Marco Drewes, Université catholique de Louvain

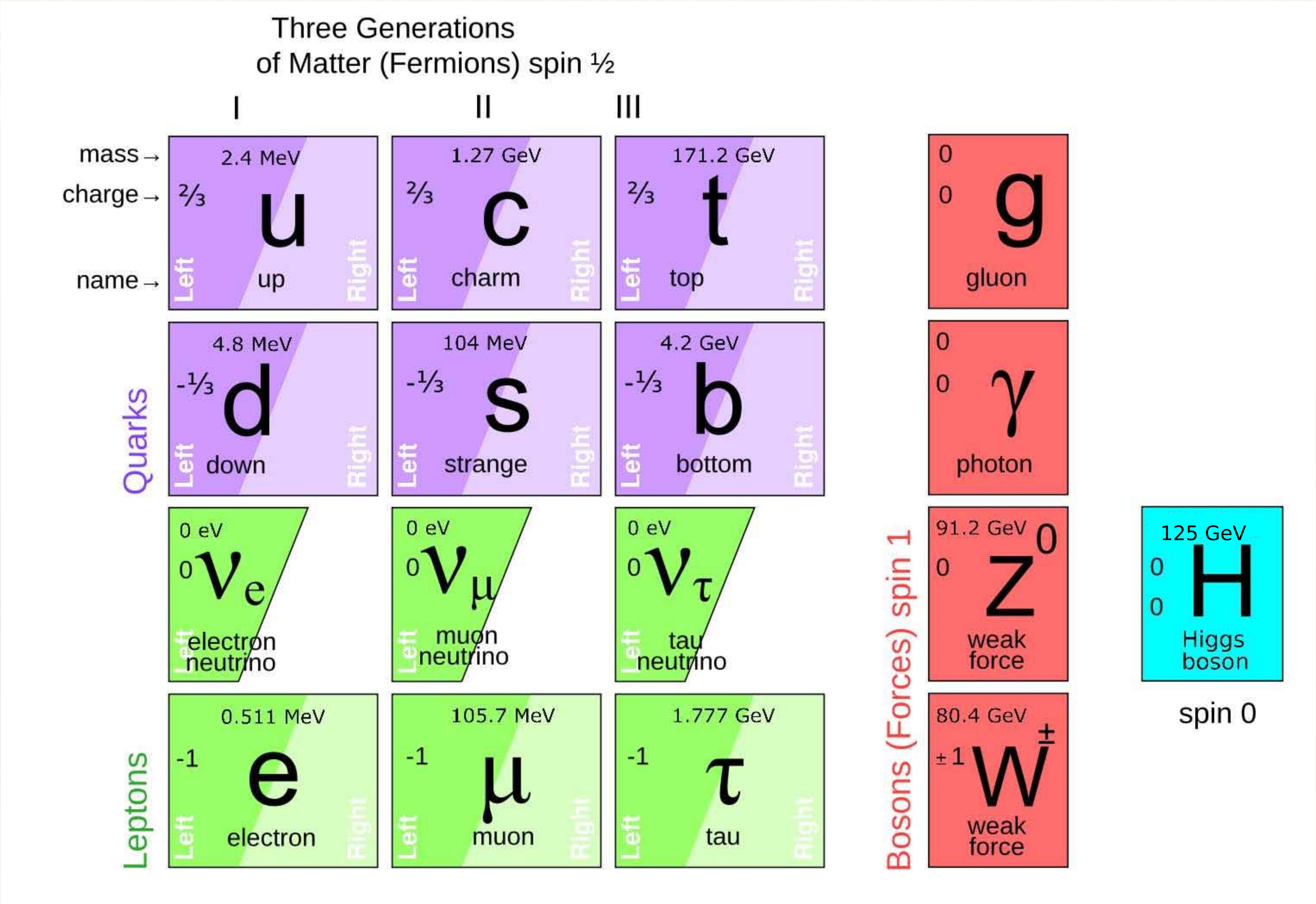
The Other Neutrinos

21.12.2017

IAP Meeting

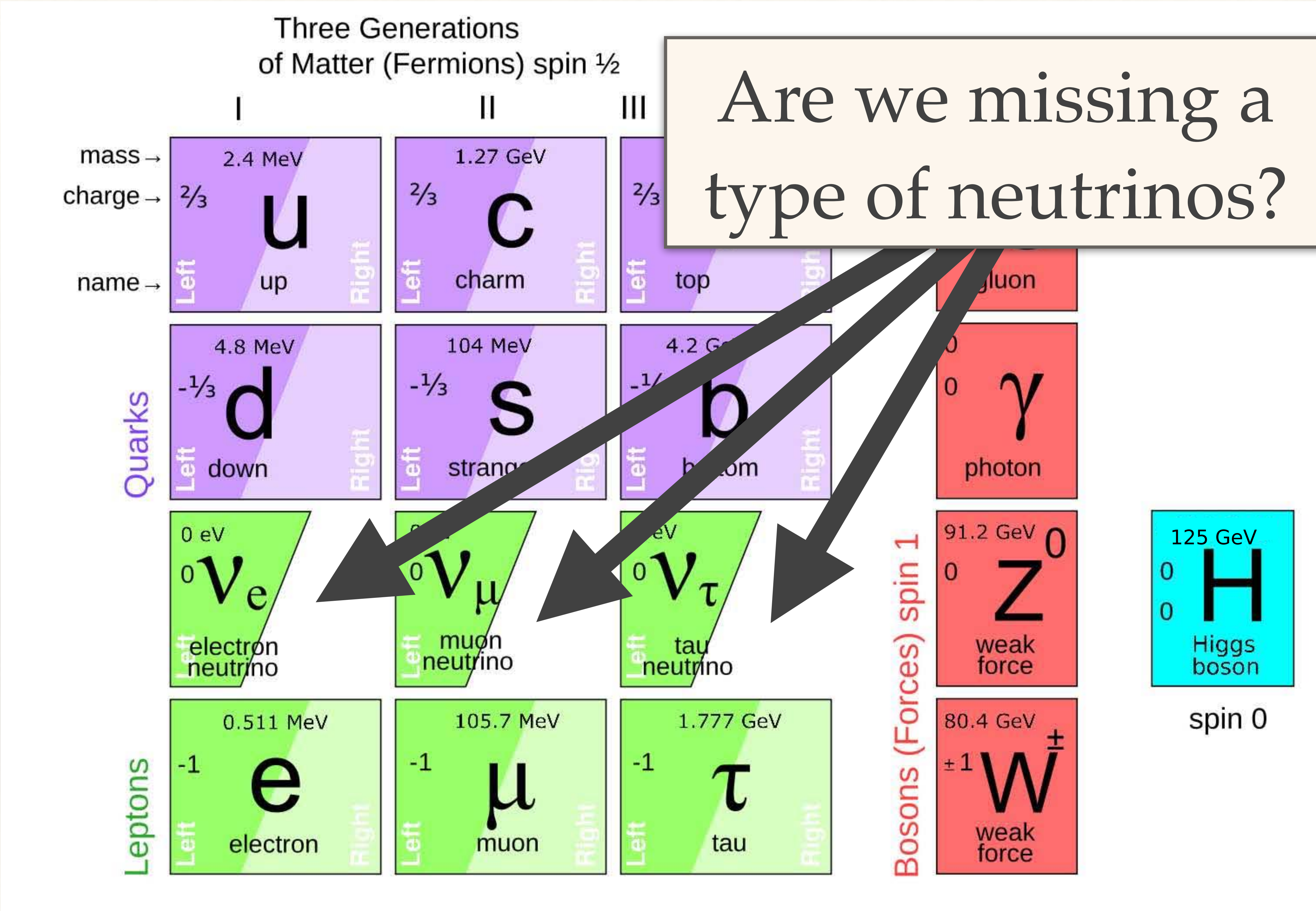
Université libre de Bruxelles

The Standard Model of Particle Physics



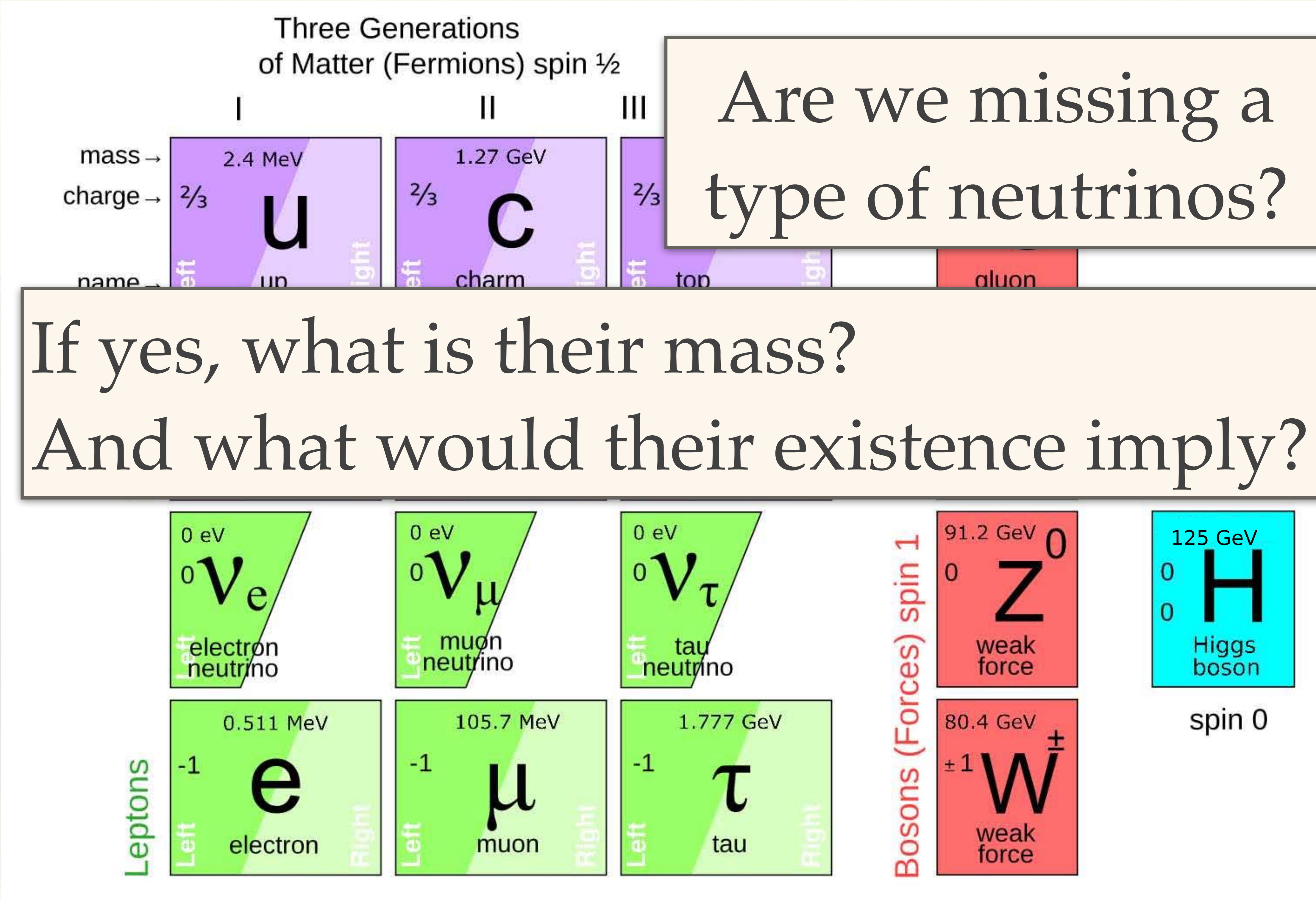
The "periodic table" of elementary particles

The Standard Model of Particle Physics



The "periodic table" of elementary particles

The Standard Model of Particle Physics

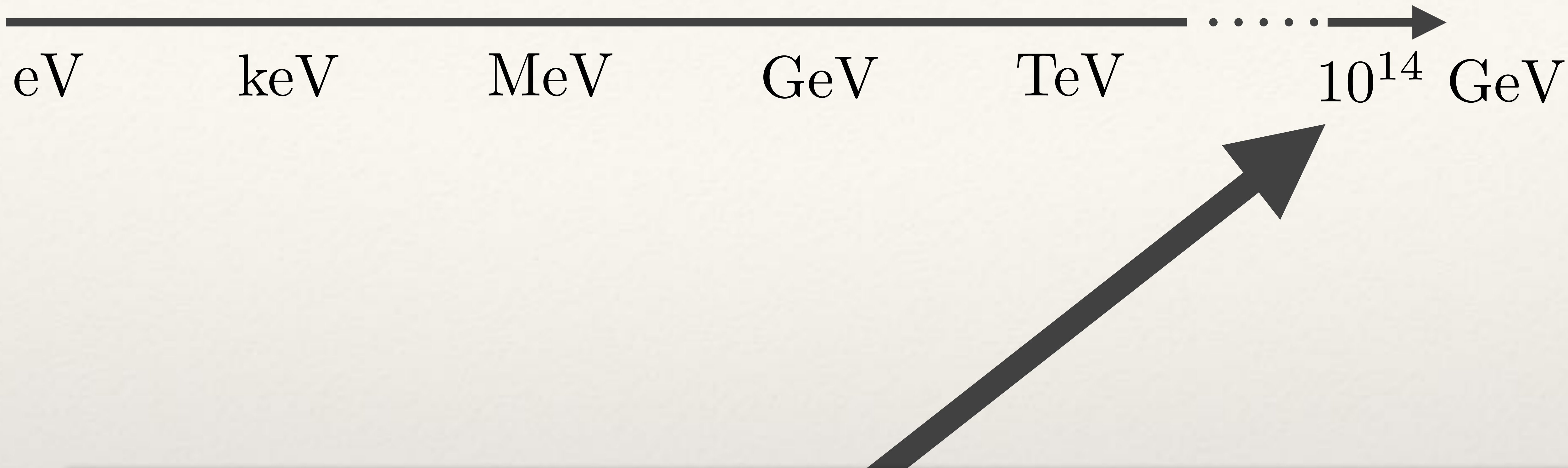


Are we missing a type of neutrinos?

If yes, what is their mass?
And what would their existence imply?

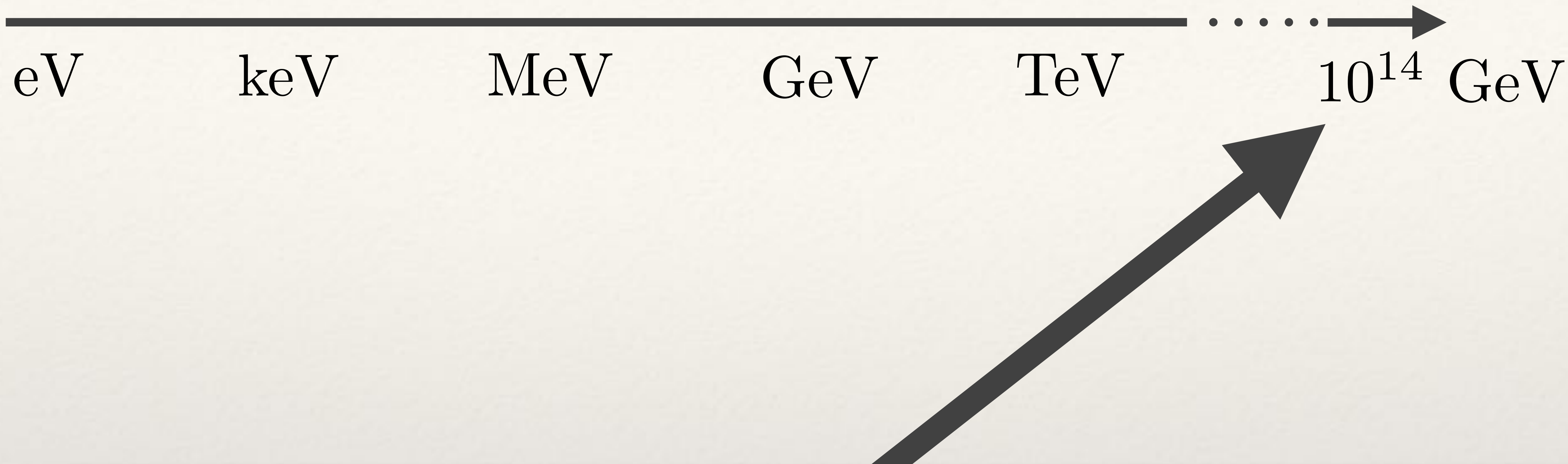
The "periodic table" of elementary particles

How Heavy are the Missing Neutrinos?



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

How Heavy are the Missing Neutrinos?



Traditionally:
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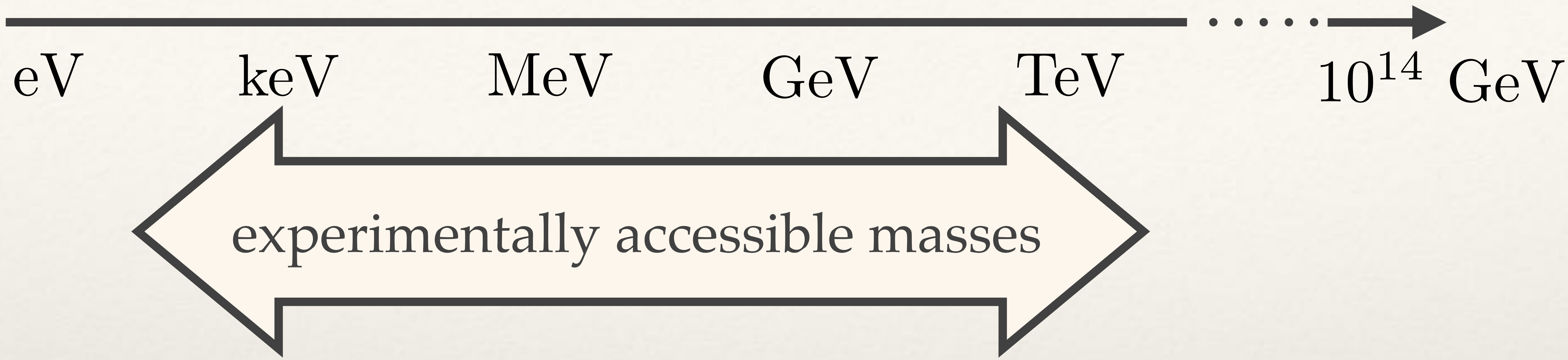
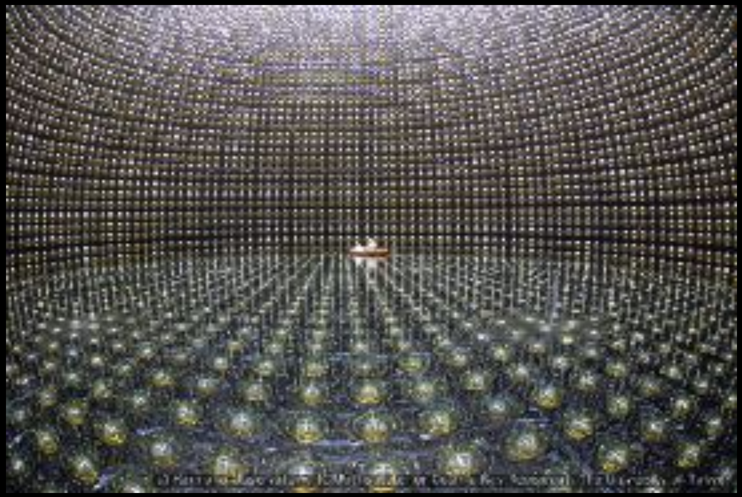
experimentally inaccessible

How Heavy are the Missing Neutrinos?



Understand the implications across the entire experimentally accessible mass range

Heavy Neutrinos Could Solve Key Problems



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

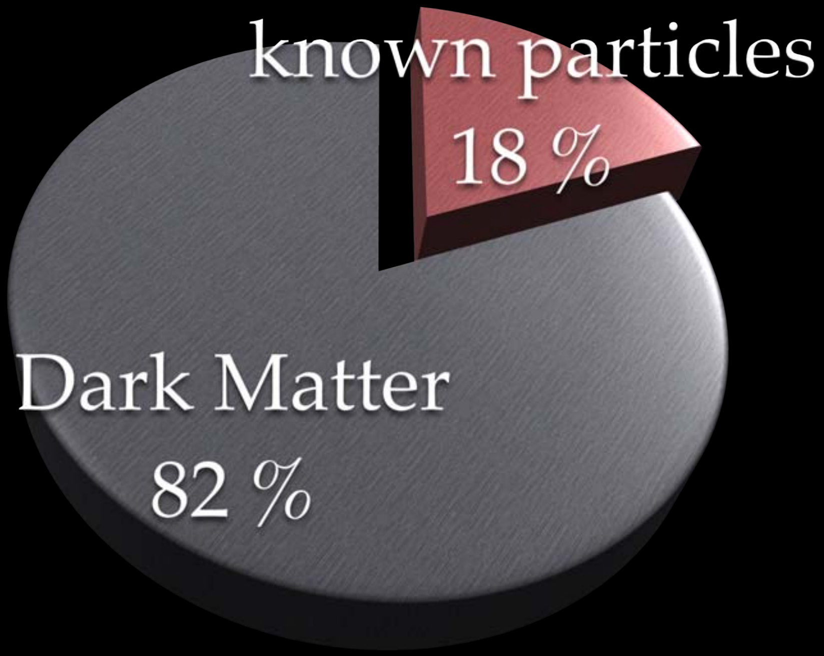
  Possible key to embed Standard Model in a more fundamental theory of Nature

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

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

- **What is the Dark Matter made of?**

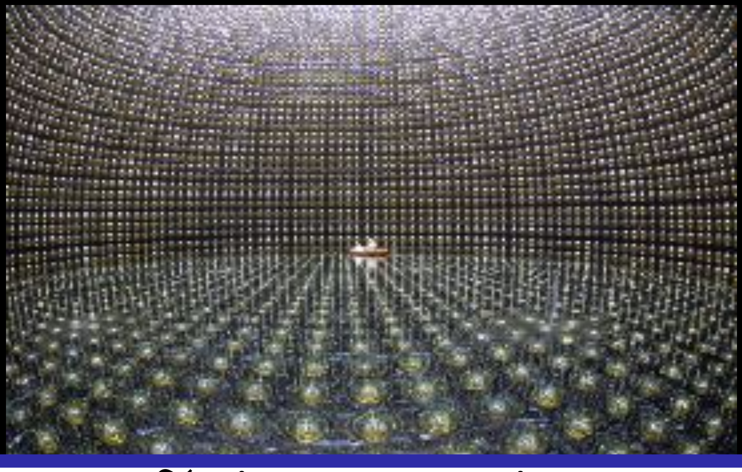
  It makes up most of the mass in the universe.



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?**

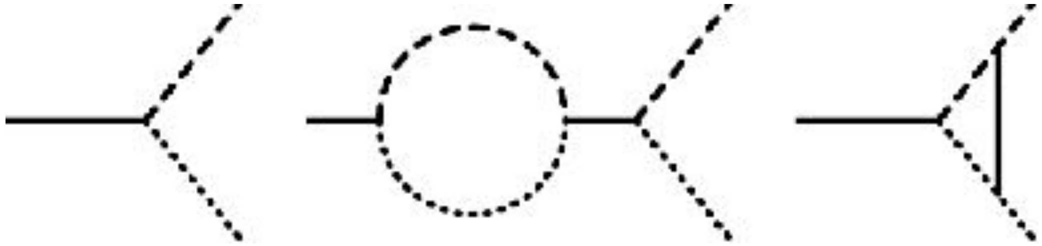
Possible key to embed Standard Model in a more fundamental theory of Nature

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

…so that some matter survived the mutua

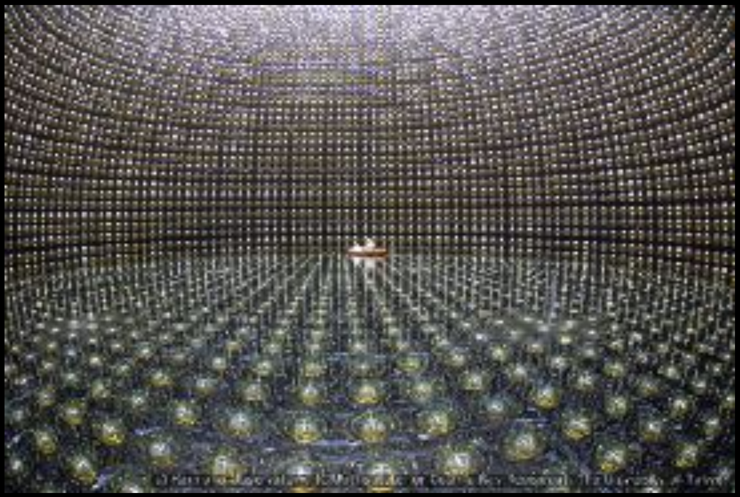
Leptogenesis

- 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

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

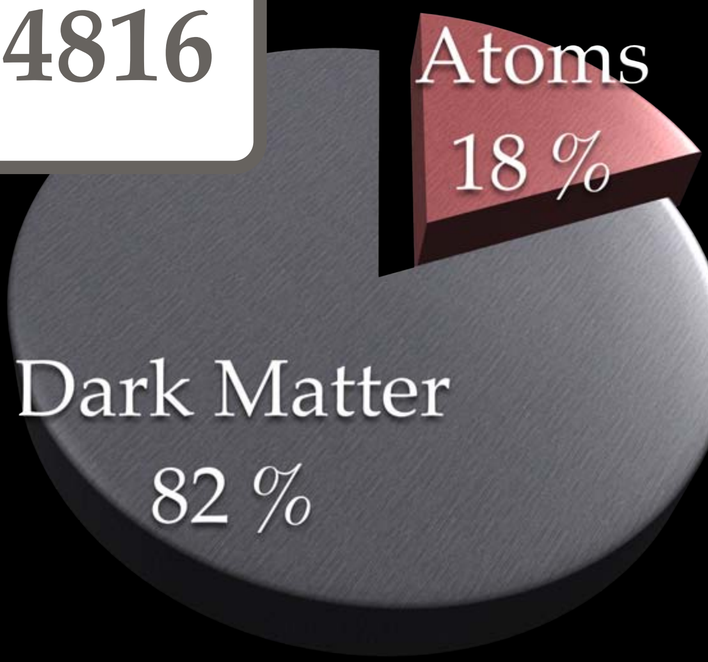
- **Why was there more matter than antimatter in the early universe?**

  nutual
  tc.

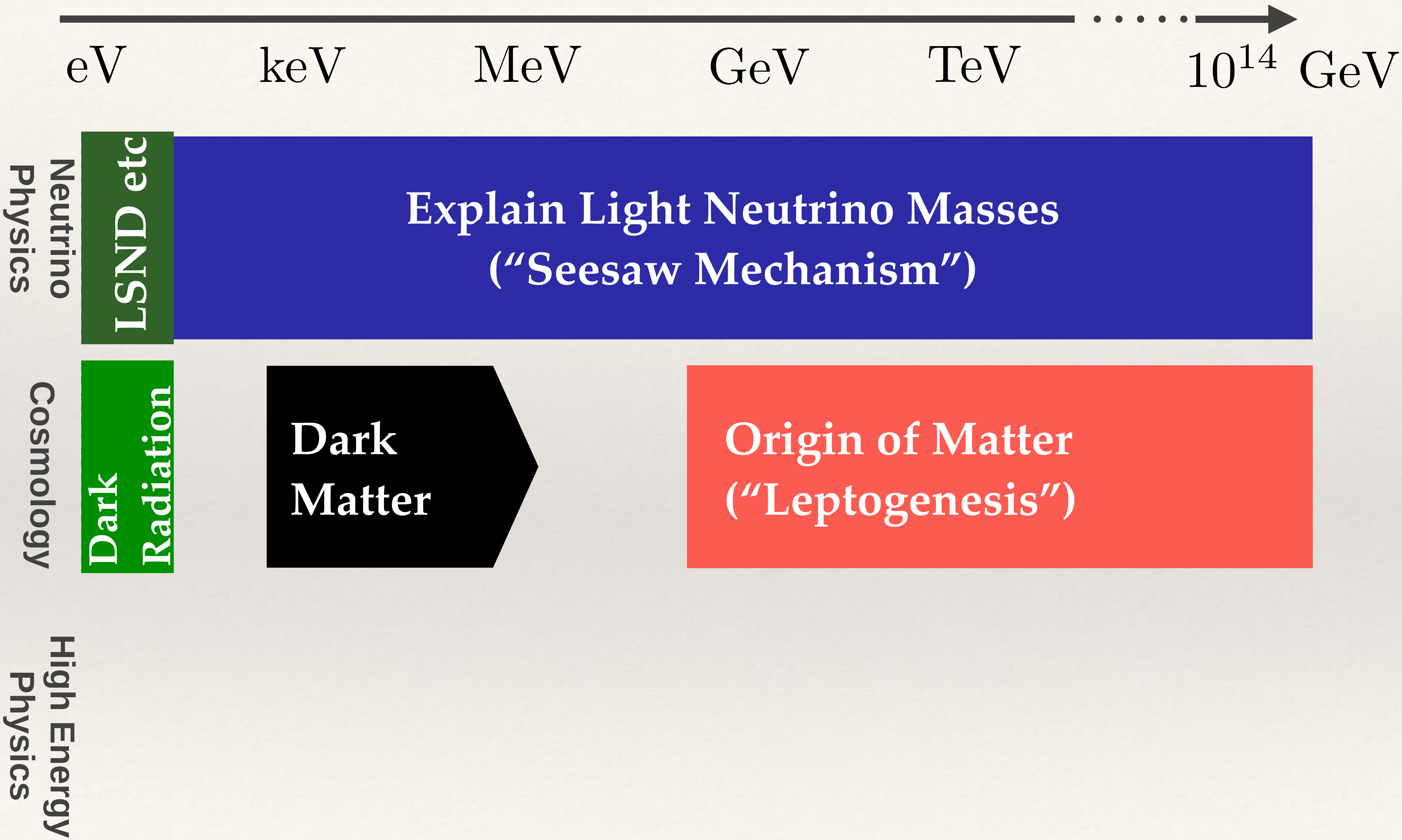
Not today's topic.
Recent review: 1602.04816

- **What is the Dark Matter made of?**

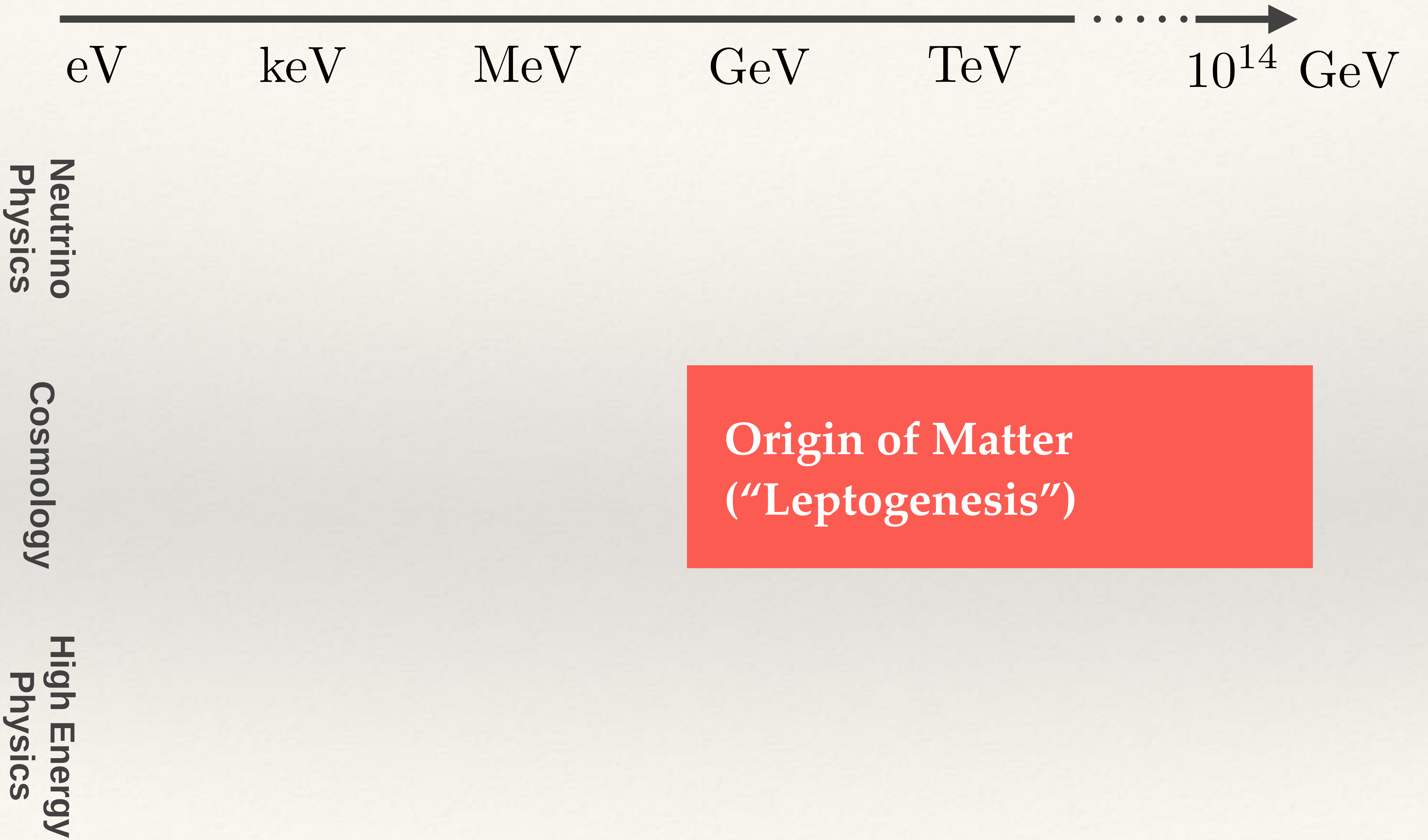
  It makes up most of the mass in the universe.



Right Handed Neutrinos and the Light Neutrino Masses



Heavy Neutrinos as the Origin of Matter



Heavy Neutrinos as the Origin of Matter

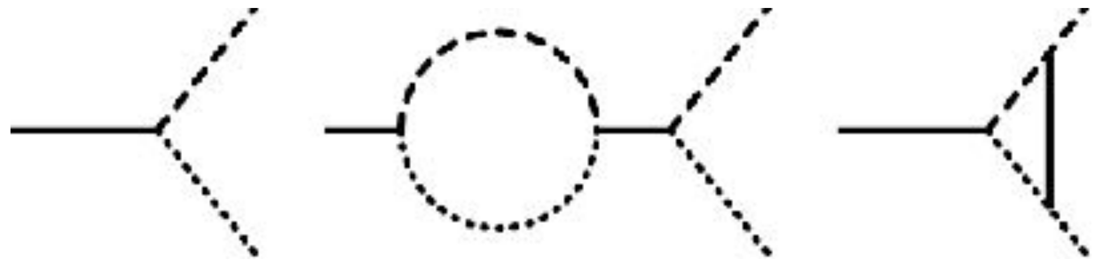
eV keV MeV GeV TeV 10^{14} GeV

Neutrino Physics

Cosmology

High Energy Physics

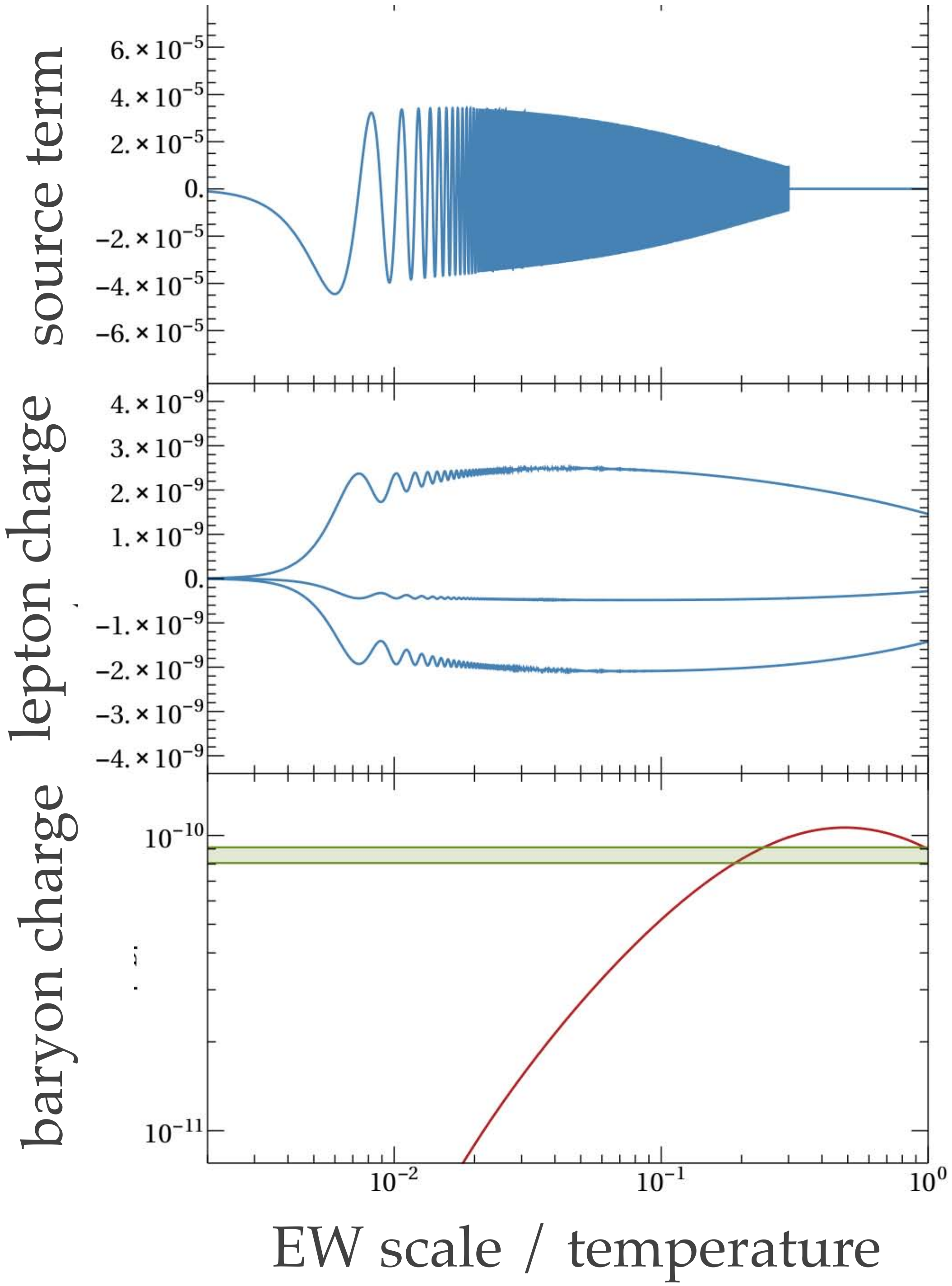
Leptogenesis in heavy neutrino decay



Origin of Matter
("Leptogenesis")

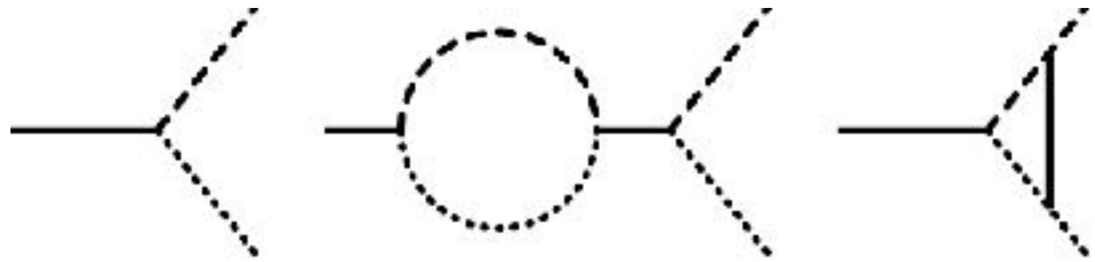
Heavy Neutrinos as the Origin of Matter

Leptogenesis from heavy neutrino oscillations



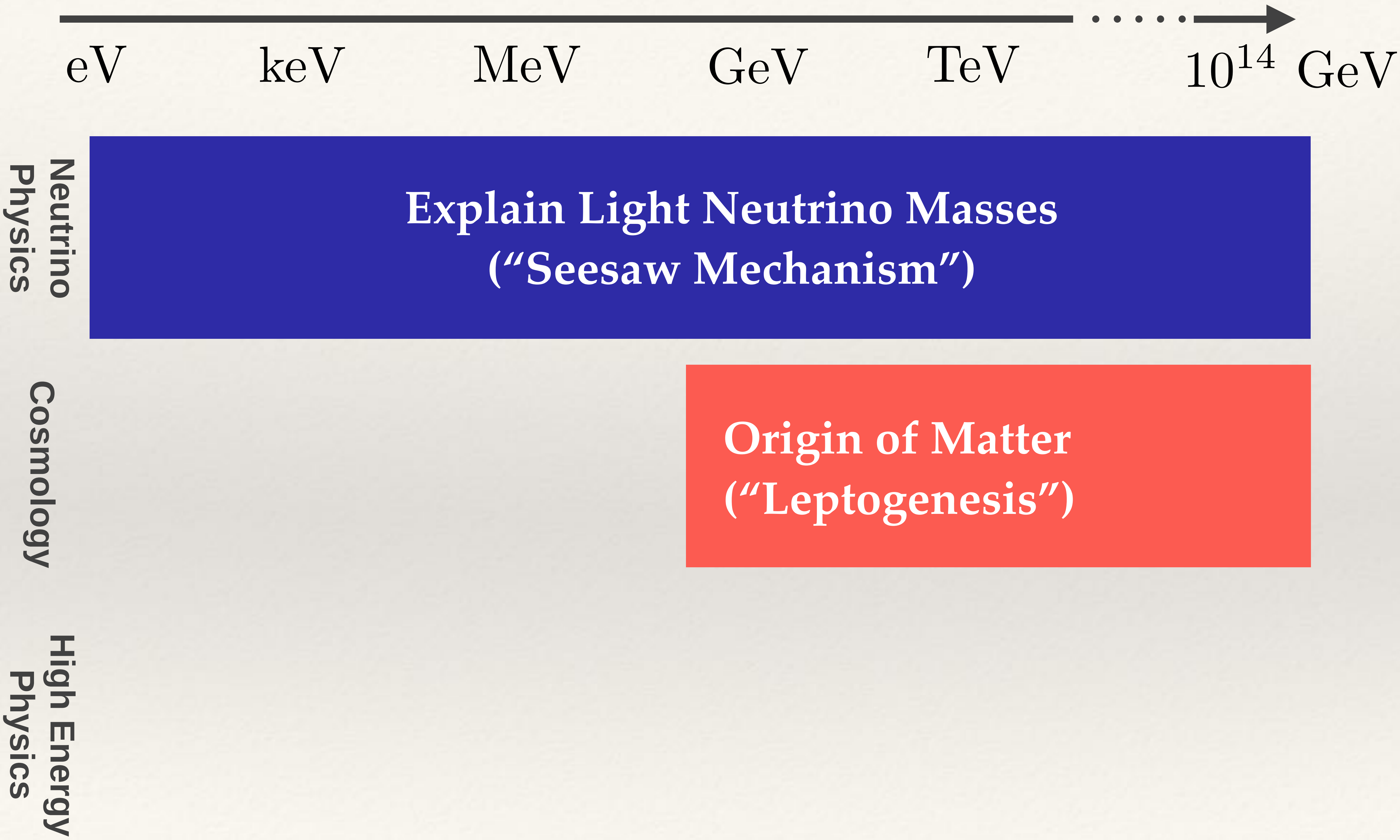
GeV TeV 10^{14} GeV

Leptogenesis in heavy neutrino decay



Origin of Matter
("Leptogenesis")

Heavy Neutrinos and the Light Neutrino Masses



Heavy Neutrinos and the Light Neutrino Masses

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

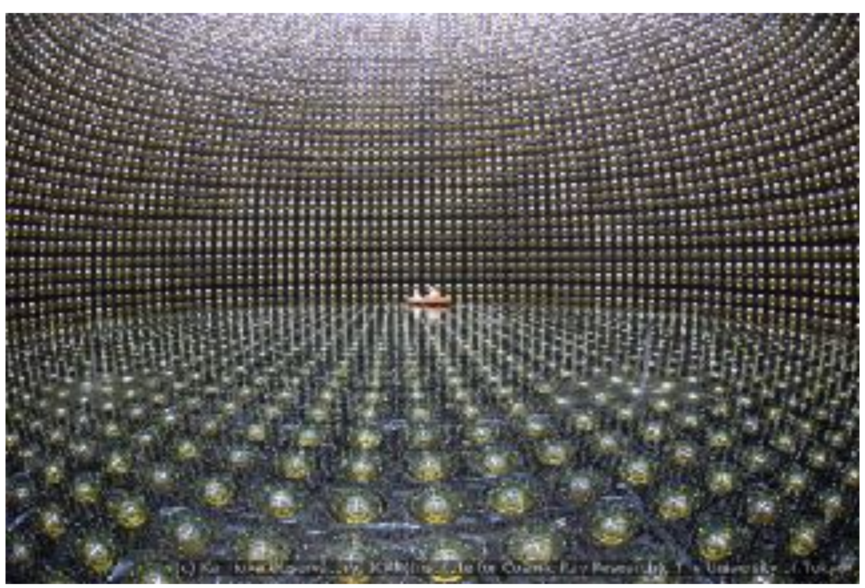
Neutrino Physics

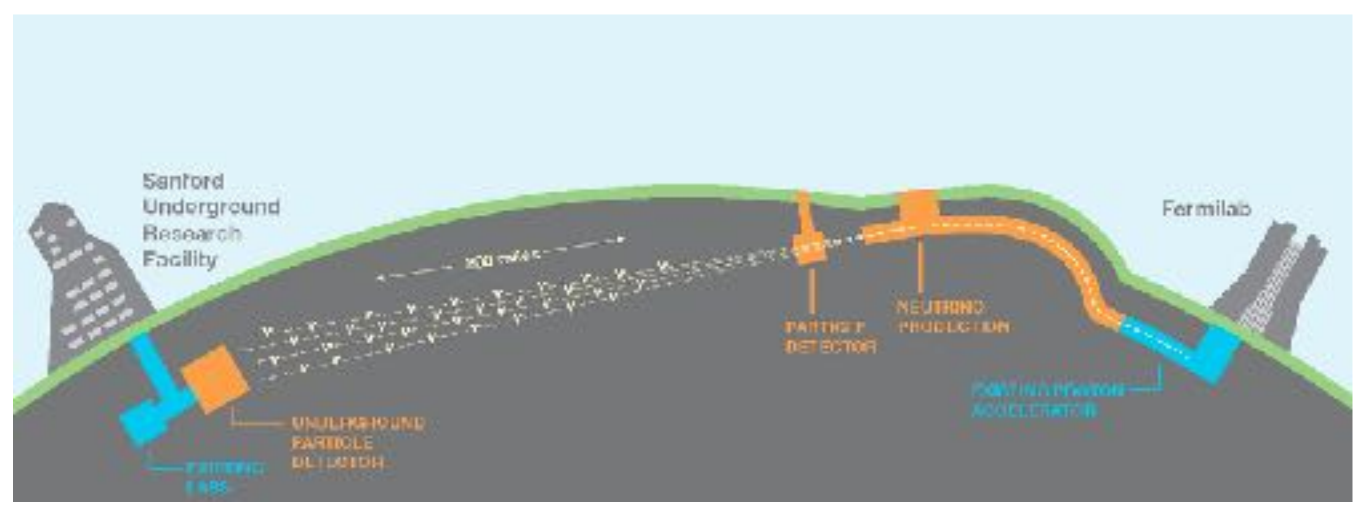
Explain Light Neutrino Masses ("Seesaw Mechanism")

Cosmology

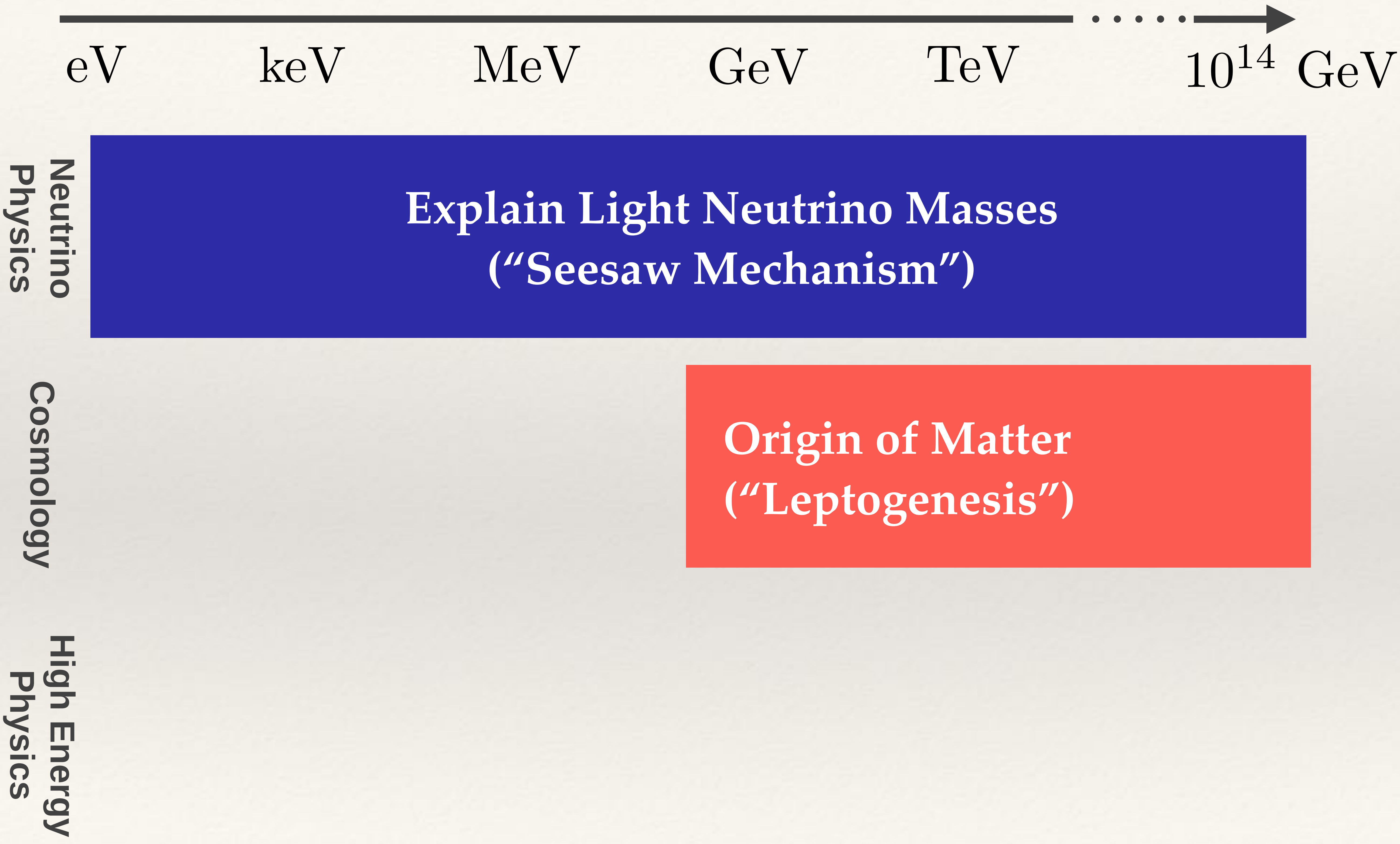
High Energy Physics

neutrino oscillation data





How to Find Heavy Neutrinos?



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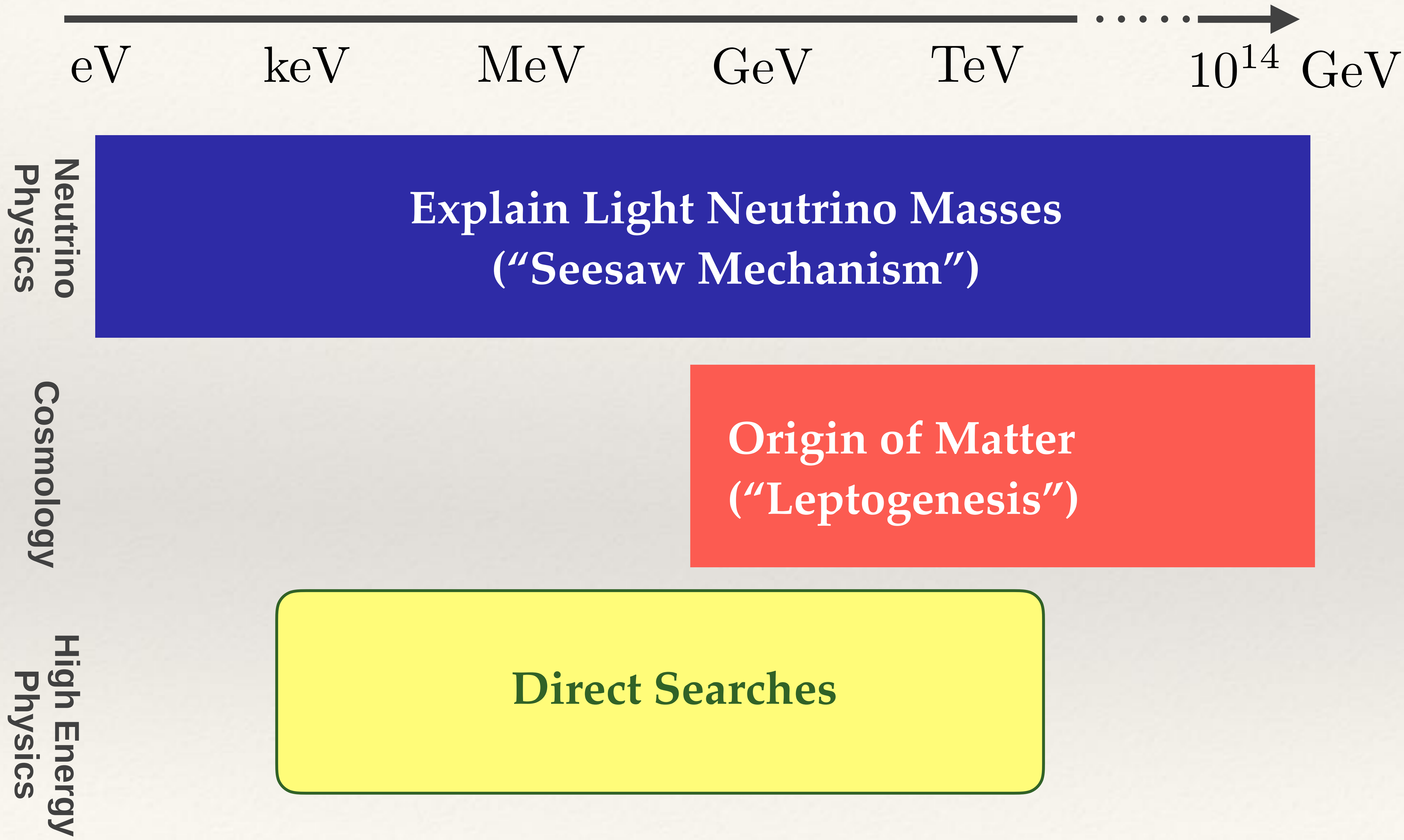


How to Find Heavy Neutrinos?

nuclear decay spectra

TRISTAN, ECHO

fixed target experiments

SHiP

Search for Hidden Particles

NA62

b factories

LHCb

Belle II

proton colliders

electron colliders

ilc

international linear collider

FCC

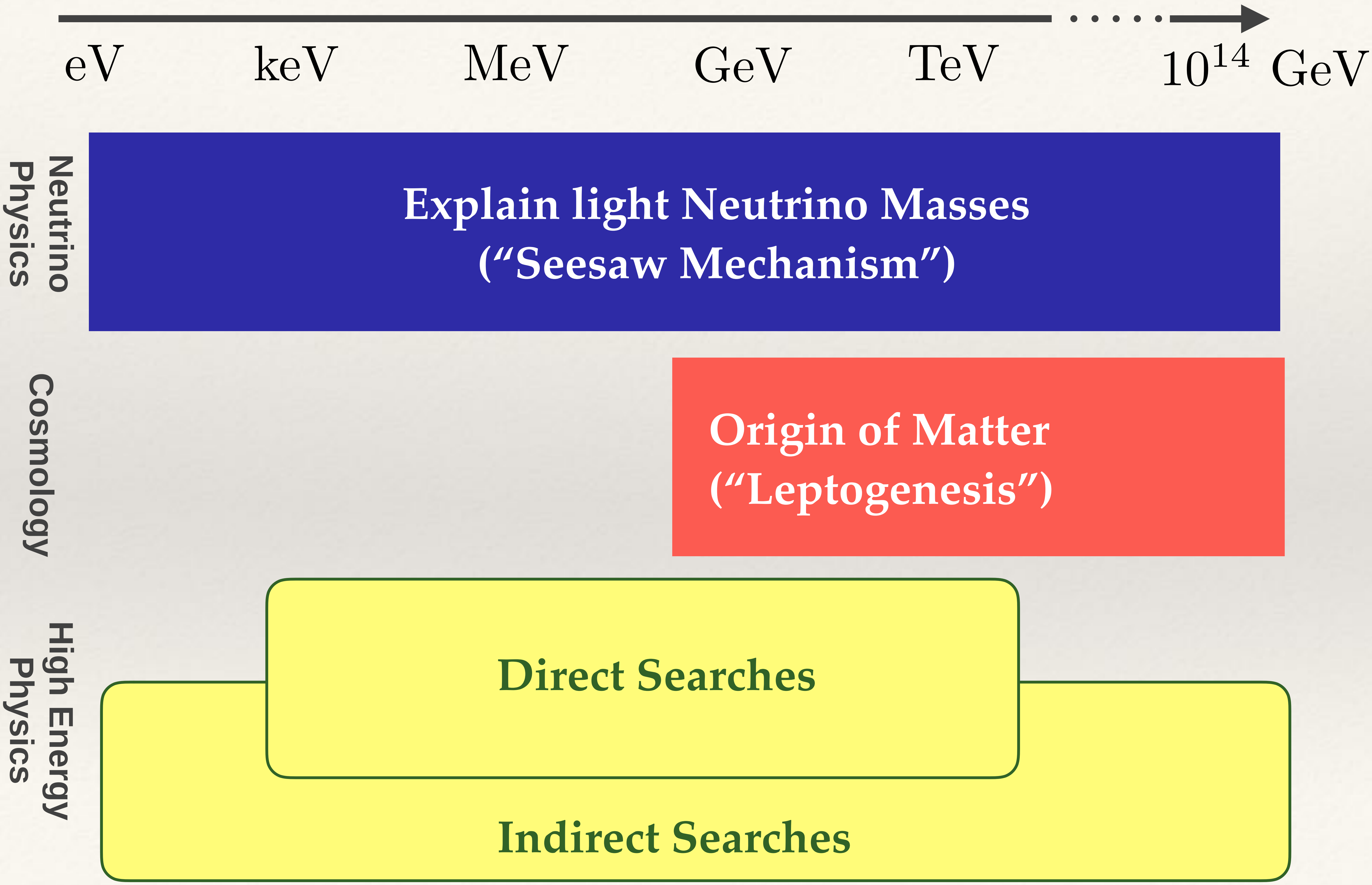
hh ee he

CEPC

Direct Searches

High Energy Physics

How to Find Heavy Neutrinos?



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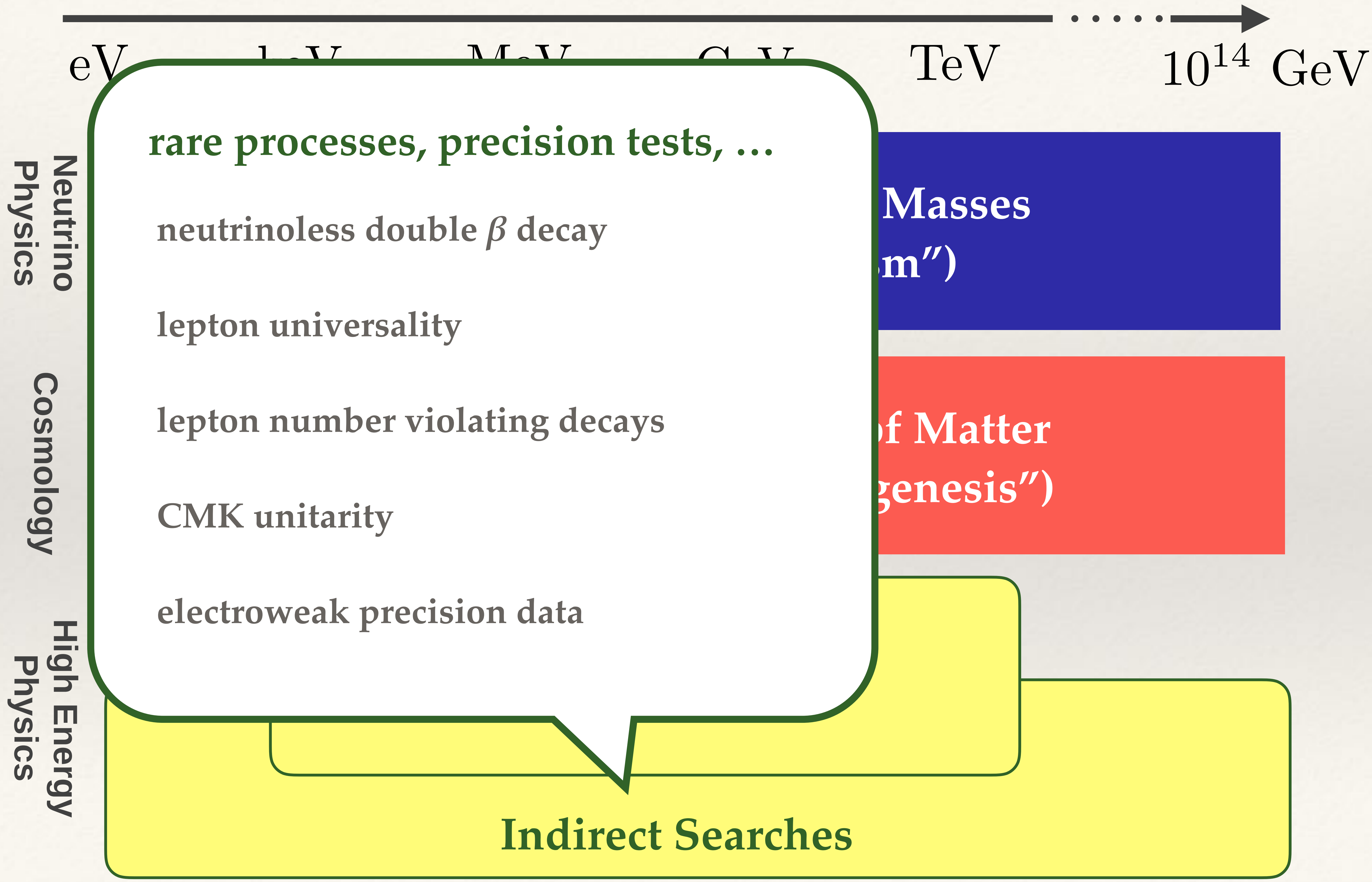
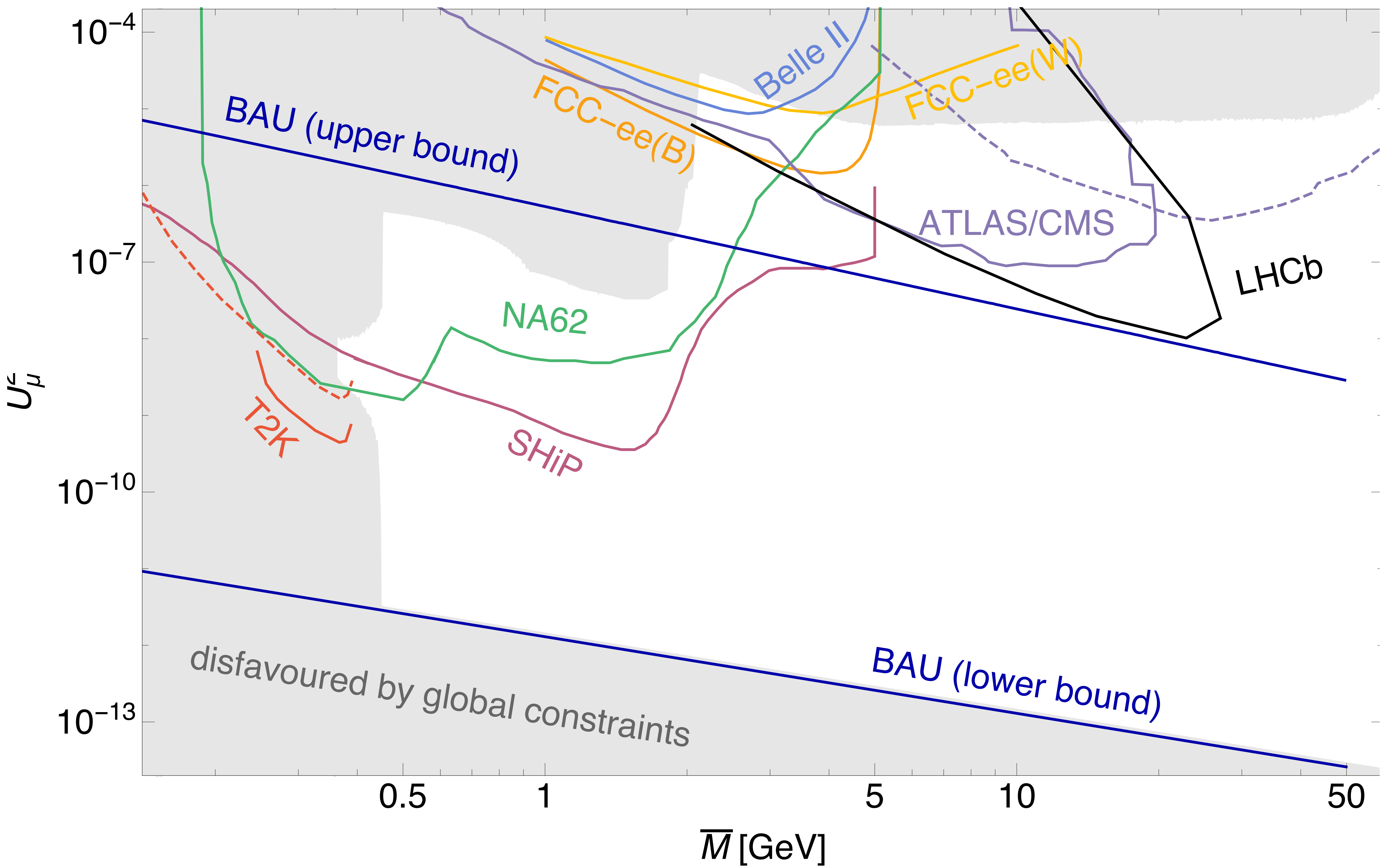
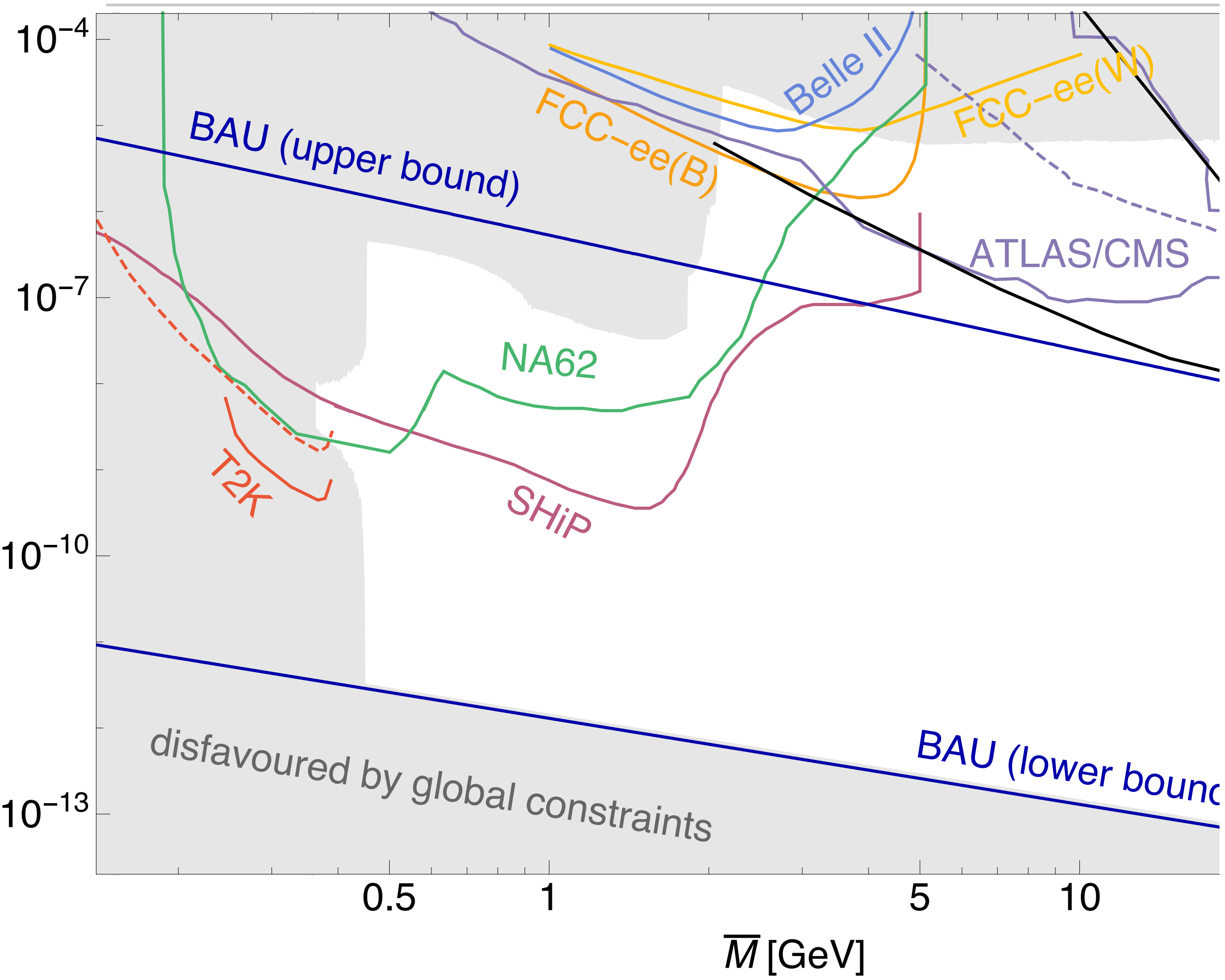


Experimental Perspectives

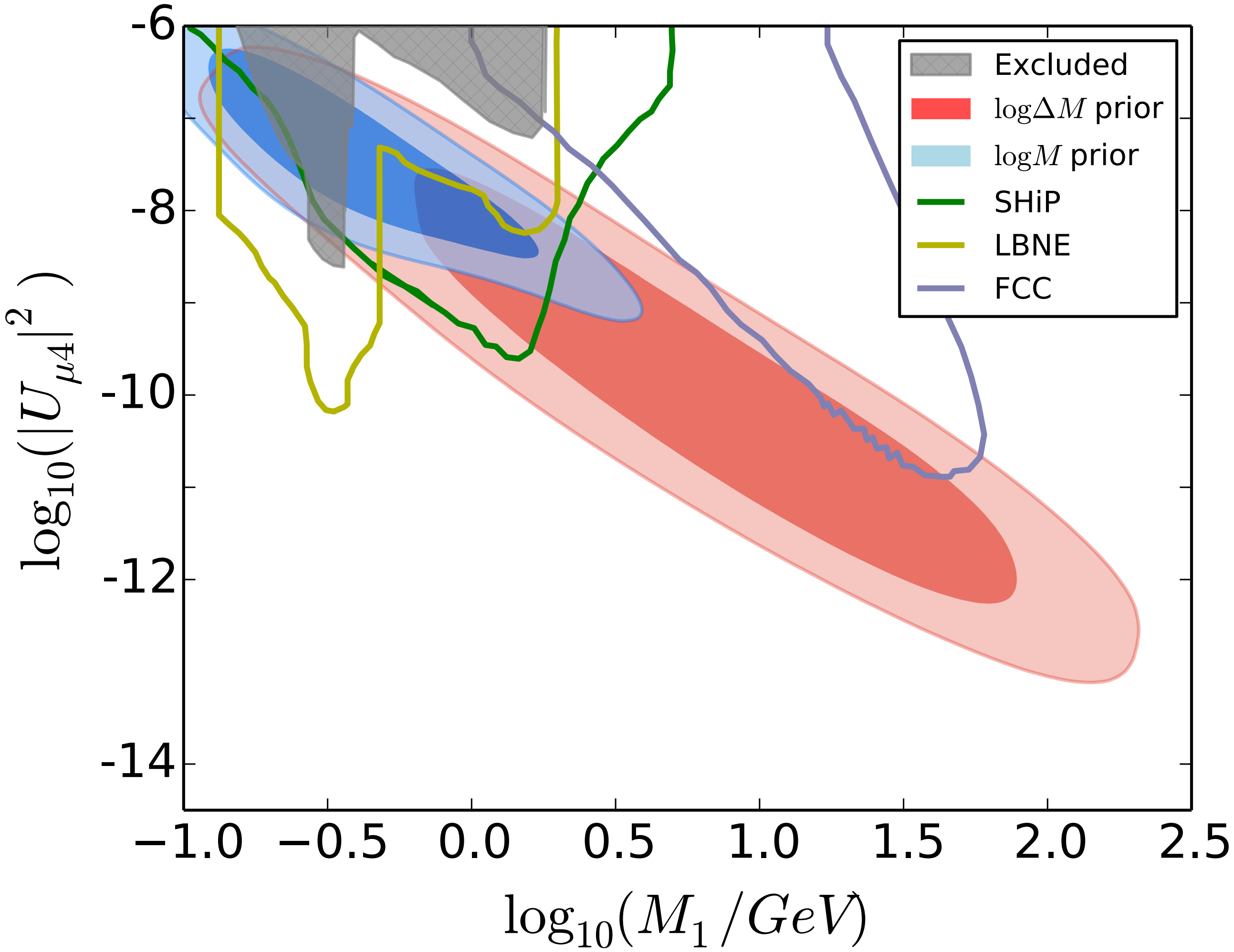


plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Priors and Assumptions



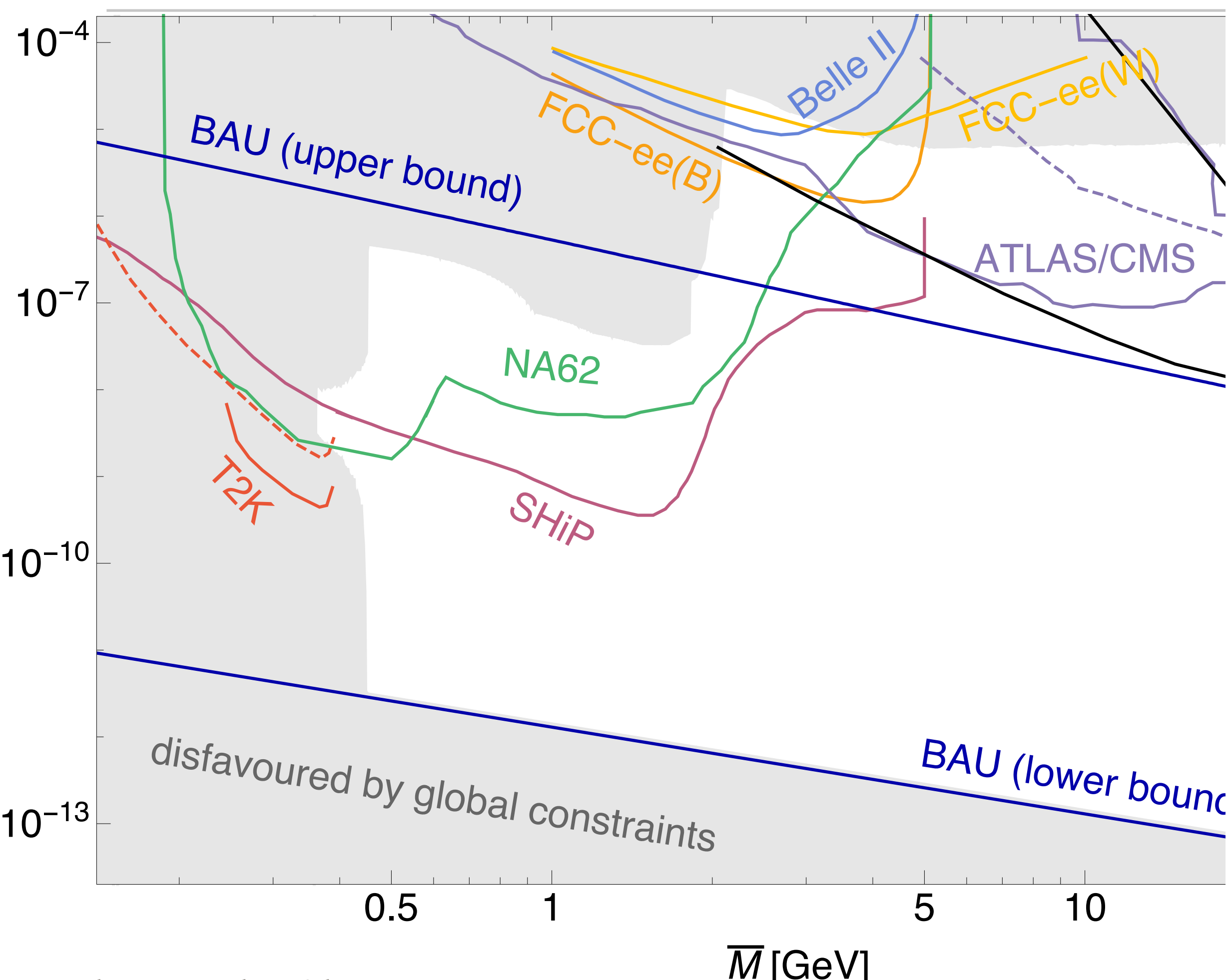
MaD/Garbrecht/Gueter/Klaric 16b



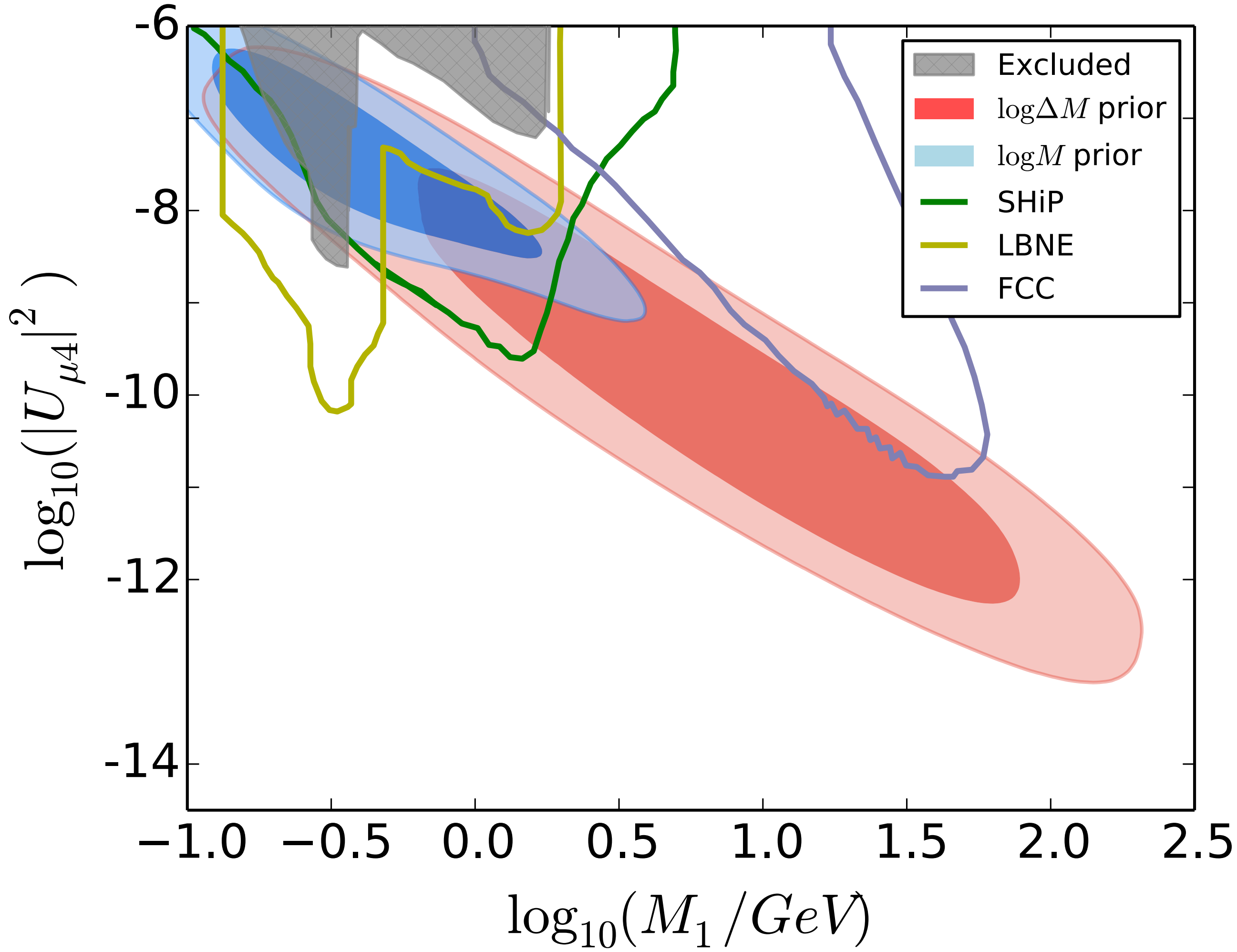
Hernandez/Kekic/Lopez-Pavon/Racker/Savaldo 16

What is the allowed range of heavy neutrino mass and mixing for leptogenesis?

What is the "most likely" place where leptogenesis will occur, given some "bottom-up" prior?



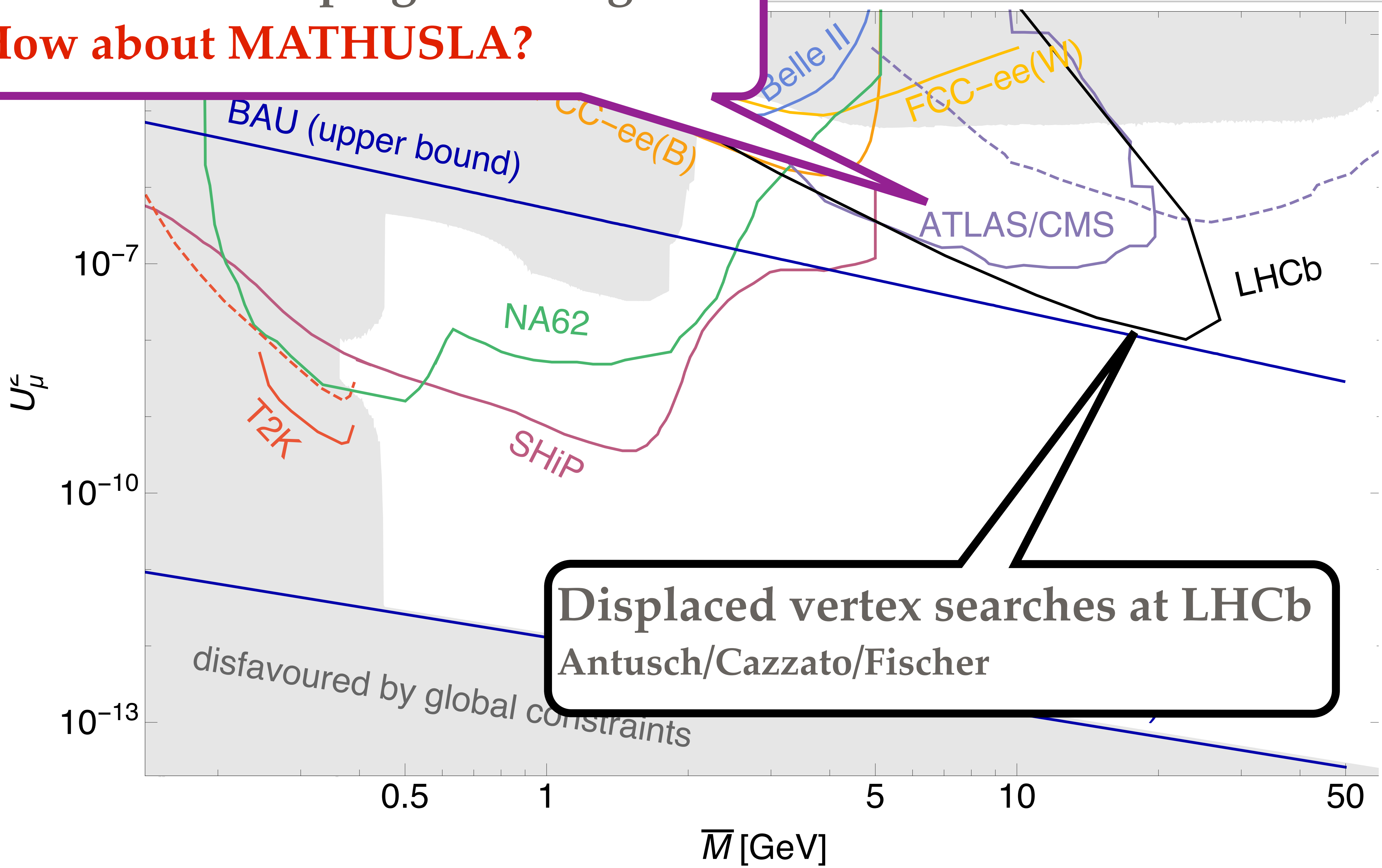
Shaposhnikov 08
Canetti/Shaposhnikov 10
Canetti/MaD/Shaposhnikov 13
Canetti/MaD/Frossard/Shaposhnikov 13
MaD/Eijima 16
MaD/Garbrecht/Gueter/Klaric 16a
MaD/Garbrecht/Gueter/Klaric 16b
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 17
Abada/Arcadi/Domcke/Lucente 17



Hernandez/Kekic/Lopez-Pavon/Racker/Rius 15
Hernandez/Kekic/Lopez-Pavon/Racker/Savaldo 16

Perspectives

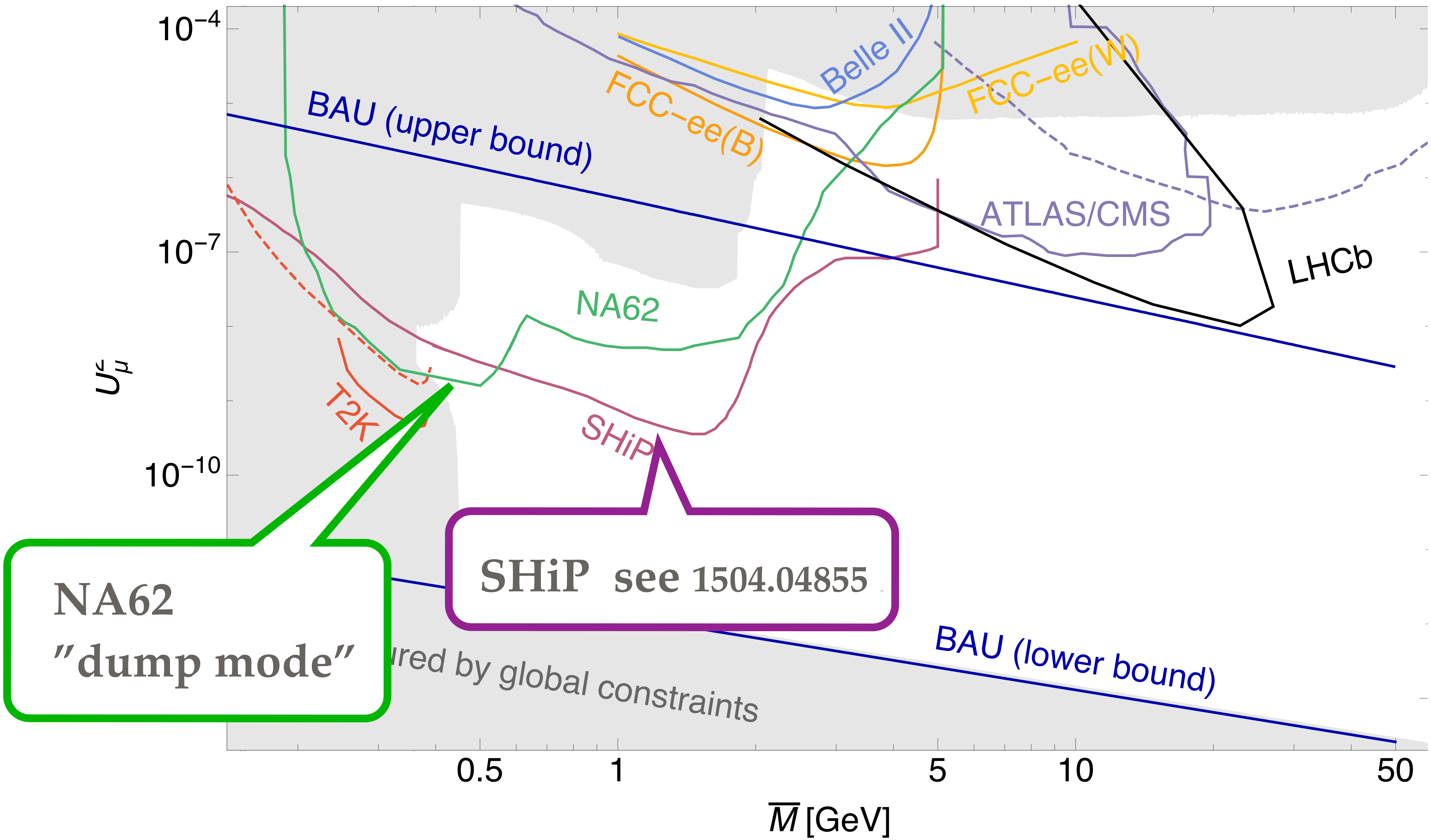
ATLAS/CMS (Izaguirre/Shuve)
Hard to reach leptogenesis region
How about MATHUSLA?



Displaced vertex searches at LHCb
Antusch/Cazzato/Fischer

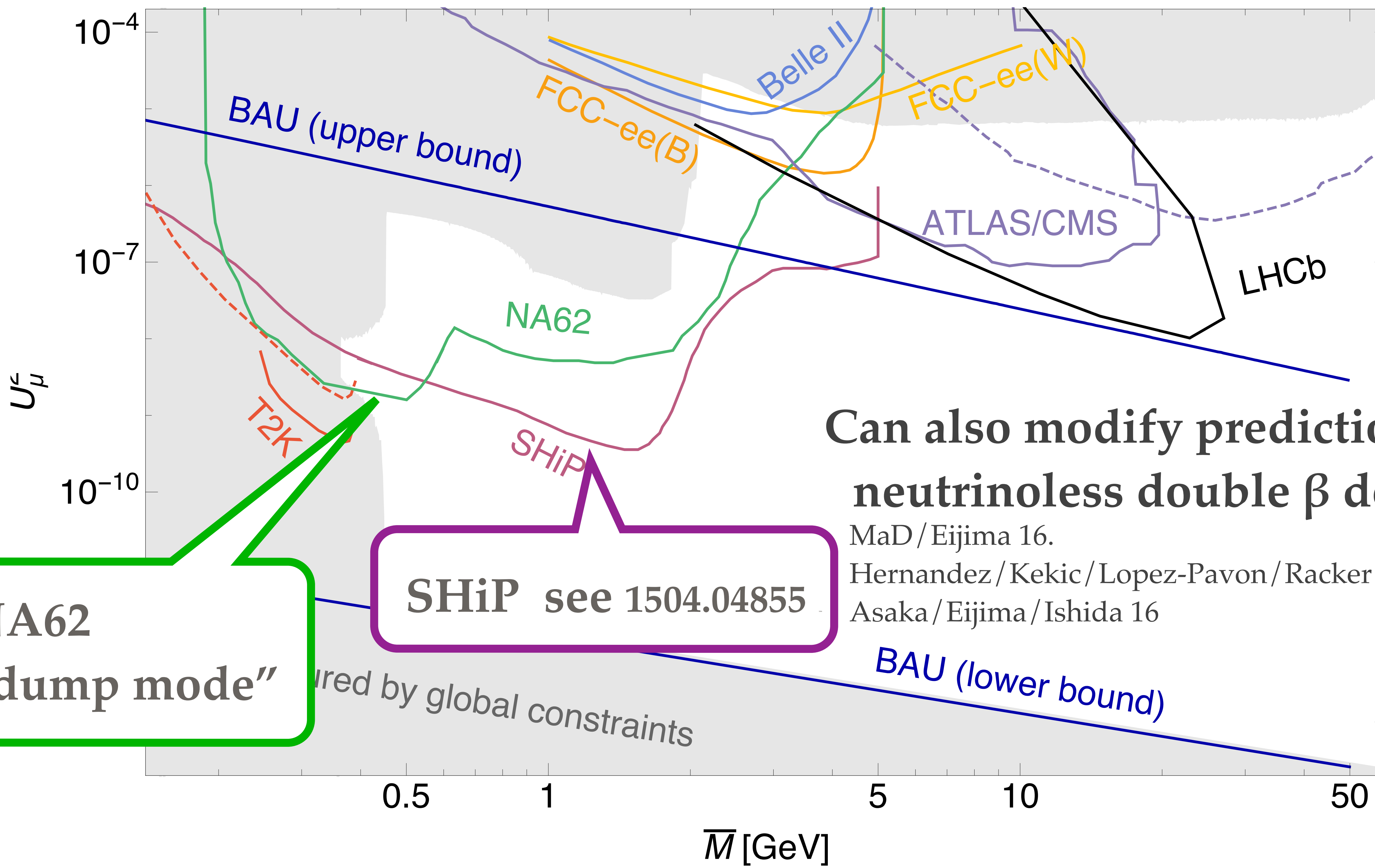
plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Experimental Perspectives



plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Experimental Perspectives



NA62 "dump mode"

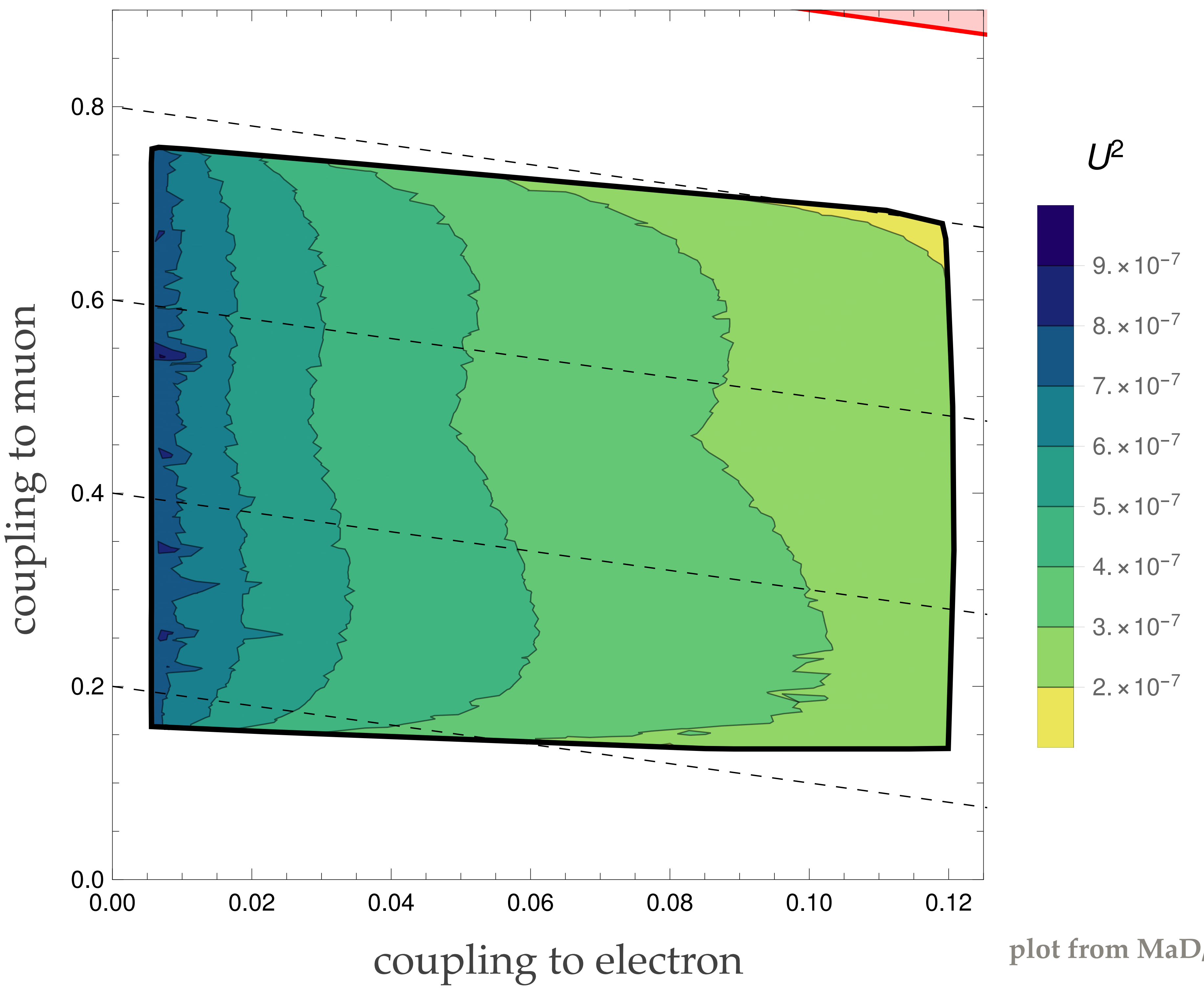
SHiP see 1504.04855

Can also modify prediction for neutrinoless double β decay

MaD/Eijima 16.
Hernandez/Kekic/Lopez-Pavon/Racker/Savaldo 16,
Asaka/Eijima/Ishida 16

plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Neutrino Mixing vs Collider Searches



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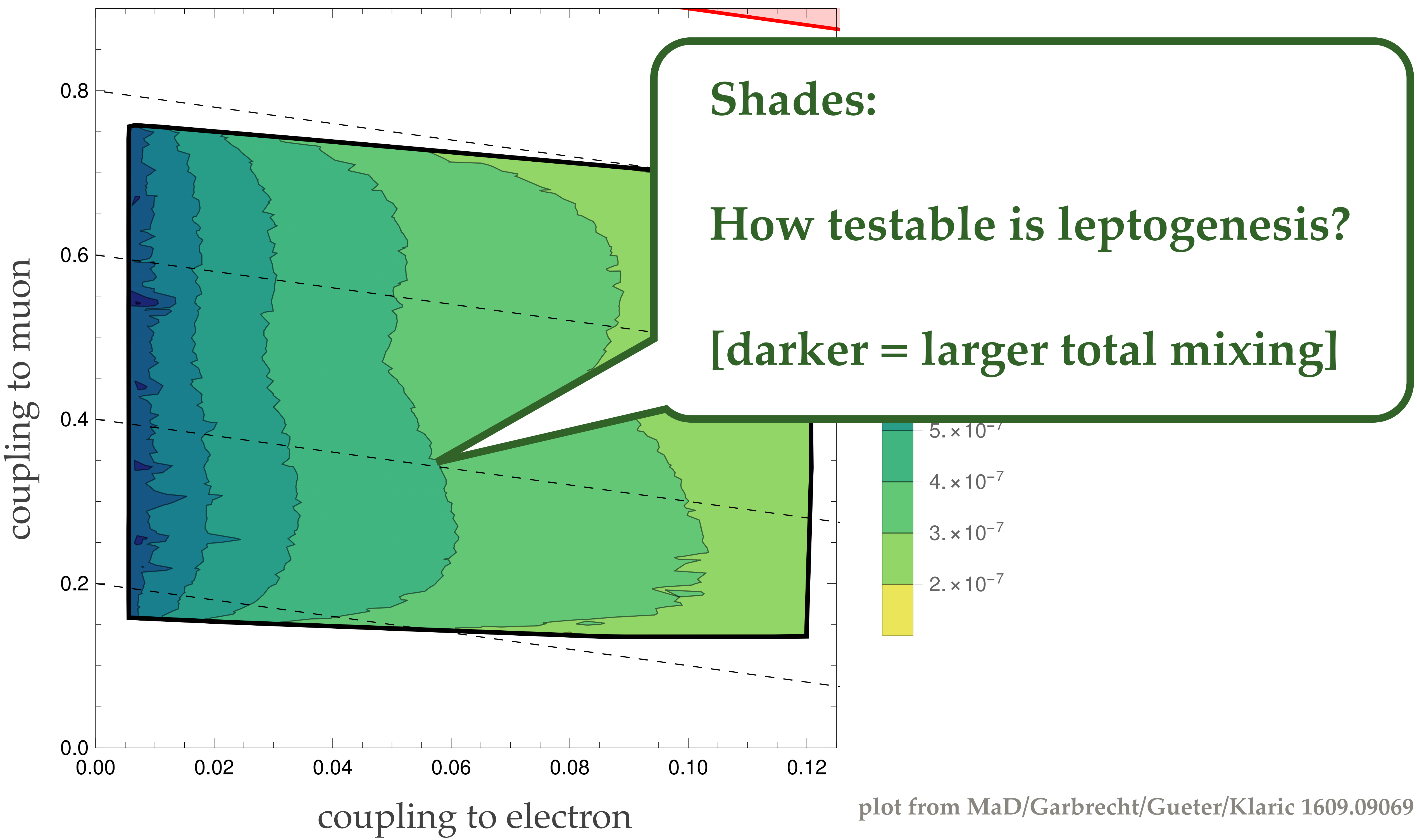

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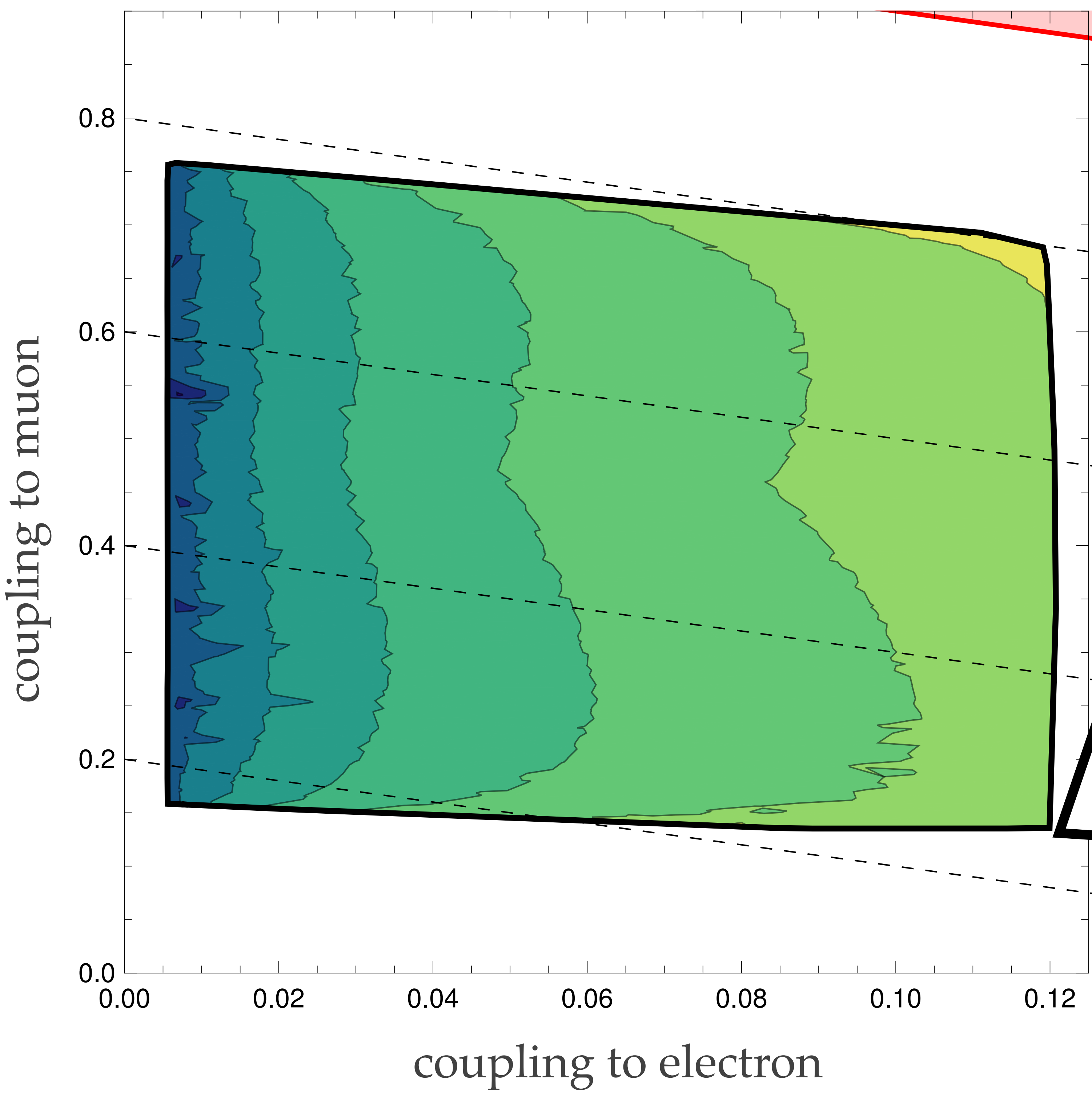


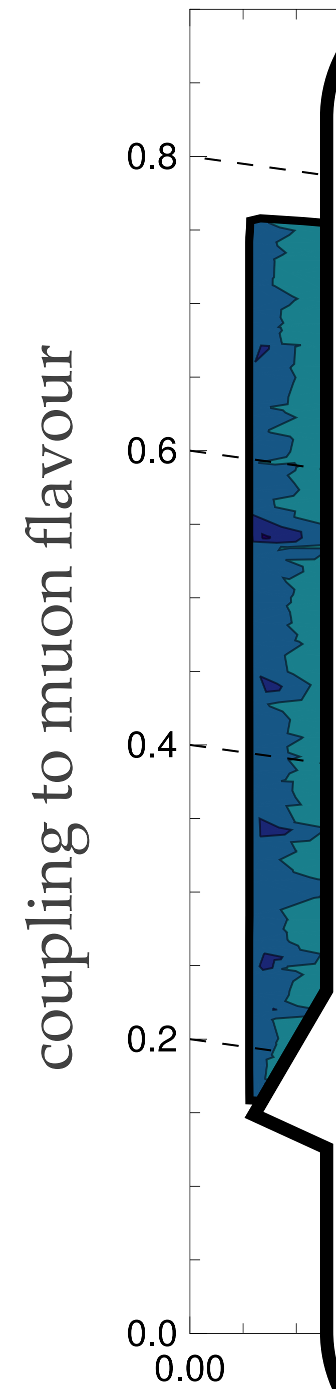
Area within black line:

allowed by neutrino oscillation data

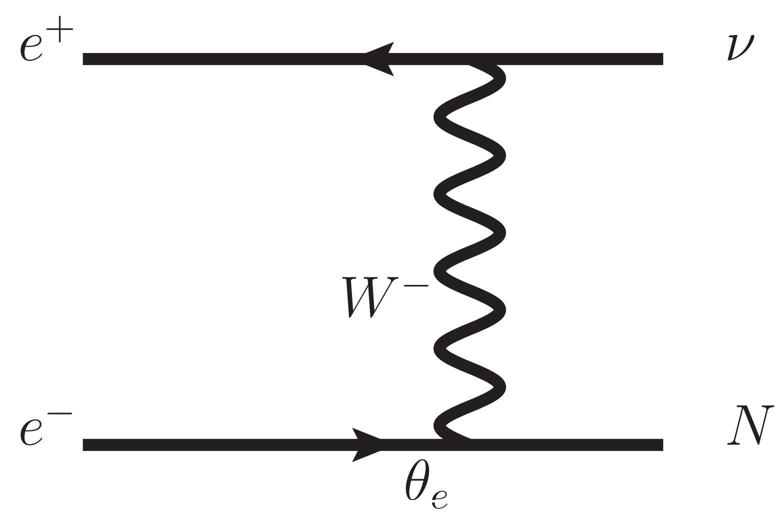
coupling to electron maximal 12%!

[for normal neutrino mass ordering]

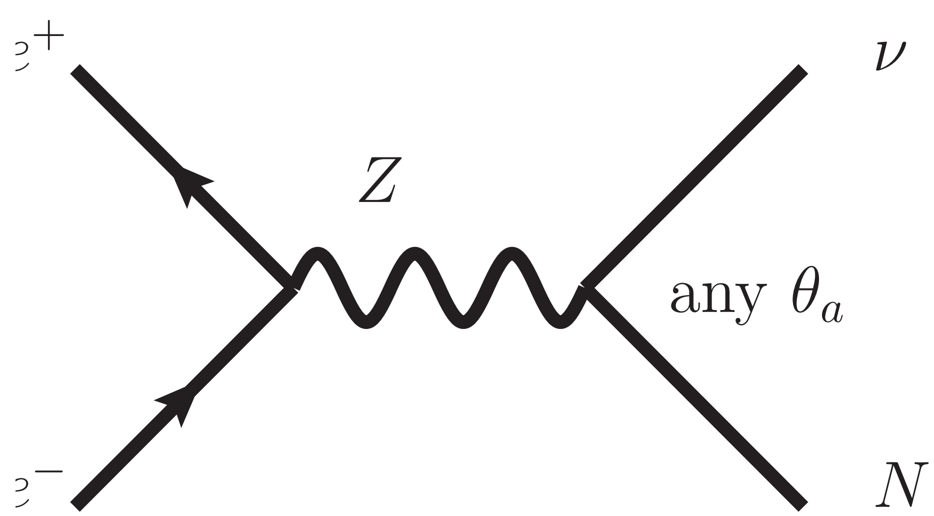
Neutrino Mixing vs Collider Searches



Effect on production at lepton colliders:



suppressed compared to



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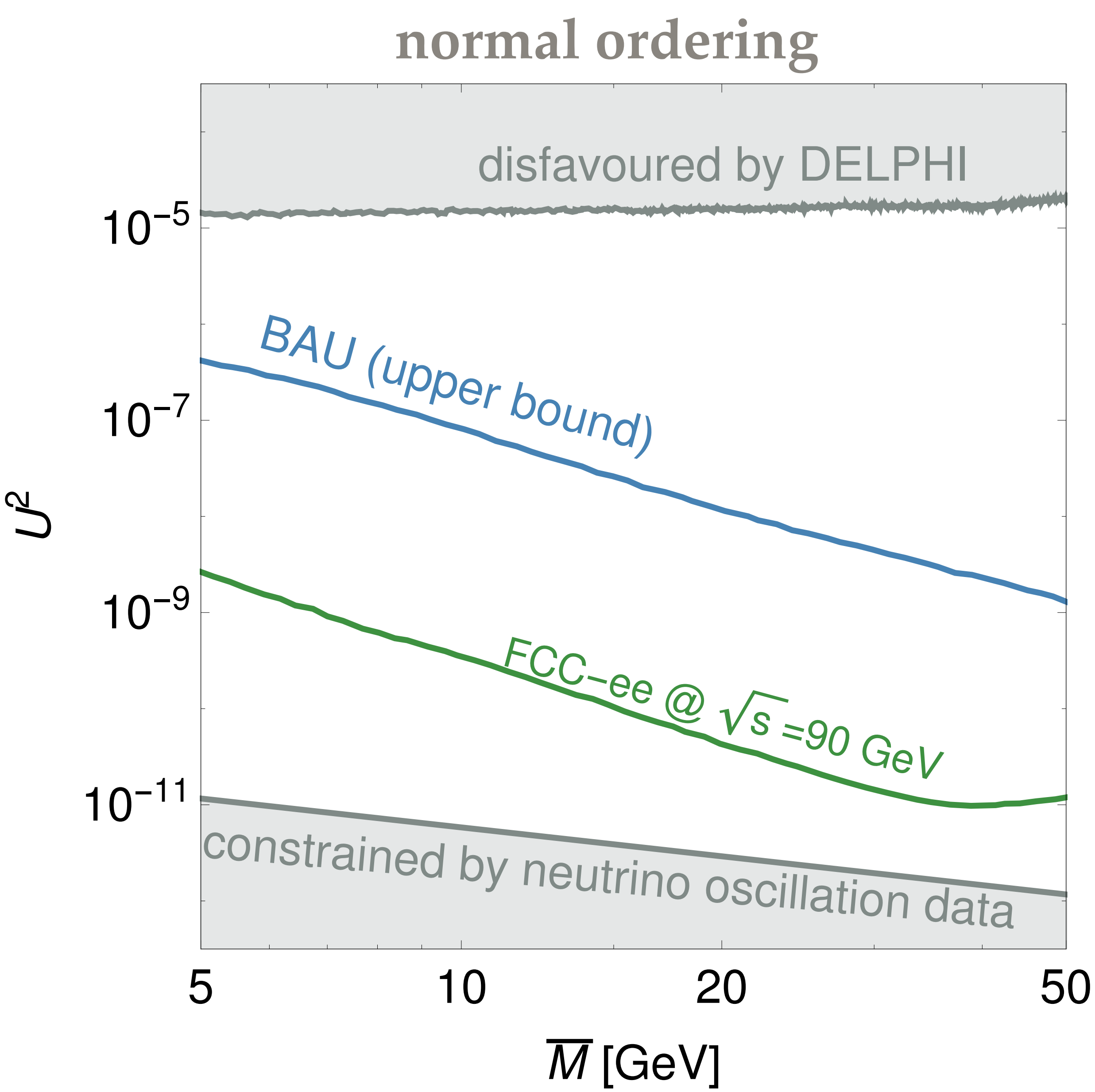
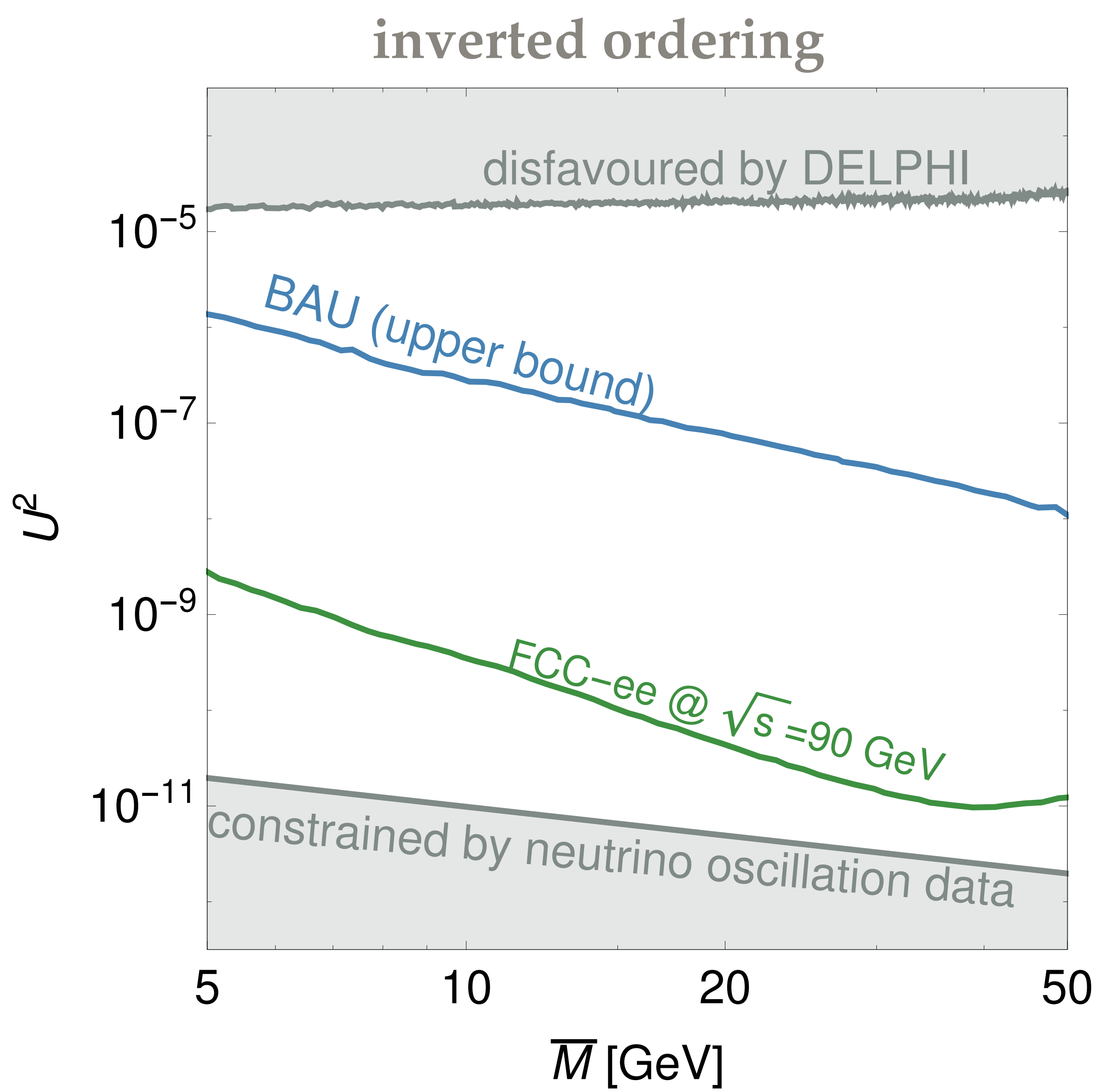
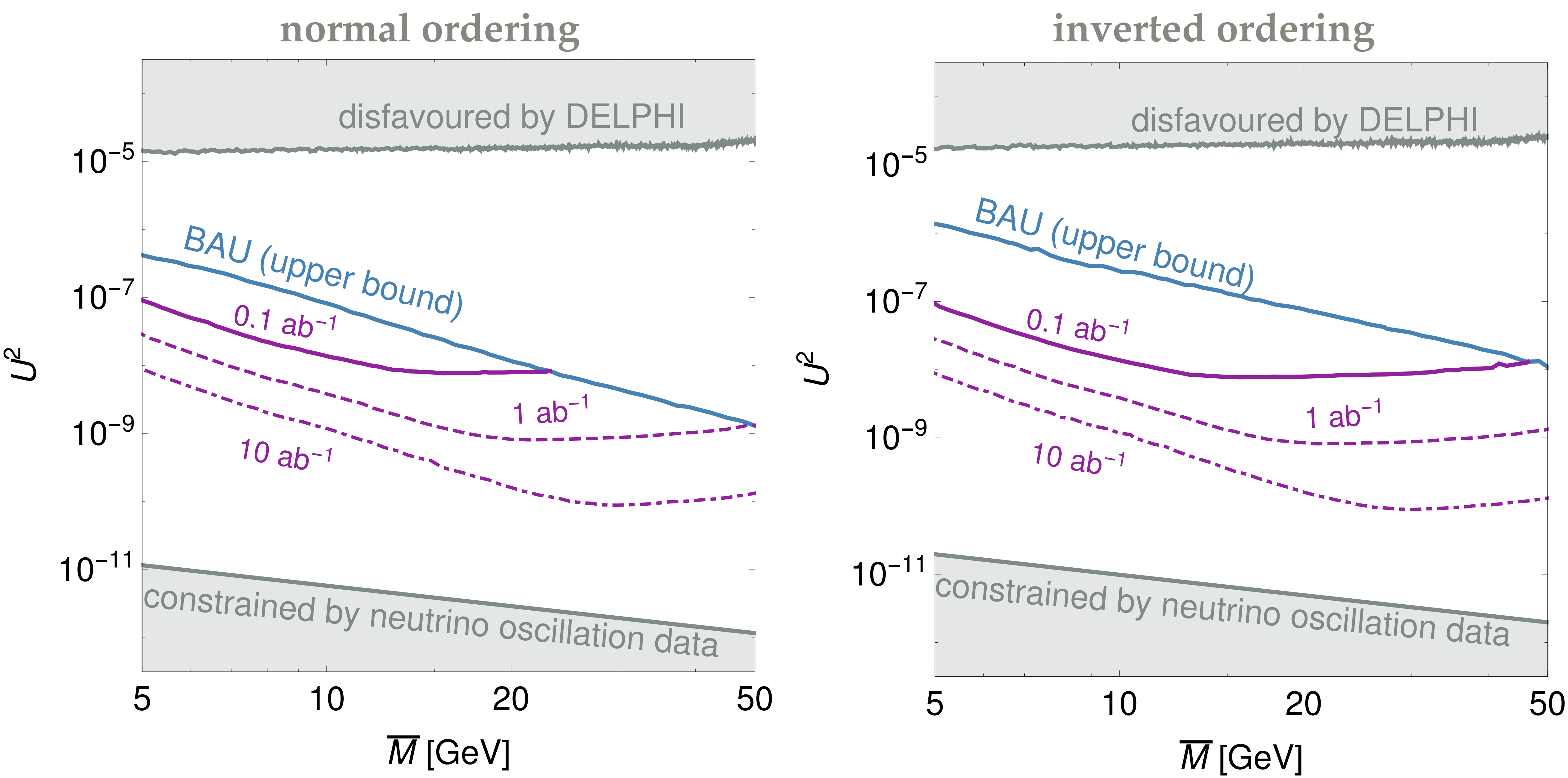
Displaced Vertices at FCC-ee





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

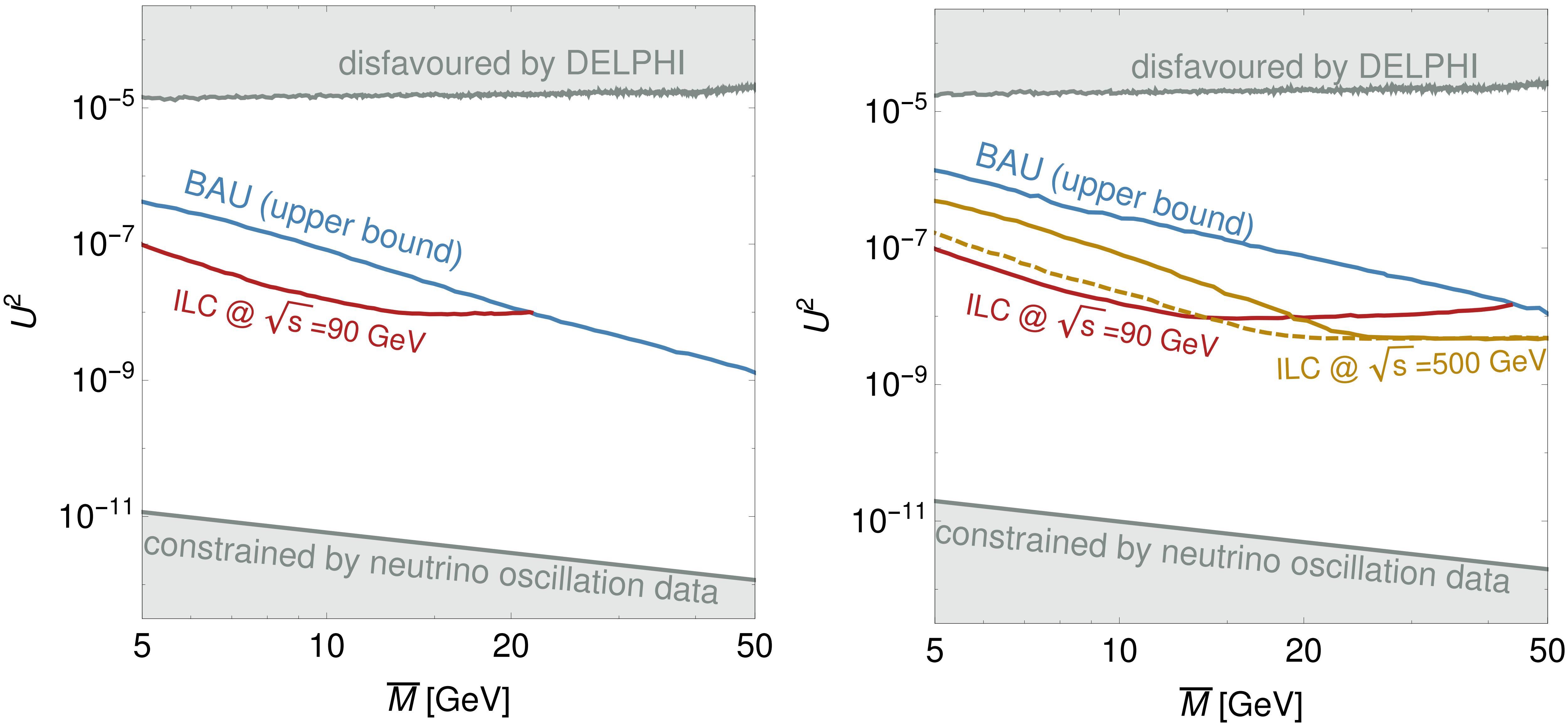
Displaced Vertices at CEPC



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

Displaced Vertices at ILC

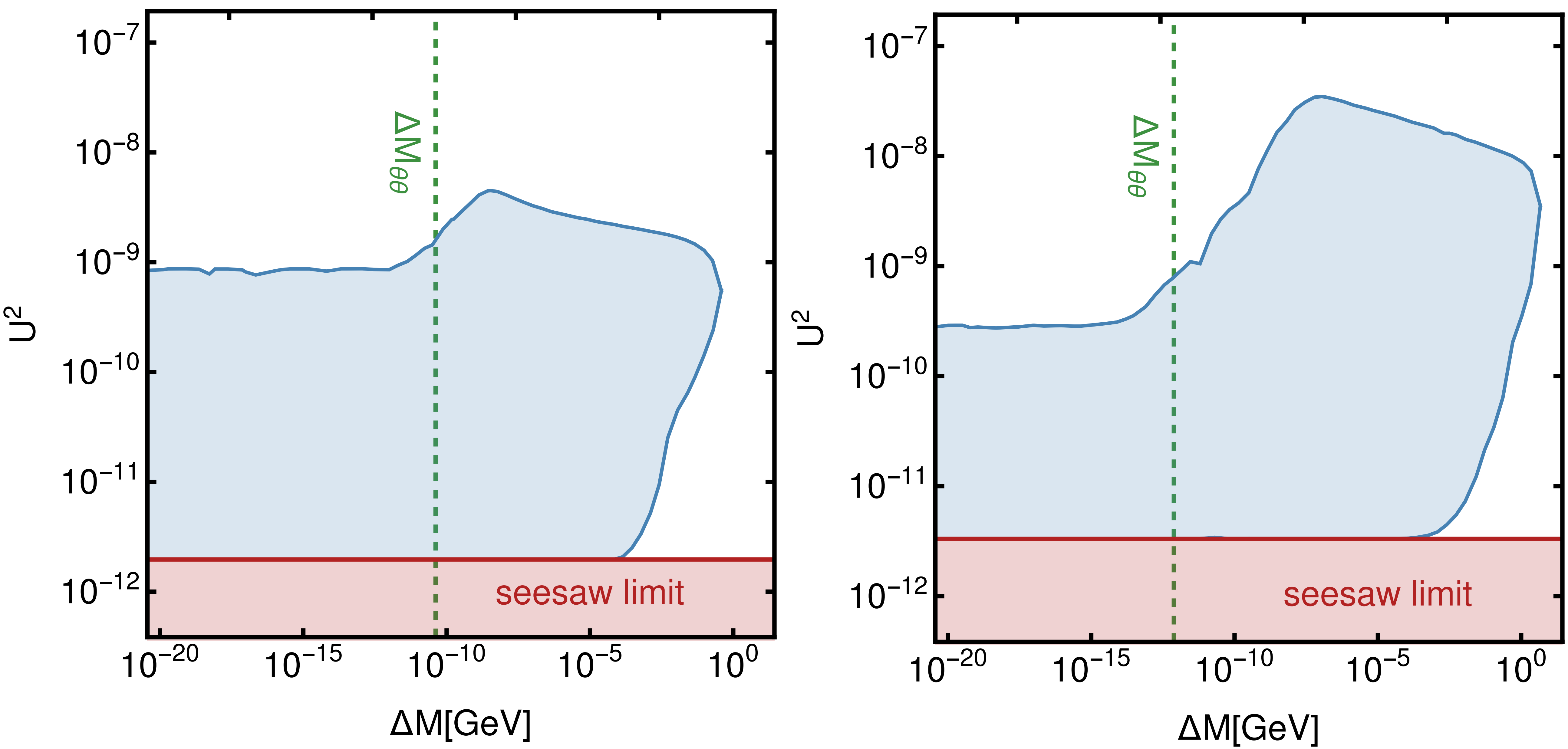
normal ordering | **inverted ordering**



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

Leptogenesis and Heavy Neutrino Mass Splitting

normal ordering — inverted ordering



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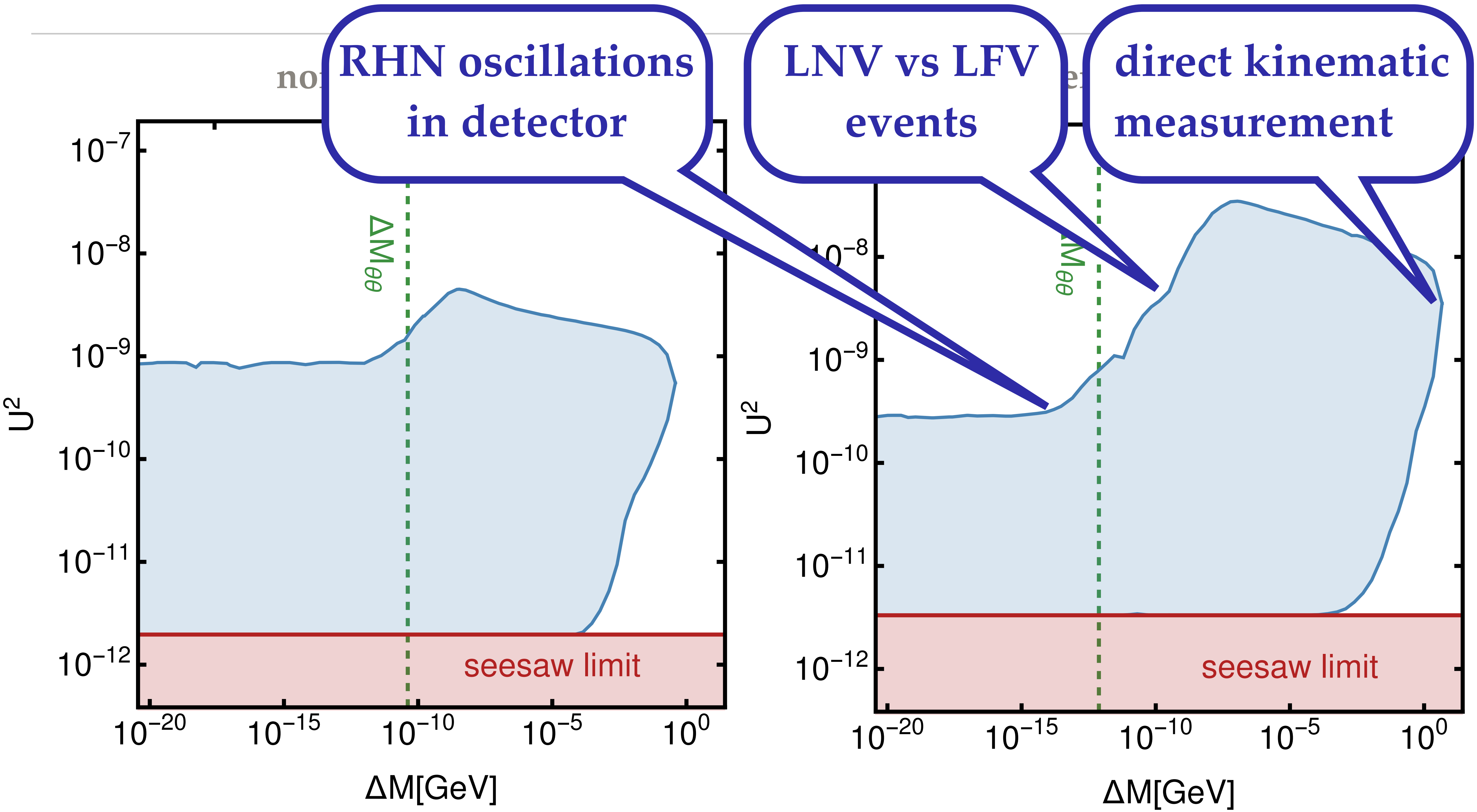

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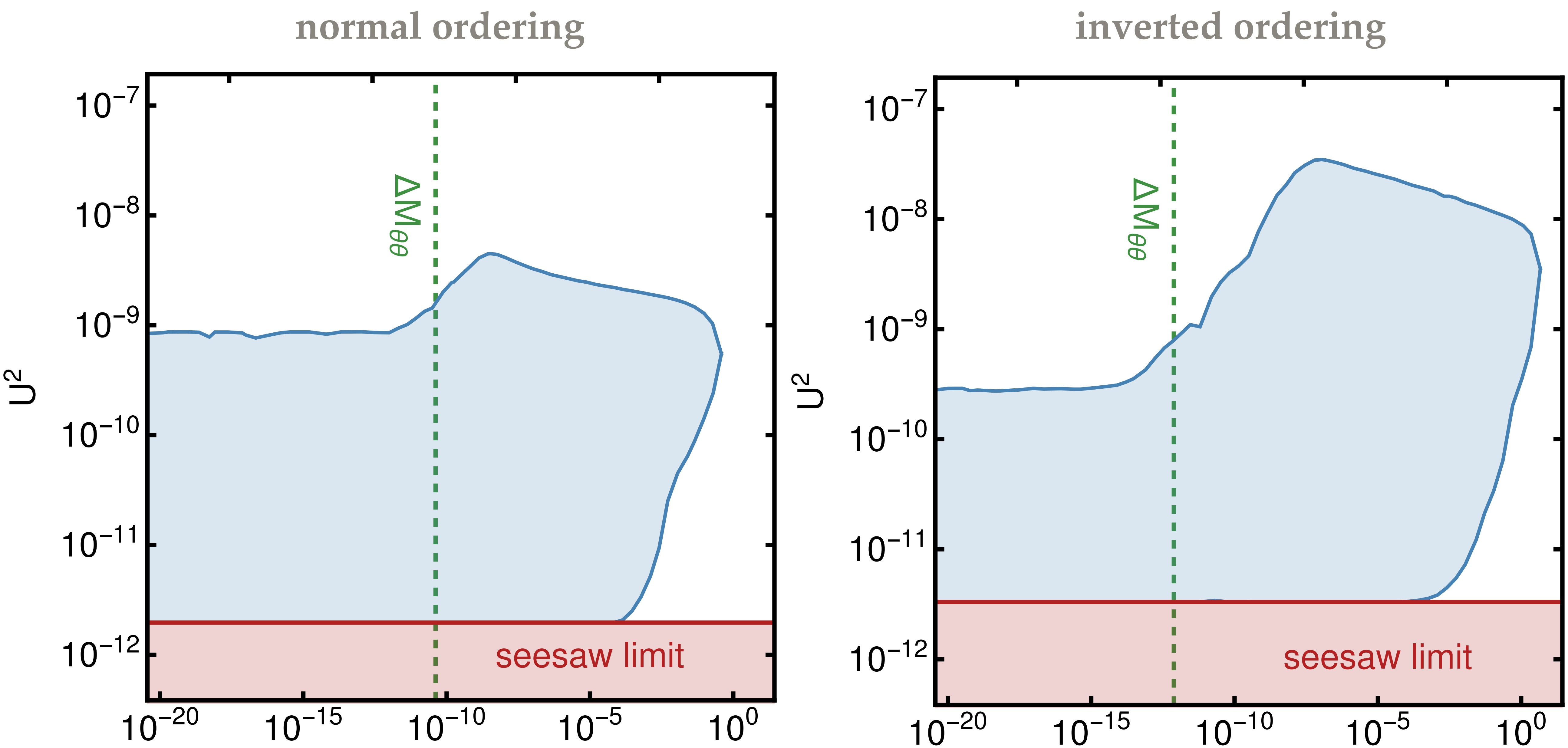
Leptogenesis and Heavy Neutrino Mass Splitting



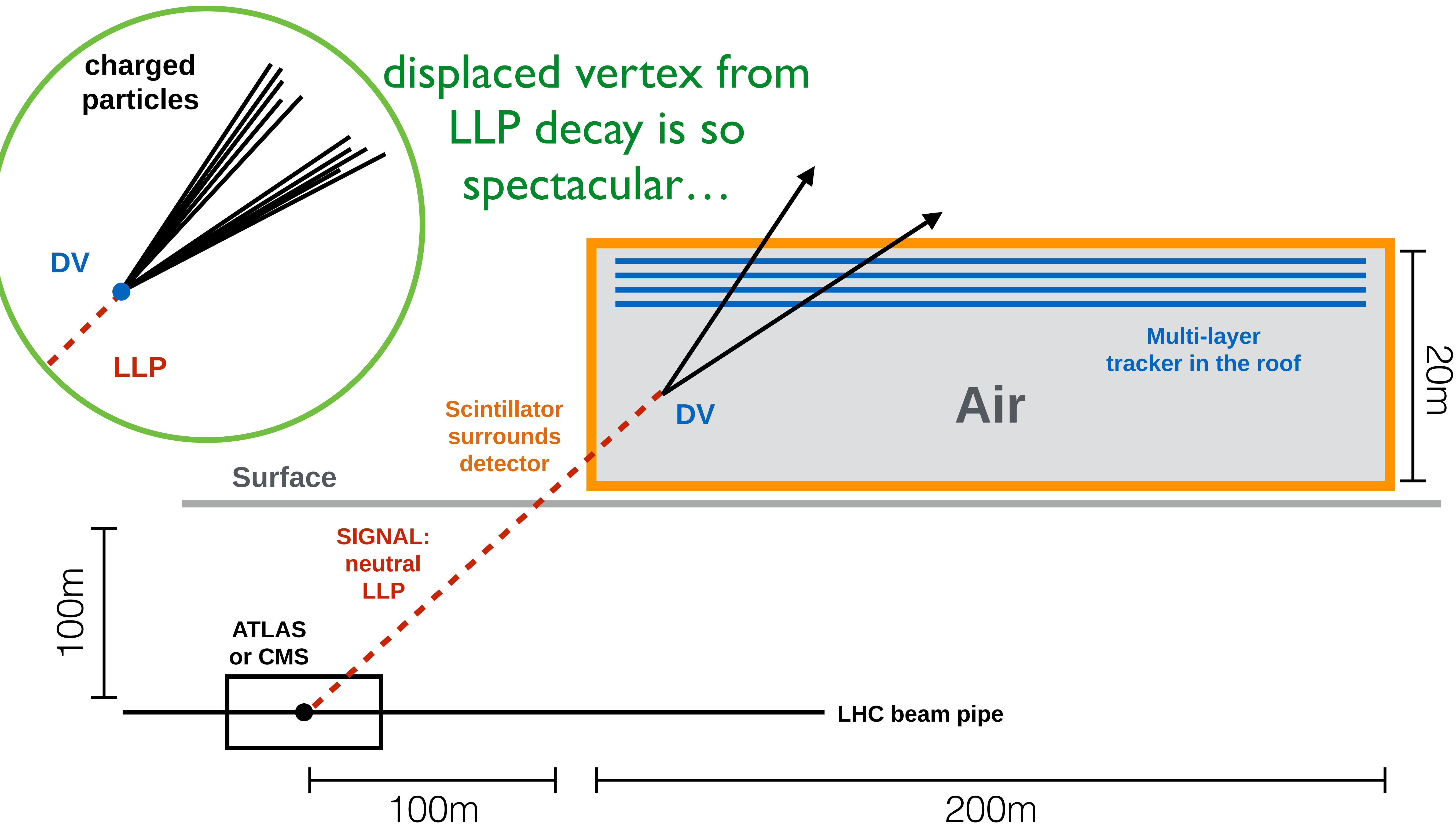
with three RH neutrinos:
no need for mass degeneracy for leptogenesis MaD/Garbrecht 12

Conclusions

- Heavy neutrinos can explain the origin of neutrino masses and matter in the universe
- Collider data + DUNE or NOvA can fully test the minimal seesaw model in the sub-TeV mass range
- non-collider data can help to guide collider searches (e.g. flavour structure, LNV vs LFV)
- several colliders can probably reach the leptogenesis region : ILC, CEPC, FCC-ee
- **Fully testable model of neutrino masses and baryogengesis**

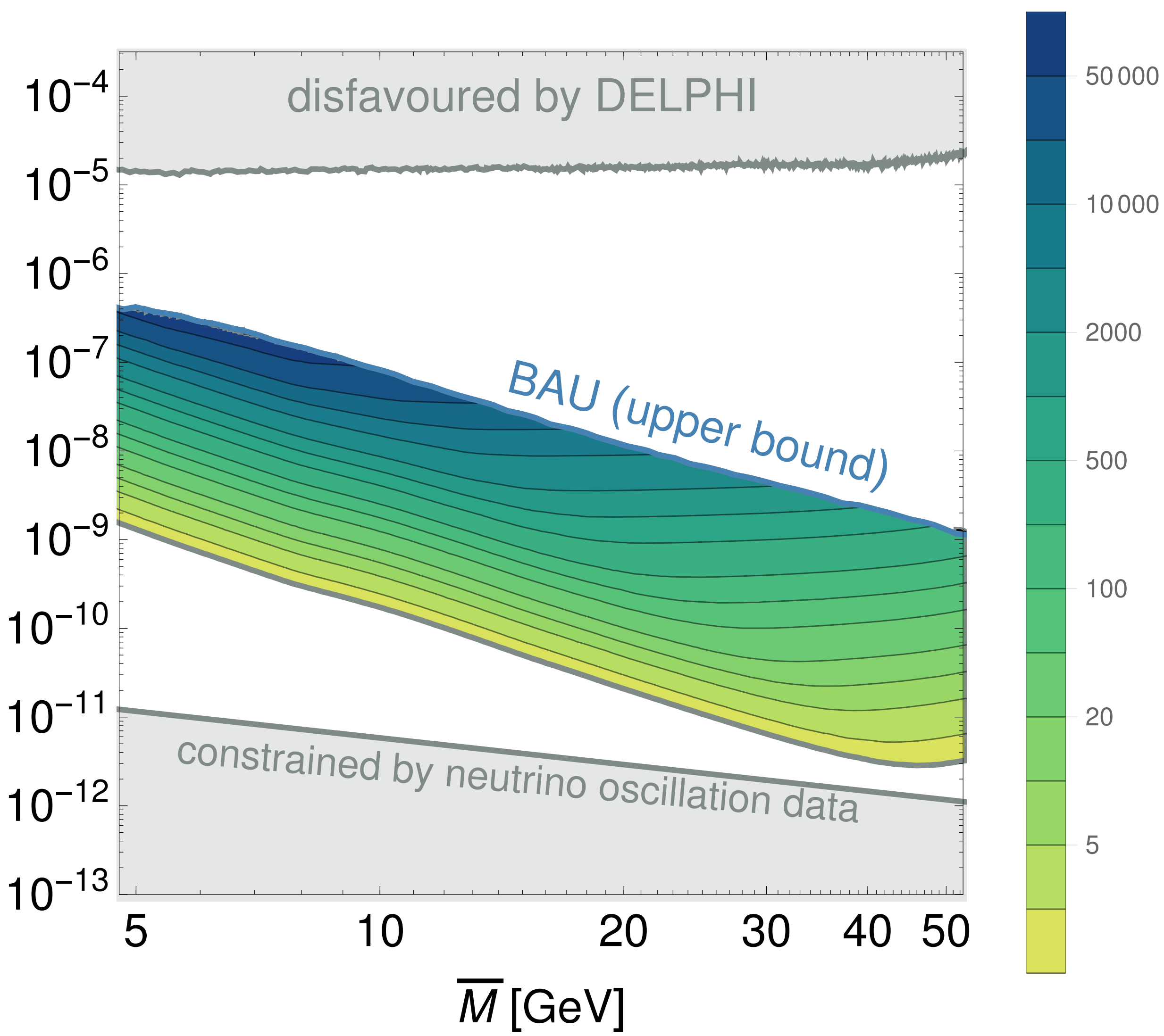
MATHUSLA

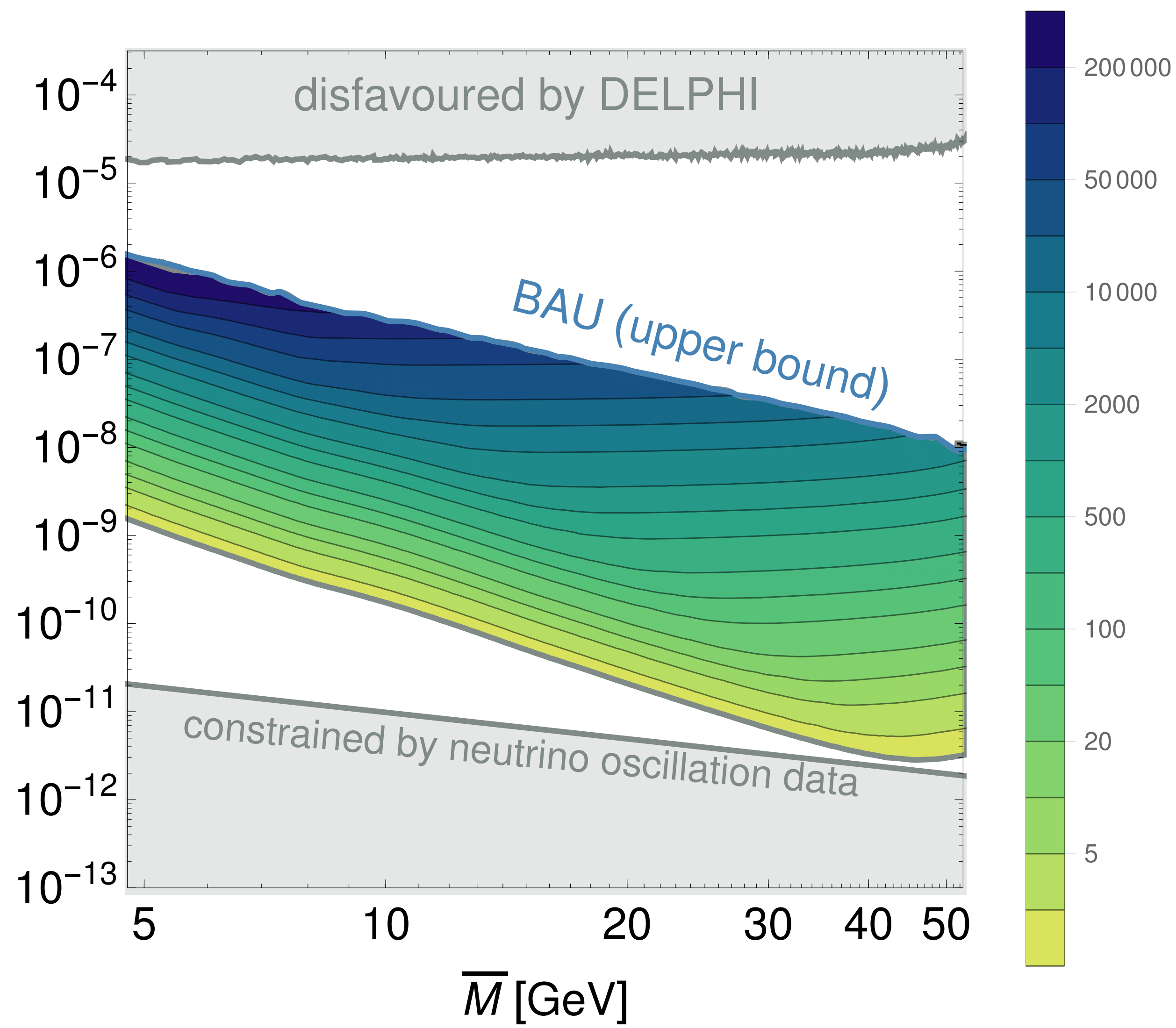
MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



slide by David Curtin

Number of Events

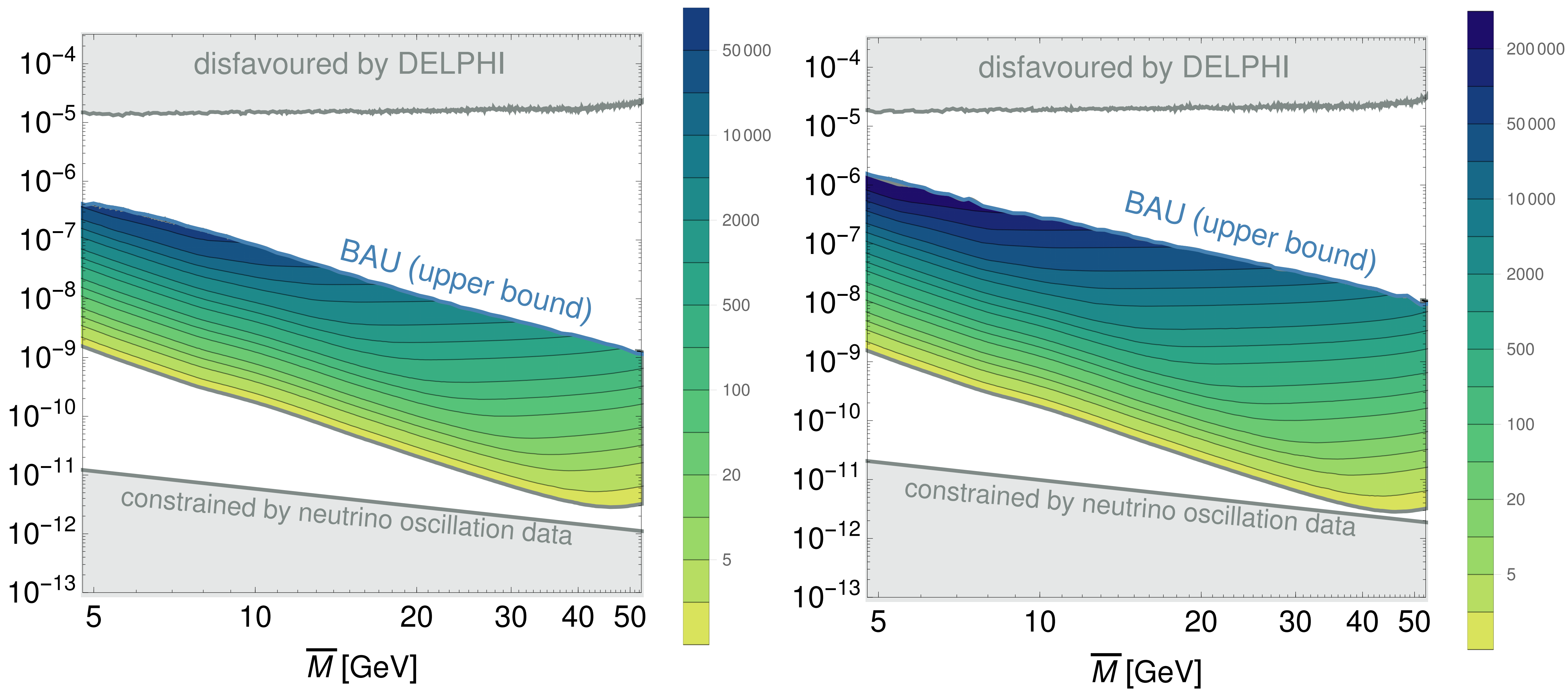




Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

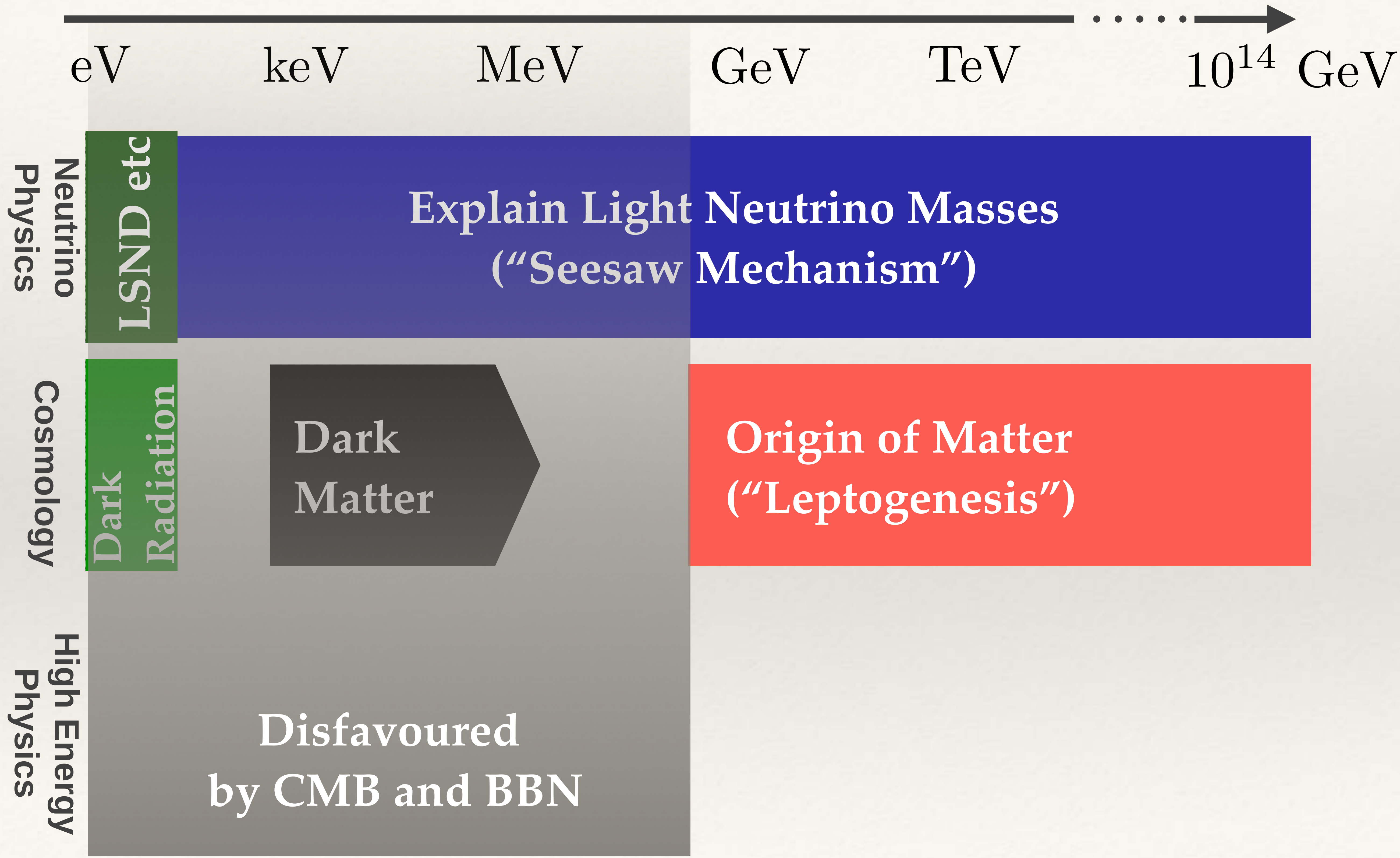
Number of Events

normal ordering **inverted ordering**



percent level measurement of flavour structure!

Right Handed Neutrinos and the Light Neutrino Masses



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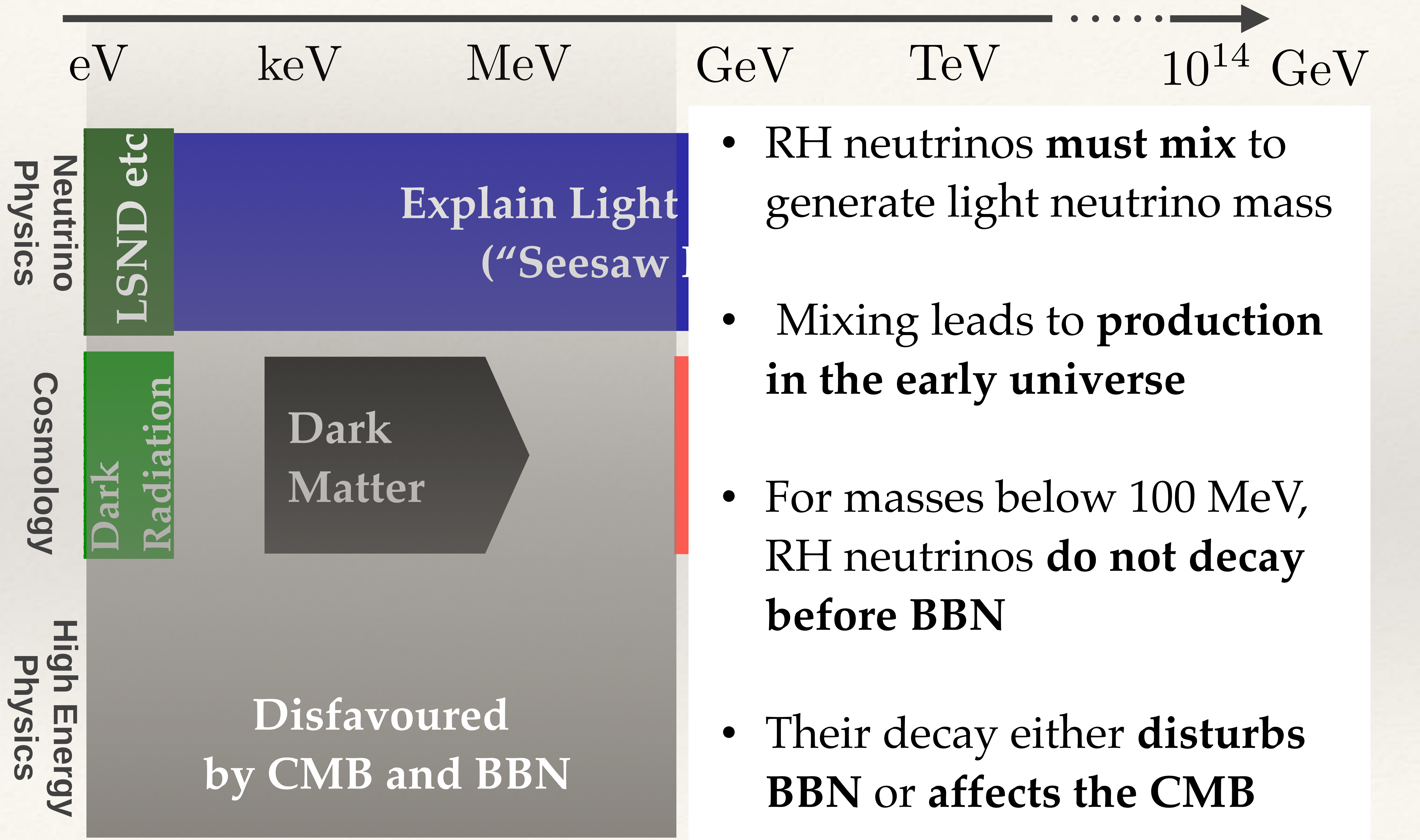
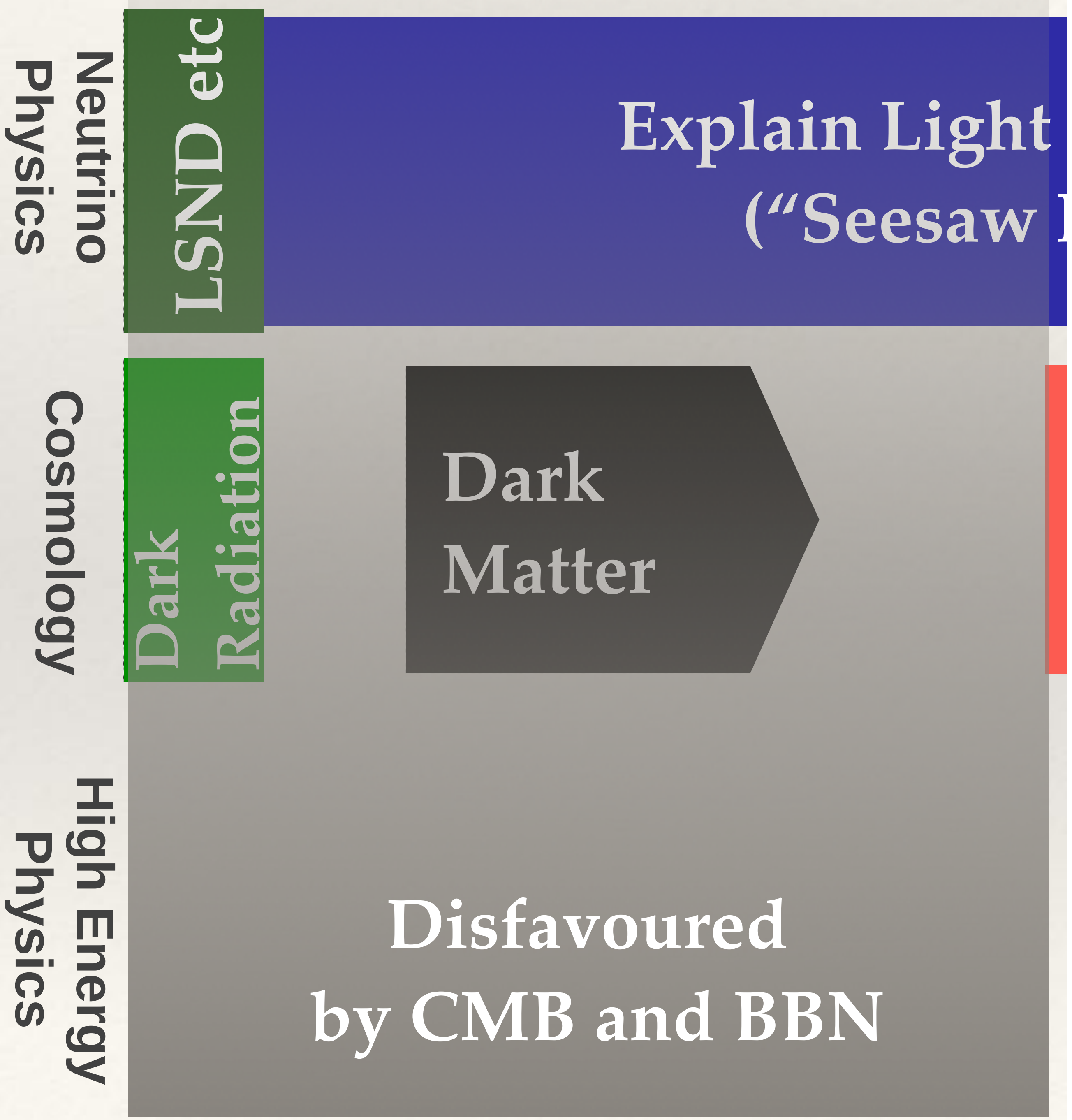
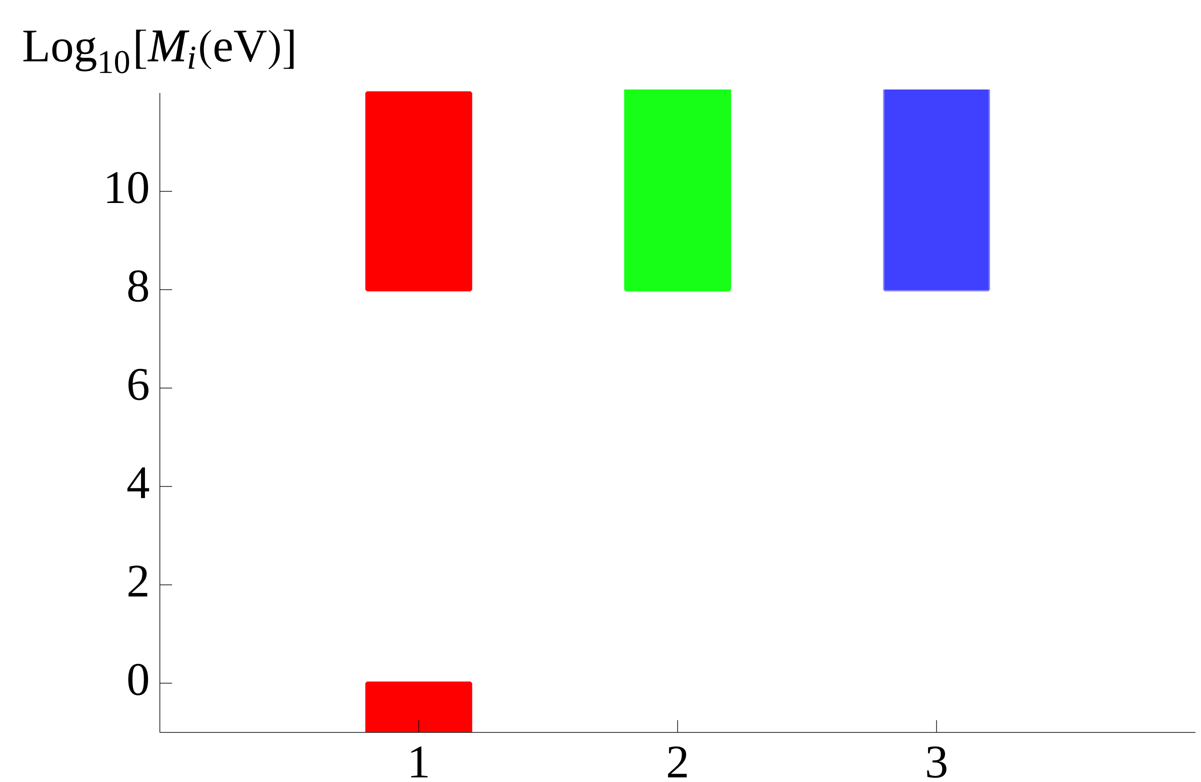


- RH neutrinos **must mix** to generate light neutrino mass
- Mixing leads to **production in the early universe**
- For masses below 100 MeV, RH neutrinos **do not decay before BBN**
- Their decay either **disturbs BBN** or **affects the CMB**

Right Handed Neutrinos and the Light Neutrino Masses

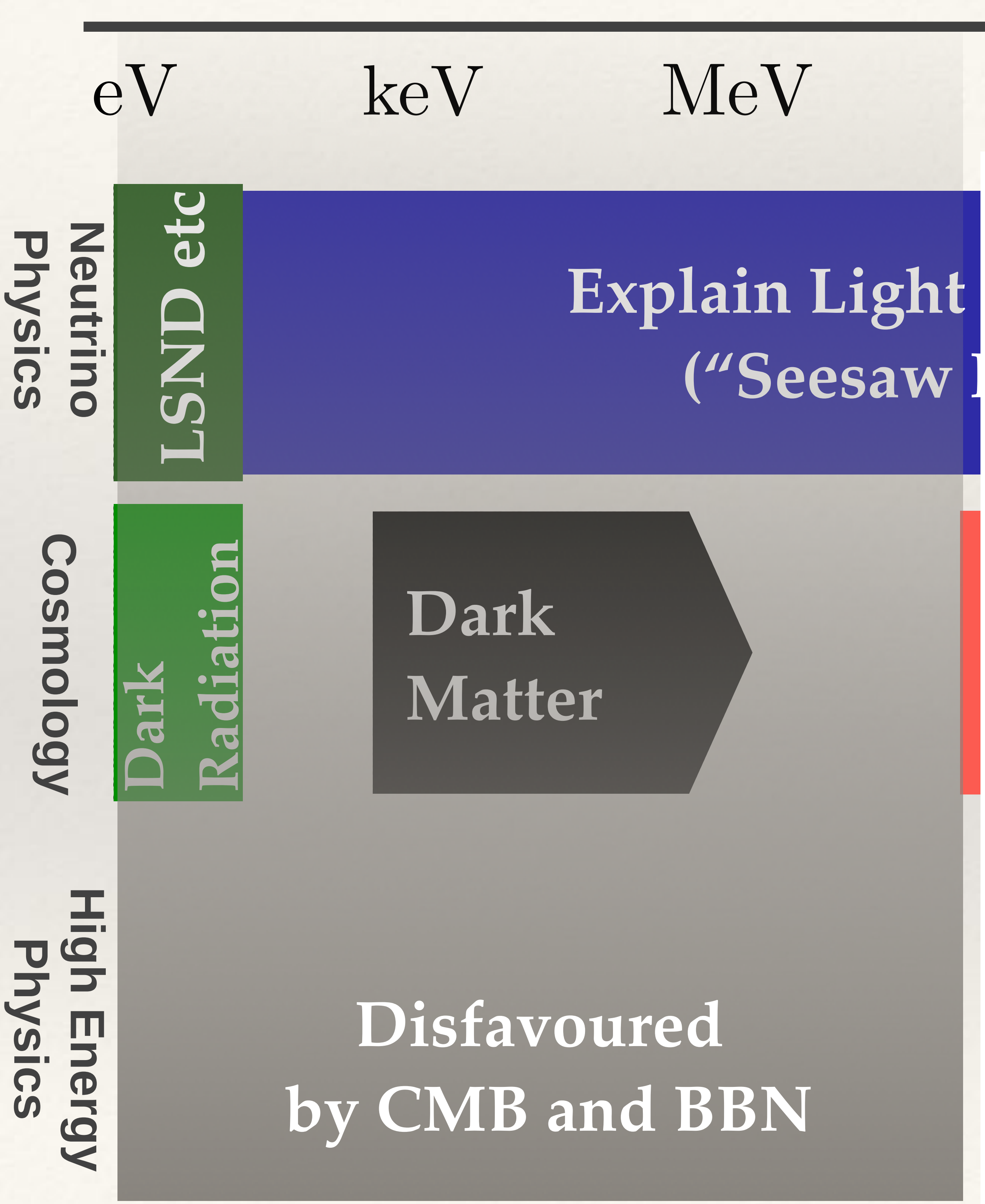


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} > 10^{-3}$ eV, three RHN reach equilibrium



Hernandez/Kekic/Lopez-Pavon 1406.2961

Right Handed Neutrinos and the Light Neutrino Masses



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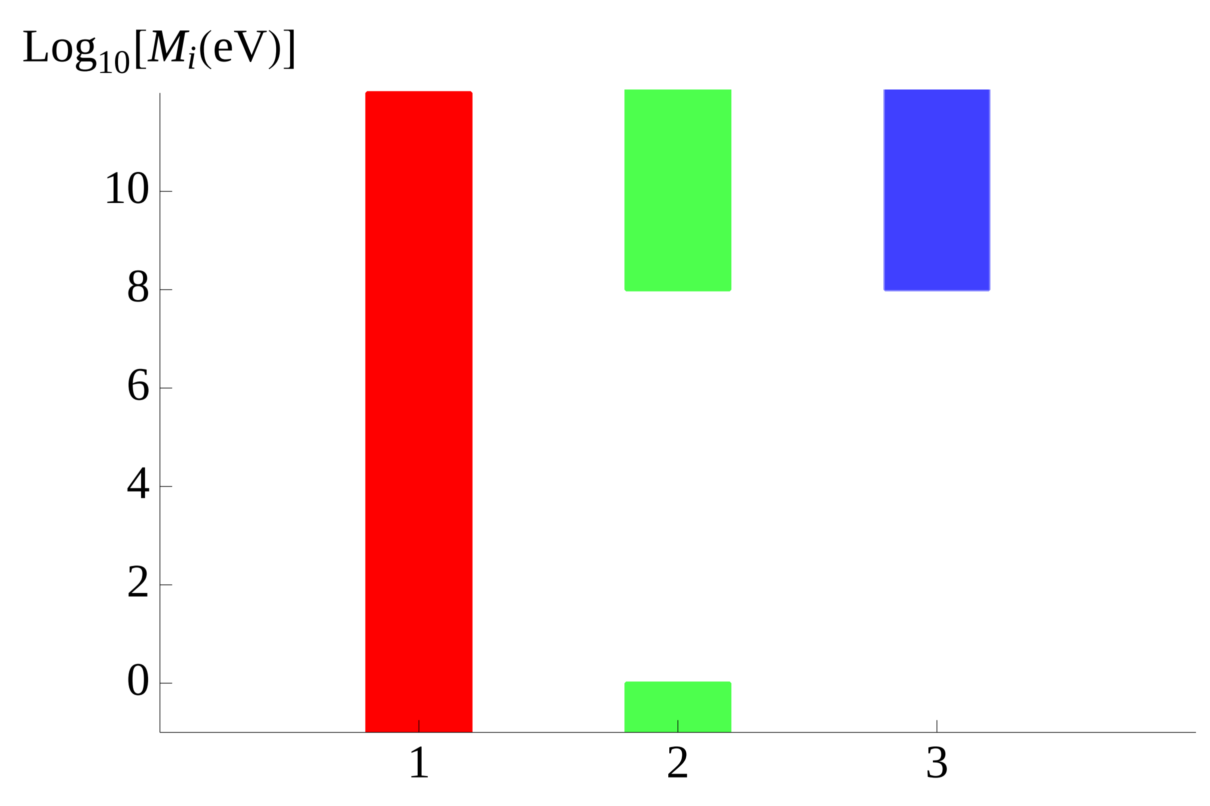
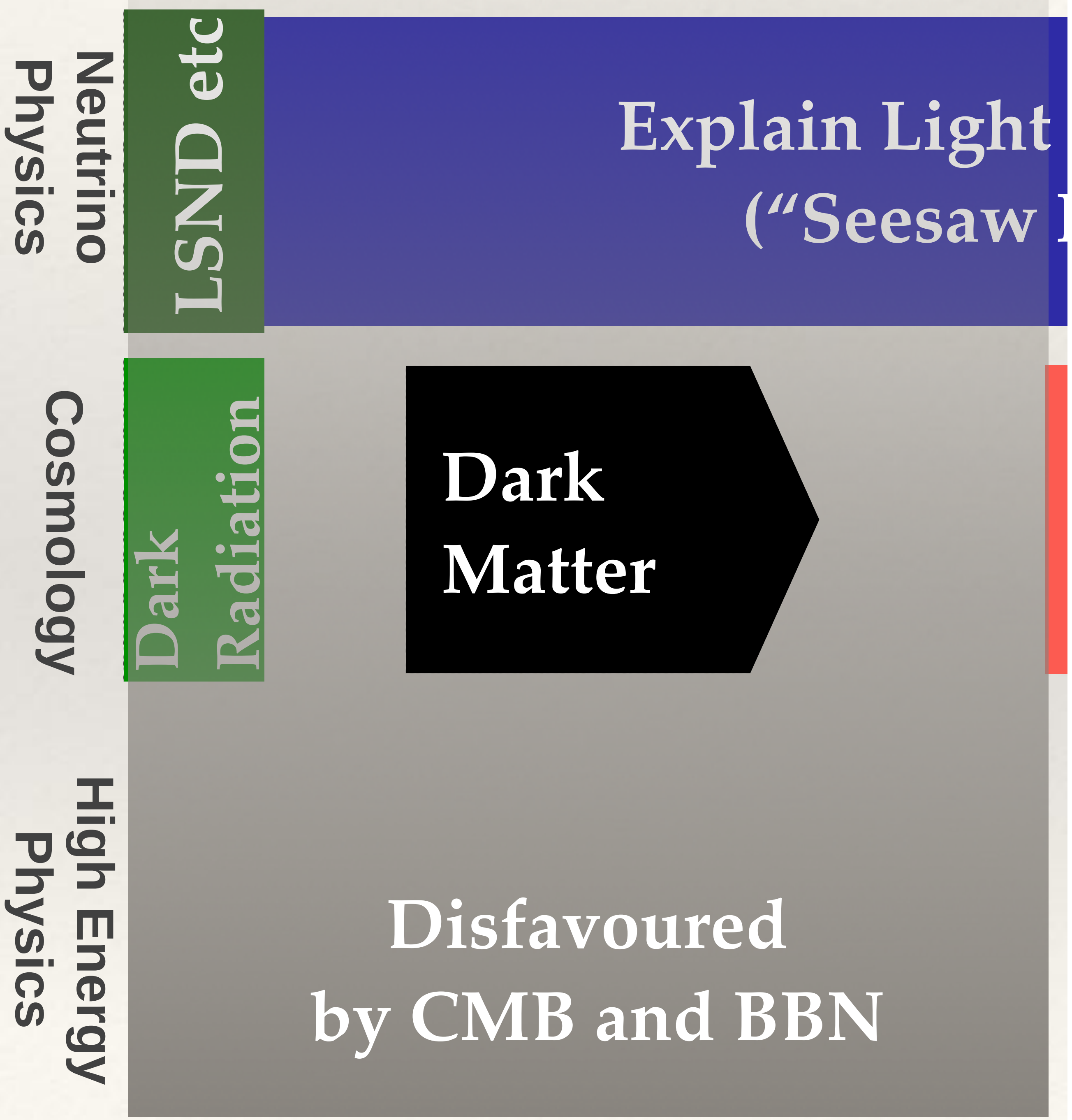
- For $m_{lightest} < 10^{-3}$ eV, one RHN almost decouples



Hernandez/Kekic/Lopez-Pavon 1406.2961

Right Handed Neutrinos and the Light Neutrino Masses



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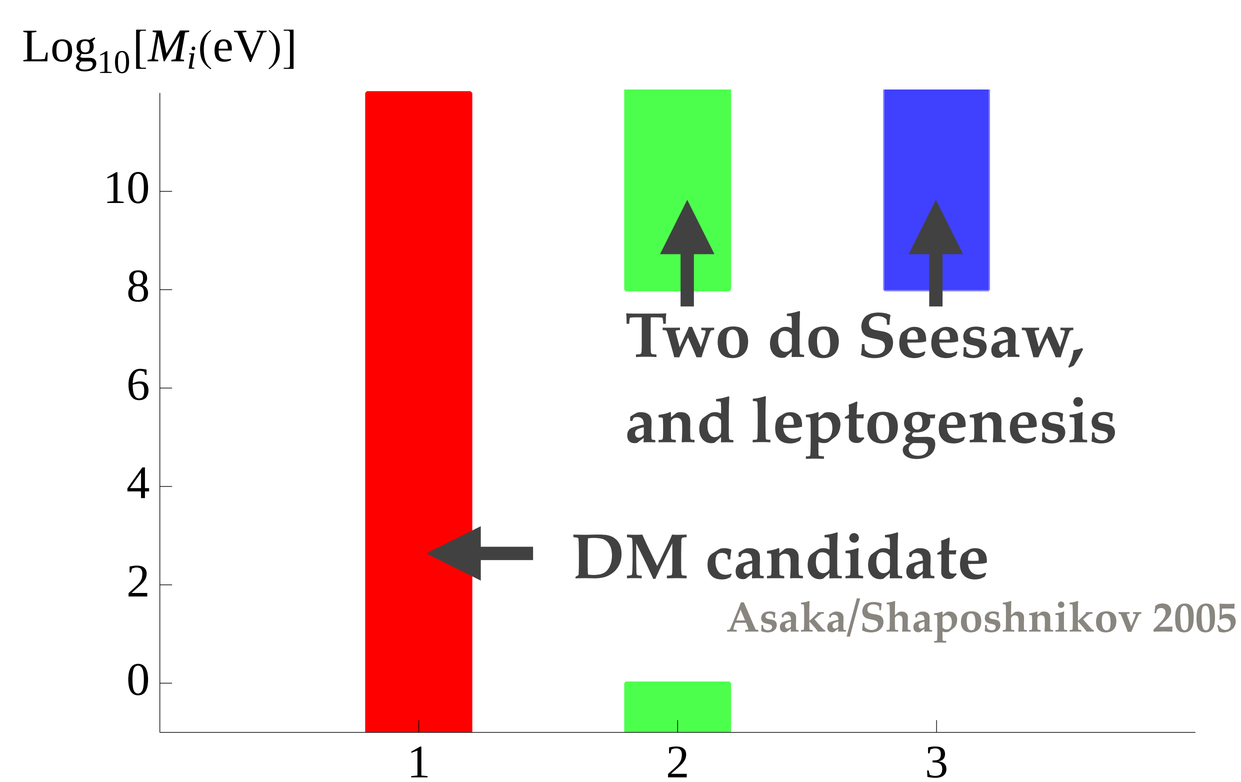

Hernandez/Kekic/Lopez-Pavon 1406.2961

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

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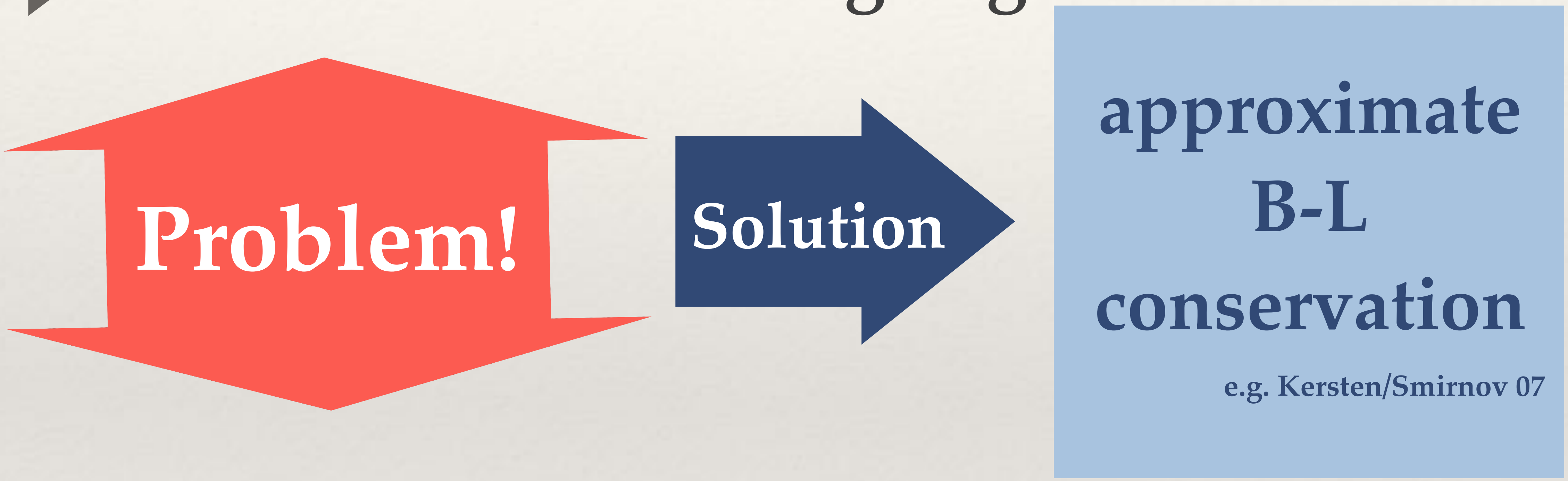

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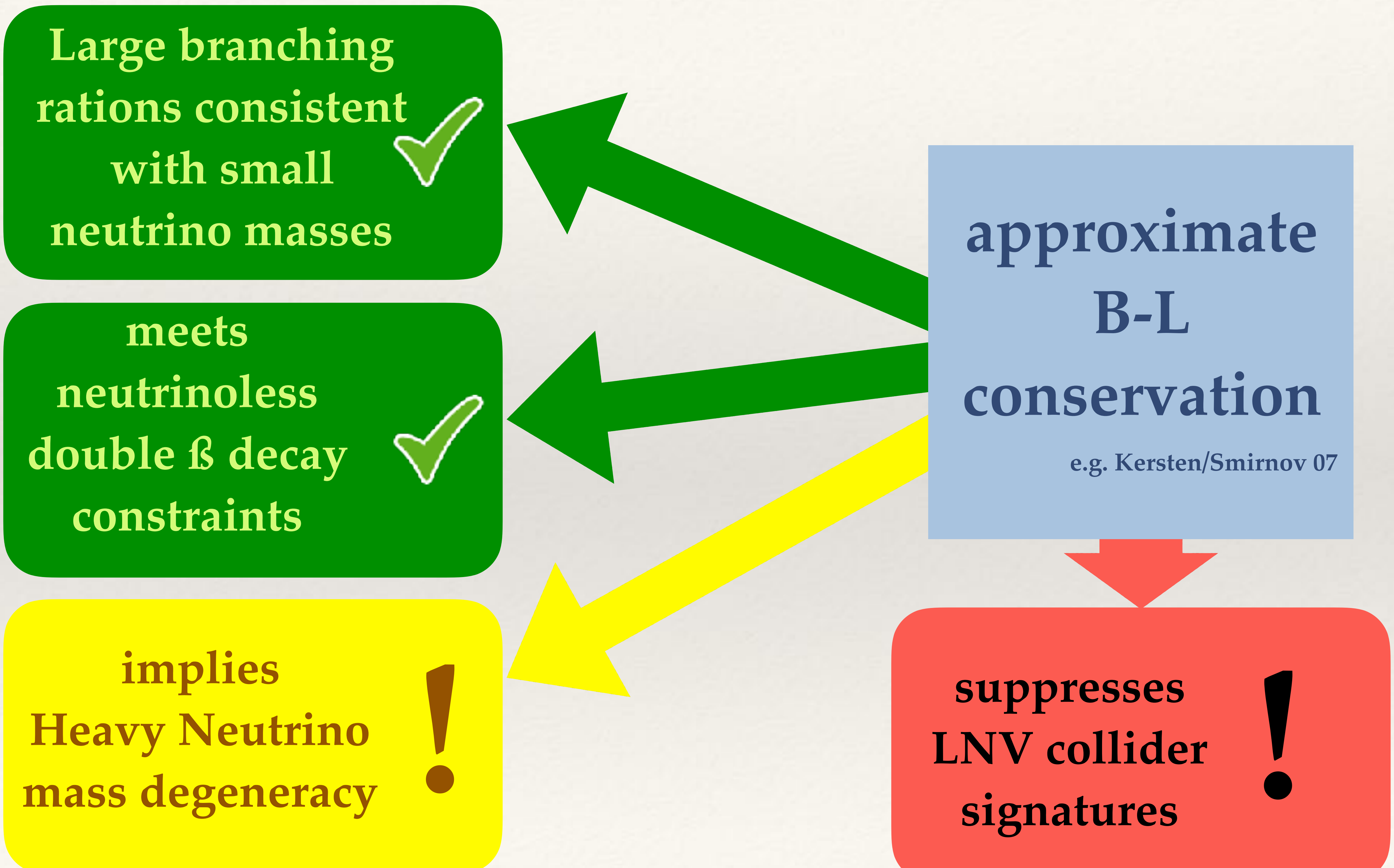
Neutrino masses vs collider searches



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
!