Quest for a Consistent Phase Transition Explanation of the PTA signal

Sudhakantha Girmohanta

IBS, CTPU-PTC

Based on:

1. S. Girmohanta, Y. Nakai, Y. Shigekami and Z. Zhang [arXiv: 2604.21168, accepted in JHEP]
2. K. Fujikura, S. Girmohanta, Y. Nakai and Z. Zhang [Phys. Lett. B 858 (2024) 139045]
3. K. Fujikura, S. Girmohanta, Y. Nakai and M. Suzuki [Phys. Lett. B 846 (2023) 138203]

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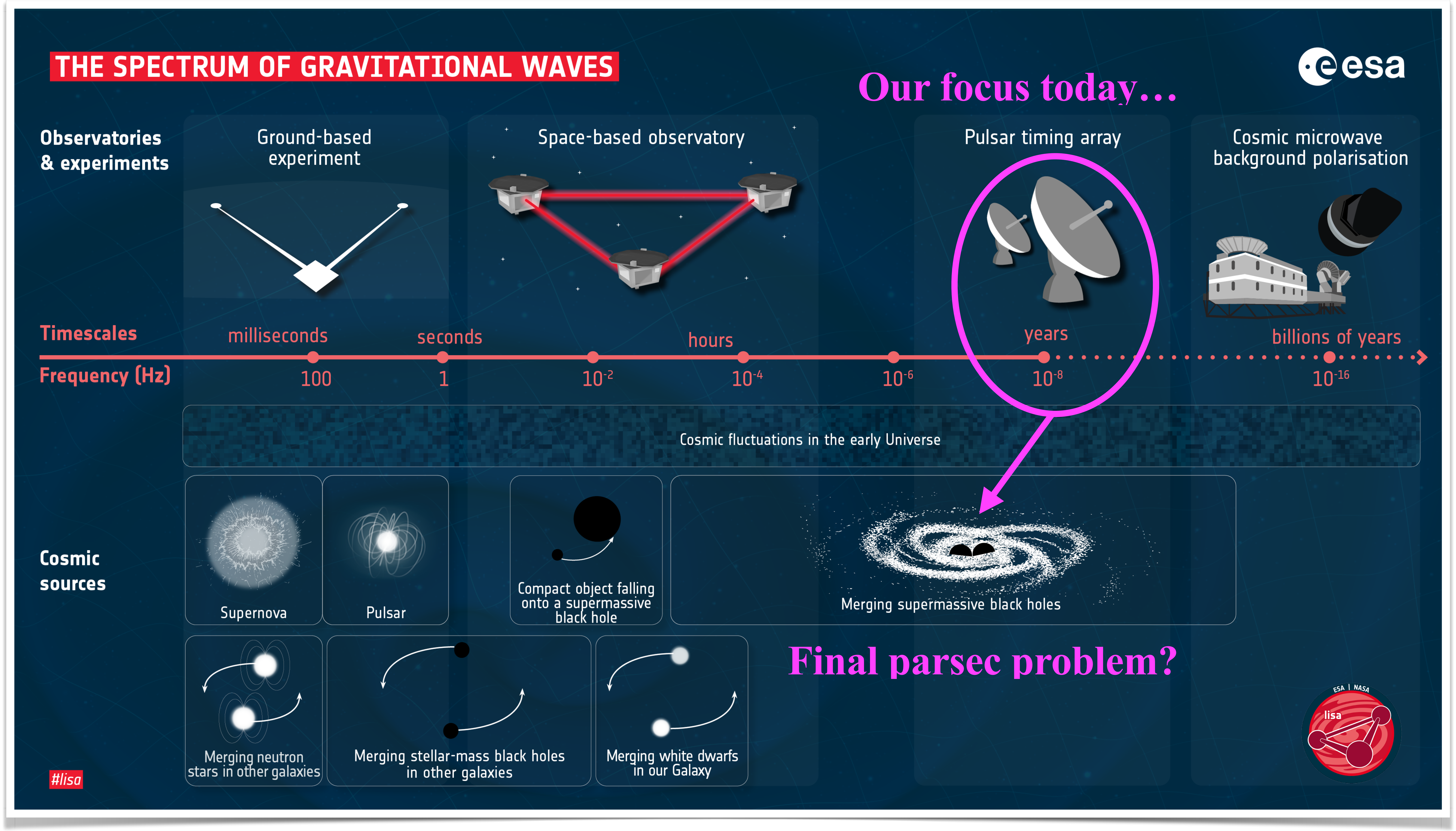
SSU 2026 Busan

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

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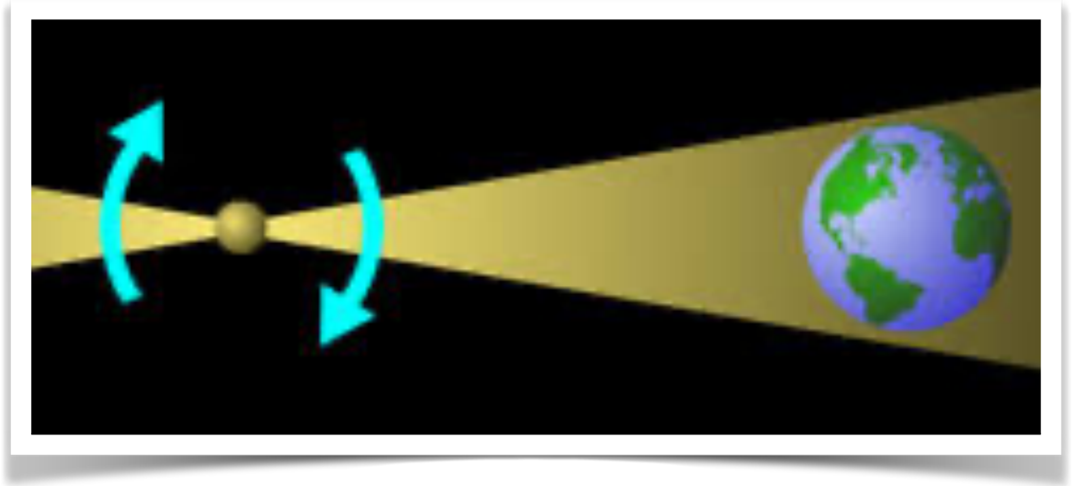
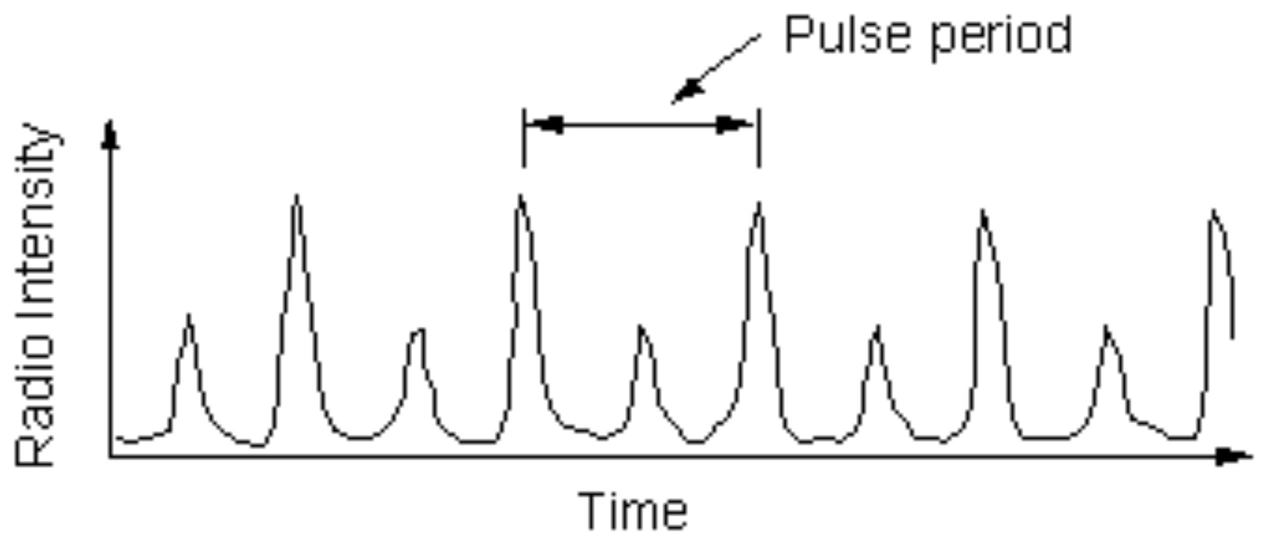
Pulsars are precise clocks.





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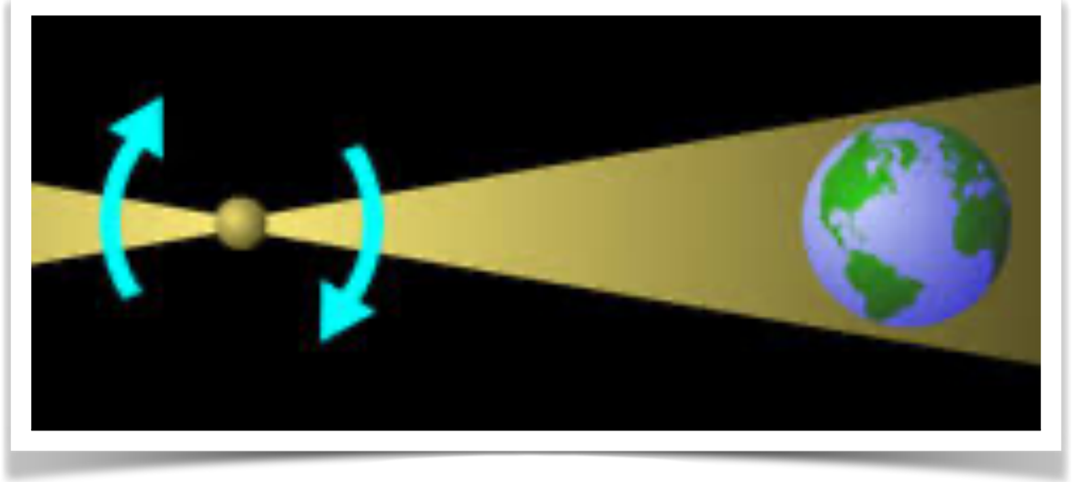

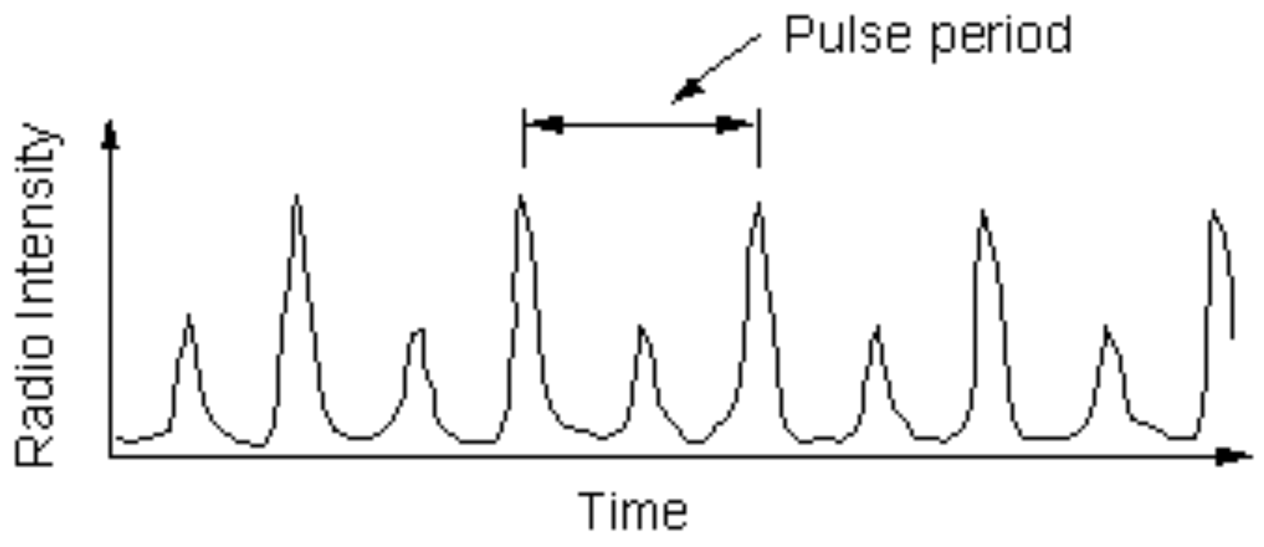

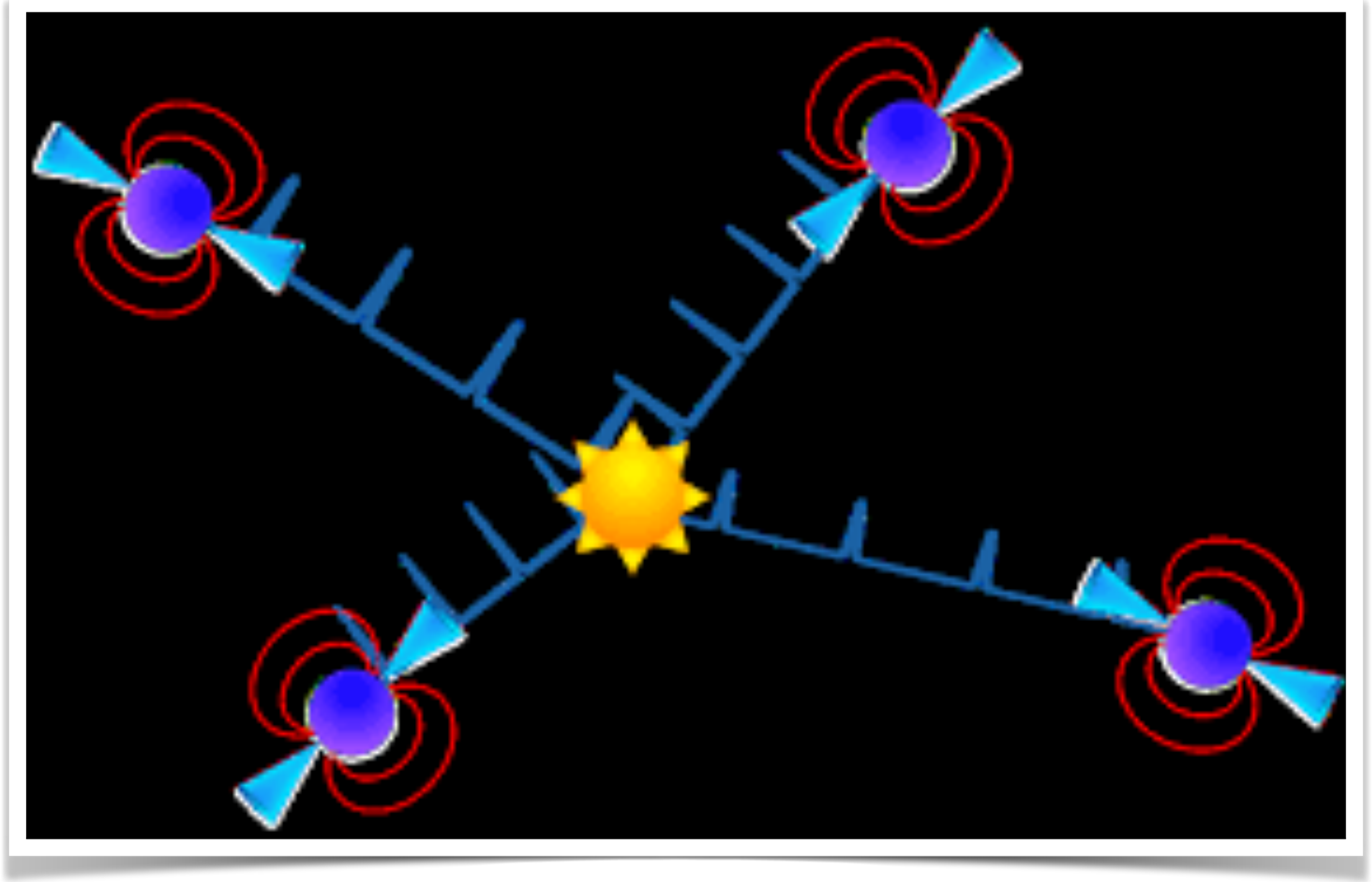

Earth-pulsar system as gravitational wave antenna.

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

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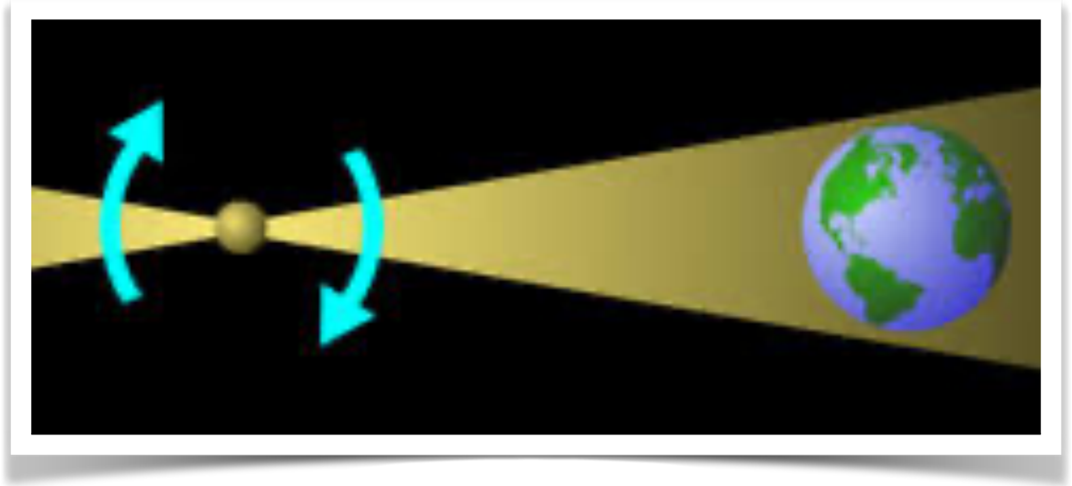

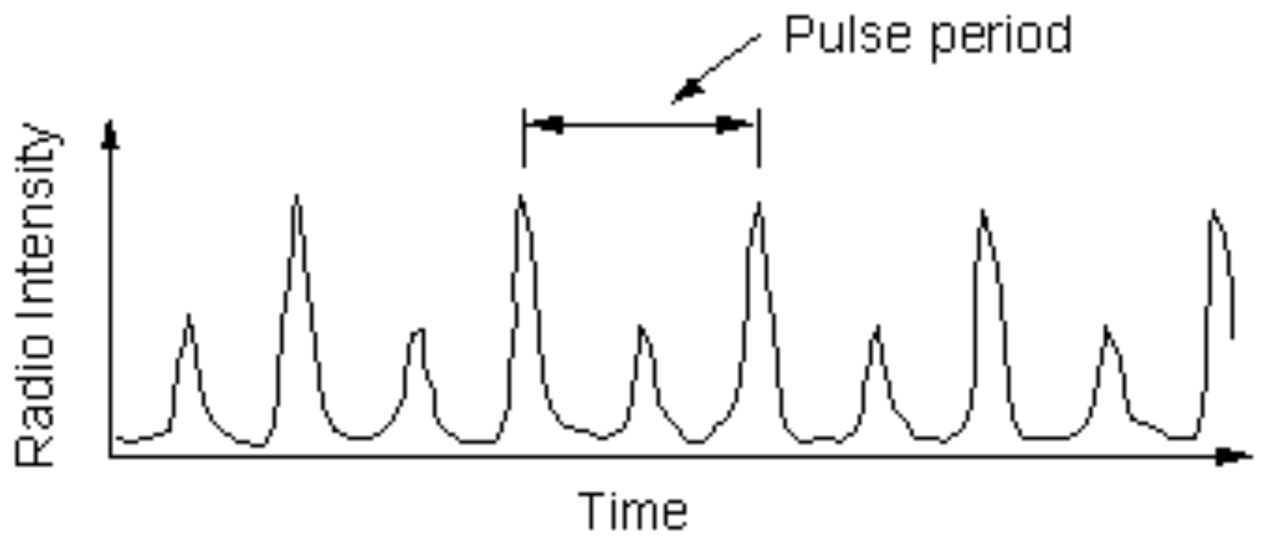

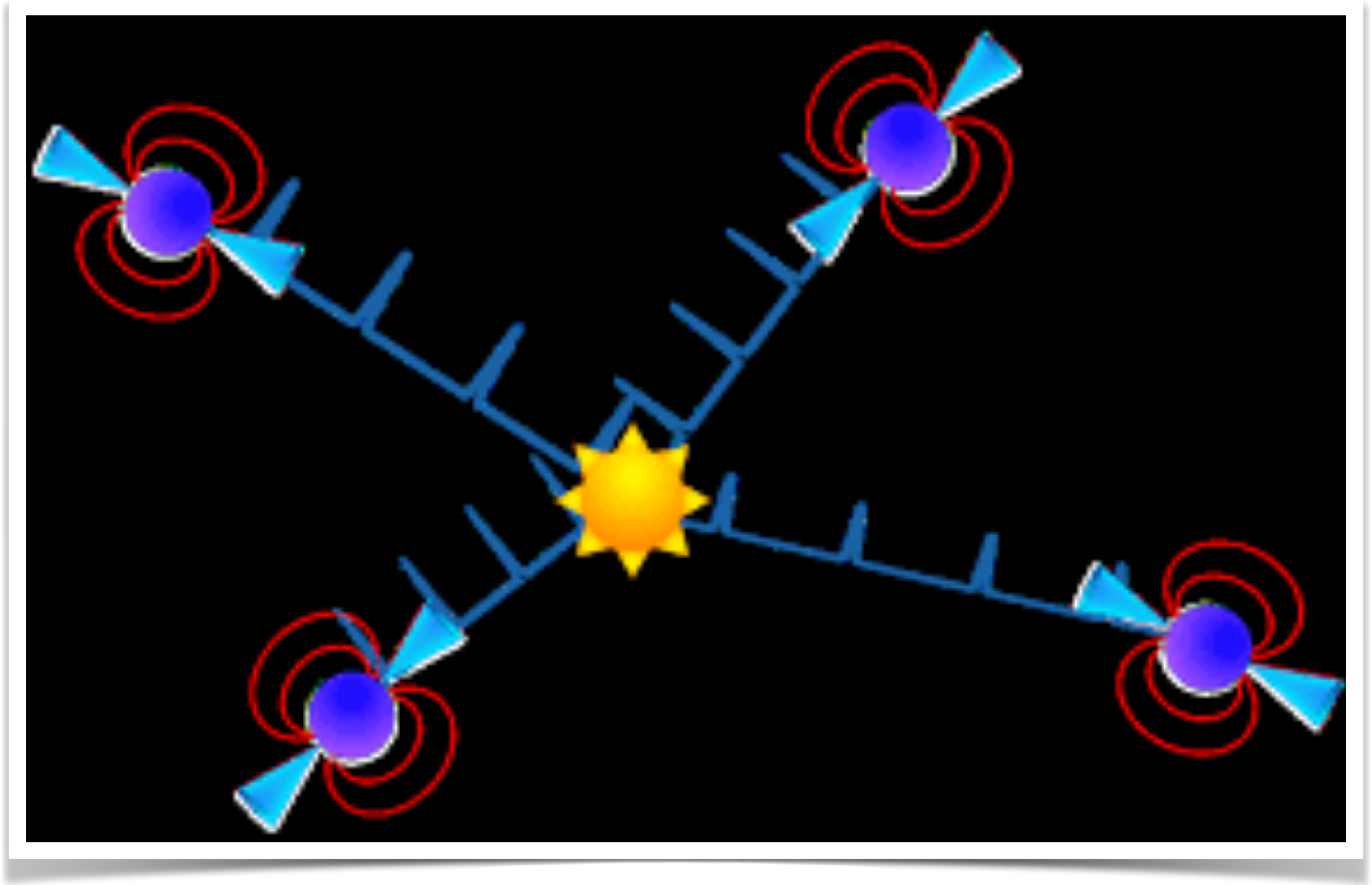

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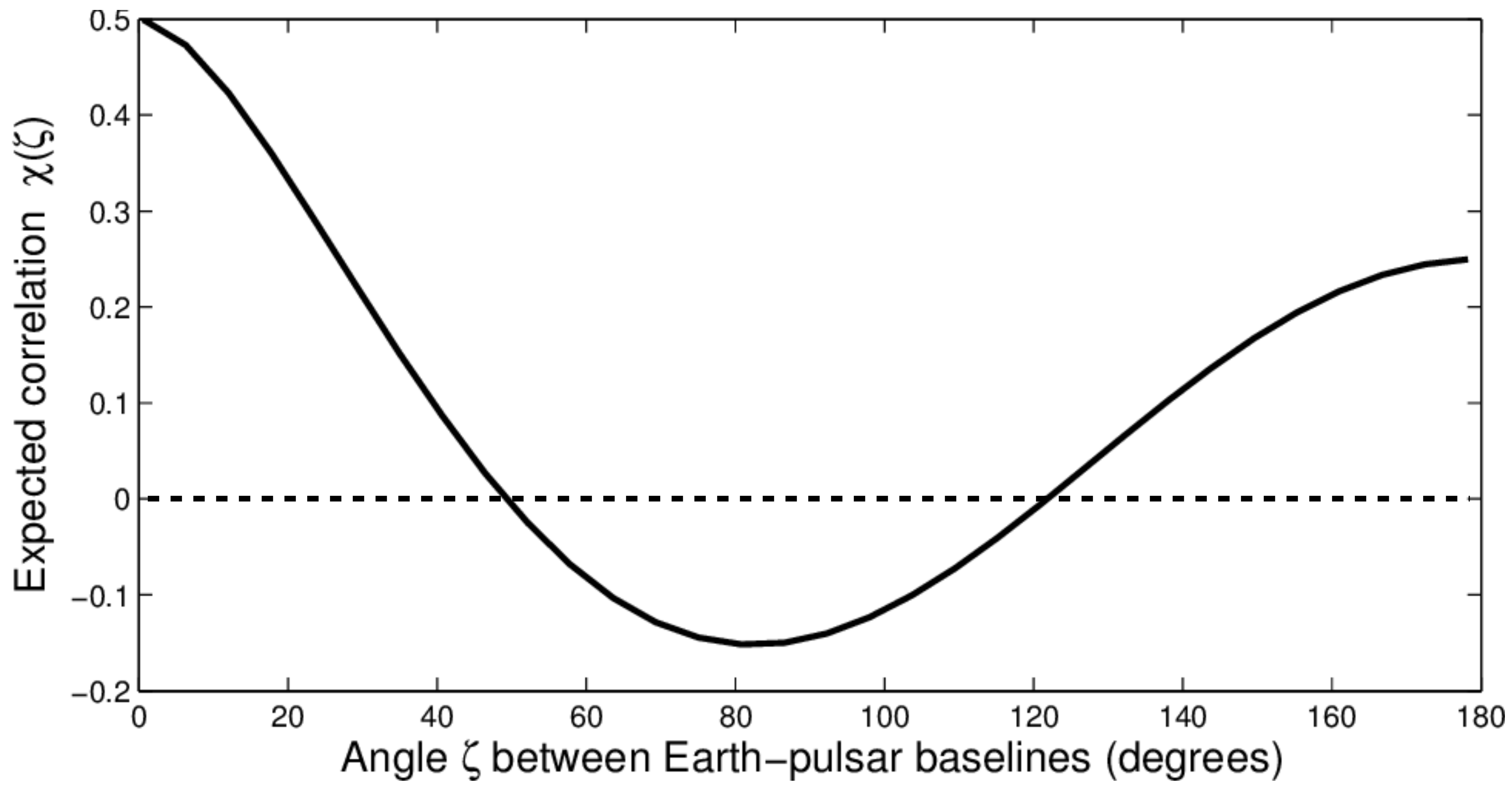
GW: distinctive quadrupolar inter-pulsar correlation.



PTA discovery of nano-Hz gravitational waves

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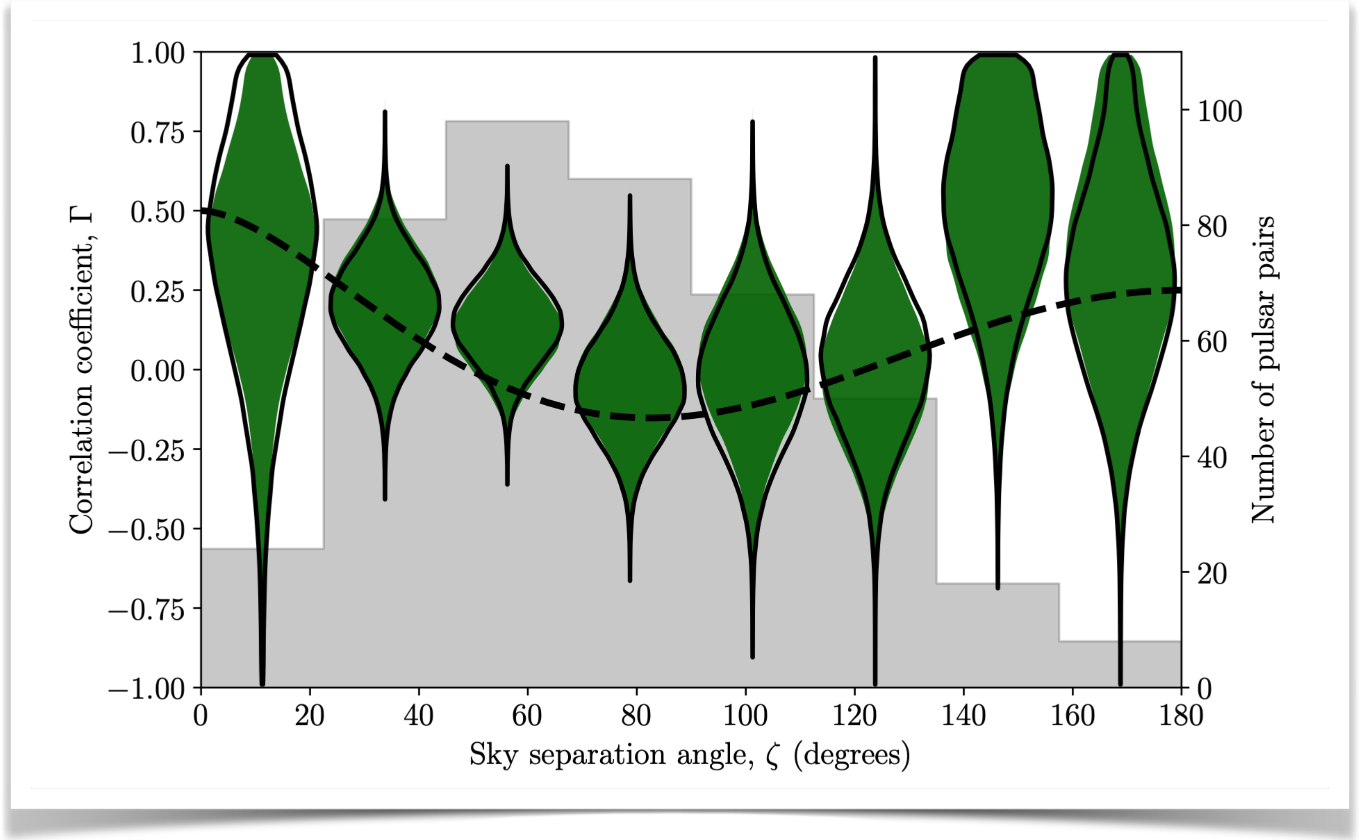
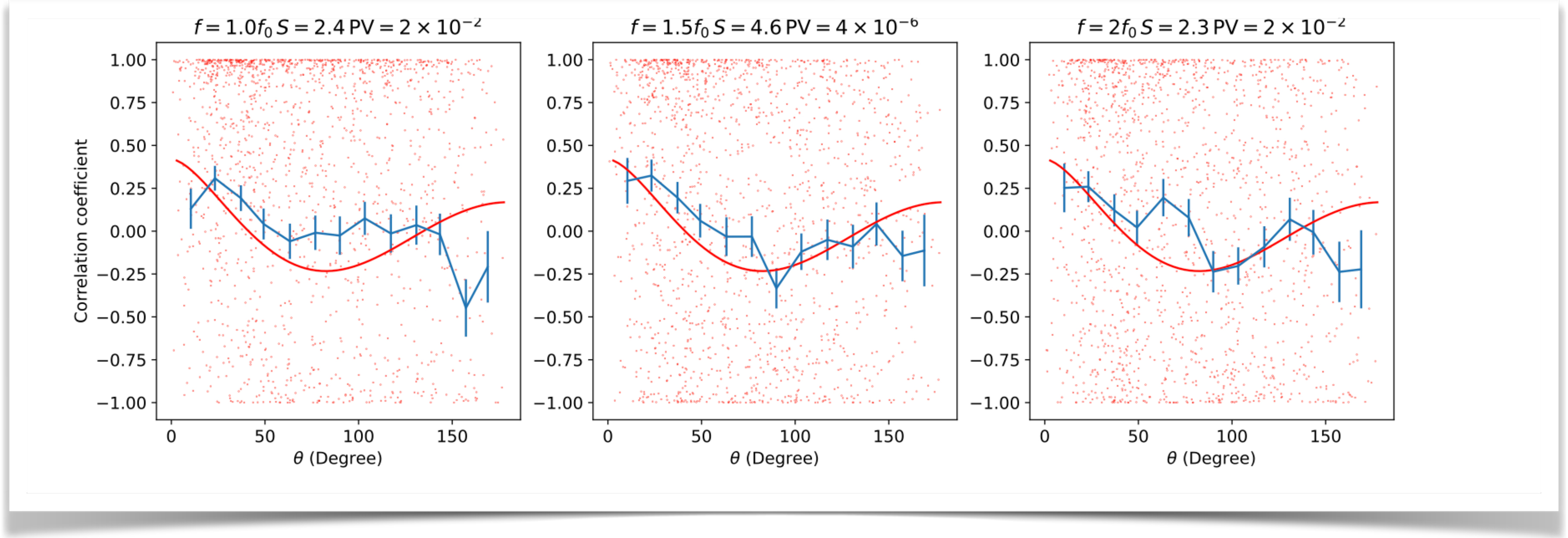
PTA collaborations have reported evidence for nano-Hz stochastic gravitational waves.

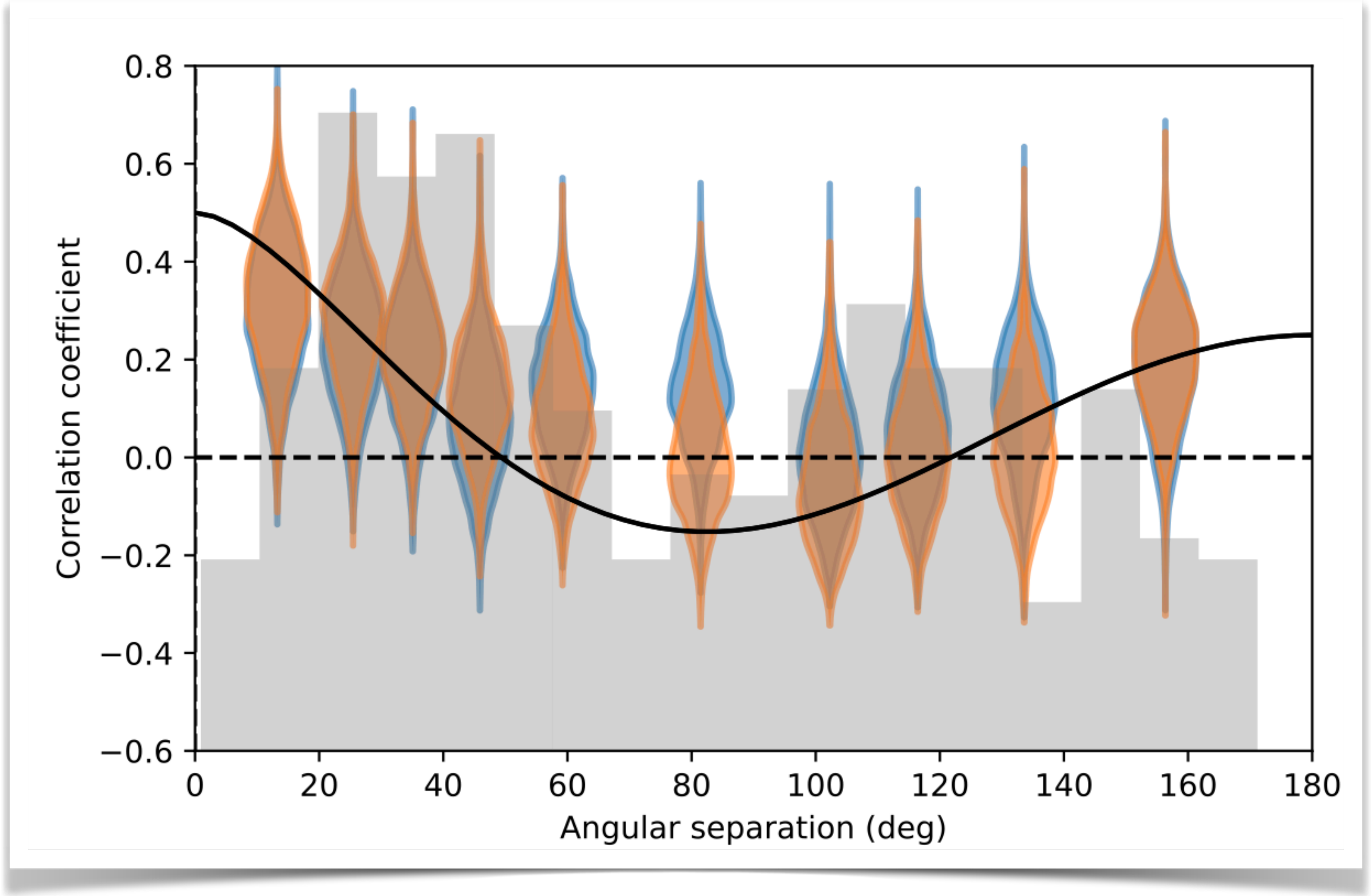
PPTA



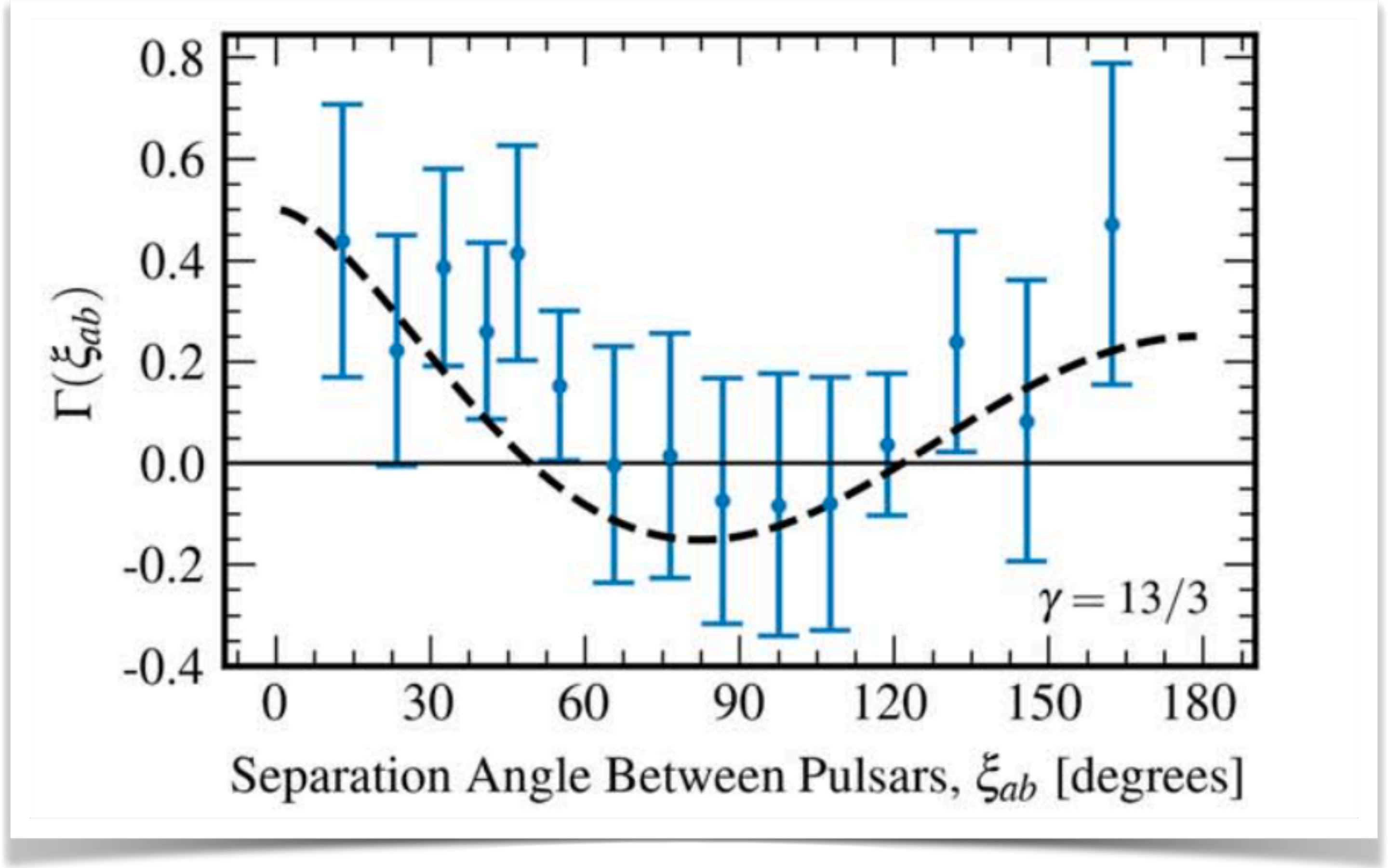
CPTA



EPTA+InPTA



NANOGrav



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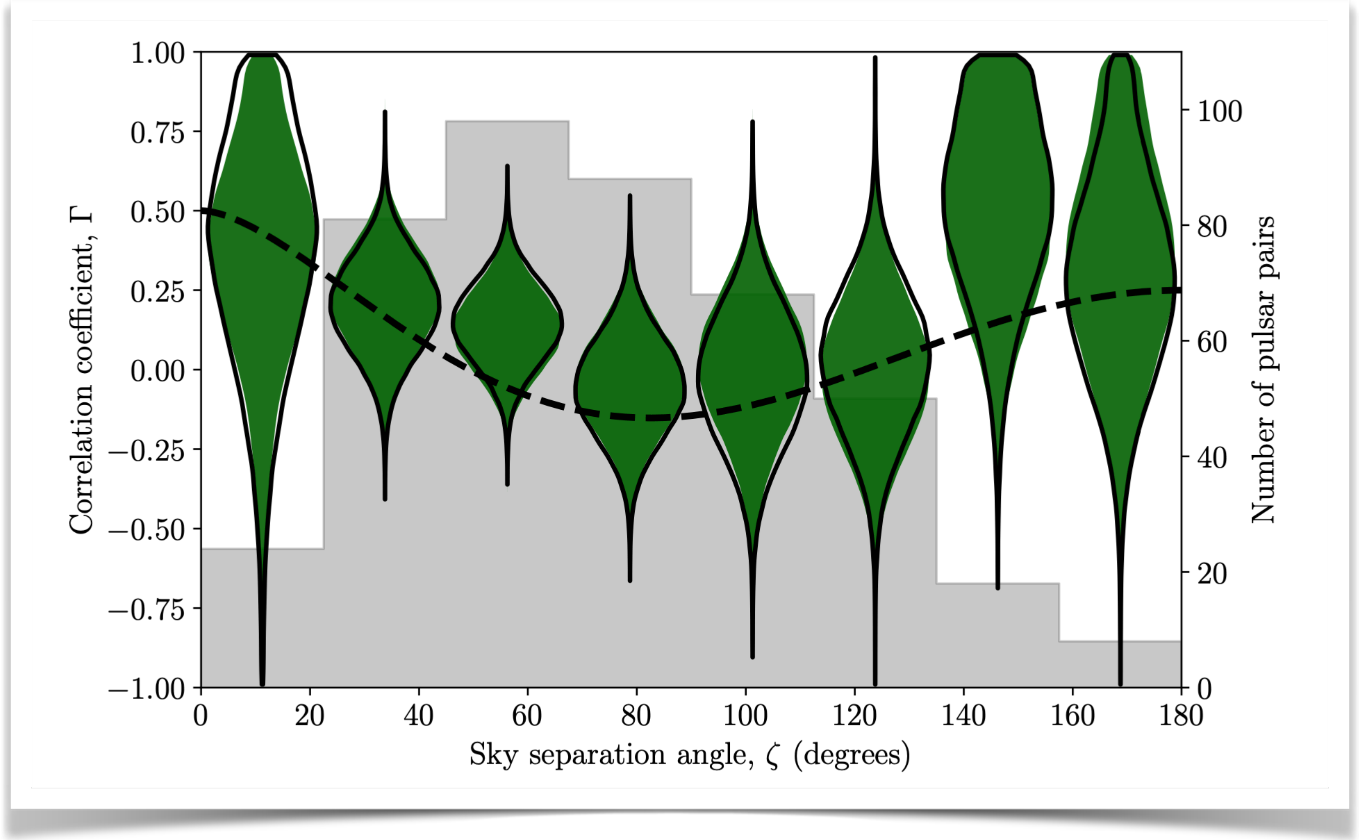

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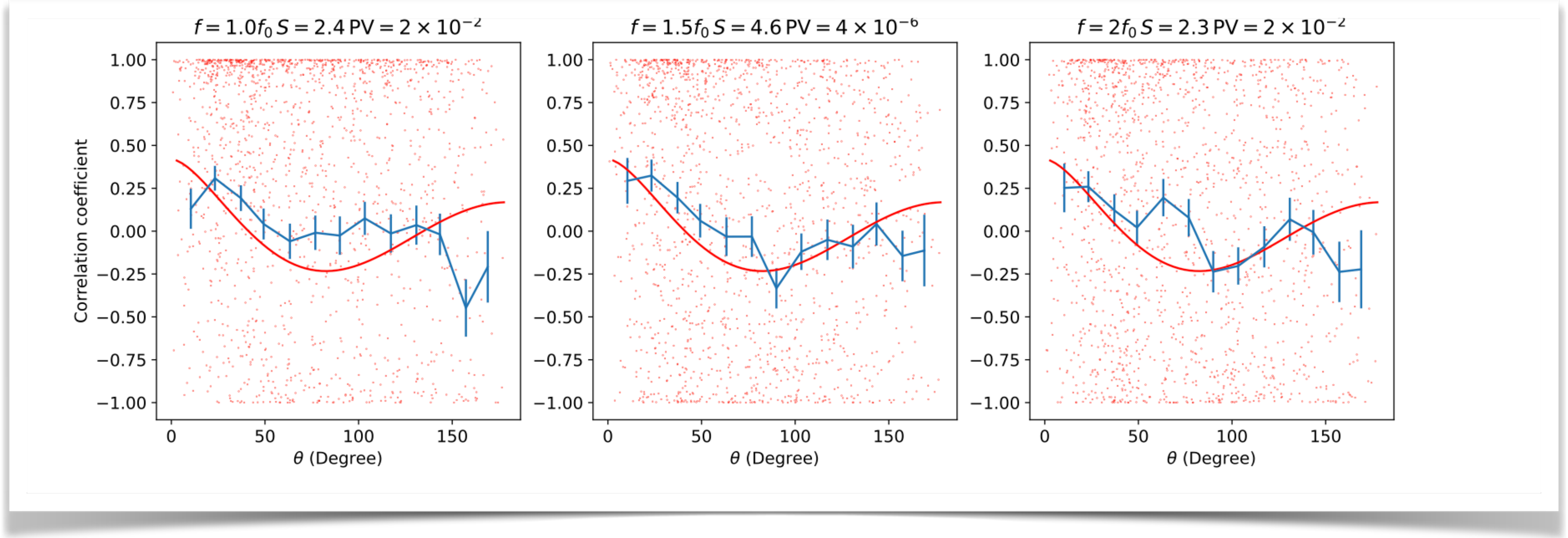

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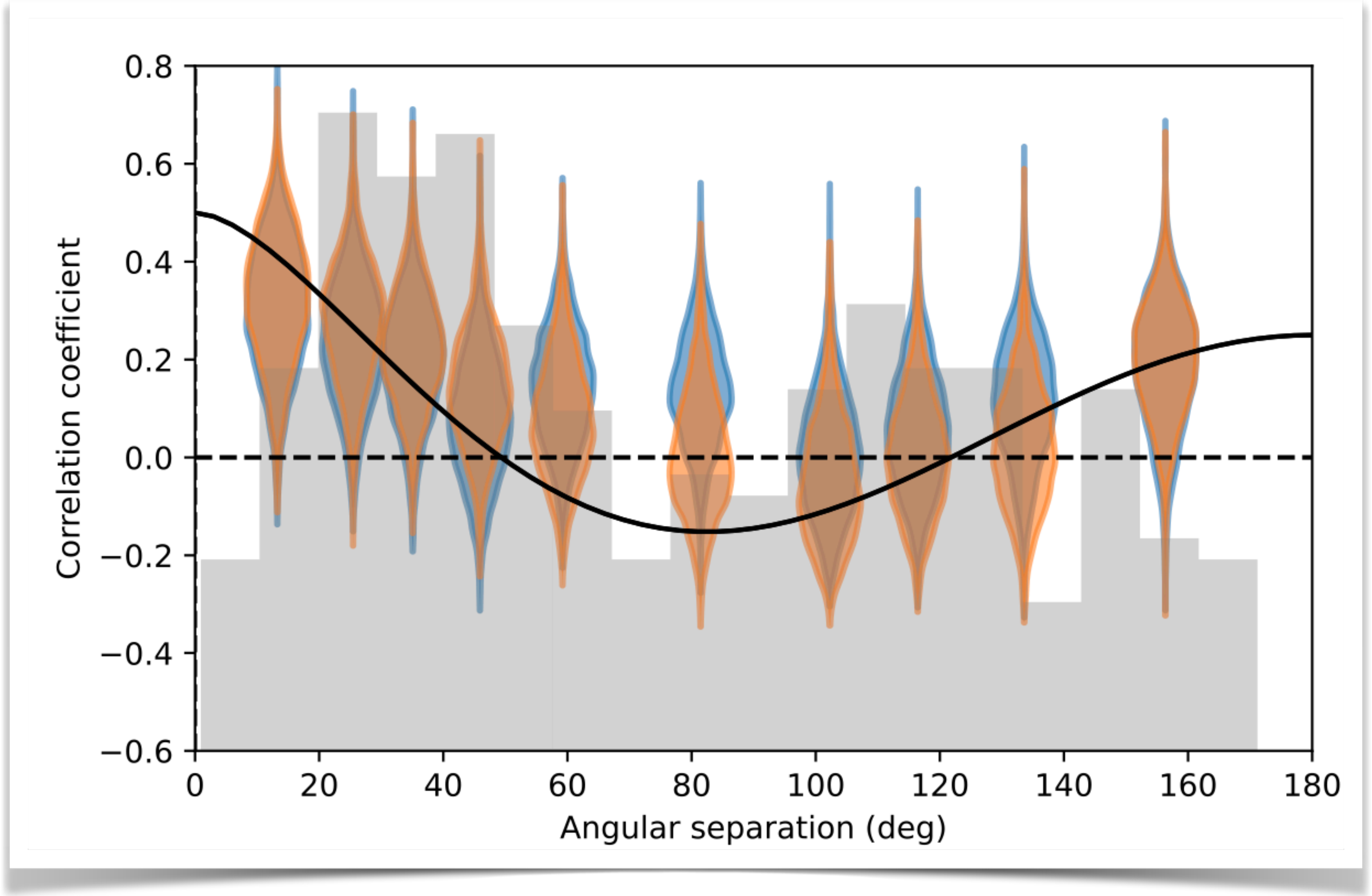
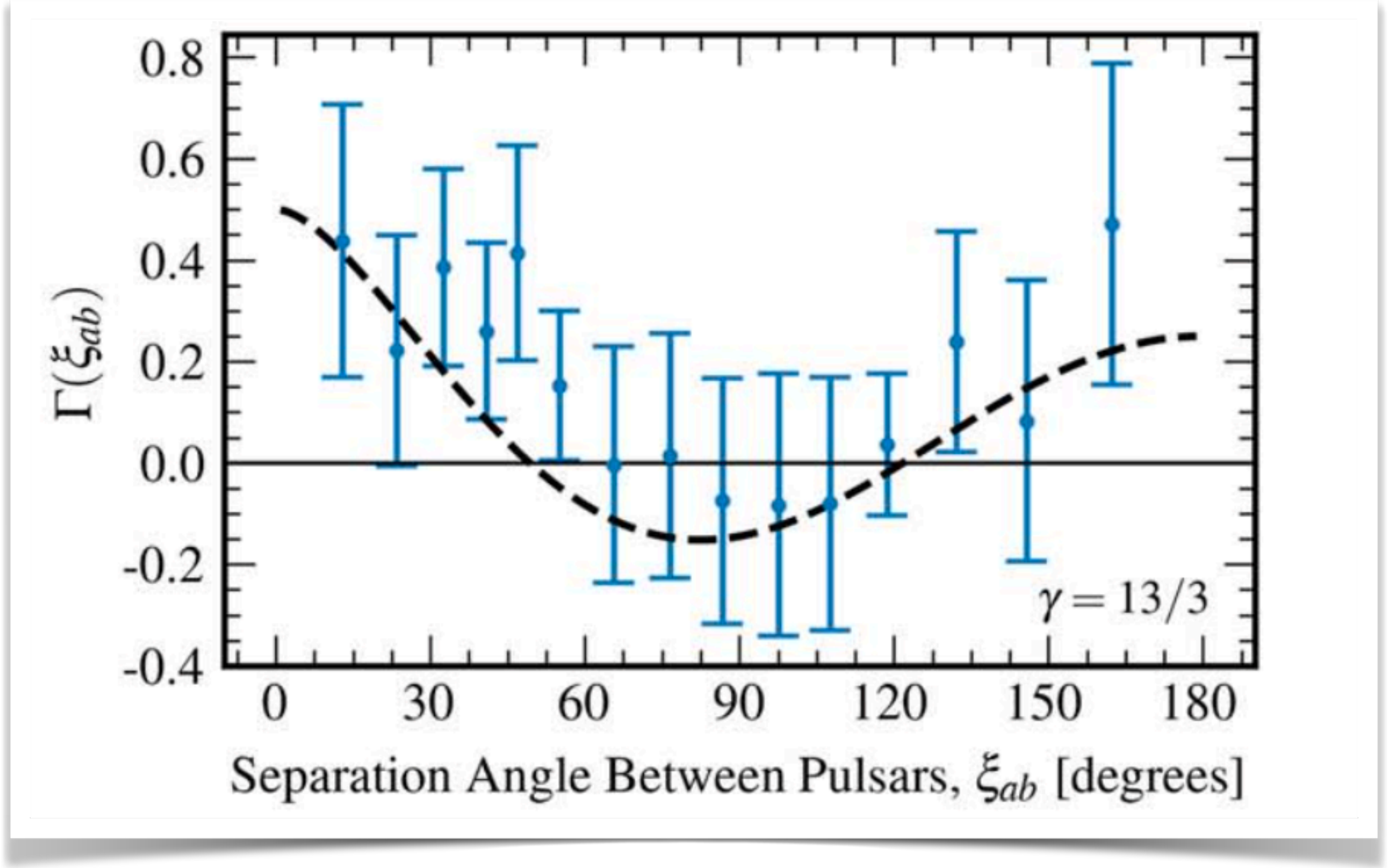


* Supermassive black hole binaries
* Defects: Cosmic strings, domain walls…

(See Peizhi Du’s talk)

* **Cosmological phase transitions**

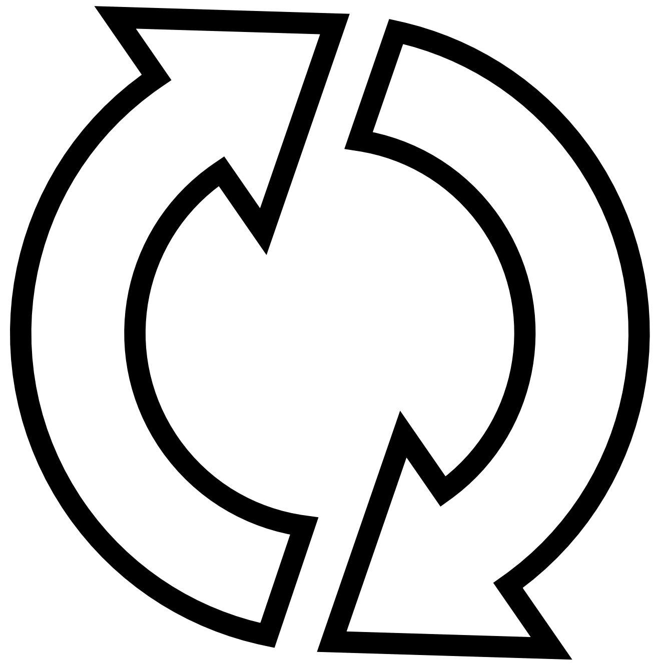
NANOGrav



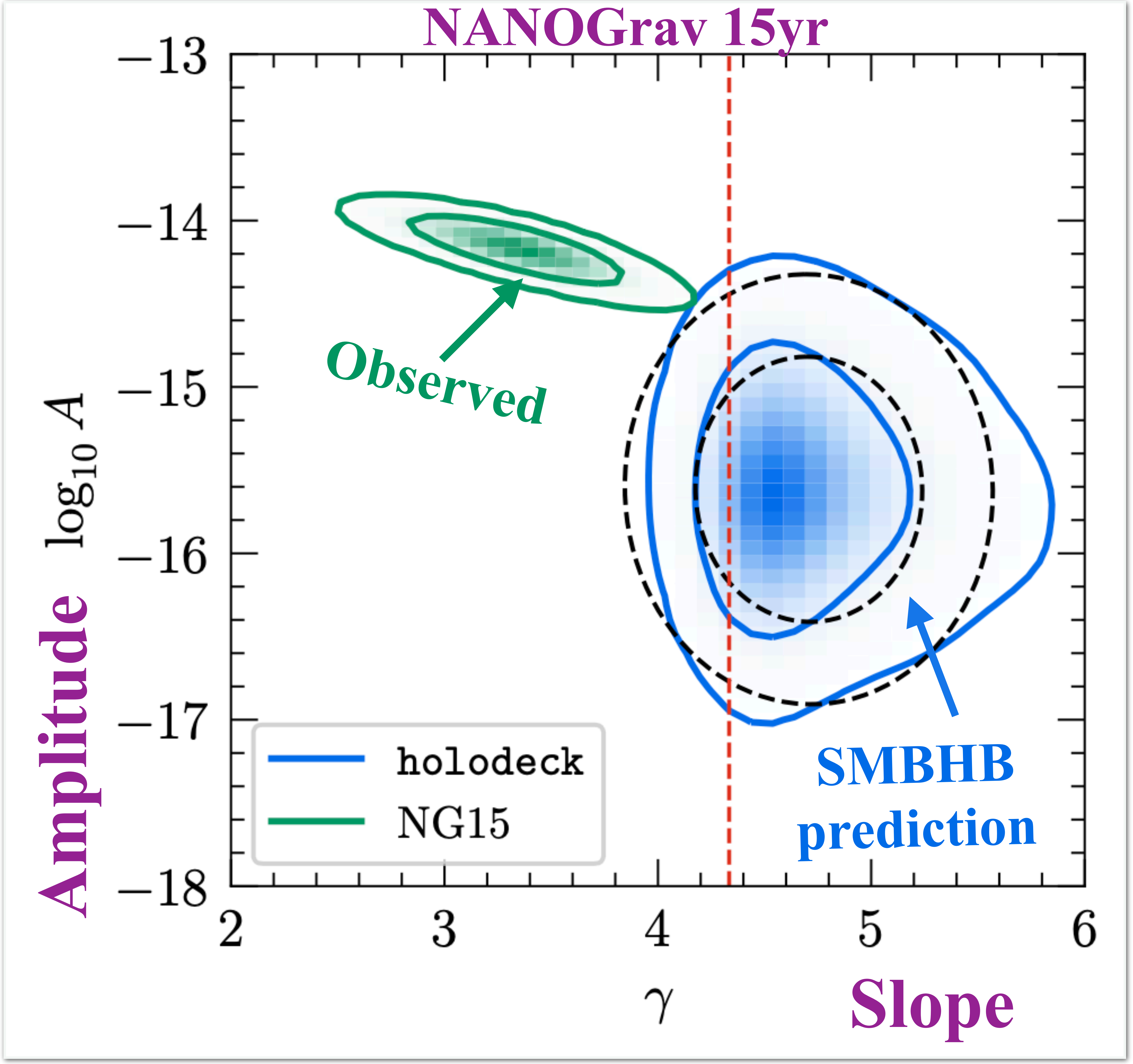
Phase transition interpretation of the PTA

Spectral Shape of the Observed GW Signal

- **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, **ask: is it consistent?**



Cosmological first-order phase transition

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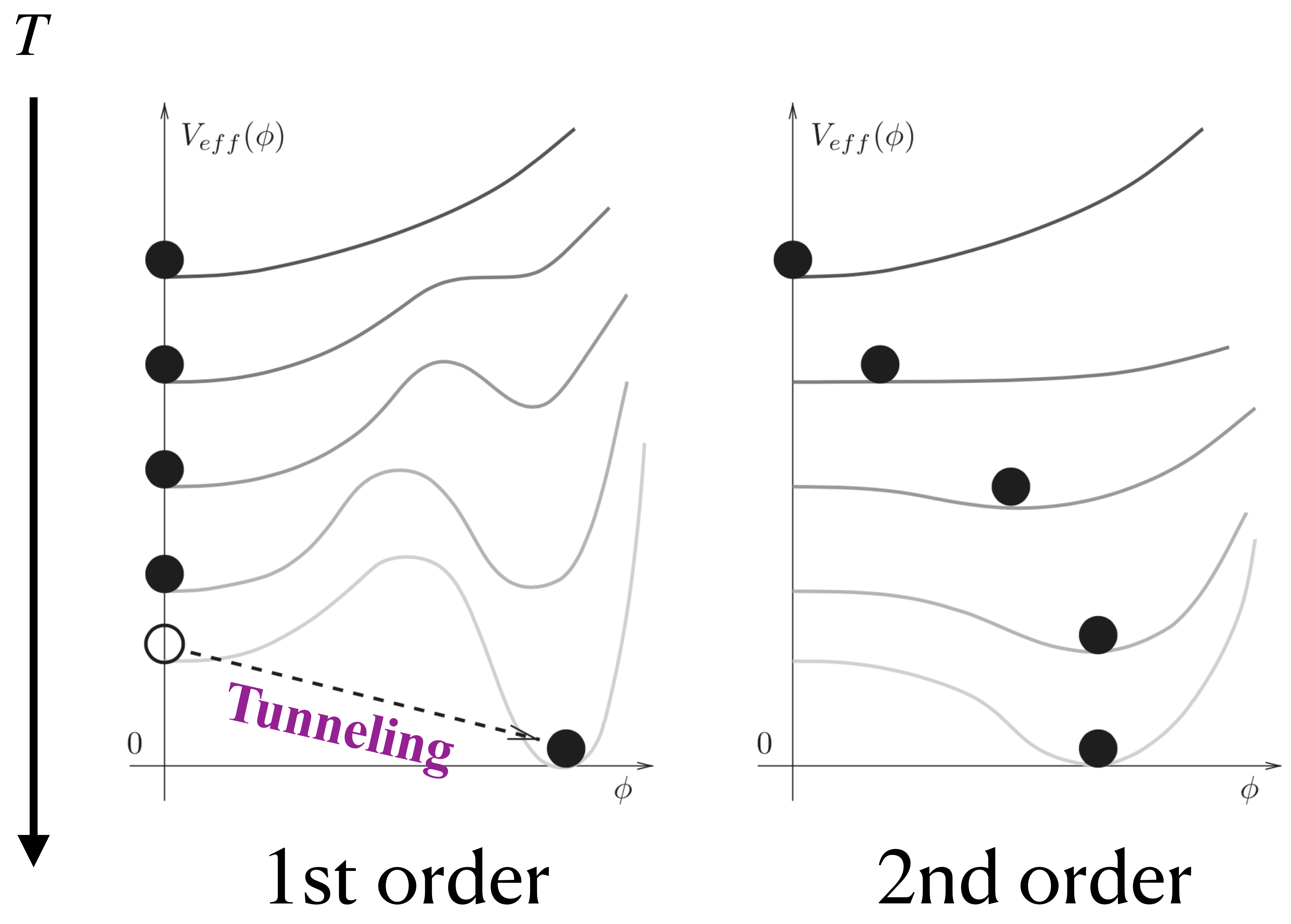
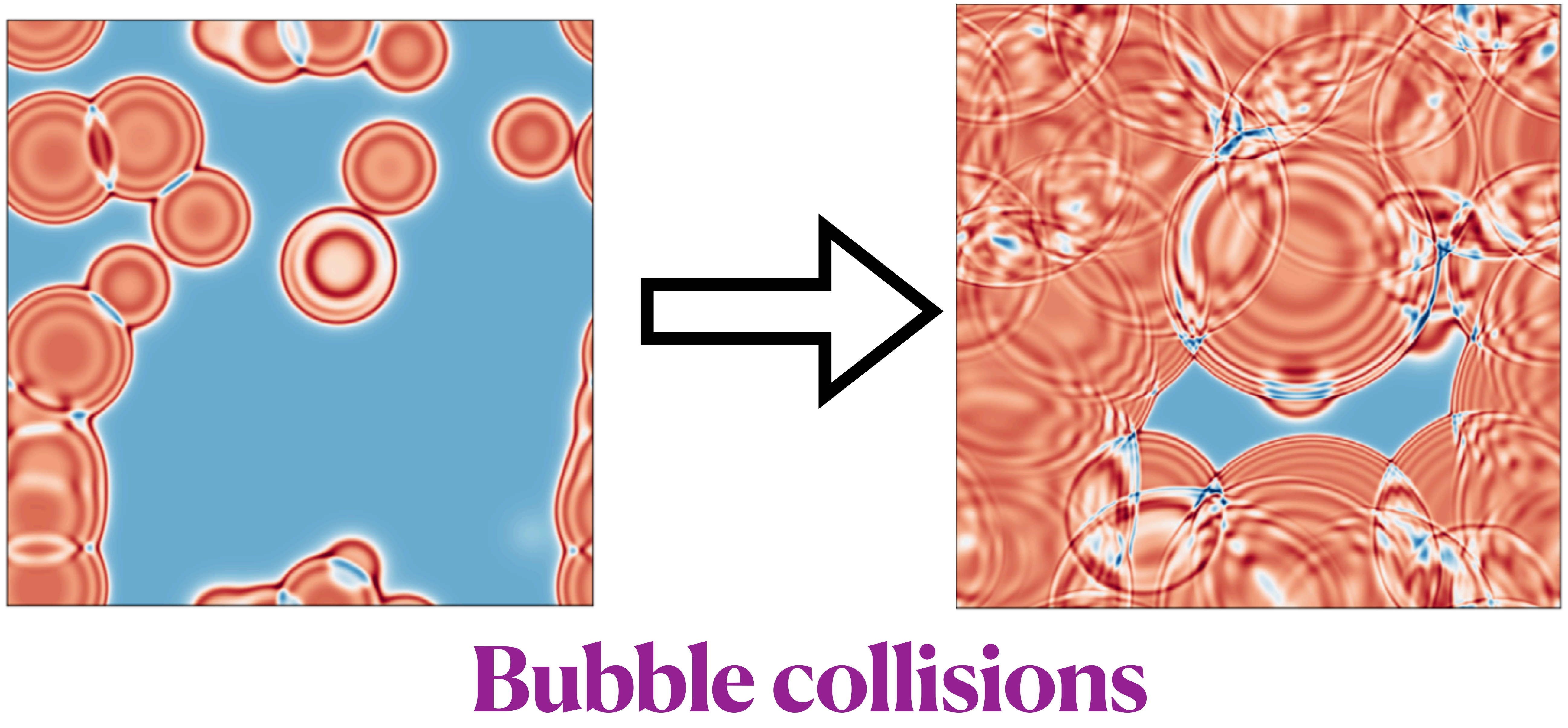


Generation of gravitational waves



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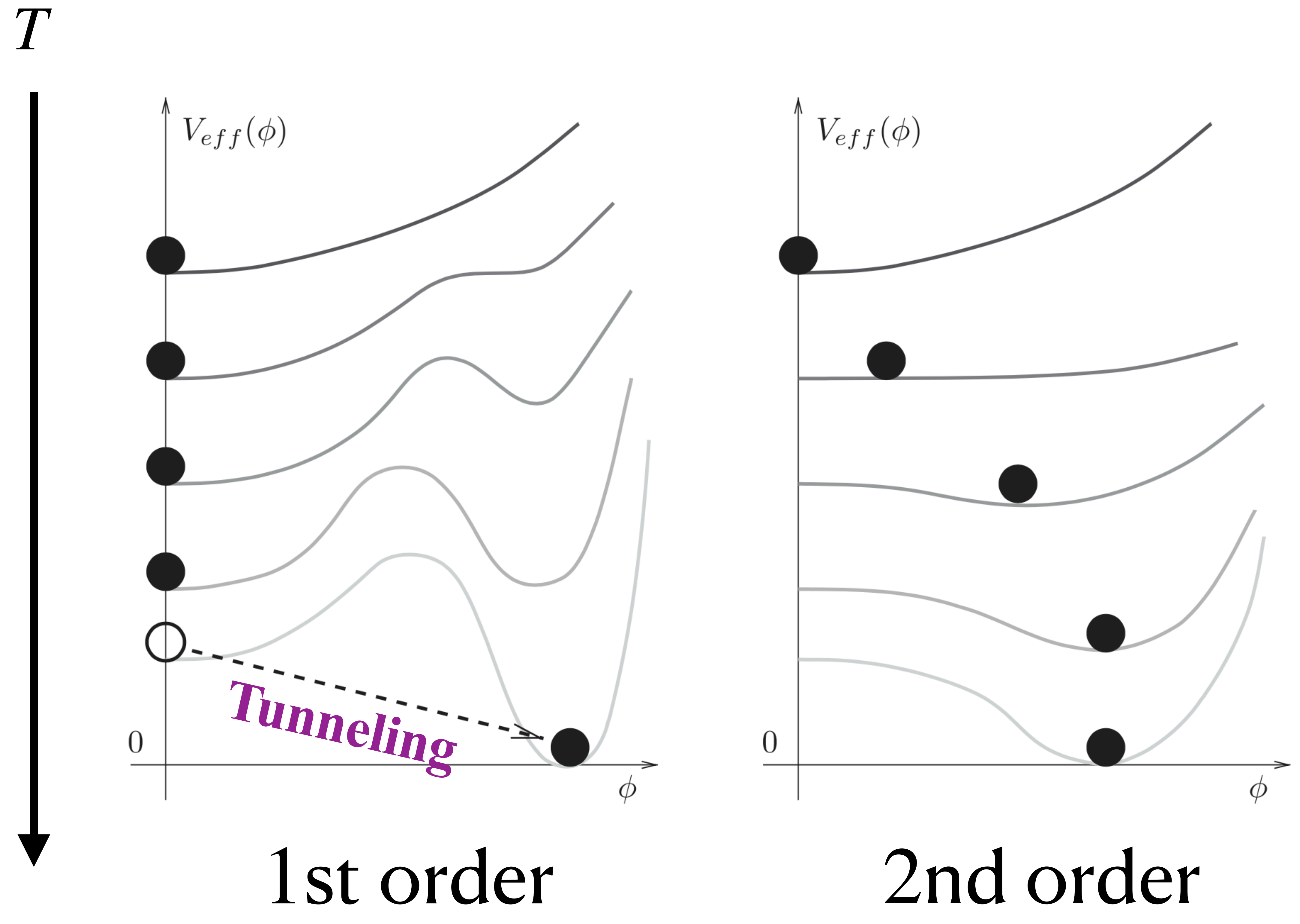

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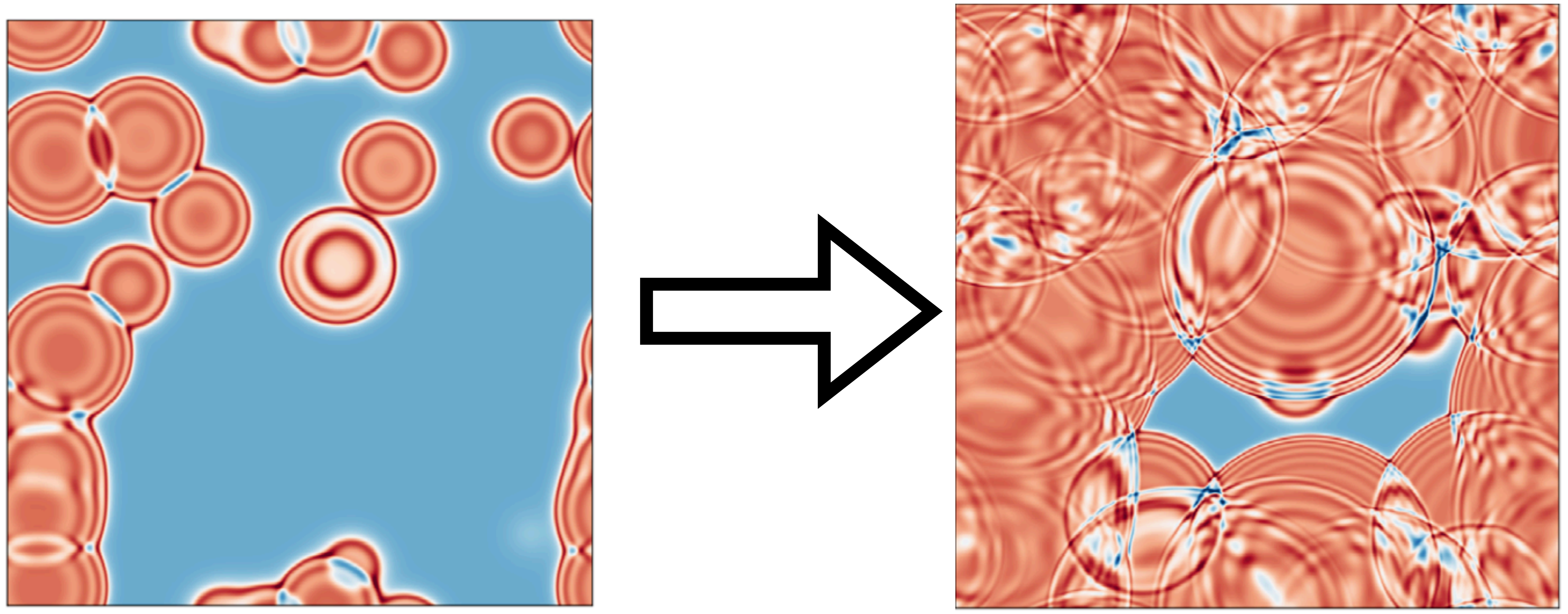

Bubble collisions

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

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

Key arguments

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The model:
Dark sector phase transition

Nearly conformal phase transition in a dark sector

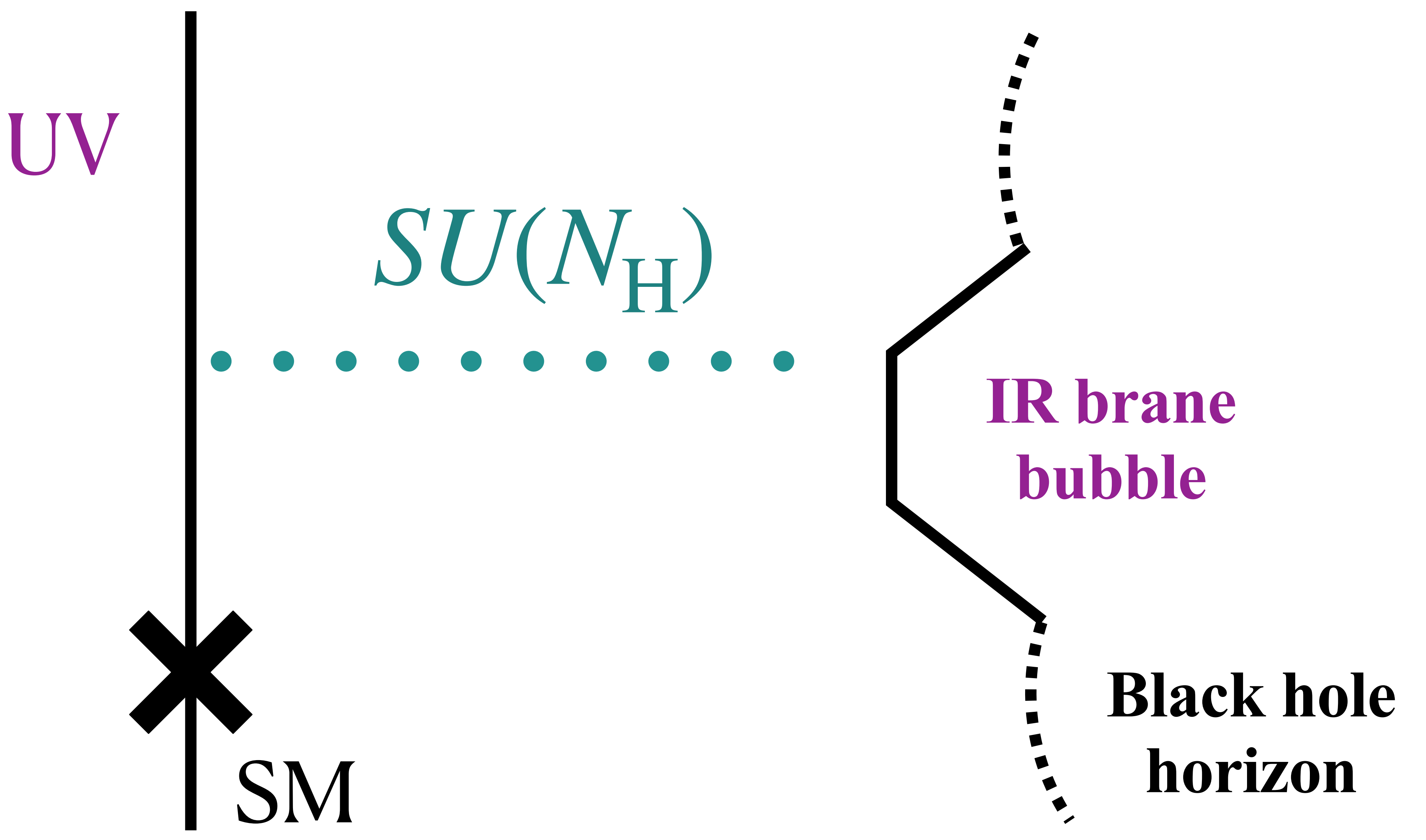
4D conformal dark sector with large N

$+$

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

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

$$\Rightarrow$$

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

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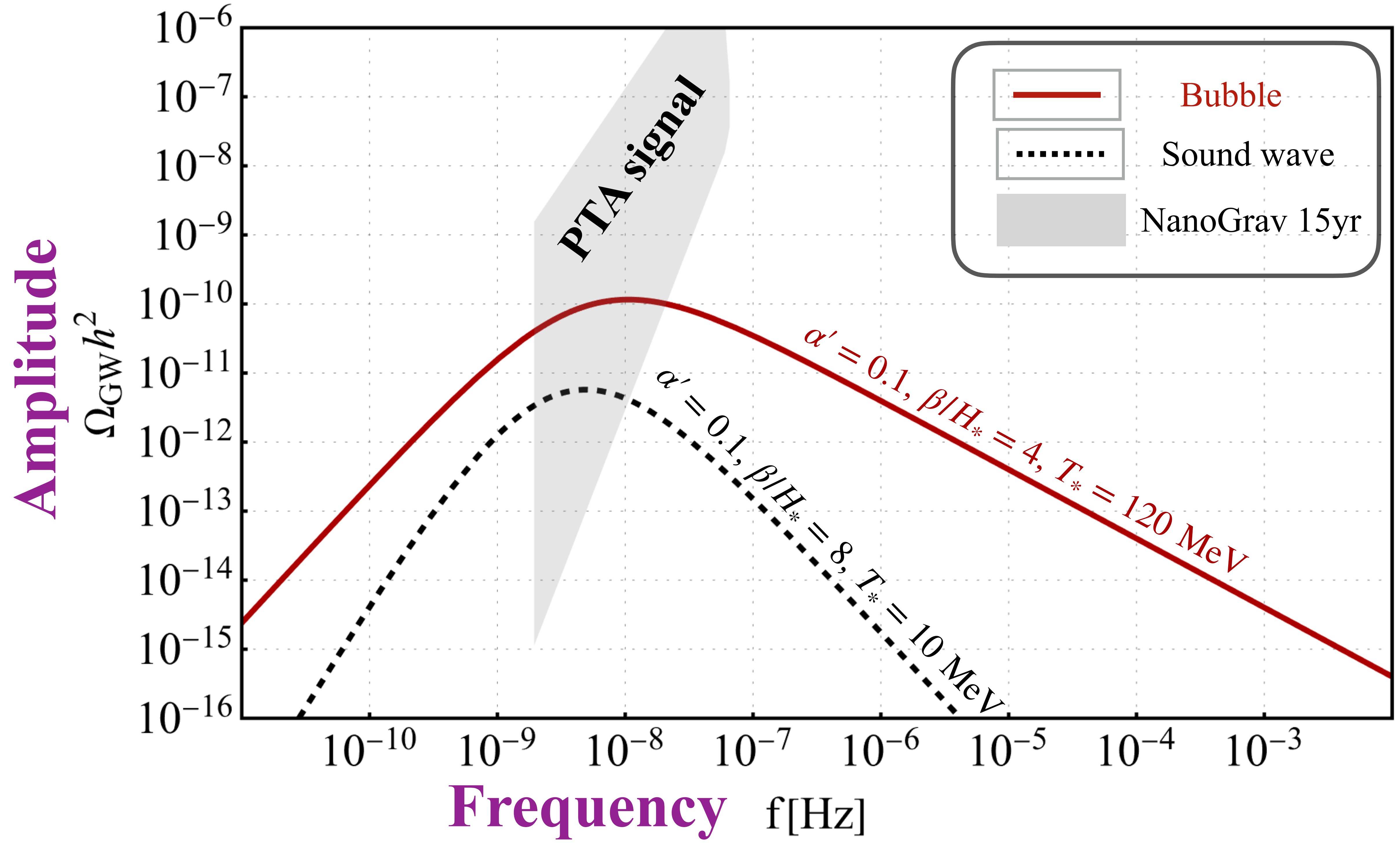
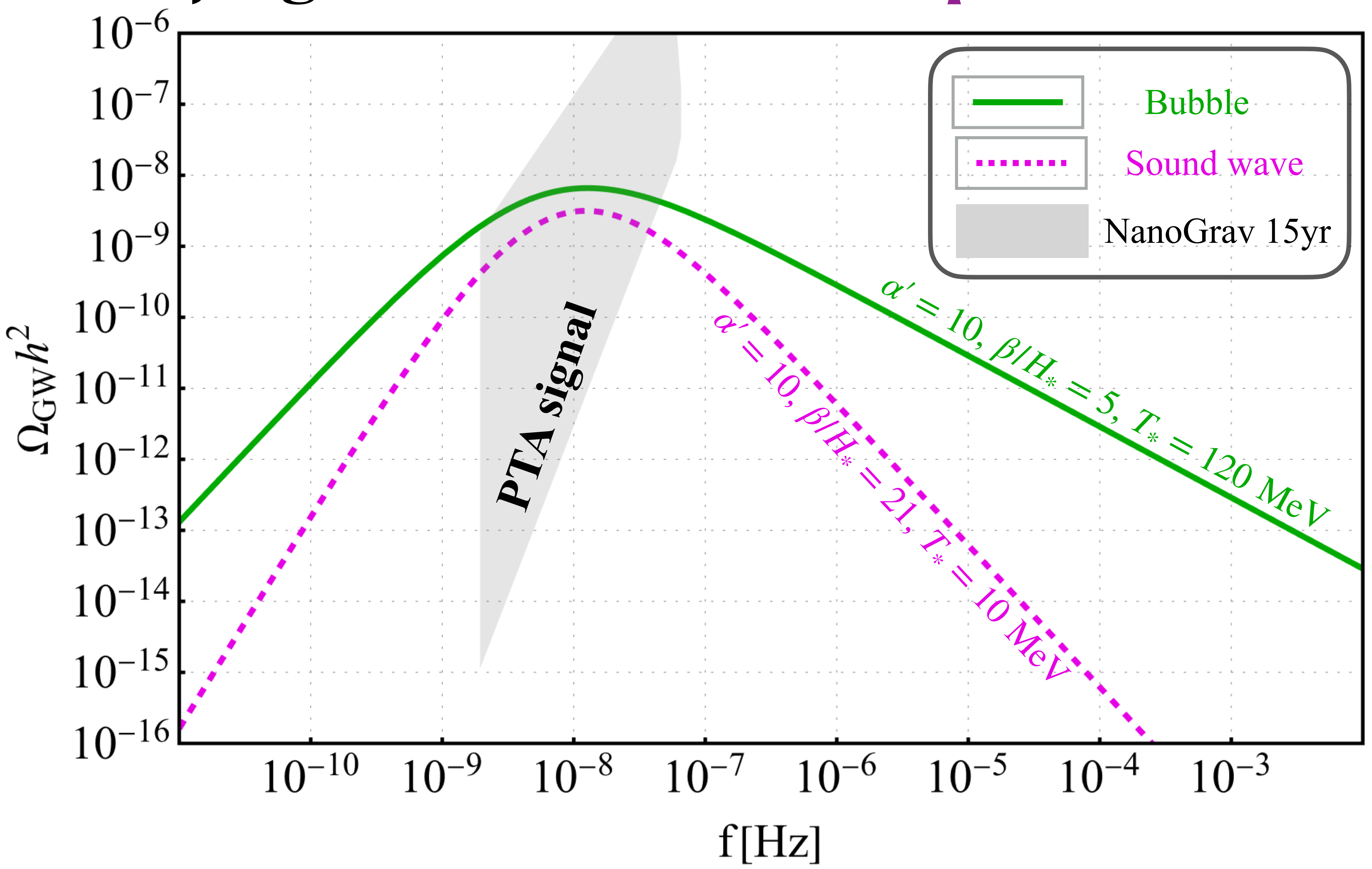
ΔN_{eff} constrains secluded dark sector



Decaying dark sector : Portal operator needed



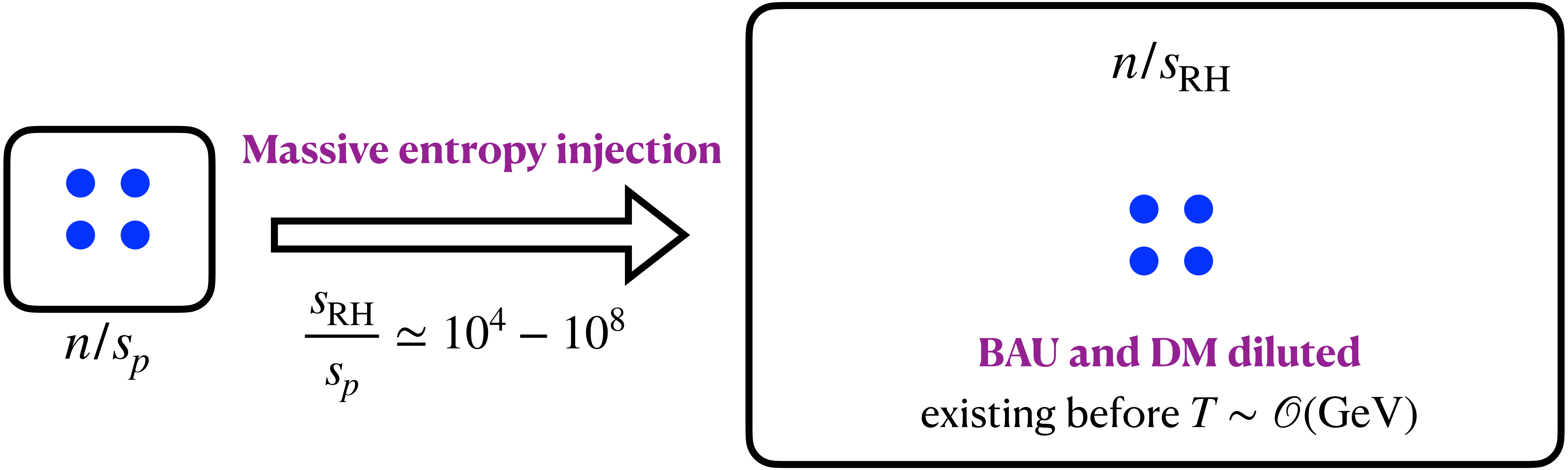
Entropy dilution problem: connection to dark matter and baryon asymmetry

Problem No. 1

The dilution problem

See eg. Schwaller + (2023)

Large supercooling is required to explain the PTA signal

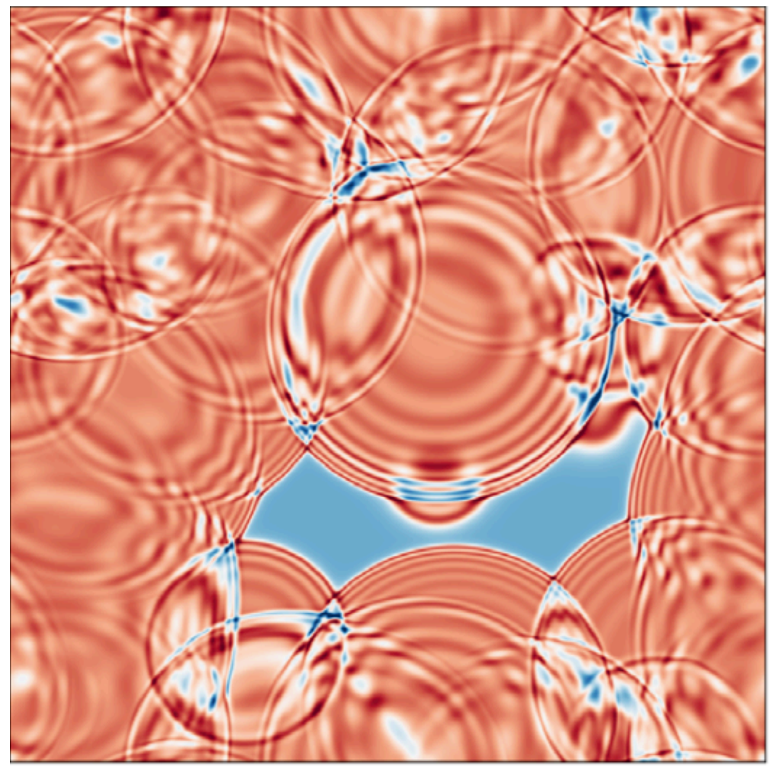


Either need a very large asymmetry before PT, **or need to create them after PT**.

Turning the problem into solution

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

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



Phase transition

Asymmetry creation

Dark sector

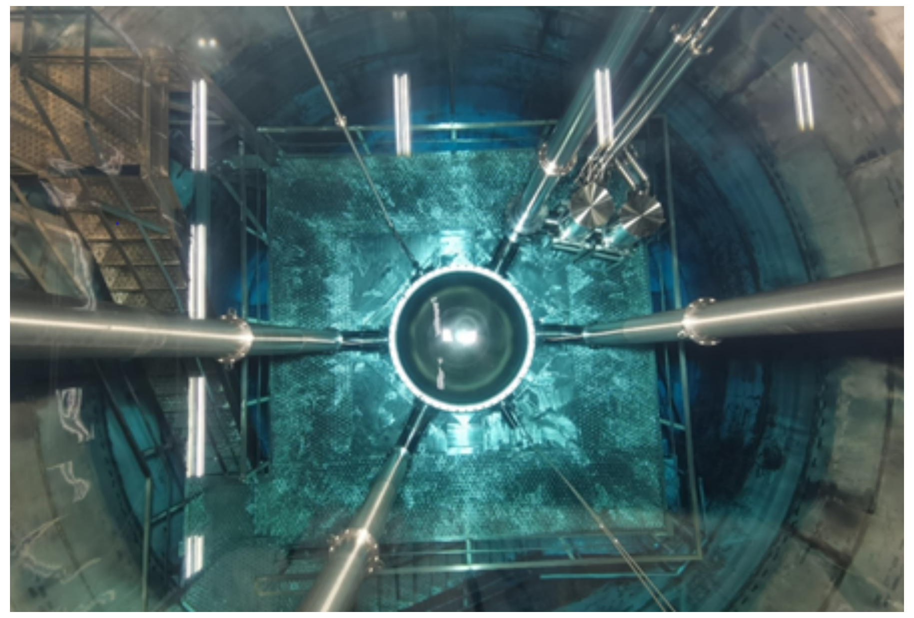
Asymmetric dark matter

Sphaleron ✕

Portal

BAU

Visible sector



Experimental signatures

1. Cold Darkogenesis

2. Post-sphaleron Darkogenesis

Cold darkogenesis: The model

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

Dark number asymmetry $\Longrightarrow$ Baryon asymmetry & **Asymmetric DM.**

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Dark QCD dilaton potential → $SU(N_{\mathrm{H}})$

Cold darkogenesis → $SU(2)_{\mathrm{D}}$

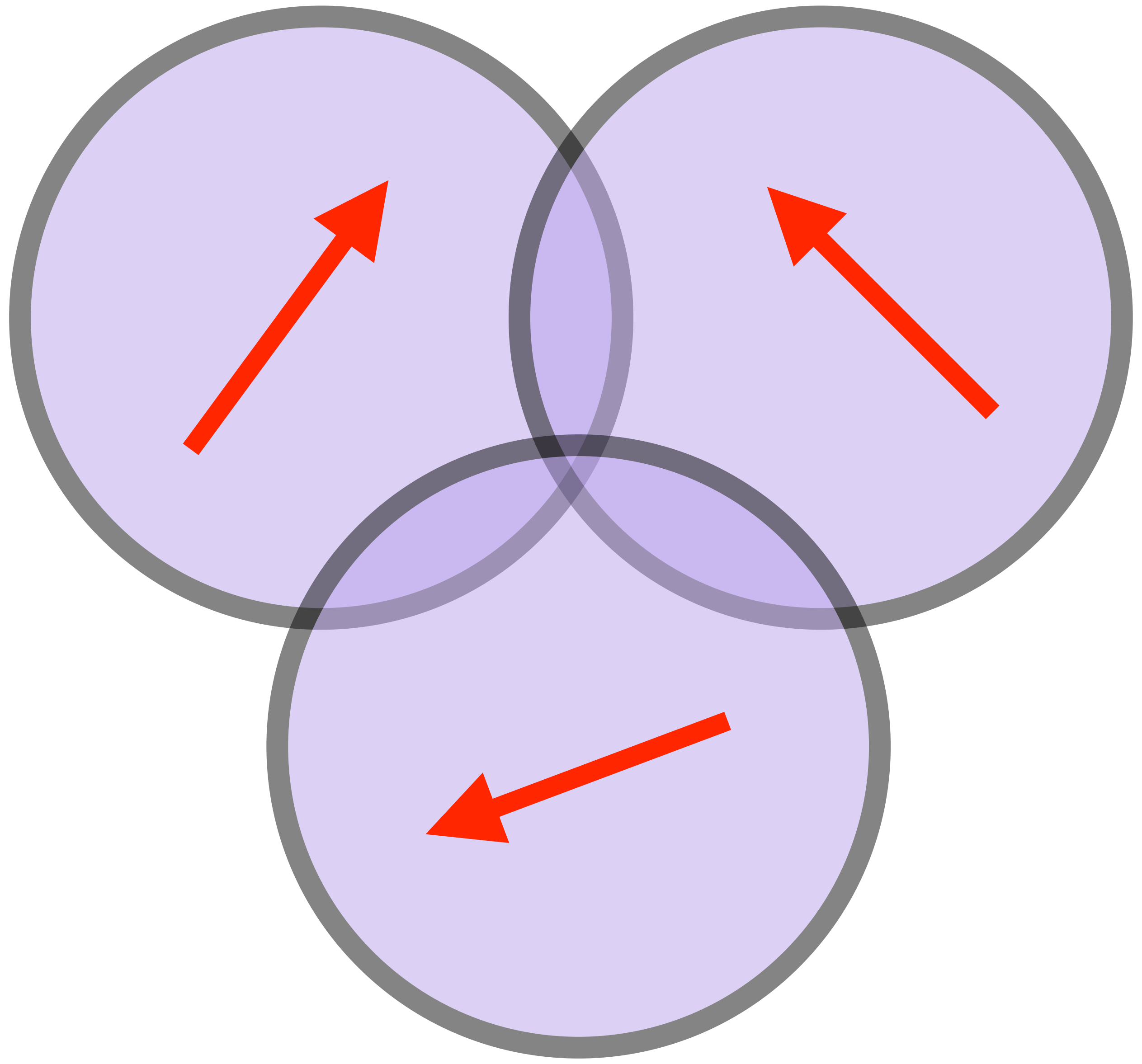
Global dark baryon number → $U(1)_{\mathrm{D}}$

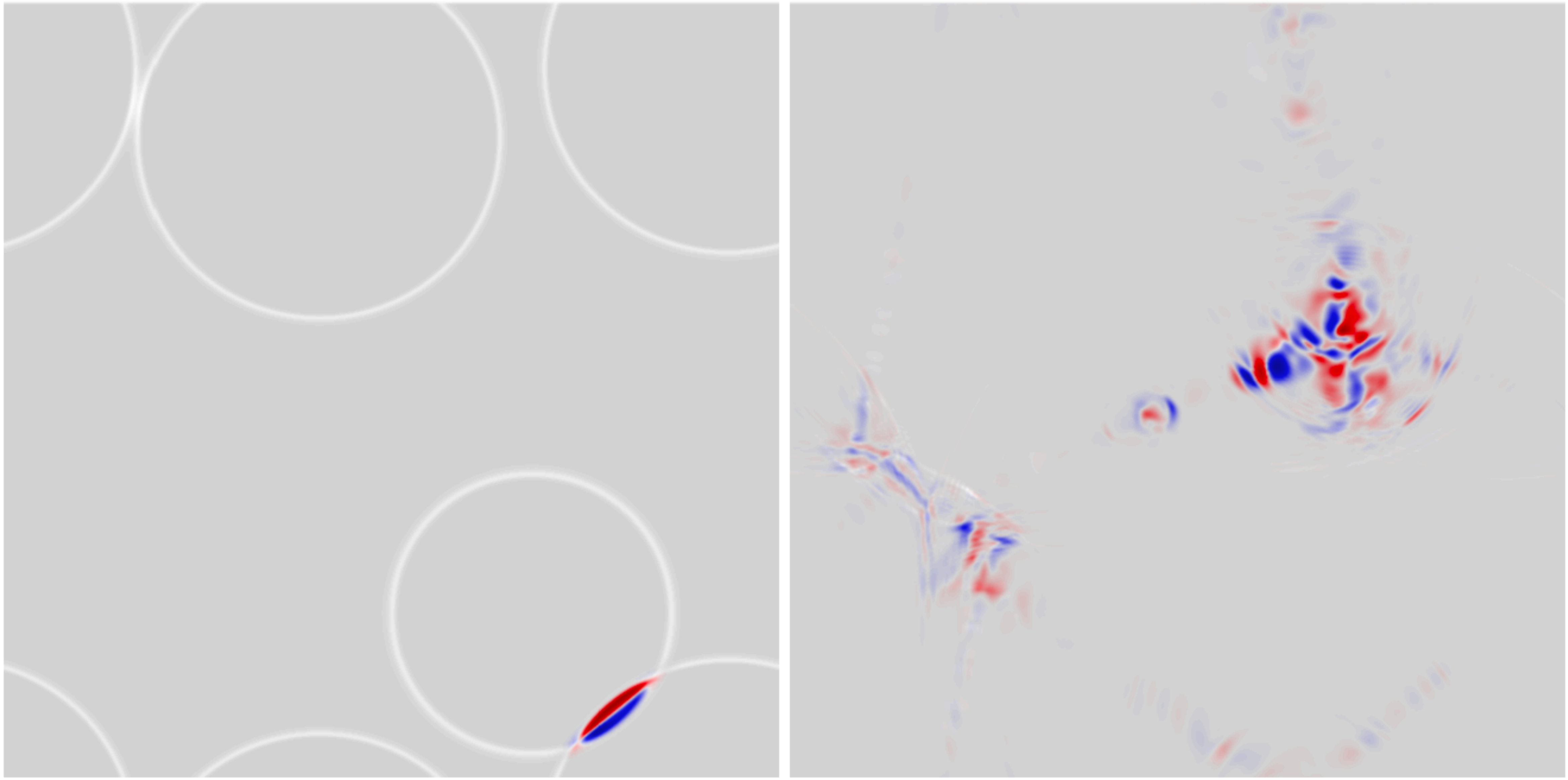
	Fields	$SU(N_{\mathrm{H}})$	$SU(2)_{\mathrm{D}}$	$U(1)_{\mathrm{D}}$	
Spin 0	H_{D}	$\mathbf{1}$	$\mathbf{2}$	0	$\Rightarrow$ **Spontaneous breaking of** $SU(2)_{\mathrm{D}}$
Dark lepton	$L_{\chi,i} \equiv \begin{pmatrix} \chi_{1,i} \\ \chi_{2,i} \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	1	$\Rightarrow$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

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

Generating the asymmetry in the dark sector

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





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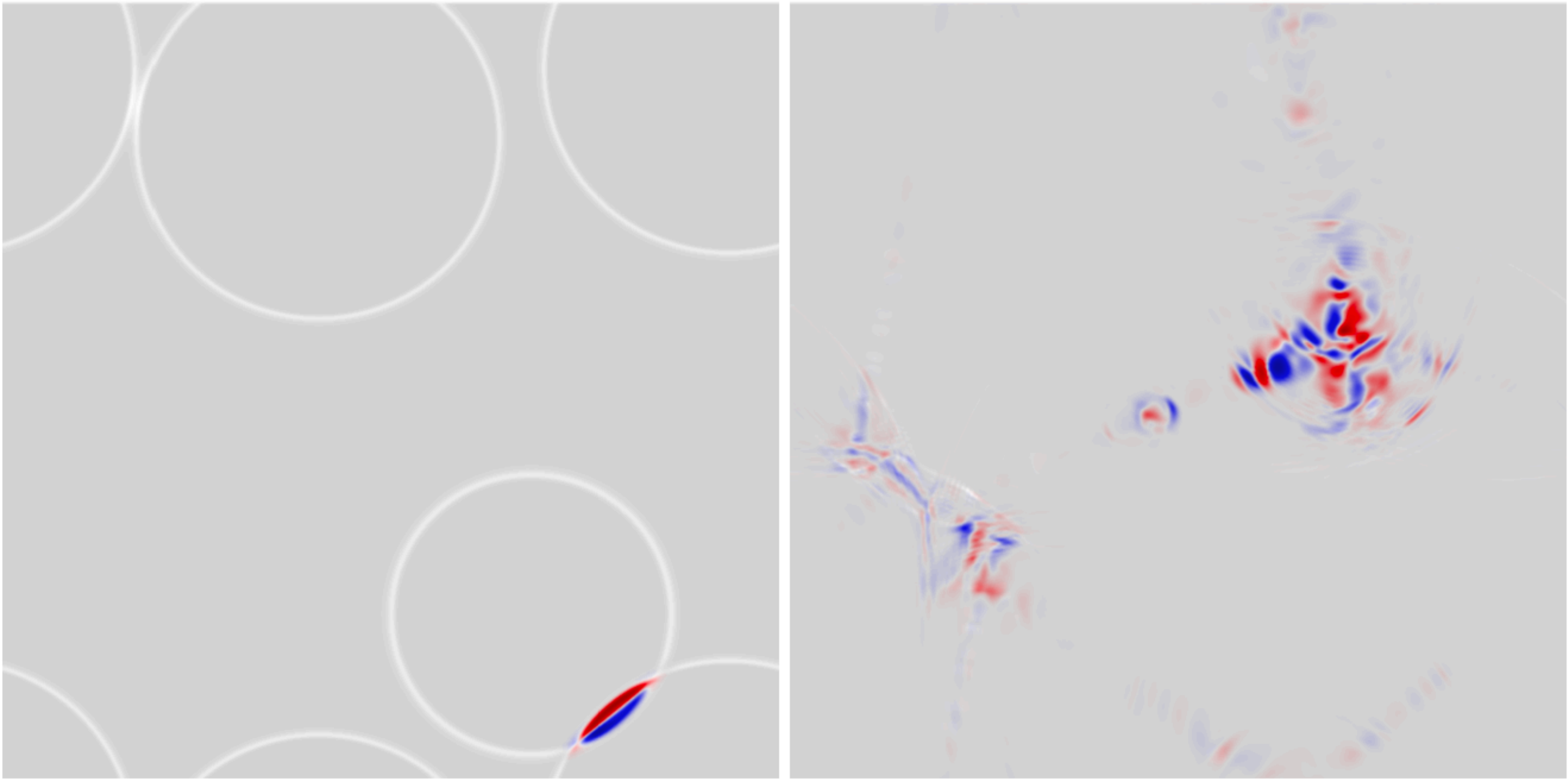
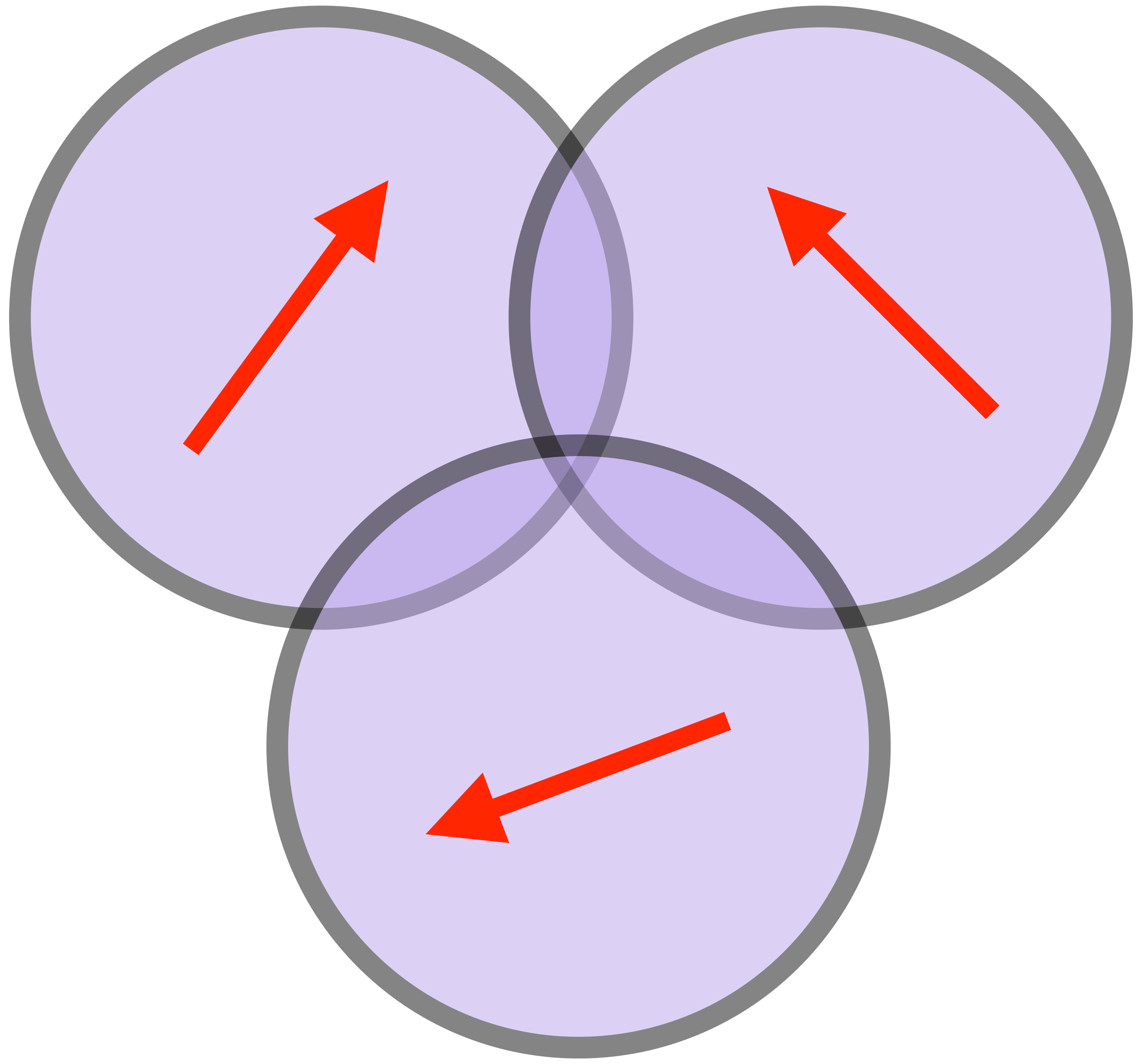
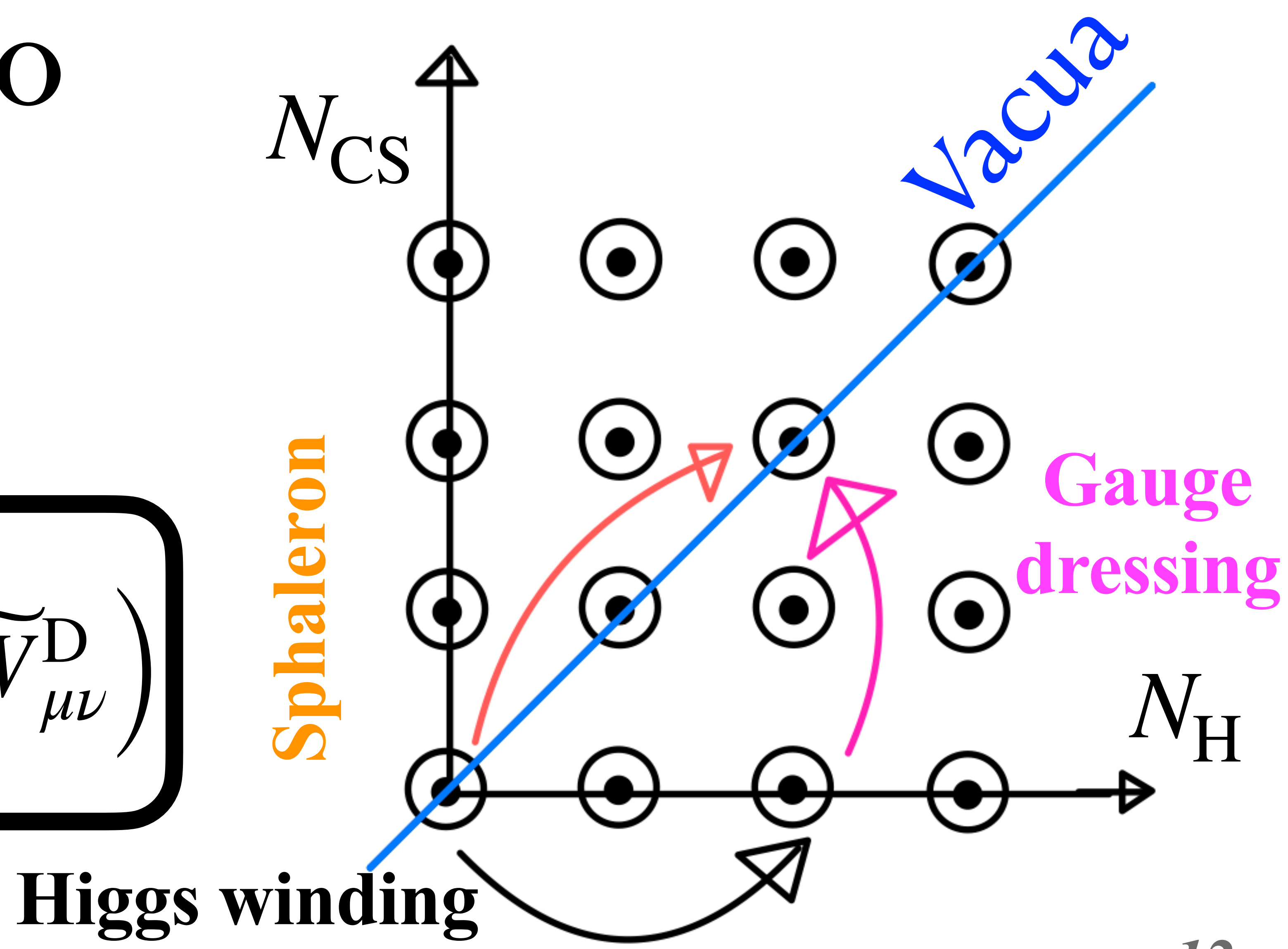




2. Gauge configuration evolves to cancel Higgs gradient energy



3. χ number violation via anomaly.

$$\boxed{\partial_\mu j^\mu_{D_L} = N_{D_L} \frac{g_D^2}{32\pi^2} \mathrm{Tr}\left(W_D^{\mu\nu} \widetilde{W}^D_{\mu\nu} \right)}$$

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.

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

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

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

Tulin Yu (2017) ; Kribs (2016)

Experimental predictions

Portal operator: π_D needs to decay before BBN.

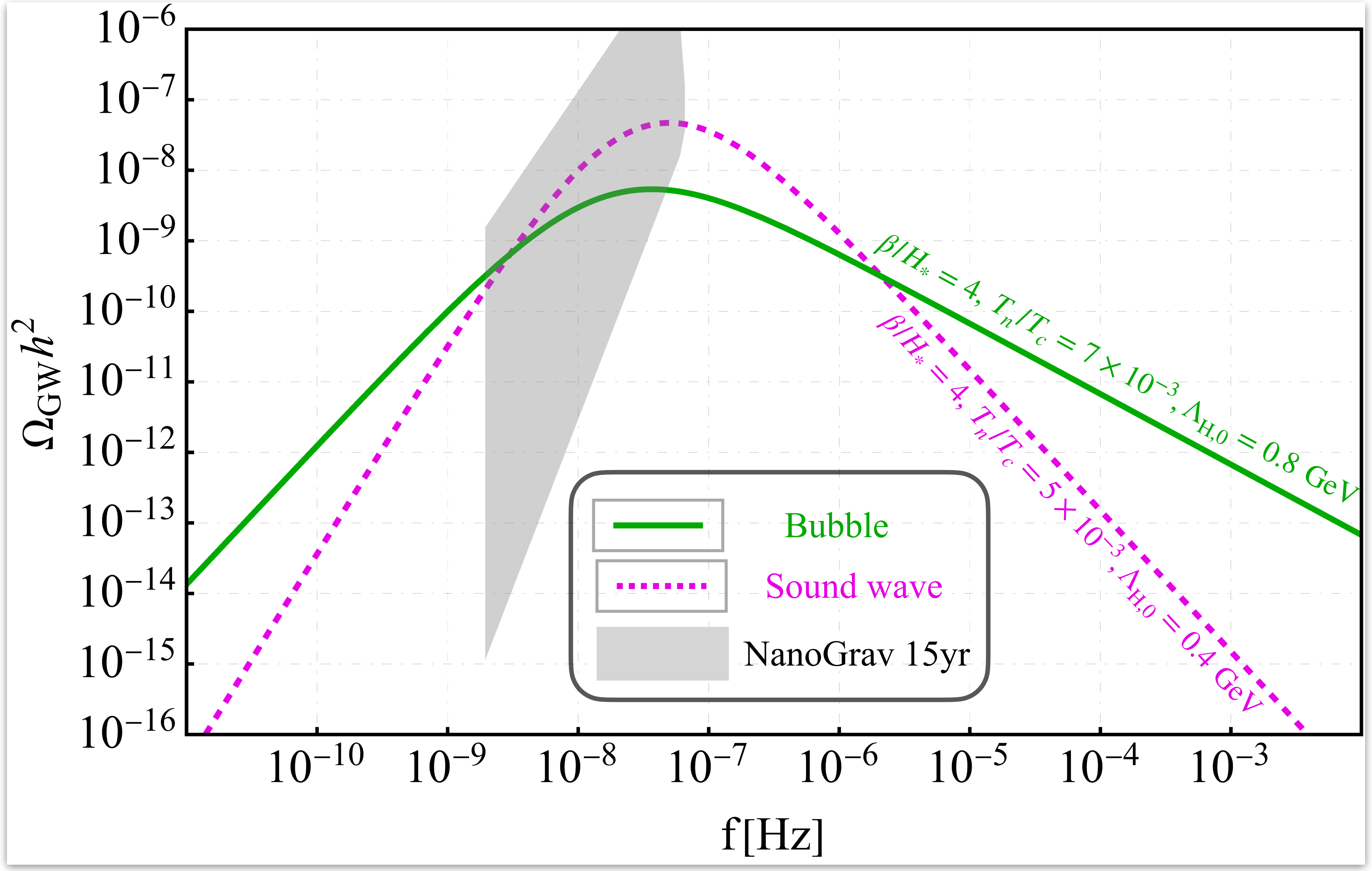
$$\mathscr{L}_H \supset -\lambda_h |H|^2 |H_D|^2$$

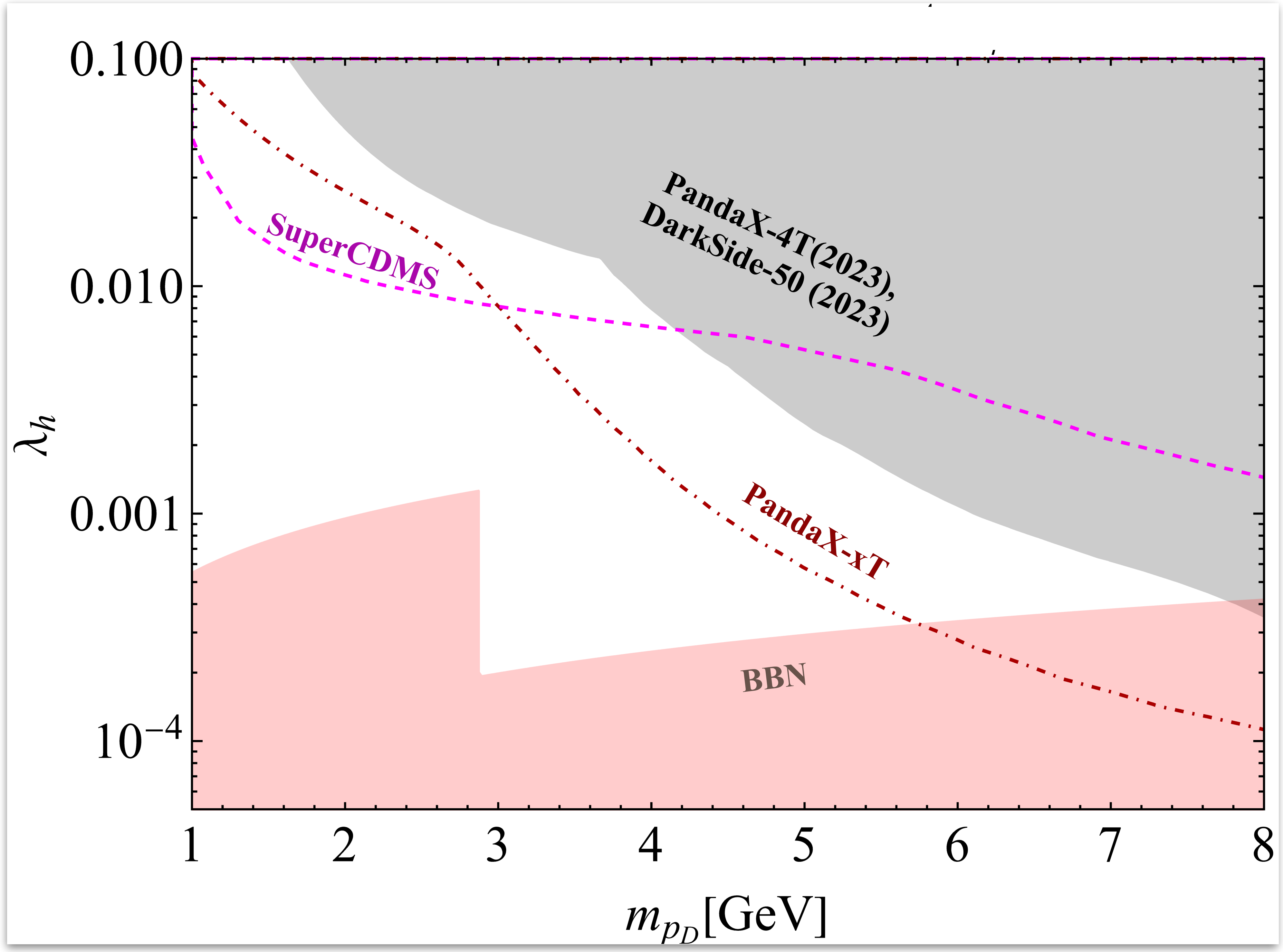
$\lambda_h \lesssim 0.1$ from Higgs invisible decay.

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

PTA signal explanation together with DM and baryon asymmetry

$\lambda_\varphi = 1,\ \eta = 8,\ N = 10,\ N_H = 5,\ N_{D_B} = 10,\ n = 0.15$





Why the GeV scale?

Coincidences

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

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

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

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

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

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

$a_{\rm D}$: **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 $\mu \sim \text{TeV}$

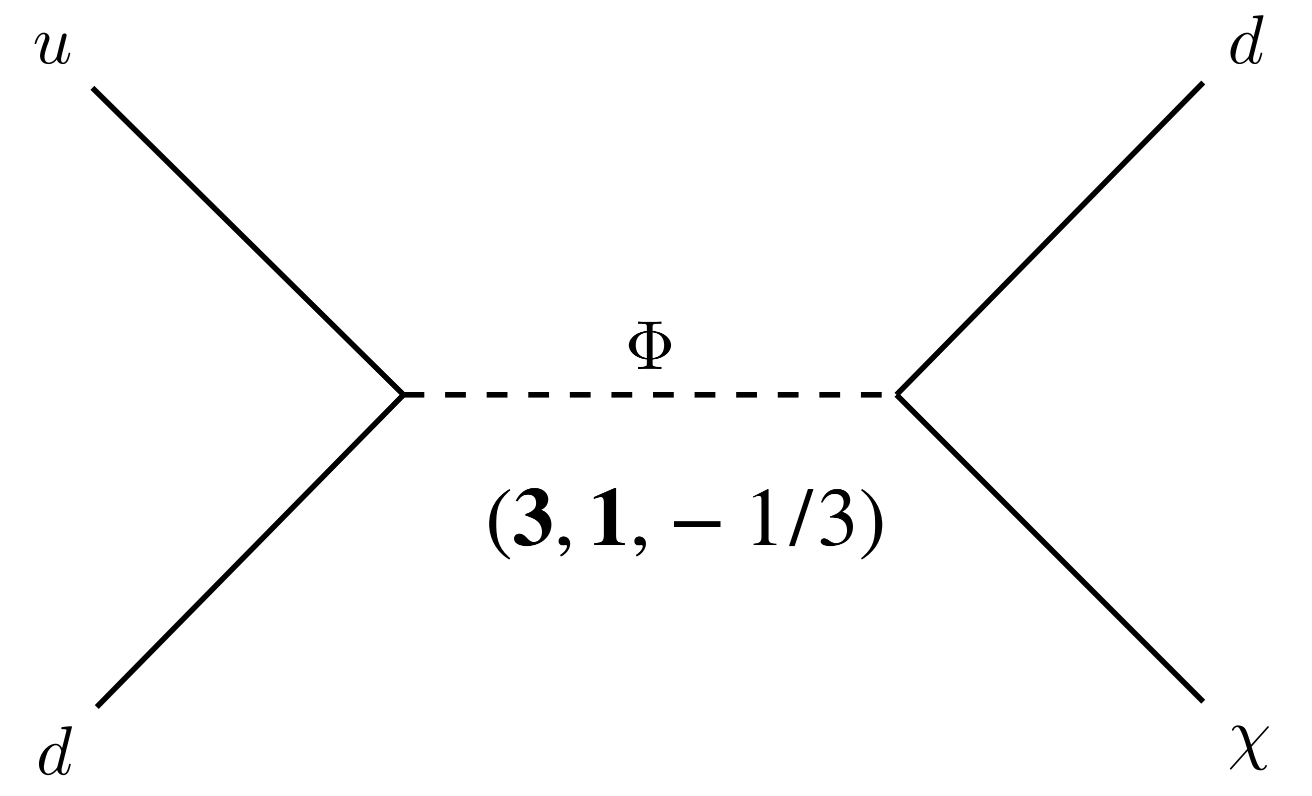
dQCD flows away from fixed point

UV completion paths

Tree level :

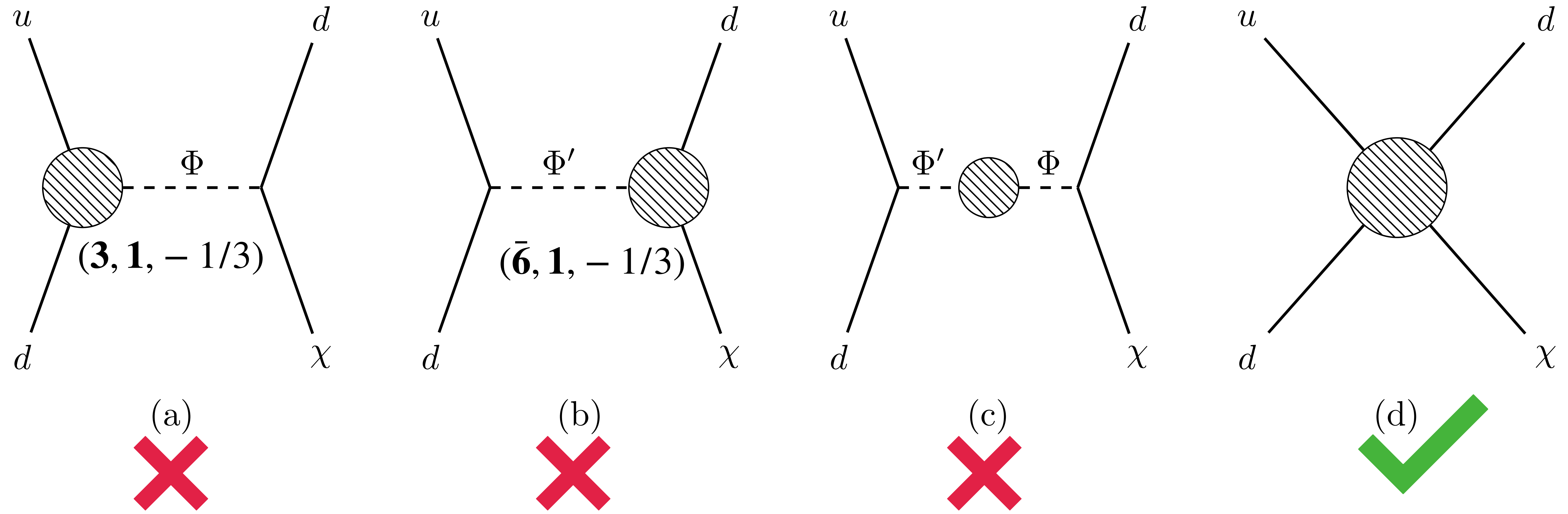
Φ **can not** have a dark QCD charge

Connection to the GeV scale is not straightforward

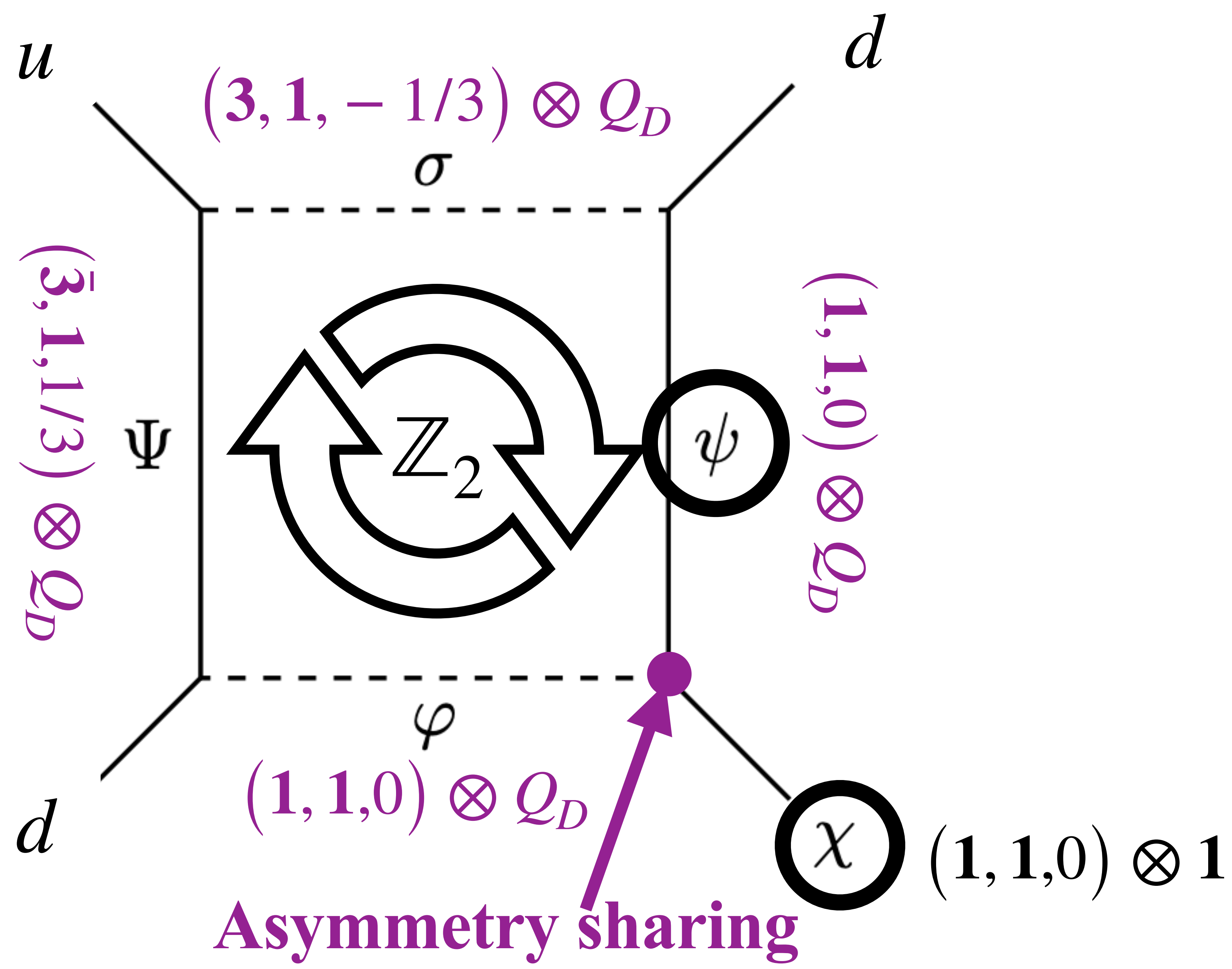


Loop level :

While not allowing tree-level



UV completion of neutron portal and Fixed point



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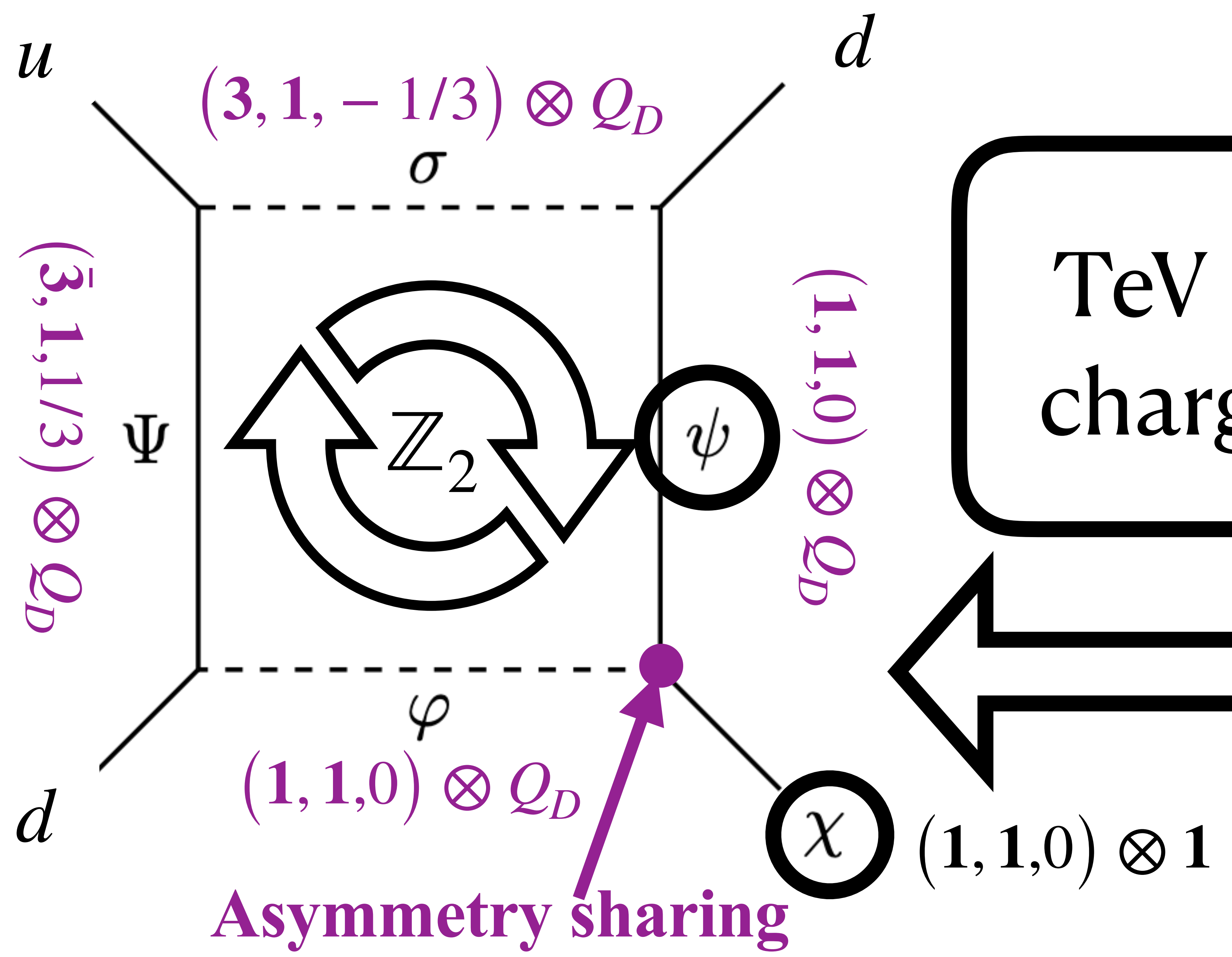
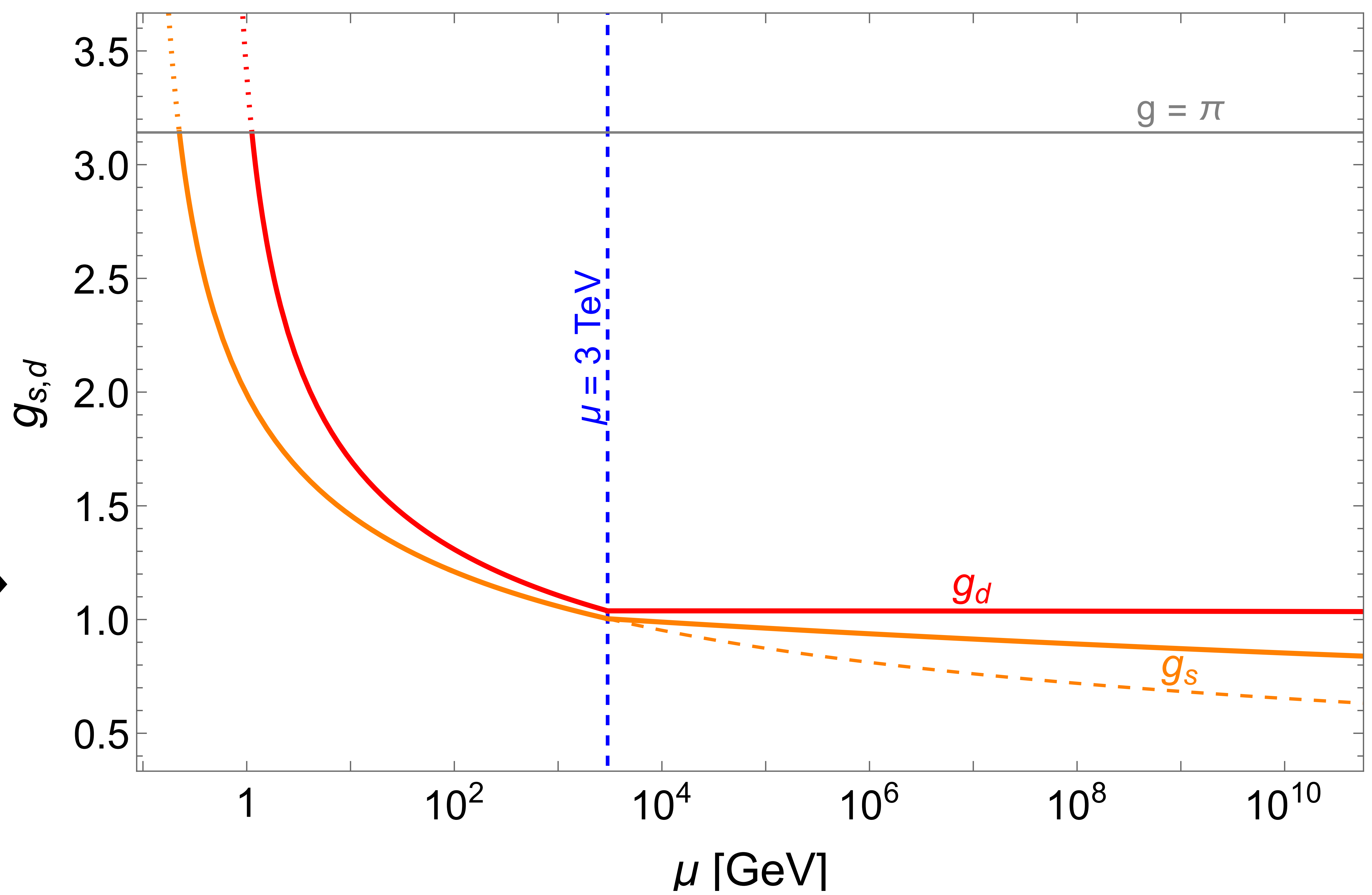


TeV scale dQCD charged particles

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

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

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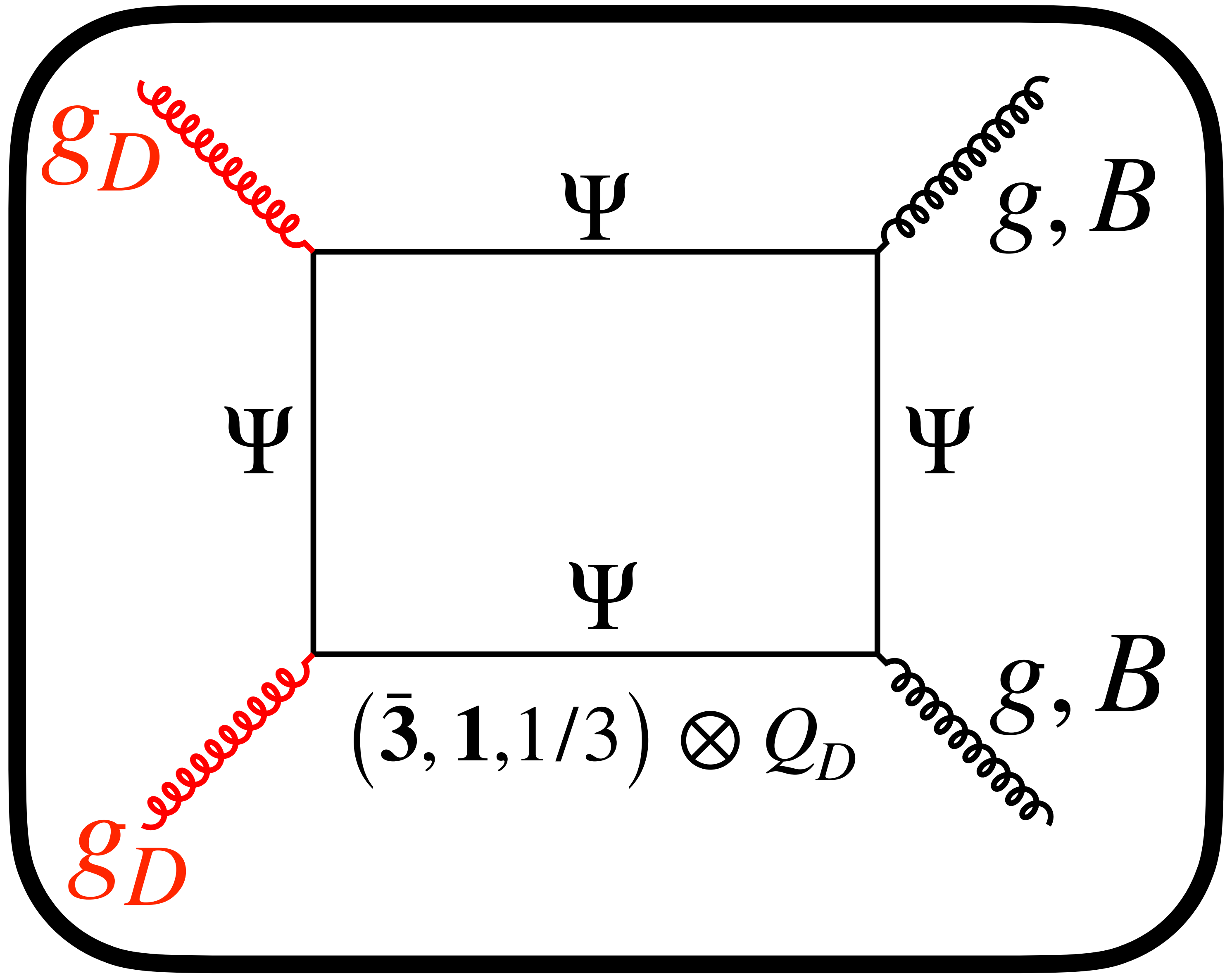

Ψ generates effective ALP portal for dark pions Juknevich (2010)

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

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

Jung+ (2026)

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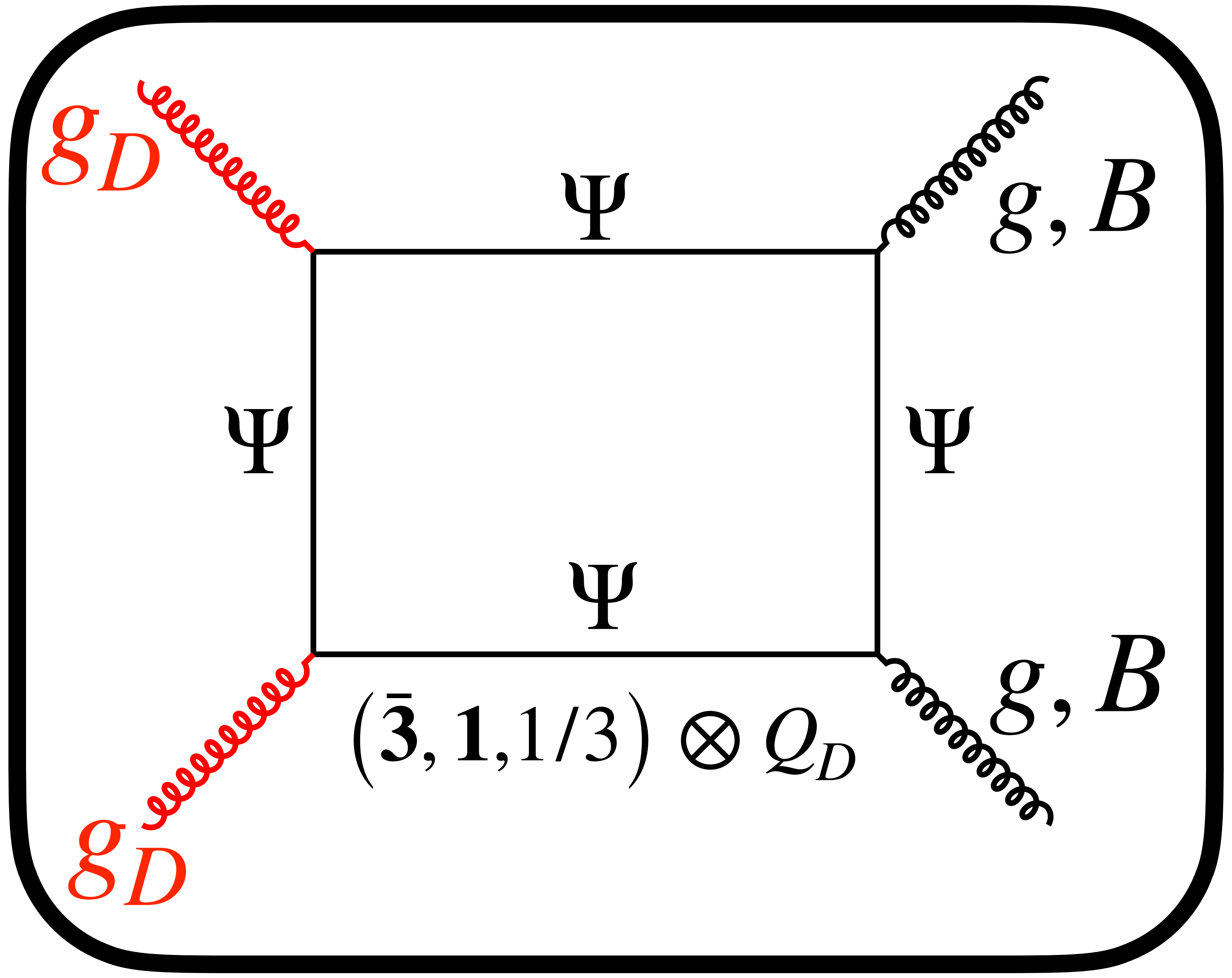

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Jung+ (2026)

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

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

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

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

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

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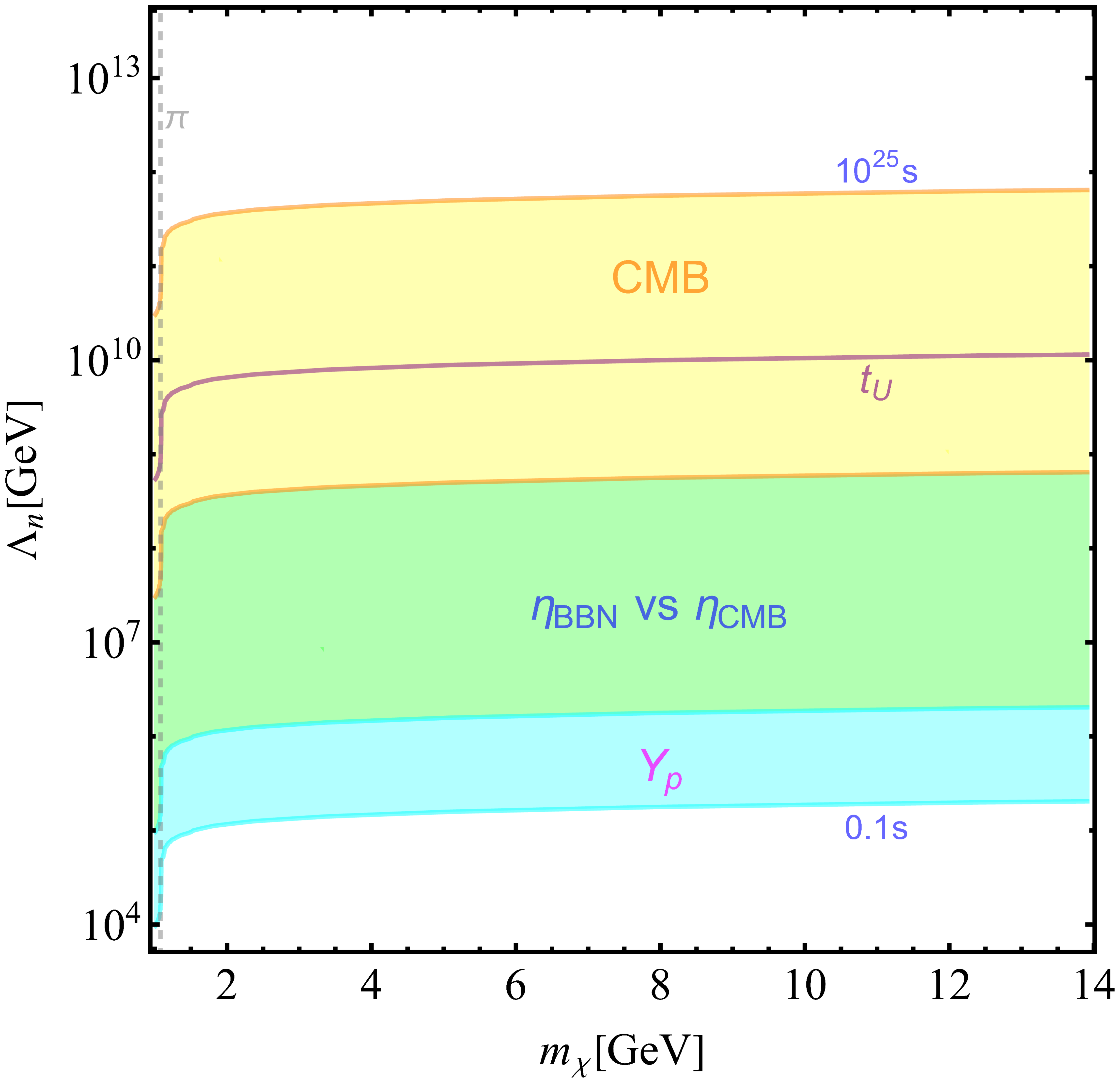
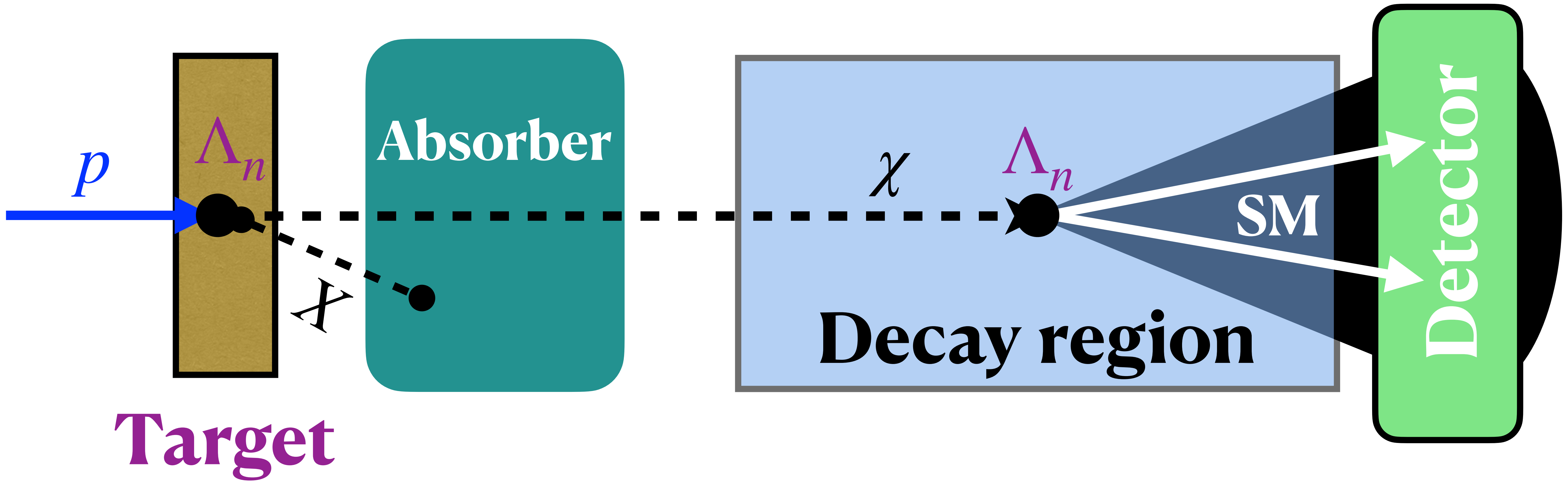
χ abundance is set by asymmetry $\simeq$ baryon abundance

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



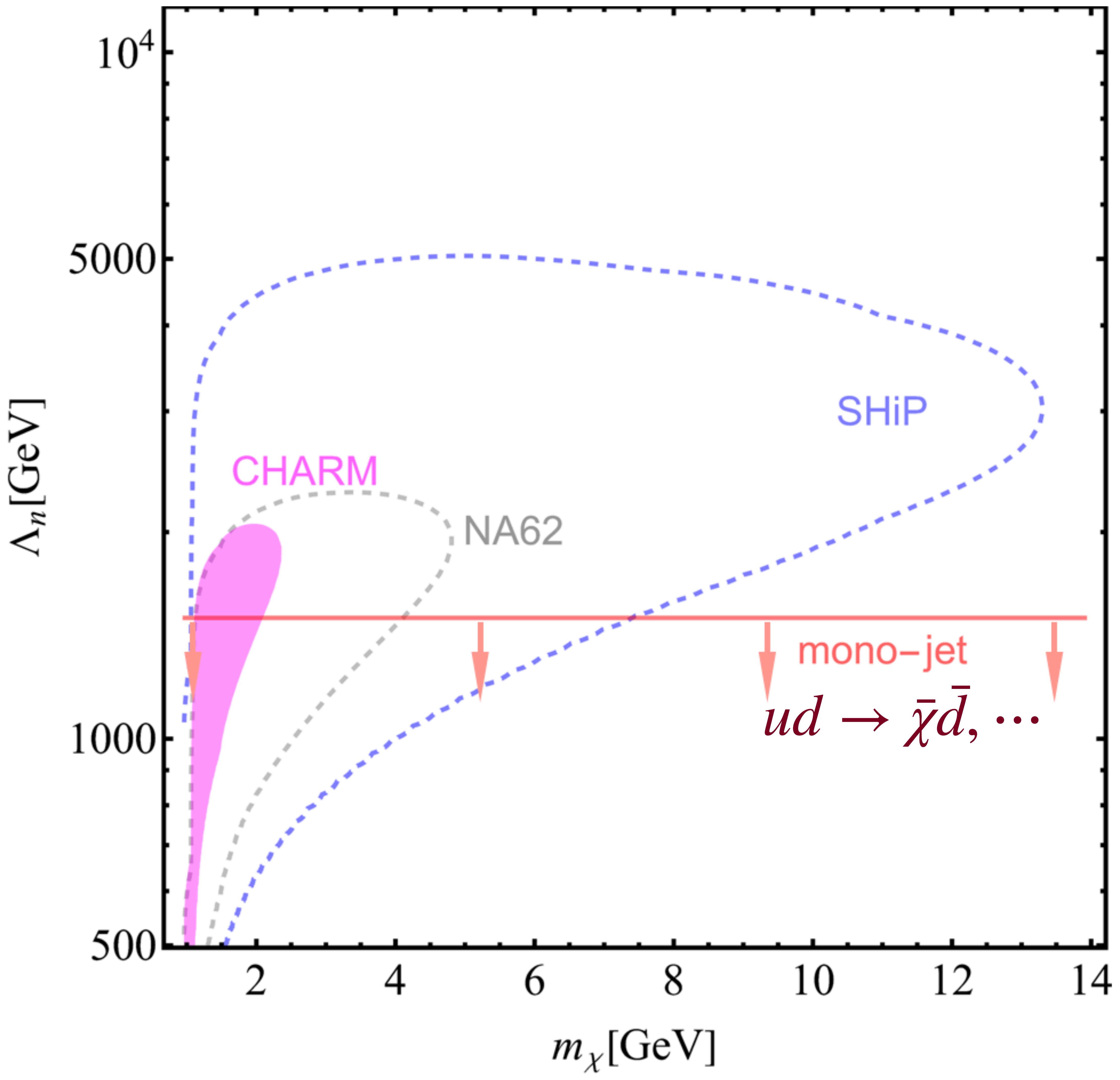
Experimental signatures of the neutron portal



Obtained from MadGraph

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

Decay probability



Inhomogeneity of Baryon Asymmetry and BBN

A possible solution: ongoing work

Problem No. 2

Inhomogeneity in η is a problem

Applegate '85, '87; Jedamzik '94; Scherrer '21
Inomata '18; Barrow '18 ; Kainulainen '99
Bagherian+ [2505.15904]

D/H abundance depends non-linearly on η .

Bagherian+ (2025)

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Bagherian+ [2505.15904]

D/H abundance depends non-linearly on η

%-level measurement of D/H constrains fluctuations in η persisting till BBN.

Baryon homogenization through diffusion is slow.

Claim: inhomogeneities generated below $\sim$ TeV scale are incompatible with BBN.

Bagherian+ (2025)

Co-moving diffusion length

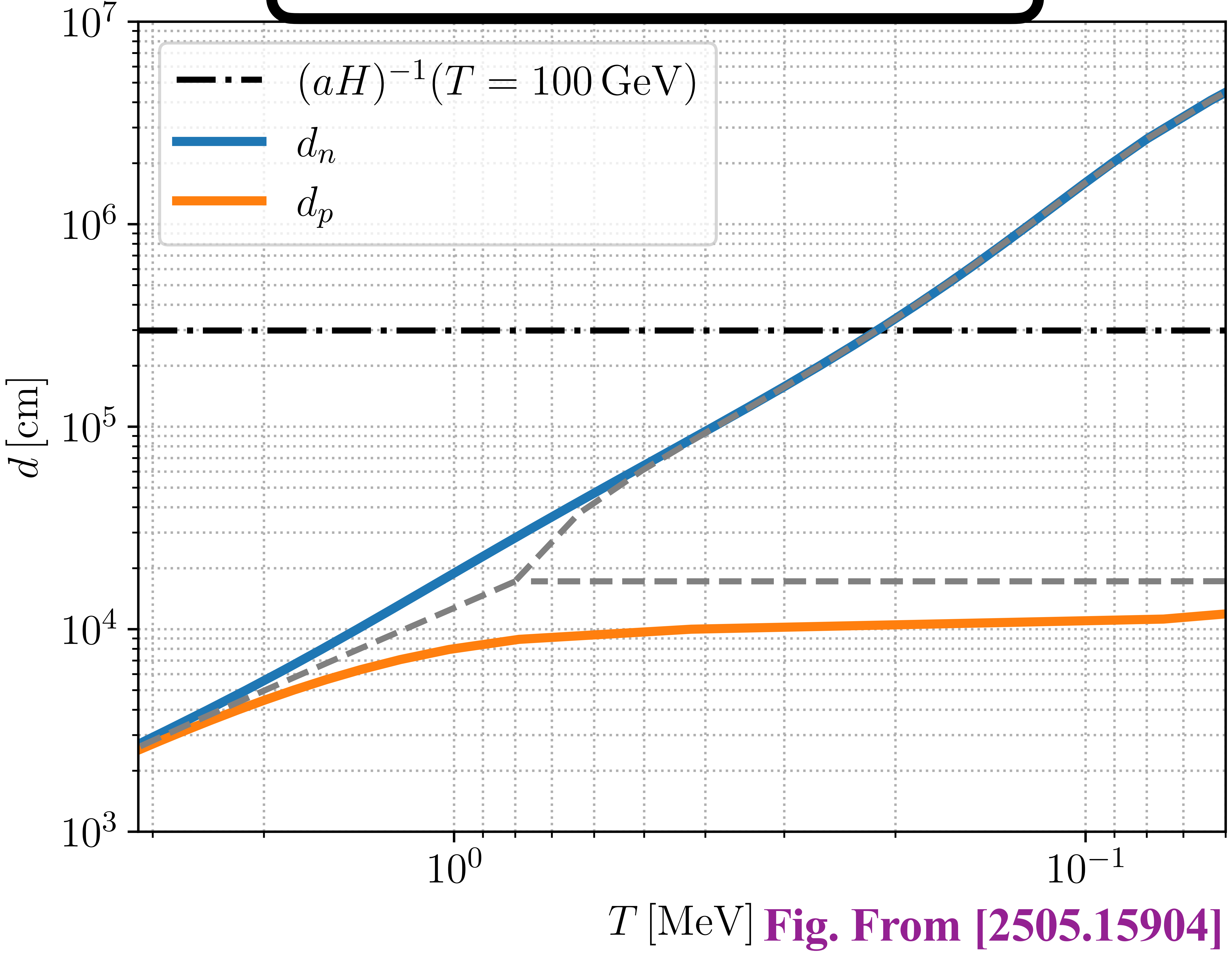

Fig. From [2505.15904]

Solution : Dark inhomogeneity may diffuse fast

Inhomogeneity created in χ may diffuse away before asymmetry transfer

Inhomogeneity scale (Bubble size at collision): $$\delta_\chi \sim R_* \sim \frac{(8\pi)^{1/3}}{\beta/H} H(T_{\rm RH})^{-1}$$

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Diffusion length for χ : $d_\chi \sim \sqrt{\frac{\tau_\chi}{l^\chi_{\rm mfp}}}\, l^\chi_{\rm mfp}$

Parameterize: $l^\chi_{\rm mfp} \sim \frac{1}{T^3 \langle \sigma v \rangle^{\rm tot}_{\chi X \to \chi X'}} = \frac{M^2}{T^3}$

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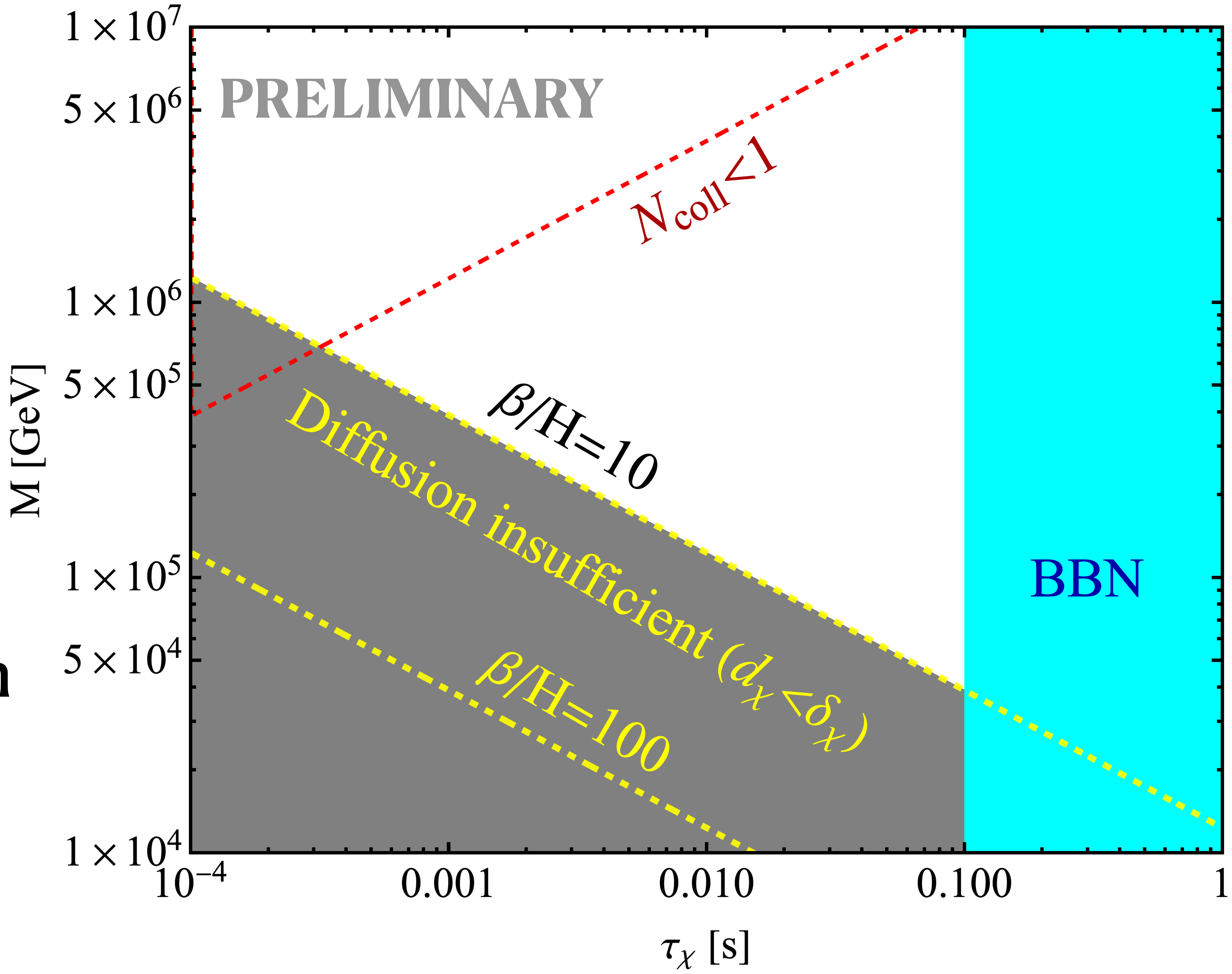
Parameterize: $l^\chi_{\rm mfp} \sim \frac{1}{T^3 \langle \sigma v \rangle^{\rm tot}_{\chi X \to \chi X'}} = \frac{M^2}{T^3}$

Condition to erase inhomogeneity: $\boxed{d_\chi(T_{\rm BBN}) \gtrsim \delta^{\rm BBN}_\chi \left(= \frac{a(T_{\rm BBN})}{a(T_{\rm RH})} \delta_\chi \right)}$ If $N_{\rm coll} = \frac{\tau_\chi}{l^\chi_{\rm mfp}} \gg 1$

Rough estimates

$$M \gtrsim 10\ \text{TeV} \left(\frac{10}{\beta/H}\right) \times \\ \times \left(\frac{T_{\rm BBN}}{\rm MeV}\right)^{1/2} \left(\frac{1\text{s}}{\tau_\chi}\right)^{1/2} \left(\frac{1\ \text{GeV}}{T_{\rm RH}}\right)$$

If $N_{\rm coll} \lesssim 1$, then velocity dispersion can drive towards homogeneity.



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.

✓ Dark sector diffusion mitigates the baryon inhomogeneity problem.

Thank you for your time. Questions?

Backup

Winding, Textures and Chern-Simons number

Winding, Textures and Chern-Simons number

$U(x) \in SU(2)$ defines a map from $R^3 \cup \{\infty\} \cong S^3$ into $SU(2) \cong S^3$

Classified by an integer degree $\pi_3(SU(2)) = \mathbb{Z}$

$$n[U] = \frac{1}{24\pi^2} \int d^3x \epsilon^{ijk} \mathrm{Tr} \left[(U^{-1}\partial_i U)(U^{-1}\partial_j U)(U^{-1}\partial_k U) \right] \in \mathbb{Z}$$

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$$\boxed{\begin{aligned} N_{\mathrm{W}} &= \frac{1}{24\pi^2}\int d^3x\ \epsilon^{ijk}\ \mathrm{Tr}\left[\Phi^\dagger(\partial_i\Phi)\Phi^\dagger(\partial_j\Phi)\Phi^\dagger(\partial_k\Phi)\right] \\ N_{\mathrm{CS}} &= \frac{g^2}{16\pi^2}\int d^3x\ \epsilon^{ijk}\ \mathrm{Tr}\left[W_i\left(W_{jk} + \frac{2}{3}igW_jW_k\right)\right] \end{aligned}}$$

$$\Phi = \frac{1}{|\phi|^2}\left(i\sigma^2\phi^*, \phi\right) \in SU(2)$$

After relaxing to the true vacuum:

$$E_{\mathrm{gradient}} \sim \left|(\partial_i - igW_i)\Phi\right| \to 0$$

$$W_i \to \frac{i}{g}\Phi\partial_i\Phi^\dagger \implies N_{\mathrm{CS}} = N_W$$

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 $\mathscr{D}_{\rm L,in}$.

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

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

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

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

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

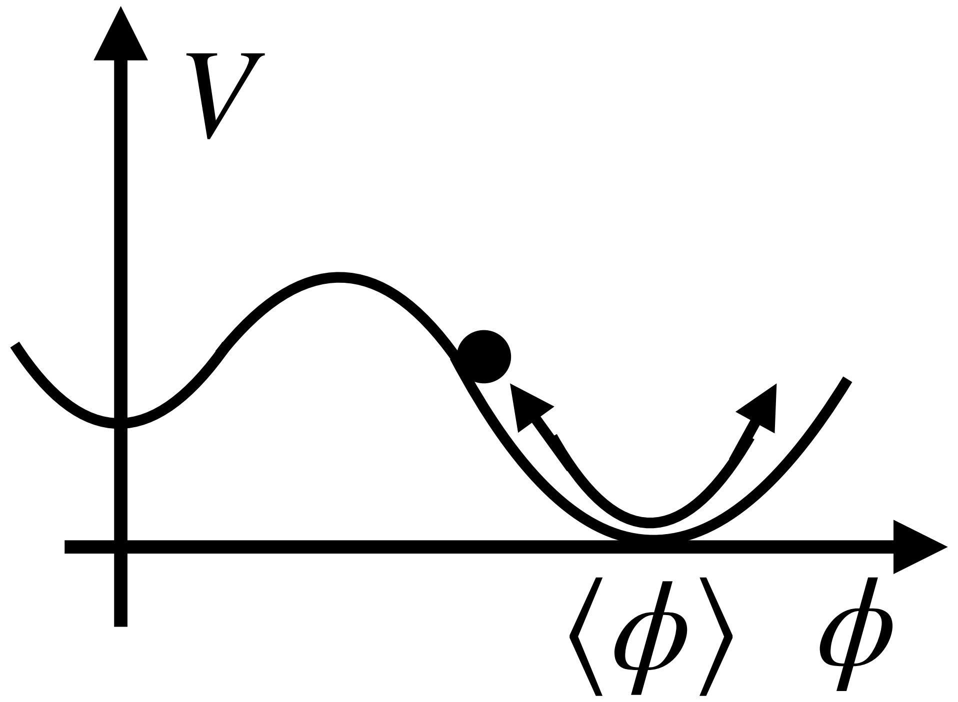
$$\mu_{\rm eff} = \frac{\delta_{\rm CP}}{\Lambda_{\rm CP}^2}\frac{d}{dt}\langle H_{\rm D}^\dagger H_{\rm D}\rangle \implies \frac{dn_{\rm L}}{dt} = \Gamma_{\rm sph}\frac{\mu_{\rm eff}}{T_{\rm D}} - \Gamma_B n_{\rm L}$$

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

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

$\mathcal{O}(1)\mathrm{GeV}$

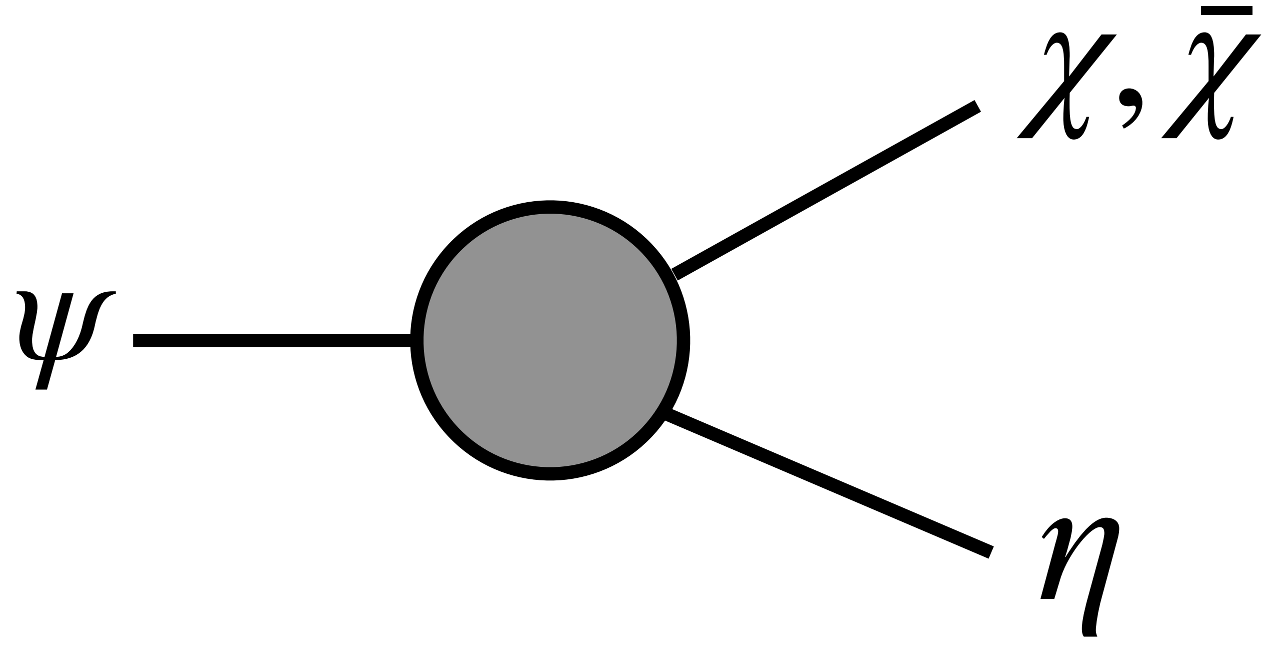
$$\phi(t) = \langle\phi\rangle + \varphi(t)$$
$$f(\varphi)\bar{\psi}^c\psi$$

Parametric excitation

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

GeV mother particle ψ
is non-thermally produced.

$\bar{\psi}y\eta\chi$

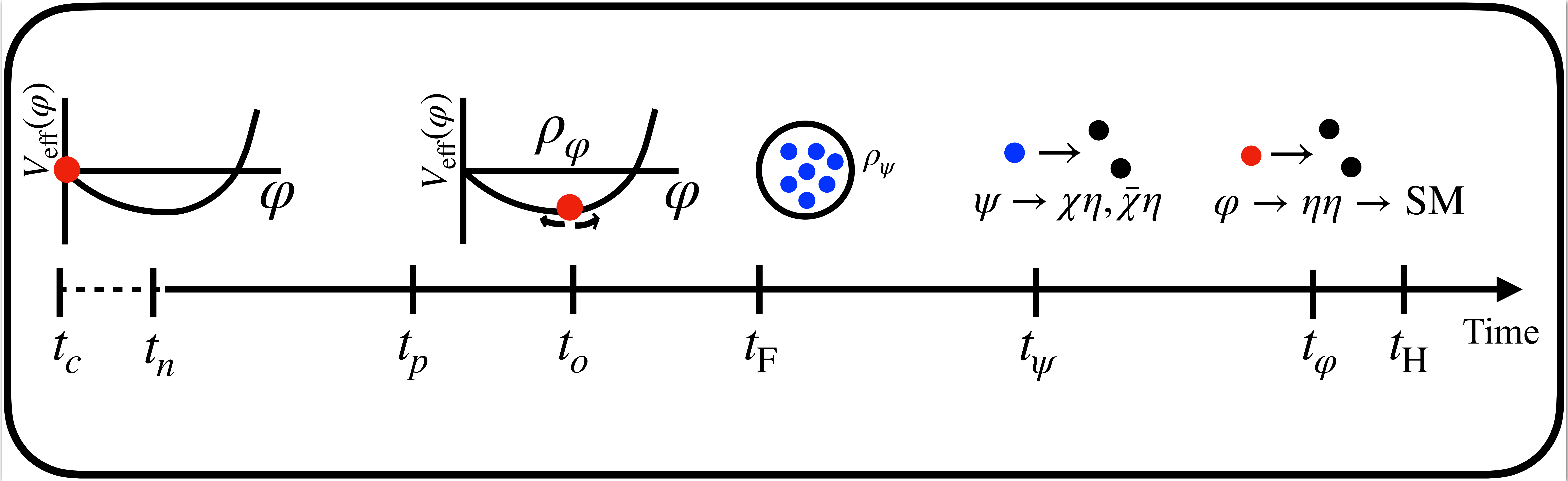


Asymmetric χ particle

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.

Number density of the mother particle

The amplitude of oscillating φ is decreasing due to back-reaction.

$$m_\psi^{\rm eff}(t) = \underset{\mathcal{O}(1)\mathrm{GeV}}{m_\psi} \left[\frac{\{1+\xi(t)\cos(m_\varphi t)\}^{2b} - r}{1-r}\right]$$

Particle production takes place when $m_\psi^{\rm eff} \simeq 0$, requiring

$$(1-\xi_0)^{2b} \le r \le (1+\xi_0)^{2b}\ ;\ \text{for } 0 < b < 1/2\ ,$$
$$(1-\xi_0)^{2b} \ge r \ge (1+\xi_0)^{2b}\ ;\ \text{for } b < 0\ ,$$

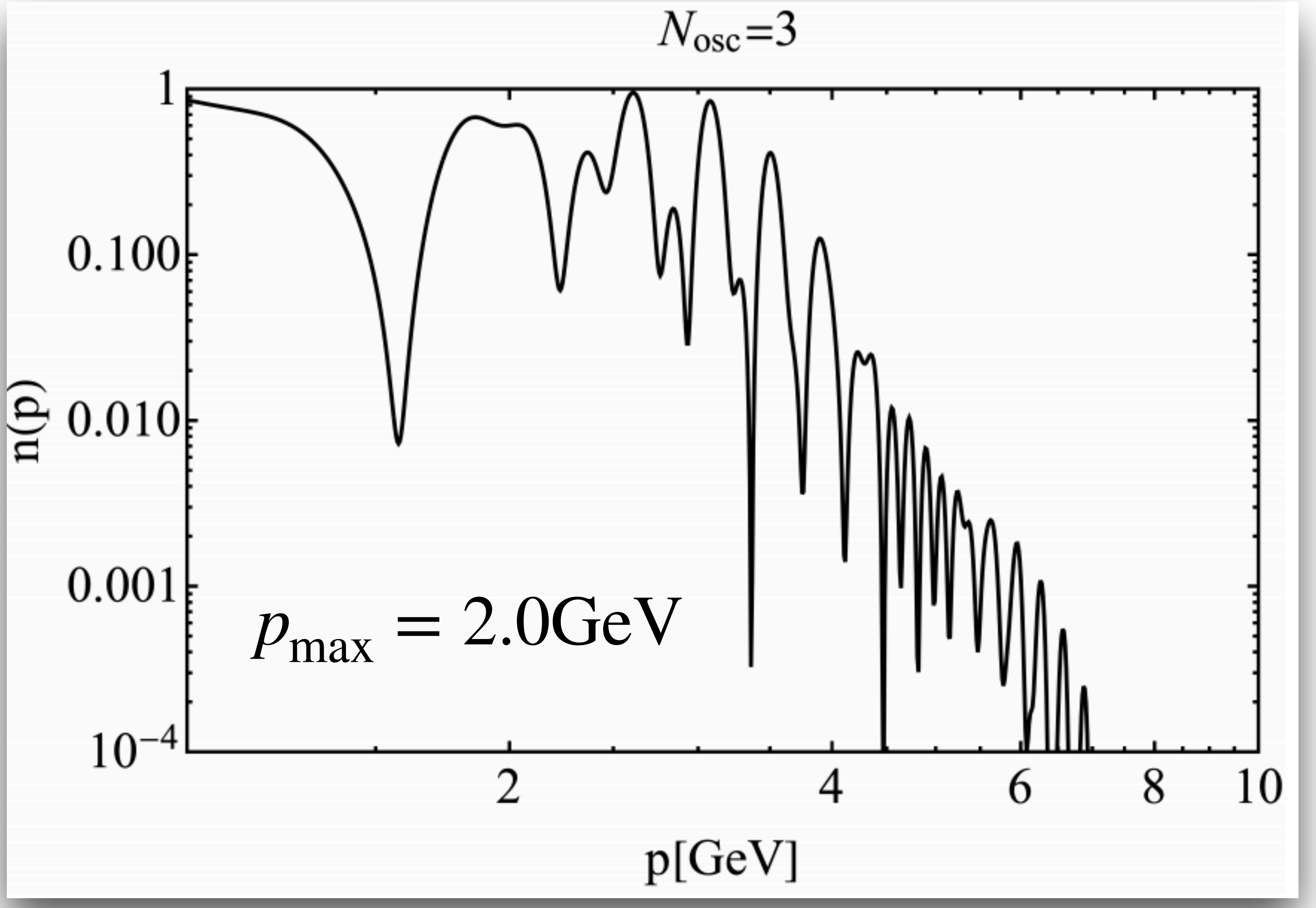
When $\xi(t)$ drops down to ξ_c, n_ψ is frozen

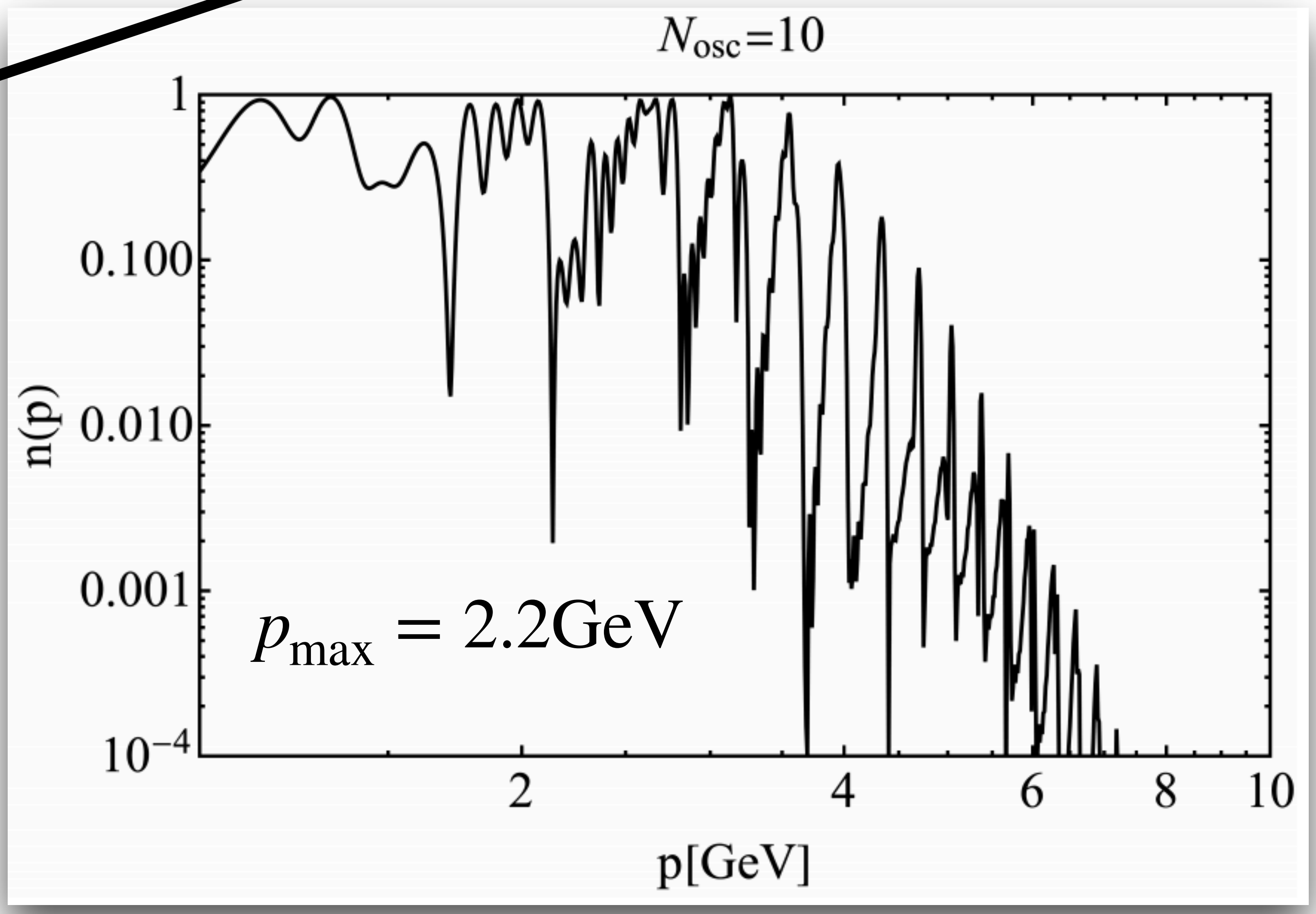
$$n_\psi^{\rm FO} = \frac{p_{\rm max}^3}{3\pi^2}$$

non-adiabatic

$$n_\psi^{\rm FO} \simeq \mathcal{M}(r,b)\left(\frac{m_\psi m_\varphi^2}{6\pi^2}\right),$$
$$\mathcal{M}(r,b) \equiv \left[\frac{2br}{1-r}\left(r^{-\frac{1}{2b}} - 1\right)\right]$$

Analytical estimation





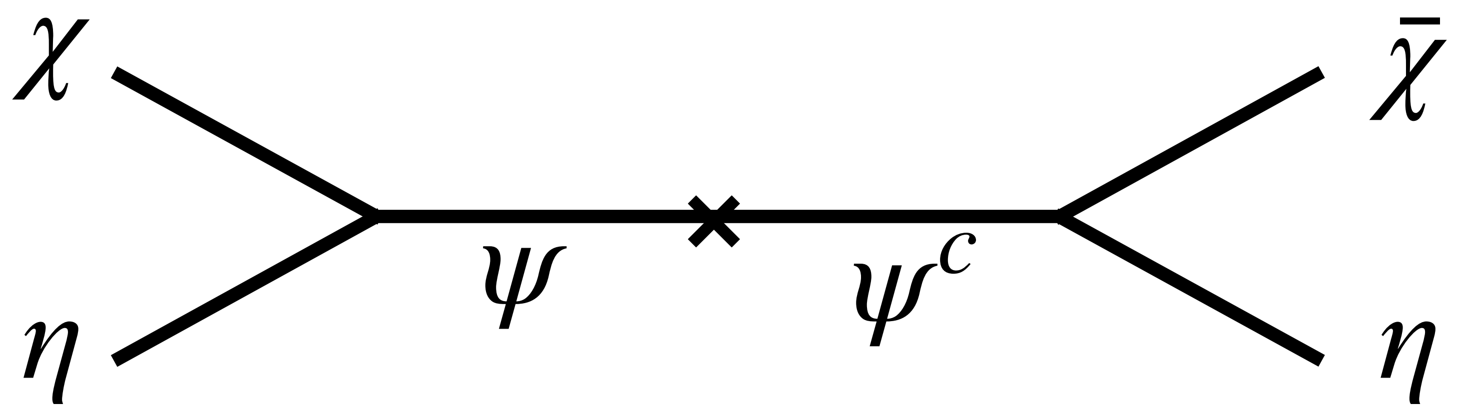
Washout and $n - \bar{n}$

Inverse-decay $\chi\eta \to \psi_1$:

$$\frac{n_\eta^{\rm eq}\langle\sigma v\rangle_{\chi\eta\to\psi_1}}{H(T_{\rm RH})} \simeq \frac{\Gamma_{\psi_1\to\chi\eta}}{H(T_{\rm RH})}\left[e^{-m_{\psi_1}/T_{\rm RH}}\left(\frac{m_{\psi_1}}{T_{\rm RH}}\right)^{3/2}\right]$$

$\ll 1$

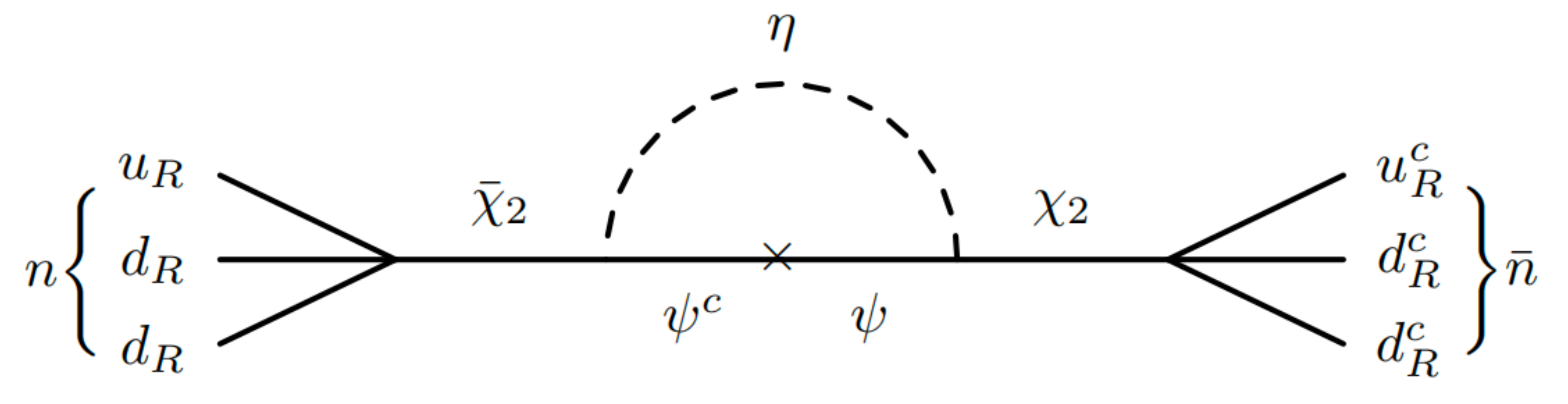
washout



$$\left(\frac{\zeta(3)}{\pi^2}T_{\rm RH}^3\right)\left(\frac{|y|^4}{8\pi m_\psi^2}\right) \lesssim 0.3\sqrt{g_*}\frac{T_{\rm RH}^2}{M_{\rm pl}} \rightarrow |y| \lesssim 2\times 10^{-4}$$

Neutron Portal

$$\mathcal{O}_n = \frac{1}{\Lambda_n^2}\chi_2 u_{R,i} d_{R,j} d_{R,k}$$

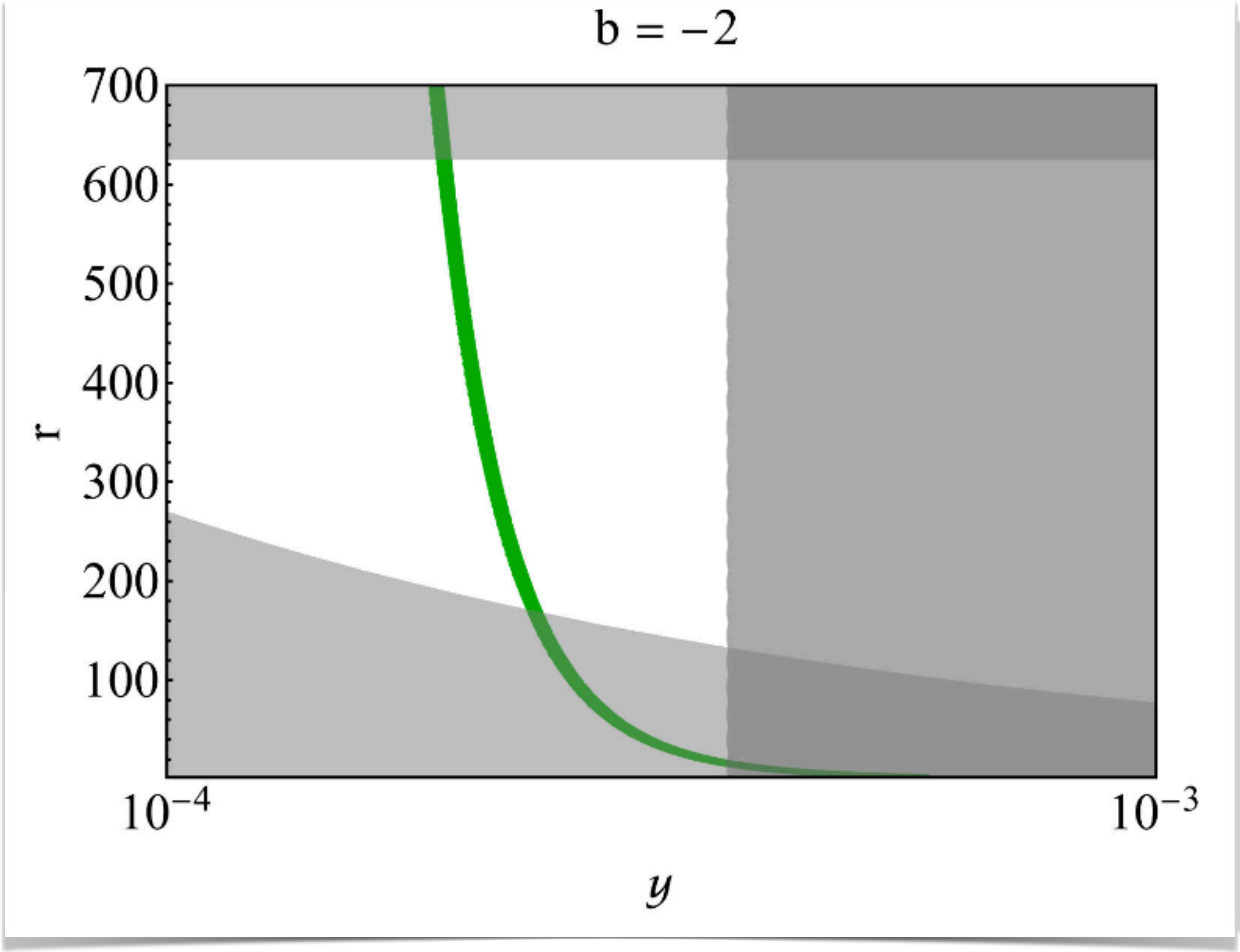


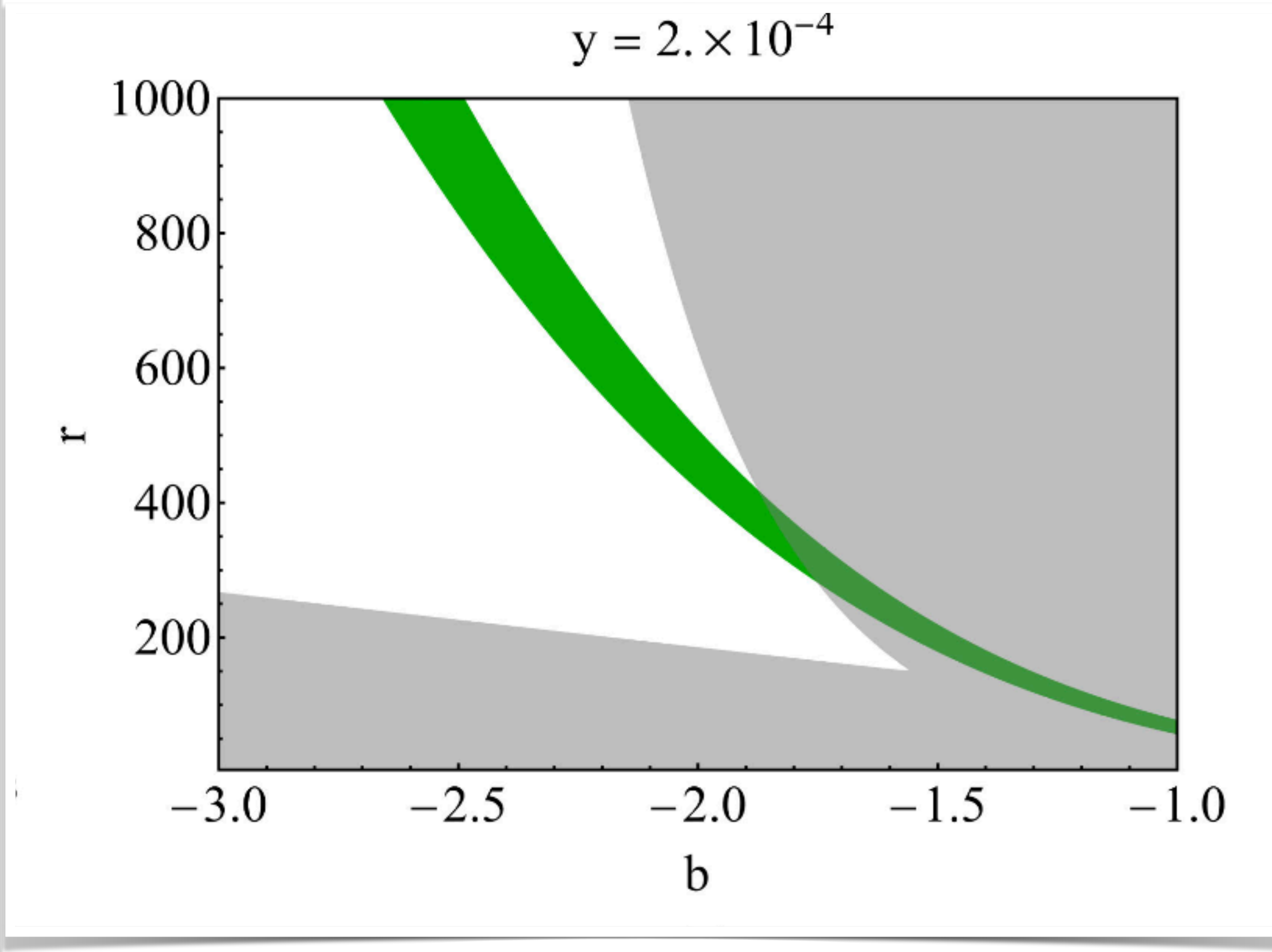
$n - \bar{n}$ oscillations

mono-jet searches $\rightarrow$ $\Lambda_n \gtrsim 2$ TeV

decay before BBN $\rightarrow$ $\Lambda_n \lesssim 200$ TeV $\rightarrow$ $\tau_{n\bar{n}} > 4.7\times 10^8 s$

Succesful BAU





Phenomenology

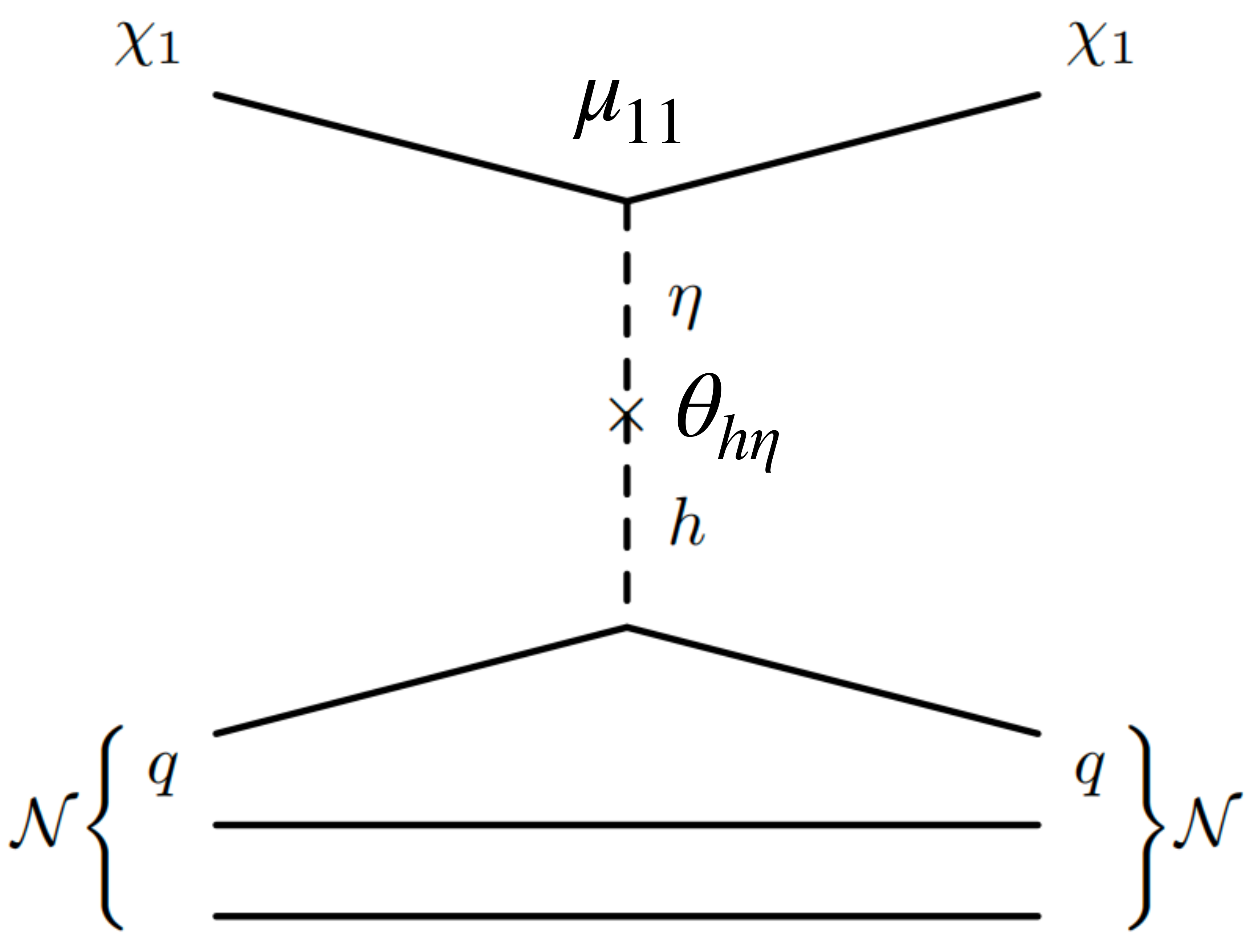
mixing angle

Higgs portal

$$-g_\eta\,\eta\left(\mathbf{H}^\dagger\mathbf{H}-\frac{v^2}{2}\right)-\frac{m_\eta^2}{2}\eta^2\left(\frac{2\varphi}{\langle\phi\rangle}+\frac{\varphi^2}{\langle\phi\rangle^2}\right)$$

$$\tan(2\theta_{h\eta})=\frac{2g_\eta v}{m_h^2-m_\eta^2}$$

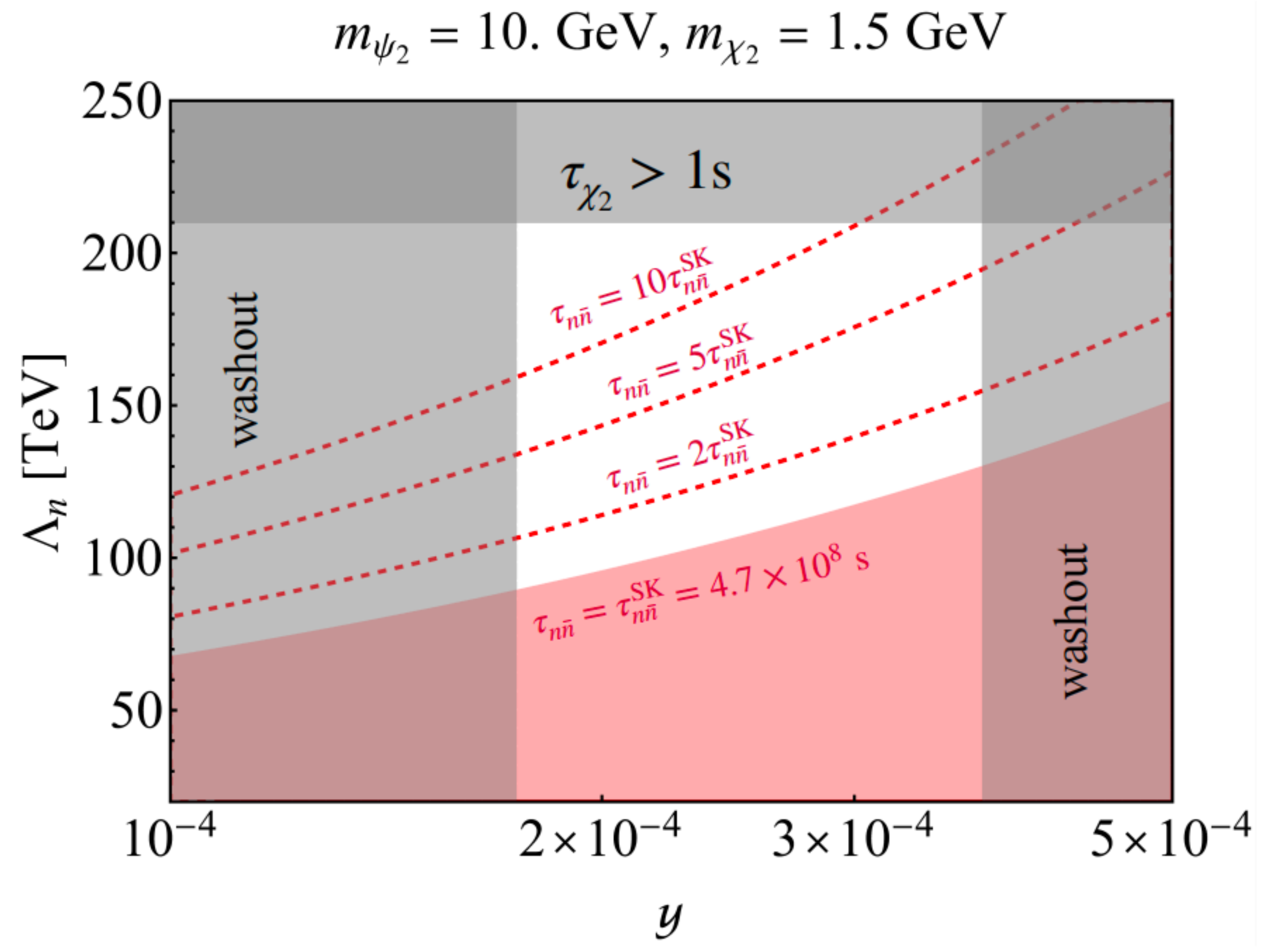
DM direct detection

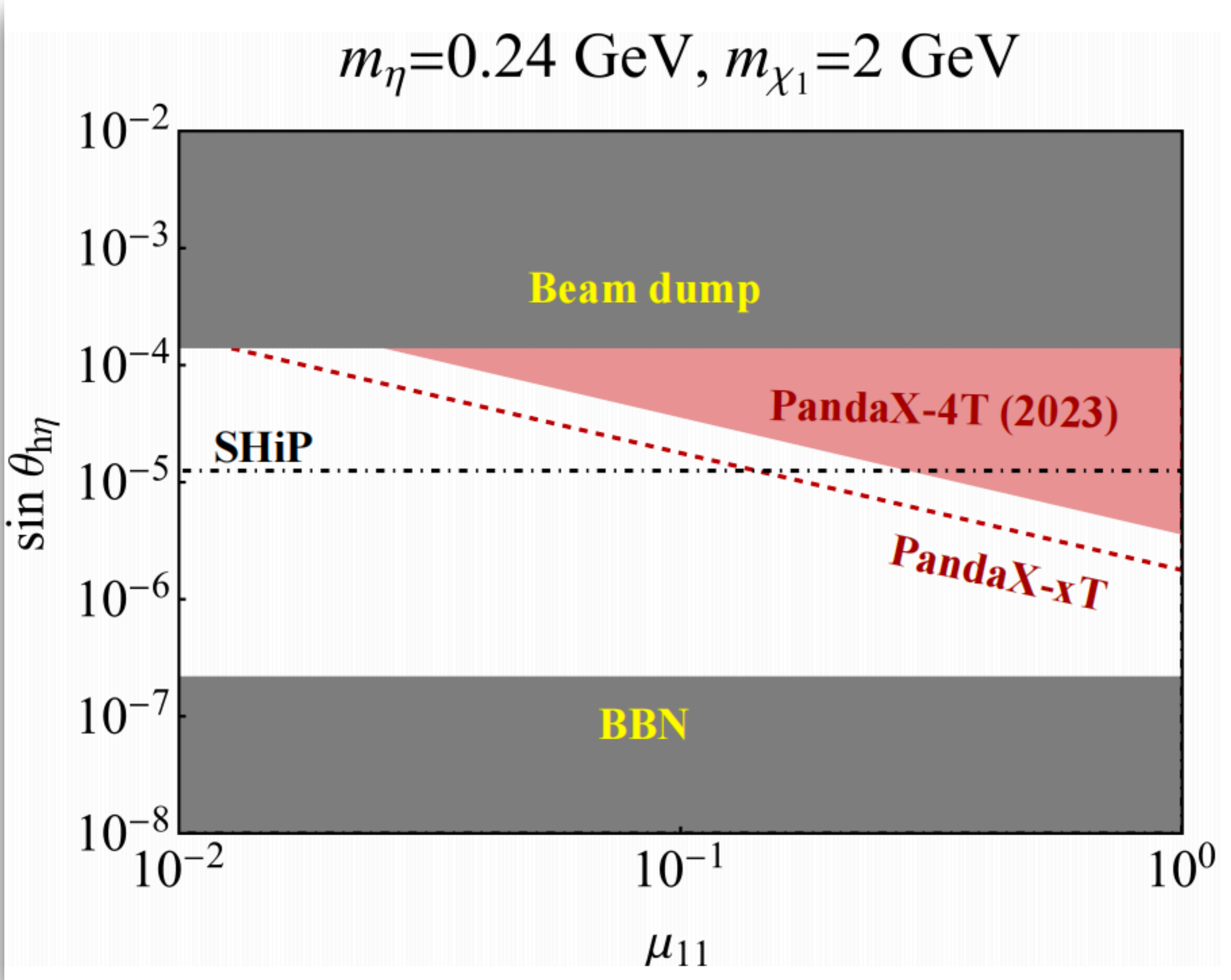


decay before BBN $\rightarrow$ $|\theta_{h\eta}| \gtrsim 10^{-7}$

$B\to K^{(*)}\eta(\to\mu^+\mu^-)$ $\rightarrow$ $|\theta_{h\eta}| \lesssim 10^{-4}$

Viable parameter space





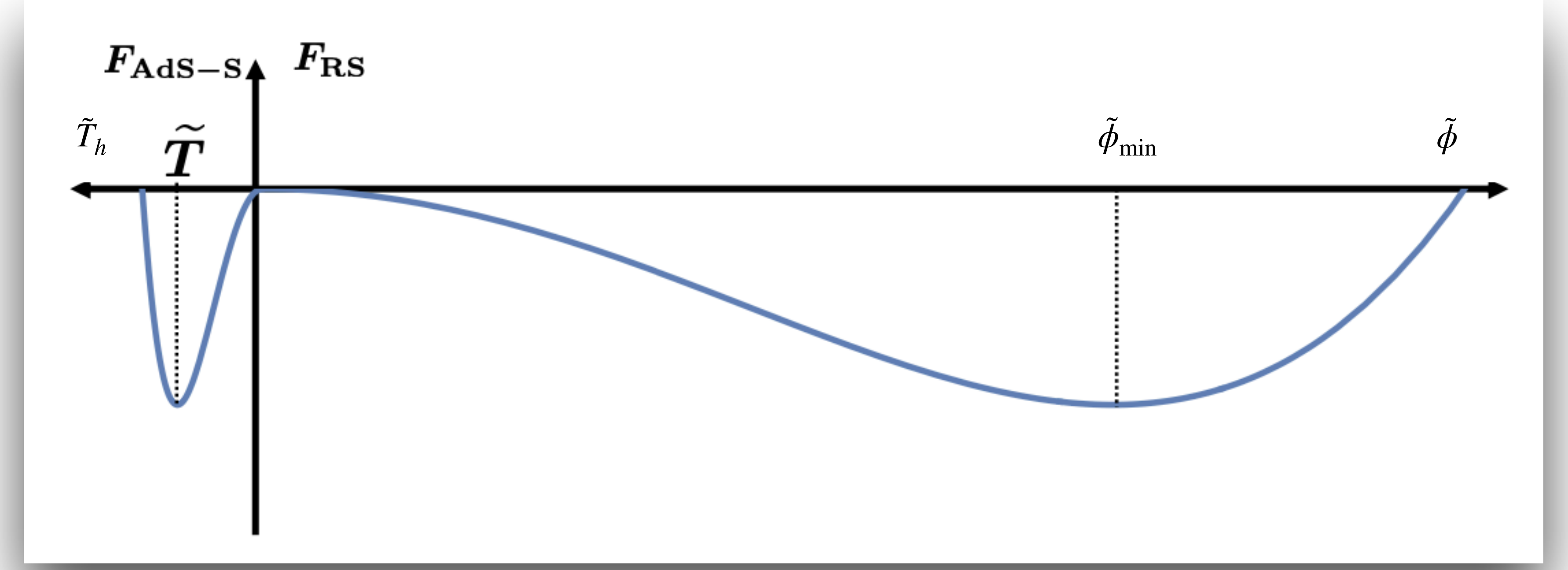
RS model at Finite Temperature and Hawking-Page Phase Transition

Hawking, Page '83 ; Witten '98 ; Arkani-Hamed+ 2000 ; Creminelli+ 2002 ; Nardini+ 2007; Harling+ 2017 ; Nakai+ 2020

Question: What is the finite temperature description of Randall-Sundrum model?

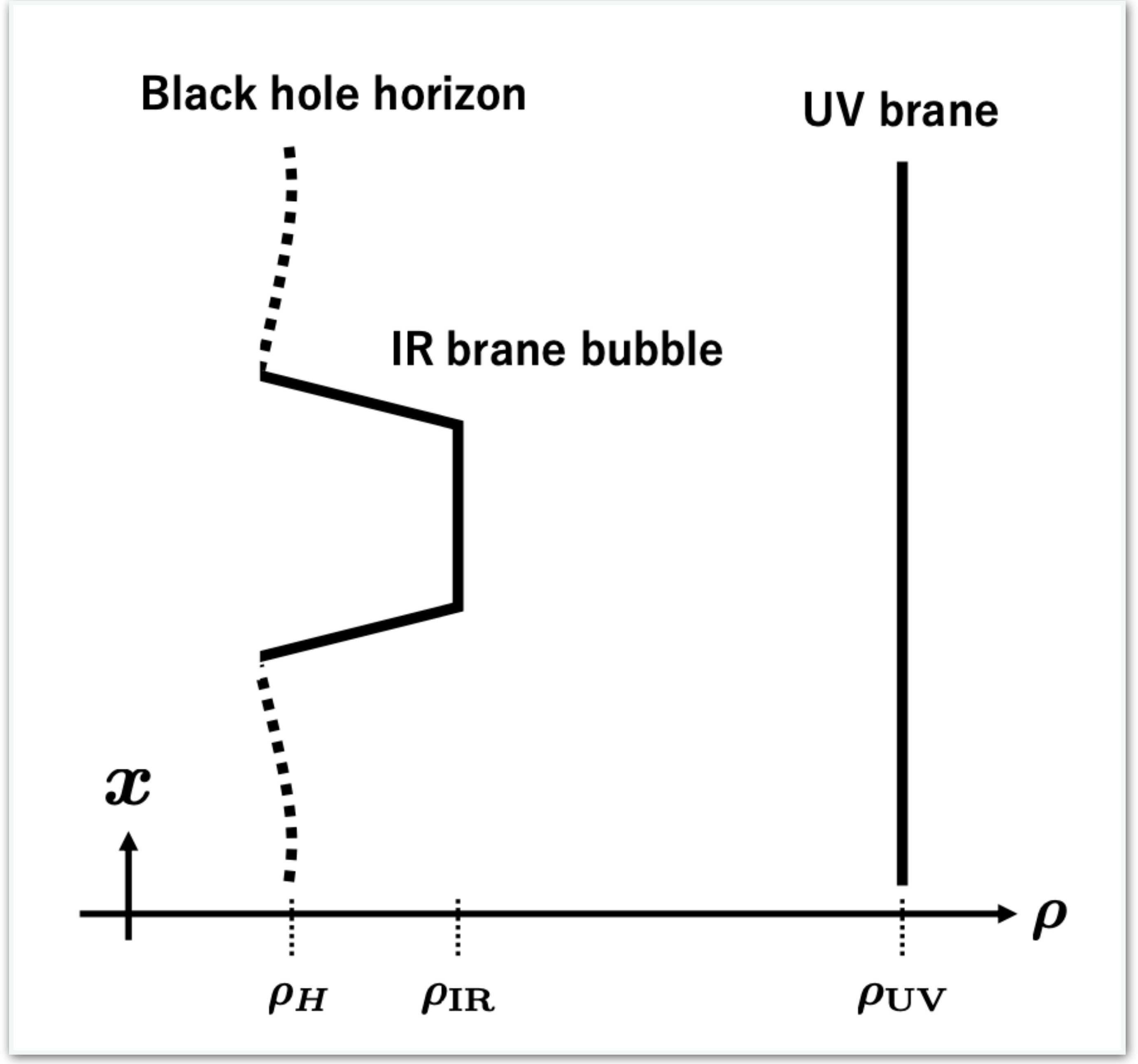
The high temperature phase of RS model is AdS-S space where the IR brane is replaced by the black-hole horizon.

This high temperature phase is dual to a hot thermal CFT.



$$\Delta F_{\rm AdS-S} = \frac{3}{8}\pi^2 N^2 T_h^4 - \frac{1}{2}\pi^2 N^2 T_h^3 T$$

$$\Delta F_{\rm RS} = V_{\rm eff}(\phi_{\rm min}) - V_{\rm eff}(0)$$



Below and above T_c two distinct phases are thermodynamically favored.

A phase transition takes place as T is lowered below T_c.

$$T_c = \left(\frac{8\,|\,\Delta F_{\rm RS}\,|}{\pi^2 N^2}\right)^{1/4}$$

The Model: Dark first-order deconfining phase transition

Rattazzi+ 2002 ; Servant+ 2017

$T^{(D)} \gg T_c^{(\mathrm{D})}$

4D conformal dark sector with large N
+
dark pure $SU(N_H)$ Yang-Mills

$SU(N_H)$ confines $\Longrightarrow$ drives spontaneous breaking of conformal invariance $\Longrightarrow$ generates dilaton (φ) effective potential

$T_c^{(\mathrm{D})}$

Confinement-deconfinement phase transition and generation of gravitational waves

Dual 5D description

IR brane replaced by an event horizon + $SU(N_H)$ in the bulk

Dark $SU(N_H)$ confinement generates radion potential

Below $T_c^{(\mathrm{D})}$: IR brane configuration has lower free-energy

IR brane bubbles appear and a strong first-order phase transition proceeds.

Secluded dark sector

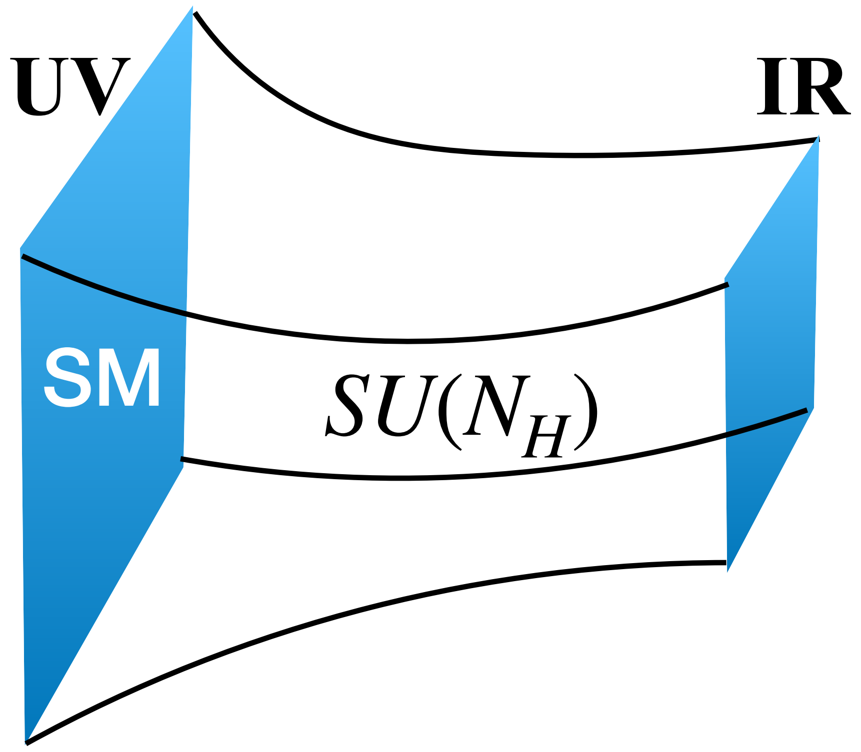
For eg: dark radiation final state.

Contributes to ΔN_{eff} and may alleviate the Hubble tension.

Decaying dark sector

$\mathscr{L}_{\mathrm{portal}} \sim O_{\mathrm{vis}} O_{\mathrm{dark}}$

Is not subject to ΔN_{eff} constraint.



$SU(N_H)$
confinement generates $V_{\mathrm{eff}}(\varphi)$

Gravitational waves: dilaton effective potential

$$\boxed{\frac{1}{g_{\rm H}^2(Q,\varphi)} = -\frac{b_{\rm CFT}}{8\pi^2}\ln\left(\frac{k}{\varphi}\right) - \frac{b_{\rm H}}{8\pi^2}\ln\left(\frac{k}{Q}\right)}$$

Running of $SU(N_{\rm H})$ coupling $g_{\rm H}$ from UV scale k to $Q \lesssim \varphi$. $b_{\rm CFT} = -\xi N$, $b_{\rm H} = 11N_{\rm H}/3 + b_f$.

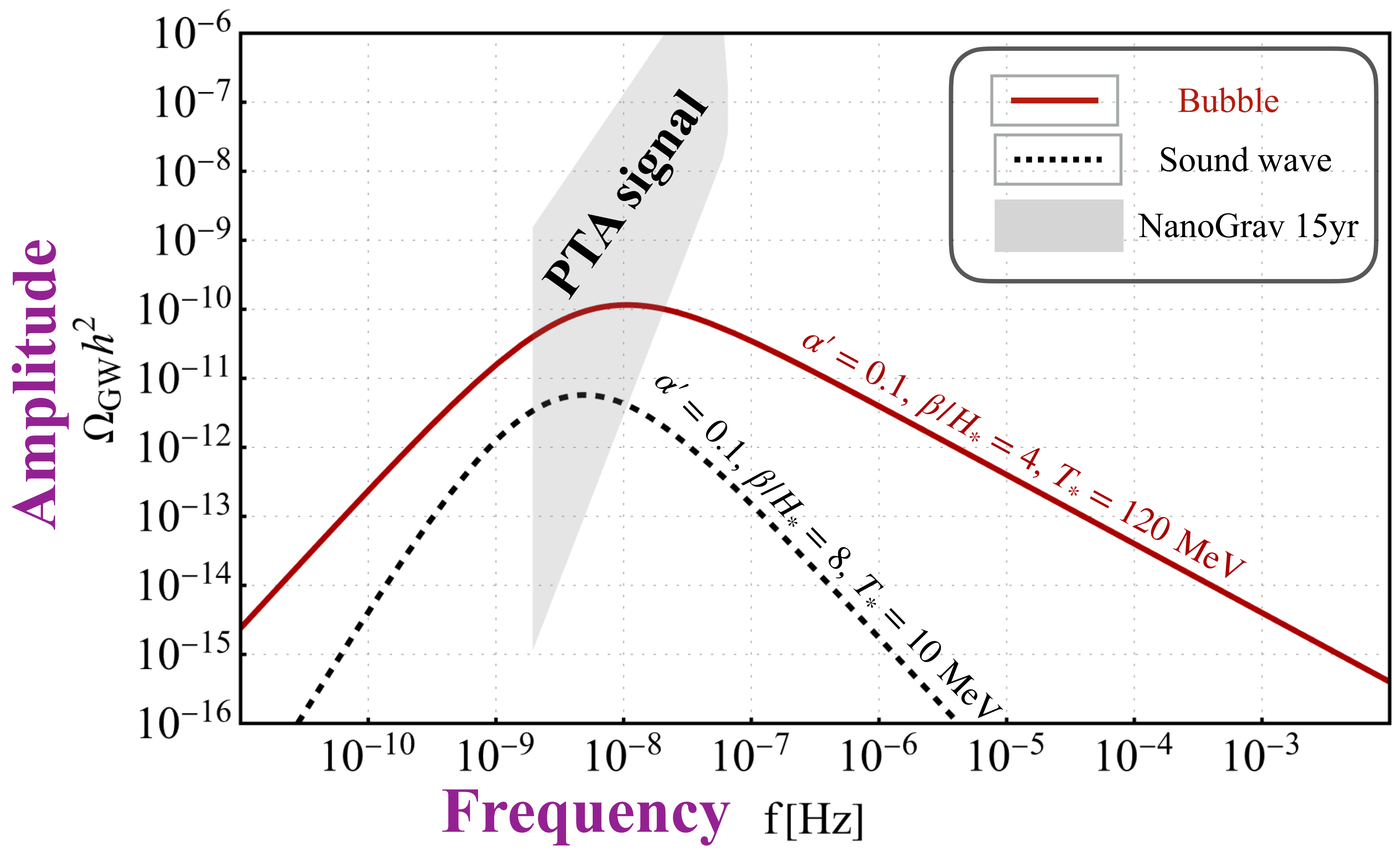
$SU(N_{\rm H})$ **confinement scale depends on φ. Condensate provides dilaton potential $V_{\rm eff}(\varphi)$.**

$$\boxed{\Lambda_{\rm H}(\varphi) = k\left(\frac{\varphi}{k}\right)^{-b_{\rm CFT}/b_{\rm H}} = \Lambda_{\rm dQCD}\left(\frac{\varphi}{\varphi_{\rm min}}\right)^{n}}$$

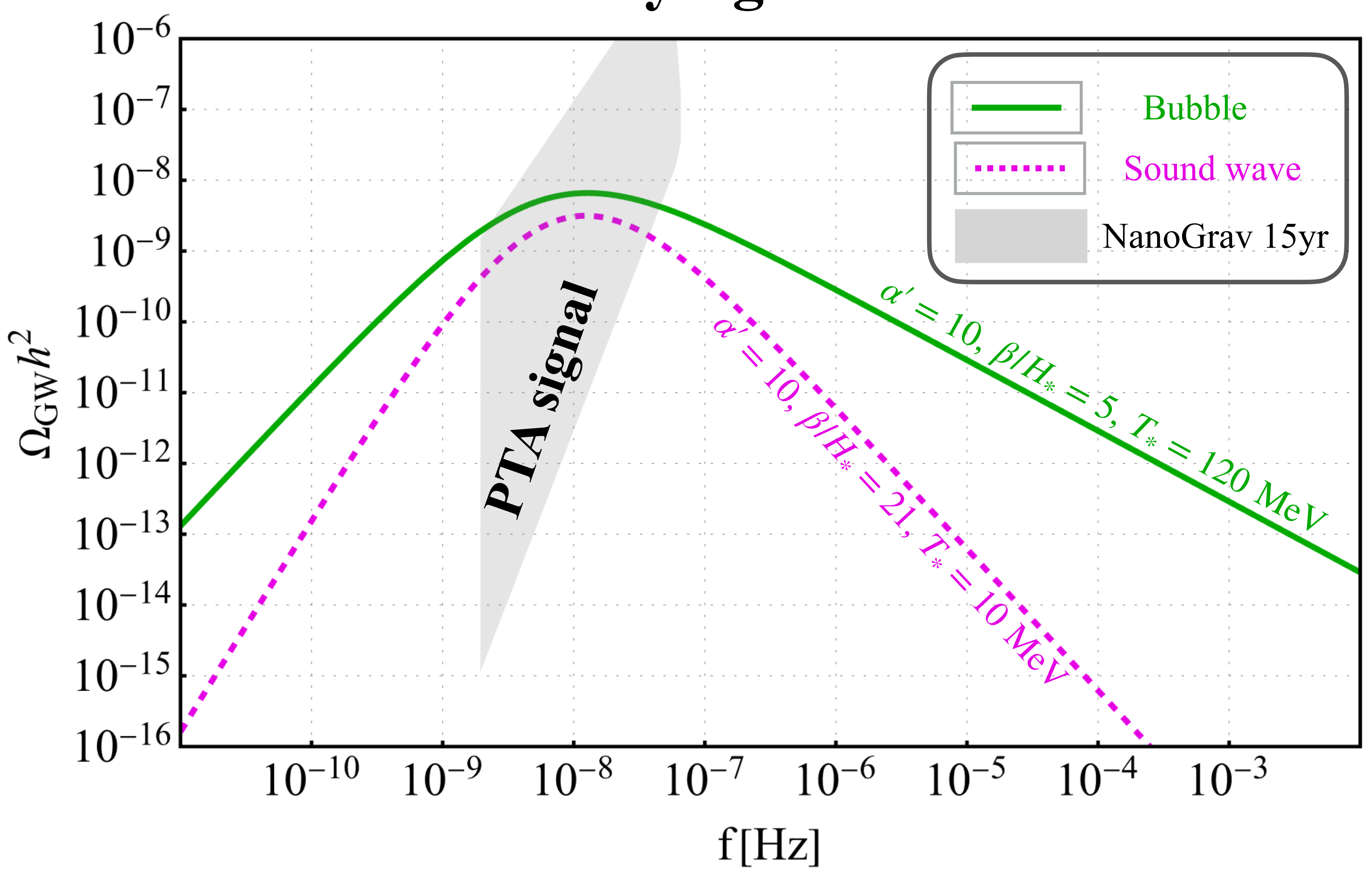
$$\boxed{V_{\rm eff}(\varphi) = \begin{cases} V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_{\rm H}}{\eta}\Lambda_{\rm dQCD}^4\left(\frac{\varphi}{\varphi_{\rm min}}\right)^{4n}, & \text{for } \varphi \geq \varphi_{\rm c} \\ V_0 + \frac{\lambda_\varphi}{4}\varphi^4 - \frac{b_{\rm H}}{\eta}\gamma_c^4\varphi_c^4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

Phase transition effective parameters α, β are determined from $V_{\rm eff}(\varphi)$, and the bounce action $S_{\rm B}$.

Secluded dark sector



Decaying dark sector



Asymmetry Sharing

✦ Generated dark asymmetry $\mathscr{D}_{\mathrm{L,in}}$ is stored in L_χ , χ :

$$\mathscr{D}_{\mathrm{L,in}} \simeq 10^{-10}\left(\frac{N_{D_{\mathrm{L}}}}{2}\right)\left(\frac{\delta_{\mathrm{CP}}}{10^{-4}}\frac{\varphi_{\min}^2}{\Lambda_{\mathrm{CP}}^2}\right)\left(\frac{\alpha_{\mathrm{D}}}{1.5\times10^{-2}}\right)^4\left(\frac{\lambda}{10^{-4}}\right)^{-3/2}\left(\frac{5v_{\mathrm{D}}}{\varphi_{\min}}\right)^{1/2}\left(\frac{\varphi_{\min}}{3T_{\mathrm{RH}}}\right)^3$$

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

Baryonic DM composed of f ($\mathbb{Z}_2$ odd)

$$\mathcal{O}_{\mathrm{D}} \sim \frac{1}{\Lambda_{\mathrm{D}}^2}\, p_{\mathrm{D}}\, p_{\mathrm{D}}\chi\chi \quad ; \quad \mathcal{O}_n \sim \frac{1}{\Lambda_n^2}\chi u_{\mathrm{R}} d_{\mathrm{R}} d_{\mathrm{R}}$$

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.

✦ Asymmetries in the visible sector $\mathscr{B}_f$ and dark baryon sector $\mathscr{D}_{\mathrm{B}}$ can be related:

$$\mathscr{B}_f = \left[\frac{2+4N_{D_{\mathrm{L}}}}{4N_{D_{\mathrm{L}}}+N_{D_{\mathrm{B}}}+2}\right]\mathscr{D}_{\mathrm{L,in}} \quad ; \quad \mathscr{D}_{\mathrm{B}} = \left[\frac{N_{D_{\mathrm{B}}}}{4N_{D_{\mathrm{L}}}+N_{D_{\mathrm{B}}}+2}\right]\mathscr{D}_{\mathrm{L,in}} \quad ; \quad m_{p_{\mathrm{D}}} \simeq 5\left|\frac{\mathscr{B}_f}{\mathscr{D}_{\mathrm{B}}}\right|\mathrm{GeV}$$

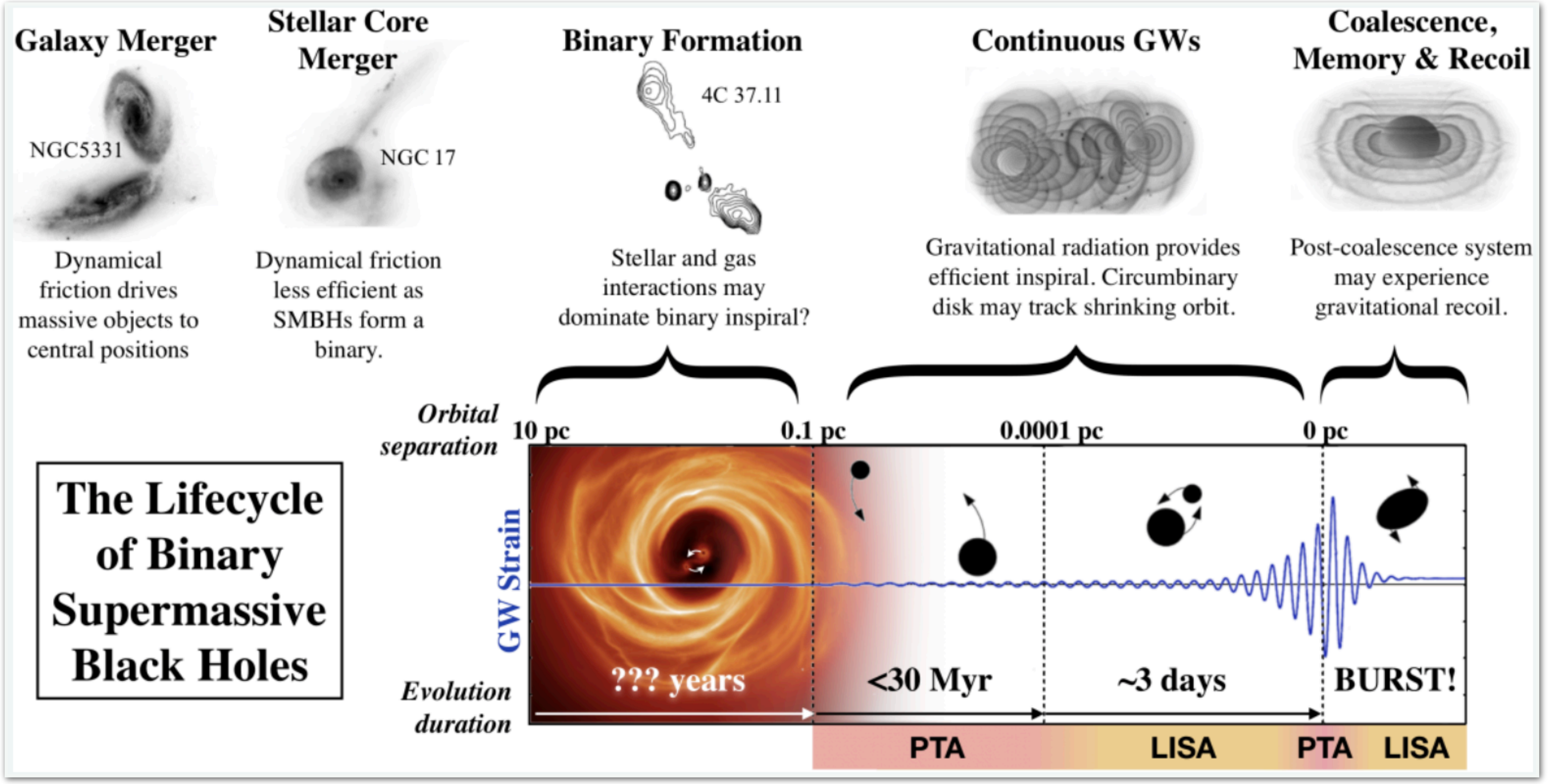
✦ The DM is **self-interacting** via the mediation of dark pions π_{D} with cross-section:

$$\frac{\sigma_{p_{\mathrm{D}}p_{\mathrm{D}}}}{m_{p_{\mathrm{D}}}} \sim 1\ \mathrm{cm}^2/\mathrm{g}\left(\frac{\Lambda_{\mathrm{H,0}}}{m_{p_{\mathrm{D}}}}\right)\left(\frac{\Lambda_{\mathrm{H,0}}}{a_{\mathrm{D}}^{-1}}\right)^2\left(\frac{150\ \mathrm{MeV}}{\Lambda_{\mathrm{H,0}}}\right)^3 \quad ;$$

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

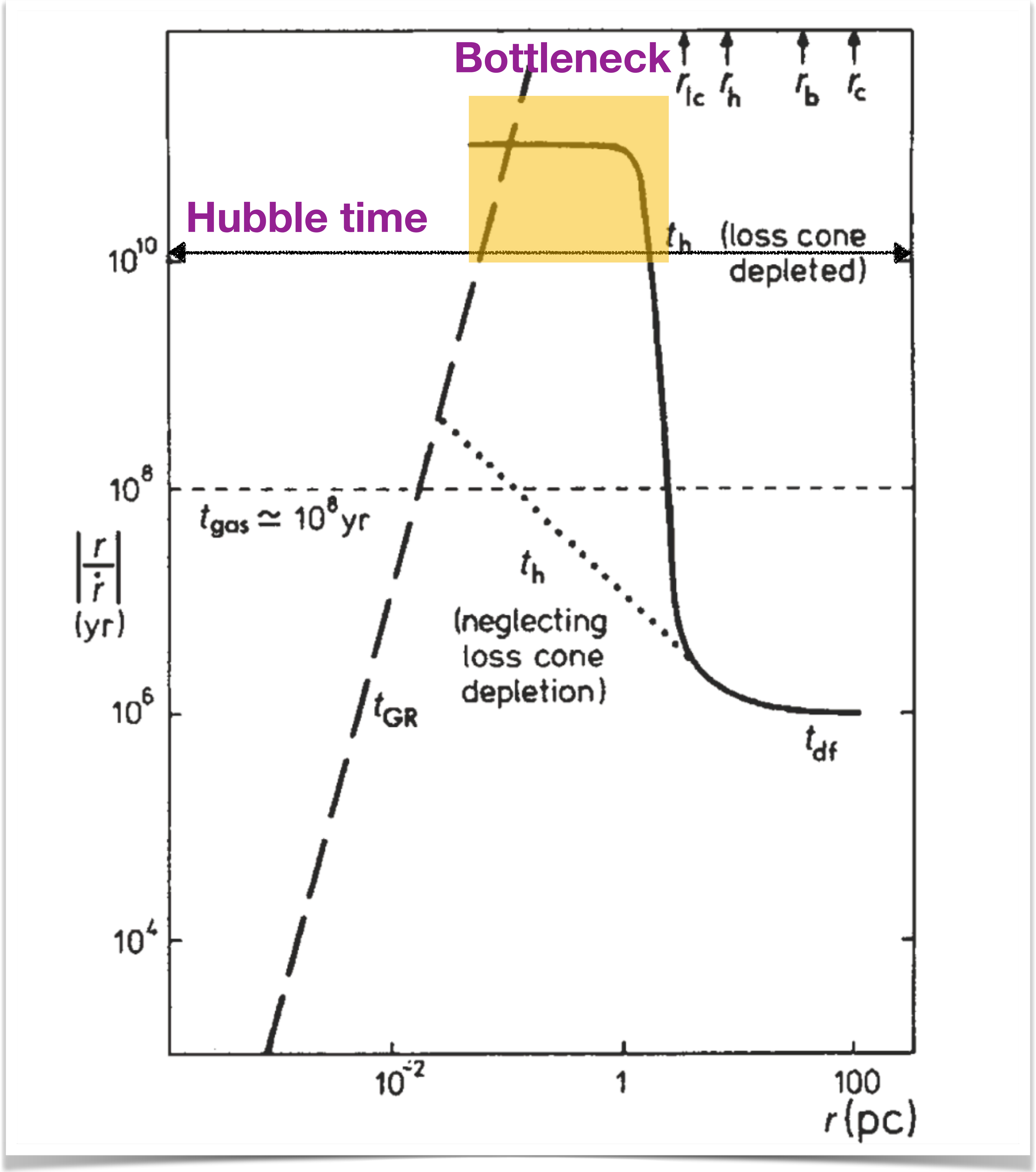
Tulin Yu (2017) ; Kribs (2016)

A note about the final parsec problem



Orbital separation of ~ 0.01 pc is needed to emit gravitational waves efficiently.

Solutions: triaxiality, multiple BHs, …



Begelman, Blandford, Rees 1980

Results from Multi-Model Analysis (MMA)

Ellis et. al. 2308.08546

Scenario	Best-fit parameters	ΔBIC	Signatures
GW-driven SMBH binaries	$p_{\rm BH} = 0.07$	6.0	FAPS, LISA, mid-f, ~~LVK, ET~~
GW + environment-driven SMBH binaries	$p_{\rm BH} = 0.84$ $\alpha = 2.0$ $f_{\rm ref} = 34$ nHz	Baseline (BIC = 53.9)	FAPS, LISA, mid-f, ~~LVK, ET~~
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$	-1.2 (4.6)	~~FAPS~~, LISA, mid-f, LVK, ET
Phase transition (PT)	$T_* = 0.34$ GeV $\beta/H = 6.0$	-4.9 (2.9)	~~FAPS, LISA, mid-f, LVK, ET~~
Domain walls (DWs)	$T_{\rm ann} = 0.85$ GeV $\alpha_* = 0.11$	-5.7 (2.2)	~~FAPS~~, LISA?, ~~mid-f, LVK, ET~~
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.7}$/Mpc $A = 0.06$ $\Delta = 0.21$	-2.1 (5.8)	~~FAPS, LISA, mid-f, LVK, ET~~
First-order GWs (FOGWs)	$\log_{10} r = -14$ $n_{\rm t} = 2.6$ $T_{\rm rh} = -0.67$ GeV	-2.0 (6.0)	~~FAPS, LISA, mid-f, LVK, ET~~
"Audible" axions	$m_a = 3.1 \times 10^{-11}$ eV $f_a = 0.87\, M_{\rm P}$	-4.2 (3.7)	~~FAPS, LISA, mid-f, LVK, ET~~

FAPS ≡ fluctuations, anisotropies, polarization, sources, mid-f ≡ mid-frequency experiment, e.g., AION [308], AEDGE [310], LVK ≡ LIGO/Virgo/KAGRA [161–163], ET ≡ Einstein Telescope [312] (or Cosmic Explorer [313]), ~~signature~~ ≡ not detectable