MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

PHASING OUT OF DARKNESS

From Sterile Neutrino Dark Matter to Neutrino Masses via Time-Dependent Mixing

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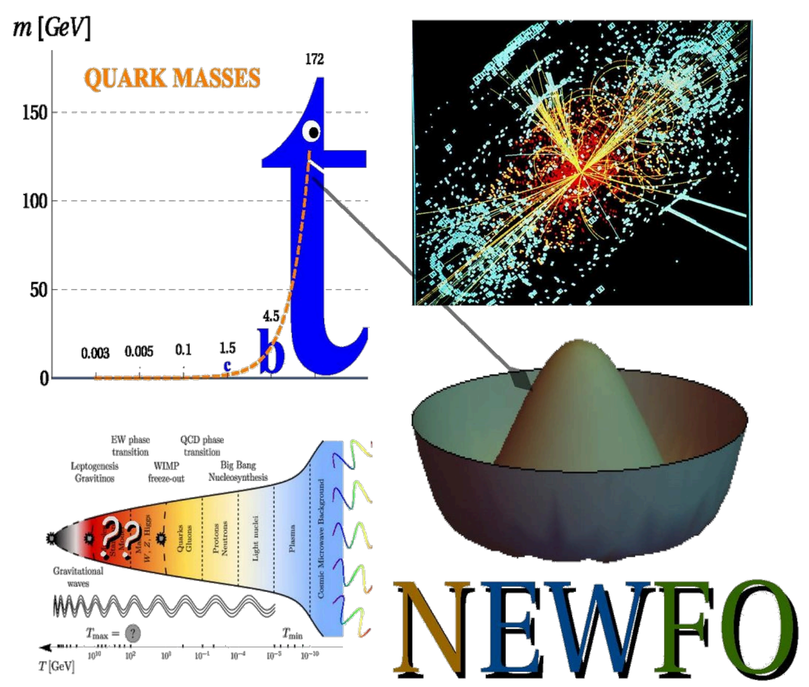


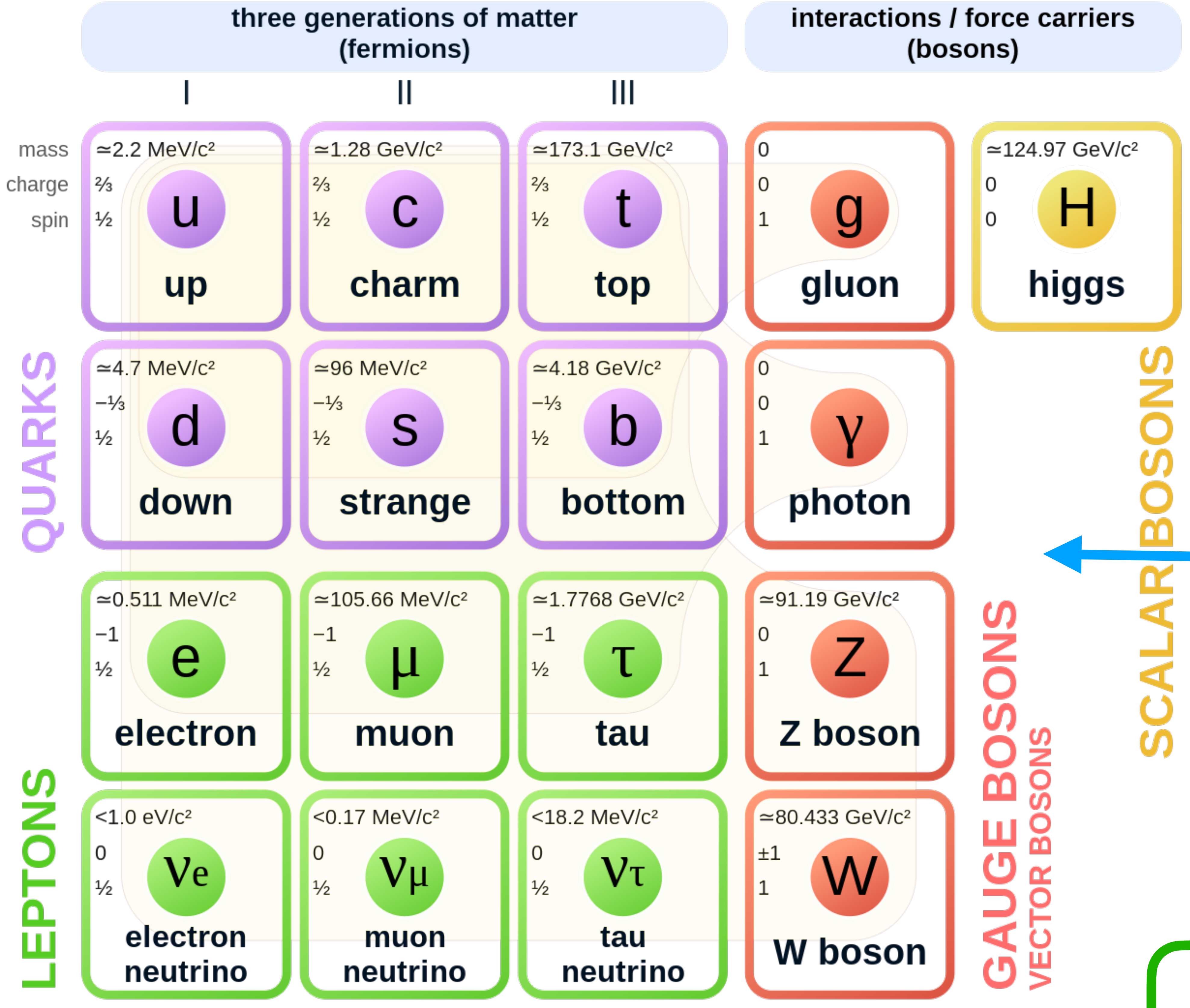
July 29, 2025
Cargese Summer School

Content…

…of my research:

- **Late Phase Transition** to Reconcile Sterile Neutrino DM with X-Ray Bounds
- **Majoron DM production** via non-minimal coupling to gravity (ongoing)
- **Characterising New Resonances** at LHC in EFT (ongoing)
- Decreasing **Tuning in CH Models** with unexplored LHC signature

…of the Standard Model:



Sandbox Studio, Chicago

see backup slides

extended scalar sectors ?

DM ?

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Two open questions of the SM

Why are neutrinos massive?

What is the nature of dark matter?

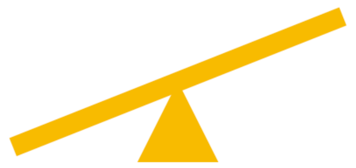
Seesaw Mechanism
(via heavy ν_R)

$\longleftrightarrow$

?

Sterile Neutrinos
(keV masses)

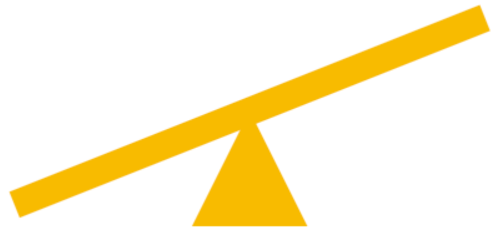
+ many more ideas…



$\boxed{\text{can they be one and the same?}}$

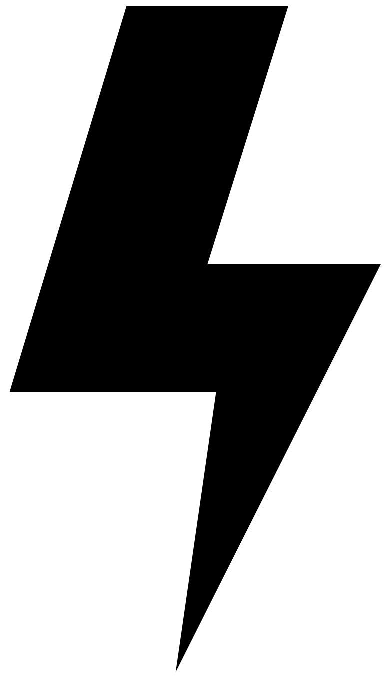
Conflicting bounds

- neutrino masses
  constrained by oscillation measurements
  → lower bound on mixing (in type-I seesaw)

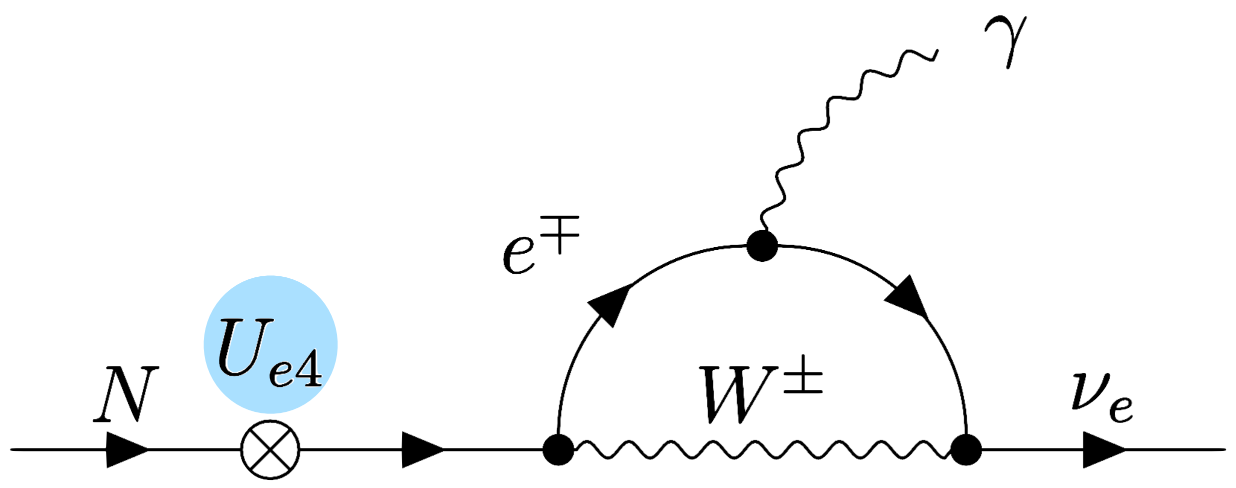


$$m_\nu \sim \frac{M_D^2}{M_R} \sim U_{\alpha I}^2 M_R$$

- radiative DM decay $N \to \nu\,\gamma$
  constrained by X-ray observations
  → upper bound on mixing (if 100% DM)



$$E_\gamma = m_N/2$$



Goertz, MH, Laverda, Rubio
arXiv:2407.04778, JHEP

How to reconcile the bounds (here)

- neutrino masses
  constrained by oscillation measurements
  → lower bound on mixing

today (1960s&later)

- radiative DM decay $N \to \nu\,\gamma$
  constrained by X-ray observations
  → upper bound on mixing

from DM dense objects
(10^4 to 10^{10} ly away)

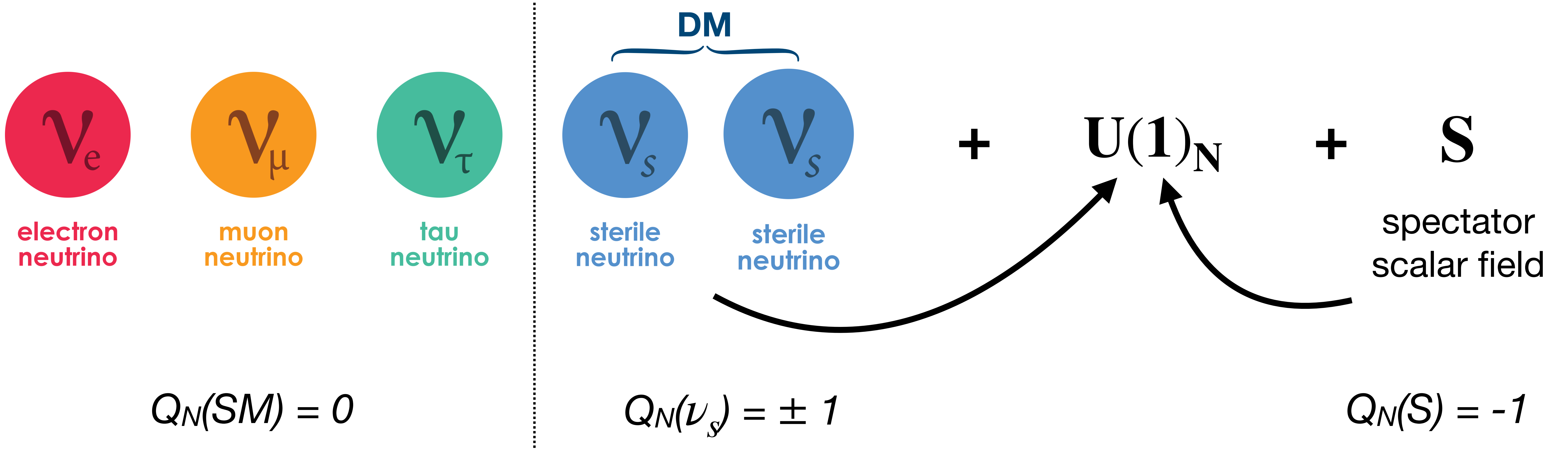
add time dependence
to mixing!
$\epsilon(t)$

→ reconciles
keV sterile neutrinos
as DM candidate
& as type-I seesaw neutrinos

Model

Goertz, MH, Laverda, Rubio
arXiv:2407.04778, JHEP

mass varying neutrinos e.g. in
Fardon, Nelson, Weiner (2004)
Brookfield et al. (2006)
Dvali, Funcke (2016)
Huang et al. (2022)
+ more…



- in the recent universe, the potential of the spectator scalar field becomes tachyonic ⇒ field starts rolling ⇒ expectation value $\bar{S}(t > t_{SB}) \neq 0$
- neutrino masses are induced!

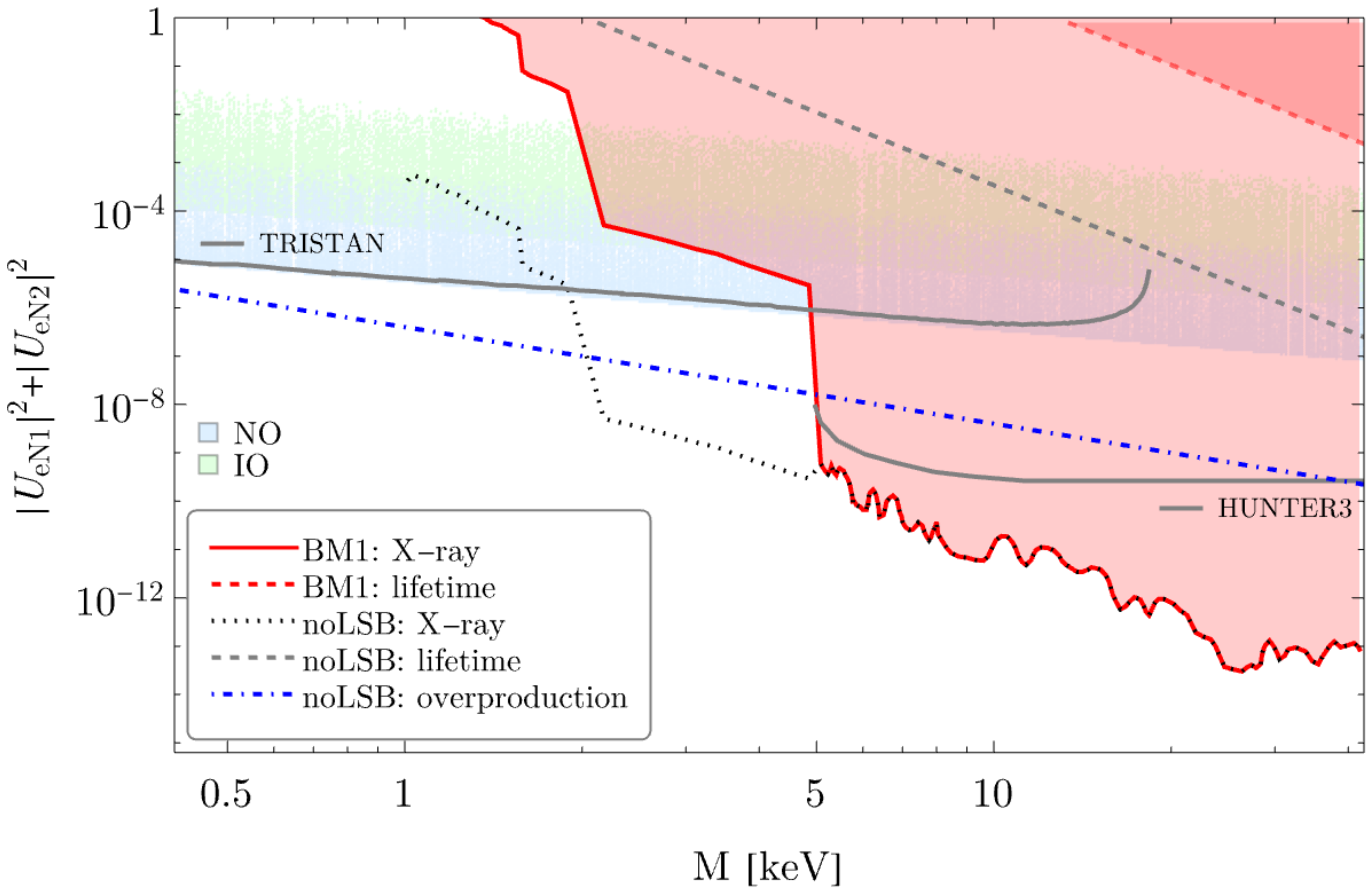
Goertz, MH, Laverda, Rubio
arXiv:2407.04778, JHEP

X-ray Constraints

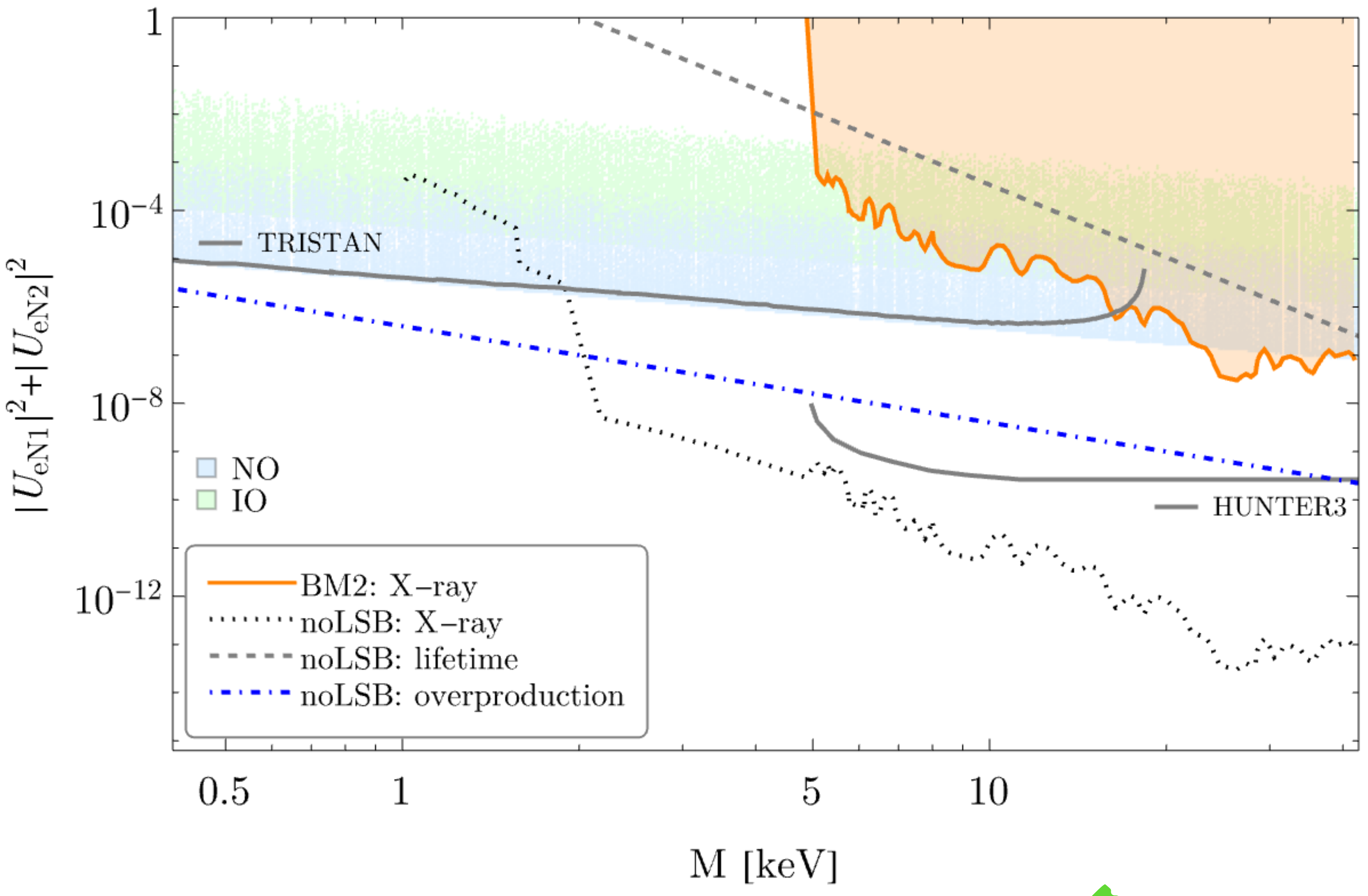
BM1: $\sim 10^6$ years ago
BM2: $\sim 10^5$ years ago

→aligns with DESI results!

BM 1



BM 2



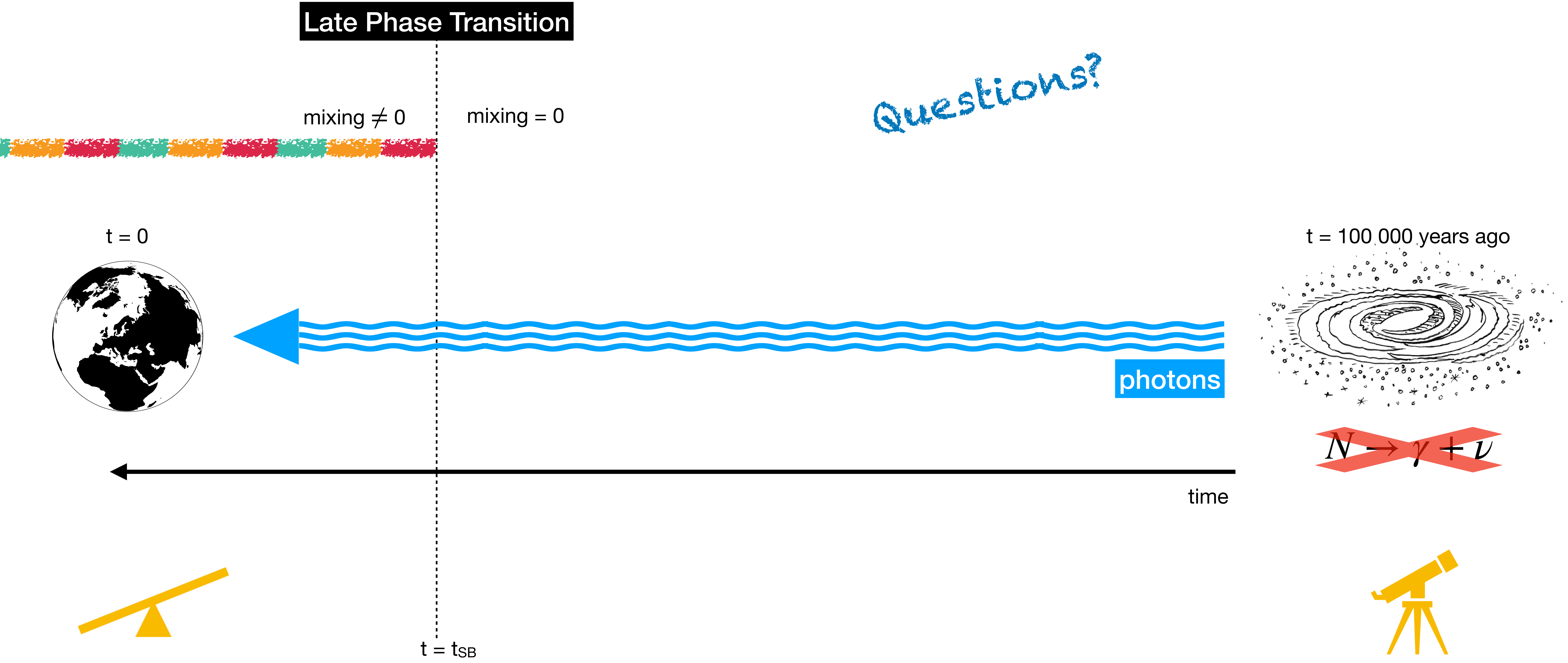
BM1: 0.4 - 5 keV DM

TRISTAN ✓

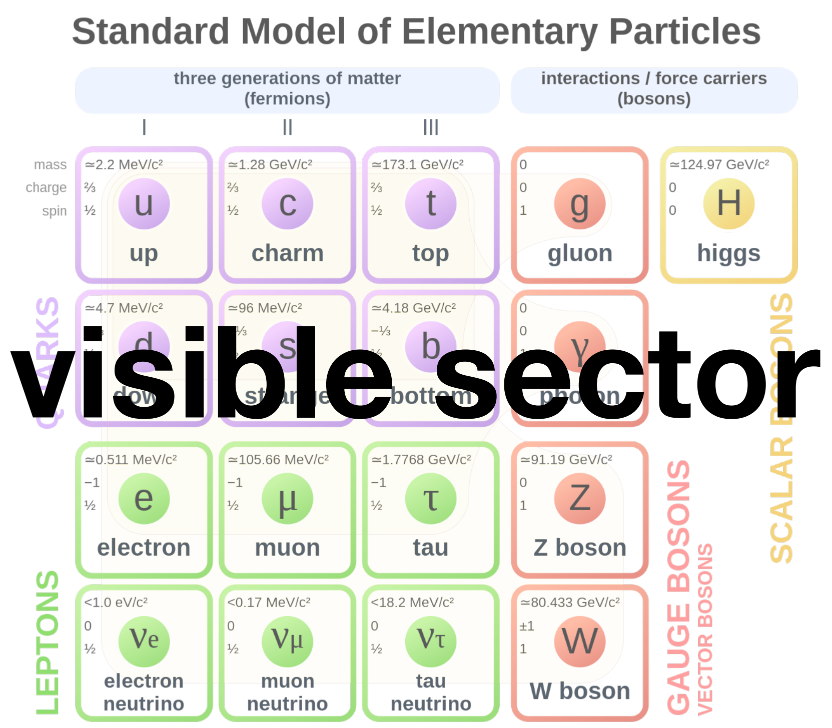
BM2: 0.4 - 22 keV DM

TRISTAN + HUNTER3 ✓

How to reconcile the bounds

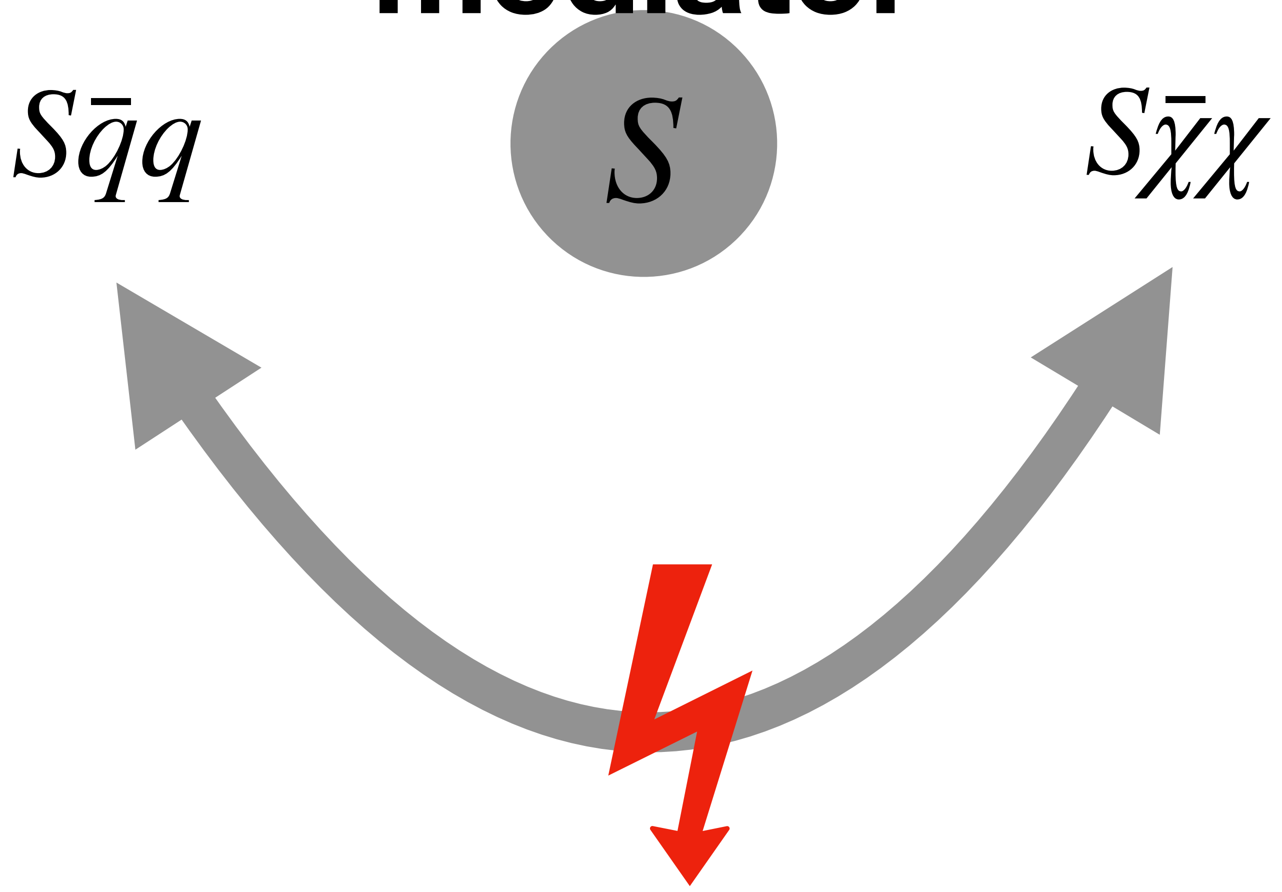


Simplified Models



visible sector

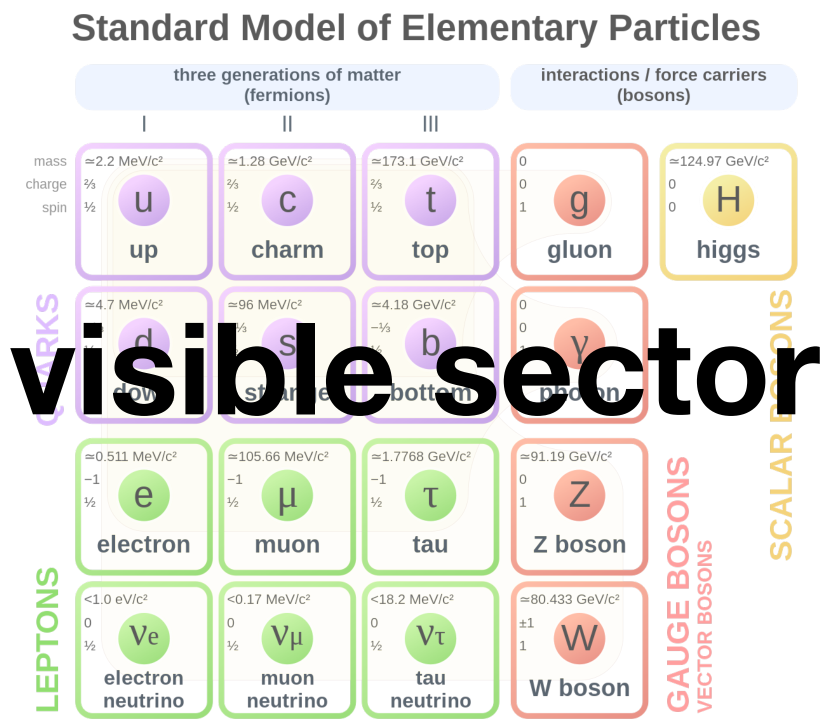
mediator

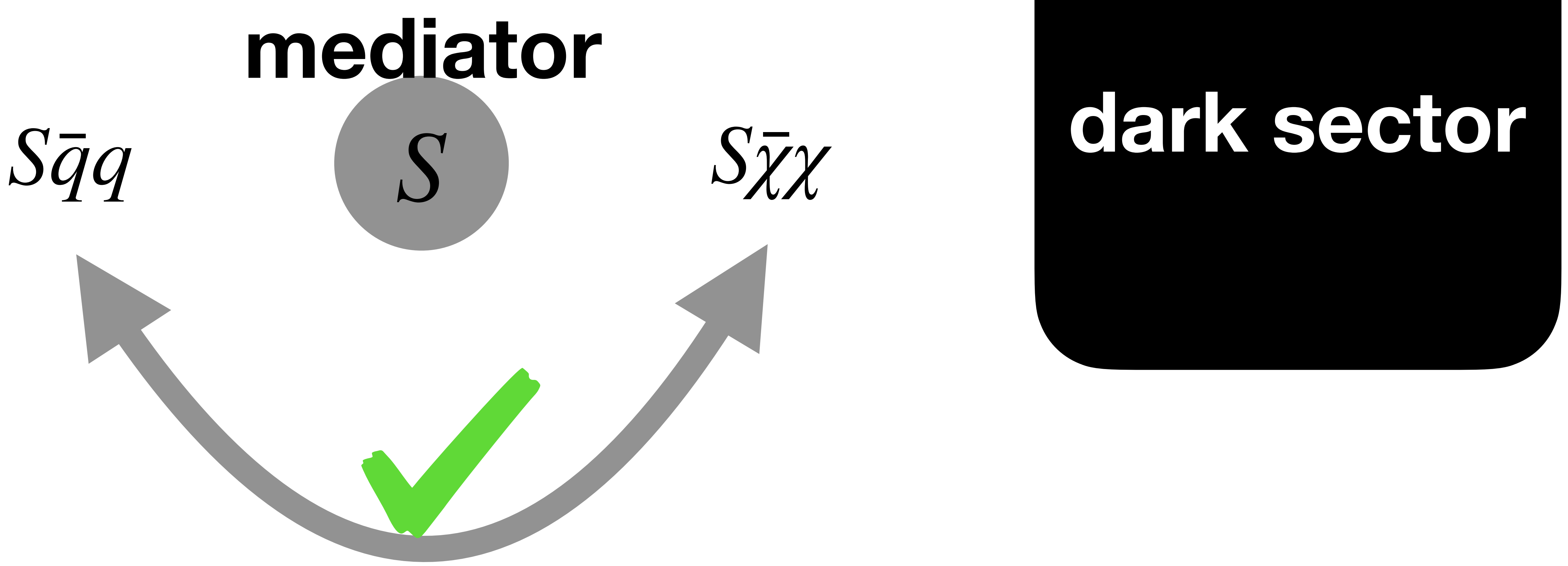


dark sector

not simultaneously gauge-invariant

extended DMEFT





up to dim-5:

$$
\begin{aligned}
\mathcal{L} \supset & \frac{1}{2}\sum_{\phi=\mathcal{S}_1,\mathcal{S}_2,h} \partial_\mu\phi\partial^\mu\phi - \mathcal{O}_5^\lambda + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger (D^\mu\Sigma)\right]\mathcal{O}_3^\kappa \\
& + i\frac{v^2}{4}\mathrm{Tr}\left[\Sigma^\dagger (D^\mu\Sigma)\,\sigma^3\right]\left(\partial_\mu h\,\mathcal{O}_2^h + \partial_\mu\mathcal{S}_1\,\mathcal{O}_2^{s1} + \partial_\mu\mathcal{S}_2\,\mathcal{O}_2^{s2}\right) \\
& - \frac{v}{\sqrt{2}}\left(\left(\overline{u_{i,L}}\ \ \overline{d_{i,L}}\right)\Sigma\begin{pmatrix} Y^u_{ij}u_{j,R} \\ Y^d_{ij}d_{j,R}\end{pmatrix}\mathcal{O}_2^{cq} + \left(\overline{\nu_{i,L}}\ \ \overline{\ell_{i,L}}\right)\Sigma\frac{1-\sigma_3}{2}Y^\ell_{ij}\begin{pmatrix}\nu_{j,R} \\ \ell_{j,R}\end{pmatrix}\mathcal{O}_2^{c\ell} + \text{h.c.}\right) \\
& - \sum_\phi \frac{\phi}{16\pi^2}\left[g'^2 c_B^\phi B^{\mu\nu}B_{\mu\nu} + g^2 c_W^\phi W^{I\mu\nu}W^I_{\mu\nu} + g_s^2 c_G^\phi G^{a\mu\nu}G^a_{\mu\nu}\right] \\
& - \sum_\phi \frac{\phi}{16\pi^2}\left[g'^2 \tilde{c}_B^\phi B^{\mu\nu}\widetilde{B}_{\mu\nu} + g^2 \tilde{c}_W^\phi W^{I\mu\nu}\widetilde{W}^I_{\mu\nu} + g_s^2 \tilde{c}_G^\phi G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\right],
\end{aligned}
\tag{2.1}
$$

non-linearly realised EW symmetry

2411.05914 Arcadi, Cabo-Almeida, Fabian, Goertz

- ✓ gauge-invariant, consistent
- ✓ richer than simplified models (interplay between different operators can become apparent)
- ✓ more hope for LHC signals compared to standard DM EFT (light mediator)

Arcadi, Cabo-Almeida, Goertz, MH
arXiv:25XX.XXXX

Characterising New Resonances At LHC in EFT

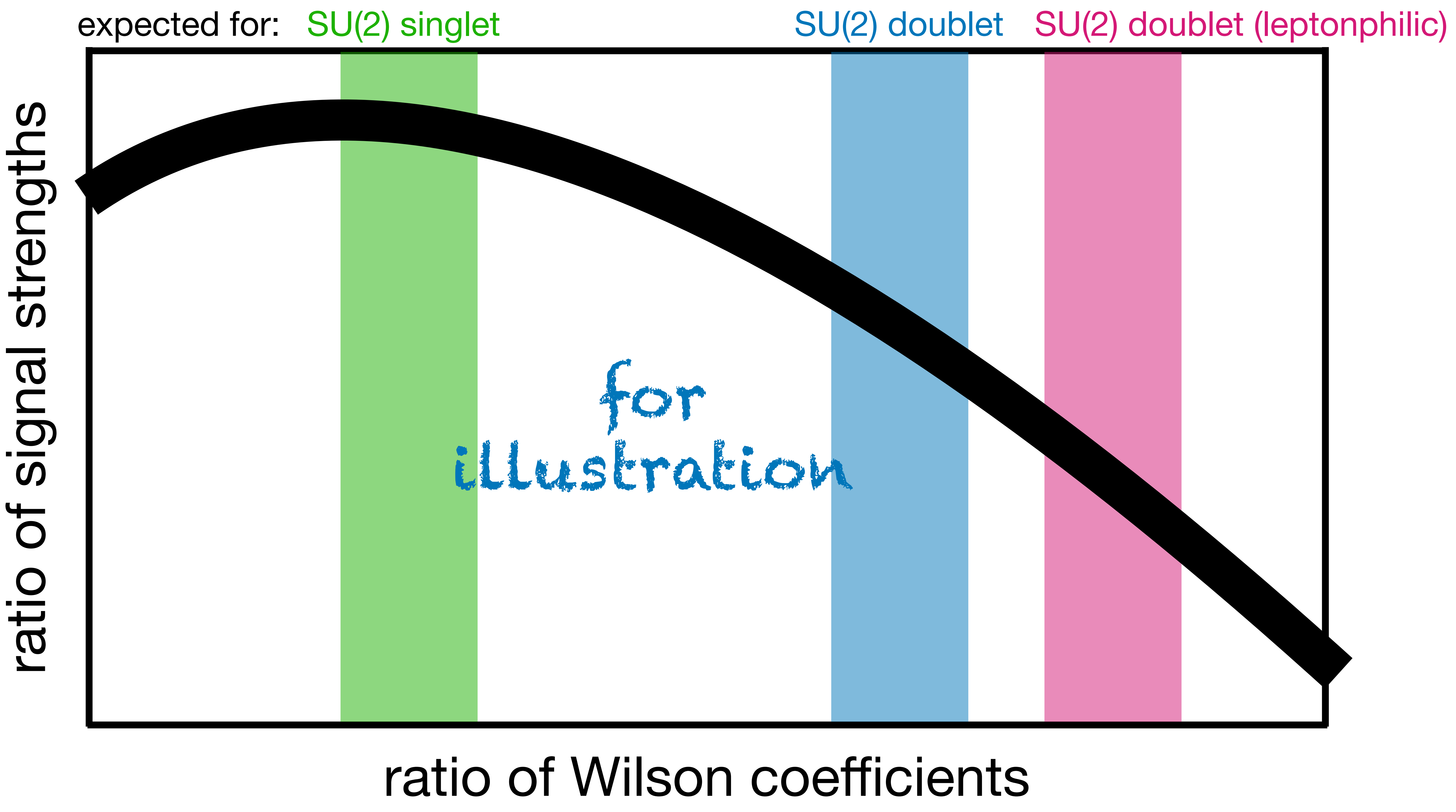
preliminary

- focus on **one new scalar degree of freedom** in a mass range **accessible at the LHC**
- input: generalised HEFT + dimensional analysis
- output sth like:
  (in ideal case)

example: $S\bar{q}q$ operator

SU(2) doublet:
allowed at dim-4

SU(2) singlet:
not gauge-inv, needs Higgs insertion
→additional suppression



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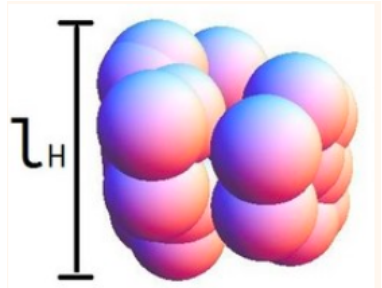
Kaplan, Georgi, Dimopoulos, …



Analogue:
Pions in QCD

Composite Higgs

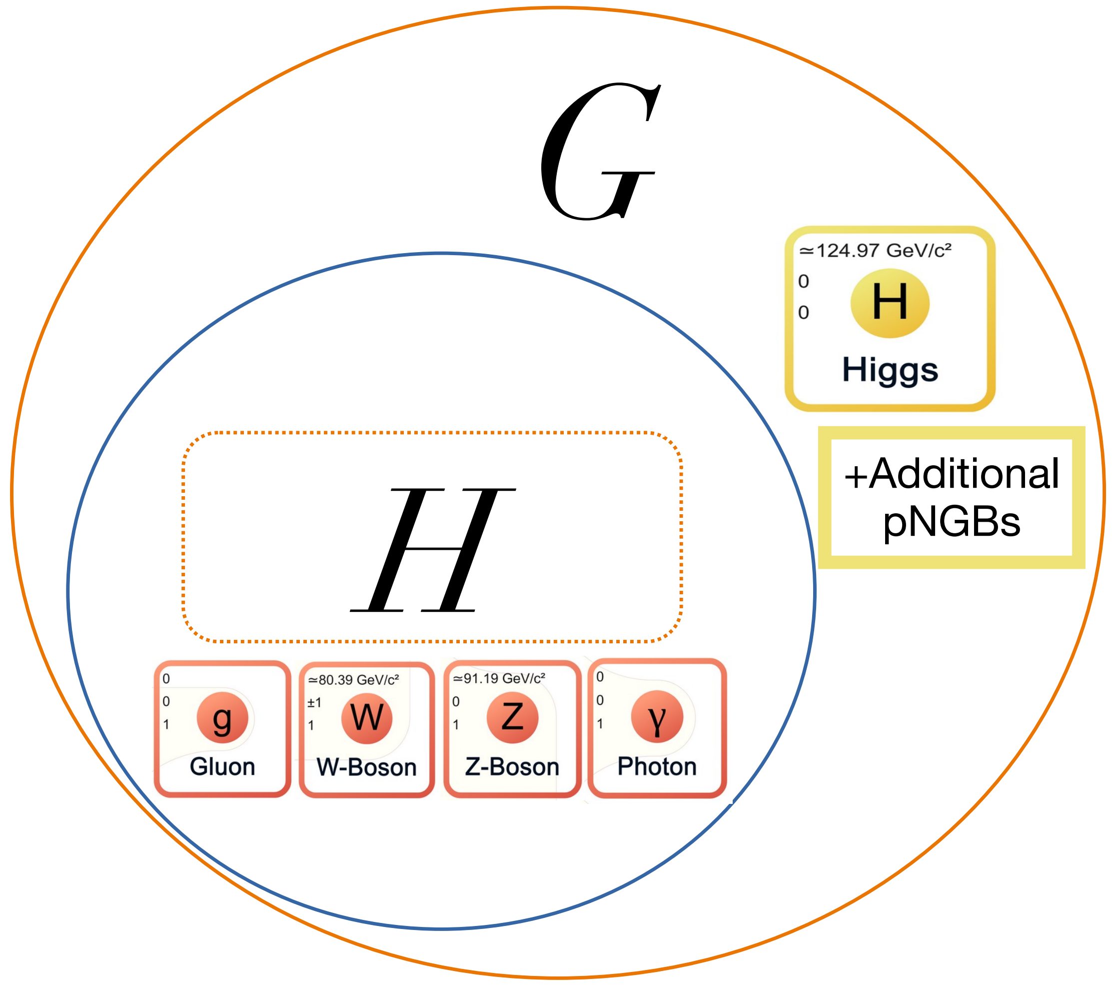
Corrections @ $\mathcal{O}$(TeV)

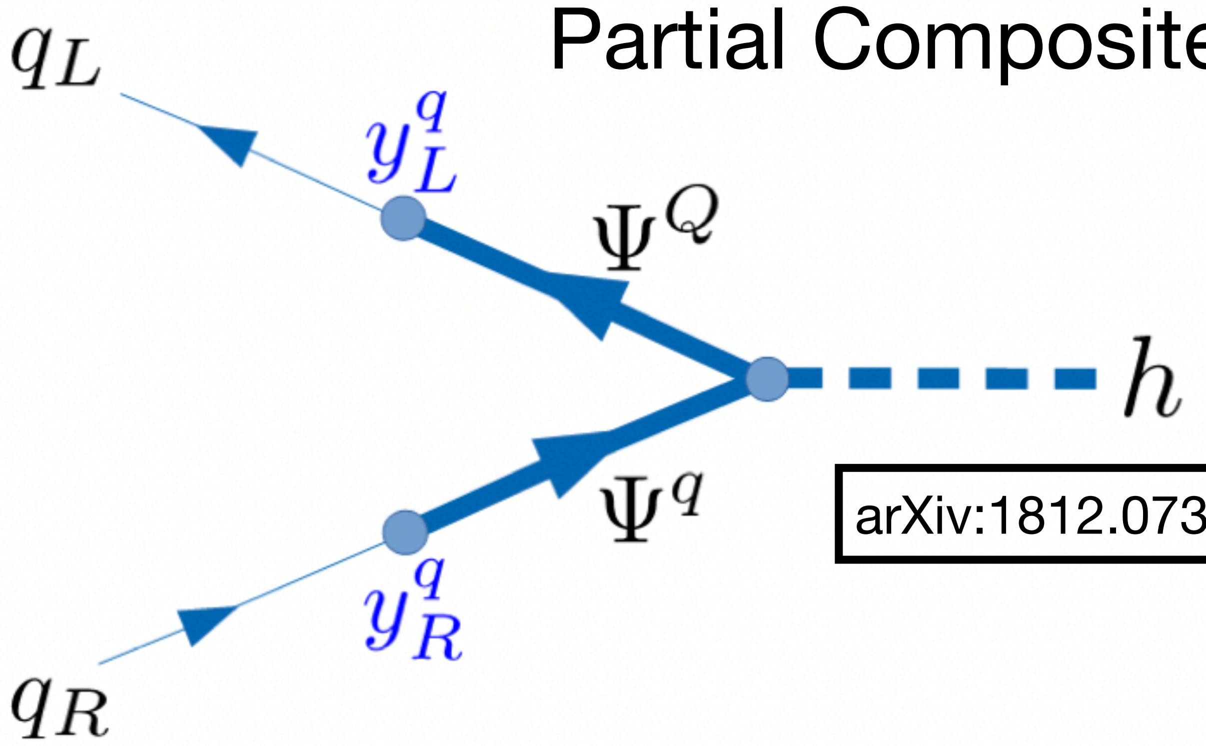
$$\mathcal{L} \supset \mathcal{L}_{\rm el} + \mathcal{L}_{\rm comp} + \mathcal{L}_{\rm mix}$$

Standard Model

Higgs

Partial Compositeness

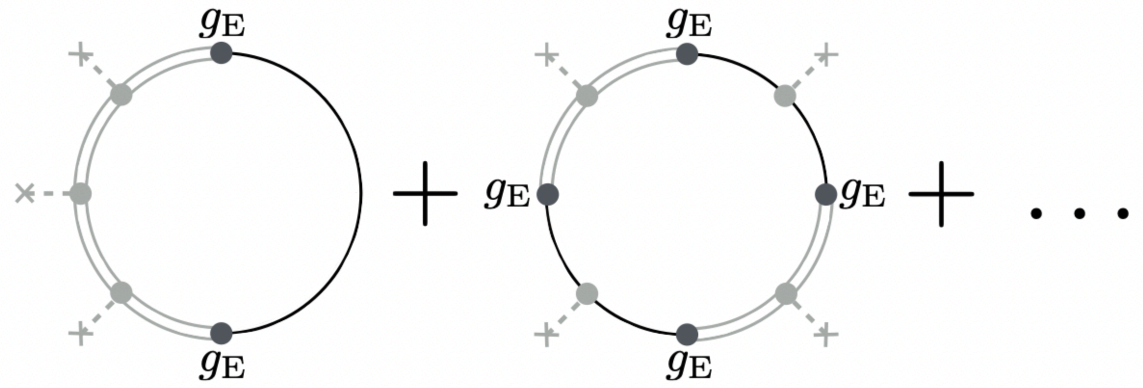




arXiv:1812.07362

Explicit Breaking of global symmetry by SM fields which transform under $G_{\rm SM}$ but not G

main source: top quark



arXiv:1506.01961

Higgs as a pseudo-Nambu Goldstone Boson

No tree-level potential ⇒ naturally light Higgs
(protected by shift symmetry & compositeness)

Common CH Problems

- **(double-)tuning** the Higgs potential

$$V_h = -\alpha \sin^2 \frac{h}{f} + \beta \sin^4 \frac{h}{f}$$

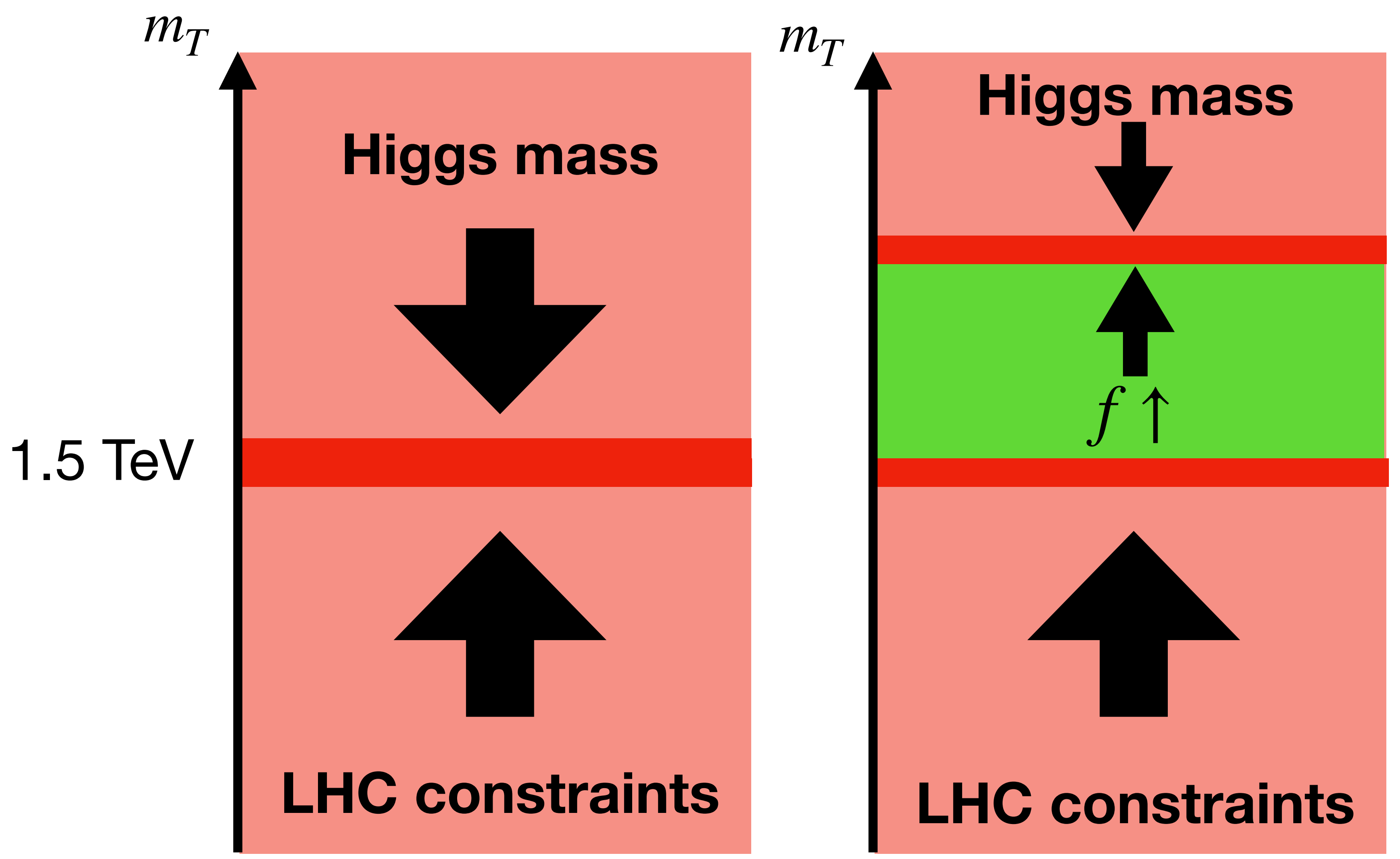
$$\boxed{\xi = \sin^2(\langle h \rangle / f) = \frac{v_{SM}^2}{f^2} \propto \frac{\alpha}{\beta}}$$

vacuum misalignment angle

- **LHC constraints**
  on light composite resonances

$$m_H \propto \frac{\min(m_T)}{f} m_t$$

analytical estimate
(from 2-site model)



little
hierarchy problem
(tuning $\propto f^2$)

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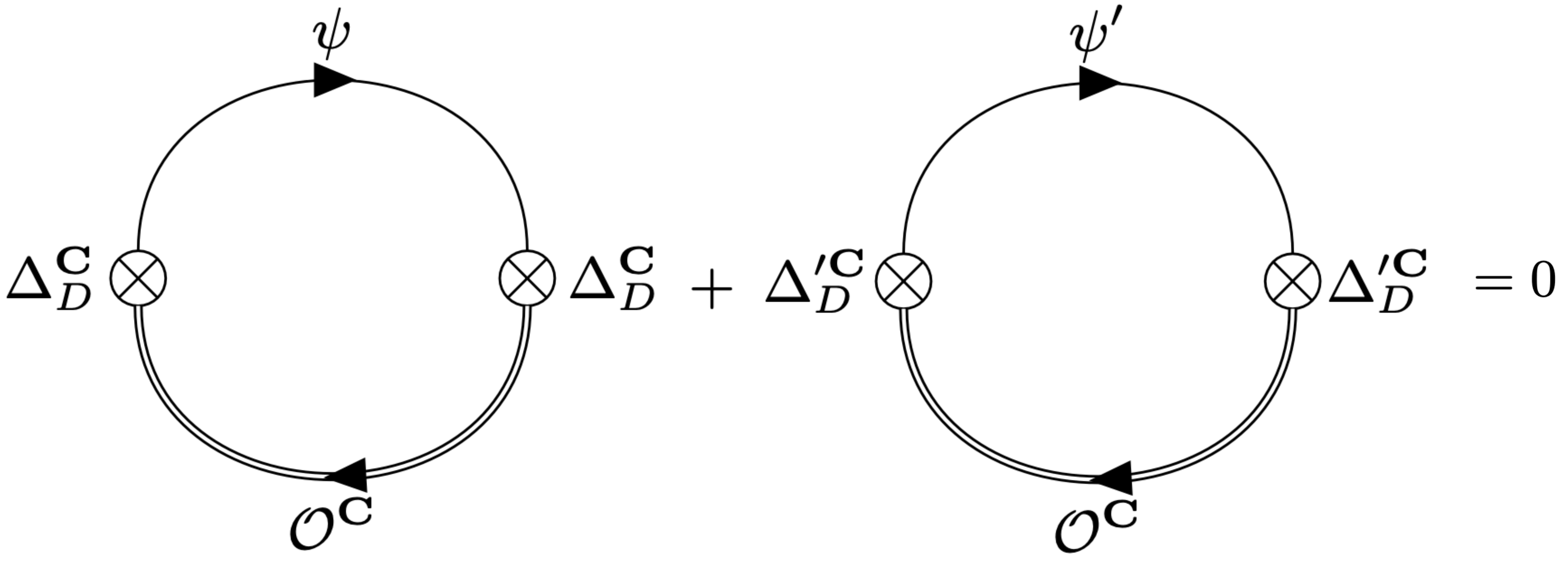
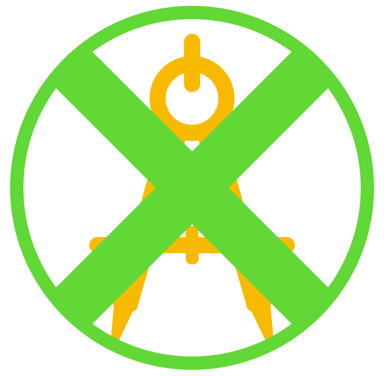
Anglescu, Bally, Goertz, MH
arXiv:2309.05698, PRD

Conjugate Fermion

Mechanism



explicitly:
The quadratic contribution of the top quark to the Higgs potential is cancelled!



*The **quadratic contribution of a chiral fermion** ψ to the pNGB potential of a coset G/H is **cancelled** when a **new chiral fermion** ψ' with **conjugated gauge quantum numbers** is added, called mirror fermion, if the fermions talk to the same composite operator in a real representation $\mathbf{R}$ of the group G which decomposes as $\mathbf{R} \to \mathbf{C} \oplus \bar{\mathbf{C}}$ under H, with $\mathbf{C}$ a complex representation and $\bar{\mathbf{C}}$ its complex conjugate.*

mirror fermion
has Dirac mass

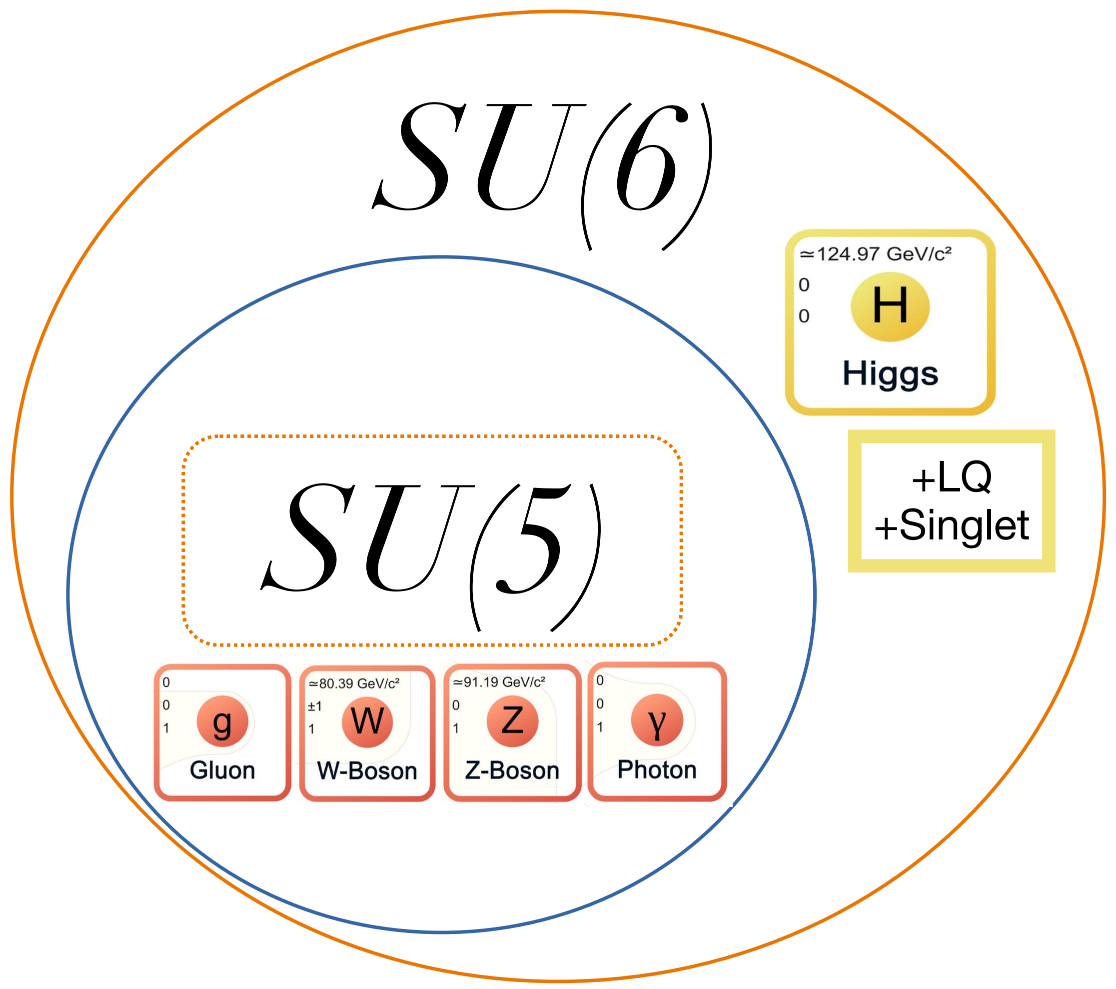
$SU(5) \supset SU(3) \times SU(2) \times U(1)$

Anglescu, Bally, Goertz, MH
arXiv:2309.05698

Conjugate Fermion

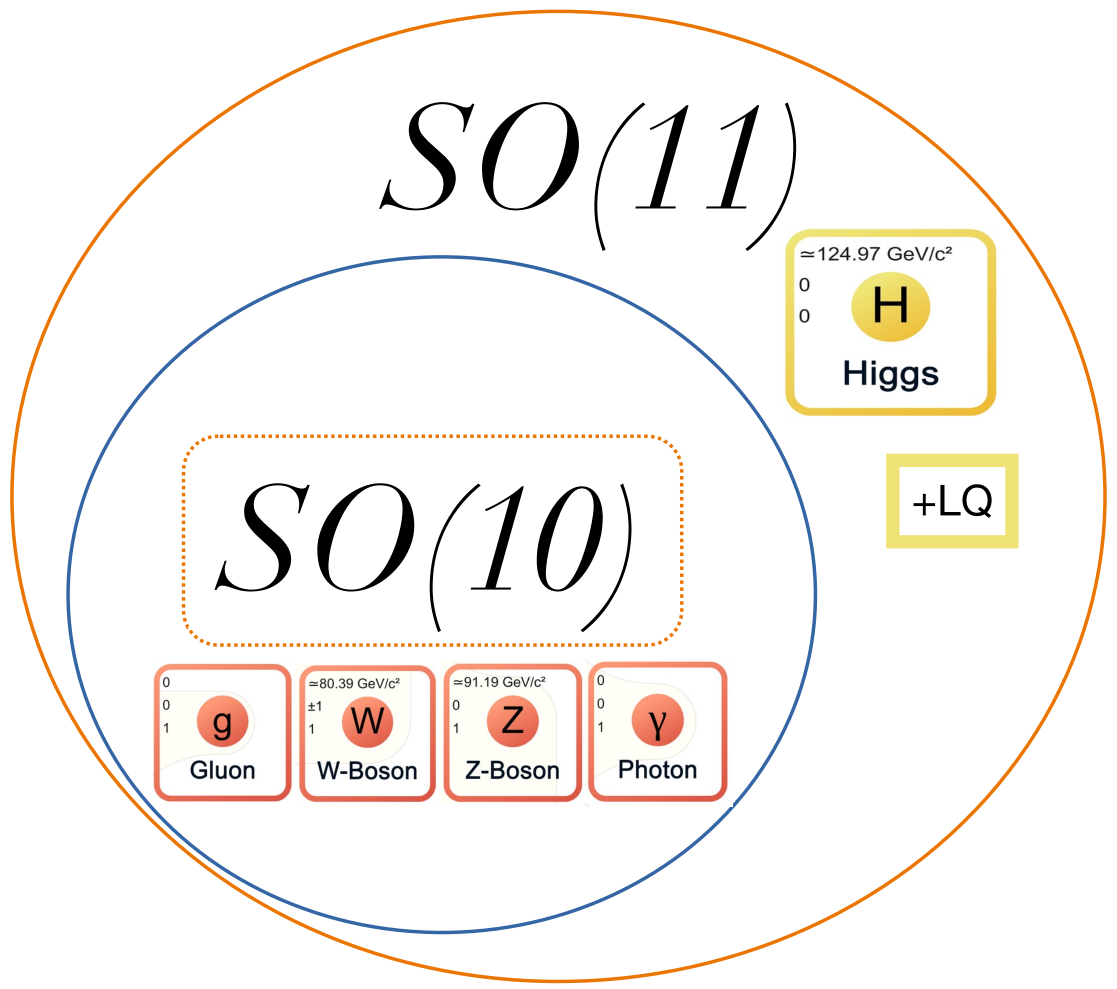
Explicit Model - Composite Grand Unified Theories

minimal:



$$\mathbf{20} \to \mathbf{10} \oplus \overline{\mathbf{10}}$$

non-custodial ⇒ tree-level corrections to T parameter



$$\mathbf{32} \to \mathbf{16} \oplus \overline{\mathbf{16}}$$

custodial!

$SO(10) \to SU(5)$
$\mathbf{16} \to \mathbf{10} \oplus \mathbf{5}^* \oplus \mathbf{1}$

$$\mathbf{10} \to \underset{\boxed{q_L}}{(\mathbf{3},\mathbf{2})_{\mathbf{1/6}}} \oplus \underset{\boxed{\omega_R}}{(\mathbf{3}^*,\mathbf{1})_{\mathbf{-2/3}}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{1}}$$

$$\mathbf{10}^* \to \underset{\boxed{\theta_L}}{(\mathbf{3}^*,\mathbf{2})_{\mathbf{-1/6}}} \oplus \underset{\boxed{t_R}}{(\mathbf{3},\mathbf{1})_{\mathbf{2/3}}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{-1}}$$

Scan:
f = 1600 GeV
$\lambda_L = \lambda_R$
m_t(f) ~ 150 GeV
parameter range [-5 f , 5 f]
b_R included
SU(6)/SU(5) or SO(11)/SO(10)

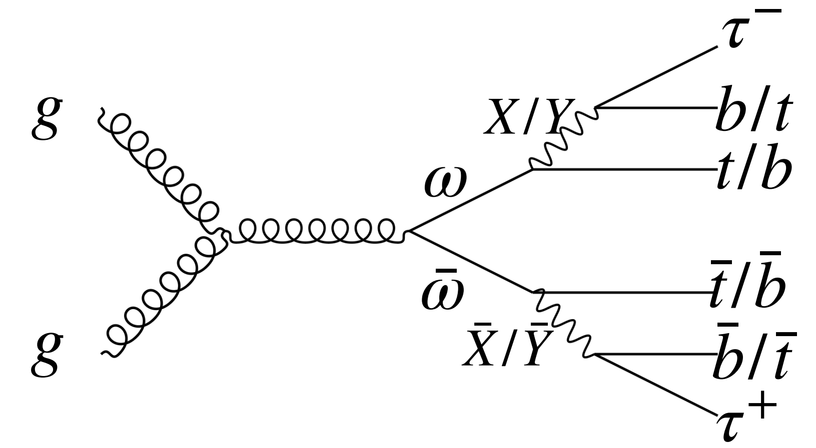
Anglescu, Bally, Goertz, MH
arXiv:2309.05698, PRD

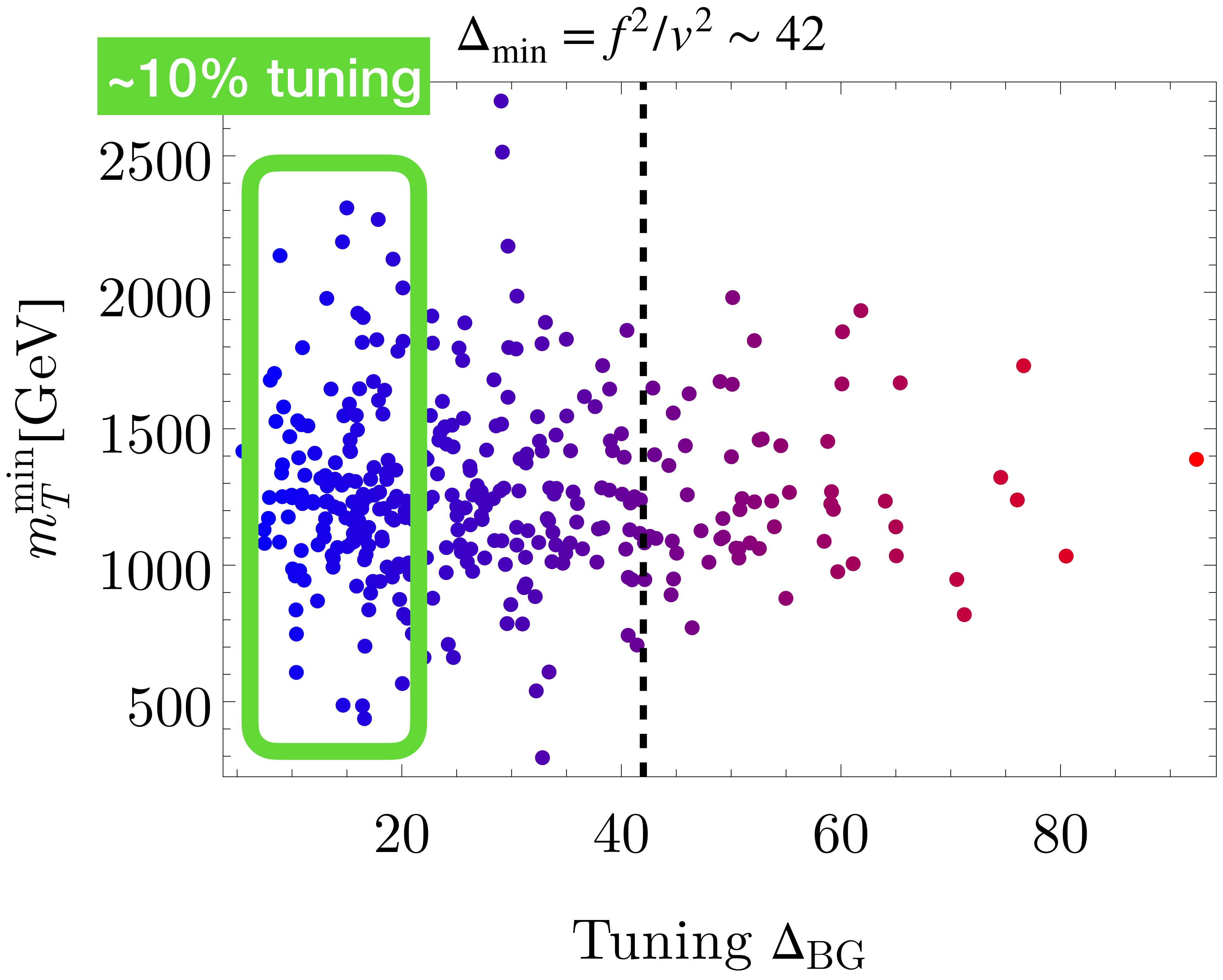
Conjugate Fermions

CMS, arXiv:2209.0737;ATLAS, arXiv:2210.15413;…
+many more!

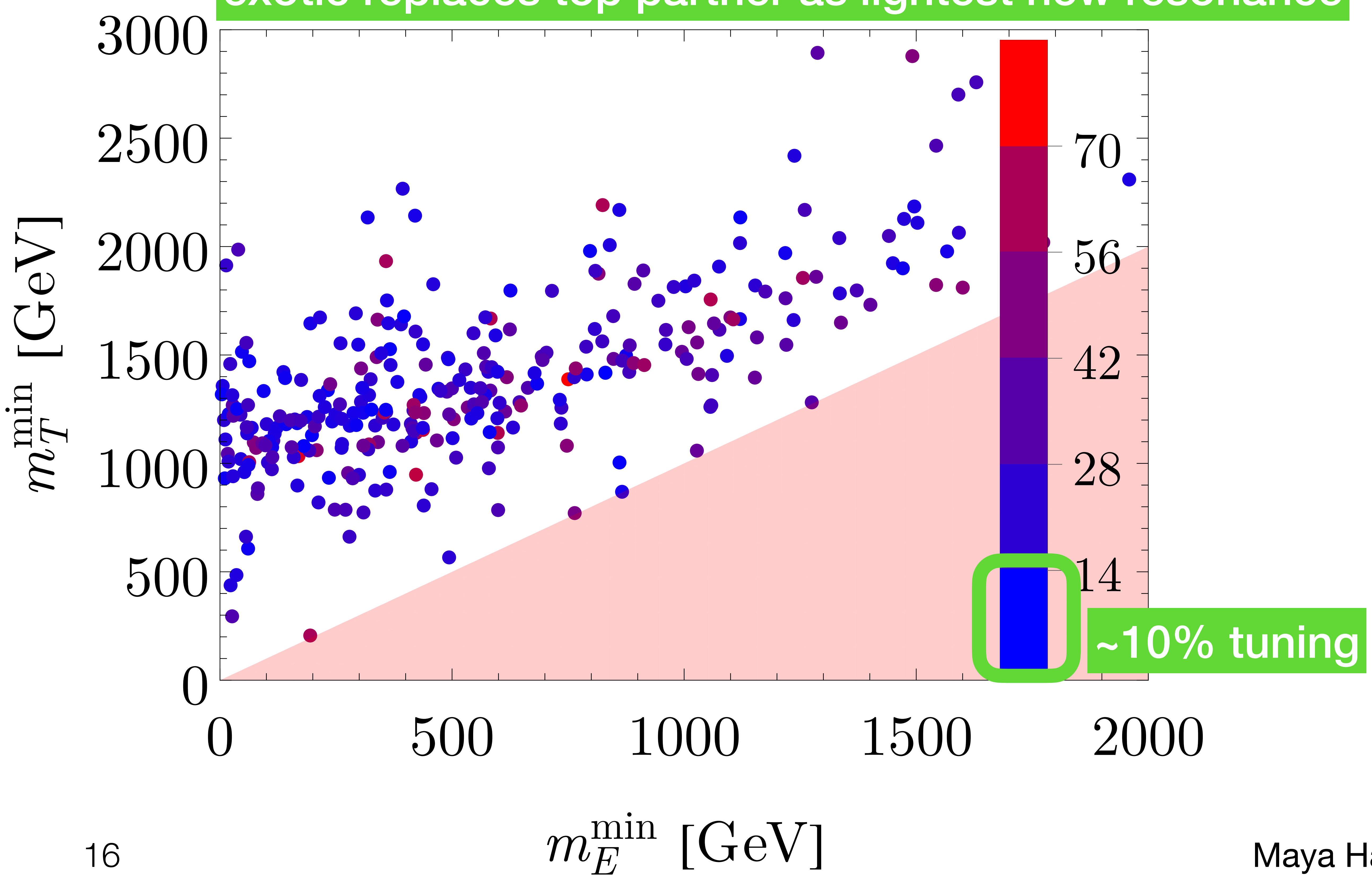
Top Partner ≥ 1500 GeV

exotics ω carry B = 2/3
⇒6 particle final state
⇒unexplored signature!





exotic replaces top partner as lightest new resonance



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Anglescu, Bally, Goertz, MH
arXiv:2309.05698

resonance mass scale

$m_* = g_* f$

Conjugate Fermion

Proof

Three ingredients why the cancellation works!

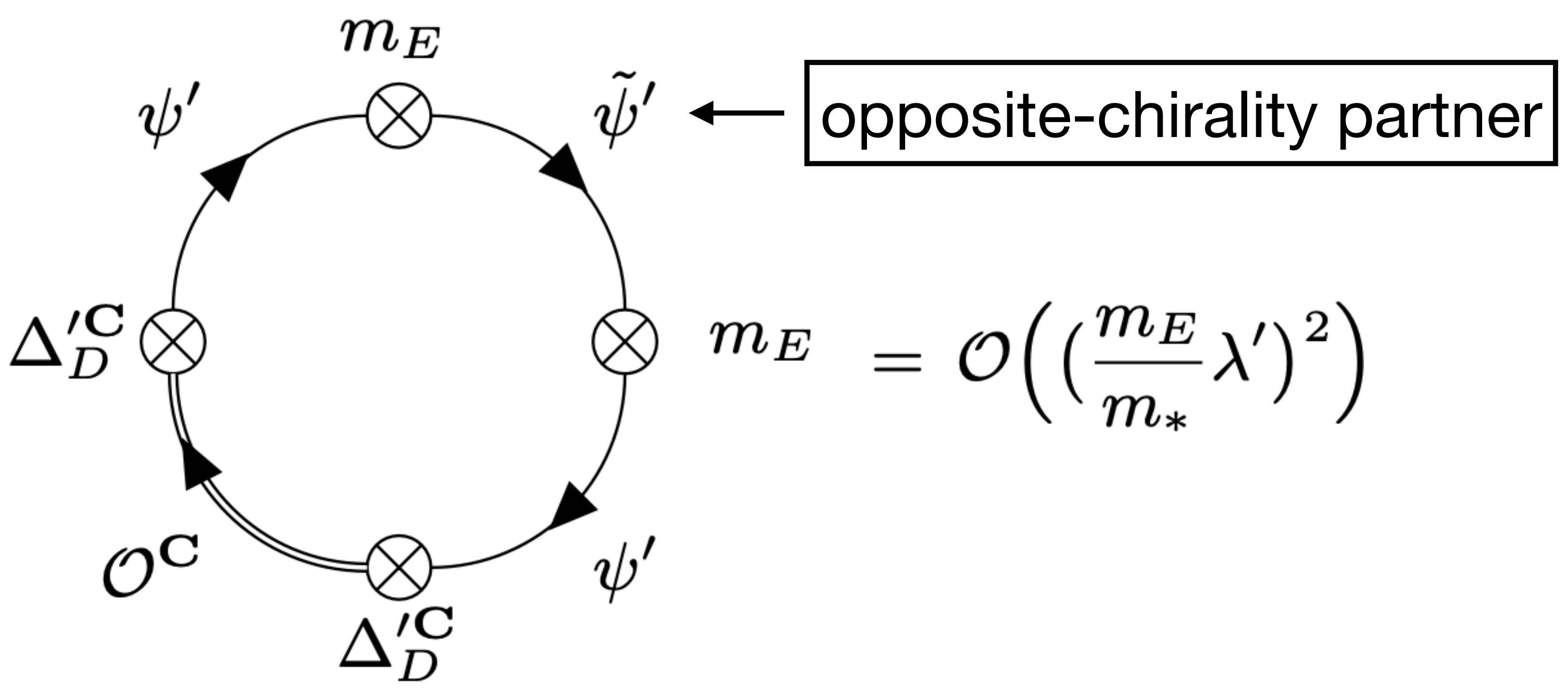
$$\boxed{(\Delta_D^{\bar{\mathbf{C}}})^\dagger \Delta_D^{\bar{\mathbf{C}}} = (\Delta_D'^{\mathbf{C}})^\dagger \Delta_D'^{\mathbf{C}}} \longleftrightarrow \boxed{\mathbf{R} \to \mathbf{C} \oplus \bar{\mathbf{C}} \quad , \quad \lambda = \lambda' \quad , \quad m_E \ll m_*}$$

embedding & quantum numbers

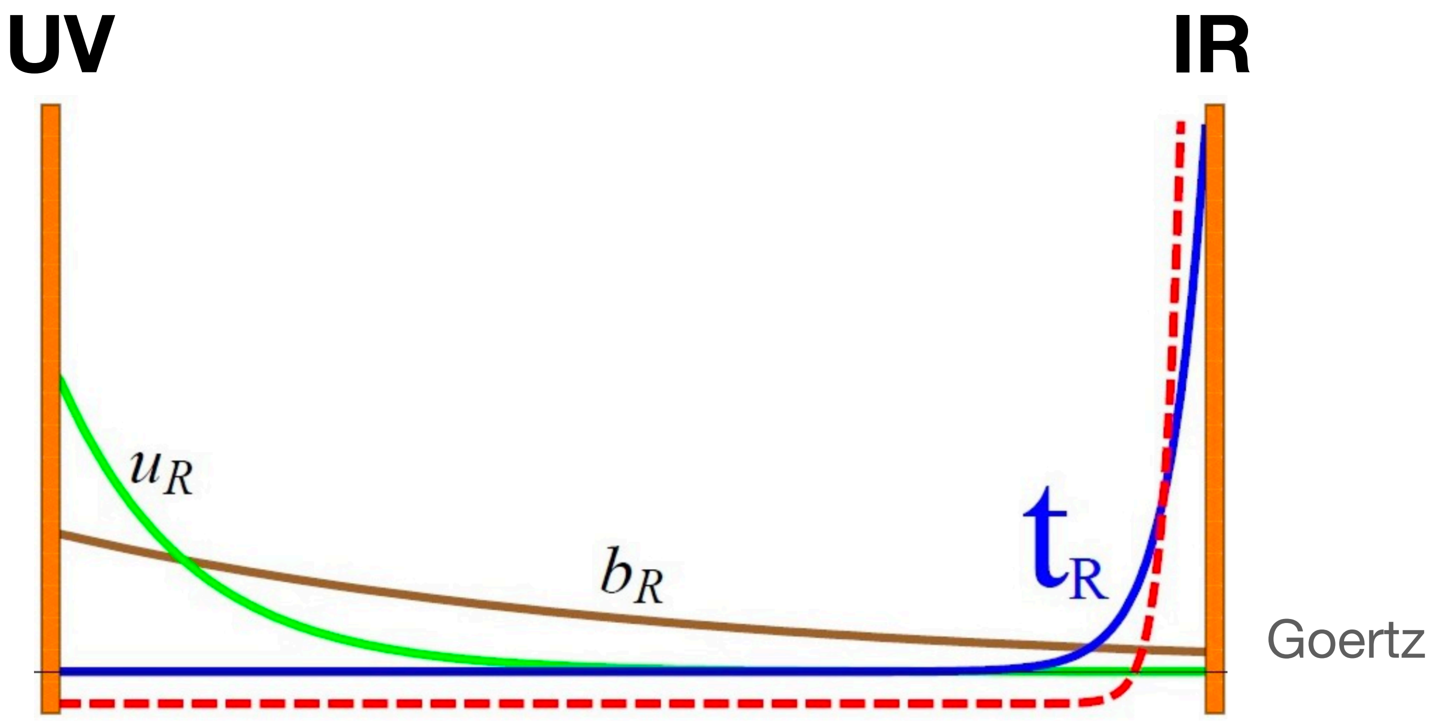
5D dual:
same bulk field
same localisation

coincidence?

Dirac mass for mirror fermion
⇒ additional contribution to potential



$$= \mathcal{O}\Big(\big(\frac{m_E}{m_*}\lambda'\big)^2\Big)$$



5D dual:
opposite-chirality partner: **UV brane-localised field**
mirror-fermion: **IR-localised field**
→ **exponential suppression of m_E**