# The Neutrino Option

**Ilaria Brivio**

Institut für Theoretische Physik, Universität Heidelberg

*based on 1703.10924, 1809.03450, 1905.12642, 2010.15428*
*with M. Trott, K. Moffat, S. Pascoli, S. Petcov, J. Talbert, J. Turner*

# The issue: origin of the Higgs potential

The Higgs potential gives a successful parameterization of the electroweak symmetry breaking

$$V(H^\dagger H) = -\frac{m_H^2}{2}\,(H^\dagger\, H) + \lambda\,(H^\dagger\, H)^2$$

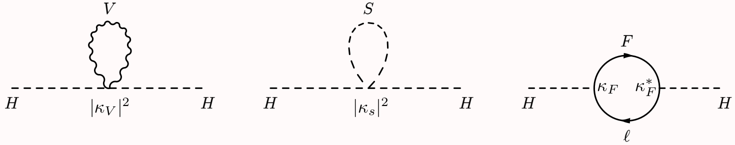
but it lacks **a dynamical origin**! $\longleftrightarrow$ several theoretical **problems**:

hierarchy, stability, triviality, phase transition? ...

# The hierarchy problem in an EFT perspective

Brivio,Trott 1706.08945

Heavy new physics can give loop corrections to $(H^\dagger H)$



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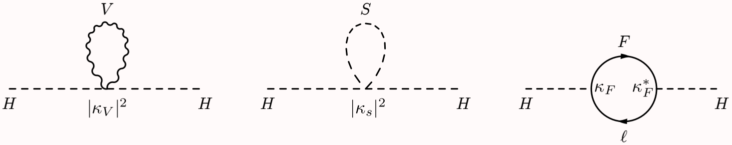


$\downarrow$ integrating it out

**threshold matching contributions** at $E < m_i$

[loops in DR+$\overline{MS}$ in the lim $v/m_i \to 0$]

$$\Delta V(H^\dagger H) \simeq H^\dagger H \left( \frac{3|\kappa_v|^2 \; m_v^2 \; N_v}{16\,\pi^2} + \frac{|\kappa_s|^2 \; m_s^2 \; N_s}{16\,\pi^2} - \frac{|\kappa_F|^2 \; m_F^2 \; N_F}{16\,\pi^2} \right) + \dots$$

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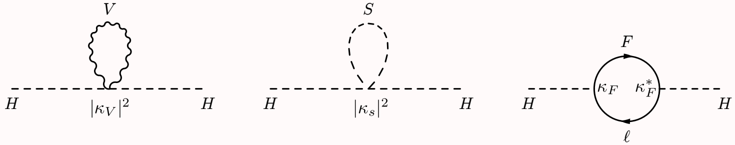


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these corrections are always proportional to the scale integrated out

$\to$ one of the main complications when UV completing the potential

# Traditional solutions

Common approaches:

**(a)** SUSY way: extra symmetry to **force cancellations** among thresholds

**(b)** Composite way: shift symmetry to protect $H^\dagger H$

$\downarrow$

potential **generated radiatively**.

$$V(H) \simeq \frac{g_{SM}^2 \Lambda^2}{8\pi^2}\left(-a\, H^\dagger H + b\,\frac{(H^\dagger H)^2}{f^2}\right)$$

Bellazzini,Csáki,Serra 1401.2457

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Bellazzini, Csáki, Serra 1401.2457

- both require resonances not far from TeV scale
- the potential must be generated at once. That's not trivial!

tuning of $a, b$ ↔ complex spectrum / symmetry setup

needed to get

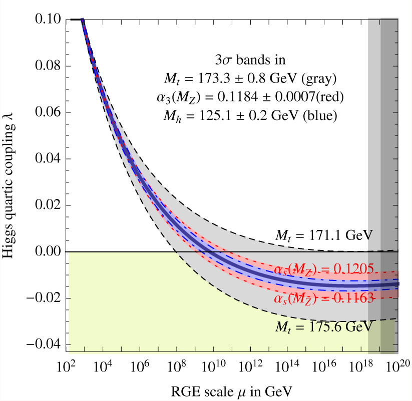
**the right shape** $+$ $\mathbf{\frac{v^2}{f^2} = \frac{a}{b} \lesssim 1}$

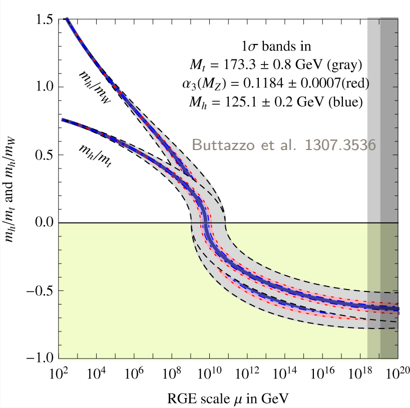
# A change in perspective

Having measured the Higgs mass opens new possibilities!

An important one: controlling the running of the potential to very high energies.

Elias-Miro et al. 1112.3022, Degrassi et al,1205.6497, Espinosa et al. 1505.04825

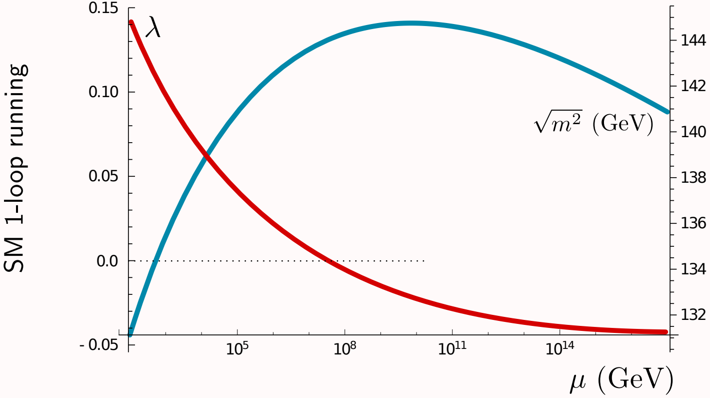



We can move the stabilization problem from the TeV to a much higher scale

# Building the potential in the UV

idea: some very heavy UV sets the initial conditions <u>at a high scale</u>



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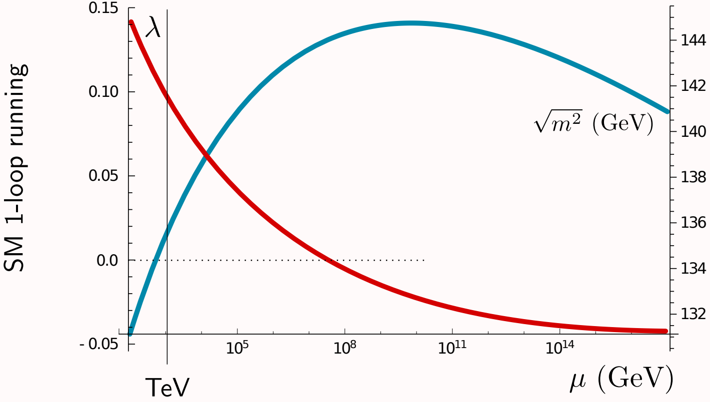

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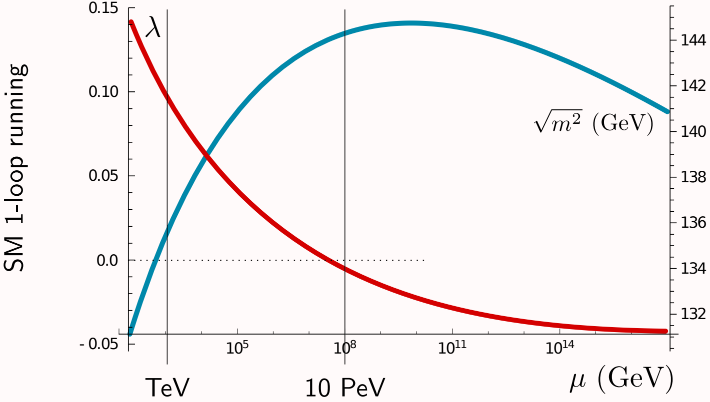

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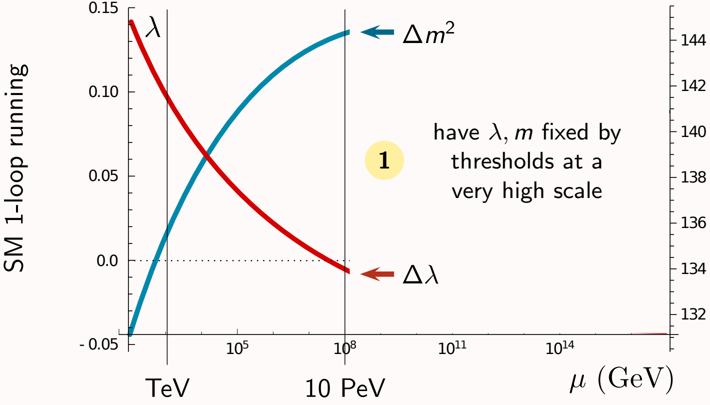

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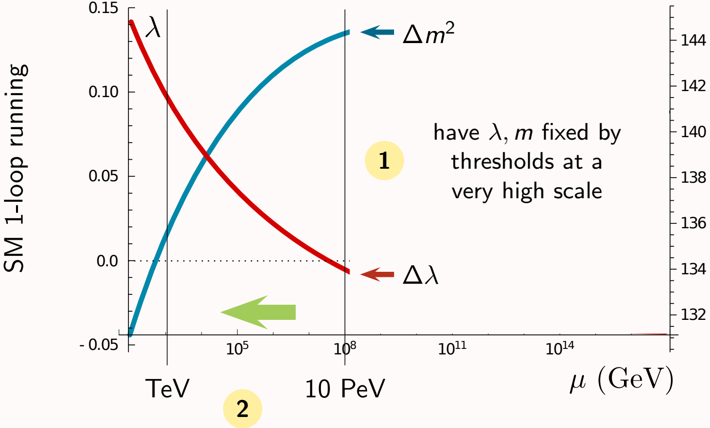



run it down with SM RGE

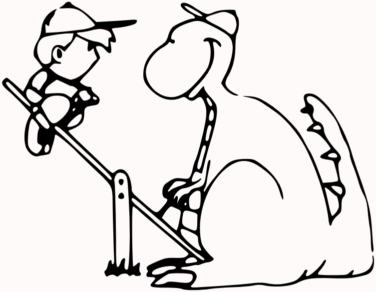
# Can type I seesaw generate the Higgs potential?

$$\mathcal{L}_N = \frac{1}{2}\overline{N}(i\partial\!\!\!/ - M)N - \left[\overline{N}\,\omega\,\tilde{H}^\dagger \ell_L + \overline{\ell_L}\,\tilde{H}\,\omega^\dagger N\right]$$

Minkowski 1977
Gell-Mann,Ramond,Slansky 1979
Mohapatra,Senjanovic 1980
Yanagida 1980

with $n$ Majorana neutrinos $N = N^c$:

$M$ real, diagonal
$\omega$ $n \times 3$ matrix in flavor space



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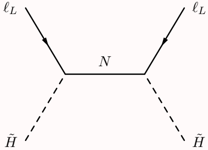
**M ≫ v**




$$m_\nu = \frac{v^2}{2}\,\omega^T M^{-1}\omega$$

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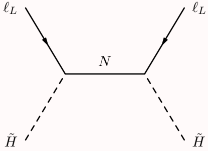


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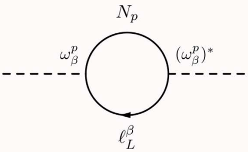
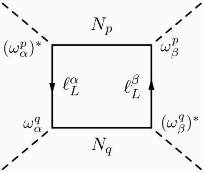



$$\Delta m_H^2 =\sim M^2\frac{|\omega|^2}{8\,\pi^2}$$




$$\Delta\lambda \sim -\frac{5}{32\pi^2}|\omega|^4$$

(flavor indices omitted)

Vissani hep-ph/9709409
Casas et al hep-ph/9904295

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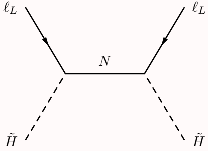
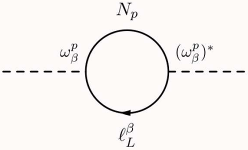
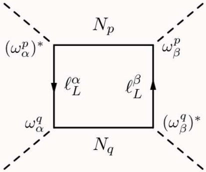
**2 free quantities**
in the UV
($\sim$ deg. $M$, no tunings)

**M ≫ v**




$$m_\nu = \frac{v^2}{2}\,\omega^T M^{-1}\omega \qquad \Delta m_H^2 = \sim M^2\frac{|\omega|^2}{8\,\pi^2} \qquad \Delta\lambda \sim -\frac{5}{32\pi^2}|\omega|^4$$

**3 constraints** at the EW scale

(flavor indices omitted)
Vissani hep-ph/9709409
Casas et al hep-ph/9904295

# Preliminary study

fix $\omega, M$ to generate $m_H$, $\lambda$ $\longrightarrow$ check $m_\nu$

Brivio, Trott 1703.10924

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**Key assumptions**

- start with nearly-vanishing classical potential at $\mu \gtrsim M$:

  approximate **scale invariance** + explicit breaking only from Majorana mass

- threshold contributions **from other NP** and **SM** contributions to the Coleman-Weinberg potential are subdominant.

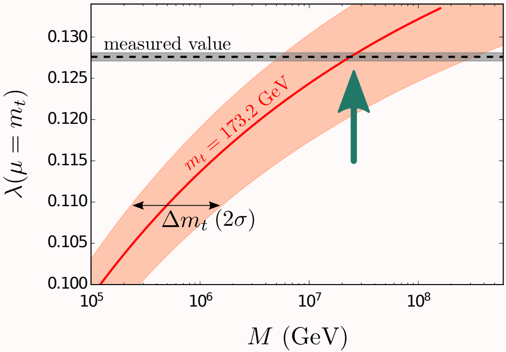
  SM: OK for $M|\omega| \gg v, \Lambda_{QCD}$.

# Preliminary study: results

$\lambda(m_t)$ is not sensitive to $|\omega|$ but depends significantly on $M$

$\downarrow$

best fit $M \simeq 10^{7.4}$ GeV $\simeq$ 25 PeV



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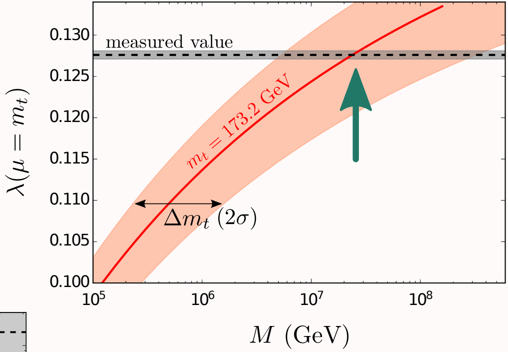


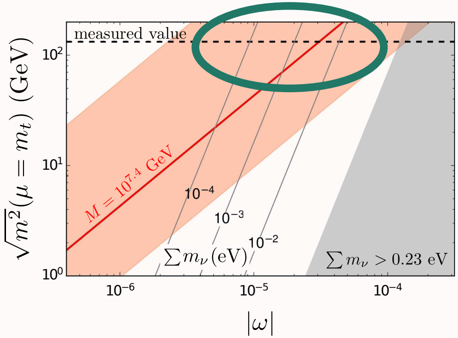


with fixed $M$, $m_H^2(m_t)$ determines uniquely $|\omega| \simeq 10^{-4.5}$

$\downarrow$

$$\sum |m_\nu| = \frac{3|\omega|^2}{2}\,\frac{v^2}{M} \simeq 3 \cdot 10^{-3}\ \text{eV}$$

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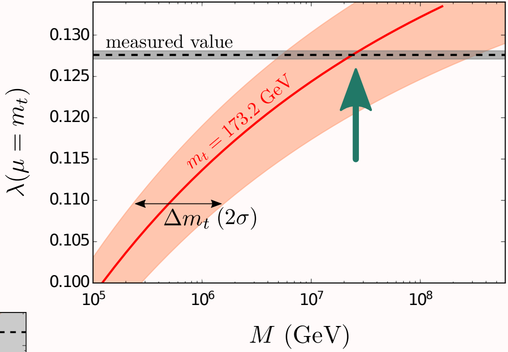


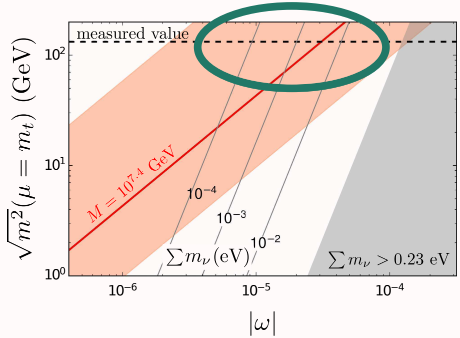


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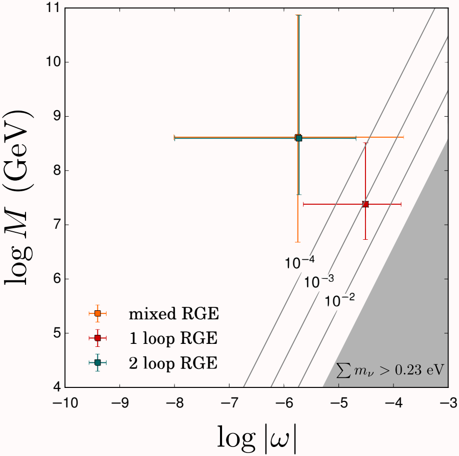
# (Un)buried bodies

- High **numerical sensitivity** to $m_t$ + RGE order
- Higher order RGEs point to lighter $m_\nu$ (too light!)



# Improved study

relax the assumption $\lambda_0 \simeq 0$

Brivio, Trott 1809.03450

simply start from a conformal potential $\mathbf{m^2_{H,0} \simeq 0}$

fix $\omega, M$ to generate

$m_H$

$m_\nu$

in agreement with the measurements

$\longrightarrow$

use the freedom to fix

$\lambda_0$

to adjust the value of

$\lambda$ independently

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consider flavor effects

- choose seesaw with **2** heavy N $\rightarrow m_{\nu,\,\text{lightest}} = 0$
- $\Delta m^2_{ij}$, $\theta_i$, $\delta$, $\alpha_i$ fully specified via Casas-Ibarra par. and varied in $3\sigma$ allowed range

Esteban et al. 1611.01514

# Improved study results: $\omega$, $M$

running effects have a small impact on both $m_H$, $m_\nu$ Brivio, Trott 1809.03450

$$m_H^2 \simeq \frac{M^2|\omega|^2}{8\pi^2} \sim (10^2\,\mathrm{GeV})^2$$

$$m_\nu \simeq \frac{|\omega|^2 v^2}{2M} \gtrsim 0.01\,\mathrm{eV}$$

$\longrightarrow$

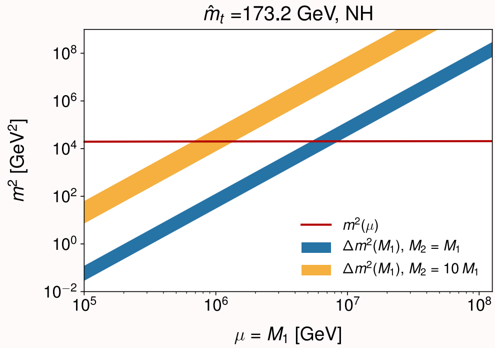
$$|\omega| \simeq \frac{1\,\mathrm{TeV}}{M}$$

$$M \lesssim 10^4\,\mathrm{TeV}$$

This result is **very stable** under variations of $m_t$ and RGE running order!

↓

**prediction** of this scenario



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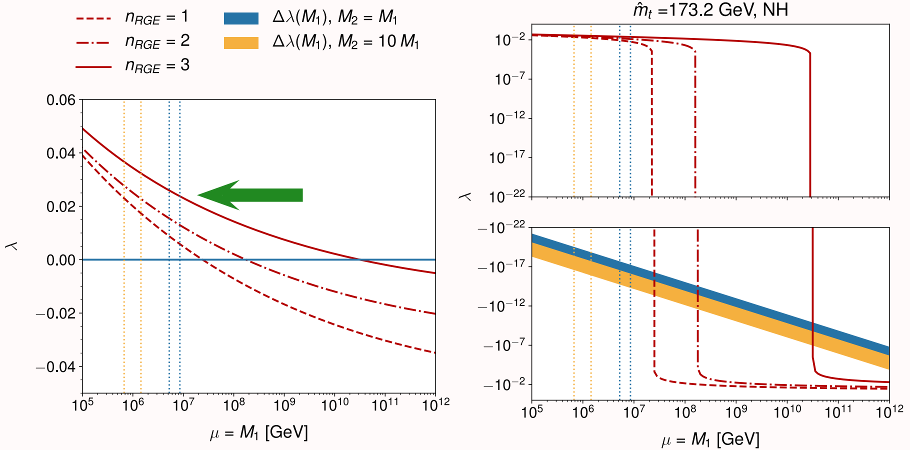


the boundary condition for $\lambda$ in the $\mu = M$ region selected by $m_\nu$, $m_H$ **cannot** be matched by the seesaw threshold contribution alone

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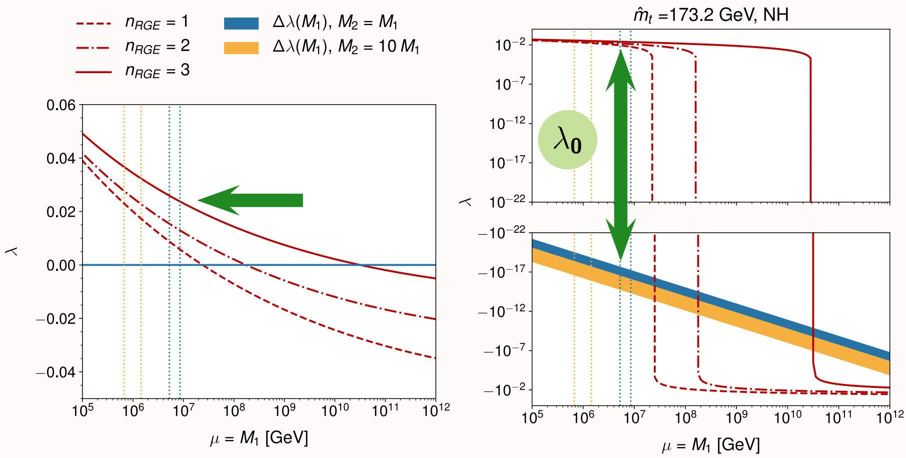


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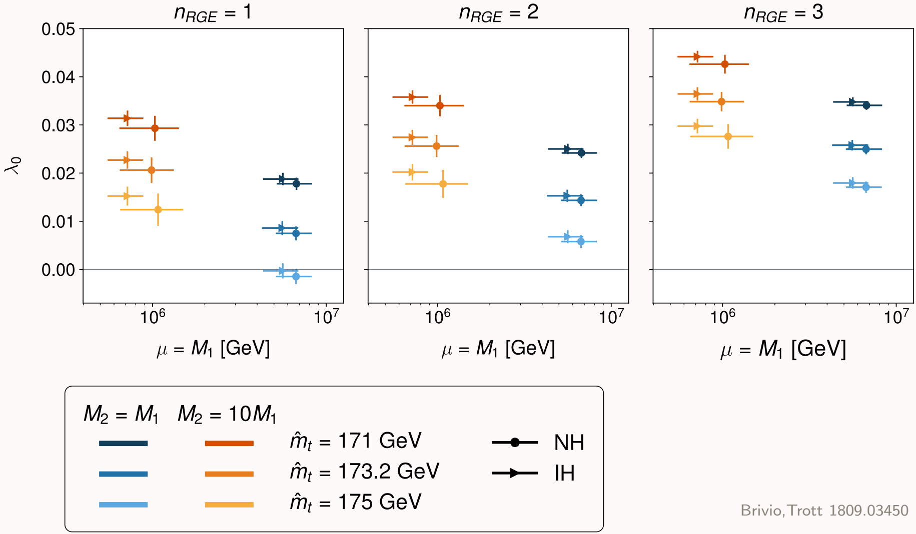
The value of $\lambda_0$ needed to obtain the SM potential depends on $m_t$, $n_{RGE}$




Brivio,Trott 1809.03450

# What about leptogenesis?

- thermal
- thermal with enhanced $R$-matrices — Moffat,Pascoli,Petcov,Schulz,Turner 1804.05066
- resonant — Pilaftsis,Underwood 0309342,0506107
- non-thermal assuming $T_{RH} < M$ — Samanta,Biswas,Battacharya 2006.02960

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minimal case: $N_1, N_2, \quad M_i = 10^6 - 10^7$ GeV

Brivio,Moffat,Pascoli,Petcov,Turner 1905.12642
Brdar,Helmboldt,Iwamoto,Schmitz 1905.12634

resonant leptogenesis ↔ $\Delta M \sim \Gamma_N \ll \dfrac{M_1 + M_2}{2}$

→ asymmetry amplified by mixing among heavy states

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are there points for which $\begin{cases} \Delta m_H^2 = m_H^2(\mu = M) \\ \eta_B = 6.1 \times 10^{-10} \end{cases}$ simultaneously?

$\lambda_0$ is irrelevant here → condition on $M$

# Resonant leptogenesis in the Neutrino Option

**(A)** approximate solution of Boltzmann equations:

largest dependence on: $M$ $y$

$$\Delta m_H^2 \sim \cosh(2y) M^3 \sum_i m_{\nu,i}$$

in Casas-Ibarra param. (NH):

$$R = \begin{pmatrix} 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \\ 1 & 0 & 0 \end{pmatrix}, \; \theta = x + iy$$

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$\min M \leftrightarrow \max y$

$$\eta_{B-L} \sim f_{res}(M_i, \Gamma_i) e^{-4y} \sin 2x$$

maximize $\eta_{B-L}$ over other params

↓

maximize $y$

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maximize $y$

$\max M \leftrightarrow y = 0$

$\eta_B$ can always be matched adjusting phases.

↓

$M$ fixed by $m_H$ constraint

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↓

$M$ fixed by $m_H$ constraint

| | [NH] / [IH] | |
|---|---|---|
| $M > 1.2 \times 10^6$ GeV, $y < 3.32$ | [NH] | $M < 8.8 \times 10^6$ GeV |
| $M > 2.4 \times 10^6$ GeV, $y < 2.06$ | [IH] | $M < 7.4 \times 10^6$ GeV |

$$\frac{\Delta M}{M} \sim 10^{-8}$$

# Resonant leptogenesis in the Neutrino Option

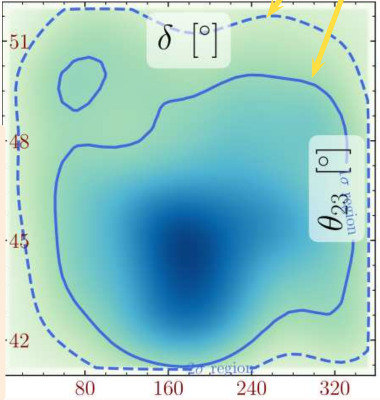
**(B)** numerical analysis with exact Boltzmann equations

fixed $M \to$ fix $y$ from $m_H$ constraint $\to$ scan over other parameters

2D projections @ min $M$:

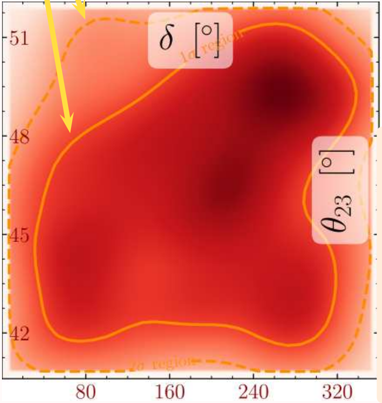
$1\sigma, 2\sigma$ compatible with $\eta_B$

NH




$M = 1.2 \times 10^6$ GeV, $y = 3.32$, $\theta_{12} = 33.63^\circ$, $\theta_{13} = 8.51^\circ$

IH



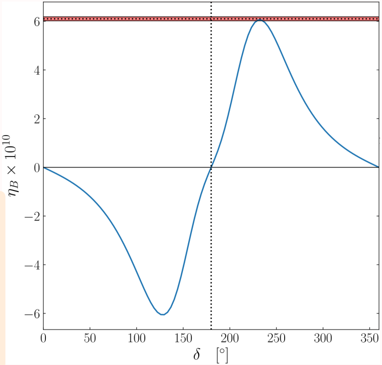

$M = 2.4 \times 10^6$ GeV, $y = 2.06$, $\theta_{12} = 33.63^\circ$, $\theta_{13} = 8.51^\circ$

# Resonant leptogenesis in the Neutrino Option

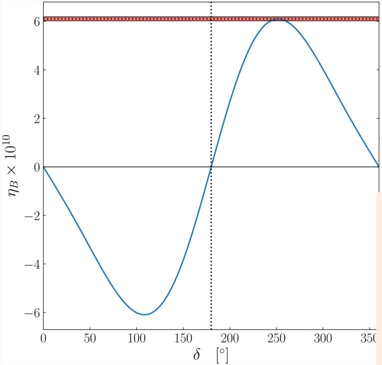
@ max $M$, $y = 0 \to$ ~~CP~~ only from SM phases $(\delta, \alpha, \alpha')$

NH

$M = 8.8 \times 10^6$ GeV
$y = 0,\ \alpha, \alpha' = 0$




IH



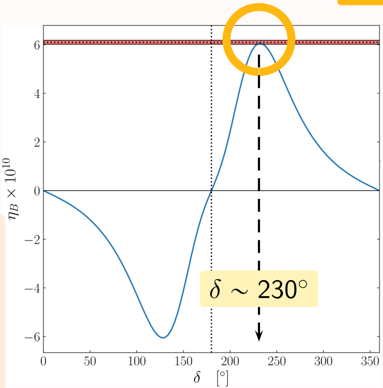

$M = 7.4 \times 10^6$ GeV
$y = 0,\ \alpha, \alpha' = 0$

# Resonant leptogenesis in the Neutrino Option

@ max $M$, $y = 0 \rightarrow$ ~~CP~~ only from SM phases $(\delta, \alpha, \alpha')$

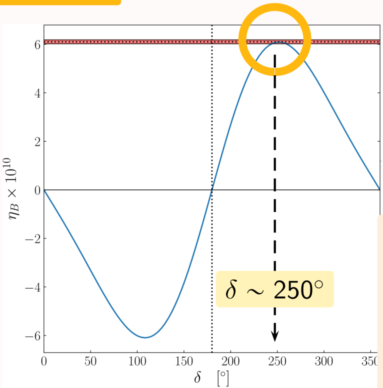
successful leptogenesis!

NH




$M = 8.8 \times 10^6$ GeV
$y = 0,\ \alpha, \alpha' = 0$

IH

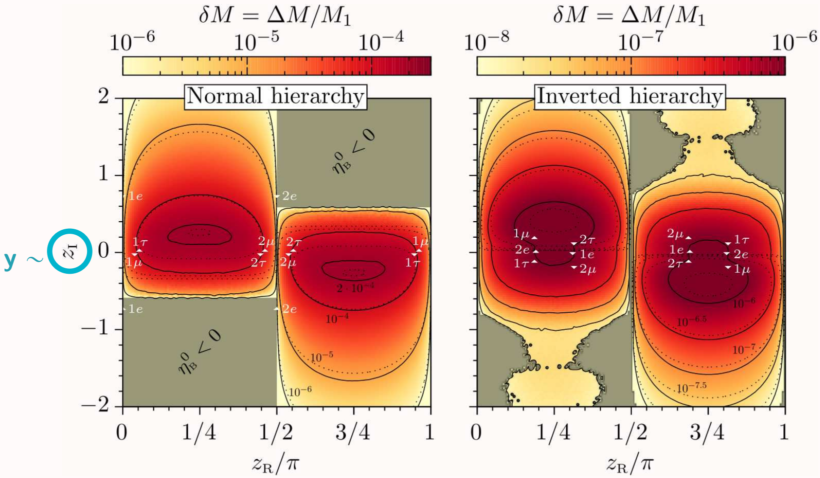



$M = 7.4 \times 10^6$ GeV
$y = 0,\ \alpha, \alpha' = 0$

# Resonant leptogenesis in the Neutrino Option

consistent results and same physical conclusions Brdar,Helmboldt,Iwamoto,Schmitz 1905.12634

different approach: look for $\max \Delta M/M$ in a fixed $y$ region



# UV completions

required to explain the **origin of the Majorana mass** in an otherwise scale-less theory

further requests:

- at least 2 eigenvalues for $M$ at PeV
- $m_H$ doesn't receive *other* large contributions ($(\bar{N}N)(H^\dagger H)$ absent)
- leads to a stable EW vacuum
- Higgs and $\nu$ RGE not spoiled by light BSM states
- avoids fine-tunings

options explored so far:

✔ **conformal** completions

Brdar,Emonds,Helmboldt,Lindner 1807.11490
Brdar,Helmboldt,Kubo 1810.12306
Aoki,Brdar,Kubo 2007.04367
Kubo,Kuntz,Lindner,Rezacek,Saake,Trautner 2012.09706
Aoki,Kubo,Yang 2109.04814

✘ **perturbative** generation from Planck scale — Brivio,Talbert,Trott 2010.15428

✔ **string theory** — Talbert 2009.11813

# Perturbative generation of $M$: no-go limitations

*can PeV Majorana masses originate from threshold corrections or RG evolution from deeper UV?*

idea: loop corrections scale as $\delta = \frac{|\omega|^2}{16\pi^2} M_{UV}$

requiring $\delta \simeq$ PeV with

$$|\omega| \simeq 10^{-4} \to M_{UV} \simeq M_{GUT}$$
$$|\omega| \simeq 10^{-5} \to M_{UV} \simeq M_{Pl}$$

start off with "democratic" $M_0 = \frac{M_{UV}}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \to \begin{pmatrix} 0 & & \\ & 0 & \\ & & M_{UV} \end{pmatrix}$

(or with 1 more eigenvalue)

and from here try to get 2+ eigenvalues in the PeV range via loops/RGE

# Perturbative generation of $M$: no-go limitations

$$M_0 = \begin{pmatrix} 0 & & \\ & (M_{UV}) & \\ & & M_{UV} \end{pmatrix}$$

1 loop

- cannot generate non-zero eigenvalues: no 1-loop diagram with $\Delta L = 2$
- can lower the size of a mass eigenvalue via RGE: $M(\mu) = \gamma(\mu, \mu_0) M(\mu_0)$

  but PeV requires $\gamma = 1 + \frac{\omega^2}{16\pi^2} \ln \frac{\mu}{\mu_0} \simeq 10^{-10} - 10^{-13}$ $\rightarrow$ tuned

2+ loops

- *can* generate non-zero eigenvalues. however $\delta^{(2)} \simeq \frac{|\omega|^4}{256\pi^4} M_{UV}$

  with $\omega \simeq 10^{-4}$, $\delta^{(2)} \sim$ PeV $\rightarrow$ $M_{UV} \simeq 10^{27}\,\mathrm{GeV}$

  with $M_{UV} \simeq 10^{19}$ GeV, $\delta^{(2)} \sim$ PeV $\rightarrow \omega \simeq 10^{-2} \rightarrow$ $\sqrt{\Delta m_H^2} \simeq 10^{16}\,\mathrm{GeV}$

  $\rightarrow$ tension between $M$ and $m_H$ generation

# Perturbative generation of $M$: no-go limitations

$$\bar{N}^T M_0 N \qquad \bar{\ell}\tilde{H}\omega N + \text{h.c.}$$

$$M_0 = \begin{pmatrix} 0 & & \\ & 0 & \\ & & M_{UV} \end{pmatrix} \qquad \omega = \begin{pmatrix} \omega_{11} & \omega_{12} & x \\ \omega_{21} & \omega_{22} & x \\ \omega_{31} & \omega_{32} & x \end{pmatrix}$$

$M_0$ invariant under $U(2) \times \mathbb{Z}_2$

$\omega$ invariant under $\mathbb{Z}_2$ *iff* $x \equiv 0$

$\mathbb{Z}_2$ preserved $\rightarrow \Delta m_H^2$ **protected** from $M_{UV}$

$\rightarrow M_{UV}$ fully **isolated**! cannot generate anything else

$\mathbb{Z}_2$ (softly) broken $\rightarrow \Delta m_H^2$ unprotected: naturally $m_H \simeq x\, M_{UV}/2\sqrt{2}\pi$

$\rightarrow$ requires **tuning** $x \simeq 10^{-14}$

this tension holds also in the presence of extra BSM states

# Conformal UV completions

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\partial_\mu R \partial^\mu R + i\bar{N}\partial\!\!\!/ N - \left[\frac{1}{2} y_M S \bar{N} N^c + y_\nu \bar{\ell} \tilde{H} N + \text{h.c.}\right] - V(H,S,R)$$

$$V(H,S,R) = \lambda (H^\dagger H)^2 + \lambda_S S^4 + \lambda_R R^4 + \lambda_{HS} S^2 (H^\dagger H) + \lambda_{HR} R^2 (H^\dagger H) + \lambda_{SR} S^2 R^2$$

take $y_M, \lambda_{SR} \sim \mathcal{O}(1)$

Brdar,Emonds,Helmboldt,Lindner 1807.11490
Brdar,Helmboldt,Kubo 1810.1230

- minimal extension: $+2$ scalar singlets $S, R$ with $\mathbb{Z}_2 : R \mapsto -R$
- conformal invariance spontaneously broken via **Gildener-Weinberg** mech.

$$\exists \Lambda_{GW} : \quad \lambda_S(\Lambda_{GW}) = 0$$

at this scale: $\langle H^\dagger H \rangle = \langle R \rangle = 0, \quad \langle S \rangle = v_S$

$\to M = y_M v_S$ dynamically generated.

$\to$ pseudo-Goldstone: $m_S^2 \sim \dfrac{v_s^2}{16\pi^2}, \quad m_R^2 \sim 2\lambda_{SR} v_S^2$. $S$ is the **scalon**.

- restrictions: $\lambda \neq 0, \lambda_S \neq 0, \lambda_R \neq 0,$ $|\lambda_{HS}| \ll 1$ , $|\lambda_{HR}| m_R^2 \ll |y_\nu|^2 M^2$ . . .

# Conformal UV completions

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\partial_\mu R \partial^\mu R + i\bar{N}\partial\!\!\!/ N - \left[\frac{1}{2} y_M S \bar{N} N^c + y_\nu \bar{\ell}\tilde{H} N + \text{h.c.}\right] - V(H,S,R)$$

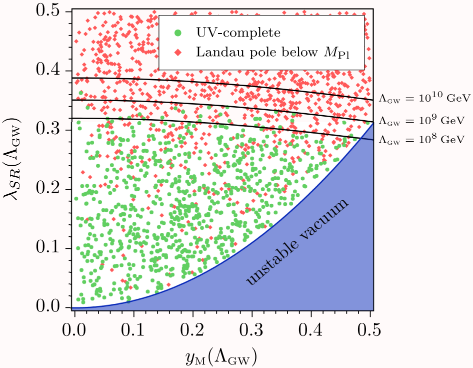
$$V(H,S,R) = \lambda (H^\dagger H)^2 + \lambda_S S^4 + \lambda_R R^4 + \lambda_{HS} S^2 (H^\dagger H) + \lambda_{HR} R^2 (H^\dagger H) + \lambda_{SR} S^2 R^2$$

take $y_M, \lambda_{SR} \sim \mathcal{O}(1)$

Brdar,Emonds,Helmboldt,Lindner 1807.11490
Brdar,Helmboldt,Kubo 1810.1230

there are regions of parameter space where simultaneously

- $m_H$, $\lambda$ at EW scale are reproduced
- there are no Landau poles until $M_{Pl}$
- $\sum m_\nu < 0.23$ eV



# Conformal UV completions

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\partial_\mu R \partial^\mu R + i\bar{N}\partial\!\!\!/ N - \left[\frac{1}{2} y_M S \bar{N} N^c + y_\nu \bar{\ell}\tilde{H} N + \text{h.c.}\right] - V(H,S,R)$$

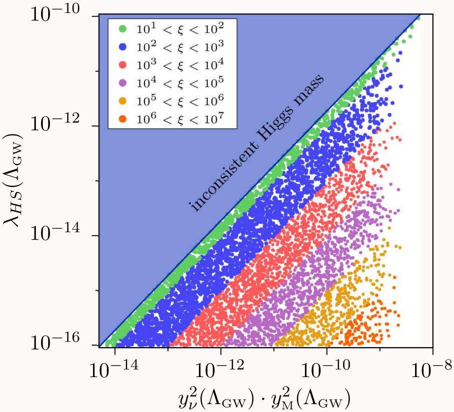
$$V(H,S,R) = \lambda (H^\dagger H)^2 + \lambda_S S^4 + \lambda_R R^4 + \lambda_{HS} S^2 (H^\dagger H) + \lambda_{HR} R^2 (H^\dagger H) + \lambda_{SR} S^2 R^2$$

take $y_M, \lambda_{SR} \sim \mathcal{O}(1)$

Brdar,Emonds,Helmboldt,Lindner 1807.11490
Brdar,Helmboldt,Kubo 1810.1230

fine tuning: $\lambda_{HS}$ naturally small
if it does not run to large values

$$\xi = \left| \frac{\lambda_{HS} - y_\nu^2 y_M^2}{\lambda_{HS}} \right|$$



# Conformal UV completions

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\partial_\mu R \partial^\mu R + i\bar{N}\not{\partial} N - \left[\frac{1}{2} y_M S \bar{N} N^c + y_\nu \bar{\ell}\tilde{H} N + \text{h.c.}\right] - V(H,S,R)$$

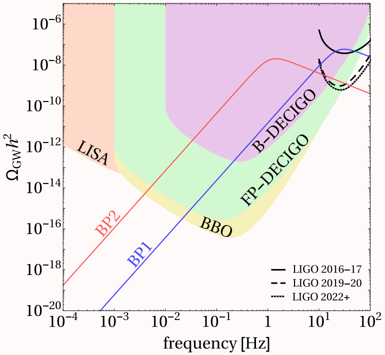
$$V(H,S,R) = \lambda (H^\dagger H)^2 + \lambda_S S^4 + \lambda_R R^4 + \lambda_{HS} S^2 (H^\dagger H) + \lambda_{HR} R^2 (H^\dagger H) + \lambda_{SR} S^2 R^2$$

take $y_M, \lambda_{SR} \sim \mathcal{O}(1)$

Brdar,Emonds,Helmboldt,Lindner 1807.11490
Brdar,Helmboldt,Kubo 1810.1230

strong **first order phase transition** realized in sub-regions of parameter space

→ predicts testable gravitational wave signal



# Conformal UV completion + Dark Matter

Aoki,Brdar,Kubo 2007.04367
Aoki,Kubo,Yang 2109.04814

- replace Gildener-Weinberg with new strongly interacting hidden sector
  $SU(n) : F^{\mu\nu}$ gauge field strength + $\psi$ vector like fermions
- only 1 scalar $S$ added

$$\mathcal{L} \supset -y\,\bar{\psi}\psi S - \frac{y_M}{2} S\, N^T CN - y_\nu\,\bar{l}\tilde{H}N - \left[\frac{\lambda_S}{4}S^4 + \lambda_H(H^\dagger H)^2 + \frac{\lambda_{SH}}{2}S^2 H^\dagger H\right]$$

$\bar{\psi}\psi$ condensates and $\langle S \rangle = \frac{v_S^2}{2}$ takes a vev $\rightarrow M = y_M v_S$

**DM candidate**: Goldstone bosons of global chiral $SU(3)$ symmetry
(equivalent of chiral symmetry in QCD → pions)

! $\lambda_{HS} < m_H^2/v_S^2 \simeq 6 \times 10^{-12}\, y_M^2$ required to suppress tree-level $m_H$ corrections

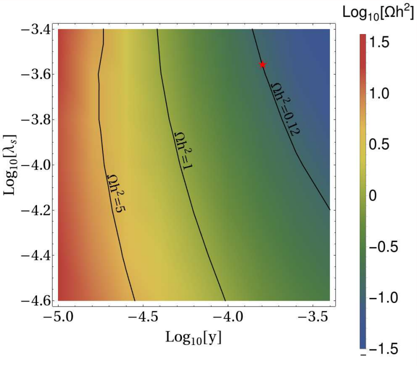
# Conformal UV completion + Dark Matter

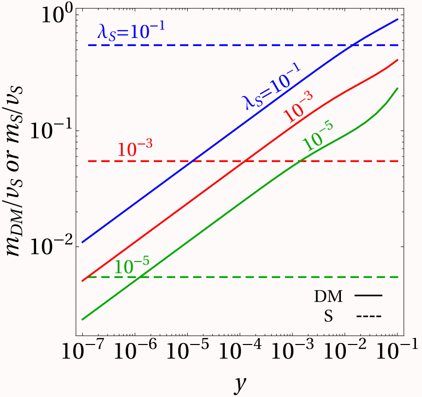
Aoki,Brdar,Kubo 2007.04367

$$\text{fixed } m_N = 50\,\text{PeV}, \lambda_{HS} \simeq 0$$

fixed

$y_M = 7 \times 10^{-4} \to v_S \sim 7 \times 10^{10}\,\text{GeV}$




relic abundance by freeze-in

# The Neutrino Option: summary

Type I seesaw **CAN** generate the Higgs potential.

Requires: $M \lesssim 10^4$ TeV $\quad |\omega| \simeq [1\,\mathrm{TeV}]/M \quad \lambda_0 \sim 0.01-0.05$

- Does NOT *solve* the hierarchy problem, but new approach
- EWSB ultimately controlled by
  **Fermi statistics + Majorana scale + RG from SM spectrum**
  $m_H^2 > 0$ conformal sym. breaking $\leftrightarrow \not{L}$ $\lambda \sim 0.15$
- no BSM signatures predicted (besides $\nu$ masses) up to the PeV
- resonant leptogenesis is consistent with this scenario!
  even with SM ~~CP~~ only
- **UV completions** ✖ perturbative $M$ from $M_{UV}$
  ✔ conformal models with spontaneous breaking
  → potential GW signal
  ✔ string models

# Backup slides

# Conformal UV completion

Brdar,Emonds,Helmboldt,Lindner 1807.11490