Leptogenesis

Thomas Leplumey

- The most general framework for Leptogenesis is the **Seesaw Model**

$$\mathcal{L}_{\text{SEFT}}^{(0)} = \boxed{\mathcal{L}_{\text{SM}}} + \boxed{i\overline{N_i}\partial\!\!\!/ N_i} - \boxed{Y_{\alpha i}\overline{L_\alpha}\tilde{\Phi}N_i} - \boxed{\frac{1}{2}M_i\overline{N_i^c}N_i} + \text{h.c.}$$

Standard Model Lagrangian (without RH neutrinos)

Kinetic term for heavy RH neutrinos

Yukawa couplings between LH doublets and RH neutrinos

Majorana mass term for heavy neutrinos

- Parameters counting:
  - 3 heavy Majorana masses
  - 9 complex Yukawa couplings (= 18 real parameters)
  - −3 phases that can be absorbed by field redefinition
- That is: **18 parameters in the neutrino sector**!

Pascoli, Petcov, Riotto
Nucl.Phys.B 774 (2007) 1-52

- The most general framework for Leptogenesis is the **Seesaw Model**

$$\mathcal{L}_{\mathrm{SEFT}}^{(0)} = \mathcal{L}_{\mathrm{SM}} + i\overline{N_i}\partial\!\!\!/ N_i - Y_{\alpha i}\overline{L_\alpha}\tilde{\Phi}N_i - \frac{1}{2}M_i\overline{N_i^c}N_i + \mathrm{h.c.}$$

- That is: **18 parameters in the neutrino sector**!

- We know that at low energies, this reduces to 9 parameters:
  - 3 light masses m_1, m_2, m_3
  - 3 mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$
  - 1 Dirac CP violating phase δ_{CP}
  - 2 Majorana CP violating phases α_{21}, α_{31}

- Therefore, there are **9 high-energy parameters invisible at low energies**

The Standard Model as an Effective Field Theory

- To understand how the Seesaw Model affects the low-energy sector, it is useful to adopt the **Effective Field Theory (EFT)** framework

- We incorporate the BSM effects inside the SM lagrangian as **new non-renormalizable operators** in a very generic way
- The SM hence becomes the **SMEFT**!

Buchmuller, Wyler
Nucl.Phys.B 268 (1986) 621-653

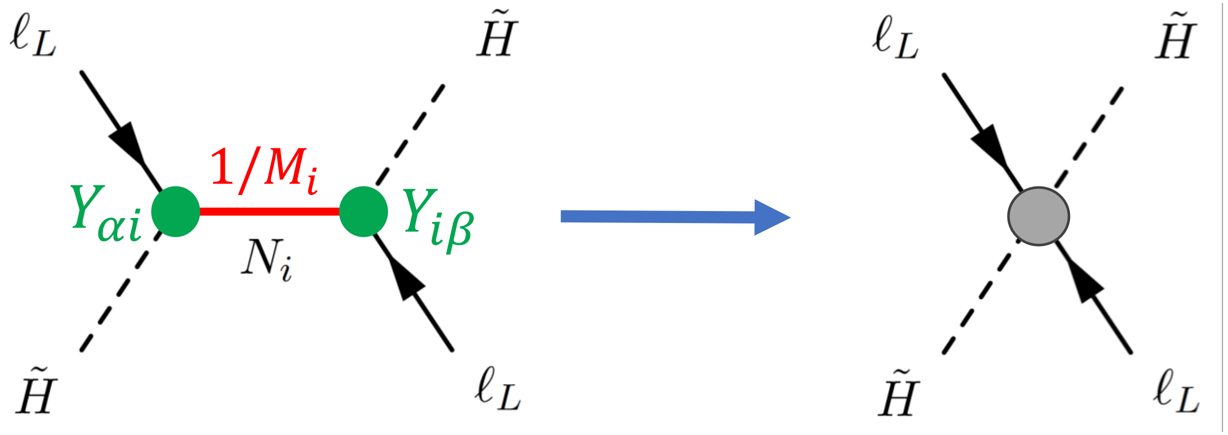
Grzadkowski, Iskrzyński, Misiak, Rosiek
JHEP 10 (2010) 085

$$\mathcal{L}^{(1)}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \boxed{\sum_{\alpha,\beta} \overline{\ell^c_{L\alpha}} \tilde{H} \tilde{H}^\dagger \ell_{L\beta}}$$

Weinberg
Phys.Rev.Lett. 43 (1979) 1566-1570

- At first order in the heavy scale (RH Majorana masses in our case), the only additional operator is the so-called **Weinberg operator**
- It gives rise to a **Majorana mass term for LH neutrinos** after Symmetry Breaking

- We link the UV theory (here, the Seesaw Model) and the SMEFT through a procedure called « **matching** »
- We integrate out all heavy particles that cannot be produced on-shell at the SMEFT energy (here, the RH neutrinos)



$= \overline{\ell^c_L}\tilde{H}\tilde{H}^+\ell_L$ **Weinberg Operator**

Weinberg
Phys.Rev.Lett. 43 (1979) 1566-1570

- This leads to the low-energy LH Majorana mass term:

$$m_{\alpha\beta} = v^2 \left(Y M^{-1} Y^T\right)_{\alpha\beta}$$

Pascoli, Petcov, Riotto
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- All the effects visible at low-energies are encapsulated in this **complex symmetric matrix** of Wilson coefficients:

$$m_{\alpha\beta} = v^2 (Y^T M^{-1} Y)_{\alpha\beta}$$

- The usual parameters are recovered with a **singular value decomposition**:

$$m = (U_{\text{PMNS}})\, m^{\text{diag}}\, (U_{\text{PMNS}})^T$$

- Now, we would like to find a parameterization for the Seesaw Model that is compatible with the low-energy parameterization
- i.e. we would like to write Y and M in terms of U_{PMNS}, m^{diag} and **9 other pure high-energy parameters**

- We want to write Y and M in terms of U_{PMNS}, m^{diag} + 9 high-energy parameters
- This can be achieved by writing Y as a product of matrices:

$$Y = \frac{1}{v} U \sqrt{m} R^T \sqrt{M}$$

Yukawa couplings in the Seesaw Model

PMNS matrix

Majorana masses of LH neutrinos (at low energy)

Complex orthogonal matrix ($R^T R = I_3$) (pure high energy)

Majorana masses of RH neutrinos

Casas, Ibarra
Nucl.Phys.B 618 (2001) 171-204

- Parameters counting:
  - 9 low-energy parameters (LH masses + PMNS matrix)
  - 3 RH Majorana masses
  - 6 remaining parameters encapsulated in the R matrix

We still have 18 parameters in total

$$Y = \frac{1}{v} U \sqrt{m}\, R^T \sqrt{M}$$

- One can check that we indeed recover what we want:

$$\begin{aligned} v^2\, Y M^{-1} Y^T &= U \sqrt{m}\, R^T \sqrt{M} M^{-1} \sqrt{M} R \sqrt{m}\, U^T \\ &= U \sqrt{m}\, R^T R \sqrt{m} U^T \\ &= U \sqrt{m} \sqrt{m}\, U^T \\ &= U m\, U^T \end{aligned}$$

- From which we deduce the condition mentioned above: $R^T R = I_3$

- The R matrix can be written as:

$$R = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\omega_1} & s_{\omega_1} \\ 0 & -s_{\omega_1} & c_{\omega_1} \end{pmatrix} \begin{pmatrix} c_{\omega_2} & 0 & s_{\omega_2} \\ 0 & 1 & 0 \\ -s_{\omega_2} & 0 & c_{\omega_2} \end{pmatrix} \begin{pmatrix} c_{\omega_3} & s_{\omega_3} & 0 \\ -s_{\omega_3} & c_{\omega_3} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- 3 complex angles: $\omega_i = x_i + iy_i$ ($c_{\omega_i} = \cos\omega_i$, $s_{\omega_i} = \sin\omega_i$)

- This parameterization is also compatible with the case of **hierarchical masses** ($M_1 \ll M_2, M_3$), where **N_2 and N_3 can be integrated out** beforehand:
  - M_2 and M_3 are degenerate with $1/m_1$ and $1/m_2$: -2 parameters
  - ω_1 (mixing between N_1 and N_2) has no effect: -2 parameters

  } **"Only" 5 high-E parameters left!**

Detailed calculation another time if you want

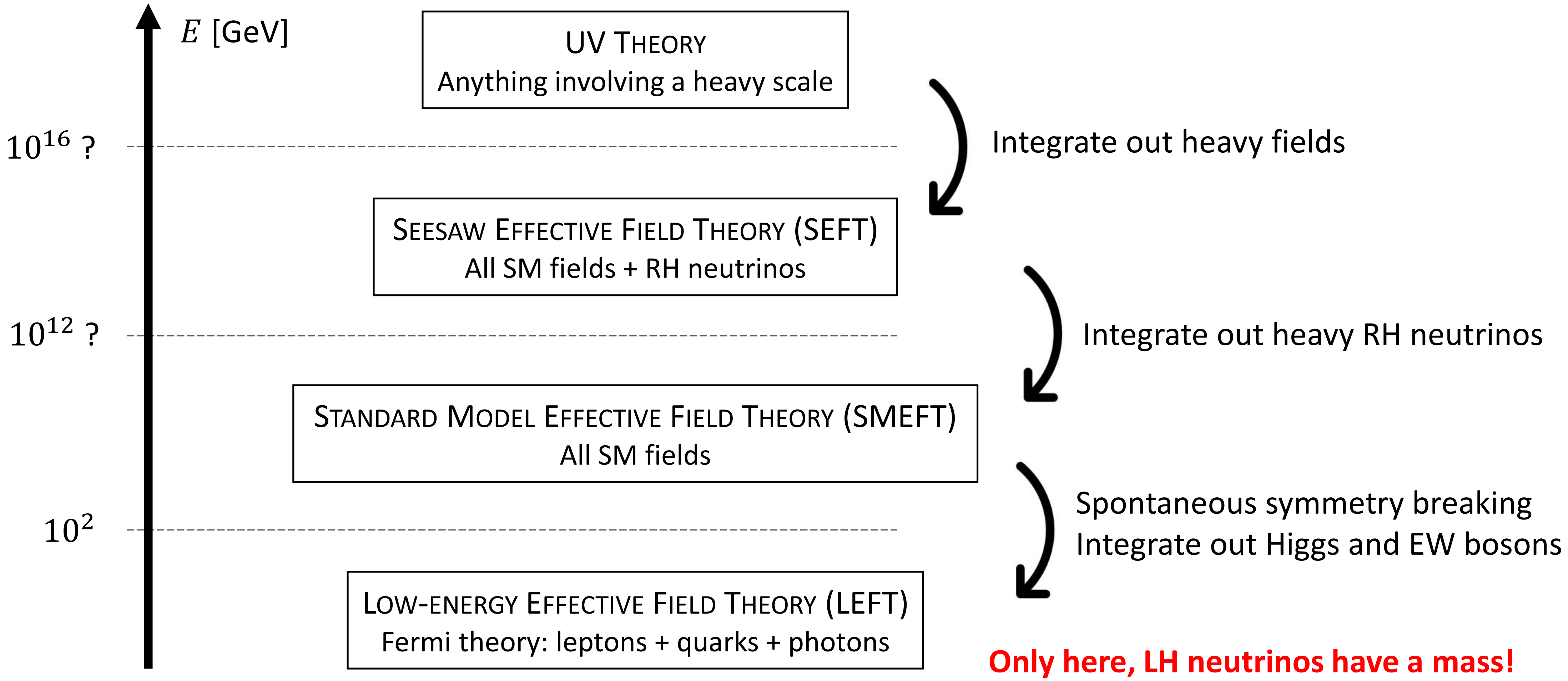
- Everything above holds if we want to probe the neutrino sector in all generality
- However, similarly as the SM, **we don't expect the Seesaw model to be complete**…

- In some (many?) Grand-Unified Theories of SUSY models, the RH neutrinos are incorporated in such a way that $M_{\mathrm{UV}} \gg M_{\mathrm{RH}\nu} \gg v$

- Therefore, **the Seesaw model can be seen as an effective field theory** itself, hence called the **SEFT**, that can be matched to any other underlying UV theory!
  - However, one may have to add non-renormalizable operators in the SEFT as well (e.g. the Weinberg operator), which means potentially more operators…

Du, Li, Yu
JHEP 09 (2022) 207

- Hence EFTs are the key tool to understand the interplay between low-energy and high-energy physics, in the neutrino sector in particular!



Granelli, Leslie, Perez-Gonzalez, Schulz, Shuve
Comput.Phys.Commun. 291 (2023) 108834

SEESAW EFFECTIVE FIELD THEORY (SEFT)

$$\mathcal{L}^{(0)}_{\text{SEFT}} = \mathcal{L}_{\text{SM}} + i\overline{N_i}\not{\partial}N_i - Y_{\alpha i}\overline{L_\alpha}\tilde{\Phi}N_i - \frac{1}{2}M_i\overline{N_i^c}N_i + \text{h.c.}$$

CASAS-IBARA PARAMETERIZATION

$$Y = \frac{1}{v}U\sqrt{m}R^T\sqrt{M}$$

(RADIATIVE CORRECTIONS)

LOW-ENERGY SECTOR

$\theta_{ij}, \delta_{CP}, m_i, \alpha_{ij}$

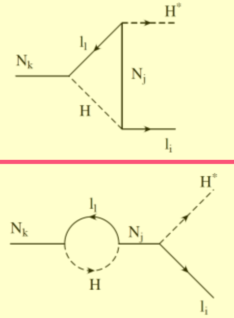
EXPERIMENTAL INPUT

- NEUTRINO OSCILLATIONS
- β-DECAY SPECTRUM
- $0\nu\beta\beta$ DECAY
- CMB
- BIG BANG NUCLEOSYNTHESIS
- …

BARYON ASYMMETRY

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

ULYSSES



CP ASYMMETRY

$$\epsilon_l = -\frac{3M_1}{16\pi v^2}\frac{\text{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{l\beta}U_{l\rho}R_{1\beta}R_{1\rho}\right)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

BOLTZMANN EQUATIONS

$$\frac{dN_{N_1}}{dz} = -(D_1 + S_1)\left(N_{N_1} - N^{eq}_{N_1}\right)$$

$$\frac{dN_{L_l}}{dz} = \sum_{l=e,\mu,\tau}\left[-\epsilon_l D_1\left(N_{N_1} - N^{eq}_{N_1}\right) - p_{1l}W_1 N_{L_l}\right]$$

SPHALERON EQUILIBRIUM

$$B = c_s \times (B - L)$$

LEPTON ASYMMETRY

$$\eta_L = \frac{n_L - n_{\overline{L}}}{n_\gamma}$$

- Currently, we have at low energy:
  - Very good sensitivity to **6/18 parameters** (osc. Params. Δm_{12}^2, Δm_{23}^2, θ_{12}, θ_{13}, θ_{23}, δ_{CP})
  - Good constraints on **1 parameter** (e.g. $\sum m_i$ or equivalent)
  - Zero constraints on **2 parameters** (Majorana phases α_{21}, α_{31})

- Currently, we have at high energy:
  - Model hypothesis on **1-3 parameters** (at least M_1 (Yukawa eq.), maybe M_2, M_3 (hierarchy))
  - Zero constraints on **7-9 parameters**

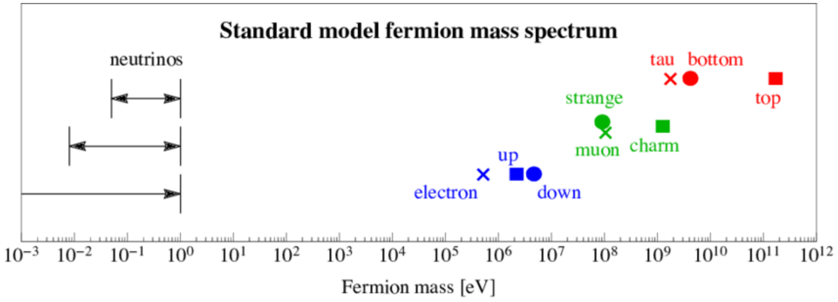
- If we want to perform a meaningful analysis with current data, we need either:
  - **Specific models** with less parameters
  - **Strong priors** on the parameters that we cannot measure directly

Model assumptions

- We can introduce model-dependency at different levels e.g.
  - The quite general asumption of hierarchical masses allows to drop 4 high-E parameters
  - The asumption of 2 RH neutrinos allows to drop 6 high-E parameters and 1 low-E parameter
  - The ad-hoc assumption that all the CP violation is in δ_{CP} induces higher model correlations between neutrino oscilations and baryon asymmetry
  - Specific models ($SO/U(whatever)$, SUSY, etc.): potentially higher correlations and less parameters
  - …

- I think one of the first two asumptions may be a good start, in order to make a simpler analysis but still be generic enough

- We can use priors from « **naturalness** »!
- For all the families of fermions, the Dirac masses have roughly the same orders of magnitude :
  - Generation 1: $10^5 - 10^7$ eV
  - Generation 2: $10^8 - 10^{10}$ eV
  - Generation 3: $10^9 - 10^{12}$ eV



- In practice, this amounts to decomposing the Yukawa matrix as:

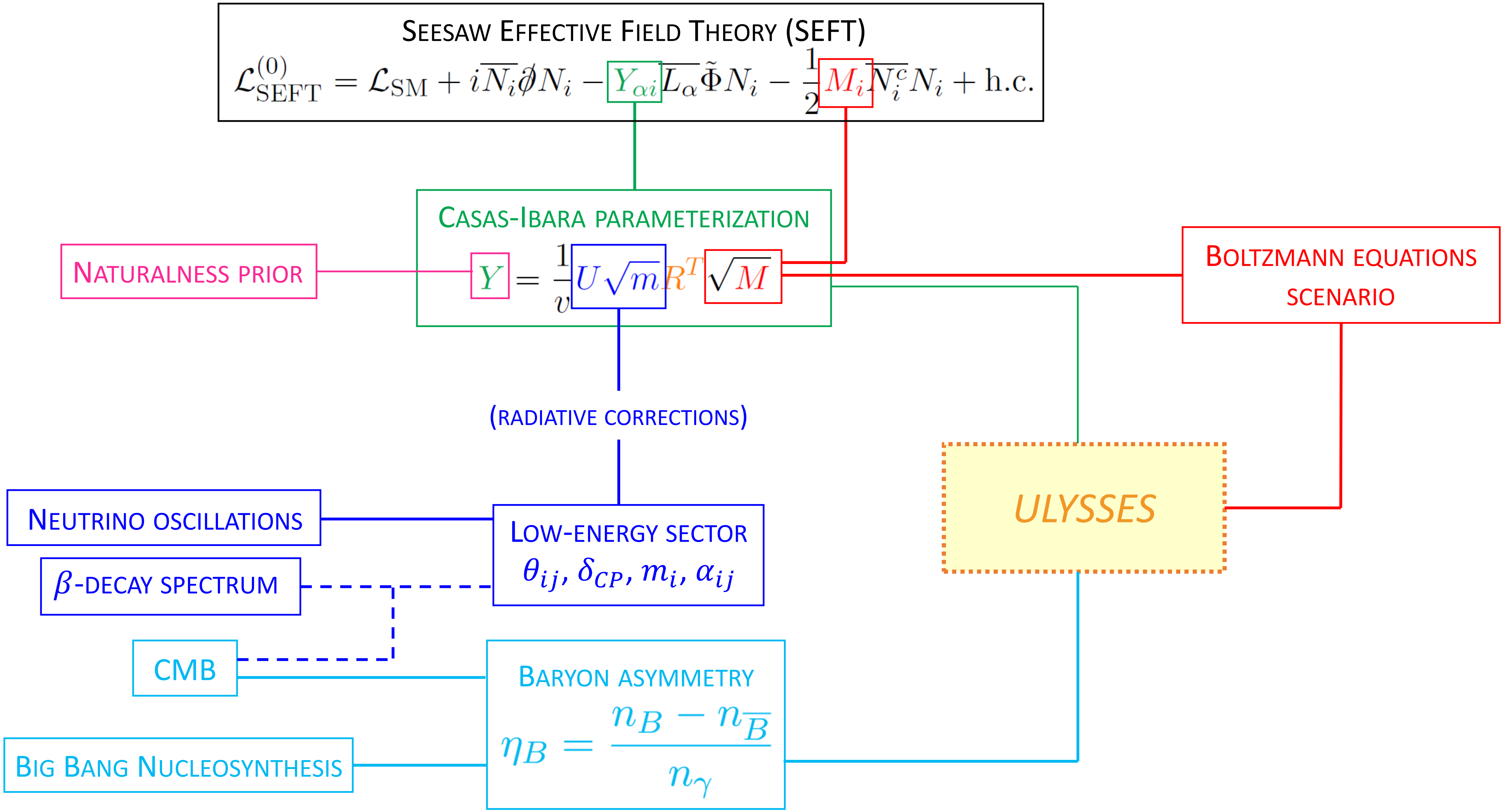
$$Y = V_1^\dagger m_D V_2$$

Naturalness prior

Uniform prior in $U(3)$

- The Majorana masses themselves are constrained by the **BE model hypothesis**

Big Picture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Casas-Ibara parameterization
$Y = \frac{1}{v}U\sqrt{m}R^T\sqrt{M}$
Naturalness prior
Boltzmann equations scenario
(radiative corrections)
Neutrino oscillations
Low-energy sector
$\theta_{ij}, \delta_{CP}, m_i, \alpha_{ij}$
β-decay spectrum
CMB
Baryon asymmetry
$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma}$
Big Bang Nucleosynthesis
ULYSSES

Proposal for leptogenesis analysis

- A first proposal for our leptogenesis analysis is to use:
  - **Posterior distribution on oscillation parameters** from T2K/SK
  - **Bound on LH neutrino masses** (from KATRIN or CMB)
  - **Naturalness prior** on Yukawa matrix (Dirac neutrino « masses »)
  - Measure of η_B **from CMB**
  - Different BE scenarii and corresponding assumptions on RH Majorana masses

- Try to extract **correlations between δ_{CP} (+ other osc. params) and η_B**
- Perform parameter scans on relevant parameters

- Then, replace the posterior distribution on oscillation parameters by a fit to data using P-theta