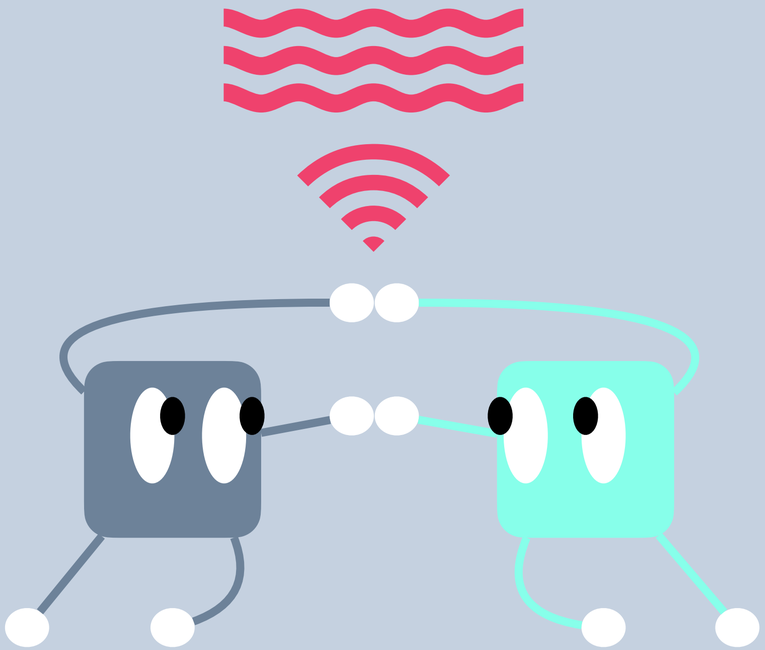
Cold Darkogenesis:

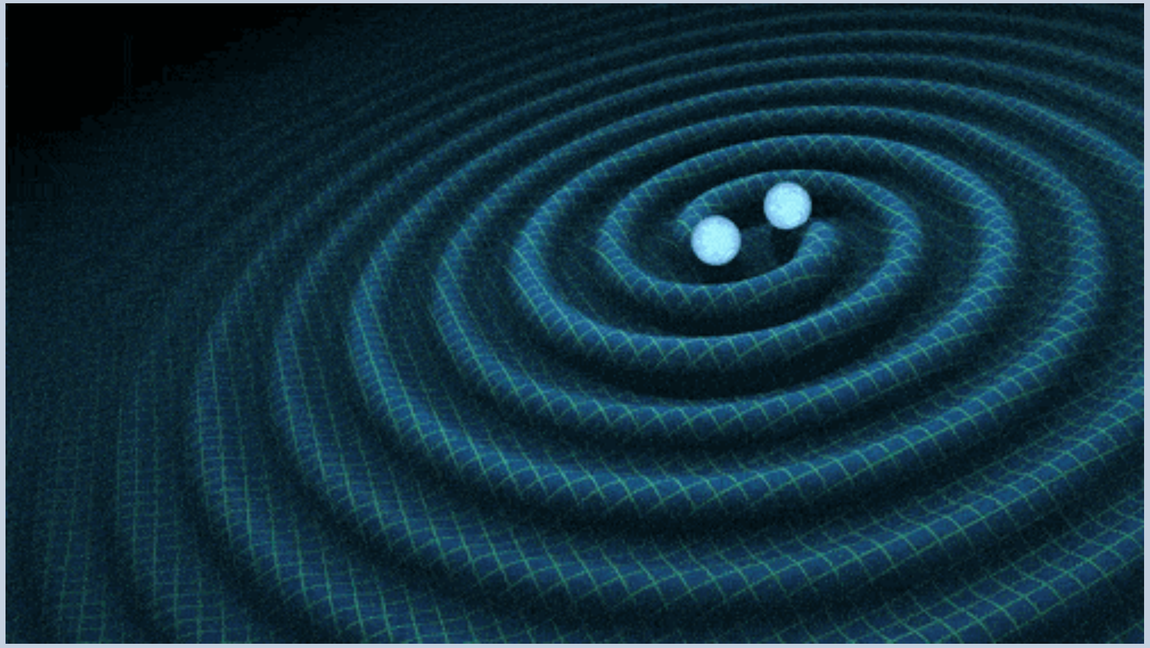
Dark Matter and Baryon Asymmetry in Light of the PTA Signal



K. Fujikura, S. Girmohanta, Y. Nakai, Z. Zhang (reporter)

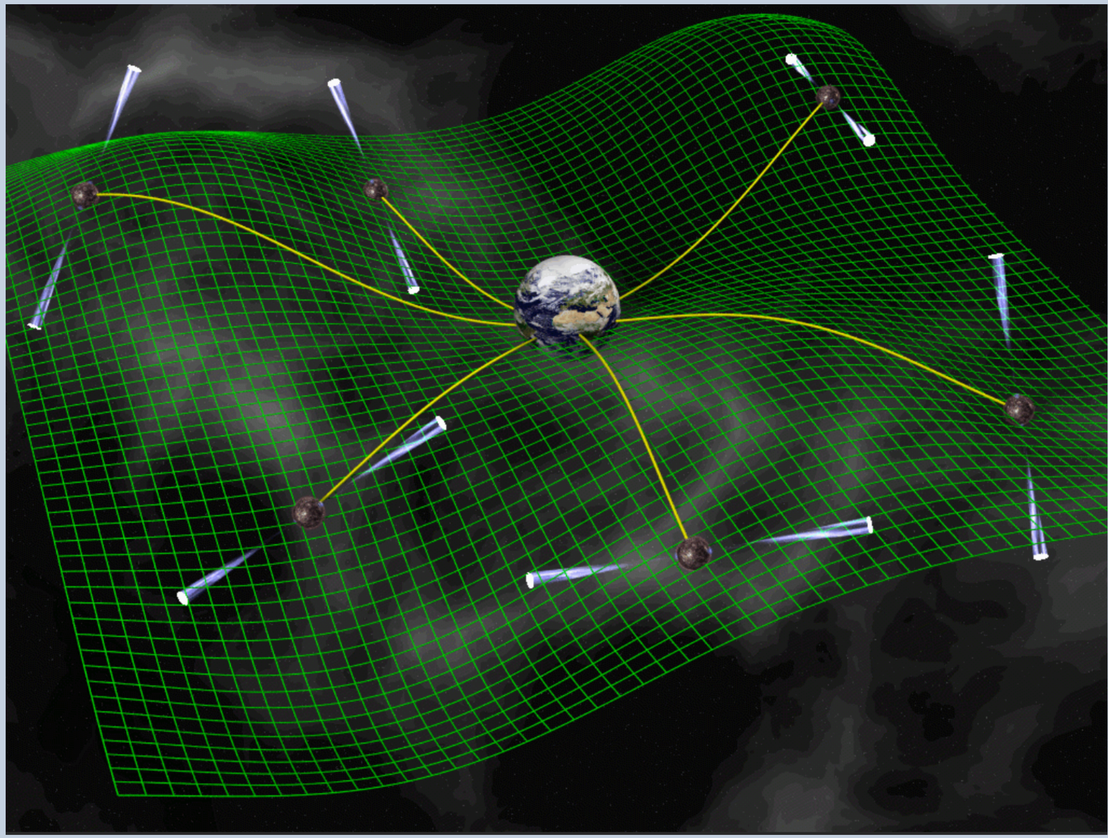
Phys.Lett.B 858 (2024) 139045

Introduction



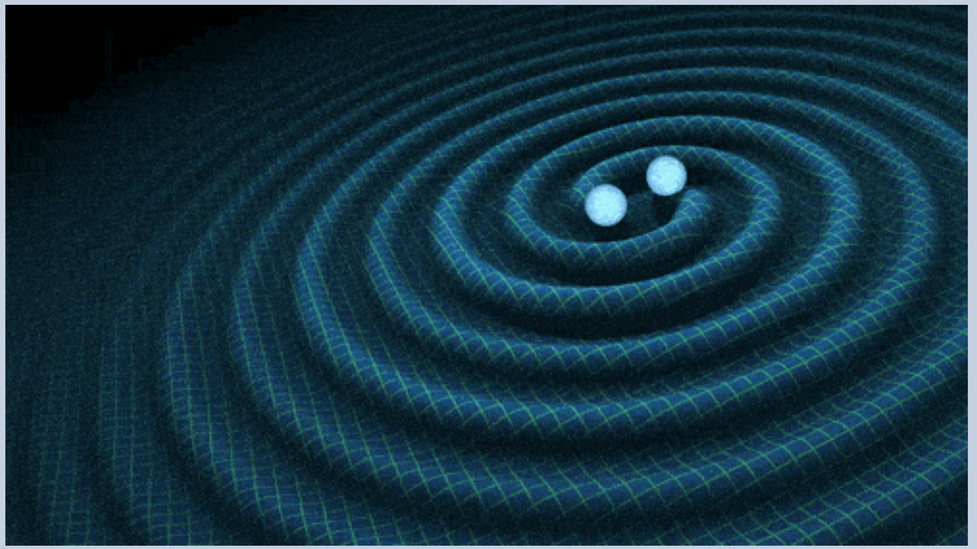
GWs, predicted by GR, have become a strong astro evidence of detecting the early universe.

Pulsar timing array (PTA) is a set of galactic pulsars that is monitored and analyzed to search for correlated signatures in the pulse arrival times on Earth, which is known as a (low-frequency) gravitational wave detector.

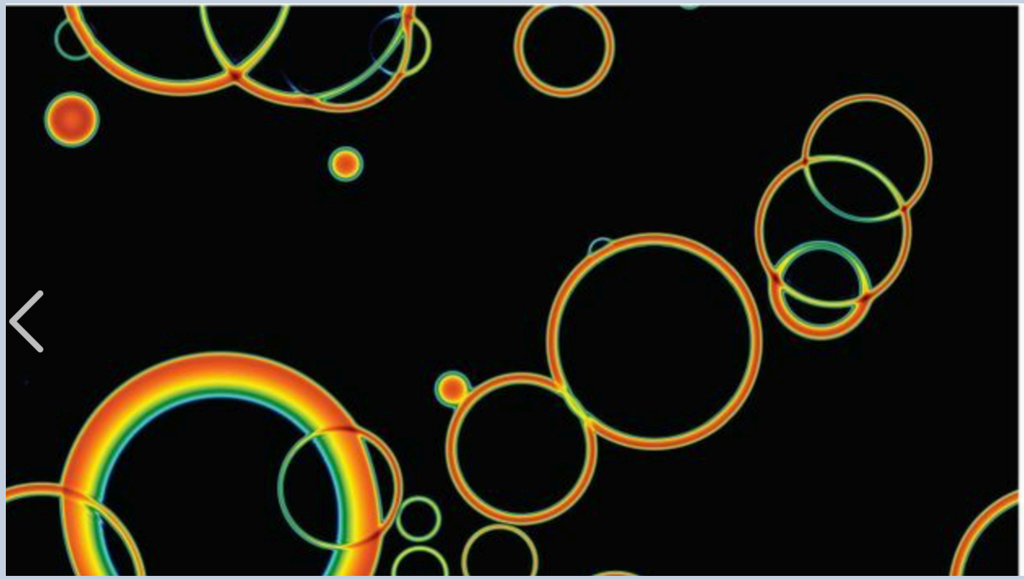


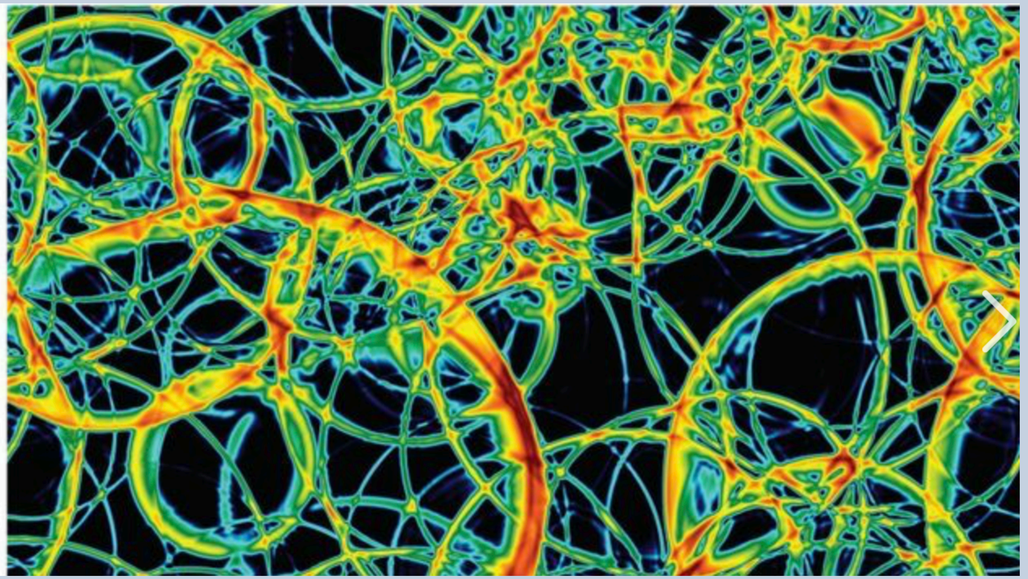
Possible sources of GWs

- **Supermassive object binaries**



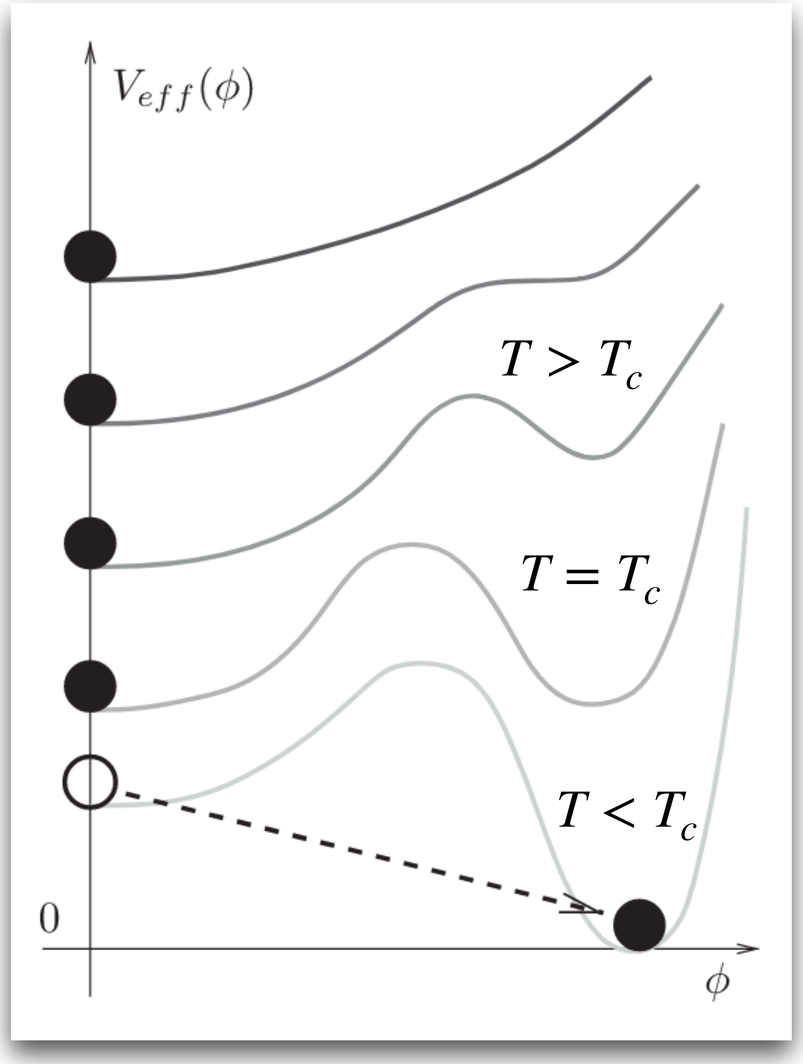
- **Topological defects: cosmic string…**
- **Cosmological phase transition**

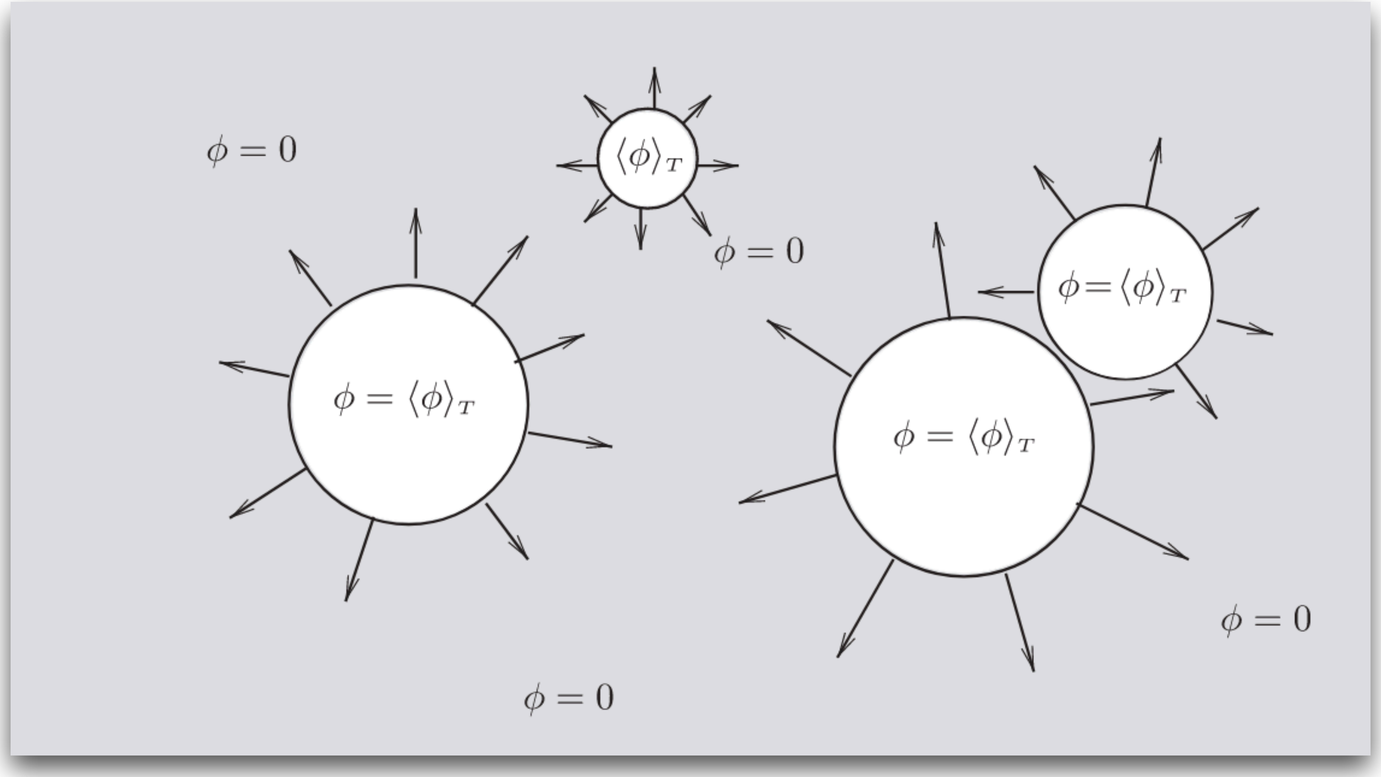




Description of phase transition

First Order Phase Transition

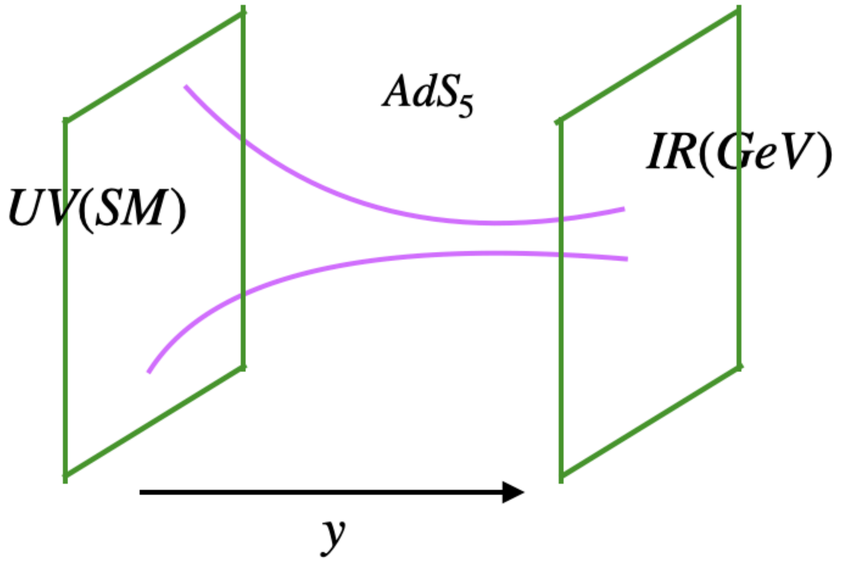




Supercooled: **even though the new phase is thermodynamically favorable, the system still remains in a supercooled state for some time.**

Supercooled PT In 5D Holographic Model

K. Fujikura, Y. Nakai, M. Yamada (2021)



Extra dimension

A 5D $SU(N_H)$ pure Yang-Mills field

$$S_{YM} = -\int d^5x\sqrt{G}\frac{1}{4g_5^2}F_{AB}F^{AB}$$

4D effective radion action

$$\varphi \sim fe^{-k\pi T(x)}$$

$$S_{eff} = \int d^4x[\frac{3N^2}{4\pi^2}(\partial\varphi)^2 - V_{eff}(\varphi)]$$

Radion potential

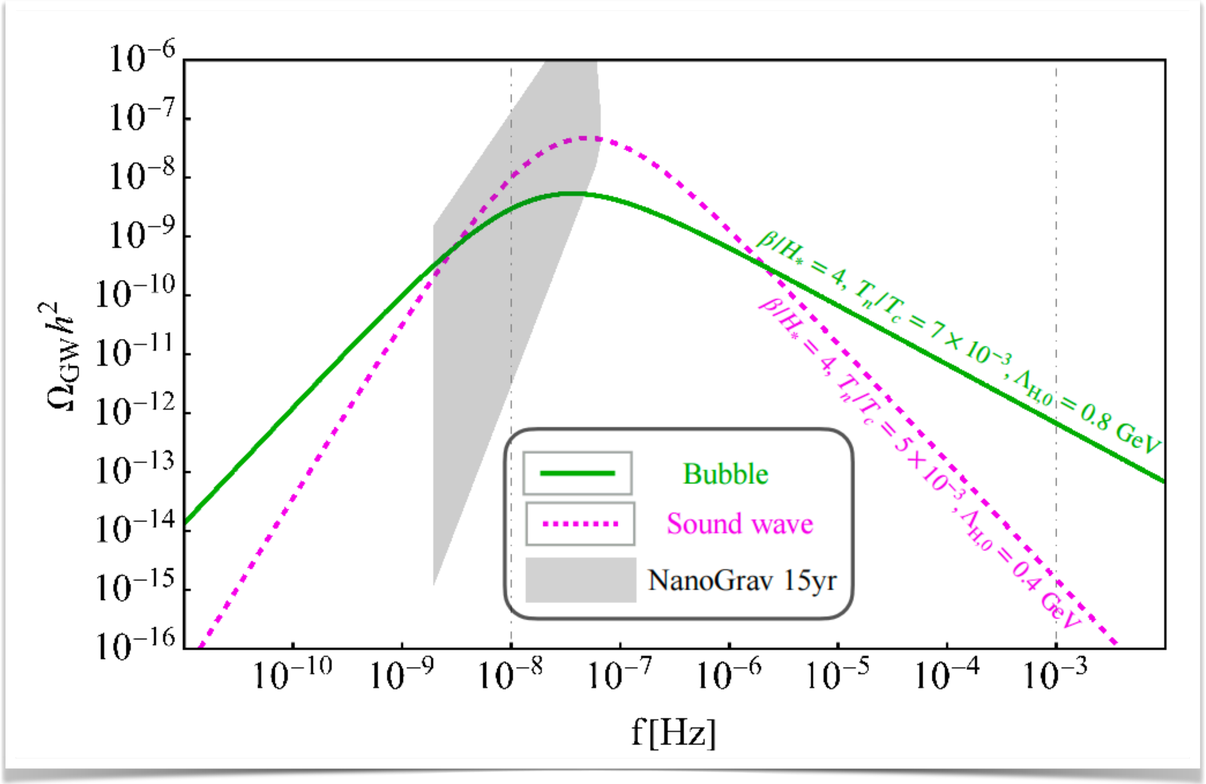
$$V_{\rm eff}(\varphi) = \begin{cases} V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_{\rm H}}{\eta}\Lambda_{\rm H,0}^4\left(\frac{\varphi}{\varphi_{\rm min}}\right)^{4n} & ;\ \varphi \geq \varphi_c \\ V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_{\rm H}}{\eta}\gamma_c^4\varphi_c^4 & ;\ \varphi < \varphi_c \end{cases}$$

The 4D dual picture

	5D	4D
φ	Radion	Dilaton
	AdS-S	Confinement
Phase transition	↓	↓
	RS	Deconfinement

GW Spectrum vs PTA Signal

K. Fujikura, S. Girmohanta, Y. Nakai, M. Suzuki (2023)



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

Problem

Explaining PTA signal requires a large supercooling, which indicates a mini-inflation due to the vacuum energy domination during the PT.

So the pre-existing DM and BAU will be diluted by such supercooled PT.

★ **We need a new mechanism for DM and BAU after PT.**

Cold darkogenesis

Cold Darkogenesis

Asymmetric dark matter

Dark number asymmetry

Baryon number asymmetry

Three Sakharov conditions (1967):

(1) Baryon (dark) number non-conservation.
(2) C and CP violation.
(3) Departure from thermal equilibrium.

$U(1)_D$ **anomalous under** $SU(2)_D$
A CP-violating term
Decay of gauged texture configuration

The Model

Radion stabilization

Cold darkogenesis

Dark number

Fields	$SU(N_{\rm H})$	$SU(2)_{\rm D}$	$U(1)_{\rm D}$
$H_{\rm D}$	$\mathbf{1}$	$\mathbf{2}$	0
$L_{\chi,i} \equiv \begin{pmatrix} \psi_{1,i} \\ \psi_{2,i} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	1
$\chi_{1,i}\ ,\ \chi_{2,i}$	$\mathbf{1}$	$\mathbf{1}$	-1
f_j	$\mathbf{N_{\rm H}}$	$\mathbf{1}$	$1/N_{\rm H}$
$\bar{f}_j$	$\overline{\mathbf{N}}_{\rm H}$	$\mathbf{1}$	$-1/N_{\rm H}$

Non-vanishing winding number

Asymmetry stored in dark lepton

Dark quarks condensate to stable dark proton

Asymmetry Stored in Dark Leptons

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

- Spinodal instability → Production of long-wavelength modes of the dark Higgs. → Non-zero **Higgs winding number** N_H

M.Shaposhnikov et al. (1999)

- System can relax to vacuum by changing the **Chern-Simons number** (N_{CS}) of the $SU(2)_D$ gauge field.

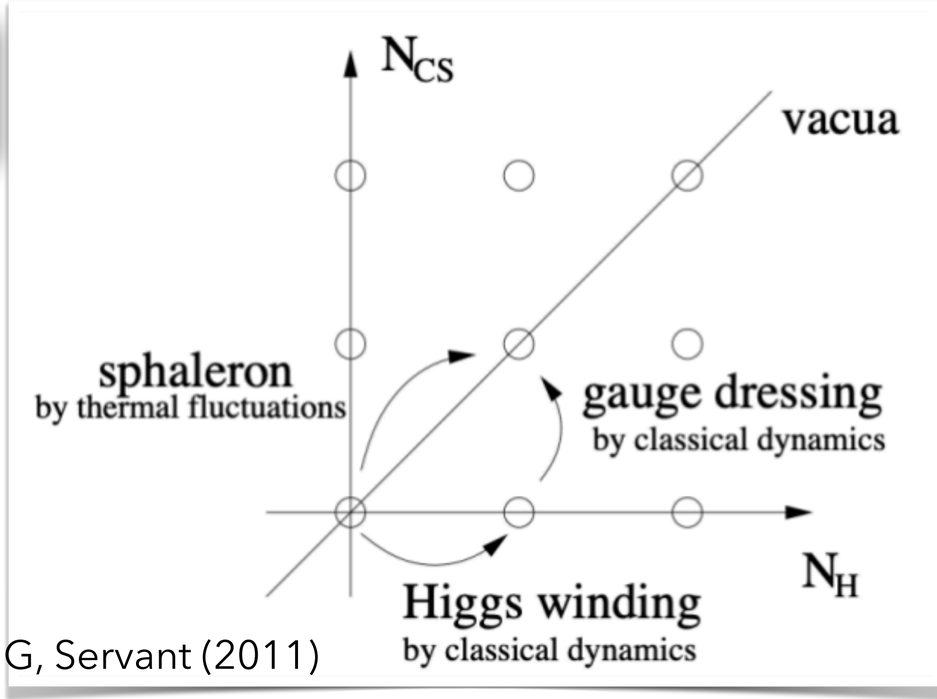
- Anomalous production of the dark leptons due to anomalous global $U(1)_D$ under $SU(2)_D$.

$$\partial_\mu j^\mu_{\rm D_L} = N_{\rm D_L}\frac{g_{\rm D}^2}{32\pi^2}{\rm Tr}\left(W_{\rm D}^{\mu\nu}\widetilde{W}_{{\rm D},\mu\nu}\right)$$

- Estimation for the asymmetry of dark leptons using **CP-violating term**.

$$\mathcal{D}_{\rm L,in} \simeq N_{D_{\rm L}}\frac{45\alpha_{\rm D}^4\delta_{\rm CP}}{\pi^2 g_*}\frac{\langle H_{\rm D}^{\dagger}H_{\rm D}\rangle}{\Lambda_{\rm CP}^2}\left(\frac{T_{\rm D}}{T_{\rm RH}}\right)^3$$

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



T. Konstandin, G, Servant (2011)

Asymmetry Sharing Mechanism

Asymmetric dark leptons

Conserves D+B

$$\mathcal{O}_{\rm D} \sim \frac{1}{\Lambda_{\rm D}^2} p_{\rm D} p_{\rm D} \chi\chi$$

$$\mathcal{O}_n \sim \frac{1}{\Lambda_n^2} \chi u_{\rm R} d_{\rm R} d_{\rm R}$$

$$\mathcal{D}_{\rm B} = \left[\frac{N_{D_{\rm B}}}{4N_{D_{\rm L}} + N_{D_{\rm B}} + 2}\right] \mathcal{D}_{\rm L,in}$$

$$\mathcal{B}_f = \left[\frac{2 + 4N_{D_{\rm L}}}{4N_{D_{\rm L}} + N_{D_{\rm B}} + 2}\right] \mathcal{D}_{\rm L,in}$$

$$m_{p_{\rm D}} \simeq 5 \left|\frac{\mathcal{B}_f}{\mathcal{D}_{\rm B}}\right| {\rm GeV} = 5 \left(\frac{2 + 4N_{D_{\rm L}}}{N_{D_{\rm B}}}\right) {\rm GeV}$$

$$\frac{\Omega_{DM}}{\Omega_B} \sim 5$$

Phenomenology

$$\mathcal{O}_n \sim \frac{1}{\Lambda_n^2}\chi u_{\mathrm{R}} d_{\mathrm{R}} d_{\mathrm{R}}$$

Mono-jet signatures

$ud \to \bar{\chi}\bar{d}\ldots$

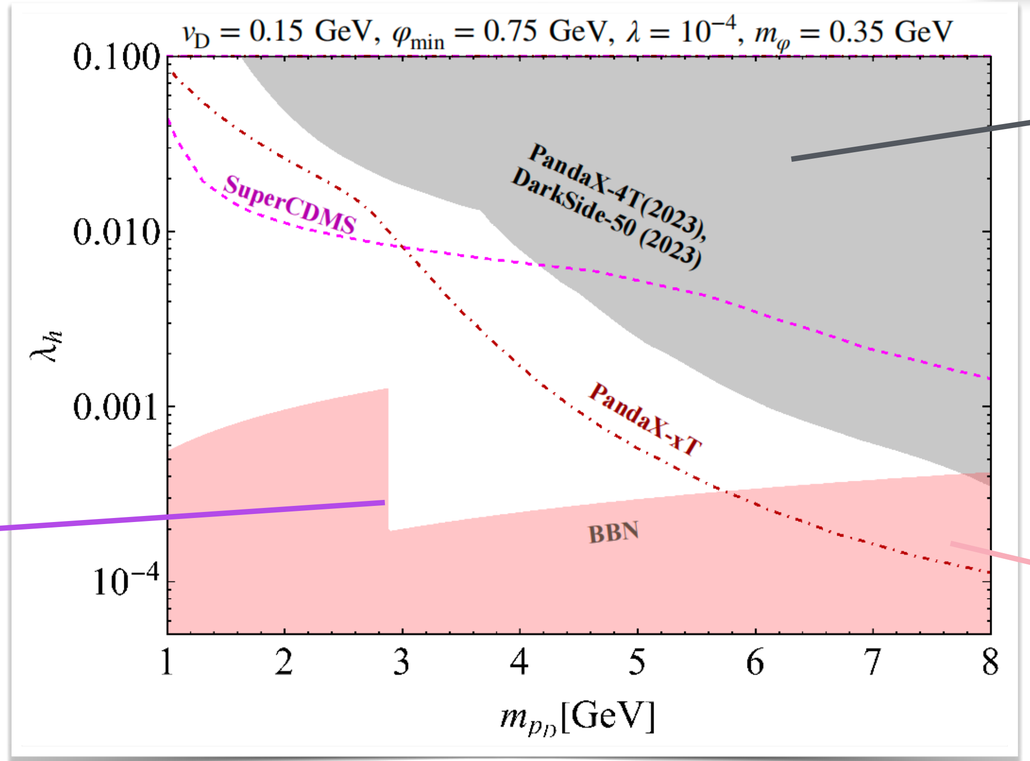
$2TeV \lesssim \Lambda_n \lesssim 15TeV$

For thermal equilibrium

DM self-annihilation

$P_D + \bar{P}_D \to \pi_D \pi_D \to SM$

$$\mathcal{L}_{\mathrm{H}} \supset -\lambda_h \left(|H|^2 - \frac{v^2}{2}\right)\left(|H_{\mathrm{D}}|^2 - \frac{v_{\mathrm{D}}^2}{2}\frac{\varphi^2}{\varphi_{\mathrm{min}}^2}\right)$$



Dark matter direct detection

Charm quark channel open

Dark pion decay before BBN

Summary

- **PTA signal** can be explained by a **supercooled FOPT** of a 5D holographic model, which has a dual 4D CFT.

- The supercooled PT will **dilute the pre-existing baryon asymmetry and dark matter**. So we need a new mechanism for generating both of them.

- A dark Higgs field configuration can carry a **non-vanishing winding number** due to the radion tunneling.

- System can relax to vacuum by changing **Chern-Simons number**, which provides the **dark number violation** stored in dark lepton due to anomalous global $U(1)_D$ under $SU(2)_D$.

- A higher dimensional operator is introduced to play a role of **sharing** between dark lepton and visible sector, leaving the remain lepton converted to stable dark proton as a DM candidate.

Thank You For Attention