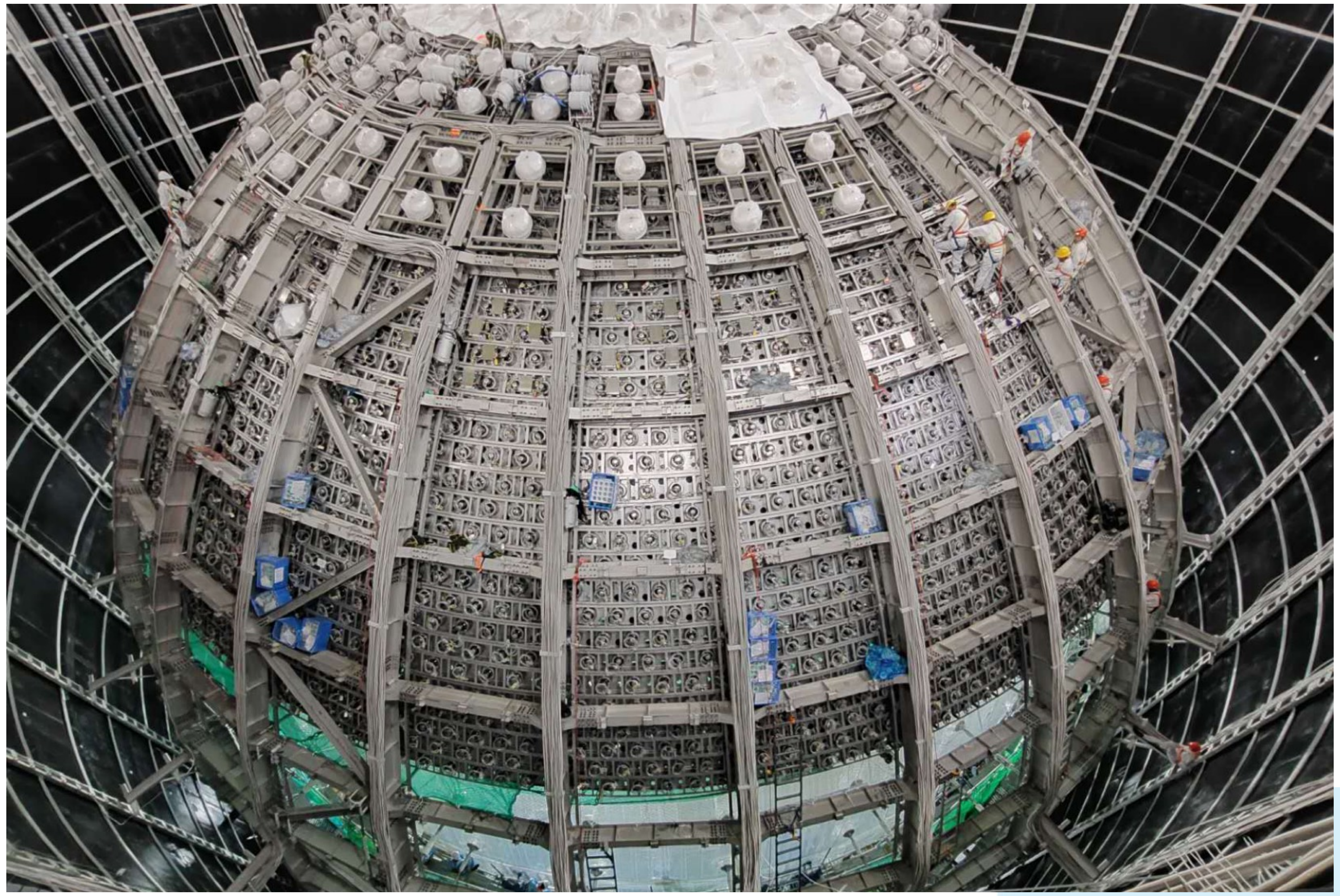
大统一理论在地下和空间实验探测中联合检验

周也铃 杭高院 2024-5-8

@邛海

地下实验探测：大型中微子实验



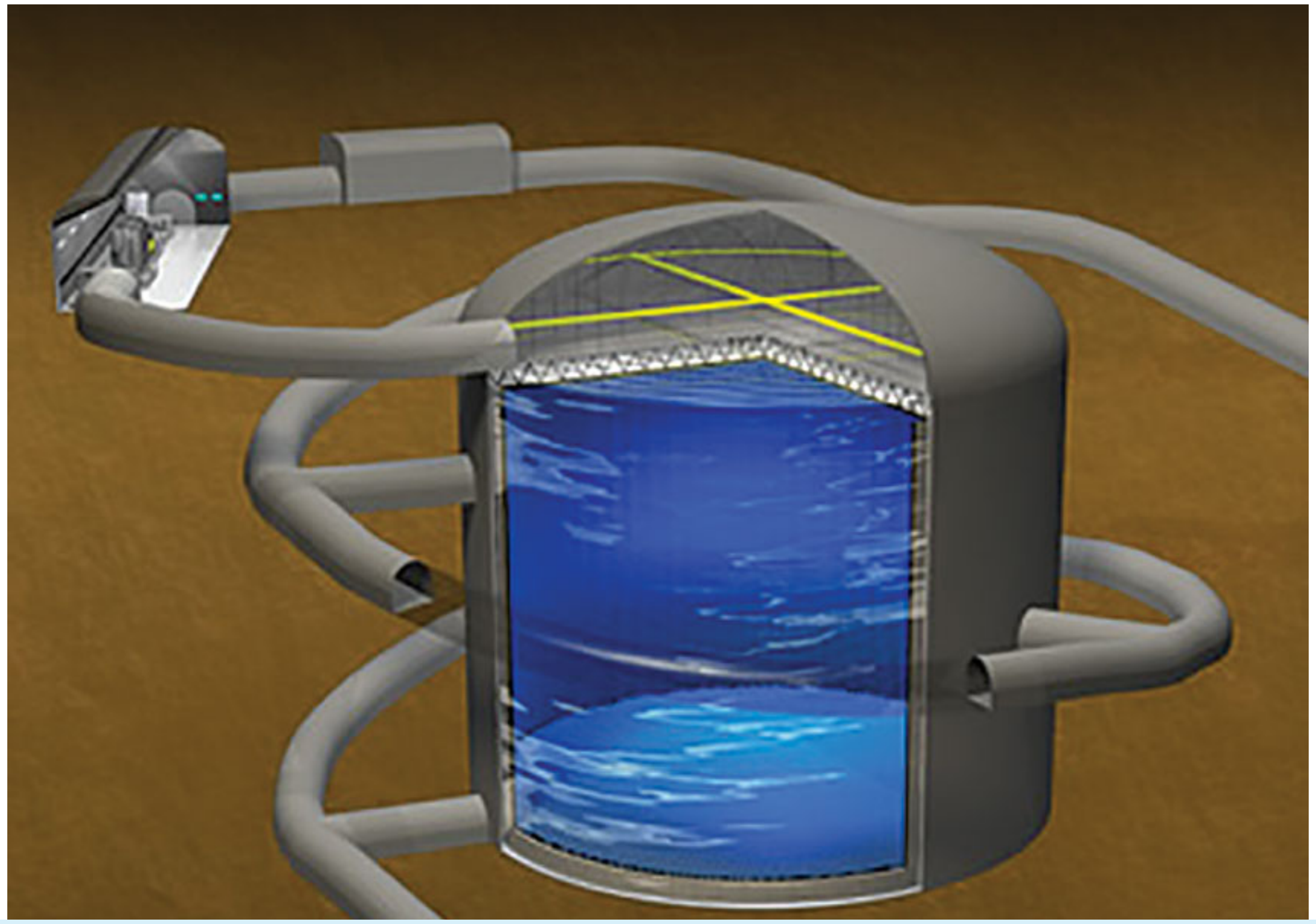
JUNO 江门地下中微子观测站

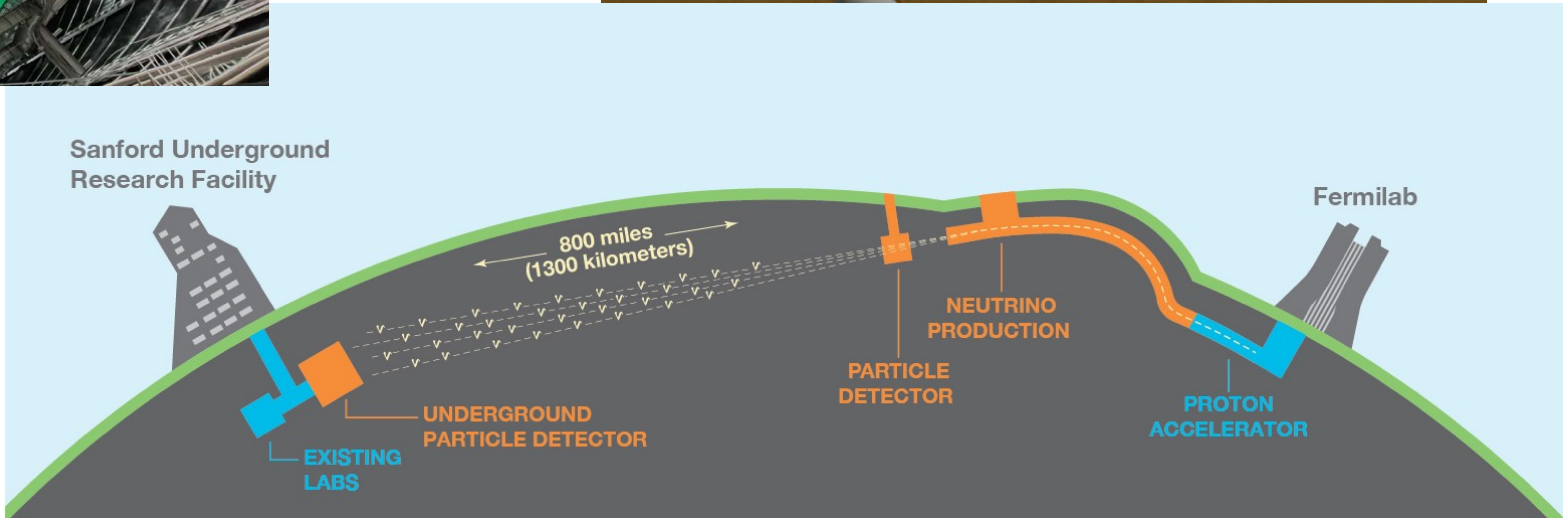
20kt FV ~ 7×10^{33} proton

Hyper-K

expected to run in 2027

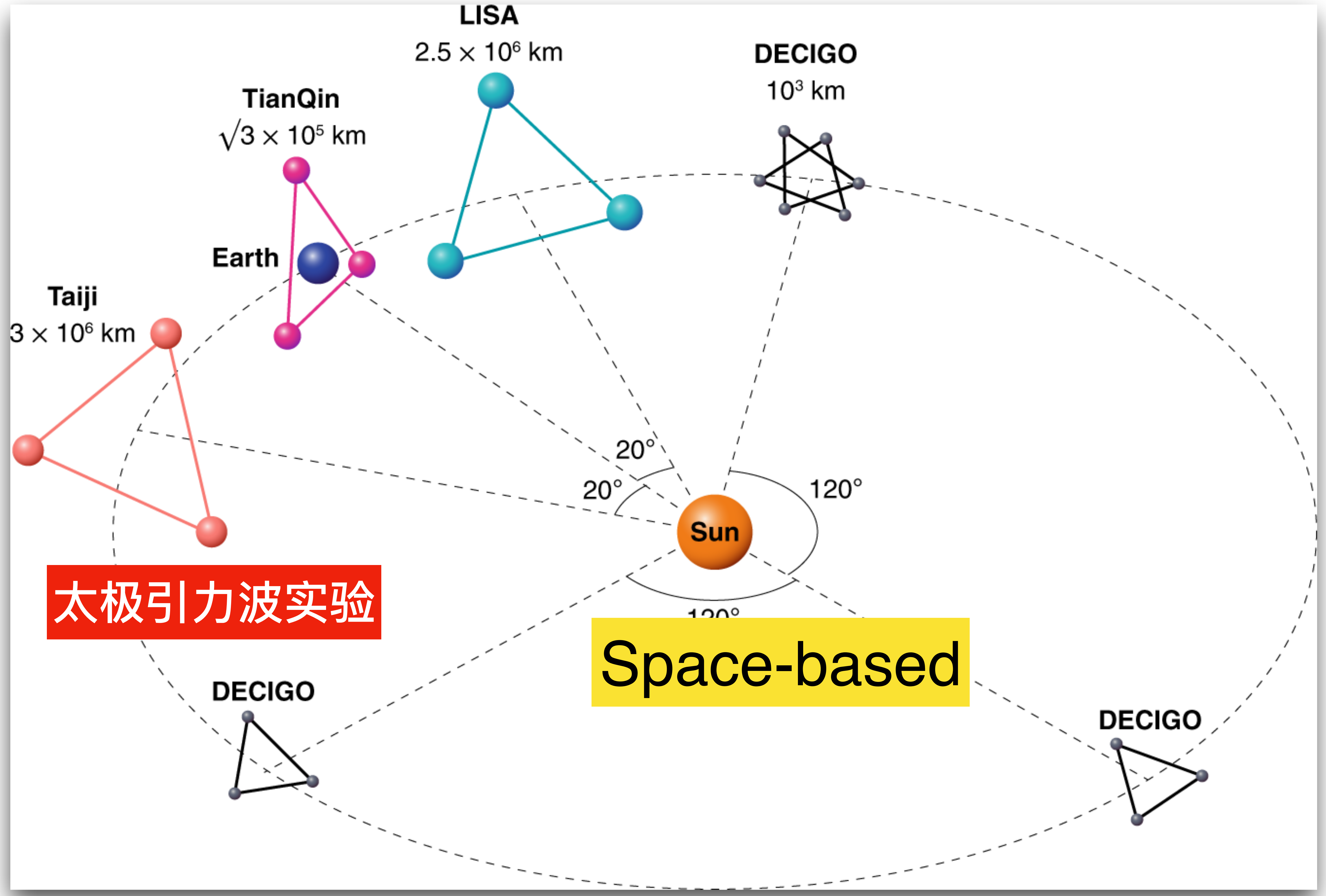
188 kt FV ~ 6×10^{34} proton



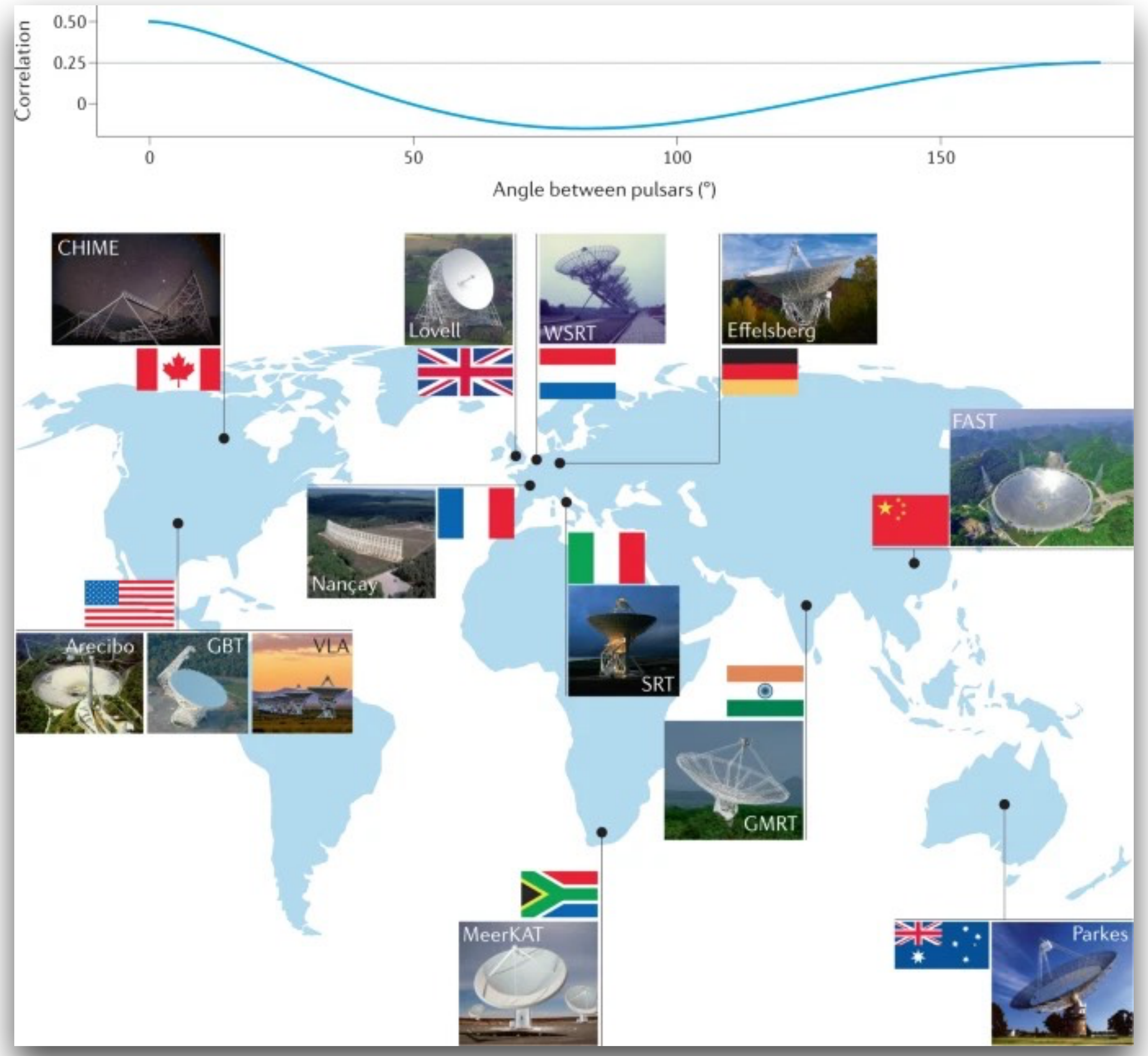


DUNE, run in 2030?

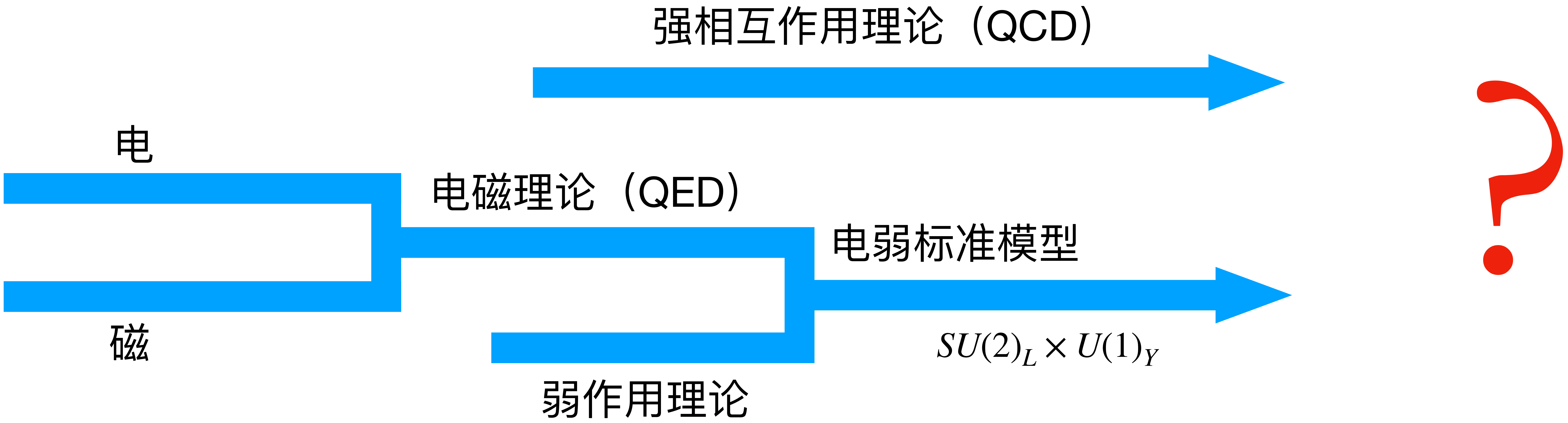
空间实验探测：引力波观测



Pulsar-Timing Arrays (PTAs)



大统一理论简介

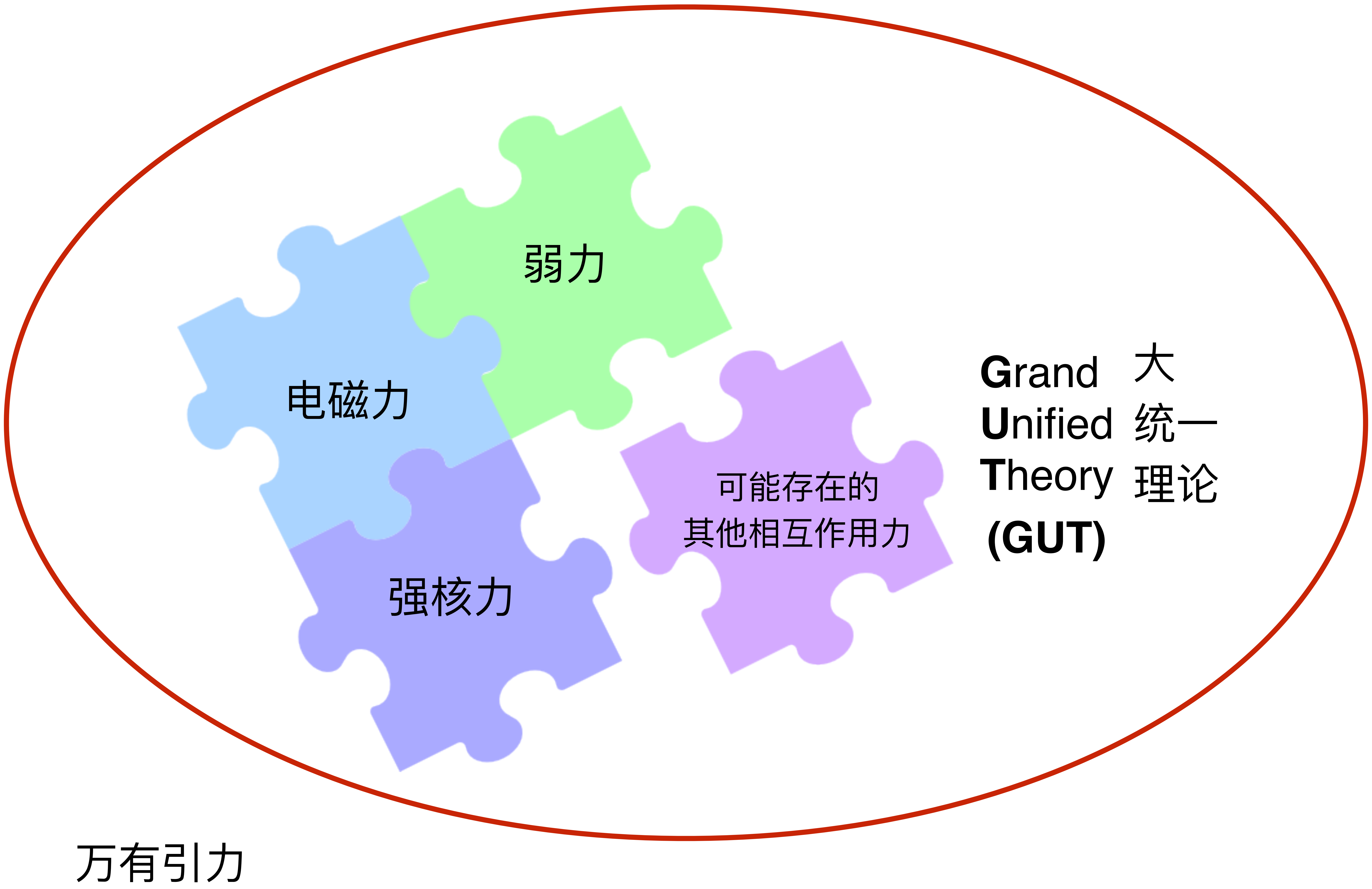


$$\nabla \cdot \mathbf{E} = 4\pi\rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial B}{\partial t}$$
$$\nabla \times \mathbf{B} = 4\pi\mathbf{J} + \frac{\partial E}{\partial t}$$

James C. Maxwell

Glashow, Salam, Weinberg

大统一理论简介


弱力
电磁力
强核力
可能存在的
其他相互作用力
Grand 大
Unified 统一
Theory 理论
(GUT)
万有引力

通往大统一之路

- 对称性的统一

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

EW

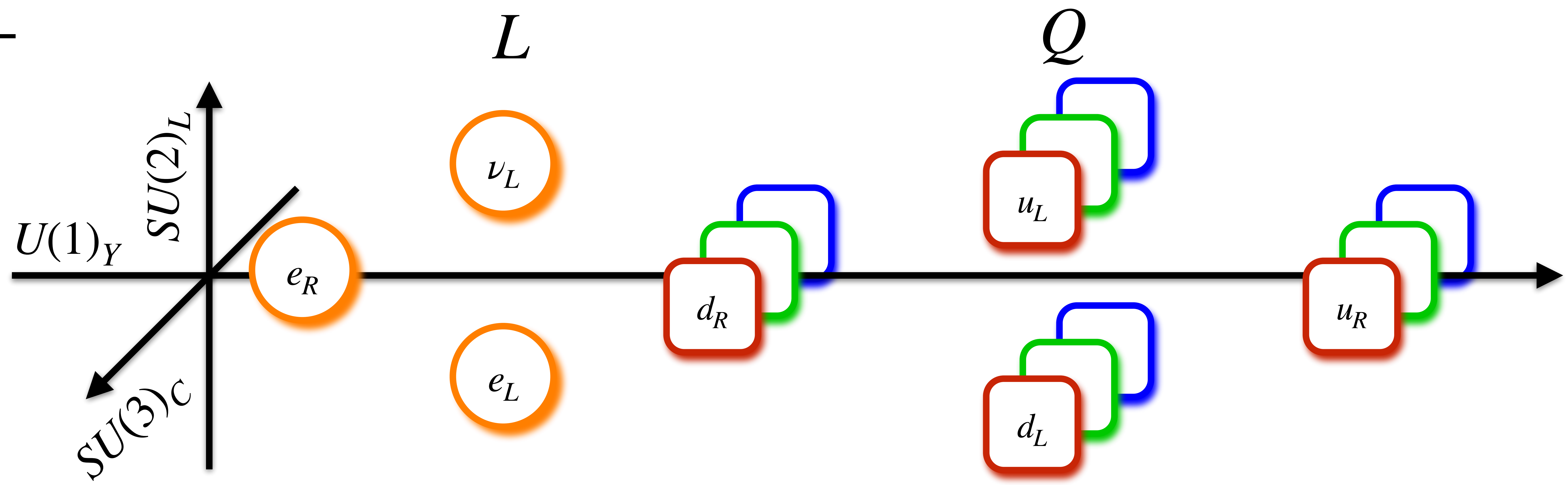
- 耦合系数的统一

$$g_3 = g_2 = g_1$$

up to a loop correction factor

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

- 物质的统一



弱超荷 $Y = -1$ $Y = -\frac{1}{2}$ $Y = -\frac{1}{3}$ $Y = \frac{1}{6}$ $Y = \frac{2}{3}$

通往大统一之路

- Georgi-Glashow model (1974) $SU(5)$
- 24 规范波色子 +15 手征费米子 + 若干Higgs粒子

$$A_a^b = \begin{pmatrix} G_1^1 - 2B' & G_2^1 & G_3^1 & \bar{X}^1 & \bar{Y}^1 \\ G_1^2 & G_2^2 - 2B' & G_3^2 & \bar{X}^2 & \bar{Y}^2 \\ G_1^3 & G_2^3 & G_3^3 - 2B' & \bar{X}^3 & \bar{Y}^3 \\ X^1 & X^2 & X^3 & W'^3 + 3B' & W^+ \\ Y^1 & Y^2 & Y^3 & W^- & -W'^3 + 3B' \end{pmatrix}, \quad A_a^b \sim \mathbf{24}$$

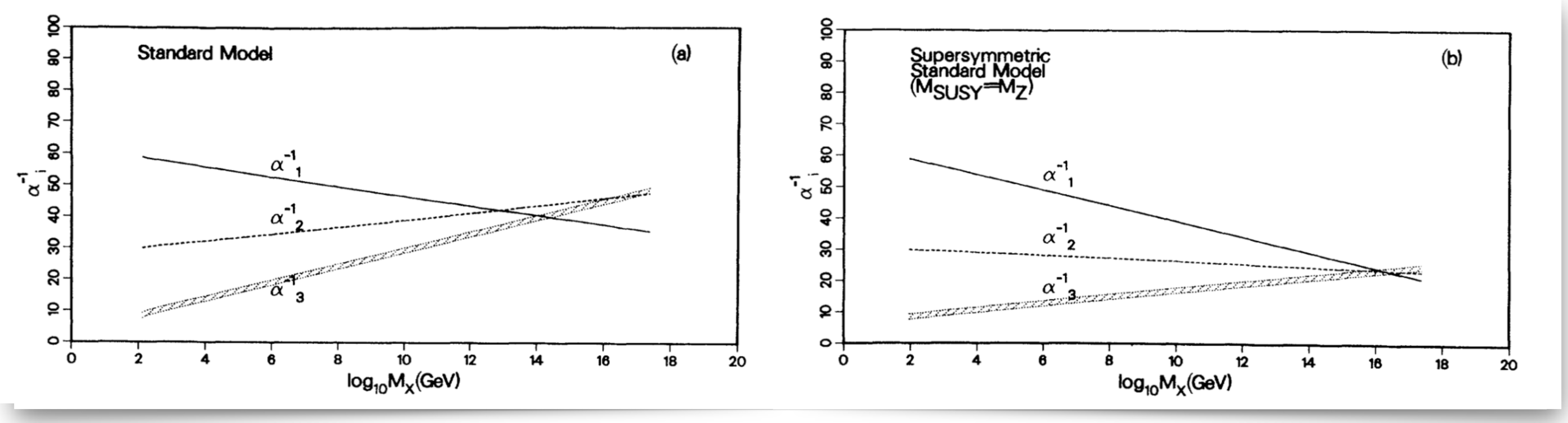
$$B' = B/\sqrt{30}, W' = W/\sqrt{2}$$

$$\psi_a = \begin{pmatrix} (d_R^1)^c \\ (d_R^2)^c \\ (d_R^3)^c \\ e_L \\ -\nu_L \end{pmatrix}, \quad \psi_a \sim \bar{\mathbf{5}}$$

$$\psi^{ab} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & (u_R^3)^c & -(u_R^2)^c & -u_L^1 & -d_L^1 \\ -(u_R^3)^c & 0 & (u_R^1)^c & -u_L^2 & -d_L^2 \\ (d_R^2)^c & -(d_R^1)^c & 0 & -u_L^3 & -d_L^3 \\ u_L^1 & u_L^2 & u_L^3 & 0 & (e_R)^c \\ d_L^1 & d_L^2 & d_L^3 & -(e_R)^c & 0 \end{pmatrix}, \quad \psi^{ab} \sim \mathbf{10}$$

- 规范统一: non-SUSY ⇒ SUSY

Langacker, Luo, 91



通往大统一之路

- More realistic $SU(5)$ 比如增加新粒子来解释中微子的质量

- $SU(5) \times U(1)_{B-L} \equiv G_{51}$ 中微子质量通过B-L的自发破缺来获得

- Flipped $SU(5) \times U(1)_X \equiv G_{51}^{\text{flip}}$ $u \leftrightarrow d,\ \nu \leftrightarrow e$

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

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

$$(\mathbf{4}, \mathbf{2}, \mathbf{1}) : \psi_L = \begin{pmatrix} u^1 & u^2 & u^3 & \nu \\ d^1 & d^2 & d^3 & e \end{pmatrix}_L, \quad (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2}) : \psi_R = \begin{pmatrix} u^1 & u^2 & u^3 & \nu \\ d^1 & d^2 & d^3 & e \end{pmatrix}_R^c$$

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

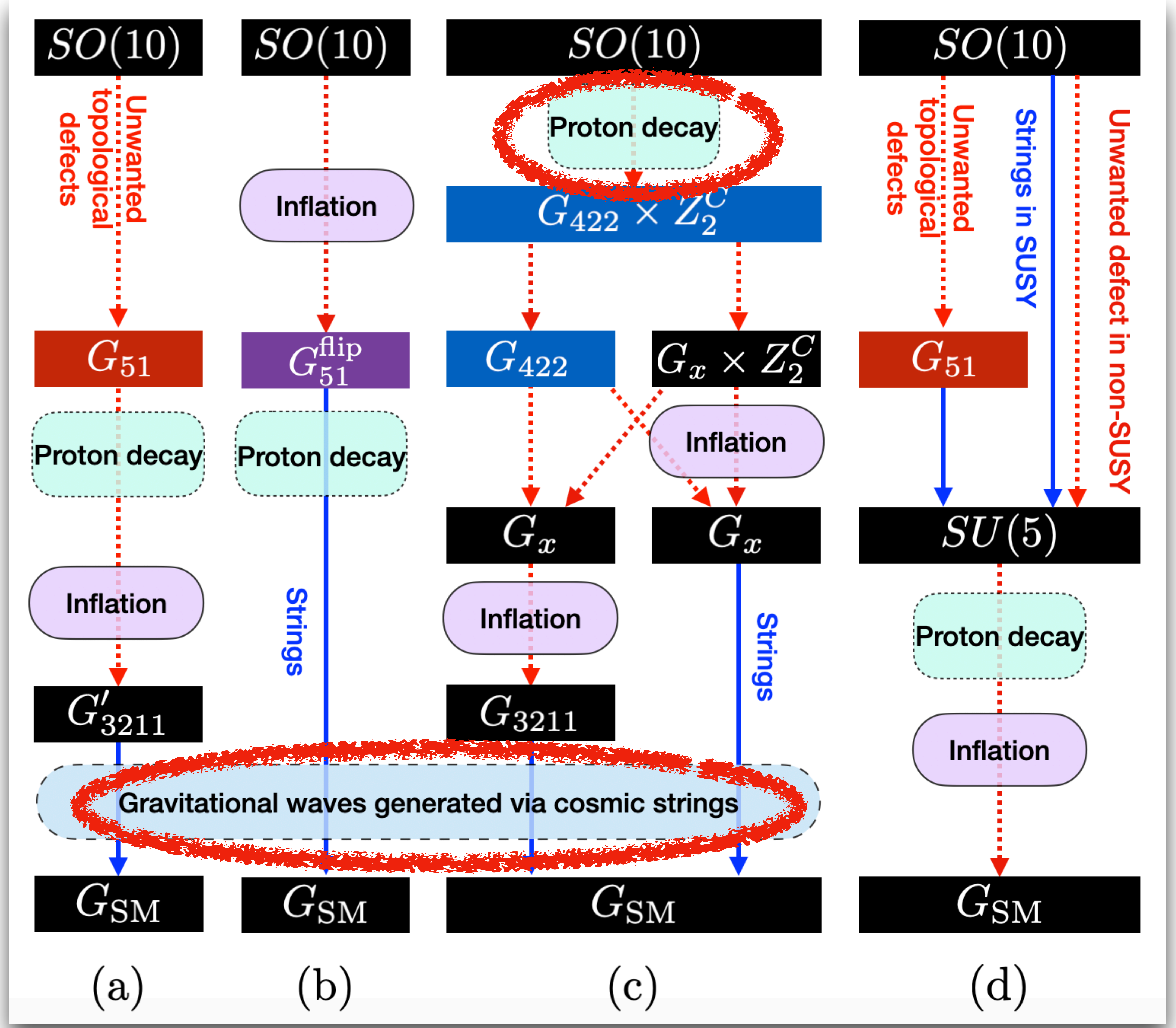
  All the above can be embedded to SO(10)

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

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

SO(10) 大统一的唯象学

Fermion masses and mixing



Unwanted topological defects: monopoles and domain walls

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

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

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

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

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

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

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

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

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

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

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

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

质子衰变

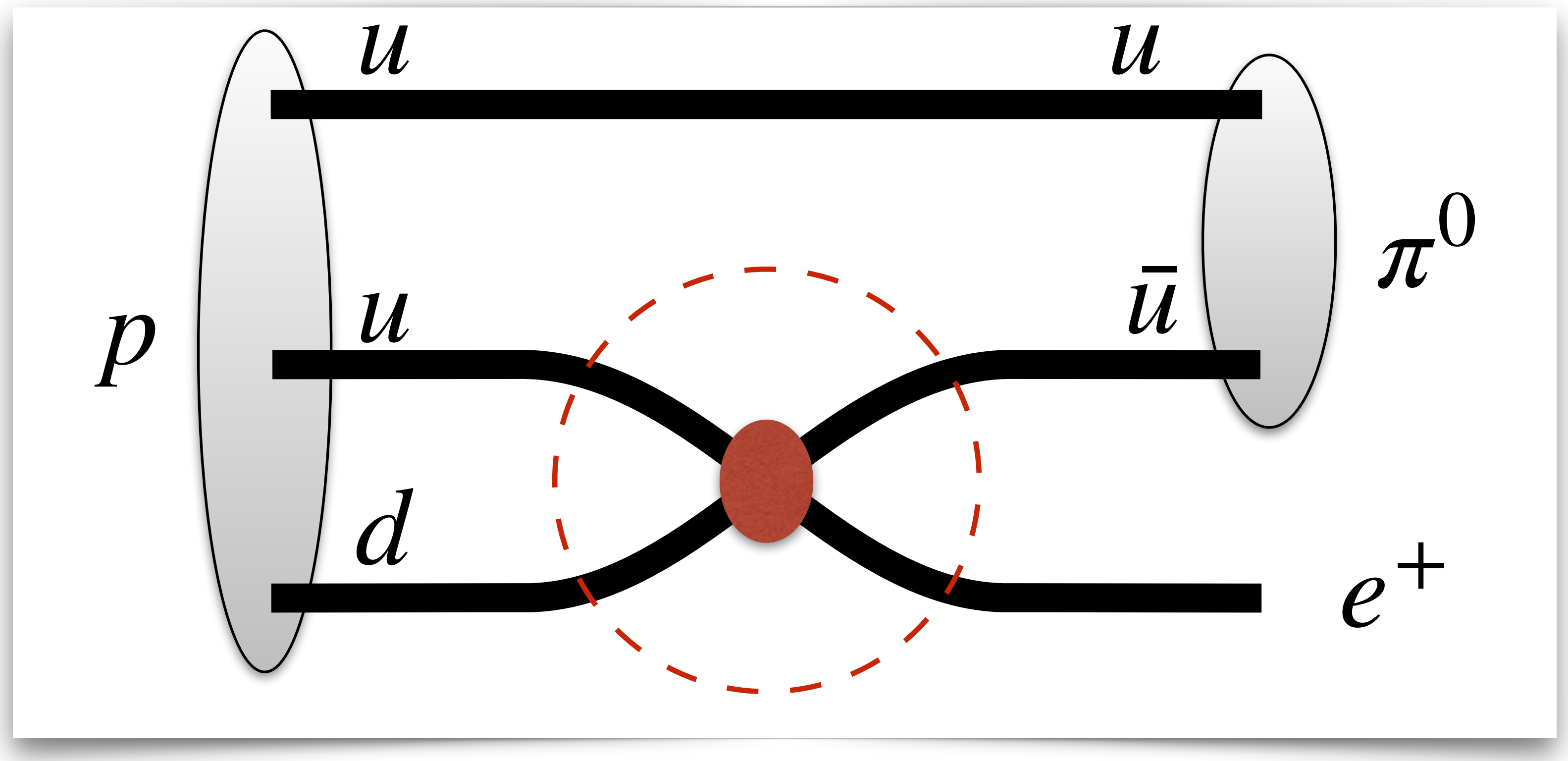
- 大统一引入传递重子数破坏的新粒子，这些粒子退耦后诱导出重子数破坏的有效算符

- Dim-6算符　　　　主要通过规范波色子传导

$$\frac{1}{\Lambda_1^2}\left[(\overline{u_R^c}\gamma^\mu Q)(\overline{d_R^c}\gamma_\mu L)+(\overline{u_R^c}\gamma^\mu Q)(\overline{e_R^c}\gamma_\mu Q)\right]$$
$$+\frac{1}{\Lambda_2^2}\left[(\overline{d_R^c}\gamma^\mu Q)(\overline{u_R^c}\gamma_\mu L)+(\overline{d_R^c}\gamma^\mu Q)(\overline{\nu_R^c}\gamma_\mu Q)\right]$$

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

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

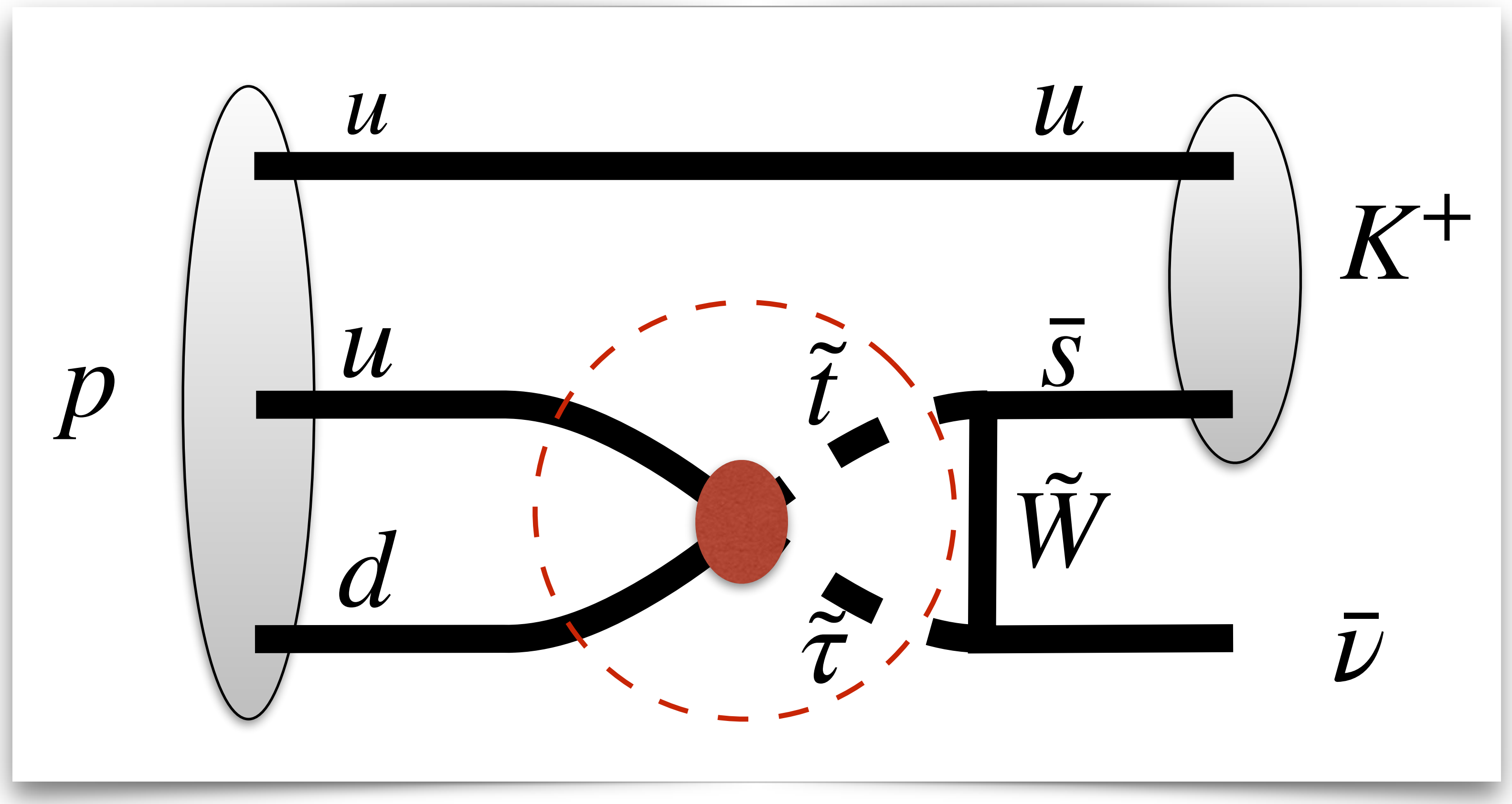


- Dim-5算符　　　　主要针对超对称大统一模型

$$\frac{c_1}{M_T}(\overline{Q^c}Q)(\tilde{L}\tilde{Q}) + \frac{c_2}{M_T}(\overline{u_R^c}d_R)(\tilde{e}_R\tilde{u}_R) + \cdots$$

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

$$\tau_{K^+\bar{\nu}} \propto (\Lambda_{\text{pd}} \cdot \Lambda_{\text{SUSY}} \cdot Y_{\text{Yukawa}})^2$$



大型中微子实验对质子衰变的探测潜力

2万吨的水（或者液闪）

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

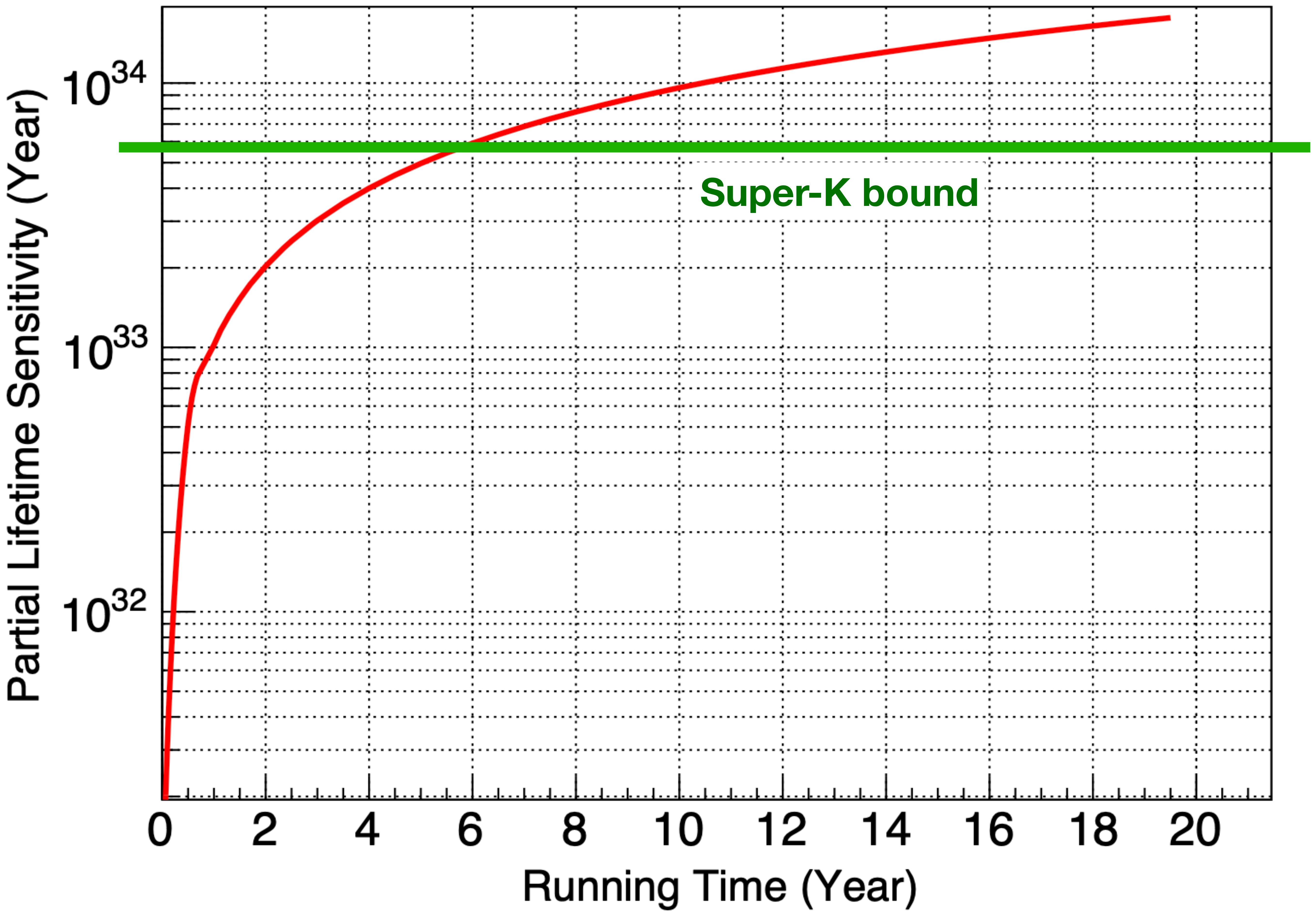
$\simeq 7 \times 10^{33}$ 个质子

JUNO的潜力

探测效率 $\epsilon_{\mathrm{JUNO}} = 36.9\,\%$

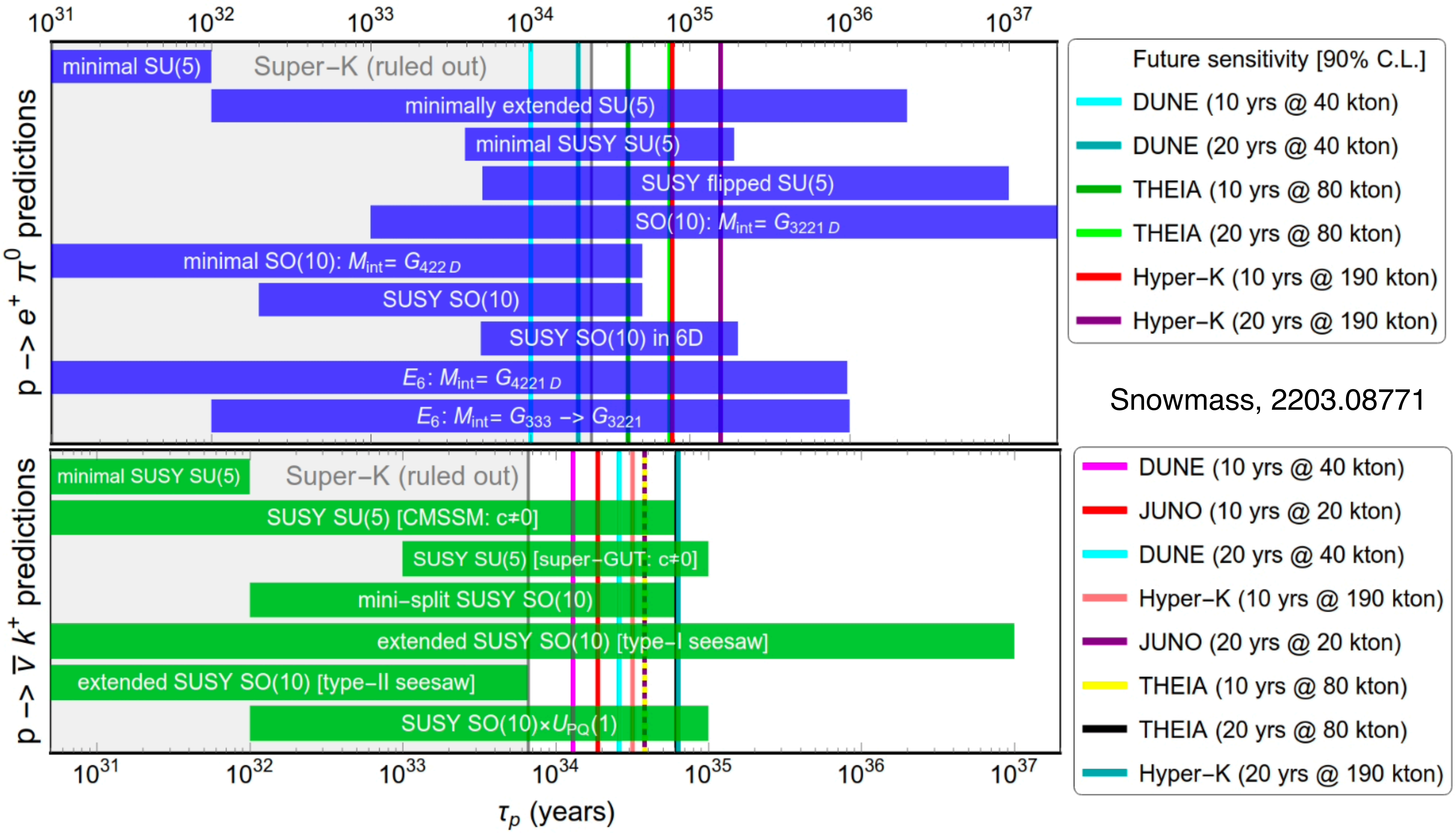
$$\tau/B(p \to \bar{\nu}K^{+}) = \frac{N_p T \epsilon}{n_{90}}$$

统计因子 (90%CL)



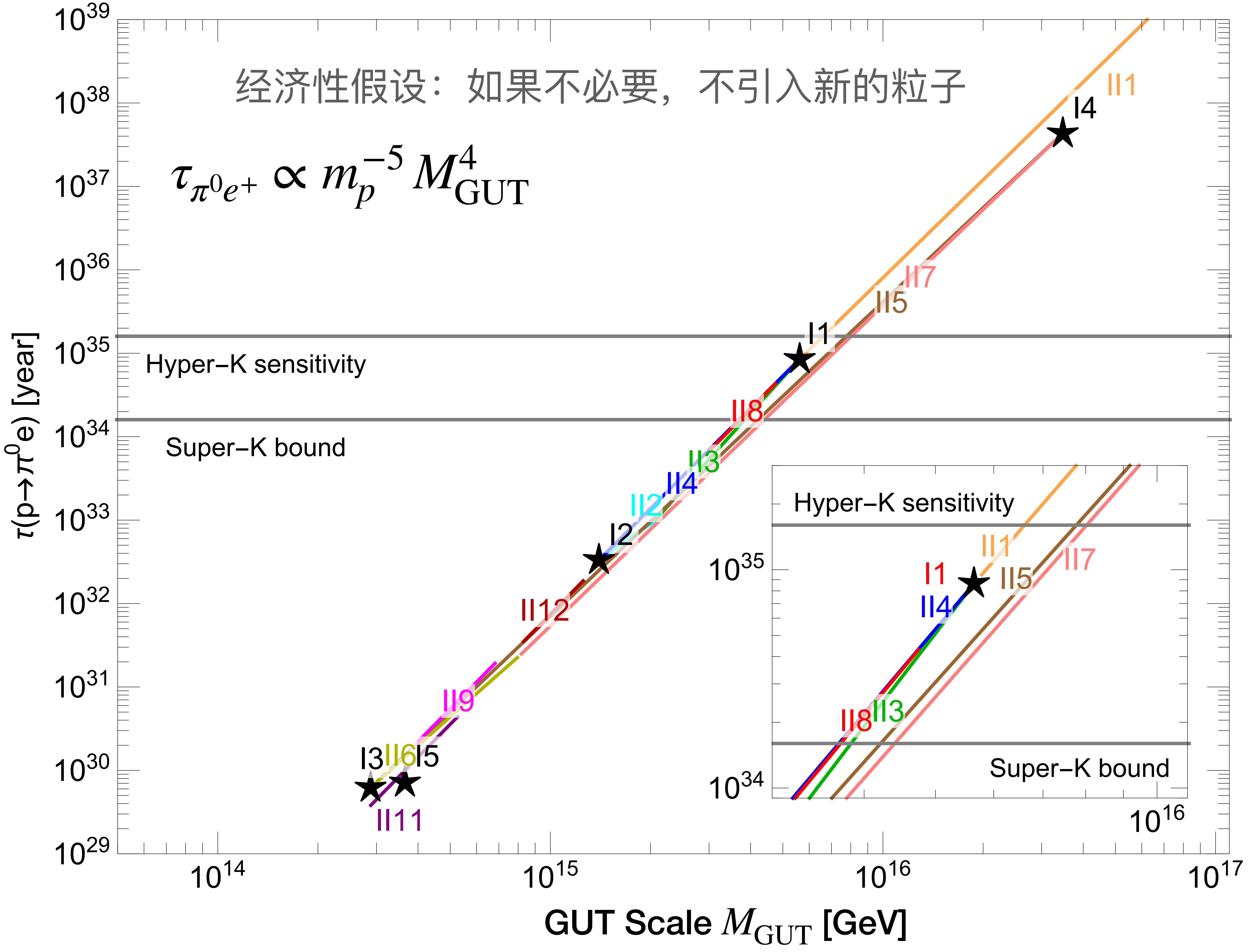
JUNO, 2212.08502

下一代中微子实验的潜力



Snowmass, 2203.08771

SO(10)中的质子衰变



$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	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

SO(10) 中的费米子质量与味混合

- 所有物质场 $\{Q=(u_L,u_R),u_R,d_R,L=(\nu_L,e_L),e_R,\nu_R\}$ 都安排在SO(10)的**16**重态中

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

- 为了得到规范不变的可重整化的Yukawa耦合，三个Higgs场可以引进来 $\mathbf{10}_H,\overline{\mathbf{126}}_H,\mathbf{120}_H$

这其中，标准模型中的Higgs是这些Higgs混合出来的最轻的那一个

- 基本的Yukawa耦合项可以写为

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

- 由此得到的各费米子场的Yukawa耦合相互关联　　Dutta, Mimura, Mohapatra, 0412105

$$Y_d=r_1(h+f+i\,h')\qquad Y_u=h+r_2f+i\,r_3h'$$

$$Y_e=r_1(h-3f+i\,c_eh')\qquad Y_\nu=h-3r_2f+i\,c_\nu h'$$

$$M_{\nu_R}=m_{\nu_R}f$$

Yukawa/mass matrices in SO(10)

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

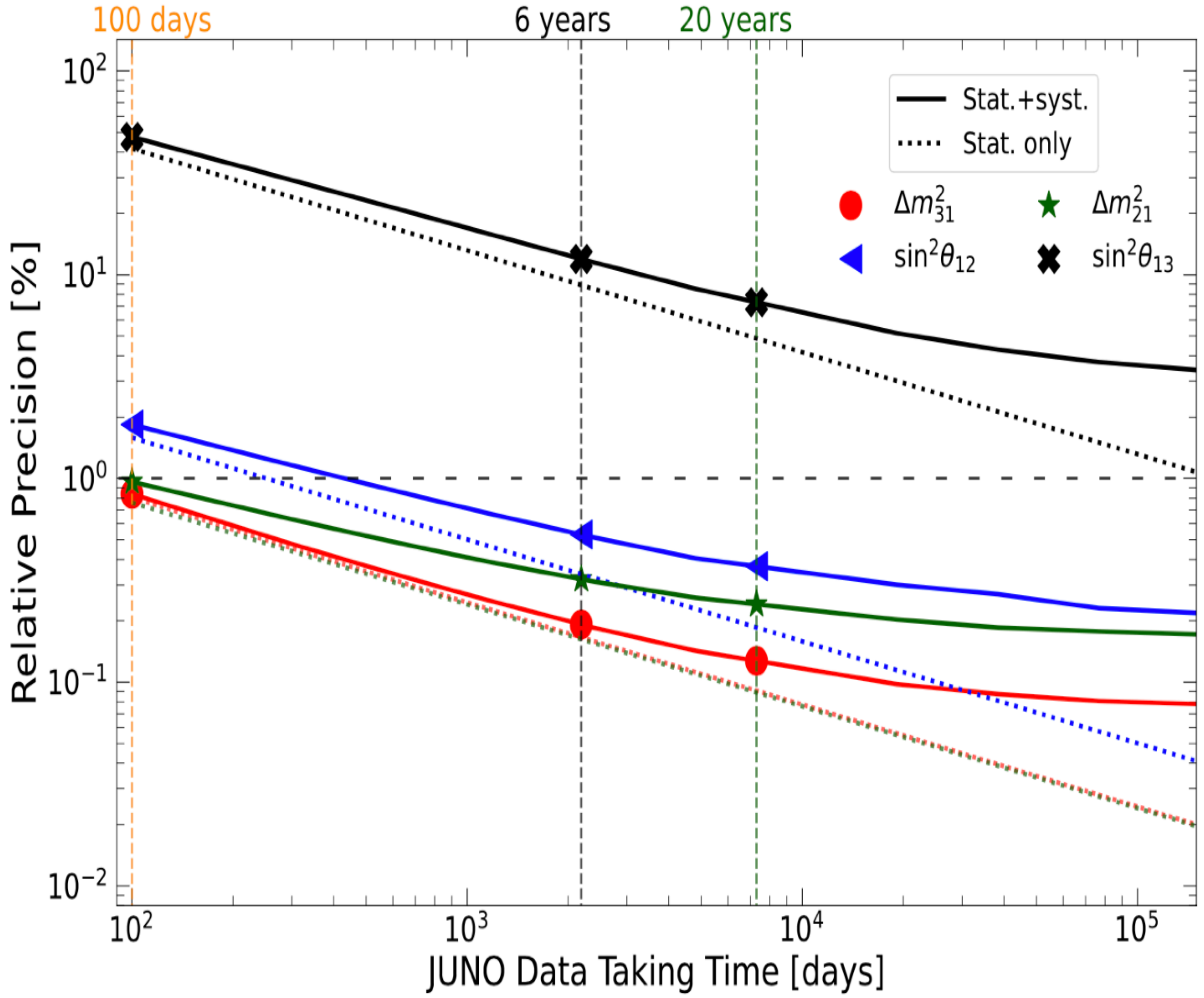
中微子实验对大统一味混合的影响

NuFIT 5.1 (2021)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

without SK atmospheric data

中微子精确测量时代已经到来！

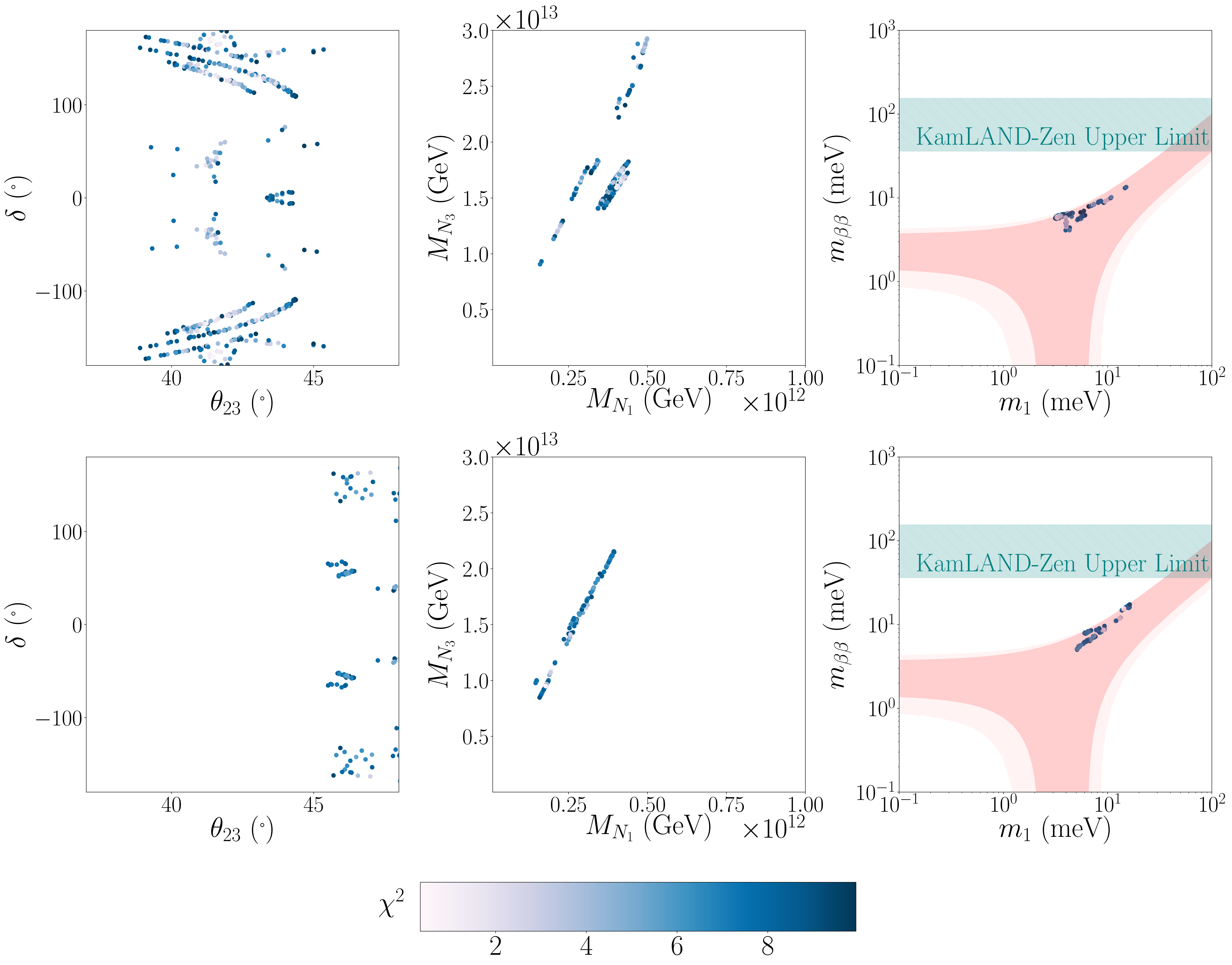


1%

0.1%

2204.13249

SO(10) 中的费米子质量与味混合



Take-away message:

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

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

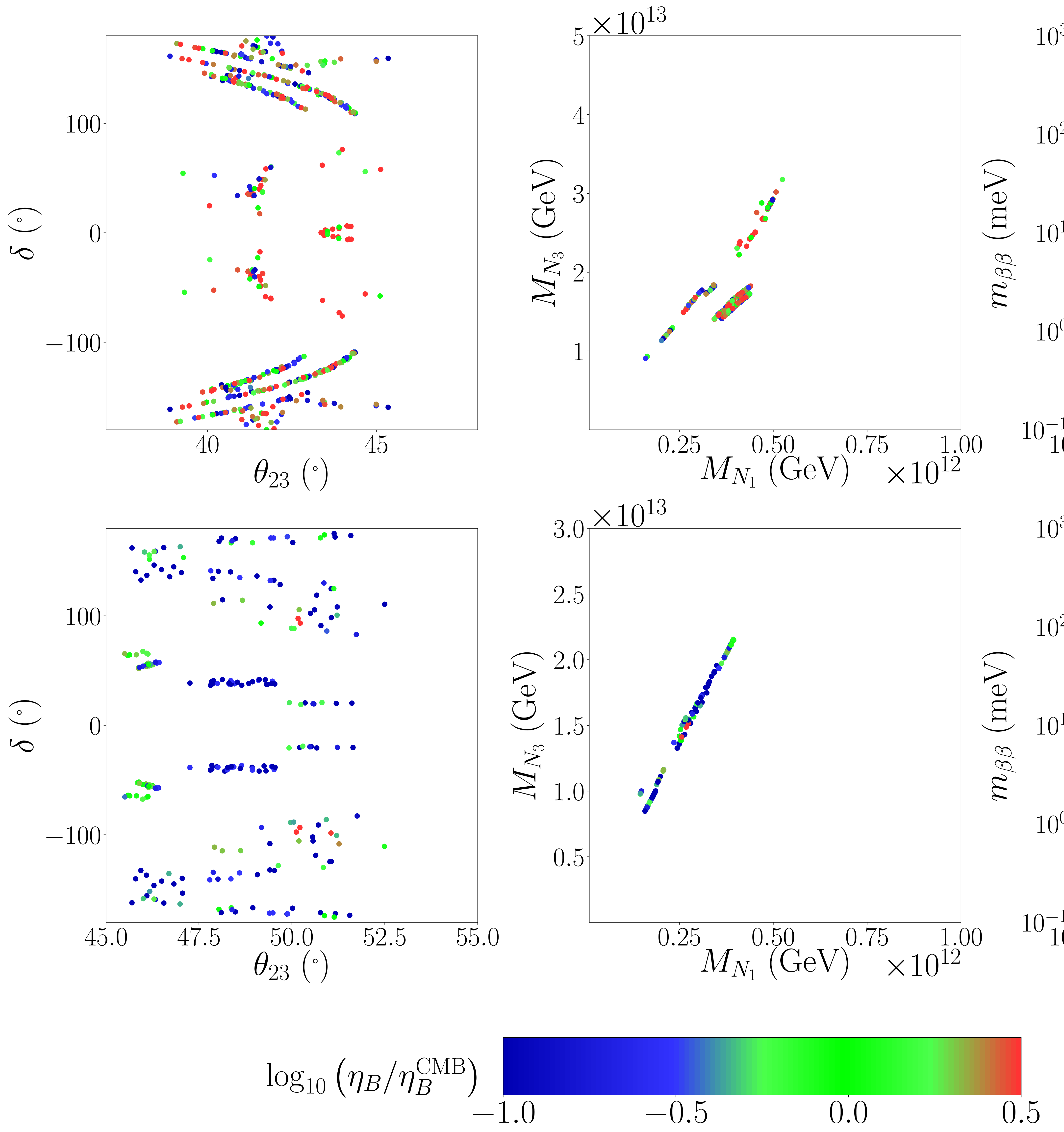
$m_{\beta\beta} \sim 10^{-2}$ eV

中微子质量次序倾向于正等级

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

SO(10) 中的费米子质量与味混合

⇒ 物质-反物质不对称



夸克、轻子的质量与味混合的所有实验数据

⇓

右手中微子的质量和Dirac耦合矩阵

⇓

右手中微子衰变的CP破坏

⇓

Thermal leptogenesis

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

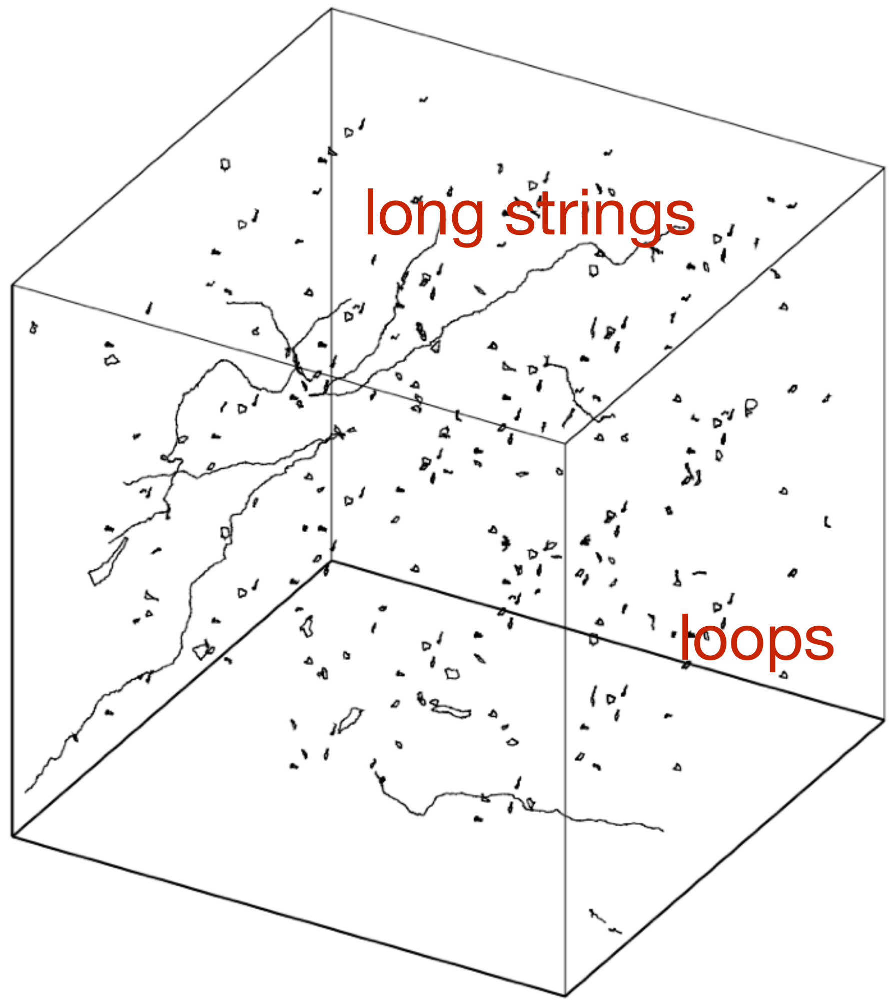
$$\eta_B^{\rm CMB} = 6.15 \times 10^{-10}$$

大统一辐射引力波

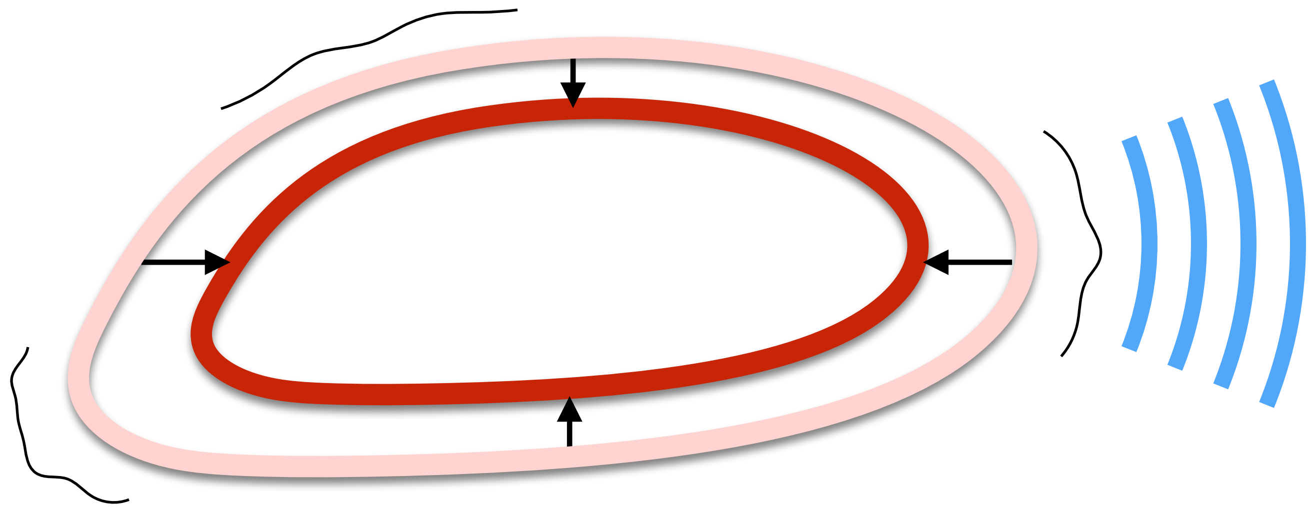
宇宙弦引力波

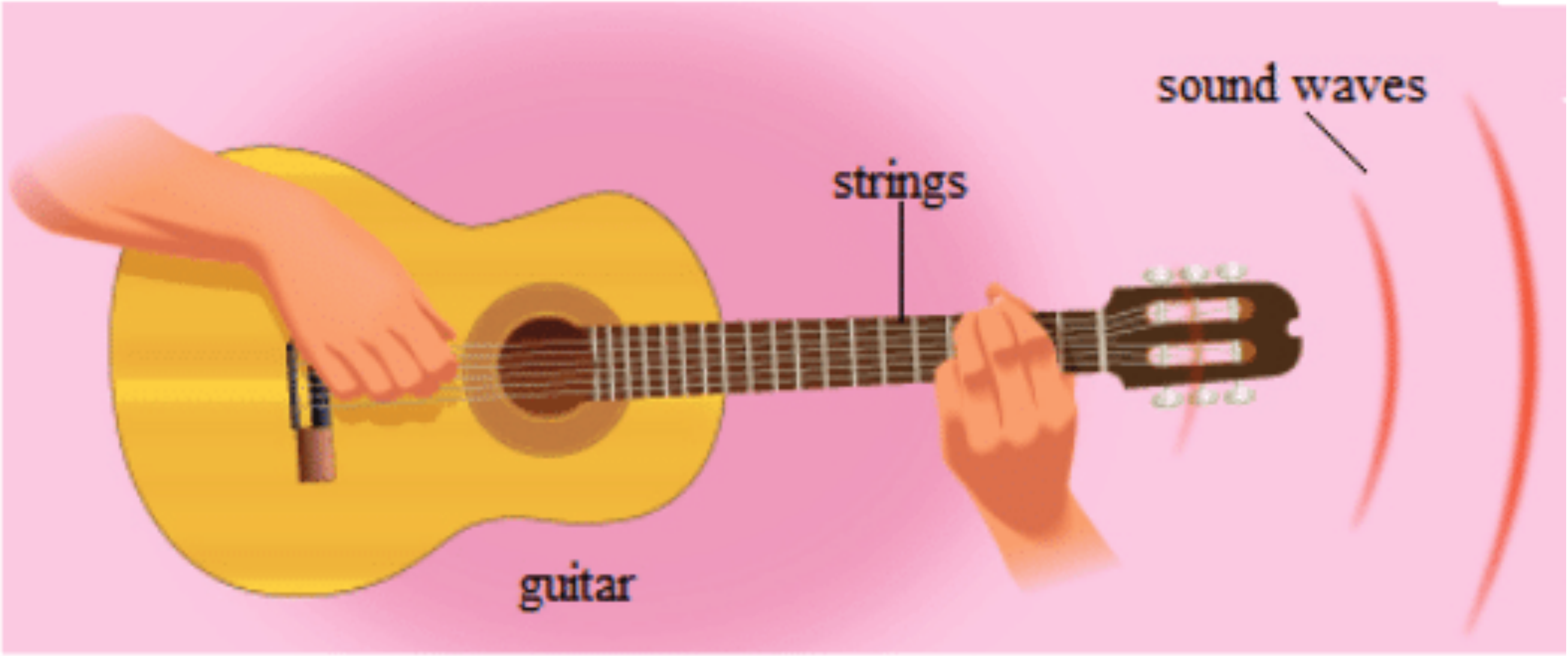
$$\pi_1(U(1)) = Z$$

- 绝大部分大统一模型都包含一个 U(1)B-L 的规范对称性
- U(1)规范对称性的自发破缺可以产生稳定的宇宙弦
- 长弦通过intersection和intercommution（俗称“打结”）产生弦圈圈
- 弦圈圈振荡，辐射出引力波



Vanchurin, Olum, Vilenkin, 0511159

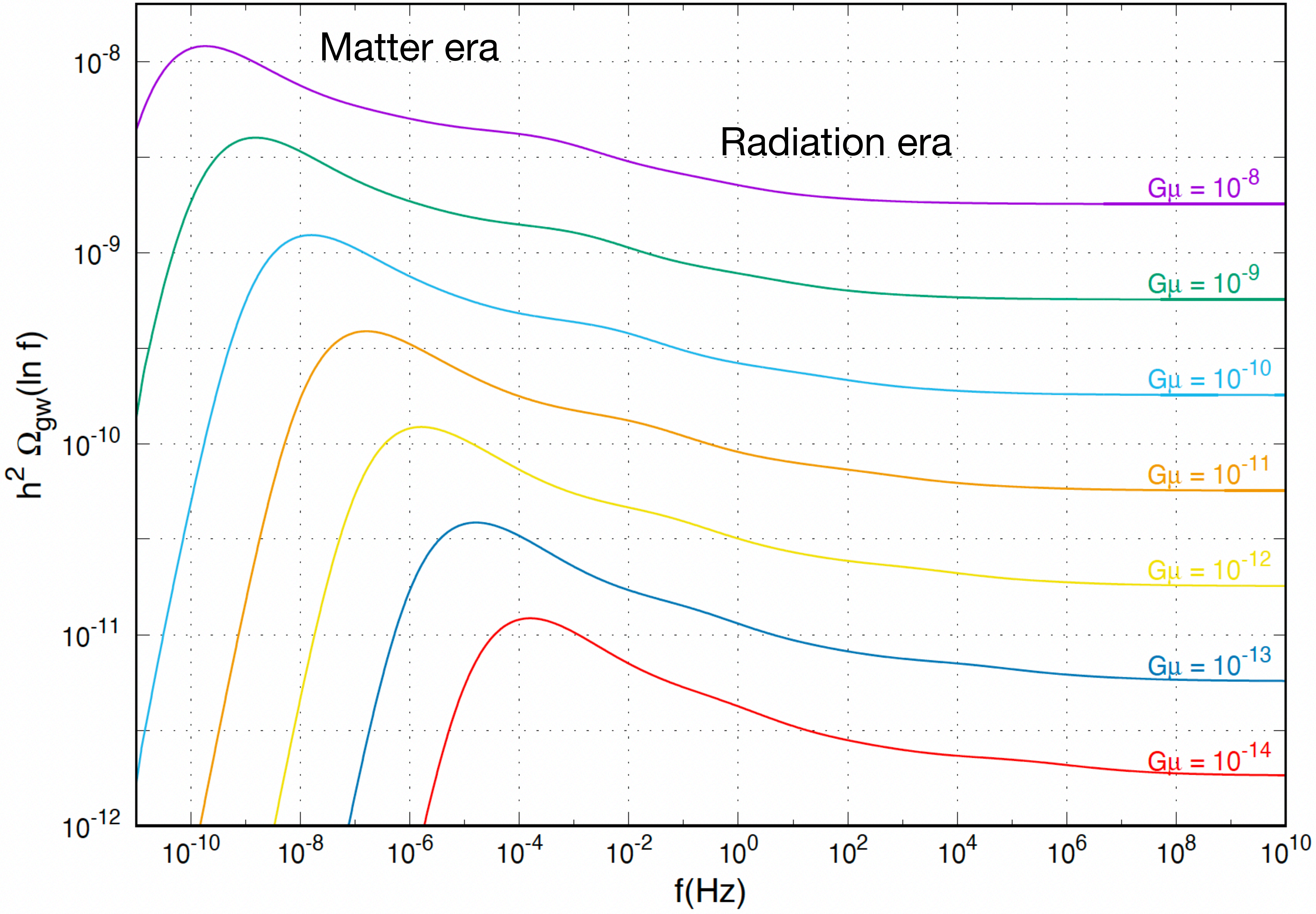




Another mechanism: GW via GUT phase transition?

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

宇宙弦引力波的典型频谱



Plateau

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

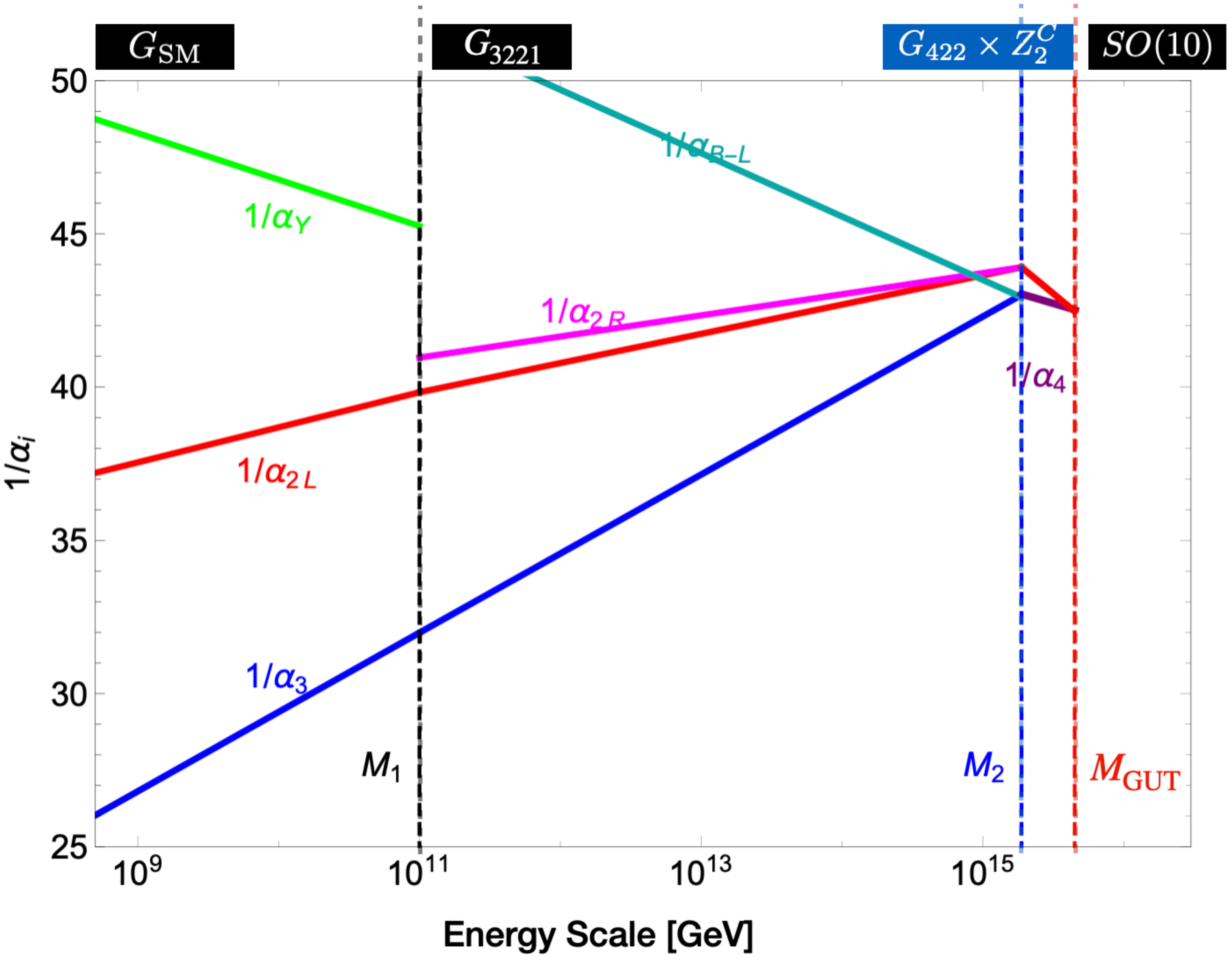
$\propto \frac{M_{B-L}}{M_{\rm Planck}}$ in GUTs

$G = M_{\rm Planck}^{-2}$ 万有引力常数

Blanco-Pillado, Olum
1709.02693

Gauge unification correlates GUT scale with intermediate scales

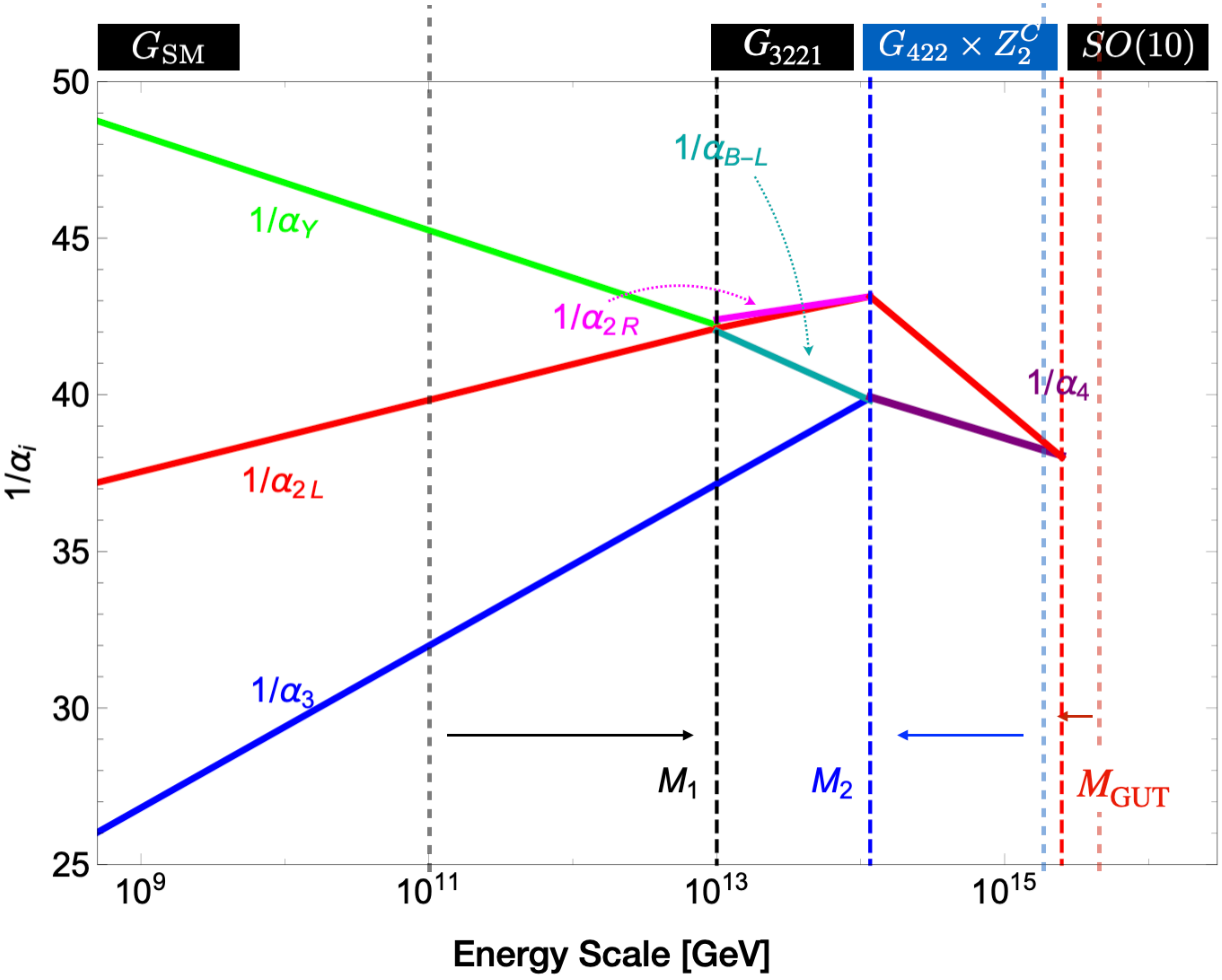
A toy model



M_i 是第 i 个中间对称性 G_i 破缺对应的规范波色子的质量

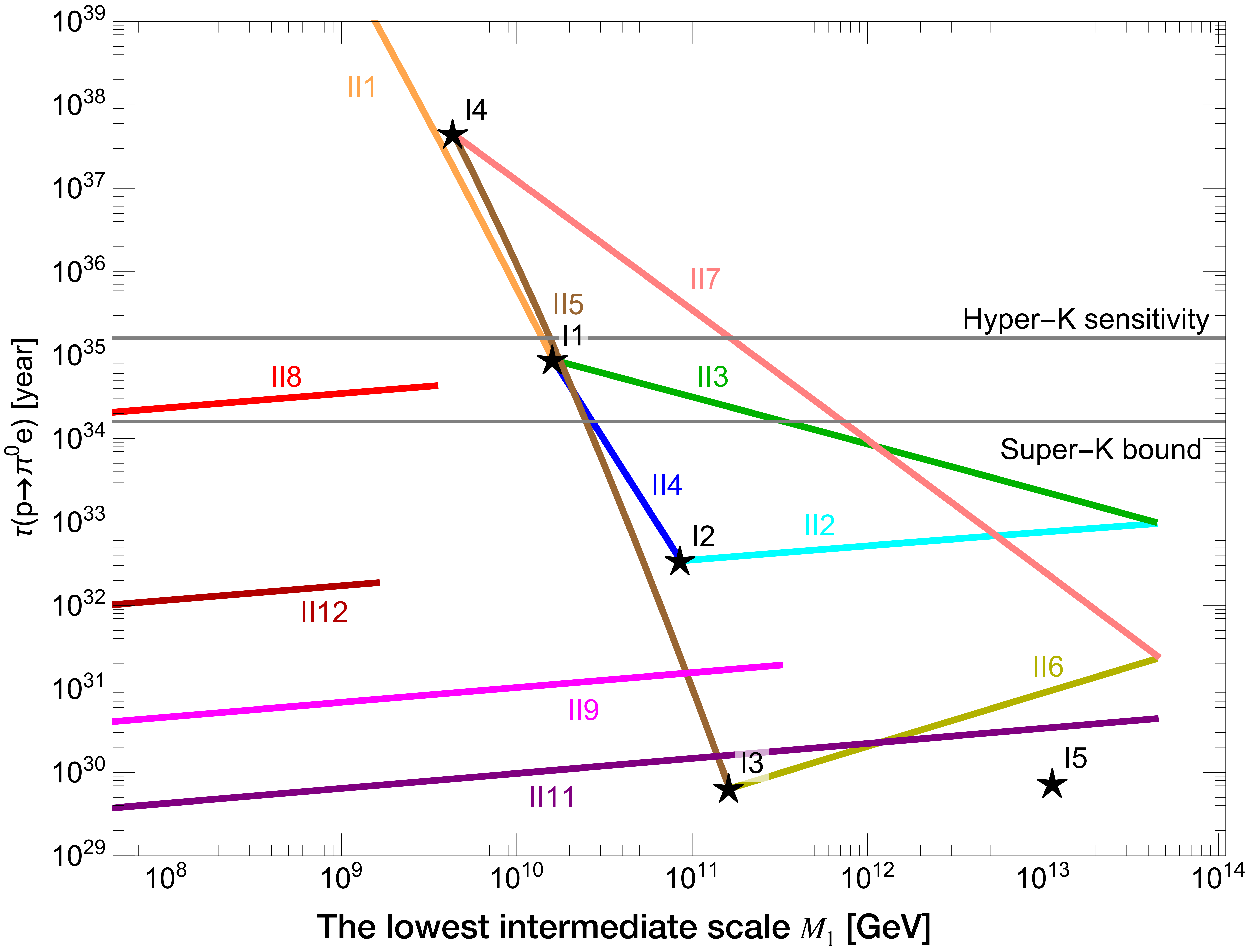
Gauge unification correlates GUT scale with intermediate scales

A toy model



M_i 是第 i 个中间对称性 G_i 破缺对应的规范波色子的质量

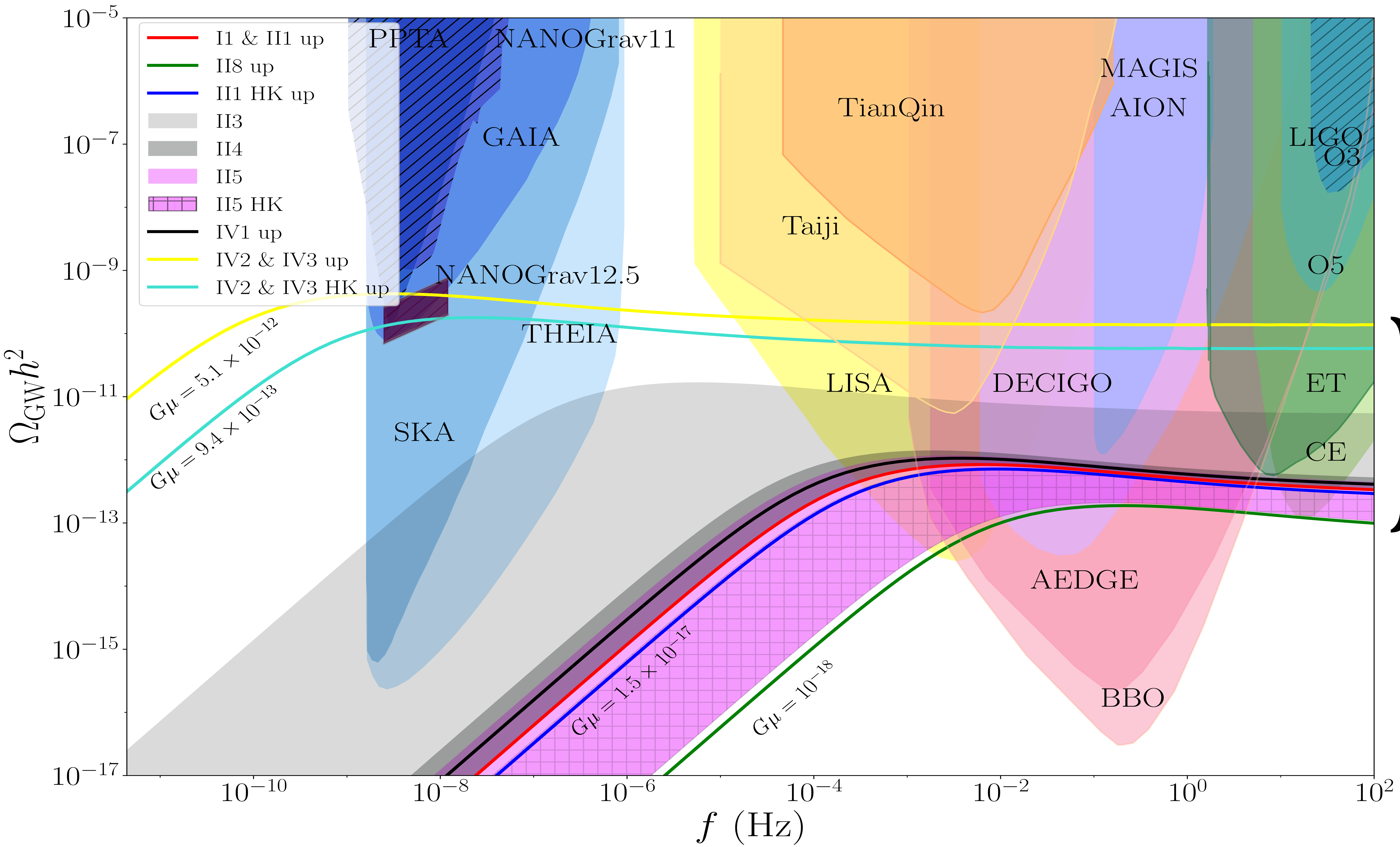
质子衰变对SO(10)框架下B-L能标的限制



$SO(10)$	$\xrightarrow[\text{Higgs}]{\text{defect}}$	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}	$\xrightarrow[\mathbf{126},\mathbf{45}]{\rm m}$	
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

SO(10)预言的宇宙弦引力波频谱

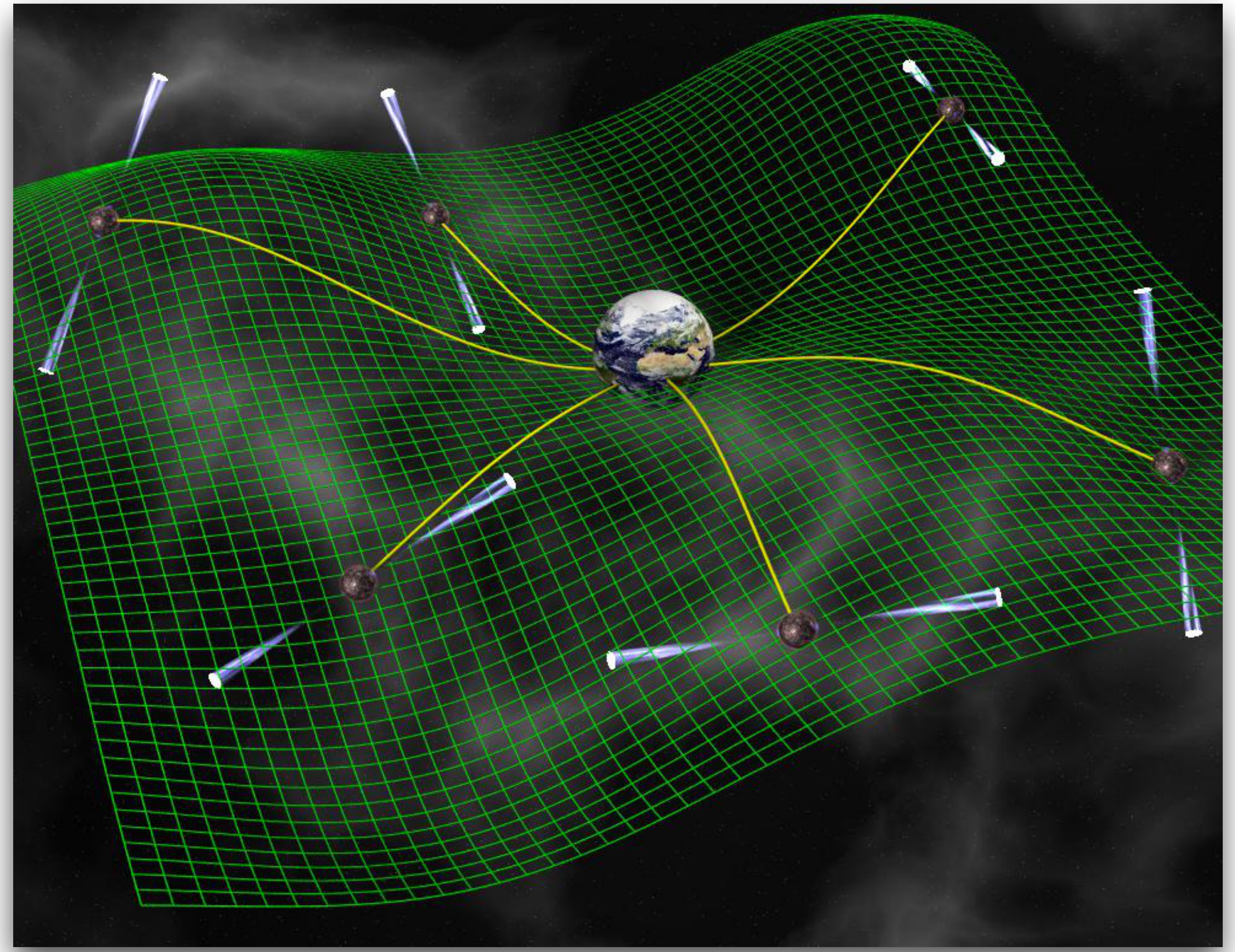


不同颜色对应
不同的破缺链

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

2023年 PTA 对引力波的观测结果

On 28 Jun 2023



The **NANOGrav** 15 yr Data Set: Evidence for a Gravitational-wave Background
2306.16213

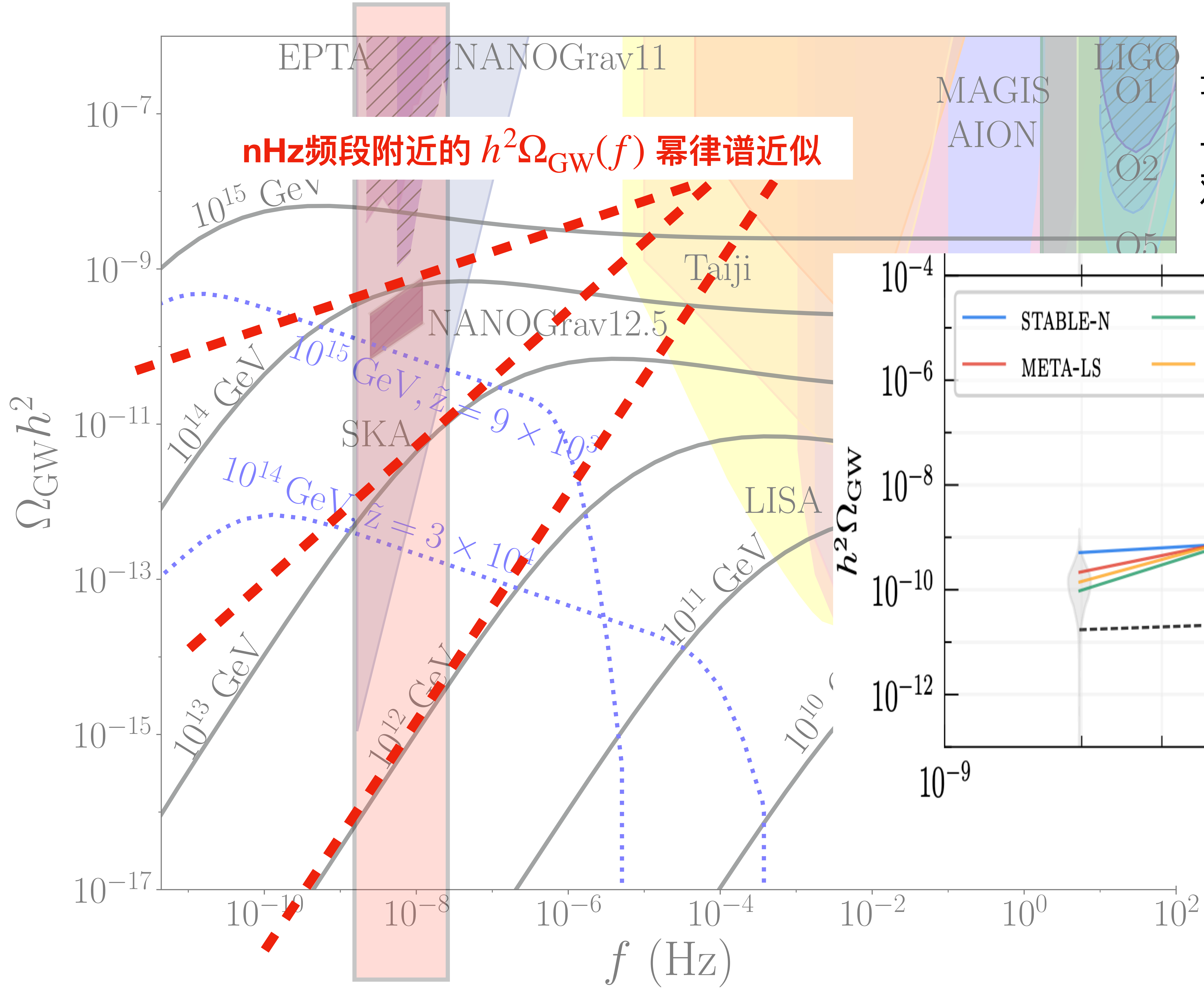
The second data release from the **European Pulsar Timing Array** III. Search for gravitational wave signals
2306.16214

Search for an isotropic gravitational-wave background with the **Parkes Pulsar Timing Array**
2306.16215

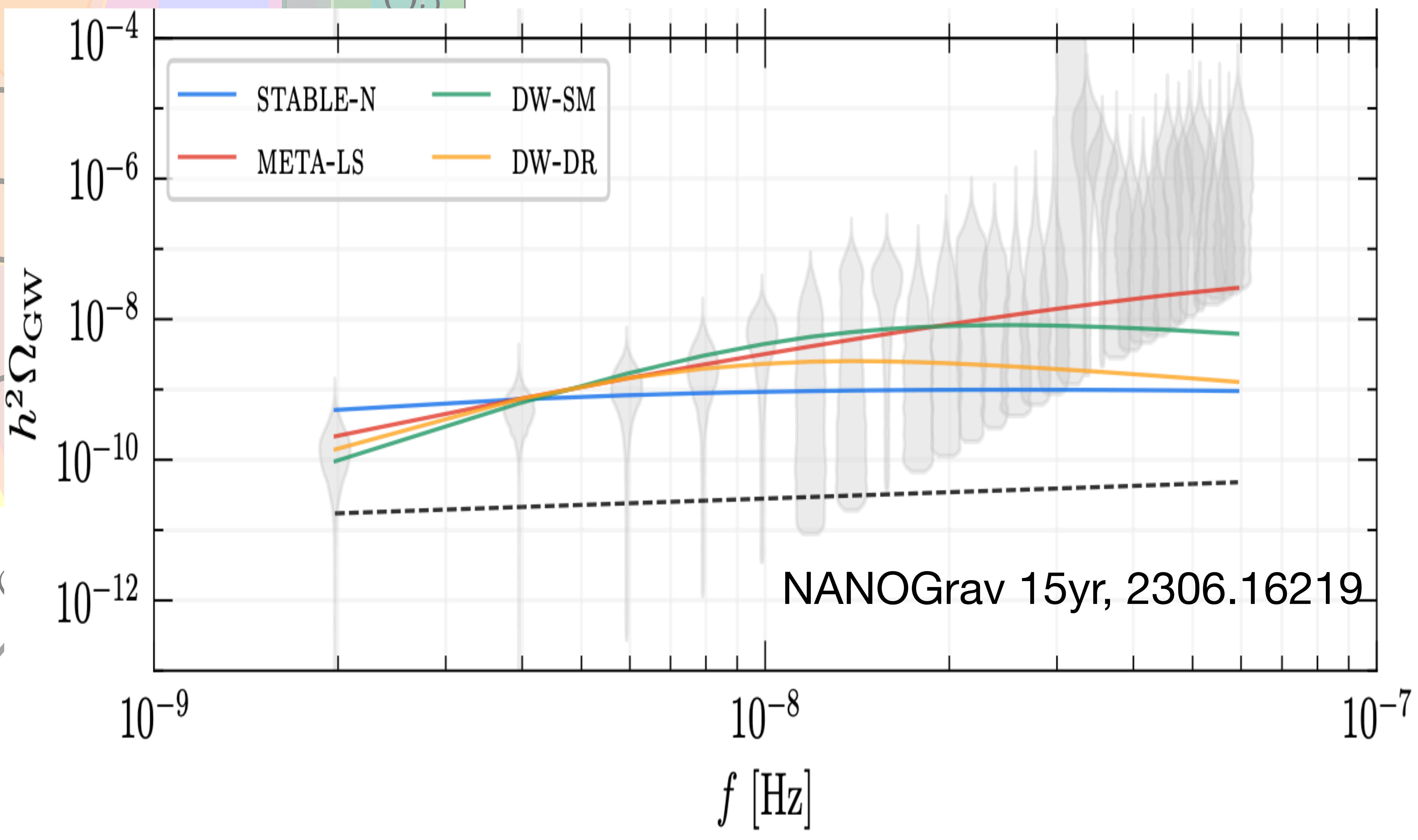
Searching for the nano-Hertz stochastic gravitational wave background with the **Chinese Pulsar Timing Array** Data Release I
2306.16216

If cosmic GW background is observed, then what is the origin?

最简单的宇宙弦引力波模型不能解释PTA观测数据



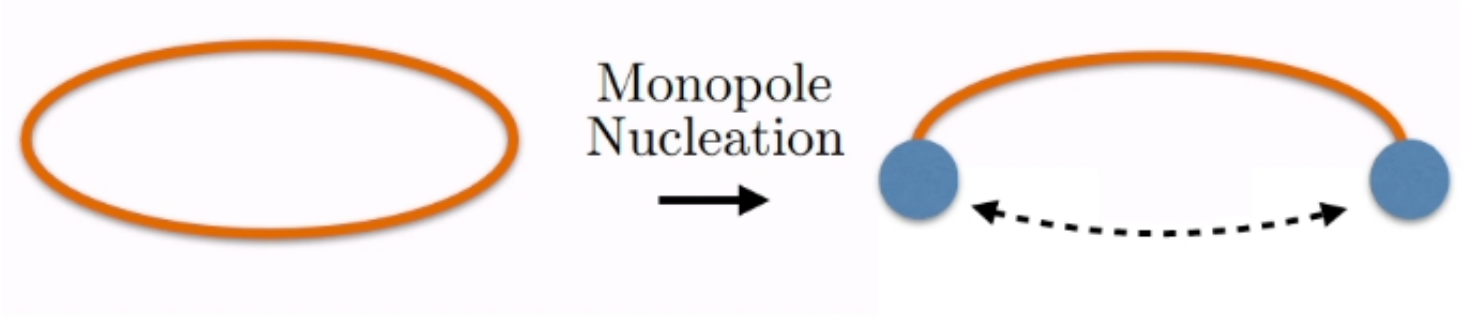
最简单的宇宙弦引力波模型（只依赖于单参数 μ） 并不能拟合 NANOGrav 15 观测到的实验数据。

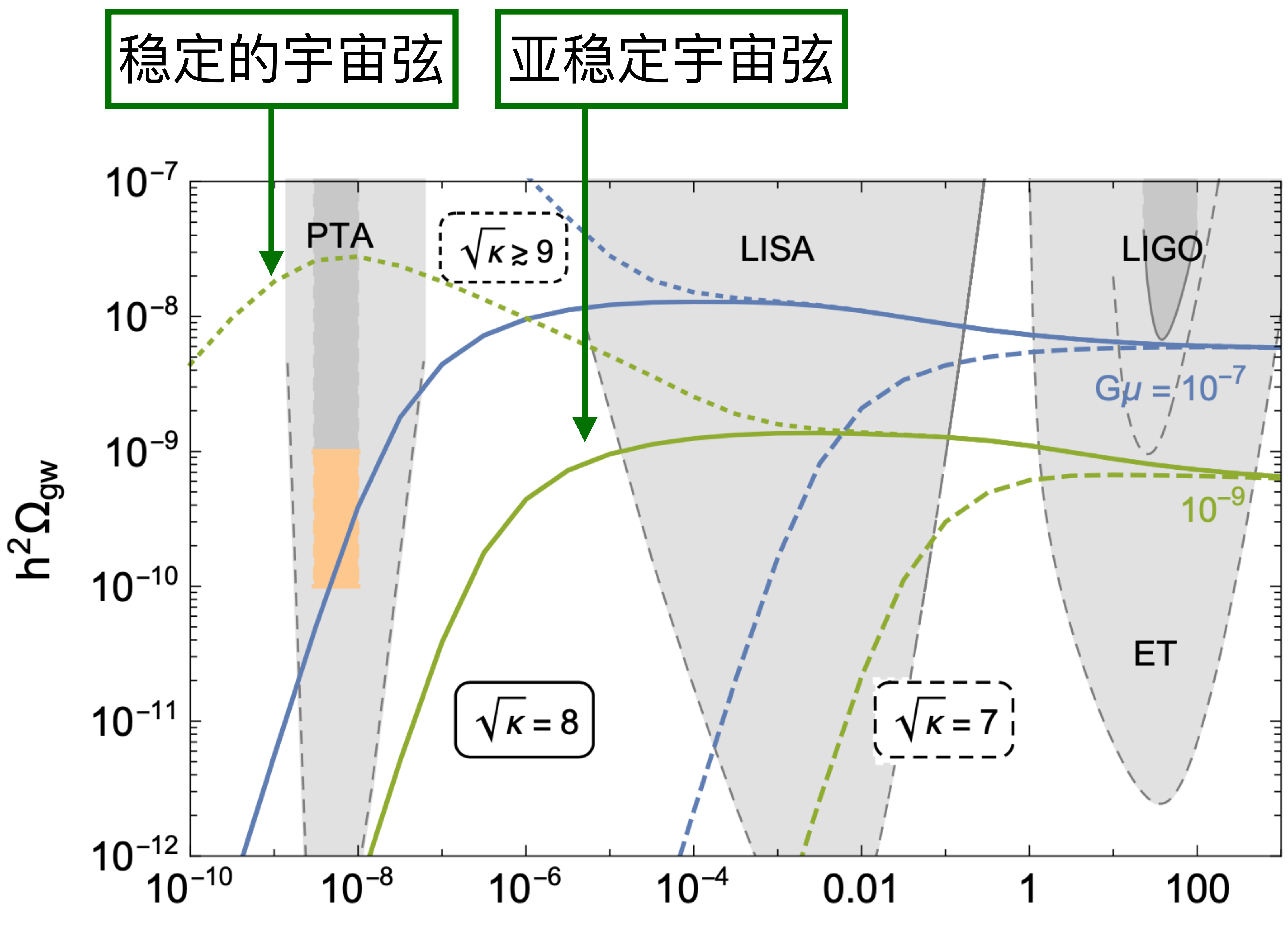


考虑亚稳定宇宙弦（metastable strings）？

大统一还会产生磁单极，如果产生磁单极的能标（往往就是大统一能标本身）跟宇宙弦能标比较接近时 …

弦圈圈会衰变，数密度在宇宙后期被压低 $n(l,t)\, e^{-\Gamma_d\, l\, t}$





Buchmuller, Domcke, Schmitz, 2307.04691

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

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

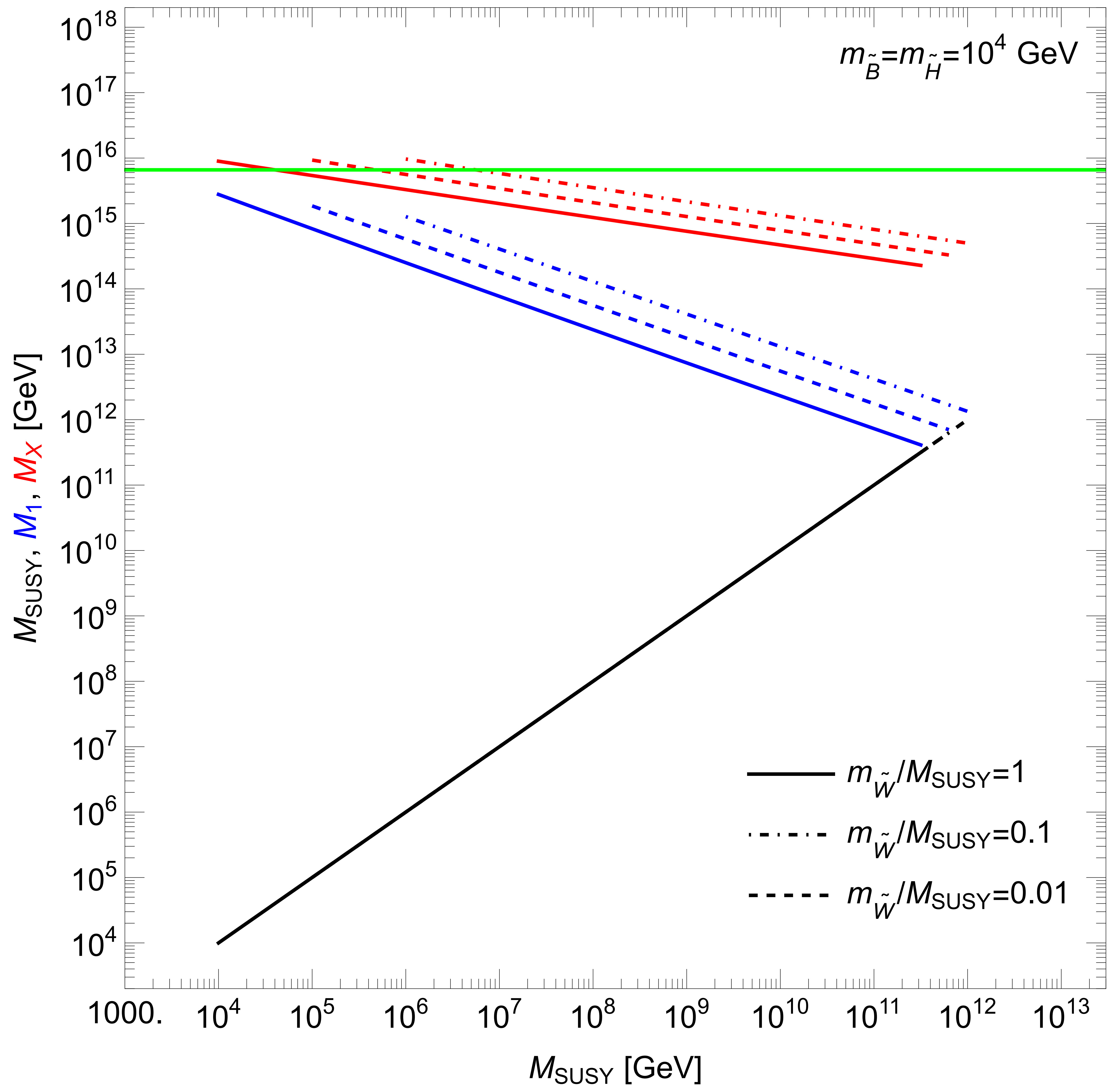
$$\sqrt{\kappa} \simeq (8{,}9) \Rightarrow M_{\text{GUT}} \sim M_{B-L}$$

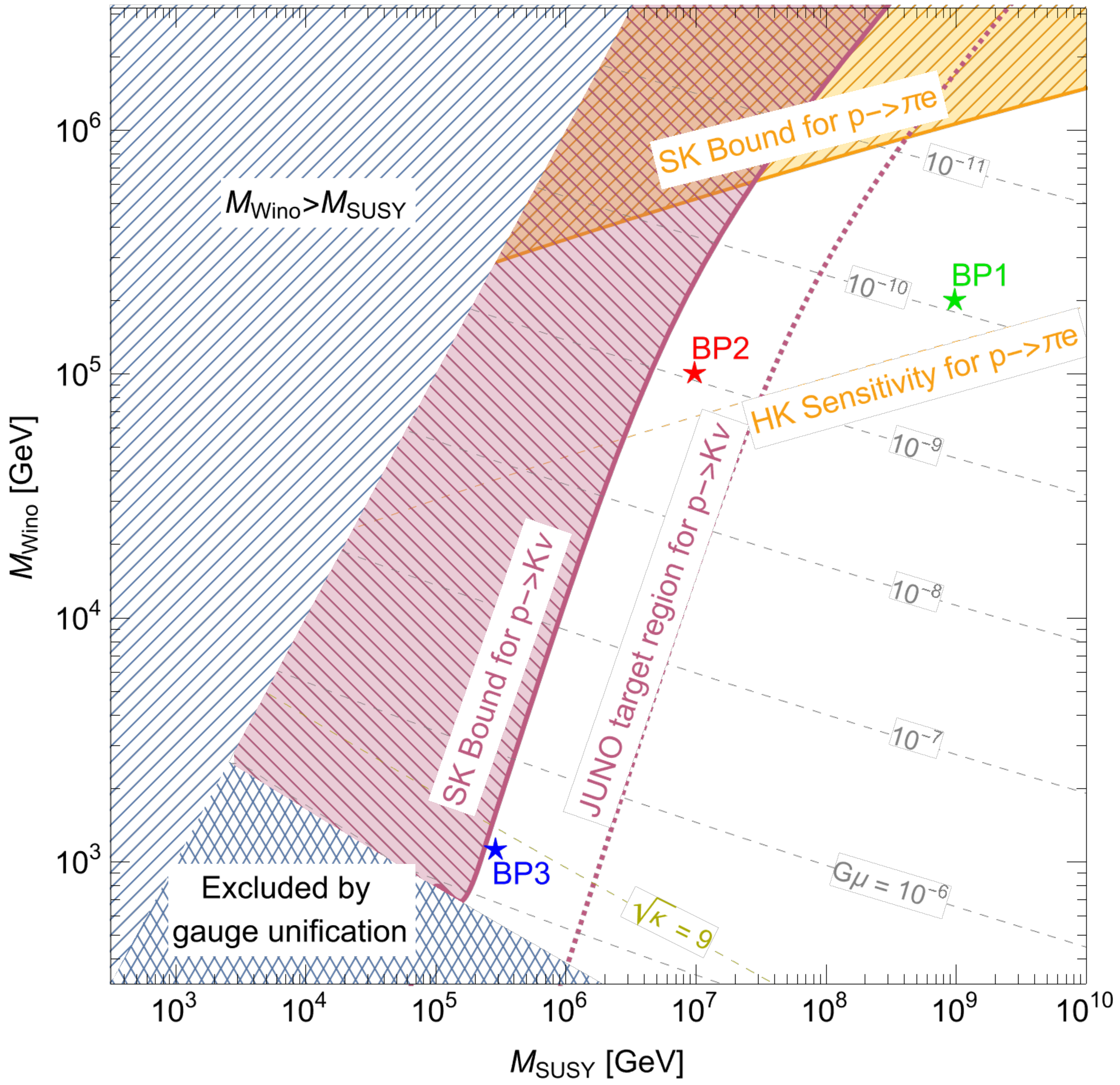
A GUT inflation separating the GUT breaking and B-L breaking in the time scale is required.

Antusch, Hinze, Saad, Steiner, 2307.04595

SUSY SO(10)可提升B-L破缺能标

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

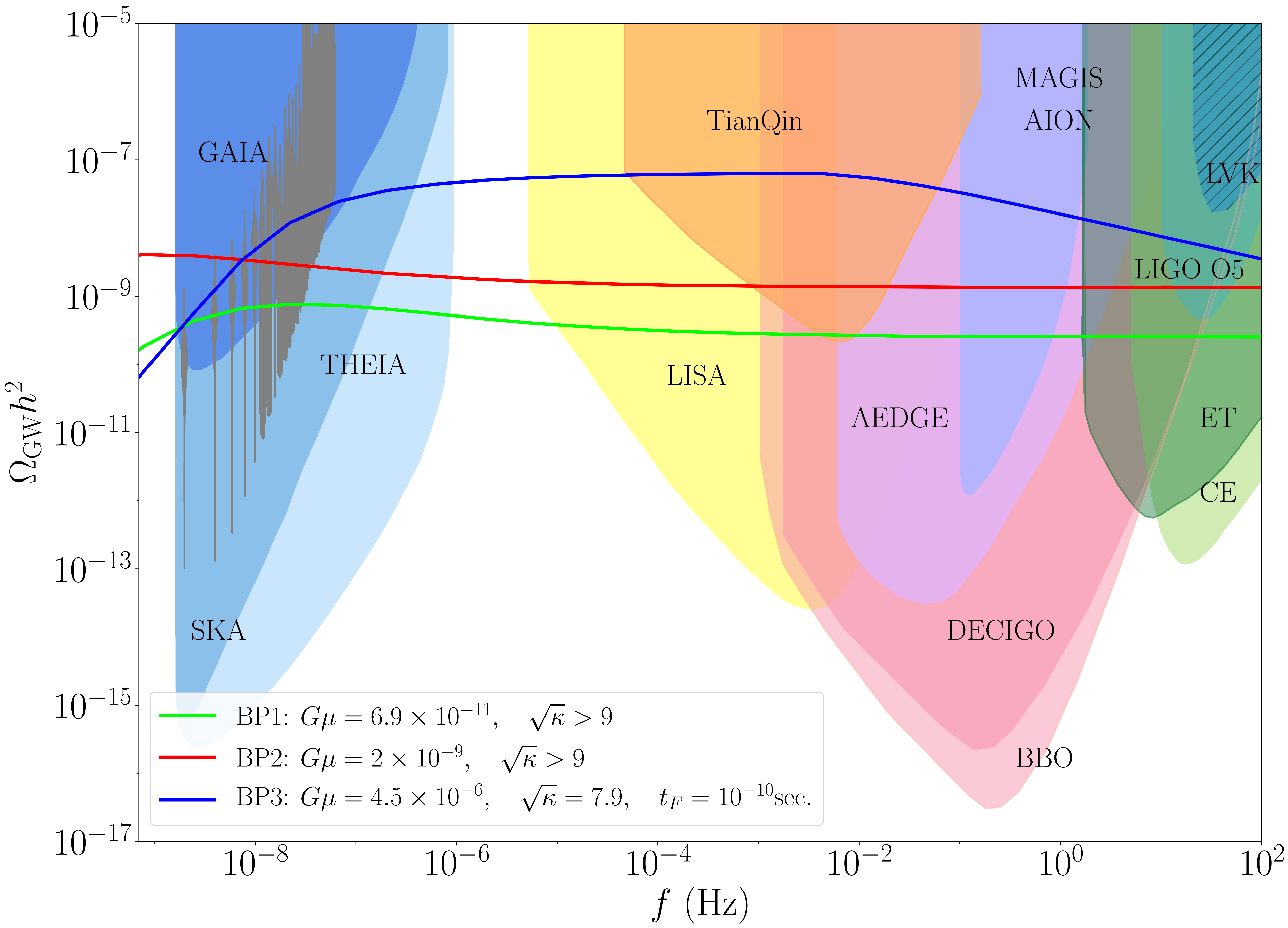




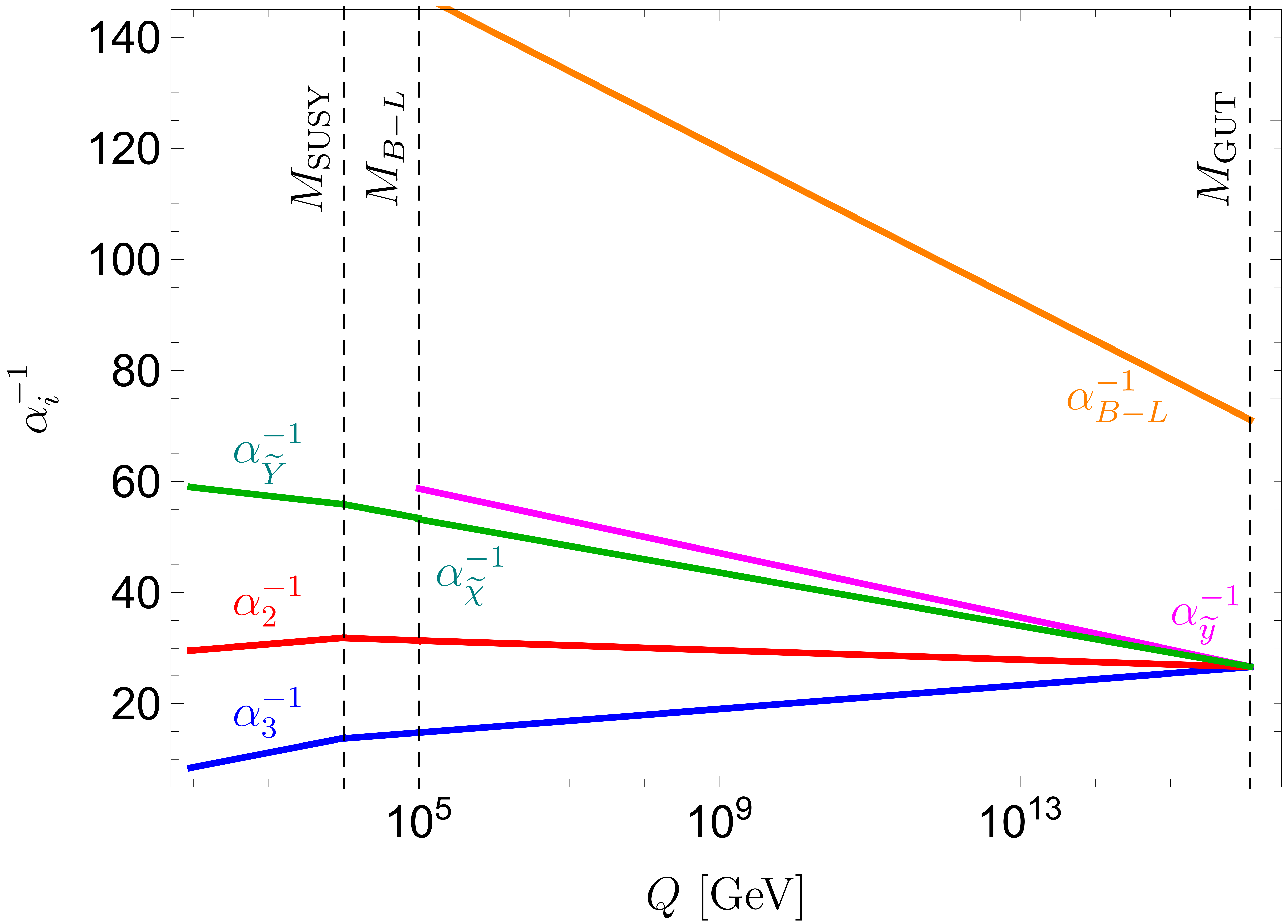
Fu, King, Marsili, Pascoli, Turner, **YLZ**, 2308.05799

SUSY SO(10) 用于解释 NANOGrav15 的数据？

可以，
但是更多的唯象学
限制需要考虑进来



另一类大统一模型：flipped SU(5)



$$G_{51}^{\rm flip,S} \equiv SU(5)\times U(1)_\chi \times \mathrm{SUSY}$$

$$(\mathbf{24},0)\ \Big\downarrow\ \text{broken at } M_{\rm GUT}$$

$$G_{3211}^{\rm S} \equiv SU(3)_c\times SU(2)_L\times U(1)_y\times U(1)_\chi\times \mathrm{SUSY}$$

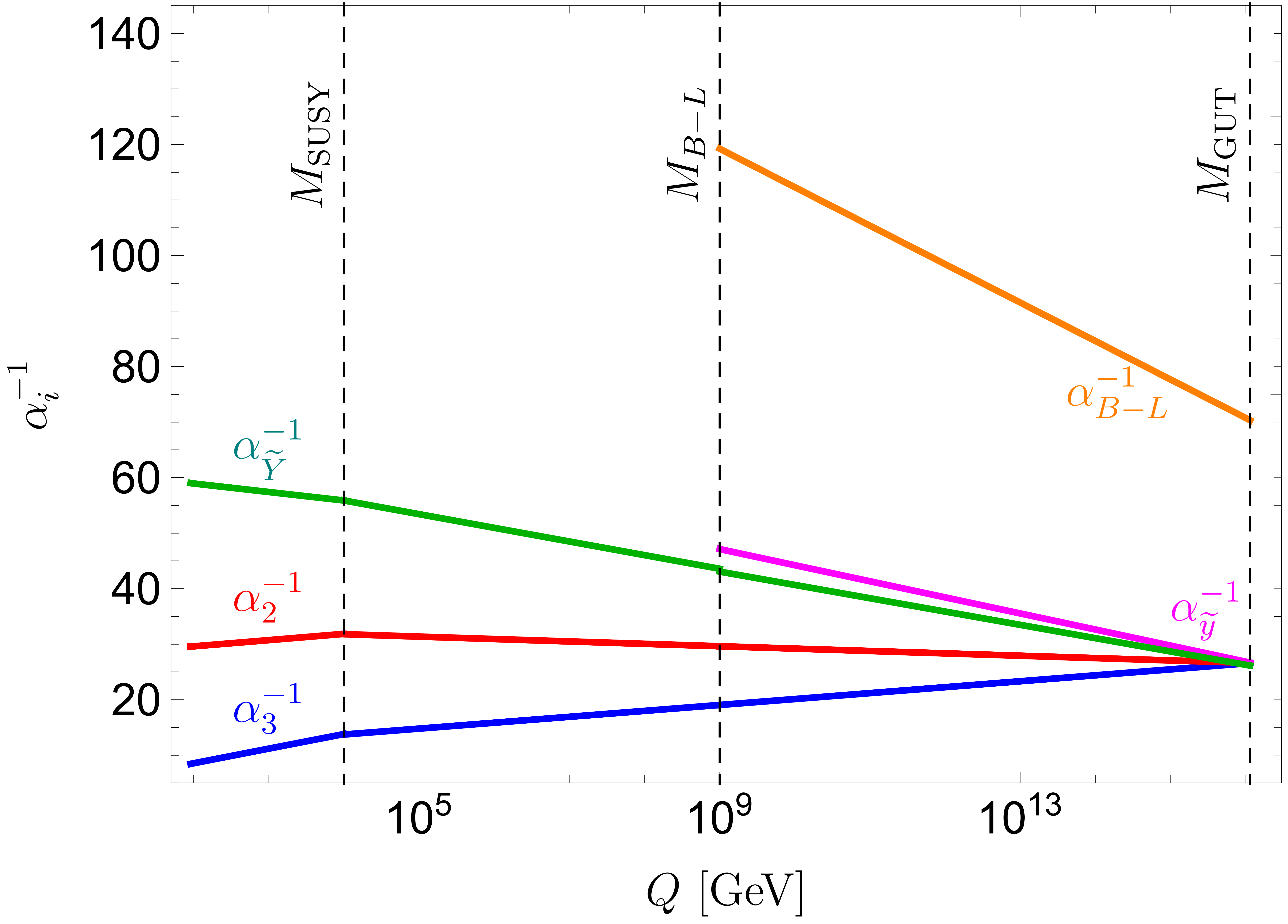
$$(\overline{\mathbf{10}},-\tfrac{1}{2})\supset(\mathbf{1},\mathbf{1},1,-\tfrac{1}{2})\ \Big\downarrow\ \text{broken at } M_{B-L}$$

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

$$\Big\downarrow$$

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

另一类大统一模型：flipped SU(5)



$$G_{51}^{\text{flip,S}} \equiv SU(5)\times U(1)_\chi \times \text{SUSY}$$

$$(\mathbf{24},0)\big\downarrow \text{ broken at } M_{\text{GUT}}$$

$$G_{3211}^{\text{S}} \equiv SU(3)_c\times SU(2)_L\times U(1)_y\times U(1)_\chi \times \text{SUSY}$$

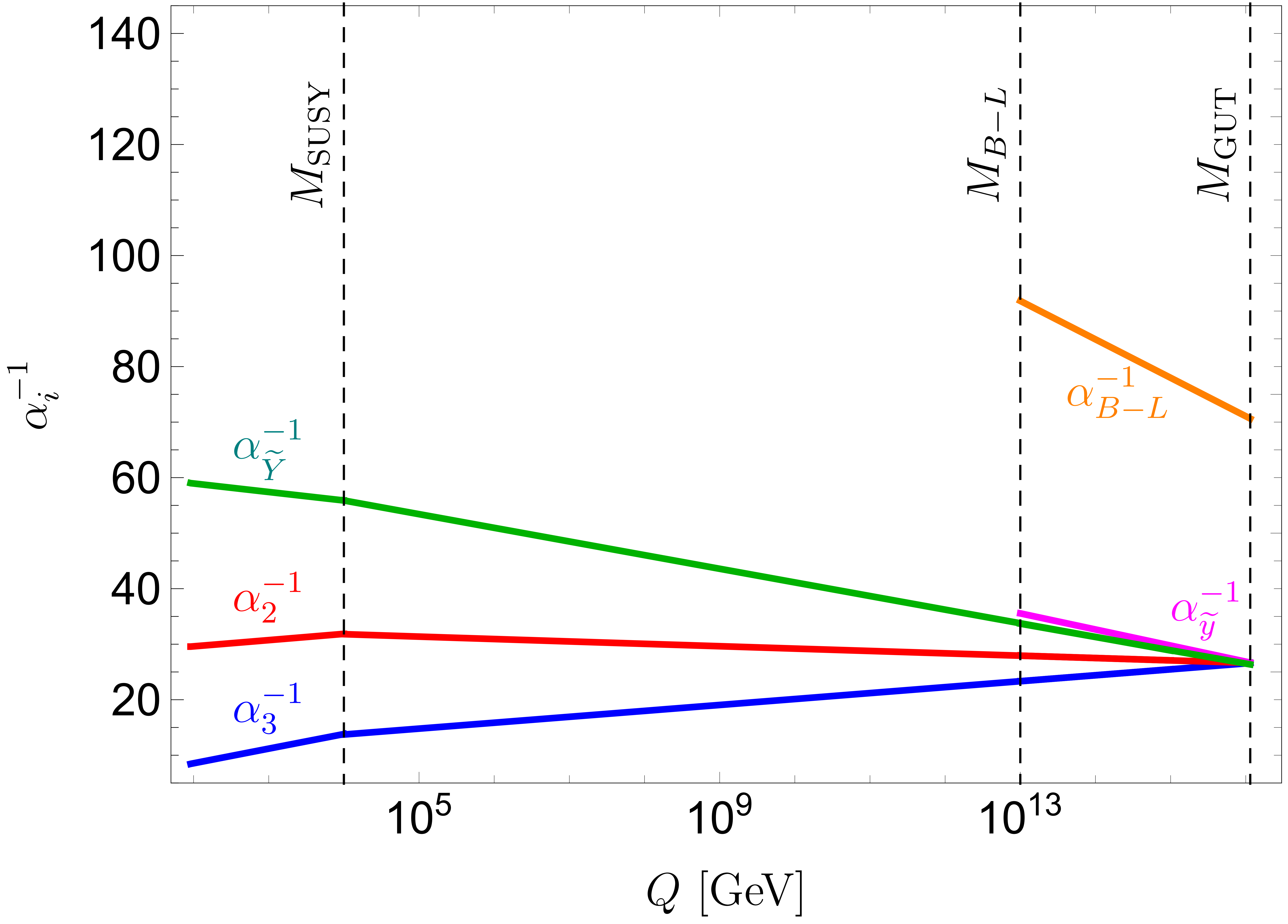
$$(\overline{\mathbf{10}},-\tfrac{1}{2})\supset(\mathbf{1},\mathbf{1},1,-\tfrac{1}{2})\big\downarrow \text{ broken at } M_{B-L}$$

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

$$\downarrow$$

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

另一类大统一模型：flipped SU(5)



$$G_{51}^{\rm flip,S} \equiv SU(5) \times U(1)_\chi \times \rm SUSY$$

$$(\mathbf{24}, 0) \downarrow \text{broken at } M_{\rm GUT}$$

$$G_{3211}^{\rm S} \equiv SU(3)_c \times SU(2)_L \times U(1)_y \times U(1)_\chi \times \rm SUSY$$

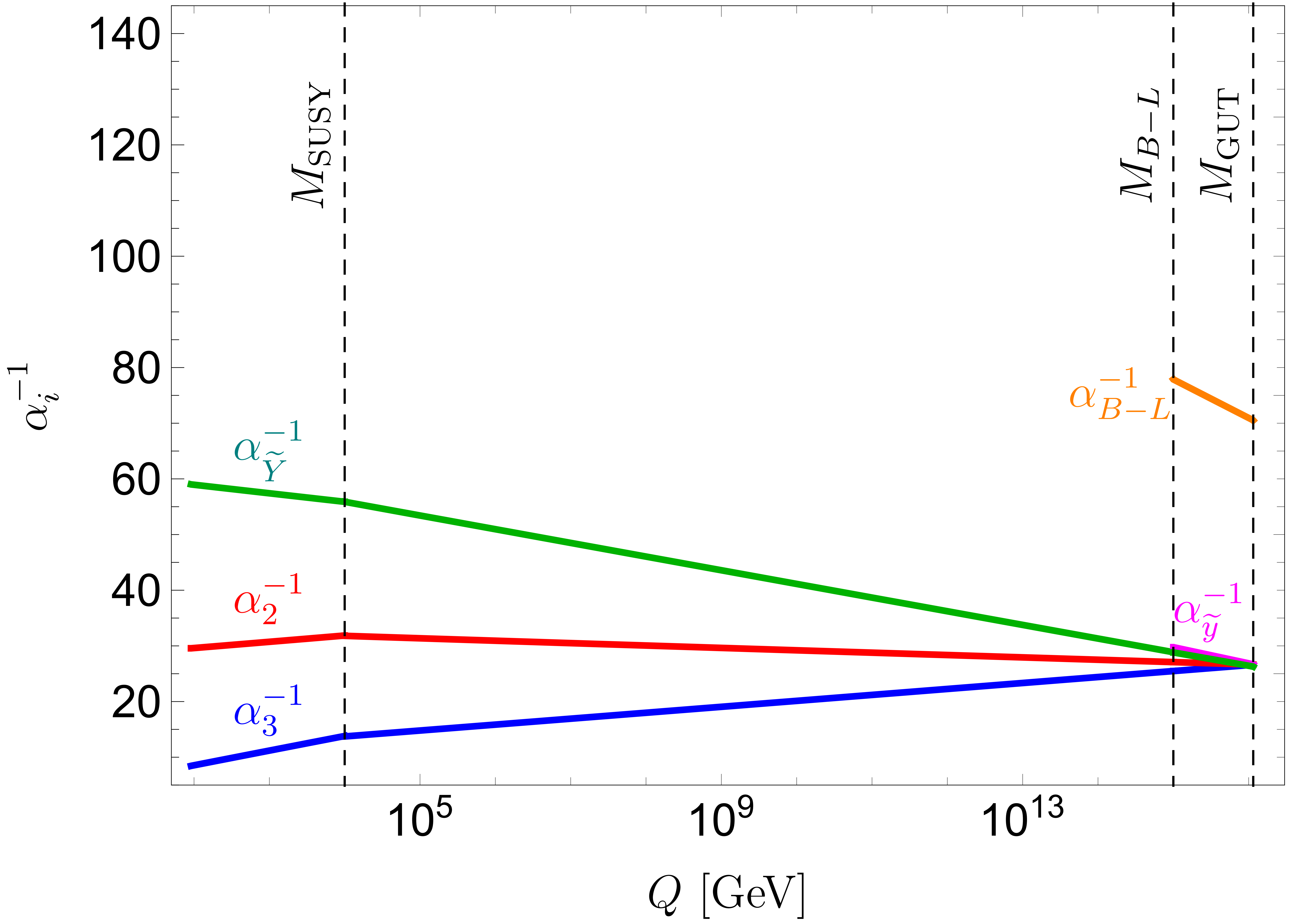
$$(\overline{\mathbf{10}}, -\tfrac{1}{2}) \supset (\mathbf{1}, \mathbf{1}, 1, -\tfrac{1}{2}) \downarrow \text{broken at } M_{B-L}$$

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

$$\downarrow$$

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

另一类大统一模型：flipped SU(5)



$$G_{51}^{\rm flip,S} \equiv SU(5) \times U(1)_\chi \times {\rm SUSY}$$

$$(\mathbf{24}, 0) \downarrow \text{ broken at } M_{\rm GUT}$$

$$G_{3211}^{\rm S} \equiv SU(3)_c \times SU(2)_L \times U(1)_y \times U(1)_\chi \times {\rm SUSY}$$

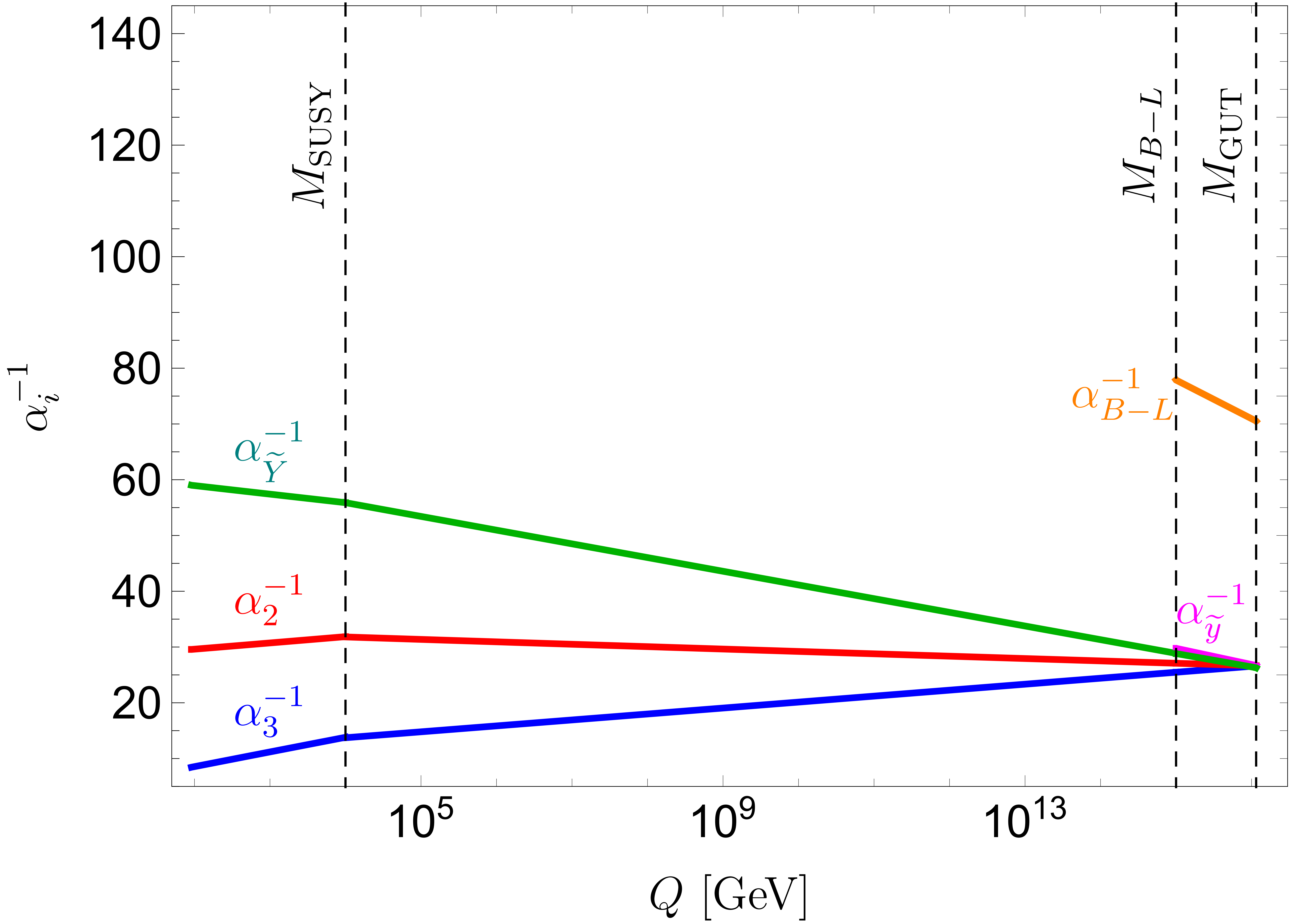
$$(\overline{\mathbf{10}}, -\tfrac{1}{2}) \supset (\mathbf{1}, \mathbf{1}, 1, -\tfrac{1}{2}) \downarrow \text{ broken at } M_{B-L}$$

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

$$\downarrow$$

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

另一类大统一模型：flipped SU(5)



$$G_{51}^{\rm flip,S} \equiv SU(5)\times U(1)_\chi \times \text{SUSY}$$

$$(\mathbf{24},0)\ \Big\downarrow\ \text{broken at } M_{\rm GUT}$$

$$G_{3211}^{\rm S} \equiv SU(3)_c\times SU(2)_L\times U(1)_y\times U(1)_\chi\times \text{SUSY}$$

$$(\overline{\mathbf{10}},-\tfrac{1}{2})\supset(\mathbf{1},\mathbf{1},1,-\tfrac{1}{2})\ \Big\downarrow\ \text{broken at } M_{B-L}$$

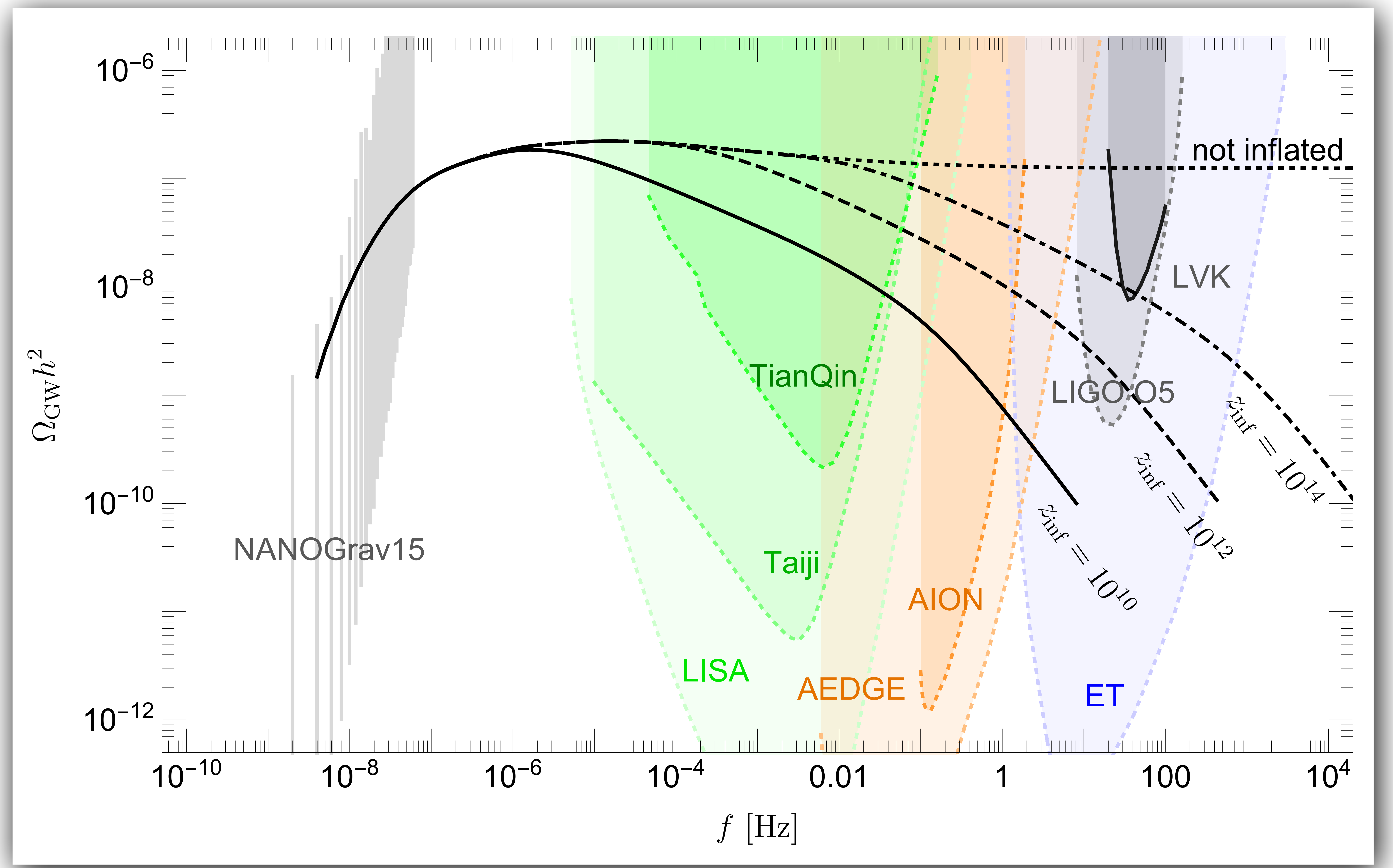
$$G_{\rm MSSM}\equiv SU(3)_c\times SU(2)_L\times U(1)_Y\times \text{SUSY}\,,$$

$$\downarrow$$

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

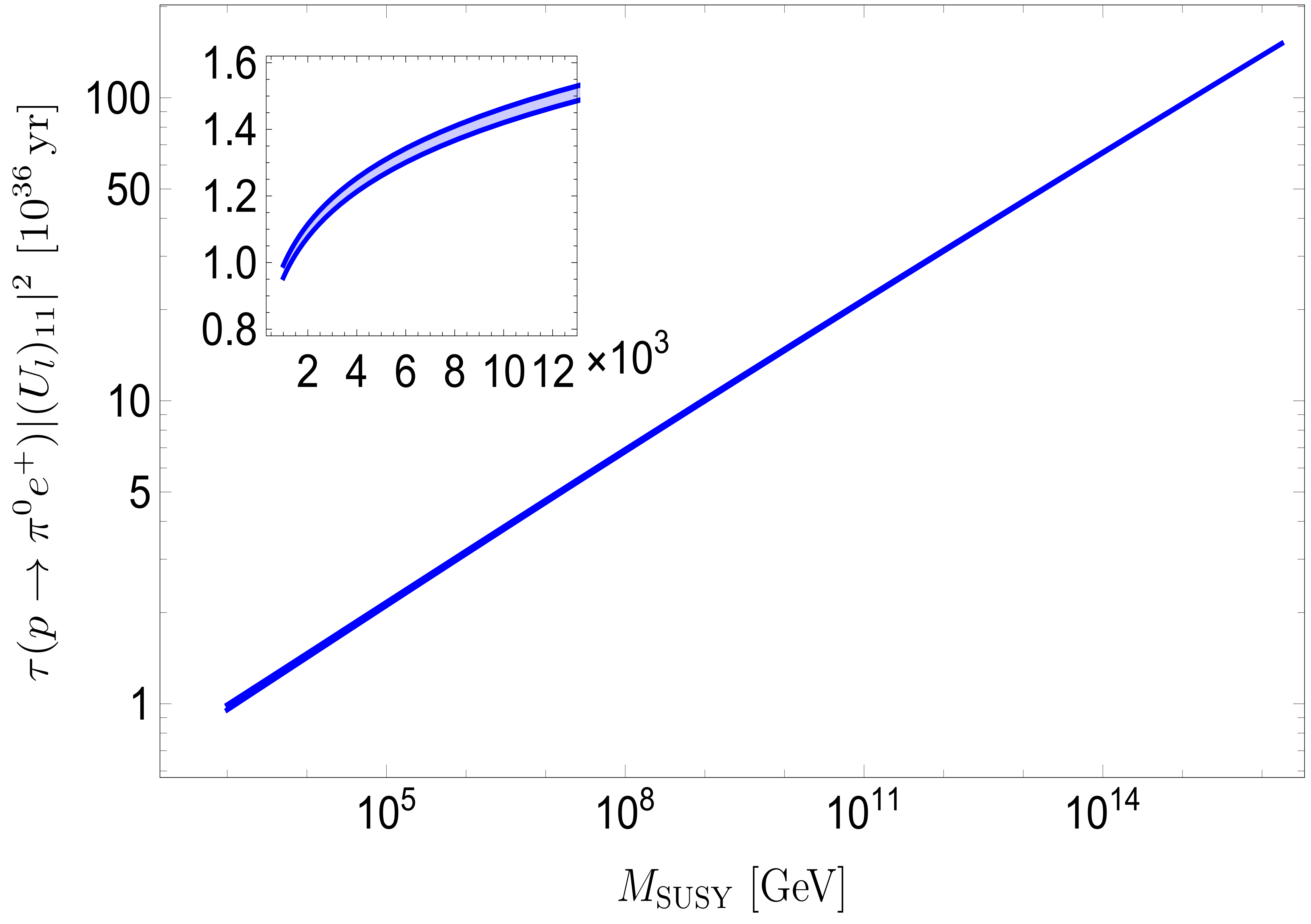
B-L能标可以很自然
得趋近于大统一能标

另一类大统一模型：flipped SU(5)

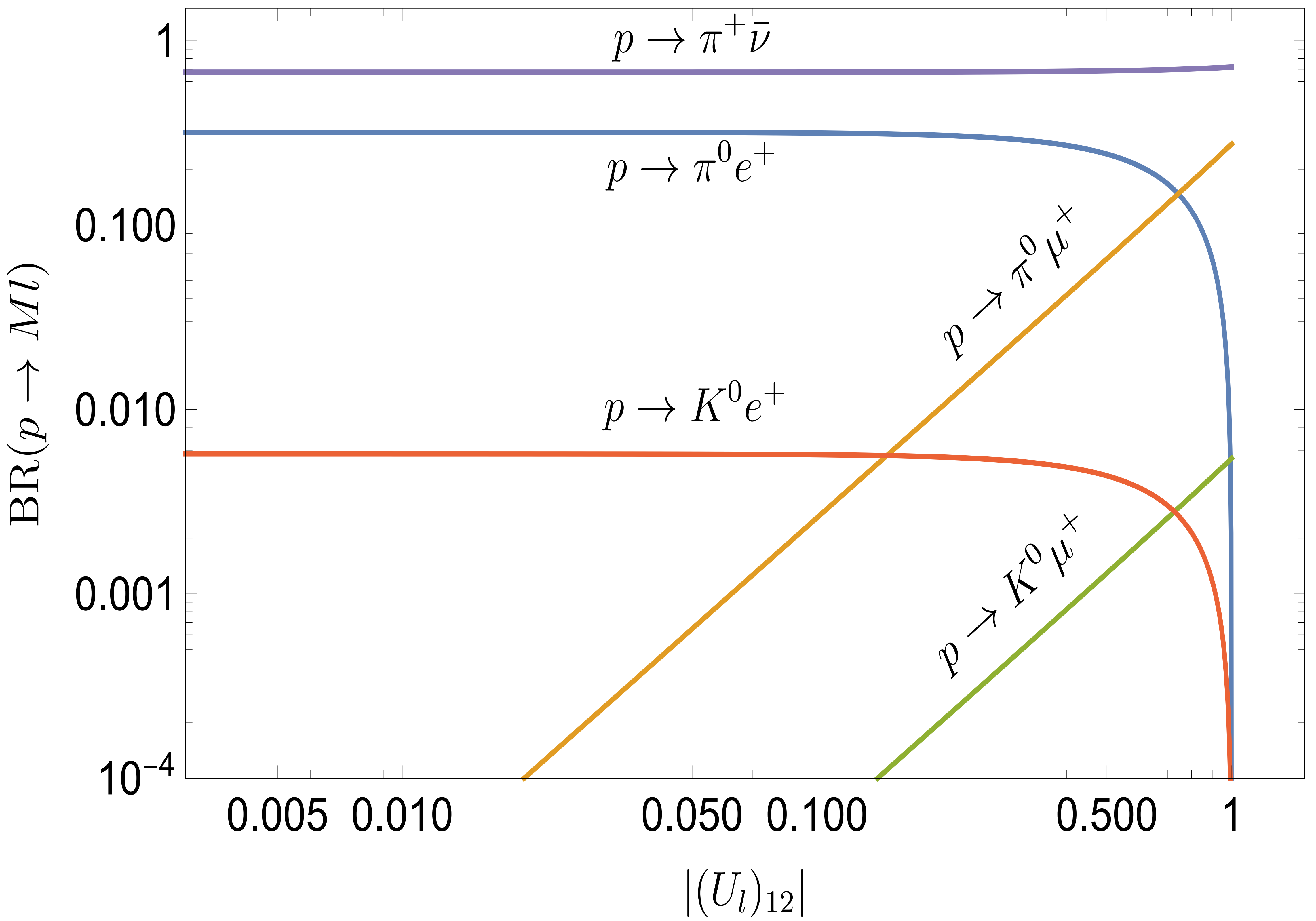


GWs in flipped SU(5)
King, Leontaris, **YLZ**,
2311.11857

另一类大统一模型：flipped SU(5)

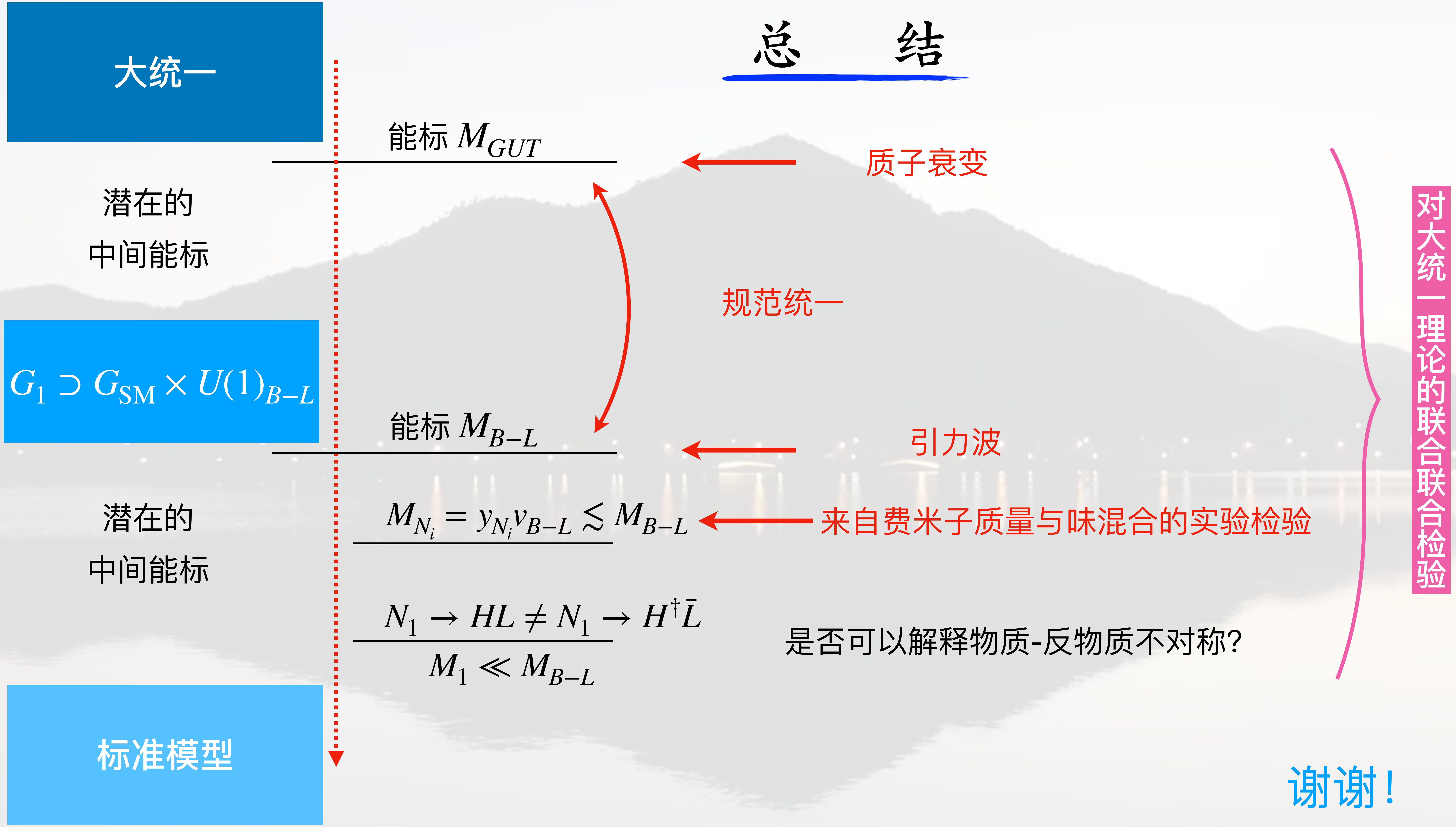


$BR(p \to K^+\bar{\nu}) \to 0$



这么长的质子寿命超出了下一代质子寿命的检测范围

总　结



大统一
能标 M_{GUT}
潜在的
中间能标
$G_1 \supset G_{SM} \times U(1)_{B-L}$
能标 M_{B-L}
潜在的
中间能标
$M_{N_i} = y_{N_i} v_{B-L} \lesssim M_{B-L}$
$N_1 \to HL \neq N_1 \to H^\dagger \bar{L}$
$M_1 \ll M_{B-L}$
标准模型
质子衰变
规范统一
引力波
来自费米子质量与味混合的实验检验
是否可以解释物质-反物质不对称?
对大统一理论的联合联合检验

谢谢!