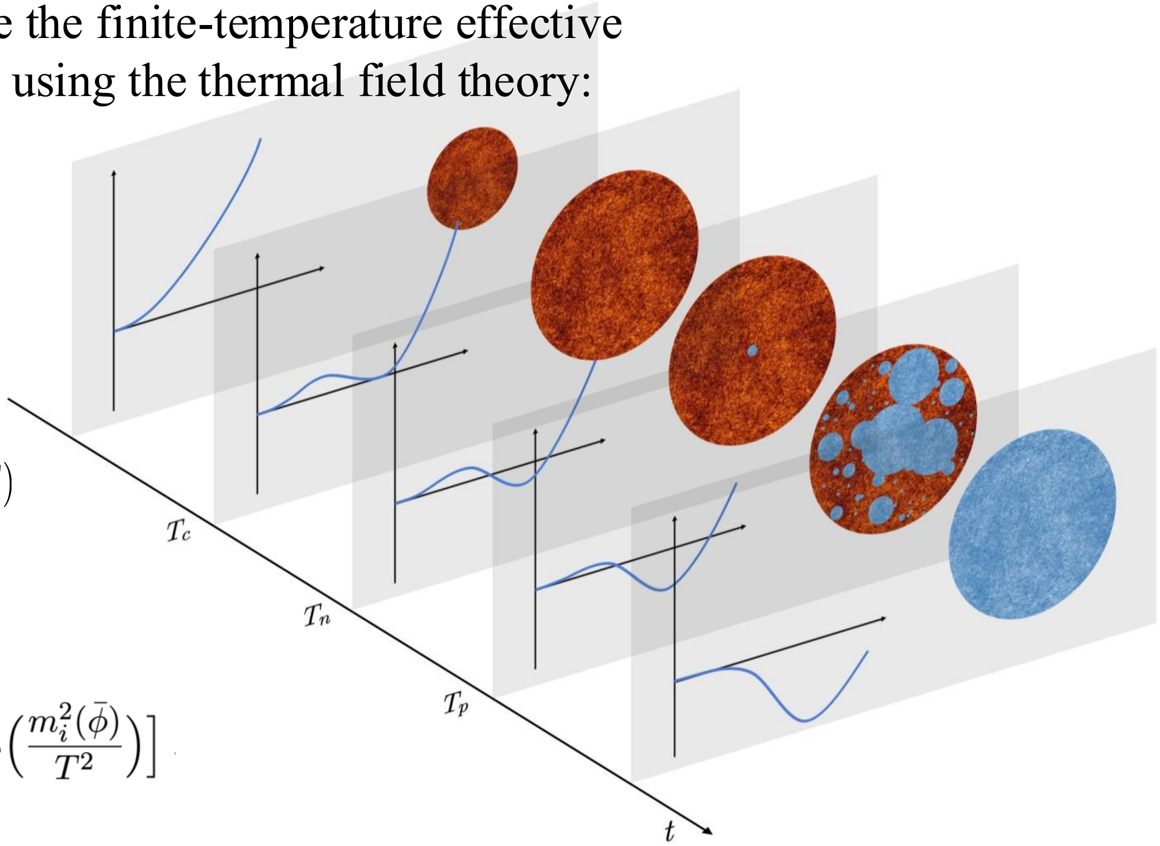
or $$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

**Produce a first-order EW phase transition, deviation of Higgs trilinear coupling and GW**

Xinmin Zhang Phys.Rev. D47 (1993) 3065-3067;C. Grojean, G. Servant, J. Well PRD71(2005)036001
D.J.H. Chung, A. J. Long, Lian-tao Wang Phys.Rev. D87(2013) 023509
FPH, et.al, Phys.Rev.D94(2016)no.4,041702 ; FPH, et.al, Phys.Rev.D93 (2016) no.10,103515
arXiv:1511.06495, Nima Arkani-Hamed et. al.; PreCDR of CEPC; arXiv: 1811.10545,CDR of CEPC

# Phase transition in a nutshell

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




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

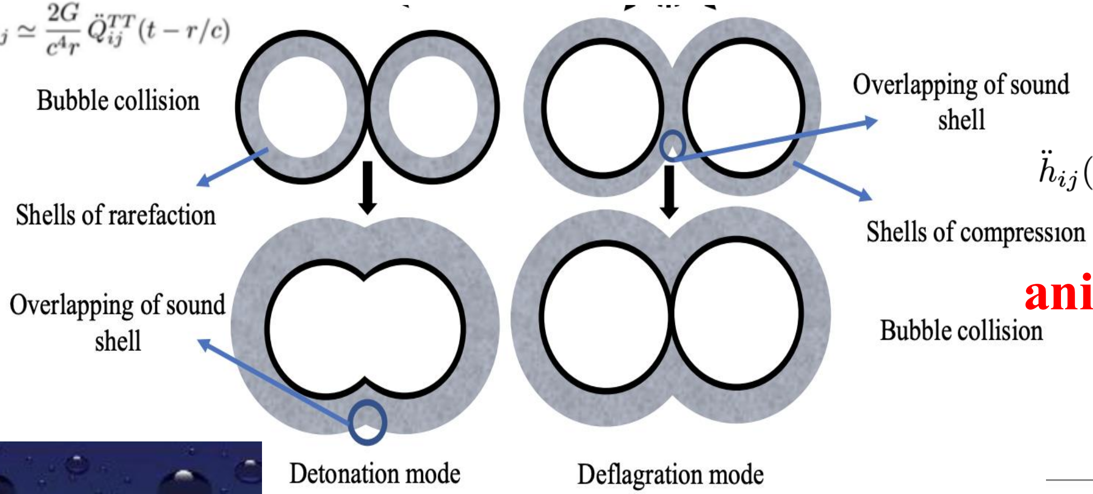
$$S(T) = \int d^4x \left[\frac{1}{2}\left(\frac{\partial\phi}{\partial x}\right)^2 + V_{\text{eff}}(\phi, T)\right]$$

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

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

# Phase transition GW in a nutshell

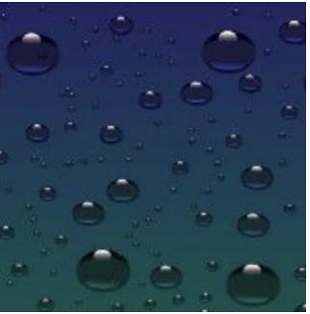
$$h_{ij} \simeq \frac{2G}{c^4 r}\ddot{Q}_{ij}^{TT}(t-r/c)$$

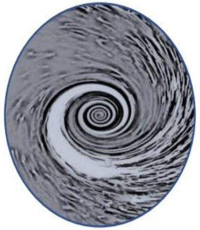



$$R_{\mu\nu} - \frac{1}{2}R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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

**anisotropic stress tenor: source of GW**






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

**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**

# Phase transition dynamics

**In theory, the most important and difficult phase transition parameter for GW, dynamical DM, baryogenesis is bubble wall velocity** $v_w$

***Finite-temperature effective potential***
$V_{eff}(\phi, T)$

$\alpha$ $T_p$ $R_* H_*$

**(1). Daisy resummation problem**
**(2). Gauge dependence problem**
**(3). No perturbative calculations: lattice calculations and dim-reduction method**

**In experiments, GW experiment is most sensitive to bubble wall velocity** $v_w$

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

***Bubble wall velocity***
***this talk*** $v_w$

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…

***Energy budget***
$\kappa$

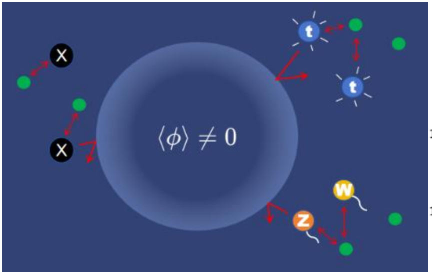
F. Giese, T. Konstandin, K. Schmitz and J. van de Vis, arXiv:2010.09744
Xiao Wang, **FPH** and Xinmin Zhang, Phys.Rev.D 103 (2021) 10, 103520
Xiao Wang, Chi Tian, **FPH**, JCAP 07 (2023) 006

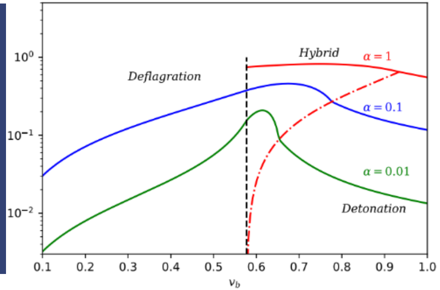
# Bubble wall is essential (like a filter)

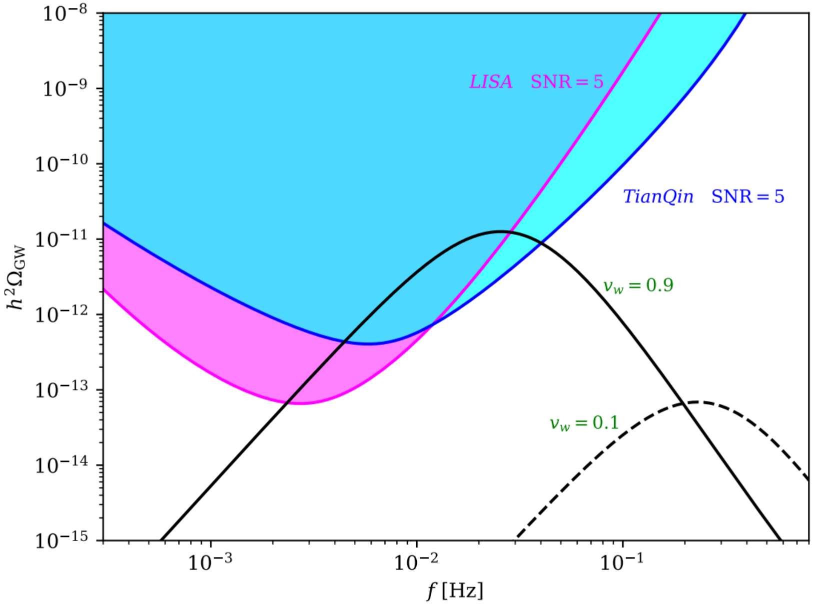
**The most essential parameter for phase transition GW, phase transition DM, baryogenesis** $v_w$

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



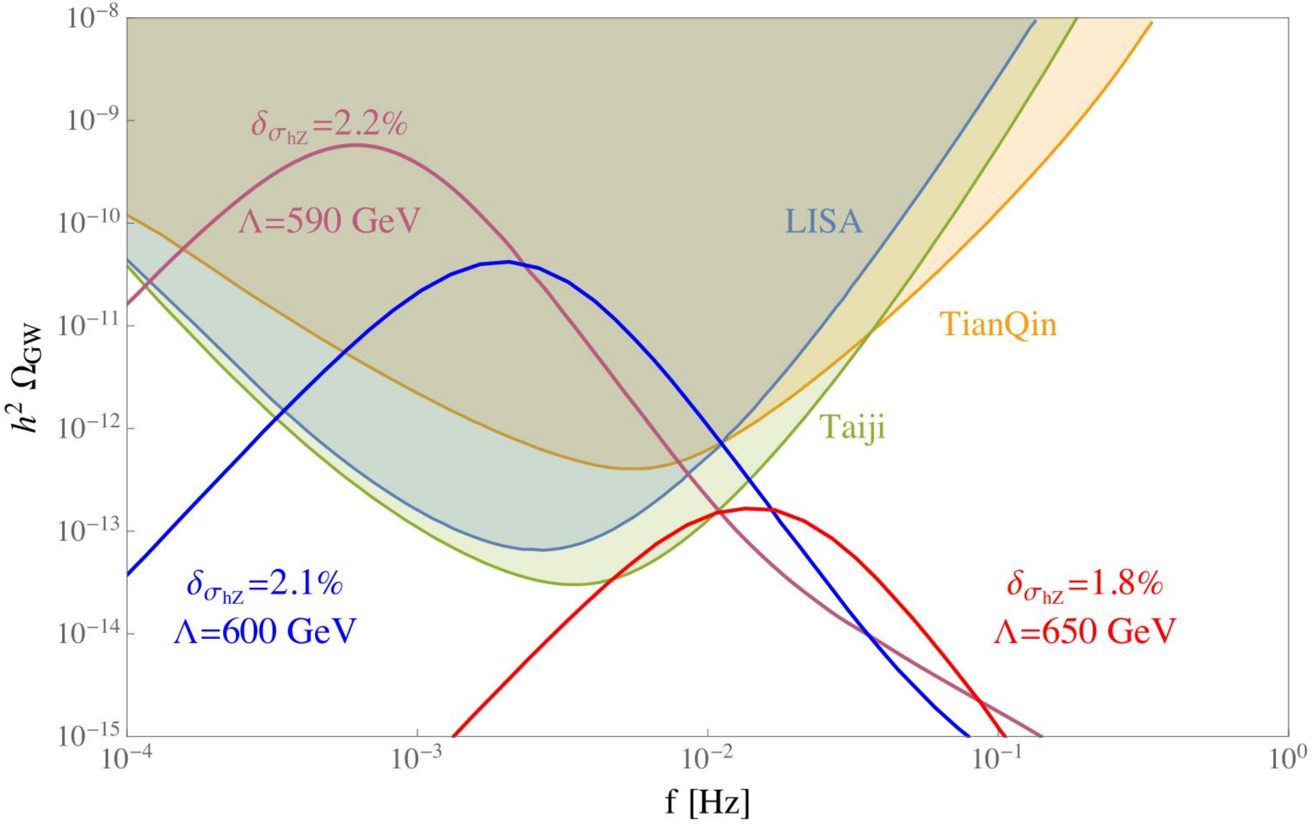



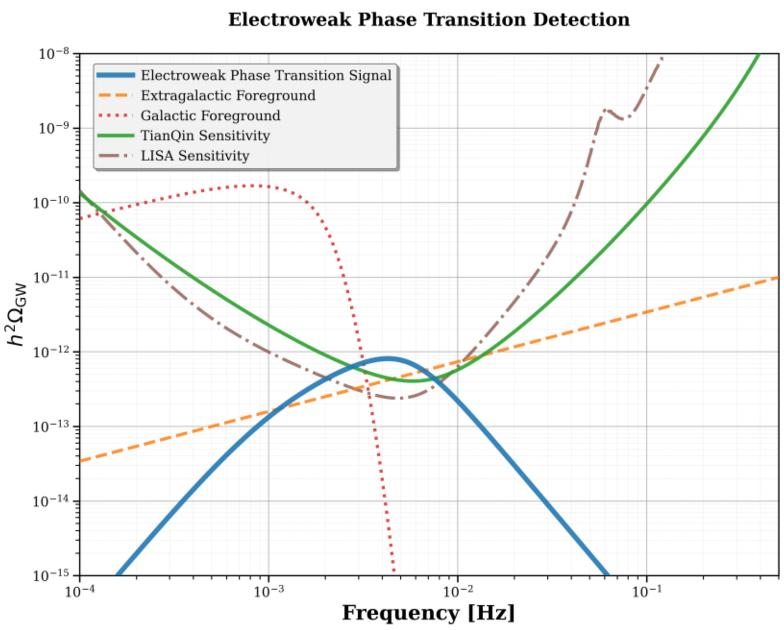

$$\rho_{DM}^4 v_w^{3/4} = 73.5(2\eta_B s_0)^3 \lambda_S \sigma^4 \Gamma^{3/4}$$

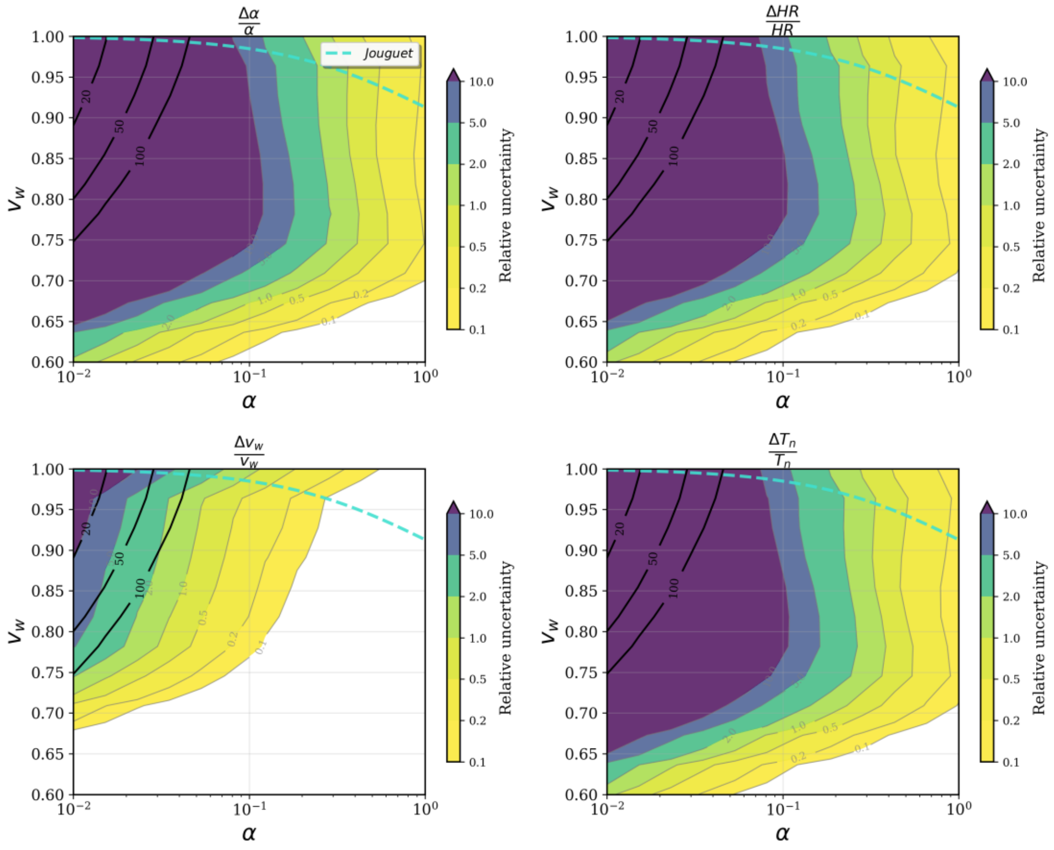
**FPH**, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028;

# Higgs potential at TianQin



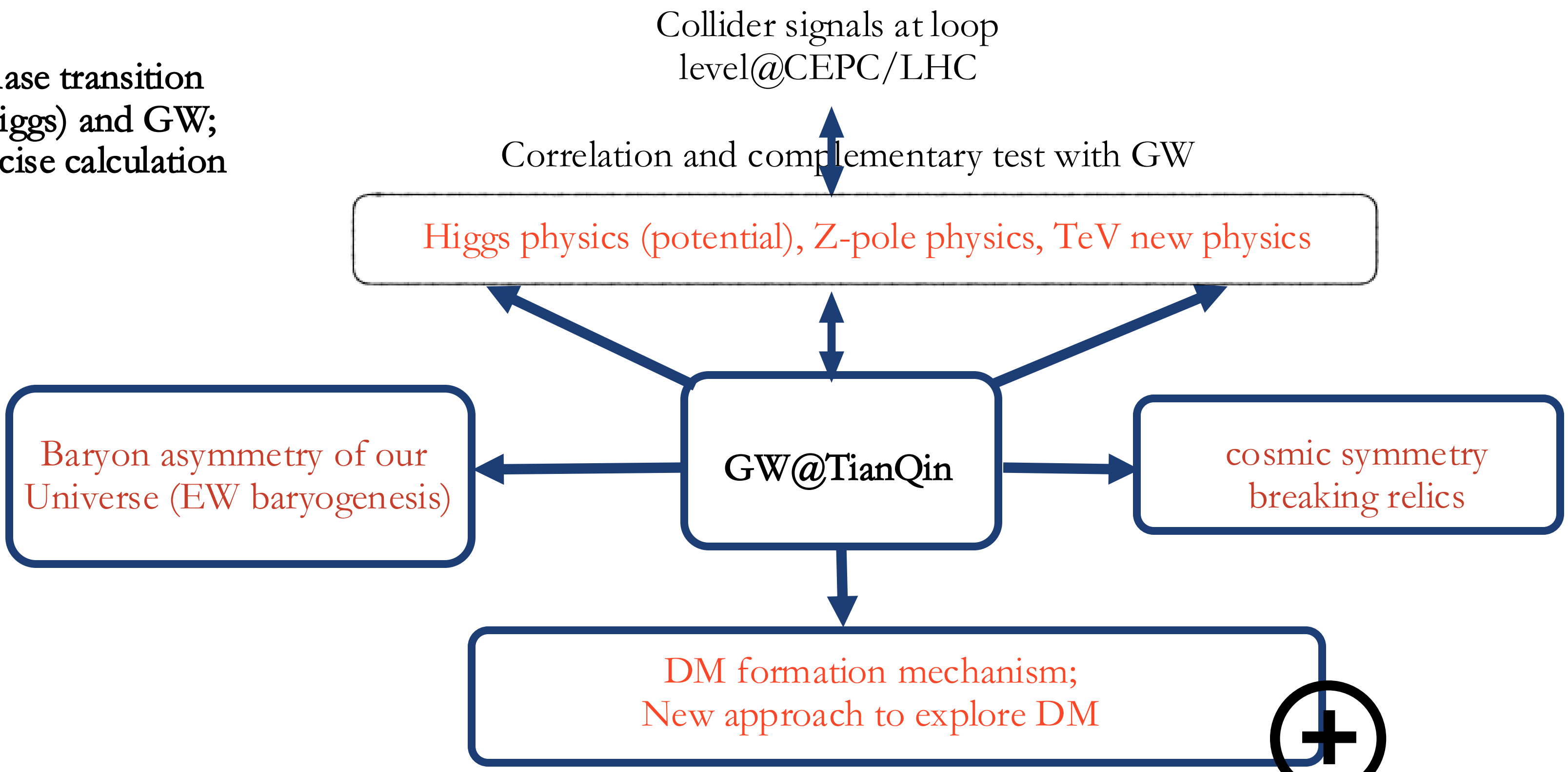
# Reconstruction at TianQin



# Particle cosmology at TianQin

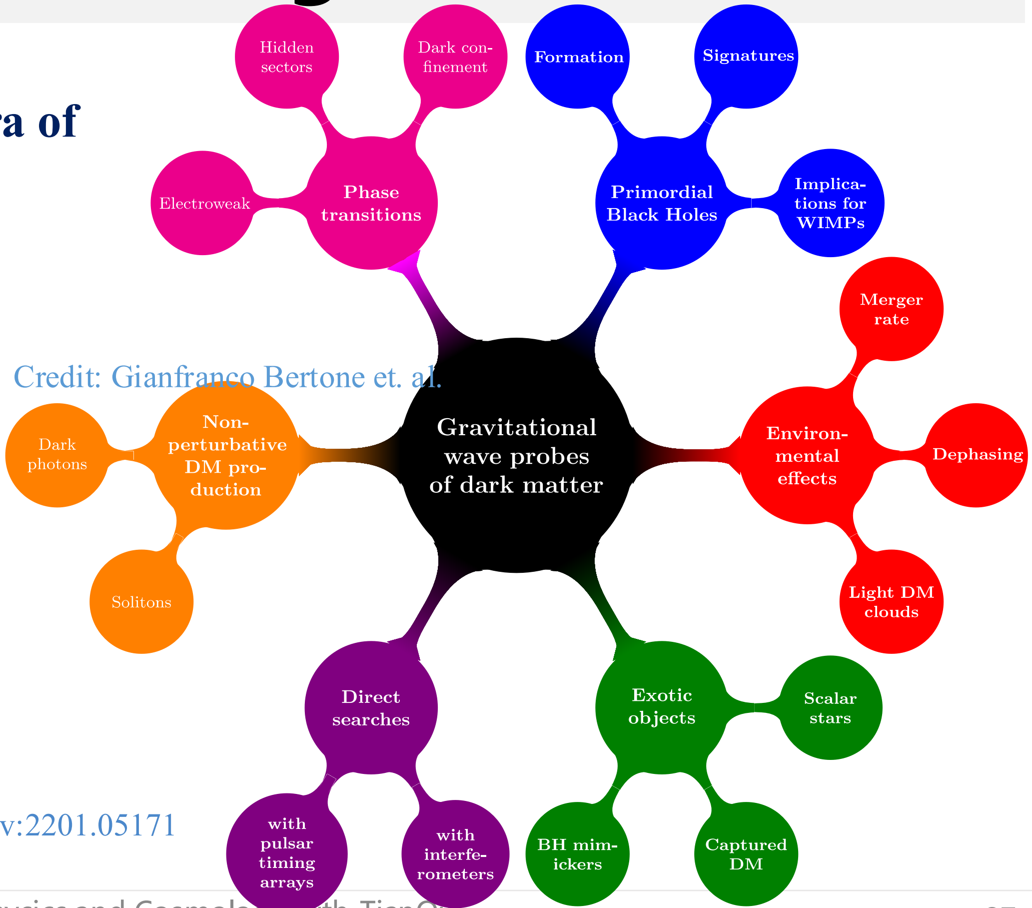
Phase transition
(Higgs) and GW;
Precise calculation




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

# New DM mechanism/signal at TianQin

- **The observation of GW@LIGO and possible hints at PTAs initiate a new era of exploring DM by GW.**
- **DM can trigger a first-order phase transition in the early universe and detectable GW signals.**

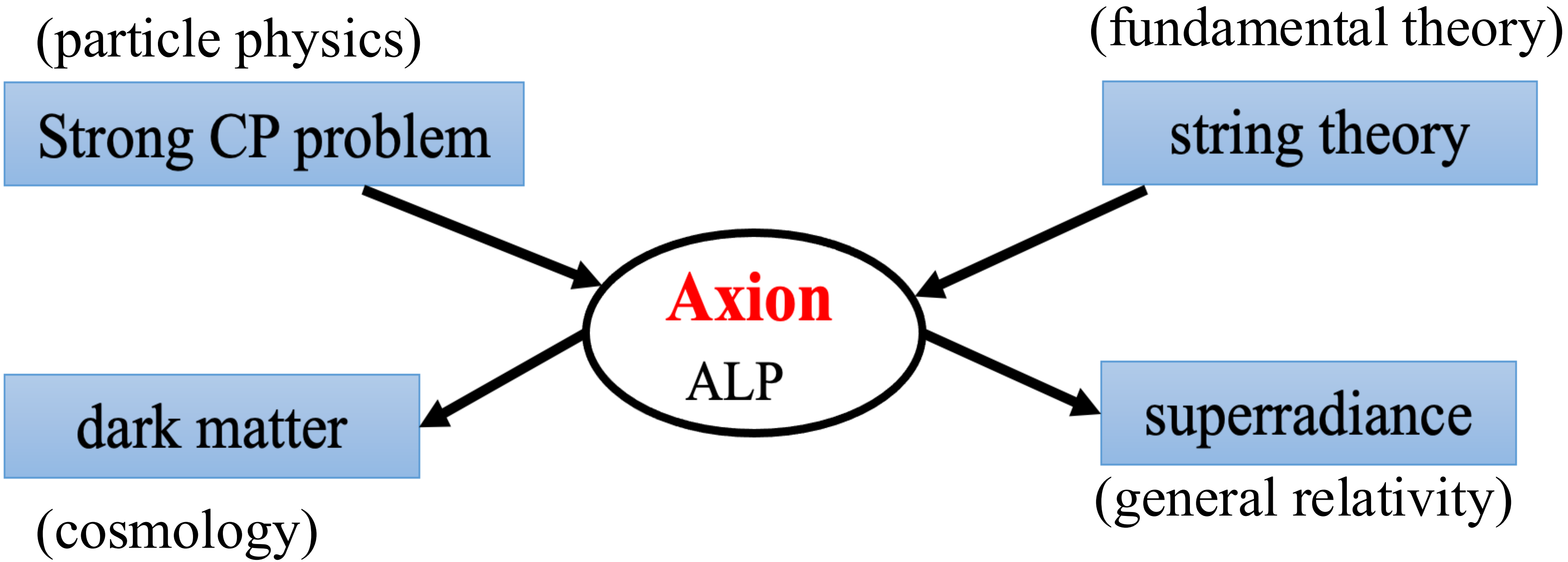



Credit: Gianfranco Bertone et. al.

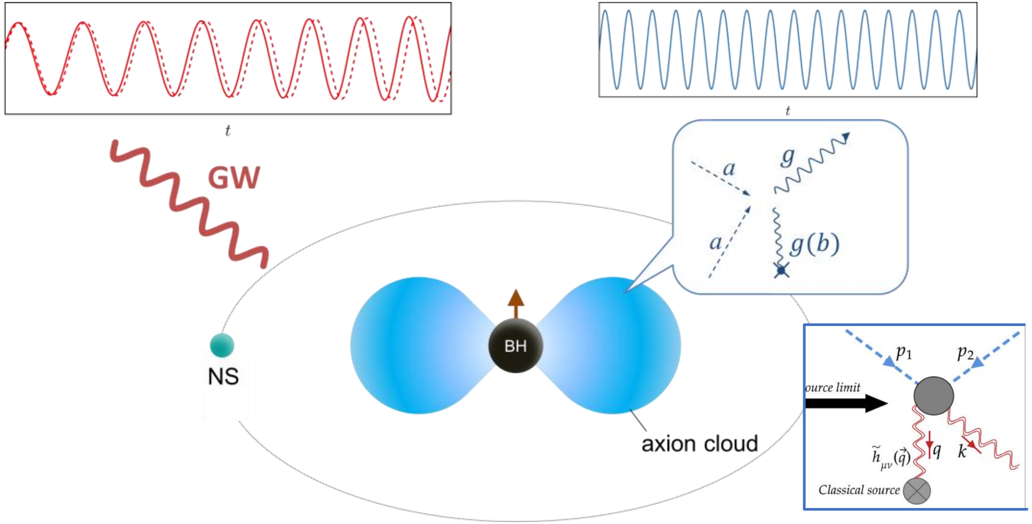
J.Jaeckel, V. V. Khoze, M. Spannowsky, Phys.Rev. D94 (2016) no.10, 103519
Zhaofeng Kang,et.al. arXiv:2101.03795, arXiv:2003.02465
Yan Wang, Chong Sheng Li, and **FPH**, arXiv:2012.03920
**FPH**, Eibun Senaha Phys.Rev. D100 (2019) no.3, 03501
**FPH** PoS ICHEP2018 (2019) 397
**FPH**, Chong Sheng Li, Phys.Rev. 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
….

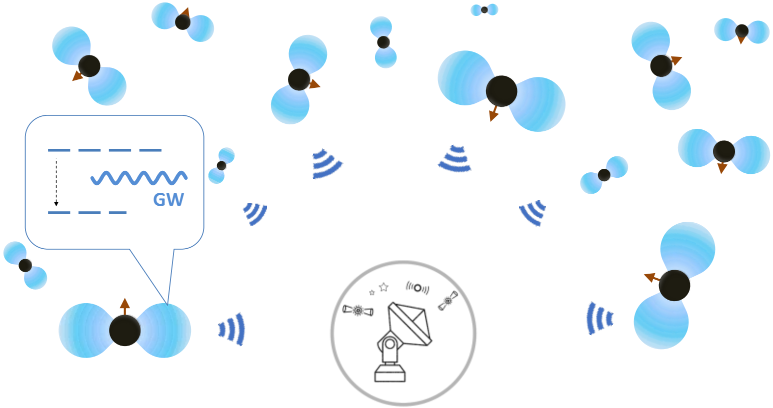
# Axion particle cosmology

Ultralight axion is a promising DM candidate.



# GW of axion from superradiance



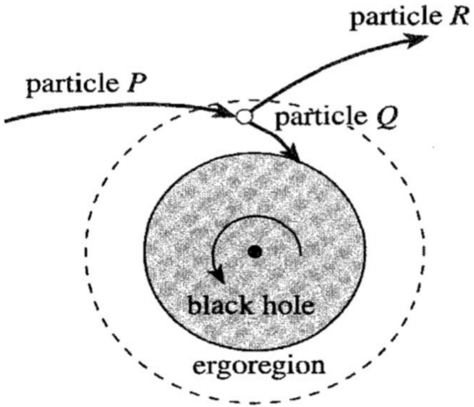

**Jing Yang, Ning Xie, FPH** **arXiv:2306.**17113, **arXiv:2404.18703 Aidi Yang, FPH**

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

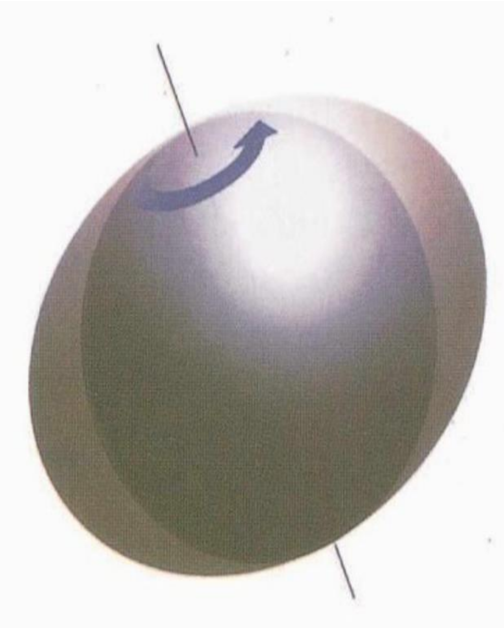
# What is superradiance ?

When Klein (-Gordon) meets Kerr (Dirac Prize 2025) superradiance occurs

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




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



S. Hawking

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

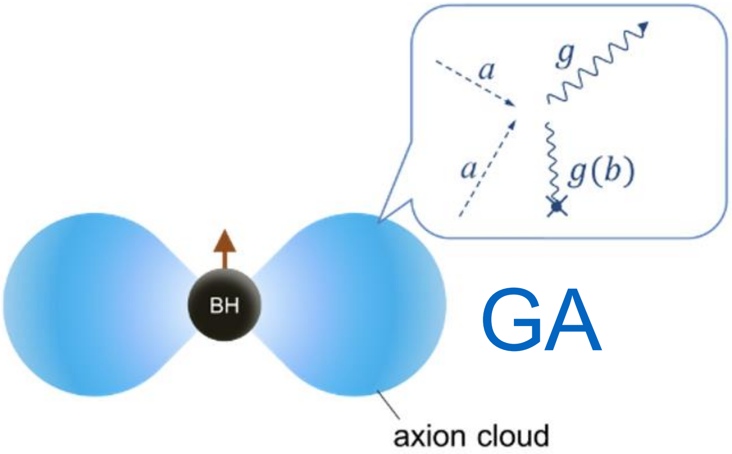
**Ultralight axion can form axion cloud around rotating BH, forming Gravitational atom (GA).**

# GW of axion from superradiance

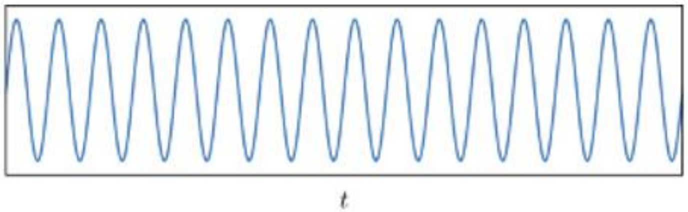
## Axions can annihilate to GWs

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

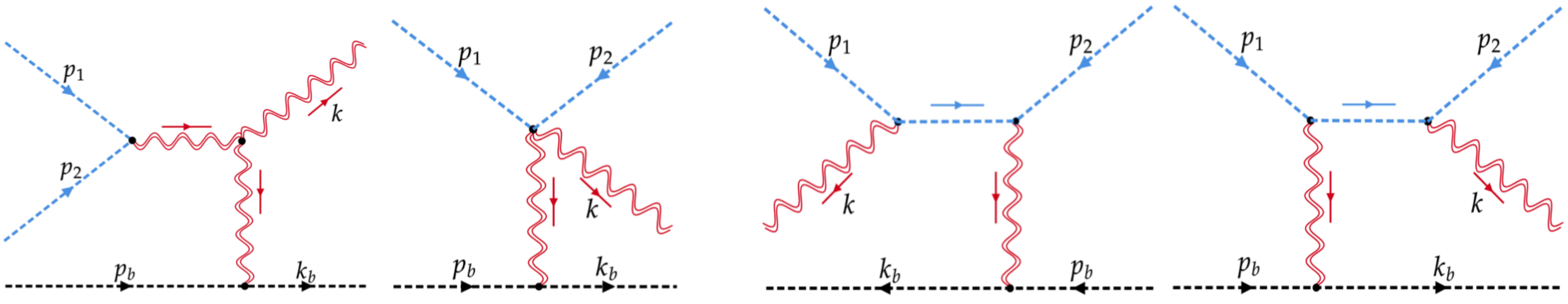
**Jing Yang, FPH**, Phys.Rev.D 108 (2023) 10, 103002




GA

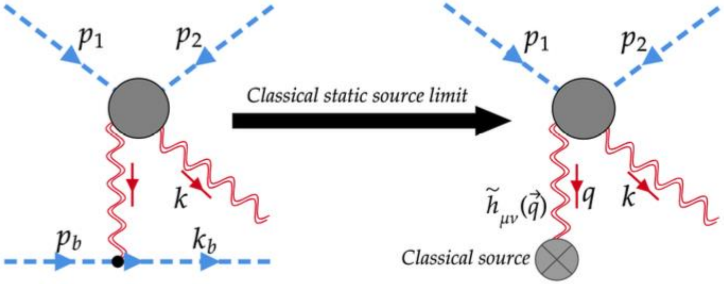


# Microscopic physics




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

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

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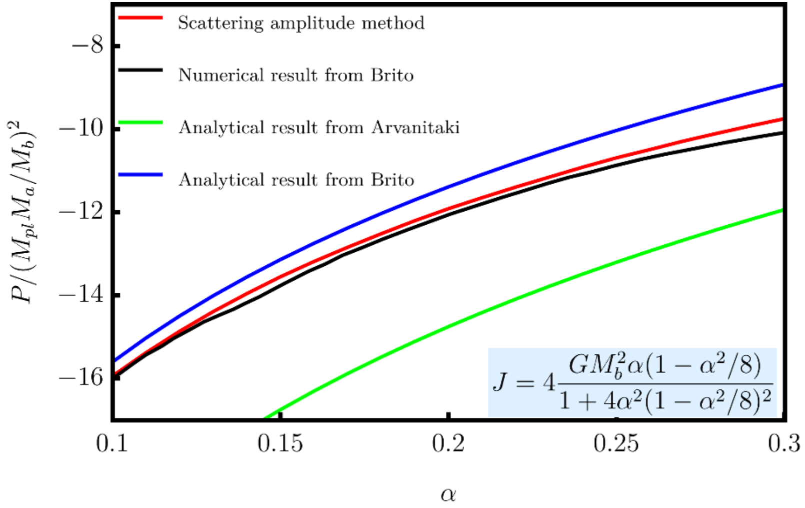
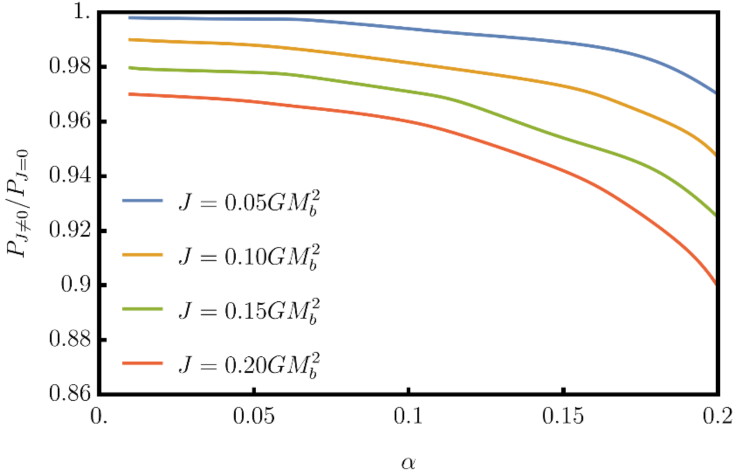
# GW radiation from axion annihilation




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

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

- ✓ monochromatic GW signal $\omega_{\text{ann}} \sim 2\ m_a$
- ✓ 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.

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

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

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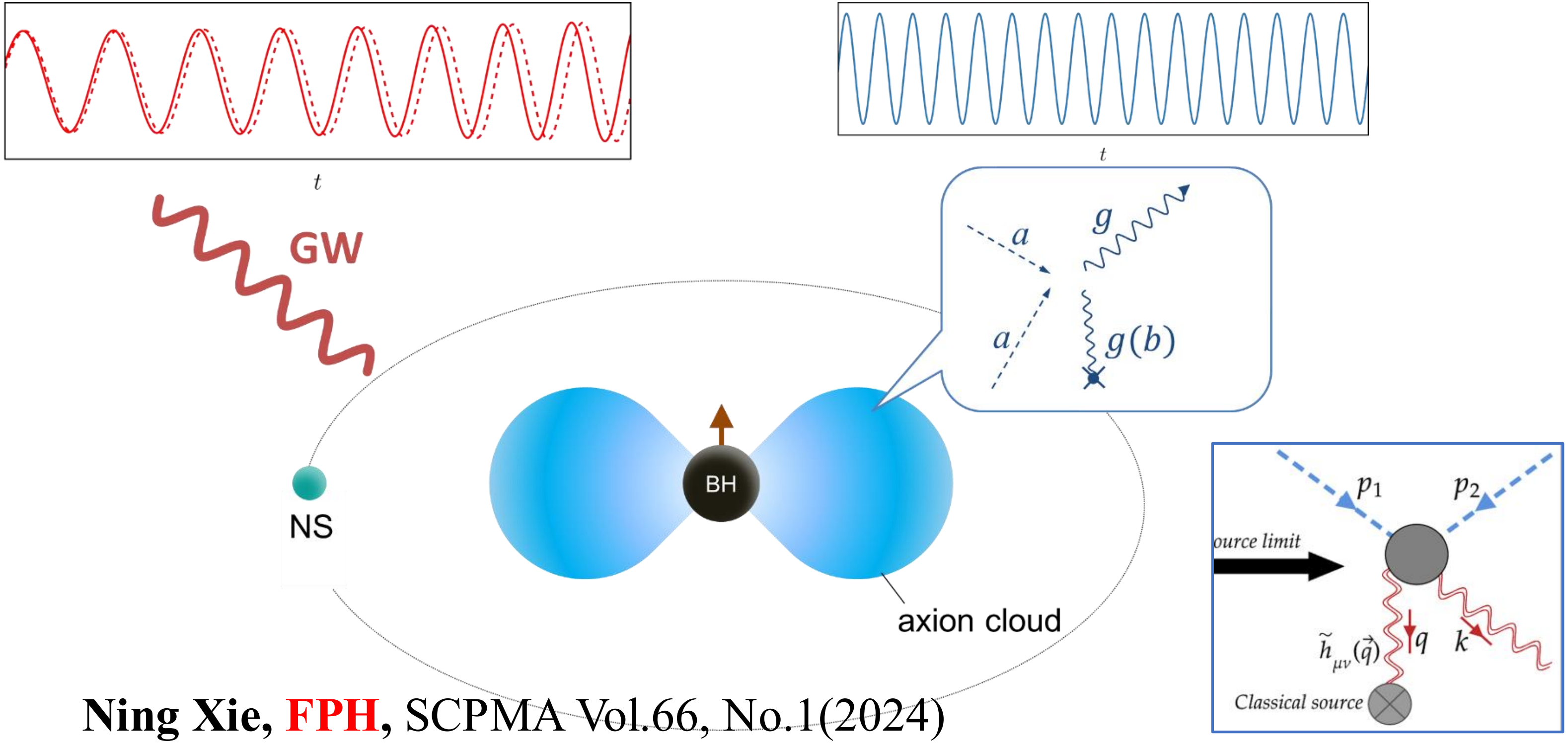
Phys.Rev.D 108 (2023) 10, 103002

# GW of axion from superradiance




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

# GW of axion from superradiance

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)

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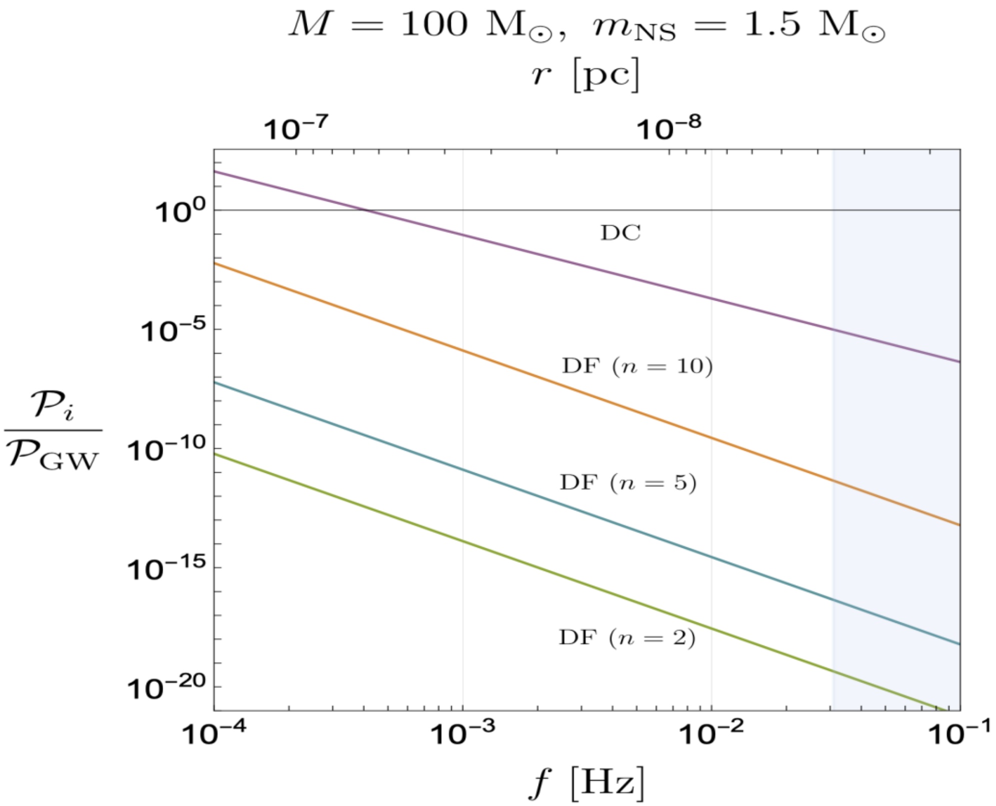
# GW of axion from superradiance



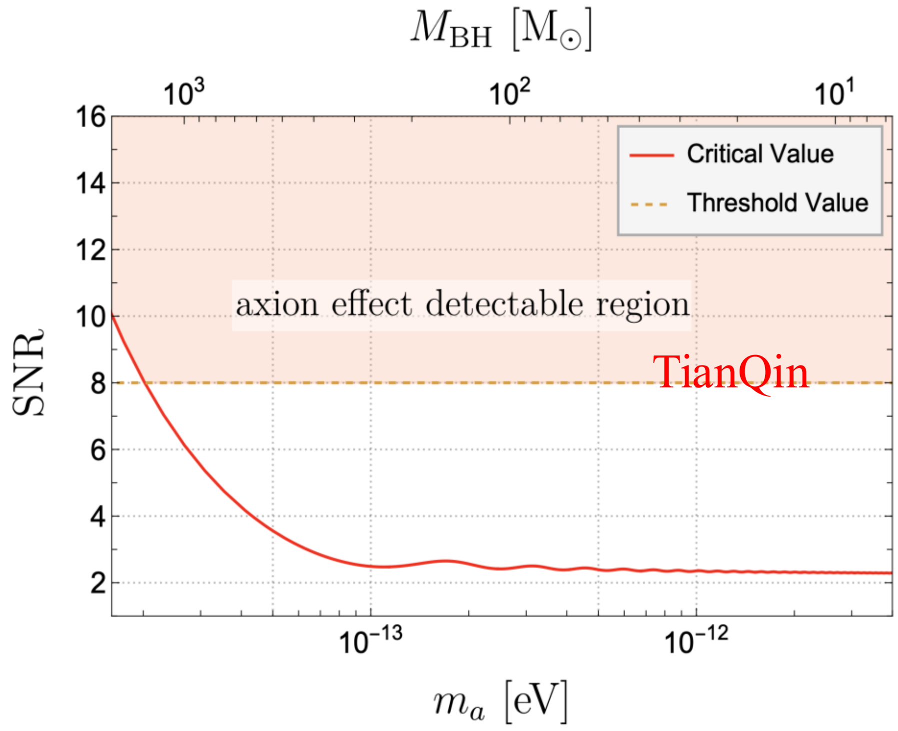
# GW of axion from superradiance

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

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

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

# Complementary search: TianQin+PTA



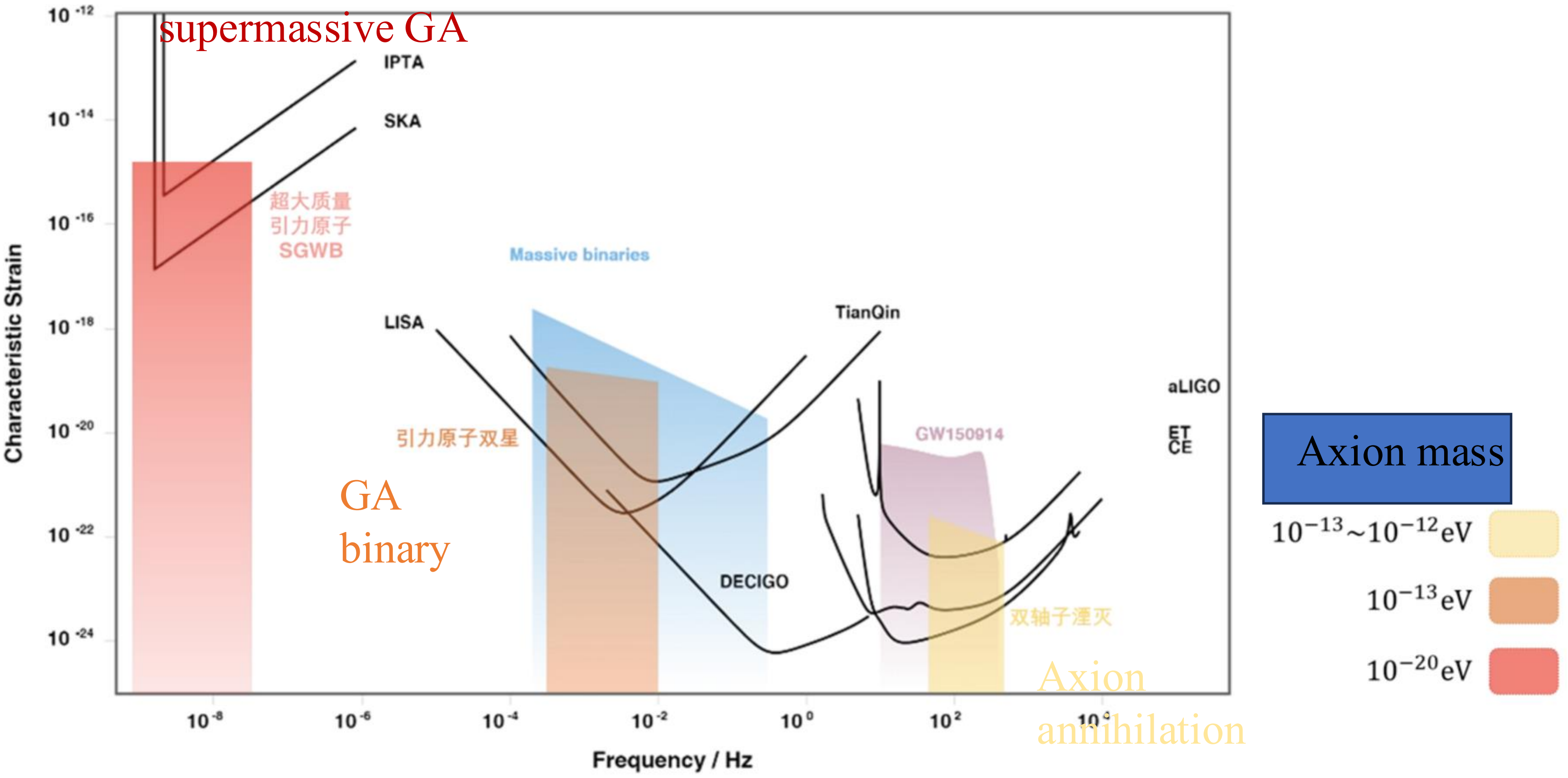

Axions modify the rate of binary period change

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

Future Pulsar timing measurement precision, such as SKA

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

# GW detection of ultralight axion



# 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 can be the “filter” to obtain the needed heavy DM when avoiding the unitarity constraints.

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

| phase transition 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 |

# 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
*Department of Physics, Columbia University, New York, NY 10027, USA*

and

Y. Pang
*Brookhaven National Laboratory, Upton, NY 11973, USA*

Received May 1992; editor: D.N. Schramm

Nuclear Physics B262 (1985) 263–283
© North-Holland Publishing Company

**Q-BALLS***

Sidney COLEMAN

*Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

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.

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

$$\delta(E - \omega Q) = 0$$

↓

$$\phi = f(r) e^{-i\omega t}$$

$$E = \int \left\{ \frac{1}{2}\left[\dot{\phi}_R^2 + \dot{\phi}_I^2 + (\nabla\phi_R)^2 + (\nabla\phi_I)^2\right] + U\left[\frac{1}{2}\left(\phi_R^2 + \phi_I^2\right)\right] \right\} dx$$

# 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)

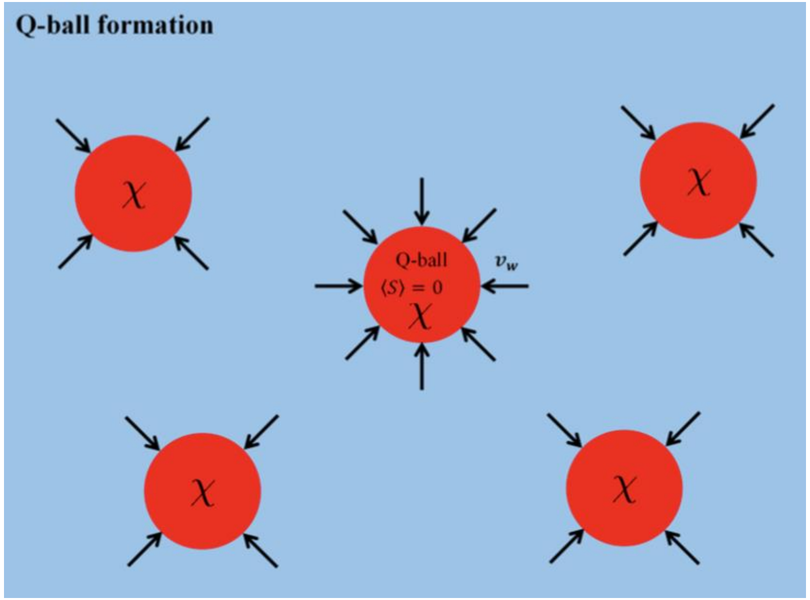
(2) and packet the same sign charge in the small size after overcoming the Coulomb repulsive interaction.

1. Supersymmetry? Affleck-Dine mechanism.

We do not observe the supersymmetry until now!

2. Q-ball formation based on first-order phase transition. →

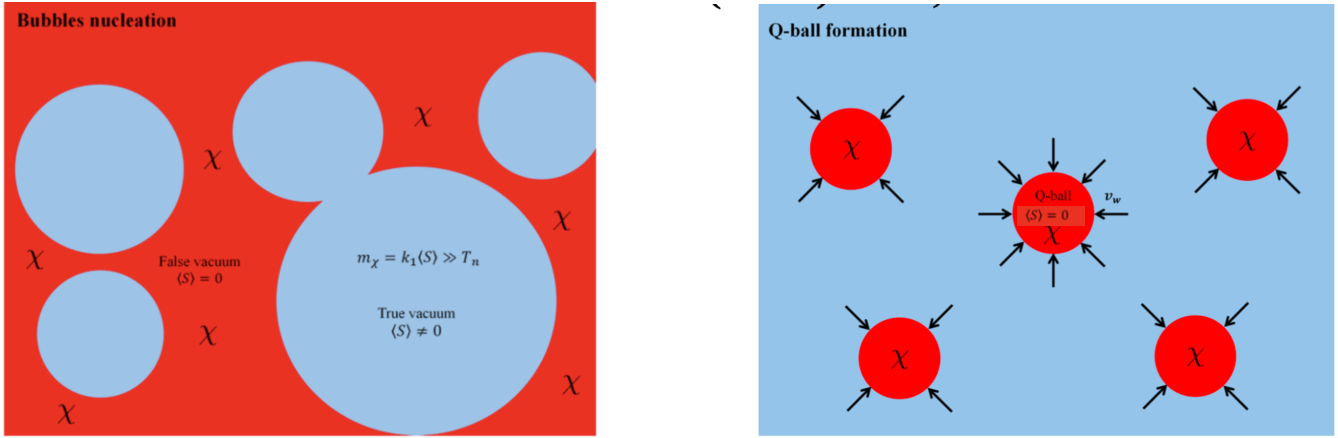
This talk



# 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:$\chi$ 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

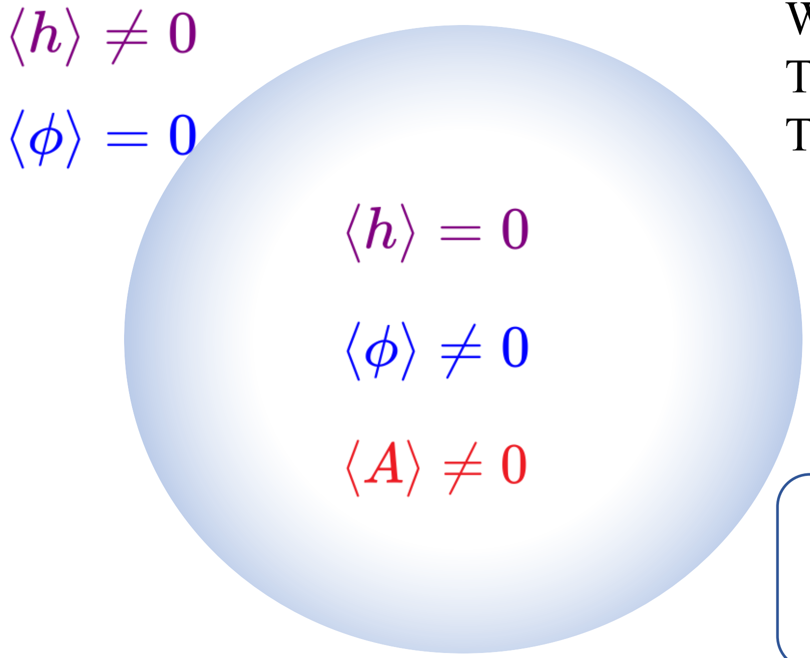
New DM production scenario by the bubbles.
The global Q-ball model proposed by T.D. Lee

Friedberg-Lee-Sirlin model

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

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

# Case I: Gauged Q-ball DM




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 first-order phase transition.

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

# Gauged Q-ball

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

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

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

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

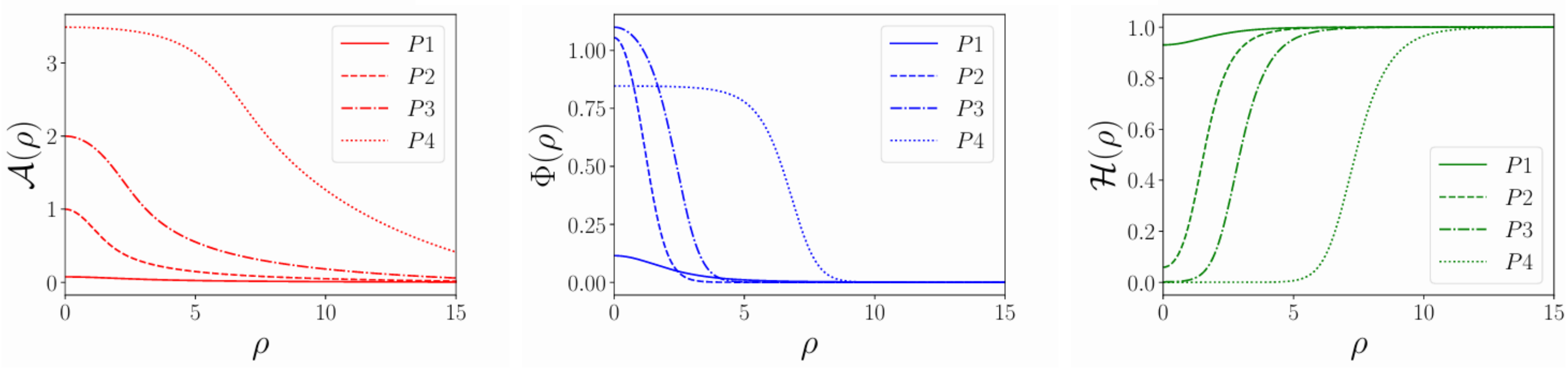
$$\frac{1}{\rho^2}\partial_\rho\left(\rho^2\partial_\rho\Phi\right) + \left[(\nu - \alpha^2\mathcal{A})^2 - k^2\mathcal{H}^2\right]\Phi = 0\,,$$

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

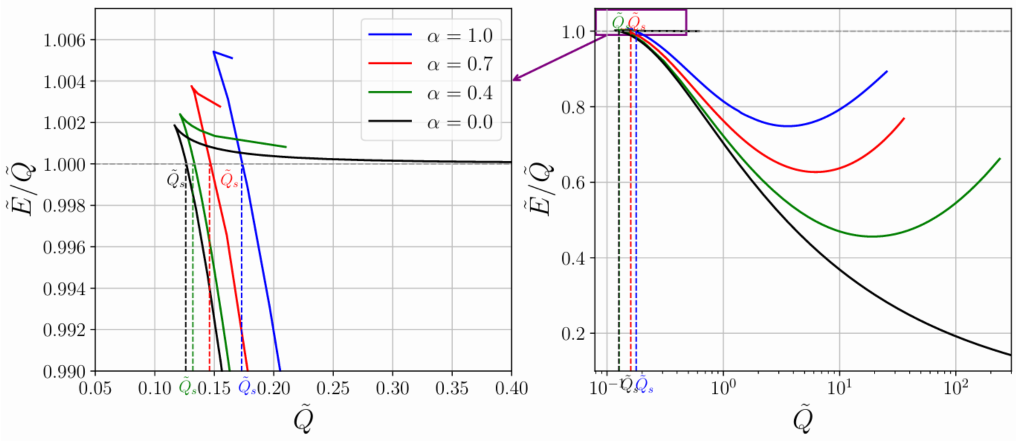
$$\alpha \equiv \frac{|\tilde{g}|}{\sqrt{2\lambda_h}},\ k \equiv \frac{\sqrt{\lambda_{\phi h}}}{2\sqrt{\lambda_h}} = \frac{m_\phi}{m_h}$$

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

relaxation method



# Gauged Q-ball stability

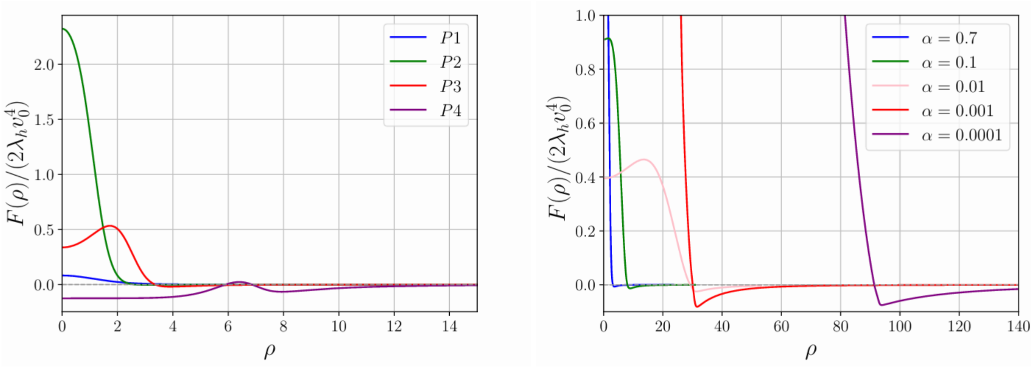



Quantum stability

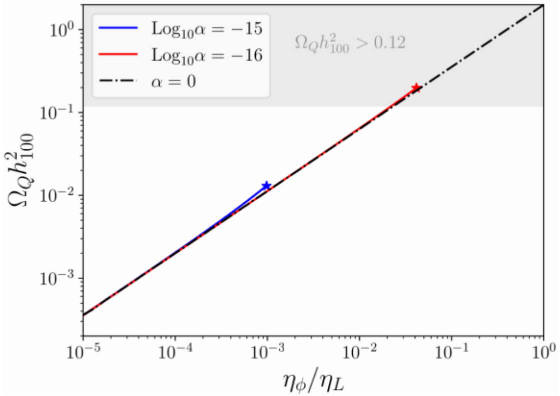
$$E < m_\phi Q \quad \text{or} \quad \tilde{E}/\tilde{Q} < 1$$

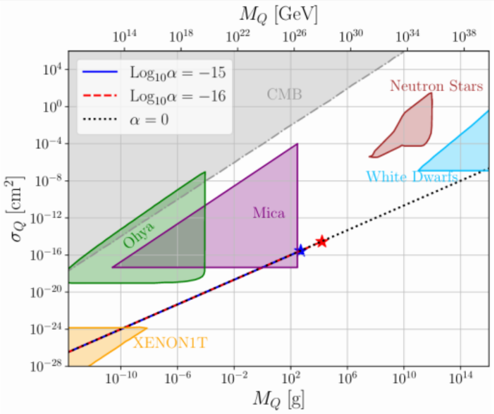
Stress stability

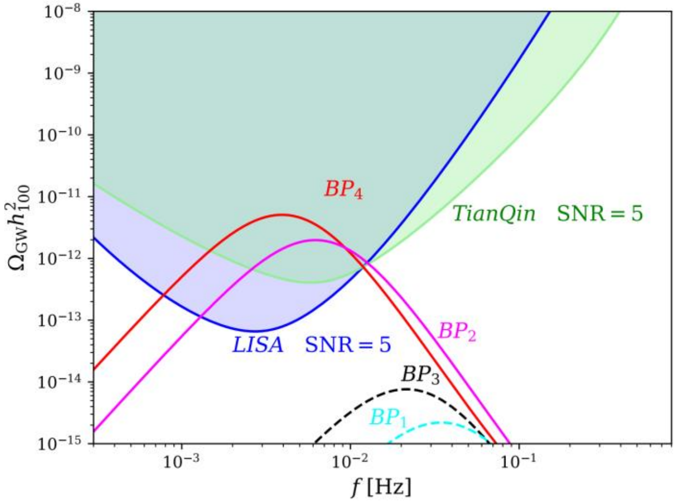
$$F(r) = \frac{2}{3}s(r) + p(r) > 0$$



# Gauged Q-ball DM at TianQin




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

| | $\lambda_{\phi h}$ | $T_p$ [GeV] | $\alpha_p$ | $\beta/H_p$ | $v_w$ | $F_\phi^{\rm trap}$ | $\eta_\phi/\eta_L$ | $\delta\sigma_{Zh}$ | GW |
|---|---|---|---|---|---|---|---|---|---|
| $BP_1$ | 6.8 | 69.8 | 0.12 | 540 | 0.1 | 0.932 | 0.48 | -0.36% | ● |
| $BP_2$ | 6.8 | 70.4 | 0.12 | 578 | 0.6 | 0.805 | 3.0 | -0.36% | ● |
| $BP_3$ | 7.0 | 63.0 | 0.15 | 372 | 0.1 | 0.965 | 3.4 | -0.37% | ● |
| $BP_4$ | 7.0 | 63.9 | 0.15 | 403 | 0.6 | 0.858 | 20.8 | -0.37% | ● |

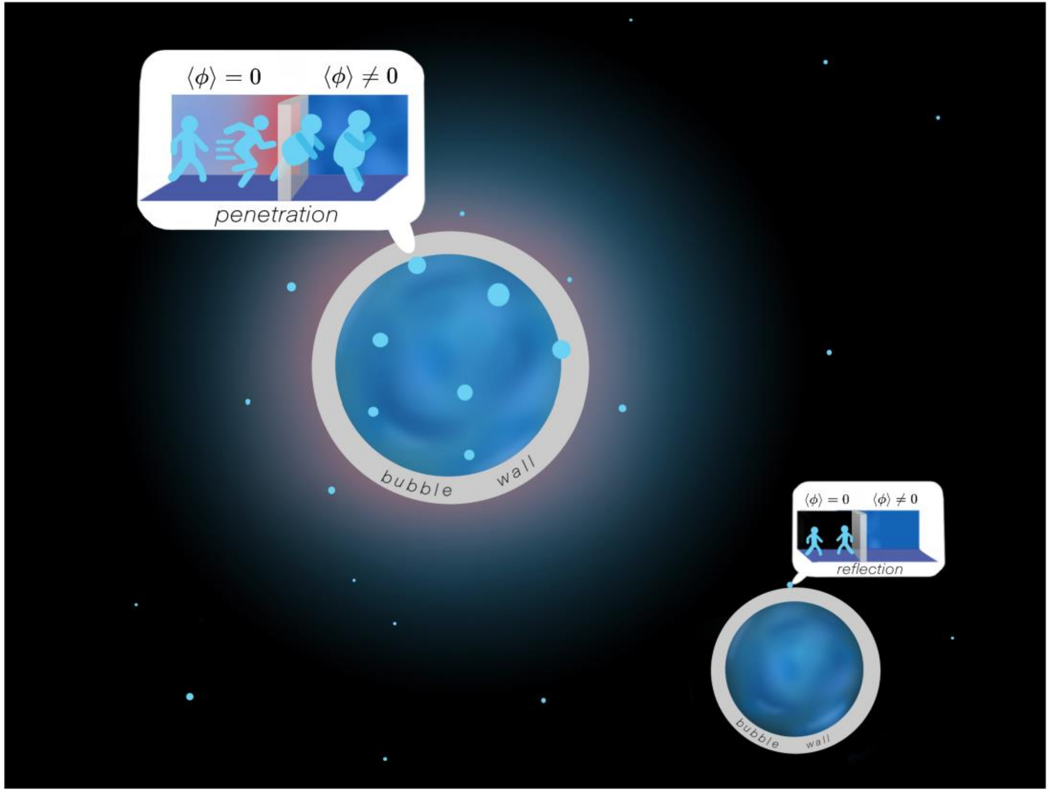
$F_\phi^{trap}$: The fraction of particles trapped into the false vacuum. It is determined by the phase transition dynamics.

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

# Case II: filtered DM from phase transition

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

DM



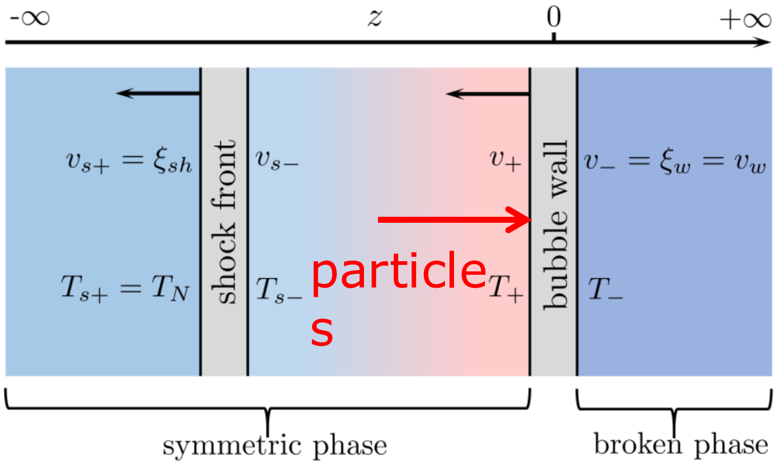

Siyu Jiang, FPH, Chong Sheng Li, Phys.Rev.D 108 (2023) 6, 063508

# Case II: filtered DM

Previous 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




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

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

$$n_\chi^{\rm in} = \frac{J_w^{\rm in}}{\gamma_w v_w}$$

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

# 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

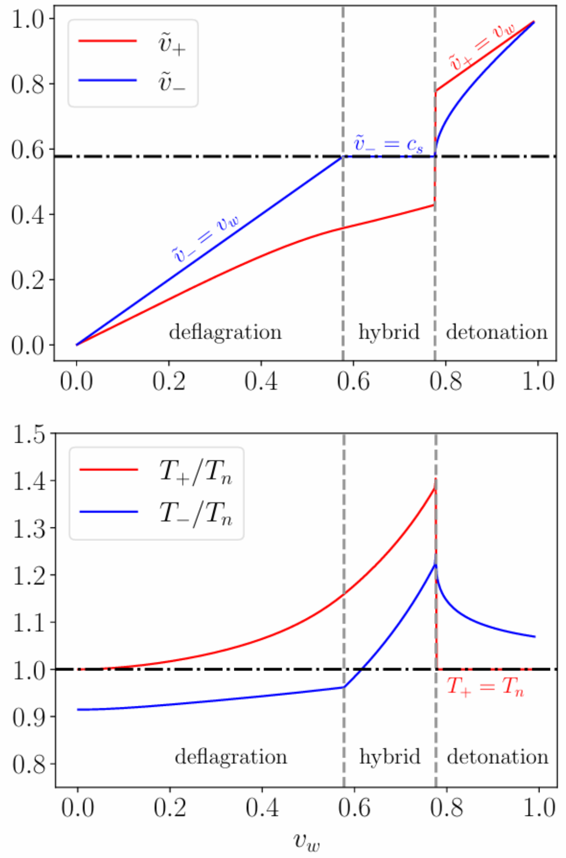
$$T_{\rm fl}^{\mu\nu} = T_{\phi}^{\mu\nu} + T_{\rm pl}^{\mu\nu} = \omega u^{\mu}u^{\nu} - p g^{\mu\nu}$$

Energy-momentum conservation

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

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

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



# Case II: filtered DM

Boltzmann equation

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

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

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

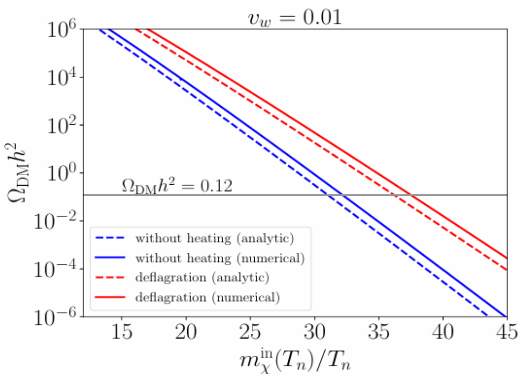
$$g_\chi \int \frac{dp_x dp_y}{(2\pi)^2} \mathbf{L}[f_\chi] \approx \left[\left(\frac{p_z}{m_\chi}\frac{\partial}{\partial z} - \left(\frac{\partial m_\chi}{\partial z}\right)\frac{\partial}{\partial p_z} - \left(\frac{\partial m_\chi}{\partial z}\right)\frac{\tilde{\gamma}_+ \tilde{v}_+}{T_+}\right)\mathcal{A}(z,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

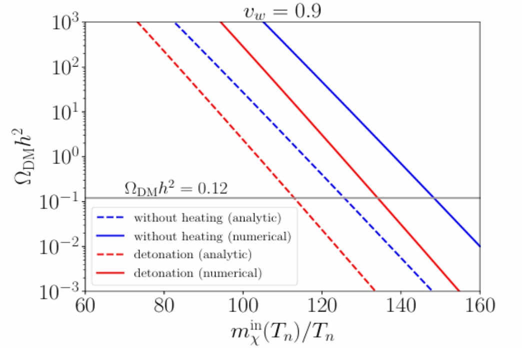
including $\chi\bar{\chi} \leftrightarrow \phi\phi, \chi\phi \leftrightarrow \chi\phi, \chi\chi \leftrightarrow \chi\chi, \chi\bar{\chi} \leftrightarrow \chi\bar{\chi}, \ldots$

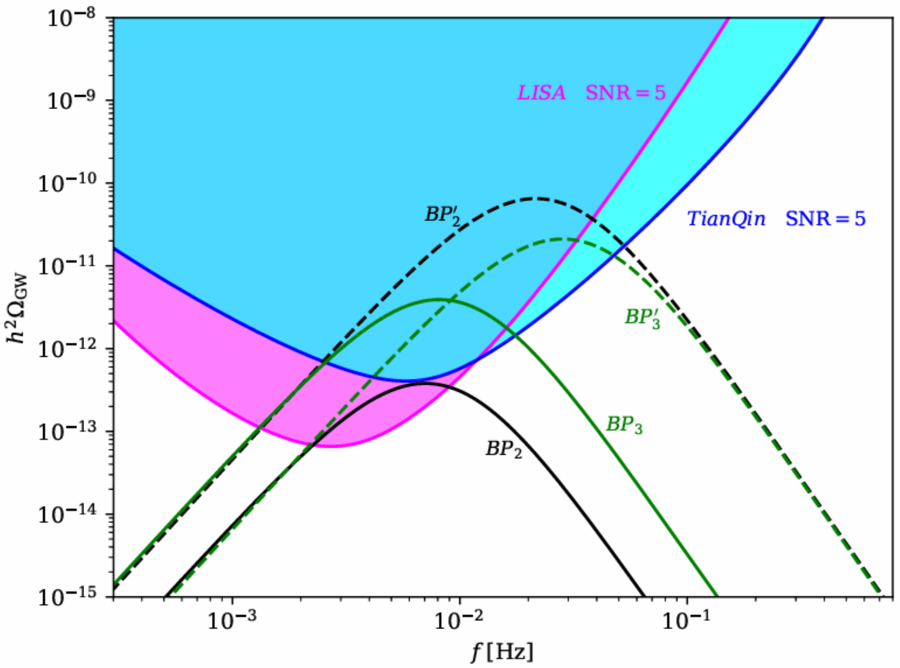
$$\begin{aligned} g_\chi \int \frac{dp_x dp_y}{(2\pi)^2} \mathbf{C}[f_\chi] &= -g_\chi g_{\bar{\chi}} \int \frac{dp_x dp_y}{(2\pi)^2 2E_p^{\mathcal{P}}} d\Pi_{q^{\mathcal{P}}} 4F\sigma_{\chi\bar{\chi}\to\phi\phi}\left[f_{\chi_p} f^{\rm eq}_{\bar{\chi}_q,+} - f^{\rm eq}_{\chi_p} f^{\rm eq}_{\bar{\chi}_q}\right]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

# Case II: filtered DM at TianQin

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

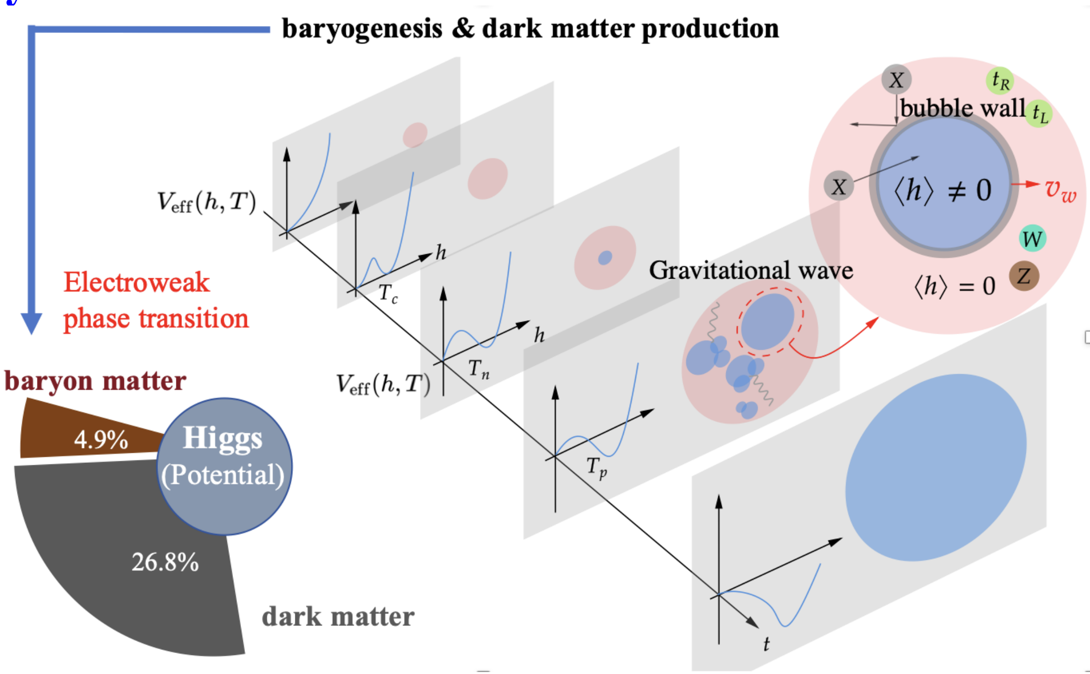


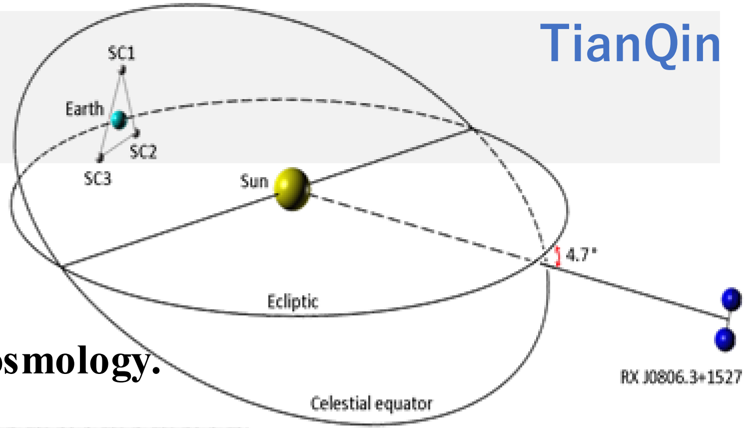
# Summary and outlook

- **Cosmic phase transition can naturally explain DM and baryogenesis.**
- **The associated GW at TianQin. provides new approaches to explore DM and cosmic symmetry breaking.**

# Summary and outlook

TianQin




Fundamental Physics and Cosmology with TianQin, arXiv: 2502.20138

**Besides direct detection of astrophysics GW sources and test of gravity theory,**
**TianQin can explore many fundamental problems in particle cosmology.**

Correlation and complementay test with CEPC
Higgs physics (potential), Z-pole physics, TeV new physics

GW @TianQin

Baryon asymmetry of our Universe (EW baryogenesis)

cosmic symmetry breaking relics

New DM formation mechanism;
New approach to explore DM

Progress of the TianQin project, arXiv: 2502.11328

Thanks for your attention !
Comments and collaborations are welcome.
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