Gravitational Imprints of Flavour Hierarchies

Toby Opferkuch

CERN Theory Department

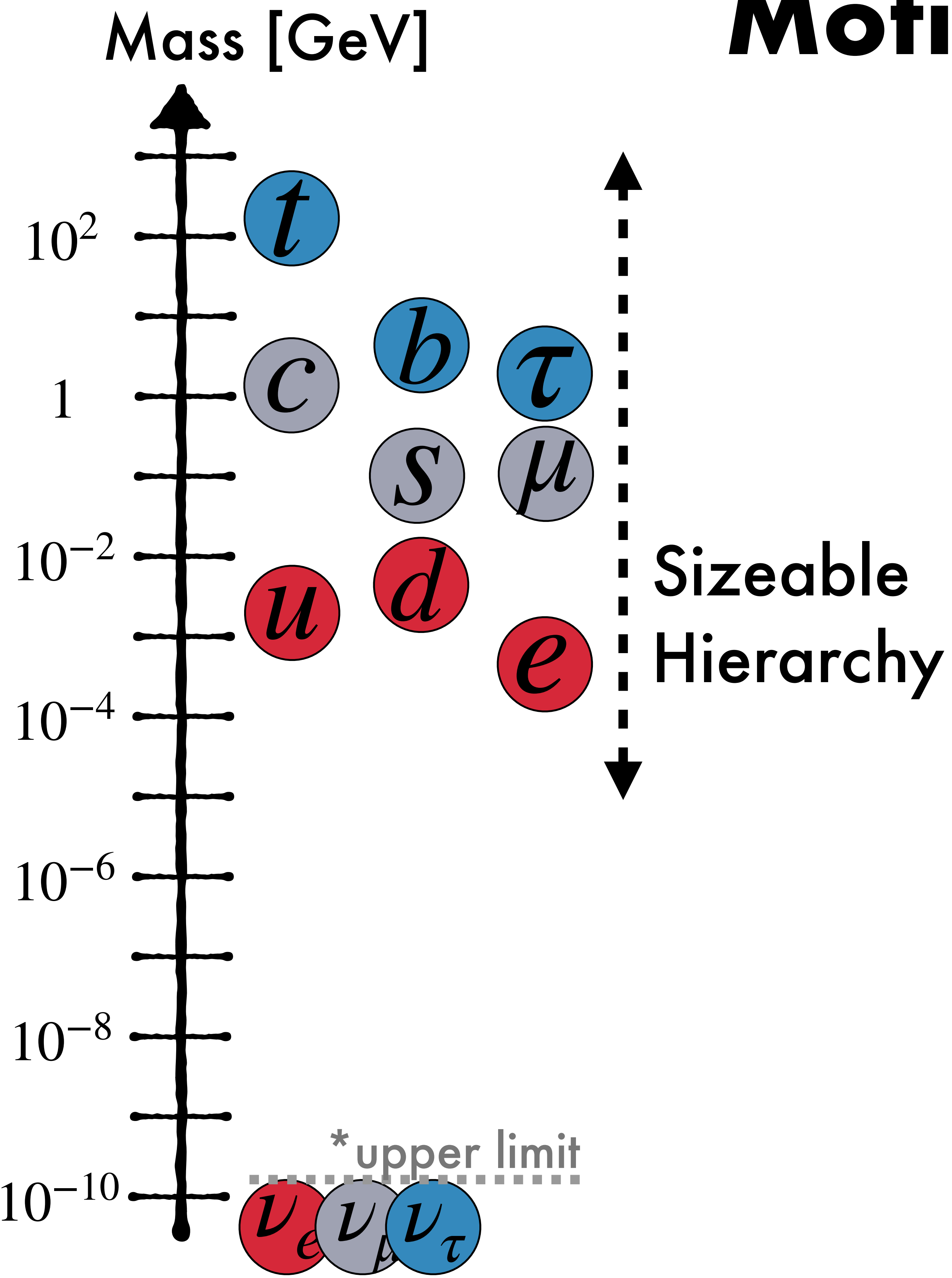
Based on 1910.02014 with Admir Greljo and Ben A. Stefanek

Challenges and Opportunities of High Frequency Gravitational Wave Detection – 14th October 2019

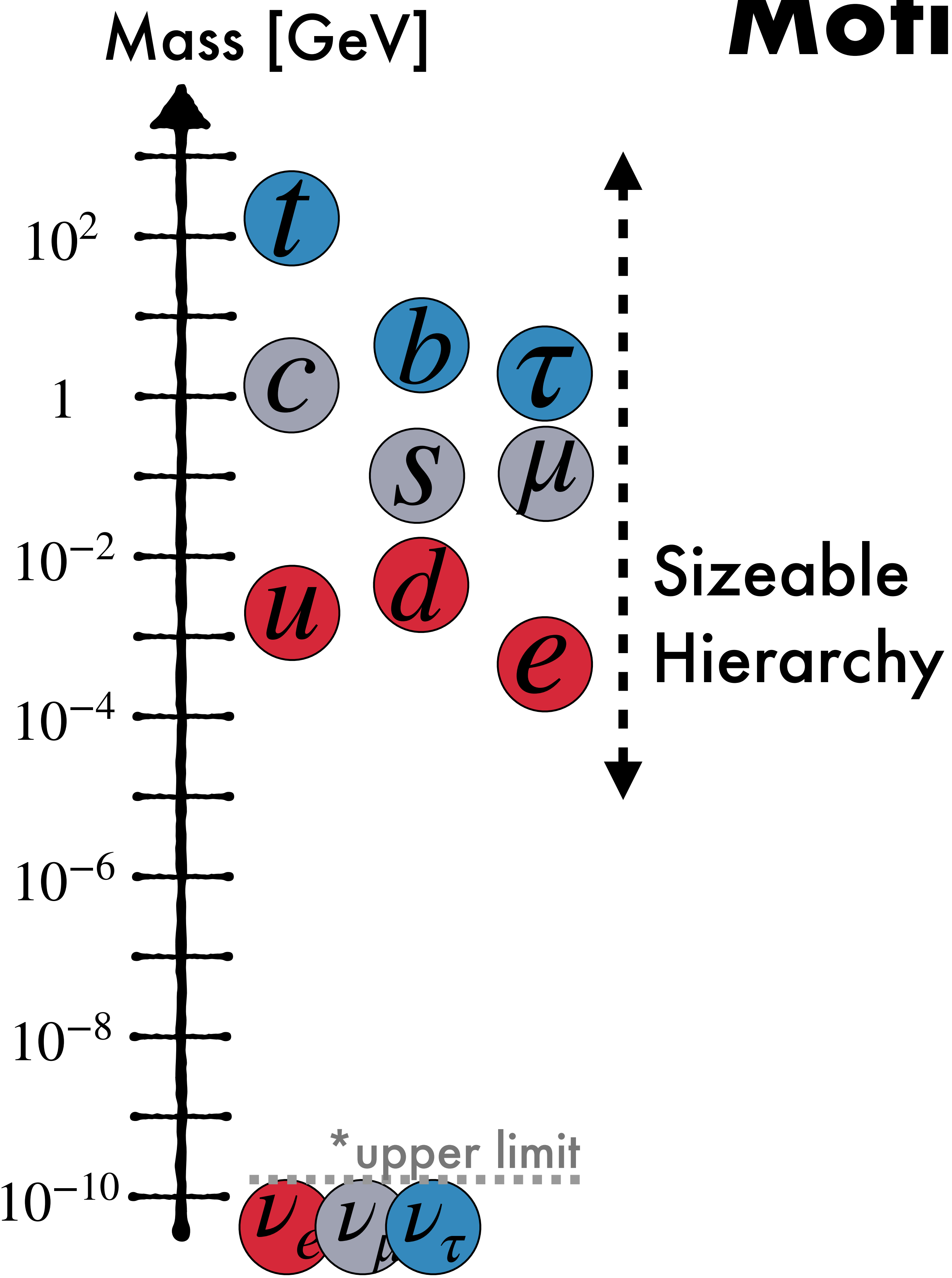
European Research Council

Established by the European Commission

Motivation


Mass [GeV]
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
t
c
b
τ
s
μ
u
d
e
*upper limit
ν_e
ν_μ
ν_τ
Sizeable
Hierarchy

Motivation



In the Standard Model:

[Hierarchal complex numbers "Yukawas"]

$$Y = \frac{\text{Mass}}{\text{Scale}}$$

[Higgs vacuum expectation value (vev)]

Motivation

Flavour hierarchies → Additional (hierarchical) symmetry breakings

Motivation

Flavour hierarchies → Additional (hierarchical) symmetry breakings

<u>New flavoured gauge symmetries:</u>

[Additional scalar vev(s)]

$$Y_i = y\left(\frac{\langle\Phi\rangle}{\Lambda}\right)^{n_i}$$

[order-one complex numbers]

[Current experimental B-anomalies provide strong motivation for TeV-scale]

Motivation

- Stochastic gravitational wave background from 1st order phase transitions *[Peak frequency proportional to vev]*
- Plethora of ground- and space-based GW observatories in 2030s *[Experiments can probe far above the TeV scale]*
- Hierarchical range of optimised frequencies: $f_{\text{opt}} \sim L^{-1}$
- Interestingly:

$$\begin{array}{ccccc} \sqrt{m_t m_b} & : & \sqrt{m_s m_c} & : & \sqrt{m_u m_d} \\ 1 & : & 10^{-2} & : & 10^{-4} \\ f_{\text{LISA}}^{-1} & : & \cdots & : & f_{\text{ET}}^{-1} \end{array}$$

Model Example

- Expand Standard Model to PS ≡ SU(4)xSU(2)xSU(2)

Quark-Lepton Unification

$$\Psi_L^i \equiv \begin{pmatrix} Q_L^i \\ L_L^i \end{pmatrix}$$

Quarks

Leptons

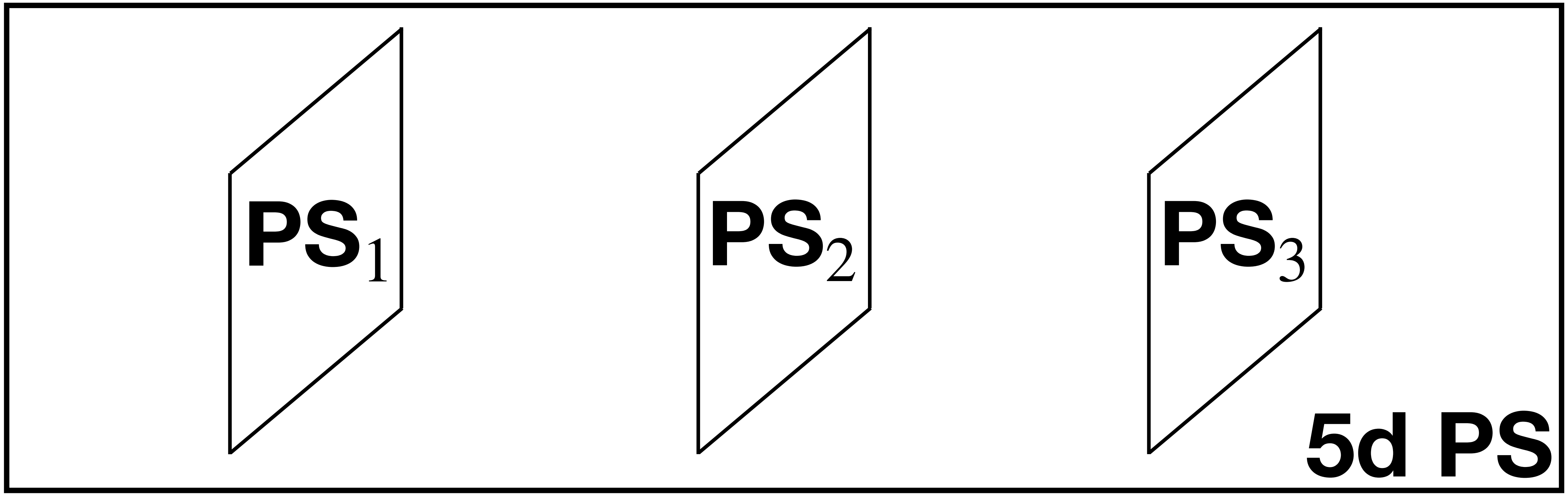
Model Example

- Expand Standard Model to PS ≡ SU(4)xSU(2)xSU(2)

Quark-Lepton Unification

$$\Psi_L^i \equiv \begin{pmatrix} Q_L^i \\ L_L^i \end{pmatrix} \begin{matrix} \text{Quarks} \\ \text{Leptons} \end{matrix}$$

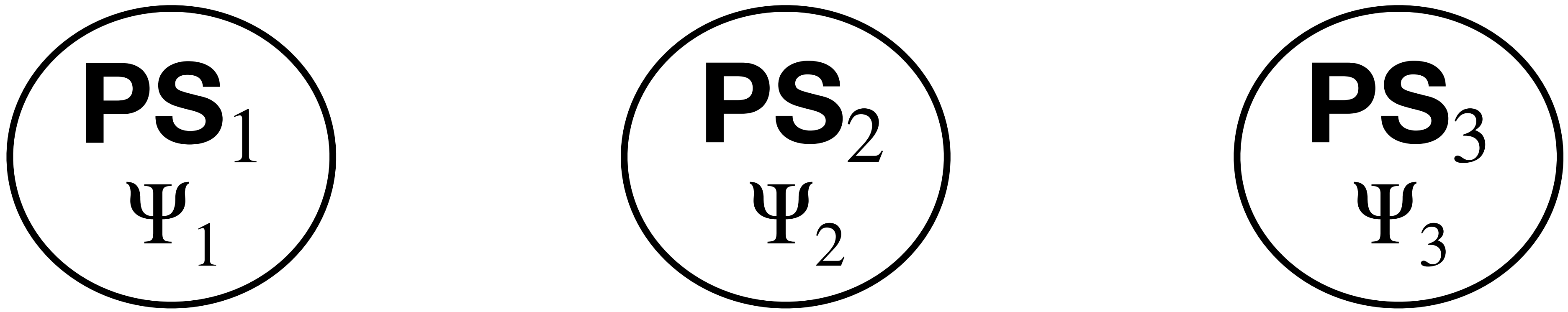
- Consider generation dependent higher-dimensional model



Model Example

- 4d Picture — "Pati-Salam Cubed"

[Bordone, Cornelle, Fuentes-Martin, Isidori 1712.01368]



Fermions:

$$\Psi^i_L \equiv (\mathbf{4}, \mathbf{2}, \mathbf{1})_i$$

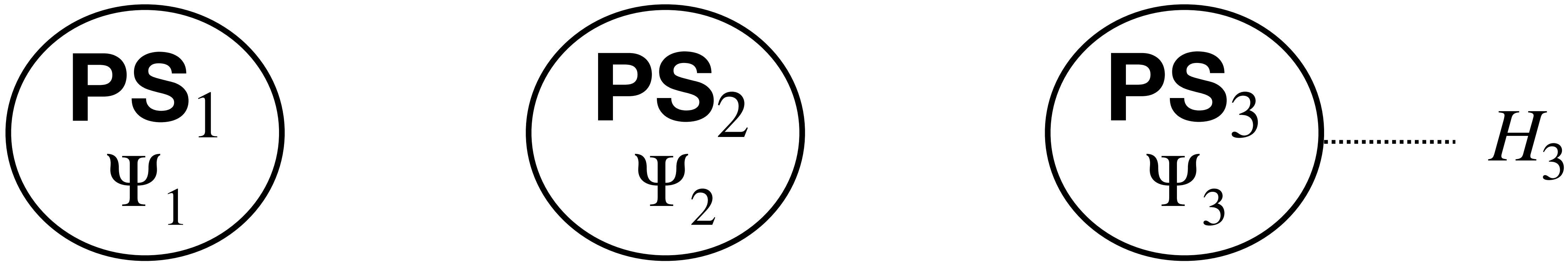
$$\Psi^i_R \equiv (\mathbf{4}, \mathbf{1}, \mathbf{2})_i$$

Reminder: $(SU(4), SU_L(2), SU_R(2))$

Model Example

- 4d Picture – “Pati-Salam Cubed”

[Bordone, Cornelle, Fuentes-Martin, Isidori 1712.01368]



Fermions:

$$\Psi_L^i \equiv (\mathbf{4}, \mathbf{2}, \mathbf{1})_i$$

$$\Psi_R^i \equiv (\mathbf{4}, \mathbf{1}, \mathbf{2})_i$$

Scalars:

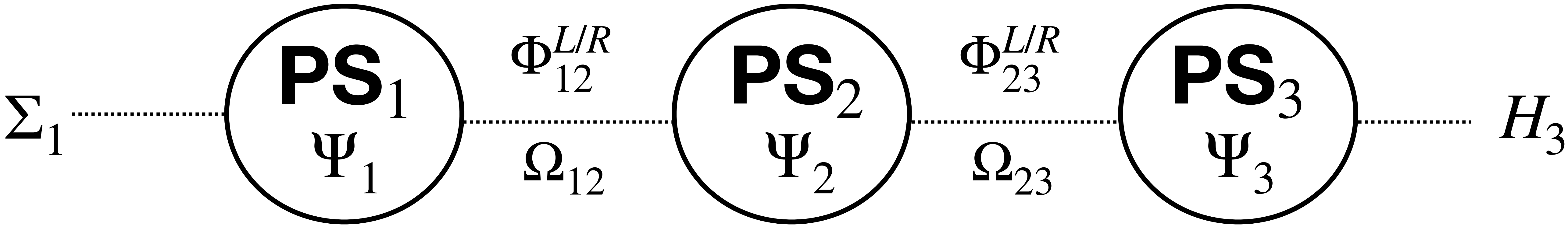
$$H_3 \equiv (\mathbf{1}, \mathbf{2}, \overline{\mathbf{2}})_3$$

Reminder: $(SU(4), SU_L(2), SU_R(2))$

Model Example

- 4d Picture — "Pati-Salam Cubed"

[Bordone, Cornelle, Fuentes-Martin, Isidori 1712.01368]



Fermions:

$$\Psi_L^i \equiv (\mathbf{4}, \mathbf{2}, \mathbf{1})_i$$

$$\Psi_R^i \equiv (\mathbf{4}, \mathbf{1}, \mathbf{2})_i$$

Scalars:

$$H_3 \equiv (\mathbf{1}, \mathbf{2}, \bar{\mathbf{2}})_3$$

$$\Sigma_1 \equiv (\mathbf{4}, \mathbf{1}, \mathbf{2})_1$$

$$\Phi_{ij}^L \equiv (\mathbf{1}, \mathbf{2}, \mathbf{1})_i \times (\mathbf{1}, \bar{\mathbf{2}}, \mathbf{1})_j$$

$$\Phi_{ij}^R \equiv (\mathbf{1}, \mathbf{1}, \mathbf{2})_i \times (\mathbf{1}, \mathbf{1}, \bar{\mathbf{2}})_j$$

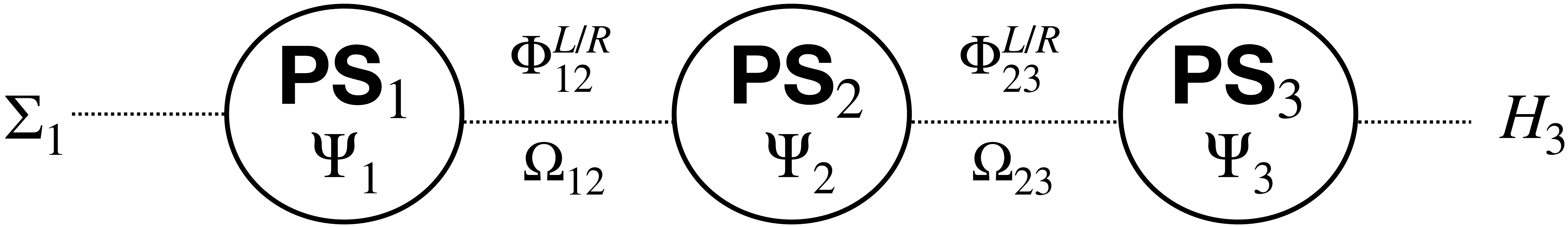
$$\Omega_{ij} \equiv (\mathbf{4}, \mathbf{2}, \mathbf{1})_i \times (\bar{\mathbf{4}}, \bar{\mathbf{2}}, \mathbf{1})_j$$

Reminder: $(SU(4), SU_L(2), SU_R(2))$

Model Example

- 4d Picture – "Pati-Salam Cubed"

[Bordone, Cornelle, Fuentes-Martin, Isidori 1712.01368]



Fermions:

$$\Psi_L^i \equiv (\mathbf{4},\mathbf{2},\mathbf{1})_i$$

$$\Psi_R^i \equiv (\mathbf{4},\mathbf{1},\mathbf{2})_i$$

Scalars:

$$H_3 \equiv (\mathbf{1},\mathbf{2},\bar{\mathbf{2}})_3$$

$$\Sigma_1 \equiv (\mathbf{4},\mathbf{1},\mathbf{2})_1$$

$$\Phi_{ij}^L \equiv (\mathbf{1},\mathbf{2},\mathbf{1})_i \times (\mathbf{1},\bar{\mathbf{2}},\mathbf{1})_j$$

$$\Phi_{ij}^R \equiv (\mathbf{1},\mathbf{1},\mathbf{2})_i \times (\mathbf{1},\mathbf{1},\bar{\mathbf{2}})_j$$

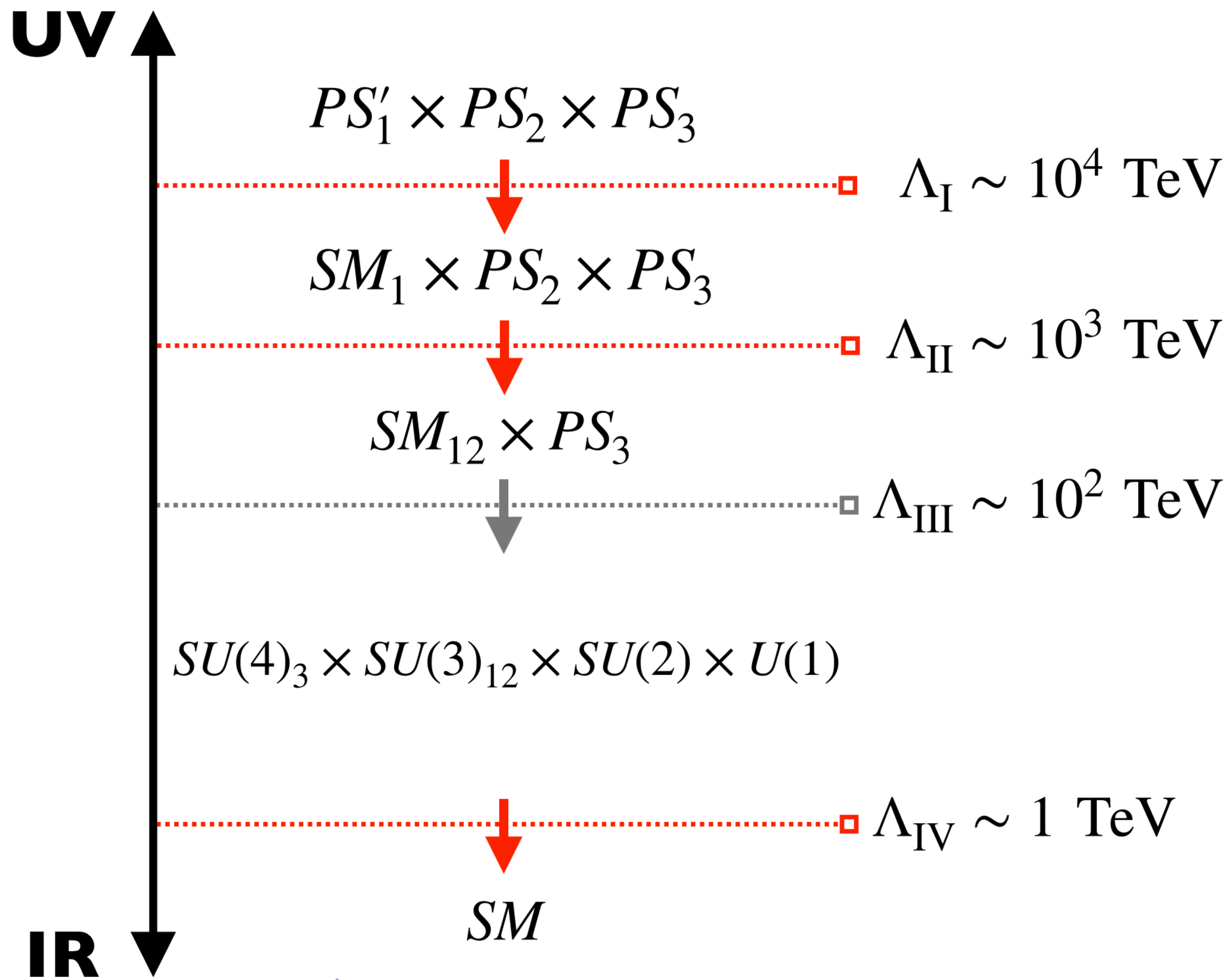
$$\Omega_{ij} \equiv (\mathbf{4},\mathbf{2},\mathbf{1})_i \times (\bar{\mathbf{4}},\bar{\mathbf{2}},\mathbf{1})_j$$

Extra-dimensional picture implies suppressed quartics

Reminder: (SU(4), $SU_L(2)$, $SU_R(2)$)

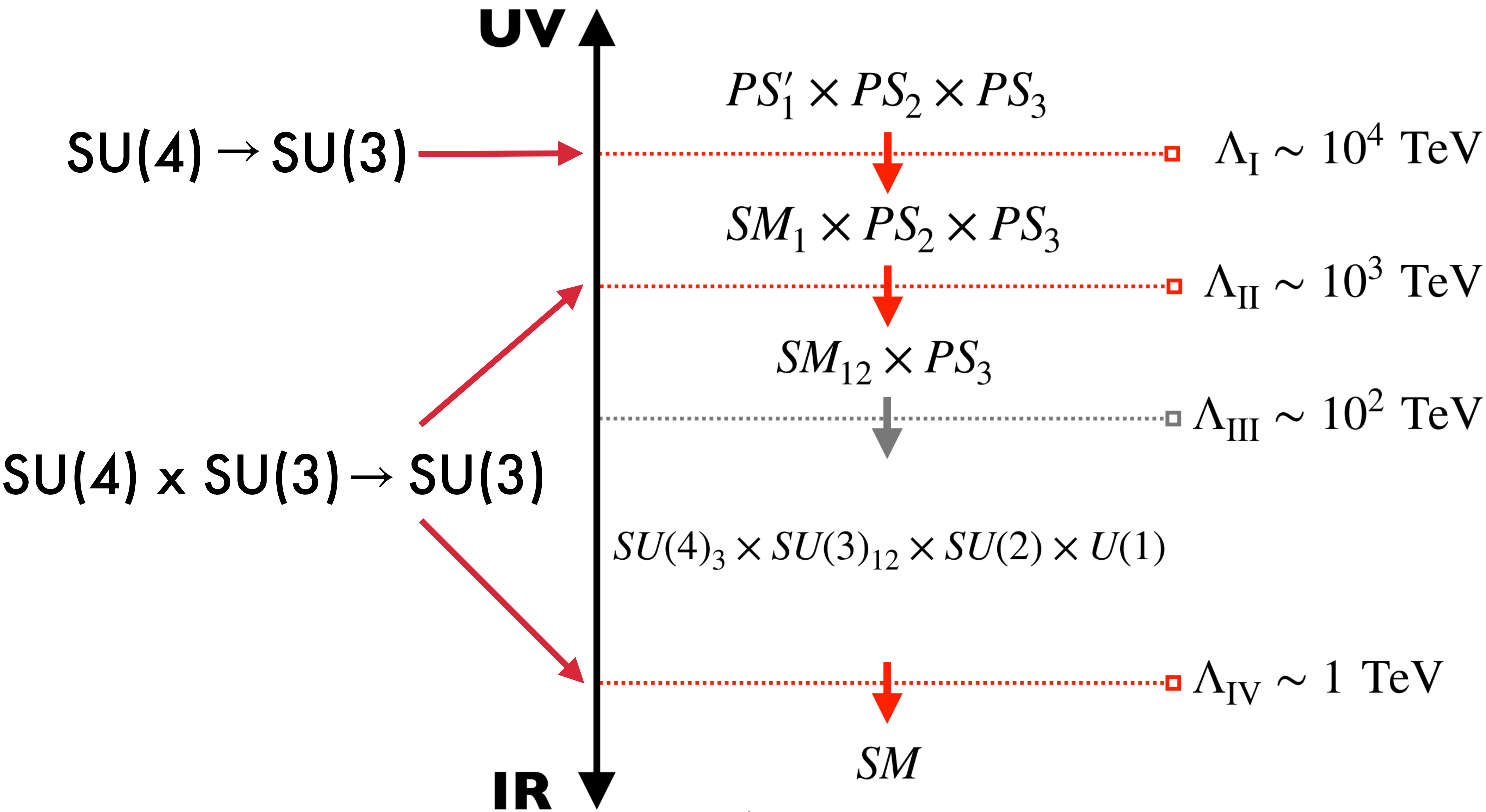
Model Example

- Relevant phase transitions:



Model Example

- Relevant phase transitions:



Cosmological Phase Transitions

Phase transition dynamics controlled by effective potential:

$$V_{\text{eff}}(\underline{g, \lambda, v}, \phi, T) = V_0 + V_{\text{CW}} + V_{T \neq 0}$$

[fundamental parameters]

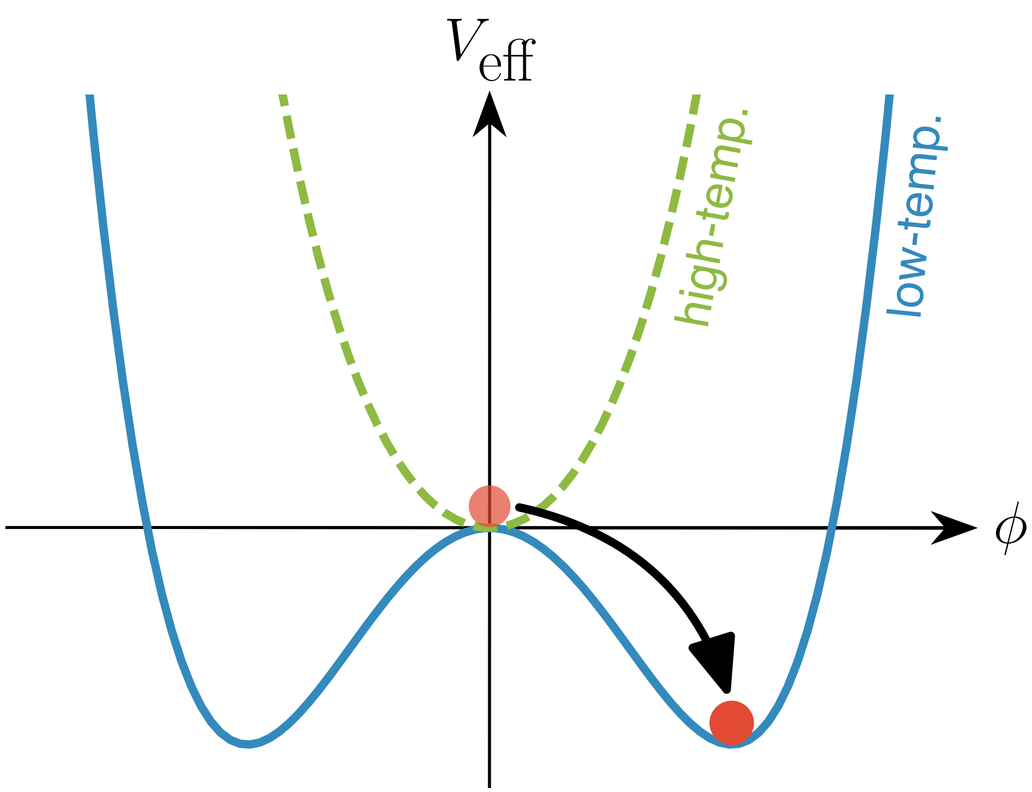
[temperature]

Cosmological Phase Transitions

Phase transition dynamics controlled by effective potential:

$$V_{\text{eff}}(g, \lambda, v, \phi, T) = V_0 + V_{\text{CW}} + V_{T\neq 0}$$

[fundamental parameters] *[temperature]*



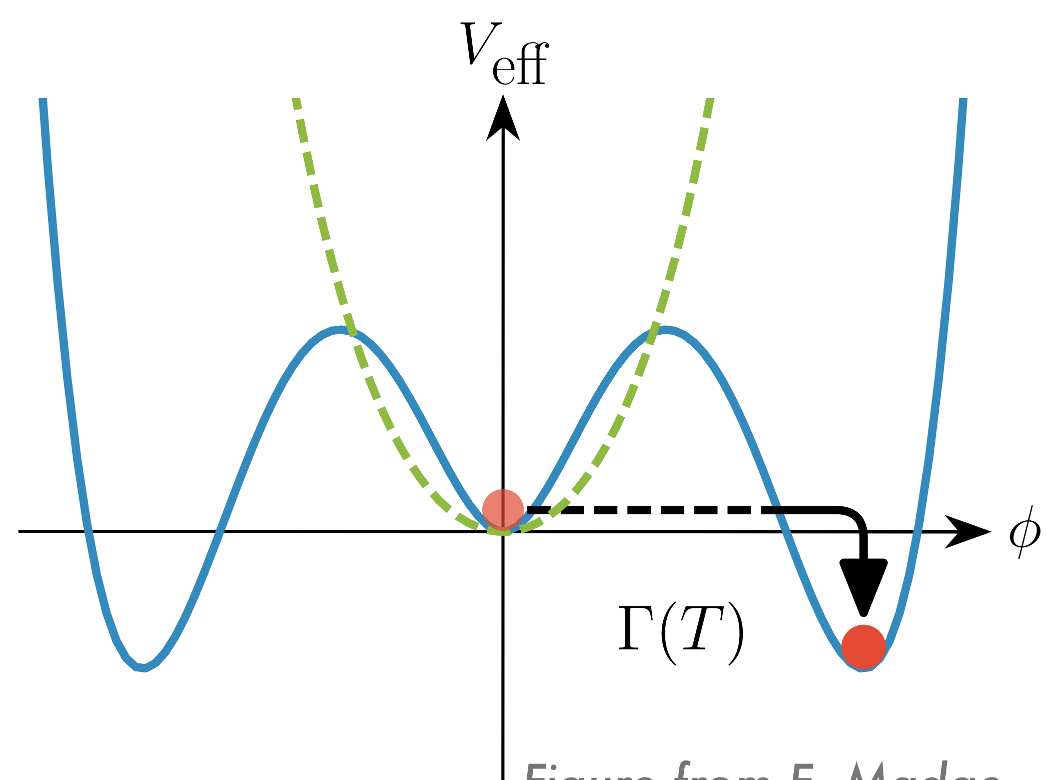


Figure from E. Madge

Cosmological Phase Transitions

- Nucleation temperature:

$$\Gamma(T_\mathrm{n}) \sim H^4(T_\mathrm{n})$$

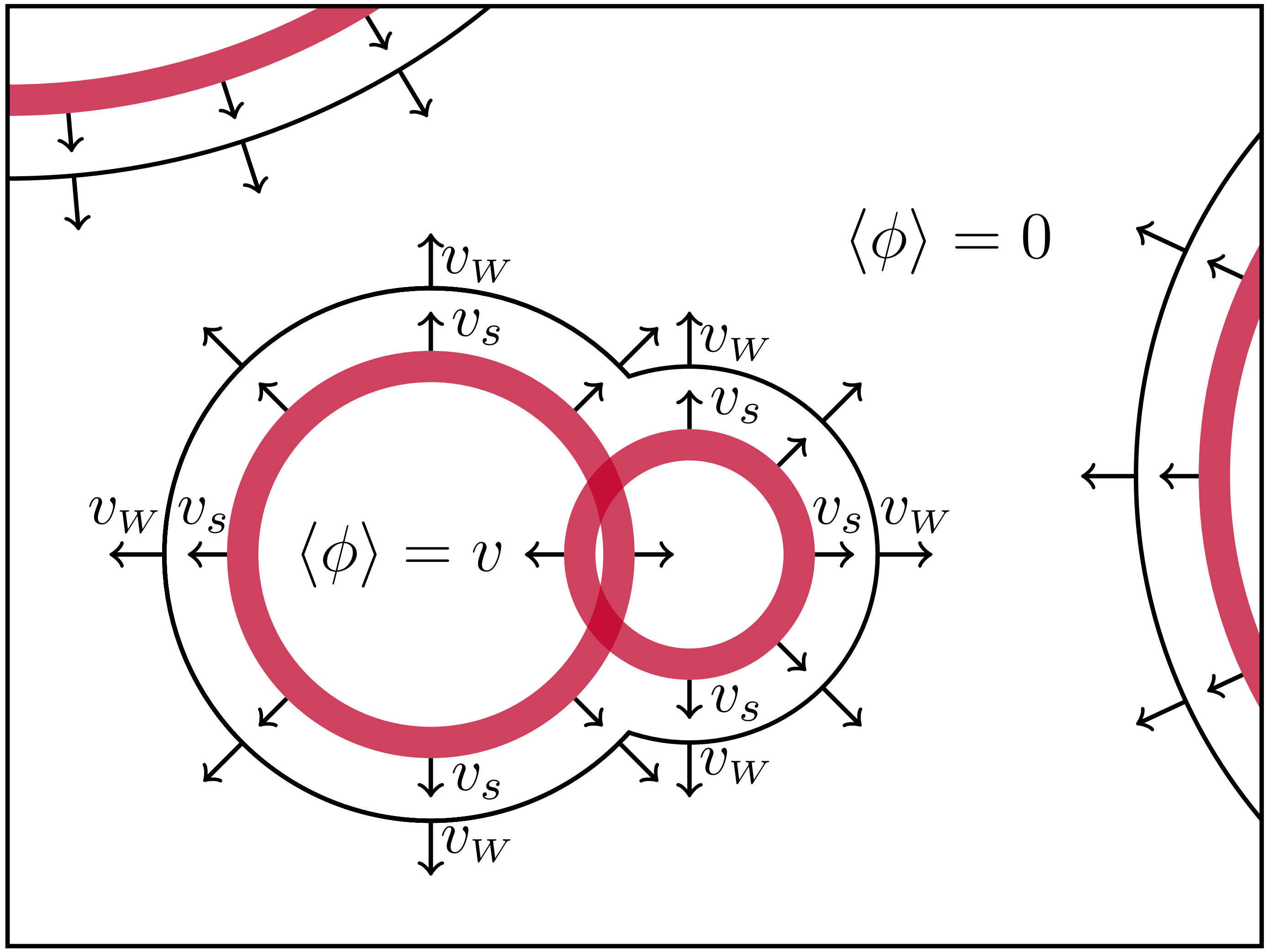


Figure from E. Madge

- Contributions to the GW spectrum:

Ω_ϕ : Collision of bubble walls

Ω_sw : Sound waves in plasma

Ω_turb : Turbulence in plasma

See for example:
[Huber, Konstandin 0806.1828]
[Hindmarsh, Huber, Rummukainen, Weir 1504.03291]
[Hindmarsh, Huber, Rummukainen, Weir 1704.05871]
[Cutting, Hindmarsh, Weir 1802.05712]
[Pol et. al. 1903.08585]
[Cutting, Hindmarsh, Weir 1906.00480]

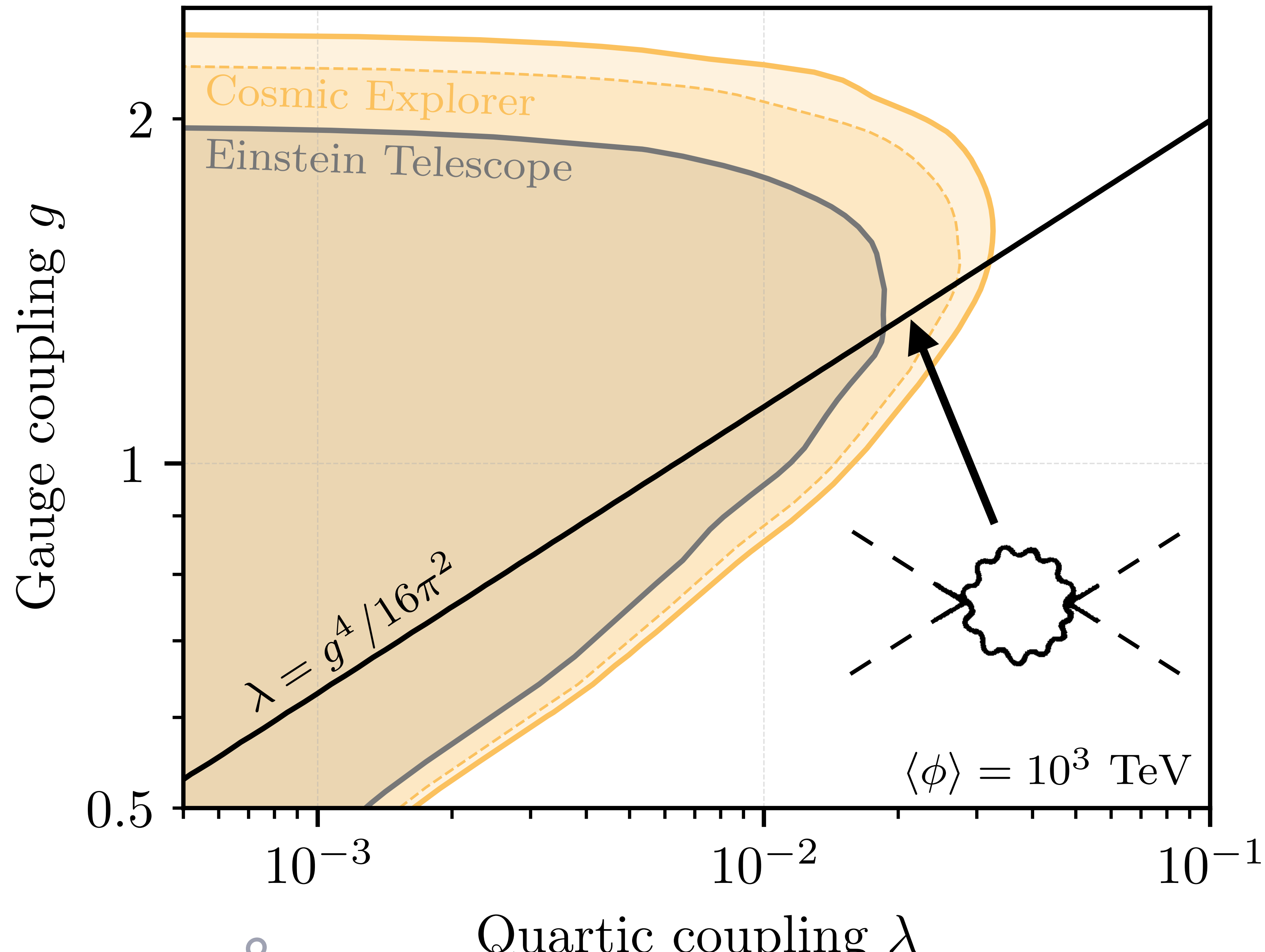
Example Transition

- SU(4) → SU(3) transition [relevant for $\Lambda_{\rm I}$]

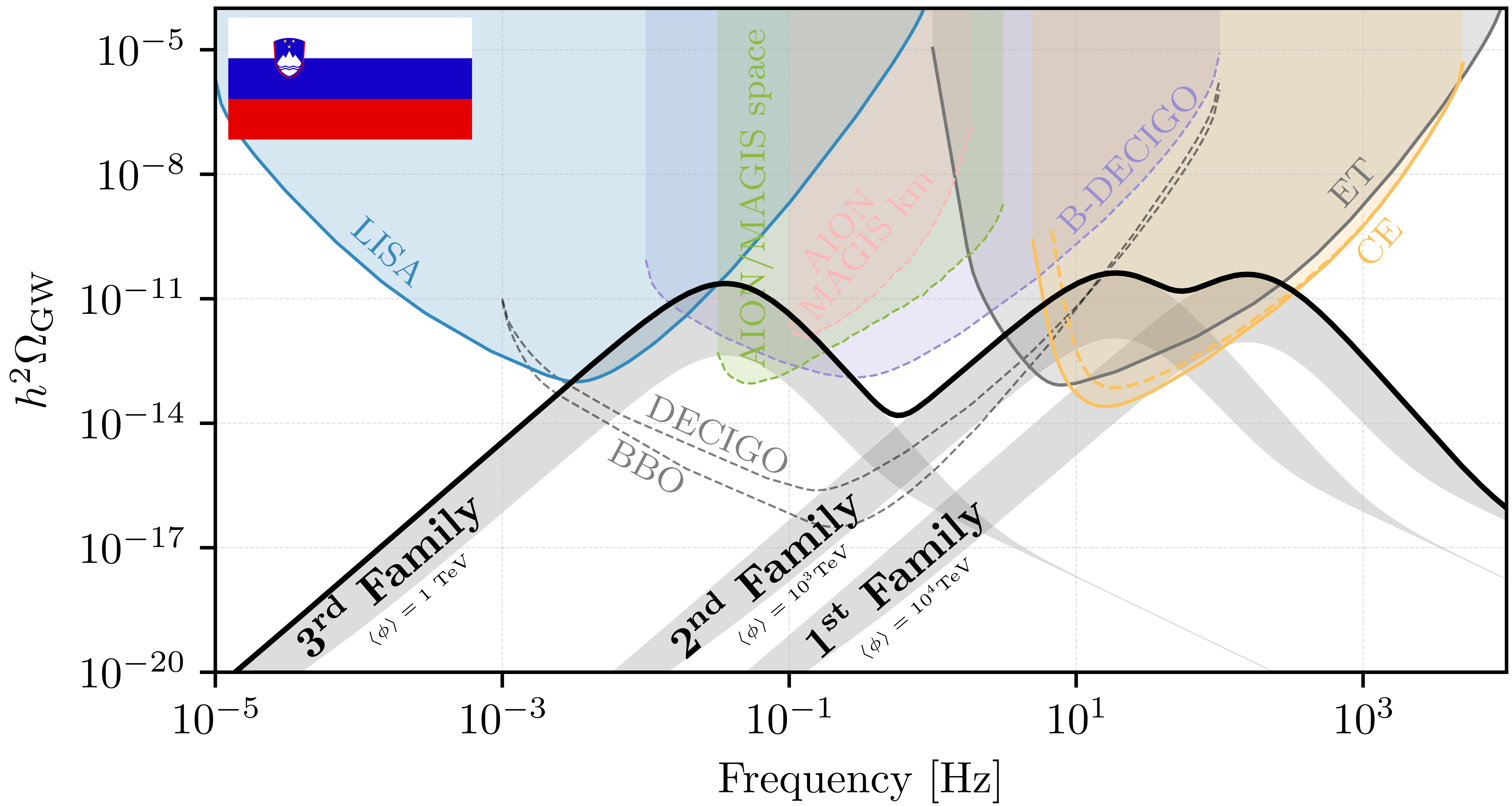
[similar transition for breaking with a ***15*** *of SU(4) considered in Croon et. al. 1812.02747]*

- SM QCD coupling requires $g \sim 1$

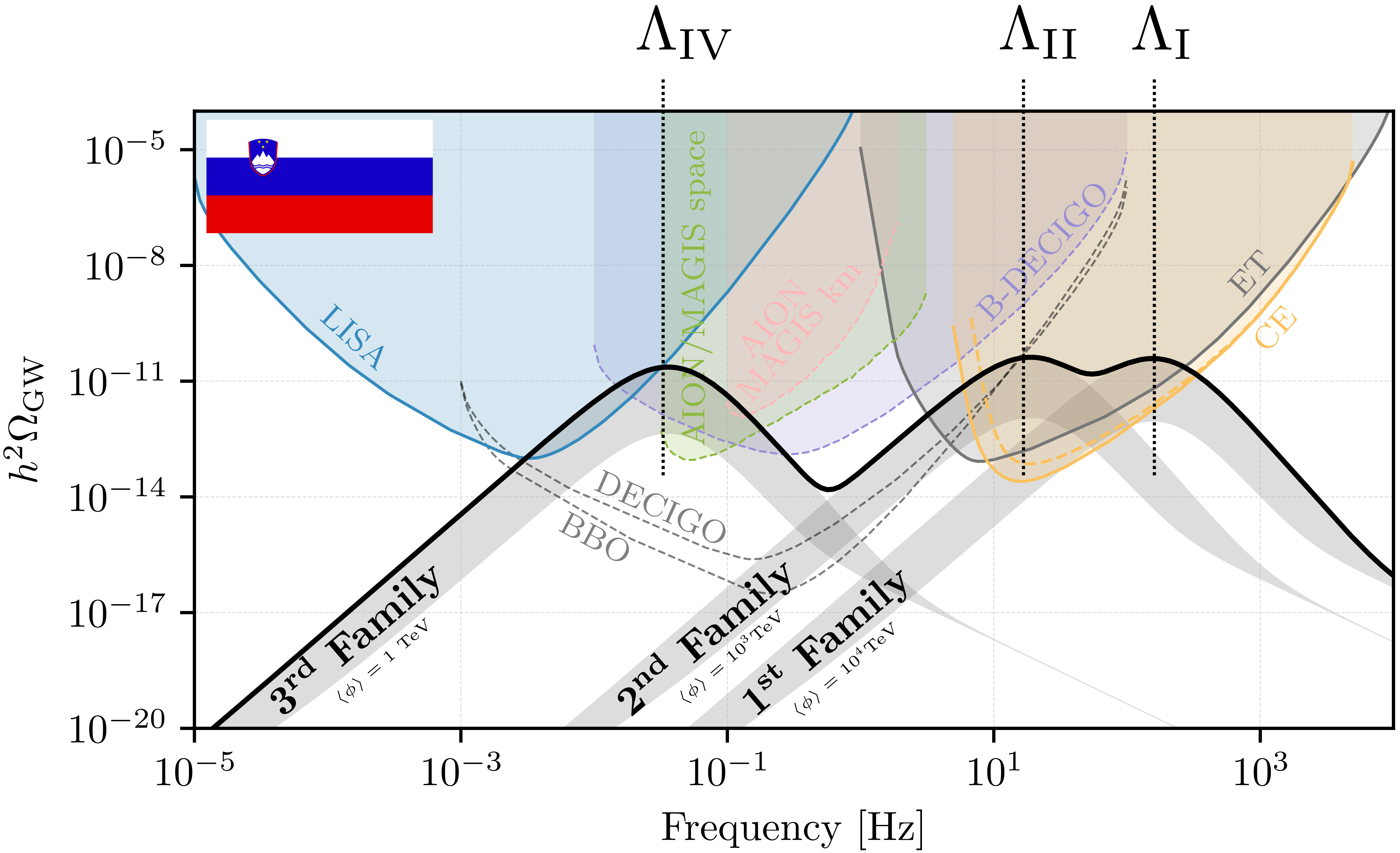
Detectability over natural range of expected parameters



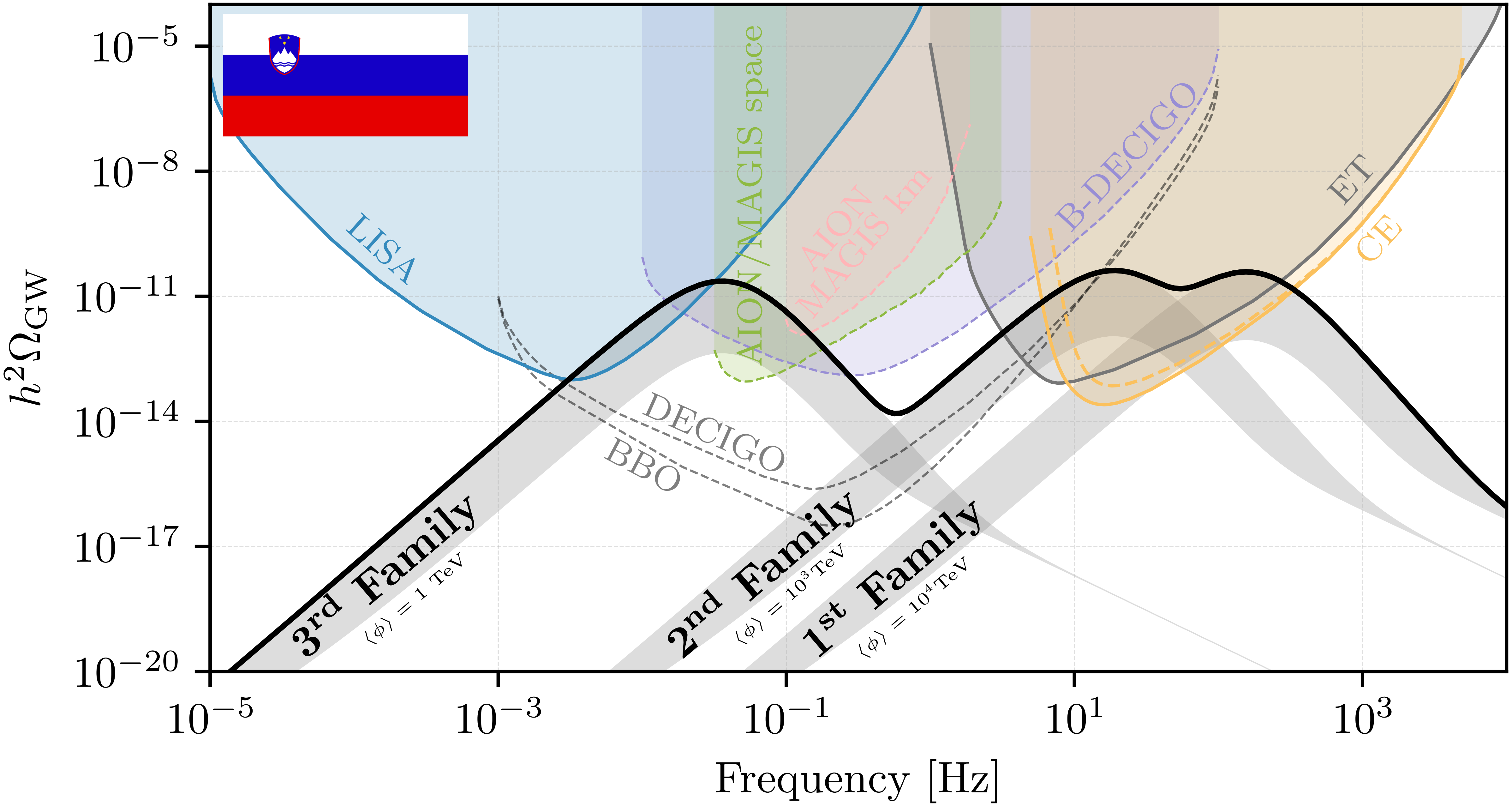
"Triglav Signature"



"Triglav Signature"

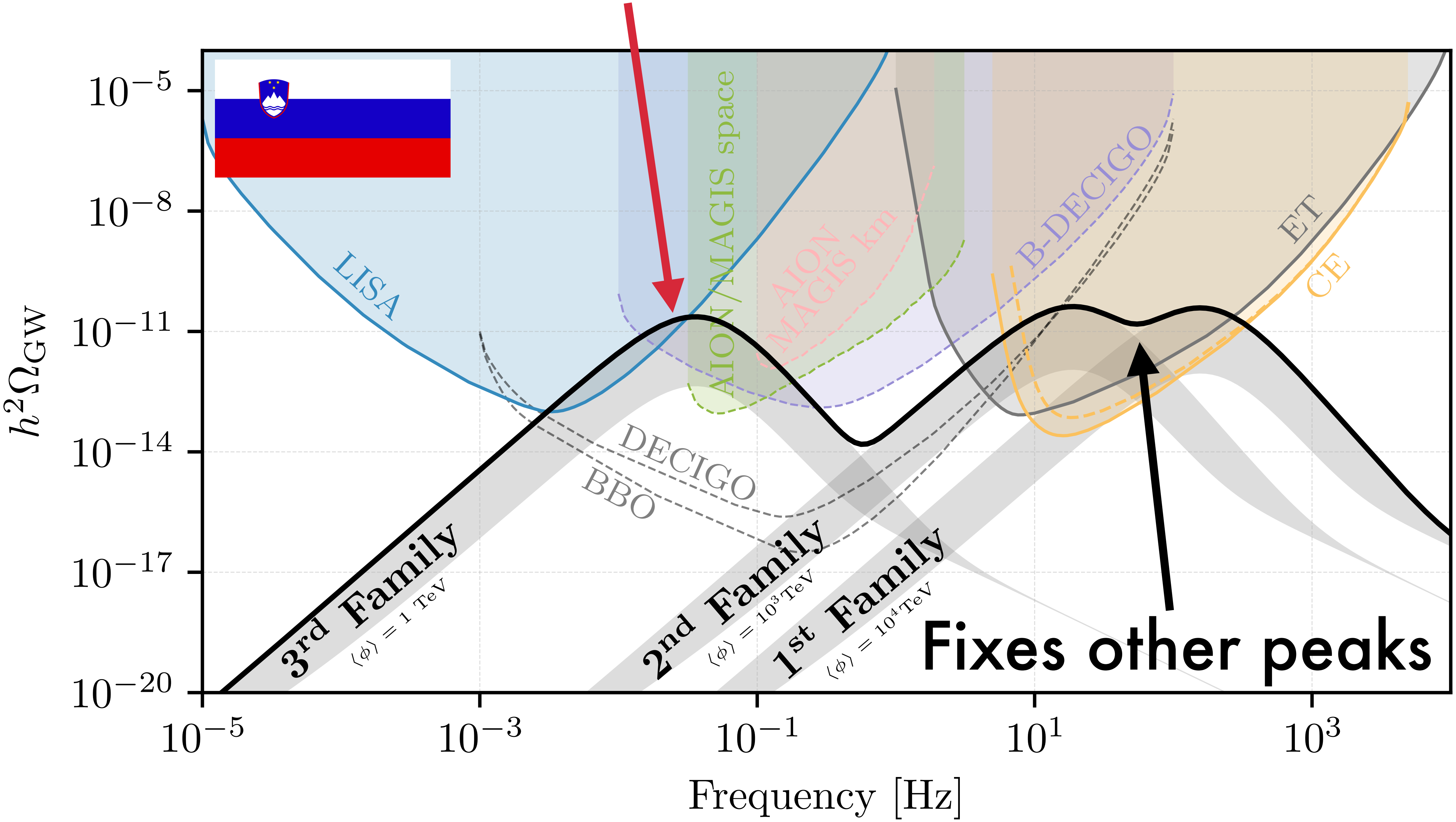


"Triglav Signature"

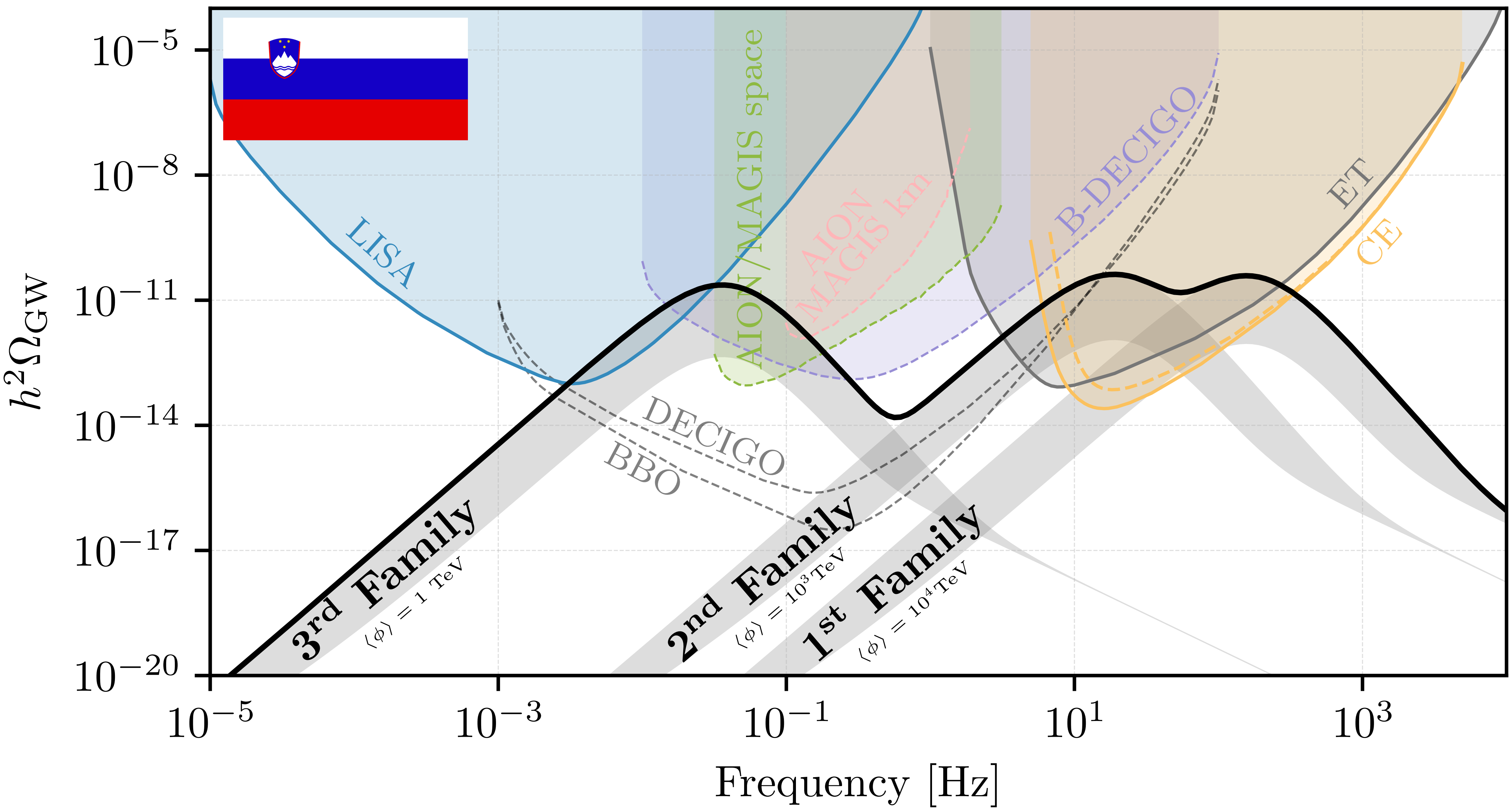


"Triglav Signature"

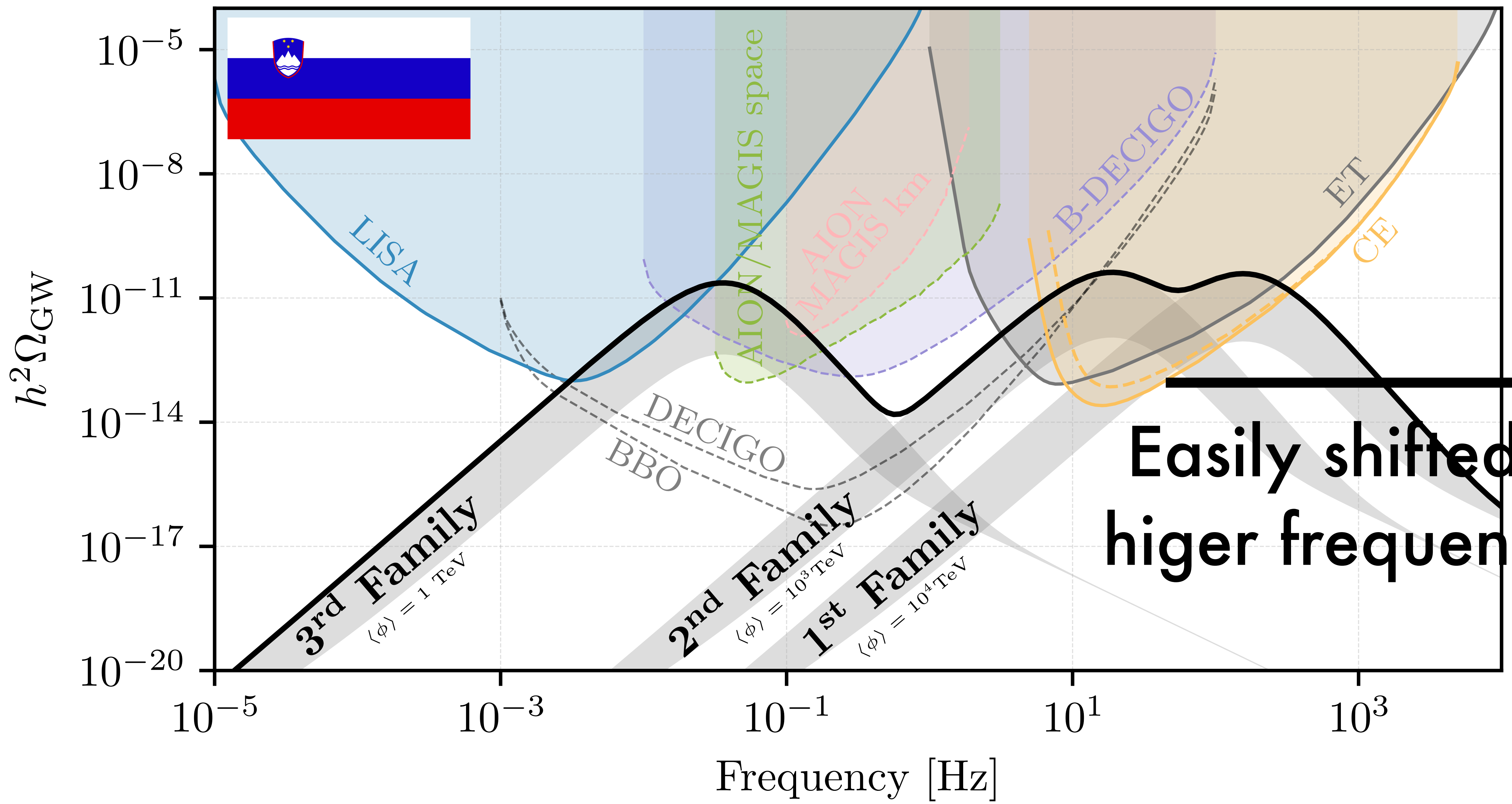
$\Lambda_{\mathrm{IV}} \sim 1\,\mathrm{TeV}$ B-anomalies motived



“Triglav Signature”



"Triglav Signature"



Easily shifted to higer frequencies

Conclusions

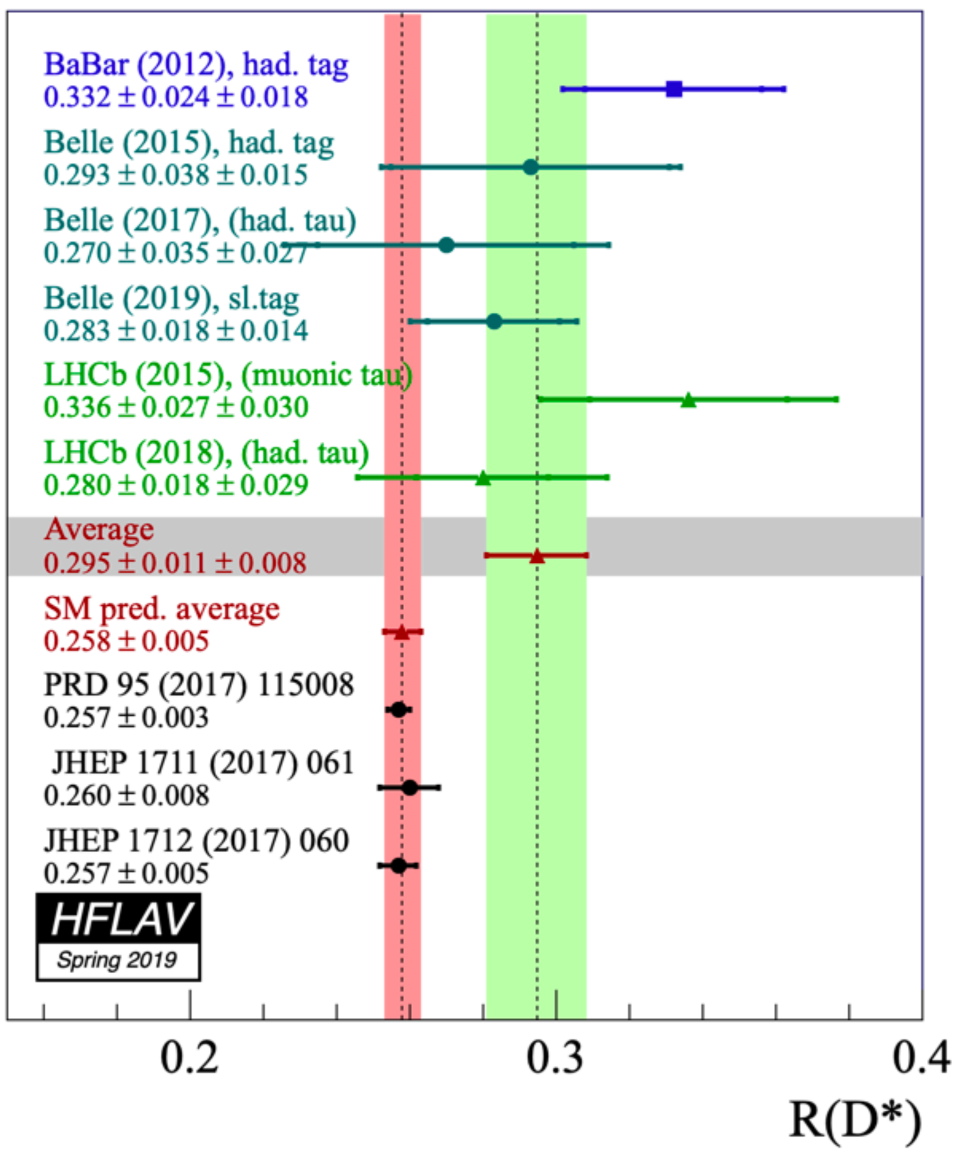
- Rich stochastic GW background from phase transitions *[Sensitive to phase transitions far beyond collider reach]*
- *Multi-peaked spectrum arising from the flavour hierarchy [Mass hierarchy encoded in relative peak frequencies]*
- *These peaks may lie above planned future experiments [Clear appeal for high frequency GW detectors!]*

Backup Slides

B-Anomalies Status

$b \to c\ell\bar{\nu}$ transitions:

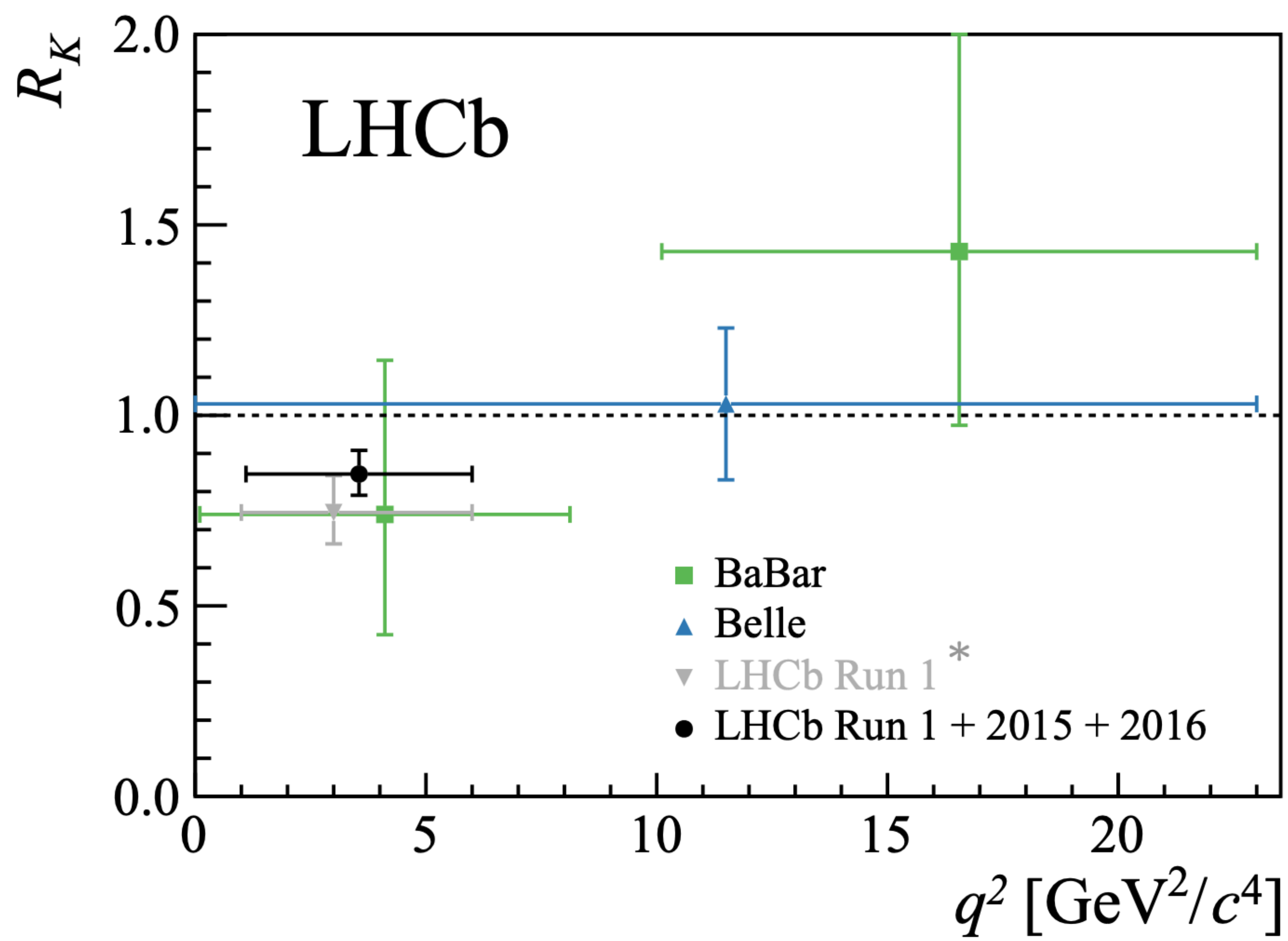
$$R(D^{(*)}) = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu_\tau)}{\mathrm{Br}(B \to D^{(*)}\ell\nu_\ell)}$$



3.1σ discrepancy

$b \to s\ell\ell$ transitions:

$$R(K^{(*)}) = \frac{\mathrm{Br}(B \to K^{(*)}\mu^+\mu^-)}{\mathrm{Br}(B \to K^{(*)}e^+e^-)}$$

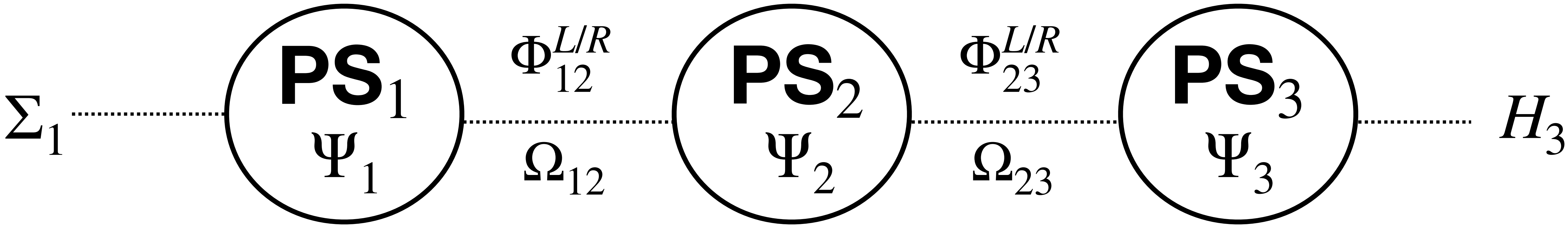


2.5σ discrepancy

Model Example

- 4d Picture – "Pati-Salam Cubed"

[Bordone, Cornelle, Fuentes-Martin, Isidori 1712.01368]



- Light Fermion interactions through mixing:

$$\mathcal{L}_{23} = \frac{1}{\Lambda_{\mathrm{III}}} \overline{\Psi}_L^{(2)} \Omega_{23} H_3 \Psi_R^{(3)} + \mathrm{h.c.} \longrightarrow |V_{ts}| \sim \frac{\langle \Omega_{23} \rangle}{\Lambda_{\mathrm{III}}} \sim \frac{\Lambda_{\mathrm{IV}}}{\Lambda_{\mathrm{III}}}$$

$$\mathcal{L}_{12} = \frac{1}{\Lambda_{\mathrm{II}}^2} \bar{\Psi}_L^{(k)} \Phi_{k3}^L H_3 \Phi_{3l}^R \Psi_R^{(l)} + \mathrm{h.c.} \longrightarrow Y_c \sim \frac{\langle \Phi_{23}^L \rangle \langle \Phi_{32}^R \rangle}{\Lambda_{\mathrm{II}}^2} \sim \frac{\Lambda_{\mathrm{III}}^2}{\Lambda_{\mathrm{II}}^2}$$

See for example:
[Greljo, Stefanek 1802.04274]

Strong coupling running