Heavy Neutral Leptons: Theoretical Overview

June 7th
LHCP 2024
Northeastern University
Boston, USA

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Universiteit van Amsterdam
Nikhef
University of Zagreb

The four Portals to Light New Physics

The four Horsemen (SM-apocalypse)
A. Durer, MFA Boston

Four portals to Light New Physics:

- Scalar (spin 0)
- Pseudo-scalar (spin 0)

  Axions or
  Axion-Like-Particles (**ALPs**)
- Vector (spin 1)

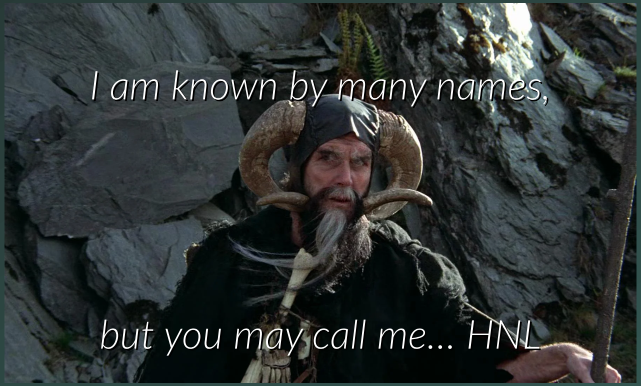
  Dark Photon
- Fermion (spin ½)

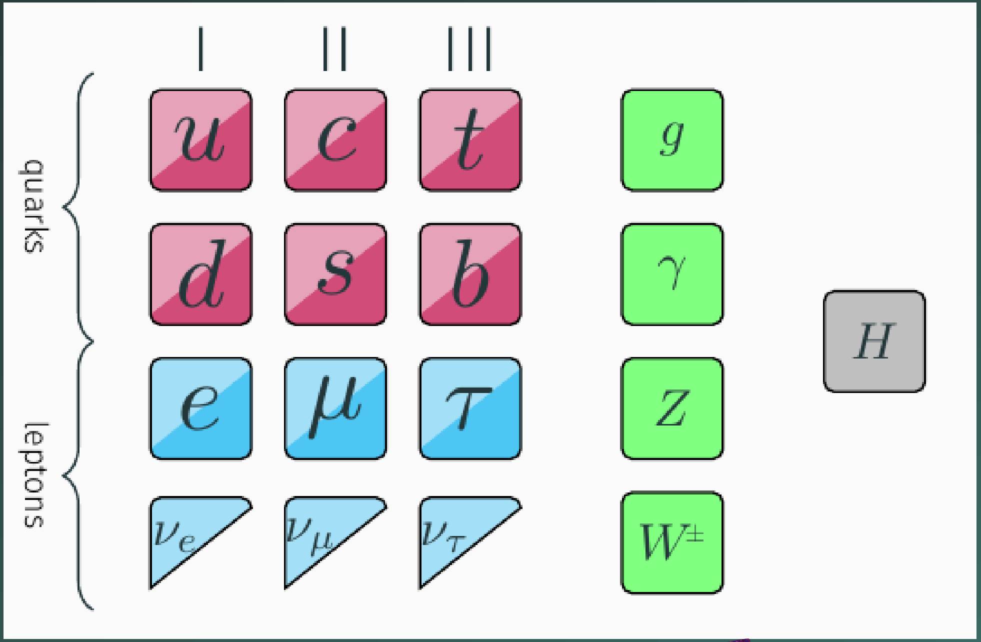
  Heavy Neutral Leptons (HNLs)

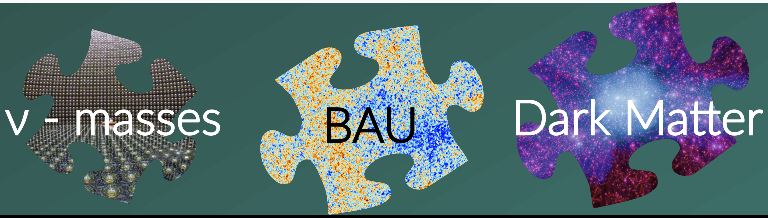
[See the Monday session for more light NP]

Heavy Neutral Leptons

- Also known as:
  - Right-handed neutrinos
  - Heavy Majorana neutrinos
  - Heavy neutrinos







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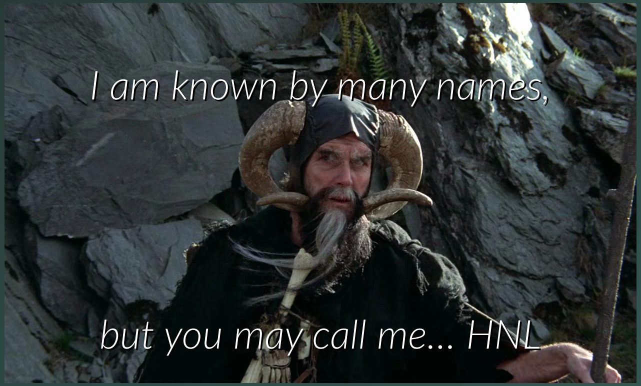
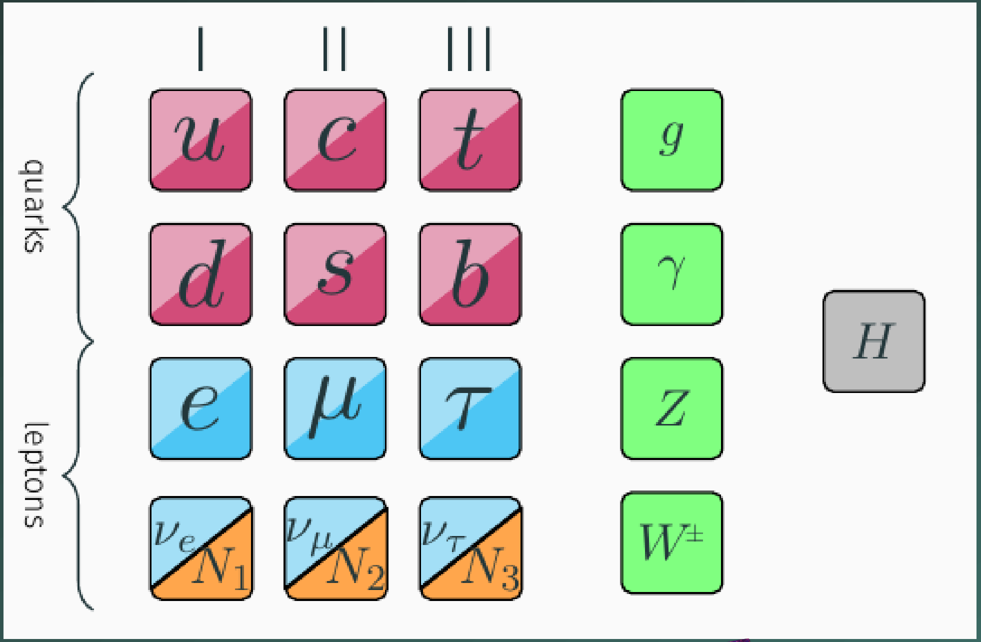
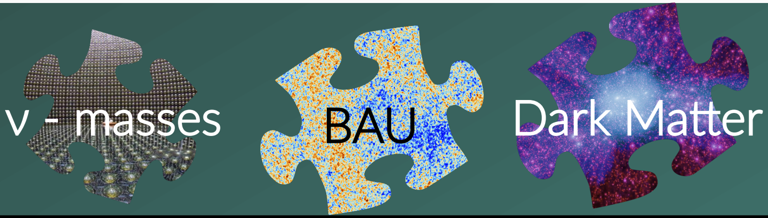






The Seesaw Mechanism

How *Heavy* are HNLs?

The Seesaw Lagrangian

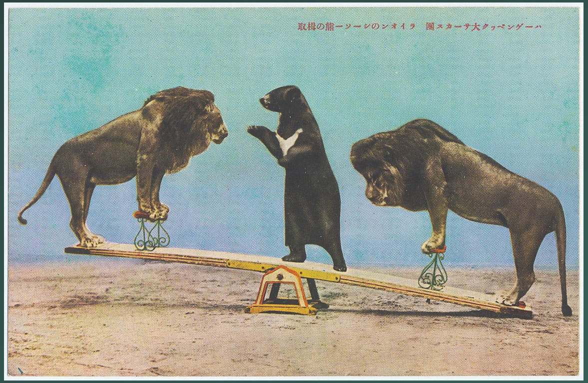
$$\mathrm{L} \supset \frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

$$m_\nu = m_D$$

Neutrino masses

are extremely small

$$m_\nu \lesssim 0.8\,\mathrm{eV}$$



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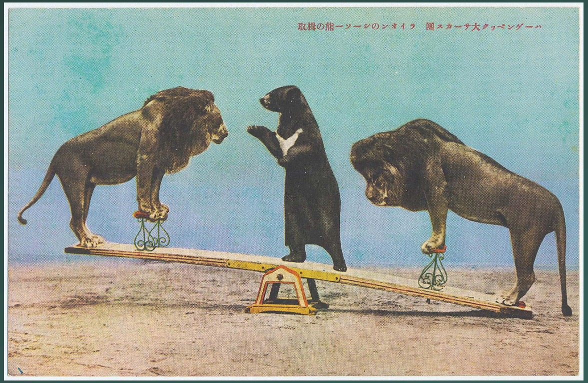

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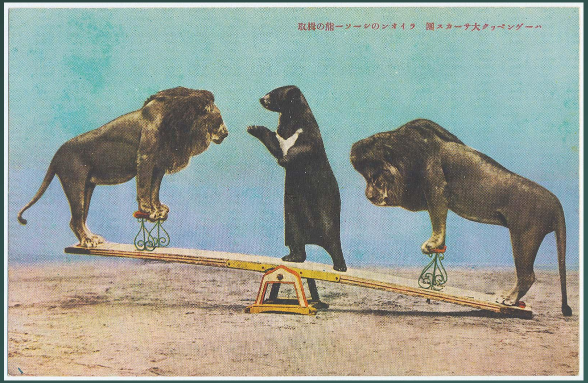

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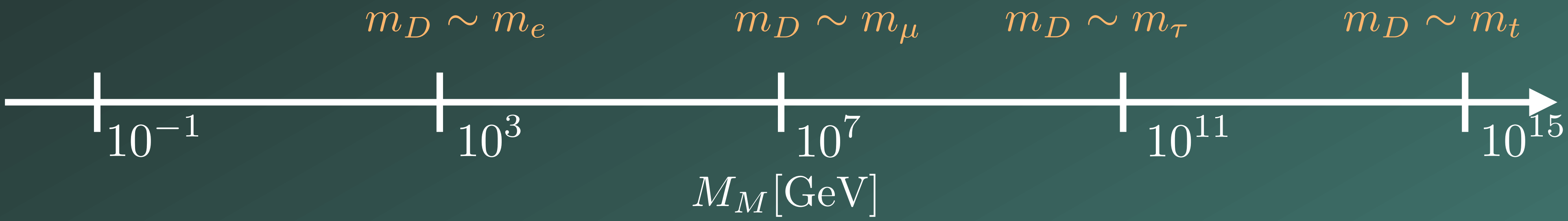

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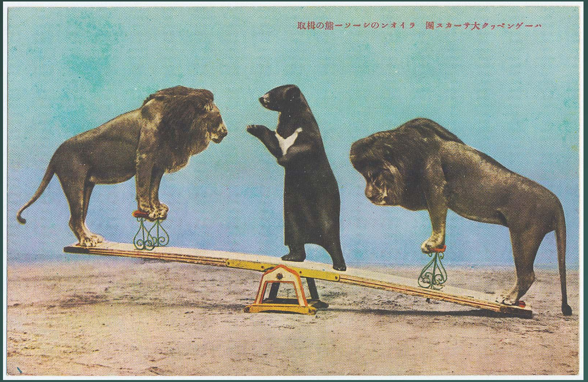

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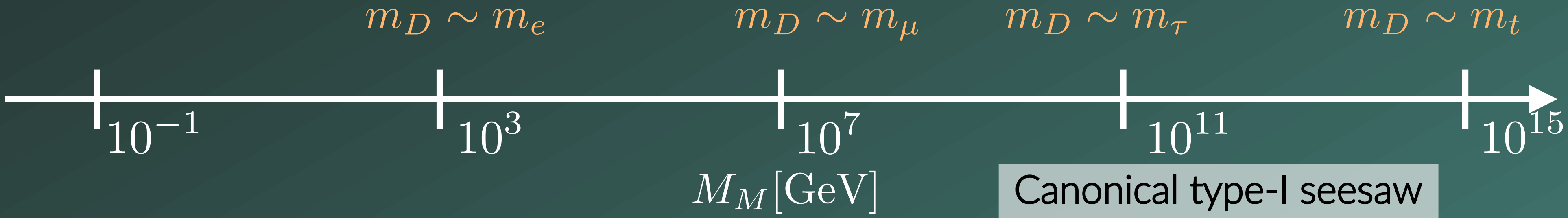

$m_D \sim m_e$ $\quad$ $m_D \sim m_\mu$ $\quad$ $m_D \sim m_\tau$ $\quad$ $m_D \sim m_t$

10^{-1} $\quad$ 10^{3} $\quad$ 10^{7} $\quad$ 10^{11} $\quad$ 10^{15}

$M_M\,[\mathrm{GeV}]$

Canonical type-I seesaw

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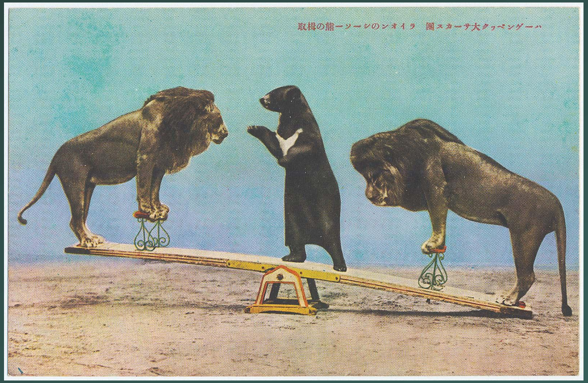

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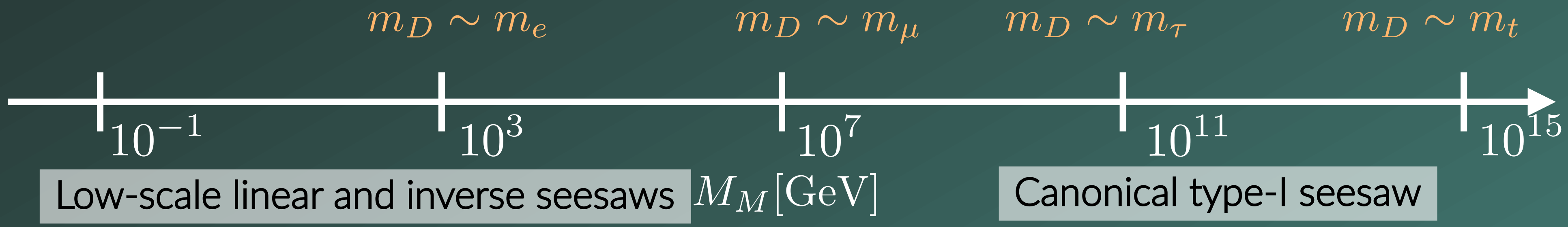

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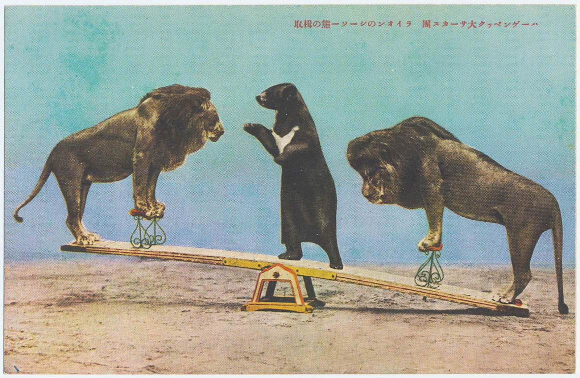

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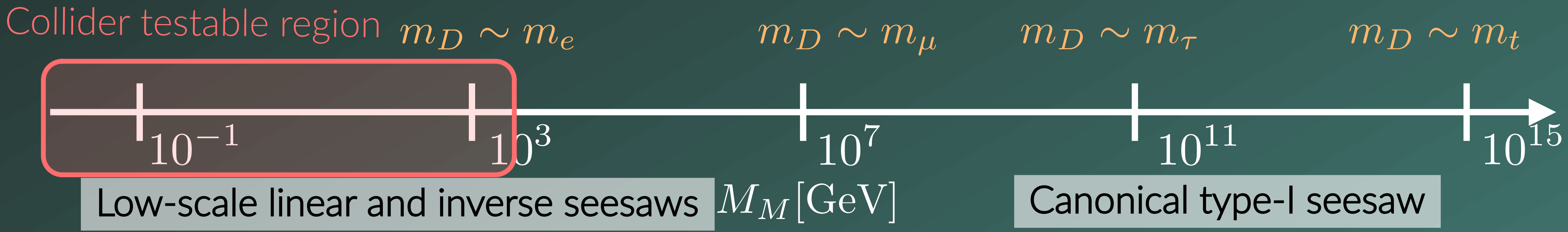

Collider testable region

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Low-scale linear and inverse seesaws

Canonical type-I seesaw

How do HNLs interact with the SM?

Minimal Renormalizable Interactions

- The only renormalizable interactions are the Yukawa couplings:

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After Electroweak Symmetry Breaking

- HNL mass eigenstates are a **mixture** of $\boldsymbol{\nu_R}$ and $\boldsymbol{\nu_L}$

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- Additional interactions are described by effective interactions
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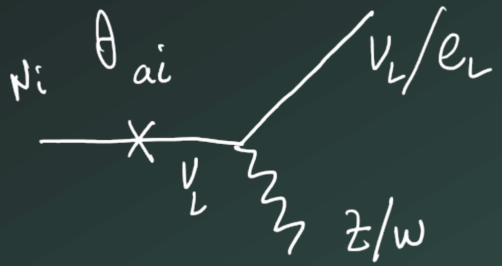
The parameter space of the minimal low-scale seesaw model



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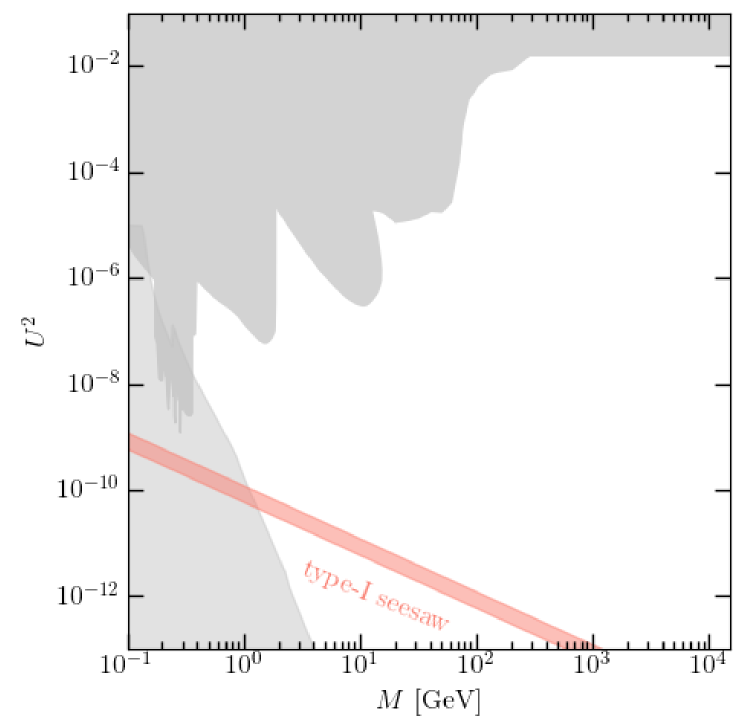

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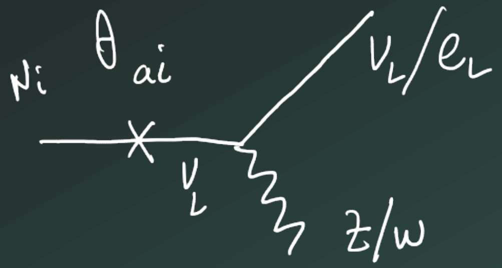

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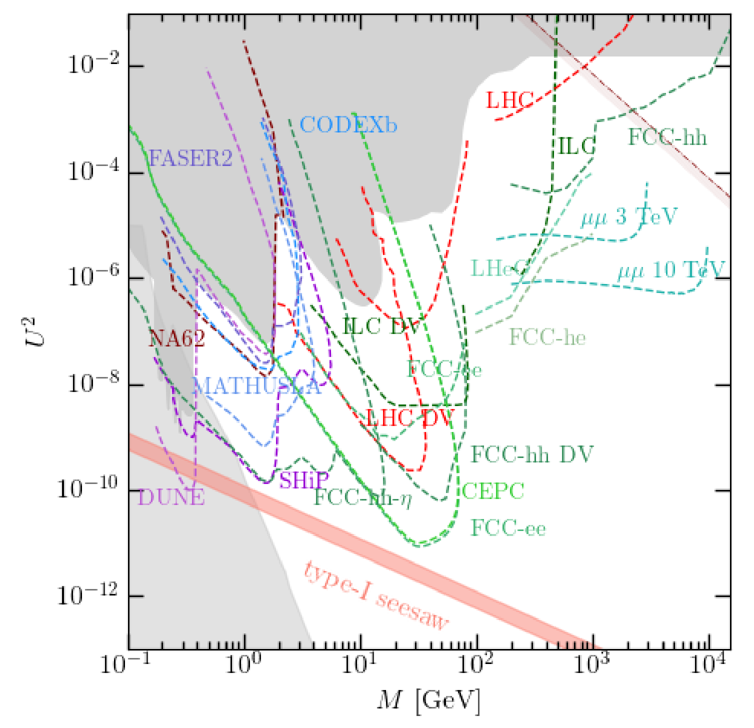

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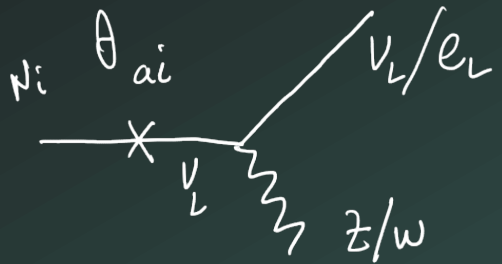

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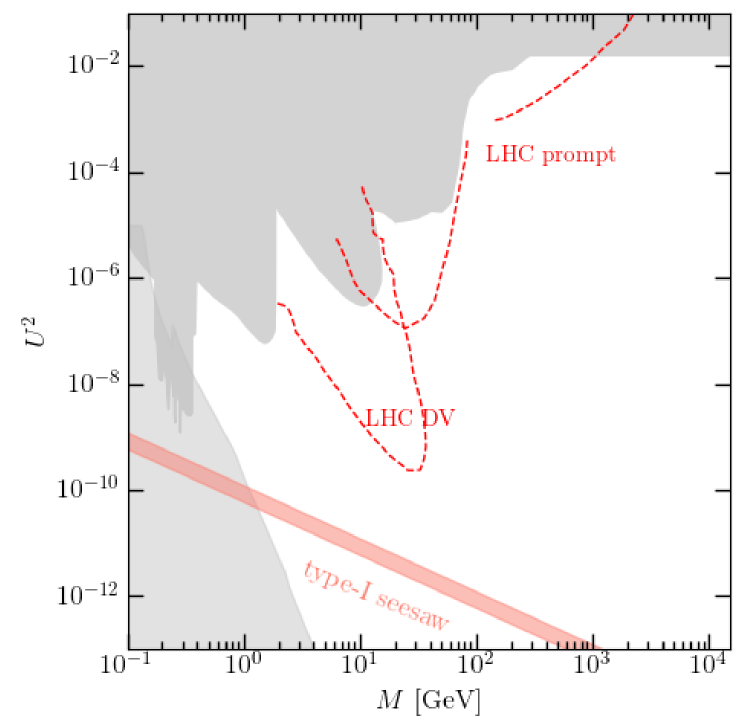
[see the talks by Frattari, Portales, Schaarschmidt, Knolle, Lunerti, Henry and Bird]



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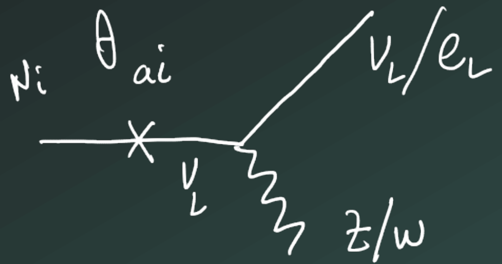

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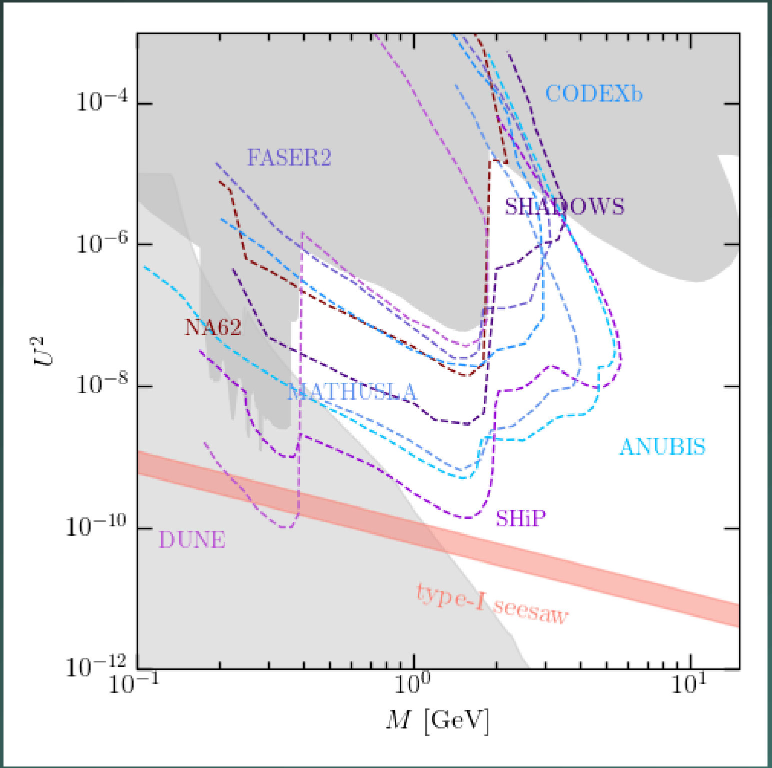
[see the session on future facilities]



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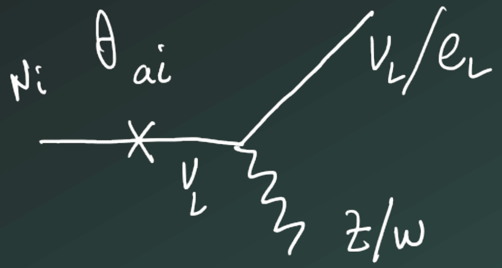

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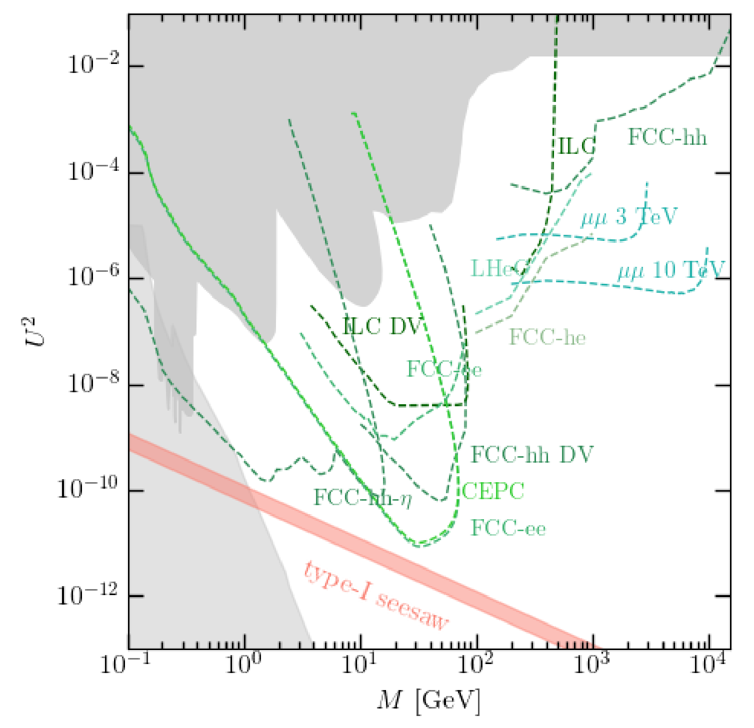

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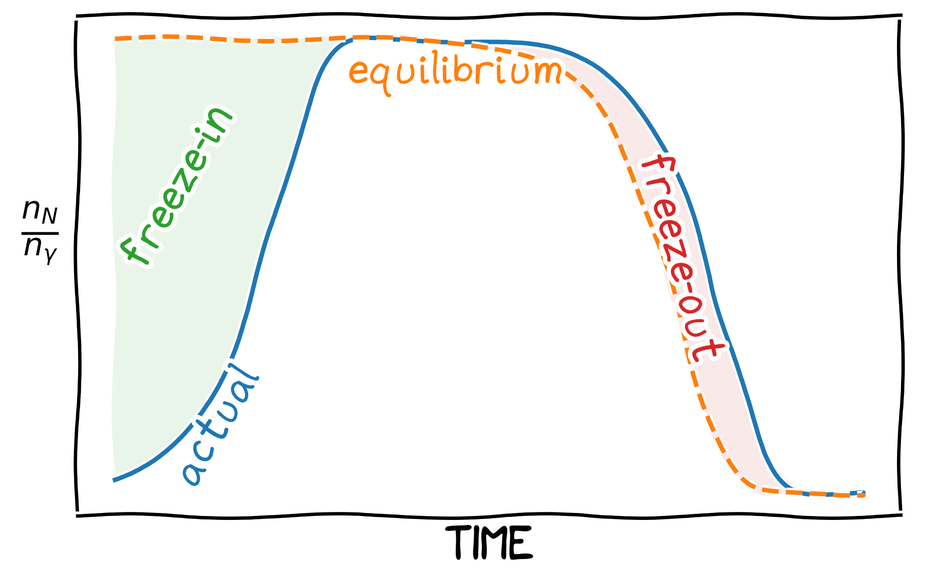
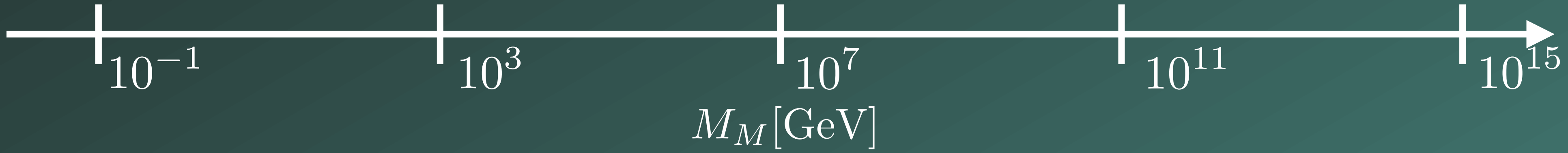
HNLs and the Baryon Asymmetry of the Universe

- Three [Sakharov '67] conditions:

1. Baryon number violation
   - sphaleron processes ✓
2. C and CP violation
   - HNL decays and oscillations ✓
3. Deviation from equilibrium
   - freeze-in and freeze-out of HNLs ✓



What does leptogenesis tell us about HNL masses?



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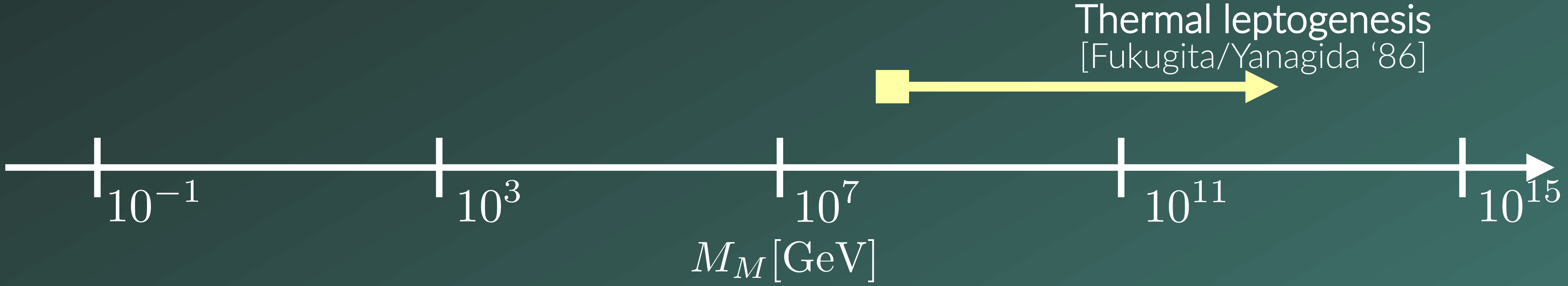

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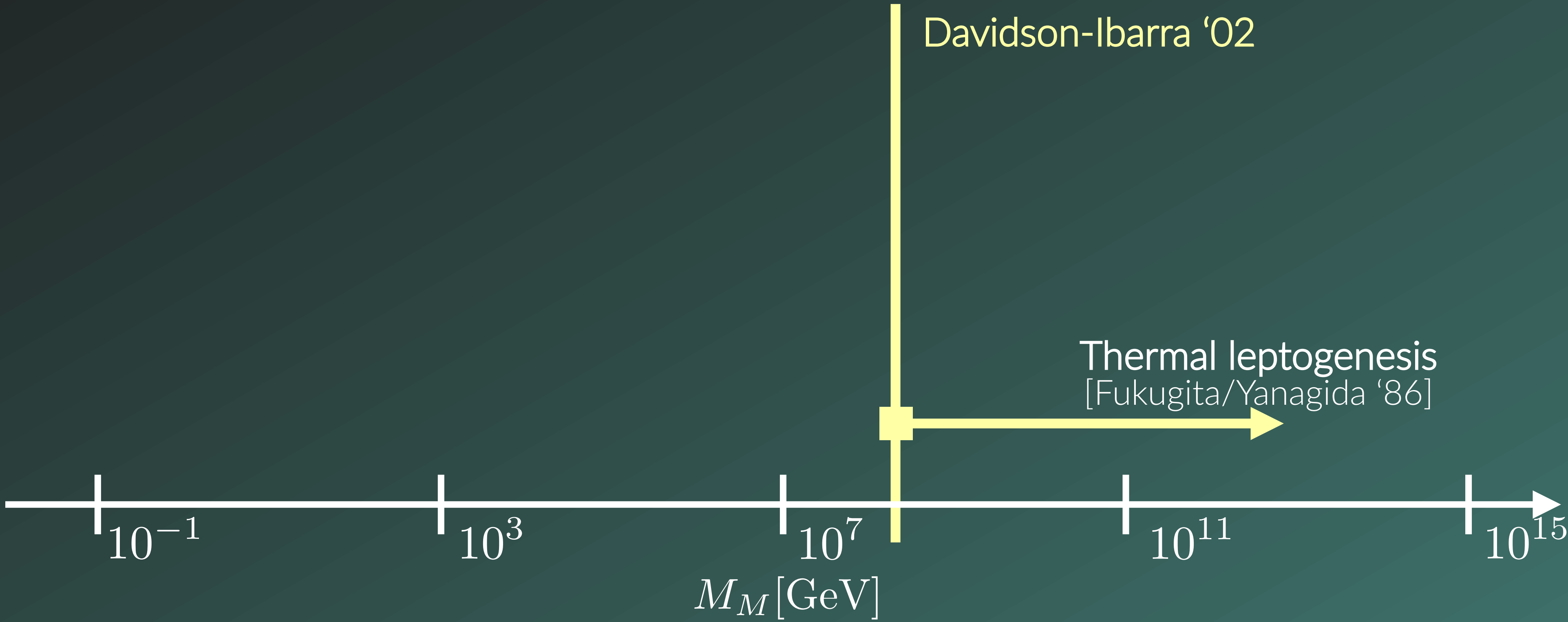

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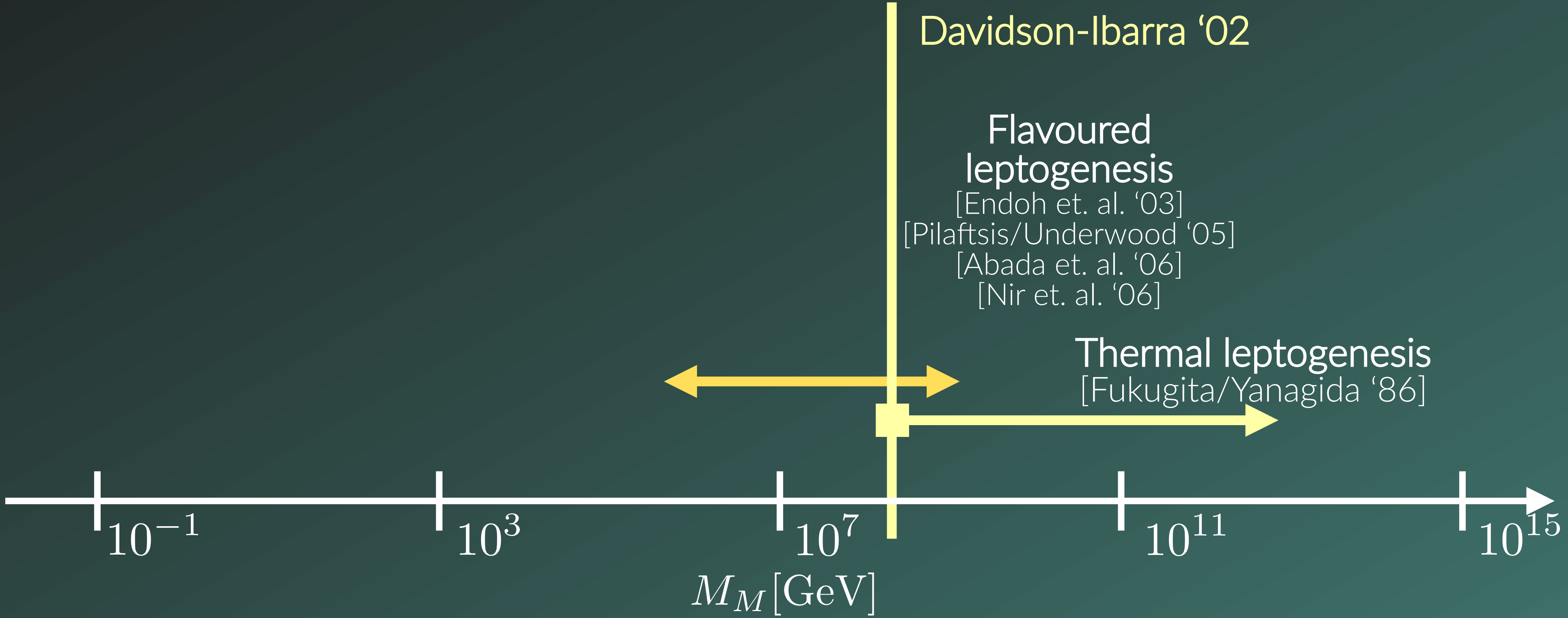

Flavoured leptogenesis
[Endoh et. al. ‘03]
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Thermal leptogenesis
[Fukugita/Yanagida ‘86]

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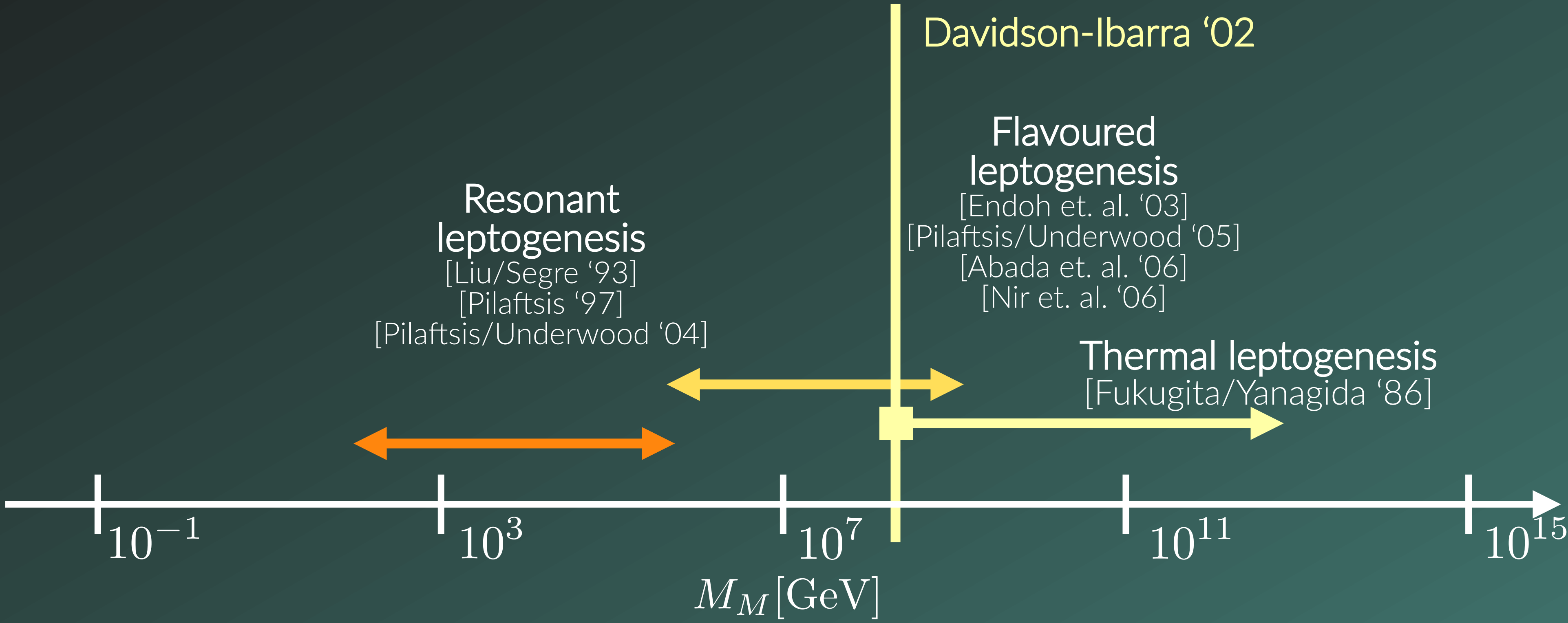

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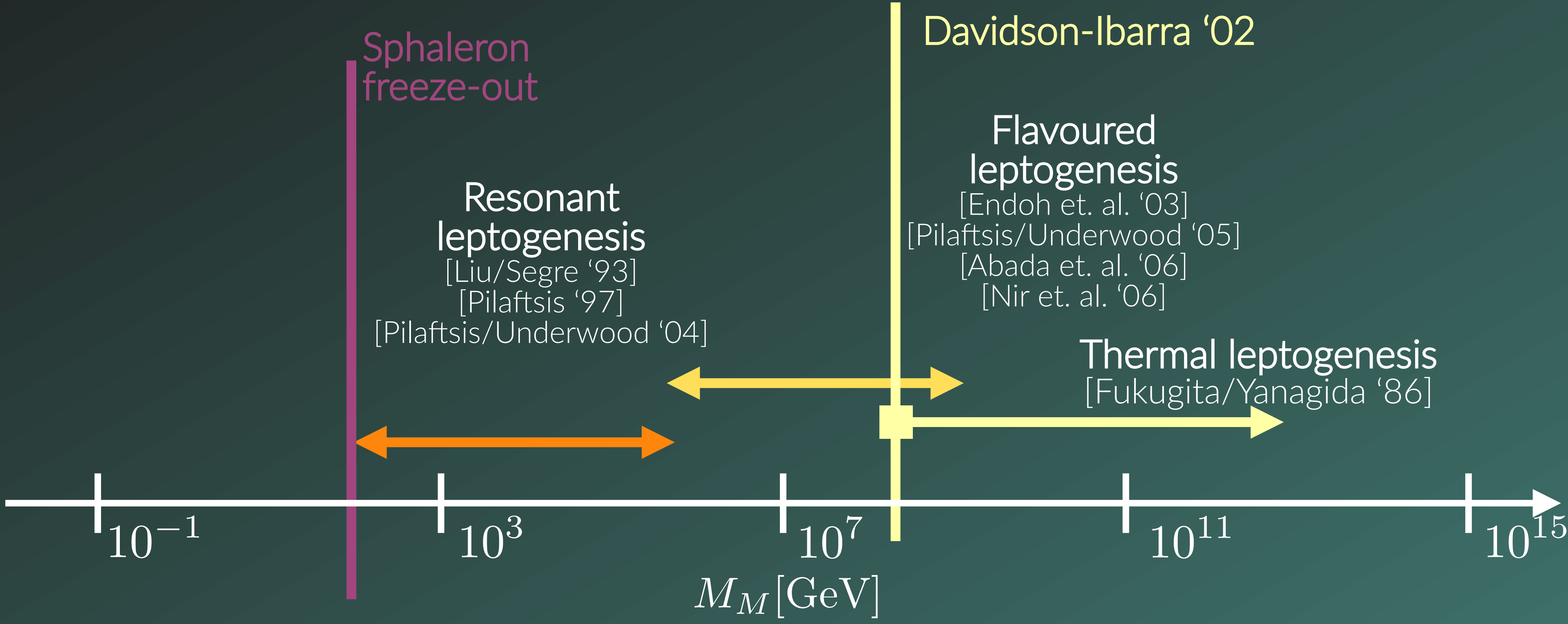

Resonant leptogenesis

[Liu/Segre '93]
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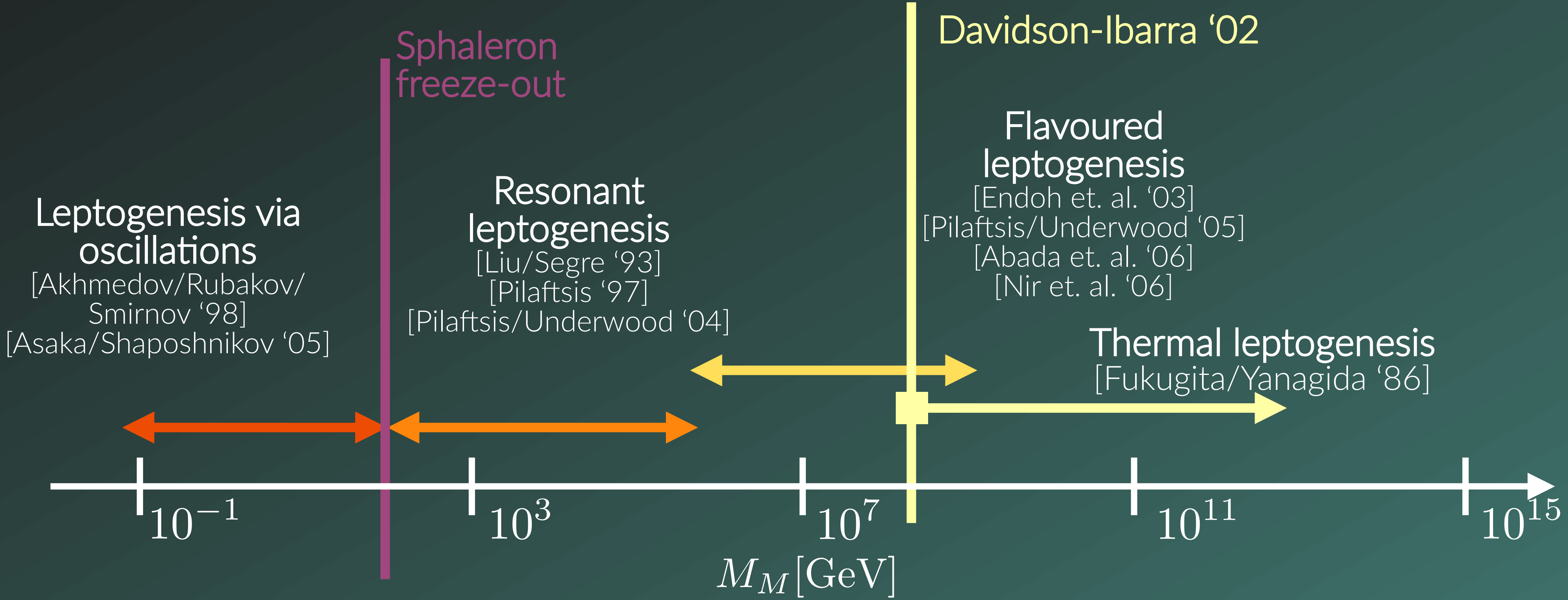

Sphaleron freeze-out

Davidson-Ibarra ‘02

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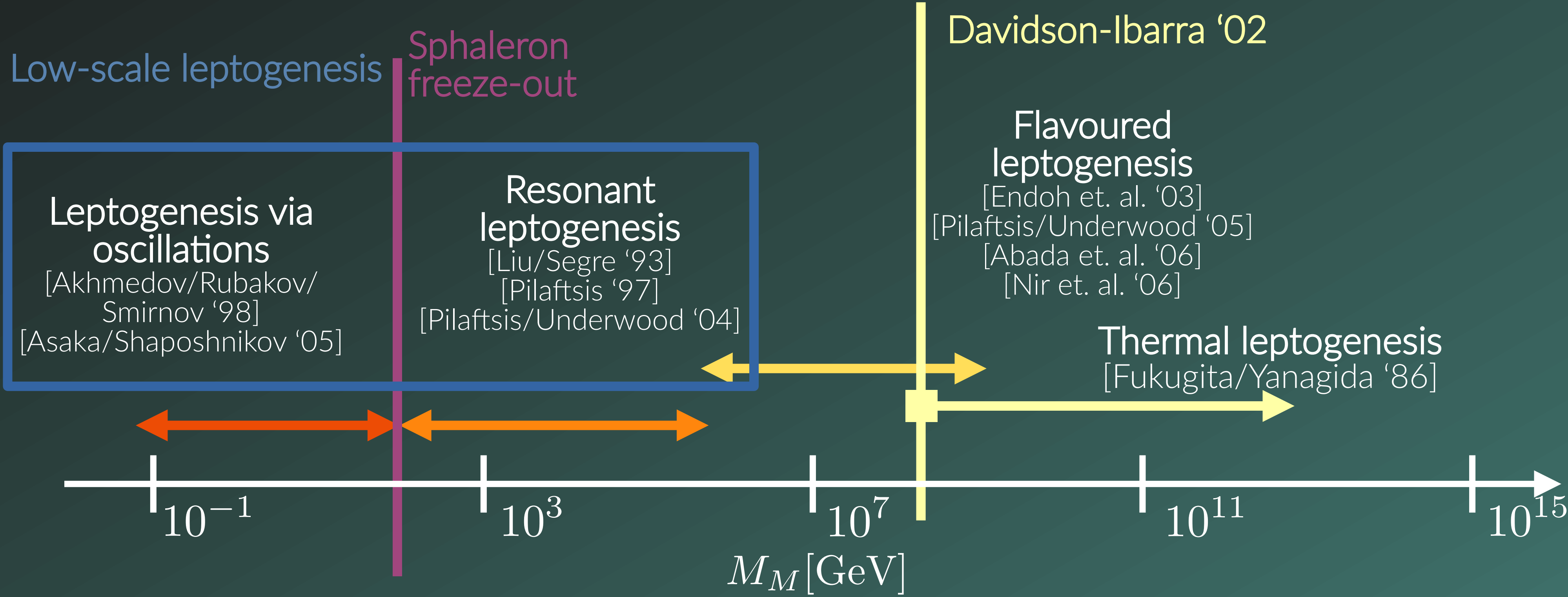

Low-scale leptogenesis

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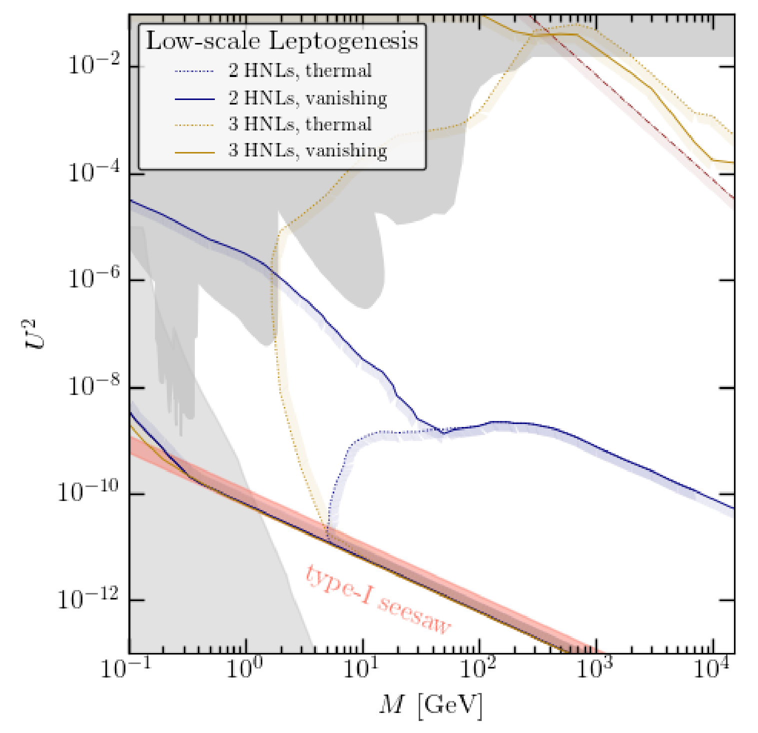
The parameter space of leptogenesis

- With 2 HNLs leptogenesis is possible for *all masses above 100 MeV*
- Leptogenesis is possible in the *entire experimentally accessible parameter space* for 3 HNLs
- Both **vanishing** *(no additional interactions)* and **thermal** *(high-scale additional interactions)* leptogeneses possible
- Leptogenesis **within reach** of HL-LHC
- High complementarity between **colliders** and **dedicated LLP** searches



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[leptogenesis bounds from JK/Timiryasov/Shaposhnikov 2103.16545 and Drewes/Georis/JK 2106.16226]

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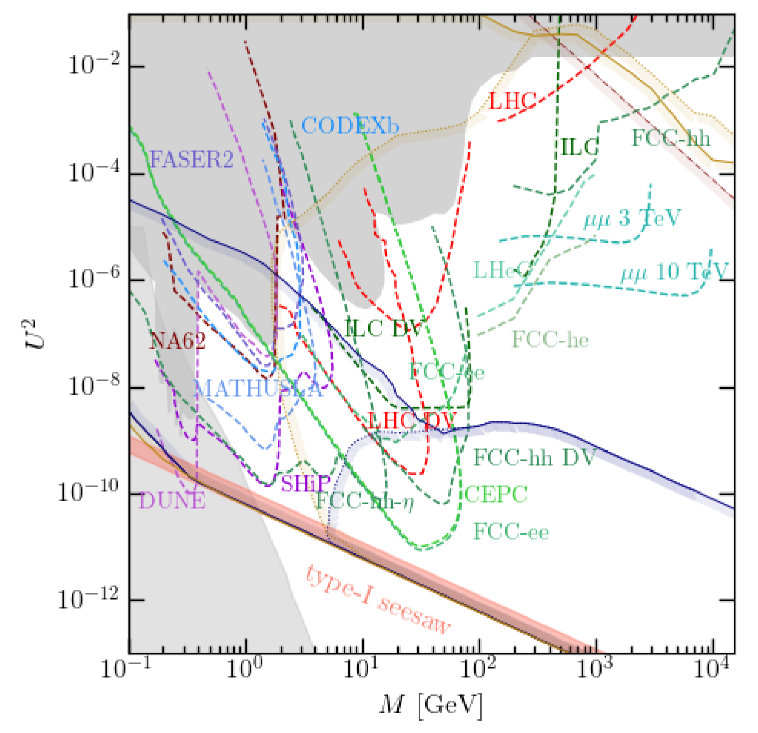

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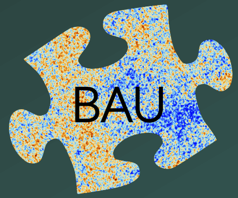
[leptogenesis bounds from JK/Timiryasov/Shaposhnikov 2103.16545 and Drewes/Georis/JK 2106.16226]

Sakharov conditions at colliders



Can we test the Sakharov conditions at colliders?

1. **Baryon number violation**
   - sphaleron processes
2. **C and CP violation**
   - HNL decays and oscillations
3. **Deviation from equilibrium**
   - freeze-in and freeze-out of HNLs

- Sphalerons processes are extremely suppressed at $T \approx 0$ GeV
- In the SM $B-L$ is conserved: **lepton number violation**
- CP violation in HNL decays is challenging – but we could measure **CPV in ν – oscillations**
- The equilibration rate of HNLs is directly probed by measuring their **couplings & branching ratios**

Deviation from Equilibrium:

HNL branching ratios

- HNL branching ratios are highly constrained by the measured parameters in the minimal model (2 HNLs)

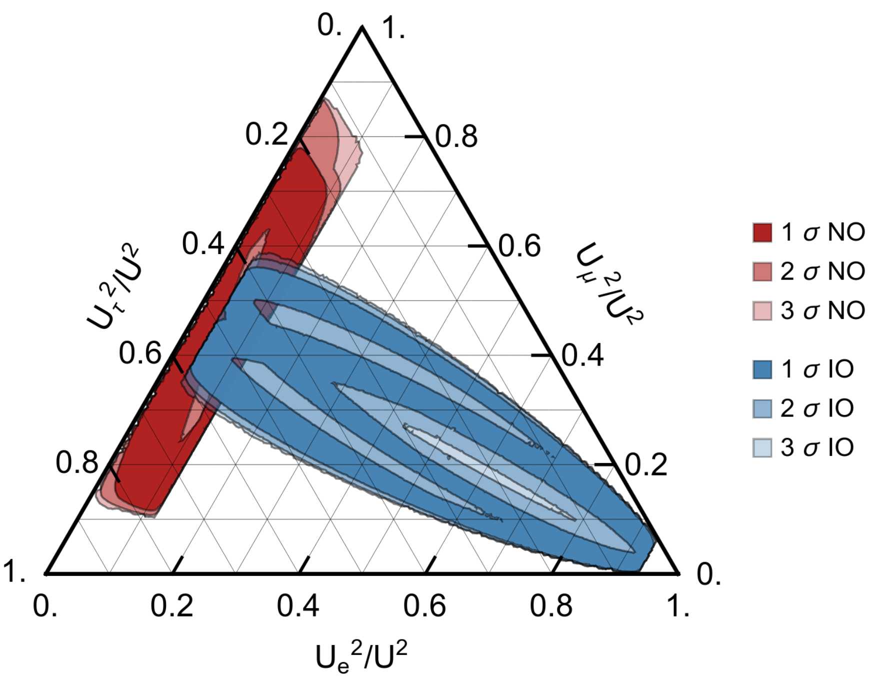
[Snowmass white paper 2203.08039]

- Leptogenesis imposes further constraints on the branching ratios

[Antusch/Cazzato/Drewes/Fischer/Garbrecht/Gueter/JK 1710.03744]

- Branching ratios become even more predictive when combined with Flavor and CP symmetries

[Drewes/Georis/Hagedorn/JK 24xx.xxxx]



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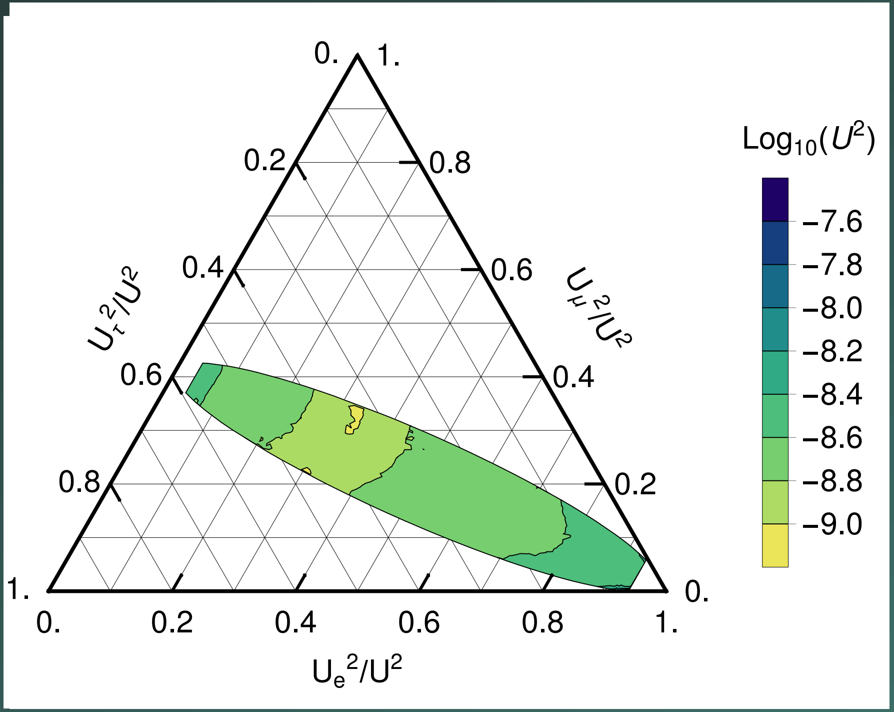

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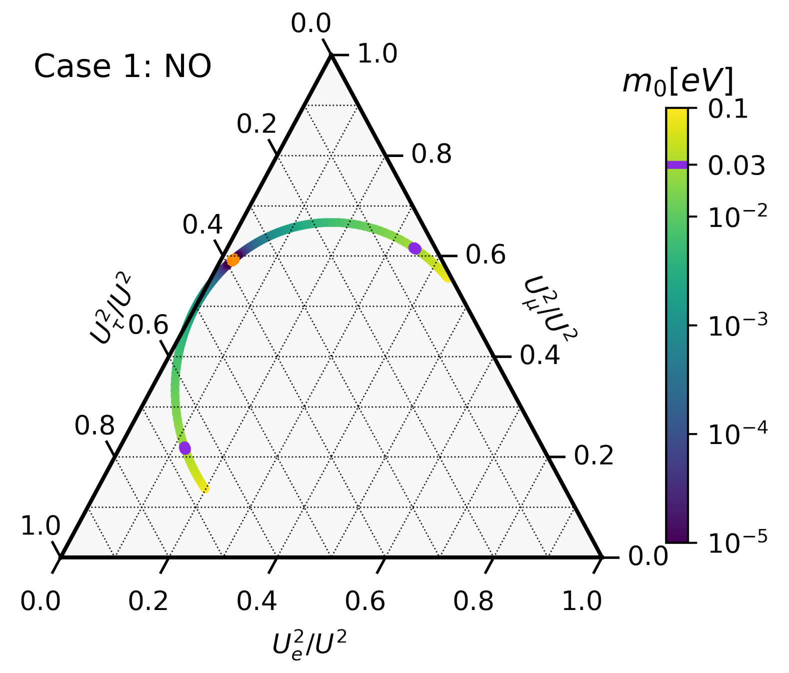
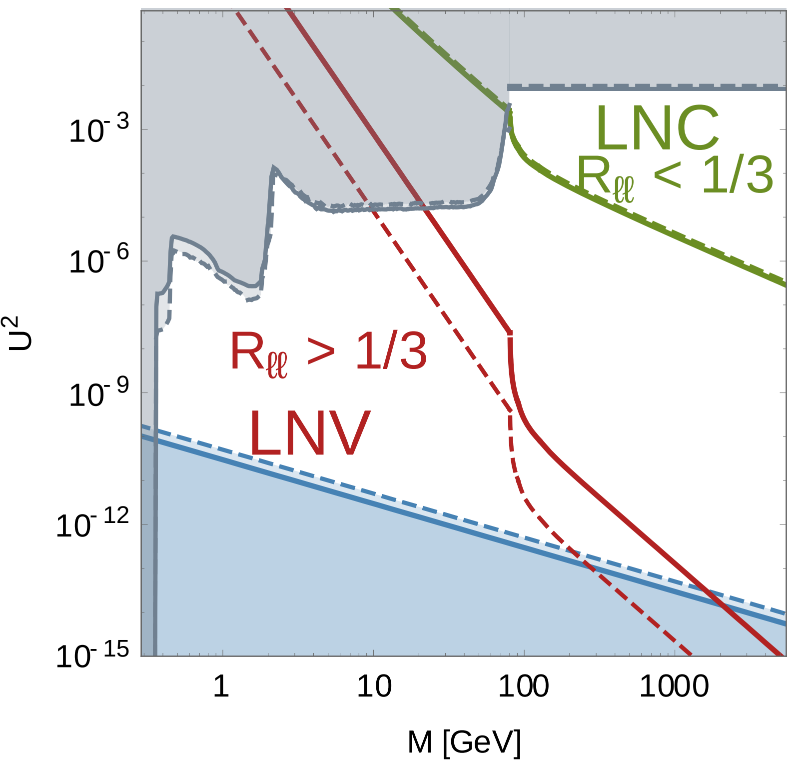


Lepton Number Violation



[Drewes/Klose/JK 1907.13034]

- In low-scale seesaw mechanisms HNLs preserve approximate $B{-}L$ symmetry
- LNC only for $\Gamma \gg \Delta M$
- Absence of fine tuning implies lower bound on HNL mass splitting $\Delta M > \Delta m_\nu$
- Prompt decays can be sensitive to decoherence effects
- For *tiny* mass splittings HNL oscillations between LNV and LNC processes possible

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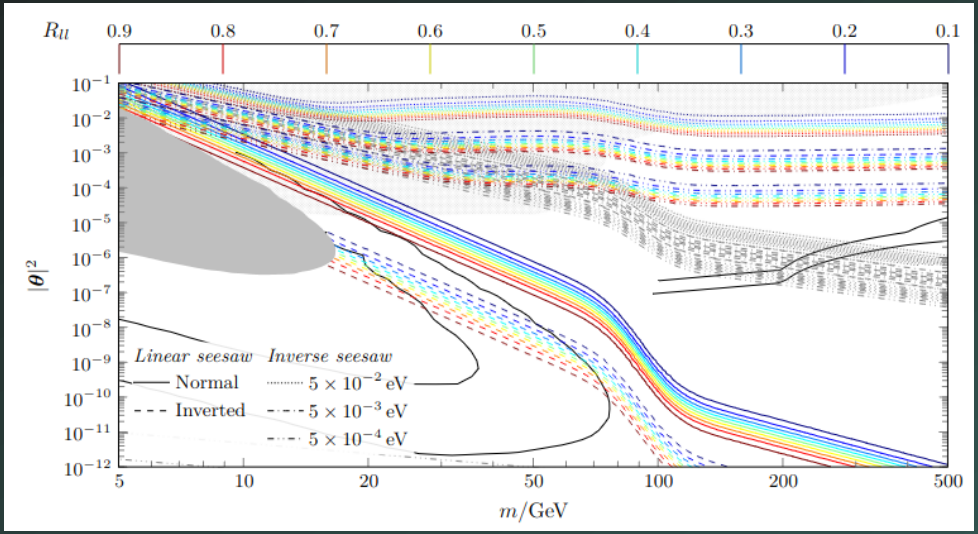

[Antusch/Hajer/Rosskopp 2308.07297]

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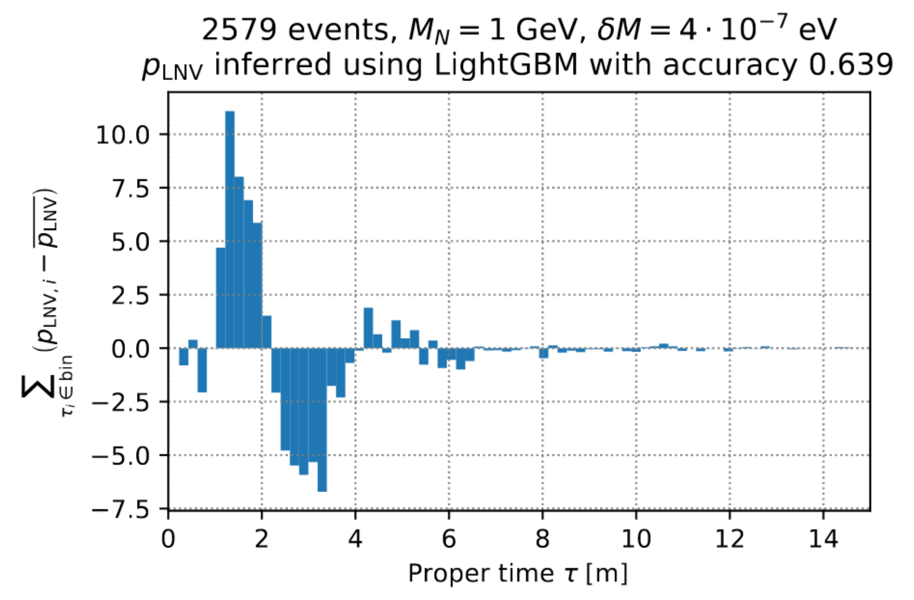

[Tastet/Timiryasov 1912.05520]

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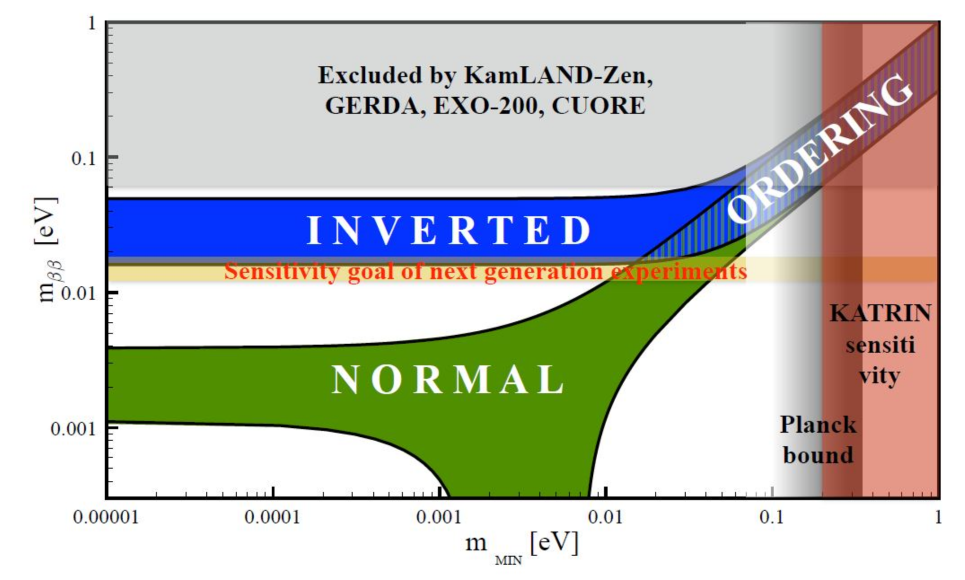
Indirect LNV:

neutrinoless double β decay

- Smoking gun signature of LNV
- GeV-scale HNLs can modify the naive expectation
- Suppression of the IO signal implies light HNLs
- Target region testable with HL-LHC, SHiP & FCC-ee



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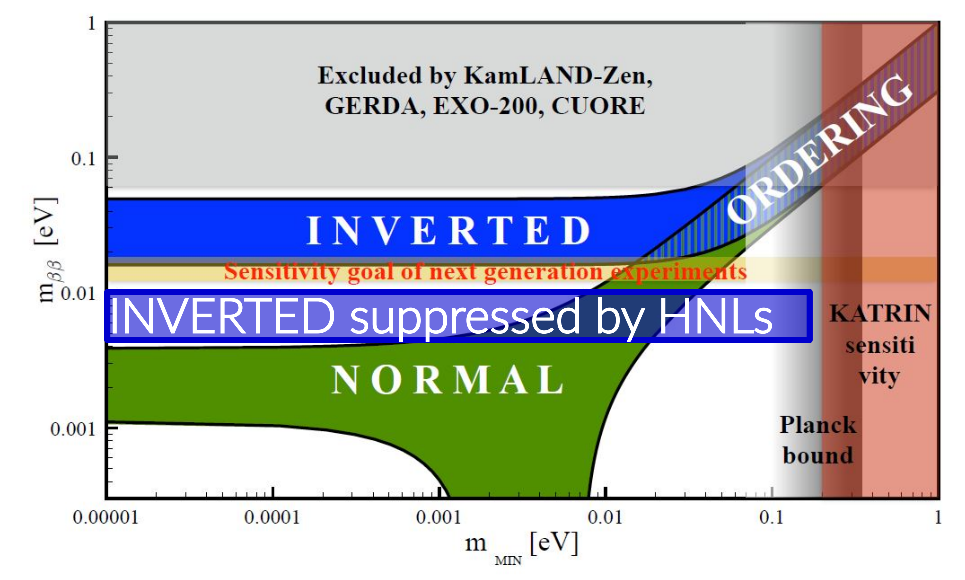

INVERTED suppressed by HNLs

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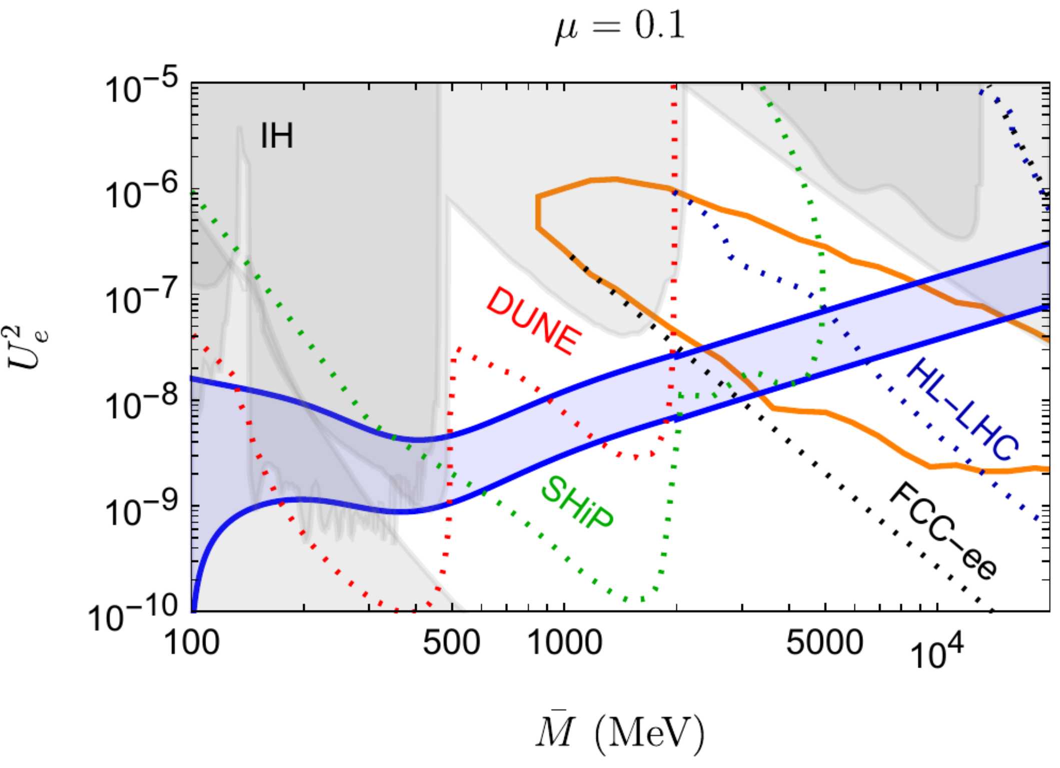

[Fig from de Vries, Drewes, Georis, JK, Plakkot 24XX.XXXX]
[figures from 1910.04688]

Conclusions

HNLs can offer a minimal solution to the origins of **neutrino masses** and the **baryon asymmetry of the Universe**

- the existence of HNLs is already being tested at existing experiments
- excellent synergy between **high-energy** and **high-intensity** experiments!
- leptogenesis is a viable baryogenesis mechanism for all HNL masses above O(100) MeV scale
- Indirect probes can lead to **clear target regions for HNLs**
- HNLs have a very rich phenomenology

Additional References

- **Canonical seesaw:** [Minkowski ’77] [Gell-Mann/Ramond/Slansky ’79] [Mohapatra/Senjanović ’80] [Yanagida ’79] [Schechter/Valle ’80]
- **Low-scale seesaws:** [Mohapatra ’93] [Mohapatra/Valle ’86] [Bernabeu/Santamaria/Vidal/Mendez/Valle ’86] [Gavela/Hambye/Hernandez/Hernandez ’09] [Branco/Grimus/Lavoura ’89] [Malinsky/Romao/Lavoura ’89]
- **Leptogenesis:** [Fukugita/Yanagida ’86]
- **Flavoured leptogenesis:** [Endoh et. al. ‘03] [Pilaftsis/Underwood ‘05] [Abada et. al. ‘06] [Nir et. al. ‘06]
- **Resonant Leptogenesis:** [Liu/Segre ’93, Pilaftsis ’97, Pilaftsis/Underwood ’04;’05]
- **Leptogenesis via neutrino oscillations:** [Akhmedov/Rubakov/Smirnov ’98, Asaka/Shaposhnikov ’05]