Darkogenesis via Supercooled Phase Transition

Yuichiro Nakai

T. D. Lee Institute & Shanghai Jiao Tong U.

Based on: JHEP (2020), PLB (2021), PLB (2023), PLB (2024), JHEP (2025), arXiv:2507.03747
with Fujikura, Girmohanta, Nakagawa, Sun, Suzuki, Takahashi, Yamada, Y. Zhang, Z. Zhang

Central Claims

1. **Phase transition interpretation of PTA signal** : Nano-Hz gravitational waves from a dark supercooled phase transition.

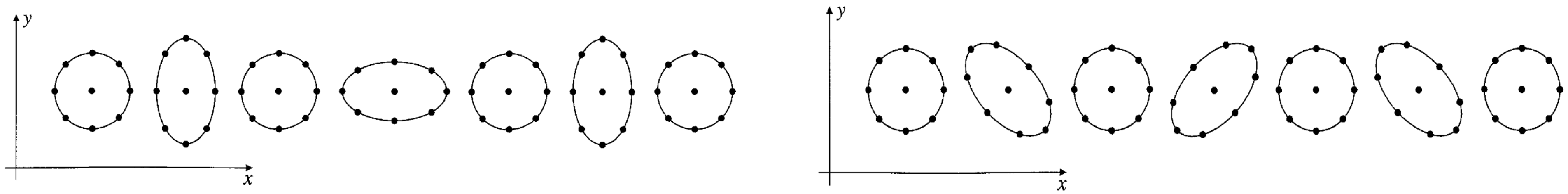
2. **Consequence of the phase transition interpretation** : Dilution of pre-existing dark matter and baryon asymmetry.

3. **Solving the dilution problem** : The same supercooled PT naturally sets a stage to create DM and baryon asymmetry.

4. **Testability** : The models can be probed by ongoing and near-future experiments!

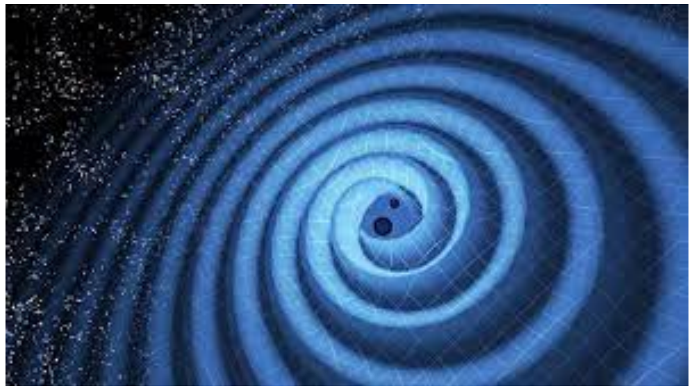
Gravitational Waves

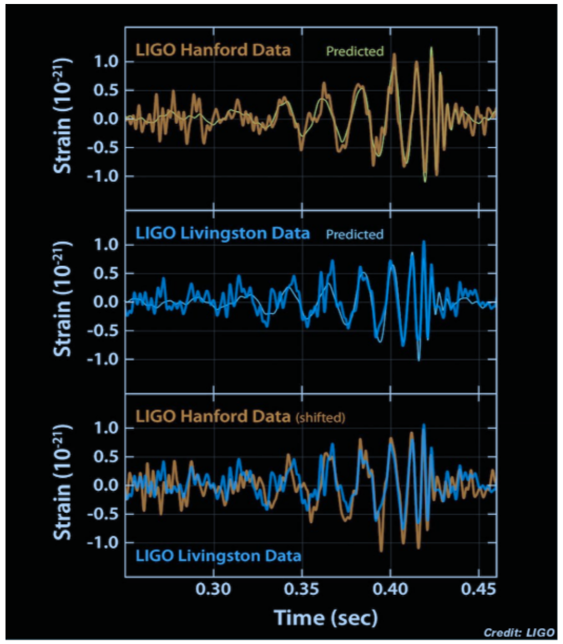
Gravitational waves (GWs) are small ripples over background spacetime predicted in Einstein equation.



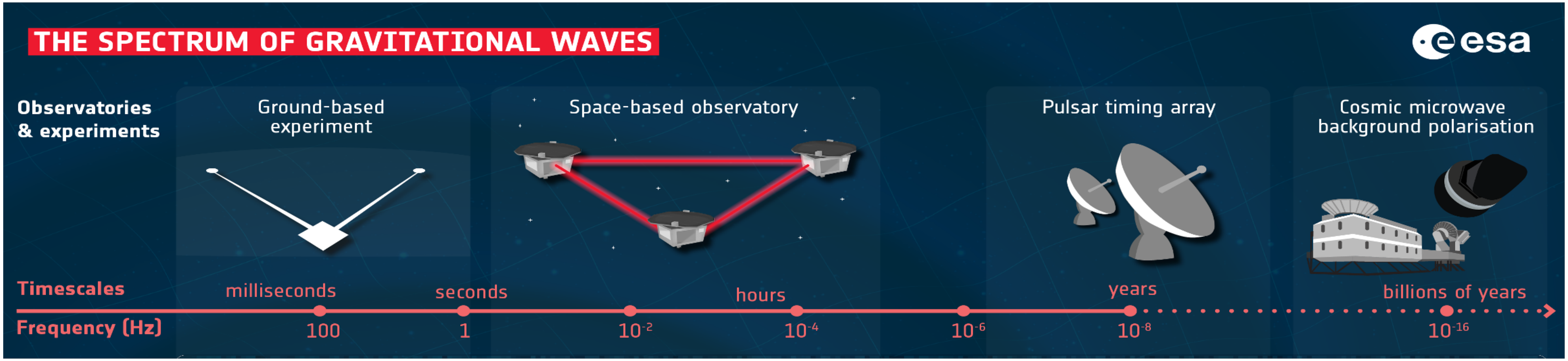
Detection of GWs from black hole & neutron star binaries

→ **GW astronomy** has started !





Credit: LIGO



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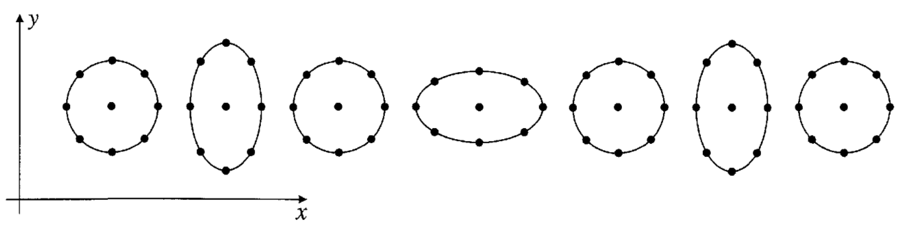

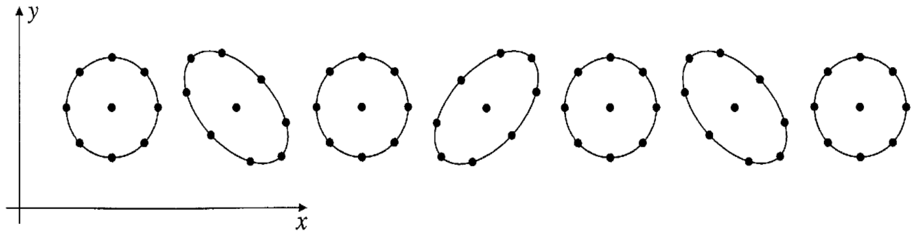

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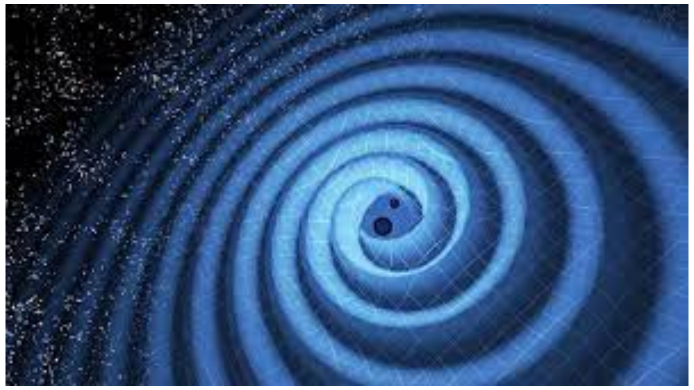
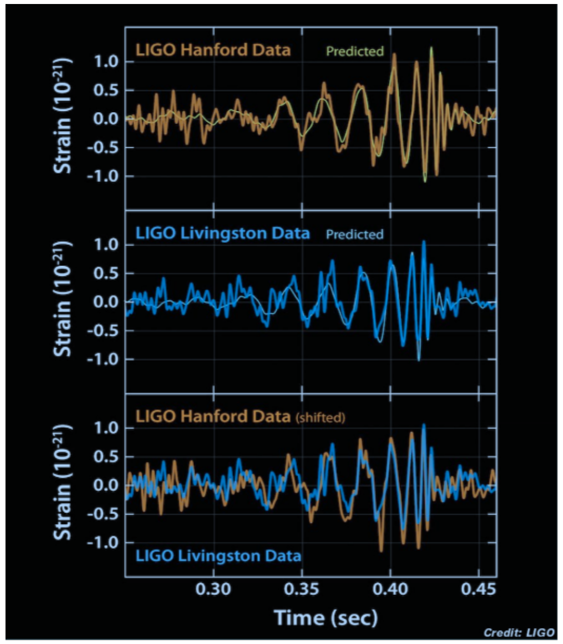
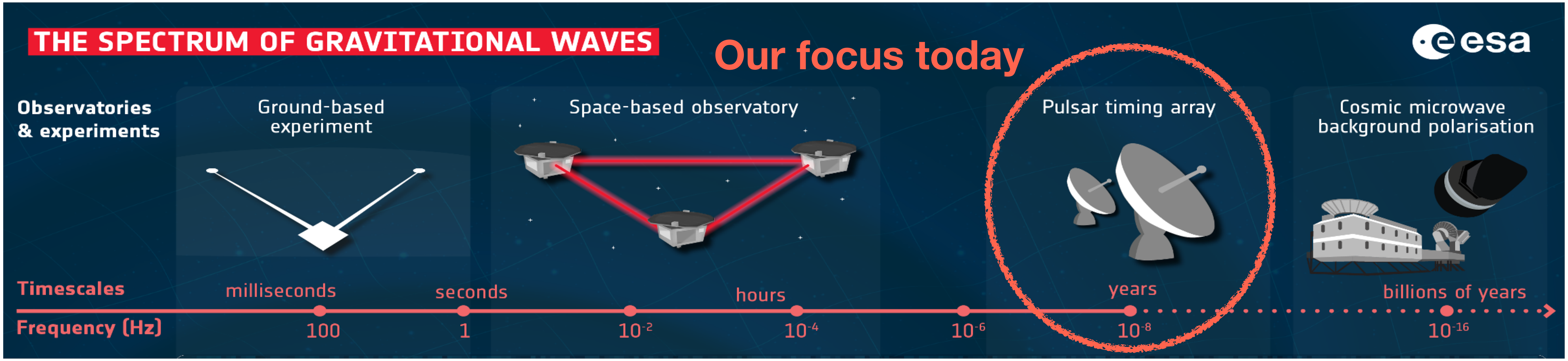


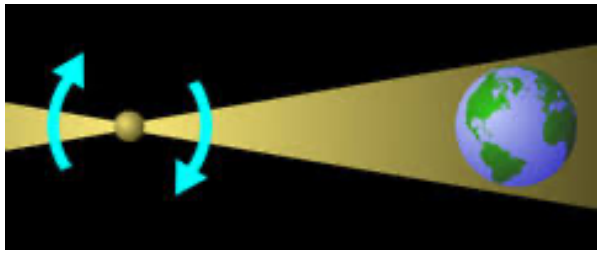


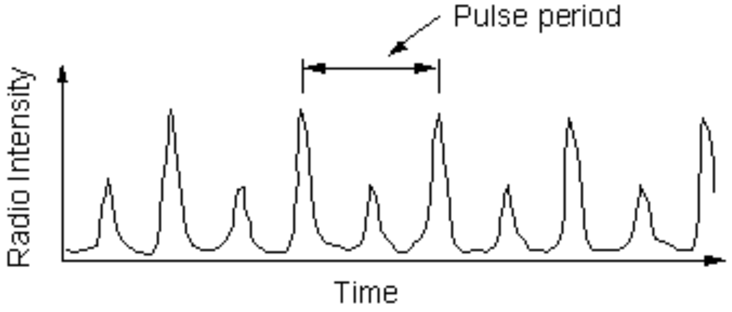


Our focus today

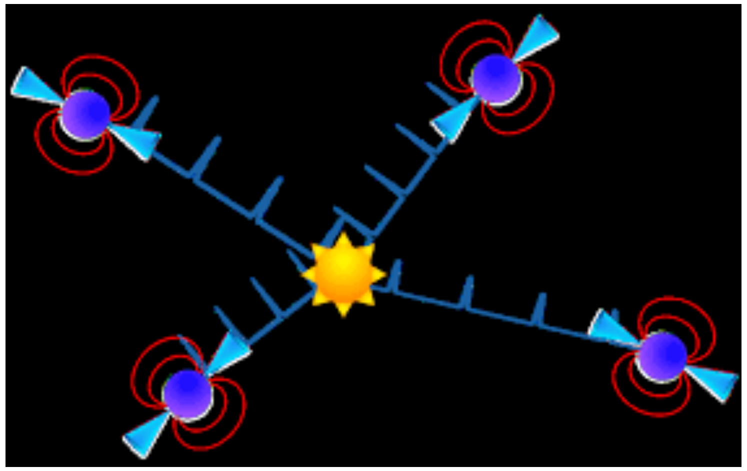
Pulsar Timing Array

- (Millisecond) pulsars are precise clocks.

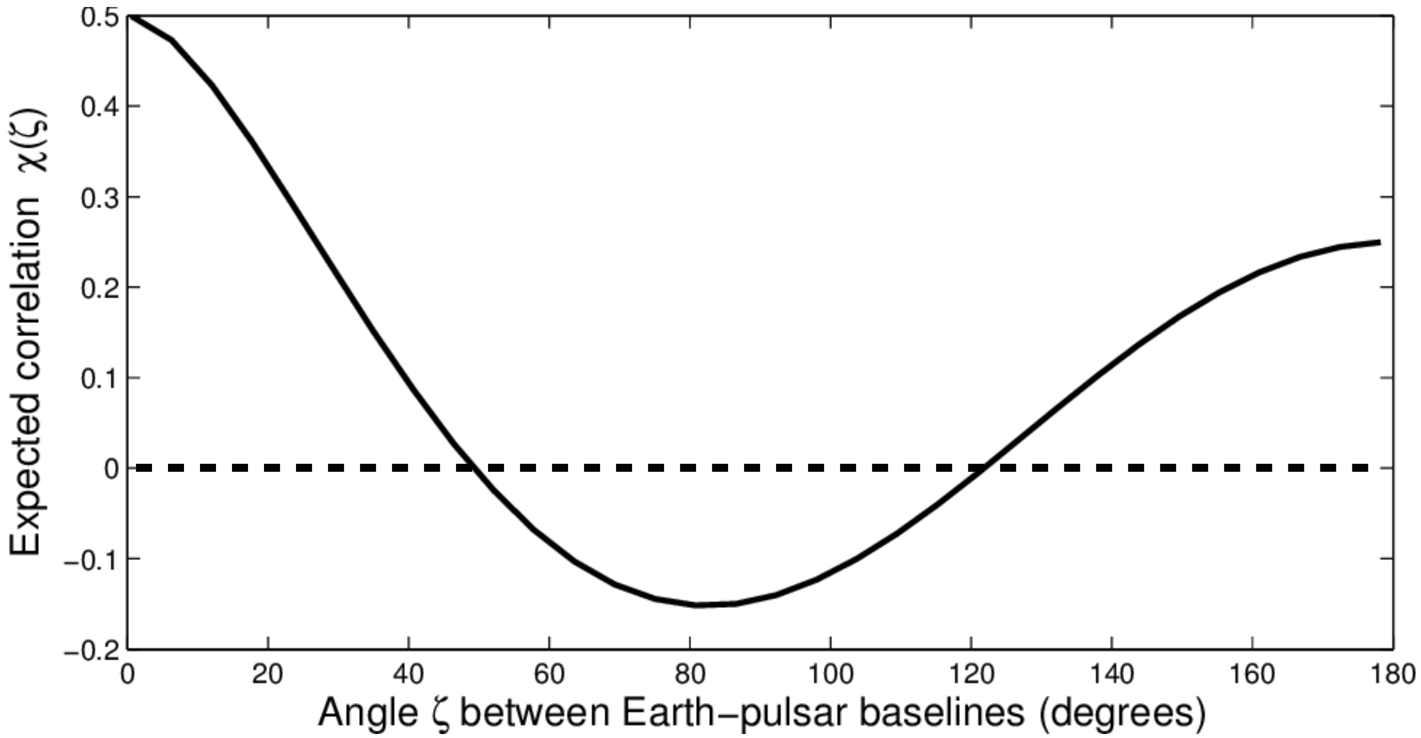


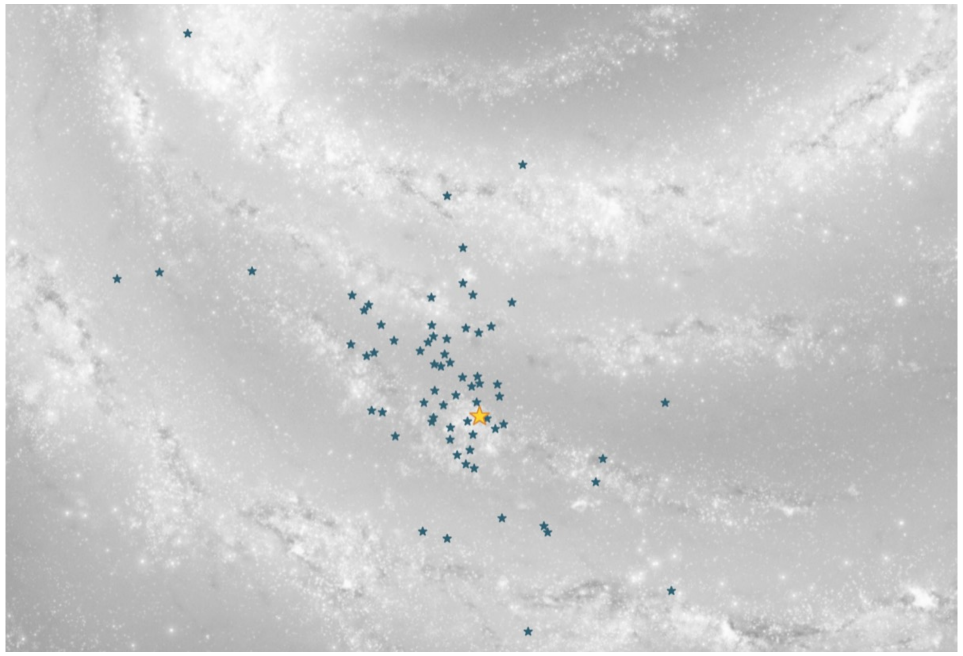


- Earth-pulsar system as GW antenna.



- GWs slightly shift the pulse-arrival time by a specific angular correlation (Hellings & Downs curve).

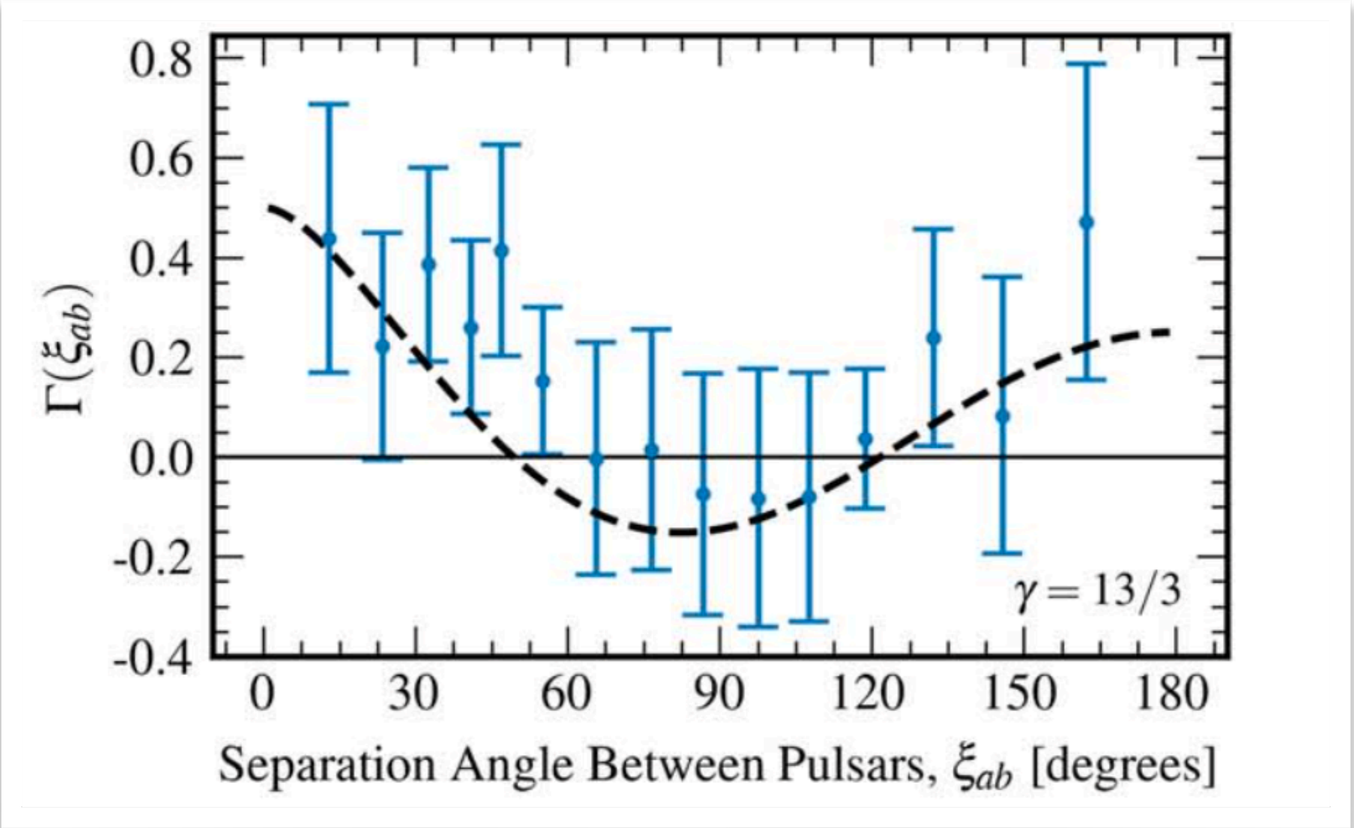




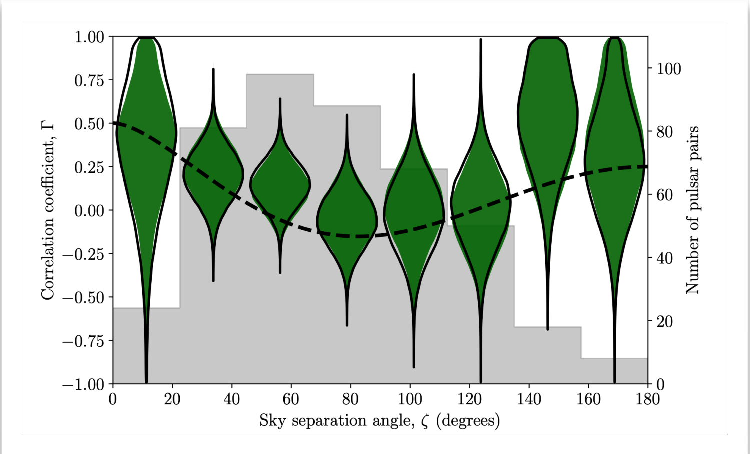
Recent Observations

CPTA, EPTA, InPTA, NANOGrav, PPTA have reported evidence for nano-Hz stochastic gravitational waves !

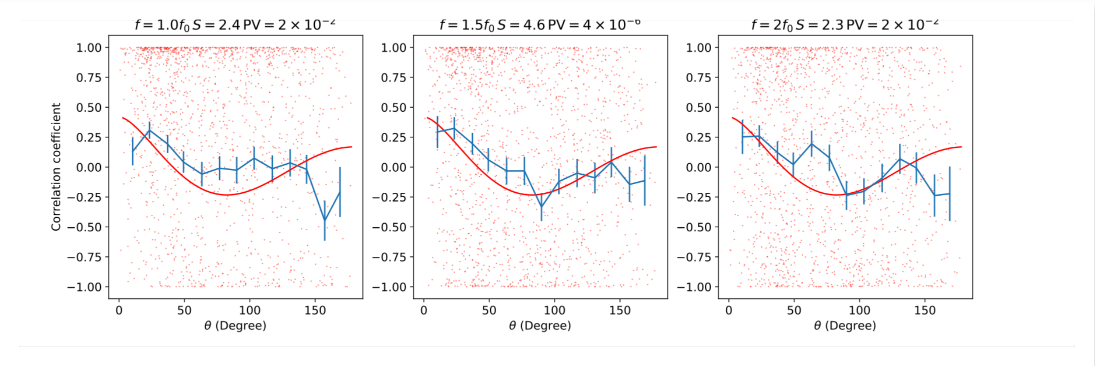
NANOGrav



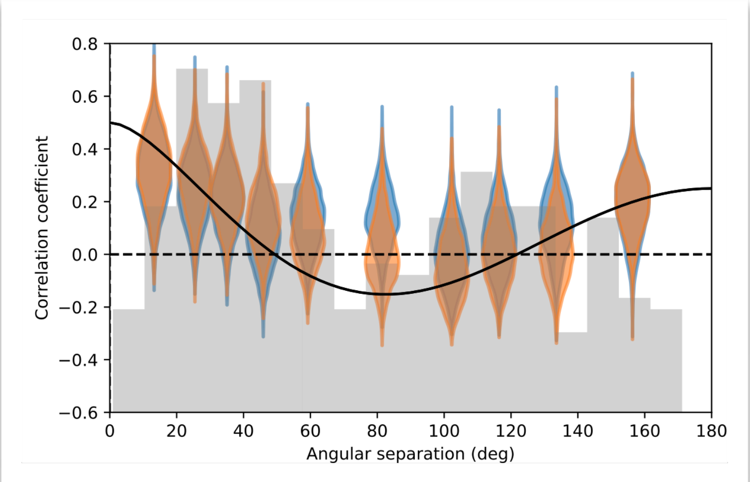
PPTA



CPTA



EPTA+InPTA



Possible Sources

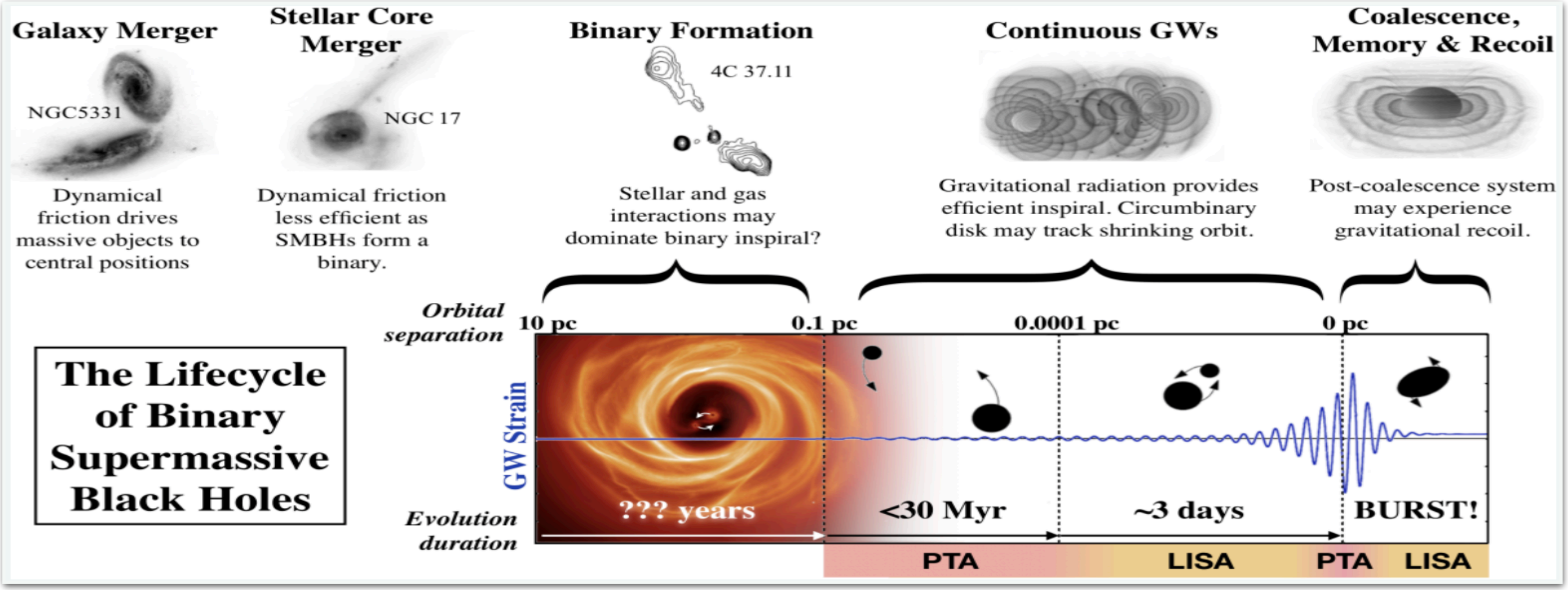
✓ Supermassive black hole binaries

(However, final parsec problem ?)

✓ Cosmological phase transitions

✓ Defects: cosmic strings, domain walls

…



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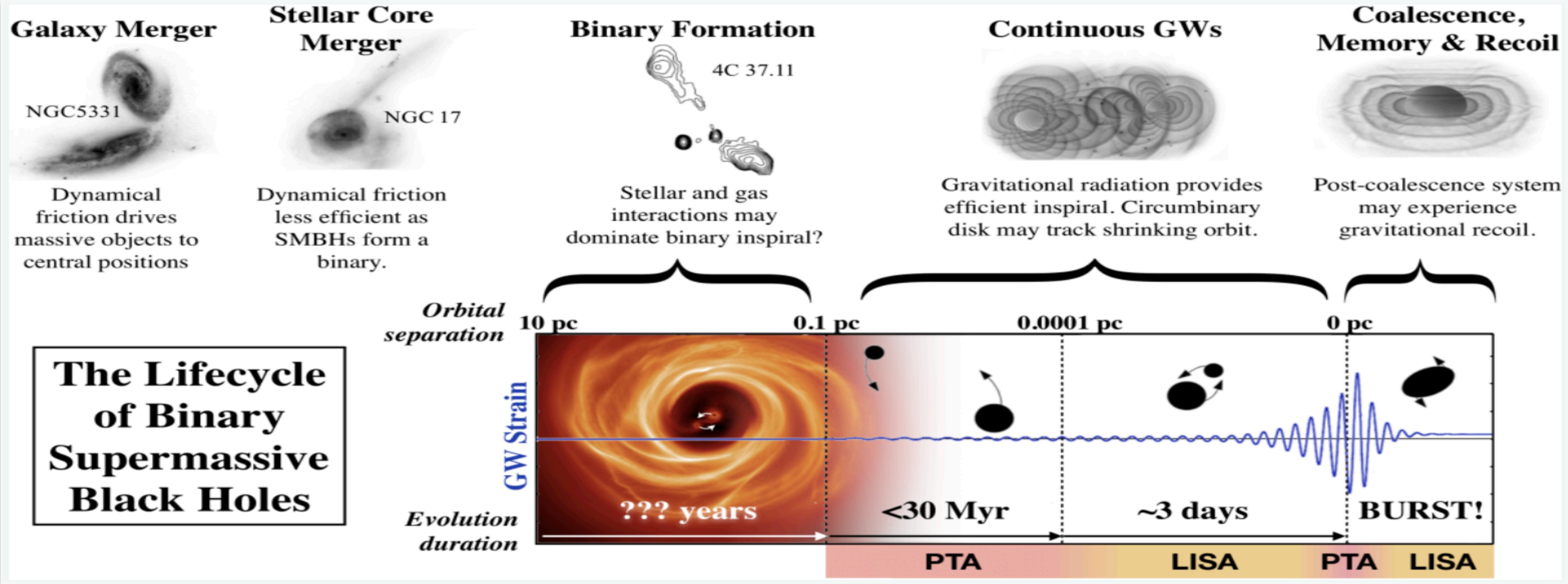
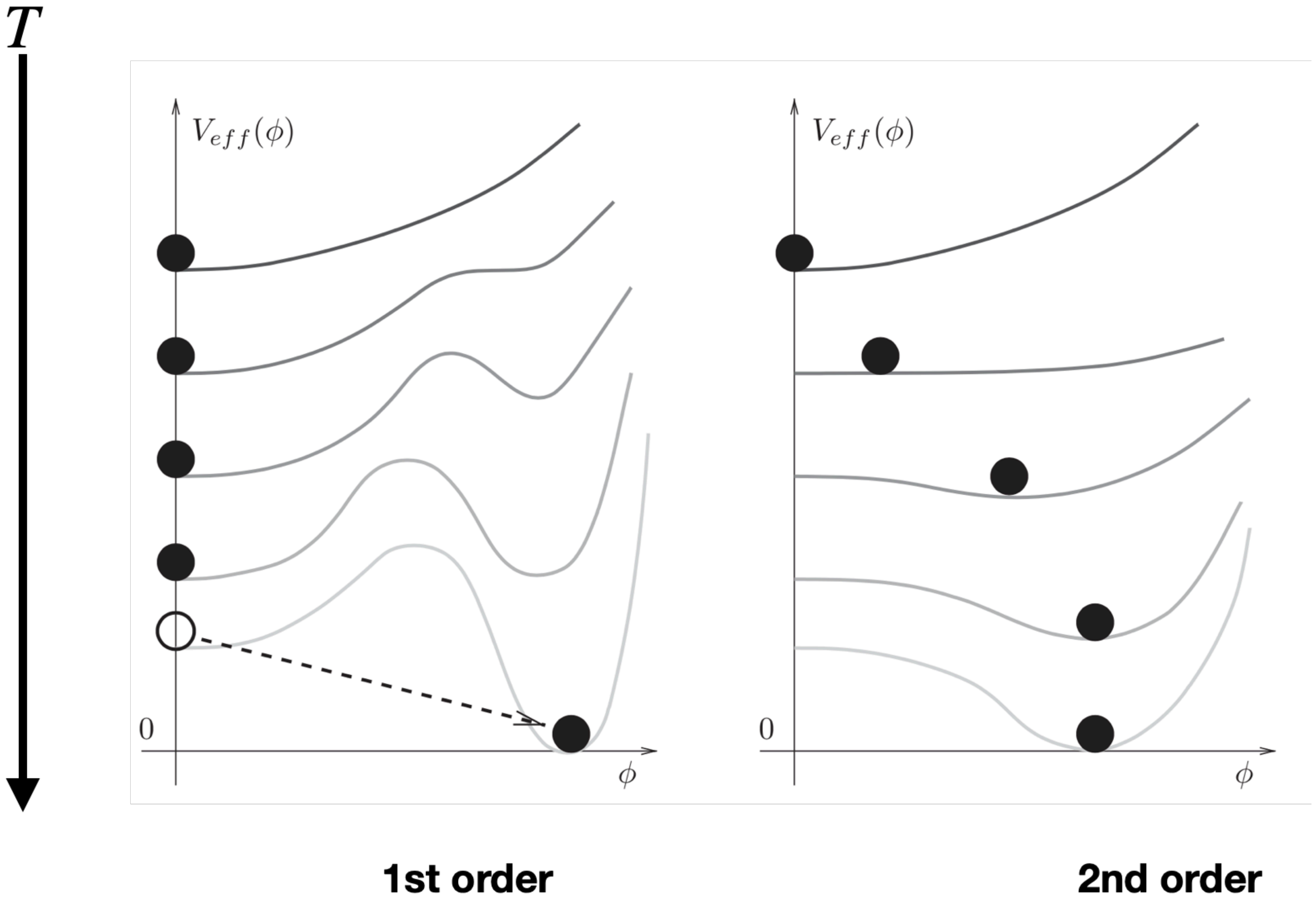


Phase Transition

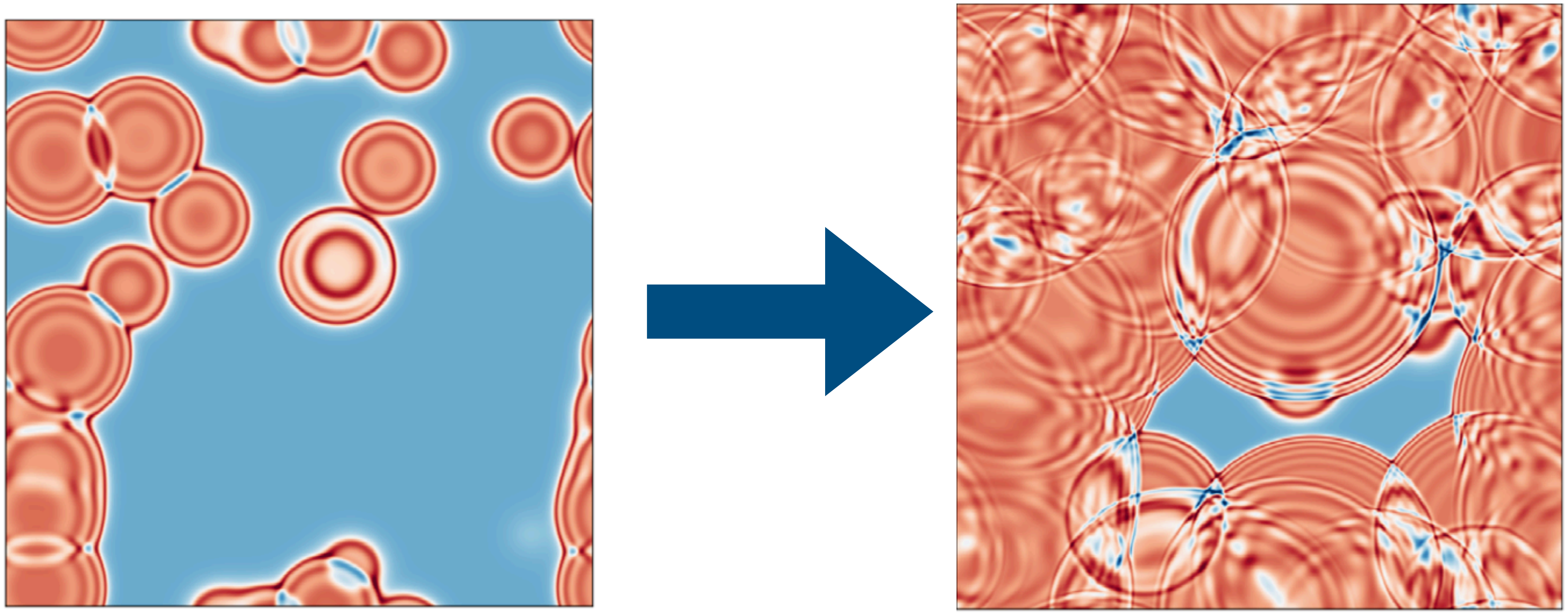
Phase transition occurs when there is a mismatch of true ground state at zero and non-zero temperatures.



1st order phase transition proceeds via nucleation, expansion and merger of bubbles of the true ground state.

GW Generation

The collision of bubbles and subsequent fluid flows produce shear stresses that source GWs.



Observed frequency f_0 is redshifted and associated with the epoch when GWs are produced.

$$f_0 \simeq 10^{-8}\ \mathrm{Hz} \left(\frac{T_*}{1\ \mathrm{GeV}} \right)$$

Dark Phase Transition

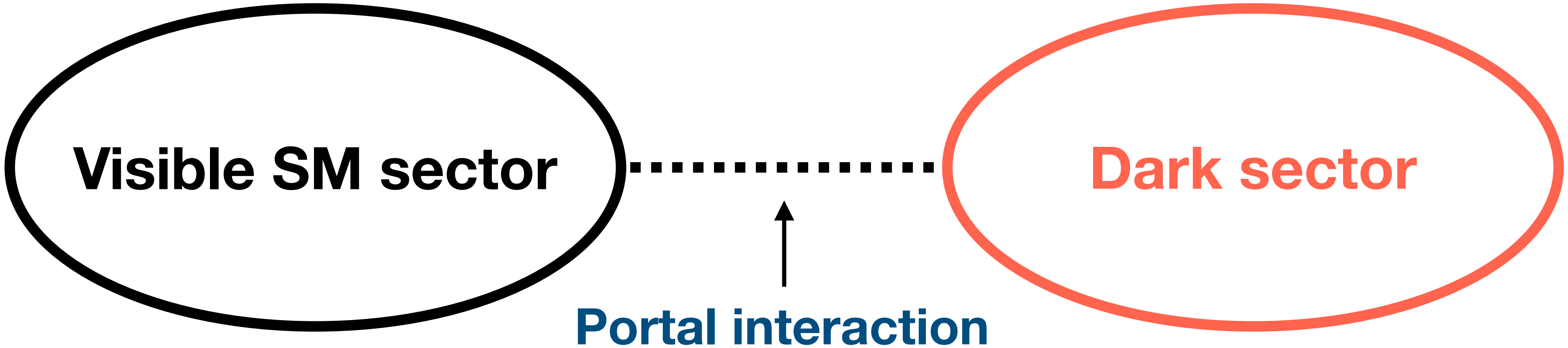
- Peak frequency in the nHz implies a phase transition temperature $T_* \sim 1$ GeV

- QCD phase transition is not 1st order,
  1st order electroweak phase transition: $f_{\mathrm{peak}}^{(\mathrm{EW})} \gtrsim 10^{-4}\ \mathrm{Hz}$

Ellis, Lewicki, No (2019)

→ **Phase transition in a dark sector**

YN, Suzuki, Takahashi, Yamada (2021)



Portal interaction

(required to satisfy **Neff** constraint)

Dark Phase Transition

- Peak frequency in the nHz implies a phase transition temperature T_* ~ 1 GeV

- QCD phase transition is not 1st order,
  1st order electroweak phase transition: $f_{\rm peak}^{\rm (EW)} \gtrsim 10^{-4}\ {\rm Hz}$

Ellis, Lewicki, No (2019)

➡ **Phase transition in a dark sector**

YN, Suzuki, Takahashi, Yamada (2021)

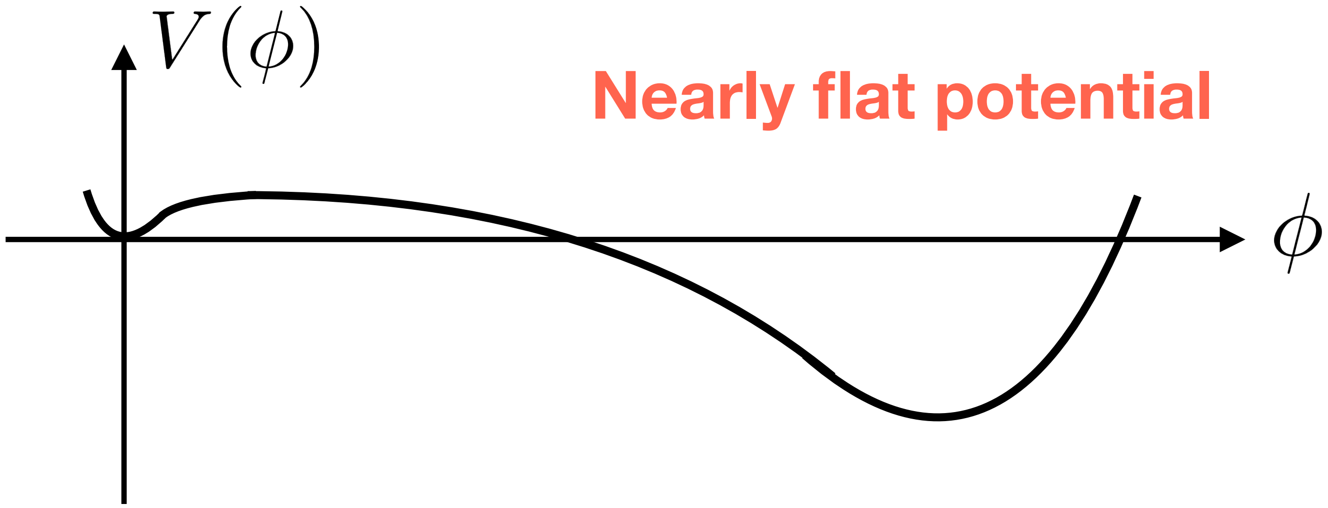
- Generically, it is not easy to reach the strength required by the PTA signal explanation.

It is important to find a particle physics model that can generate the reported signal.

Scale Invariance

A strong first-order phase transition with a large discontinuity in the order parameter can generate a large GW amplitude.

A widely shared characteristic in theories to show a strong first order PT is the presence of **an approximate scale invariance**.



e.g. Radiative symmetry breaking with a classical scale invariance (via Coleman-Weinberg mechanism)

Witten (1981)

↑

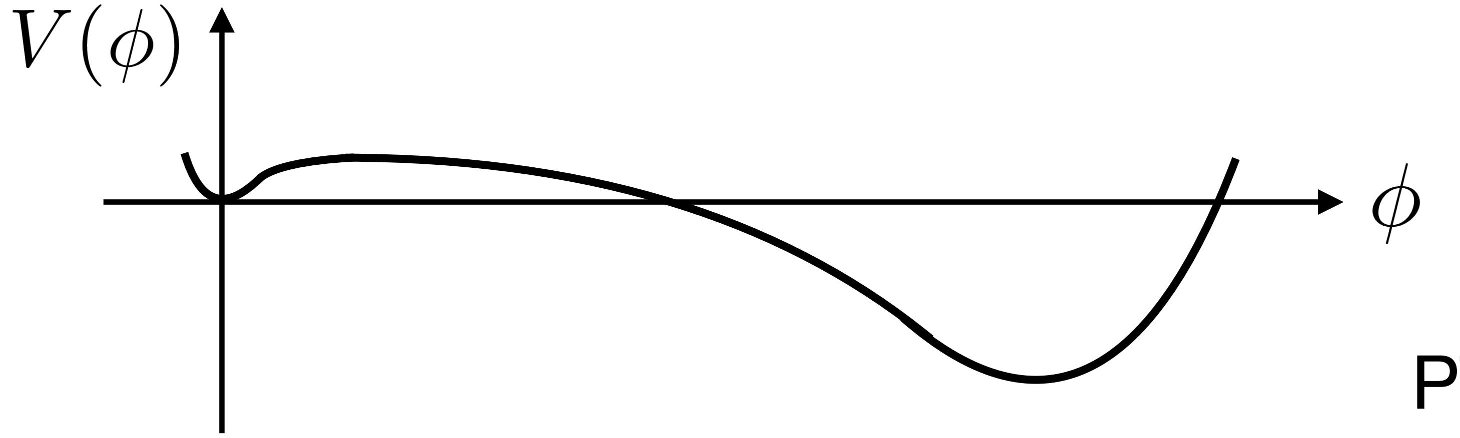
A significant amount of fine-tuning on a mass parameter is required.

Conformal PT

Conformal field theory (CFT) offers a more natural way to implement scale invariance at the quantum level.

A marginally relevant deformation drives the spontaneous breaking of (approximate) scale invariance at a certain energy scale.

A pseudo-Nambu-Goldstone boson called **dilaton**.



PT dynamics may be studied in terms of the dilaton EFT.

However …

This possibility is usually discussed without an explicit model of CFT due to its non-perturbative nature.

Conformal PT

Model of CFT

SUSY **AdS/CFT**

Supersymmetric QCD

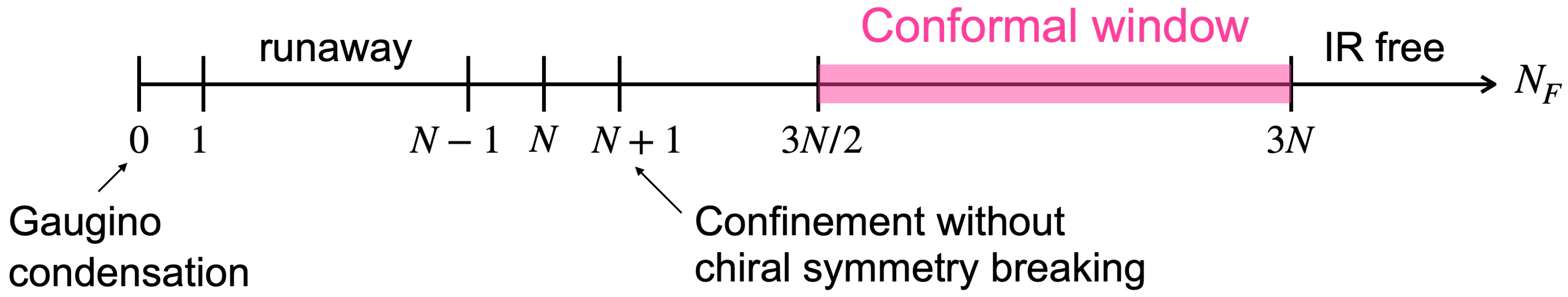
- **IR fixed point** gives CFT.
- SUSY makes it possible to get a handle on non-perturbative dynamics.

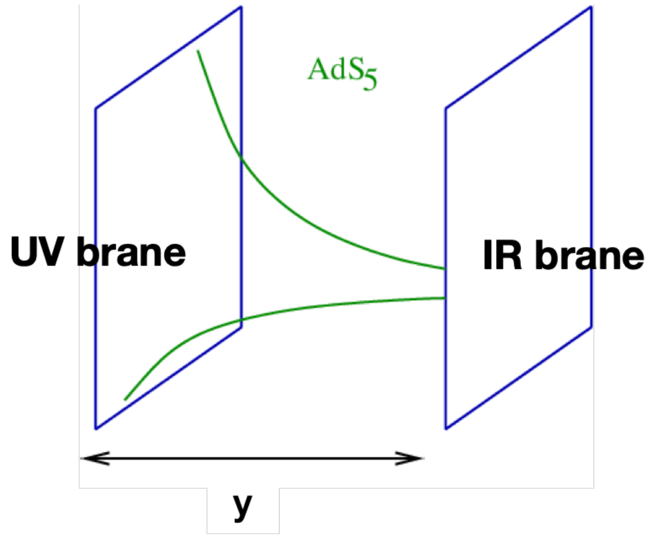
Fujikura, Nakagawa, YN, Sun, Zhang (2025)

5D holographic model

- It gives a concrete weakly-coupled description.
- **Radion** can be identified as dilaton.

Fujikura, Girmohanta, YN, Suzuki (2023)





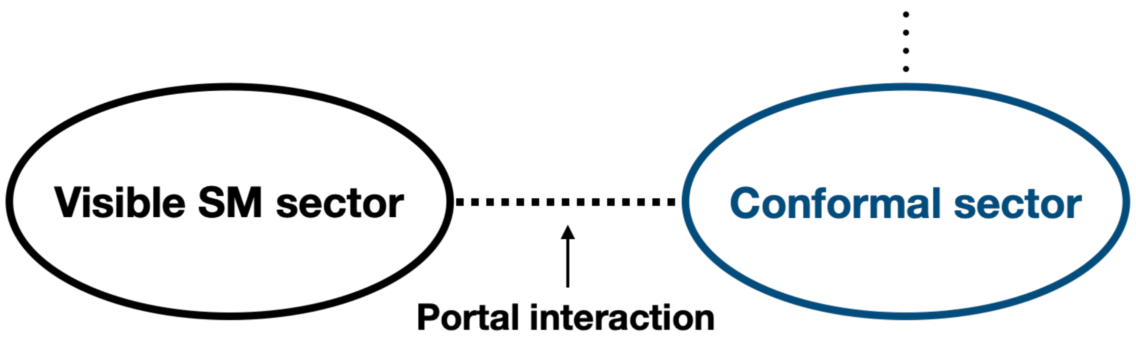
Conformal PT

Model of CFT

AdS/CFT

4D dual setup

Dark Yang-Mills



Confinement of dark Yang-Mills drives **spontaneous breaking of conformal invariance**.

Fujikura, YN, Yamada (2020)

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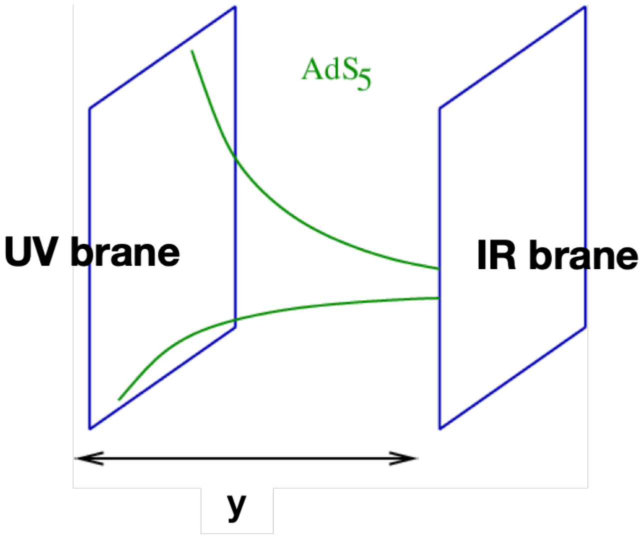
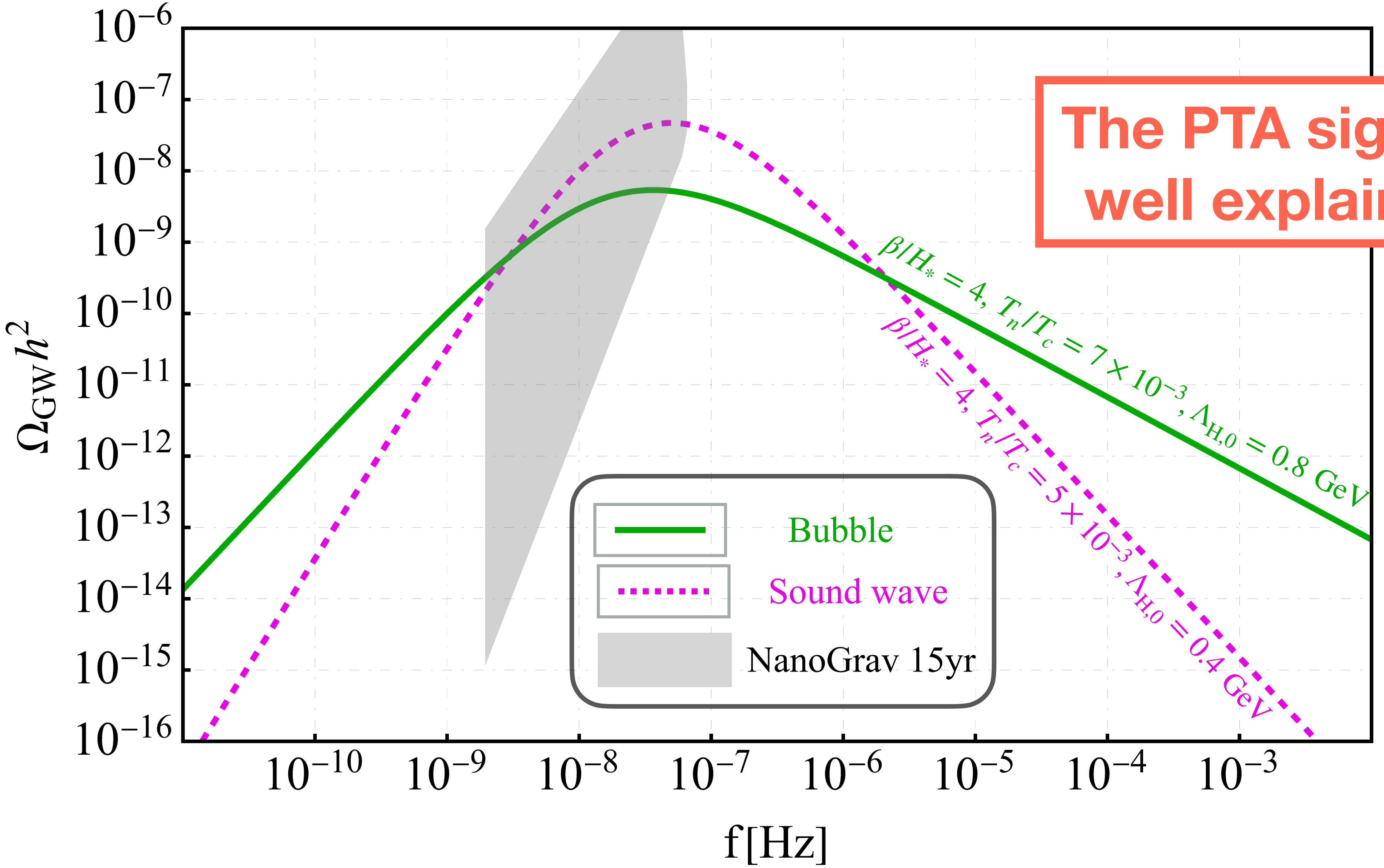


Fitting the Data

A GW background produced by the dark conformal phase transition

Fujikura, Girmohanta, YN, Suzuki (2023)



The PTA signal is well explained !

Supercooling

The phase transition takes place via a supercooling phase.

The vacuum energy dominates the energy density of the Universe and **mini-inflation** takes place before the phase transition is completed.

The e-folding number of mini-inflation :

$$N_e \simeq \log\left(\frac{T_c}{T_n}\right)$$

Critical temperature

Nucleation temperature

➡ Dilution of dark matter and baryon asymmetry if they are produced before the phase transition.

Dilution factor ~10^{-9}

We need a very large amount of dark matter and baryon asymmetry before the phase transition or need to produce them after the phase transition.

Cold Darkogenesis

Fujikura, Girmohanta, YN, Zhang (2024)

Supercooled phase transition naturally provides a setting of **cold baryogenesis**.

Konstandin, Servant (2011)

Dark sector asymmetry ➡ Baryon asymmetry & **asymmetric DM**

Dilaton stabilization ↘ $SU(N_{\rm H})$

Cold baryogenesis ↓ $SU(2)_{\rm D}$

Dark baryon number ↙ $U(1)_{\rm D}$

	Fields	$SU(N_{\rm H})$	$SU(2)_{\rm D}$	$U(1)_{\rm D}$	
Spin 0	$H_{\rm D}$	$\mathbf{1}$	$\mathbf{2}$	0	➡ Spontaneous breaking of SU(2)D
Spin 1/2	$L_{\chi,i} \equiv \begin{pmatrix} \psi_{1,i} \\ \psi_{2,i} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	1	➡ U(1)D anomaly
	$\chi_{1,i}\ ,\ \chi_{2,i}$	$\mathbf{1}$	$\mathbf{1}$	-1	➡ Neutron portal interaction for asymmetry sharing with SM
	f_j	$\mathbf{N}_{\rm H}$	$\mathbf{1}$	$1/N_{\rm H}$	➡ Baryon dark matter
	$\bar{f}_j$	$\overline{\mathbf{N}}_{\rm H}$	$\mathbf{1}$	$-1/N_{\rm H}$	

$i = 1, \cdots, N_{D_{\rm L}}\ ;\ j = 1, \cdots, N_{D_{\rm B}}$

Cold Baryogenesis

I. $SU(2)_D$ PT is triggered after the dark supercooled PT.

- The dark Higgs field is produced.
- The $SU(2)_D$ orientation of the Higgs field is inhomogeneous in space, abundantly producing **the Higgs winding number (N_H)**.

II. The configurations relax to the vacuum state, either by changing N_H or **the Chern-Simons number of the $SU(2)_D$ gauge field (N_{CS})**.

- The change of N_{CS} induces fermion number violation via anomaly.

III. With C & CP violation, $\delta N \equiv N_{CS} - N_H > 0$ and $\delta N < 0$ winding configurations evolve differently, generating a net fermion number.

(I) Dark Higgs Production

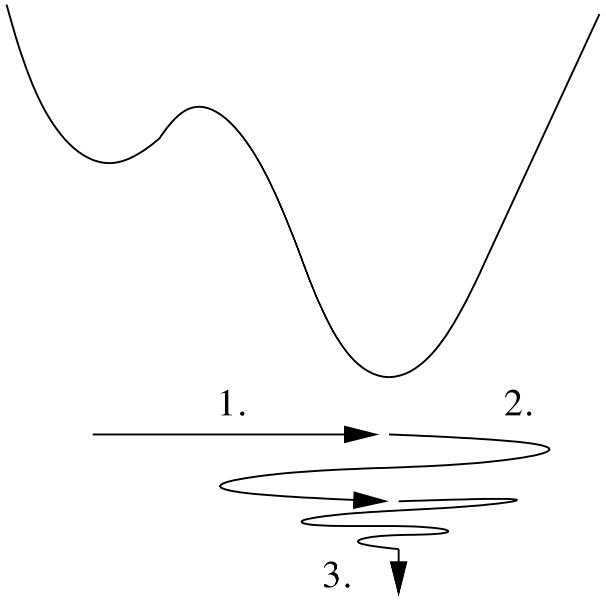
SU(2)D PT is triggered after the dark supercooled PT.

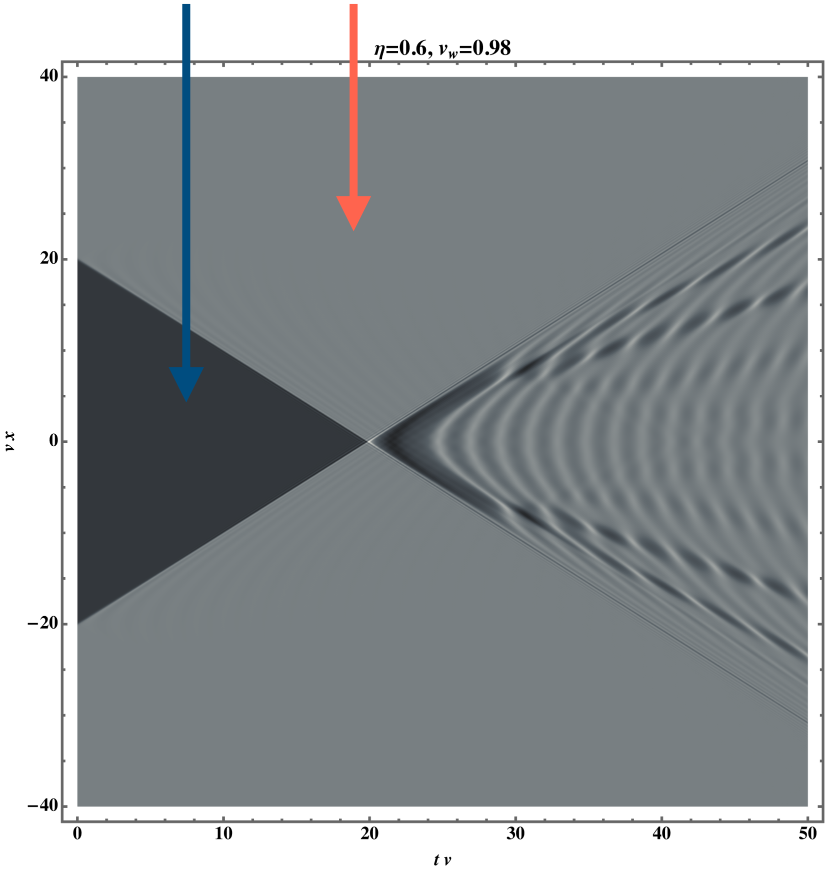
$$V(\phi, H_{\rm D}) = \underline{V_{\rm eff}(\phi)} + \frac{\lambda}{4}\left[H_{\rm D}^{\dagger}H_{\rm D} - \frac{v_{\rm D}^2}{2}\left(\frac{\phi}{\phi_{\rm min}}\right)^2\right]^2$$

Dilaton effective potential

False vacuum **True vacuum**

When bubbles collide, the dilaton field bounces and oscillates around the minimum.





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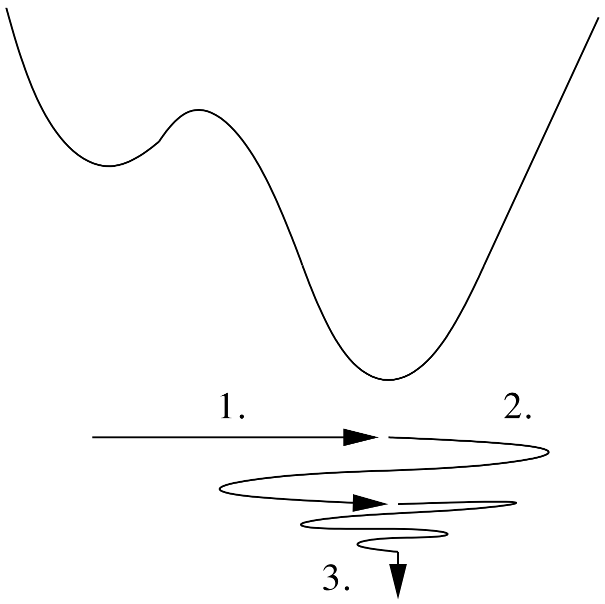


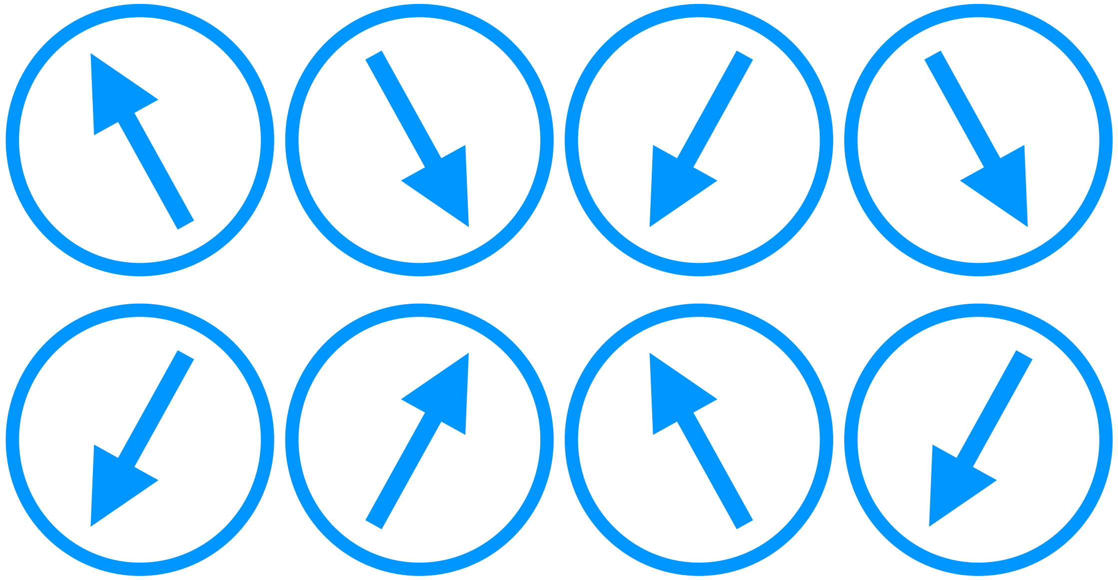
When bubbles collide, the dilaton field bounces and oscillates around the minimum.

This very much resembles the situation of **parametric resonance** after inflation.

➡ **Long-wavelength modes** of the dark Higgs field are abundantly produced.

(I) Dark Higgs Production

The dark Higgs field is abundantly produced whose "SU(2)D orientation" is randomly distributed by bubble dynamics.



$$V \sim \lambda \left(\mathrm{Tr}[\Phi\Phi^\dagger] - v_D^2 \left(\frac{\phi}{\phi_{\mathrm{min}}} \right)^2 \right)^2$$

$$\Phi = (\epsilon H_D^*, H_D) = \frac{\sigma}{\sqrt{2}} U$$

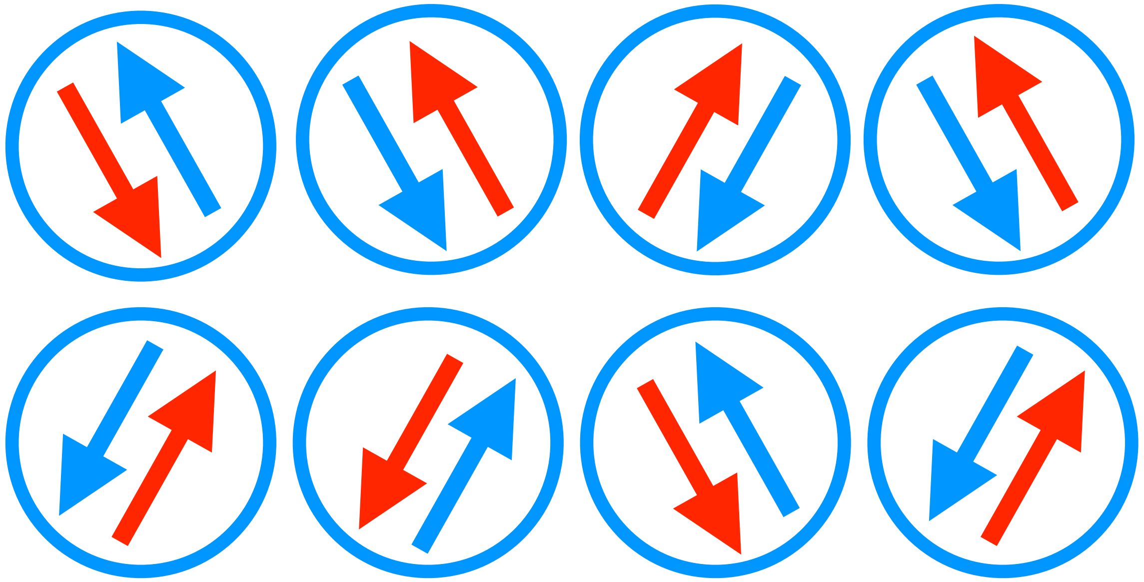
$$\sigma^2 = \mathrm{Tr}[\Phi^\dagger \Phi] \qquad U(\mathbf{x}) \in SU(2)$$

Dark Higgs winding number :

$$N_H = \frac{1}{24\pi^2} \int \mathrm{d}^3\mathbf{x} \epsilon^{ijk} \mathrm{Tr}\left[U^\dagger(\partial_i U) U^\dagger(\partial_j U) U^\dagger(\partial_k U) \right]$$

(II) Fermion # Violation

Gauge field configuration changes such that the gradient energy of the dark Higgs is canceled by the gauge field.

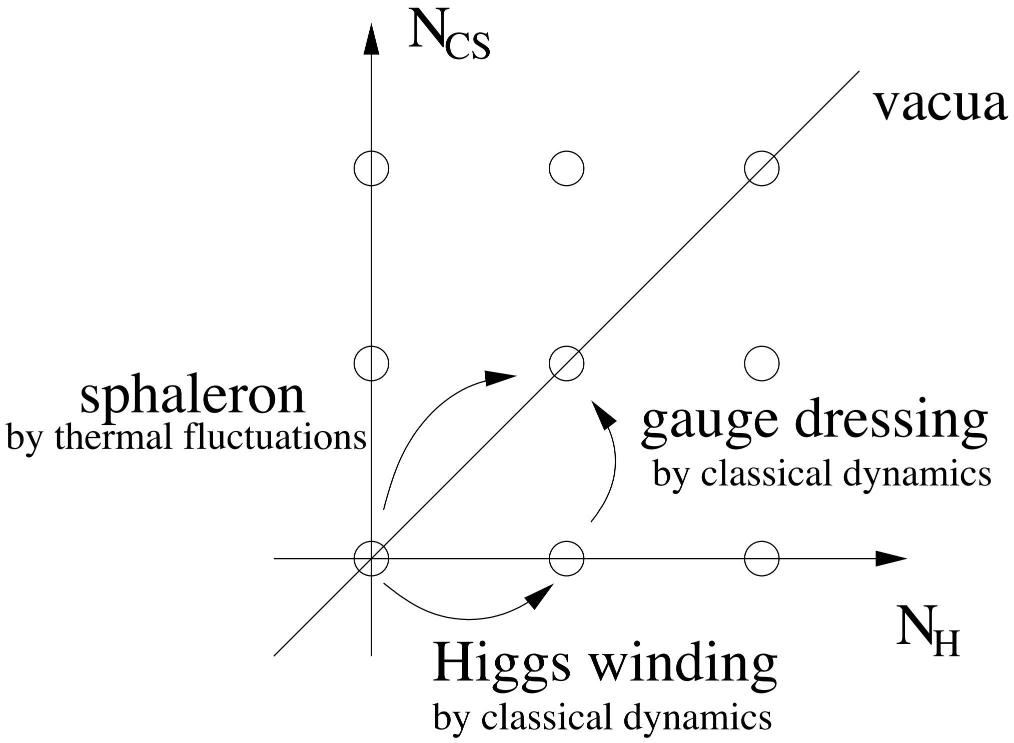


$$E_{\text{gradient}} \sim |(\partial_i - igA_i^a)\Phi|^2 \to 0$$

$$A_i^a \to \frac{1}{ig}(\partial_i U)U^\dagger$$

It corresponds to the change of **the Chern-Simons number** :

$$\Delta N_{\rm CS} = \frac{g_D^2}{32\pi^2}\int \mathrm{d}t\mathrm{d}^3x\, W_{\mu\nu}\tilde{W}^{\mu\nu} \neq 0$$



(II) Fermion # Violation

The change of Ncs induces fermion number violation via **anomaly** :

$$\partial_\mu j^\mu = \frac{g_D^2}{32\pi^2} W^a_{\mu\nu} \tilde{W}^{a\mu\nu}$$

$$\Rightarrow \Delta N_L = \Delta N_{\rm CS}$$

Caution :

L asymmetry is *locally* generated, but **its average is zero** if CP violation is absent.

$$\sum \Delta N_i = 0$$

(III) CP Violation

CP violation is induced by the following operator :

$$\mathcal{O}_{\mathrm{CPV}} = \delta_{\mathrm{CP}} \frac{H_{\mathrm{D}}^{\dagger} H_{\mathrm{D}}}{\Lambda_{\mathrm{CP}}^{2}} \frac{g_{\mathrm{D}}^{2}}{32\pi^{2}} \left(W_{\mathrm{D}}^{\mu\nu} \widetilde{W}_{\mathrm{D},\mu\nu} \right)$$

δ_{CP} : a dimensionless CP violating phase

Λ_{CP} : a new physics mass scale leading to the operator

With C & CP violation, $\delta N \equiv N_{CS} - N_{H} > 0$ and $\delta N < 0$ winding configurations evolve differently, **generating a net fermion number**.

Asymmetry Sharing

- The generated dark asymmetry is transferred to the SM sector via a neutron portal interaction :

$$\mathcal{L} \supset \frac{1}{\Lambda_n^2} \chi u_R d_R d_R + \mathrm{h.c.}$$

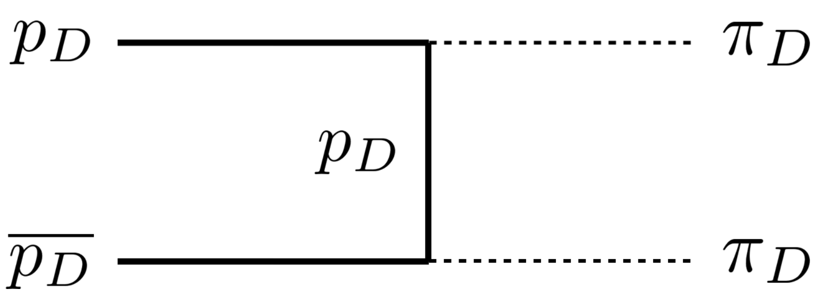
Jet plus missing energy signature at LHC !

Equilibrium at GeV requires $\Lambda_n \lesssim 15$ TeV. Current constraint : $\Lambda_n \gtrsim 2$ TeV.

- **Dark baryon DM** (Z2 odd, ~5 GeV) : $p_D \sim f f f$

- DM relic density is set by the dark baryon asymmetry just like the baryonic relic density.

$$\mathcal{L} \supset \frac{1}{\Lambda_D^2} p_D p_D \chi\chi + \mathrm{h.c.}$$



Correct DM abundance is realized.

Phenomenology

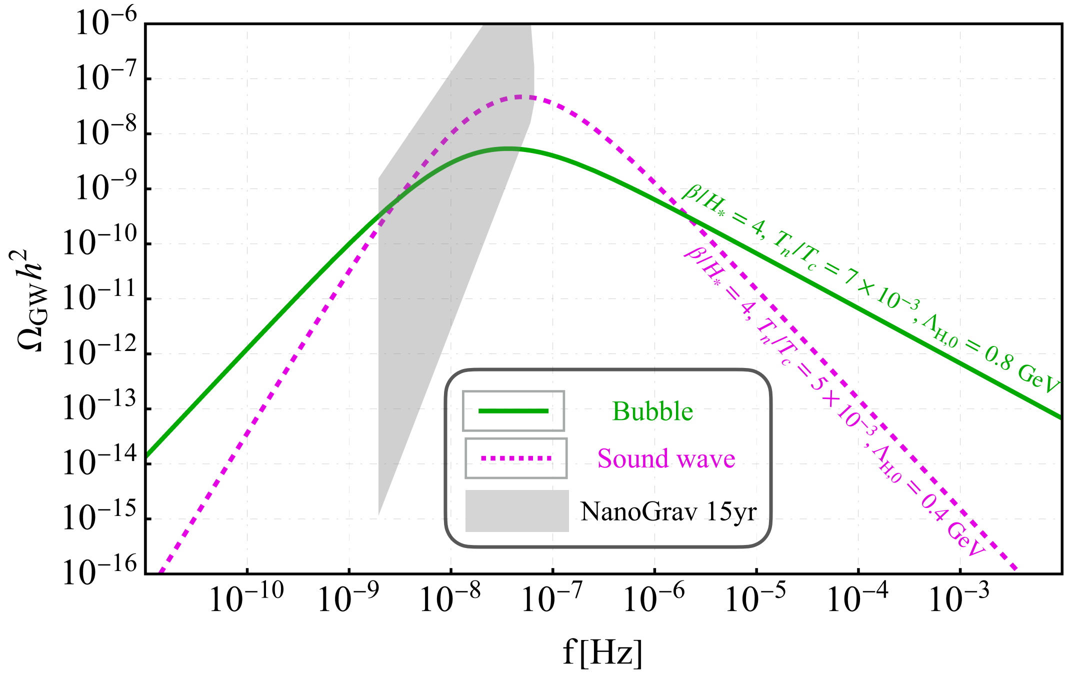
- Higgs portal operator is introduced so that $\pi_{\rm D}$ decays before BBN :

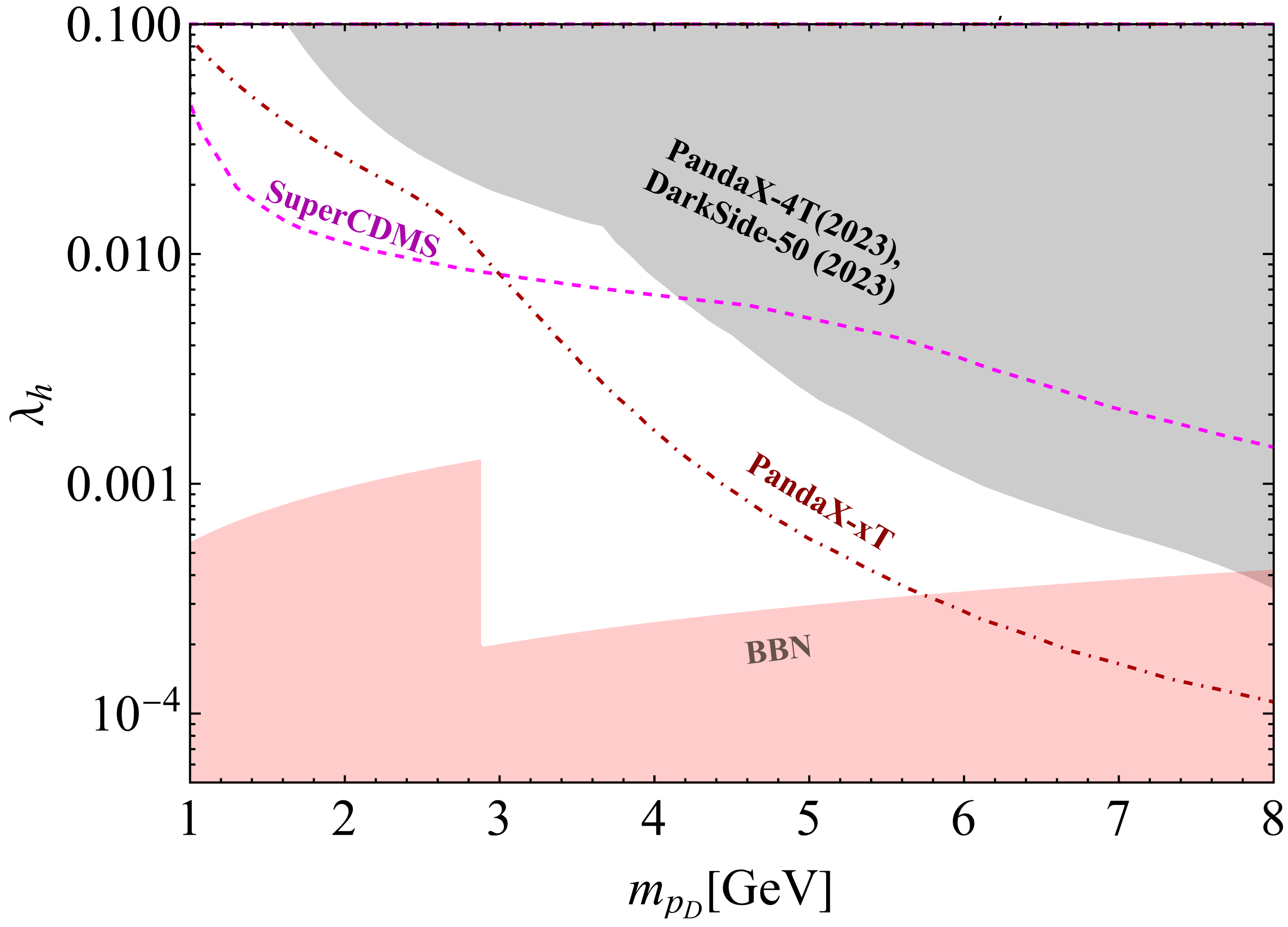
$$\mathcal{L} \supset \lambda_h |H|^2 |H_{\rm D}|^2$$

$\lambda_h \lesssim 0.1$ from Higgs invisible decay.

Lower bound from **BBN**,
Upper bound from **DM direct detection**.

PTA signal explanation leads us to the prediction for DM direct detection !





Alternative Scenario

Girmohanta, YN, Zhang (2025)

It is natural to ask if the decay of some GeV-scale Majorana fermion in a dark sector can account for BAU and DM after a dark supercooled PT.

Such a Majorana fermion *usually* needs to be **very heavy**, which does not fit the present exploration.

However , …

If a dark supercooled PT provides an environment for **out-of-equilibrium dynamics to abundantly produce a GeV-scale Majorana fermion** (ψ), successful production of BAU and DM may be possible !

$$
\begin{aligned}
V_{\rm DS} = {} & \bar{\chi}\mu\chi\eta + m_\chi\bar{\chi}\chi + \frac{1}{2}m_\psi\bar{\psi}^c\psi + \frac{1}{2}m_\eta^2\eta^2 \\
& + \bar{\psi}y\eta\chi + \text{h.c.}\ ,
\end{aligned}
$$

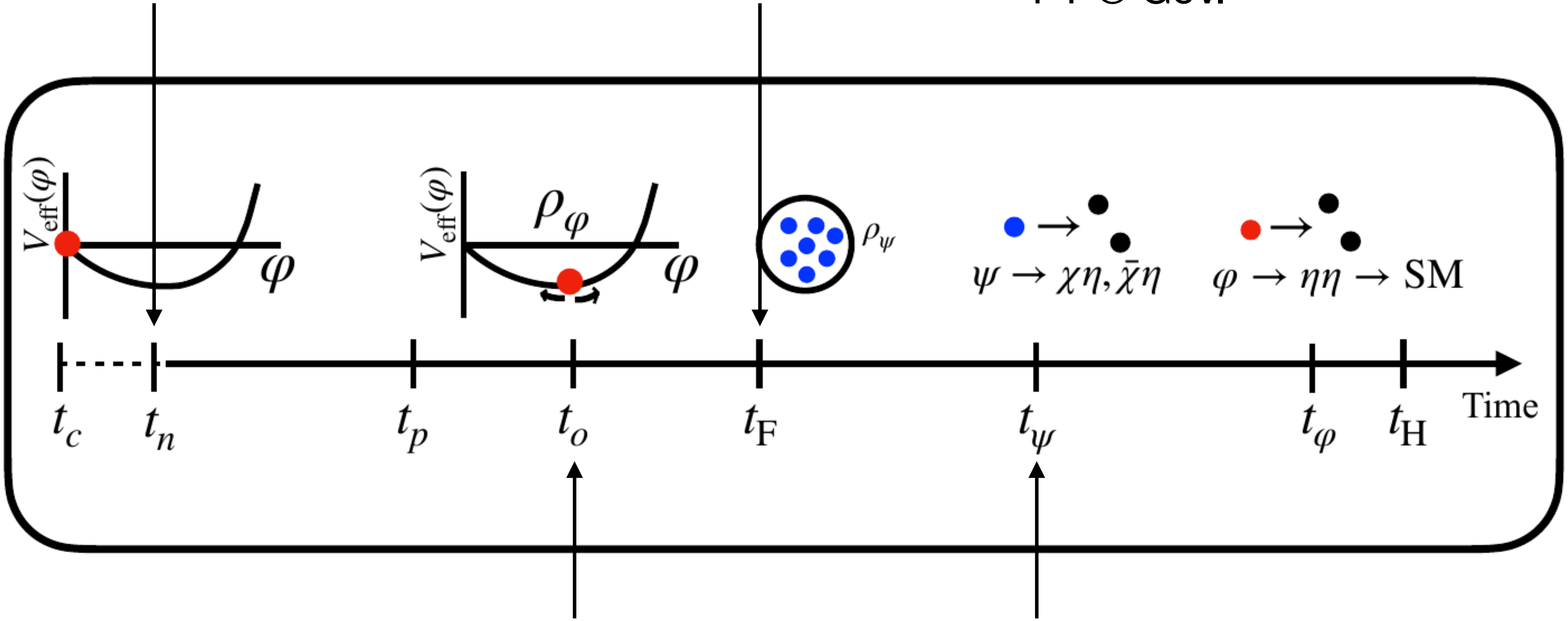
CPV **DM** Portal scalar

	Fields	$U(1)_{\rm D}$
	ψ_i	-1
$\mathcal{O}(1)$GeV	χ_j	-1
	η	0

$N_\psi = 2 \qquad N_\chi = 2$

Alternative Scenario

All the relevant time scales are **smaller** than Hubble time for PT @ GeV.



Bubble nucleation starts

Production freezes

ψ is produced via **parametric resonance** induced by dilaton oscillation.

ψ decays generate asymmetry

- χ_2 transfers dark asymmetry to the visible sector via **neutron portal** $\frac{1}{\Lambda_n^2}\chi udd$
- χ_1 acts as **asymmetric DM**

Alternative Scenario

Effective fermion mass vanishes during dilaton coherent oscillation.

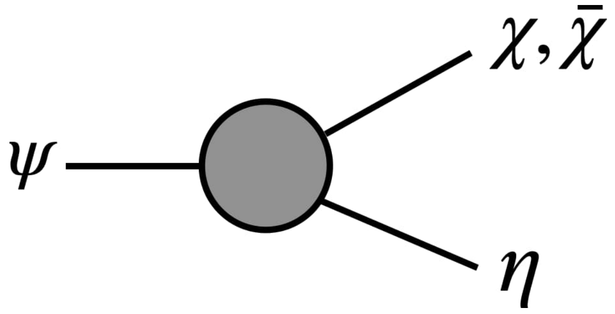
➡ **Fermion parametric excitation** Greene, Kofman (1999)

$$\left(i\gamma^{\mu}\partial_{\mu} - m_{\psi}^{\mathrm{eff}}(t)\right)\psi = 0 \qquad m_{\psi}^{\mathrm{eff}}(t) = m_{\psi}\left[\frac{\{1+\xi(t)\cos(m_{\varphi}t)\}^{2b} - r}{1-r}\right]$$

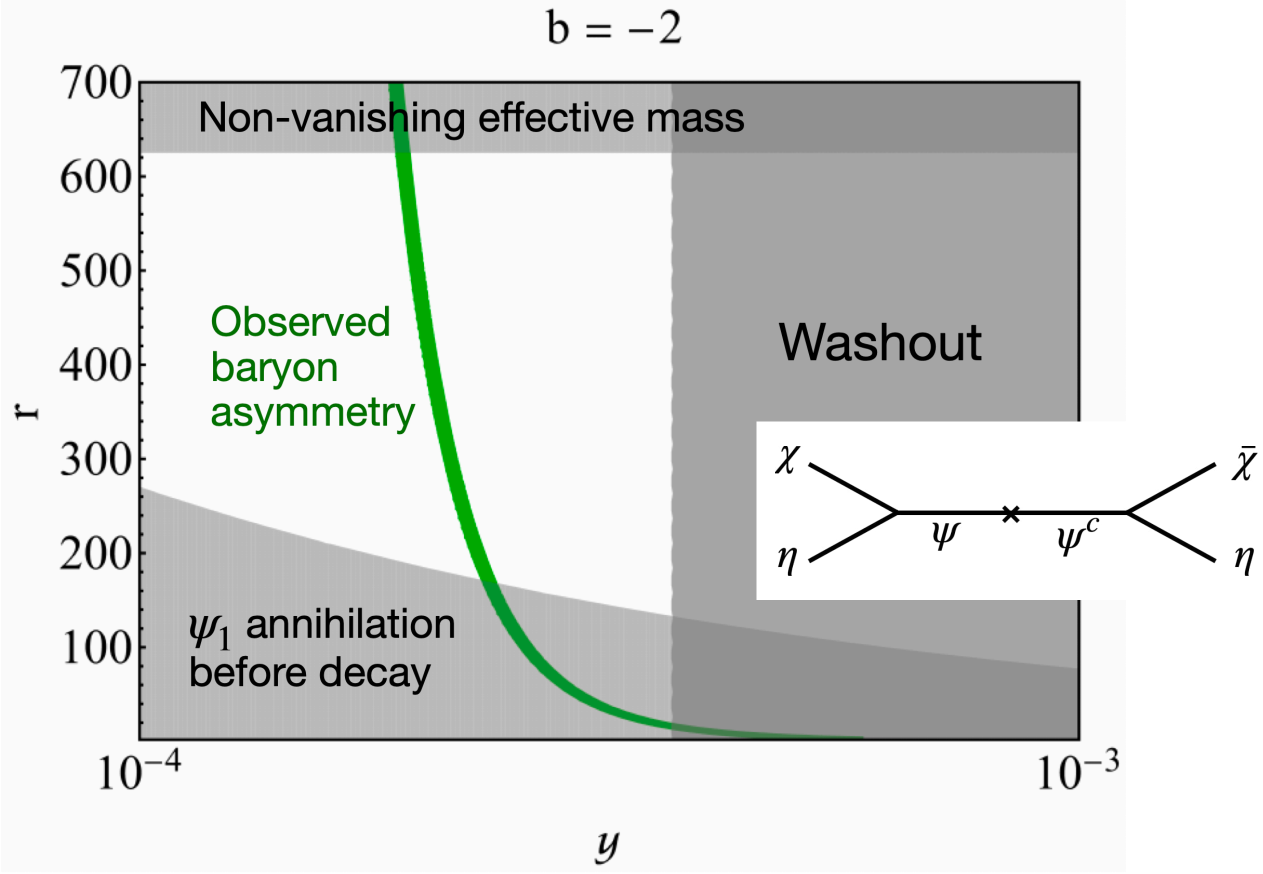
Oscillation amplitude

Model dependent

- Produced ψ decays, generating dark asymmetry



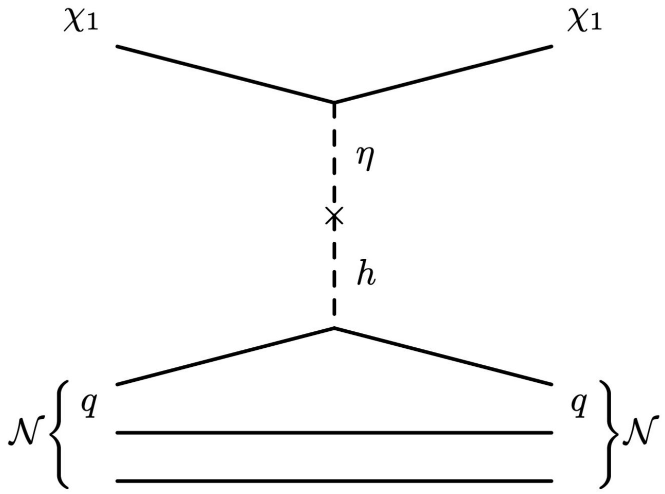
- Dark asymmetry is transferred to the visible sector through **neutron portal** $\dfrac{1}{\Lambda_n^2}\chi udd$

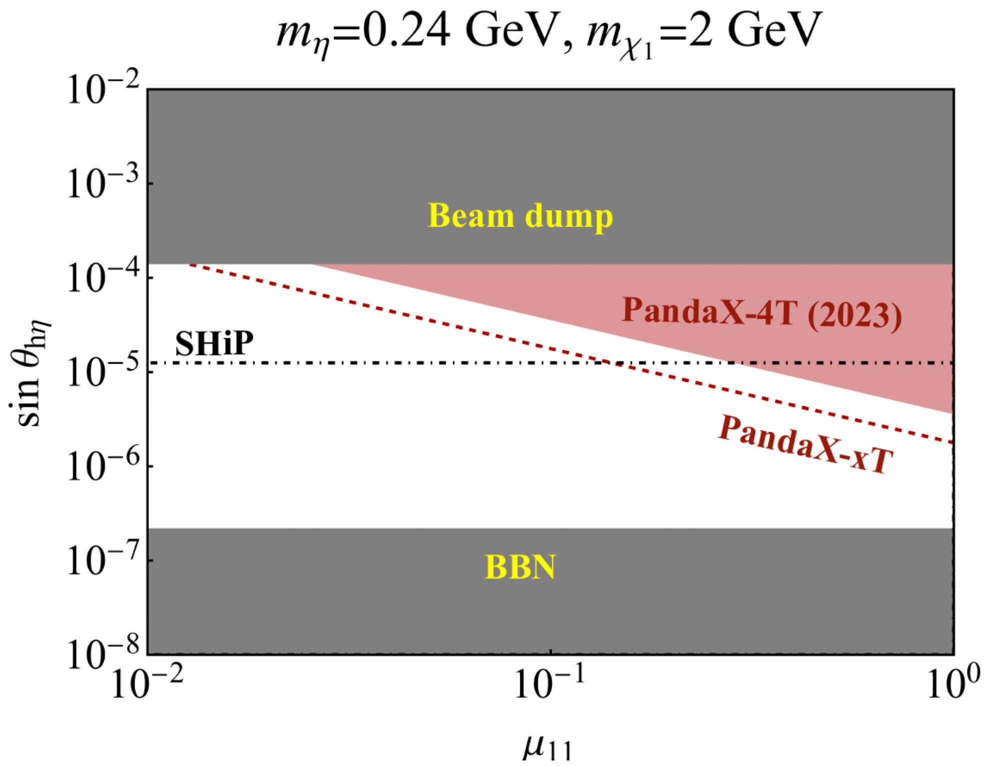


Alternative Scenario

- Higgs portal operator is introduced so that η decays before BBN :

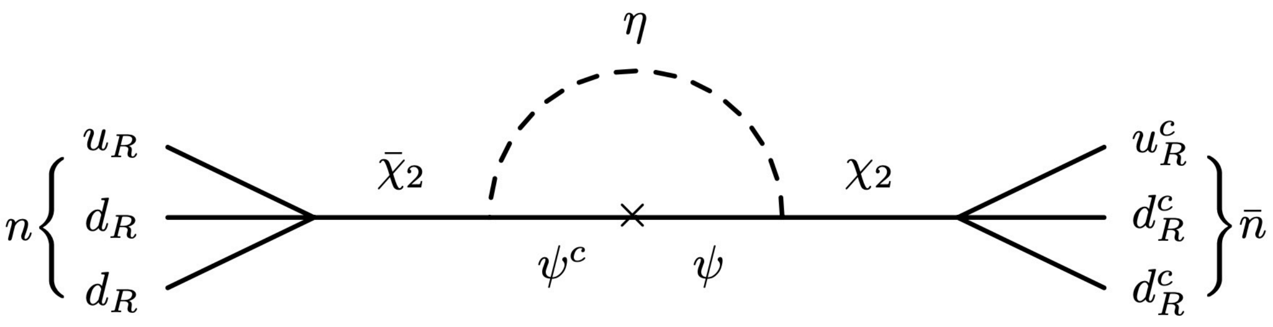
DM direct detection

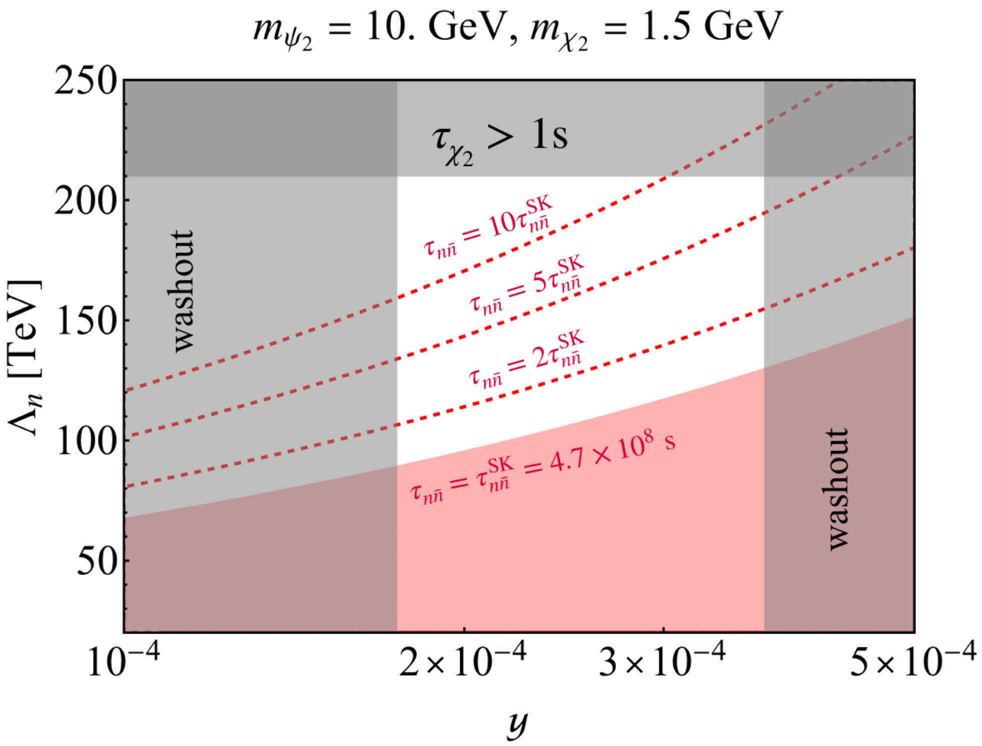




- U(1)D is violated by Majorana mass

$n - \bar{n}$ oscillation





Summary

✓ Dark first-order phase transition is a promising interpretation of the observed PTA signal.

✓ **Confining nearly conformal phase transition** can realize a supercooled phase transition to explain the data.

✓ Strong supercooling significantly dilutes away pre-existing baryon asymmetry and DM, calling for a new paradigm of their productions.

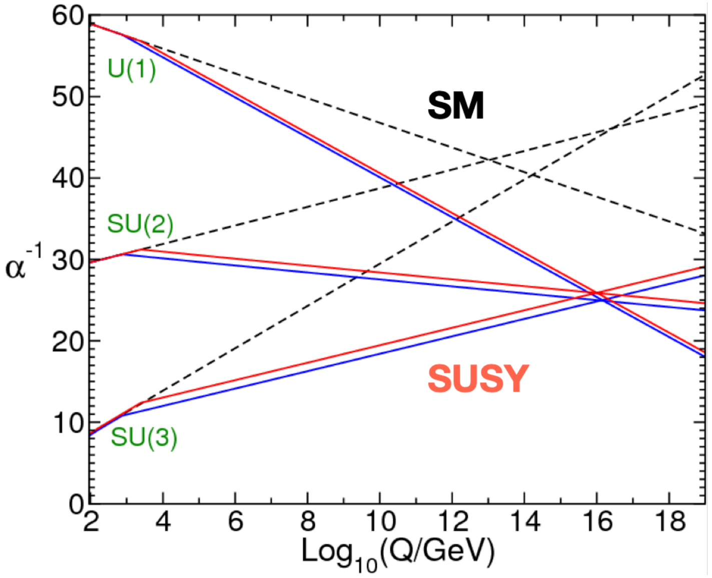
✓ Supercooled phase transition naturally provides a setting of **baryogenesis & asymmetric dark matter**.

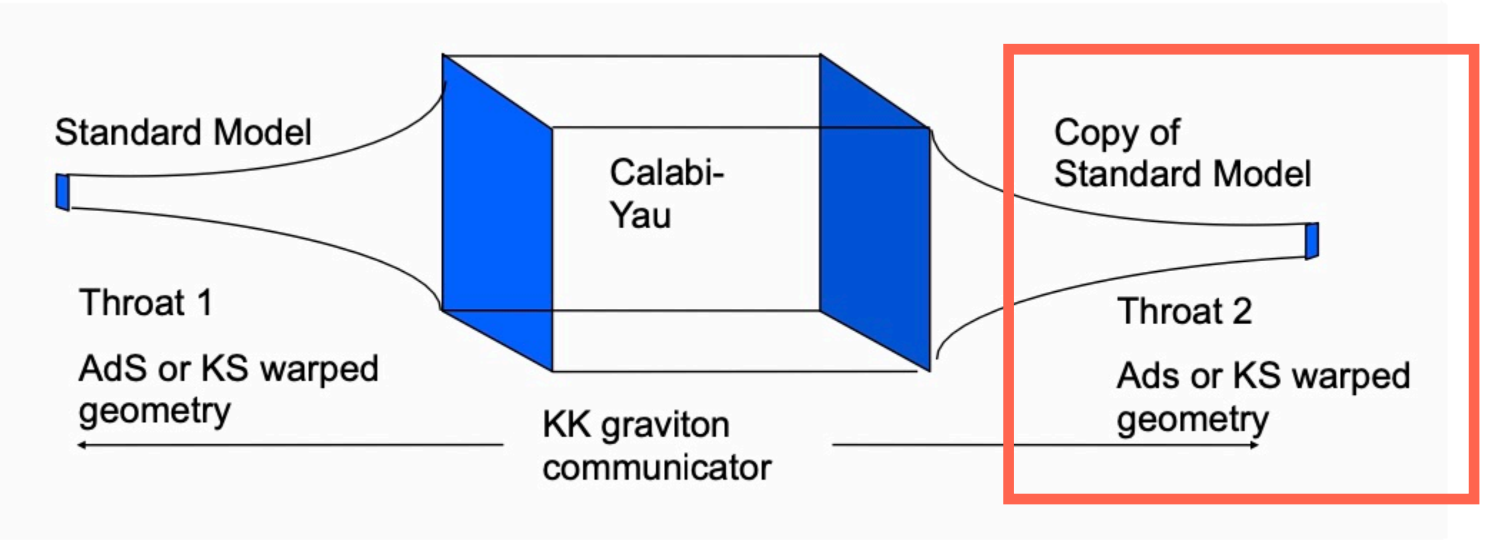
✓ The model is probed by mono-jet searches at the LHC and DM direct detection (+ $n-\bar{n}$ oscillation).

Discussion

- The scenario is consistent with SUSY GUT framework.

No apparent obstacle to consider **a supersymmetric version** which gives an automatic gauge coupling unification.





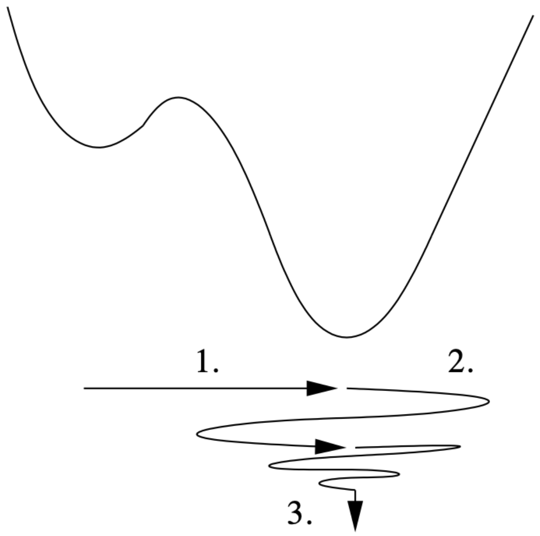
Dark sector

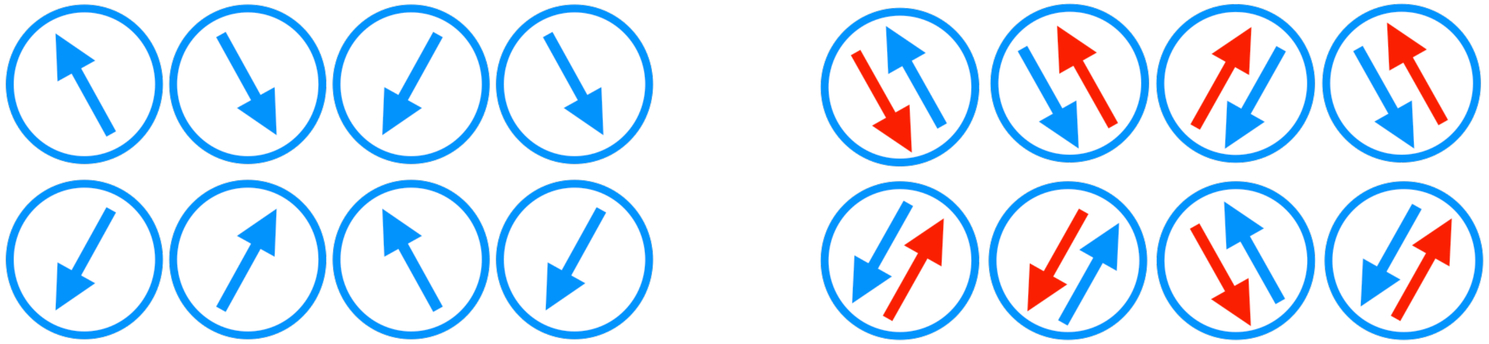
- The scenario is motivated by string theory.

Can we build a concrete stringy setup of a dark supercooled PT ?

Discussion

- Confirmation of PT dynamics for baryogenesis.





Finally, **numerical simulation** is needed.

- Coincidence between QCD and dark sector mass scales.
- Neutron portal interaction predicts a TeV-scale colored particle.

Thank you.