Thermal inflation, GWs & UHECRs in a SUSY local U(1)B-L

(with Kwang Sik Jeong, arXiv: 2305.11143)

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PPC 2023, Daejeon, Jun. 13 (2023)

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.

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

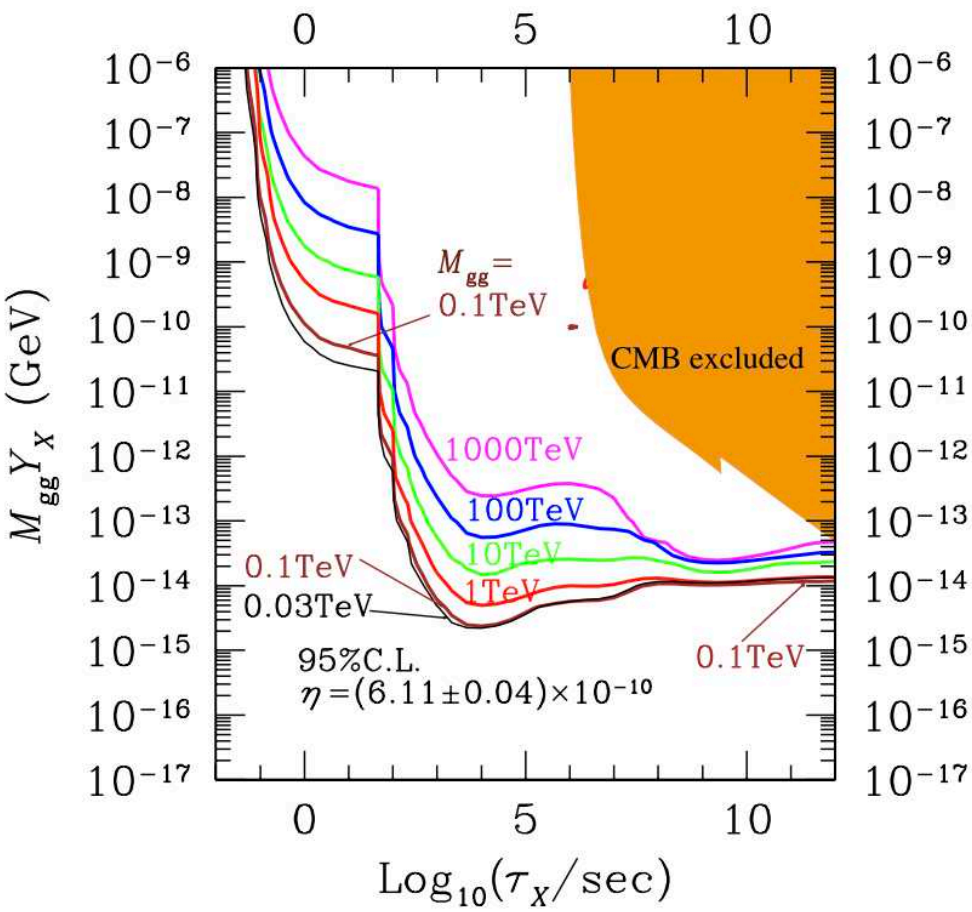
  - Long life time, but too abundant(due to large coherent oscillations)! ⇒ danger in BBN

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

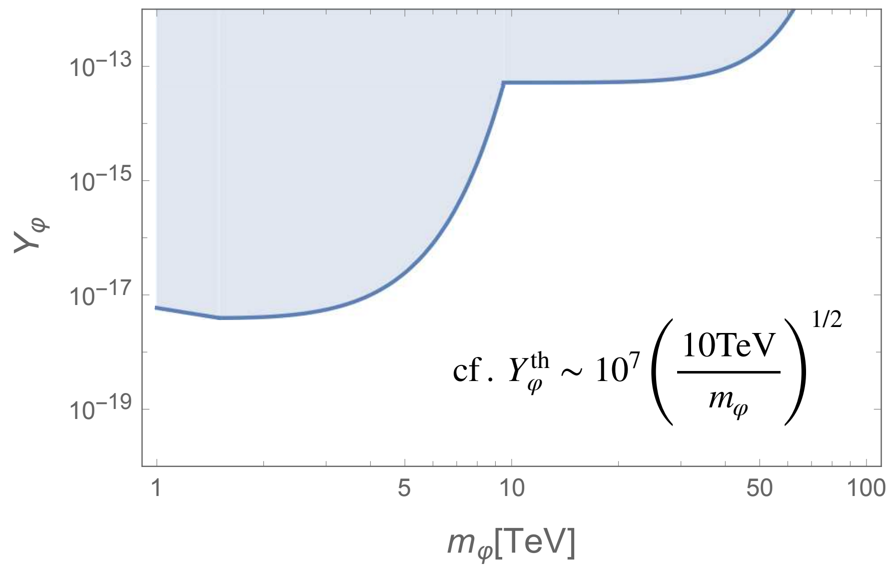
$$\frac{n_\phi}{s}\Big|_{\rm osc} \sim \left(\frac{M_{\rm P}}{m_\varphi}\right)^{1/2} \sim 10^7 \left(\frac{10{\rm TeV}}{m_\varphi}\right)^{1/2}$$

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

[Kawasaki et al, PRD 97, 2018]



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

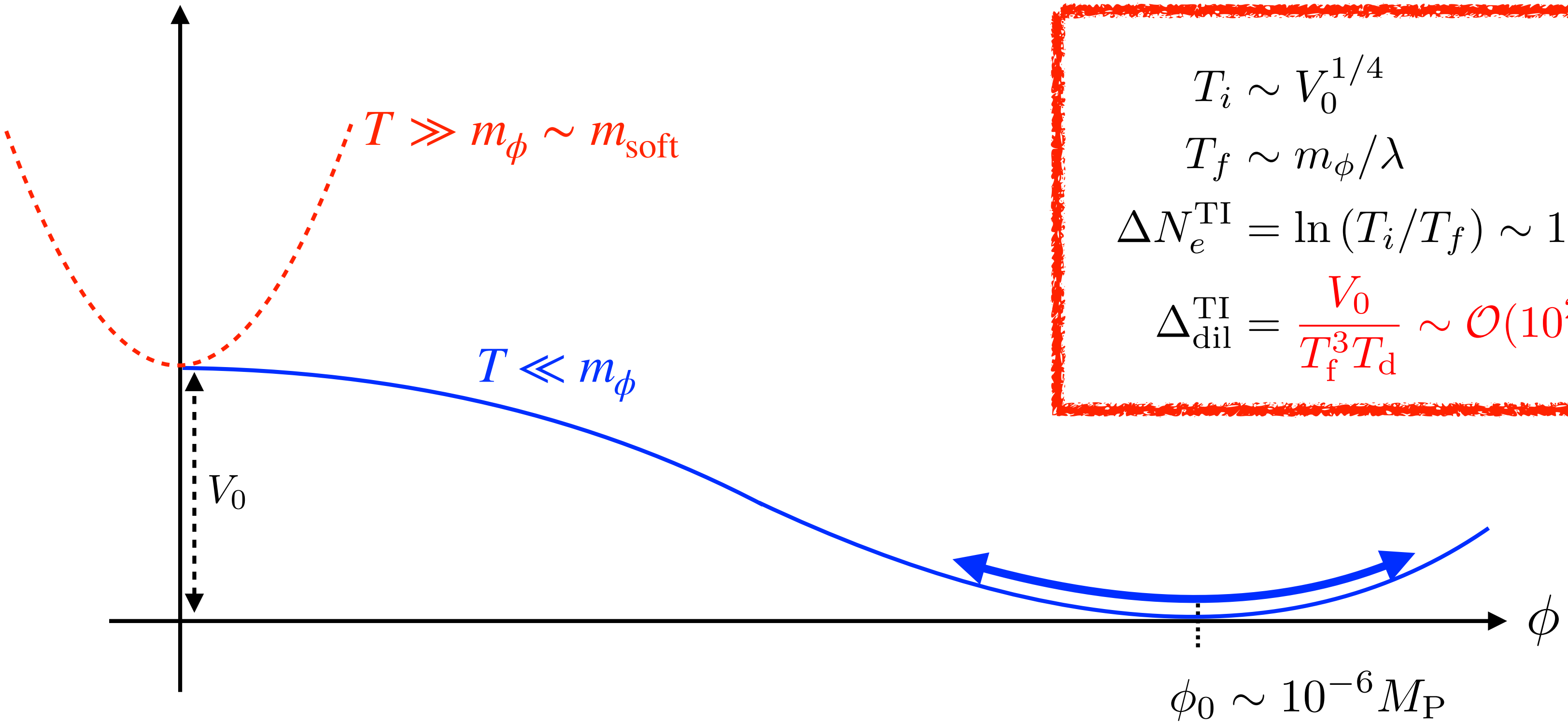


A dilution by a factor of $\mathcal{O}(10^{21})$ is necessary!

- **Thermal inflation** (as a sol. to the moduli problem)

[Lyth & Stewart, 1995]

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



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

The most compelling sol. to the moduli problem!

A SUSY local 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 ($SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$)** [Kwang Sik Jeong & **WIP**, 2305.11143]

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

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

* $Q_{B-L}(\Phi_1, \Phi_2) = (1, -1)$

* $\phi^2 \equiv \phi_1 \phi_2$ is B-L D-flat direction.

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

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

$$\phi_0 \approx \frac{A_\Phi M}{3\lambda_\Phi}\left[1 + \sqrt{1 + \frac{12\overline{m^2}}{A_\Phi^2}}\right], \quad \overline{m^2} \equiv -\left(m_1^2 + m_2^2\right)/2 > 0$$

- **Assumptions on mass parameters**

$$\mu_H, \mu_\Phi \ll m_{\rm soft}$$

$$\mu_{\rm eff} \equiv \mu_H + \frac{\lambda_\mu}{M}\langle \Phi_1 \Phi_2 \rangle \sim m_{\rm soft}$$

$$m_{LH_u}^2 \equiv \frac{1}{2}\left(m_L^2 + m_{H_u}^2 + |\mu_{\rm eff}^2|\right) > 0$$

$$m_{LH_u,0}^2 \equiv \frac{1}{2}\left(m_L^2 + m_{H_u}^2\right) < 0$$

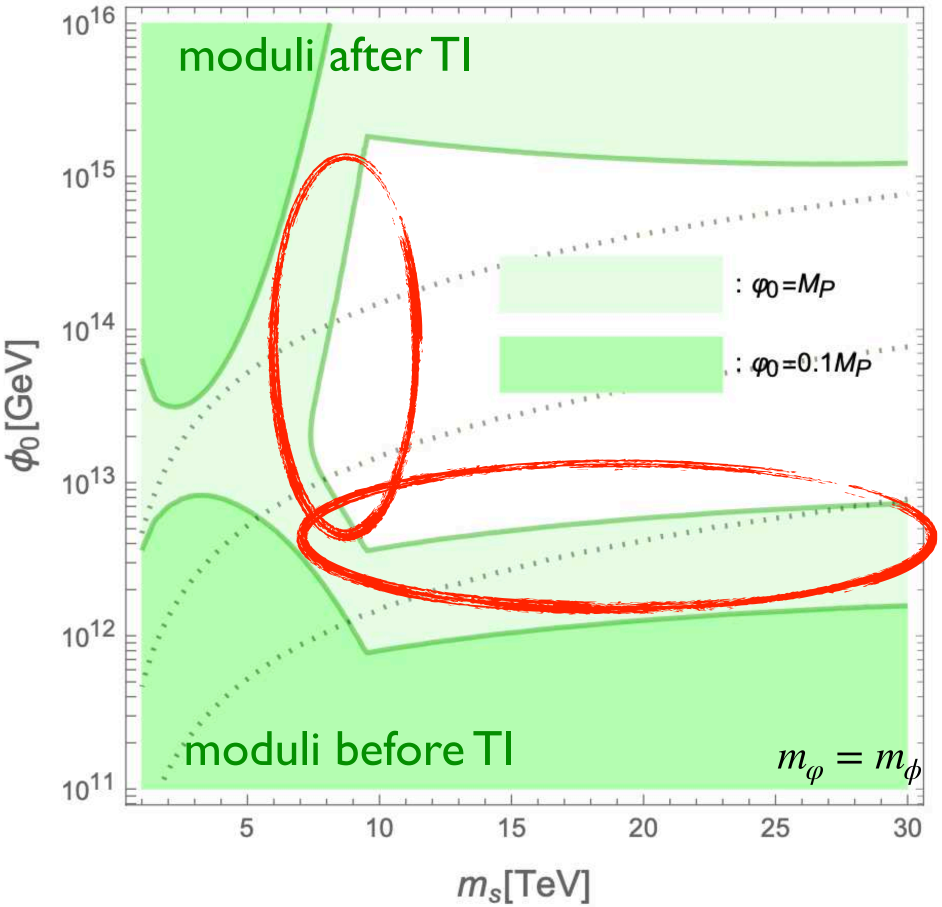
$$|\overline{m}^2| < |m_{LH_u,0}^2|$$

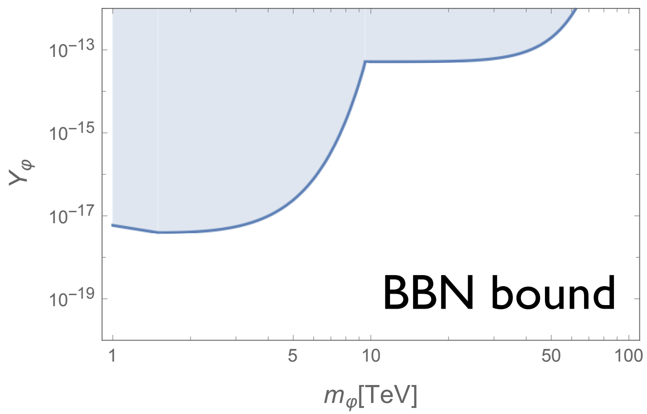
LH_u flat-direction is destabilized earlier than ϕ (B-L flat direction)

Cosmology

TI & moduli

- **Dilution by thermal inflation** $\begin{cases} Y_\varphi^{\rm BB,0} \propto m_s^2/\phi_0^3 \longrightarrow \phi_0 \propto m_s^{2/3} \\ Y_\varphi^{\rm TI,0} \propto m_s^{1/2}\phi_0 \longrightarrow \phi_0 \propto m_s^{-1/2} \end{cases}$





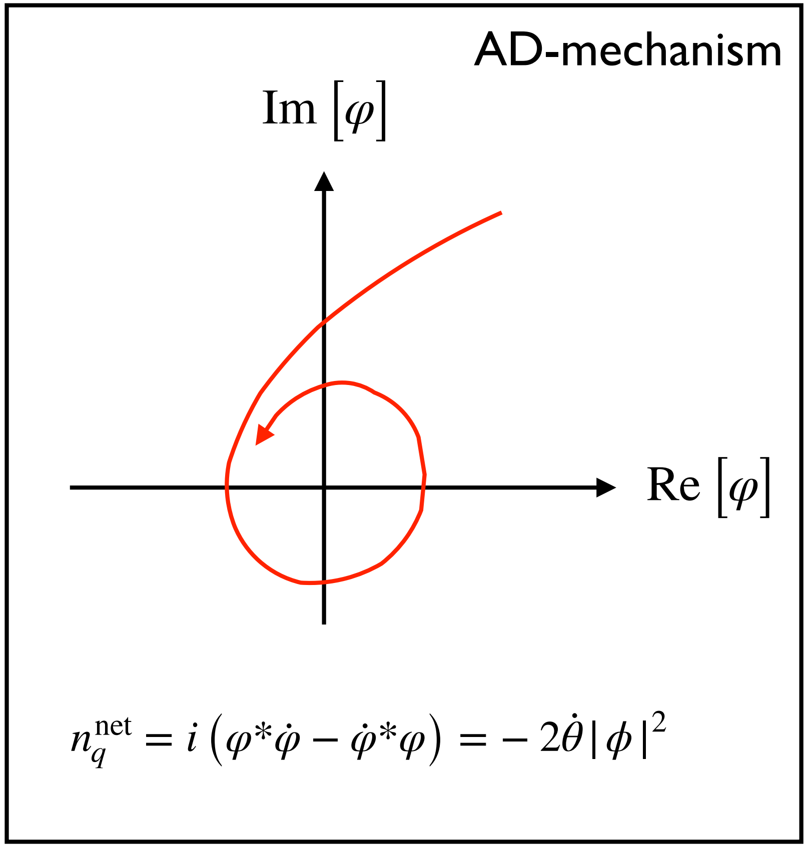
For $\varphi_0 = M_{\rm P}$,

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

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

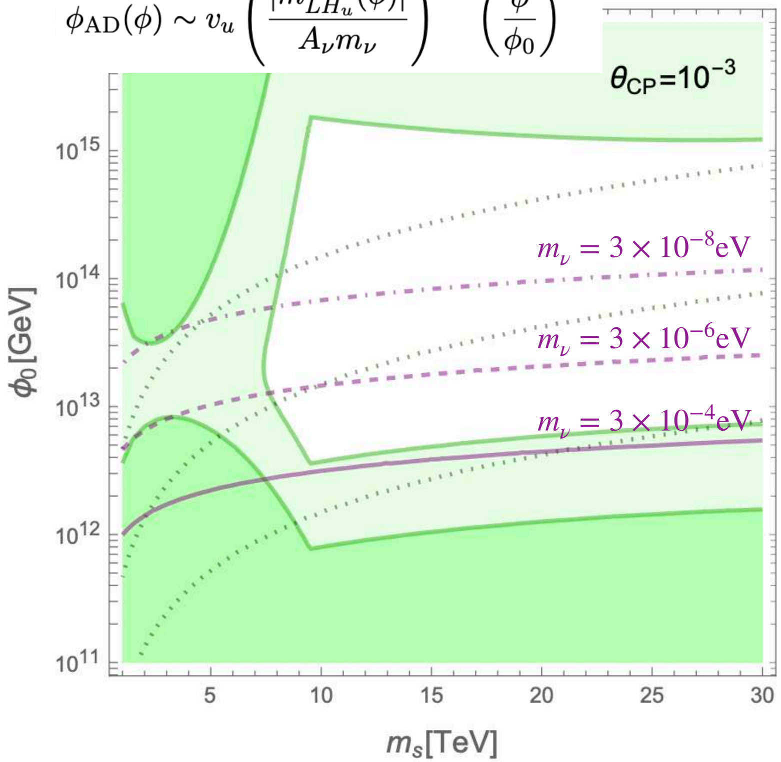
Baryogenesis

- **Late time Affleck-Dine leptogenesis**
  [**WIP**, JHEP 07 (2010) 085; Jeong, Kadota, **WIP** & Stewart, JHEP 11 (2004) 046]



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

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



Dark matter

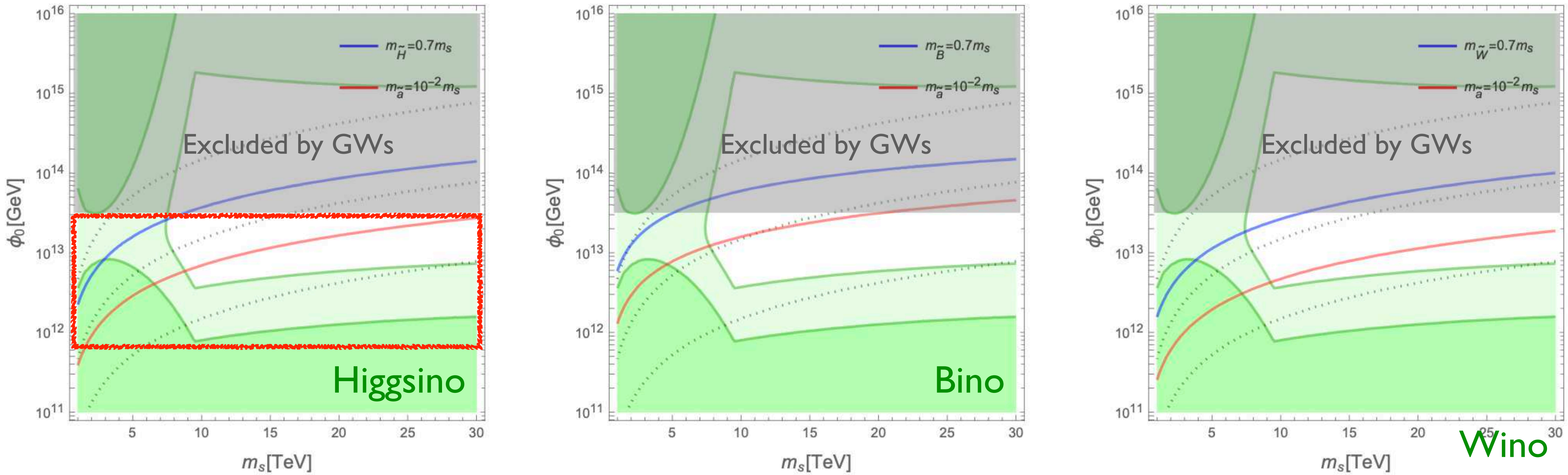
- **Candidates**

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

$$T_{\mathrm{d}} \simeq 7\mathrm{GeV}\left(\frac{m_{\mathrm{LSP}}}{1\mathrm{TeV}}\right)\left(\frac{\langle\sigma v_{\mathrm{rel}}\rangle}{10^{-9}\mathrm{GeV}^{-2}}\right)^{1/3}\left(\frac{20}{x_{\mathrm{fo}}}\right)^{11/6}$$

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

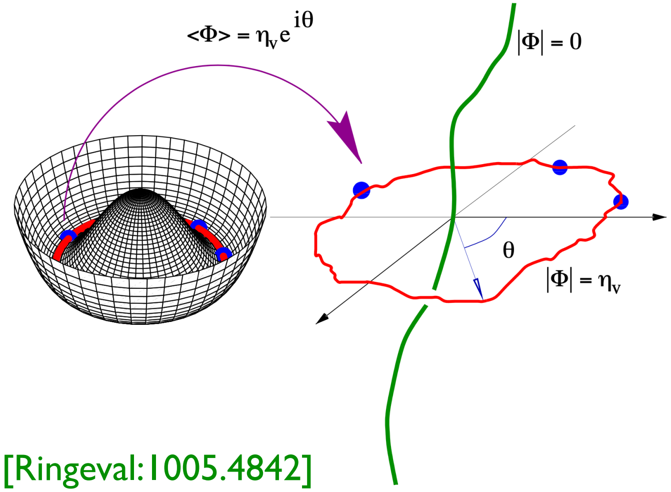
$$\Omega_{\tilde{a}} = \left(m_{\tilde{a}}/m_{\tilde{\chi}}\right)\Omega_{\tilde{\chi}}$$



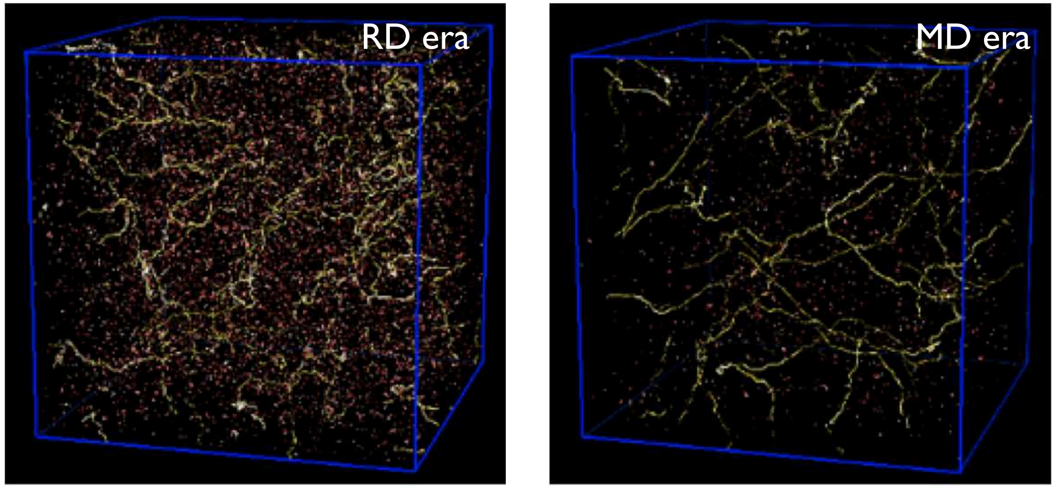
✓ Gray regions are excluded by PPTA bound on GWs (next slides)

SGWBs

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



[Ringeval:1005.4842]



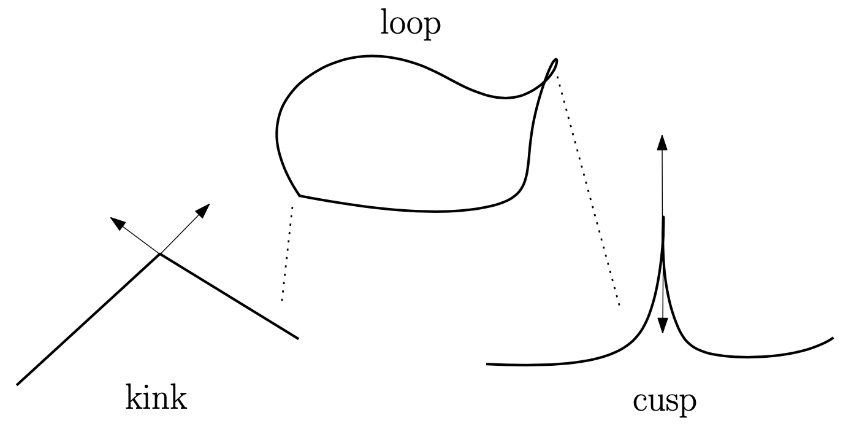
- formed when vacuum manifold is non-trivially connected ($\pi_1(\mathscr{M}) \neq I$)
- characterized by string tension: $\mu \sim \pi\phi_0^2$
- Network falls to the scaling regime: typical length $\xi \sim \alpha t$, $\alpha = \mathcal{O}(0.1)$.

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

- Composition: Network + string loops of various sizes

• GWs from (thick) cosmic string loops

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



[Gottenoire, Servant, Simakachorn: 1912.02569]

String width(w_s) & tension (μ_s):

$$w_s \sim m_{\rm soft}^{-1} \ggg \phi_0^{-1}$$

$$\frac{\mu_s(N_w)}{\pi\phi_0^2} \approx c_1\,(1 + c_2 \ln N_w)\ \left(c_{1,2} = \mathcal{O}(0.1)\right)$$

Radiation power:

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

- $\ell_{\rm s} < \ell_{\rm c} \sim 1/m_\phi \left(\Gamma G\mu\right)^2$: particle production dominates
- $\ell_{\rm s} > \ell_{\rm c}$: GW production dominates

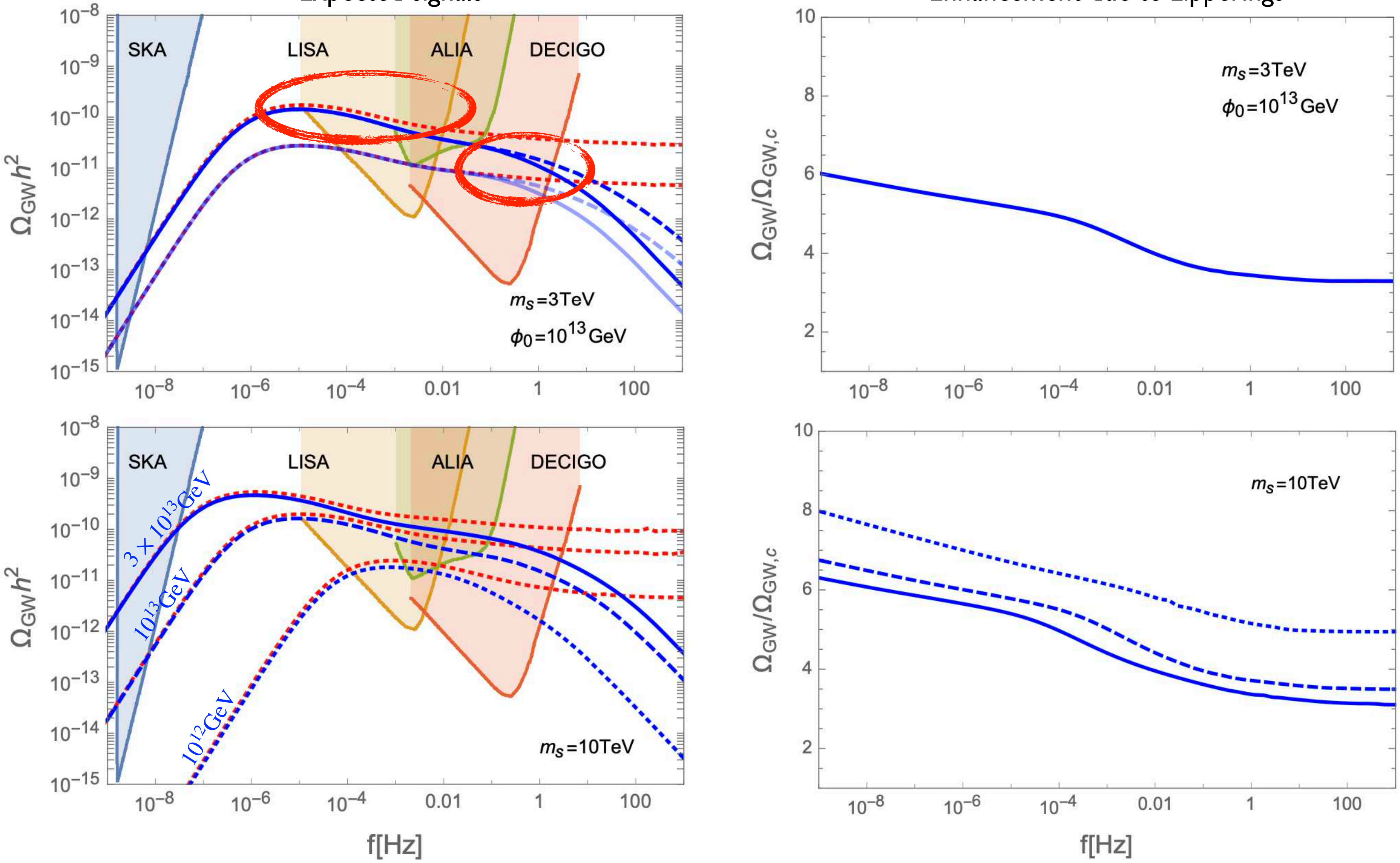
● Forecast (for thick strings with TI)

due to the thickness of the core ($w_s \gg \phi_0^{-1}$)

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

< Expected signals >

< Enhancement due to zipperings >



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.

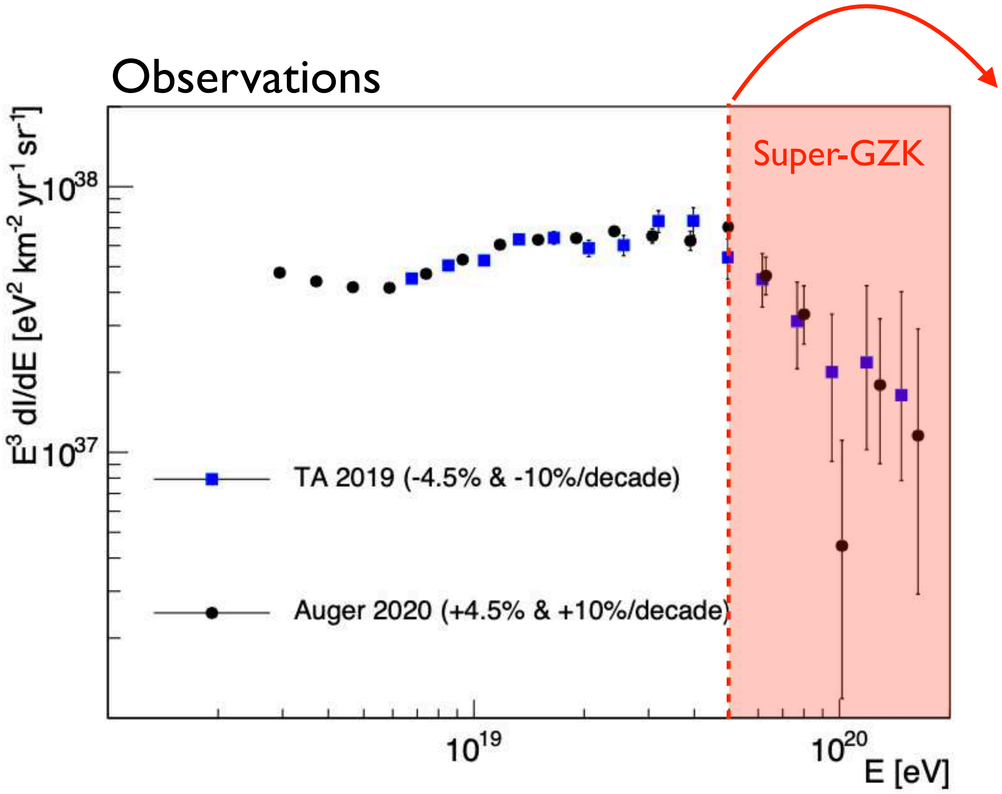
A hint of flat-direction from GWs ⇨ A signal of SUSY

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

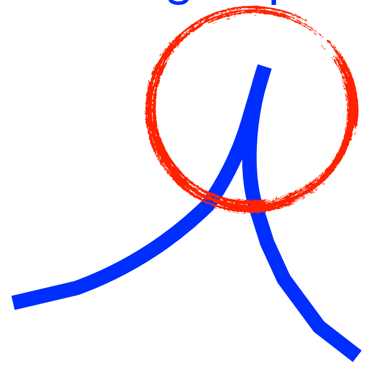
$$k \frac{d\Phi}{dAdk}\Big|^{\rm obs} \sim \frac{10^{-3}}{\rm km^2 \cdot yr \cdot sr}$$

Yet no astrophysical explanations!

- **Sources**

- Source 1: A linear coupling of a scalar field φ with mass m to strings

Very-high-energy particles can be emitted toward the earth at cusps of cosmic string loops.
A linear coupling of a light scalar field can enhance the radiation power.
[T. Damour & A.Vilenkin, PRL 78 (1997) 2288; T.Vachaspati, PRD81, 043531 (2010);]



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

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

$$\Rightarrow \text{Emission power}(P_{\rm lin}) \sim \frac{|c_s|^2}{\sqrt{m w_s}}\sqrt{\frac{w_s}{\ell}}$$ (cf. $P^{\rm thin}_{\rm cusp} \sim \mu\sqrt{\frac{w_s}{\ell}}$)

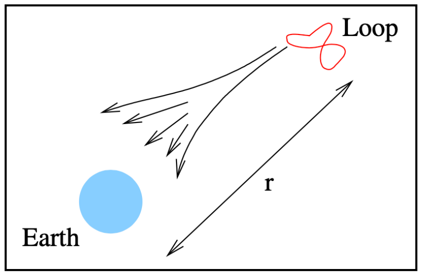
$$\frac{P_{\rm lin}}{P^{\rm thin}_{\rm cusp}} \sim \frac{|c_s|^2}{\mu}\sqrt{\frac{\phi_0}{m}} \xrightarrow{|c_s|^2\sim\mu} 10^5\sqrt{\frac{\phi_0/10^{13}}{m/10^3}}$$

< Realization: Condensation of LH_u flat-direction in string cores >

The linear coupling of LH_u flat-direction to a string is given by

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

The expected direct flux is



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

- Source 2: Thin vs thick strings (even without a linear coupling)

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

- **Extra feature of our scenario: Extremely boosted LSPs**

< 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.

Conclusions

- *Thermal inflation(TI)* is still the most compelling sol. to the moduli problem, and it may have to be realized in *a* SUSY $U(1)_{B-L}$ model.
- *Higgs VEV is constrained as* $10^{12} \lesssim \phi_0/\mathrm{GeV} \lesssim 10^{13}$.
- *For* $\varphi_0 \approx M_\mathrm{P}$*, the soft mass is constrained as* $m_\mathrm{soft} \gtrsim 8\mathrm{TeV}$.
- BAU can be obtained via a late-time Affleck-Dine leptogenesis.
- DM can be mainly either neutralino LSP or KSVZ axino.
- SGWBs are expected within the reach of at least LISA and DECIGO.
- TI can be probed by LISA &DECIGO type exps. $\Rightarrow$ **Perhaps, a signal of SUSY**
- UHECRs matching observations can be produced.
- EHE neutrinos & boosted LSPs are also expected and correlated with UHECRs.

Thank you!