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Flavour Effects in Low Scale Leptogenesis

04.07.2018

FLASY 2018

Basel, Switzerland

Recent review:
Leptogenesis: Current Challenges for Model Building, Phenomenology and Non-Equilibrium Field Theory
https://www.worldscientific.com/toc/ijmpa/33/05n06

Low Scale Leptogenesis

Flavour Effects

What can ν oscillation data “predict”?

What can Leptogenesis “predict”?

Experimental Searches

Flavour Mixing Pattern + Dirac Phase
= Fully Testable Leptogenesis!

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Baryon Asymmetry of the Universe

The observable universe contains almost no antimatter and a lot more photons than baryons. e.g. Canetti/MaD/Shaposhnikov arXiv:1204.4186

CMB constraint on baryon-to-photon ratio η:

$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$

(Planck Collaboration)

BBN constraint on baryon-to-photon ratio η:

$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

(PDG)

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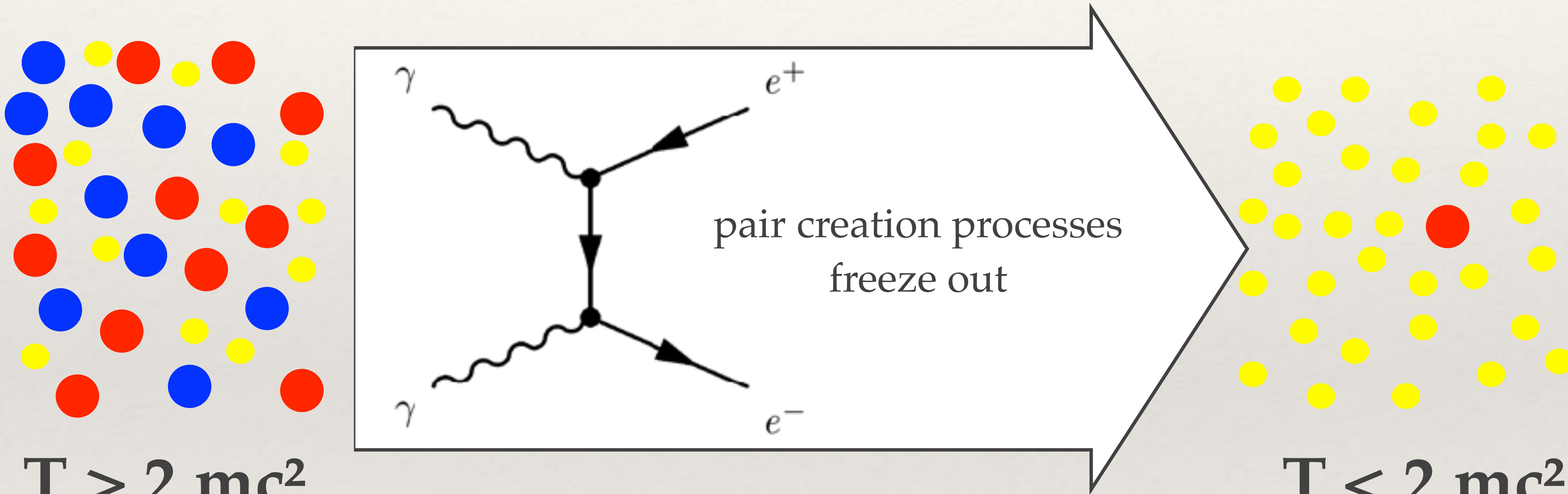

$T > 2\ mc^2$ **$T < 2\ mc^2$**

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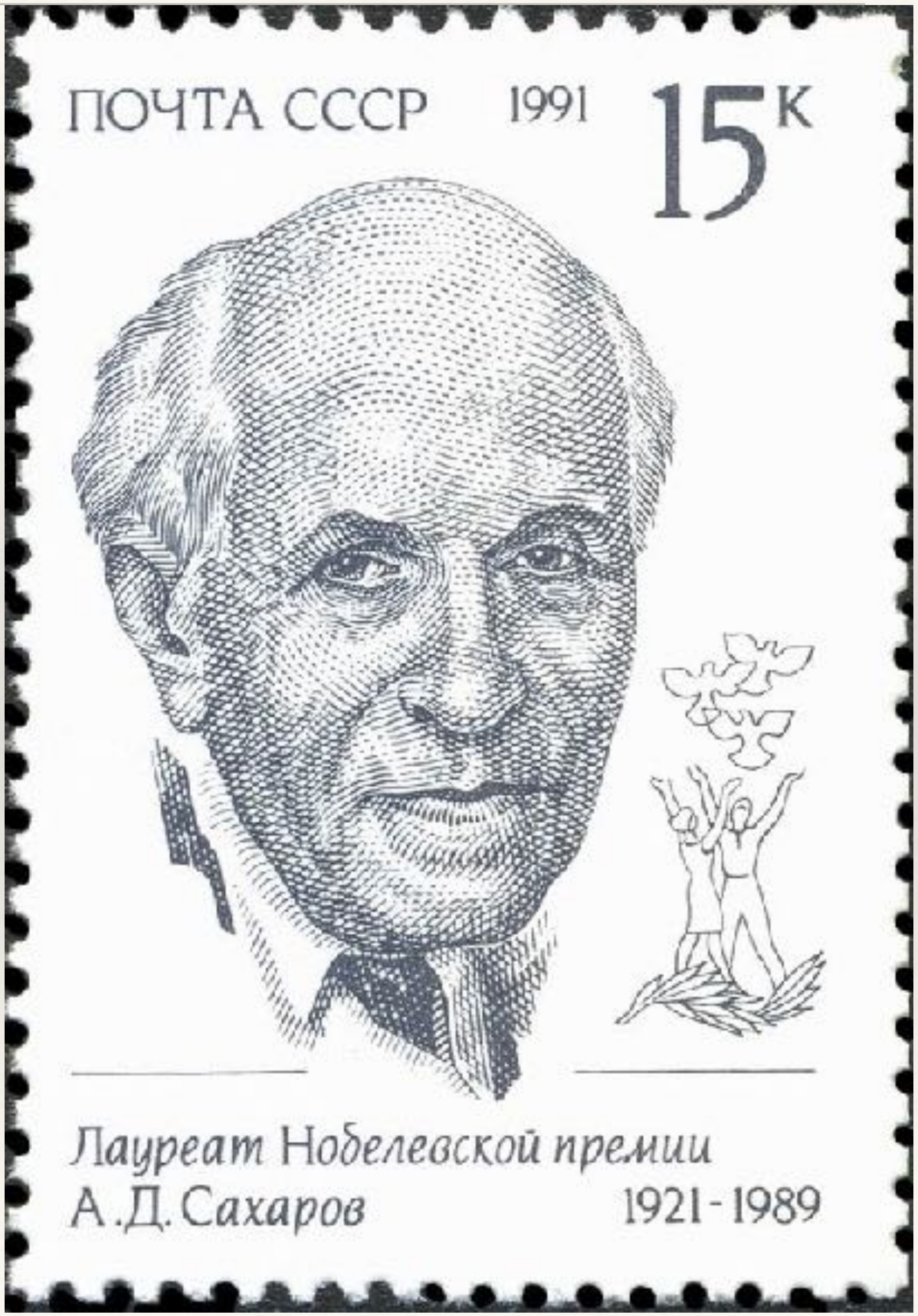
Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium



Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium

Exists in Standard Model
at T > 130 GeV
(sphaleron)

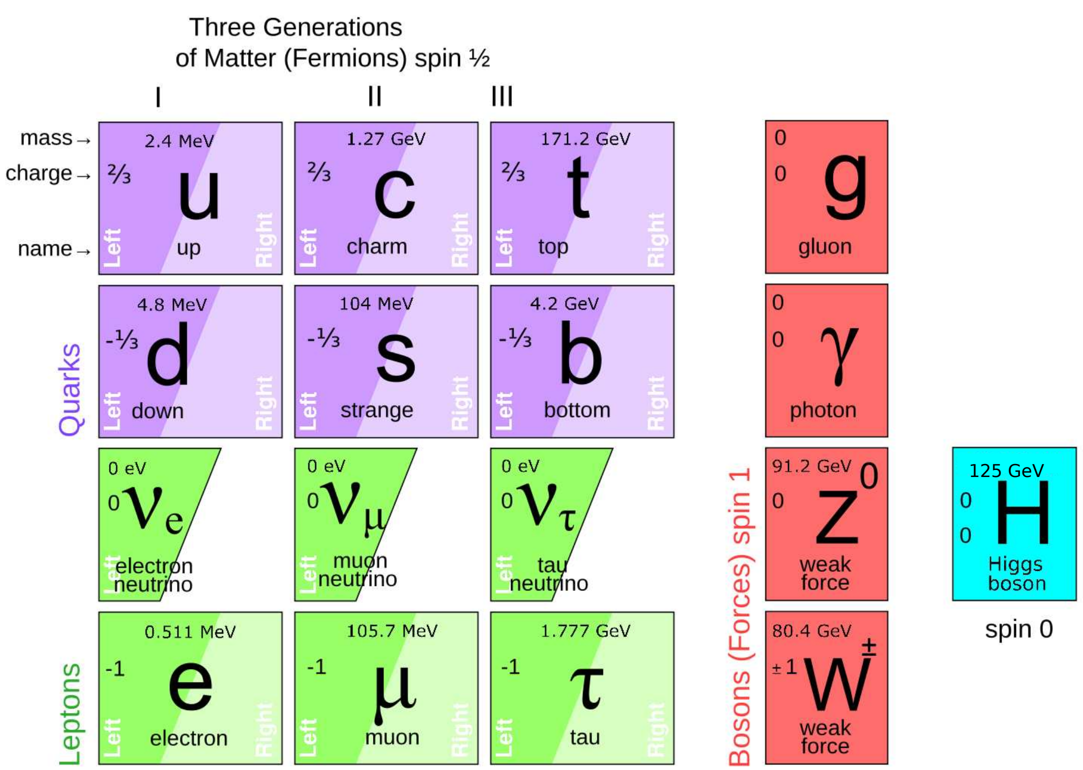
Exists in Standard Model
(weak interaction, CKM phase)

…but Jarlskogg invariant too small!

Exists in Standard Model
(Hubble expansion of the universe)
…but deviation too small!

Type I Seesaw: Right Handed Neutrinos

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



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

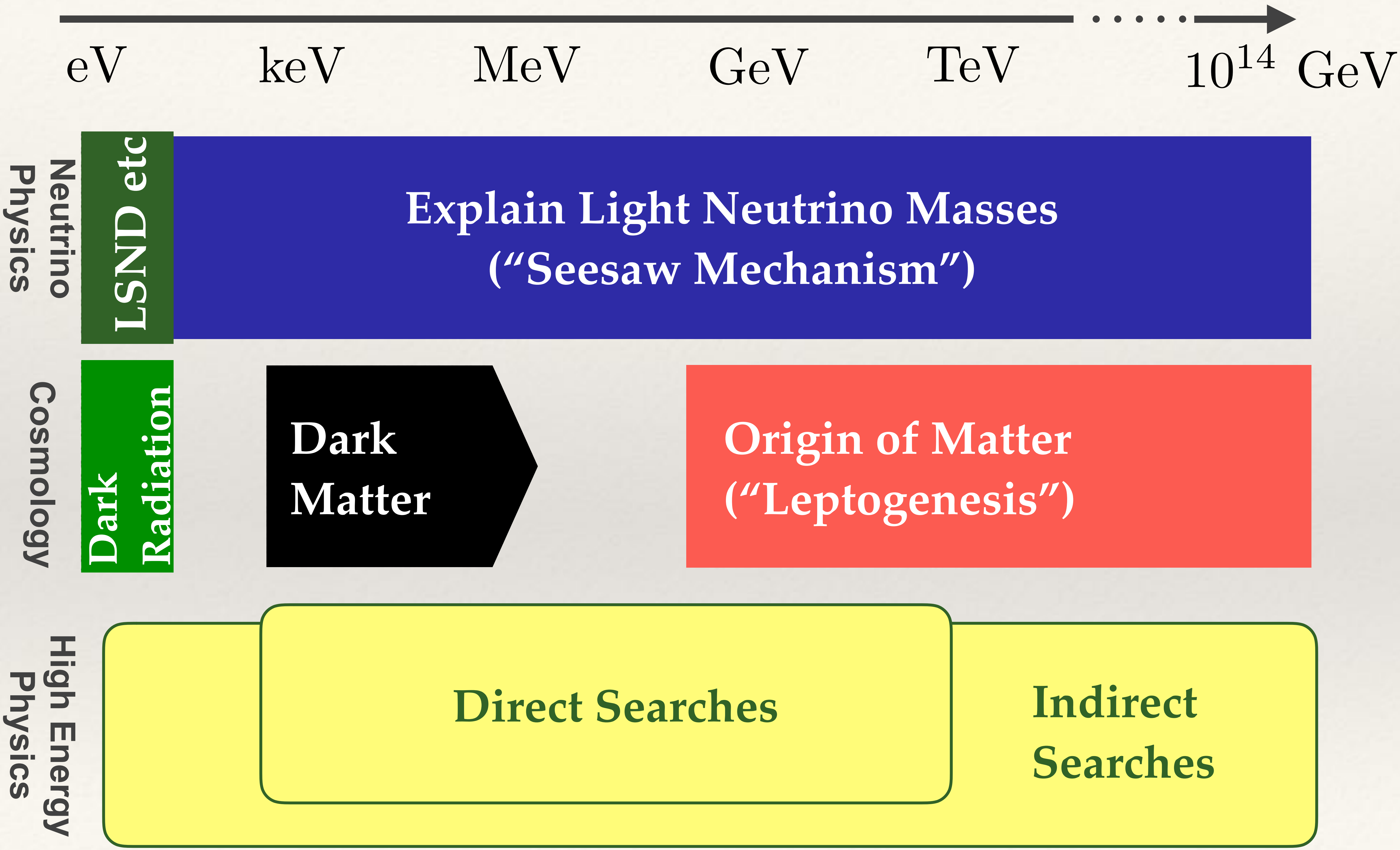
In the following:
Minimal model with two right handed neutrinos.

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 $\boldsymbol{M_N \simeq M_M}$

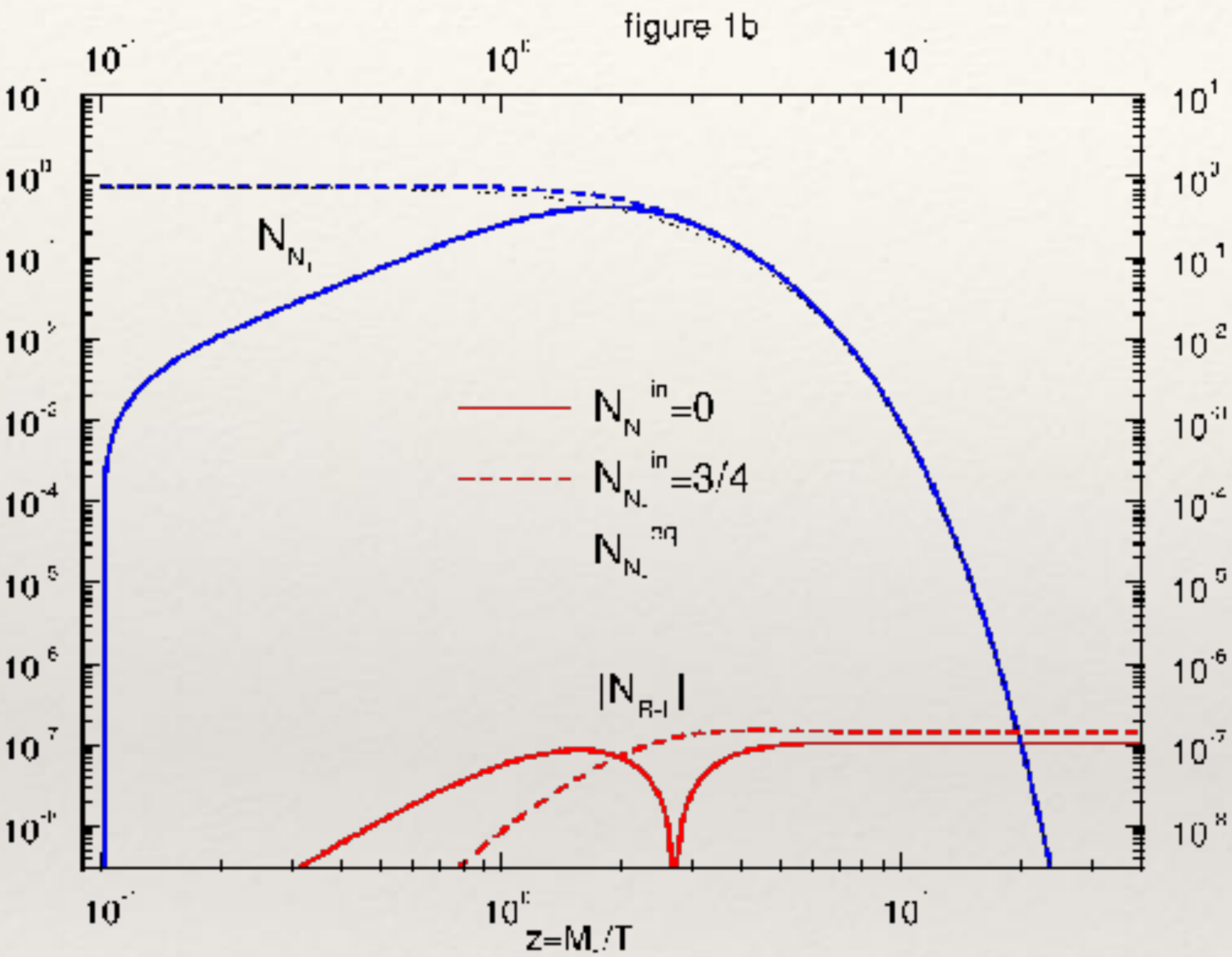
Minkowski 79, Gell-Mann/Ramond/Slansky 79, Mohapatra/Senjanovic 79, Yanagida 80, Schechter/Valle 80

Right Handed Neutrino Mass Scale



see e.g. MaD 1303.6912

Leptogenesis with small M?



Buchmuller / Di Bari / Plumacher 0205349

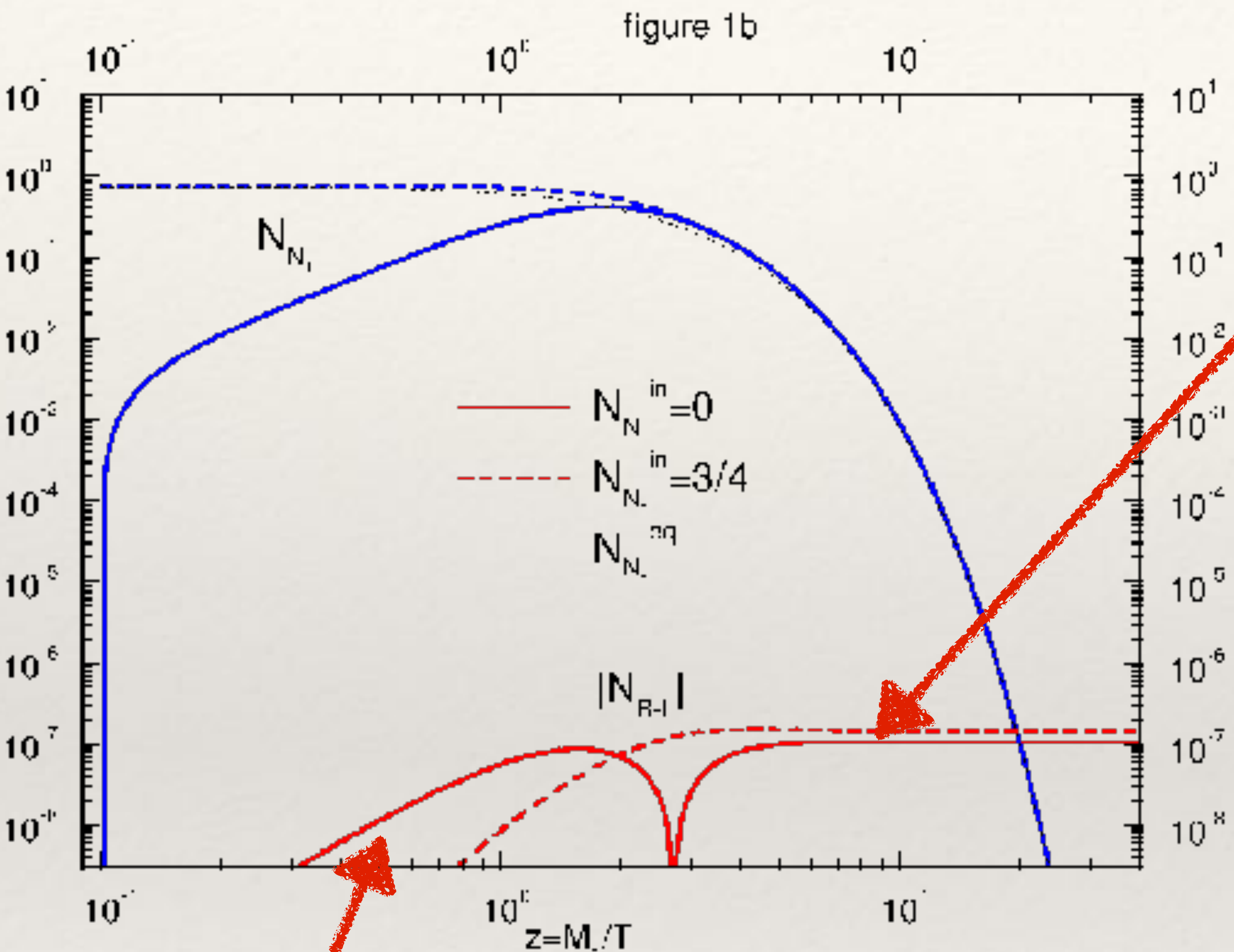
What about the famous Davidson-Ibarra bound $M > 10^{9}$ GeV? 0202239

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{eq}) \qquad x = M/T$$

$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"

Leptogenesis with small M?



asymmetry generated during N decay ("freeze-out scenario")

Sakharov's nonequilibrium condition can be fulfilled in two ways.

asymmetry generated during N production ("freeze-in scenario")

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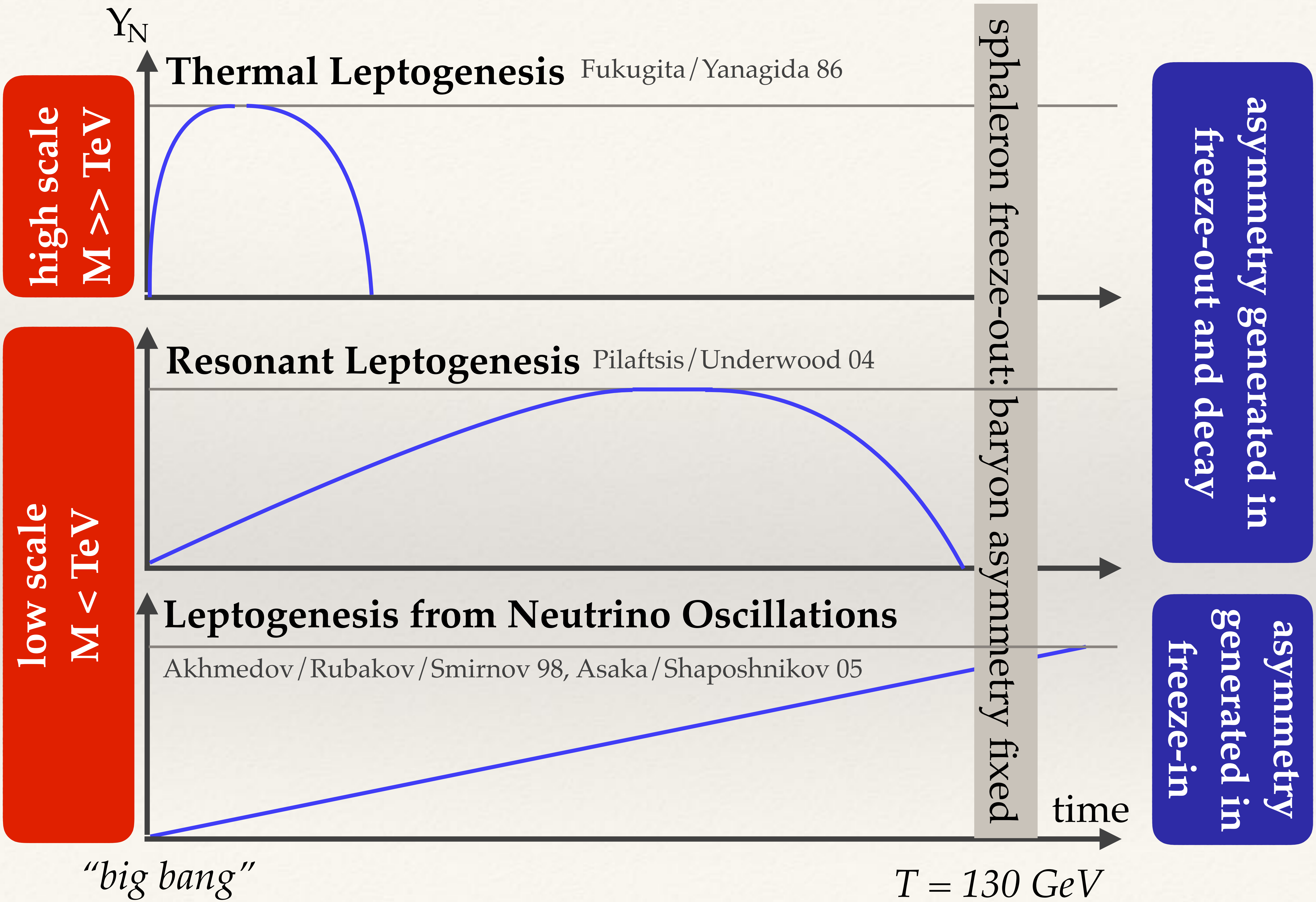

Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
high scale
M >> TeV
Resonant Leptogenesis
Pilaftsis/Underwood 04
low scale
M < TeV
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98, Asaka/Shaposhnikov 05
sphaleron freeze-out: baryon asymmetry fixed
asymmetry generated in freeze-out and decay
asymmetry generated in freeze-in
time
"big bang"
T = 130 GeV

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What can ν oscillation data “predict”?

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"Vanilla Leptogenesis"

Temperature $T > 10^{12}$ GeV

- **gauge interactions in equilibrium**
- **charged lepton Yukawa interactions slower than cosmic expansion**

SM flavours indistinguishable!

CP violating parameter ϵ

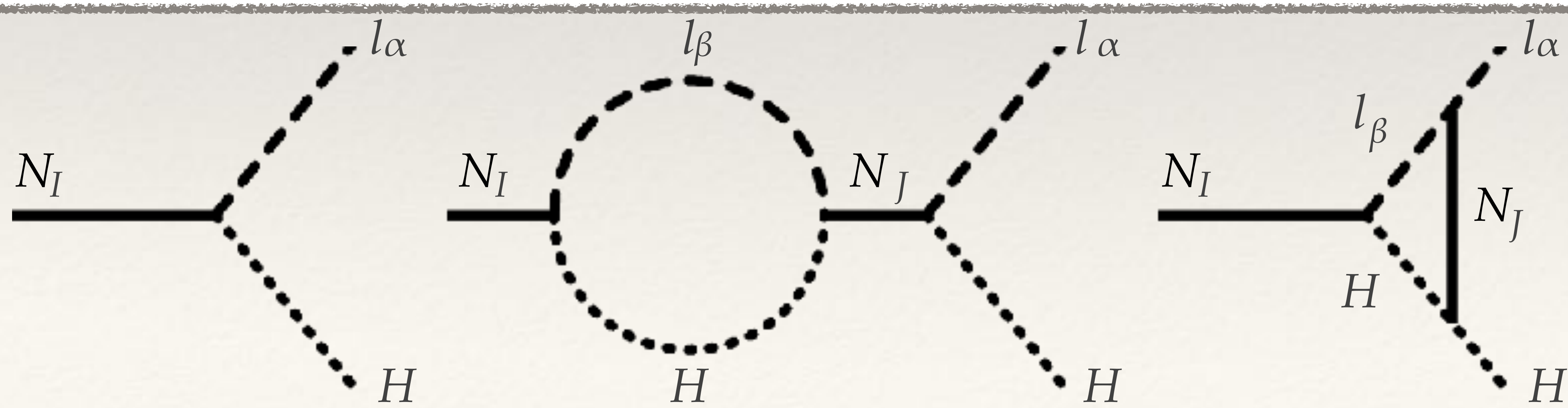
$$\epsilon = \frac{\Gamma_{N\to \ell H} - \Gamma_{N\to \bar{\ell} H^*}}{\Gamma_{N\to \ell H} + \Gamma_{N\to \bar{\ell} H^*}}$$

final asymmetry

$$Y_{B-L} \propto \epsilon / g_*$$

Asymmetry only depends on the combination $F^\dagger F$

$$\epsilon \simeq -\frac{3}{16\pi} \frac{1}{(F^\dagger F)_{11}} \sum_I \mathrm{Im}\left[(F^\dagger F)_{I1}\right]^2 \frac{M_1}{M_I}$$



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But $F = \frac{1}{v}U_\nu\sqrt{m_\nu^{\mathrm{diag}}}\mathcal{R}\sqrt{M^{\mathrm{diag}}}$ Casas/Ibarra

gives $F^\dagger F = \sqrt{M^{\mathrm{diag}}}\mathcal{R}^\dagger\frac{m_\nu^{\mathrm{diag}}}{v^2}\mathcal{R}\sqrt{M^{\mathrm{diag}}}$

ϵ is independent of the PMNS matrix!

So is the asymmetry…

"Flavoured Leptogenesis"

10^{12} GeV > T > 160 GeV

- gauge interactions in equilibrium
- charged lepton Yukawa interactions faster than cosmic expansion

SM flavours distinguishable!

CP violating parameters $\epsilon_{\alpha\beta}$

Lepton number matrix $(Y_{B\text{-}L})_{\alpha\beta}$

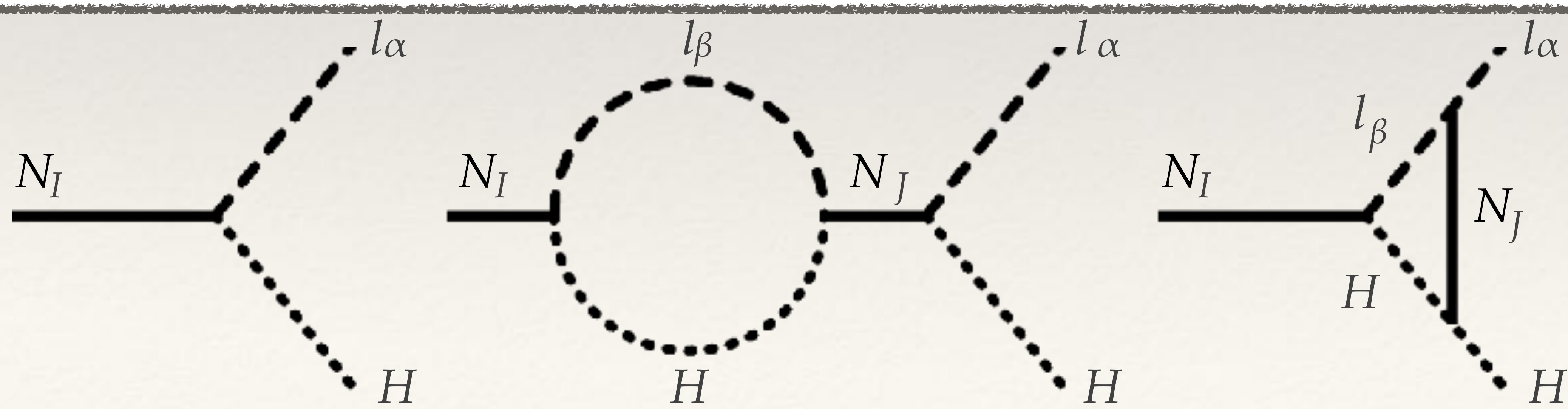
$(Y_{B\text{-}L})_{\alpha\alpha}$ is charge in flavour α

Barbieri et al 9911315, Blanchet/Di Bari 0607330, Abada et al 0605281 and 0601083, Nardi et al 0601084, Beneke et al 1007.4783

Flavoured asymmetries depend on individual $F_{\alpha I}$ $\Longrightarrow$ **Baryon asymmetry depends on PMNS!**

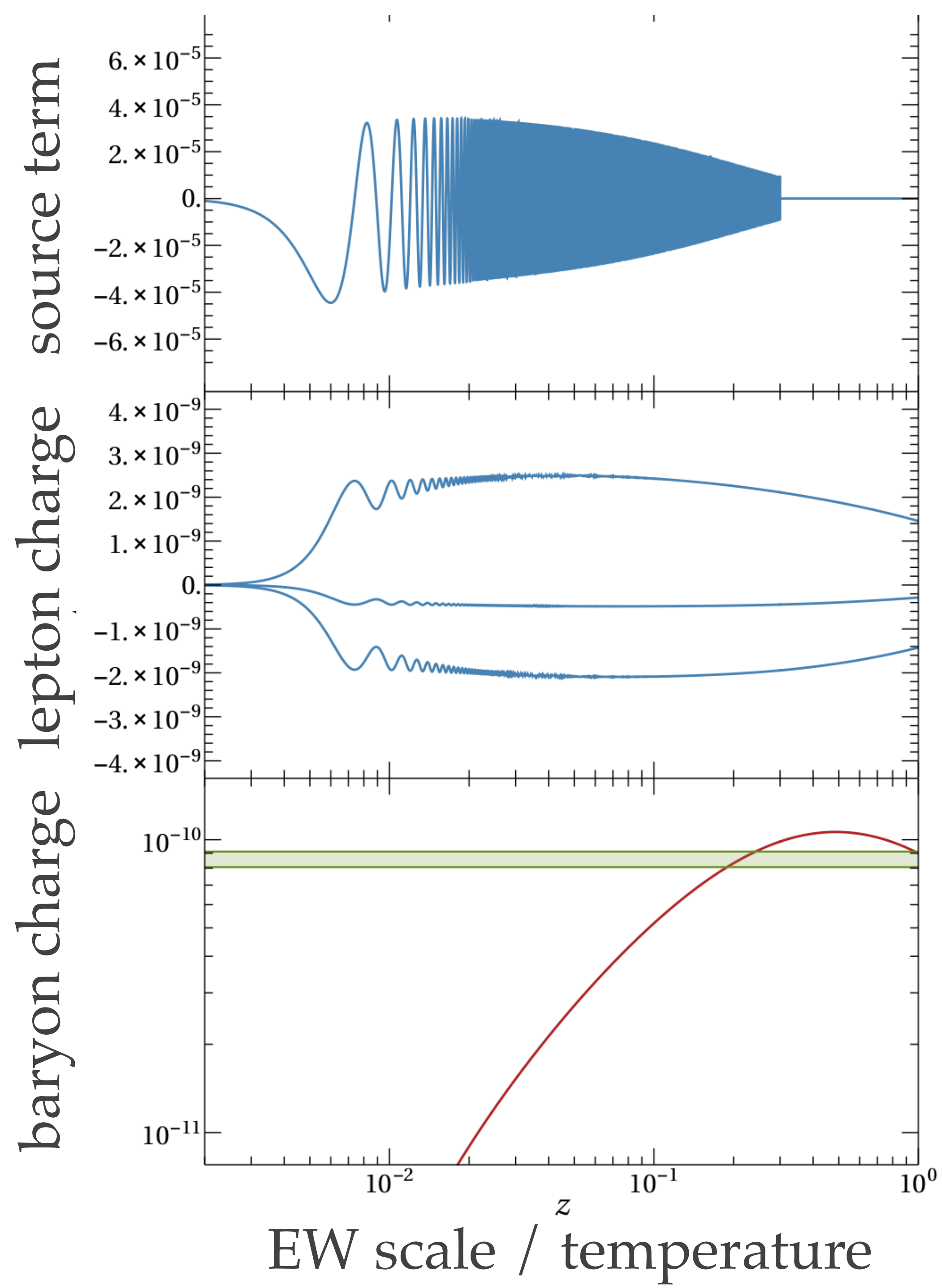
…δ alone is even sufficient

Pascoli/Petcov/Riotto 0611338



sub-EW Scale Leptogenesis: "freeze in"

Akhmedov/Rubakov/Smirnov 98, Asaka/Shaposhnikov 05



For masses M below the EW scale:

- asymmetry generated at T >> M
- helicity states of the Majorana particles act as "particle" and "antiparticle"
- total *B-L* is suppressed by $(M/T)^2$
- flavour asymmetric washout generates total *L* and hence *B*
- mechanism primarily relies on flavour effects…

…though LNV effects can affect parameter space
(cf. Hambye/Teresi 1606.00017, Ghiglieri/Laine 1703.06087, Eijima et al 1703.06085, Antusch et al 1710.03744)

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Flavour Mixing Pattern + Dirac Phase
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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 →

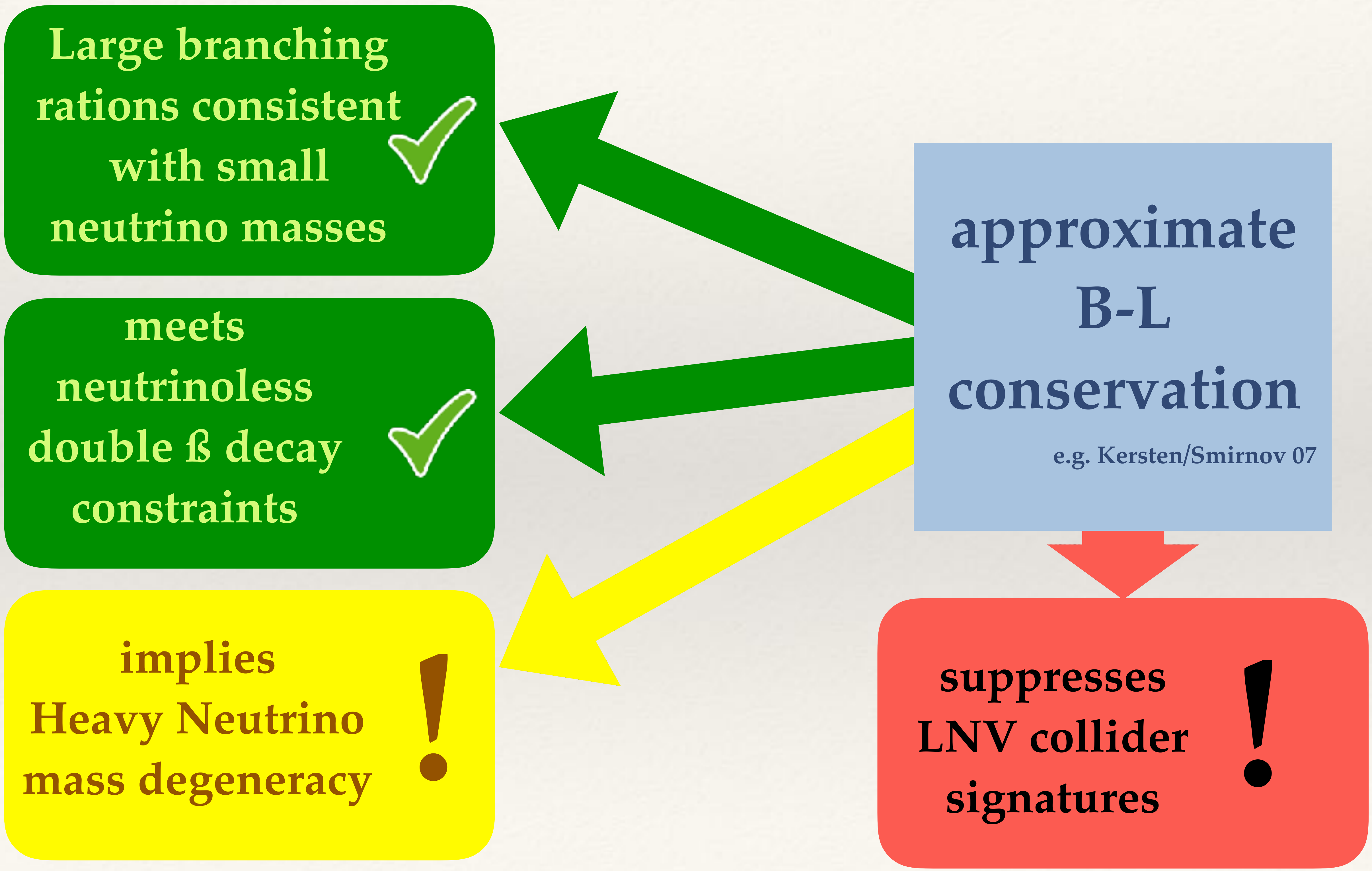
approximate B-L conservation

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

may observe CP violation in Heavy Neutrino decay

Cvetic/Kim/Saa 1403.2555

connection to leptogenesis?

“golden channels” may be suppressed

need to use other channels (LFV, displaced vertices)

implies Heavy Neutrino mass degeneracy !

suppresses LNV collider signatures !

Predicted Flavour Structure

$$M_M = \bar{M} \begin{pmatrix} 1-\mu & 0 & 0 \\ 0 & 1+\mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

$$F = \frac{1}{\sqrt{2}} \begin{pmatrix} F_e + \epsilon_e & i(F_e - \epsilon_e) & \epsilon'_e \\ F_\mu + \epsilon_\mu & i(F_\mu - \epsilon_\mu) & \epsilon'_\mu \\ F_\tau + \epsilon_\tau & i(F_\tau - \epsilon_\tau) & \epsilon'_\tau \end{pmatrix}$$

B-L **violating parameters**

$$\mu, \;\; \mu', \;\; \epsilon_\alpha, \;\; \epsilon'_\alpha$$

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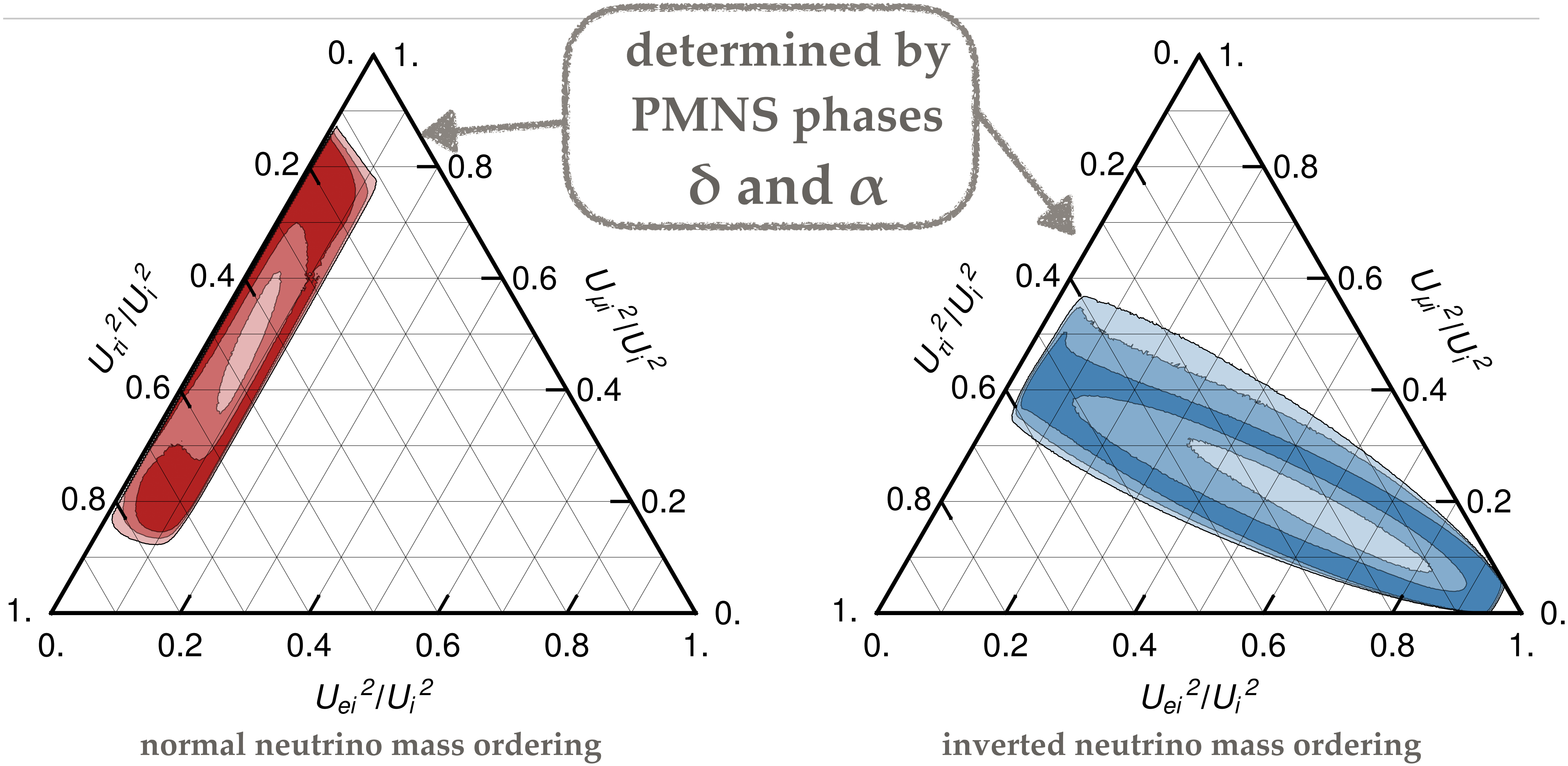
light ν masses: pseudo Dirac pair — feebly coupled heavy neutrino

***B-L* violating parameters**

$\mu, \ \mu', \ \epsilon_\alpha, \ \epsilon'_\alpha$

Heavy Neutrino Mixing: Constraints from ν-oscillation Data



coloured areas: consistent with ν-oscillation data at 1σ, 2σ and 3σ in minimal model with two right handed neutrinos

from MaD/Hajer/Klaric/Lafranchi 1801.04207

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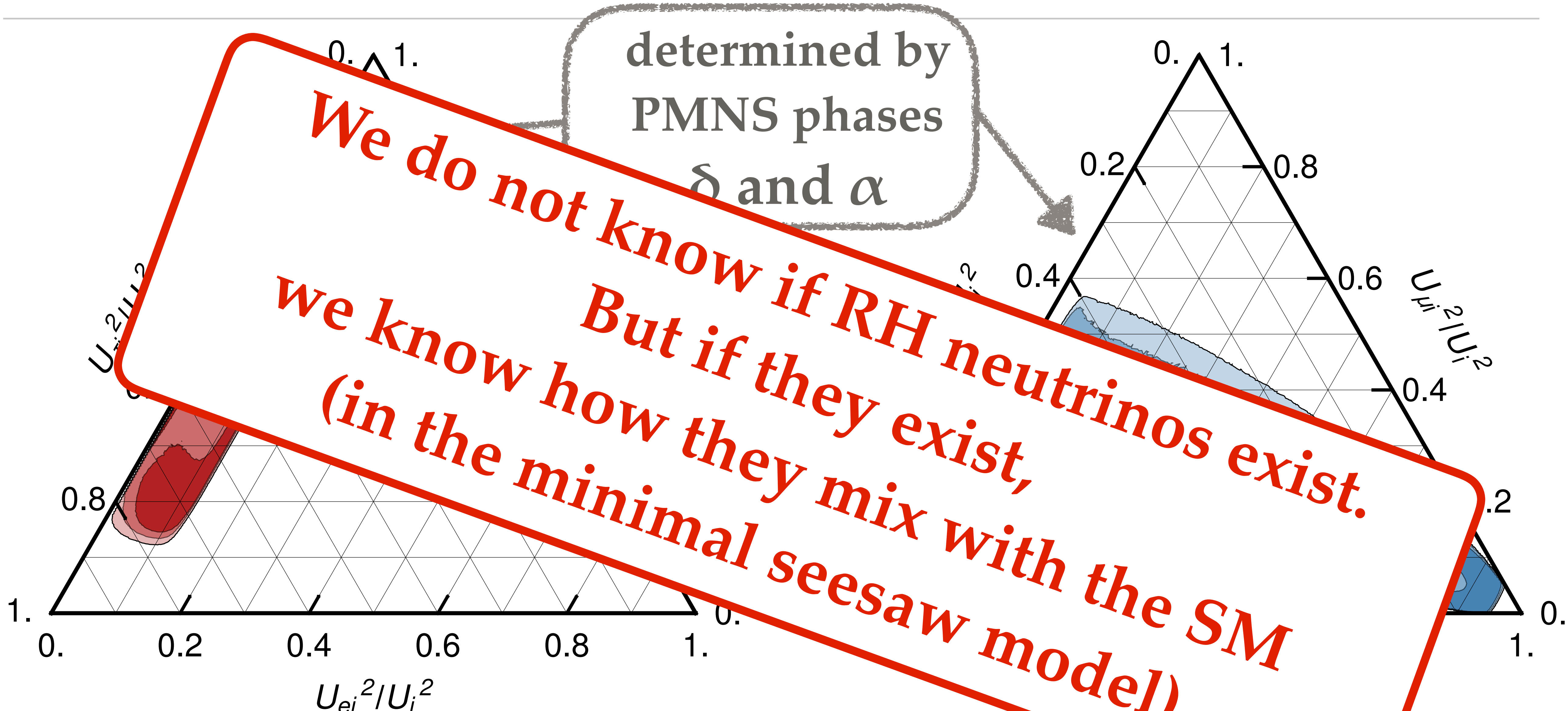

normal neutrino mass ordering

inverted ne... ...ng

We do not know if RH neutrinos exist. But if they exist, we know how they mix with the SM (in the minimal seesaw model)

coloured areas: consistent with ν-oscillation data at 1σ, 2σ and ...σ in minimal model with two right handed neutrinos

from MaD/Hajer/Klaric/Lafranchi 1801.04207

Connection to Low Energy CP Violation

- **Proof of principle: CP is violated in the lepton sector.**

- **There exist models that predict δ.**
  In some of them the CP violation that drives leptogenesis is solely due to the PMNS phases
  see e.g. Meroni et al 1203.4435, Gehrlein et al 1502.00110+1508.07930, Zhang/Zhou 1505.04858, Chen et al 1602.03873 , Hagedorn/Molinari 1602.04206
  In some models leptogenesis is possible solely with δ.
  see e.g. Meroni et al 1203.4435, Canetti et al 1208.4607 , Chen et al 1602.03873, Hagedorn/Molinari 1602.04206, Dolan et al 1802.08373

- **The PMNS phases govern the heavy neutrino flavour mixing pattern.**
  see e.g. Shaposhnikov 0804.4542, Gavela et al 0906.1461, Asaka/Eijima 1101.1382, Ivashko/Ruchayskiy 1112.3319, Hernandez at al 1606.06719, MaD et al 1609.09069, MaD et al 1801.04207

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light ν mixing:
constrains
relative size

light ν masses: pseudo Dirac pair | feebly coupled heavy neutrino

***B-L* violating parameters**

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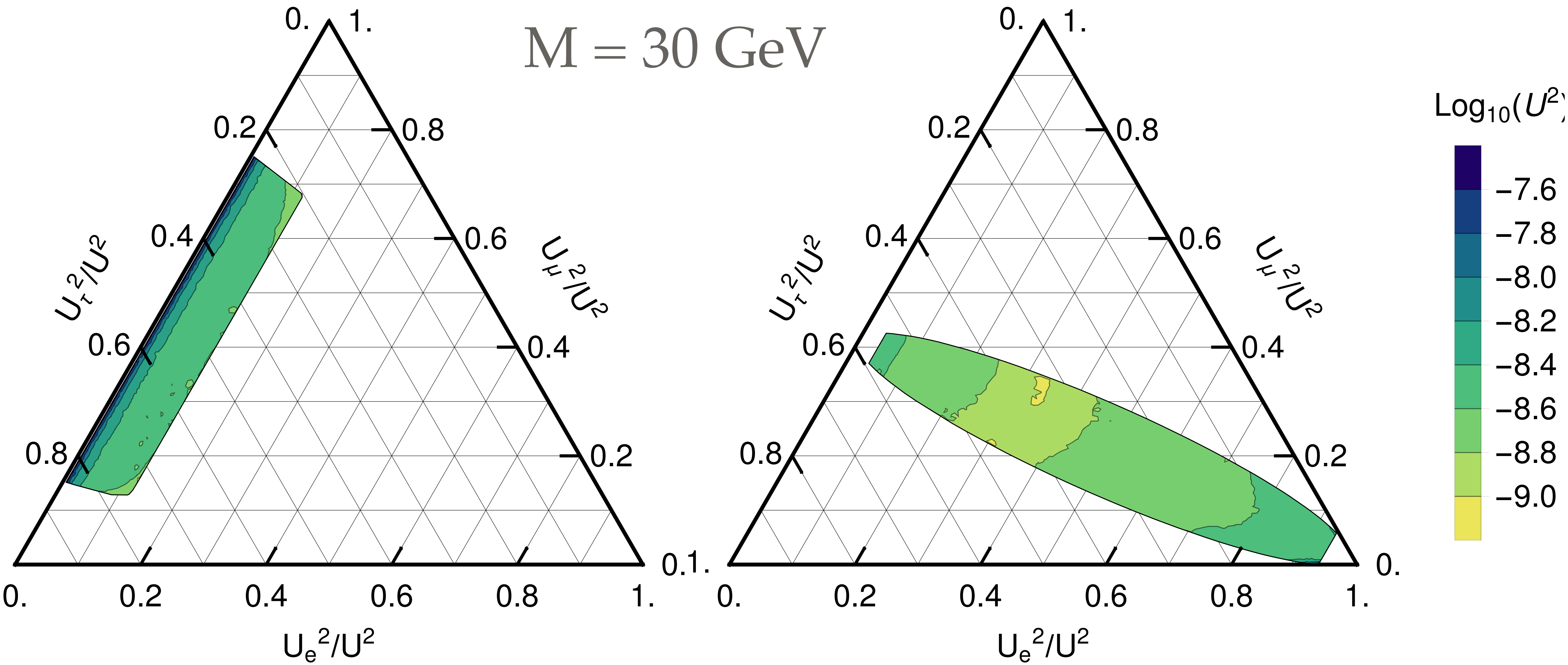
Heavy Neutrino Mixing: Constraints from Leptogenesis

M = 30 GeV



normal neutrino mass ordering **inverted neutrino mass ordering**

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

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leptogenesis:
mass degeneracy for
free for pseudo Dirac

further constrains
relative size

$$F = \frac{1}{\sqrt{2}} \begin{pmatrix} F_e + \epsilon_e & i(F_e - \epsilon_e) & \epsilon'_e \\ F_\mu + \epsilon_\mu & i(F_\mu - \epsilon_\mu) & \epsilon'_\mu \\ F_\tau + \epsilon_\tau & i(F_\tau - \epsilon_\tau) & \epsilon'_\tau \end{pmatrix}$$

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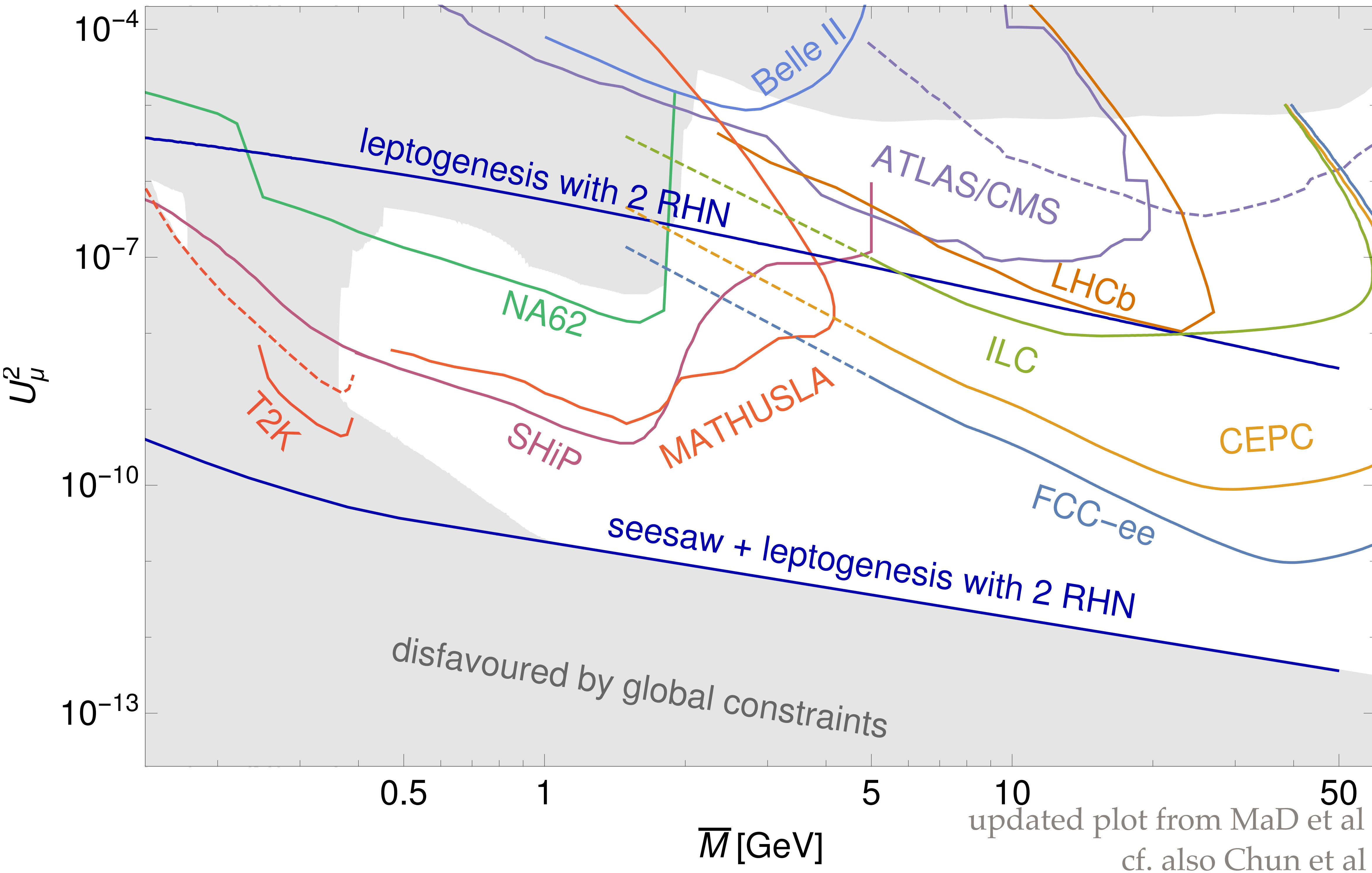
Minimal Seesaw Model



updated plot from MaD et al 1609.09069
cf. also Chun et al 1711.02865
Cai et al 1711.02180

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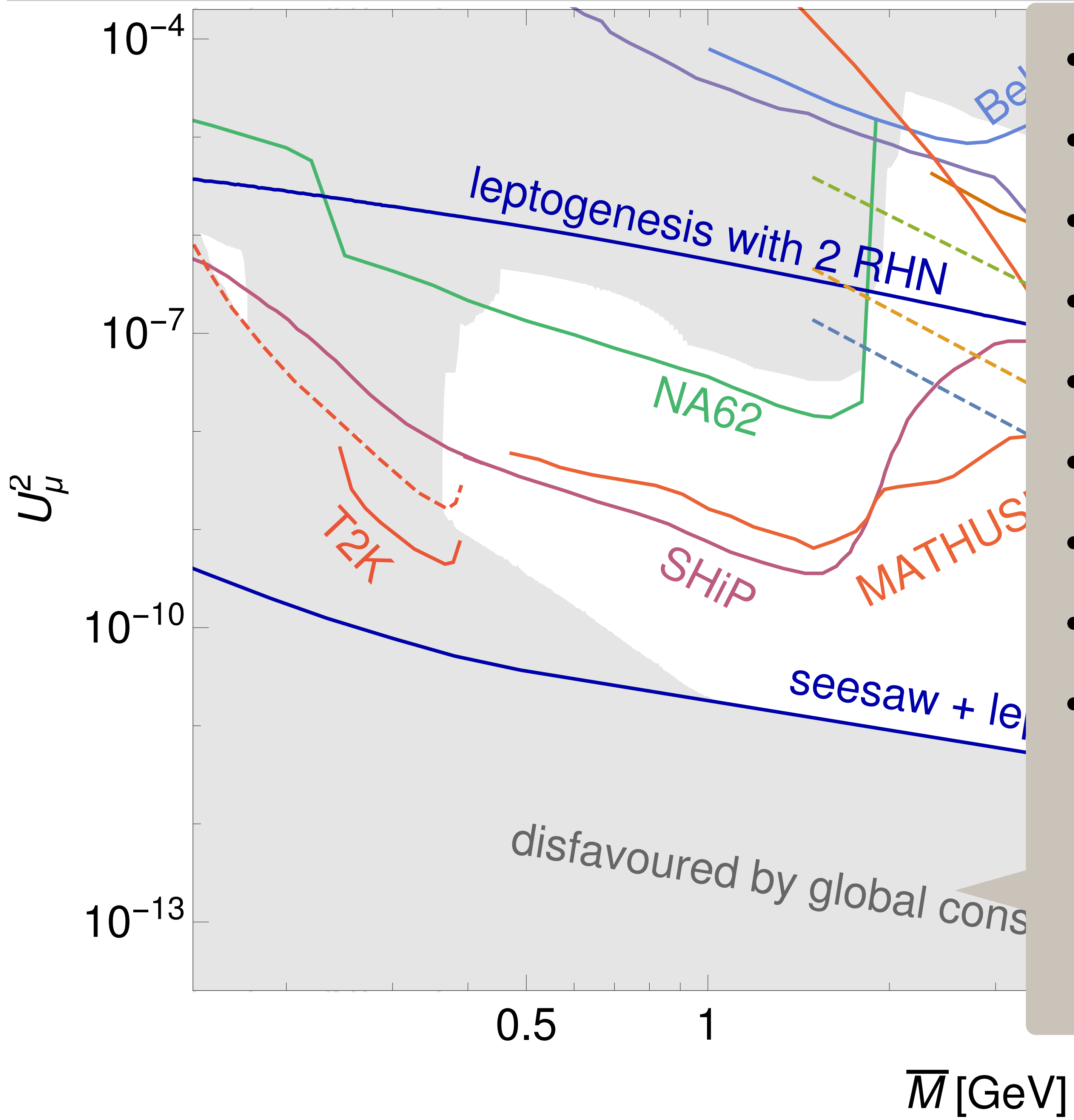

- **collider constraints**
- **fixed target experiments**
- **neutrino oscillation data**
- **neutrinoless double β decay**
- **lepton universality**
- **cLFV decays**
- **CMK unitarity**
- **electroweak precision data**
- **big bang nucleosynthesis**

in minmal model (2 RH neutrinos) 1609.09069

bounds weaken with 3 RH neutrinos cf. e.g. 1502.00477

updated plot from MaD et al 1609.09069
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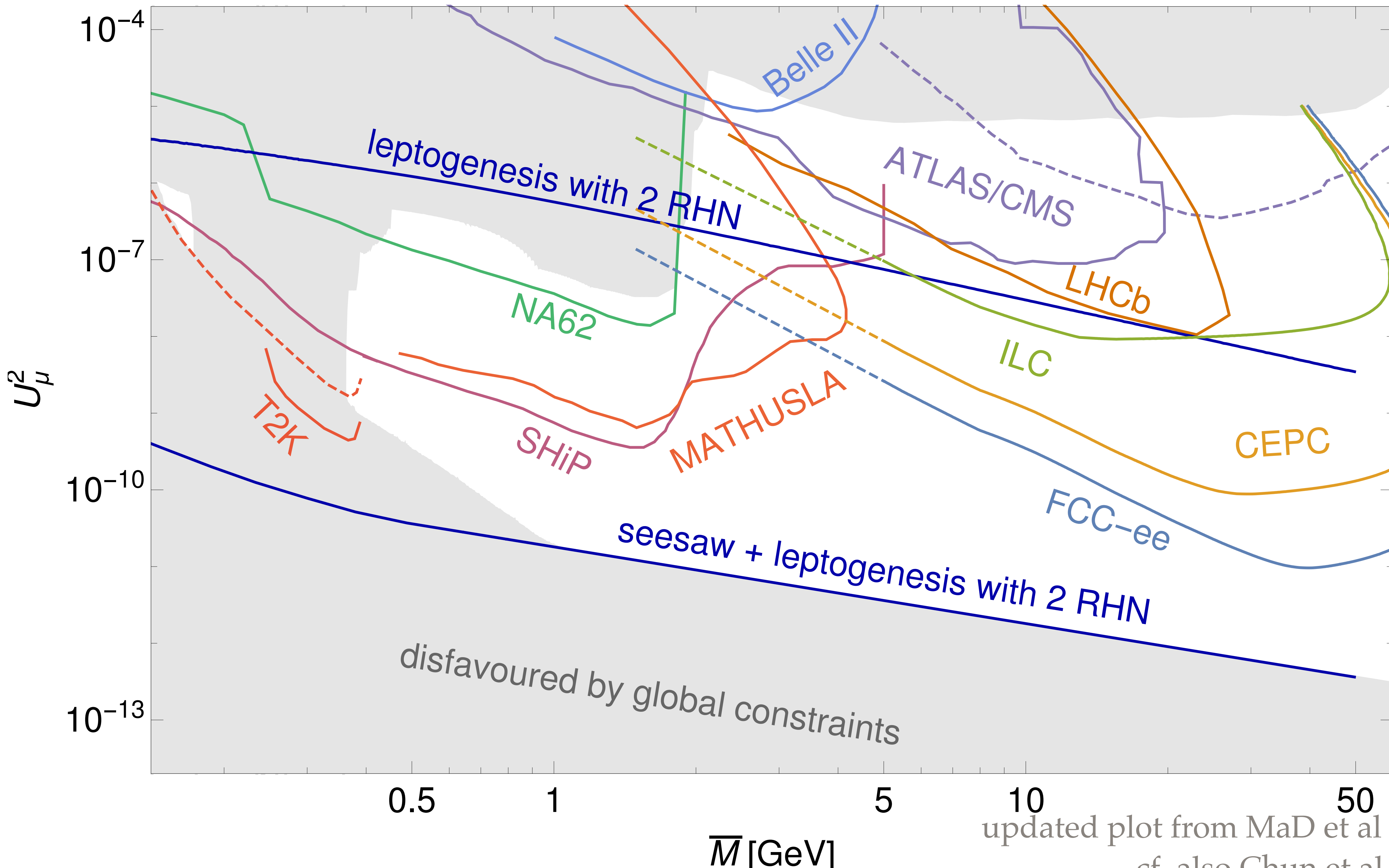
Cai et al 1711.02180

Future LHC Searches



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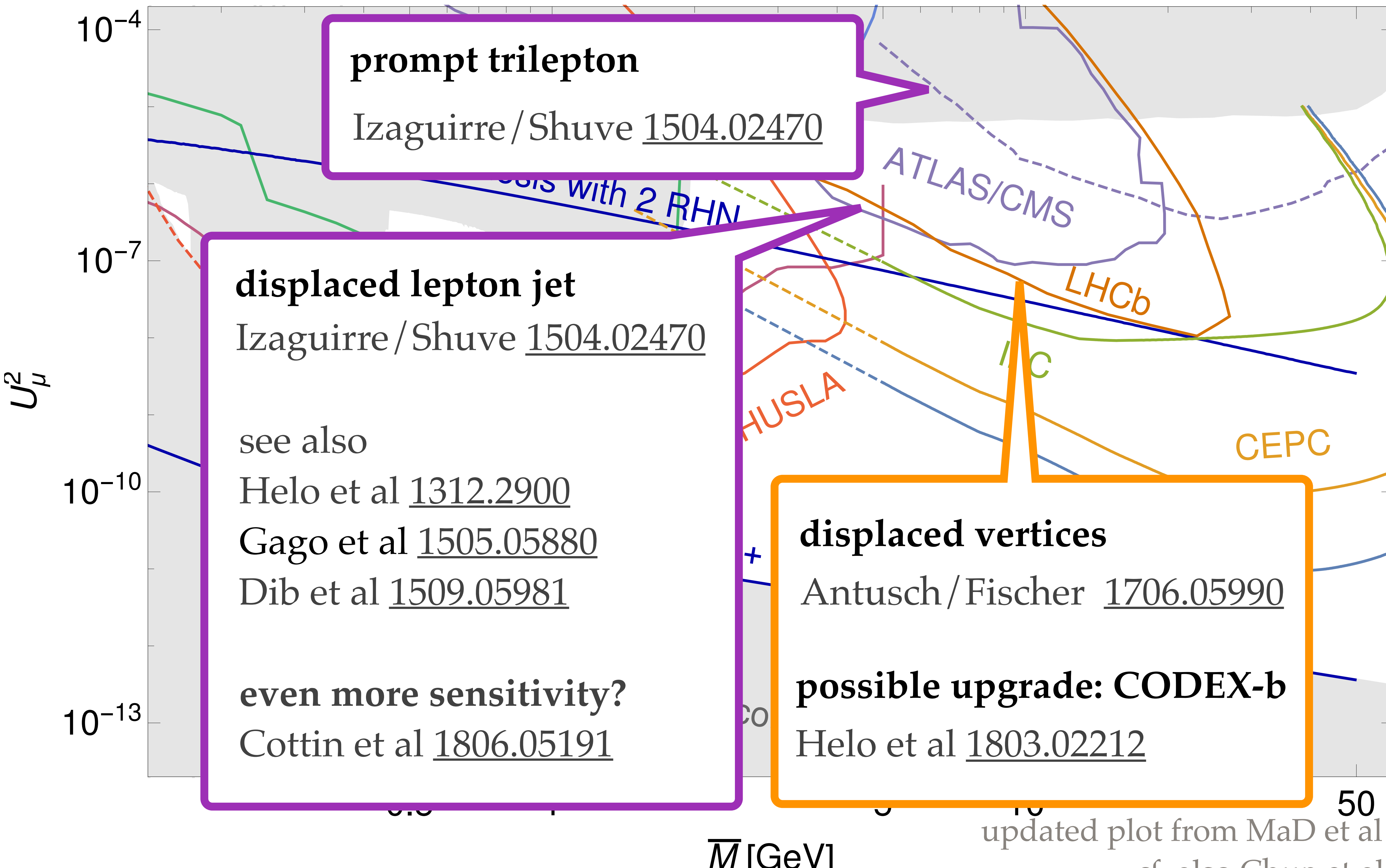

prompt trilepton
Izaguirre/Shuve 1504.02470

displaced lepton jet
Izaguirre/Shuve 1504.02470

see also
Helo et al 1312.2900
Gago et al 1505.05880
Dib et al 1509.05981

even more sensitivity?
Cottin et al 1806.05191

displaced vertices
Antusch/Fischer 1706.05990

possible upgrade: CODEX-b
Helo et al 1803.02212

updated plot from MaD et al 1609.09069
cf. also Chun et al 1711.02865
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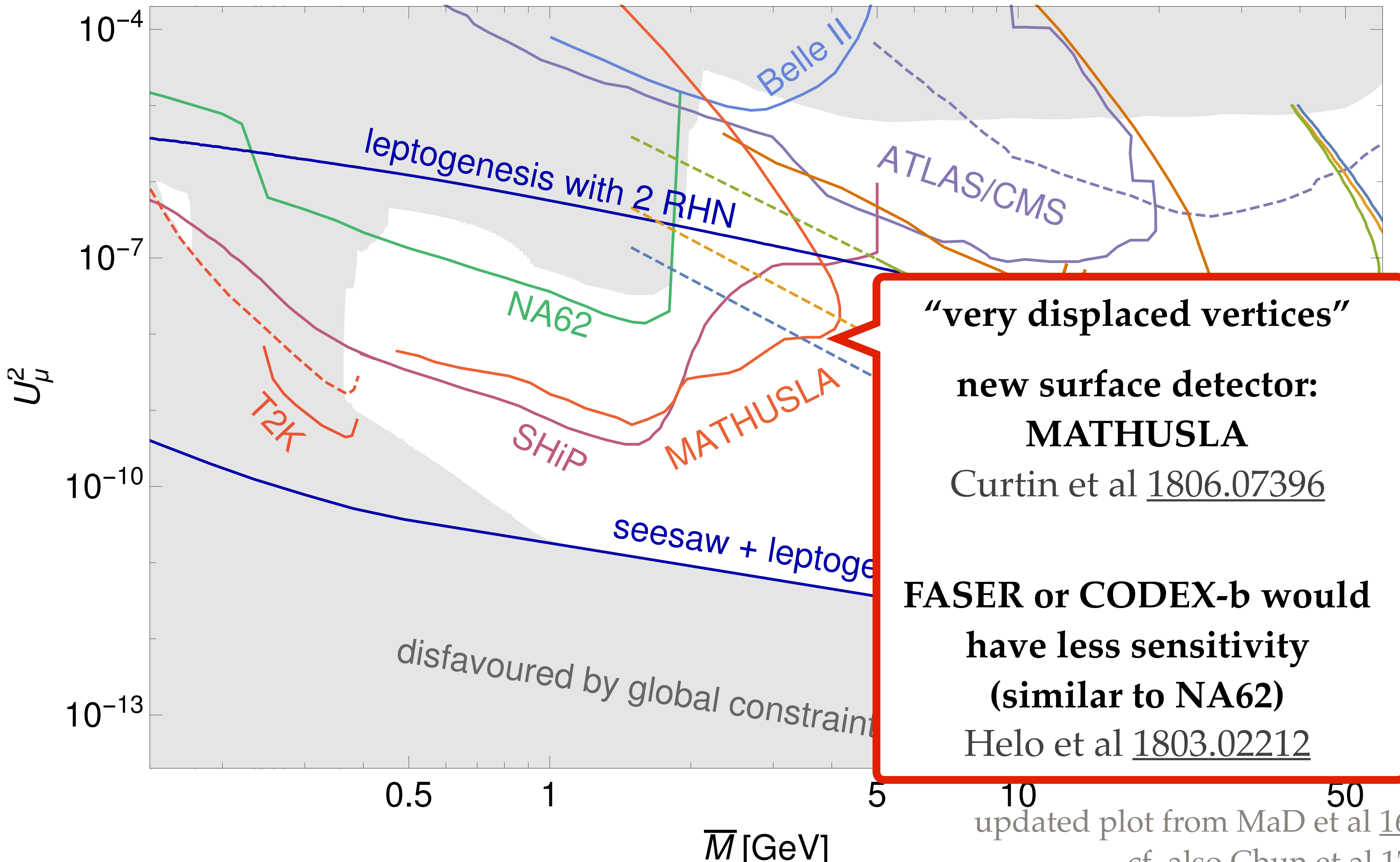
Future LHC Searches



"very displaced vertices"

new surface detector: MATHUSLA

Curtin et al 1806.07396

FASER or CODEX-b would have less sensitivity (similar to NA62)

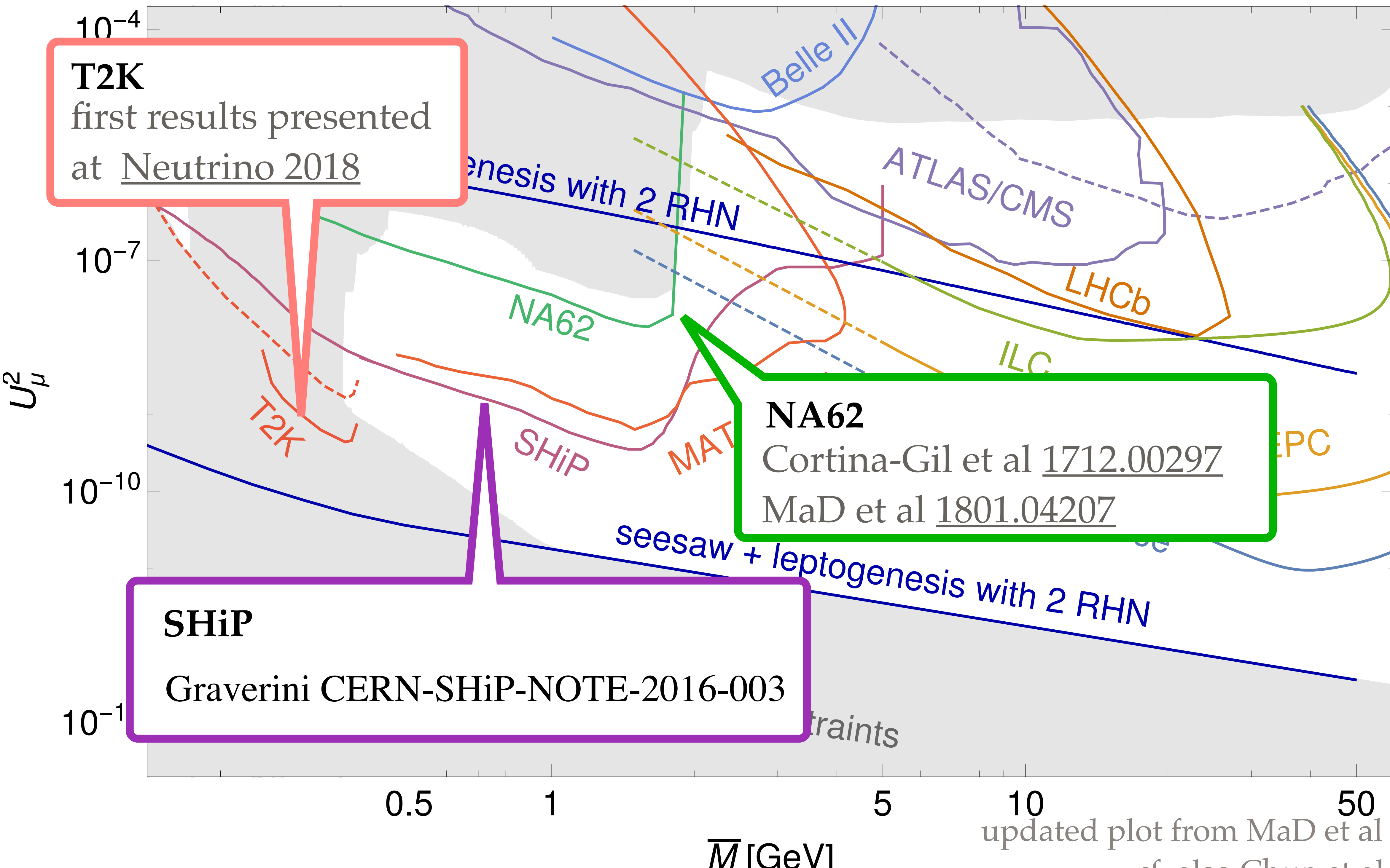
Helo et al 1803.02212

updated plot from MaD et al 1609.09069

cf. also Chun et al 1711.02865

Cai et al 1711.02180

Searches at Fixed Target Experiments



T2K
first results presented
at Neutrino 2018

NA62
Cortina-Gil et al 1712.00297
MaD et al 1801.04207

SHiP
Graverini CERN-SHiP-NOTE-2016-003

updated plot from MaD et al 1609.09069
cf. also Chun et al 1711.02865
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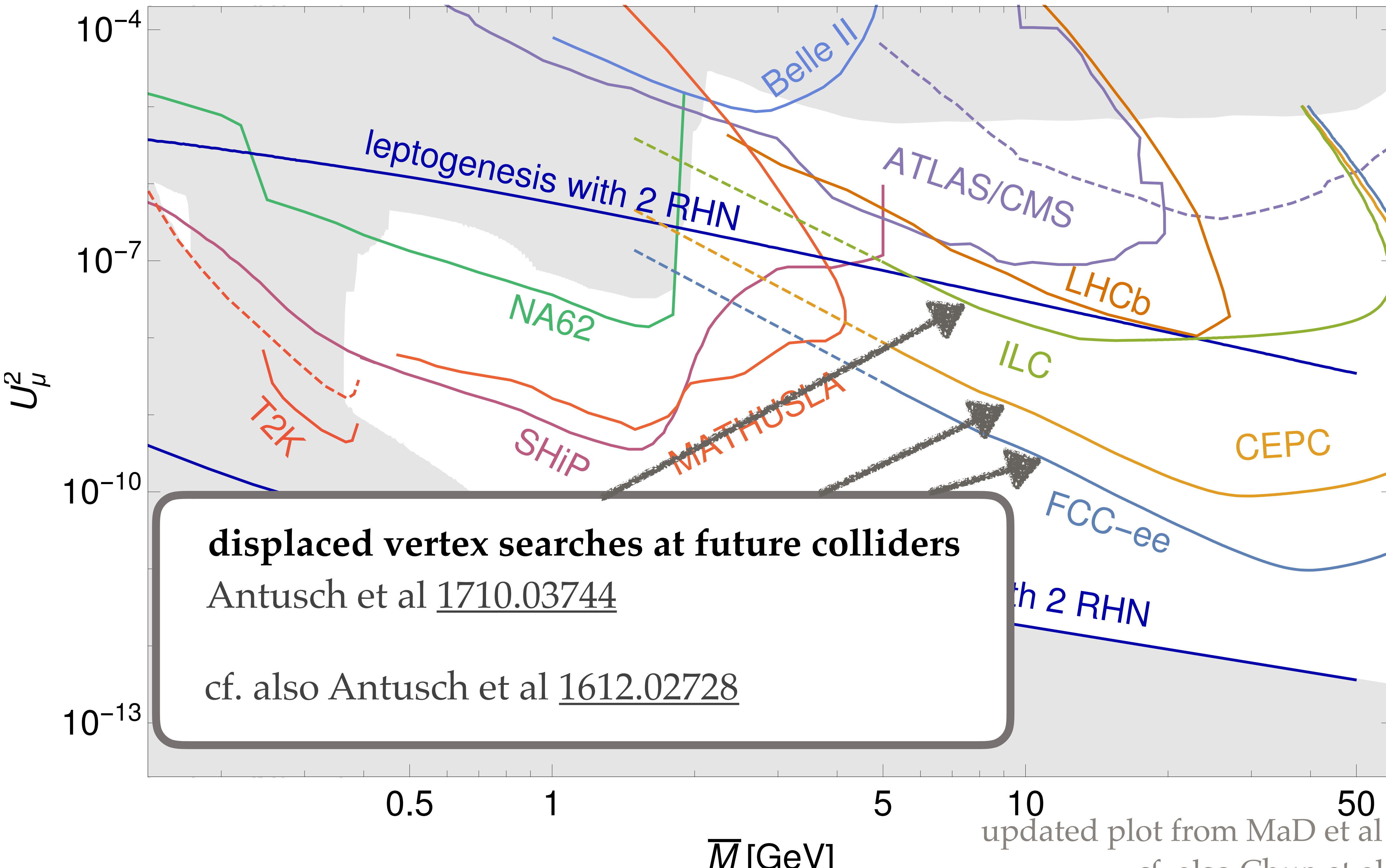
Searches at Future Colliders



displaced vertex searches at future colliders

Antusch et al 1710.03744

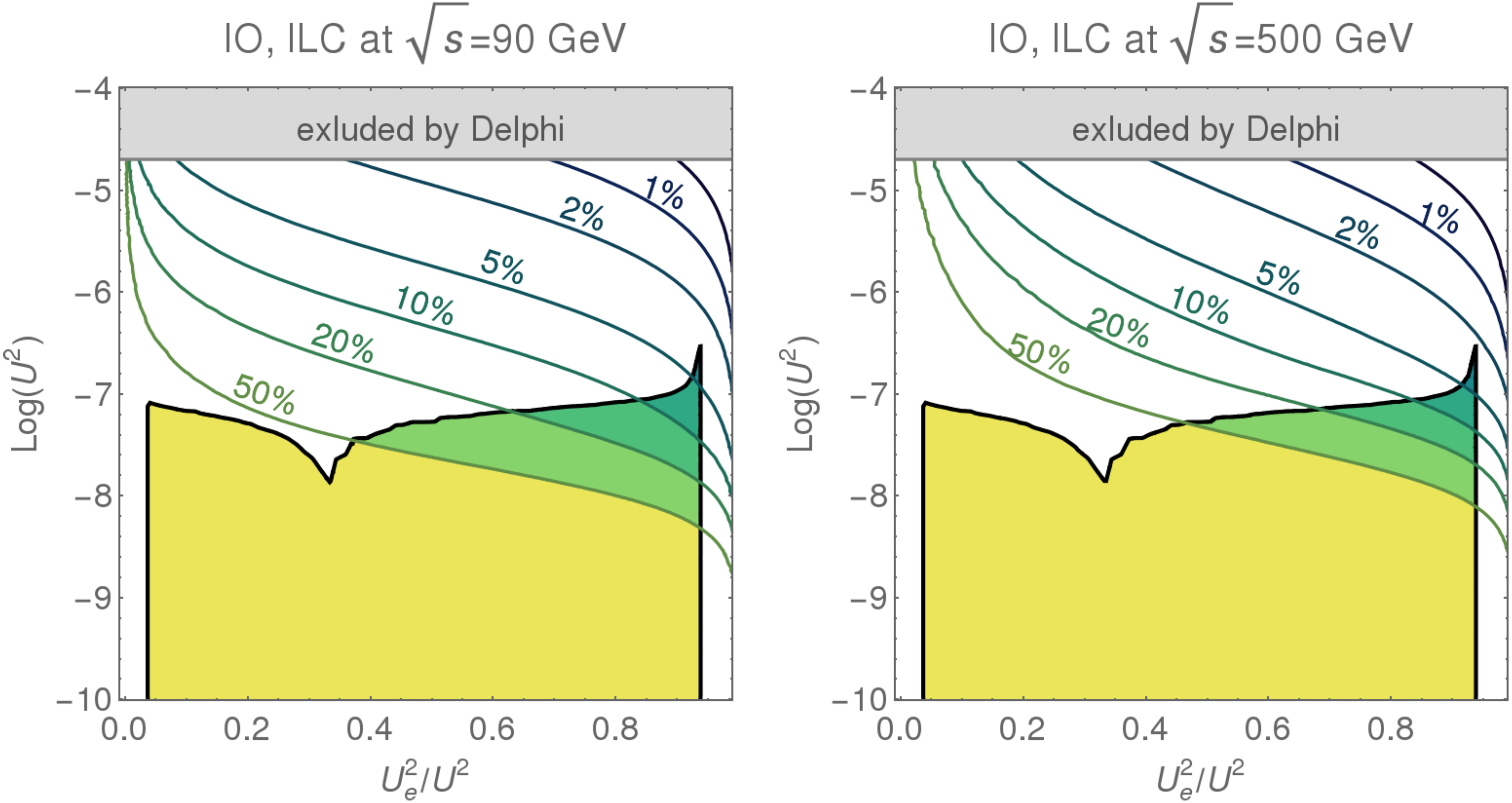
cf. also Antusch et al 1612.02728

updated plot from MaD et al 1609.09069

cf. also Chun et al 1711.02865

Cai et al 1711.02180

Example: Flavour Mixing at ILC

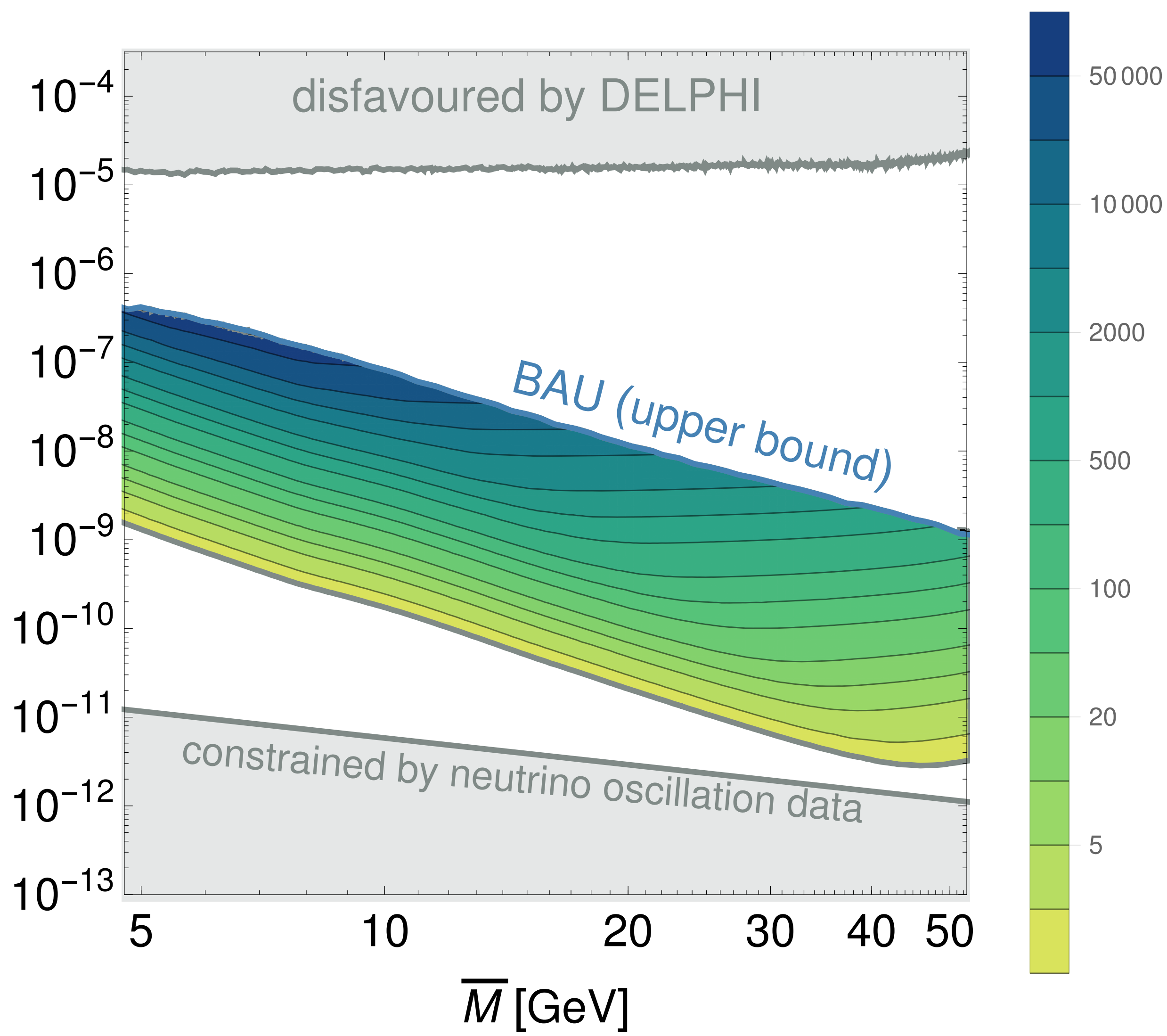


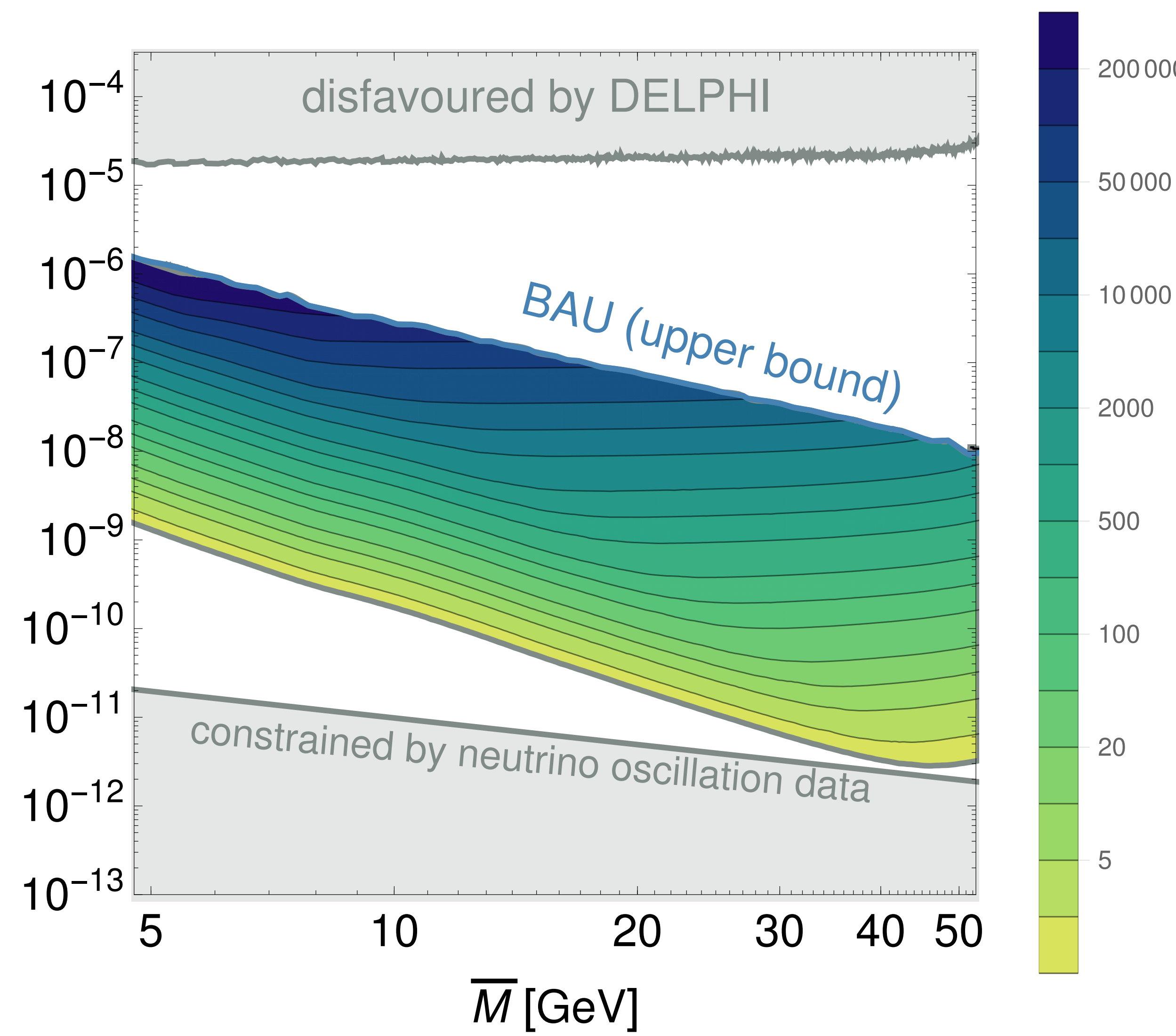
with 0.1 / ab | with 5 / ab

Antusch / Cazzato / MaD / Fischer / Garbrecht / Gueter / Klaric 1801.06534

Number of Events at FCC-ee

normal ordering | **inverted ordering**





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

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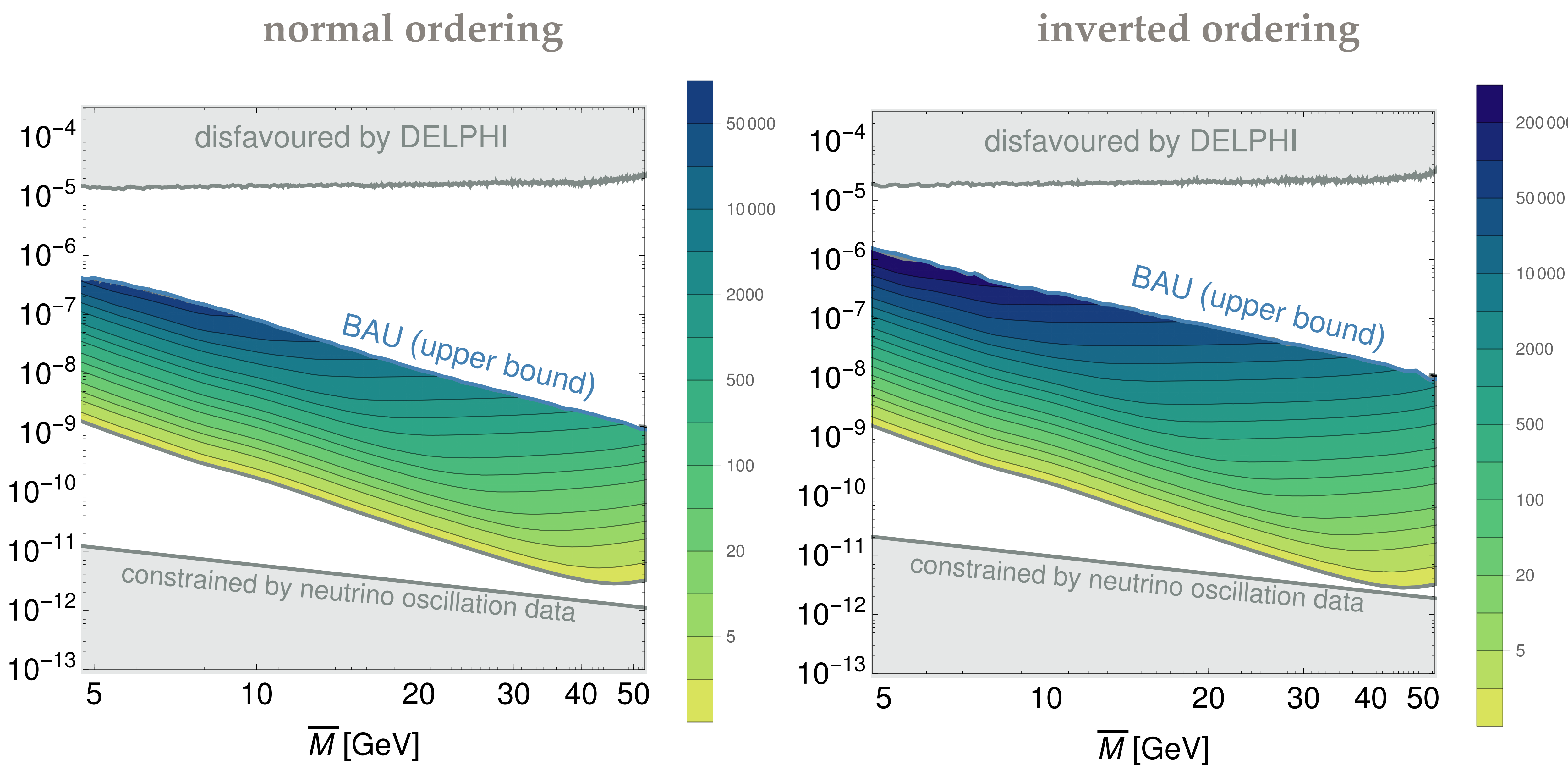

percent level measurement of flavour structure!

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Verifying Leptogenesis?

Minimal model of neutrino mass and baryogenesis:

Type I seesaw with two RH Neutrinos below EW scale

[effectively describes νMSM (Asaka/Shaposhnikov 0503065, 0505013) as observational constraints on DM candidate (cf. e.g. 1602.04816) imply that it must have very feeble couplings]

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

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$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\rm diag}} \mathcal{R} \sqrt{M^{\rm diag}}$$

- Higgs vev v
- light neutrino mixing angles
- light neutrino mass splittings
- Dirac phase δ, Majorana phase α
- lightest ν mass (almost) vanishes
- complex angle ω
- N-mass M and splitting ΔM

Verifying Leptogenesis?

Minimal model of neutrino mass and baryogenesis:

Type I seesaw with two RH Neutrinos below EW scale

Unknown parameters:

M, ΔM, Reω, Imω, δ, α

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}} \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

Dirac phase δ
Majorana phase α

lightest ν mass (almost) vanishes

complex angle ω

N-mass M and splitting ΔM

Verifying Leptogenesis?

heavy neutrino masses

size of N_1 and N_2 couplings relative to each other

overall N_i coupling strength

DUNE, NOvA, …

Unknown parameters:

M, ΔM, Reω, Imω, δ, α

N_i flavour mixing pattern

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\mathrm{diag}}}\, \mathcal{R} \sqrt{M^{\mathrm{diag}}}$$

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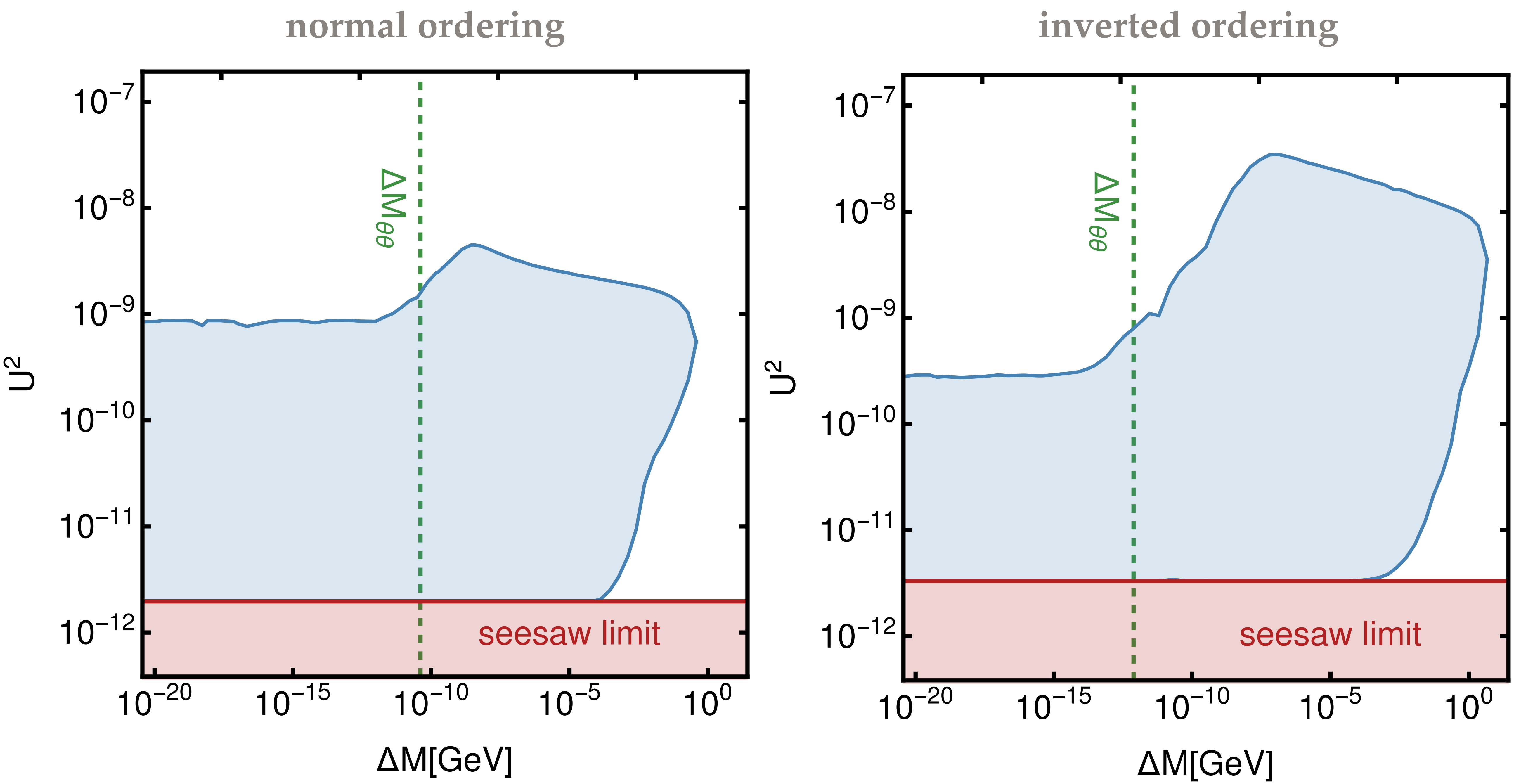
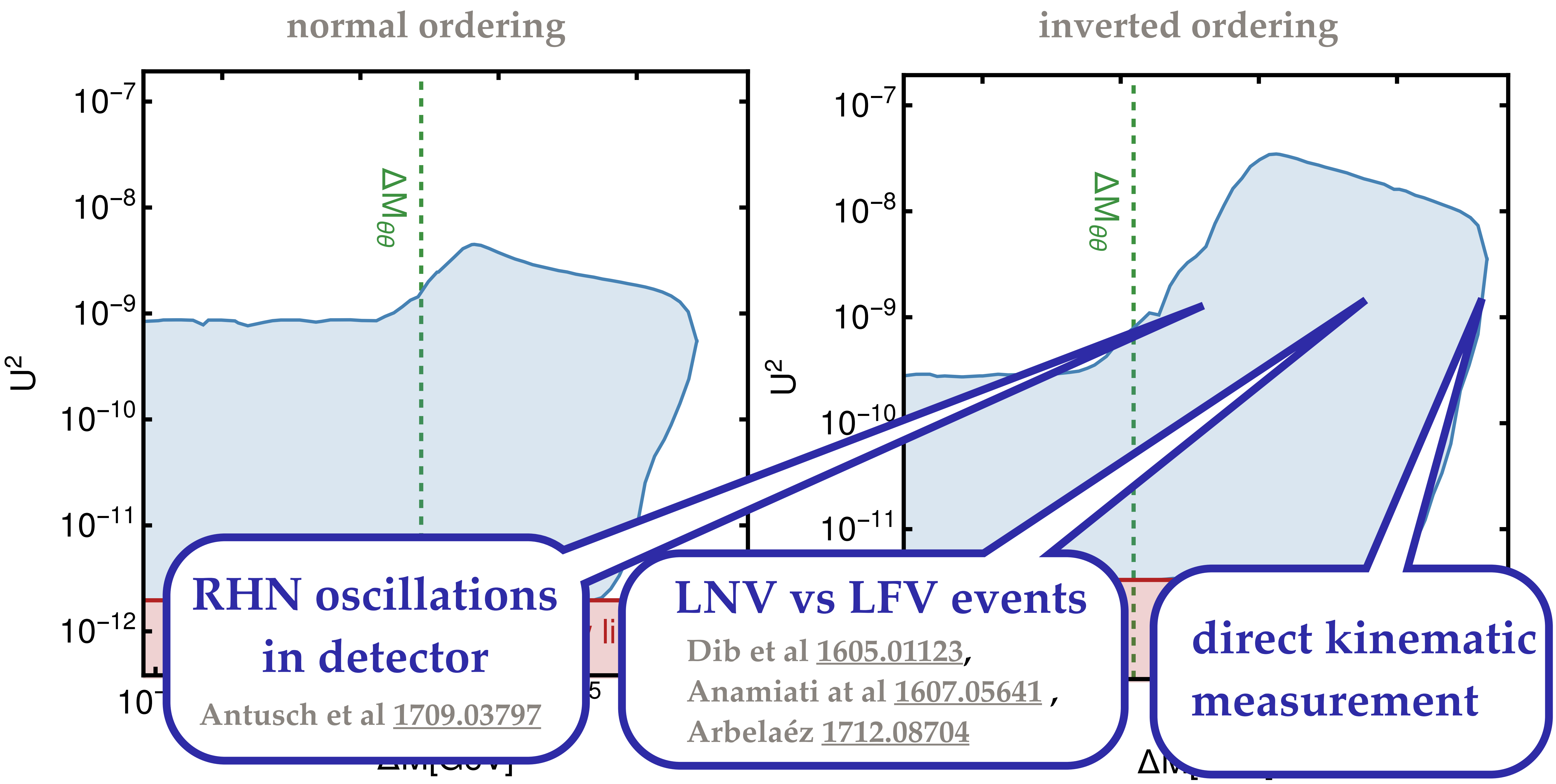
Leptogenesis and Heavy Neutrino Mass Splitting



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

Leptogenesis and Heavy Neutrino Mass Splitting



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

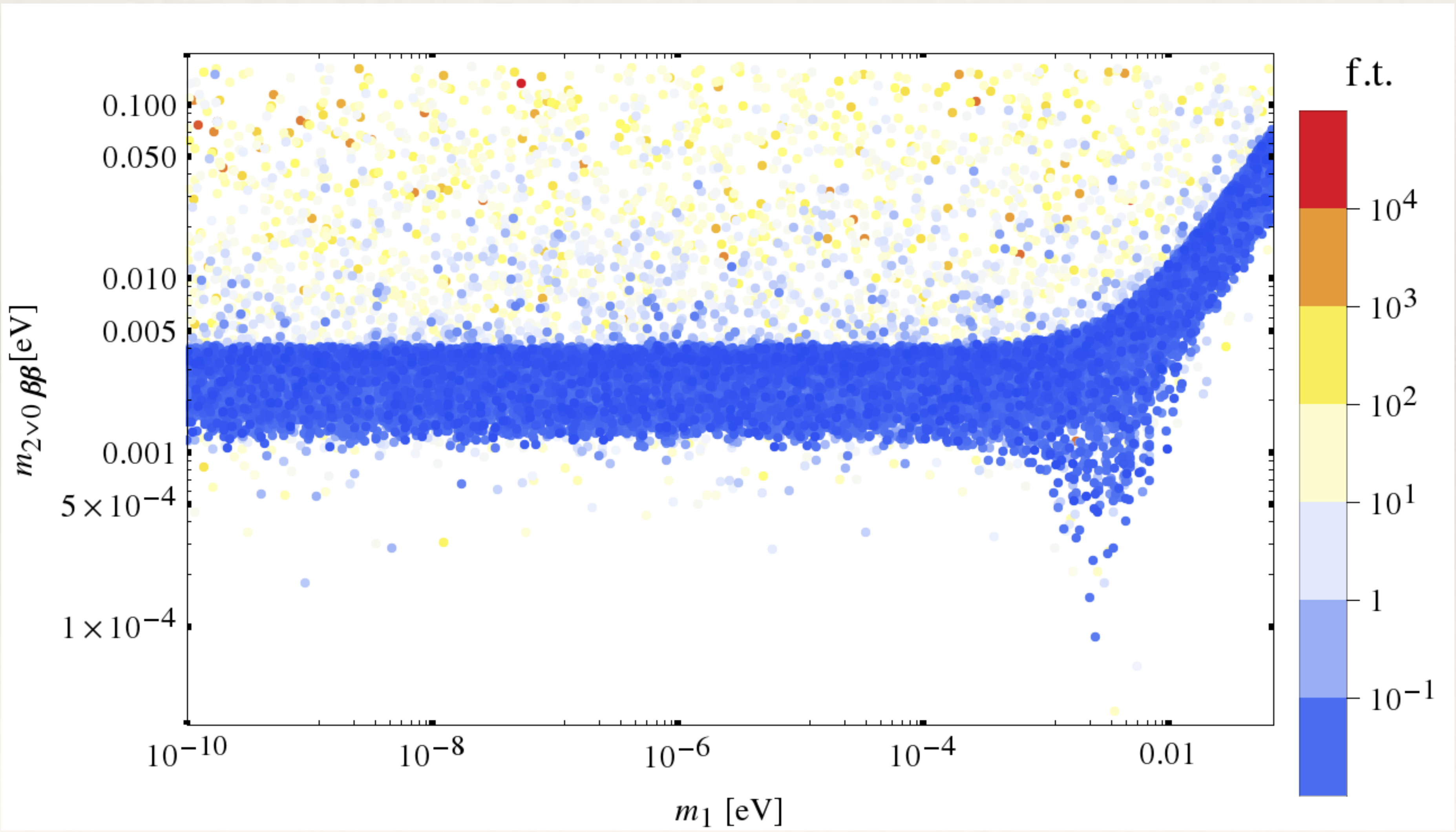
The 0νββ Connection

Heavy neutrino exchange can dominate 0νββ…

…even in the leptogenesis region

⇒ additional probe of Reω !

Bezrukov 0505247
Blennow et al 1005.3240
Lopez Pavon et al 1209.5342
MaD/Eijima 1606.06221,
Hernandez et al 1606.06719,
Asaka et al 1606.06686



plot: preliminary work with Abada/Arcadi/Domcke/Klaric/Lucente

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Heavy neutrino exchange can dominate 0νββ…
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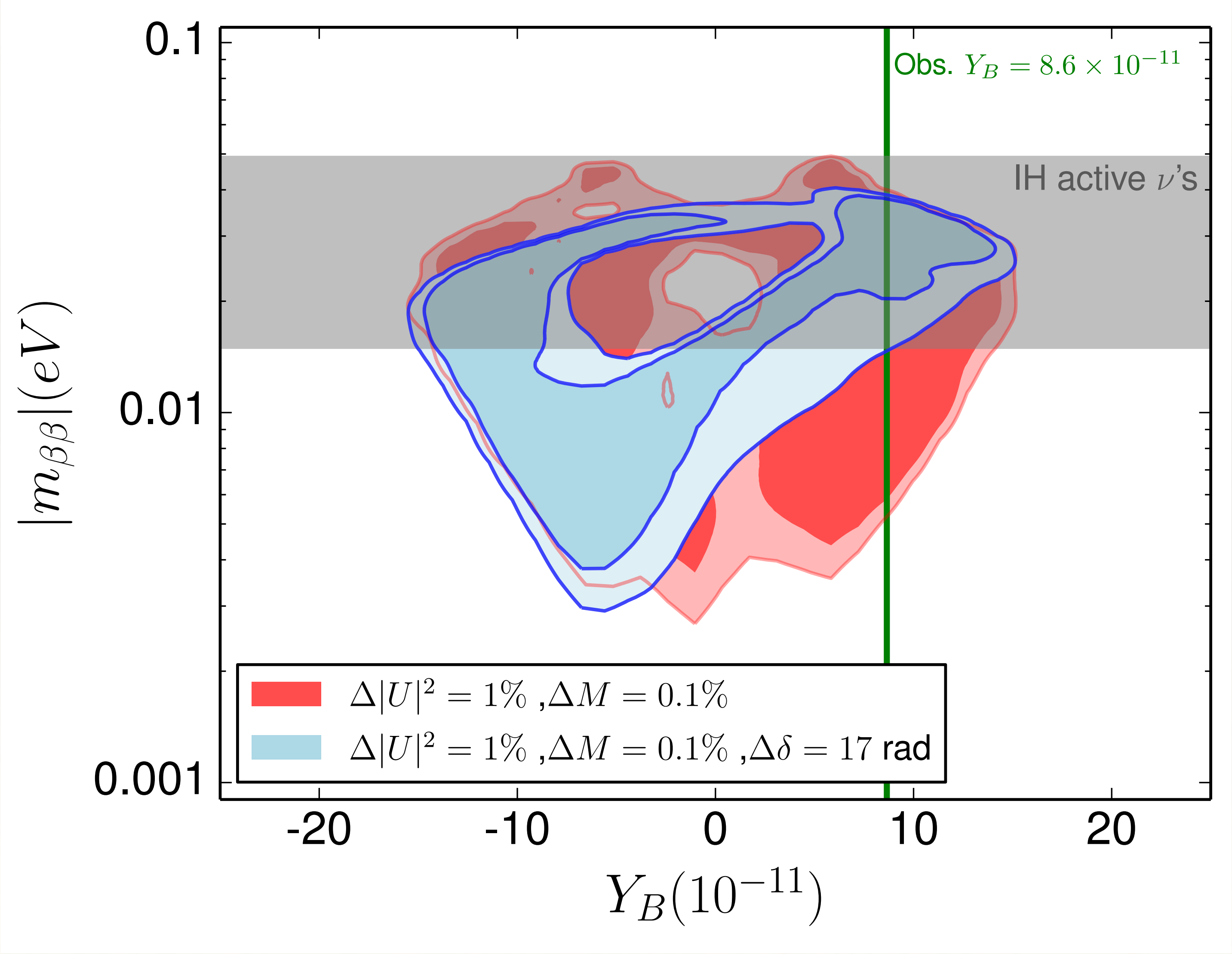
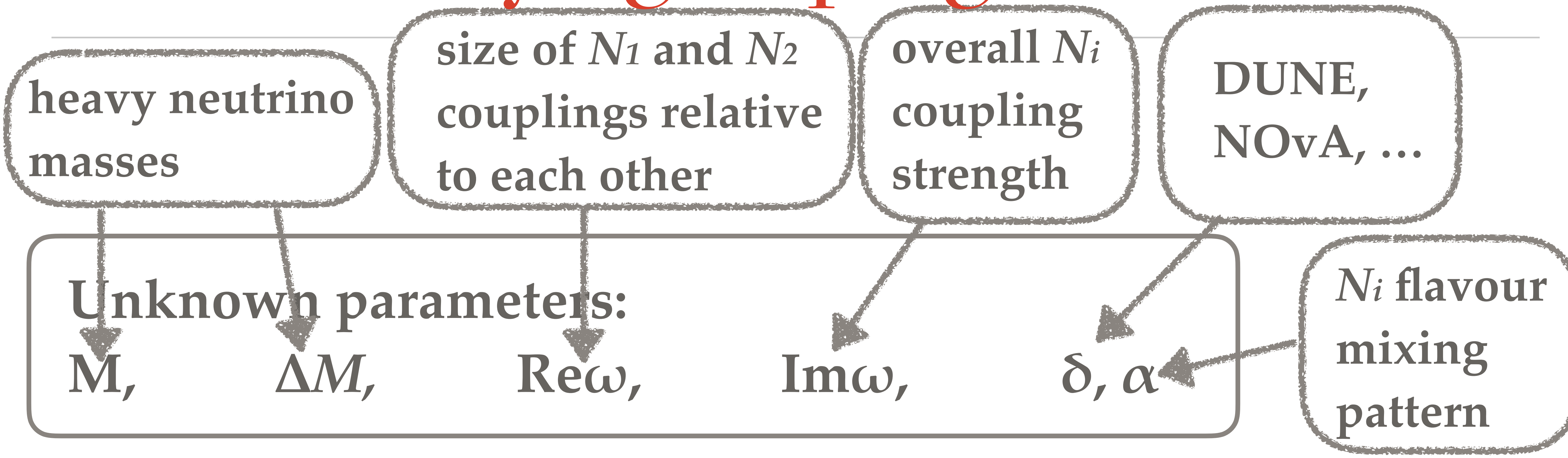


Hernandez et al 1606.06719,

Verifying Leptogenesis?



- In principle all parameters can be measured
  ⇒ fully testable model of neutrino masses and baryogenesis
- This requires a combination of collider/fixed target experiment data and ν-osc. data (and possibly $0\nu\beta\beta$)
  ⇒ poster child example for synergy between collider and long baseline programs!

Conclusions

- Low scale leptogenesis is inherently flavoured.
- Scenarios that are testable in collider experiments favour
  - an approximate *B-L* symmetry
  - strong hierarchies in the mixings with individual SM flavours
- The PMNS parameters provide information about the heavy neutrino mixing pattern. In the minimal model (2 RH neutrinos) these are fully predictive.
- In the minimal model all parameters in the Lagrangian can in principle be extracted from observables
  - testable model of neutrino masses and baryogenesis
  - synergies between collider/fixed target and long baseline programs (and possibly $0\nu\beta\beta$)

A Multi-Frontier Problem

Collider Probes of the origin of neutrino mass

neutrino oscillation experiments
mass differences, mixings…
… hierarchy, CP violation…
…light sterile neutrinos?

absolute neutrino
mass searches
(KATRIN ect.)

neutrinoless
double β decay:
Dirac or Majorana?

fixed target
experiments
(SHiP, NA62, …)

CMB and LSS :
absolute neutrino mass

CMB and BBN :
light sterile neutrinos?

IceCube
“neutrino astronomy”

Cosmic Neutrino
Background

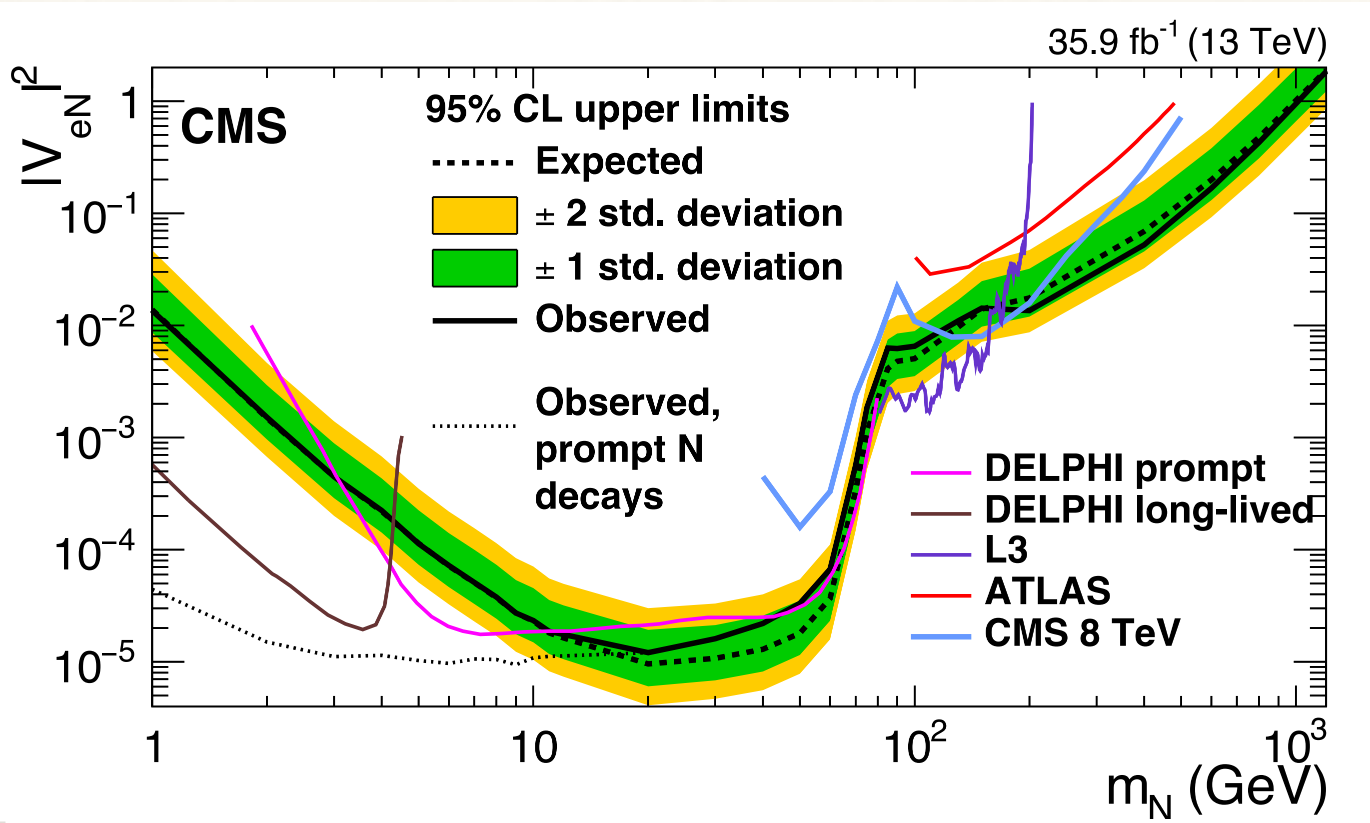
Leptogenesis?

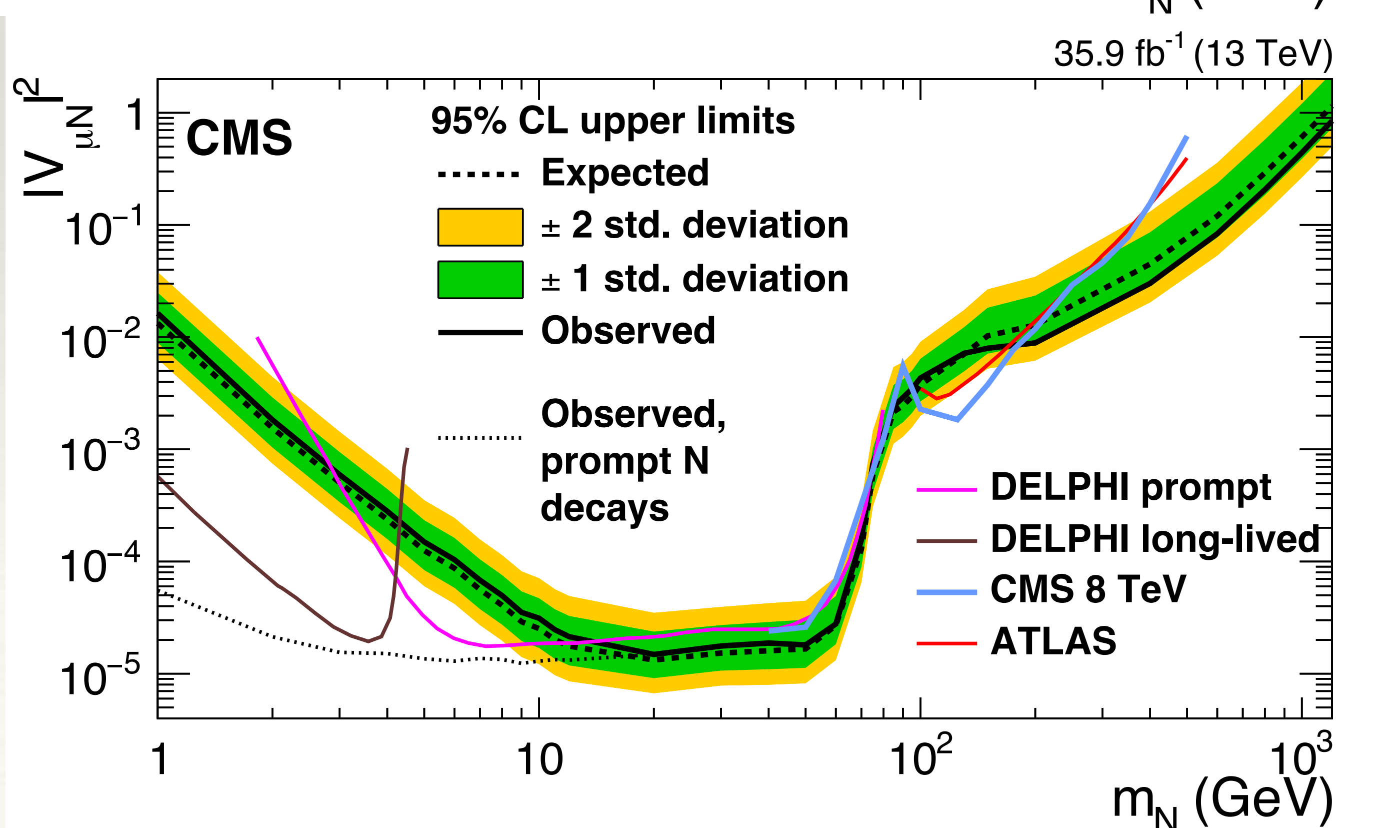
Sterile Neutrino
Dark Matter?

Backup Slides

Experimental Searches

Minimal Type I Seesaw



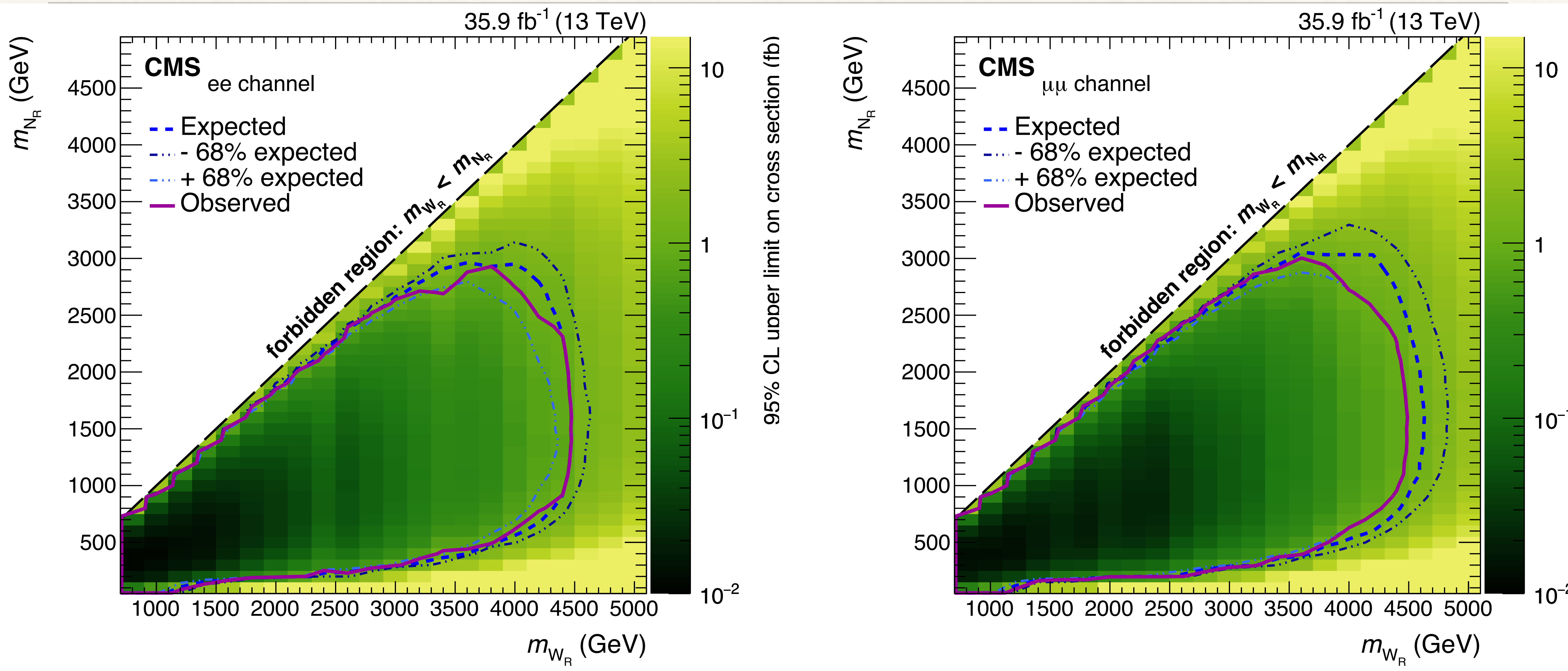


recent CMS results based on process

$$W \to N\ell \to \ell\ell\ell$$

from 1802.02965

Left-Right-Symmetric Model



recent CMS results 1803.11116 based on process

$$W_R \to \ell N \to \ell\ell W_{R^*} \to \ell\ell q\bar{q}'$$

Future Searches

- **LHC upgrades**
  trigger upgrades
  new detectors (e.g. MATHUSLA)

- **fixed target experiments**
  NA62
  SHiP

- **future colliders**
  ILC, FCC, CEPC, SPPC

recent review: Cai/Han/Li/Ruiz 1711.02180

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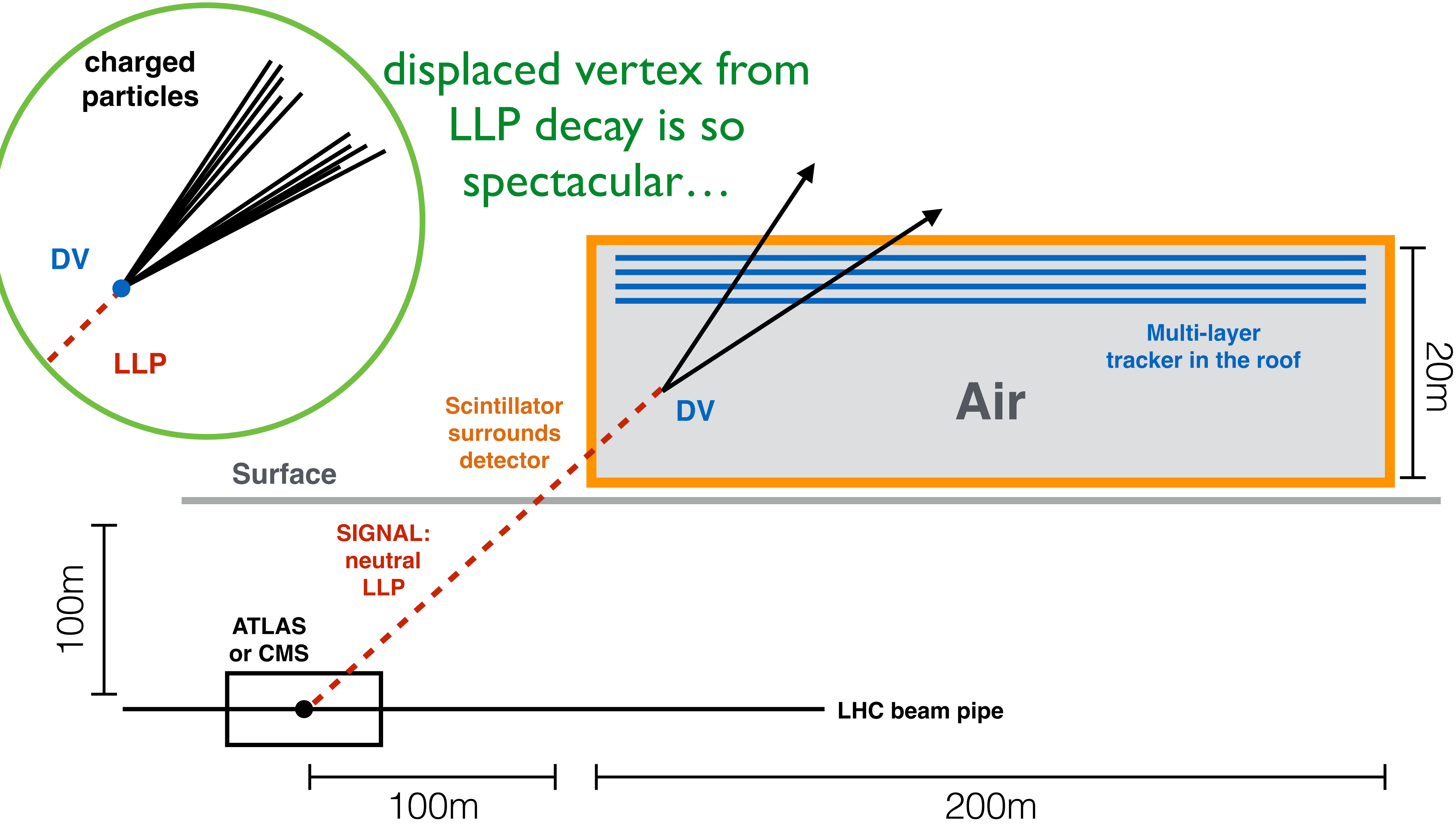
MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



slide by David Curtin

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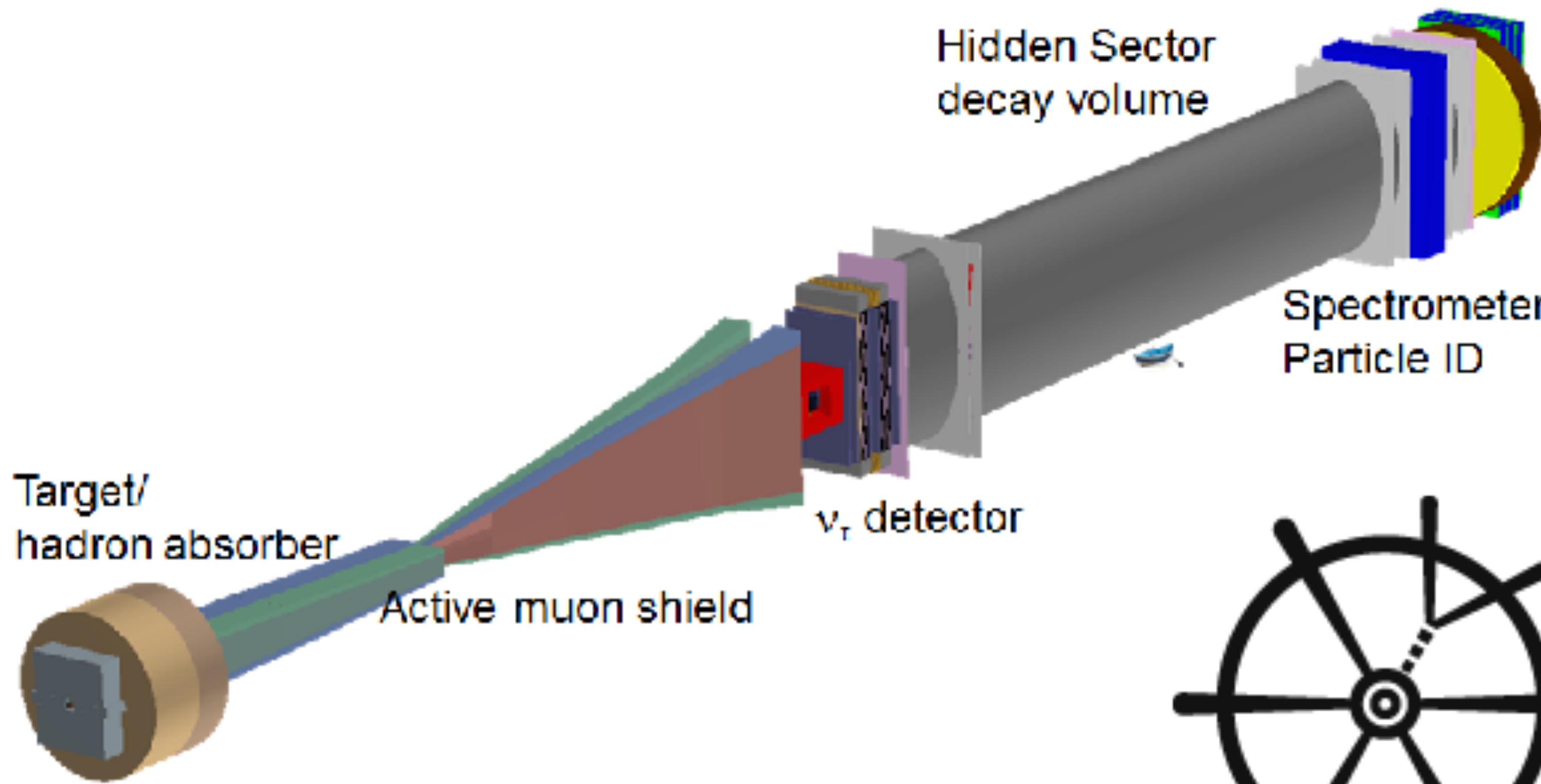
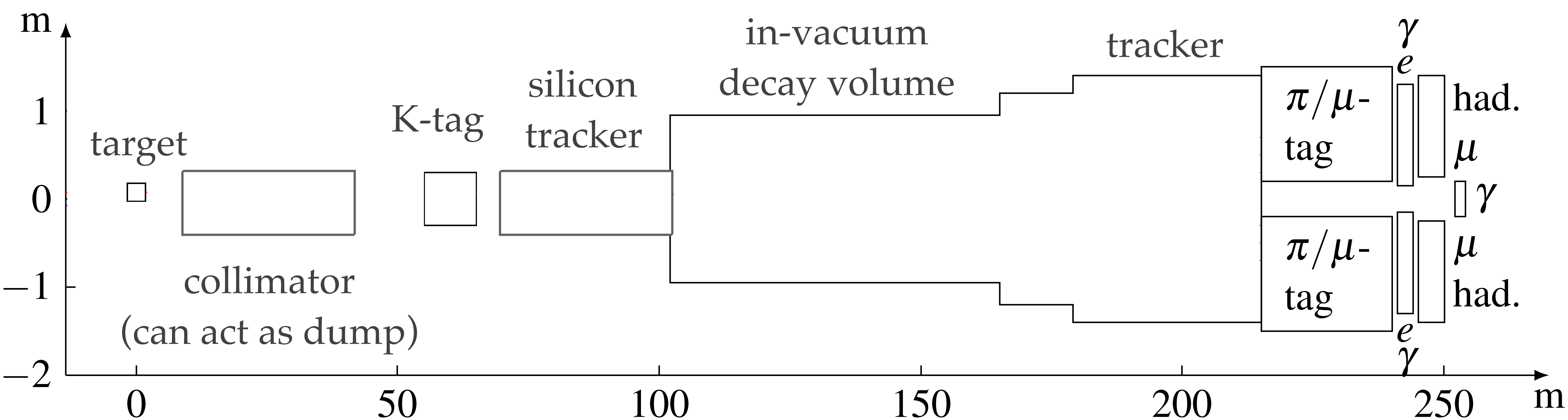


see 1504.04956 , 1504.04855

SHiP
Search for Hidden Particles

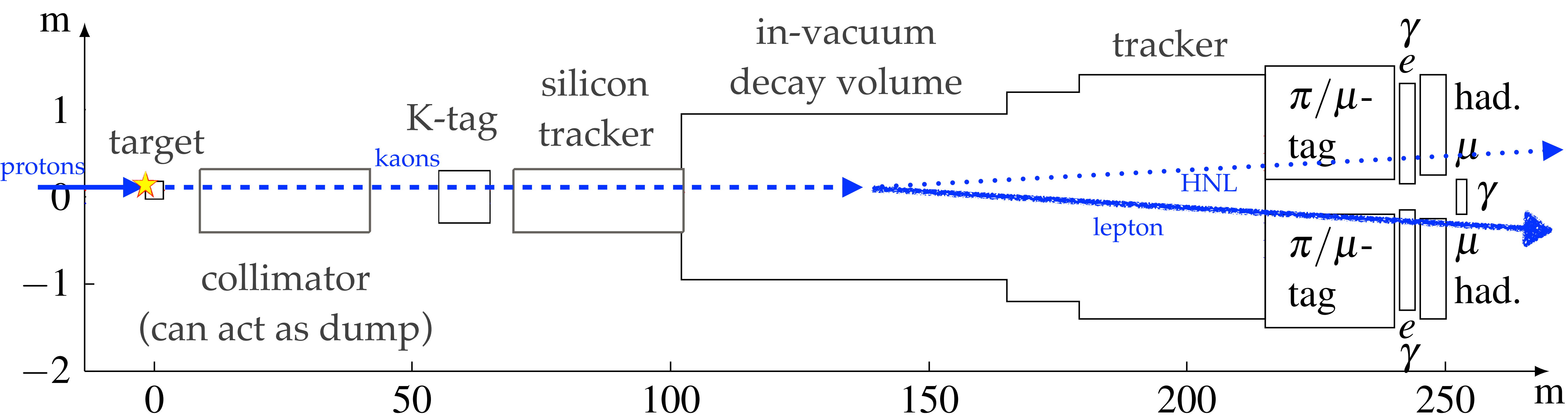
The NA62 Experiment



- **fixed target experiment in CERN's North Area**
- **primary purpose: measure kaon decay into pion + neutrino + antineutrino**

pictureFigure/picture from the NA62 collaboration

The NA62 Experiment

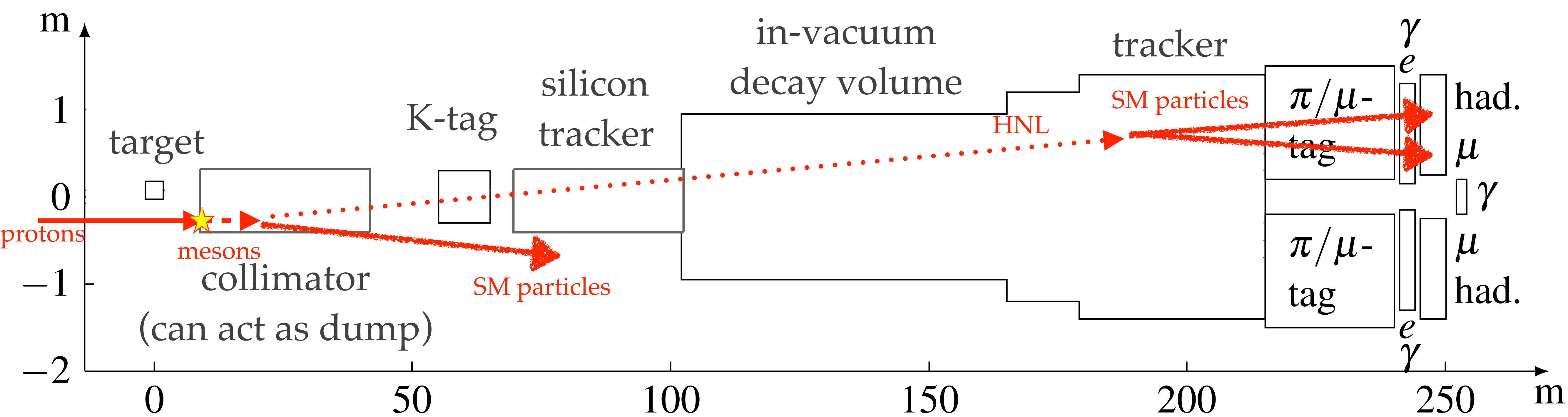


Target Mode: **cf. 1712.00297 for recent results**

- protons hit target ⇒ produce 75 GeV beam hadrons, leptons
- tag kaons
- kaons decay into HNL + lepton in the in-vacuum decay volume

  ⇒ **search for peak in lepton spectrum**

The NA62 Experiment

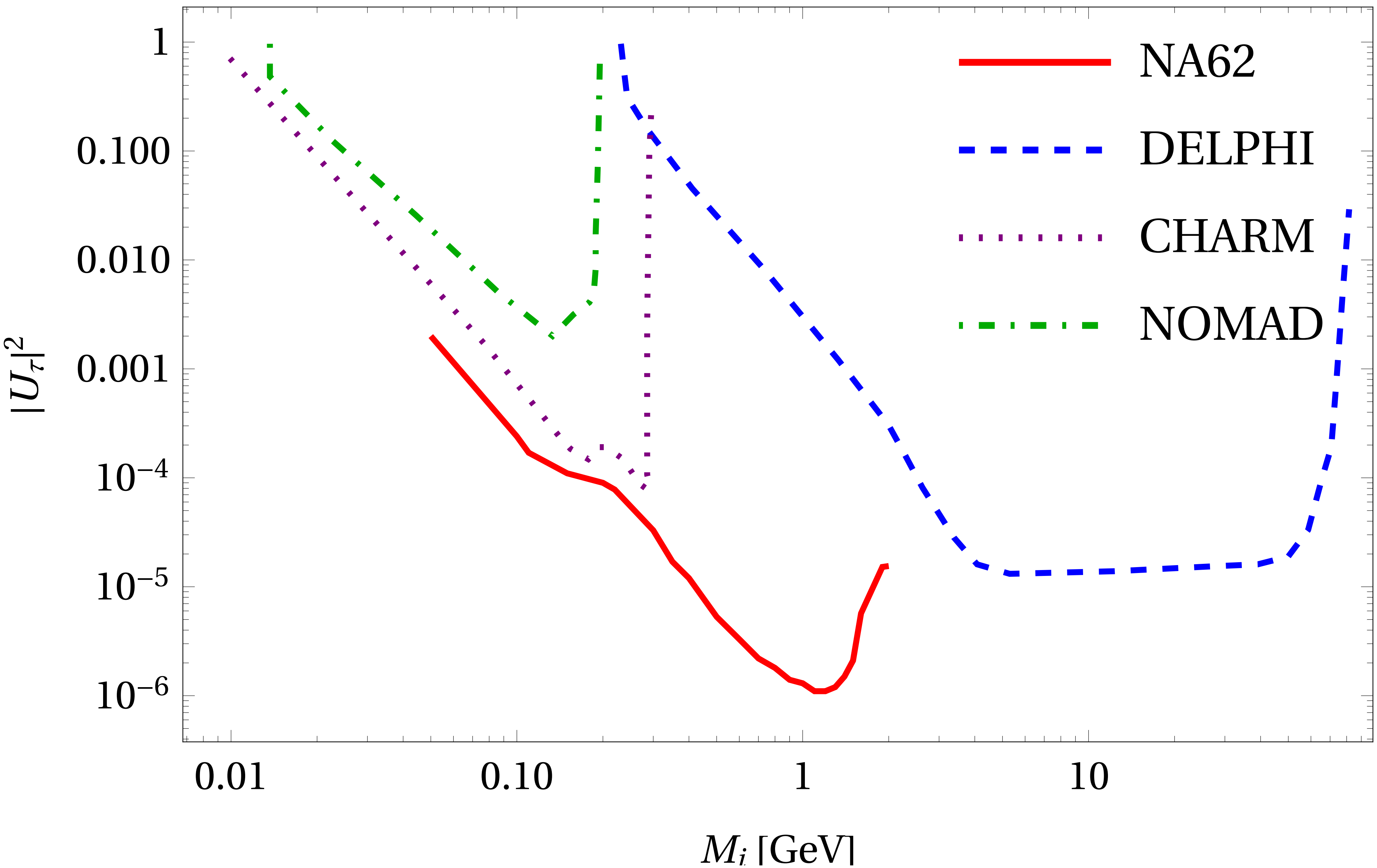


Dump mode

- target removed, protons hit collimator ⇒ produce mesons, leptons
- mesons / tauons decay into HNL + SM particles
- HNL pass all components and decay in the in-vacuum decay volume

⇒ **search for decay nothing → leptons/hadrons in vacuum chamber**

NA62 Dump Mode Sensitivity for Heavy Neutrinos



based on
[1801.04207]

Future Searches

- **LHC upgrades**
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  NA62
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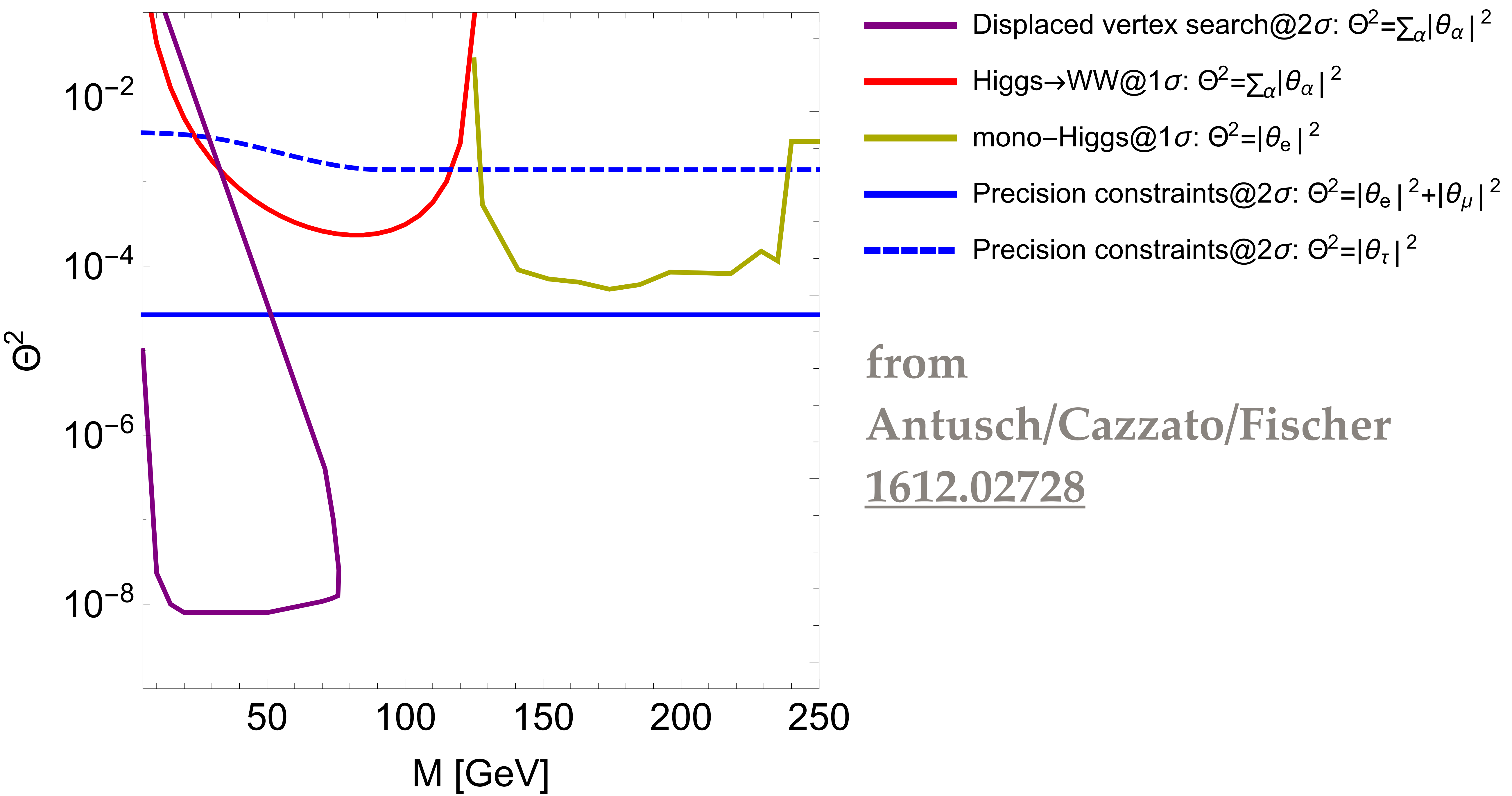
Future Lepton Colliders: Type I



from
Antusch/Cazzato/Fischer
1612.02728

The νMSM

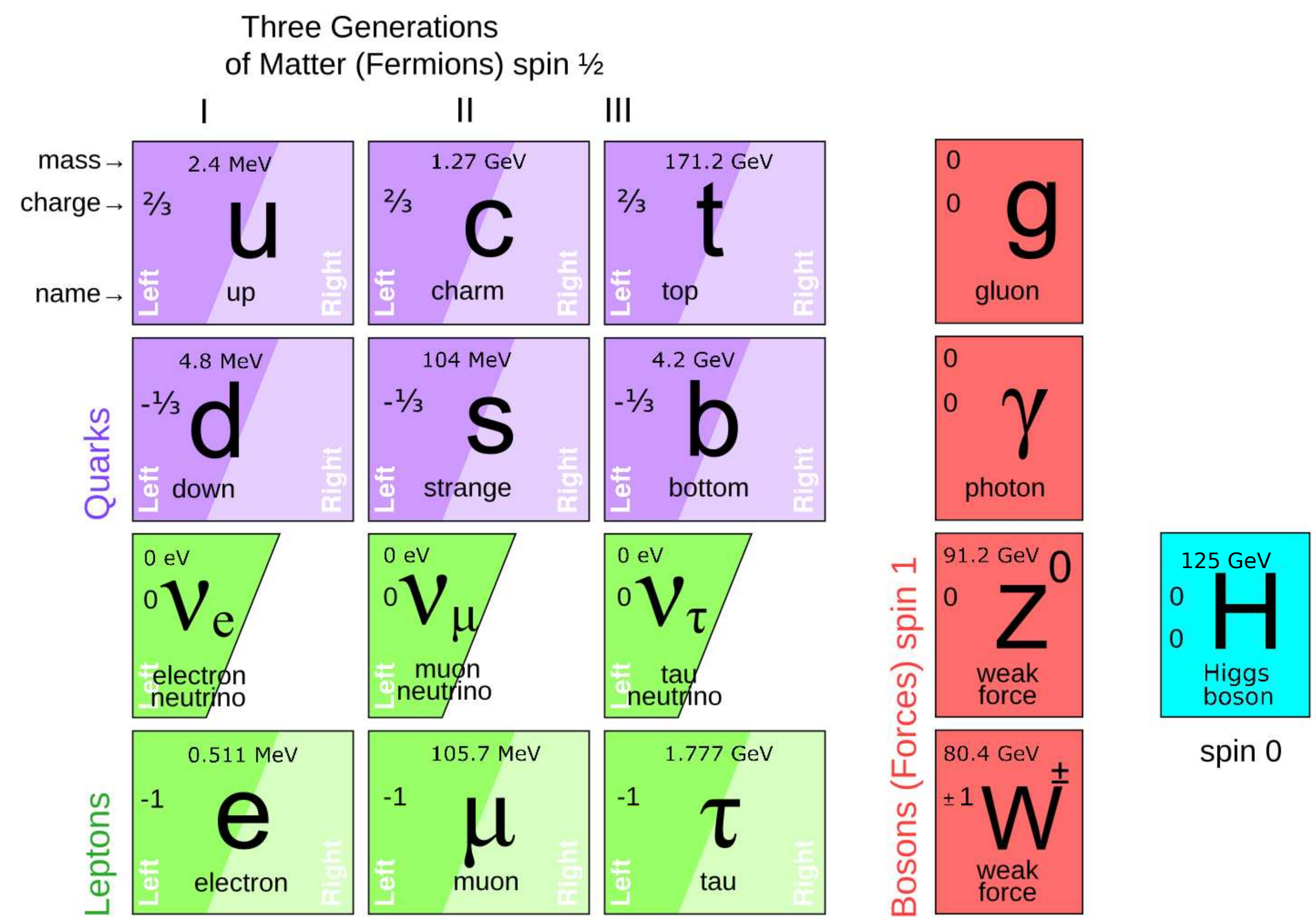
A Minimal Model: The νMSM

Pure Type I seesaw with RH Neutrinos below EW scale

Asaka/Shaposhnikov 0503065, 0505013

- **two RH Neutrinos have degenerate ~GeV masses**
  seesaw + leptogenesis

- **one has a ~keV mass and feeble couplings**
  Dark Matter candidate

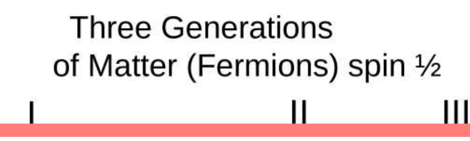


$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$
$$-\frac{1}{2}(\bar{\nu^c}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu^c_R)$$

A Minimal Model: The νMSM

Pure Type I seesaw with RH Neutrinos below EW scale

Asaka/Shaposhnikov 0503065, 0505013



- **No new scale**

  Shaposhnikov 0708.3550

  Higgs potential, flavour physics may indicate this!

- **Common origin of EW and seesaw scale?**

  Khoze/Ro 1307.3764

- **Result of approximate B-L conservation?**

  Shaposhnikov 0605047

- **Ockham's razor:**

  ν-masses + baryogenesis + DM

  Canetti/MaD/Frossard/Shaposhnikov 1208.4607