

Cosmic origin of matter from proton stability

Xavier Ponce Díaz

with Admir Greljo, Anders Eller Thomsen

[arXiv:2505.18259](https://arxiv.org/abs/2505.18259)

Proton Decay (or lack thereof)

$\mathcal{L} = \sum_{\mathcal{O}}^{\infty} \mathcal{C}_{\mathcal{O}} \mathcal{O}(x)$ the SM global symmetries $U(1)_B, U(1)_L^3$ are **accidental** at $\dim \mathcal{O} \leq 4$

However, natural new physics **extensions** tend to predict proton decay, e.g.
GUTs, Gravity, SMEFT ($\dim \mathcal{O} > 4$), ...

Proton lifetime lower bound:

$$\tau_p > 0.96 \times 10^{30} \text{yr} \quad (90 \% \text{ C.L.})$$

$$p \rightarrow \text{invisible} \quad \text{SNO+ '22}$$

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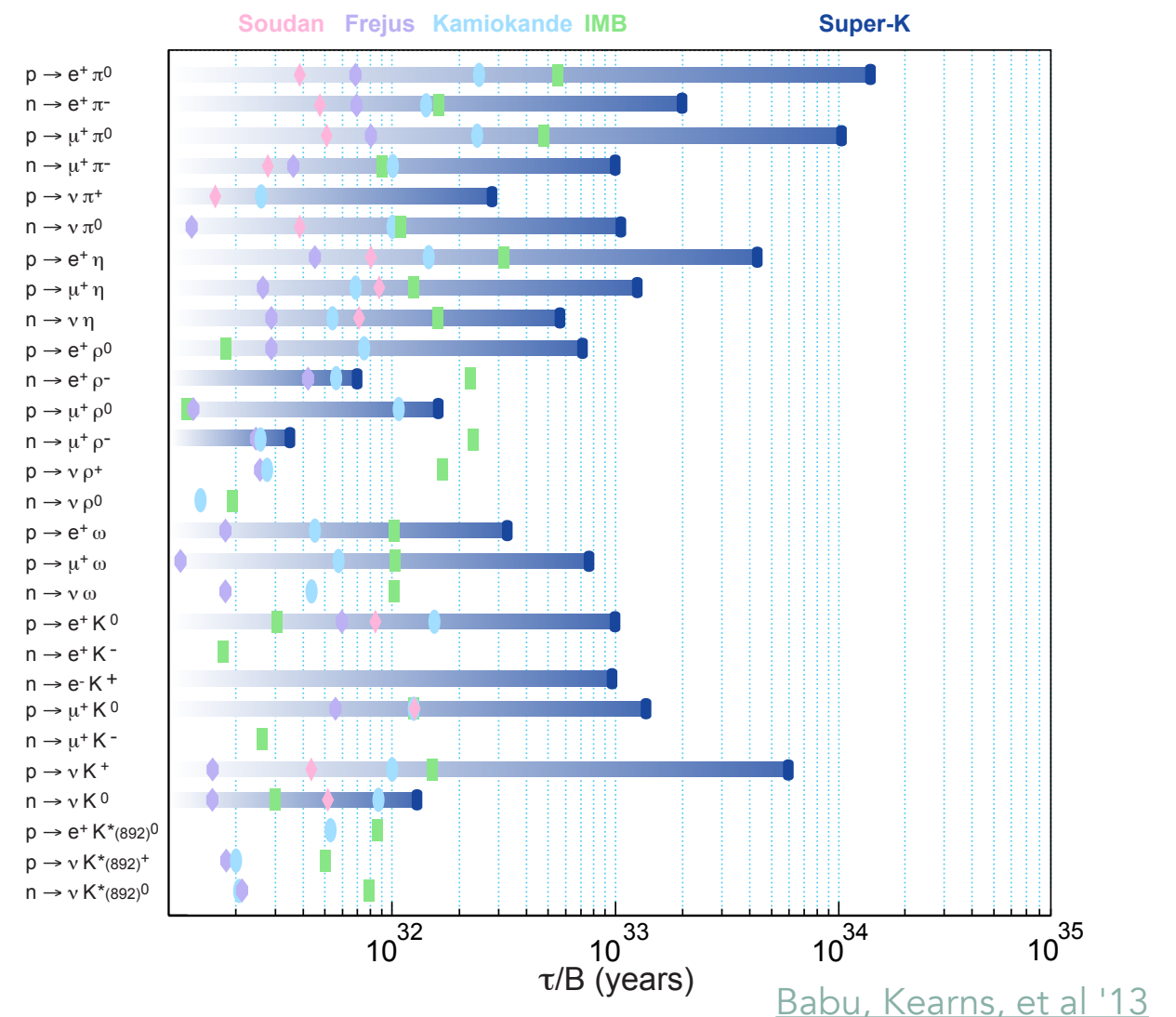
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$p \rightarrow \text{invisible}$ [SNO+ '22](#)

Other modes: $\tau_p \gtrsim 10^{33} \text{yr}$

$$\Lambda_{\text{GUT}} \gtrsim 10^{16} \text{GeV}$$

see [Arnau Bas i Beneito](#) talk.



[Babu, Kearns, et al '13](#)

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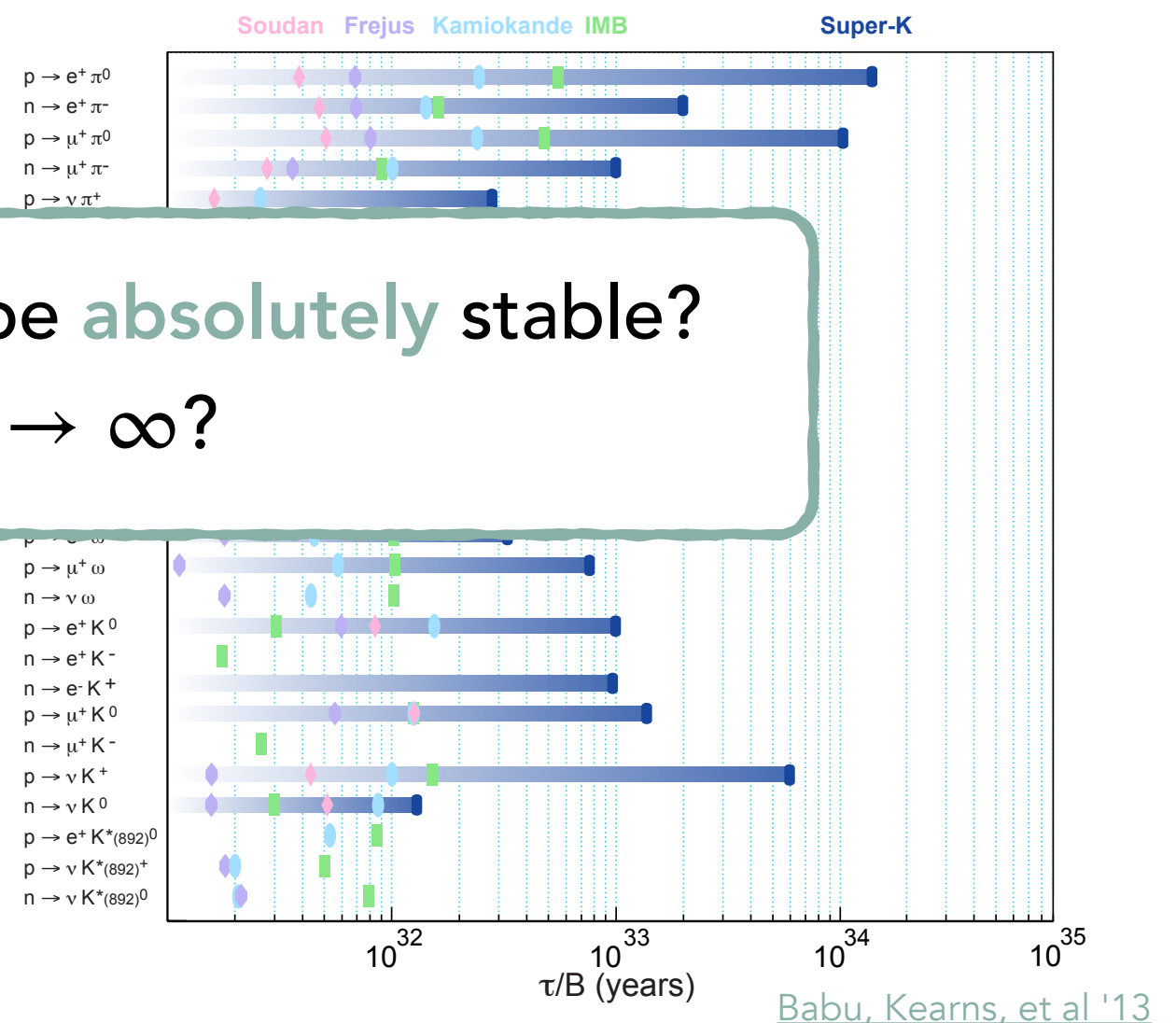
Can the proton be **absolutely** stable?

$$\tau_p \rightarrow \infty?$$

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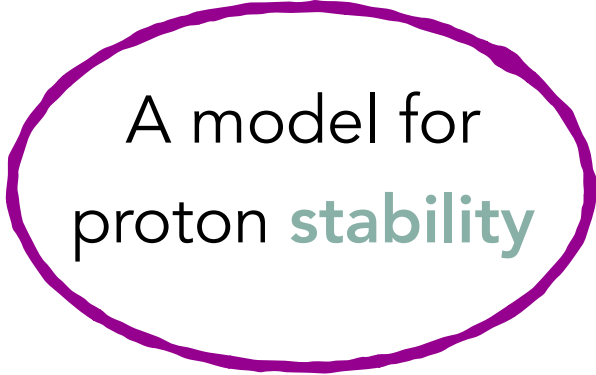


Babu, Kearns, et al '13

What is this talk about

Purely academic: What if the proton is **absolutely** stable?

[Davighi, Greljo, Thomsen '22](#)



A model for
proton **stability**

see also previous work

[Babu, Gogoladze, Wang '03](#)

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[Greljo, XPD, Thomsen '25](#)

Empirical evidence of **BSM**

Neutrino masses
& mixing

matter-antimatter
asymmetry

Dark Matter

$$\Delta m_{21}^2 \simeq 7.49 \times 10^{-5} \text{ eV}^2, \\ \Delta m_{31}^2 \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

[Nu-fit 6.0, '24](#)

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

[Planck 2018](#)

$$\Omega_{\text{CDM}} h^2 = 0.1200 \pm 0.0012$$

[Planck 2018](#)

Outline of the talk

1. Introduction
2. A model for **Proton Stability**
3. **Neutrino masses, mixing** and a **prediction**
4. **Leptogenesis**
5. **Cold Dark Matter**
6. Conclusions

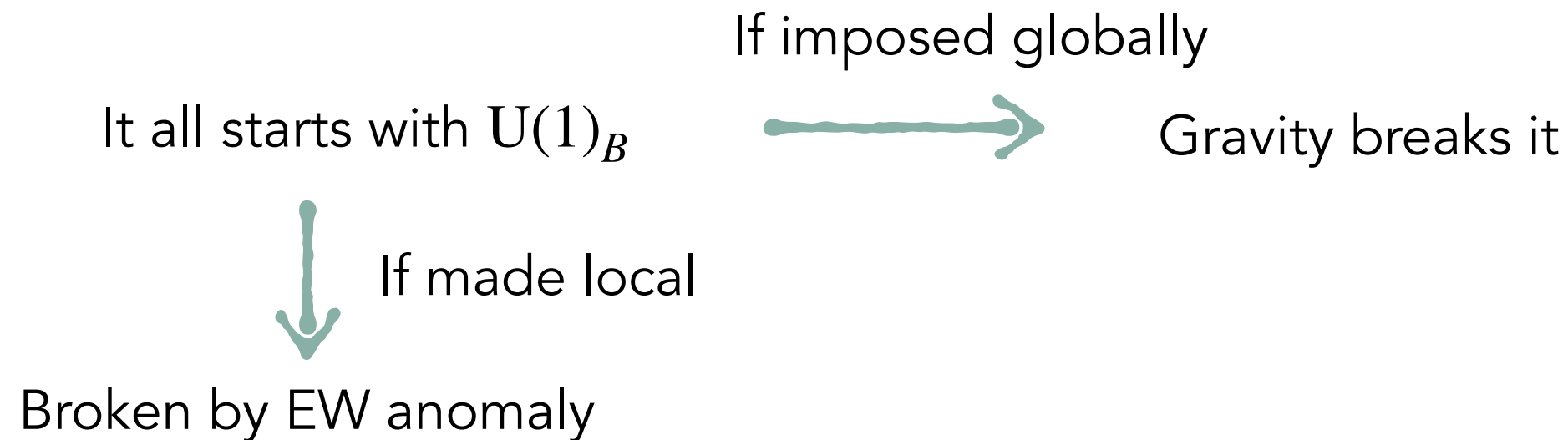
A model for proton stability

It all starts with $U(1)_B$

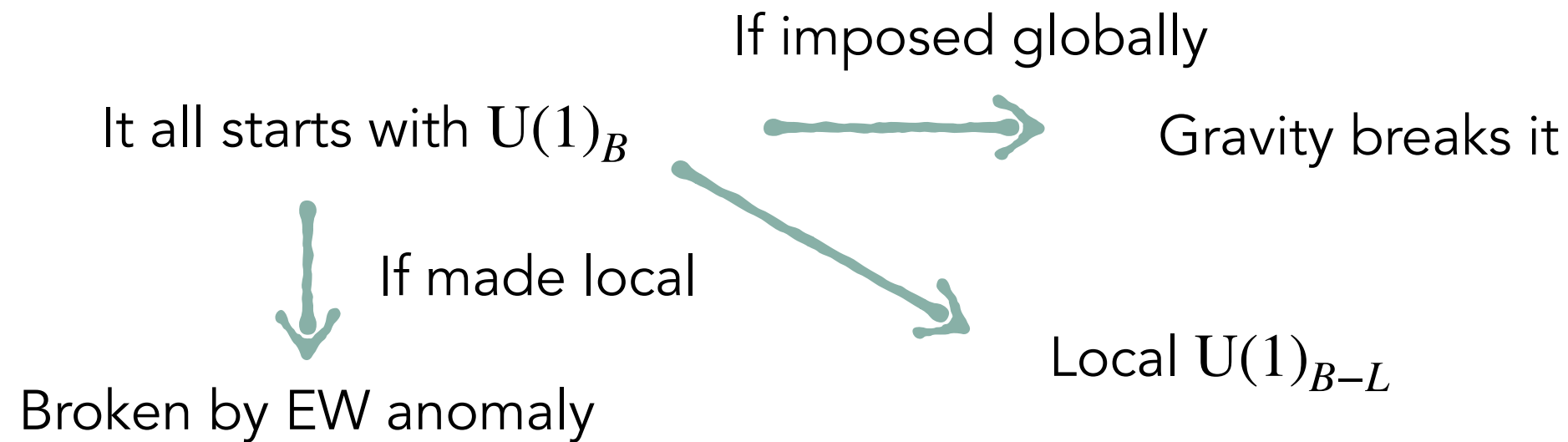
A model for proton stability

It all starts with $U(1)_B$ If imposed globally  Gravity breaks it

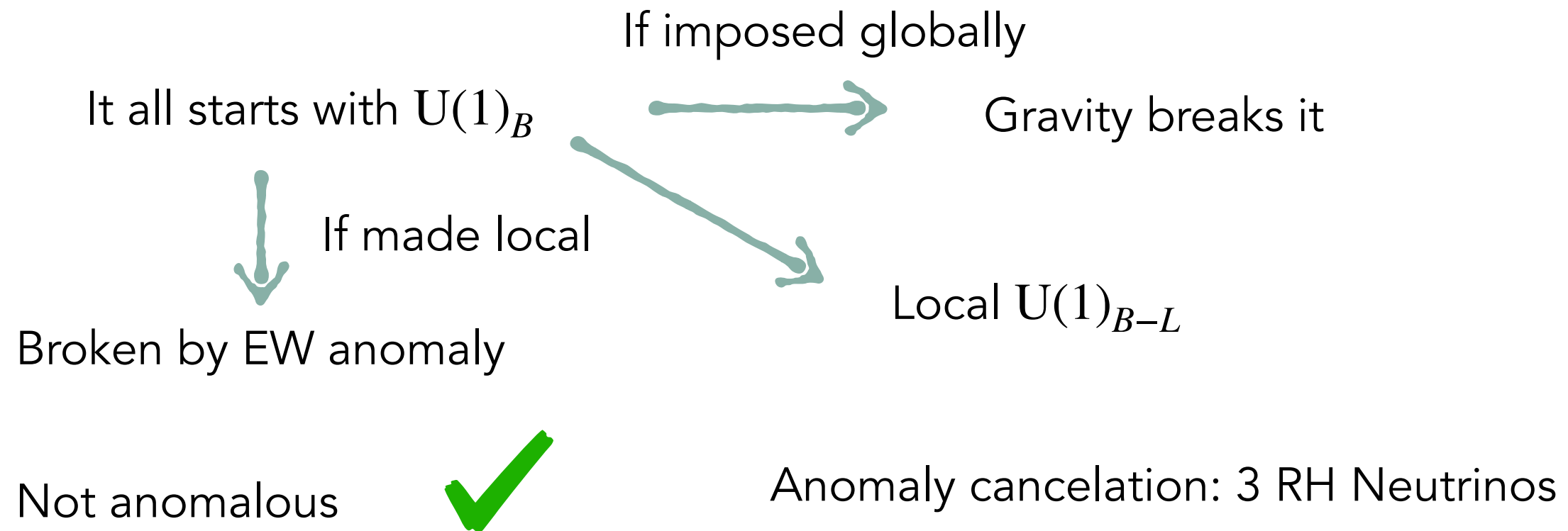
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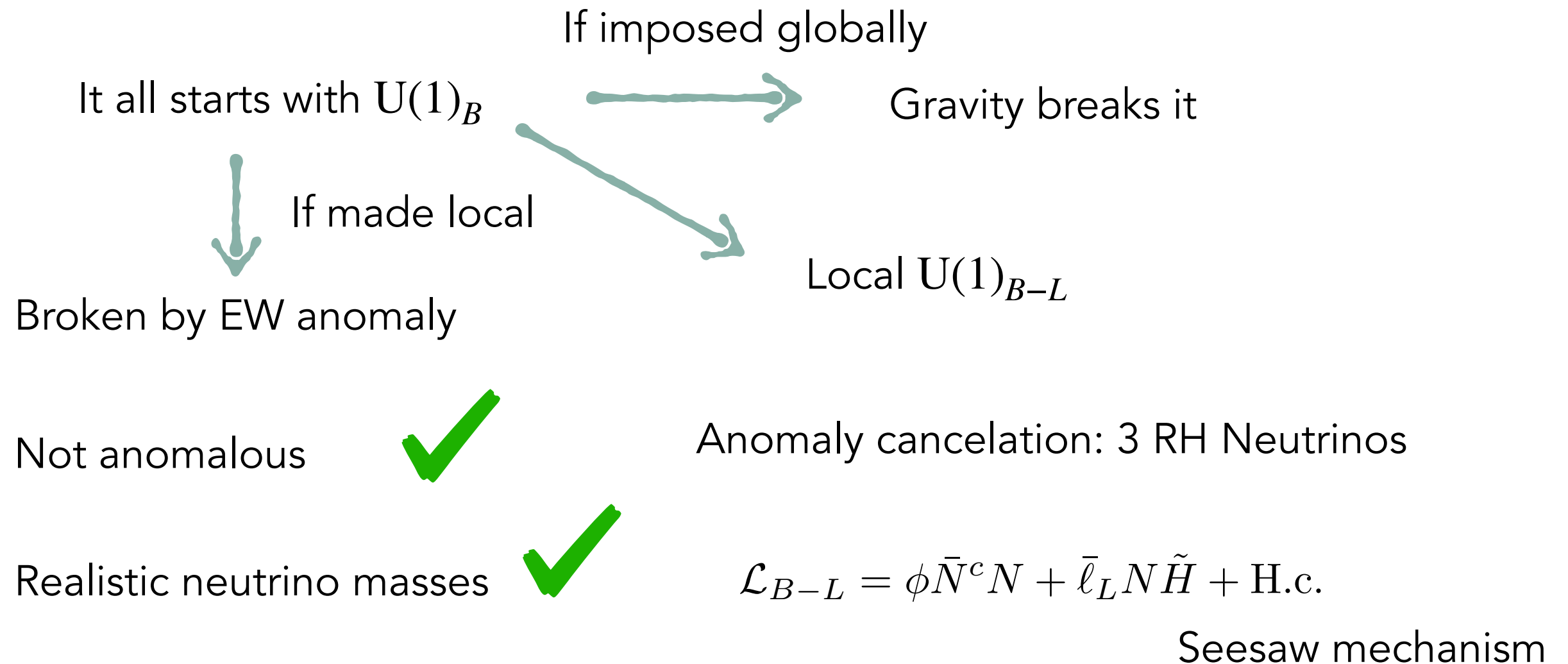


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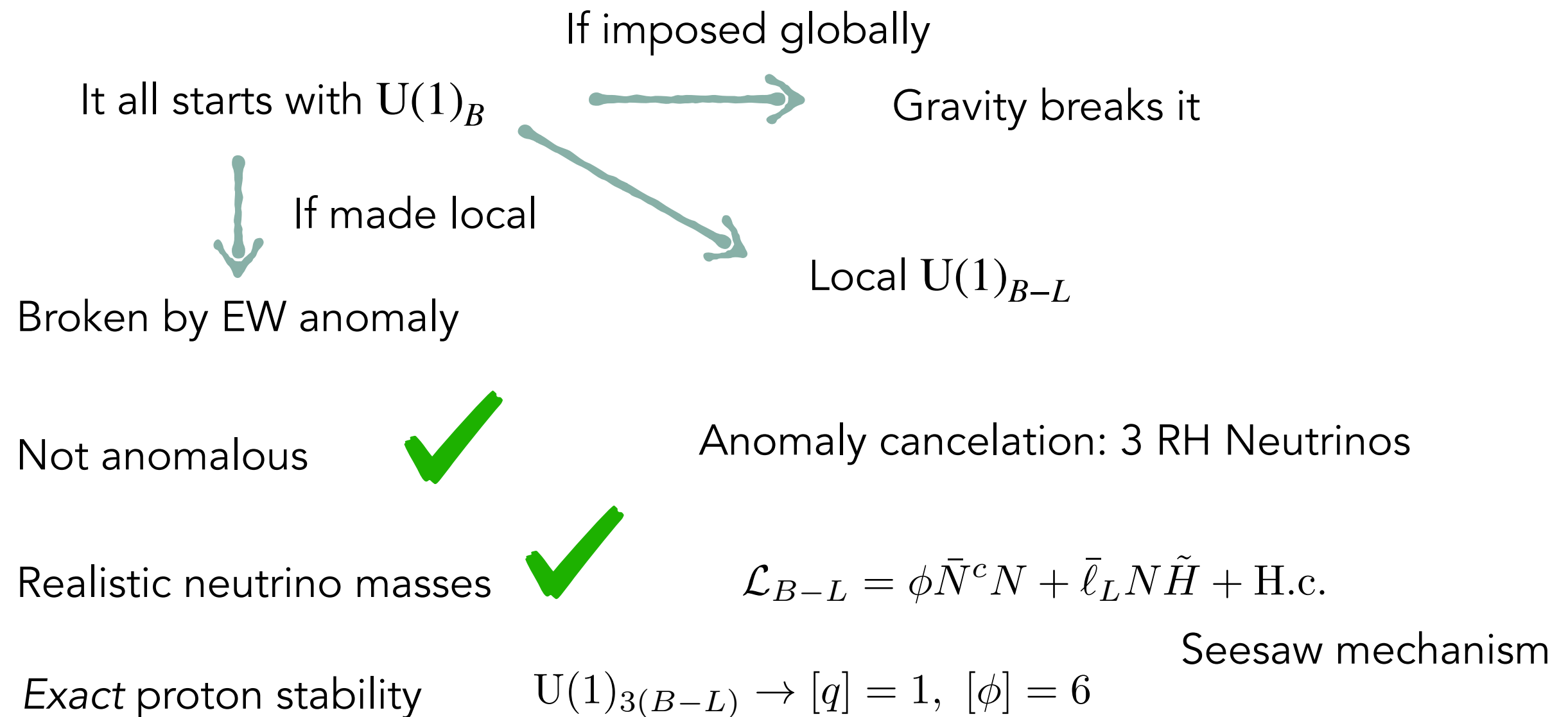


$$\mathcal{L}_{B-L} = \phi \bar{N}^c N$$

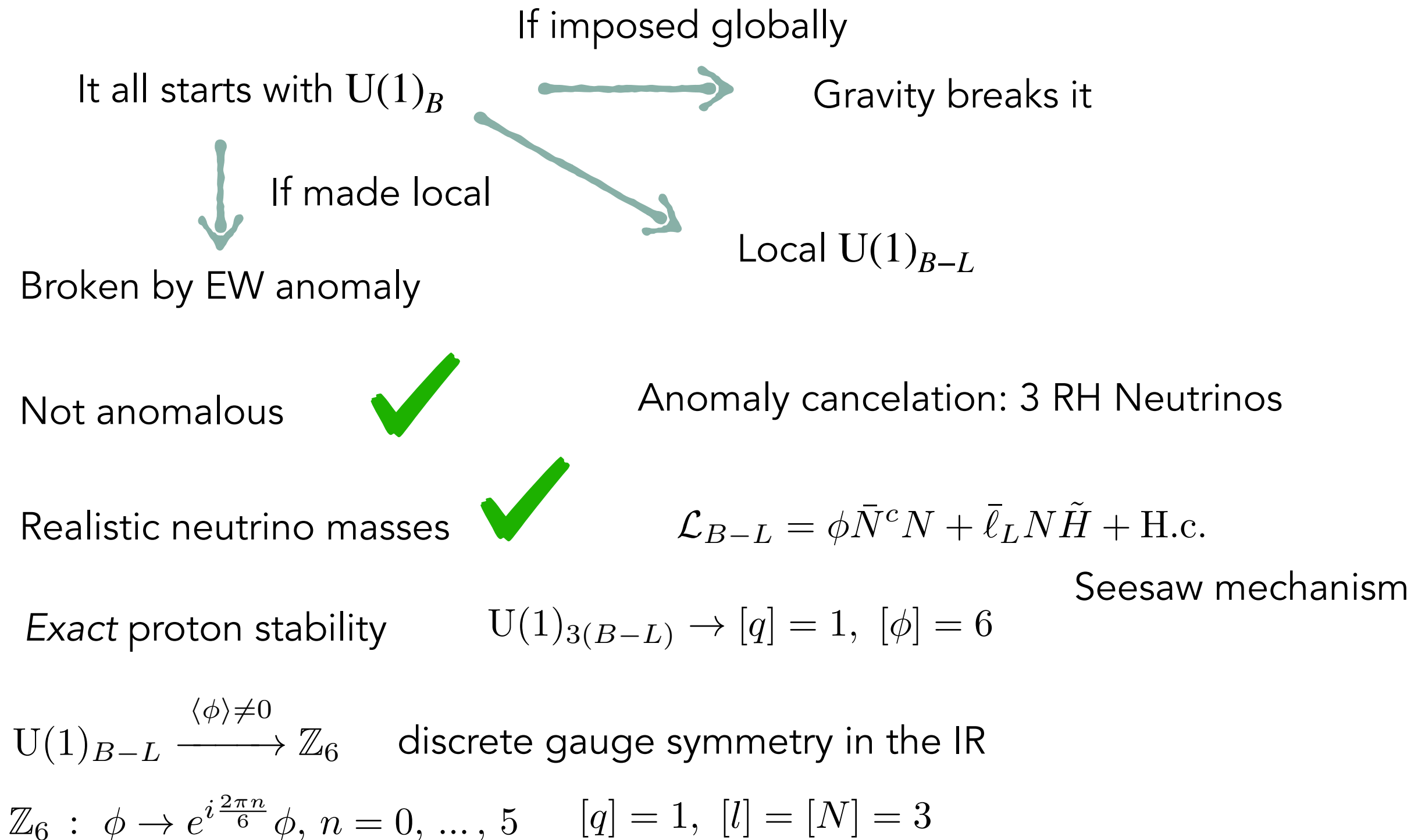
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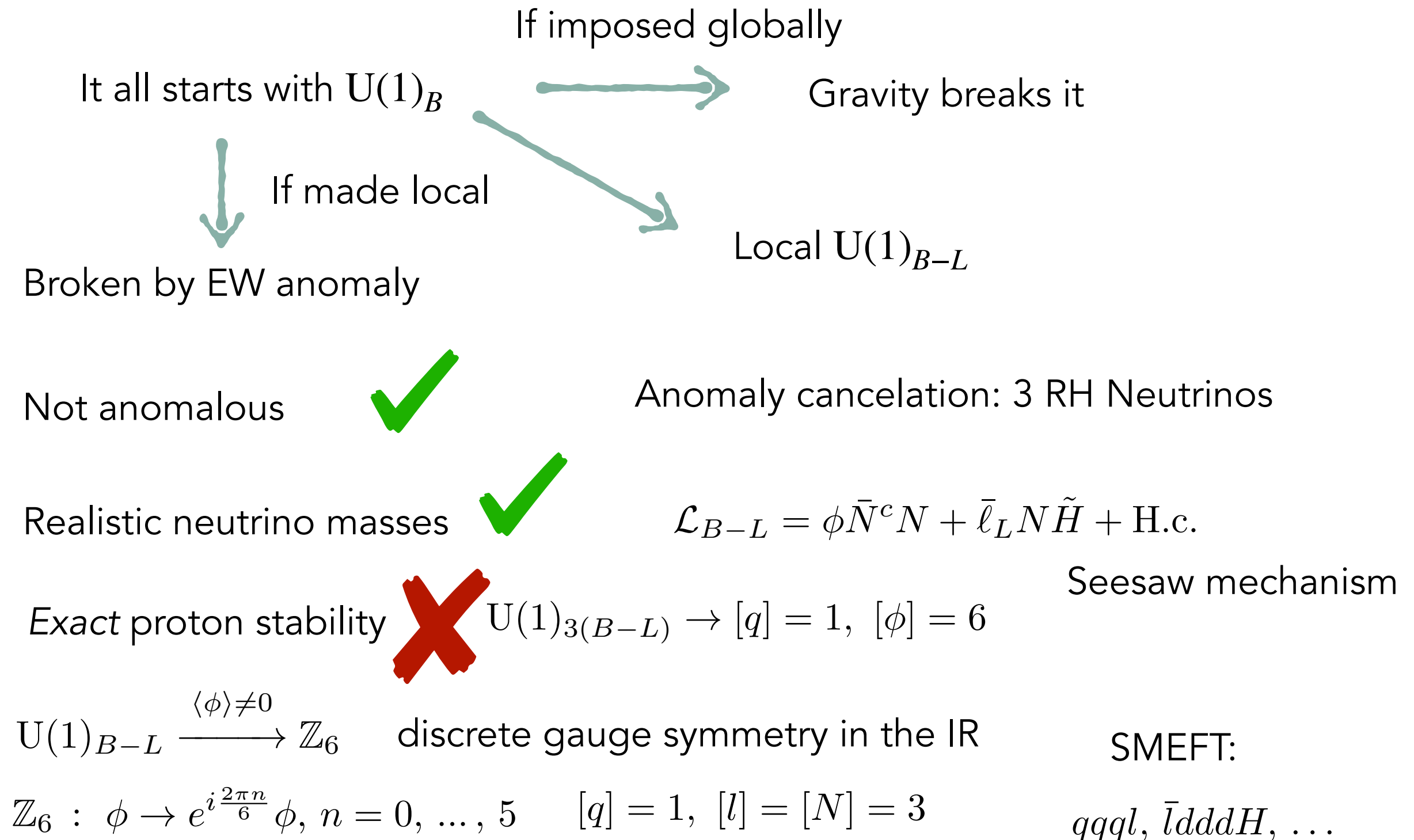
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A model for proton stability

The **idea**: [Davighi, Greljo, Thomsen '22](#)

Gauge $U(1)_{X_p} \xrightarrow{\langle \phi \rangle \gg \langle H \rangle} \mathbb{Z}_k$

Such that proton decay is forbidden in the SMEFT to all orders

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How: $\frac{3(B - L)}{L_i - L_j}$ Not anomalous general symmetry $U(1)_{X_p} \rightarrow X_p = 3m(B - L) - n(3L_p - L)$

↑

p : specific lepton flavour $p = e, \mu, \tau$ $\gcd(m, n) = 1$

.....

(*gcd): greatest common divisor

A model for proton stability

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$$\bar{\ell}_L N H \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

need two SM-singlet scalars for PMNS

$$\bar{N}^c N \phi_1 \sim \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix}$$

$$\bar{N}^c N \phi_2 \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

Scalar charges:

$$\begin{pmatrix} [\phi_1]_{X_p} \\ [\phi_2]_{X_p} \end{pmatrix} = \begin{pmatrix} 6m + n \\ 6m - 2n \end{pmatrix}$$

(*gcd): greatest common divisor

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Consider the following **charges**:

[Davighi, Greljo, Thomsen '22](#)

$$(m, n) = (3a + 1, 9b + 3), \quad \text{for } (a, b) \in \mathbb{Z}^2$$

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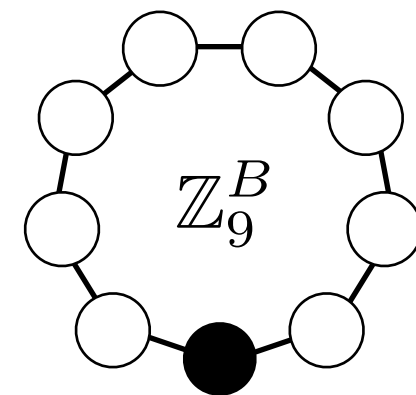
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$$k = \gcd([\phi_1]_{X_p}, [\phi_2]_{X_p}) = 9\gcd(n, 2)$$

$$\text{U}(1)_{X_p} \xrightarrow{\langle \phi_{1,2} \rangle \neq 0} \Gamma \cong \begin{cases} \mathbb{Z}_9^B, & \text{for } n \in 2\mathbb{Z} + 1 \\ \mathbb{Z}_9^B \times \mathbb{Z}_2^f, & \text{for } n \in 2\mathbb{Z} \end{cases},$$



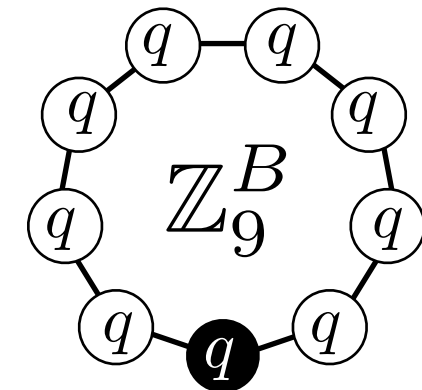
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$$U(1)_{X_p} \xrightarrow{\langle \phi_1 \rangle, \langle \phi_2 \rangle \neq 0} \mathbb{Z}_9^B$$

	Fields	$U(1)_{X_p}$	$\mathbb{Z}_9 \subseteq \Gamma$
Quarks	q_i, u_i, d_i	m	1
Specific leptons	ℓ_p, e_p, N_p	$-2n - 3m$	0
Common leptons ($q \neq p$)	ℓ_q, e_q, N_q	$n - 3m$	0
Higgs	H	0	0
New scalars	ϕ_1	$6m + n$	0
	ϕ_2	$6m - 2n$	0

$\mathbb{Z}_9^B$ -singlets



Exact discrete gauge symmetry **unbroken** in the **IR**

[Davighi, Greljo, Thomsen '22](#)

$$\mathbb{Z}_9^B\text{-singlet : } (qqq)(qqq)(qqq)$$

SMEFT selection rule

$$\Delta B = 0 \pmod{3}$$

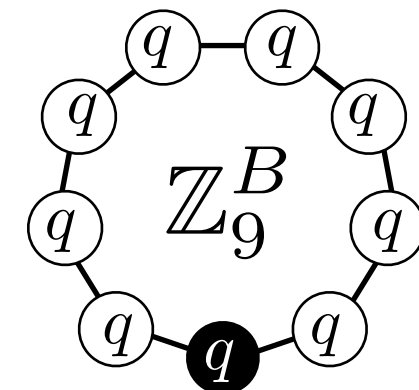
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proton decay $qqql, \bar{l}dddH, \dots$ $\Delta B = 1$



neutron-antineutron oscillations $(\bar{q}^c q)(\bar{q}^c q)(\bar{q}^c q)$ $\Delta B = 2$



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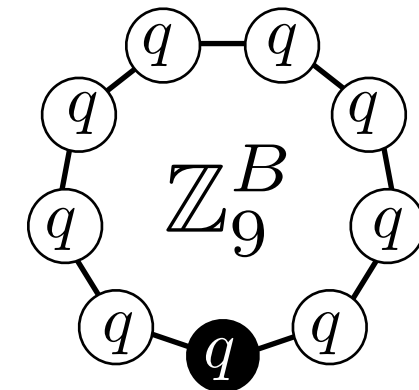
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neutron-antineutron
oscillations

$$(\bar{q}^c q)(\bar{q}^c q)(\bar{q}^c q)$$

$$\Delta B = 2$$



Sphalerons

$$\bar{\nu}_e \bar{\nu}_\mu \bar{\nu}_\tau \rightarrow u_L d_L d_L c_L b_L d_L t_L b_L b_L$$

$$\Delta B = 3$$



Neutrino Masses

$$M_N \sim \langle \phi_1 \rangle \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix} + \langle \phi_2 \rangle \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix} \quad + \text{p-permutations}$$

$$Y_N \sim \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix} \quad \text{majorana phases}$$

The seesaw

Minkowski '77, Gell-Mann, Ramond, Slansky '79, Yanagida '80,
Mohapatra, Senjanovic '80, Schechter, Valle '80

$$m_\nu = -\langle H \rangle^2 Y_\nu^* M_N^{-1} Y_\nu^\dagger = U^* \hat{m}_\nu U$$

$$U = V_{\text{PMNS}} \text{diag}(e^{i\alpha/2}, e^{i\beta/2}, 1)$$



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The **flavour-specific** local symmetry imposes the following tree-level **condition**:

The **p-minor** = 0

$$m_\nu^{22} \times m_\nu^{33} - (m_\nu^{23})^2 = 0$$

[Greljo, XPD, Thomsen '25](#)

$$\text{e-specific case} \implies 0 = \frac{1}{m_3} s_{13}^2 + \frac{e^{i(\beta+2\delta_{\text{CP}})}}{m_2} s_{12}^2 c_{13}^2 + \frac{e^{i(\alpha+2\delta_{\text{CP}})}}{m_1} c_{12}^2 c_{13}^2$$

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- Triangle equation in the complex plane
- Triangle inequality $\Rightarrow$ **lower limit** on the lightest neutrino

e-specific case

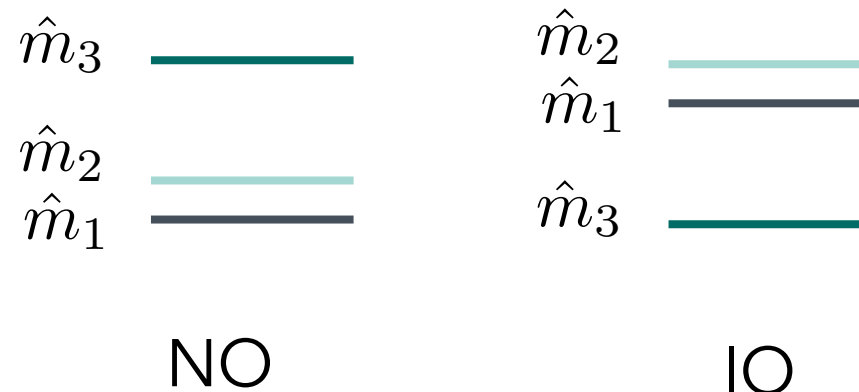
$$\frac{|s_{13}|^2}{m_3} \leq \frac{|s_{12}^2 c_{13}^2|}{m_2} + \frac{|c_{12}^2 c_{13}^2|}{m_1}$$

Neutrino Masses

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Six scenarios: $p = e, \mu, \tau$ + two orderings, but only **three** are consistent with experimental data:

- e -specific IO
- μ -specific NO
- τ -specific NO



If m_ν and δ_{CP} are **known** we can make a **prediction** on the Majorana phases

*Complex triangle equations have a second conjugate solution

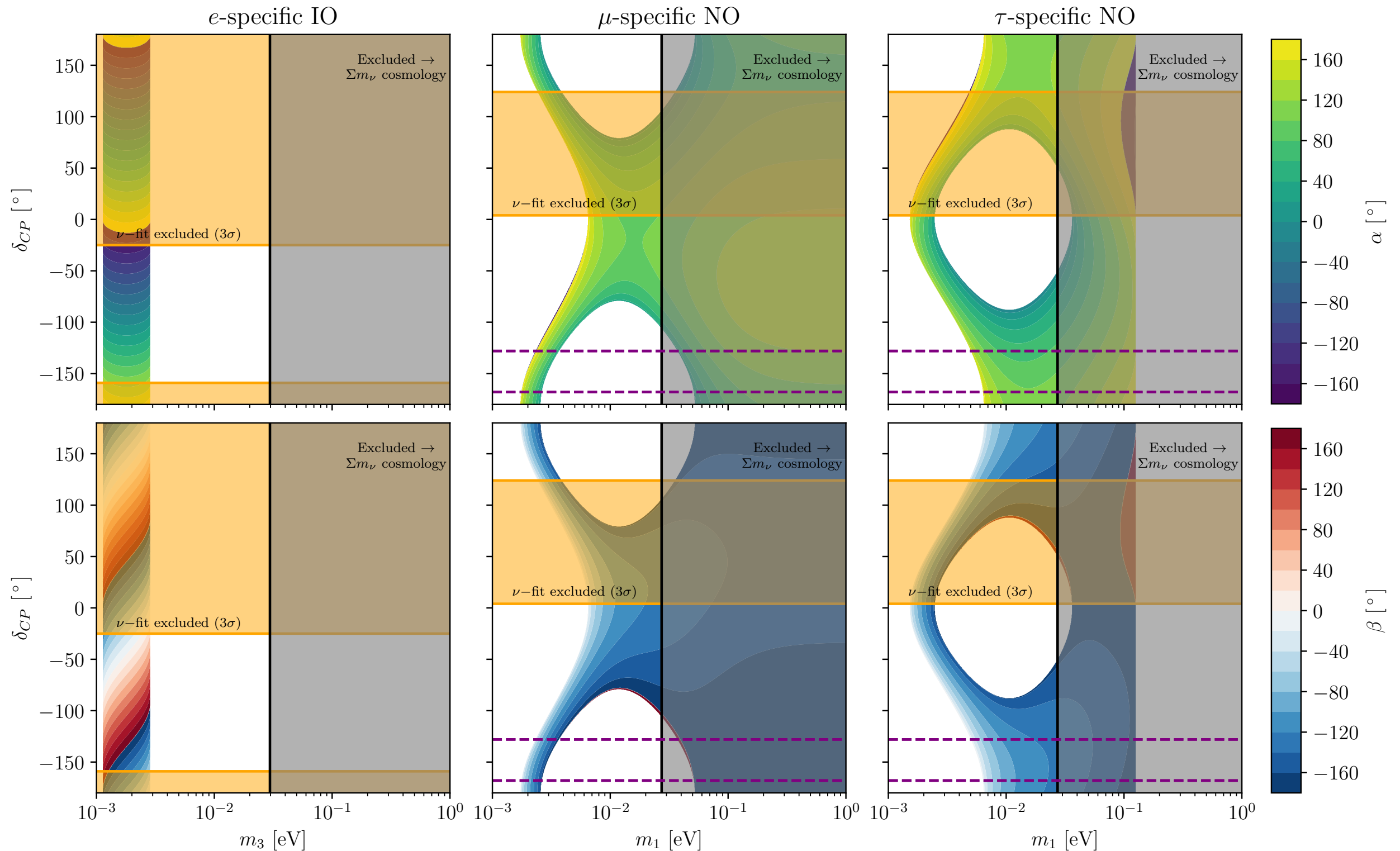
$$\alpha \rightarrow -\alpha - \arg c_1$$

$$\beta \rightarrow -\beta - \arg c_2$$

c_1, c_2 : the sides of the triangle

Neutrino Masses

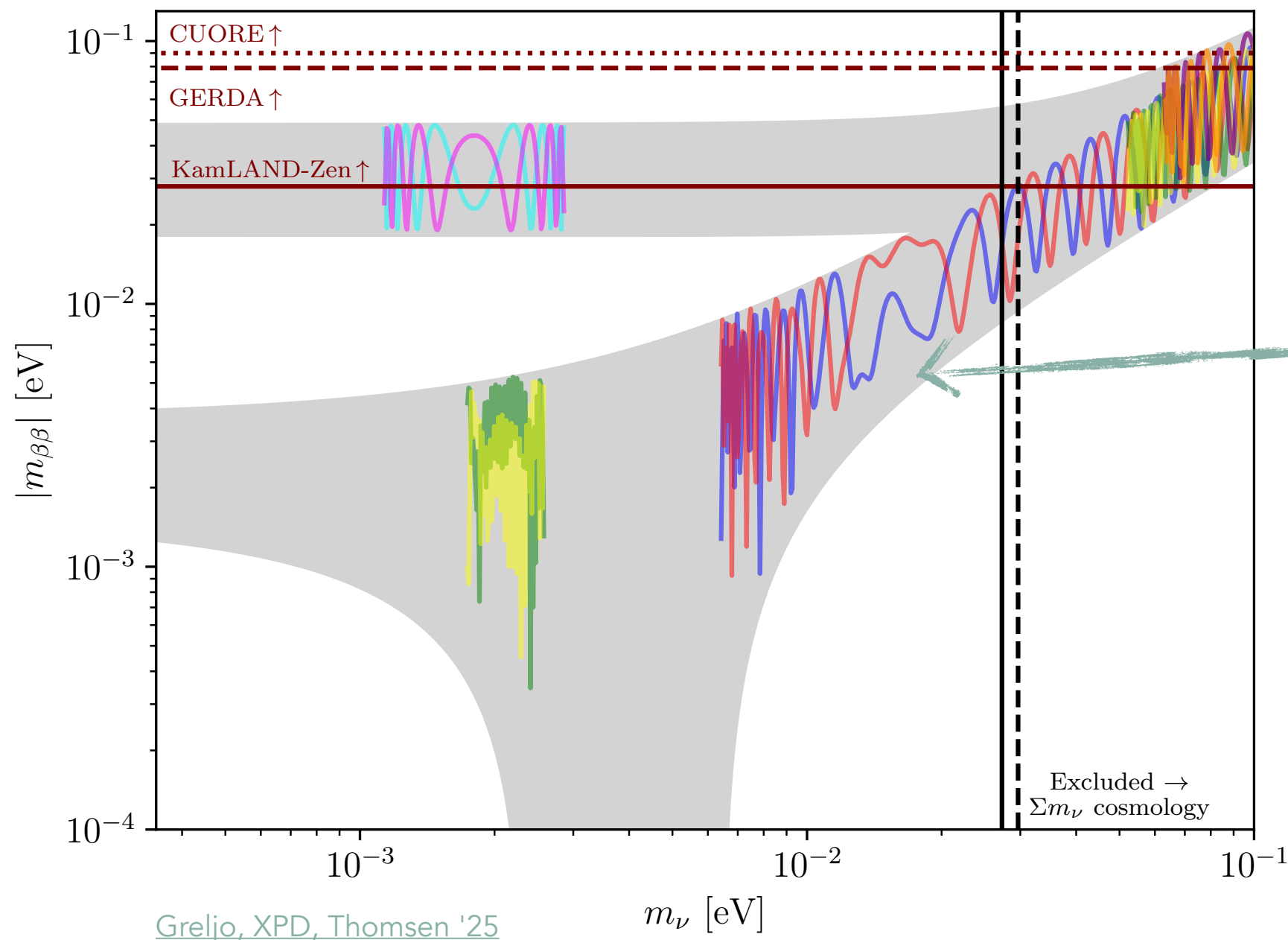
Greljo, XPD, Thomsen '25



Neutrino Masses

The future neutrino program is crucial!

Given δ_{CP} we can predict $|m_{\beta\beta}|$ as a function of m_ν



Two solutions to the triangle equations

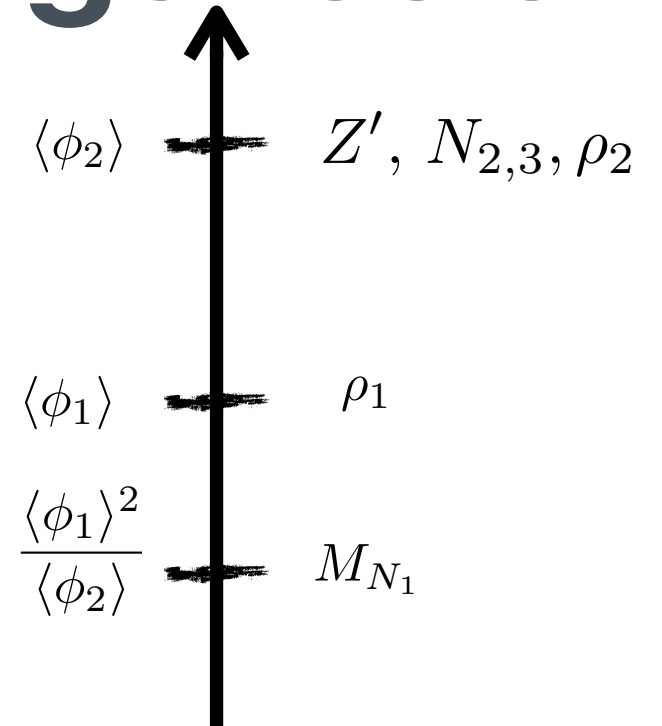
Models clearly **distinguishable** if the Dirac phase is known to $\delta_{\text{CP}} \sim 50^\circ$

The origin of matter: Leptogenesis

Assuming $\lambda \sim y_N \sim g_X \sim \mathcal{O}(1)$ Seesaw structure for RH neutrinos

$$M_N \sim \langle \phi_1 \rangle \begin{pmatrix} 0 & \times & \times \\ \times & 0 & 0 \\ \times & 0 & 0 \end{pmatrix} + \langle \phi_2 \rangle \begin{pmatrix} 0 & 0 & 0 \\ 0 & \times & \times \\ 0 & \times & \times \end{pmatrix}$$

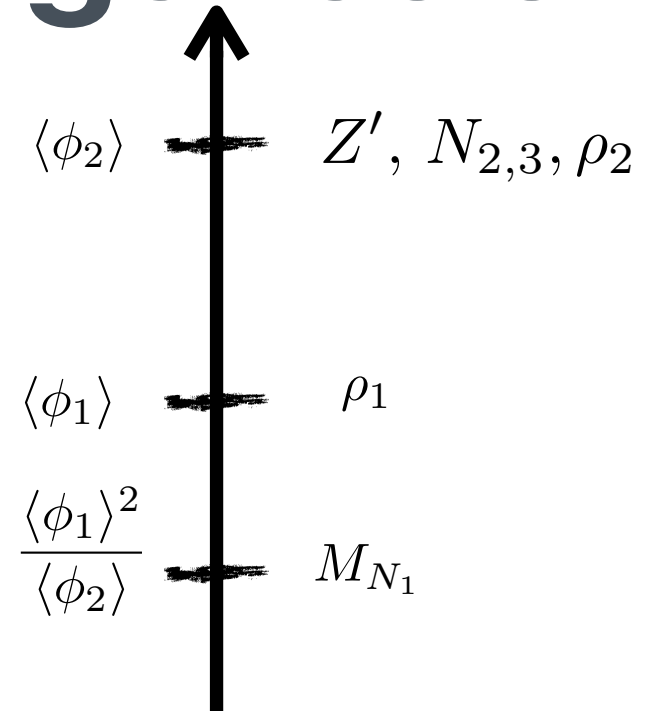
If $\langle \phi_1 \rangle \ll \langle \phi_2 \rangle \rightarrow M_{N_1} \ll M_{N_{2,3}}$



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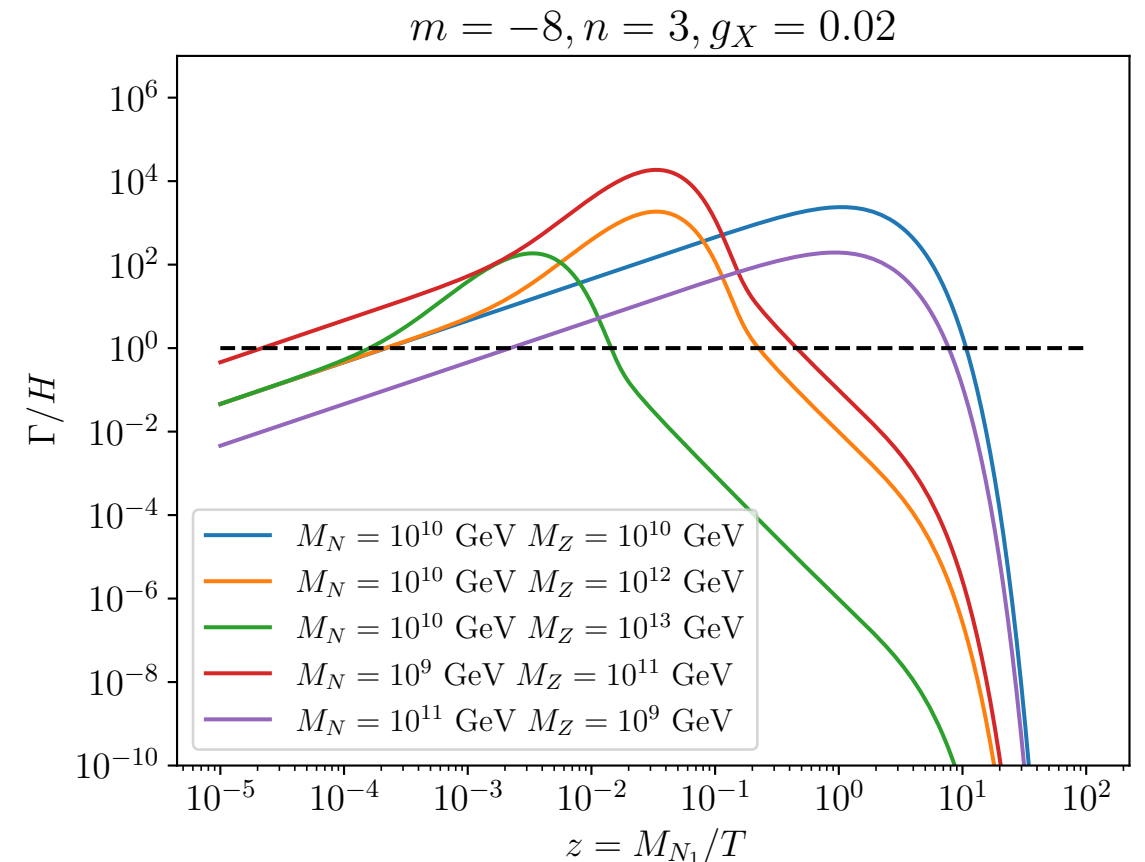


If $\langle \phi_1 \rangle \ll \langle \phi_2 \rangle \rightarrow M_{N_1} \ll M_{N_{2,3}}$

Z' Interactions must **decouple** at
 $\Gamma < H|_{T=M_{N_1}}$, for N_1 to decay **out of**
equilibrium

$$M_{Z'} \gtrsim 10^2 M_{N_1}$$

*analogous to light neutrinos in the SM
 and EW interactions

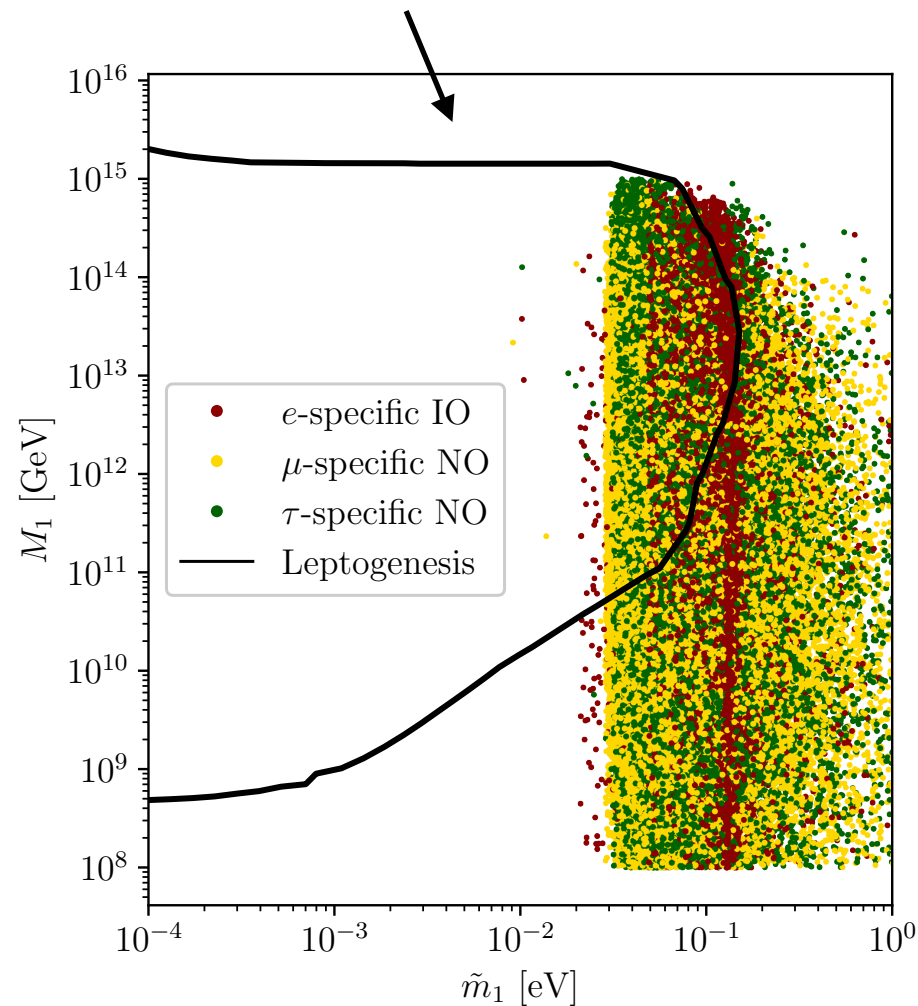


The origin of matter: Leptogenesis

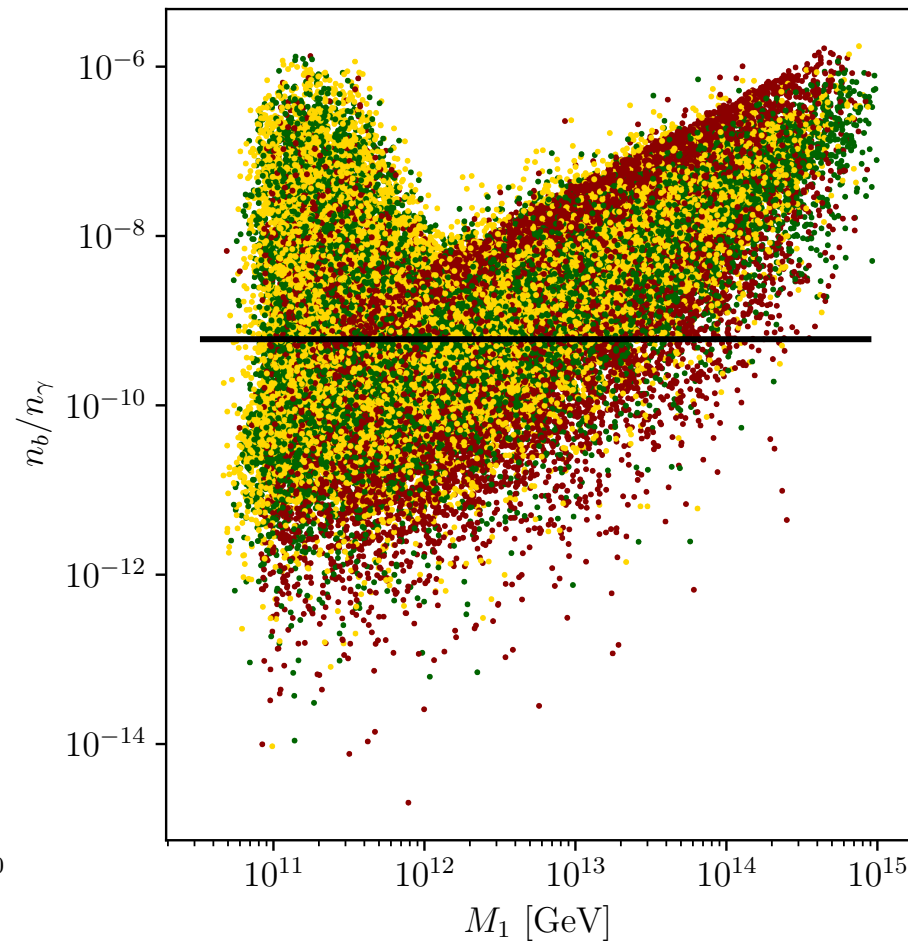
Leptogenesis happens **only** via N_1 ($N_{2,3}$ decay **in equilibrium** due to Z')

Baryogenesis via minimal thermal leptogenesis

[Giudice, Notari, Raidal, Riotto, Strumia '03](#)



[Greljo, XPD, Thomsen '25](#)



$$\tilde{m}_1 = v_{\text{EW}}^2 \frac{(Y_N^\dagger Y_N)_{11}}{M_{N_1}}$$

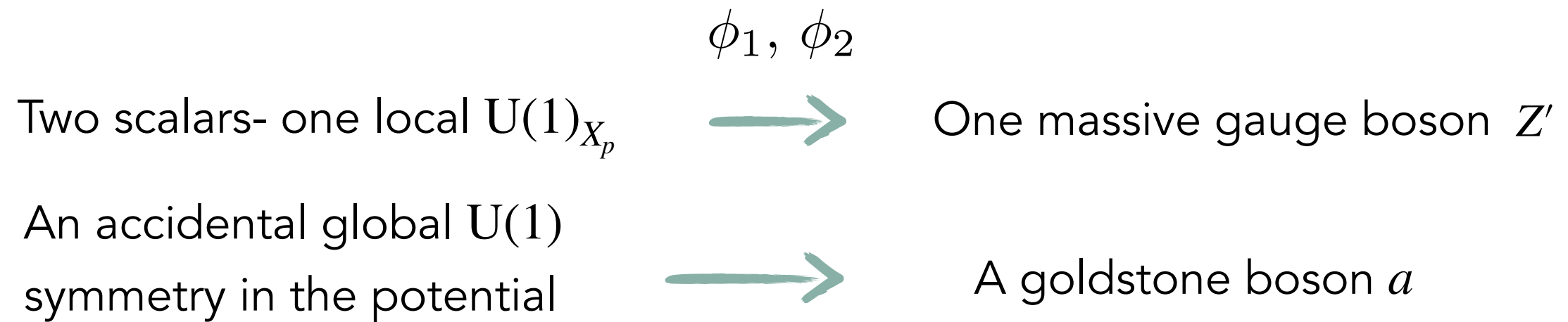
Triangle inequalities
 $\Rightarrow$ lower bound
 neutrino mass
 $\Rightarrow$ Strong-washout
 regime

UV scan of parameters which **fit** neutrino **mass splittings** and **mixings**

The origin of matter: Dark Matter

Two scalars- one local $U(1)_{X_p}$ $\xrightarrow{\phi_1, \phi_2}$ One massive gauge boson Z'

The origin of matter: Dark Matter



The origin of matter: Dark Matter

Two scalars- one local $U(1)_{X_p}$ ϕ_1, ϕ_2 $\longrightarrow$ One massive gauge boson Z'

An accidental global $U(1)$ symmetry in the potential $\longrightarrow$ A goldstone boson a

Leading Planck-suppressed operator $\min(|s| + |t|)$

pseudo-Nambu Goldstone Boson

$\Rightarrow$ **majoron**

$$V_{\text{grav.}} = (4\pi)^2 \frac{\eta}{M_{\text{Pl}}^{|s|+|t|-4}} \phi_1^{[s]} \phi_2^{[t]} + \text{h.c.}$$

		-5	-4	-3	-2	-1	0	1	2	3	4	5
	b											
	-5		15		17		19				23	
	-4	7		6	13	7	15	8	17	9	19	10
	-3		11		9		11		13		15	
	-2	7	11	4		3	7	4	9		13	8
	-1		11		5				7		13	
a	0	7	11	4	5				7	5	13	8
	1		11		7		5		7		13	
	2		13	6	11	5	9	4		5	13	8
	3		17				13		11		13	
	4	11	21	10	19	9	17	8	15	7		8
	5		25		23		21		19		17	

*colors see backup

The origin of matter: Dark Matter

Two scalars- one local $U(1)_{X_p}$ ϕ_1, ϕ_2 $\longrightarrow$ One massive gauge boson Z'

An accidental global $U(1)$ symmetry in the potential $\longrightarrow$ A goldstone boson a

Leading Planck-suppressed operator $\min(|s| + |t|)$

pseudo-Nambu Goldstone Boson

$\Rightarrow$ **majoron**

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**Majoron
DM**

If $\langle \phi_1 \rangle \ll \langle \phi_2 \rangle$

$$a \simeq a_1, f_a \simeq v_1$$

		-5	-4	-3	-2	-1	0	1	2	3	4	5
	-5		15		17		19				23	
	-4	7		6	13	7	15	8	17	9	19	10
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	5		25		23		21		19		17	

*colors see backup

Correct relic abundance + stable for a high-scale $\langle \phi_1 \rangle$

Class of models of
[Babu, Rothstein, Seckel '93](#)

The origin of matter: Dark Matter

$$T_{\text{RH}} > \langle \phi_2 \rangle \gg \langle \phi_1 \rangle \quad \text{Post-inflationary scenario} \quad \mathcal{L} \supset \frac{a}{v_1} M_N N^c N$$

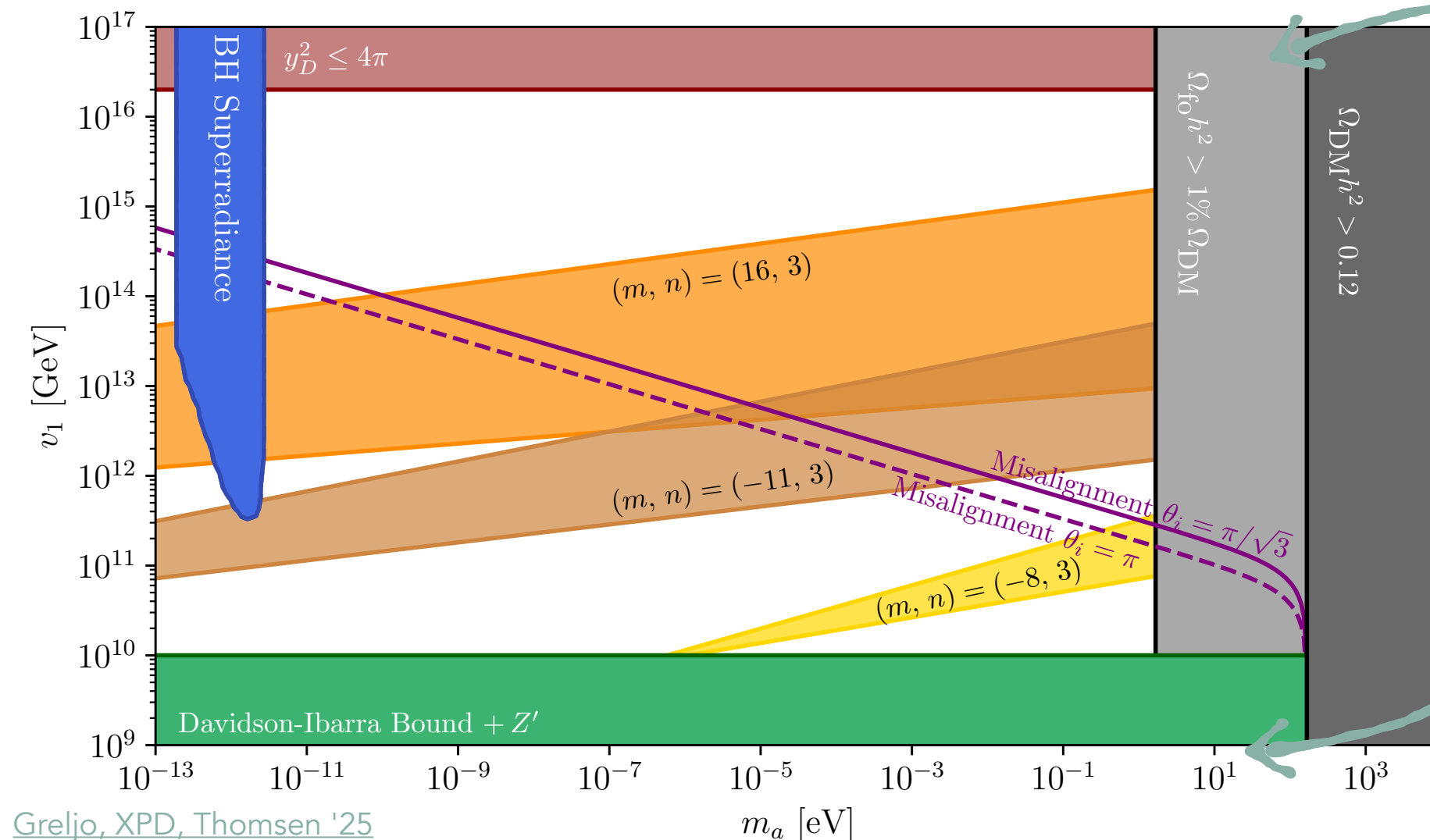
Majoron **thermalizes** via **RH neutrinos**, in thermal equilibrium via Z'

The origin of matter: Dark Matter

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Majoron **thermalizes** via **RH neutrinos**, in thermal equilibrium via Z'



Hot DM contribution too large for CMB measurements

$$M_{N_1} \gtrsim 4.9 \times 10^8 \text{ GeV} + Z' \text{ decoupling}$$

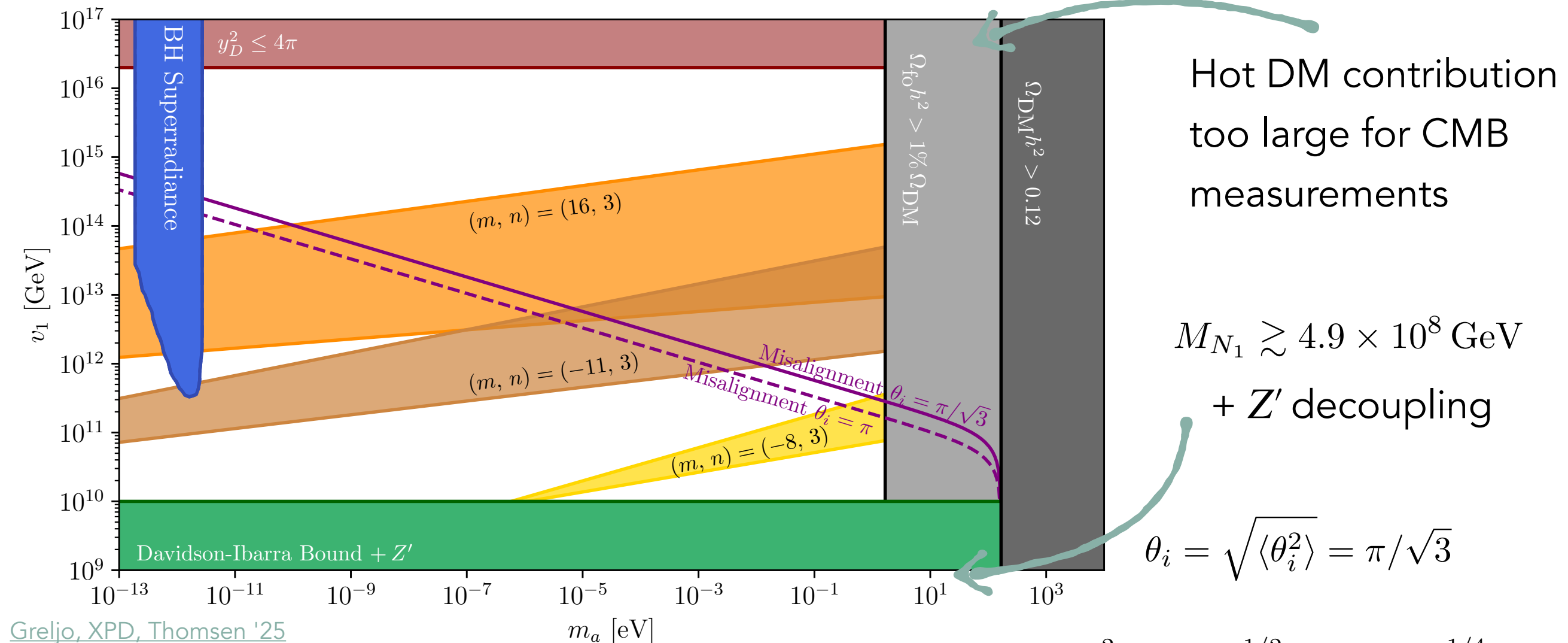
Greljo, XPD, Thomsen '25

The origin of matter: Dark Matter

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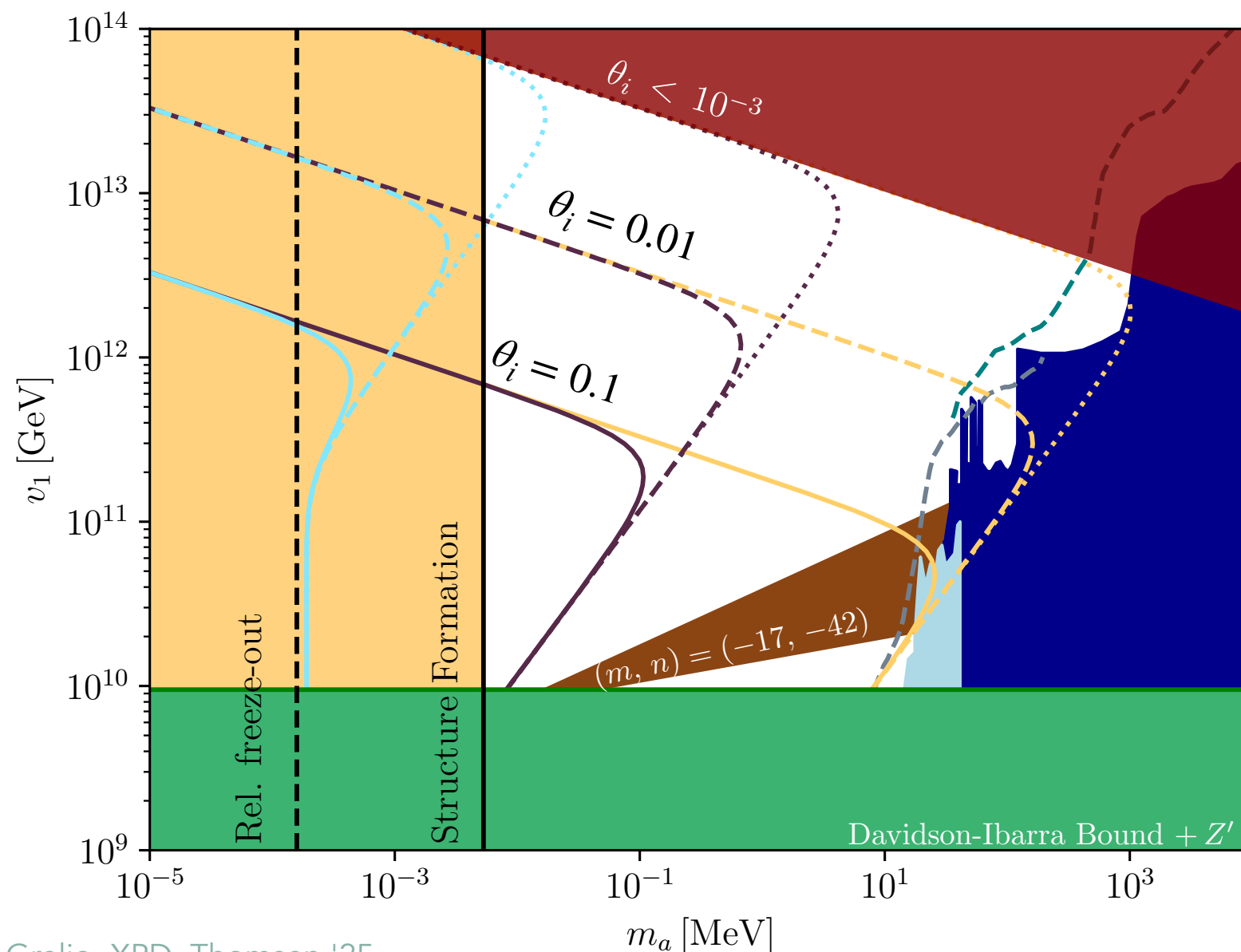
Misalignment mechanism:
$$\Omega_{\text{DM}} h^2 \simeq 0.12 \left(\frac{\theta_i f_a}{1.9 \times 10^{13}} \right)^2 \left(\frac{m_a}{1 \mu\text{eV}} \right)^{1/2} \left(\frac{90}{g_*(T_{\text{osc}})} \right)^{1/4}.$$

Testable! $\Delta N_{\text{eff}} = 0.027$ [CMB-S4 sensitivity 0.0156]

The origin of matter: Dark Matter

$\langle \phi_1 \rangle \simeq T_{\text{RH}} > M_{N_1} = \frac{\langle \phi_1 \rangle^2}{\langle \phi_2 \rangle}$ Pre-inflationary scenario: symmetry never restored

N_1 in thermal equilibrium (strong washout ℓHN -interactions or Z')

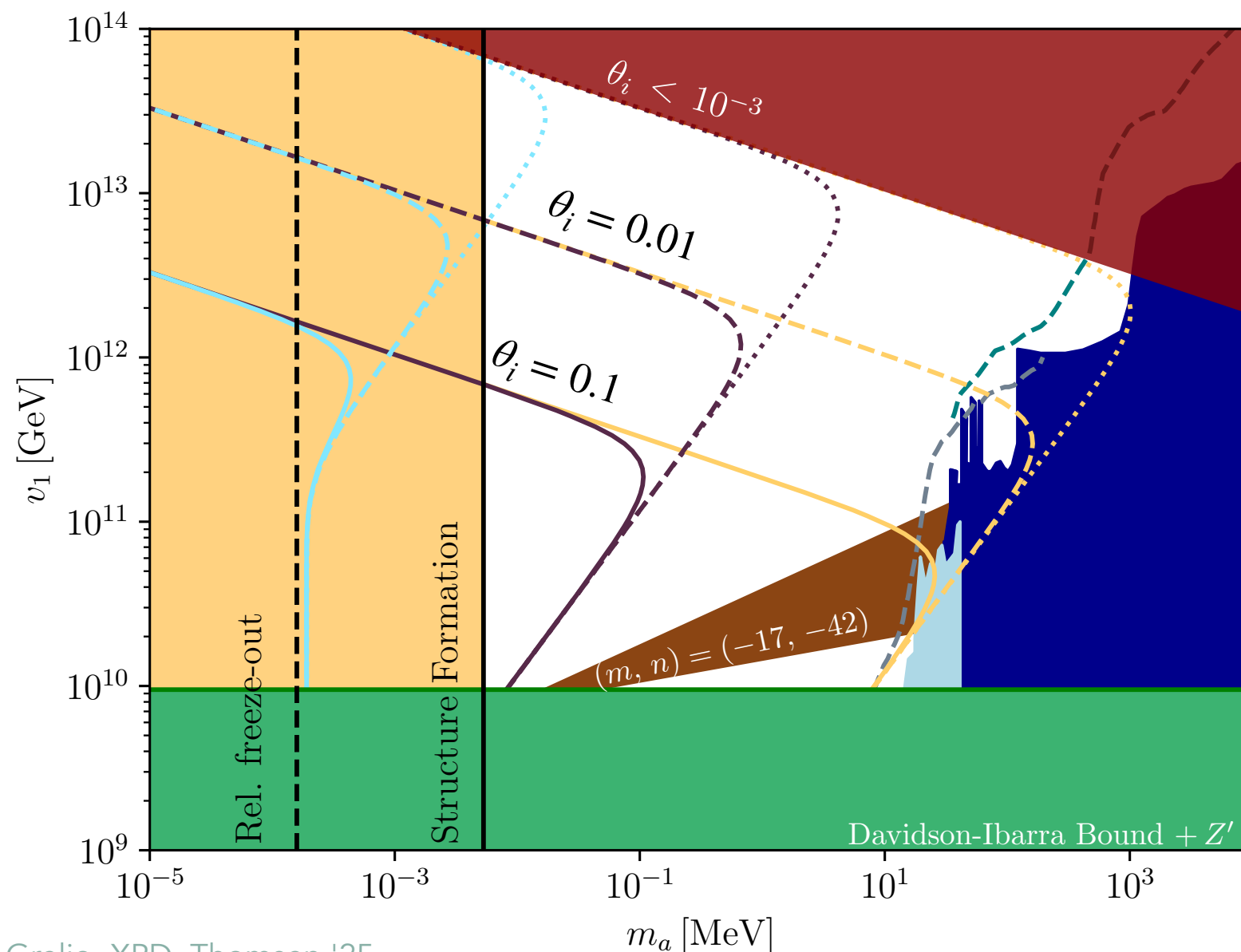


Greljo, XPD, Thomsen '25

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Freeze-in via RH neutrinos

$$N_1 N_1 \rightarrow aa$$

+ misalignment

θ_i can take any value

Effective Yukawa: $M_{N_1}/v_1 = v_1/v_2$

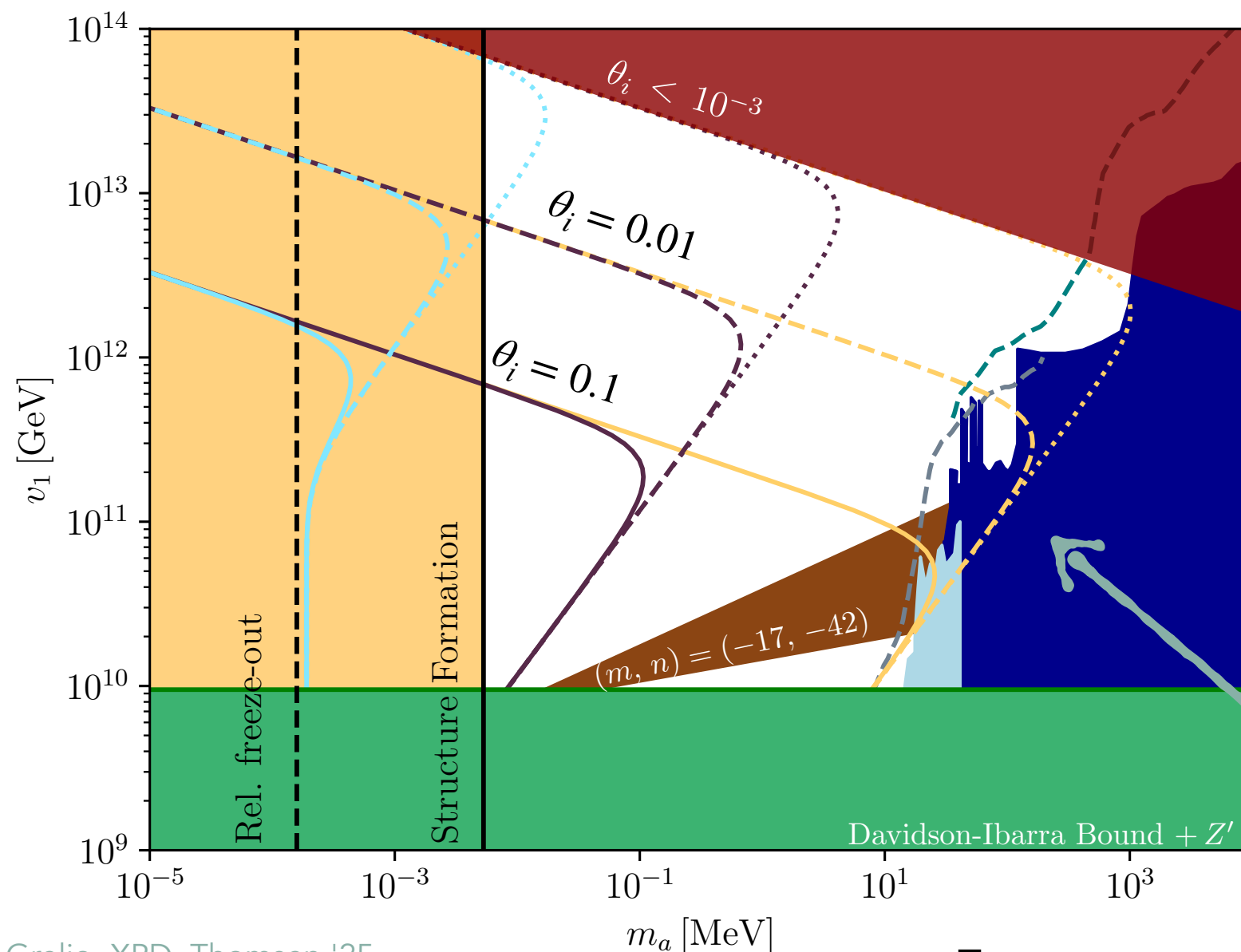
$$v_1/v_2 = 0.001, 0.01, 0.1$$

Greljo, XPD, Thomsen '25

The origin of matter: Dark Matter

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Neutrino telescope searches

Garcia-Cely, Heeck '17,
Akita, Niibo '22

Greljo, XPD, Thomsen '25

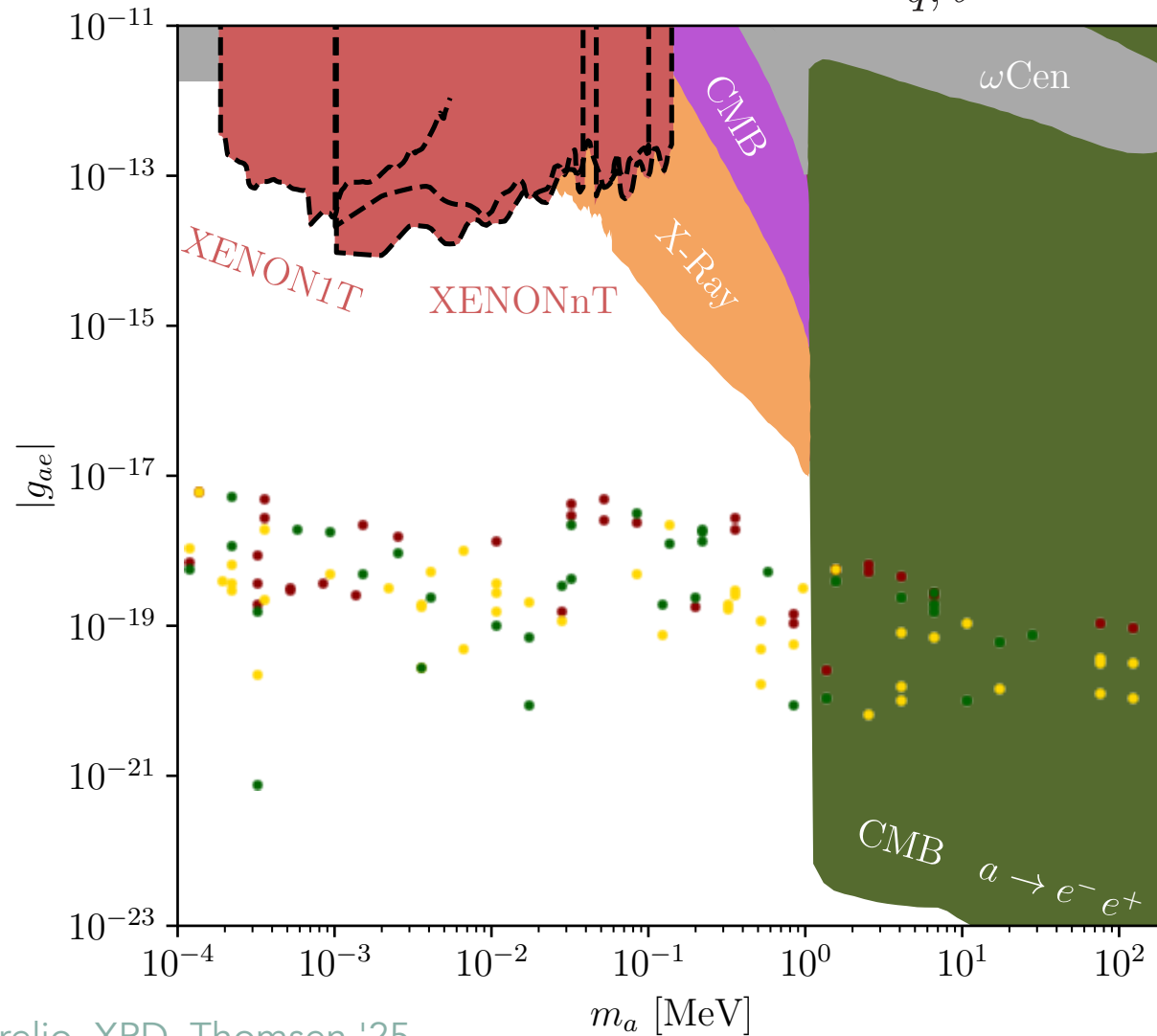
Future experiments: JUNO & HK

Dark Matter Searches

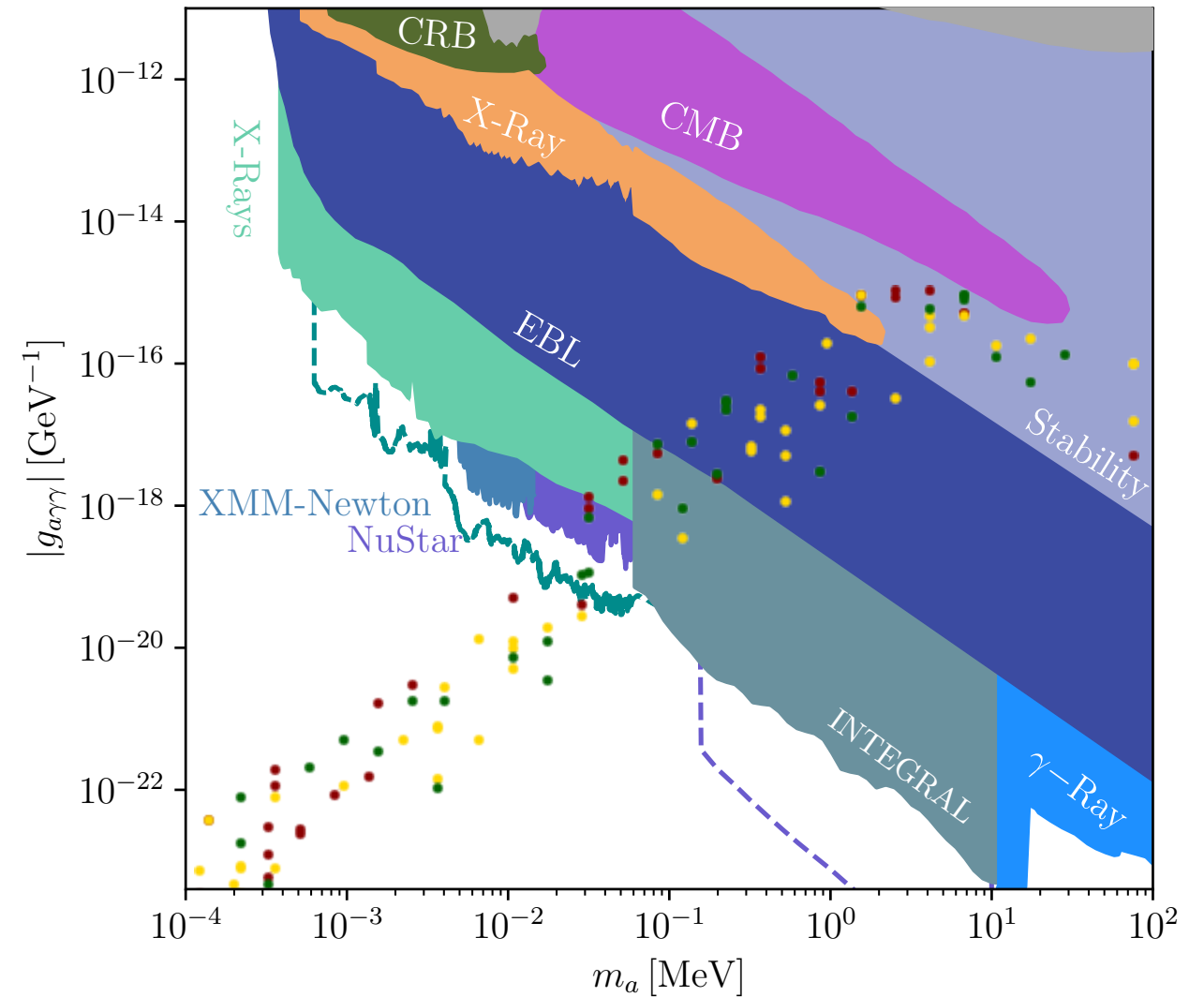
Heeck, Patel '19

$$\mathcal{L} \supset \frac{m_e}{16\pi v_1} a \bar{e} \gamma_5 e \quad a \text{ --- } \begin{array}{c} n_i \\ \circlearrowleft \\ n_j \end{array} \text{---} Z \begin{array}{l} \nearrow q, \ell \\ \searrow \bar{q}, \bar{\ell} \end{array}$$

$$\mathcal{L} \supset \frac{m_a^2}{(16\pi)^2 v_1} h \left(\frac{m_a^2}{4m_f^2} \right) a F \tilde{F} \quad a \text{ --- } \begin{array}{c} n_i \\ \circlearrowleft \\ n_j \end{array} \text{---} Z \begin{array}{l} \nearrow V \\ \searrow V' \end{array}$$



Greljo, XPD, Thomsen '25



Electron and photon DM searches constrain the model to lower masses $m_a \lesssim 0.1\text{MeV}$

Future γ - and X-ray telescopes are **sensitive** to further test this scenario

Conclusions

A model of **exact** proton stability

[Davighi, Greljo, Thomsen '22](#)

$$U(1)_{X_p} \rightarrow X_p = 3m(B - L) - n(3L_p - L) \qquad U(1)_{X_p} \xrightarrow{\langle \phi_1 \rangle, \langle \phi_2 \rangle \neq 0} \mathbb{Z}_9^B$$

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[Greljo, XPD, Thomsen '25](#)

1) **Neutrino masses**: via a
high-scale type-I seesaw.

Lepton-flavour non-universal $U(1)_{X_p}$



Complex triangle equations:

$$(m_\nu, \delta_{CP}) \rightarrow |m_{\beta\beta}|$$

predicted!

δ_{CP} known $\rightarrow$ lower limit
neutrino mass

Conclusions

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[Davighi, Greljo, Thomsen '22](#)

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1) **Neutrino masses**: via a high-scale type-I seesaw.

2) **Matter-antimatter asymmetry**

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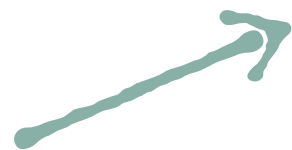


Complex triangle equations:

$$(m_\nu, \delta_{CP}) \rightarrow |m_{\beta\beta}|$$

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δ_{CP} known $\rightarrow$ lower limit
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$$\langle \phi_1 \rangle \ll \langle \phi_2 \rangle$$

$$M_{N_1} \sim \frac{\langle \phi_1 \rangle^2}{\langle \phi_2 \rangle} \ll M_{N_{2,3}} \sim Z'$$

minimal thermal

leptogenesis

Strong washout regime

N_1 thermalizes

Conclusions

A model of **exact** proton stability

[Davighi, Greljo, Thomsen '22](#)

$$U(1)_{X_p} \rightarrow X_p = 3m(B - L) - n(3L_p - L) \quad U(1)_{X_p} \xrightarrow{\langle \phi_1 \rangle, \langle \phi_2 \rangle \neq 0} \mathbb{Z}_9^B$$

[Greljo, XPD, Thomsen '25](#)

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3) **Dark Matter**

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minimal thermal

leptogenesis

Accidental global symmetry

Majoron

Dark-matter via

misalignment $m_a \leq 1 \text{ eV}$

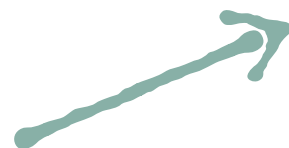
Strong washout regime

N_1 thermalizes

+ freeze in

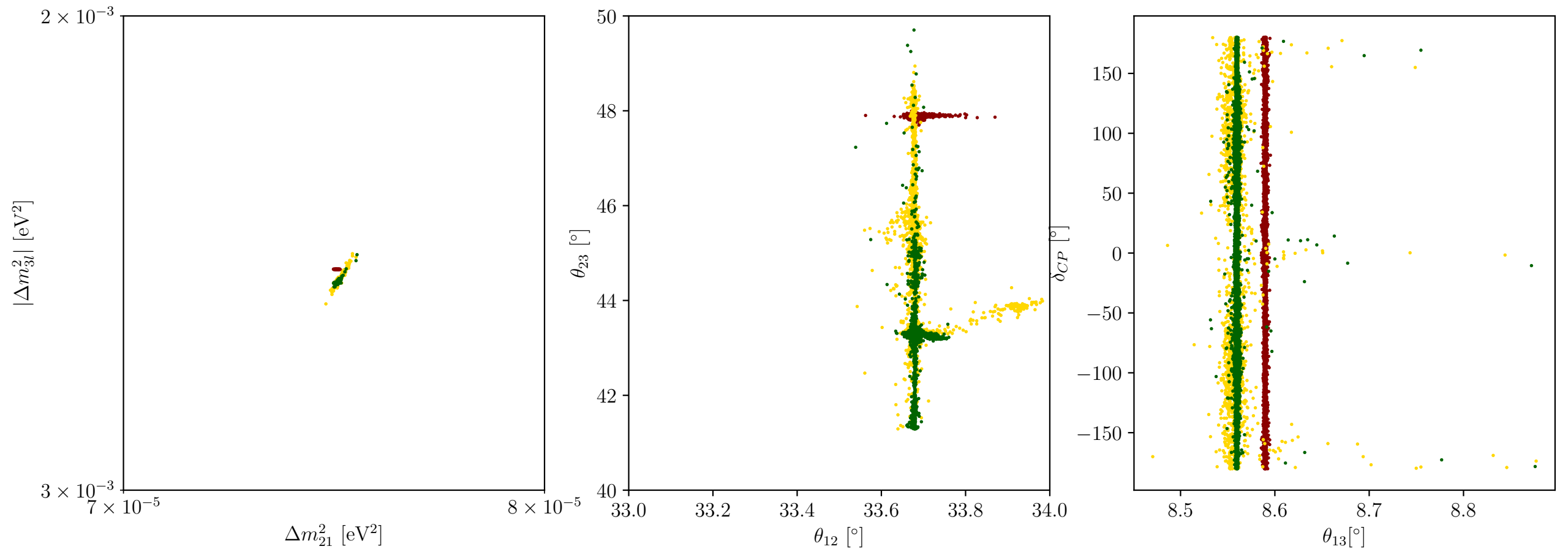
$$m_a \leq 0.1 \text{ MeV}$$

bounded by DM searches



Back Up

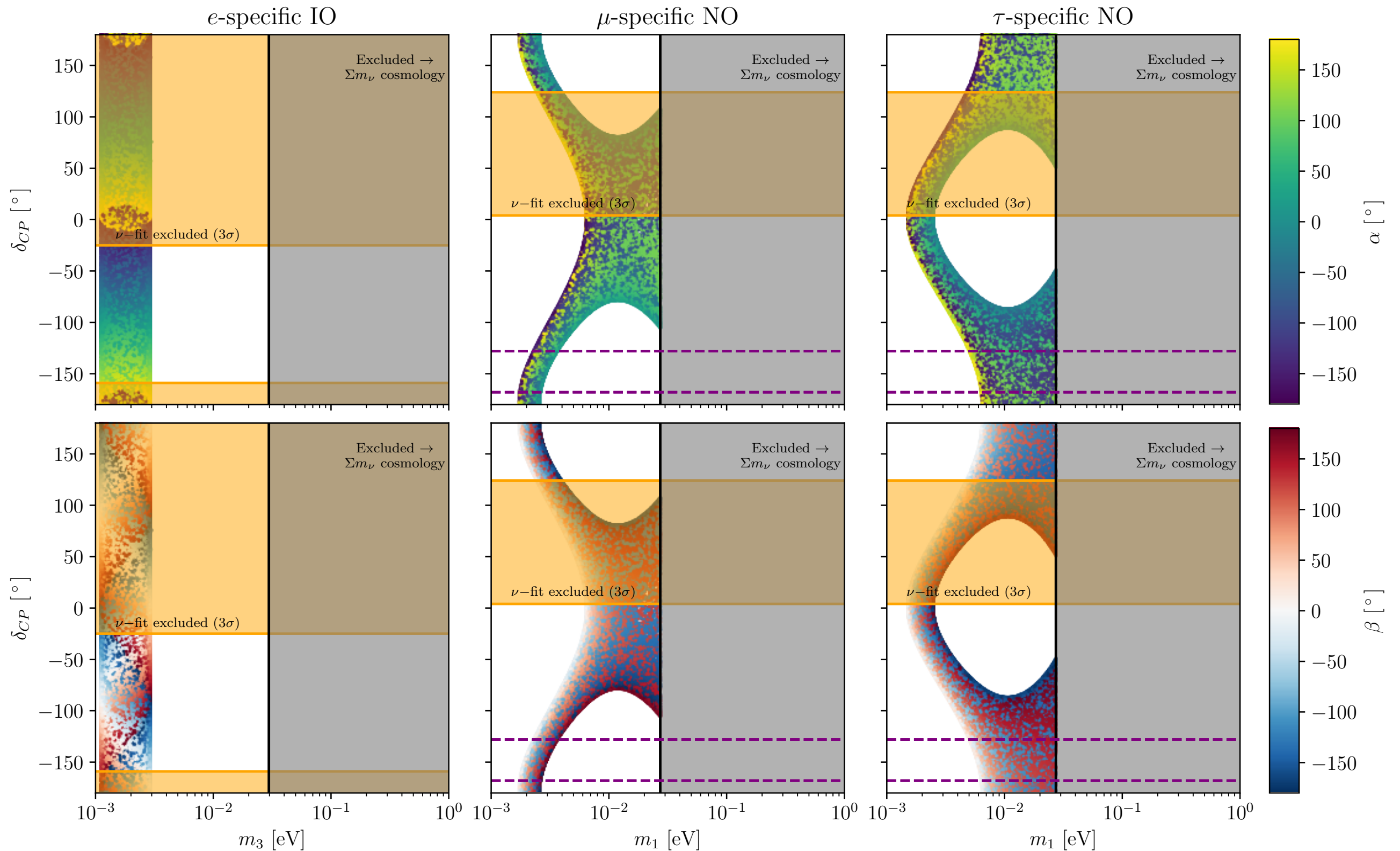
Parameter Scan



We leave δ_{CP} unconstrained

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2 \theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \rightarrow 35.95$
	$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \rightarrow 0.585$	$0.550^{+0.012}_{-0.015}$	$0.440 \rightarrow 0.584$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \rightarrow 49.9$	$47.9^{+0.7}_{-0.9}$	$41.5 \rightarrow 49.8$
	$\sin^2 \theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \rightarrow 0.02388$	$0.02231^{+0.00056}_{-0.00056}$	$0.02060 \rightarrow 0.02409$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \rightarrow 8.89$	$8.59^{+0.11}_{-0.11}$	$8.25 \rightarrow 8.93$
	$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \rightarrow 364$	274^{+22}_{-25}	$201 \rightarrow 335$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \rightarrow 8.05$
	$\frac{\Delta m_{3l}^2}{10^{-3} \text{ eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \rightarrow +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \rightarrow -2.421$

Parameter Scan



Triangle equations

Different scenarios: $p = \{e, \mu, \tau\}$

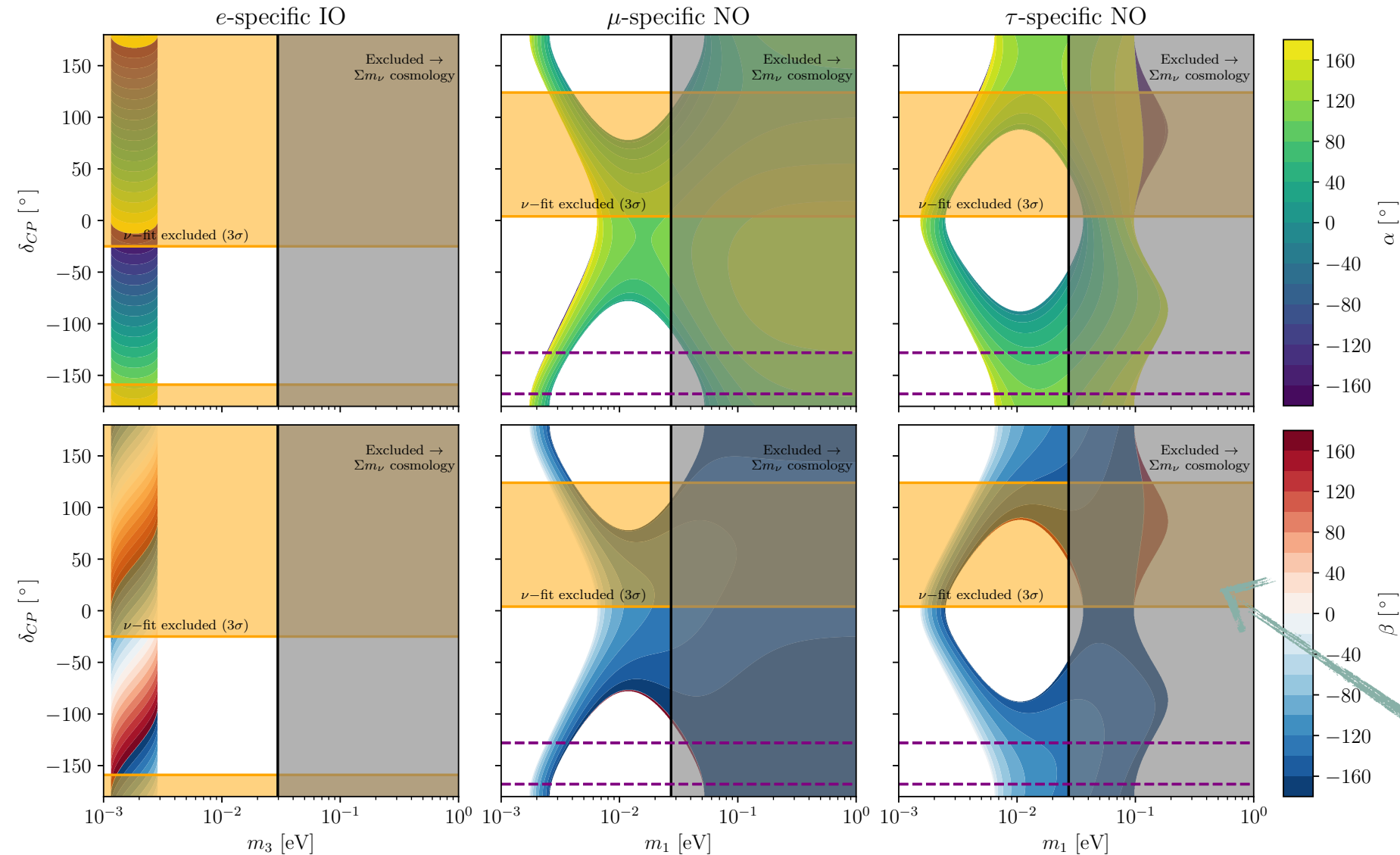
$$\begin{aligned}\frac{e^{i(\alpha+\beta+2\delta_{\text{CP}})}}{m_1 m_2 m_3} [m]_{11} &= \frac{1}{m_3} s_{13}^2 + \frac{e^{i(\beta+2\delta_{\text{CP}})}}{m_2} s_{12}^2 c_{13}^2 + \frac{e^{i(\alpha+2\delta_{\text{CP}})}}{m_1} c_{12}^2 c_{13}^2 \\ \frac{e^{i(\alpha+\beta)}}{m_1 m_2 m_3} [m]_{22} &= \frac{1}{m_3} c_{13}^2 s_{23}^2 + \frac{e^{i\beta}}{m_2} (c_{12} c_{23} - s_{23} s_{12} s_{13} e^{i\delta_{\text{CP}}})^2 + \frac{e^{i\alpha}}{m_1} (s_{12} c_{23} + c_{12} s_{23} s_{13} e^{i\delta_{\text{CP}}})^2 \\ \frac{e^{i(\alpha+\beta)}}{m_1 m_2 m_3} [m]_{33} &= \frac{1}{m_3} c_{13}^2 c_{23}^2 + \frac{e^{i\beta}}{m_2} (c_{12} s_{23} + c_{23} s_{12} s_{13} e^{i\delta_{\text{CP}}})^2 + \frac{e^{i\alpha}}{m_1} (s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{\text{CP}}})^2\end{aligned}$$

EW-running of the Weinberg operator

$$\begin{aligned}[m_\nu^*]_{pp} &= \det(-v_{\text{EW}}^2 Y A_{\text{eff}} Y^\top) \\ &\simeq -\gamma t \det(v_{\text{EW}}^2 Y M^{-1} Y^\top)\end{aligned}\quad \gamma = \frac{1}{16\pi^2} \left(2\lambda + \frac{1}{2}g_1^2 - \frac{3}{2}g_2^2 \right) \quad t = \log\left(\sqrt{M_{N_2} M_{N_3}}/M_{N_1}\right)$$

$$\text{Numerical estimate} \quad |[m_\nu]_{pp}| \stackrel{?}{\lesssim} 0.01 \cdot \begin{cases} m_2 m_3 & (\text{NO}) \\ m_1 m_2 & (\text{IO}) \end{cases}.$$

One-loop correction



$$[m_\nu^*]_{pp} = \det(-v_{\text{EW}}^2 Y A_{\text{eff}} Y^\top) \simeq -\gamma t \det(v_{\text{EW}}^2 Y M^{-1} Y^\top)$$

$$\gamma = \frac{1}{16\pi^2} \left(2\lambda + \frac{1}{2}g_1^2 - \frac{3}{2}g_2^2 \right)$$

$$t = \log\left(\sqrt{M_{N_2} M_{N_3}} / M_{N_1}\right)$$

$$|[m_\nu]_{pp}| \stackrel{?}{\lesssim} 0.01 \cdot \begin{cases} m_2 m_3 & (\text{NO}) \\ m_1 m_2 & (\text{IO}) \end{cases}.$$

Freeze-in majoron

t – channel : $N_1 N_1 \rightarrow aa$

Reach thermal equilibrium, and
freezes-out relativistically

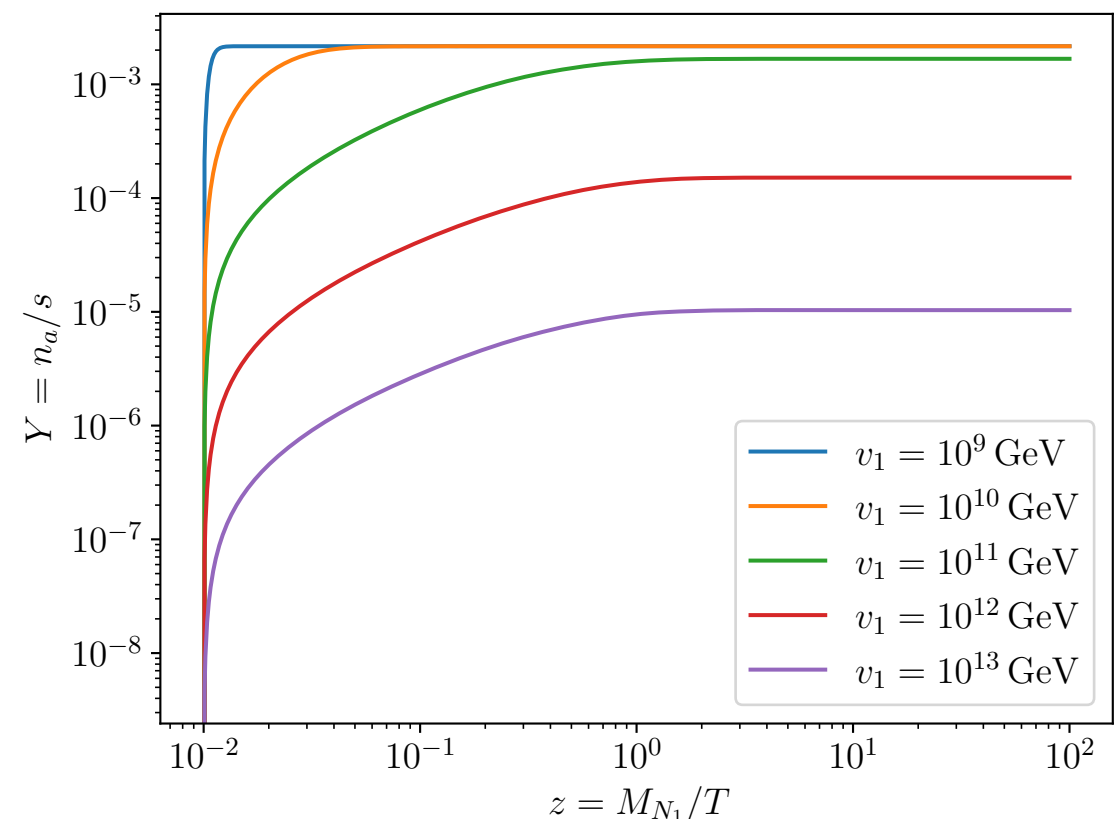
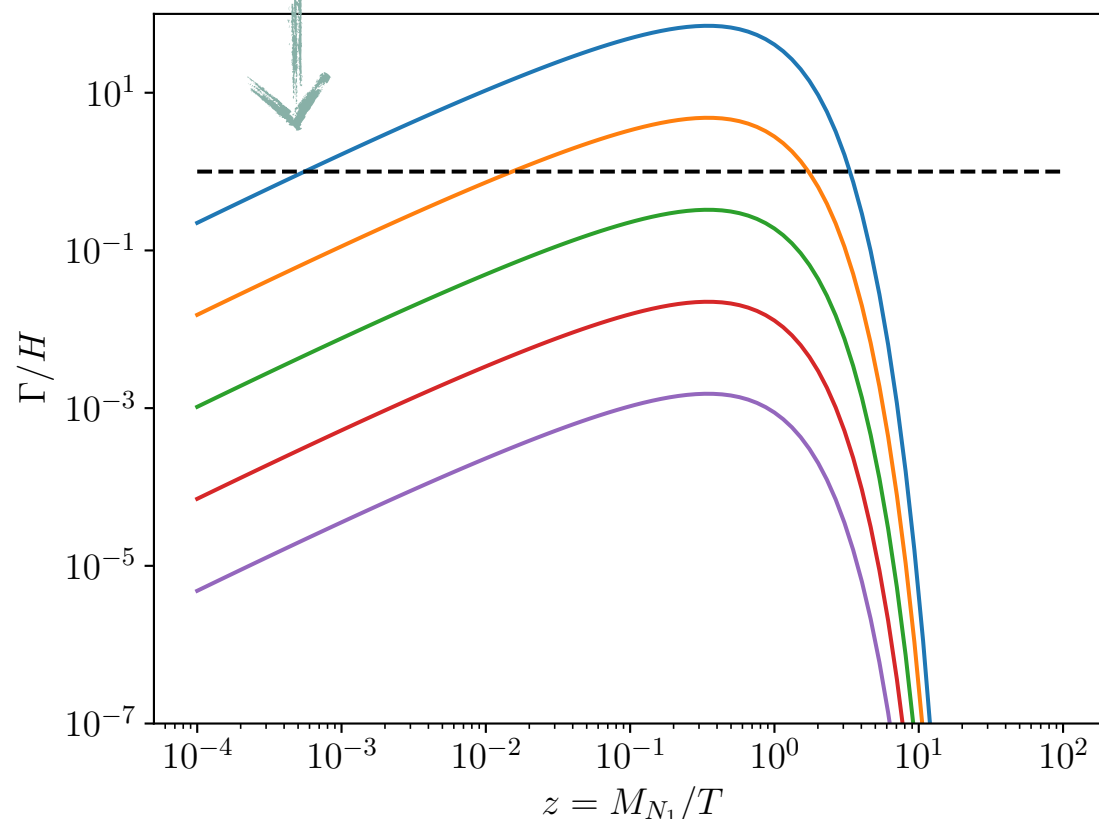
$$\Omega_{\text{fo}} h^2 = \frac{\zeta(3) g_s(T_0) m_a T_0^3}{\pi^2 g_s(T_{\text{dec}}) \rho_c} h^2 = 0.12 \frac{m_a}{166.62 \text{ eV}} \frac{106.75}{g_s(T_{\text{dec}})},$$

[Gu, Sarkar'09,](#)
[Hambye, Frigerio, Masso '11](#)
[Boulebnane, Heeck, Nguyen, Teresi '17](#)

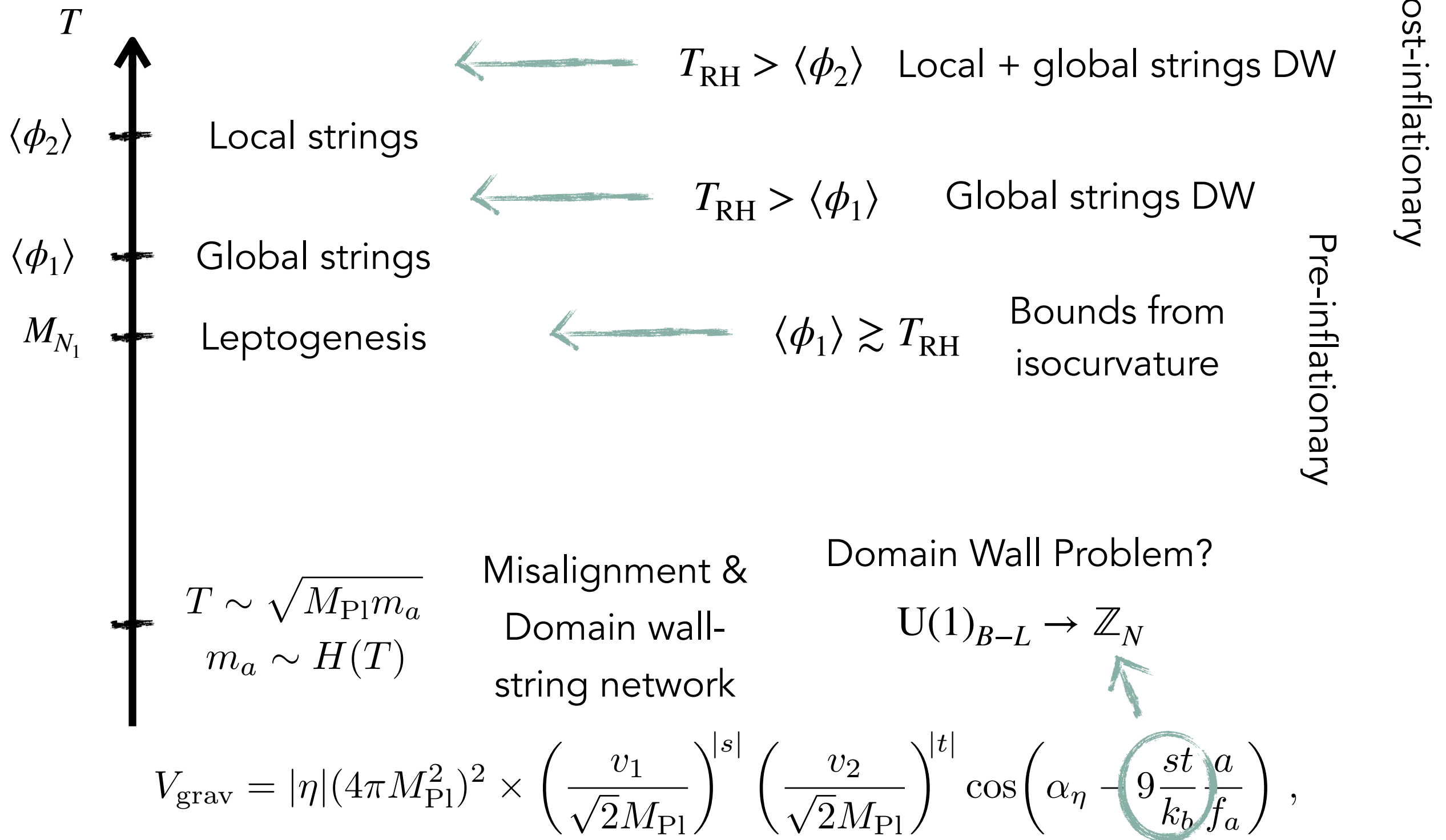
$$\gamma_{\text{ann.}} = N_a \frac{T}{64\pi^4} \int_{4M_N^2}^{\infty} ds \hat{\sigma}(s) \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T} \right)$$

Freeze-in: $z H s \frac{dY}{dz} = \gamma_{\text{ann}} \left(1 - \frac{Y^2}{Y_{\text{eq}}^2} \right)$

$$\hat{\sigma}(ab \rightarrow 12) = \frac{g_a g_b}{c_{ab}} \frac{2 \left[((s - m_a^2 - m_b^2)^2 - 4m_a^2 m_b^2) \right]}{s} \sigma(s)$$



Cosmological History



Domain Wall Problem?

Winding numbers of the strings

$$\mathcal{E}_{\text{kin}} \sim \int d^2x |\partial_i \bar{\phi}'_1|^2 \quad \text{with} \quad \bar{\phi}'_1(\theta) \sim \frac{1}{\sqrt{2}} v_1 e^{i\theta(w_1 - w_2 \mathcal{X}_1 / \mathcal{X}_2)}$$

scalar charges

$$\mathcal{E}_{\text{kin}} \sim |w_1 \mathcal{X}_2 - w_2 \mathcal{X}_1| = \min_{w \in \mathbb{Z}} |w \mathcal{X}_2 - w_2 \mathcal{X}_1| \rightarrow |sw_1 + tw_2| = \min_{w \in \mathbb{Z}} |sw + tw_2|$$

$$V_{\text{grav.}}(\bar{\phi}_1, \bar{\phi}_2) \rightarrow V_{\text{grav.}}(v_1, v_2) \cos(sw_1 \theta + tw_2 \theta).$$

$$N_W = |sw_1 + tw_2|$$

- local strings: $N_W = \min_{w \in \mathbb{Z}} |sw + t|$,
- global strings: $N_W = |s|$.

Automatic solution if $N_W = 1$

Domain Wall Problem?

$$N_W = |sw_1 + tw_2|$$

Automatic solution if $N_W = 1$

- local strings: $N_W = \min_{w \in \mathbb{Z}} |sw + t|$,
- global strings: $N_W = |s|$.

		b											
		-5	-4	-3	-2	-1	0	1	2	3	4	5	
a	-5		15		17		19				23		
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	-1		11		5				7		13		
	0	7	11	4	5				7	5	13	8	
	1		11		7		5		7		13		
	2		13	6	11	5	9	4		5	13	8	
	3		17				13		11		13		
	4	11	21	10	19	9	17	8	15	7		8	
	5		25		23		21		19		17		

Green: $|s| = 1$

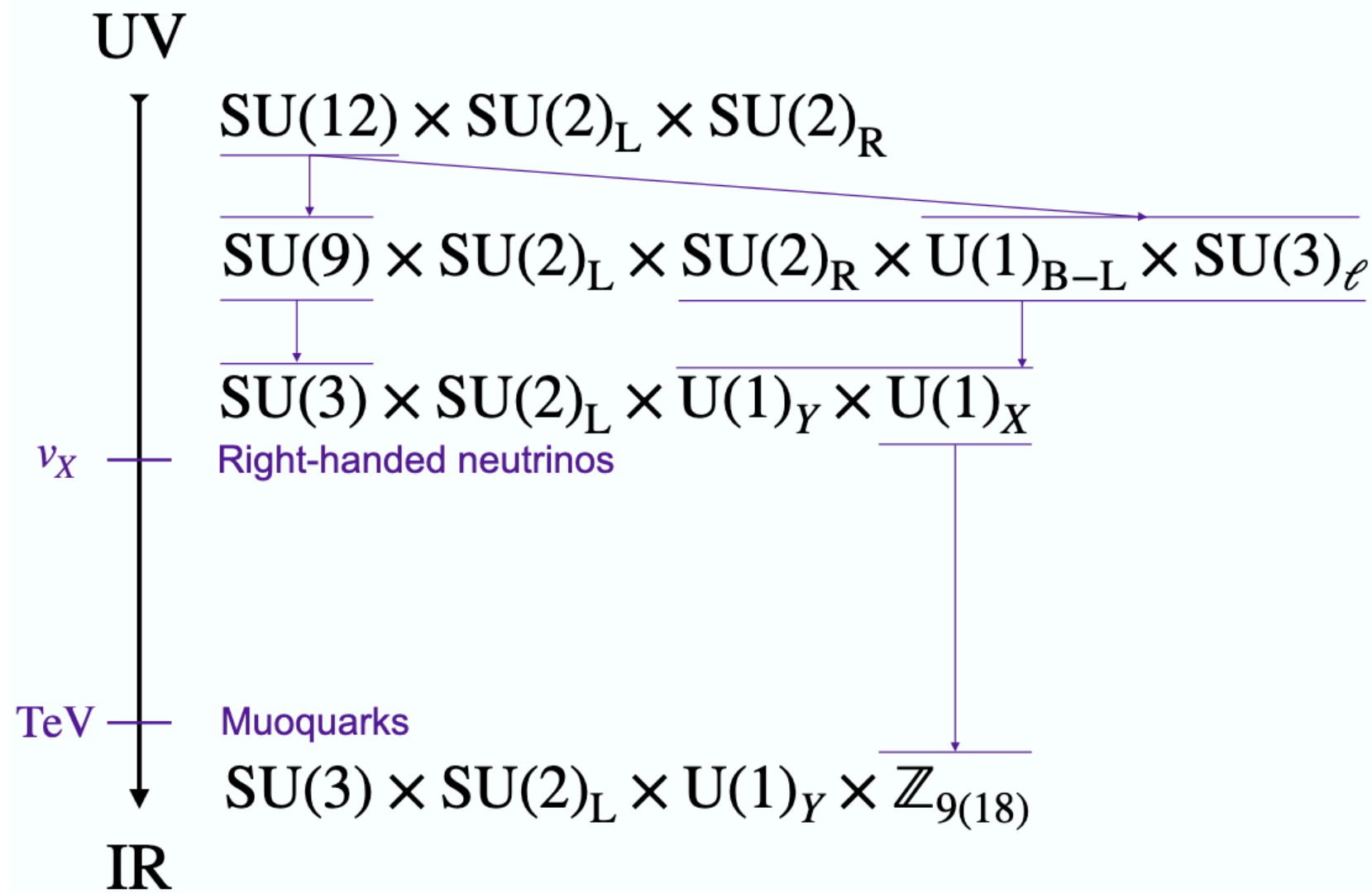
Blue: $N_W = \min_{w \in \mathbb{Z}} |sw + t|$

Automatic solution of a Domain Wall problem via the charges of the model

A Unification Path

[Davighi, Greljo, Thomsen '22](#)

$$\Psi_L \sim (\mathbf{12}, \mathbf{2}, \mathbf{1}) \quad \Psi_R \sim (\mathbf{12}, \mathbf{1}, \mathbf{2})$$



Tentative flavour-gauge unification