GUTs in light of neutrino precision measurements

Ye-Ling Zhou, HIAS, 2026-08-16

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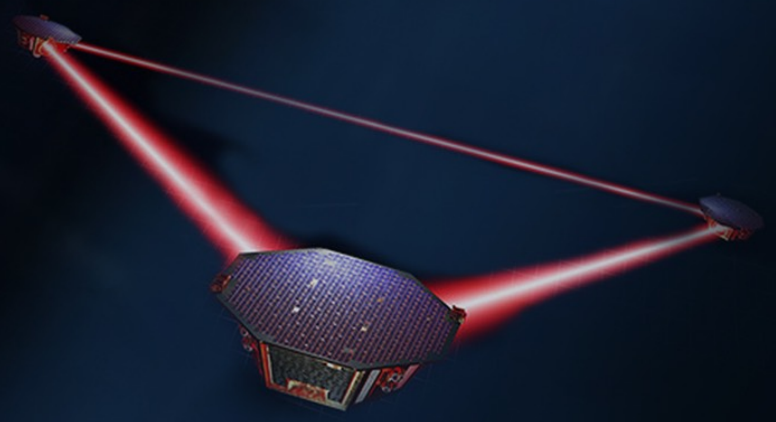
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

Grand unified theories in era of neutrino precision measurements and gravitational wave observations



Ye-Ling Zhou (HIAS-UCAS) 2024-07-21

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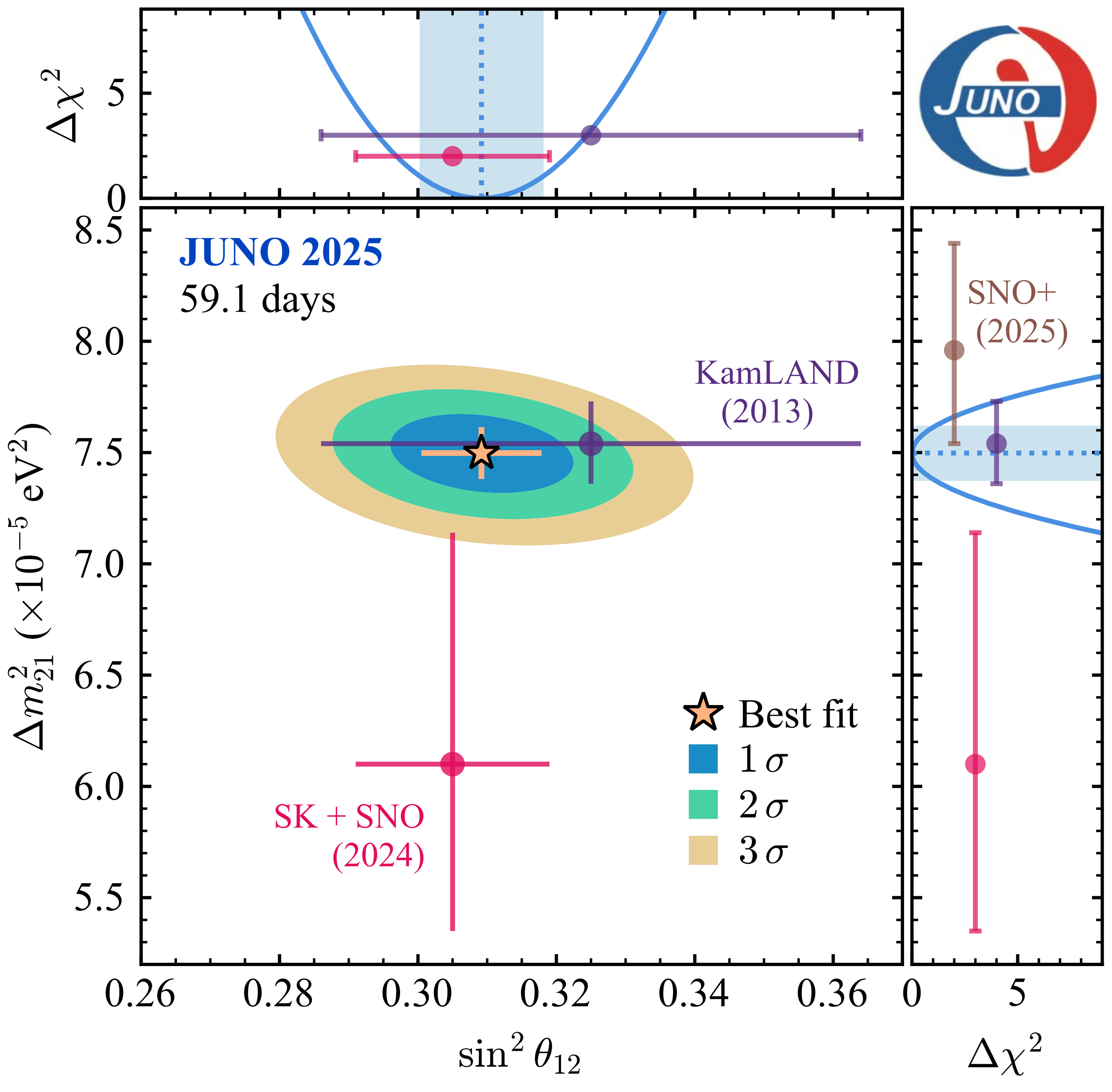
After 1 year following the beginning of the precision era

JUNO data first release

$$\sin^2\theta_{12} = 0.3092 \pm 0.0087$$

$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \mathrm{eV}^2$$

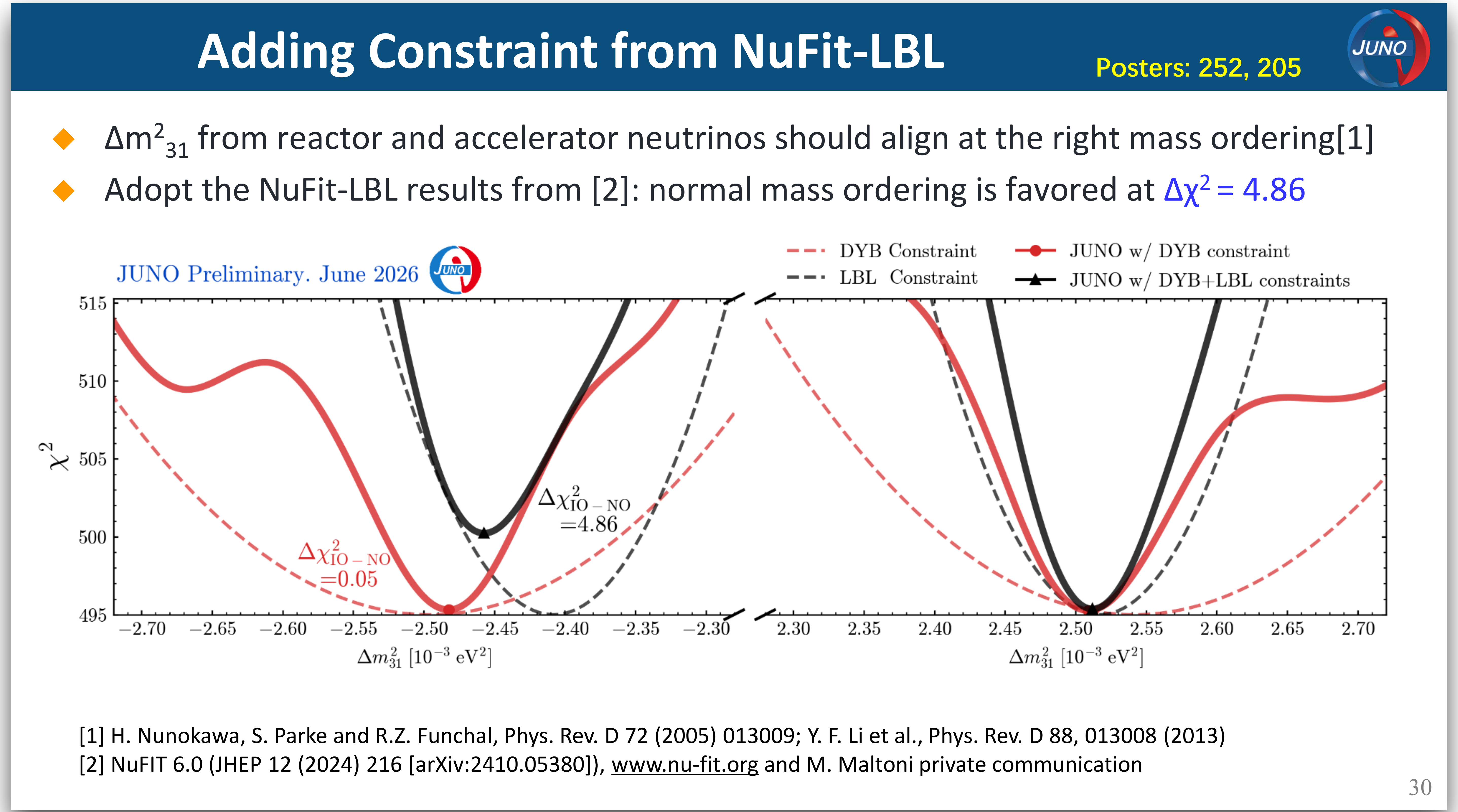
2511.14593



First results using 59 days' data

See Yi Jia' talk

Yifang Wang's talk in Neutrino 2026



Hint to neutrino mass ordering using 207 days' data

This talk will discuss

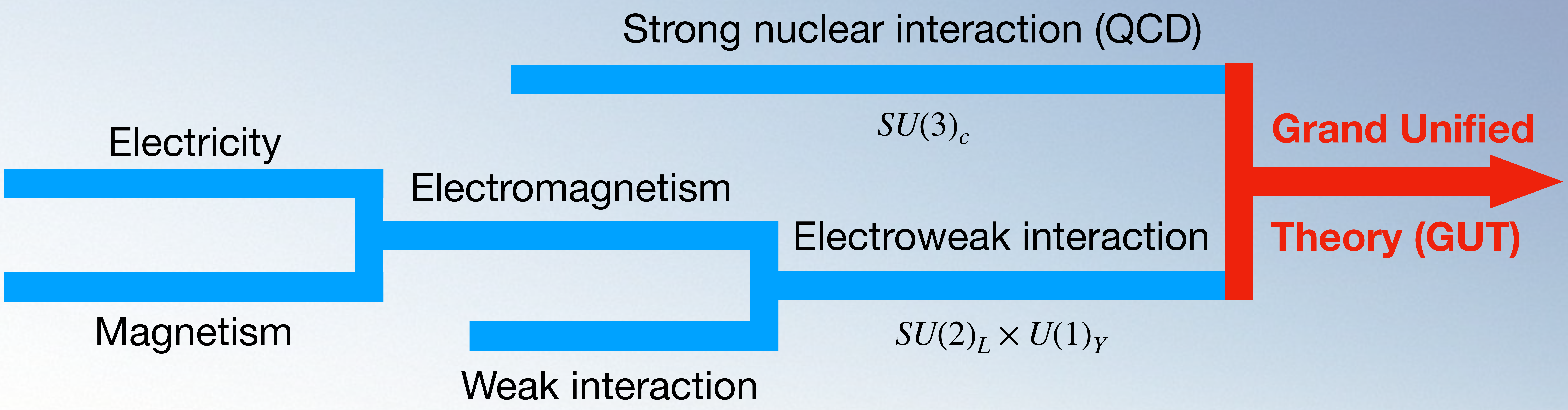
- How GUTs provide insight to neutrino physics?
- What GUTs benefit from recent neutrino precision measurements?

Talk based on

[1] Z. Q. Chen (陈子强), G. X. Fang (方高祥) and Y. L. Zhou,
``Probing quark-lepton correlation in GUTs with high-precision neutrino measurements,''
[arXiv:2511.16196 [hep-ph]].

[2] Z. Q. Chen (陈子强), W. H. Jiang (蒋文皓), and Y. L. Zhou,
``Universal two-zero texture in SO(10): implications of JUNO and realization from non-invertible symmetries,''
[arXiv:2606.24571 [hep-ph]].

Road to unifications



GUTs unify forces, also matters, and lead to rich phenomenology

- Unification of gauge symmetries

$$G_{\rm GUT} \supset G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

- Unification of gauge couplings

Three gauge couplings, are running to be unified at the GUT scale $M_{\rm GUT}$

- Unification of matters

ν_τ	τ	t	b
ν_μ	μ	c	s
ν_e	e	u	d

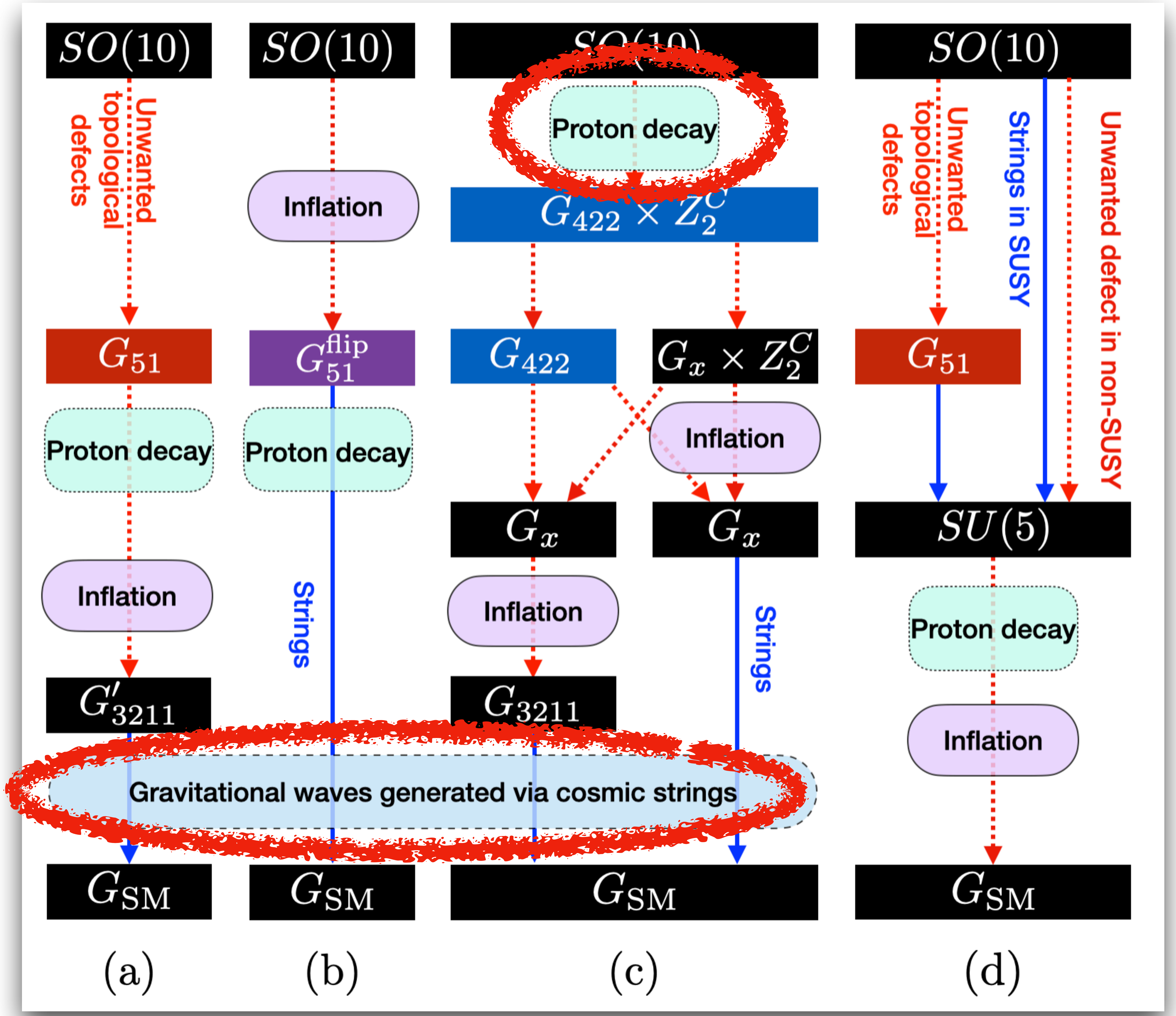
In SO(10) GUT, all matter fields are arranged in **16** representations

$$\nu_{L,R}, e_{L,R}, u^{1,2,3}_{L,R}, d^{1,2,3}_{L,R}$$

$$2+2+2\times 3+2\times 3=16$$

⇓

Quark-lepton correlation



King, Pascoli, Turner, **YLZ**, 2005.13549

Rich phenomenology in GUTs

GUTs

Broken at $M_{\rm GUT}$ → Proton decay

Potentially
intermediate
New Physics
……

Gauge unification

$G_{\rm SM} \times U(1)_{B-L}$

Broken at M_{B-L} → Gravitational waves

Potentially
intermediate
New Physics
……

Standard Model

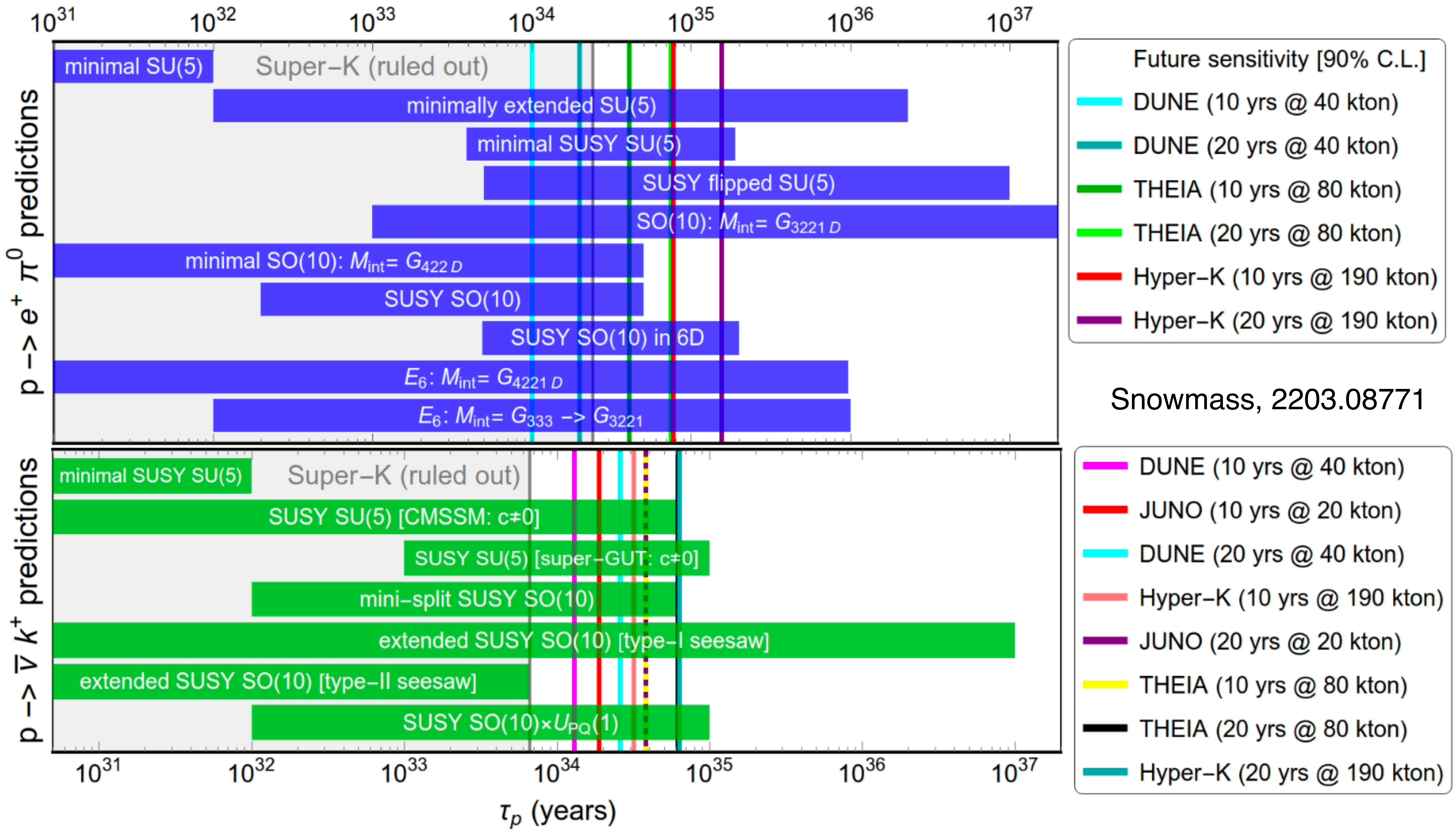
Majorana masses of right-handed neutrinos
& origin of light neutrino masses

Explaining matter-antimatter asymmetry

Quark-lepton correlation of masses and mixing

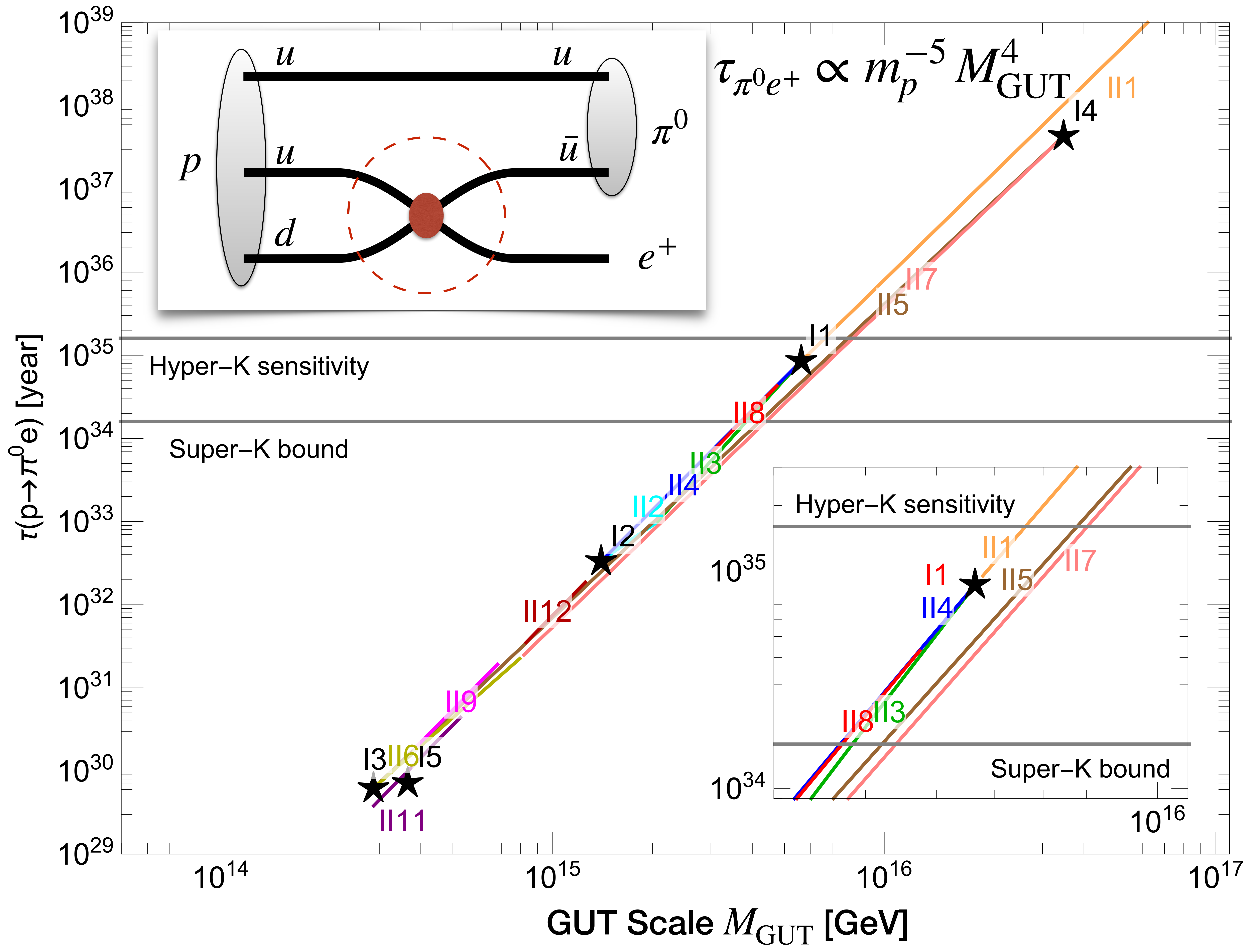
A lot of refs…

Proton decay constraints in the future



Snowmass, 2203.08771

Proton decay in SO(10) GUTs



$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	$G_{\rm SM}$
II1:	$\xrightarrow[\mathbf{210}]{\rm m}$	G_{422}	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{3221}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II2:	$\xrightarrow[\mathbf{54}]{\rm m,s}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\rm m}$	G^C_{3221}	$\xrightarrow[\mathbf{126}]{\rm s,w}$	
II3:	$\xrightarrow[\mathbf{54}]{\rm m,s}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\rm m,w}$	G_{3221}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II4:	$\xrightarrow[\mathbf{210}]{\rm m,s}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\rm w}$	G_{3221}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II5:	$\xrightarrow[\mathbf{210}]{\rm m}$	G_{422}	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{421}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II6:	$\xrightarrow[\mathbf{54}]{\rm m,s}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{421}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II7:	$\xrightarrow[\mathbf{54}]{\rm m,s}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\rm w}$	G_{422}	$\xrightarrow[\mathbf{126,45}]{\rm m}$	
II8:	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II9:	$\xrightarrow[\mathbf{210}]{\rm m,s}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\rm m,w}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II10:	$\xrightarrow[\mathbf{210}]{\rm m}$	G_{422}	$\xrightarrow[\mathbf{210}]{\rm m}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II11:	$\xrightarrow[\mathbf{54}]{\rm m,s}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\rm m,w}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II12:	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{421}	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\rm s}$	

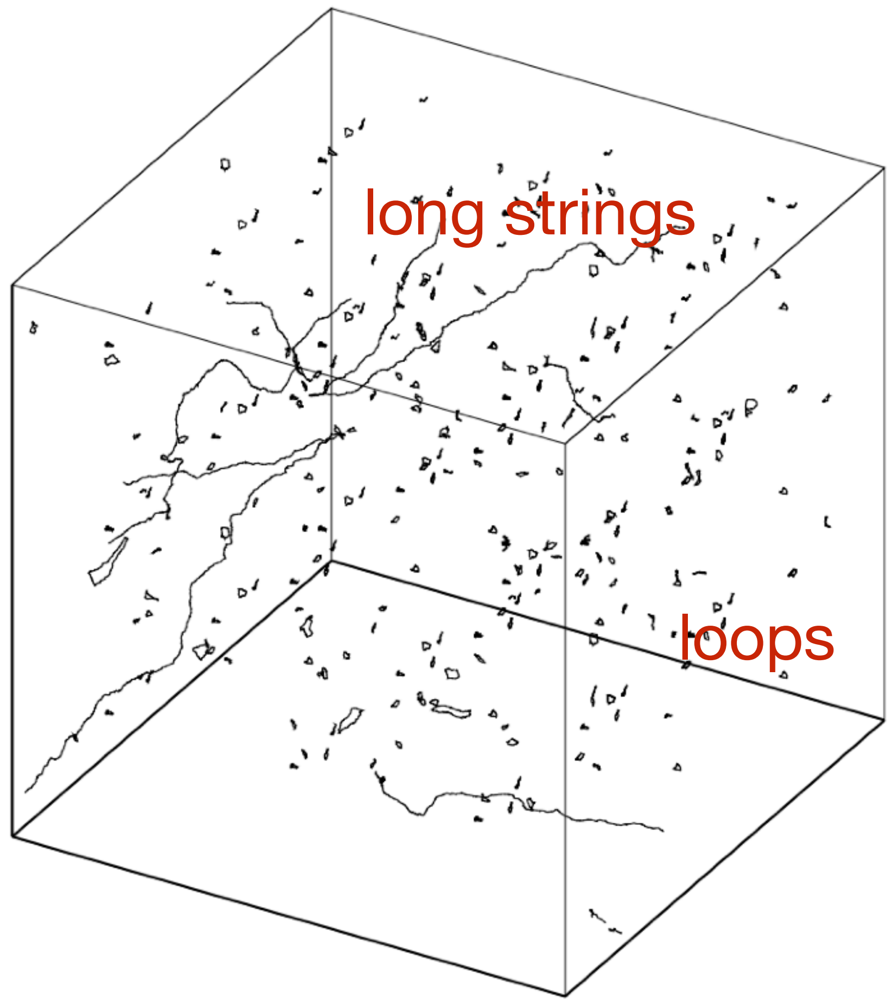
King, Pascoli, Turner, **YLZ**, 2106.15634

Mechanisms of gravitational wave (GW) genesis in GUTs

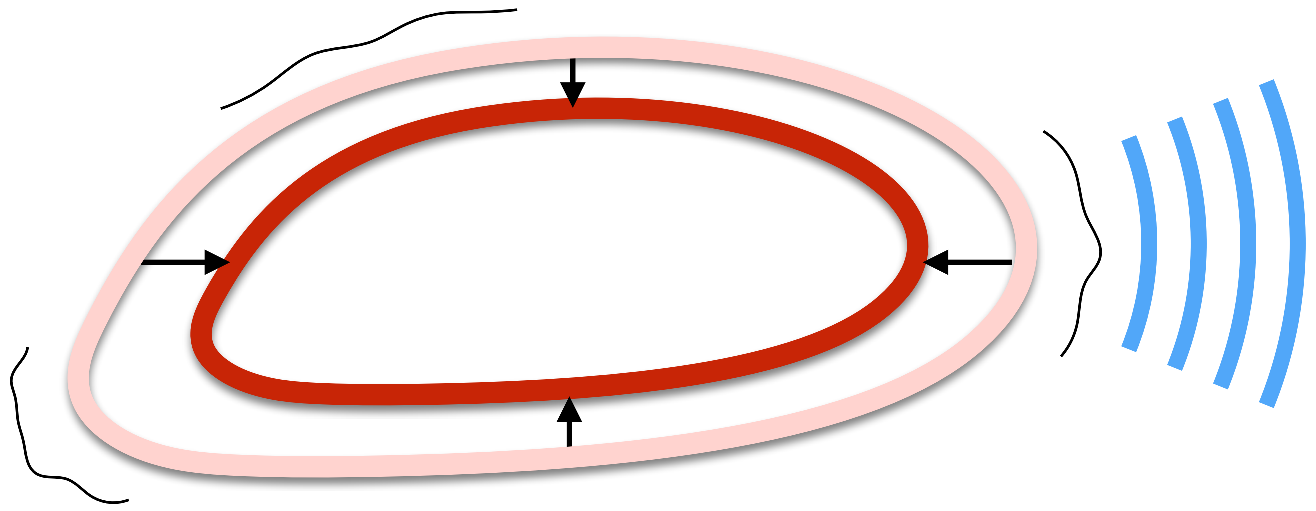
GW via cosmic strings

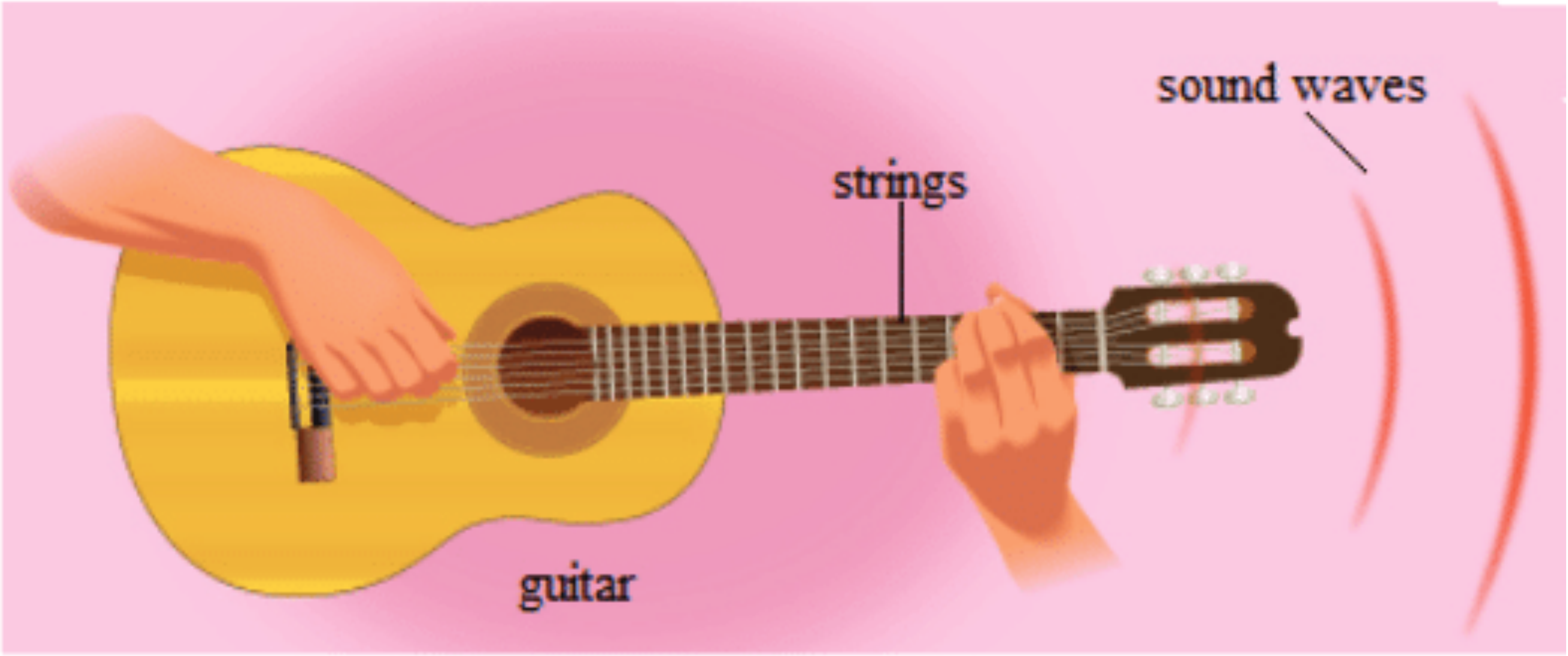
$$\pi_1(U(1)) = Z$$

- Most GUTs include $U(1)_{B-L}$, denotes the scale as M_{B-L}
- Spontaneous breaking of $U(1)_{B-L}$ generates cosmic strings.
- Strings intersect and intercommute to form loops and cusps
- Loops oscillates via gravitational radiation



Vanchurin, Olum, Vilenkin, 0511159

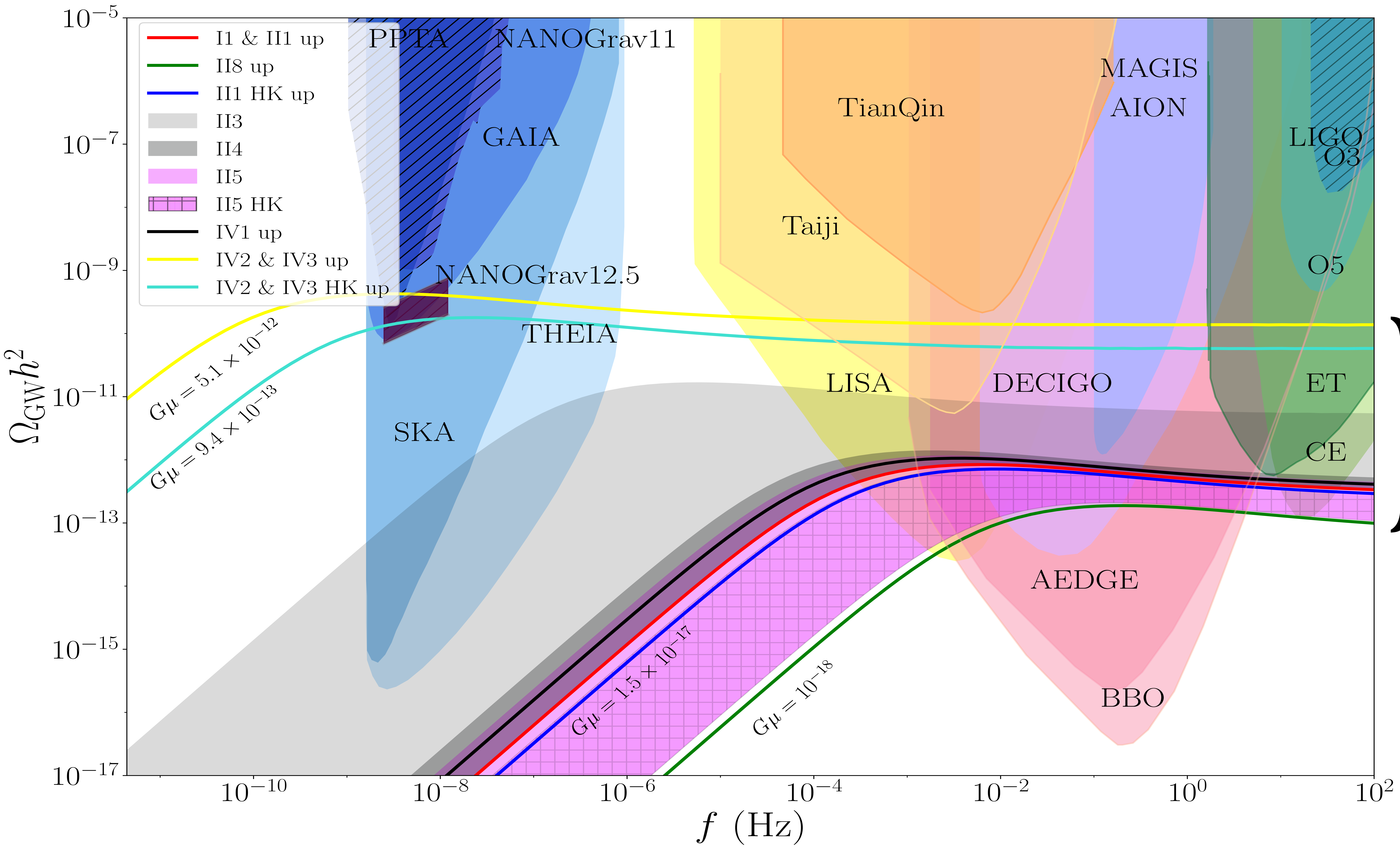




Another mechanism: GW via GUT phase transition?

——require technique developments to measure high-frequency GW, see e.g., 2011.12414, 2310.06607

GWs predicted in non-SUSY SO(10)

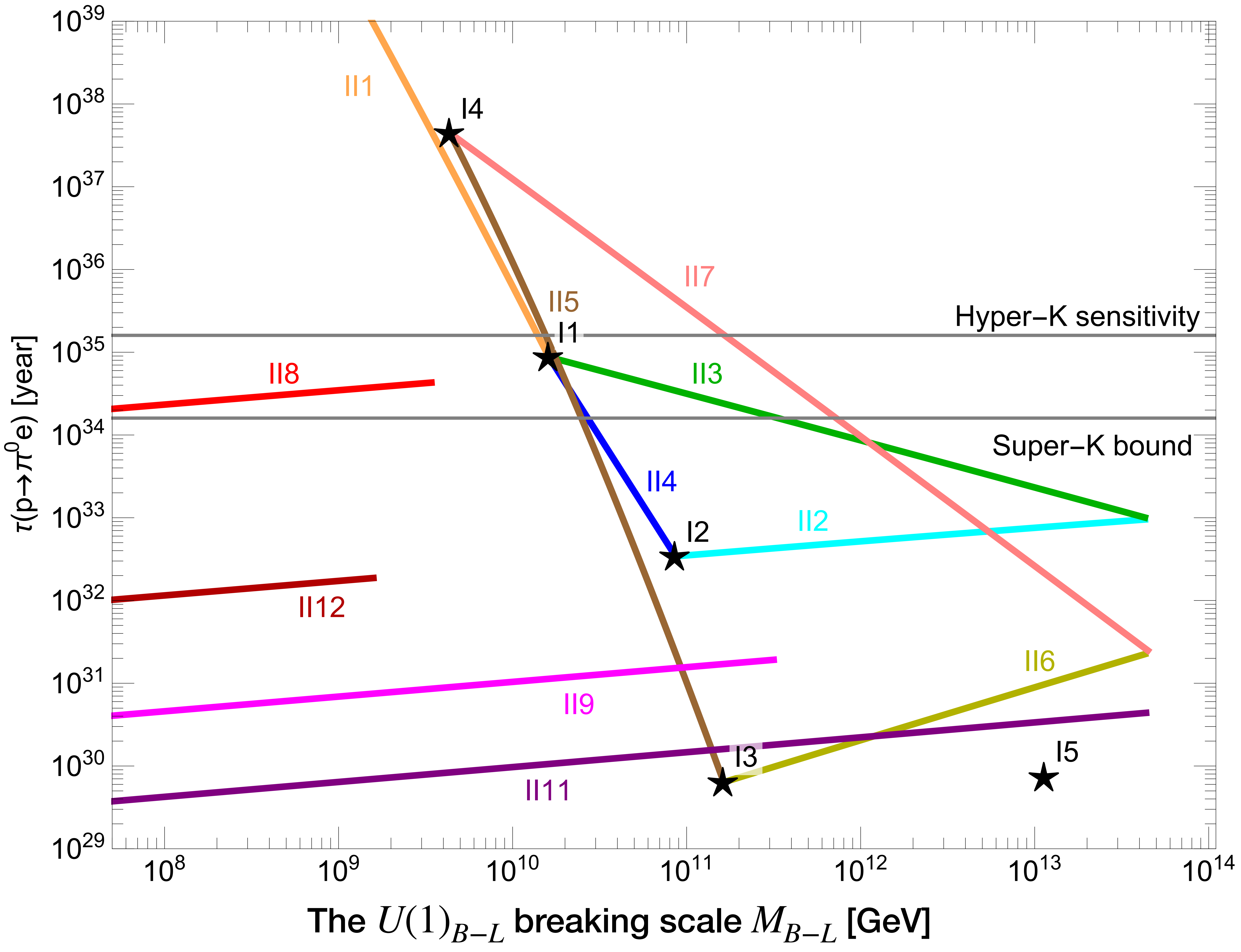


$\Omega_{\rm GW} h^2 \propto M_{B-L}$

Different colours for different breaking chains

King, Pascoli, Turner, **YLZ**, 2106.15634

Constraint to $B - L$ breaking scale



	$SO(10) \xrightarrow[\text{Higgs}]{\text{defect}}$	G_2	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_1	$\xrightarrow[\text{Higgs}]{\text{defect}}$	G_{SM}
II1:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
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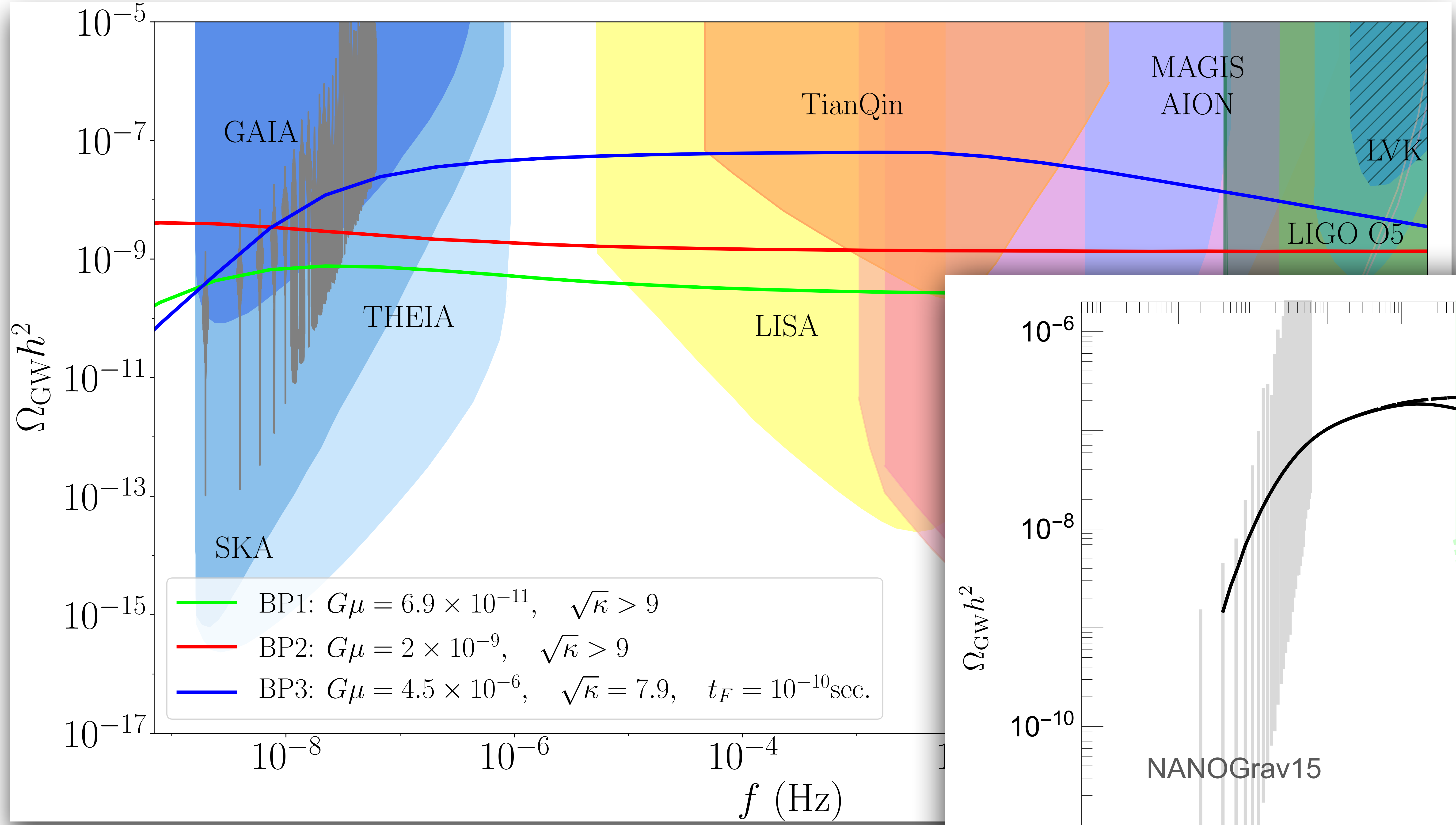
II7:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{w}}$	G_{422}	$\xrightarrow[\mathbf{126,45}]{\text{m}}$	
II8:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3221}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II9:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II10:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II11:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m,w}}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II12:	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\text{s}}$	

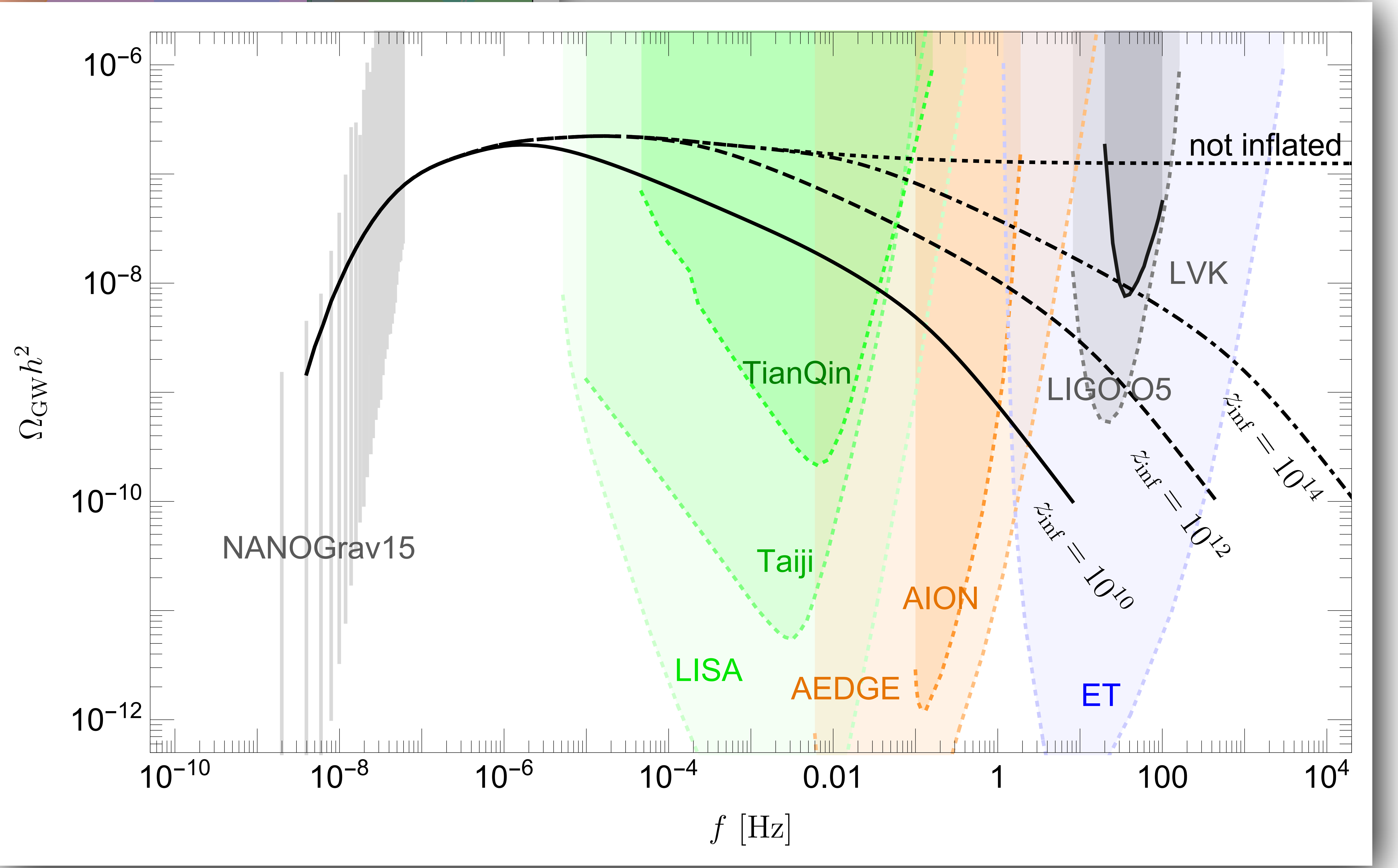
King, Pascoli, Turner, **YLZ**, 2106.15634

GUTs meet PTA 2023



GWs in SUSY SO(10) GUTs

Fu, King, Marsili, Pascoli, Turner, **YLZ**, 2308.05799



GWs in flipped SU(5)

King, Leontaris, **YLZ**, 2311.11857

Quark-lepton correlation in SO(10) GUTs

- Field arrangements: fermions $\sim \mathbf{16}_F$, $\mathbf{16}\times\mathbf{16} = \mathbf{10}_{\text{symm}} + \mathbf{120}_{\text{anti-symm}} + \mathbf{126}_{\text{symm}}$

  $\Rightarrow$ Three higgses can be introduced $\sim \mathbf{10}_H, \overline{\mathbf{126}}_H, \mathbf{120}_H$ Dutta, Mimura, Mohapatra, hep-ph/0406262

- Quark-lepton correlation $\mathscr{L}_Y = \mathbf{16}_F \left[Y_{10}\mathbf{10}_H + Y_{120}\mathbf{120}_H + Y_{126}\overline{\mathbf{126}}_H \right] \mathbf{16}_F$

$$Y_u = c^u_{10} Y_{10} + c^u_{126} Y_{126} + (c^u_{120_1} + c^u_{120_{15}}) Y_{120} \qquad Y_\nu = c^u_{10} Y_{10} - 3c^u_{126} Y_{126} + (c^u_{120_1} - 3c^u_{120_{15}}) Y_{120}$$

$$Y_d = c^d_{10} Y_{10} + c^d_{126} Y_{126} + (c^d_{120_1} + c^d_{120_{15}}) Y_{120} \qquad M_R = v_S Y_{126}$$

$$Y_e = c^d_{10} Y_{10} - 3c^d_{126} Y_{126} + (c^d_{120_1} - 3c^d_{120_{15}}) Y_{120} \qquad M_\nu = Y_{126} v_\Delta - Y_\nu M_R^{-1} Y_\nu^T v^2$$

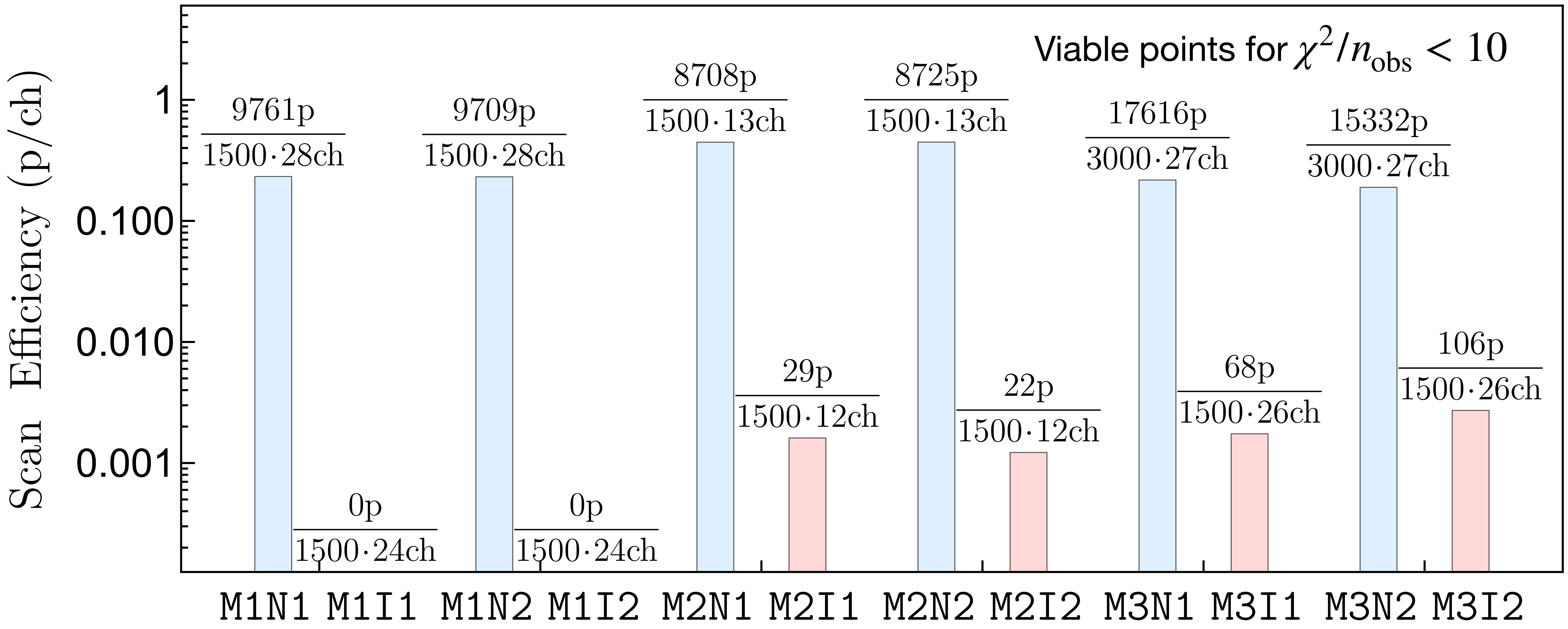
General formula with **Peccei-Quinn symm**

- A complete list of possible combinations of Higgs content in renormalisable SO(10) GUTs

Higgs content	Whether realistic in fitting fermion data
Only one Higgs	No, no flavor mixing
$10_H^{\mathbb{R},\mathbb{C}}, 120_H^{\mathbb{R},\mathbb{C}}$	No, massless light neutrinos
$10_H^{\mathbb{R}}, \overline{126}_H^{\mathbb{C}}$	No, small hierarchy between m_b and m_t
$120_H^{\mathbb{R},\mathbb{C}}, \overline{126}_H^{\mathbb{C}}$	No, inconsistent with mixing data
$10_H^{\mathbb{C}}, \overline{126}_H^{\mathbb{C}}$	Yes, imposing $U(1)_{\text{PQ}}$ leads to Model 1
$10_H^{\mathbb{R}}, \overline{126}_H^{\mathbb{C}}, 120_H^{\mathbb{R}}$	Yes, assuming SCPV leads to Model 2
$10_H^{\mathbb{C}}, \overline{126}_H^{\mathbb{C}}, 120_H^{\mathbb{C}}$	Yes, imposing $U(1)_{\text{PQ}} \times Z_2^P$ leads to Model 3

$\Longrightarrow$ We perform scan of these models

Mass ordering predicted in GUTs after JUNO first data release



JUNO 59 days' data $\sin^2\theta^l_{12} = 0.3092 \pm 0.0087\,.$ $\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\text{eV}^2$

NuFIT 6.0

$$\sin^2\theta_{23} = 0.470 \pm 0.015\,,\ \sin^2\theta_{13} = 0.02215 \pm 0.00057$$
$$\Delta m^2_{31} = (2.513 \pm 0.020) \times 10^{-3}\text{eV}^2\,; \qquad \text{(N1)}$$

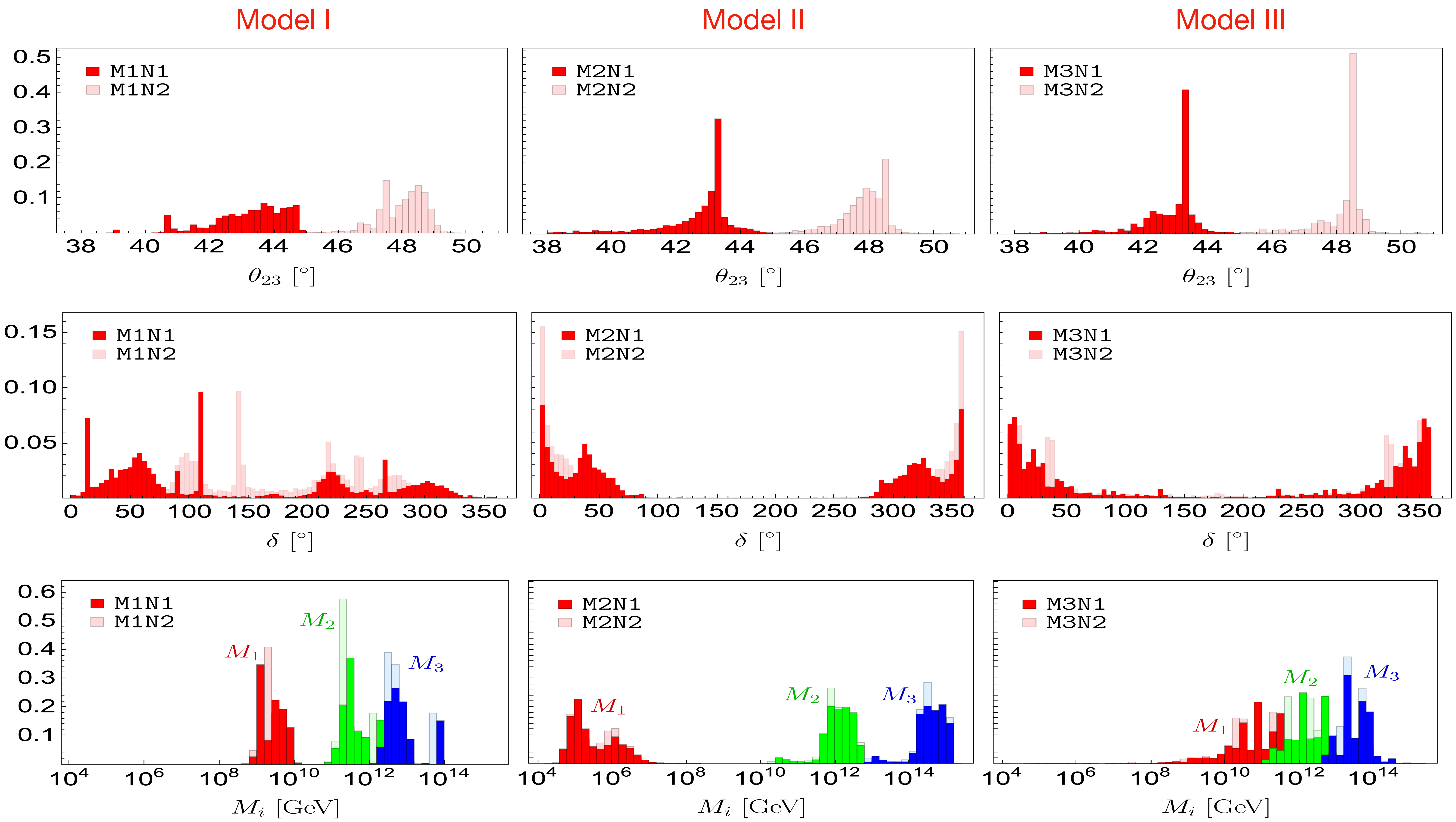
$$\sin^2\theta_{23} = 0.550 \pm 0.014\,,\ \sin^2\theta_{13} = 0.02231 \pm 0.00056$$
$$\Delta m^2_{32} = (-2.484 \pm 0.020) \times 10^{-3}\text{eV}^2\,; \qquad \text{(I1)}$$

$$\sin^2\theta_{23} = 0.561 \pm 0.014\,,\ \sin^2\theta_{13} = 0.02195 \pm 0.00056$$
$$\Delta m^2_{31} = (2.534 \pm 0.024) \times 10^{-3}\text{eV}^2\,; \qquad \text{(N2)}$$

$$\sin^2\theta_{23} = 0.562 \pm 0.014\,,\ \sin^2\theta_{13} = 0.02224 \pm 0.00057$$
$$\Delta m^2_{32} = (-2.510 \pm 0.025) \times 10^{-3}\text{eV}^2\,. \qquad \text{(I2)}$$

Quark, charged lepton and CKM data run to GUT scale   Babu, Bajc, Saad, 1612.04329

Other neutrino observables in GUTs after JUNO first data release



Predictions via quark-lepton correlation

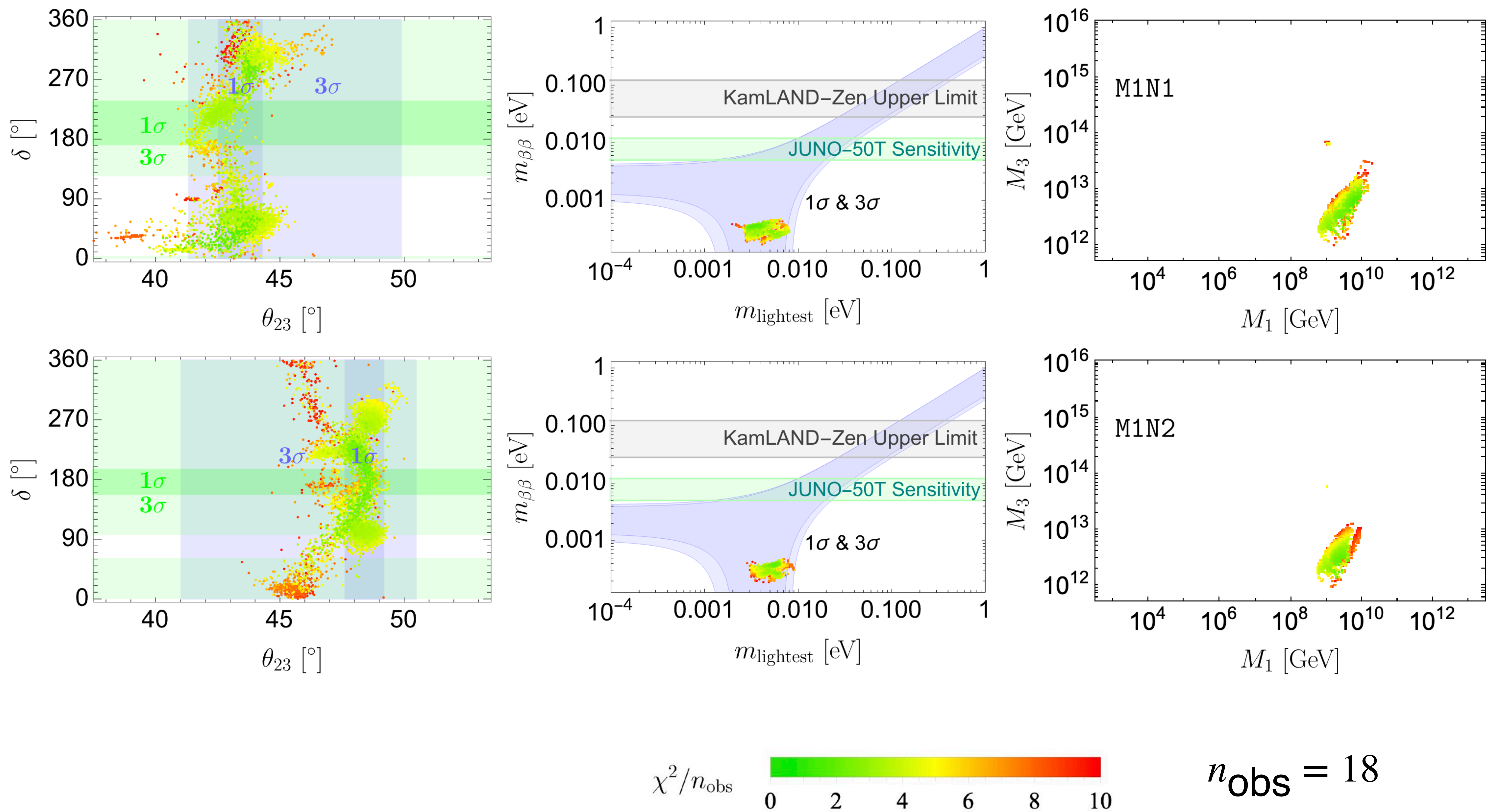
- Model 1, $(\mathbf{10}_{\mathbb{C}}, \overline{\mathbf{126}}_{\mathbb{C}})$ with $U(1)_{\rm PQ}$

  The minimal Higgs content

  # of free parameters: $n_{\rm para} = 19$

$$Y_u = S + D$$
$$Y_d = r_2 S + e^{i\omega} r_1 D$$
$$Y_e = r_2 S - 3e^{i\omega} r_1 D \qquad M_R = v_R D,$$
$$Y_\nu = S - 3D \qquad M_\nu = -Y_\nu M_R^{-1} Y_\nu^T v^2$$

Altarelli, Meloni, 1305.1001;
Babu, Khan, 1507.06717;
Ohlsson, Pernow, 1903.08241;
Mummidi, Patel, 2109.04050



$n_{\rm obs} = 18$

- CP phase uniformly distributed
- 0νββ not testable
- Prediction on RHN masses

  large hierarchy

  $M_1 \sim 10^{9-10}$ GeV

  $M_3 \sim 10^{12-13}$ GeV

- The B-L breaking scale

  $M_{B-L} \gtrsim 10^{12-13}$ GeV
- Thermal leptogenesis favoured

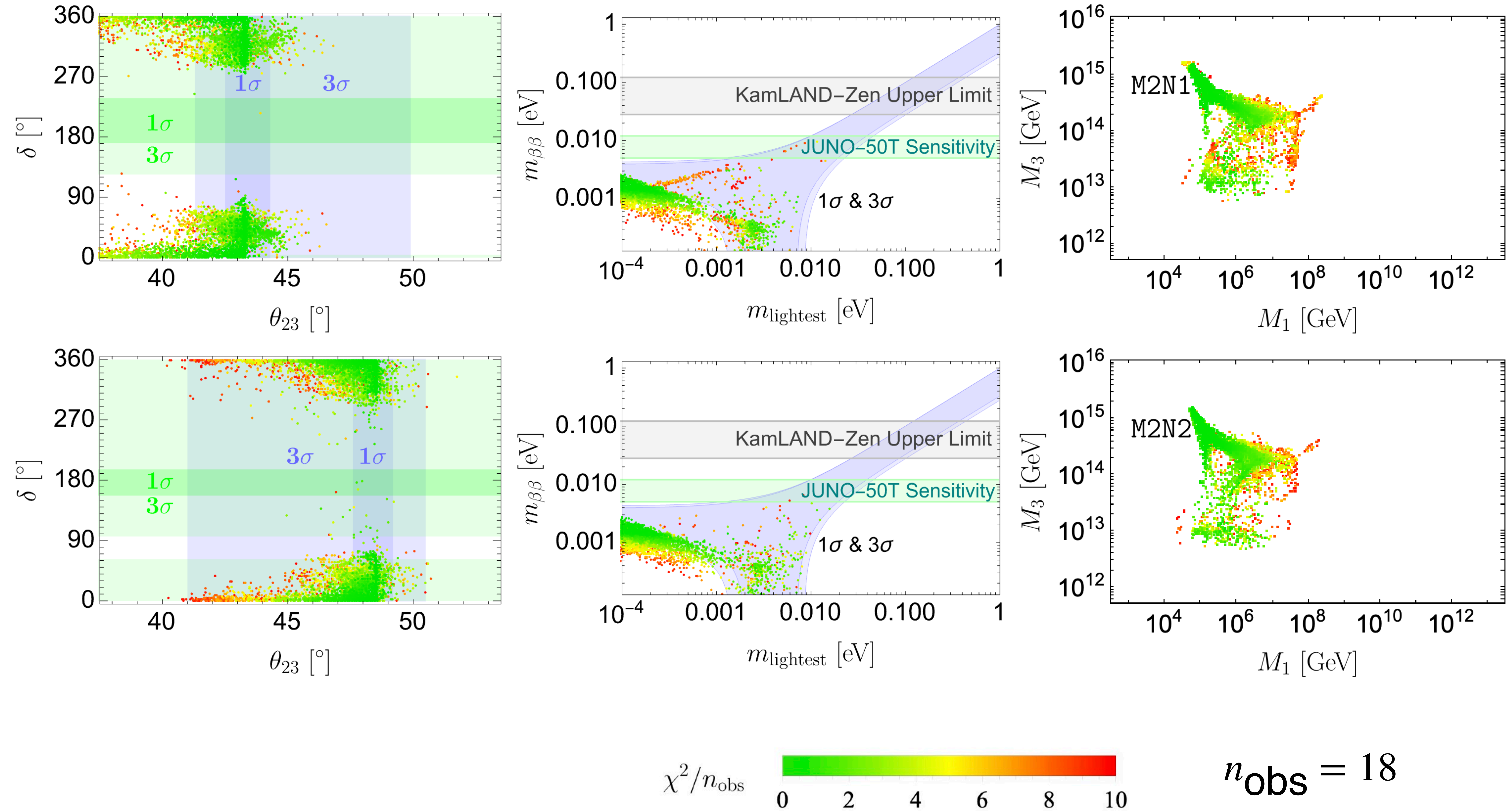
Predictions via quark-lepton correlation

- Model 2, $(\mathbf{10}_\mathbb{R}, \overline{\mathbf{126}}_\mathbb{C}, \mathbf{120}_\mathbb{R})$ with SCPV
  All Yukawa at GUT scales are real

  # of free parameters: $n_{\text{para}} = 19$

$$Y_u = e^{i\alpha}S + D + e^{i\lambda}A$$
$$Y_d = e^{-i\alpha}S + e^{i\omega}r_1 D + e^{-i\lambda}A$$
$$Y_e = e^{-i\alpha}S - 3e^{i\omega}r_1 D + e^{-i\gamma}r_4 A \qquad M_R = v_R D,$$
$$Y_\nu = e^{i\alpha}S - 3D + e^{i\gamma}r_4 A \qquad M_\nu = -Y_\nu M_R^{-1} Y_\nu^T v^2$$

Babu, Bajc, Saad, 1612.04329;
Saad, 2212.05291;
Babu, Di Bari, Fong, Saad, 2409.03840
Babu, Fong, Saad, 2508.14969



$n_{\text{obs}} = 18$

- CPV not maximal
- 0νββ not testable
- Prediction on RHN masses
  very large hierarchy,
- $M_1 \sim (10^5, 10^8)$ GeV, regime not
  found before

- B-L breaking scale close to GUT scale
- Leptogenesis: Davidson-Ibarra bound not satisfied
  $\Rightarrow N_2$ leptogenesis?

Predictions via quark-lepton correlation

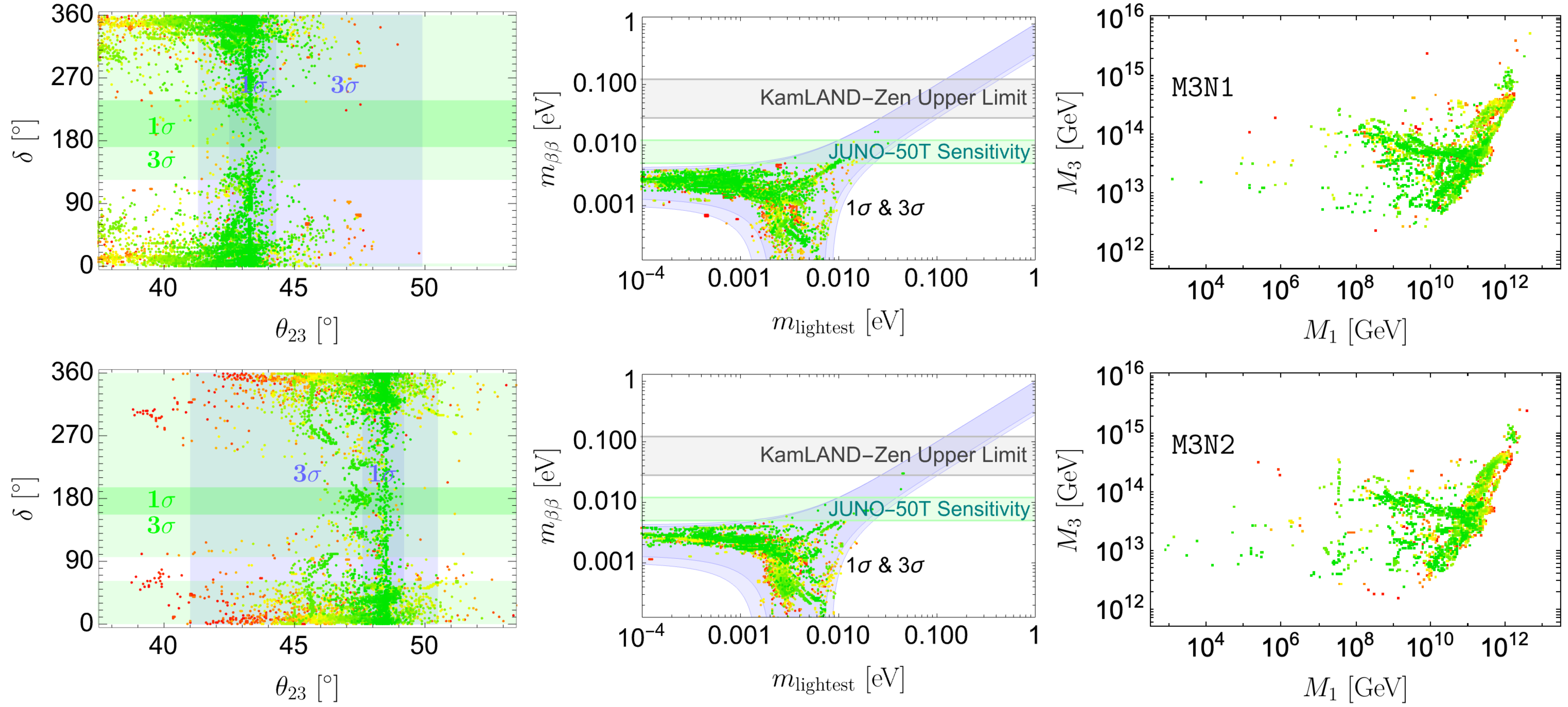
- Model 3, $(\mathbf{10}_{\mathbb{C}}, \overline{\mathbf{126}}_{\mathbb{C}}, \mathbf{120}_{\mathbb{C}})$ with $U(1)_{\rm PQ} \times Z_2^P$

  All Yukawa's at EW scale are Hermitian

  Minimal # of free parameters: $n_{\rm para} = 18$

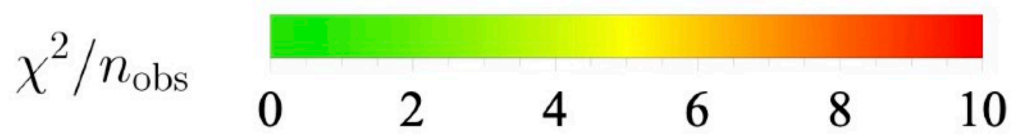
$$Y_u = S + D + iA$$
$$Y_d = r_2 S + r_1 D + i r_3 A$$
$$Y_e = r_2 S - 3 r_1 D + i r_4 A \qquad M_R = v_R D,$$
$$Y_\nu = S - 3D + i r_5 A \qquad M_\nu = -\, Y_\nu M_R^{-1} Y_\nu^T v^2$$

Joshipura, Patel, 1102.5148
Dueck, Rodejohann, 1306.4468
Fu, King, Marsili, Pascoli, Turner, YLZ, 2209.00021



- CPV most likely not maximal
- 0νββ partially testable
- Prediction on RHN masses smaller hierarchy

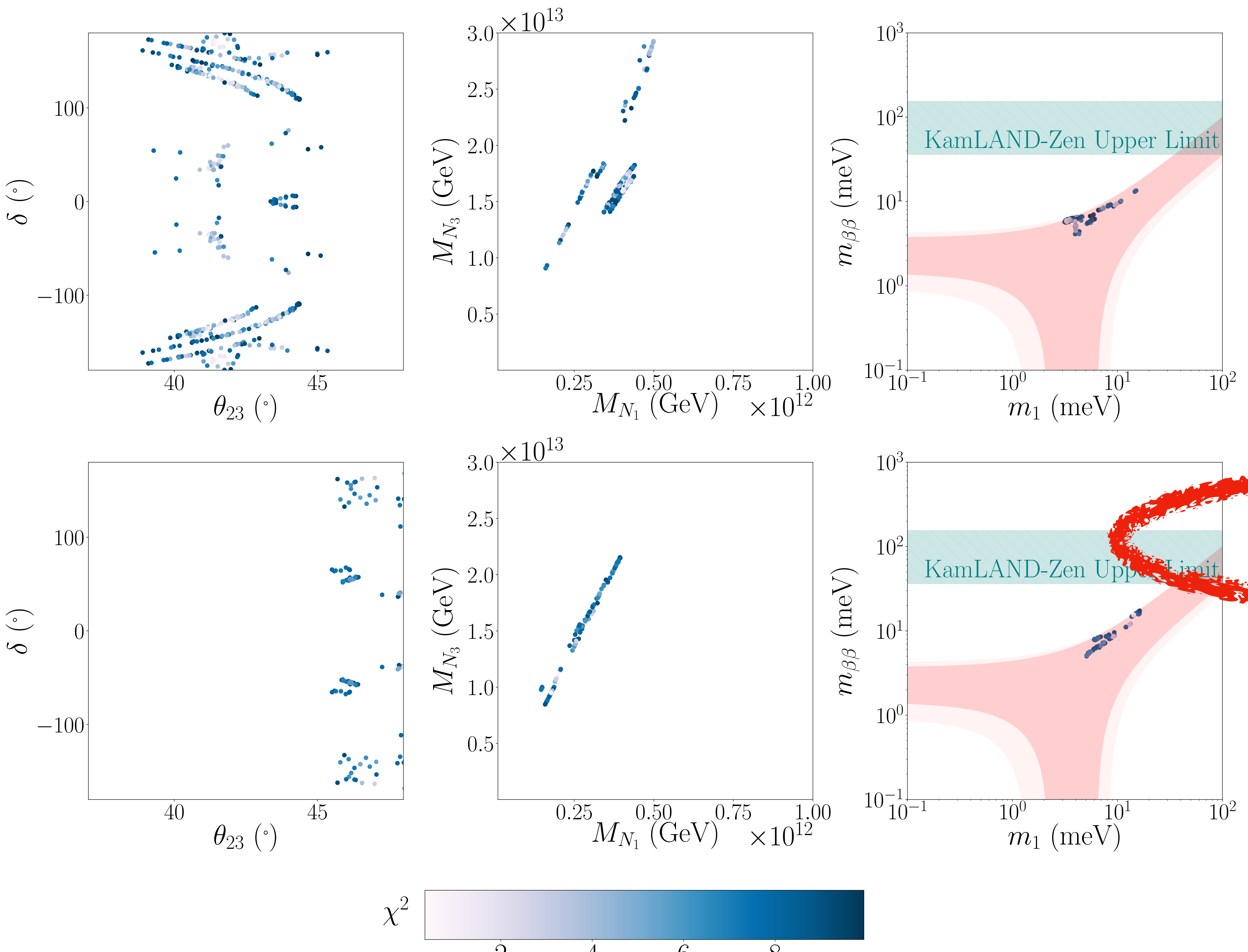
- B-L breaking scale less restricted
- Thermal leptogenesis works



$n_{\rm obs} = 18$

A slide in NOPP 2024

Fermion masses and mixing in SO(10) in Model 3



NuFIT 5.1

Take-away message:

$M_1 \sim (2,\ 5) \times 10^{11}$ GeV

$M_3 \sim (1,\ 3) \times 10^{13}$ GeV

$m_{\beta\beta} \sim 10^{-2}$ eV

And normal ordering preferred

Fu, King, Marsili, Pascoli, Turner, **YLZ**, 2209.00021

20

Universal Two-Zero Textures in SO(10), UTZT-SO(10)

- Adding flavour structures to Yukawas, reducing # of parameters & enhancing predictions

$\Rightarrow$ UTZT-SO(10)

- Breaking chain: $SO(10)$ GUT → Pati-Salam with D parity → Left-Right Symm → SM

- In the Model 3 framework with type I + II seesaw mechanism two-zero textures

$$
\begin{aligned}
Y_u &= H + r_2 F + i r_3 G\,, \\
Y_d &= r_1 (H + F + iG)\,, \\
Y_\nu &= H - 3 r_2 F + i c_\nu G\,, \\
Y_e &= r_1 (H - 3F + i c_e G)\,,
\end{aligned}
$$

$$M_R = \frac{v^2}{2m_R} F$$

$$M_\nu = m_L F - m_R Y_\nu F^{-1} Y_\nu^T$$

- All Dirac Yukawa matrices take Hermitian UTZT textures. RHN mass matrix is real

$$Y_f = \zeta_f \begin{pmatrix} 0 & C_f & 0 \\ C_f^* & \tilde{B}_f & B_f \\ 0 & B_f^* & A_f \end{pmatrix}$$

$$M_R = \begin{pmatrix} 0 & C_R & 0 \\ C_R & \tilde{B}_R & B_R \\ 0 & B_R & A_R \end{pmatrix}$$

There are several types of two-zero textures, we here focus only on the one extended from the Fritzsch three-zero texture (PLB 78, NPB 79)

$f = u, d, e, \nu$

M_ν inherits the two-zero texture via seesaw formula, Xing, Zhang, hep-ph/0304234

UTZT-SO(10): reduce free parameters in SO(10)

- Special parametrisation of two-zero textures. Fritzsch, Xing, hep-ph/0212195

$$\overline{Y}_u \equiv P_u Y_u P_u^* = \begin{pmatrix} 0 & |C_u| & 0 \\ |C_u| & \tilde{B}_u & |B_u| \\ 0 & |B_u| & A_u \end{pmatrix}$$

Two phases can be rotated away.

Then, the real matrix is analytically diagonalised. $\overline{Y}_u = O_u \hat{Y}_u O_u^T$

$$\begin{aligned} \tilde{B}_u &= -\eta_u y_u + \eta_u y_c + y_t - A_u\,, \\ |B_u| &= \sqrt{(A_u + \eta_u y_u)(A_u - \eta_u y_c)(y_t - A_u)/A_u}\,, \\ |C_u| &= \sqrt{y_u y_c y_t / A_u}\,. \end{aligned}$$

$$O_u = \begin{pmatrix} \sqrt{\frac{y_c y_t (A_u+\eta_u y_u)}{A_u(y_u+y_c)(\eta_u y_u+y_t)}} & \eta_u\sqrt{\frac{y_u y_t (A_u-\eta_u y_c)}{A_u(y_u+y_c)(y_t-\eta_u y_c)}} & \sqrt{\frac{y_u y_c (y_t-A_u)}{A_u(\eta_u y_u+y_t)(y_t-\eta_u y_c)}} \\ -\eta_u\sqrt{\frac{y_u (A_u+\eta_u y_u)}{(y_u+y_c)(\eta_u y_u+y_t)}} & \sqrt{\frac{y_c (A_u-\eta_u y_c)}{(y_u+y_c)(y_t-\eta_u y_c)}} & \sqrt{\frac{y_t (y_t-A_u)}{(\eta_u y_u+y_t)(y_t-\eta_u y_c)}} \\ \eta_u\sqrt{\frac{y_u (y_t-A_u)(A_u-\eta_u y_c)}{A_u(y_u+y_c)(\eta_u y_u+y_t)}} & -\sqrt{\frac{y_c (y_t-A_u)(A_u+\eta_u y_u)}{A_u(y_u+y_c)(y_t-\eta_u y_c)}} & \sqrt{\frac{y_t (A_u+\eta_u y_u)(A_u-\eta_u y_c)}{A_u(\eta_u y_u+y_t)(y_t-\eta_u y_c)}} \end{pmatrix}$$

$$V_{\rm CKM} = O_u^T P_q O_d \qquad P_q = P_u P_d^* = {\rm diag}(1,\, e^{i\phi_1},\, e^{i\phi_2})$$

All Quark Yukawa eigenvalues are taken as inputs, leaving 4 free parameters $\{A_u,\, A_d,\, \phi_1,\, \phi_2\}$

- Lepton Yukawa matrices are represented in terms of Y_u, Y_d. Then c_e, r_1, r_2 are solved by

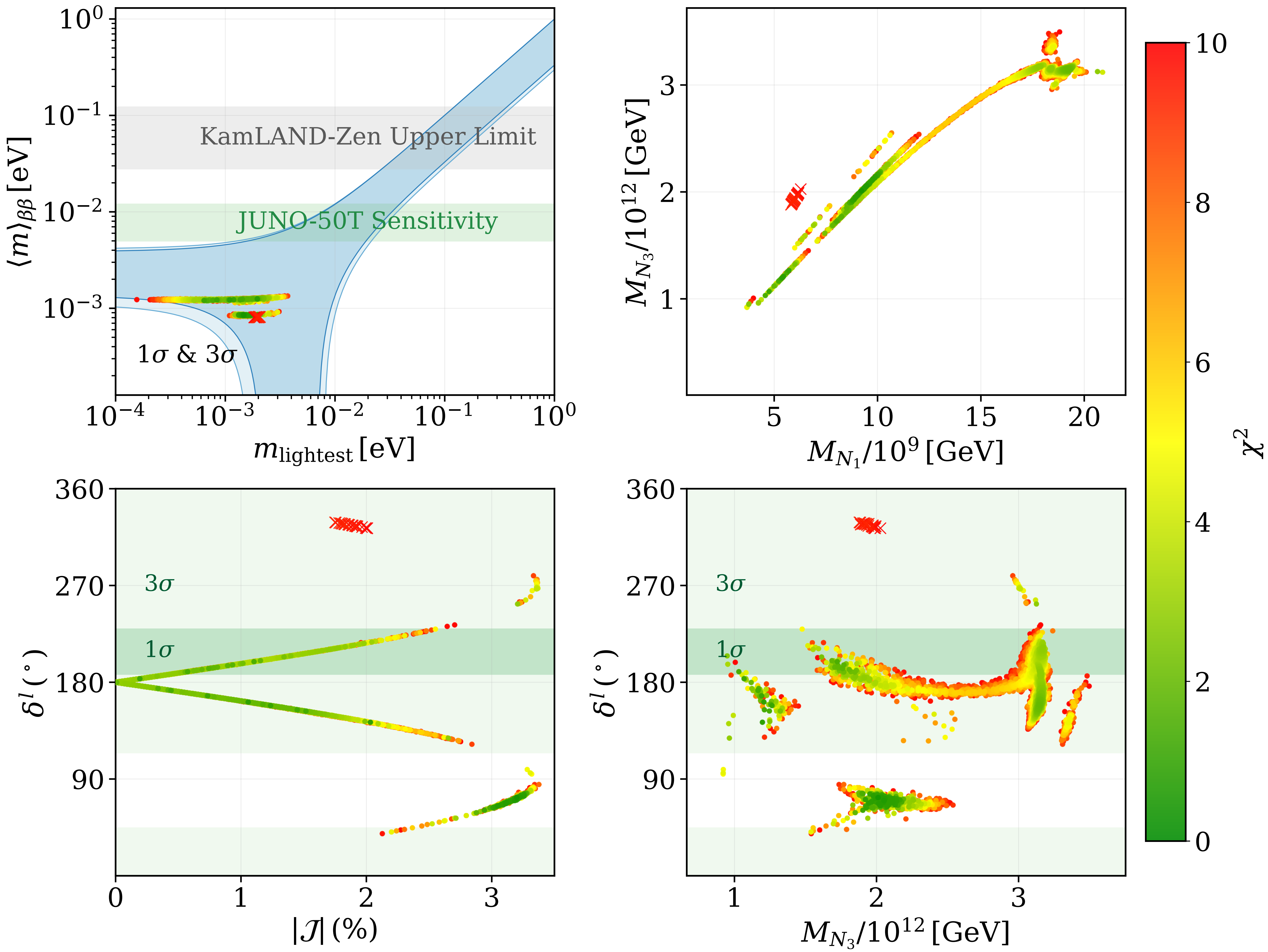
$$\begin{aligned} \tilde{B}_e &= -\eta_e y_e + \eta_e y_\mu + y_\tau - A_e\,, \\ |B_e| &= \sqrt{(A_e + \eta_e y_e)(A_e - \eta_e y_\mu)(y_\tau - A_e)/A_e}\,, \\ |C_e| &= \sqrt{y_e y_\mu y_\tau / A_e}\,, \end{aligned}$$

give 3 extra free parameters $\{m_L, m_R, c_\nu\}$

up to the sign ambiguities $\{\eta_u,\, \eta_d,\, \eta_e, \zeta_d\}$

- 7 parameters to fit 9 observables $\text{obs} \in \{\theta_{12}^q, \theta_{13}^q, \theta_{23}^q, \delta^q, \theta_{12}^l, \theta_{13}^l, \theta_{23}^l, \Delta m_{21}^2, \Delta m_{31}^2\}$,

Predictions of UTZT-SO(10)



Inputs:

JUNO 207 days' result

$$\Delta m^2_{31} = (2.509^{+0.027}_{-0.025}) \times 10^{-3}\ \text{eV}^2\,,$$
$$\Delta m^2_{21} = (7.388 \pm 0.078) \times 10^{-5}\ \text{eV}^2\,,$$
$$\sin^2\theta^l_{12} = 0.3036 \pm 0.0064\,.$$

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$$\sin^2\theta^l_{23} = 0.470^{+0.017}_{-0.014}\,,$$
$$\sin^2\theta^l_{13} = 0.02249 \pm 0.00057\,.$$

CKM data run to GUT scale

$$\theta^q_{12} = 13.028^\circ \pm 0.034^\circ,$$
$$\theta^q_{13} = 0.2408^\circ \pm 0.0074^\circ,$$
$$\theta^q_{23} = 2.783^\circ \pm 0.034^\circ,$$
$$\delta^q = 69.16^\circ \pm 3.09^\circ.$$

UTZT realised with non-invertible symmetries (NIS)

- NIS, a kind of generalised symmetry, is applied in pheno study recently and very quickly.

Choi, Lam, Shao, 2205.05086;
Cordova, Ohmori, 2205.06243;
Cordova, Hong, Koren, Ohmori, 2211.07639;
Cordova, Hong, Koren, 2402.12453.

- Using NIS to realise texture zeros provide a physically economical approach because it avoids to introduce new fields in the effective theory.

Kobayashi, Otsuka, Tanimoto, 2409.05270;
Jiang, Qu, Ding, 2510.07236;
Kobayashi, Otsuka, Tanimoto, Uchida, 2505.07262;
Kobayashi, Otsuka, Yanagida, 2508.12287;
Qu, Jiang, Ding, 2602.24214

By contrast, in canonical flavour symmetry approach, new flavoscalars (flavons) are introduced to breaking the symmetry. They enhance the RG running and may lead to Landau pole.

- Z_3 gauging of Z_7: minimal realization of two-zero textures

Conjugacy classes

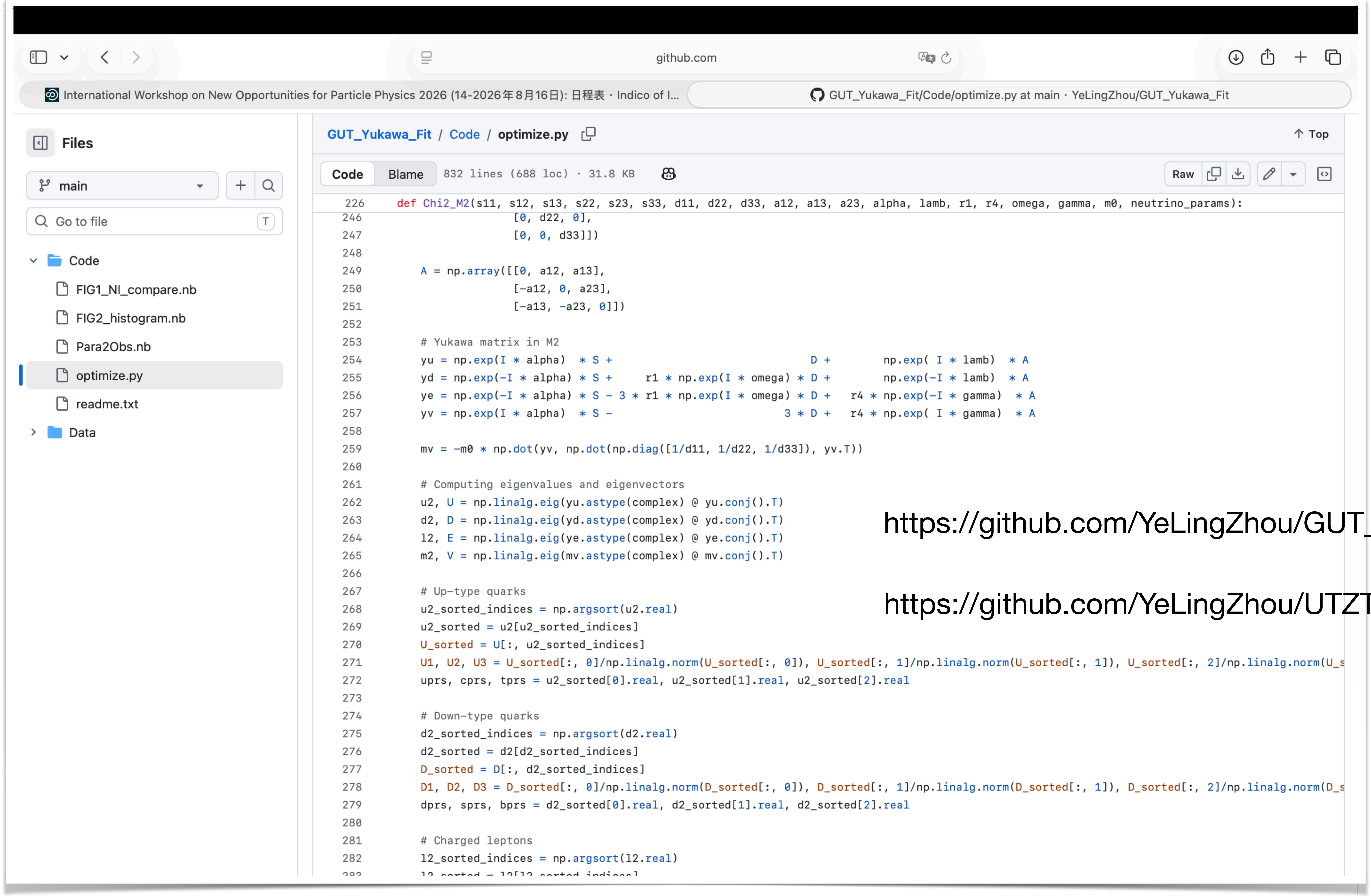
$$C_1 = \{e\}\,,$$
$$C_3^1 = \{a,\, a^2,\, a^4\}\,,$$
$$C_3^2 = \{a^3,\, a^6,\, a^5\}\,,$$

	C_1	C_3^1	C_3^2
C_1	C_1	C_3^1	C_3^2
C_3^1	C_3^1	$C_3^1 + 2C_3^2$	$3C_1 + C_3^1 + C_3^2$
C_3^2	C_3^2	$3C_1 + C_3^1 + C_3^2$	$2C_3^1 + C_3^2$

	Particles in $SO(10)$	Class assignment in Z_3 gauged Z_7
Fermions	$\mathbf{16}_F^i$	(C_1, C_3^1, C_3^2)
Higgses	$\mathbf{10}_H, \mathbf{120}_H$	C_3^2
	$\overline{\mathbf{126}}_H$	C_3^2
	$\mathbf{54}_H$	C_3^2
	$\mathbf{45}_H$	C_3^2

- Different from [2602.24214], where the minimal NIS to realise the texture is claimed to be Z_3 gauging of Z_{13}. The difference is that Higgs in that work does not take a NIS charge.

Code and data release



https://github.com/YeLingZhou/GUT_Yukawa_Fit

https://github.com/YeLingZhou/UTZT_SO10

Summary and outlook

- JUNO data taking represents the beginning of the era of neutrino precision measurements. After one year, some delighted results have been obtained, including improvement measurements of mixing parameters and hint on normal mass ordering.

- GUTs unify forces and also unify matters, leading to quark-lepton correlation between quark and lepton masses and mixing.

- Quark-Lepton correlation in SO(10) favours normal mass ordering, consistent the most recent JUNO data.

- The more precision data motivates us to further study the flavour textures in SO(10) GUTs. Universal two-zero texture, UTZT-SO(10), is a good example. It reduces free parameters in GUTs, fits data very well, and gives clear predictions. We also considered its realisation in non-invertible symmetries

Backup: benchmarks of SO(10) GUTs

normal ordering

Physical Quantity	M1		M2				M3			
	M1N1B1	M1N2B1	M2N1B1	M2N1B2	M2N2B1	M2N2B2	M3N1B1	M3N1B2	M3N2B1	M3N2B2
$y_u/10^{-6}$	2.65	2.75	2.55	3.07	2.53	4.85	0.637	2.54	0.744	2.54
$y_c/10^{-3}$	1.40	1.39	1.37	1.35	1.37	1.37	1.37	1.37	1.37	1.37
y_t	0.429	0.427	0.428	0.429	0.428	0.430	0.428	0.428	0.428	0.428
$y_d/10^{-6}$	3.87	3.13	6.56	7.29	6.56	7.14	5.28	6.56	5.28	6.56
$y_s/10^{-4}$	1.37	1.32	1.24	1.17	1.24	1.11	1.24	1.24	1.25	1.24
$y_b/10^{-2}$	0.571	0.571	0.570	0.570	0.570	0.568	0.569	0.570	0.569	0.570
$y_e/10^{-6}$	2.69604	2.70309	2.70346	2.70190	2.70339	2.70629	2.70318	2.70346	2.70345	2.70341
$y_\mu/10^{-4}$	5.65981	5.68560	5.70708	5.72116	5.70713	5.70725	5.71839	5.70706	5.71432	5.70698
$y_\tau/10^{-2}$	0.97358	0.97054	0.97021	0.96623	0.97020	0.97211	0.97154	0.97020	0.97124	0.97020
θ^q_{12}	0.22750	0.22749	0.22739	0.22760	0.22739	0.22721	0.22745	0.22739	0.22745	0.22739
$\theta^q_{23}/10^{-2}$	4.904	4.872	4.858	4.876	4.858	4.835	4.858	4.858	4.856	4.858
$\theta^q_{13}/10^{-3}$	4.252	4.215	4.202	4.201	4.202	4.237	4.202	4.202	4.202	4.202
δ^q	1.269	1.251	1.207	1.253	1.207	1.227	1.201	1.207	1.203	1.207
$\Delta m^2_{21}/10^{-5}\,\mathrm{eV}^2$	7.53	7.50	7.50	7.50	7.50	7.48	7.50	7.50	7.50	7.50
$\Delta m^2_{3\ell}/10^{-3}\,\mathrm{eV}^2$	2.515	2.535	2.513	2.512	2.534	2.539	2.513	2.513	2.534	2.534
$\sin^2\theta^l_{12}$	0.313	0.309	0.309	0.303	0.309	0.308	0.309	0.309	0.309	0.309
$\sin^2\theta^l_{23}$	0.456	0.561	0.470	0.460	0.561	0.540	0.471	0.470	0.561	0.561
$\sin^2\theta^l_{13}$	0.02152	0.02180	0.02215	0.02235	0.02195	0.02223	0.02217	0.02215	0.02194	0.02195
$\chi^2/(n_{\mathrm{obs}}=18)$	1.54	1.71	$5.88\cdot10^{-6}$	0.312	$7.60\cdot10^{-6}$	0.958	0.495	$3.41\cdot10^{-7}$	0.462	$3.39\cdot10^{-7}$
m_l/eV	$3.34\cdot10^{-3}$	$5.60\cdot10^{-3}$	$5.29\cdot10^{-5}$	$7.81\cdot10^{-4}$	$5.41\cdot10^{-5}$	$1.52\cdot10^{-3}$	$3.82\cdot10^{-3}$	$5.46\cdot10^{-4}$	$3.44\cdot10^{-3}$	$1.03\cdot10^{-3}$
m_β/eV	$9.40\cdot10^{-3}$	$1.05\cdot10^{-2}$	$8.85\cdot10^{-3}$	$8.88\cdot10^{-3}$	$8.85\cdot10^{-3}$	$9.02\cdot10^{-3}$	$9.64\cdot10^{-3}$	$8.87\cdot10^{-3}$	$9.49\cdot10^{-3}$	$8.91\cdot10^{-3}$
$m_{\beta\beta}/\mathrm{eV}$	$3.67\cdot10^{-4}$	$3.85\cdot10^{-4}$	$2.47\cdot10^{-3}$	$1.40\cdot10^{-3}$	$2.54\cdot10^{-3}$	$1.17\cdot10^{-3}$	$9.06\cdot10^{-4}$	$3.15\cdot10^{-3}$	$8.36\cdot10^{-4}$	$1.70\cdot10^{-3}$
$\delta/^\circ$	38.816	210.46	43.046	11.532	341.29	6.4034	186.19	14.663	189.07	351.61
M_1/GeV	$7.48\cdot10^{9}$	$2.56\cdot10^{9}$	$9.95\cdot10^{4}$	$7.36\cdot10^{6}$	$8.43\cdot10^{4}$	$7.13\cdot10^{6}$	$1.01\cdot10^{3}$	$1.37\cdot10^{10}$	$9.09\cdot10^{2}$	$2.71\cdot10^{10}$
M_2/GeV	$4.95\cdot10^{11}$	$2.14\cdot10^{11}$	$2.14\cdot10^{12}$	$6.96\cdot10^{10}$	$3.64\cdot10^{12}$	$9.07\cdot10^{10}$	$6.36\cdot10^{11}$	$2.57\cdot10^{11}$	$5.60\cdot10^{11}$	$5.01\cdot10^{11}$
M_3/GeV	$5.61\cdot10^{12}$	$2.48\cdot10^{12}$	$7.51\cdot10^{14}$	$2.29\cdot10^{13}$	$1.02\cdot10^{15}$	$2.97\cdot10^{13}$	$1.36\cdot10^{13}$	$9.45\cdot10^{12}$	$1.19\cdot10^{13}$	$2.09\cdot10^{13}$

inverted ordering

Physical Quantity	M2				M3			
	M2I1B1	M2I1B2	M2I2B1	M2I2B2	M3I1B1	M3I1B2	M3I2B1	M3I2B2
$y_u/10^{-6}$	2.79	4.03	2.77	3.49	2.56	2.54	2.56	2.54
$y_c/10^{-3}$	1.37	1.44	1.37	1.36	1.38	1.36	1.38	1.36
y_t	0.428	0.427	0.428	0.428	0.428	0.428	0.428	0.428
$y_d/10^{-6}$	6.92	6.82	6.60	8.92	5.95	8.05	5.95	7.93
$y_s/10^{-4}$	1.27	0.740	1.24	1.11	1.21	1.10	1.22	1.11
$y_b/10^{-2}$	0.572	0.570	0.570	0.567	0.571	0.570	0.571	0.570
$y_e/10^{-6}$	2.70369	2.70455	2.70332	2.70702	2.70333	2.70326	2.70337	2.70348
$y_\mu/10^{-4}$	5.71365	5.73366	5.70814	5.68800	5.70707	5.71460	5.70701	5.71393
$y_\tau/10^{-2}$	0.96303	0.97624	0.96926	0.98031	0.97013	0.97102	0.97008	0.97048
θ^q_{12}	0.22740	0.22733	0.22739	0.22735	0.22742	0.22741	0.22742	0.22740
$\theta^q_{23}/10^{-2}$	4.864	4.884	4.859	4.860	4.870	4.871	4.870	4.869
$\theta^q_{13}/10^{-3}$	4.140	4.194	4.195	4.036	4.201	4.146	4.200	4.152
δ^q	1.210	1.157	1.206	1.023	1.216	1.217	1.216	1.214
$\Delta m^2_{21}/10^{-5}\,\mathrm{eV}^2$	7.49	7.46	7.49	7.28	7.49	7.50	7.49	7.49
$\Delta m^2_{3\ell}/10^{-3}\,\mathrm{eV}^2$	−2.484	−2.483	−2.510	−2.509	−2.484	−2.484	−2.510	−2.510
$\sin^2\theta^l_{12}$	0.308	0.306	0.308	0.357	0.308	0.308	0.308	0.308
$\sin^2\theta^l_{23}$	0.569	0.556	0.565	0.520	0.550	0.567	0.562	0.578
$\sin^2\theta^l_{13}$	0.02232	0.02228	0.02224	0.02241	0.02231	0.02237	0.02224	0.02230
$\chi^2/(n_{\mathrm{obs}}=18)$	0.205	4.31	0.00721	3.54	0.0680	0.717	0.0680	0.598
m_l/eV	$2.53\cdot10^{-4}$	$1.78\cdot10^{-2}$	$2.07\cdot10^{-4}$	$2.02\cdot10^{-2}$	$9.83\cdot10^{-3}$	$1.48\cdot10^{-2}$	$9.60\cdot10^{-3}$	$1.41\cdot10^{-2}$
m_β/eV	$4.88\cdot10^{-2}$	$5.19\cdot10^{-2}$	$4.90\cdot10^{-2}$	$5.31\cdot10^{-2}$	$4.97\cdot10^{-2}$	$5.10\cdot10^{-2}$	$5.00\cdot10^{-2}$	$5.10\cdot10^{-2}$
$m_{\beta\beta}/\mathrm{eV}$	$2.88\cdot10^{-2}$	$3.30\cdot10^{-2}$	$4.37\cdot10^{-2}$	$1.43\cdot10^{-2}$	$4.92\cdot10^{-2}$	$3.96\cdot10^{-2}$	$4.95\cdot10^{-2}$	$3.95\cdot10^{-2}$
$\delta/^\circ$	307.27	101.18	326.05	69.966	327.06	347.86	202.42	14.403
M_1/GeV	$7.60\cdot10^{3}$	$4.73\cdot10^{6}$	$5.12\cdot10^{3}$	$1.84\cdot10^{6}$	$5.90\cdot10^{5}$	$7.09\cdot10^{9}$	$5.93\cdot10^{5}$	$7.14\cdot10^{9}$
M_2/GeV	$2.15\cdot10^{12}$	$1.45\cdot10^{10}$	$2.97\cdot10^{12}$	$1.67\cdot10^{10}$	$7.07\cdot10^{10}$	$8.17\cdot10^{10}$	$7.14\cdot10^{10}$	$8.39\cdot10^{10}$
M_3/GeV	$6.55\cdot10^{14}$	$4.30\cdot10^{12}$	$8.61\cdot10^{14}$	$5.22\cdot10^{12}$	$3.14\cdot10^{12}$	$6.45\cdot10^{12}$	$3.17\cdot10^{12}$	$6.53\cdot10^{12}$