Neutron Portal and the Dark Matter-Baryon Coincidence

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Asymmetry Essential Asymmetries of Nature

Asymmetry Webinar

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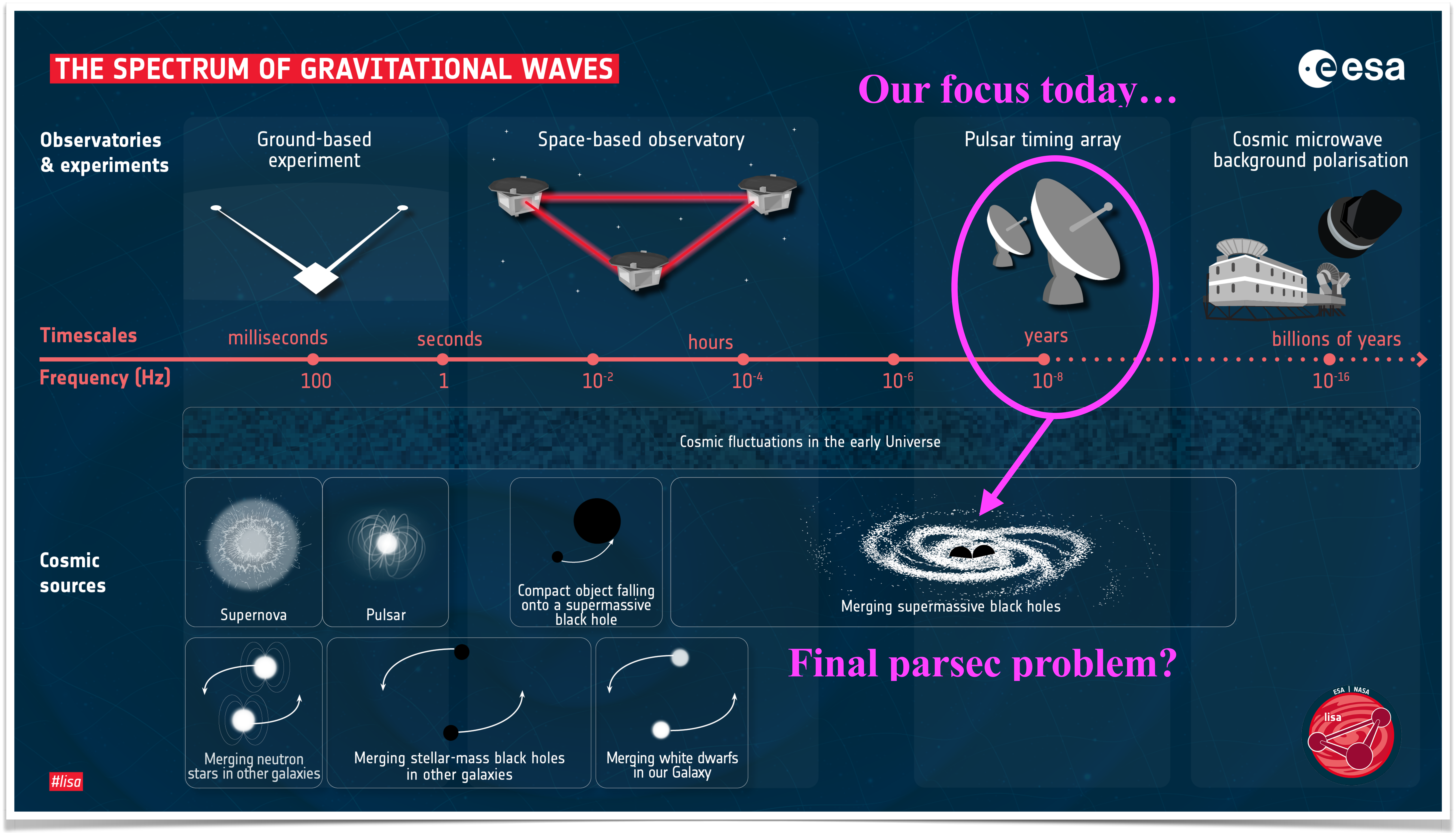
ibs 기초과학연구원 Institute for Basic Science

Nano-Hz stochastic gravitational waves and the PTA

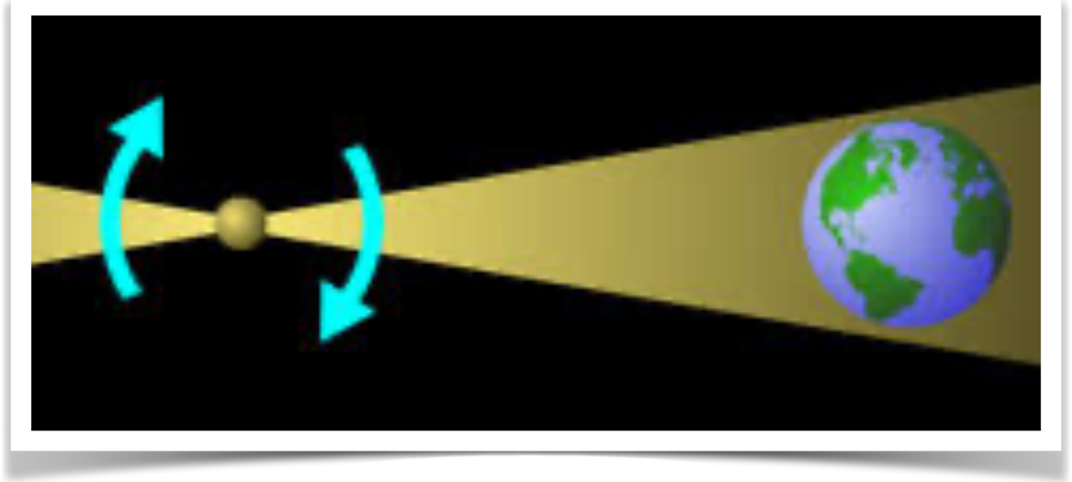
The spectrum of gravitational waves

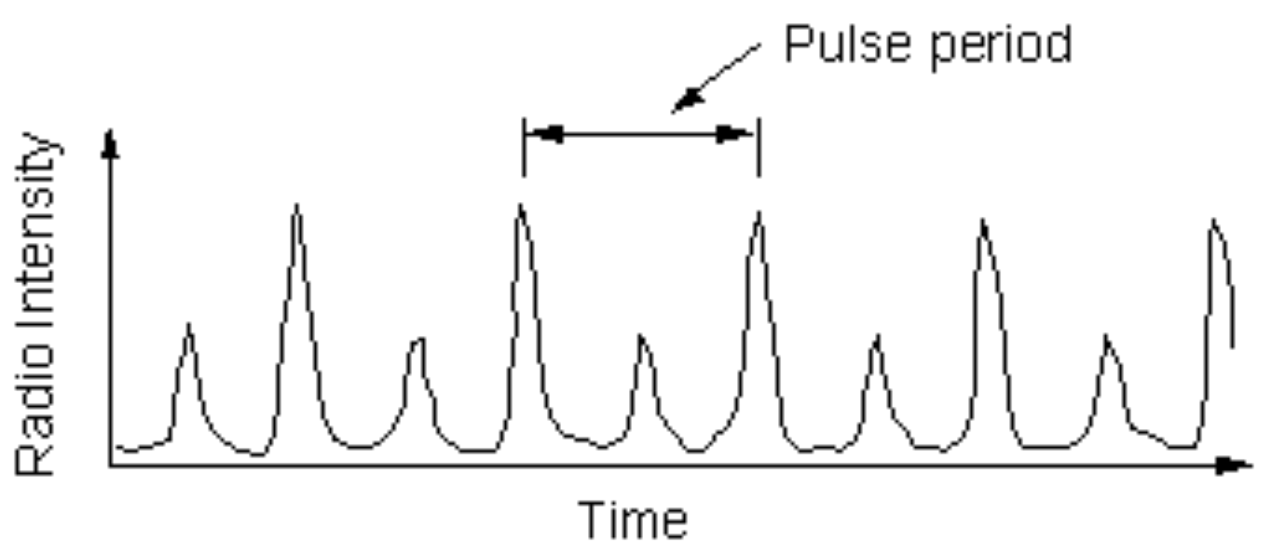
Gravitational waves: Small ripples over background spacetime.

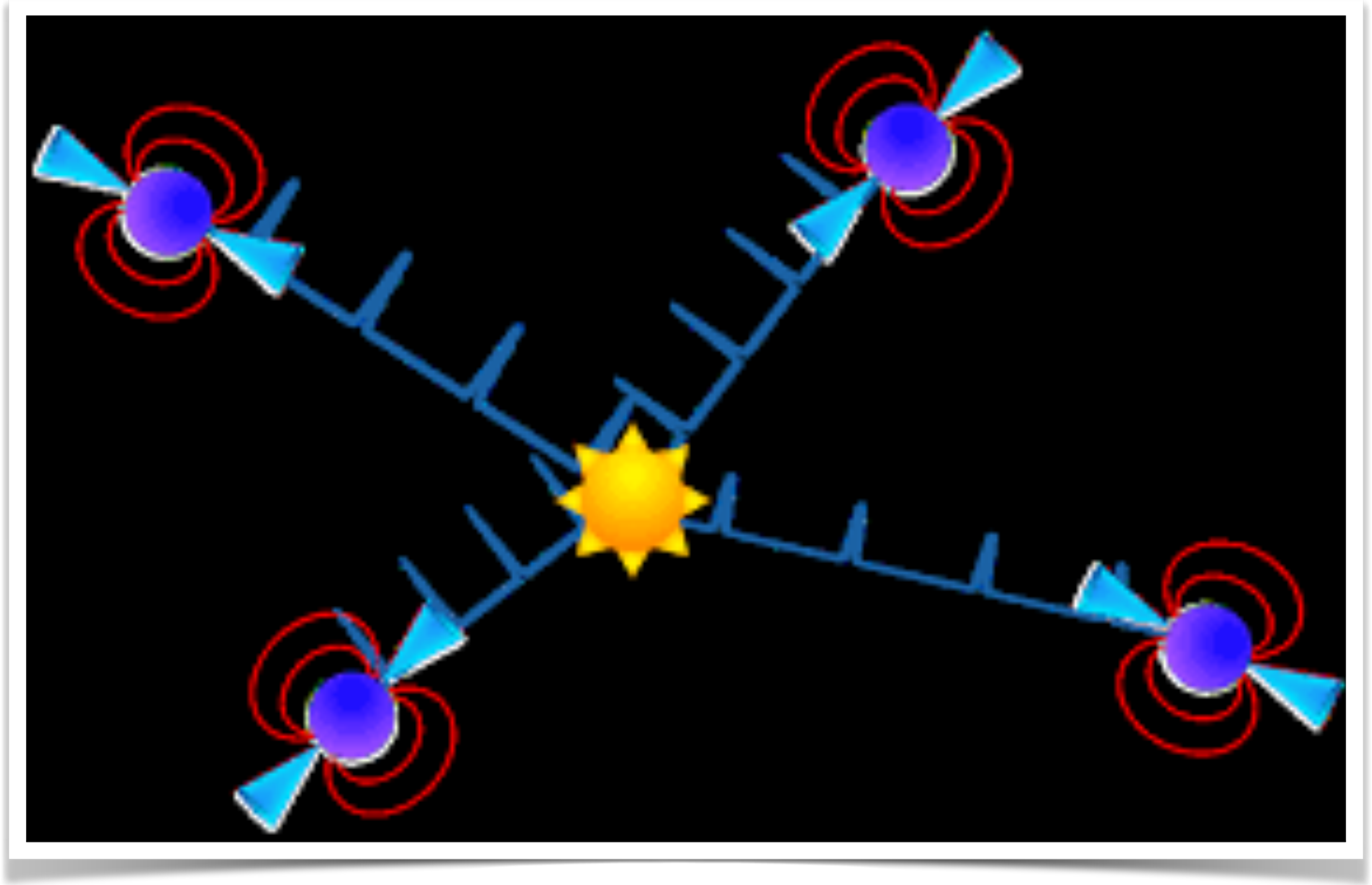


Pulsar Timing Array as GW detector

Pulsars are precise clocks.



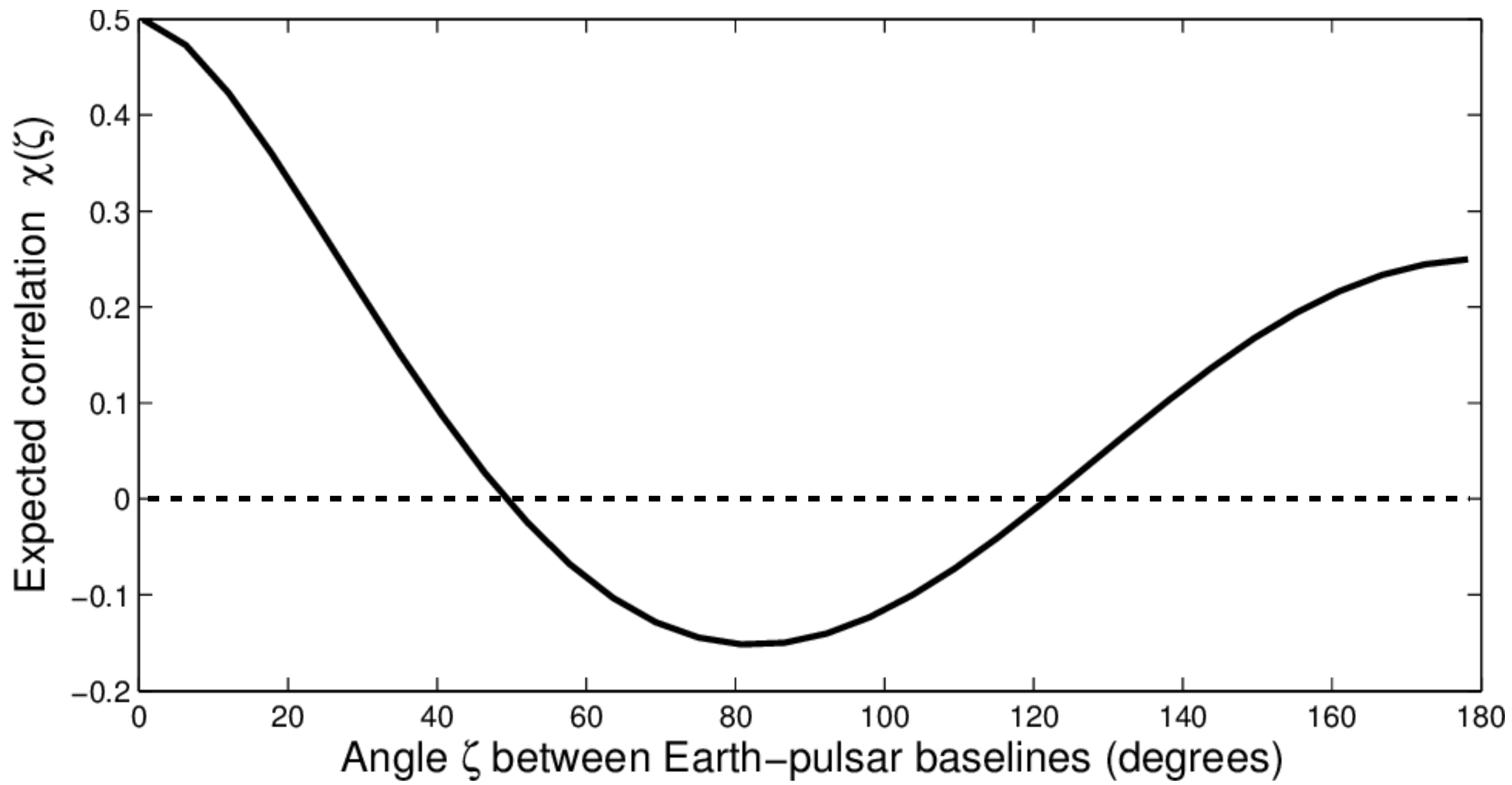




Earth-pulsar system as gravitational wave antenna.

Estabrook, Wahlquist ’75; Sazhin ’77; Detweiler ’79 Hellings, Downs ’82

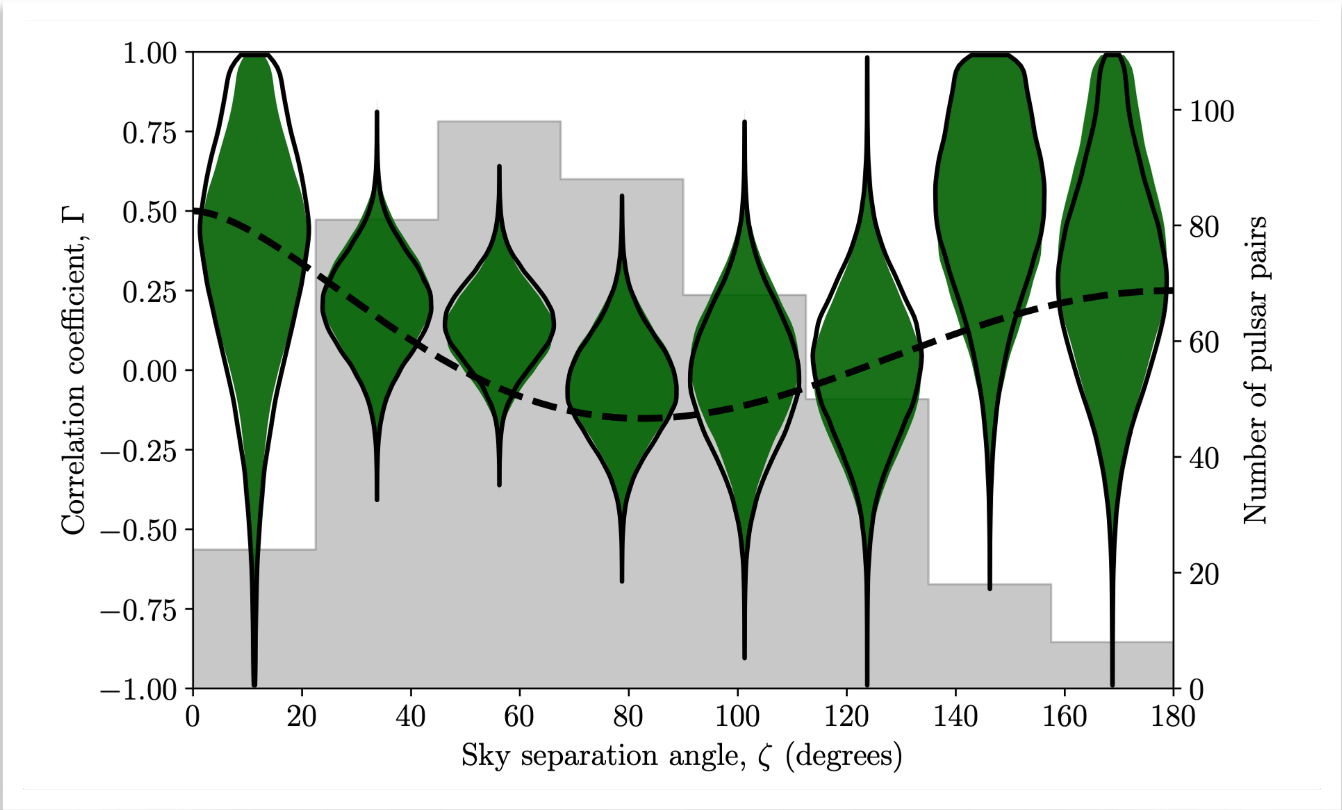
GW: distinctive quadrupolar inter-pulsar correlation.



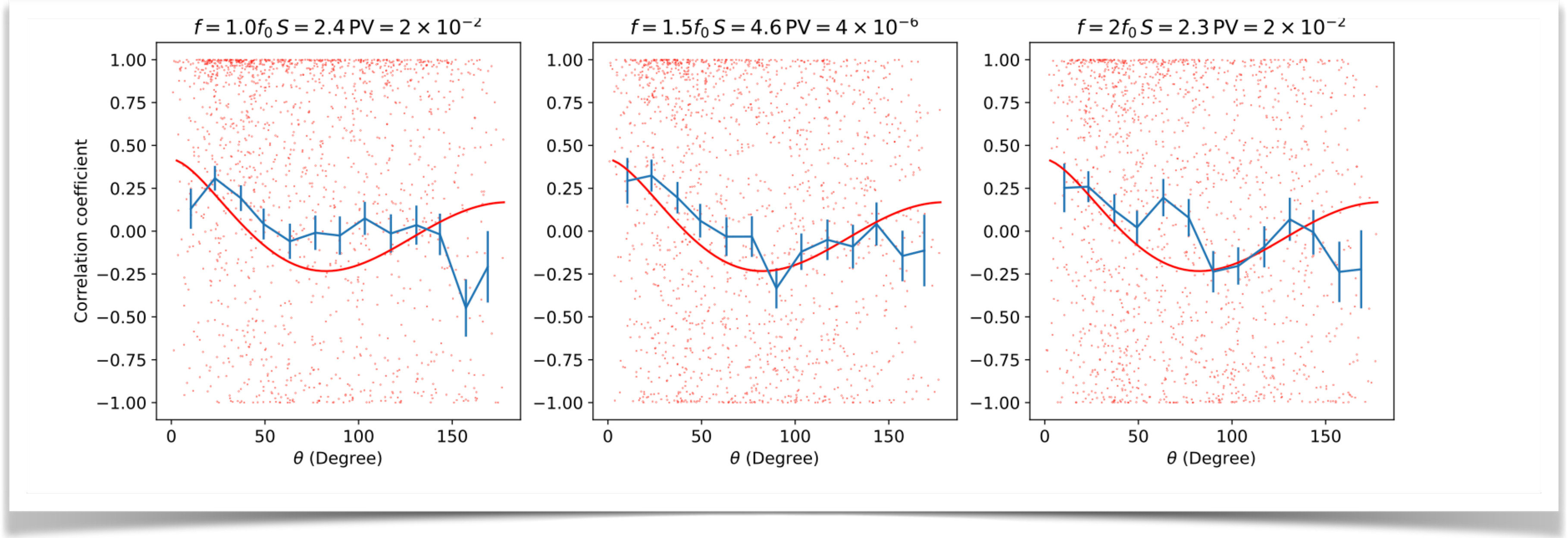
PTA discovery of nano-Hz gravitational waves

PTA collaborations have reported evidence for nano-Hz stochastic gravitational waves.

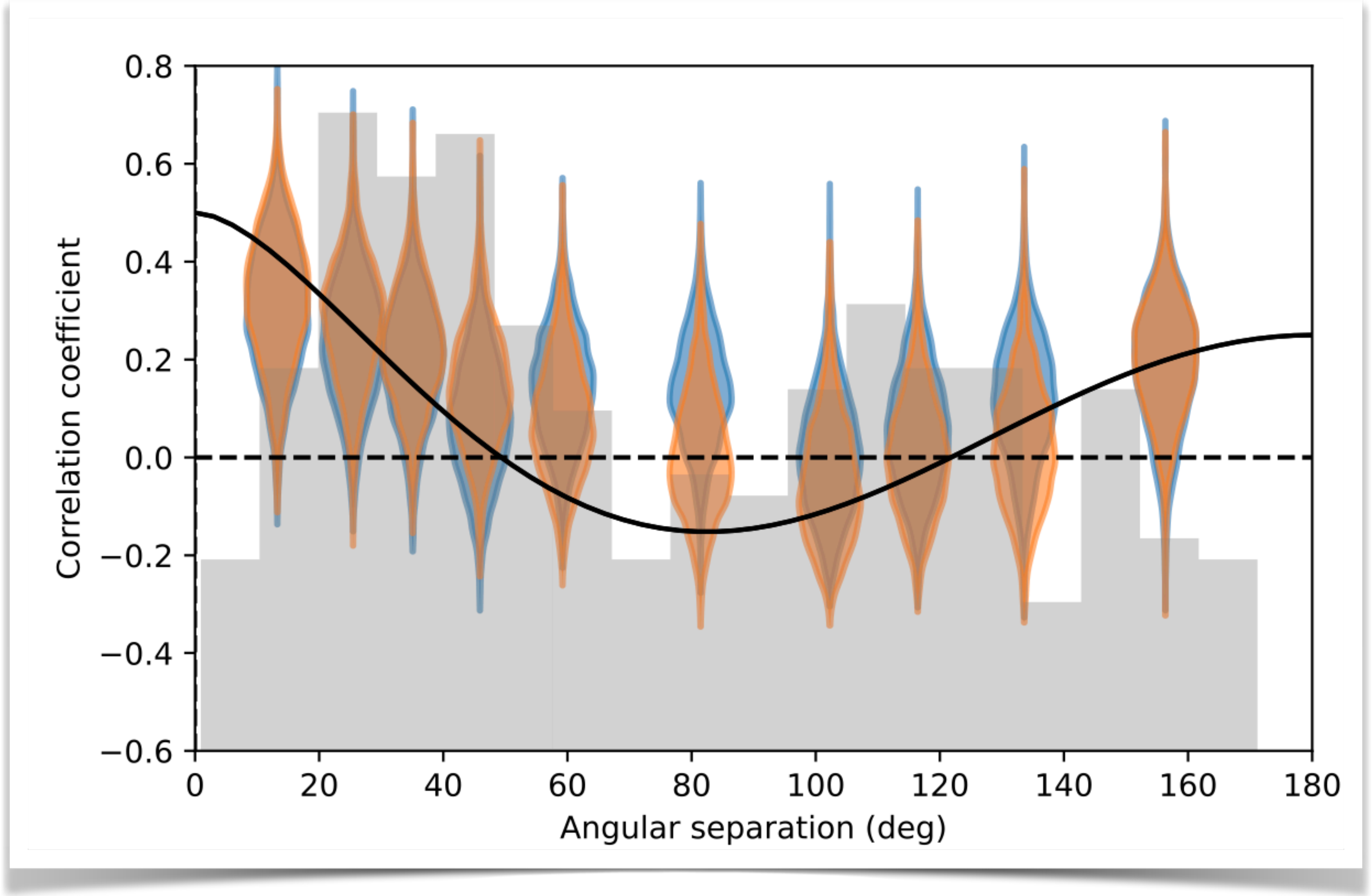
PPTA



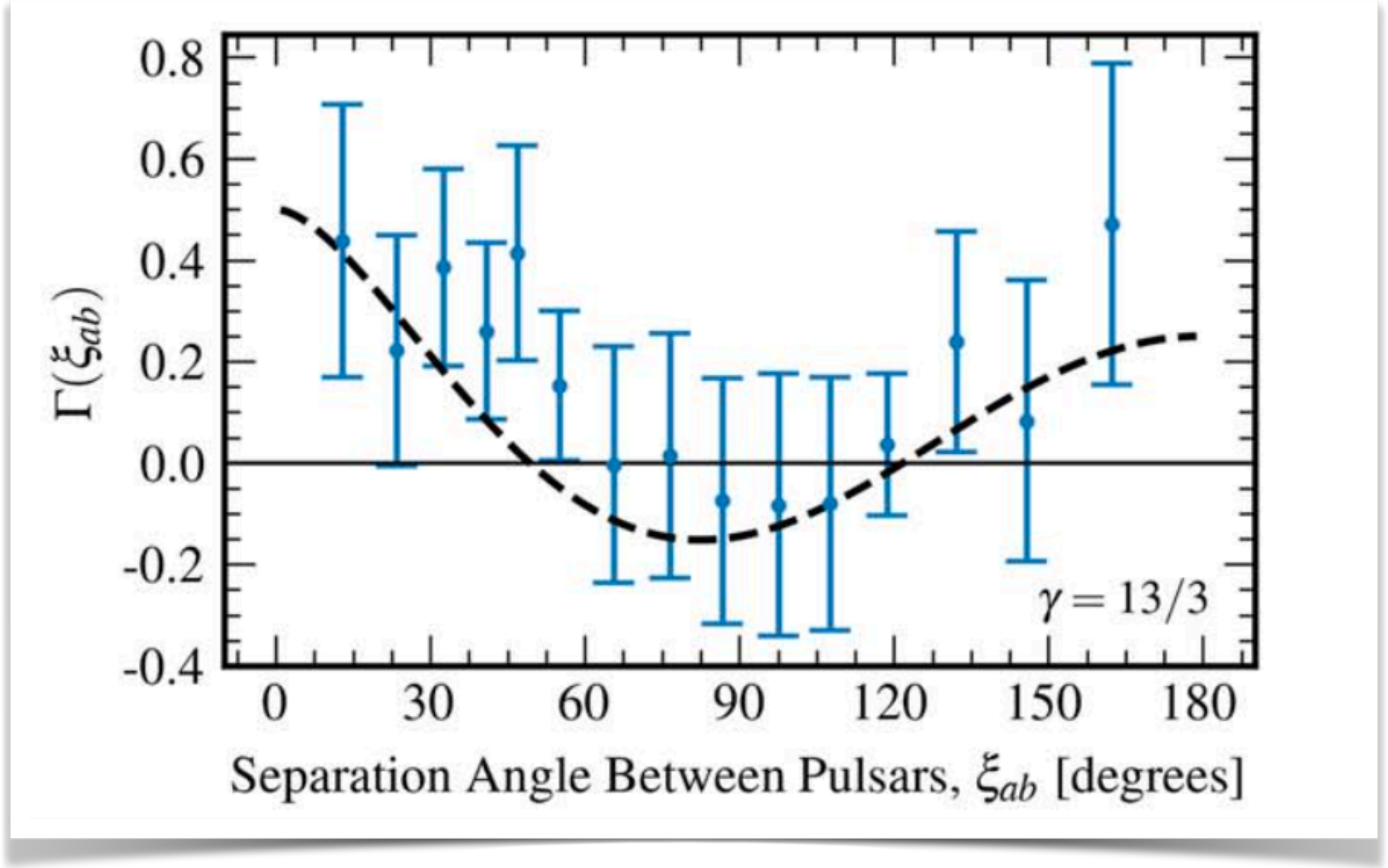
CPTA



EPTA+InPTA



NANOGrav

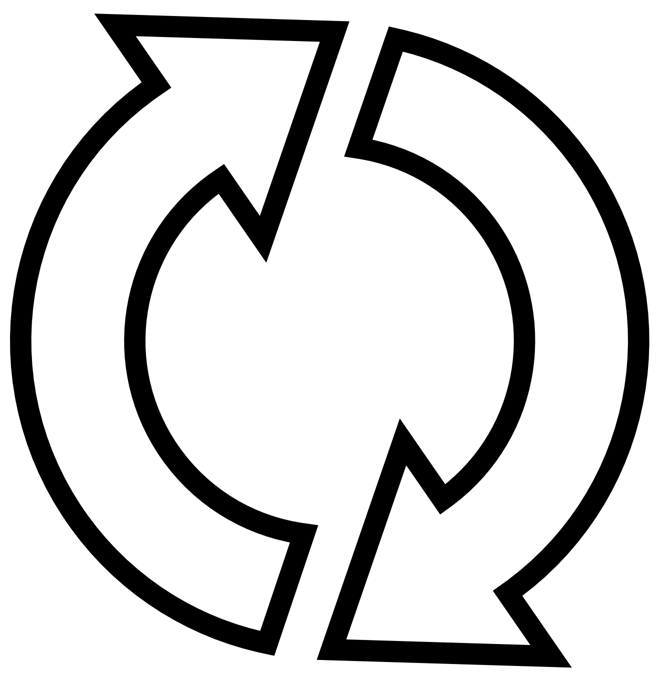


- ✻ Supermassive black hole binaries
- ✻ Defects: Cosmic strings, domain walls...
- ✻ **Cosmological phase transitions**

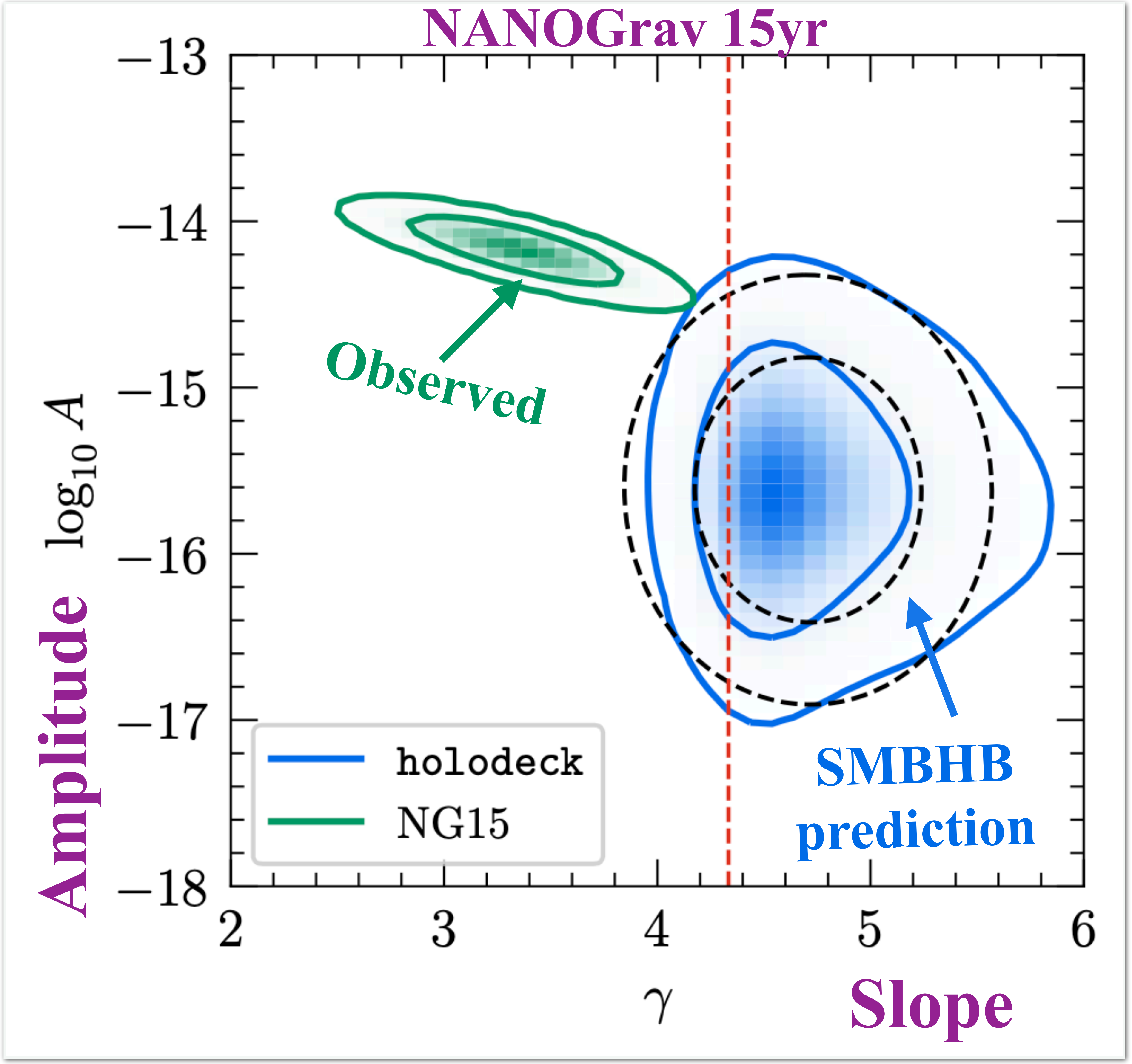
Phase transition interpretation of the PTA

PTA signal from phase transition: Motivation

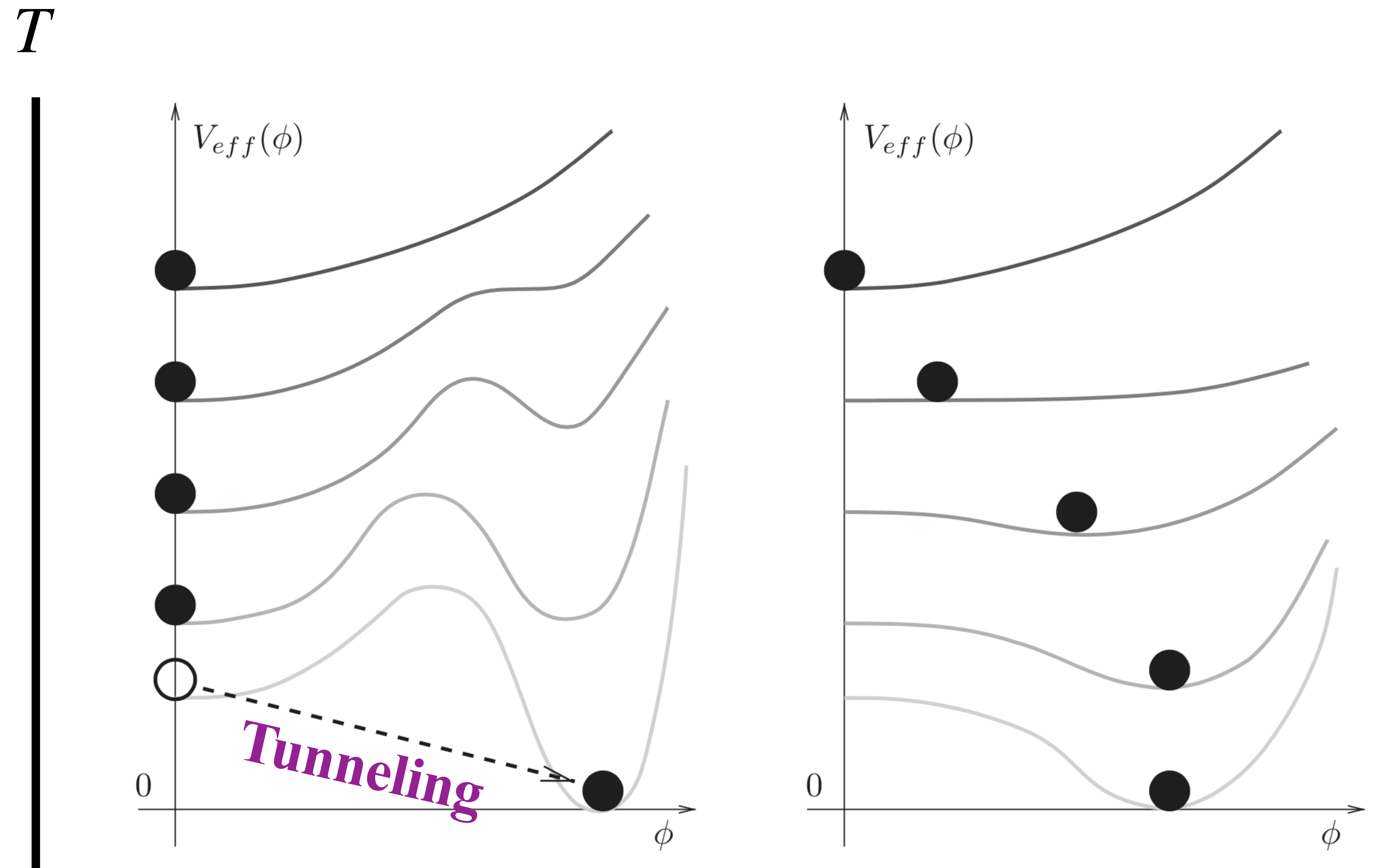
- **Hint from experiment:** phase transition can better fit the observed spectral shape of GW. **Ellis et. al. (2023)**



- **Theory challenge:** find concrete field theoretic models, predict spectral shape, **is it consistent?**

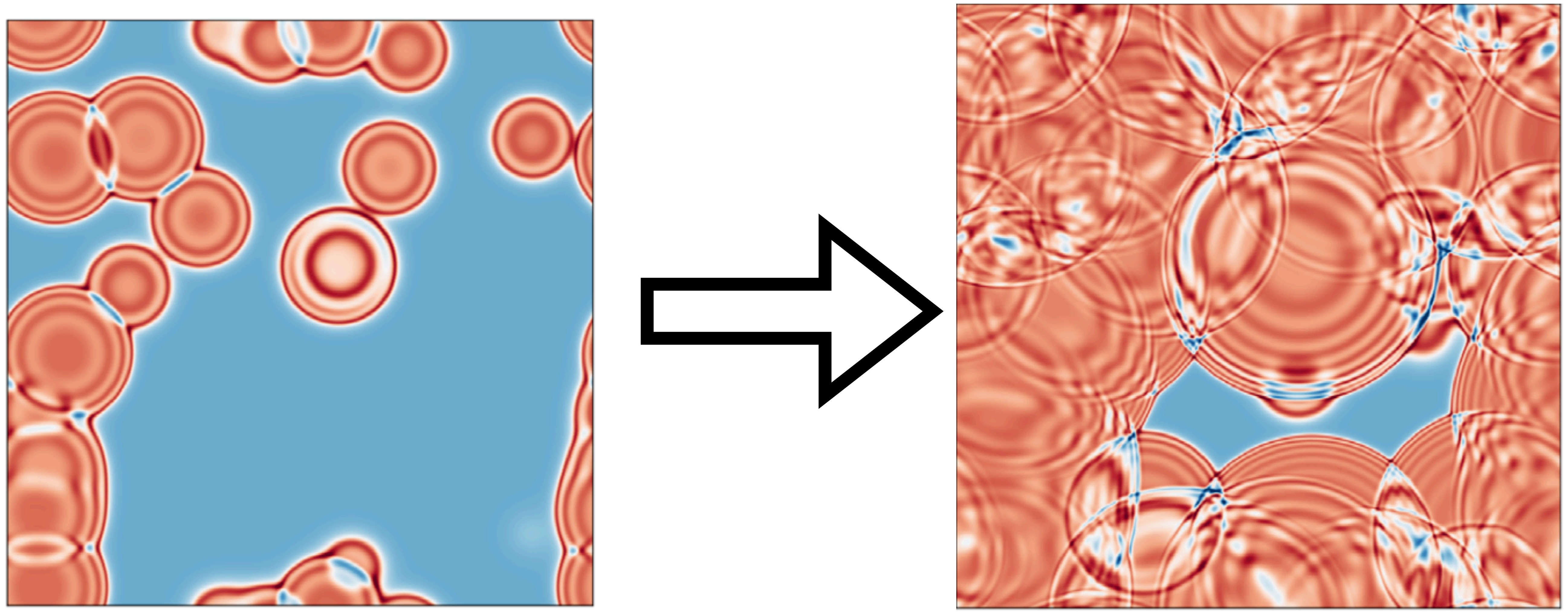


Cosmological first-order phase transition



1st order 2nd order

Generation of gravitational waves



Bubble collisions

- Observed nano-Hz peak frequency implies phase transition at $\sim \mathcal{O}(\text{GeV})$ temperature.

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

Key arguments

1. **Phase transition interpretation of PTA:** Nano-Hz stochastic gravitational waves from a **GeV-scale** first-order phase transition in a nearly conformal dark sector.

2. **Consequence of the phase transition —dilution problem:** Dilution of pre-existing baryon asymmetry and dark matter is **inevitable** to fit data.

3. **Turning the problem into a solution:** Utilizing the phase transition to create baryon asymmetry and dark matter, and **explain the GeV scale.**

The model:
Dark sector phase transition

Nearly conformal phase transition in a dark sector

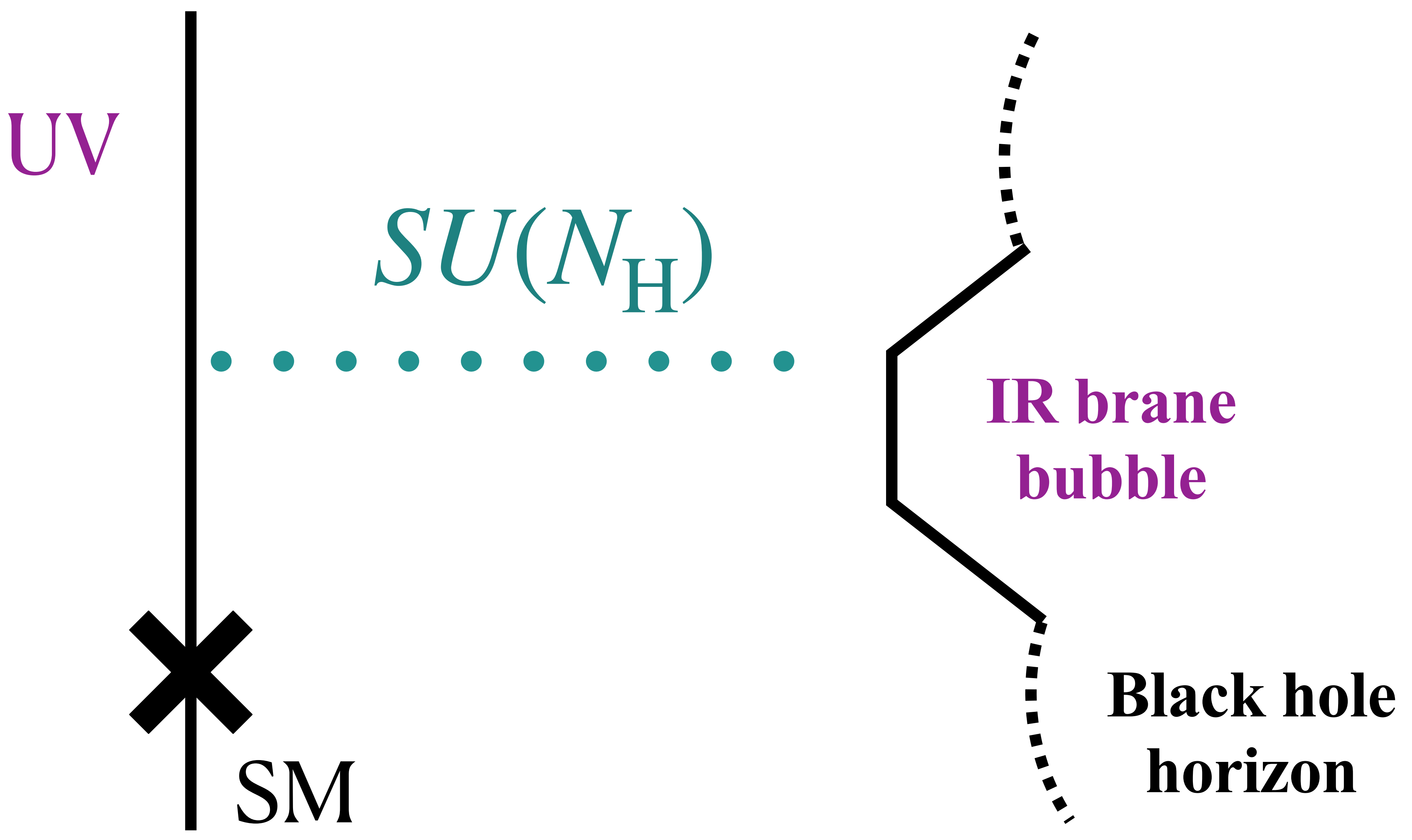
4D conformal dark sector with large N

$+$

dark pure $SU(N_H)$ Yang-Mills

Deconfining phase transition: strong dynamics

Holographic 5D ⟺



Weakly coupled dual Rattazzi + ‘02

Phase transition dynamics is obtained by the dilaton effective potential

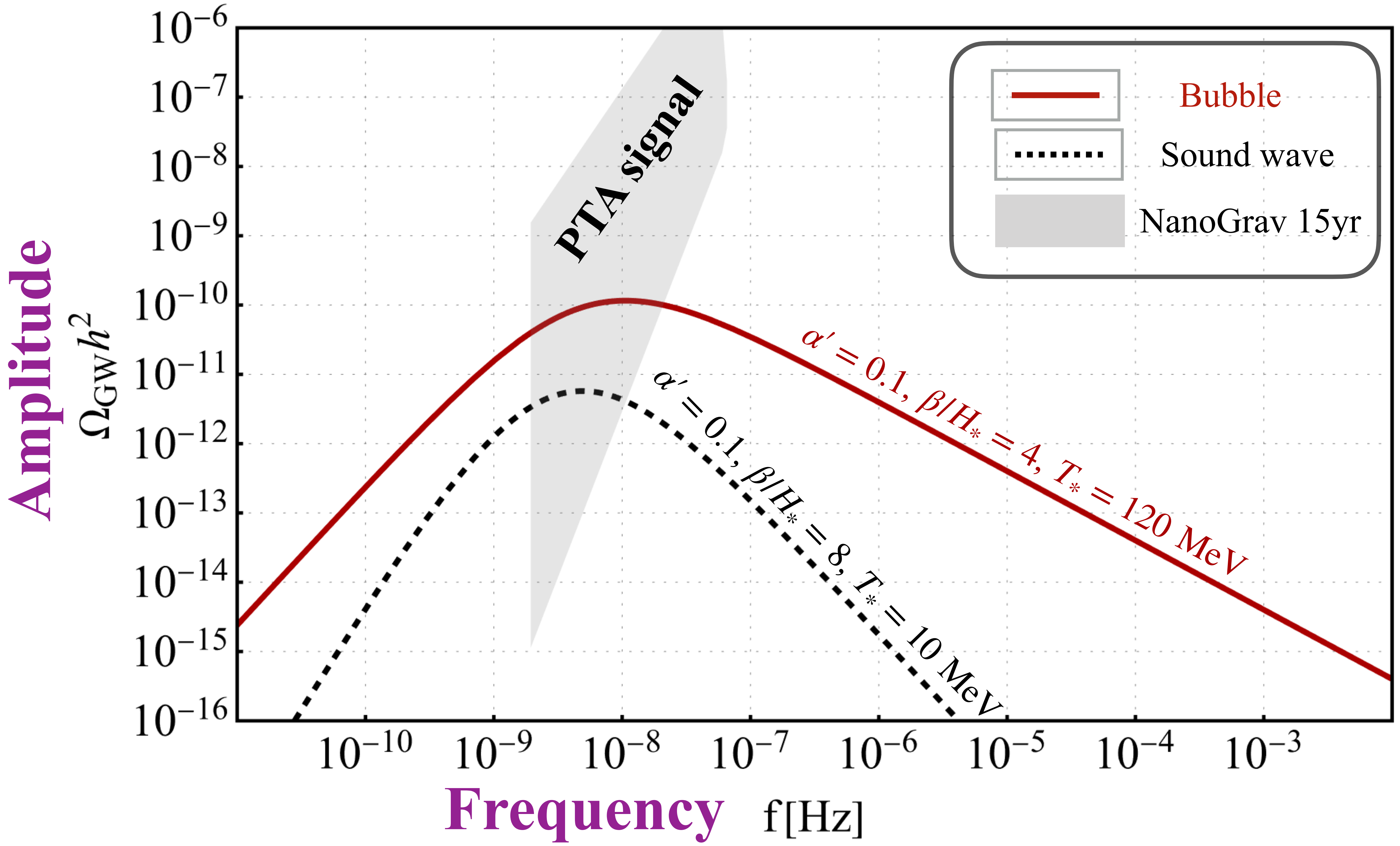
Gravitational waves from dilaton effective potential

$$\frac{1}{g_H^2(Q,\varphi)} = -\frac{b_{CFT}}{8\pi^2}\ln\left(\frac{k}{\varphi}\right) - \frac{b_H}{8\pi^2}\ln\left(\frac{k}{Q}\right)$$

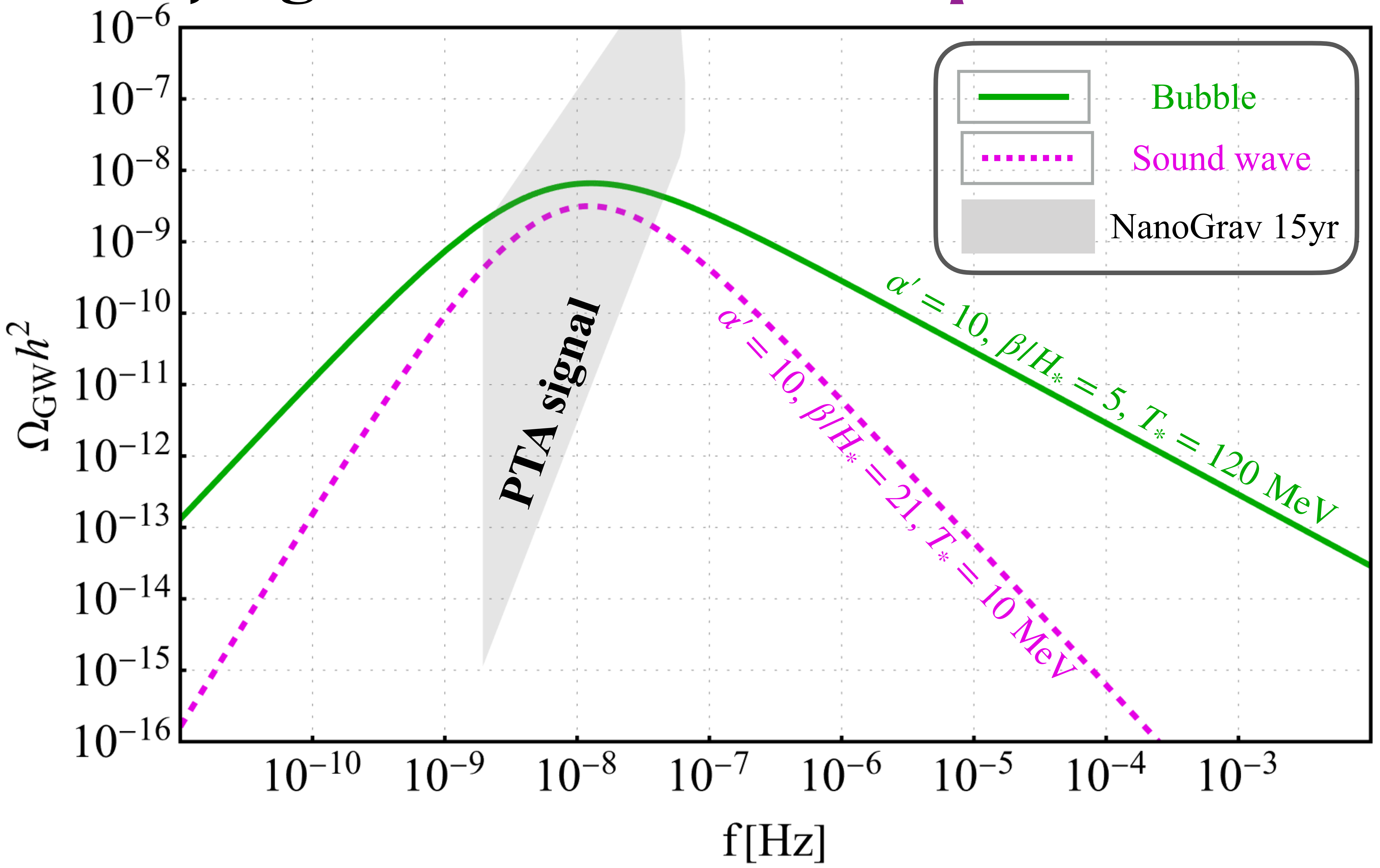
$$\Rightarrow$$

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

$\Delta N_{\rm eff}$ constraints secluded dark sector



Decaying dark sector : Portal operator needed

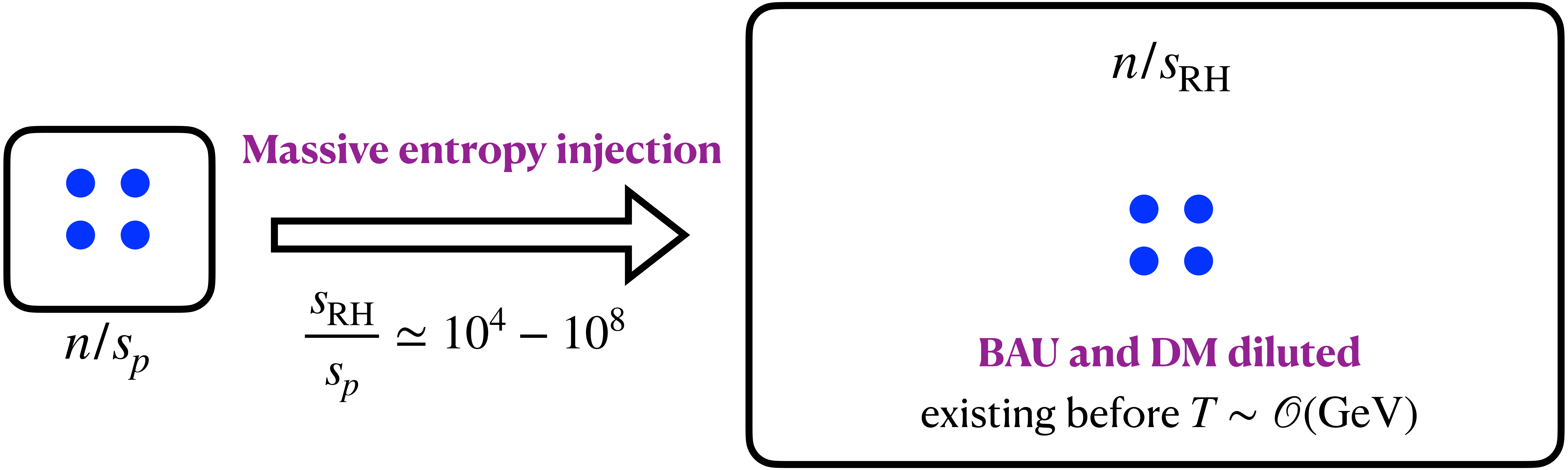


Entropy dilution problem: connection to dark matter and baryon asymmetry

The dilution problem

See eg. Schwaller + (2023)

Large supercooling is required to explain the PTA signal

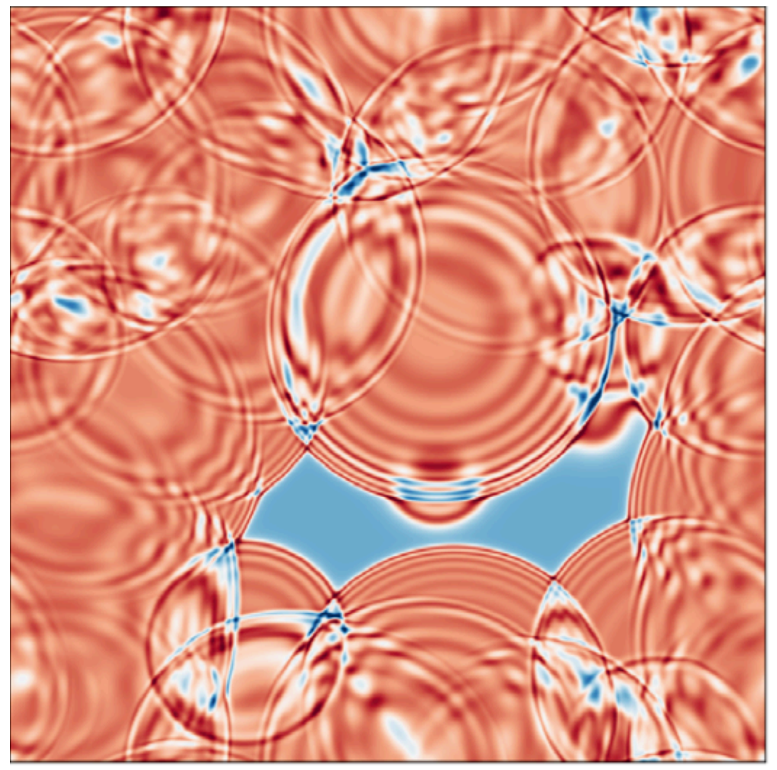


Either need a very large asymmetry before PT, **or need to create them after PT**.

Turning the problem into solution

Supercooled phase transition naturally provides **out of equilibrium condition.**

Shaposnikov et. al. (1999) ; Konstandin, Servant (2011)



Asymmetry creation

Dark sector

Sphaleron ✗

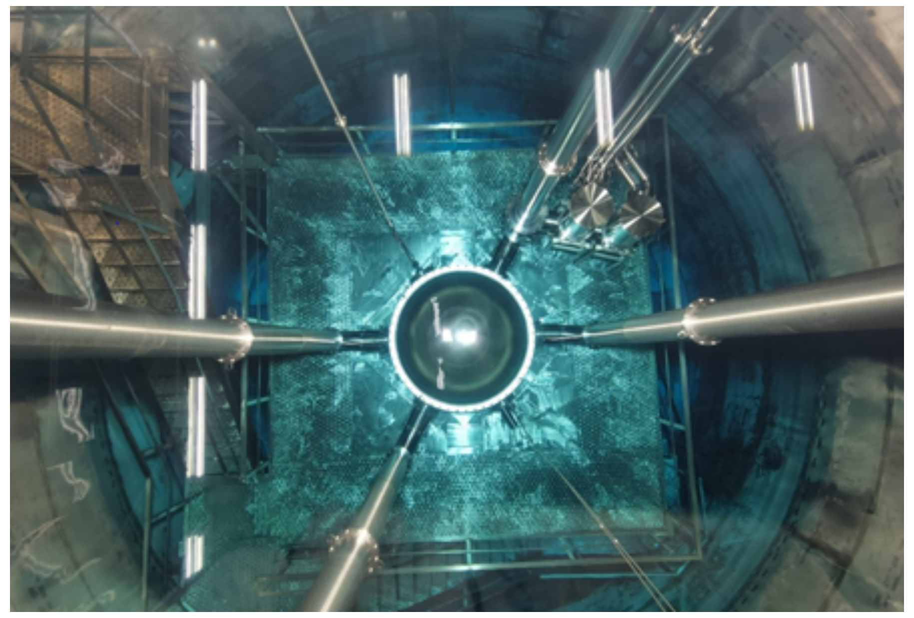
Portal

BAU

Visible sector

Phase transition

Asymmetric dark matter



Experimental signatures

1. Cold Darkogenesis

2. Post-sphaleron Darkogenesis

Cold darkogenesis: The model

Fujikura, Girmohanta, Nakai, Zhang PLB 858 139045 (2024)

Dark number asymmetry ⇒ Baryon asymmetry & **Asymmetric DM.**

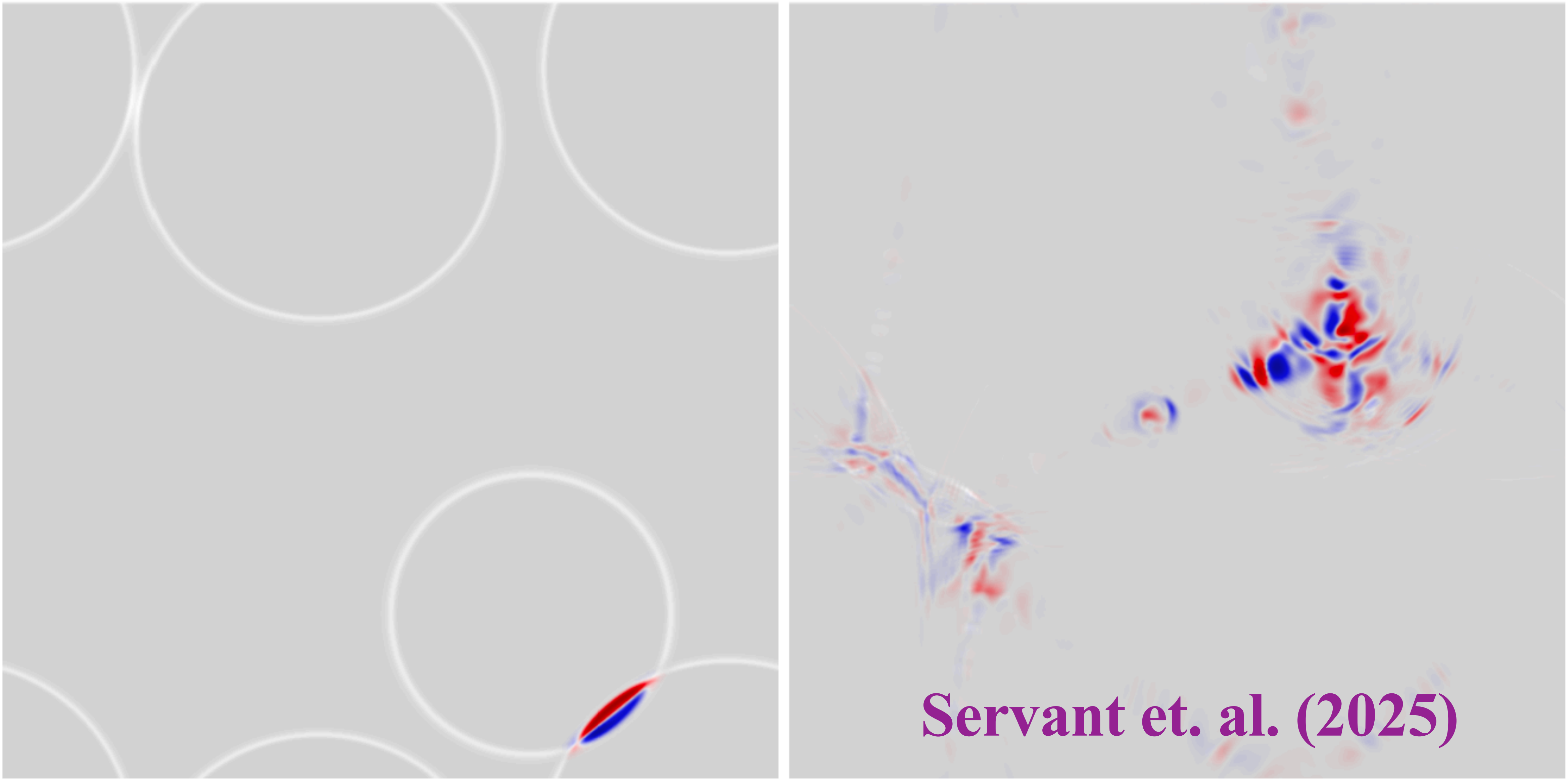
Dark QCD dilaton potential → $SU(N_H)$; Cold darkogenesis → $SU(2)_D$; Global dark baryon number → $U(1)_D$

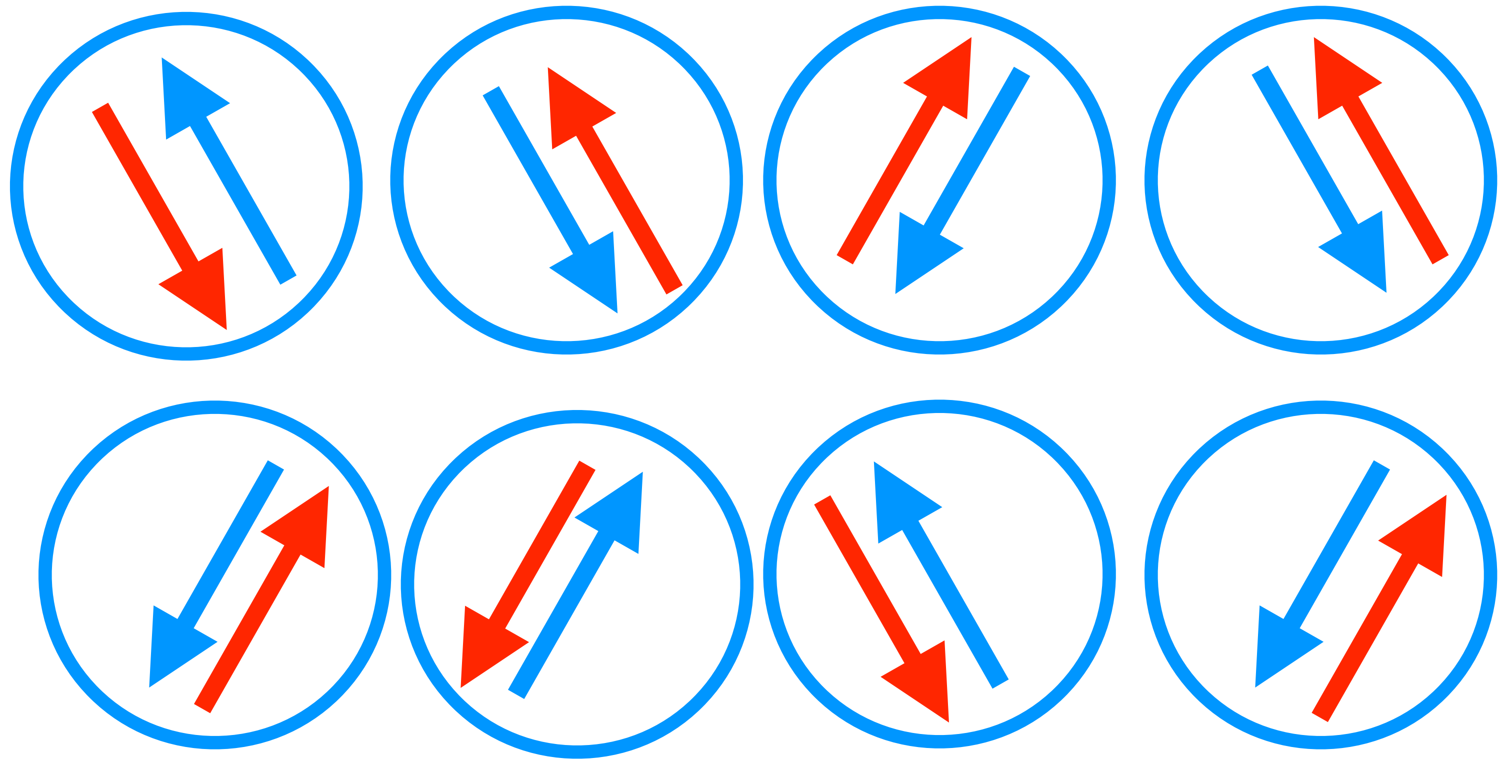
	Fields	$SU(N_{\rm H})$	$SU(2)_{\rm D}$	$U(1)_{\rm D}$	
Spin 0	$H_{\rm D}$	**1**	**2**	0	⇒ Spontaneous breaking of $SU(2)_{\rm D}$
Spin 1/2, Dark lepton	$L_{\chi,i} \equiv \begin{pmatrix} \chi_{1,i} \\ \chi_{2,i} \end{pmatrix}$	**1**	**2**	1	⇒ $U(1)_{\rm D}$ anomalous under $SU(2)_{\rm D}$
Spin 1/2, Dark lepton	$\bar{\chi}_{1,i},\ \bar{\chi}_{2,i}$	**1**	**1**	-1	⇒ Neutron portal $(1/\Lambda_n^2)\,\bar{\chi}udd$ for asymmetry sharing
Spin 1/2, Dark quarks	ψ_j	$\mathbf{N}_{\rm H}$	**1**	$1/N_{\rm H}$	
Spin 1/2, Dark quarks	$\bar{\psi}_j$	$\overline{\mathbf{N}}_{\rm H}$	**1**	$-1/N_{\rm H}$	⇒ Baryon dark matter

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

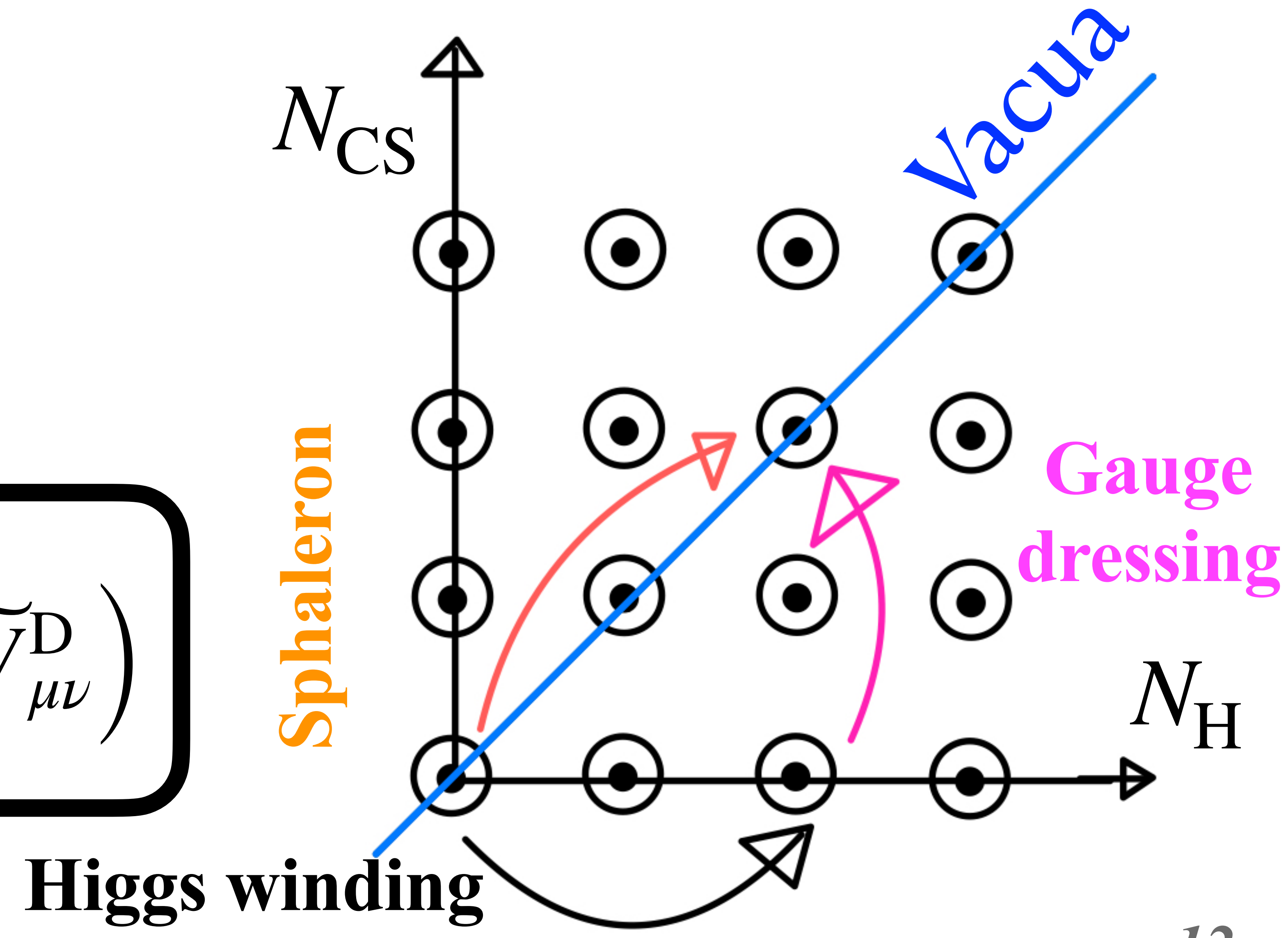
Generating the asymmetry in the dark sector

1. Higgs winding number ($N_{\rm H}$) production





2. Gauge configuration evolves to cancel Higgs gradient energy



3. χ number violation via anomaly.

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

With **C & CP violation**, $\delta N \equiv N_{\rm CS} - N_{\rm H} > 0$ and $\delta N < 0$ **winding configurations evolve differently**, generating a net dark lepton number $\mathscr{D}_{\rm L,in}$.

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

The produced $H_{\rm D}$ reaches **local equilibrium with the temperature**:

$$T_{\rm D}^4 \sim \text{released energy} \sim \lambda v_{\rm D}^4$$

$$\text{Sphaleron-like transition rate}: \quad \Gamma_{\rm sph} \sim \left(\frac{g_{\rm D}^2}{4\pi}T_{\rm D}\right)^4$$

$\mathcal{O}_{\rm CPV}$ acts as an effective chemical potential for χ, L_χ

$$\mu_{\rm eff} = \frac{\delta_{\rm CP}}{\Lambda_{\rm CP}^2}\frac{d}{dt}\langle H_{\rm D}^\dagger H_{\rm D}\rangle \implies \frac{dn_{\rm L}}{dt} = \Gamma_{\rm sph}\frac{\mu_{\rm eff}}{T_{\rm D}} - \Gamma_B n_{\rm L}$$

[Garcia-Bellido, Grigoriev, Kusenko,Shaposhnikov (1999)]

Sharing the asymmetry with the visible sector

The asymmetry is shared with the dark baryon and SM via effective interactions:

Baryonic DM composed of f ($\mathbb{Z}_2$ odd) $$\mathcal{O}_{\rm D} \sim \frac{1}{\Lambda_{\rm D}^2} p_{\rm D} p_{\rm D} \chi\chi$$	$$\mathcal{O}_n \sim \frac{1}{\Lambda_n^2} \chi u_{\rm R} d_{\rm R} d_{\rm R}$$ **Mono-jet searches ($ud \to \bar{\chi}\bar{d}, dd \to \bar{\chi}\bar{u}$) in colliders. Current constraint $\Lambda_n \gtrsim 2$ TeV. For equilibrium at GeV $\Lambda_n \lesssim 15$ TeV.**

The DM is **self-interacting** via the mediation of dark pions $\pi_{\rm D}$ with cross-section:

$$\frac{\sigma_{p_{\rm D}p_{\rm D}}}{m_{p_{\rm D}}} \sim 1\ {\rm cm}^2/{\rm g} \left(\frac{\Lambda_{\rm dQCD}}{m_{p_{\rm D}}}\right)\left(\frac{\Lambda_{\rm dQCD}}{a_{\rm D}^{-1}}\right)^2\left(\frac{150\ {\rm MeV}}{\Lambda_{\rm dQCD}}\right)^3 ;$$

$a_{\rm D}$: scattering length .

Tulin Yu (2017) ; Kribs (2016)

Experimental predictions

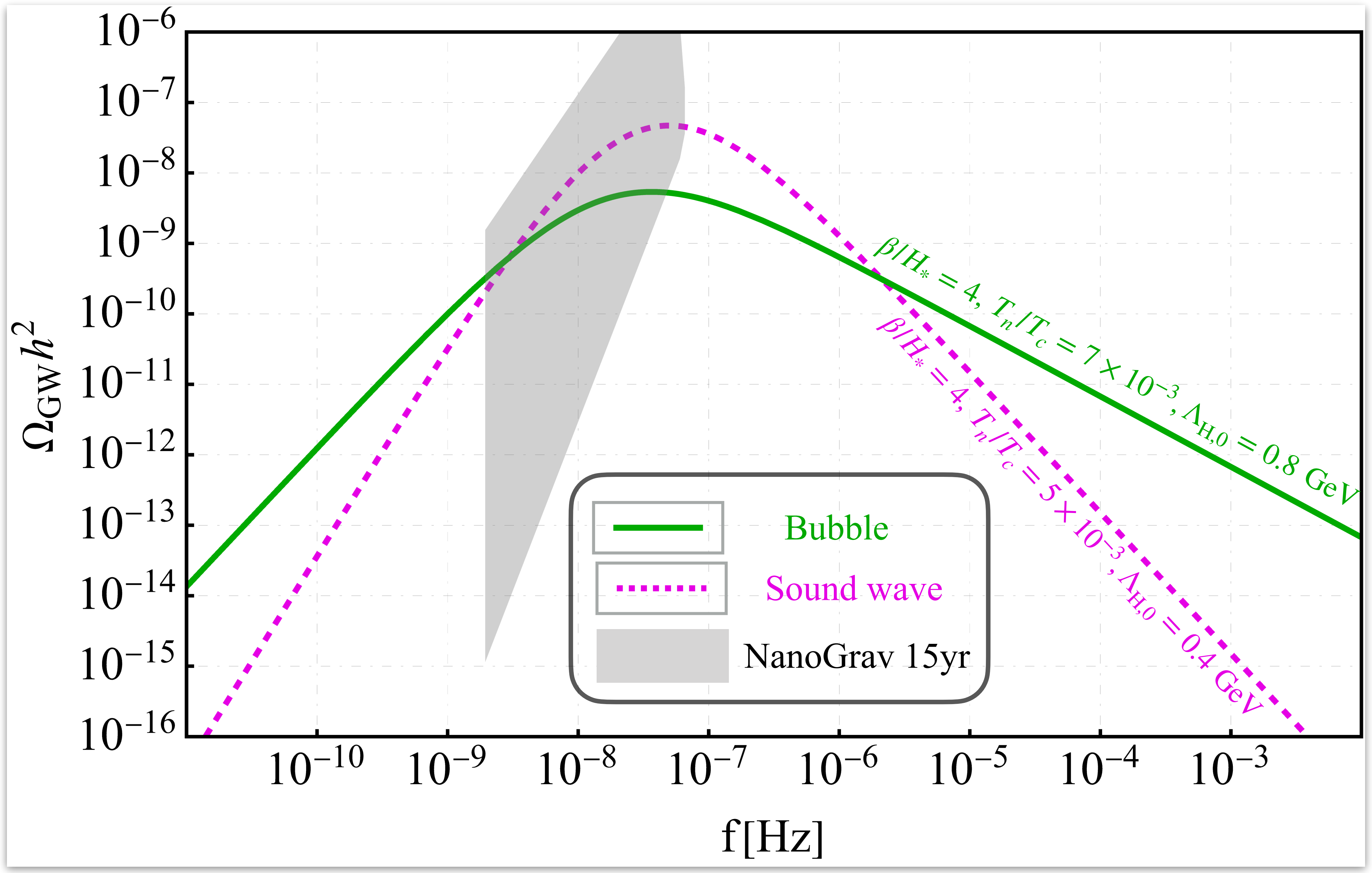
Portal operator: π_D decays before BBN. $\Lambda_n \lesssim 15$ TeV for equilibrium at GeV temperature.

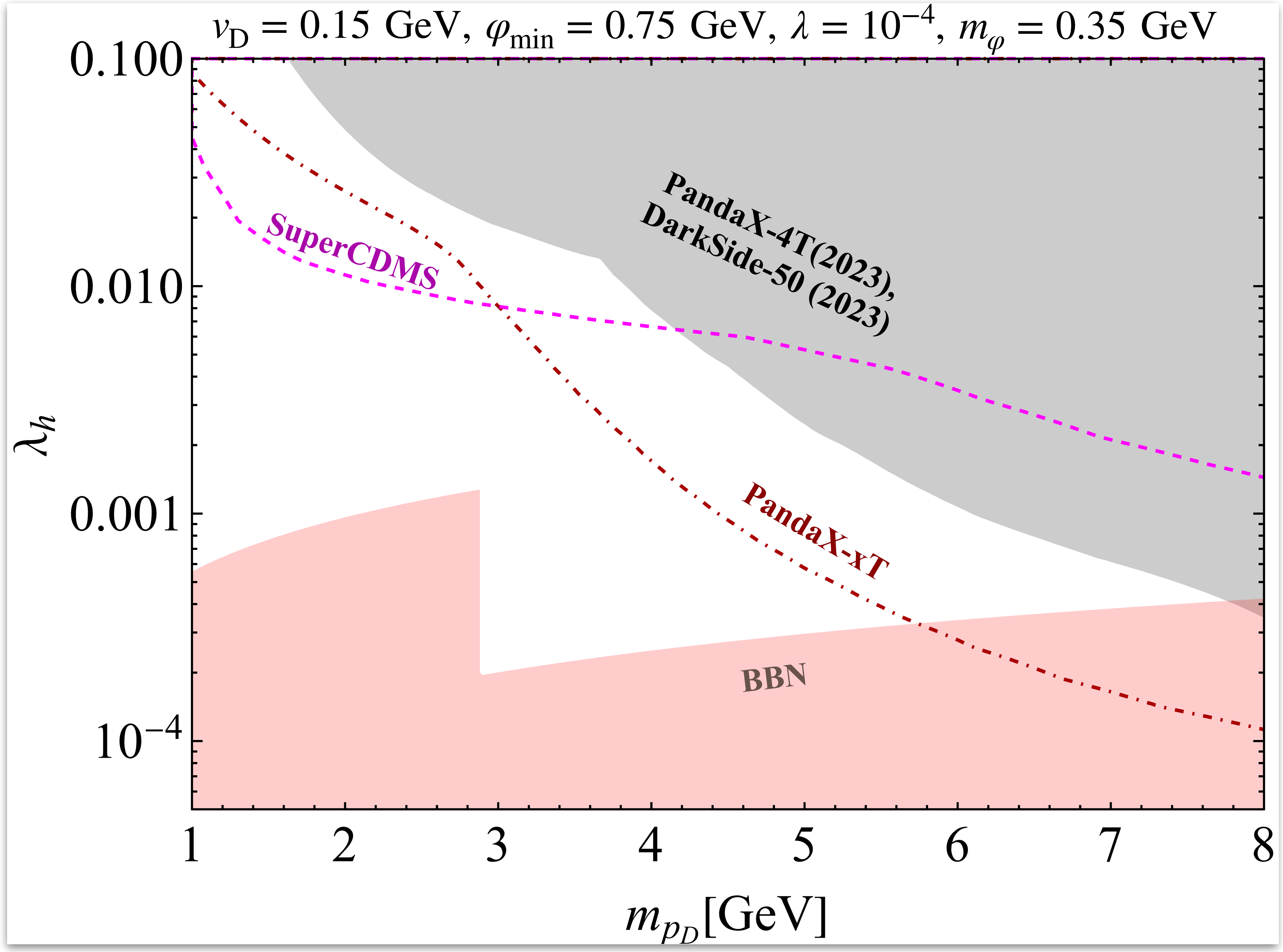
$$\mathcal{L}_H \supset -\lambda_h |H|^2 |H_D|^2$$

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

Lower bound from BBN, upper bound from DM direct detection.

PTA signal explanation together with DM and baryon asymmetry

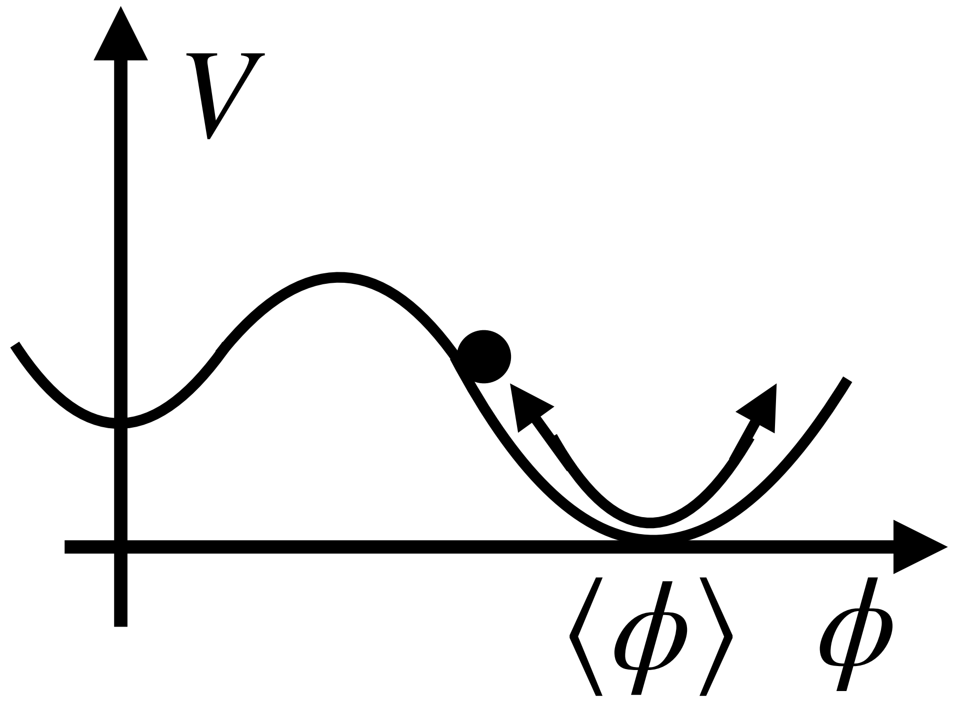




Post-sphaleron darkogenesis : The Model

Girmohanta, Nakai, Zhang PRD 112 075028 (2025)

Majorana ψ produced via **parametric excitation** during the phase transition.



oscillation of field ϕ

$\mathcal{O}(1)$GeV

$$\phi(t) = \langle\phi\rangle + \varphi(t)$$
$$f(\varphi)\bar{\psi}^c\psi$$

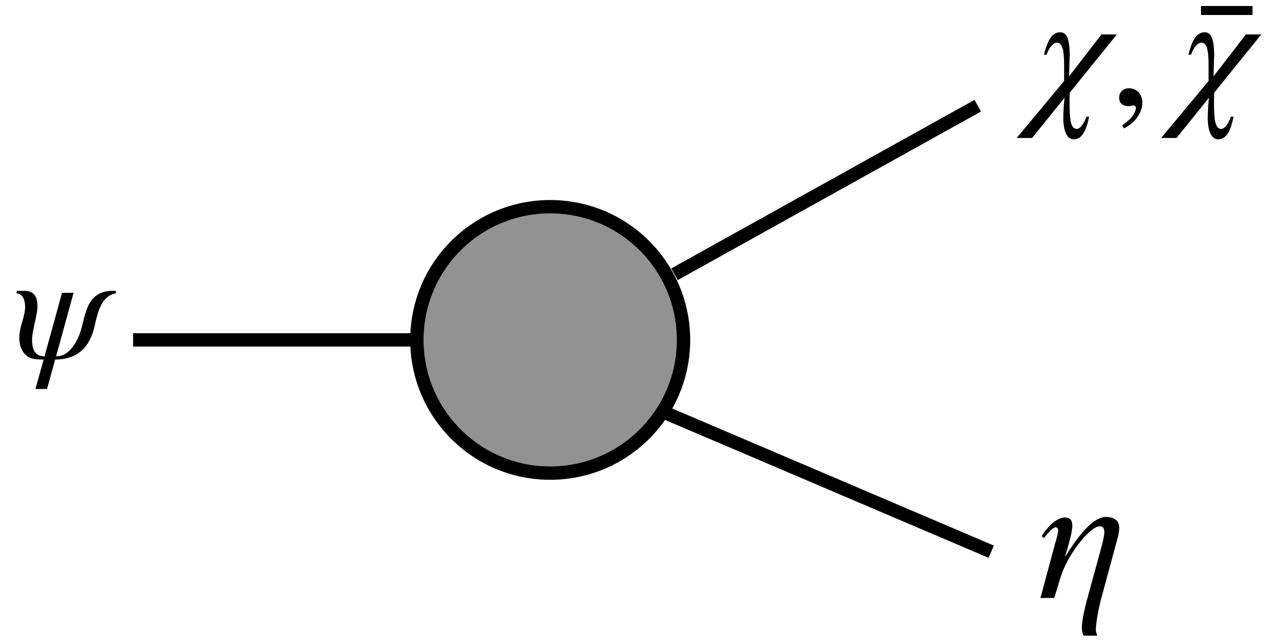
⇒

Parametric excitation

$$\left(i\gamma^\mu\partial_\mu - m_\psi^{\rm eff}(t)\right)\psi = 0$$

GeV mother particle ψ
is non-thermally produced.

$\bar{\psi}y\eta\chi$ ⇒

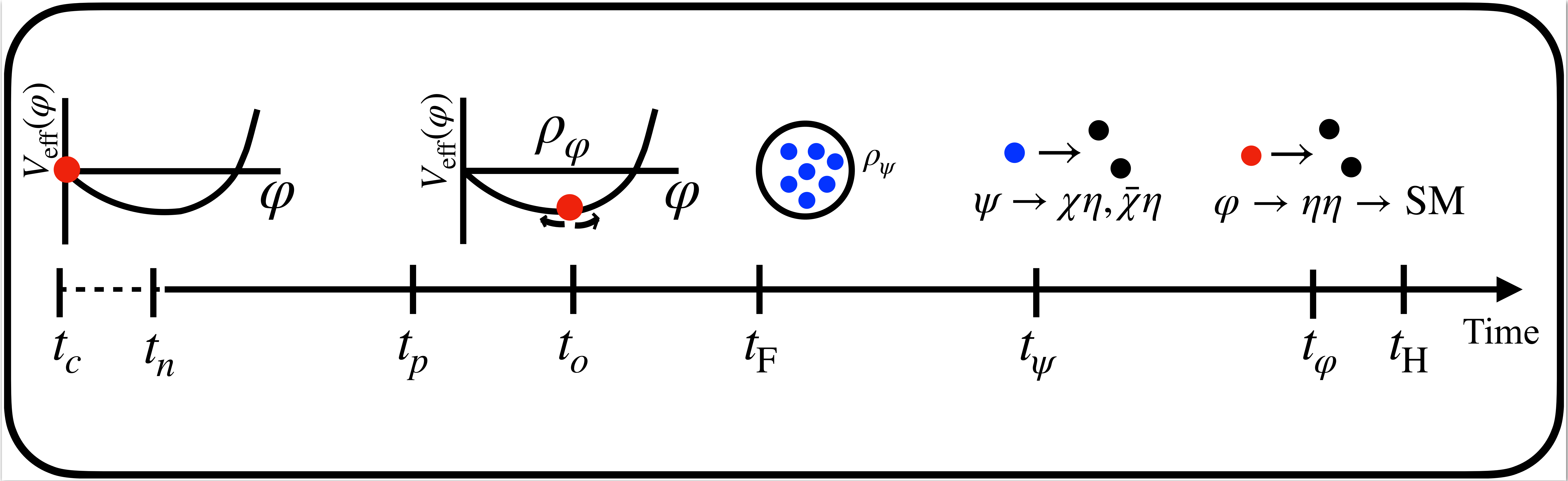


⇒ Asymmetric χ particle

Model

$$V_{\rm DS} = \bar{\chi}\mu\chi\eta + m_\chi \bar{\chi}\chi + \frac{1}{2} m_\psi \bar{\psi}^c_{\rm R} \psi_{\rm R} + \frac{1}{2} m_\eta^2 \eta^2 + \bar{\psi}_{\rm R} y \eta \chi_{\rm L} + {\rm h.c.}$$

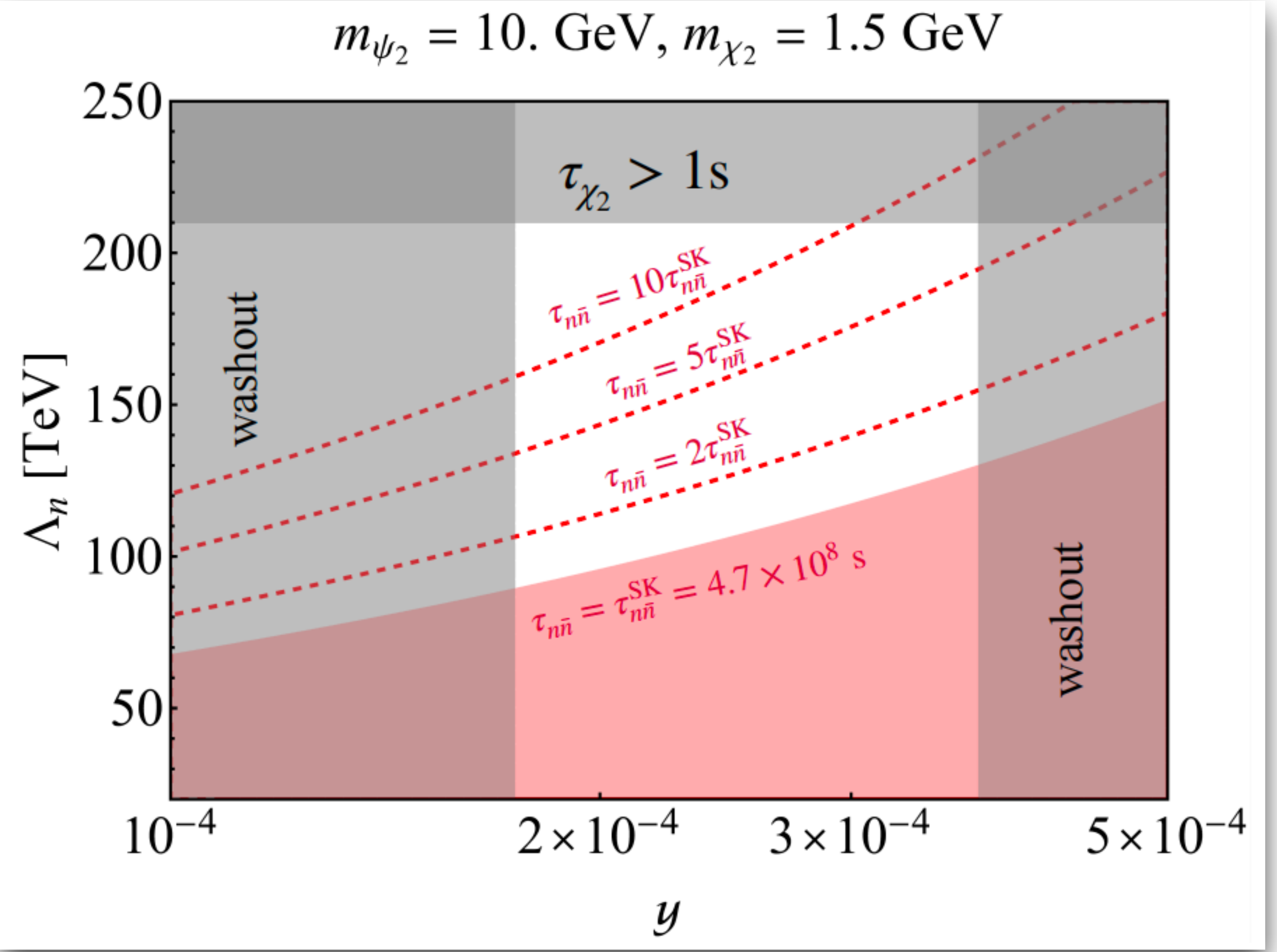
Fields	$U(1)_{\rm D}$
ψ_i	-1
χ_j	-1
η	0

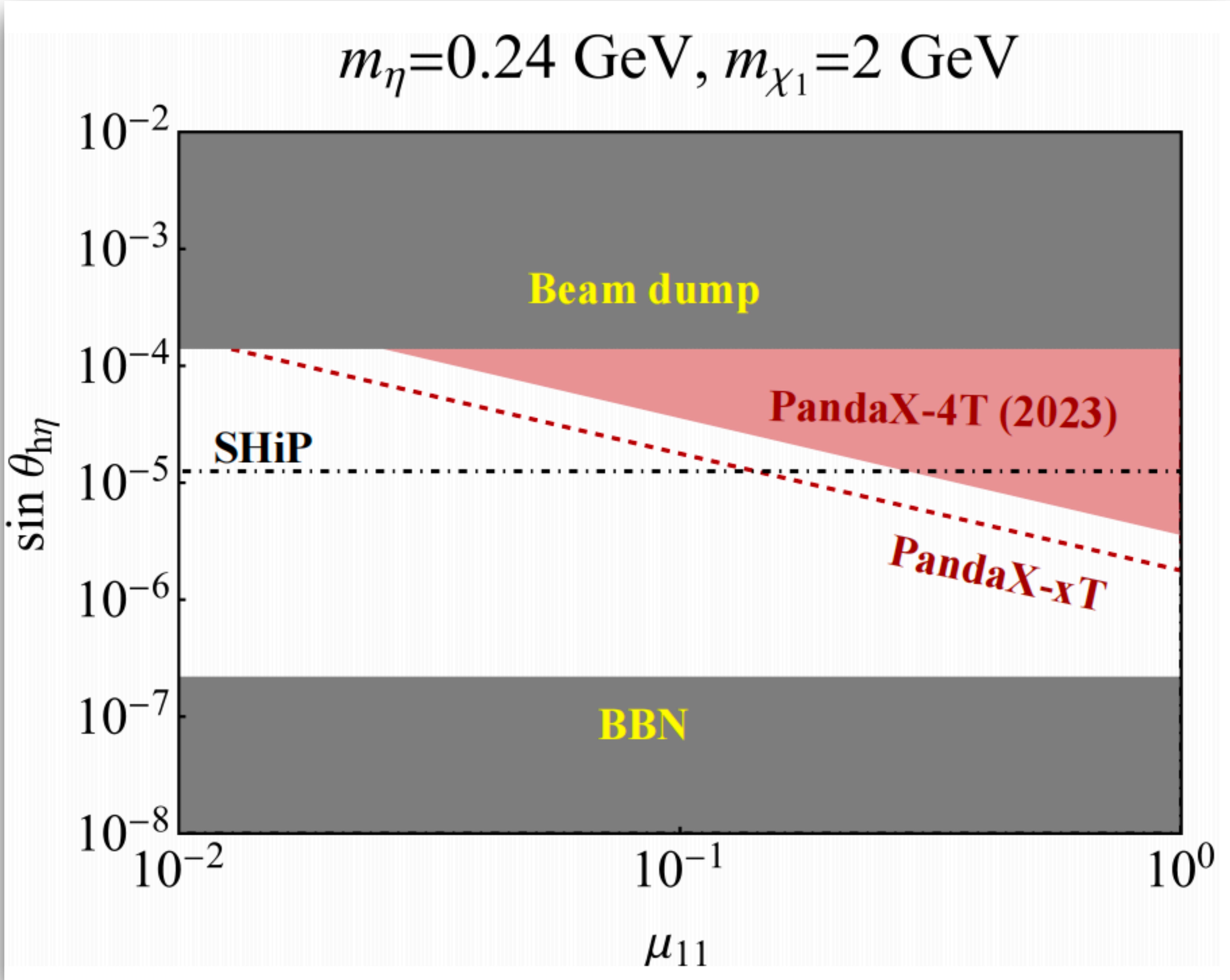


Neutron portal shares the asymmetry with the visible sector.

η acts as Higgs-portal scalar.

Viable parameter space





Why the GeV scale?

$\Lambda_{\mathrm{dQCD}} \sim$ GeV and the three coincidences

1. Dark QCD generates the mass gap in the CFT sector, and $\Lambda_{\mathrm{dQCD}} \simeq \mathcal{O}(\mathrm{GeV})$ explains **PTA**.

$$\varphi_{\min} \simeq \Lambda_{\mathrm{dQCD}} \simeq T_{\mathrm{RH}} \simeq \mathcal{O}(\mathrm{GeV})$$

2. $\Lambda_{\mathrm{dQCD}} \simeq \mathcal{O}(\mathrm{GeV})$ can explain the **DM-baryon coincidence** problem for dark baryon DM.

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{b}}} = \frac{m_{\mathrm{DM}}(n_{\mathrm{DM}} - n_{\overline{\mathrm{DM}}})}{m_p(n_{\mathrm{b}} - n_{\bar{\mathrm{b}}})} \simeq \frac{m_{\mathrm{DM}}}{m_p} \simeq \frac{\Lambda_{\mathrm{dQCD}}}{\Lambda_{\mathrm{QCD}}} \simeq 5.4$$

3. $\Lambda_{\mathrm{dQCD}} \simeq \mathcal{O}(\mathrm{GeV})$ can yield desired **self-interaction for DM** via π_D mediation.

$$\frac{\sigma_{\mathrm{DM-DM}}}{m_{\mathrm{DM}}} \sim 1\ \mathrm{cm}^2/\mathrm{g} \left(\frac{\Lambda_{\mathrm{dQCD}}}{m_{\mathrm{DM}}}\right) \left(\frac{\Lambda_{\mathrm{dQCD}}}{a_{\mathrm{D}}^{-1}}\right)^2 \left(\frac{0.2\ \mathrm{GeV}}{\Lambda_{\mathrm{dQCD}}}\right)^3 ;$$

a_{D} : **scattering length .**

Tulin Yu (2017) ; Kribs (2016)

Main idea: neutron portal and the GeV scale

Neutron portal with $2\ \text{TeV} \lesssim \Lambda_n \lesssim 100\ \text{TeV}$ is key to share asymmetry between χ and SM.

$$\mathcal{O}_{n\chi} = \frac{1}{\Lambda_n^2}\left(\overline{\chi^c} d_R^c\right)\left(\overline{u_R} d_R^c\right)$$

TeV scale particles are needed for the UV completion

Connection to μ-problem in SUSY

Dark QCD has IR fixed point

Dynamical generation of $\Lambda_{\text{dQCD}} \simeq \text{GeV}$

Integrated out at $\mu \sim \text{TeV}$

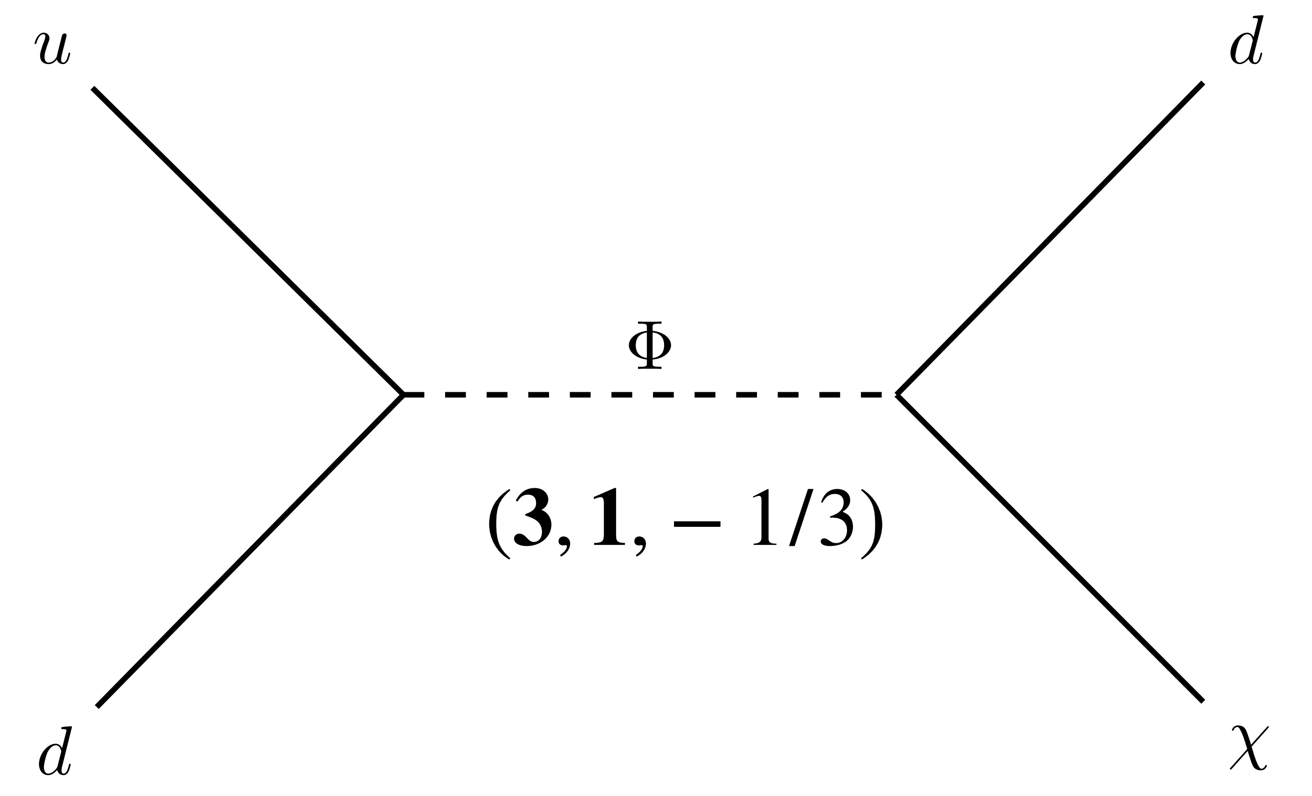
dQCD flows away from fixed point

UV completion paths

Tree level :

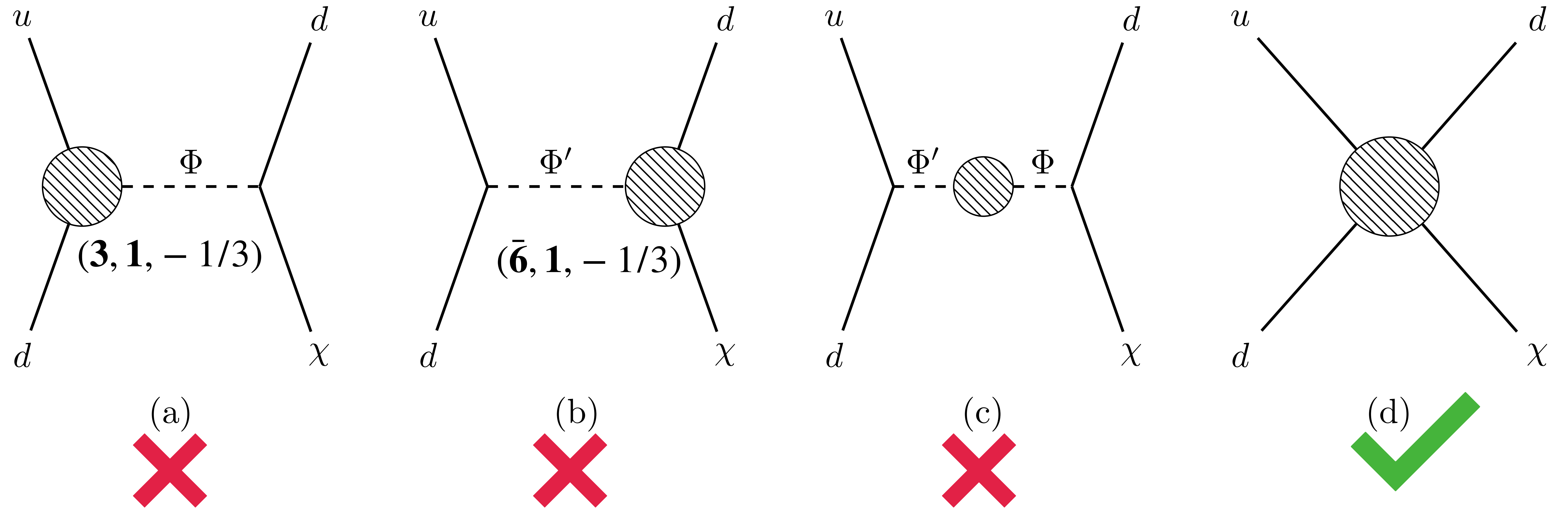
Φ **can not** have a dark QCD charge

Connection to the GeV scale is not straightforward

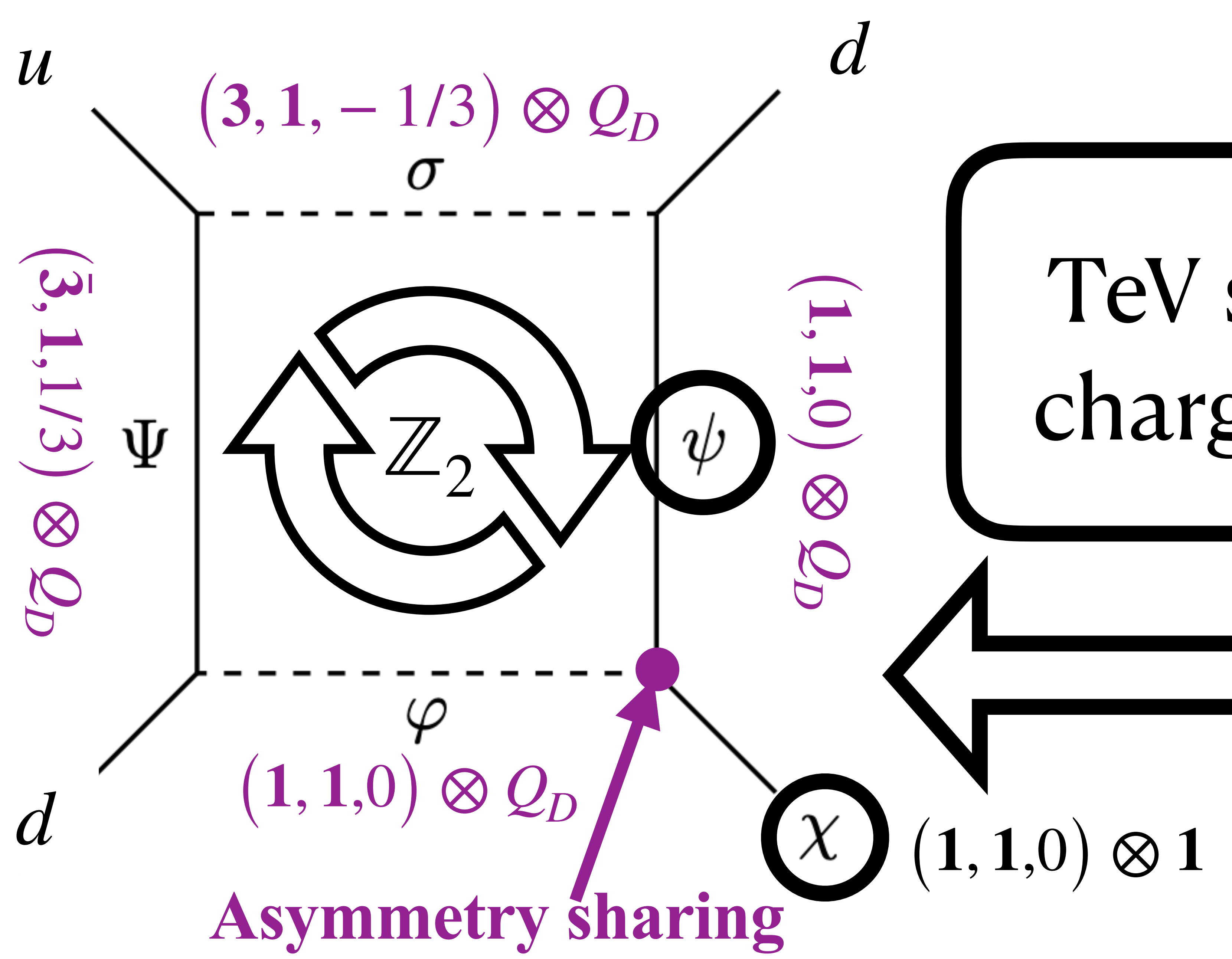


Loop level :

While not allowing tree-level

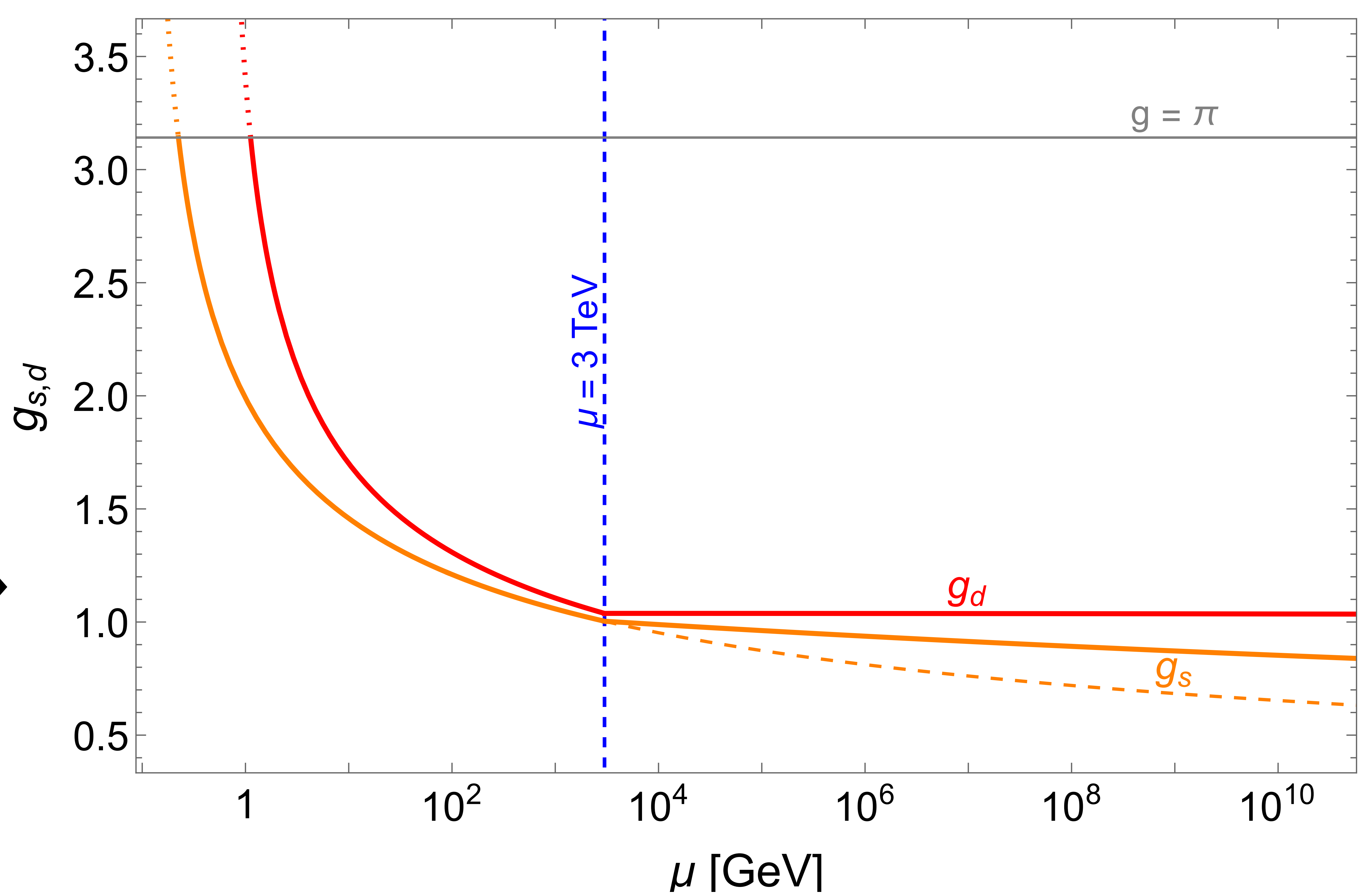


UV completion of neutron portal and Fixed point



TeV scale dQCD charged particles

$(n_\Psi, n_\psi, n_\sigma, n_\varphi) = (2,5,1,14)$; $4\bar{n}_\psi + \bar{n}_\varphi = 20$; $SU(3)$; $M_D = 3$ TeV



From loop diagram calculation

Benchmark case: $\Lambda_{\rm dQCD} \simeq 1$ GeV, $\Lambda_n \simeq 3-8$ TeV .

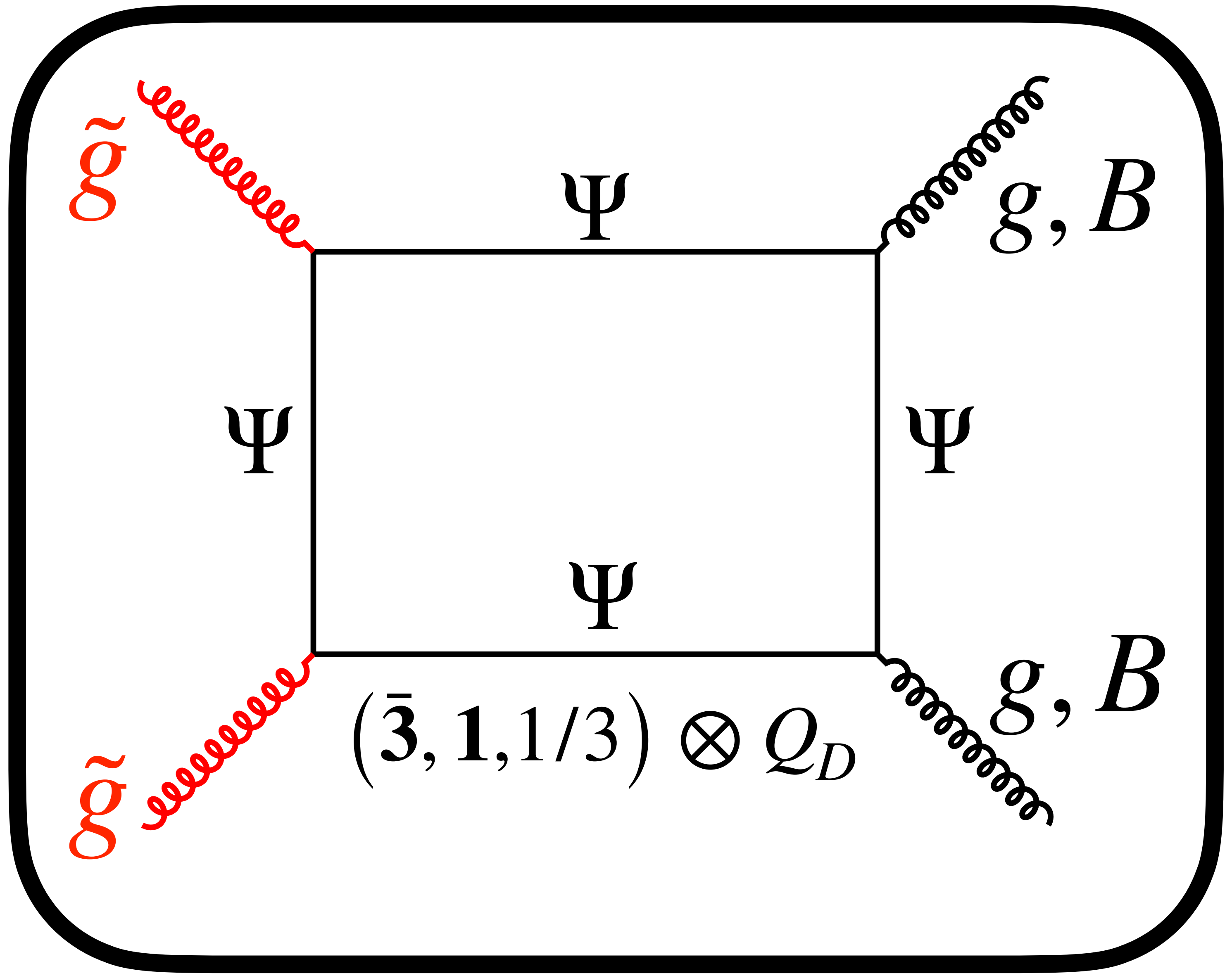
Fixed point behavior

Bai, Schwaller (2014), Ritter, Volkas (2024)…

Portal operators from UV

Symmetric component of DM energy density ends up in dark pions. π_D must decay before BBN.

$$\langle \sigma v \rangle_{p_D \bar{p}_D \to \pi_D \pi_D} \simeq \frac{4\pi}{m_{\rm DM}^2} \gg 10^{-25}\ {\rm cm}^3/{\rm s}$$



Ψ generates effective ALP portal for dark pions **Juknevich (2010)**

$$\mathscr{L}_{\rm ALP} \supset \frac{\alpha_s}{8\pi}\frac{\pi_D}{f_{\rm A}} G\tilde{G} + \frac{\alpha_Y}{36\pi}\frac{\pi_D}{f_{\rm A}} B\tilde{B} \quad ; \quad f_{\rm A} \simeq \frac{45}{32\pi^2}\Lambda_{\rm dQCD}\left(\frac{m_\Psi}{\Lambda_{\rm dQCD}}\right)^4 \simeq 10^{11}\ {\rm GeV}$$

GeV scale meson lifetime $\simeq \mathcal{O}(1{\rm s})$, likely ruled out by BBN.

Jung+ (2026)

Higgs portal is likely needed: $-\mathscr{L}_S \supset \bar{\psi} i \gamma^5 \psi S + \mu_S S |H|^2 \implies \theta_{h\pi_D} \simeq \frac{v\mu_S}{m_S^2}\frac{\Lambda_{\rm dQCD}^2}{4\pi}\frac{1}{m_h^2 - m_S^2}\,.$

Phenomenology of neutron portal

Decay channels

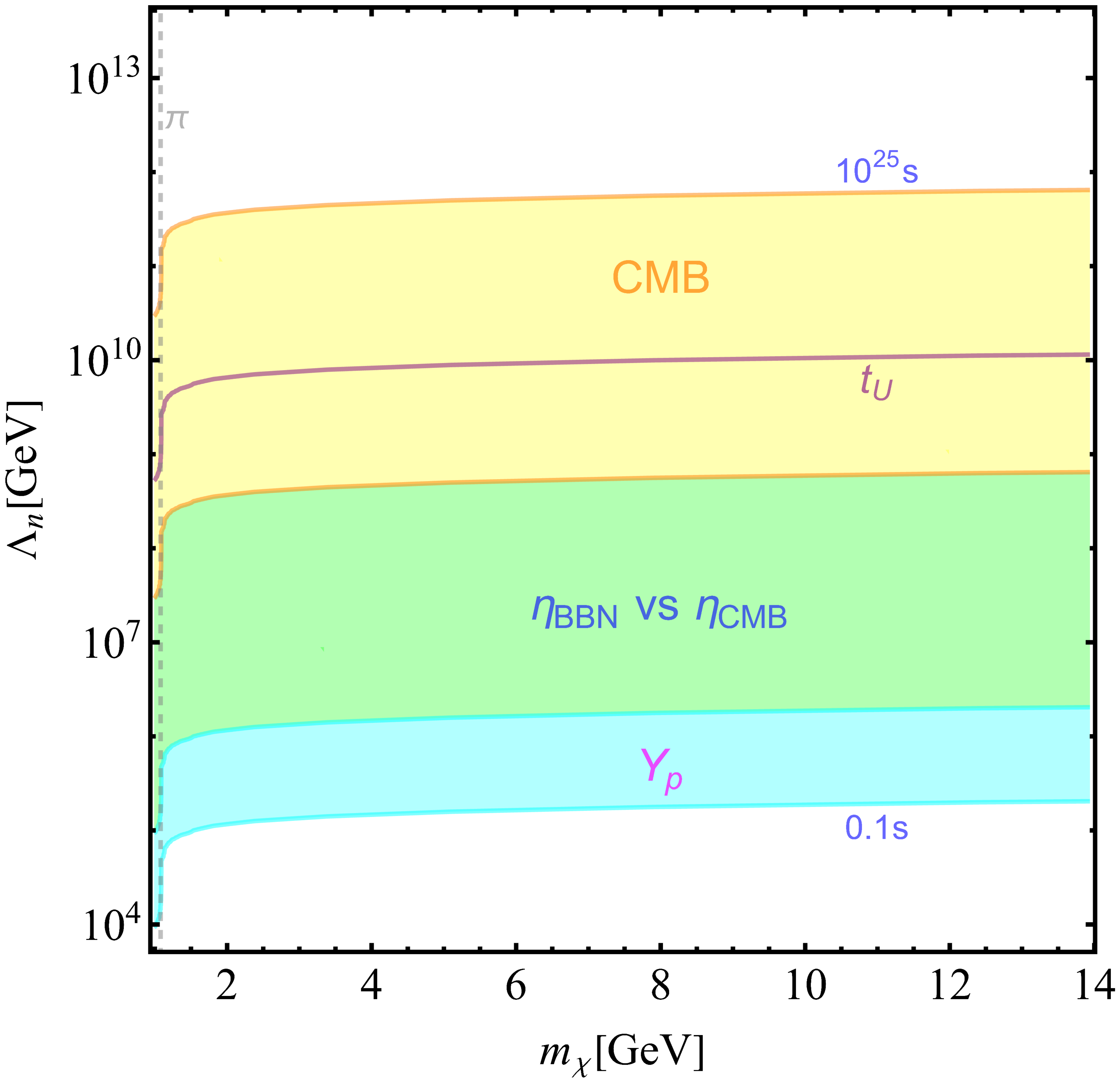
$$m_\chi < m_n + m_\pi : \quad \chi \to n\gamma,\ \chi \to p e^- \bar{\nu}$$

$$m_\chi > m_n + m_\pi : \quad \chi \to n\pi^0,\ \chi \to p\pi^-$$

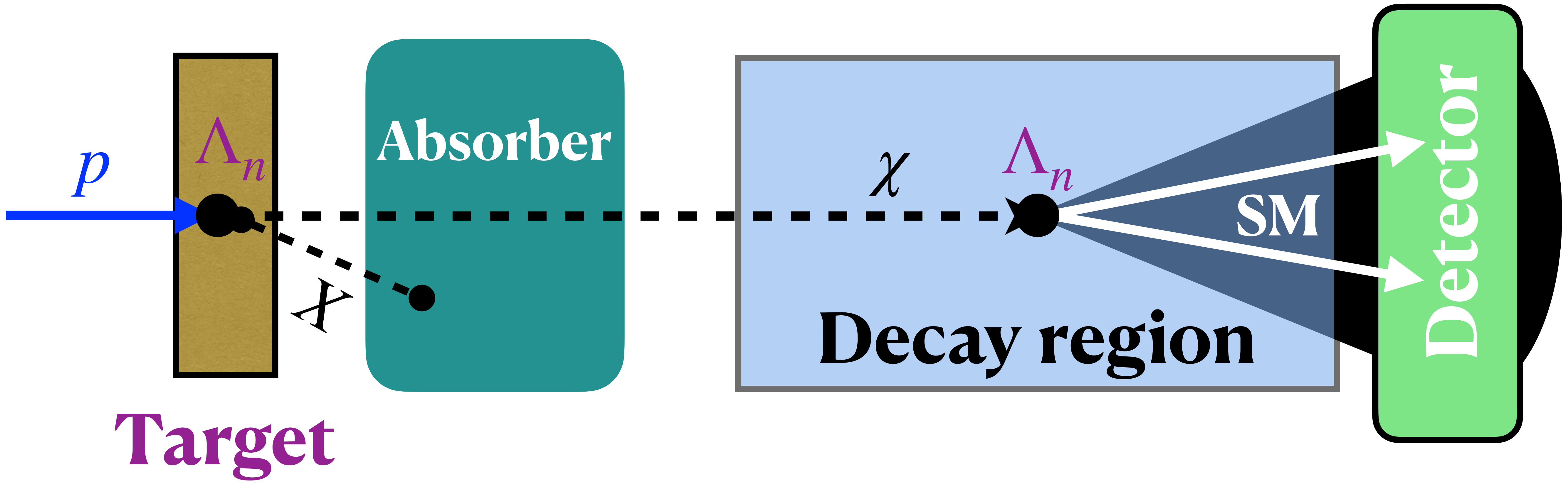
These meson induced $\Gamma^{\text{strong}}_{n\leftrightarrow p}$ never dominates $\Gamma^{\text{weak}}_{n\leftrightarrow p}$

χ abundance is set by asymmetry $\simeq$ baryon abundance

Decay time (s)	Constraint
$1 - 200$	$\delta Y_p \lesssim 0.01$
$10^3 - 10^{13}$	$\delta\eta/\eta \lesssim 0.039$
$10^{13} - 10^{25}$	CMB ionization



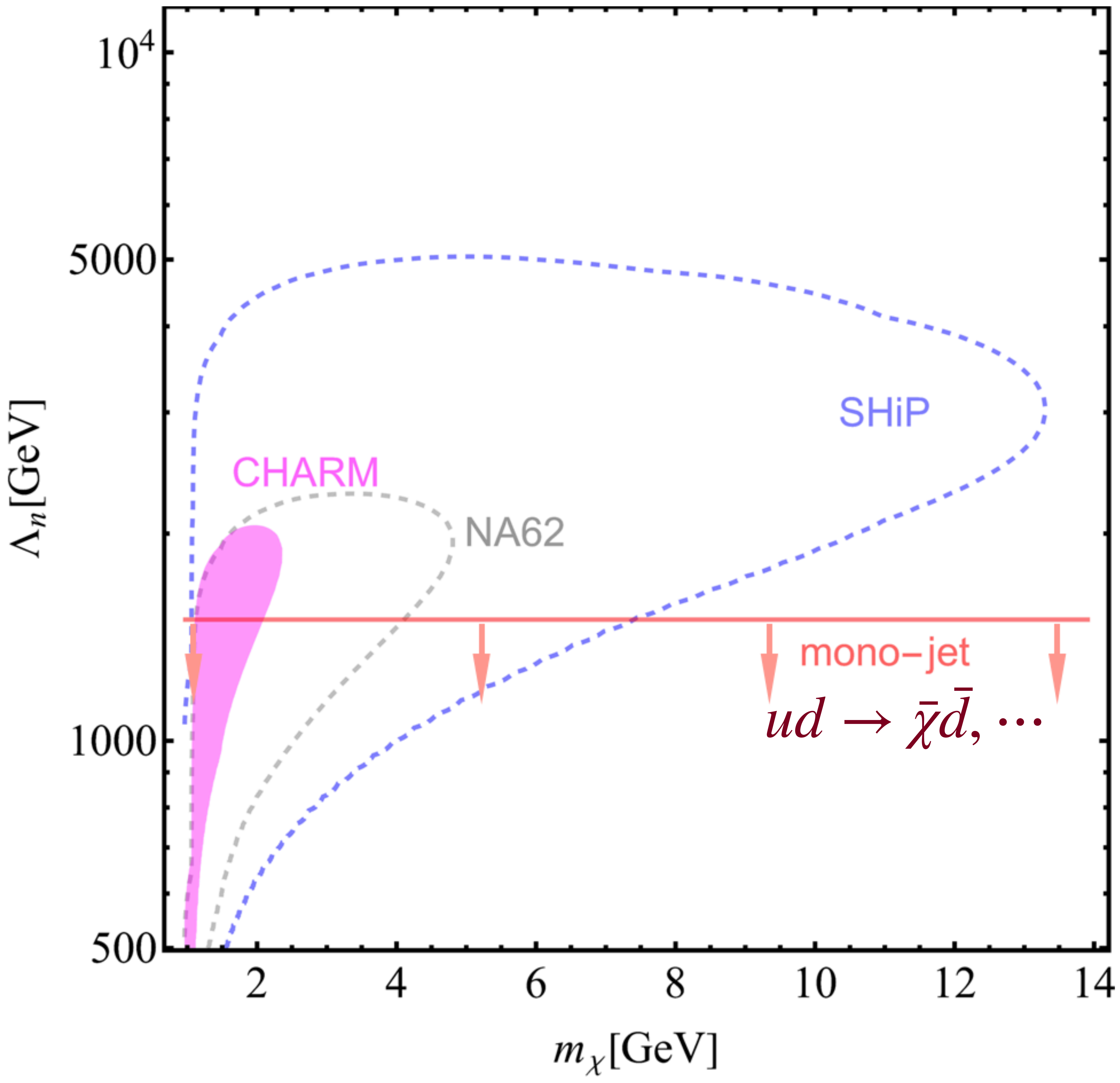
Experimental signatures of the neutron portal



Obtained from MadGraph

$$N_\chi = \frac{N_{\rm p.o.t}}{\sigma_{pN}} \int \frac{d\sigma_{pN\to\chi+X}}{dE_\chi d\theta}\, p(\ell_\chi)\, \varepsilon_{\rm rec}\, dE_\chi d\theta \geq 3$$

Decay probability



Conclusions

- ✓ **Dark first-order phase transition** is a promising interpretation of the observed PTA signal.
- ✓ The strong supercooling needed dilutes away pre-existing baryon asymmetry and DM, posing a challenge to this scenario.
- ✓ We provide **new mechanisms** where the baryon asymmetry and DM are produced utilizing the phase transition.
- ✓ **GeV scale emerges** from the UV completion of the neutron portal.

Thank you for your time. Questions?