Phenomenological tests of supersymmetric SO(10) grand unified theories

Bowen Fu

Hangzhou Institute for Advanced Study (HIAS), 10 April 2024
Workshop on Grand Unified Theory, Phenomenology and Cosmology (GUTPC)

李政道研究所
Tsung-Dao Lee Institute

SUSY SO(10)

2308.05799 **BF**, King, Marsili, Pascoli, Turner, Zhou

2308.05799 **BF**, King, Marsili, Pascoli, Turner, Zhou

Gauge Unification

$$
\begin{array}{c}
SO(10) \times \mathrm{SUSY} \\
\Big\downarrow \ \text{broken at } M_{\mathrm{GUT}} \\
SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times \mathrm{SUSY} \\
\Big\downarrow \ \text{broken at } M_{B-L} \\
SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathrm{SUSY} \\
\Big\downarrow \ \text{broken at } M_{\mathrm{SUSY}} \\
SU(3)_c \times SU(2)_L \times U(1)_Y
\end{array}
$$

Gauge Unification

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

Monopole Formation $\longrightarrow$ $\bigg\downarrow$ broken at M_{GUT}

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

$$\bigg\downarrow \text{ broken at } M_{B-L}$$

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

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

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

Gauge Unification

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

Monopole Formation $\longrightarrow$ $\Big\downarrow$ broken at M_{GUT}

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

Cosmic String Formation $\longrightarrow$ $\Big\downarrow$ broken at M_{B-L}

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathrm{SUSY}$$

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

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

Gauge Unification

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

Monopole Formation $\longrightarrow$ $\Big\downarrow$ broken at M_{GUT}

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

Cosmic String Formation $\longrightarrow$ $\Big\downarrow$ broken at M_{B-L}

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

Proton Decay $\longrightarrow$ $\Big\downarrow$ broken at M_{SUSY}

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

Gauge Unification

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

Monopole Formation → $\Big\downarrow$ broken at M_{GUT}

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

Cosmic String Formation → $\Big\downarrow$ broken at M_{B-L}

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathrm{SUSY}$$

Proton Decay → $\Big\downarrow$ broken at M_{SUSY}

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

Split supersymmetry

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

Gauge Unification

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

Monopole Formation → $\downarrow$ broken at M_{GUT}

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

Cosmic String Formation → $\downarrow$ broken at M_{B-L}

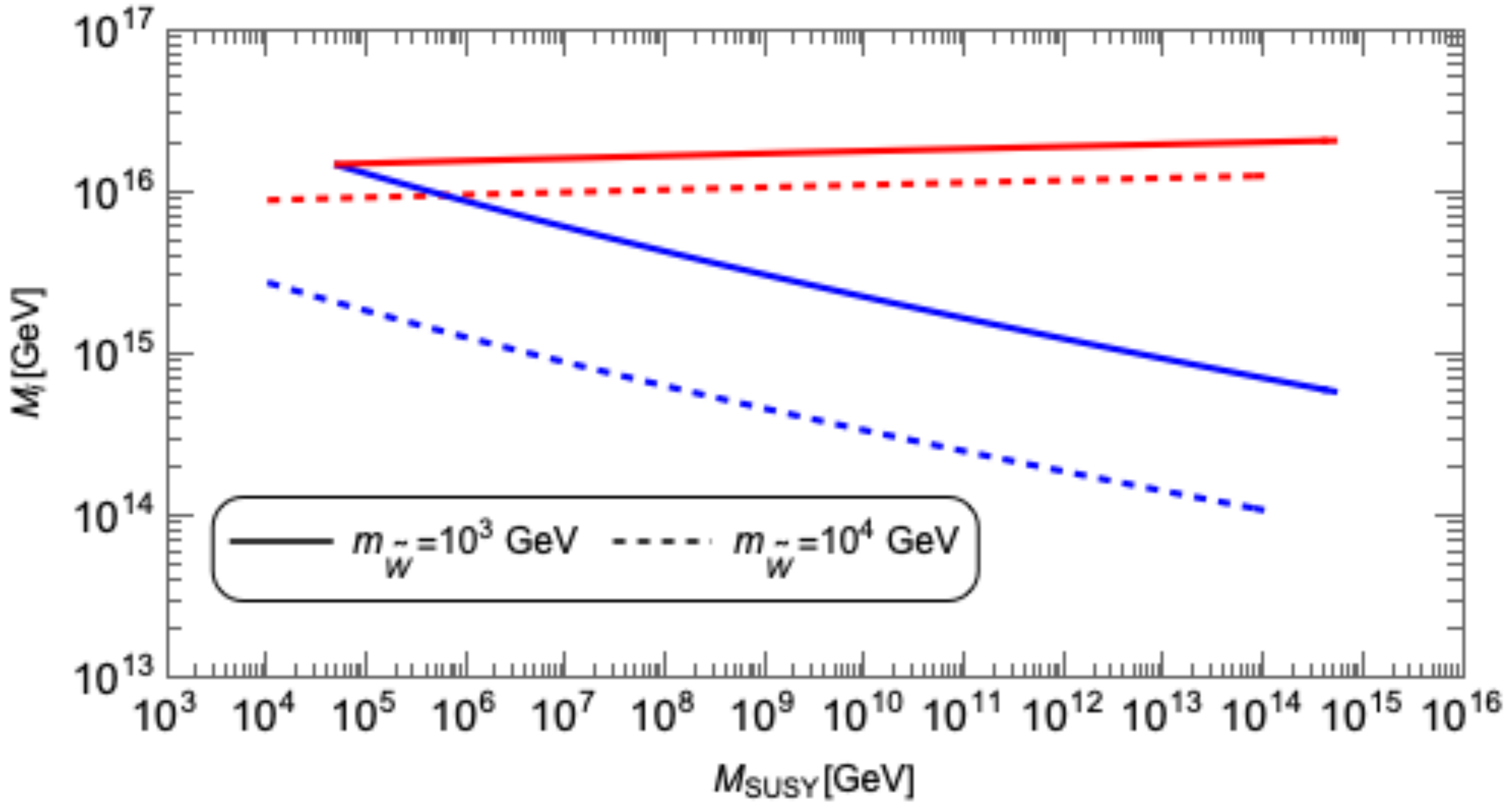
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathrm{SUSY}$$

Proton Decay → $\downarrow$ broken at M_{SUSY}

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

Split supersymmetry

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



Gauge Unification

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

Monopole Formation → $\big\downarrow$ broken at M_{GUT}

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

Cosmic String Formation → $\big\downarrow$ broken at M_{B-L}

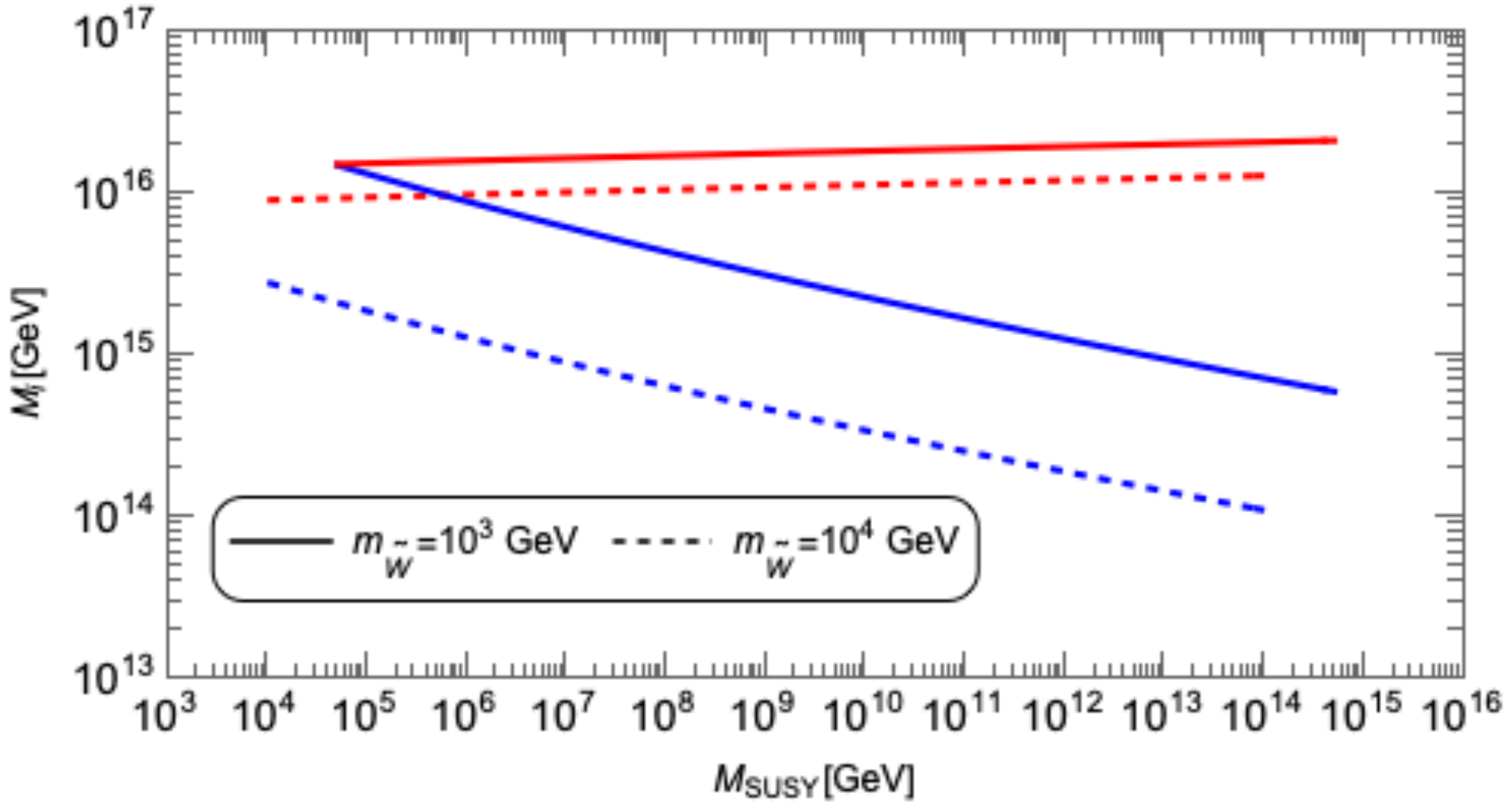
$$SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathrm{SUSY}$$

Proton Decay → $\big\downarrow$ broken at M_{SUSY}

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

Split supersymmetry

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



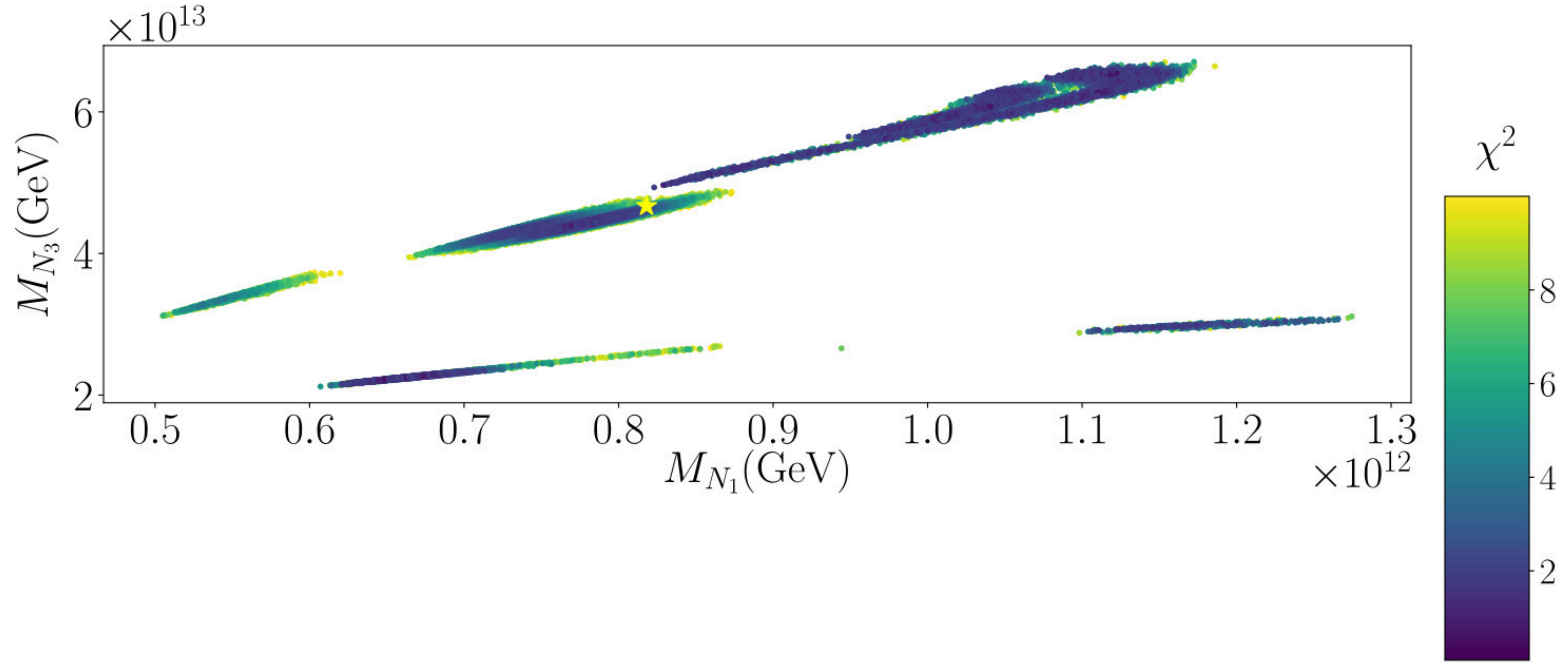
Lower SUSY breaking $\Longrightarrow$

closer GUT and B-L breaking scale

Neutrino Phenomenology

Leptogenesis

- $M_{N_3} \sim 10^{13}\,\mathrm{GeV}$
- mild mass hierarchy
- viable leptogenesis



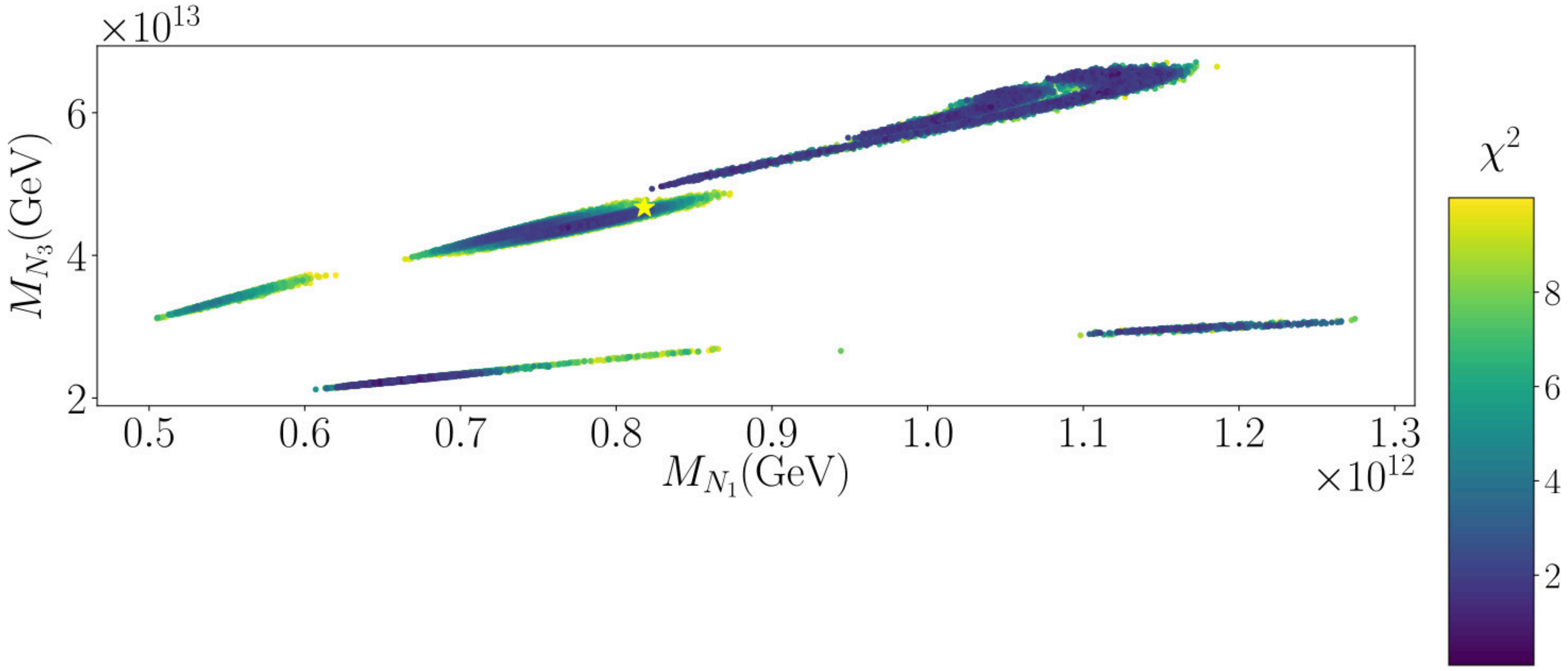
Neutrino Phenomenology

Leptogenesis

- $M_{N_3} \sim 10^{13}$ GeV
- mild mass hierarchy
- viable leptogenesis

Example benchmark point $\eta_B \sim 6.2 \times 10^{-10}$

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



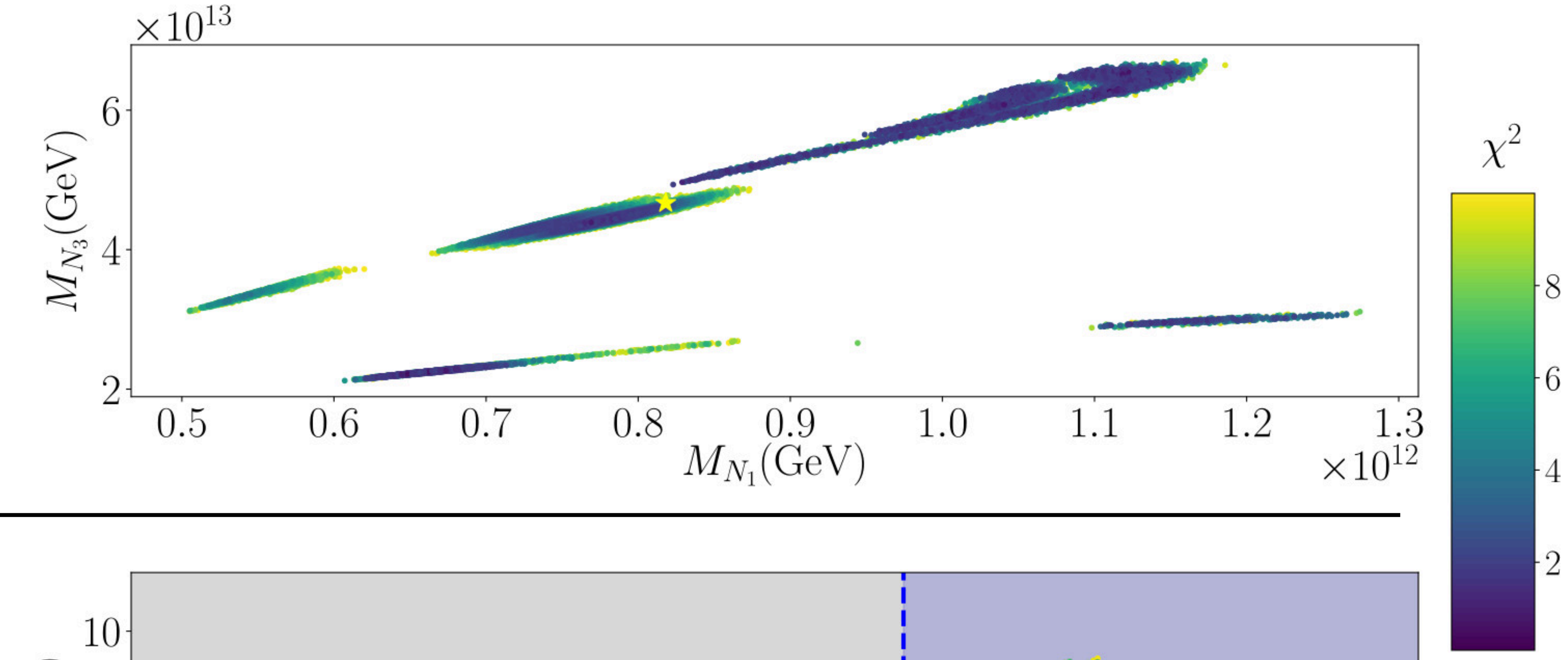
Neutrino Phenomenology

Leptogenesis

- $M_{N_3} \sim 10^{13}\,\mathrm{GeV}$
- mild mass hierarchy
- viable leptogenesis

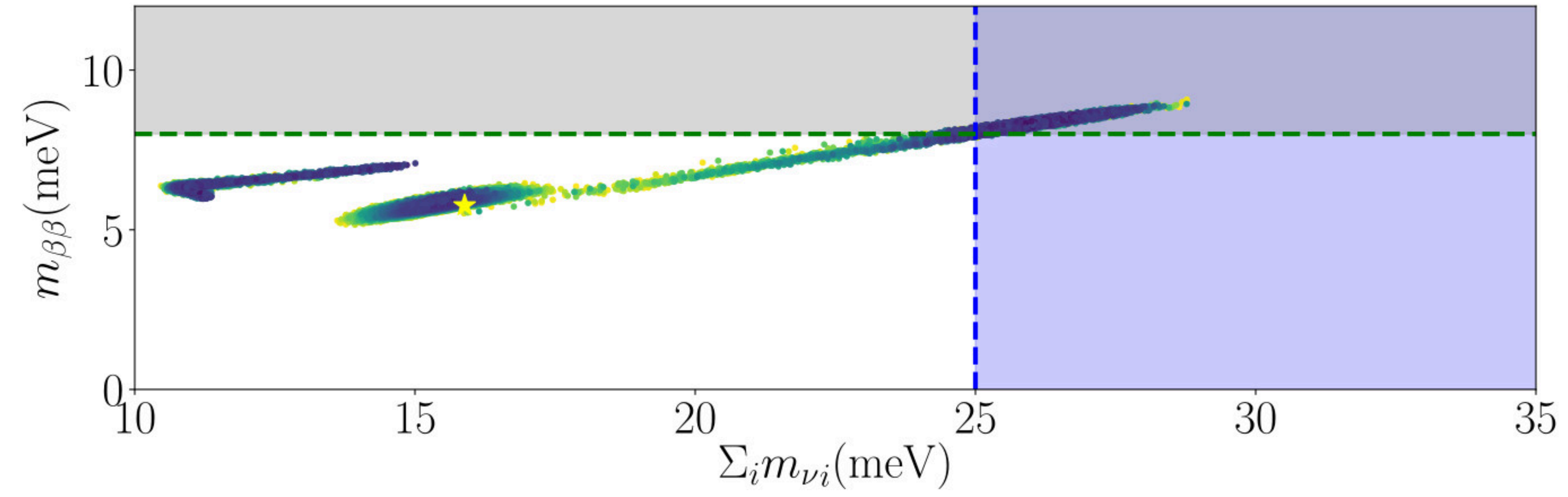
Example benchmark point $\eta_B \sim 6.2 \times 10^{-10}$

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 meV	$(-,+,+;+,-,-)$
Outputs	θ_{13}	θ_{12}	θ_{23}	δ	m_1
	8.66°	33.19°	44.14°	131.57°	5.29 meV
$(\chi^2 = 8.22)$	$m_{\beta\beta}$		M_{N_1}	M_{N_2}	M_{N_3}
	5.76 meV		$8.18 \cdot 10^{11}$ GeV	$1.53 \cdot 10^{12}$ GeV	$4.67 \cdot 10^{13}$ GeV



Double beta decay

$$5 \lesssim m_{\nu_1}\,(\mathrm{meV}) \lesssim 10$$



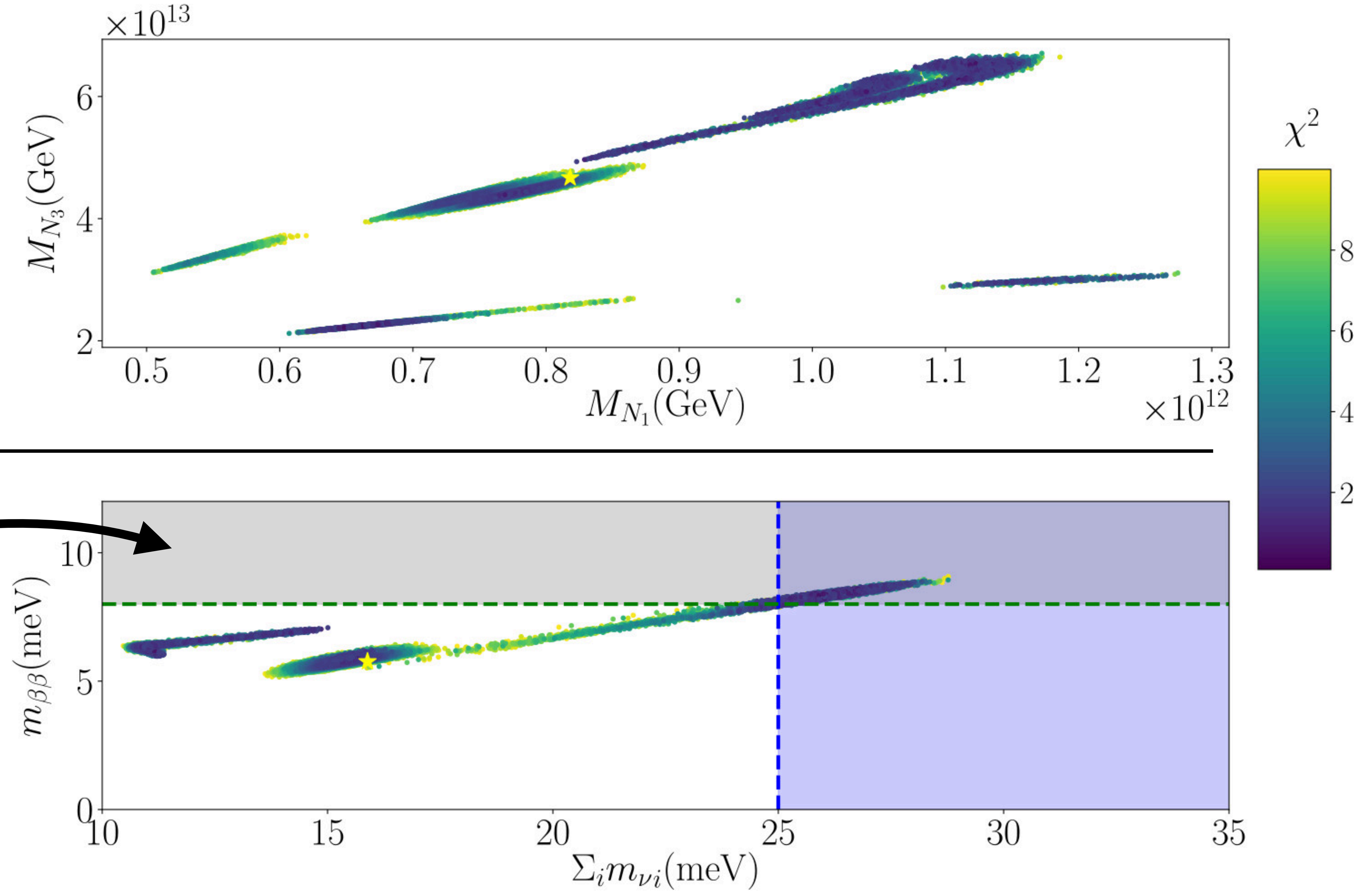
Neutrino Phenomenology

Leptogenesis

- $M_{N_3} \sim 10^{13}\,\text{GeV}$
- mild mass hierarchy
- viable leptogenesis

Example benchmark point $\eta_B \sim 6.2 \times 10^{-10}$

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 meV	$(-,+,+;+,-,-)$
Outputs	θ_{13}	θ_{12}	θ_{23}	δ	m_1
	8.66°	33.19°	44.14°	131.57°	5.29 meV
$(\chi^2 = 8.22)$	$m_{\beta\beta}$		M_{N_1}	M_{N_2}	M_{N_3}
	5.76 meV		$8.18 \cdot 10^{11}$ GeV	$1.53 \cdot 10^{12}$ GeV	$4.67 \cdot 10^{13}$ GeV



Double beta decay

$$5 \lesssim m_{\nu_1}\,(\text{meV}) \lesssim 10$$

Next generation experiment

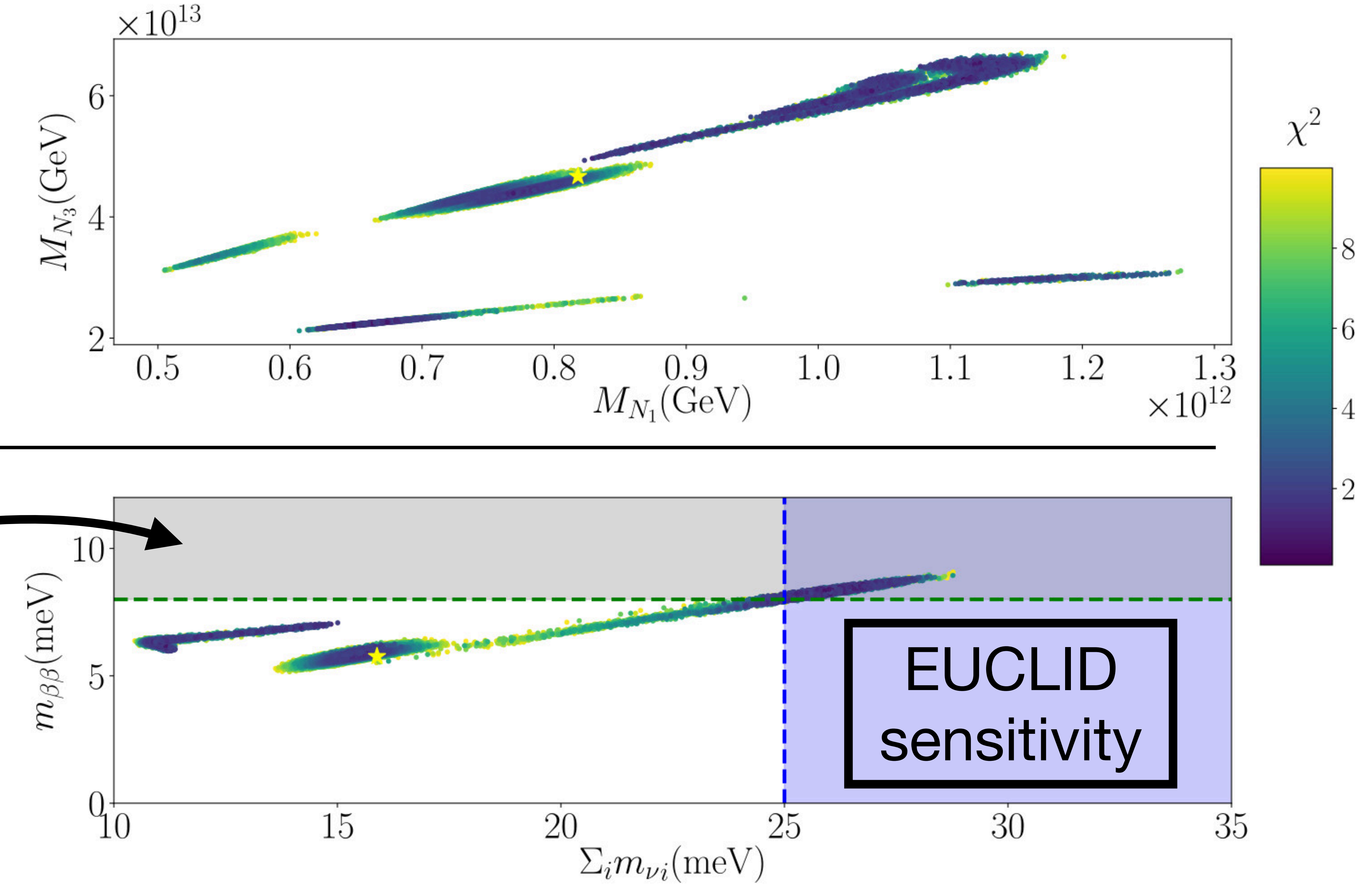
Neutrino Phenomenology

Leptogenesis

- $M_{N_3} \sim 10^{13}\,\mathrm{GeV}$
- mild mass hierarchy
- viable leptogenesis

Example benchmark point $\eta_B \sim 6.2 \times 10^{-10}$

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 meV	$(-, +, +; +, -, -)$
Outputs	θ_{13}	θ_{12}	θ_{23}	δ	m_1
	8.66°	33.19°	44.14°	131.57°	5.29 meV
$(\chi^2 = 8.22)$	$m_{\beta\beta}$		M_{N_1}	M_{N_2}	M_{N_3}
	5.76 meV		$8.18 \cdot 10^{11}$ GeV	$1.53 \cdot 10^{12}$ GeV	$4.67 \cdot 10^{13}$ GeV



Double beta decay

$5 \lesssim m_{\nu_1}\,(\mathrm{meV}) \lesssim 10$

Next generation experiment

Proton Decay

- Pion channel $p \to \pi^0 + e^+$:
  - $\frac{\epsilon_{\alpha\beta}}{\Lambda^2}\left[(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{d_R^c}\gamma_\mu L_\beta) + \ldots\right]$
  - $\tau \propto \frac{M_{\mathrm{GUT}}^2}{g_{\mathrm{GUT}}^2}$
  - fully determined by gauge unification

- Kaon channel $p \to K^+ + \bar{\nu}$:
  - $\frac{\epsilon_{abc}}{M_T}\left(C^L_{\alpha\beta\gamma\delta} Q^a_\alpha Q^b_\beta Q^c_\gamma L_l + \ldots\right)$
  - $\tau \propto M_{\mathrm{GUT}}^2 M_{\mathrm{SUSY}}^2 \times \frac{M_{\mathrm{SUSY}}^2}{m_{\widetilde{W}}^2}$
  - Wino-mediated processes depend on the Higgs mixing parameter which cannot be fully fixed by data

Proton Decay

- Pion channel $p \to \pi^0 + e^+$:
  - $\frac{\epsilon_{\alpha\beta}}{\Lambda^2}\left[(\overline{u_R^c}\gamma^\mu Q_\alpha)(\overline{d_R^c}\gamma_\mu L_\beta) + \ldots\right]$
  - $\tau \propto \frac{M_{\mathrm{GUT}}^2}{g_{\mathrm{GUT}}^2}$
  - fully determined by gauge unification
- Kaon channel $p \to K^+ + \bar{\nu}$:
  - $\frac{\epsilon_{abc}}{M_T}\left(C^L_{\alpha\beta\gamma\delta} Q^a_\alpha Q^b_\beta Q^c_\gamma L_l + \ldots\right)$
  - $\tau \propto M_{\mathrm{GUT}}^2 M_{\mathrm{SUSY}}^2 \times \frac{M_{\mathrm{SUSY}}^2}{m_{\widetilde{W}}^2}$
  - Wino-mediated processes depend on the Higgs mixing parameter which cannot be fully fixed by data

uncertainty!

Metastable Cosmic String

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

Monopole Formation at M_{GUT} → $\downarrow$

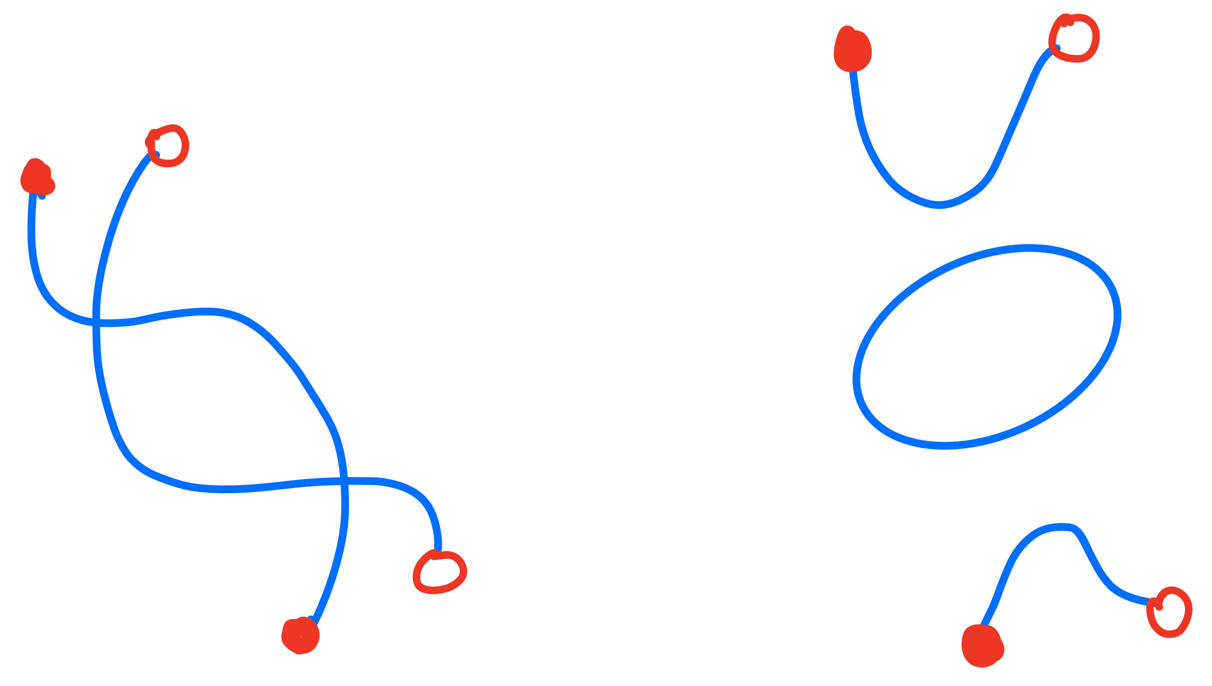
$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times \text{SUSY}$$

Cosmic String Formation at M_{B-L} → $\downarrow$

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

$$\cancel{\textbf{SUSY}} \downarrow$$

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



$m^2_{\text{mono}} \sim \mu \implies$ monopoles & antimonopoles can nucleate on string & annihilate $\implies$ **metastable string**

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

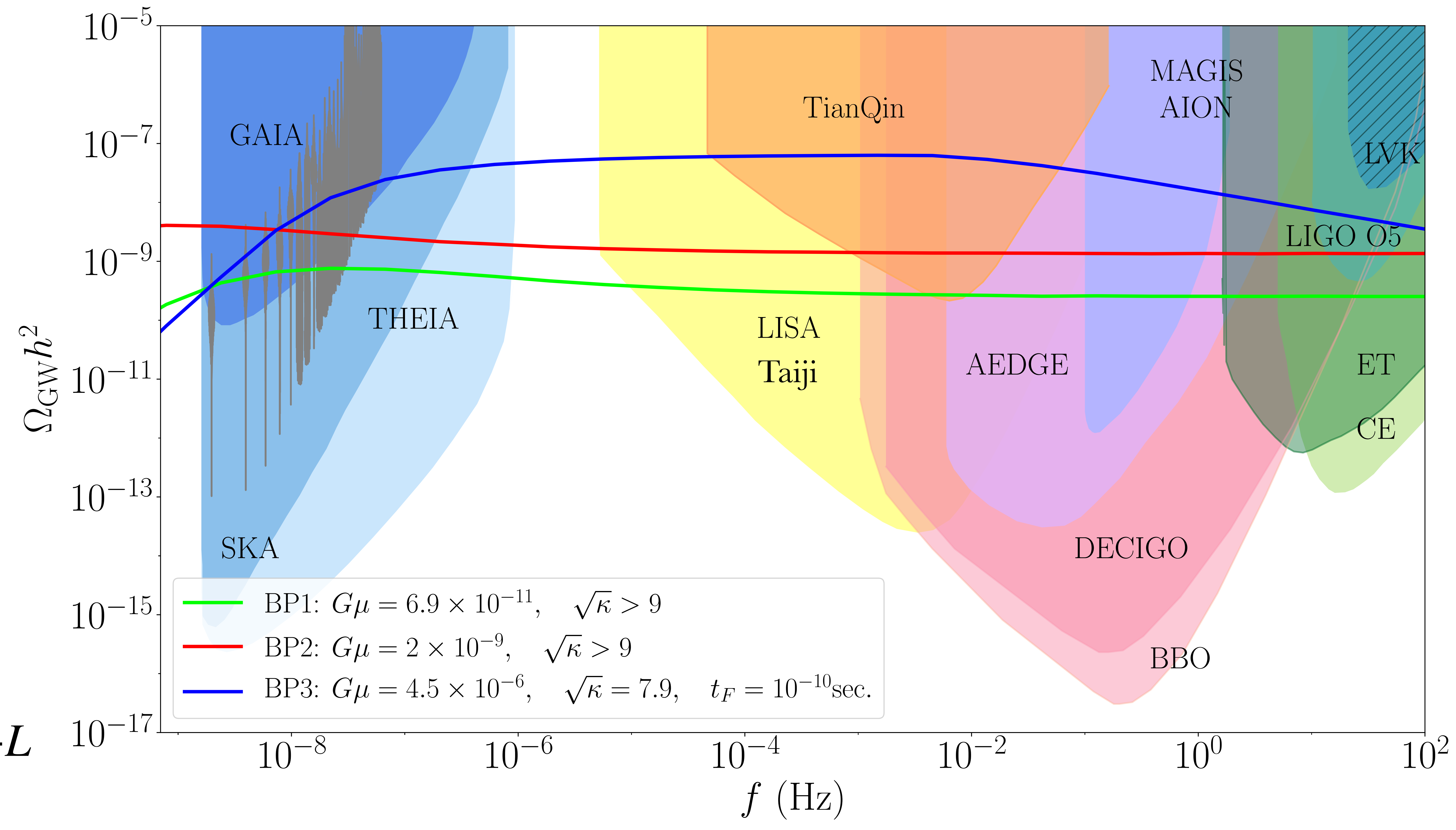
$$\mu \simeq \frac{1}{\alpha_{\text{GUT}}} M^2_{B-L}, m = \frac{M_{\text{GUT}}}{\alpha_{\text{GUT}}} \Rightarrow \sqrt{\kappa} \simeq \alpha_{\text{GUT}}^{-1/2} \frac{M_{\text{GUT}}}{M_{B-L}}$$

Vilenkin [1982], Leblond, Shlaer, Siemens [2009], Monin & Voloshin [2009], Buchmuller, Domcke, Schmitz [2021]

Gravitational Wave

- BP1: Stable string allowed by NG15
- BP2: Stable string ruled out by NG15
- BP3: Metastable string explaining NG15

$$\sqrt{\kappa} \sim 7.9 \implies M_{\rm GUT} \sim 1.5\, M_{B-L}$$



Pulsar Timing Array results

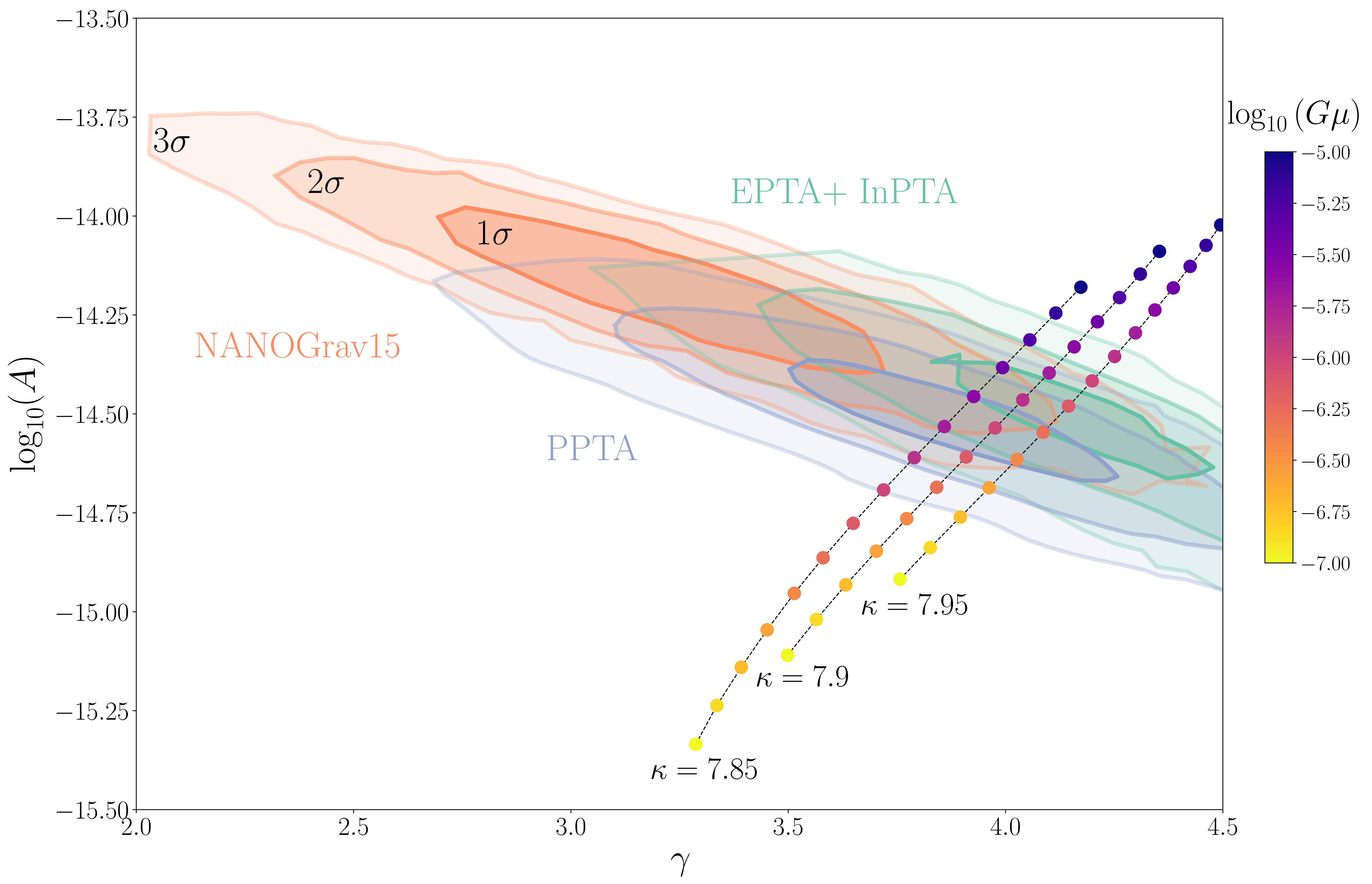
power-law spectrum: amplitude parameter A and power parameter γ

characteristic strain:

$$h_c(f) = A\left(\frac{f}{f_{\rm yr}}\right)^{\gamma}$$

energy density spectrum:

$$\Omega(f) = \Omega_{yr}\left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma}$$



Pulsar Timing Array results

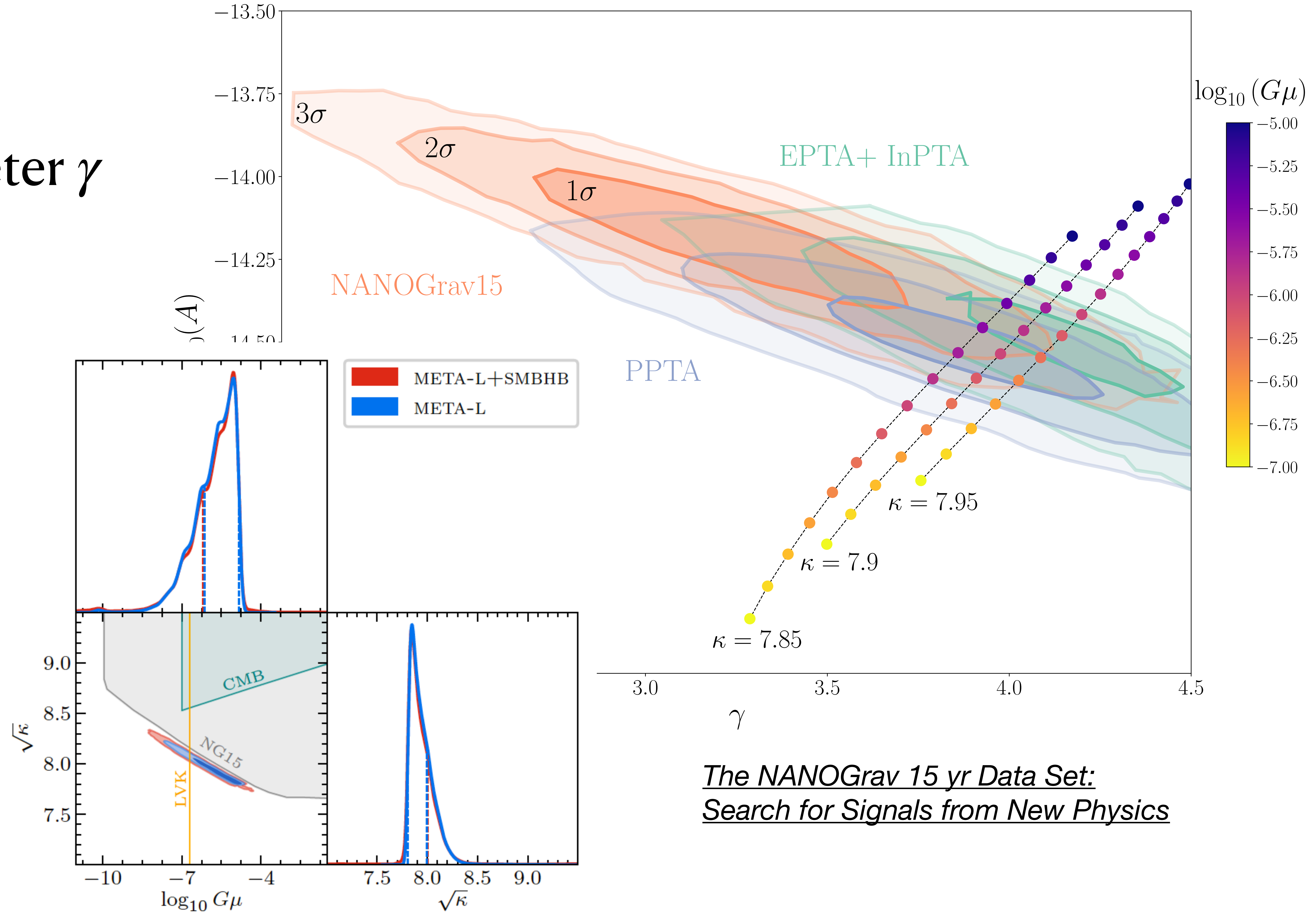
power-law spectrum: amplitude parameter A and power parameter γ

characteristic strain:

$$h_c(f) = A\left(\frac{f}{f_{\rm yr}}\right)^{\gamma}$$

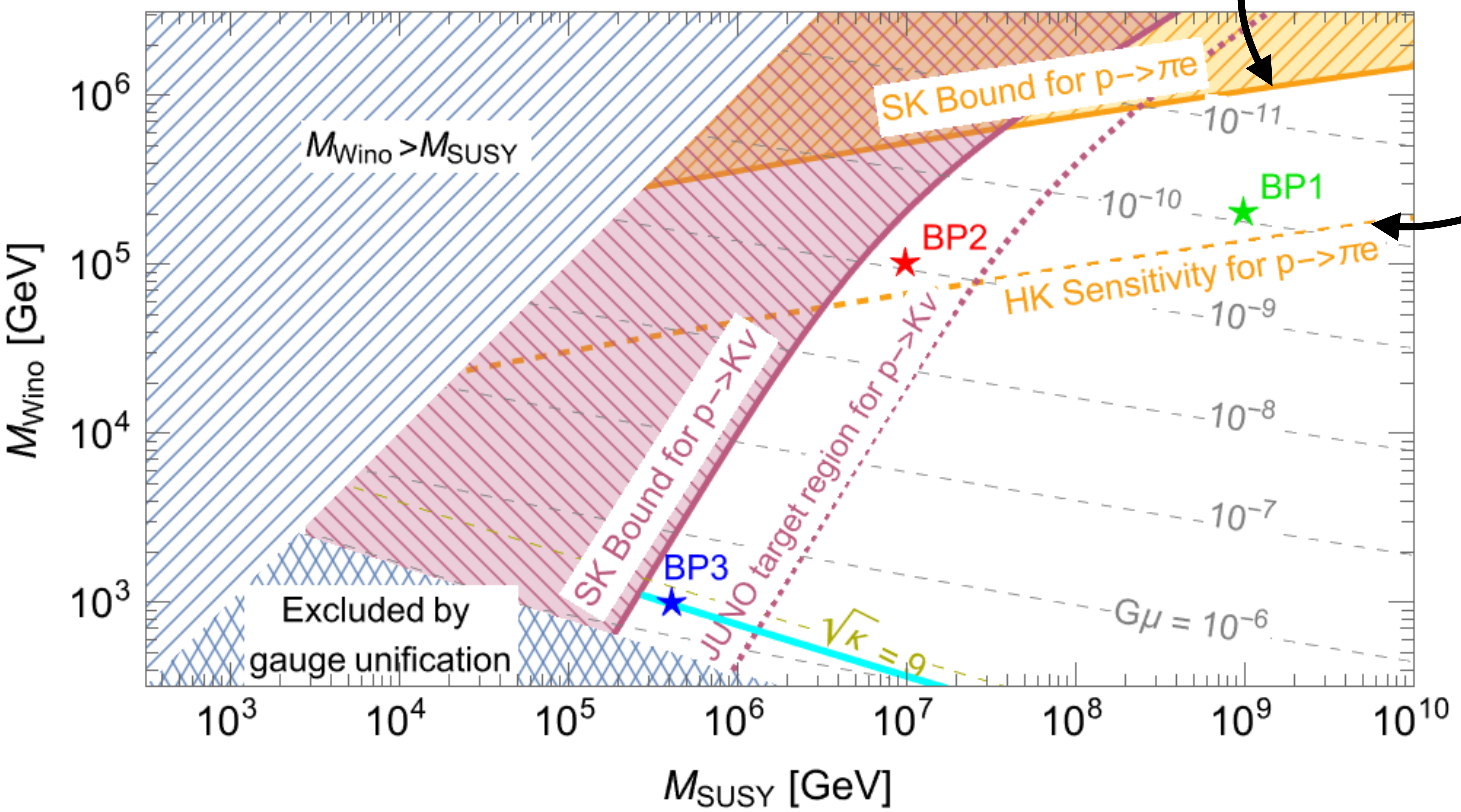
energy density spectrum:

$$\Omega(f) = \Omega_{yr}\left(\frac{f}{f_{\rm yr}}\right)^{5-\gamma}$$



The NANOGrav 15 yr Data Set: Search for Signals from New Physics

Constraints, Sensitivities and Signals

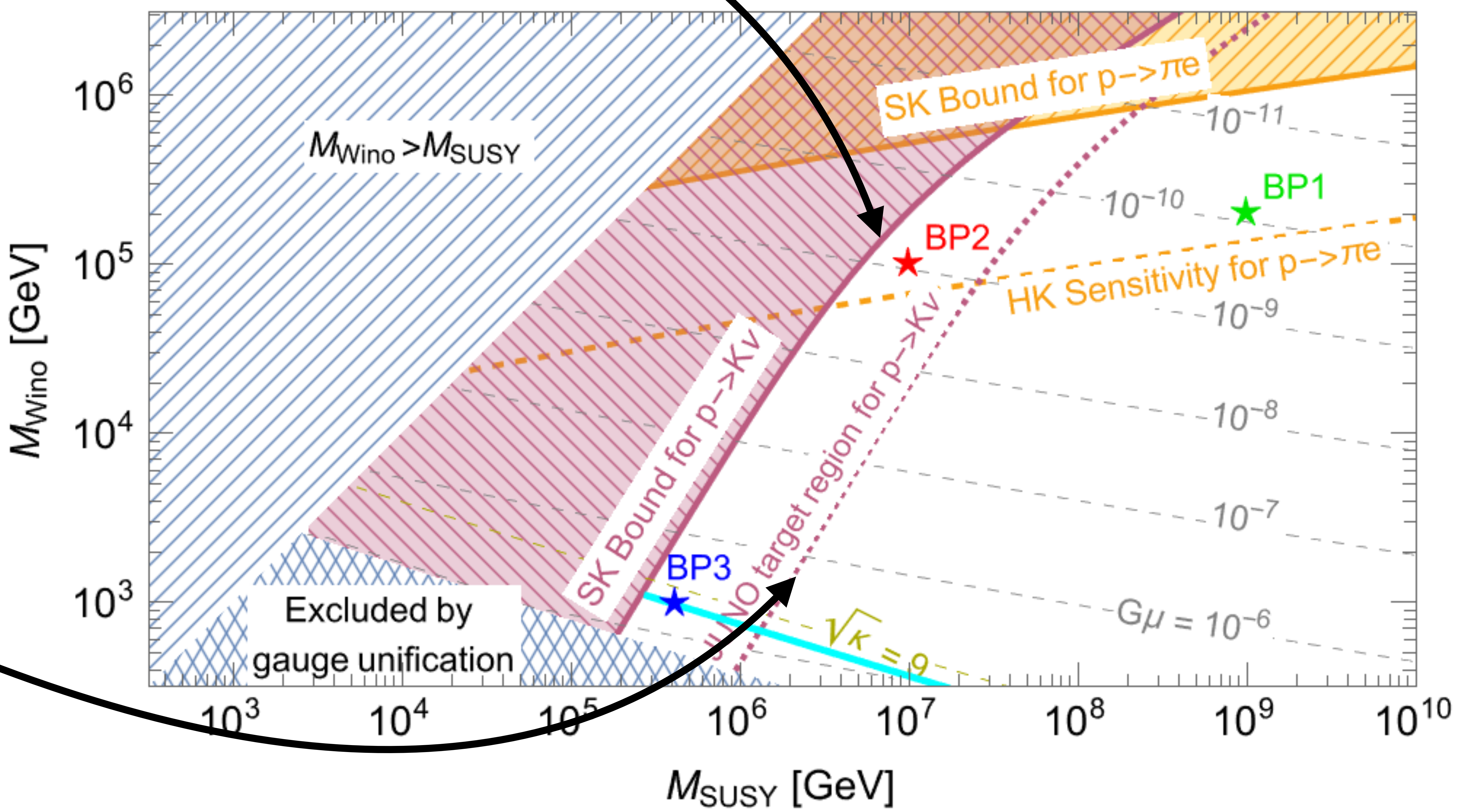


Current bound on pion channel proton decay

Future sensitivity on pion channel proton decay

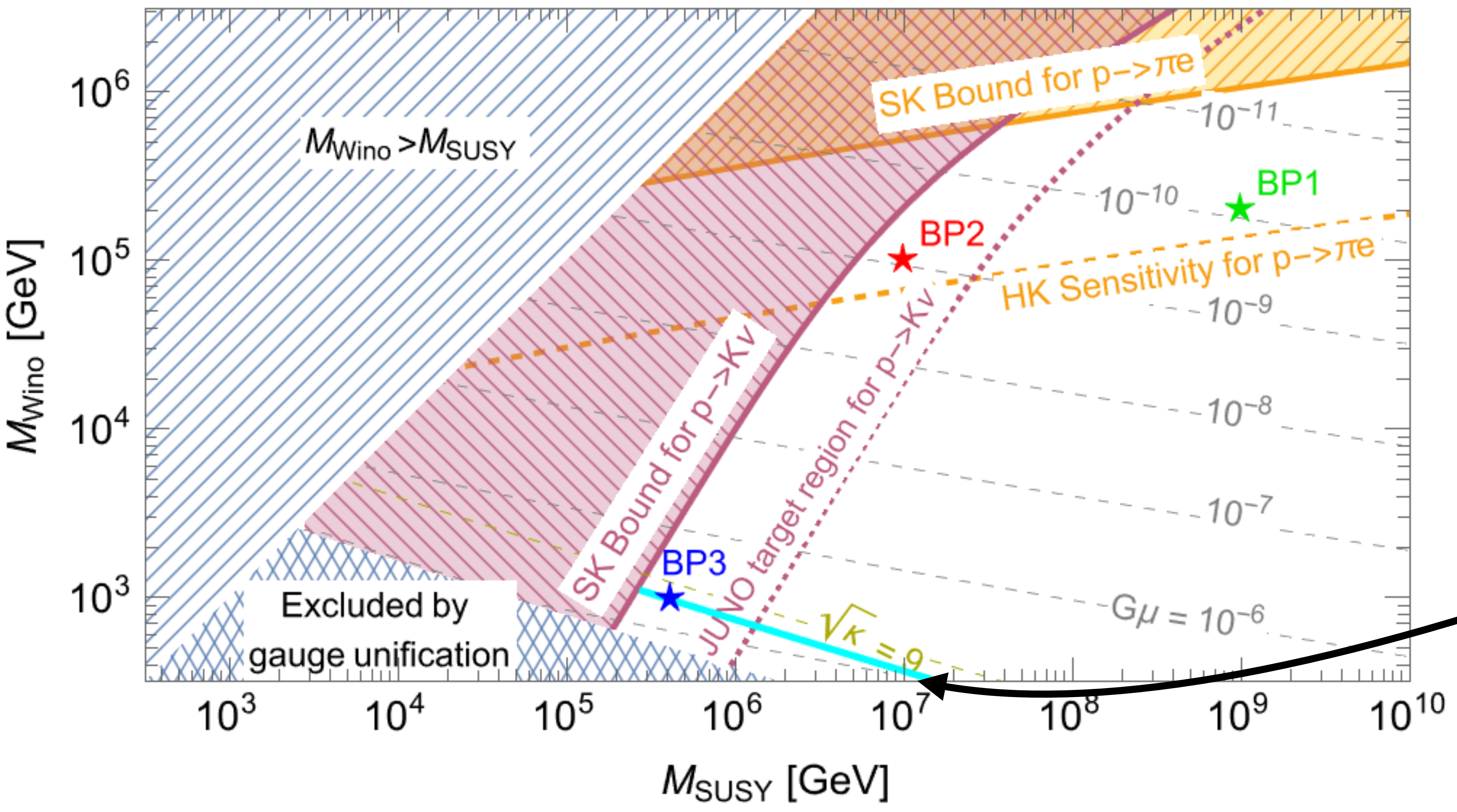
Constraints, Sensitivities and Signals

Left: can only predicts kaon channel proton decay that is excluded by SK
Right: can predict kaon channel proton decay that is not excluded by SK yet



Left: can predict kaon channel proton decay that can be measured by JUNO
Right: cannot predict kaon channel proton decay that can be measured by JUNO

Constraints, Sensitivities and Signals

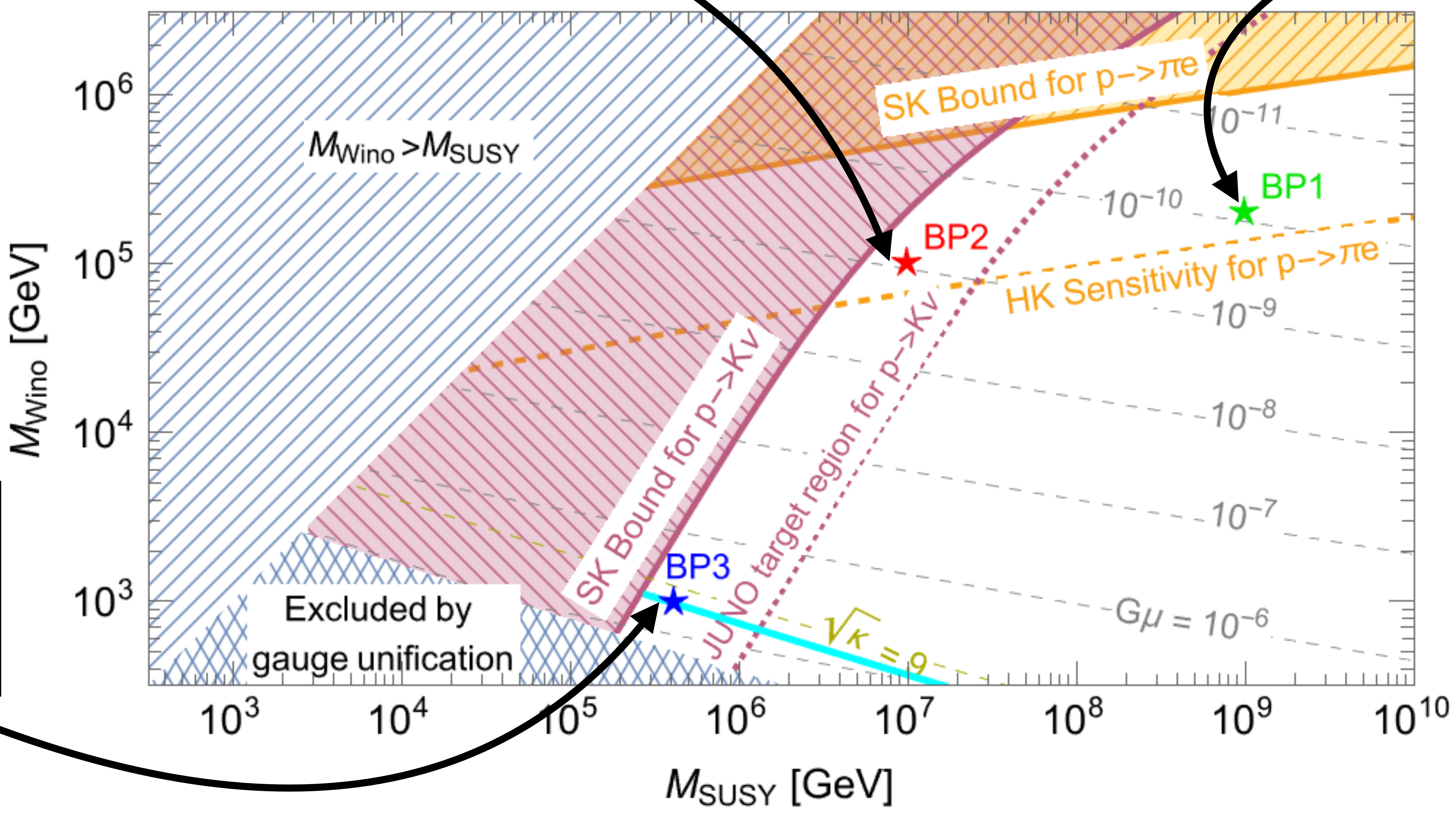


3σ region for NG15

Constraints, Sensitivities and Signals

Testable by Hyper-K
JUNO can observe $p \to K^+\bar{\nu}$
Inconsistent with PTA signal

Testable by Hyper-K
Cannot explain PTA signal



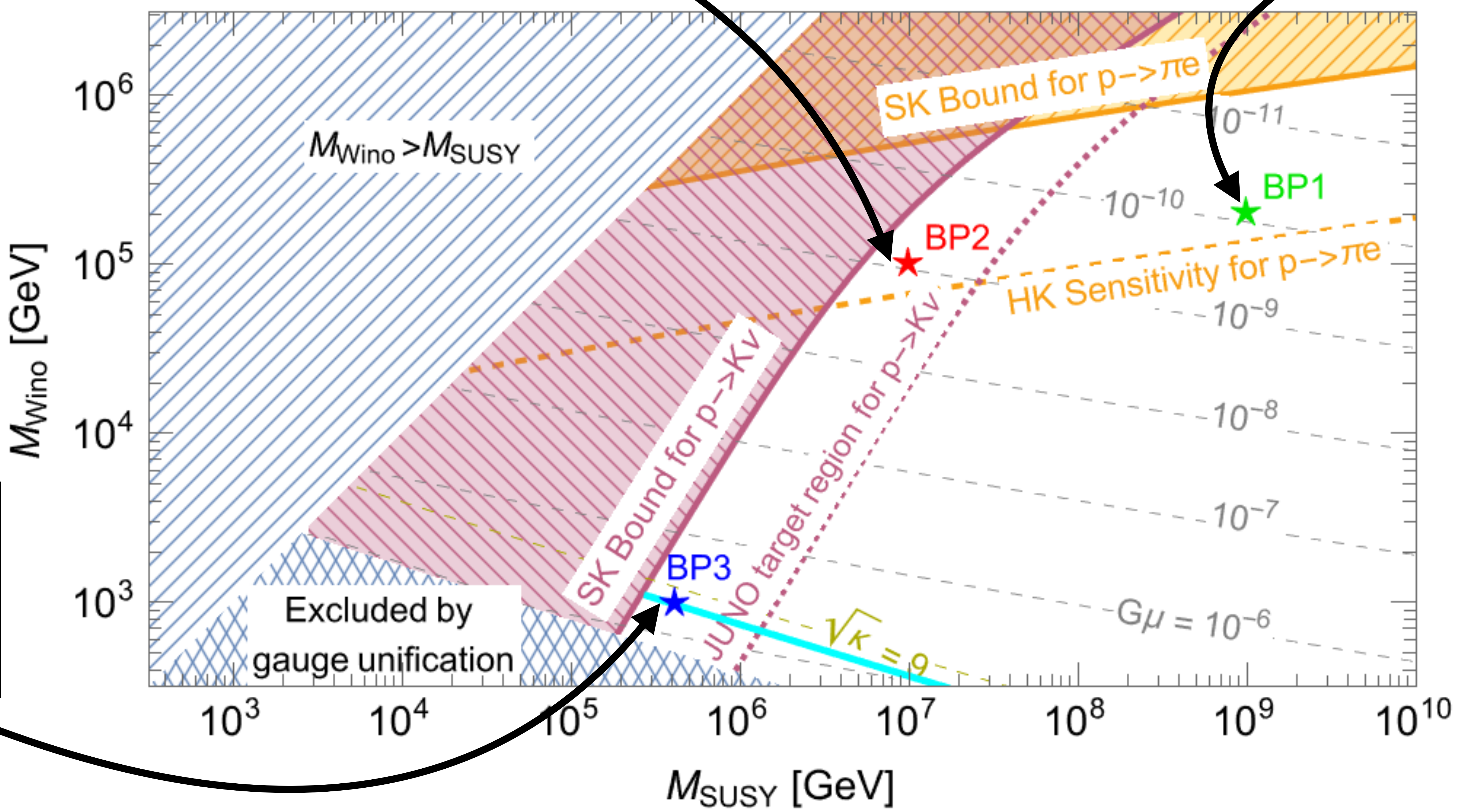
JUNO can observe
$p \to K^+\bar{\nu}$
Can explain PTA signal

Constraints, Sensitivities and Signals

Testable by Hyper-K
JUNO can observe $p \to K^+\bar{\nu}$
Inconsistent with PTA signal

Testable by Hyper-K
Cannot explain PTA signal

JUNO can observe
$p \to K^+\bar{\nu}$
Can explain PTA signal



	HK	JUNO	NG15
BP1	✅	N	N
BP2	✅	?	❌
BP3	N	?	✅

Summary

- Successful prediction of fermion masses and mixing angles, leptogenesis
- Natural proximity of the intermediate scale and the GUT scale, leading to metastable cosmic strings
- Proton decay measurements and PTA observations cover complementary regions of the parameter space in the split-SUSY scenario
- An eventual observation of proton decay from both the pion and kaon channels is not consistent with the current PTA observations

Thank you!