Probing SUSY at Gravitational Wave Observatories

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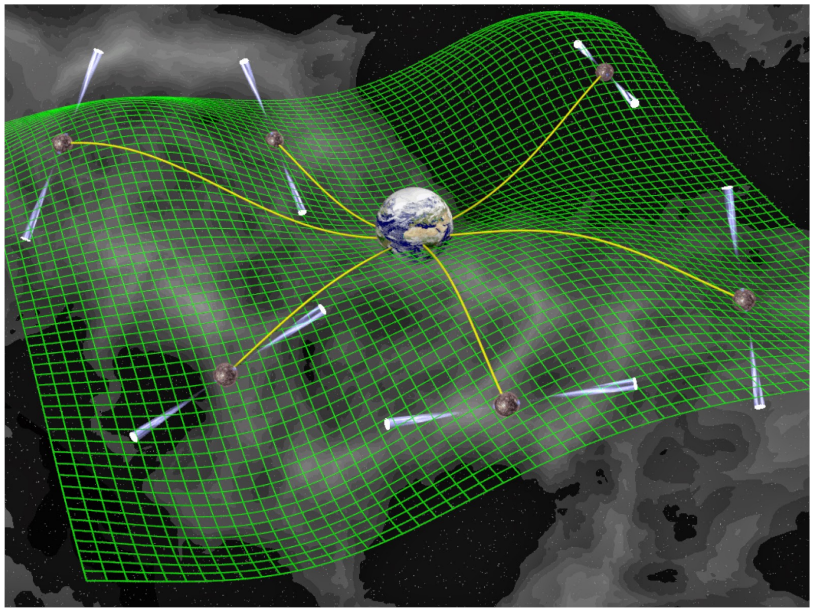
SUSY 2024
Madrid
10-14 June 2024

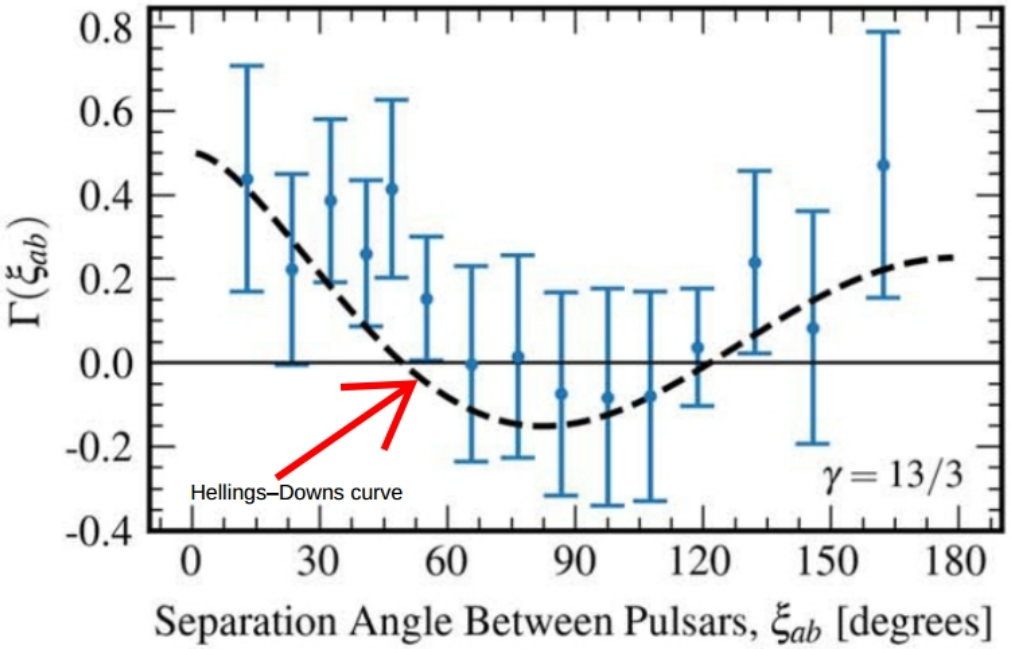
Phys.Rev.D 108 (2023) 9, 095053, arXiv: 2405.03746, arXiv:2406.xxxxx
(S. Antusch, K. Hinze, S. **Saad**, J. Steiner)

Outline

- Pulsar Timing Array data
- Metastable cosmic strings and GW signals
- Probing SUSY at GW detectors
- Origin of strings: Promising SO(10) GUT

Pulsar Timing Arrays: 2023

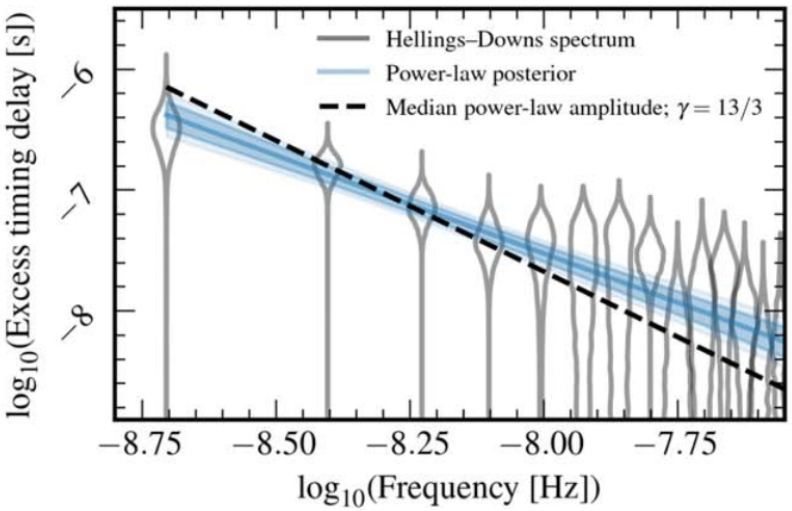


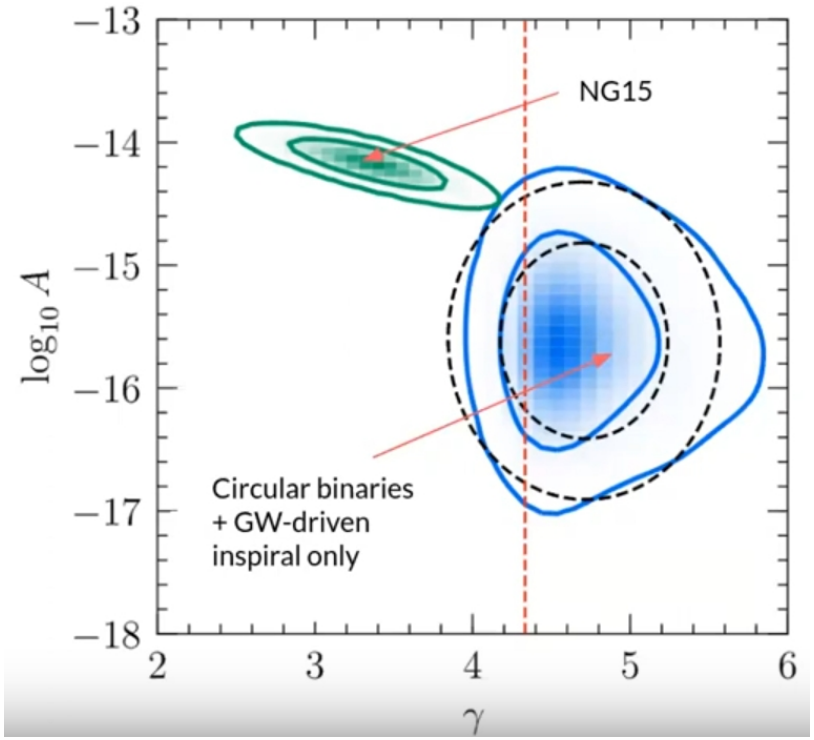


Gabriella Agazie et al 2023 ApJL 951 L8

- First evidence of Stochastic Gravitational Wave Background at nHz frequencies
- NANOGrav, EPTA, InPTA, CPTA, PPTA

PTA Data: 2023



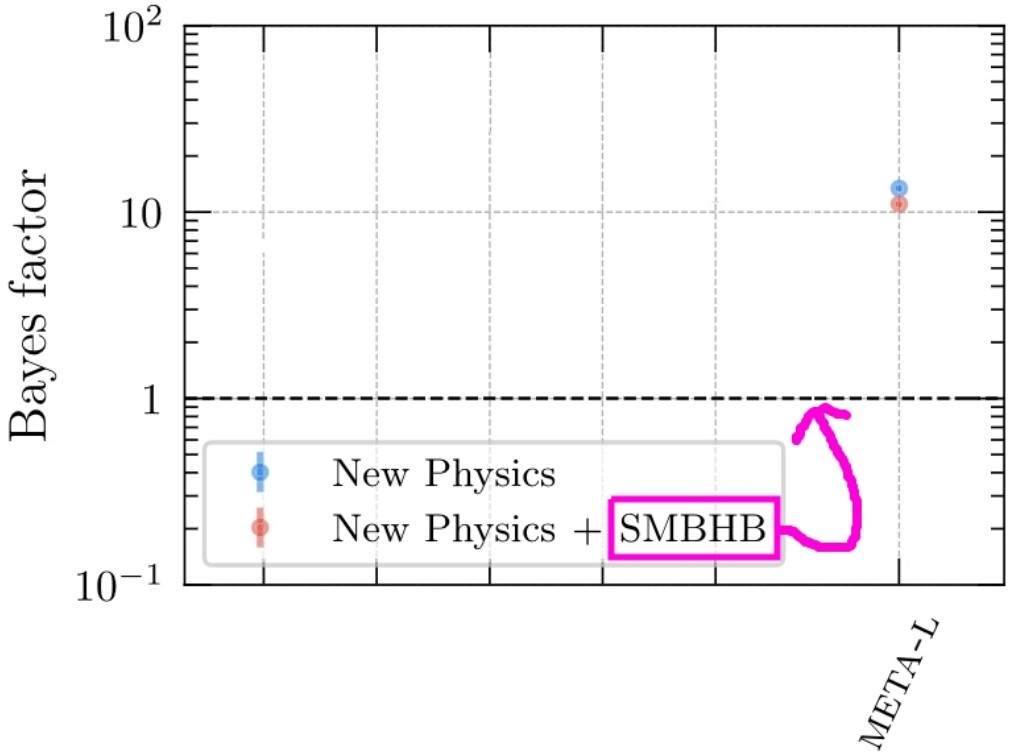


Gabriella Agazie et al 2023 ApJL 951 L8

Adeela Afzal et al 2023 ApJL 951 L11

→ Supermassive Black Hole Binaries (SMBHB): tension with data?

Signals from New Physics?

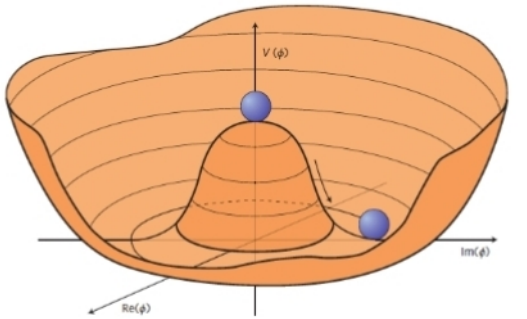


Adeela Afzal et al 2023 ApJL 951 L11

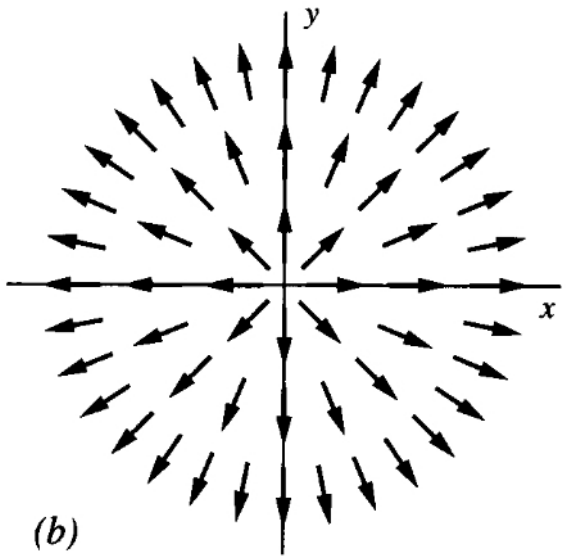
- Metastable Cosmic Strings?
- naturally arise from Grand Unified Theories $\rightarrow$SO(10)

Cosmic Strings

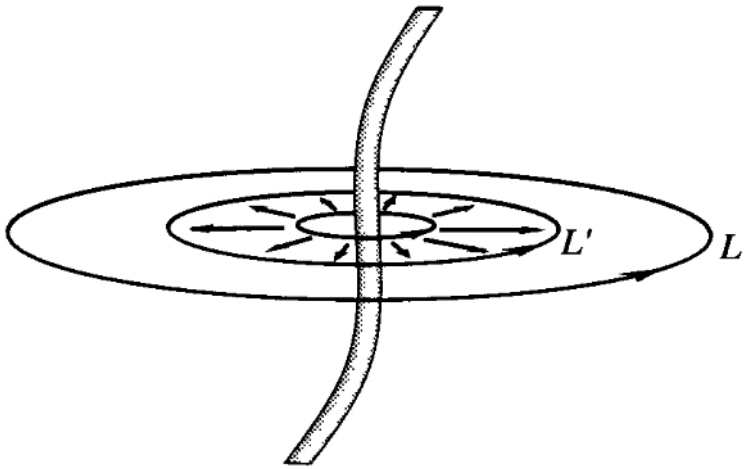
$U(1) \rightarrow$ nothing



(a)



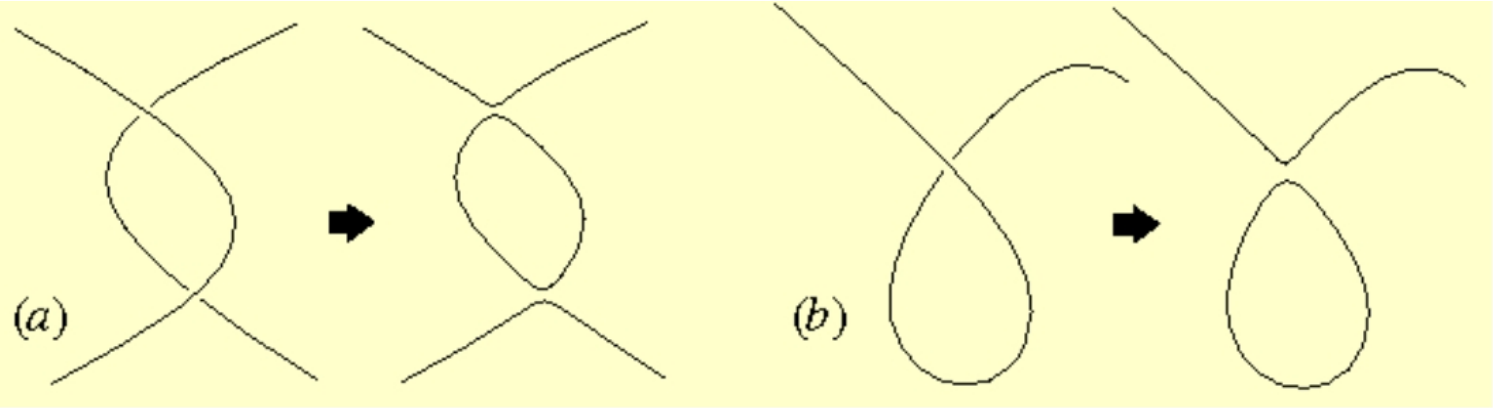
(b)

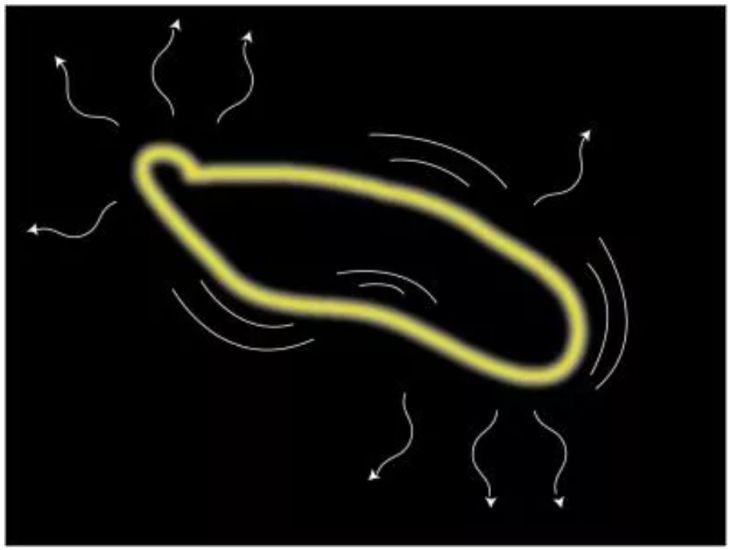


$\mu \sim 2\pi v_s^2$

Loop enclosing non-zero flux in 2-D space.

Cosmic String dynamics



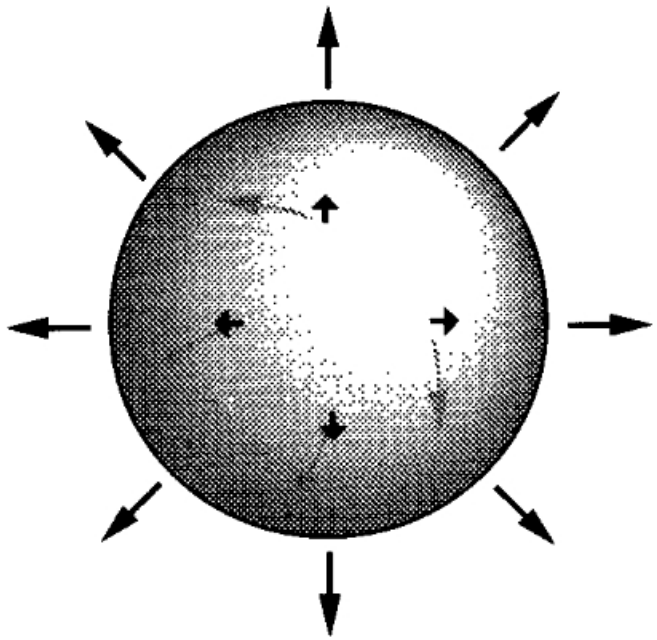


Cosmic-string loops wiggle and oscillate, producing gravitational waves, then slowly shrink as they lose energy until they disappear. (Image credit: Matt DePies/UW)

Monopoles

$SU(2) \xrightarrow{v_m} U(1)$

$$m = \frac{4\pi v_m}{g}$$

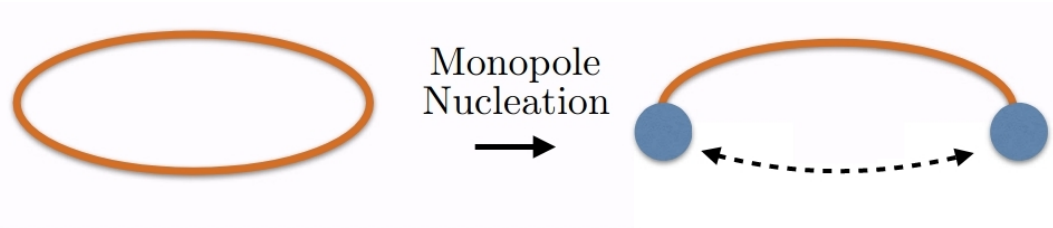


Sphere enclosing non-zero flux in 3-D space.

Metastable strings

P. Langacker and S. Y. Pi, 1980

- Example: $SU(2) \xrightarrow{v_m} U(1) \xrightarrow{v_s}$ broken



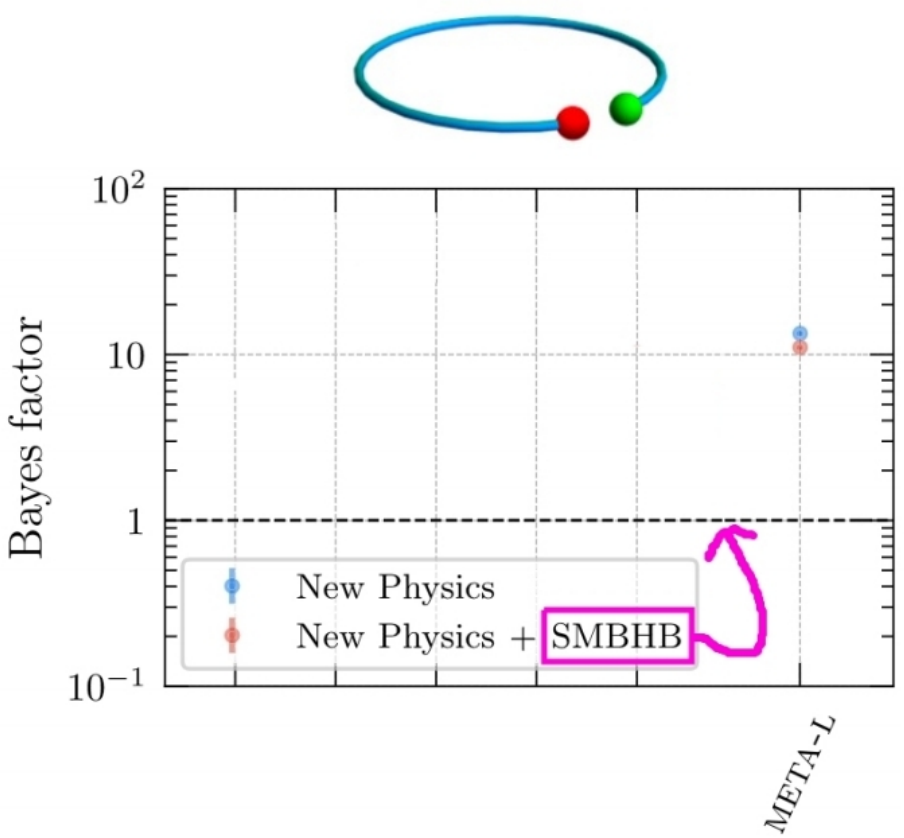
- lifetime determined by:

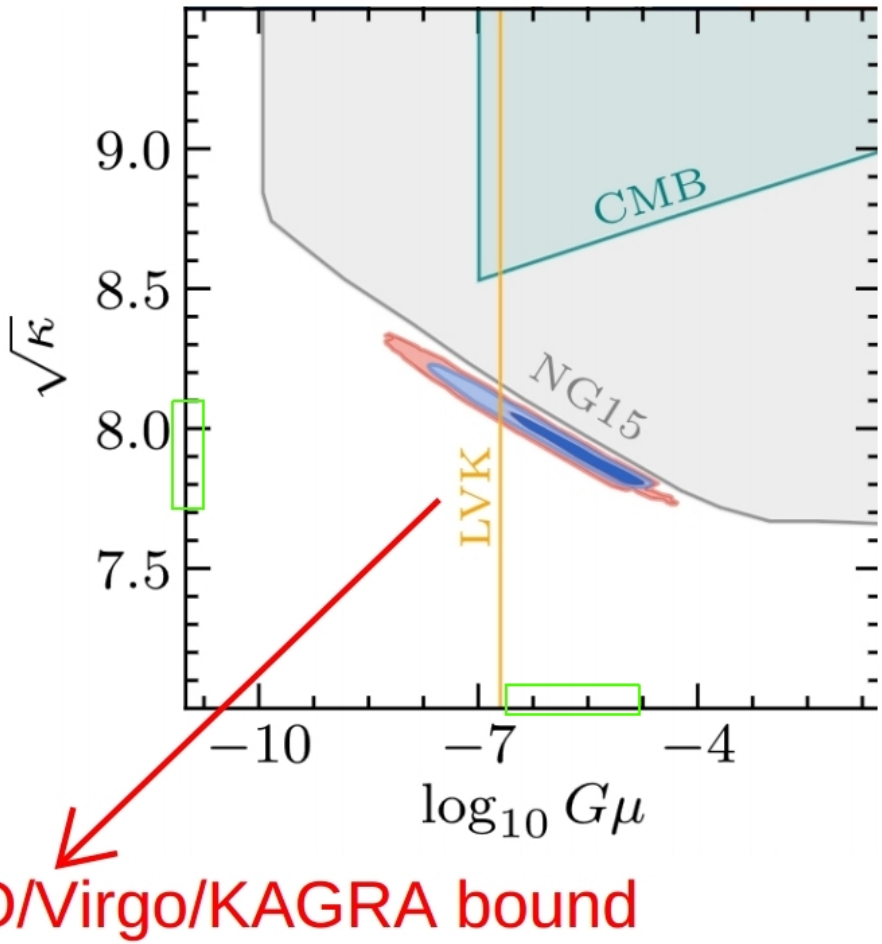
$$t_s = \Gamma_d^{-1/2}, \qquad \Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa}$$

$$\kappa = \frac{m^2}{\mu} \sim \frac{8\pi}{g^2} \left(\frac{v_m}{v_s} \right)^2$$

$(\kappa^{1/2} < 9$ metastable $) \quad \rightarrow v_{\text{monopole}} \sim v_{\text{string}}$

PTA data: Metastable strings





LIGO/Virgo/KAGRA bound

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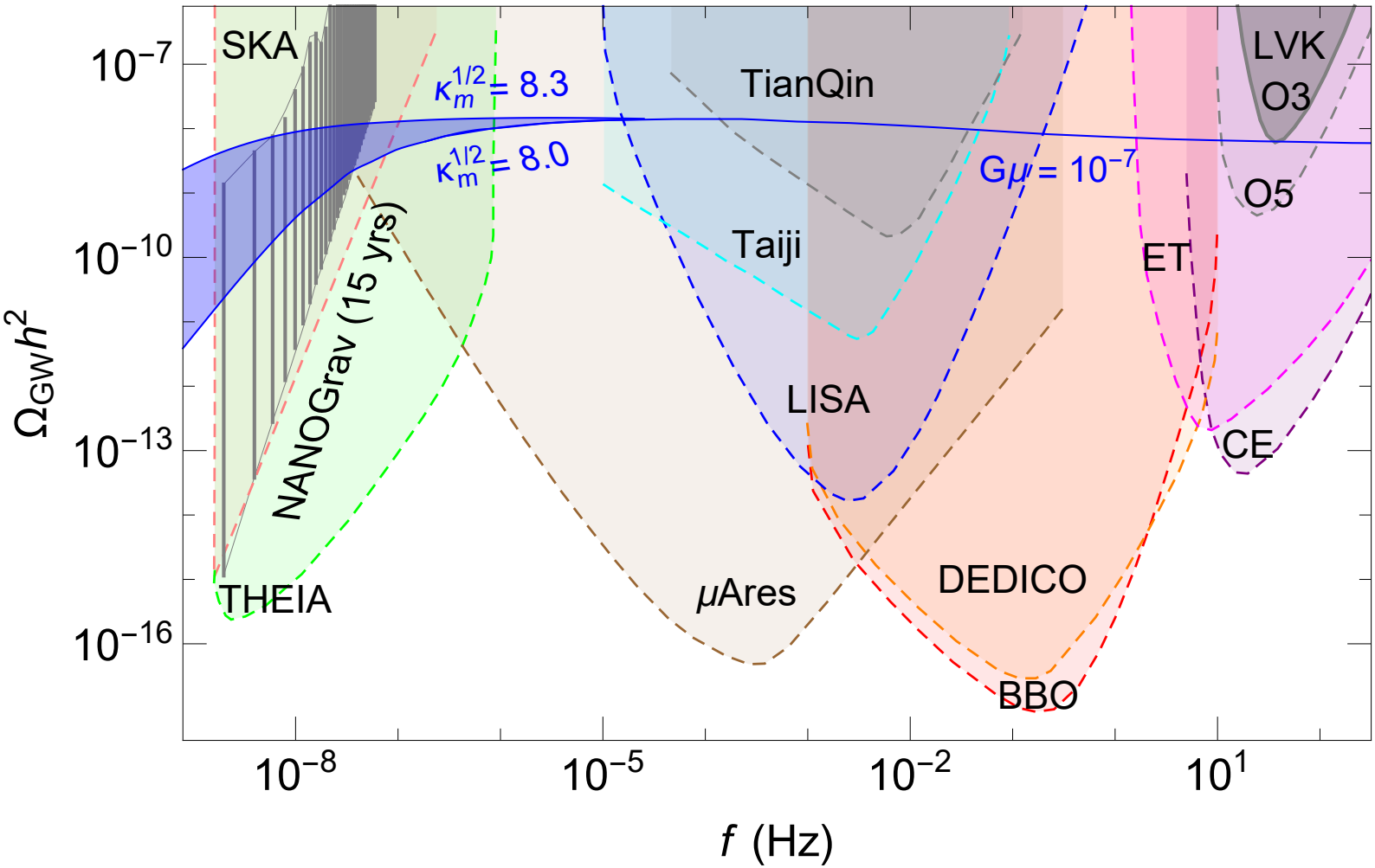
Gravitational Wave signal: Metastable



$v_s \sim 10^{15}$ GeV

Soon to be discovered at LIGO?!!!

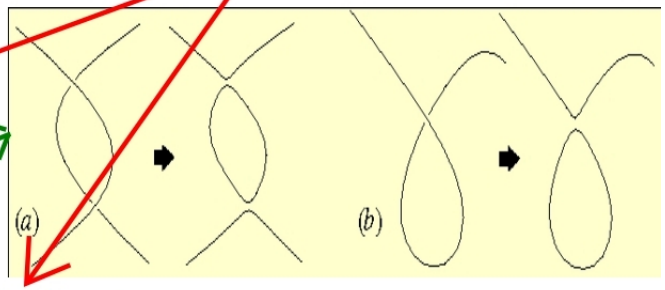
Antusch, Hinze, **Saad**, Steiner 2023

GW spectrum

loop number density

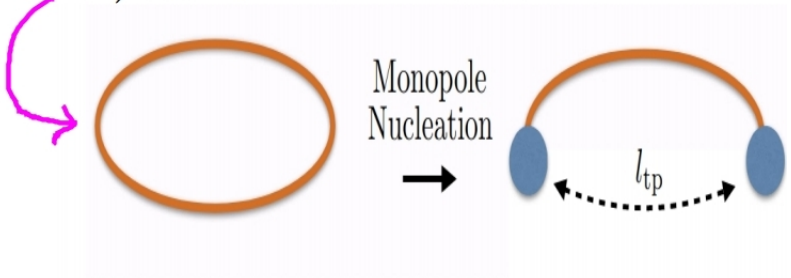
$$\Omega_{\rm GW}(f,t) = \frac{8\pi(G\mu)^2}{3H^2(t)} \sum_{n=1}^{\infty} C_n P_n, \quad C_n = \frac{2n}{f^2} \int_{z(t)}^{z_c} \frac{dz}{H(z)(1+z)^6} n\left(\frac{2n}{f(1+z)}, t(z)\right)$$

spectrum



$$\left[-\Gamma\, G\mu\, \partial_\ell + \partial_t\right] n(\ell,t) = S(\ell,t) - \left(3H(t) + \Gamma_d \ell\right) n(\ell,t)$$

expansion history of the universe



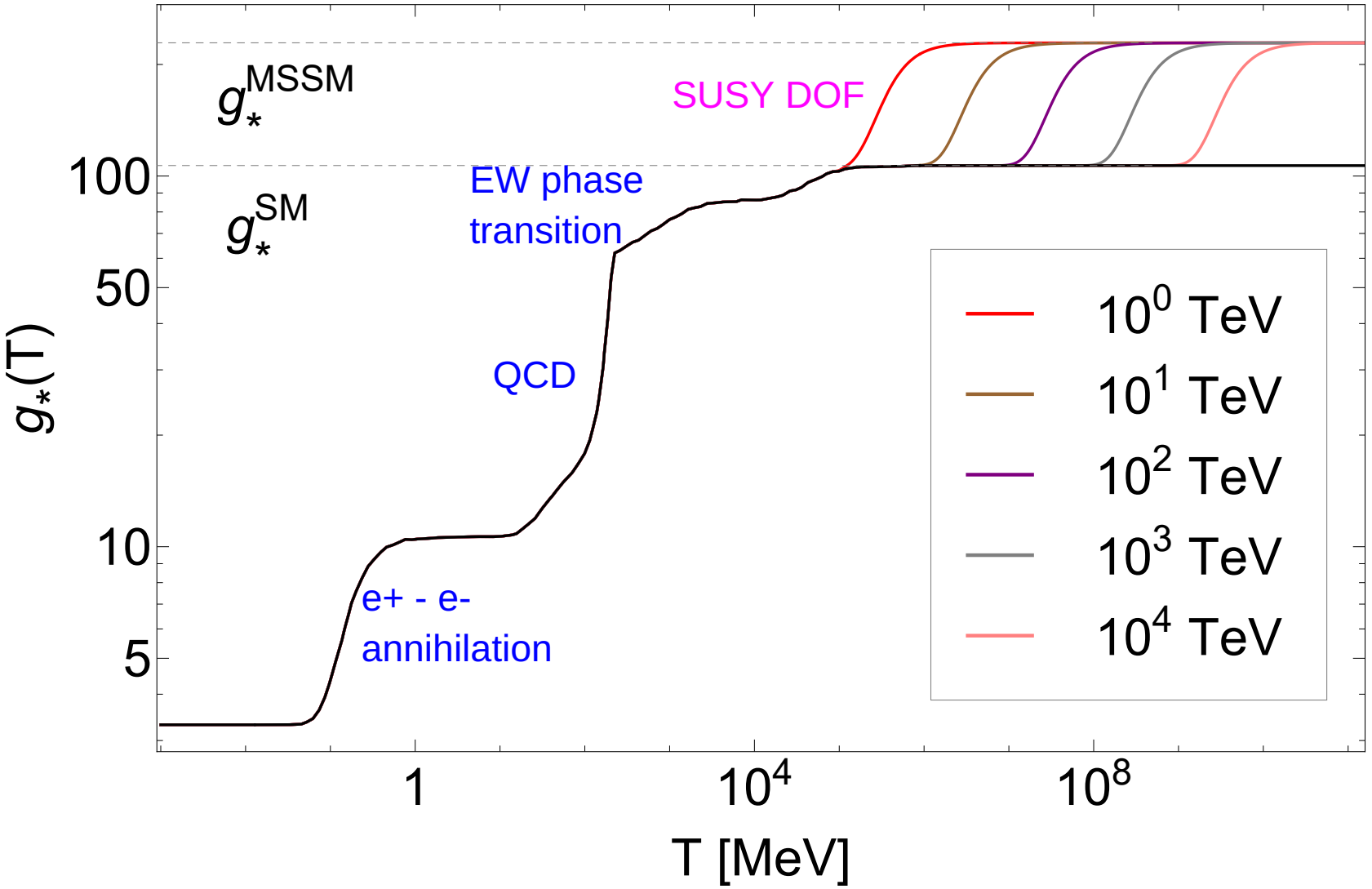
$$H(z) = H_0 \left(\Omega_\Lambda + (1+z)^3 \Omega_{\rm mat} + (1+z)^4 \mathcal{G}(z) \Omega_{\rm rad}\right)^{1/2}$$

$$\mathcal{G}(z) = \frac{g_*(z) g_{\rm S}^{4/3}(z_0)}{g_*(z_0) g_{\rm S}^{4/3}(z)}$$

varies as the universe cools when species become non-relativistic

Blanco-Pillado, Olum, and Shlaer 2013, 2017; Buchmuller, Domcke, Schmitz 2021; Antusch, Hinze, **Saad**, Steiner 2024

SUSY Degrees of Freedom



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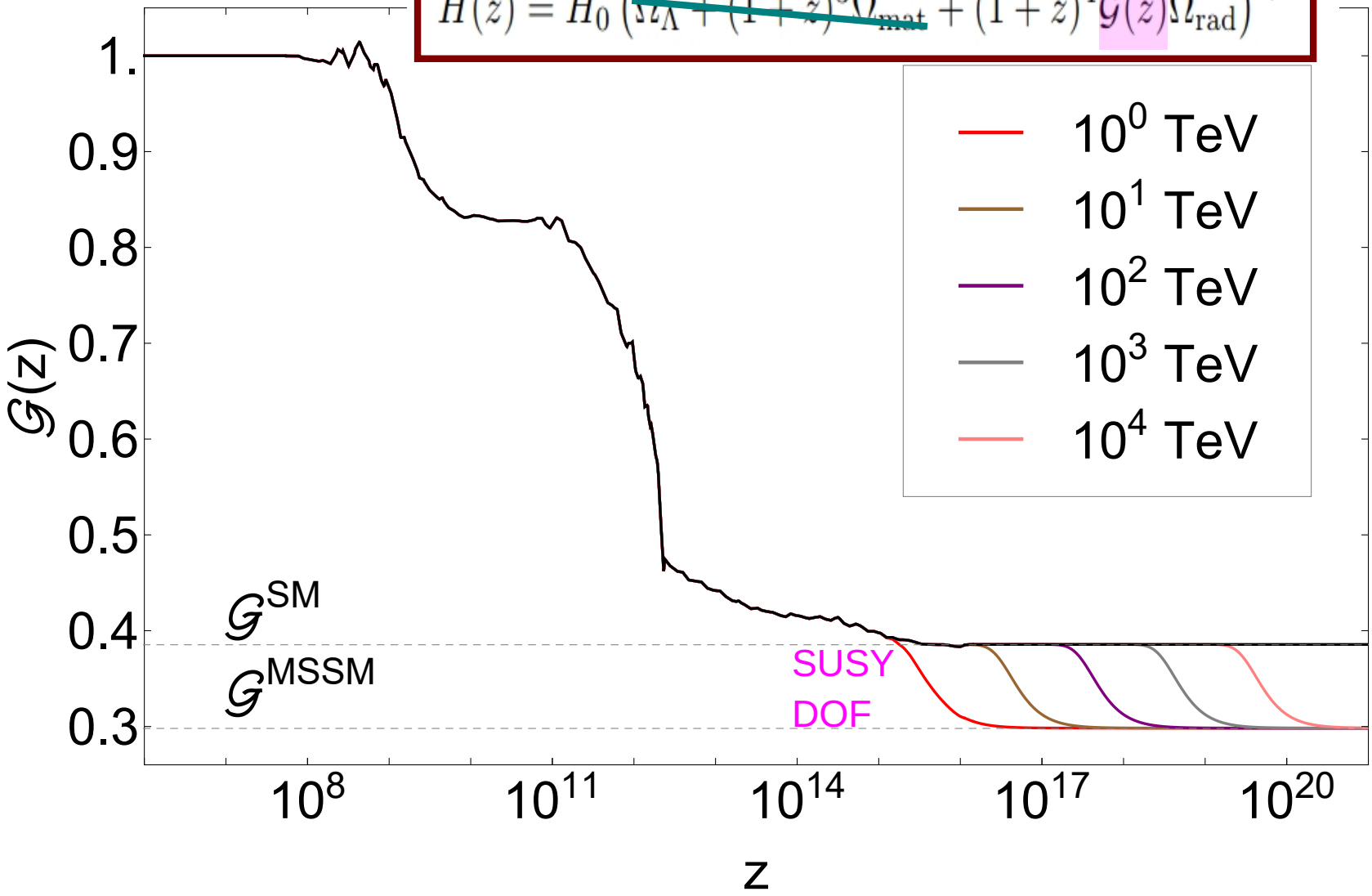
SUSY DOF

$$H(z) = H_0 \left(\Omega_\Lambda + (1+z)^3 \Omega_{\rm mat} + (1+z)^4 \mathcal{G}(z) \Omega_{\rm rad} \right)^{1/2}$$



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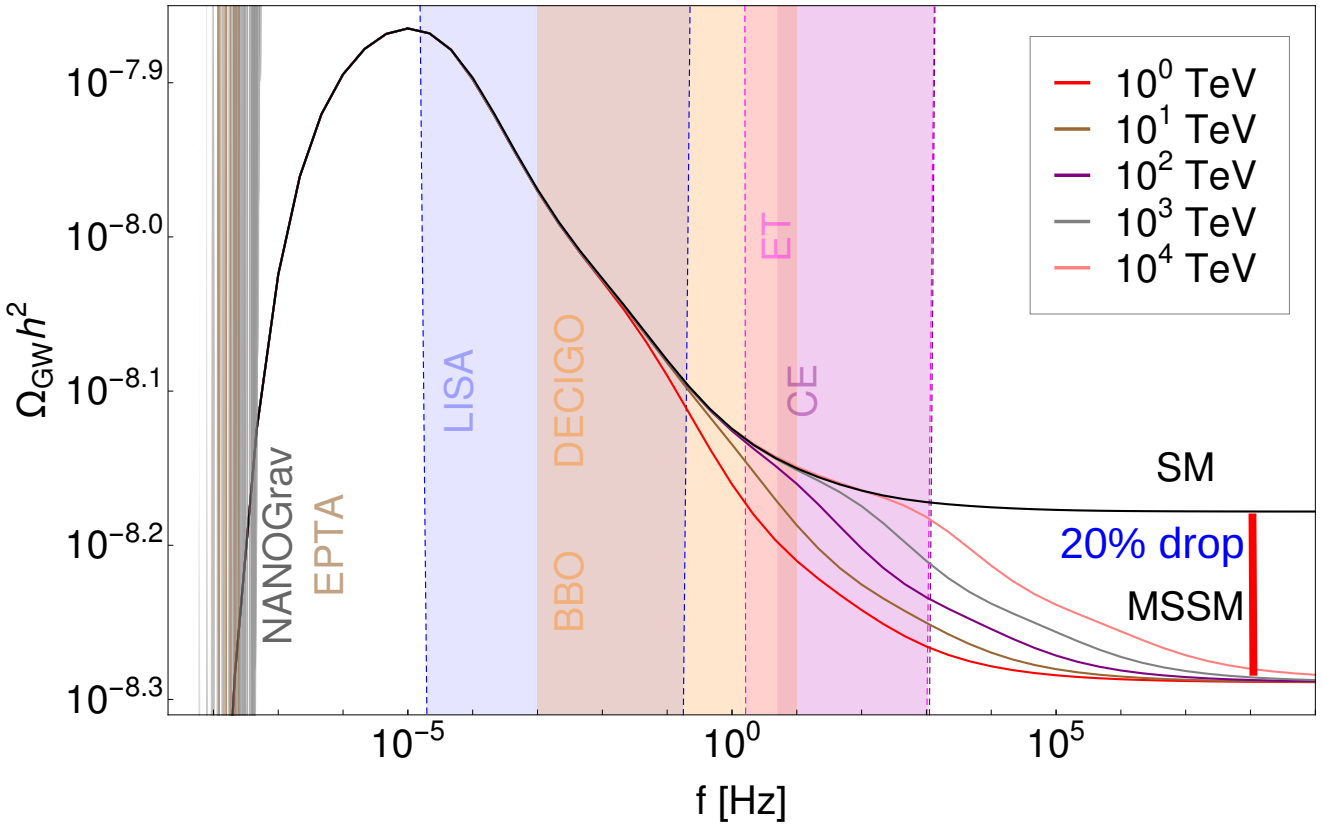
Probing SUSY



$$\Omega_{\rm GW}^{\rm NP} \sim \Omega_{\rm GW}^{\rm SM} \left(\frac{g_*^{\rm SM}}{g_*^{\rm SM} + \Delta g_*^{\rm NP}} \right)^{1/3} \quad \longleftarrow \quad \Delta g_*^{\rm SUSY} = 122 \quad \longrightarrow \quad \Omega_{\rm GW}^{\rm SUSY} / \Omega_{\rm GW}^{\rm SM} \approx 0.8$$

$$f_{\rm S} \sim (2.1 \times 10^{-9}\ {\rm Hz}) \left(\frac{m_{\rm S}}{\rm GeV} \right) (\alpha\, \Gamma\, G\mu)^{-1/2} \times \left(g_*^{\rm SM}(T_{\rm S}) + \Delta g_* \right)^{5/2} \left(g_*^{\rm SM}(T_{\rm S}) \right)^{-8/6} \left(g_{\rm S}^{\rm SM}(T_{\rm S}) \right)^{-7/6}$$

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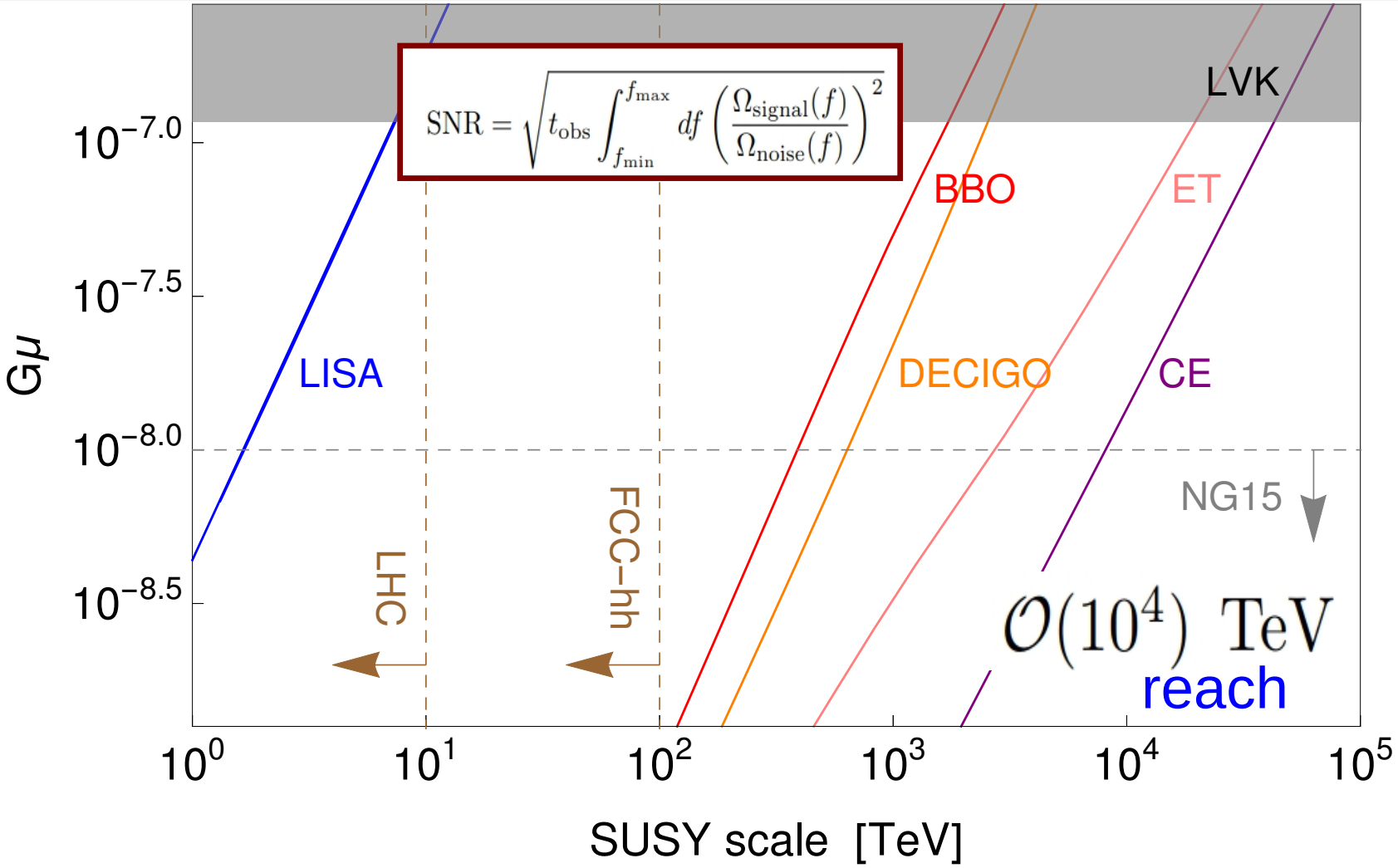
Probing SUSY



Fisher analysis: uncertainties of 10% for the number of DOF and 5% for the m_{SUSY} (ET and CE)

Antusch, Hinze, **Saad**, Steiner 2024

Origin of Metastable Cosmic Strings?

Promising SO(10) GUT models: $\rightarrow$ **SUSY** GUT

- Gauge coupling unification
- Cosmic inflation
- Doublet-Triplet splitting
- Fermion mass
- Proton decay under control
- ...

DTS problem

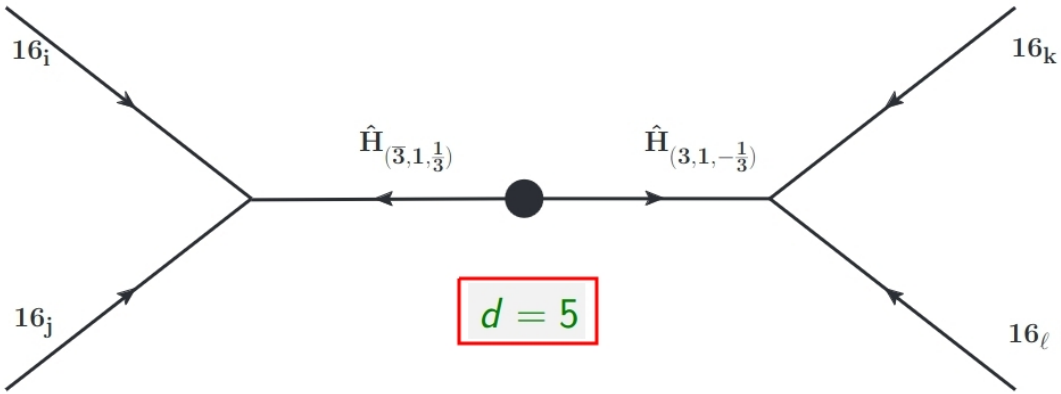
- Doublets & Triplets

$$10_H = (2_H + 3_H) + (\overline{2}_H + \overline{3}_H)$$
$$= (1, 2, 1/2) + (3, 1, -1/3) + c.c.$$

- $\langle 45_H \rangle \propto i\tau_2 \otimes \mathrm{diag}(a_1, a_2, a_3, a_4, a_5)$

- GUT scale mass:

$$10_{1H}\langle 45_H \rangle 10_{2H} = \overline{2}_{1H}2_{2H} + \overline{2}_{2H}2_{1H} + \overline{3}_{1H}3_{2H} + \overline{3}_{2H}3_{1H}$$



Features of our models

- Lower-dimensional reps.: 10 , 16 , 45
- Superpotential: Antusch, Hinze, **Saad**, Steiner 2023

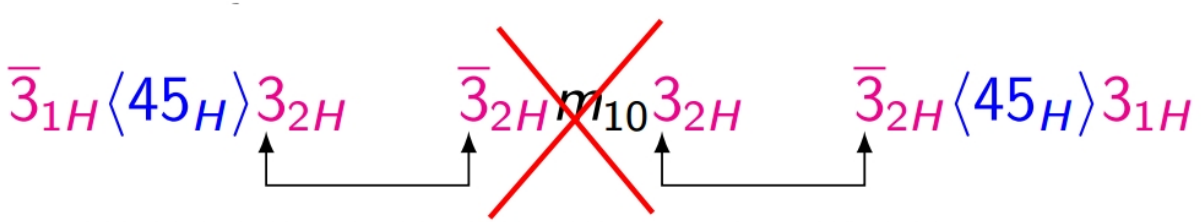
$$W = W_{\mathrm{GUT-breaking}} + \underbrace{W_{\mathrm{Inflation}} + W_{\mathrm{Mixed}}}_{W_{\mathrm{Intermedite-breaking}}} + W_{\mathrm{DTS}} + W_{\mathrm{Yukawa}}$$

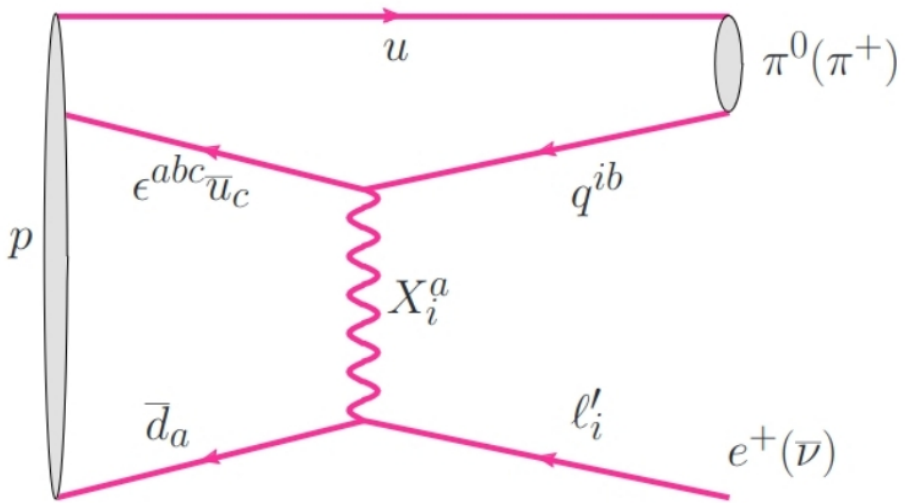
DTS without fine-tuning: S. Dimopoulos, F. Wilczek 1981, M. Srednicki 1982

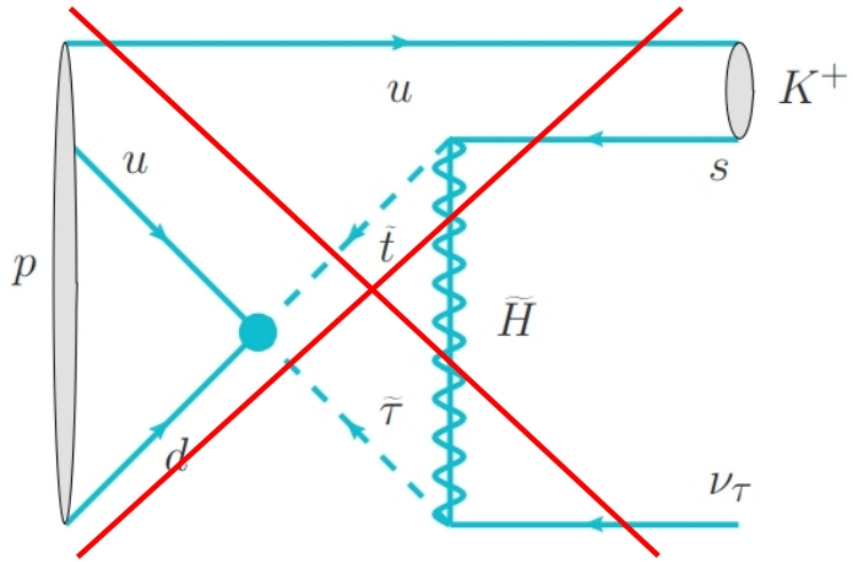
- $\langle 45_H \rangle \propto B - L \propto i\tau_2 \otimes \mathrm{diag}(a, a, a, 0, 0)$
- $\langle 45'_H \rangle \propto I_{3R} \propto i\tau_2 \otimes \mathrm{diag}(0, 0, 0, b, b)$

K.S. Babu, S. M. Barr, Z. Berezhiani, R. N. Mohapatra, J. C. Pati, S. Raby, ...

DTS & Proton Decay







Antusch, Hinze, **Saad**, Steiner 2023

Promising SO(10) GUT

- $\langle 45_H \rangle \propto i\tau_2 \otimes \mathrm{diag}(a, a, a, 0, 0)$, $\langle 45'_H \rangle \propto i\tau_2 \otimes \mathrm{diag}(0, 0, 0, b, b)$

- Symmetry breaking:

$$SO(10) \xrightarrow[45_H]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

monopole

$$\xrightarrow[45'_H]{M_I} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$$

string

$$\text{Inflation} \xrightarrow[16_H+\overline{16}_H]{M_{II}} SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Metastable cosmic string network

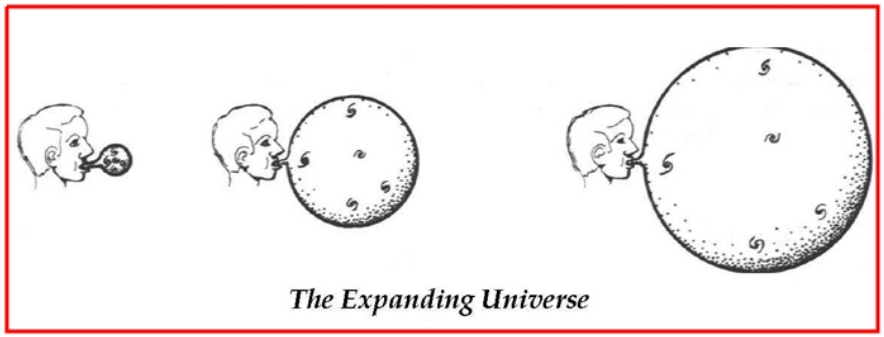
Antusch, Hinze, **Saad**, Steiner 2023

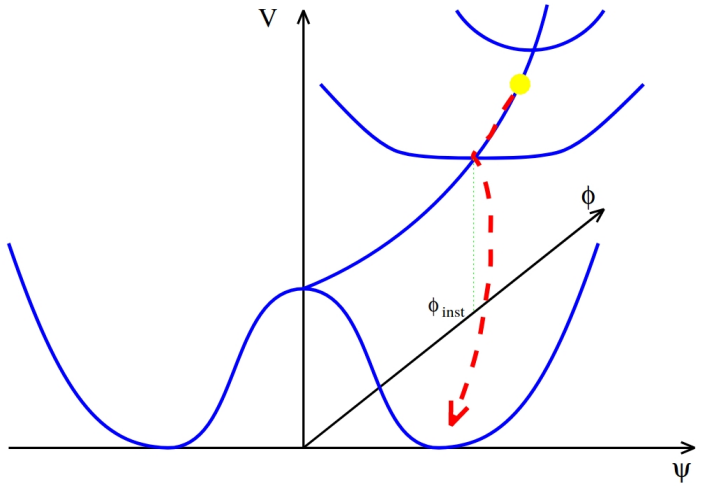
Inflation

- Hybrid inflation

A. Linde 1991, G. R. Dvali et. al. 1994

$$V_F^{\rm SUSY} \subset \varkappa^2 \left(\phi^2 - m_{16}^2\right) \psi^2$$





$$W_{\rm Inflation} \supset \varkappa \underbrace{S}_{\textit{inflaton}} \left(\overline{16}_H 16_H - m_{16}^2\right)$$

(flat direction along $\psi = 0$)

Antusch, Hinze, **Saad**, Steiner 2023

- Vacuum energy $V \sim \varkappa^2 m_{16}^4$
- Waterfall$\rightarrow$ cosmic string

A Common Scale

- Cosmic string : $v_s = m_{16}$
- Inflation : $V_{\rm inflation} \sim \varkappa^2 m_{16}^4$
- Neutrino mass :

$$m_\nu \sim \frac{10 M_{\rm GUT} v_{\rm ew}^2}{m_{16}^2}$$

$m_{16} \sim 10^{15-16}$ GeV

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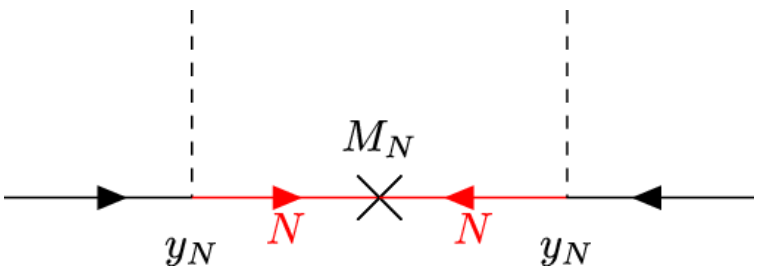
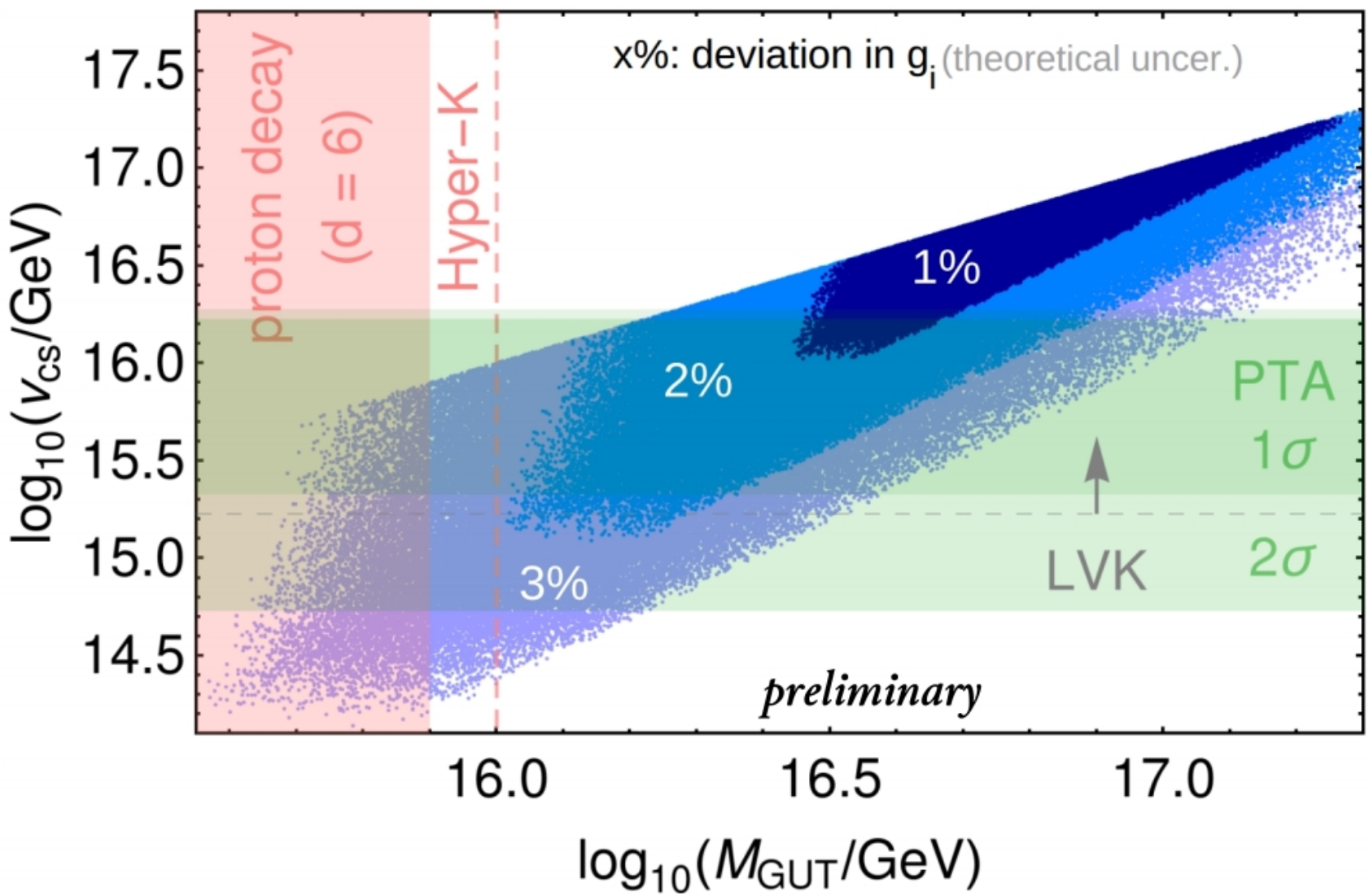
Type-I seesaw



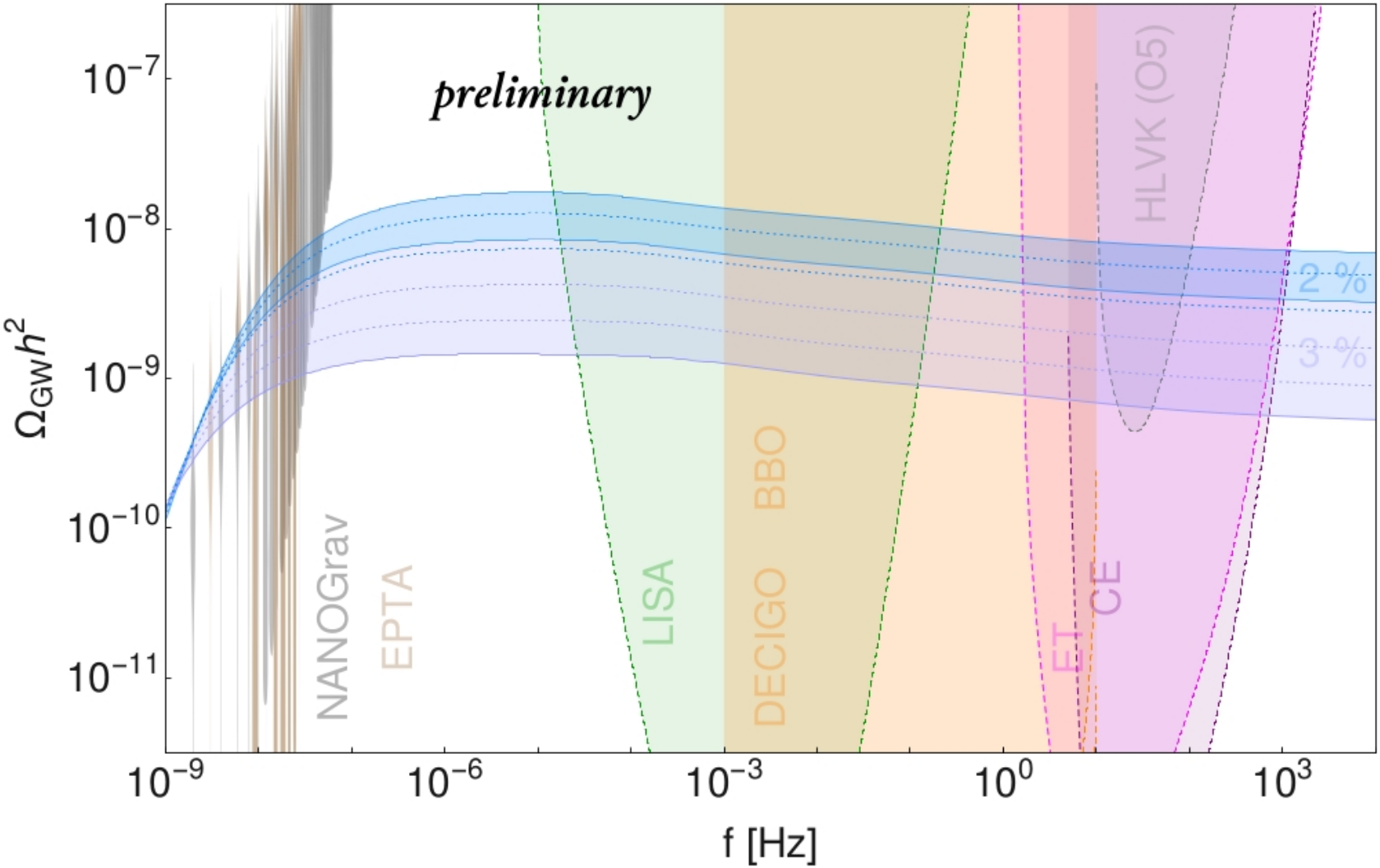
Proton decay?
Gauge coupling unification?

Unification, Proton Decay, and PTA data



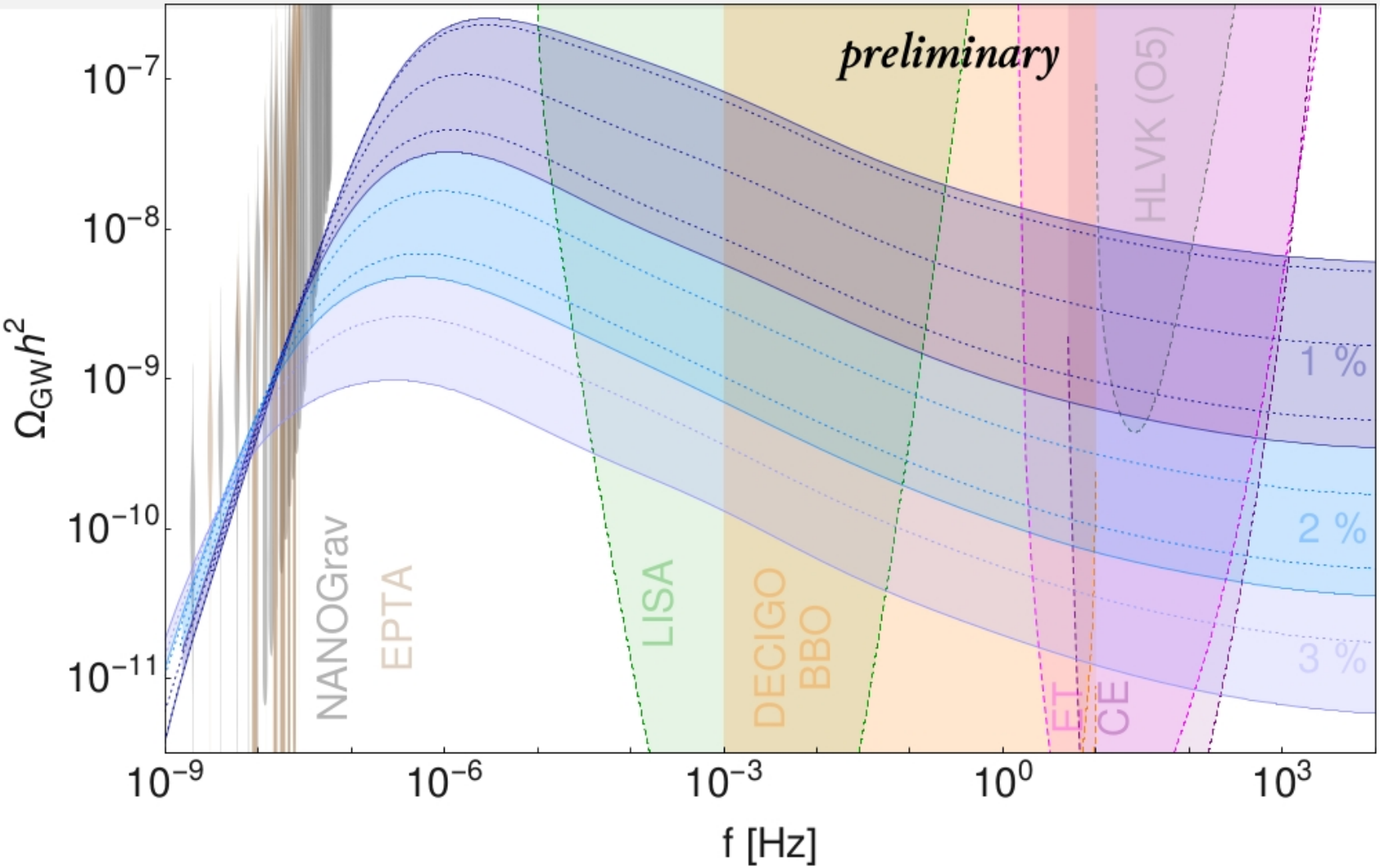
Antusch, Hinze, **Saad** 2024 (arXiv: 2406.xxxxx)

GW Spectrum and PTAs



Satisfies LVK bound Antusch, Hinze, **Saad** 2024 (arXiv: 2406.xxxxx)

Dilution



Early Matter Domination from SUSY Moduli fields

Antusch, Hinze, **Saad** 2024 (arXiv: 2406.xxxxx)

Summary

- PTAs : exciting new data $\rightarrow$ New Physics?
- New Physics $\rightarrow$ Metastable Cosmic Strings
- Promising models towards SO(10) GUT $\rightarrow$
  Inflation, DTS, Unification, Fermion mass, Gravitational waves
- Probing SUSY DOF at GW detectors
- GW/PTAs: $v_{\rm monopole} \sim v_{\rm string} \sim v_{\rm inflation} \sim v_{\rm seesaw} \sim 10^{15}$ GeV
- Fully testable in a number of gravitational wave observatories

THANK YOU!