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Phenomenological tests of supersymmetric SO(10) grand unified theories

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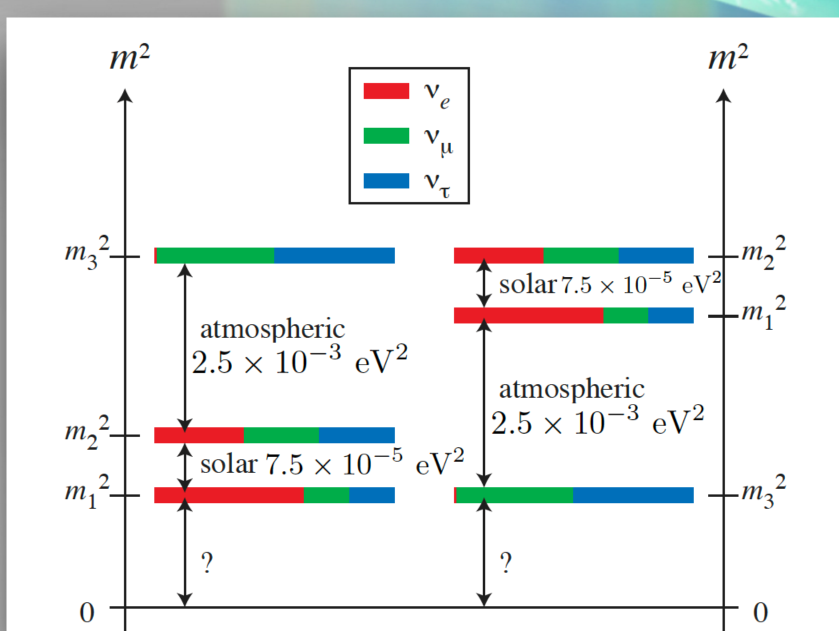
- Model framework
- Phenomenology
  - fermion mass and mixing in SO(10) SUSY GUT
  - leptogenesis and $0\nu\beta\beta$
  - proton decay
  - gravitational wave
- Result

Motivation

$SU(3)_c \times SU(2)_L \times U(1)_Y$

$SO(10)$

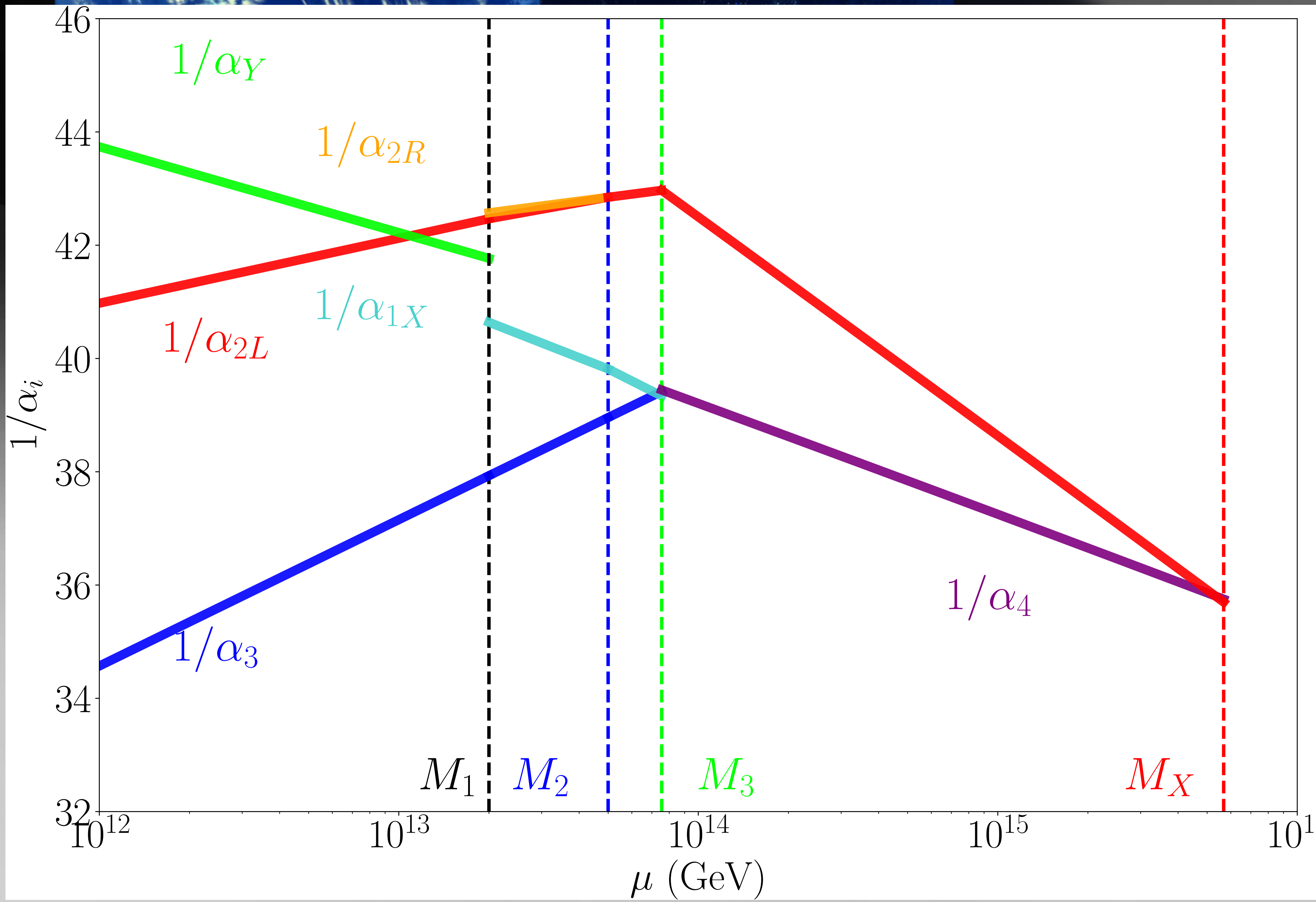


Motivation

- Fermion masses and mixing are highly correlated in the framework of SO(10)
- $U(1)_{B-L}$ gauge symmetry can appear as an intermediate symmetry and its breaking scale is associated with RH neutrino masses
- Limit on proton life time put constraint on the SO(10) breaking scale

Neutrino Physics GW Proton decay

Non-SUSY SO(10)



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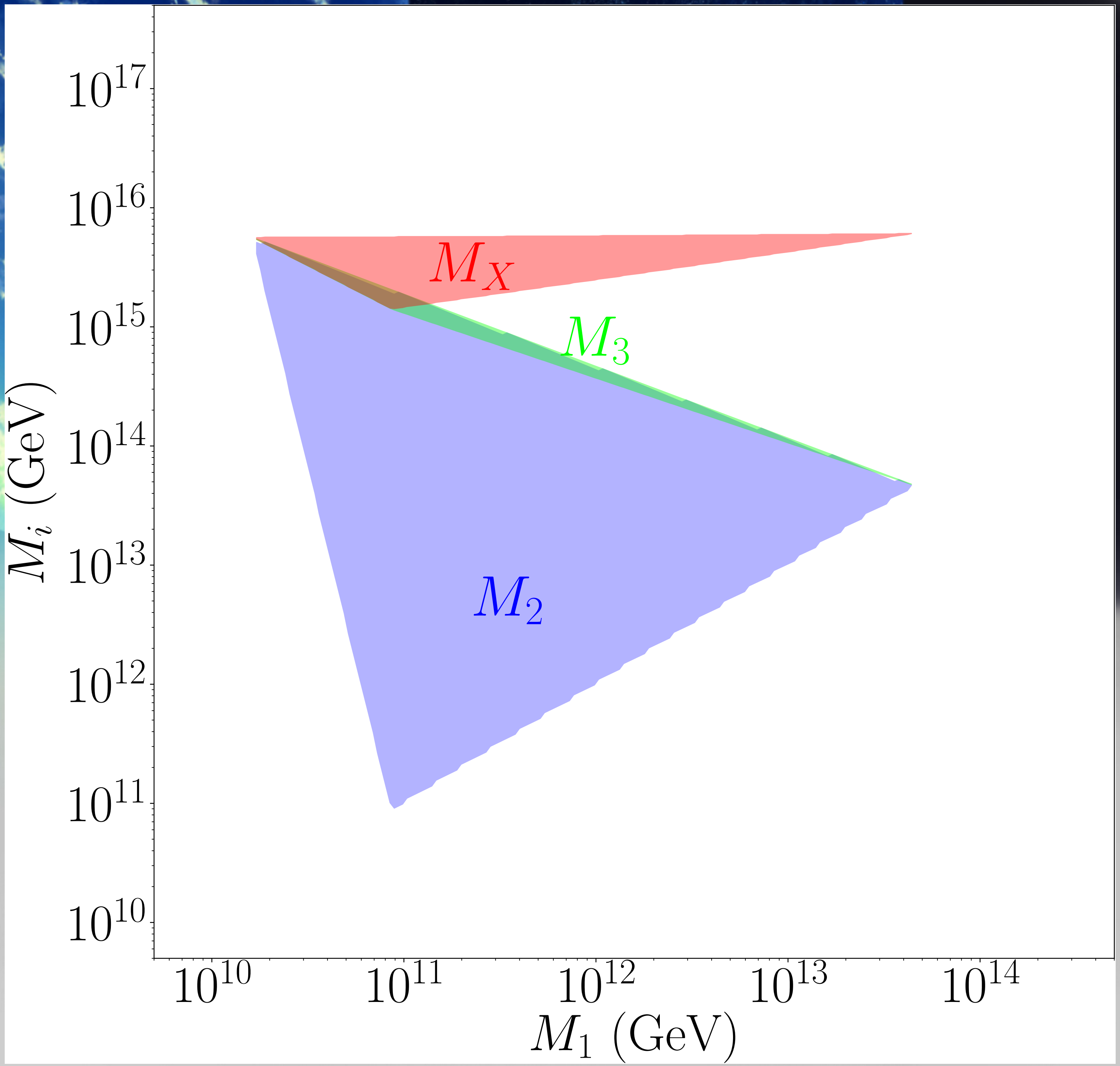
Non-SUSY SO(10)



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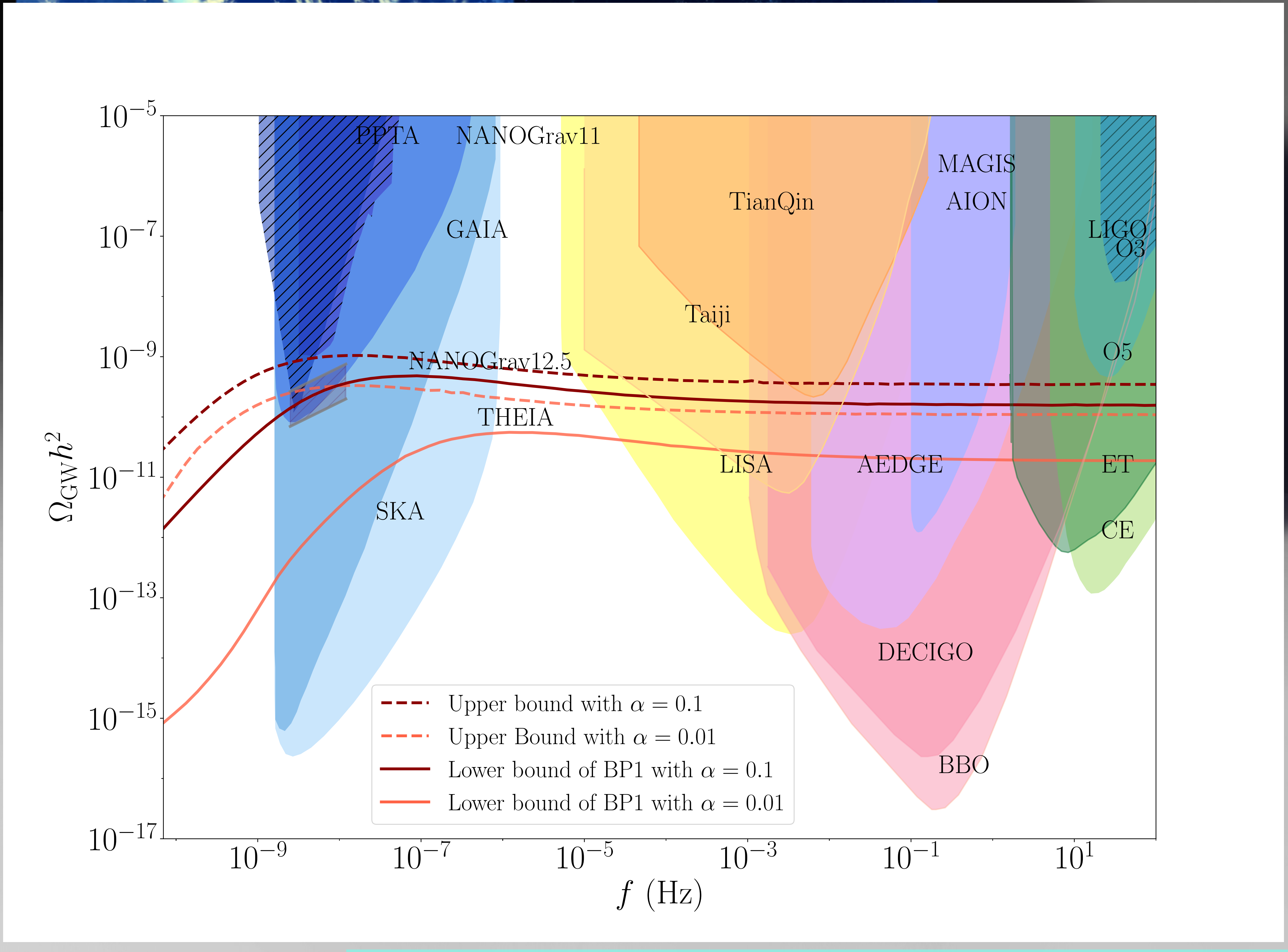
GW signal in non-SUSY SO(10)



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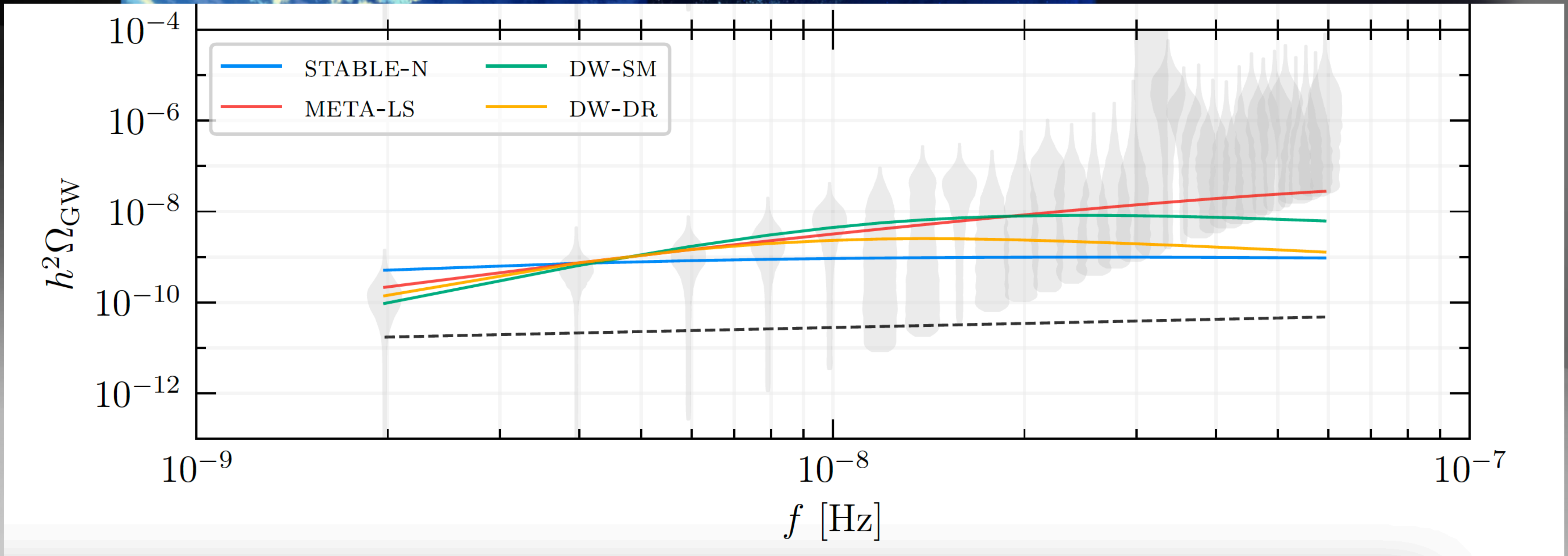
NANOGrav 15



NANOGrav Collaboration *Astrophys.J.Lett.* 951 (2023) 1, L11

model framework

Symmetry breaking of SO(10)

We consider a specific breaking chain of SUSY SO(10)

$$SO(10) \times \text{SUSY}$$

$$\mathbf{45} \Big\downarrow \ \text{broken at } M_{\text{GUT}}$$

$$G_{\text{LRSM}} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times \text{SUSY}$$

$$\overline{\mathbf{126}} \Big\downarrow \ \text{broken at } M_{B-L}$$

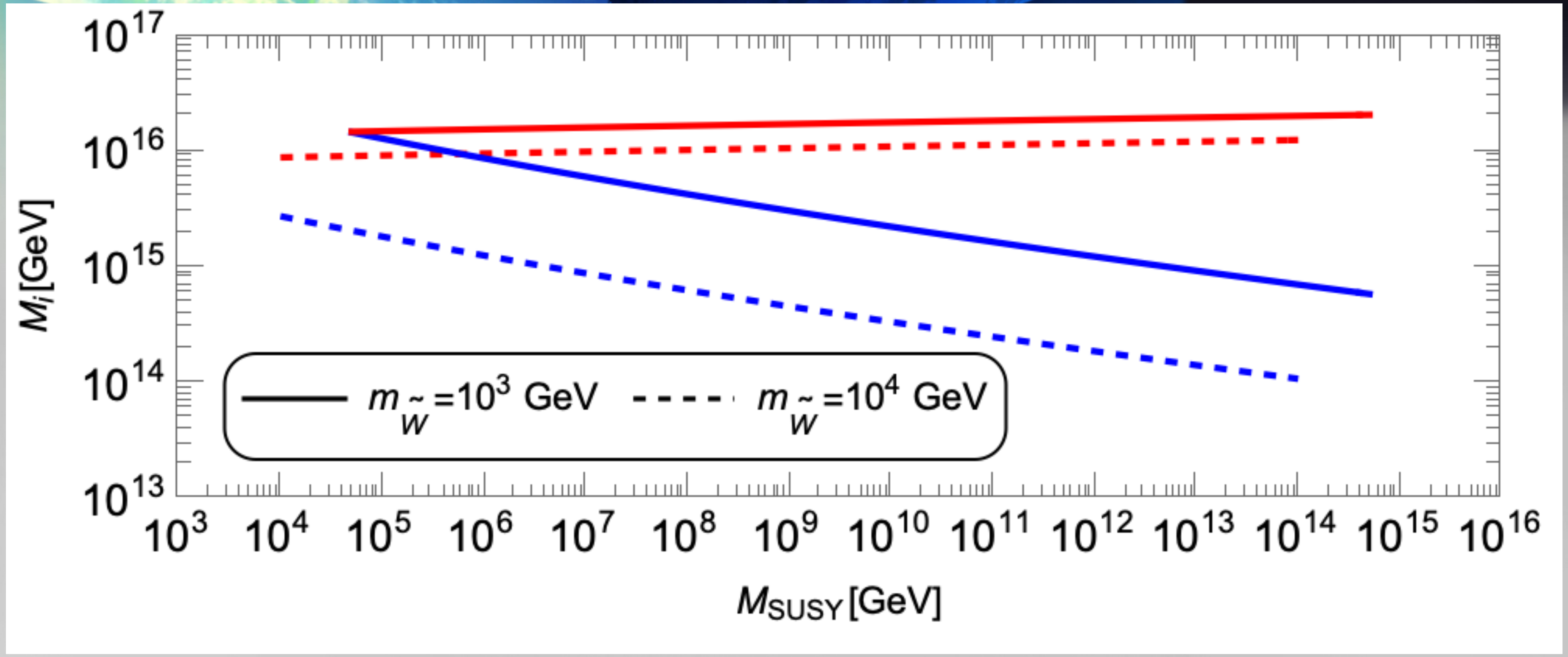
$$G_{\text{MSSM}} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \times \text{SUSY}$$

$$\Big\downarrow \ \text{broken at } M_{\text{SUSY}}$$

$$G_{\text{SM}} \equiv SU(3)_c \times SU(2)_L \times U(1)_Y$$

Gauge Unification

- Split supersymmetry
  - M_{SUSY}: mass of sfermions
  - $M_{\tilde{W}}$: mass of gauginos and higgsinos




Phenomenology

Fermion mass and mixing

- To fit the fermion mass and mixing, we consider three Higgs multiplets in the Yukawa sector

$$Y^*_{\mathbf{10}}\, \mathbf{16}\cdot\mathbf{16}\cdot\mathbf{10} + Y^*_{\overline{\mathbf{126}}}\, \mathbf{16}\cdot\mathbf{16}\cdot\overline{\mathbf{126}} + Y^*_{\mathbf{120}}\, \mathbf{16}\cdot\mathbf{16}\cdot\mathbf{120} + \text{h.c.}$$

- CP symmetry at GUT scale — real Yukawa couplings
- The up, down, neutrino, charged lepton Yukawa couplings are Hermitian and can be parameterised as

$$Y_u = h + r_2 f + i\, r_3 h' \,, \qquad Y_d = r_1 (h + f + i\, h') \,,$$
$$Y_\nu = h - 3 r_2 f + i\, c_\nu h' \,, \quad Y_e = r_1 (h - 3 f + i\, c_e h')$$

  - h, f are real symmetric and h' is real antisymmetric
  - $r_1, r_2, r_3, c_e, c_\nu$ are all real parameters ($r_3 = 0$)
- The neutrino mass matrix is determined by $M_\nu = m_0 Y_\nu f^{-1} Y_\nu$

Fitting the parameters

- Choose a basis where the up-type quark Yukawa matrix is diagonalised

$$Y_u = \mathrm{diag}\{\eta_u y_u, \eta_c y_c, \eta_t y_t\}$$

$$Y_d = P_a V_{\mathrm{CKM}}\, \mathrm{diag}\{\eta_d y_d, \eta_s y_s, \eta_b y_b\}\, V_{\mathrm{CKM}}^\dagger P_a^*$$

  - $P_a = \mathrm{diag}\{e^{ia_1}, e^{ia_2}, 1\}$ contains 2 phases
  - η_q are signs that cannot be determined by the real-orthogonal transformation

- By fixing the quark Yukawa couplings and CKM mixing, the matrices h, f and h' can be solved as

$$h = -\frac{Y_u}{r_2 - 1} + \frac{r_2 \mathrm{Re} Y_d}{r_1(r_2 - 1)} \qquad f = \frac{Y_u}{r_2 - 1} - \frac{\mathrm{Re} Y_d}{r_1(r_2 - 1)} \qquad h' = i\,\frac{\mathrm{Im} Y_d}{r_1}$$

Fitting the parameters

$$Y_e = -\frac{4r_1}{r_2-1}Y_u + \frac{r_2+3}{r_2-1}\mathrm{Re}Y_d + ic_e\mathrm{Im}Y_d$$

$$M_\nu = m_0\left(\frac{8r_2(r_2+1)}{r_2-1}Y_u - \frac{16r_2^2}{r_1(r_2-1)}\mathrm{Re}Y_d + \frac{r_2-1}{r_1}\left(r_1Y_u + ic_\nu\mathrm{Im}Y_d\right)\left(r_1Y_u - \mathrm{Re}Y_d\right)^{-1}\left(r_1Y_u - ic_\nu\mathrm{Im}Y_d\right)\right)$$

- 7 remaining free parameters: $\{a_1, a_2, r_1, r_2, c_e, c_\nu, m_0\}$
- Undetermined signs: η_q
- 8 observables: $\{y_e, y_\mu, y_\tau, \Delta m_{21}^2, \Delta m_{31}^2, \theta_{12}, \theta_{13}, \theta_{23}\}$

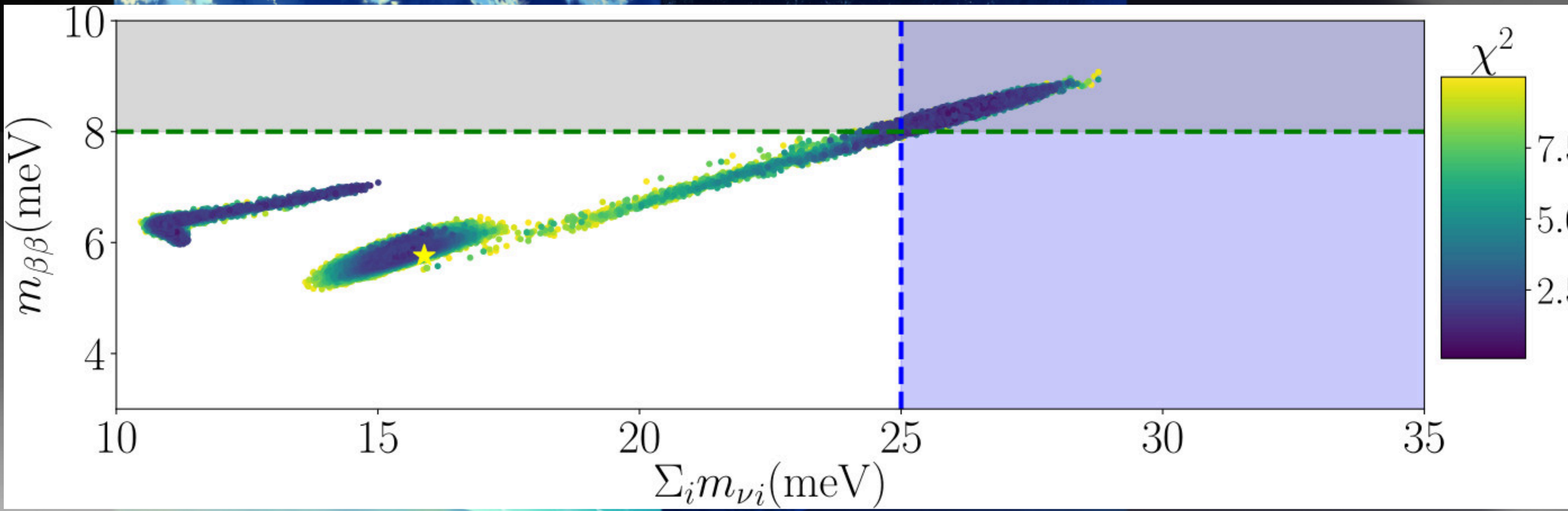
Leptogenesis

- **ULYSSES** and the associated “3DME” code (which accounts for the decays and washout of all three RH neutrinos)
- Example benchmark point

Inputs	a_1	a_2	c_ν	m_0	$(\eta_u, \eta_c, \eta_t; \eta_d, \eta_s, \eta_b)$
	$35, 40^\circ$	221.27°	-1.49	$44.24\,\mathrm{meV}$	$(-,+,+;+,-,-)$
Outputs	θ_{13}	θ_{12}	θ_{23}	δ	m_1
	8.66°	33.19°	44.14°	131.57°	$5.29\ \mathrm{meV}$
$(\chi^2 = 8.22)$	$m_{\beta\beta}$		M_{N_1}	M_{N_2}	M_{N_3}
	$5.76\,\mathrm{meV}$		$8.18 \cdot 10^{11}$ GeV	$1.53 \cdot 10^{12}$ GeV	$4.67 \cdot 10^{13}$ GeV

- ○ Baryon-to-photon ratio $\eta_B \sim 6.16 \times 10^{-10}$

Neutrinoless Double Beta Decay



- The lightest neutrino mass: $5 \lesssim m_{\nu_1}\,(\mathrm{meV}) \lesssim 10$
- Partly testable for the next generation of $\nu 0\beta\beta$ and CMB experiments

Proton Decay

- Pion channel
  - Dimension-6 operators

$$(\overline{u^c_R}\gamma^\mu Q_\alpha)(\overline{d^c_R}\gamma_\mu L_\beta)\,,(\overline{u^c_R}\gamma^\mu Q_\alpha)(\overline{e^c_R}\gamma_\mu Q_\beta)\,,$$
$$(\overline{d^c_R}\gamma^\mu Q_\alpha)(\overline{u^c_R}\gamma_\mu L_\beta)\,,(\overline{d^c_R}\gamma^\mu Q_\alpha)(\overline{\nu^c_R}\gamma_\mu Q_\beta)$$

HK

- Kaon channel
  - dimension-5 operators

$$Q^a_\alpha Q^b_\beta Q^c_\gamma L_l\,, U^{\mathcal{C}a}_\alpha D^{\mathcal{C}b}_\beta U^{\mathcal{C}c}_\gamma E^{\mathcal{C}}_\delta$$

Juno

$$\tau \propto M^2_{\rm SUSY}/m^2_{\widetilde{W}}$$

Proton Decay

$$\frac{\epsilon_{abc}}{M_T}\left(C^L_{\alpha\beta\gamma\delta}Q^a_\alpha Q^b_\beta Q^c_\gamma L_l + C^R_{[\alpha\beta\gamma]\delta}U^{\mathcal{C}a}_\alpha D^{\mathcal{C}b}_\beta U^{\mathcal{C}c}_\gamma E^{\mathcal{C}}_\delta\right)$$

$$\begin{aligned}
C^R_{\alpha\beta\gamma\delta} &= (Y_{\mathbf{10}})_{\alpha\beta}(Y_{\mathbf{10}})_{\gamma\delta} + x_1(Y_{\overline{\mathbf{126}}})_{\alpha\beta}(Y_{\overline{\mathbf{126}}})_{\gamma\delta} + x_2(Y_{\mathbf{120}})_{\alpha\beta}(Y_{\mathbf{120}})_{\gamma\delta} \\
&+ x_3(Y_{\mathbf{10}})_{\alpha\beta}(Y_{\overline{\mathbf{126}}})_{\gamma\delta} + x_4(Y_{\overline{\mathbf{126}}})_{\alpha\beta}(Y_{\mathbf{10}})_{\gamma\delta} + x_5(Y_{\overline{\mathbf{126}}})_{\alpha\beta}(Y_{\mathbf{120}})_{\gamma\delta} \\
&+ x_6(Y_{\mathbf{120}})_{\alpha\beta}(Y_{\overline{\mathbf{126}}})_{\gamma\delta} + x_7(Y_{\mathbf{10}})_{\alpha\beta}(Y_{\mathbf{120}})_{\gamma\delta} + x_8(Y_{\mathbf{120}})_{\alpha\beta}(Y_{\mathbf{10}})_{\gamma\delta} \\
&+ x_9(Y_{\overline{\mathbf{126}}})_{\alpha\delta}(Y_{\mathbf{120}})_{\beta\gamma} + x_{10}(Y_{\mathbf{120}})_{\alpha\delta}(Y_{\mathbf{120}})_{\beta\gamma} \\
C^L_{\alpha\beta\gamma\delta} &= (Y_{\mathbf{10}})_{\alpha\beta}(Y_{\mathbf{10}})_{\gamma\delta} + x_1(Y_{\overline{\mathbf{126}}})_{\alpha\beta}(Y_{\overline{\mathbf{126}}})_{\gamma\delta} - x_3(Y_{\mathbf{10}})_{\alpha\beta}(Y_{\overline{\mathbf{126}}})_{\gamma\delta} \\
&- x_4(Y_{\overline{\mathbf{126}}})_{\alpha\beta}(Y_{\mathbf{10}})_{\gamma\delta} + y_5(Y_{\overline{\mathbf{126}}})_{\alpha\beta}(Y_{\mathbf{120}})_{\gamma\delta} + y_7(Y_{\mathbf{10}})_{\alpha\beta}(Y_{\mathbf{120}})_{\gamma\delta} \\
&+ y_9(Y_{\mathbf{120}})_{\alpha\gamma}(Y_{\overline{\mathbf{126}}})_{\beta\delta} + y_{10}(Y_{\mathbf{120}})_{\alpha\gamma}(Y_{\mathbf{120}})_{\beta\delta}
\end{aligned}$$

$$Y_{\mathbf{10}} = \frac{h}{V_{11}}\,,\, Y_{\overline{\mathbf{126}}} = -f\,\frac{v_u^2}{m_0\,v_S}\,,\, Y_{\mathbf{120}} = i\,h'\,\frac{c_\nu}{4V_{13}}$$

GW from cosmic strings

- GW relic density depends on the string tension $G\mu$

$$G\mu \simeq \frac{1}{2(\alpha_{2R}(M_{B-L}) + \alpha_{1X}(M_{B-L}))} \frac{M_{B-L}^2}{M_{\rm pl}^2}$$

- In SUSY GUT

$$M_{B-L} \sim M_{\rm GUT}$$

$$\Downarrow$$

$$\alpha_{2R}(M_{B-L}) \simeq \alpha_{1X}(M_{B-L}) \simeq \alpha_{\rm GUT}(M_{\rm GUT})$$

$$\Downarrow$$

$$G\mu \simeq \frac{1}{4\alpha_{\rm GUT}(M_{\rm GUT})} \frac{M_{B-L}^2}{M_{\rm pl}^2}$$

GW from cosmic strings

- Decay rate of cosmic strings into monopoles

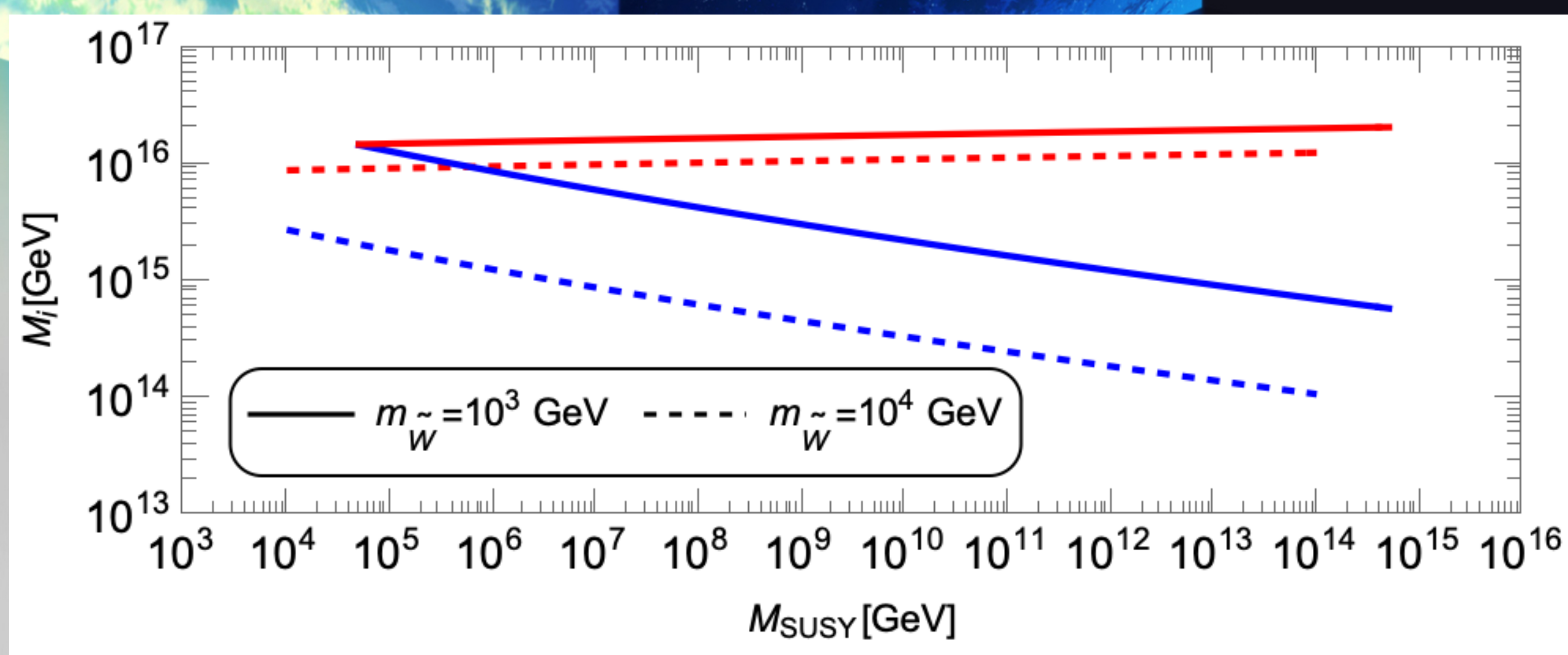
$$\Gamma_d = \frac{\mu}{2\pi} e^{-\pi\kappa}, \quad \kappa = \frac{m^2}{\mu}$$

  - Monopole mass $m = \frac{M_V}{\alpha} f_{\rm m}$
  - $\mu \simeq \frac{1}{\alpha_{\rm GUT}} M_{B-L}^2, m = \frac{M_{\rm GUT}}{\alpha_{\rm GUT}} \Rightarrow \sqrt{\kappa} \simeq \alpha_{\rm GUT}^{-1/2} \frac{M_{\rm GUT}}{M_{B-L}}$

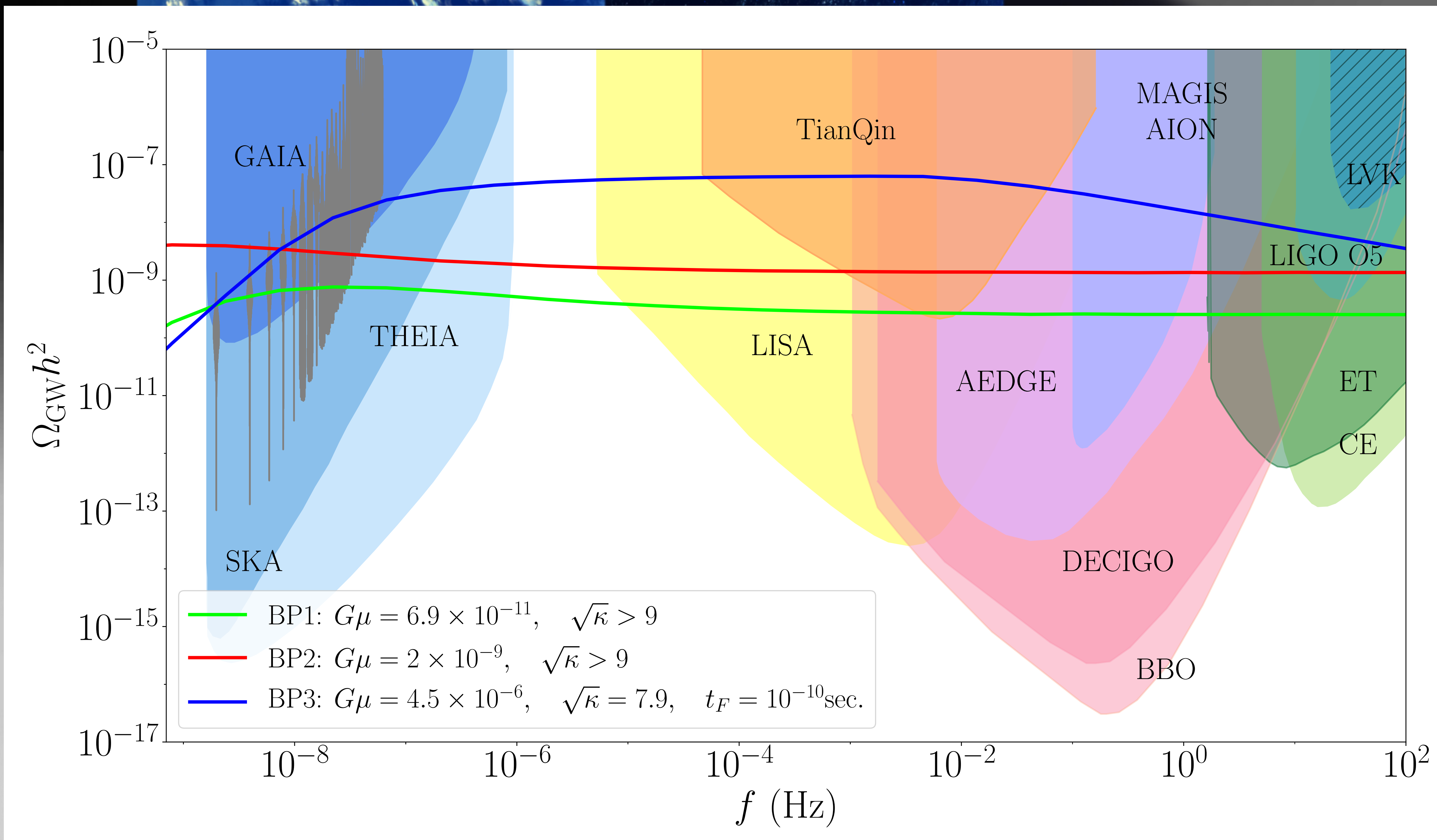
- Stability of cosmic strings
  - Stable: $M_{B-L} \ll M_{\rm GUT} \quad (\sqrt{\kappa} > 9)$
  - Metastable: $M_{B-L} \lesssim M_{\rm GUT} \quad (\sqrt{\kappa} < 9)$

GW from cosmic strings

- Small M_{SUSY}, small $\sqrt{\kappa}$, metastable string
- Small $M_{\tilde{W}}$, small $\sqrt{\kappa}$, metastable string

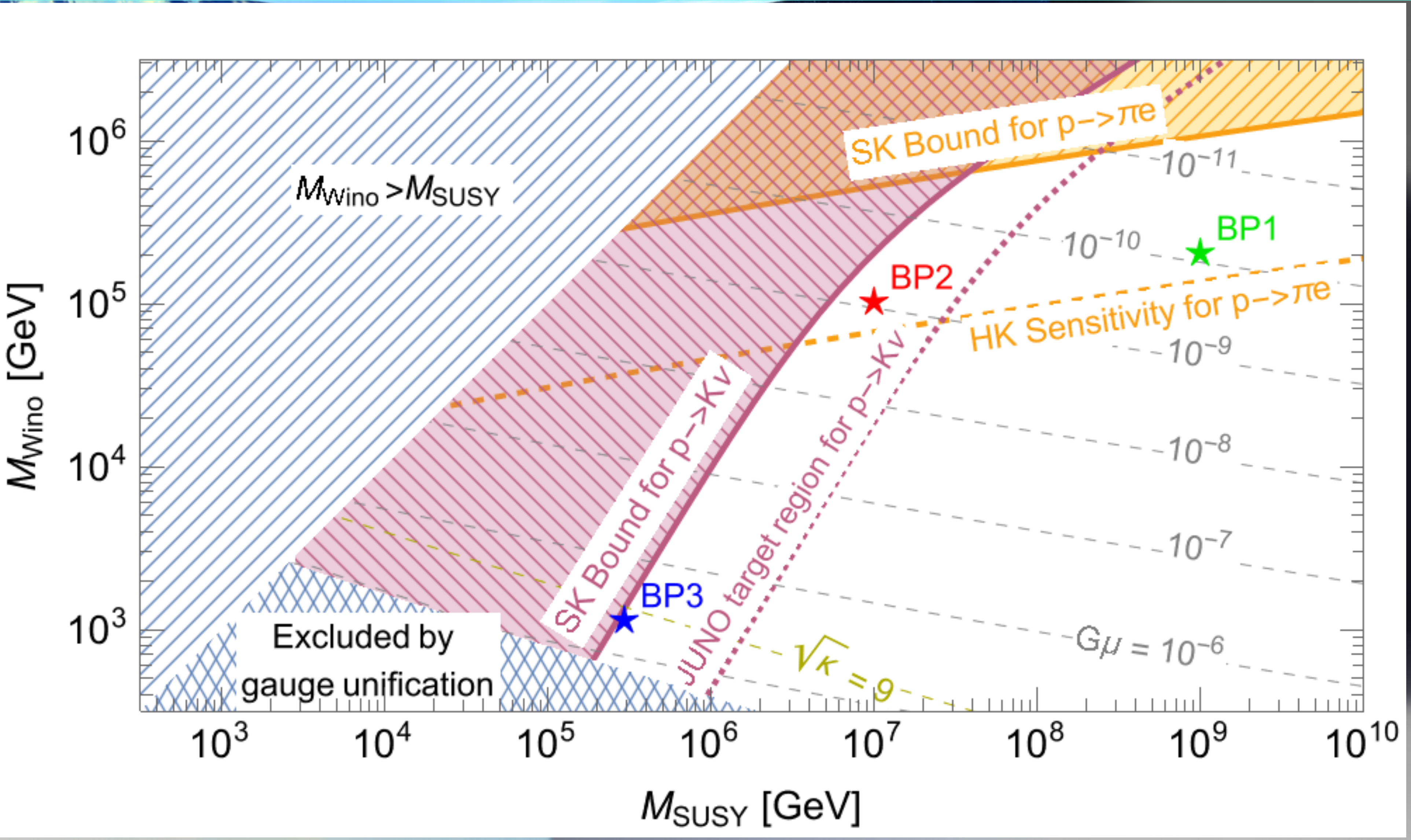


Gravitational Waves



Results

Predictions of Benchmark Points



	HK sensitivity	JUNO target	NANOGrav15
BP1	testable	no signal	consistent
BP2	testable	targeted	inconsistent
BP3	no signal	targeted	support

Thank you