JEONBUK NATIONAL UNIVERSITY

K. S. Jeong & **WIP**, JCAP 11 (2023) 016
R. Maji & **WIP,** JCAP 01 (2024) 015

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

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(collaborated with **K.S. Jeong** & **R. Maji**)

Hearing beyond the standard model with cosmicsources of Gravitational Waves,
ICTS (Bangalore), Jan. 07 (2025)

Outline

- **Motivation**
  - Cosmological moduli problem
  - Thermal inflation
- **A model**
  - An extension of MSSM based on $G_{\rm SM} \times U(1)_{B-L}$
  - 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.

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

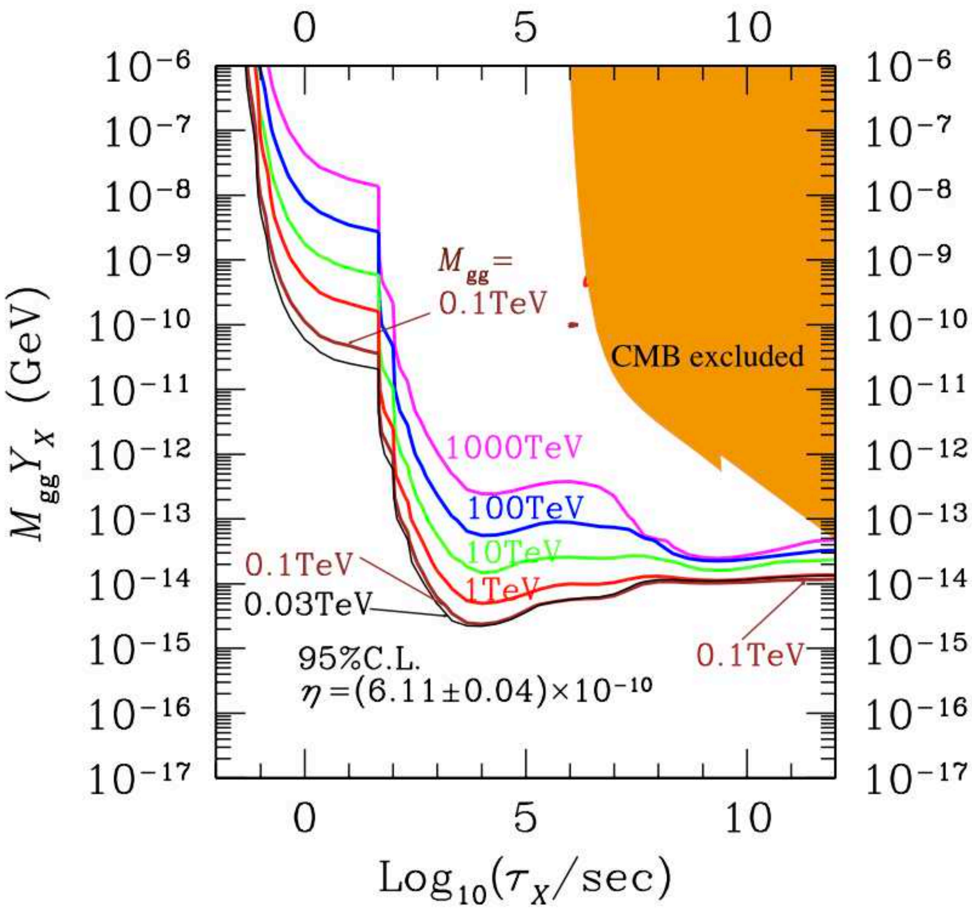
- Long life time, but too abundant(due to large coherent oscillations)! ⇒ danger in BBN

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

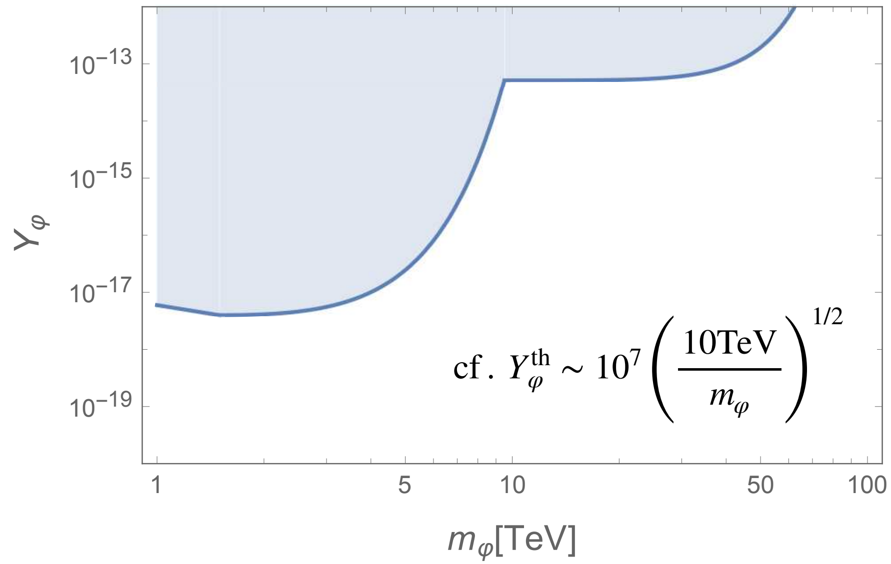
$$\left.\frac{n_\phi}{s}\right|_{\rm osc} \sim \left(\frac{M_{\rm P}}{m_\varphi}\right)^{1/2} \sim 10^7\left(\frac{10{\rm TeV}}{m_\varphi}\right)^{1/2}$$

• 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.



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



cf. $Y_\varphi^{\text{th}} \sim 10^7 \left(\frac{10\text{TeV}}{m_\varphi}\right)^{1/2}$

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

• A simple solution to the moduli problem?

Pushing up mass scale:

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

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

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

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

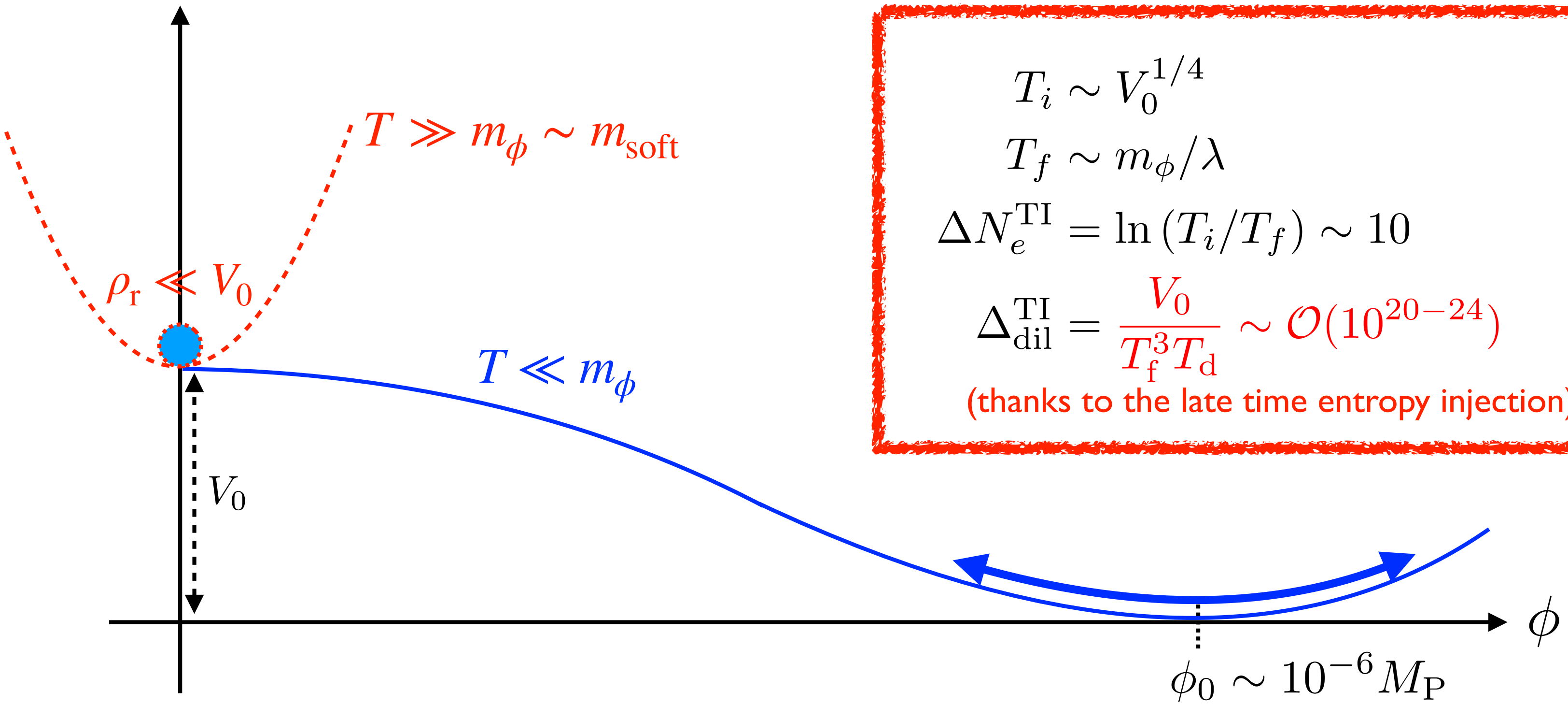
$$\Gamma_{3/2} \gtrsim H_{fo} \sim \frac{m_{\mathrm{LSP}}/20}{M_{\mathrm{P}}} \Leftrightarrow \underline{m_{3/2} \gtrsim \mathcal{O}(100)\mathrm{PeV}}$$

* If R-parity is violated, $m_\varphi, m_{3/2} \gtrsim \mathcal{O}(100)\mathrm{TeV}$ 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.

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



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

(thanks to the late time entropy injection)

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

• A realization of TI ($U(1)_{\rm PQ}$-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 $U(1)_{\rm PQ}$ sym. is a good candidate for the flaton.

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

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

problematic!

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

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

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

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

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

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

$(\Phi_1 \ \& \ \Phi_2 = B - L \text{ Higgs fields})$

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

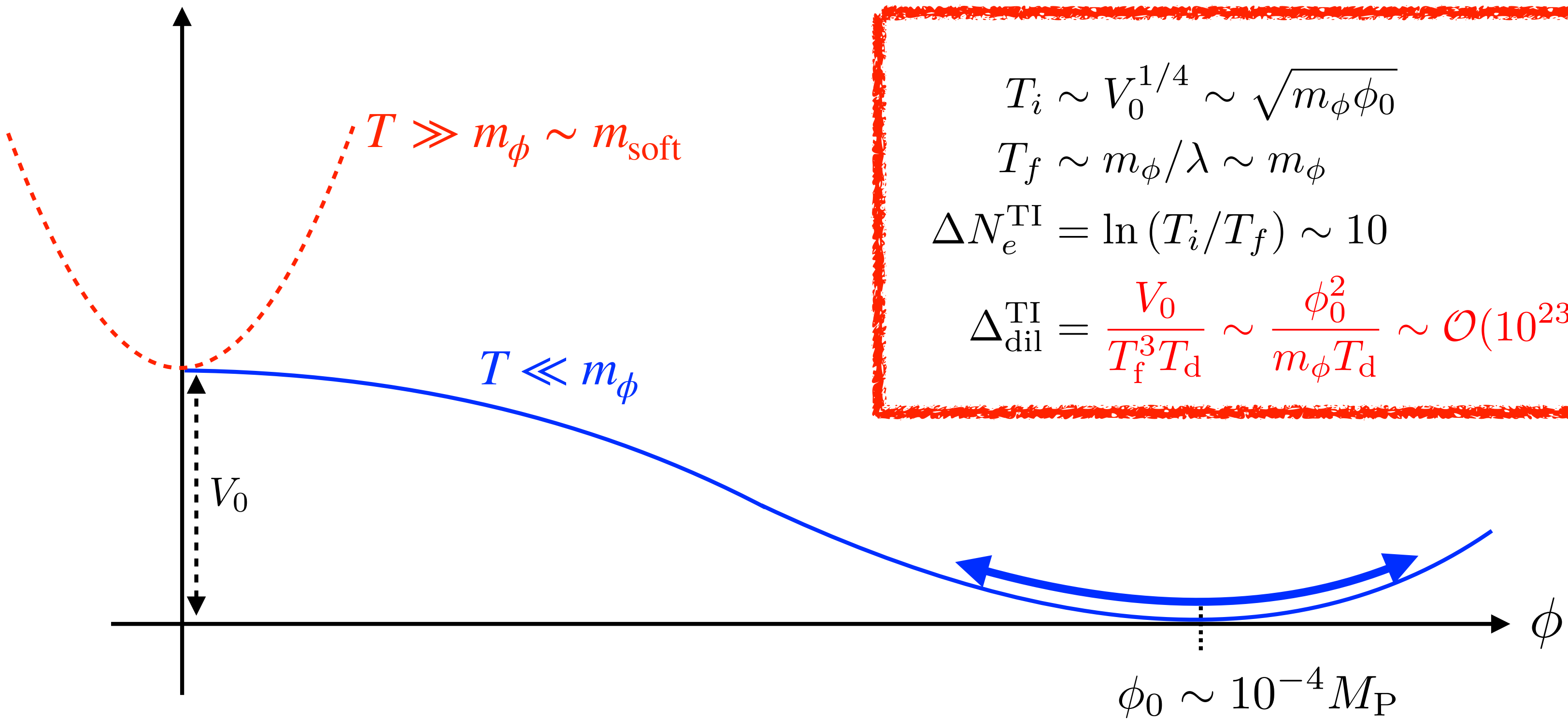
Potential along B-L D-flat direction with $LH_u = 0 \ \& \ H_u H_d = 0$:

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

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

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

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

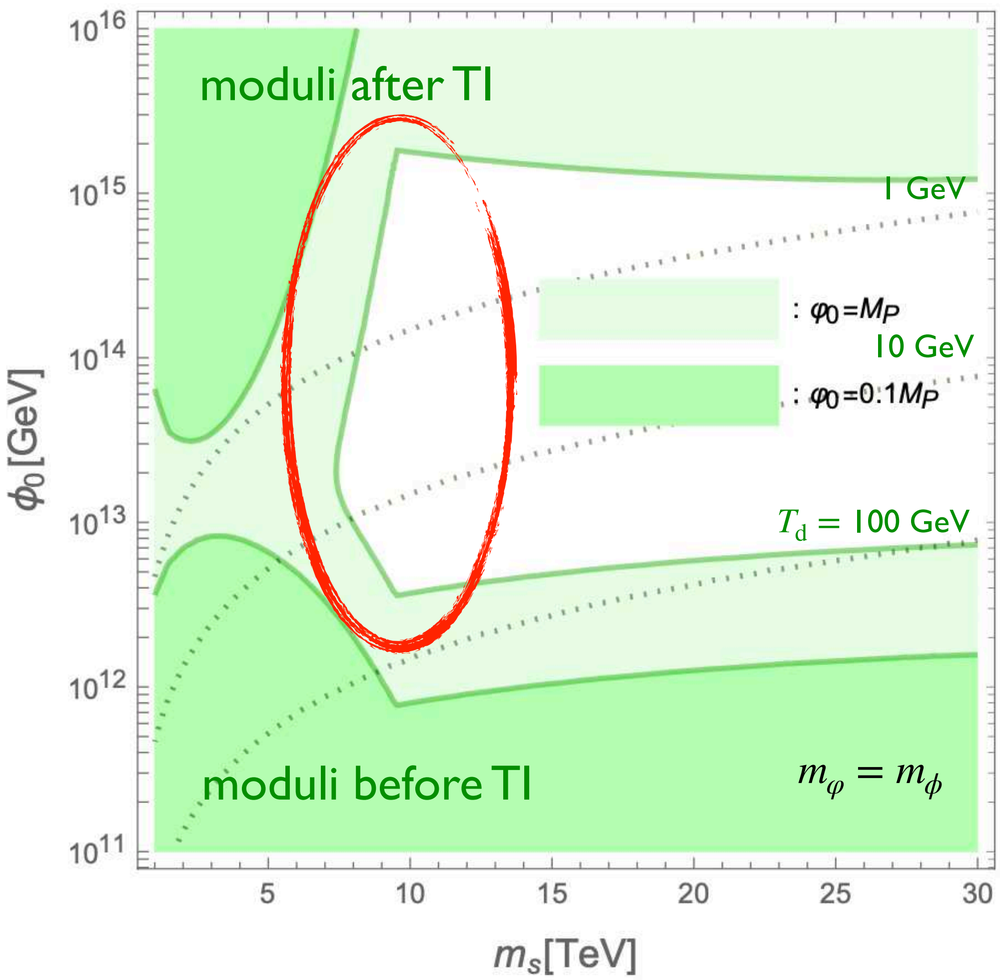


$$T_i \sim V_0^{1/4} \sim \sqrt{m_\phi \phi_0}$$
$$T_f \sim m_\phi/\lambda \sim m_\phi$$
$$\Delta N_e^{\rm TI} = \ln\left(T_i/T_f\right) \sim 10$$
$$\Delta_{\rm dil}^{\rm TI} = \frac{V_0}{T_{\rm f}^3 T_{\rm d}} \sim \frac{\phi_0^2}{m_\phi T_{\rm d}} \sim \mathcal{O}(10^{23-24})$$

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

$$\Rightarrow \quad T_{\rm d} = \mathcal{O}(1){\rm GeV} \times \left(\frac{m_\phi}{10{\rm TeV}}\right)^{3/2}\left(\frac{10^{14}{\rm GeV}}{\phi_0}\right)\left(\frac{|\mu_{\rm eff}|}{m_\phi}\right)^2$$

- **Parameter space safe from the moduli problem**



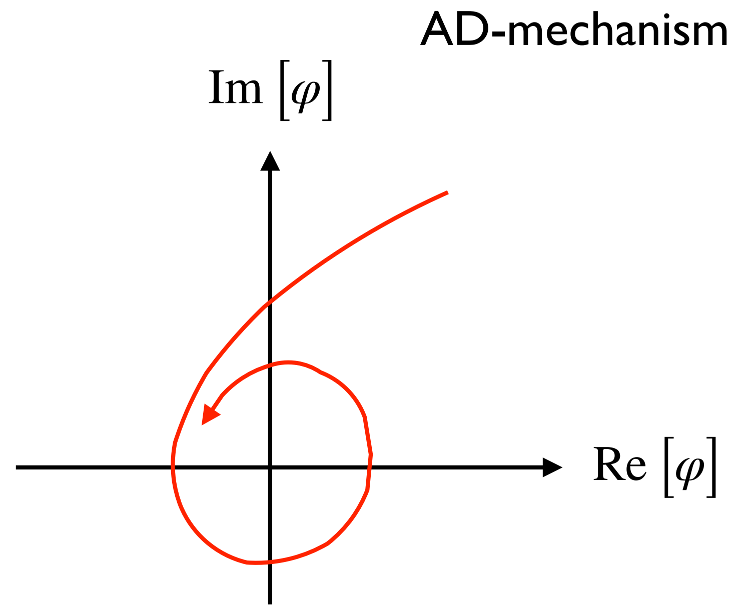
If $\varphi_0 = M_{\rm P}$,

$$m_s \gtrsim 8 \text{ TeV} ,$$
$$3 \times 10^{12} \lesssim \frac{\phi_0}{\text{GeV}} \lesssim 2 \times 10^{15}$$

• Baryogenesis (Late time Affleck-Dine leptogenesis)

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

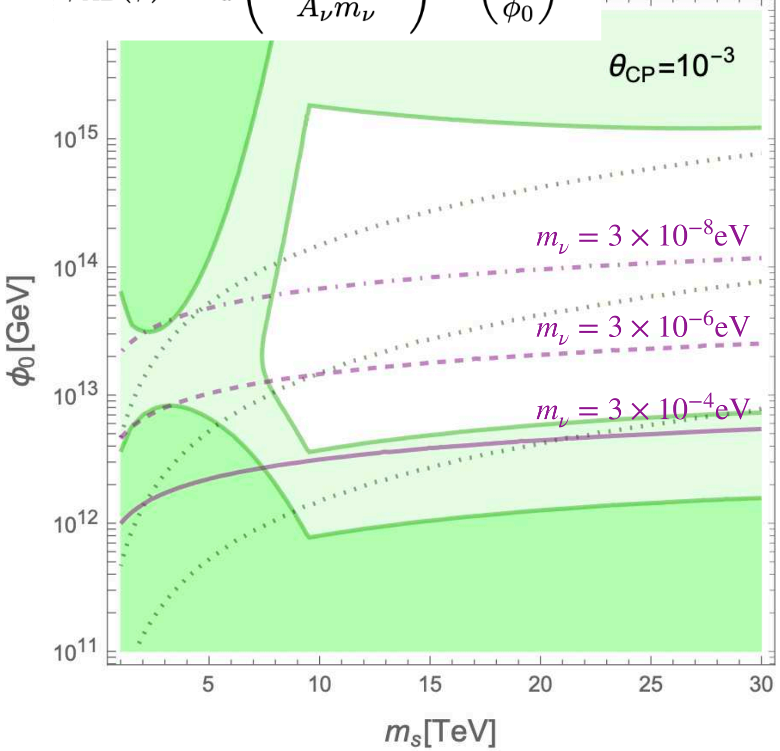
$$m^2_{LH_u} < 0 \xrightarrow{\phi\sim 0\to\phi_0} m^2_{LH_u} > 0 \;\; \left(\because \mu_{\rm MSSM} = \mu_{\rm MSSM}(\phi)\right)$$



$$n_q^{\rm net} = i\left(\varphi^*\dot{\varphi} - \dot{\varphi}^*\varphi\right) = -2\dot{\theta}|\phi|^2$$

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

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



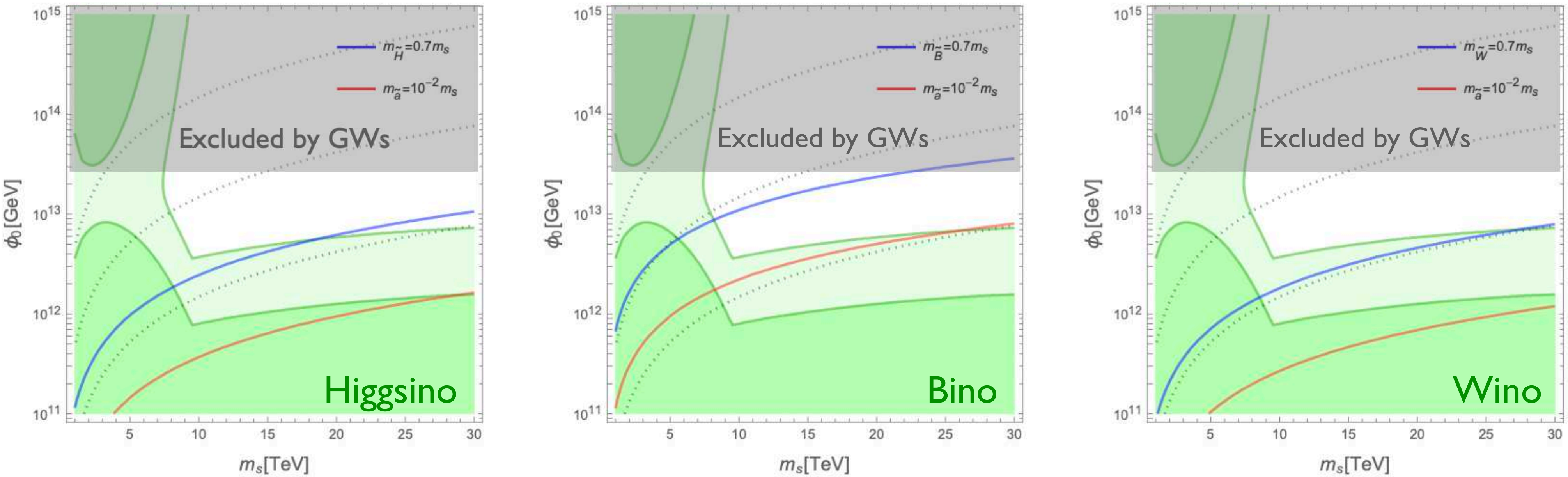
• Dark Matter Candidates

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

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

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

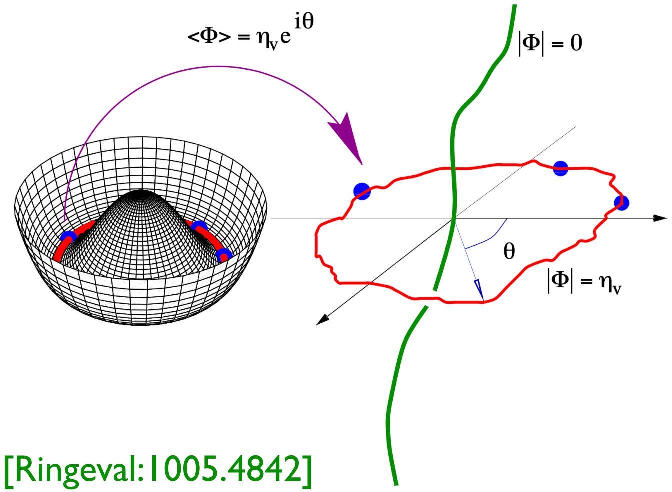
$$\Omega_{\tilde{a}} = \left(m_{\tilde{a}}/m_{\tilde{\chi}}\right) \Omega_{\tilde{\chi}}$$



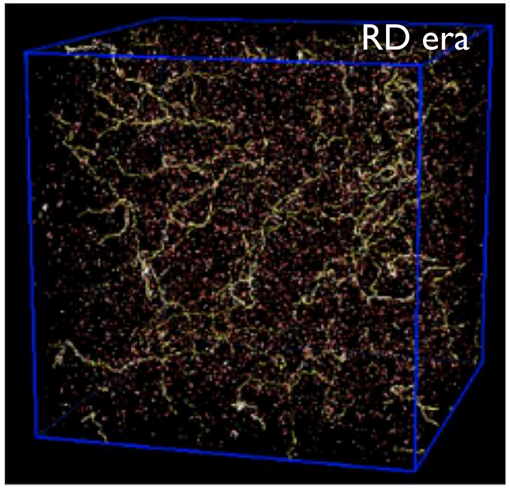
✓ Gray regions might be excluded by PPTA bound on GWs

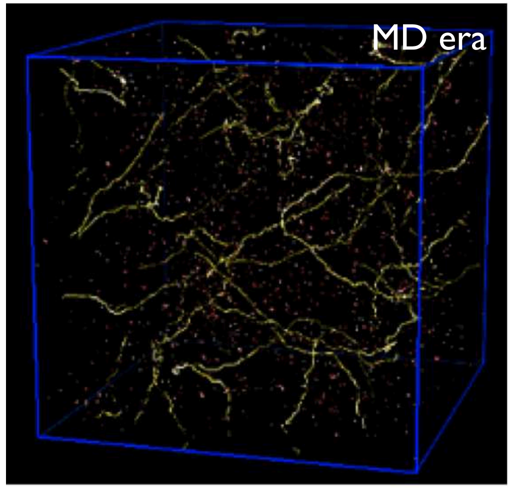
SGWBs from TCSs

- **Cosmic string network** [E.g.,Vilenkin & Shellard, 1994]
  - It can be formed when vacuum manifold is non-trivially connected ($\pi_1(\mathscr{M}) \neq I$)



[Ringeval:1005.4842]





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

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

  - Composition: Network + string loops of various sizes

Barreiro, Copelend, Lyth & Prokopec, PRD 54 (1996) 1379
Perkins & Davis, PLB 428 (1998) 254
Y. Cui et al., PRD77 (2008) 043528

• 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:

$$\mu/\pi v^2 \simeq \left[\frac{4.2}{\ln(1/\Delta)} + \frac{14}{\ln^2(1/\Delta)}\right] \times \left\{1 + \left[\frac{2.6}{\ln(1/\Delta)} + \frac{57}{\ln^2(1/\Delta)}\right] \ln N_{\rm w}\right\}$$
$$= c_1 \times (1 + c_2 \ln N_{\rm w})$$

winding #-dependence!

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

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

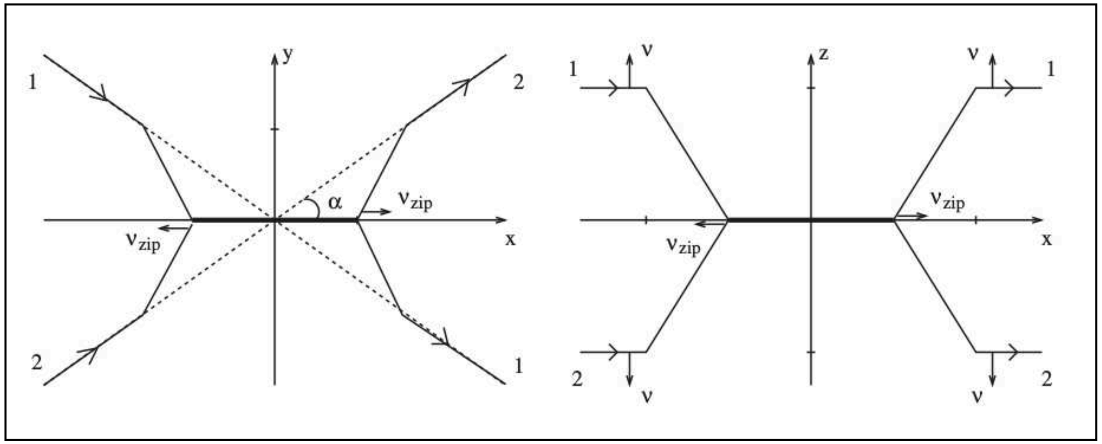
⇒ zipping effect between strings

⇒ formation of higher winding number (N_w) states if

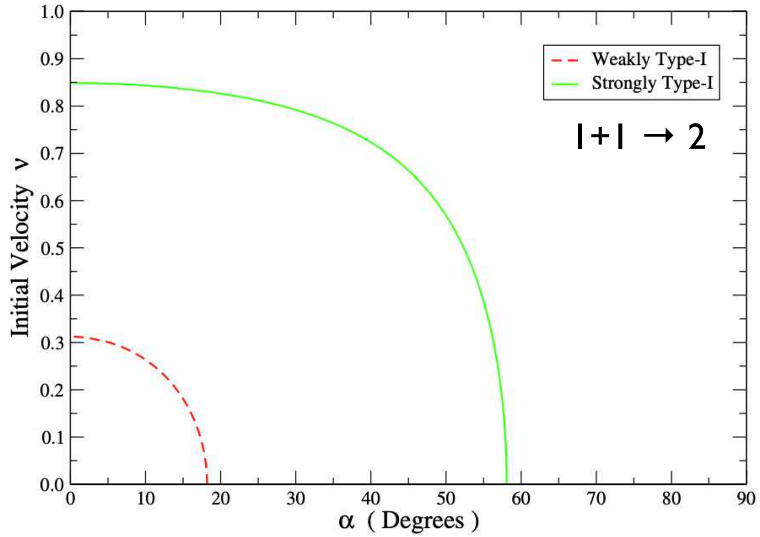
$$\sqrt{1-\nu^2}\cos\alpha > \frac{\mu_{2N}}{2\mu_N}$$

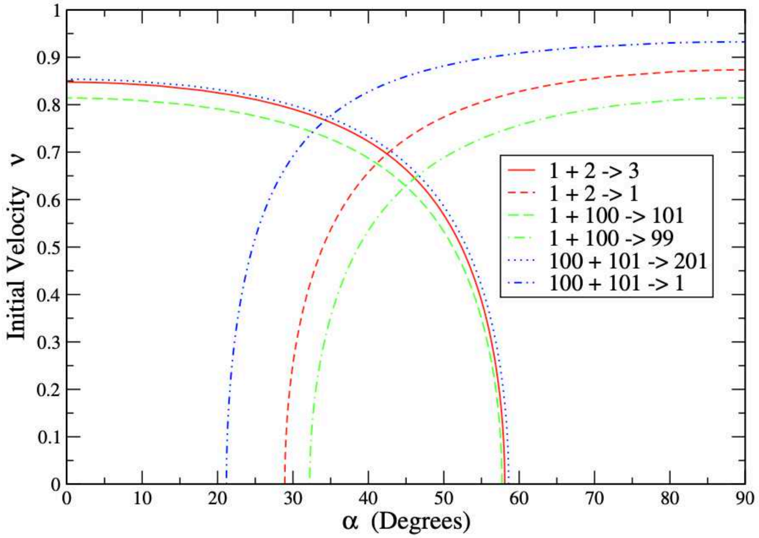
(a kinetic constraint due to energy conservation)

Zipping configuration



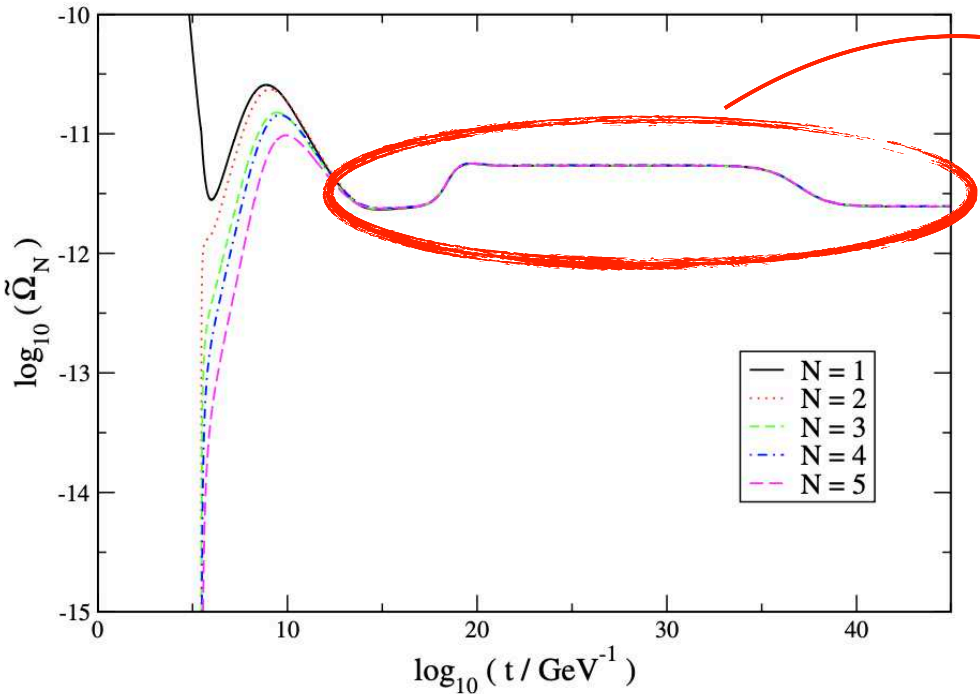
Kinetic para. space for Zipping





- **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., $n_a \to$ const .)

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

$$N_w^{\rm max}(t) \sim N_{\rm c}\left(\frac{t}{t_i}\right)^{0.22}$$

$$t_i \sim 10 t_{\rm c}$$

Barreiro, Copelend, Lyth & Prokopec, PRD 54 (1996) 1379
Perkins & Davis, PLB 428 (1998) 254
Y. Cui et al., PRD77 (2008) 043528

• GWs from TCS loops

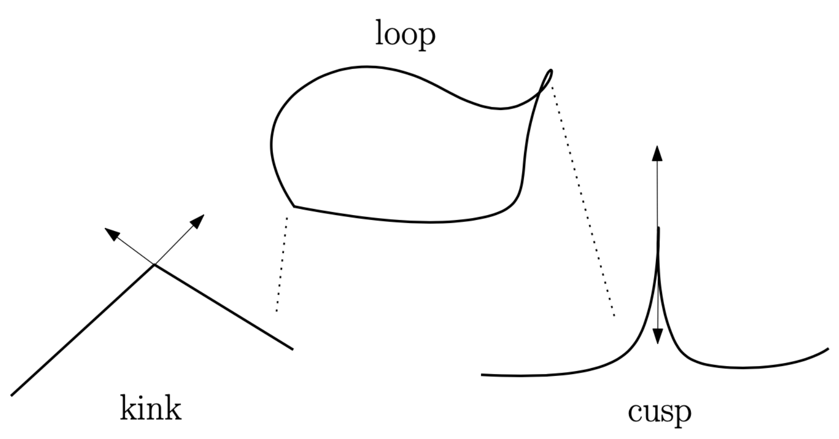
- Radiation power of GWs:

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

- Radiation power of particles:

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

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



[Gottenoire, Servant, Simakachorn: 1912.02569]

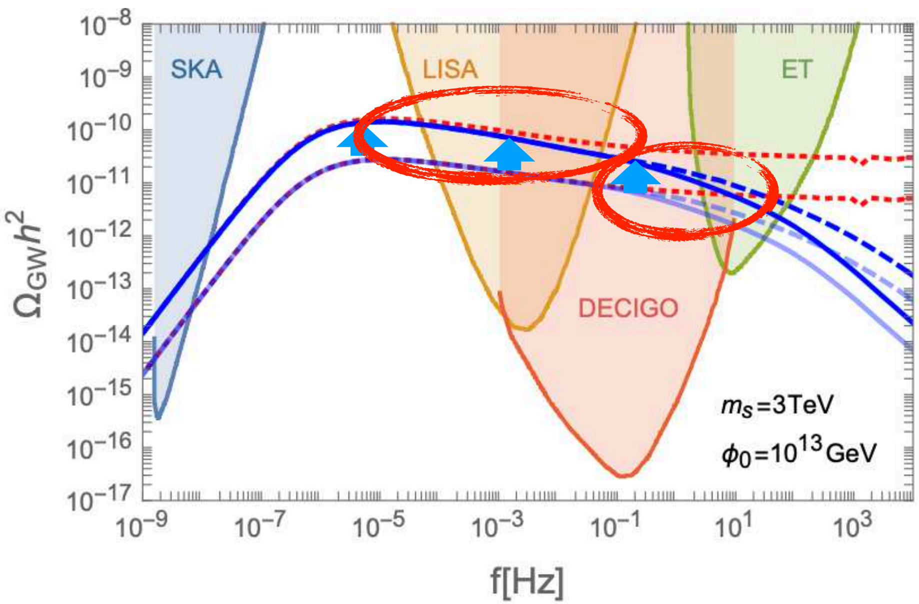
- Thick vs think CSs in regard of ℓ_*:

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

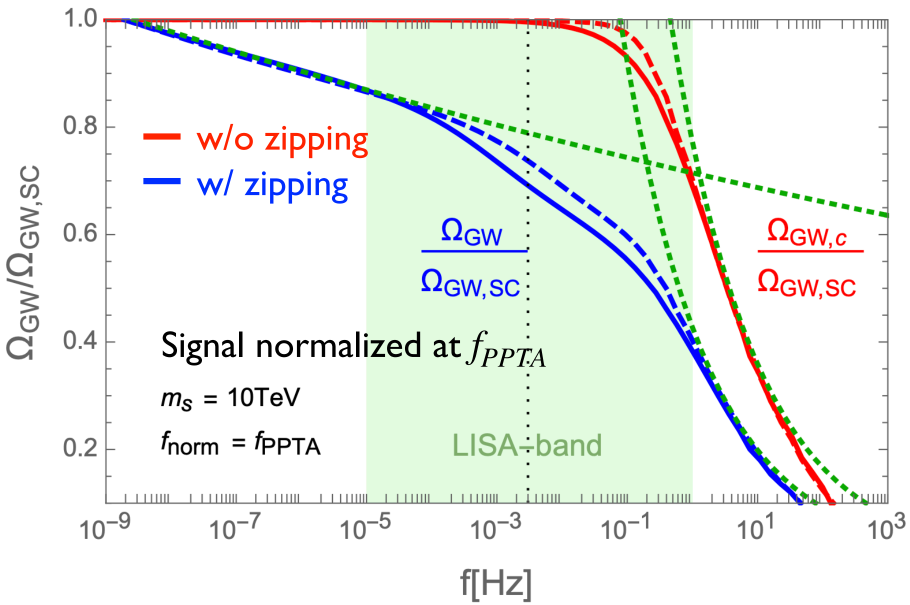
• Signals expected - Stable TCSs of $U(1)_{B-L}$ Higgs

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

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



Characteristic features
- Enhancement (w.r.t the case w/o zipping)
- Spectral distortion
- Bending feature (related to $T_{\rm d}$ or T_*)

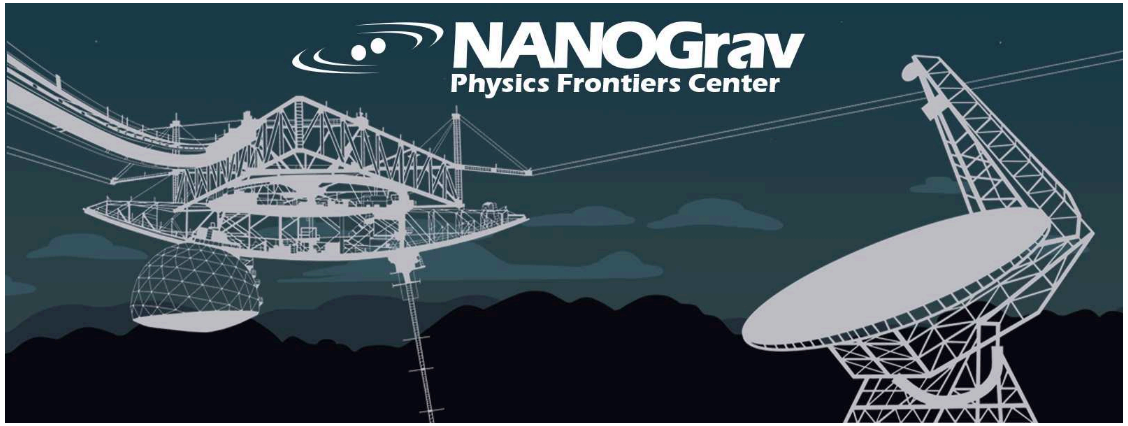


Clear spectral difference
relative to the one without zipping
⇒ can be distinguished.

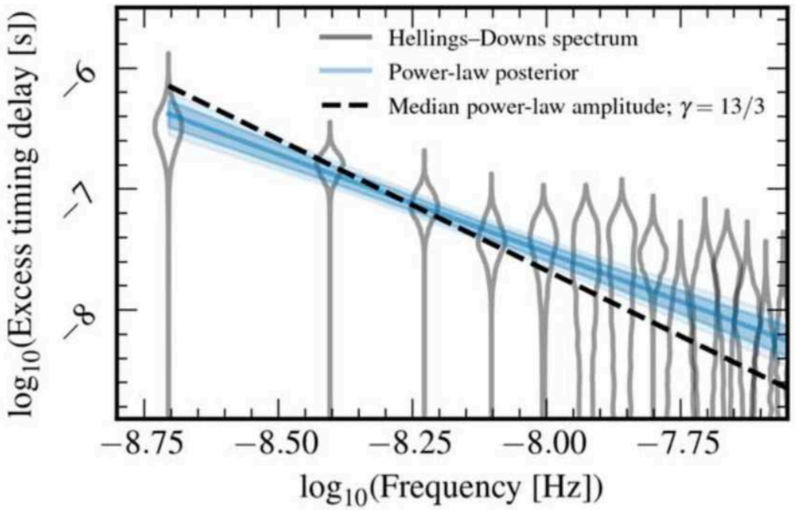
[Kwang Sik Jeong & **WIP**, JCAP 11 (2023) 016]

NANOGrav 15yr & SUSY B-L

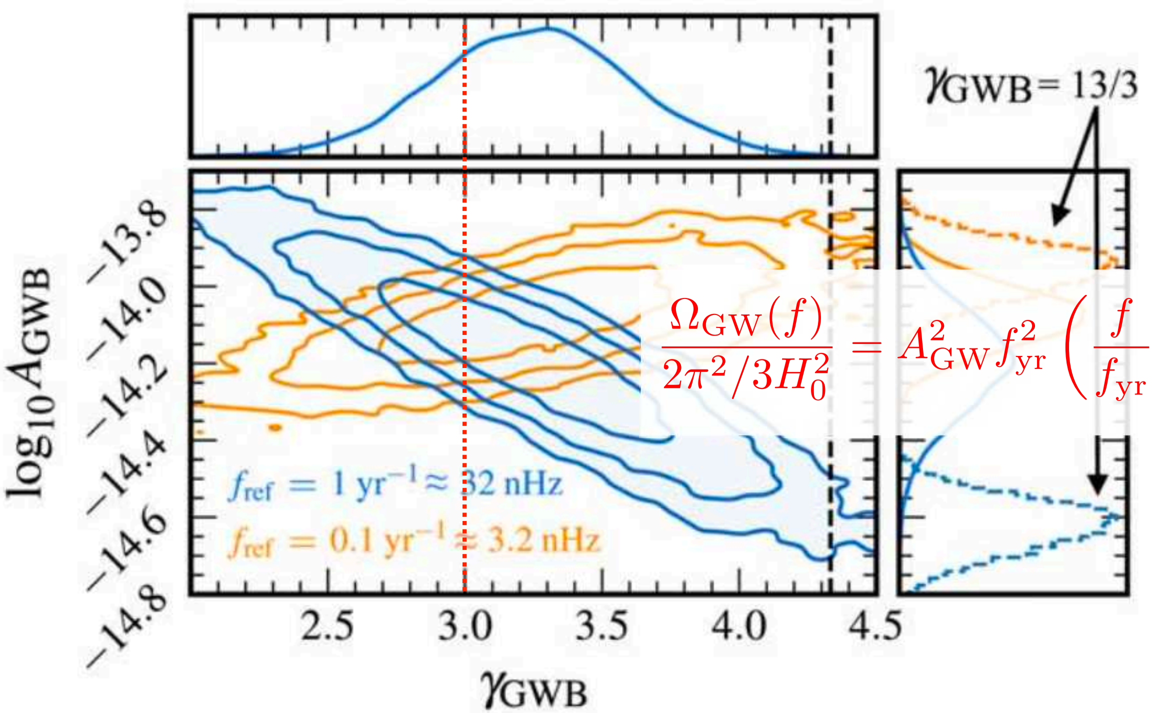
North American Nanohertz Observatory for Gravitational Waves



(a)

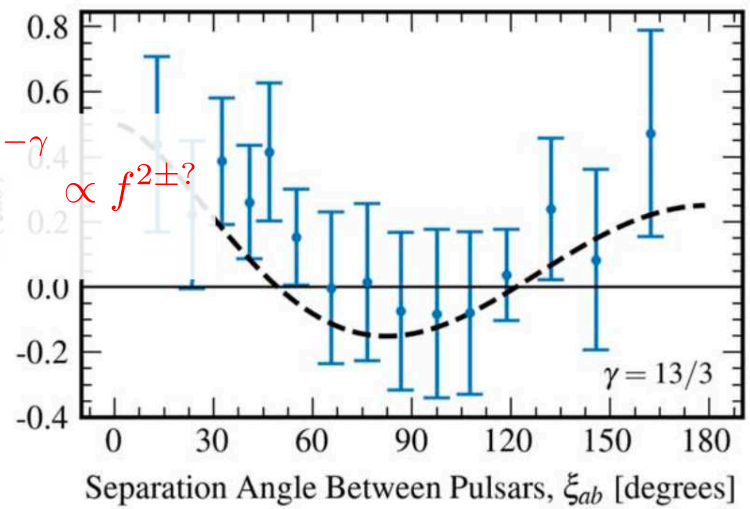


(b)



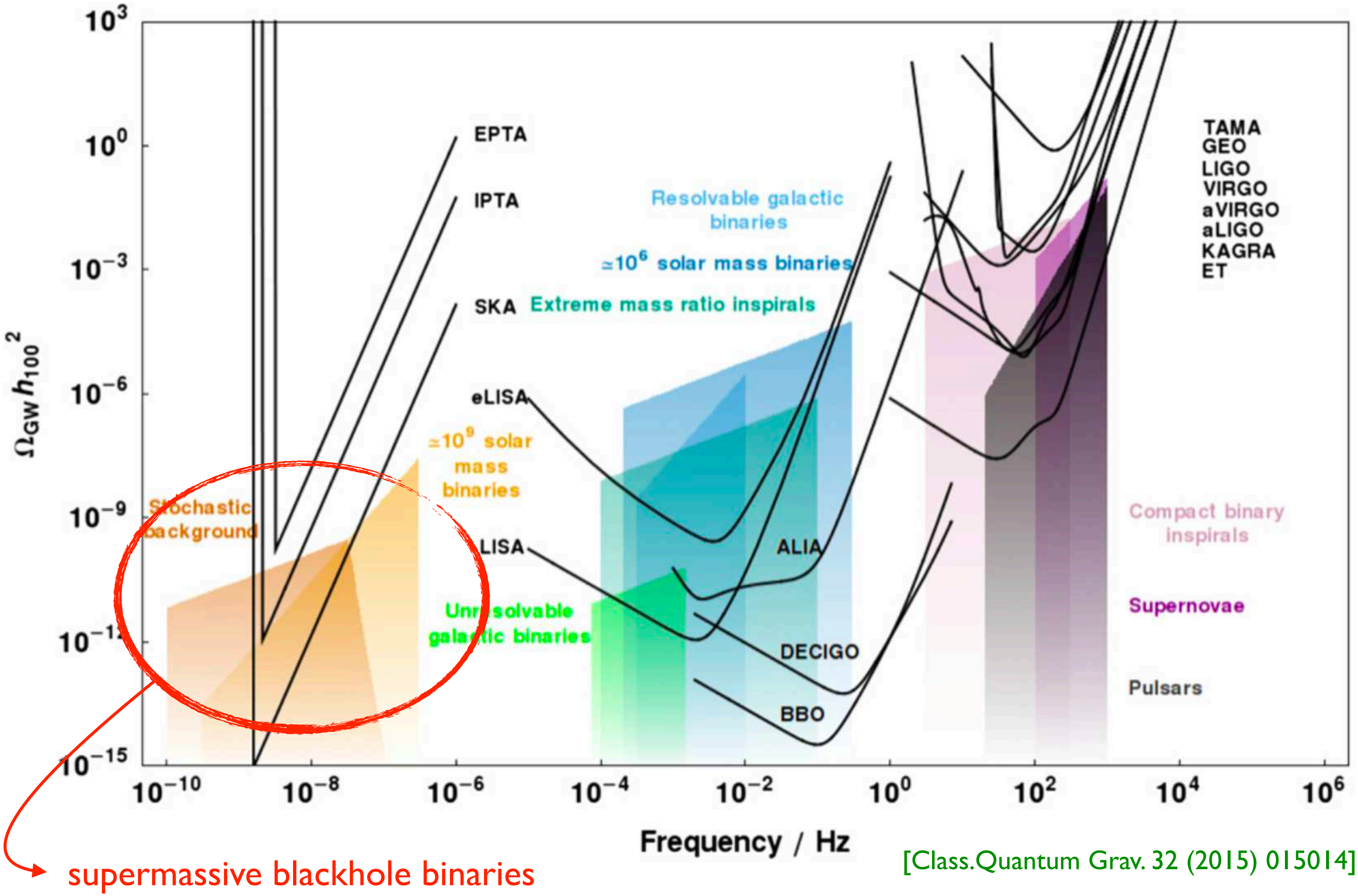
$$\frac{\Omega_{GW}(f)}{2\pi^2/3H_0^2} = A_{GW}^2 f_{yr}^2 \left(\frac{f}{f_{yr}}\right)^{5-\gamma} \propto f^{2\pm?}$$

(c)



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

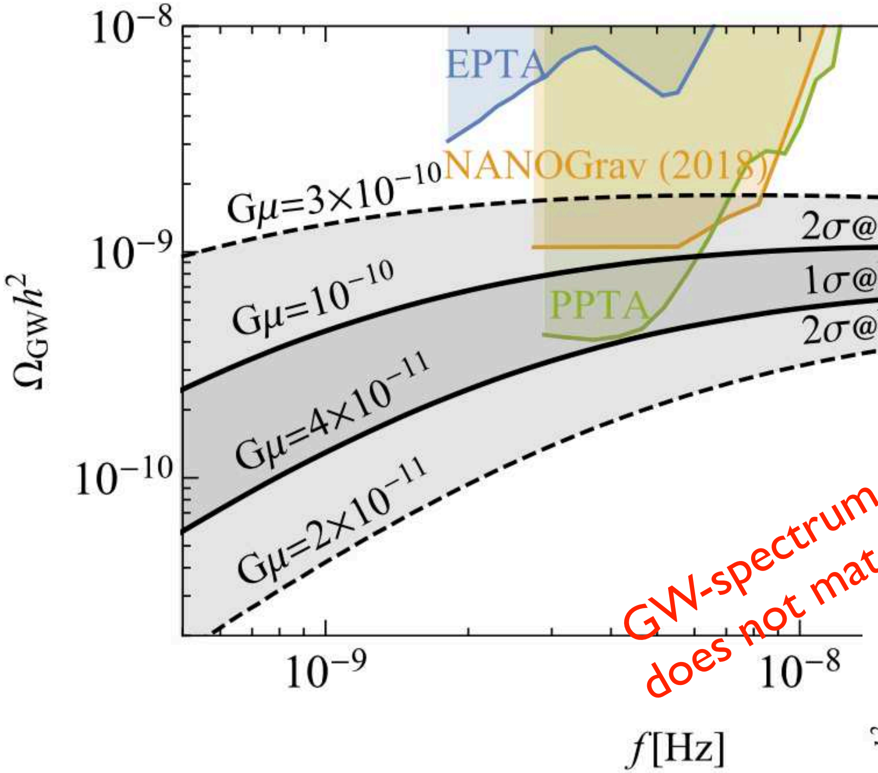
- **Astrophysical source?**

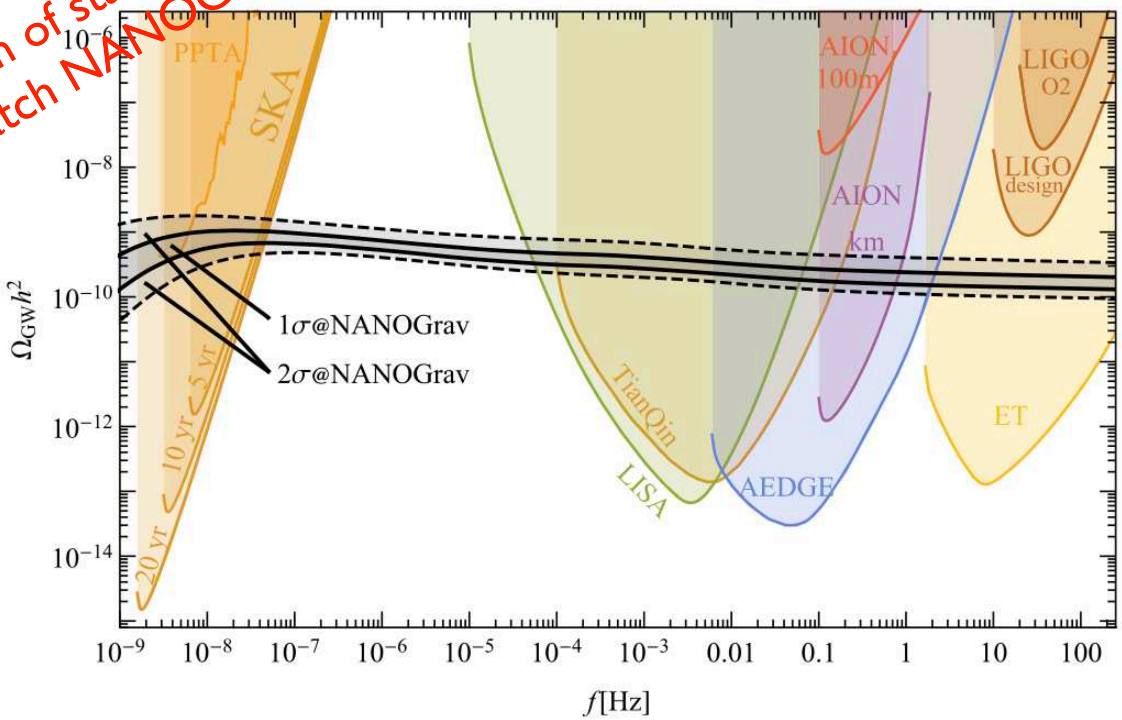


[Class.Quantum Grav. 32 (2015) 015014]

• Stable cosmic strings?

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





GW-spectrum of stable cosmic strings does not match NANOGrav 15yr data.

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

• 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]

$$SU(3)_c \times SU(2)_L \times U(2) \;\; (U(2) = SU(2)_{\rm R} \times U(1)_{B-L}/\mathbb{Z}_2)$$

$$\xrightarrow{M_R} SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$

$$\pi_2\left(\frac{SU(2)_R}{U(1)_R}\right) = \pi_2(S^2) = Z$$

$$\xrightarrow{M_{BL}} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\pi_1\left(\frac{U(1)_R \times U(1)_{B-L}}{U(1)_Y}\right) = \pi_1(S^1) = Z$$

{ 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.

Low energy EFT:

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

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

[R. Maji & **WIP**, JCAP 01 (2024) 016]

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

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

Pair nucleation rate per unit length:

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

$\Rightarrow$ Segmentation of strings in a string network ($\overline{M}SM$ configurations - "dumbbells")
$\Rightarrow$ Energy loss due to emission of radiation by accelerated (anti)monopoles:

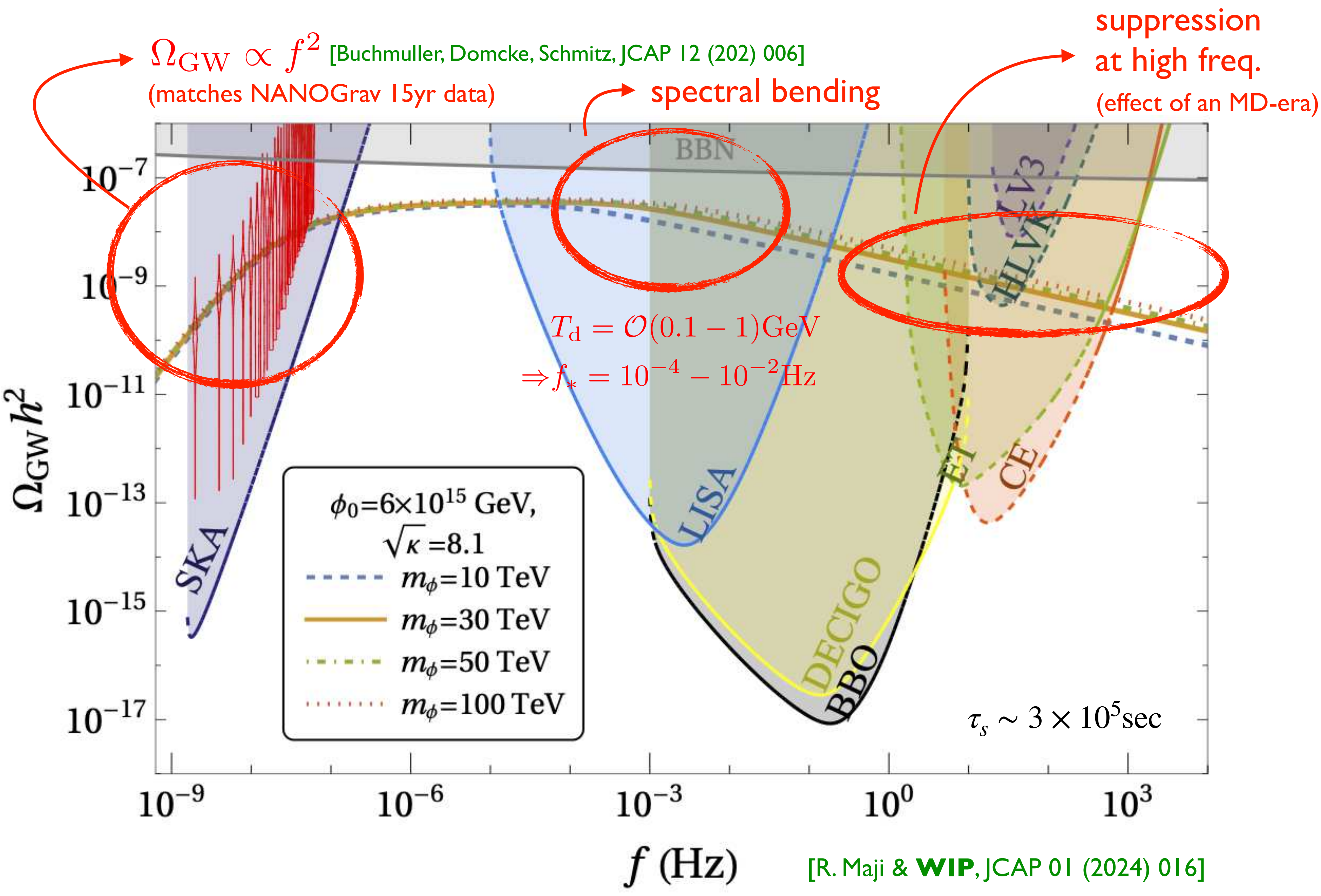
$$\dot{E}_s = -\frac{g_M^2}{6\pi}\left(\frac{\mu_s}{m_{\rm M}}\right)^2, \; g_M = \frac{4\pi}{g_R}$$

$\Rightarrow$ Decay of the string network:

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

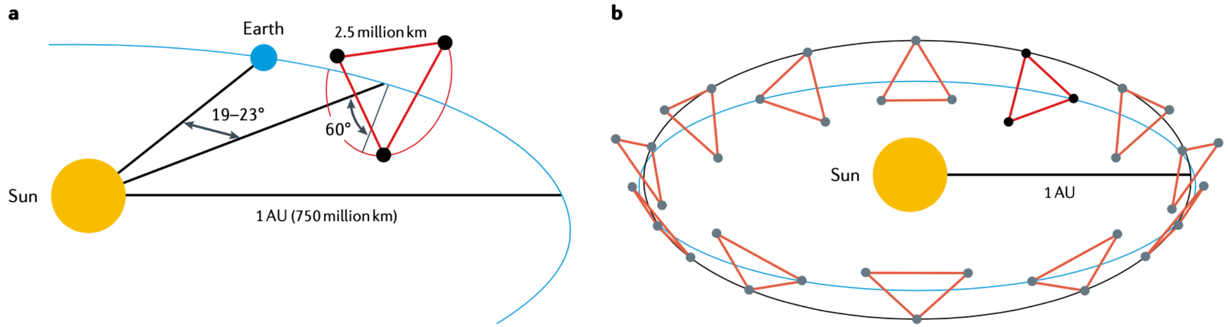
* high-frequency signals should be suppressed (e.g., by partially inflating away strings)

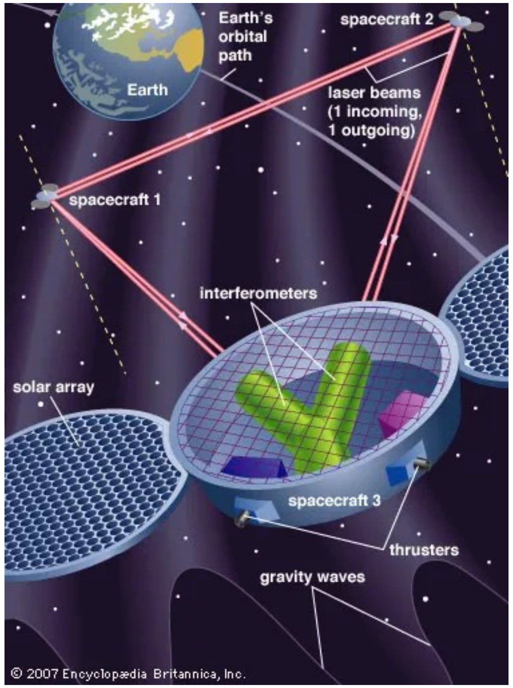
- **Signal expected - Unstable TCSs of the $U(1)_{B-L}$ Higgs**

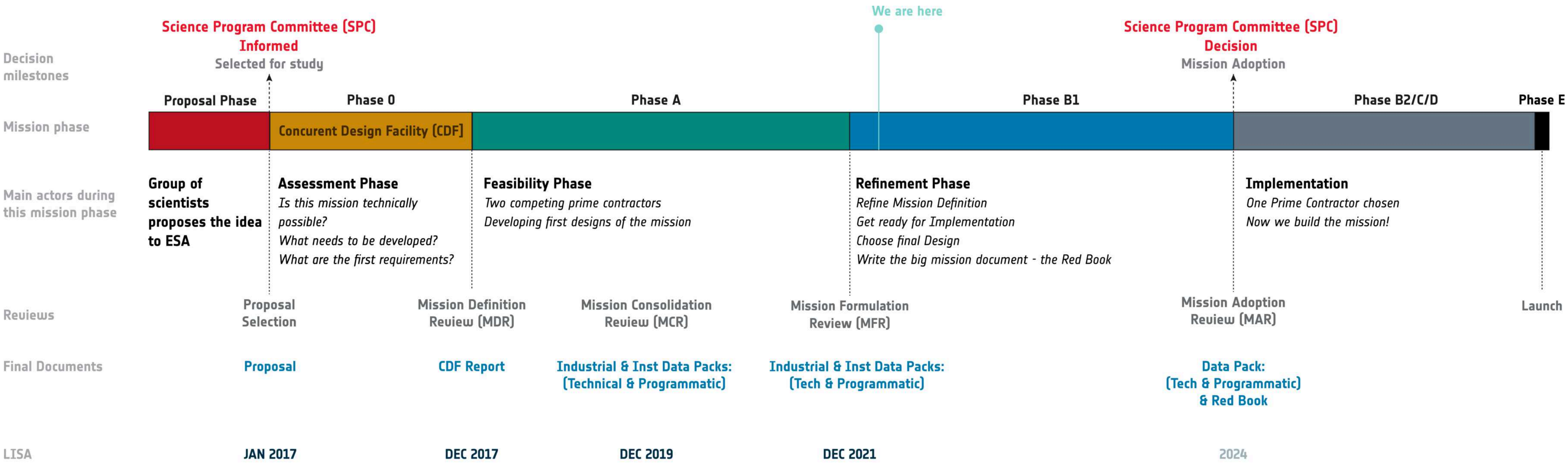


[R. Maji & **WIP**, JCAP 01 (2024) 016]

• Timeline of LISA







LISA mission timeline. Credit: ESA.

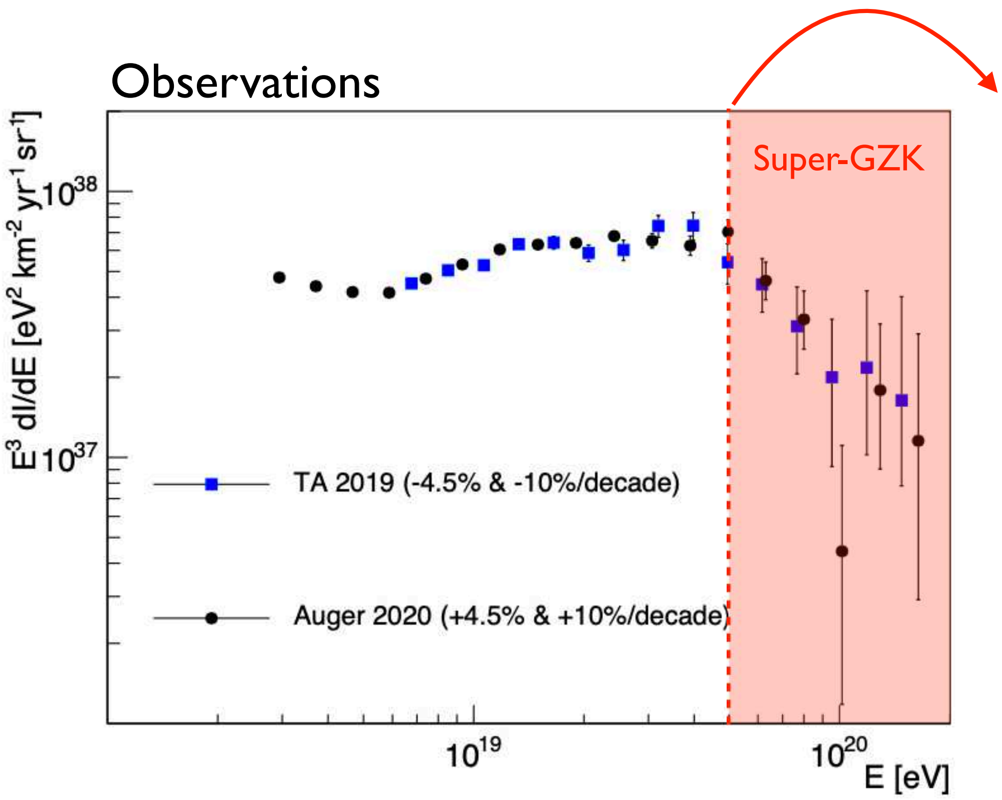
Scheduled for lunch in the mid-2030s!

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**

Observations



[PoS (ICRC2021) 337]

GZK limit

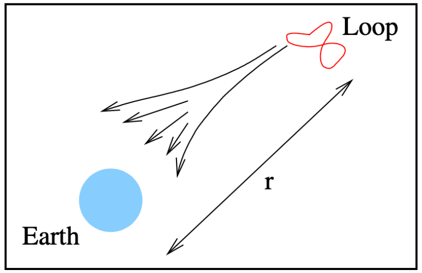
A theoretical upper bnd. of cosmic ray protons due to proton - CMB photon interactions

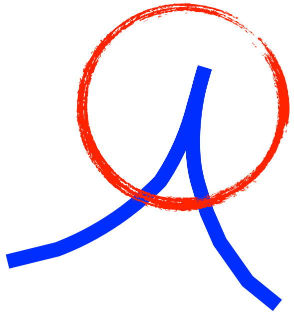
Observed flux over GZK limit

$$k\frac{d\Phi}{dAdk}\Big|^{\rm obs} \sim \frac{10^{-3}}{\rm km^2 \cdot yr \cdot sr}$$

Yet no astrophysical explanations!

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





- Source 1: 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);]

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

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

$$S_{\rm int} = \kappa \int d^2\sigma \int d^2x_\perp \sqrt{-\gamma} (\Phi^\dagger \Phi - M^2) H^\dagger H$$

$$= \kappa \int d^2\sigma \sqrt{-\gamma} \int d^2x_\perp (\Phi^\dagger \Phi - M^2)(\langle H \rangle_{\rm in} + h)^\dagger$$

$$\times (\langle H \rangle_{\rm in} + h)$$

$$\approx -\kappa M \int d^2\sigma \sqrt{-\gamma} h + \cdots .$$

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

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

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

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

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

$\Rightarrow$ Huge enhancement of the radiation power!

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

Within the core of stings,

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

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

The expected direct flux:

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

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

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

* Once ϕ_0 is fixed by PTA data sets, either $\phi_{\rm AD,in}$ 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:

$$\tilde{\nu}_\alpha \to \nu_\alpha + \tilde{\chi},$$

Extremely energetic neutrinos and neutralinos are expected.

- Axino LSP

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

$$\tilde{\chi} \to q_\alpha + \bar{q}_\alpha + \tilde{a},$$

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* $10^{12} \lesssim \phi_0/\mathrm{GeV} \lesssim 10^{16}$ *to resolve the moduli problem.*
- *The soft SUSY-breaking mass is constrained as* $m_{\rm soft} \gtrsim 8\mathrm{TeV}$.
- 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!