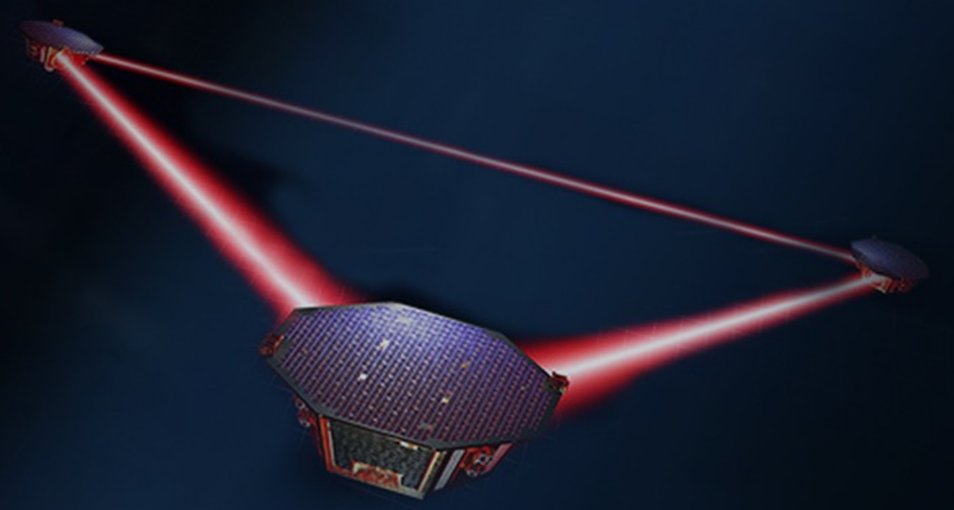
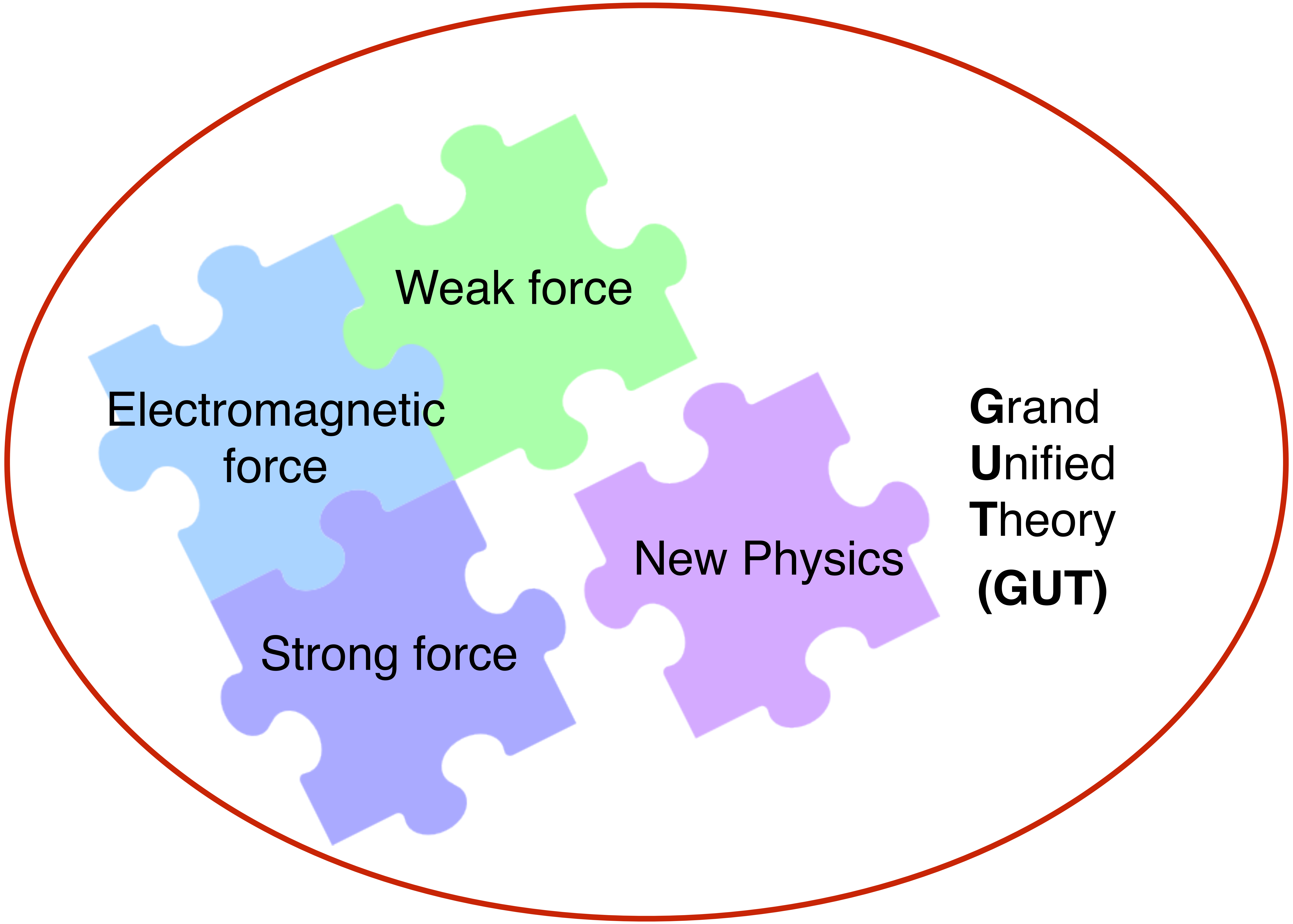
中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

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



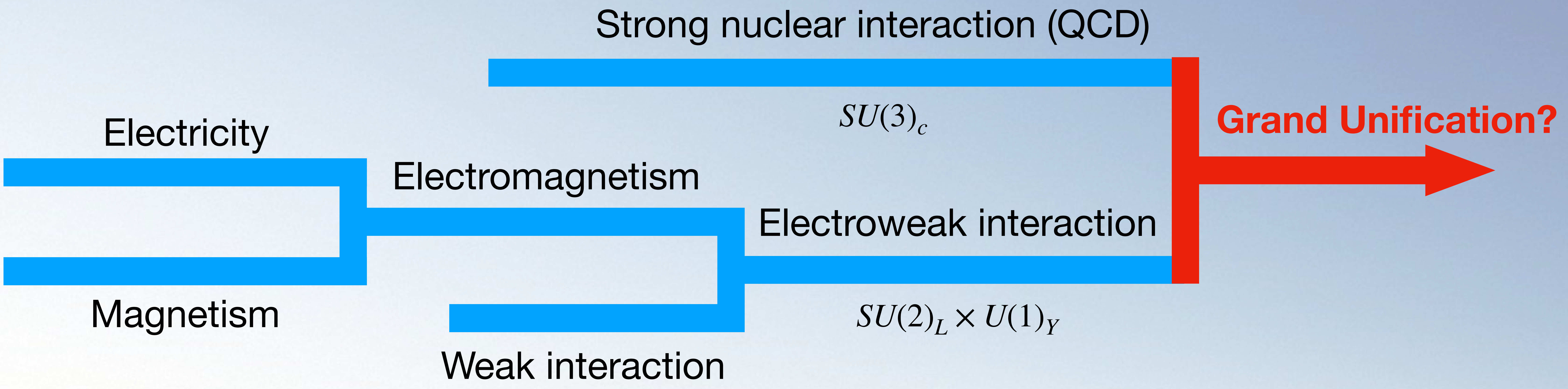
Ye-Ling Zhou (HIAS-UCAS) 2024-07-21

Framework of GUTs

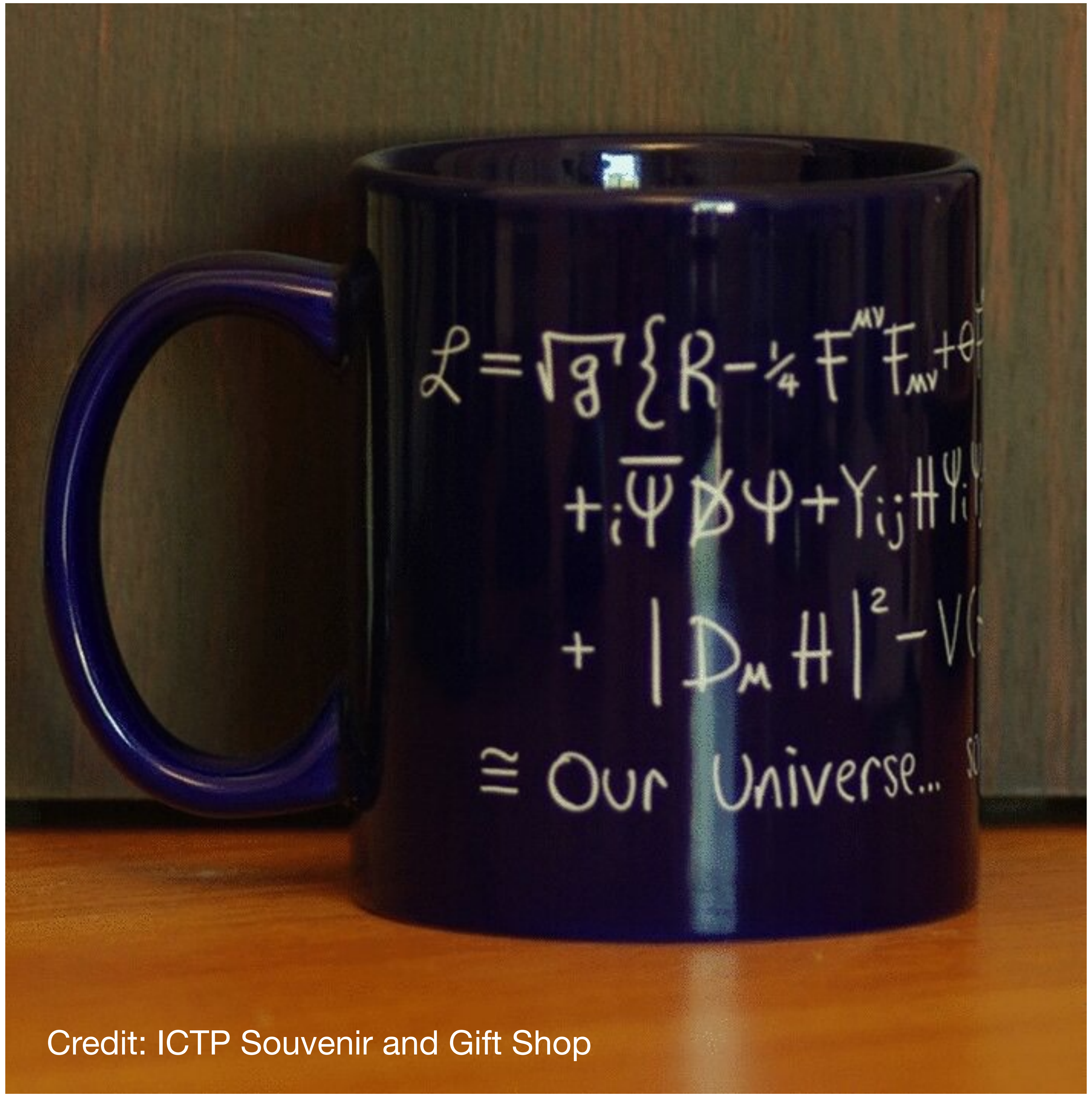


Gravity… not included

Road to unifications



What we know so far…



Credit: ICTP Souvenir and Gift Shop

The Standard Model of Particle Physics

- Gauge theories in

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

Strong force — Weak & EM force

- Particle content

ν_τ	τ	t	b	γ	$W^\pm$	H
ν_μ	μ	c	s	g	Z^0	
ν_e	e	u	d			

- Yukawa couplings
- Higgs mechanism

And neutrinos have masses…

How to get a GUT?

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

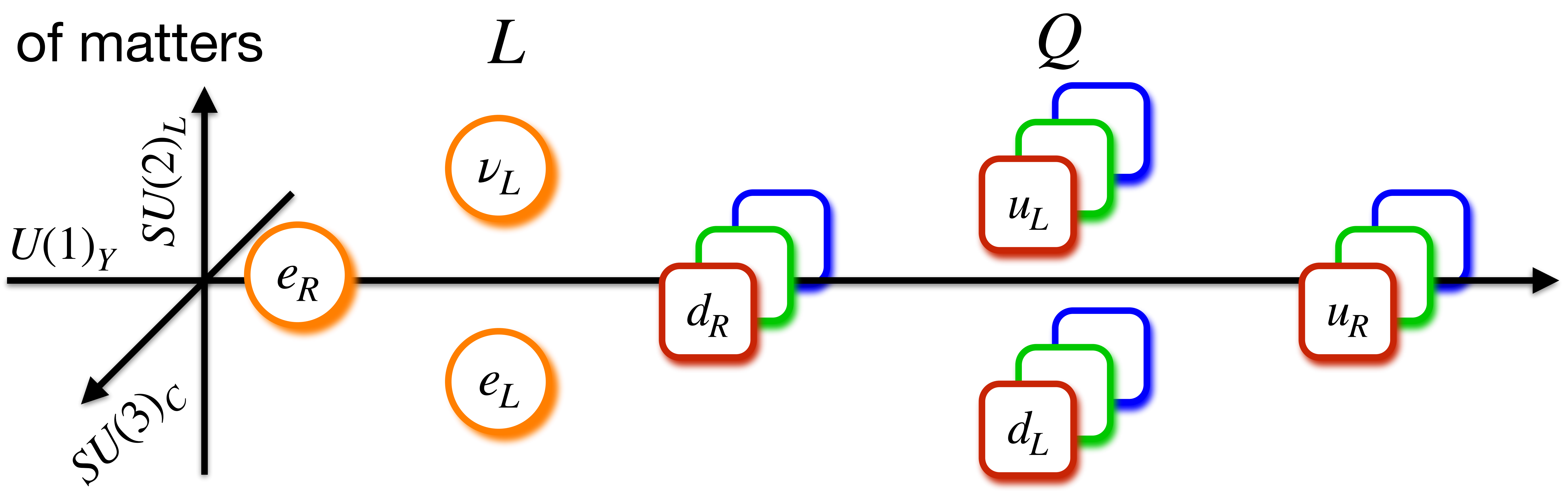
EW

- Unification of couplings $g_3 = g_2 = g_1$

(up to loop correction factors, and if $G_{\rm GUT}$ is a simple Lie group)

The scale where three gauge couplings are unified, denoted as $M_{\rm GUT}$ in this talk

- Unification of matters



Weak hypercharge: $Y = -1$ $Y = -\frac{1}{2}$ $Y = -\frac{1}{3}$ $Y = \frac{1}{6}$ $Y = \frac{2}{3}$

The beginning of GUTs

Pati-Salam (1973, 1974) $SU(4)_c \times SU(2)_L \times SU(2)_R := G_{422}$

PHYSICAL REVIEW D VOLUME 8, NUMBER 4 15 AUGUST 1973

Unified Lepton-Hadron Symmetry and a Gauge Theory of the Basic Interactions*

Jogesh C. Pati†
Department of Physics and Astronomy, University of Maryland, College Park, Maryland

Abdus Salam
International Centre for Theoretical Physics, Miramare, Trieste, Italy
and Imperial College, London
(Received 5 February 1973)

An attempt is made to unify the fundamental hadrons and leptons into a common irreducible representation F of the same symmetry group G and to generate a gauge theory of strong, electromagnetic, and weak interactions. Based on certain constraints from the hadronic side, it is proposed that the group G is SU(4′)×SU(4″), which contains a Han-Nambu-type SU(3′)×SU(3″) group for the hadronic symmetry, and that the representation F is (4,4*). There exist four possible choices for the lepton number L and accordingly four possible assignments of the hadrons and leptons within the (4,4*). Two of these require

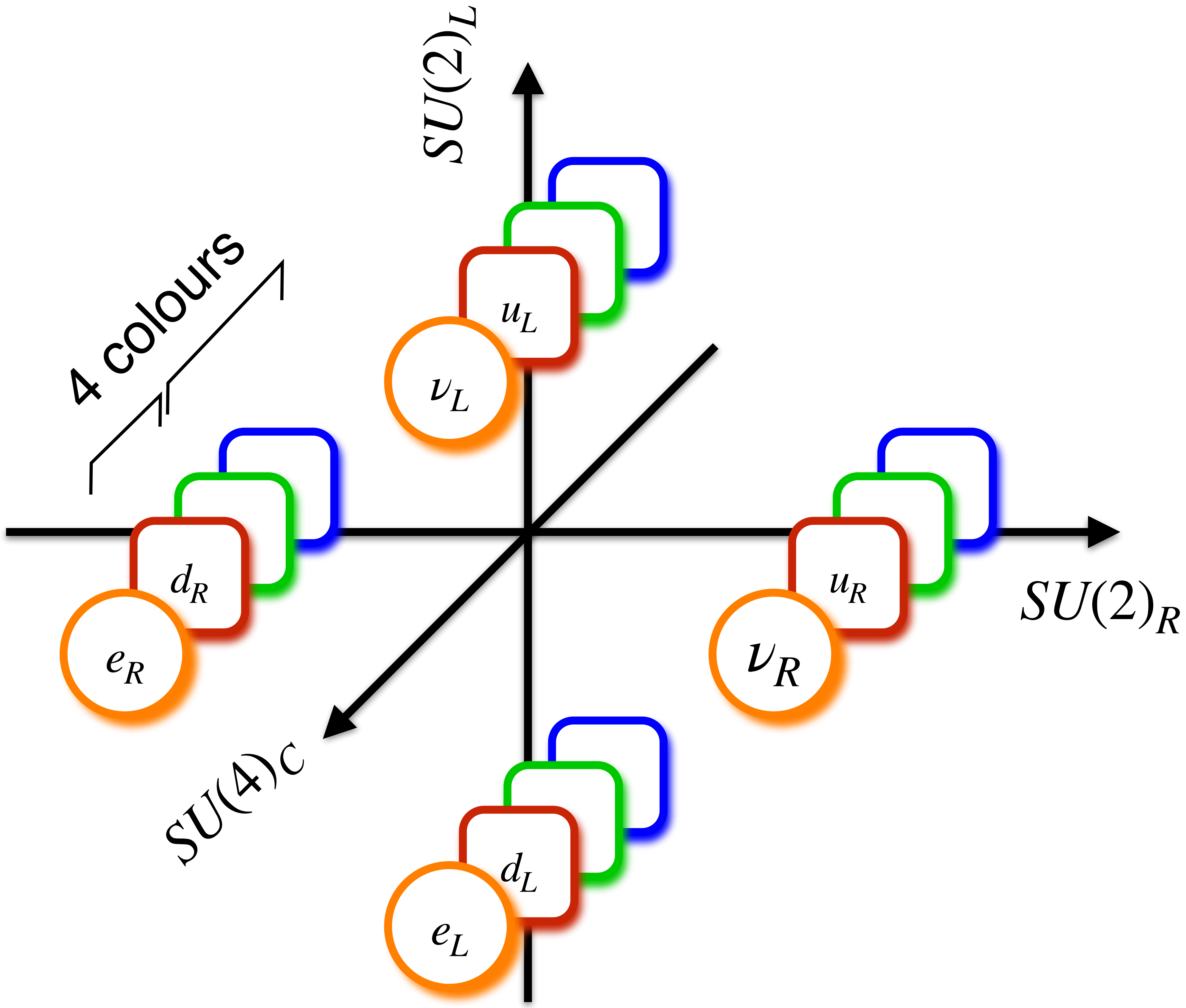
PHYSICAL REVIEW D VOLUME 10, NUMBER 1 1 JULY 1974

Lepton number as the fourth "color"

Jogesh C. Pati*
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

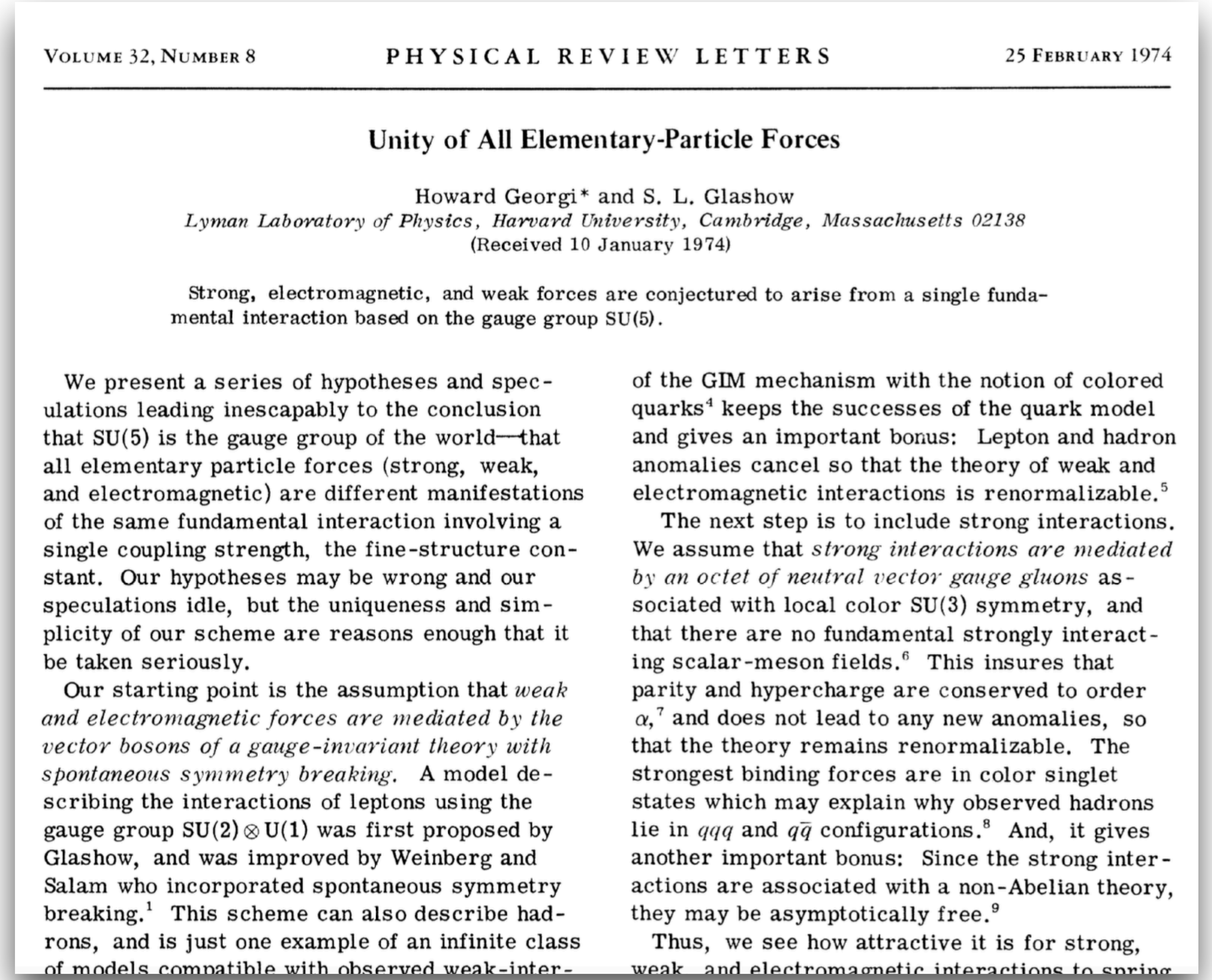
Abdus Salam
International Centre for Theoretical Physics, Trieste, Italy
and Imperial College, London, England
(Received 25 February 1974)

Universal strong, weak, and electromagnetic interactions of leptons and hadrons are generated by gauging a non-Abelian renormalizable anomaly-free subgroup of the fundamental symmetry structure $SU(4)_L \times SU(4)_R \times SU(4')$, which unites three quartets of "colored" baryonic quarks and the quartet of known leptons into 16-folds of chiral fermionic multiplets, with lepton number treated as the fourth "color" quantum number. Experimental consequences of this scheme are discussed. These include (1) the emergence and effects of exotic gauge mesons carrying both baryonic as well as leptonic quantum numbers, particularly in semileptonic processes, (2) the manifestation of anomalous strong interactions among leptonic and semi-leptonic processes at high energies, (3) the independent possibility of baryon-lepton number violation in quark and proton decays, and (4) the occurrence of $(V+A)$ weak-current effects.



The beginning of GUTs

Georgi-Glashow (1974), $SU(5)$ GUT



VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

Our starting point is the assumption that *weak and electromagnetic forces are mediated by the vector bosons of a gauge-invariant theory with spontaneous symmetry breaking.* A model describing the interactions of leptons using the gauge group SU(2)⊗U(1) was first proposed by Glashow, and was improved by Weinberg and Salam who incorporated spontaneous symmetry breaking.[1] This scheme can also describe hadrons, and is just one example of an infinite class of models compatible with observed weak-inter-

of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.[5]

The next step is to include strong interactions. We assume that *strong interactions are mediated by an octet of neutral vector gauge gluons* associated with local color SU(3) symmetry, and that there are no fundamental strongly interacting scalar-meson fields.[6] This insures that parity and hypercharge are conserved to order α,[7] and does not lead to any new anomalies, so that the theory remains renormalizable. The strongest binding forces are in color singlet states which may explain why observed hadrons lie in qqq and $q\bar{q}$ configurations.[8] And, it gives another important bonus: Since the strong interactions are associated with a non-Abelian theory, they may be asymptotically free.[9]

Thus, we see how attractive it is for strong, weak, and electromagnetic interactions to spring

$$\bar{\mathbf{5}} \Rightarrow \begin{pmatrix} (d_R^1)^c \\ (d_R^2)^c \\ (d_R^3)^c \\ e_L \\ -\nu_L \end{pmatrix}$$

$$\mathbf{10} \Downarrow \begin{pmatrix} 0 & (u_R^3)^c & -(u_R^2)^c & -u_L^1 & -d_L^1 \\ -(u_R^3)^c & 0 & (u_R^1)^c & -u_L^2 & -d_L^2 \\ (d_R^2)^c & -(d_R^1)^c & 0 & -u_L^3 & -d_L^3 \\ u_L^1 & u_L^2 & u_L^3 & 0 & (e_R)^c \\ d_L^1 & d_L^2 & d_L^3 & -(e_R)^c & 0 \end{pmatrix}$$

And Higgses $\mathbf{5}, \mathbf{45}, \mathbf{24}$.

The beginning of GUTs

- $SO(10)$ GUTs Fritzsch, Minkowski (1975)

$$\mathbf{16} = \bar{\mathbf{5}} + \mathbf{10} + \mathbf{1} = (\mathbf{4}, \mathbf{2}, \mathbf{1}) + (\mathbf{4}, \mathbf{1}, \mathbf{2})$$

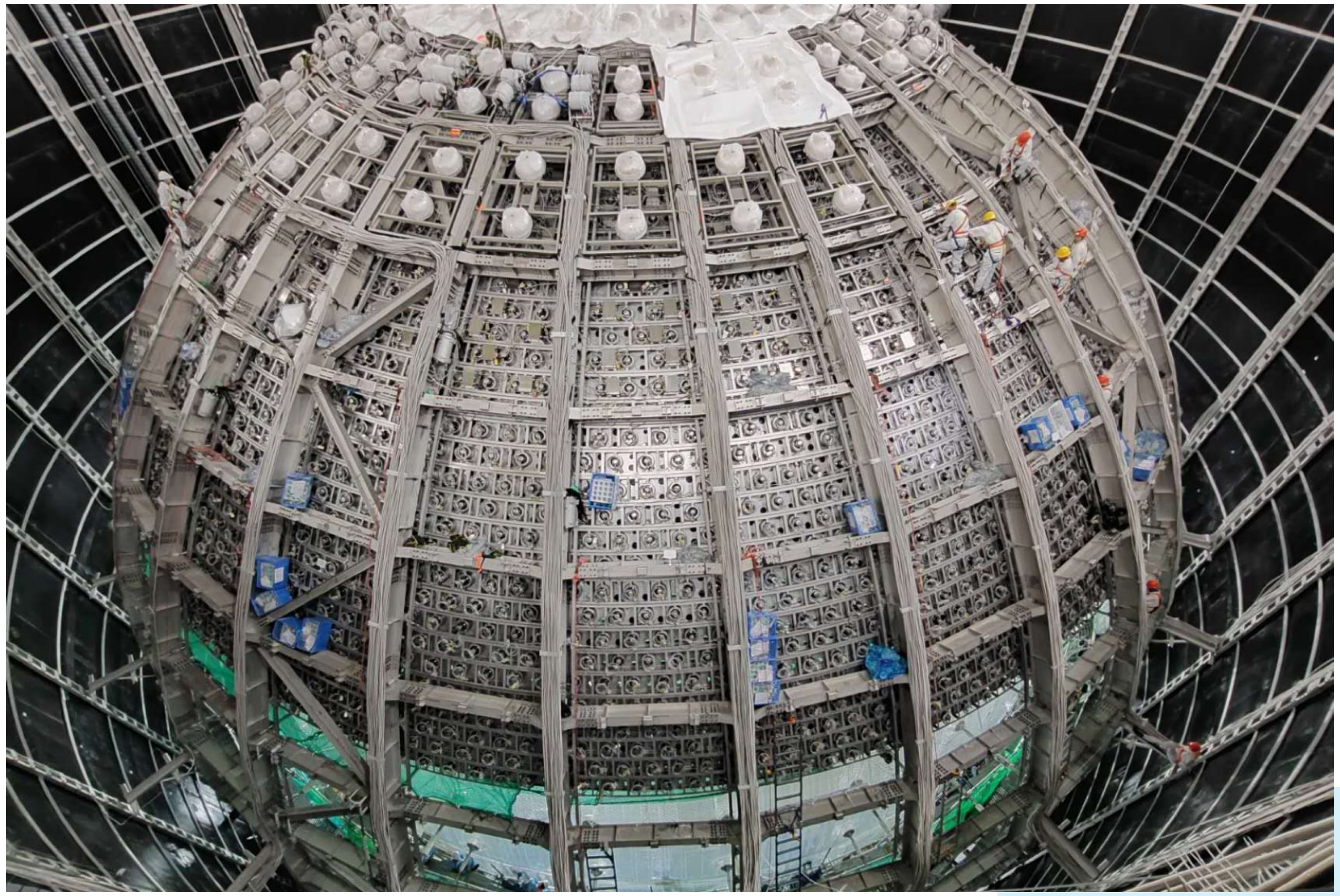
$$SO(10) \quad SU(5) \qquad SU(4)_c \times SU(2)_L \times SU(2)_R$$

Contains SU(5) and Pati-Salam, and more …

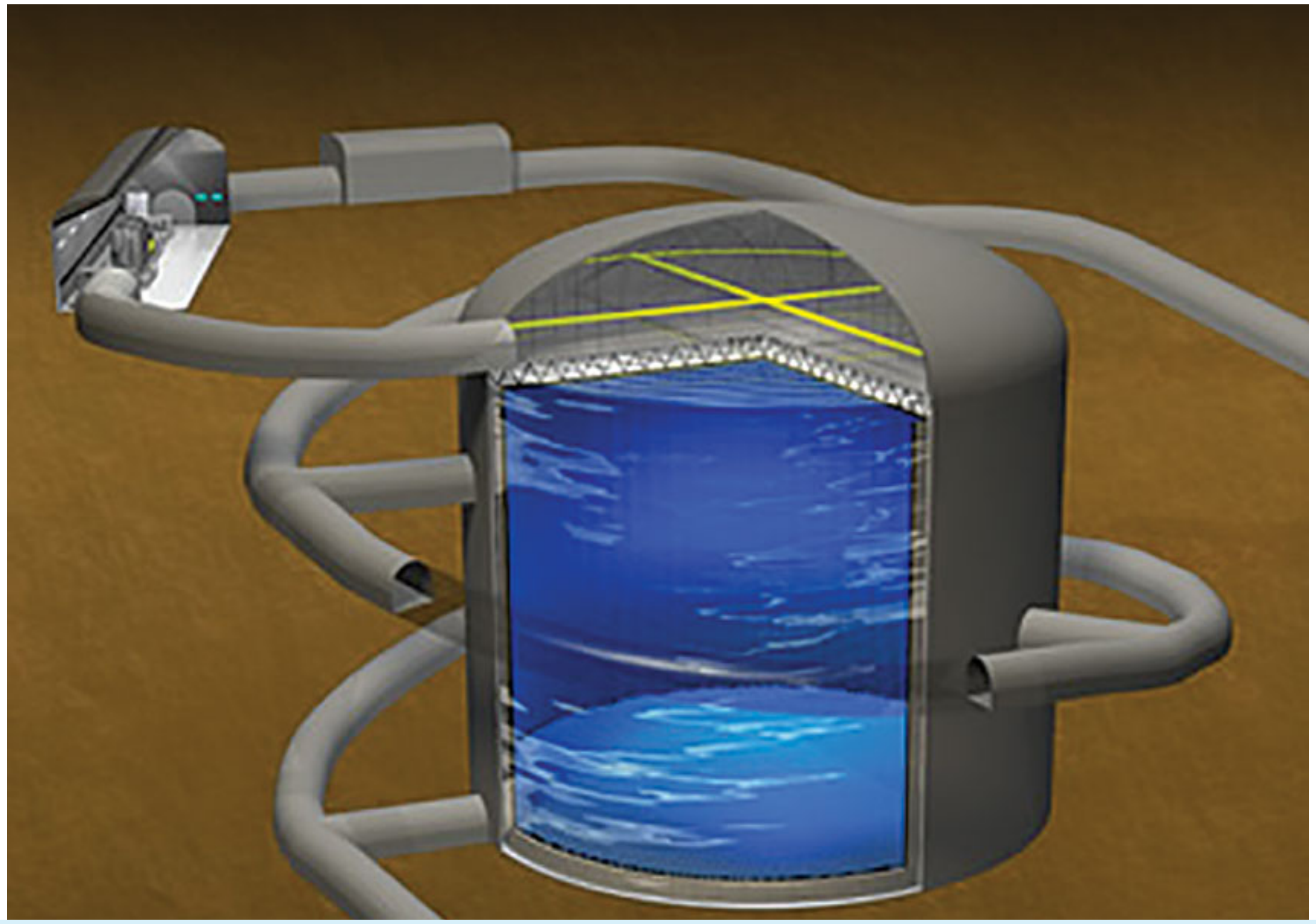
- Not minimal but realistic $SU(5)$ e.g., with extra $\mathbf{15}_H, \quad \mathbf{24}_F$
- $SU(5) \times U(1)_{B-L} := G_{51}$ $\bar{\mathbf{5}} + \mathbf{10} + \mathbf{1},\ \nu_{\mathrm{R}} \sim \mathbf{1}$
- Flipped $SU(5) \times U(1)_\chi := G_{51}^{\text{flip}}$ $u \leftrightarrow d,\ \nu \leftrightarrow e$ ⇒ See Tianjun's talk

Rujula, Georgi, Glashow (1980); Barr,(1982); Derendinger, Kim, Nanopoulos (1984); Antoniadis, Ellis, Hagelin, Nanopoulos (1989)

Upcoming large-scale neutrino experiments



JUNO, about to run very soon



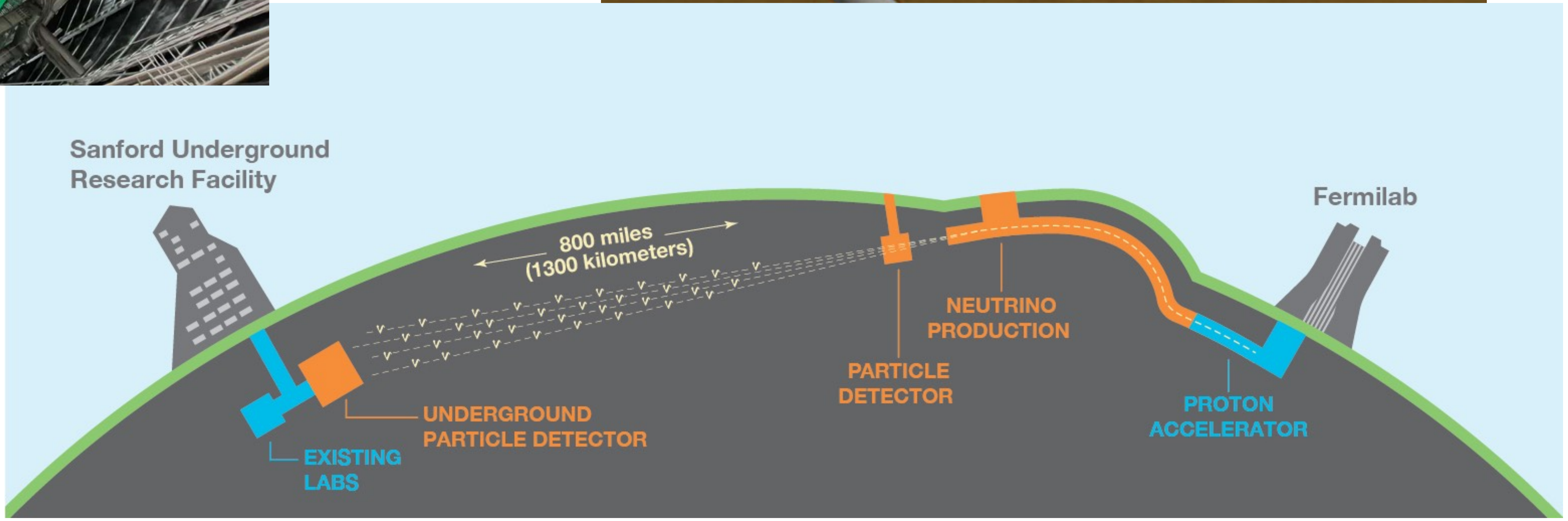
Hyper-K

expected to run in 2027

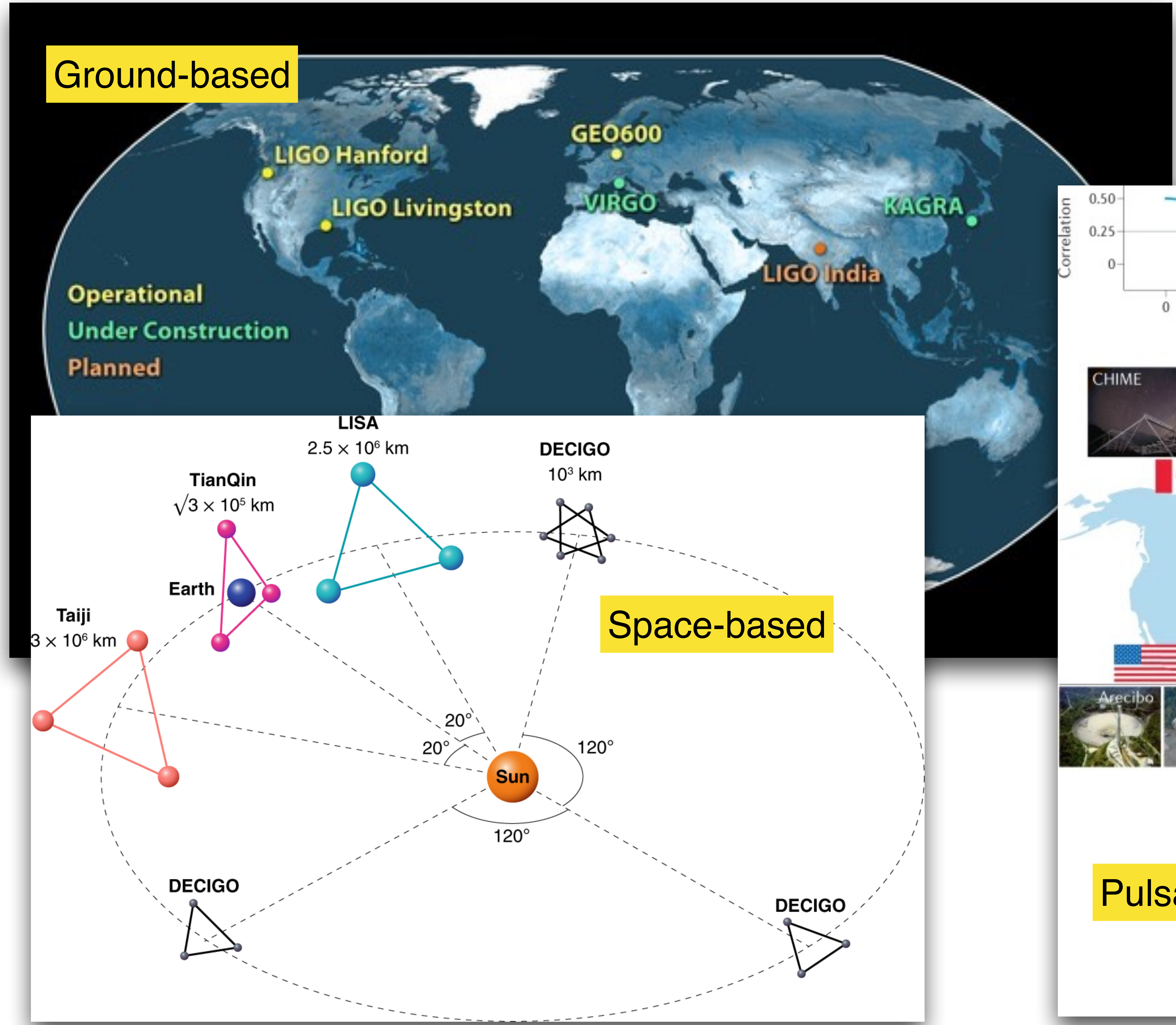
Neutrino precision measurements is coming!

DUNE

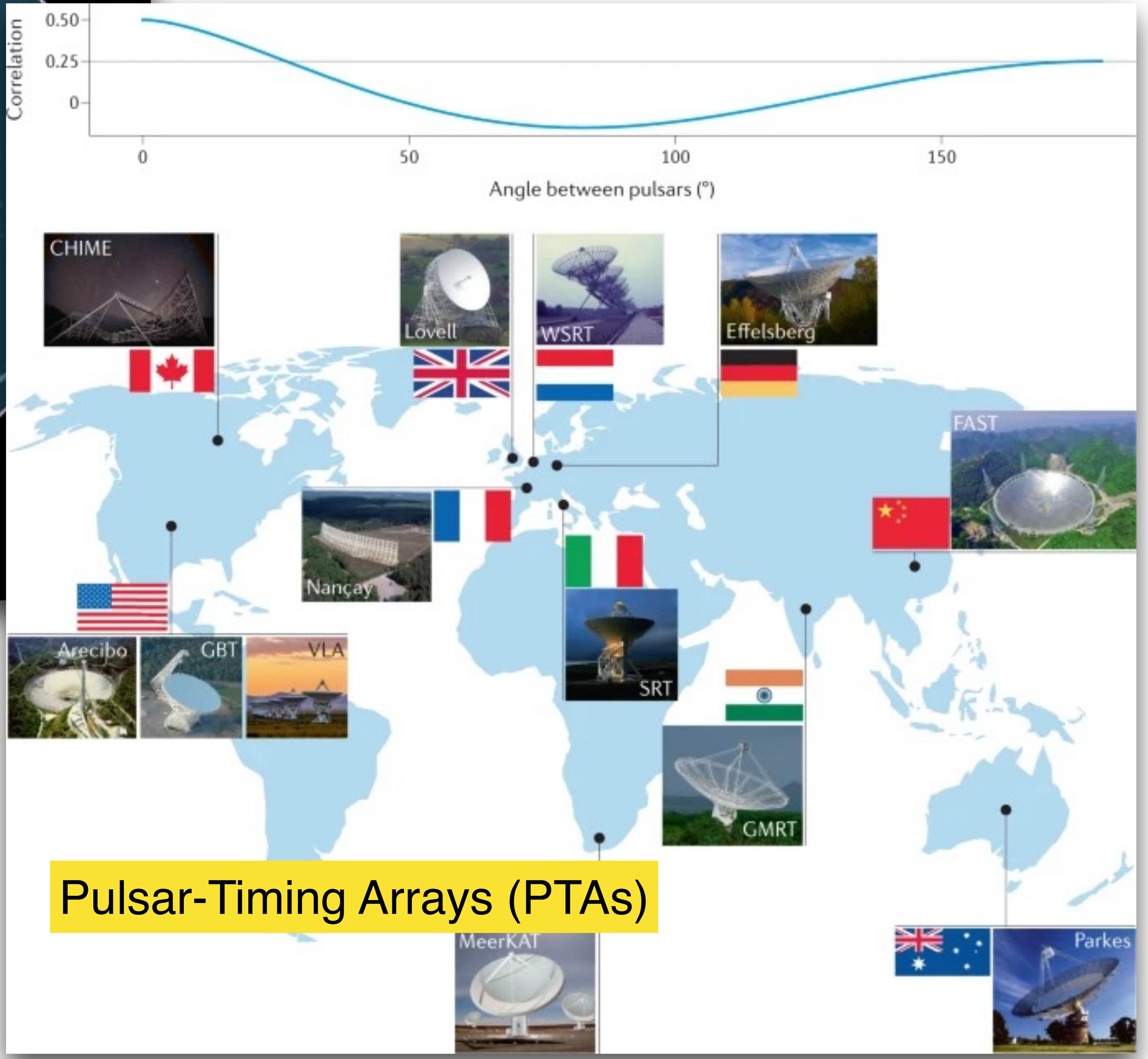
supposed to run in 2030?



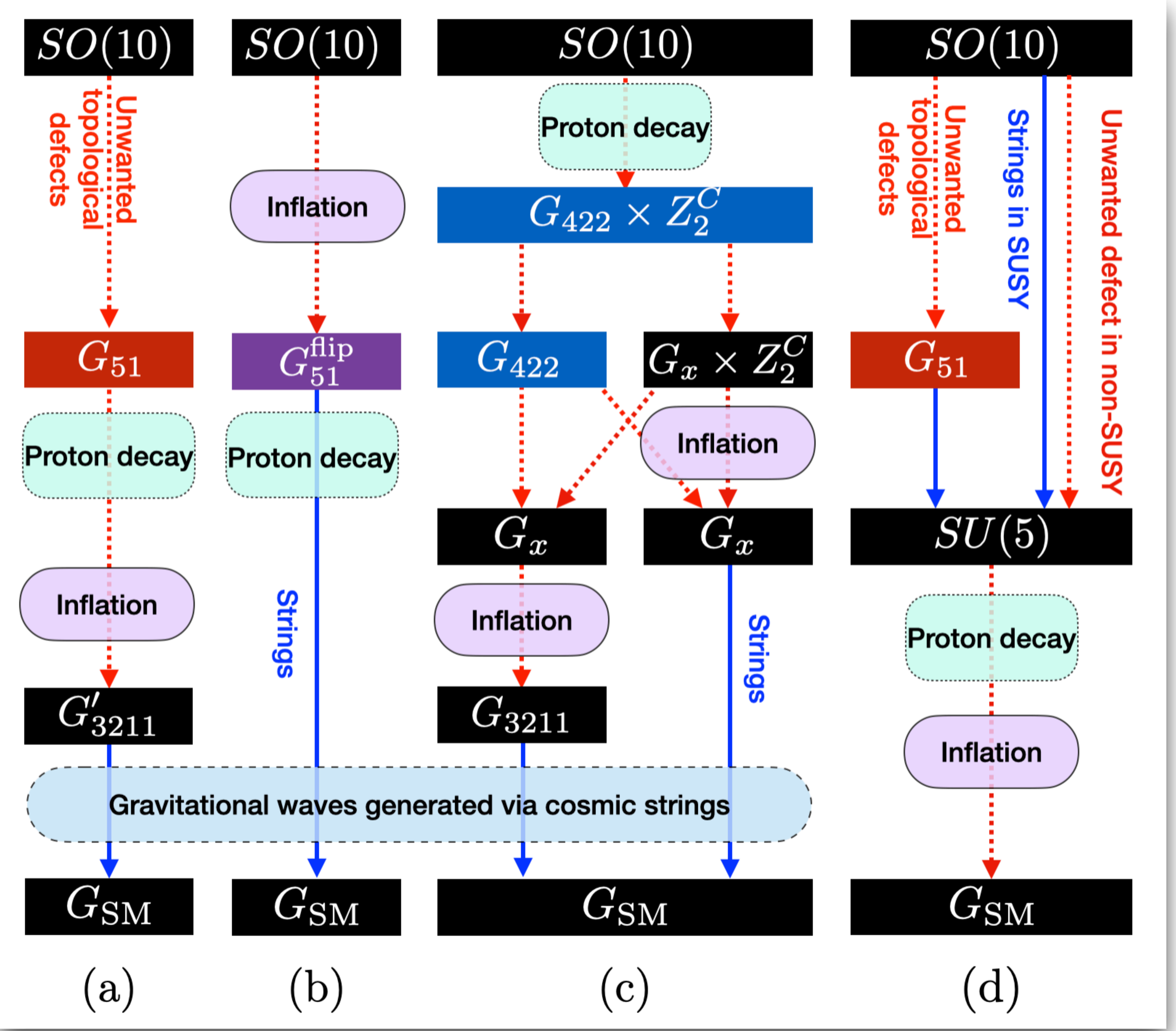
Undergoing and upcoming GW measurements



Era of GW observation!



GUT phenos



Unwanted topological defects: monopoles and domain walls

In any breaking chains, inflation has to been introduced to inflate unwanted defects

$G_{422} = SU(4)_C \times SU(2)_L \times SU(2)_R$

$G_{51} = SU(5) \times U(1)_X$

$G_{51}^{\rm flip} = SU(5)_{\rm flip} \times U(1)_{\rm flip}$

$Z_2^C: \quad \psi_L \leftrightarrow \psi_R^c$

$G_x = G_{421}$ or G_{3221}

$G_{3221} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$G_{421} = SU(4)_C \times SU(2)_L \times U(1)_Y$

$G_{3211} = SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$

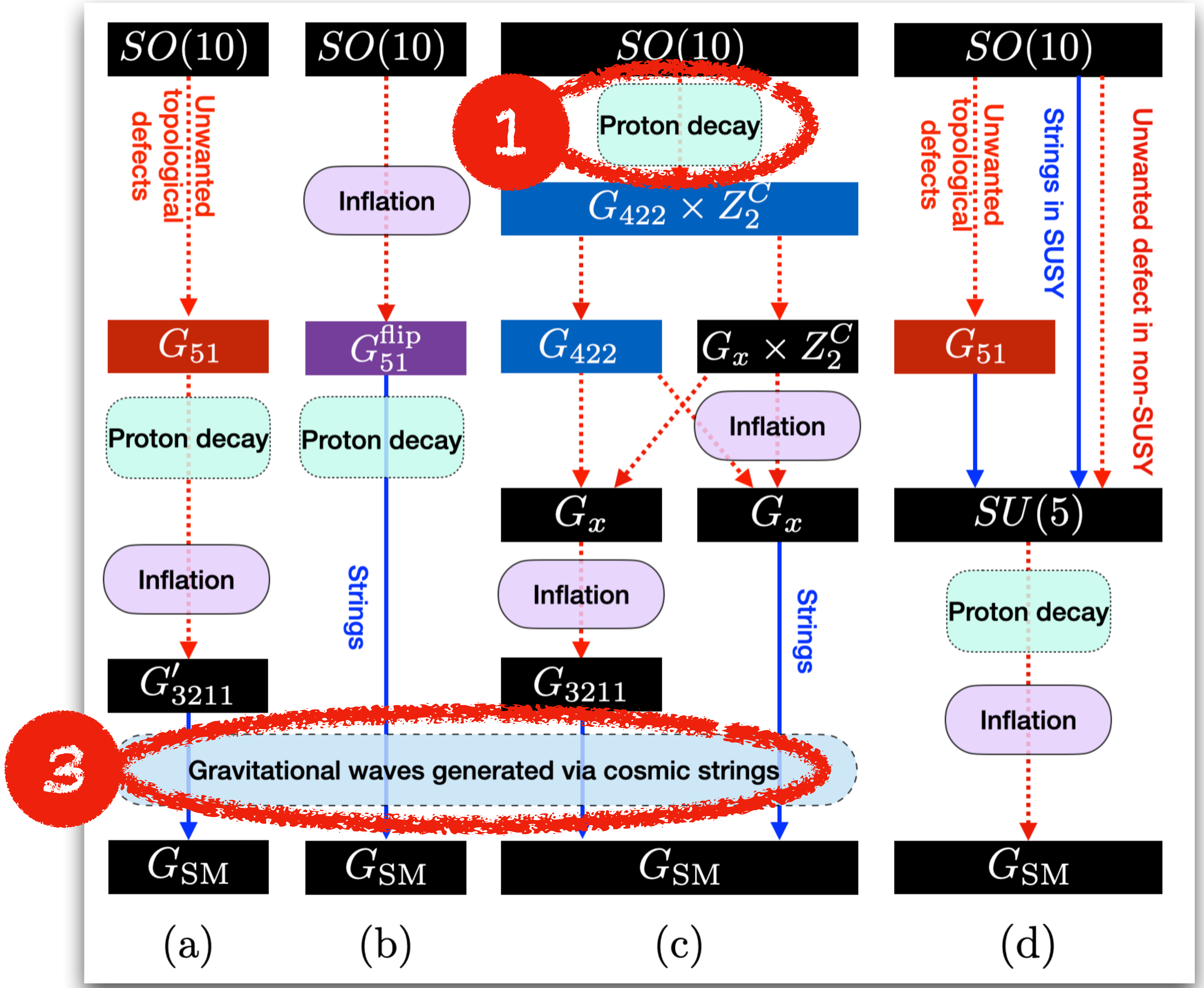
$G'_{3211} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

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

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

GUT phenos

2 Fermion masses and mixing



Unwanted topological defects: monopoles and domain walls

In any breaking chains, inflation has to been introduced to inflate unwanted defects

$G_{422} = SU(4)_C \times SU(2)_L \times SU(2)_R$

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$G_{3211} = SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$

$G'_{3211} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$

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

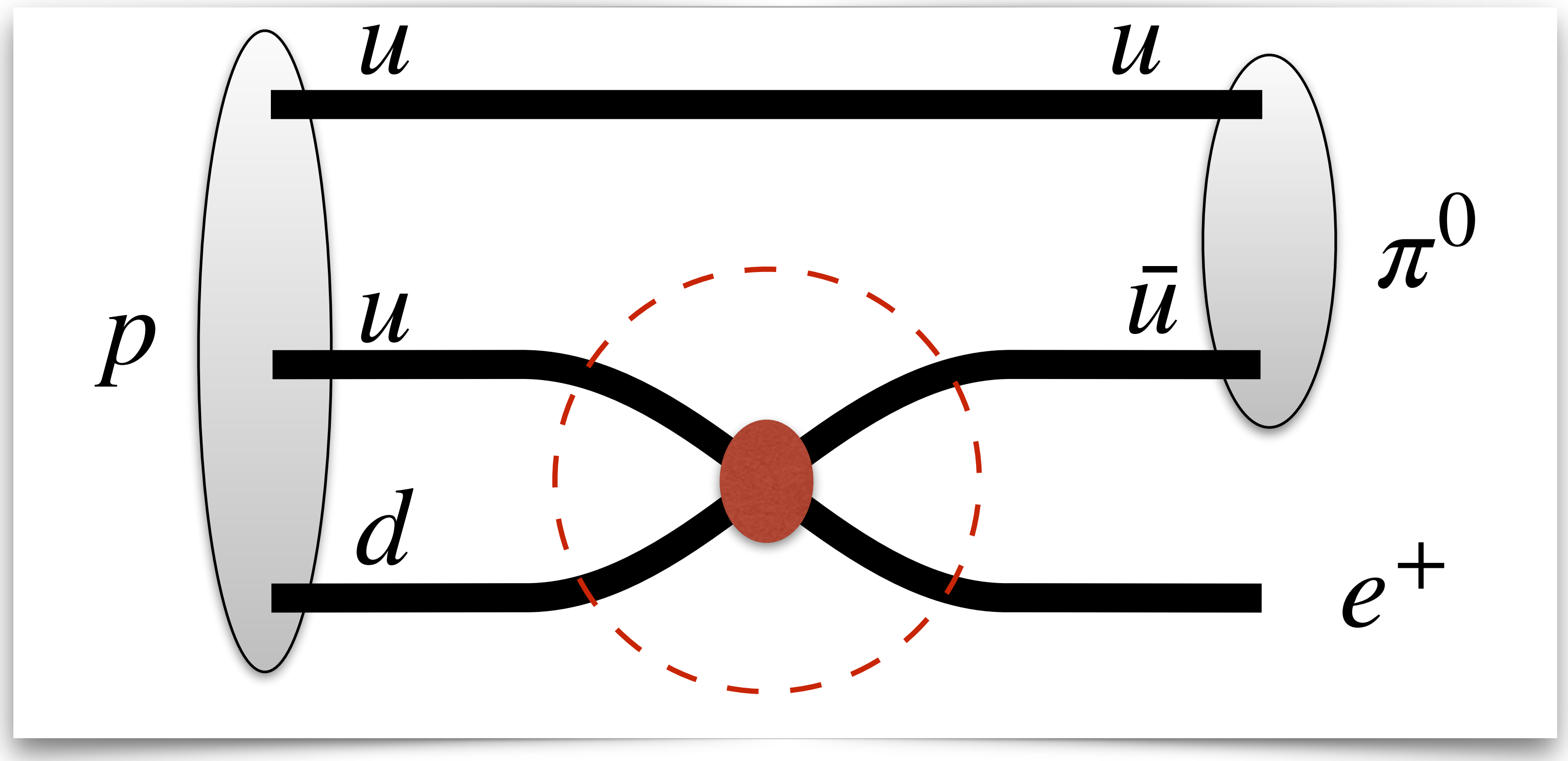
King, Pascoli, Turner, **YLZ**, 2005.13549

Proton decay

- GUTs unify baryons and leptons and naturally induce baryon-violating interactions, which appear as higher dimensional operators at low energy.

- Dim-6 operators

Dominated by gauge mediators

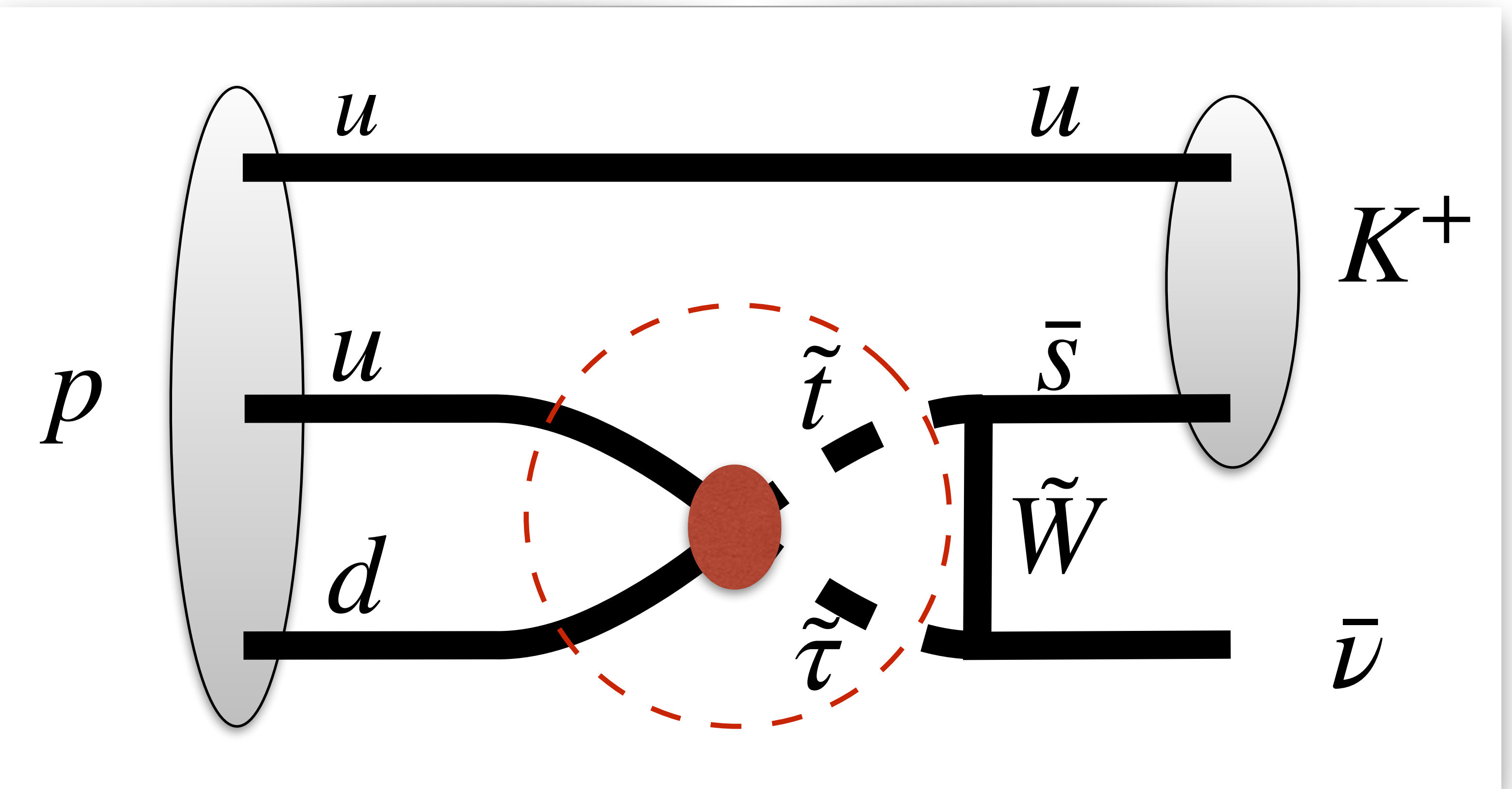


$p \to \pi^0 e^+$

$$\tau_{\pi^0 e^+} \sim 10^{35}\,\text{years} \times \left(\frac{M_{\rm GUT}}{10^{16}\,\text{GeV}}\right)^4$$

- Dim-5 operators

Induced by SUSY



$p \to K^+ \bar{\nu}$

$$\tau_{K^+\bar{\nu}} \propto (M_{\rm GUT} \cdot M_{\rm SUSY} \cdot Y_{\rm Yukawa})^2$$

Measuring proton decay in neutrino experiments

20 kton water / liquid scintillator

$\simeq 2 \times 10^{10}$ g $\times (2+8)/18$ mol/g $\times N_A$ /mol

$\simeq 7 \times 10^{33}$ proton

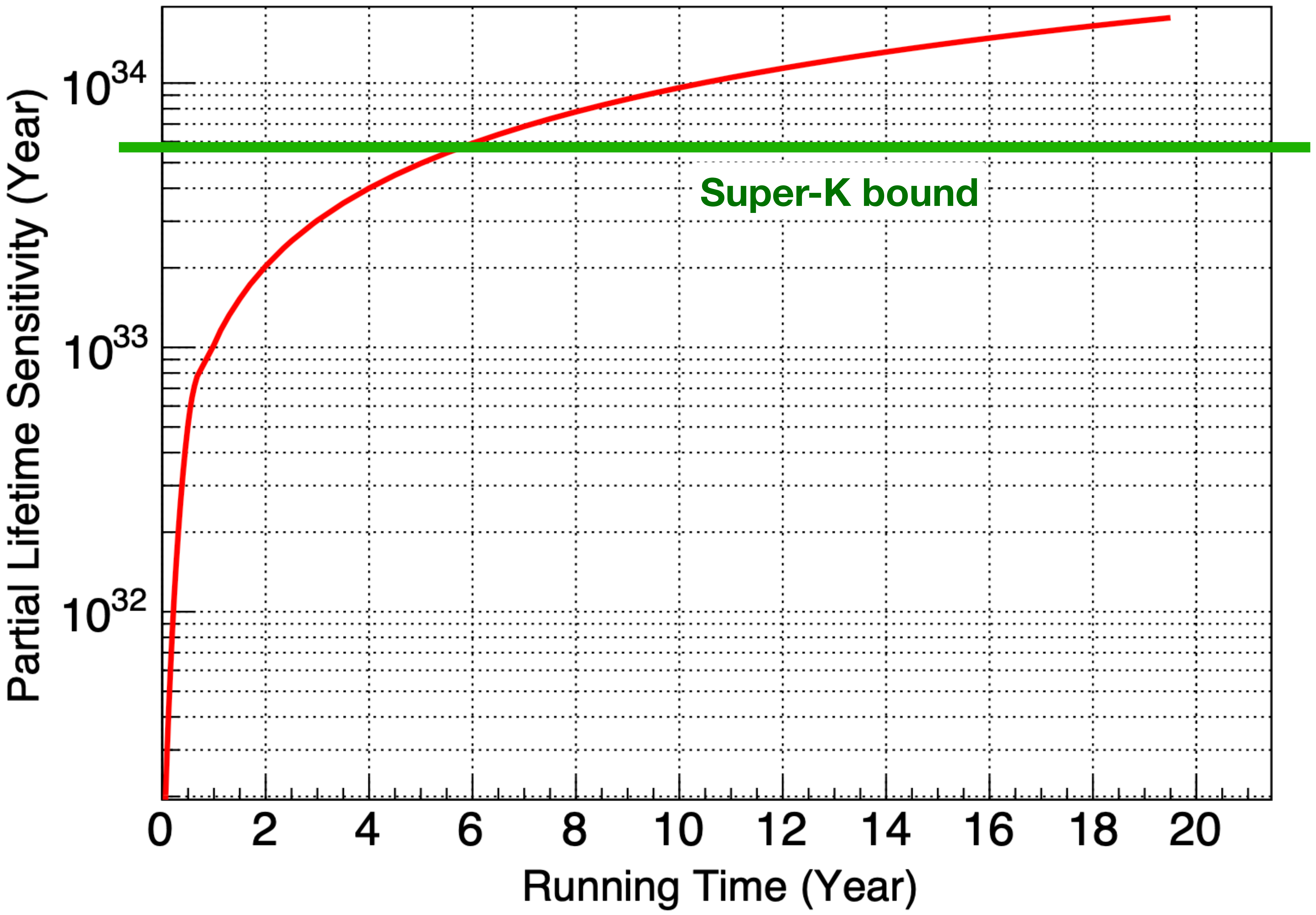
Capability of JUNO

Efficiency $\epsilon_{\rm JUNO} = 36.9\,\%$

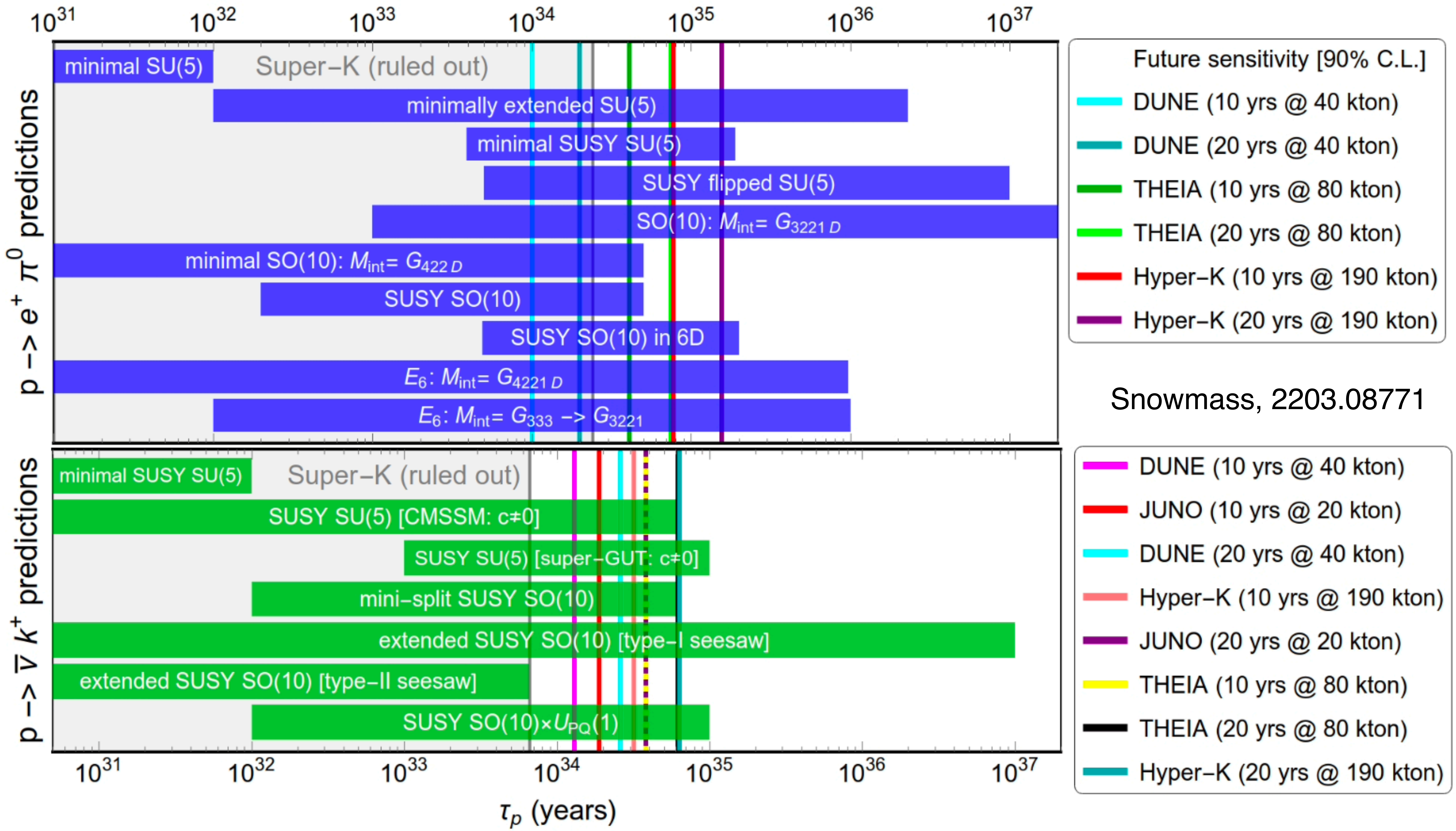
$$\tau/B(p \to \bar{\nu}K^+) = \frac{N_p T \epsilon}{n_{90}}$$

Statistics (90%CL)

JUNO, 2212.08502

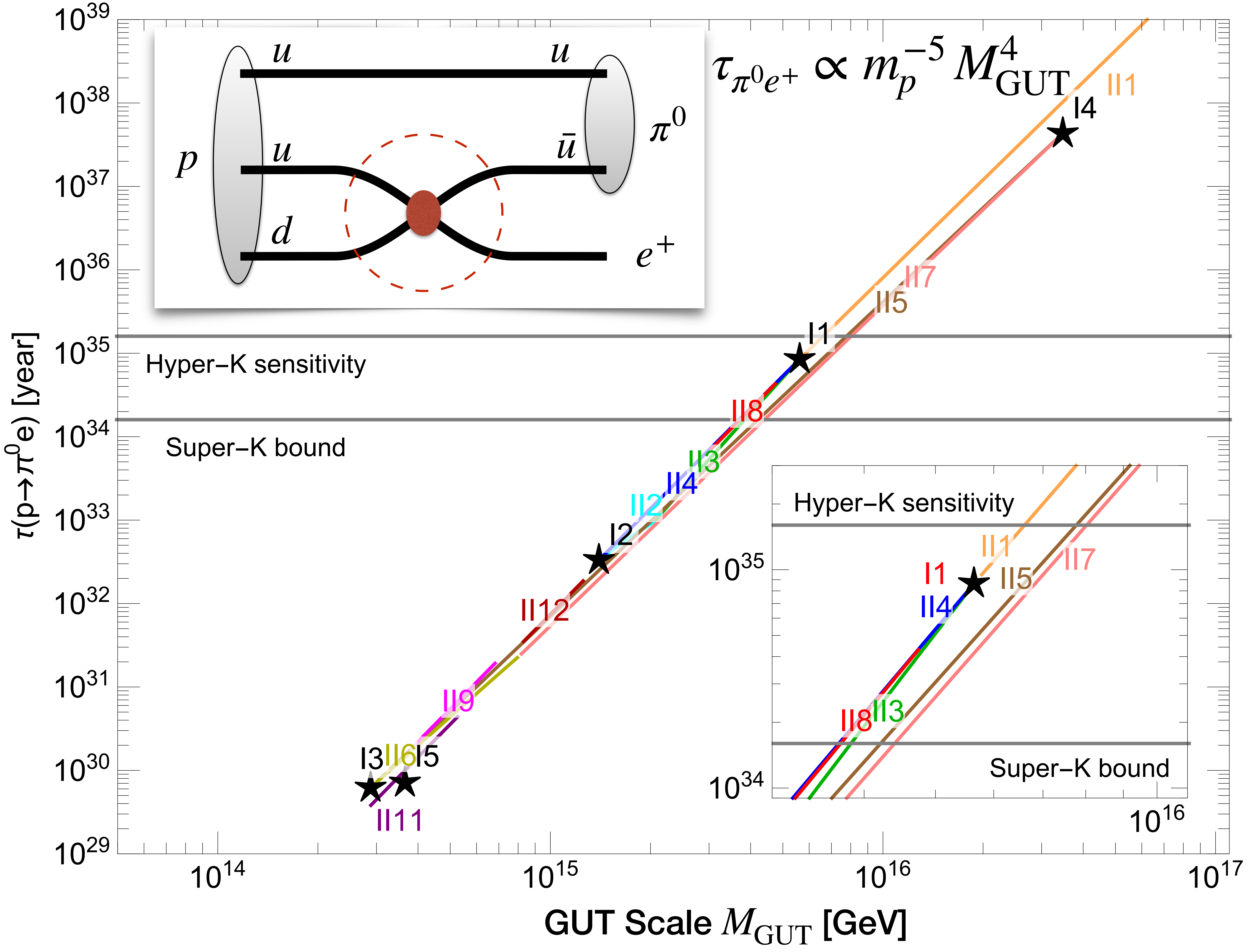


Potential in upcoming neutrino experiments



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_{422}^C	$\xrightarrow[\mathbf{210}]{\rm m}$	G_{3221}^C	$\xrightarrow[\mathbf{126}]{\rm s,w}$	
II3:	$\xrightarrow[\mathbf{54}]{\rm m,s}$	G_{422}^C	$\xrightarrow[\mathbf{45}]{\rm m,w}$	G_{3221}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II4:	$\xrightarrow[\mathbf{210}]{\rm m,s}$	G_{3221}^C	$\xrightarrow[\mathbf{45}]{\rm w}$	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_{422}^C	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{421}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II7:	$\xrightarrow[\mathbf{54}]{\rm m,s}$	G_{422}^C	$\xrightarrow[\mathbf{210}]{\rm w}$	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_{3221}^C	$\xrightarrow[\mathbf{45}]{\rm m,w}$	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_{422}^C	$\xrightarrow[\mathbf{210}]{\rm m,w}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\rm s}$	
II12:	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{421}	$\xrightarrow[\mathbf{45}]{\rm m}$	G_{3211}	$\xrightarrow[\mathbf{126}]{\rm s}$	

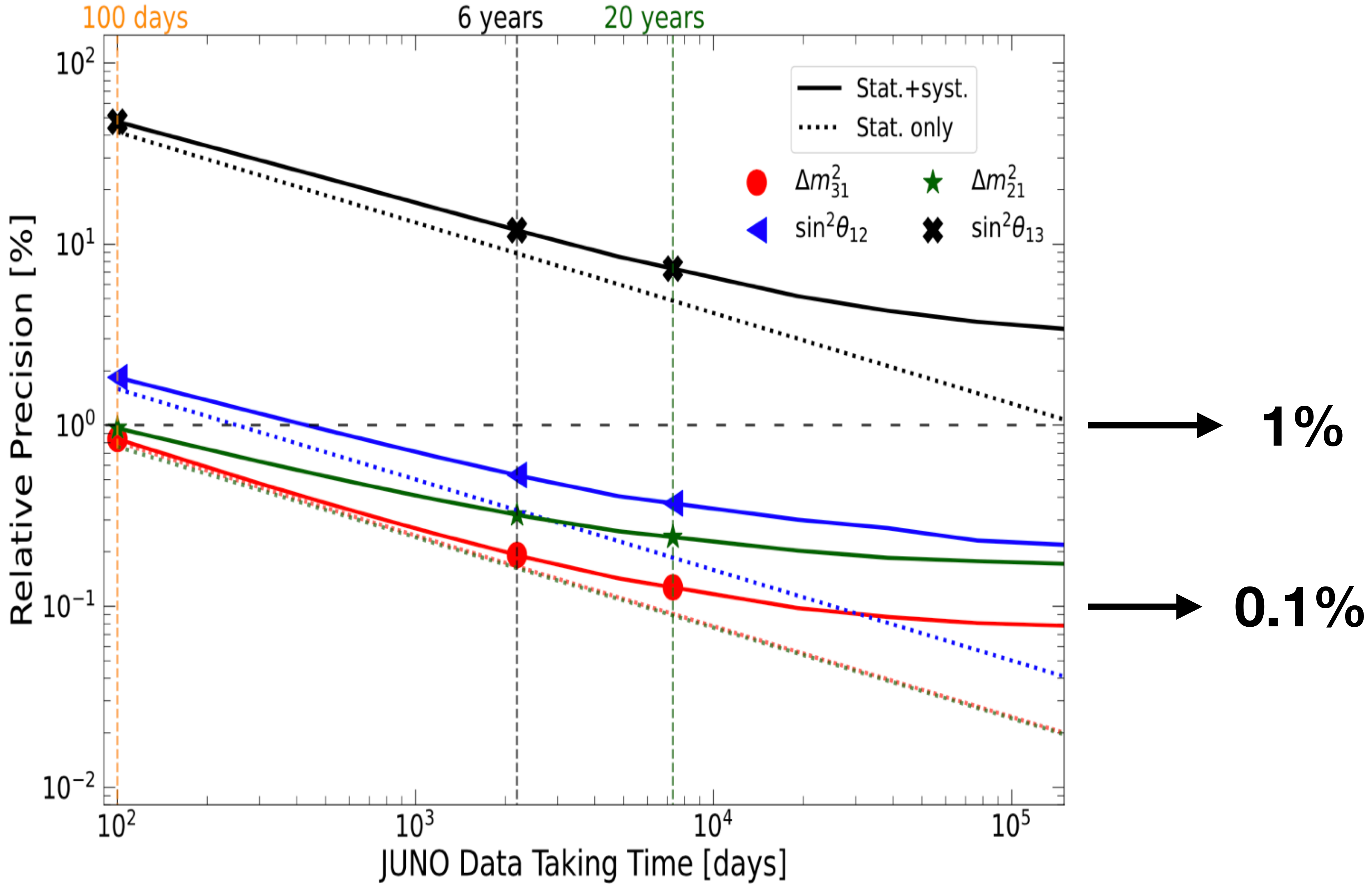
King, Pascoli, Turner, **YLZ**, 2106.15634

Fermion masses and mixing

NuFIT 5.3 (2024)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$



2204.13249

Fermion masses and mixing in SO(10)

- Matter fields $\{Q=(u_L,u_R),u_R,d_R,L=(\nu_L,e_L),e_R,\nu_R\}$ are arranged in a single $\mathbf{16}$ of SO(10)

$$\mathbf{16}\times\mathbf{16}=\mathbf{10}+\mathbf{126}+\mathbf{120}$$

- Three Higgs fields $\mathbf{10}_H,\overline{\mathbf{126}}_H,\mathbf{120}_H$ can be introduced

  And the SM Higgs should be the lightest one after mixing

- Gauge-invariant Yukawa interactions

$$\mathscr{L}_Y=Y^*_{\mathbf{10}}\mathbf{16}\cdot\mathbf{16}\cdot\mathbf{10}_H+Y^*_{\overline{\mathbf{126}}}\mathbf{16}\cdot\mathbf{16}\cdot\overline{\mathbf{126}}_H+Y^*_{\mathbf{120}}\mathbf{16}\cdot\mathbf{16}\cdot\mathbf{120}_H+\mathrm{h.c.}$$

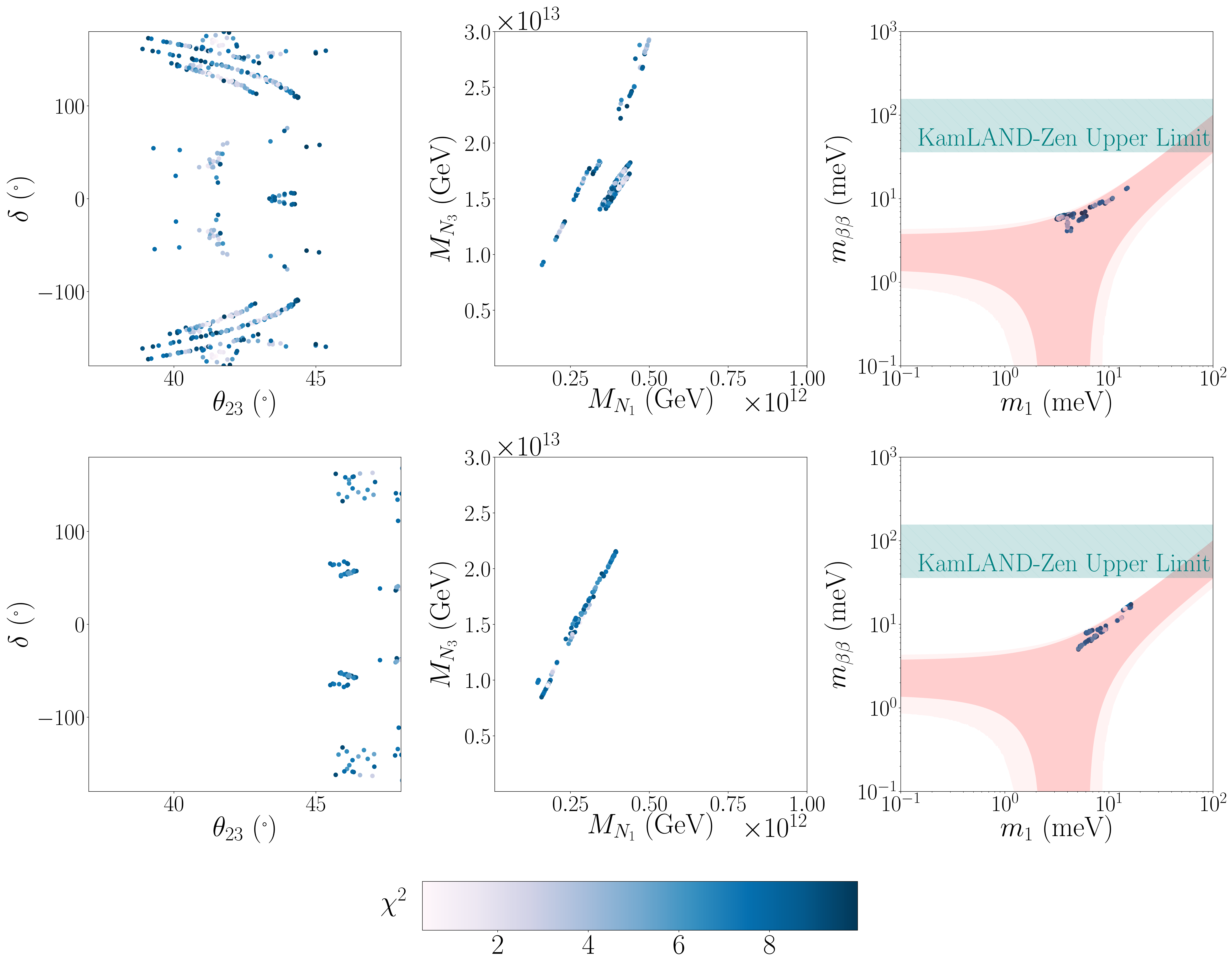
- Correlations of Yukawa matrices of quarks and leptons   Dutta, Mimura, Mohapatra, 0412105

$$Y_d=r_1(h+f+i\,h') \qquad Y_u=h+r_2f+i\,r_3h' \qquad M_{\nu_R}=m_{\nu_R}f$$
$$Y_e=r_1(h-3f+i\,c_eh') \qquad Y_\nu=h-3r_2f+i\,c_\nu h'$$

Yukawa/mass matrices in SO(10)

3×3 matrices $h\propto Y_{\mathbf{10}}$ $f\propto Y_{\overline{\mathbf{126}}}$ $h'\propto Y_{\mathbf{120}}$

Fermion masses and mixing in SO(10)



Take-away message:

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

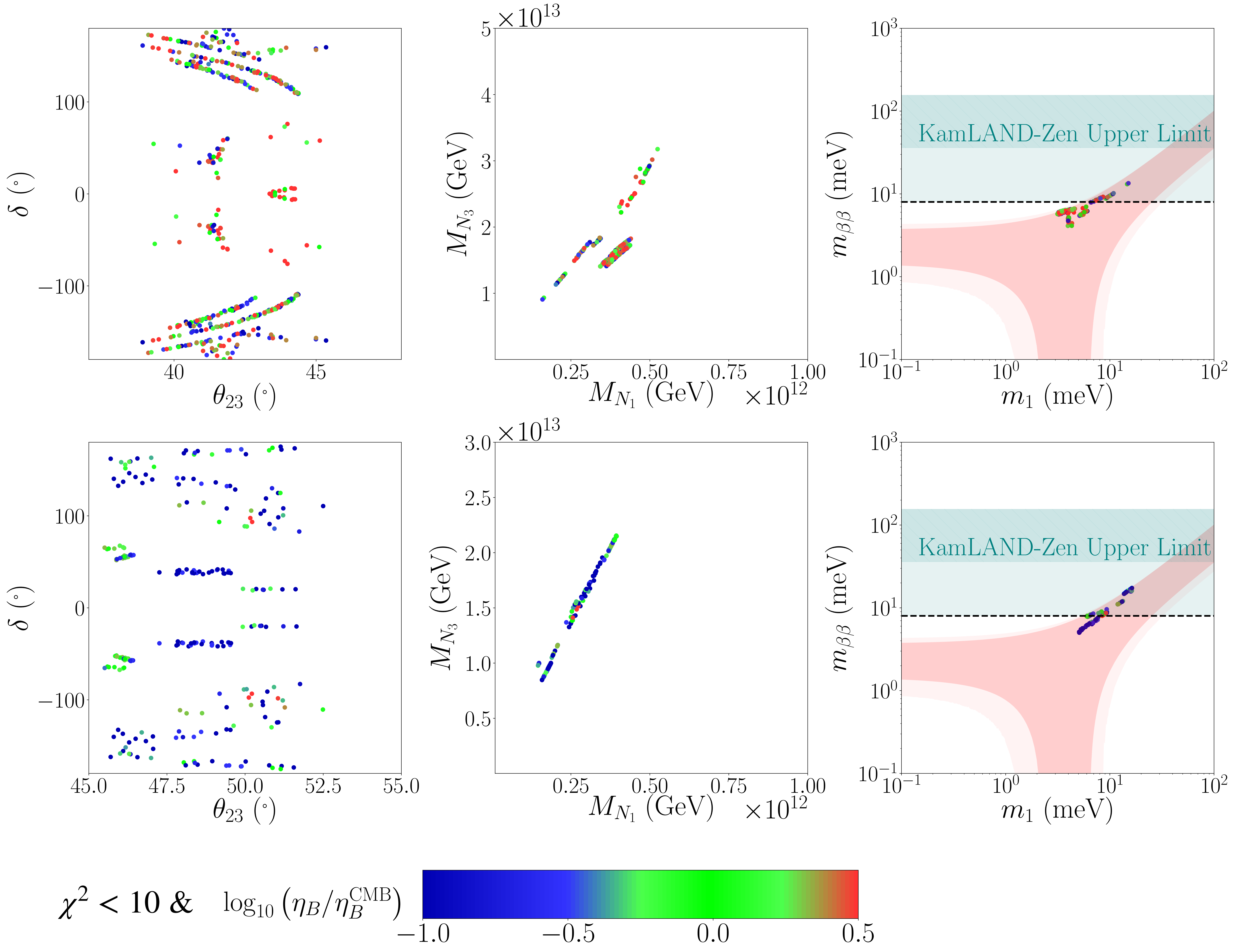
$M_3 \sim (1,\ 3) \times 10^{13}$ GeV

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

And normal ordering preferred

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

Thermal leptogenesis in SO(10)



Data of quark masses, CKM mixing, lepton masses, PMNS mixing

⇓

Heavy neutrino masses and Dirac ν Yukawa couplings

⇓

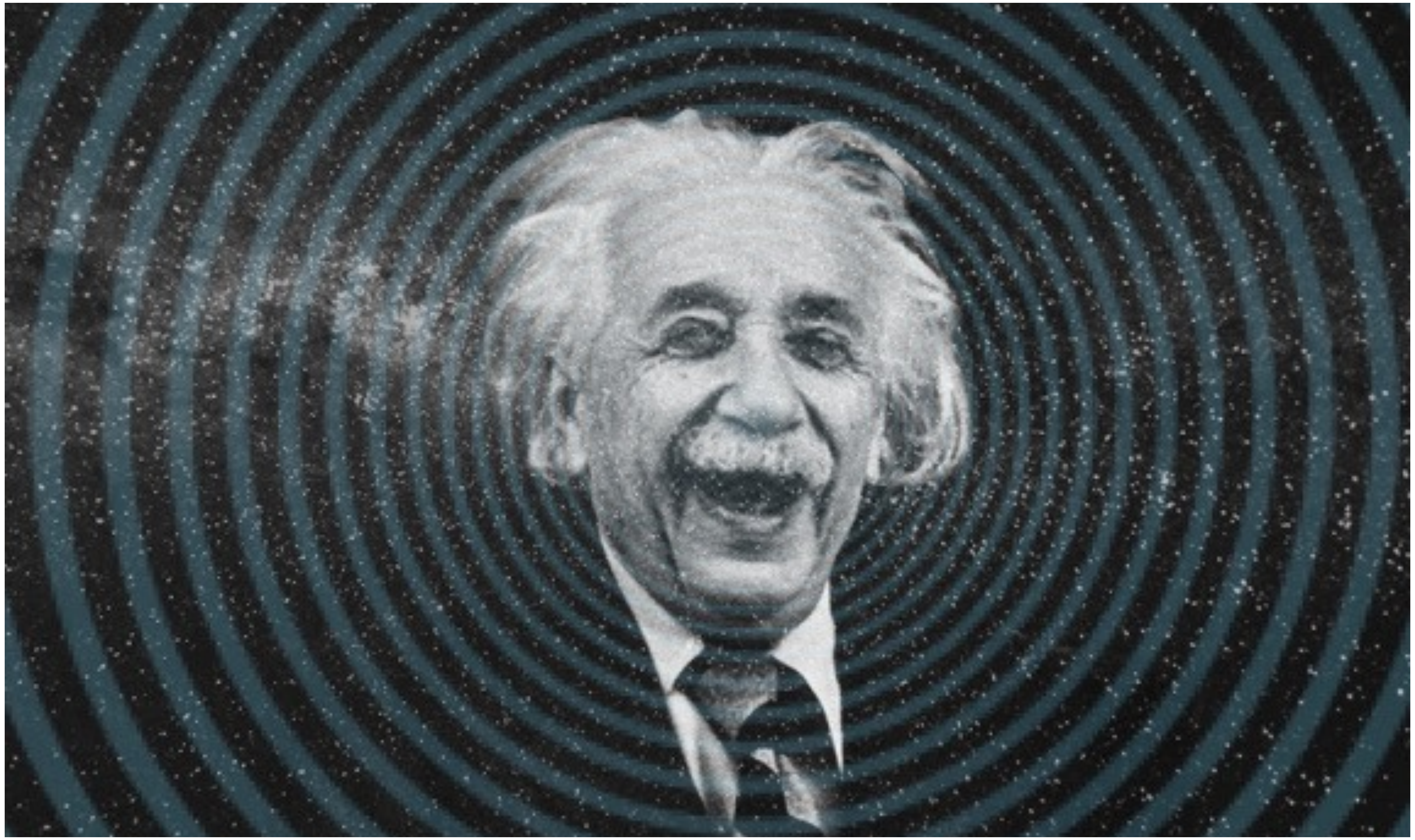
CP violation in heavy neutrino decay

⇓

Thermal leptogenesis

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

Gravitational waves as a probe to GUTs

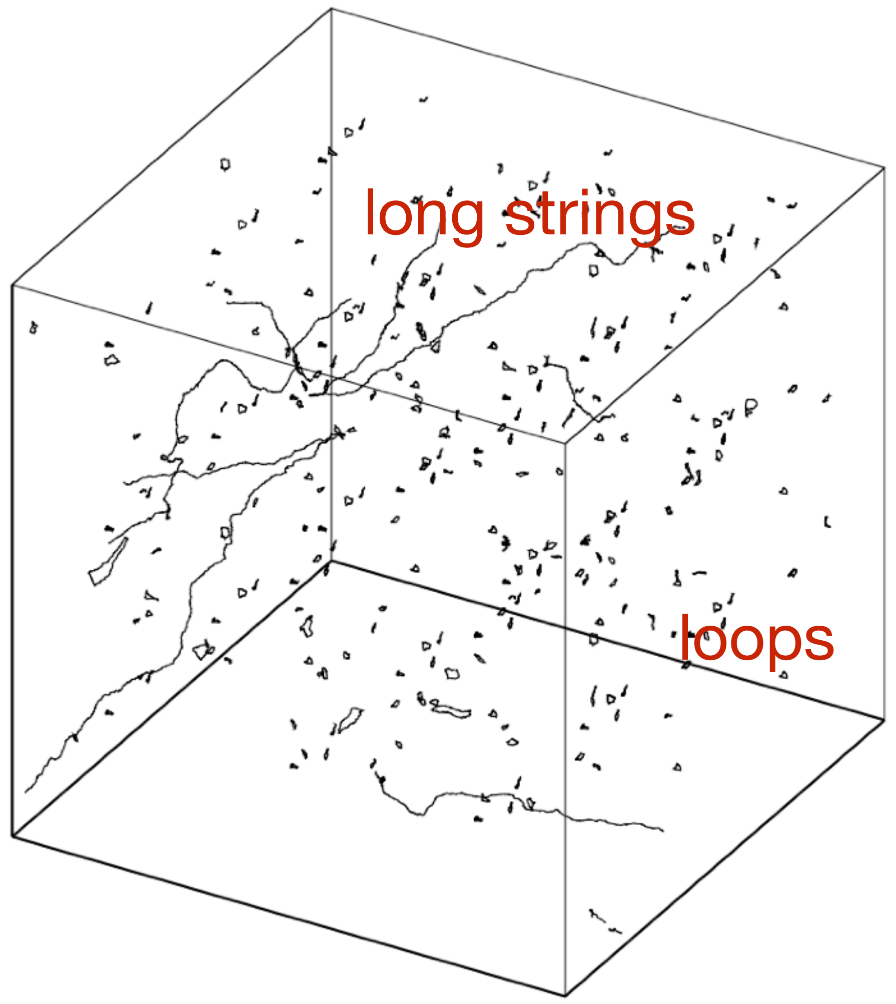


Mechanisms of gravitational wave (GW) genesis in GUTs

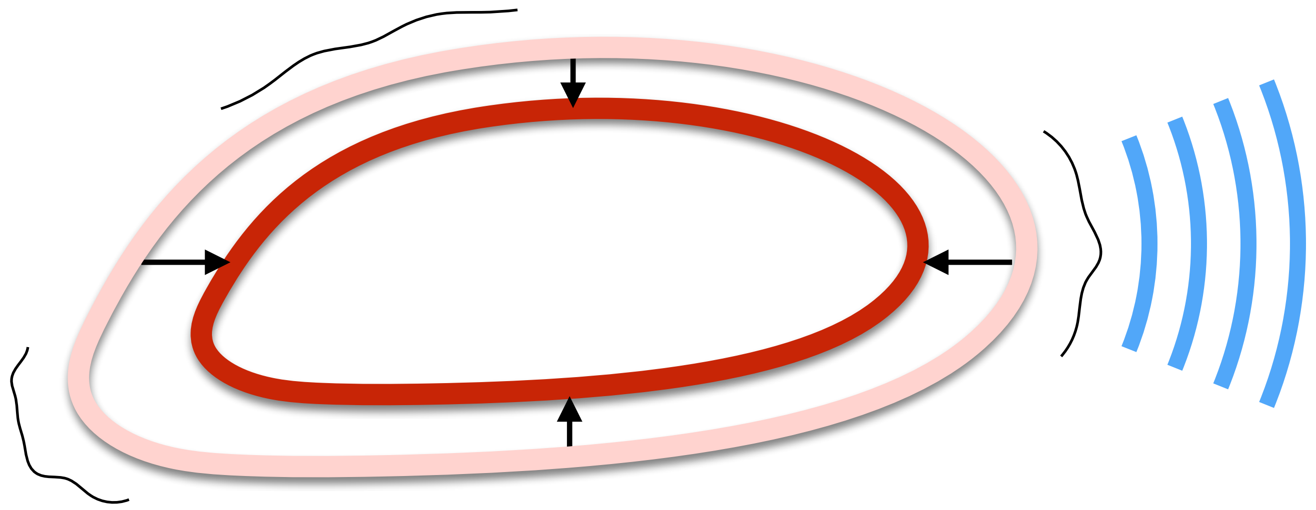
GW via cosmic strings

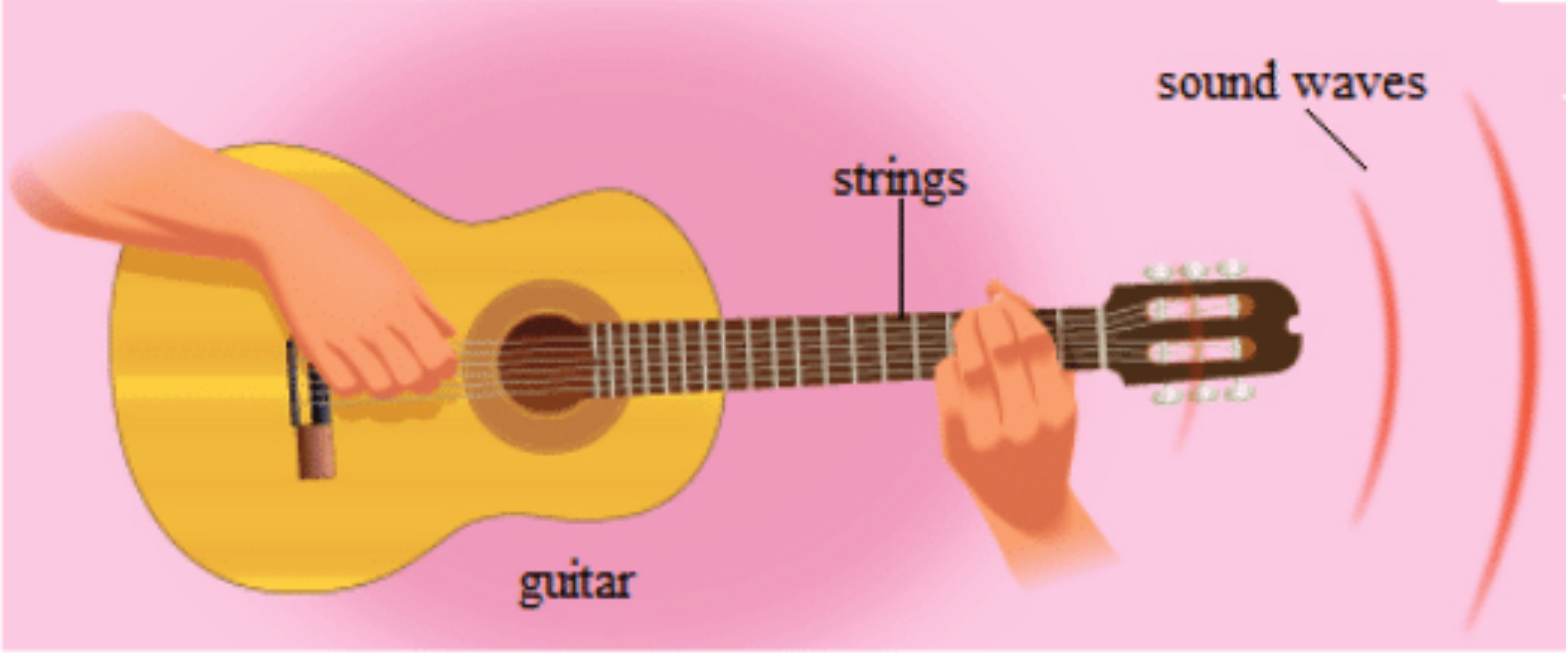
$$\pi_1(U(1)) = Z$$

- Most GUTs include a $U(1)_{B-L}$ symmetry.
- Spontaneous breaking of this U(1) generates cosmic strings.
- Strings intersect and intercommute to form loops and cusps
- Loops oscillates via gravitational radiation



Vanchurin, Olum, Vilenkin, 0511159

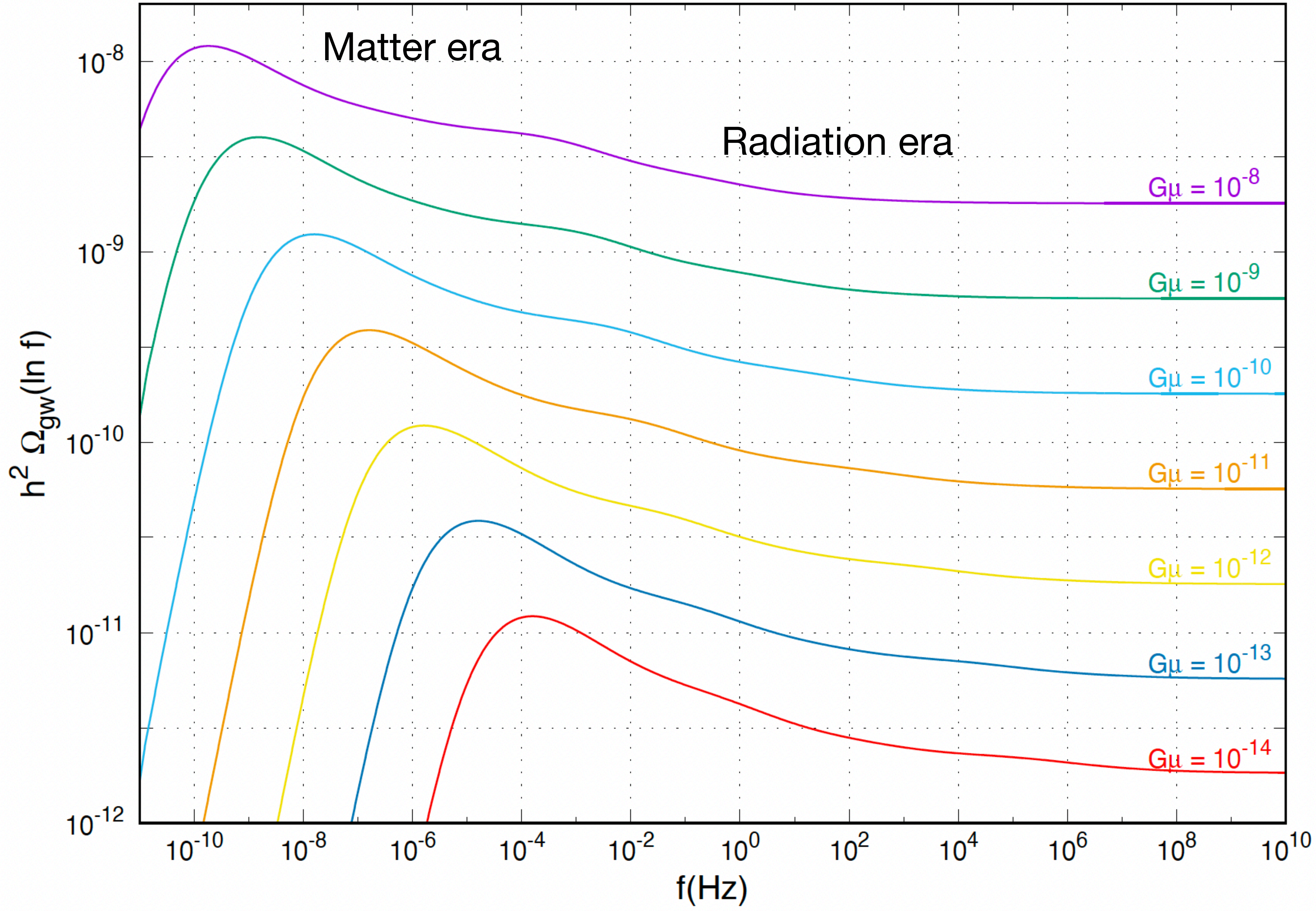




Another mechanism: GW via GUT phase transition?

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

Typical GW spectrum from string loops



In the Nambu-Goto case, the spectrum depends on one single parameter μ (string tension)

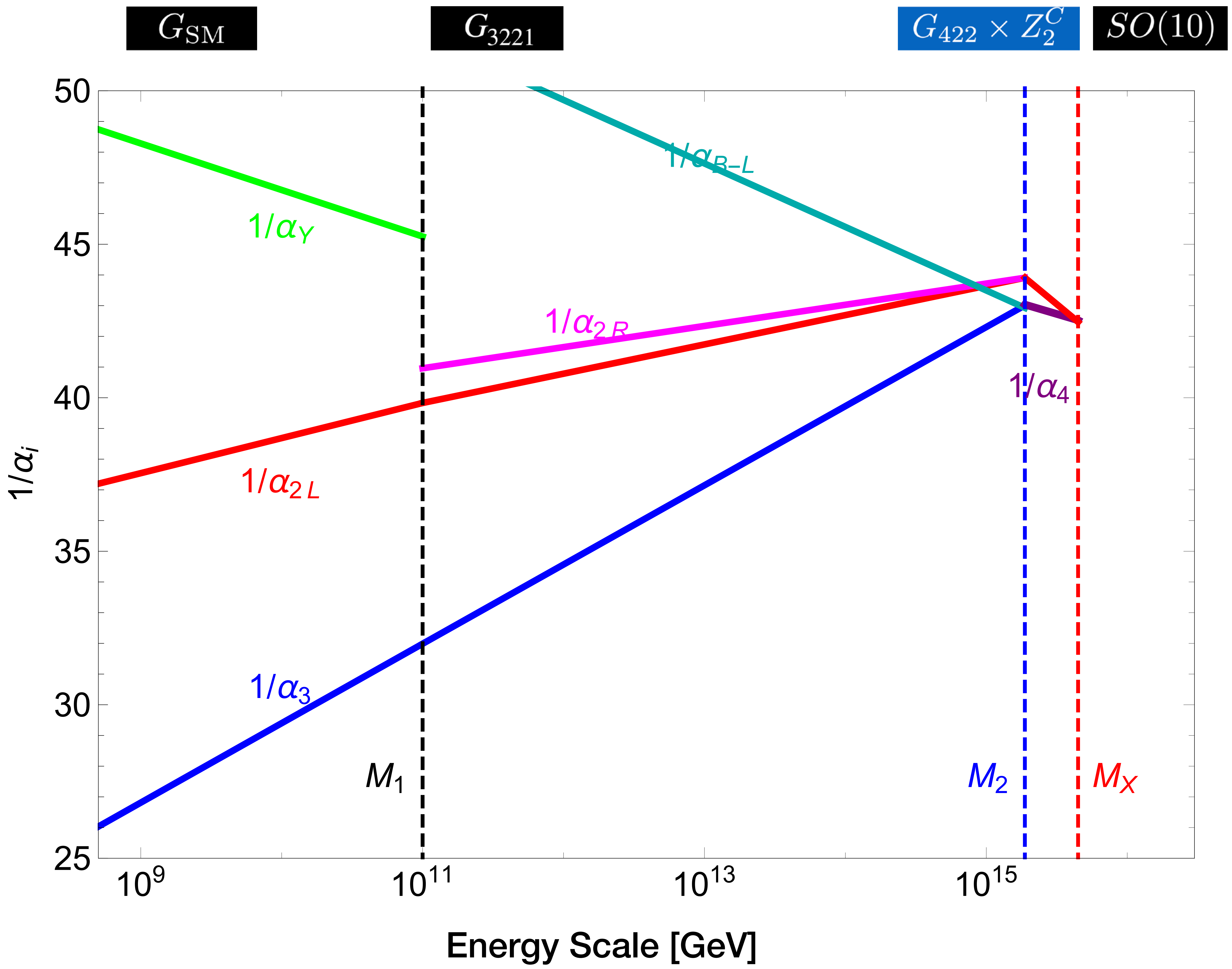
$$\Omega_{\rm GW} h^2 \sim 5 \times 10^{-5} \sqrt{G\mu}$$

$$\propto \frac{M_{B-L}}{M_{\rm Planck}} \quad \text{in GUTs}$$

$$G = M_{\rm Planck}^{-2}$$

Blanco-Pillado, Olum
1709.02693

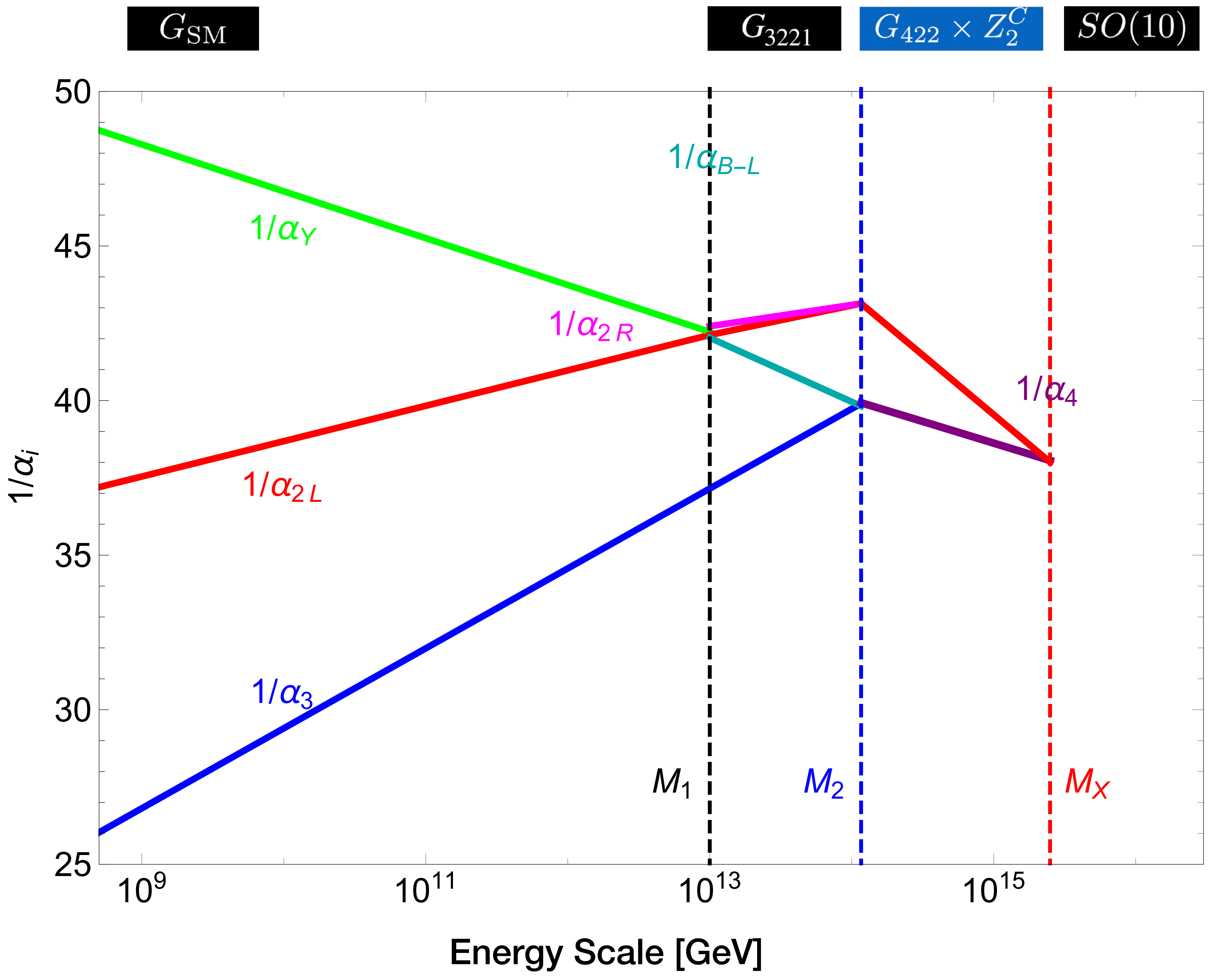
Gauge unification correlates GUT scale with intermediate scales



M_i refers to the gauge boson mass of the i-th gauge symmetry G_i

No new particle introduced if not necessary

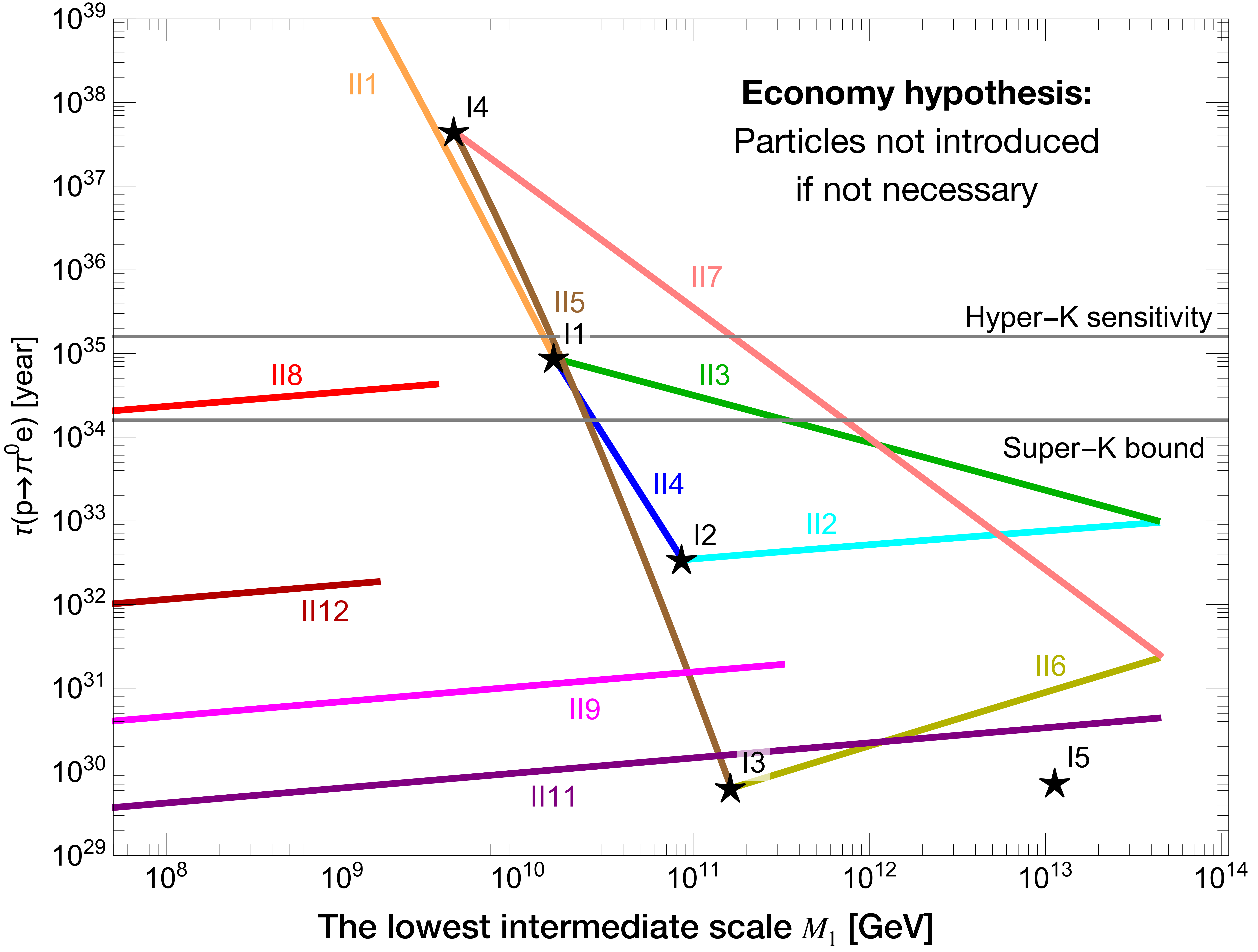
Gauge unification correlates GUT scale with intermediate scales



M_i refers to the gauge boson mass of the i-th gauge symmetry G_i

No new particle introduced if not necessary

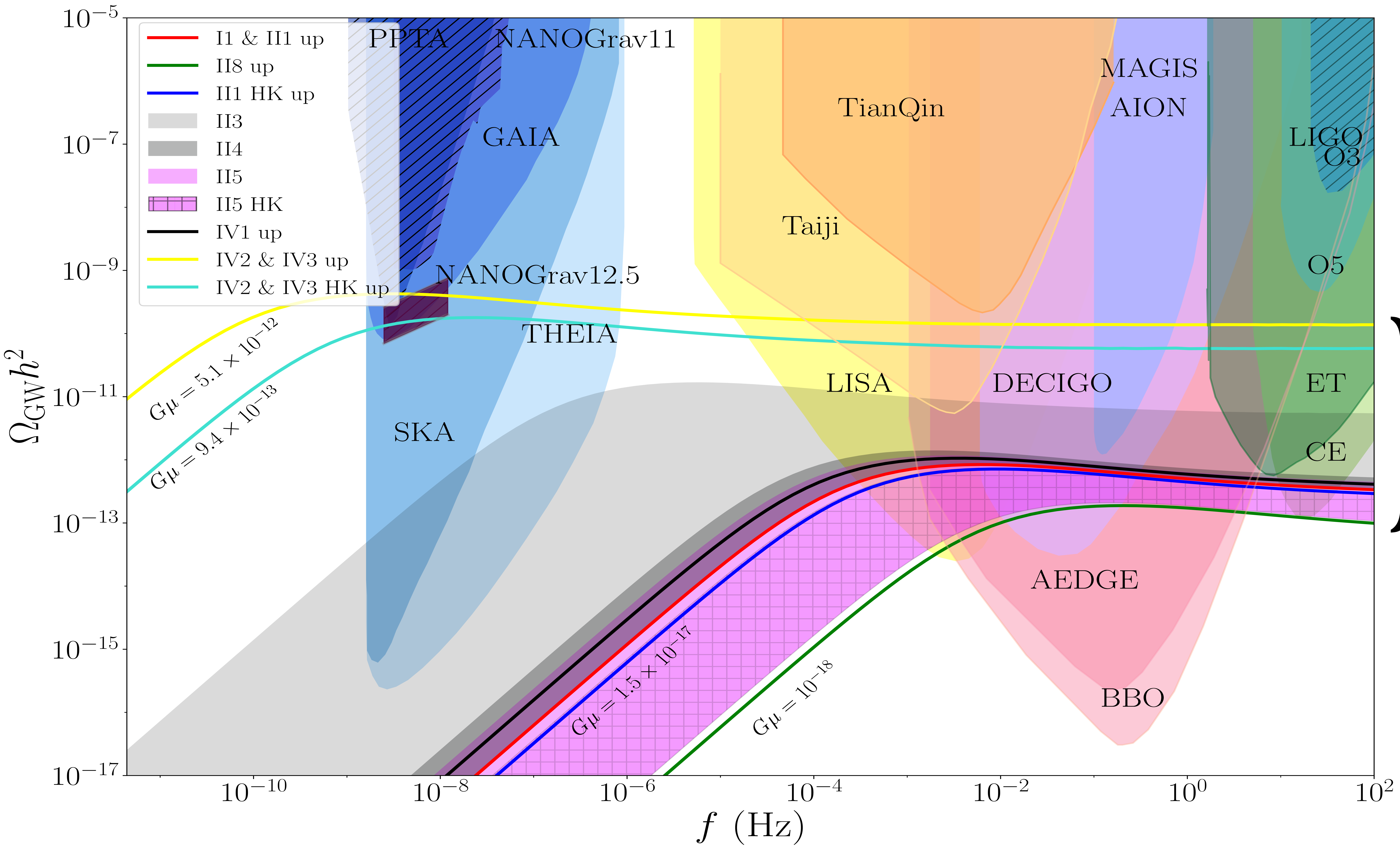
Constraints on B-L scale in SO(10)



$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	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}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II2:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{210}]{\text{m}}$	G^C_{3221}	$\xrightarrow[\mathbf{126}]{\text{s,w}}$	
II3:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m,w}}$	G_{3221}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II4:	$\xrightarrow[\mathbf{210}]{\text{m,s}}$	G^C_{3221}	$\xrightarrow[\mathbf{45}]{\text{w}}$	G_{3221}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II5:	$\xrightarrow[\mathbf{210}]{\text{m}}$	G_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
II6:	$\xrightarrow[\mathbf{54}]{\text{m,s}}$	G^C_{422}	$\xrightarrow[\mathbf{45}]{\text{m}}$	G_{421}	$\xrightarrow[\mathbf{126}]{\text{s}}$	
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

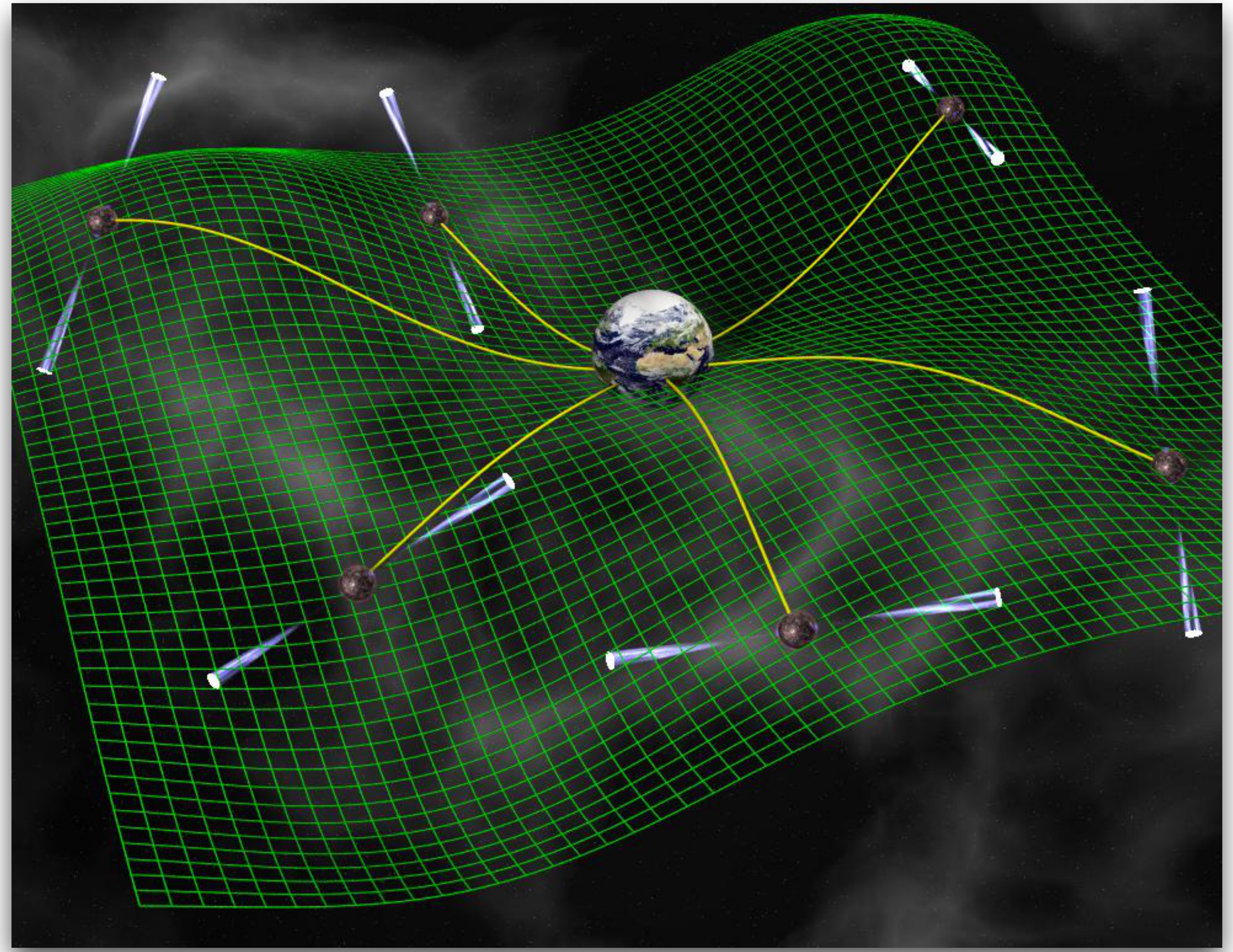
Predictions for GW spectrum in SO(10) GUTs



Different colours for different breaking chains

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

Influence of recent PTA measurements



On 28 Jun 2023

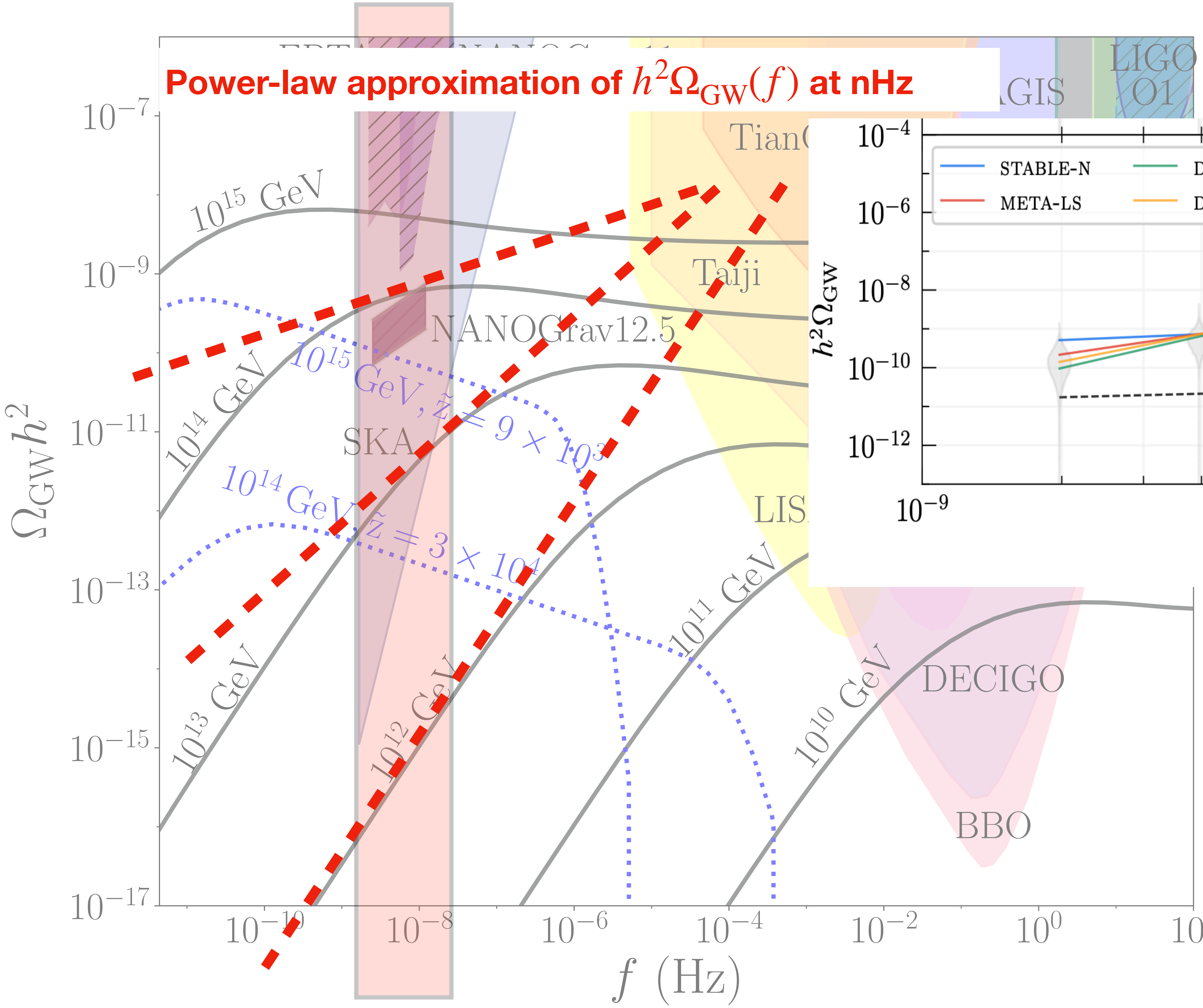
NANOGrav 15yr,
2306.16213

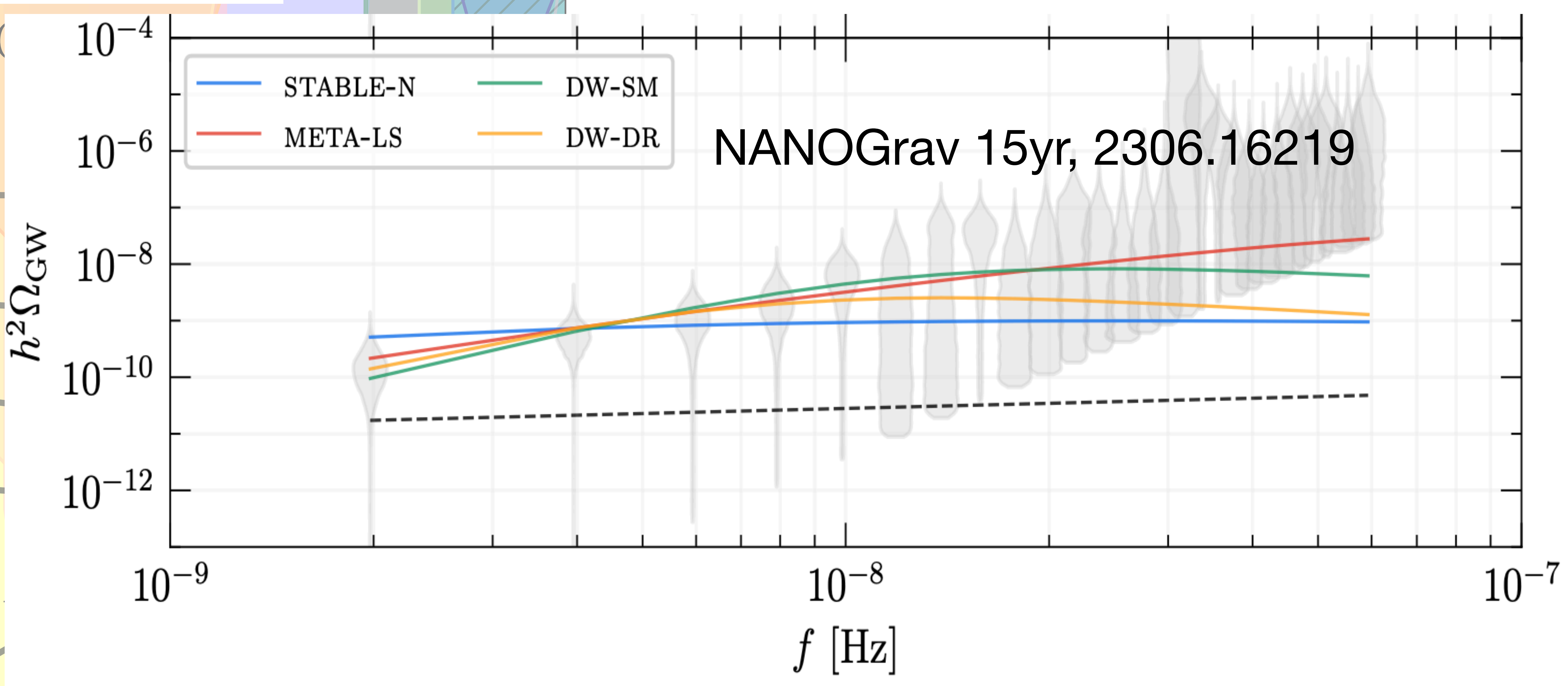
European Pulsar Timing Array III,
2306.16214

Parkes Pulsar Timing Array III,
2306.16215

Chinese Pulsar Timing Array,
2306.16216

Tensions between NANOGrav and GWs via Nambu-Goto strings

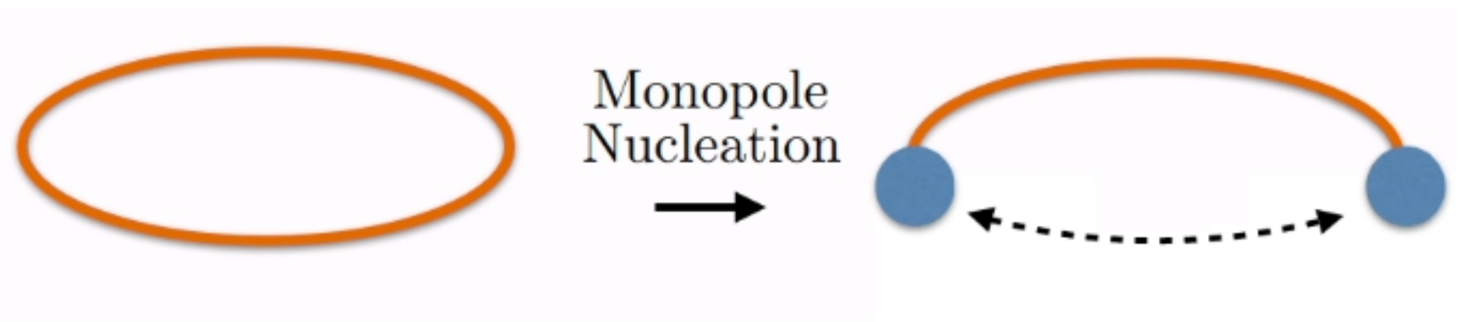




Solutions with strings:

1) Superstring ⇒ John's talk
2) Metastable strings

GWs via metastable strings

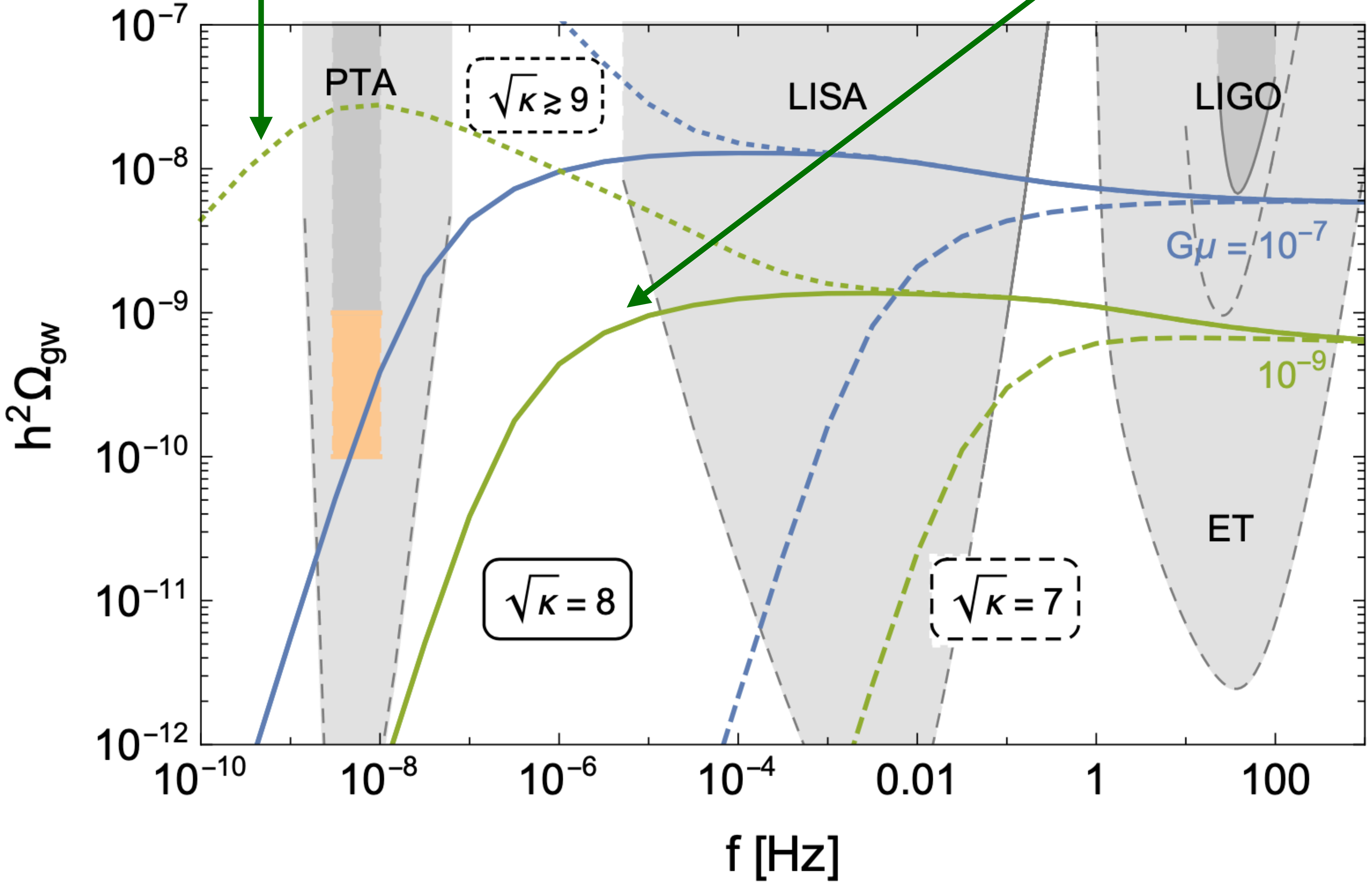


Vilenkin, NPB(1982); Preskill, Vilenkin, 9209210; Leblond, Shlaer, Siemens, 0903.4686; Monin, Voloshin, 0808.1693; Buchmuller, Domcke, Schmitz, 2107.04578

$n(l, t)$ of loops from NG strings

$n(l, t)\, e^{-\Gamma_d\, l\, t}$ of metastable loops

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



$$\sqrt{\kappa} = \frac{m_{\text{monopole}}}{\sqrt{\mu_{\text{string}}}} \sim \alpha_{\text{GUT}}^{-1/2} \frac{M_{\text{GUT}}}{M_{B-L}}$$

$$\sqrt{\kappa} \simeq (8,9) \Rightarrow M_{\text{GUT}} \sim M_{B-L}$$

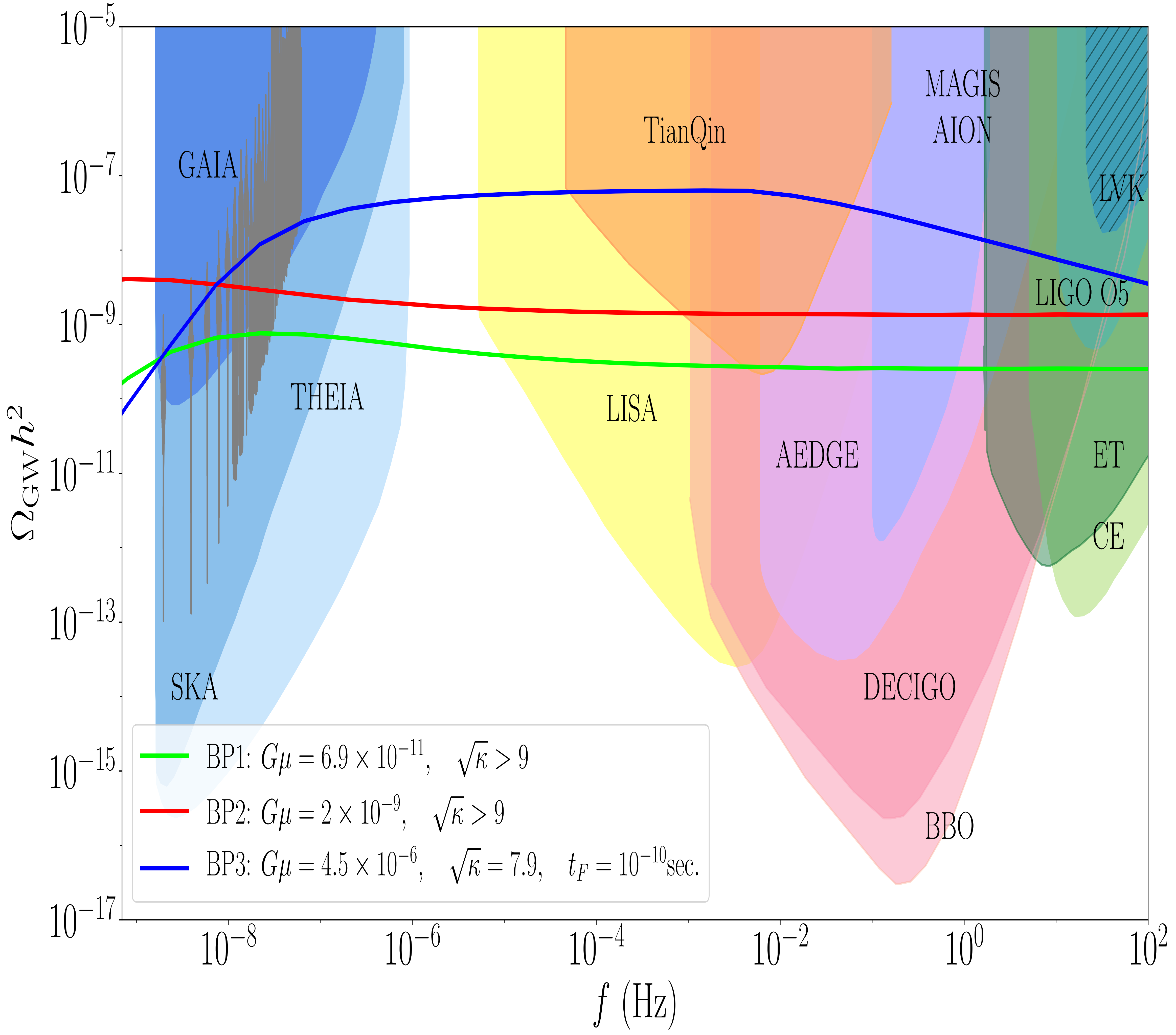
Buchmuller, Domcke, Schmitz, 2307.04691

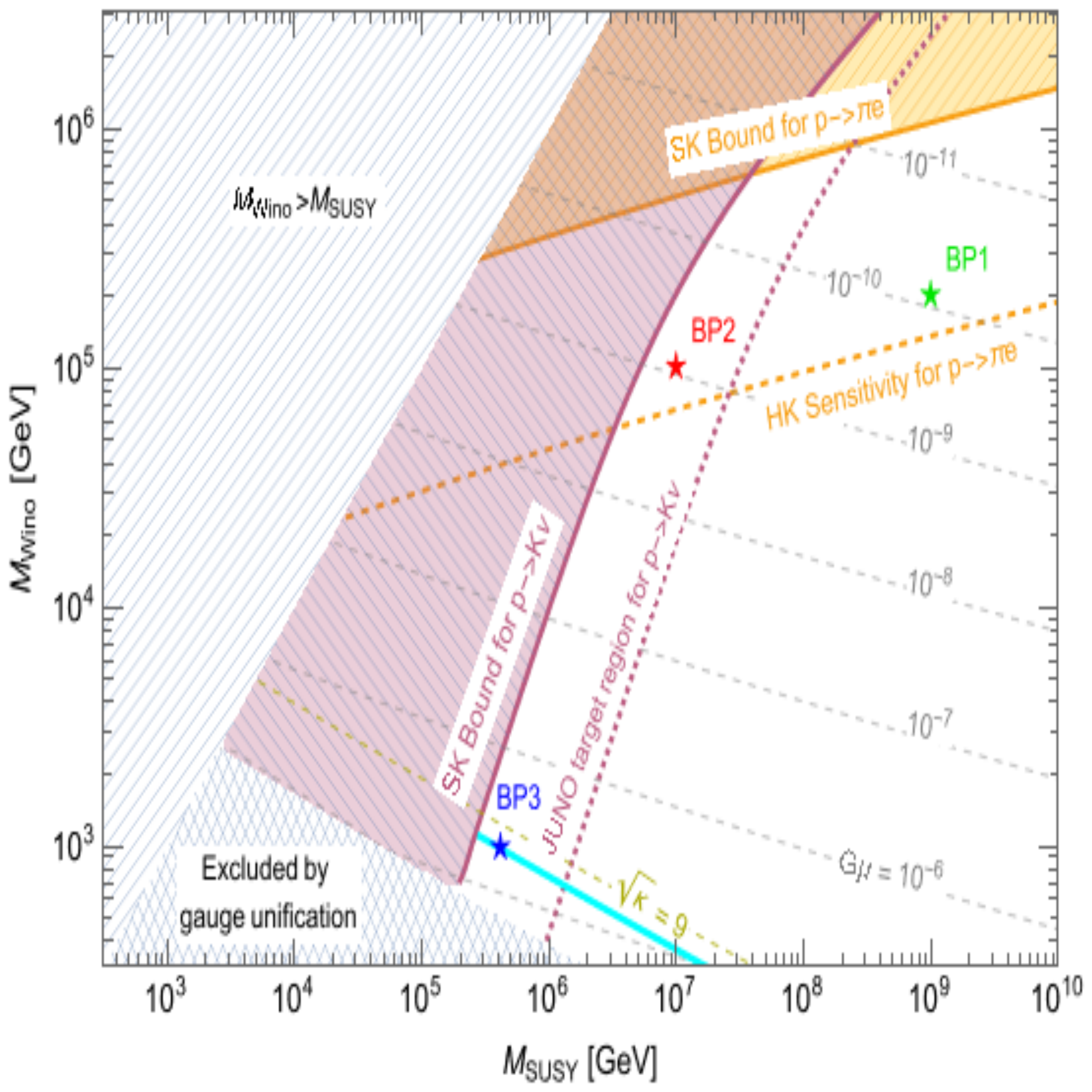
A GUT inflation separates the GUT breaking and B-L breaking in the time scale is required.

Antusch, Hinze, Saad, Steiner, 2307.04595

See also Lazarides, Maji, Moursy, Shafi, 2308.07094

PTA-favoured GUTs: SUSY SO(10)

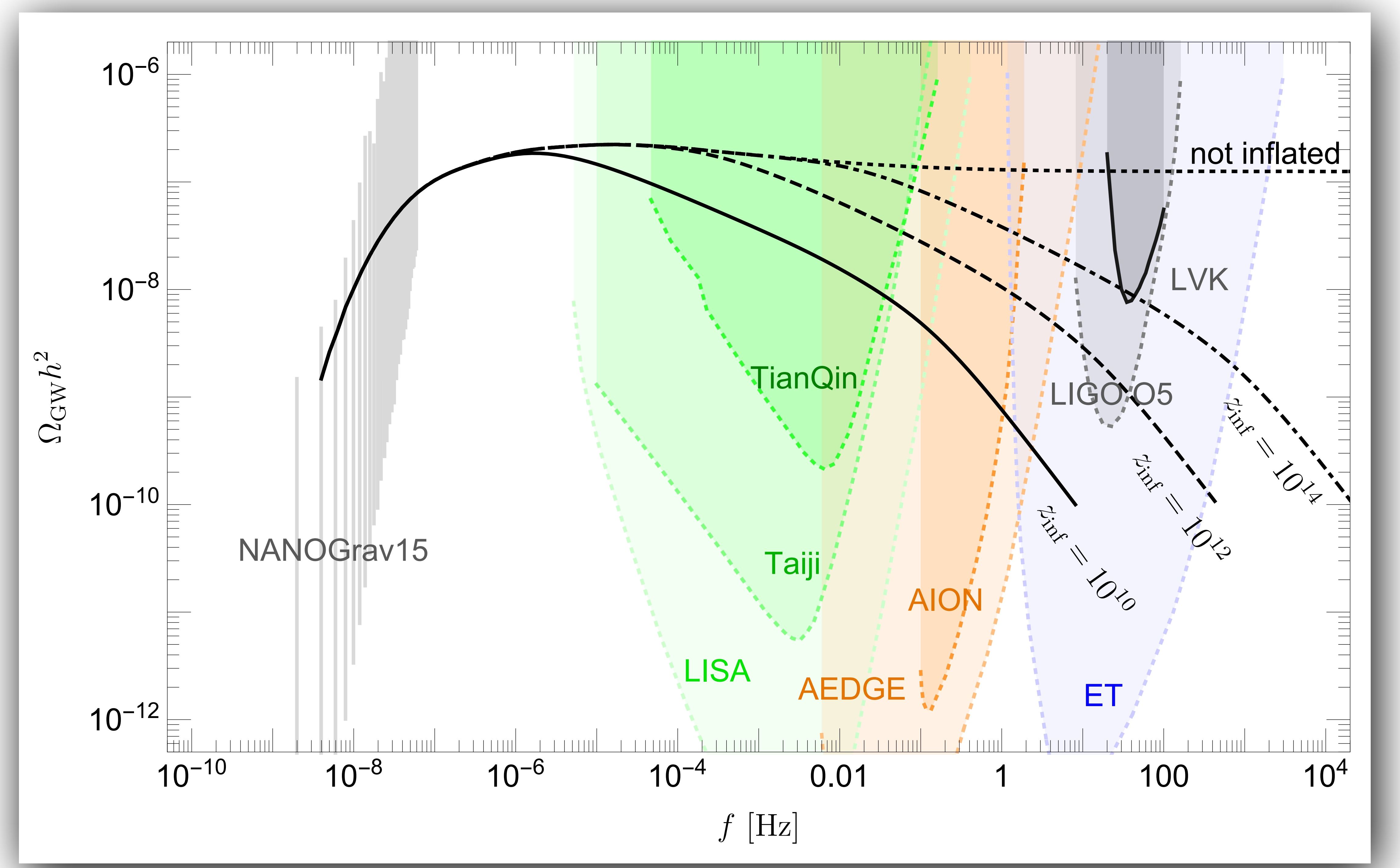


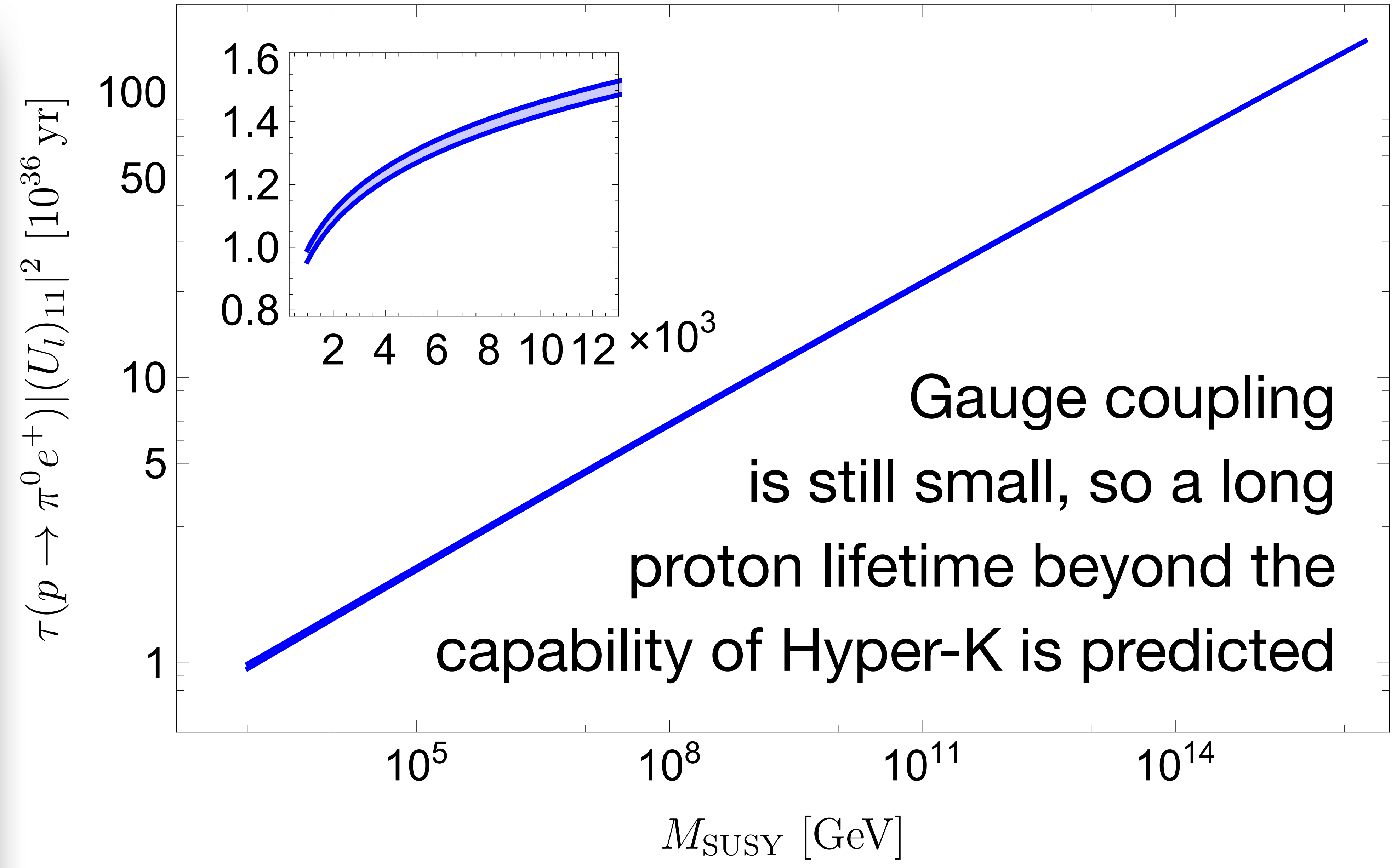


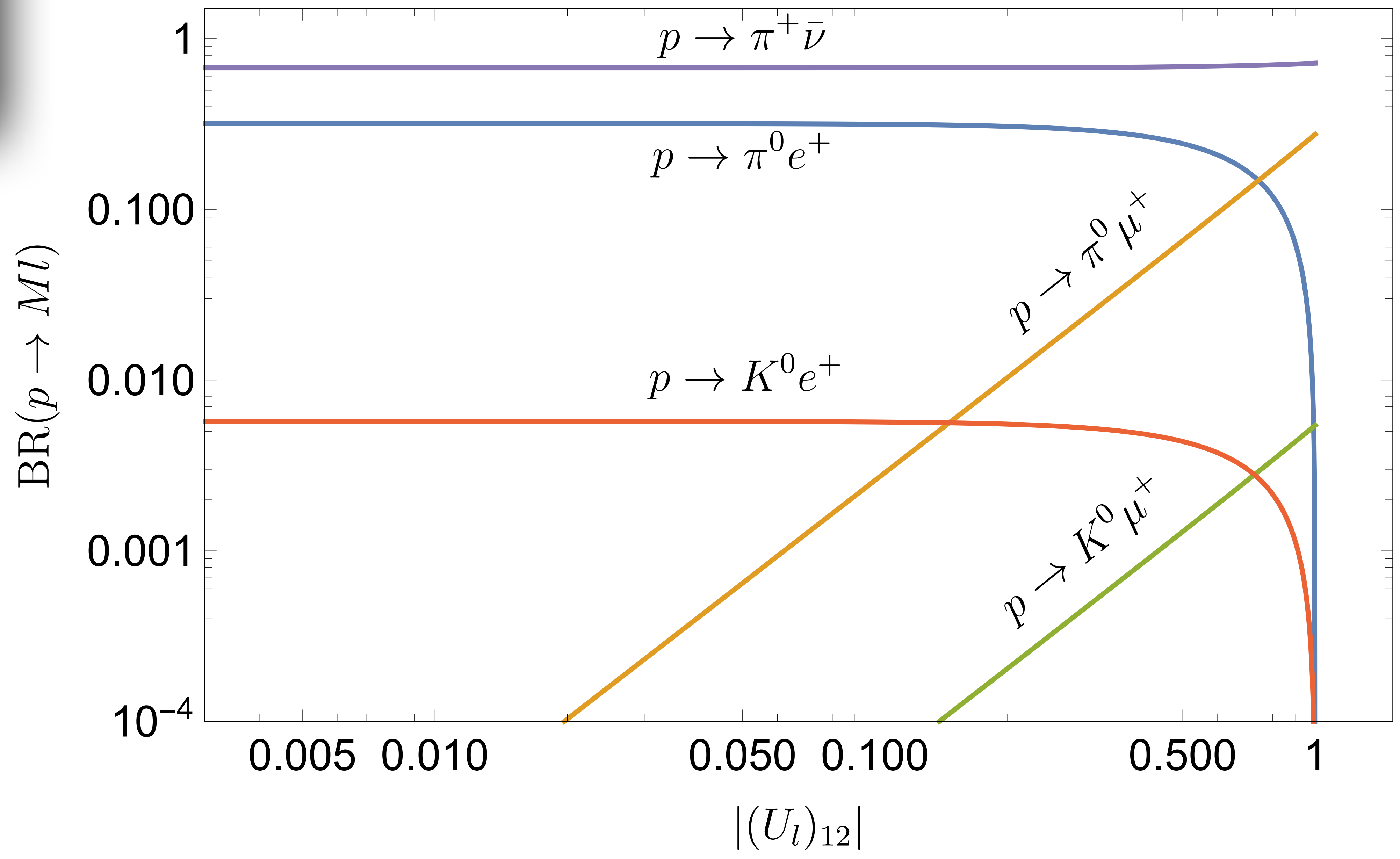
Fu, King, Marsili, Pascoli, Turner, **YLZ**, 2308.05799

PTA-favoured GUTs: flipped SU(5)

$u \leftrightarrow d,\ \nu \leftrightarrow e$







King, Leontaris, **YLZ**,
2311.11857

Leptogensis in flipped SU(5)

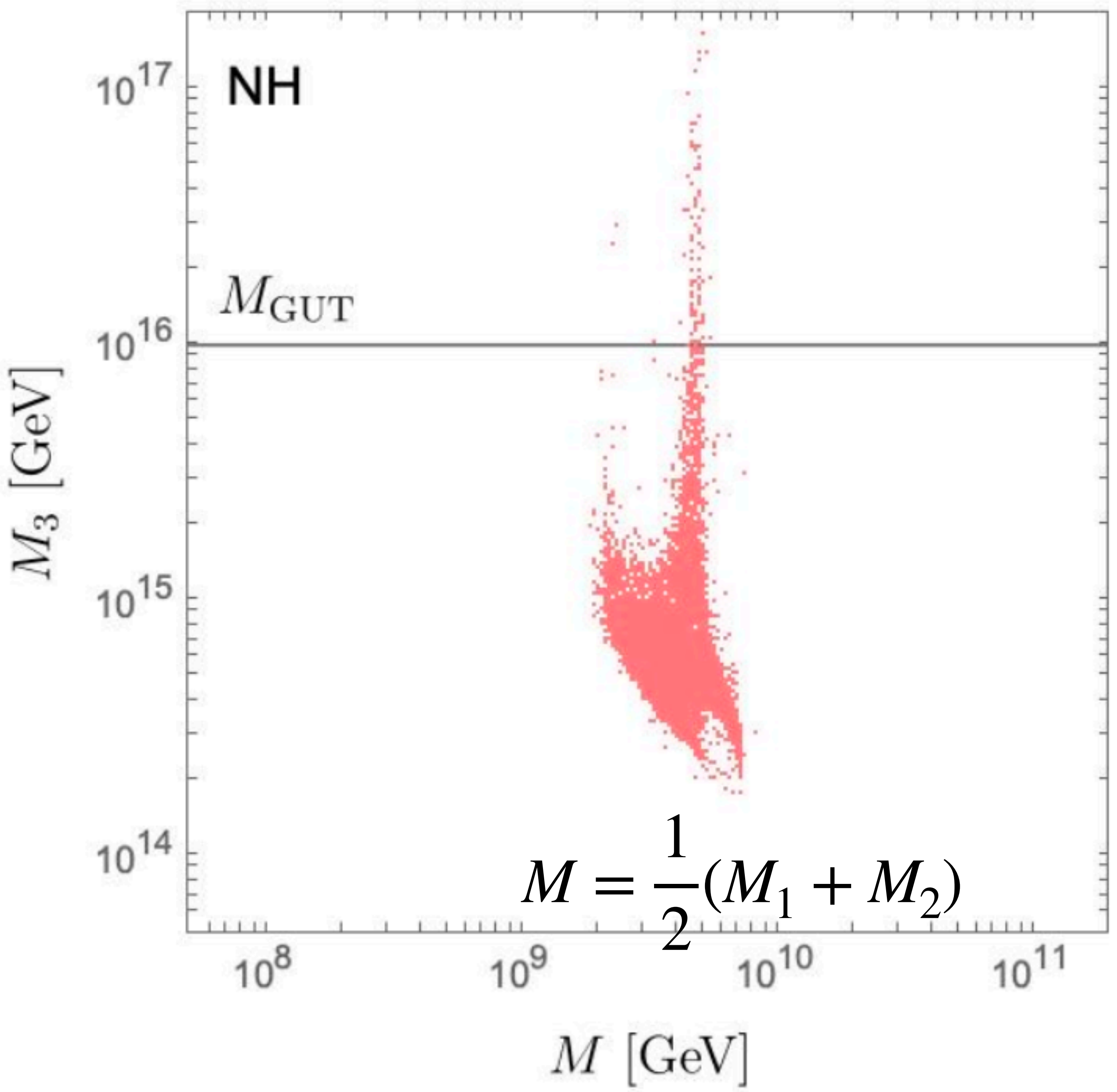
King, Leontaris, Marsili, **YLZ**, 2407.02701

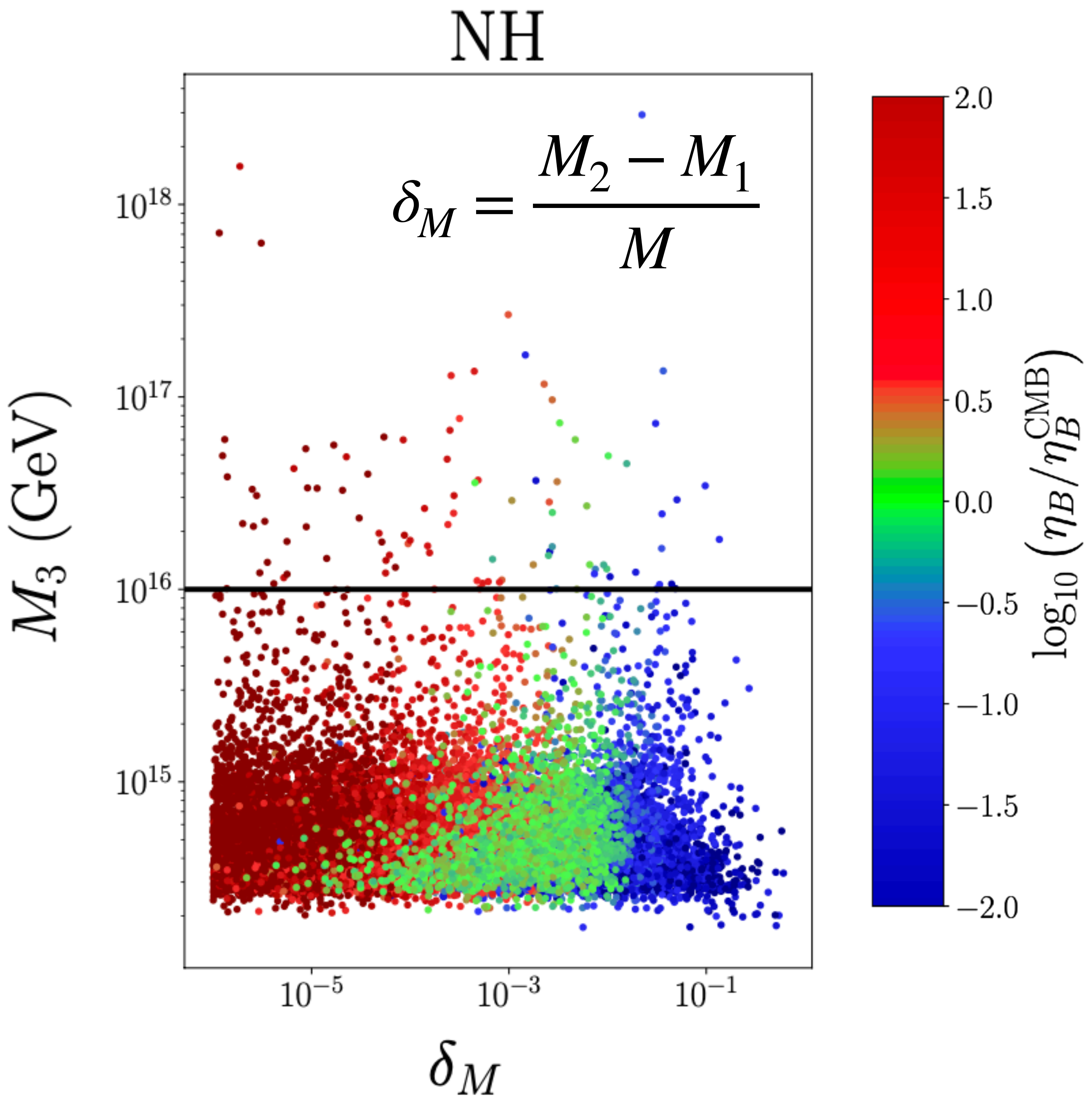
- Flipped SU(5) usually predicts very hierarchical RHN masses,

$$M_u = M_D, \quad M_R = M_D^T M_\nu^{-1} M_D \qquad \Rightarrow \qquad M_1 : M_2 : M_3 \simeq m_u^2 : m_c^2 : m_t^2$$

The lightest RHN neutrino is too light and cannot be used to achieve leptogenesis

- But it is not always true, with special flavour texture assumed, $M_1 \sim M_2 \ll M_3$ achieved





$$a = \left(\frac{y_t}{y_c}\sin\theta_{13}^R\right)^2, \quad b = \left(\frac{y_t}{y_c}\sin\theta_{23}^R\right)^2$$

$$m_1 \simeq \frac{m_c^2}{M}\frac{y_t^2\kappa}{y_c^2 a'}\frac{y_u^2}{y_c^2}, \quad \lesssim 10^{-7}\ \mathrm{eV}$$

$$m_{2,3} \simeq \frac{m_c^2}{2M}\left[1 + a' + b \mp \sqrt{(1 + a' + b)^2 - 4a'}\right]$$

Both Normal Hierarchy (NH) and Inverted Hierarchy (IH) are predicted. Here we show NH for illustration

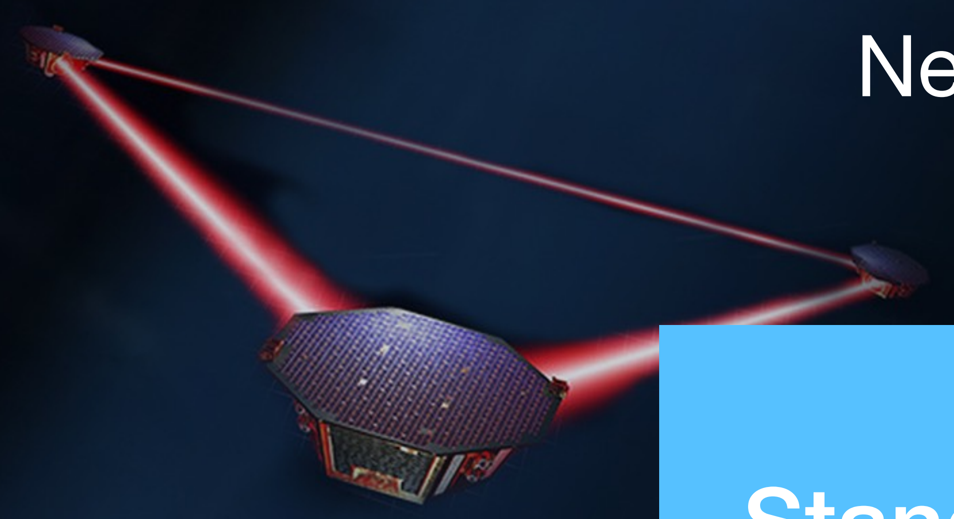
Summary

GUT	Broken at M_{GUT}	← Proton decay
Potentially intermediate New Physics ……		Gauge unification
$G_1 \supset G_{\rm SM} \times U(1)_{B-L}$	Broken at M_{B-L}	← Gravitational waves
Potentially intermediate New Physics ……		
Standard Model		

Checking correlation of fermion masses and mixing

Predicting right neutrino mass spectrum

Explaining matter-antimatter asymmetry



Thank you for listening