Marco Drewes, Université catholique de Louvain

Probing Leptogenesis with Z pole searches at the CEPC

09.11.2017

Electroweak and Flavour Physics at the CEPC

IHEP Beijing

Two Key Problems

- **What is the origin of neutrino mass?**

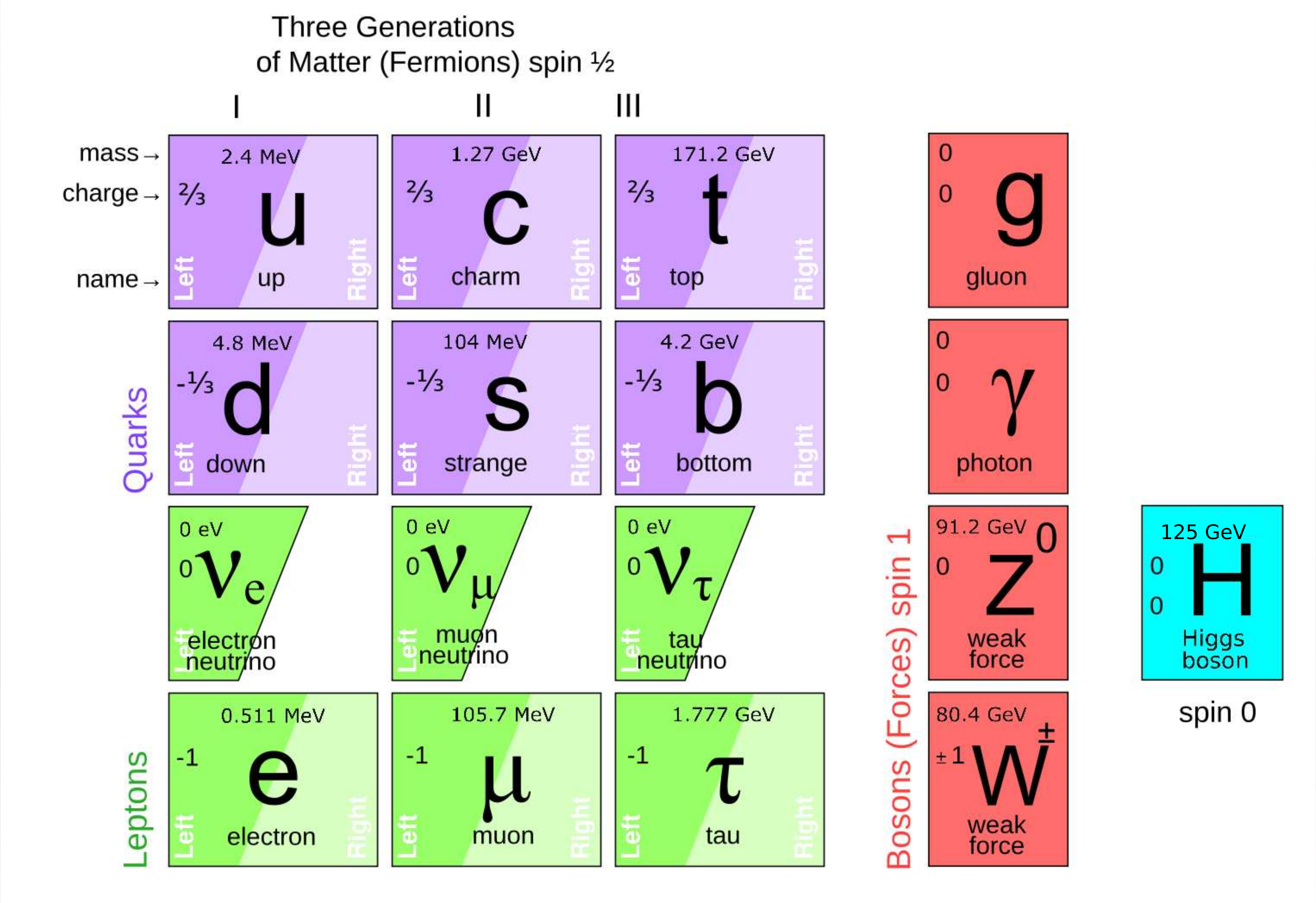
Possible key to embed Standard Model in a more fundamental theory of Nature

- **Why was there more matter than antimatter in the early universe?**

…so that some matter survived the mutual annihilation to form galaxies, stars etc.

The "Neutrino Portal" to New Physics

The Standard Model of Particle Physics



The "periodic table" of elementary particles

Heavy Neutrinos Could Solve Key Problems

- **What is the origin of neutrino mass?**

  Possible key to embed Standard Model in a more fundamental theory of Nature

- **Why was there more matter than antimatter in the early universe?**

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The "Neutrino Portal" to New Physics

Heavy Neutrinos Could Solve Key Problems

- **What is the origin of neutrino mass?**

Possible key to embed Standard Model in a more fundamental theory of Nature

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L - \frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

three heavy mostly singlet neutrinos
$N \simeq \nu_R + \theta^T \nu_L^c$
with masses $\boldsymbol{M_N \simeq M_M}$

Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

Heavy Neutrinos Could Solve Key Problems

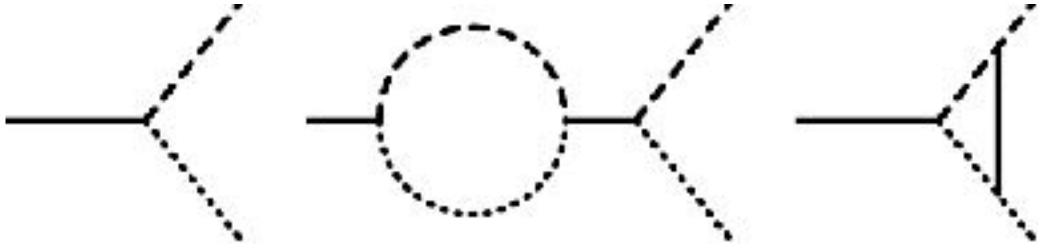
- **What is the origin of neutrino mass?**

Possible key to embed Standard Model in a more fundamental theory of Nature

- **Why was there more matter than antimatter in the early universe?**

…so that some matter survived the mutua

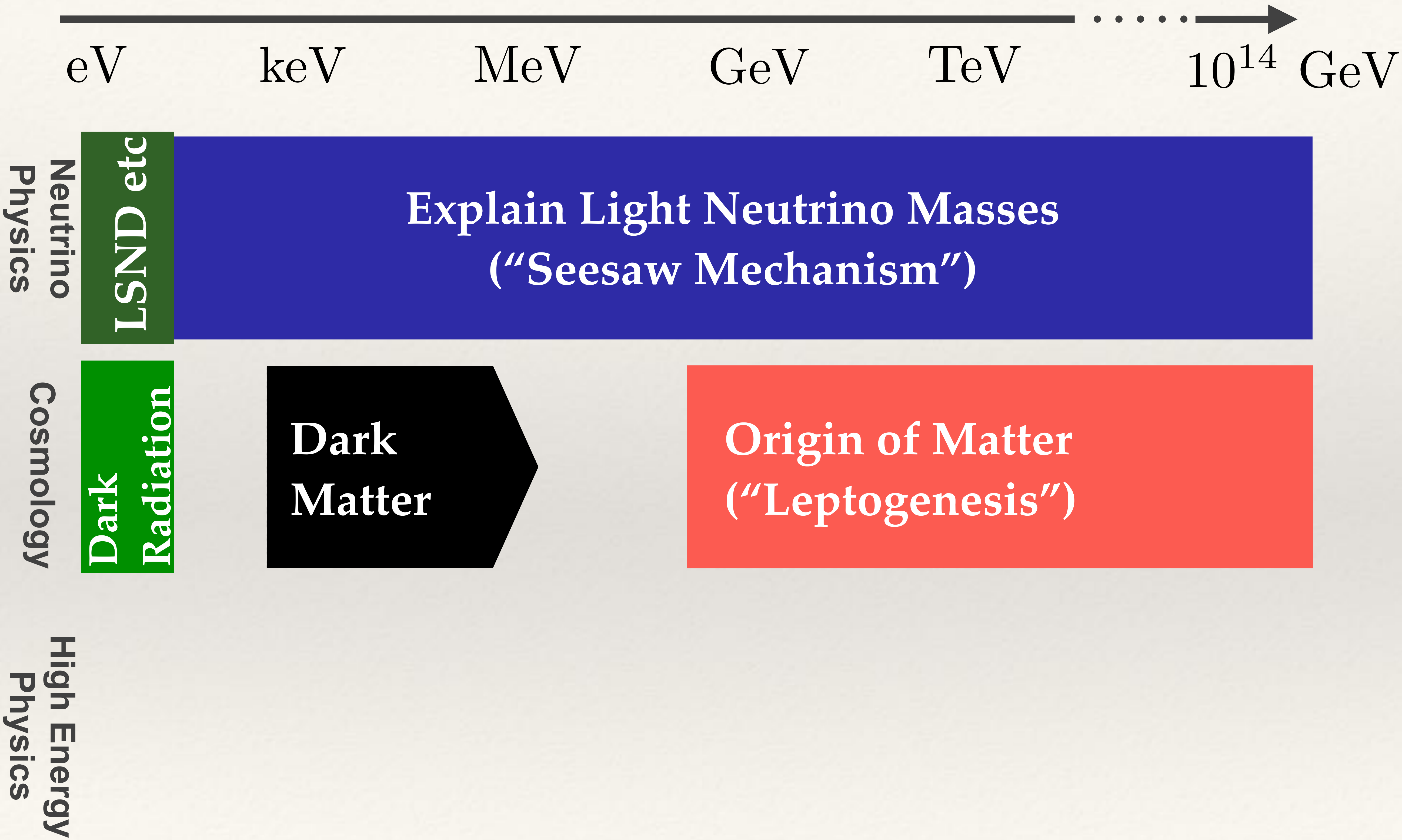
Leptogenesis



- Heavy neutrinos are unstable particles
- Can decay into matter or antimatter
- Quantum effects can make decay into matter more likely

$\Rightarrow$ Nonequilibrium quantum process produces matter excess

Right Handed Neutrinos in Cosmology



Heavy Neutrinos as the Origin of Matter

Neutrino Physics

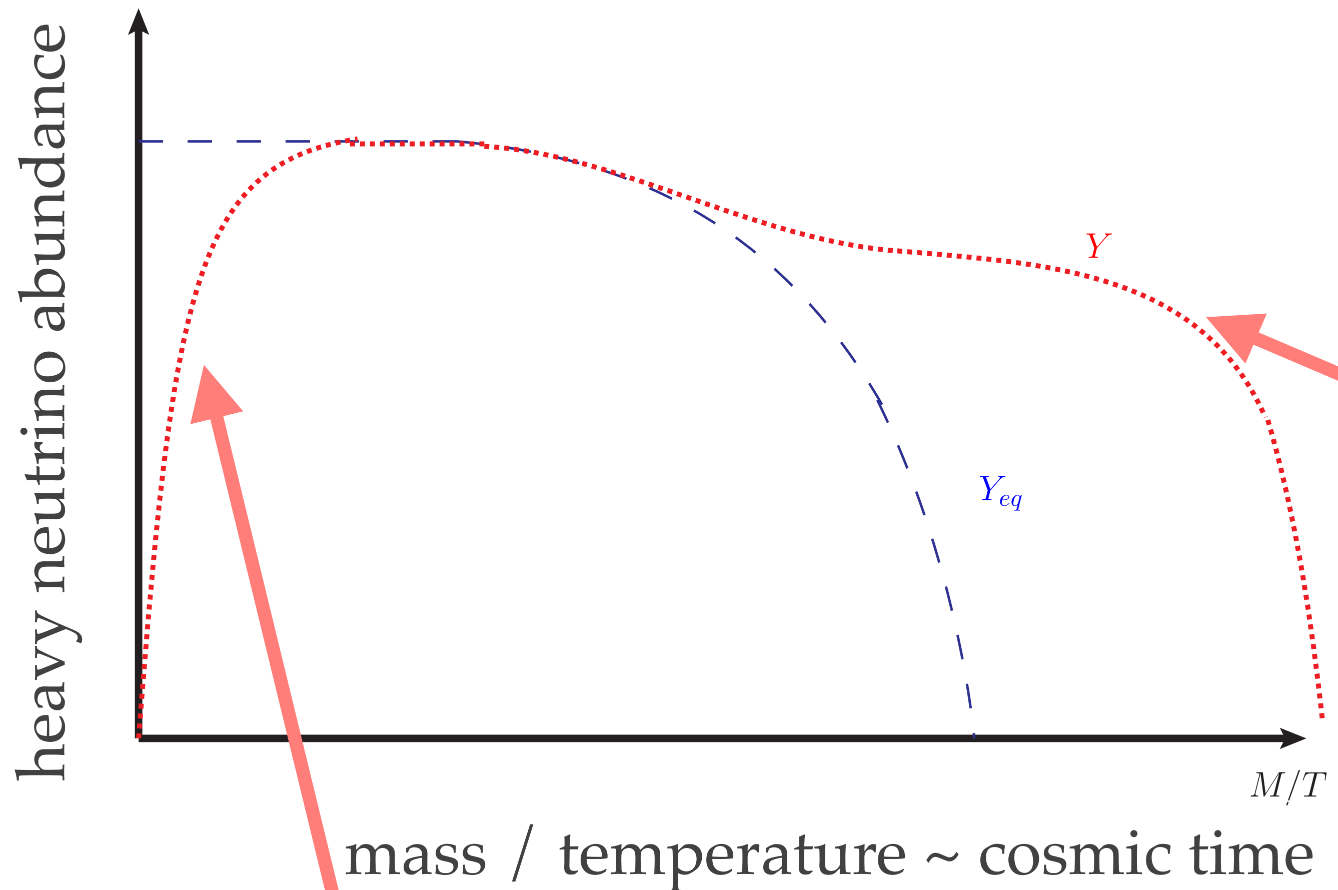
Cosmology

High Energy Physics

Origin of Matter (“Leptogenesis”)

Sakharov Conditions

- baryon number violation
- C and CP violation
- nonequilibrium



rigin of Matter

TeV ⋯ 10^{14} GeV

M above EW scale:
(resonant) leptogenesis
in heavy neutrino decay
("freeze-out scenario")

Fukugita/Yanagida, Pilaftsis/Underwood

M below EW scale:
leptogenesis
in heavy neutrino production
("freeze-in scenario")

Akhmedov/Rubakov/Smirnov,
Asaka/Shaposhnikov

Cosmology

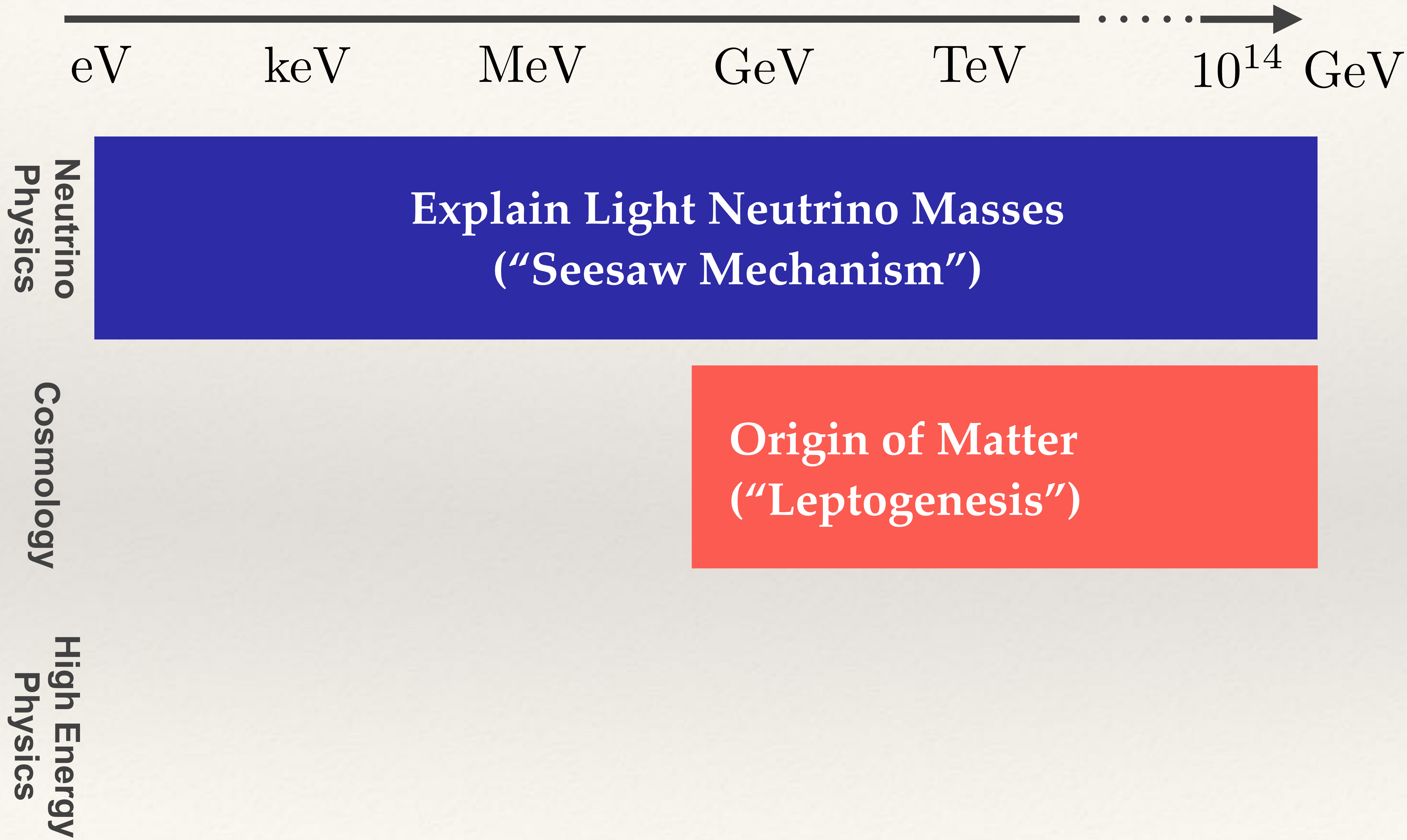
High Energy Physics

Origin of Matter
("Leptogenesis")

Sakharov Conditions

- baryon number violation
- C and CP violation
- nonequilibrium

Heavy Neutrinos and the Light Neutrino Masses



Heavy Neutrinos and the Light Neutrino Masses

eV — keV — MeV — GeV — TeV ····· 10^{14} GeV

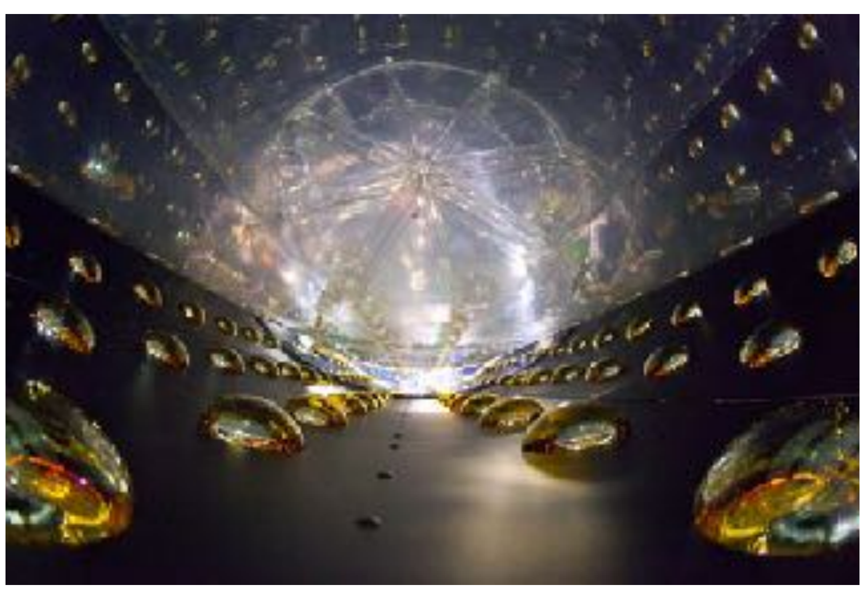
Neutrino Physics

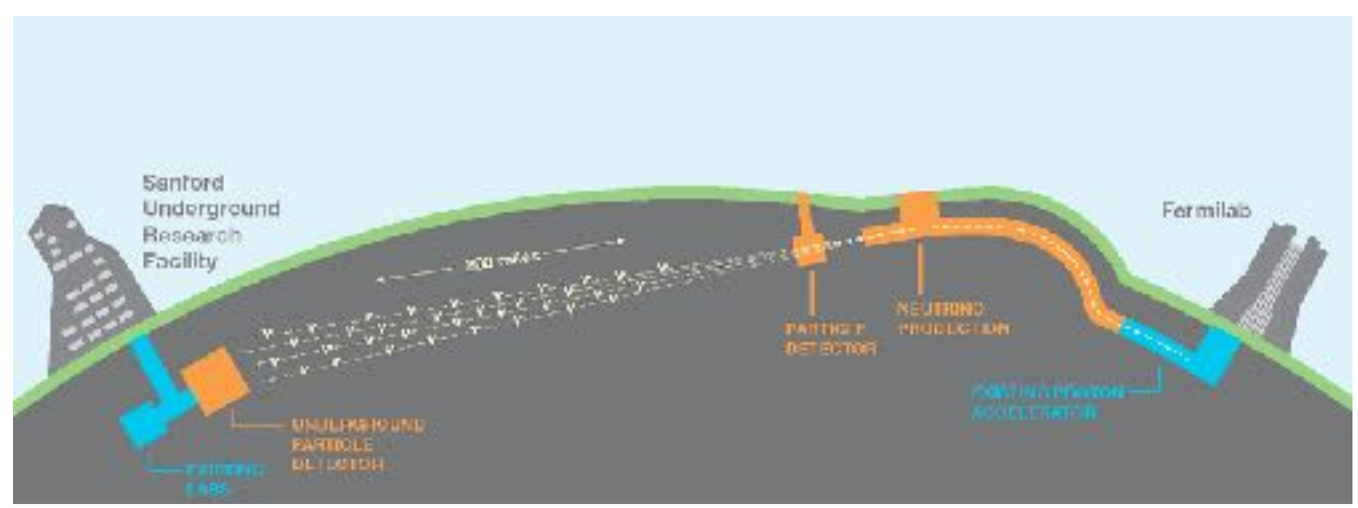
Explain Light Neutrino Masses
(“Seesaw Mechanism”)

Cosmology

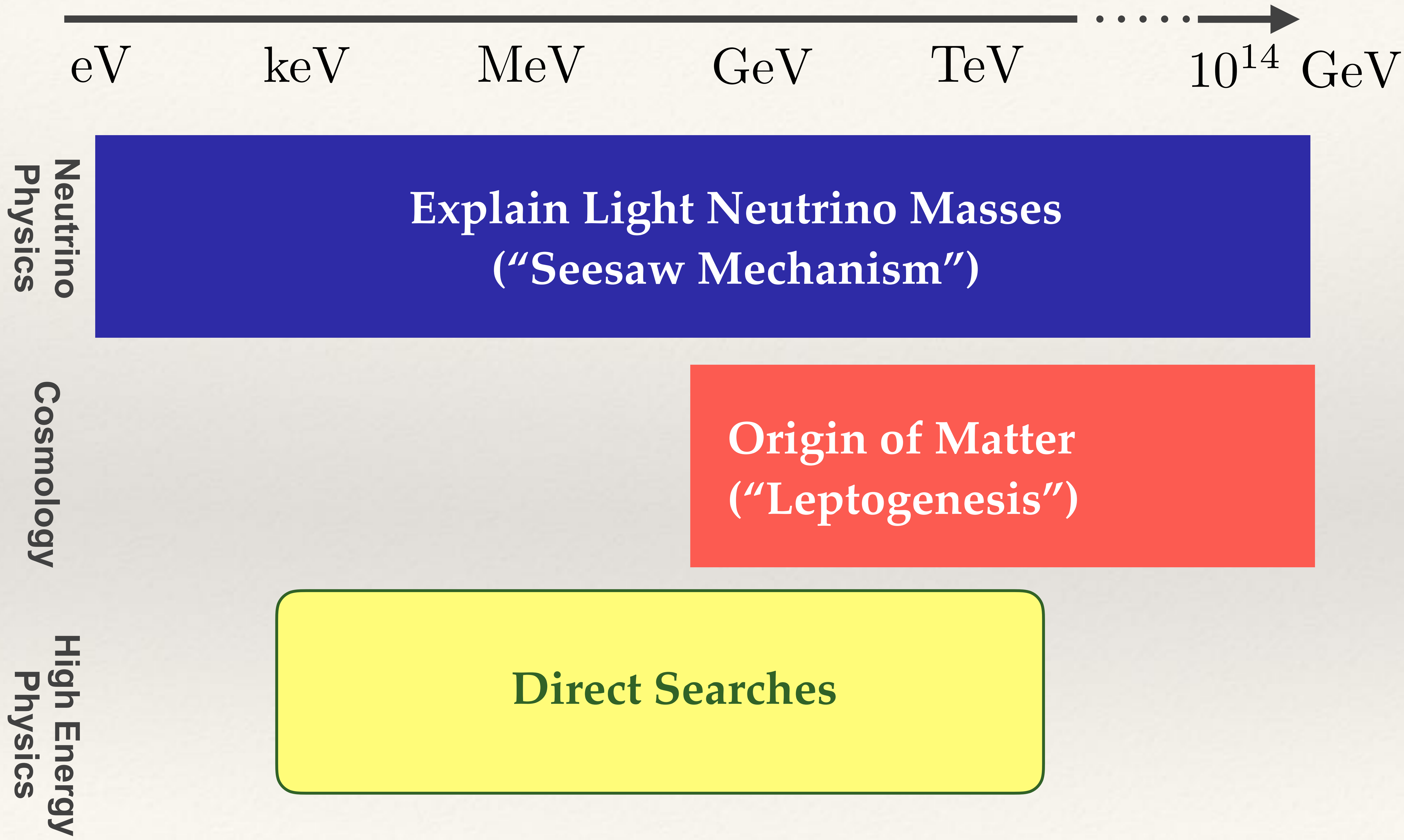
High Energy Physics

neutrino oscillation data





How to Find Heavy Neutrinos?



How to Find Heavy Neutrinos?

nuclear decay spectra

TRISTAN, ECHO

fixed target experiments

SHiP
Search for Hidden Particles

NA62

b factories

LHCb

Belle II

proton colliders

electron colliders

CEPC

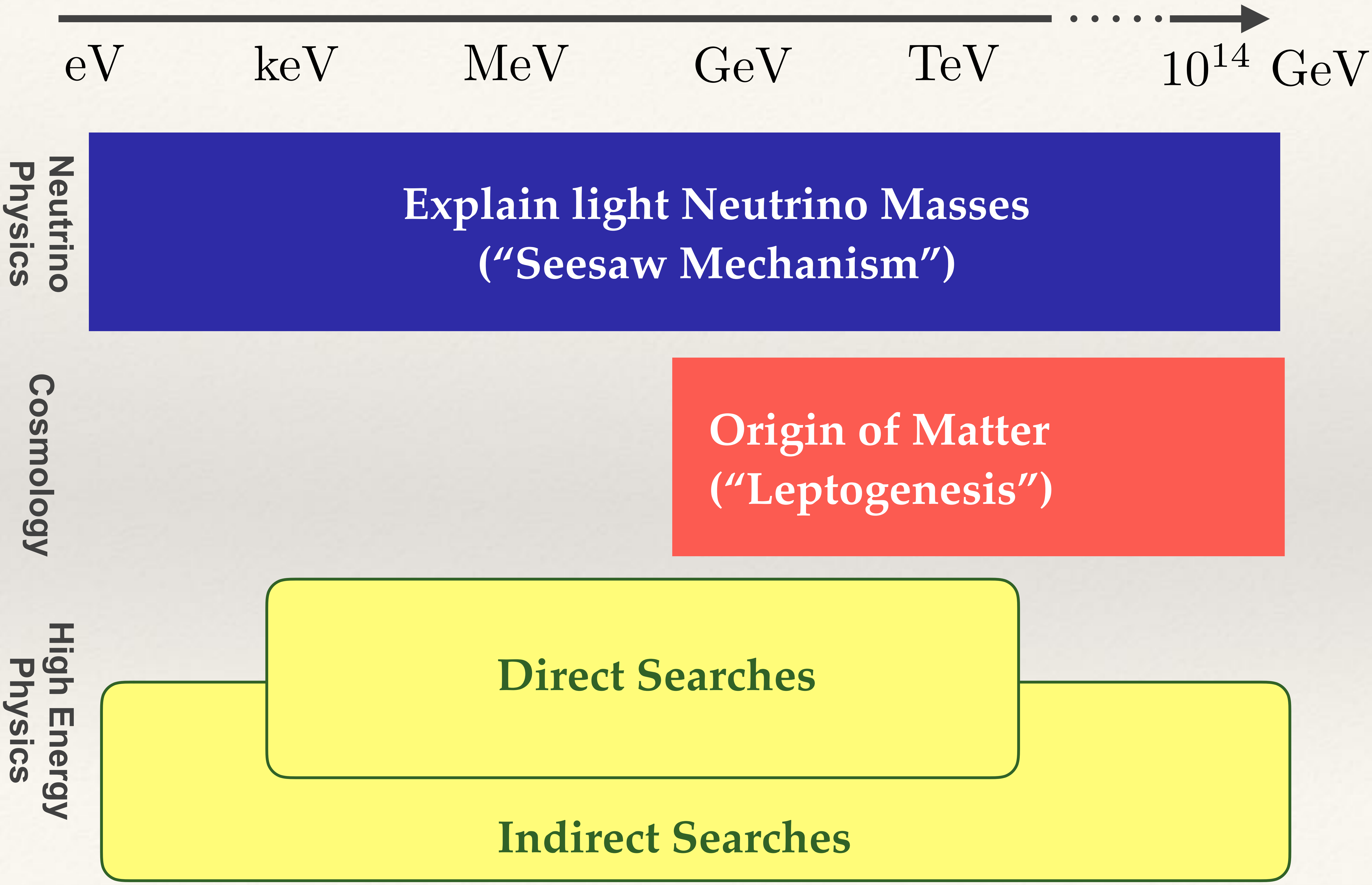
FCC
hh ee he

ilc
international linear collider

Direct Searches

High Energy Physics

How to Find Heavy Neutrinos?



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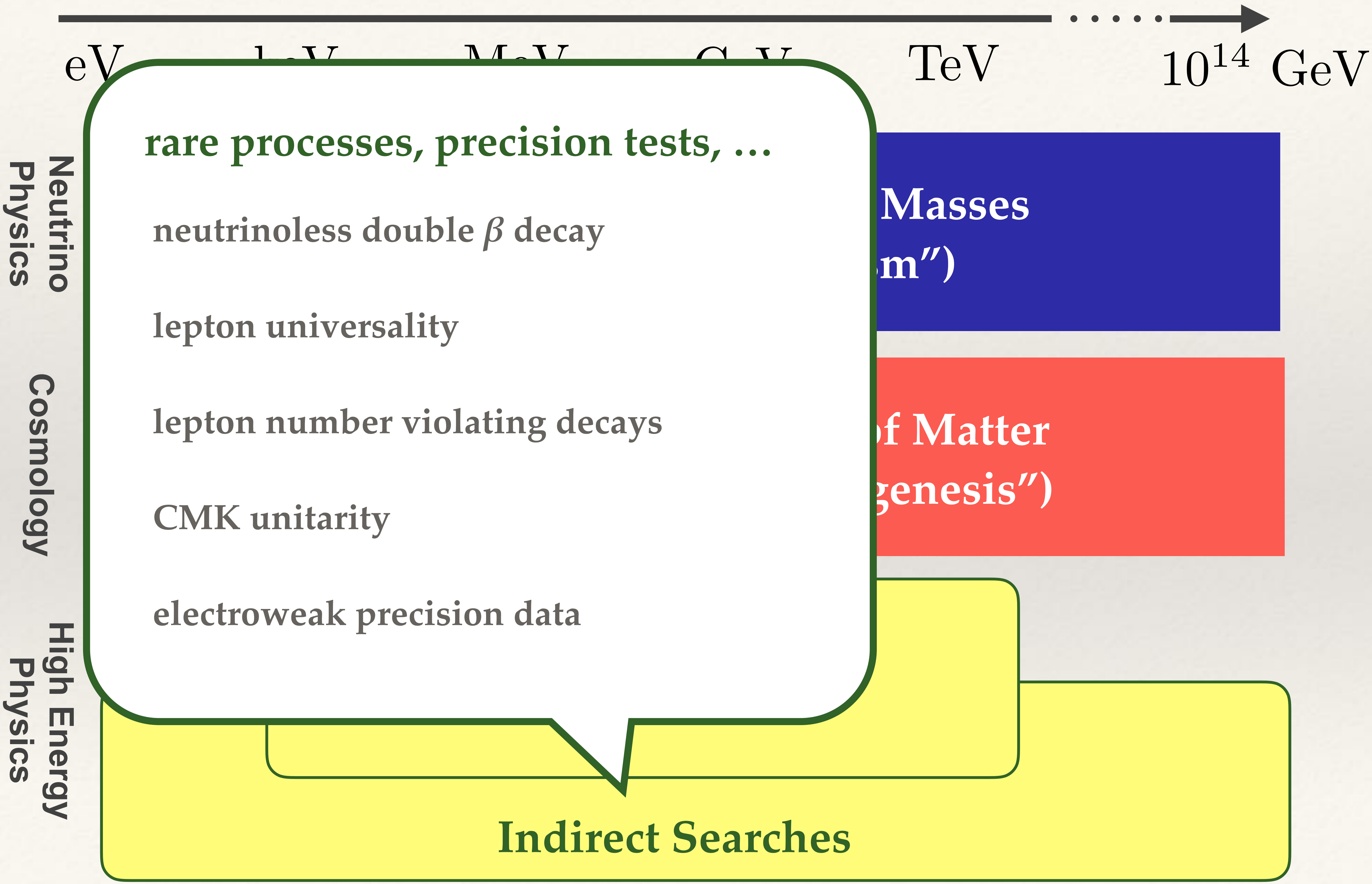


Neutrino masses vs collider searches

neutrino masses m_i are small (sub eV)

→ **active-sterile mixing angle θ must be small**

Problem?

colliders rely on branching ratio

→ **active-sterile mixing angle θ must be large**

Neutrino masses vs collider searches

neutrino masses m_i are small (sub eV)

→ active-sterile mixing angle θ must be small

Problem?

Solution →

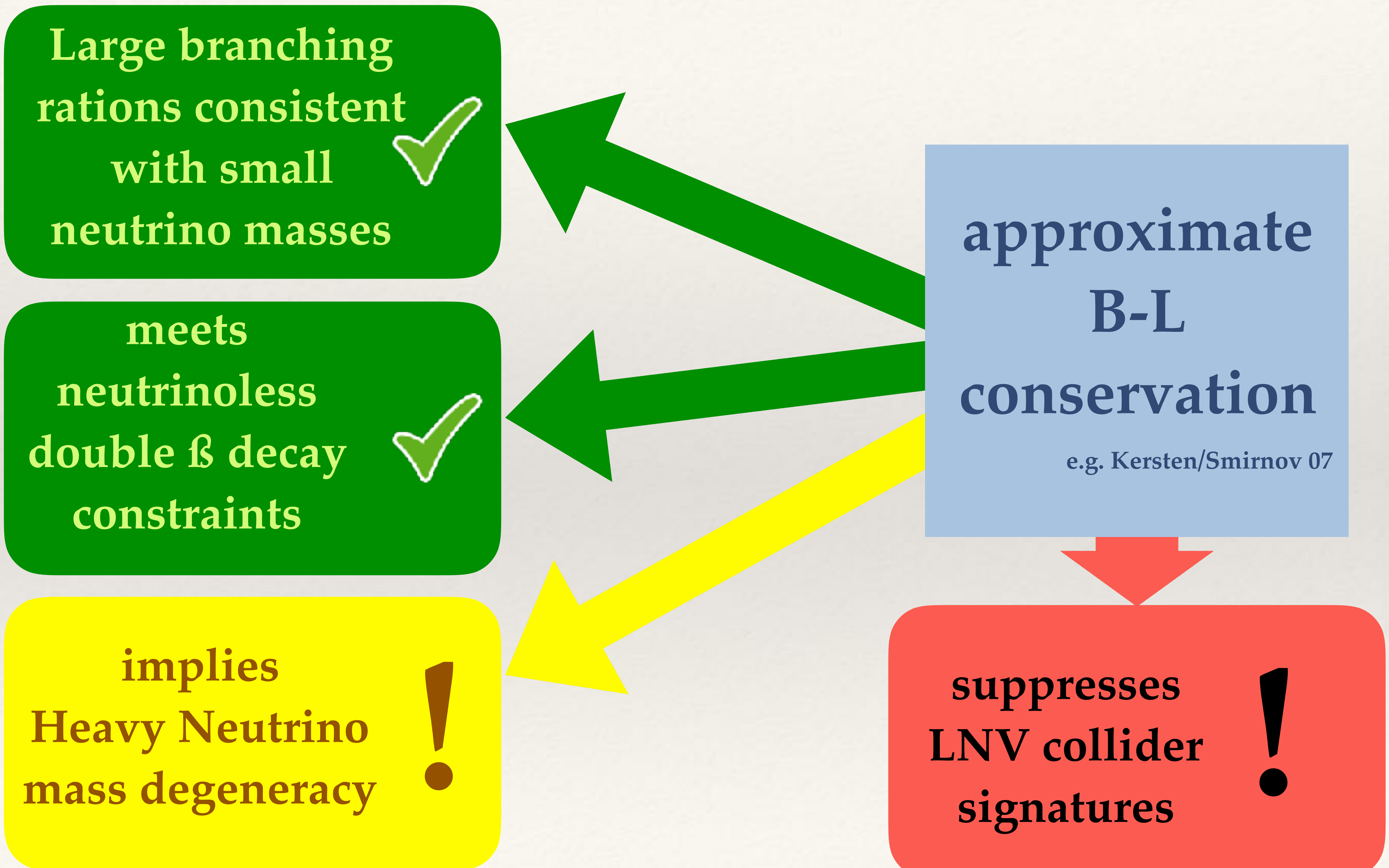
approximate B-L conservation

e.g. Kersten/Smirnov 07

colliders rely on branching ratio

→ active-sterile mixing angle θ must be large

Neutrino masses vs collider searches



Neutrino masses vs collider searches

hard to distinguish signatures kinematically

cannot study heavy "flavours" individually

great for leptogenesis!

may observe CP violation in Heavy Neutrino decay

Cvetic/Kim/Saa 14

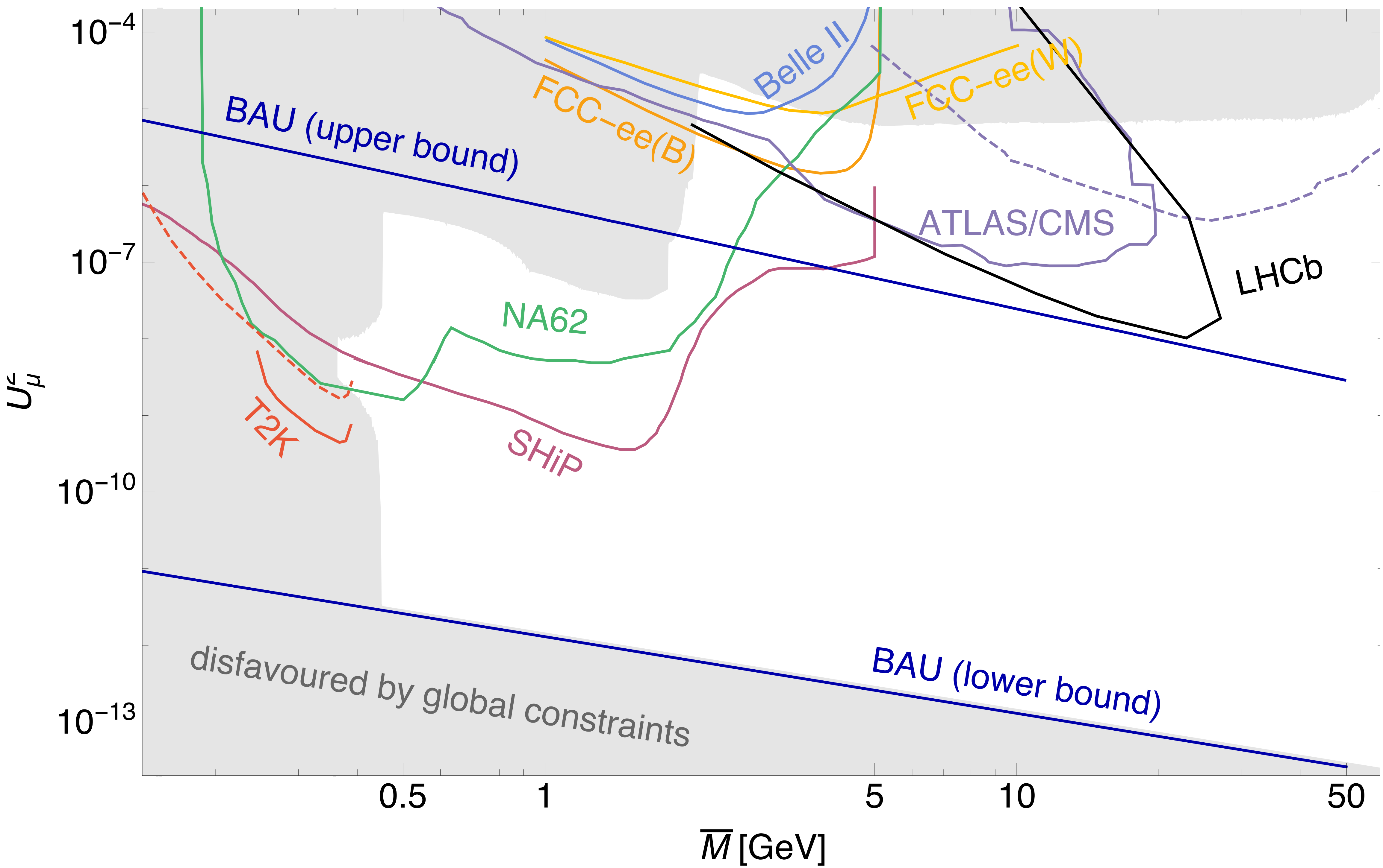
"golden channels" suppressed

need to use other channels (LFV, displaced vertices)

implies Heavy Neutrino mass degeneracy !

suppresses LNV collider signatures !

Experimental Perspectives

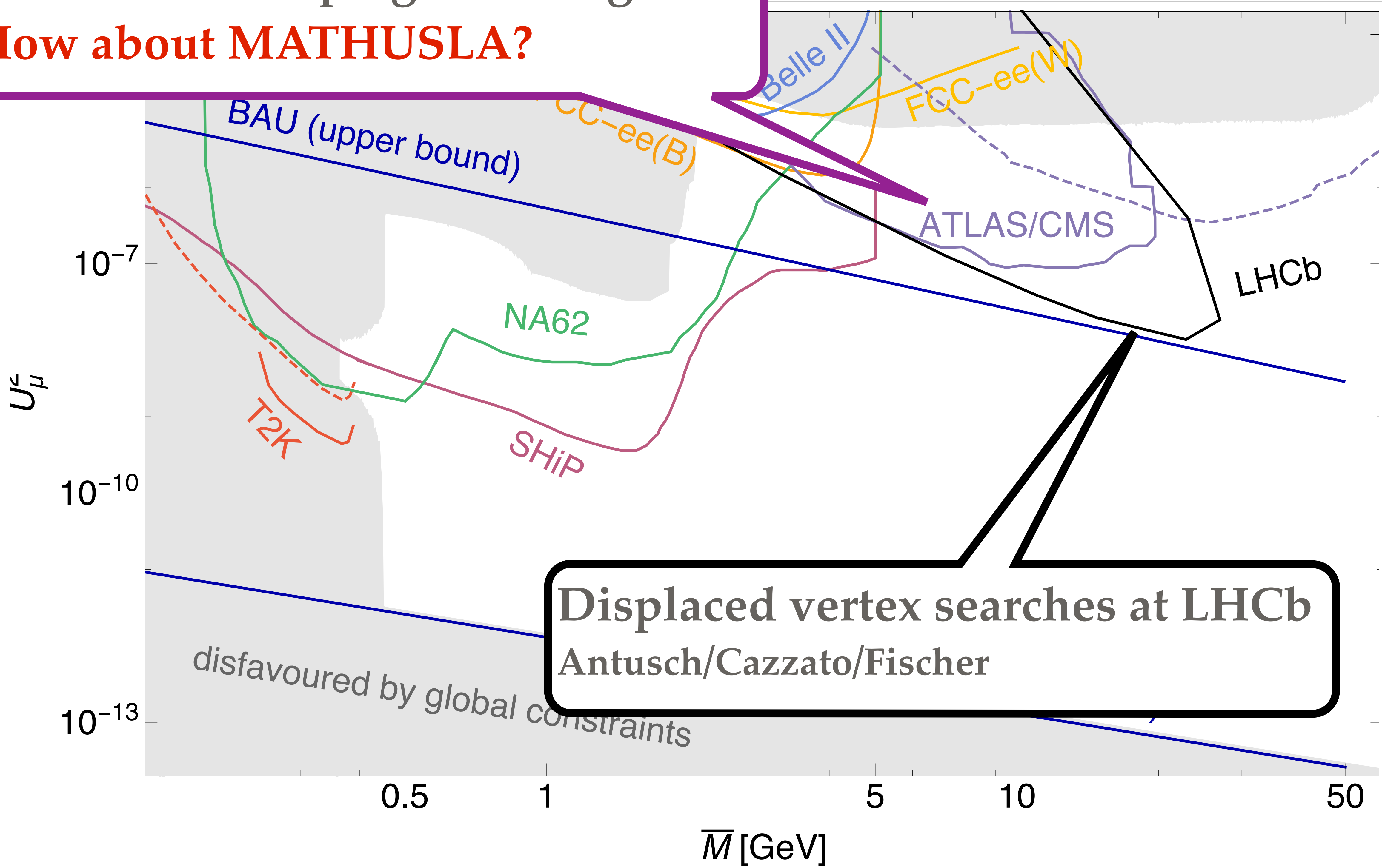


plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Perspectives

ATLAS/CMS (Izaguirre/Shuve)
Hard to reach leptogenesis region
How about MATHUSLA?

Displaced vertex searches at LHCb
Antusch/Cazzato/Fischer



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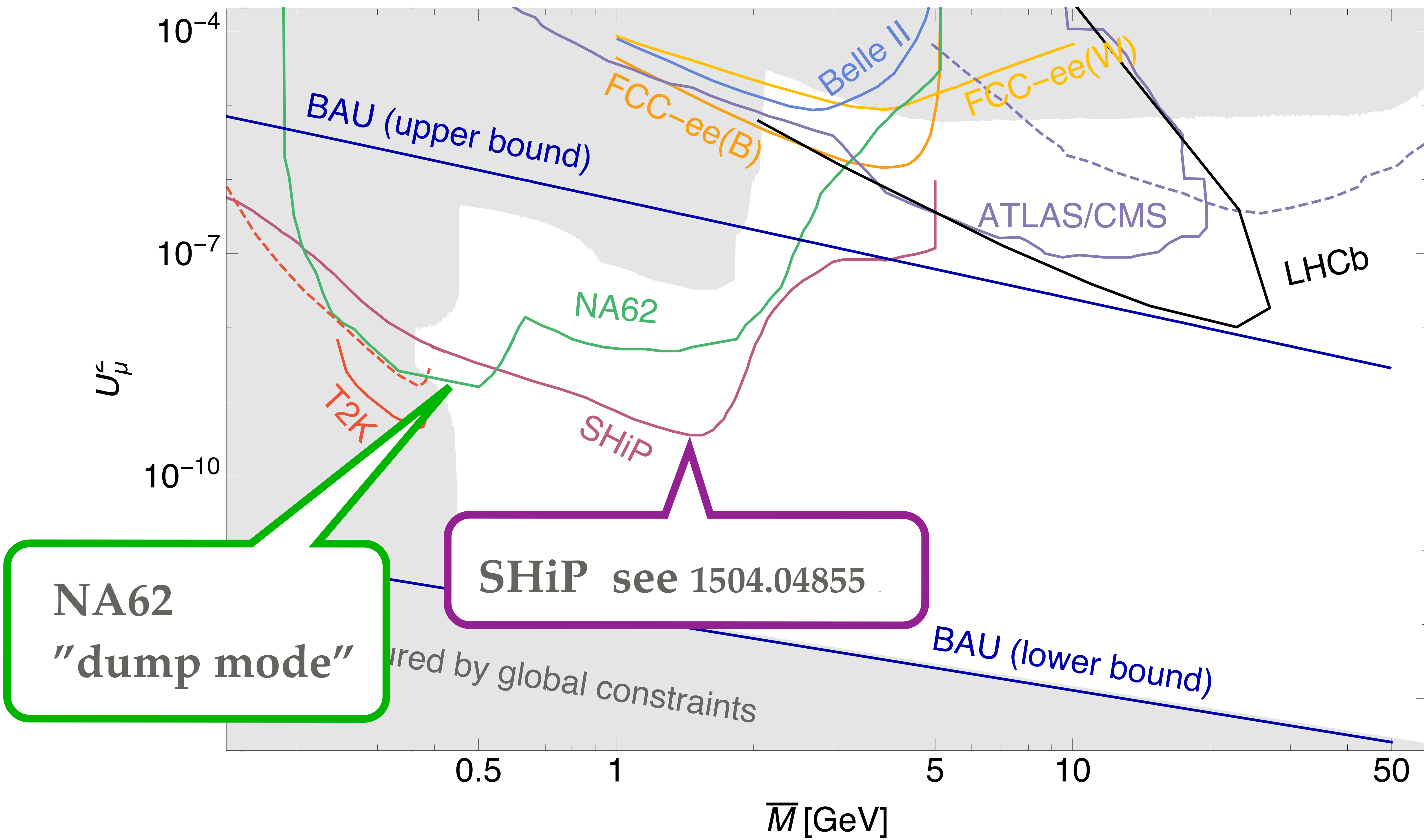
Experimental Perspectives



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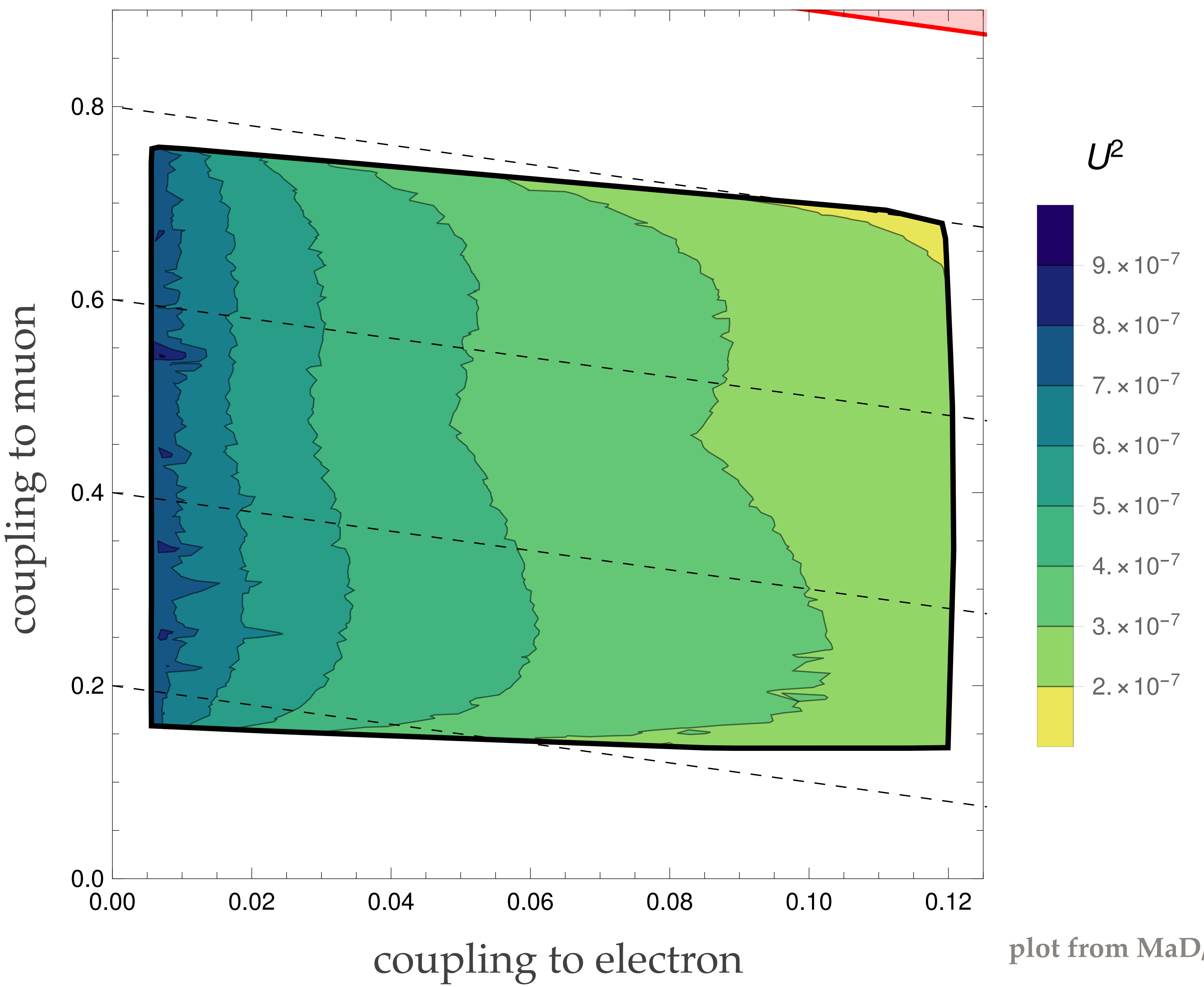
Neutrino Mixing vs Collider Searches



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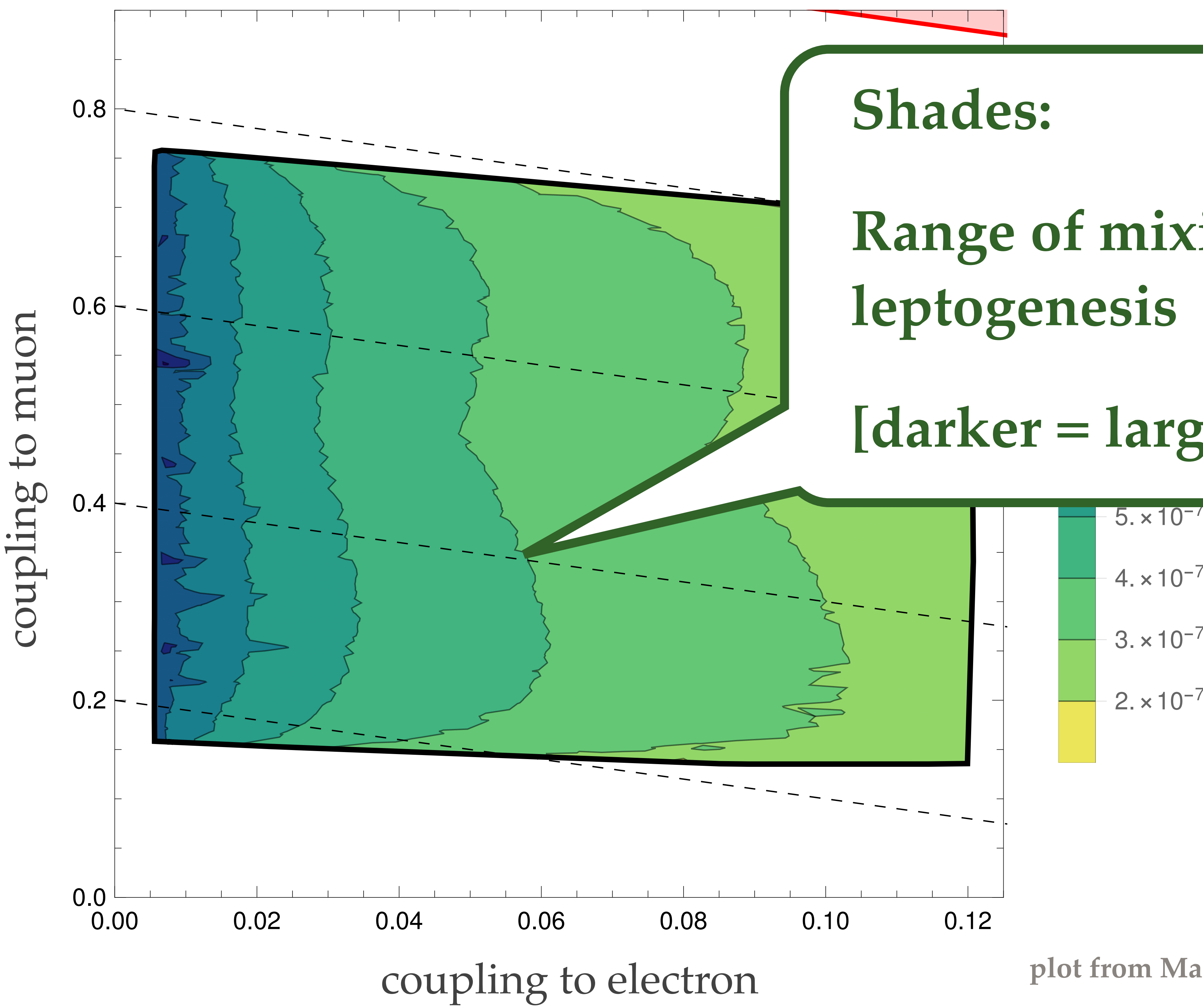


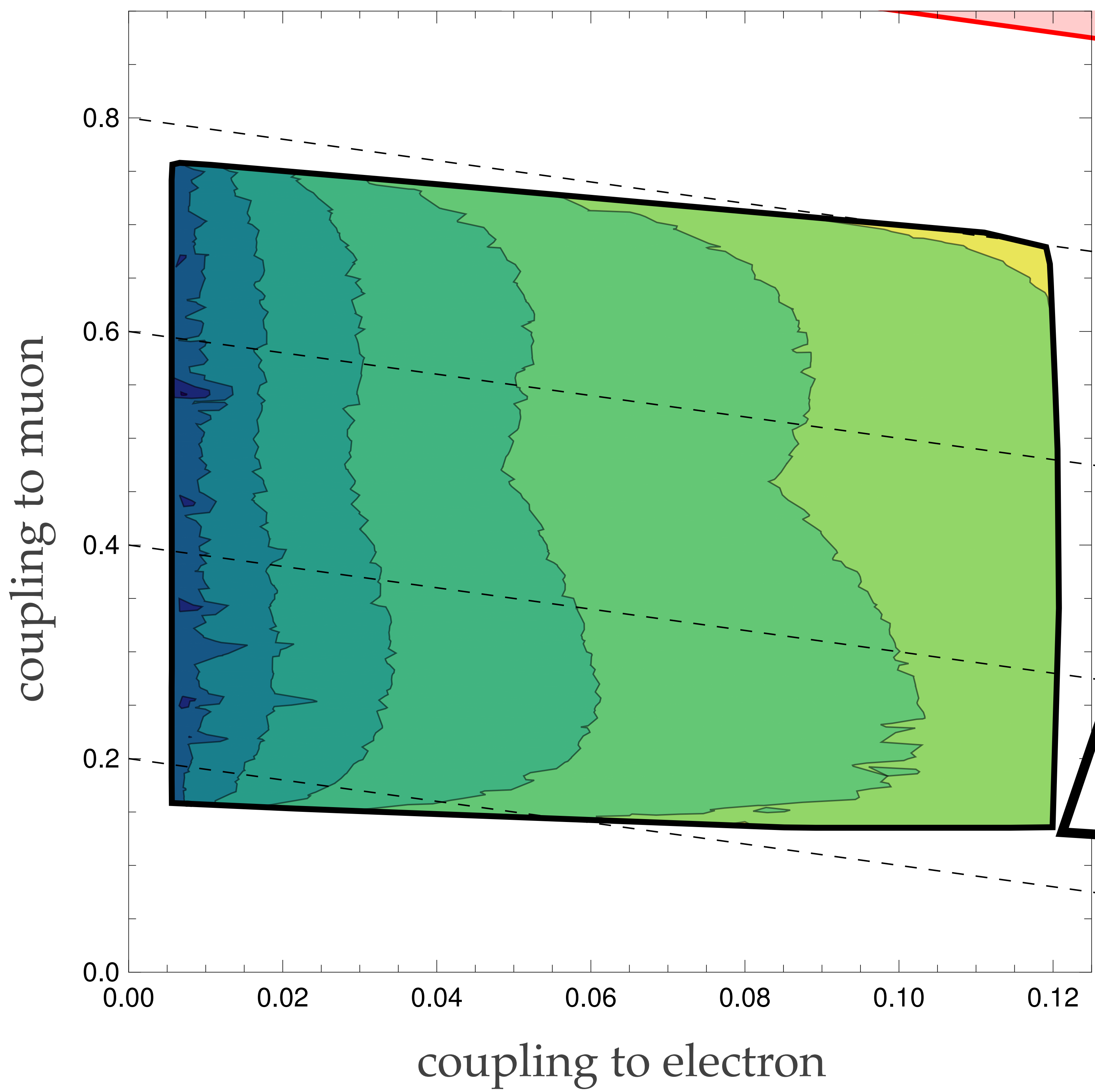
Shades:

Range of mixing that allows leptogenesis

[darker = larger total mixing]

plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Neutrino Mixing vs Collider Searches



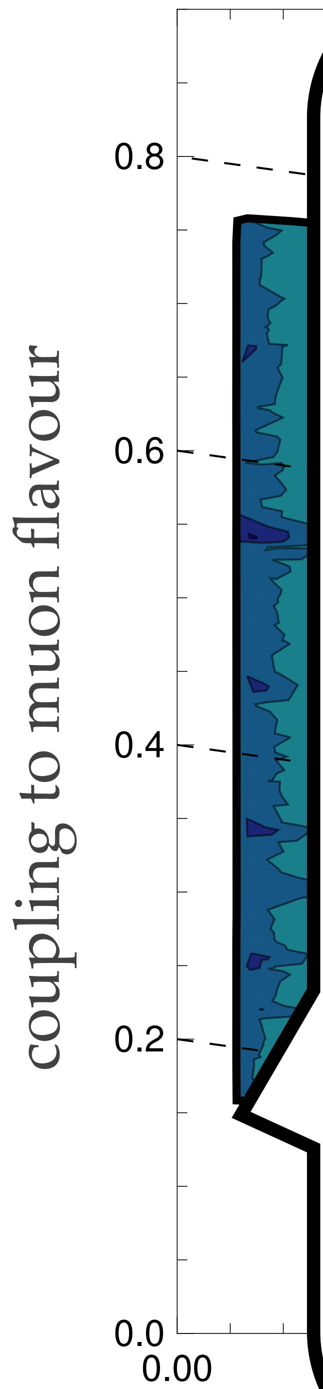
Area within black line:

allowed by neutrino oscillation data

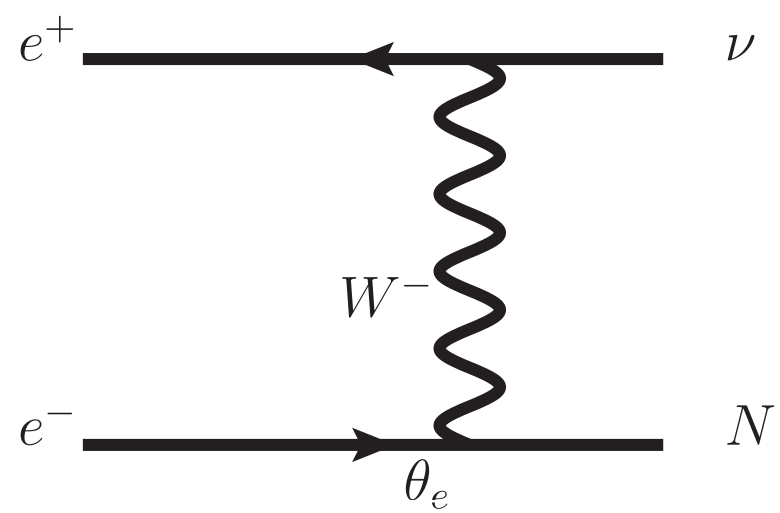
coupling to electron maximal 12%!

[for normal neutrino mass ordering]

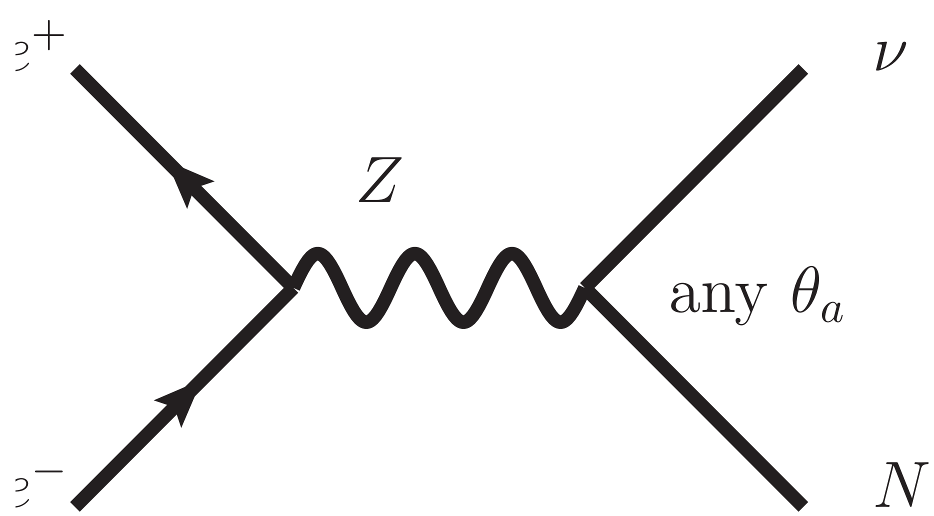
Neutrino Mixing vs Collider Searches



Effect on production at lepton colliders:



suppressed compared to



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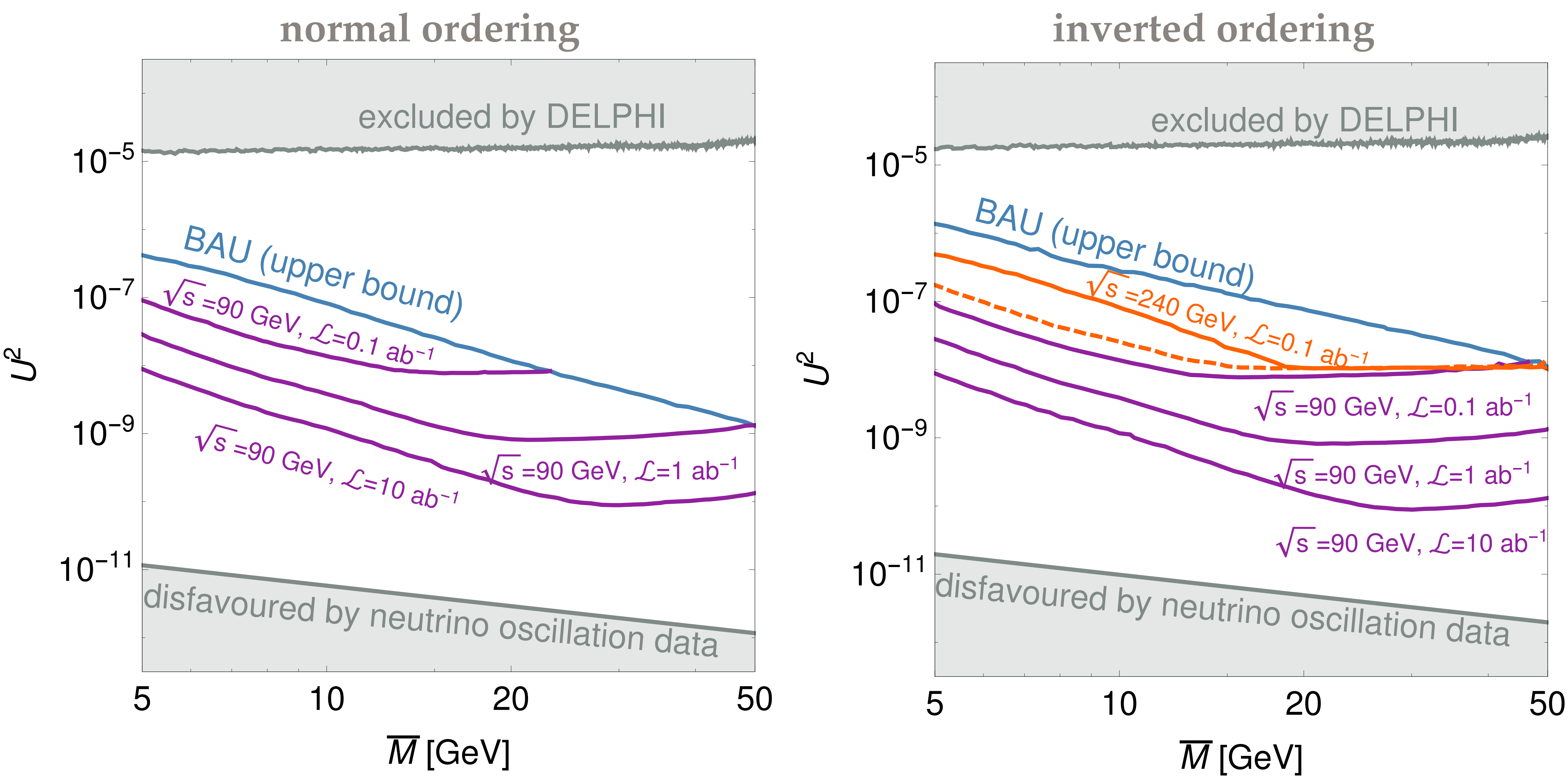
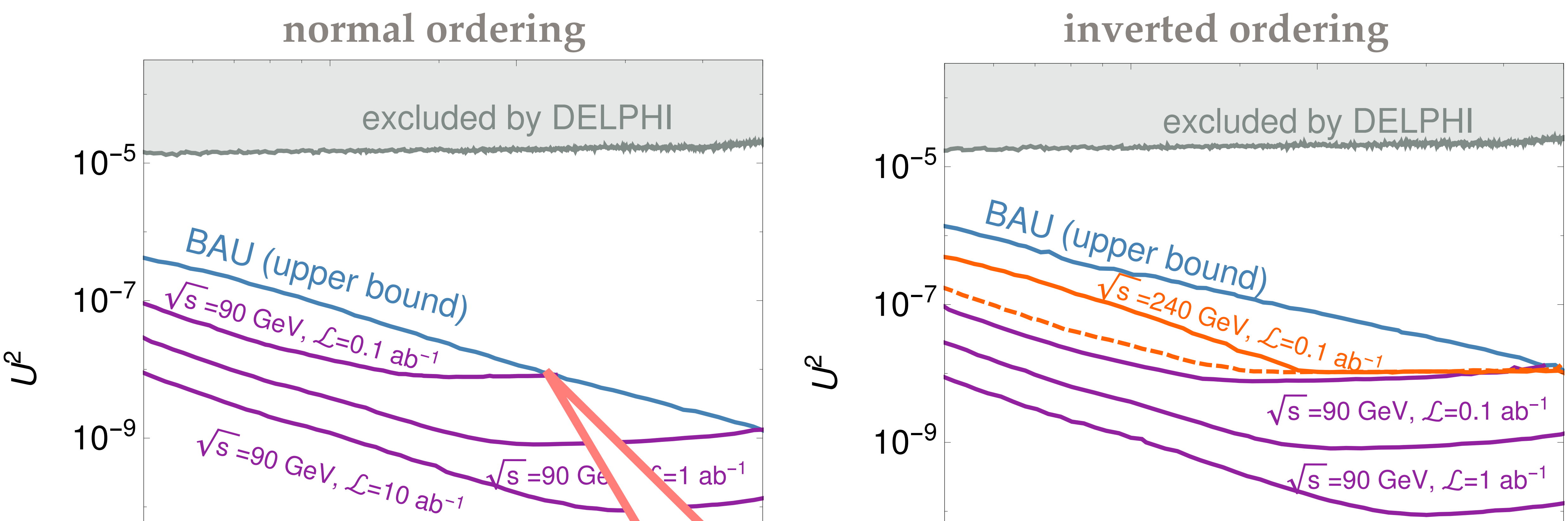
Displaced Vertices at CEPC



Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Displaced Vertices at CEPC

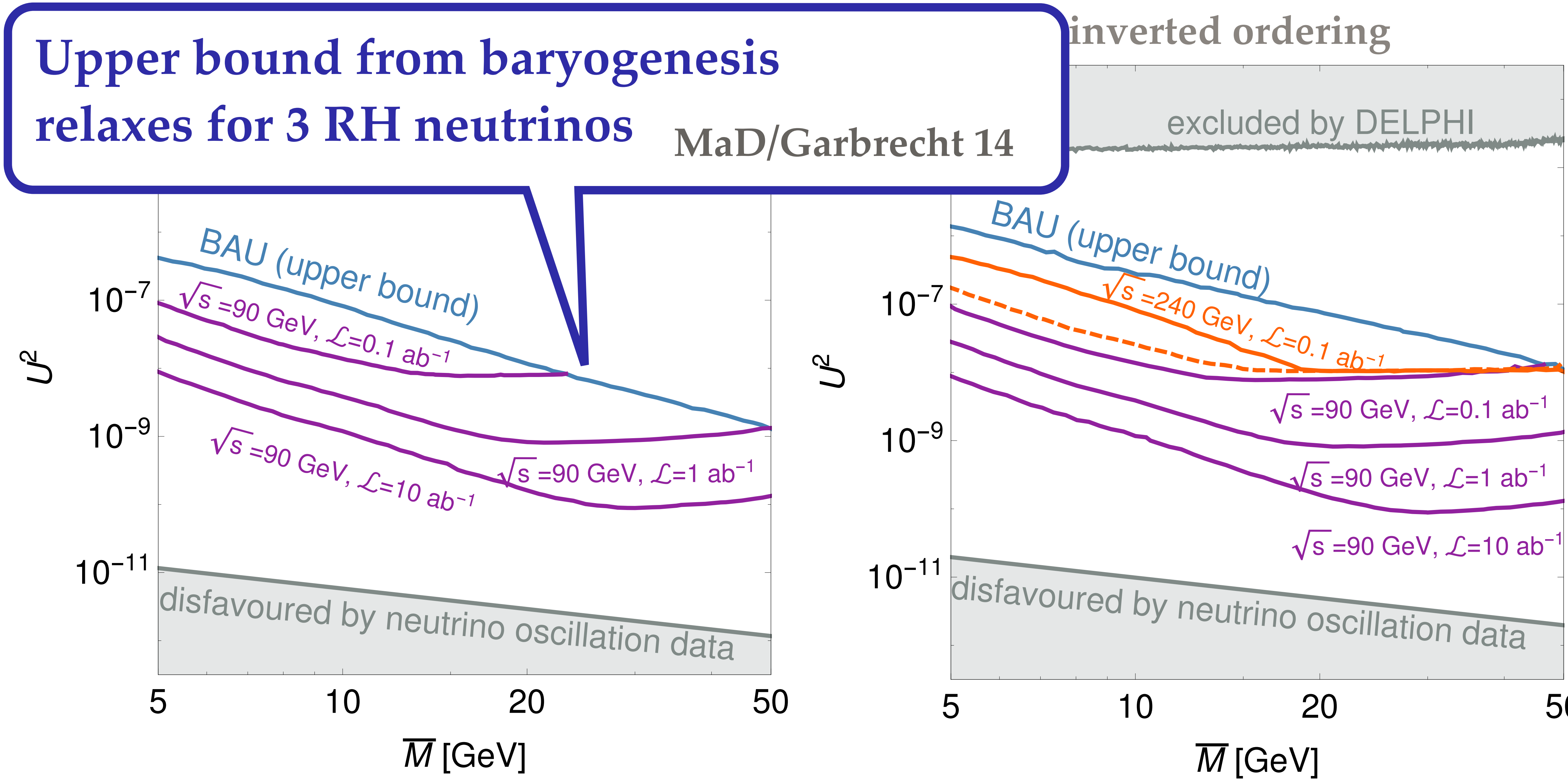


At 240 GeV:
production in t channel W exchange
relies on mixing with electron
is suppressed for normal ordering in minimal model with 2 RHN

Strongly depends on number of RHN..
Perspectives are better with more than 2!

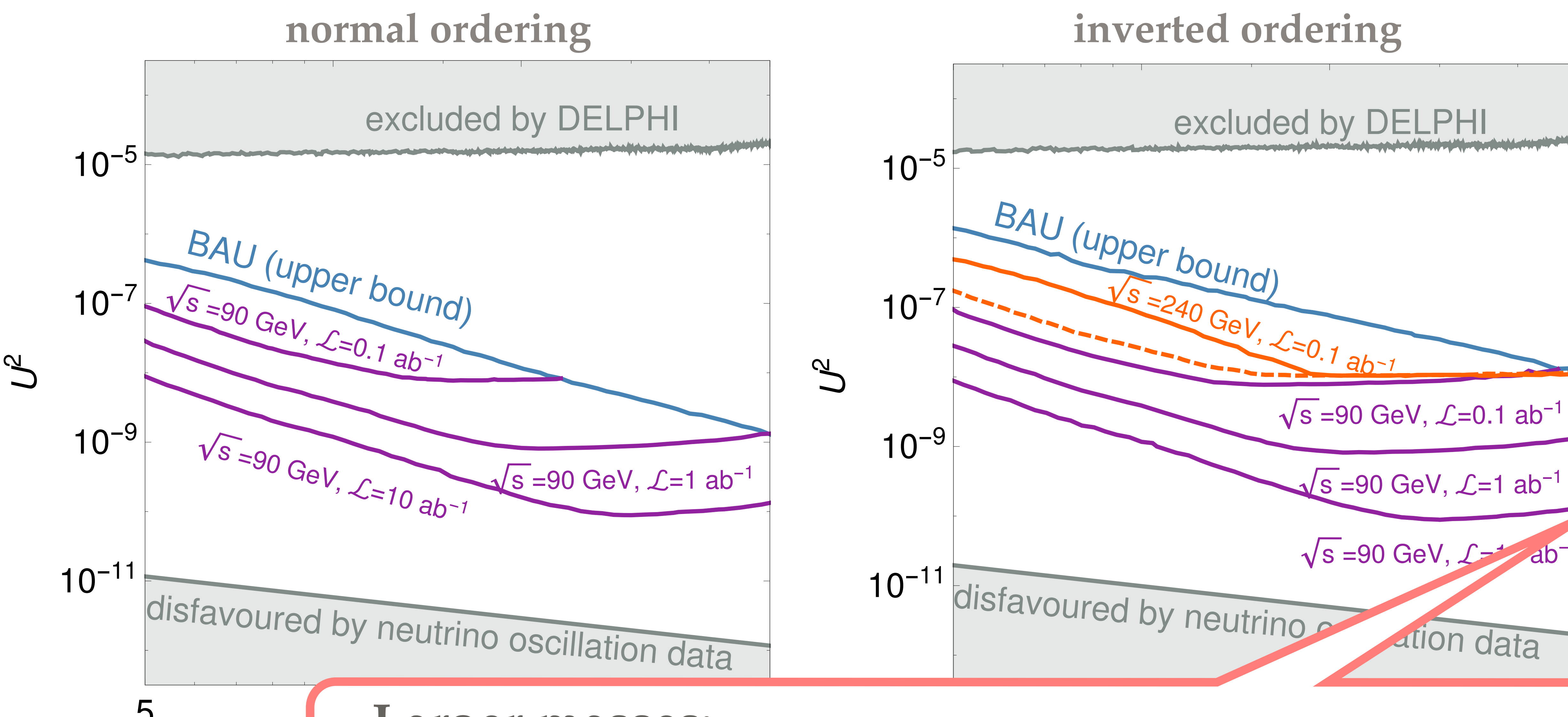
Displaced Vertices at CEPC

Upper bound from baryogenesis relaxes for 3 RH neutrinos MaD/Garbrecht 14



Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Displaced Vertices at CEPC

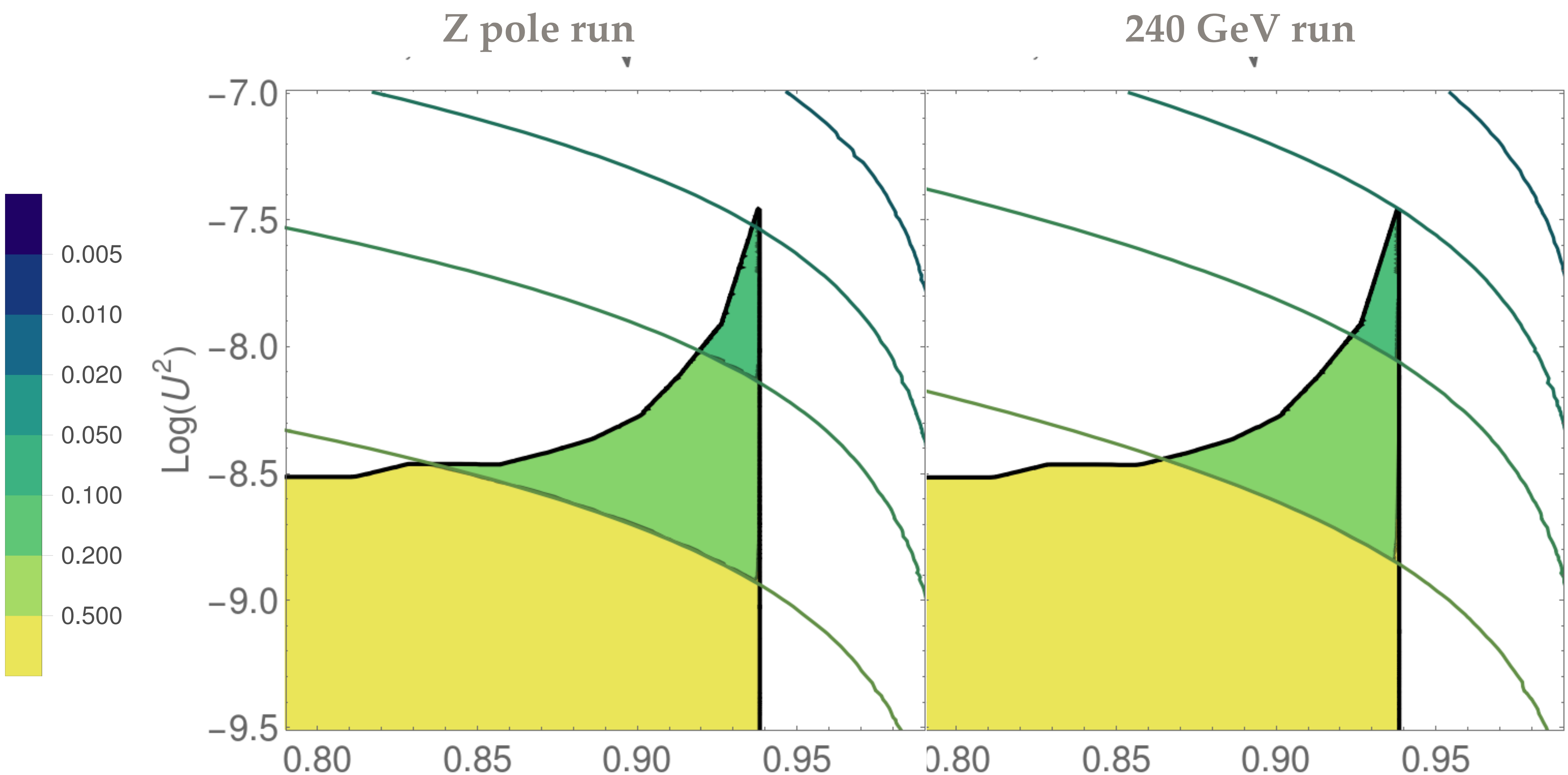


Ant

Larger masses:

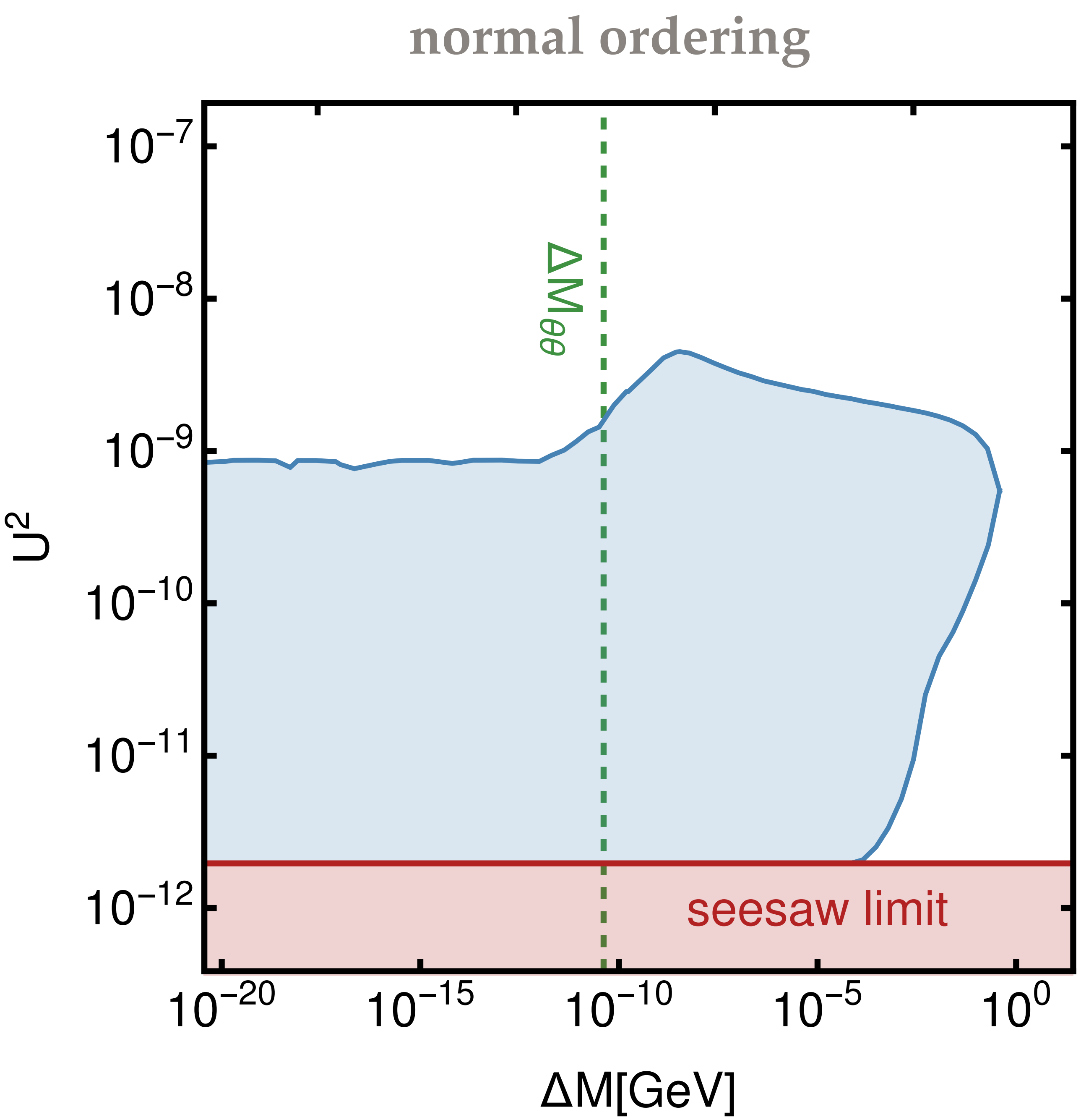
240 GeV run beats Z pole run…
…but reliable leptogenesis calculation still in progress

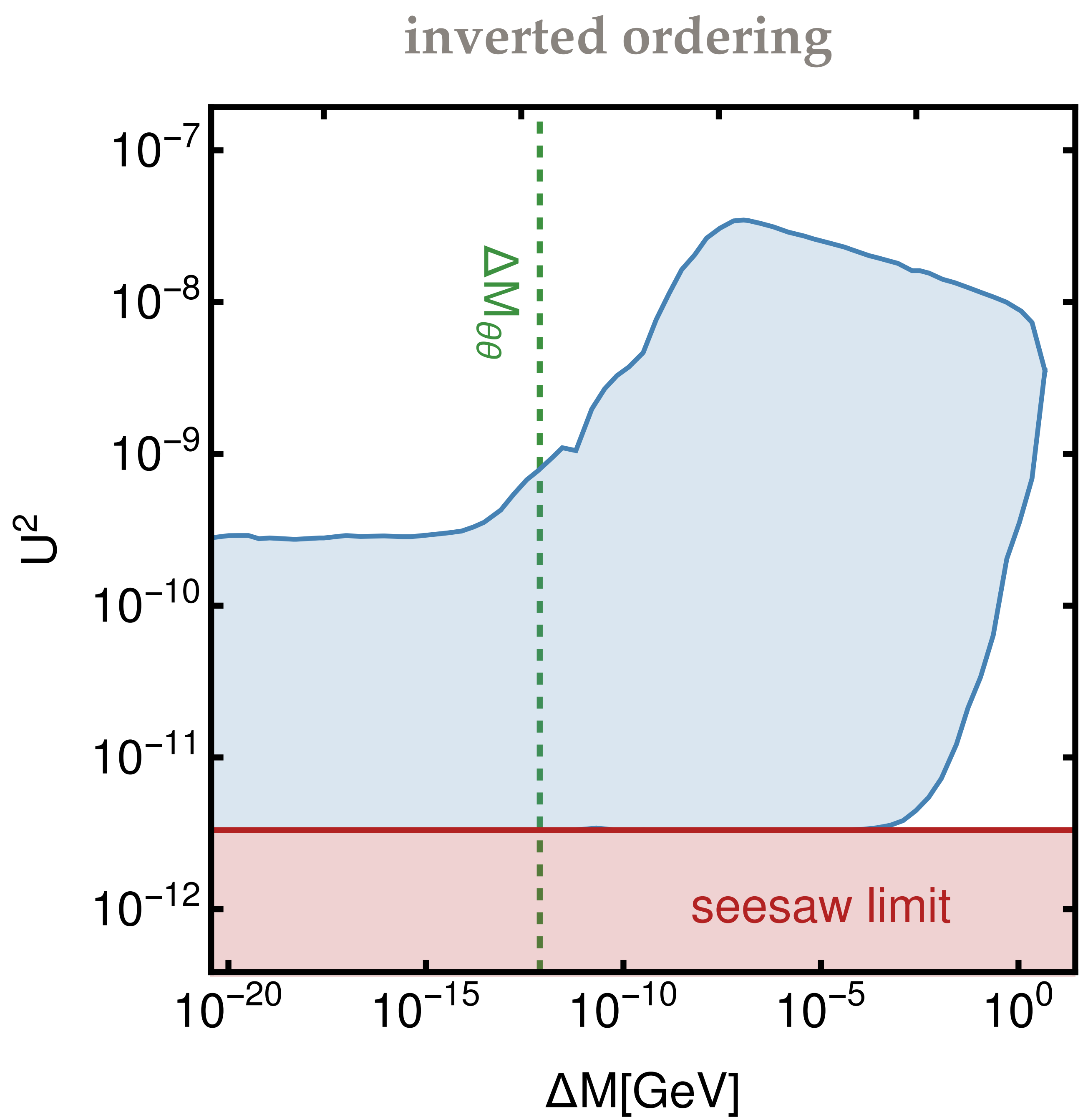
Precision of Flavour Mixing Pattern Measurements



Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Leptogenesis and Heavy Neutrino Mass Splitting





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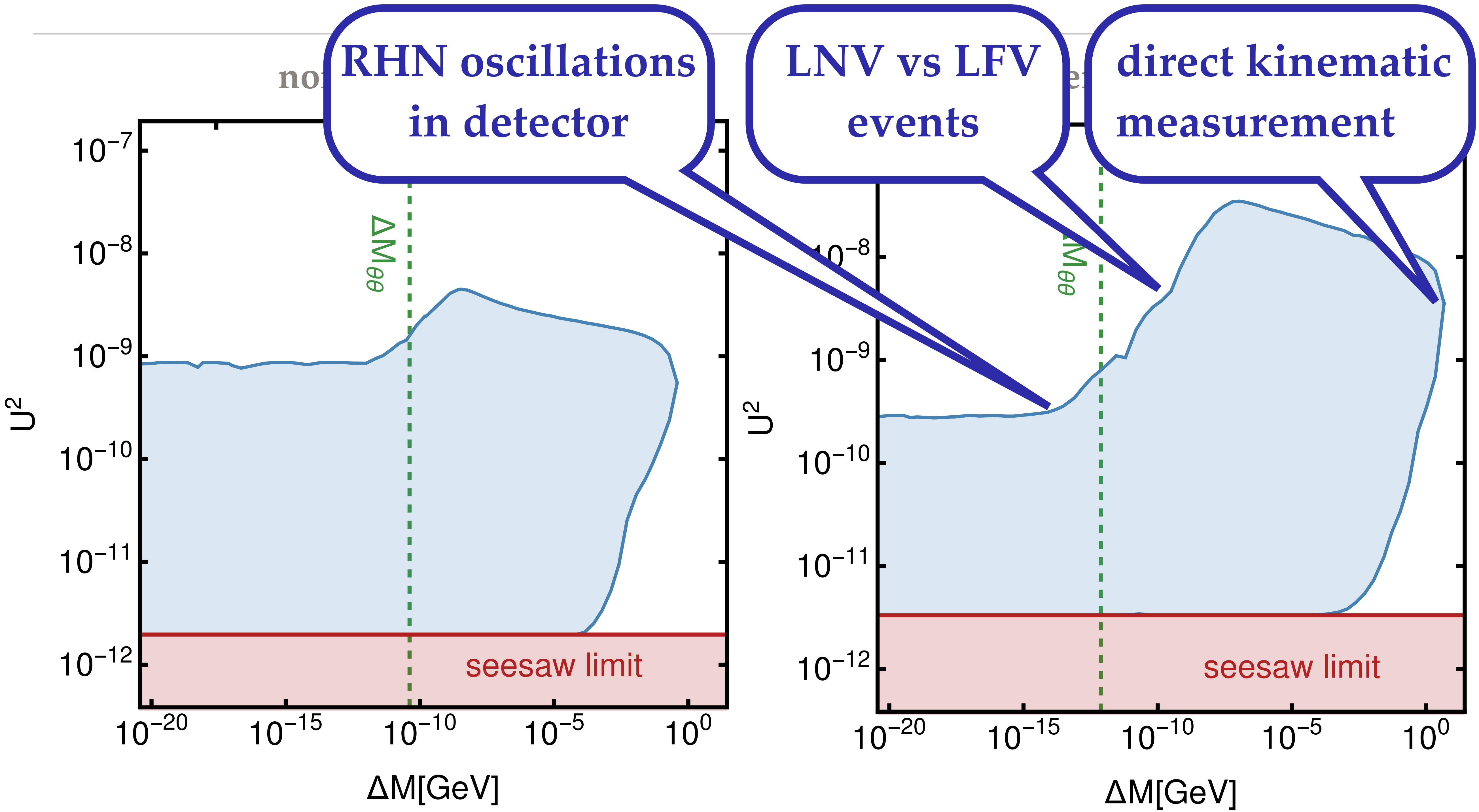

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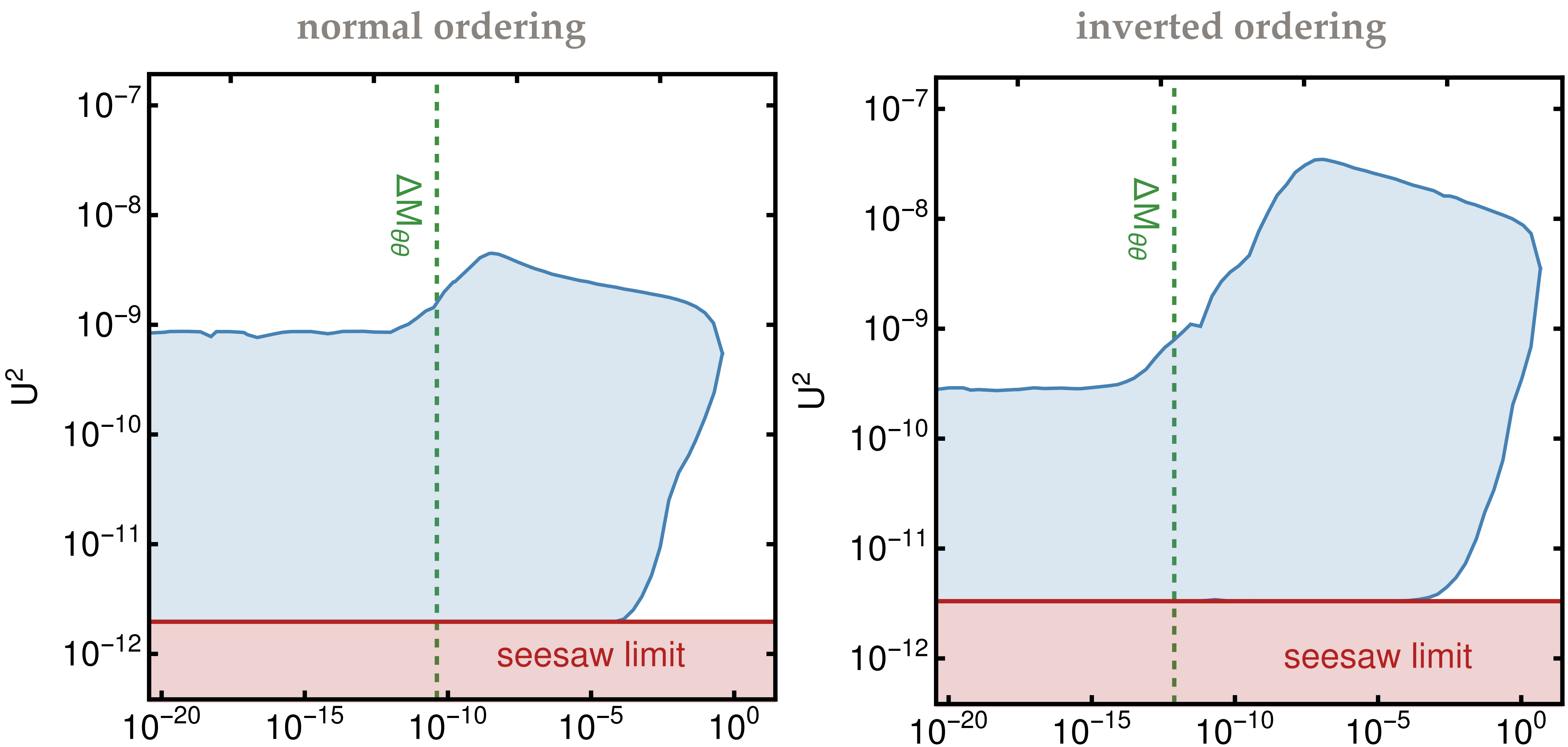


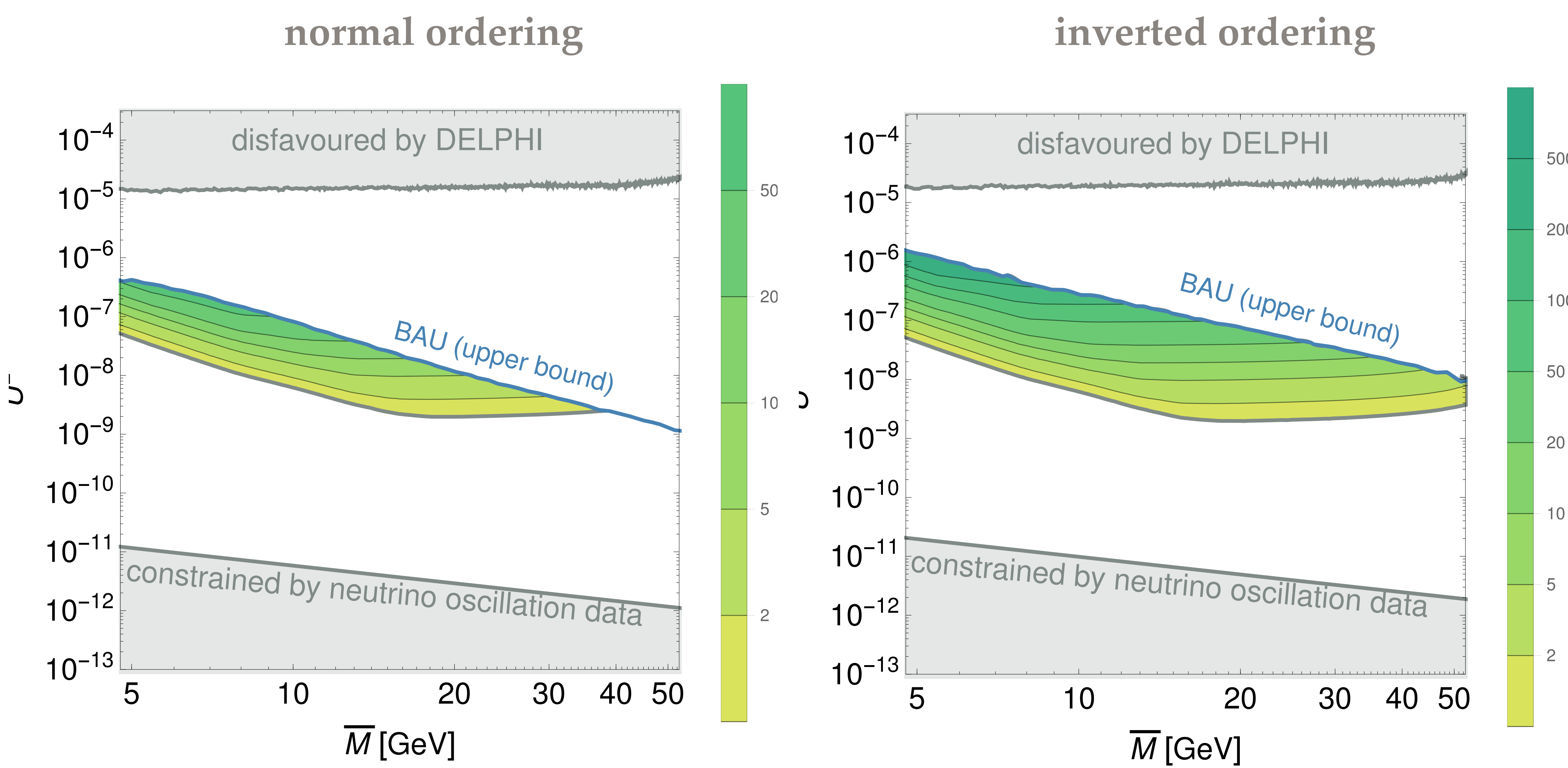
with three RH neutrinos:
no need for mass degeneracy for leptogenesis MaD/Garbrecht 12

Conclusions

- CEPC can probe the "neutrino portal" to New Physics in the Z-pole and high energy runs
- CEPC may unveil the origin of neutrino masses and provide a first test for leptogenesis as the origin of matter!
- M below Z mass: Z pole run is more promising
- M above Z mass: high energy run wins
- Flavour mixing pattern is key to test seesaw and leptogenesis hypotheses

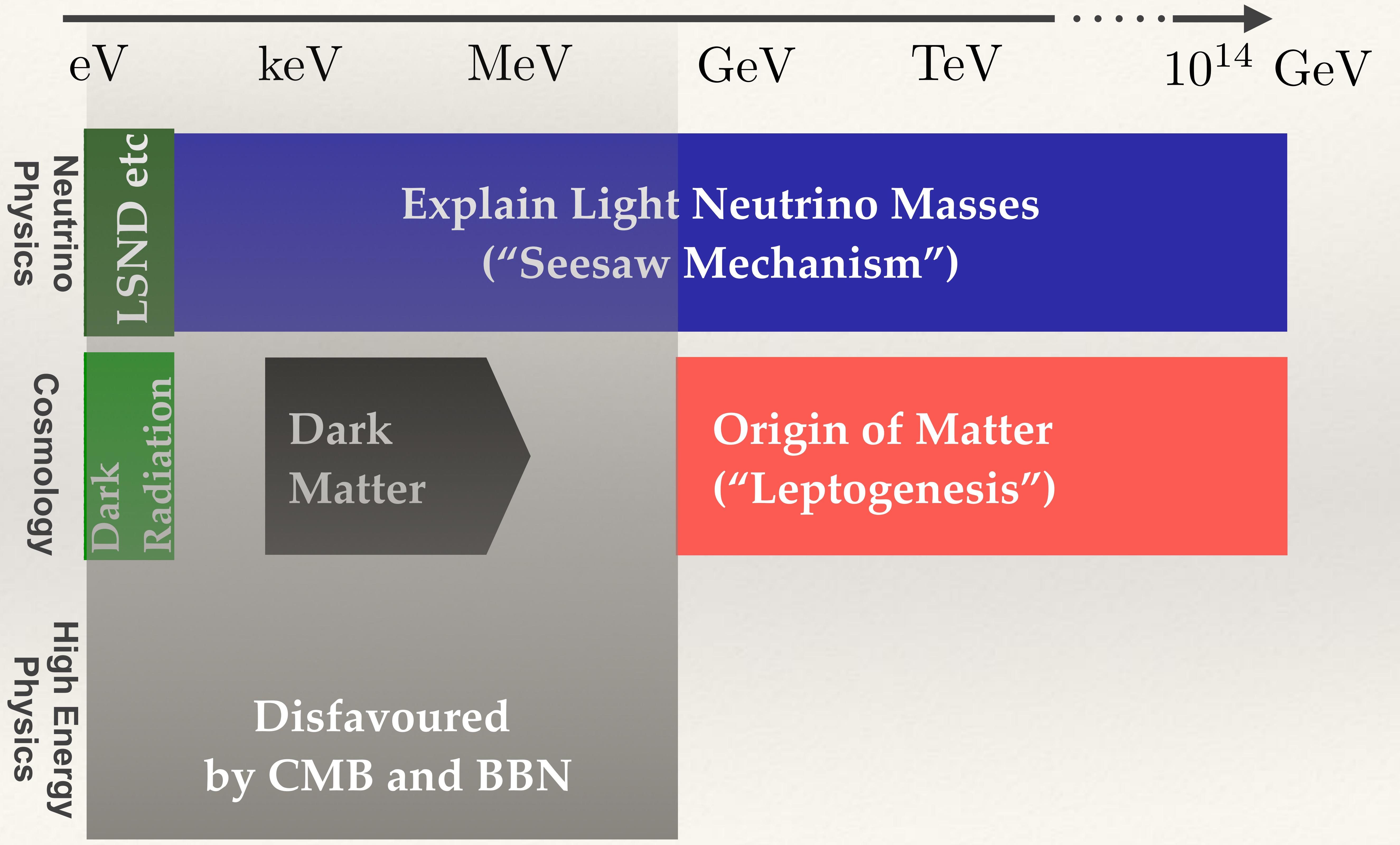
Backup Slides

Number of Events

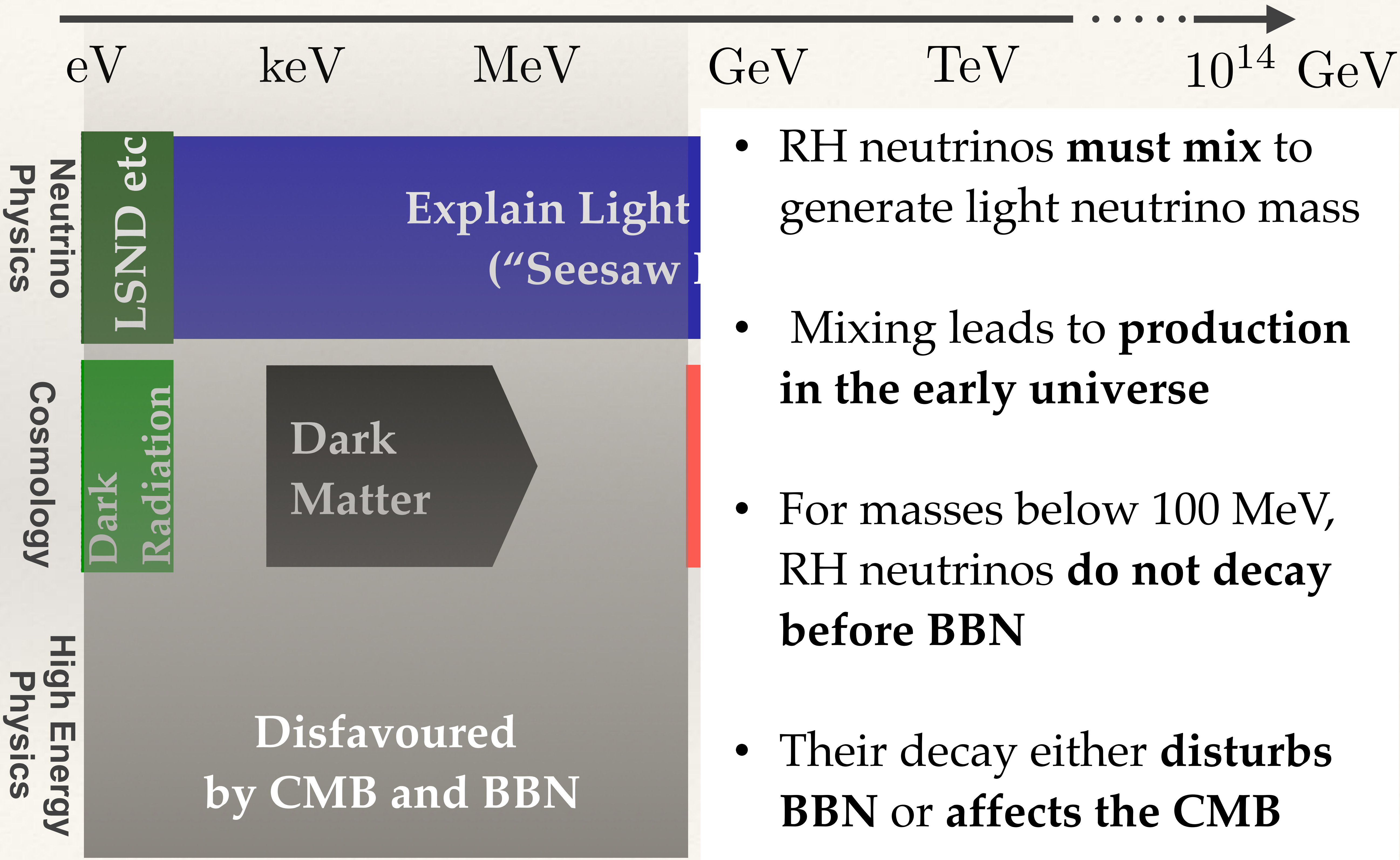


Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Right Handed Neutrinos and the Light Neutrino Masses

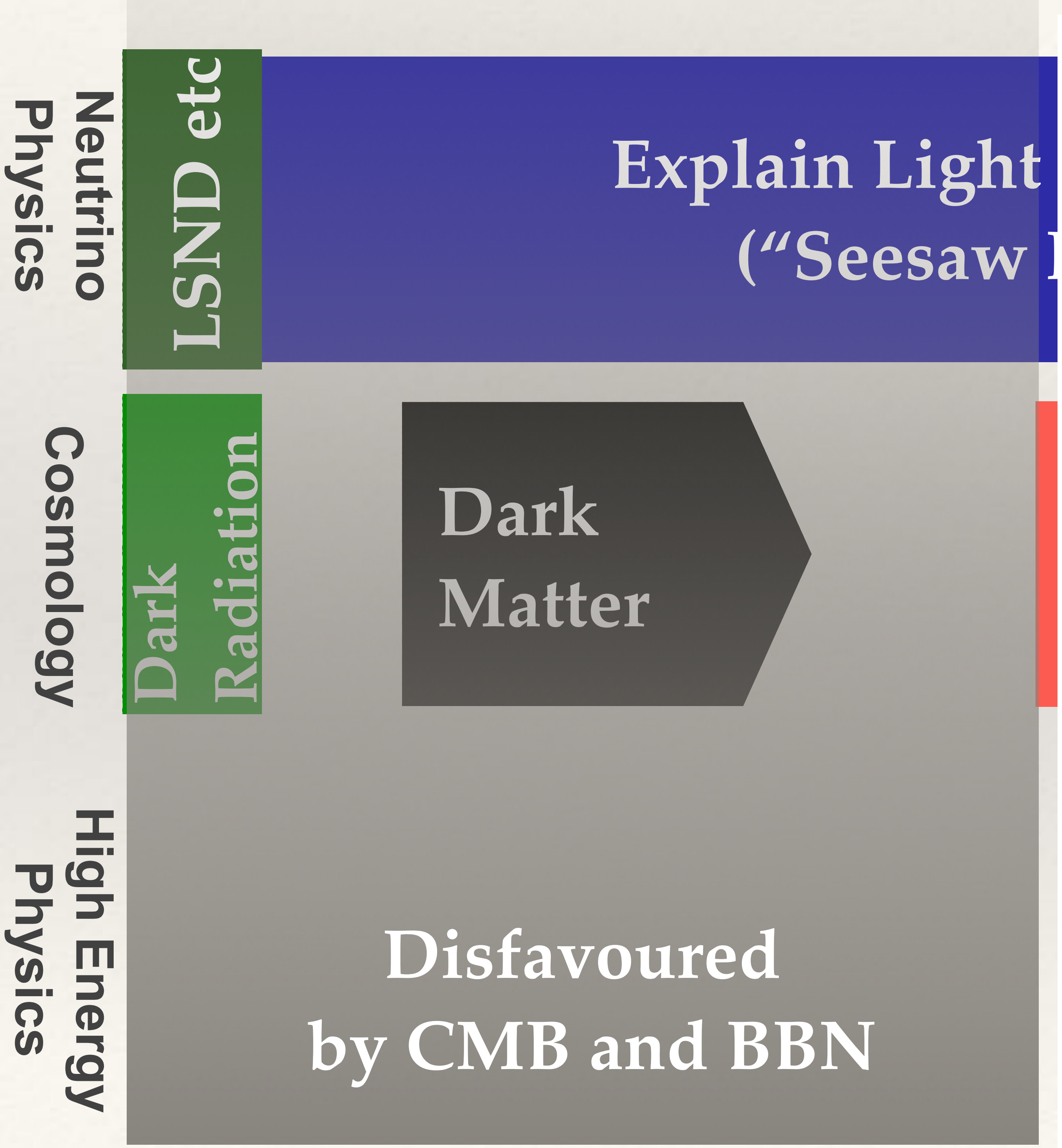


Right Handed Neutrinos and the Light Neutrino Masses

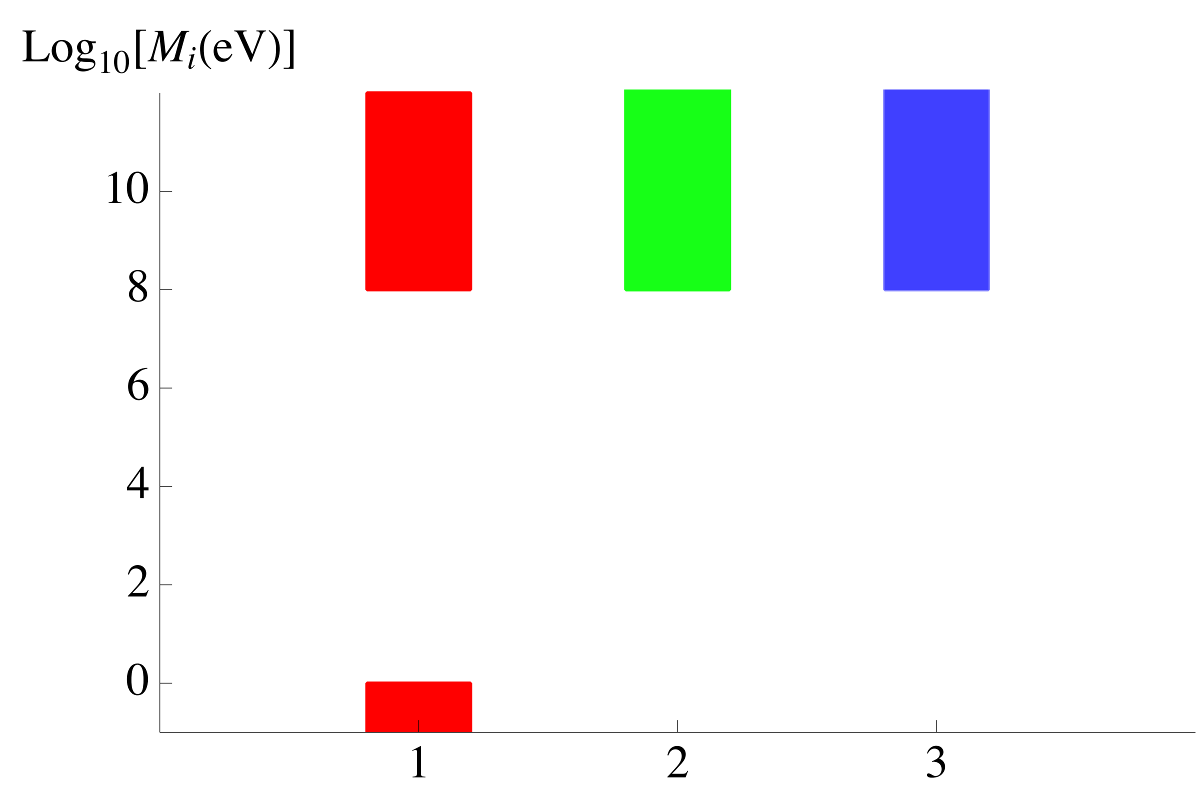


- RH neutrinos **must mix** to generate light neutrino mass
- Mixing leads to **production in the early universe**
- For masses below 100 MeV, RH neutrinos **do not decay before BBN**
- Their decay either **disturbs BBN** or **affects the CMB**

Right Handed Neutrinos and the Light Neutrino Masses

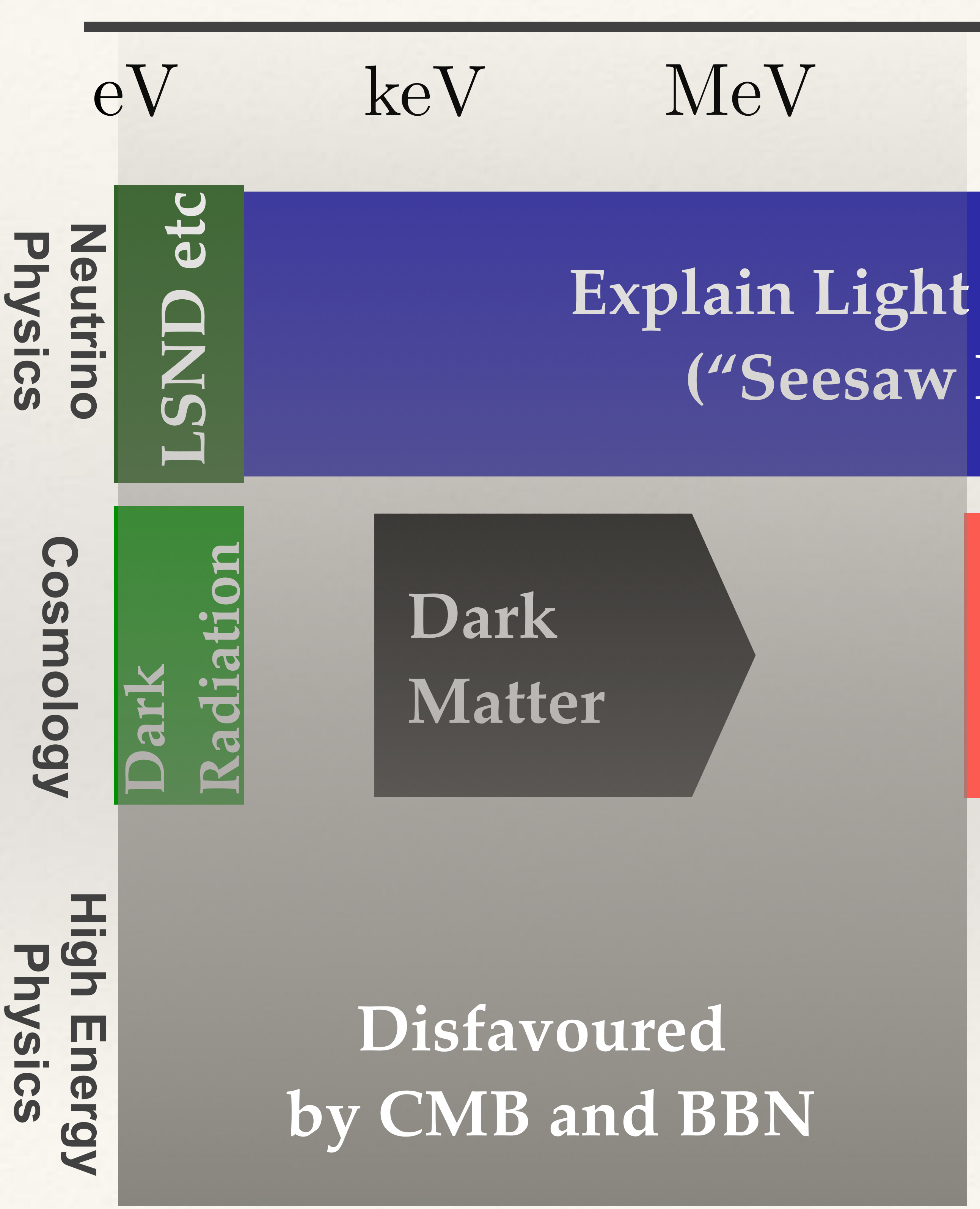


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} > 10^{-3}$ eV, three RHN reach equilibrium

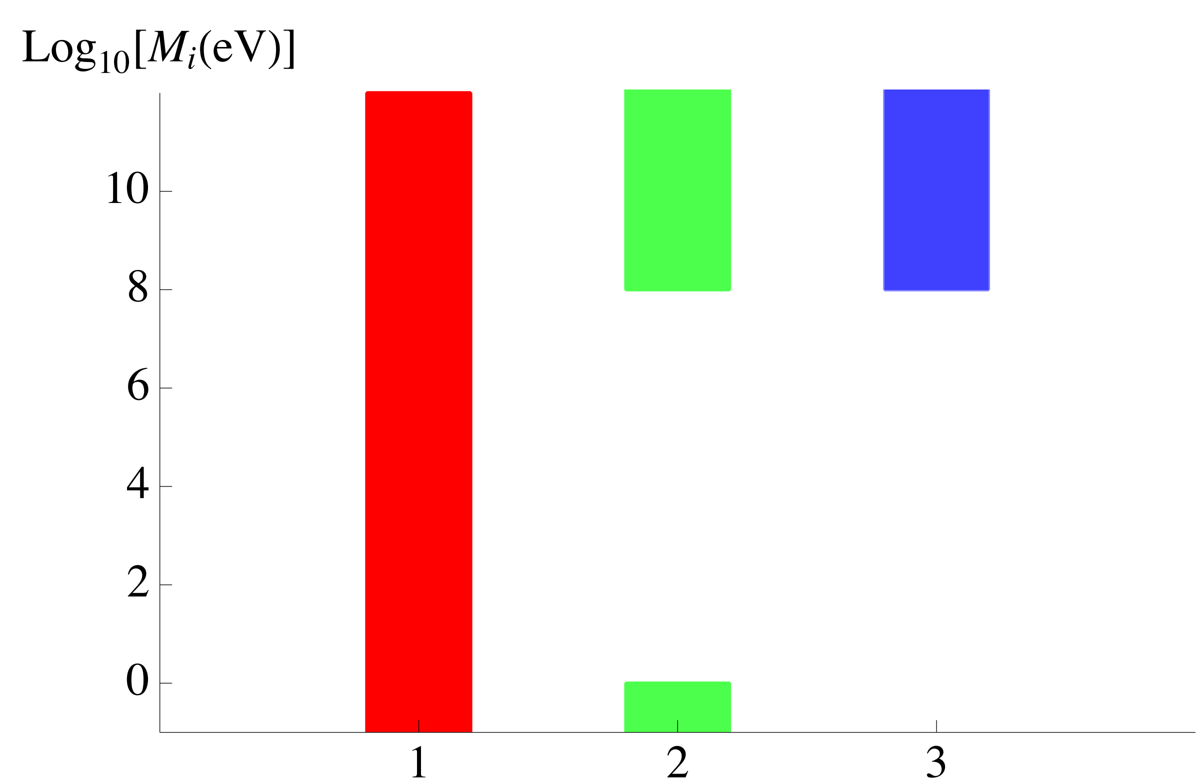


Hernandez/Kekic/Lopez-Pavon 1406.2961

Right Handed Neutrinos and the Light Neutrino Masses



- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} < 10^{-3}$ eV, one RHN almost decouples



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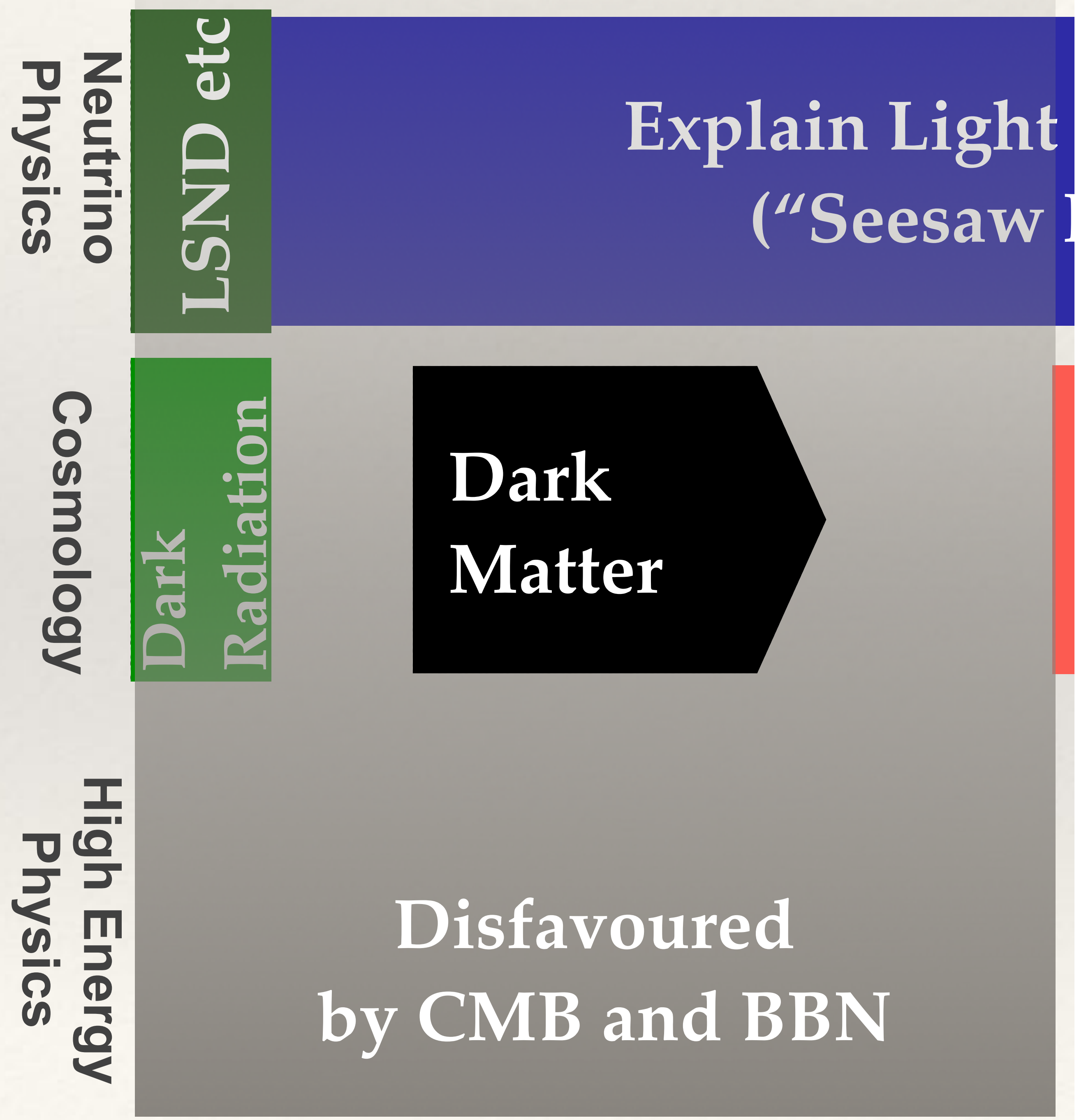
Right Handed Neutrinos and the Light Neutrino Masses



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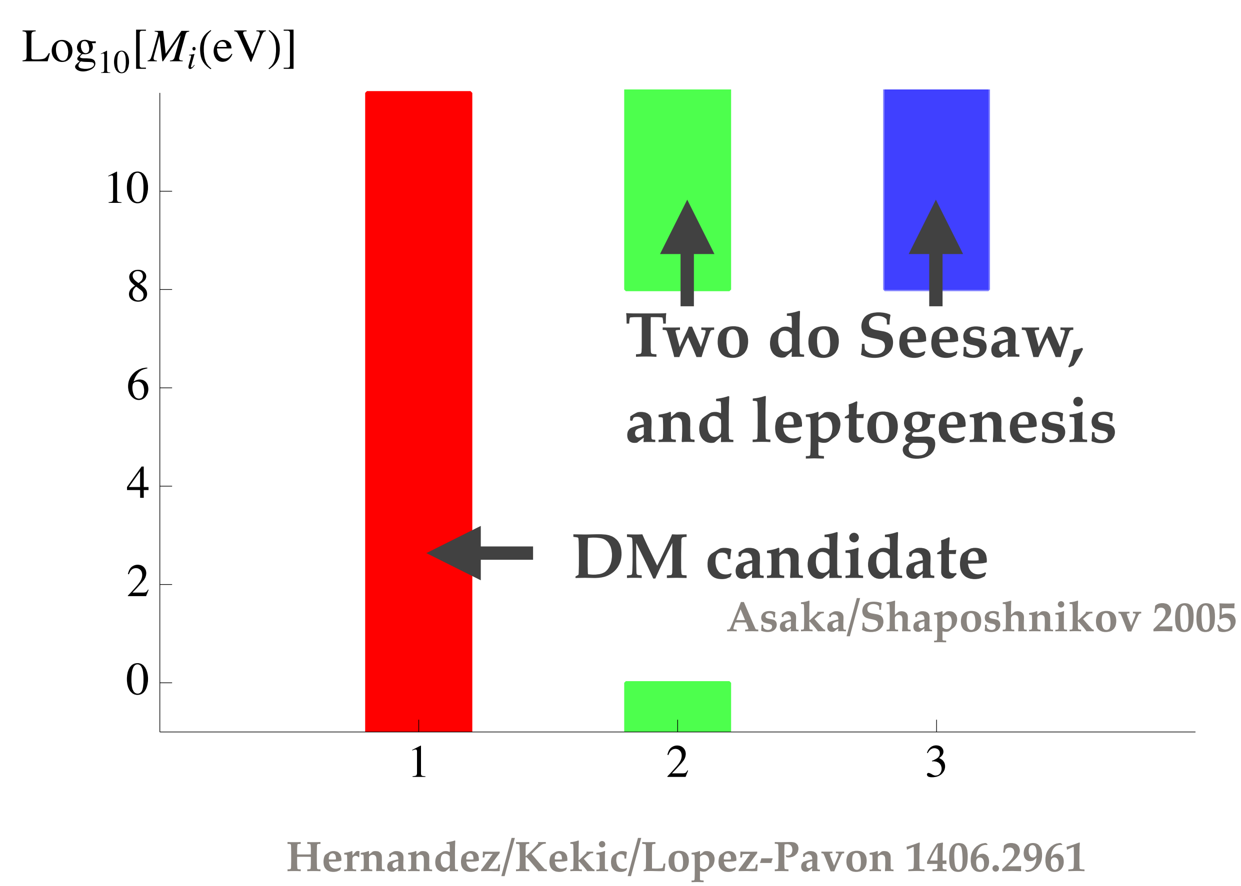
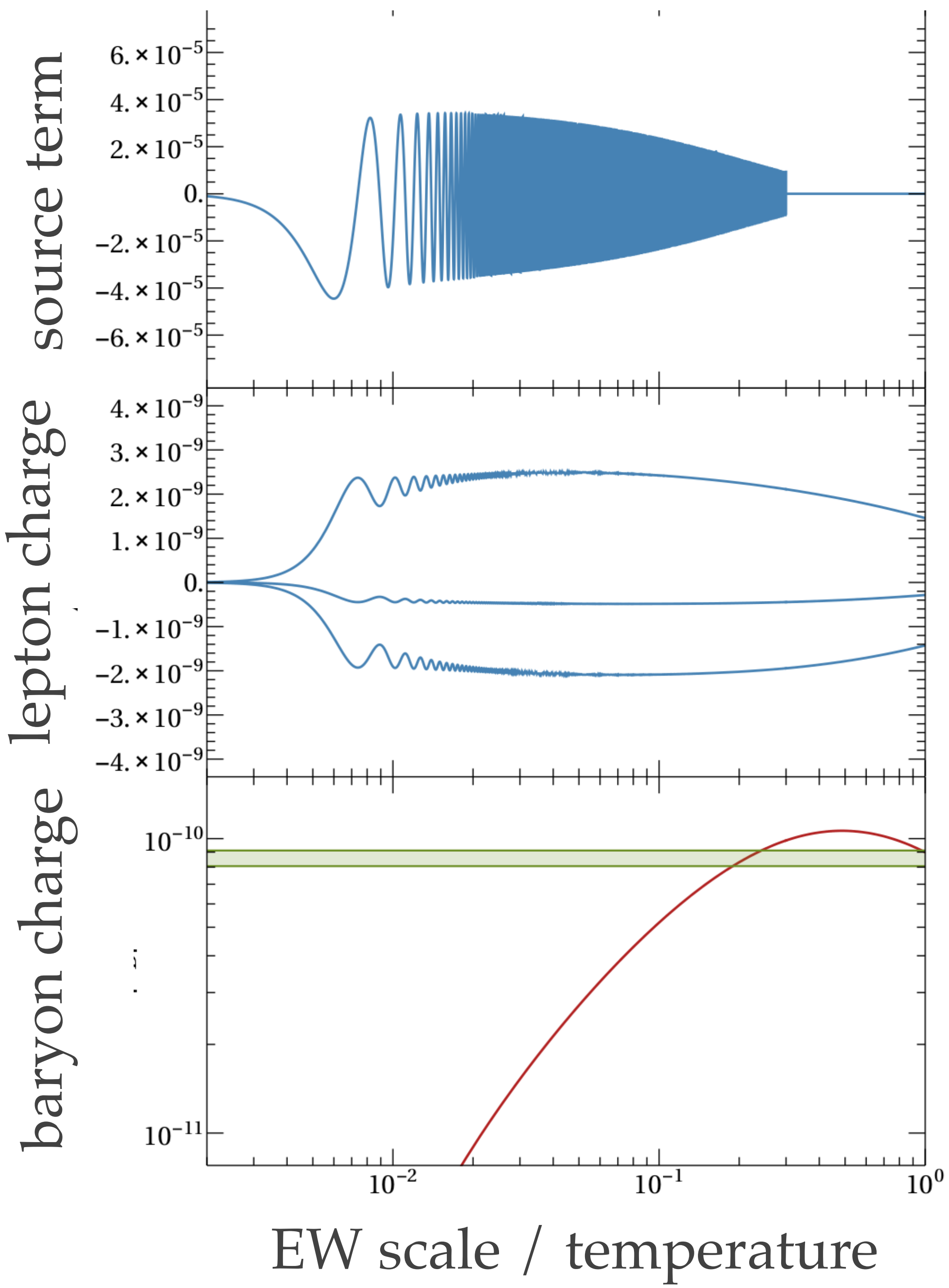


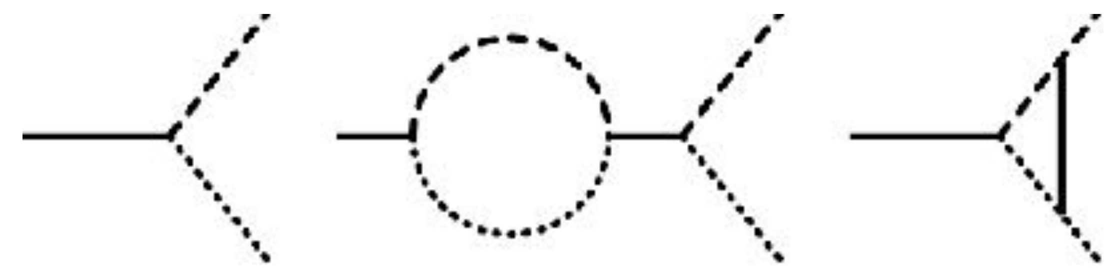
Heavy Neutrinos as the Origin of Matter

Leptogenesis from heavy neutrino oscillations



GeV TeV 10^{14} GeV

Leptogenesis in heavy neutrino decay



Origin of Matter (“Leptogenesis”)