



GWs from TCSs (Thick Cosmic Strings) **of** **a SUSY flat direction**

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Outline

- **Motivation**

- Cosmological moduli problem
- Thermal inflation

- **A model**

- An extension of MSSM based on $G_{\text{SM}} \times U(1)_{B-L}$
- Cosmological aspects

- **SGWBs**

- Thick cosmic strings & their properties
- SGWBs from cosmic string loops

- **NANOGrav 15yr Data & SUSY B-L model**

- **UHECRs**

- Sources (Scalar condensation & TCS itself)
- Extra feature

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**.

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

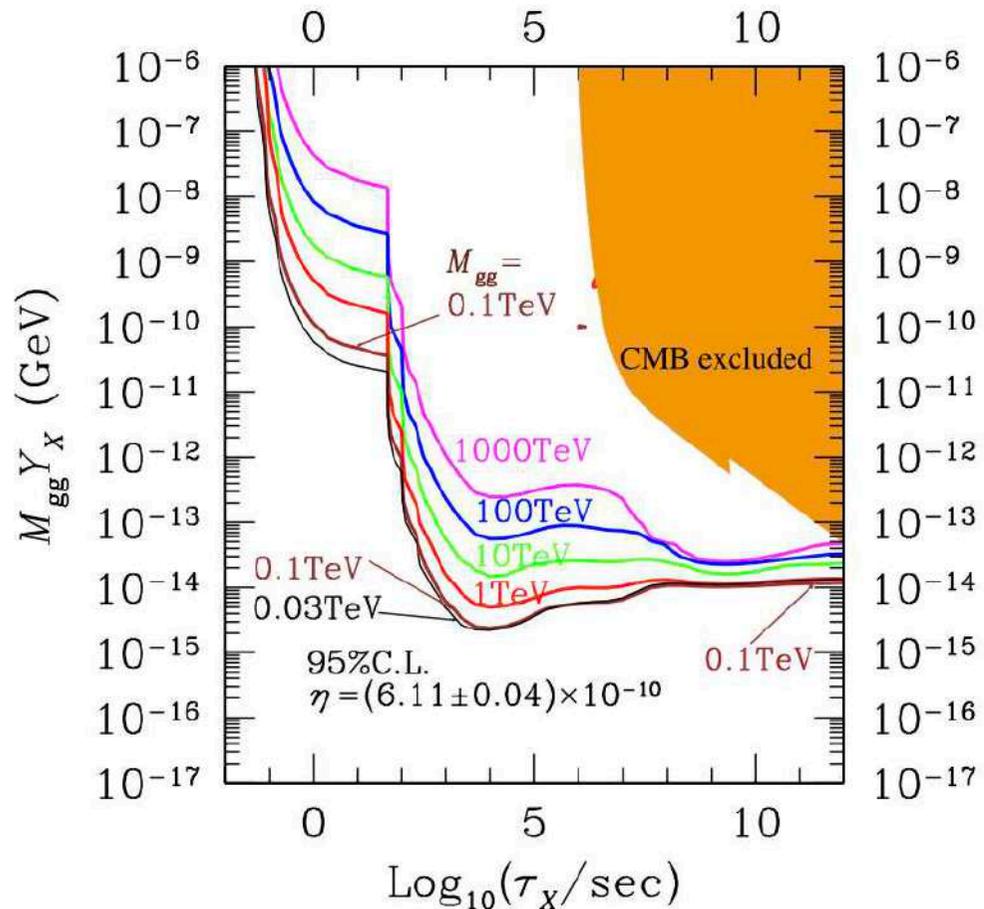
- Long life time, but too abundant(due to large coherent oscillations)! \Rightarrow danger in BBN

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

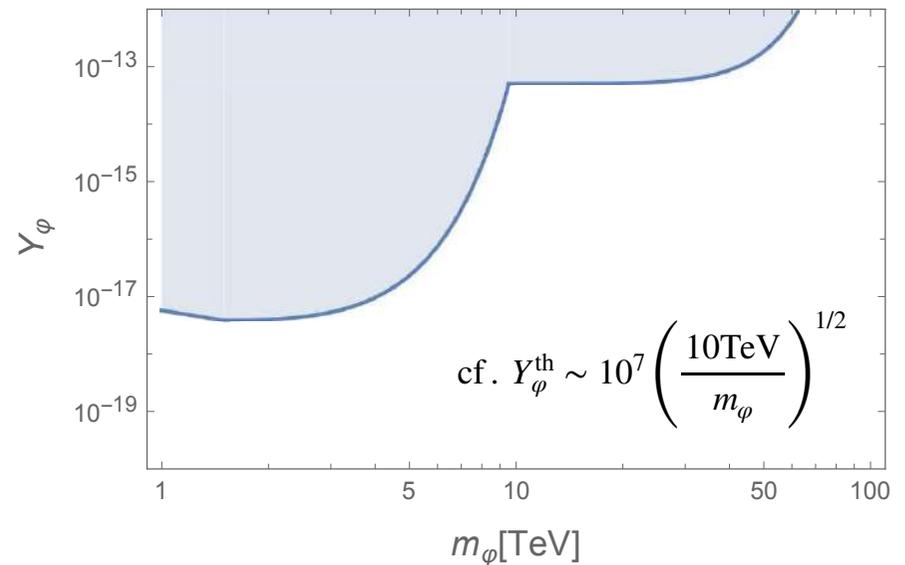
$$\frac{n_{\phi}}{s} \Big|_{\text{osc}} \sim \left(\frac{M_{\text{P}}}{m_{\varphi}} \right)^{1/2} \sim 10^7 \left(\frac{10\text{TeV}}{m_{\varphi}} \right)^{1/2}$$

• **BBN bound on long-living particles ($\phi, \psi_{3/2}$)** [Kawasaki et al, PRD 97, 2018]

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



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



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

● A simple solution to the moduli problem?

Pushing up mass scale:

$$m_\varphi \gtrsim m_{3/2} \gtrsim \mathcal{O}(100)\text{TeV} \Rightarrow \Gamma_\varphi, \Gamma_{3/2} \gtrsim H_{\text{BBN}} (\sim 10^{-24}\text{GeV})$$

Note! If R-parity is conserved, the LSP becomes dark matter &

$$m_{\text{LSP}} \sim m_{\text{soft}} = \mathcal{O}(1)\text{TeV}$$

⇒ **LSP over-production** (from the decay of moduli & gravitinos) unless

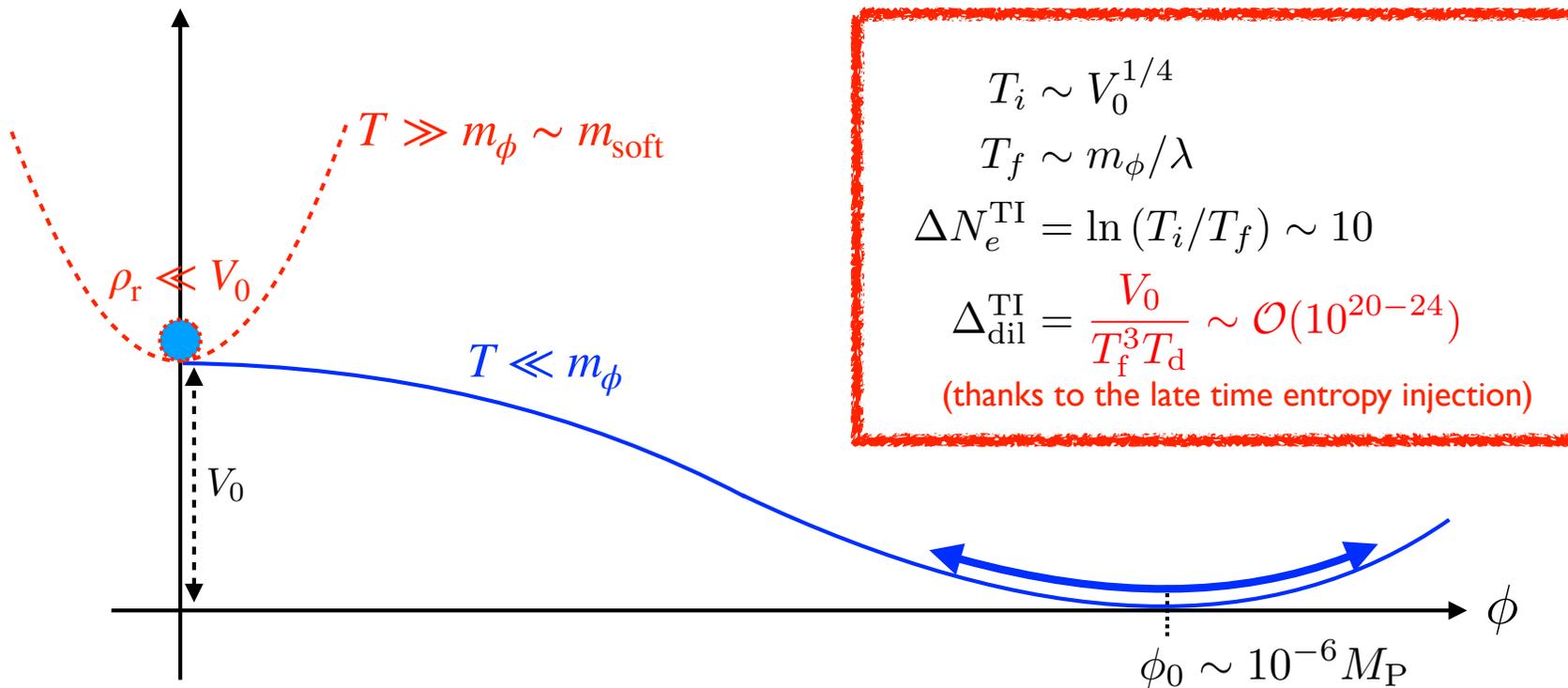
$$\Gamma_{3/2} \gtrsim H_{fo} \sim \frac{m_{\text{LSP}}/20}{M_{\text{P}}} \Leftrightarrow \underline{m_{3/2} \gtrsim \mathcal{O}(100)\text{PeV}}$$

* If R-parity is violated, $m_\varphi, m_{3/2} \gtrsim \mathcal{O}(100)\text{TeV}$ would be enough to solve the problem.

• **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 ($\langle \phi \rangle \gg m_\phi$) as long as λ is not very small.

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



- Realized very naturally in SUSY.
- The most compelling sol. to the moduli problem!

• A realization of TI ($U(1)_{\text{PQ}}$ -model)

- ϕ should be a flat direction (i.e., $\langle \phi \rangle \gg m_\phi$)
- It should couple to SM particles (to recover the standard RD universe).
- The Peccei-Quinn field of $U(1)_{\text{PQ}}$ sym. is a good candidate for the flaton.

$$\Delta W \ni \frac{\lambda_\mu \phi^2 H_u H_d}{M} + \frac{\lambda_\phi \phi^4}{M} \quad \longrightarrow \quad \phi_0 \sim \sqrt{\frac{m_{\text{soft}} M_{\text{P}}}{\lambda_\phi}}, \quad \mu = \lambda_\mu \phi_0^2 / M$$

- DM = GeVish axino (if $\lambda_\phi = 0$, & $m_{\text{soft}} \sim \mathcal{O}(10^2)$ GeV) + axion

- However, no SUSY signals at EW scale: $m_{\text{soft}} \uparrow \Rightarrow m_{\tilde{a}} \uparrow$

- $\mathcal{O}(10^9) \lesssim \frac{\phi_0}{\text{GeV}} \lesssim \mathcal{O}(10^{10})$ (due to SN cooling & axion DM abundance)

- $T_{\text{d}} \propto 1/\phi_0$ becomes higher \Rightarrow over-production axino/neutralino LSPs

Problematic!

A SUSY local $U(1)_{B-L}$ model

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

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

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

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

(Φ_1 & $\Phi_2 = B - L$ Higgs fields)

(c.f., global sym. (?) \Rightarrow may work, but need care of domain-walls or the light PNGB)

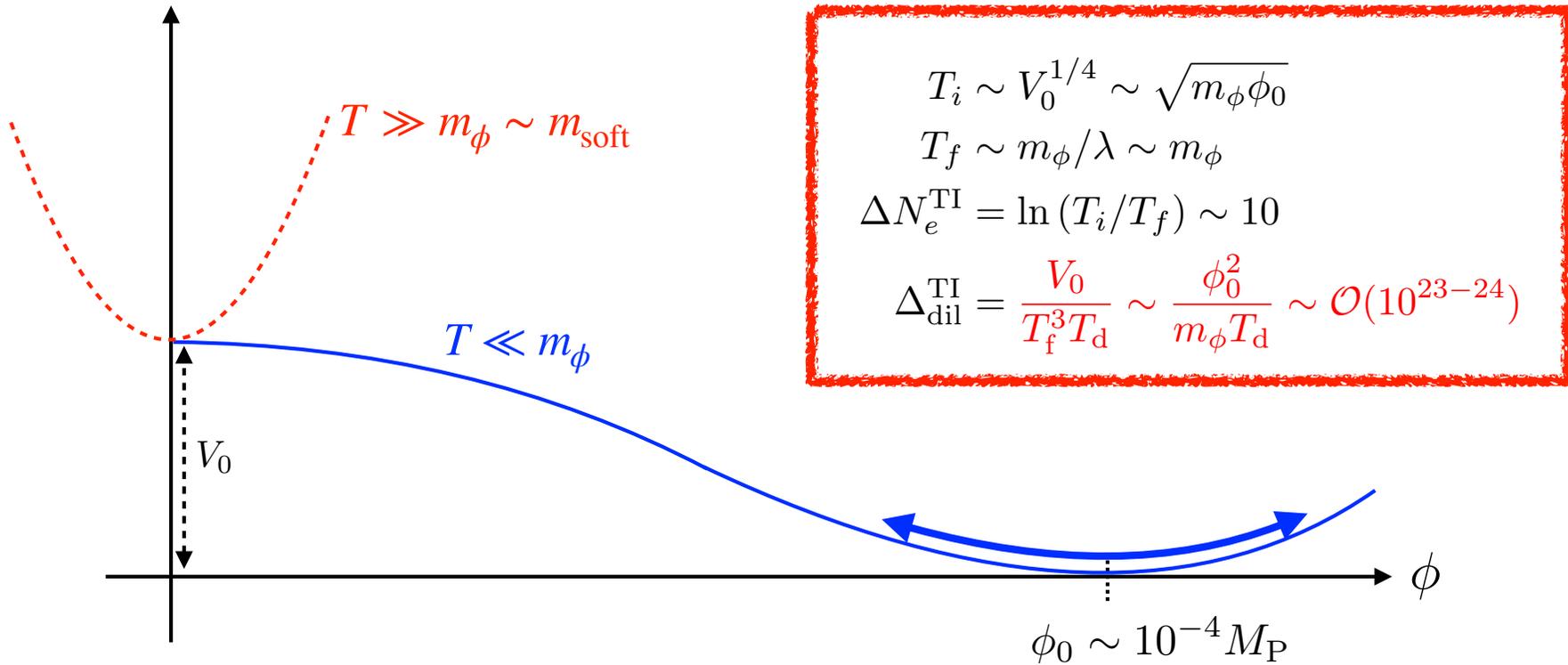
Potential along B-L D-flat direction with $LH_u = 0$ & $H_u H_d = 0$:

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

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

$$\left(\sqrt{|m_1^2|} \sim \sqrt{|m_2^2|} \sim B_{\Phi} \sim \mu_{\phi} \sim A_{\Phi} \sim m_{\text{soft}} \right)$$

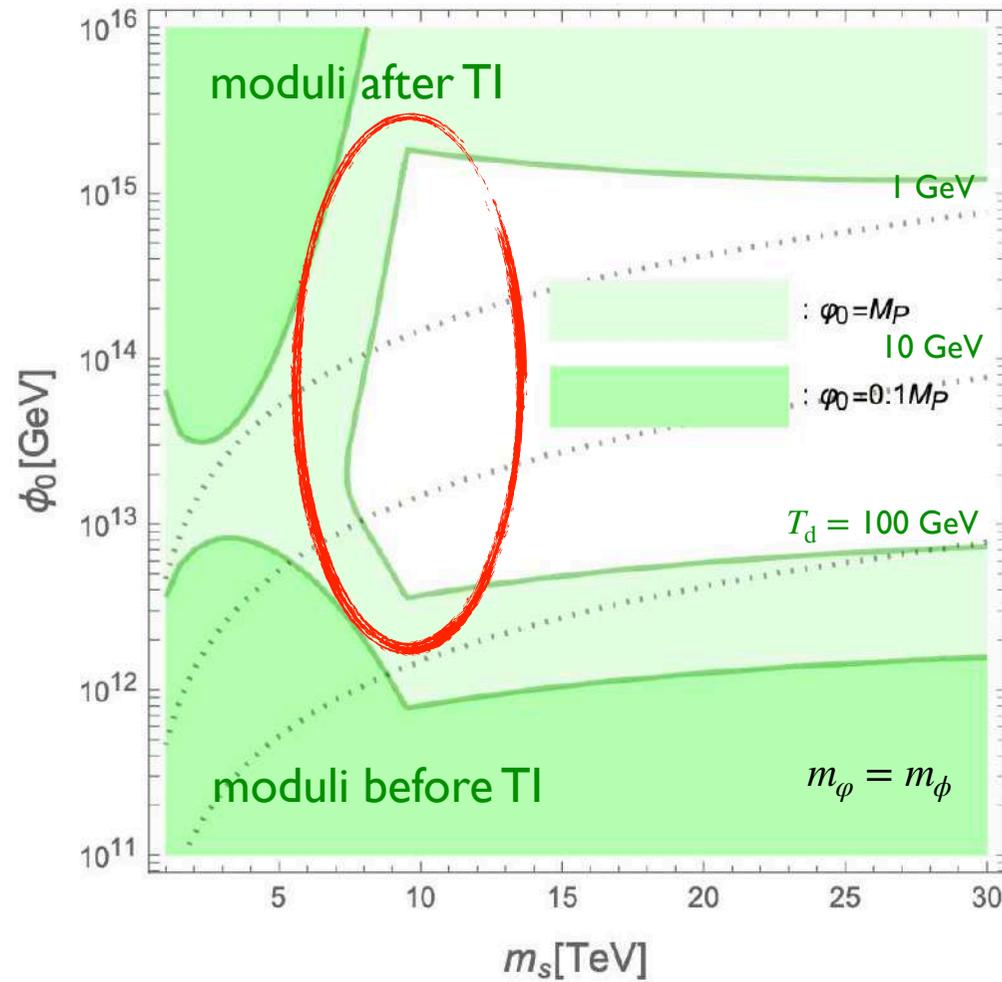
• **Thermal inflation** (thanks to the B-L D-flat direction) [Jeannerot, PRD 59 (1999)]



$$\Delta W_{\text{high}} \supset \frac{\lambda_\mu}{M} \Phi_1 \Phi_2 H_u H_d \quad \longrightarrow \quad \Gamma_{hh}^\phi = \frac{1}{4\pi} \frac{m_\phi^3}{\phi_0^2} \left(\frac{m_A^2 - |B|^2}{m_A^2} \right)^2 \left(\frac{|\mu|}{m_\phi} \right)^4 \sim \frac{1}{4\pi} \frac{m_\phi^3}{\phi_0^2} \left(\frac{|\mu|}{m_\phi} \right)^4$$

$$\longrightarrow T_d = \mathcal{O}(1) \text{GeV} \times \left(\frac{m_\phi}{10 \text{TeV}} \right)^{3/2} \left(\frac{10^{14} \text{GeV}}{\phi_0} \right) \left(\frac{|\mu_{\text{eff}}|}{m_\phi} \right)^2$$

- Parameter space safe from the moduli problem



If $\phi_0 = M_P$,

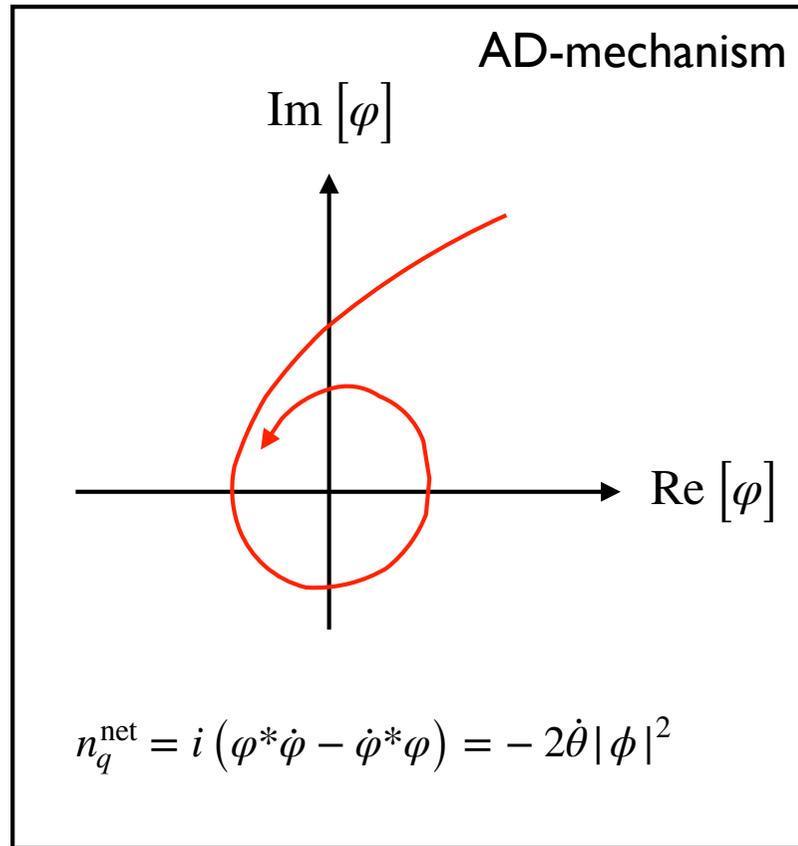
$$m_s \gtrsim 8 \text{ TeV} ,$$

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

● Baryogenesis (Late time Affleck-Dine leptogenesis)

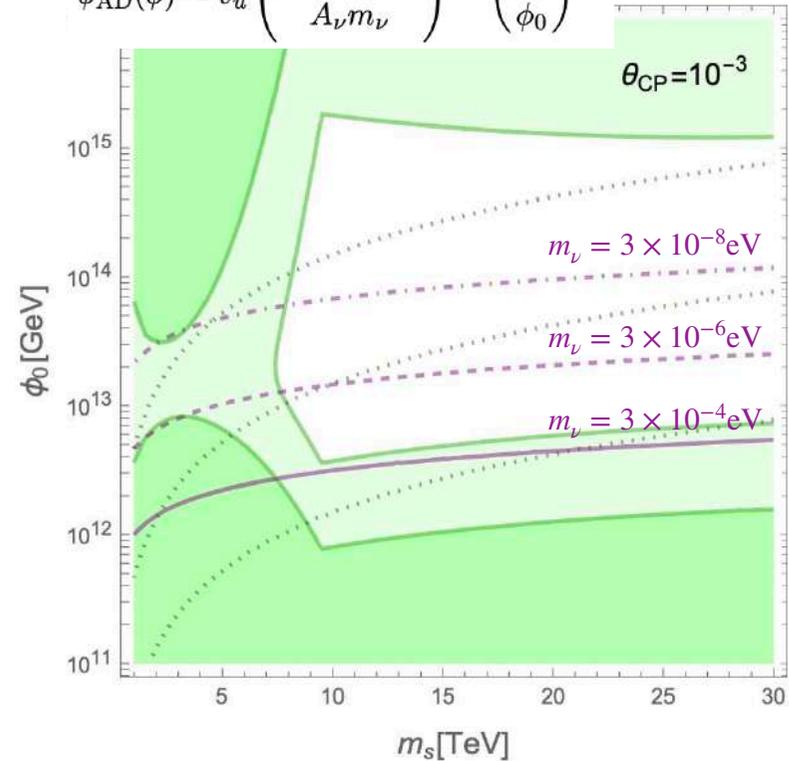
[**WIP**, JHEP 07 (2010) 085; Jeong, Kadota, **WIP** & Stewart, JHEP 11 (2004) 046]

$$m_{LH_u}^2 < 0 \xrightarrow{\phi \sim 0 \rightarrow \phi_0} m_{LH_u}^2 > 0 \quad (\because \mu_{\text{MSSM}} = \mu_{\text{MSSM}}(\phi))$$



$$Y_L \sim \frac{\theta_{\text{CP}} T_d m_{\text{AD}} \phi_{\text{AD,osc}}^2}{V_{\text{TI}}} = \frac{\theta_{\text{CP}} T_d m_{\text{AD}}}{\beta^2 m_\phi m_\phi} \left(\frac{\phi_{\text{AD,osc}}}{\phi_0} \right)^2$$

$$\phi_{\text{AD}}(\phi) \sim v_u \left(\frac{|m_{LH_u}^2(\phi)|}{A_\nu m_\nu} \right)^{1/2} \left(\frac{\phi}{\phi_0} \right)^{1/2}$$



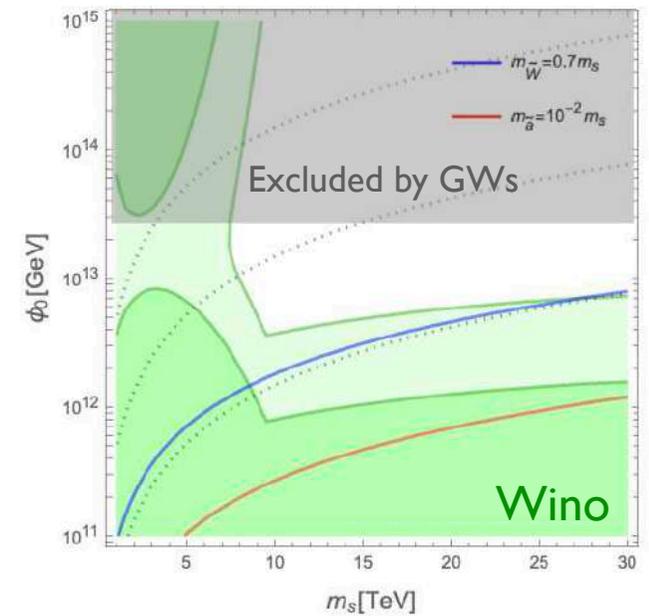
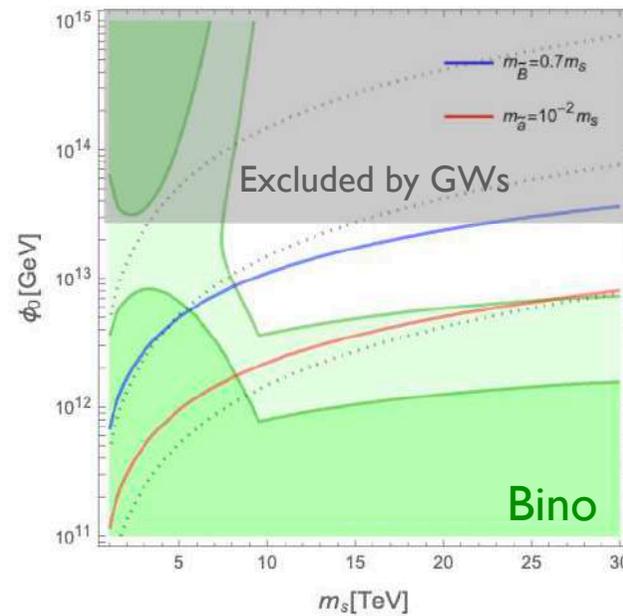
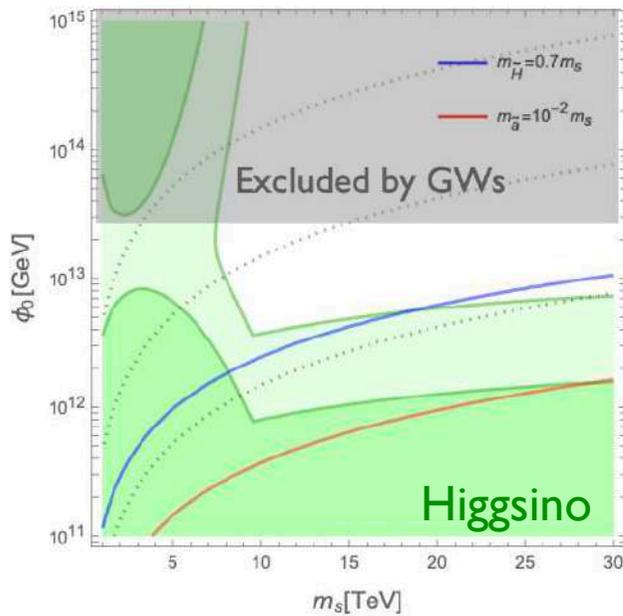
● Dark Matter Candidates

- **Neutralinos:** from freeze-out during MD era & later entropy injection

$$T_d \simeq 52\text{GeV} \left(\frac{m_{\tilde{\chi}}}{1\text{TeV}} \right) \left(\frac{\langle \sigma v_{\text{rel}} \rangle}{10^{-9}\text{GeV}^{-2}} \right)^{1/3} \left(\frac{20}{x_{\text{fo}}} \right)^{4/3}$$

- **KSVZ-axinos (& axions):** from decay of neutralino NLSPs

$$\Omega_{\tilde{a}} = \left(m_{\tilde{a}}/m_{\tilde{\chi}} \right) \Omega_{\tilde{\chi}}$$

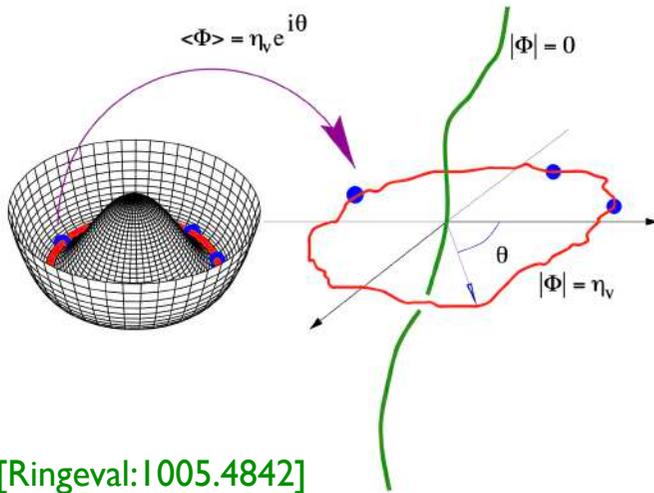


✓ Gray regions might be excluded by PPTA bound on GWs

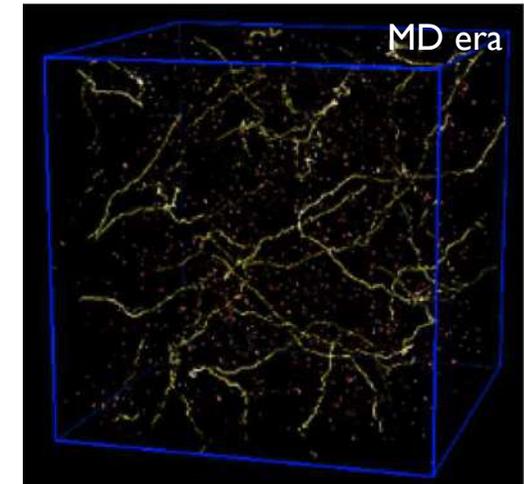
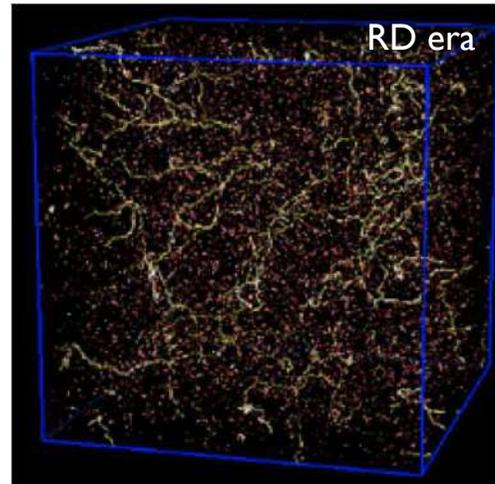
SGWBs from TCSs

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

- It can be formed when vacuum manifold is non-trivially connected ($\pi_1(\mathcal{M}) \neq I$)



[Ringeval:1005.4842]



- characterized by string tension: $\mu \sim \pi\phi_0^2$
- falls to the scaling regime: typical length $\xi \sim \alpha t$, $\alpha = \mathcal{O}(0.1)$.

$$\frac{\rho_s}{\rho_c} \sim \frac{\mu}{M_{\text{P}}^2} \sim \left(\frac{\phi_0}{m_{\text{P}}} \right)^2 = \text{const.}$$

- Composition: Network + string loops of various sizes

● Thick cosmic strings (TCSs) (=Type I)

- In Abelian Higgs model, it is the case of the scalar field much lighter than the gauge field

- Core width: $w_S \sim m_\phi^{-1} \gg m_A^{-1} \sim 1/\phi_0$

- String tension:

$$\mu/\pi v^2 \simeq \left[\frac{4.2}{\ln(1/\Delta)} + \frac{14}{\ln^2(1/\Delta)} \right] \times \left\{ 1 + \left[\frac{2.6}{\ln(1/\Delta)} + \frac{57}{\ln^2(1/\Delta)} \right] \ln N_w \right\}$$

$$= c_1 \times (1 + c_2 \ln N_w)$$

where $\Delta \approx m_\phi^2/m_A^2 \equiv \beta \ll 1$

winding #-dependence!

cf. For thin strings (Type-II),

$$w_s \sim m_\phi^{-1} \sim m_A^{-1}, \quad \mu \approx \pi\phi_0^2$$

● Zipping of TCSs [Y. Cui et al., PRD77 (2008) 043528]

A flat-potential ($\beta \equiv m_\phi^2/m_A^2 \lll 1$)

⇒ attractive force between strings

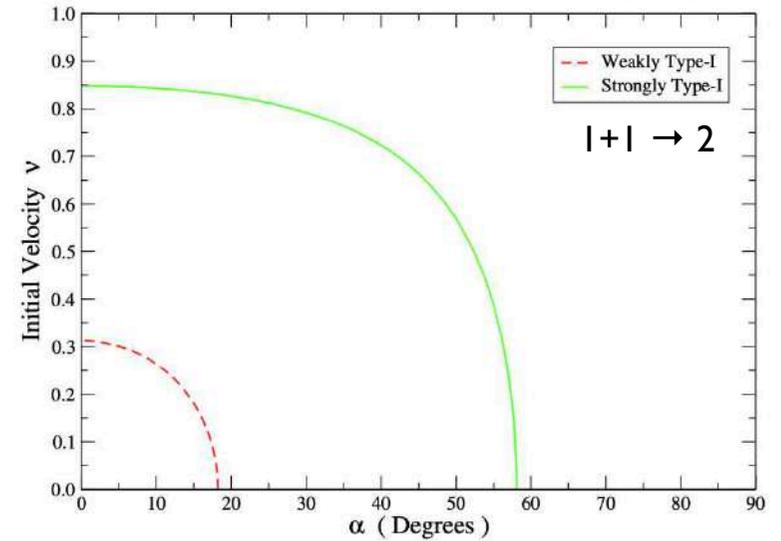
⇒ zipping effect between strings

⇒ formation of higher winding number (N_w) states if

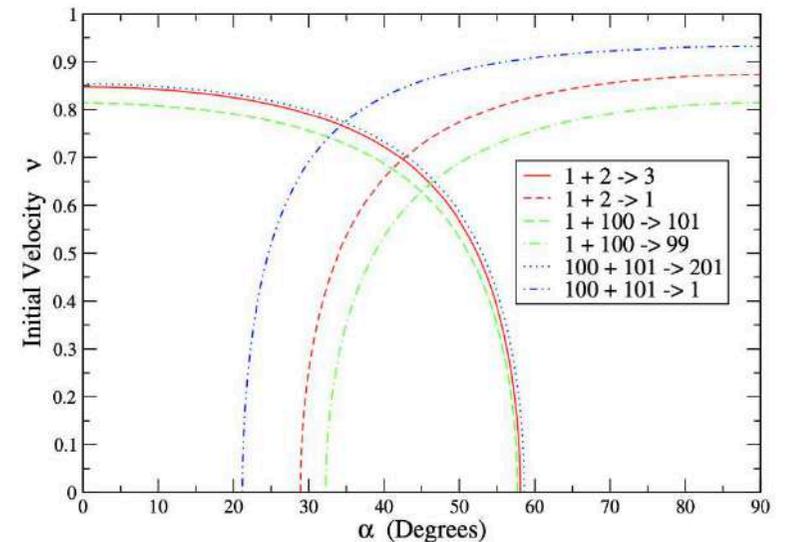
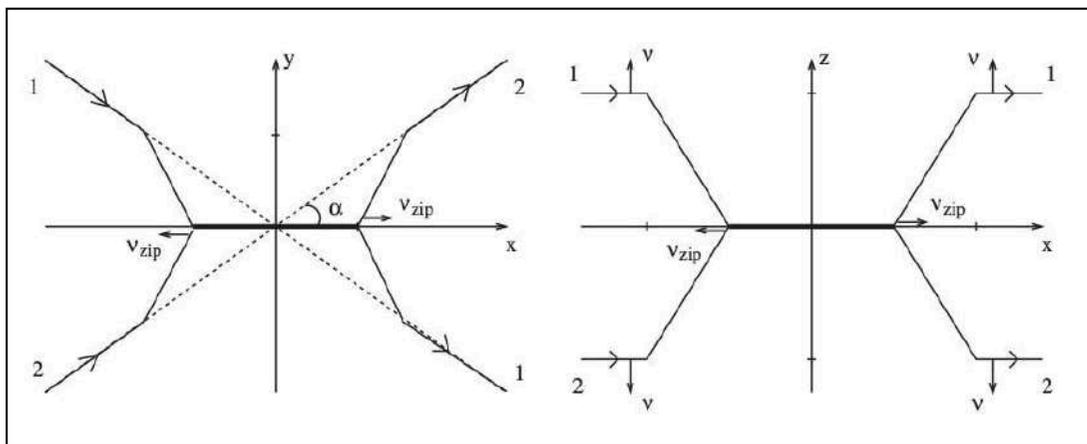
$$\sqrt{1 - v^2} \cos\alpha > \frac{\mu_{2N}}{2\mu_N}$$

(a kinetic constraint due to energy conservation)

Kinetic para. space for Zipping

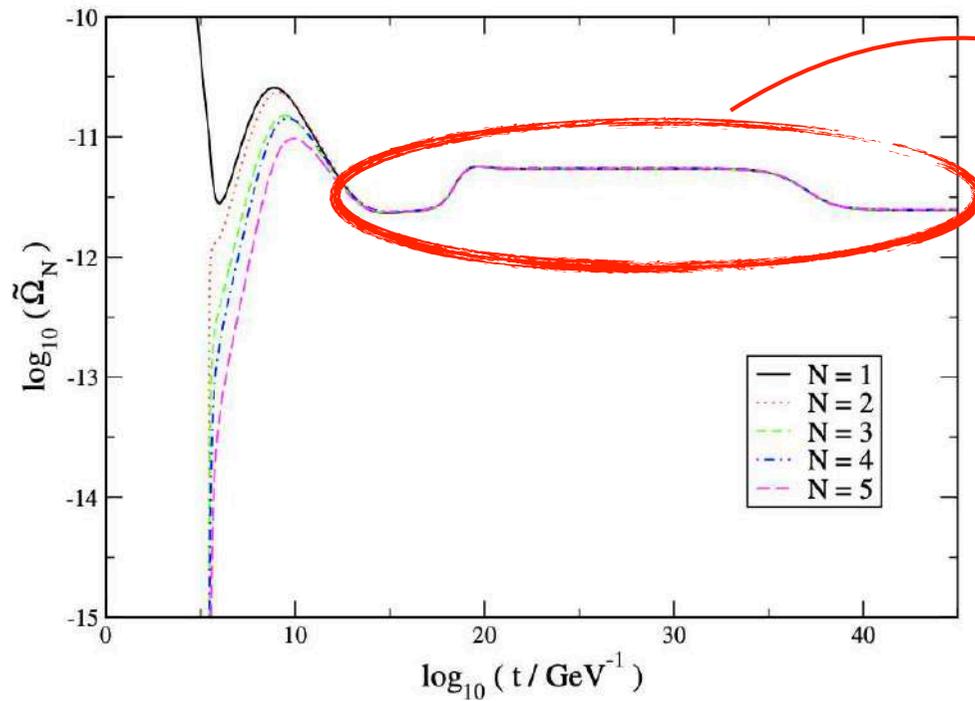


Zipping configuration



● **Energy dist. of TCSs** Y. Cui et al., PRD77 (2008) 043528

$$\tilde{\Omega}_a = \frac{\mu_1}{\mu_a} \Omega_a = \frac{\mu_1 n_a}{\rho_c \sqrt{1 - v^2}},$$



equilibration of string species!
(i.e., $n_a \rightarrow \text{const.}$)

$$\rho_{\text{tot}} \propto \frac{1}{N_{\text{max}}} \sum_{a=1}^{N_{\text{max}}} \ln a \simeq \ln N_{\text{max}},$$

$$N_w^{\text{max}}(t) \sim N_c \left(\frac{t}{t_i} \right)^{0.22}$$

$$t_i \sim 10t_c$$

● GWs from TCS loops

- Radiation power of GWs:

$$P_{\text{GW}} = \Gamma G \mu^2 \quad (\Gamma \approx 50)$$

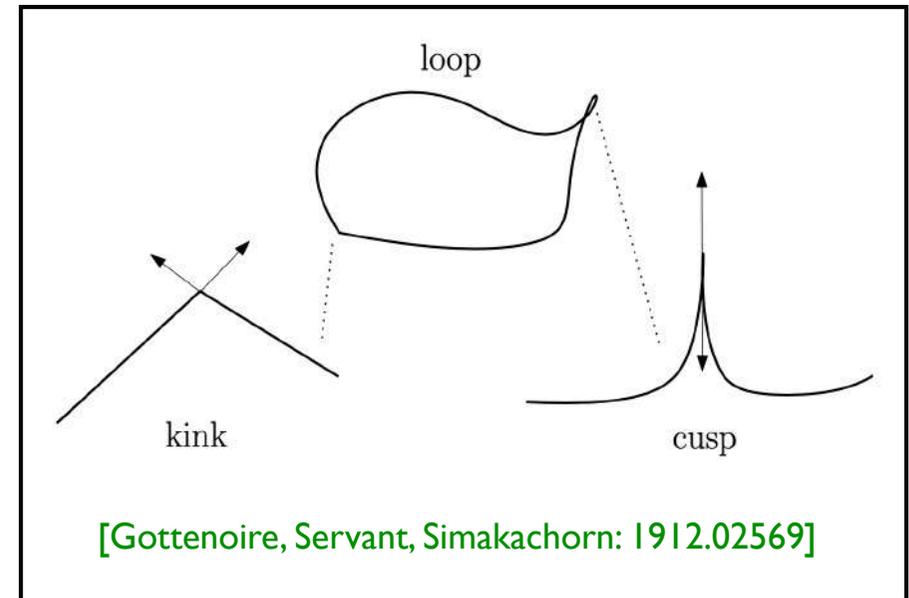
- Radiation power of particles:

$$P_{\text{cusp}} \approx 2\mu_s \sqrt{w_s/\ell}$$

$$\begin{cases} \ell < \ell_* \sim 1/m_\phi (\Gamma G \mu)^2 : \text{particle regime} \\ \ell > \ell_* : \text{GW regime} \end{cases}$$

- Thick vs thin CSs in regard of ℓ_* :

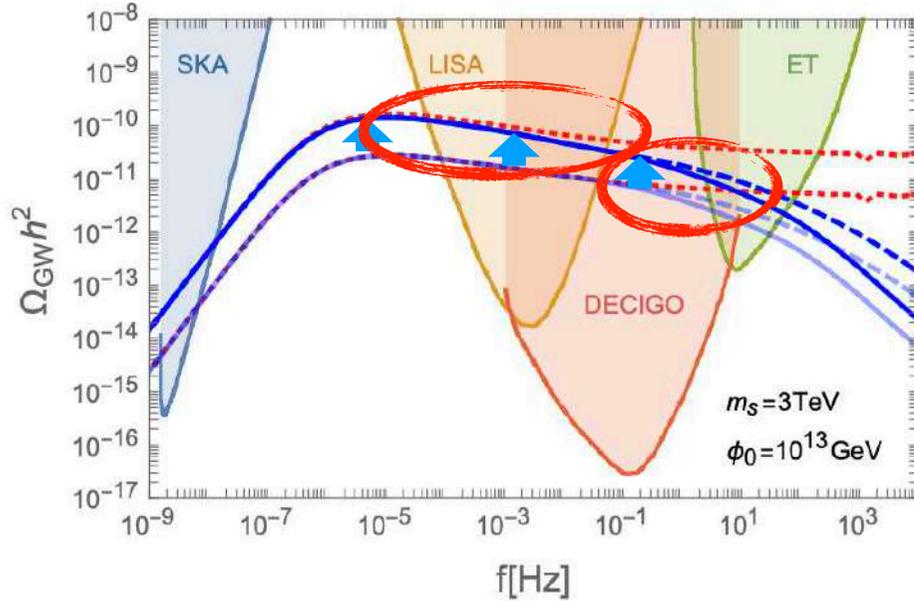
$$\frac{\ell_*^{\text{thick}}}{\ell_*^{\text{thin}}} \sim \frac{\phi_0}{m_\phi} = 10^{10} \left(\frac{\phi_0}{10^{13} \text{GeV}} \right) \left(\frac{1 \text{TeV}}{m_\phi} \right) \Rightarrow \text{causes a critical impact on GW-spectrum}$$



● Signals expected - Stable TCSs of $U(1)_{B-L}$ Higgs

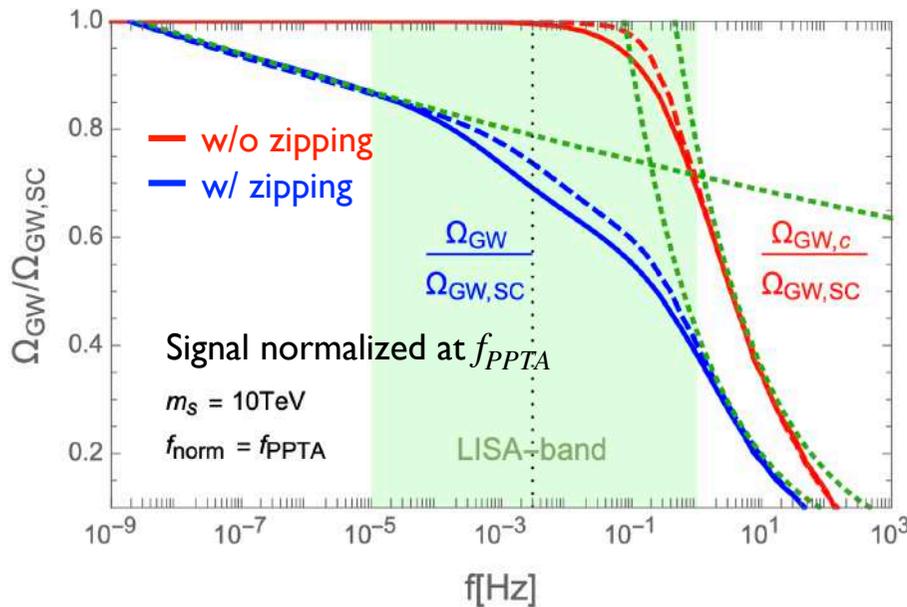
due to zippering effects ($\because w_s \gg \phi_0^{-1}$)

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



Characteristic features

- Enhancement (w.r.t the case w/o zippering)
- Spectral distortion
- Bending feature (related to T_d or T_*)

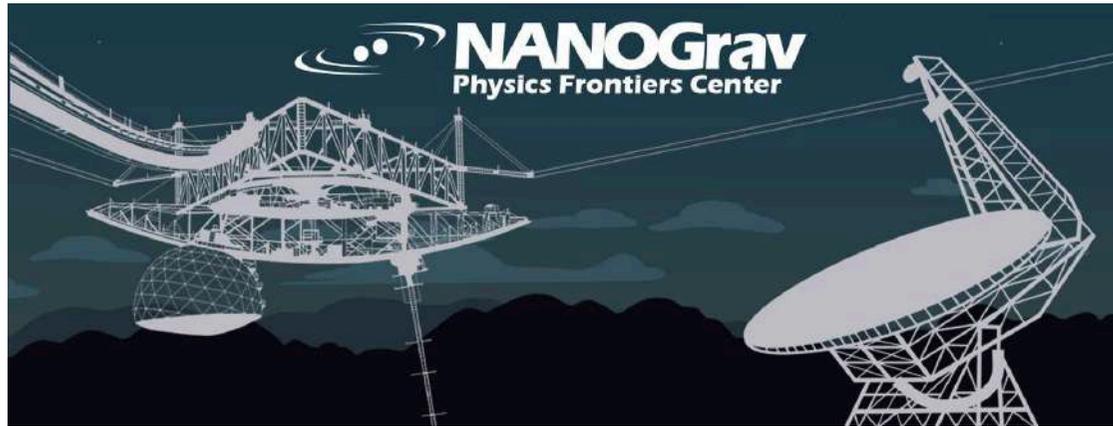


Clear spectral difference relative to the one without zippering \Rightarrow can be distinguished.

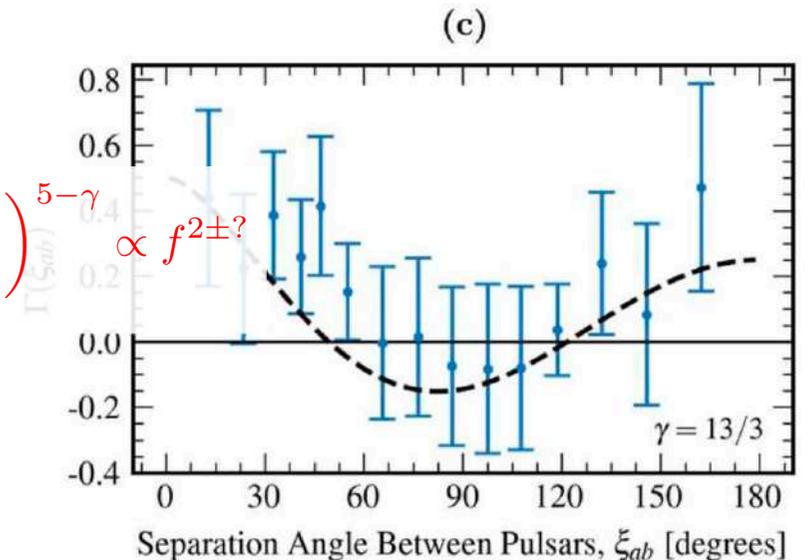
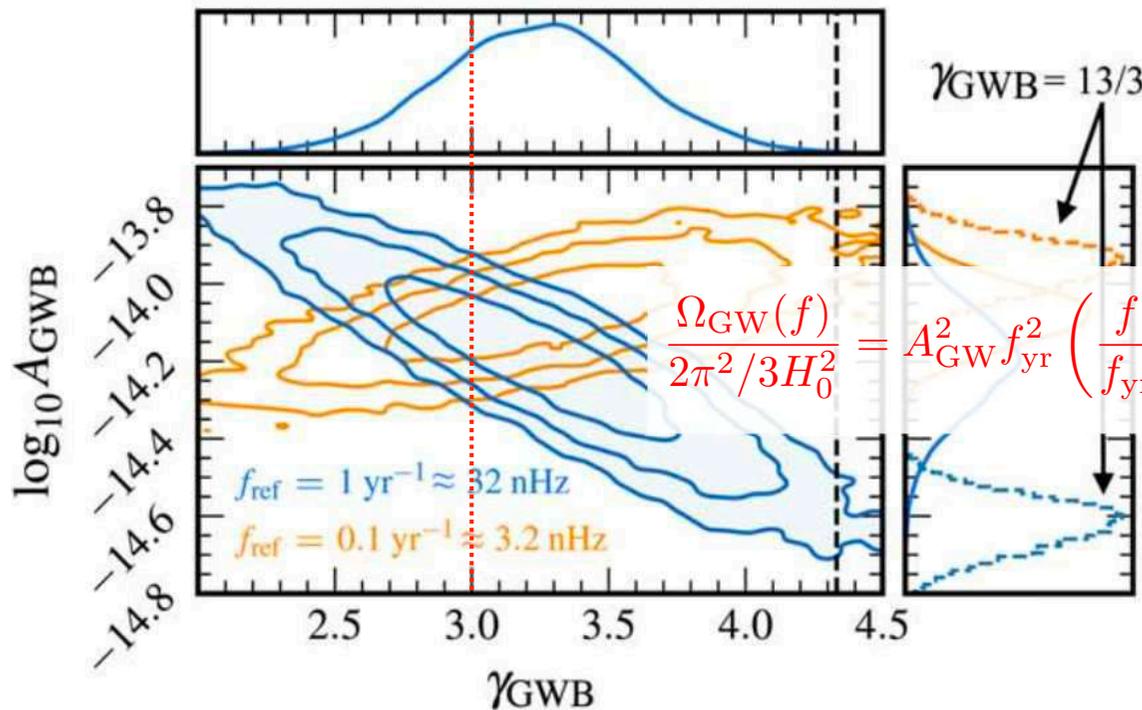
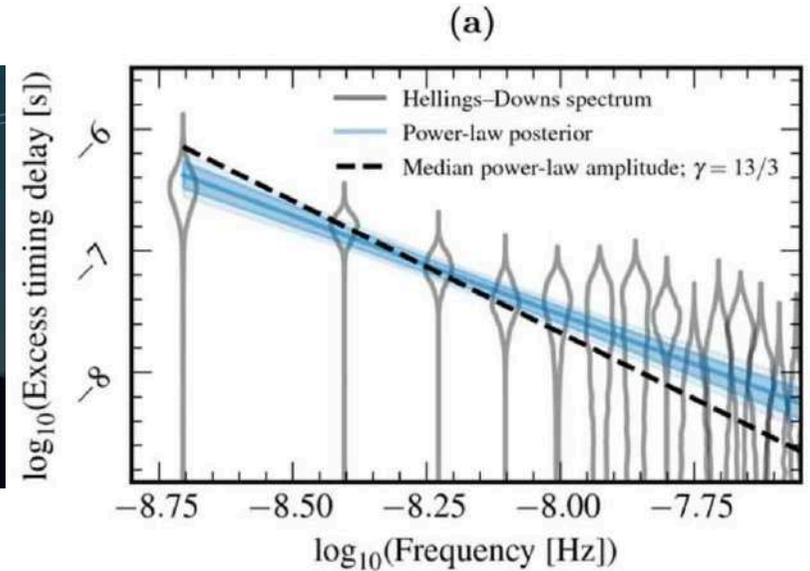
[Kwang Sik Jeong & **WIP**, JCAP 11 (2023) 016]

NANOGrav 15yr & SUSY B-L

North American Nanohertz Observatory for Gravitational Waves

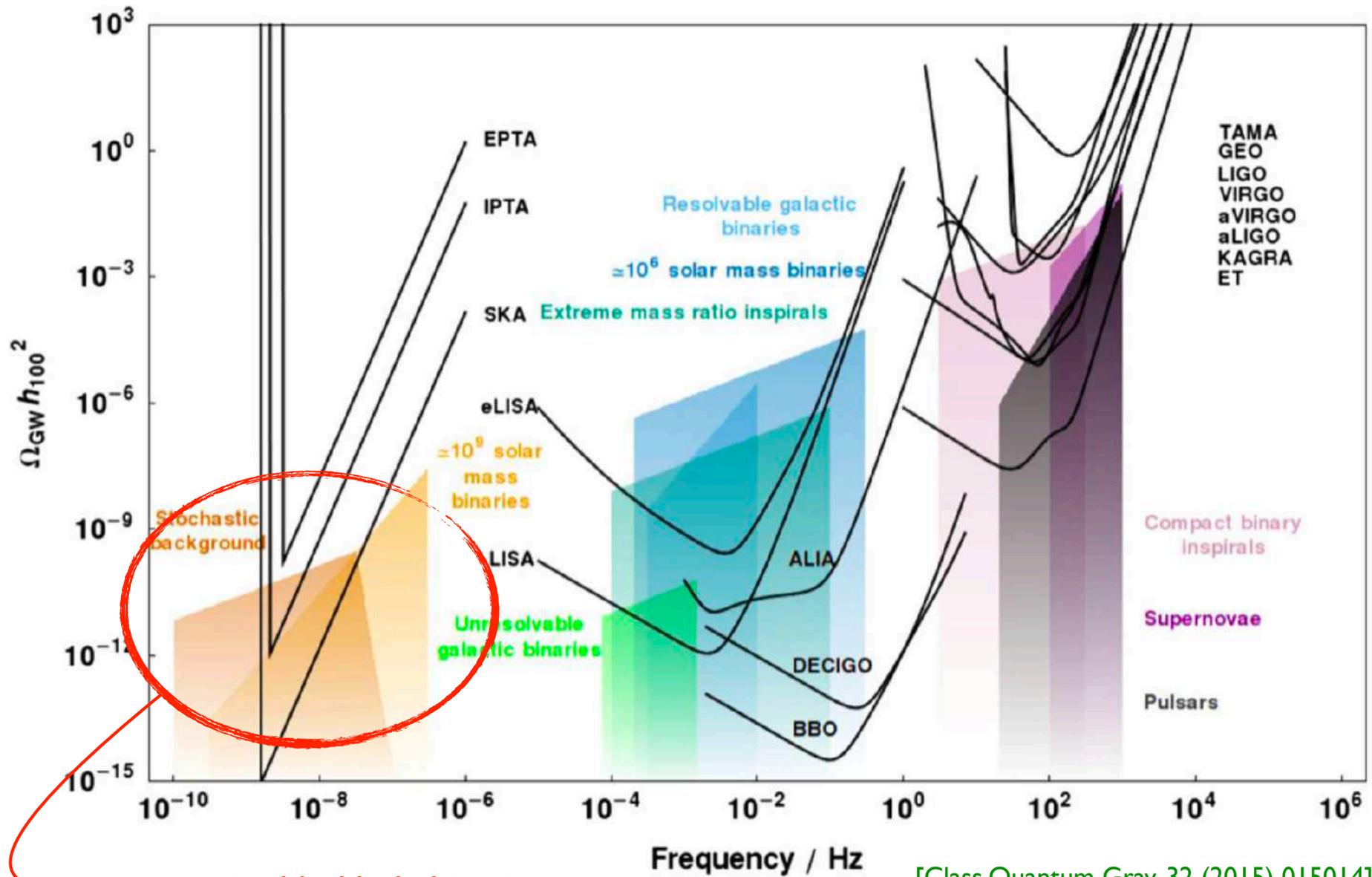


(b)



[Astroph. J. Lett. 951 (2023) 1, L8]

● Astrophysical source?

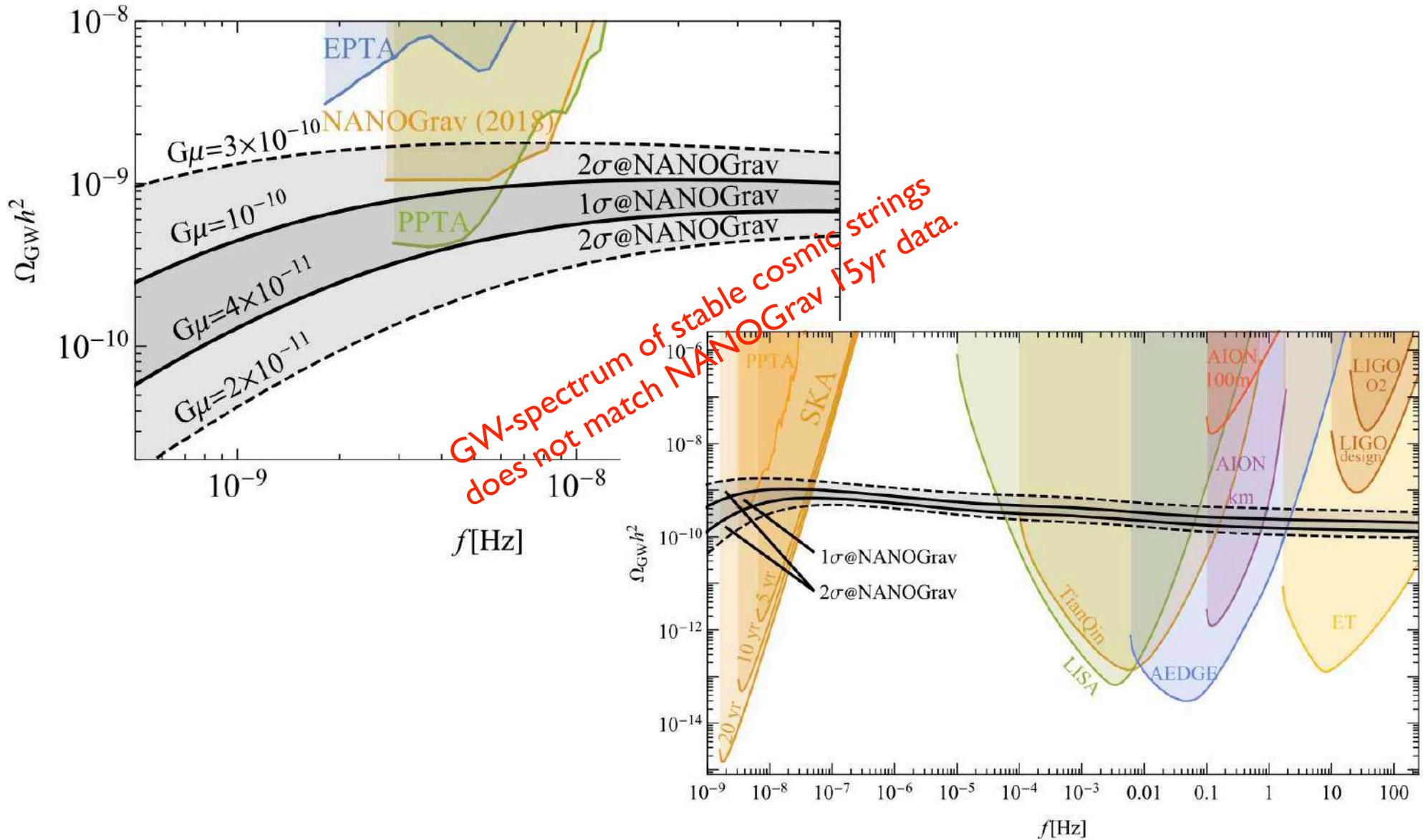


supermassive blackhole binaries

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

● Stable cosmic strings?

[Ellis & Lewicki, PRL 126, 041304 (2021) (see also PRL 125, 211302(2020), ...)]



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

- **A UV structure of the gauge group:** [Buchmüller, Domcke, Schmitz, 2307.04691]

$$\begin{aligned}
 & SU(3)_c \times SU(2)_L \times U(2) \quad (U(2) = SU(2)_R \times U(1)_{B-L} / \mathbb{Z}_2) \\
 \xrightarrow{M_R} & SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \quad \leftarrow \pi_2 \left(\frac{SU(2)_R}{U(1)_R} \right) = \pi_2(S^2) = \mathbb{Z} \\
 \xrightarrow{M_{BL}} & SU(3)_c \times SU(2)_L \times U(1)_Y \quad \leftarrow \pi_1 \left(\frac{U(1)_R \times U(1)_{B-L}}{U(1)_Y} \right) = \pi_1(S^1) = \mathbb{Z}
 \end{aligned}$$

{ It might be originated from Pati-Salam model - $(SU(4)_c \times SU(2)_L \times SU(2)_R) / \mathbb{Z}_2$
 't Hooft-Polyakov monopoles could be inflated away.

Low energy EFT:

$$\begin{aligned}
 W = & W_{\text{MSSM}-\mu} + \mu_H H_u H_d + \mu_\Phi \Phi_1 \Phi_2 + y_\nu L H_u N \\
 & + \frac{\lambda_N}{M} \Phi_1^2 N^2 + \frac{\lambda_H}{M} (H_u H_d)^2 + \frac{\lambda_\mu}{M} \Phi_1 \Phi_2 H_u H_d + \frac{\lambda_\Phi}{M} (\Phi_1 \Phi_2)^2 \\
 & (D_1 \supset \Phi_1, D_2 \supset \Phi_2)
 \end{aligned}$$

- **Quantum population of monopole-antimonopole pairs (\overline{MSM}):**

Pair nucleation rate per unit length:

$$\Gamma_s = \frac{\mu_s}{2\pi} e^{-\pi\kappa} \left(\kappa = \frac{m_M^2}{\mu_s} \right)$$

⇒ Segmentation of strings in a string network (\overline{MSM} configurations - “dumbbells”)

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

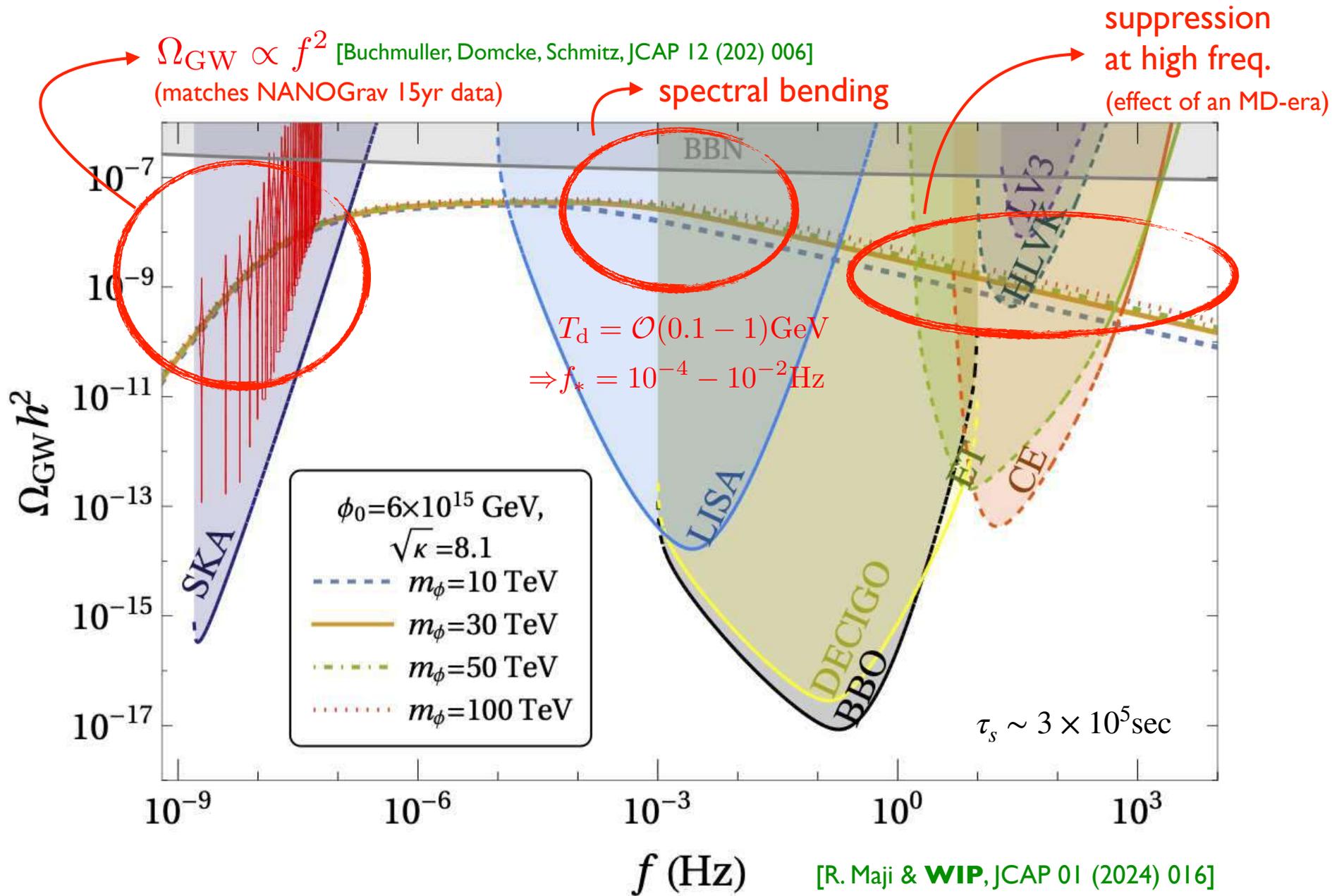
$$\dot{E}_s = -\frac{g_M^2}{6\pi} \left(\frac{\mu_s}{m_M} \right)^2, \quad g_M = \frac{4\pi}{g_R}$$

⇒ Decay of the string network:

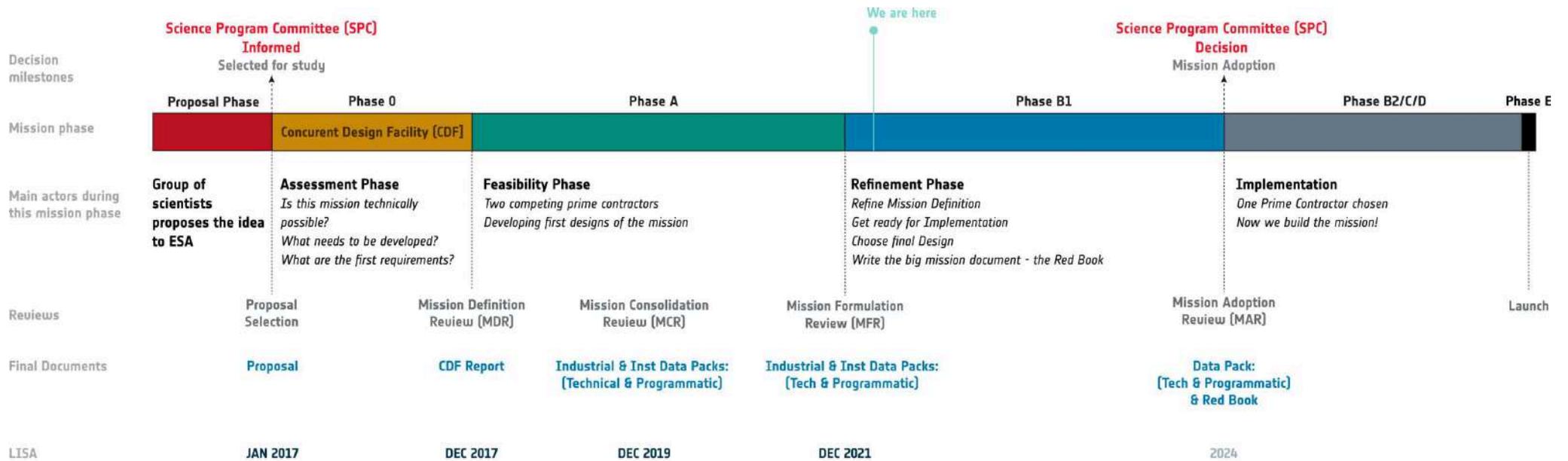
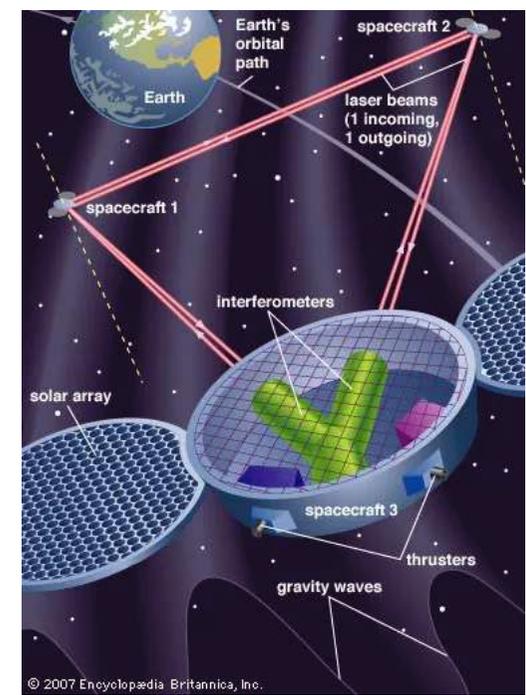
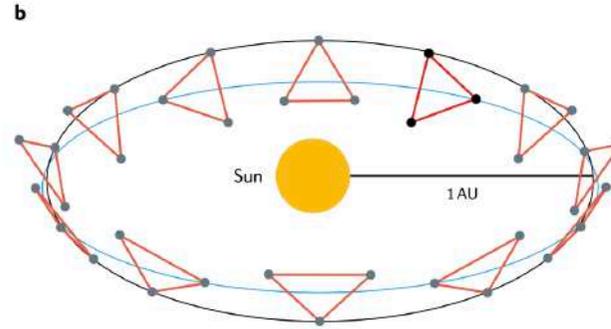
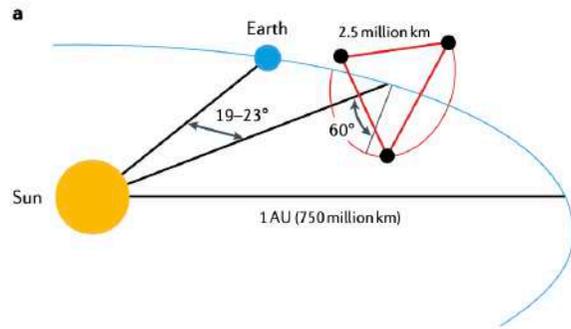
$$\tau_s \sim \Gamma_s^{-1/2}$$

* high-frequency signals should be suppressed (e.g., by partially inflating away strings)

● Signal expected - Unstable TCSs of the $U(1)_{B-L}$ Higgs



● Timeline of LISA



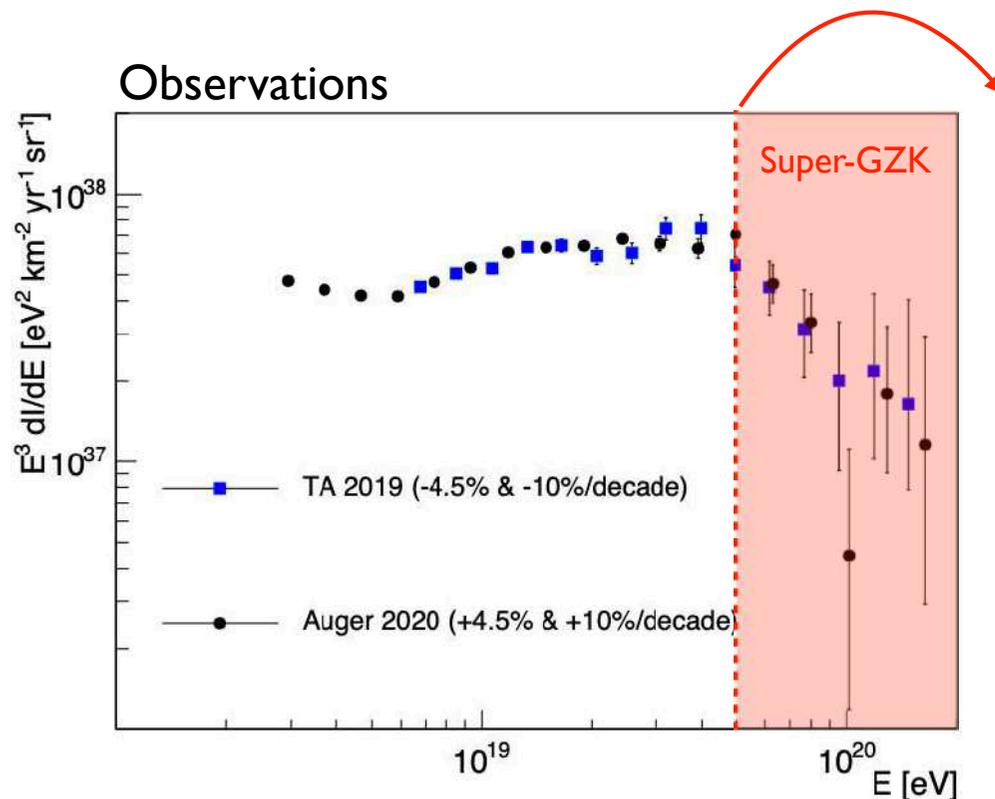
LISA mission timeline. Credit: ESA.

Scheduled for lunch in the mid-2030s!

UHECRs over GZK limit

[T. Damour & A. Vilenkin, PRL 78 (1997) 2288; T. Vachaspati, PRD81, 043531 (2010);]

• Ultra-high-energy cosmic rays (UHECRs) & GZK limit



GZK limit

A theoretical upper bnd. of cosmic ray protons due to proton - CMB photon interactions

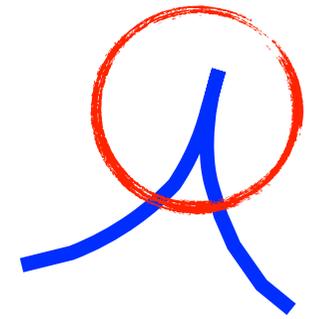
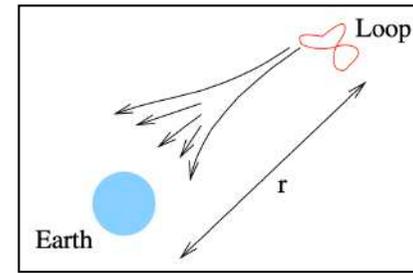
Observed flux over GZK limit

$$k \left. \frac{d\Phi}{dAdk} \right|^{obs} \sim \frac{10^{-3}}{\text{km}^2 \cdot \text{yr} \cdot \text{sr}}$$

Yet no astrophysical explanations!

[PoS (ICRC2021) 337]

- **Sources** (at cusps of cosmic string loops.)



- Source I: A linear coupling of a light scalar field φ with mass m to strings

[T. Damour & A. Vilenkin, PRL 78 (1997) 2288; T. Vachaspati, PRD81, 043531 (2010);]

$$S = S_0[\Phi, H, \dots] + \kappa \int d^4x (\Phi^\dagger \Phi - M^2) H^\dagger H,$$

$$\left(\kappa = \mathcal{O}(1), \text{ \& } \langle \Phi \rangle = M \sim \sqrt{\mu_s} \right)$$

$$\begin{aligned} S_{\text{int}} &= \kappa \int d^2\sigma \int d^2x_\perp \sqrt{-\gamma} (\Phi^\dagger \Phi - M^2) H^\dagger H \\ &= \kappa \int d^2\sigma \sqrt{-\gamma} \int d^2x_\perp (\Phi^\dagger \Phi - M^2) (\langle H \rangle_{\text{in}} + h)^\dagger \\ &\quad \times (\langle H \rangle_{\text{in}} + h) \\ &\approx -\kappa M \int d^2\sigma \sqrt{-\gamma} h + \dots \end{aligned}$$

[T. Vachaspati, PRD81, 043531 (2010);]

$$S \supset -c_s \int d^2\sigma \sqrt{-\gamma} \delta\varphi$$

$$\Rightarrow \# \text{ of ptls per cusp} \sim \frac{|c_s|^2}{m^2} \text{ (with } k \sim m\sqrt{m\ell}\text{)}$$

$$\Rightarrow \text{Emission power } (P_{\text{lin}}) \sim \frac{|c_s|^2}{\sqrt{m w_s}} \sqrt{\frac{w_s}{\ell}}$$

$$\frac{P_{\text{lin}}}{P_{\text{cusp}}^{\text{thin}}} \sim \frac{|c_s|^2}{\mu} \sqrt{\frac{\phi_0}{m}} \xrightarrow{|c_s|^2 \sim \mu} 10^5 \sqrt{\frac{\phi_0/10^{13}}{m/10^3}}$$

\Rightarrow Huge enhancement of the radiation power!

Our realization: Condensation of LH_u flat-direction in string cores

Within the core of stings,

$$V \supset m_{LH_u}^2(0) |\phi_{LH_u}|^2 + \dots \supset m_{LH_u}^2(0) \langle \phi_{LH_u} \rangle \delta \phi_{LH_u} + \dots$$


 $c_s = \pi w_s^2 |m_{LH_u}^2(0)| \phi_{AD,in} \Rightarrow \frac{|c_s|^2}{\mu} \sim \mathcal{O}(10^{1-2}) \left(\frac{\phi_{AD,in}}{\phi_0} \right)^2$

The expected direct flux:

$$k \frac{d\Phi}{dAdk} \simeq \frac{1.4 \times 10^{-4} (m_\phi w_s)^2 |m_{LH_u}^2(0)|}{\text{km}^2 \cdot \text{yr} \cdot \text{sr}} \frac{1}{m_\phi^2} \times \left(\frac{\phi_{AD,in}}{10^{11} \text{GeV}} \right)^2 \left(\frac{10^{13} \text{GeV}}{\phi_0} \right)^2 \left(\frac{10^{11} \text{GeV}}{k} \right)^2 \left(\frac{R}{15 \text{Mpc}} \right)^3 \left(\text{cf. } k \frac{d\Phi}{dAdk} \Big|_{\text{obs}} \sim \frac{10^{-3}}{\text{km}^2 \cdot \text{yr} \cdot \text{sr}} \right)$$

- Source 2: Thick string itself (even without a linear coupling)

$$\frac{P_{\text{cusp}}^{\text{thick}}}{P_{\text{cusp}}^{\text{thin}}} = \mathcal{O}(0.1) \sqrt{\frac{w_s^{\text{thick}}}{w_s^{\text{thin}}}} \sim \mathcal{O}(0.1) \sqrt{\frac{\phi_0}{m_\phi}}$$

* Once ϕ_0 is fixed by PTA data sets, either $\phi_{AD,in}$ or m_ϕ may be fixed by UHECR data.

- **Extra feature (Extremely boosted LSPs)**

The boosting at cusps: $\gamma_c \sim \sqrt{\ell/w_s}$ [Blanco-Pillado & Olum, PRD59, 063508 (1999);]

- **Neutralino LSP**

Decays of LH_u flat-direction produce SUSY particles:

$$\tilde{\nu}_\alpha \rightarrow \nu_\alpha + \tilde{\chi};$$

Extremely energetic neutrinos and neutralinos are expected.

- **Axino LSP**

If the LSP is axino, neutralinos can decay to axinos such as

$$\tilde{\chi} \rightarrow q_\alpha + \bar{q}_\alpha + \tilde{a};$$

Cascade processes will produce diffuse neutrino flux.

Details are under investigation.

Summary

- Sym.-breaking flat directions appear naturally in SUSY theories.
- A simple and well-motivated example is with SUSY local $U(1)_{B-L}$ sym..
- It can realize *thermal inflation(TI)*.
- Higgs VEV is constrained as $10^{12} \lesssim \phi_0/\text{GeV} \lesssim 10^{16}$ to resolve the moduli problem.
- The soft SUSY-breaking mass is constrained as $m_{\text{soft}} \gtrsim 8\text{TeV}$.
- SGWBs are expected within the reach of at least LISA and DECIGO.
- A simple UV-realization of the model can explain the NANOGrav discovery.
- Spectral distortion & bending freq. may deliver a hint of SUSY at LISA/DECIGO type exps.
- EHE neutrinos & boosted LSPs are also expected and correlated with UHECRs.

Thank you!