中国科学技术大学 交叉学科理论研究中心
Interdisciplinary Center for Theoretical Study

[English Version]

# Secondary but more fascinating phenomenology in the next-generation large-scale neutrino experiments

Ye-Ling Zhou (HIAS) 2023-12-7

國科大杭州高等研究院
Hangzhou Institute for Advanced Study,UCAS

基础物理与数学科学学院
School of Fundamental Physics and Mathematical Sciences

# Some important neutrino experiments in the past

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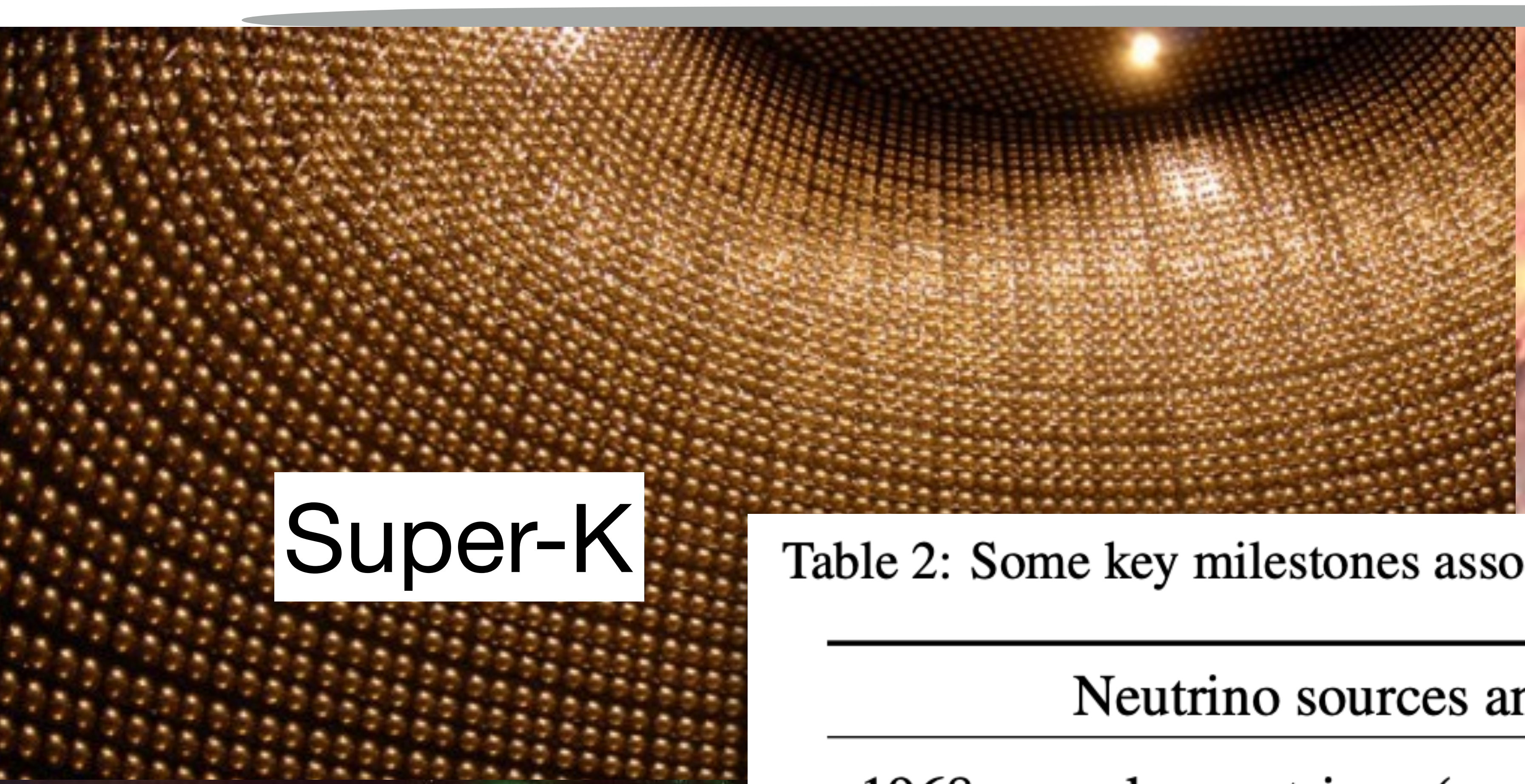
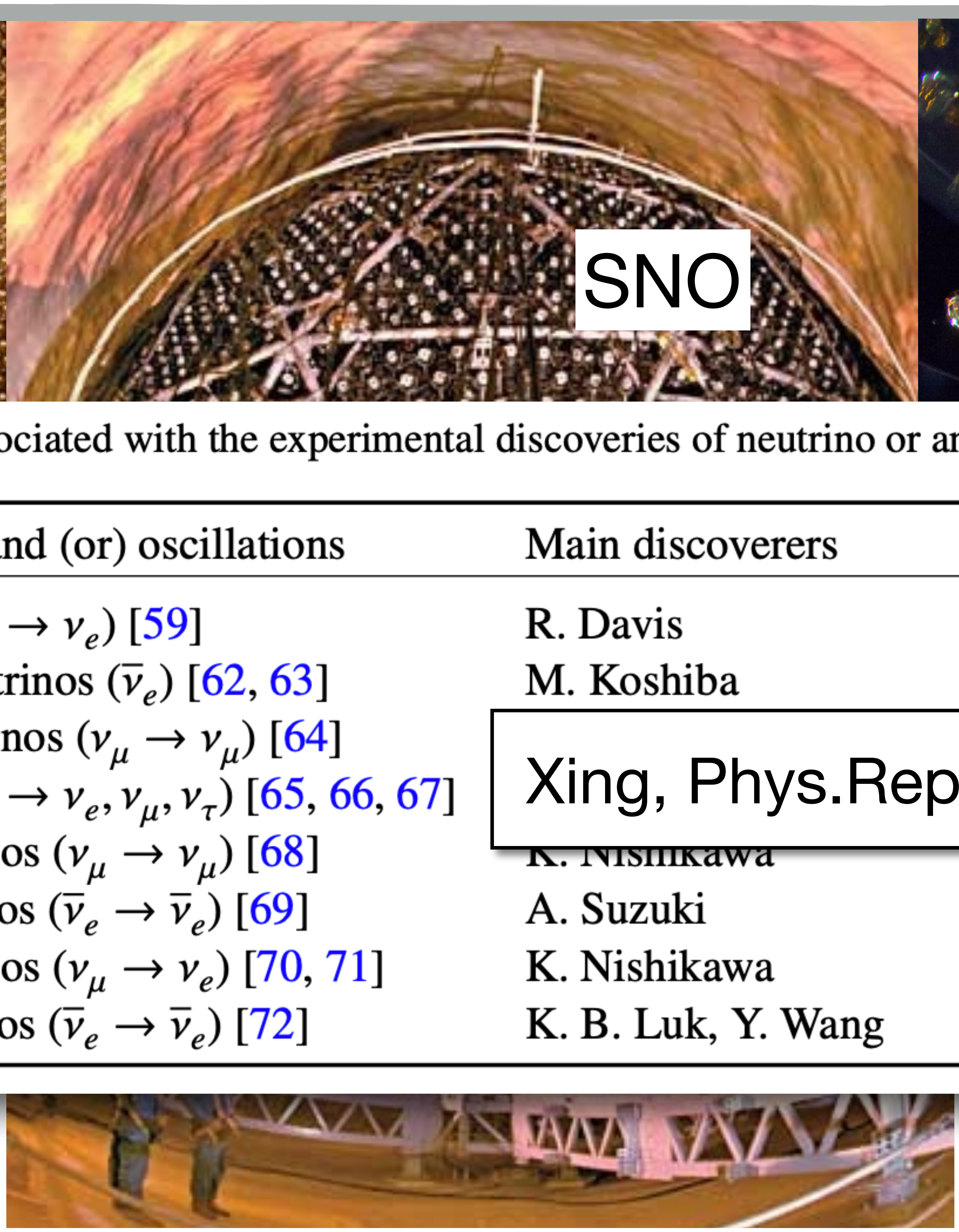
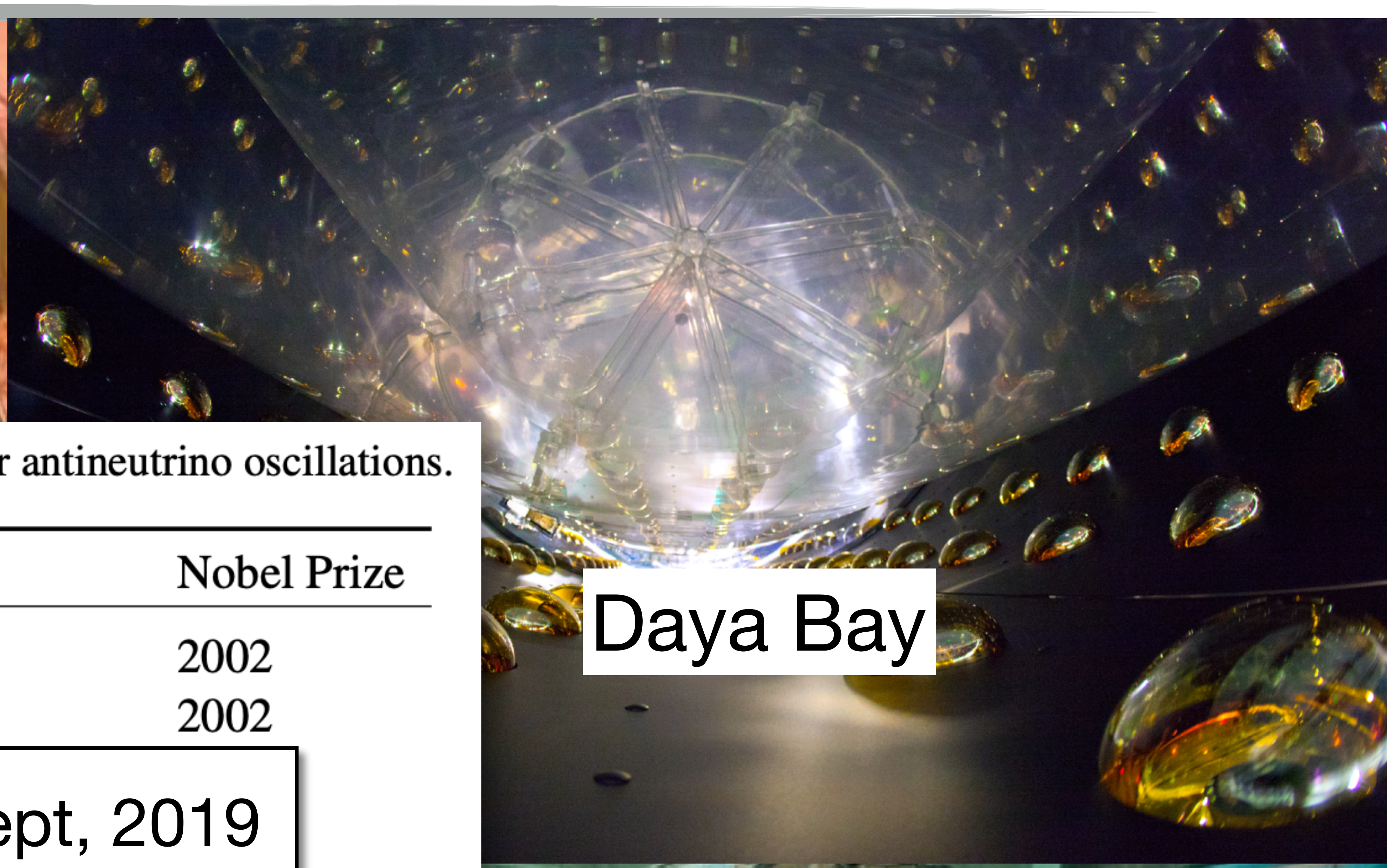
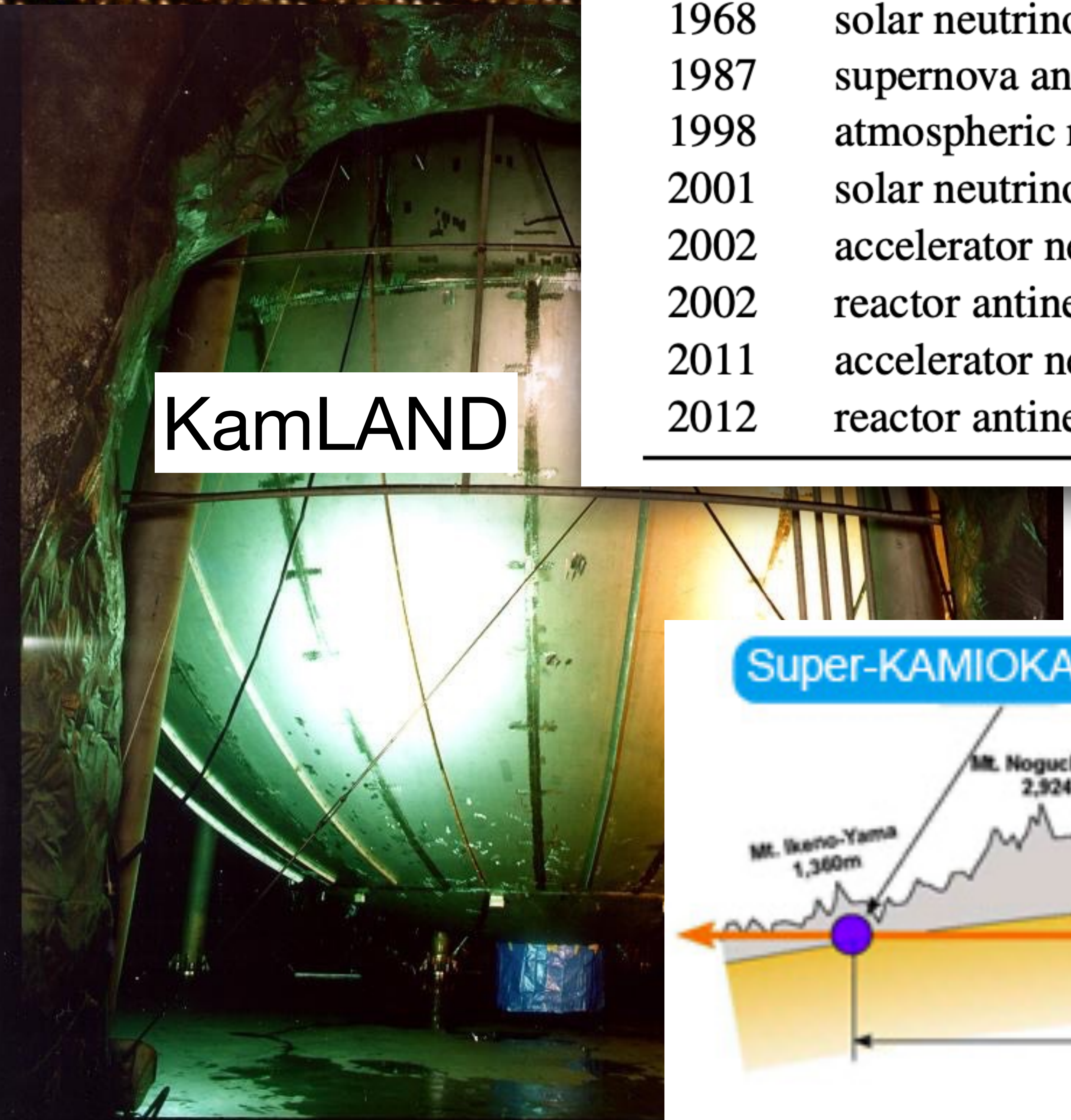
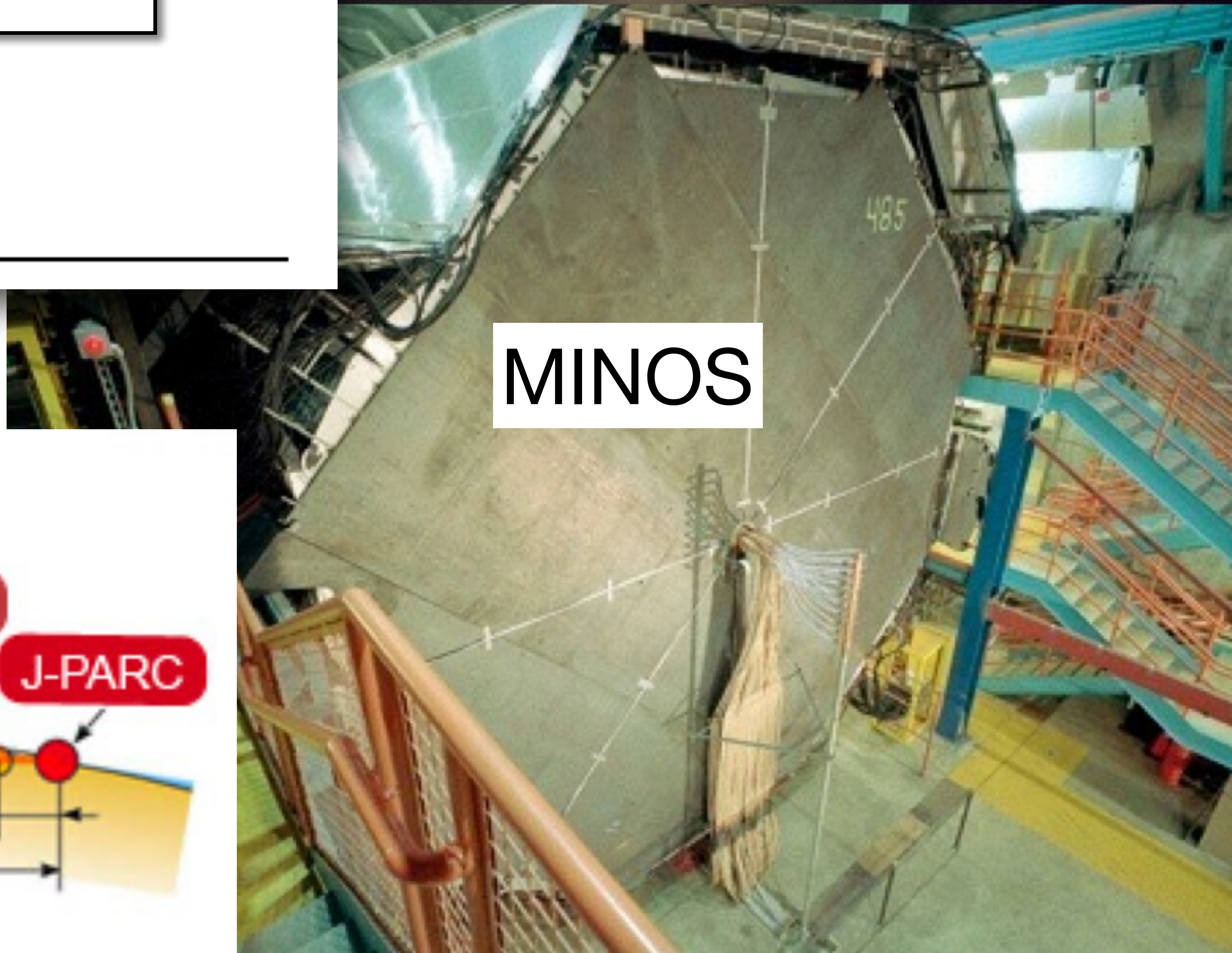


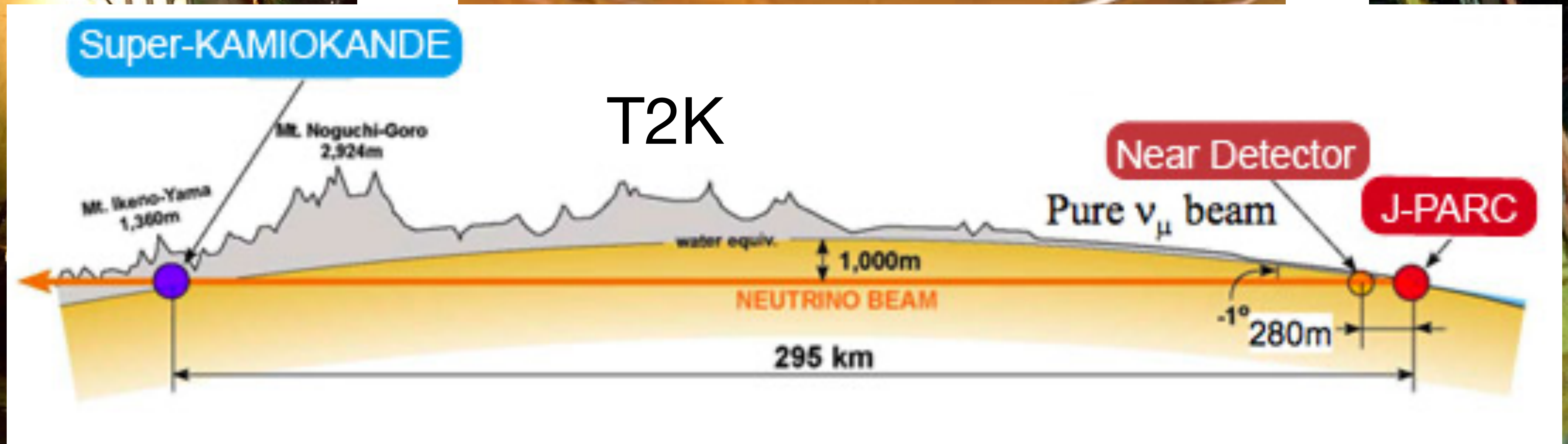




Table 2: Some key milestones associated with the experimental discoveries of neutrino or antineutrino oscillations.

| | Neutrino sources and (or) oscillations | Main discoverers | Nobel Prize |
|---|---|---|---|
| 1968 | solar neutrinos ($\nu_e \to \nu_e$) [59] | R. Davis | 2002 |
| 1987 | supernova antineutrinos ($\overline{\nu}_e$) [62, 63] | M. Koshiba | 2002 |
| 1998 | atmospheric neutrinos ($\nu_\mu \to \nu_\mu$) [64] | | |
| 2001 | solar neutrinos ($\nu_e \to \nu_e, \nu_\mu, \nu_\tau$) [65, 66, 67] | | |
| 2002 | accelerator neutrinos ($\nu_\mu \to \nu_\mu$) [68] | K. Nishikawa | |
| 2002 | reactor antineutrinos ($\overline{\nu}_e \to \overline{\nu}_e$) [69] | A. Suzuki | |
| 2011 | accelerator neutrinos ($\nu_\mu \to \nu_e$) [70, 71] | K. Nishikawa | |
| 2012 | reactor antineutrinos ($\overline{\nu}_e \to \overline{\nu}_e$) [72] | K. B. Luk, Y. Wang | |

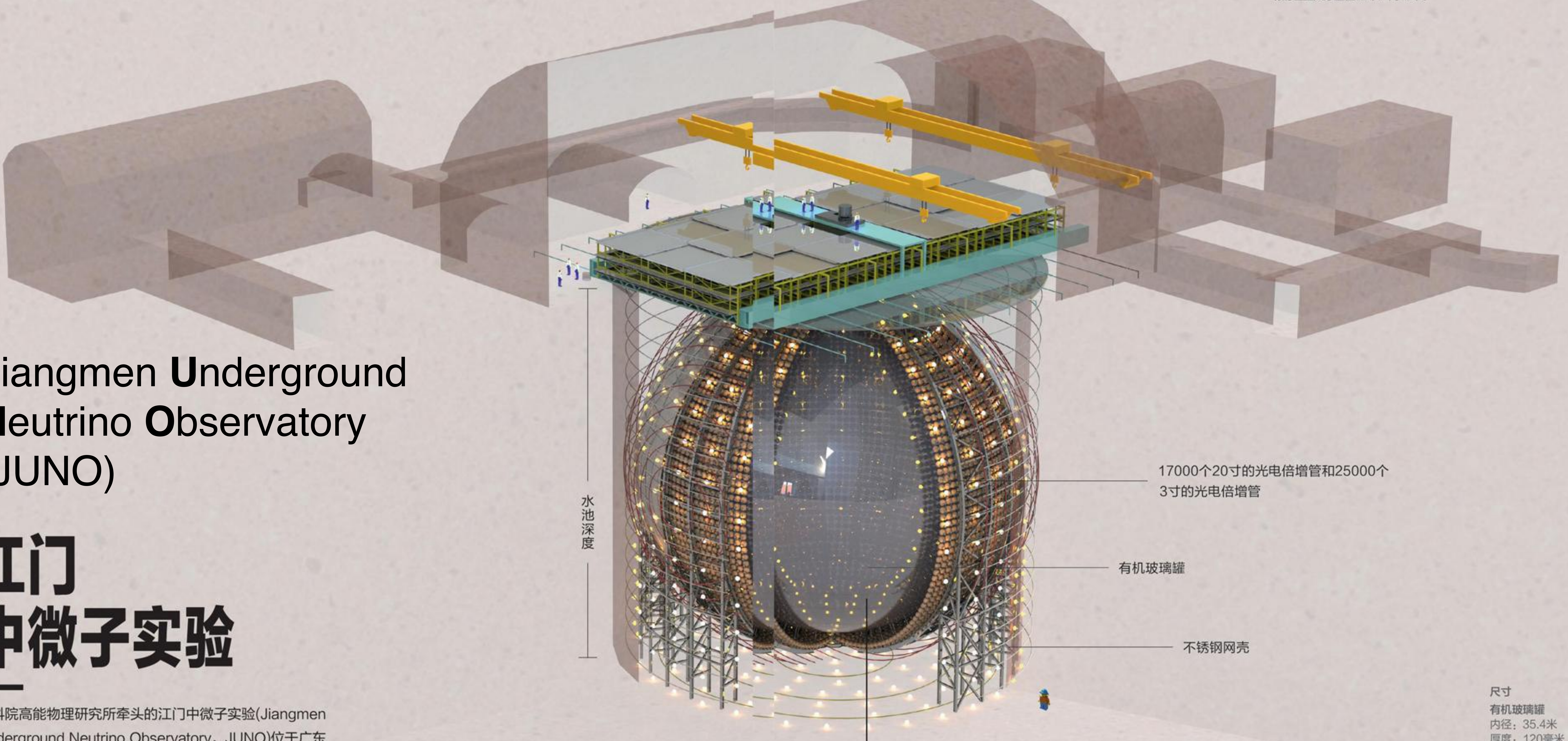
Xing, Phys.Rept, 2019

光，从而被光敏器件（光电倍增管）探测到。

切的巨型大厅直径50米、高70米。

# **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO)

# 江门中微子实验




中科院高能物理研究所牵头的江门中微子实验(Jiangmen Underground Neutrino Observatory，JUNO)位于广东江门市开平附近埋深700米的地下实验室内。通过测量来自广东阳江和台山核电站的中微子，实验可以来测定中微子质量顺序、精确测量中微子振荡，同时开展对超新星中微子、大气中微子、太阳中微子、地球中微子、惰性中微子、核子衰变、暗物质间接探测等前沿方向的研究。

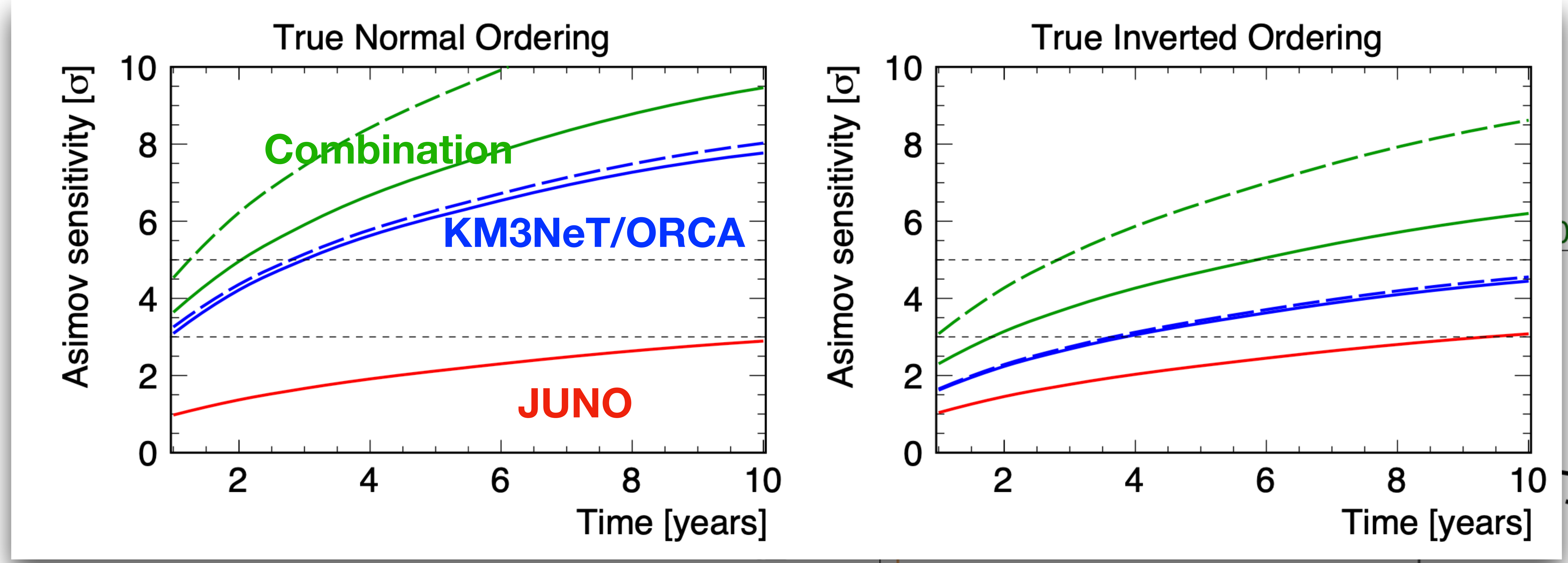
**尺寸**

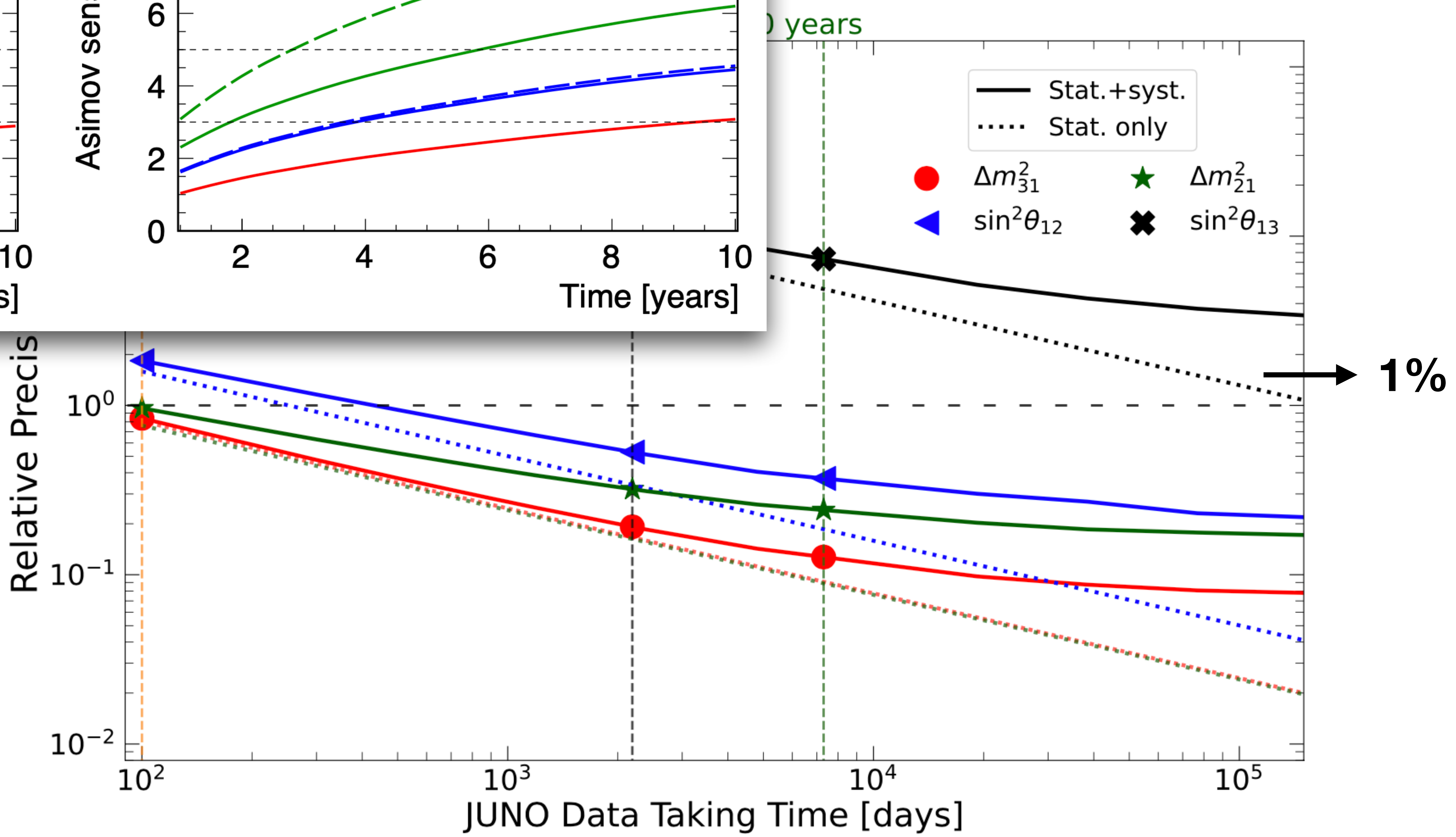
**有机玻璃罐**
内径：35.4米
厚度：120毫米

**不锈钢网壳**
内径：40.1米
外径：41.1米

**水池**
内径：43.5米
深度：44米
水深：43.5米

# JUNO



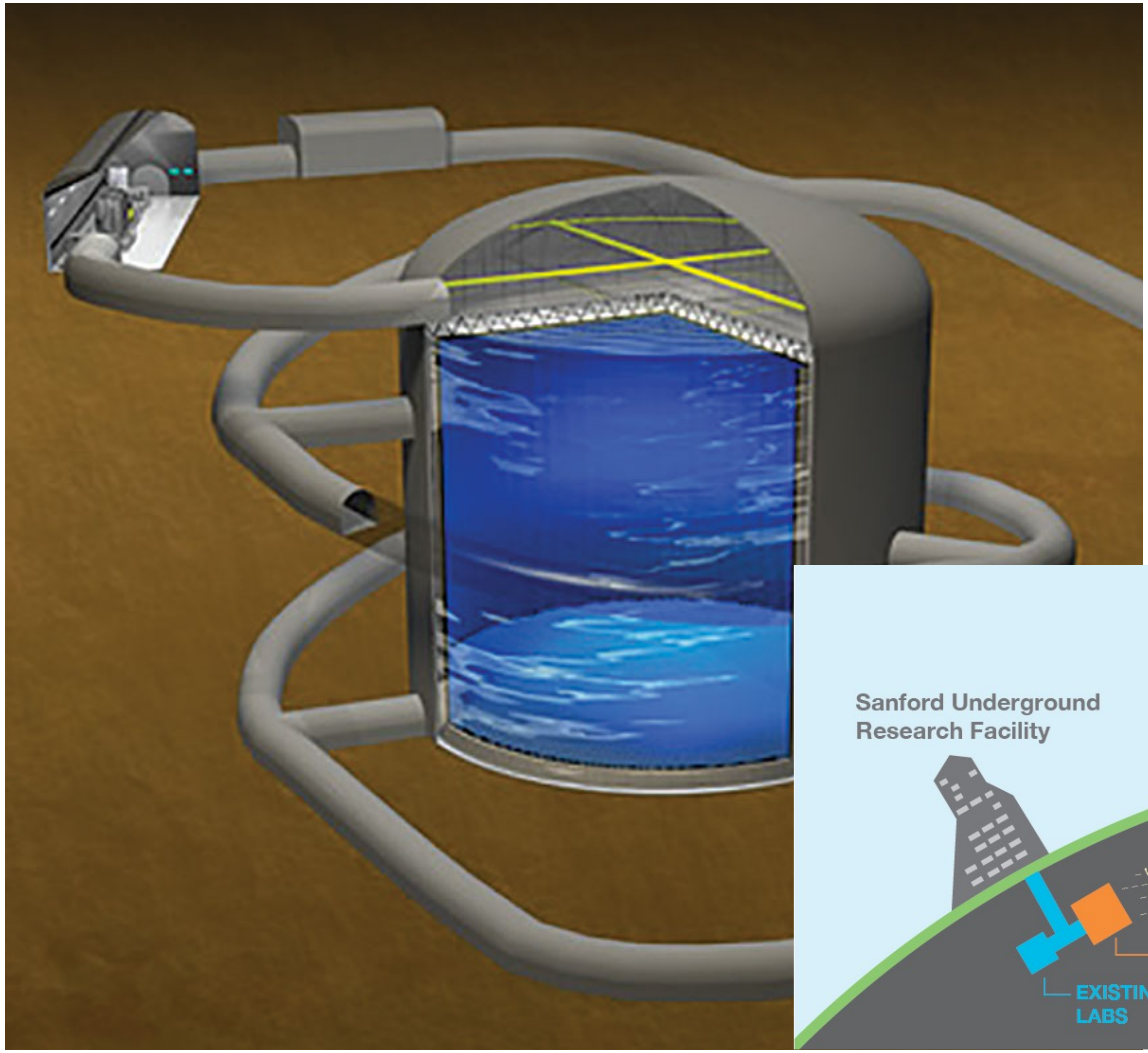




Mass Hierarchy determination,
state-of-art sensitivity performance

2108.06293

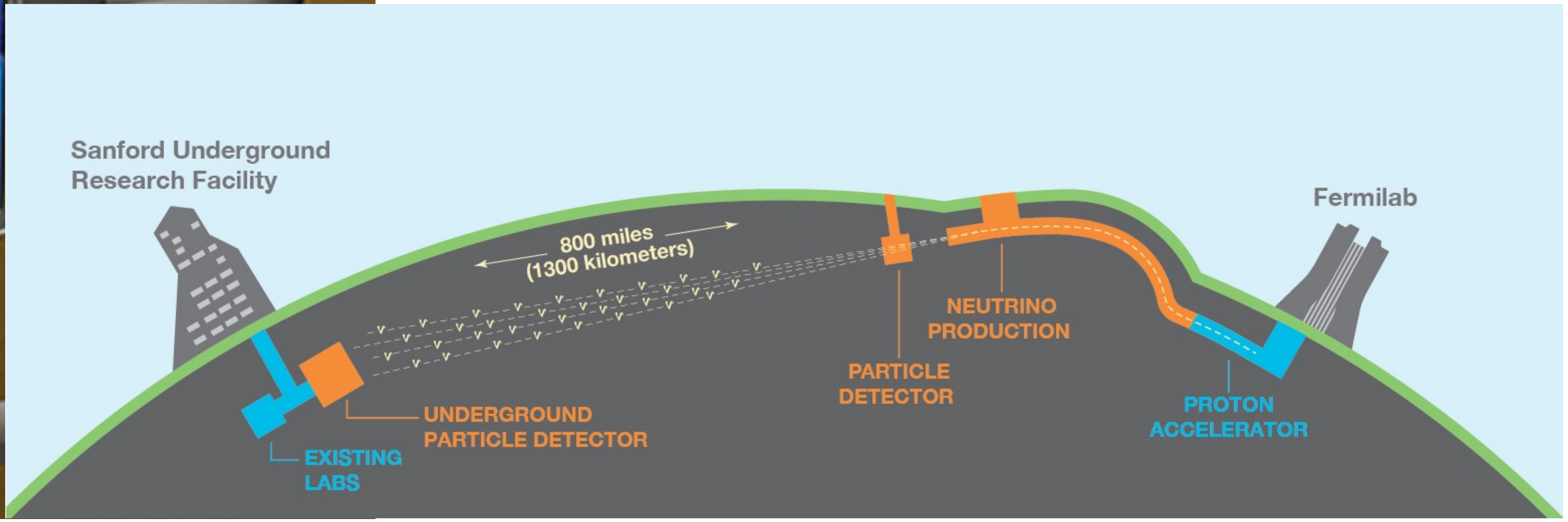
JUNO collaboration 2204.13249

# Hyper-K & DUNE



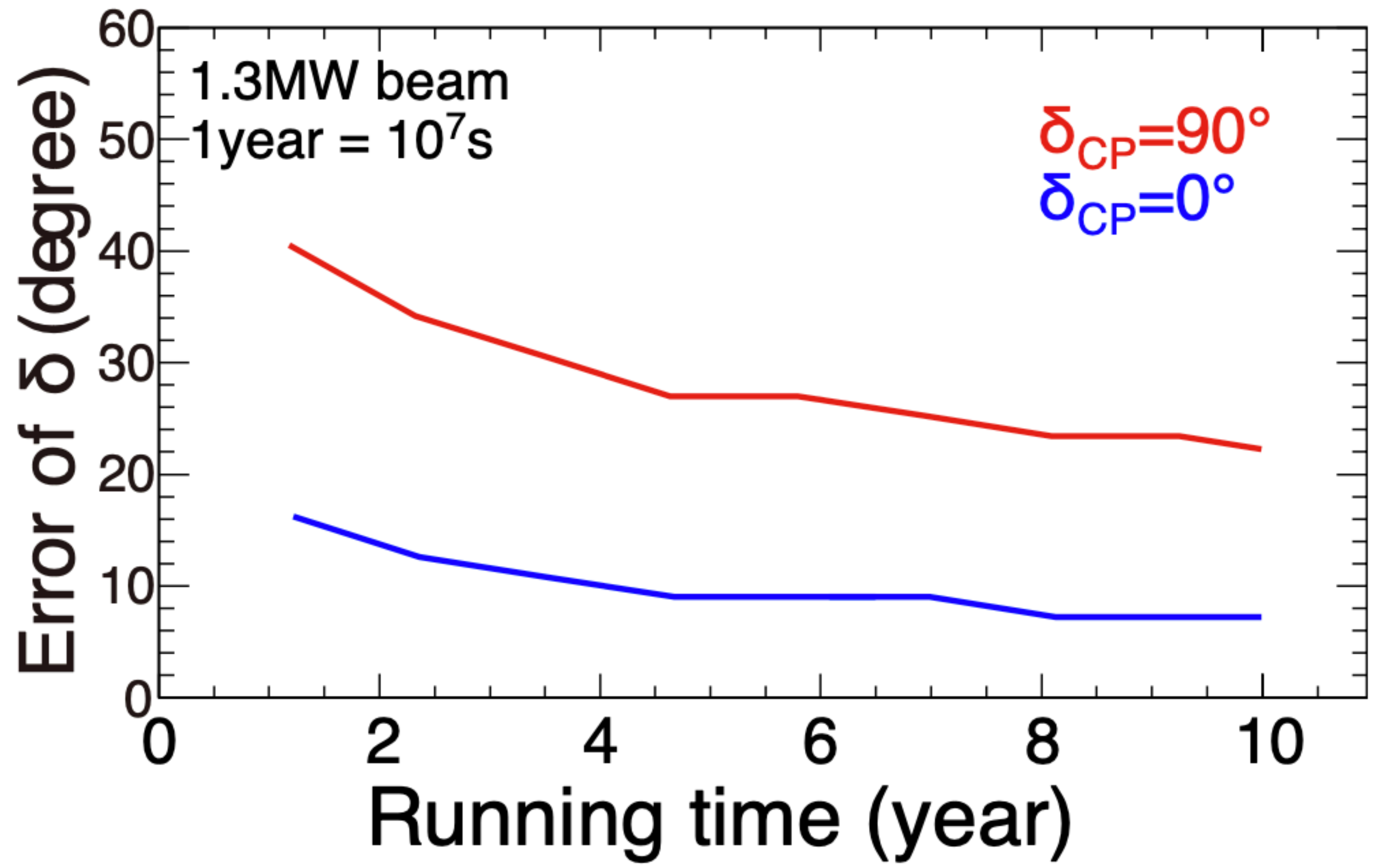
Hyper-K, 188kton FV, expected to run in 2027

DUNE, run in 2030?



# Hyper-K & DUNE

**Hyper-K**
**1805.04163**



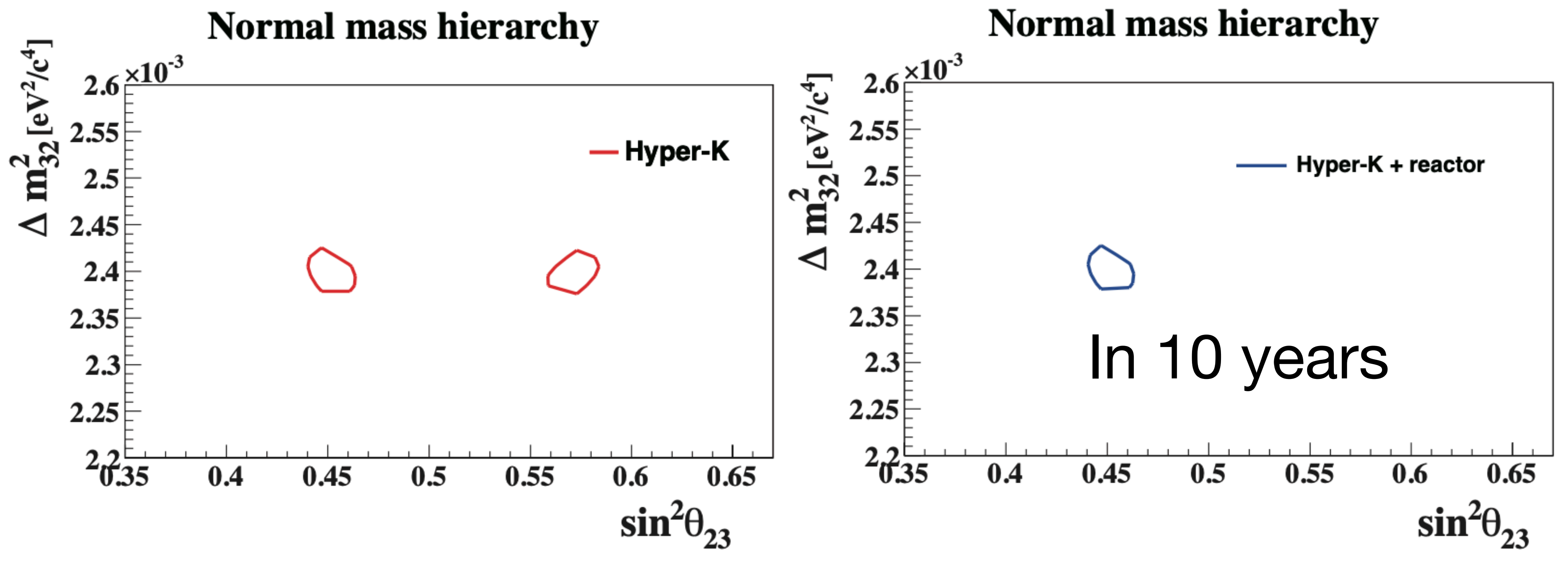
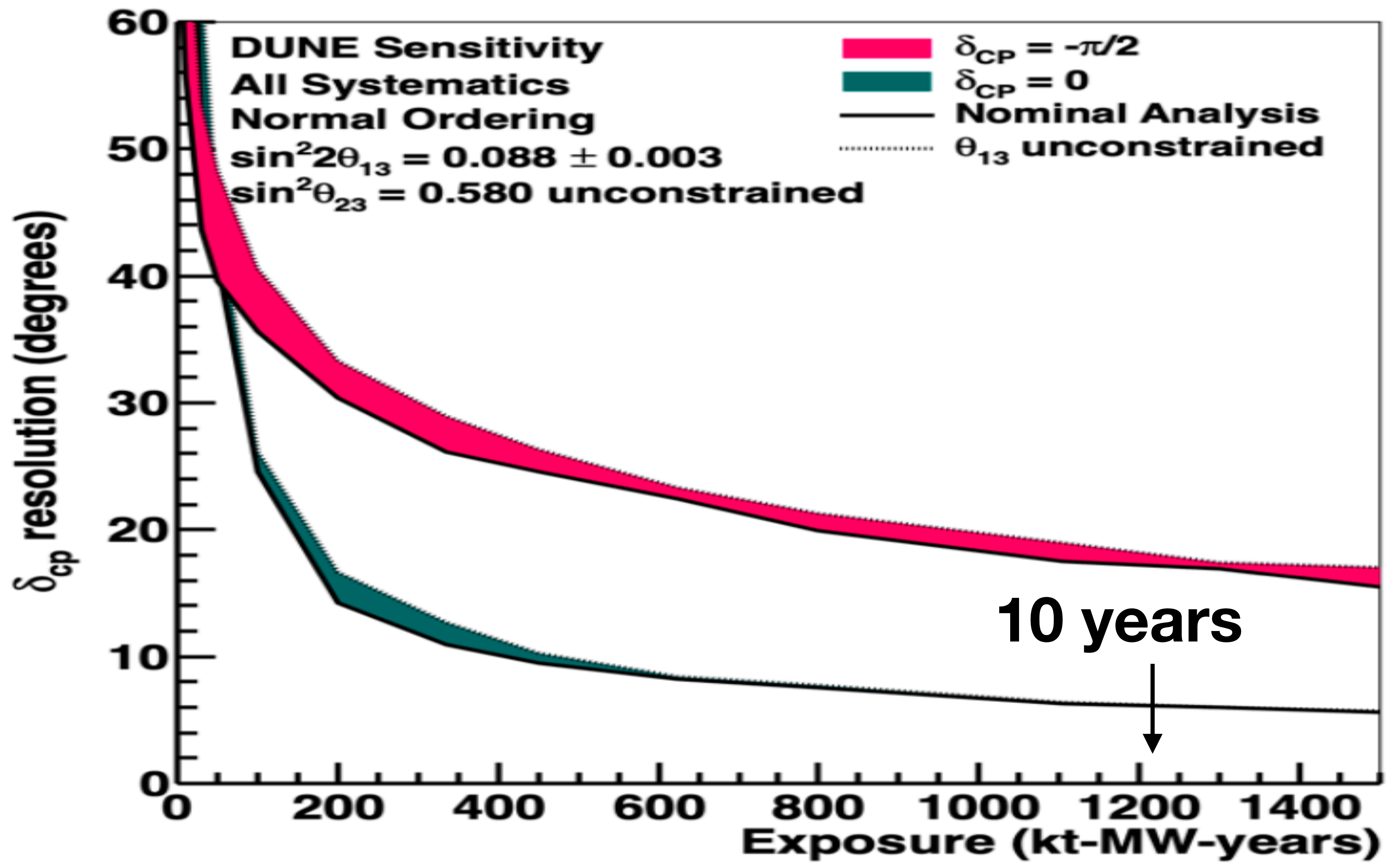
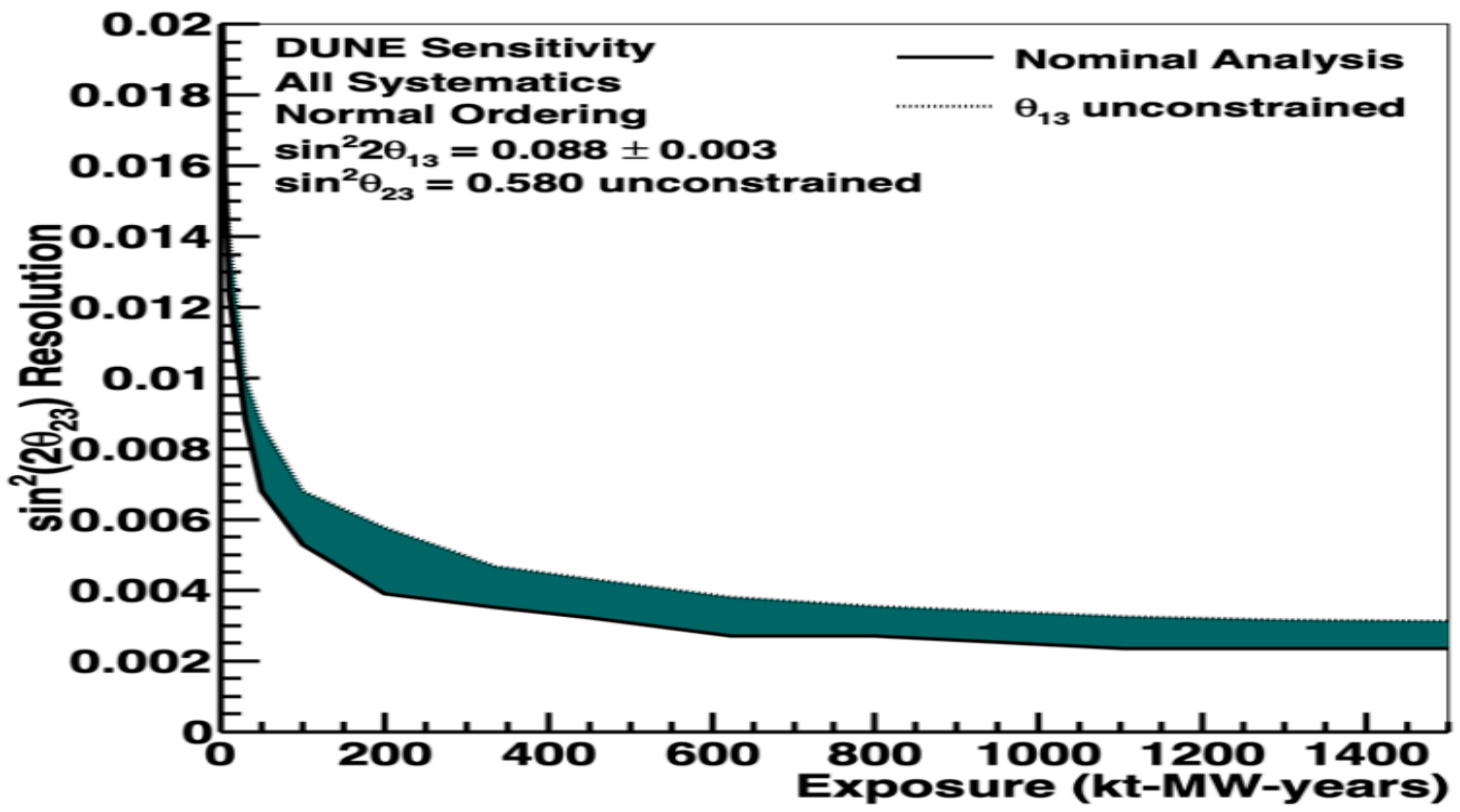




FIG. 144. 90% CL allowed regions in the $\sin^2\theta_{23}$–$\Delta m^2_{32}$ plane. The true values are $\sin^2\theta_{23} = 0.45$ and $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV$^2$. Effect of systematic uncertainties is included. Left: Hyper-K only. Right: With a reactor constraint.

**DUNE**
**2002.03005**



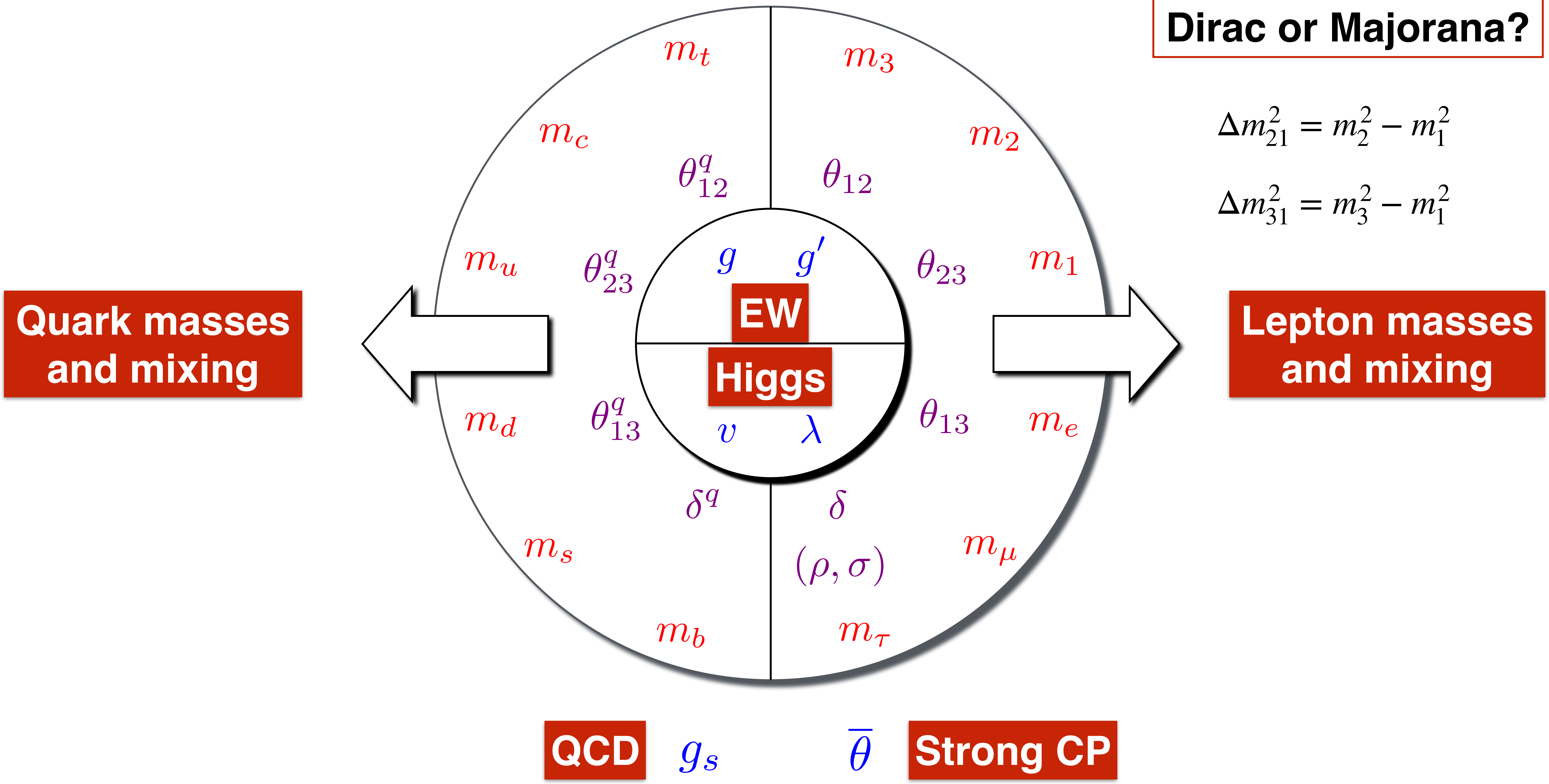
# SM+3 massive neutrinos

**24(26)+2 fundamental parameters**

**Neutrino Dirac or Majorana?**

$$\Delta m^2_{21} = m^2_2 - m^2_1$$

$$\Delta m^2_{31} = m^2_3 - m^2_1$$



We are entering an era of precision measurement of neutrino physics!

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It will give us a deeper understanding of neutrino masses and mixing!

Origin of neutrino masses, lepton mixing and CP violation

We are entering an era of precision measurement of neutrino physics!

It will give us a deeper understanding
...utron masses a... ...xing!

No, I do not want to talk about them

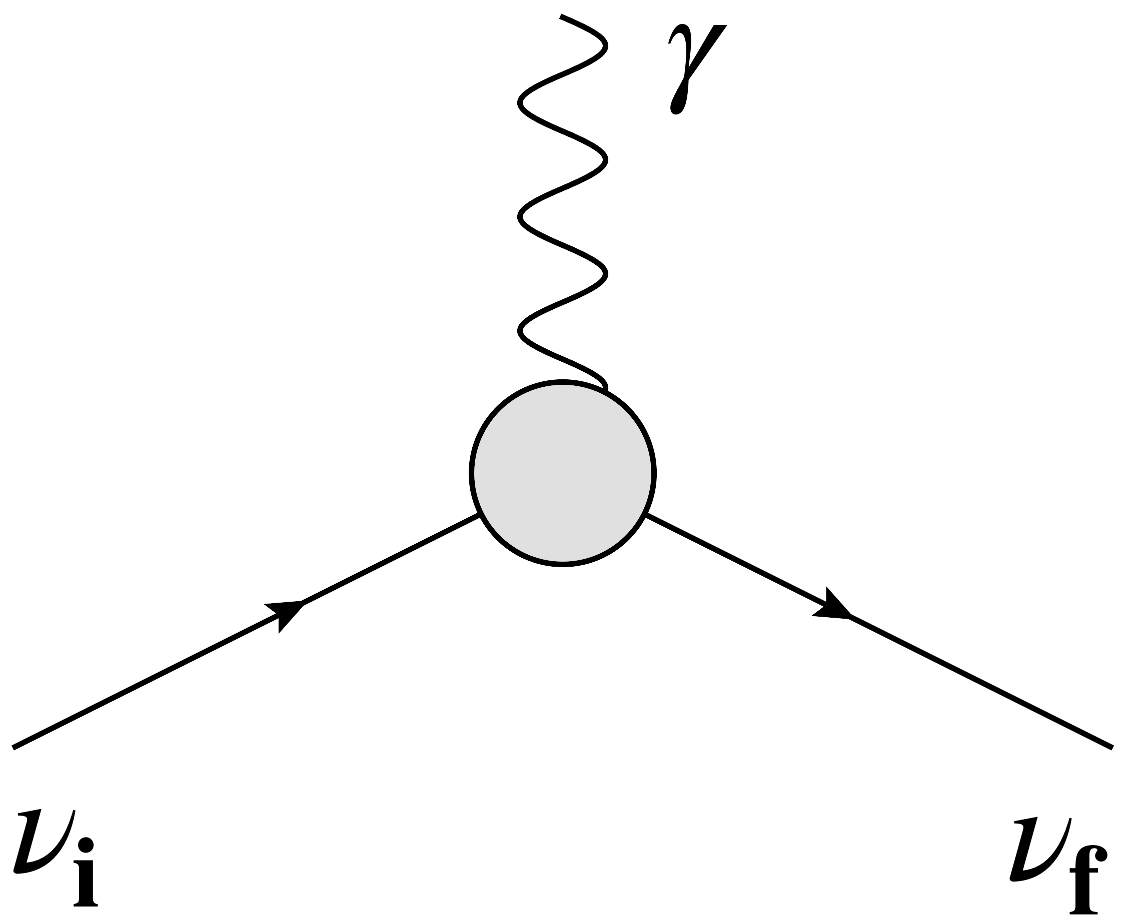
...of neutrino masses, lepton
mixing and CP violation

# Not primary, but more fascinating phenos

Neutrino electromagnetic property and CP-violating radiative decay

Proton decay and its probe to grand unified theories (GUT)

# Neutrino electromagnetic property and CP-violating radiative decay



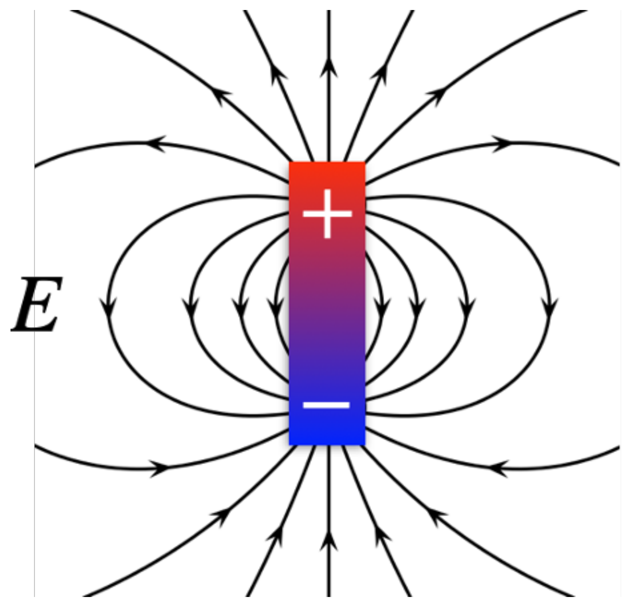

**i**: initial state

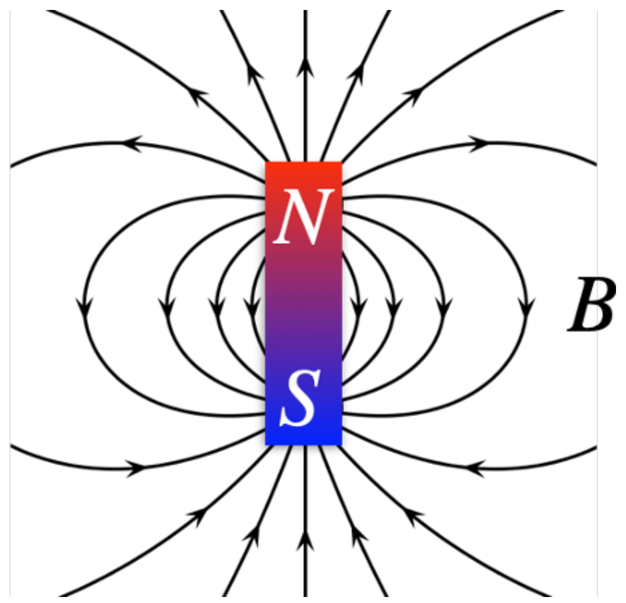
**f**: final state

# Neutrino electromagnetic dipole moment

- Neutral fermions may have electromagnetic dipole moment (EMDM)

electric dipole moment $d$




magnetic dipole moment $\mu$

- EMDM form factor

$$\mathcal{H}_{\mathrm{EMDM}} = j_\mu A^\mu \qquad \langle \nu_{\mathbf{f}} | j_\mu | \nu_{\mathbf{i}} \rangle = \bar{u}_{\mathbf{f}} \Gamma^\mu_{\mathbf{fi}}(q^2) u_{\mathbf{i}}$$

$$\Gamma^\mu_{\mathbf{fi}}(q^2) = -\mu_{\mathbf{fi}}(q^2) i\sigma^{\mu\nu} q_\nu + d_{\mathbf{fi}}(q^2) i\sigma^{\mu\nu} q_\nu \gamma_5$$

- Diagonal ( $\mathbf{i} = \mathbf{f}$ ) EMDM is zero for Majorana particles

- Transition ( $\mathbf{i} \neq \mathbf{f}$ ) EMDM $\Rightarrow \nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma$ if $m_{\mathbf{i}} > m_{\mathbf{j}}$

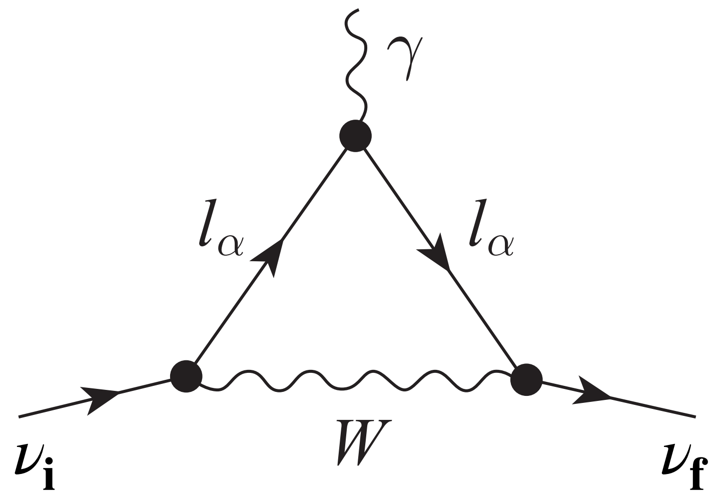
- Early studies: Shrock, 1974; Petcov; Goldman & Stephenson, 1977; Schechter & Valle, 1981; Pal & Wolfenstein, Schechter & Valle; Shrock; Nieves; Kayser, 1982 …

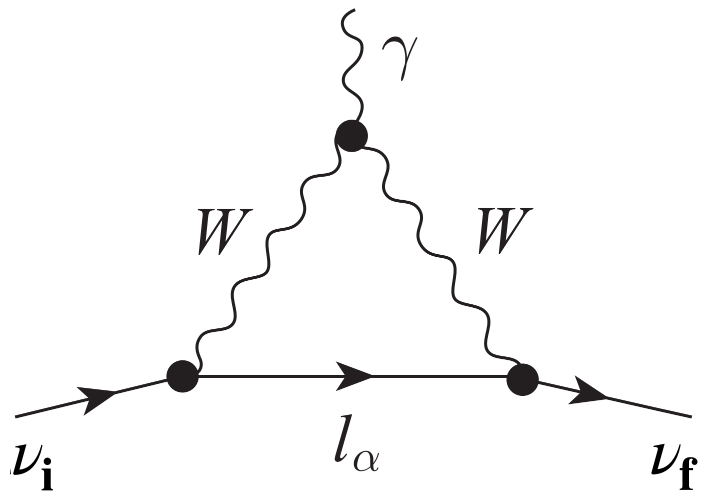
See review by Giunti & Studenikin, 1403.6344

# General electromagnetic property of light neutrinos

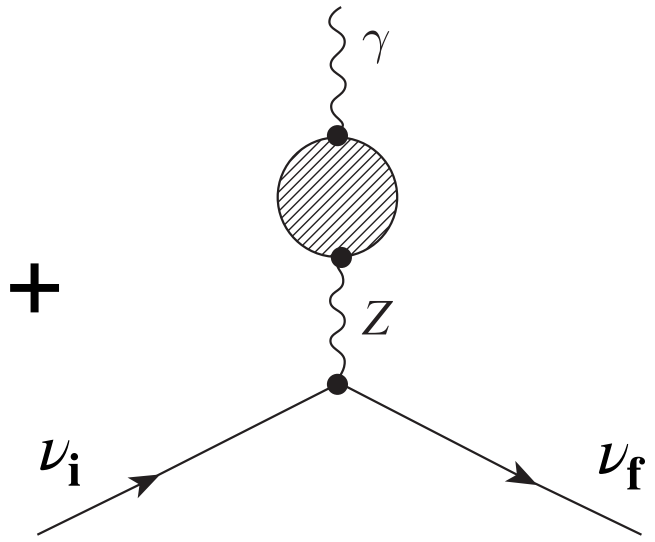
- Neutrino EMDM is generated via weak interaction of the SM

Full one-loop calc in electroweak symm with $R_\xi$ gauge: Dvornikov & Studenikin, hep-ph/0305206; 0411085




+ diagrams of Goldstone and ghost +




Theoretical predictions: $d, \mu \sim \frac{eg^2}{16\pi^2}\frac{m_\nu}{M_W^2} \sim 10^{-20}\mu_{\rm B}$ (diagonal), $\sim \frac{eg^2}{16\pi^2}\frac{m_\nu}{M_W^2}\frac{m_\tau^2}{M_W^2} \sim 10^{-24}\mu_{\rm B}$ (transition)

Including non-unitarity effect: $d \sim \mu \lesssim 10^{-22}\mu_{\rm B}$ (transition)
and $\gamma - Z$ self diagram is necessary to cancel infinity and electric charge.

For a full calc, see Xing & **YLZ**, 1201.2543

- Experimental progress

$\mu \leqslant 2.9 \times 10^{-11}\mu_{\rm B}$ 90%CL @ GEMMA (diagonal MDM)

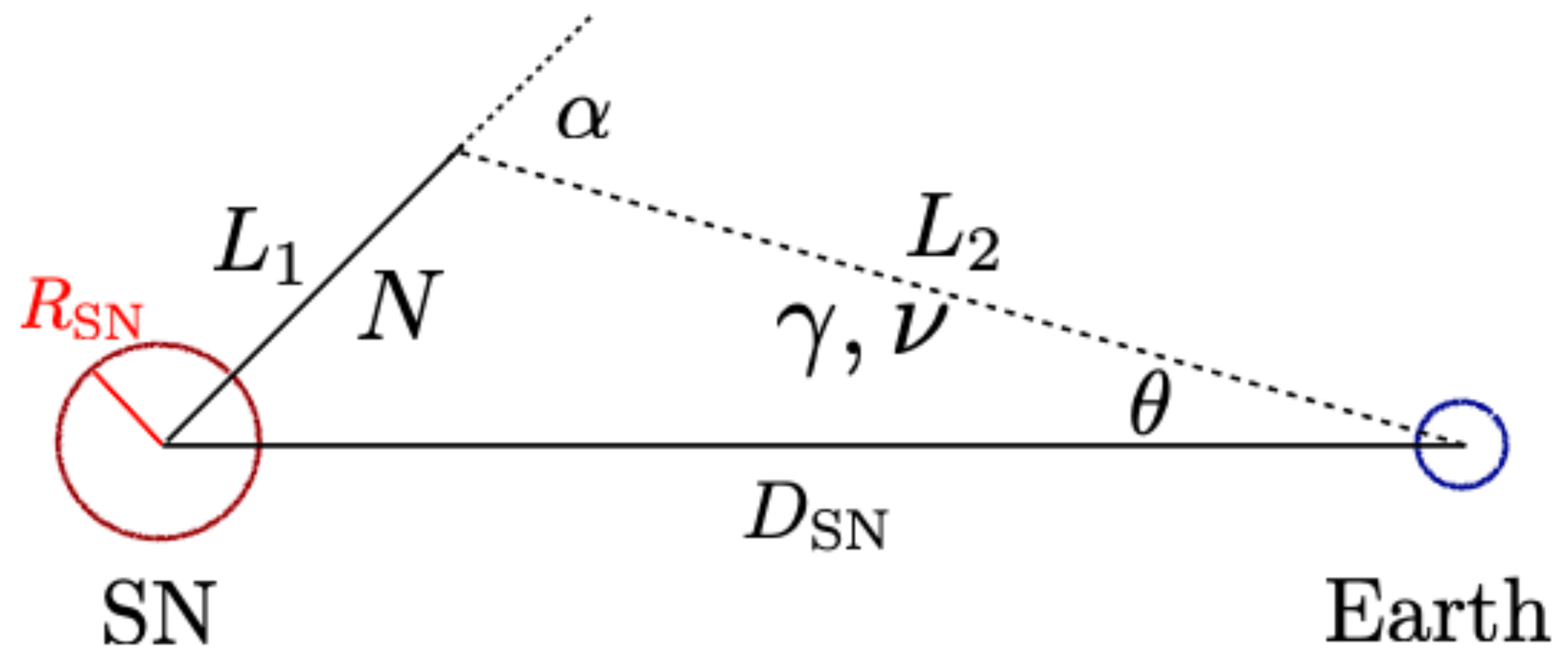
$\mu \in (1.4, 2.9) \times 10^{-11}\mu_{\rm B}$ 90% CL @XENON1T, 2006.09721

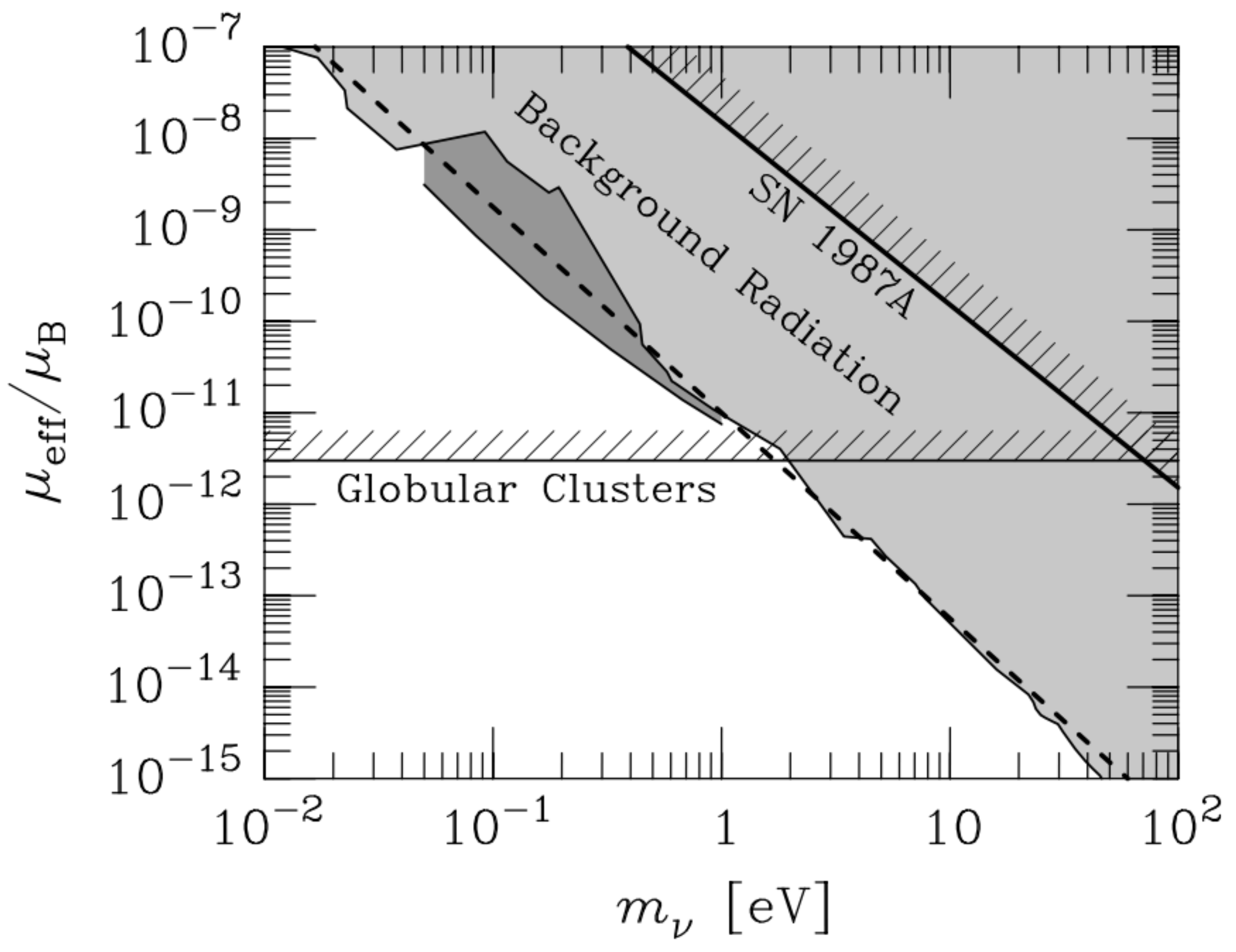
Borexino, Super-K, TEXONO, DARWIN …

# Electromagnetic property of heavier neutrinos

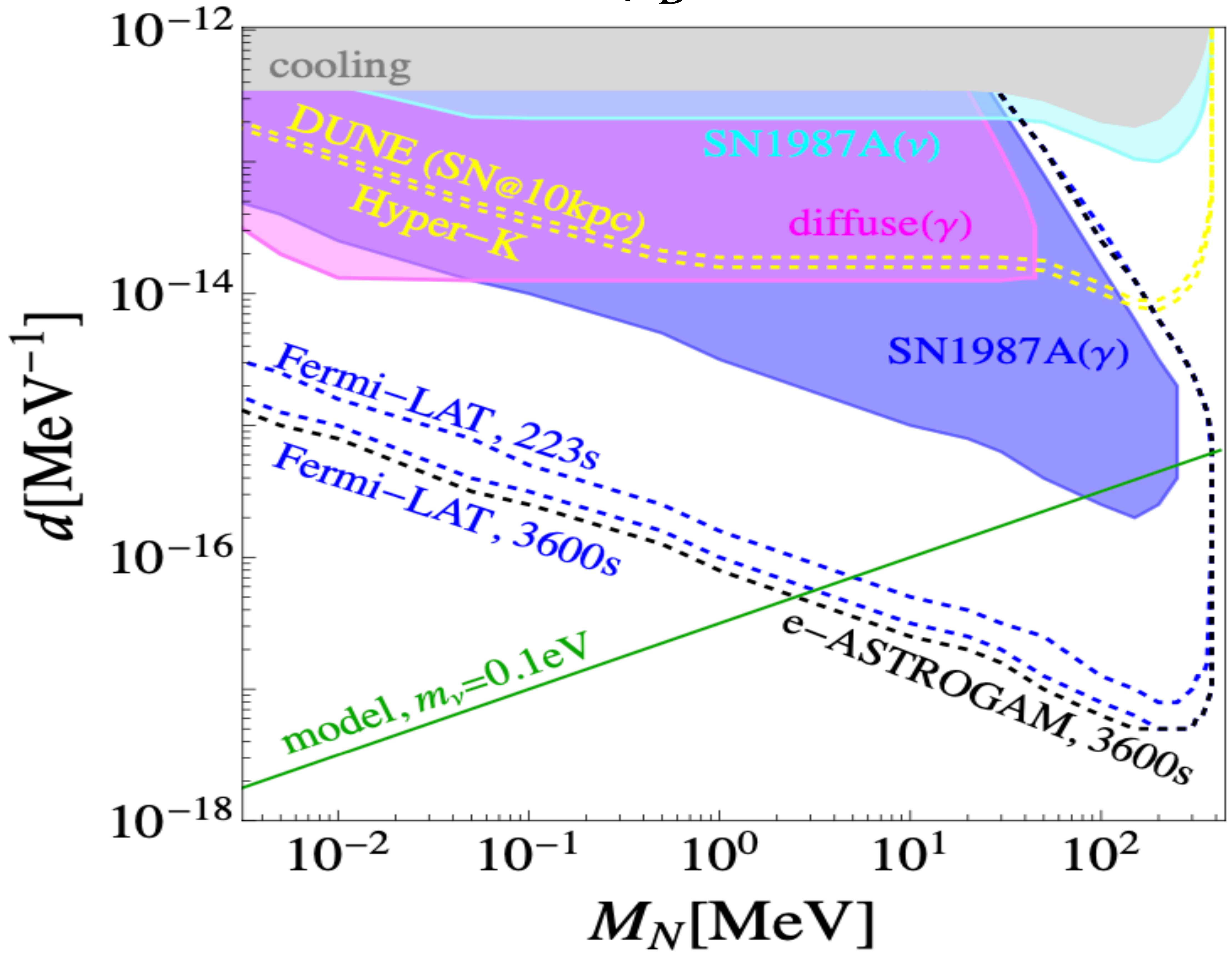
- Heavier neutrinos, $d, \mu \sim 10^{-20} \mu_B \frac{m_N}{m_\nu} \times$ (active-sterile mixing)

MeV$^{-1} \simeq 3.3\mu_B$




Giunti & Studenikin, 1403.6344

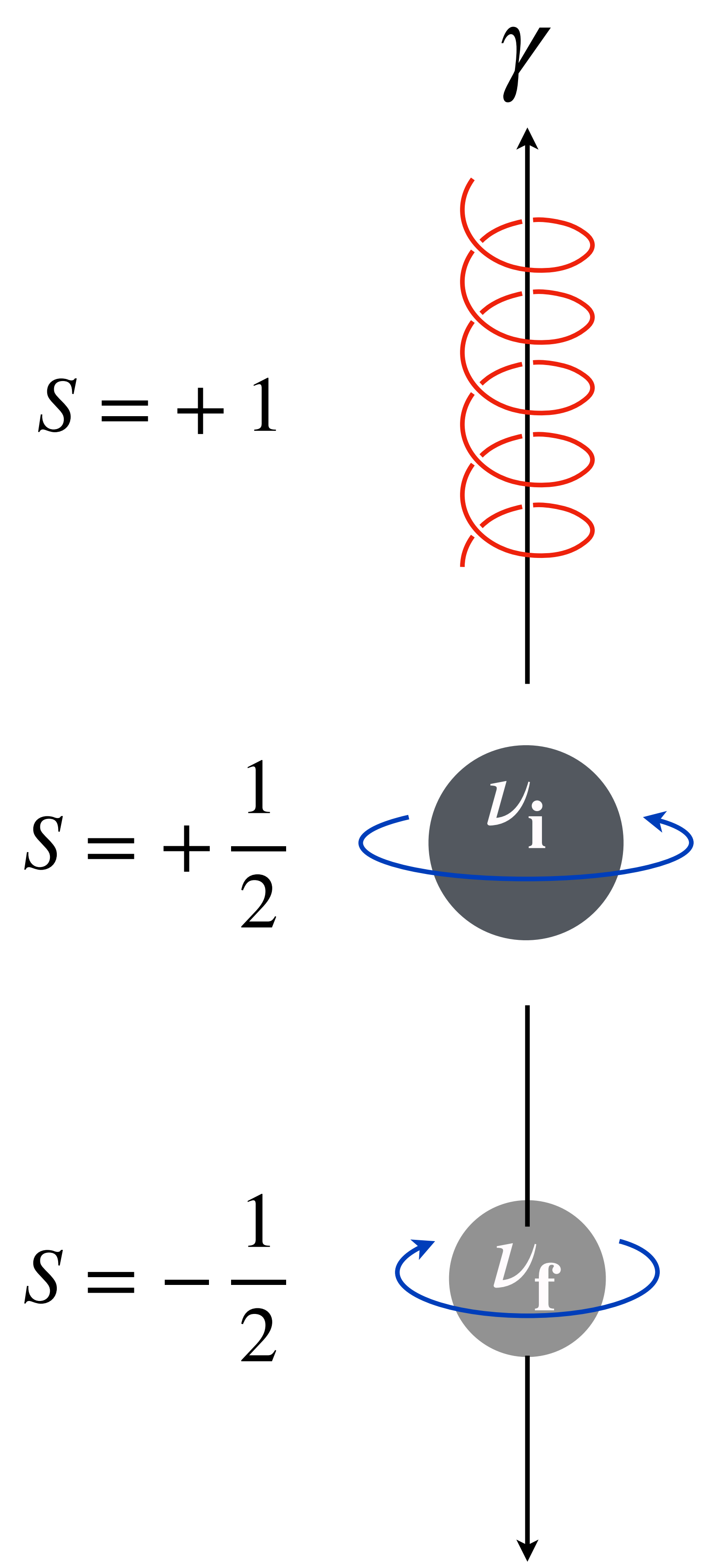



Brdar, de Gouvêa, Ying-Ying Li, Machado, 2302.10965

# CP transformation in the Dirac neutrino case

Balaji, Ramirez-Quezada,
**YLZ**, 1910.08558

In the rest frame with photon released in +z direction



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Balaji, Ramirez-Quezada, **YLZ**, 1910.08558

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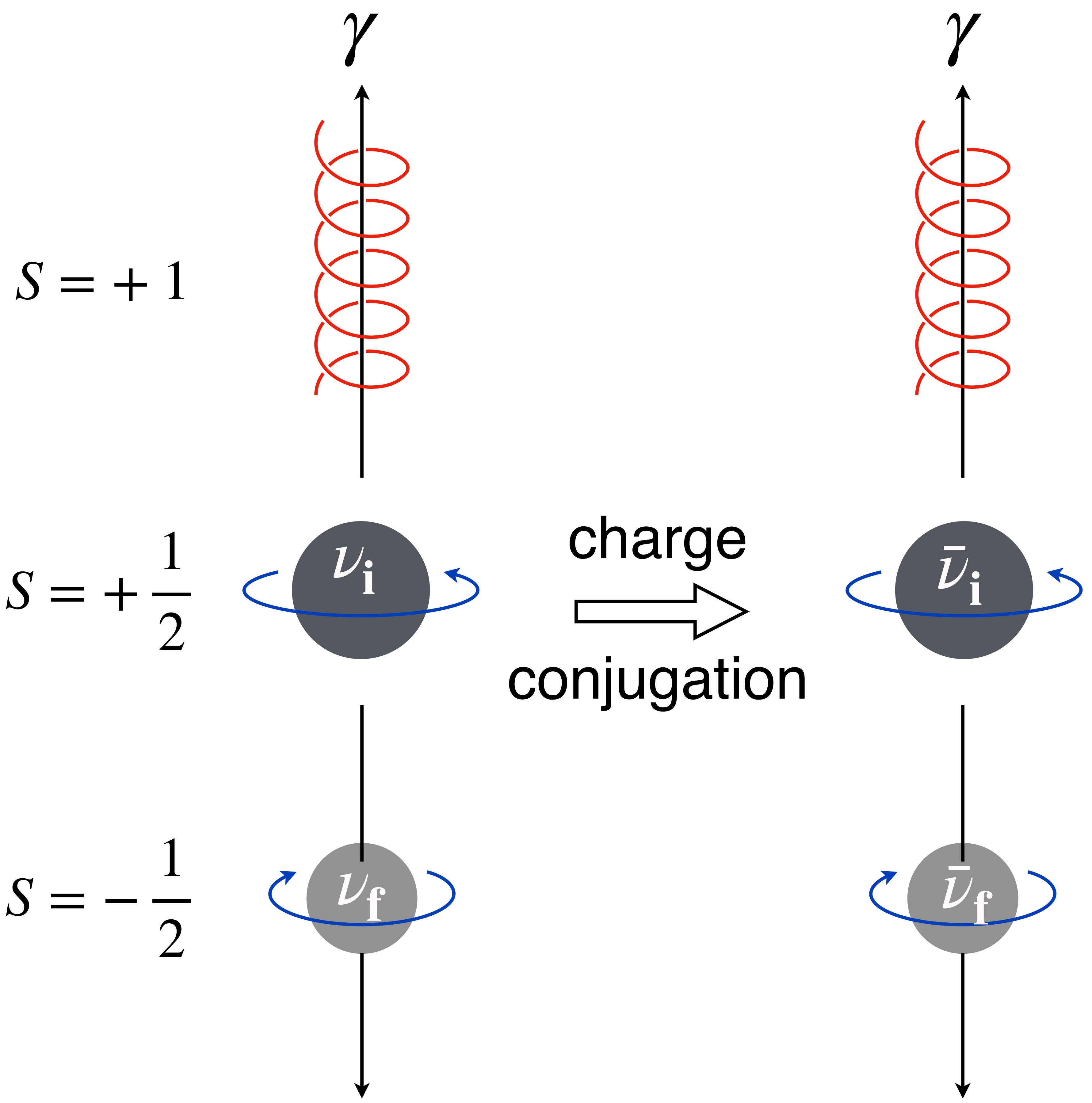

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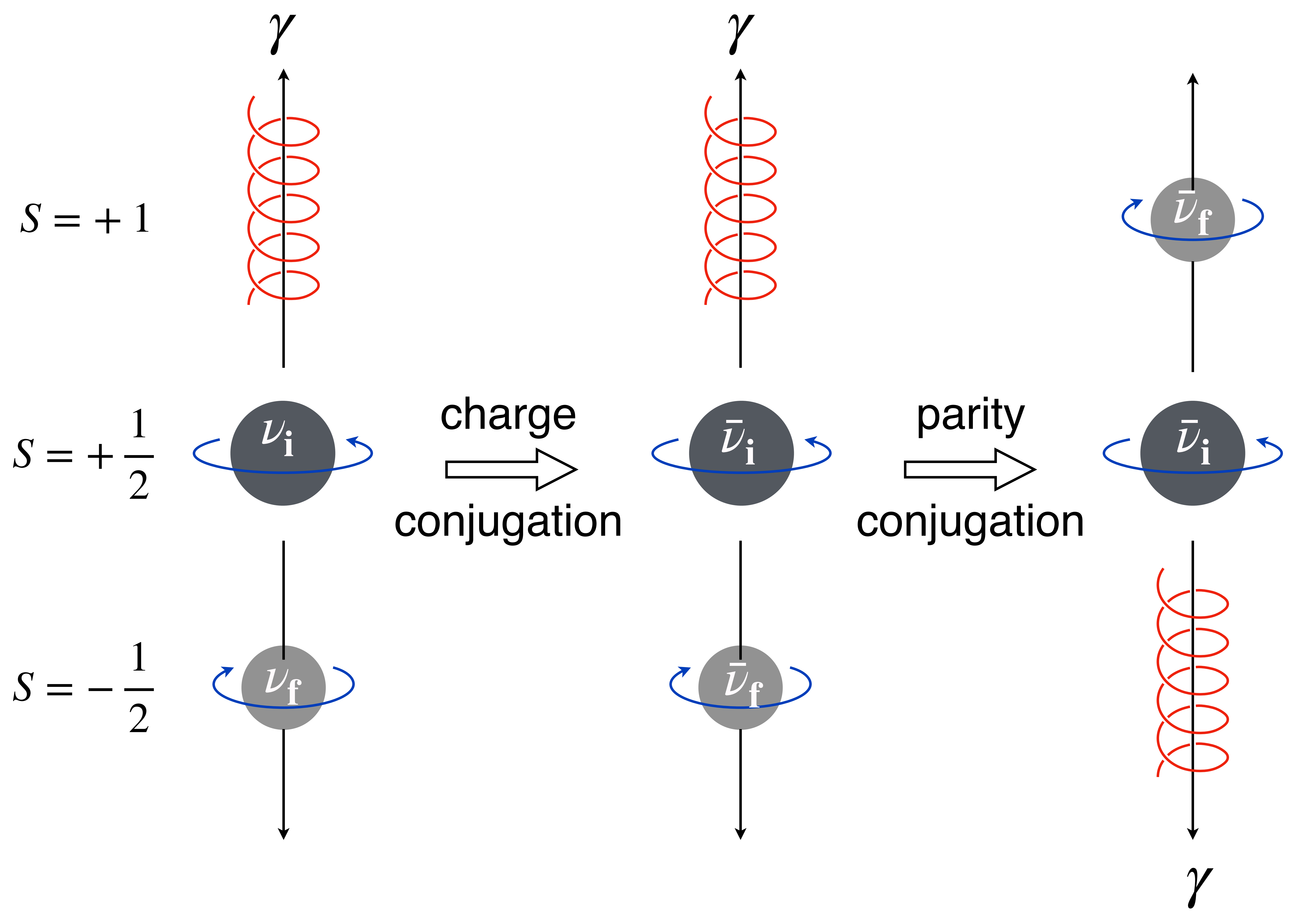
Balaji, Ramirez-Quezada, **YLZ**, 1910.08558



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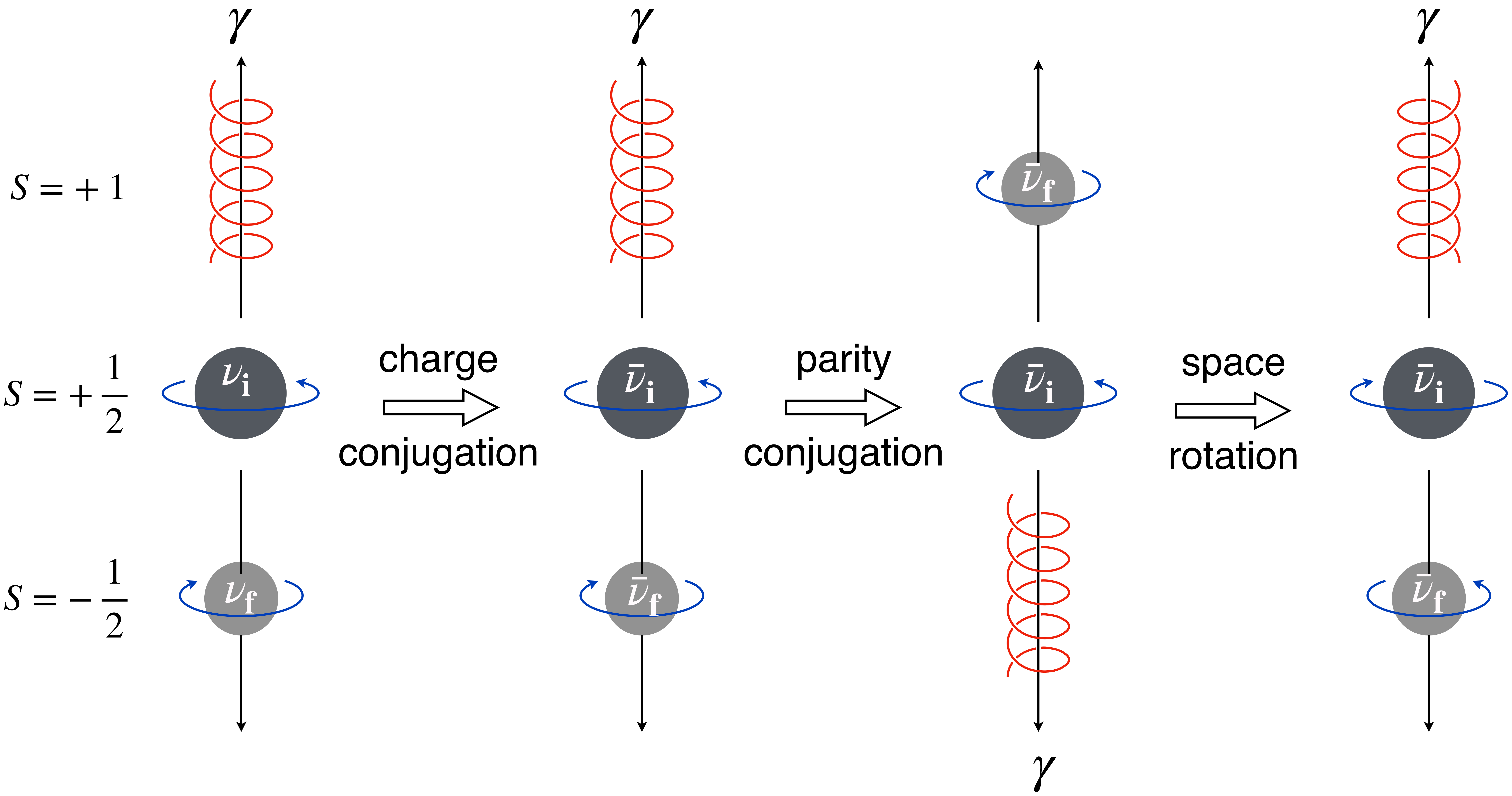

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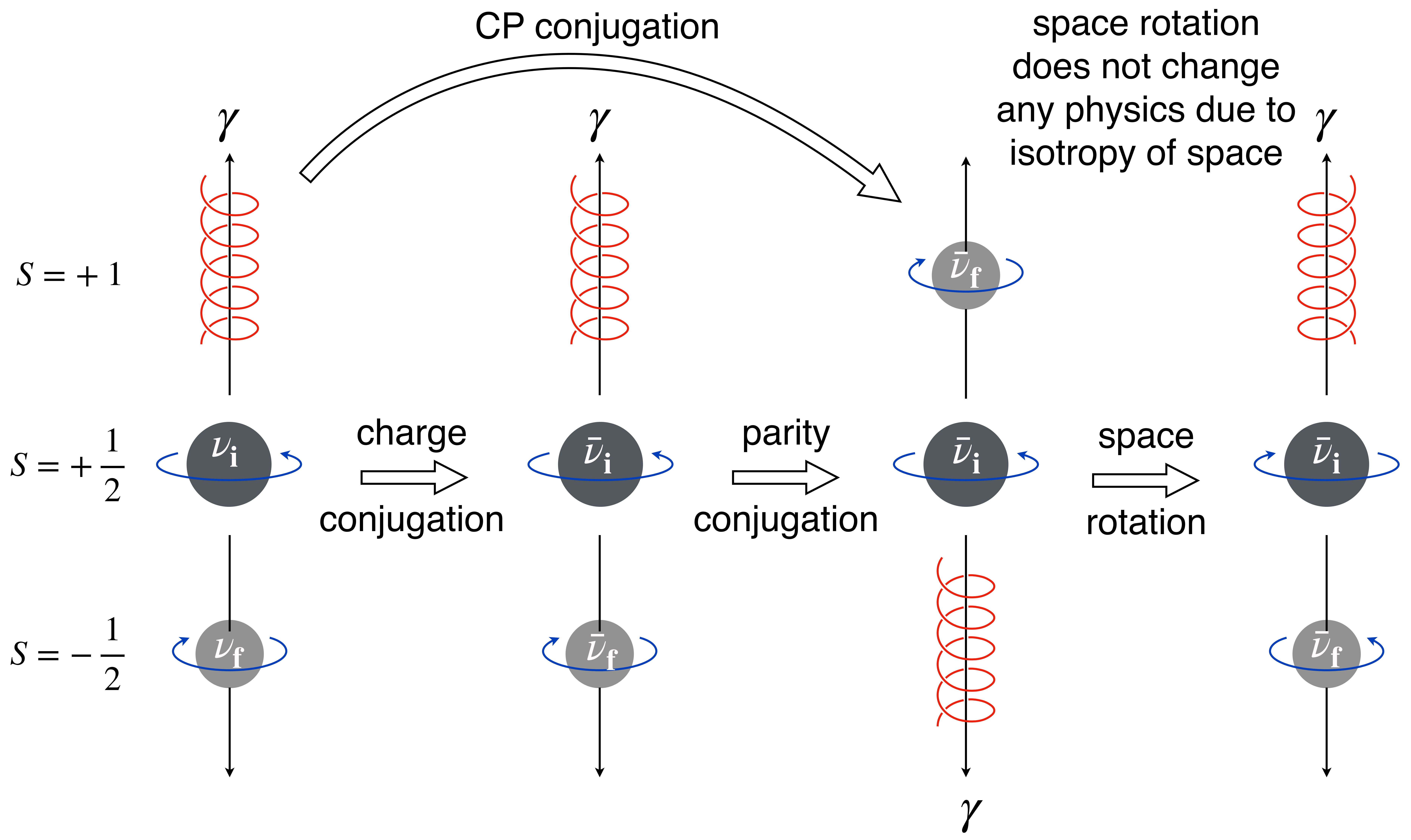
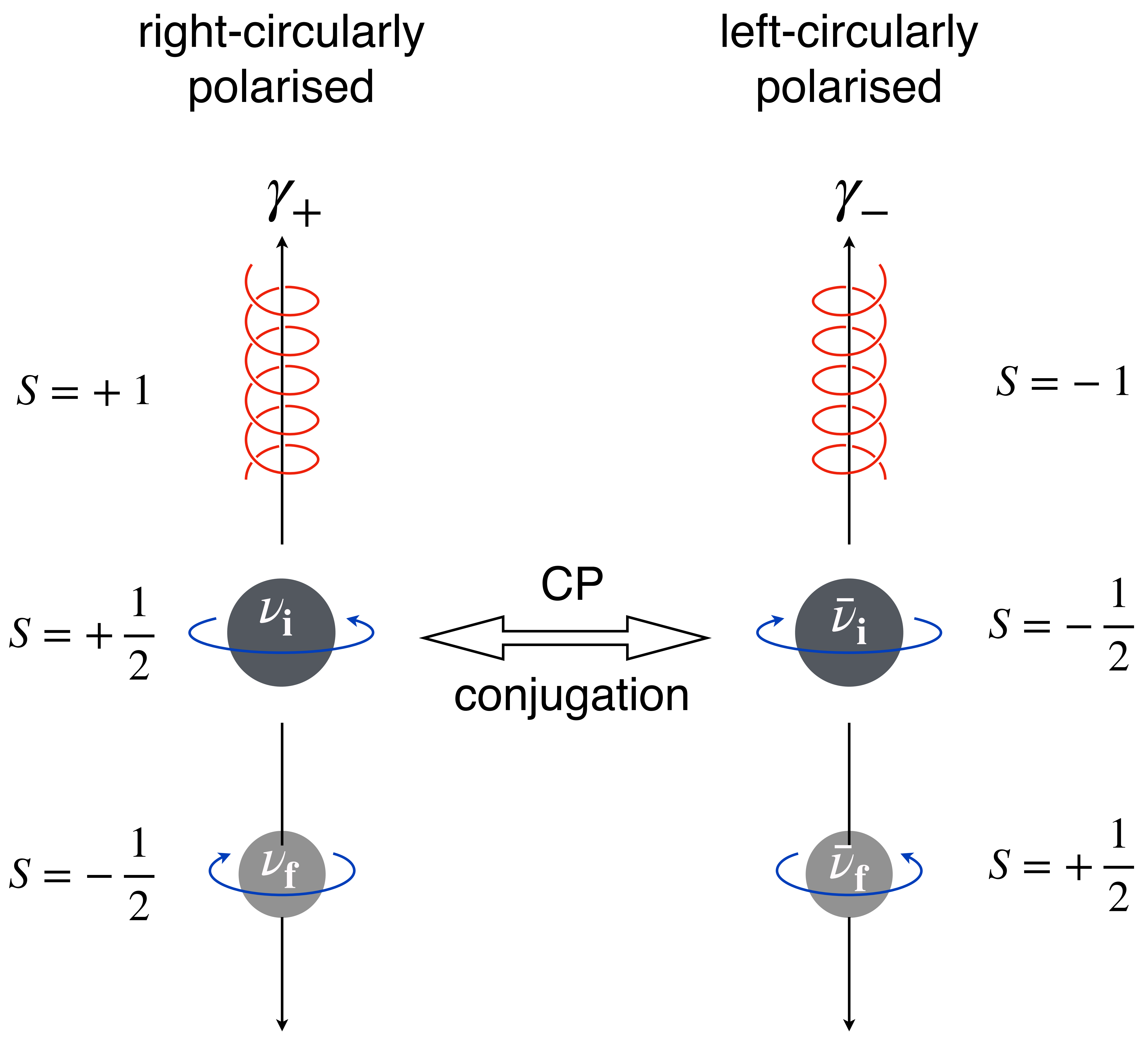
Balaji, Ramirez-Quezada, **YLZ**, 1910.08558



# CP transformation for Dirac neutrinos

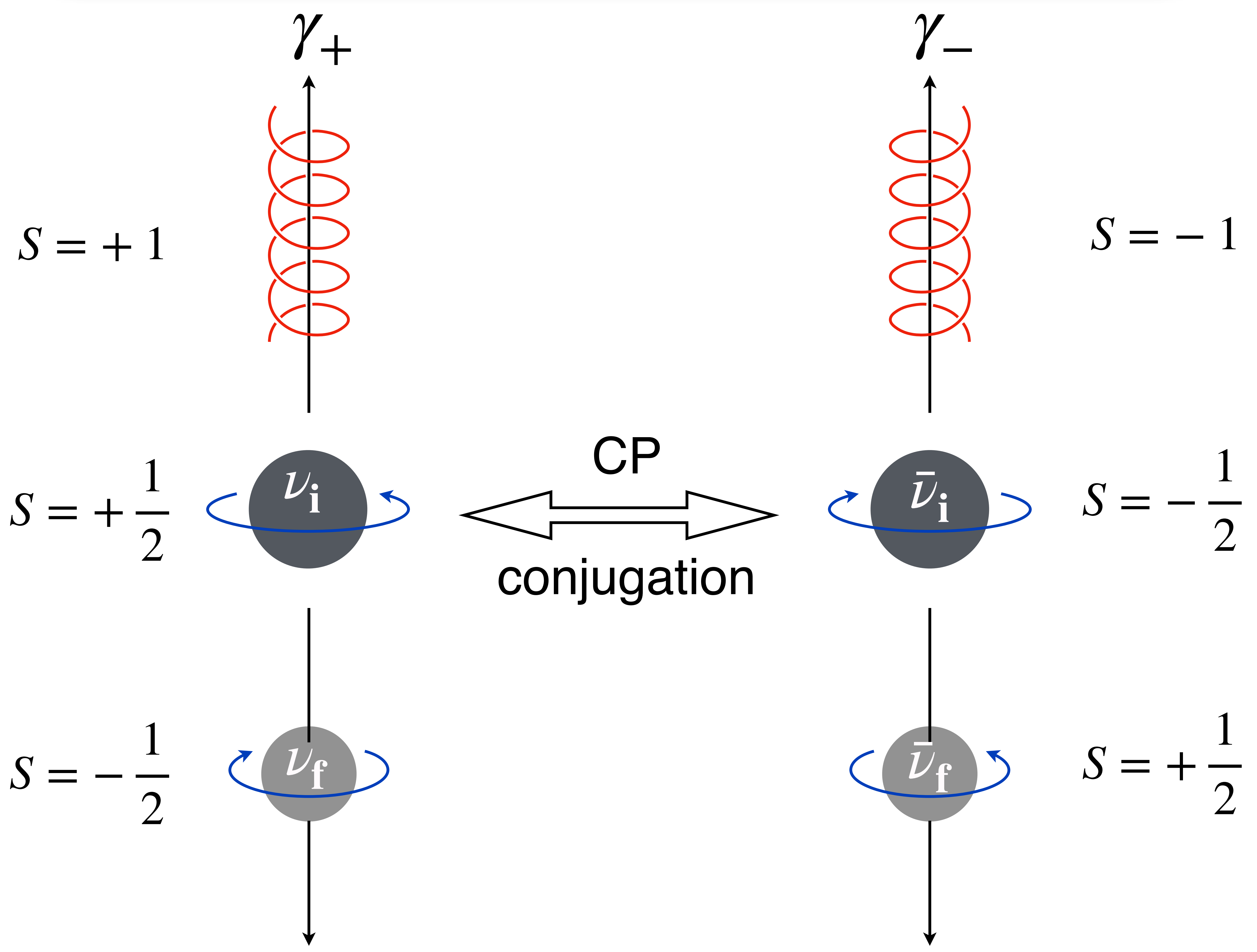
Balaji, Ramirez-Quezada, **YLZ**, 1910.08558



# CP transformation for Dirac neutrinos

Balaji, Ramirez-Quezada, **YLZ**, 1910.08558

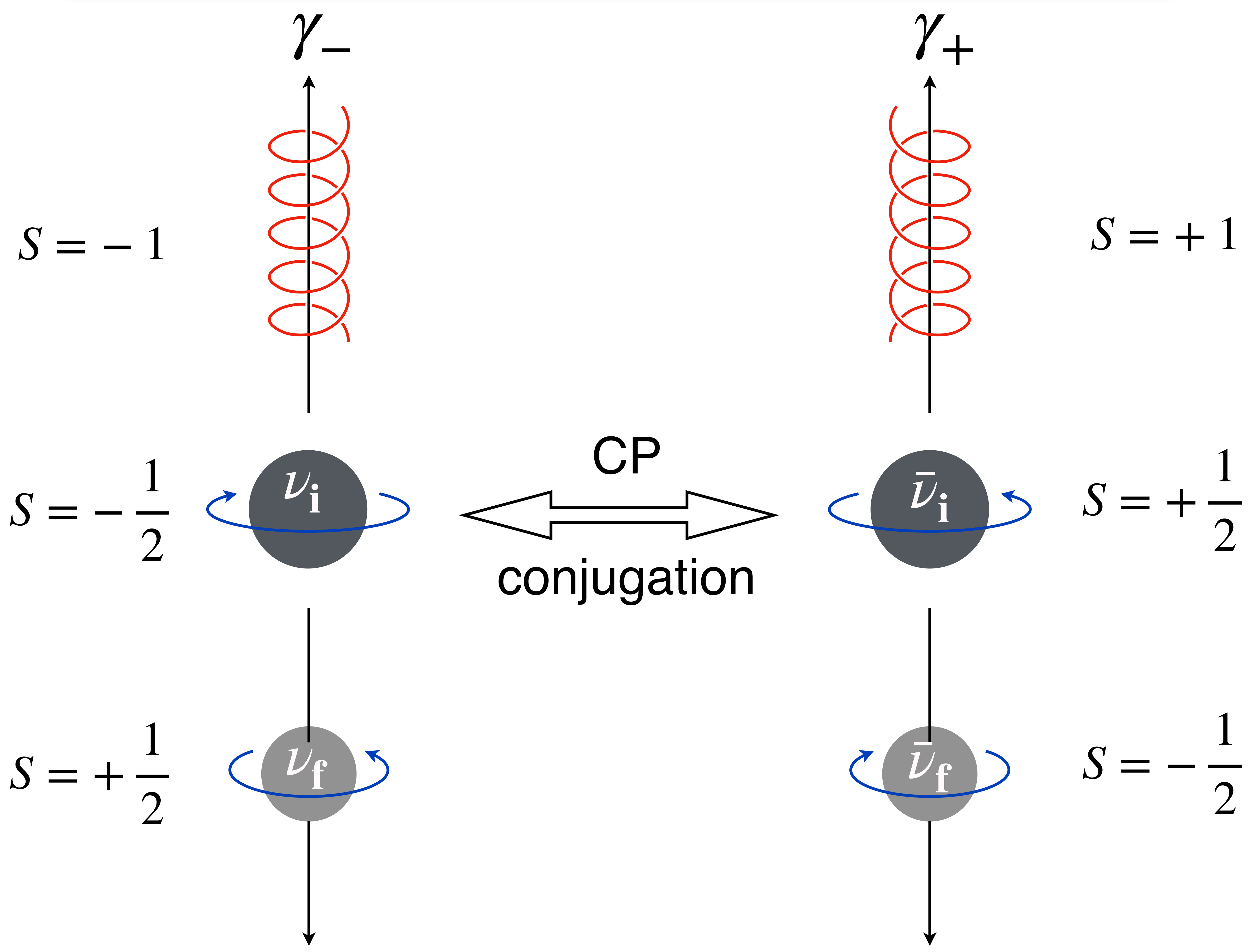
$$\Delta_{CP,+} = \frac{\Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma_+) - \Gamma(\bar{\nu}_{\mathbf{i}} \to \bar{\nu}_{\mathbf{f}} + \gamma_-)}{\Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma) + \Gamma(\bar{\nu}_{\mathbf{i}} \to \bar{\nu}_{\mathbf{f}} + \gamma)}$$



# CP transformation for Dirac neutrinos

Balaji, Ramirez-Quezada, **YLZ**, 1910.08558

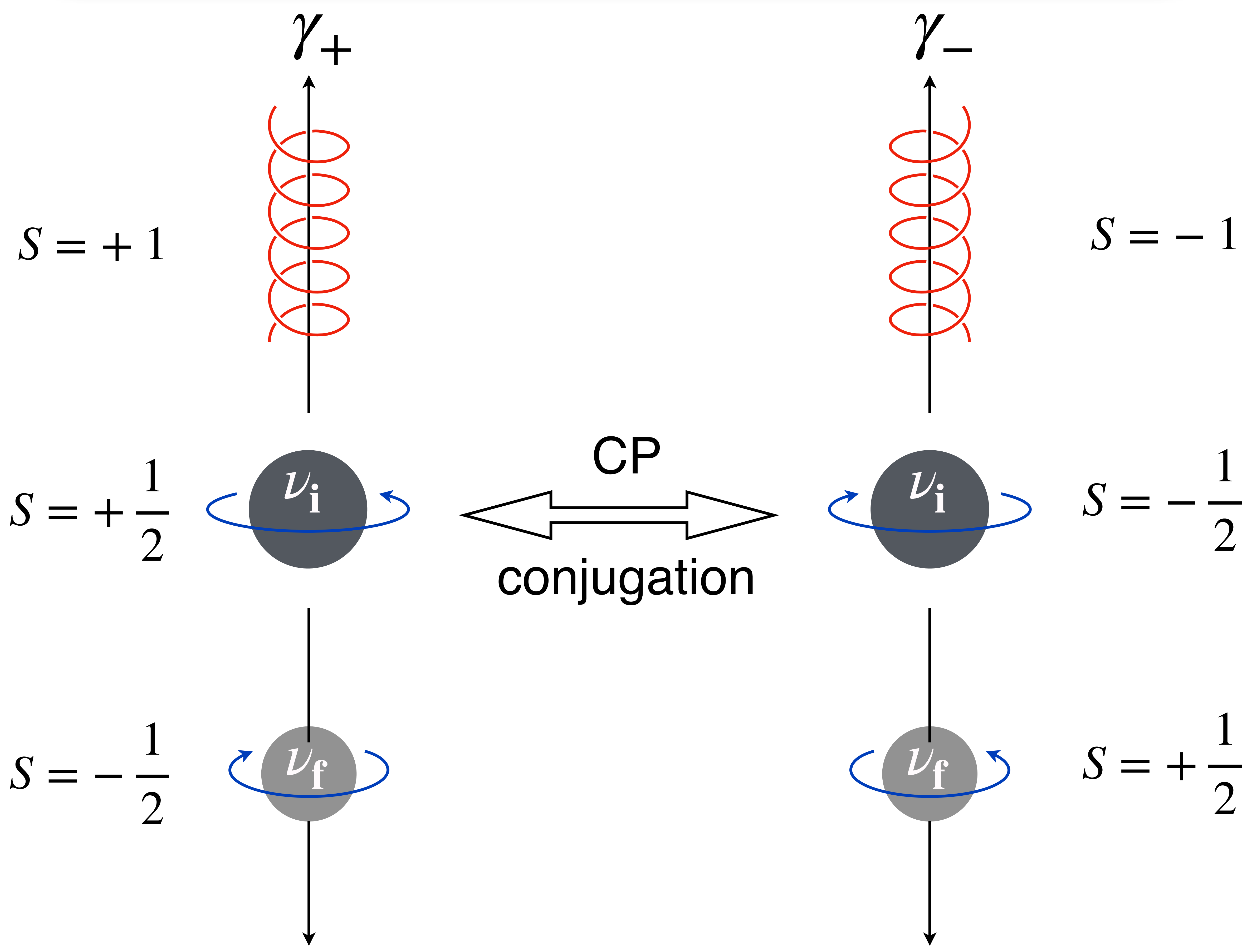
$$\Delta_{CP,-} = \frac{\Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma_-) - \Gamma(\bar{\nu}_{\mathbf{i}} \to \bar{\nu}_{\mathbf{f}} + \gamma_+)}{\Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma) + \Gamma(\bar{\nu}_{\mathbf{i}} \to \bar{\nu}_{\mathbf{f}} + \gamma)}$$



# CP transformation for Majorana neutrinos

Balaji, Ramirez-Quezada, **YLZ**, 1910.08558

$$\Delta_{CP}^{\mathrm{M}} = \frac{\Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma_+) - \Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma_-)}{\Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma) + \Gamma(\nu_{\mathbf{i}} \to \nu_{\mathbf{f}} + \gamma)}$$



# CP asymmetry in terms of form factors

Balaji, Ramirez-Quezada, **YLZ**, 1910.08558

- Re-express the form factor in the chiral representation

**Form factor for $\nu$**

$$\Gamma^\mu_{\mathbf{fi}}(q^2) = +i\sigma^{\mu\nu}q_\nu[\, f^{\mathrm{L}}_{\mathbf{fi}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathbf{fi}} P_{\mathrm{R}}\,]$$

$$f^{\mathrm{L,R}}_{\mathbf{fi}} = -\mu_{\mathbf{fi}} \pm i d_{\mathbf{fi}}$$

$$P_{\mathrm{L,R}} = (\mathbf{1} \pm \gamma_5)/2$$

**Form factor for $\bar{\nu}$**

$$\bar{\Gamma}^\mu_{\mathbf{if}}(q^2) = +i\sigma^{\mu\nu}q_\nu[\, \bar{f}^{\mathrm{L}}_{\mathbf{if}} P_{\mathrm{L}} + \bar{f}^{\mathrm{R}}_{\mathbf{if}} P_{\mathrm{R}}\,]$$

$$\langle \nu_{\mathbf{f}} | j_\mu | \nu_{\mathbf{i}} \rangle = \bar{u}_{\mathbf{f}} \Gamma^\mu_{\mathbf{fi}}(q^2) u_{\mathbf{i}}$$

$$\langle \bar{\nu}_{\mathbf{f}} | j_\mu | \bar{\nu}_{\mathbf{i}} \rangle = \bar{v}_{\mathbf{i}} \Gamma^\mu_{\mathbf{if}}(q^2) v_{\mathbf{f}}$$

CPT invariance $\quad \mathcal{M}(\bar{\nu}_{\mathbf{i}} \to \bar{\nu}_{\mathbf{f}} + \gamma) = \mathcal{M}(\nu_{\mathbf{f}} + \gamma \to \nu_{\mathbf{i}}) \Rightarrow \bar{f}^{\mathrm{L,R}}_{\mathbf{if}} = -f^{\mathrm{L,R}}_{\mathbf{if}}$

$$\bar{\Gamma}^\mu_{\mathbf{if}}(q^2) = -i\sigma^{\mu\nu}q_\nu[\, f^{\mathrm{L}}_{\mathbf{if}} P_{\mathrm{L}} + f^{\mathrm{R}}_{\mathbf{if}} P_{\mathrm{R}}\,]$$

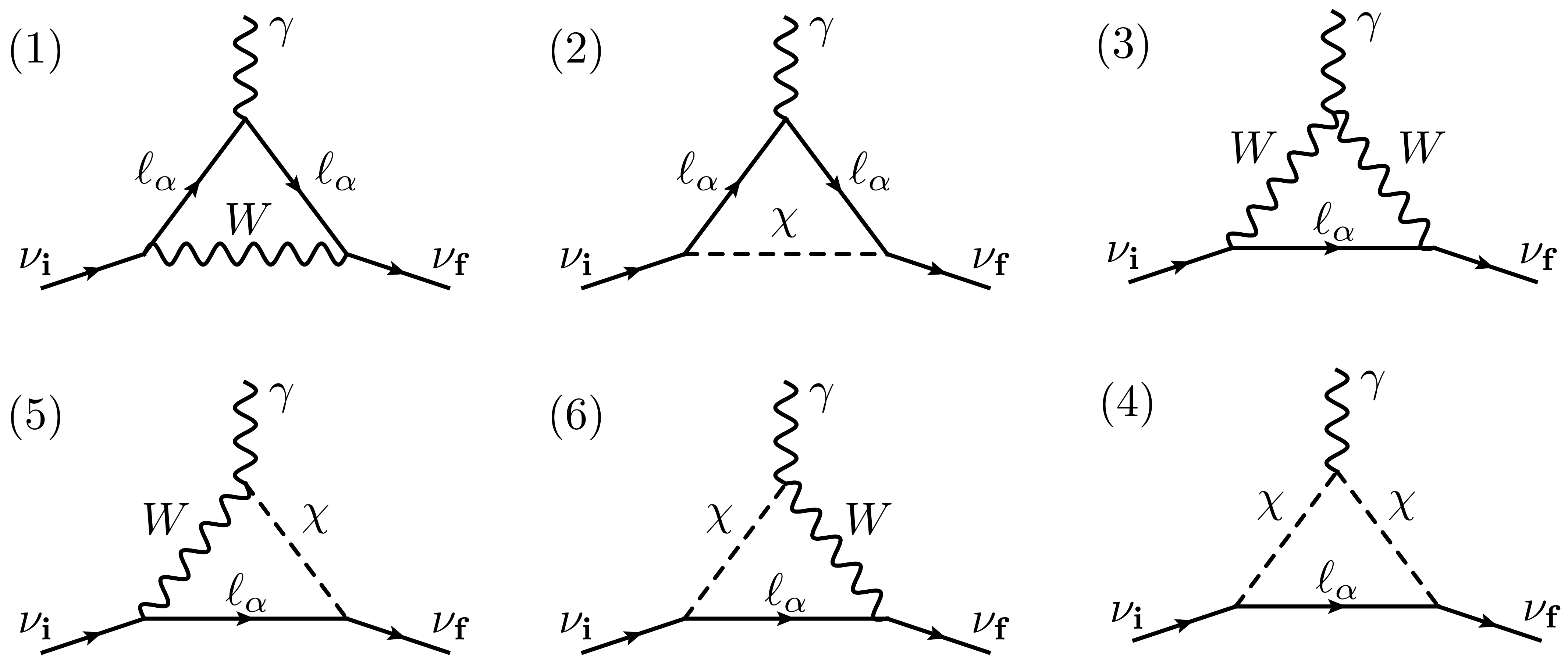
**CP asymmetry for Dirac $\nu$**

$$\Delta_{CP,+} = \frac{|f^{\mathrm{L}}_{\mathbf{fi}}|^2 - |f^{\mathrm{R}}_{\mathbf{if}}|^2}{|f^{\mathrm{L}}_{\mathbf{fi}}|^2 + |f^{\mathrm{R}}_{\mathbf{fi}}|^2 + |f^{\mathrm{R}}_{\mathbf{if}}|^2 + |f^{\mathrm{L}}_{\mathbf{if}}|^2},$$

$$\Delta_{CP,-} = \frac{|f^{\mathrm{R}}_{\mathbf{fi}}|^2 - |f^{\mathrm{L}}_{\mathbf{if}}|^2}{|f^{\mathrm{L}}_{\mathbf{fi}}|^2 + |f^{\mathrm{R}}_{\mathbf{fi}}|^2 + |f^{\mathrm{R}}_{\mathbf{if}}|^2 + |f^{\mathrm{L}}_{\mathbf{if}}|^2},$$

# Loop calc in type-I seesaw

Balaji, Ramirez-Quezada, **YLZ**, 2008.12795




Summation $\sum_{\alpha}$ for charged leptons $\alpha = e, \mu, \tau$ in the loop

$$\Gamma^{\mu,(1)}_{\mathbf{fi},\alpha} = i\frac{eg^2}{2}\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}^*_{\alpha\mathbf{f}}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{\gamma_\nu P_\mathrm{L}(\not{p}_\mathbf{f}-\not{p}+m_\alpha)\gamma^\mu(\not{p}_\mathbf{i}-\not{p}+m_\alpha)\gamma^\nu P_\mathrm{L}}{[(p_\mathbf{f}-p)^2-m_\alpha^2][(p_\mathbf{i}-p)^2-m_\alpha^2][p^2-m_W^2]}\,,$$

$$\Gamma^{\mu,(2)}_{\mathbf{fi},\alpha} = i\frac{eg^2}{2}\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}^*_{\alpha\mathbf{f}}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{(m_\mathbf{f}P_\mathrm{L}-m_\alpha P_\mathrm{R})(\not{p}_\mathbf{f}-\not{p}+m_\alpha)\gamma^\mu(\not{p}_\mathbf{i}-\not{p}+m_\alpha)(m_\alpha P_\mathrm{L}-m_\mathbf{i}P_\mathrm{R})}{m_W^2[(p_\mathbf{f}-p)^2-m_\alpha^2][(p_\mathbf{i}-p)^2-m_\alpha^2][p^2-m_W^2]}\,,$$

$$\Gamma^{\mu,(3)}_{\mathbf{fi},\alpha} = i\frac{eg^2}{2}\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}^*_{\alpha\mathbf{f}}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{\gamma_\rho P_\mathrm{L}(\not{p}+m_\alpha)\gamma_\nu P_\mathrm{L}V^{\mu\nu\rho}}{[(p_\mathbf{f}-p)^2-m_W^2][(p_\mathbf{i}-p)^2-m_W^2][p^2-m_\alpha^2]}\,,$$

$$\Gamma^{\mu,(4)}_{\mathbf{fi},\alpha} = i\frac{eg^2}{2}\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}^*_{\alpha\mathbf{f}}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{(2p-p_\mathbf{i}-p_\mathbf{f})^\mu(m_\mathbf{f}P_\mathrm{L}-m_\alpha P_\mathrm{R})(\not{p}+m_\alpha)(m_\alpha P_\mathrm{L}-m_\mathbf{i}P_\mathrm{R})}{m_W^2[(p_\mathbf{f}-p)^2-m_W^2][(p_\mathbf{i}-p)^2-m_W^2][p^2-m_\alpha^2]}\,,$$

$$\Gamma^{\mu,(5)}_{\mathbf{fi},\alpha} = i\frac{eg^2}{2}\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}^*_{\alpha\mathbf{f}}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{\gamma^\mu P_\mathrm{L}(\not{p}+m_\alpha)(m_\alpha P_\mathrm{L}-m_\mathbf{i}P_\mathrm{R})}{[(p_\mathbf{f}-p)^2-m_W^2][(p_\mathbf{i}-p)^2-m_W^2][p^2-m_\alpha^2]}\,,$$

$$\Gamma^{\mu,(6)}_{\mathbf{fi},\alpha} = i\frac{eg^2}{2}\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}^*_{\alpha\mathbf{f}}\int\frac{\mathrm{d}^4p}{(2\pi)^4}\frac{(m_\alpha P_\mathrm{R}-m_\mathbf{f}P_\mathrm{L})(\not{p}+m_\alpha)\gamma^\mu P_\mathrm{L}}{[(p_\mathbf{f}-p)^2-m_W^2][(p_\mathbf{i}-p)^2-m_W^2][p^2-m_\alpha^2]}\,,$$

$$V^{\mu\nu\rho} = g^{\mu\nu}(2p_\mathbf{i}-p-p_\mathbf{f})^\rho+g^{\rho\mu}(2p_\mathbf{f}-p-p_\mathbf{i})^\nu+g^{\nu\rho}(2p-p_\mathbf{i}-p_\mathbf{f})^\mu\,.$$

# Factorisation of CP asymmetry

Balaji, Ramirez-Quezada, **YLZ**, 2008.12795

- Neutrino form factor in radiative decay

$$\Gamma^{\mu,(\mathrm{k})}_{\mathbf{fi},\alpha} = \frac{eG_{\mathrm{F}}}{4\sqrt{2}\pi^2}\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}^*_{\alpha\mathbf{f}} \qquad i\sigma^{\mu\nu}q_\nu(\mathcal{F}_{\mathbf{fi},\alpha}m_{\mathbf{i}}P_{\mathrm{R}} + \mathcal{F}_{\mathbf{if},\alpha}m_{\mathbf{f}}P_{\mathrm{L}})\,.$$

coefficients in the coupling kinetic term

- Loop function in the kinetic term

$$\mathcal{F}_{\mathbf{fi},\alpha} = \int_0^1 \mathrm{d}x \left\{ \frac{\left(m_{\mathbf{i}}^2 - m_\alpha^2 - 2m_W^2\right)\left(m_\alpha^2 + m_{\mathbf{f}}^2x^2\right) + m^4_{\mathbf{fi},\alpha}x}{\left(m_{\mathbf{i}}^2 - m_{\mathbf{f}}^2\right)^2 x} \log\left(\frac{m_\alpha^2 + \left(m_W^2 - m_\alpha^2 - m_{\mathbf{i}}^2\right)x + m_{\mathbf{i}}^2x^2}{m_\alpha^2 + \left(m_W^2 - m_\alpha^2 - m_{\mathbf{f}}^2\right)x + m_{\mathbf{f}}^2x^2}\right) \right.$$
$$\left. + \frac{\left(m_{\mathbf{i}}^2 - m_\alpha^2 - 2m_W^2\right)\left(m_\alpha^2 + m_{\mathbf{f}}^2(1-x)^2\right) + m^4_{\mathbf{fi},\alpha}(1-x)}{\left(m_{\mathbf{i}}^2 - m_{\mathbf{f}}^2\right)^2 x} \log\left(\frac{m_W^2 + \left(m_\alpha^2 - m_W^2 - m_{\mathbf{i}}^2\right)x + m_{\mathbf{i}}^2x^2}{m_W^2 + \left(m_\alpha^2 - m_W^2 - m_{\mathbf{f}}^2\right)x + m_{\mathbf{f}}^2x^2}\right)\right\}$$
$$+ \frac{m_{\mathbf{f}}^2 - m_\alpha^2 - 2m_W^2}{m_{\mathbf{i}}^2 - m_{\mathbf{f}}^2}\,, \qquad m^4_{\mathbf{fi},\alpha} = -(m_{\mathbf{i}}^2 - m_\alpha^2 - m_W^2)(m_{\mathbf{f}}^2 + m_\alpha^2 - 2m_W^2) + 2m_\alpha^2 m_W^2$$

# Factorisation of CP asymmetry

Balaji, Ramirez-Quezada, YLZ, 2008.12795

- Neutrino form factor in radiative decay

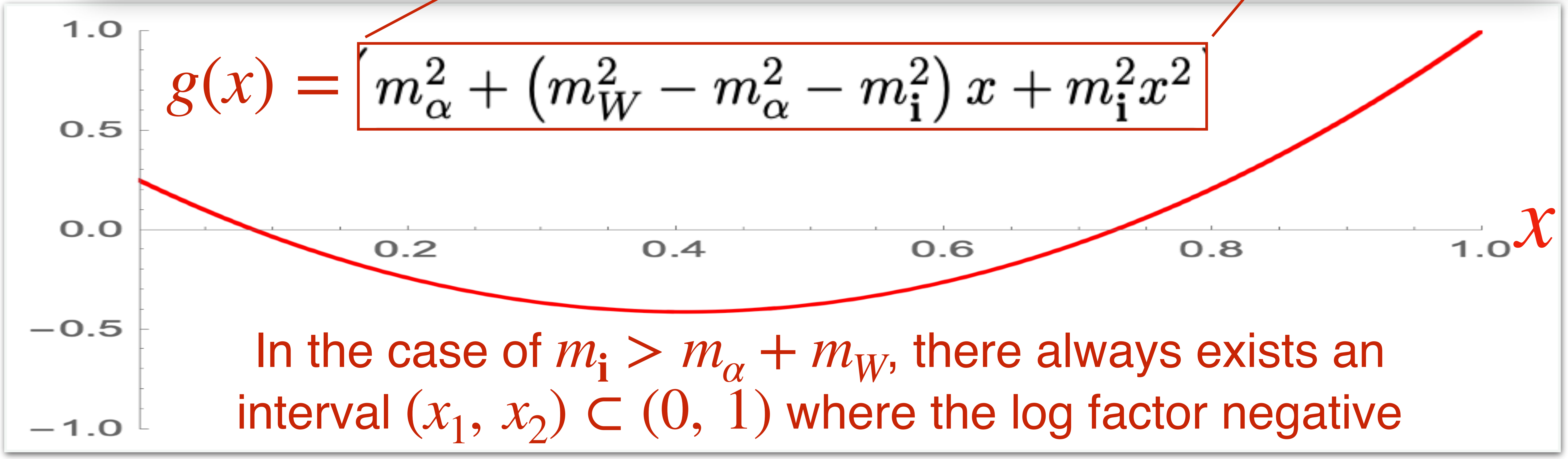
$$\Gamma^{\mu,(\mathrm{k})}_{\mathrm{fi},\alpha} = \frac{eG_{\mathrm{F}}}{4\sqrt{2}\pi^2}\mathcal{U}_{\alpha\mathrm{i}}\mathcal{U}^*_{\alpha\mathrm{f}} \quad i\sigma^{\mu\nu}q_\nu(\mathcal{F}_{\mathrm{fi},\alpha}m_{\mathrm{i}}P_{\mathrm{R}} + \mathcal{F}_{\mathrm{if},\alpha}m_{\mathrm{f}}P_{\mathrm{L}})\,.$$

coefficients in the coupling — kinetic term

- Loop function in the kinetic term

$$\mathcal{F}_{\mathrm{fi},\alpha} = \int_0^1 \mathrm{d}x \left\{ \frac{\left(m_{\mathrm{i}}^2 - m_\alpha^2 - 2m_W^2\right)\left(m_\alpha^2 + m_{\mathrm{f}}^2x^2\right) + m^4_{\mathrm{fi},\alpha}x}{\left(m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2\right)^2 x} \log\left(\frac{m_\alpha^2 + \left(m_W^2 - m_\alpha^2 - m_{\mathrm{i}}^2\right)x + m_{\mathrm{i}}^2x^2}{m_\alpha^2 + \left(m_W^2 - m_\alpha^2 - m_{\mathrm{f}}^2\right)x + m_{\mathrm{f}}^2x^2}\right) + \frac{\left(m_{\mathrm{i}}^2 - m_\alpha^2 - 2m_W^2\right)\left(m_\alpha^2 + m_{\mathrm{f}}^2(1-x)^2\right) + m^4_{\mathrm{fi},\alpha}(1-x)}{\left(m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2\right)^2 x} \log\left(\frac{m_W^2 + \left(m_\alpha^2 - m_W^2 - m_{\mathrm{i}}^2\right)x + m_{\mathrm{i}}^2x^2}{m_W^2 + \left(m_\alpha^2 - m_W^2 - m_{\mathrm{f}}^2\right)x + m_{\mathrm{f}}^2x^2}\right)\right\} + \frac{m_{\mathrm{f}}^2 - m_\alpha^2 - 2m_W^2}{m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2}\,,$$

$$m^4_{\mathrm{fi},\alpha} = -(m_{\mathrm{i}}^2 - m_\alpha^2 - m_W^2)(m_{\mathrm{f}}^2 + m_\alpha^2 - 2m_W^2) + 2m_\alpha^2 m_W^2$$



# Explicit result of the imaginary part of loop integration

- Using the following formula, we finally obtain

$$\int_0^1 \mathrm{d}x\, f(x) \log g(x) = \int_0^1 \mathrm{d}x\, f(x) \log |g(x)| + i\pi \int_{x_1}^{x_2} \mathrm{d}x\, f(x)\,.$$

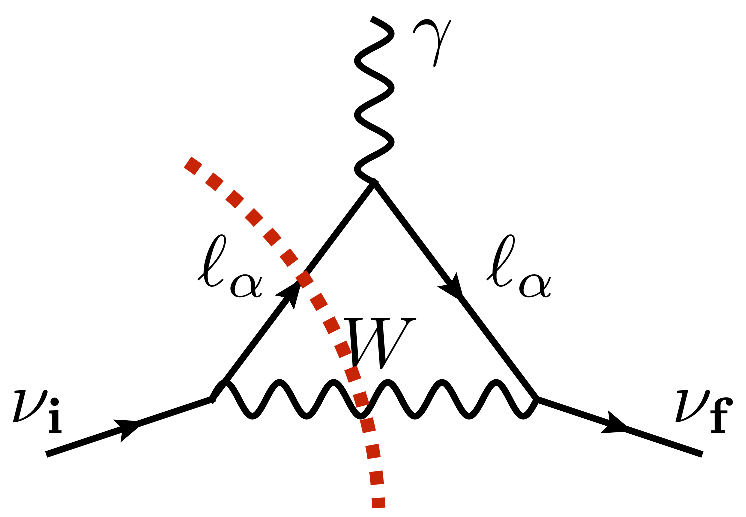
$$\begin{aligned}
\mathrm{Im}(\mathcal{F}_{\mathrm{fi},\alpha}) = \pi\vartheta(m_{\mathrm{i}} - m_W - m_\alpha) \Bigg\{ & \frac{m_{\mathrm{i}}^2 - m_\alpha^2 - 2m_W^2}{(m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2)^2} \left[ -\mu_{\mathrm{i}}^2 \frac{m_{\mathrm{f}}^2}{m_{\mathrm{i}}^2} + m_\alpha^2 \log\left( \frac{m_{\mathrm{i}}^2 + m_\alpha^2 - m_W^2 + \mu_{\mathrm{i}}^2}{m_{\mathrm{i}}^2 + m_\alpha^2 - m_W^2 - \mu_{\mathrm{i}}^2} \right) \right] \\
& + \frac{(2m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2 - m_\alpha^2 - 2m_W^2)\, m_W^2}{(m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2)^2} \log\left( \frac{m_{\mathrm{i}}^2 - m_\alpha^2 + m_W^2 + \mu_{\mathrm{i}}^2}{m_{\mathrm{i}}^2 - m_\alpha^2 + m_W^2 - \mu_{\mathrm{i}}^2} \right) \Bigg\} \\
+\pi\vartheta(m_{\mathrm{f}} - m_W - m_\alpha) \Bigg\{ & -\frac{m_{\mathrm{i}}^2 - m_\alpha^2 - 2m_W^2}{(m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2)^2} \left[ -\mu_{\mathrm{f}}^2 + m_\alpha^2 \log\left( \frac{m_{\mathrm{f}}^2 + m_\alpha^2 - m_W^2 + \mu_{\mathrm{f}}^2}{m_{\mathrm{f}}^2 + m_\alpha^2 - m_W^2 - \mu_{\mathrm{f}}^2} \right) \right] \\
& + \frac{(2m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2 - m_\alpha^2 - 2m_W^2)\, m_W^2}{(m_{\mathrm{i}}^2 - m_{\mathrm{f}}^2)^2} \log\left( \frac{m_{\mathrm{f}}^2 - m_\alpha^2 + m_W^2 + \mu_{\mathrm{f}}^2}{m_{\mathrm{f}}^2 - m_\alpha^2 + m_W^2 - \mu_{\mathrm{f}}^2} \right) \Bigg\},
\end{aligned}$$

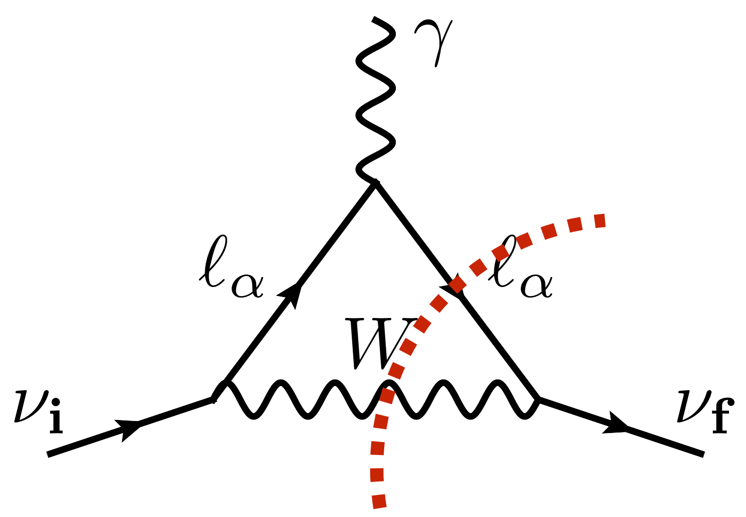
$$\mu_{\mathrm{i}}^2 = \sqrt{m_{\mathrm{i}}^4 + m_\alpha^4 + m_W^4 - 2m_{\mathrm{i}}^2 m_\alpha^2 - 2m_{\mathrm{i}}^2 m_W^2 - 2m_\alpha^2 m_W^2}\,,$$

$$\mu_{\mathrm{f}}^2 = \sqrt{m_{\mathrm{f}}^4 + m_\alpha^4 + m_W^4 - 2m_{\mathrm{f}}^2 m_\alpha^2 - 2m_{\mathrm{f}}^2 m_W^2 - 2m_\alpha^2 m_W^2}\,.$$

In the case $m_{\mathbf{f}} > m_\alpha + m_W$, log of the $m_{\mathbf{f}}$ -dependent term generates another imaginary term, which partially cancel the one from the $m_{\mathbf{i}}$ -dependent term.

The result is consistent with optical theorem:



# CP asymmetry

Balaji, Ramirez-Quezada, **YLZ**, 2008.12795

- Factorisation of coefficient contributions

| | Imaginary (Jarlskog-like parameters) | Real |
|---|---|---|
| Dirac & Majorana | $\mathcal{J}_{\alpha\beta}^{\mathbf{if}} = \mathrm{Im}(\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}_{\alpha\mathbf{f}}^*\mathcal{U}_{\beta\mathbf{i}}^*\mathcal{U}_{\beta\mathbf{f}})\,,$ | $\mathcal{R}_{\alpha\beta}^{\mathbf{if}} = \mathrm{Re}(\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}_{\alpha\mathbf{f}}^*\mathcal{U}_{\beta\mathbf{i}}^*\mathcal{U}_{\beta\mathbf{f}})\,.$ |
| Majorana | $\mathcal{V}_{\alpha\beta}^{\mathbf{if}} = \mathrm{Im}(\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}_{\alpha\mathbf{f}}^*\mathcal{U}_{\beta\mathbf{i}}\mathcal{U}_{\beta\mathbf{f}}^*)\,,$ | $\mathcal{C}_{\alpha\beta}^{\mathbf{if}} = \mathrm{Re}(\mathcal{U}_{\alpha\mathbf{i}}\mathcal{U}_{\alpha\mathbf{f}}^*\mathcal{U}_{\beta\mathbf{i}}\mathcal{U}_{\beta\mathbf{f}}^*)\,.$ |

- CP asymmetry for Dirac neutrinos

$$\Delta^{\mathrm{D}}_{CP,+} = \frac{-\sum_{\alpha,\beta}\mathcal{J}_{\alpha\beta}^{\mathbf{if}}\mathrm{Im}(\mathcal{F}_{\mathbf{if},\alpha}\mathcal{F}_{\mathbf{if},\beta}^*)m_{\mathbf{f}}^2}{\sum_{\alpha,\beta}\mathcal{R}_{\alpha\beta}^{\mathbf{if}}\left[\mathrm{Re}(\mathcal{F}_{\mathbf{fi},\alpha}\mathcal{F}_{\mathbf{fi},\beta}^*)m_{\mathbf{i}}^2 + \mathrm{Re}(\mathcal{F}_{\mathbf{if},\alpha}\mathcal{F}_{\mathbf{if},\beta}^*)m_{\mathbf{f}}^2\right]}\,,$$

$$\Delta^{\mathrm{D}}_{CP,-} = \frac{-\sum_{\alpha,\beta}\mathcal{J}_{\alpha\beta}^{\mathbf{if}}\mathrm{Im}(\mathcal{F}_{\mathbf{fi},\alpha}\mathcal{F}_{\mathbf{fi},\beta}^*)m_{\mathbf{i}}^2}{\sum_{\alpha,\beta}\mathcal{R}_{\alpha\beta}^{\mathbf{if}}\left[\mathrm{Re}(\mathcal{F}_{\mathbf{fi},\alpha}\mathcal{F}_{\mathbf{fi},\beta}^*)m_{\mathbf{i}}^2 + \mathrm{Re}(\mathcal{F}_{\mathbf{if},\alpha}\mathcal{F}_{\mathbf{if},\beta}^*)m_{\mathbf{f}}^2\right]}\,,$$

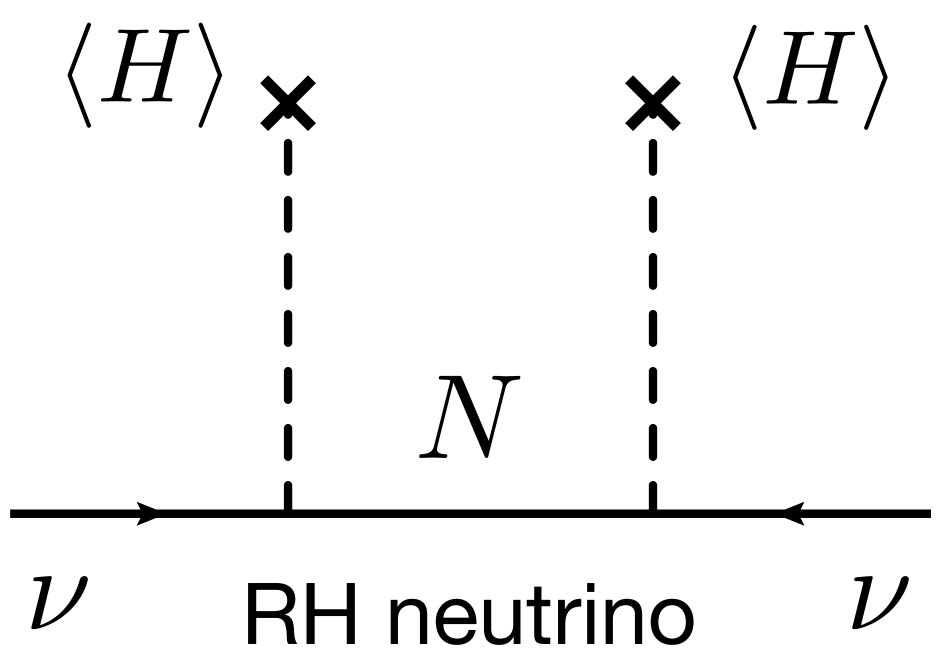
Interference between charged leptons with different masses (always satisfied)

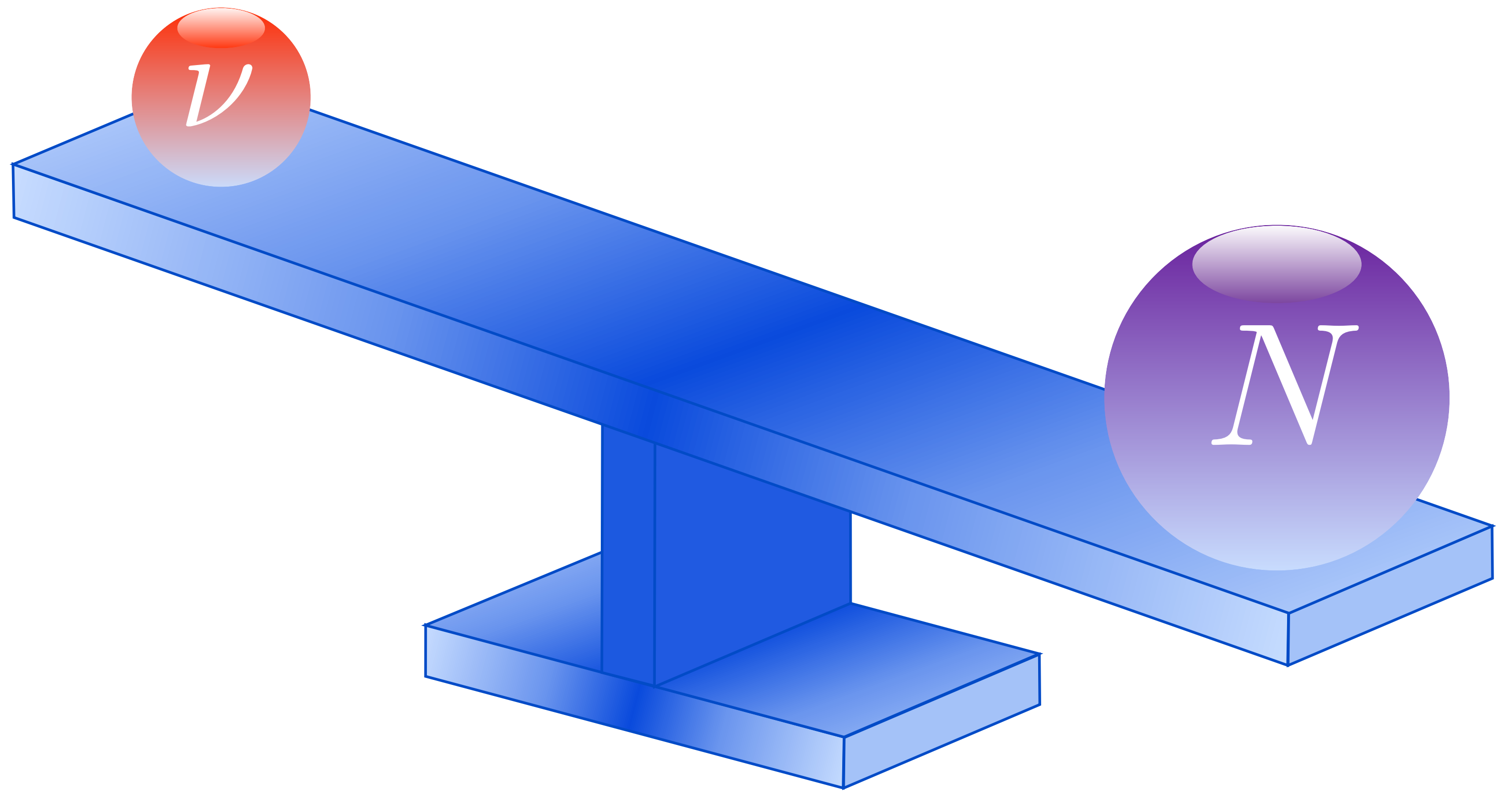
- CP asymmetry for Majorana neutrinos

$$\Delta^{\mathrm{M}}_{CP} = \frac{\sum_{\alpha,\beta}\mathcal{J}_{\alpha\beta}^{\mathbf{if}}\left[\mathrm{Im}(\mathcal{F}_{\mathbf{fi},\alpha}\mathcal{F}_{\mathbf{fi},\beta}^*)m_{\mathbf{i}}^2 - \mathrm{Im}(\mathcal{F}_{\mathbf{if},\alpha}\mathcal{F}_{\mathbf{if},\beta}^*)m_{\mathbf{f}}^2\right] - 2\mathcal{V}_{\alpha\beta}^{\mathbf{if}}\mathrm{Im}(\mathcal{F}_{\mathbf{fi},\alpha}\mathcal{F}_{\mathbf{if},\beta}^*)m_{\mathbf{i}}m_{\mathbf{f}}}{\sum_{\alpha,\beta}\mathcal{R}_{\alpha\beta}^{\mathbf{if}}\left[\mathrm{Re}(\mathcal{F}_{\mathbf{fi},\alpha}\mathcal{F}_{\mathbf{fi},\beta}^*)m_{\mathbf{i}}^2 + \mathrm{Re}(\mathcal{F}_{\mathbf{if},\alpha}\mathcal{F}_{\mathbf{if},\beta}^*)m_{\mathbf{f}}^2\right] - 2\mathcal{C}_{\alpha\beta}^{\mathbf{if}}\mathrm{Re}(\mathcal{F}_{\mathbf{fi},\alpha}\mathcal{F}_{\mathbf{if},\beta}^*)m_{\mathbf{i}}m_{\mathbf{f}}}\,,$$

# CP asymmetries in different channels in seesaw

- Seesaw mechanism




$$\mathcal{M}_{\nu+N} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \Rightarrow \begin{cases} M_\nu = -M_D M_R^{-1} M_D^T \\ \mathcal{U} = \begin{pmatrix} U & R \\ \times & \times \end{pmatrix} \end{cases}$$

*R*: active-sterile mixing

- minimal seesaw: two RH neutrinos $N_1$ and $N_2$ $\Rightarrow m_1 = 0$

We fix the mass ordering $M_2 > M_1$ such that $N_2$ can decay to $N_1$

Casas-Ibarra parametrisation

$$R_{\alpha I} = \sum_{i=1,2} U_{\alpha i} \Omega_{iI} \sqrt{\frac{m_{i+1}}{M_I}}. \qquad \Omega = \begin{pmatrix} \cos\omega & \sin\omega \\ -\zeta \sin\omega & \zeta \cos\omega \end{pmatrix}$$

$\omega$ is a complex mixing angle

$\zeta = \pm 1$

# CP asymmetries in all radiative decay channels

Balaji, Ramirez-Quezada, **YLZ**, 2008.12795

- $\nu_i \to \nu_j + \gamma$ $\Rightarrow$ no CP violation

- $N_I \to \nu + \gamma$ with $M_I > M_W$

$$\Delta_{CP}(N_I \to \nu\gamma) = \frac{\sum_i \sum_{\alpha,\beta} \mathcal{J}_{\alpha\beta}^{(I+3)i} \mathrm{Im}(\mathcal{F}_{i(I+3),\alpha} \mathcal{F}^*_{i(I+3),\beta})}{\sum_i \sum_{\alpha,\beta} \mathcal{R}_{\alpha\beta}^{(I+3)i} \mathrm{Re}(\mathcal{F}_{i(I+3),\alpha} \mathcal{F}^*_{i(I+3),\beta})} \lesssim 10^{-17}$$

$\Rightarrow$ very small CP violation

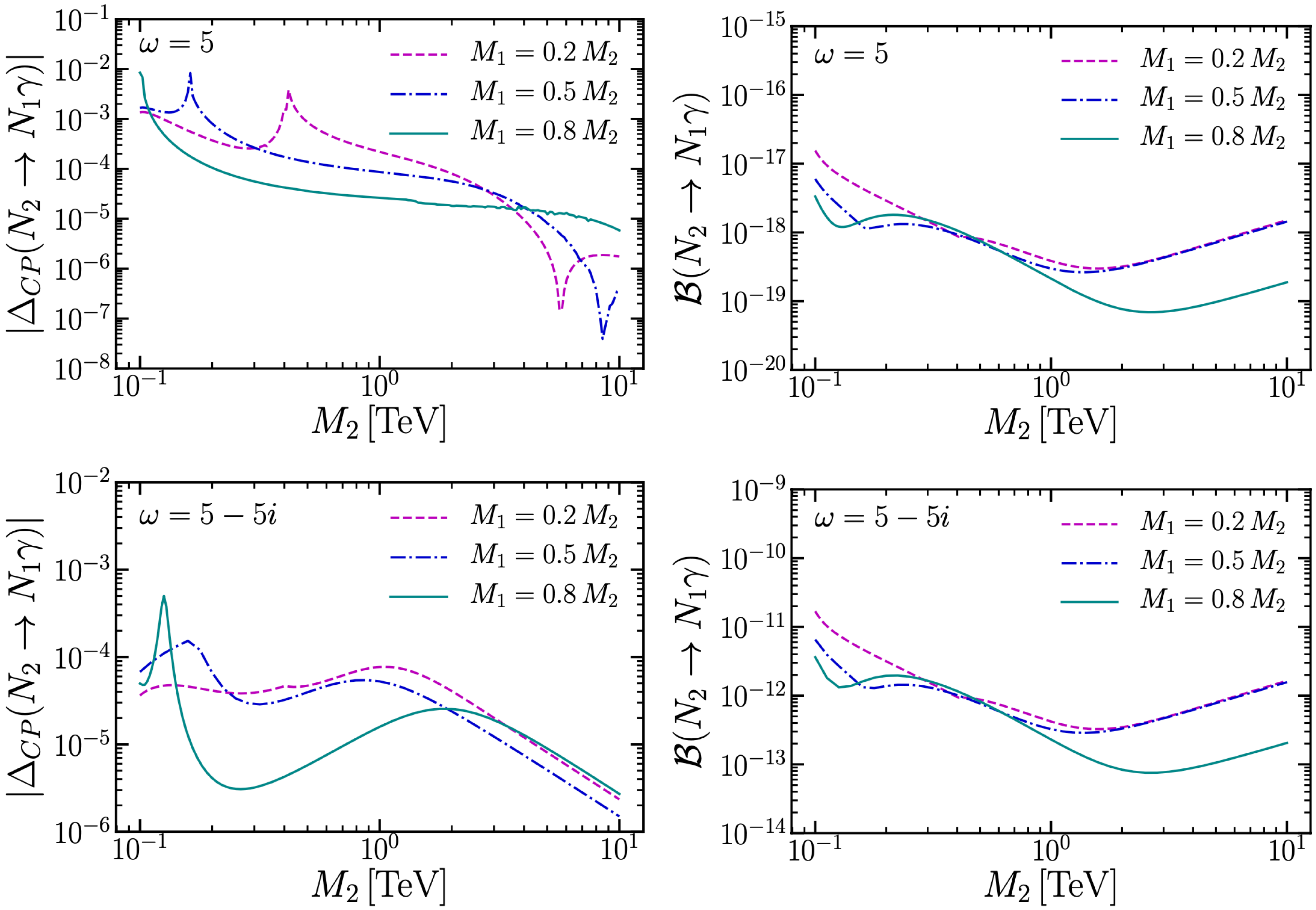
- $N_2 \to N_1 + \gamma$

$$\Delta_{CP}(N_2 \to N_1\gamma) = \frac{\sum_{\alpha,\beta} \mathcal{J}_{\alpha\beta}^{54} \left[\mathrm{Im}(\mathcal{F}_{45,\alpha}\mathcal{F}^*_{45,\beta}) M_2^2 - \mathrm{Im}(\mathcal{F}_{54,\alpha}\mathcal{F}^*_{54,\beta}) M_1^2\right] - 2\mathcal{V}_{\alpha\beta}^{54} \mathrm{Im}(\mathcal{F}_{45,\alpha}\mathcal{F}^*_{54,\beta}) M_2 M_1}{\sum_{\alpha,\beta} \mathcal{R}_{\alpha\beta}^{54} \left[\mathrm{Re}(\mathcal{F}_{45,\alpha}\mathcal{F}^*_{45,\beta}) M_2^2 + \mathrm{Re}(\mathcal{F}_{54,\alpha}\mathcal{F}^*_{54,\beta}) M_1^2\right] - 2\mathcal{C}_{\alpha\beta}^{54} \mathrm{Re}(\mathcal{F}_{45,\alpha}\mathcal{F}^*_{54,\beta}) M_2 M_1}.$$

This channel may lead to large CP violation.

# Benchmark plot of CP asymmetries

Balaji, Ramirez-Quezada, **YLZ**, 2008.12795




Oscillation parameters all fixed at there best-fit values, and $2\sigma = 180°$ assumed

# Scan plot of CP symmetries

Balaji, Ramirez-Quezada, **YLZ**, 2008.12795

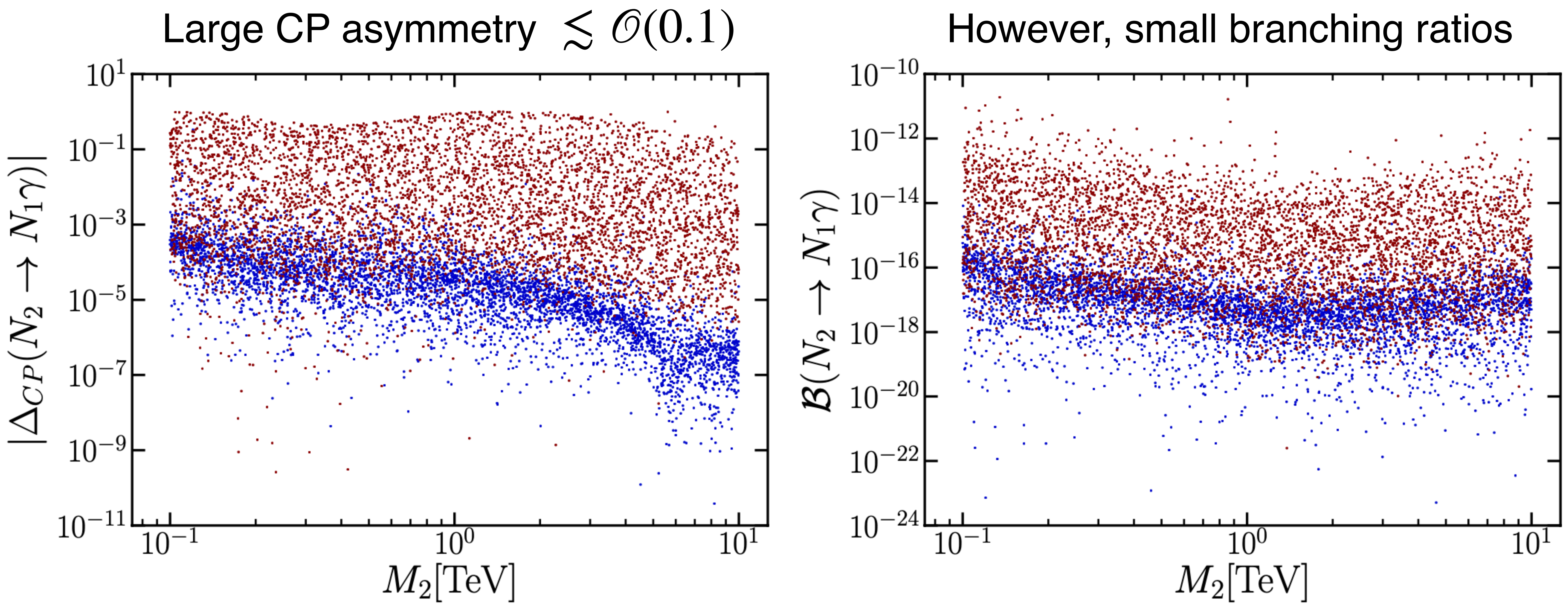
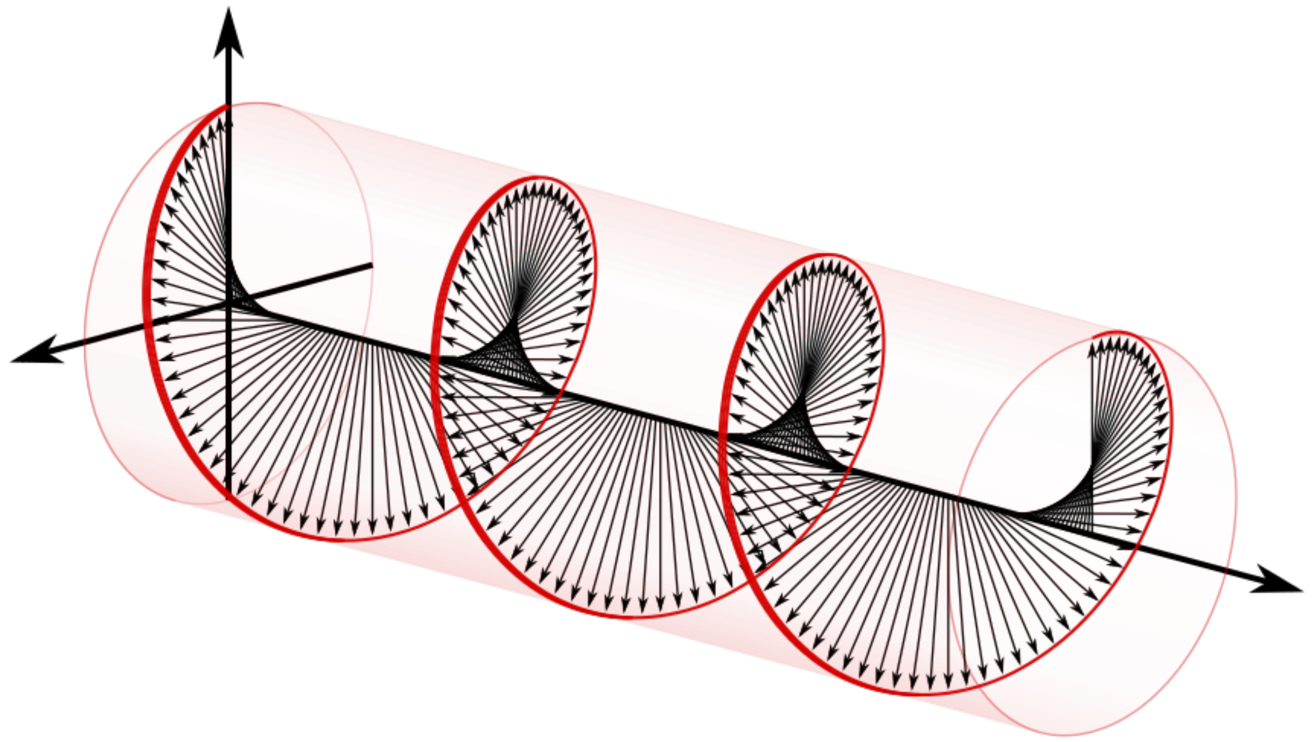



Figure 3: The $CP$ asymmetry parameter $\Delta_{CP}$ (left) and branching ratio (right) scanned in the region $M_2$ in $[0.1, 10]$ TeV and the ratio $M_1/M_2$ in $[0.1,\ 1)$, where both masses are scanned in the logarithmic scale. The red region refers to $\omega = [0, 2\pi] + i[-5, 5]$ while the blue region is the smaller $\omega = [0, 2\pi]$. All oscillation parameters are scanned in the $3\sigma$ ranges, $\omega = [0, 2\pi]$ and $\zeta = +1$ are used. The scan performed for the $\zeta = -1$ branch gives the same distribution and is thus omitted.

# A new source of photon circular polarisation

Balaji, Ramirez-Quezada, **YLZ**, 1910.08558

- In a flux of photon, a net circular polarisation represents the number density asymmetry between left- and right-circularly-polarised photons. It is chariceterised by the Stokes parameter
  $V = |\vec{\epsilon}_+ \cdot \vec{E}| - |\vec{\epsilon}_- \cdot \vec{E}|$



- Astrophysical sources

  Faraday conversion, Bi-refringence, Synchrotron emission, …

- Astroparticle sources: P and CP violation must be required

  Boehm, Degrande, Mattelaer, Vincent, 1701.02754

- A net circular polarisation can be obtained CPV radiative decay of keV neutrino dark matter

$V \sim \Delta^{\rm D}_{CP,+} - \Delta^{\rm D}_{CP,+}$ for Dirac DM

$V \sim \Delta^{\rm M}_{CP}$ for Majorana DM

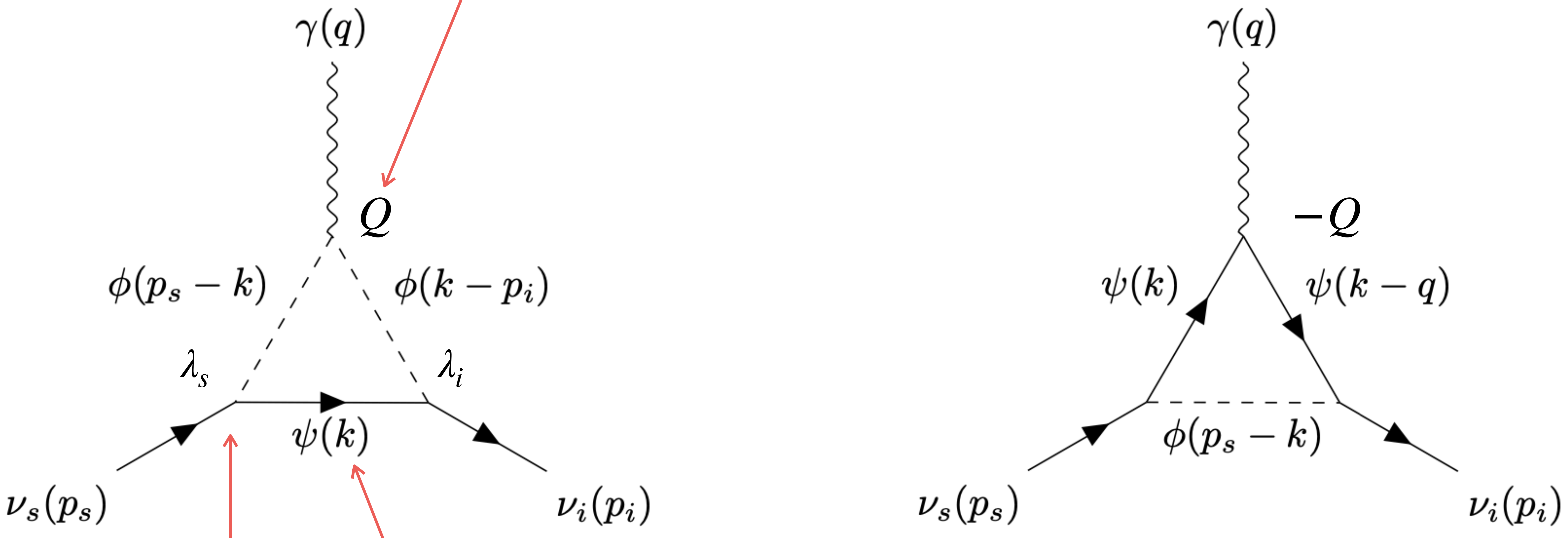
Balaji, Ramirez-Quezada, **YLZ**, 1910.08558

# Circular polarisation released from decaying DM

- A toy model: keV neutrino $\nu_s$ $\Rightarrow$ DM

  + a pair of opposite millicharged particles $\phi$ & $\psi$

small millicharge $Q < 10^{-4}e$ to avoid QED precision measurement

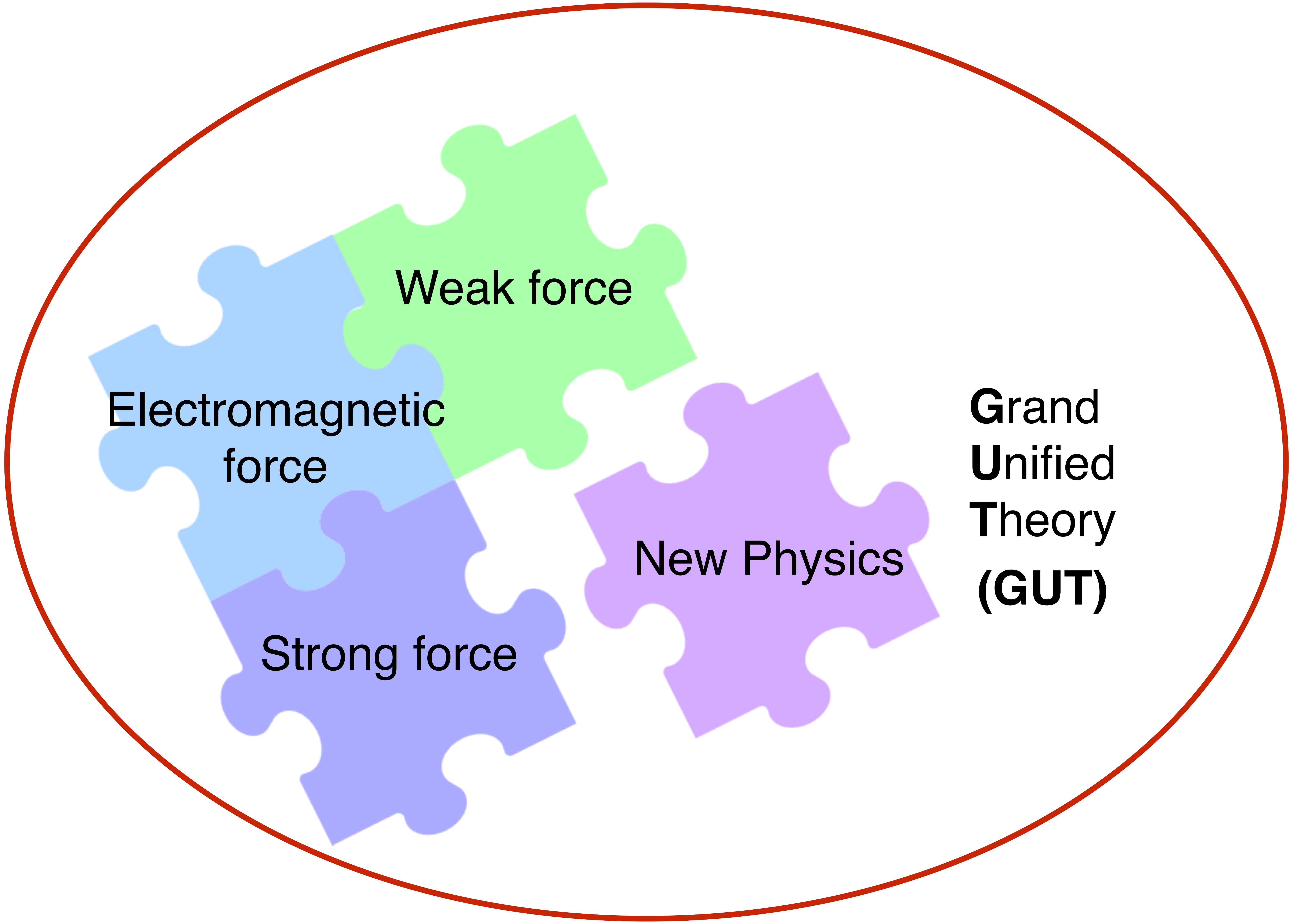



$m_\phi + m_\psi < m_s$ to generate imaginary part of loop integration

tiny $\lambda_s$ to forbid fast decay of DM, and $\mathrm{Im}(\lambda_i (U^\dagger U)_{is} \lambda_s^*) \neq 0$ for CPV

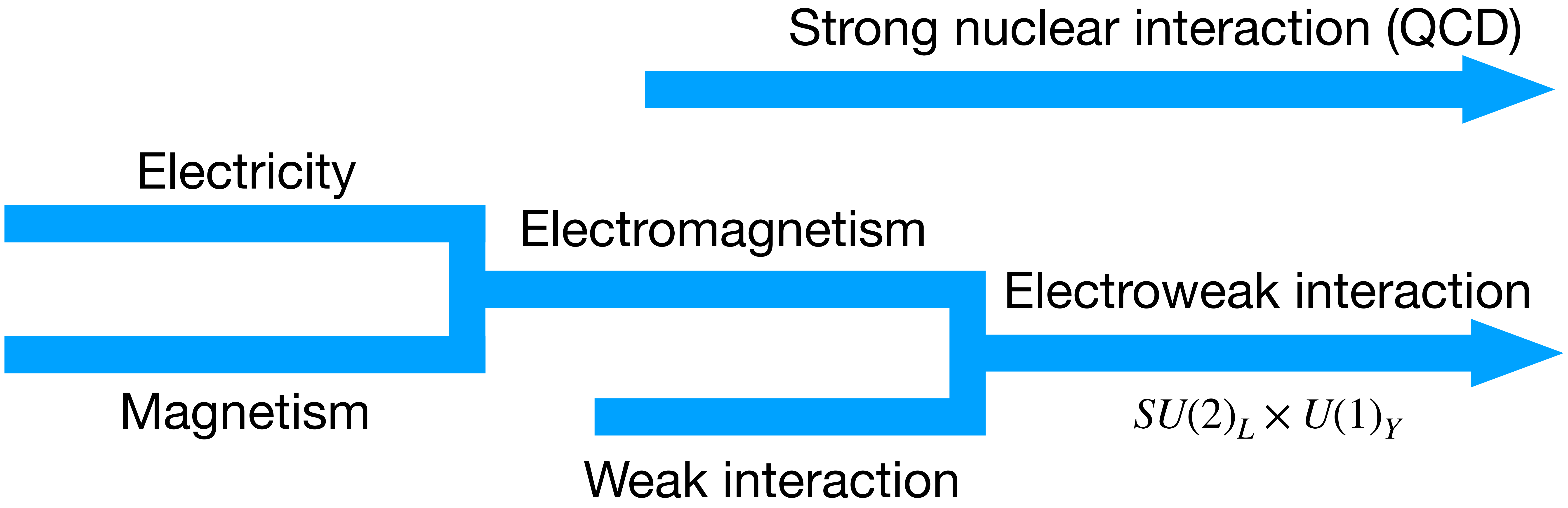
$\Rightarrow V \sim \Delta^{\mathrm{M}}_{CP} \sim 10^{-5}$ still far away from being detectable

# Probe GUTs via proton decay




Gravity… not included

# A long road of unifications

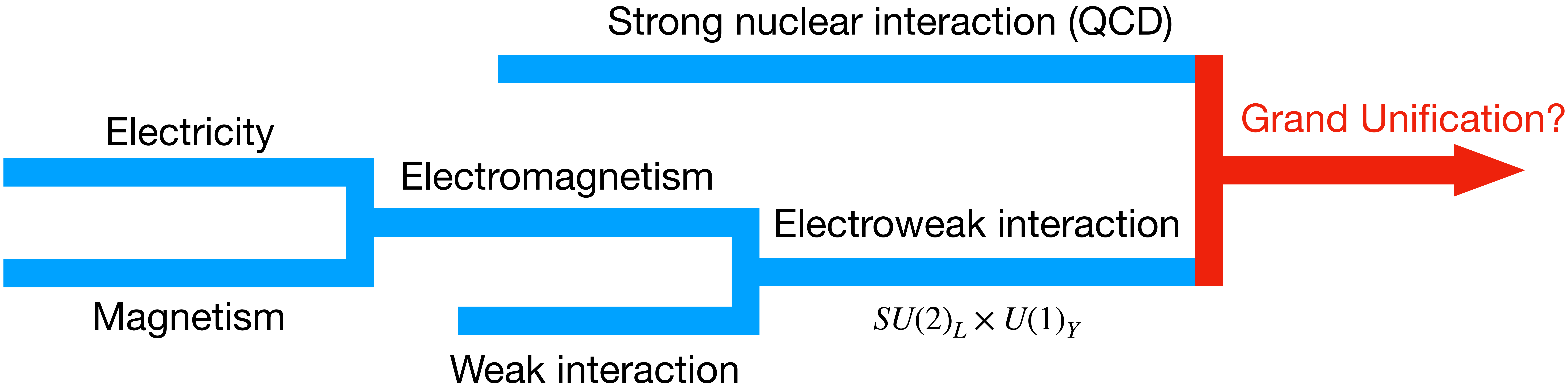



$$\nabla \cdot \mathbf{E} = 4\pi\rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial B}{\partial t}$$
$$\nabla \times \mathbf{B} = 4\pi\mathbf{J} + \frac{\partial E}{\partial t}$$

James C. Maxwell

Glashow, Salam, Weinberg

# A long road of unifications




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

James C. Maxwell

Glashow, Salam, Weinberg

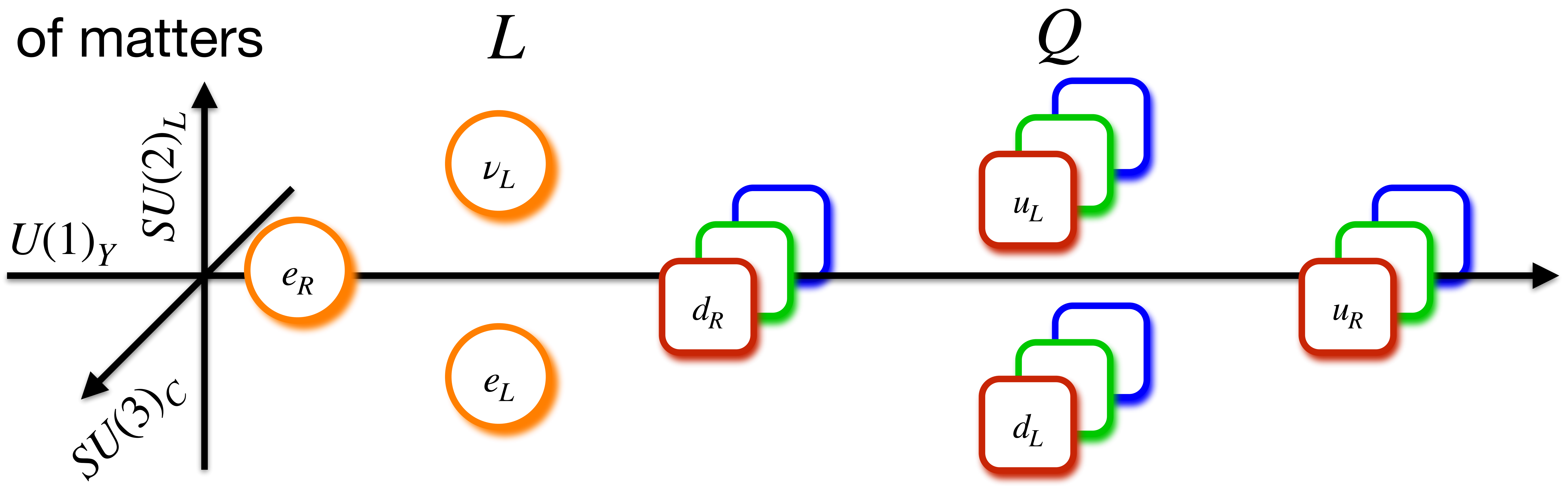
# Roads to GUTs

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

- Unification of couplings $g_3 = g_2 = g_1$ up to a loop correction factor

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

- Unification of matters




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

# Roads to GUTs

- Georgi-Glashow (1974) $SU(5)$ Quarks & leptons ~ $\bar{\mathbf{5}} + \mathbf{10}$
- More realistic $SU(5)$ e.g., including new particles to generate neutrino masses
- $SU(5) \times U(1)_{B-L}$ $\bar{\mathbf{5}} + \mathbf{10} + \mathbf{1},\ \nu_{\mathrm{R}} \sim \mathbf{1}$
- Flipped $SU(5) \times U(1)_X$ Rujula, Georgi, Glashow (1980); Barr,(1982); Derendinger, Kim, Nanopoulos (1984); Antoniadis, Ellis, Hagelin, Nanopoulos (1989)

  $u \leftrightarrow d,\ \nu \leftrightarrow e$
- Pati-Salam (1973), $SU(4)_c \times SU(2)_L \times SU(2)_R = G_{422}$

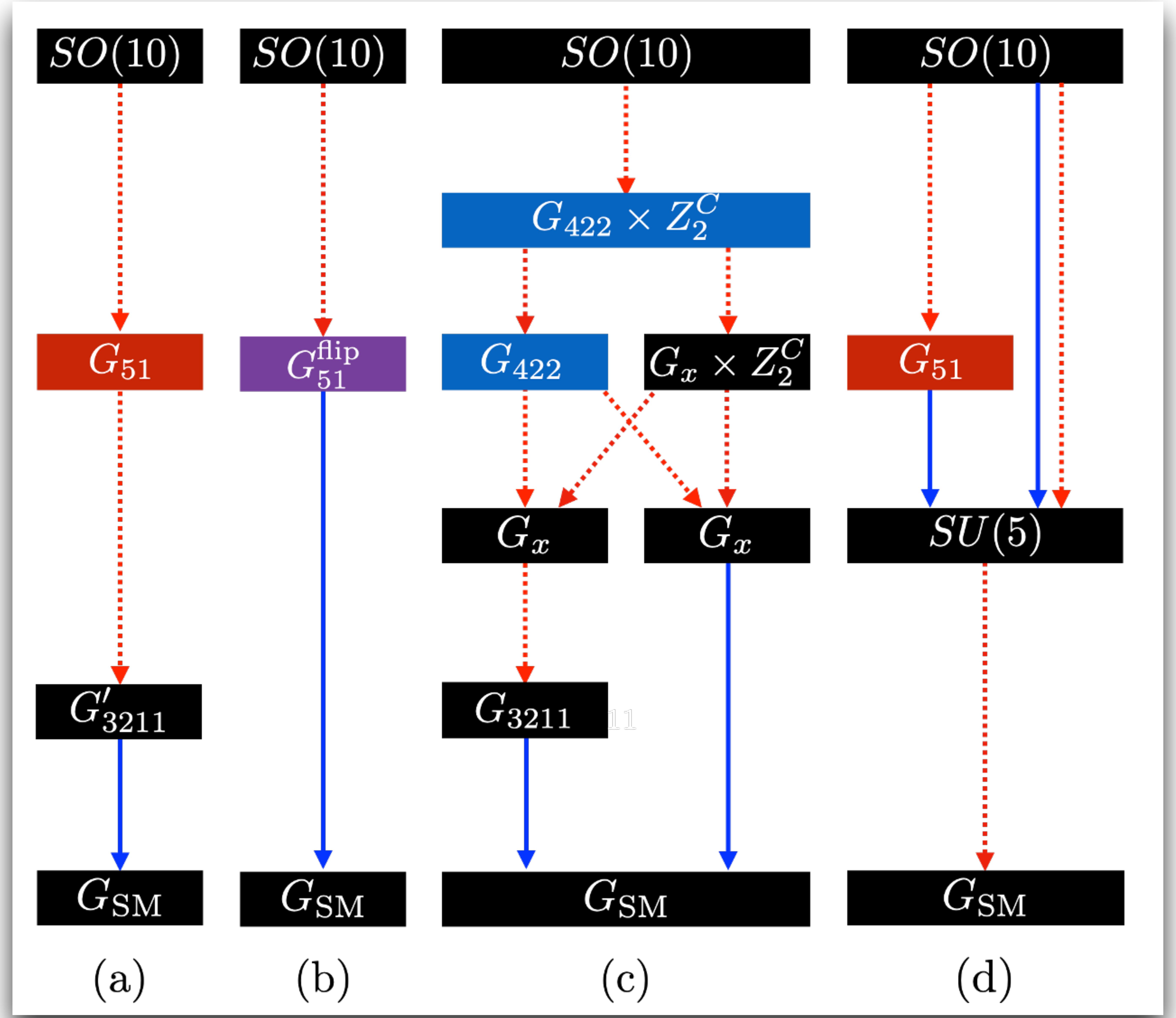
$$(\mathbf{4}, \mathbf{2}, \mathbf{1}) : \psi_L = \begin{pmatrix} u^1 & u^2 & u^3 & \nu \\ d^1 & d^2 & d^3 & e \end{pmatrix}_L, \quad (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2}) : \psi_R = \begin{pmatrix} u^1 & u^2 & u^3 & \nu \\ d^1 & d^2 & d^3 & e \end{pmatrix}_R^c$$

- $SO(10)$ GUTs

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

  Fritzsch, Minkowski (1975) $SO(10)$ $SU(5)$ $SU(4)_c \times SU(2)_L \times SU(2)_R$

# 1st entity: groups & representations




SO(10) breaking chain

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

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

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

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

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

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

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

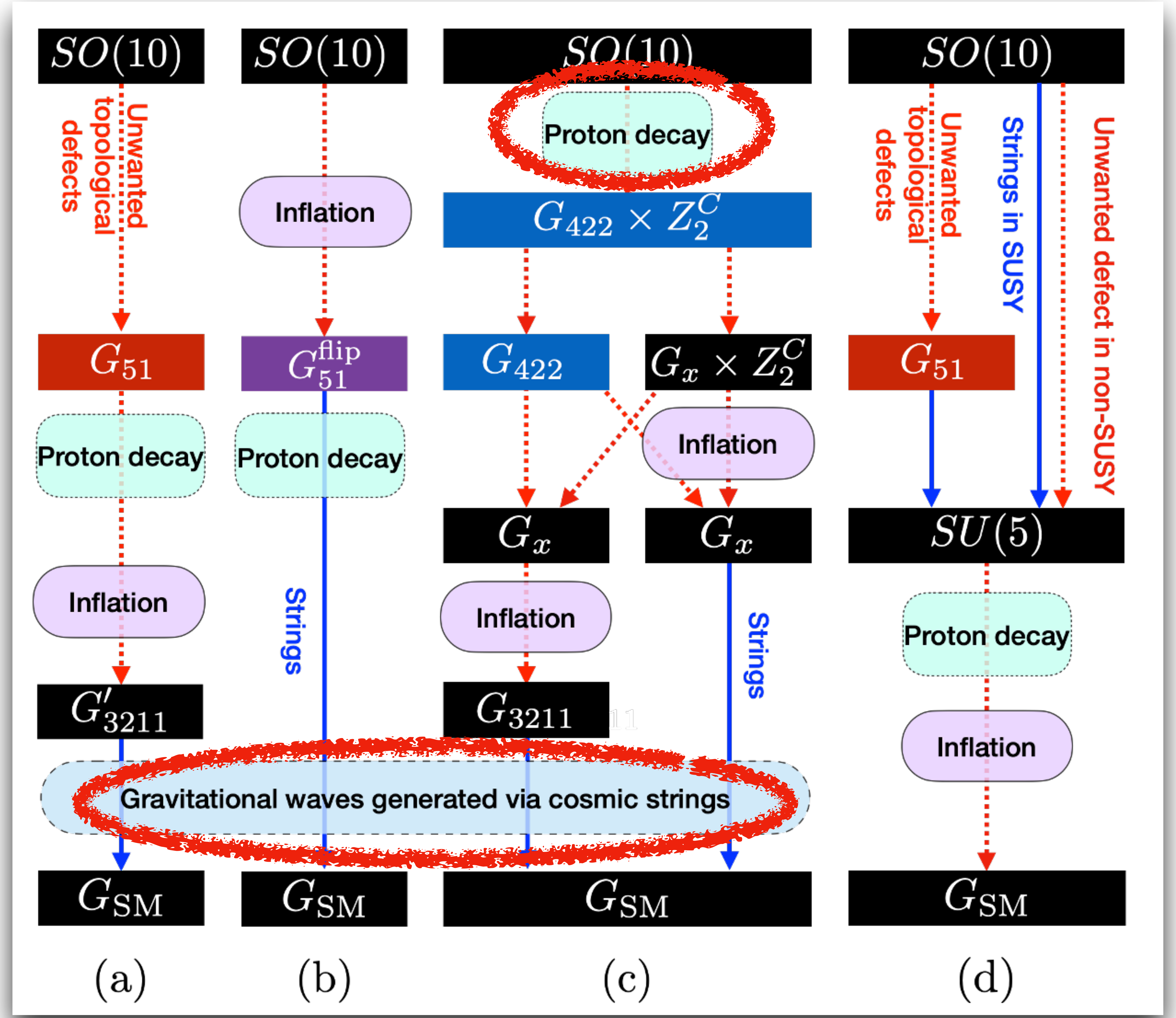
$G_{3211} = SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$

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

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

# SO(10) phenos

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 $G_{3221}$

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

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

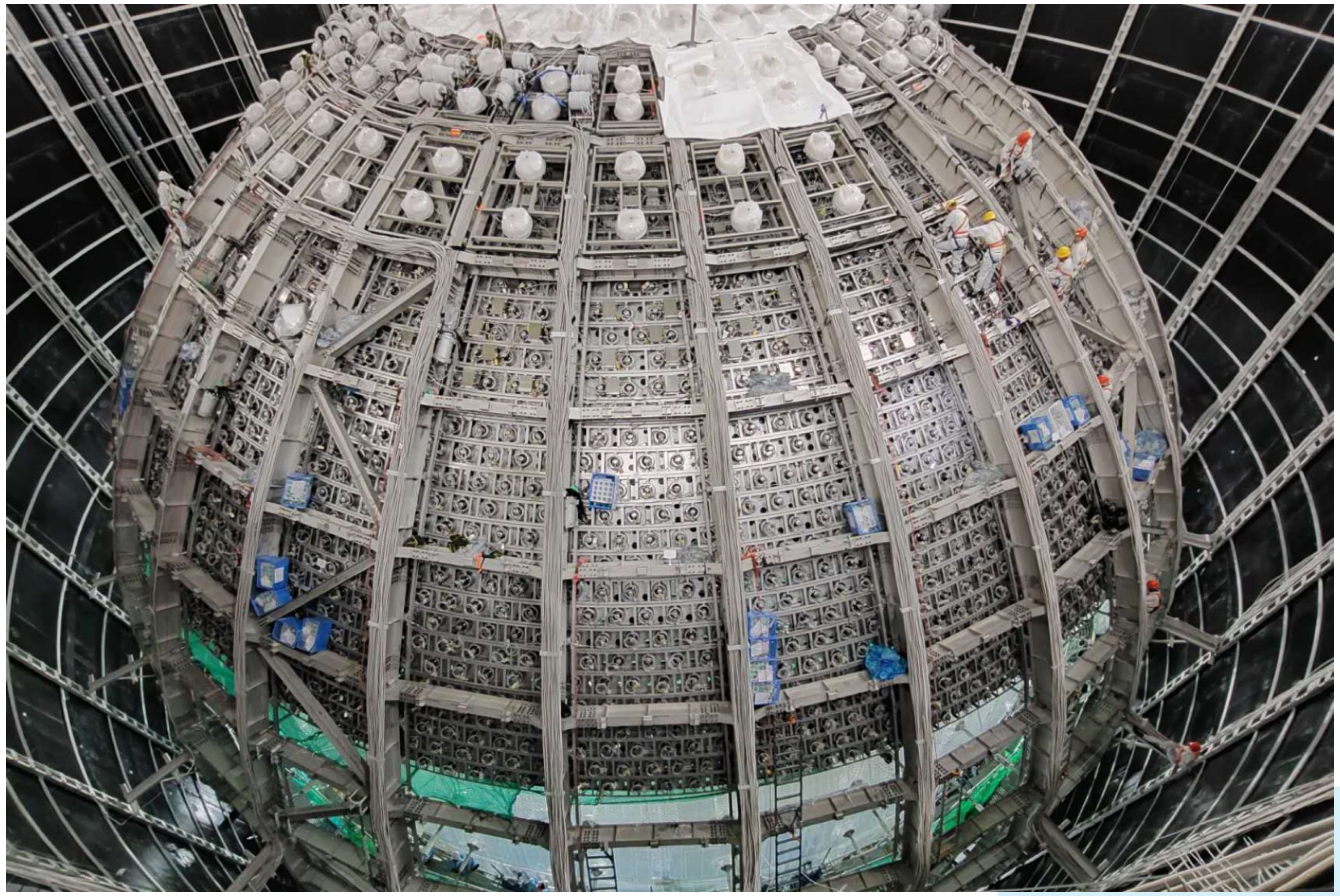
$G_{3211} = SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L}$

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

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

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

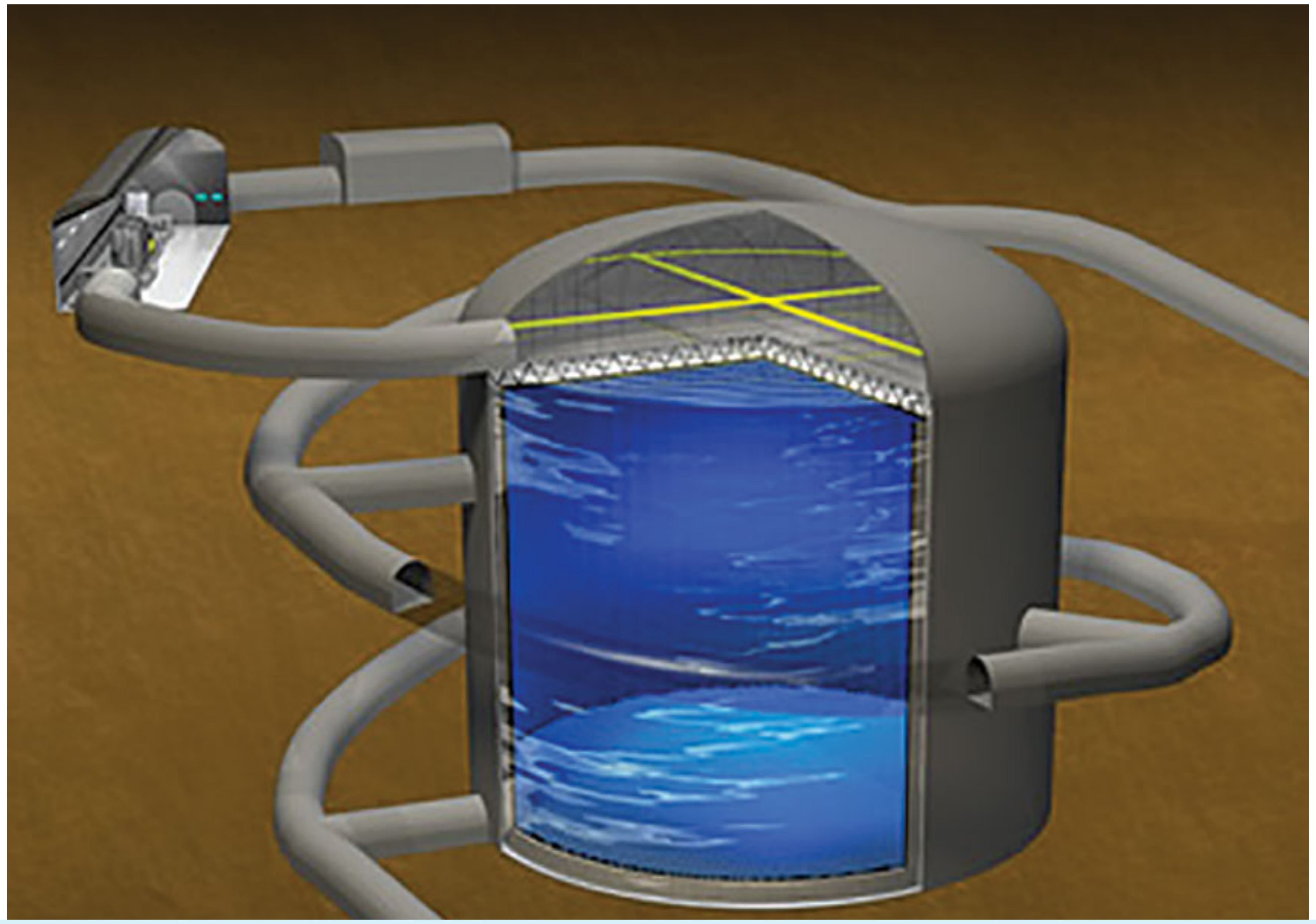
# Upcoming large-scale neutrino experiments



Hyper-K

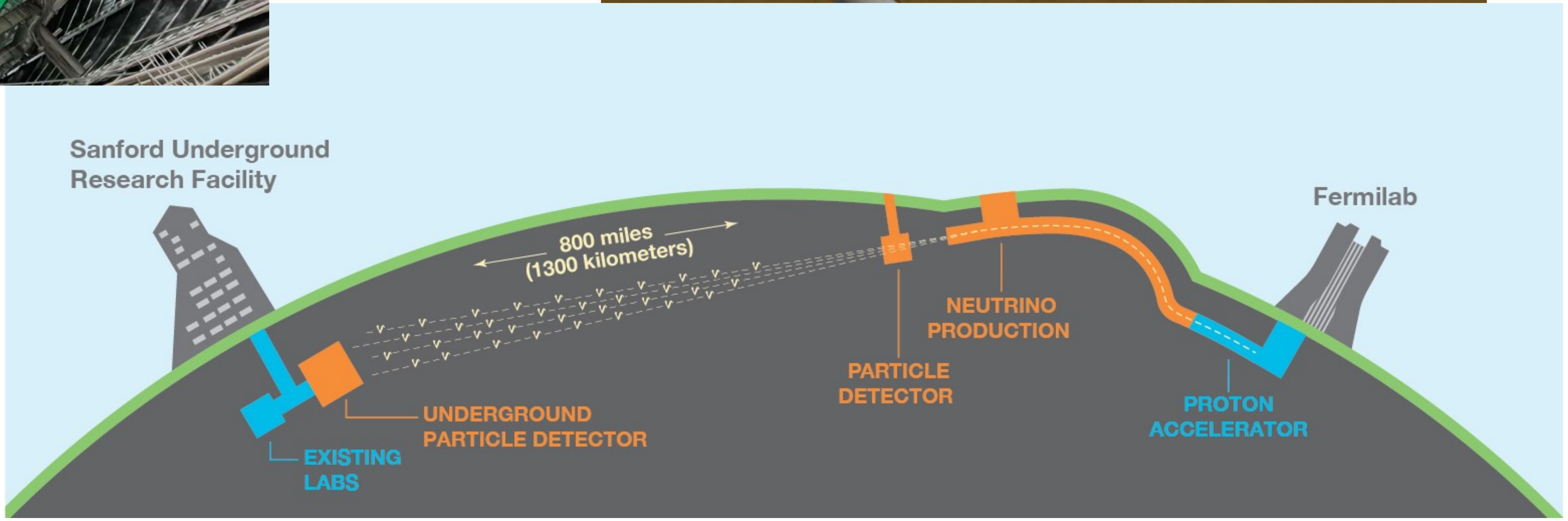
expected to run in 2027

188 kt FV
$\sim 6 \times 10^{34}$ proton



JUNO, run next year
20kt FV $\sim 7 \times 10^{33}$ proton

DUNE, run in 2030?



# Binding between GUTs and neutrino experiments

**KamiokaNDE** [ edit ] https://en.wikipedia.org/wiki/Kamioka_Observatory#KamiokaNDE

The first of the Kamioka experiments was named KamiokaNDE for **Kamioka Nucleon Decay Experiment**. It was a large water Čerenkov detector designed to search for proton decay. To observe the decay of a particle with a lifetime as long as a proton an experiment must run for a long time and observe an enormous number of protons. This can be done most cost effectively if the target (the source of the protons) and the detector itself are made of the same material. Water is an ideal candidate because … production of Čeren… background from cosmic ray muons in such a large detector located on the surface of the Earth would be far too large. The muon rate in the KamiokaNDE experiment was about 0.4 events per second, roughly five orders of magnitude smaller than what it would have been if the detector had been located at the surface.[4]

KamiokaNDE for **Kamioka Nucleon Decay Experiment.**

A model of KamiokaNDE

The distinct pattern produced by Čerenkov radiation allows for particle identification, an important tool both understanding the potential proton decay signal and for rejecting backgrounds. The ID is possible because the sharpness of the edge of the ring depends on the particle producing the radiation. Electrons (and therefore also gamma rays) produce fuzzy rings due to the multiple scattering of the low mass electrons. Minimum ionizing muons, in contrast produce very sharp rings as their heavier mass allows them to propagate directly.

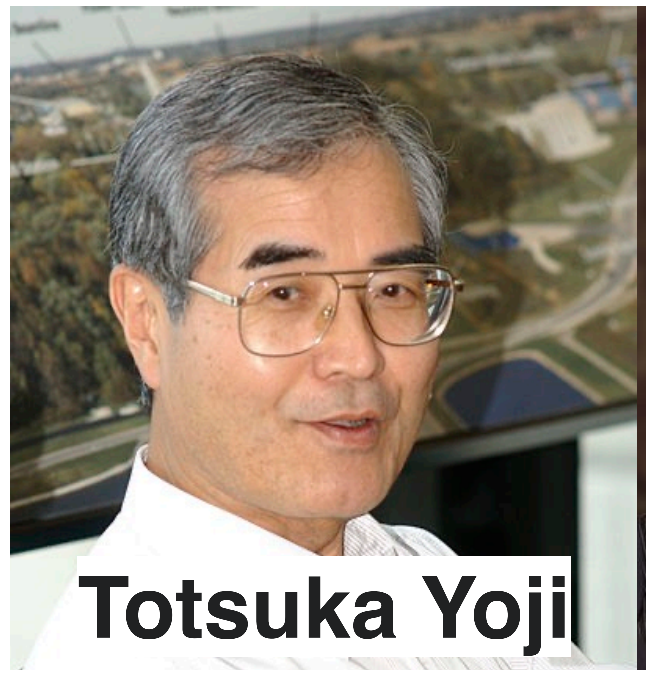
Construction of Kamioka Underground Observatory (the predecessor of the present Kamioka Observatory, Institute for Cosmic Ray Research, University of Tokyo) began in 1982 and was completed in April, 1983. The detector was a cylindrical tank which contained 3,000 tons of pure water and had about 1,000 50 cm diameter photomultiplier tubes (PMTs) attached to the inner surface. The size of the outer detector was 16.0 m in height and 15.6 m in diameter. The detector failed to observe proton decay, but set what was then the world's best limit on the lifetime of the proton.

KamiokaNDE → Kamiokande-II → Super-Kamiokande → …


**Masatoshi Koshiba**

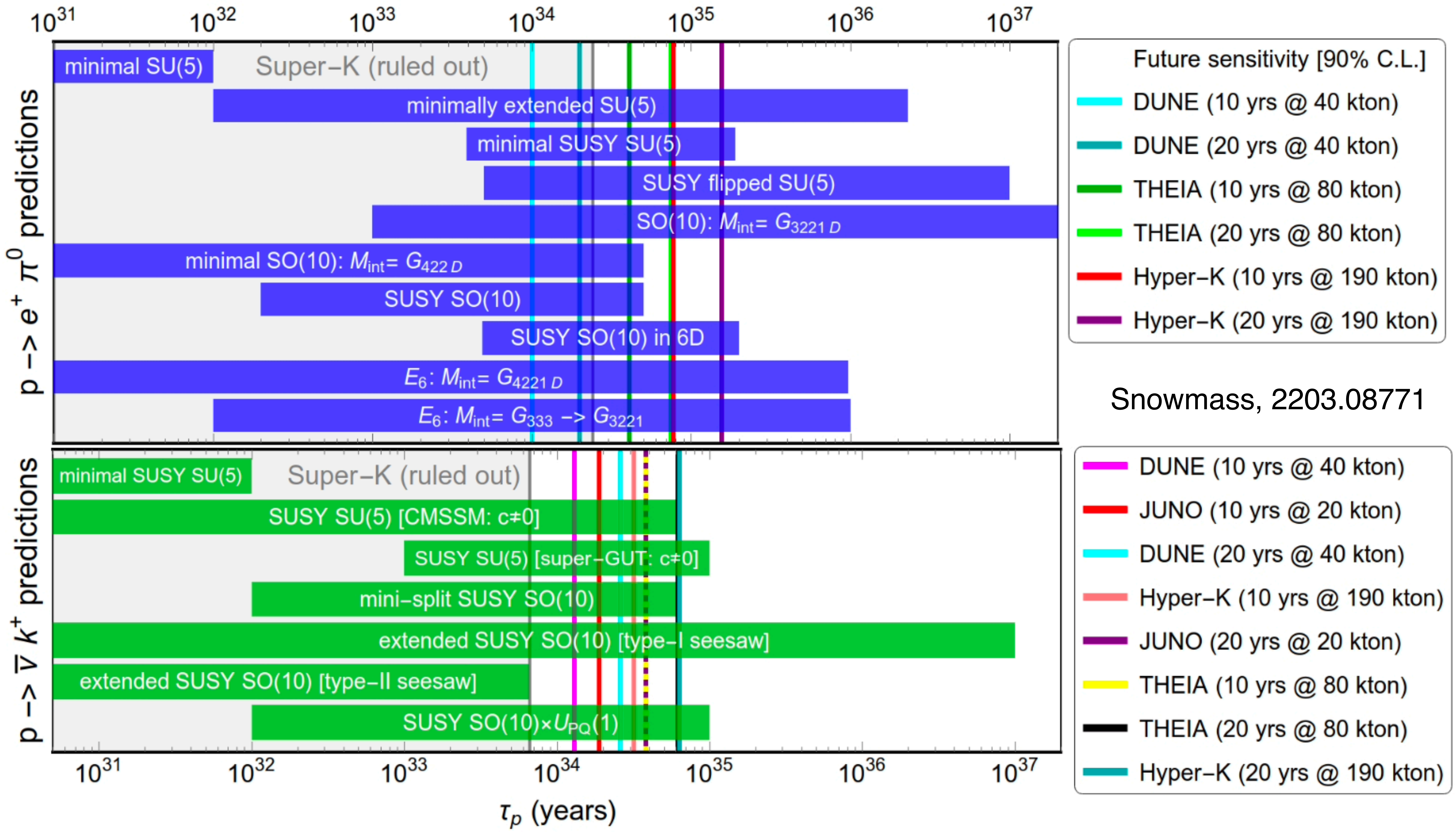
Observe neutrino flux from SN 1987A

Observe neutrino oscillation in 1998


**Totsuka Yoji**

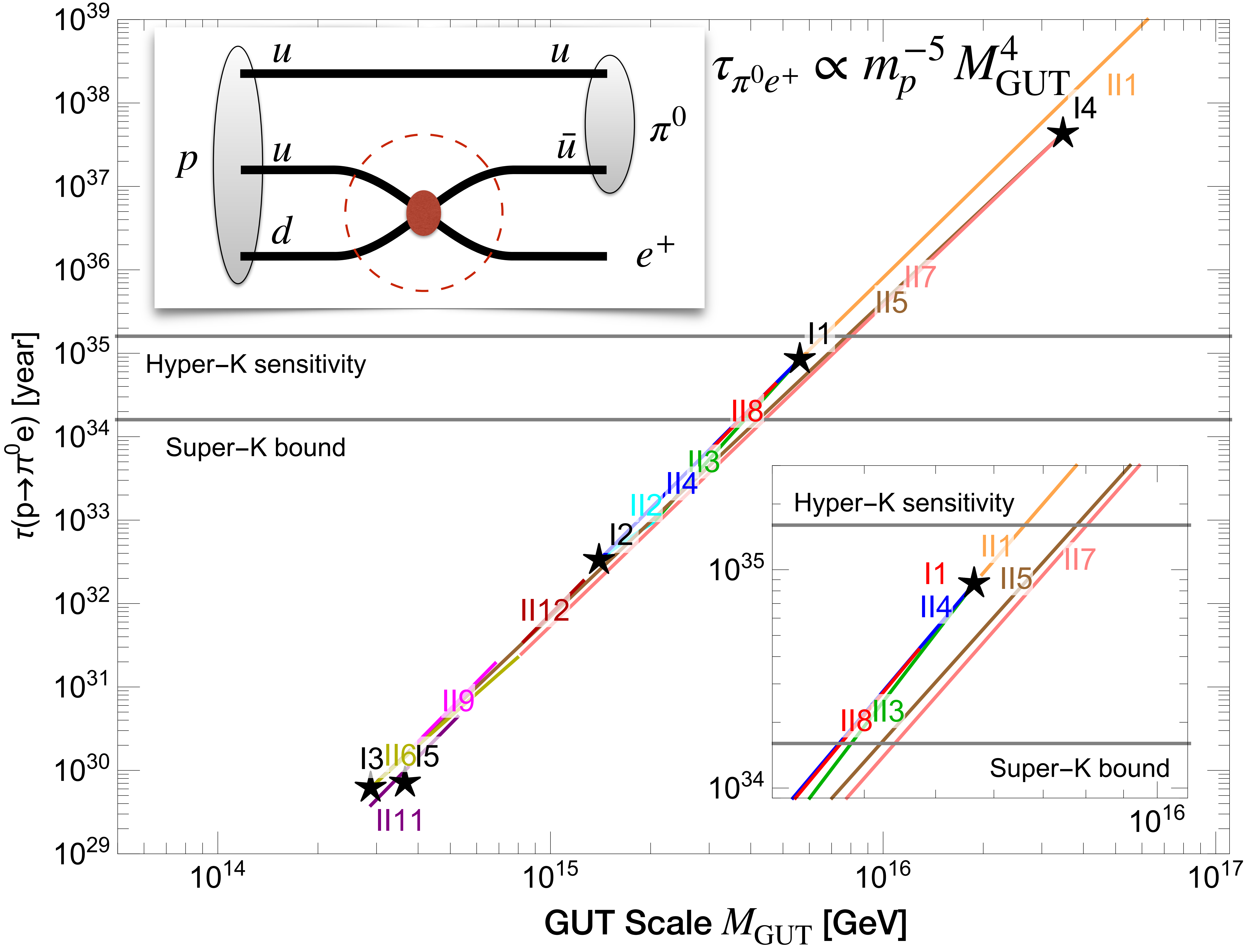

**Takaaki Kajita**

# Proton decay measurements in upcoming neutrino experiments




Snowmass, 2203.08771

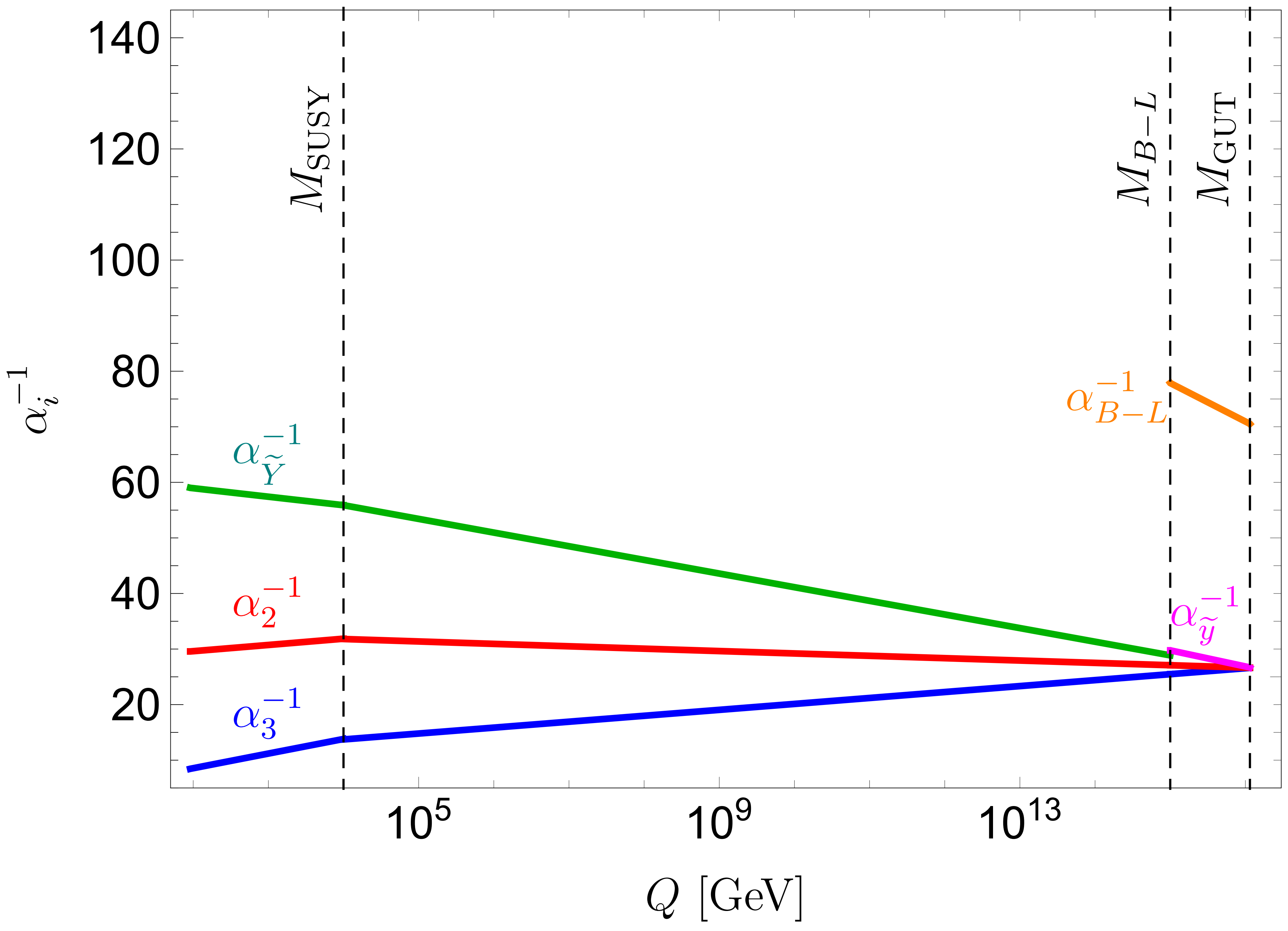
# Proton decay in SO(10) GUTs

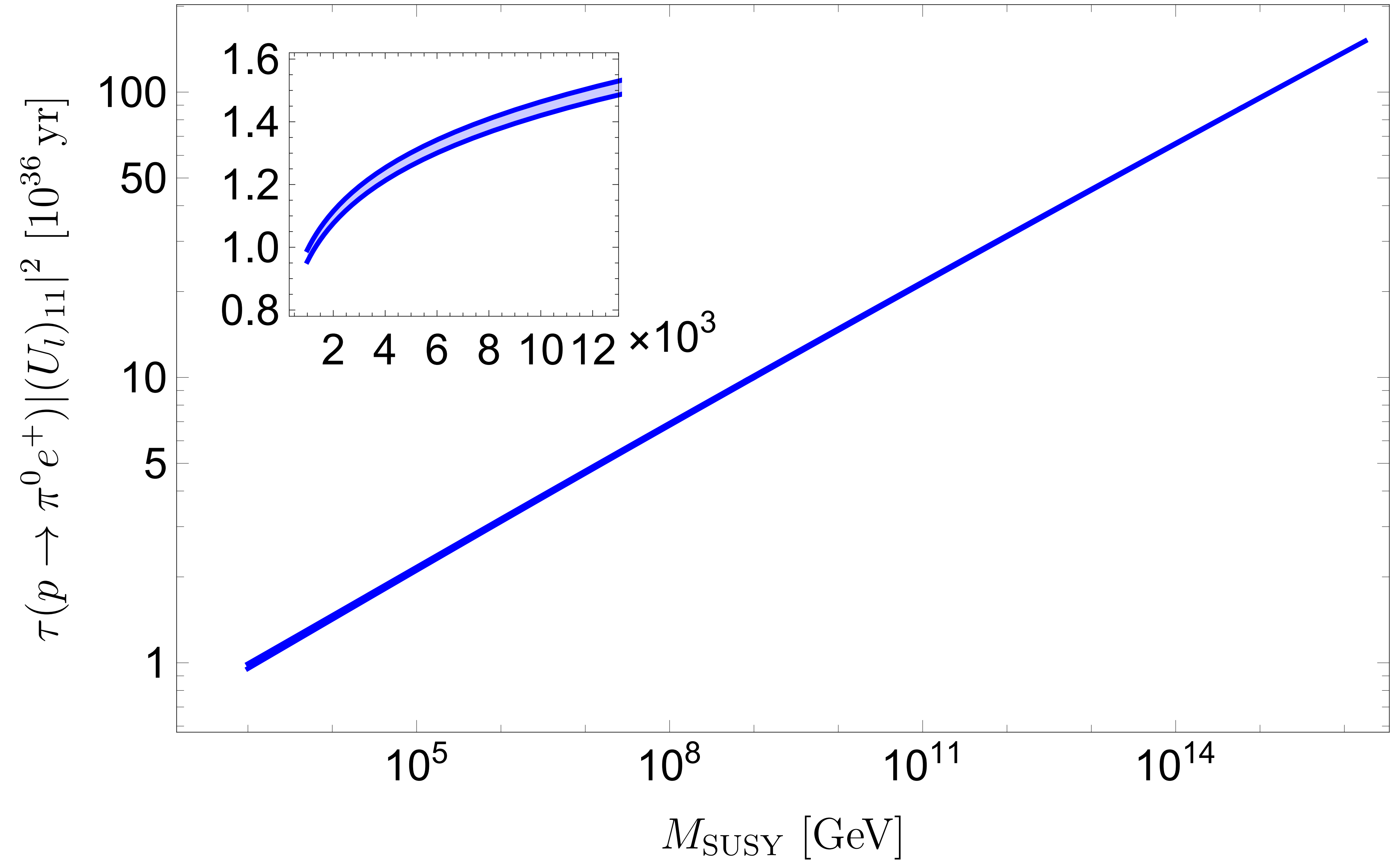


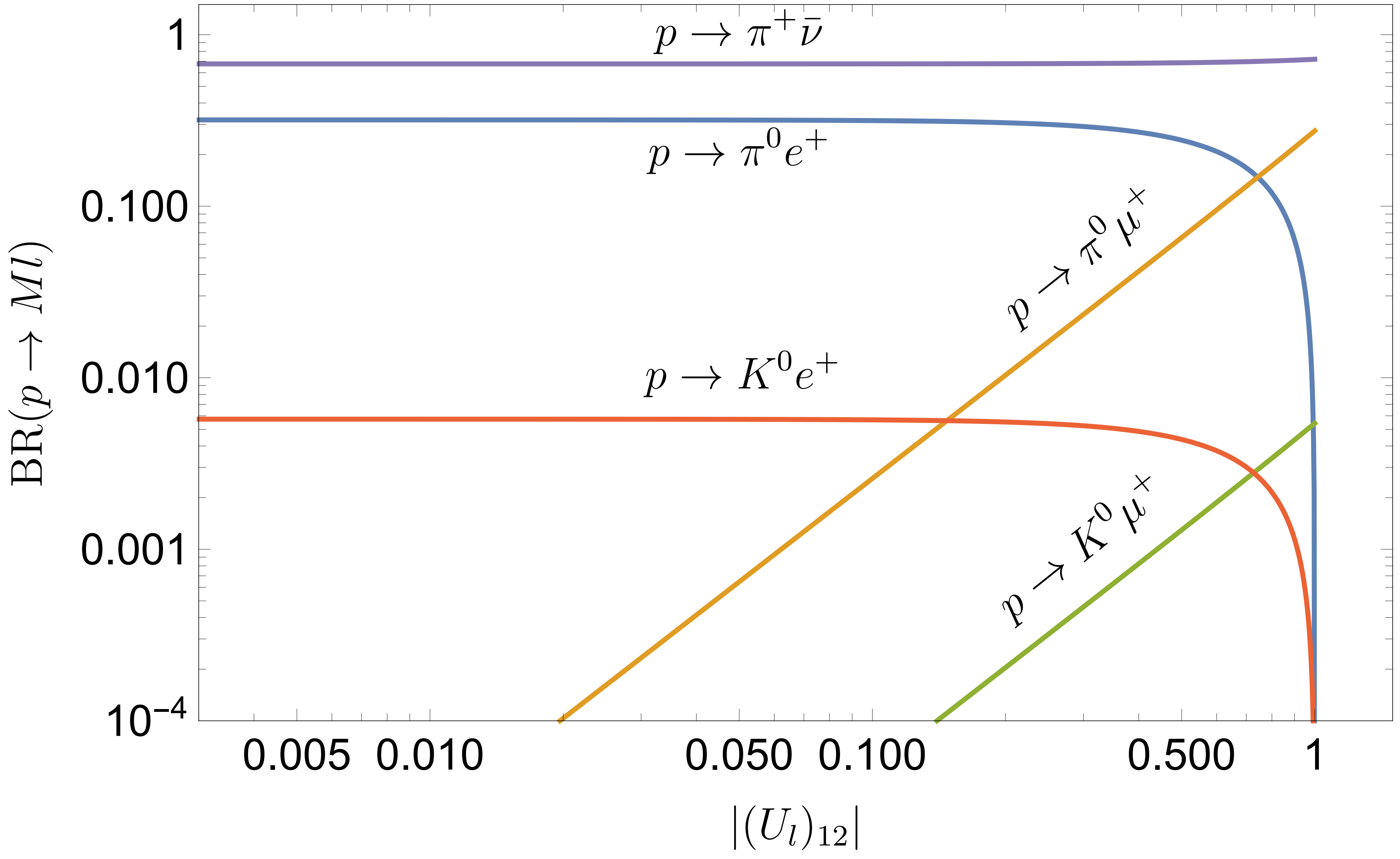

| $SO(10)$ | $\xrightarrow[\text{Higgs}]{\text{defect}}$ | $G_2$ | $\xrightarrow[\text{Higgs}]{\text{defect}}$ | $G_1$ | $\xrightarrow[\text{Higgs}]{\text{defect}}$ | $G_{\rm SM}$ |
|---|---|---|---|---|---|---|
| II1: | $\xrightarrow[\mathbf{210}]{\text{m}}$ | $G_{422}$ | $\xrightarrow[\mathbf{45}]{\text{m}}$ | $G_{3221}$ | $\xrightarrow[\mathbf{126}]{\text{s}}$ | |
| 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

# Proton decay in flipped SU(5)  $u \leftrightarrow d,\ \nu \leftrightarrow e$



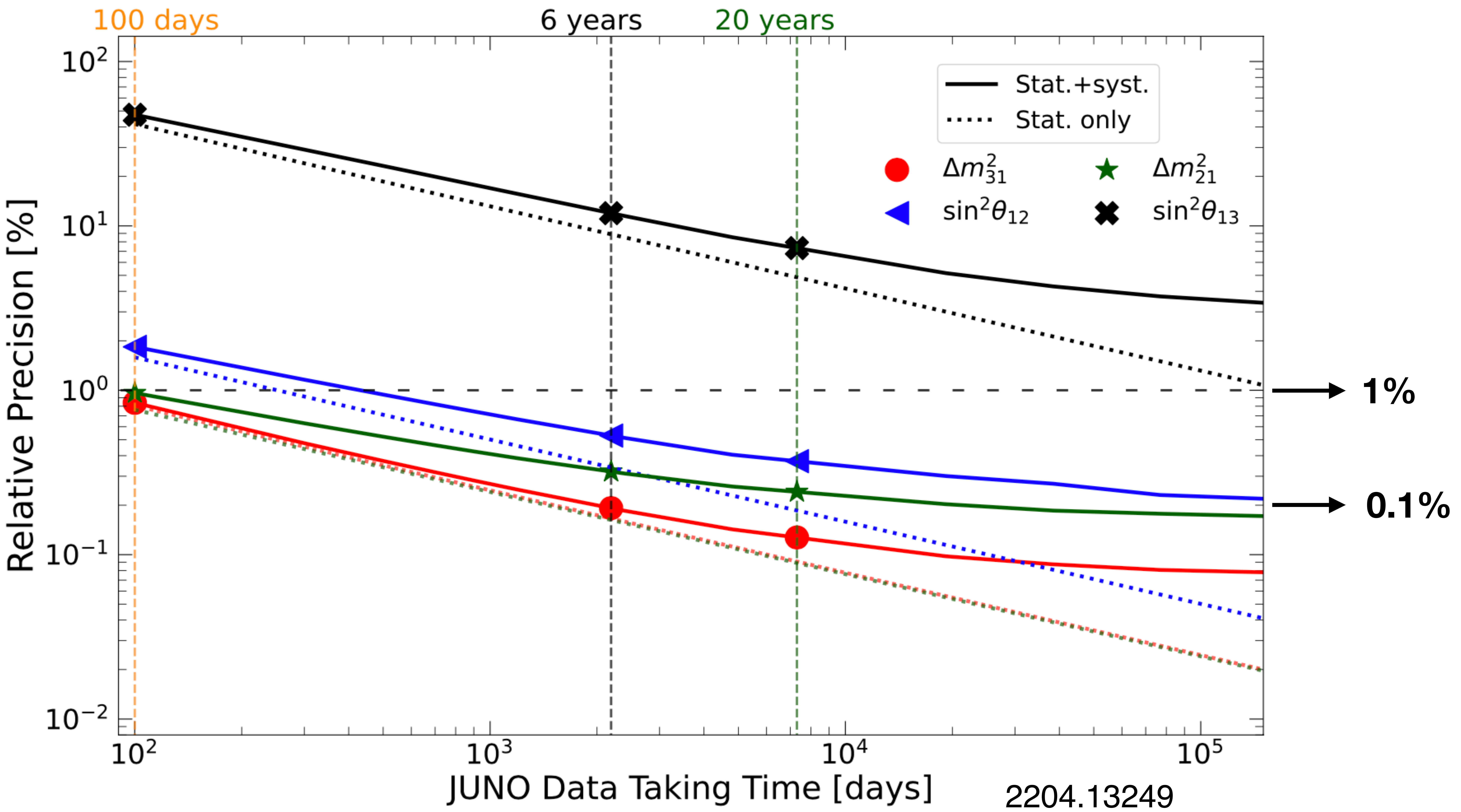




King, Leontaris, **YLZ**,
2311.11857

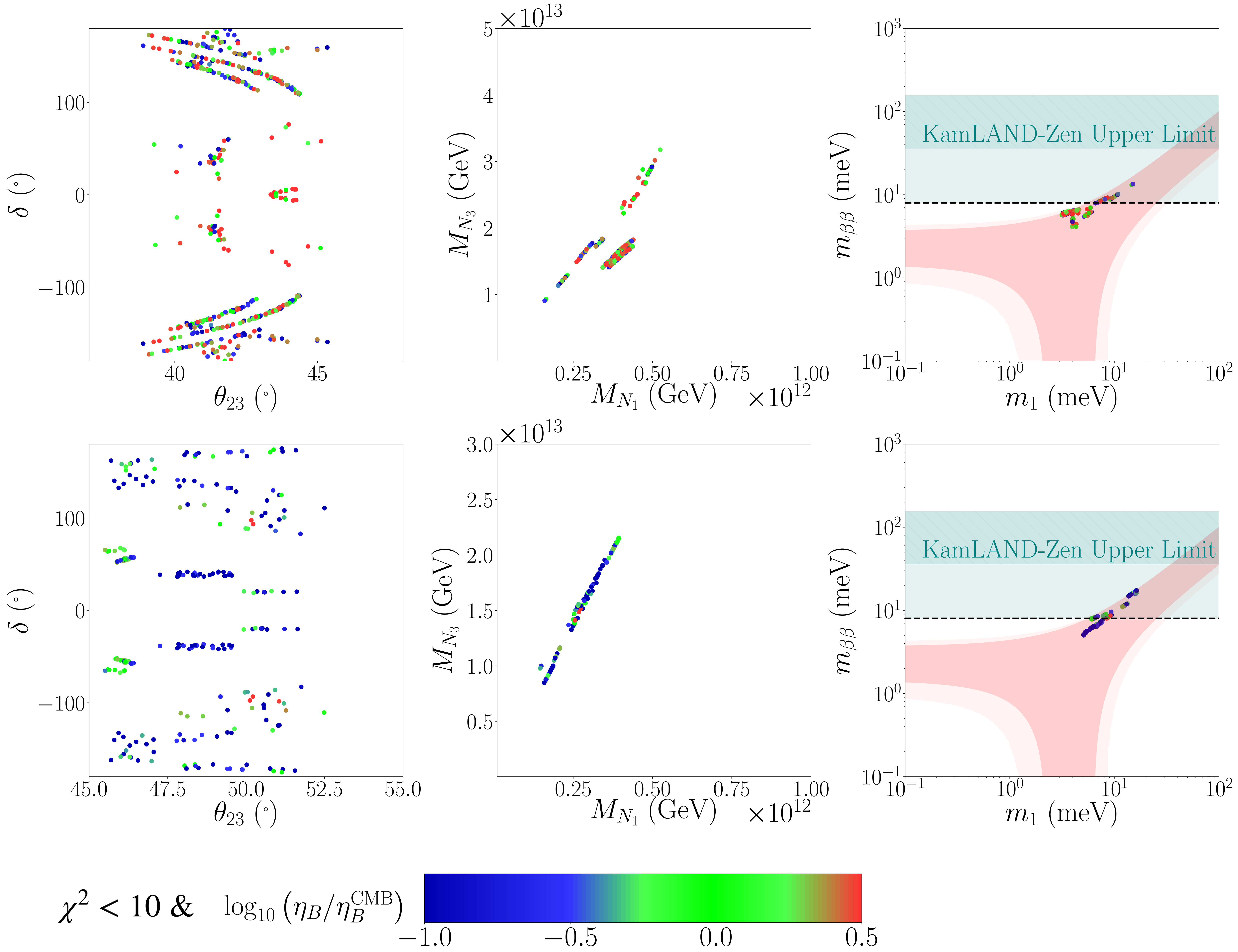
# Precision measurements of lepton mixing in upcoming neutrino experiments

An era of precision measurement of neutrino oscillations!




2204.13249

# Thermal leptogenesis in SO(10)




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

⇓

Heavy neutrino masses and Dirac ν Yukawa couplings

⇓

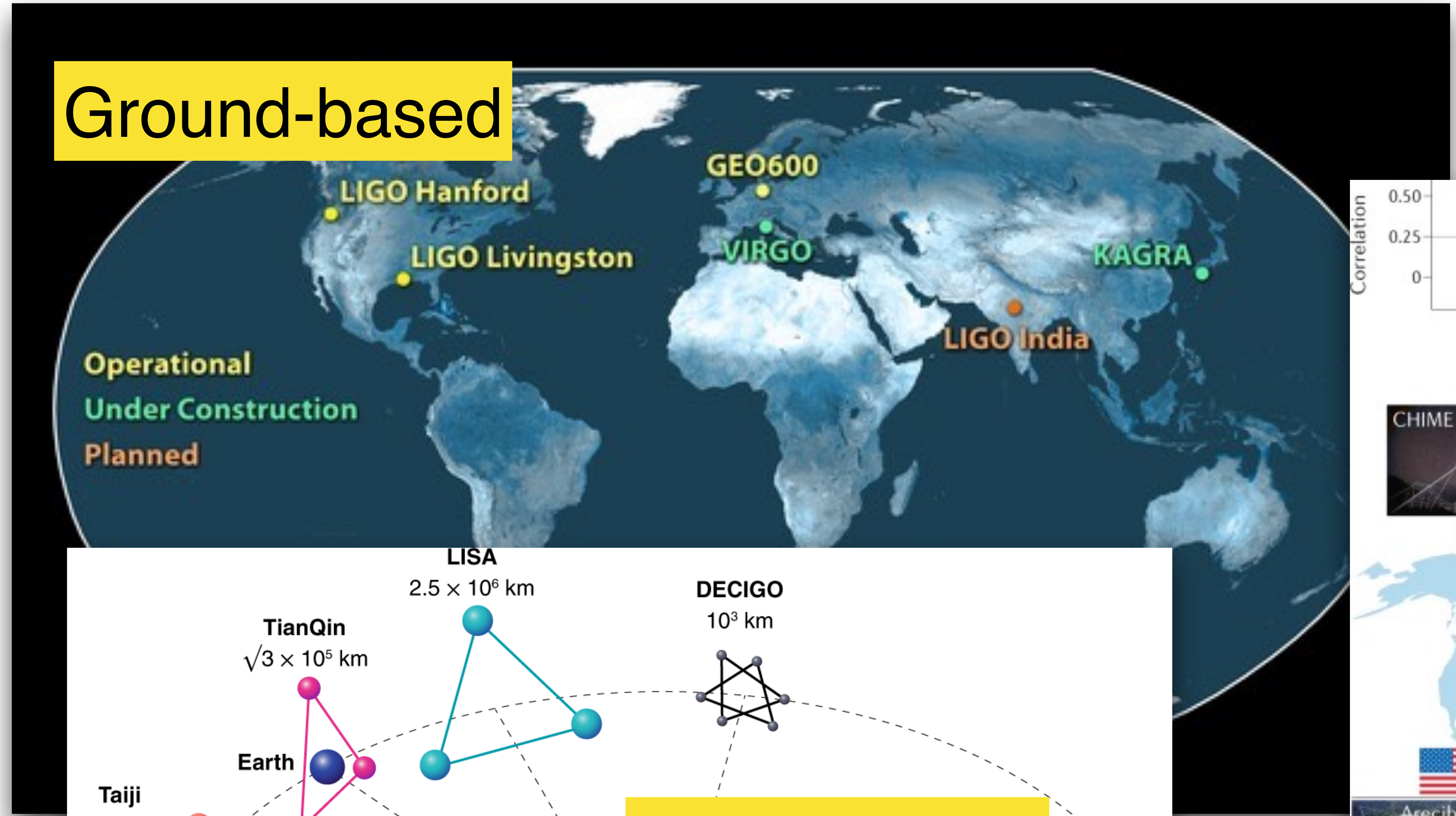
CP violation in heavy neutrino decay

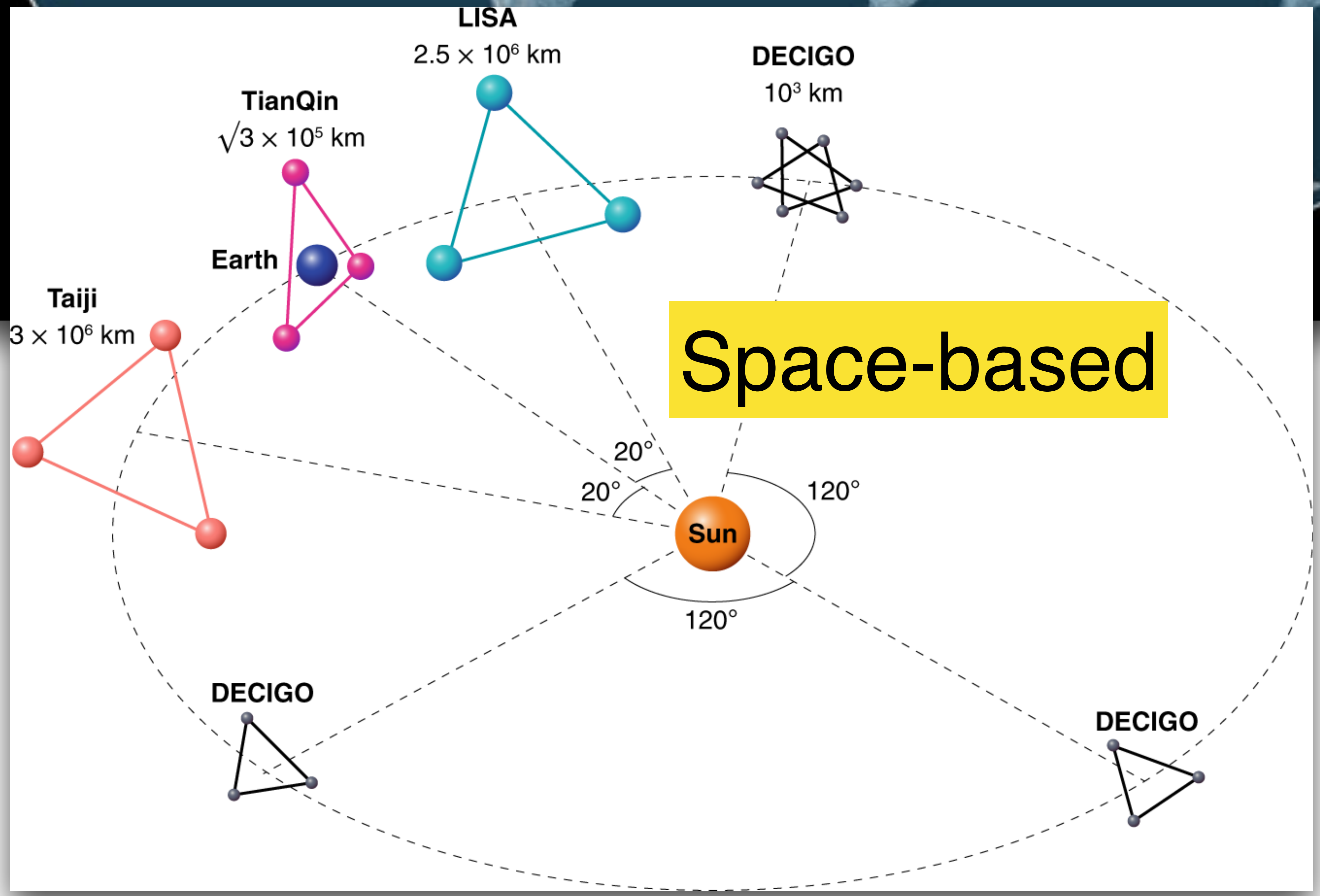
⇓

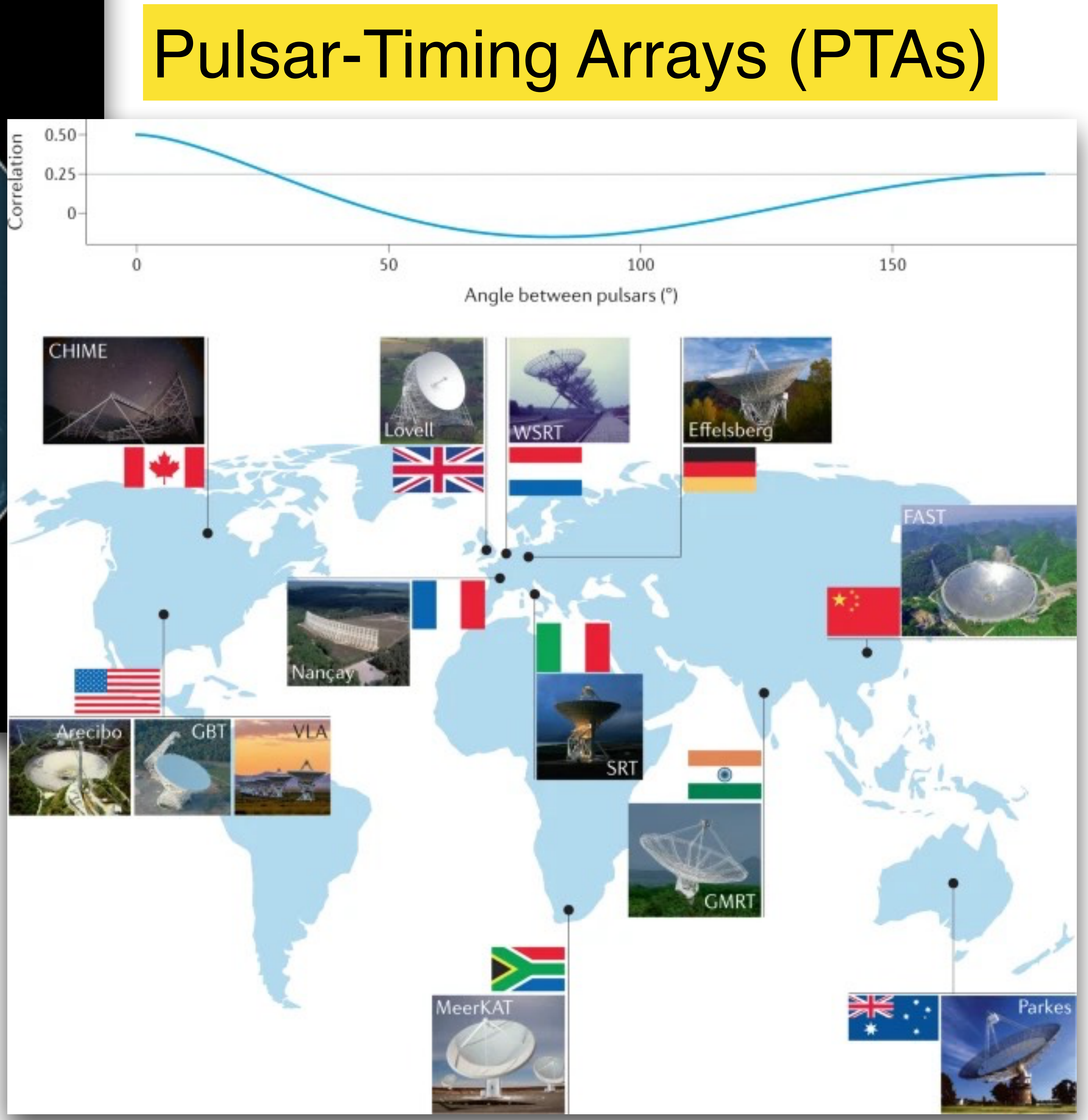
**Thermal leptogenesis**

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

# Undergoing and upcoming GW measurements



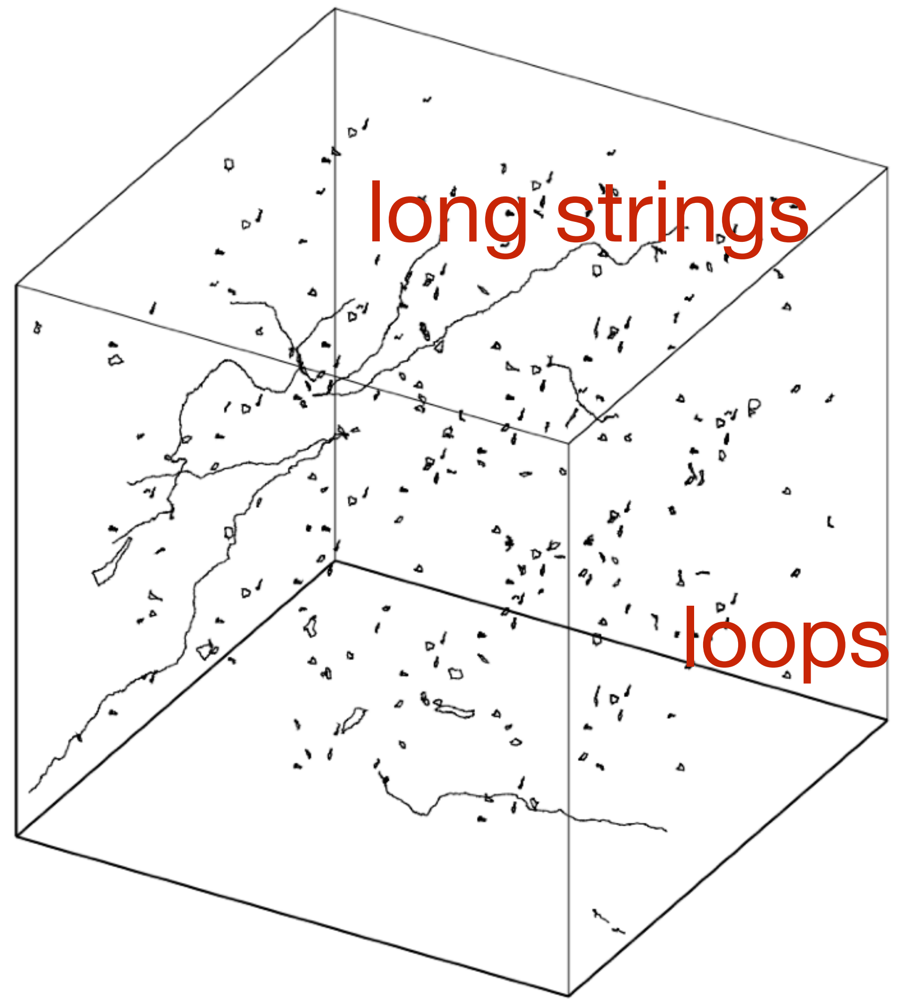



# Mechanisms of gravitational wave (GW) genesis in GUTs

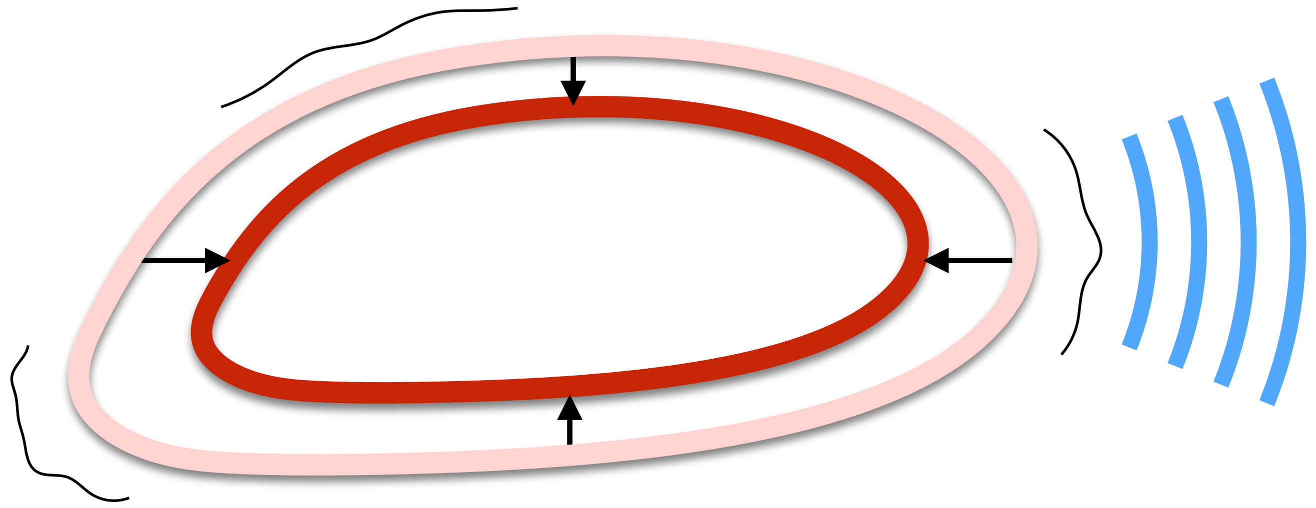
## GW via cosmic strings

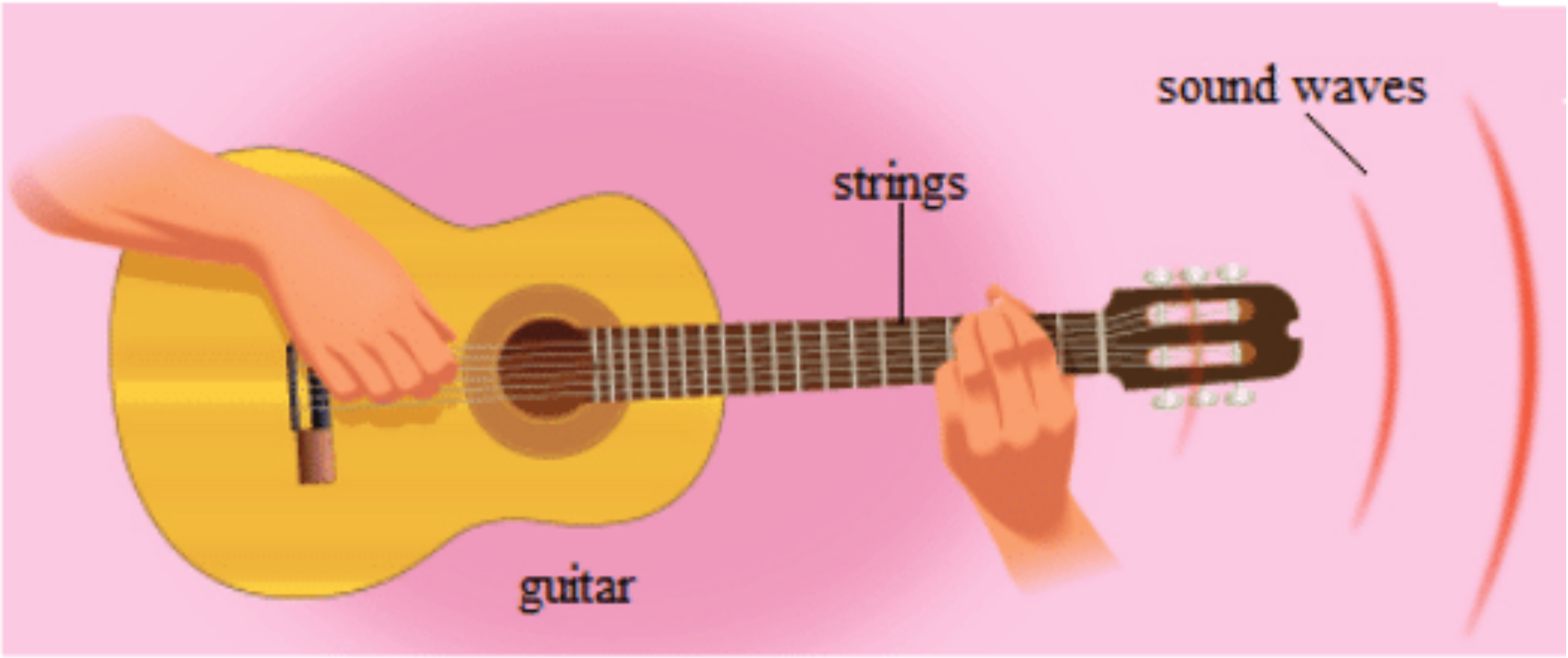
$$\pi_1(U(1)) = Z$$

- 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

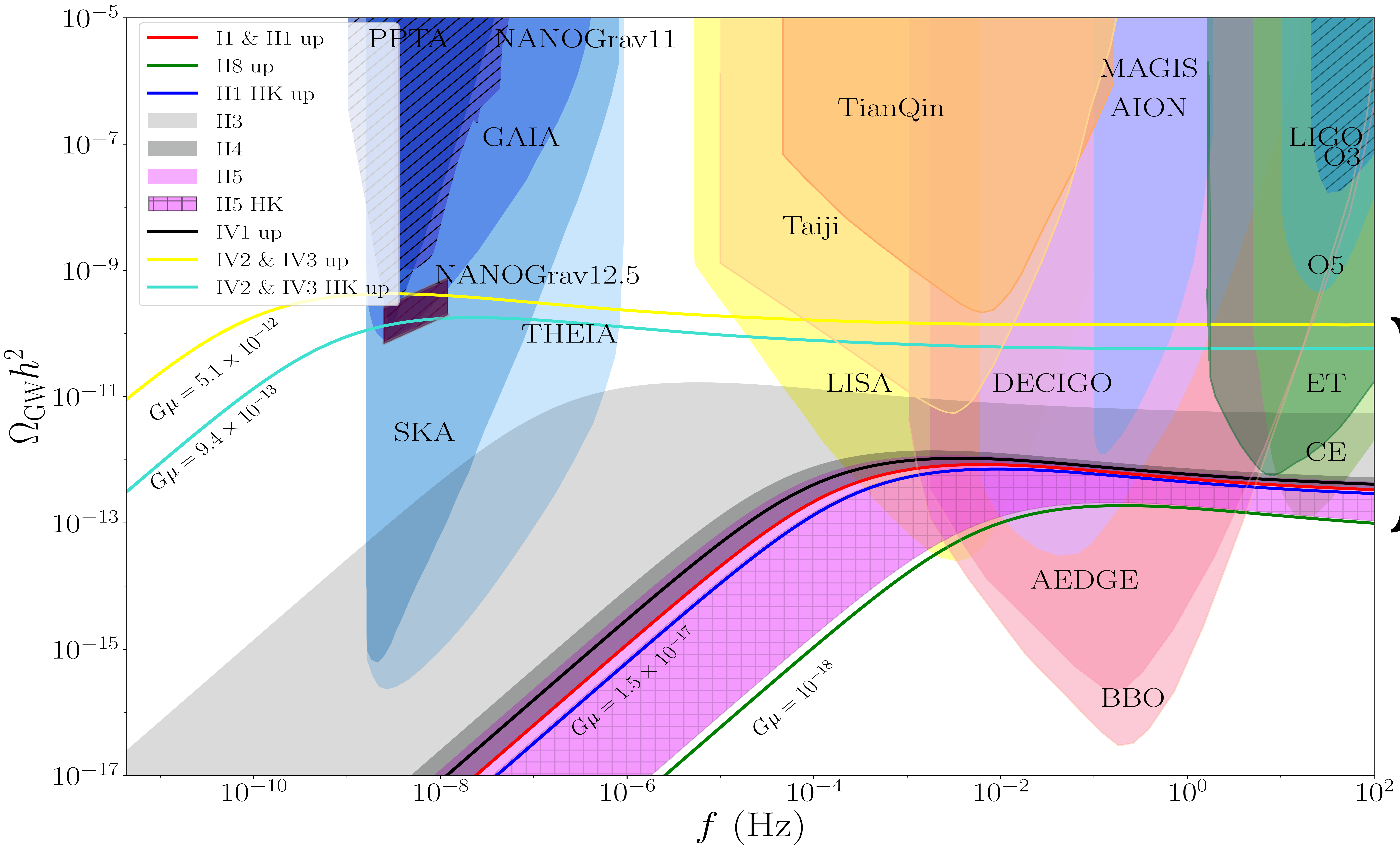



Vanchurin, Olum, Vilenkin, 0511159





# Predictions for GW spectrum in SO(10) GUTs

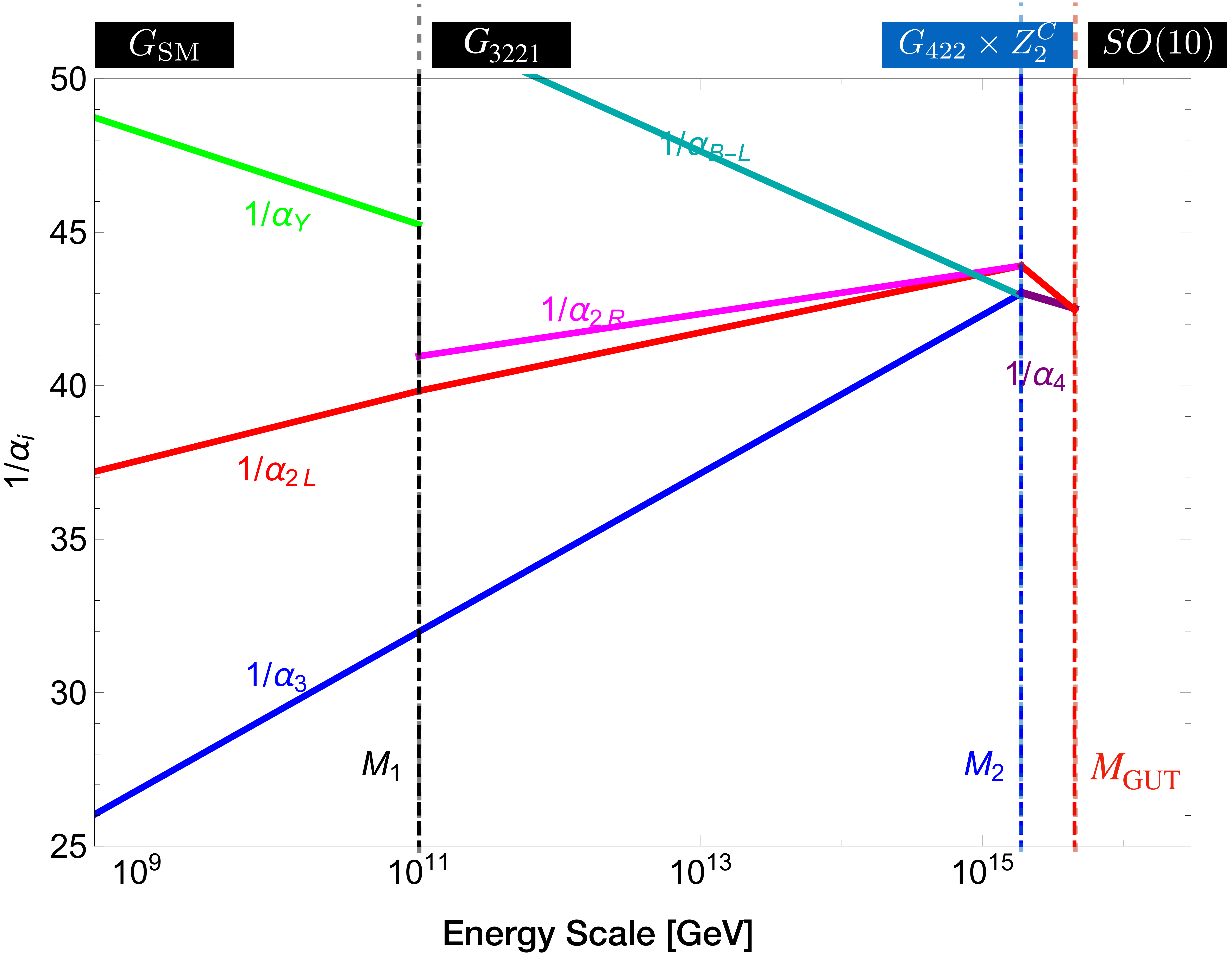



Different colours for different breaking chains

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

# Gauge unification correlates GUT scale with intermediate scales

A toy model

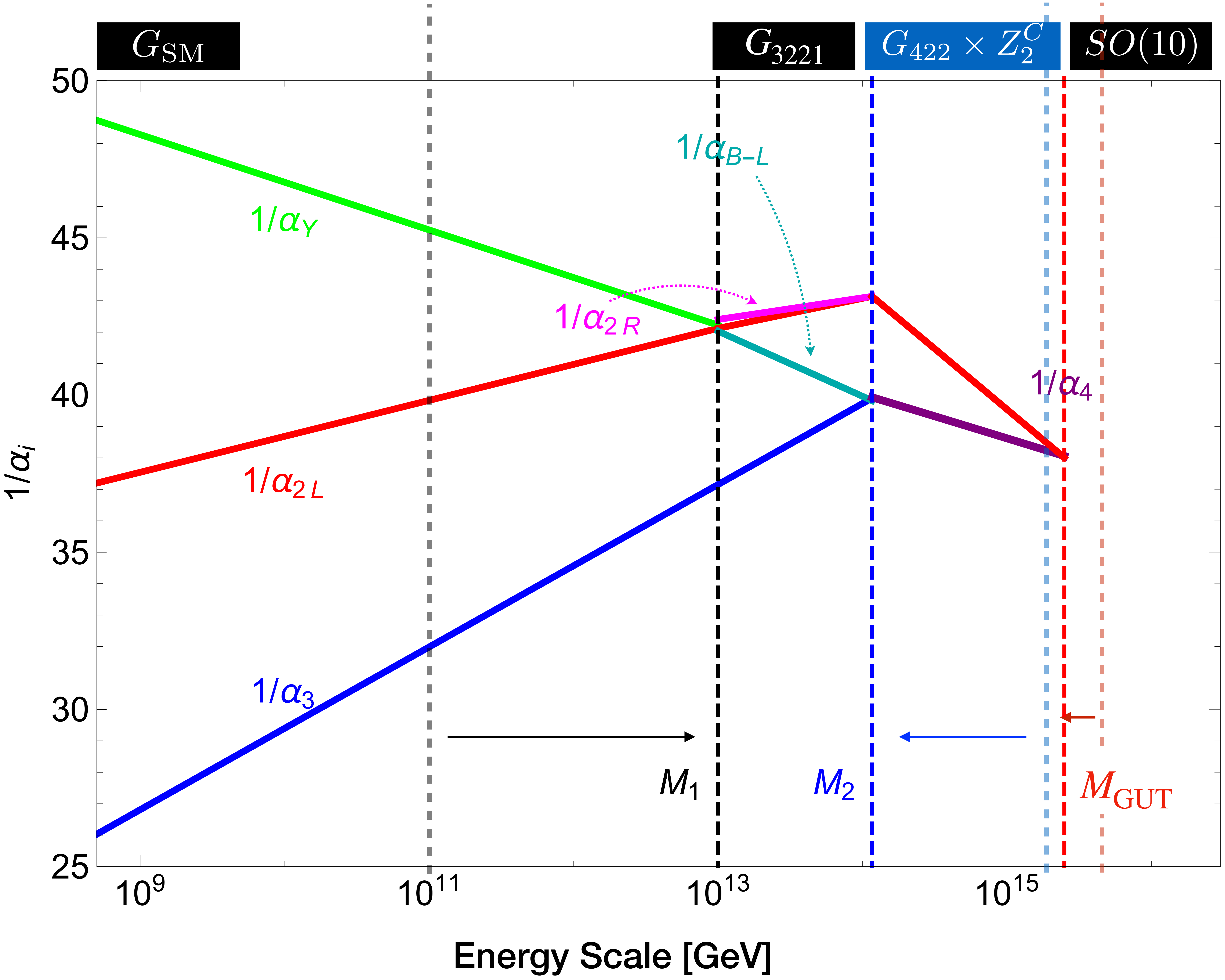



$M_i$ understood as the mass of heavy gauge boson there

No new particle introduced if not necessary

# Gauge unification correlates GUT scale with intermediate scales

A toy model

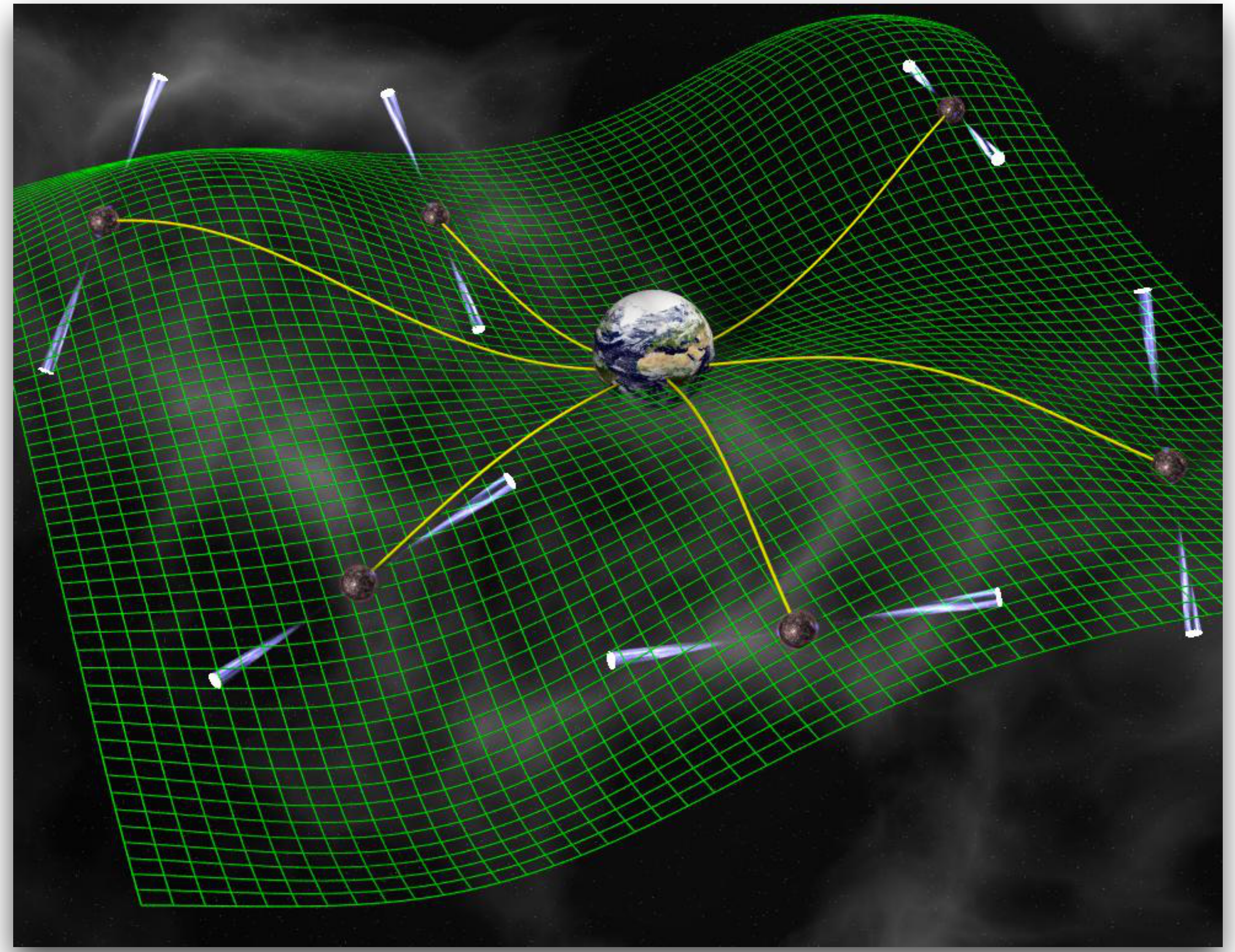



$M_i$ understood as the mass of heavy gauge boson there

No new particle introduced if not necessary

# Announcement of PTA measurements this summer

On 28 Jun 2023



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

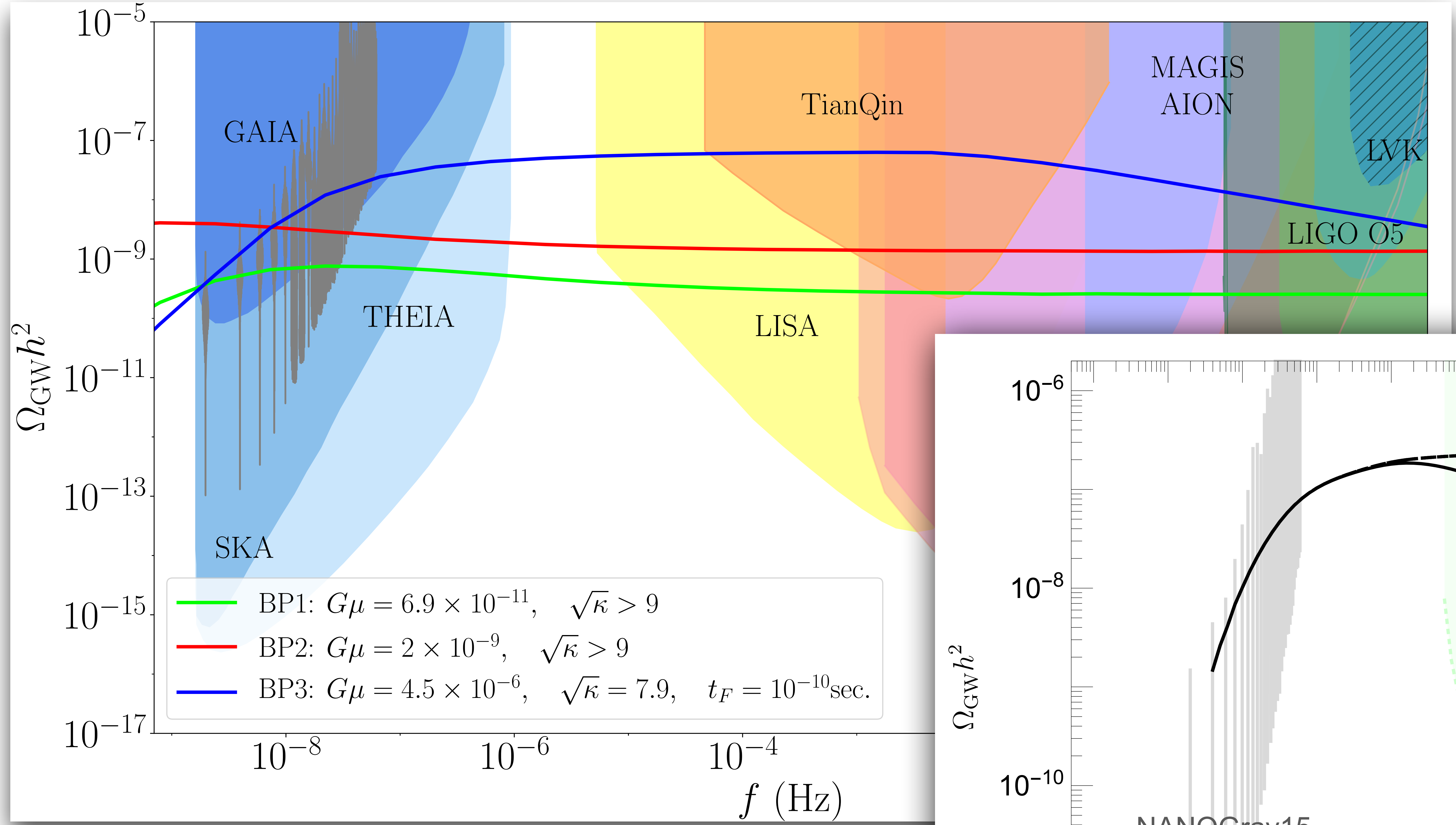
The second data release from the **European Pulsar Timing Array** III. Search for gravitational wave signals
2306.16214

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

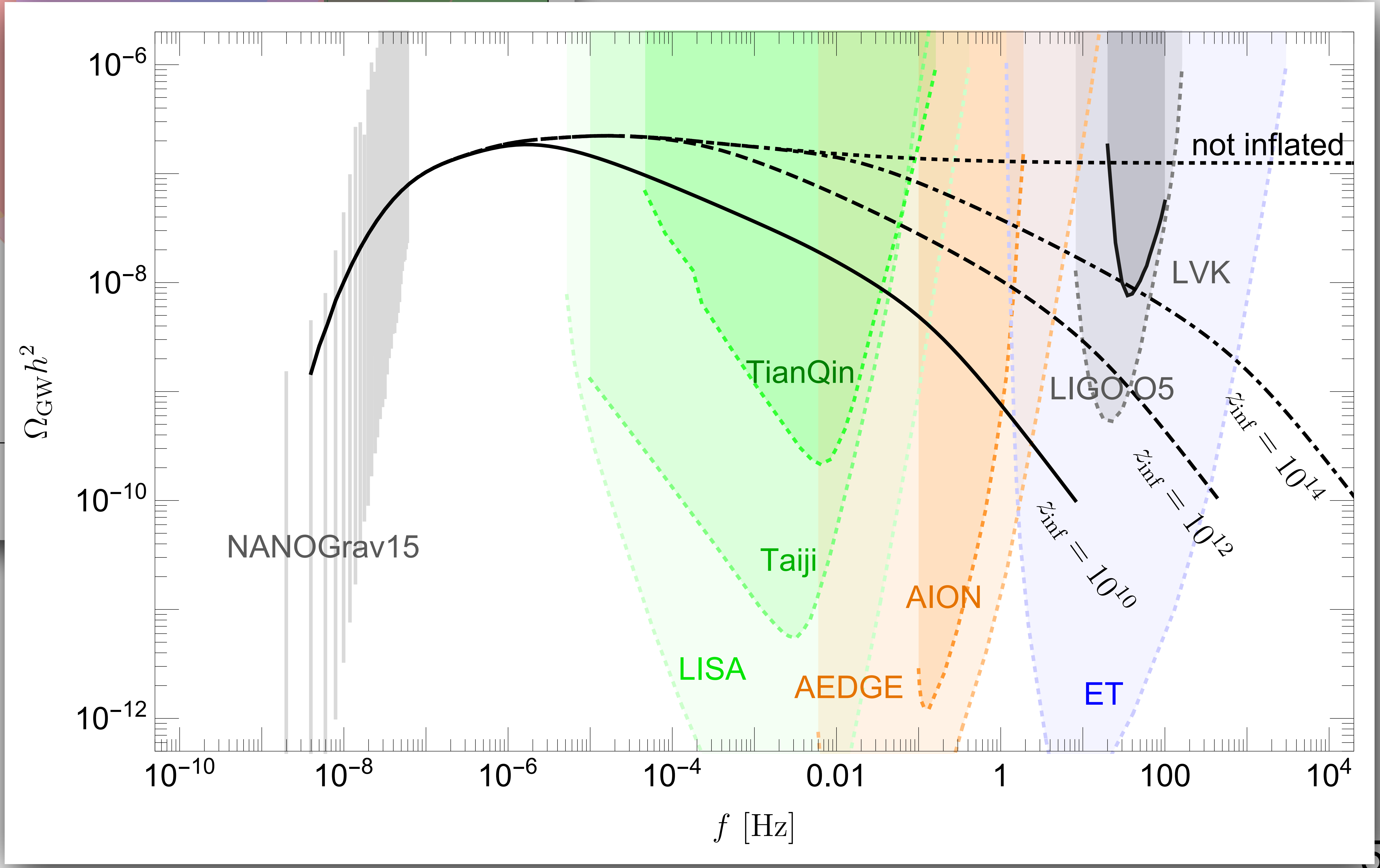
Searching for the nano-Hertz stochastic gravitational wave background with the **Chinese Pulsar Timing Array** Data Release I
2306.16216

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

# GW from metastable cosmic strings in GUTs, supported by NANOGrav 15




GWs in SUSY SO(10) GUTs
Fu, King, Marsili, Pascoli, Turner, **YLZ**, 2308.05799




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

# Complementary test of GUTs

$SO(10)$ GUT

Potentially intermediate New Physics

……

$G_1 \supset G_{\rm SM} \times U(1)_{B-L}$

Potentially intermediate New Physics

……

Standard Model

Broken at $M_{GUT}$

Broken at $M_{B-L}$

$M_{N_i} = y_{N_i} v_{B-L} \lesssim M_{B-L}$

$N_1 \to HL \neq N_1 \to H^\dagger \bar{L}$

$M_1 \ll M_{B-L}$

Proton decay

Gauge unification

Gravitational waves

consistency with fermion masses and mixing

Successful leptogenesis?


Thank you for your listening!
@ 铜 鉴 湖
Tongjian Lake