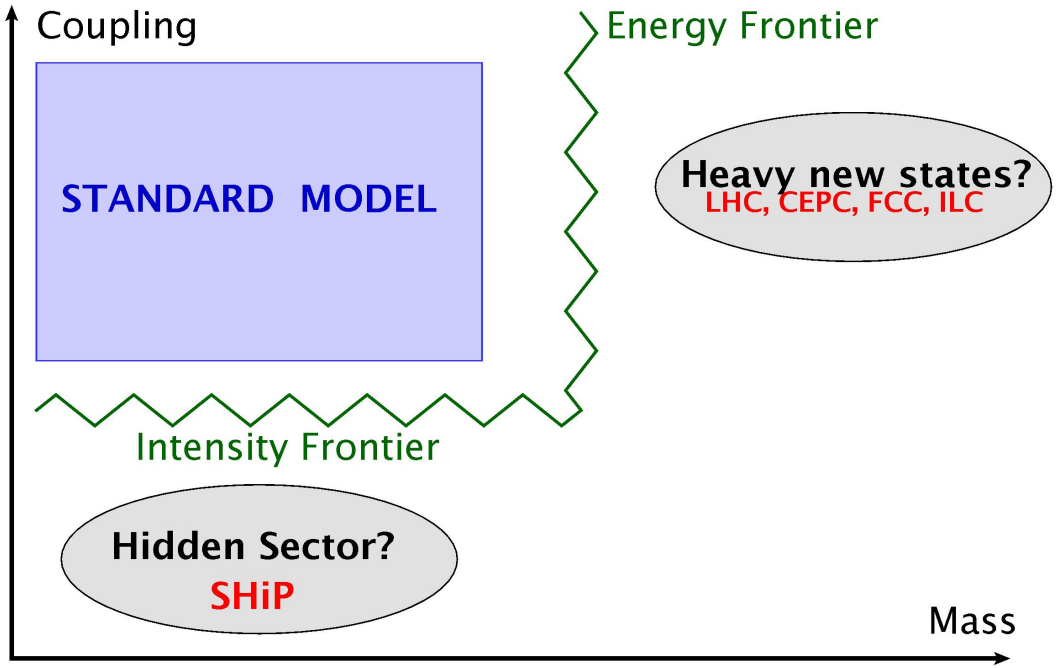
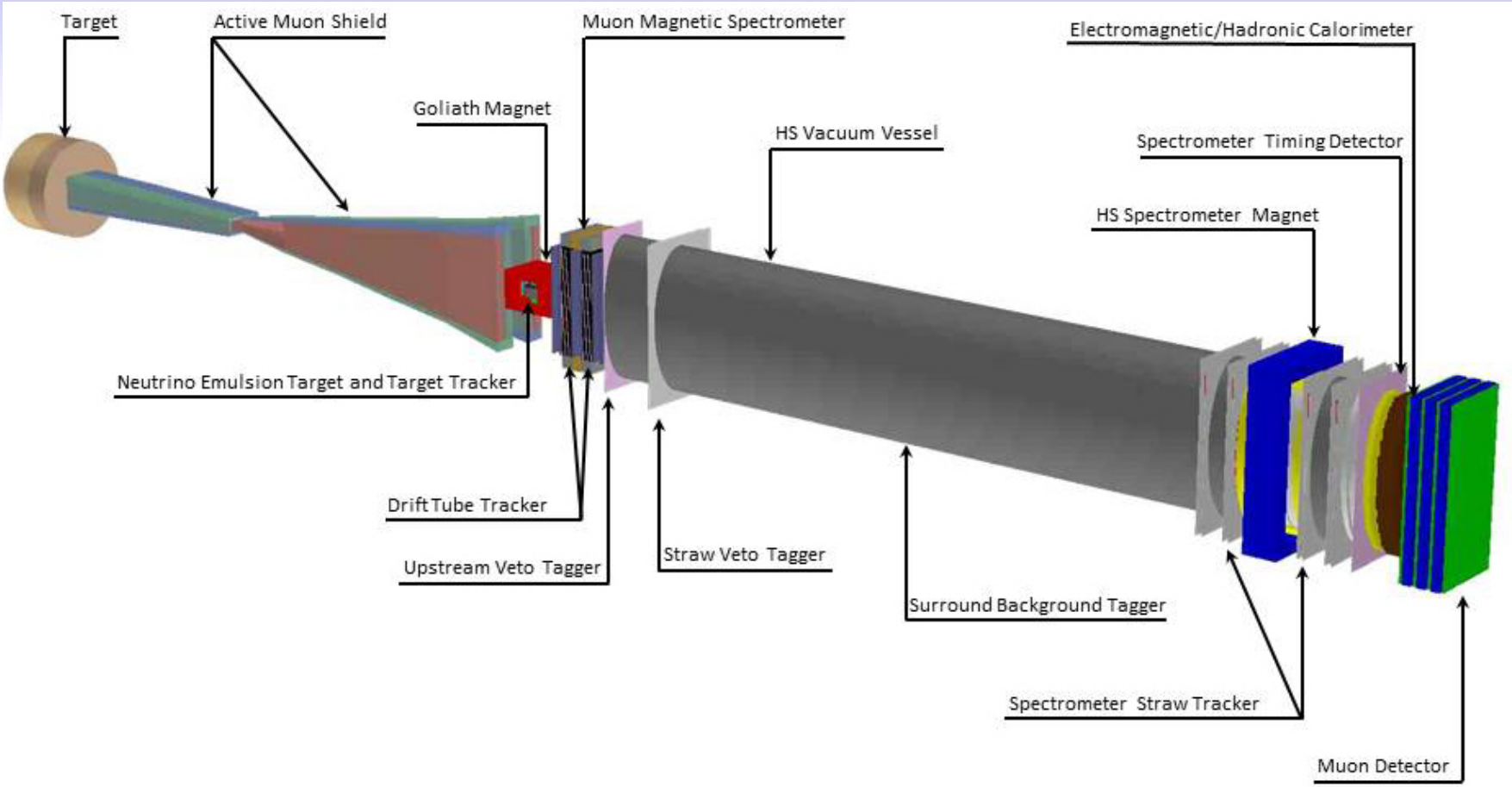
# **S**earch for **Hi**dden **P**articles

- neutrino portal
- scalar / Higgs portal
- vector portal
- axion-like particles
- $\nu_\tau$ physics
- LFV in $\tau$-decays
- very light neutralino?
- your proposal!




see arXiv:1504.04855 [hep-ph] for details
**great opportunity at the intensity frontier**




- intensity frontier experiment using CERN SPS beam
- fixed target experiment with strong shield
- technical report arXiv:1504.04956 [physics.ins-det]

# Heavy Neutral Leptons (RH neutrinos)

$m_\nu$ open questions:

- absolute mass scale
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- flavour puzzle
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**Cosmology connection**

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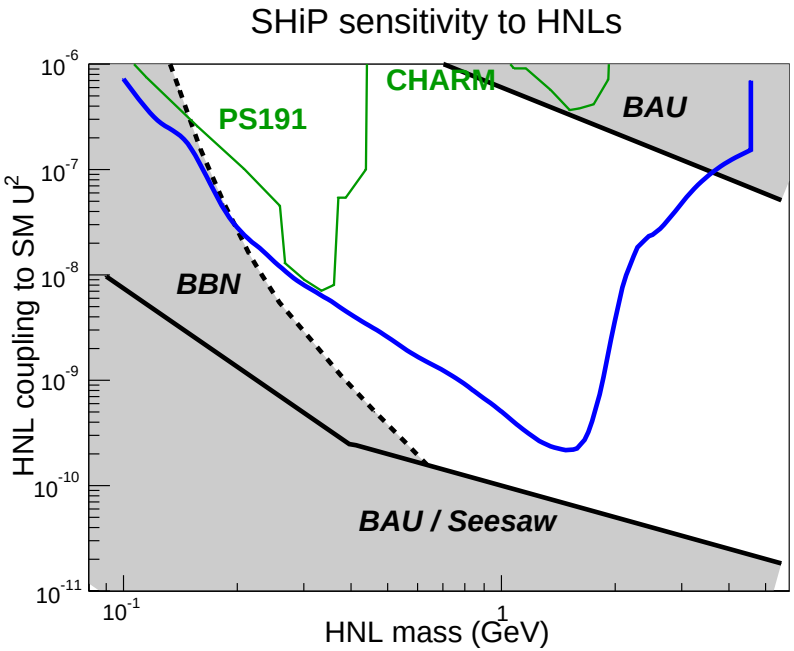
**Cosmology connection**
Low scale seesaw, $\nu$MSM

- TeV: LHC, FCC, CEPC
- GeV: SHiP

Plot: Elena Graverini



The **Standard Model** and **General Relativity** together explain *almost* all phenomena observed in nature, but. . .

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- a handful of observations remain unexplained
  - neutrino oscillations
  - baryon asymmetry of the universe
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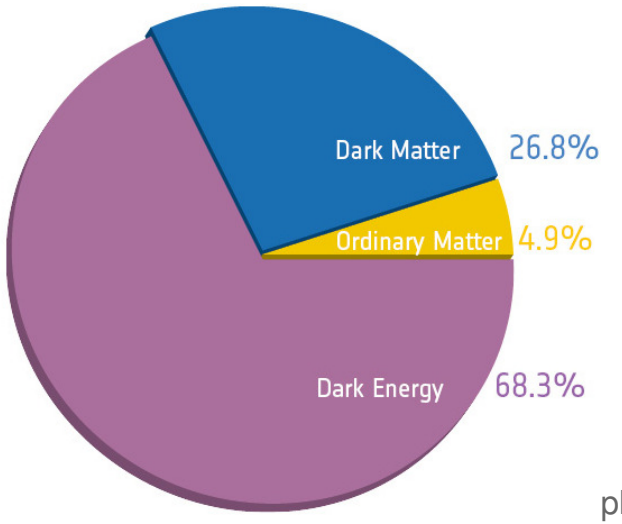


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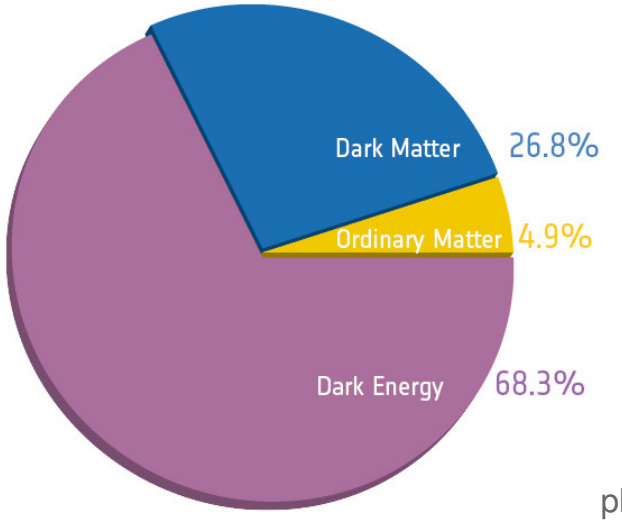


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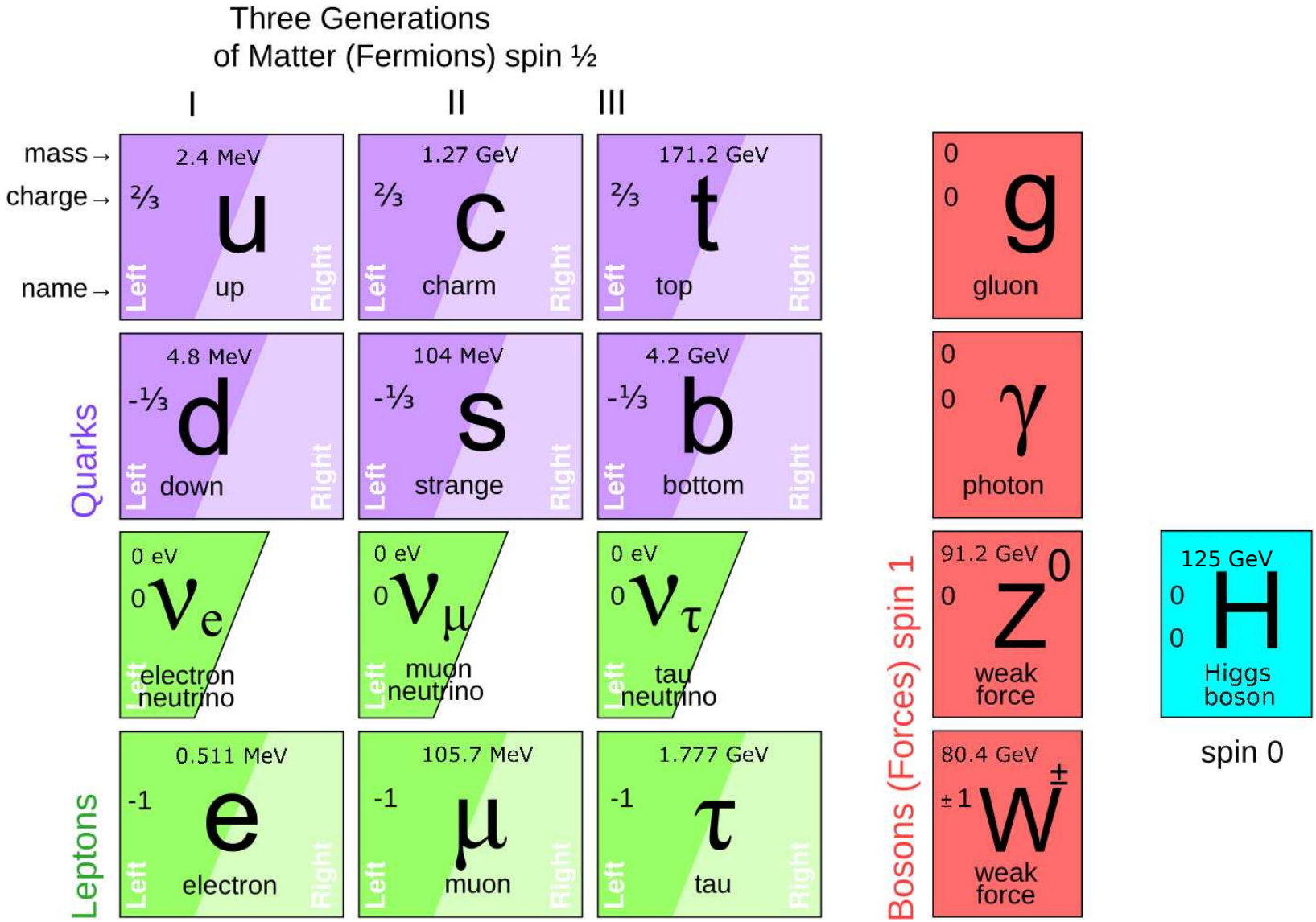
Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
Left
Right
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
Quarks
0 eV
0
νe
electron neutrino
0 eV
0
νμ
muon neutrino
0 eV
0
ντ
tau neutrino
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
Leptons
0
0
g
gluon
0
0
γ
photon
91.2 GeV
0
Z0
weak force
80.4 GeV
±1
W±
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Bosons (Forces) spin 1
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0
0
H
Higgs boson
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# Neutrino masses: Seesaw mechanism

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

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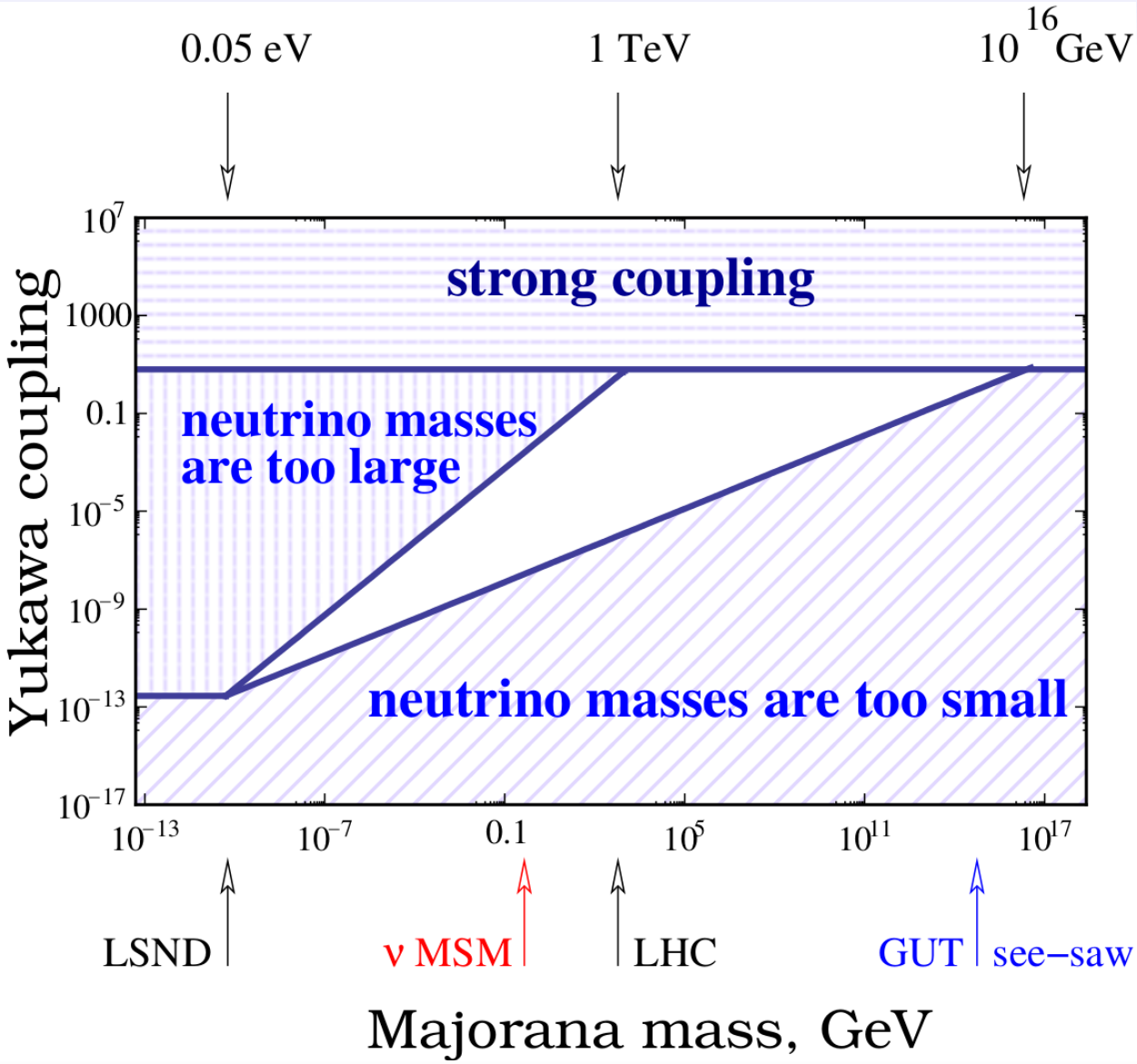
- three light neutrinos $\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
  - mostly "active" SU(2) doublet
  - light masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$
- three heavy neutrinos $N \simeq \nu_R + \theta^T \nu_L^c$
  - mostly "sterile" singlets
  - heavy masses $\boldsymbol{M_N \simeq M_M}$
- Majorana masses $M_M$ introduce new mass scale(s)
- new heavy states only interact via small mixing $\theta \ll 1$

# $\nu$-oscillation data and the seesaw scale



# The low scale seesaw

## Pros:

- some theoretical arguments (no new scale Asaka/Shaposhnikov, classical scale invariance Khoze/Ro,. . .)
- allows for leptogenesis
  - during $\nu_R$ decay Pilaftsis 9707235
  - during $\nu_R$ production Akhmedov/Rubakov/Smirnov 9803255, Asaka/Shaposhnikov 0505013 without mass degeneracy MaD/Garbrecht 1206.5537, Canetti/MaD/Garbrecht 1404.7114
- new states can be found at colliders Gorbunov/Shaposhnikov, Kersten/Smirnov, Atre/Han/Pascoli/Zhang, Dev/Pilaftsis/Yang, Izaguirre/Shuve, Castillo-Felisola/Dib/Helo/Kovalenko/Ortiz, Ng/de la Puente/Pan, others. . .

## Cons:

- very small Yukawa couplings $F$ or cancellations in $m_\nu$
- accessible regime constrained from low energy observations, in particular $\nu \to e\gamma$, $0\nu\beta\beta$-decay, PMNS-unitarity

Ibarra/Molinaro/Petcov 1103.6217, Abada/Das/Teixeira/Vicente/Weiland 1311.2830, Basso/Fischer/van der Bij 1310.2057, Endo/Yoshinaga 1404.4498, Asaka/Eijima/Takeda 1506.00417, MaD/Garbrecht 1502.00477

# Where to see the $N_I$

- **Indirect searches**
- **Direct searches**
- **Cosmology**: BBN and $N_{\text{eff}}$

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  - neutrino oscillation data
  - LFV in rare lepton decays
  - violation of lepton universality,
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  - neutrinoless double $\beta$-decay
  - EW precision data
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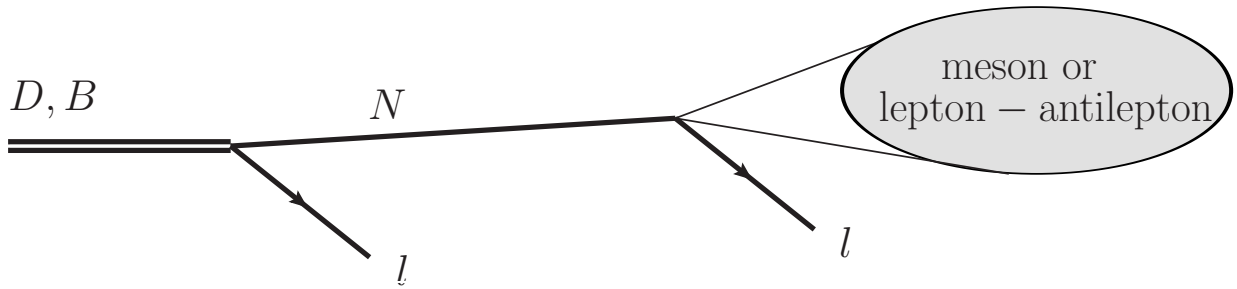
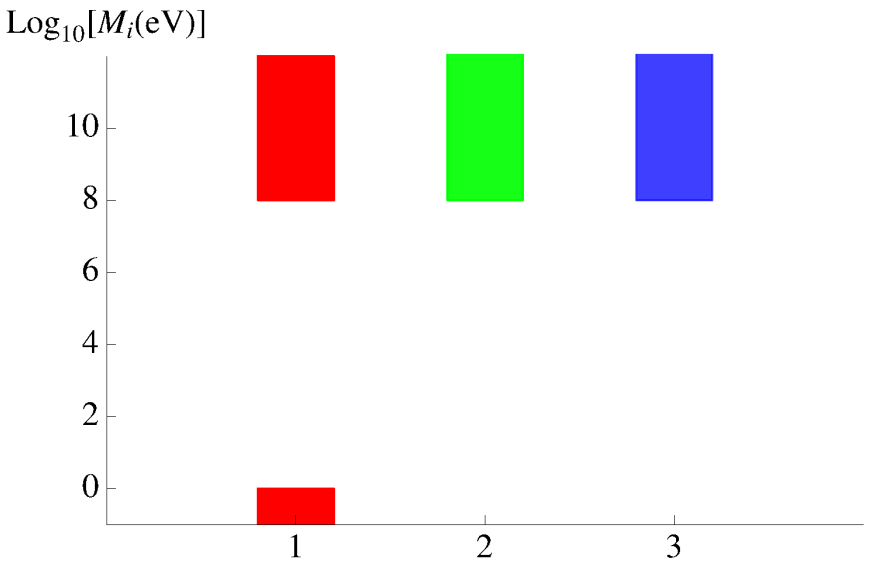
- **Direct searches**
  - LNV and LFV in gauge boson or meson decays

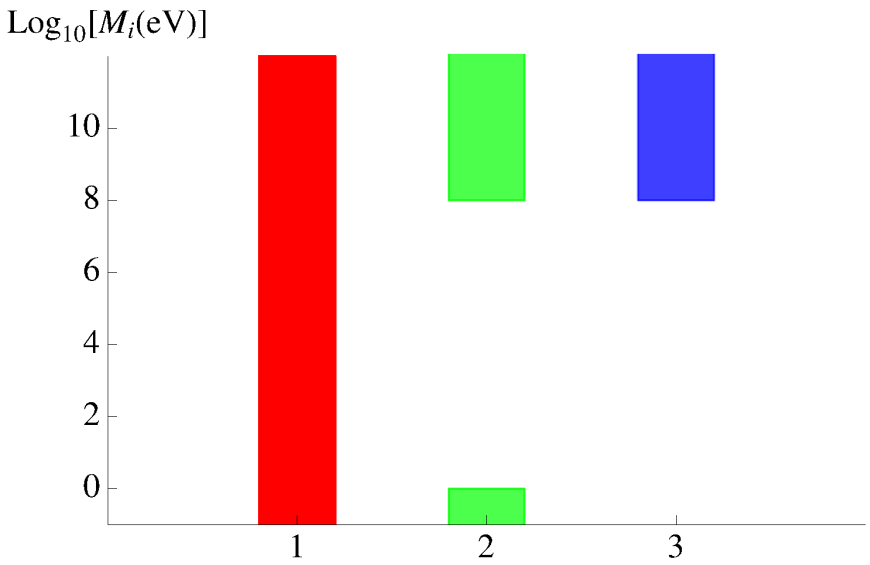



  - displaced vertices
  - peak searches, missing 4-momentum
- **Cosmology**: BBN and $N_{\text{eff}}$

# Bounds from cosmology: $N_{\rm eff}$ and BBN



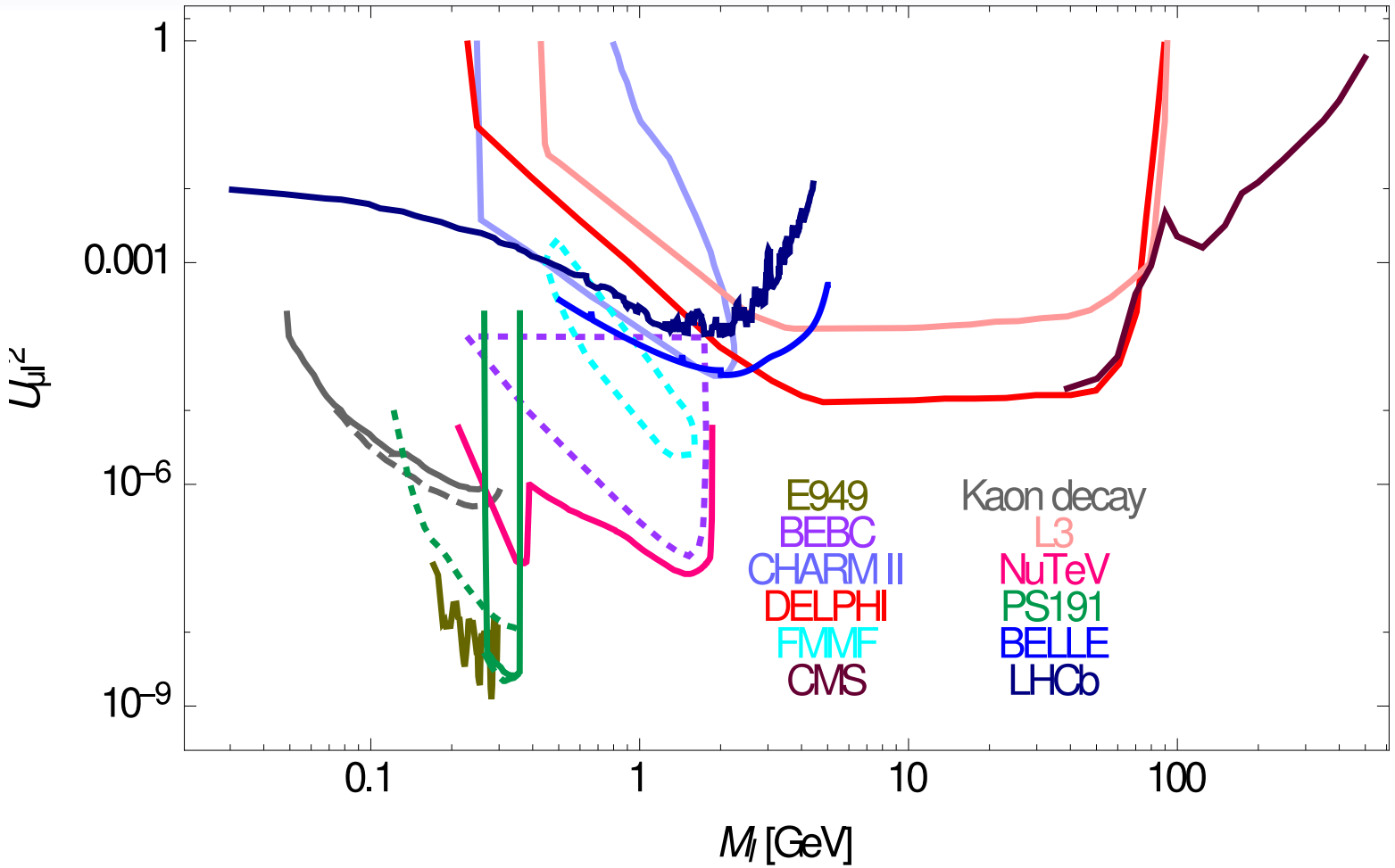

$m_{\rm lightest} > 10^{-3} eV$




$m_{\rm lightest} < 10^{-3} eV$

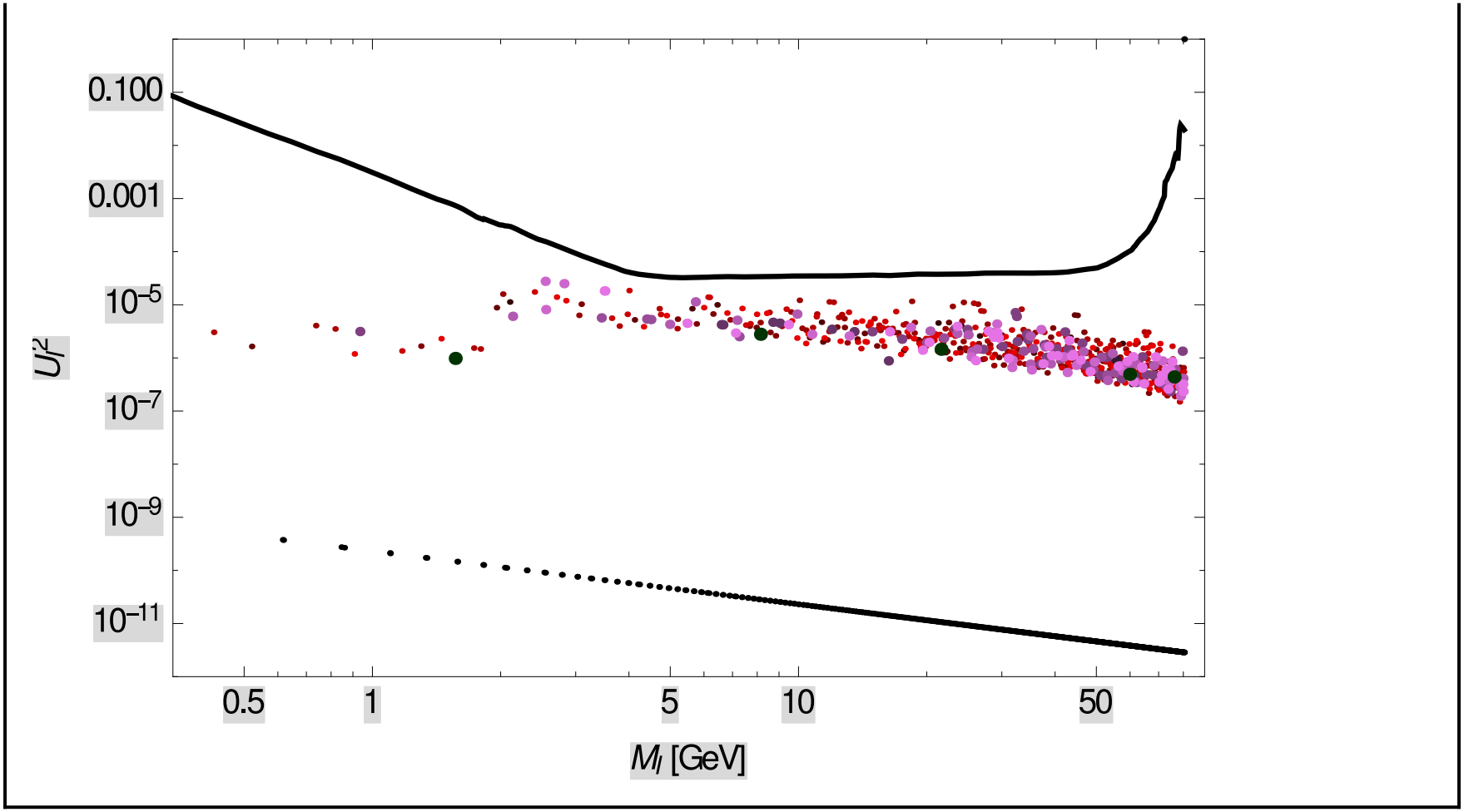
from Hernandez/Kevic/Lopez-Pavon 1406.2961

# Bounds from Colliders



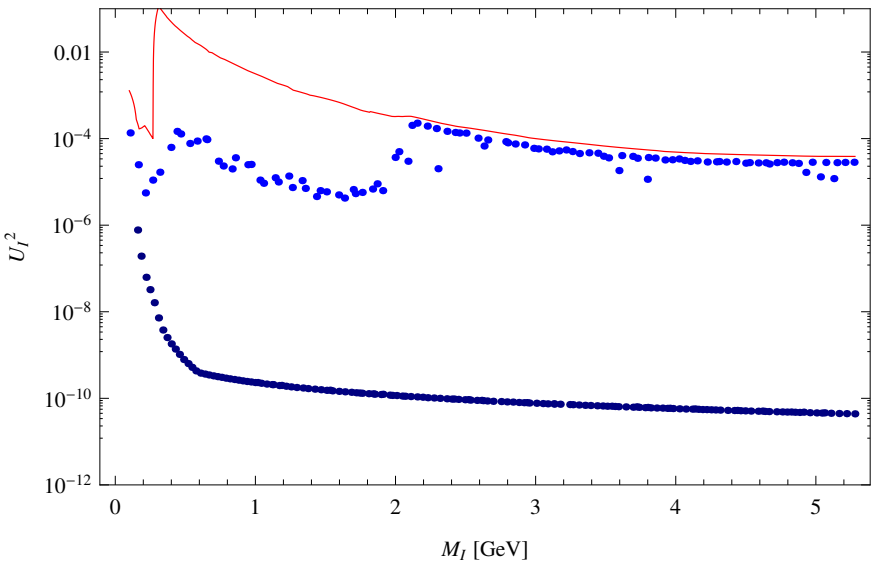

plot from MaD/Garbrecht 1502.00477

# Combining direct and indirect bounds: EW scale

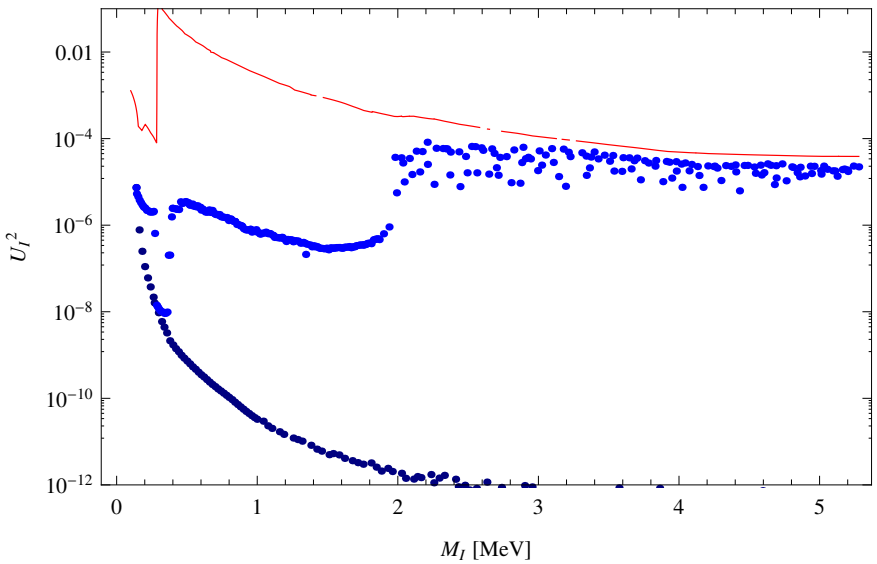



to be updated in arXiv:1502.00477 [hep-ph]

# Present direct and indirect constraints: GeV scale




$m_{\text{lightest}} = 0.23\text{eV}$

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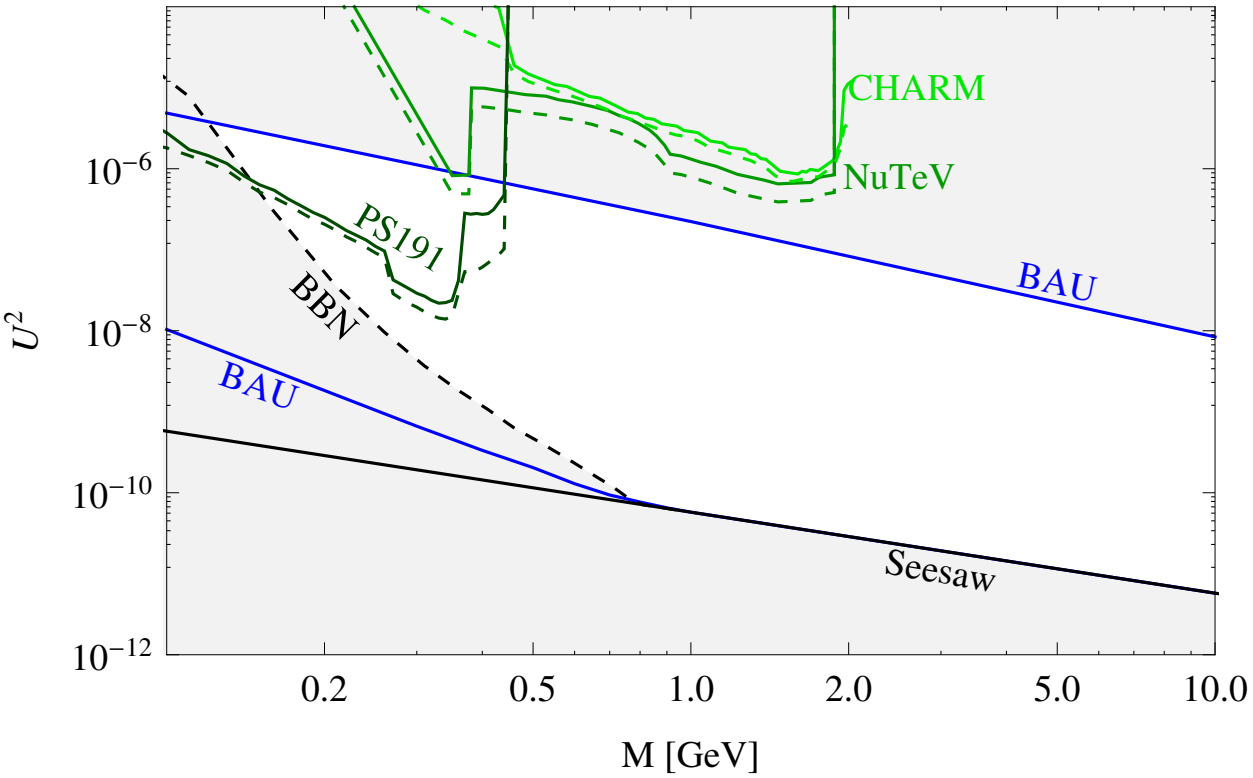
# Leptogenesis with 2 GeV scale RH neutrinos

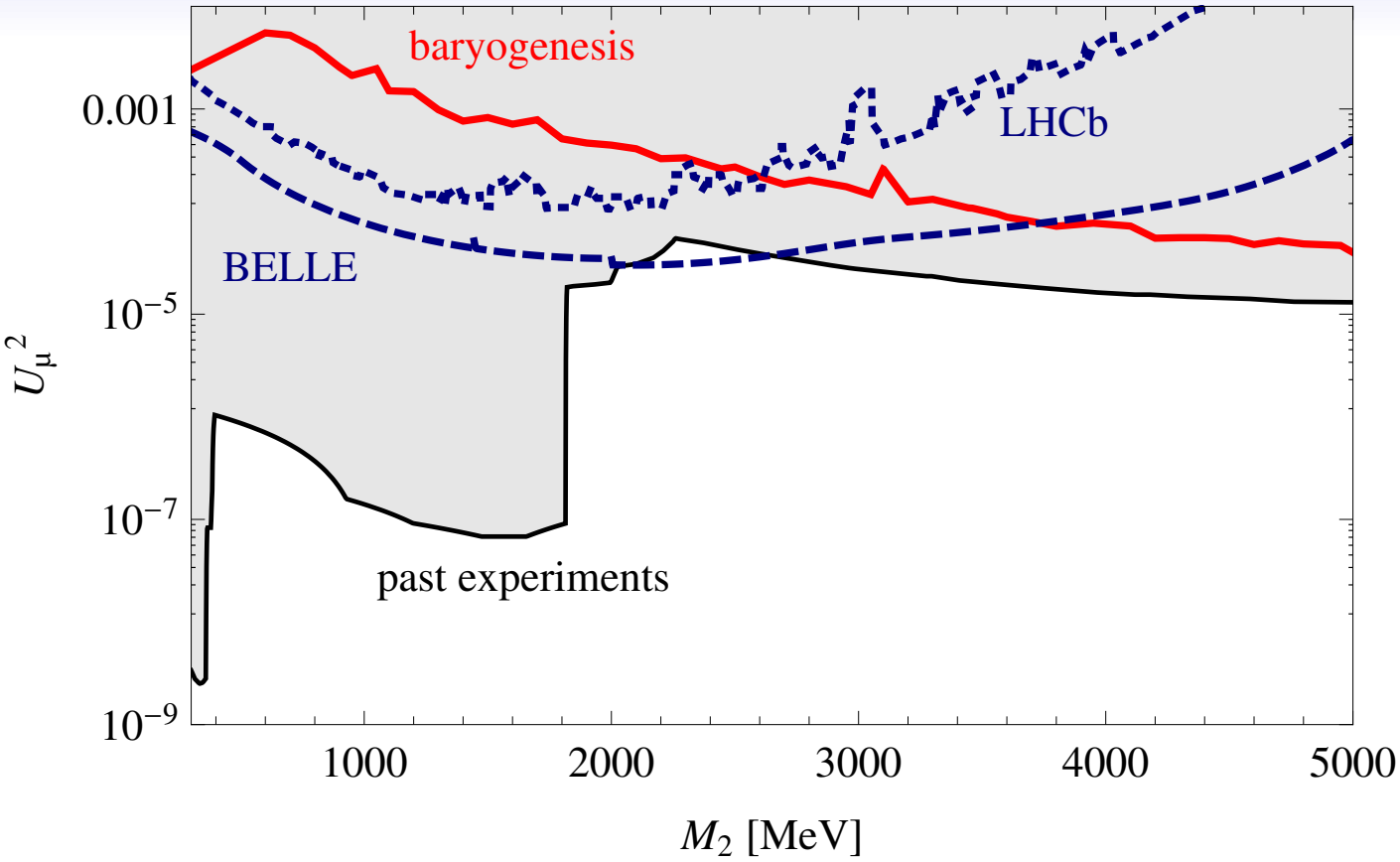



Canetto/MaD/Frossard/Shaposhnikov 1208.4607

Requires mass degeneracy and small mixing. . .

. . .but CP-violation may also be measurable Cvetic/Kim/Zamora-Saa 1403.2555

# Leptogenesis with 3 GeV scale RH neutrinos

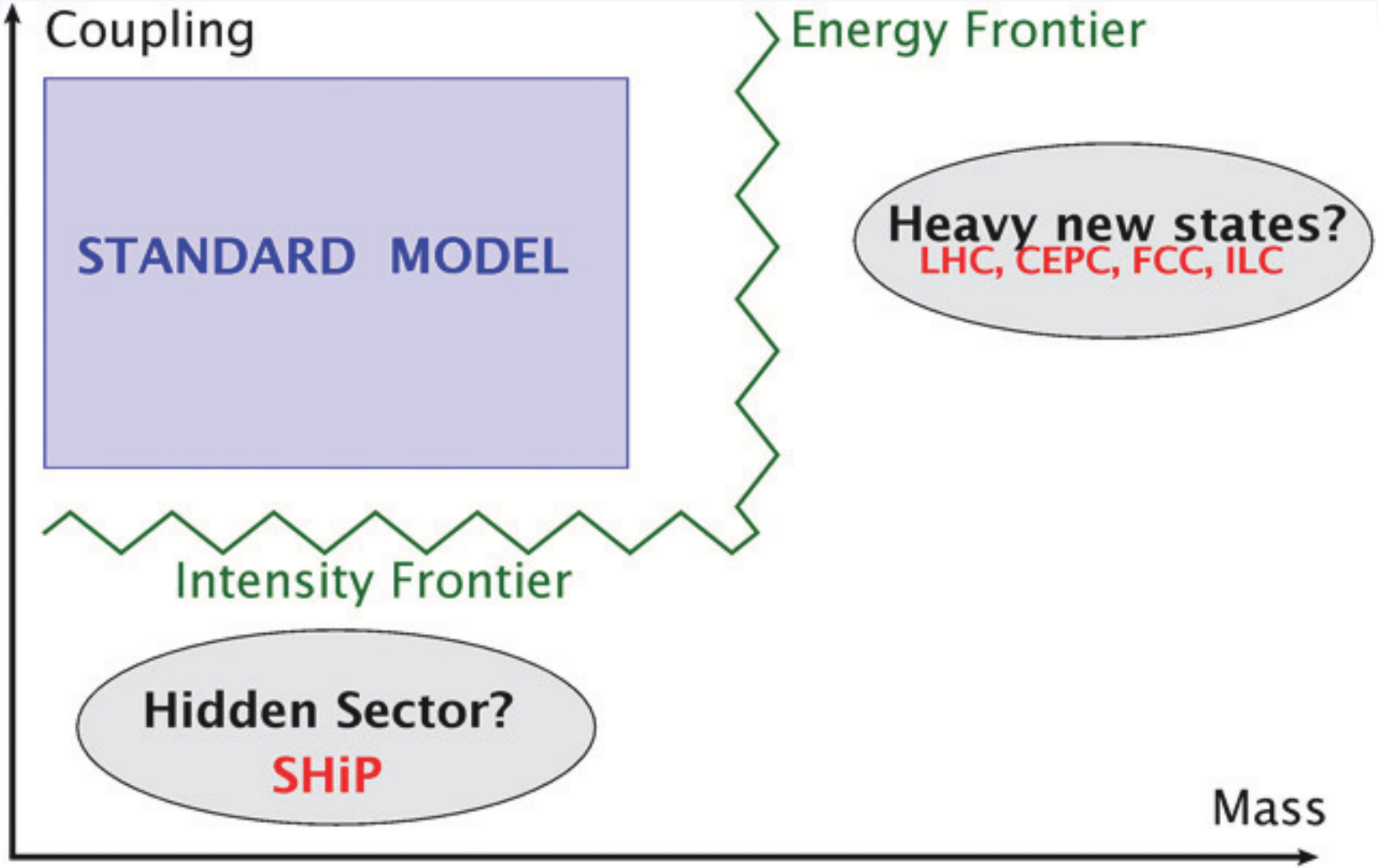



$M_1 = 1$ GeV, $M_3 = 3$ GeV plot updated from Canetti/MaD/Garbrecht 1404.7114

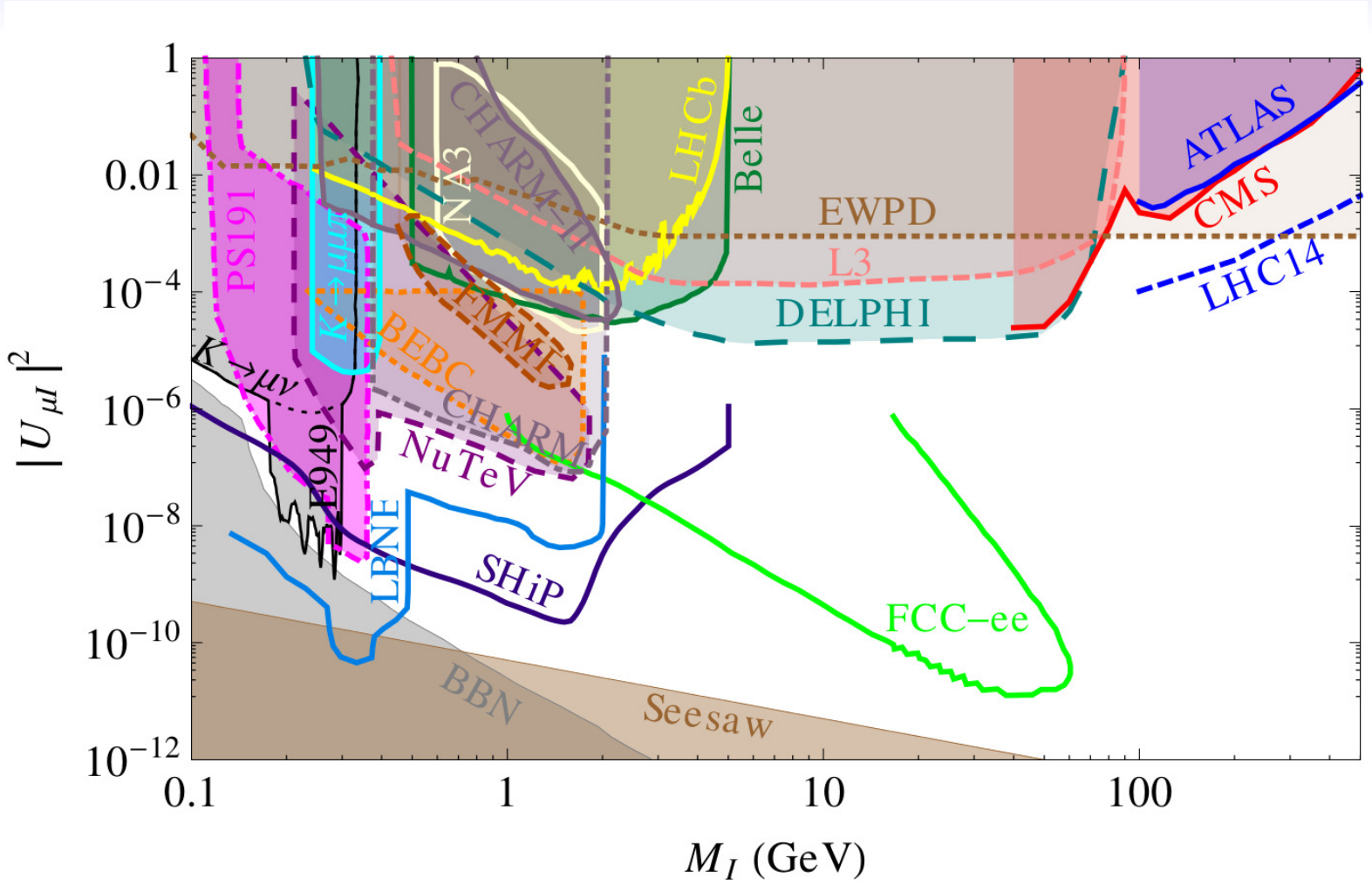
CP-violation may also be measurable Cvetic/Kim/Zamora-Saa 1403.2555

$\Rightarrow$ **LHCb, BELLE, SHIP may unveil the origin of matter!**

# Where is the New Physics hiding?

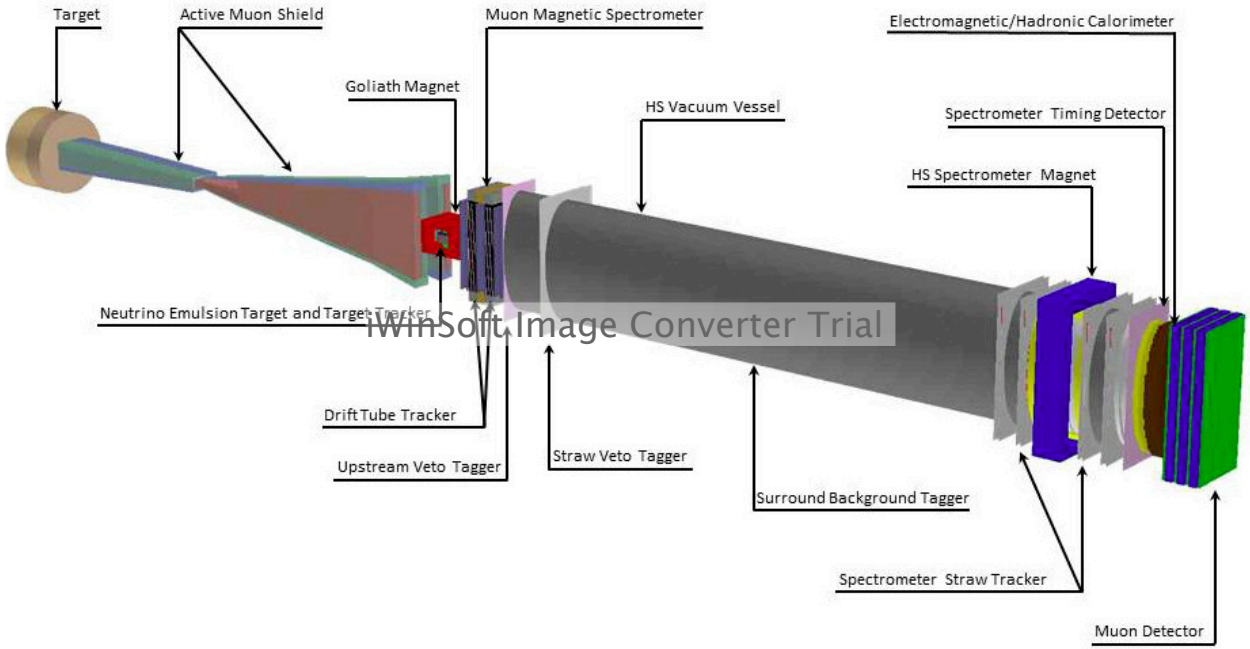


# Future searches




Plot from arXiv:1504.04855 [hep-ph]

# The SHiP Experiment





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# Summary

- $\nu$-oscillations are the only BSM signal seen in the lab
  **definitely** require new BSM degrees of freedom!
- the new particles are RH neutrinos, they may be related to
  cosmological puzzles (Dark Matter, baryogenesis, Dark Radiation)
- if new particles are below the electroweak scale, they can be found
  experimentally $\Rightarrow$ experimental search for exciting New Physics!
- even if they are heavier, indirect probes involve
  - neutrino oscillation experiments
  - neutrinoless double $\beta$-decay
  - lepton flavour violation
  - lepton universality violation
  - unitarity of the observed CKM matrix

**We are looking forward to exciting new data**. . .