Marco Drewes, Université catholique de Louvain

The minimal seesaw: Turning every stone

09/11/2018

NuTheories Workshop

University of Pittsburgh
Pittsburgh, USA

Where is the New Physics hiding?

Where is the New Physics hiding?

A small coupling explains why we have not seen New Physics.

It also tends to make particles long lived!

Coupling

Mass

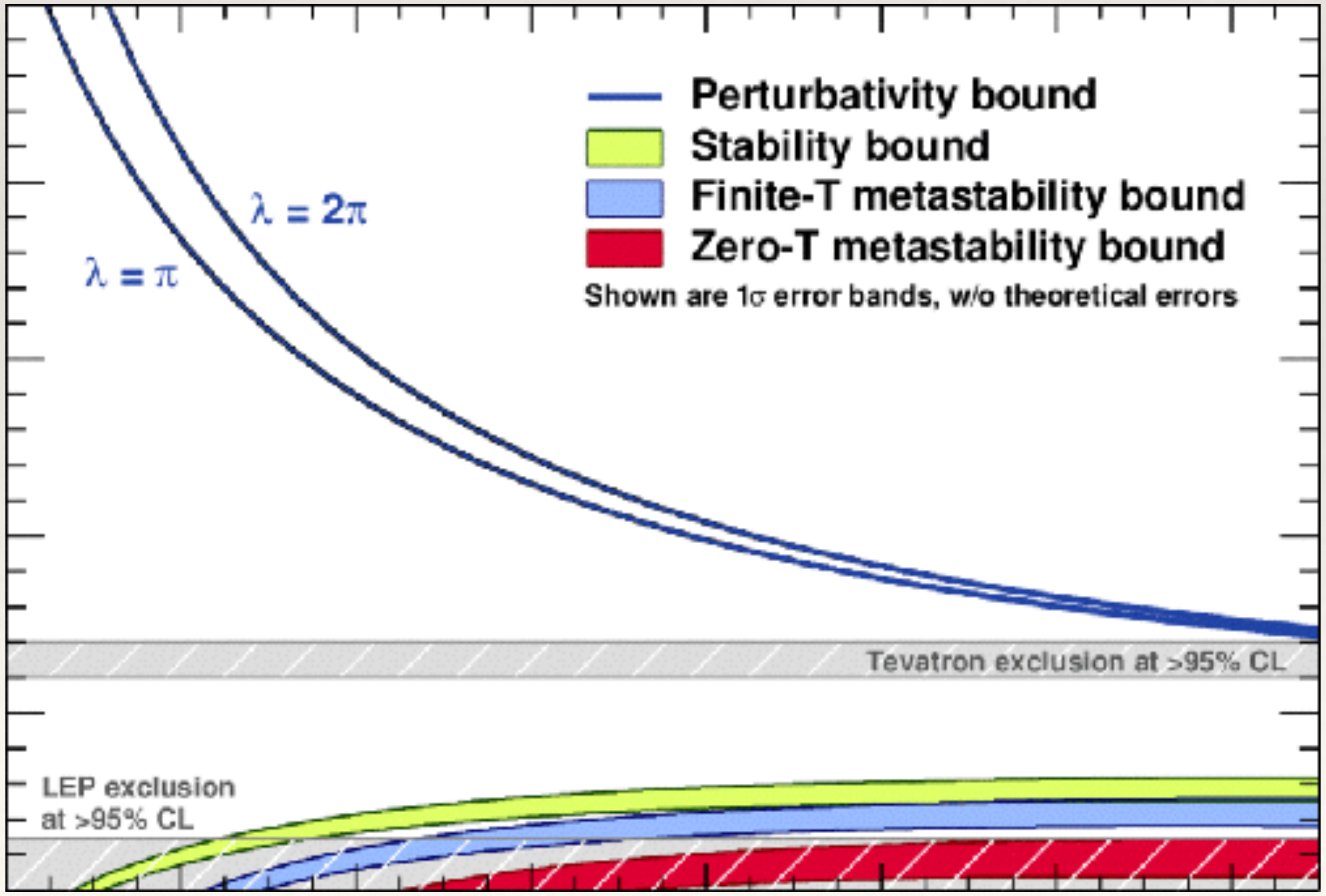
Where is the New Physics hiding?

Hierarchy Problem

- Adding heavy states leads to electroweak hierarchy problem
- No problem if all masses below electroweak scale Bardeen 95, Shaposhnikov 07

Higgs properties / vacuum stability

- Higgs properties are just in critical regime



Ellis et et al 09

Degrassi et al 1205.6497

Where is the New Physics hiding?

Hierarchy Problem

- A … heavy states leads to electroweak hierarchy problem
- N … es below electroweak scale

Bardeen 95,
Shaposhnikov 07

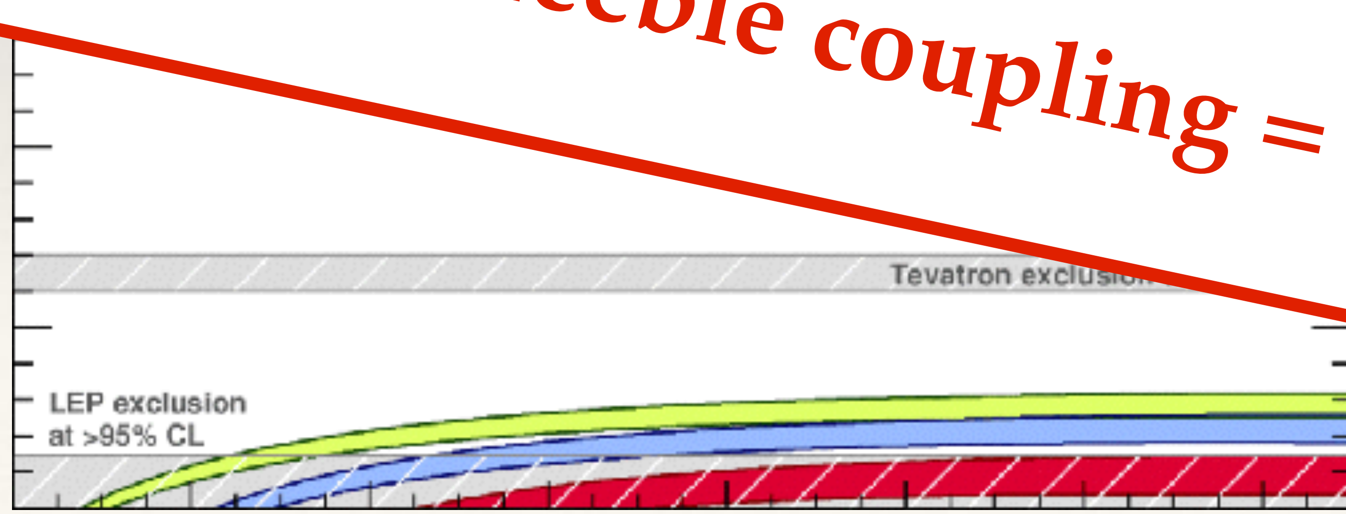
Hi…

-

Points to relatively light New Physics

Must be weakly coupled to avoid discovery

Low mass + feeble coupling = LLP!

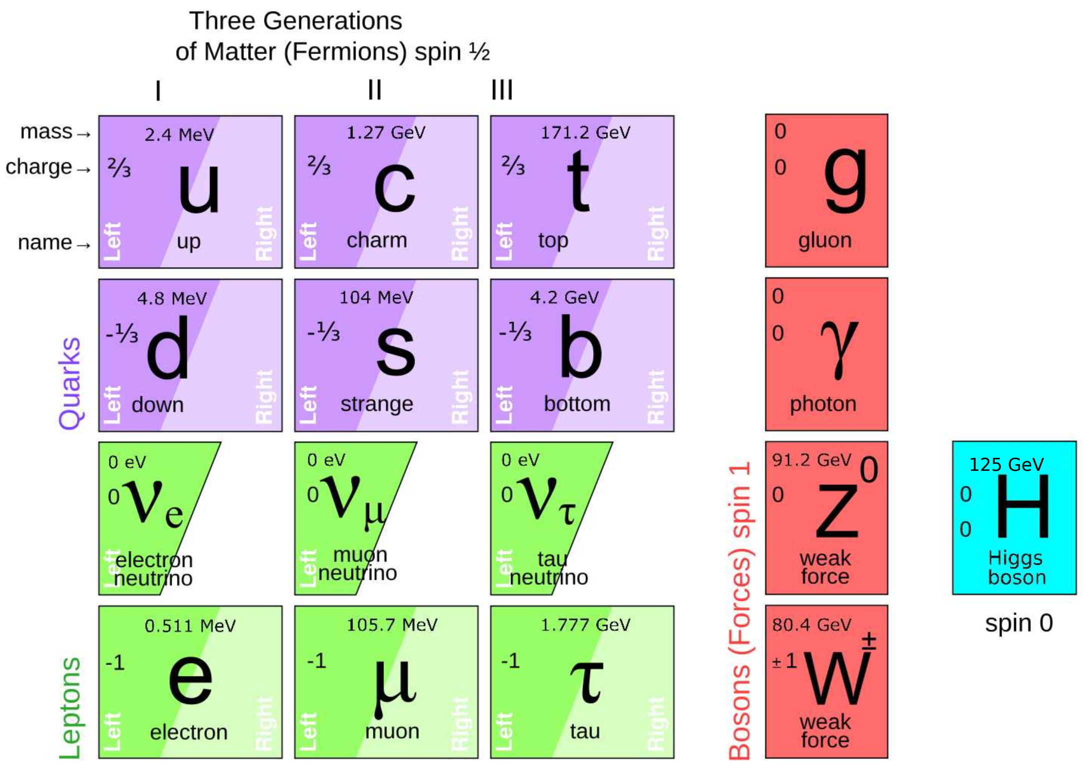


Ellis et et al 09

Degrassi et al 1205.6497

Example: Low Scale Seesaw (type I)

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



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

May explain

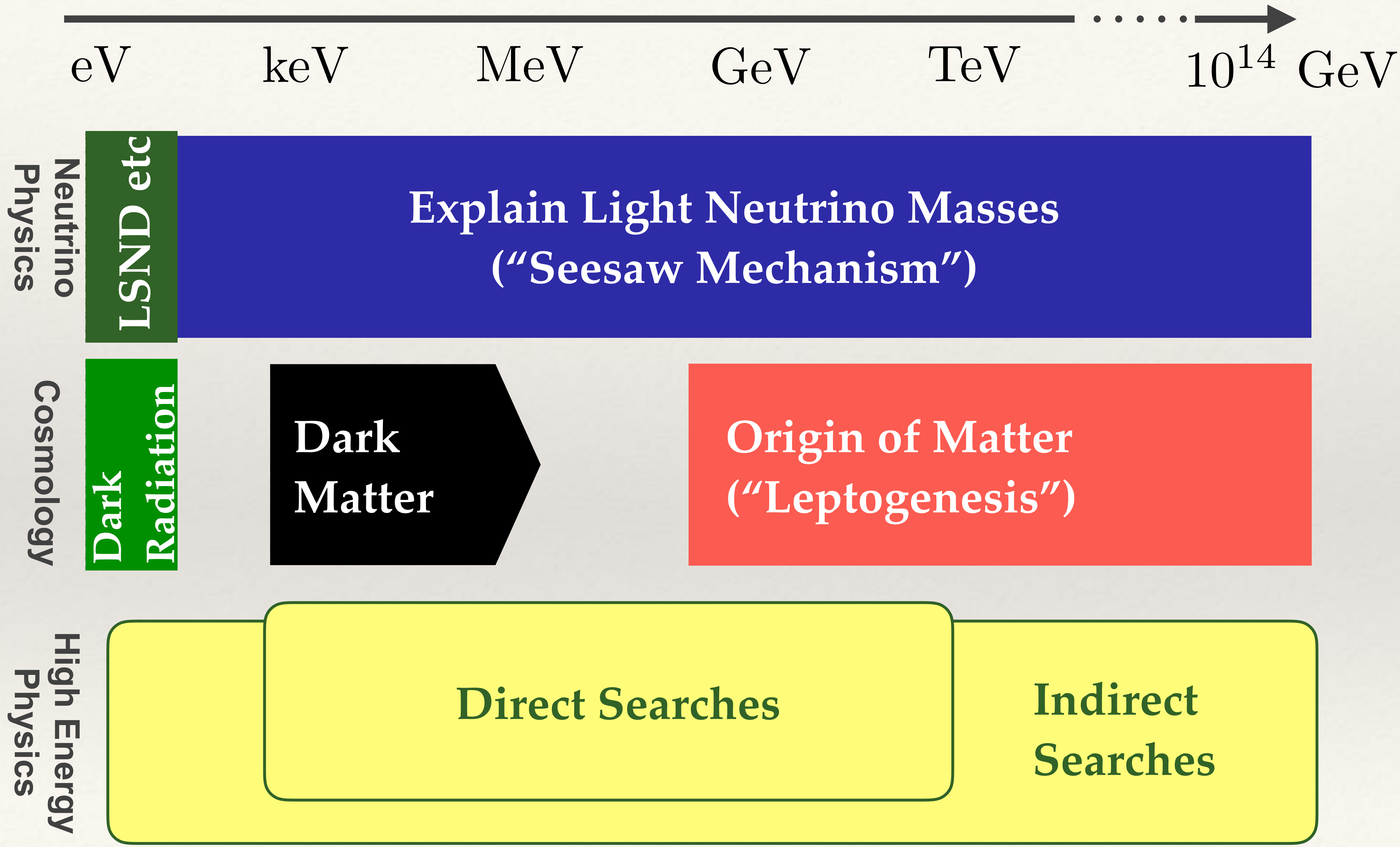
- **Neutrio masses**
- **Leptogenesis**
- **Dark Matter**
- **Oscillation anomalies**

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



Overview

- Motivation
- Bounds from cosmology
- The νMSM: a “fully testable” model
- Optimising the LHC main detectors
- Additional detectors: MATHUSLA
- Fixed Target: NA62
- Utilising heavy ion runs

Overview

Motivation

Bounds from cosmology

The νMSM: a “fully testable” model

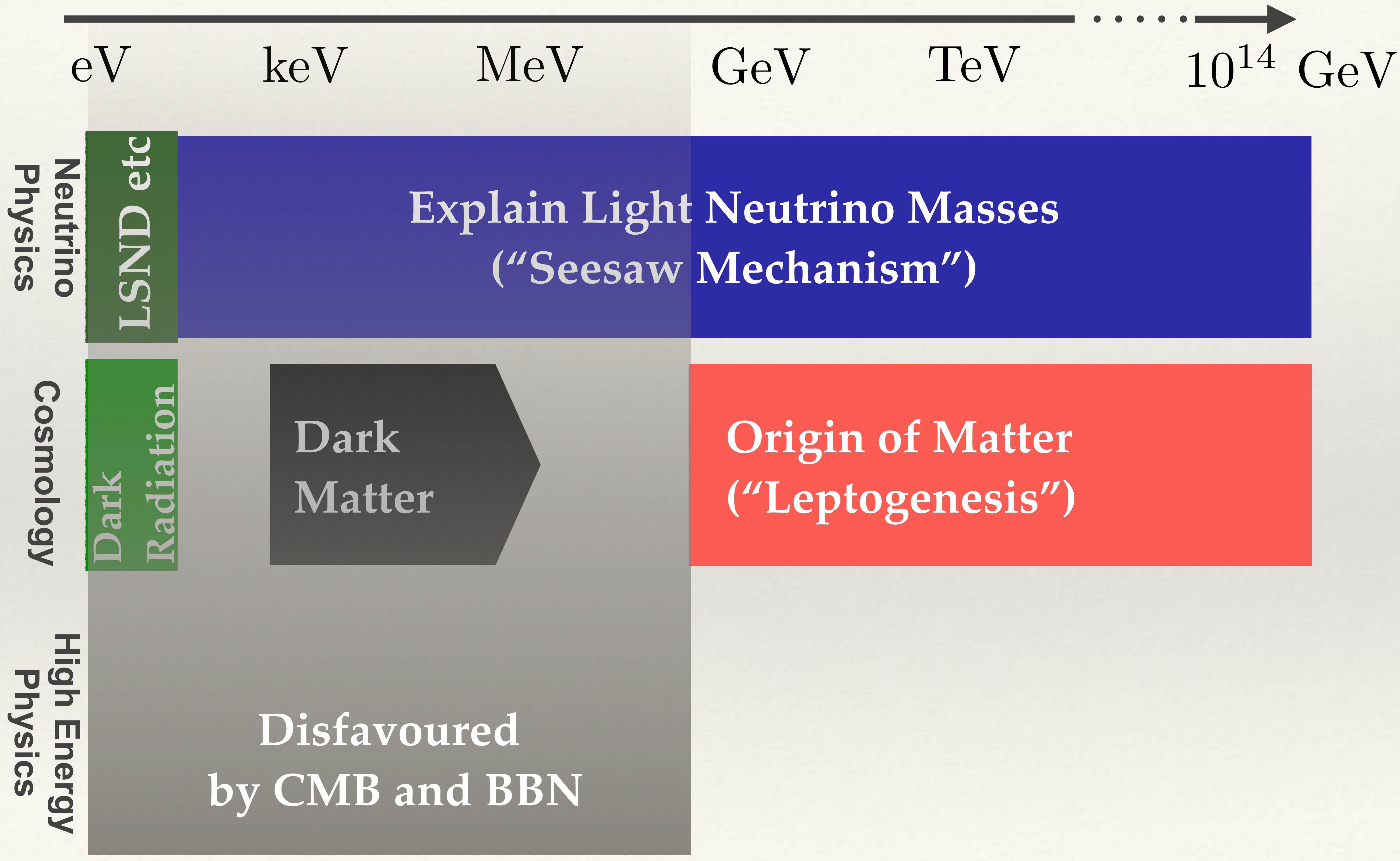
Optimising the LHC main detectors

Additional detectors: MATHUSLA

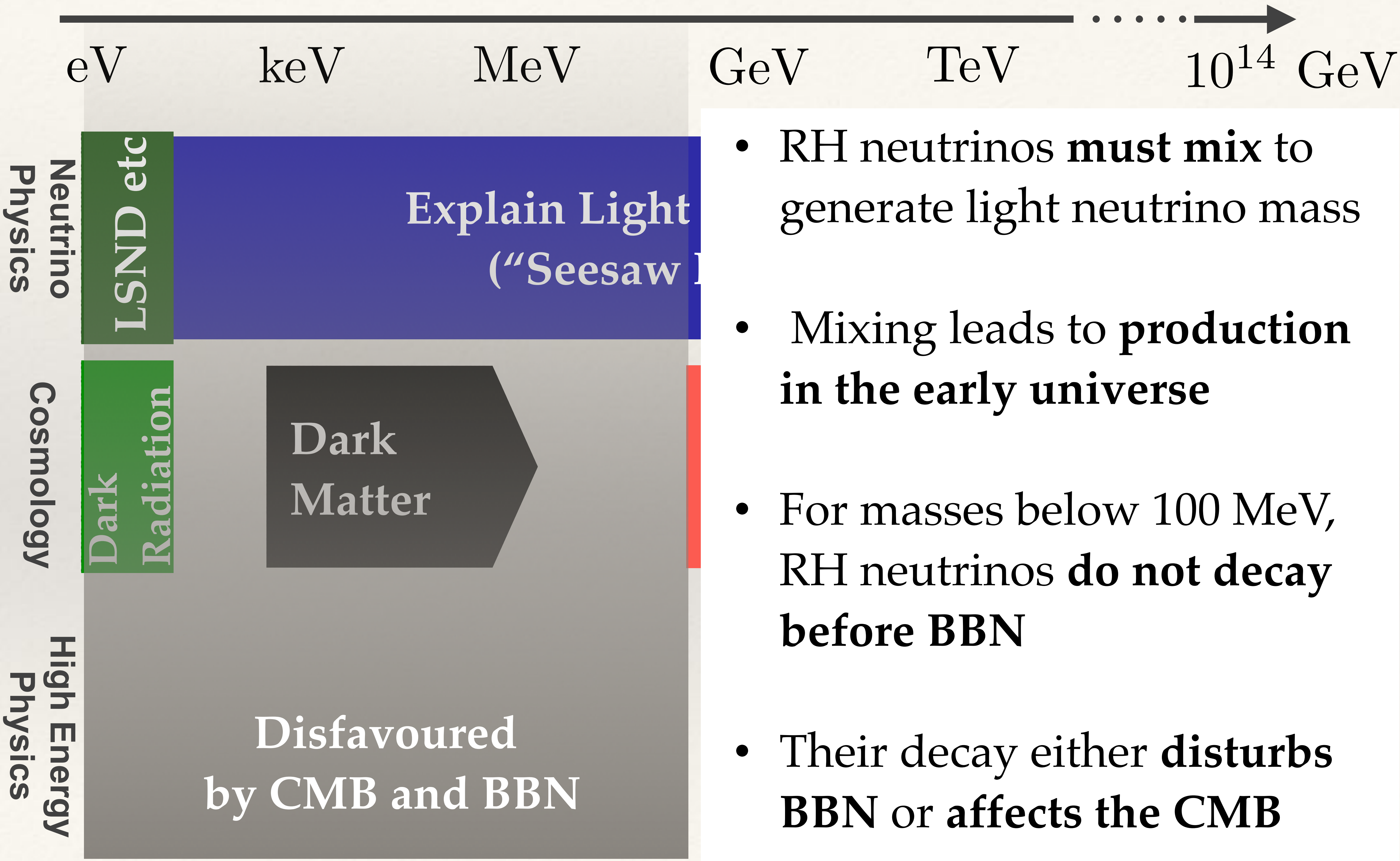
Fixed Target: NA62

Utilising heavy ion runs

BBN + CMB + ν-Osc. + Fixed Target

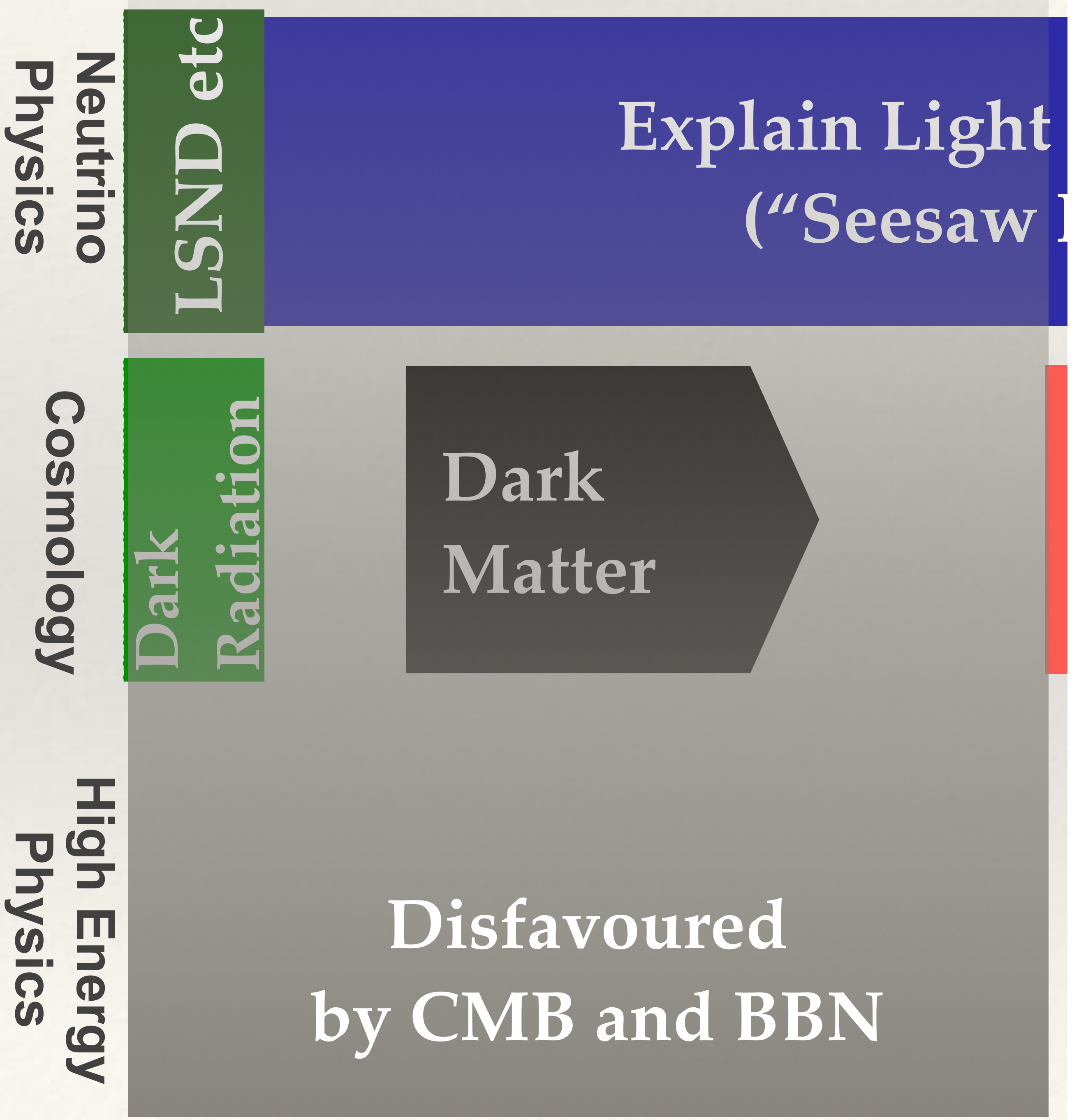


BBN + CMB + ν-Osc. + Fixed Target

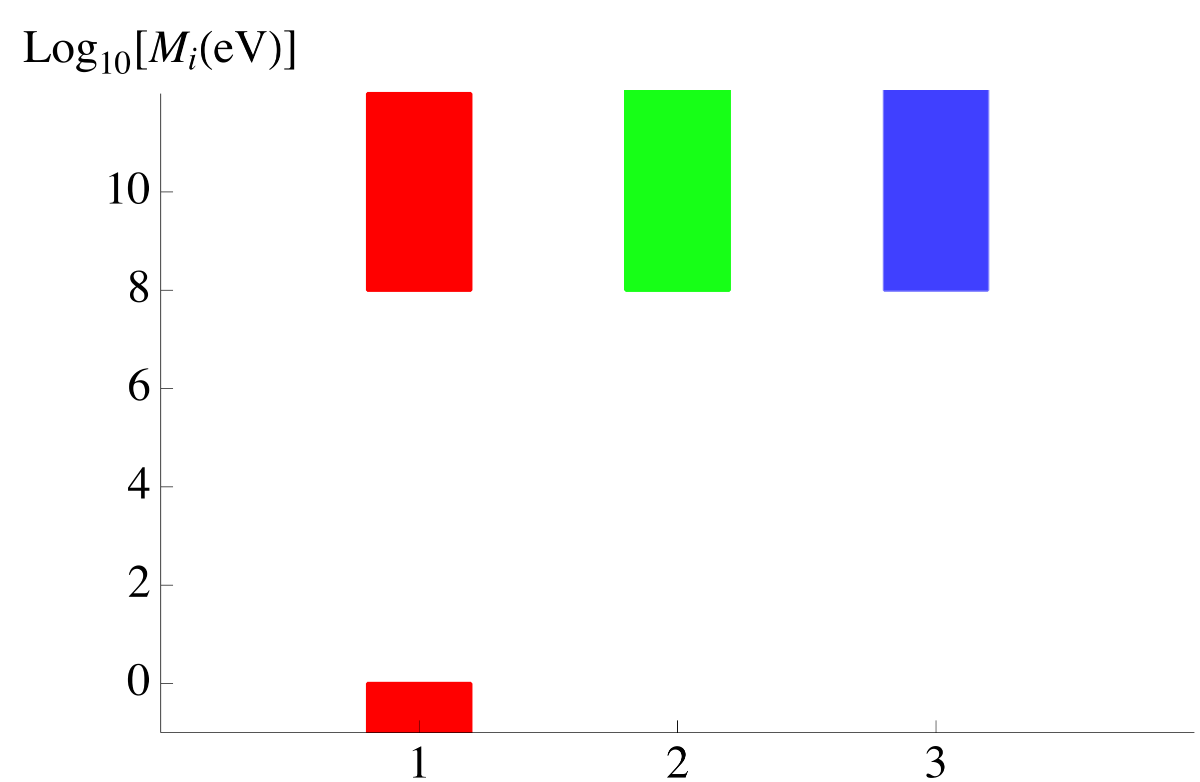


- RH neutrinos **must mix** to generate light neutrino mass
- Mixing leads to **production in the early universe**
- For masses below 100 MeV, RH neutrinos **do not decay before BBN**
- Their decay either **disturbs BBN** or **affects the CMB**

BBN + CMB + ν-Osc. + Fixed Target

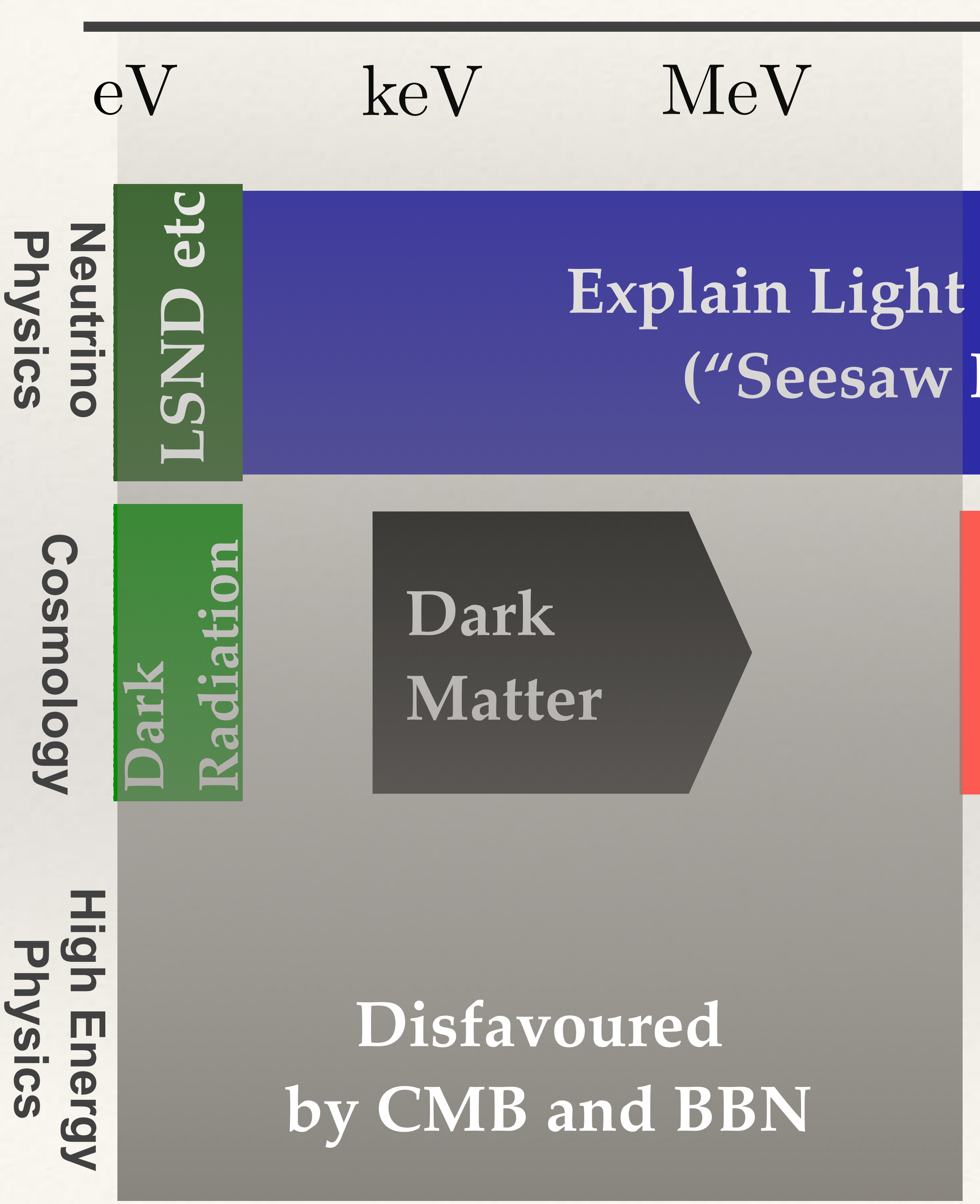


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} > 10^{-3}$ eV, three RHN reach equilibrium

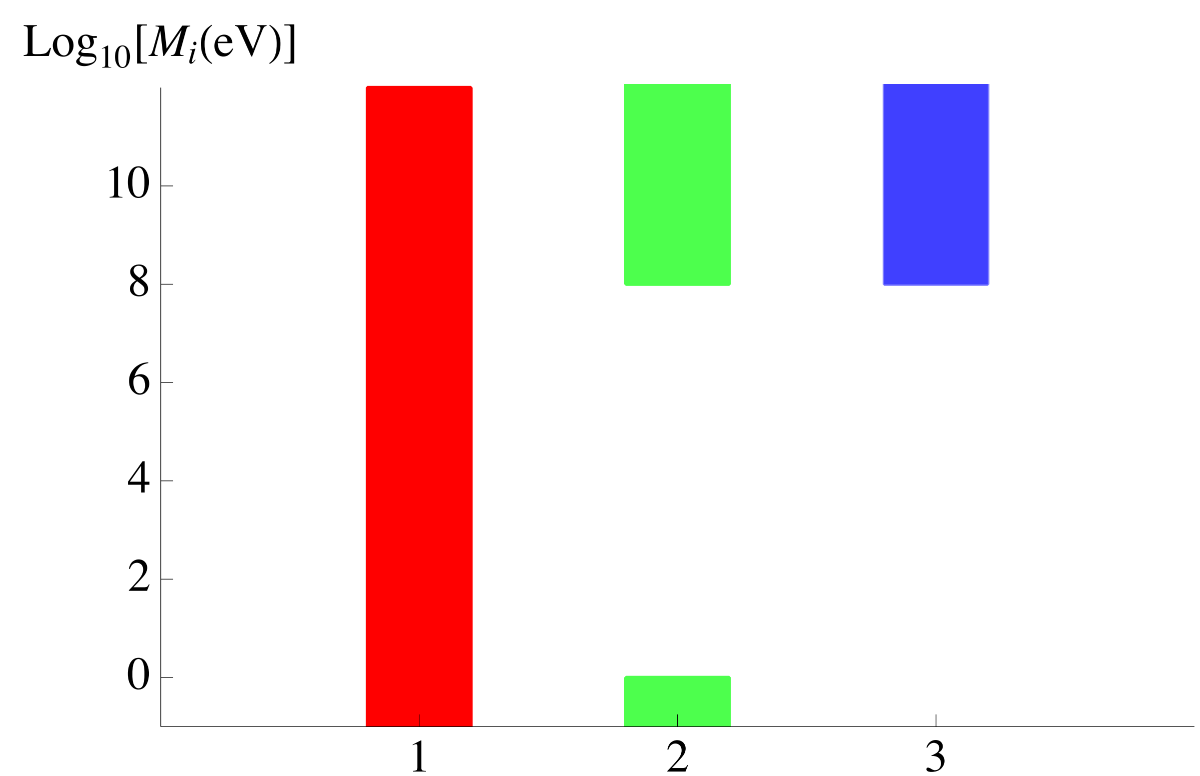


Hernandez/Kekic/Lopez-Pavon 1406.2961

BBN + CMB + ν-Osc. + Fixed Target



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



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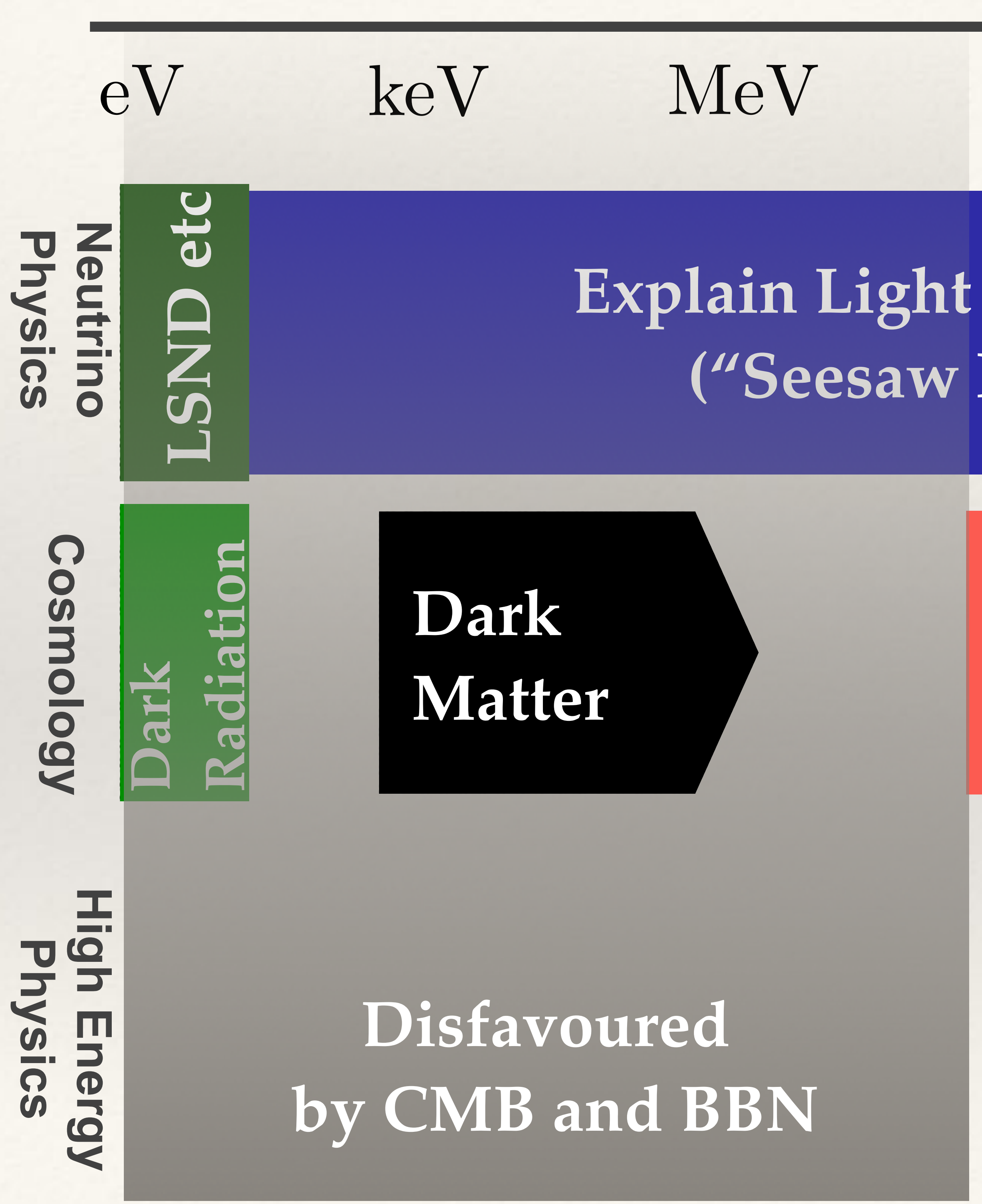

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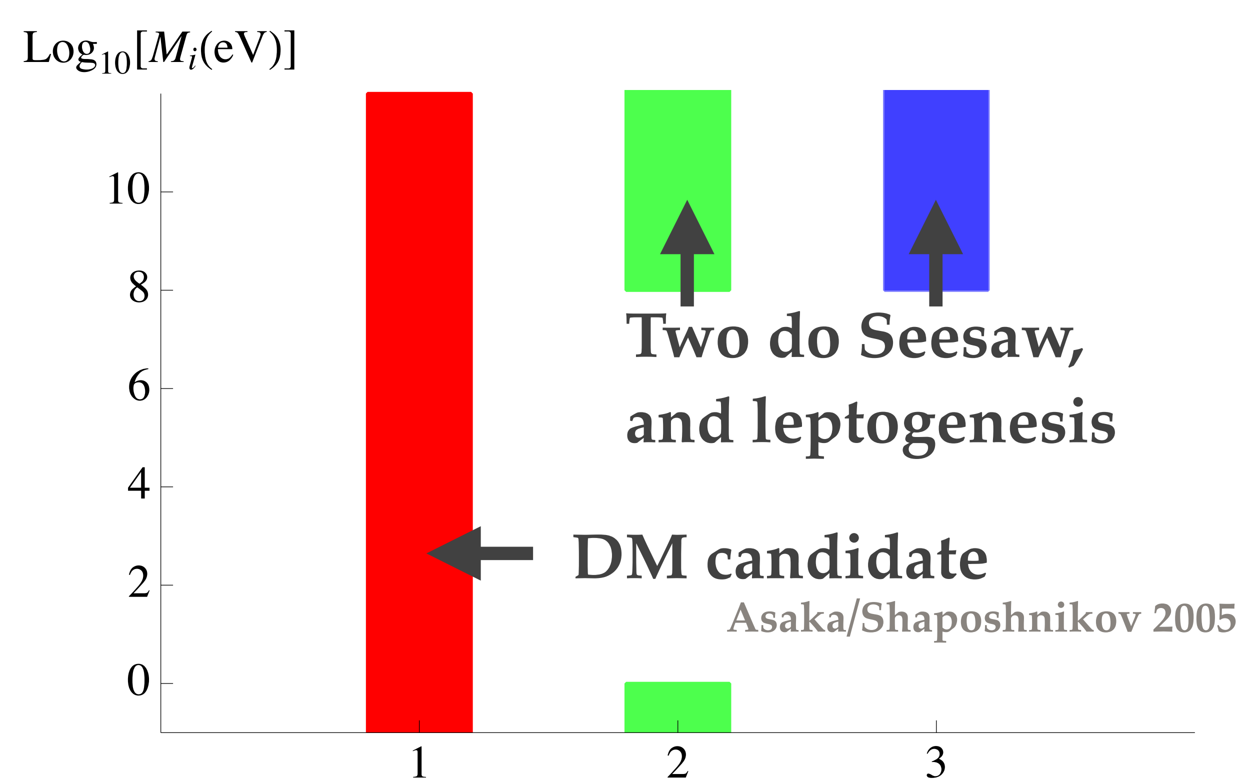


Hernandez/Kekic/Lopez-Pavon 1406.2961

A Multi-Frontier Problem

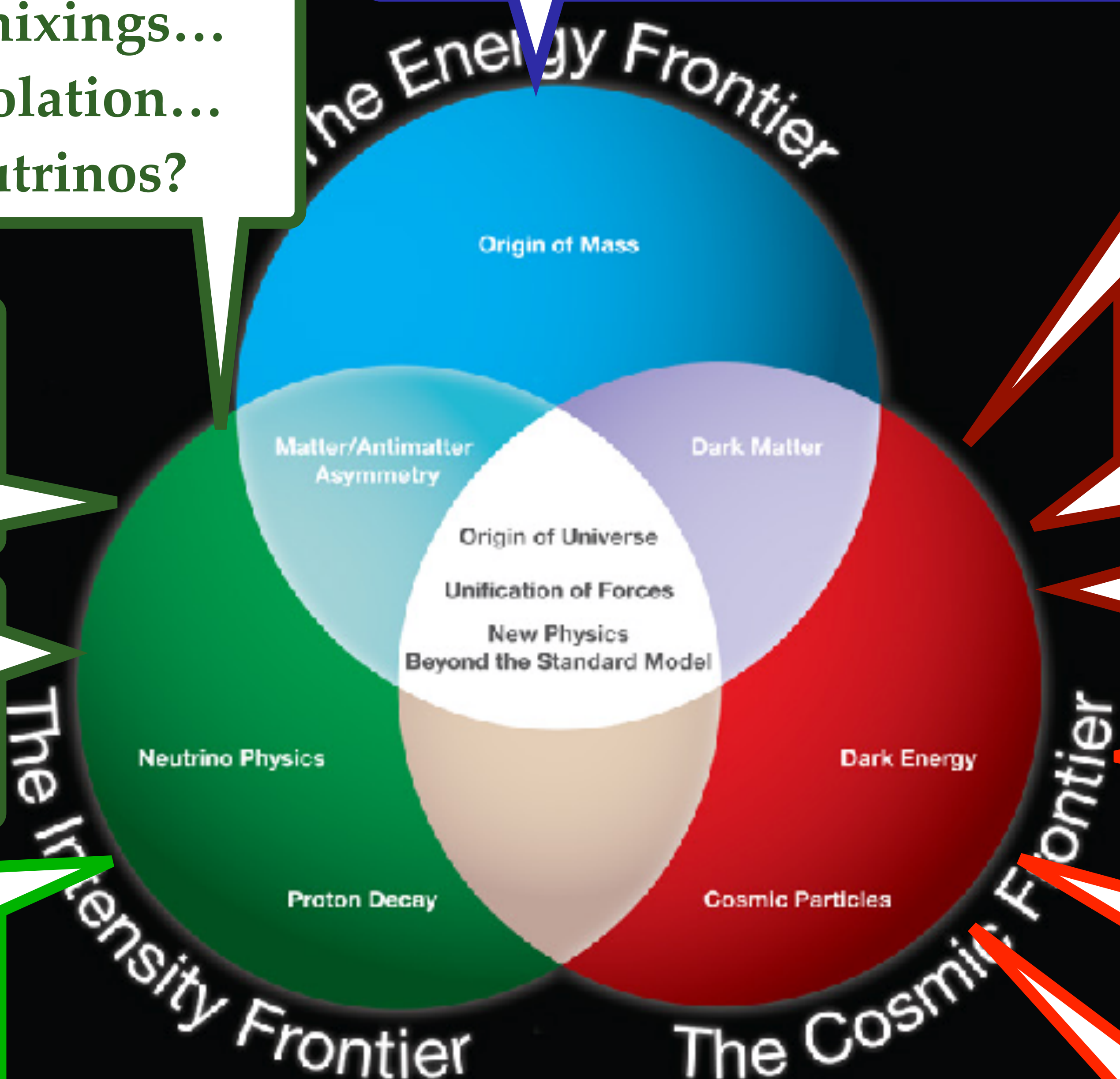
Collider Probes of the origin of neutrino mass

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?

Overview

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Bounds from cosmology

The νMSM: a "fully testable" model

Optimising the LHC main detectors

Additional detectors: MATHUSLA

Fixed Target: NA62

Utilising heavy ion runs

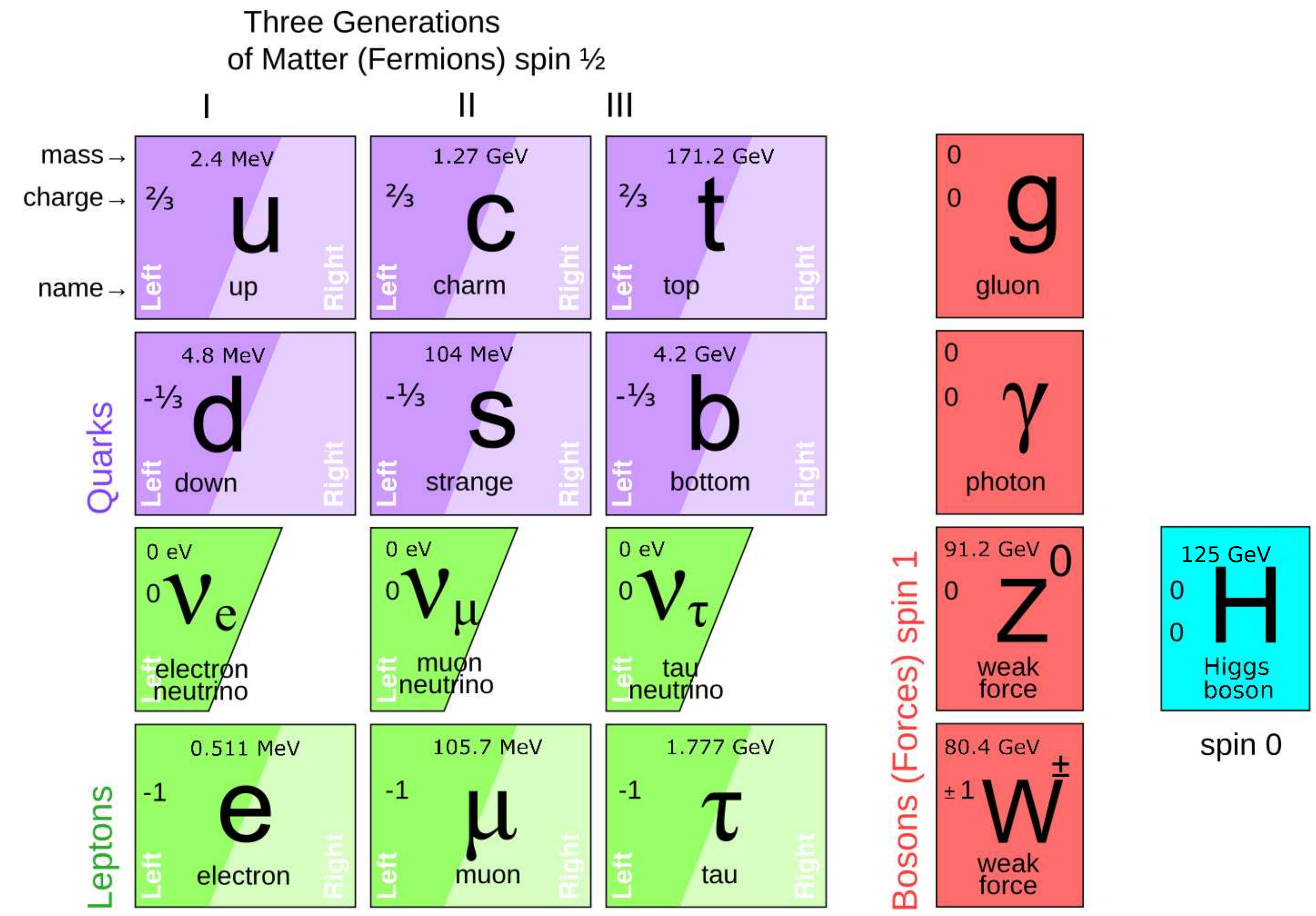
A Minimal Model: The νMSM

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



νMSM from B-L Violation

Shaposhnikov 06

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

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

B-L **violating parameters**

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

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Vacuum metastable

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

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leptogenesis:
mass degeneracy for free for pseudo Dirac

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Dark Matter:
lighter (keV) mass
feeble coupling

light ν masses: pseudo Dirac pair; feebly coupled sterile neutrino

B-L **violating parameters**

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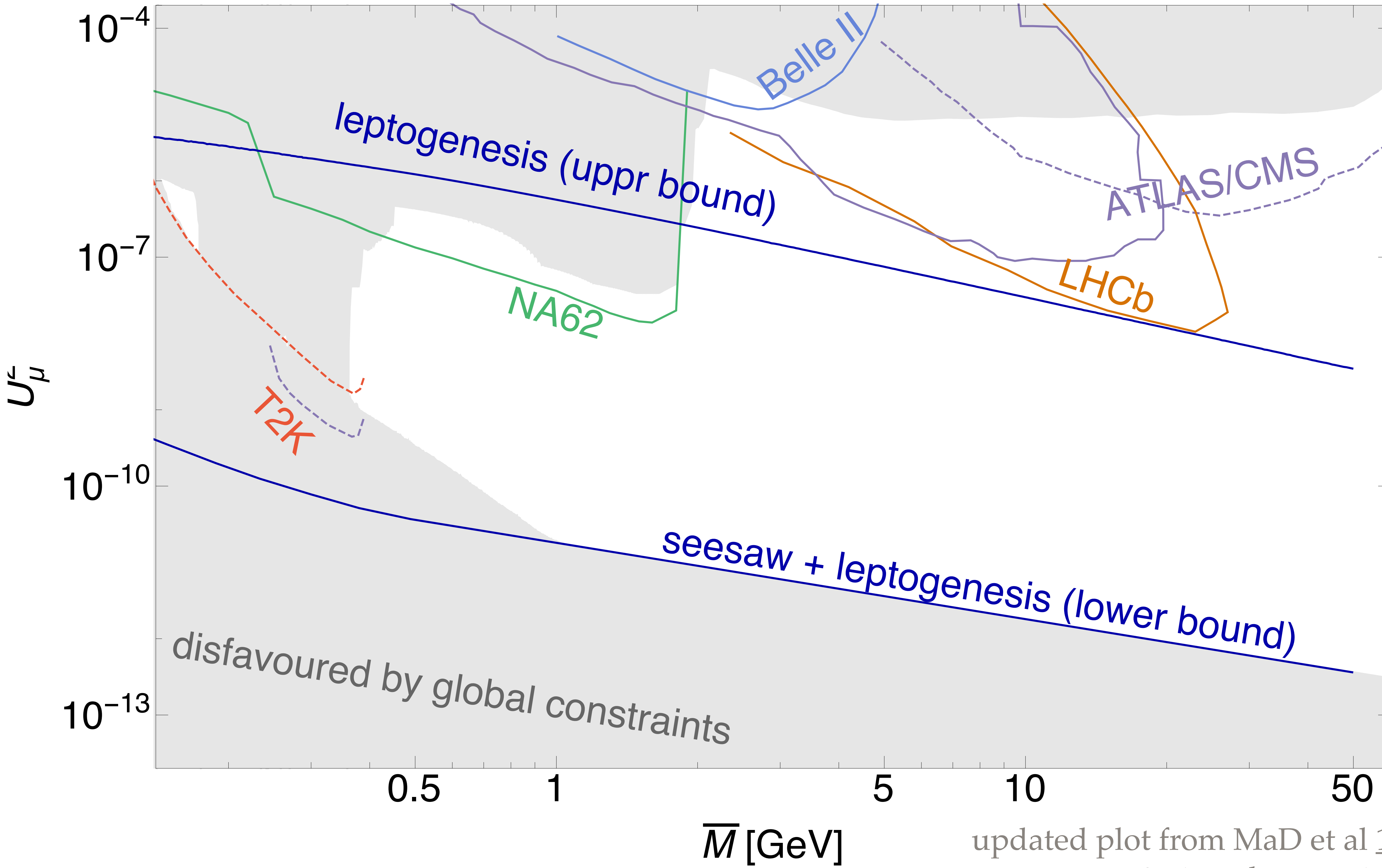
Global Constraints in the νMSM

Effective theory for νMSM collider/fixed target phone:

Type I seesaw with two RH Neutrinos below EW scale

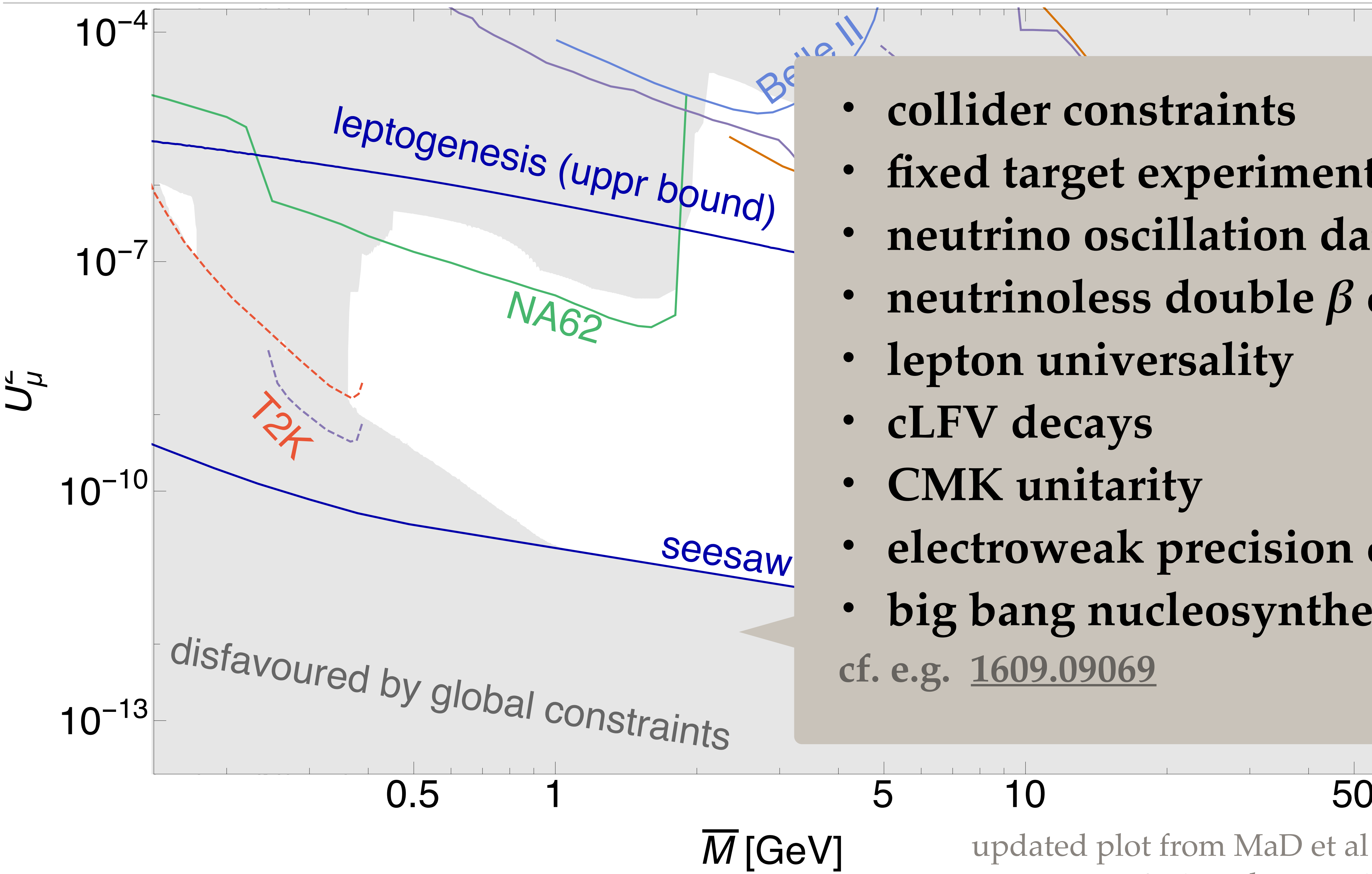
[observational constraints on DM candidate (cf. e.g. 1602.04816, 1807.07938) imply that it must have very feeble couplings]

Global Constraints in the νMSM



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

Global Constraints in the νMSM



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

cf. e.g. 1609.09069

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

Full Testability of the νMSM

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$$F = \frac{1}{v} U_\nu \sqrt{m_\nu^{\rm diag}} \mathcal{R} \sqrt{M^{\rm diag}}$$ Casas/Ibarra 01

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Casas/Ibarra 01

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

Full Testability of the νMSM

Effective theory for νMSM collider/fixed target phone:

Type I seesaw with two RH Neutrinos below EW scale

Unknown parameters:

M, ΔM, **Re**ω, **Im**ω, δ, α

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

Casas/Ibarra 01

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Full Testability of the νMSM

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

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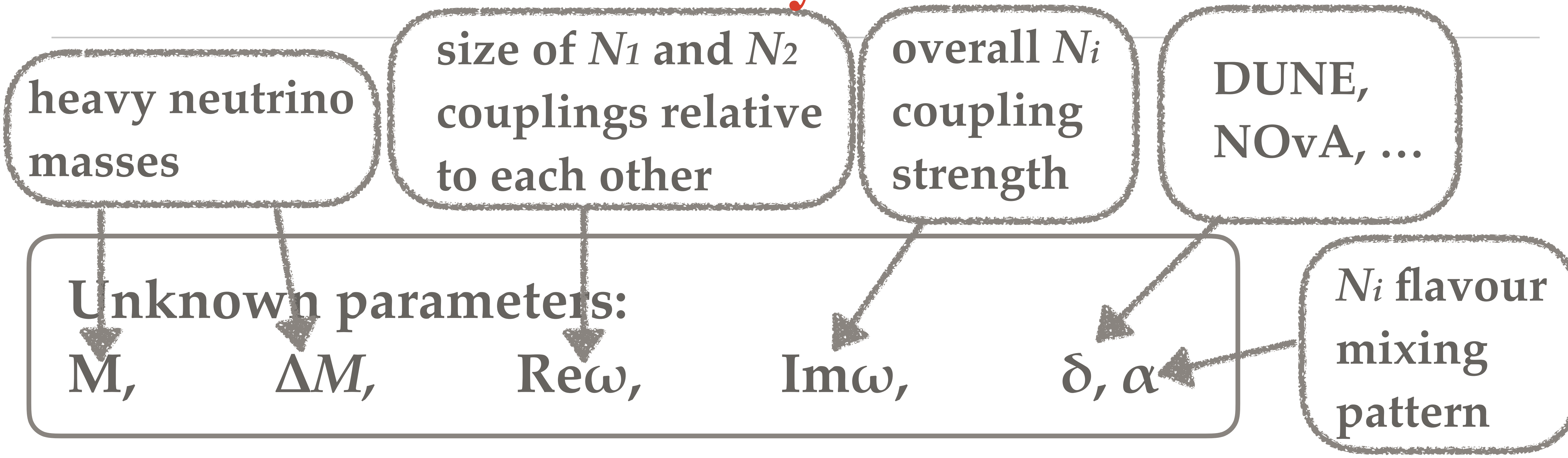
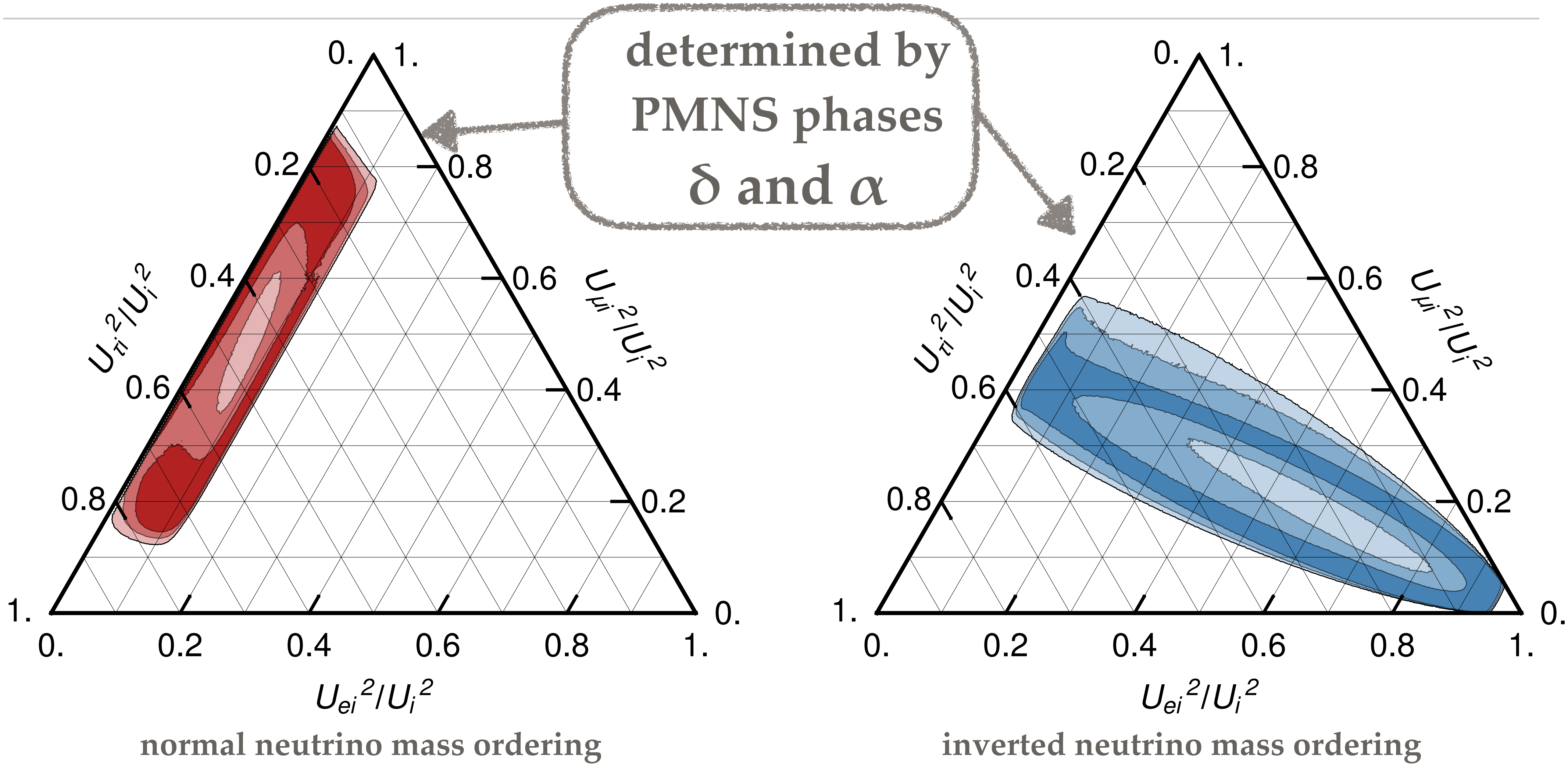
Full Testability of the νMSM



- 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 0νββ)
  ⇒ poster child example for synergy between collider and long baseline programs! cf. Hernandez et al 1606.06719, MaD et al 1609.09069

Current Status: Constraints from ν-oscillation Data

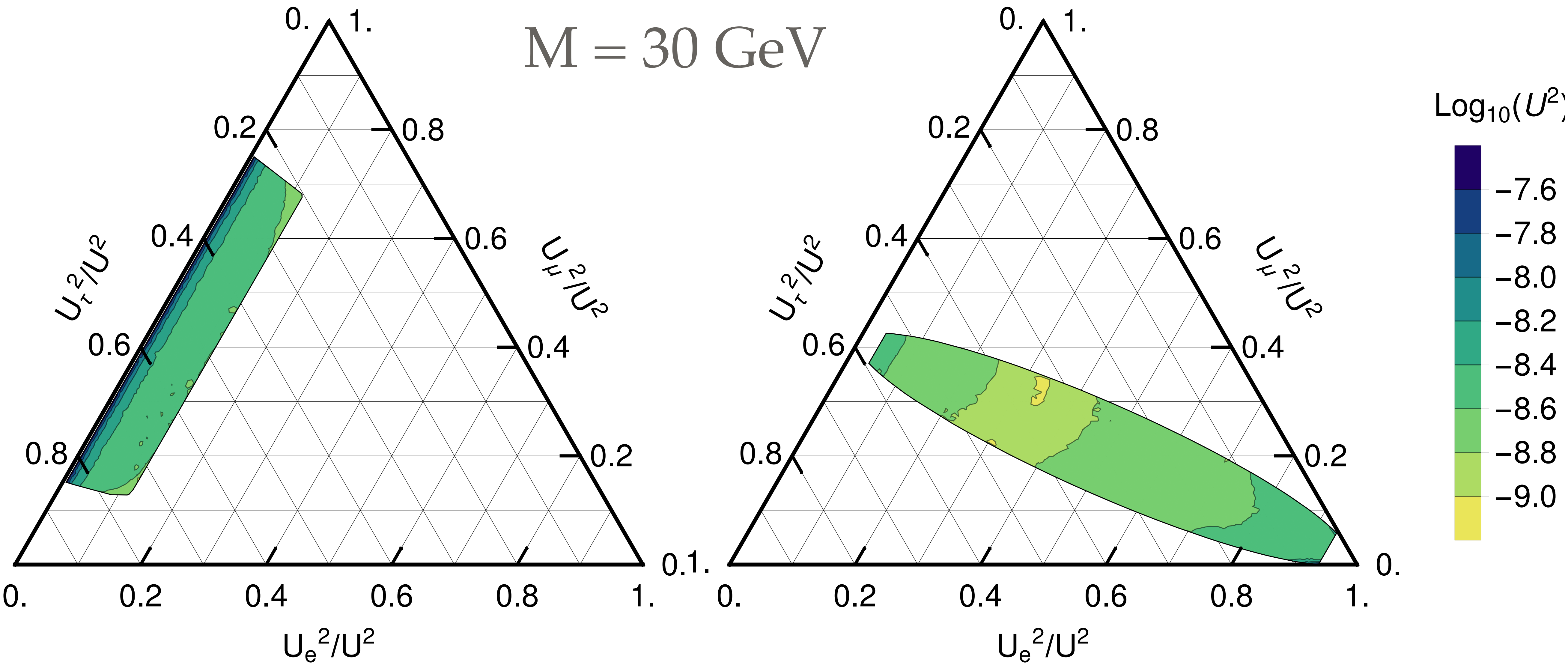


coloured areas: consistent with ν-oscillation data at 1σ, 2σ and 3σ

from MaD / Hajer / Klaric / Lafranchi 1801.04207

Current Status:
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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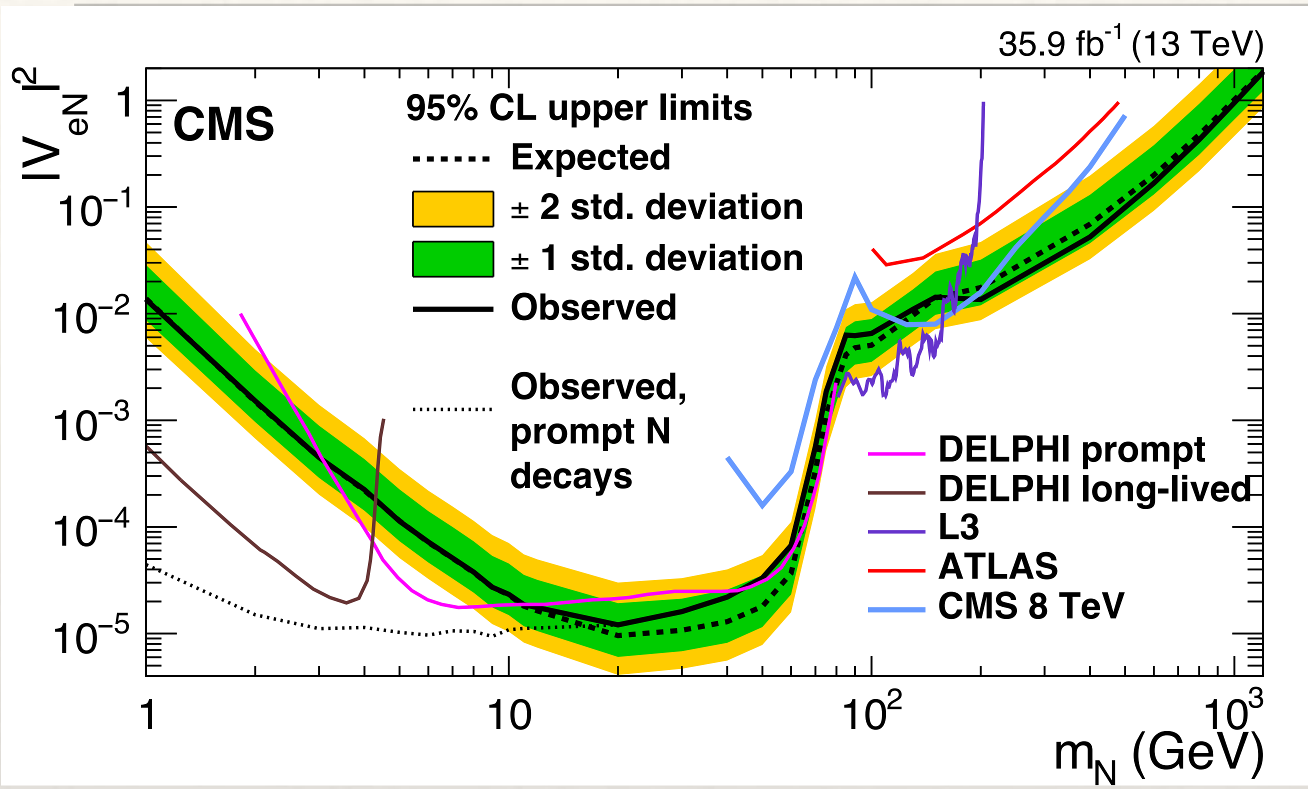
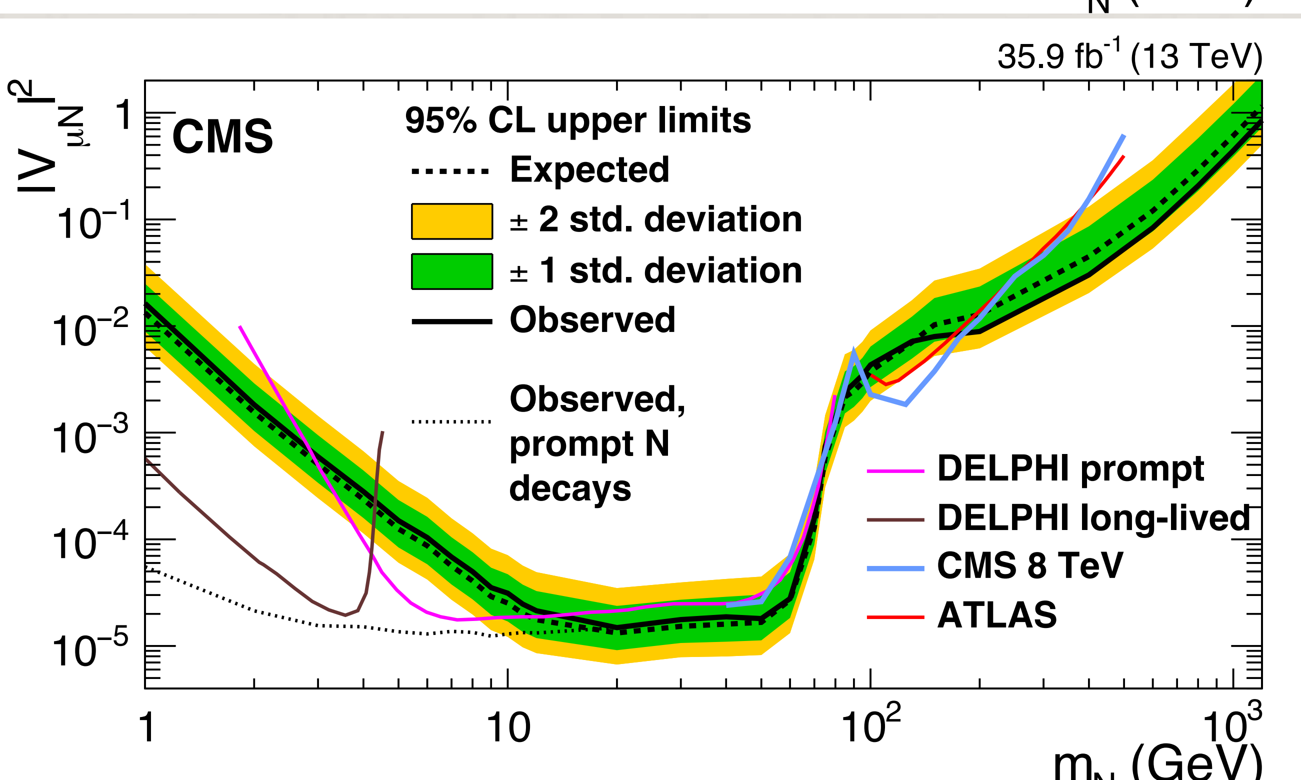
Current LHC Constraints





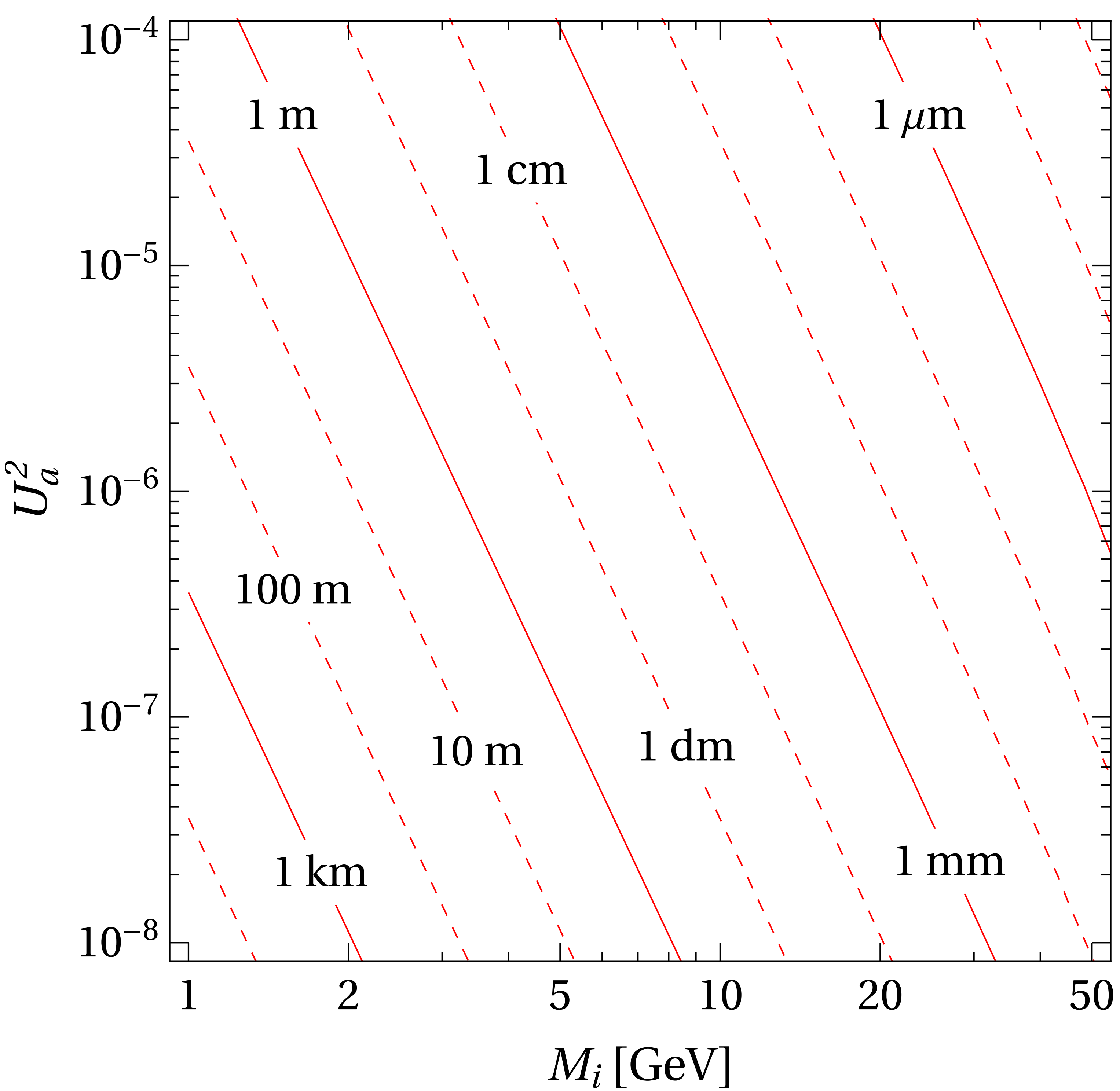
recent CMS results based on process

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

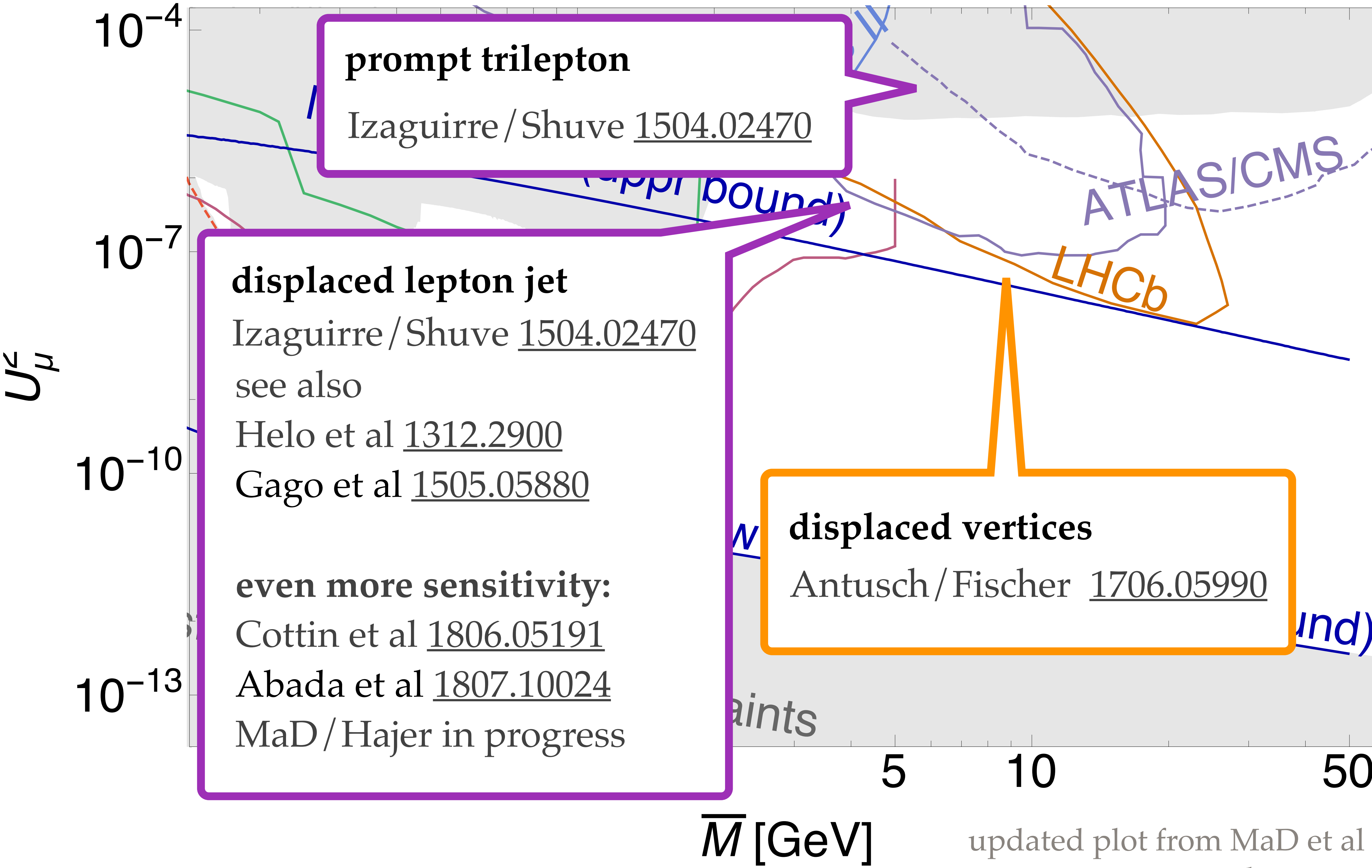
from 1802.02965

Heavy Neutrino Lifetime

$$\Gamma \propto U^2 M^5$$



LHC Searches (current setup)



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

even more sensitivity:

Cottin et al 1806.05191

Abada et al 1807.10024

MaD/Hajer in progress

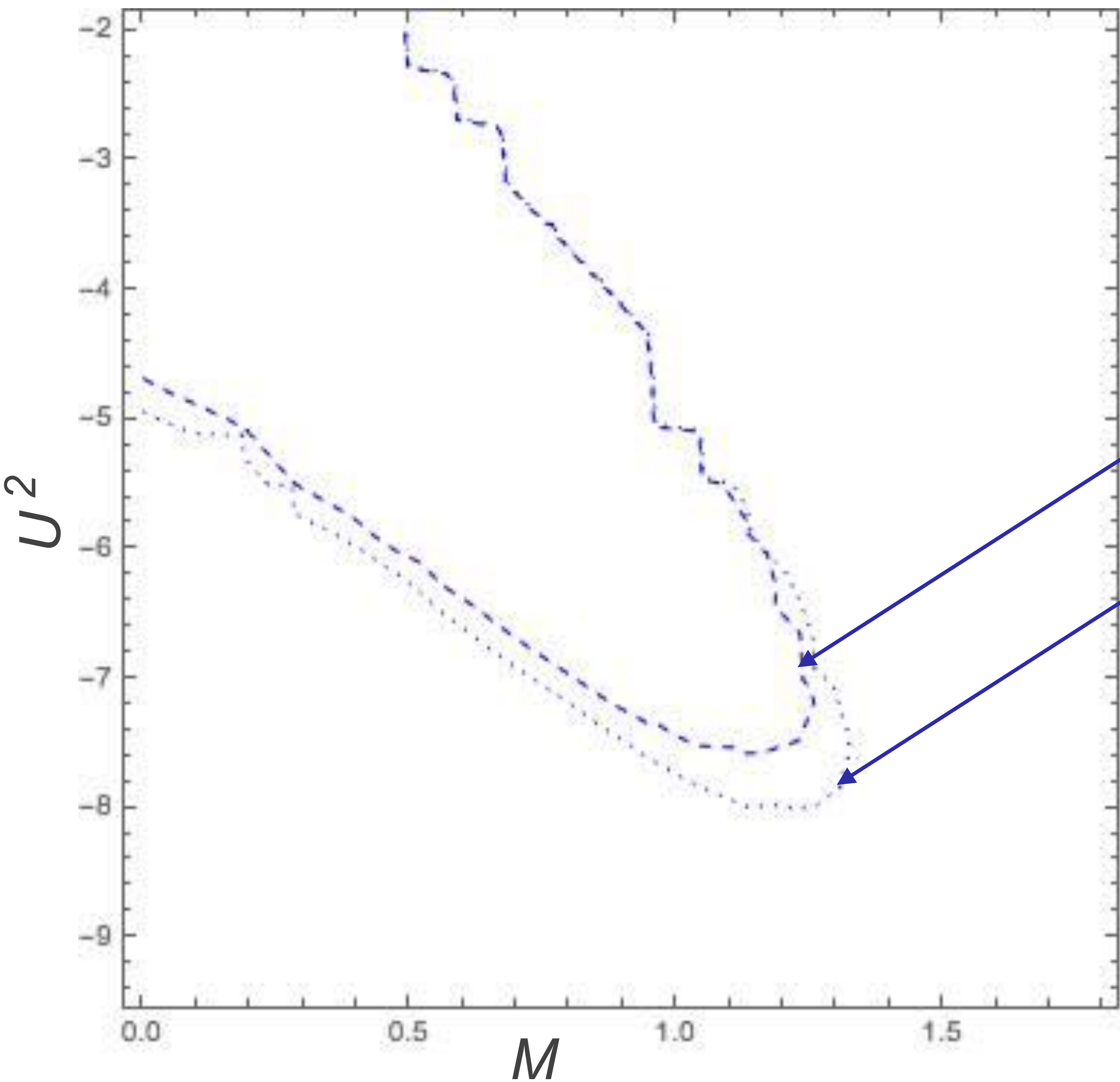
displaced vertices

Antusch/Fischer 1706.05990

updated plot from MaD et al 1609.09069

cf. also Chun et al 1711.02865

CMS: Search for Displaced Muon



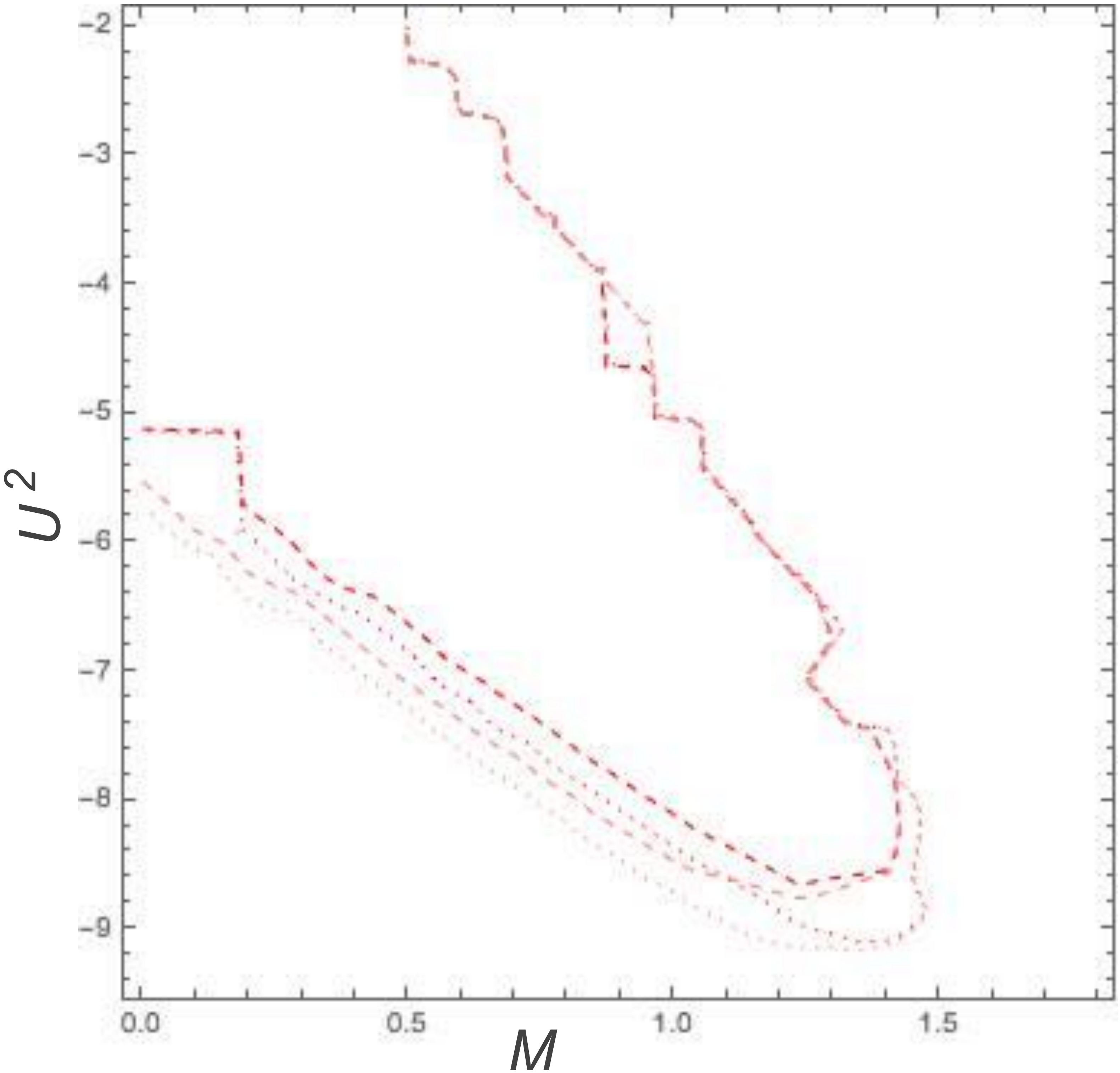
[preliminary results MaD/Hajer]

25 events

9 events

13 TeV, 300/fb

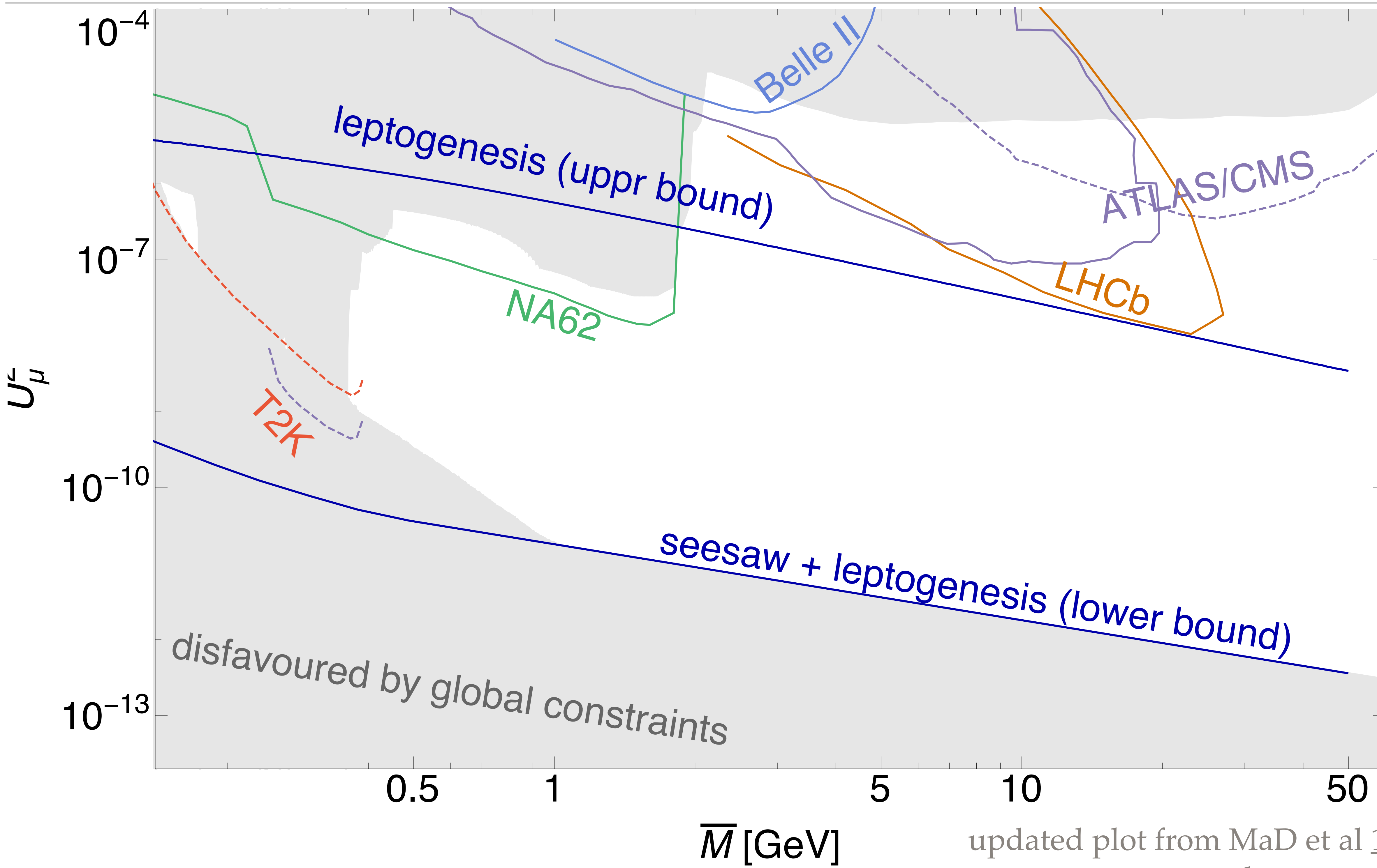
HL-LHC: How much better?



[preliminary results MaD / Hajer]

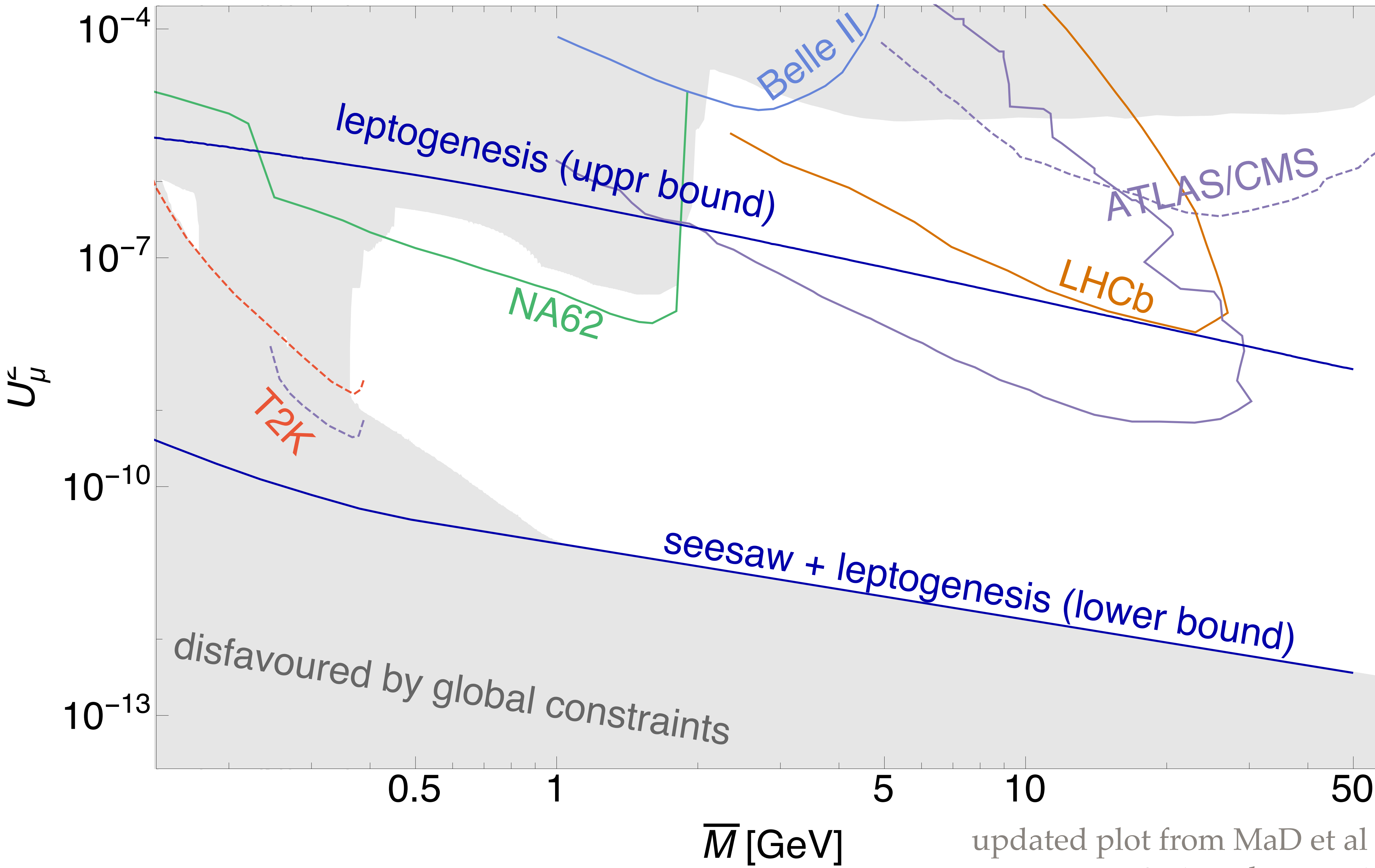
14 TeV, 3000 / fb

LHC Searches (current setup)



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

HL LHC Perspective



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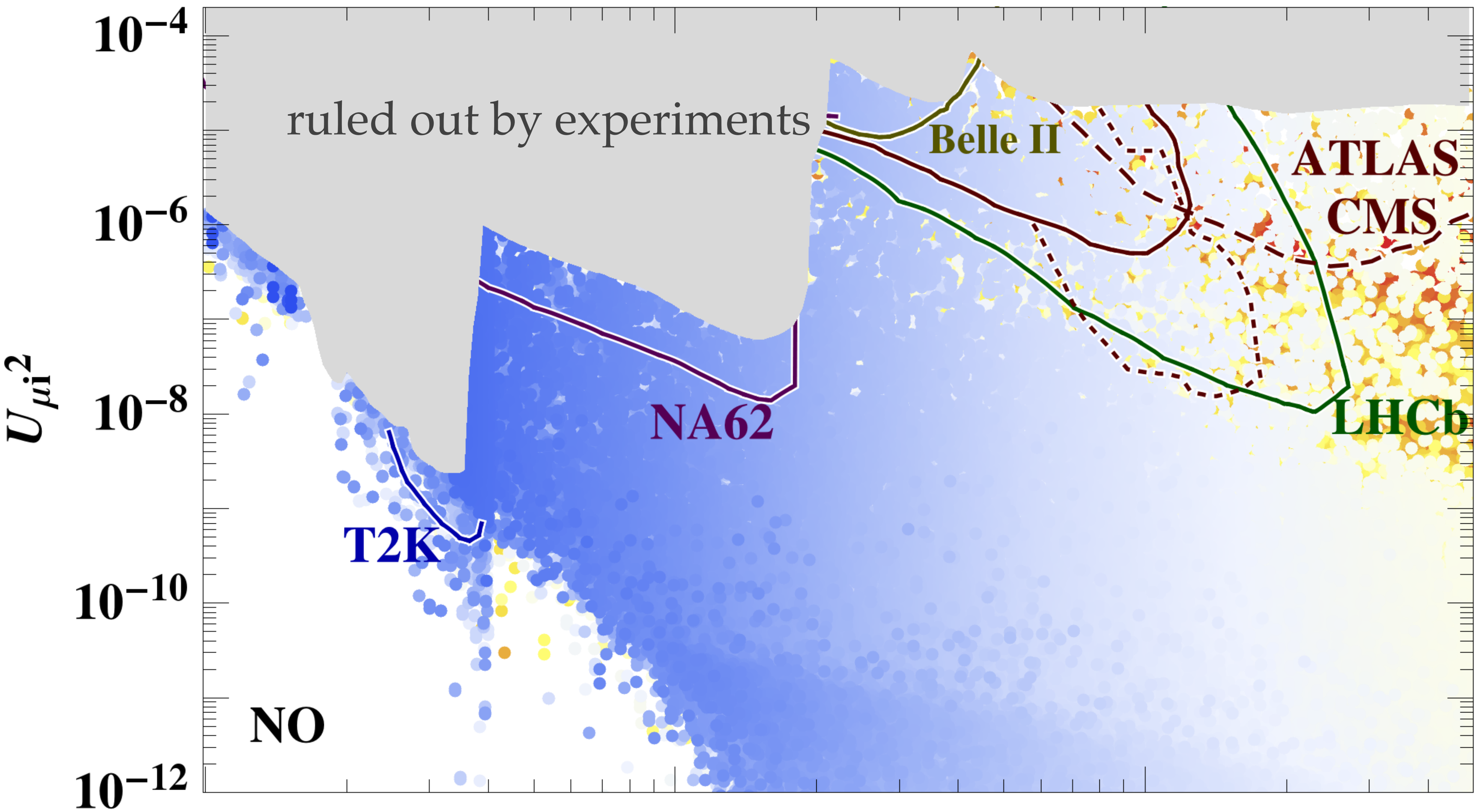
Beyond the Minimal Model: 3 HNLs

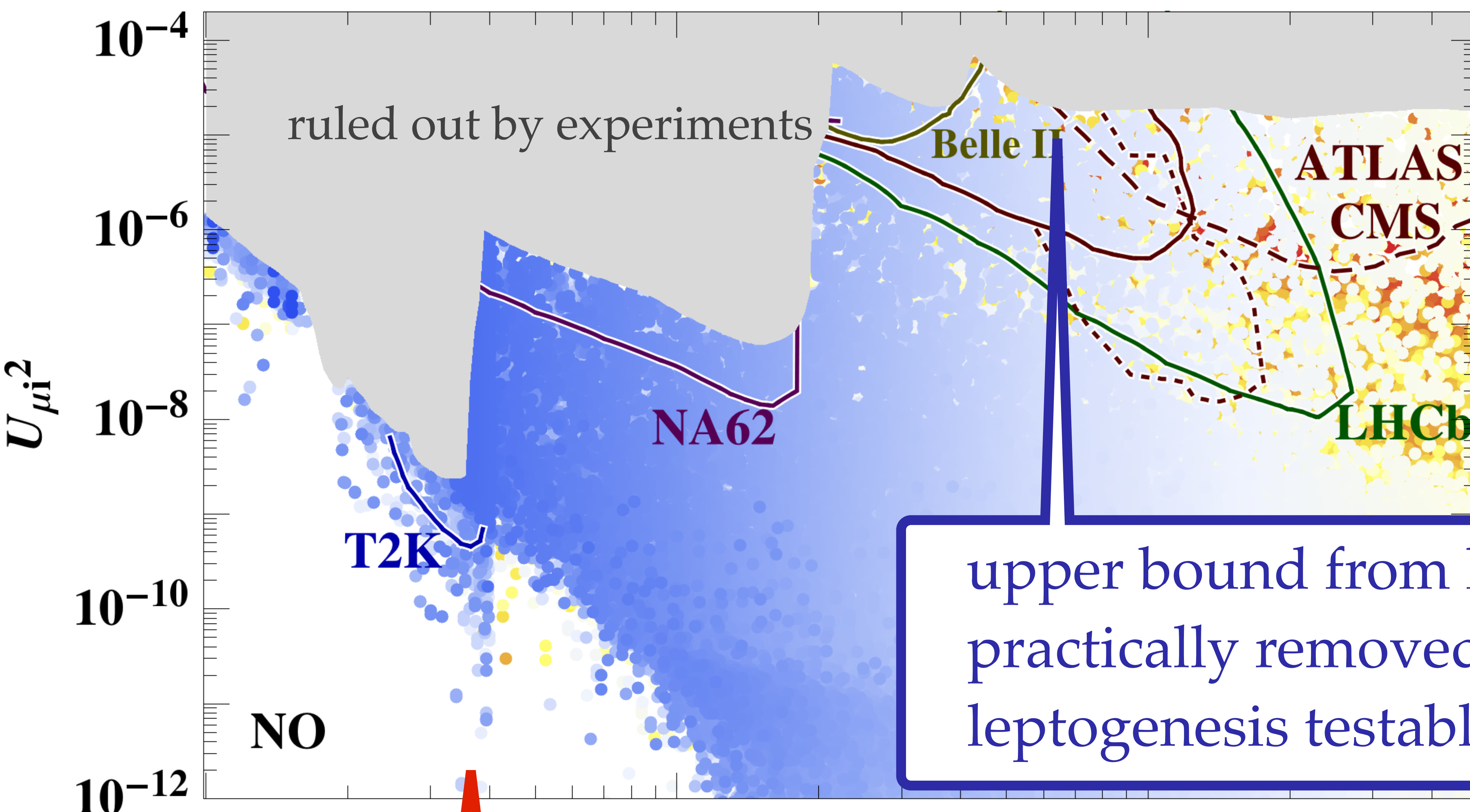


global constraints: MaD/Garbrecht 1502.00477

colourful points = leptogenesis works
colour indicates fine tuning (blue = low, red = high)

plot from Abada/Arcadi/MaD/Domcke/Klaric/Lucente 1810.12463

Beyond the Minimal Model: 3 HNLs



global constraints:
MaD/Garbrecht
1502.00477

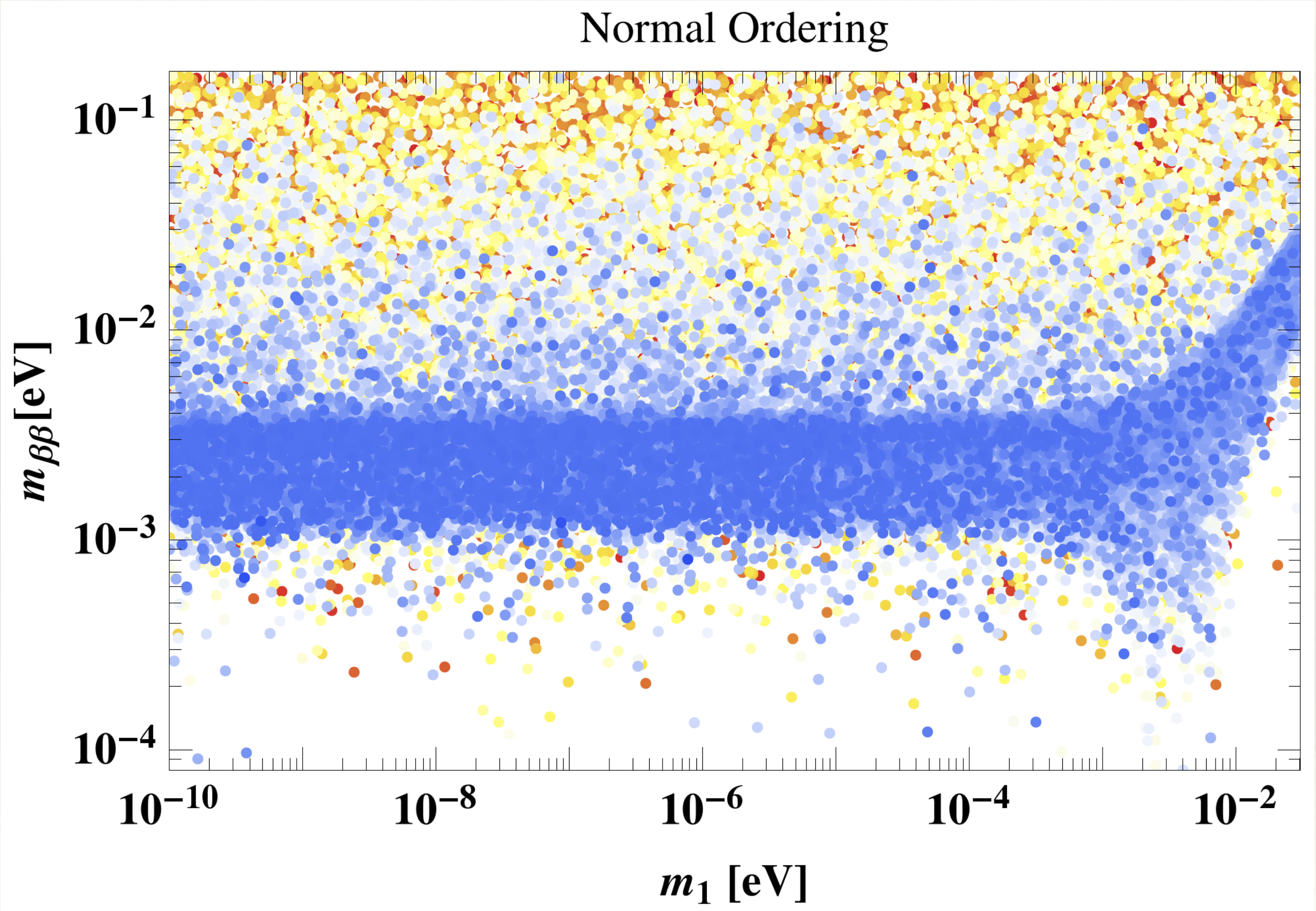
upper bound from leptogenesis
practically removed (> exp. bound)
leptogenesis testable at LHC!

lower bound on mixing depends on lightest neutrino mass
for sufficiently small value it can be very low!

Abada/Arcadi/MaD/Domcke/Klaric/Lucente 1810.12463

The 0νββ Connection

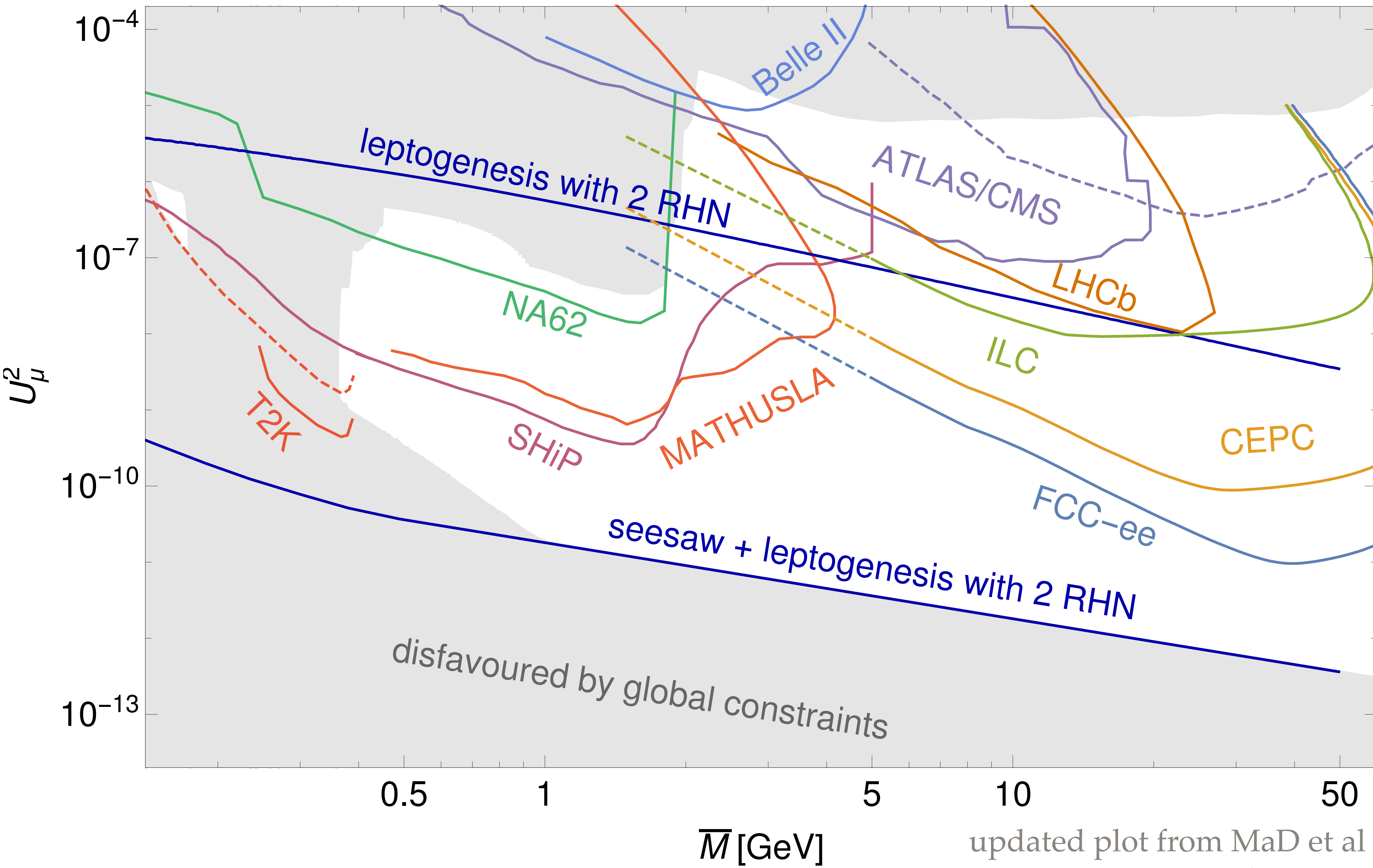
Heavy neutrino exchange can massively alter the rate within the viable leptogenesis parameter space



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
Abada et al 1810.12463

plot from Abada et al 1810.12463

Searches at Future Colliders



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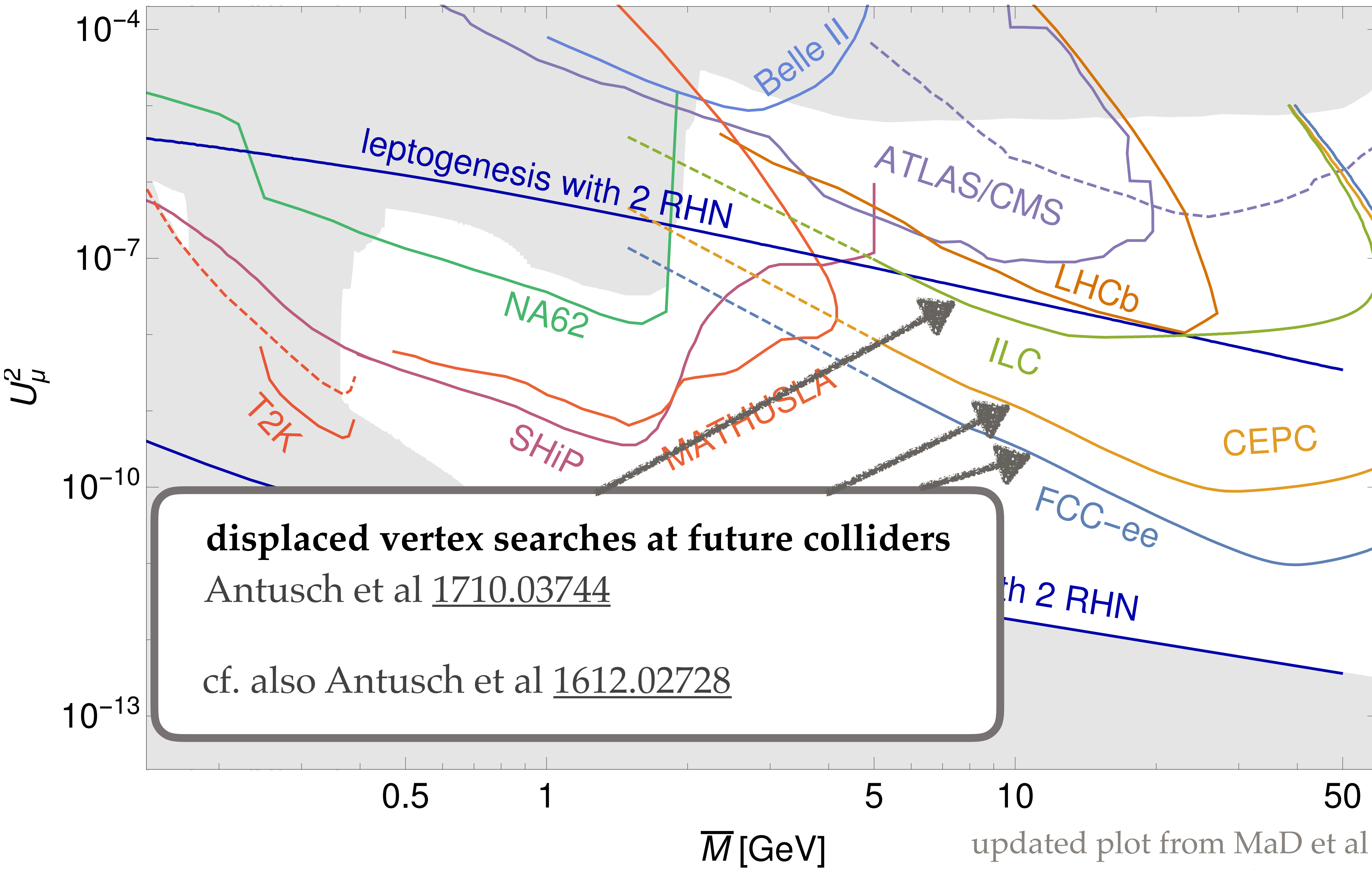

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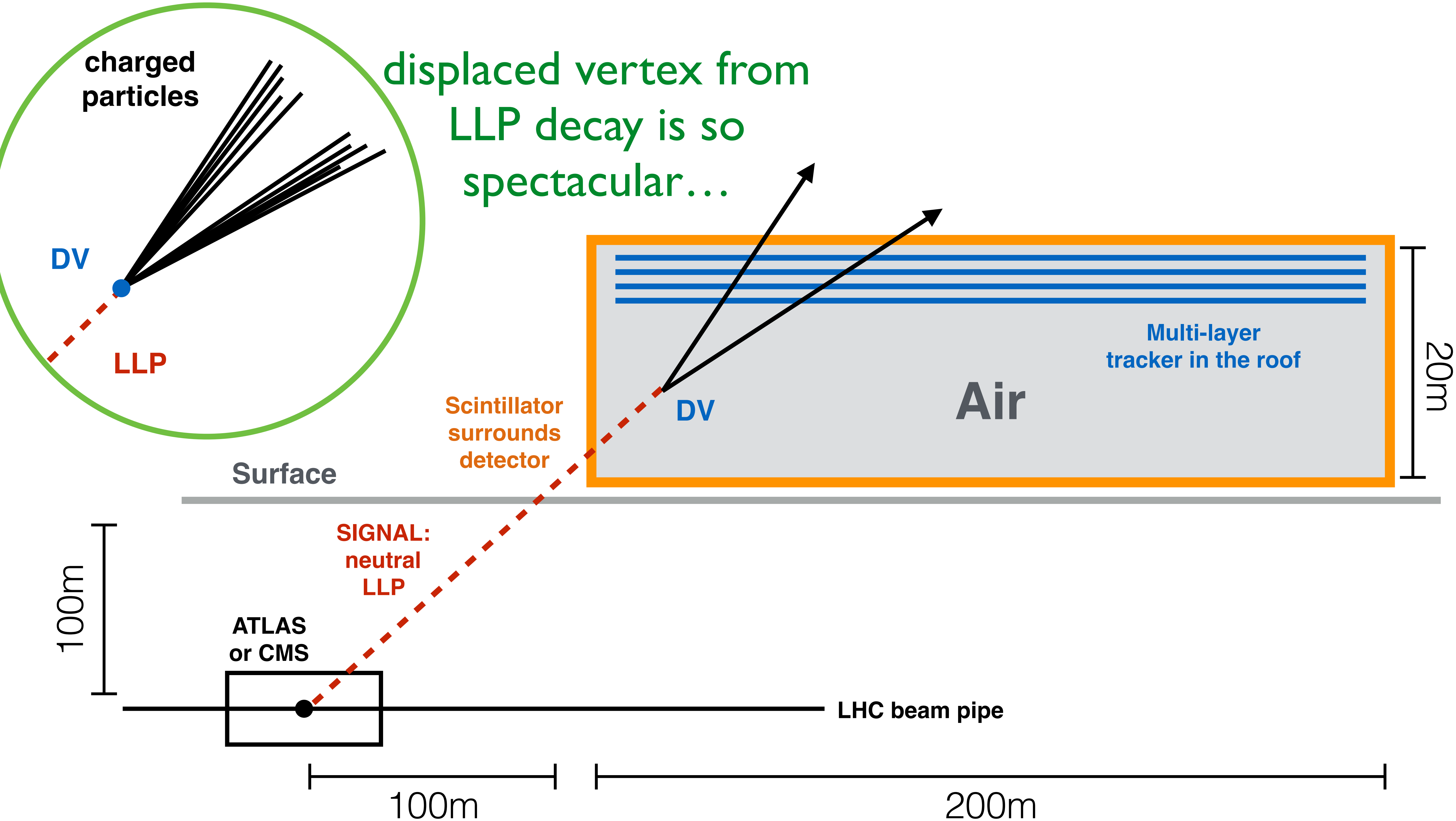
MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



slide by David Curtin

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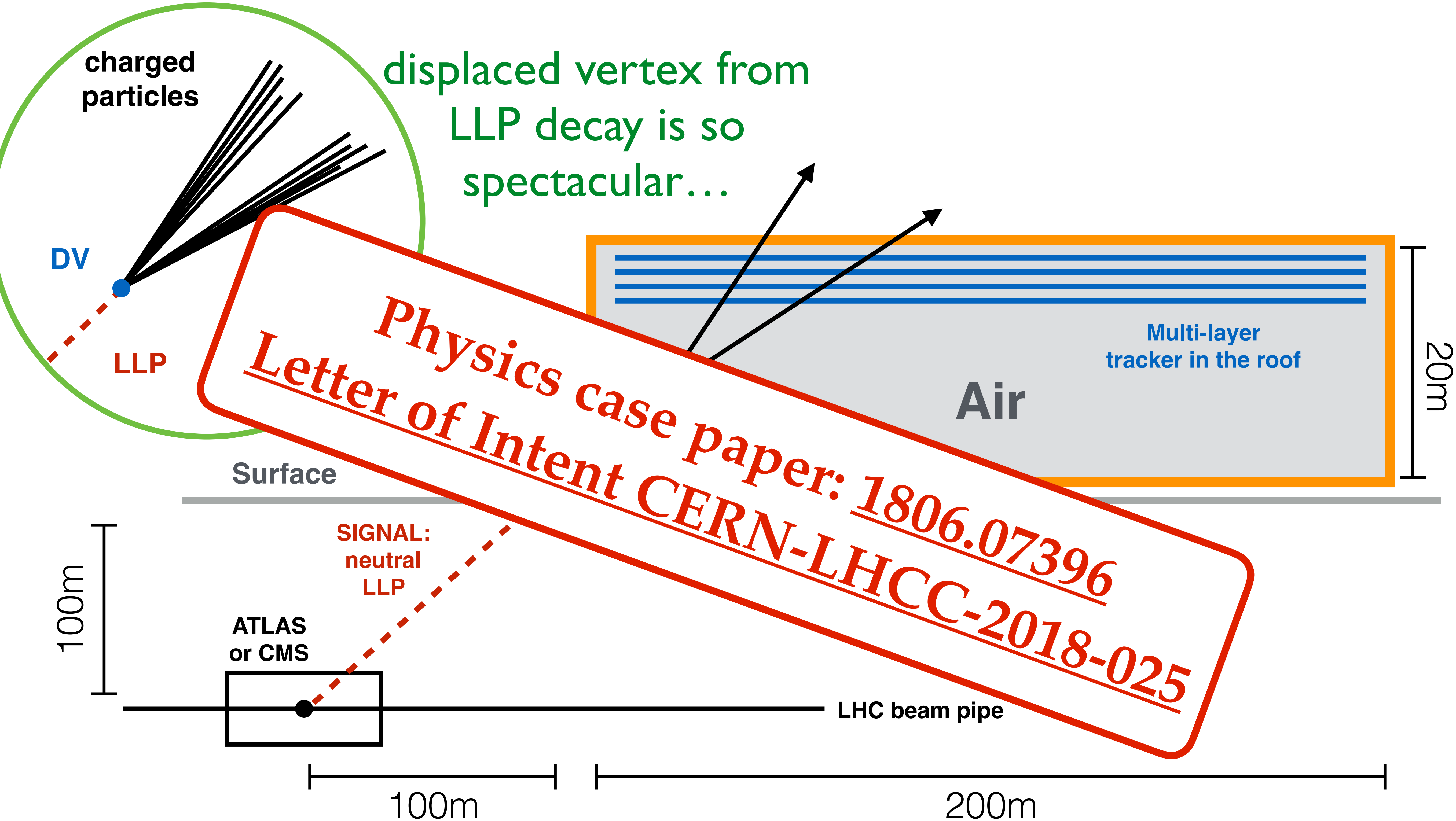

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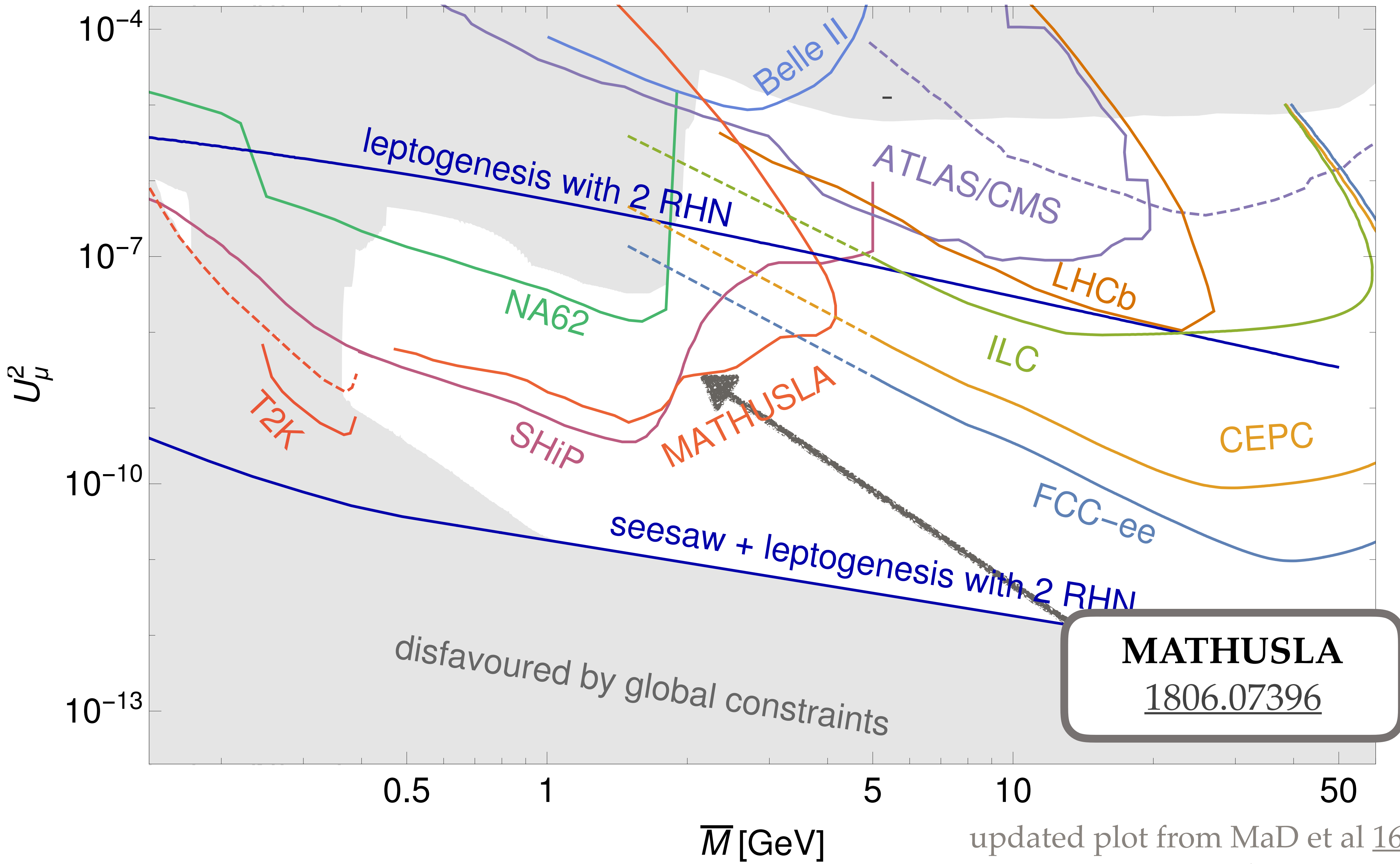
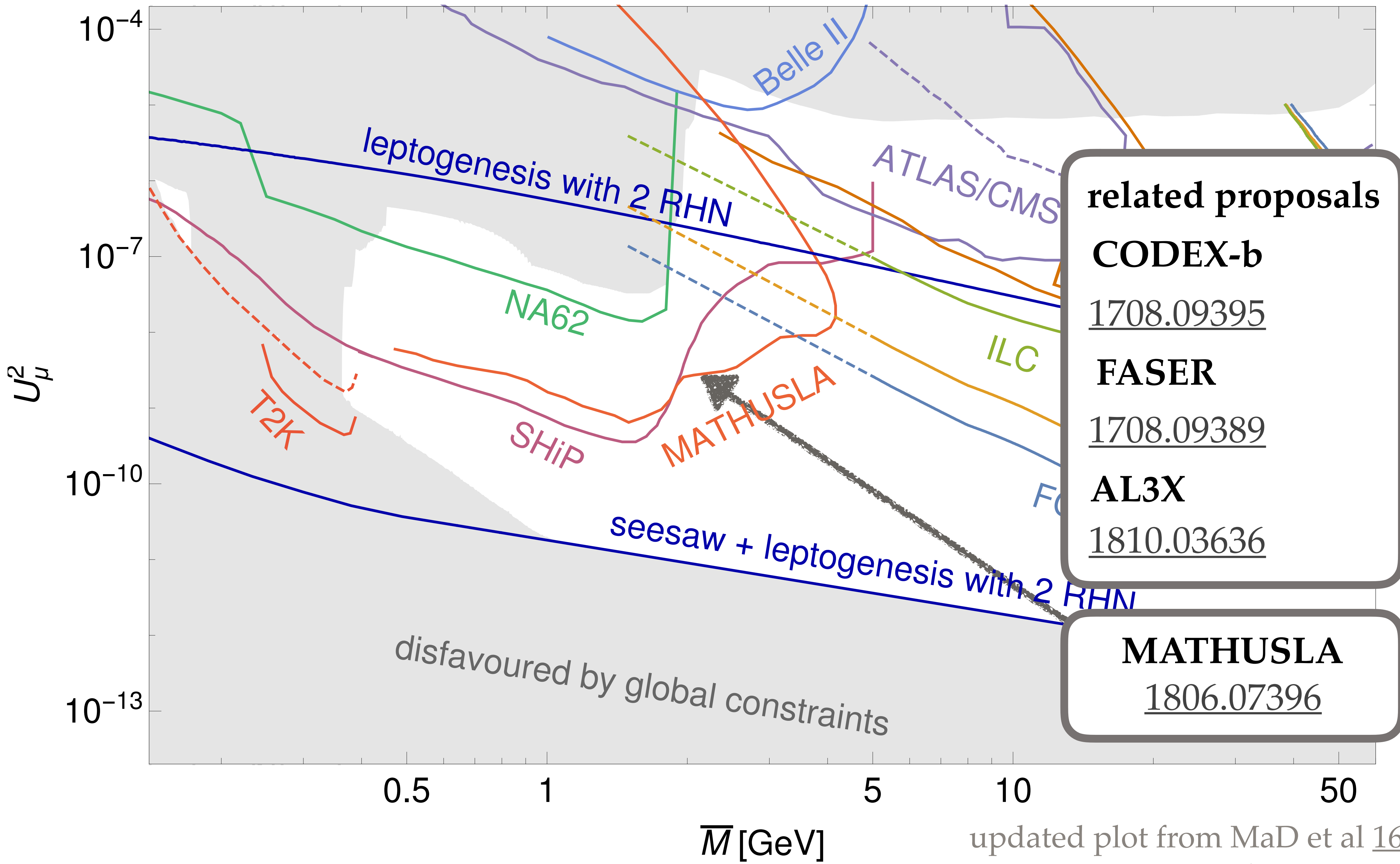
MATHUSLA vs NA62 vs SHiP



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

MATHUSLA vs NA62 vs SHiP



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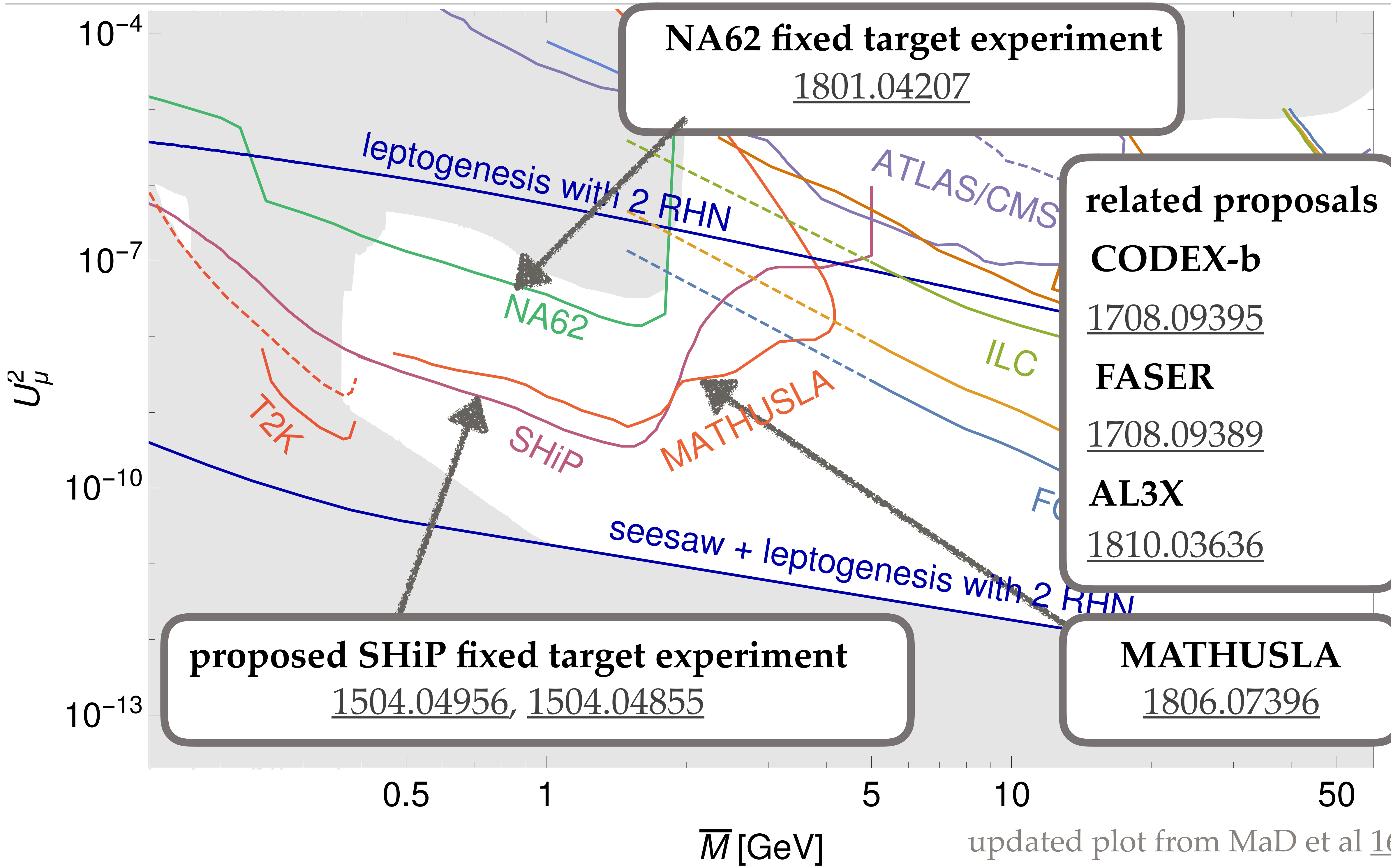
MATHUSLA vs NA62 vs SHiP



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Overview

Motivation

Bounds from cosmology

The νMSM: a “fully testable” model

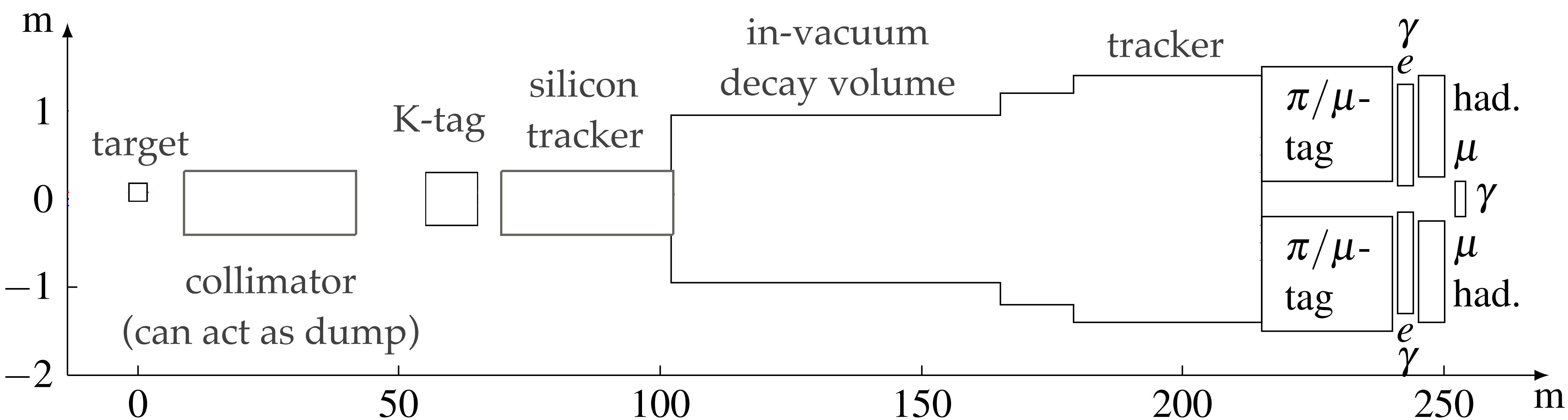
Optimising the LHC main detectors

Additional detectors: MATHUSLA

Fixed Target: NA62

Utilising heavy ion runs

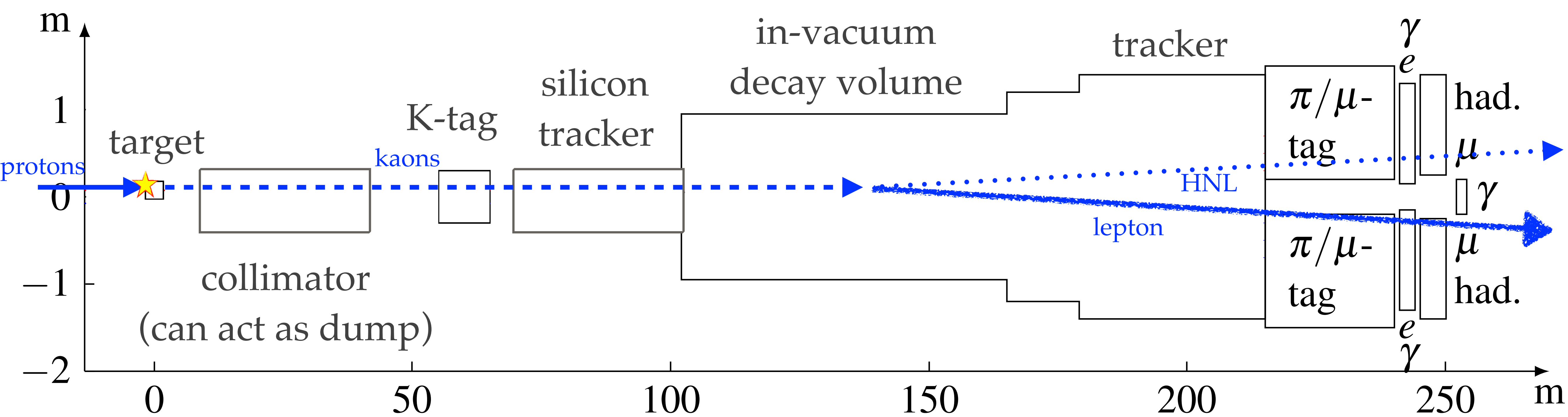
The NA62 Experiment



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

pictureFigure/picture from the NA62 collaboration

NA62 Kaon Mode

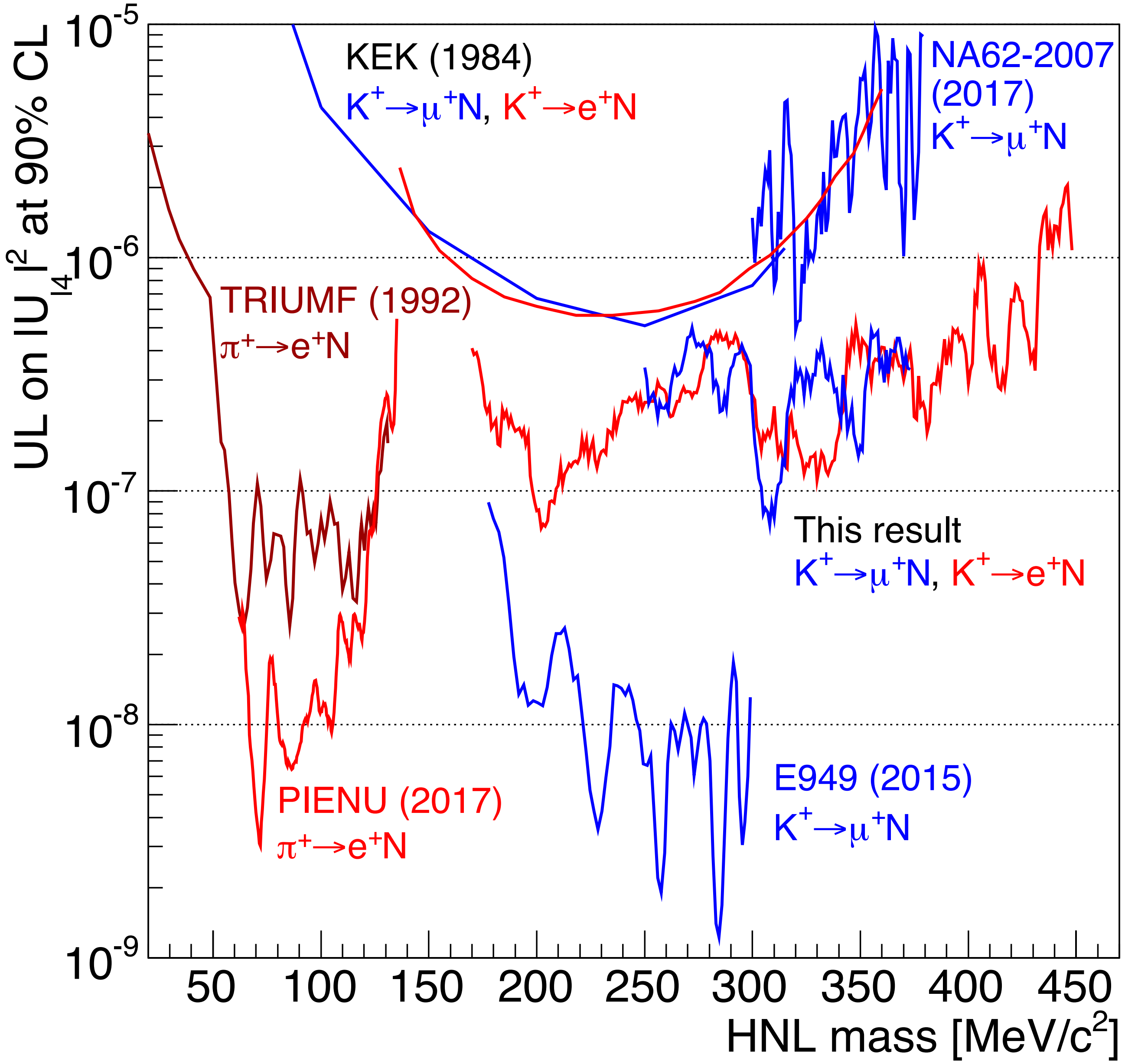


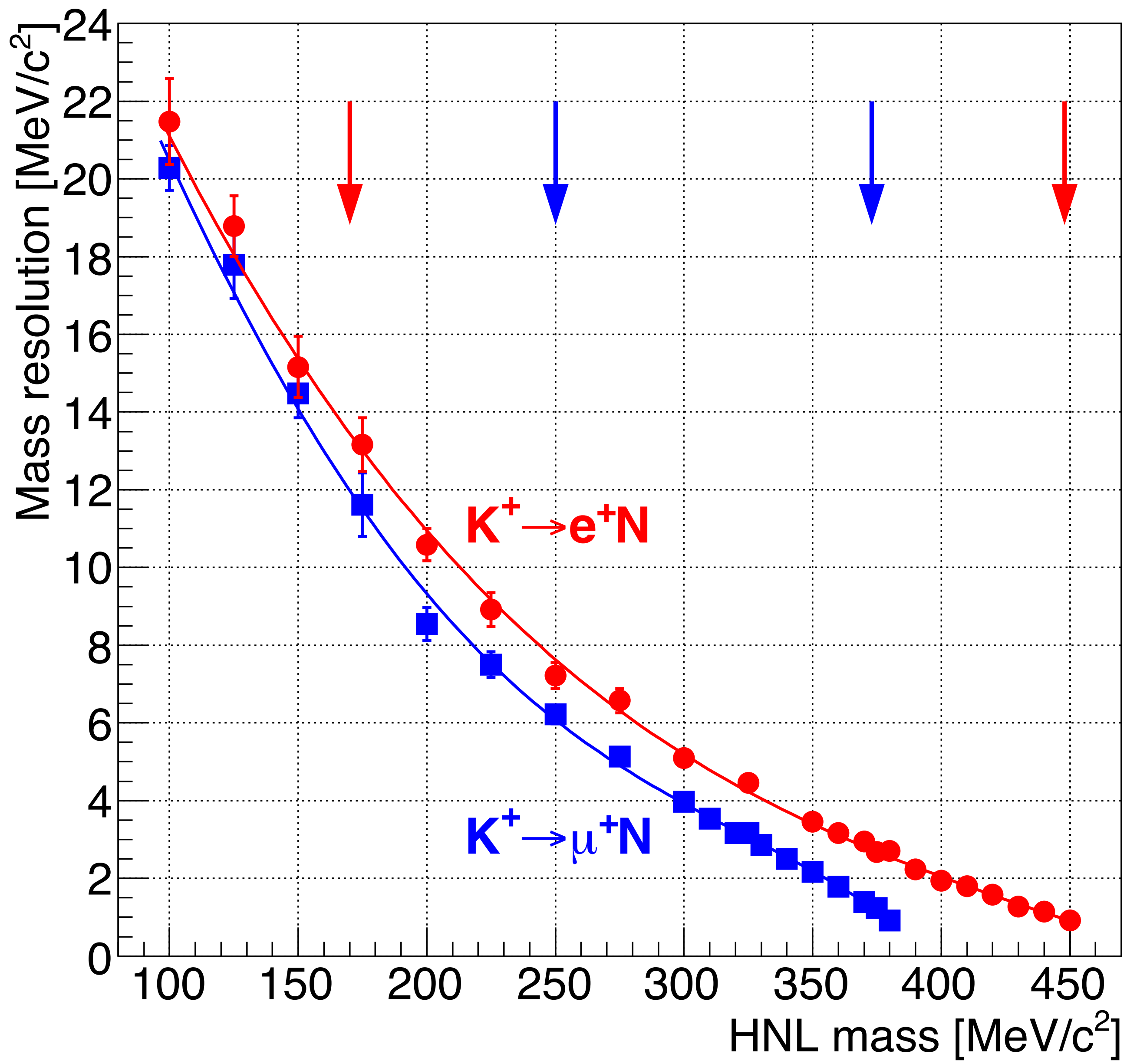
Target Mode: cf. 1712.00297 for recent results

- 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**

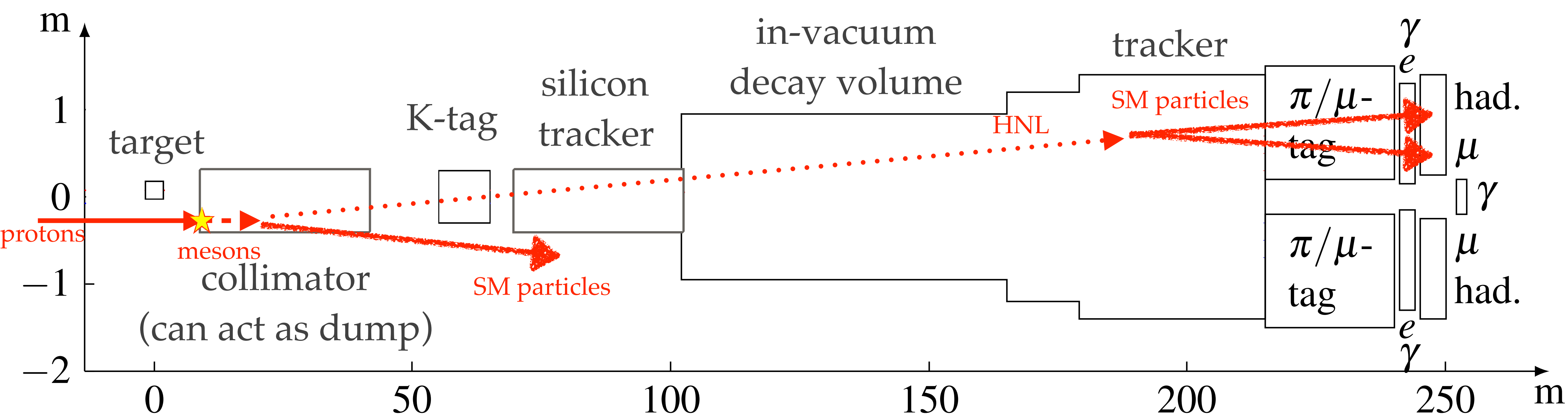
NA62 Kaon Mode: First Results





Cortina-Gil et al 1712.00297

NA62 Dump Mode

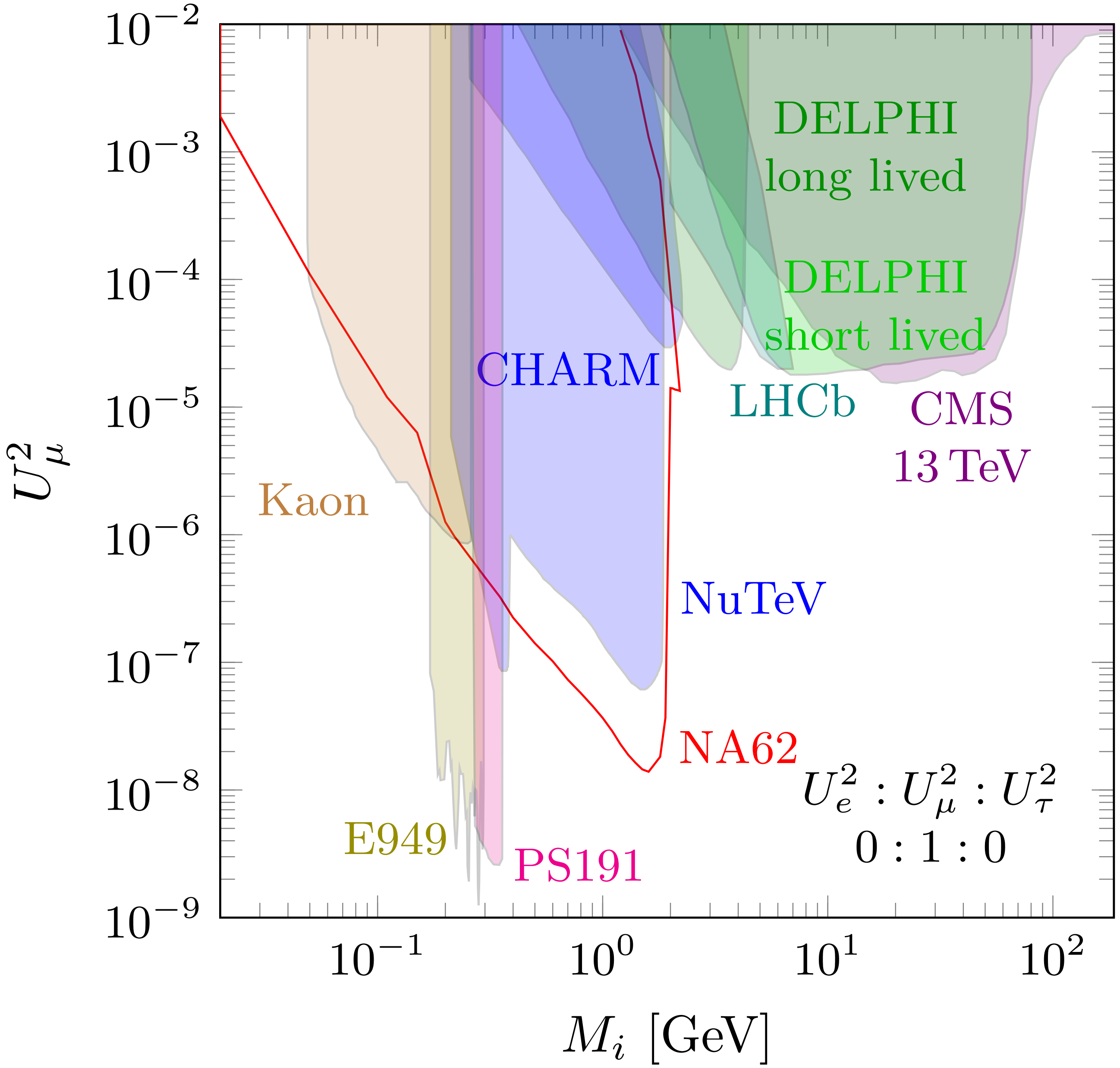


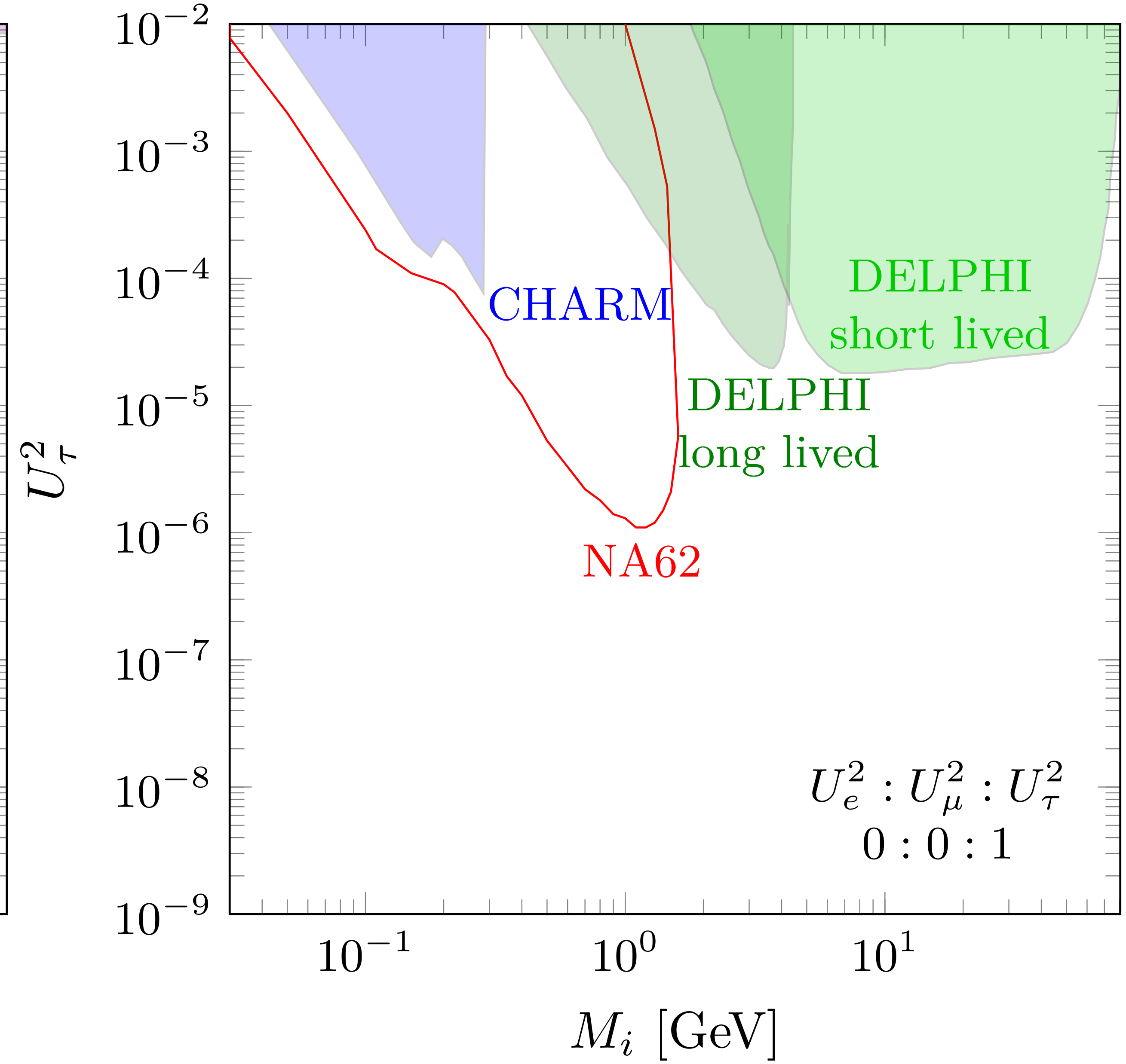
Dump mode

- 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





MaD / Hajer / Klaric / Lafranchi 1801.04207

Overview

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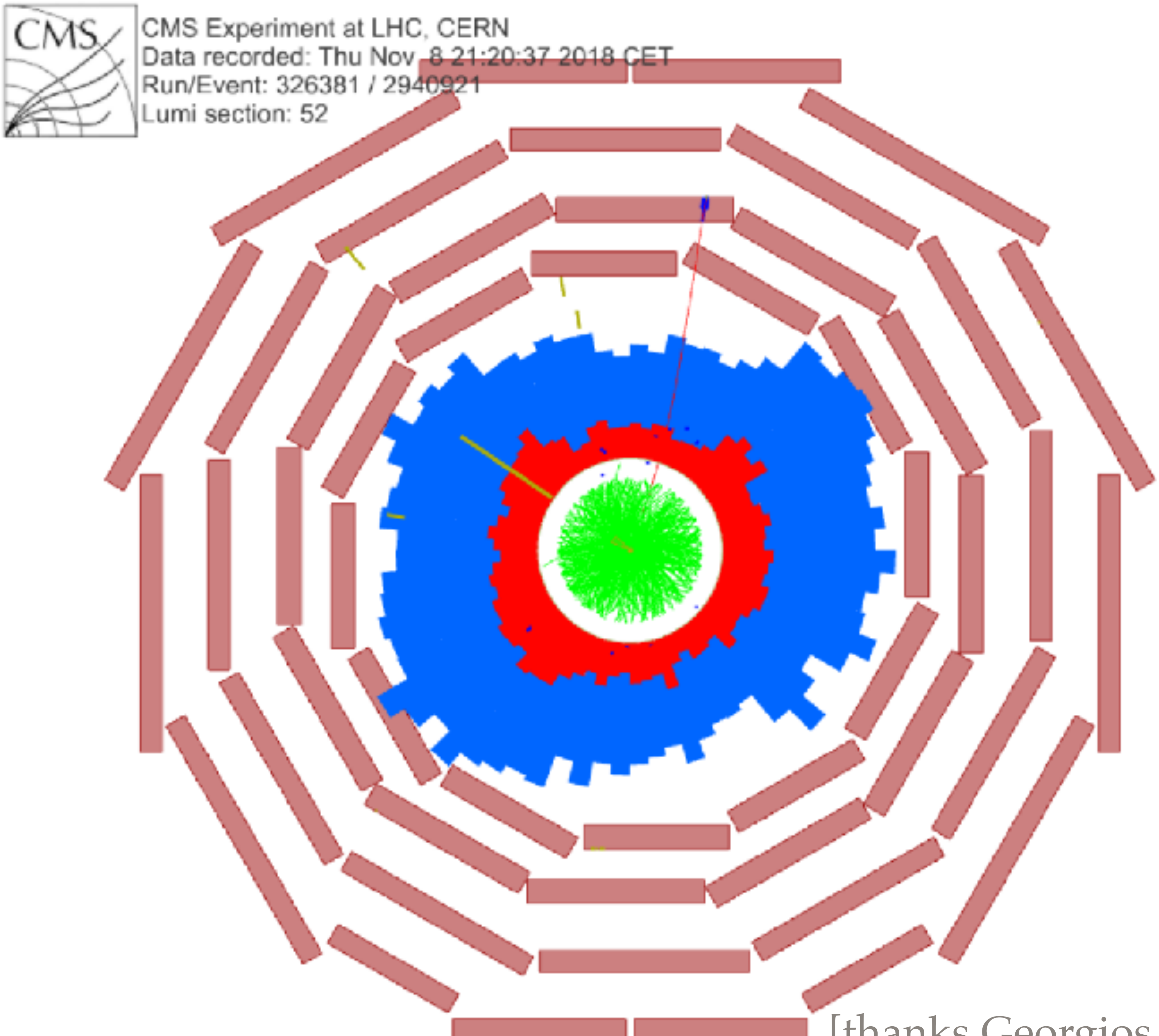
Additional detectors: MATHUSLA

Fixed Target: NA62

Utilising heavy ion runs

Yesterday at CERN…



Head-on PbPb collision…

…first lab events with PeV energies!

Can we use this for something?

[thanks Georgios Krintiras for providing the picture]

LLP searches in Heavy Ion Runs?

Con

1. high track multiplicity
2. low instantaneous luminosity
3. lower collision energy per nucleon
4. runs are shorter

Pro

1. A^2 enhancement of # of nucleon collisions
2. no pile up
3. can operate main detectors with very low triggers

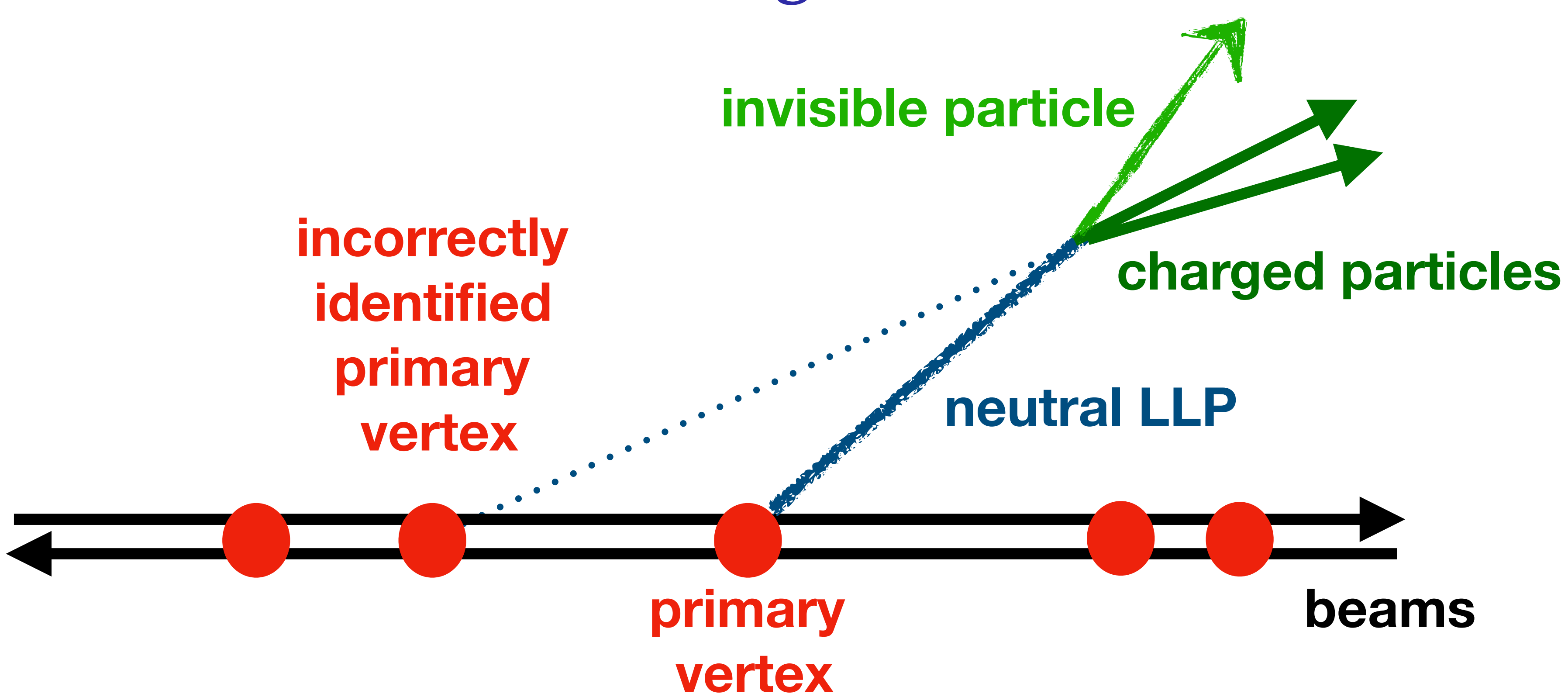
MaD / Giammanco / Hajer / Lucente / Mattelaer 1810.09400

Luminosities and Cross Sections

	$A^2\sigma_W$ [μb]	L_0 [$1/\mu$b s]	τ_b [h]	L_{ave} [$1/\mu$b s]	$N/N(p)$ [1]
$^{1}_{1}H$	0.056	21.0×10^3	75.0	15.0×10^3	1
$^{16}_{8}O$	7.17	94.3	6.16	35.2	0.30
$^{40}_{18}Ar$	40.3	4.33	11.2	2.00	0.0957
$^{40}_{20}Ca$	44.8	2.90	12.4	1.38	0.0735
$^{78}_{36}Kr$	157	0.311	9.40	0.135	0.0253
$^{84}_{36}Kr$	169	0.311	8.77	0.132	0.0266
$^{129}_{54}Xe$	390	0.0665	4.73	0.0223	0.0103
$^{208}_{82}Pb$	955	0.0136	1.50	2.59×10^{-3}	0.0029

No Pile-Up

Advantage 2:
No mis-identification of primary vertex location
Can make additional use of timing information?



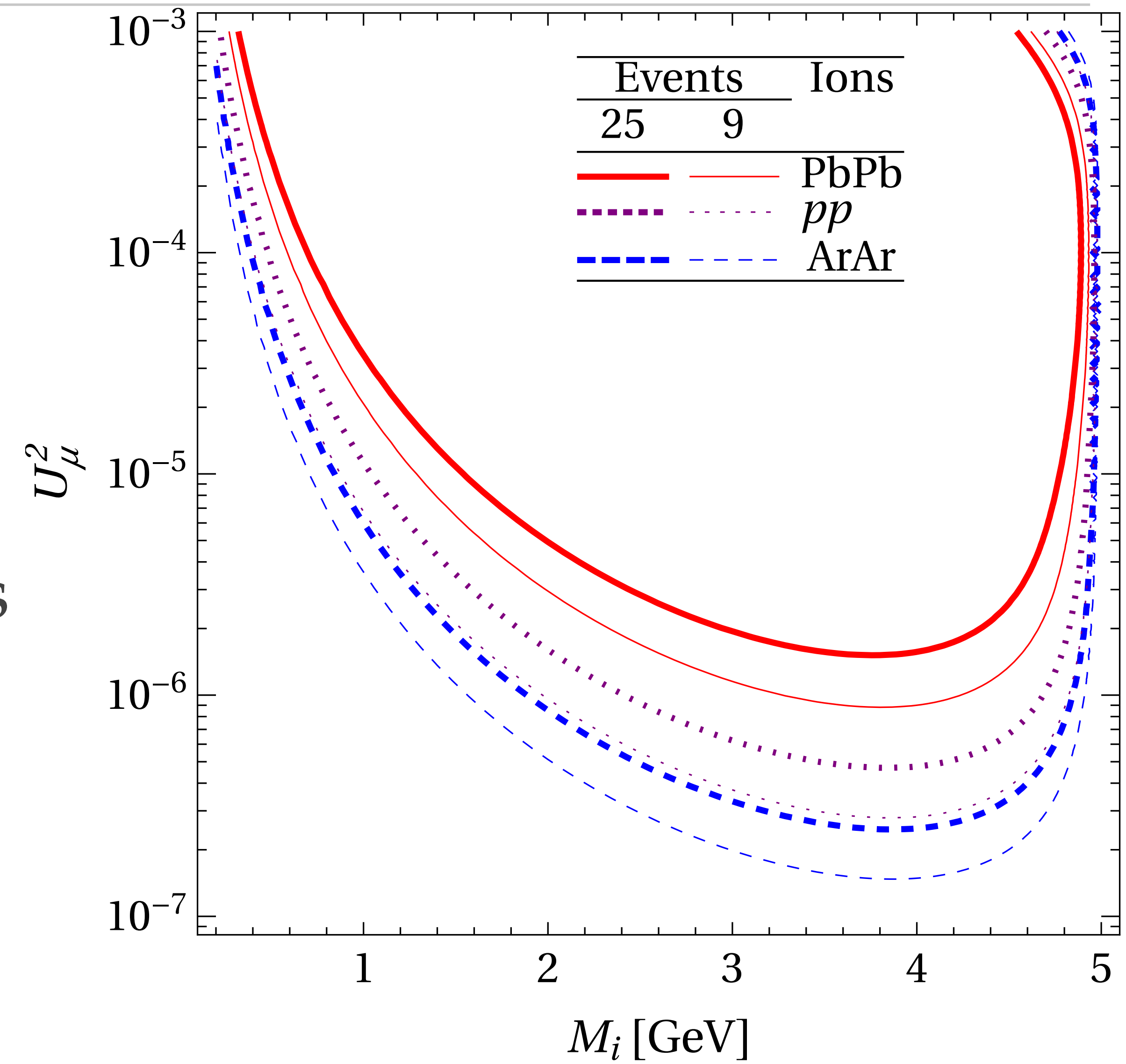
We have not worked this out yet - input is welcome!

MaD / Giammanco / Hajer / Lucente / Mattelaer 1810.09400

HNL Production in B Meson Decays

Advantage 3:
One can run with very low triggers.
Allows to search for low p_T events!

- HNLs with masses below 5 GeV can be produced in B meson decays
- Searches at CMS and ATLAS are difficult because of the low transverse momentum (more than 99% of them have below 25 GeV)
- Low triggers in heavy ion runs allow to collect this data



MaD / Giammanco / Hajer / Lucente / Mattelaer 1810.09400

Heavy Ions and Hidden Sectors

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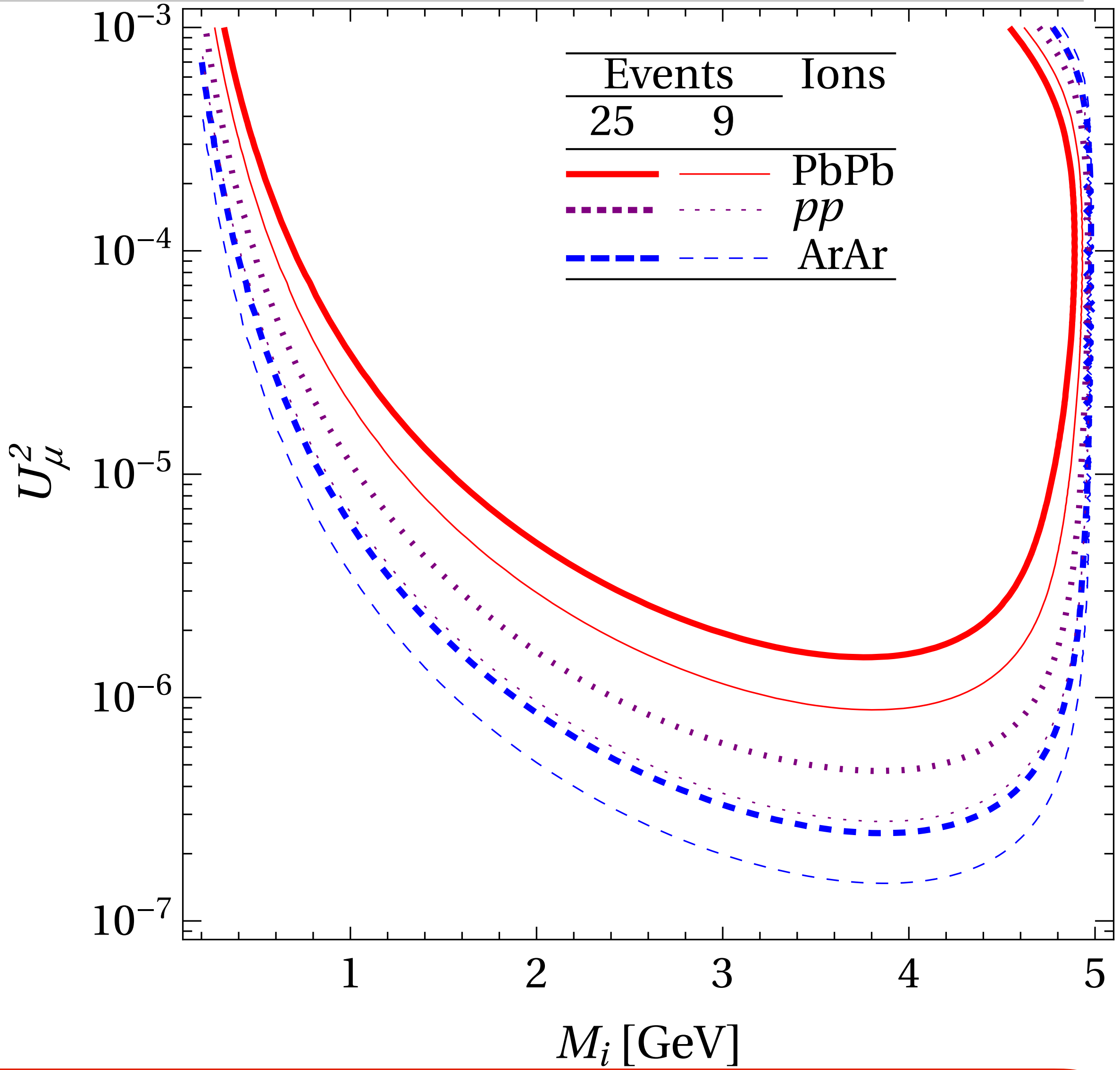

Workshop *"Heavy Ions and Hidden Sectors"*
December 4/5 in Louvain La Neuve - come and join!
https://agenda.irmp.ucl.ac.be/event/3186/

Summary

The (probably) simplest and most minimal model of neutrino mass and baryogenesis still works very well.

Existing facilities offer numerous ways to search for heavy neutrinos at all frontiers.

Most of them can be used to search for a much wider range of weakly coupled new particles.

Let’s turn every stone before we give up on finding New Physics at the LHC!

Backup Slides

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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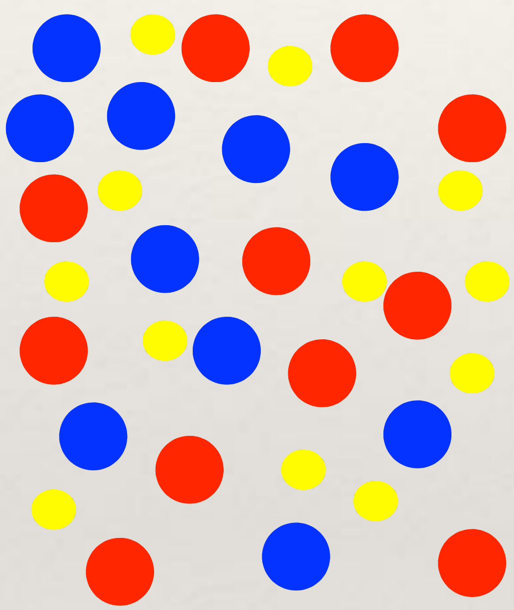
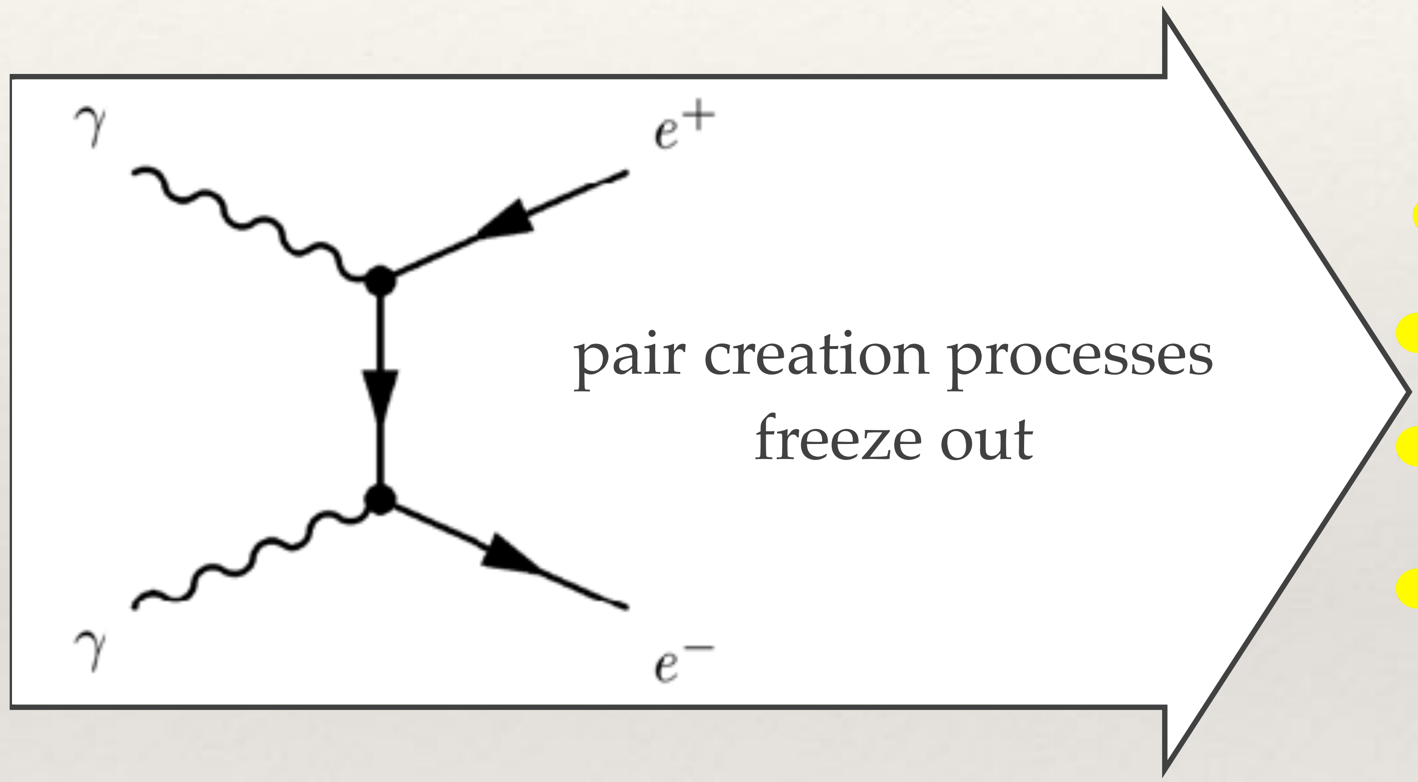
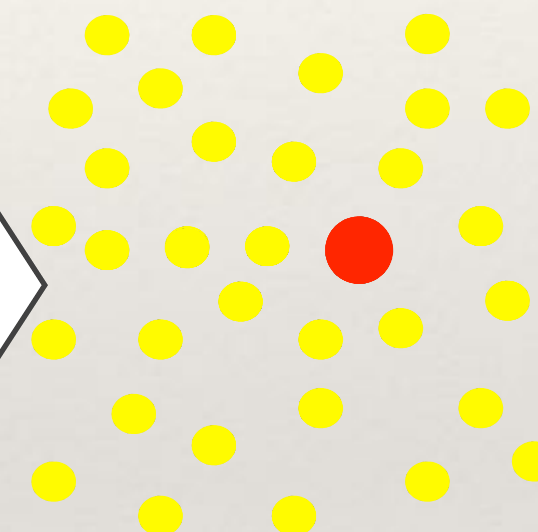


$T > 2\,mc^2$





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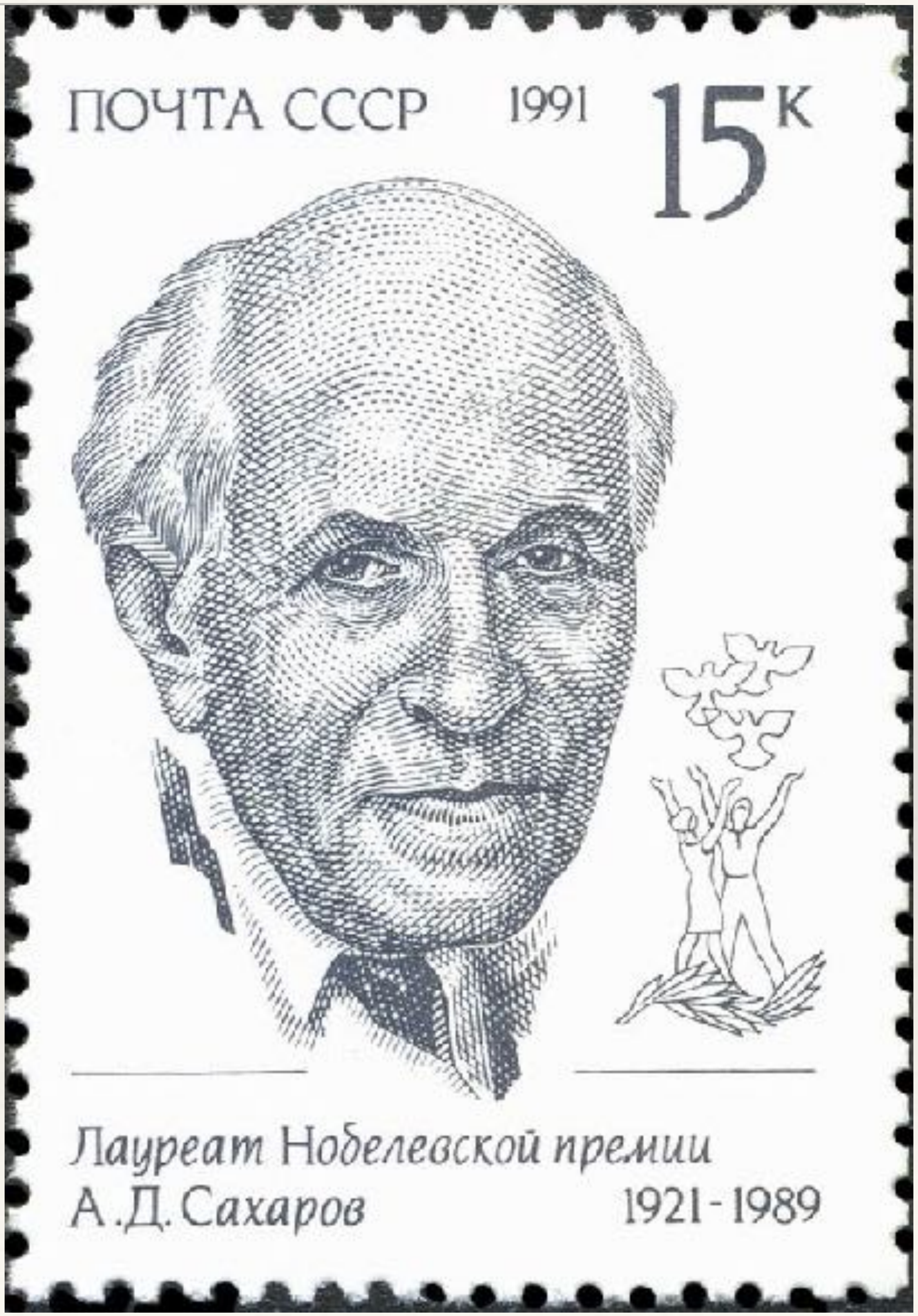
Where does the asymmetry come from?

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!

Thermal Leptogenesis

Basic idea Fukugita / Yanagida 86

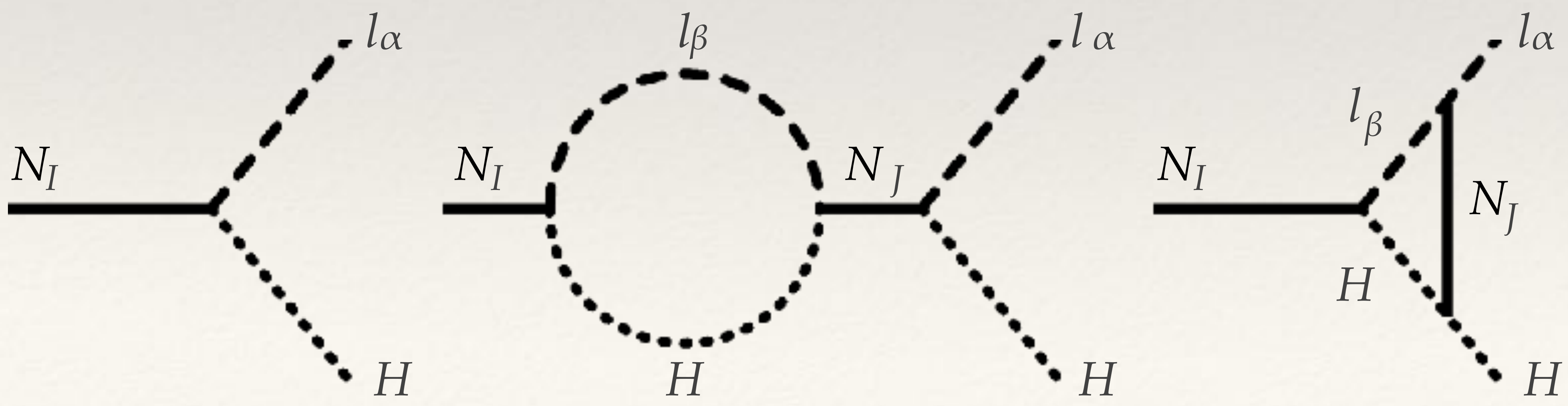
- ***N*** **are around in the early universe**
- **Yukawas *F* are CP violating**
- ***N*** **may preferably decay into matter**

CP violating parameter ϵ

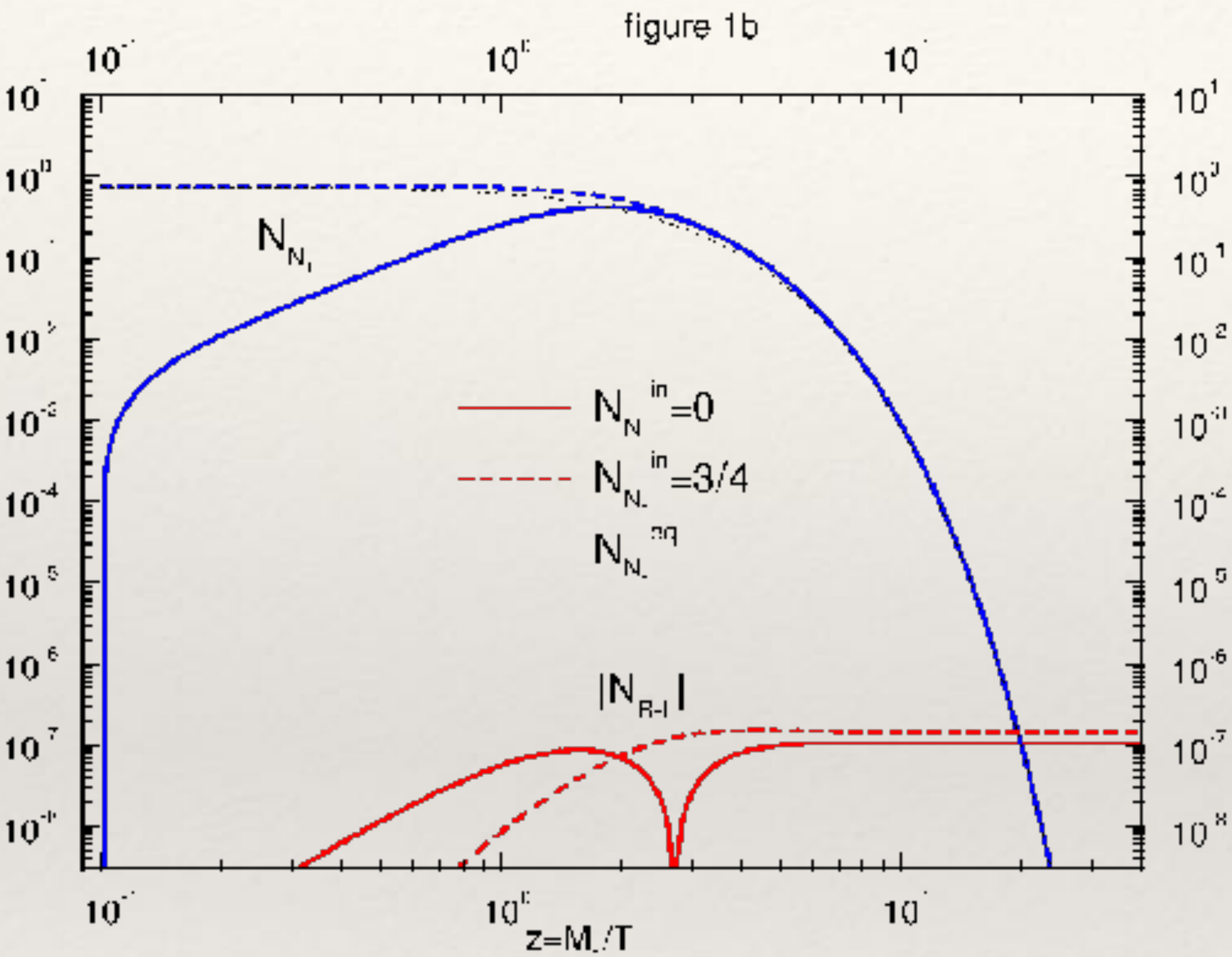
$$\epsilon = \frac{\Gamma_{N \to \ell H} - \Gamma_{N \to \bar{\ell} H^*}}{\Gamma_{N \to \ell H} + \Gamma_{N \to \bar{\ell} H^*}}$$

final asymmetry

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



Leptogenesis with small M?



Buchmuller / Di Bari / Plumacher 0205349

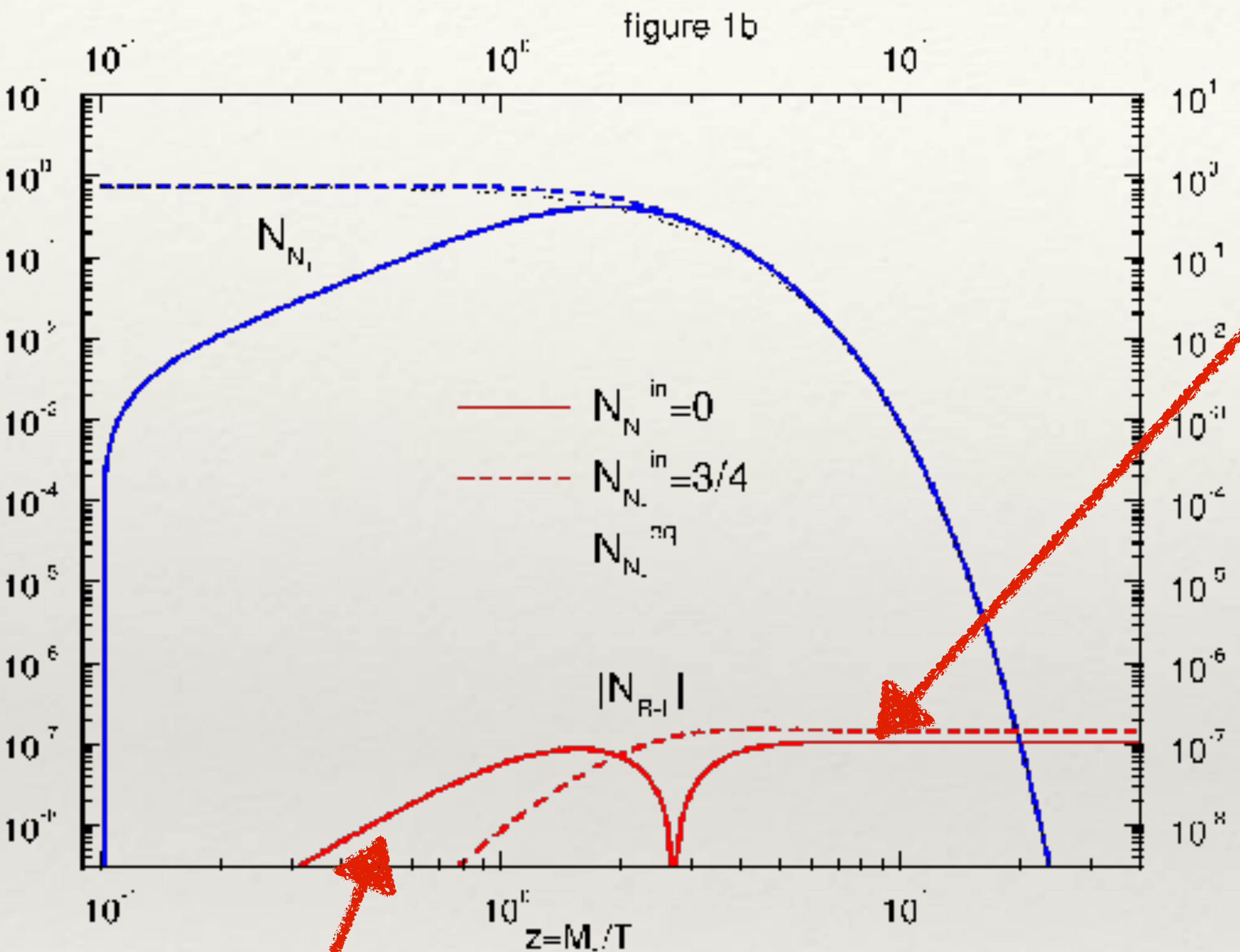
What about the famous Davidson-Ibarra bound M > 10 ^{9} GeV? 0202239

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

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

"source" "washout"

Leptogenesis with small M?



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

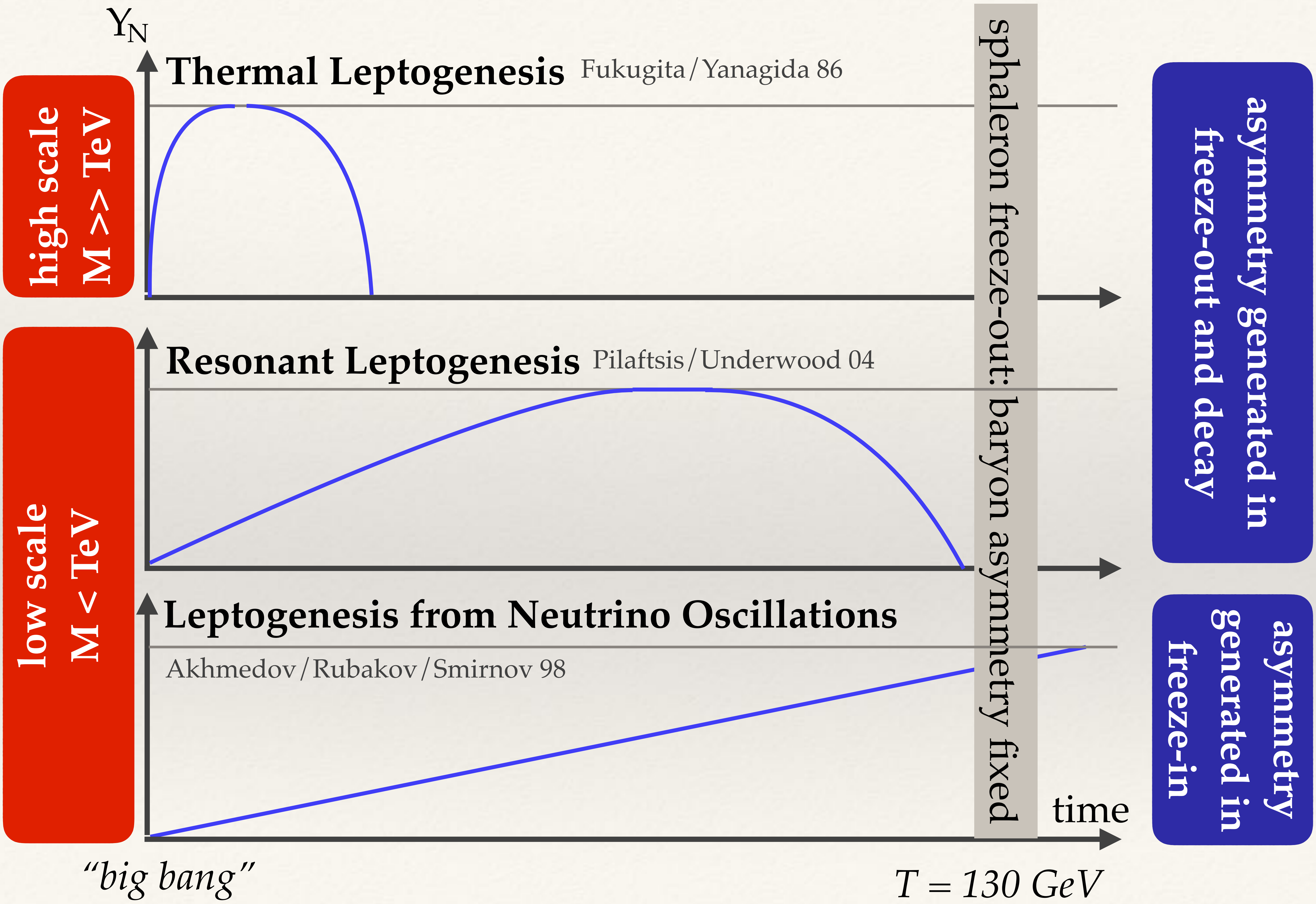
asymmetry generated during N production ("freeze-in scenario")

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

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

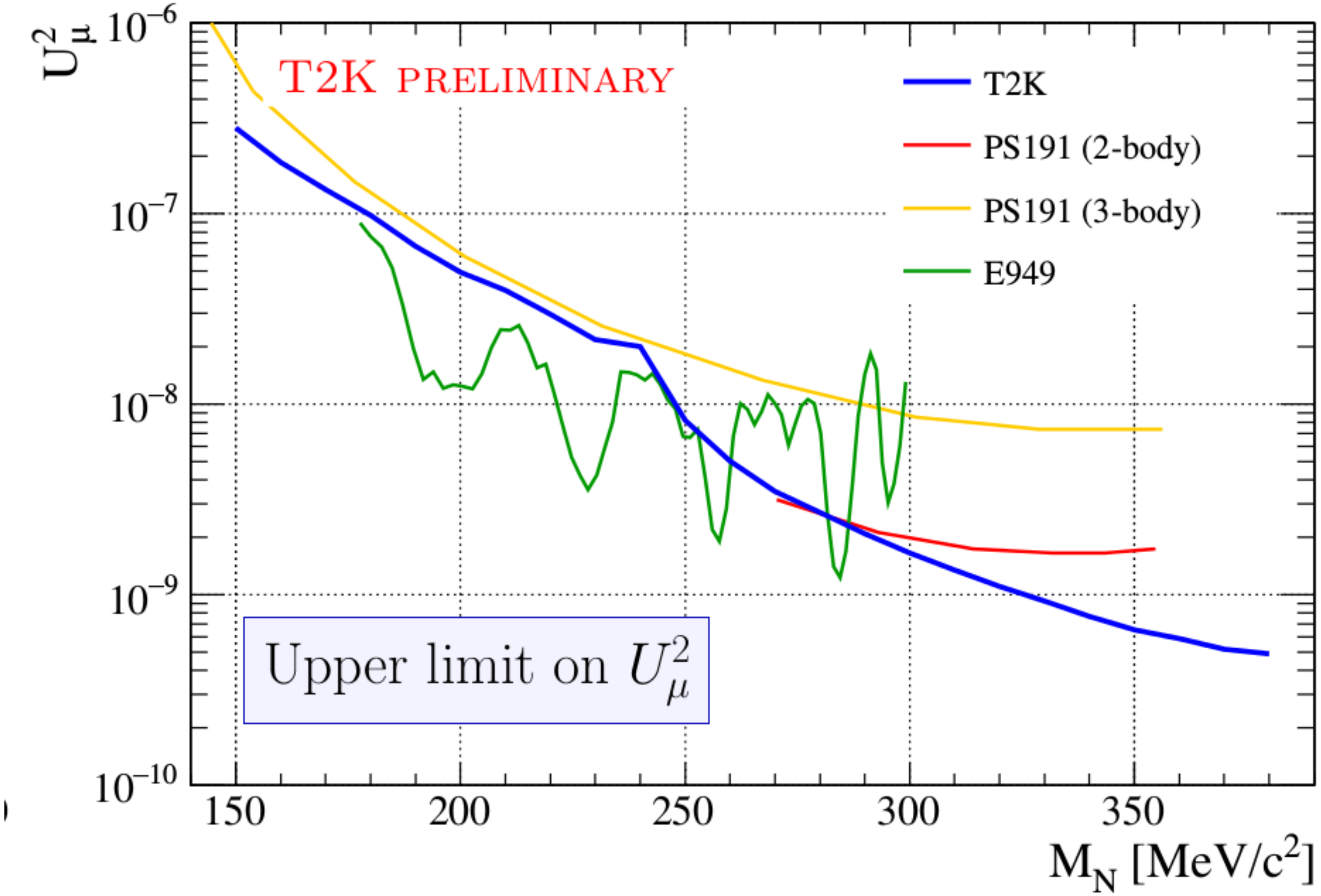
$$xH\frac{dY_{\mathrm{B-L}}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{\mathrm{eq}}) - c_W\Gamma_N Y_{\mathrm{B-L}}$$

"source" "washout"



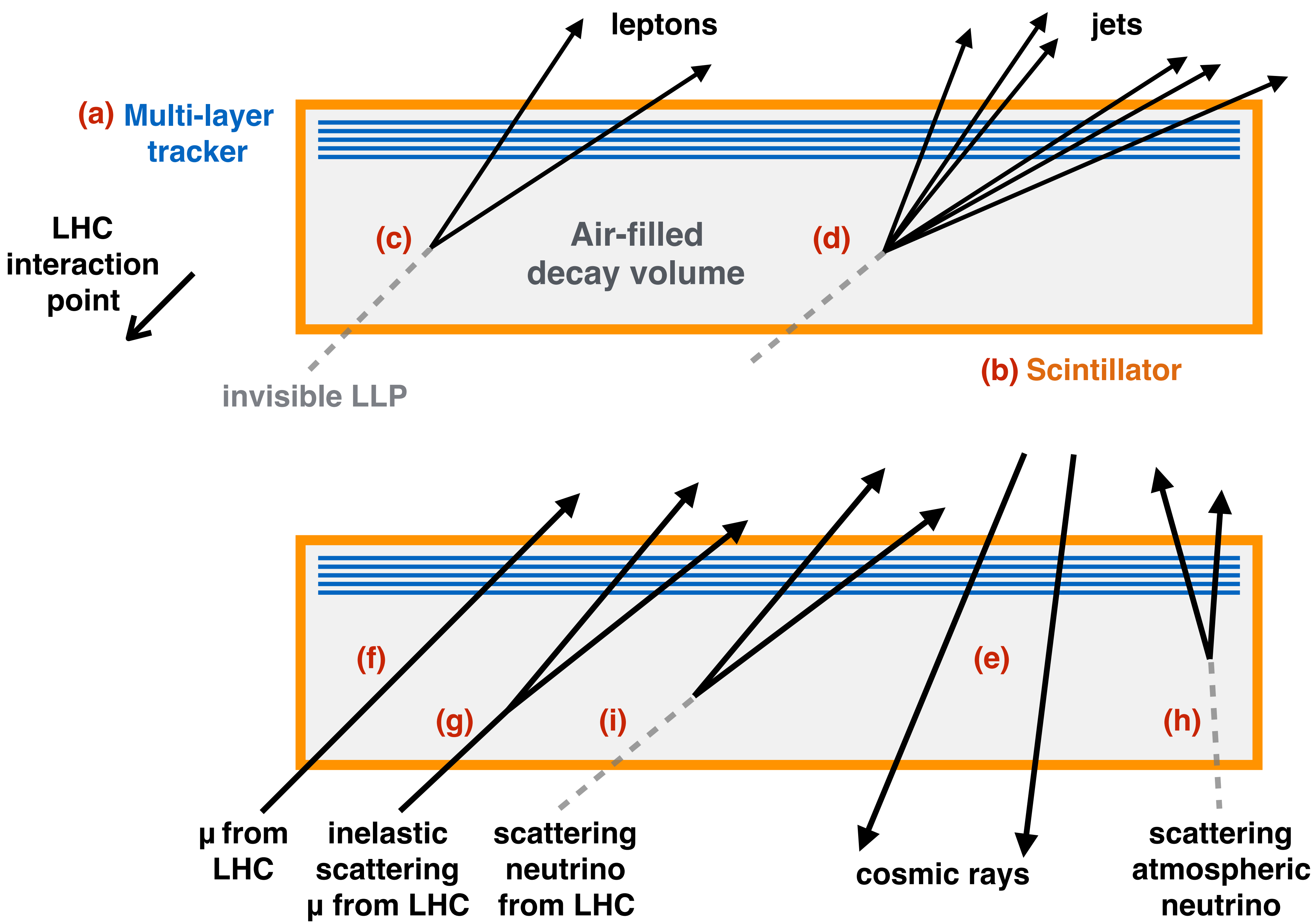
Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
high scale
M >> TeV
Resonant Leptogenesis
Pilaftsis/Underwood 04
low scale
M < TeV
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98
sphaleron freeze-out: baryon asymmetry fixed
asymmetry generated in freeze-out and decay
asymmetry generated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

T2K: Preliminary Results

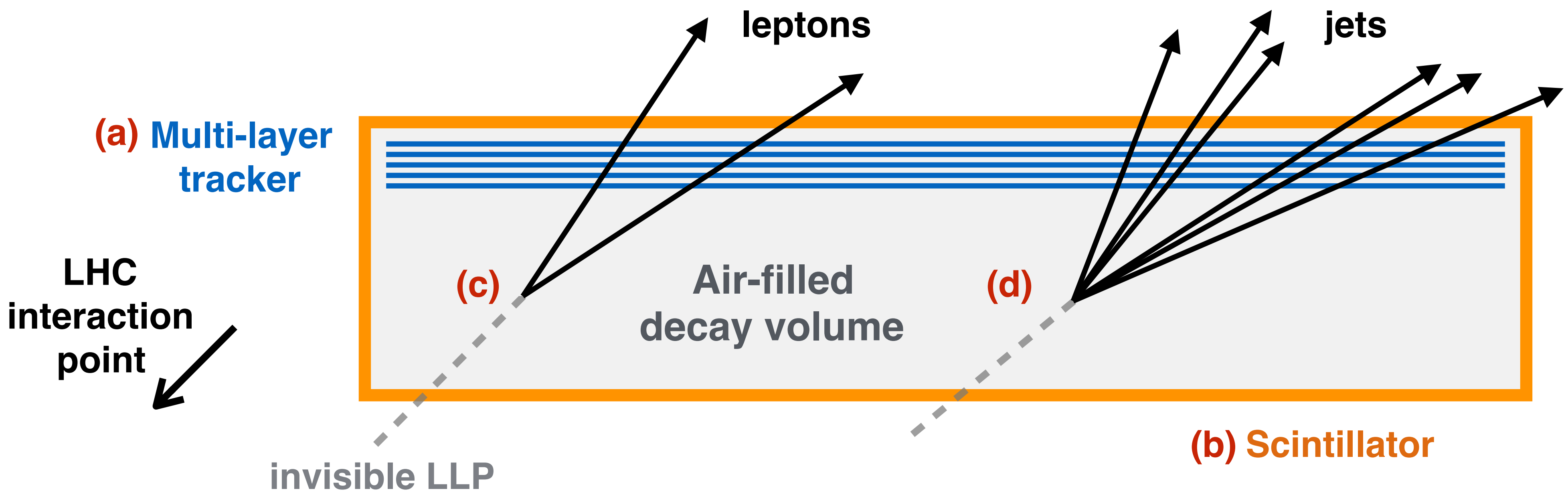


https://indico.desy.de/indico/event/18342/session/35/contribution/132/material/poster/0.pdf

Schematic Design



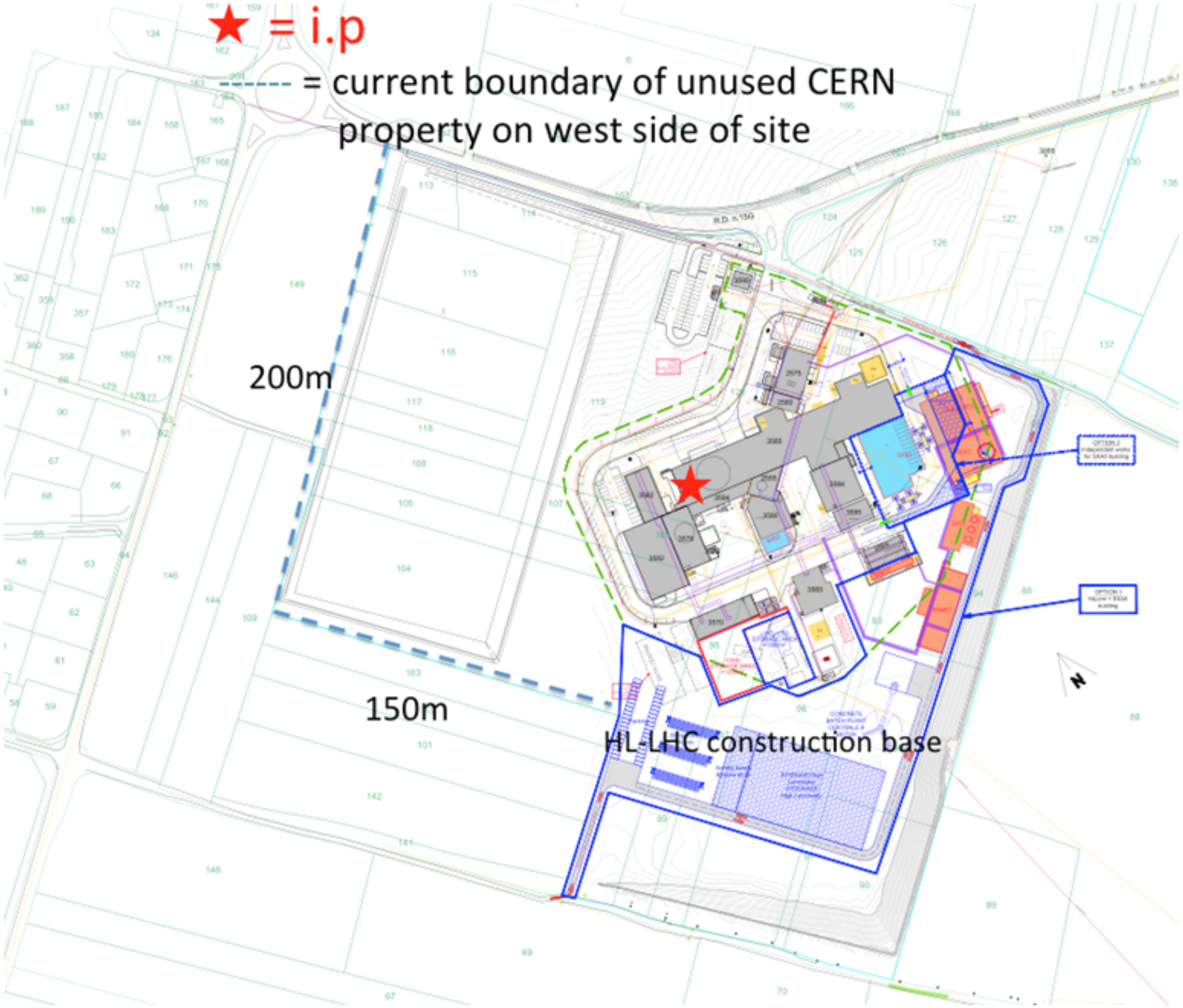
Schematic Design



Possible improvements:

- add iron plate at bottom to distinguish e from mu?
- add detector at bottom for additional rejection/veto?
- digg it into the earth?
- bring more close to IP?

Where to put this?



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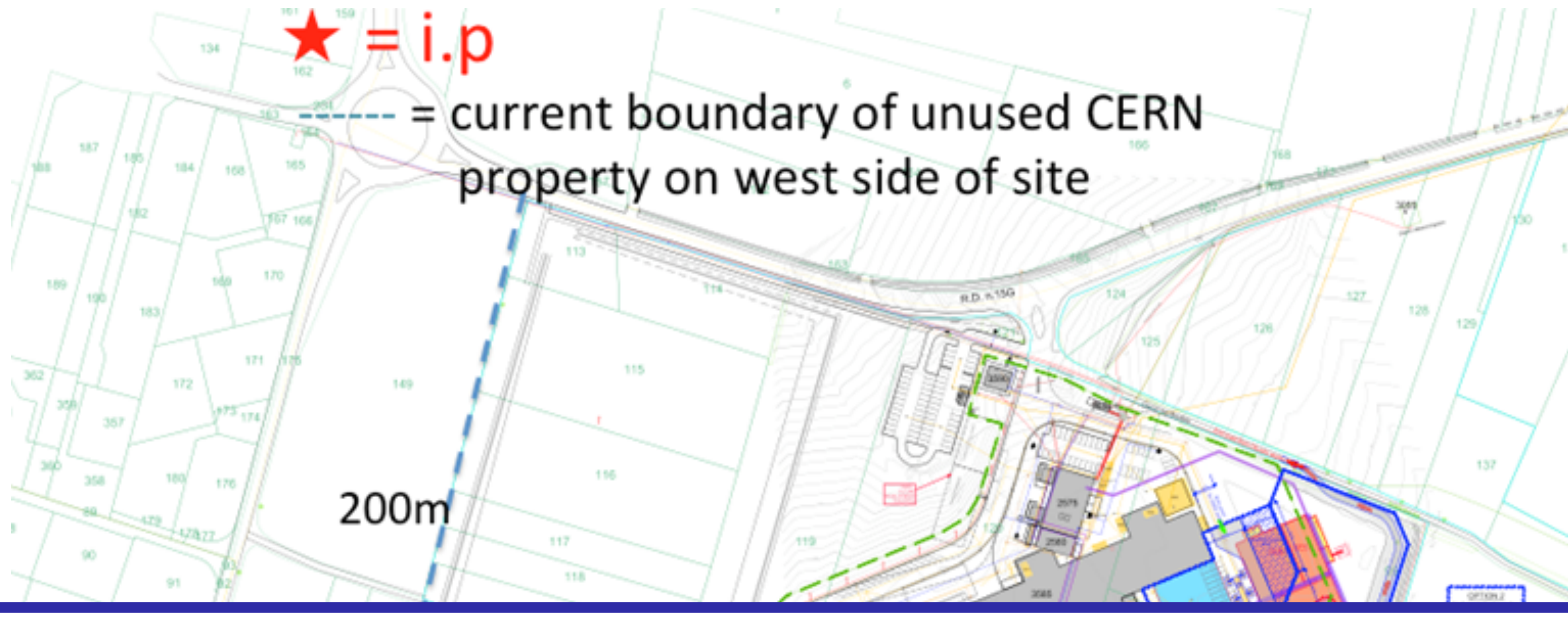
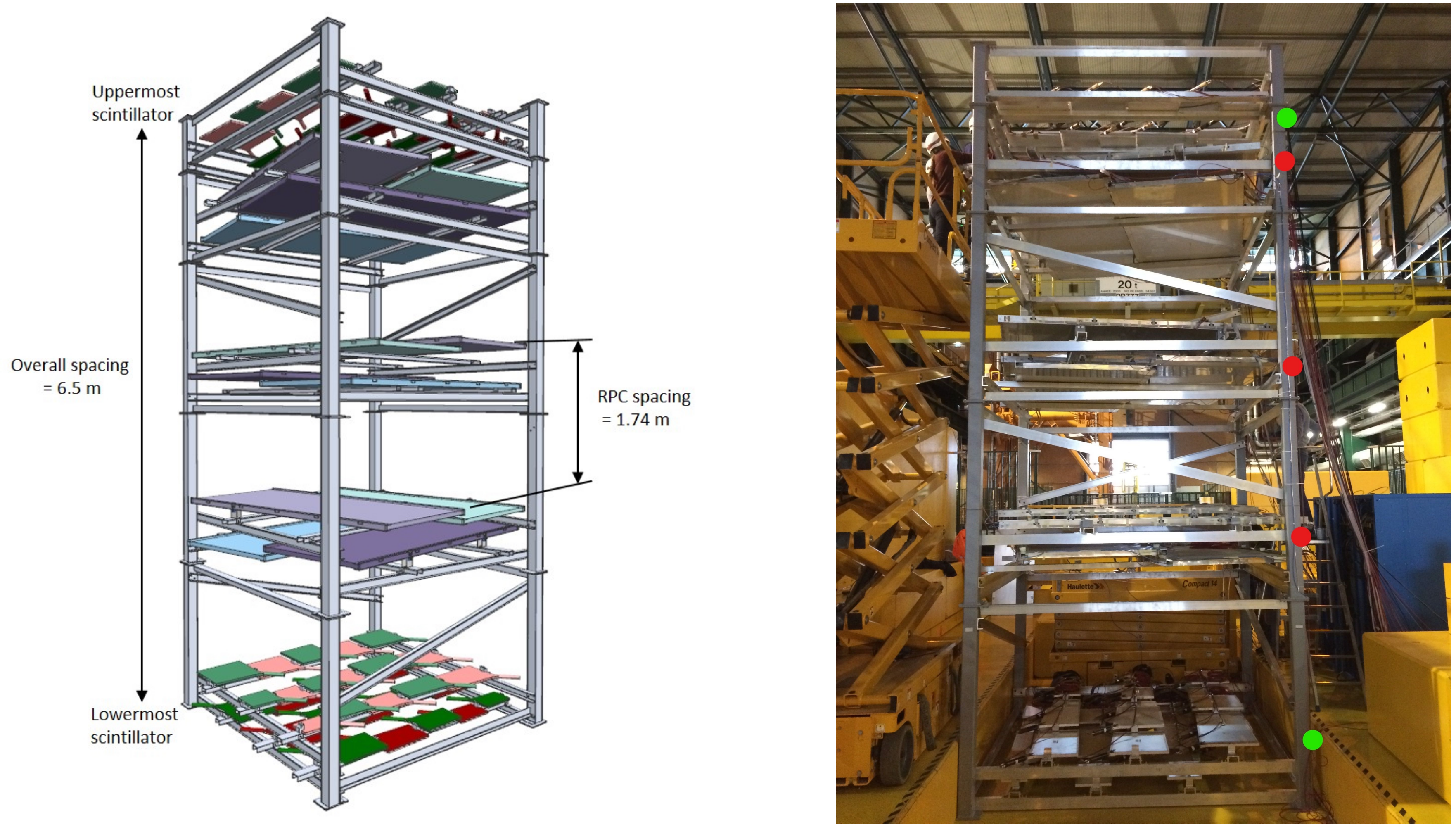


Open questions:

- **MATHUSLA100 vs MATHUSLA200**
- **location?**
- **digging?**

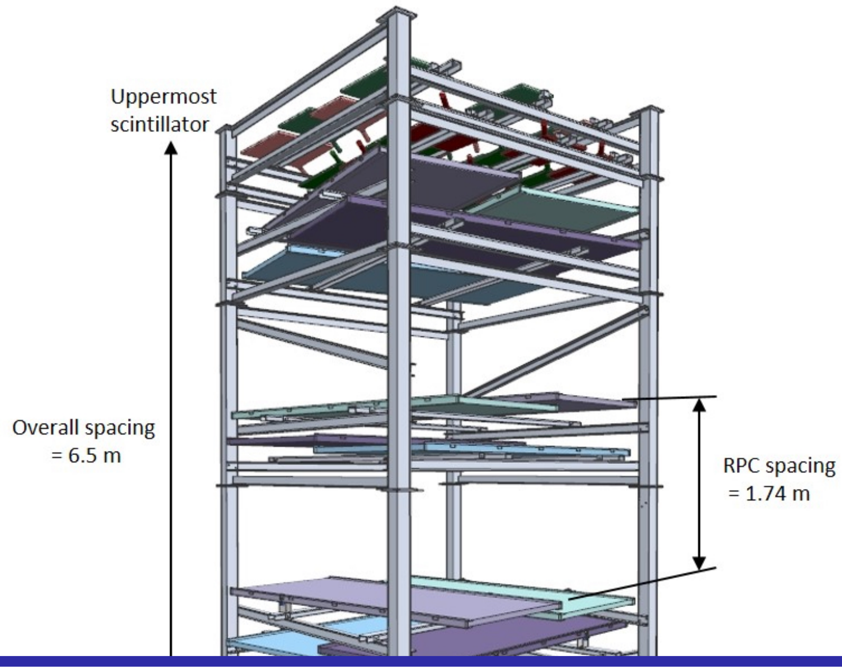
MATHUSLA Test Stand



(a) (b)

Figure 20. (a): schematic view of the MATHUSLA test stand. (b): picture of the final assembled structure in his test area in the ATLAS SX1 building at CERN. The green dots identify the two scintillator layers used for triggering, while the red dots the three RPC layers used for tracking.

MATHUSLA Test Stand



Now:
Apply for 1% size prototype
Cost: ~ 1 million $

Final cost: tens of millions