Probing SUSY at Gravitational Wave Observatories

based on: S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2307.04595
S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2405.03746
S.A, K. Hinze, S. Saad, arXiv:2406.17014
S.A, K. Hinze, S. Saad, arXiv:2503.05868

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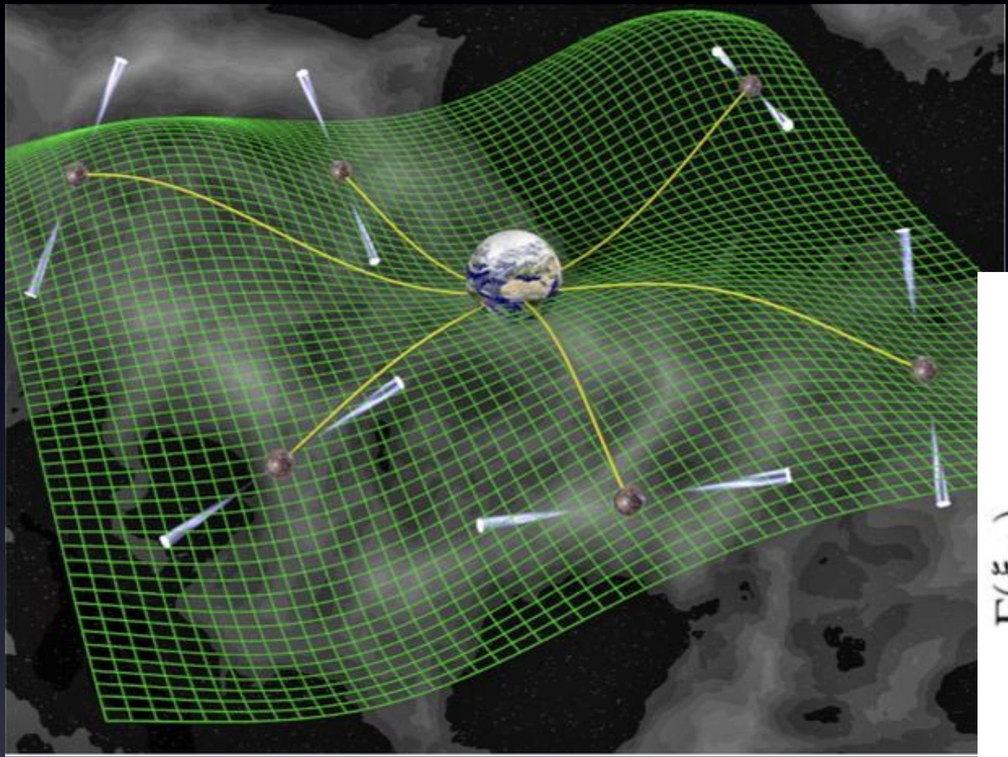
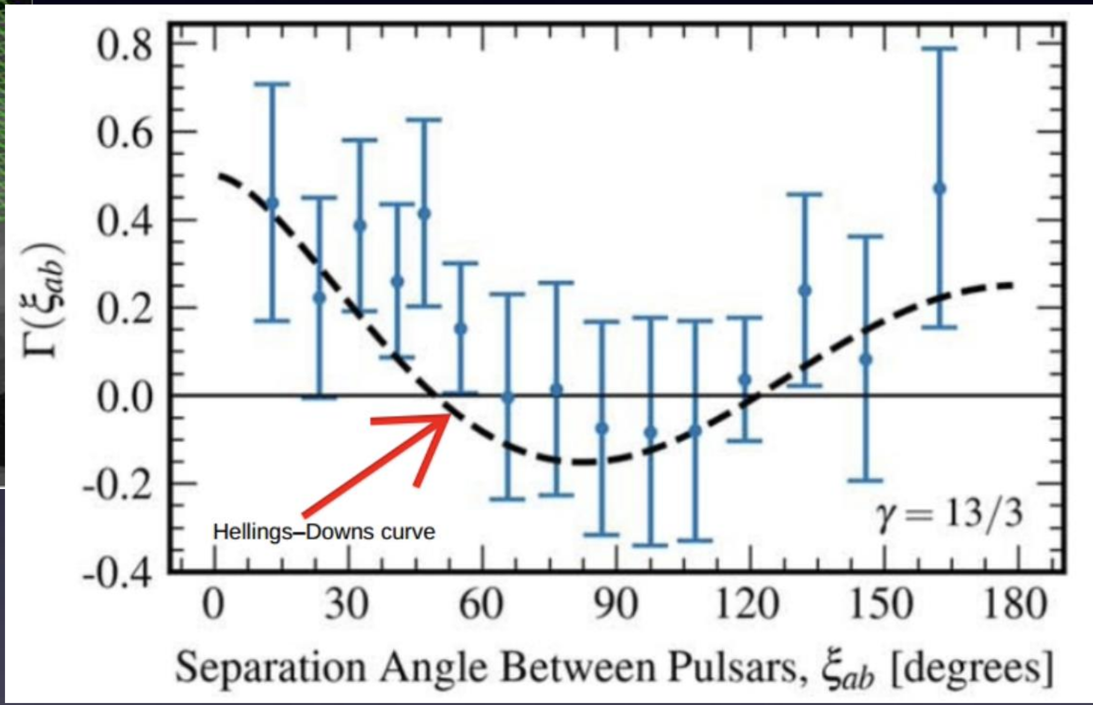
PTA results 2023 point at Stochastic Gravitational Wave Background (SGWB)

at nanohertz frequencies

NanoGrav, EPTA+InPTA, PPTA, CPTA

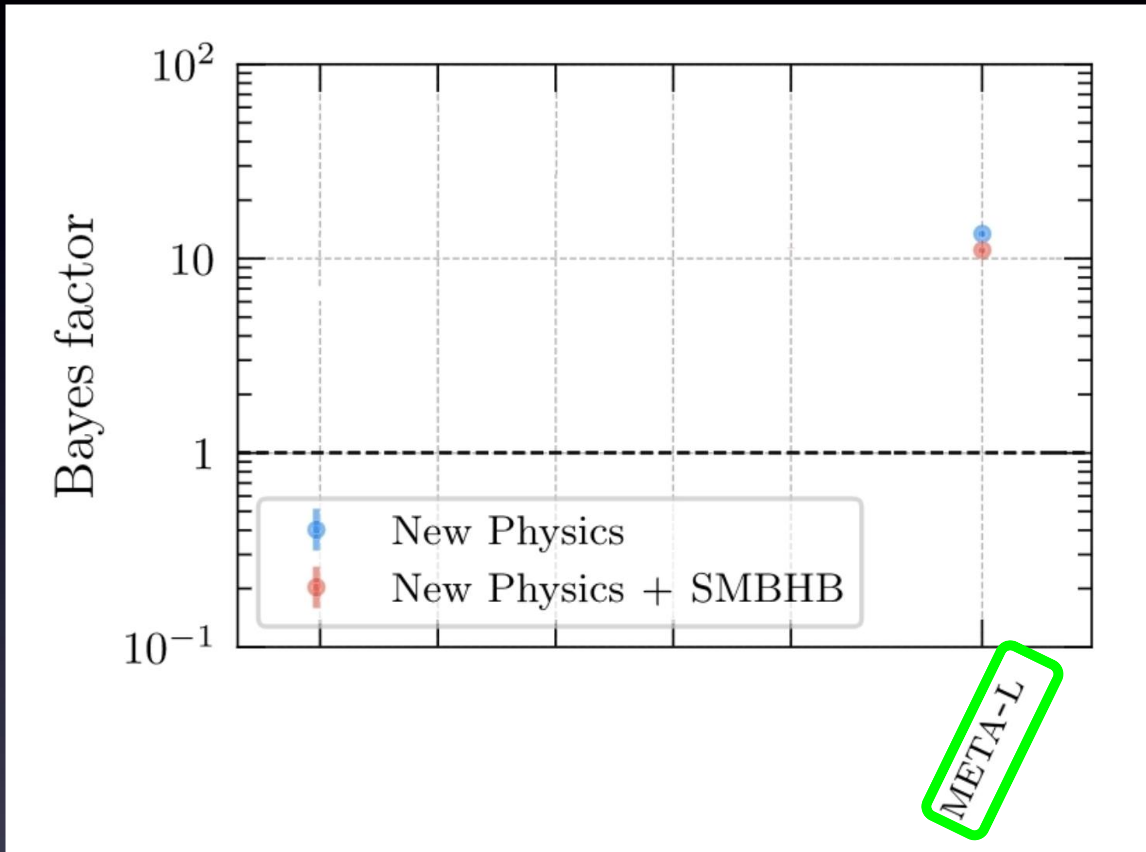




Gabriella Agazie et al 2023 ApJL 951 L8

- What is its physics origin? Supermassive BH binaries? Or BSM physics?

Among best fitting explanations: local Metastable cosmic strings



Adeela Afzal et al. (2023)

- MSCS provide a significantly better fit than SMBHB. Can arise in BSM scenarios with extended gauge symmetry (e.g. SO(10) GUTs, gauged G_F)

Outline of my talk

When the 2023 PTA results for a SGWB at nanoherz frequencies are caused by metastable cosmic strings:

- Potential to discover signs of SUSY [or other NP with extra DOF] up to m_{SUSY} ~ $O(10^4$ TeV)

- MSCS from SO(10) GUTs → would help to "single out" promising model classes

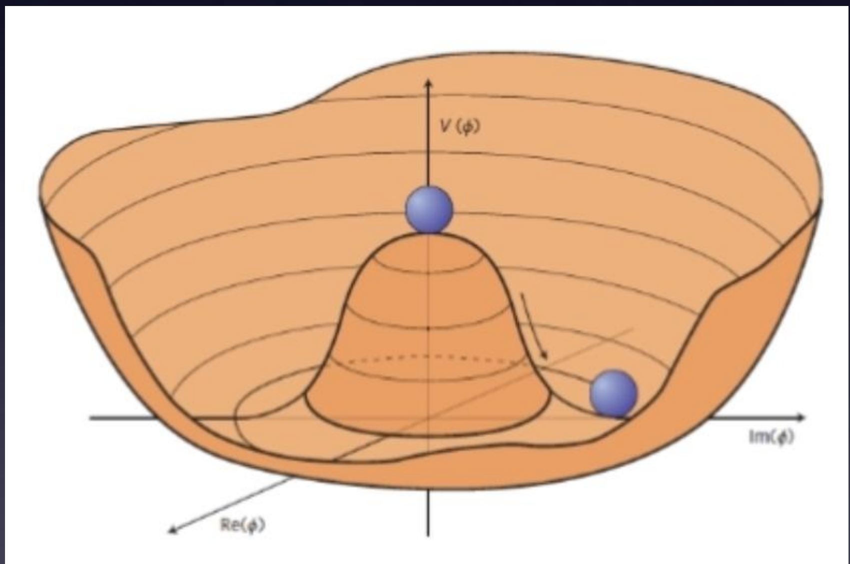
- Alternative attractive explanation: MSCSs from breaking of flavour symmetry (e.g. $SU(2)_F$, potentially in GUT framework)

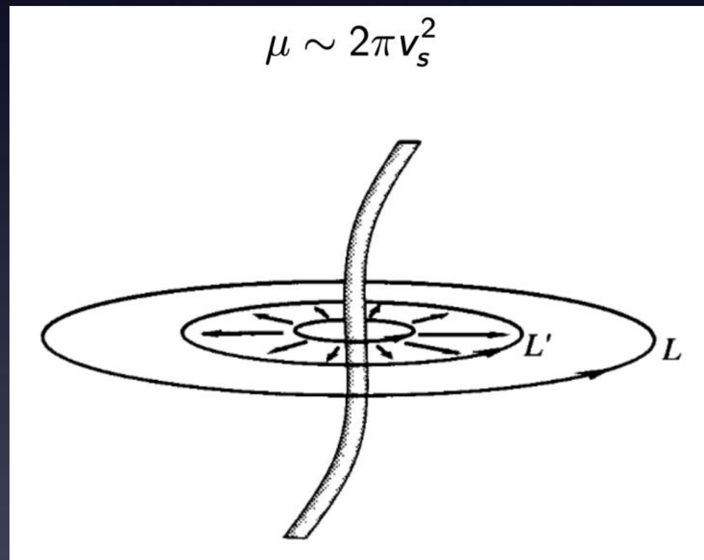
... but first: what are metastable cosmic strings?

Cosmic strings ...

- Cosmic string production: spontaneous symmetry breaking H → K with nontrivial homotopy group π_1 of H/K (vacuum manifold with "unshrinkable loops"), e.g.

$$U(1) \xrightarrow{v_s} \text{nothing}$$



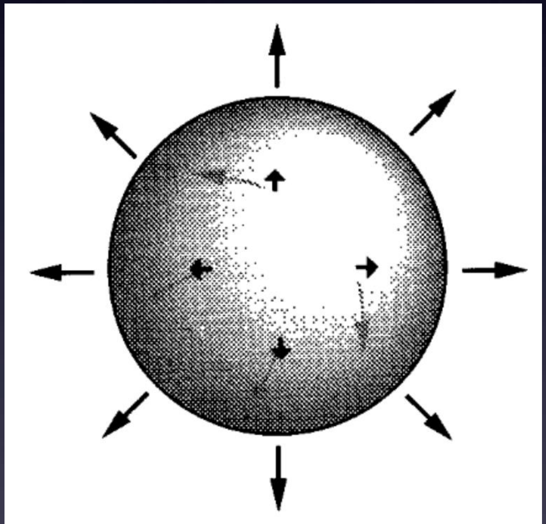


Dimensionless string tension $= G\mu$ $\quad$ (G = Newton's constant)

... can be metastable when the theory allows for monopoles

- Monopole production: spontaneous symmetry breaking G → H with nontrivial homotopy group π_2 of G/H (vacuum manifold with "unshrinkable spheres"), e.g. when compact simple group G breaks into H that contains a U(1) factor

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



monopole mass:

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

- Important: Monopoles have to be diluted by inflation, in order not to (i) overclose the universe (GUTs), or (ii) not to destabilize the CS too fast

Metastable cosmic strings

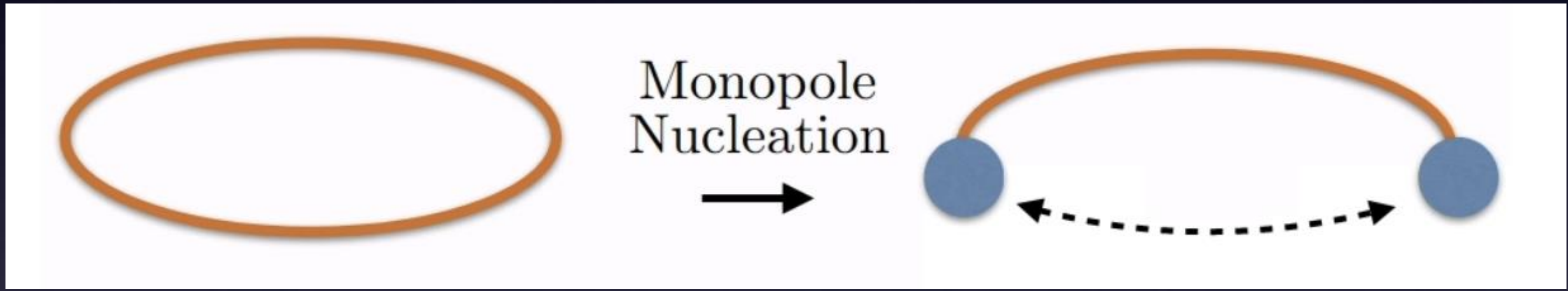
P. Langacker, S.Y. Pi (1980)

- Appear in multi-step SSB, when e.g. the U(1) from CS generation is involved in monopole formation: CS can decay via monopole-antimonopole production

monopole production — Inflation* — cosmic string production

*) dilutes the monopoles

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



- Lifetime depends on

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

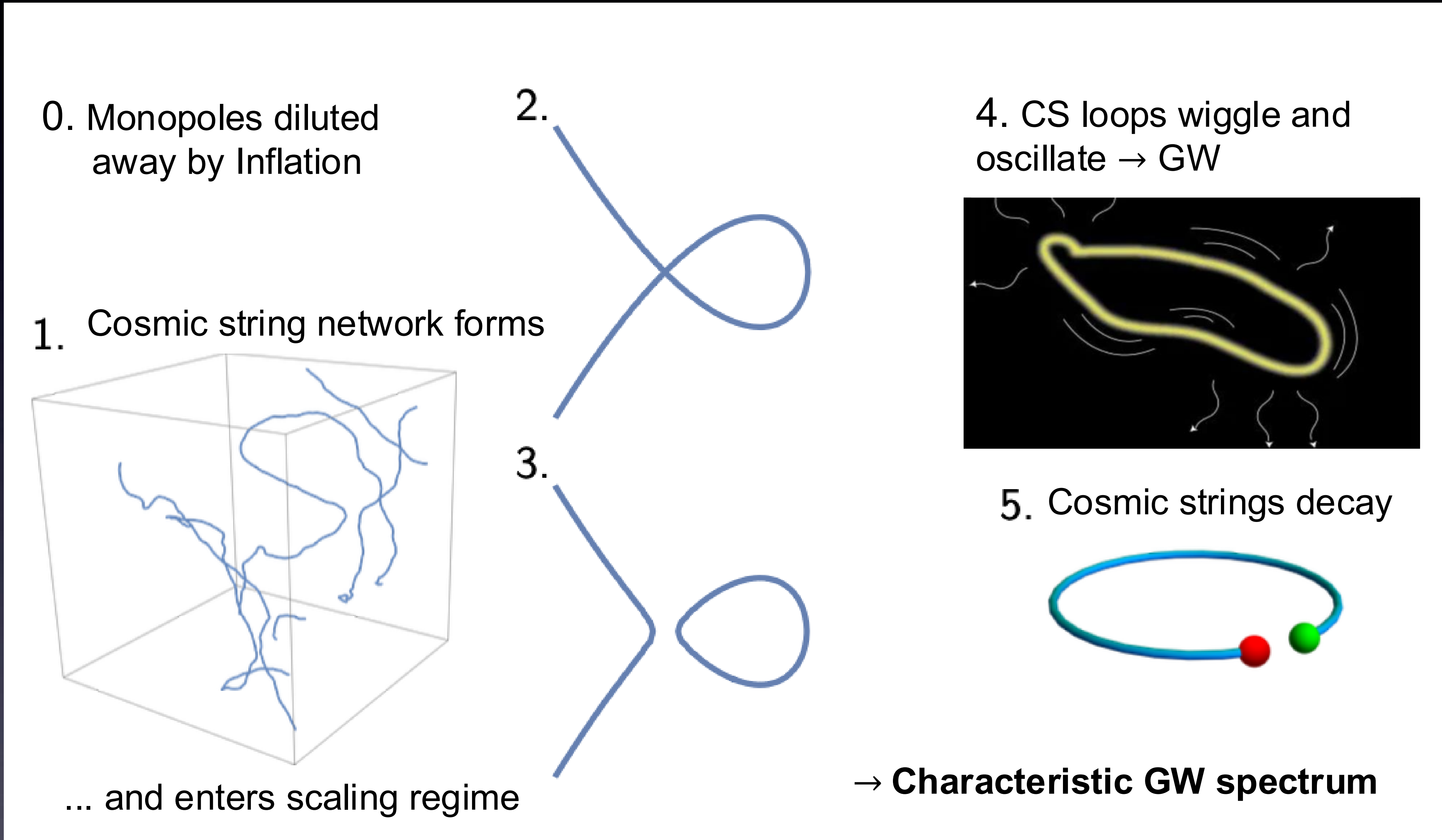
Γ_d: decay rate per string unit length

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

$(\kappa_m^{1/2} < 9$ metastable $)$

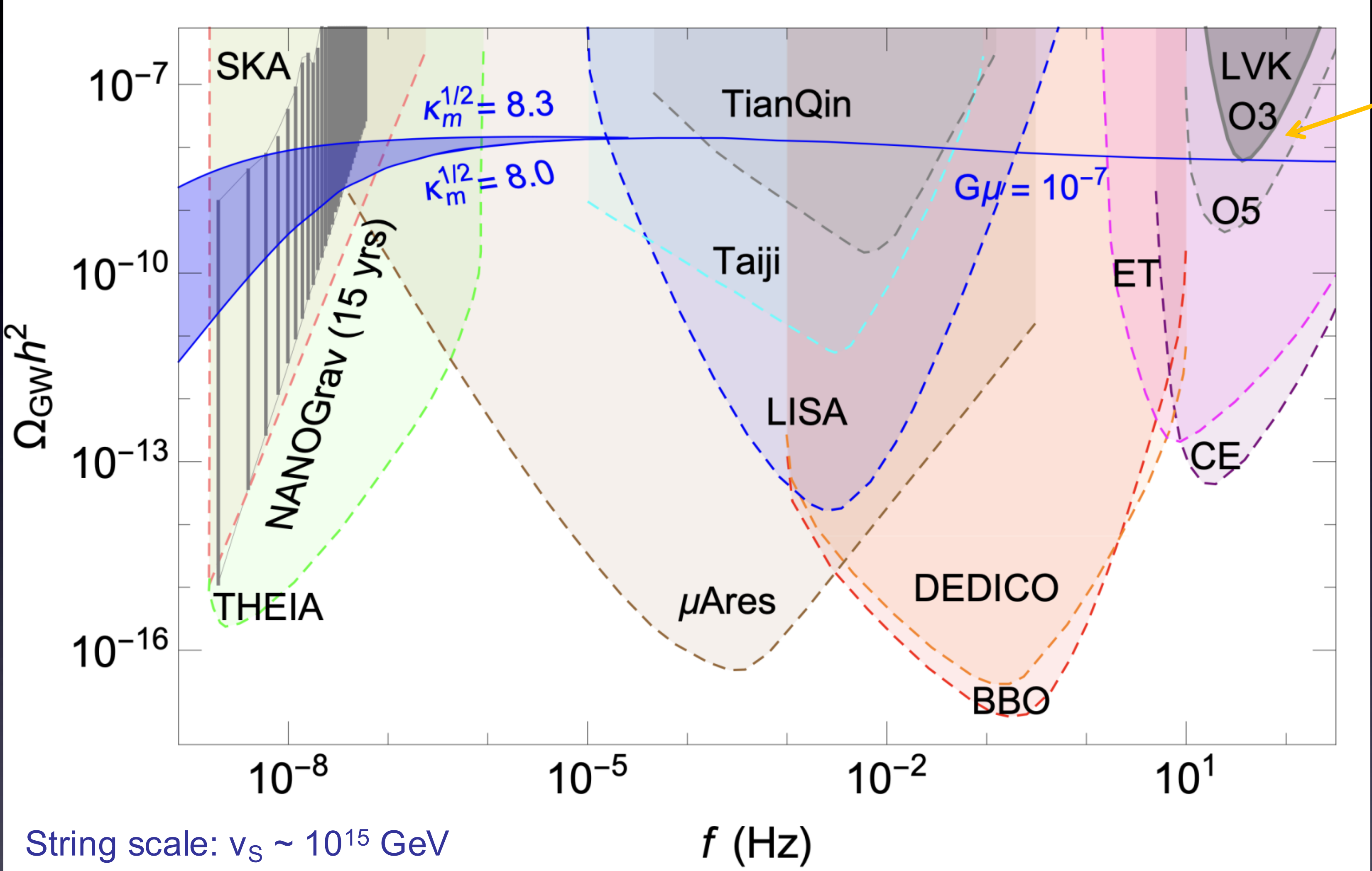
Vilenkin ('82), Preskill, Vilenkin ('92), Monin, Voloshin ('08), Leblond, Shlaer, Siemens ('09), Chitose, Ibe, Nakayama, Shirai, Watanabe (arXiv:2312.15662)

Gravitational waves from metastable CS



Characteristic SGWB spectrum

- Spans over large frequency range!



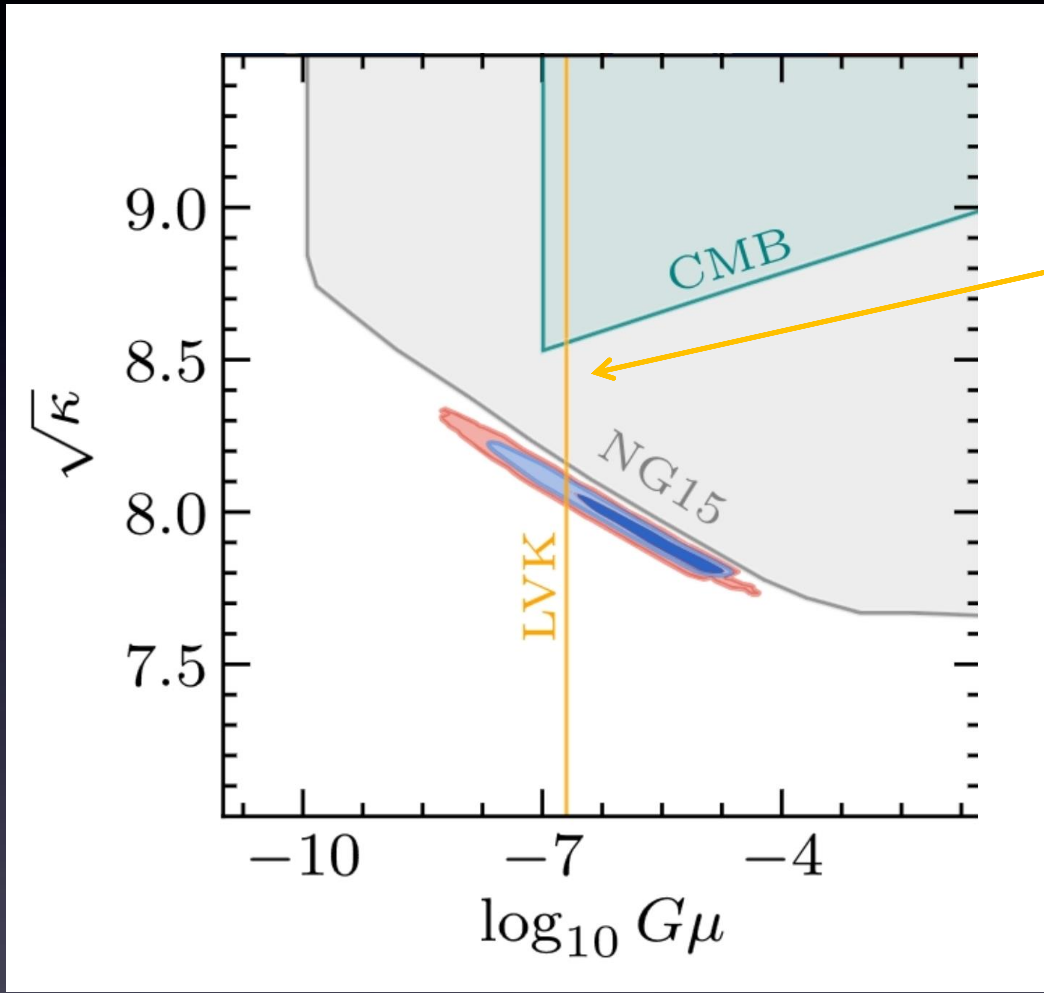
Constraints from LIGO-Virgo-Kagra (LVK)!

plot from: S.A, K. Hinze, S. Saad, J. Steiner (arXiv:2307.04595)

- MSCS explanation will be confirmed/dismissed at (future) GW ovservatories!

Preferred metastable CS parameters from PTA results

Adeela Afzal et al. (2023)



Constraints from LVK (for standard cosmology)

Preferred range: (kappa)$^{1/2}$ ~ 8

Preferred range for $G\mu$: 10^{-8} – 10^{-4}
→ v_s: $5\text{x}10^{14}$ – $5\text{x}10^{16}$ GeV

- PTA data points at CS generation scale $v_s \sim v_m$ close to the (typical) GUT scale

If the metastable CS explanation of the PTA results will be confirmed:

Potential to discover signs of SUSY up to $m_{SUSY} \sim O(10^4$ TeV)

Note: Also applies to other new physics (NP) that predicts a signifficant increase of particle degrees of freedom (DOF)

Computation of the metastable cosmic string GW spectrum

for details, see Appendix of: S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2405.03746

- Step 1: Determine expansion history of the universe (→ Friedmann eq.)
- Step 2: Compute CS loop number density
- Step 3: Compute GW spectrum

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- Step 1: Determine expansion history of the universe (→ Friedmann eq.)

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

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

→ # DOF modified by NP (SUSY)

- Step 2: Compute CS loop number density

- Step 3: Compute GW spectrum

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→ # DOF modified by NP (SUSY)

- Step 2: Compute CS loop number density

energy loss due to GW emission (Γ ~ 50)

dilution from expansion

decay due to monopole nucleation

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

W. Buchmuller, V. Domcke, K. Schmitz (arXiv:2107.04578)

loop production function S (simulation result)
from: J. J. Blanco-Pillado, K. D. Olum, and B. Shlaer (arXiv:1309.6637)

- Step 3: Compute GW spectrum

z_c: creation of CS network

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

P_n (power spectrum per mode, simulation result) from: J. J. Blanco-Pillado and K. D. Olum (arXiv:1709.02693)

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

→ # DOF modified by NP (SUSY)

density

General, also beyond MSCS and # DOF: via H(z) a "loud" SGWB source with predicted shape allows to test for deviations from standard cosmic history

dilution from expansion ↖

decay due to monopole nucleation ↑

$$= S(\ell, t) - \left(3H(t) + \Gamma_d \ell\right) n(\ell, t)$$

W. Buchmuller, V. Domcke, K. Schmitz (arXiv:2107.04578)

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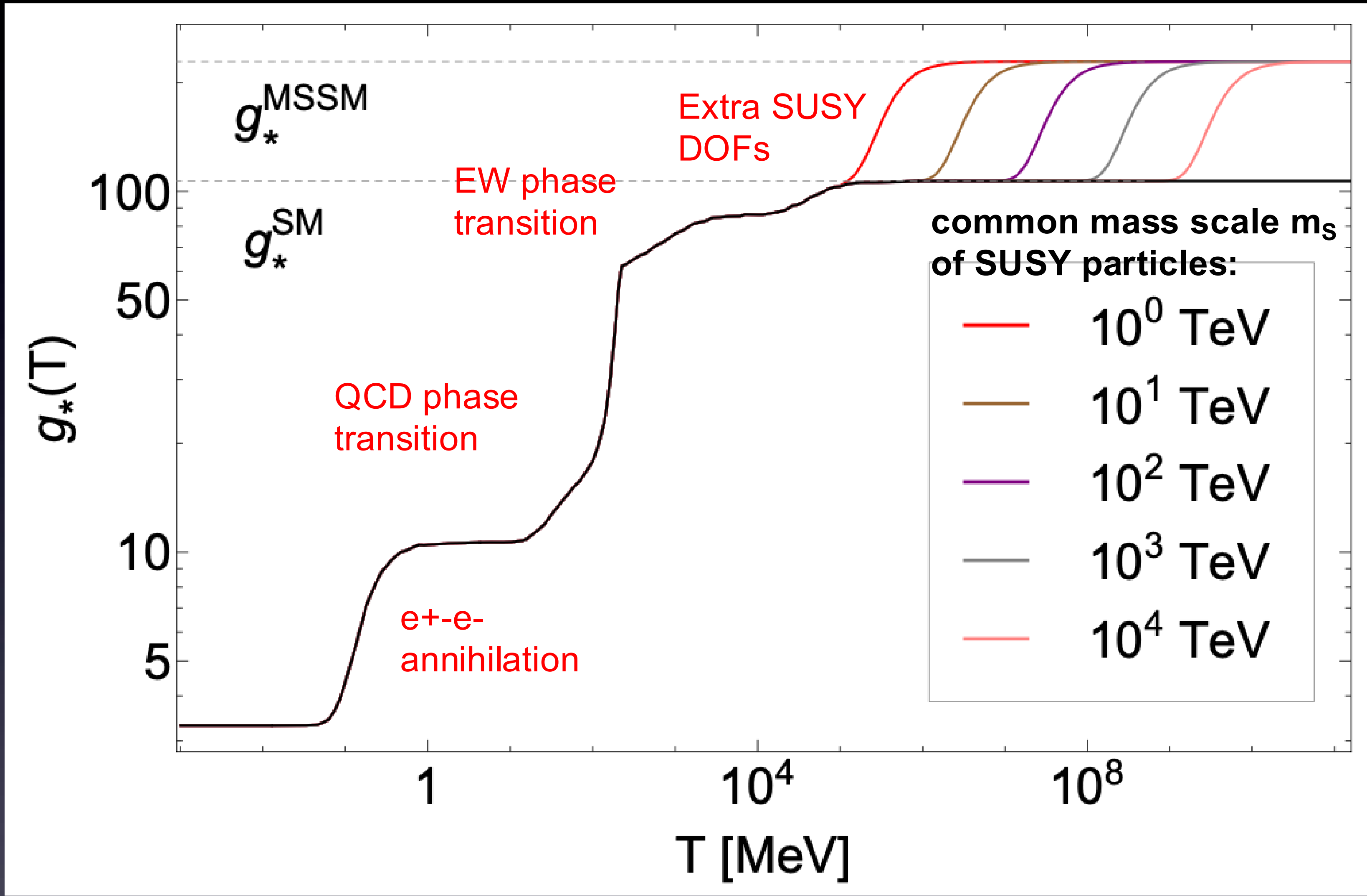
P_n (power spectrum per mode, simulation result) from: J. J. Blanco-Pillado and K. D. Olum (arXiv:1709.02693)

Main effect: SUSY particles modify g_*

Charaxteristic for SUSY:
DOF ~ 2x SM-DOF

Effective number of relativistic degrees of freedom

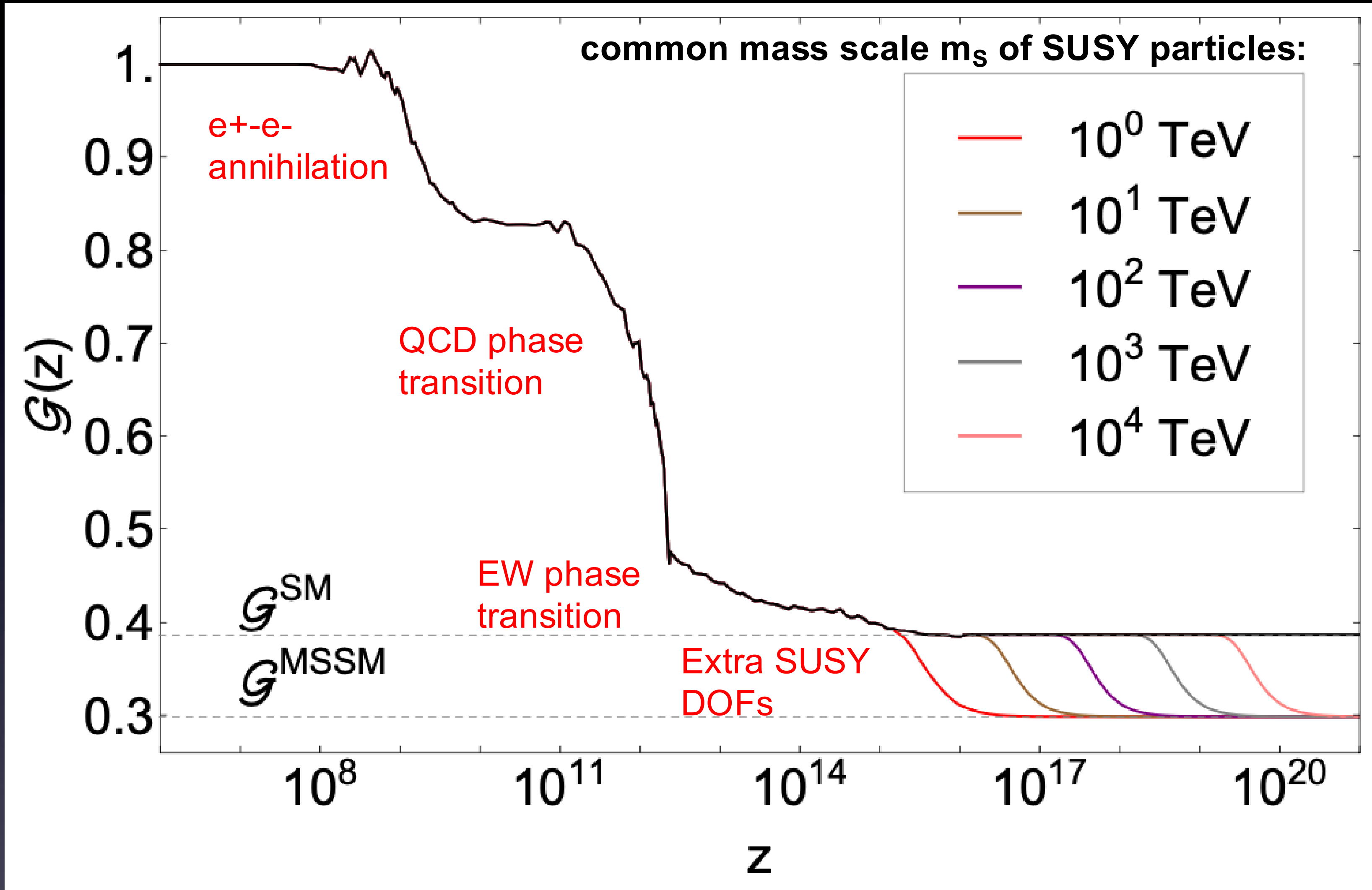


plot from: S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2405.03746

For discussions of effects of extra DOF on GW from CS, cf. also e.g.:
P. Auclair et al. (arXiv:1909.00819), Cui, Lewicki, Morrissey, Wells (arXiv:1808.08968), Battye, Caldwell, Shellard ('97)

... which enters G(z)

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

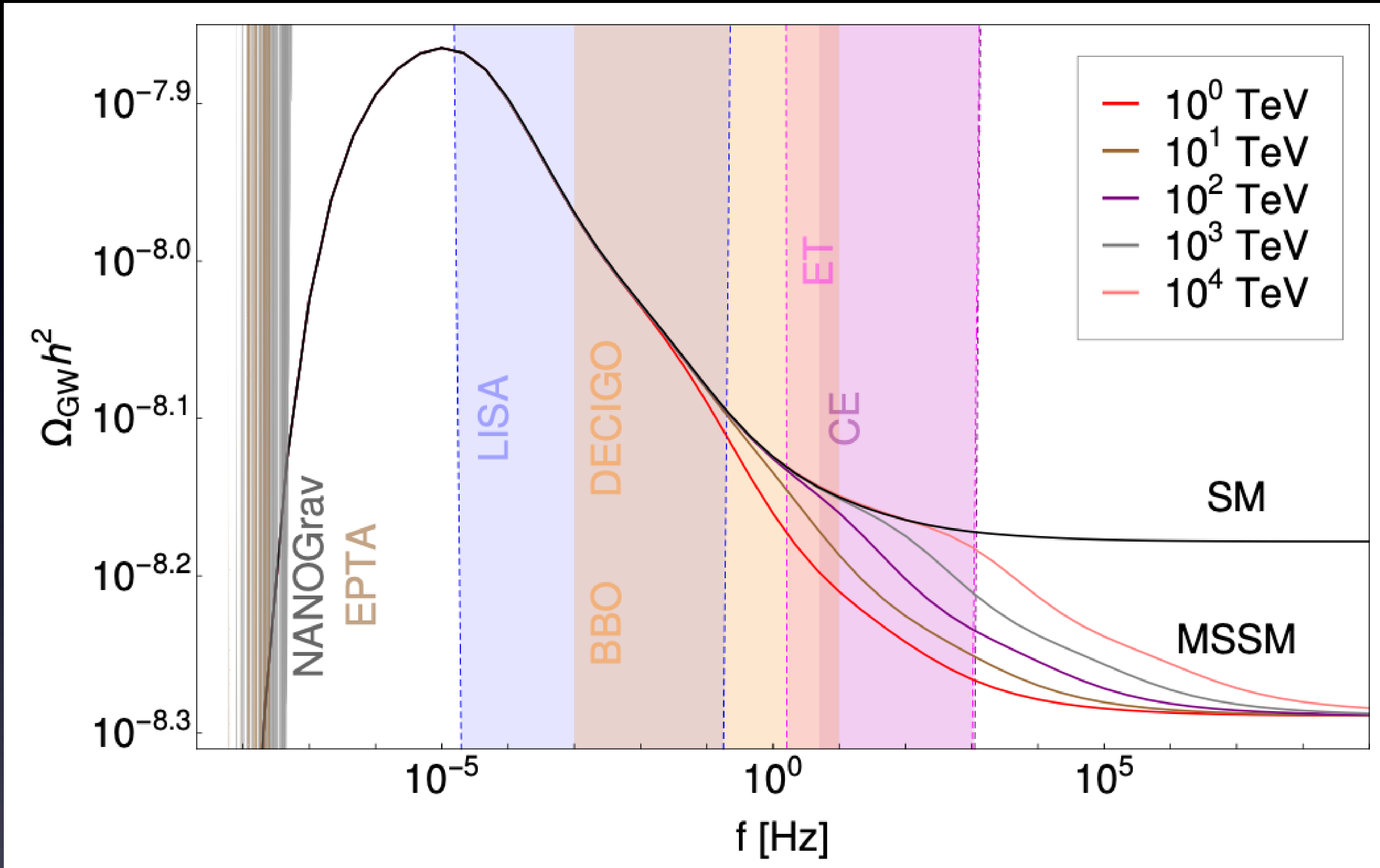


plot from: S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2405.03746

- Via H(z), extra DOF leave imprint on the GW spectrum produced by MSCSs

Imprint of SUSY on the GW spectrum

plot from: S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2405.03746



20% drop due to extra SUSY DOF

NP DOF lower the "plateau" at high frequencies:

$$\Omega_{\rm GW}^{\rm NP} \sim \Omega_{\rm GW}^{\rm SM} \left(\frac{g_*^{\rm SM}}{g_*^{\rm SM} + \Delta g_*^{\rm NP}} \right)^{1/3}$$

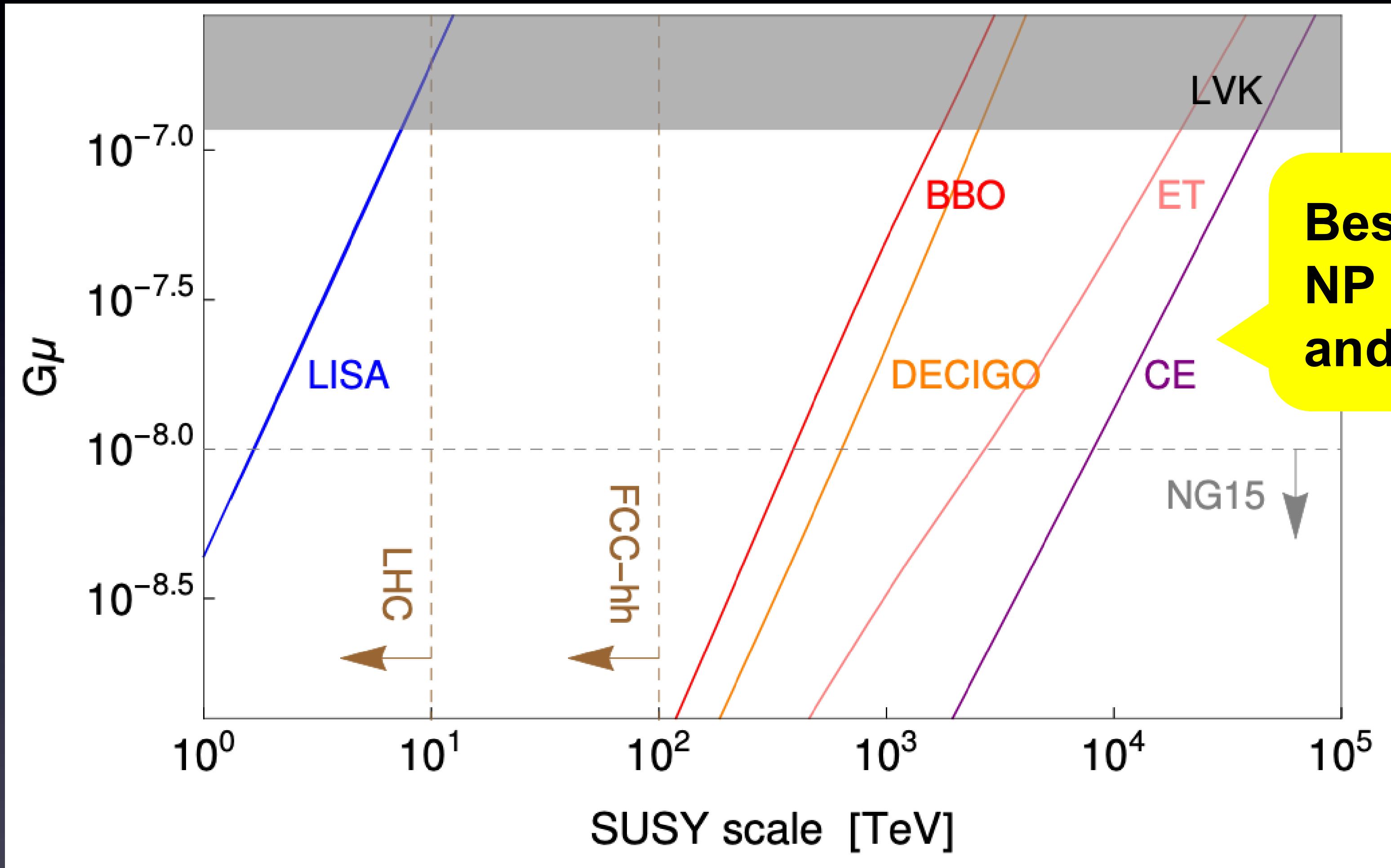
$$\Delta g_*^{\rm SUSY} = 122$$

$$\Omega_{\rm GW}^{\rm SUSY} / \Omega_{\rm GW}^{\rm SM} \approx 0.8$$

Discovery reach for signs of SUSY

S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2405.03746

- Signal-to-noise ratio analysis: Sensitivity to the SUSY scale

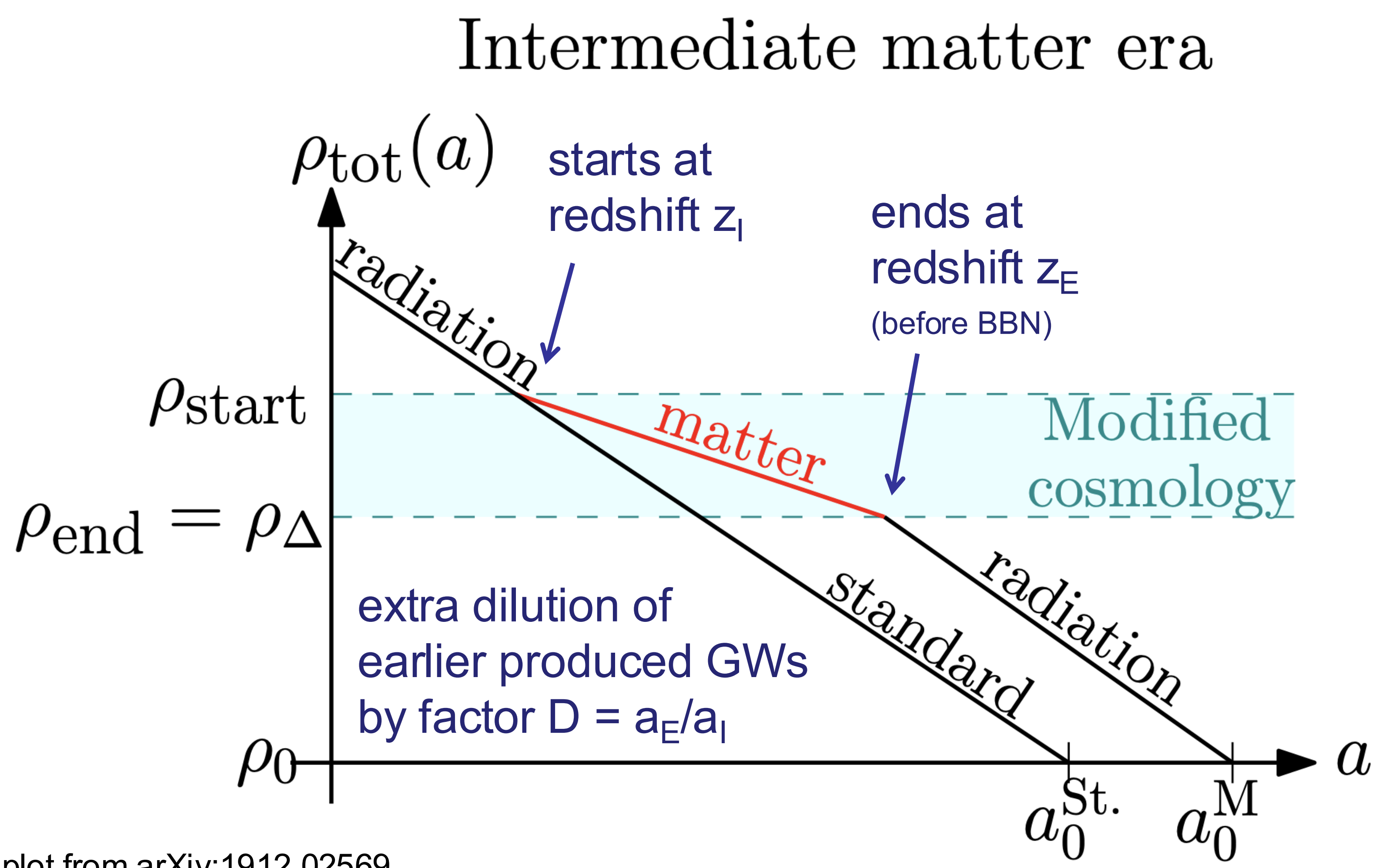


Best reach to high NP masses by ET and CE: O(10^4 TeV)

- From Fisher analysis: uncertainty of 10% for the # of DOF and 5% for the scale of NP (i.e. for m_{SUSY}) possible with ET and CE

Possible non-standard cosmology effect in SUSY models: Late-time entropy production

- Modeled by intermediate phase of matter domination (MD), changing H(z)



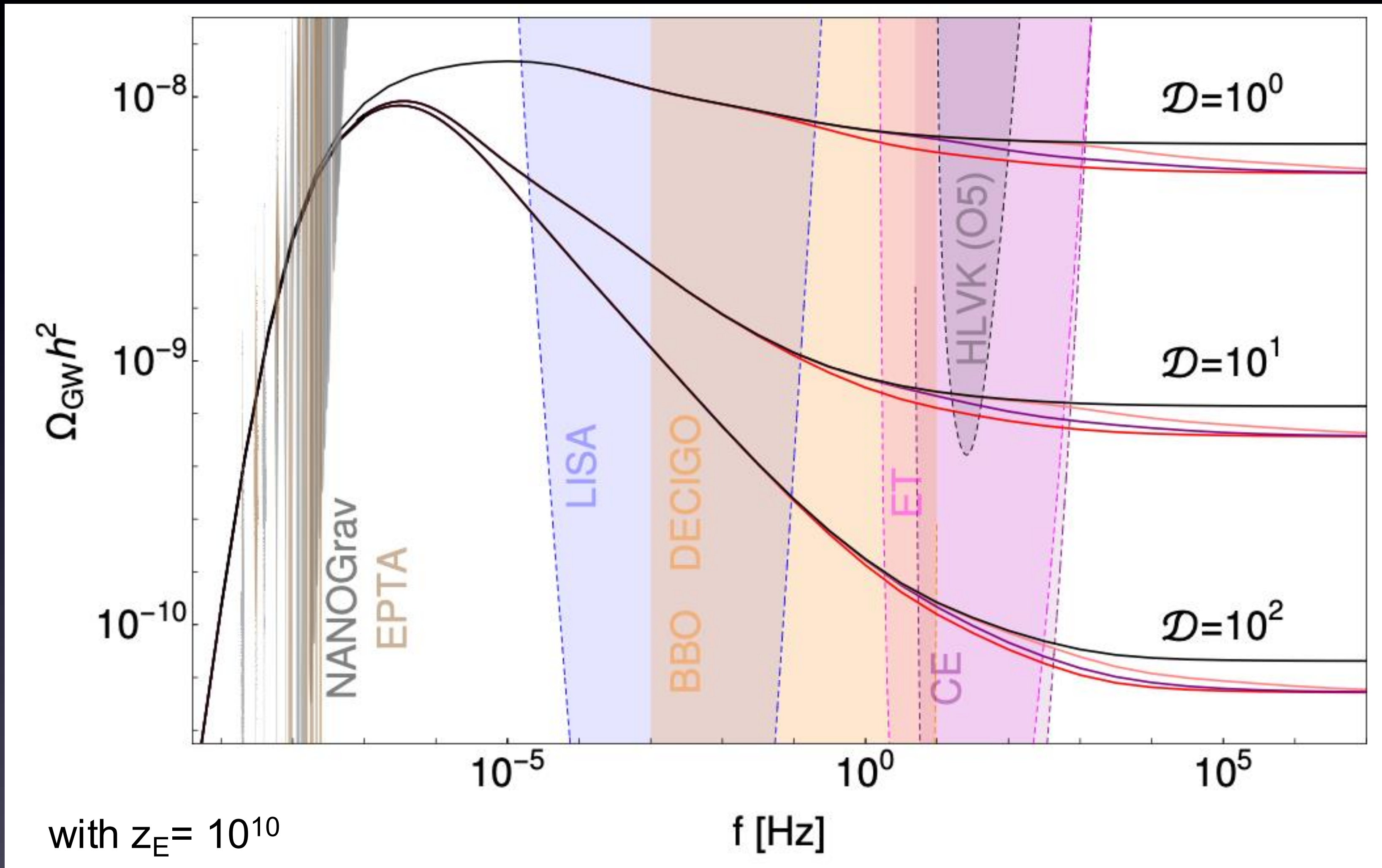
plot from arXiv:1912.02569

Caused e.g. by:
- sgoldstino (from SUSY breaking)
- gravitinos
- string moduli, ...

Affects CS GW spectrum, cf. e.g.:
P. Auclair et al. (arXiv:1909.00819), Cui, Lewicki, Morrissey, Wells (arXiv:1711.03104, arXiv:1808.08968), Gouttenoire, Servant, Simakachorn (arXiv:1912.02569, arXiv:1912.03245) Blasi, Brdar, Schmitz (arXiv:2004.02889)

MSCS spectrum with SUSY DOF and extra dilution by factor D

S.A, K. Hinze, S. Saad, J. Steiner, arXiv:2405.03746



- LISA could measure $G\mu$ and dilution factor D; SGWB detection at LVK delayed, but still possible to see signs of SUSY at ET and CE

Assuming metastable CS explanation of PTA results will be confirmed:

"Singling out" promising SO(10) GUT scenarios

Which "promising SO(10) model routes" can explain the PTA results?

S.A, K. Hinze, S. Saad, J. Steiner arXiv:2307.04595
S.A, K. Hinze, S. Saad, arXiv:2406.17014

- Superpotential:

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

Our criteria:

Promising models:

- Gauge coupling unification
- Cosmic inflation
- Doublet-Triplet splitting

(without large tuning)

- Fermion mass
- Proton decay bounds
- ...

We use these criteria to "single out" "promising" classes of SO(10) GUT models ...

- Lower-dimensional reps.: 10, 16, 45

Which "promising SO(10) model routes" can explain the PTA results?

S.A, K. Hinze, S. Saad, J. Steiner (arXiv:2307.04595)

- SO(10) breaking by two 45-plets (in B-L & I_{3R} direction) + 16 $\overline{16}$:

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

(a) $\langle 45_H \rangle > \langle 45'_H \rangle > \langle 16_H \rangle, \langle \overline{16}_H \rangle$:

$$SO(10) \xrightarrow[45_H]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow[45'_H]{M_I} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16_H + \overline{16}_H]{M_{II}} SU(3)_C \times SU(2)_L \times U(1)_Y$$

(b) $\langle 45'_H \rangle > \langle 45_H \rangle > \langle 16_H \rangle, \langle \overline{16}_H \rangle$:

$$SO(10) \xrightarrow[45'_H]{M_{\rm GUT}} SU(4)_C \times SU(2)_L \times U(1)_R \xrightarrow[45_H]{M_I} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16_H + \overline{16}_H]{M_{II}} SU(3)_C \times SU(2)_L \times U(1)_Y$$

(c) $\langle 45_H \rangle = \langle 45'_H \rangle > \langle 16_H \rangle, \langle \overline{16}_H \rangle$:

$$SO(10) \xrightarrow[45_H + 45'_H]{M_{\rm GUT}} SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \xrightarrow[16_H + \overline{16}_H]{M_I} SU(3)_C \times SU(2)_L \times U(1)_Y$$

These are the only breaking chains that allow for "promising" (with our criteria) SO(10) models with metastable cosmic strings

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

Metastable CS from multi-step SO(10) breaking - with inflation before last breaking step

S.A, K. Hinze, S. Saad, J. Steiner (arXiv:2307.04595)

- Step 1: Adjoints (45-plets) get their vevs (example: case (a))

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

Monopoles

$$SO(10) \xrightarrow{45_H} \underbrace{3_c 2_L 2_R 1_{B-L}}_{\text{LR symm. extension of SM}} \xrightarrow[45'_H]{} 3_c 2_L 1_R 1_{B-L} \xrightarrow{16_H + \overline{16}_H} 3_c 2_L 1_Y$$

- Step 2: **Inflation**

E.g.: via SUSY hybrid inflation: Linde ('91), Dvali, Shafi, Schaefer ('94)
or via Tribrid inflation: cf. S.A., Bastero-Gil, Baumann, Dutta, S.F. King ('10)
(where the **sneutrino can act as the inflaton**)

Inflation ends by the last step of SO(10) breaking: Dilutes away the monololes, production of CS after inflation

For example :

$W_{\text{Inflation}} \supset \kappa S (\overline{16}_H 16_H - m_{16}^2)$

- Step 3: 16-plets get their vevs

Monopoles

$$SO(10) \xrightarrow{45_H} 3_c 2_L 2_R 1_{B-L} \xrightarrow[45'_H]{} 3_c 2_L 1_R 1_{B-L} \xrightarrow{16_H + \overline{16}_H} 3_c 2_L 1_Y$$

CS

→ Metastable cosmic strings!

Other promising classes of models for explaining the PTA GW signal:

MSCS from favour symmetry breaking

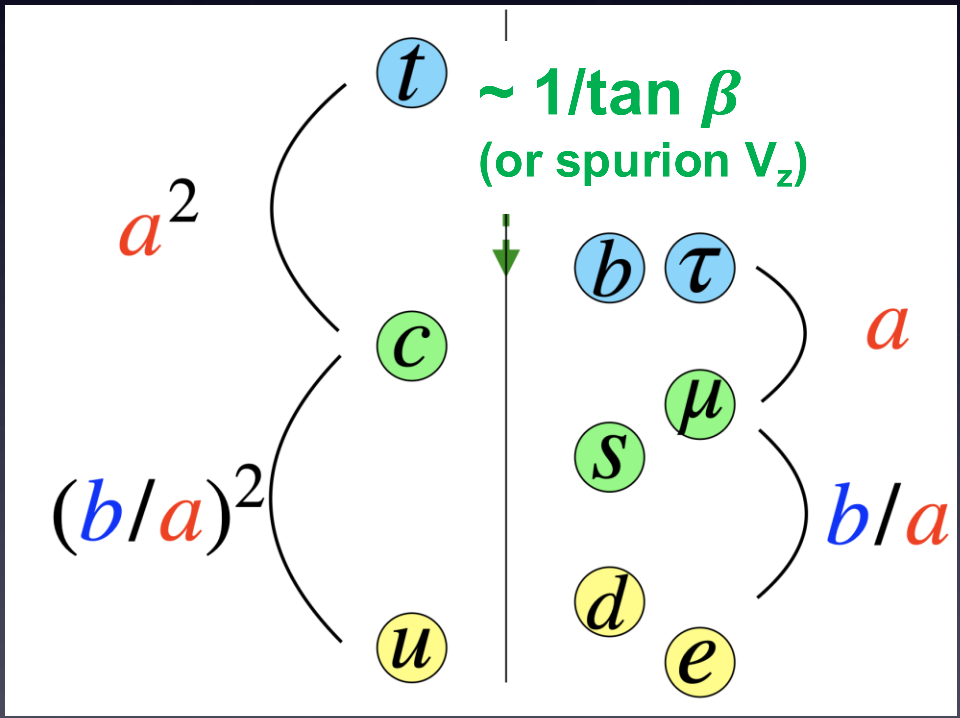
(e.g. gauged $SU(2)_F$ in SU(5) GUTs)

Prolog: U(2) that is "right for leptons": $U(2)_{10}$ (= $SU(2)_{10} \times U(1)_{10}$)

S.A, A. Greljo, B.A. Stefanek, A.E. Thomsen, arXiv: 2311.09288

- Can nicely explain the charged fermion mass hierarchies, while allowing for "anarchic" neutrino mass matrix (large PMNS mixing)

Strategy: **(10_1,10_2) of SU(5) fermions form doublet "$SU(2)_{10}$" flavour symmetry**



from $V_{i\alpha} V_{j\beta} \mathbf{10}^\alpha \mathbf{10}^\beta \mathbf{5}_H$

$$Y_u = \begin{pmatrix} z_{u1} b^2 & z_{u2} ab & z_{u3} b \\ y_{u1} ab & y_{u2} a^2 & y_{u3} a \\ x_{u1} b & x_{u2} a & x_{u3} \end{pmatrix}$$

from $V_{i\alpha} \bar{\mathbf{5}}\, \mathbf{10}^\alpha \mathbf{5}^*_H$ V_Z

$$Y_d = V_Z \begin{pmatrix} z_{d1} b & z_{d2} b & z_{d3} b \\ & y_{d2} a & y_{d3} a \\ & & x_{d3} \end{pmatrix}$$

$$Y_e = V_Z \begin{pmatrix} z_{\ell 1} b & & \\ z_{\ell 2} b & y_{\ell 2} a & \\ z_{\ell 3} b & y_{\ell 3} a & x_{\ell 3} \end{pmatrix}$$

Example model: MSCSs from $SU(2)_{10}$ breaking

S.A, K. Hinze, S. Saad, arXiv:2503.05868

➢ $SU(2)_{10}$ flavour symmetry breaking with embedded inflation

$$SU(2)_{10} \xrightarrow{\langle\Delta\rangle} \underbrace{U(1)_{10} \xrightarrow{\langle\phi\rangle+\langle\overline{\phi}\rangle} nothing}_{\text{inflation}},$$

- Fit to charged fermion masses and U_{CKM} with O(1) coefficients
- "anarchic" neutrino mass matrix with large mixing
- MSCSs from $SU(2)_{10}$ breaking, (monopoles diluted by inflation)
- Range for the cosmic string (cs) scale linked to the GUT scale:

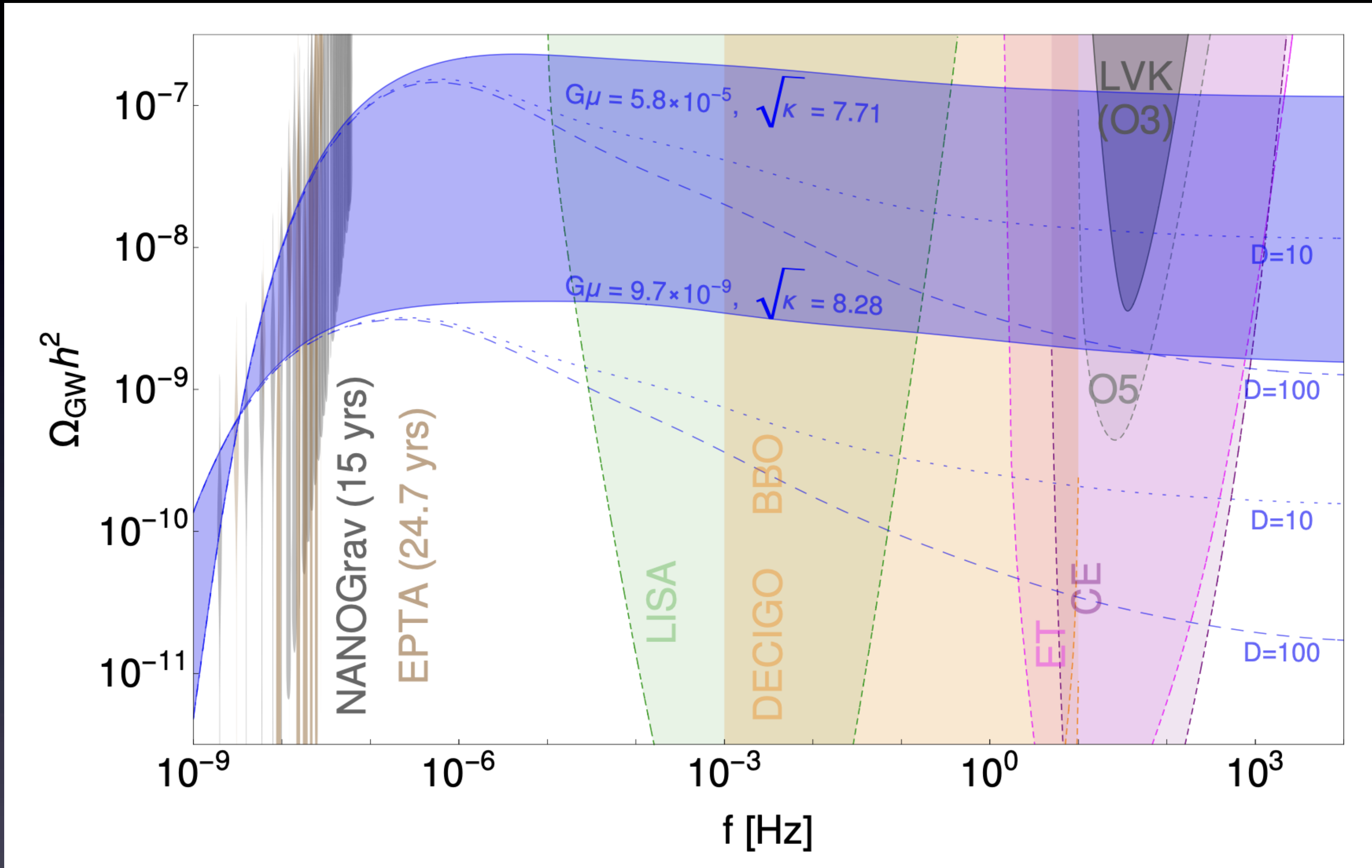
$$v_{cs} \in [3.6 \times 10^{14},\ 4.4 \times 10^{16}]\ \text{GeV}$$

defects also diluted by inflation

Symbol	$SU(5)$	$SU(2)_{10}$	$U(1)_g$	$\mathbb{Z}_4$
ψ^i	10^i_F	2	+1	+2
ψ^3	10^3_F	1	0	0
χ^p	$\overline{5}^p_F$	1	0	+2
Φ	24_H	1	0	+2
H	5_H	1	0	0
$\overline{H}$	$\overline{5}_H$	1	0	0
Δ	1	3	−1	+3
ϕ	1	2	+1	+2
$\overline{\phi}$	1	$\overline{2}$	−1	+2
S	1	1	0	0
ν^p_R	1^p	1	0	+2

GW spectrum from example model

S.A, K. Hinze, S. Saad, arXiv:2503.05868



blue: standard cosmology

D=10, D=100 (dashed lines): possible dilution from late matter phase

- With standard cosmology: SGWB from MSCS within sensitivity of HLVK (05). Dilution (factor D) from late-time entropy production can suppress signal.

Summary

When the MSCS explanation of PTA result gets confirmed ...

- Fantastic reach for NP with signifficant extra DOF (such as SUSY)
  - Best reach by Einstein Telescope (ET) and Cosmic Explorer (CE): Can detecxt signs of extra DOF up to O(10^4 TeV), with uncertainty of 10% for the # of DOF and 5% for the scale of NP

- Interesing prospects to find signs of non-standard cosmic history, e.g. late time entropy production typical for some SUSY scenarios.

- PTA signal can be explained by, e.g.:
  - "Promising" SO(10) GUT scenarios (MSCS from last step SO(10) breaking)
  - Flavour symmetry breaking, e.g. in example SU(5) x $SU(2)_{10}$ flavour model (MSCS from last step $SU(2)_{10}$ breaking)

Thanks for your attention!