A SUSY B-L model & NANOGrav 15yr data

Wan-il Park
(Jeonbuk National University, U. of Valencia & IFIC)

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K. S. Jeong & **WIP**, JCAP 11 (2023) 016
R. Maji & **WIP**, 2308.11439

Outline

- **Motivation**
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  - BBN bound
  - Thermal inflation
- **A model**
  - An extension of MSSM based on $G_{\rm SM} \times U(1)_{B-L}$
  - Resolution of moduli problem
- **GWs from cosmic strings**
  - Cosmic string network
  - Forecast of SGWBs from cosmic string loops
- **NANOGrav 15yr data & SUSY B-L model**
  - NANOGrav 15yr data
  - Meta-stable strings from a SUSY B-L model
- **Conclusions**

Motivations

(Cosmological moduli problem in SUGRA)

[Dine, Fishler & Nemeschansky, PLB 136, 169 (1983); …]

- **Moduli & their cosmological implications**

  - Moduli = Planckian flat directions in the field space of a given theory.
  - Their presence is quite generic in UV theories inspired by superstring theories.
  - Some of moduli has Planckian VEVs and masses only from SUSY-breaking.

$$\langle \varphi_i \rangle \sim M_{\rm P}, \quad m_{\varphi_i} \sim \frac{M_{\rm SUSY}^2}{M_{\rm P}} \gtrsim \mathcal{O}(1){\rm TeV}$$

  - Long life time, but too abundant(due to large coherent oscillations)! $\Rightarrow$ danger in BBN

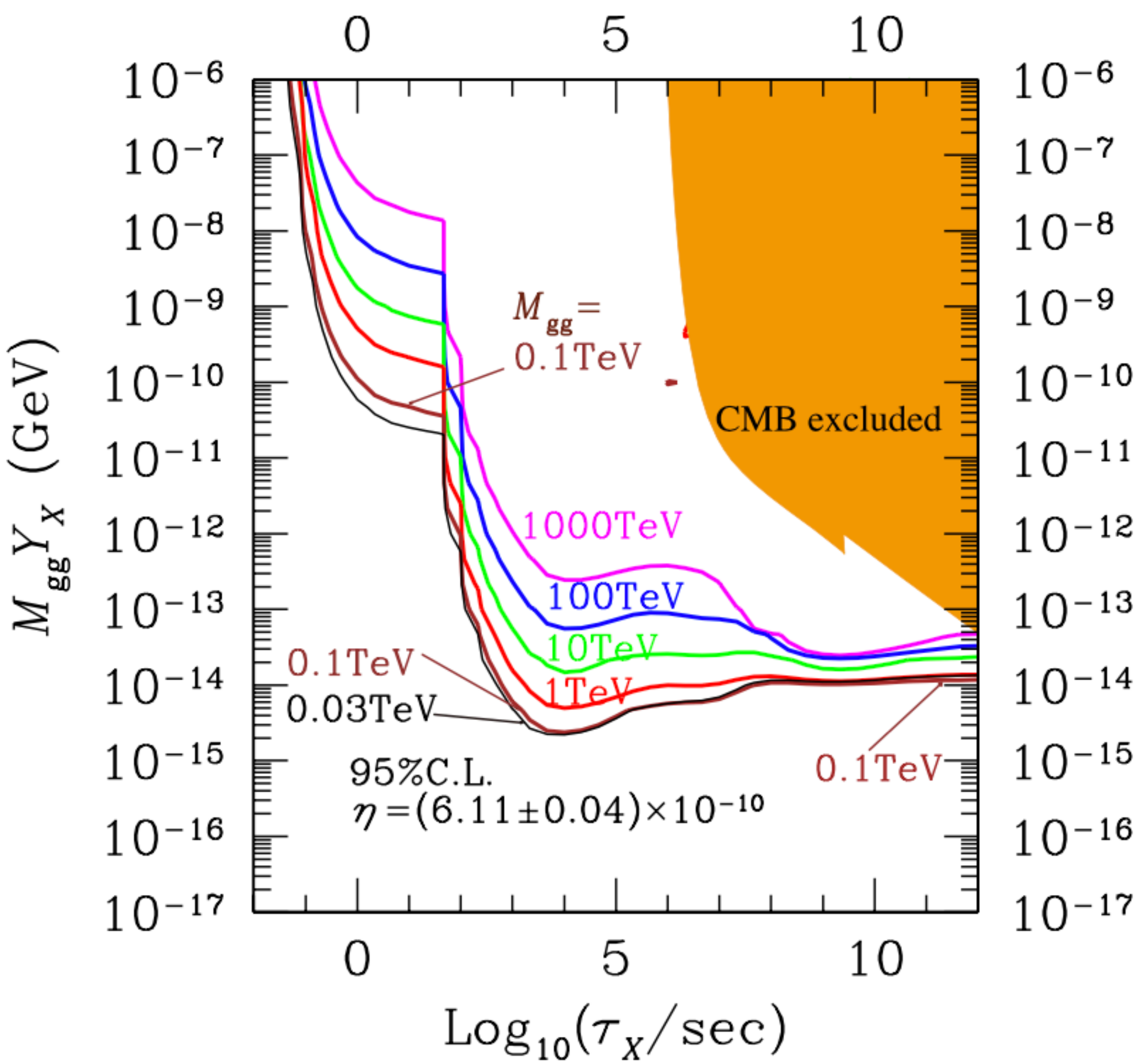
$$\Gamma_\varphi = \frac{\gamma_\varphi}{32\pi}\frac{m_\varphi^3}{M_{\rm P}^2} \ \ (\gamma_\varphi = \mathcal{O}(1)) \sim 10^{-29}{\rm GeV}\left(\frac{m_\varphi}{1{\rm TeV}}\right)$$

$$\frac{n_\phi}{s}\Big|_{\rm osc} \sim \left(\frac{M_{\rm P}}{m_\varphi}\right)^{1/2} \sim 10^7 \left(\frac{10{\rm TeV}}{m_\varphi}\right)^{1/2}$$

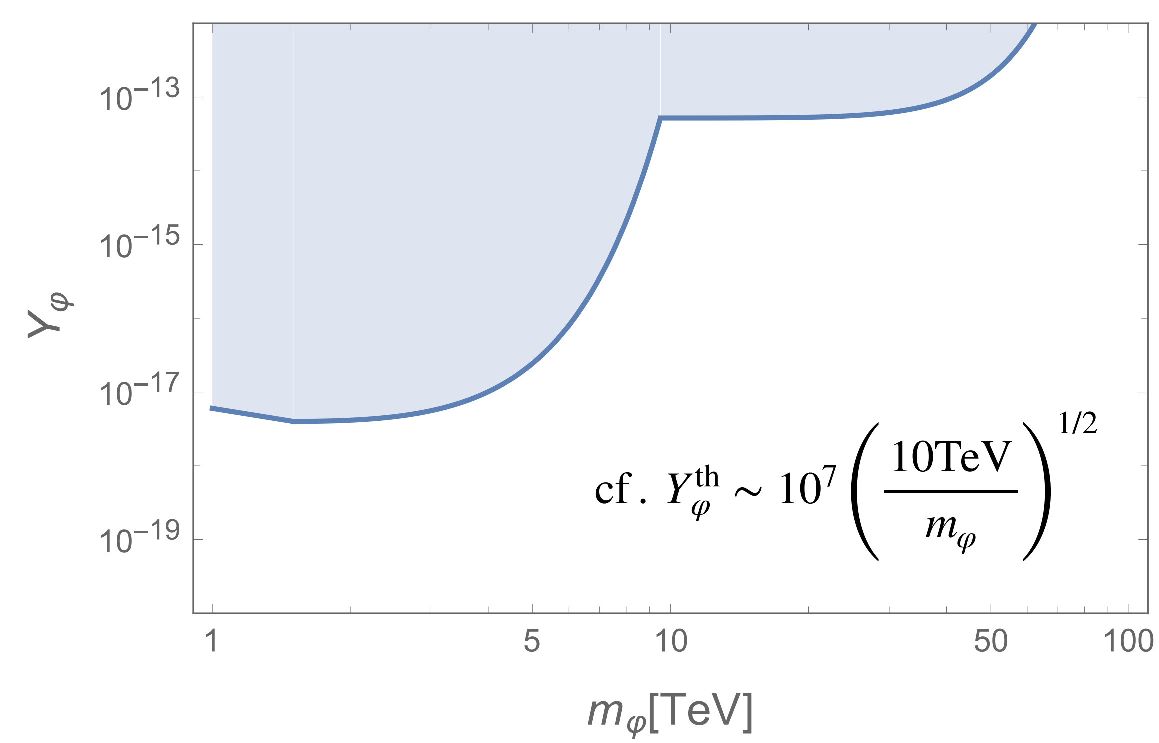
- **BBN bound on long-living particles (φ, $\psi_{3/2}$):**

  [Kawasaki et al, PRD 97, 2018]

  Injection of energetic SM particles disturbs the abundances of light elements.



$$
Y_\varphi \lesssim \begin{cases} 10^{-17}\left(\frac{1\mathrm{TeV}}{m_\varphi}\right) & : \ 10^3\mathrm{s} \lesssim \tau_\varphi \\ 10^{-13}\left(\frac{10\mathrm{TeV}}{m_\varphi}\right) \sim 10^{-17}\left(\frac{1\mathrm{TeV}}{m_\varphi}\right) & : \ 10\mathrm{s} \lesssim \tau_\varphi \lesssim 100\mathrm{s} \\ 10^{-13}\left(\frac{100\mathrm{TeV}}{m_\varphi}\right) & : \ \tau_\varphi \sim 1\mathrm{s} \end{cases}
$$

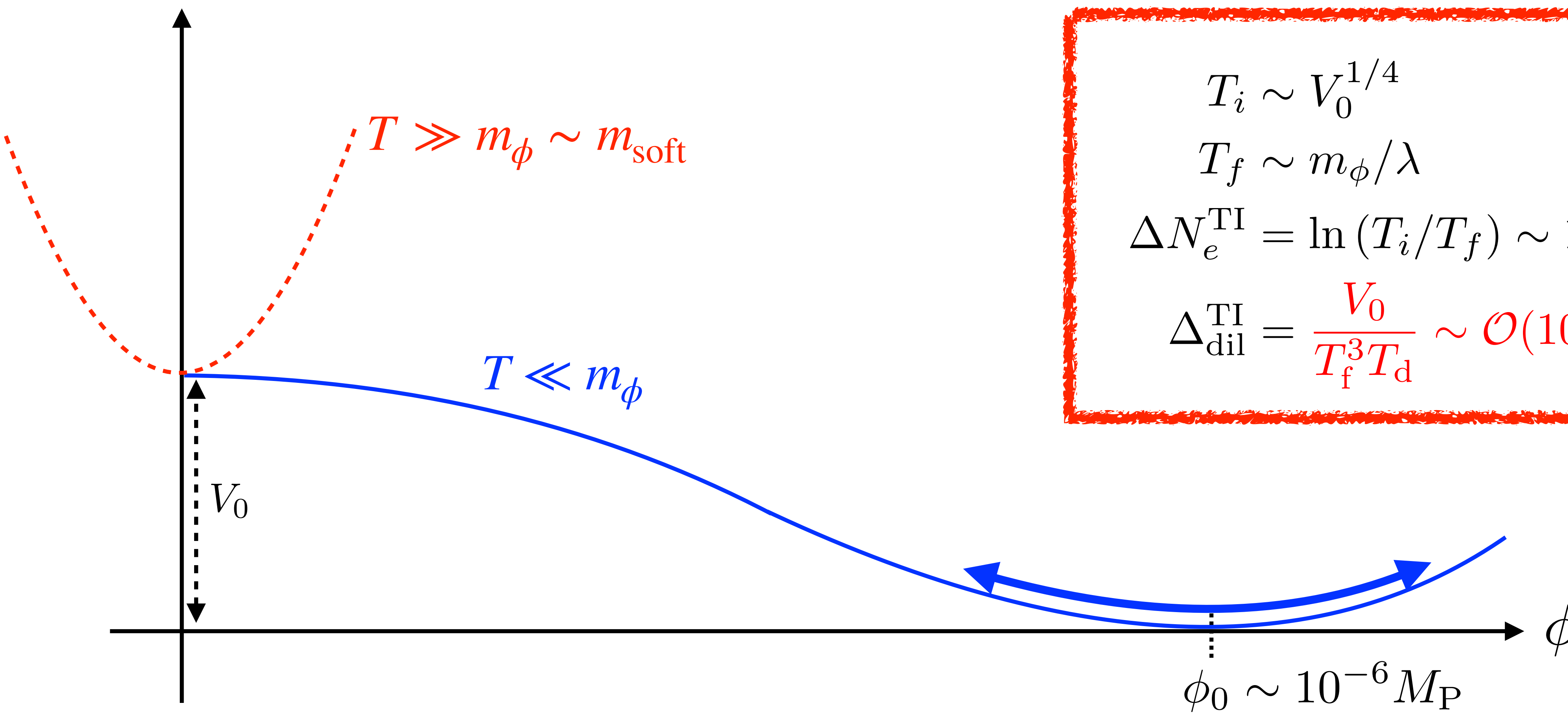


A dilution by a factor larger than $\mathcal{O}(10^{21})$ is necessary!

- **Thermal inflation** (as a sol. to the moduli problem) [Lyth & Stewart, 1995]

  - A short inflation well after the primordial inflation, caused by thermal effect.
  - Usually expected for a flat potential with thermal interactions.

$$V(\phi) = V_0 + \frac{1}{2}\left(\lambda^2 T^2 - m_\phi^2\right)^2 \phi^2 + \cdots$$



$$T_i \sim V_0^{1/4}$$
$$T_f \sim m_\phi / \lambda$$
$$\Delta N_e^{\rm TI} = \ln\left(T_i / T_f\right) \sim 10$$
$$\Delta_{\rm dil}^{\rm TI} = \frac{V_0}{T_{\rm f}^3 T_{\rm d}} \sim \mathcal{O}(10^{20-24})$$

The most compelling sol. to the moduli problem!

A SUSY U(1) B-L model

[Jeannerot, PRD 59 (1999)); Jeff A. Dror et al., PRL 124, 041804 (2020); W. Buchmuller et al., PLB 809 (2020) 135764; …]

- **The model ($G_{\rm SM} \times U(1)_{B-L}$)** [Kwang Sik Jeong & **WIP**, JCAP 11 (2023) 016]

$$W = W_{\rm MSSM} + \mu_\Phi \Phi_1 \Phi_2 + \frac{1}{2} y_N \Phi_1 N^2 + y_\nu L H_u N + \Delta W_{\rm high}$$

$$\Delta W_{\rm high} = \frac{\lambda_H}{2M} (H_u H_d)^2 + \frac{\lambda_\mu}{M} \Phi_1 \Phi_2 H_u H_d + \frac{\lambda_\Phi}{2M} (\Phi_1 \Phi_2)^2$$

< Potential along B-L D-flat direction with $LH_u = 0$ & $H_u H_d = 0$ >

$$V = \frac{1}{2}\left(m_1^2 + m_2^2\right)|\phi|^2 - \frac{1}{2}\left[B_\Phi \mu_\Phi \phi^2 + \frac{A_\Phi \lambda_\Phi}{4M}\phi^4 + {\rm c.c.}\right] + \left|\mu_\Phi + \frac{\lambda_\Phi \phi^2}{2M}\right|^2 |\phi|^2$$

$$\phi_0 \sim \sqrt{m_{\rm soft} M_{\rm P} / \lambda_\Phi} \sim 10^{11}{\rm GeV}\left(\frac{m_{\rm soft}}{10\lambda_\Phi {\rm TeV}}\right)^{1/2}$$

- **Resolving moduli problem**

  (via thermal inflation thanks to B-L D-flat direction - late time entropy injection)

Late-time decay of B-L Higgs:

$$\Delta W_{\rm high} \supset \frac{\lambda_\mu}{M}\Phi_1\Phi_2 H_u H_d$$

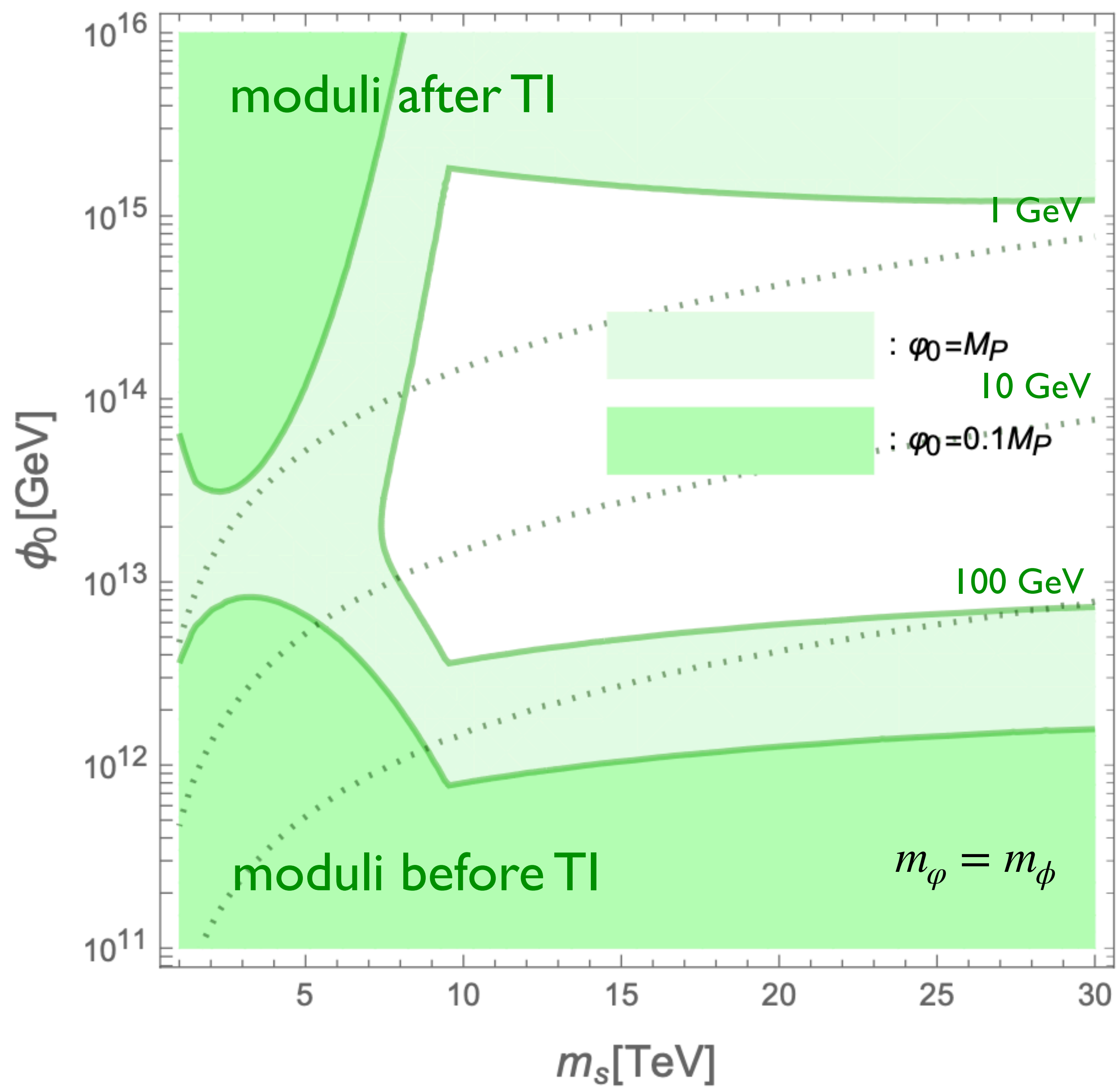
$$\Rightarrow \Gamma_\phi \sim \frac{1}{4\pi}\frac{m_\phi^3}{\phi_0^2}\left(\frac{|\mu|}{m_\phi}\right)^4$$

$$\Rightarrow T_{\rm d} \sim \sqrt{\Gamma_\phi M_{\rm P}} \sim m_\phi \left(\frac{m_\phi M_{\rm P}}{\phi_0^2}\right)^{1/2}$$

If $\varphi_0 = M_{\rm P}$,

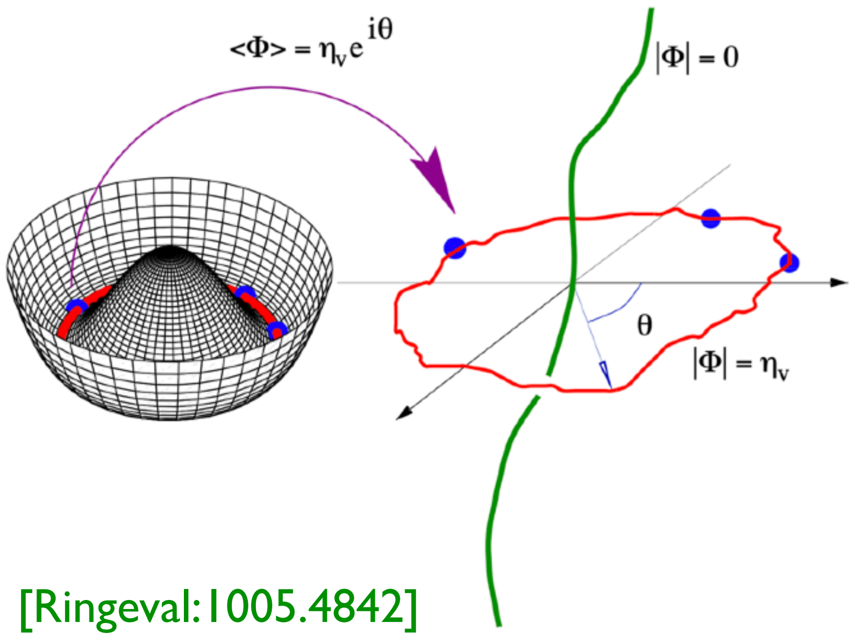
$$m_s \gtrsim 7 \text{ TeV}$$

$$3\times 10^{12} \lesssim \frac{\phi_0}{\rm GeV} \lesssim 2\times 10^{15}$$

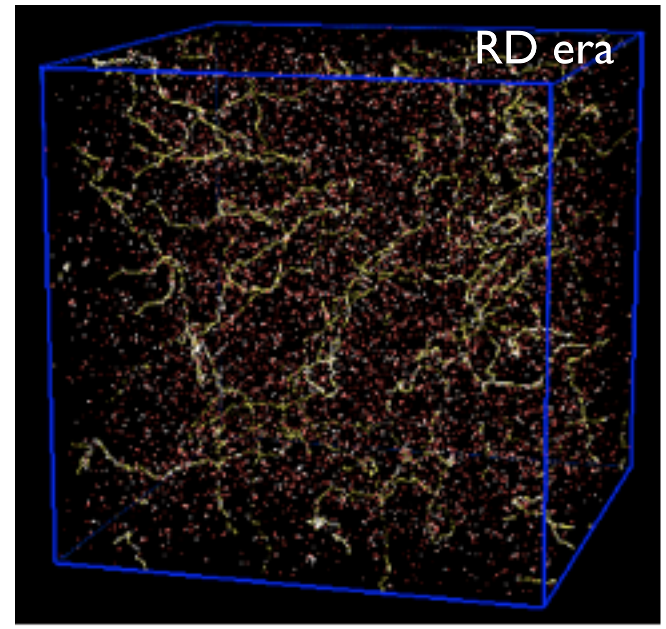


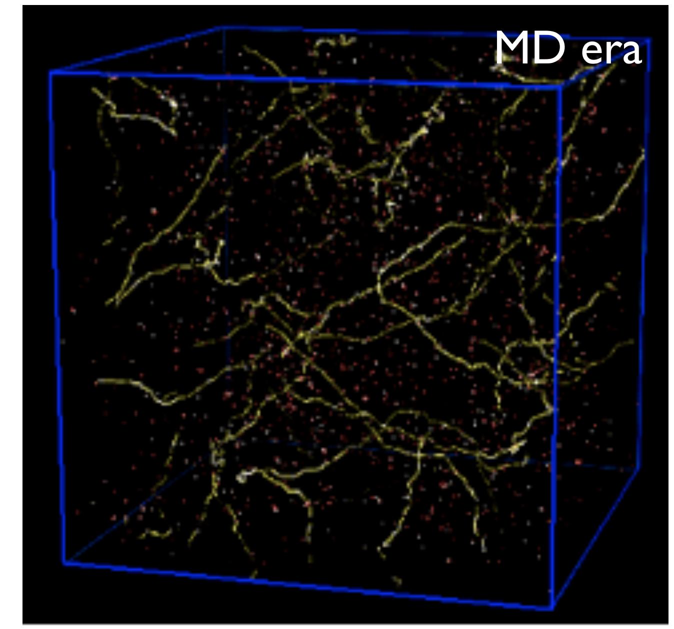
GWs from Cosmic Strings

- **Cosmic string network** [E.g.,Vilenkin & Shellard, 1994]



[Ringeval:1005.4842]





- formed when vacuum manifold is non-trivially connected ($\pi_1(\mathscr{M}) \neq I$)
- characterized by string tension: $\mu \sim \pi\phi_0^2$
- Network falls to the scaling regime: typical length $\xi \sim \alpha t$, $\alpha = \mathcal{O}(0.1)$.

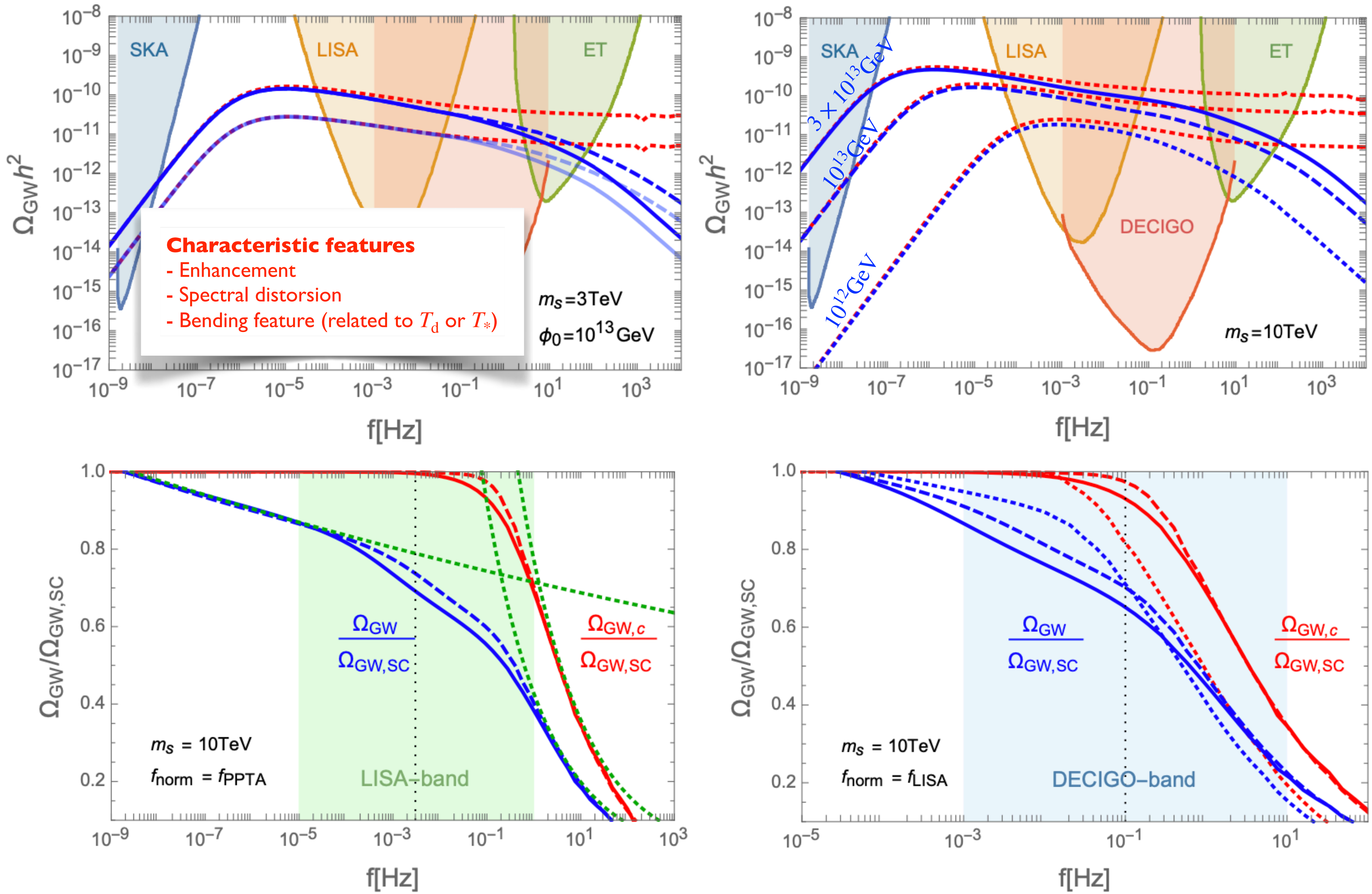
$$\frac{\rho_s}{\rho_c} \sim \frac{\mu}{M_P^2} \sim \left(\frac{\phi_0}{m_P}\right)^2 = \text{const}\,.$$

- Composition: Network + string loops of various sizes

- **Forecast of GWs (in our model)**

due to the zippering effects ($\because w_s \gg \phi_0^{-1}$)

$$\Omega_{\rm GW}(f) = \sum_k \Omega^{(k)}_{\rm GW}(f),\quad \overline{\Omega^{(k)}_{\rm GW}}(f) \equiv \frac{1}{\rho_c}\frac{2k}{f}\frac{\mathcal{F}_\xi \Gamma^{(k)} G\mu^2_{s,c}}{\xi(\xi+\Gamma G\mu_{s,c})}\int_{t_{\rm osc}}^{t_0} d\tilde{t}\,(1+c_2\ln N_w^{\max}(t_i))^2\,\frac{C_{\rm eff}(t_i)}{t_i^4}\left[\frac{a(\tilde{t})}{a_0}\right]^5\left[\frac{a_i}{a(\tilde{t})}\right]^3\Theta(t_i-t_{\rm osc})\Theta(t_i-\ell_*/\xi)$$



A remark

Hint of SUSY? (Flat direction)

- Unified models require the strength of gauge couplings of $\mathcal{O}(10^{-2} - 1)$.
- Non-SUSY scenario is difficult to have flat directions if they are gauge-charged.
- Hence, gauge-charged flat direction can be regarded as a characteristic of SUSY theories.

A hint of flat-direction from GWs ⇨ A signal of SUSY

NANOGrav 15yr & SUSY B-L

Pulsar Timing

- **Pulsar timing** = Tracking of pulsar rotation by very accurately measuring pulse arrival times (TOAs)

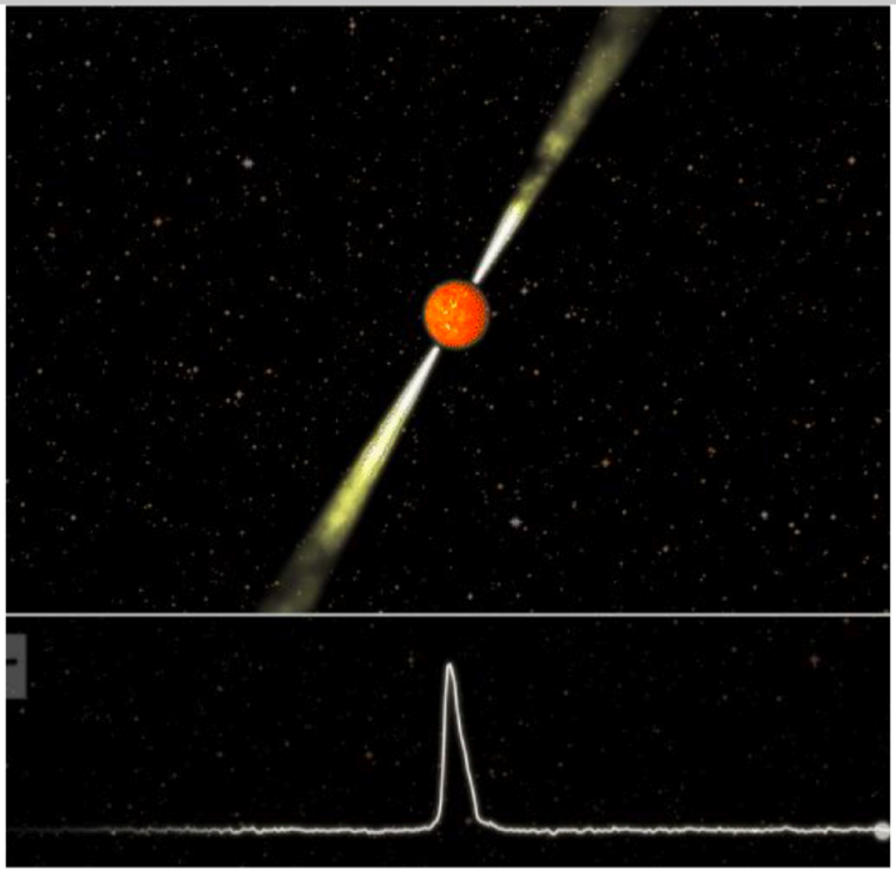
- Passing GWs induces a shift in Pulsar's intrinsic spin frequency $\nu_0 \Rightarrow \nu(t)$.

- Observable timing residuals, induced by GWs, are given by the time integral of $\Delta\nu_0/\nu_0$.

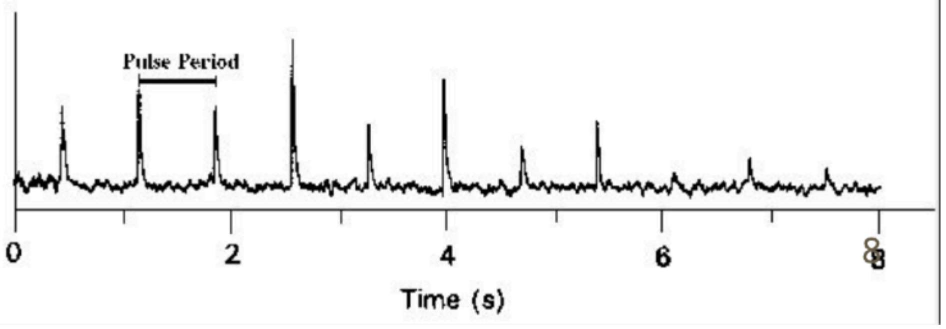
- **Timing Residual R(t):**

$$R(t) = \int_0^t \frac{\nu_0 - \nu(t')}{\nu_0}\, dt'$$

[Hobbs, & Dai 2017 (arXiv:1707.01615) (We model the expected R(t) from SMBH Binaries using GR approaches)



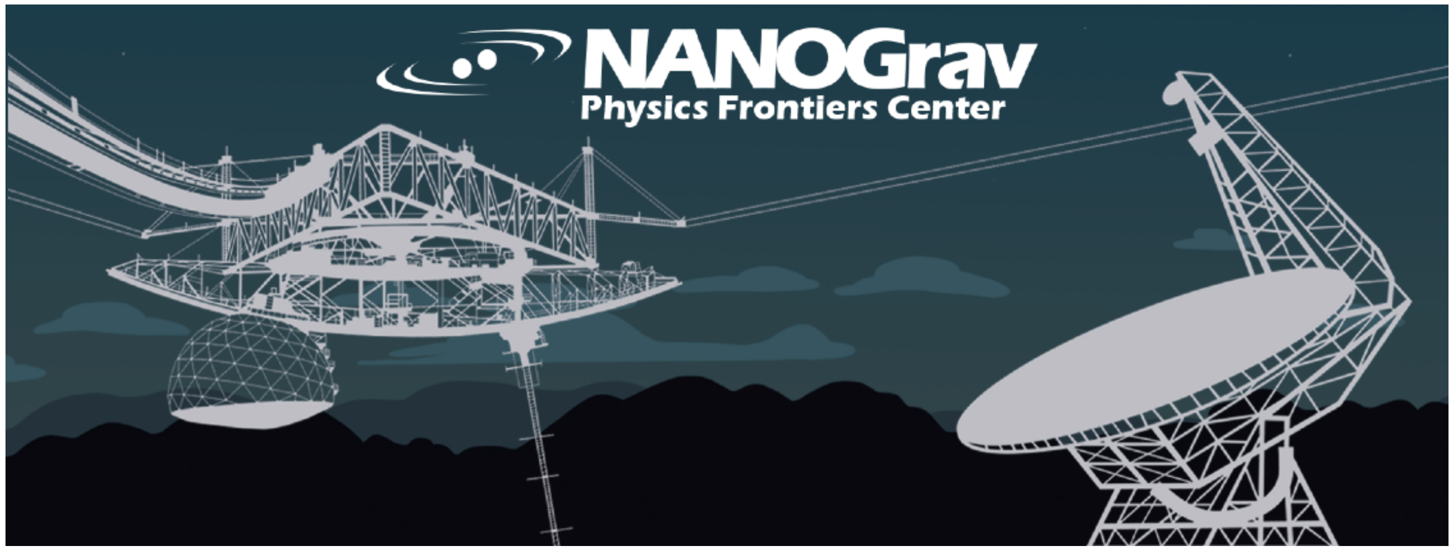
Source : astron.nl



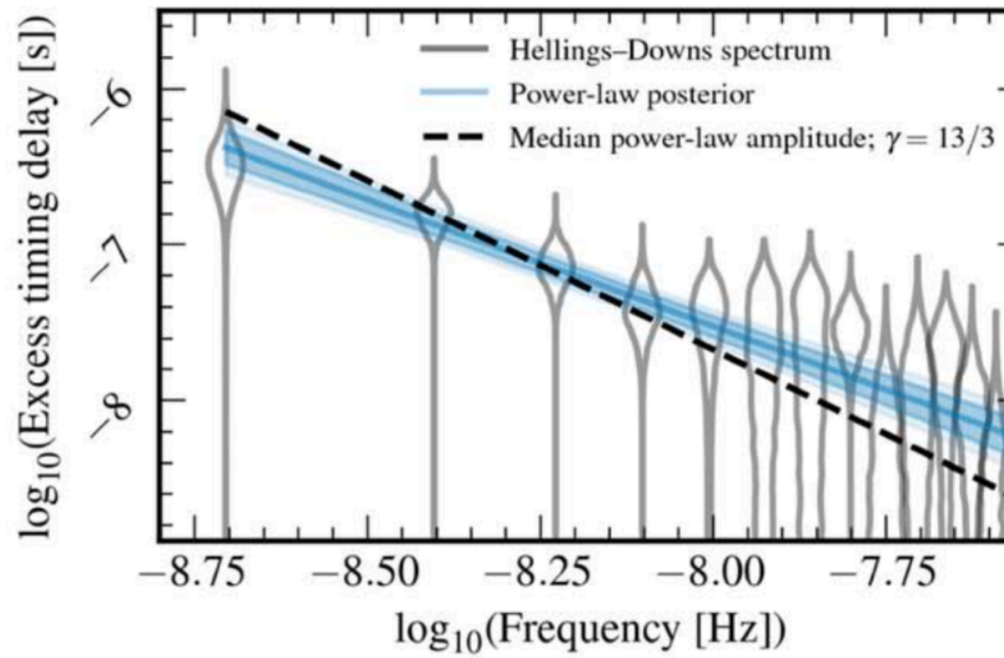
[From Achamveedu Gopakumar's talk at PPC2023]

- **NANOGrav 15yr Data** [Astrophy. J. Lett. 951 (2023) 1, L8]

North American Nanohertz Observatory for Gravitational Waves



(a)



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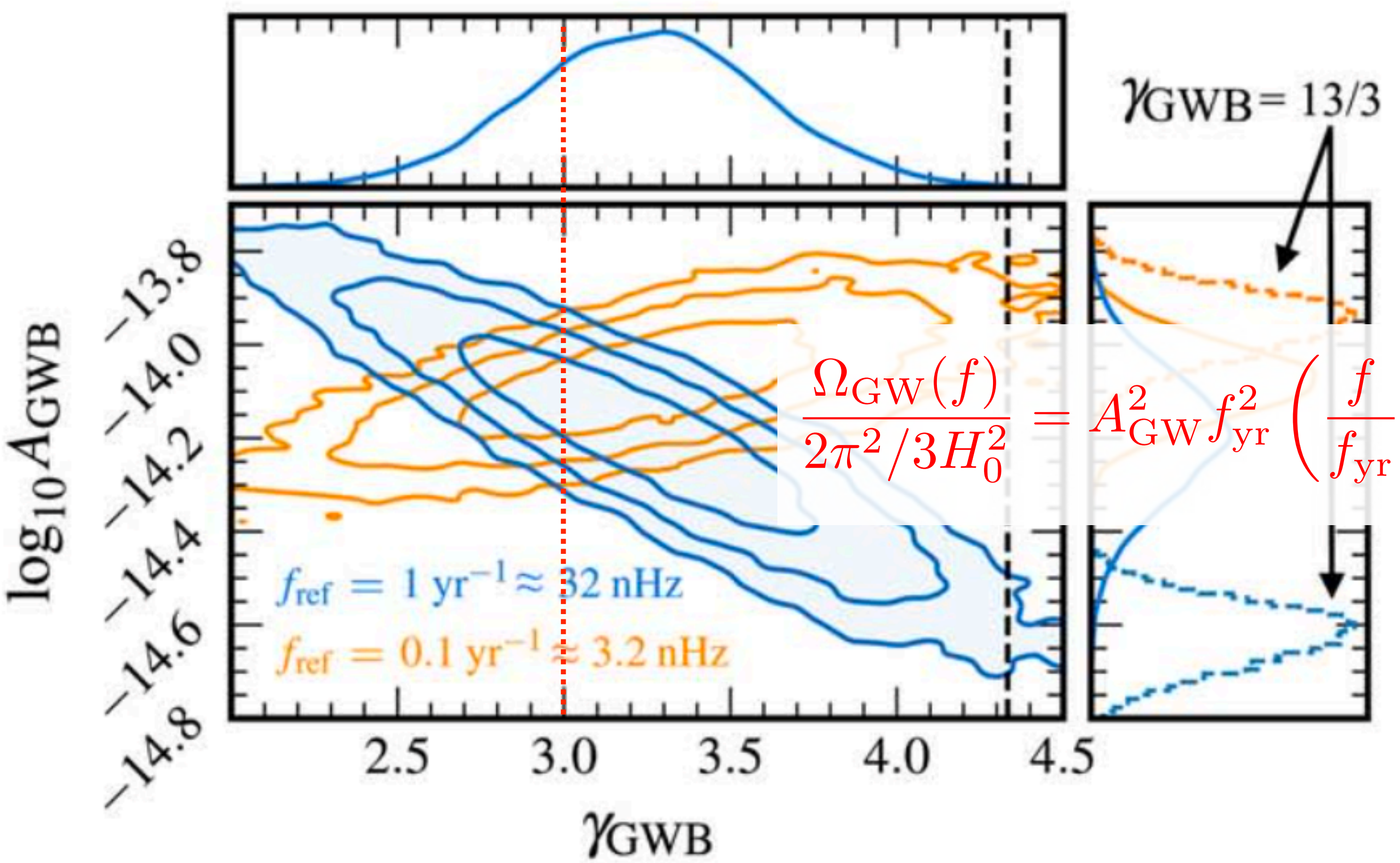
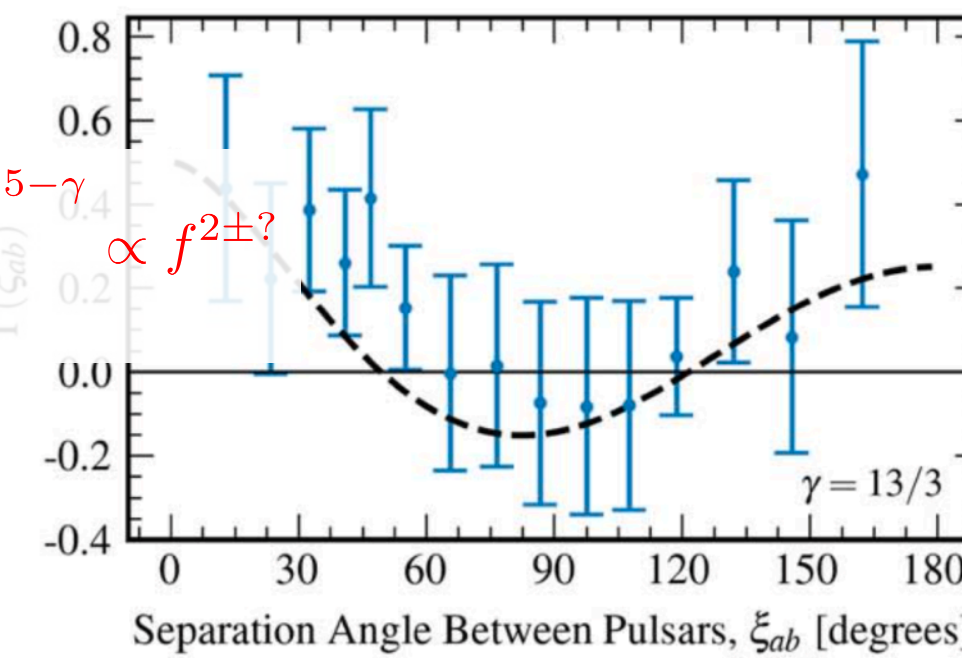
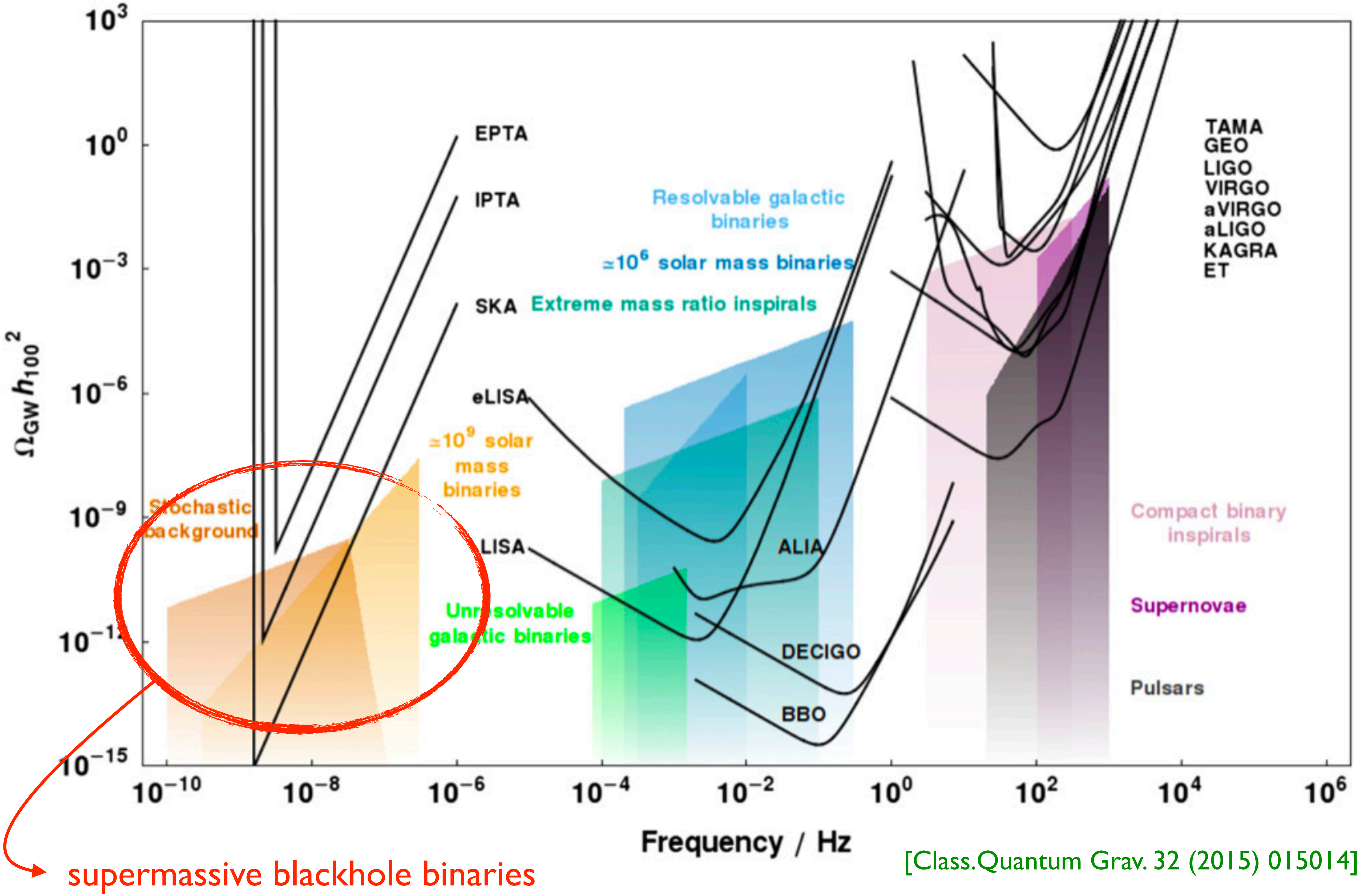


(c)



$$\frac{\Omega_{\rm GW}(f)}{2\pi^2/3H_0^2} = A_{\rm GW}^2 f_{\rm yr}^2 \left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma} \propto f^{2\pm ?}$$

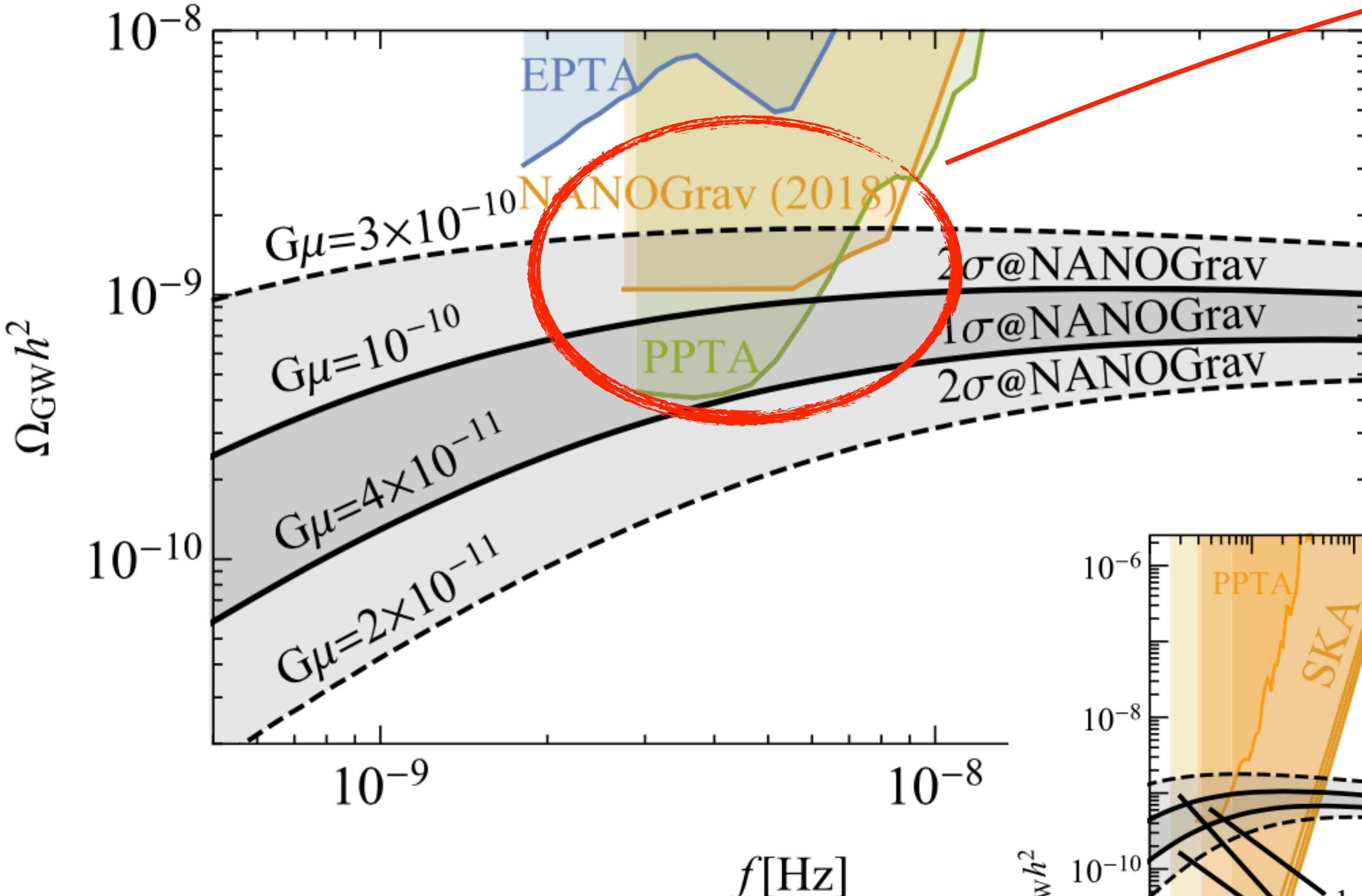
< GW-sensitivity curves & source >



[Class.Quantum Grav. 32 (2015) 015014]

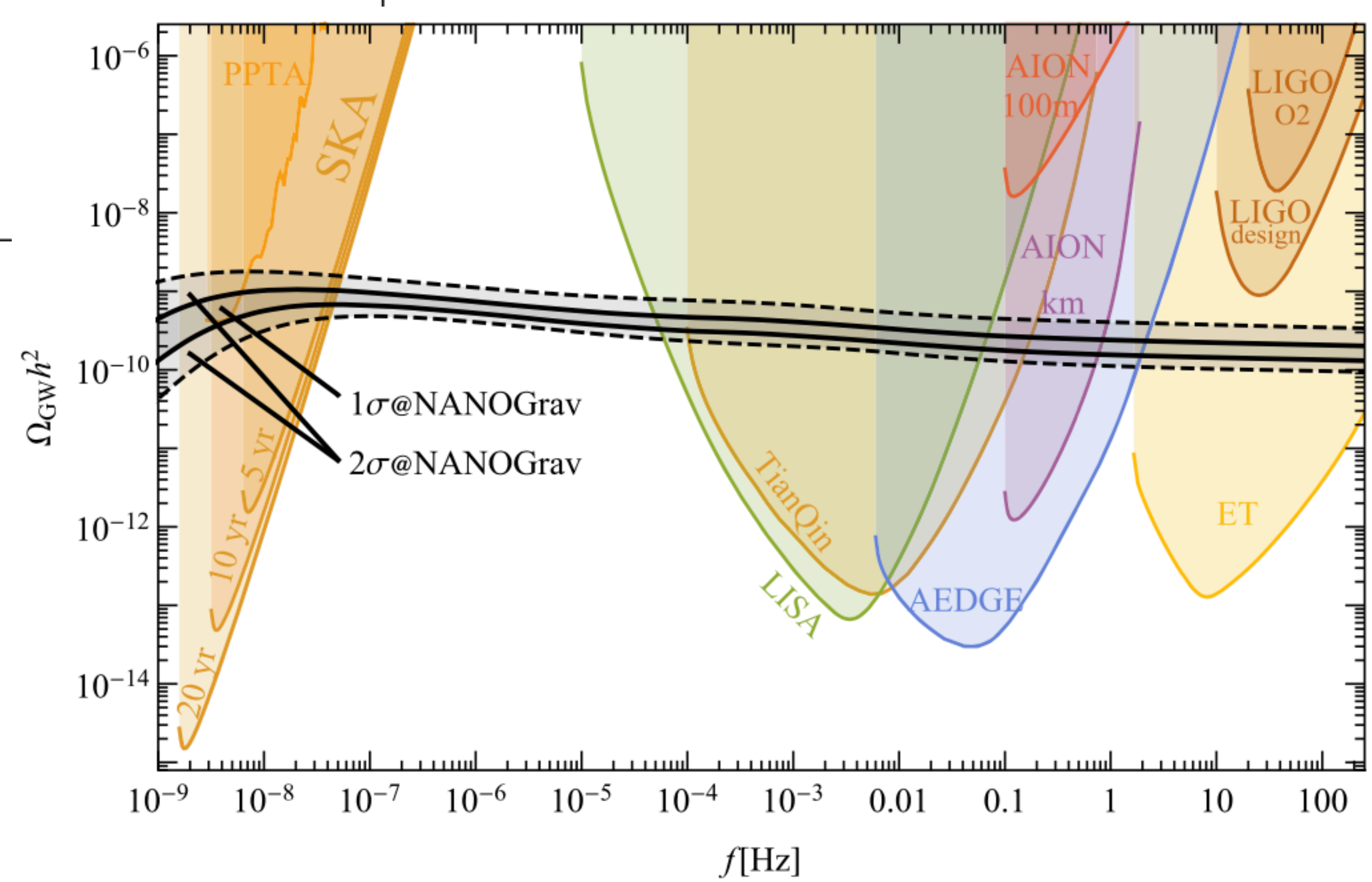
< Cosmic strings as a possible source > - a case of stable thin strings

[Ellis & Lewicki, PRL 126, 041304 (2021) (see also PRL125, 211302(2020), …)]



- It does not match to $\sim f^2$ behavior.
- LV-O3 constraints: $G\mu \lesssim \mathcal{O}(10^{-8})$

[LIGO, Virgo & KAGRA coll., PRL 126 (2021) 24]



- **A SUSY B-L model with meta-stable strings**
  (cosmic strings segmented by monopole-antinopole pairs)

Buchmüller, Docke, Schmitz, 2307.04691
Ahmed et al., 2308.13248

- A UV structure of gauge group: [Buchmüller, Docke, Schmitz, 2307.04691]

$$SU(3)_c \times SU(2)_L \times U(2) \;\; (U(2) = SU(2)_{\mathrm{R}} \times U(1)_{B-L}/\mathbb{Z}_2)$$
$$\xrightarrow{M_R} SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \qquad \pi_2\left(\frac{SU(2)_R}{U(1)_R}\right) = \pi_2\left(S^2\right) = Z$$
$$\xrightarrow{M_{BL}} SU(3)_c \times SU(2)_L \times U(1)_Y \qquad \pi_1\left(\frac{U(1)_R \times U(1)_{B-L}}{U(1)_Y}\right) = \pi_1\left(S^1\right) = Z$$

{ It might be originated from Pati-Salam model - $\left(SU(4)_c \times SU(2)_L \times SU(2)_R\right)/Z_2$
’t Hooft-Polyakov monopoles could be inflated away.

A realization:

$$W_{\rm UV} \supset \lambda\Phi\left(v_u^2 - U^T U\right) + \lambda'\Phi'\left(v_u^2 - U^T U\right) + 2y_D D_2^T \tilde{U} D_1 - y_D v_u D_2^T D_1$$

$$(\text{where } U \sim (3,0)\,,\;\; D_1 \sim (2,q)\,,\;\; D_2 \sim (\bar{2},-q) \;\;\text{under } SU(2)_R \times U(1)_{B-L})$$

Symmetry-breakings:

$$SU(2) \times U(1)_{B-L} \xrightarrow{\langle U\rangle = (0,0,v_u)} U(1)_R \times U(1)_{B-L} \xrightarrow{\langle D_1, D_2\rangle = (v_s, 0)} U(1)_Y$$
$$(\text{where } v_u, v_s \sim M_{\rm GUT})$$

- Alternative & low energy EFT [R. Maji & **WIP**, 2307.04691]

D-term potential of $SU(2)_R$-doublets (cf. MSSM Higgses):

$$V_D = \frac{1}{8}\left(g_R^2 + g_{BL}^2\right)\left[\left(|D_1^+|^2 - |D_2^-|^2\right) + \left(|D_1^0|^2 - |D_2^0|^2\right)\right]^2 + \frac{1}{2} g_R^2 \left|D_1^+ D_2^{0*} + D_1^0 D_2^{-*}\right|^2$$

Two possible neutral flat-directions

$$\begin{cases} \langle D_1^+ \rangle = \langle D_2^- \rangle \neq v_D & \Rightarrow \ U(1)_Y \text{ is broken} \\ \langle D_1^0 \rangle = \langle D_2^0 \rangle \neq v_D & \Rightarrow \ U(1)_Y \text{ survives - our world!} \end{cases}$$

$$W_{\rm UV} \supset \lambda\Phi\left(v_u^2 - U^T U\right) + \lambda'\Phi'\left(v_u^2 - U^T U\right) + 2y_D D_2^T \tilde{U} D_1 - y_D v_u D_2^T D_1$$

(?)

(i.e., $\lambda = \lambda' = 0$ & $y_D = 0$ (or $\lesssim \mathcal{O}(10^{-12})$))

How to break the symmetries?

Tachyonic soft-SUSY breaking mass-squared parameters along D-flat directions!

Low energy EFT:

$$W = W_{\text{MSSM}-\mu} + \mu_H H_u H_d + \mu_\Phi \Phi_1 \Phi_2 + y_\nu L H_u N + \frac{\lambda_N}{M}\Phi_1^2 N^2 + \frac{\lambda_H}{M}\left(H_u H_d\right)^2 + \frac{\lambda_\mu}{M}\Phi_1\Phi_2 H_u H_d + \frac{\lambda_\Phi}{M}\left(\Phi_1\Phi_2\right)^2$$

$(\ D_1 \supset \Phi_1,\ D_2 \supset \Phi_2\ )$

- Quantum population of monople-antimonopole pairs ($\overline{M}SM$):

[Vilenkin,Nucl. Phys. B196 (1982) 240; Schwinger, Phys. Rev. APS 82 (5) 664]

Pair nucleation rate per unit length:

$$\Gamma_{\rm d} = \frac{\mu_s}{2\pi} e^{-\pi\kappa} \quad \left(\kappa = \frac{m_{\rm M}^2}{\mu_s}\right)$$

⇒ Segmentation of strings in a string network ($\overline{M}SM$ configurations - "dumbbells")

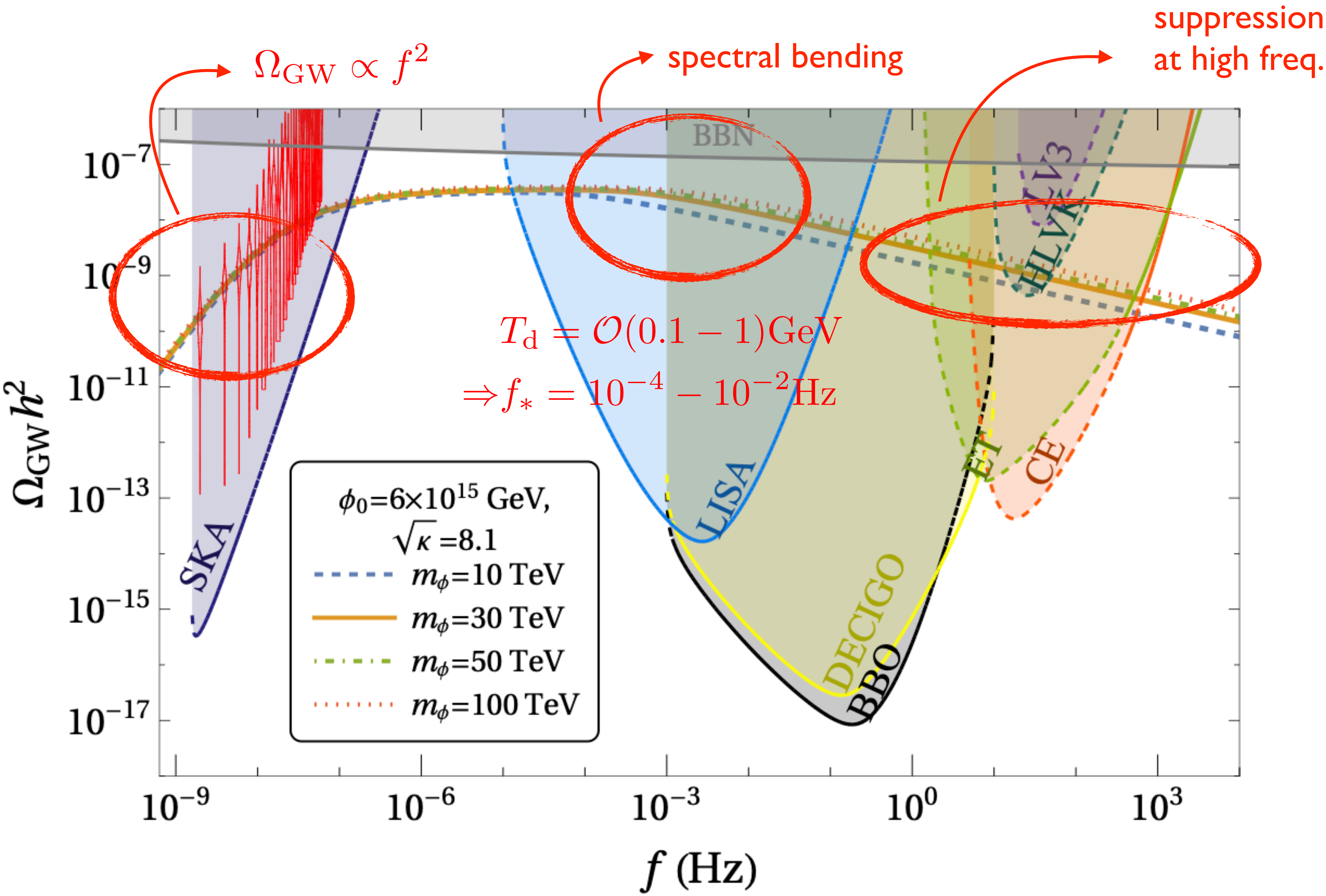
⇒ Energy loss due to emission of radiation by accelerated (anti)monopoles:

$$\dot{E}_s = -\frac{g_M^2}{6\pi}\left(\frac{\mu_s}{m_{\rm M}}\right)^2, \; g_M = \frac{4\pi}{g_R}$$

⇒ Decay of the string network:

$$\tau_{\rm d} \sim \Gamma_{\rm d}^{-1/2}$$

- A signal matching to NANOGrav 15yr data



Summary

- A SUSY $U(1)_{B-L}$ model realizes *thermal inflation(TI)* resolving the moduli problem.
- *Higgs VEV is constrained as* $10^{12} \lesssim \phi_0/\mathrm{GeV} \lesssim 10^{16}$ *for* $\varphi_0 = \mathcal{O}(0.1-1)M_\mathrm{P}$.
- *For* $\varphi_0 \approx M_\mathrm{P}$, *the soft mass is constrained as* $m_\mathrm{soft} \gtrsim 8\mathrm{TeV}$.
- SGWBs are expected within the reach of at least LISA and DECIGO.
- A UV-realization of the model can explain the NANOGrav discovery.
- m_soft can be probed by LISA &DECIGO type exps.
- Spectral distortion & bending freq. can be regarded as a hint of SUSY.
- Baryogenesis & DM are also addressed.
- Depending on ϕ_0, UHECRs over GZK limit can be explained.

Thank you!