Marco Drewes, Université catholique de Louvain

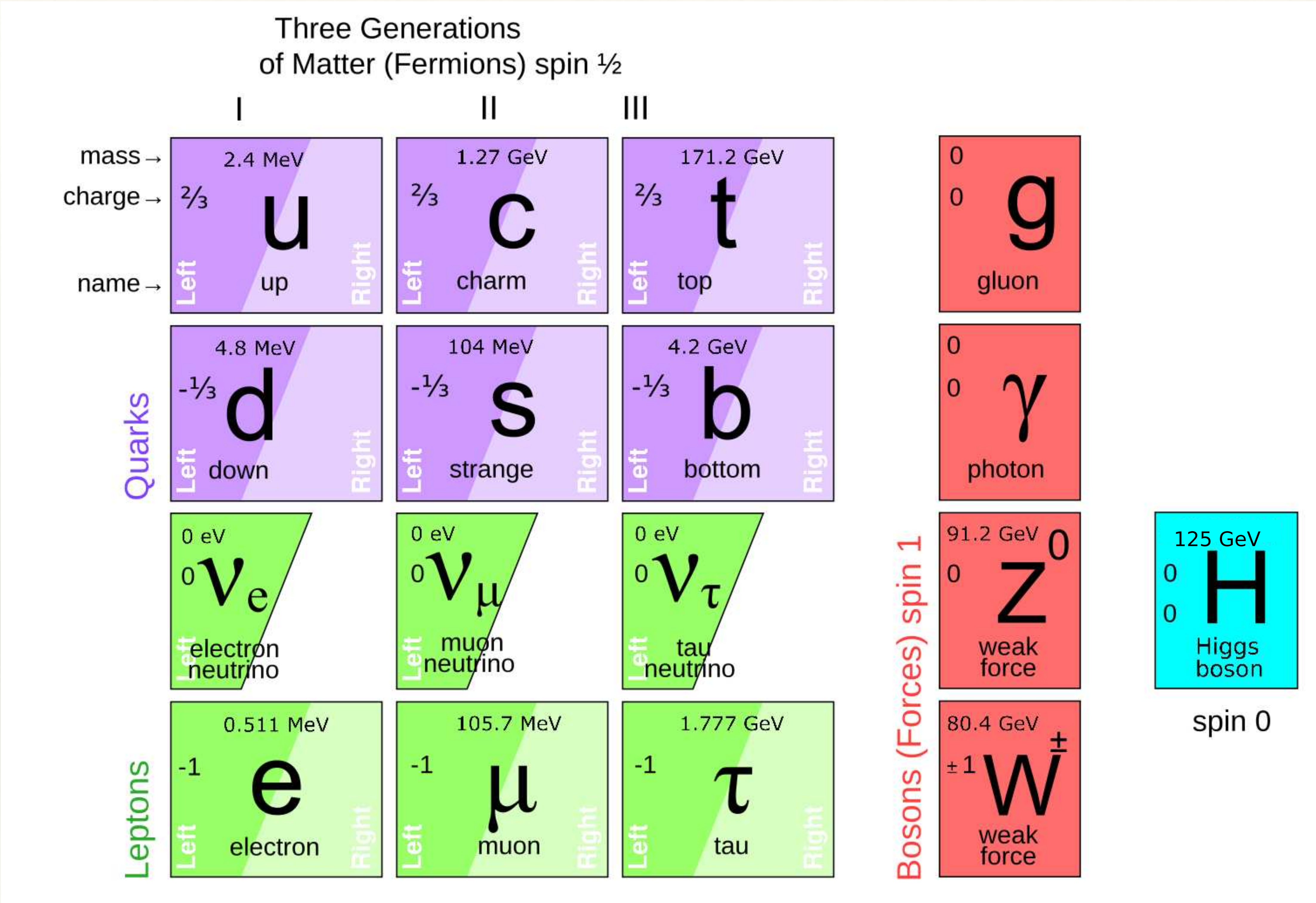
Leptogenesis and colliders

11.10.2017

Collider Physics and the Cosmos

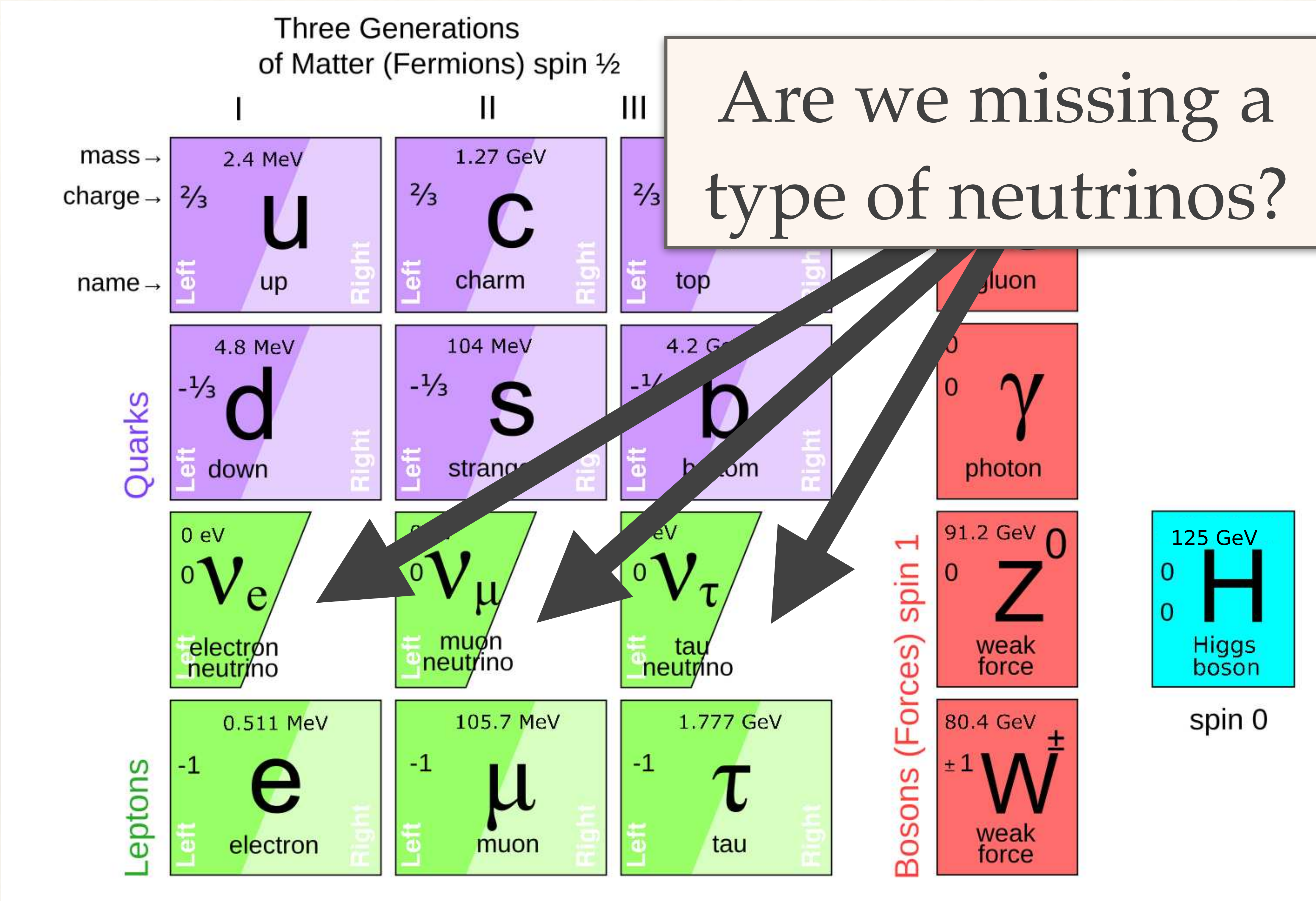
GGI Florence

The Standard Model of Particle Physics



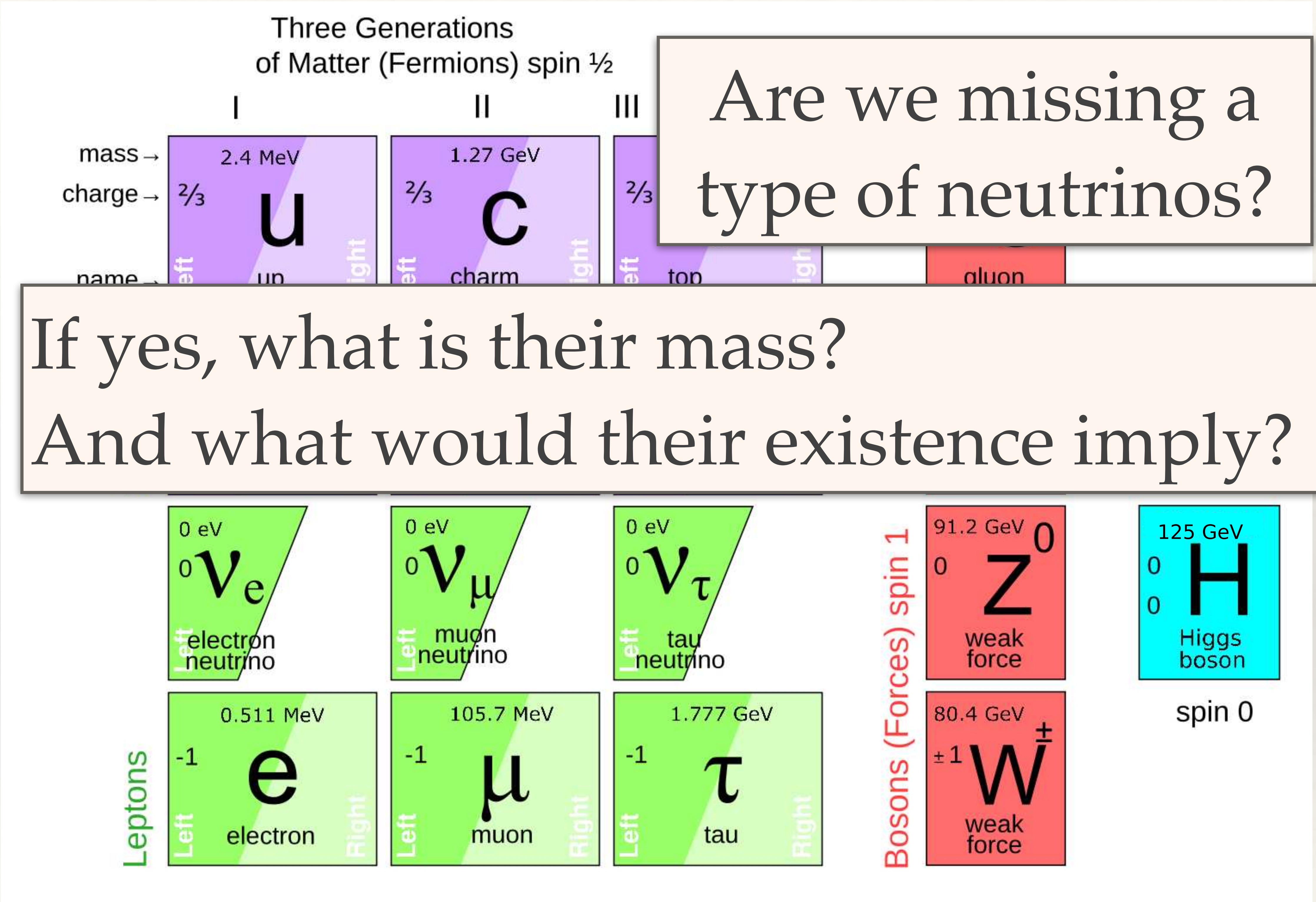
The "periodic table" of elementary particles

The Standard Model of Particle Physics



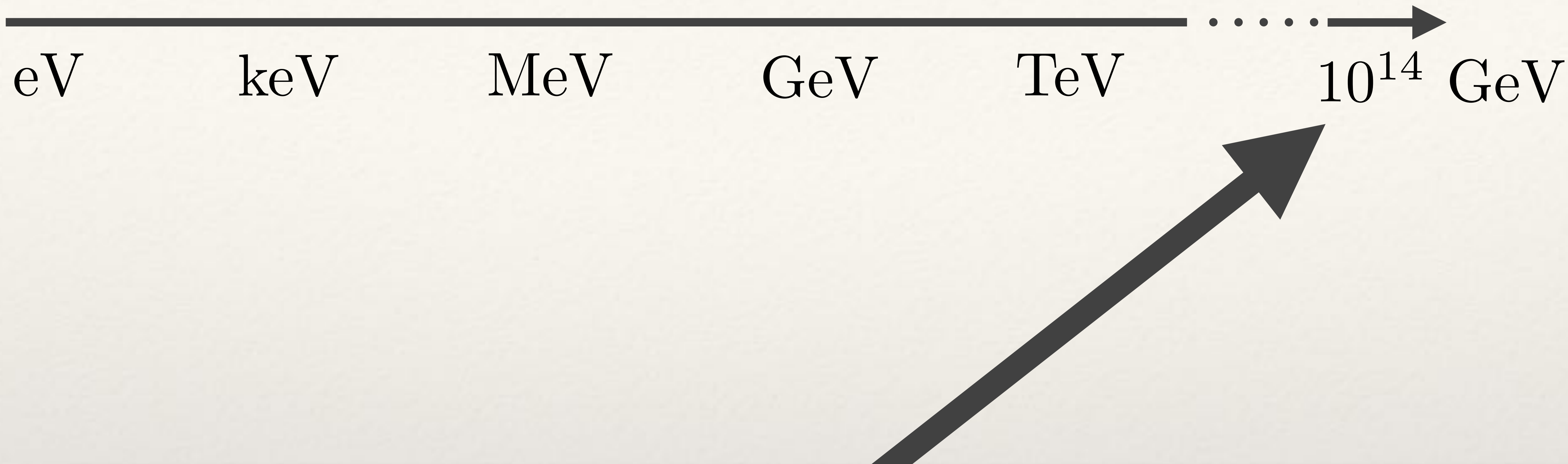
The "periodic table" of elementary particles

The Standard Model of Particle Physics



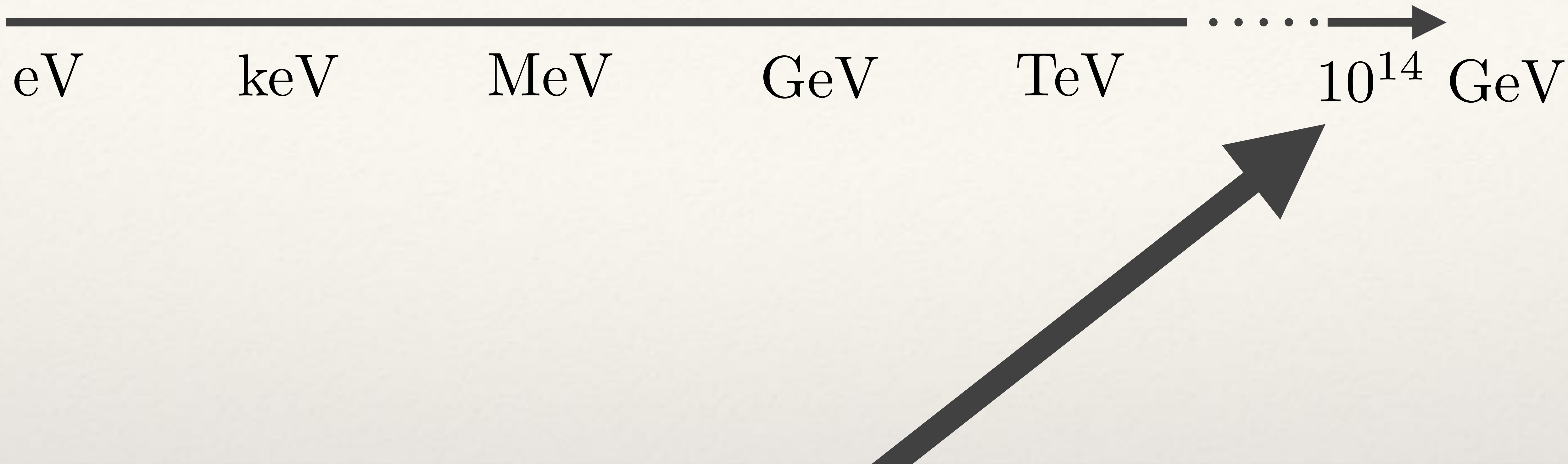
The "periodic table" of elementary particles

How Heavy are the Missing Neutrinos?



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

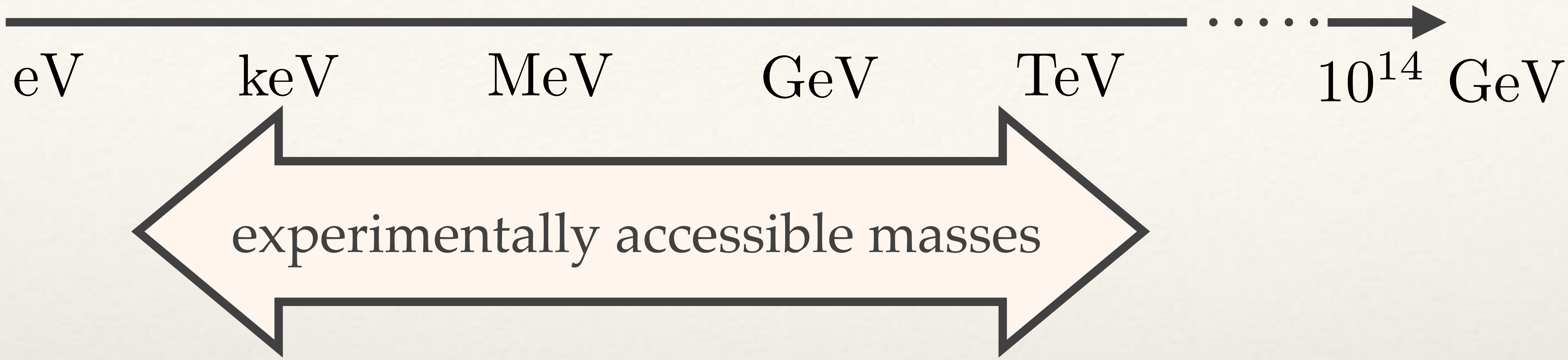
How Heavy are the Missing Neutrinos?



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

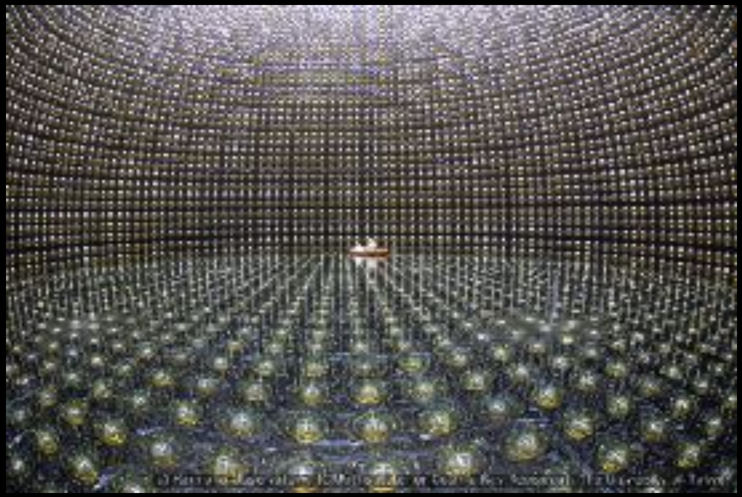
experimentally inaccessible

How Heavy are the Missing Neutrinos?



Understand the implications across the entire experimentally accessible mass range

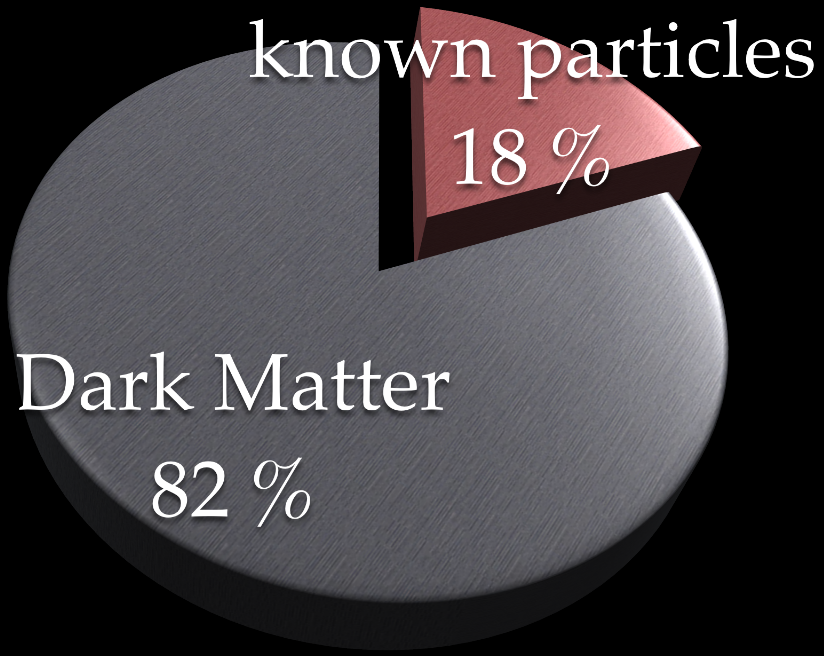
Heavy Neutrinos Could Solve Key Problems



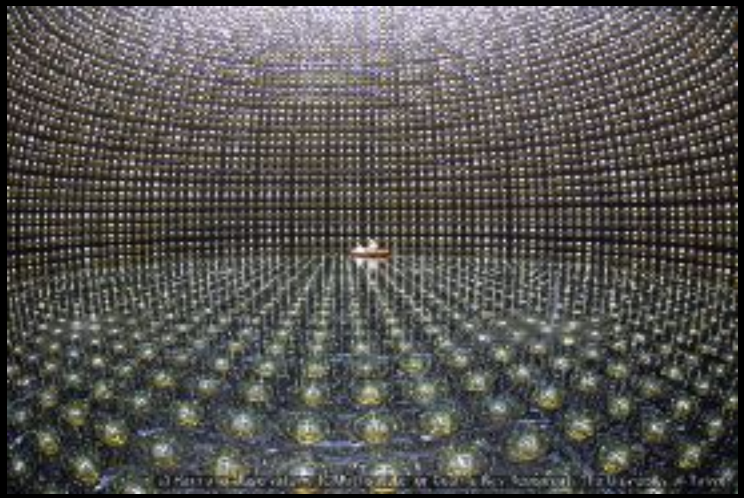
- What is the origin of neutrino mass?

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

- What is the Dark Matter made of?



Heavy Neutrinos Could Solve Key Problems

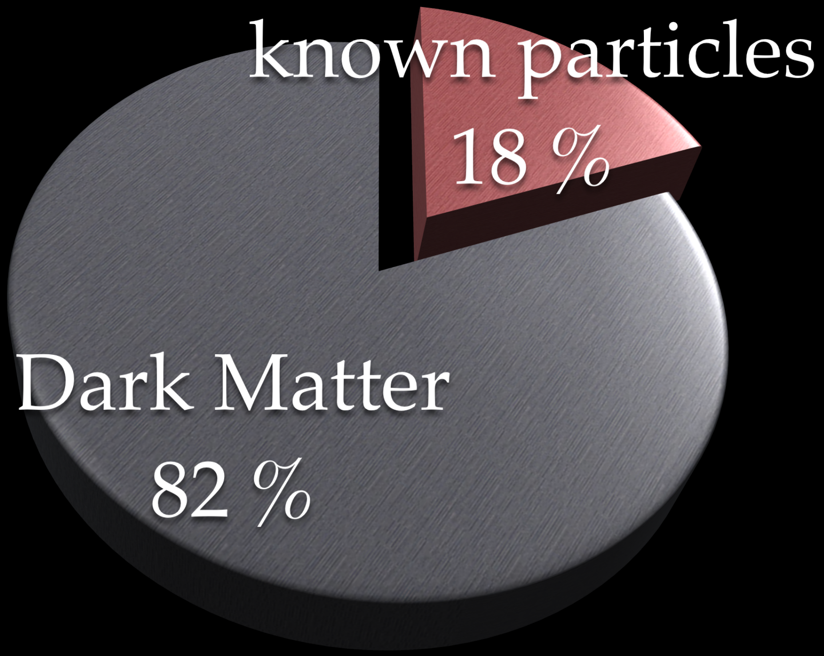


- **What is the origin of neutrino mass?**

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

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

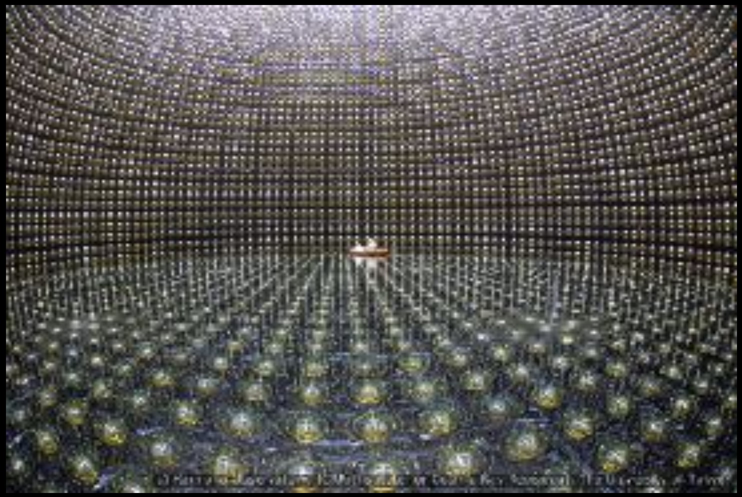
- **What is the Dark Matter made of?**



Heavy Neutrinos Could Solve Key Problems

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

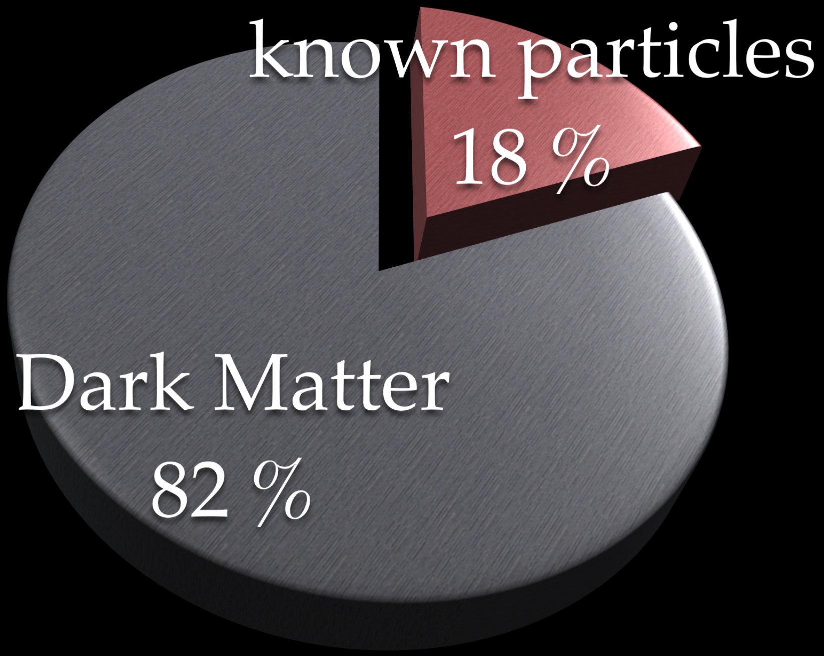
  Possible key to embed Standard Model in a more fundamental theory of Nature



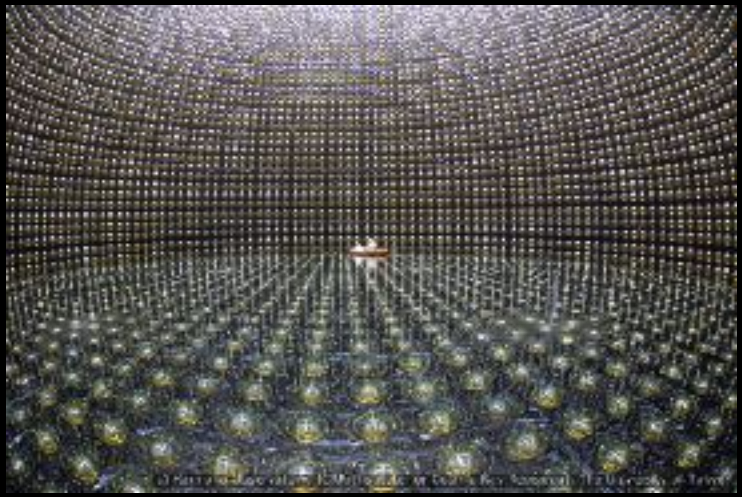
- **Why was there more matter than antimatter in the early universe?**

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

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



Heavy Neutrinos Could Solve Key Problems



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

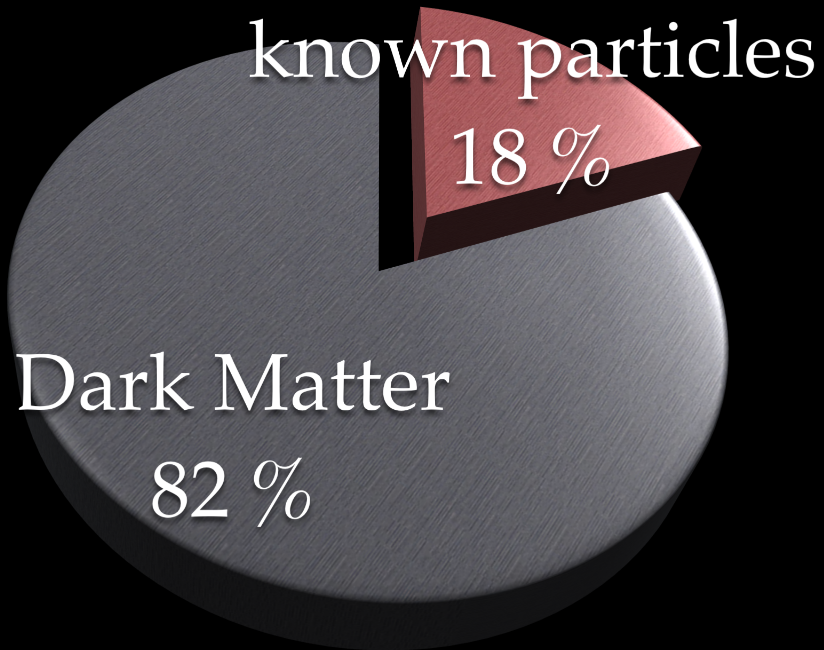
Possible key to embed Standard Model in a more fundamental theory of Nature

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

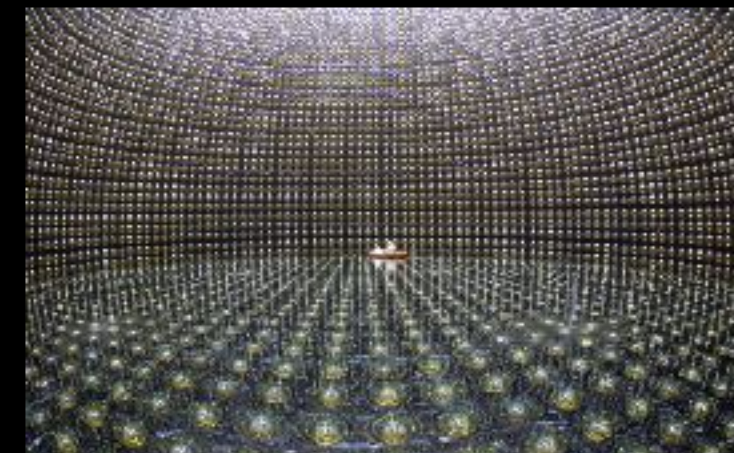
…so that some matter survived the mutual annihilation to form galaxies, stars etc.

- **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

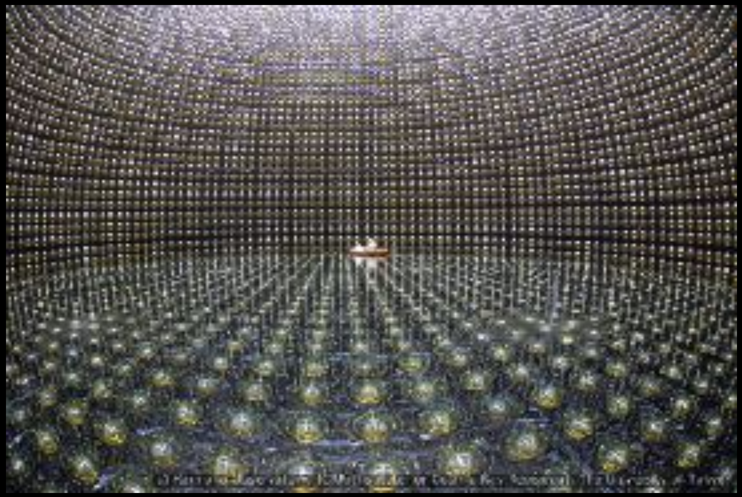
$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$
$$- \frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

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



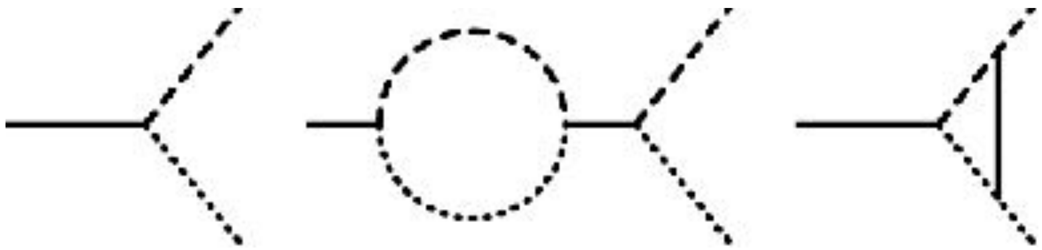
- **What is the origin of neutrino mass?**

  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 mutu

Leptogenesis



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

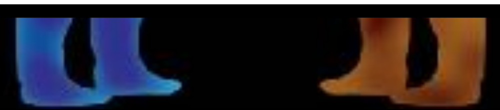
$\Rightarrow$ Nonequilibrium quantum process produces matter excess

Heavy Neutrinos Could Solve Key Problems

Heavy "Sterile" Neutrino Dark Matter

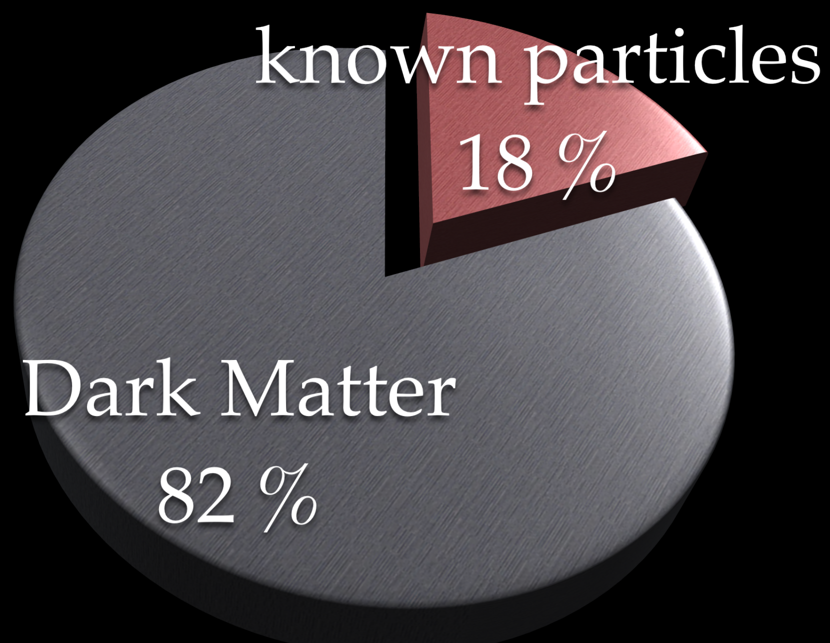
Dark Matter Particles are

- heavy
- long lived
- neutral
- feebly interacting



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

It makes up most of the mass in the universe.



Heavy Neutrinos Could Solve Key Problems

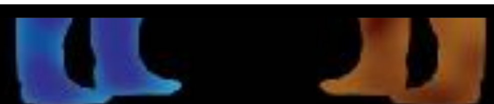
Heavy "Sterile" Neutrino Dark Matter

Dark Matter Particles are

- **heavy**
- **long lived**
- **neutral**
- **feebly interacting**

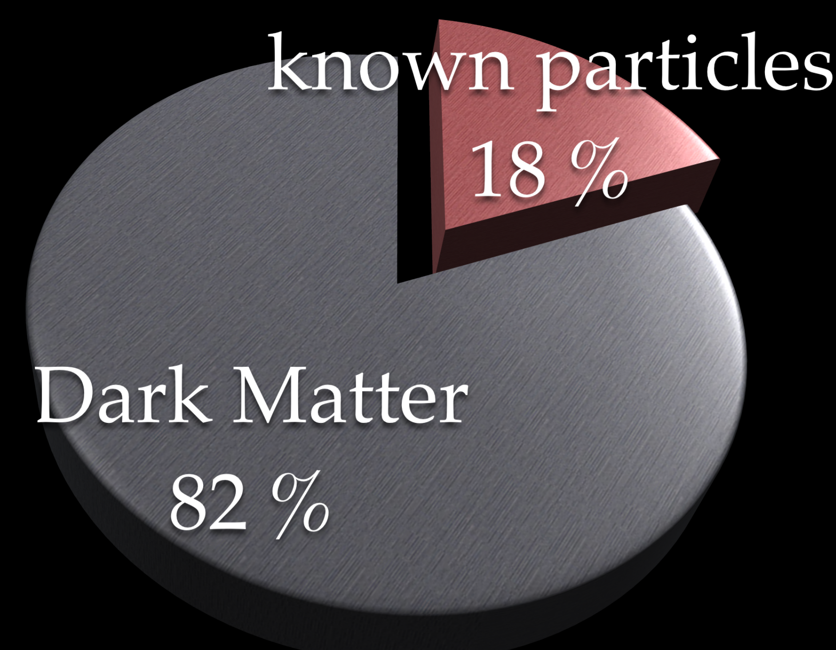
} **Neutrinos are the only known particles that fulfil three conditions…**

…but they are too light



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

It makes up most of the mass in the universe.



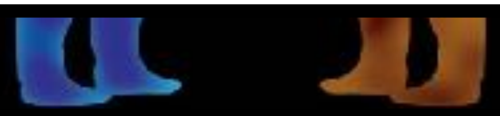
Heavy Neutrinos Could Solve Key Problems

Heavy "Sterile" Neutrino Dark Matter

Dark Matter Particles are

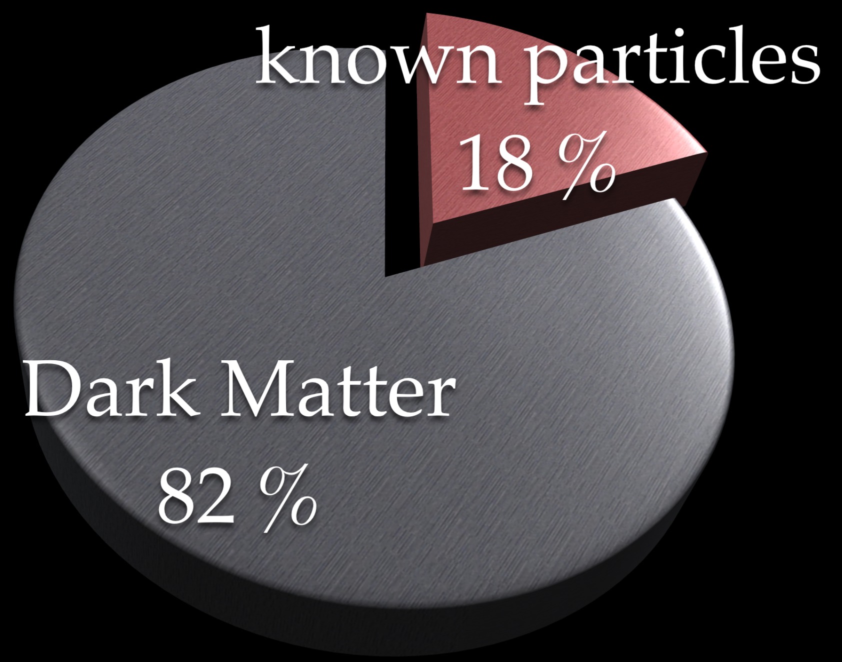
- **heavy**
- **long lived**
- **neutral**
- **feebly interacting**

} **RH neutrinos can fulfil all conditions!**



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

It makes up most of the mass in the universe.



Heavy Neutrinos Could Solve Key Problems

Heavy "Sterile" Neutrino Dark Matter

Dark Matter Particles are

- heavy
- long lived
- neutral
- feebly interacting

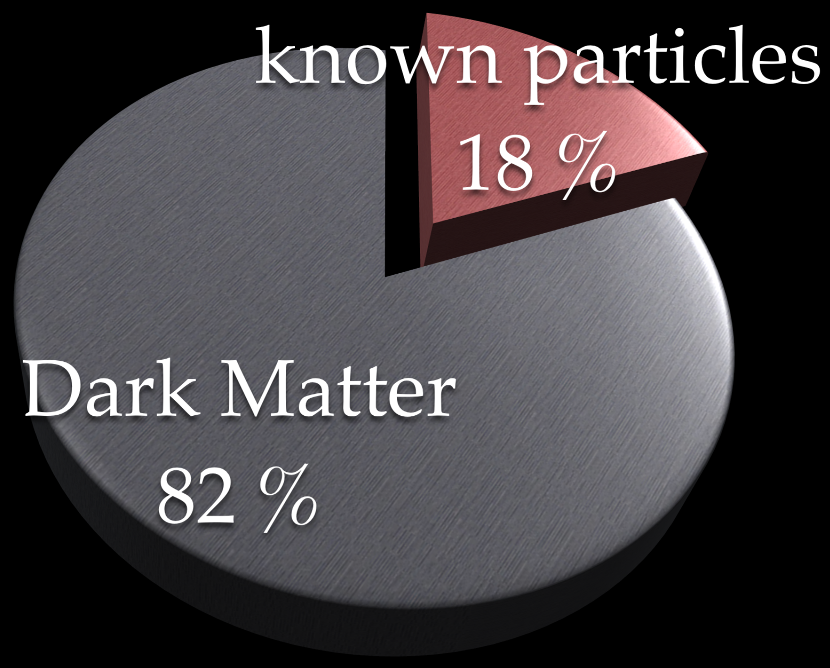
Not today's topic.

Recent review: 1602.04816

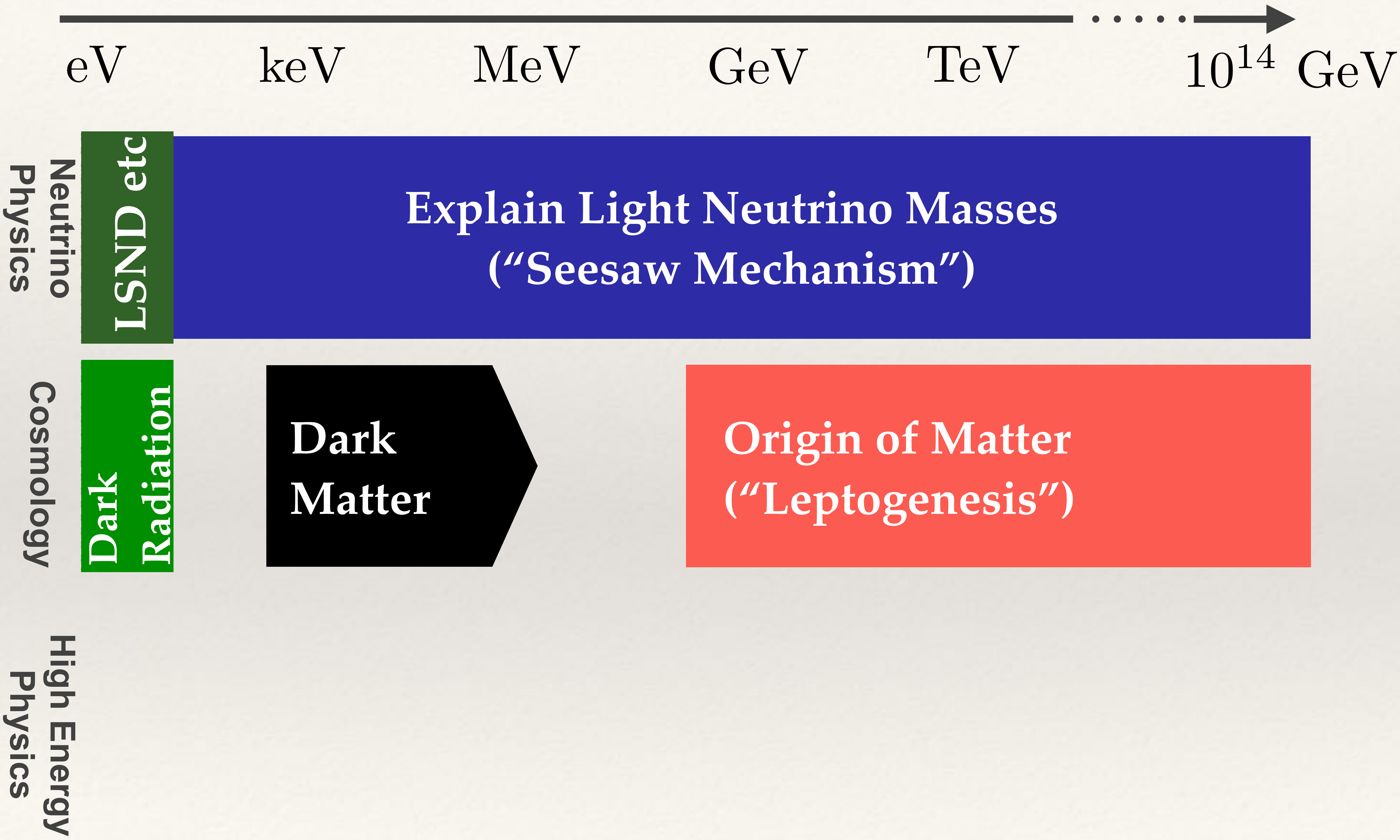
RH neutrinos can fulfil all conditions!

- 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

eV keV MeV GeV TeV 10^{14} GeV

Neutrino Physics

Cosmology

High Energy Physics

Origin of Matter (“Leptogenesis”)

Heavy Neutrinos as the Origin of Matter

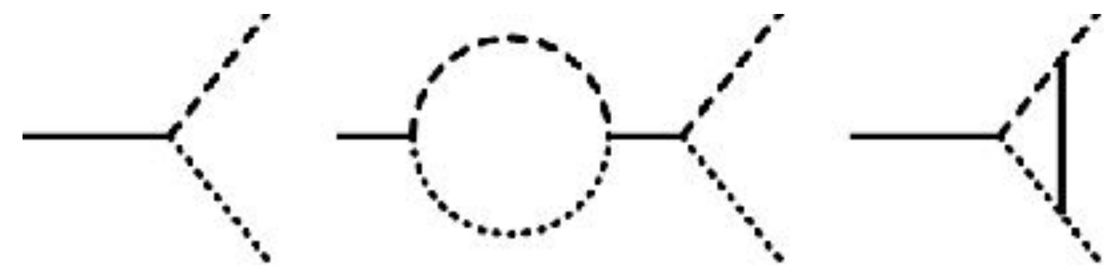
eV · keV · MeV · GeV · TeV · 10^{14} GeV

Neutrino Physics

Cosmology

High Energy Physics

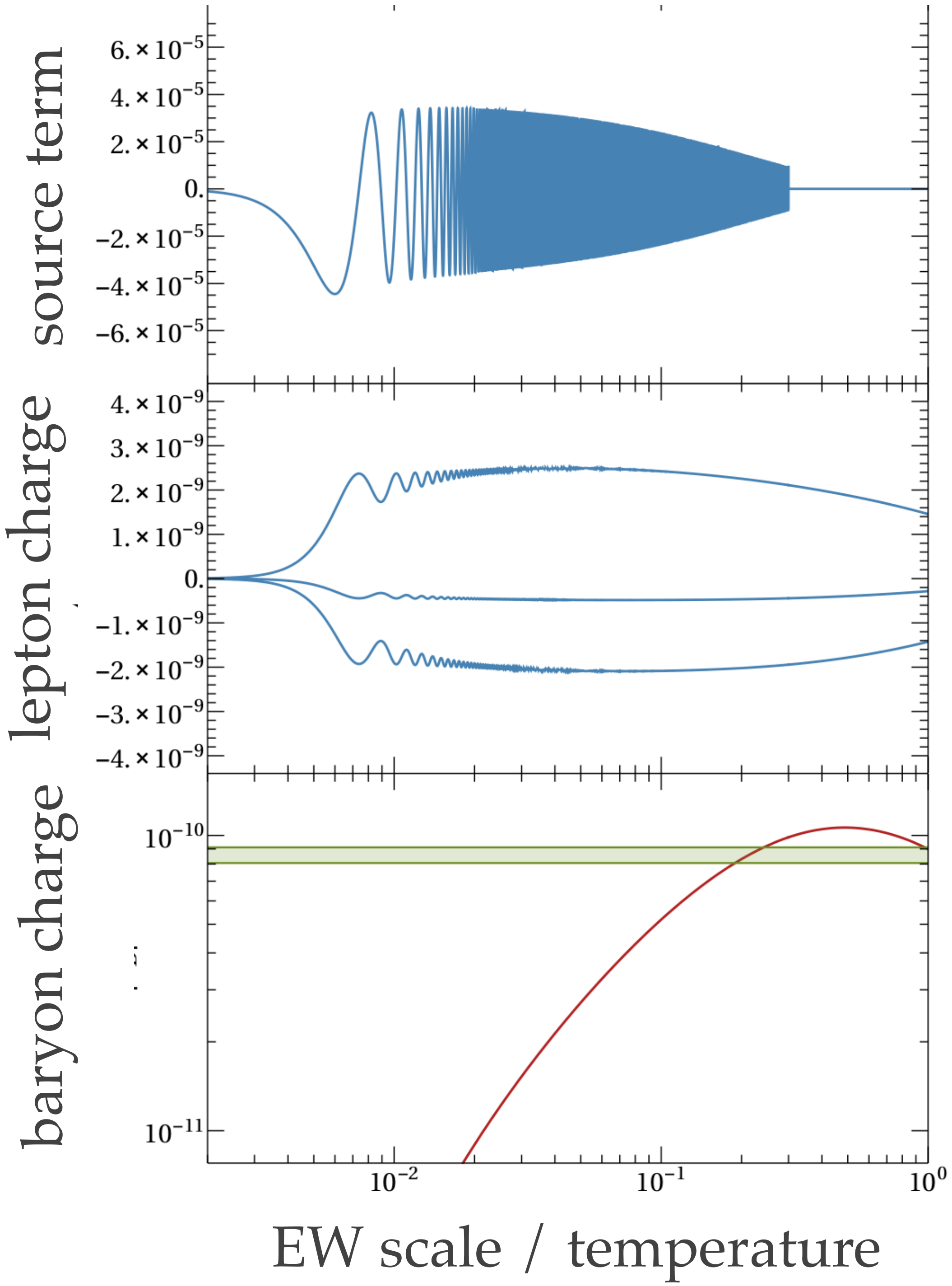
Leptogenesis in heavy neutrino decay



Origin of Matter
("Leptogenesis")

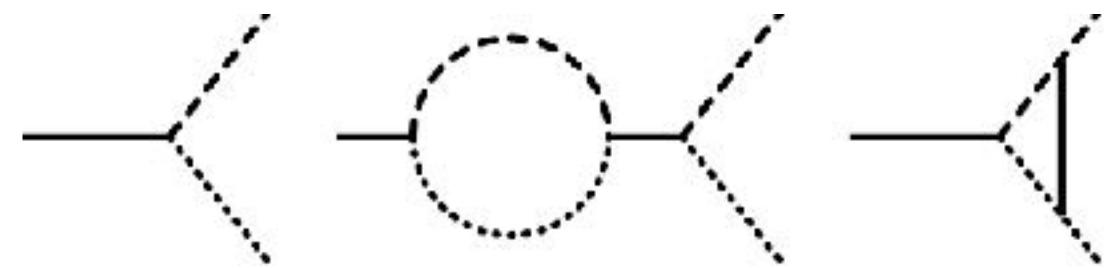
Heavy Neutrinos as the Origin of Matter

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

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

Neutrino Physics

Explain Light Neutrino Masses
(“Seesaw Mechanism”)

Cosmology

Origin of Matter
(“Leptogenesis”)

High Energy Physics

Heavy Neutrinos and the Light Neutrino Masses

eV keV MeV GeV TeV ...... 10^{14} GeV

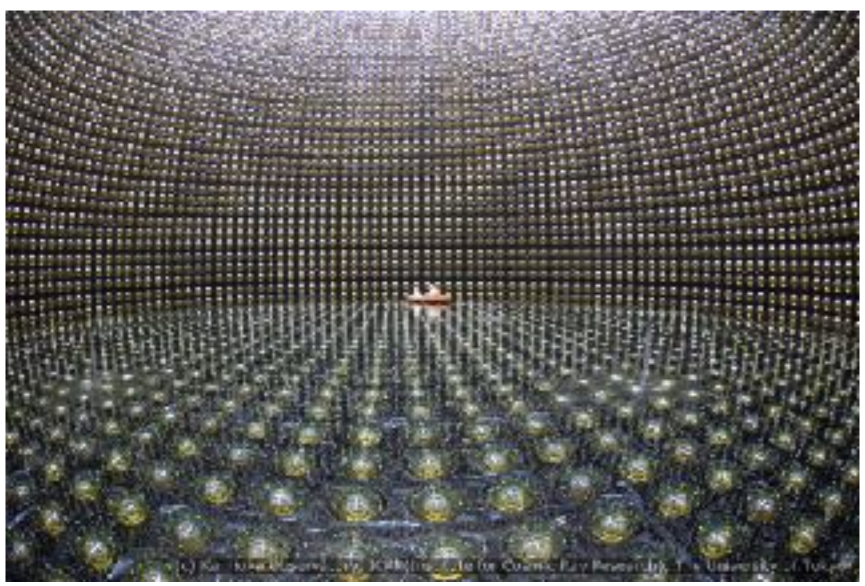
Neutrino Physics

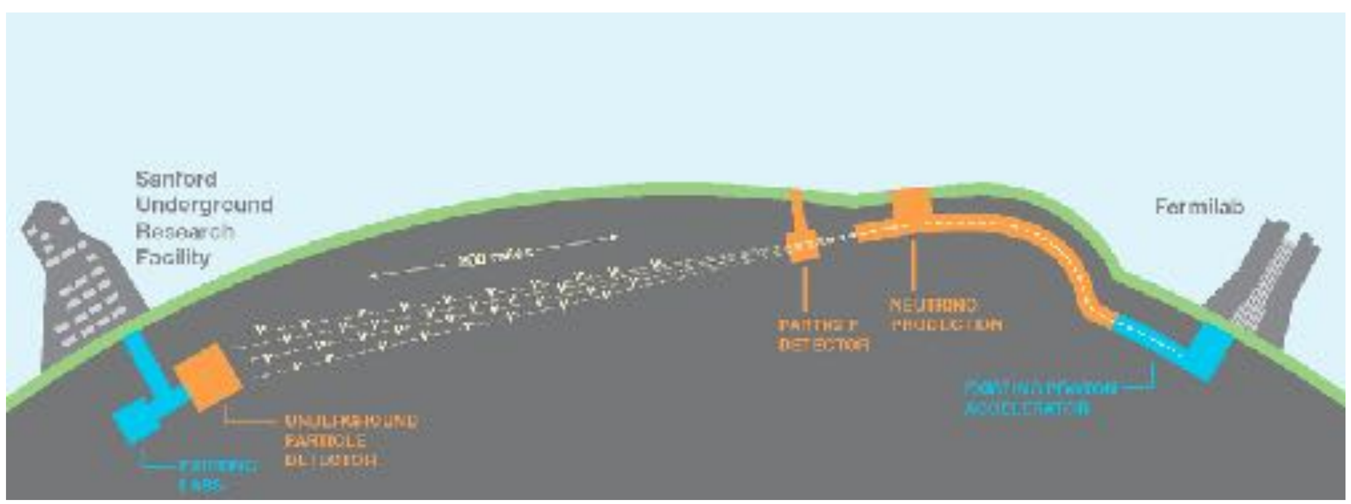
Explain Light Neutrino Masses
("Seesaw Mechanism")

Cosmology

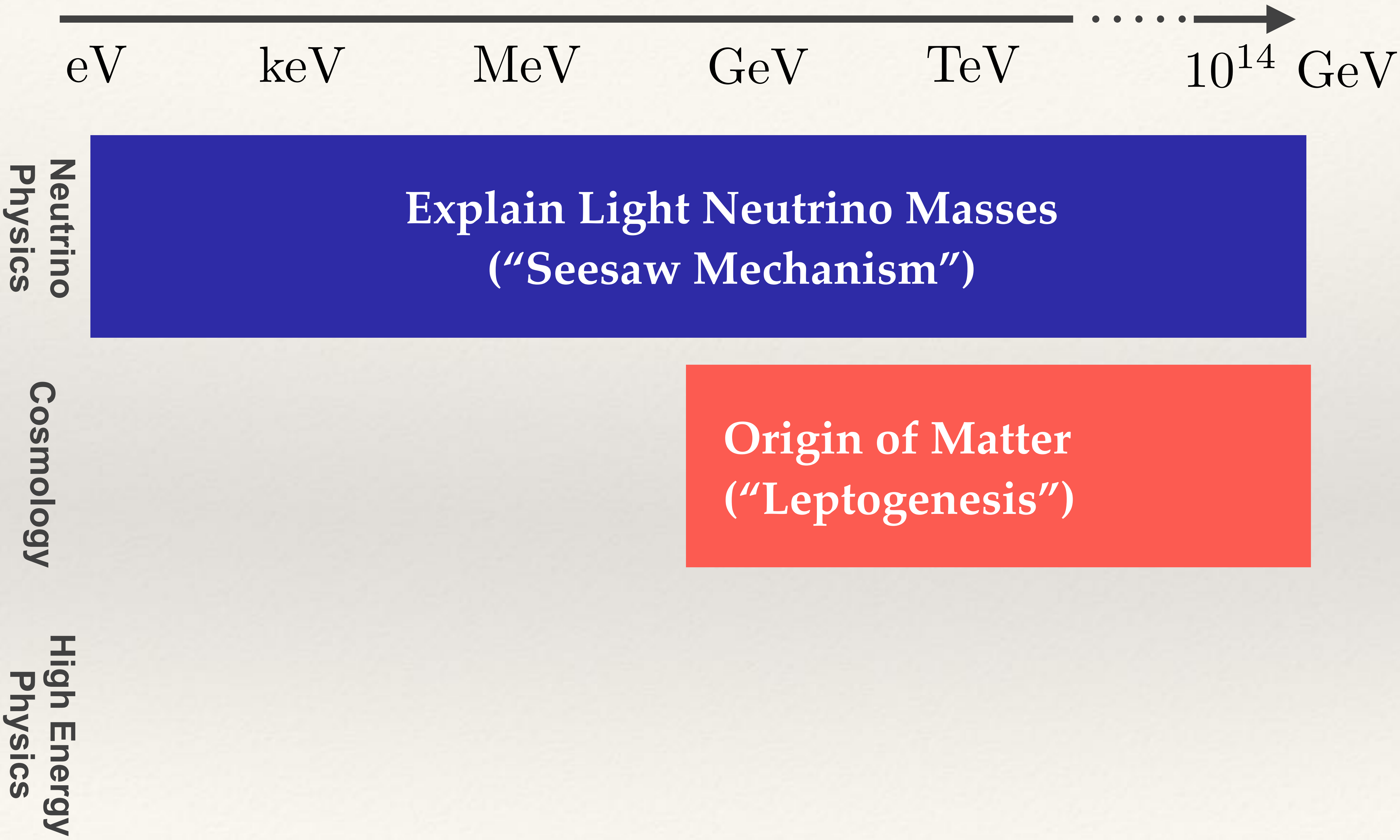
High Energy Physics

neutrino oscillation data

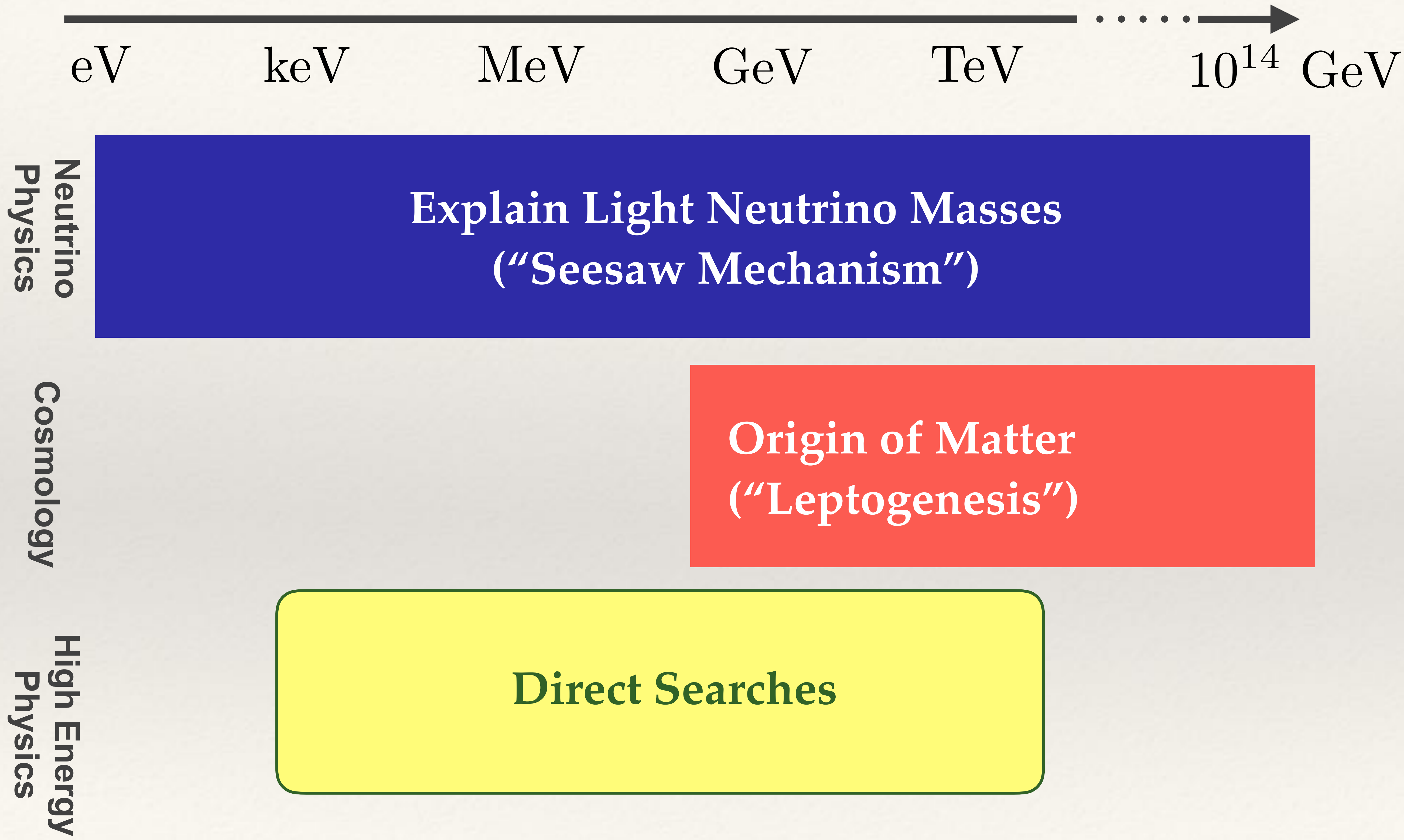




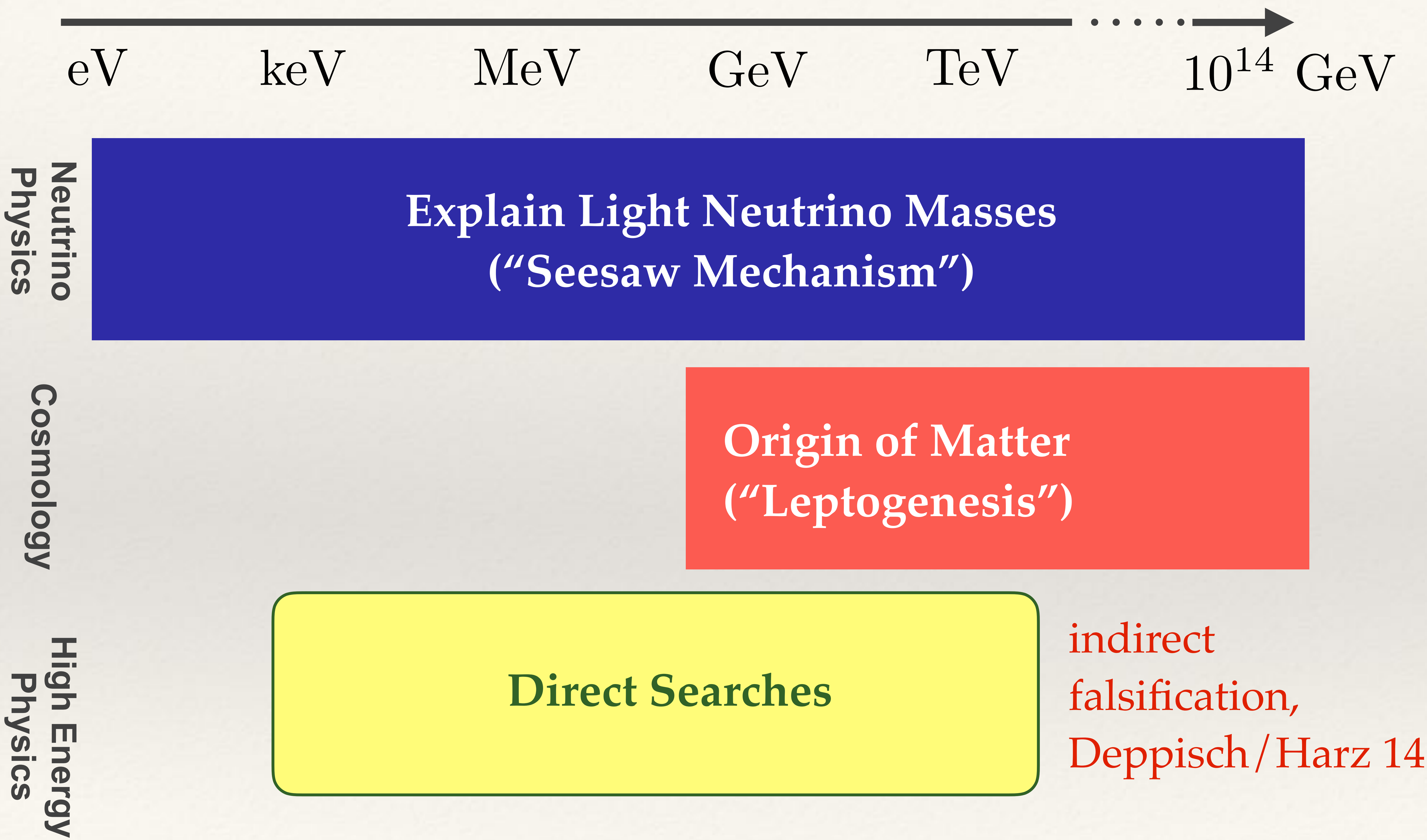
How to Find Heavy Neutrinos?



How to Find Heavy Neutrinos?



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

ilc
international linear collider

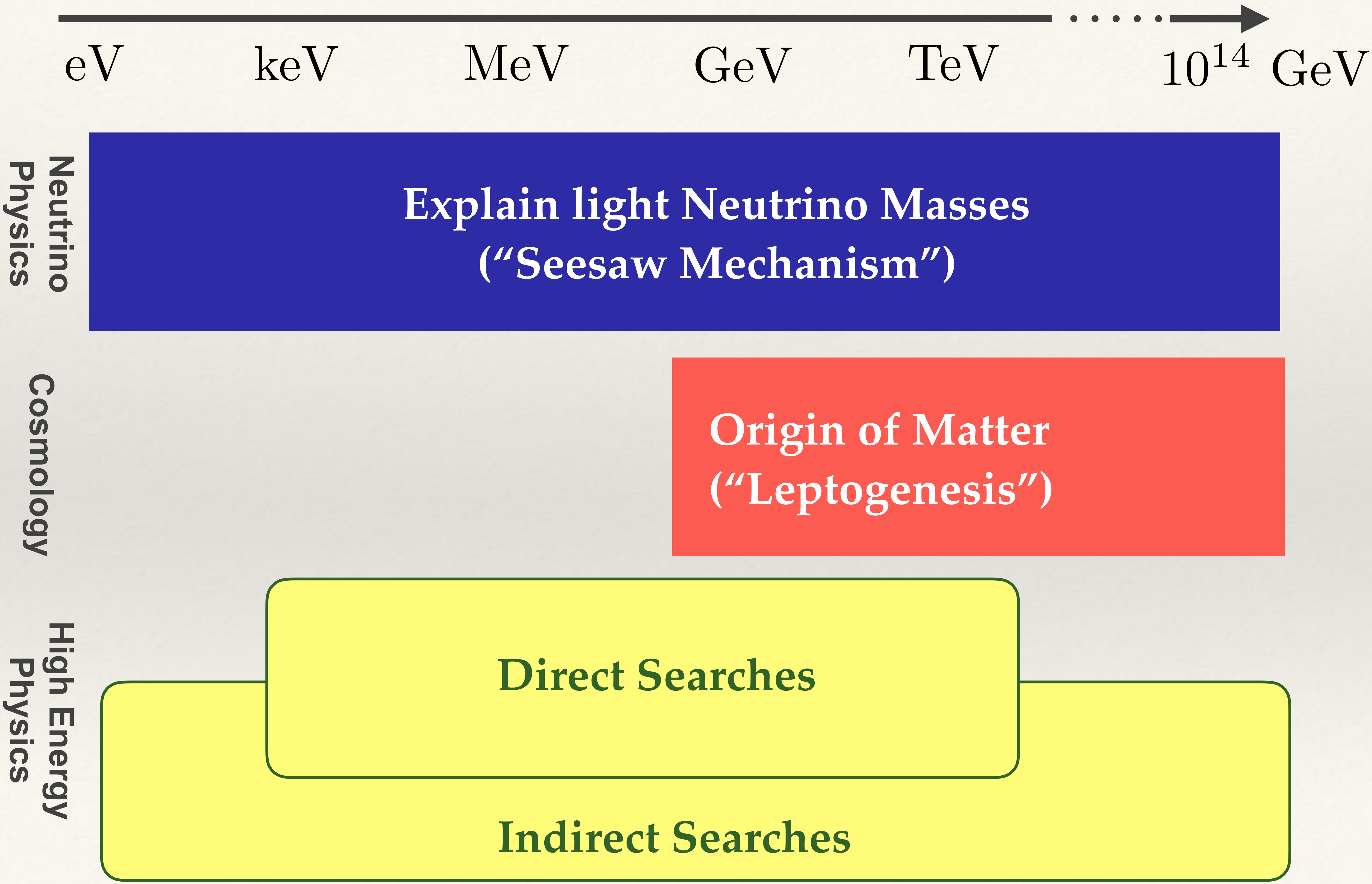
FCC
hh ee he

CEPC

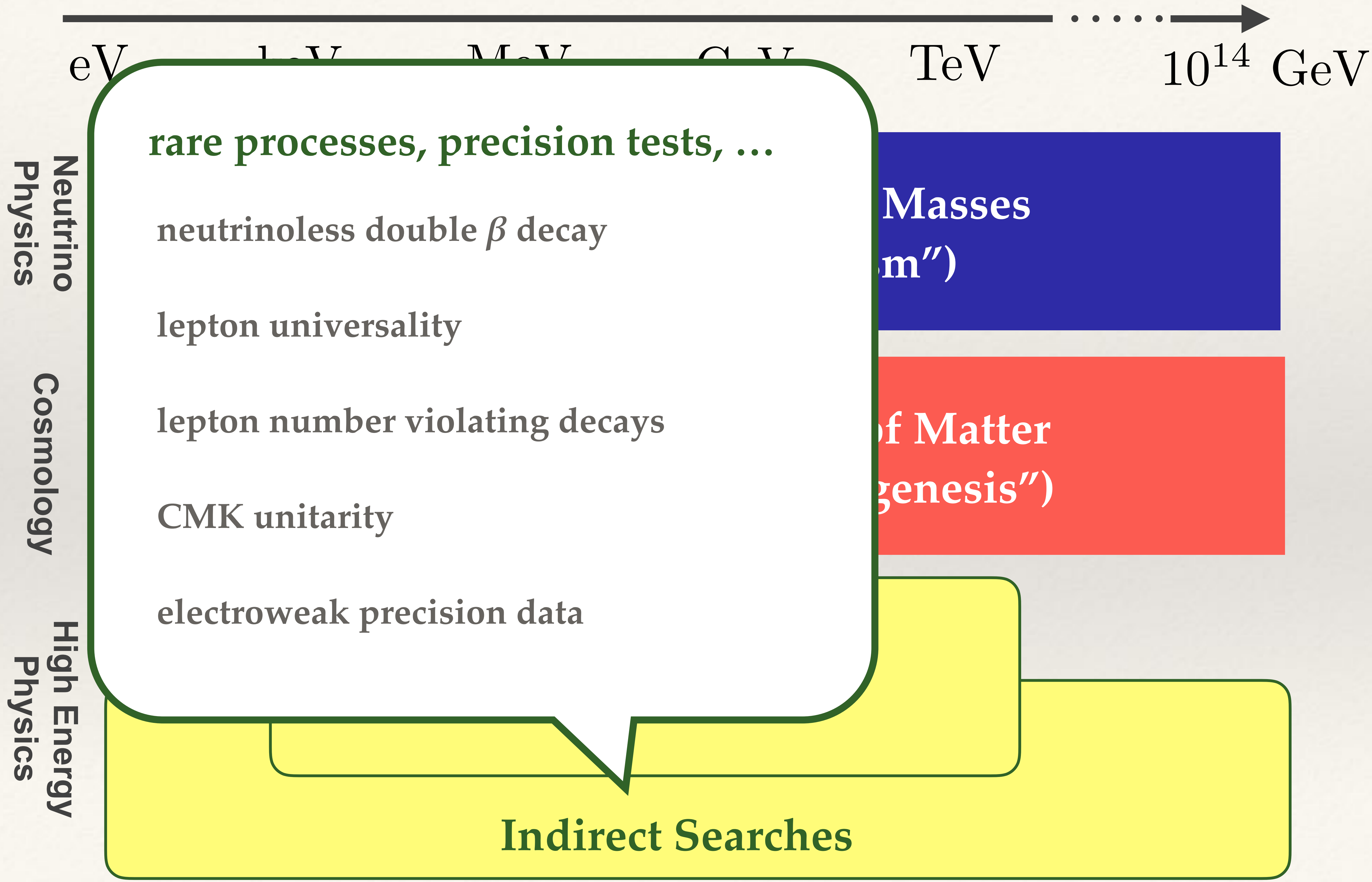
Direct Searches

High Energy Physics

How to Find Heavy Neutrinos?



How to Find Heavy Neutrinos?



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 ➡

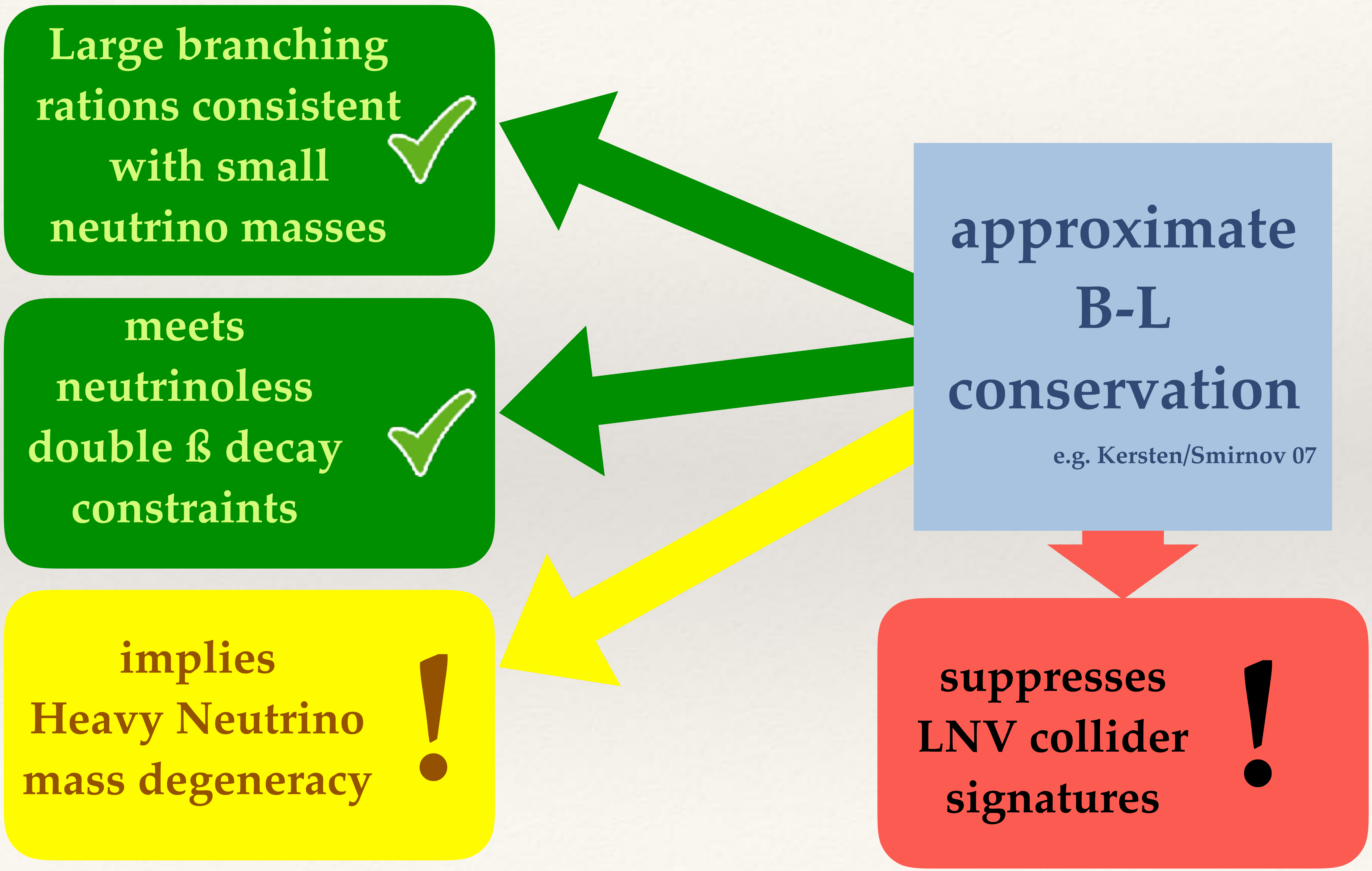
approximate B-L conservation

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?

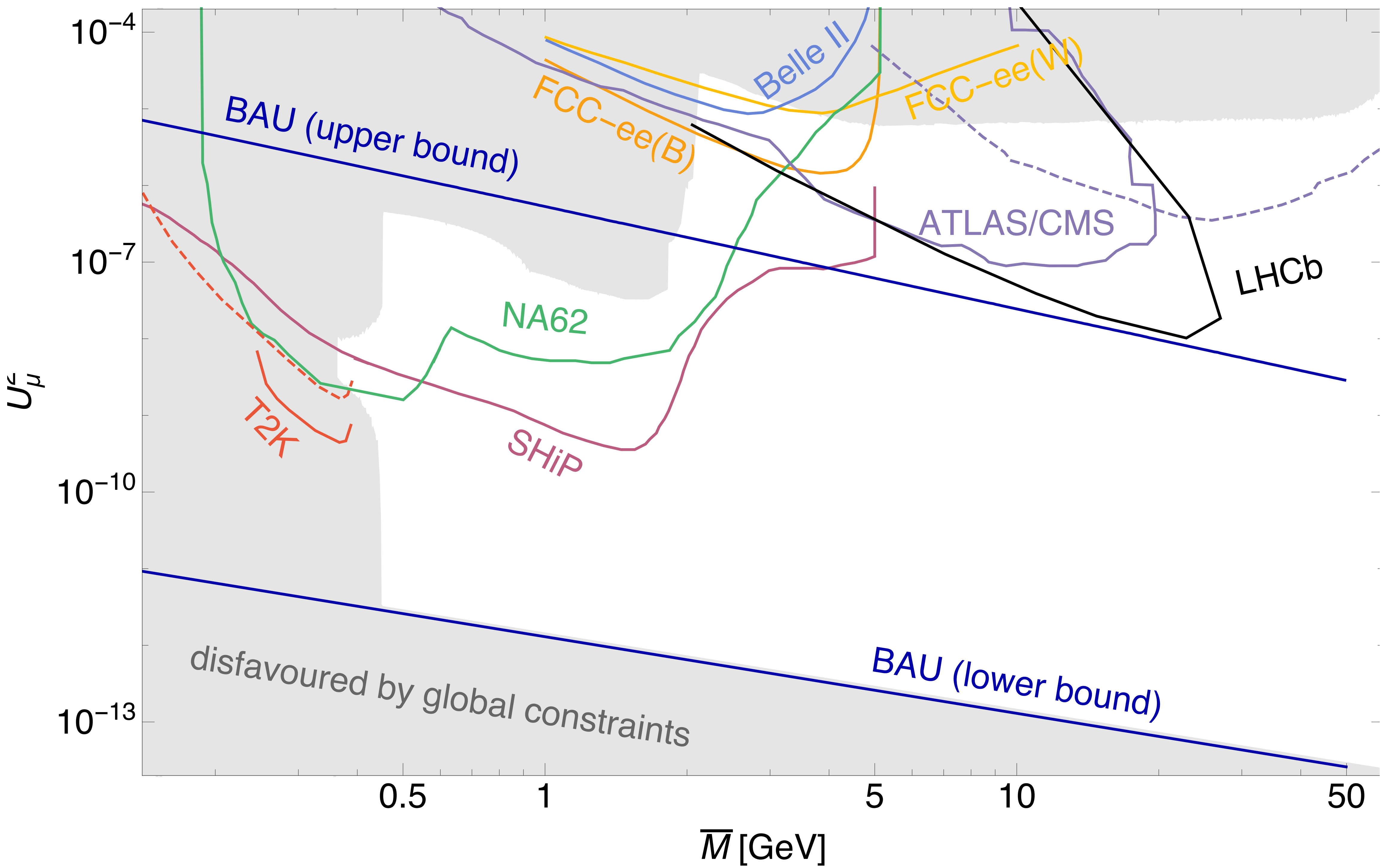
"golden channels" suppressed

need to use other channels (LFV, displaced vertices)

implies Heavy Neutrino mass degeneracy !

suppresses LNV collider signatures !

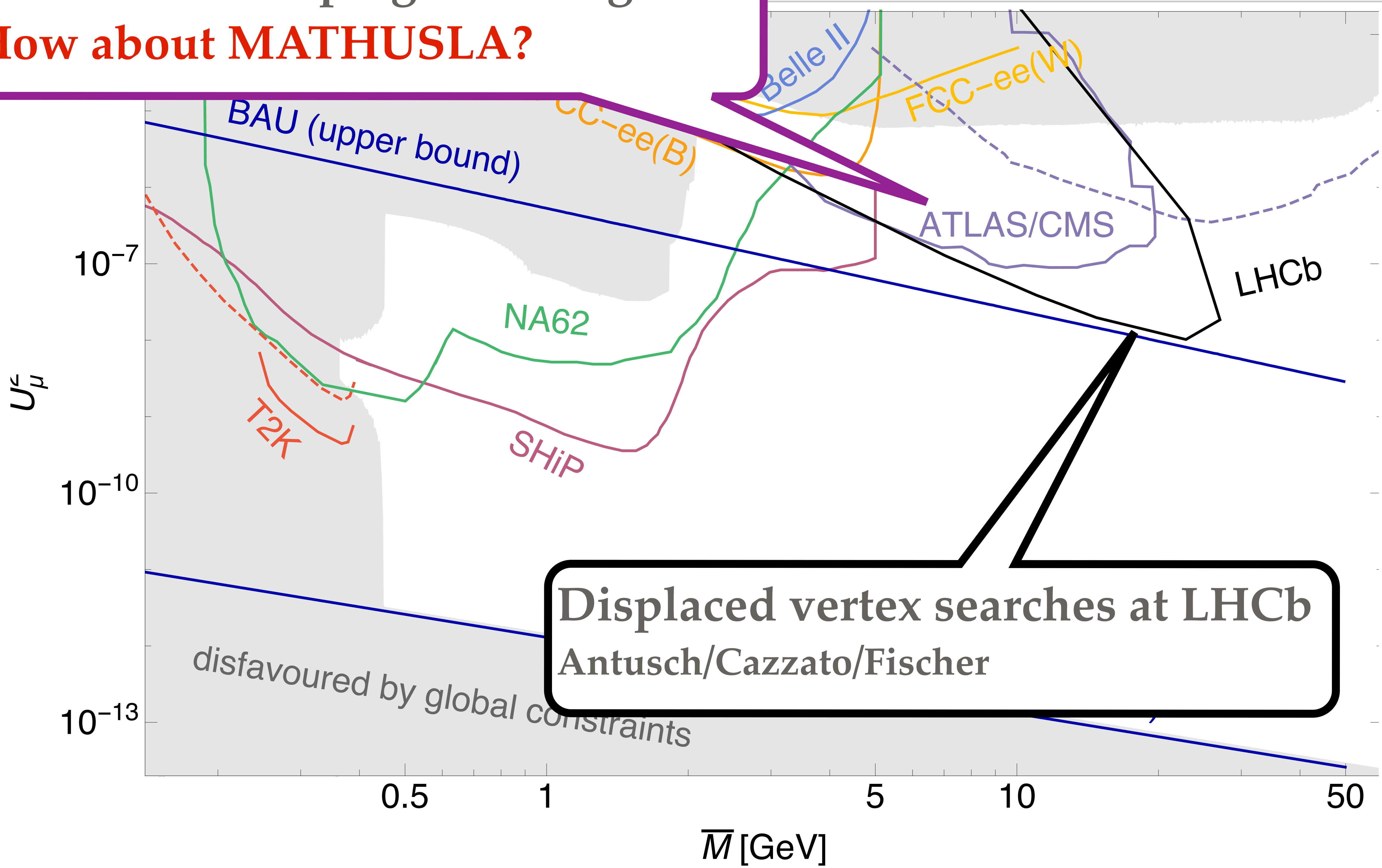
Experimental Perspectives



plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Perspectives

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

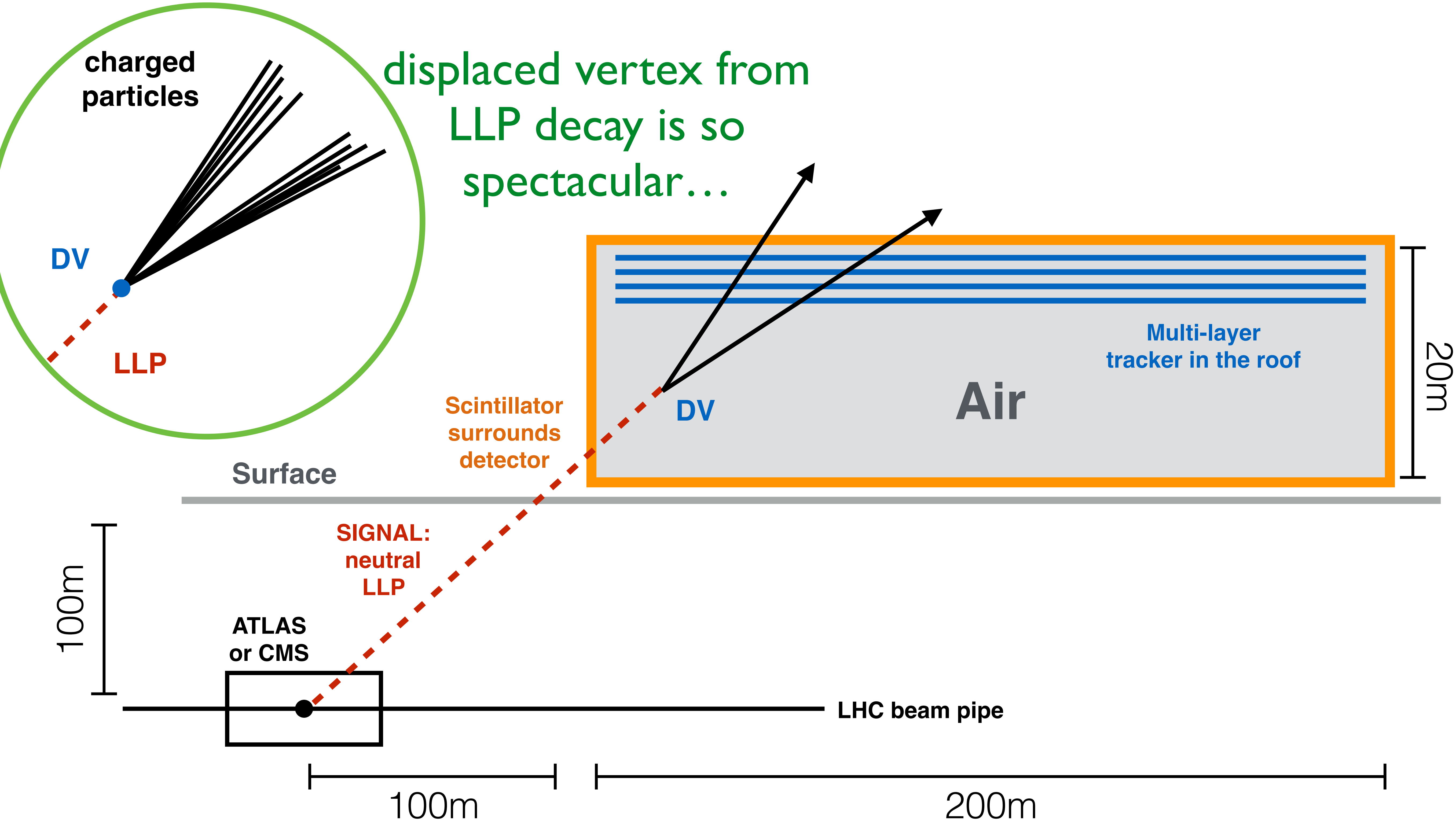


Displaced vertex searches at LHCb
Antusch/Cazzato/Fischer

plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

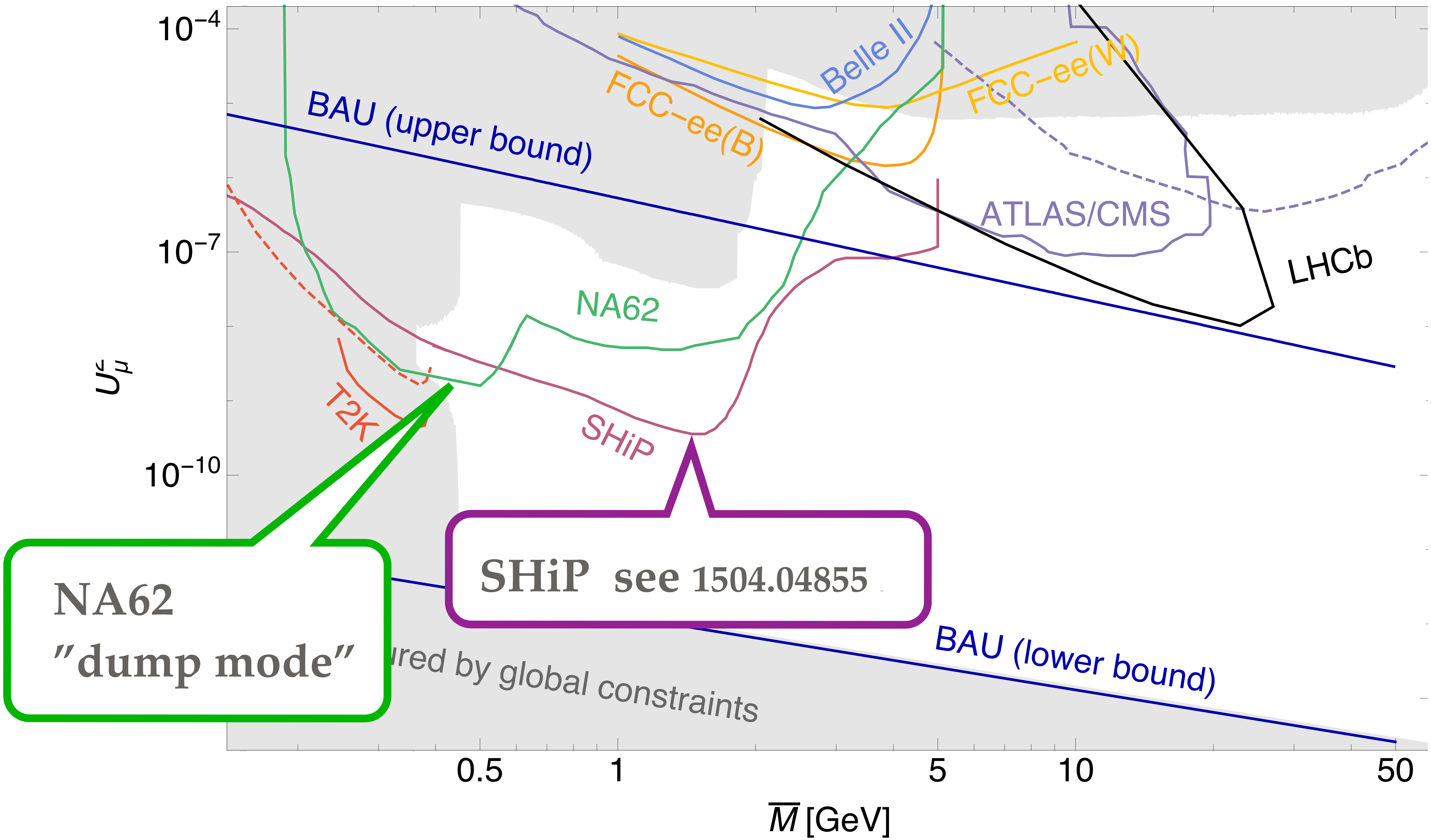
MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



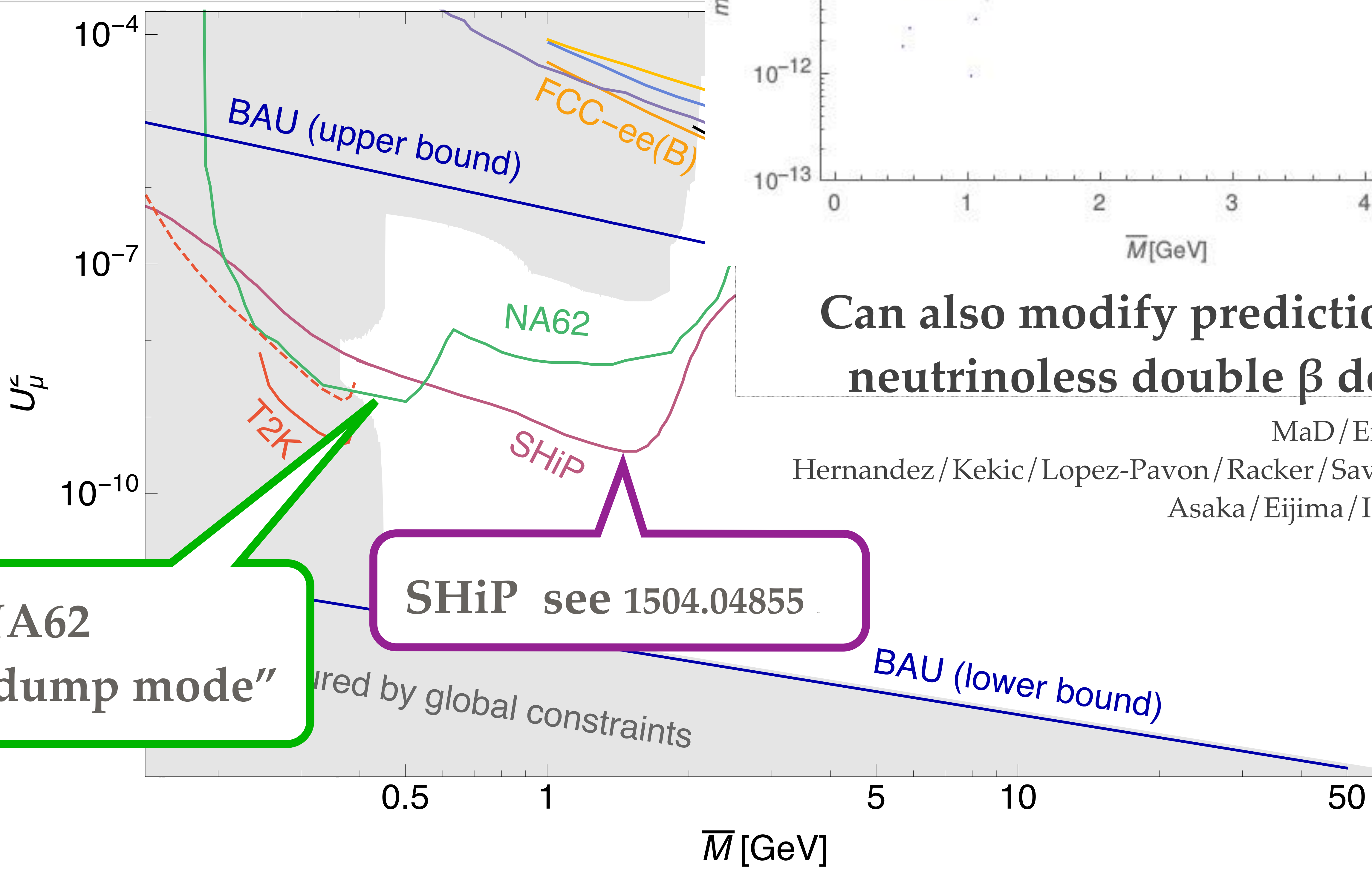
slide by David Curtin

Experimental Perspectives



plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

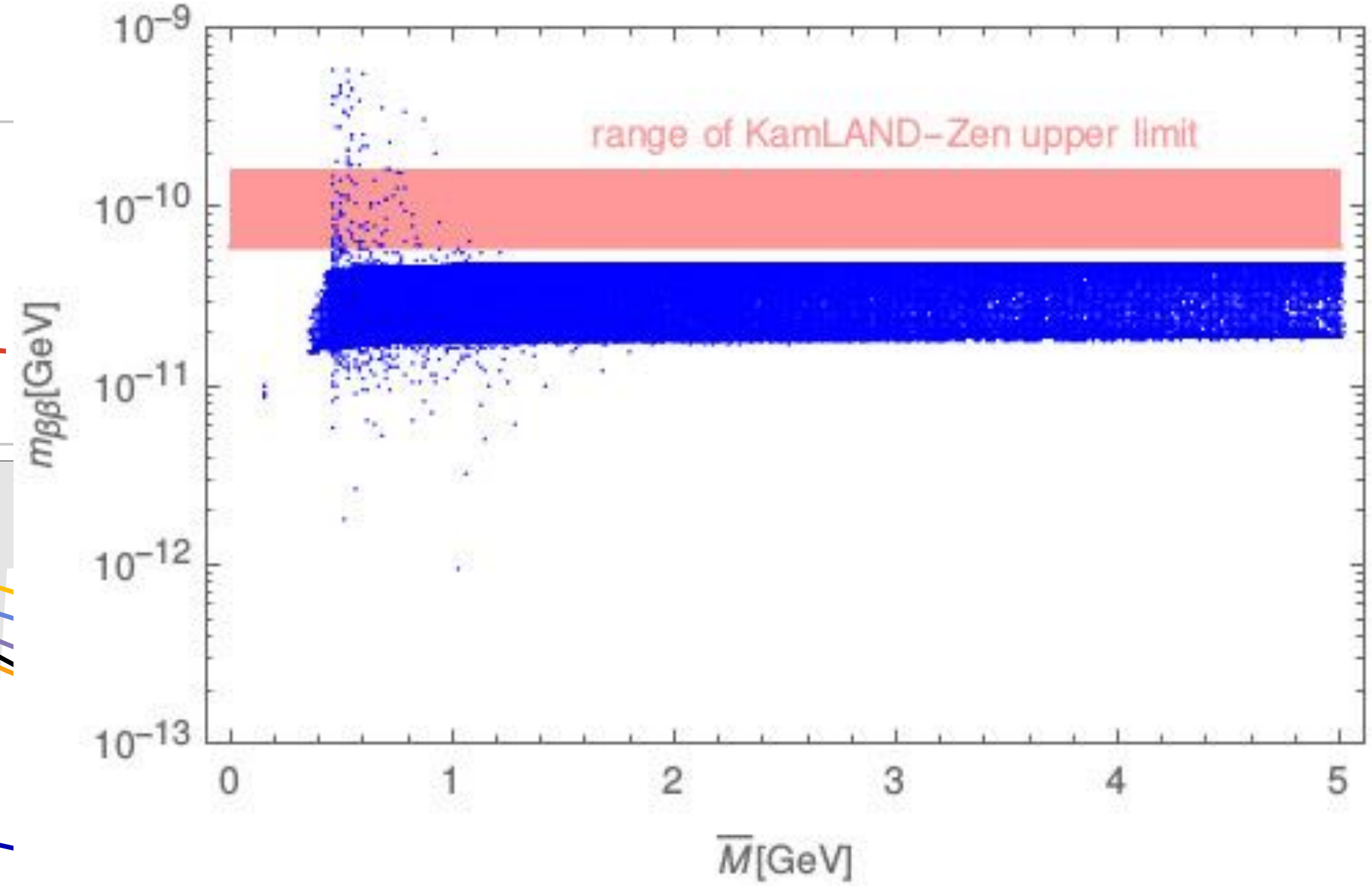
Experimenta



NA62
"dump mode"

SHiP see 1504.04855

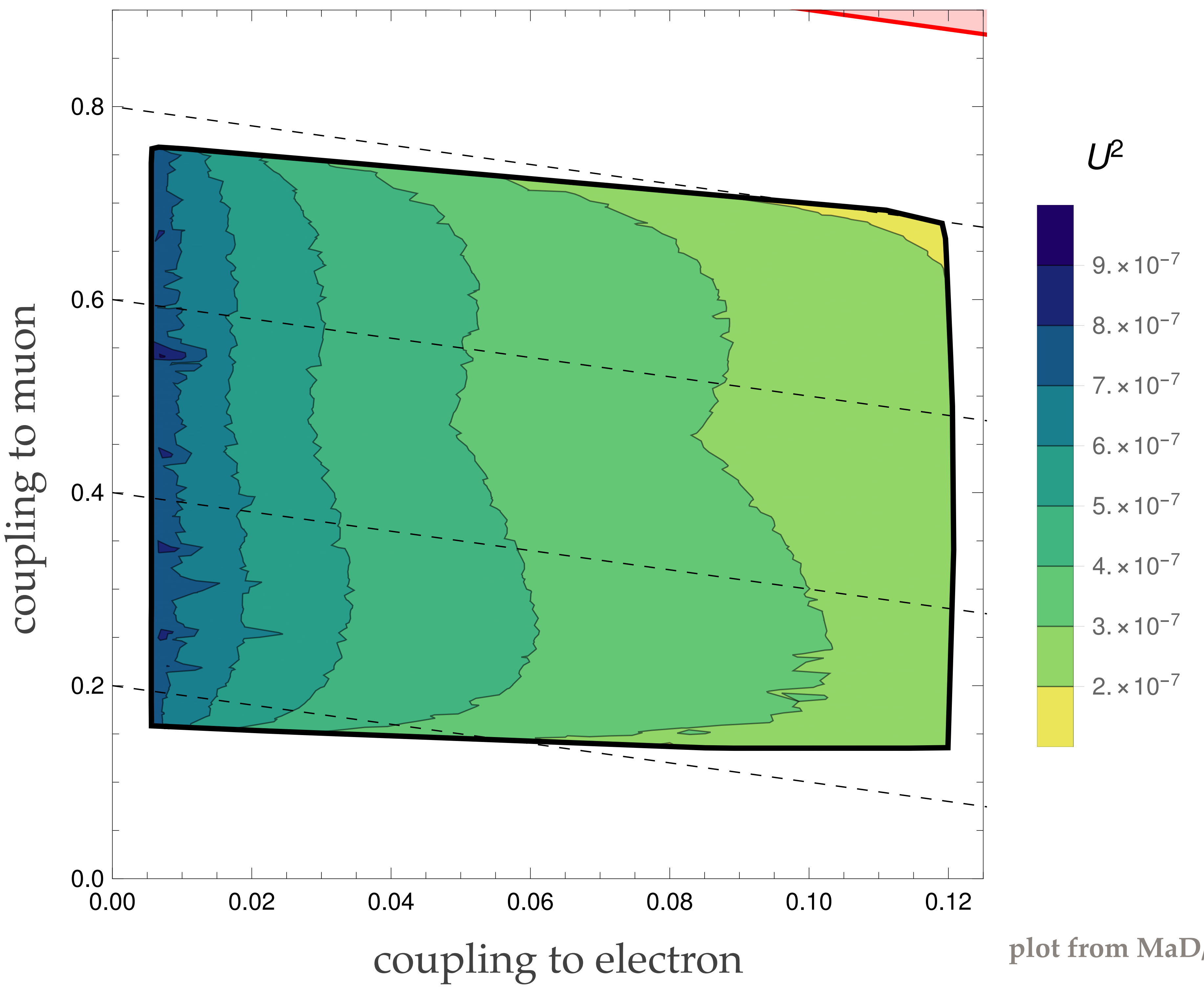
plot from MaD/Garbrecht/Gueter/Klaric 1609.09069



Can also modify prediction for neutrinoless double β decay

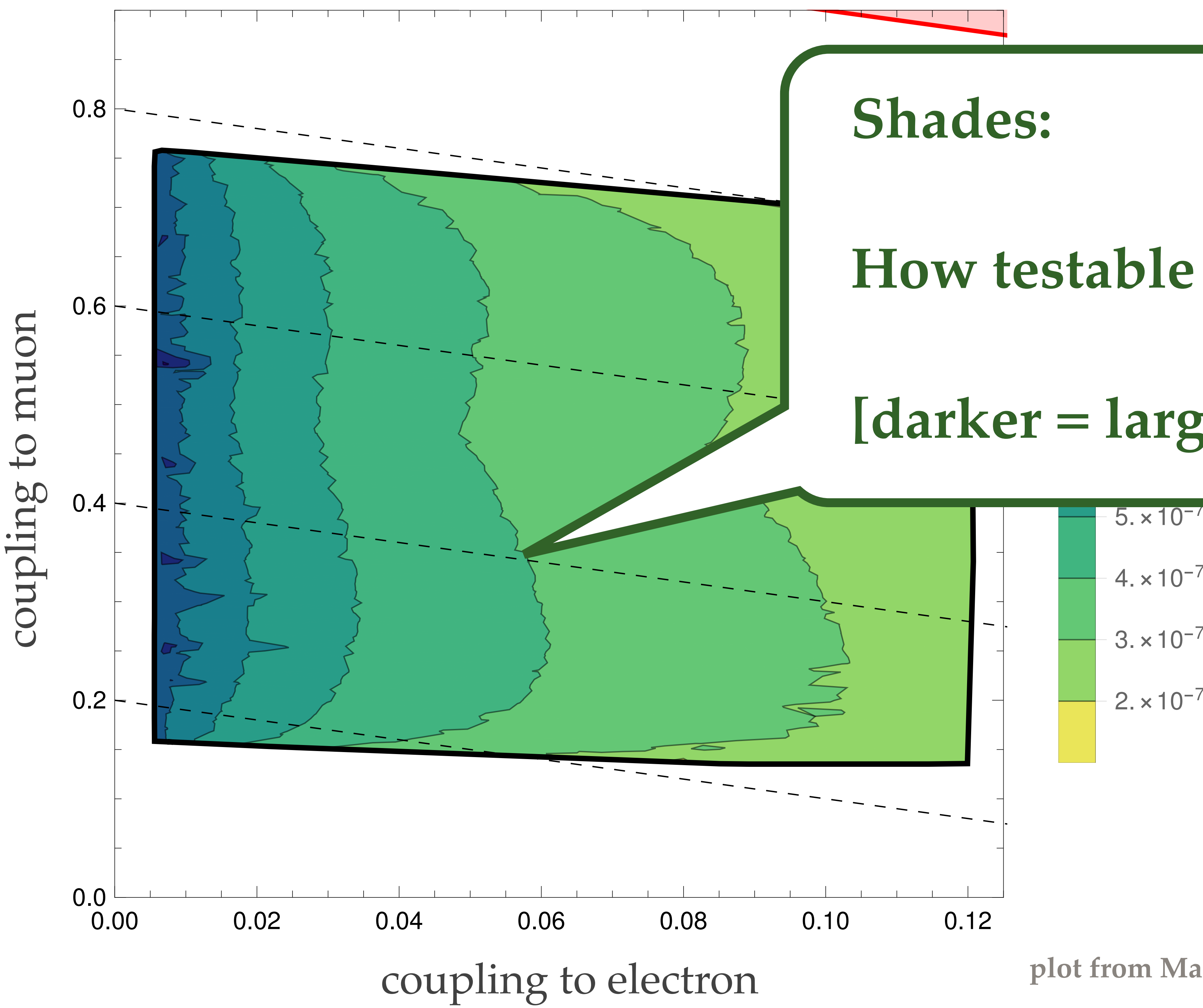
MaD/Eijima 16.
Hernandez/Kekic/Lopez-Pavon/Racker/Savaldo 16,
Asaka/Eijima/Ishida 16

Neutrino Mixing vs Collider Searches



plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Neutrino Mixing vs Collider Searches



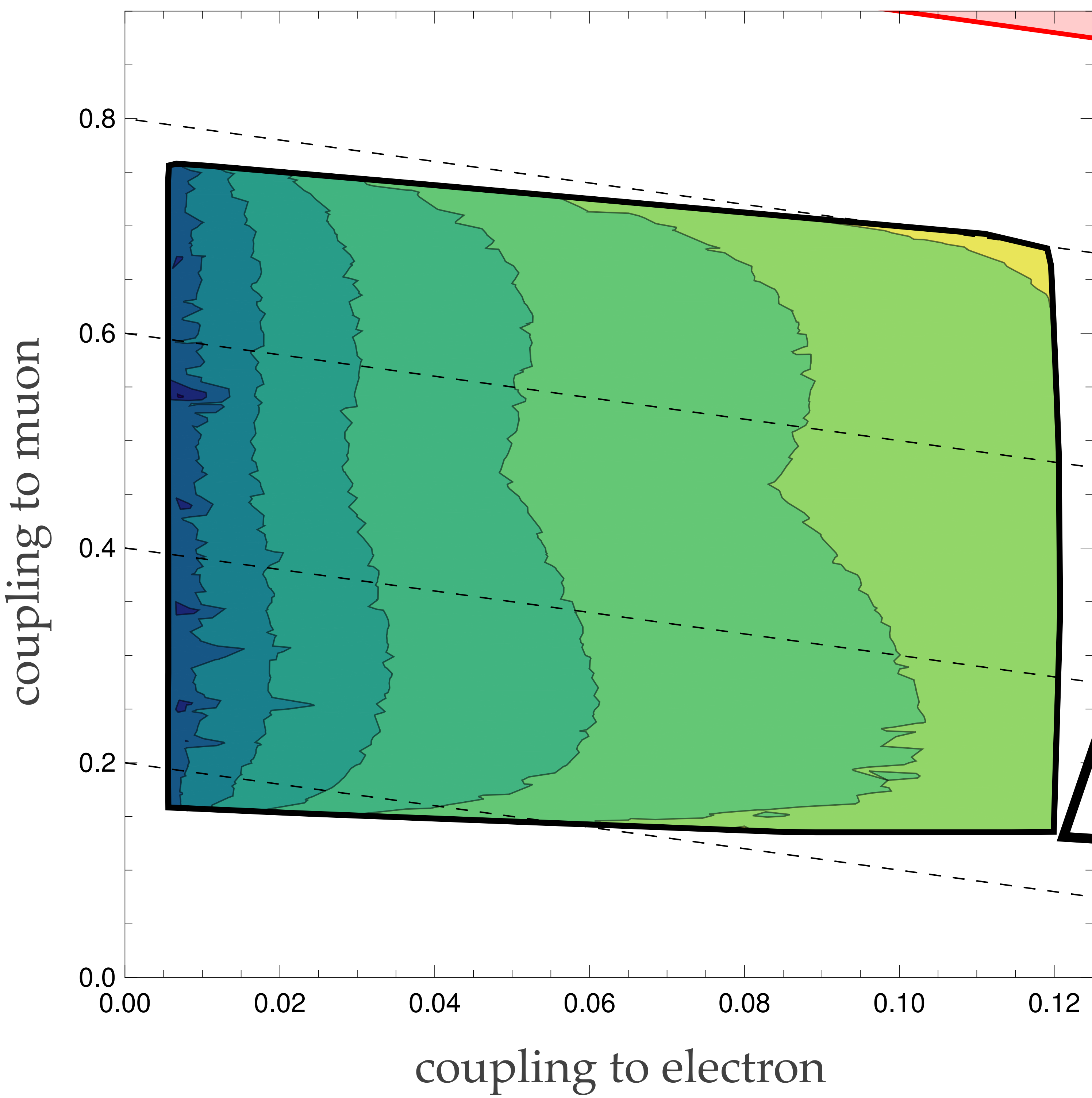
Shades:

How testable is leptogenesis?

[darker = larger total mixing]

plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Neutrino Mixing vs Collider Searches

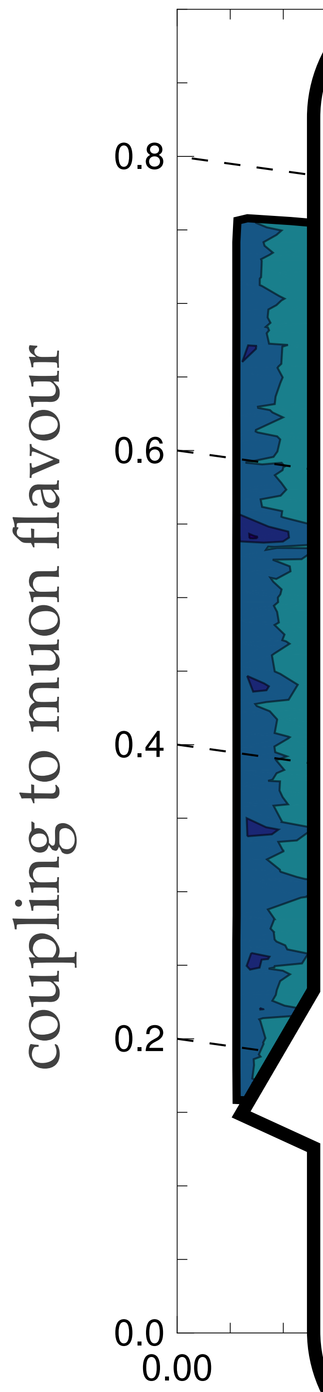


Area within black line:

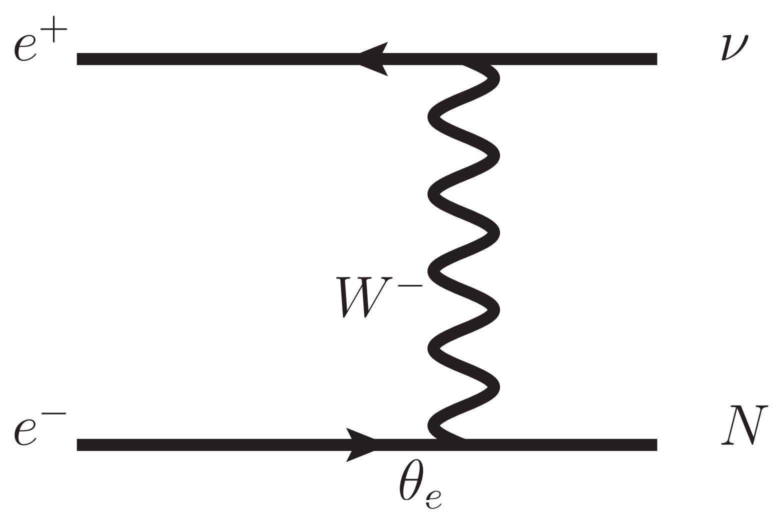
allowed by neutrino oscillation data

coupling to electron maximal 12%!
[for normal neutrino mass ordering]

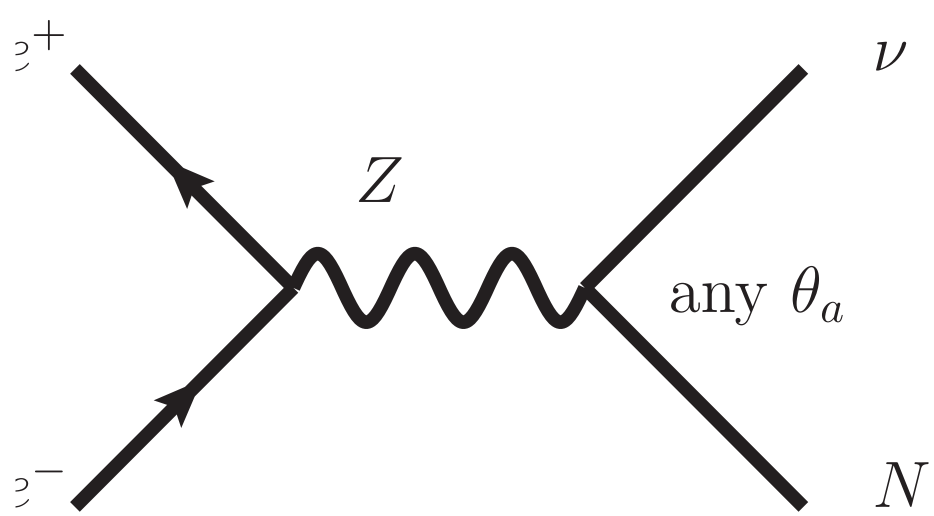
Neutrino Mixing vs Collider Searches



Effect on production at lepton colliders:



suppressed compared to



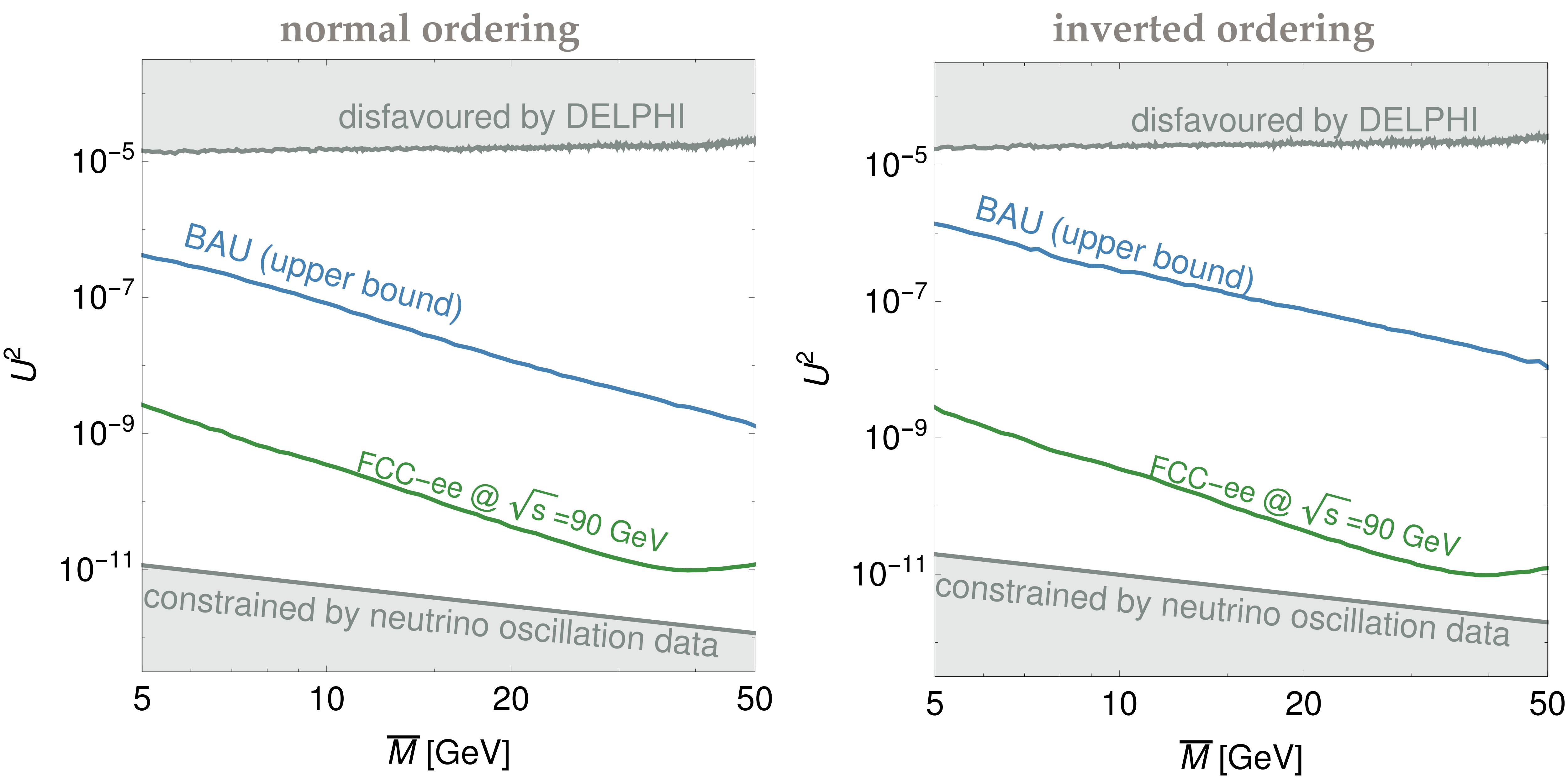
Area within black line:

allowed by neutrino oscillation data

coupling to electron maximal 12%!

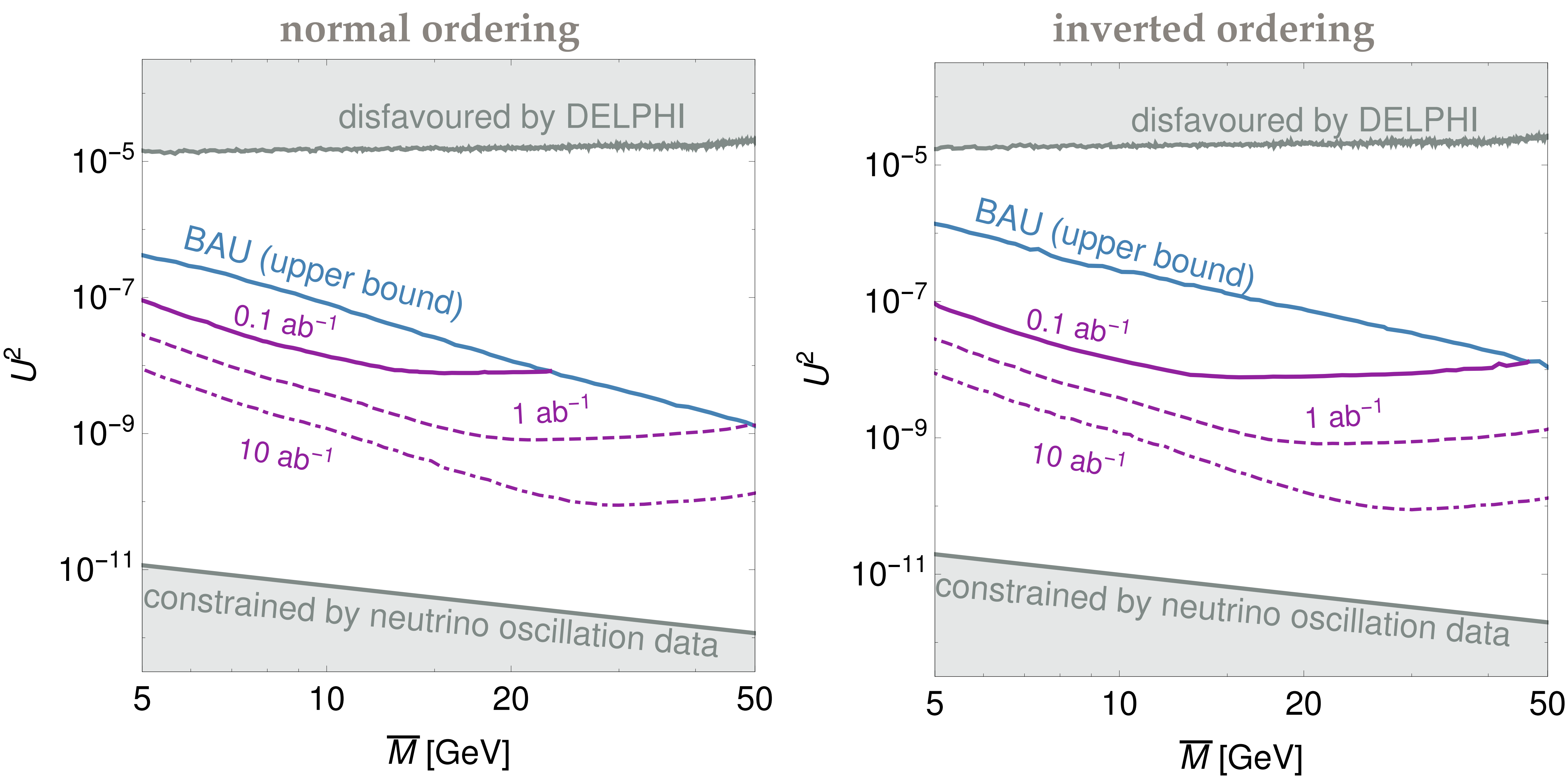
[for normal neutrino mass ordering]

Displaced Vertices at FCC-ee



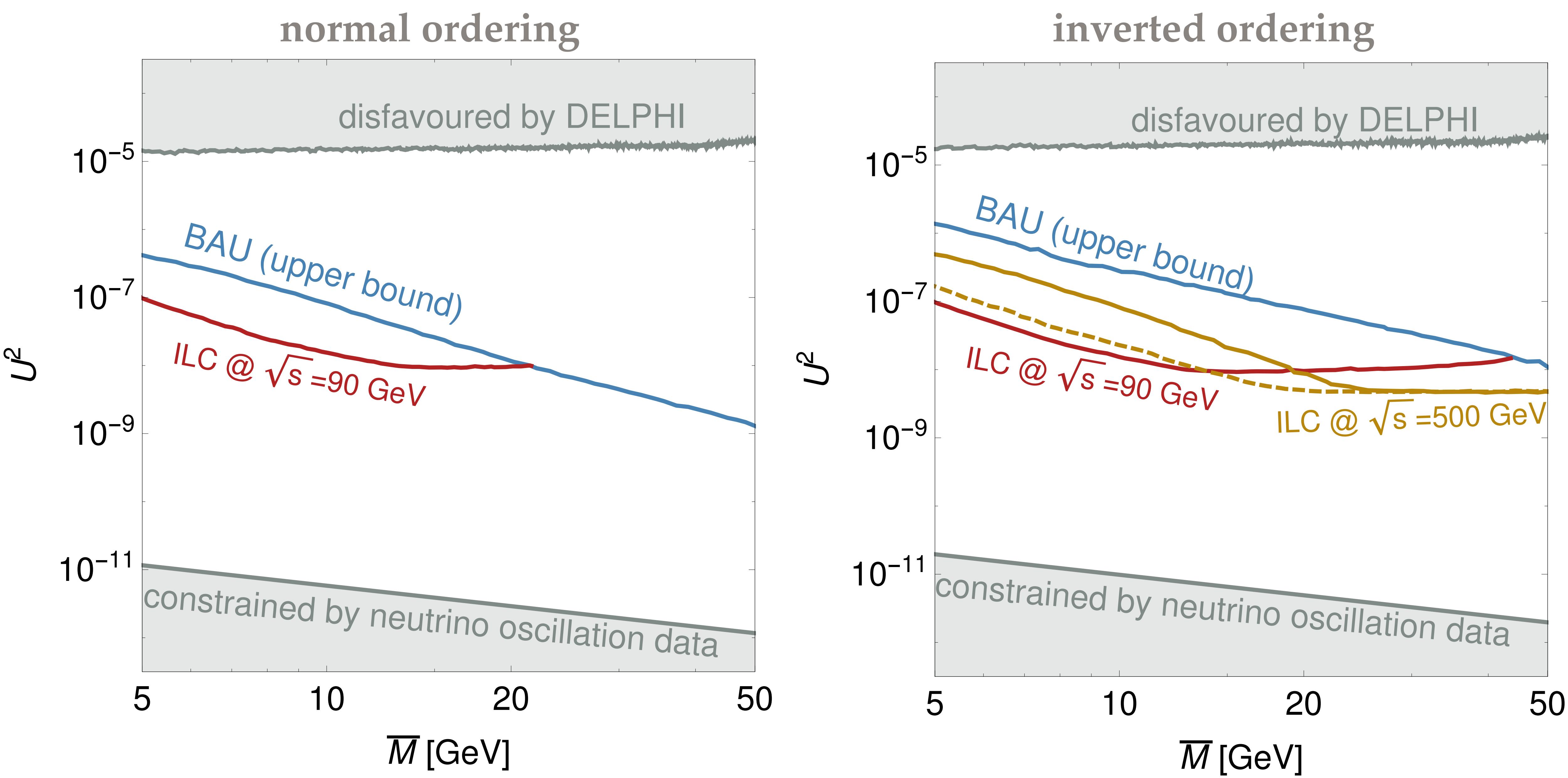
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Displaced Vertices at CEPC



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

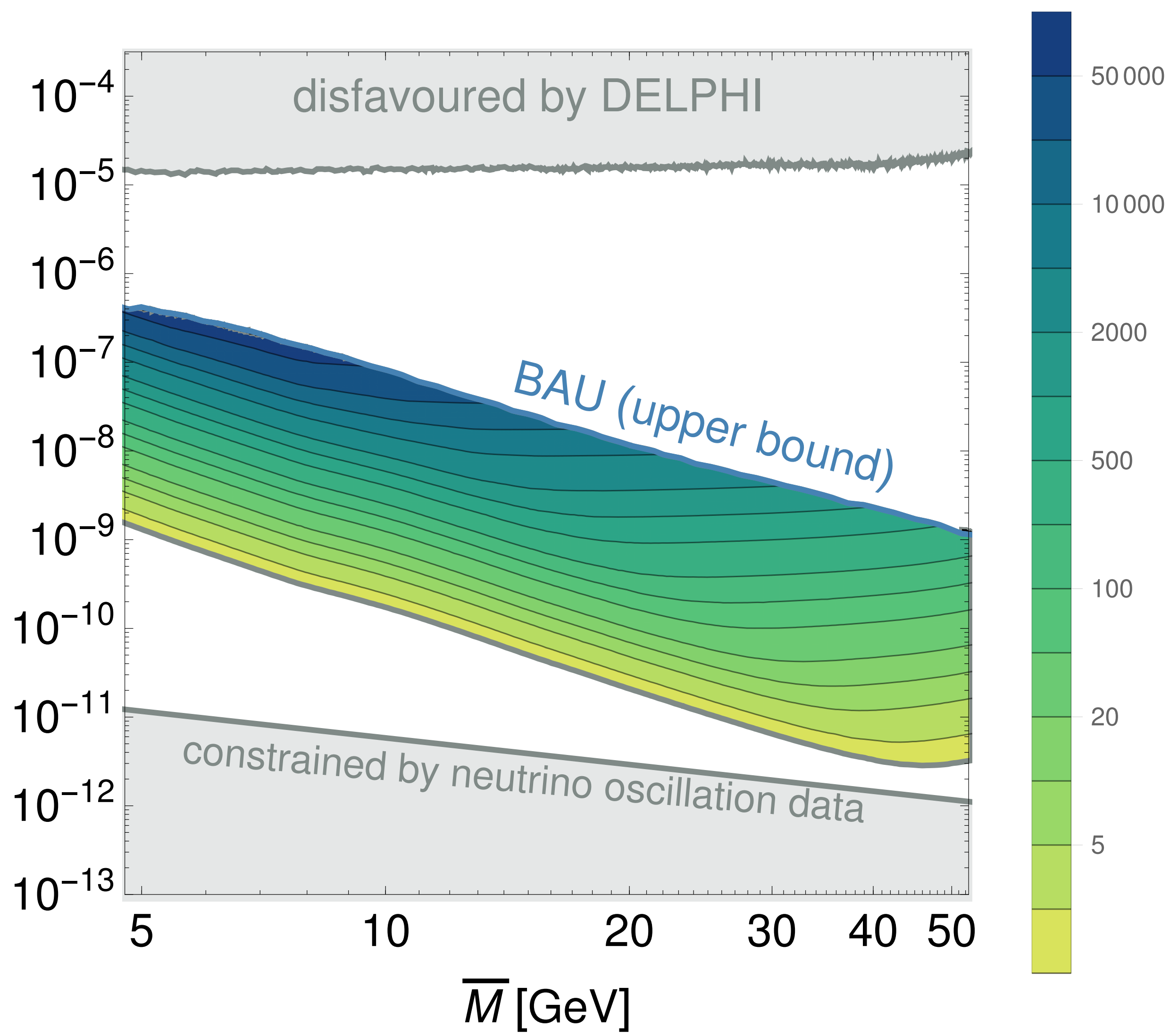
Displaced Vertices at ILC



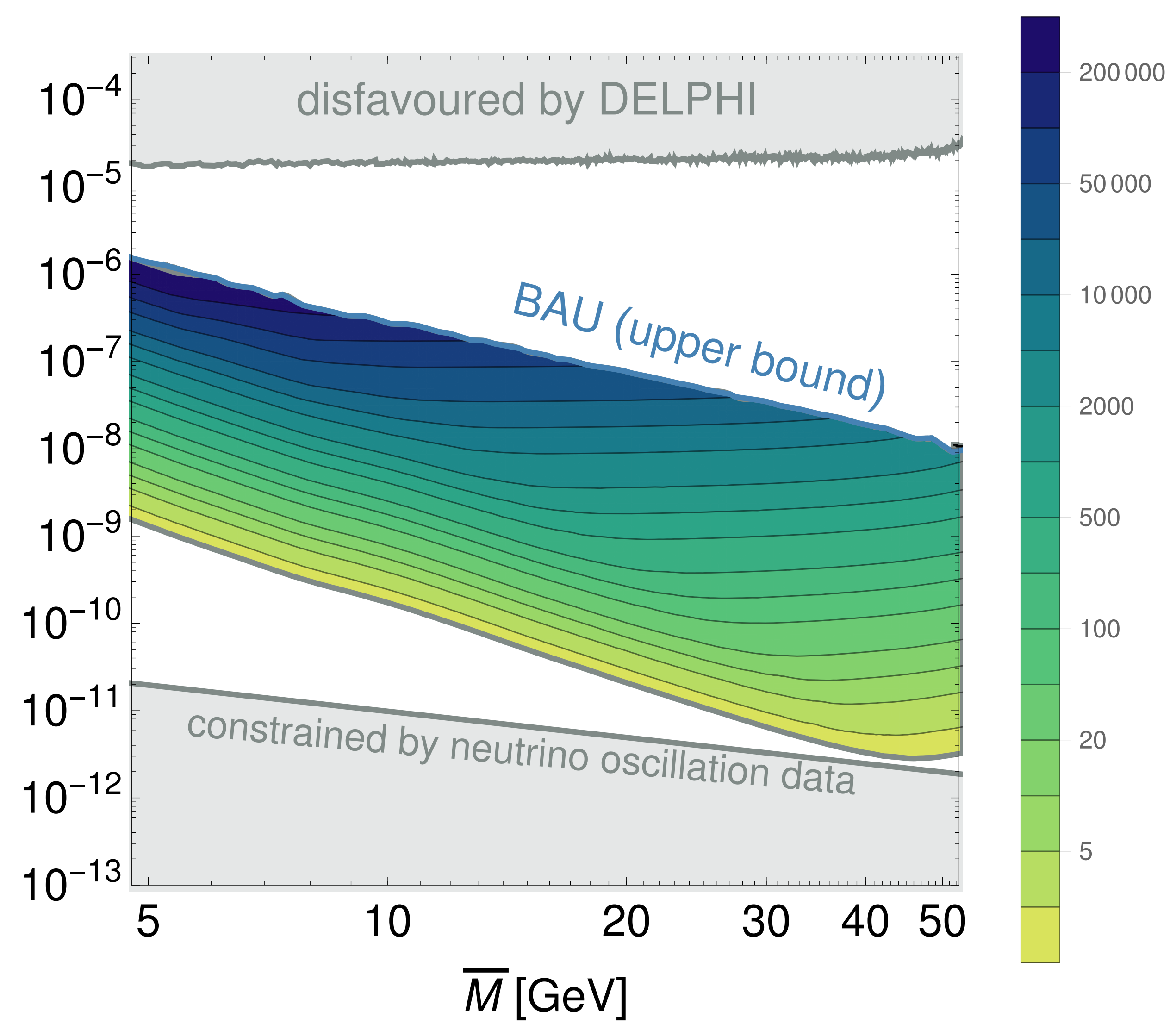
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Number of Events

normal ordering

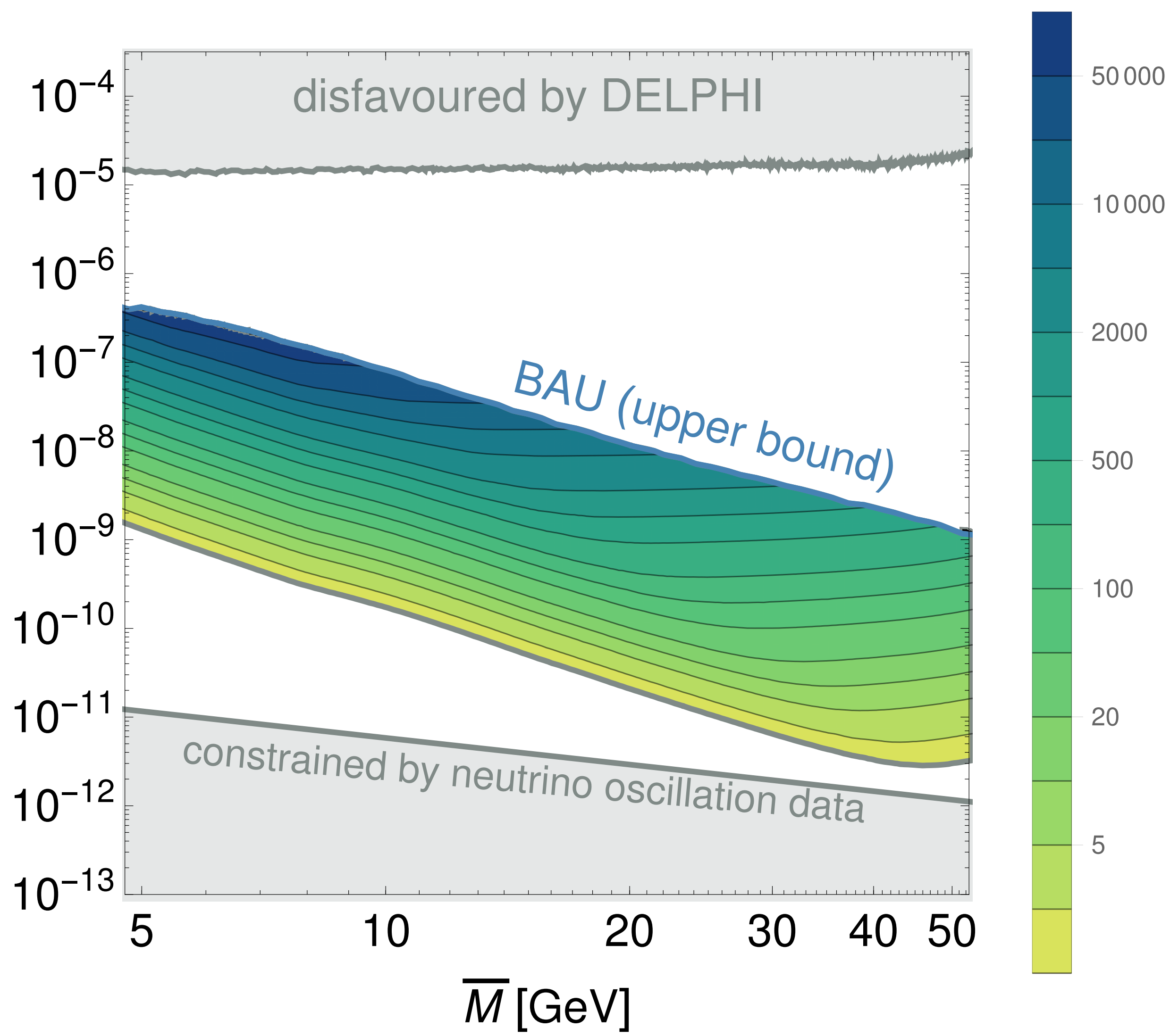


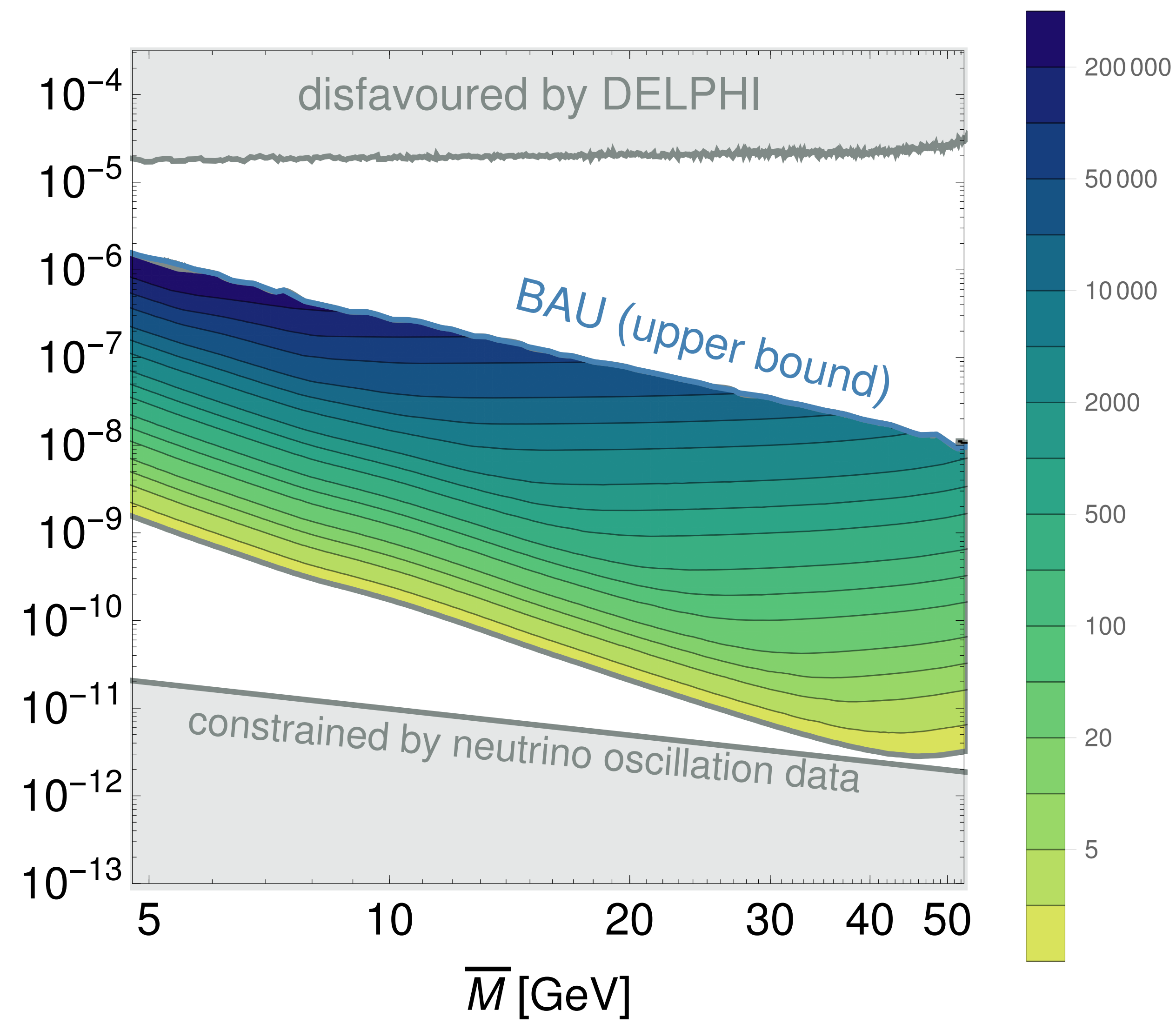
inverted ordering



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

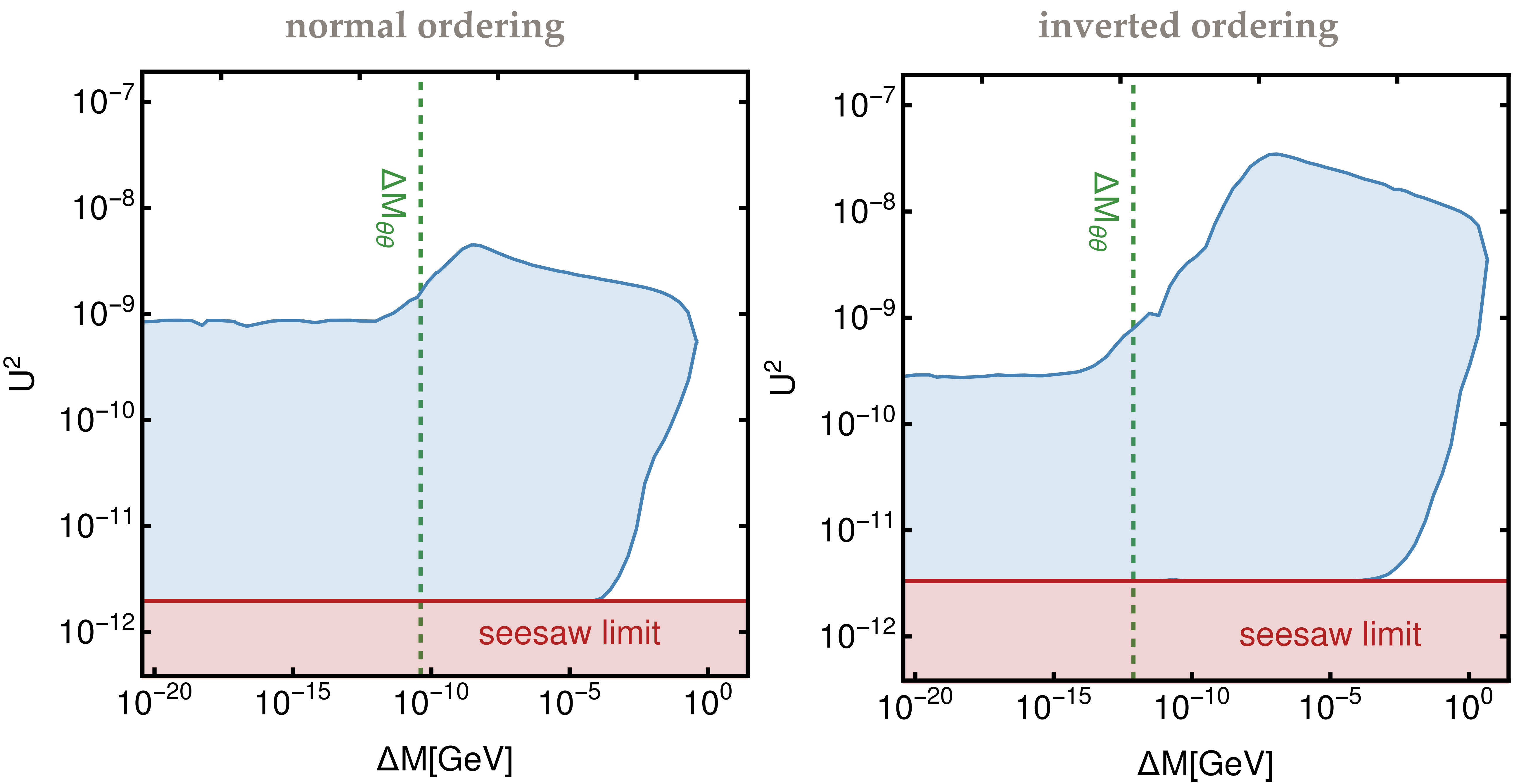
Number of Events





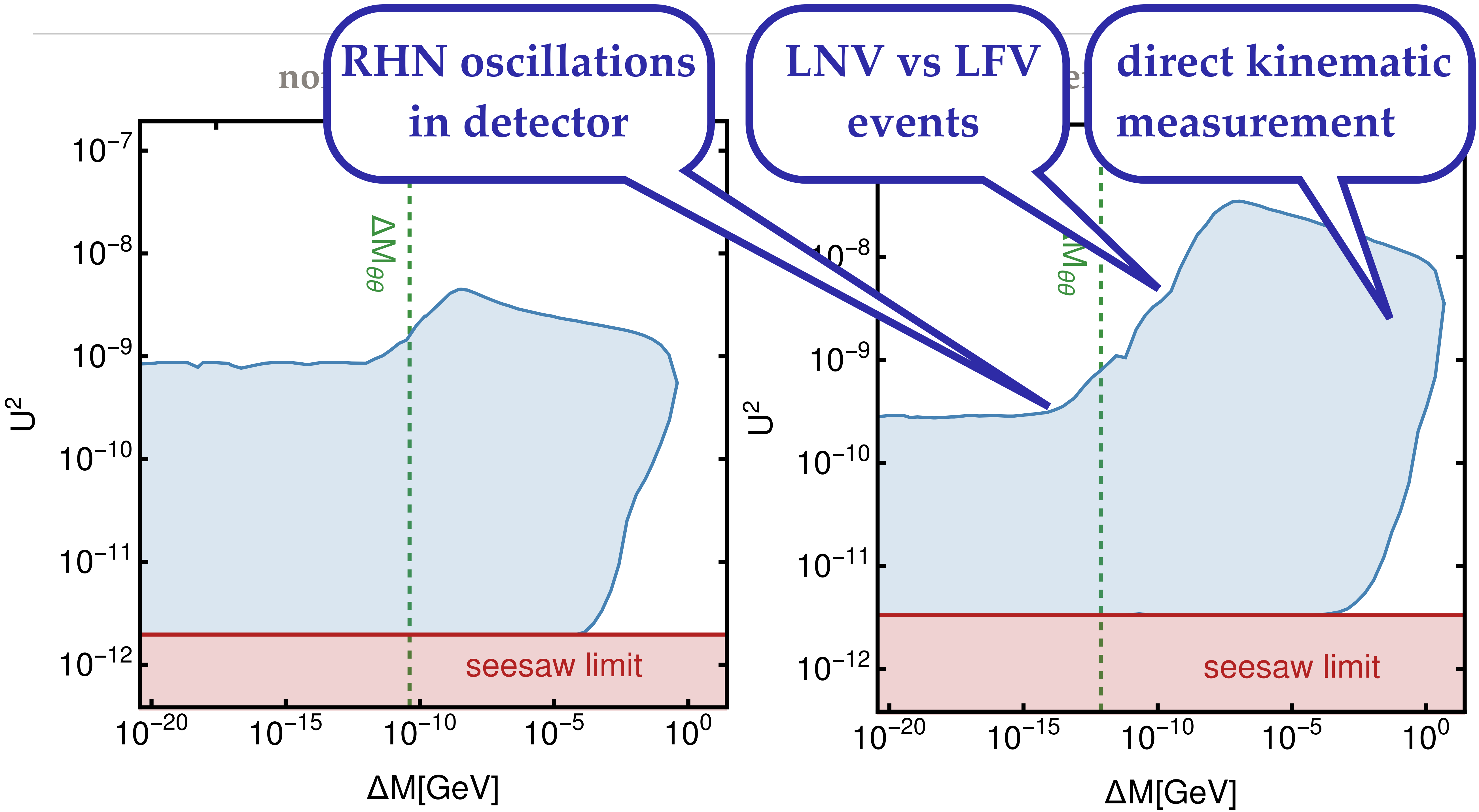
percent level measurement of flavour structure!

Leptogenesis and Heavy Neutrino Mass Splitting



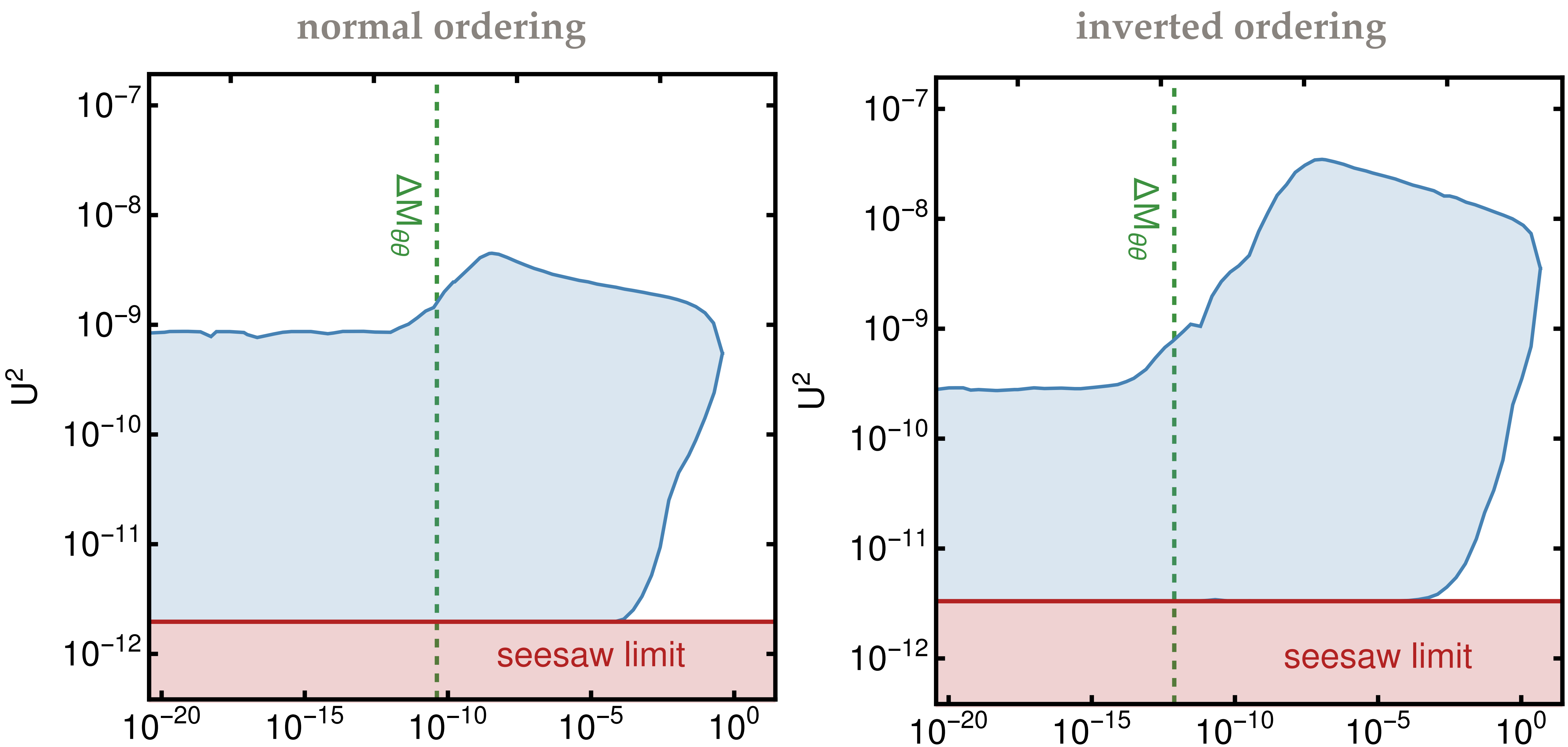
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Leptogenesis and Heavy Neutrino Mass Splitting



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

Leptogenesis and Heavy Neutrino Mass Splitting

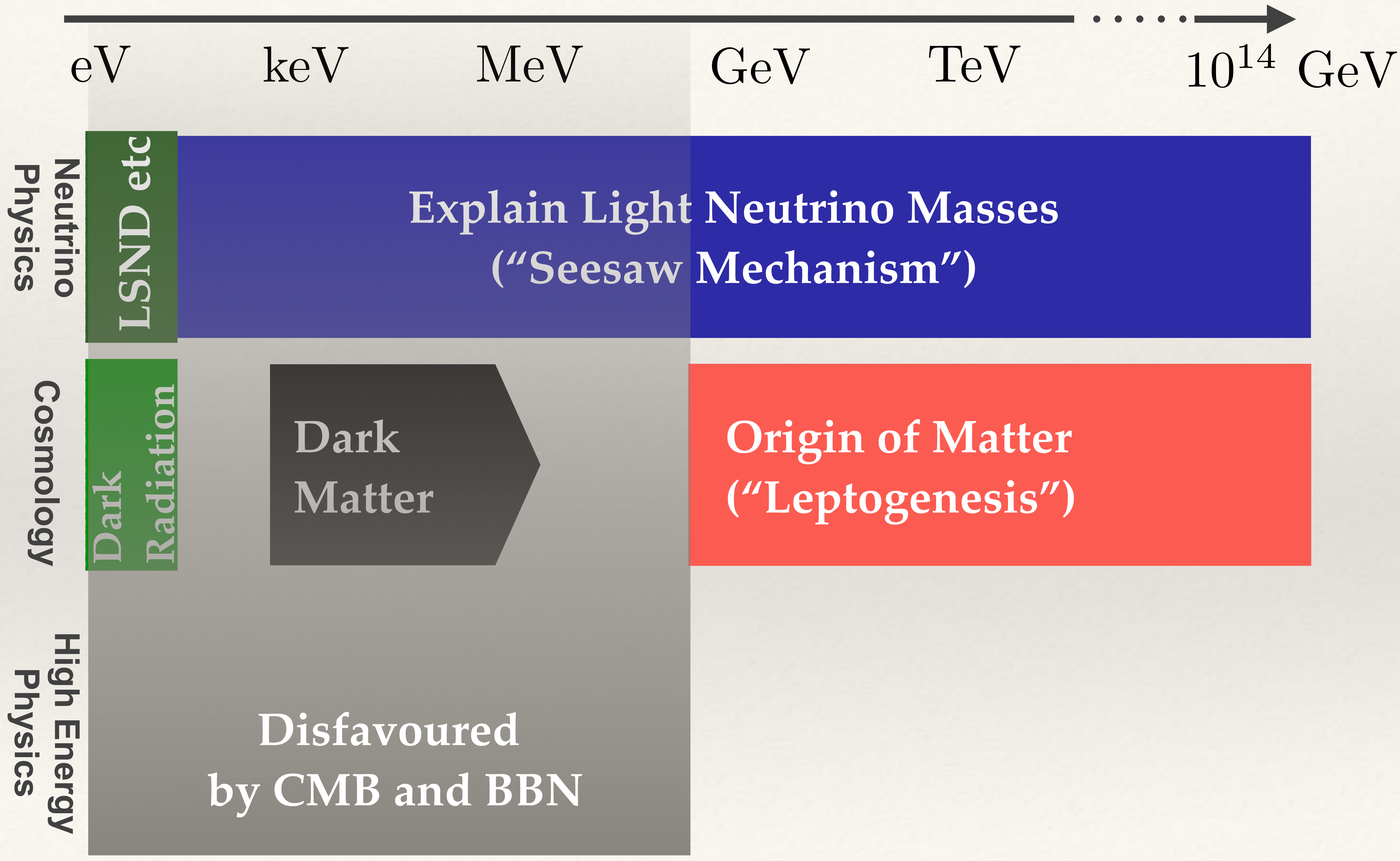


with three RH neutrinos:
no need for mass degeneracy for leptogenesis MaD/Garbrecht 12

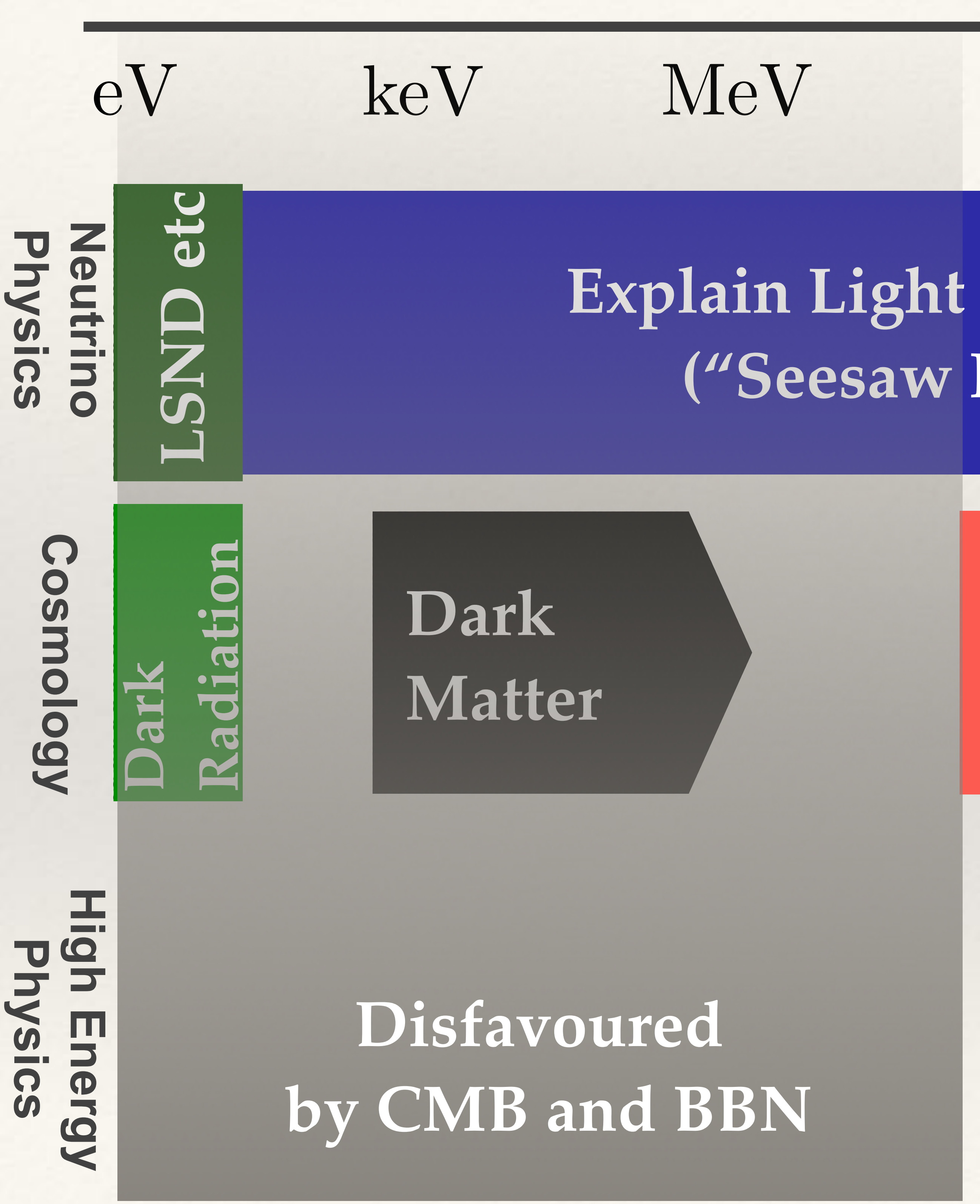
Conclusions

- 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**

Right Handed Neutrinos and the Light Neutrino Masses

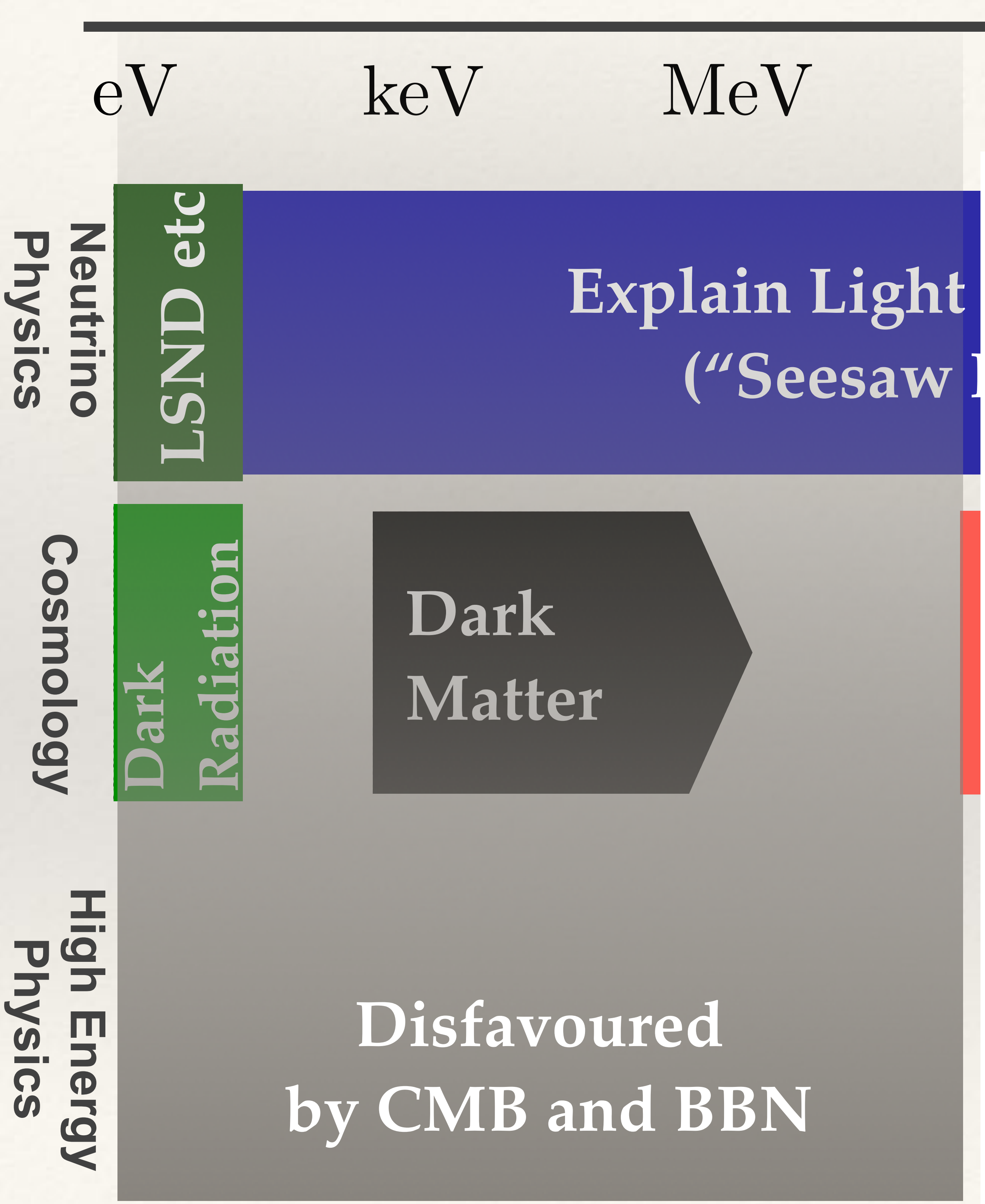


Right Handed Neutrinos and the Light Neutrino Masses

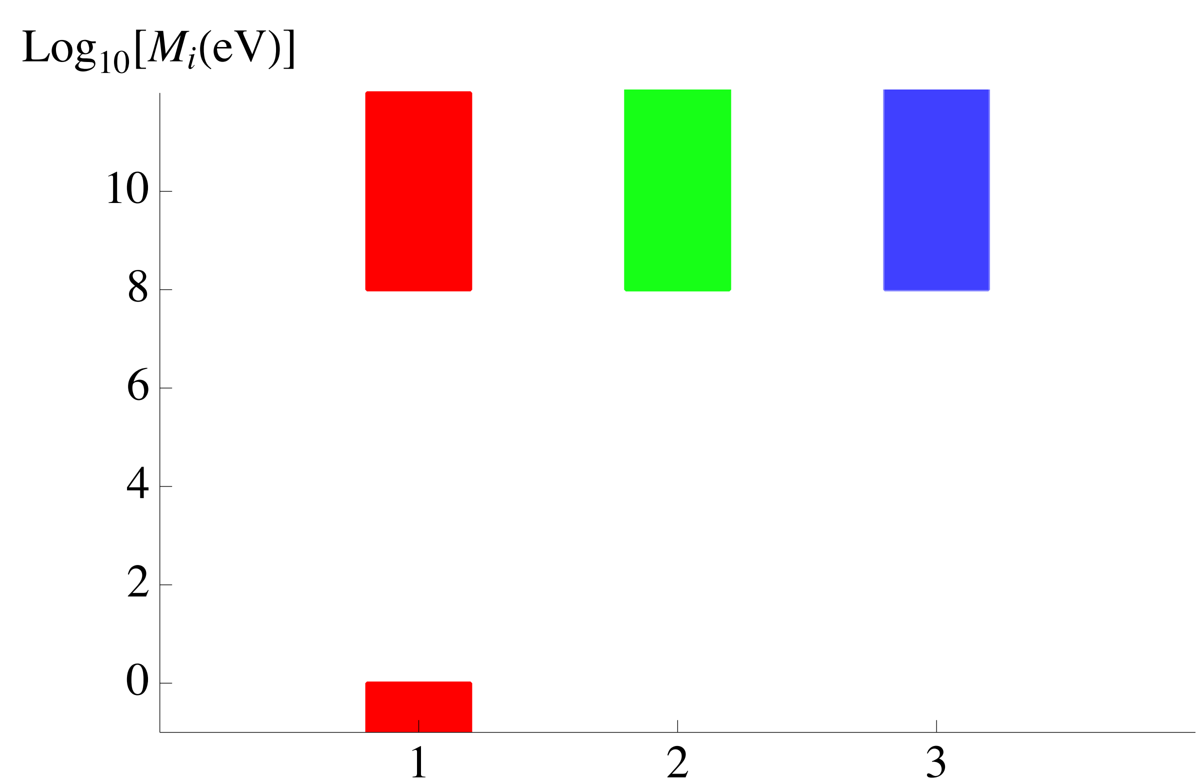


- RH neutrinos **must mix** to generate light neutrino mass
- Mixing leads to **production in the early universe**
- For masses below 100 MeV, RH neutrinos **do not decay before BBN**
- Their decay either **disturbs BBN** or **affects the CMB**

Right Handed Neutrinos and the Light Neutrino Masses

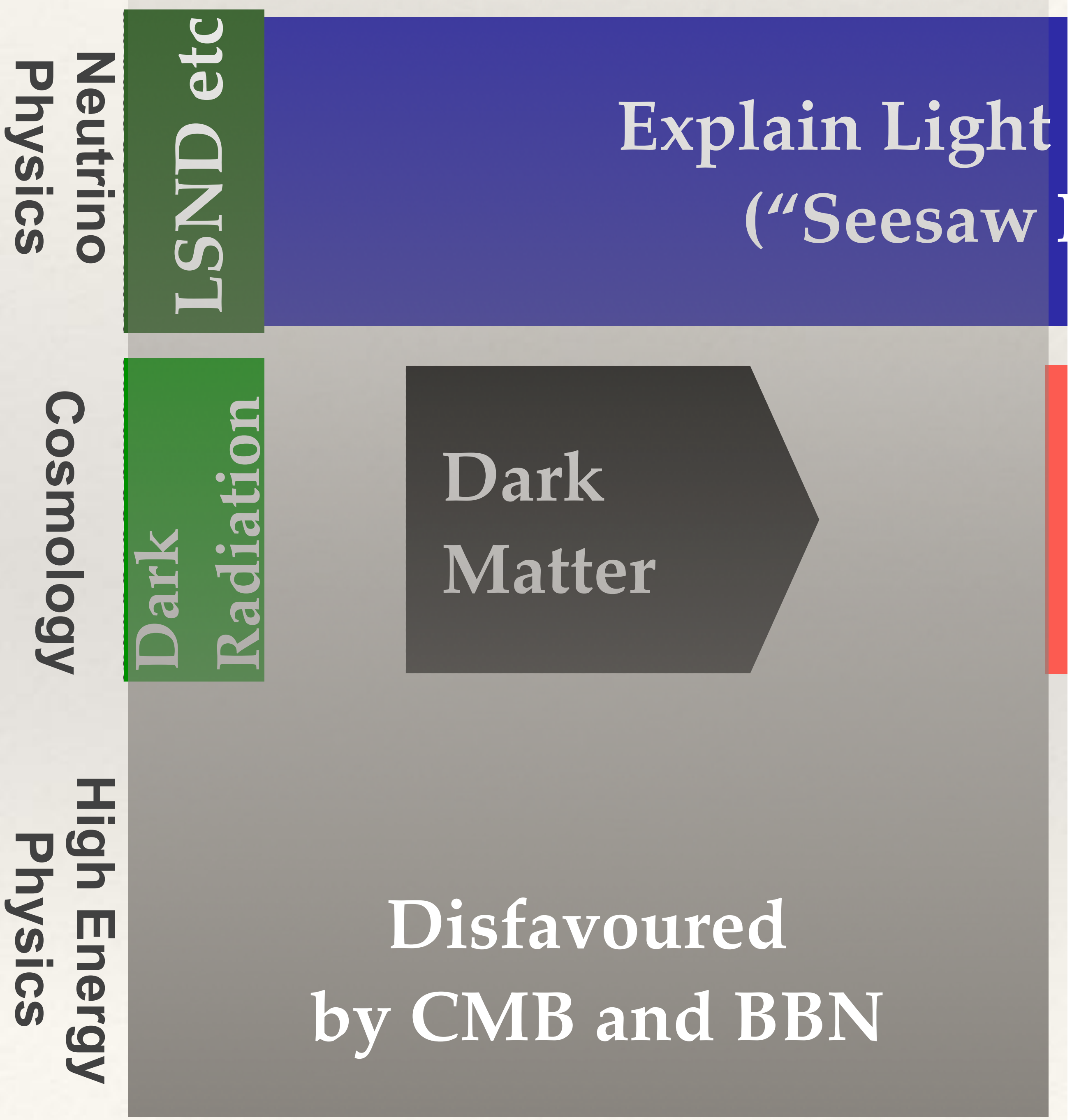


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} > 10^{-3}$ eV, three RHN reach equilibrium

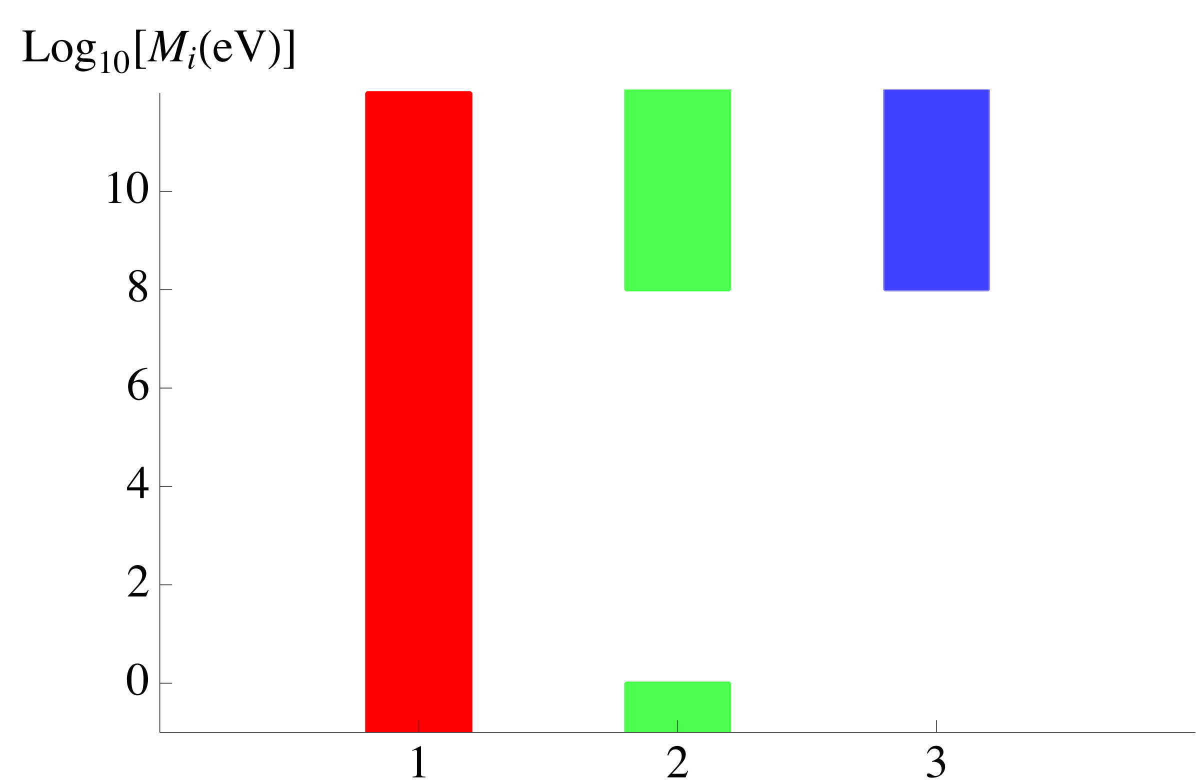


Hernandez/Kekic/Lopez-Pavon 1406.2961

Right Handed Neutrinos and the Light Neutrino Masses

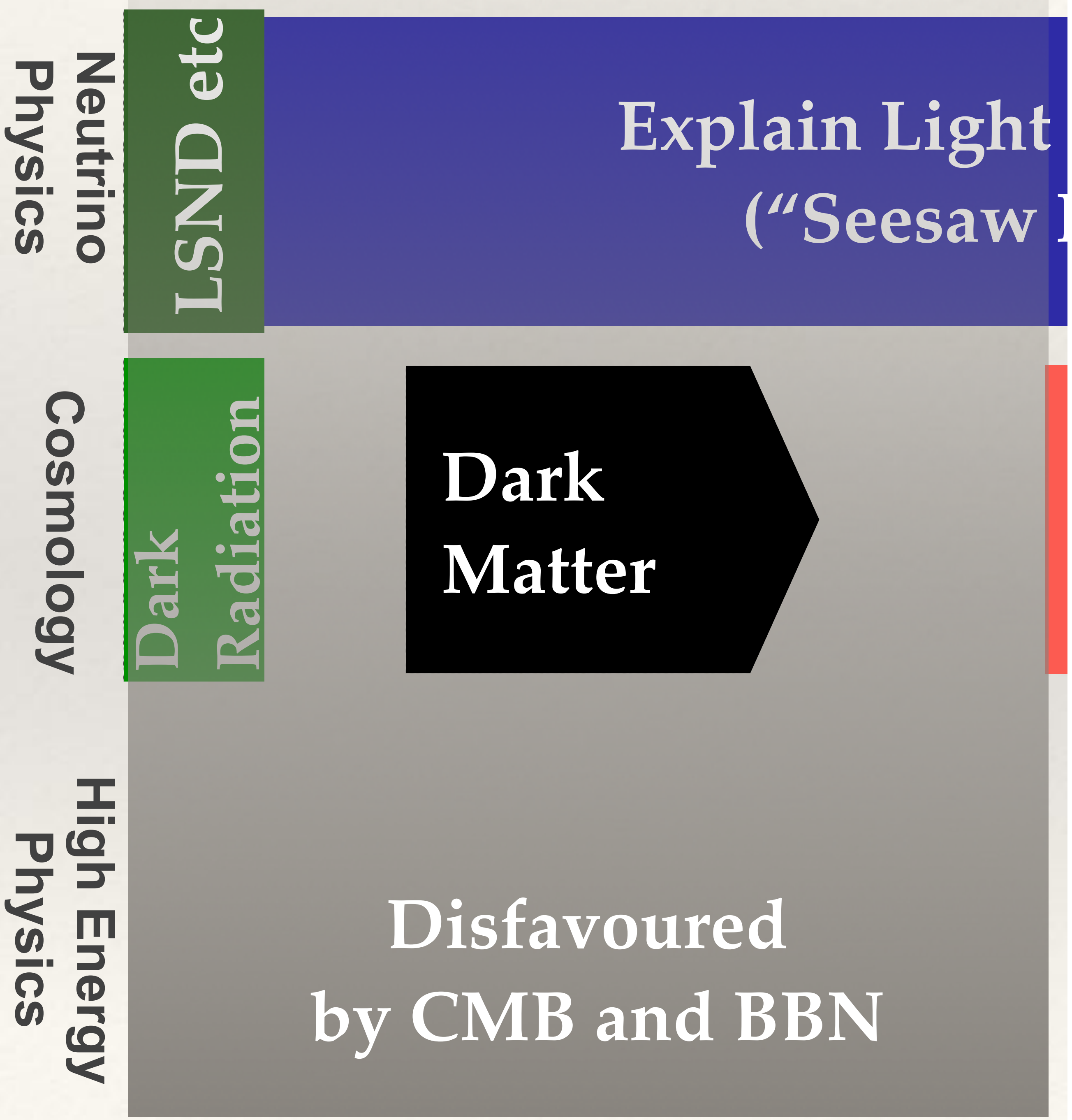


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} < 10^{-3}$ eV, one RHN almost decouples

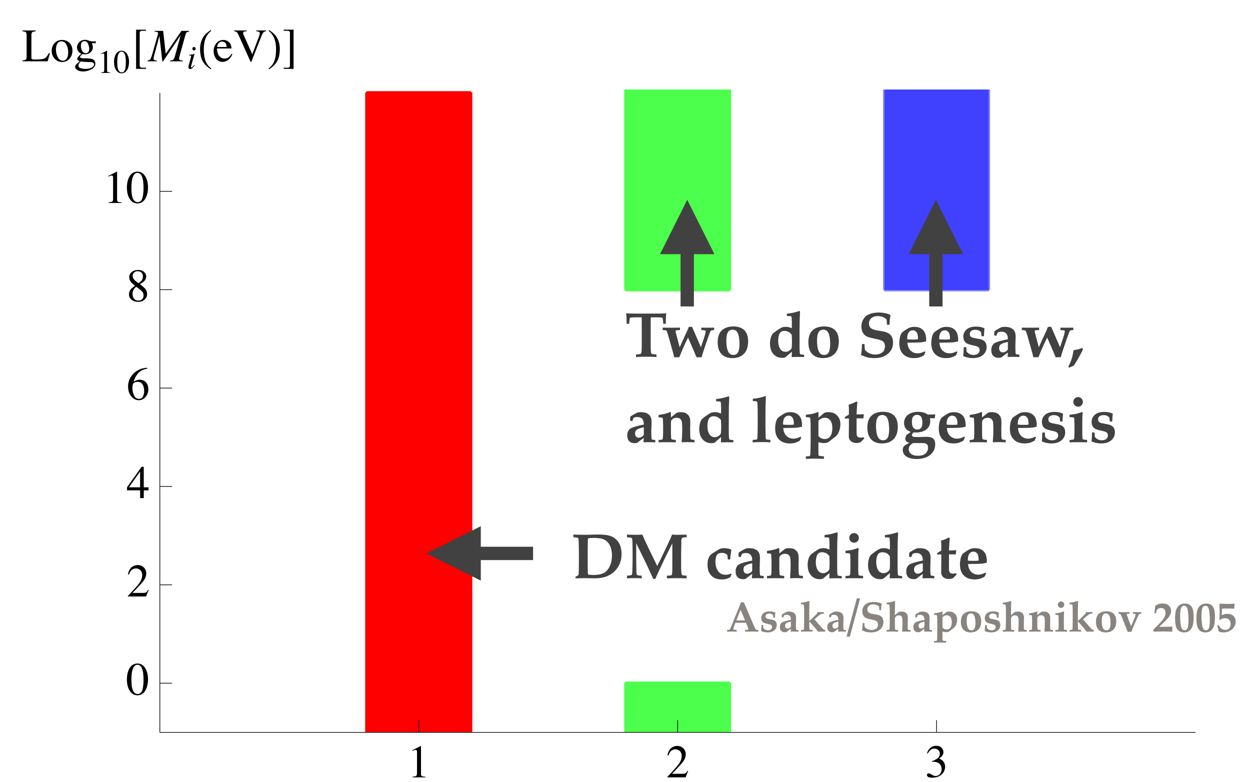


Hernandez/Kekic/Lopez-Pavon 1406.2961

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



Hernandez/Kekic/Lopez-Pavon 1406.2961