Marco Drewes, Université catholique de Louvain

06.11.2017

CEPC and The Neutrino Connection

International Workshop on
High Energy Circular Electron
Positron Collider

IHEP Beijing

Two Key Problems

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

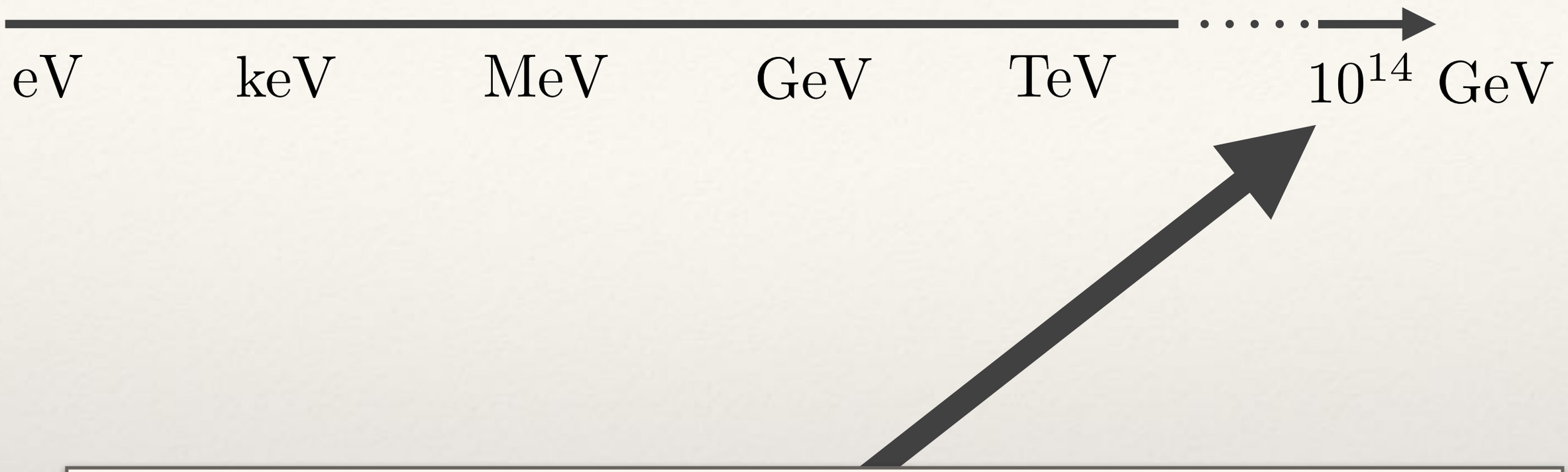
  Possible key to embed Standard Model in a more fundamental theory of Nature

- **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

Where are the new particles?



Traditionally:
assume large mass for theoretical reasons
("naturalness", grand unification)

experimentally inaccessible

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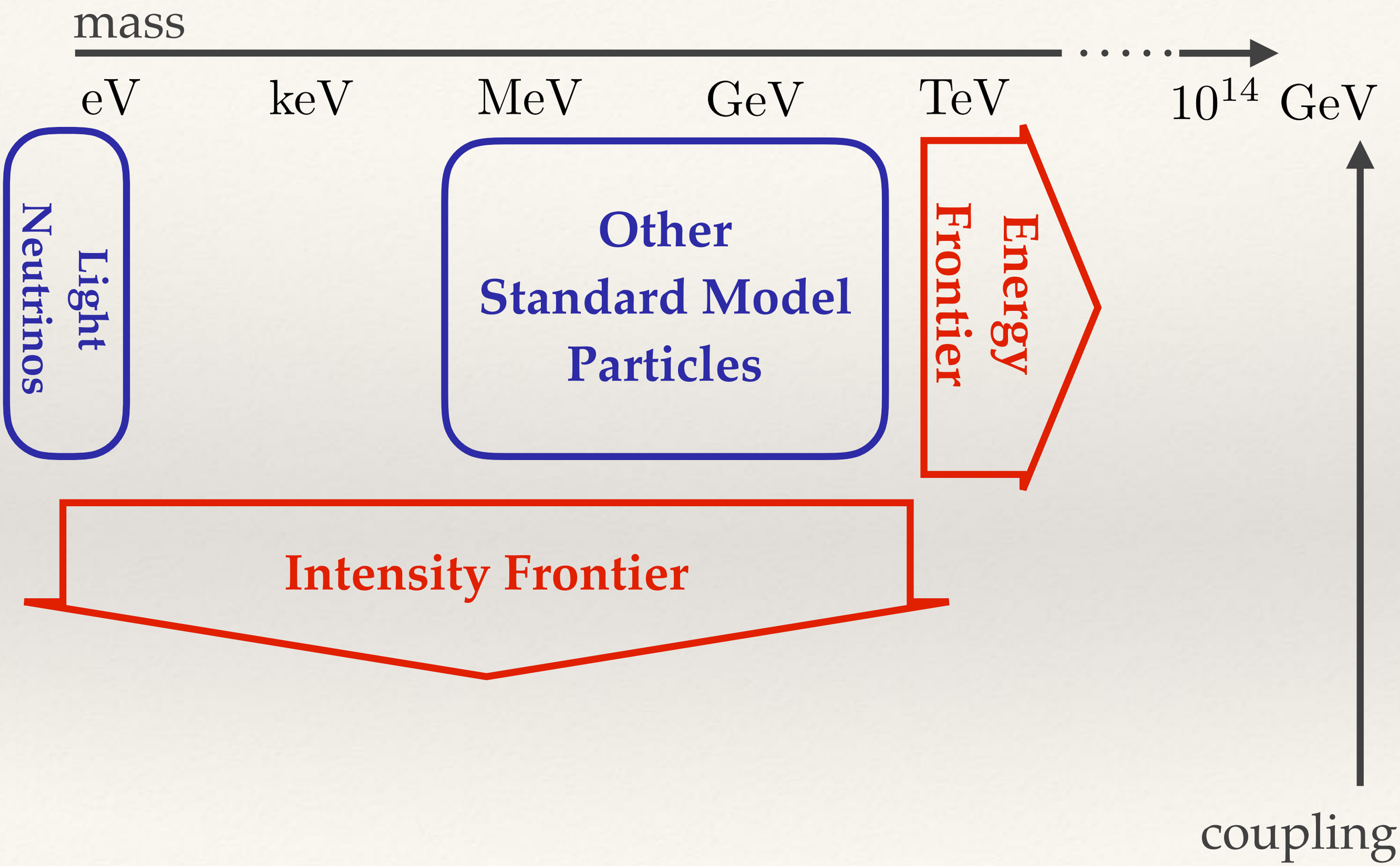

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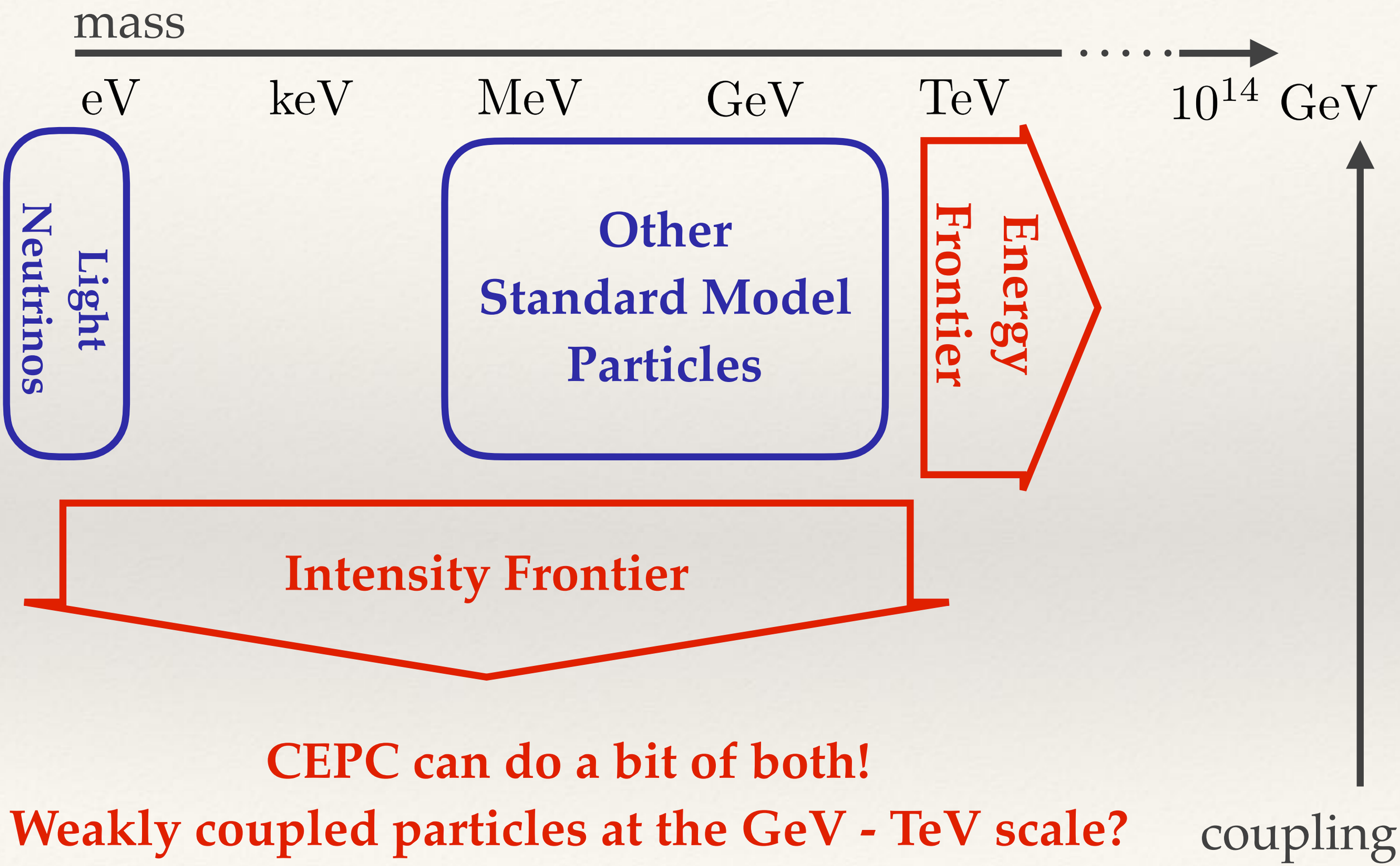
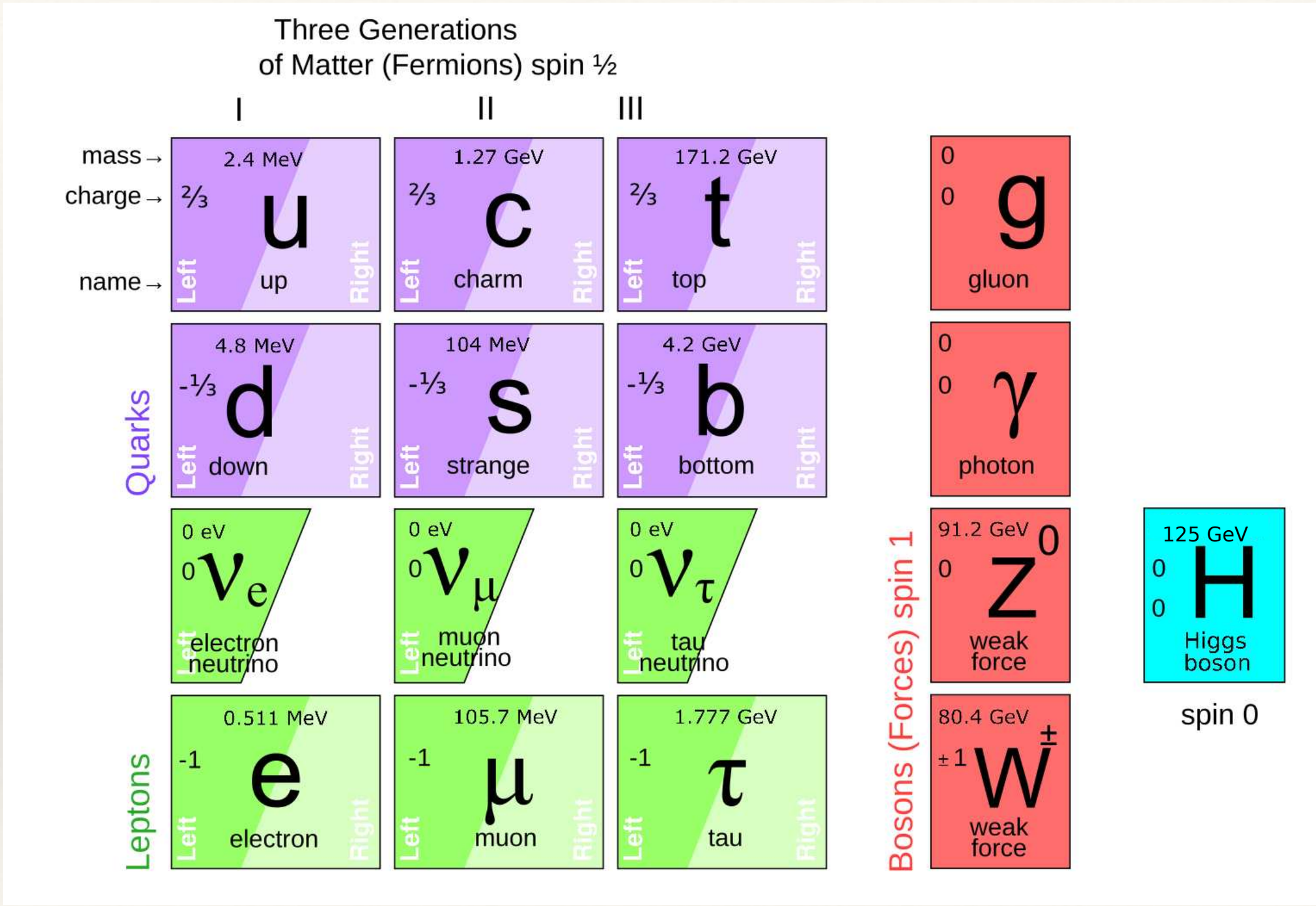


CEPC can do a bit of both!

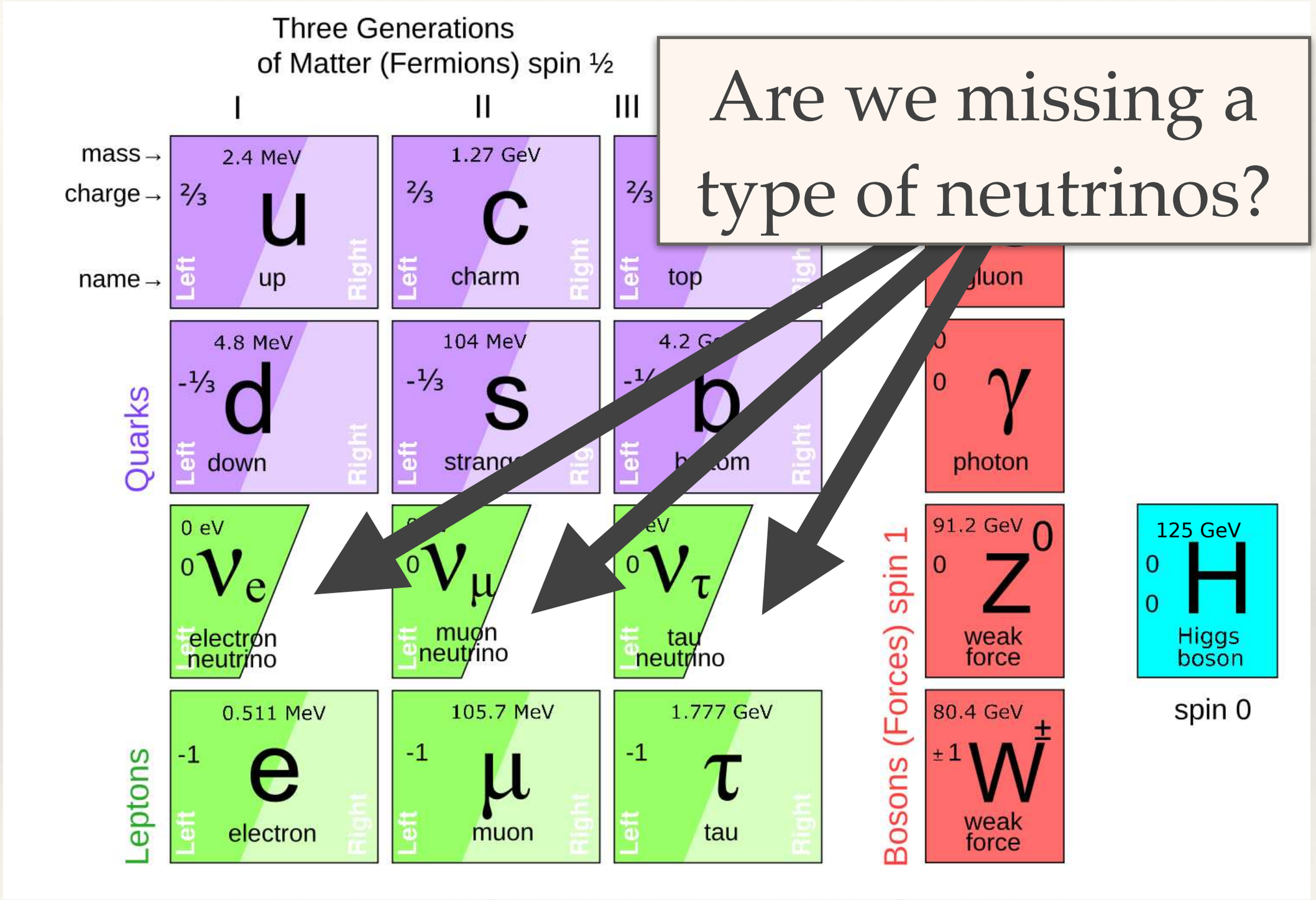
Weakly coupled particles at the GeV - TeV scale?

The Standard Model of Particle Physics



The "periodic table" of elementary particles

The Standard Model of Particle Physics



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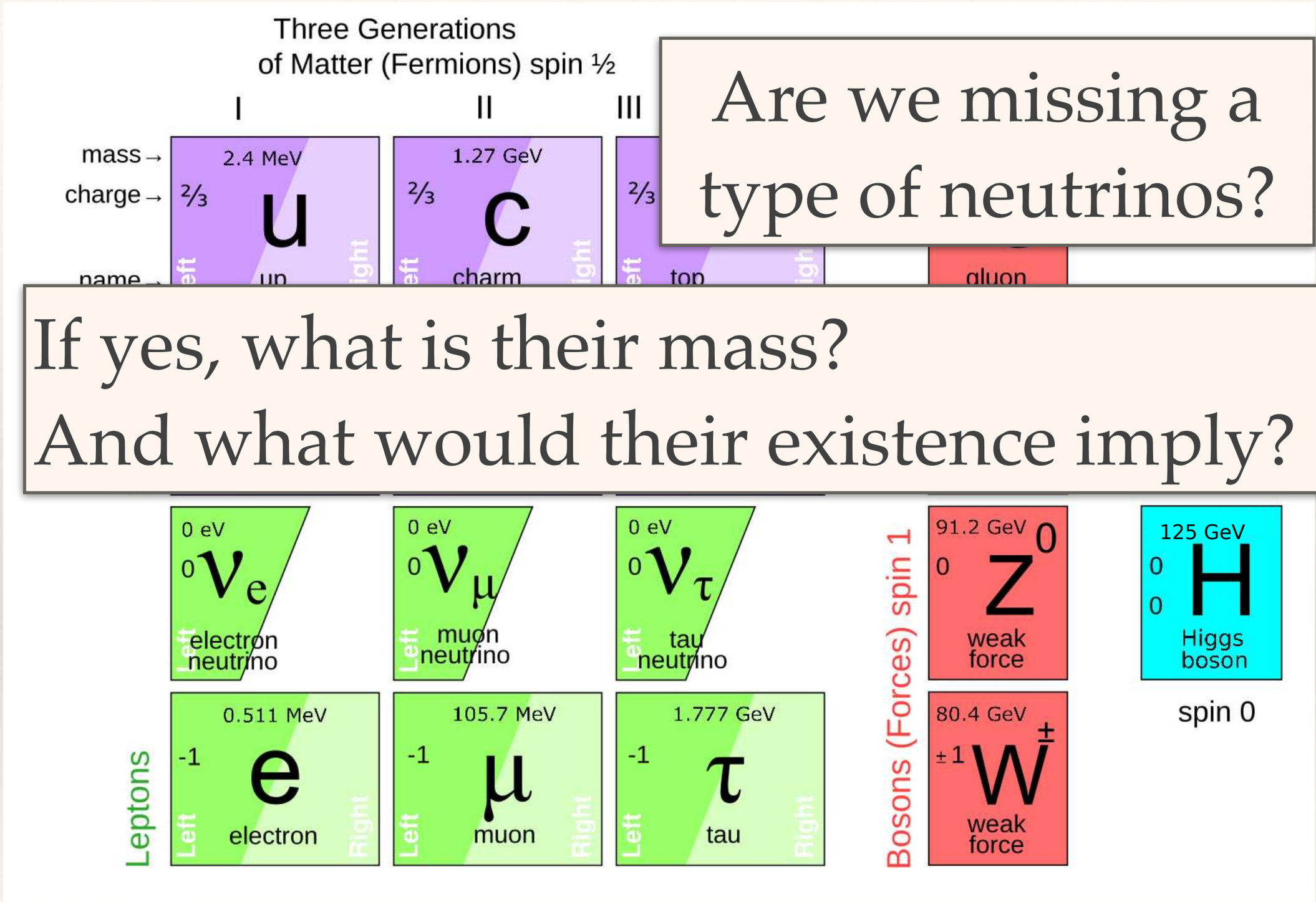

Are we missing a type of neutrinos?

If yes, what is their mass?

And what would their existence imply?

The "periodic table" of elementary particles

Heavy Neutrinos Could Solve Key Problems

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

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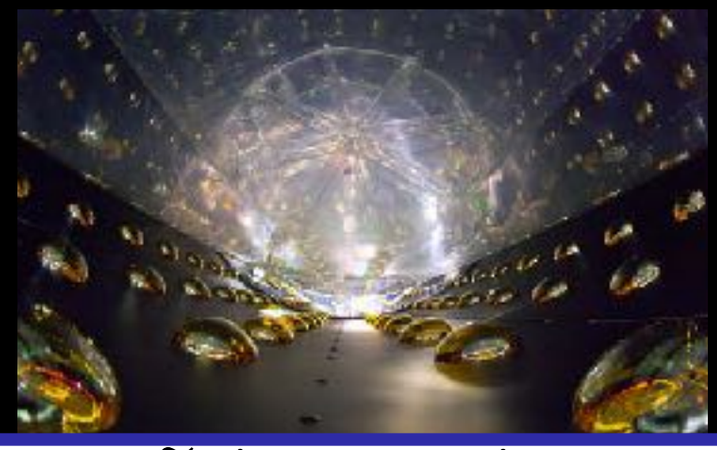

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$

$$-\frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

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

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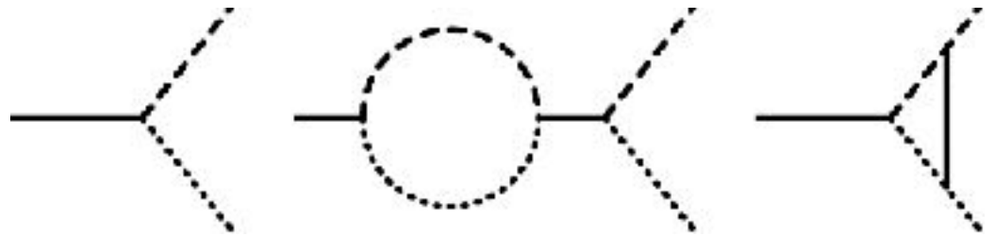
Leptogenesis

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



⇒ Nonequilibrium quantum process produces matter excess

Right Handed Neutrinos in Cosmology

Neutrino Physics

LSND etc

Explain Light Neutrino Masses ("Seesaw Mechanism")

Cosmology

Dark Radiation

Dark Matter

Origin of Matter ("Leptogenesis")

High Energy Physics

Heavy Neutrinos as the Origin of Matter

Neutrino Physics

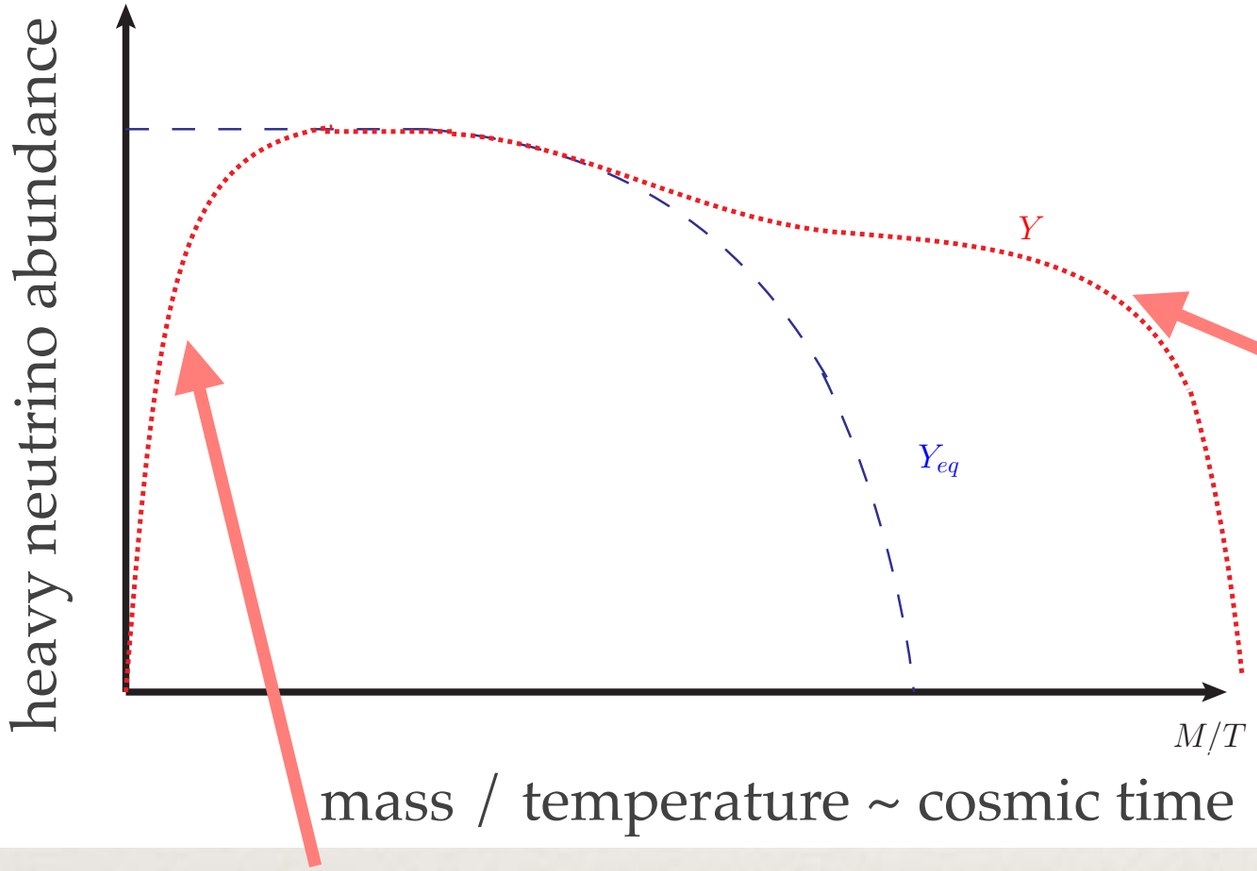
Cosmology

High Energy Physics

Origin of Matter ("Leptogenesis")

Sakharov Conditions

- baryon number violation
- C and CP violation
- nonequilibrium



Origin 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

Neutrino Physics

Explain Light Neutrino Masses ("Seesaw Mechanism")

Cosmology

High Energy Physics

Origin of Matter ("Leptogenesis")

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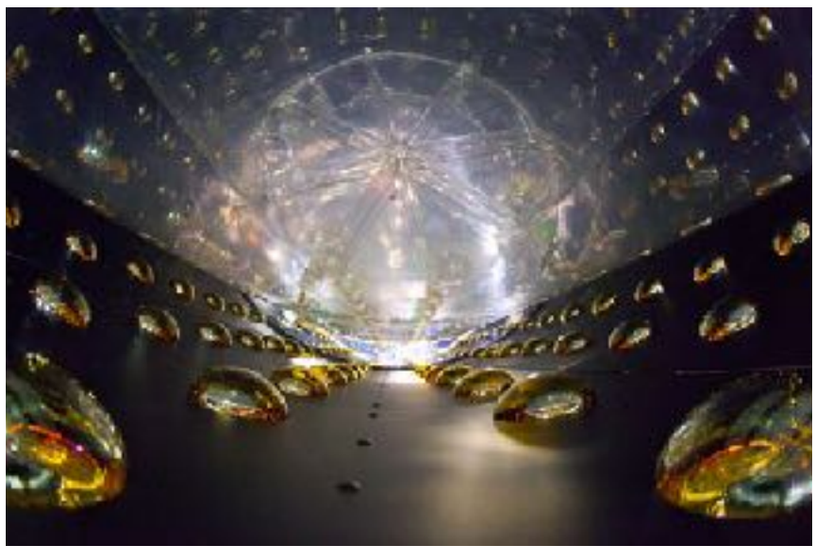
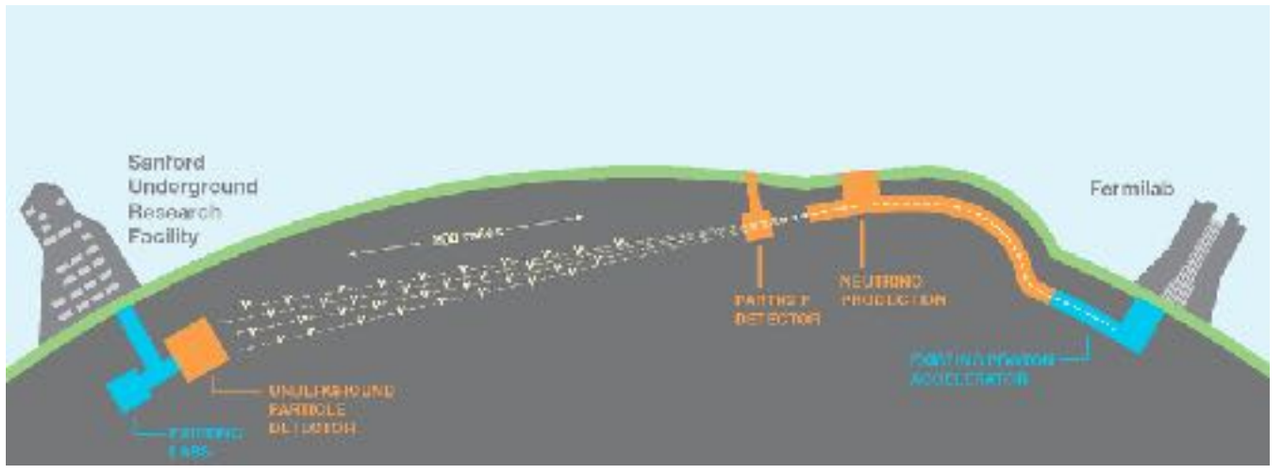


neutrino oscillation data



How to Find Heavy Neutrinos?

Neutrino Physics

Explain Light Neutrino Masses ("Seesaw Mechanism")

Cosmology

Origin of Matter ("Leptogenesis")

High Energy Physics

Direct Searches

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?

Neutrino Physics

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Origin of Matter ("Leptogenesis")

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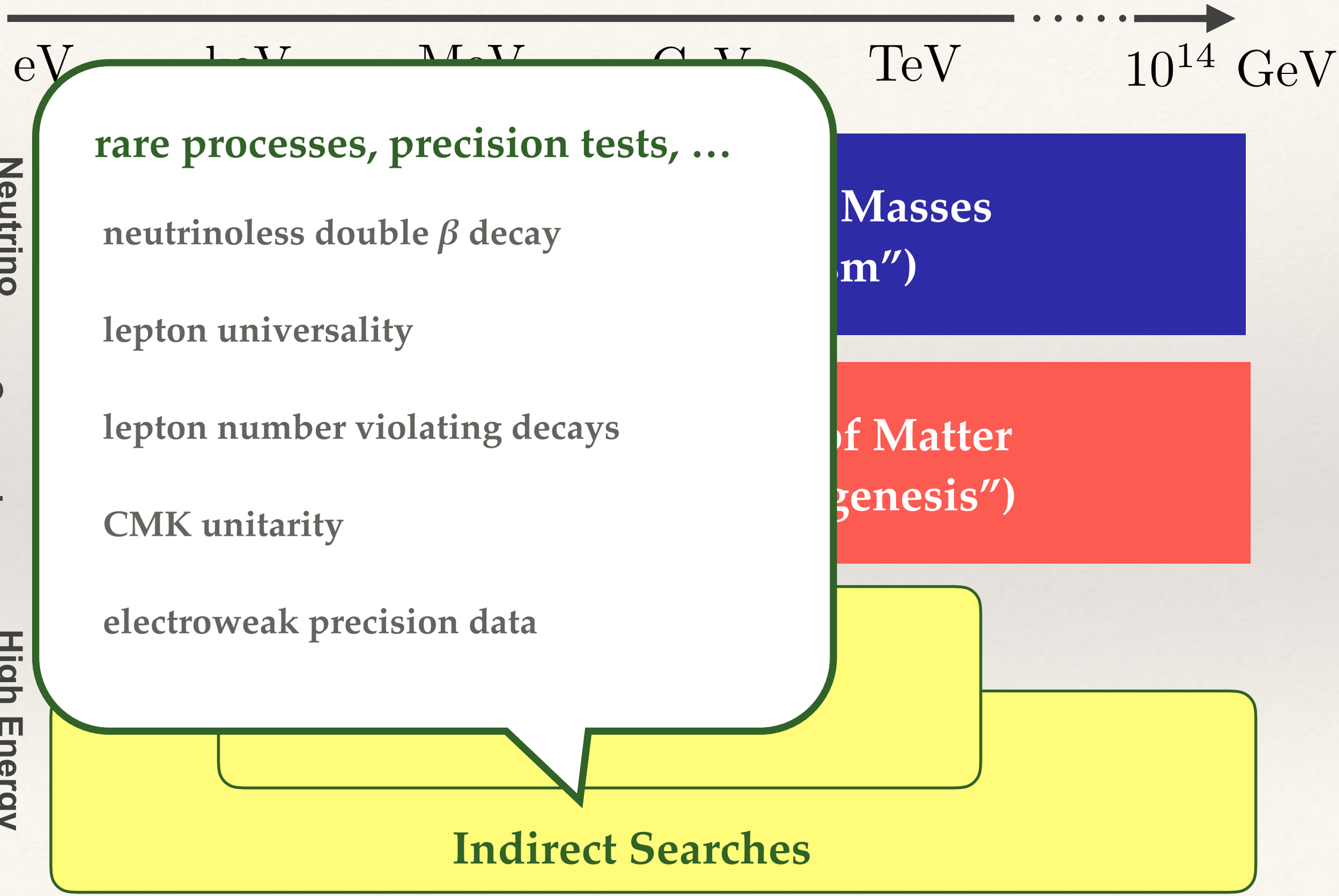
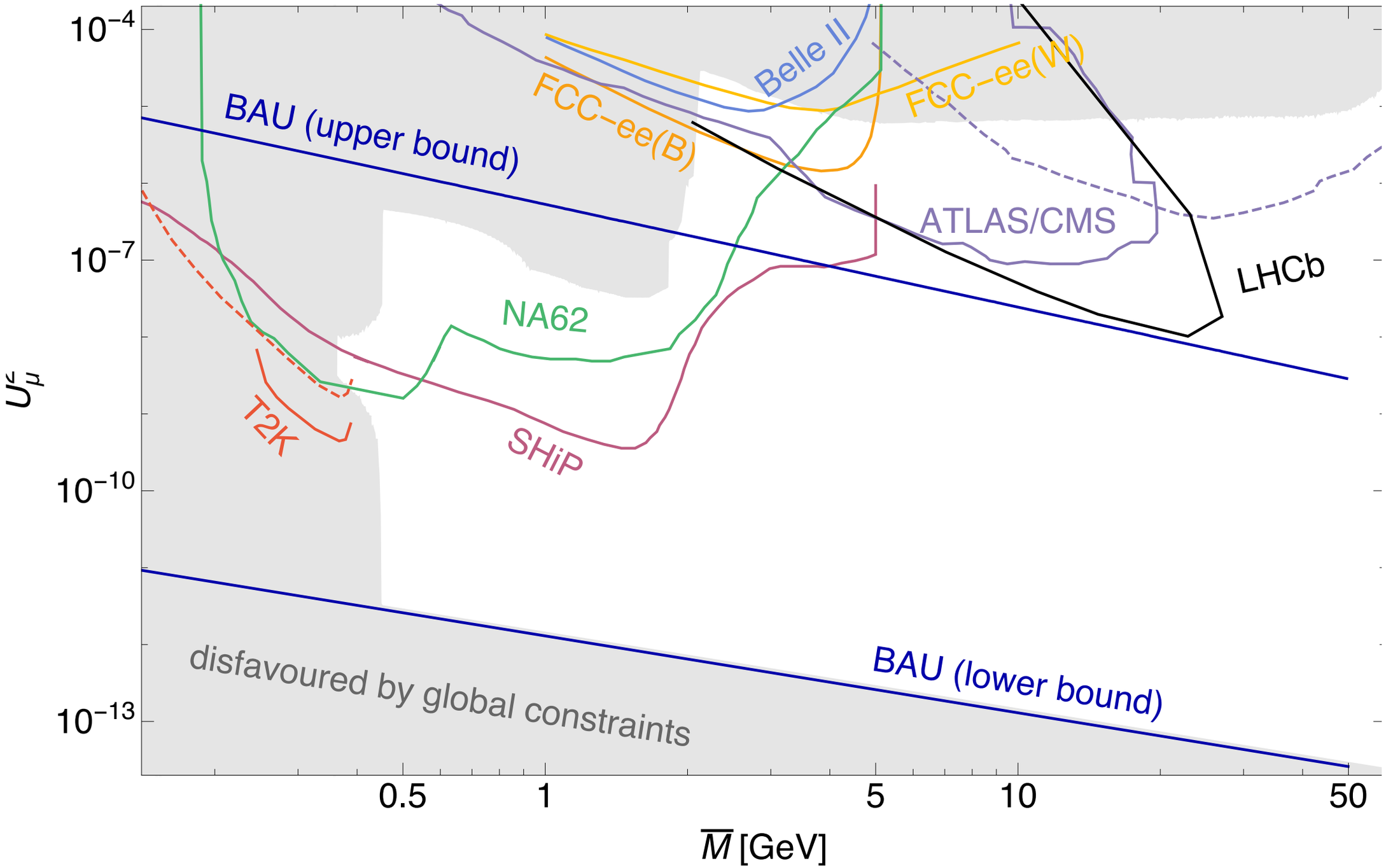
Direct Searches

Indirect Searches

How to Find Heavy Neutrinos?



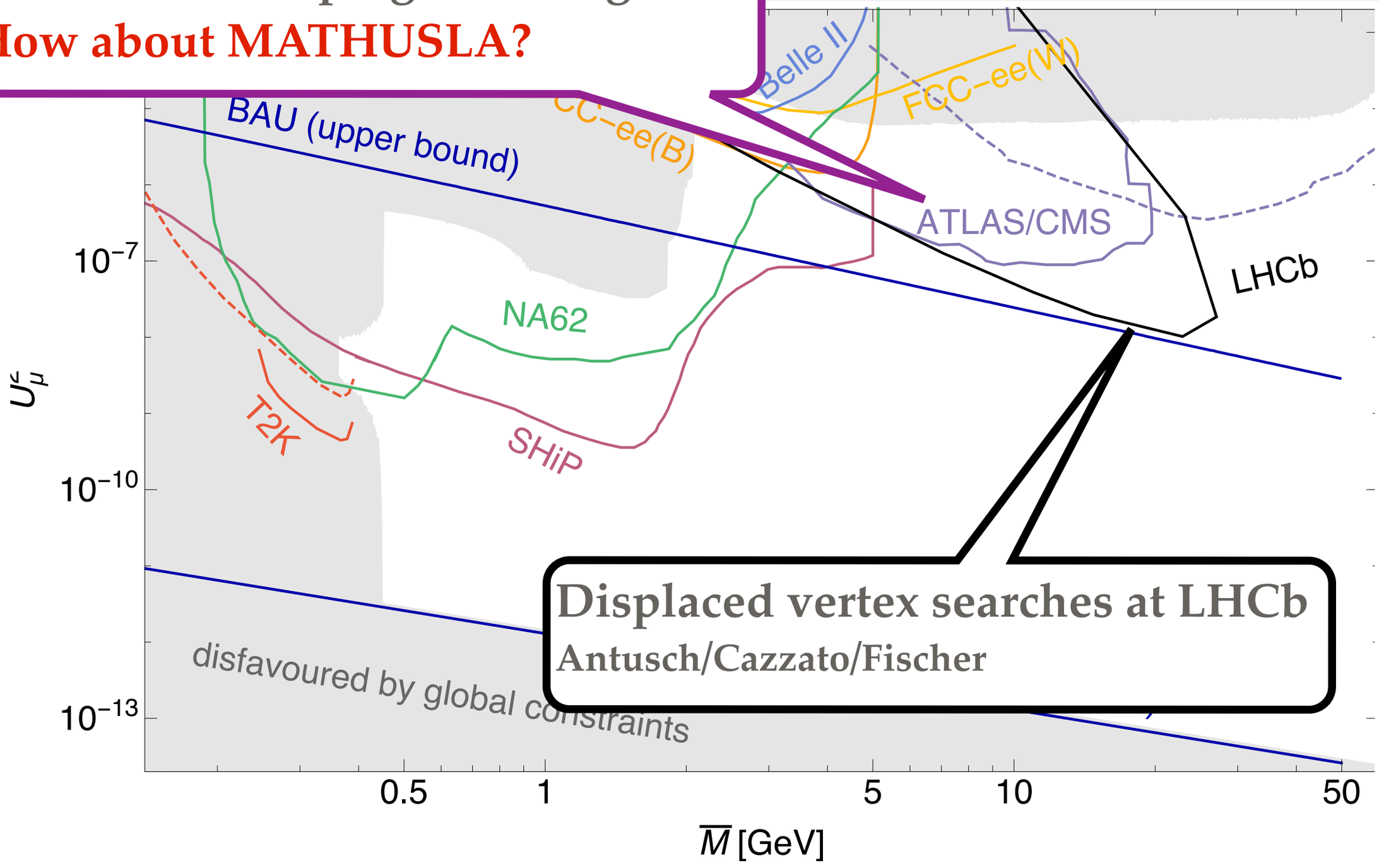
Experimental Perspectives



plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Perspectives

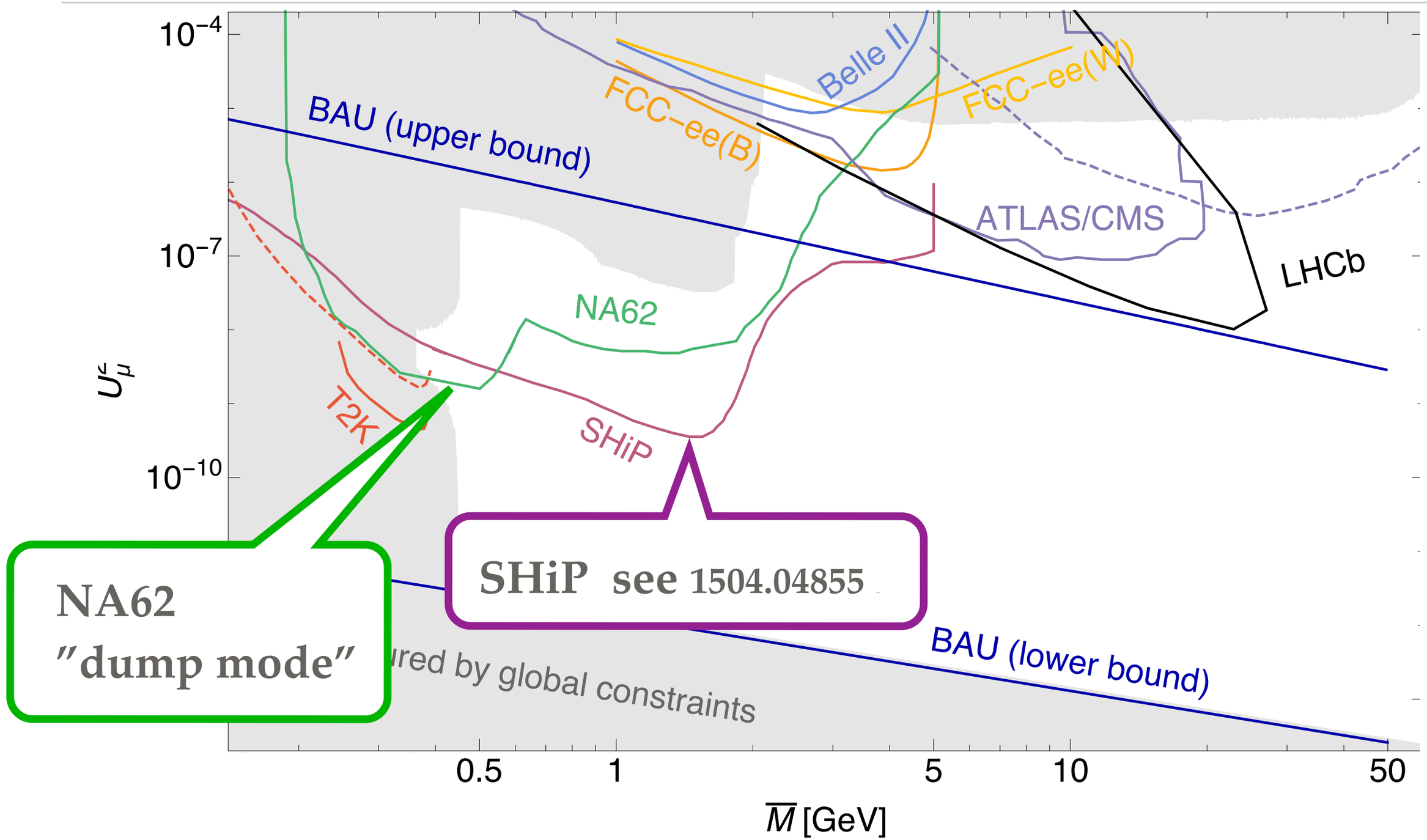
ATLAS/CMS (Izaguirre/Shuve)
Hard to reach leptogenesis region
How about MATHUSLA?



Displaced vertex searches at LHCb
Antusch/Cazzato/Fischer

plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Experimental Perspectives



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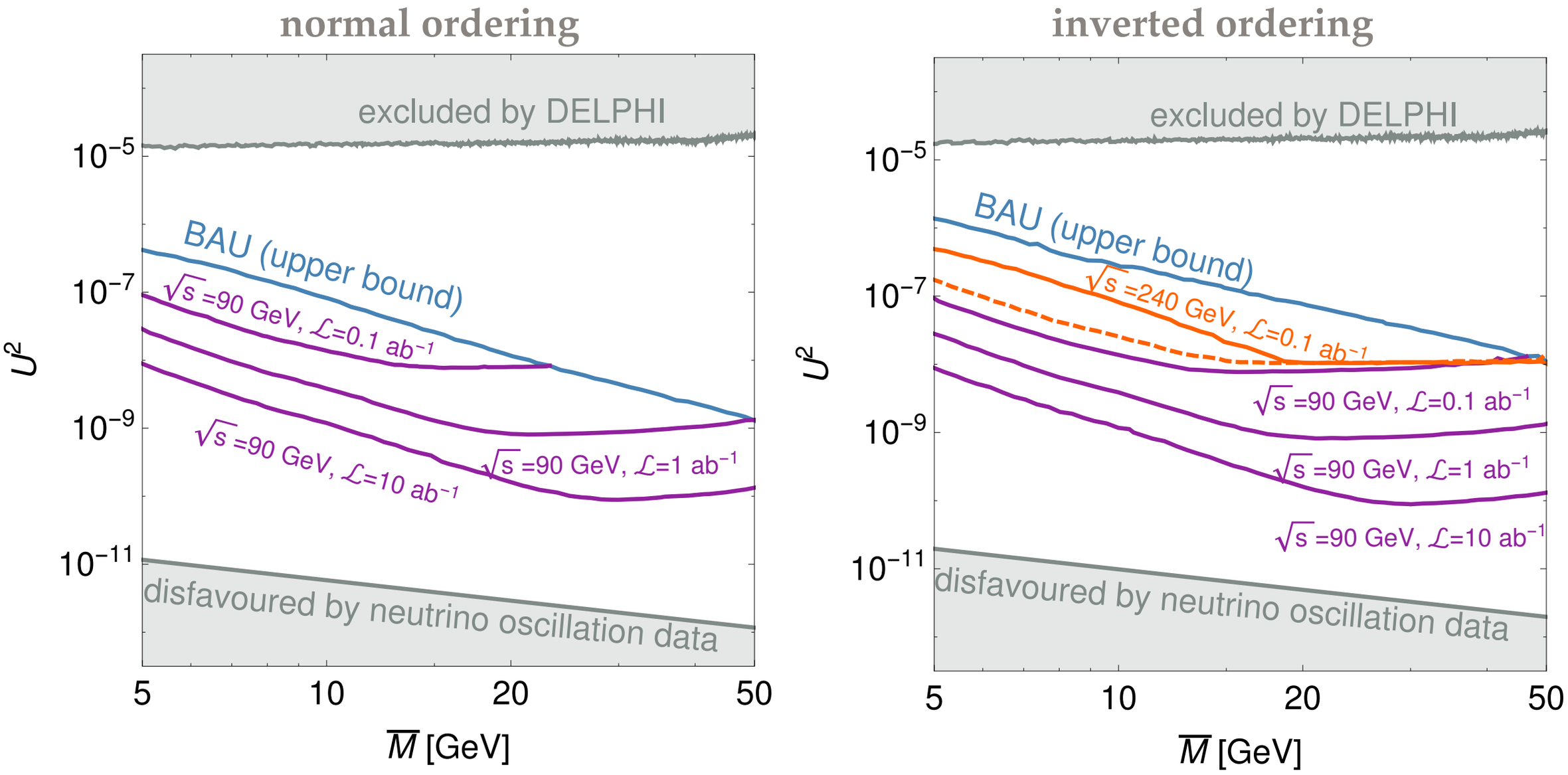
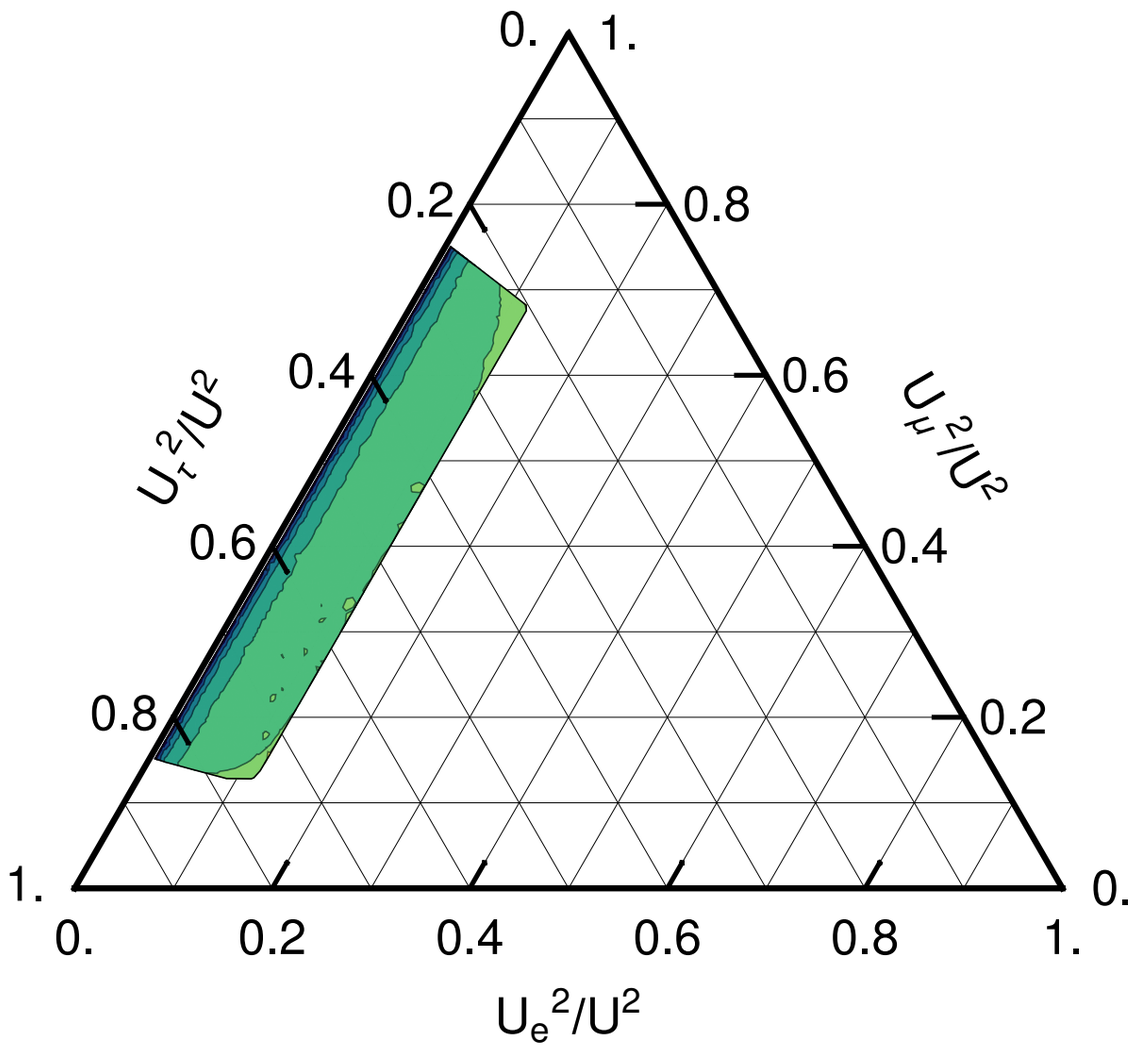
Displaced Vertices at CEPC



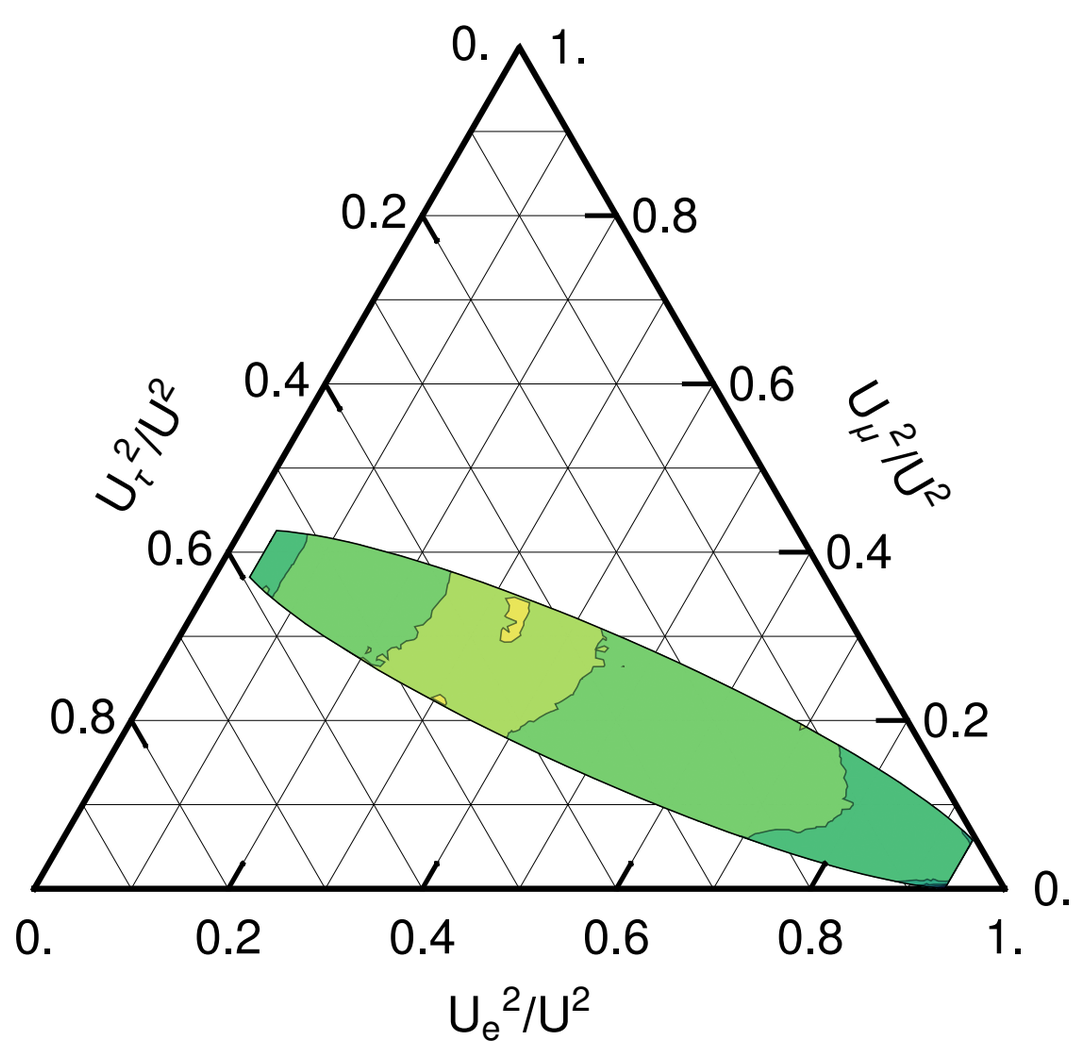
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

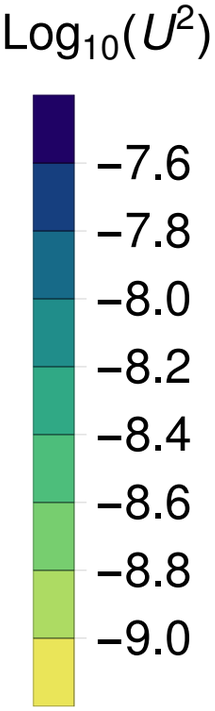
Flavour Mixing Pattern

normal ordering



inverted ordering





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

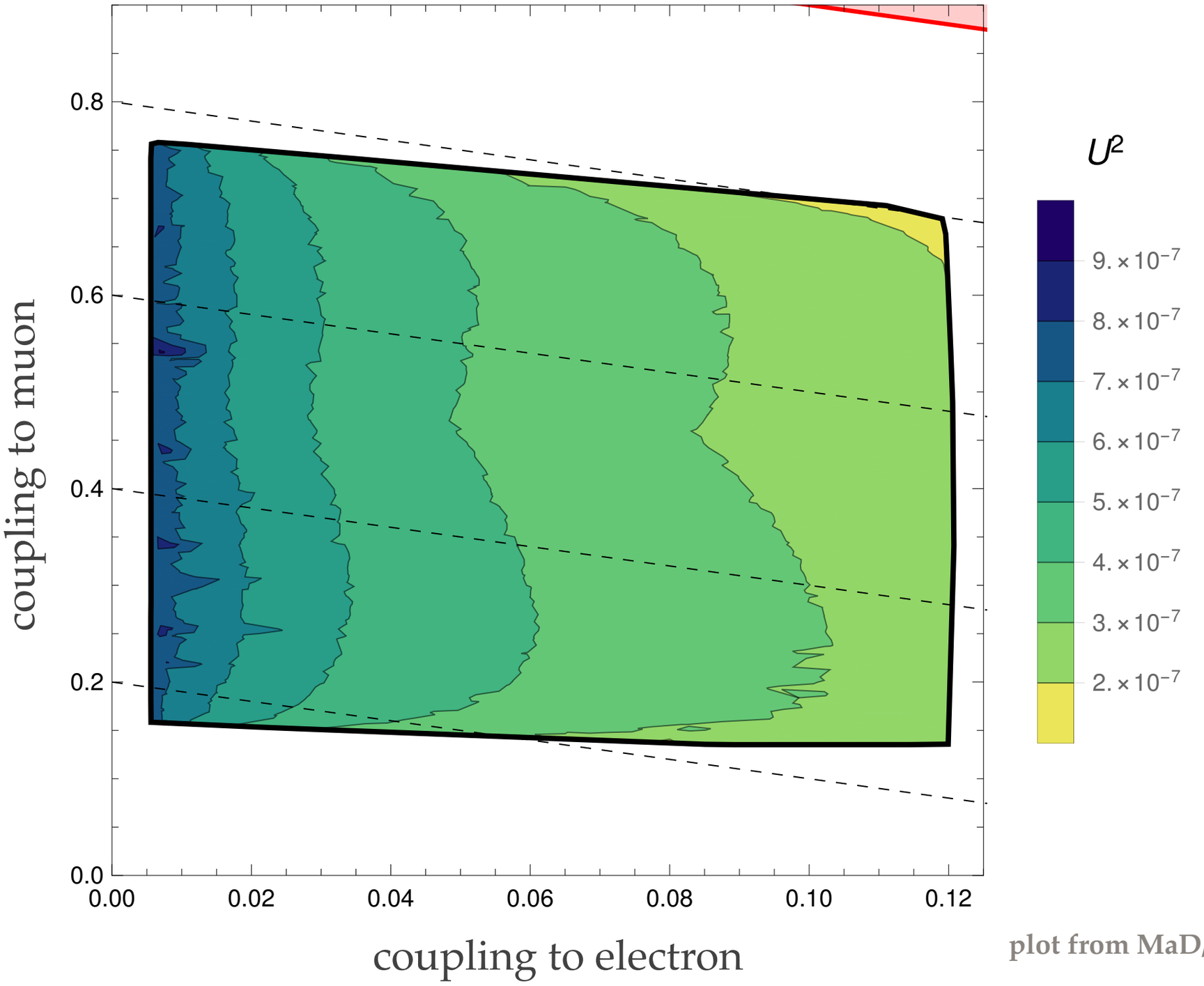
Conclusions

- CEPC has potential to be a discovery machine for hidden particles
- CEPC can probe the “neutrino portal” 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!

Important: SM flavour reconstruction and mass resolution [see talk on Thursday]

Backup Slides

Neutrino Mixing vs Collider Searches



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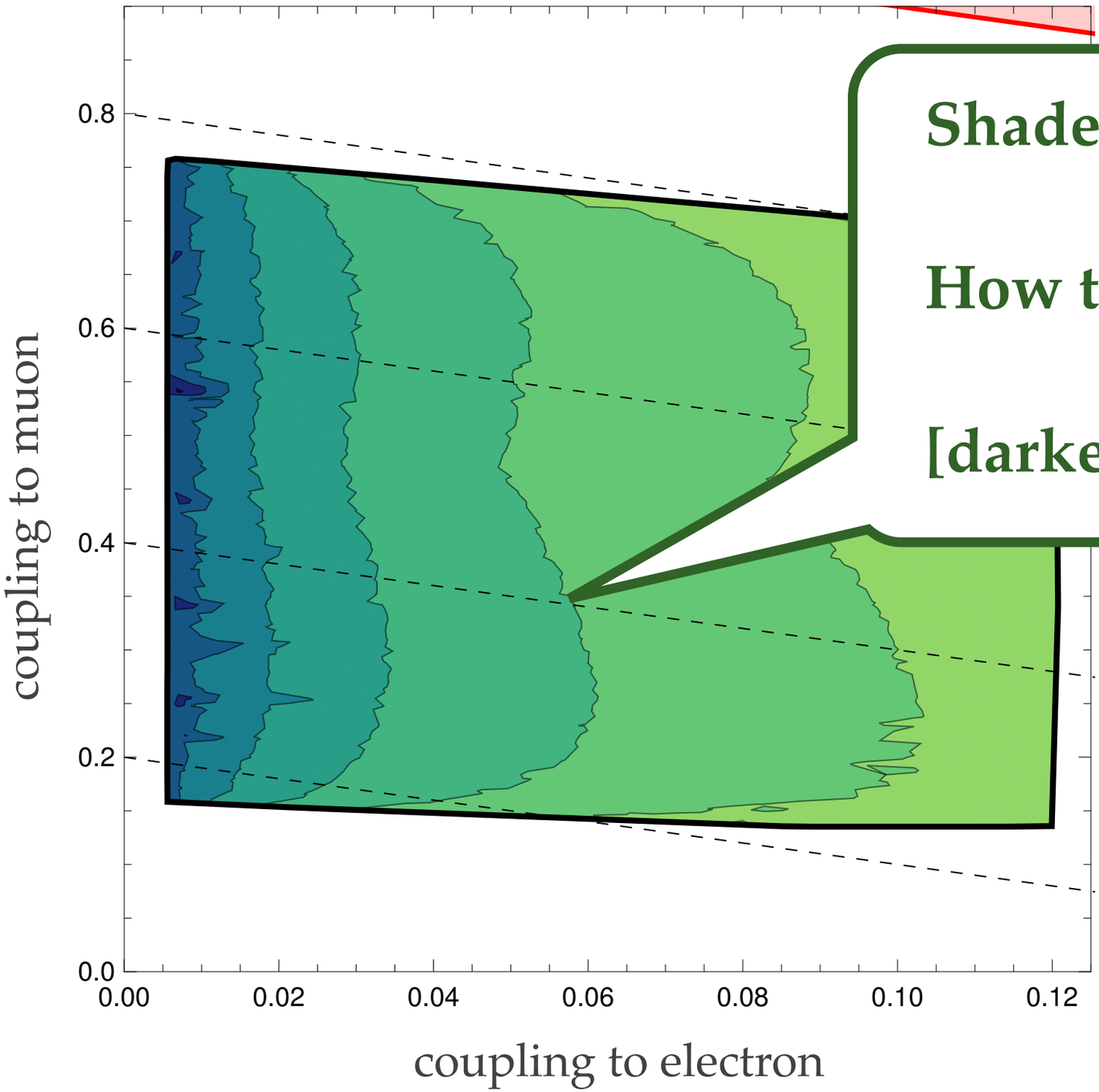


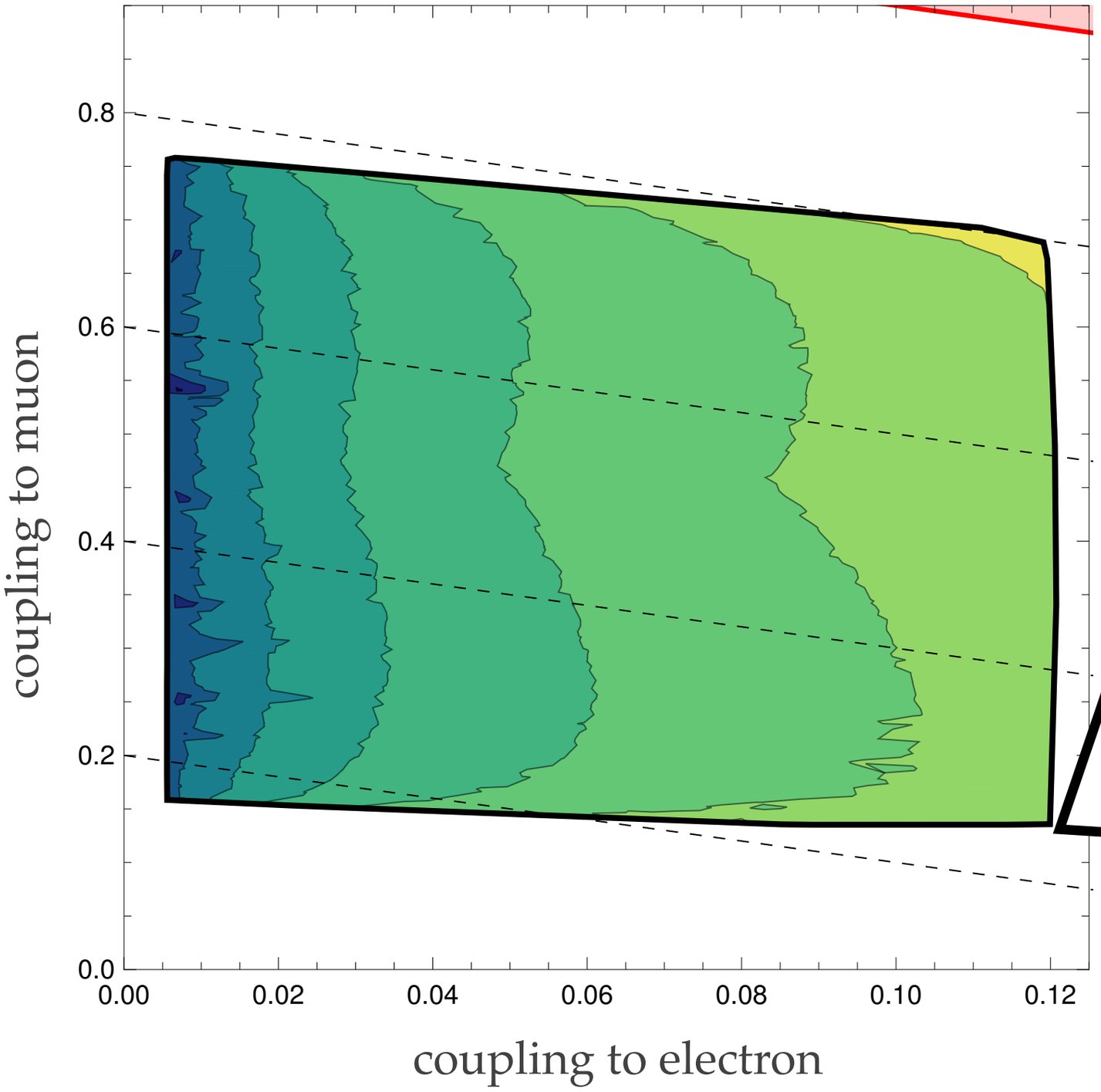
Shades:

How testable is leptogenesis?

[darker = larger total mixing]

plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Neutrino Mixing vs Collider Searches



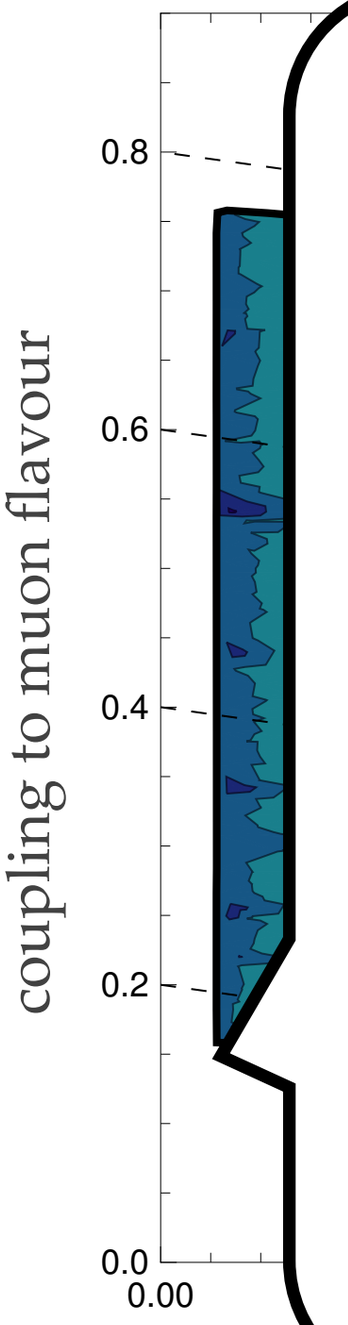
Area within black line:

allowed by neutrino oscillation data

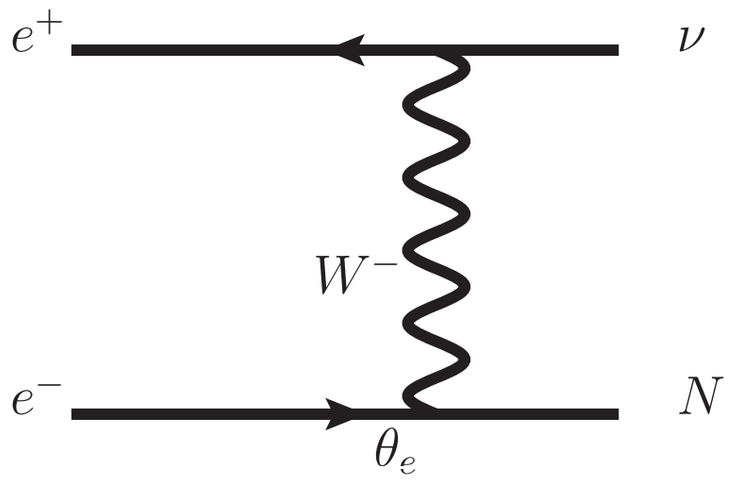
coupling to electron maximal 12%!

[for normal neutrino mass ordering]

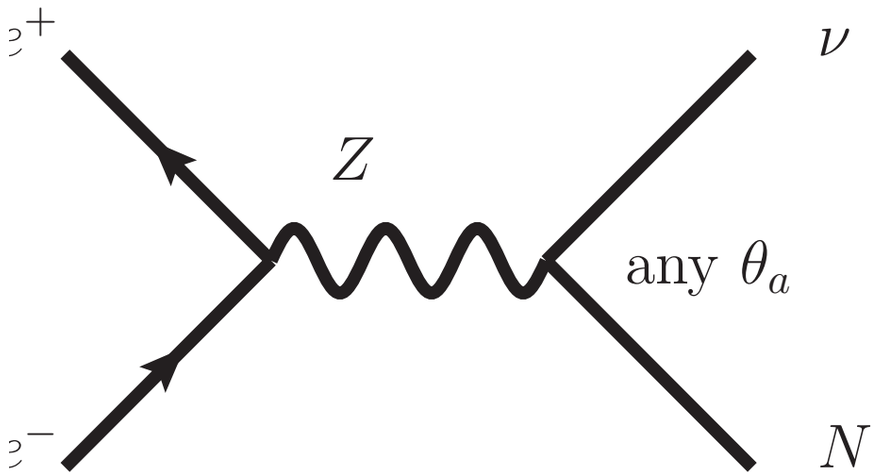
Neutrino Mixing vs Collider Searches



Effect on production at lepton colliders:



suppressed compared to



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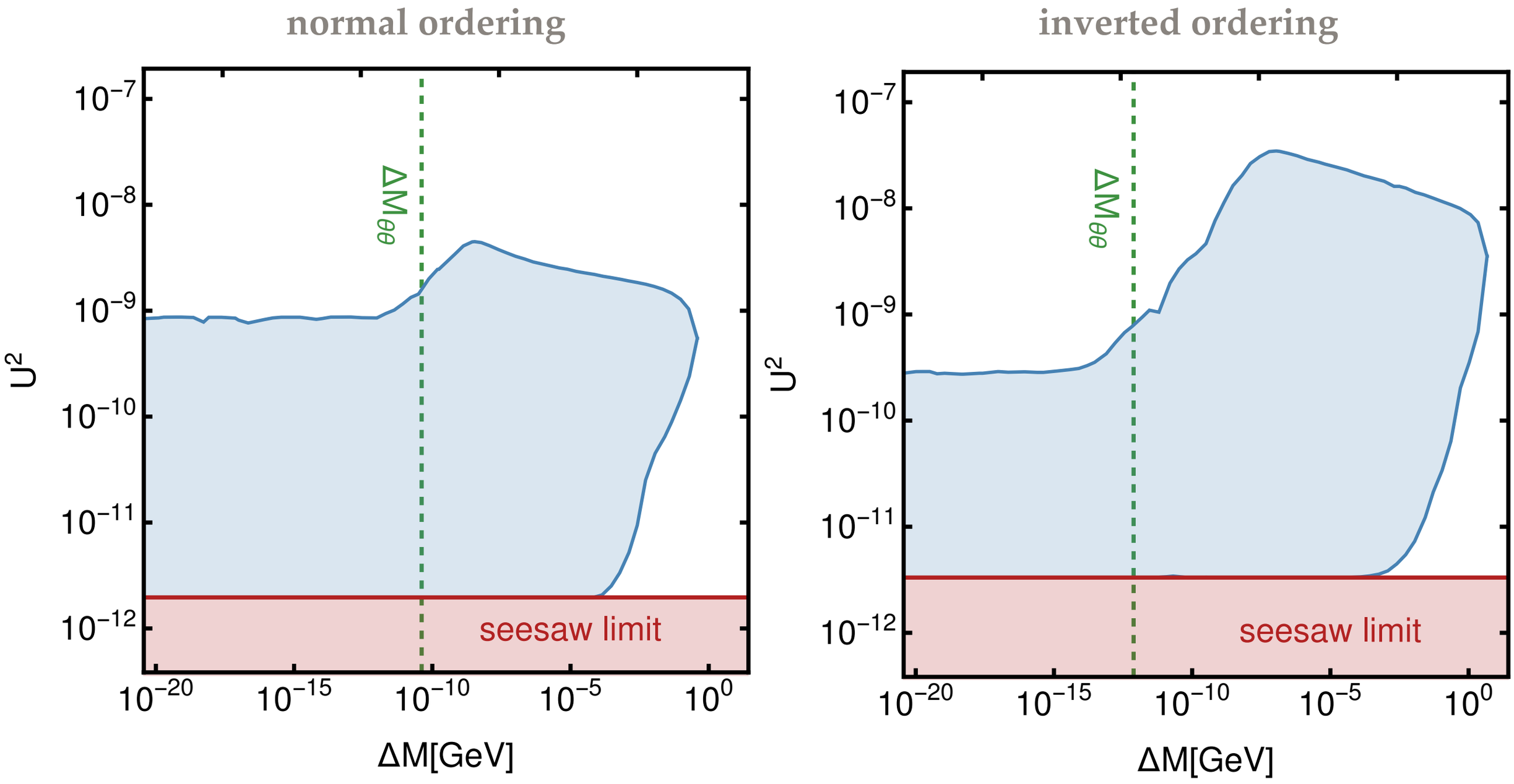
Leptogenesis and Heavy Neutrino Mass Splitting



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

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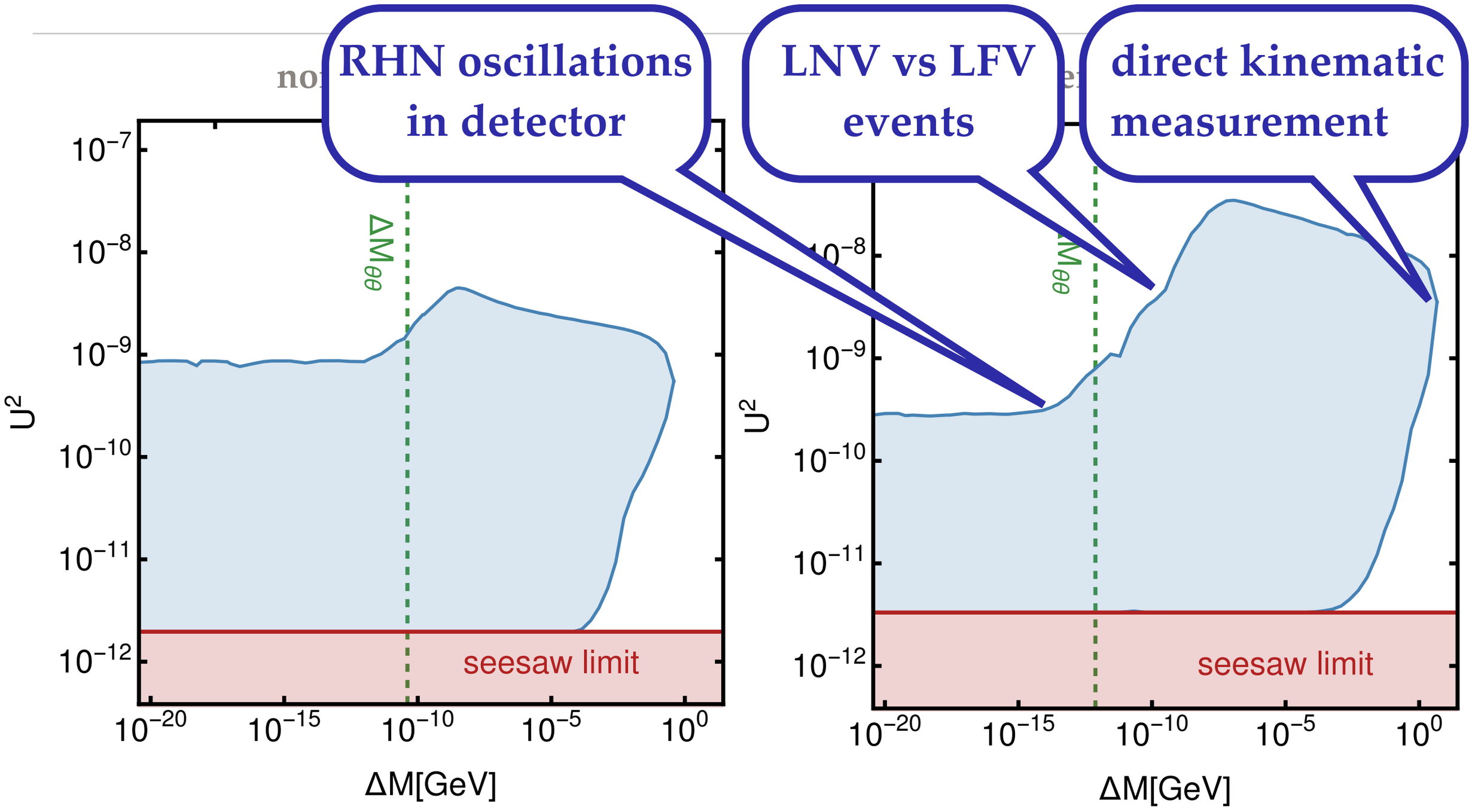

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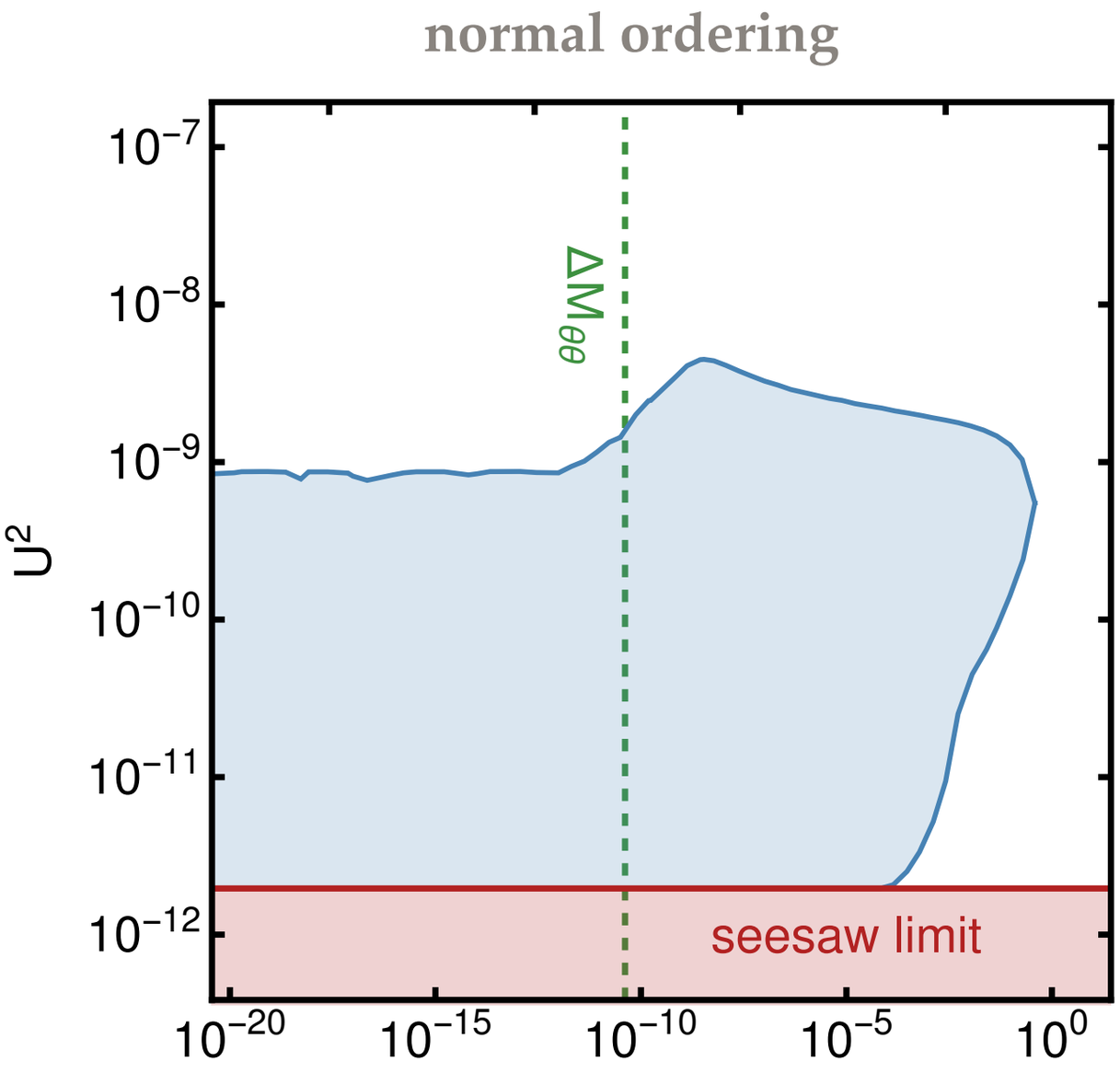
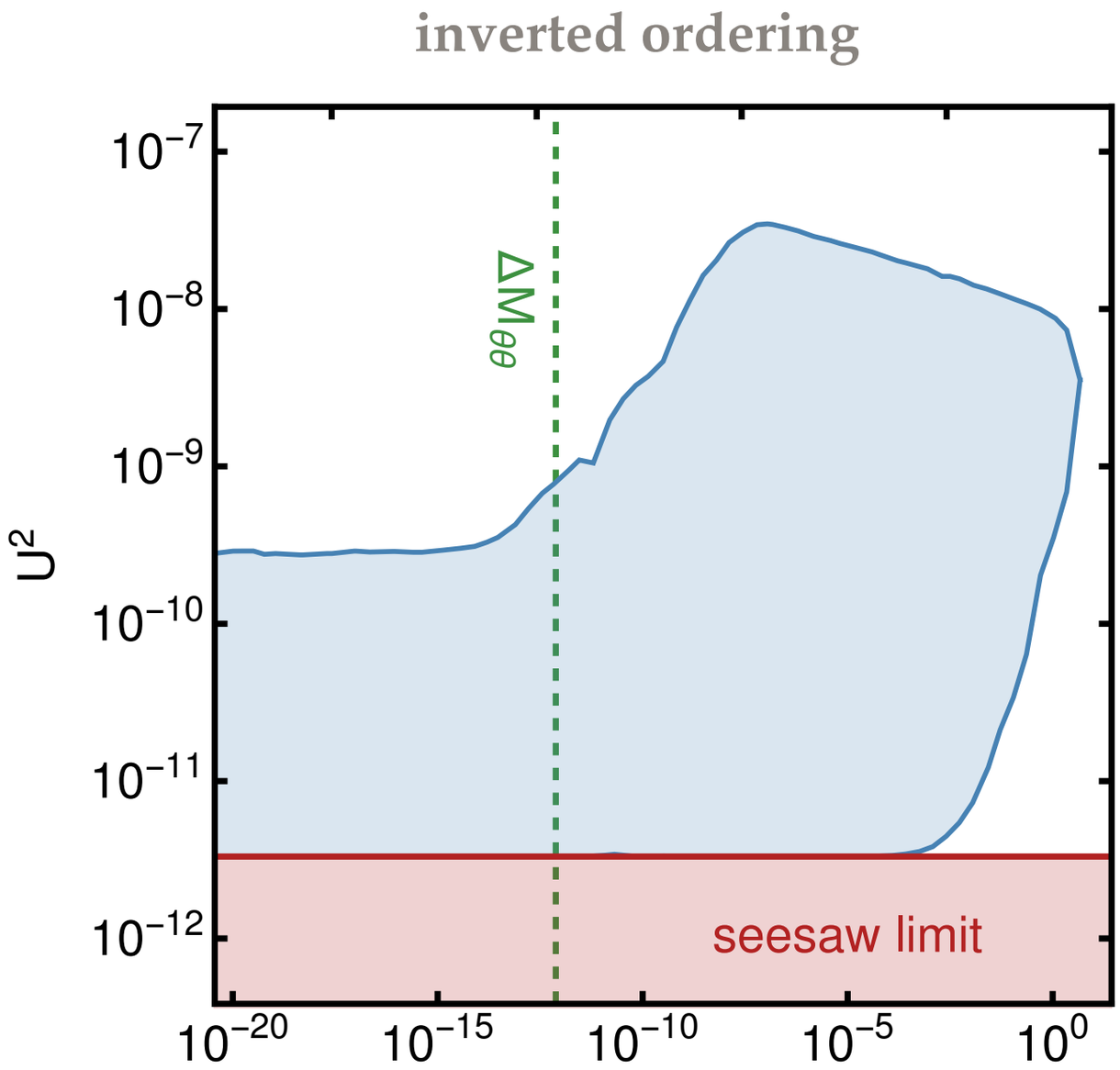




with three RH neutrinos:
no need for mass degeneracy for leptogenesis MaD/Garbrecht 12

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

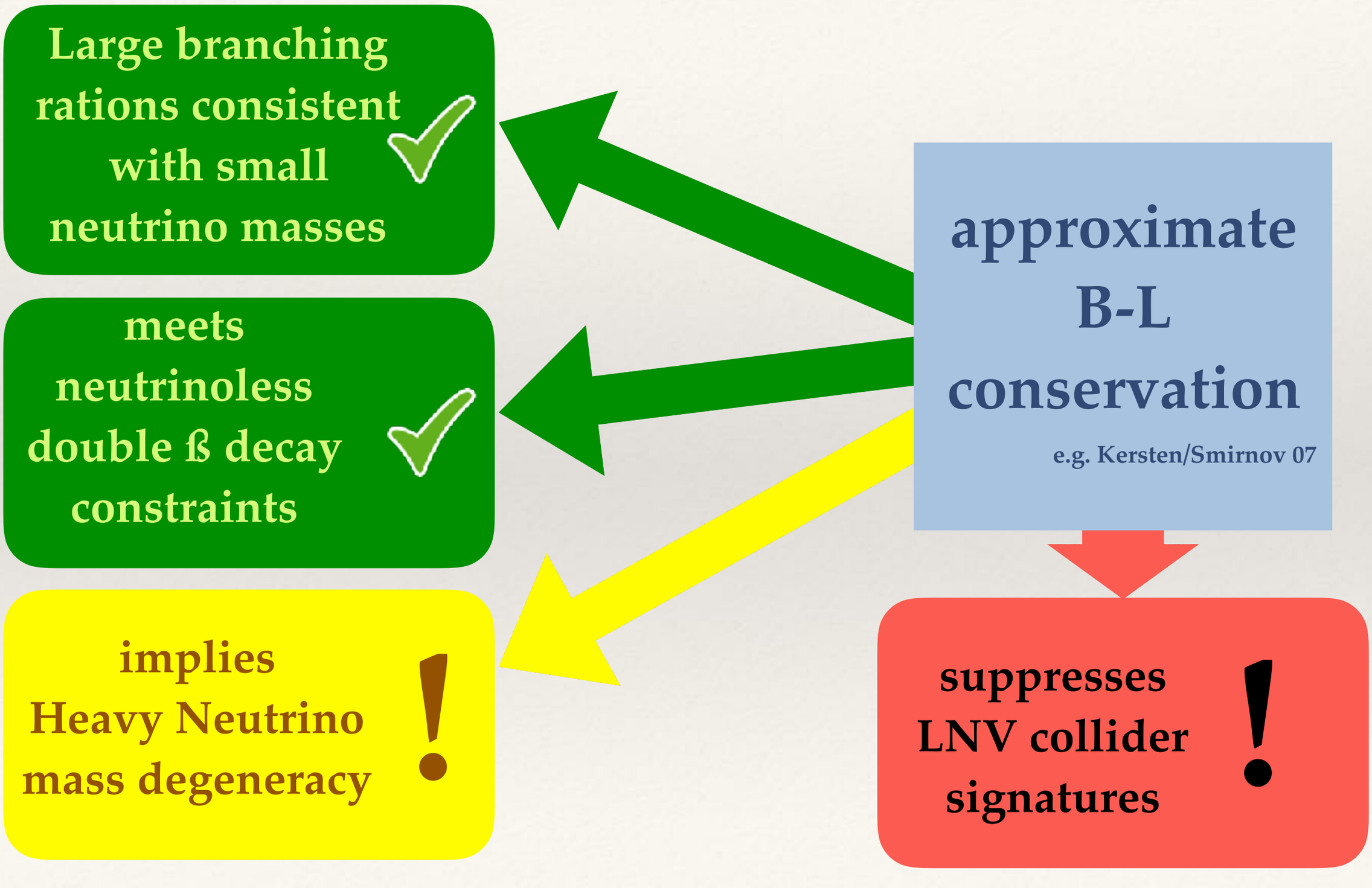
approximate B-L conservation

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

may observe CP violation in Heavy Neutrino decay

Cvetic/Kim/Saa 14

connection to leptogenesis?

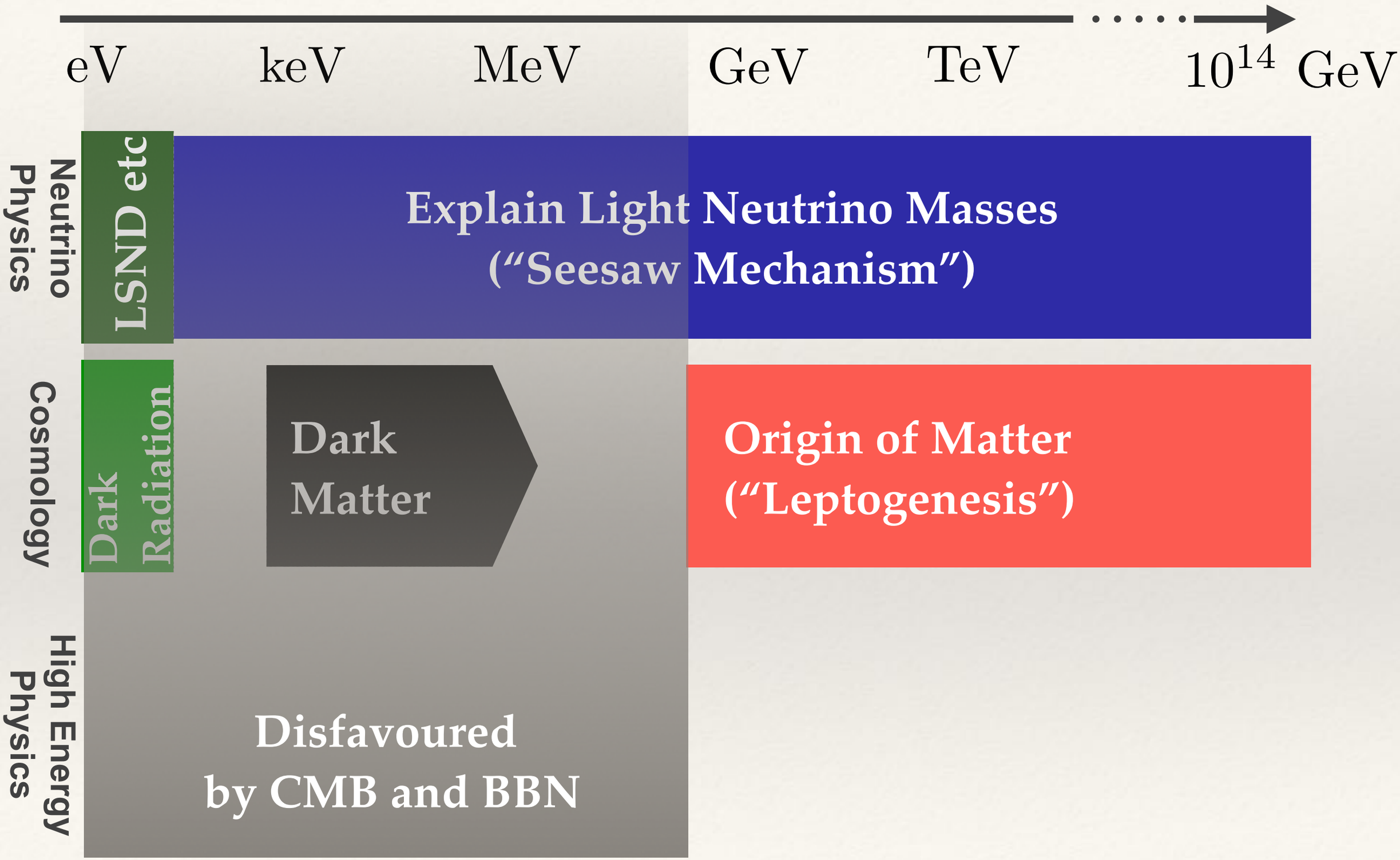
"golden channels" suppressed

need to use other channels (LFV, displaced vertices)

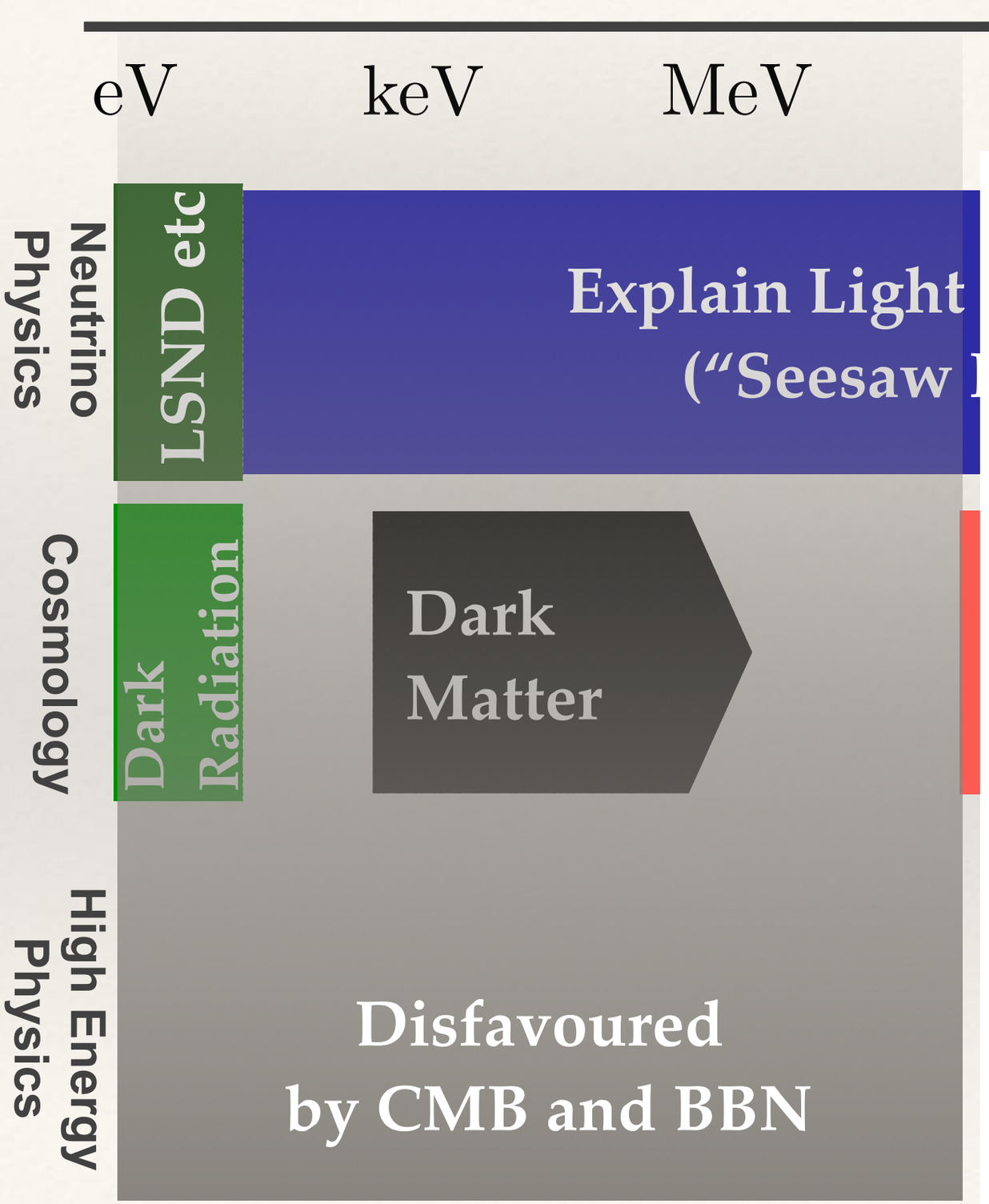
implies Heavy Neutrino mass degeneracy !

suppresses LNV collider signatures !

Right Handed Neutrinos and the Light Neutrino Masses



Right Handed Neutrinos and the Light Neutrino Masses



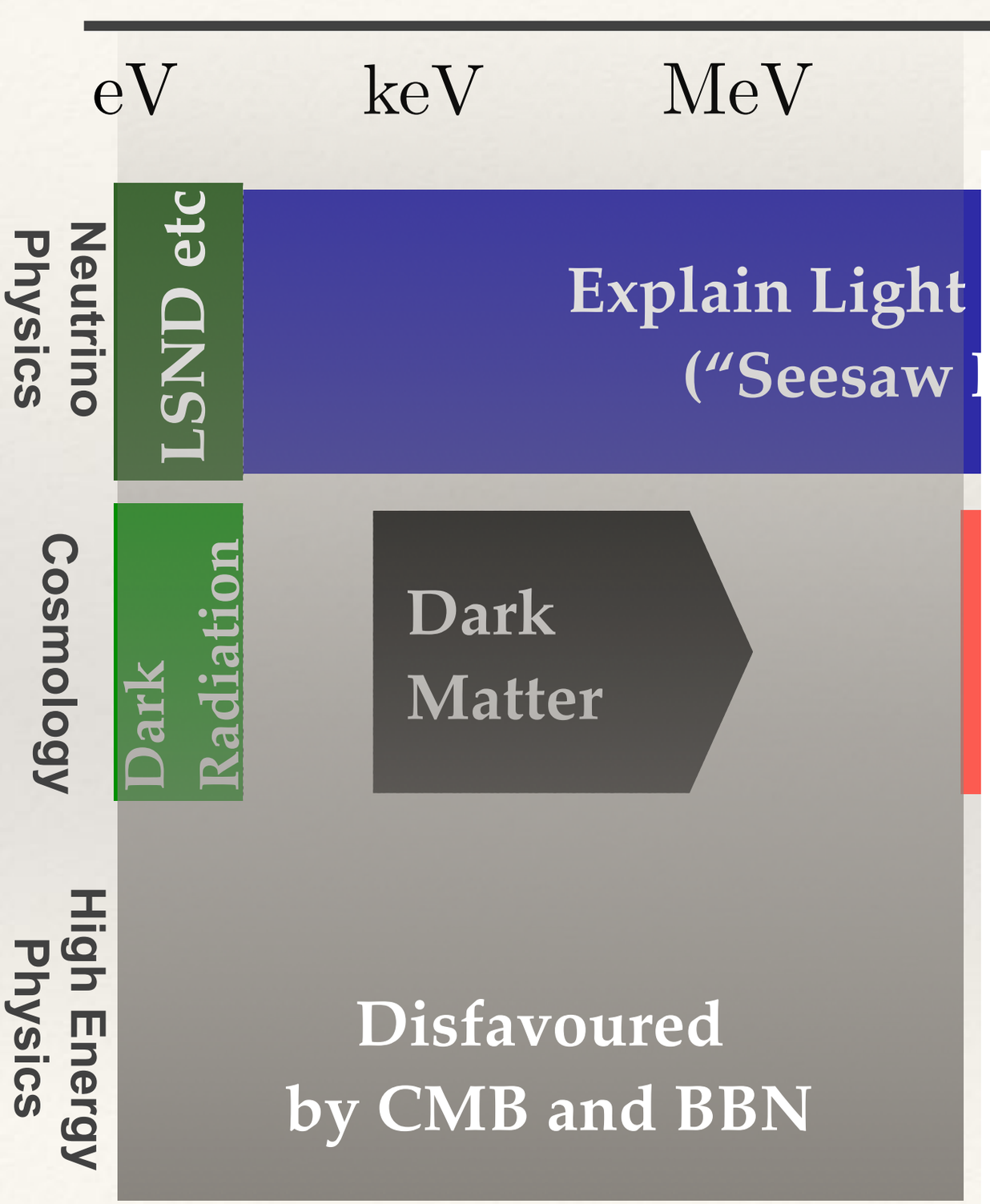
- RH neutrinos **must mix** to generate light neutrino mass

- Mixing leads to **production in the early universe**

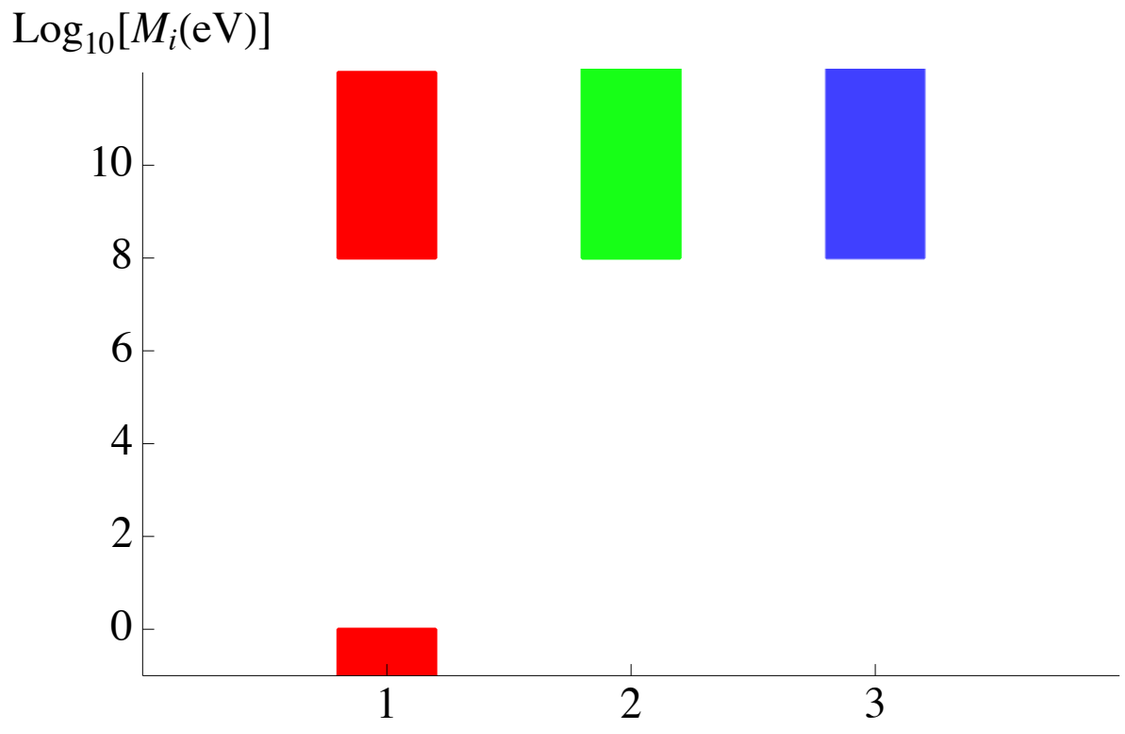
- For masses below 100 MeV, RH neutrinos **do not decay before BBN**

- Their decay either **disturbs BBN** or **affects the CMB**

Right Handed Neutrinos and the Light Neutrino Masses

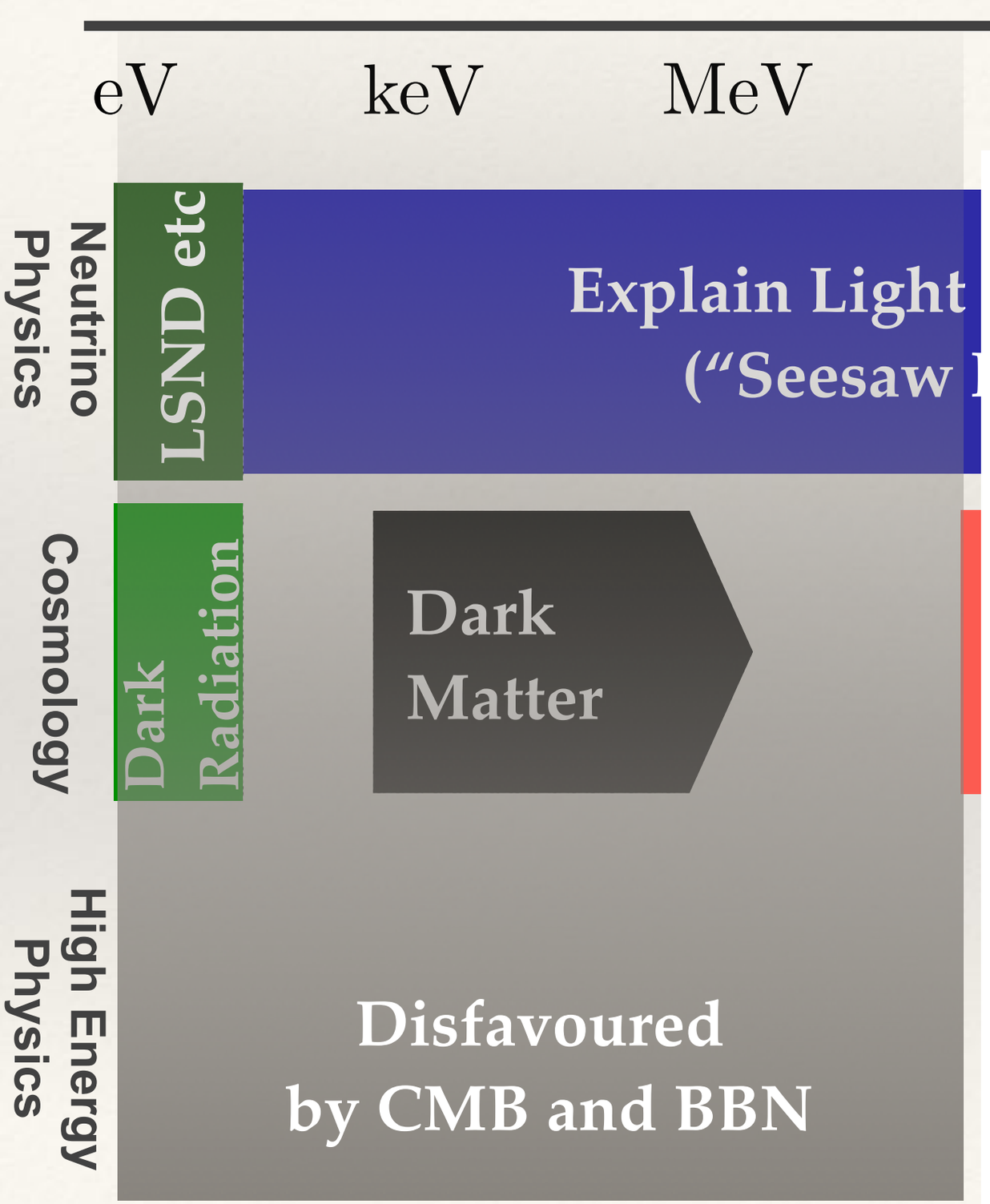


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} > 10^{-3}$ eV, three RHN reach equilibrium



Hernandez/Kekic/Lopez-Pavon 1406.2961

Right Handed Neutrinos and the Light Neutrino Masses



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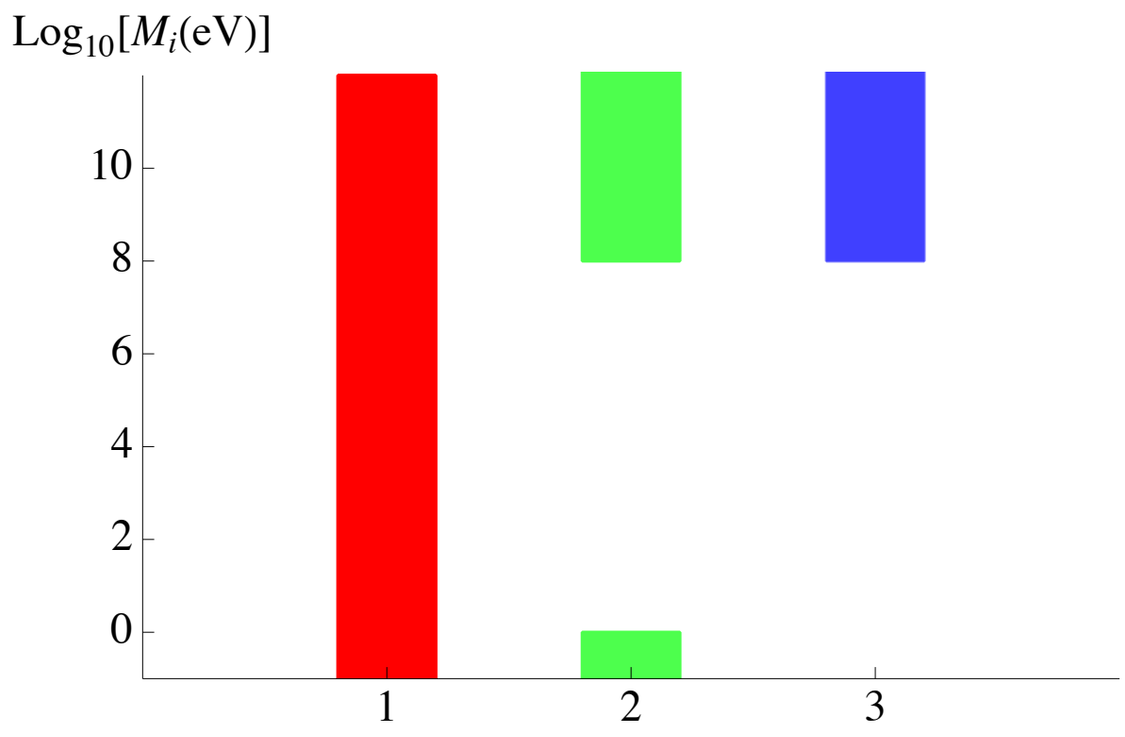

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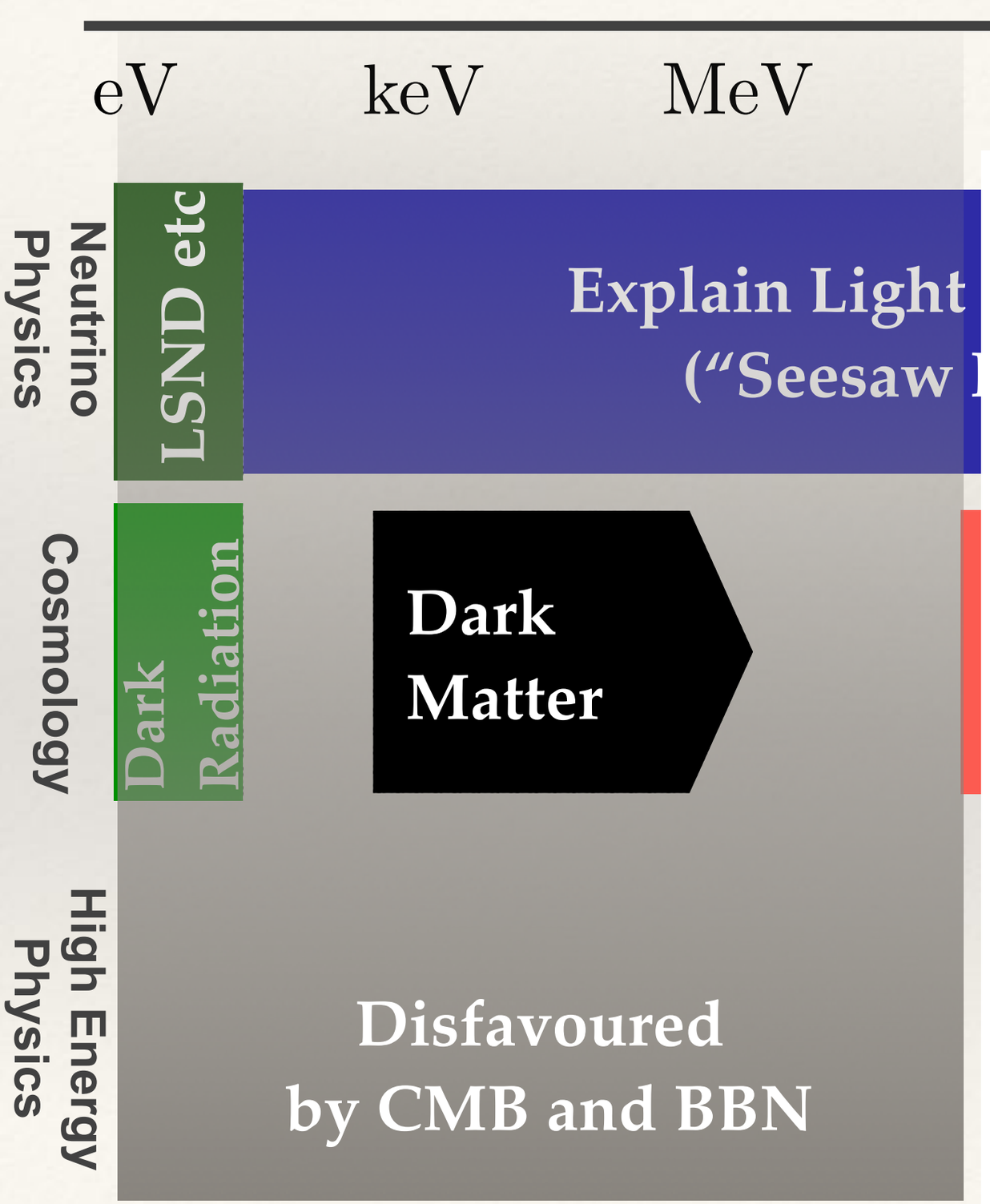
Right Handed Neutrinos and the Light Neutrino Masses



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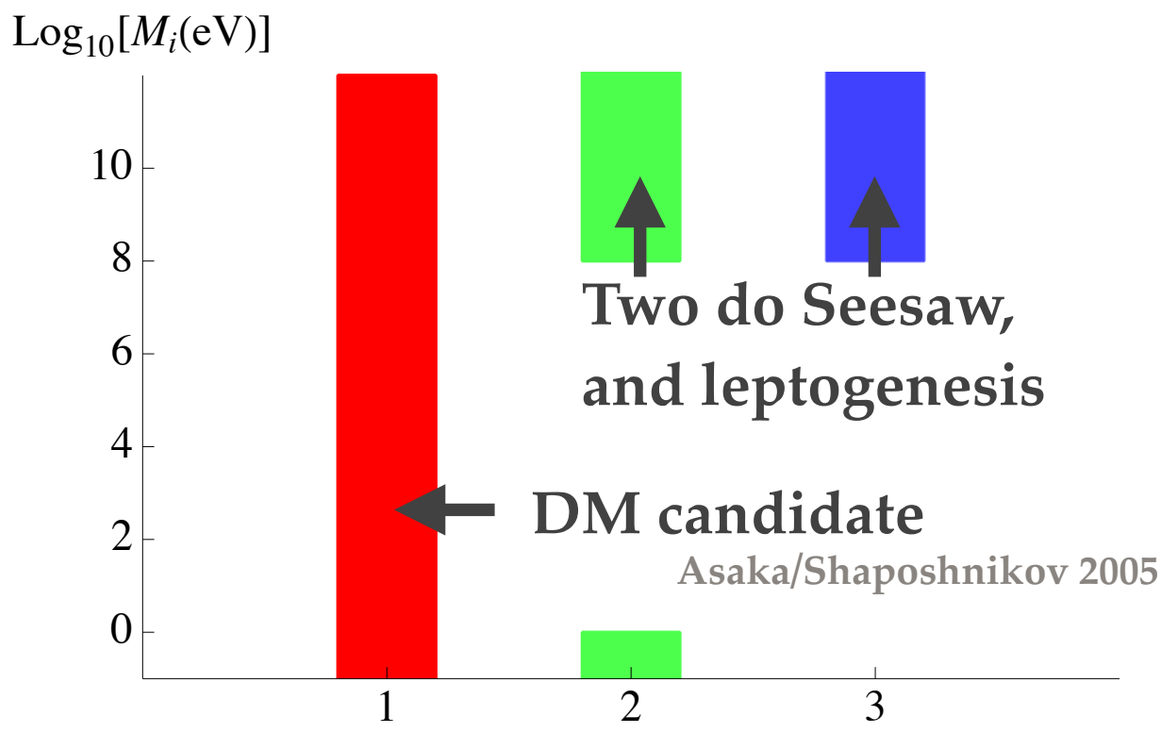
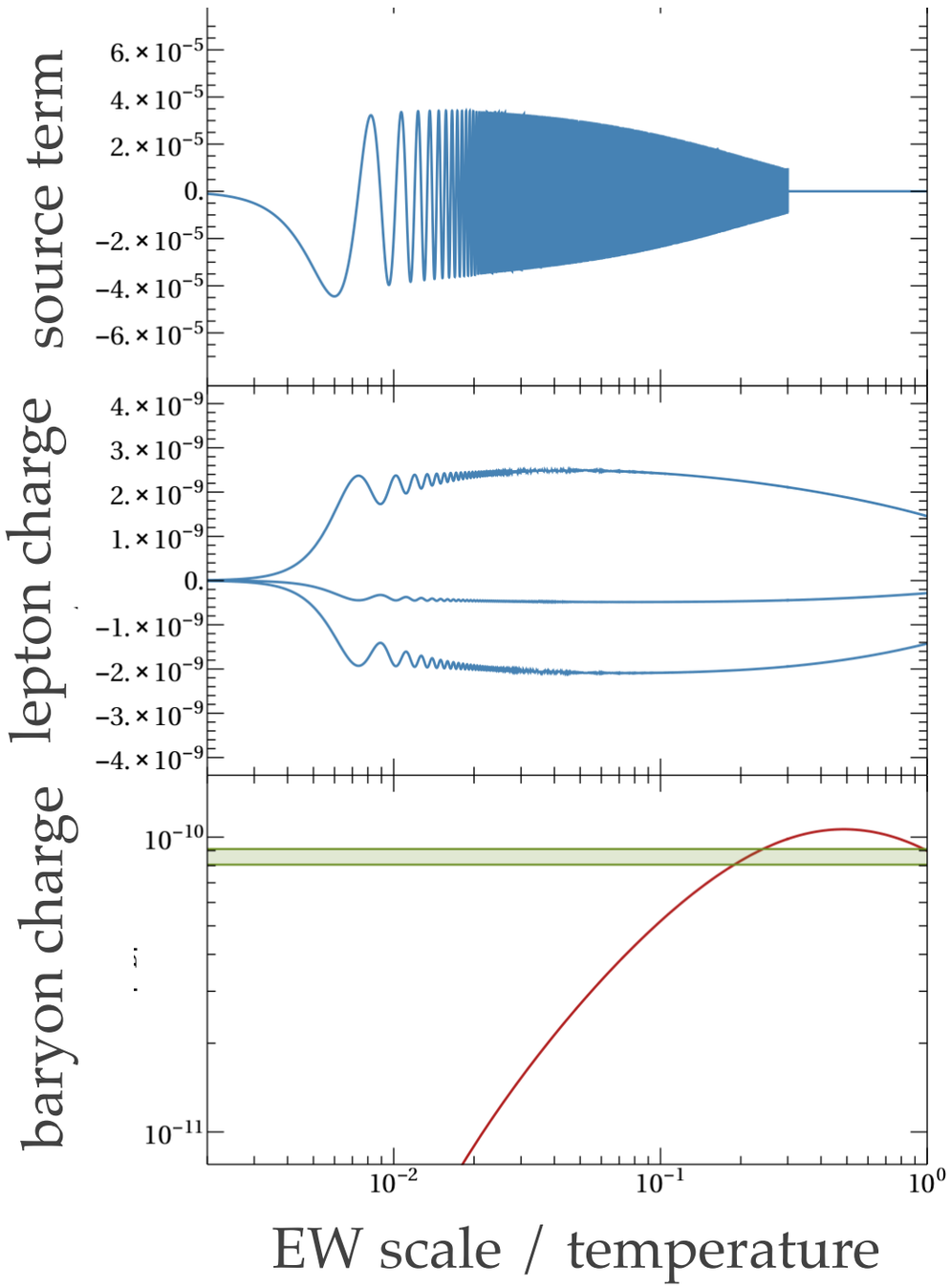


Hernandez/Kekic/Lopez-Pavon 1406.2961

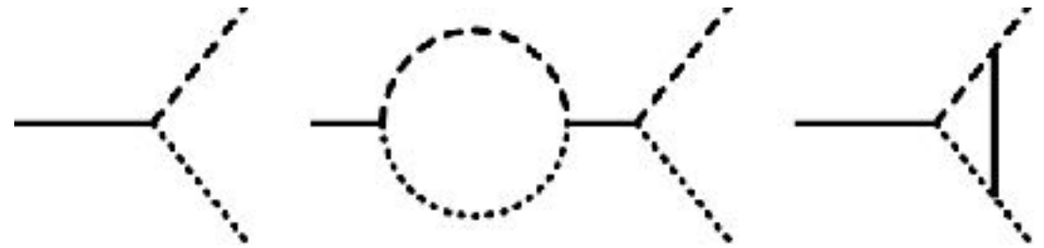
Heavy Neutrinos as the Origin of Matter

Leptogenesis from heavy neutrino oscillations



GeV TeV ..... 10^{14} GeV

Leptogenesis in heavy neutrino decay



Origin of Matter ("Leptogenesis")