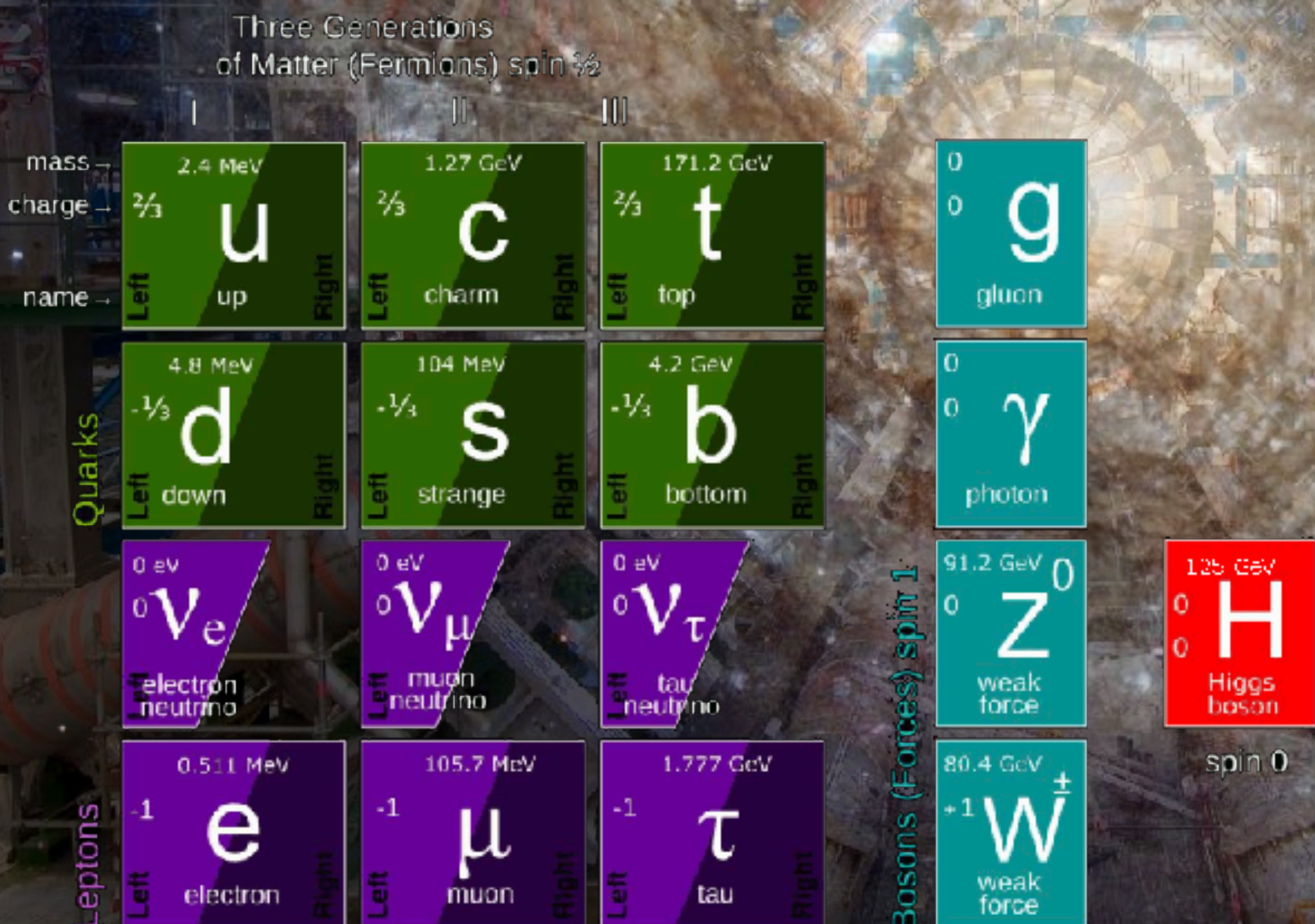
How many new particles do we need after the Higgs boson?

Marco Drewes , Université catholique de Louvain

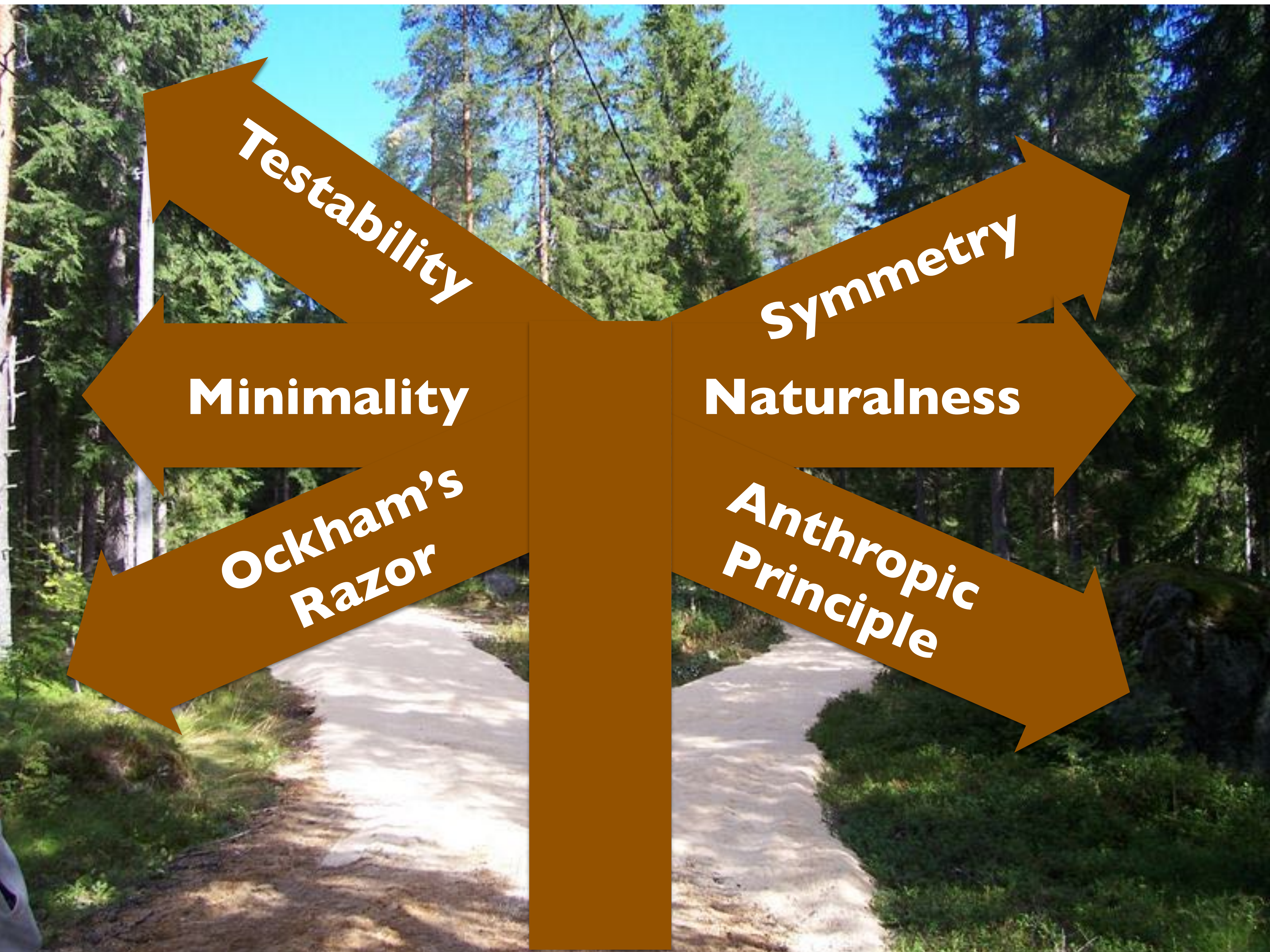
The Future of Particle Physics:
A Quest for Guiding Principles

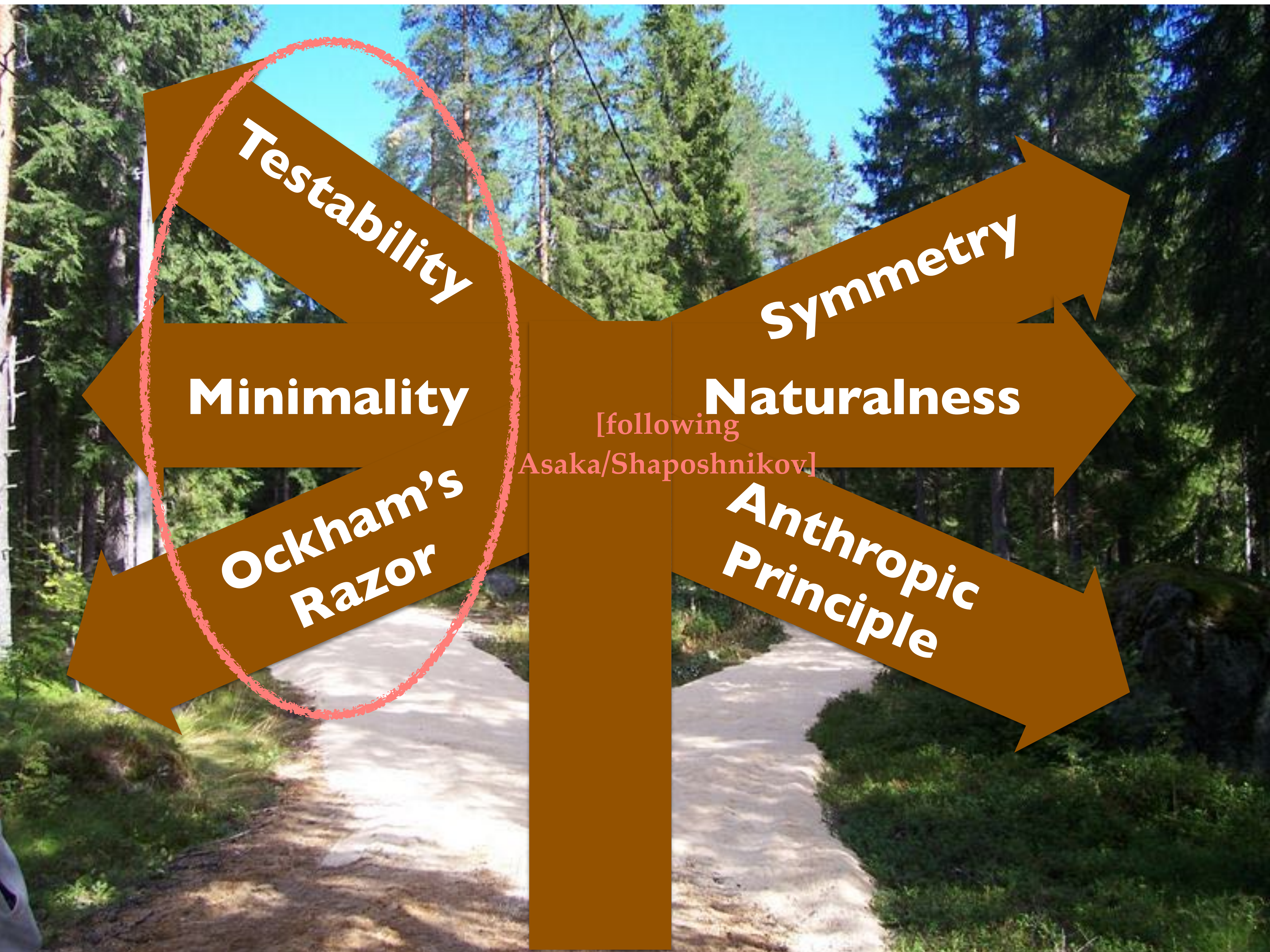
KIT, Karlsruhe

01.10.2018

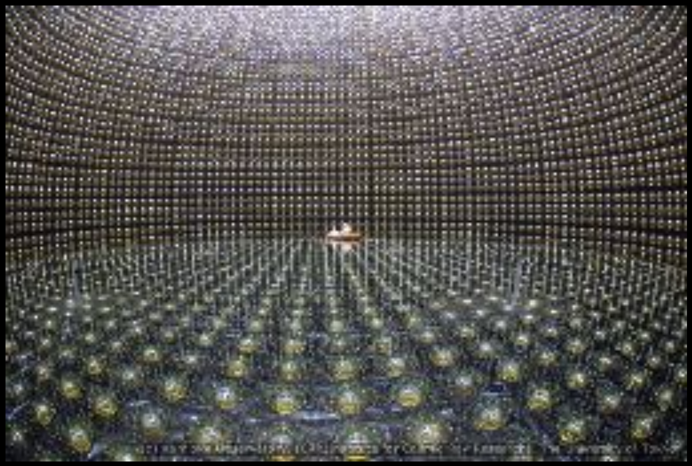


The “periodic table” of elementary particles - who is missing?

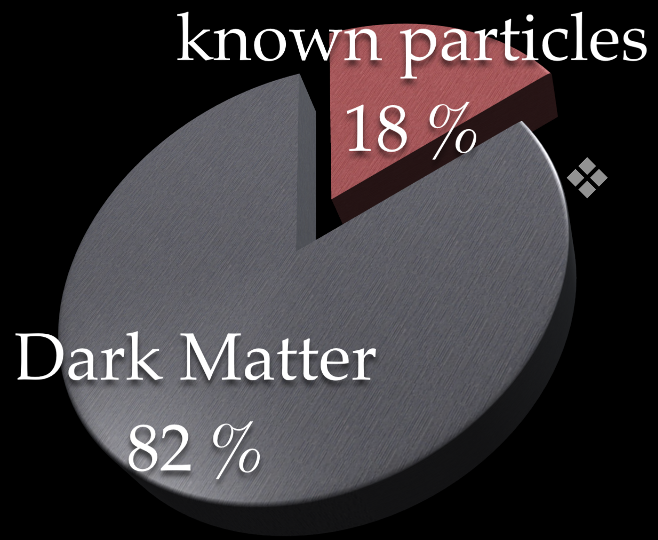

Testability
Symmetry
Minimality
Naturalness
Ockham's Razor
Anthropic Principle


Testability
Minimality
Ockham's Razor
Symmetry
Naturalness
Anthropic Principle
[following Asaka/Shaposhnikov]

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



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

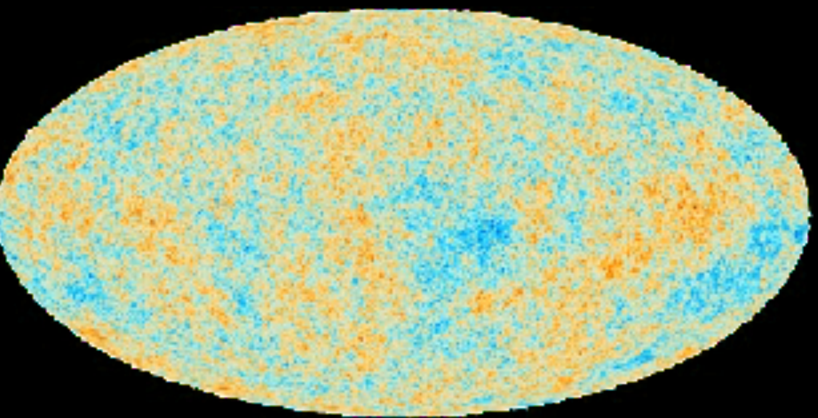


- **What is the Dark Matter made of?**

It makes up most of the mass in the universe.

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

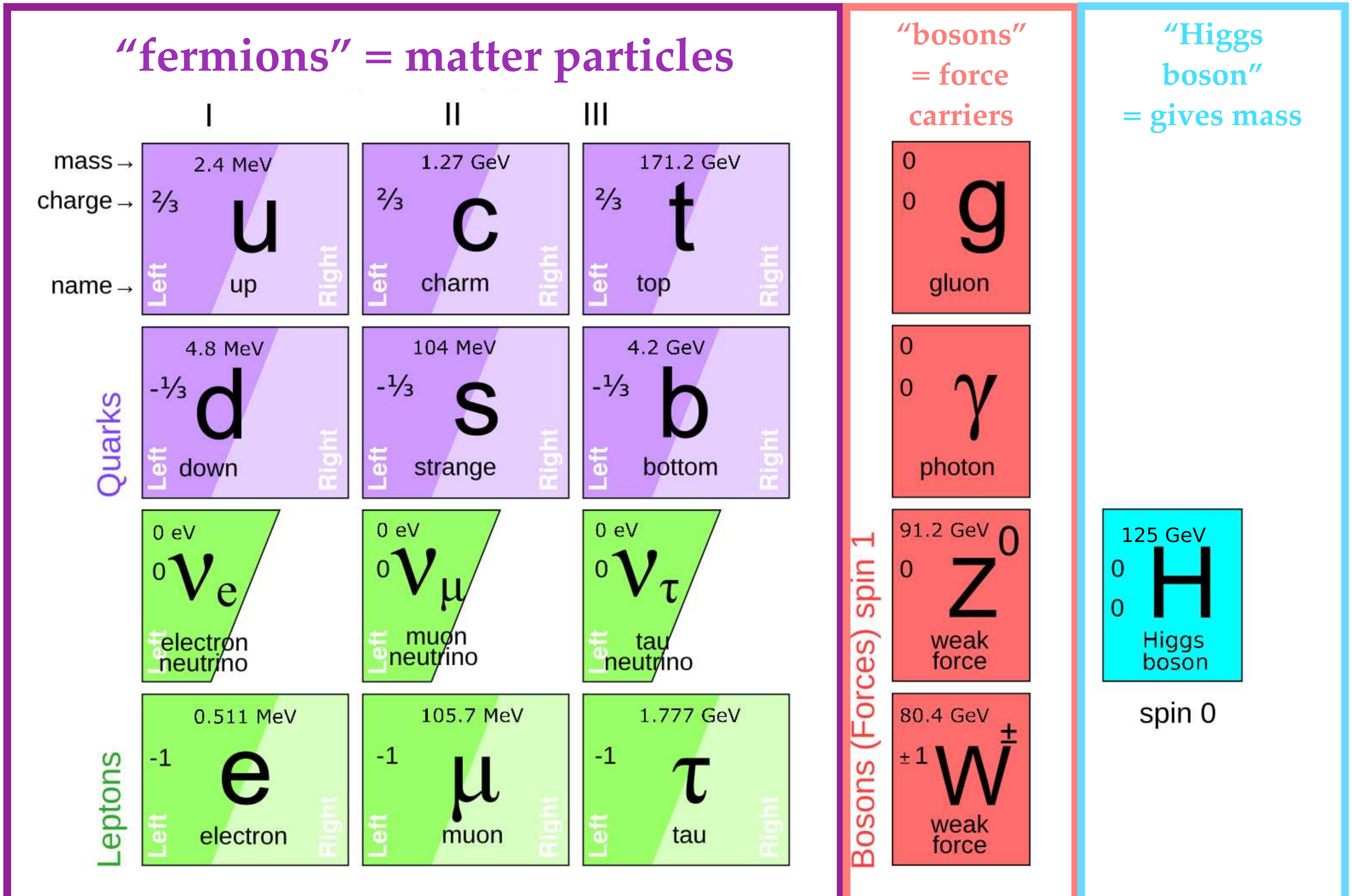
…so that some matter survived the mutual
annihilation to form galaxies, stars etc.



- **What set the initial conditions for the "hot big bang"?**

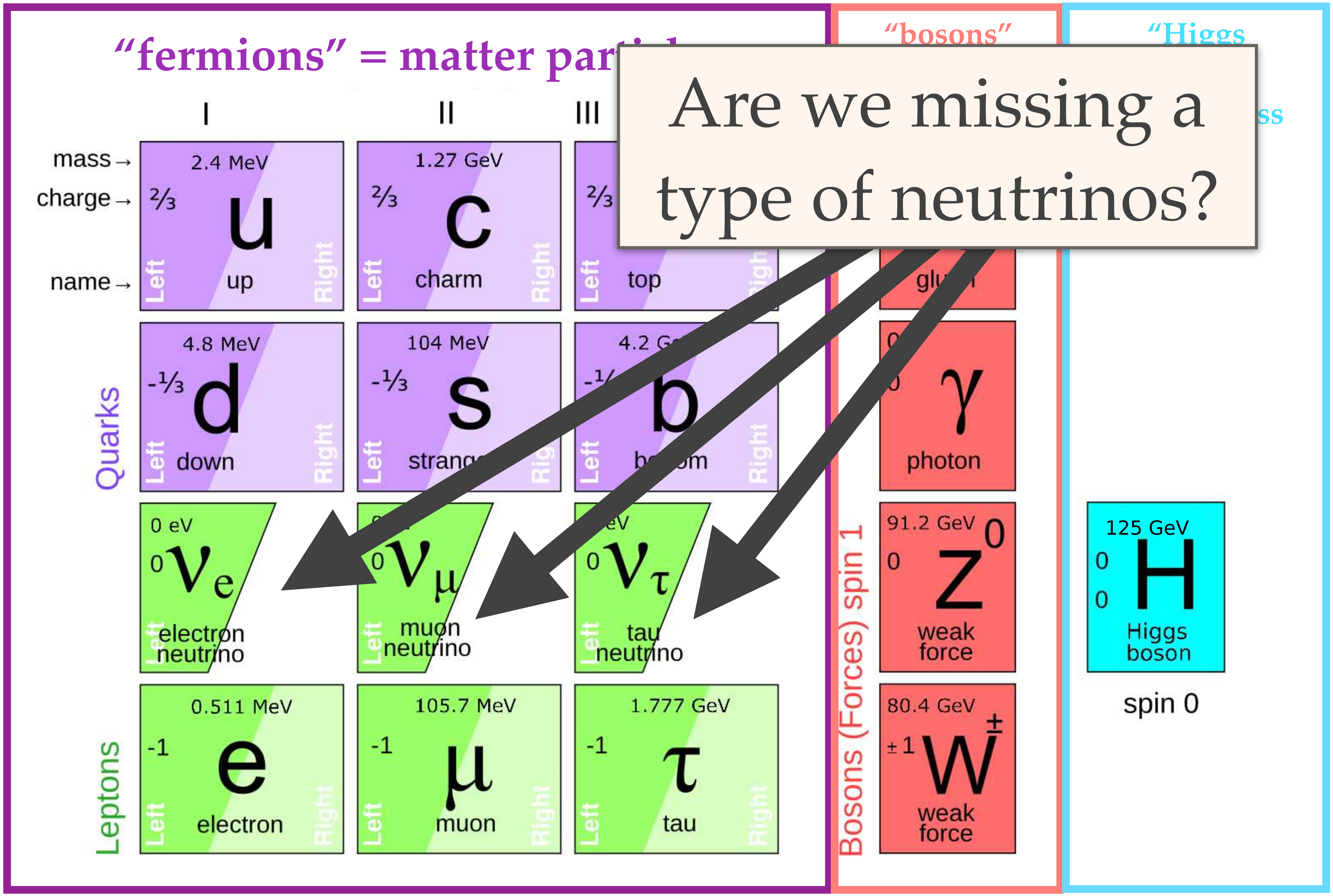
Cosmic inflation? How did the transition to the radiation
dominated epoch happen?

The Standard Model of Particle Physics



The "periodic table" of elementary particles - who is missing?

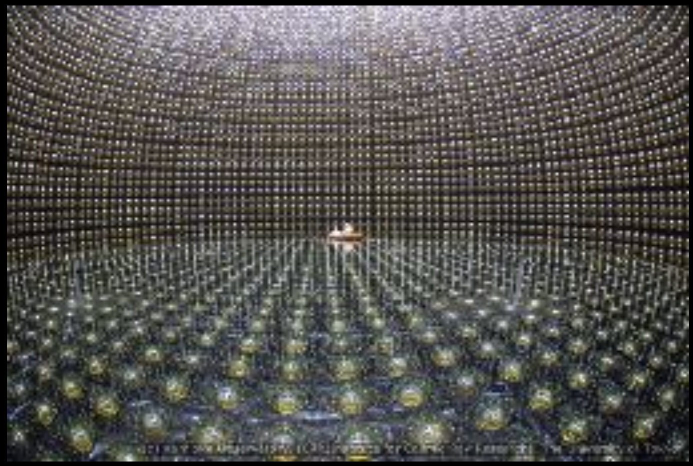
The Standard Model of Particle Physics

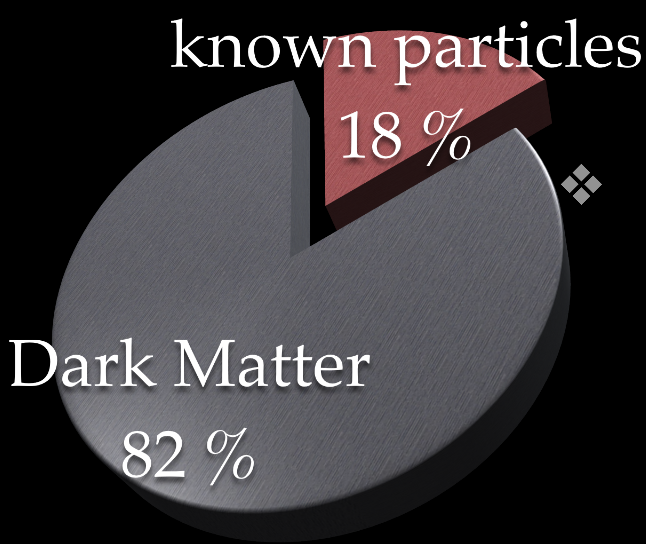


The "periodic table" of elementary particles - who is missing?

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

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



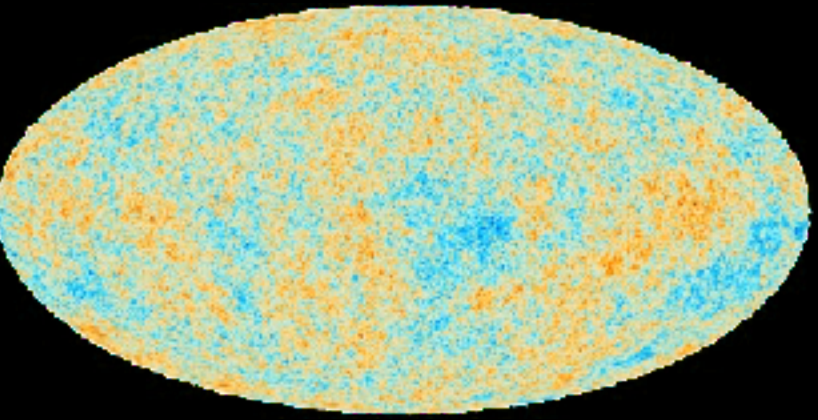


- **What is the Dark Matter made of?**

  It makes up most of the mass in the universe.

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

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

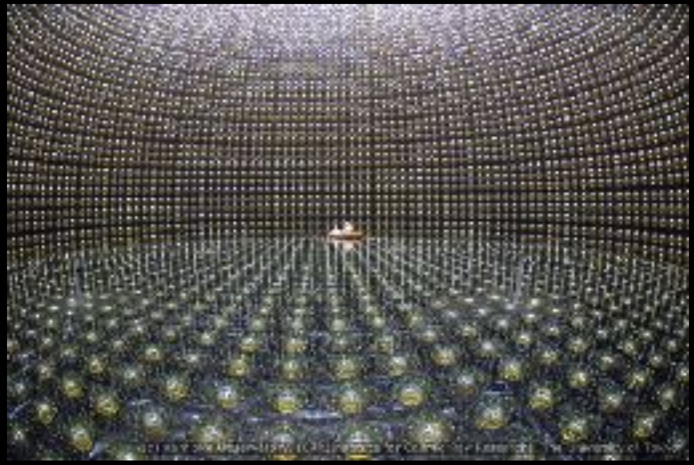


- **What set the initial conditions for the "hot big bang"?**

  Cosmic inflation? How did the transition to the radiation dominated epoch happen?

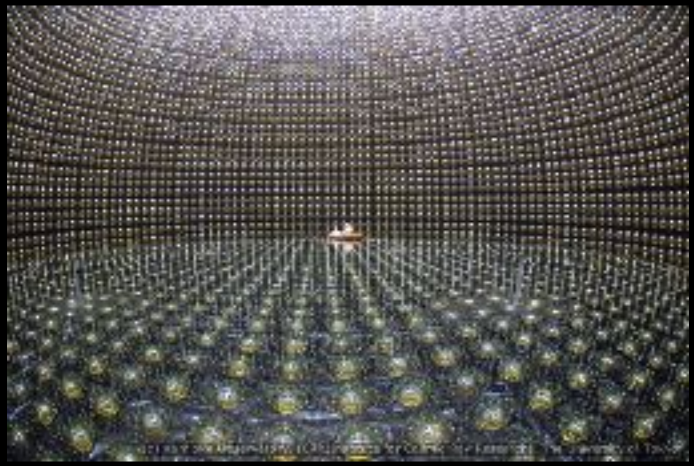
- **What is the origin of neutrino mass?**

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



The only one found in laboratory!

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



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

The only one found in laboratory!

Seesaw Mechanism

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

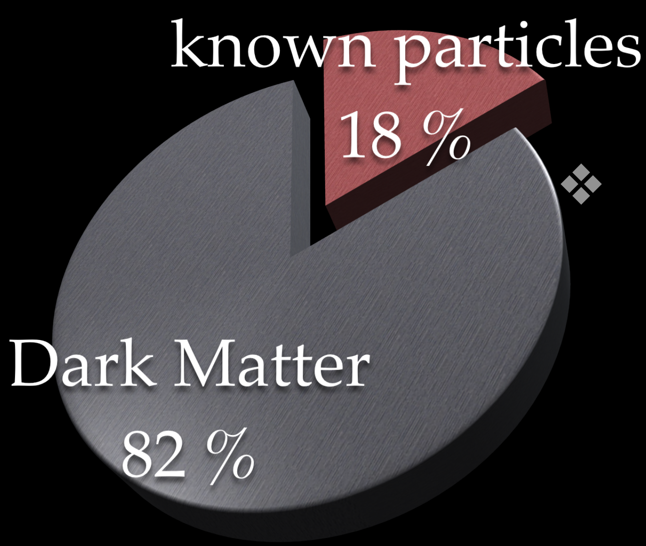
three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

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

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

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

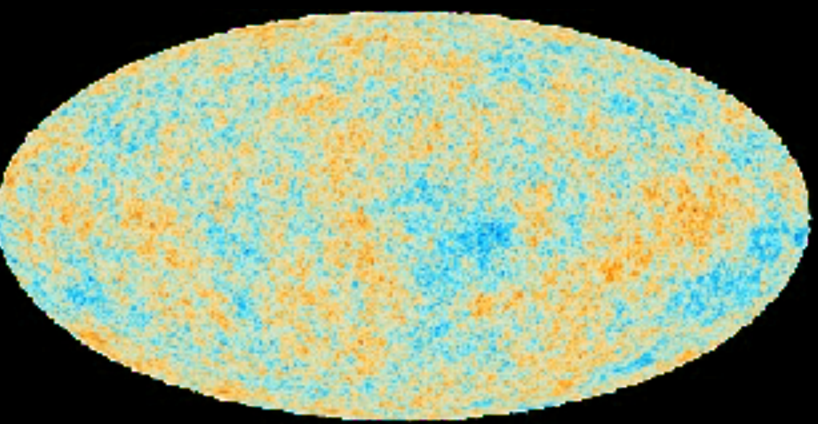


- **What is the Dark Matter made of?**

It makes up most of the mass in the universe.

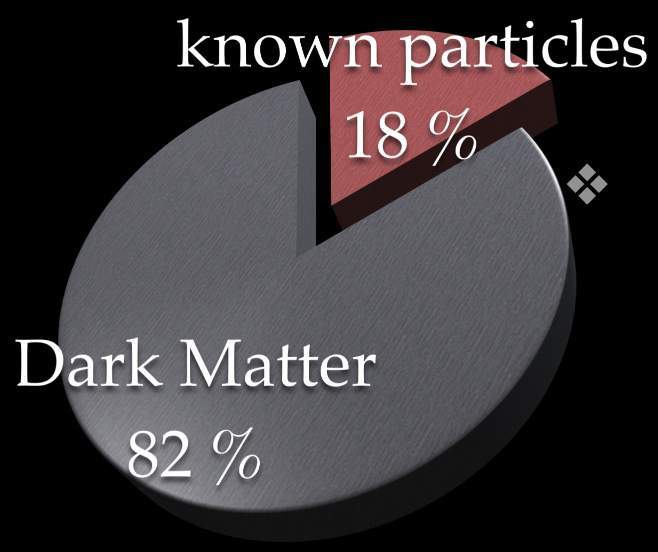
- **Why was there more matter than antimatter in the early universe?**

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



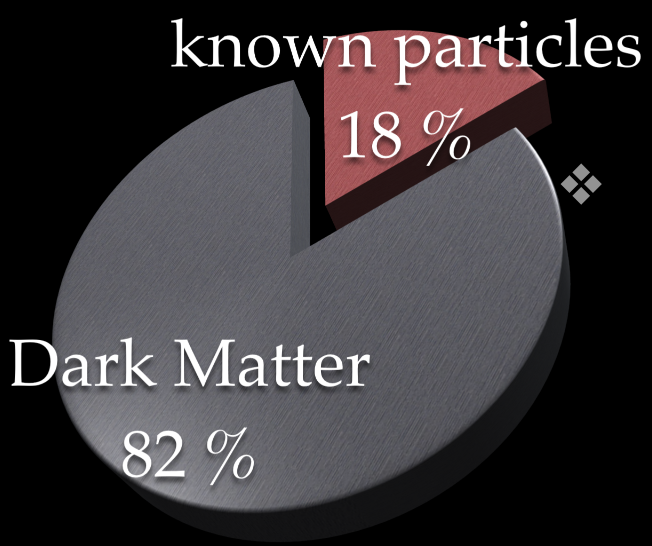
- **What set the initial conditions for the "hot big bang"?**

Cosmic inflation? How did the transition to the radiation dominated epoch happen?



What is the Dark Matter made of?

It makes up most of the mass in the universe.



What is the Dark Matter made of?

It makes up most of the mass in the universe.

Heavy "Sterile" Neutrino Dark Matter

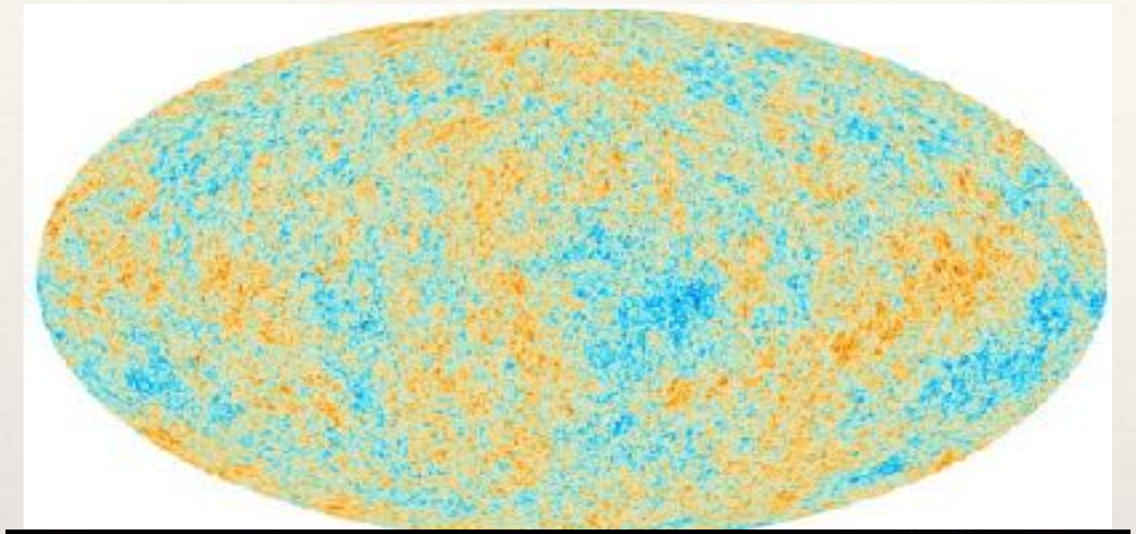
Dark Matter Particles are

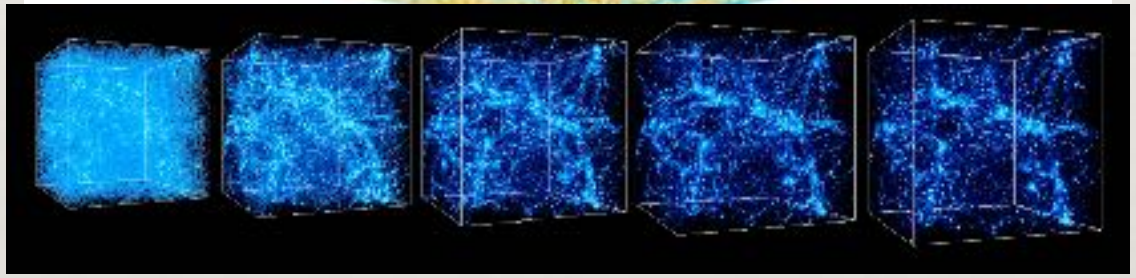
- **massive**
- **neutral**
- **collisionless**
- **long lived**

Neutrinos are the only known particles that fulfil these conditions…

…but they are too light,
Heavy sterile neutrinos do the job just perfectly!

Dark Matter is cold-ish

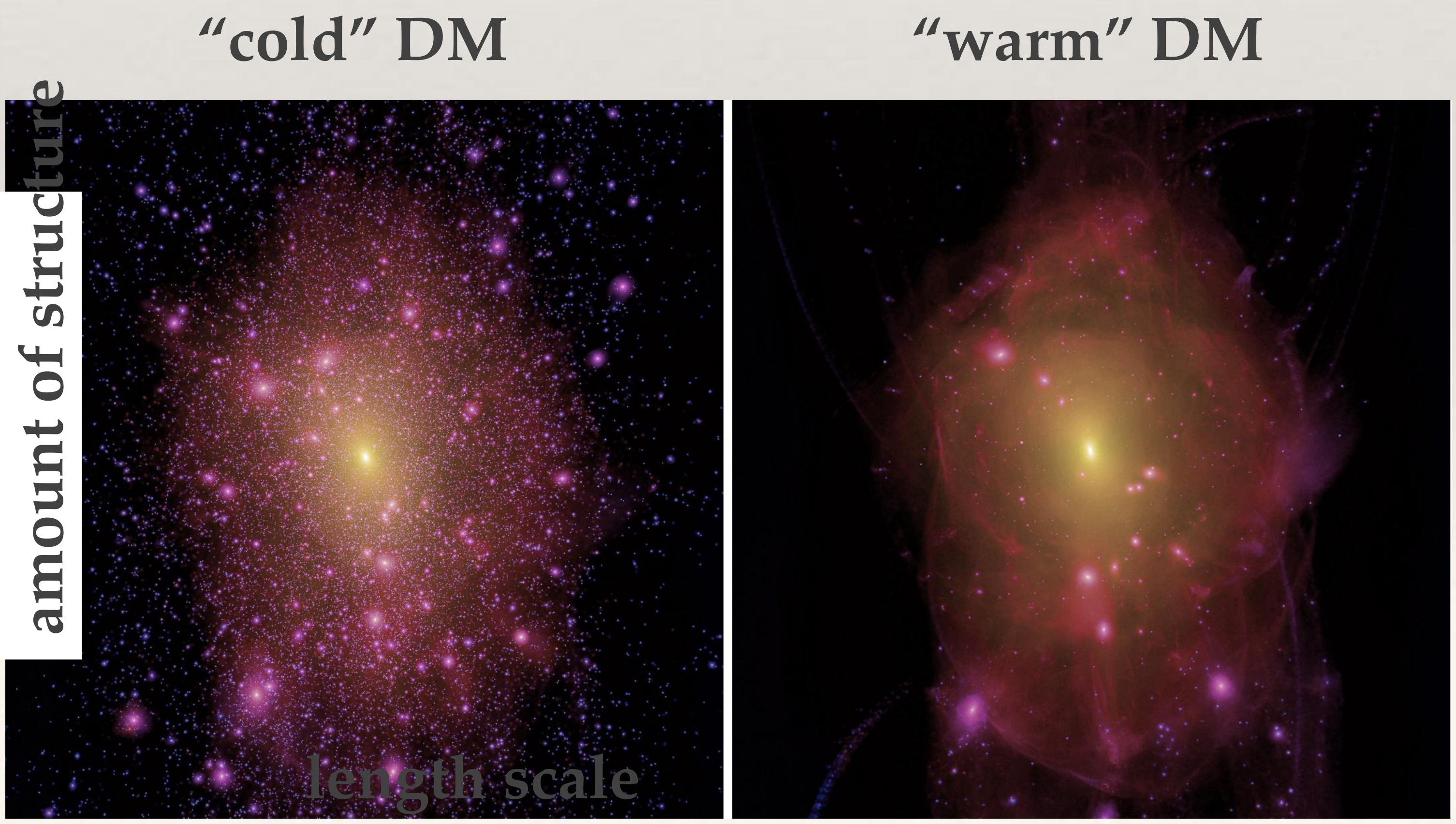




Streaming of DM particles during structure formation "smears out" small scale structures

Rules out keV sterile neutrino DM with thermal spectrum!

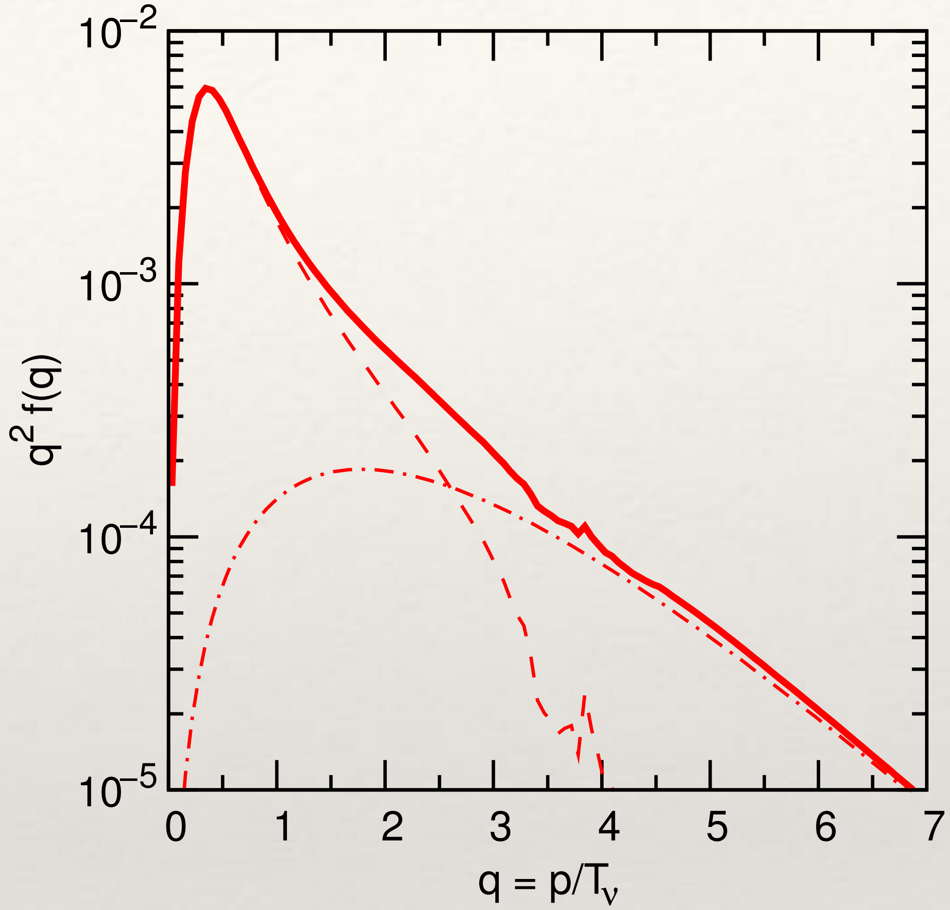
Thermally produced sterile neutrinos **cannot be heavier than ~100 keV** to avoid indirect detection

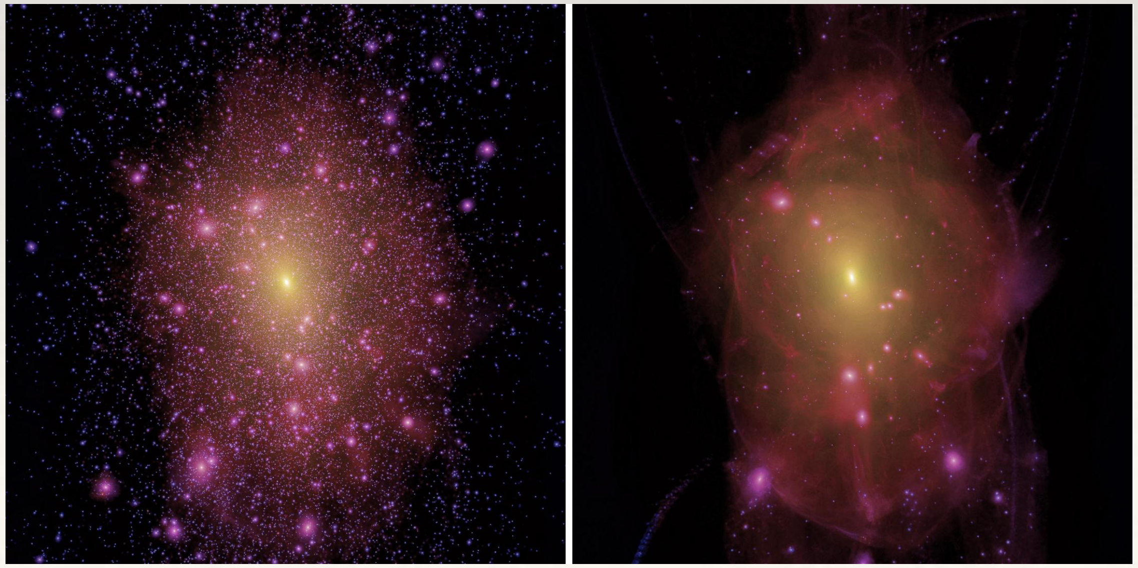


How to make Sterile Neutrino Dark Matter?

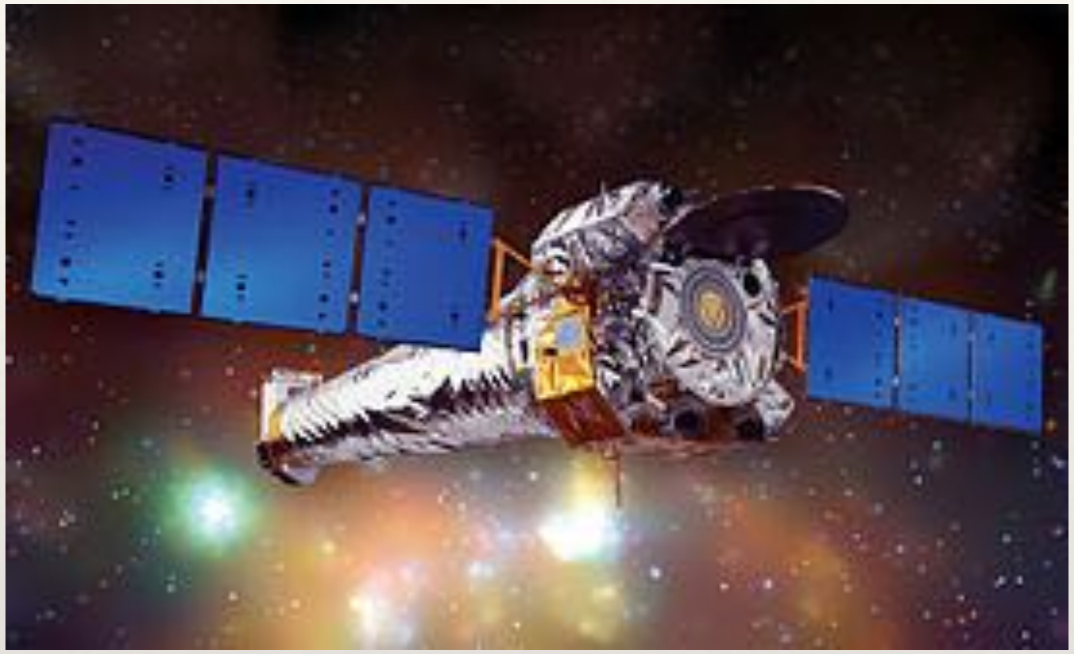
Thermal production via their mixing θ

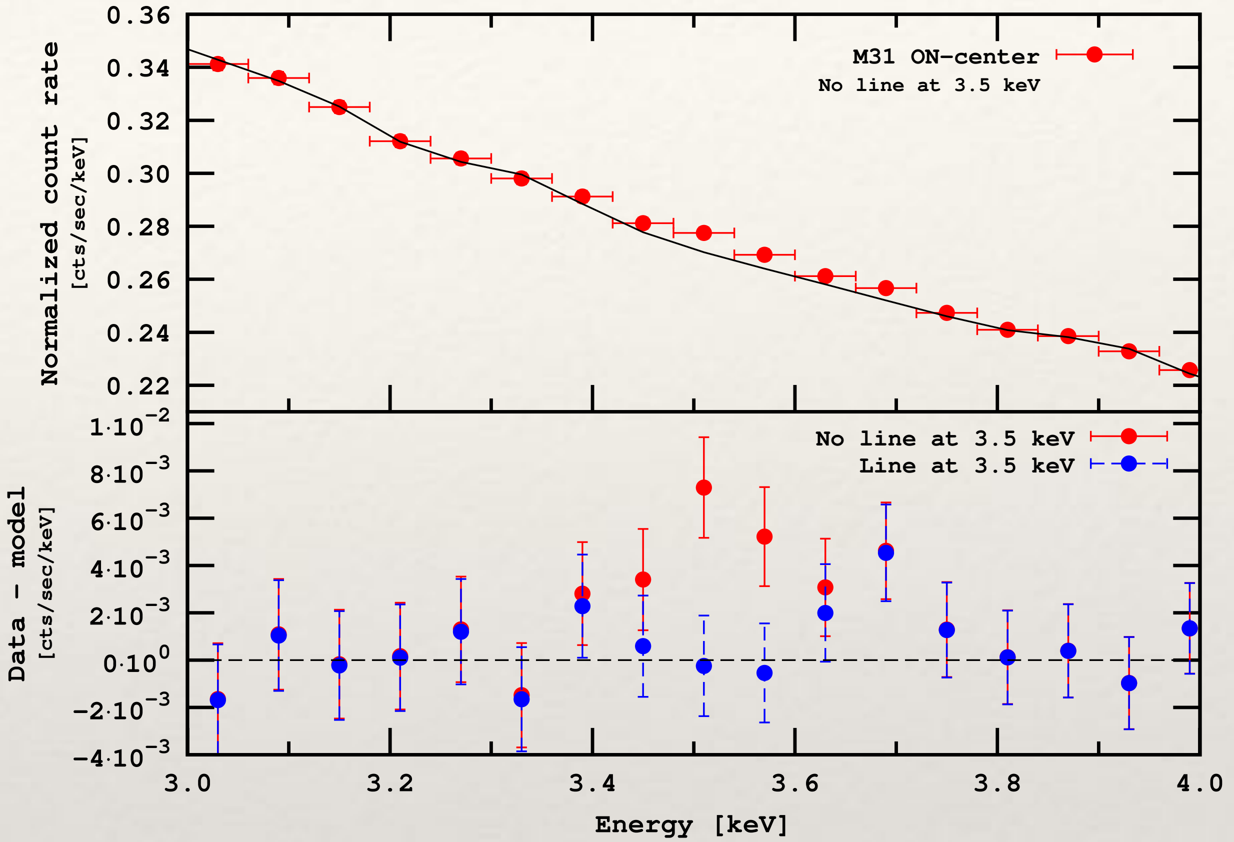
- Sterile neutrinos are produced in decoherent scatterings via their mixing θ Barbieri/Dolgov 91, Dodelson/Widrow 94
- never reach equilibrium for realistic θ ("freeze in DM", "FIMP DM") ⇒ non-thermal spectrum!
- production can be resonantly enhanced by MSW effect in presence of lepton asymmetries Shi/Fuller 99
- νMSM can provide the required lepton asymmetry Canetti/MaD/Frossard/Shaposhnikov 12
- State of the art computations: Ghiglieri/Laine 15, Venumadhav/Cyr-Racine/Abazajian/Hirata 15





How to find Sterile Neutrino Dark Matter?





Boyarsky/Ruchayskiy/Iakubovskyi/Franse 2014
see also Bulbul/Markevitch/Foster/Smith/Loewenstein/
Randall 2014

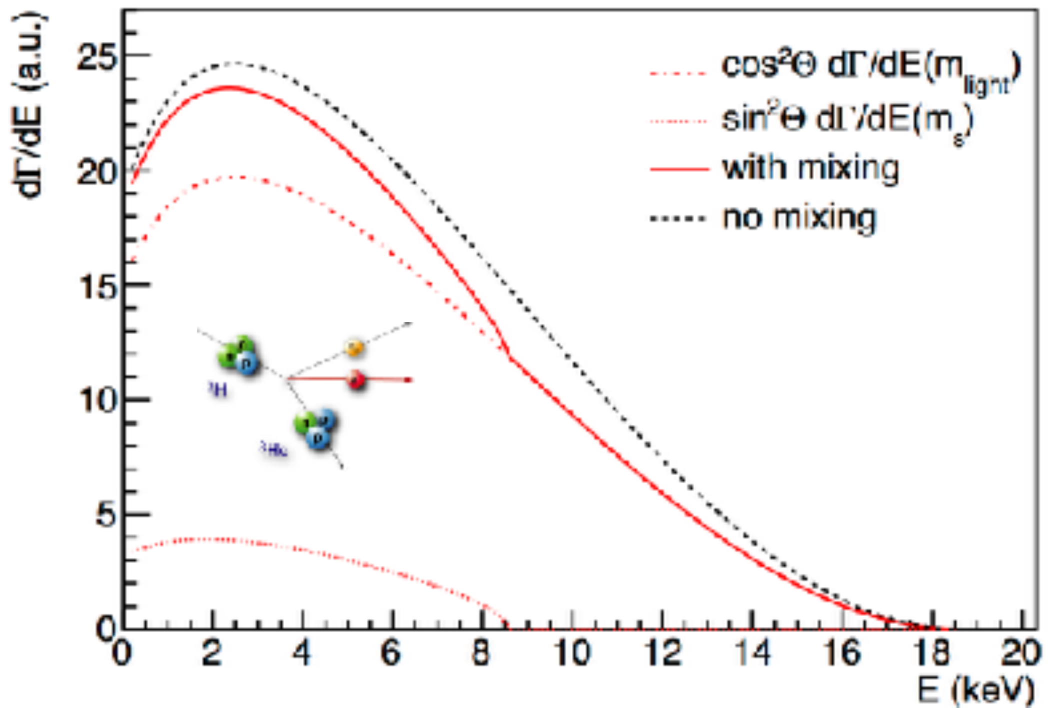
Sterile Neutrinos are unstable particles.

Dark Matter decay produces a narrow emission line...
... but it is smeared by the instrumental resolution

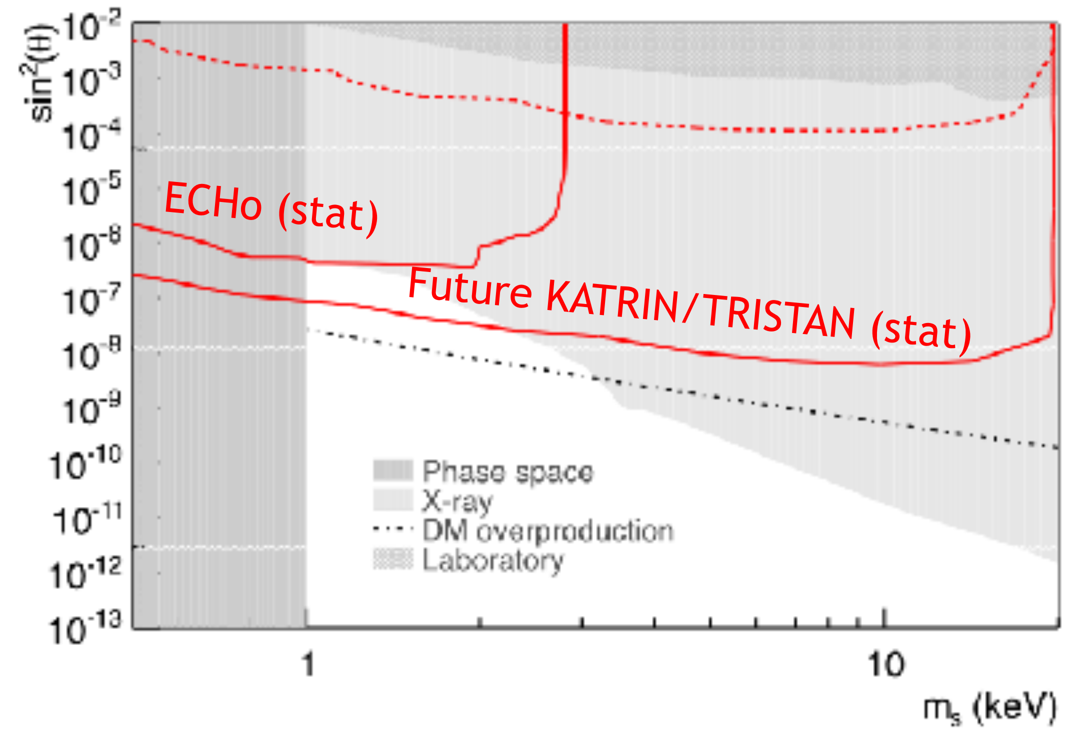
OK for exclusion, but for a discovery need better spectral resolution
Future missions XARM and ATHENA have

KATRIN/TRISTAN & keV Sterile Neutrinos

mprint of keV Neutrinos on Tritium β-spectrum

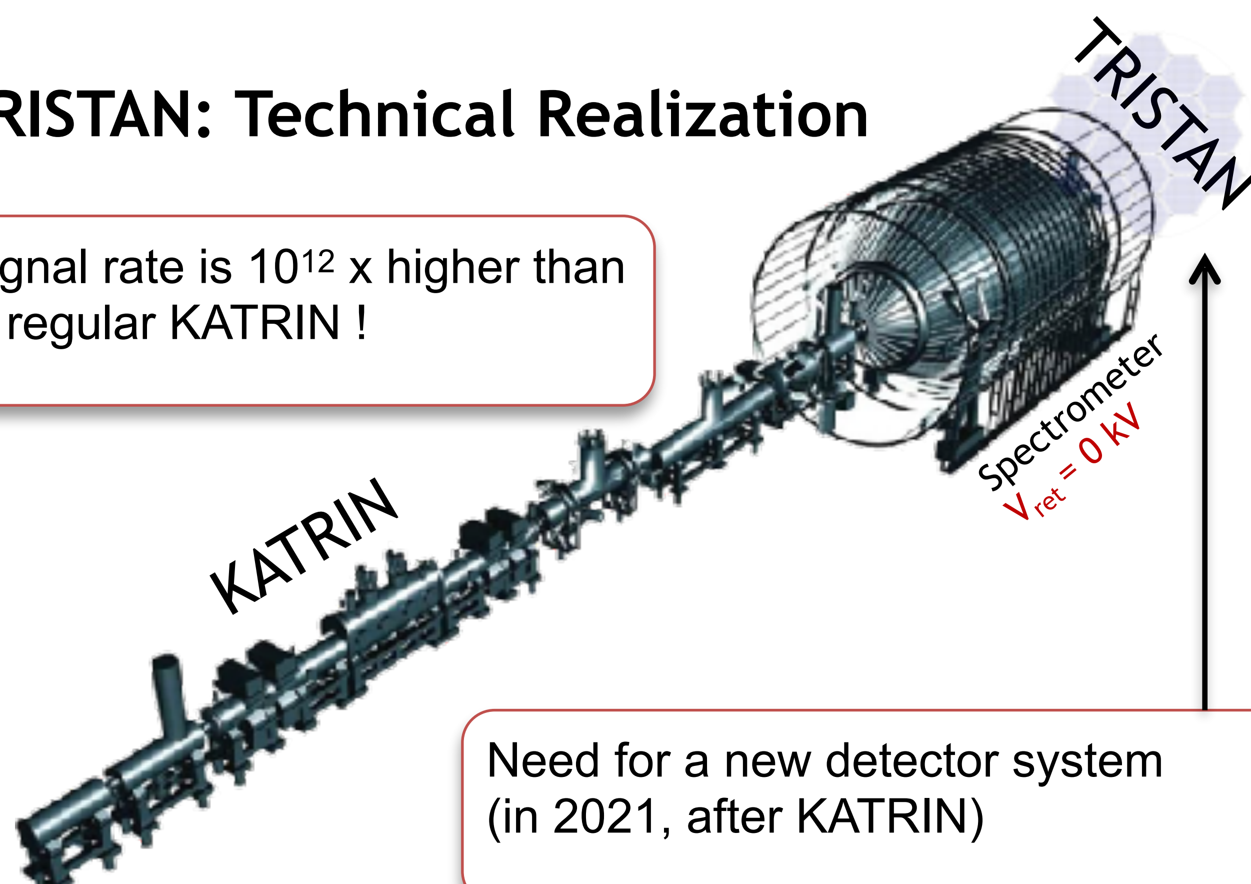


Statistical Sensitivity



TRISTAN: Technical Realization

Signal rate is 10^{12} x higher than in regular KATRIN !



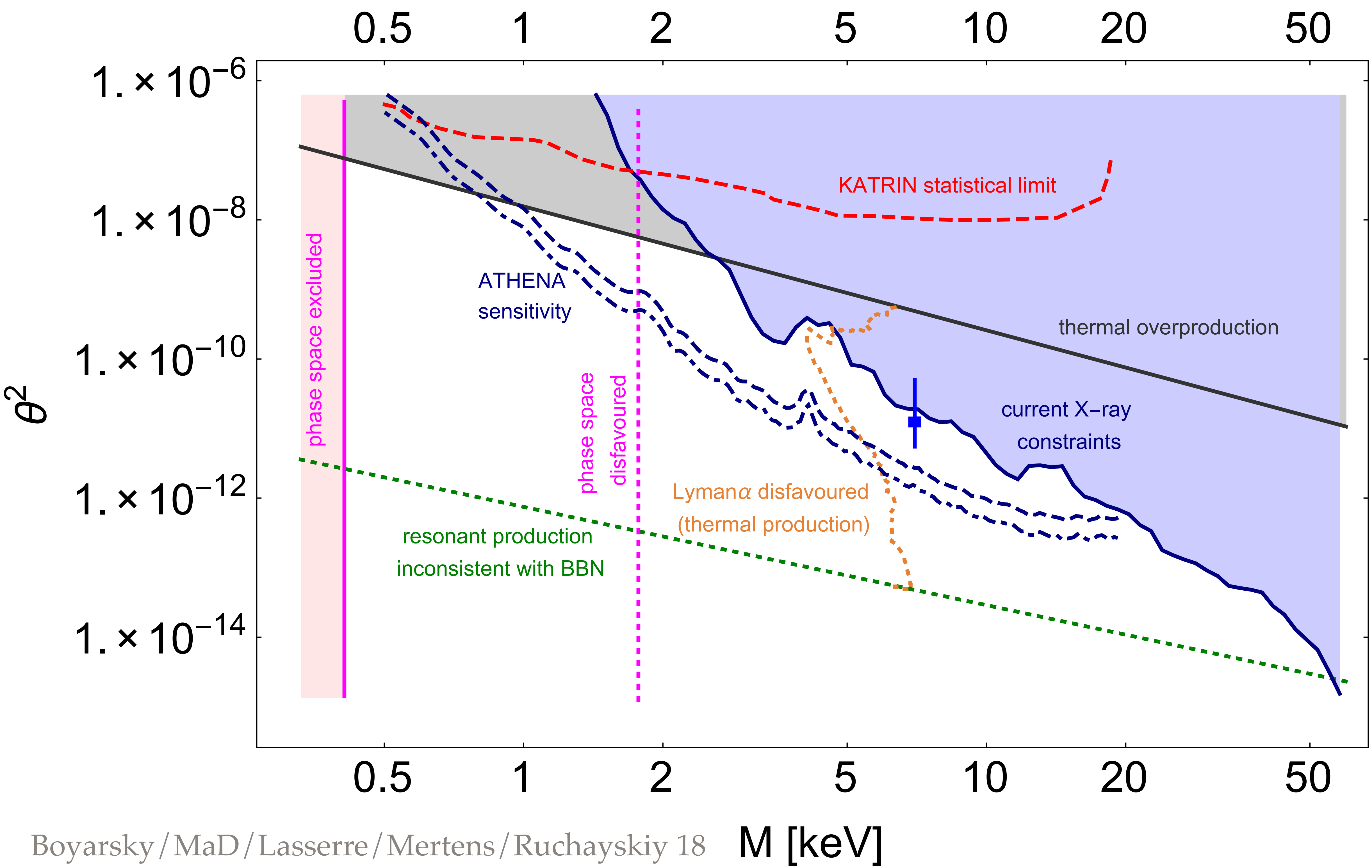
Need for a new detector system (in 2021, after KATRIN)

Novel Silicon Detector System (R&D)

- Handling high rates (10^9 cts/s)
  - >10 000 pixels
- 300 eV energy resolution & 1 keV threshold
  - Thin deadlayer (~10 nm)
- 1 mm pixels with <0.2 pF capacity
  - Multi-drift-ring design (SDD)
- Minimize systematics (ppm-level)
  - Low ADC non-linearity read-out, etc...

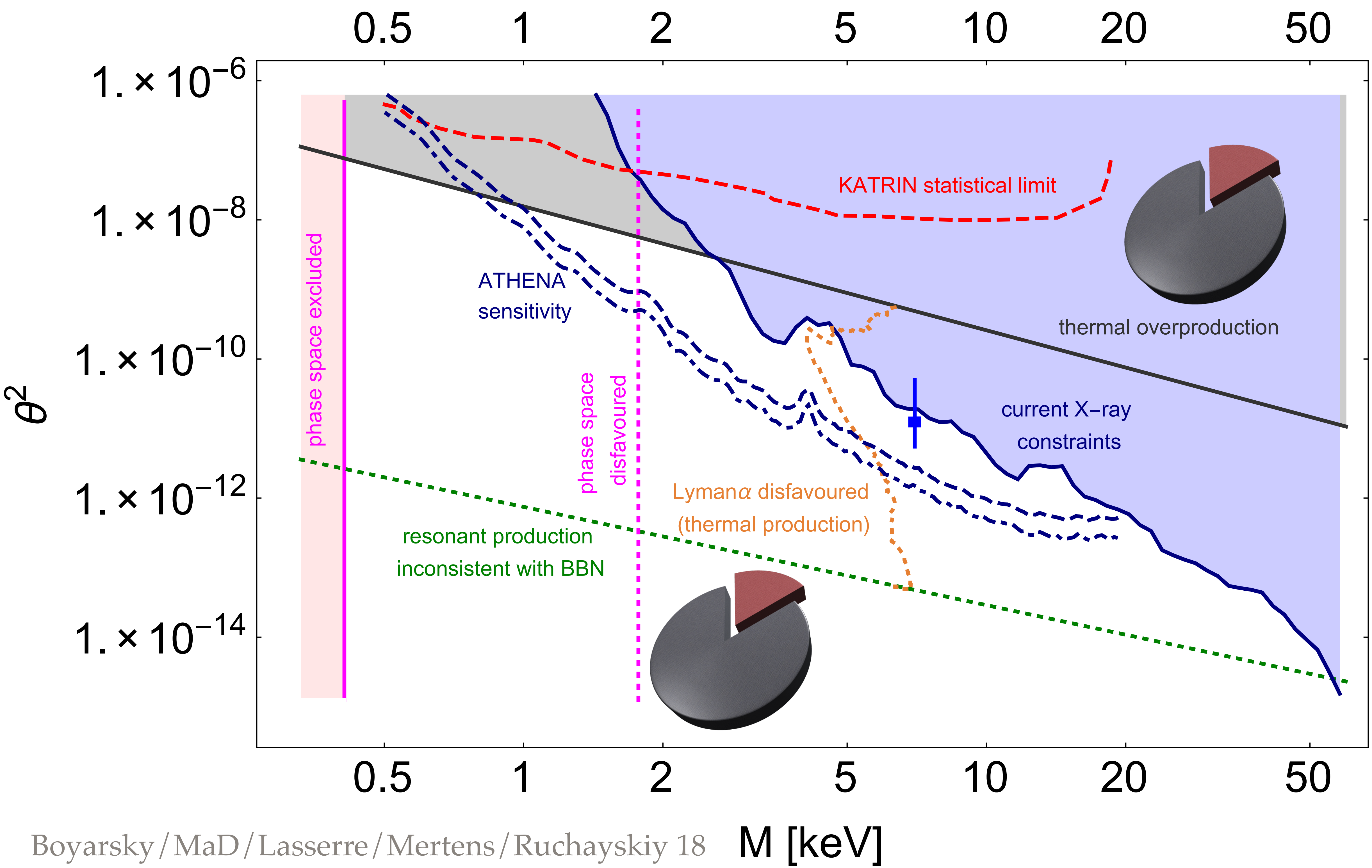
contact: smertens@lbl.gov

Sterile Neutrino Dark Matter



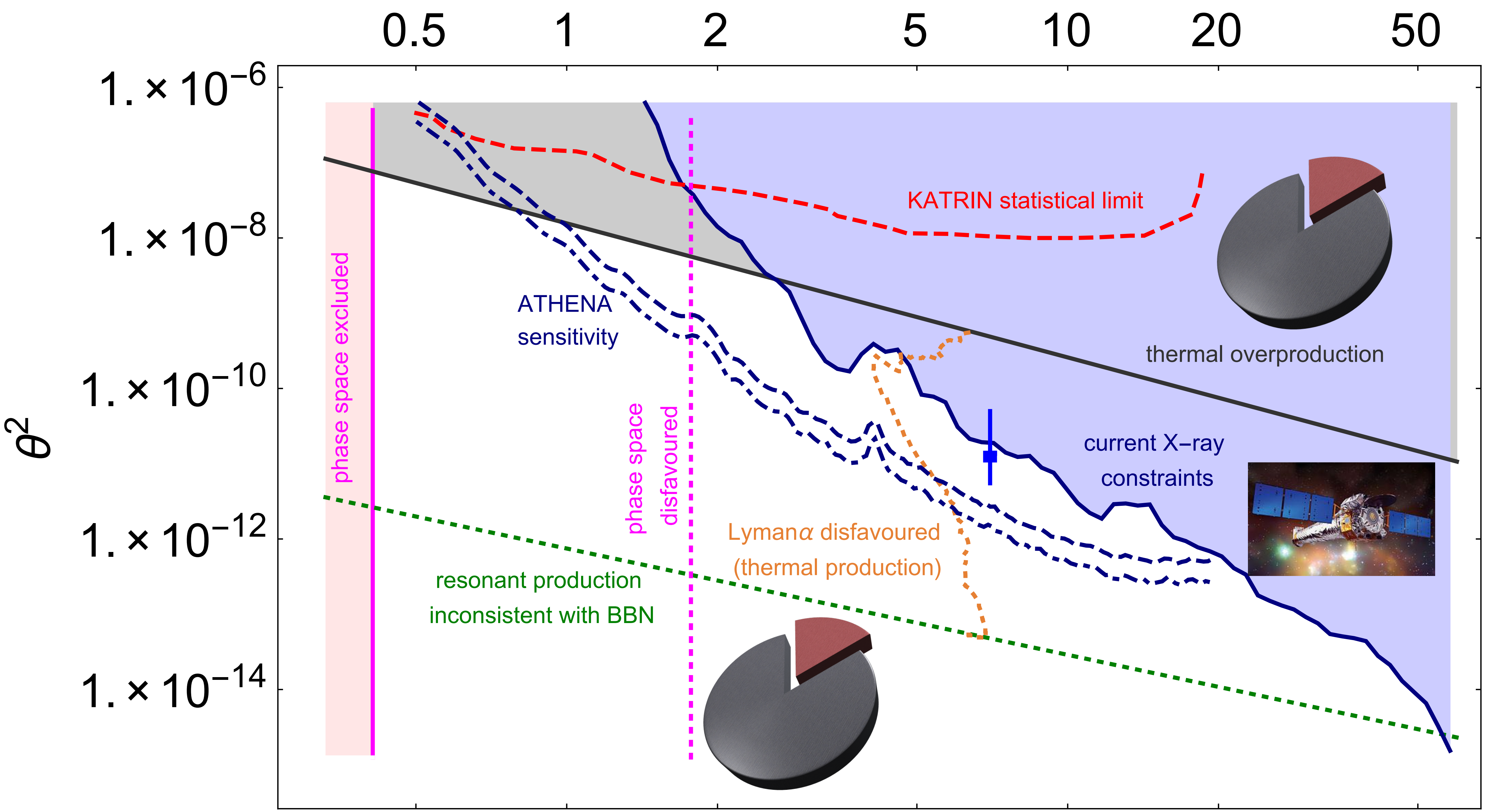
Boyarsky / MaD / Lasserre / Mertens / Ruchayskiy 18

Sterile Neutrino Dark Matter



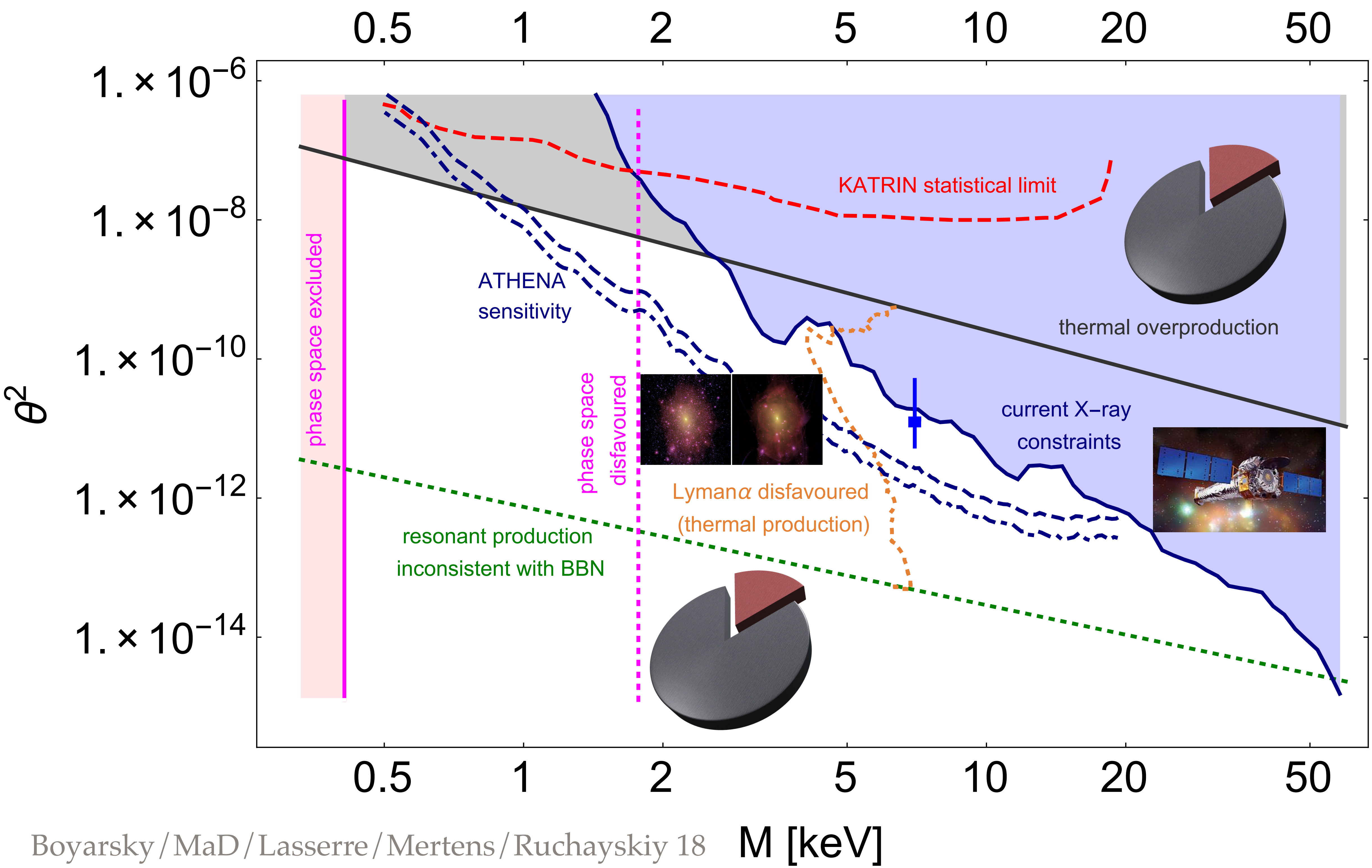
Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

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

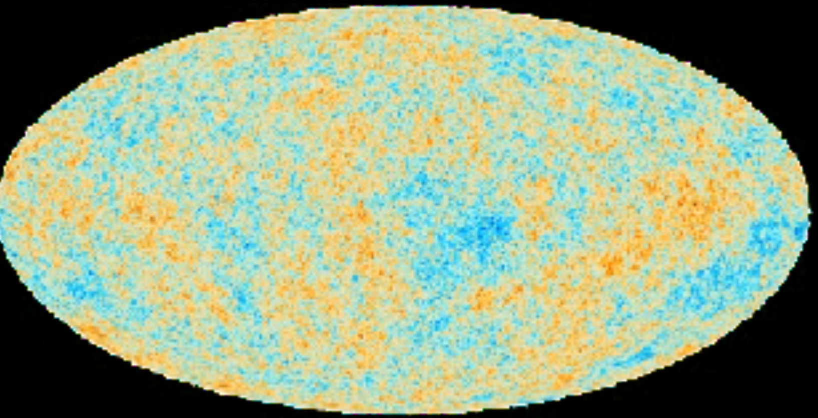
Possible key to embed Standard Model in a more fundamental theory of Nature

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

It makes up most of the mass in the universe.

- **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 set the initial conditions for the "hot big bang"?**

Cosmic inflation? How did the transition to the radiation dominated epoch happen?

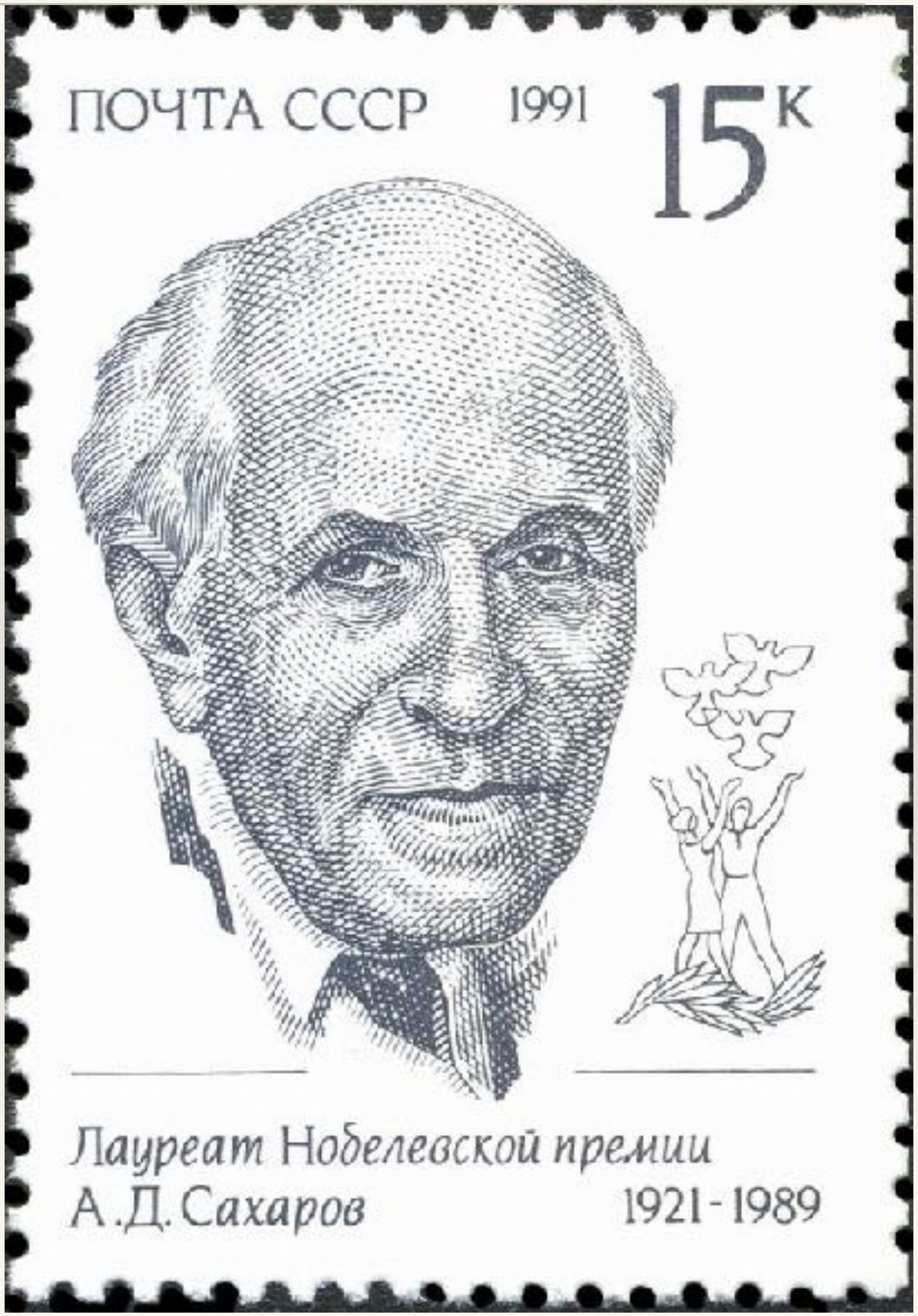
- **Why was there more matter than antimatter in the early universe?**

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

Sakharov Conditions

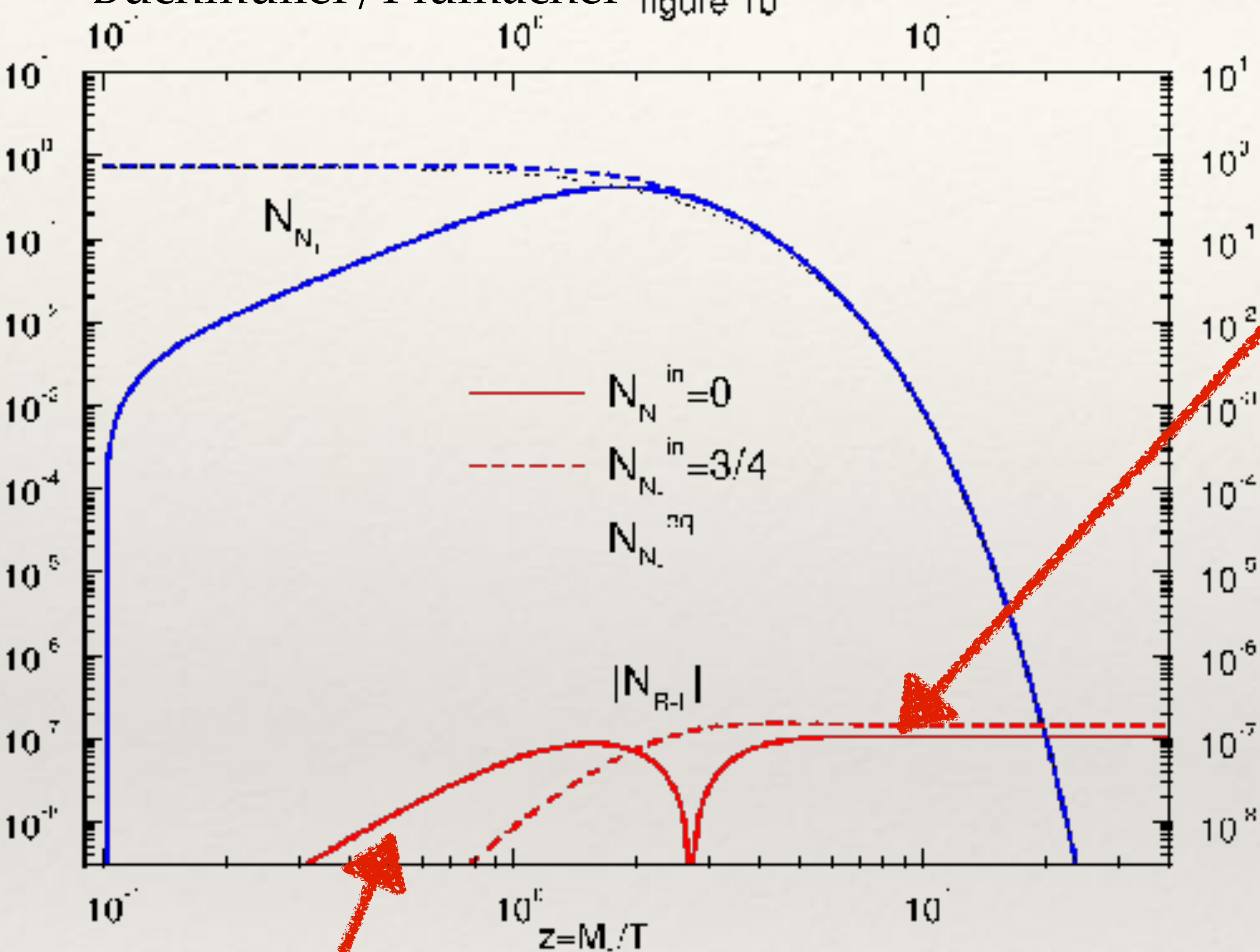
Sakharov Conditions (1967)

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



Leptogenesis with small M?

Buchmuller / Plumacher figure 1b



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

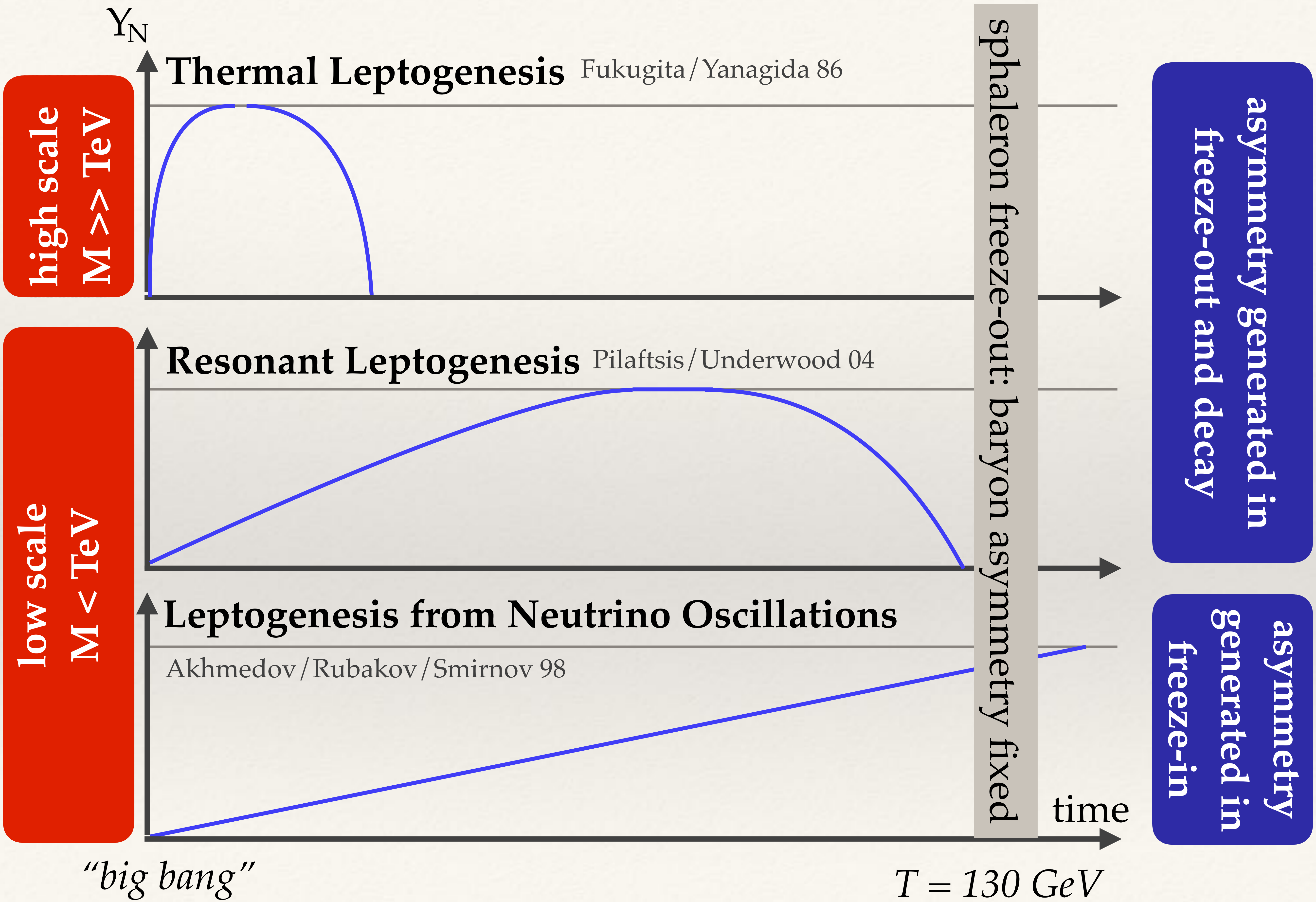
asymmetry generated during N production ("freeze-in scenario")

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

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

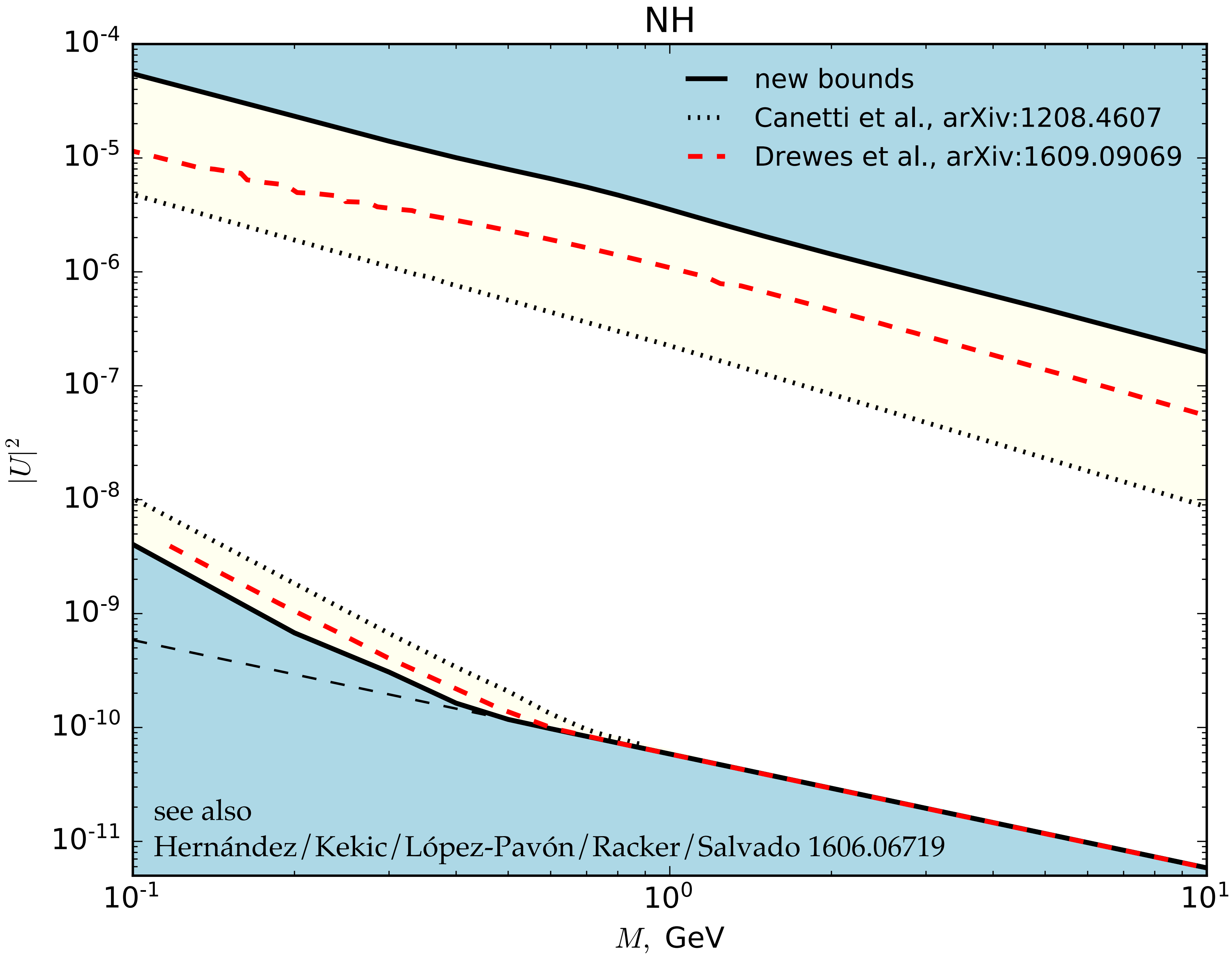
$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"



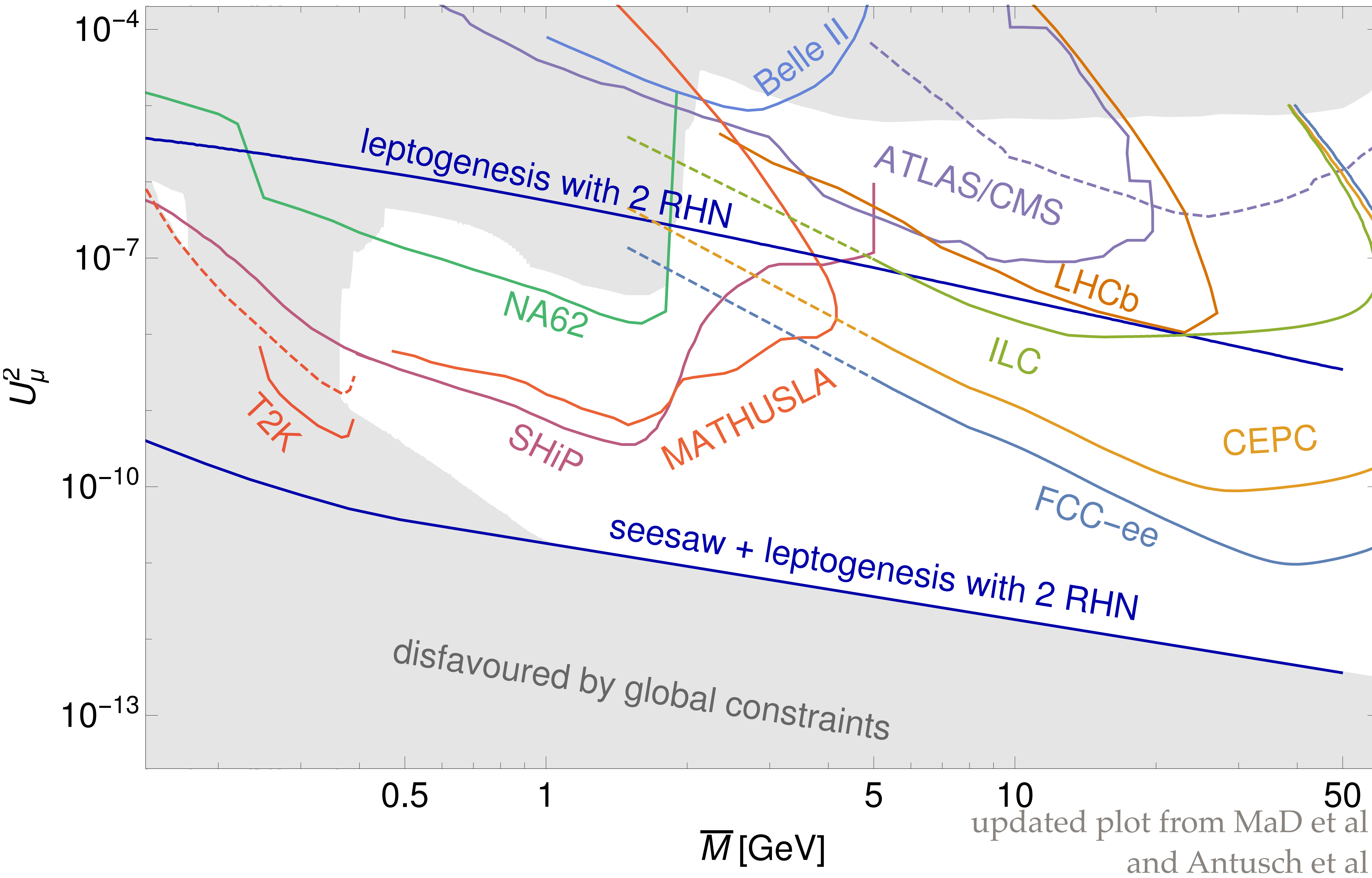
Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
Resonant Leptogenesis
Pilaftsis/Underwood 04
Leptogenesis from Neutrino Oscillations
Akhmedov/Rubakov/Smirnov 98
high scale
M >> TeV
low scale
M < TeV
sphaleron freeze-out: baryon asymmetry fixed
asymmetry generated in freeze-out and decay
asymmetry generated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

Leptogenesis Parameter Space



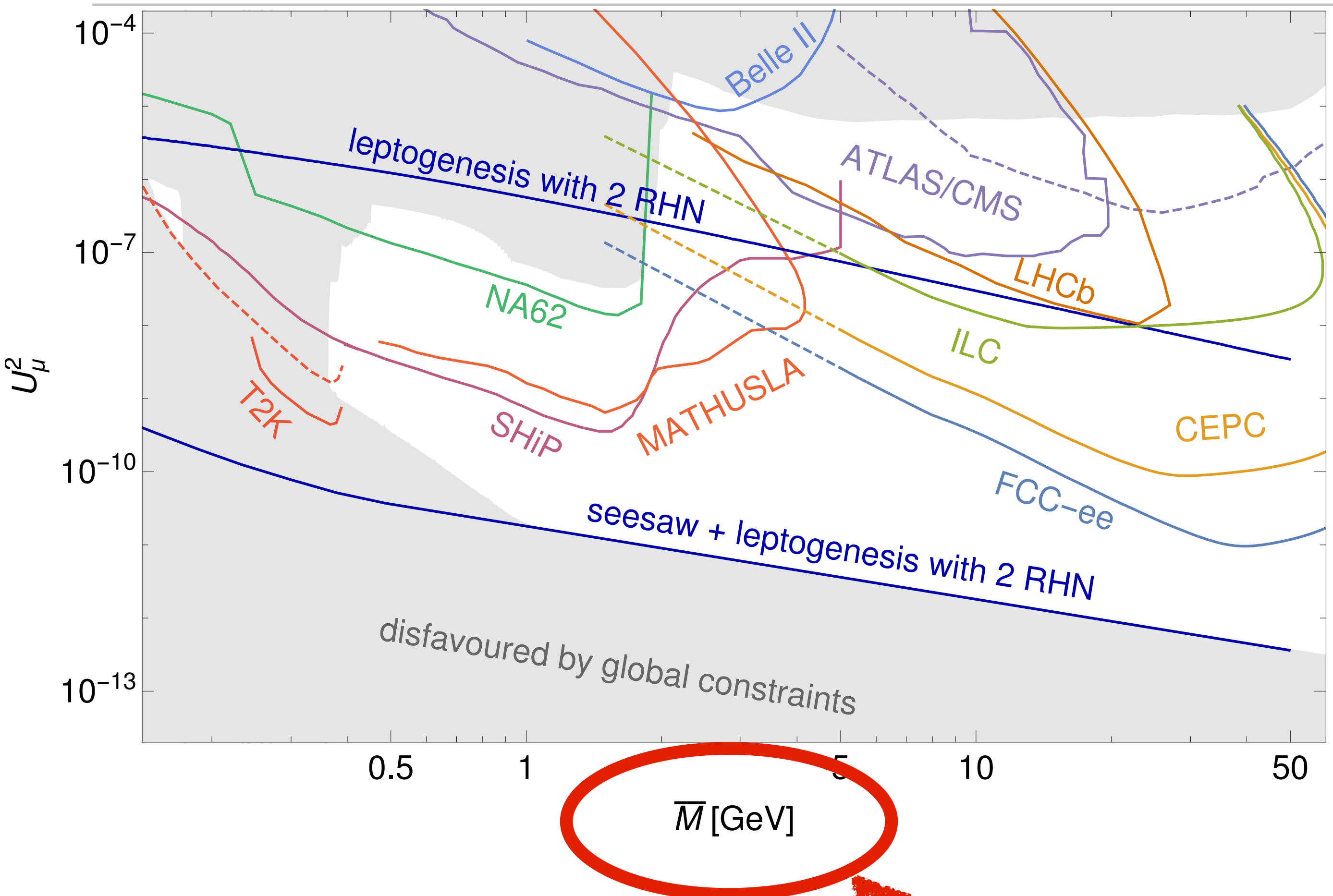
plot from Eijima/Shaposhikov/Timiryasov 1808.10833

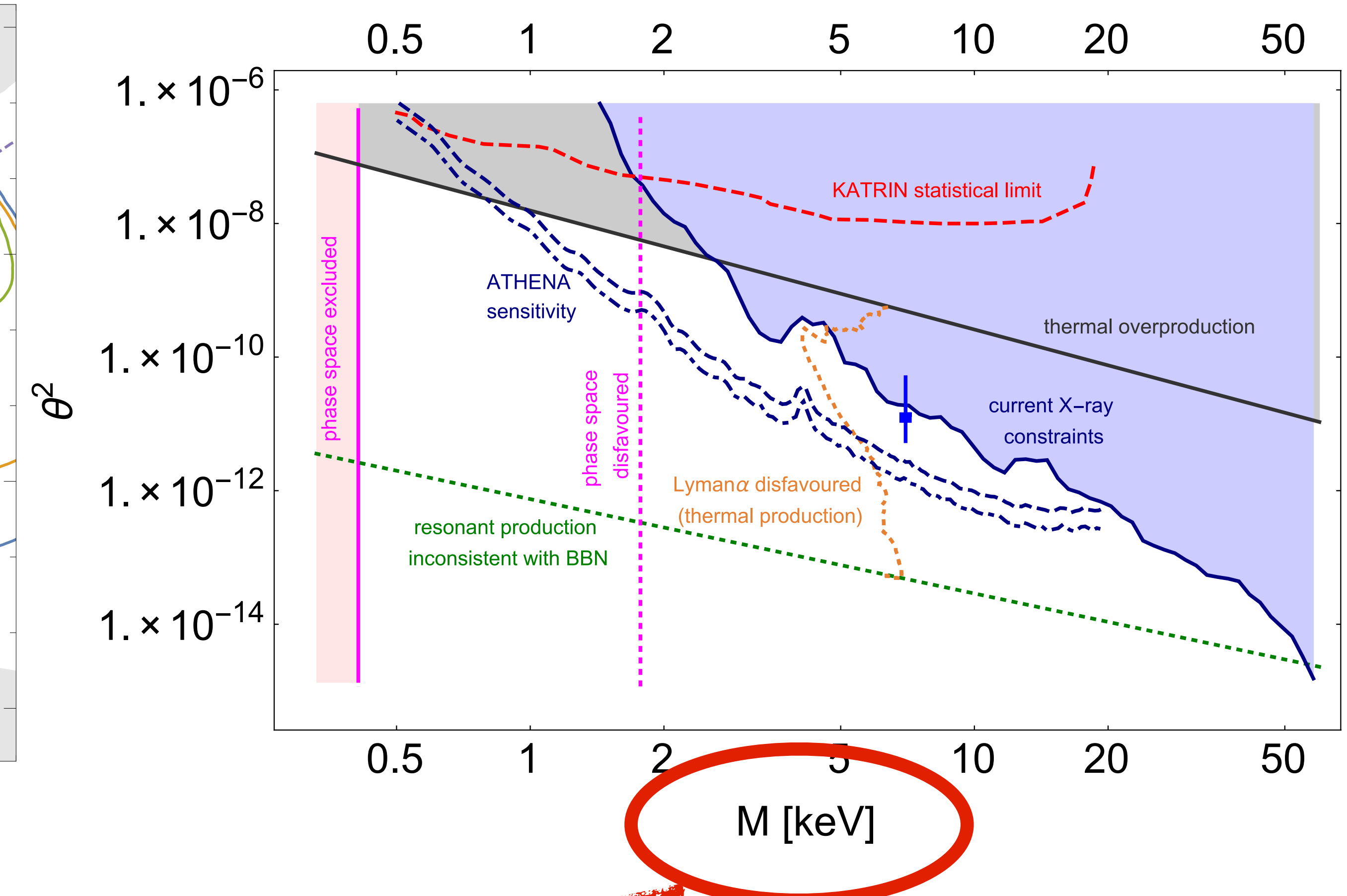
Constraints and Future Searches



updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

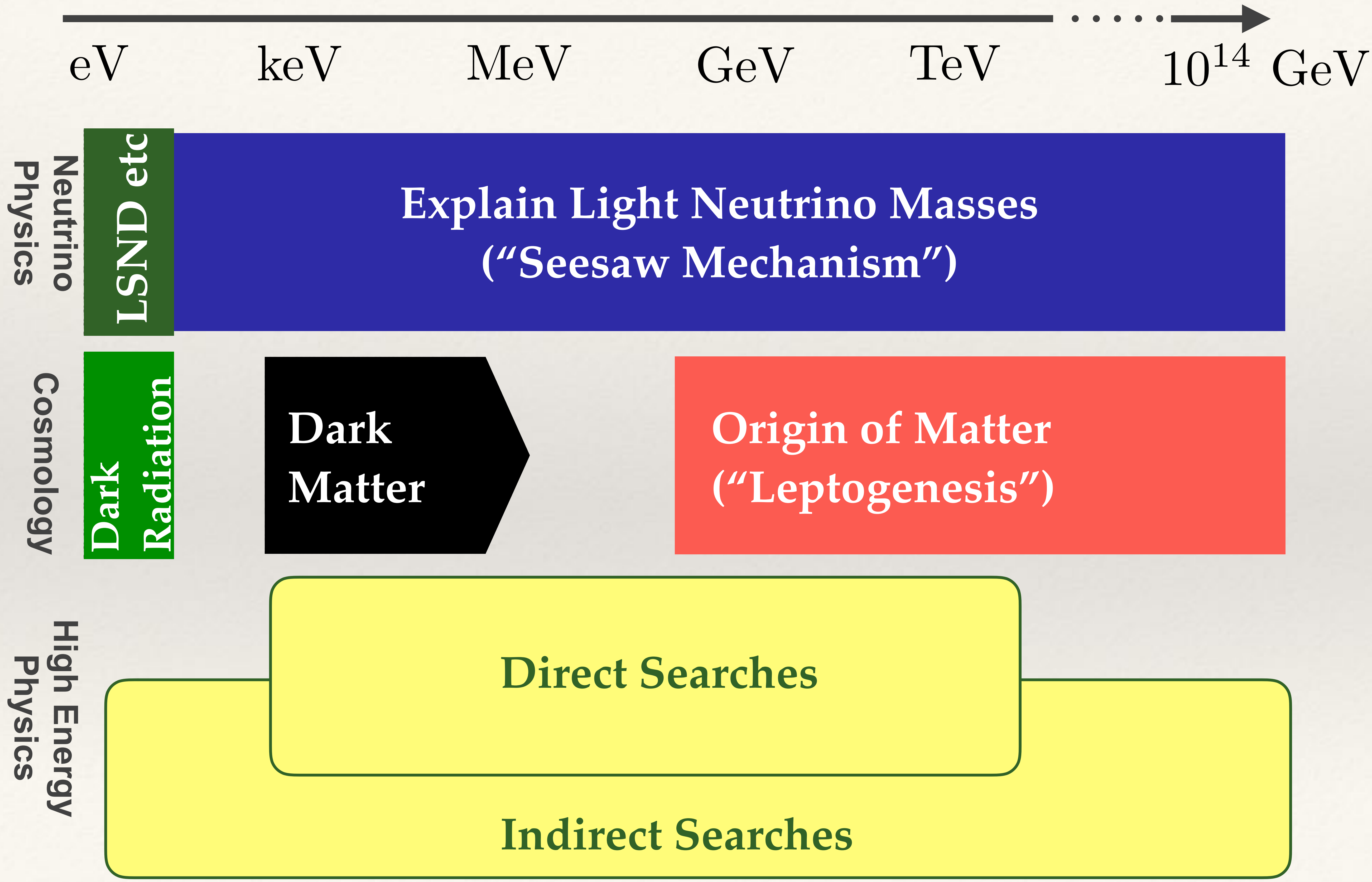
I want it all!





Dark Matter and Leptogenesis cannot be solved by the same heavy neutrino!

Right Handed Neutrino Mass Scale



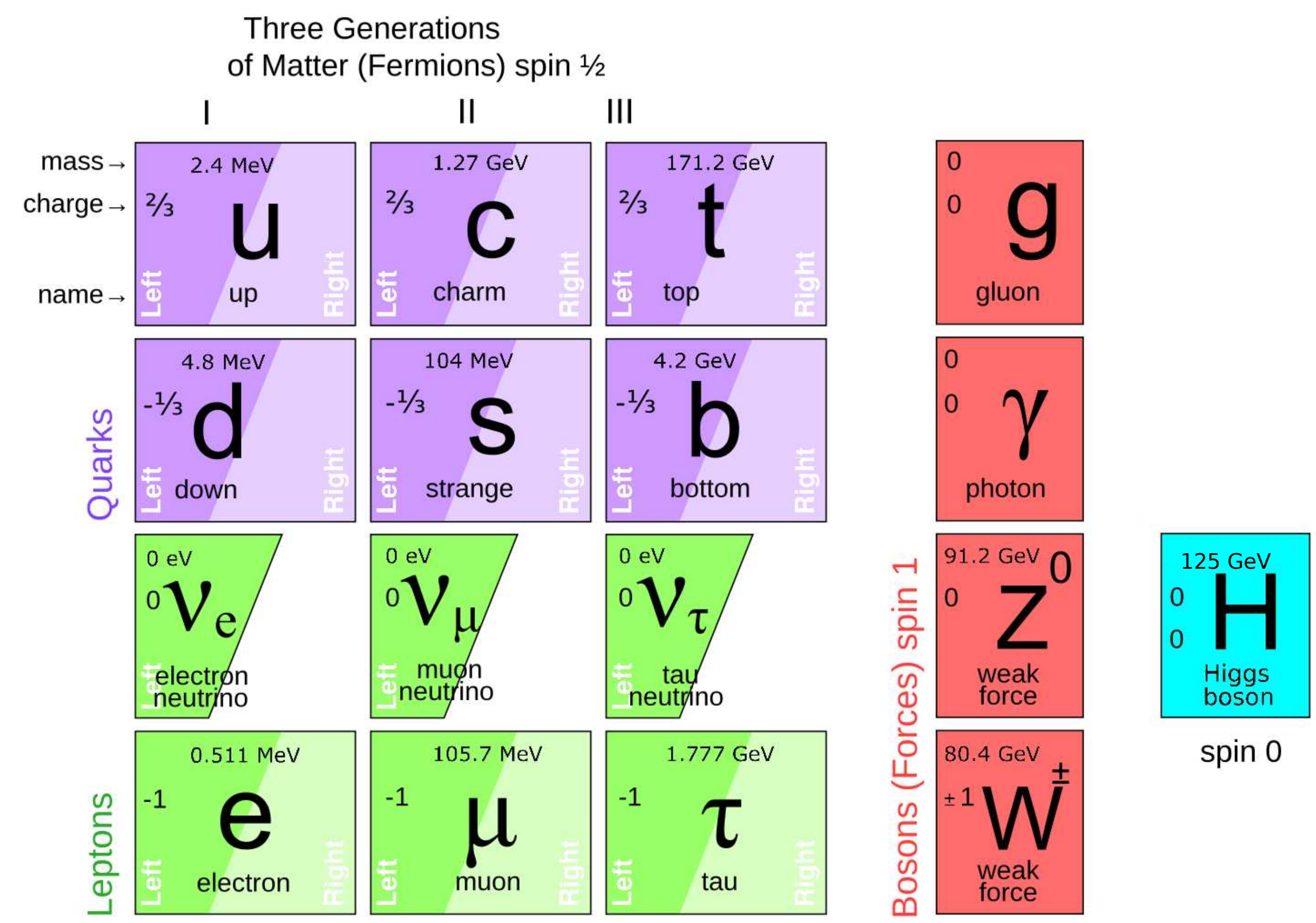
A Minimal Model: The νMSM

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

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

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

B-L **violating parameters**

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

νMSM from B-L Violation

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

No hierarchy problem
Vacuum metastable

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

***B-L* violating parameters**

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

νMSM from B-L Violation

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

No hierarchy problem
Vacuum metastable

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

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

B-L **violating parameters**

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

νMSM from B-L Violation

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

leptogenesis:
mass degeneracy for
free for pseudo Dirac

No hierarchy problem
Vacuum metastable

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

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

***B-L* violating parameters**

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

νMSM from B-L Violation

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

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

leptogenesis:
mass degeneracy for
free for pseudo Dirac

No hierarchy problem
Vacuum metastable

Dark Matter:
lighter (keV)
mass
feeble coupling

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

B-L **violating parameters**

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

νMSM from B-L Violation

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

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

leptogenesis:
mass degeneracy for
free for pseudo Dirac

No hierarchy problem
Vacuum metastable

Dark Matter:
lighter (keV)
mass
feeble coupling

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

***B-L* violating parameters**

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

“Full Testability”

Colliders: effectively as theory with two RH neutrinos
(as far as baryogenesis and ν-masses are concerned)

Unknown parameters:
M, ΔM, Reω, Imω, δ, α

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass
(almost) vanishes

complex
angle ω

N-mass M
and splitting ΔM

“Full Testability”

heavy neutrino masses

size of N_1 and N_2 couplings relative to each other

overall N_i coupling strength

N_i flavour mixing pattern

Unknown parameters:

M, ΔM, Reω, Imω, δ, α

Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass (almost) vanishes

complex angle ω

N-mass M and splitting ΔM

"Full Testability"

heavy neutrino masses

size of N_1 and N_2 couplings relative to each other

overall N_i coupling strength

N_i flavour mixing pattern

Unknown parameters:

M, ΔM, Reω, Imω, δ, α

- In principle all parameters can be measured MaD/Garbrecht/Gueter/Klaric 1609.09069

  ⇒ fully testable model of neutrino masses and baryogenesis
- This requires a combination of collider/fixed target experiment data and ν-osc. date (and possibly 0νββ)

  ⇒ poster child example for synergy between collider and long baseline programs!

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

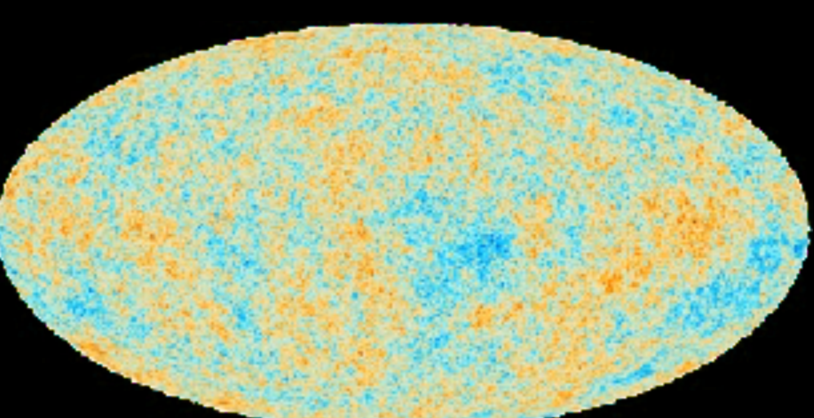
Possible key to embed Standard Model
in a more fundamental theory of Nature

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

It makes up most of the mass in the universe.

- **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 set the initial conditions for the "hot big bang"?**

Cosmic inflation? How did the transition to the radiation
dominated epoch happen?

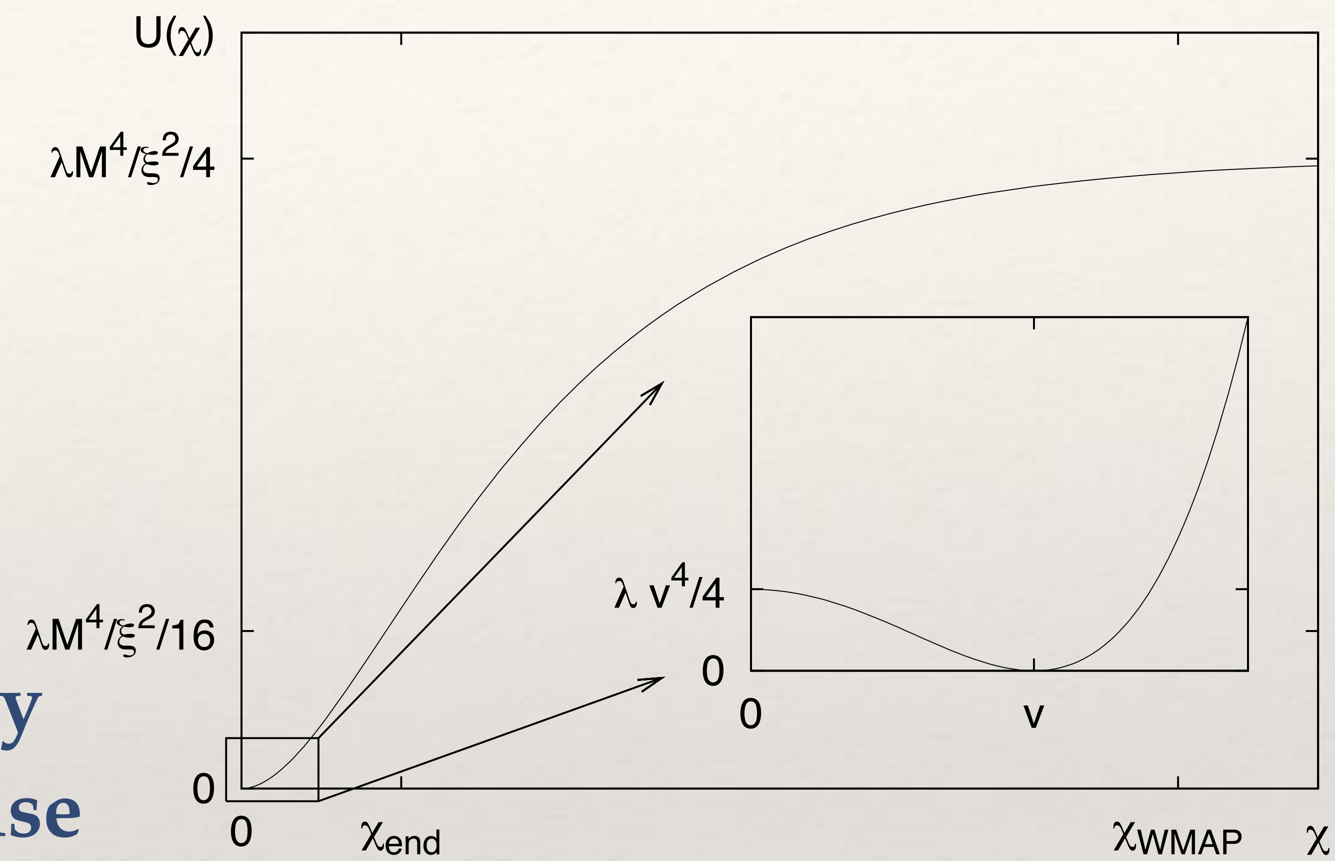
Higgs Inflation

- The Higgs field gives masses to elementary particles

- Its energy density behaves like Dark Energy

- If it dominated the energy density in the early universe, it could cause accelerated expansion

- This requires a “non-minimal coupling” to gravity, but no new particles Bezrukov/Shaposhnikov 08



for details see e.g.
Bezrukov/Gorbunov/Shaposhnikov 08

$$\mathcal{L} \supset \xi H^\dagger H R$$

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

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

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

  It makes up most of the mass in the universe.

- **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 set the initial conditions for the "hot big bang"?**

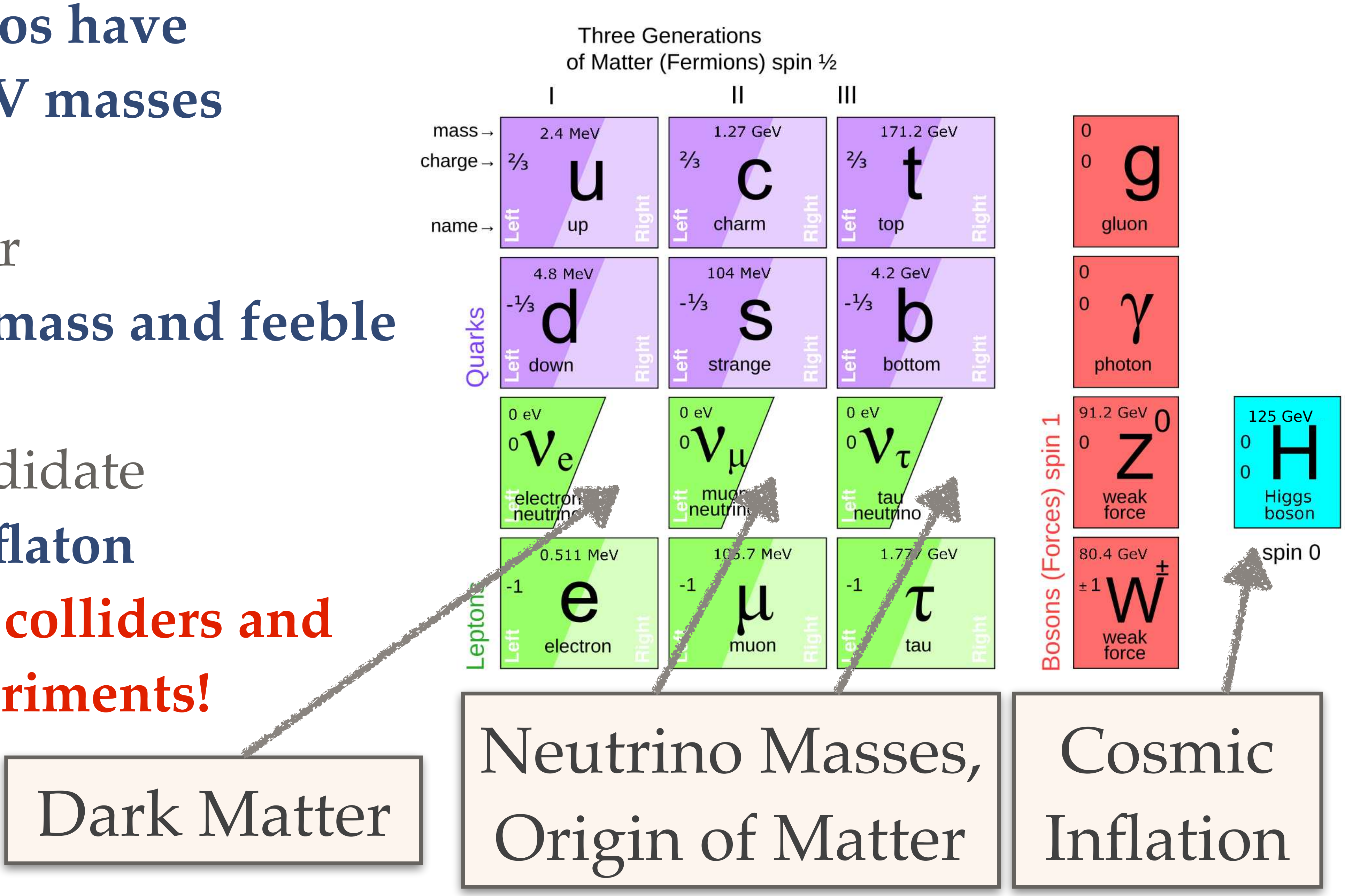
  Cosmic inflation? How did the transition to the radiation
  dominated epoch happen?

A Theory of (almost) Everything

"Neutrino Minimal Standard Model"

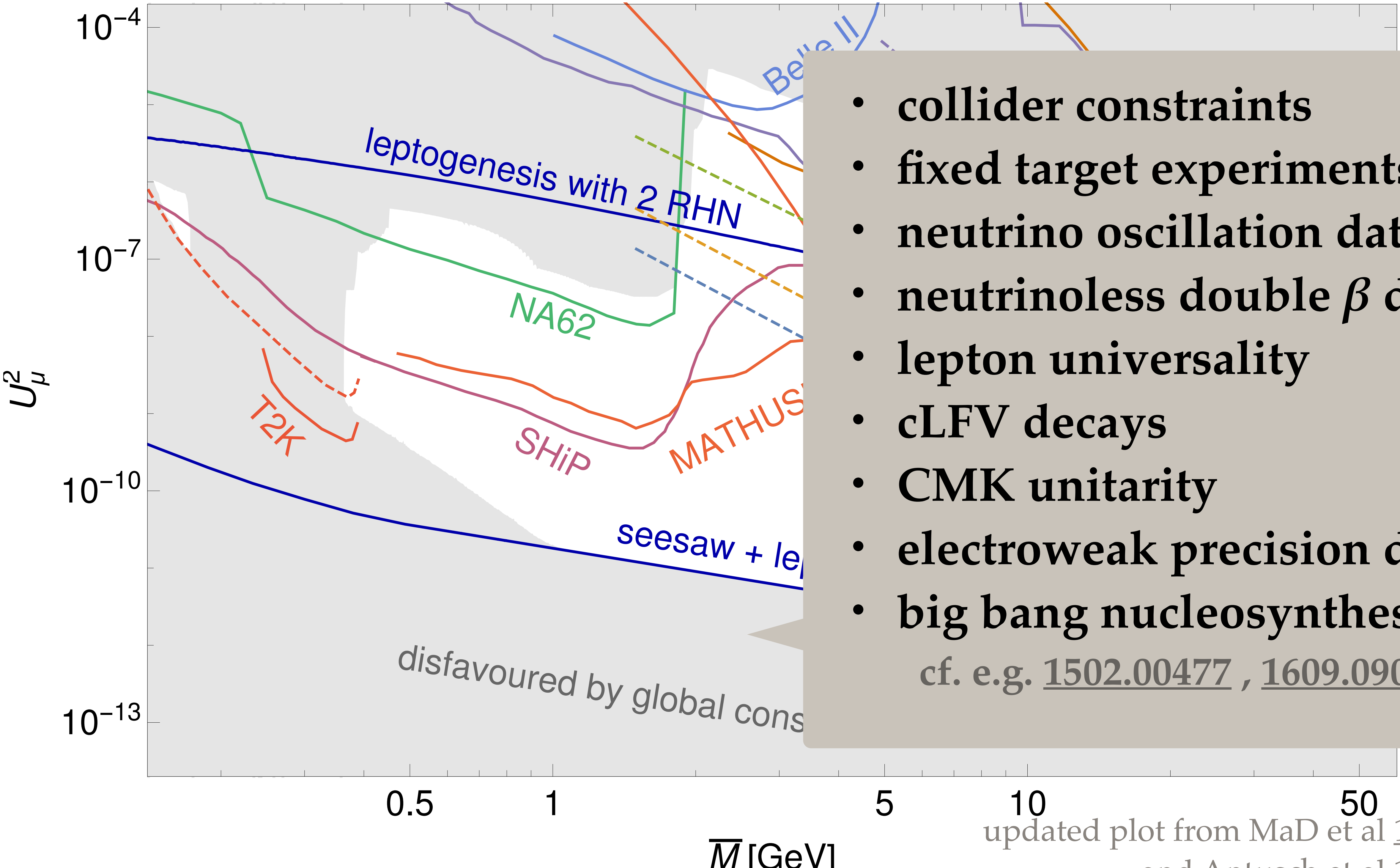
Asaka/Shaposhnikov 0503065, 0505013

- **two RH Neutrinos have degenerate ~GeV masses**
  neutrino mass
  + origin of matter
- **one has a ~keV mass and feeble couplings**
  Dark Matter candidate
- **Higgs field is inflaton**
- **Can be tested at colliders and fixed target experiments!**



Backup Slides

Constraints and Future Searches

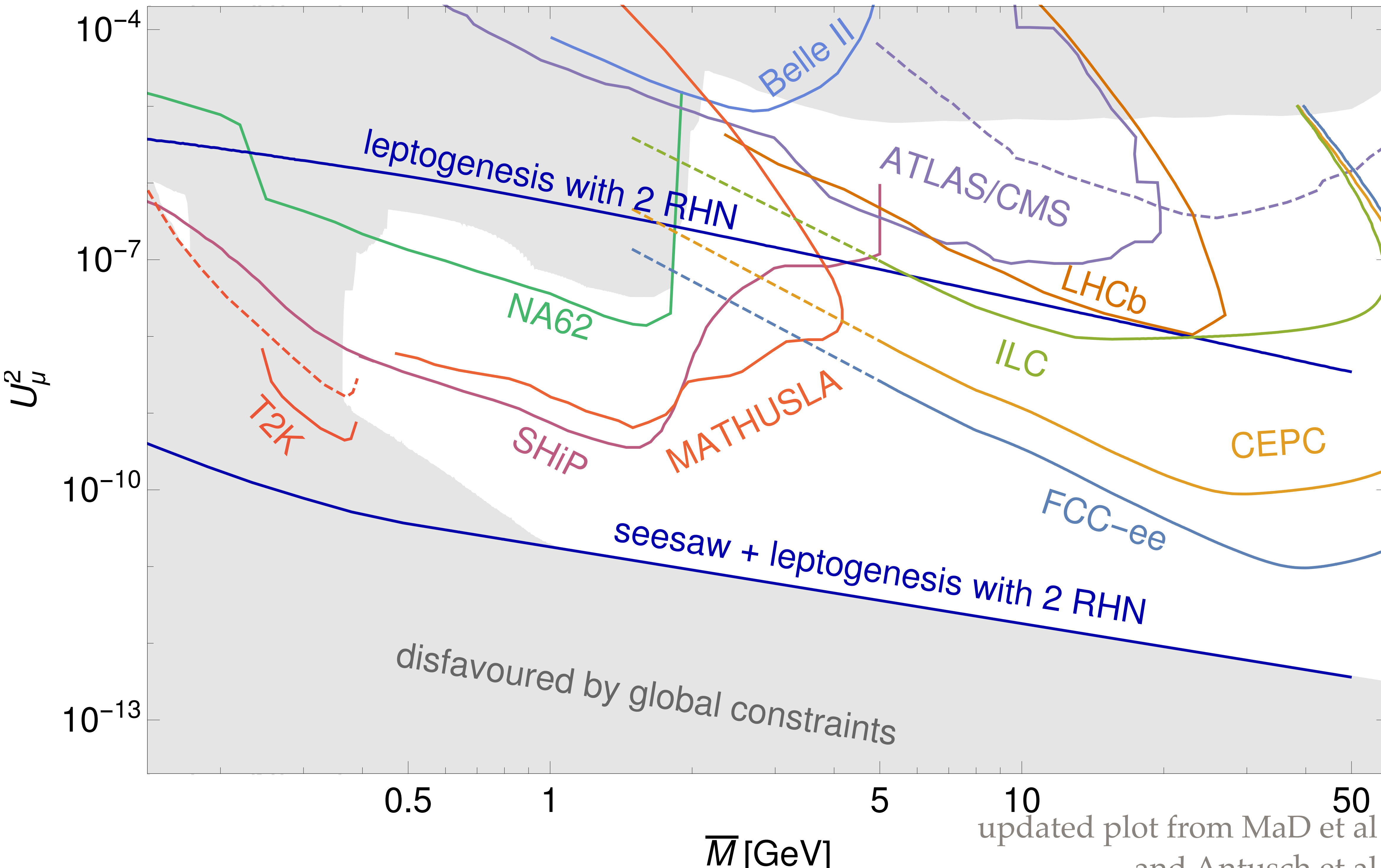


- collider constraints
- fixed target experiments
- neutrino oscillation data
- neutrinoless double β decay
- lepton universality
- cLFV decays
- CMK unitarity
- electroweak precision data
- big bang nucleosynthesis

cf. e.g. 1502.00477 , 1609.09069

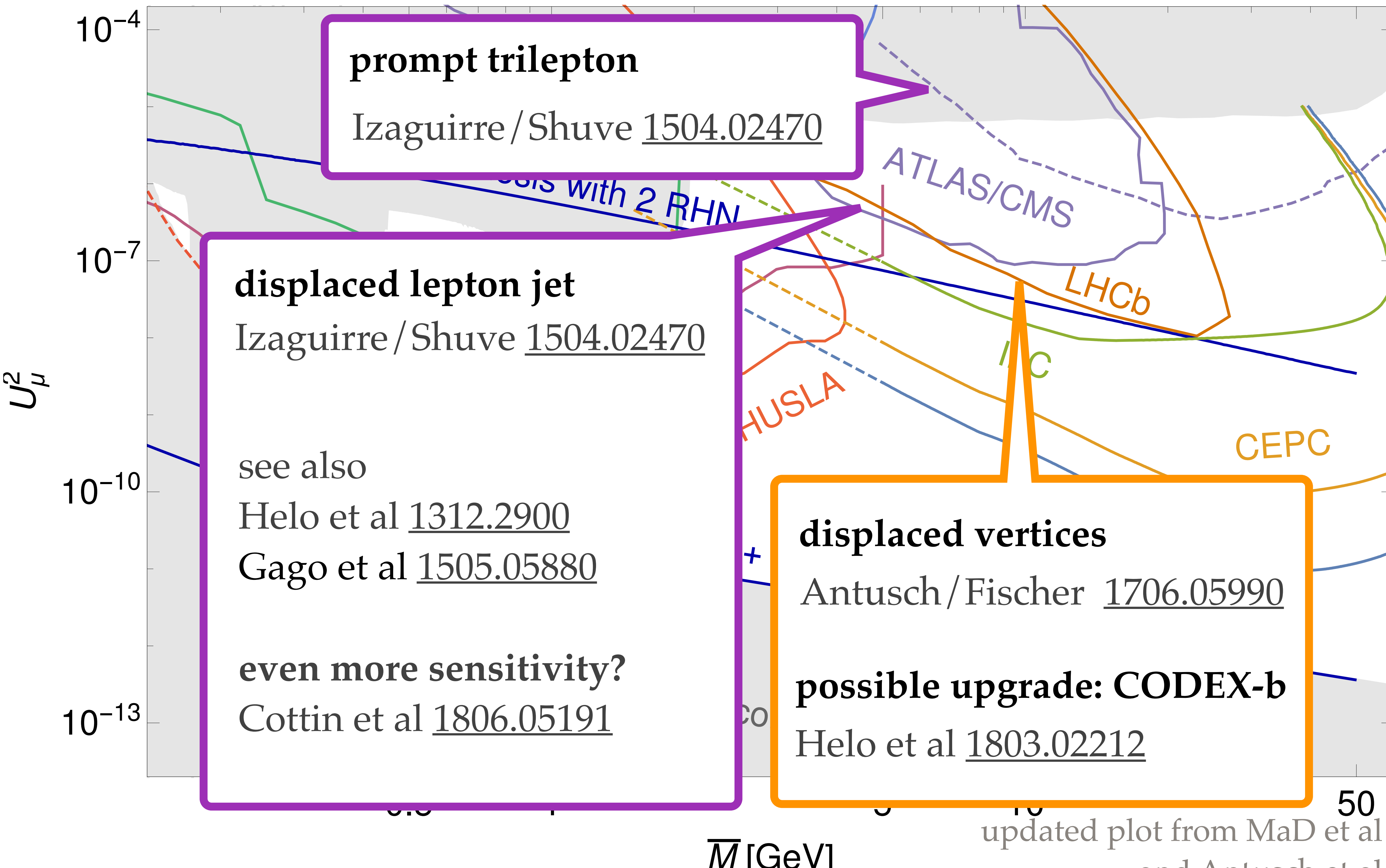
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

Constraints and Future Searches



updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

Future LHC Searches



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

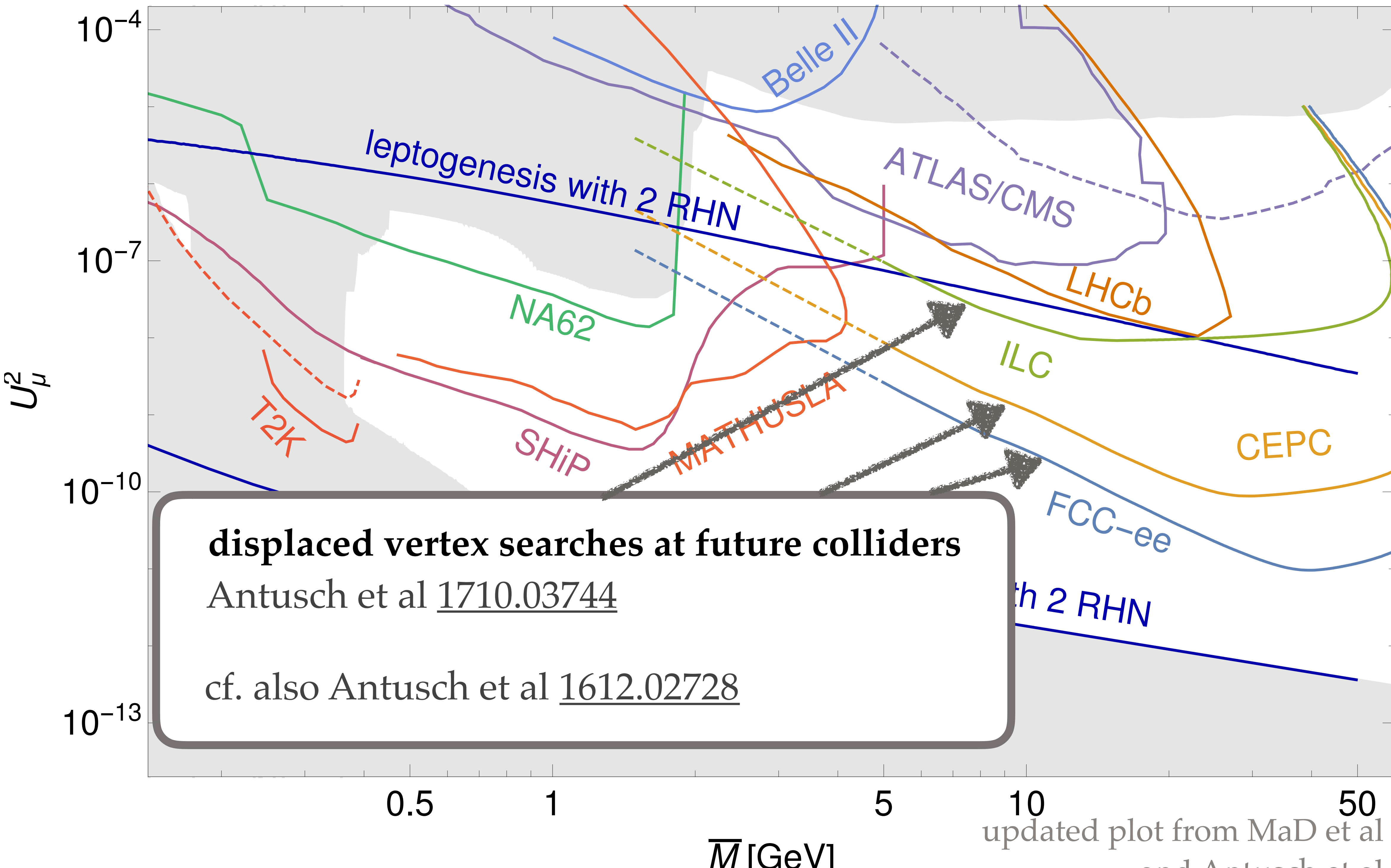
even more sensitivity?
Cottin et al 1806.05191

displaced vertices
Antusch/Fischer 1706.05990

possible upgrade: CODEX-b
Helo et al 1803.02212

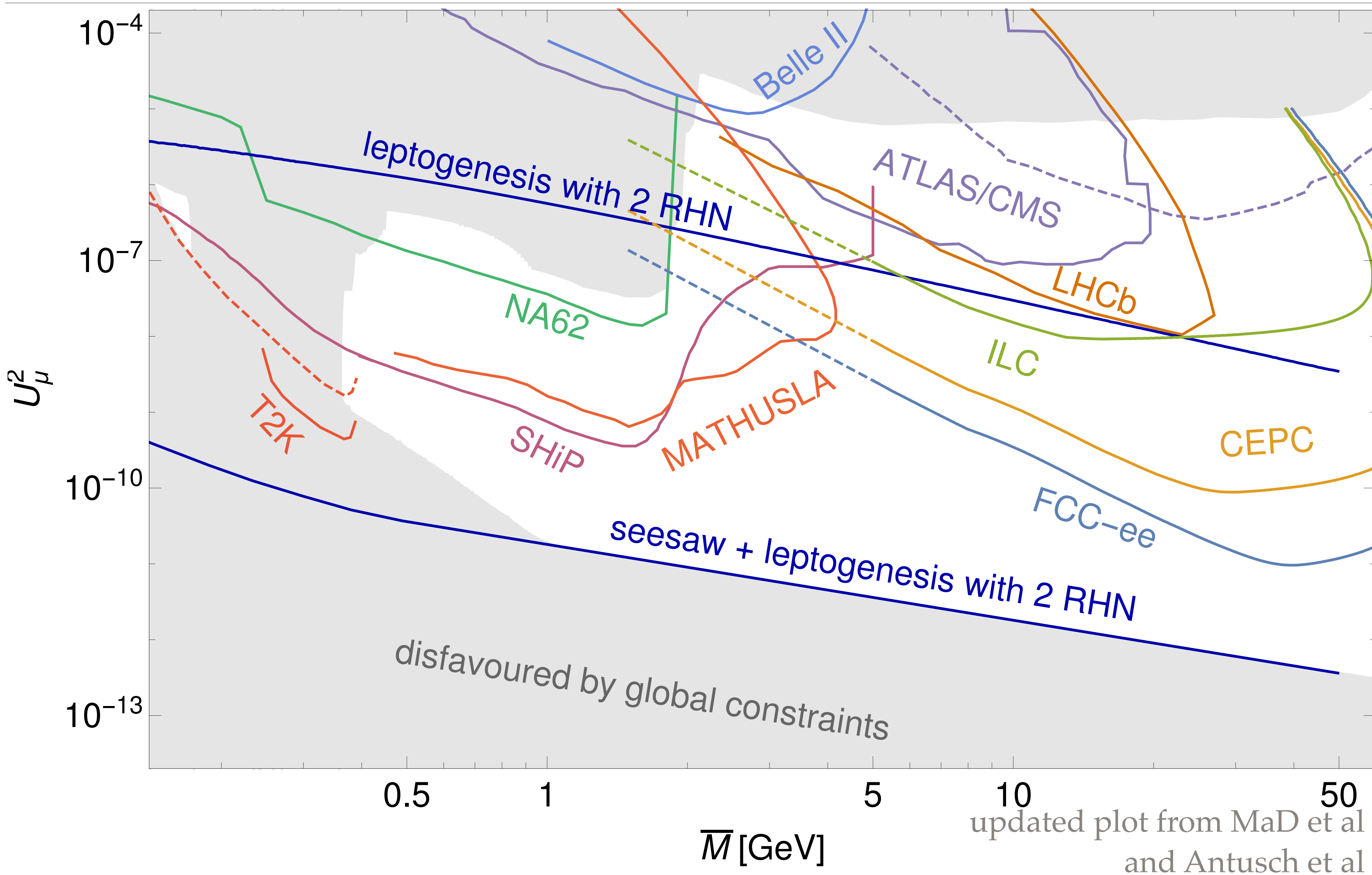
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

Searches at Future Colliders



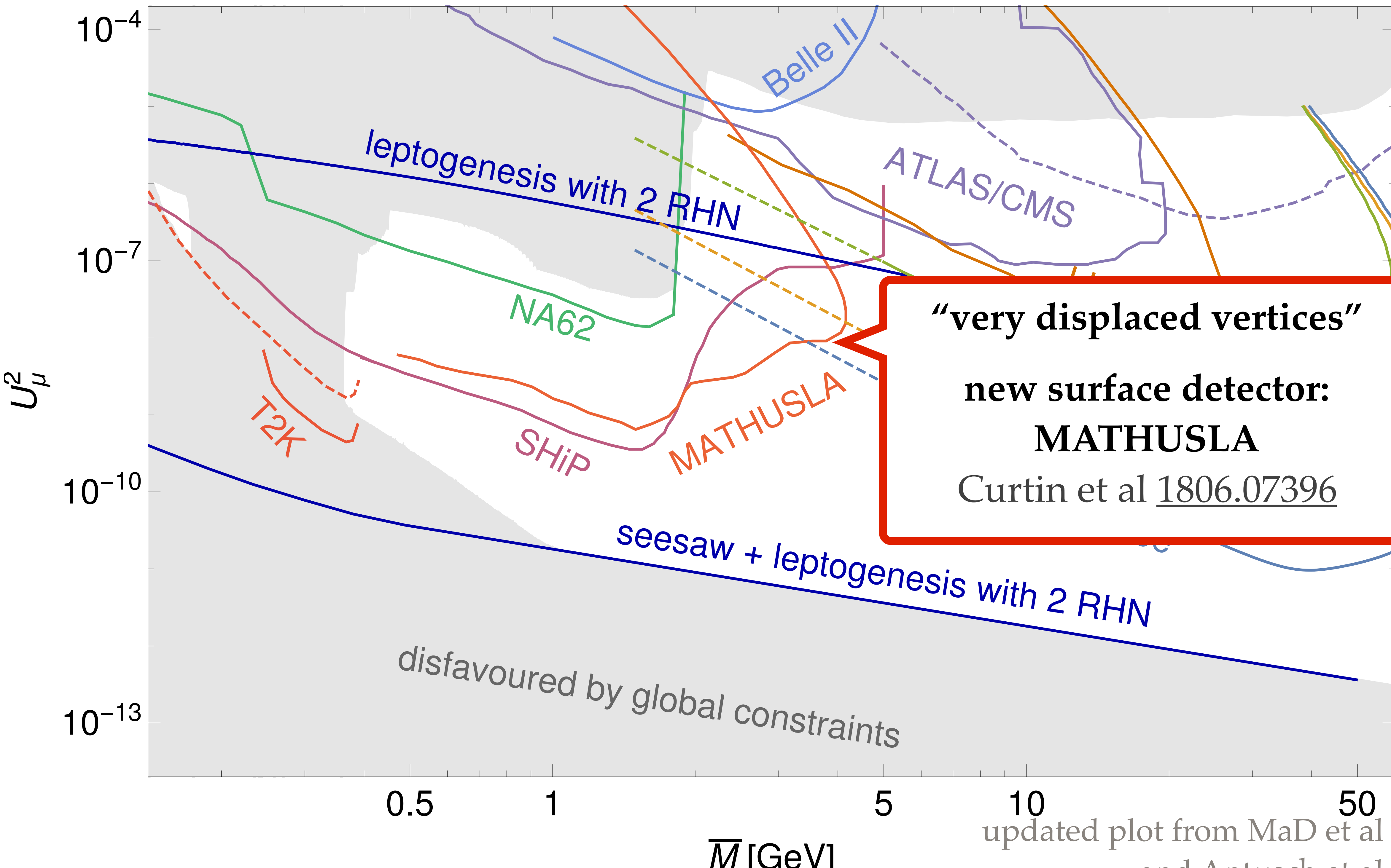
updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

Future LHC Searches



updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

Future LHC Searches



“very displaced vertices”

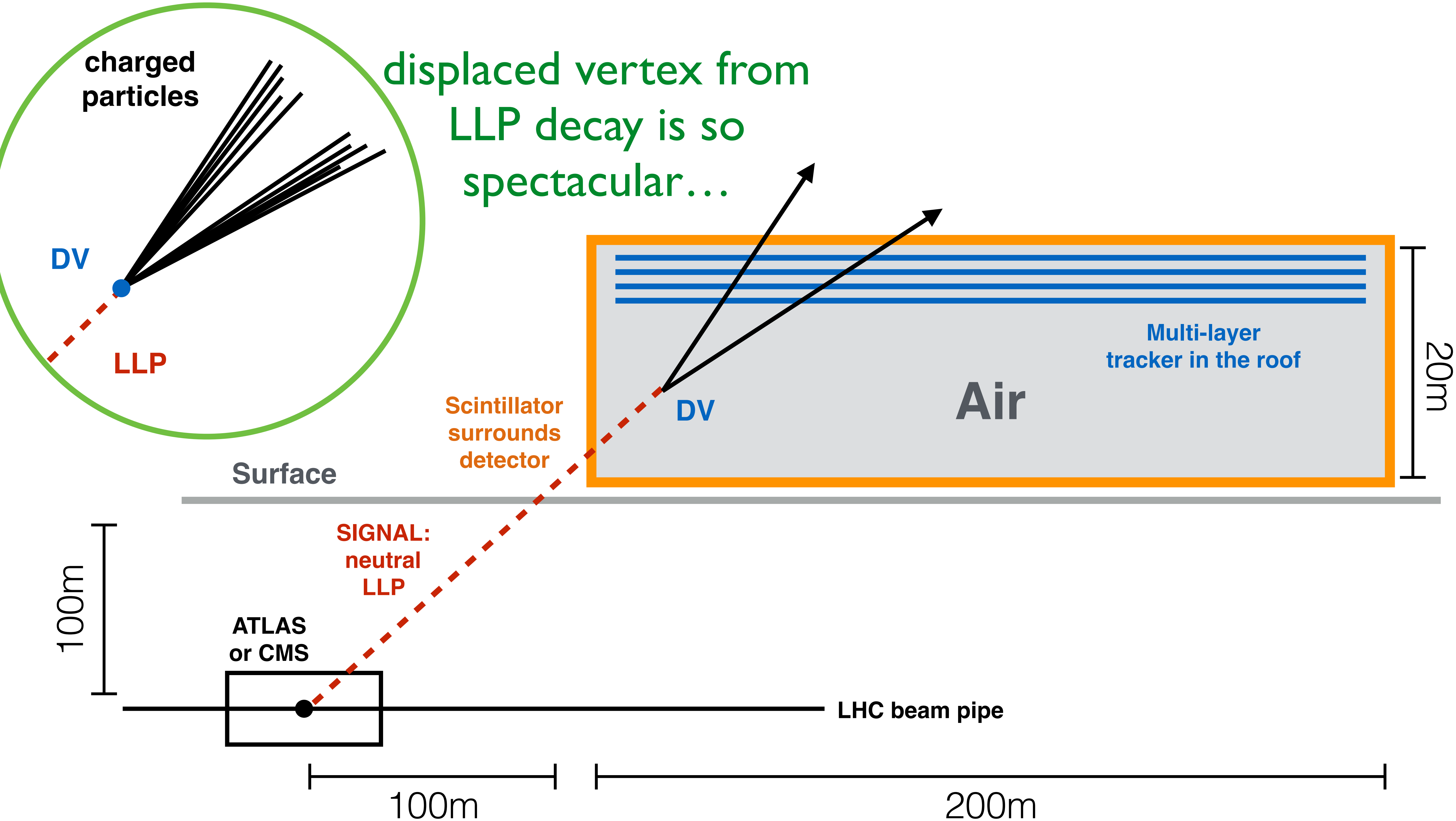
new surface detector: MATHUSLA

Curtin et al 1806.07396

updated plot from MaD et al 1609.09069
and Antusch et al 1710.03744
cf. also Cai et al 1711.02180

MATHUSLA

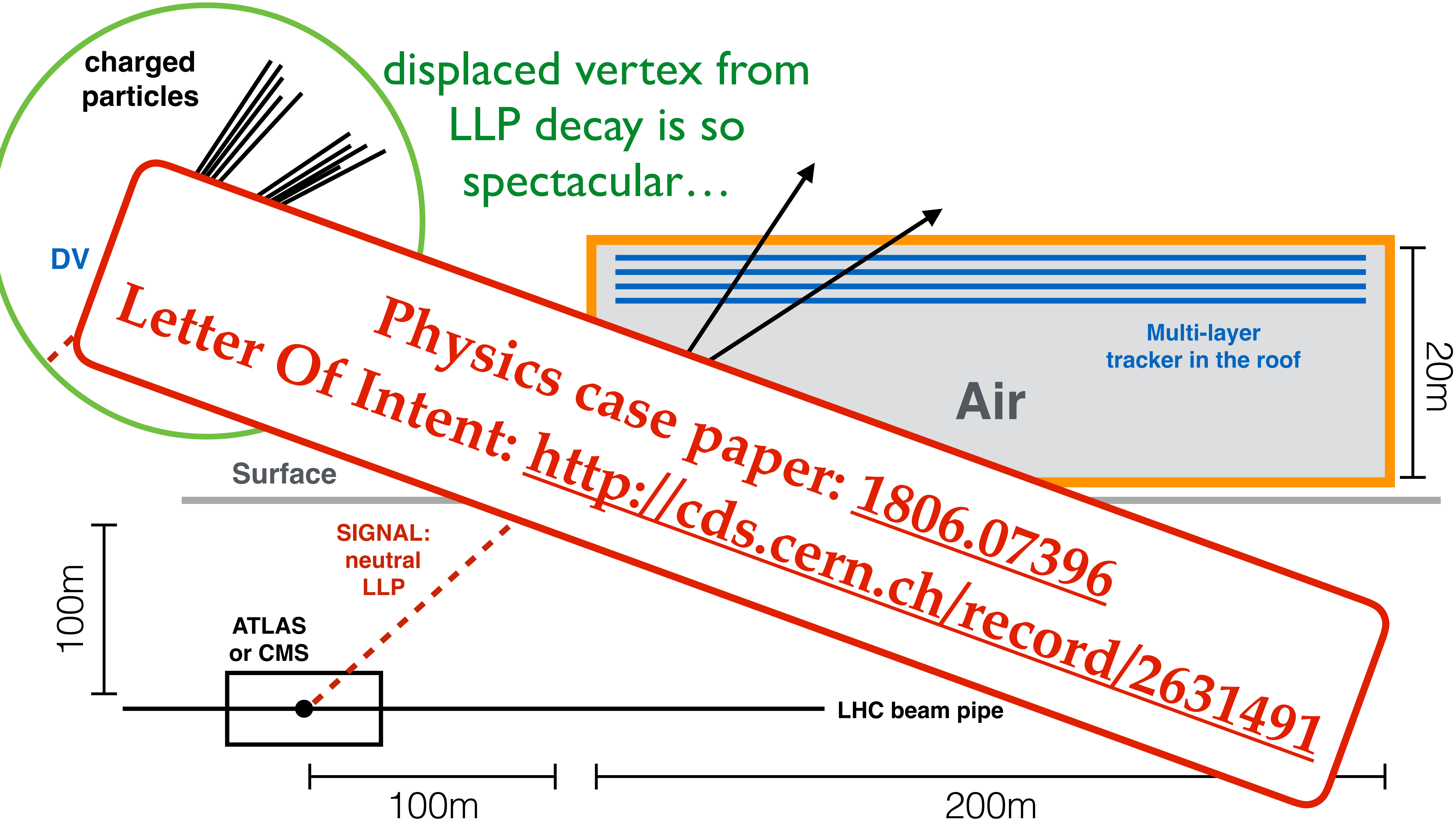
MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



slide by David Curtin

MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

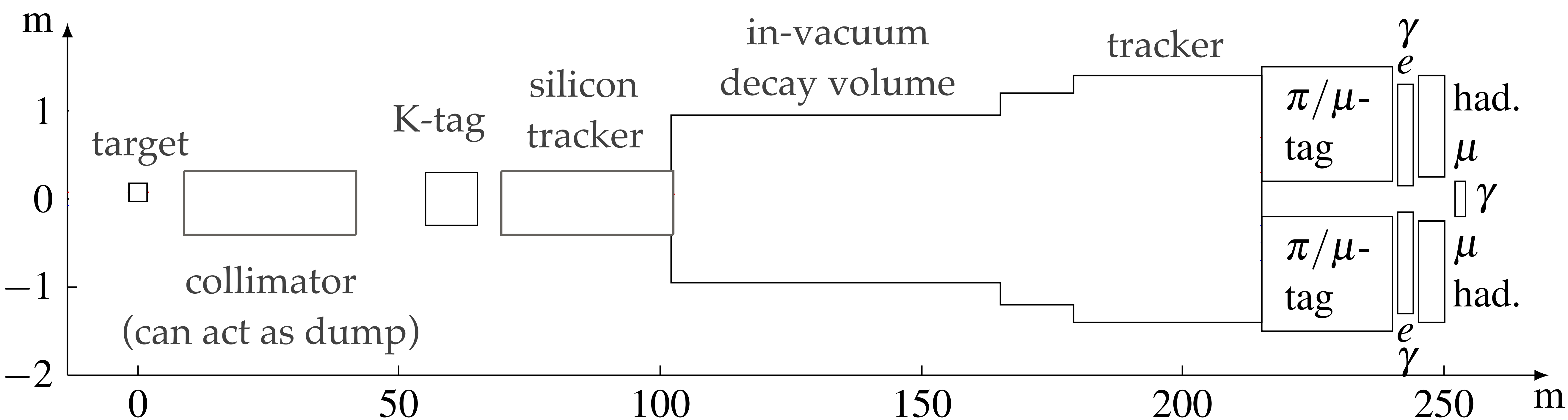


Physics case paper: 1806.07396

Letter Of Intent: http://cds.cern.ch/record/2631491

slide by David Curtin

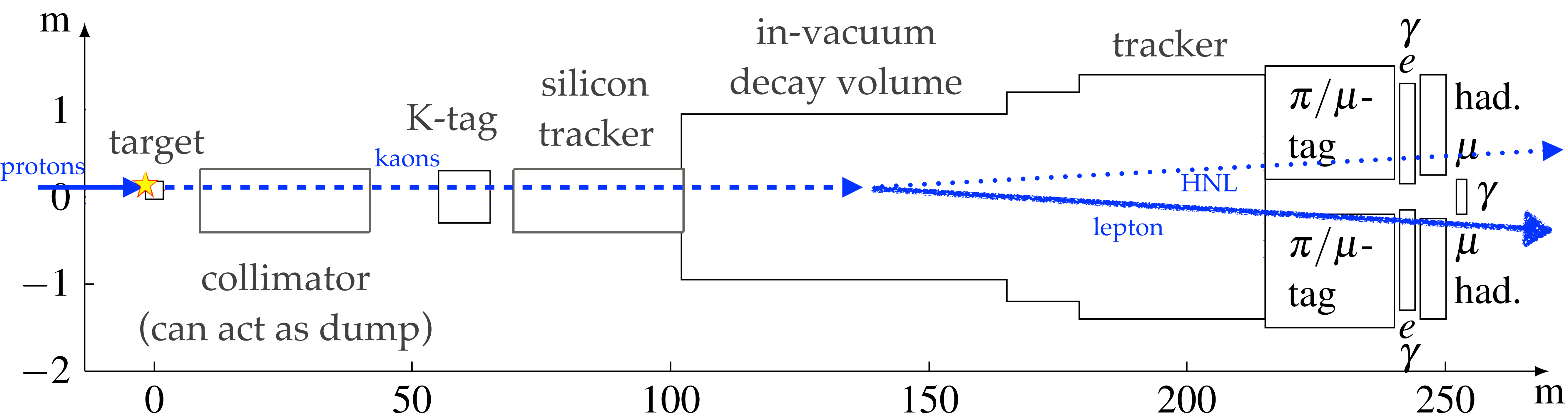
The NA62 Experiment



- **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

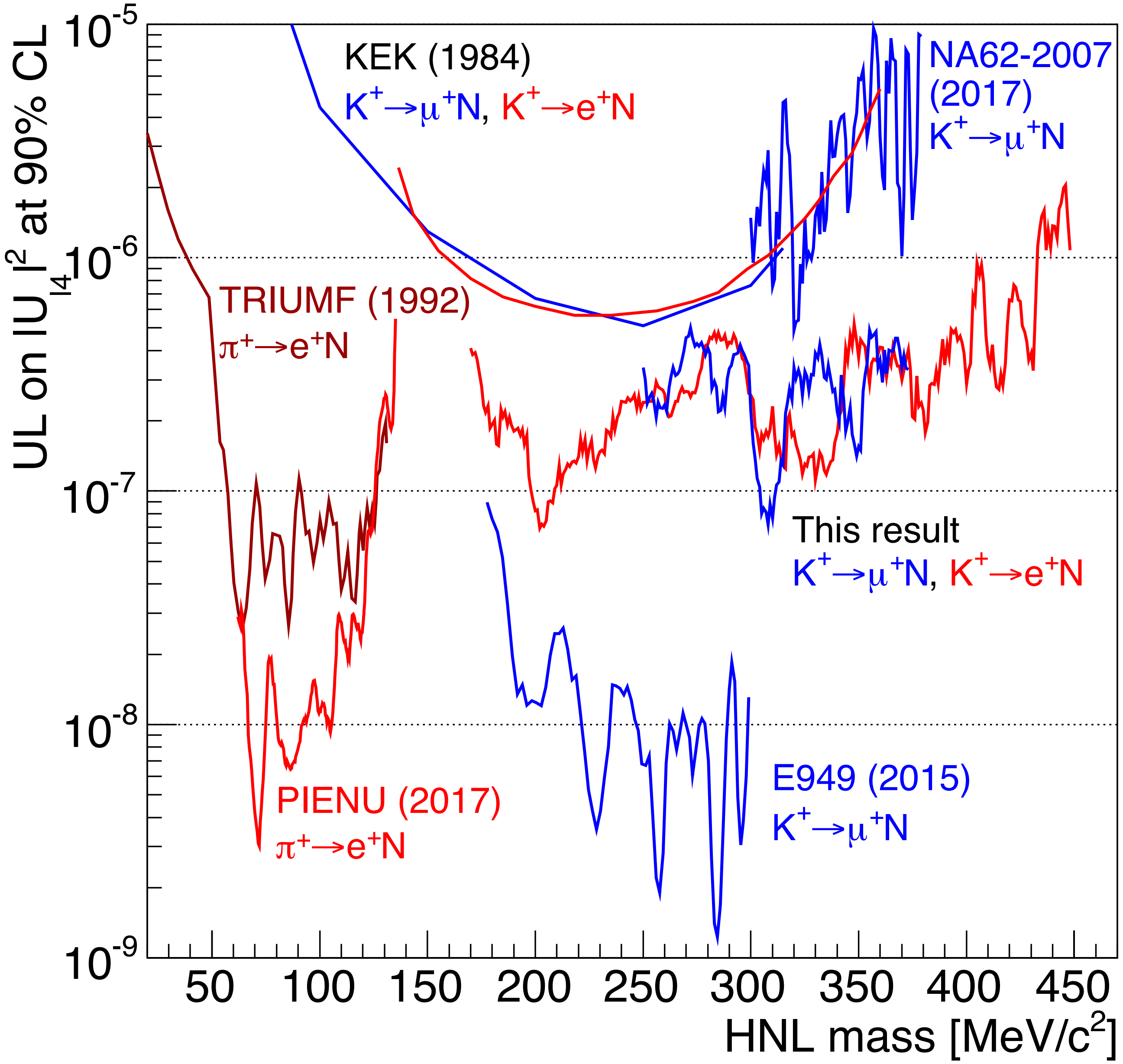


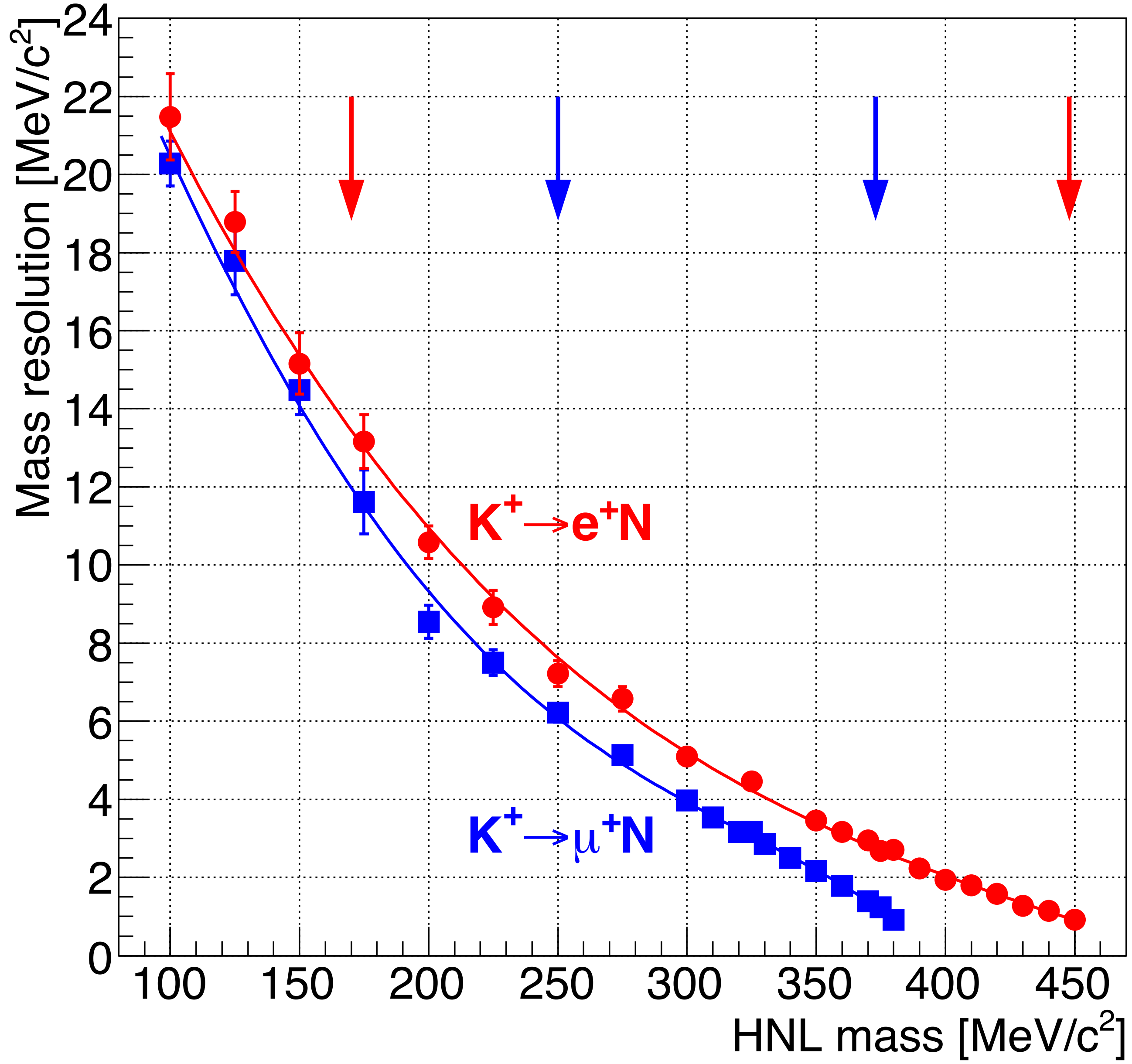
Target Mode: **cf. 1712.00297 for recent results**

- 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**

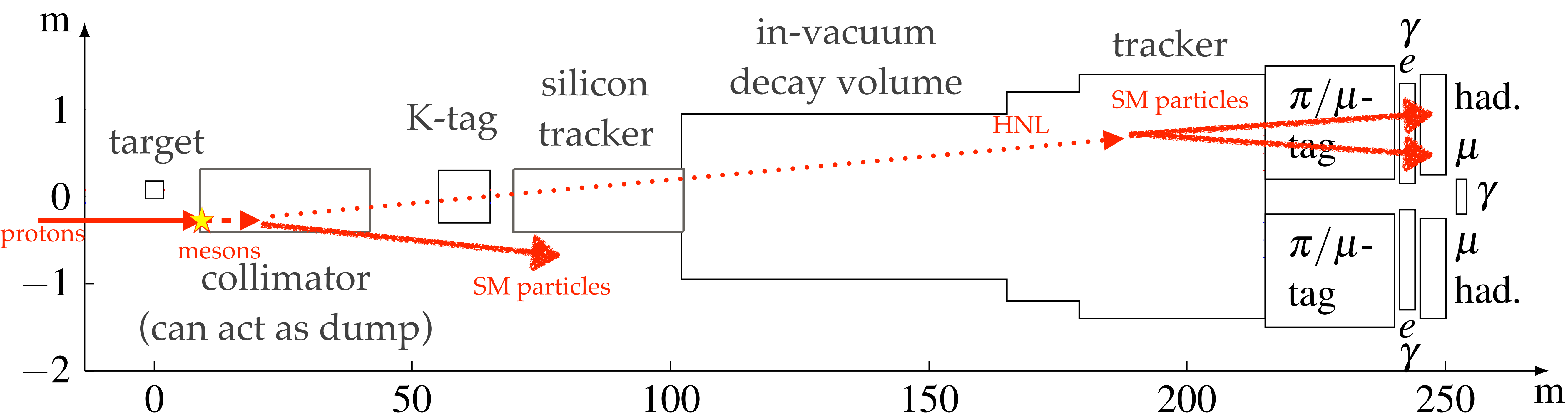
NA62 Kaon Mode: First Results





Cortina-Gil et al 1712.00297

NA62 Dump Mode

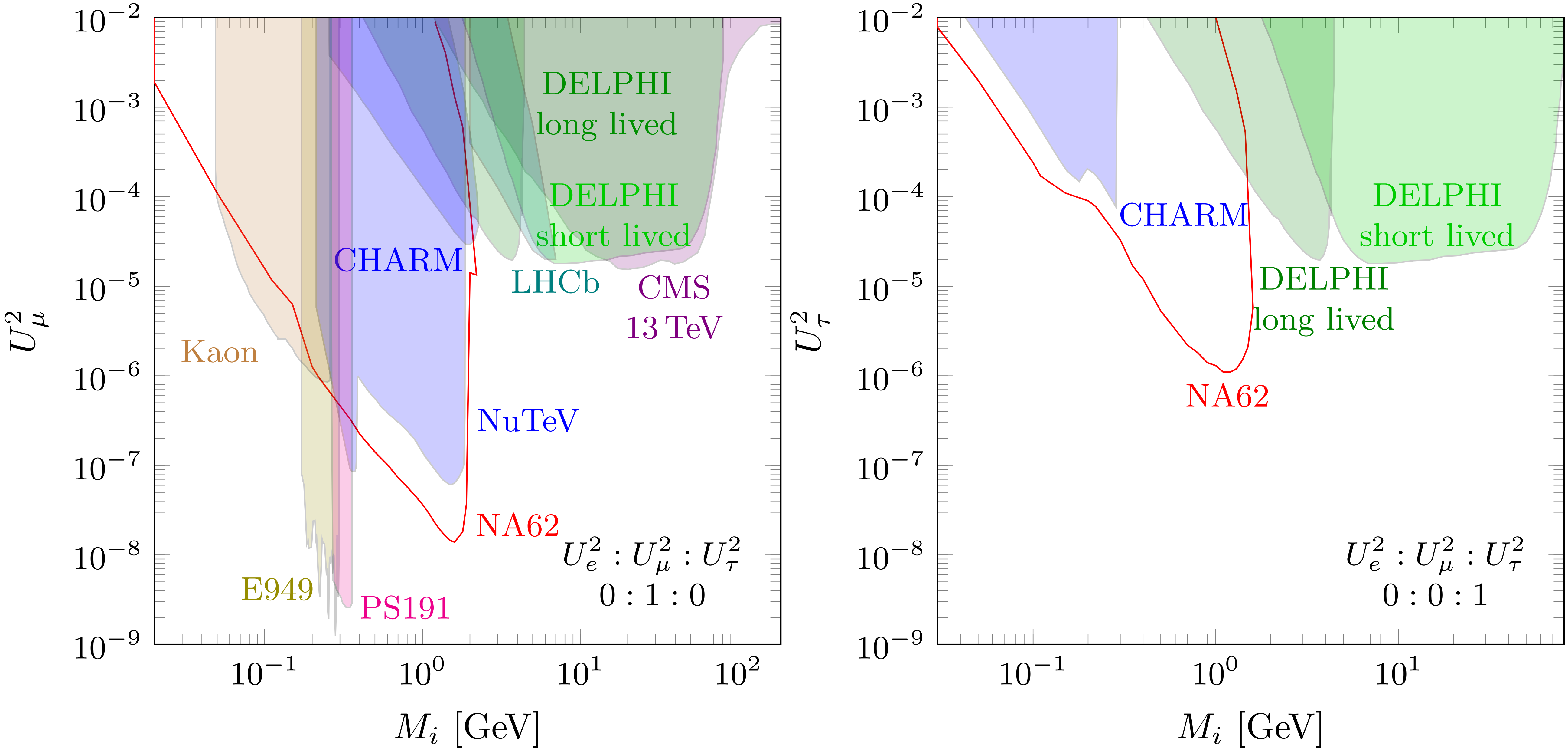


Dump mode

- 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

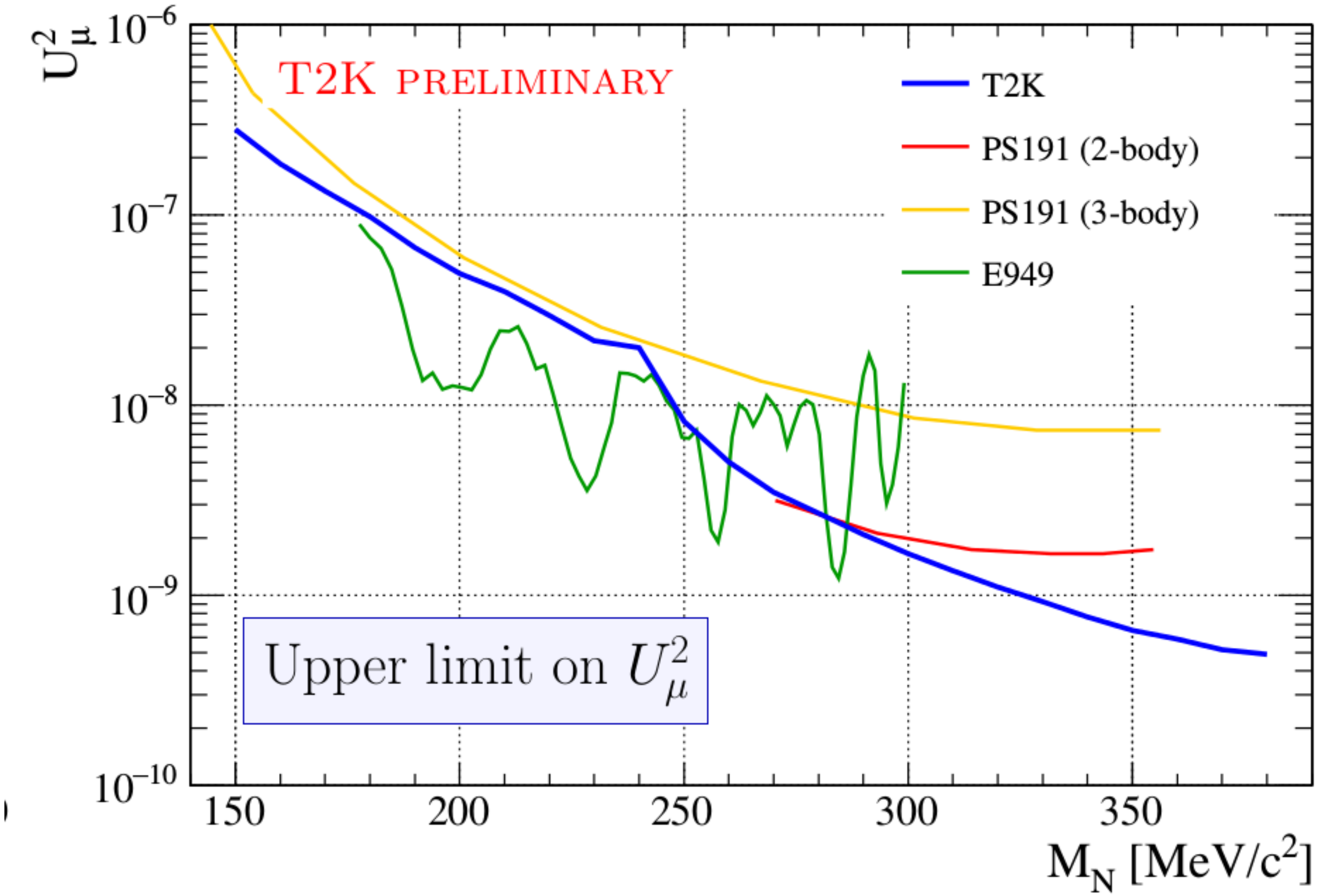
⇒ **search for decay nothing → leptons/hadrons in vacuum chamber**

NA62 Dump Mode Sensitivity



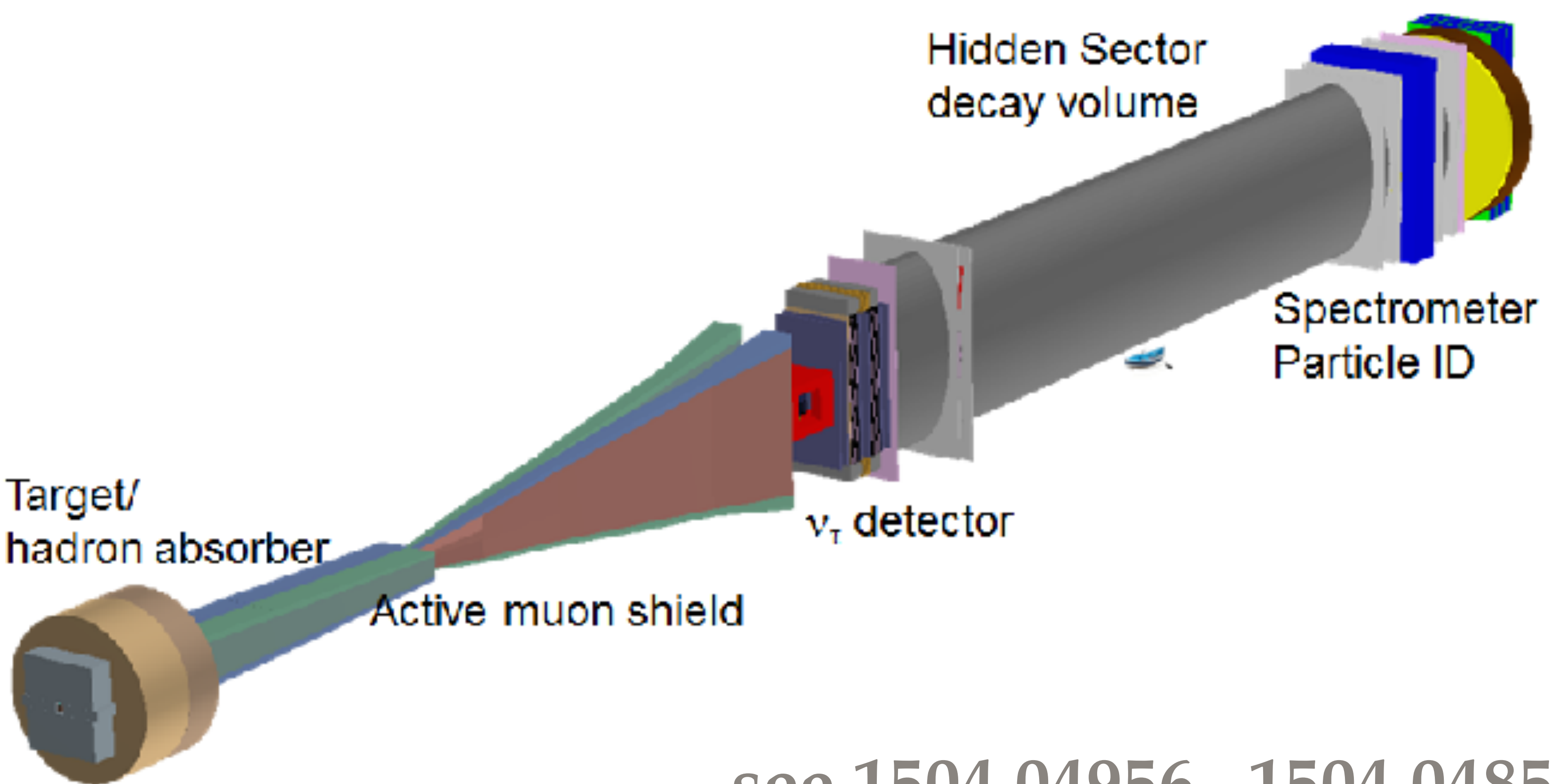
MaD / Hajer / Klaric / Lafranchi 1801.04207

T2K: Preliminary Results



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

The SHiP Proposal



SHiP
Search for Hidden Particles

see 1504.04956 , 1504.04855

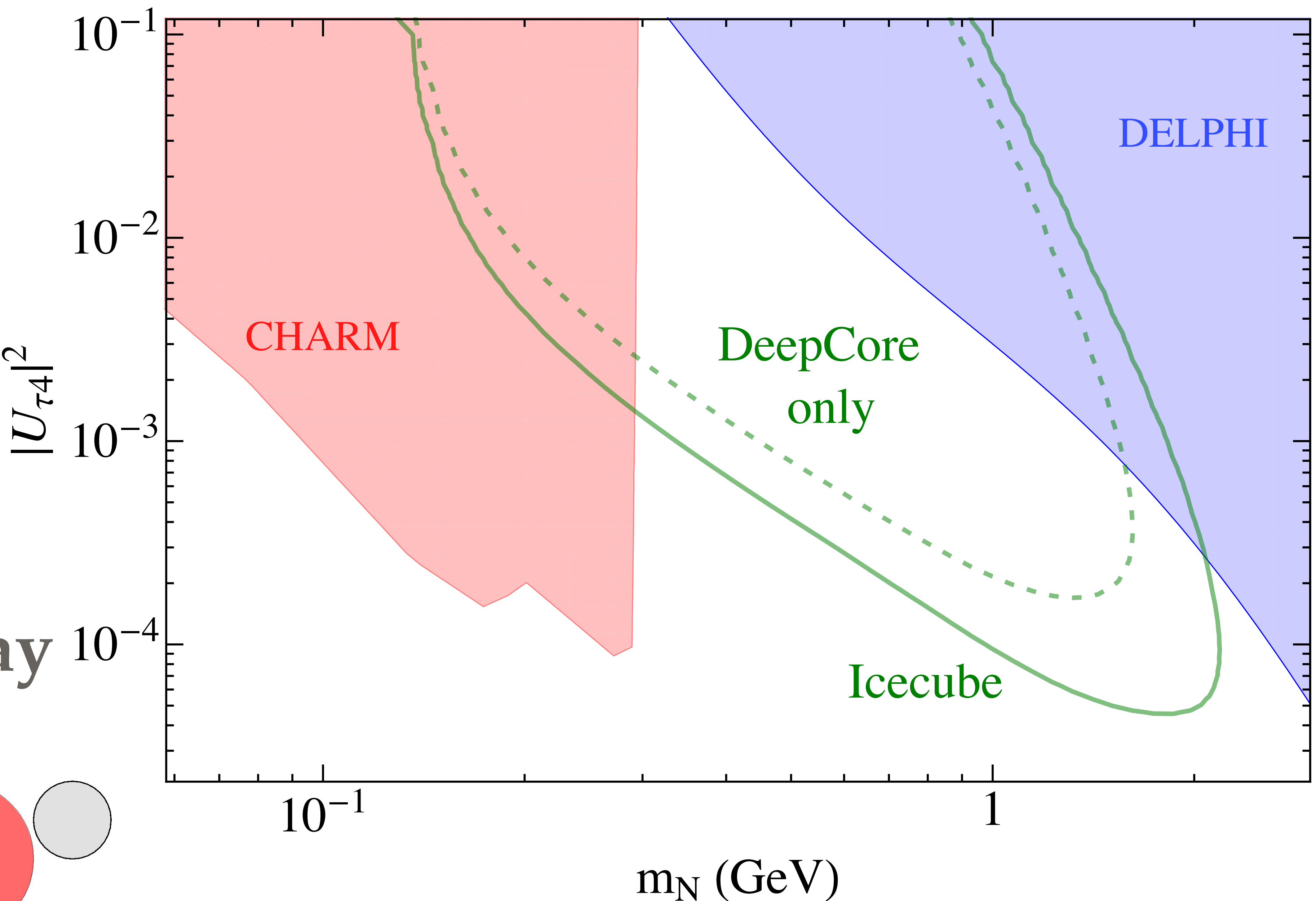
Search for Hidden Particles

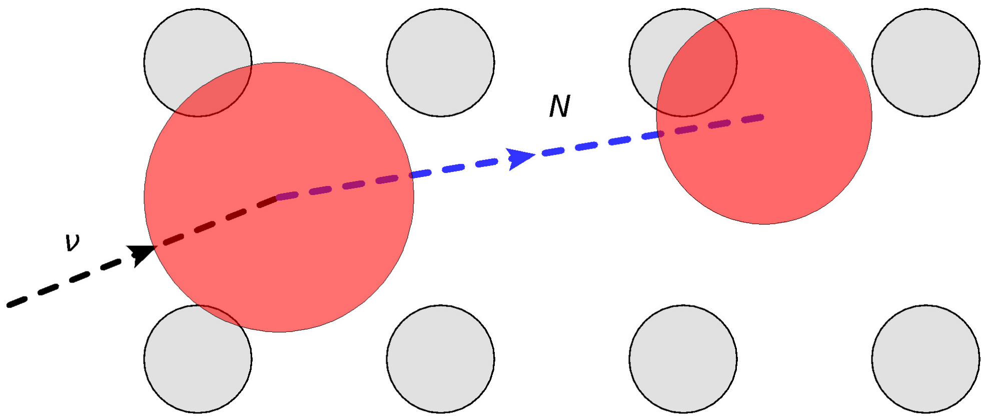
- new fixed target experiment using SPS beam
- see https://indico.cern.ch/event/706741/timetable/#20180613.detailed

Searching for HNLs with Ice Cube

search for "double cascade" events:

- one in HNL production
- one in HNL decay





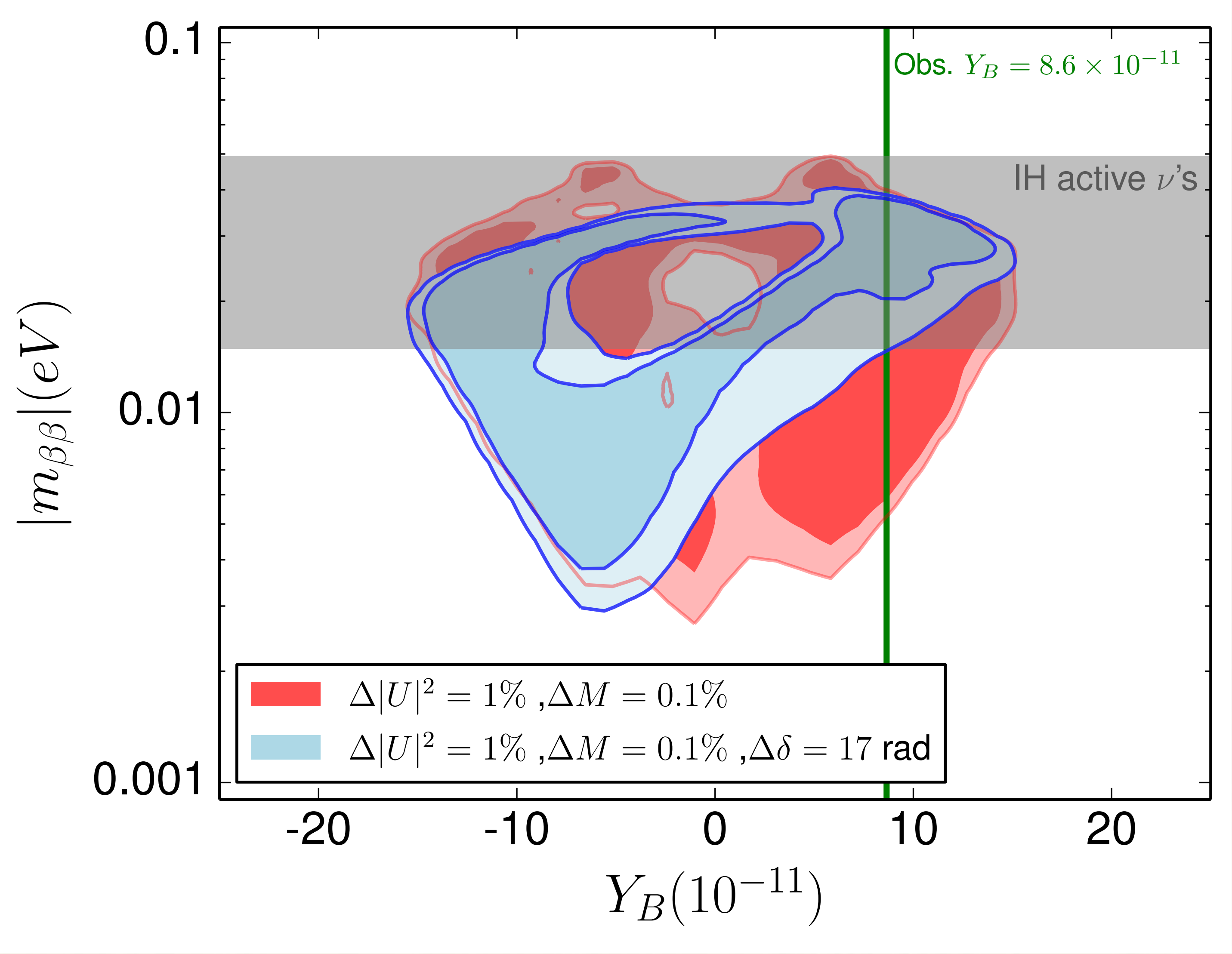
Coloma et al 1707.08573

The 0νββ Connection

Heavy neutrino exchange can dominate 0νββ…

…even in the leptogenesis region

$\Rightarrow$ additional probe of Reω !



Hernandez et al 1606.06719,

Bezrukov 0505247

Blennow et al 1005.3240

Lopez Pavon et al 1209.5342

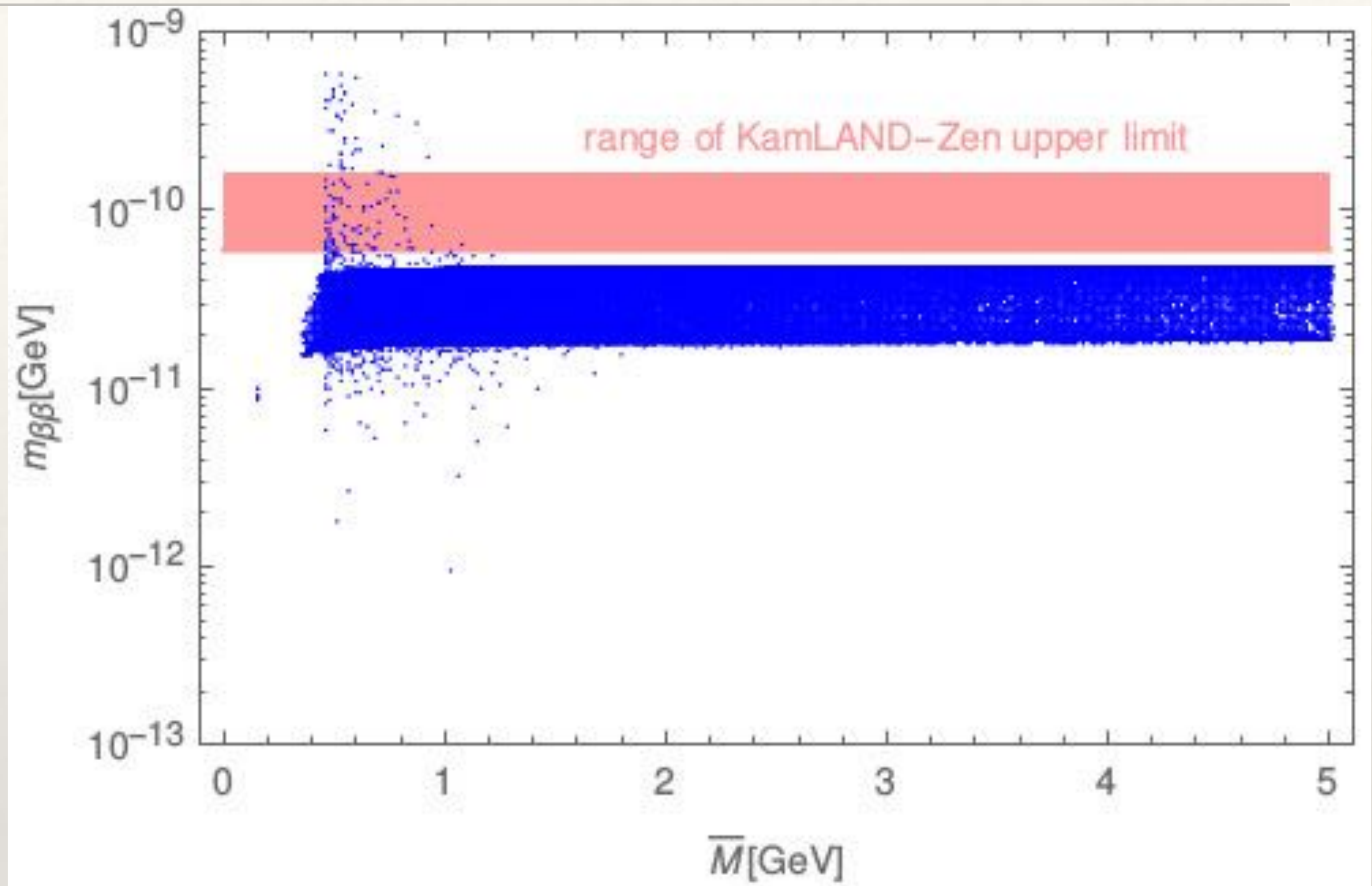
MaD/Eijima 1606.06221,

Hernandez et al 1606.06719,

Asaka et al 1606.06686

Neutrinoless Double β Decay

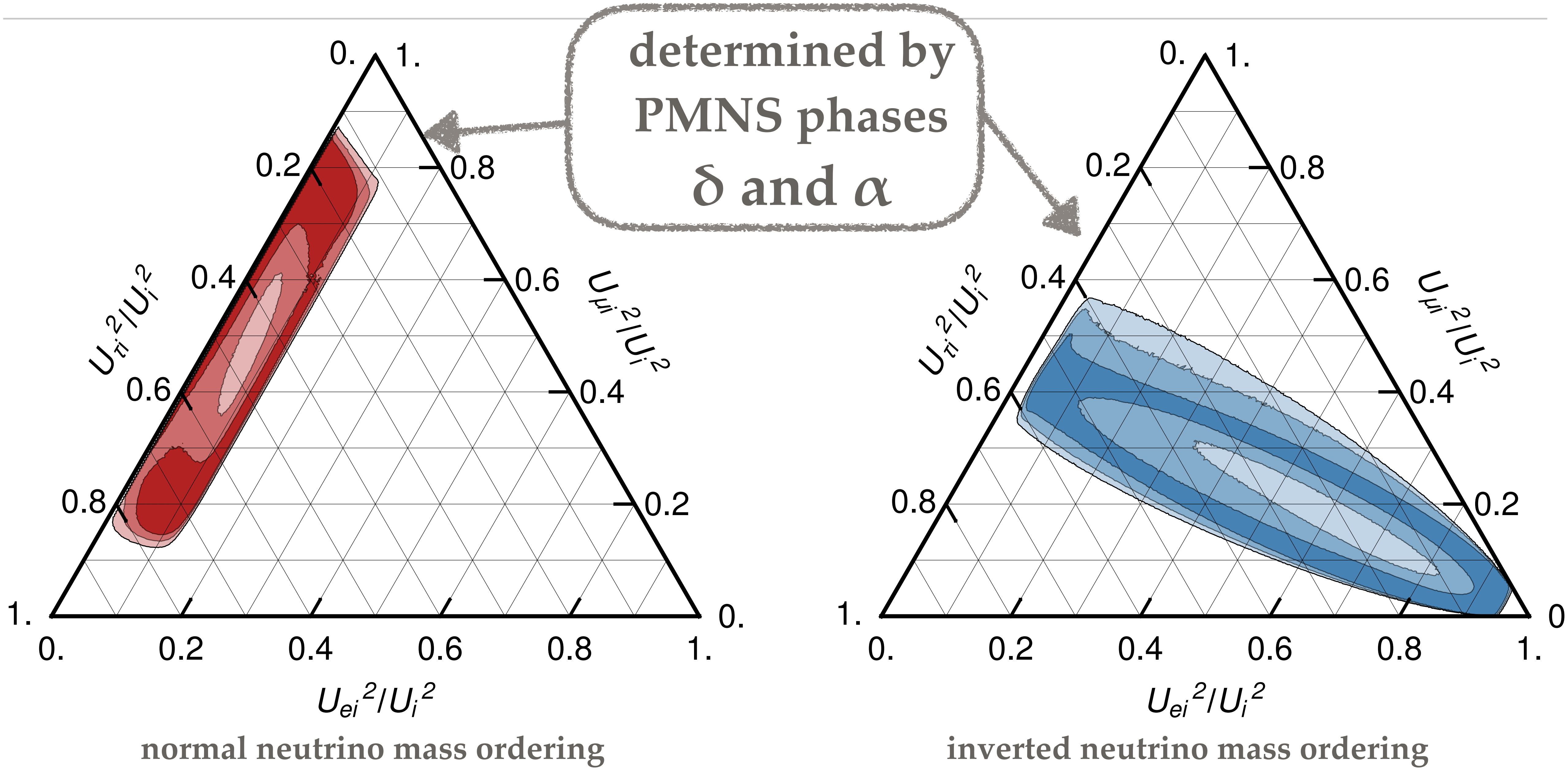
- **heavy neutrino exchange can dominate neutrinoless double β decay**
- **gives access to parameter Reω for M~GeV**
- **Reω is important for leptogenesis**



MaD/Eijima 1606.06221,
Hernandez/Kekic/Lopez-Pavon/Racker/Savaldo 1606.06719,
Asaka/Eijima/Ishida 1606.06686

$$m_{\beta\beta} \simeq \Big| [1 - f_A(\bar{M})] m^{\nu}_{\beta\beta} + 2 f_A^2(\bar{M}) \frac{\bar{M}^2}{\mathrm{p}^2} \frac{\Delta M}{\bar{M}} |\Delta m_{\mathrm{atm}}| e^{-2i\delta} \sin^2\theta_{13} \cos(2\omega) \Big|$$

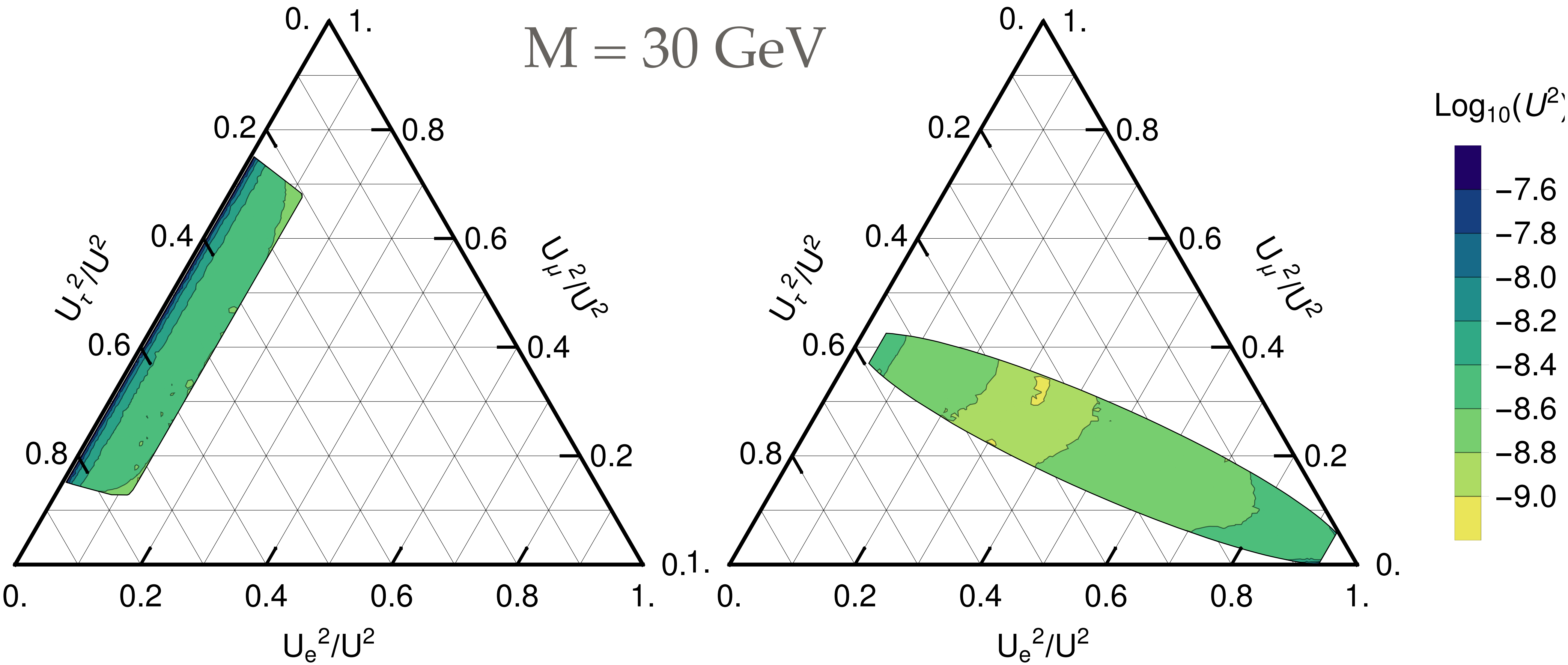
Heavy Neutrino Mixing: Constraints from ν-oscillation Data



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

from MaD / Hajer / Klaric / Lafranchi 1801.04207

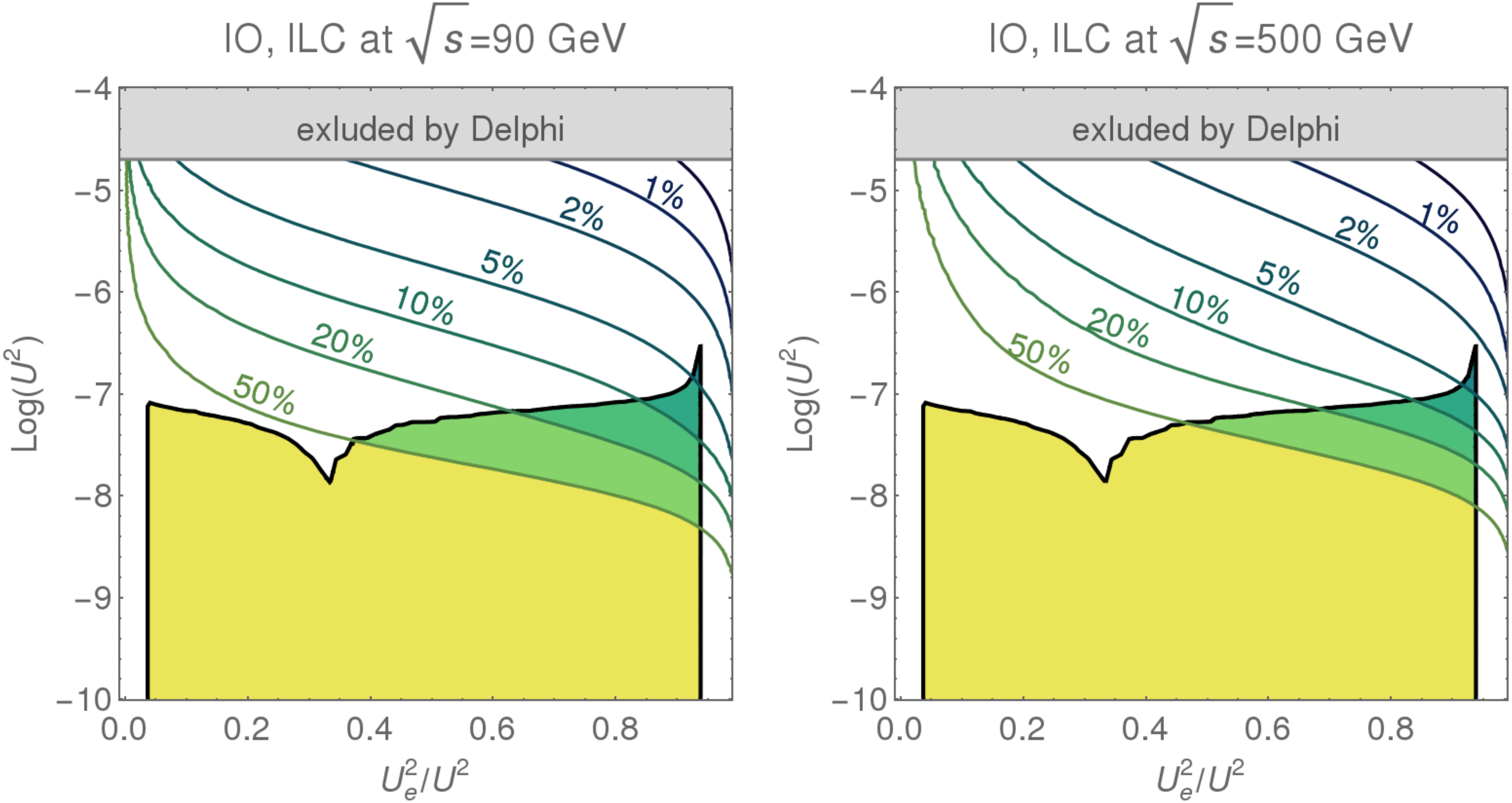
Heavy Neutrino Mixing: Constraints from Leptogenesis



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

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

Flavour Mixing at ILC

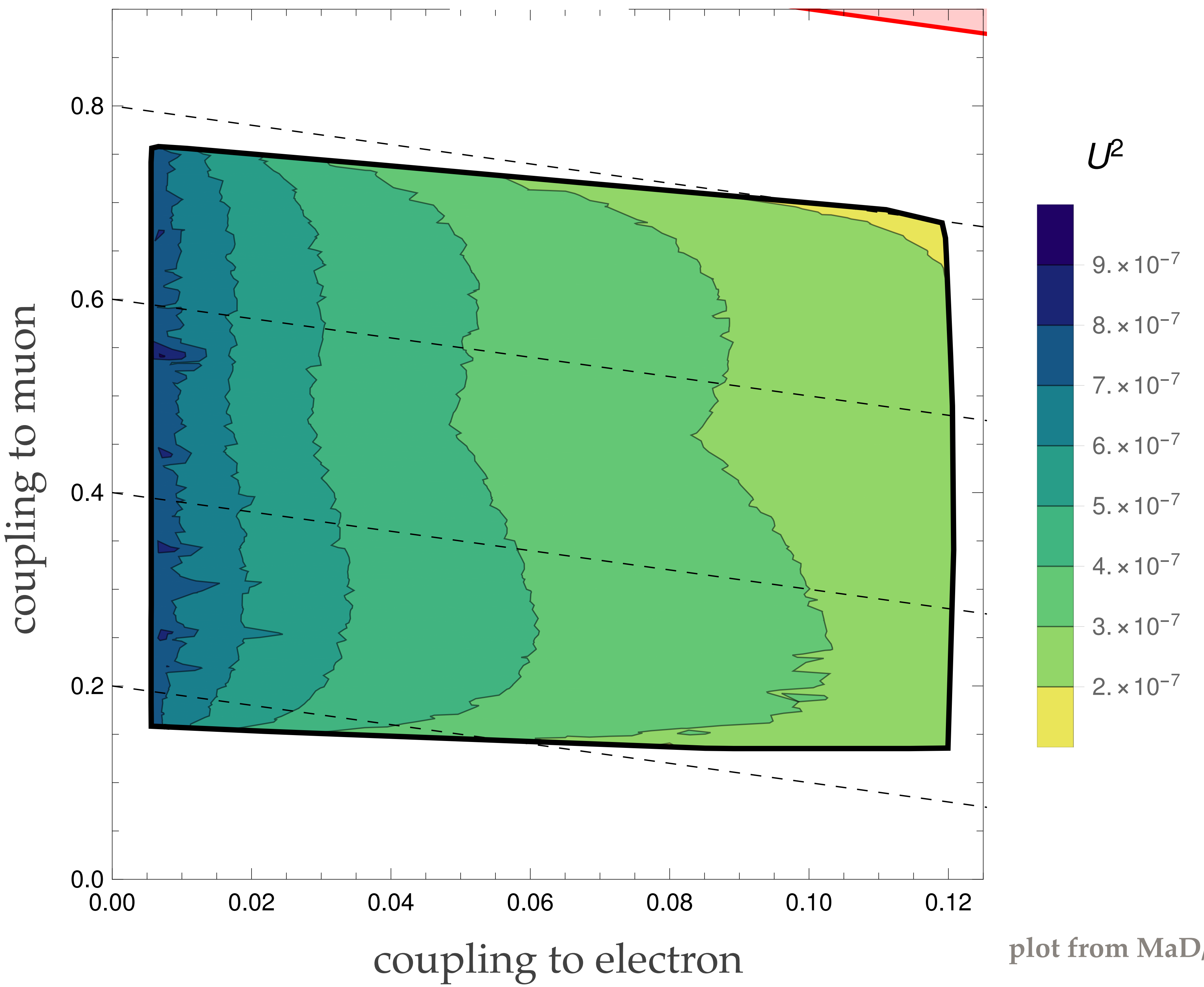


with 0.1 / ab

with 5 / ab

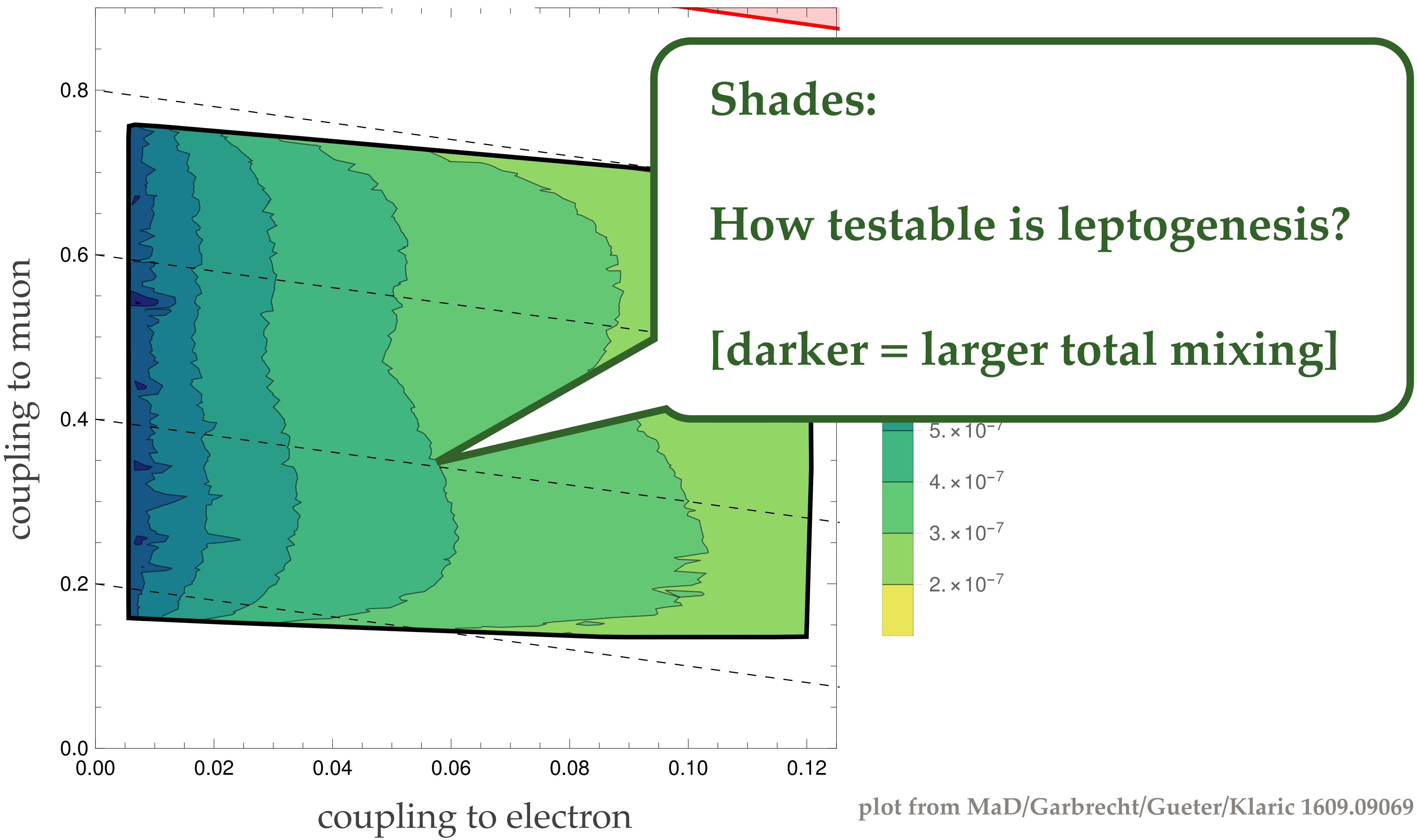
Antusch / Cazzato / MaD / Fischer / Garbrecht / Gueter / Klaric 1801.06534

Neutrino Mixing vs Collider Searches



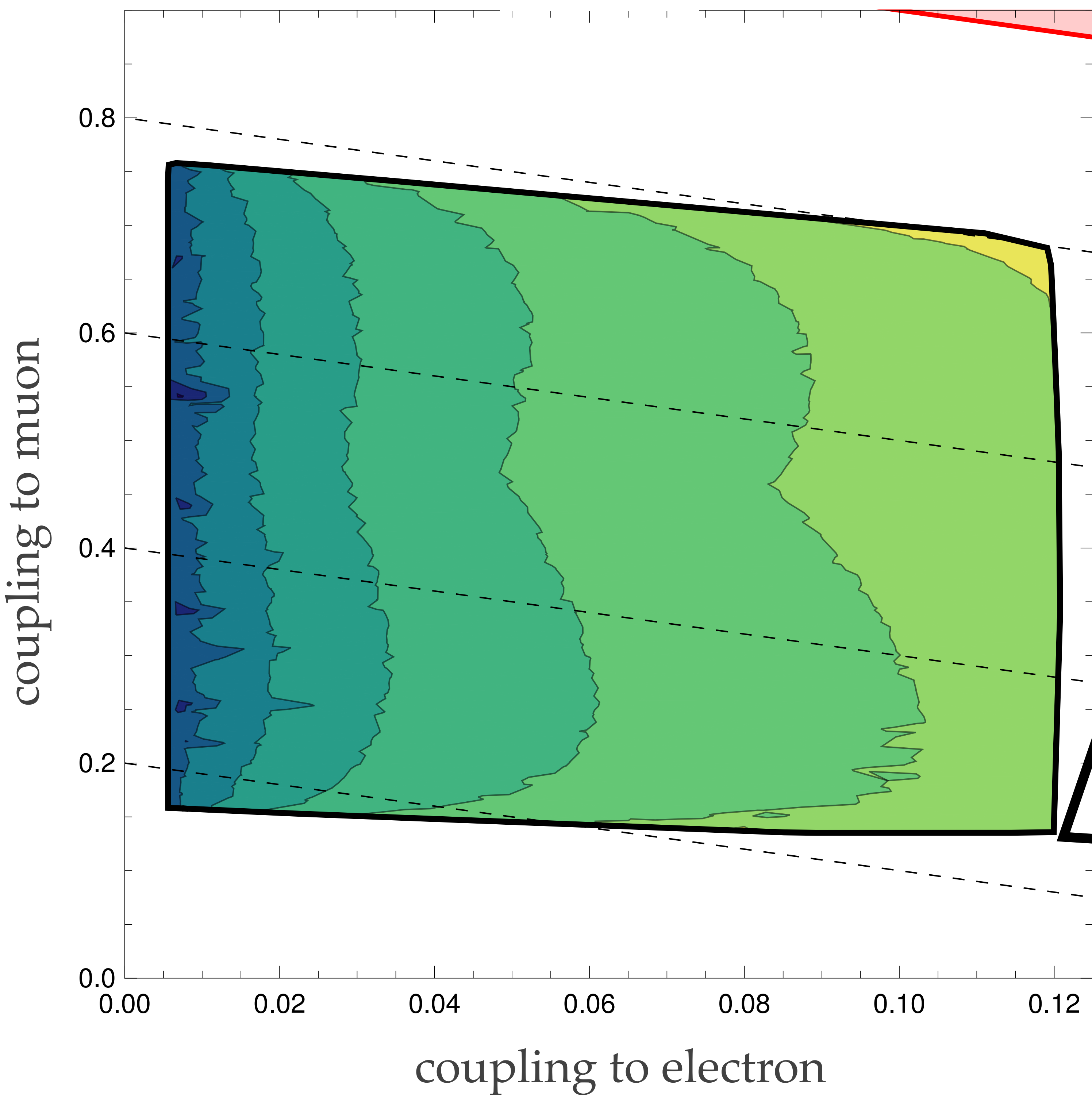
plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Neutrino Mixing vs Collider Searches



plot from MaD/Garbrecht/Gueter/Klaric 1609.09069

Neutrino Mixing vs Collider Searches



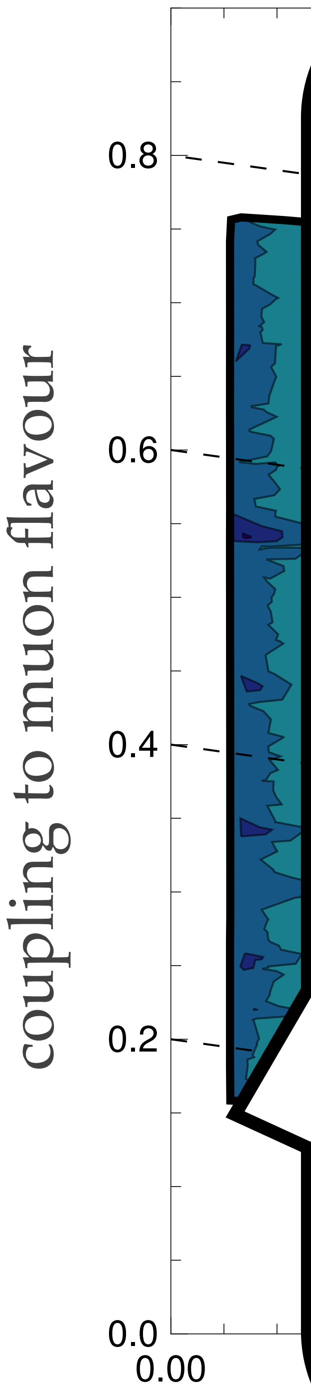
Area within black line:

allowed by neutrino oscillation data

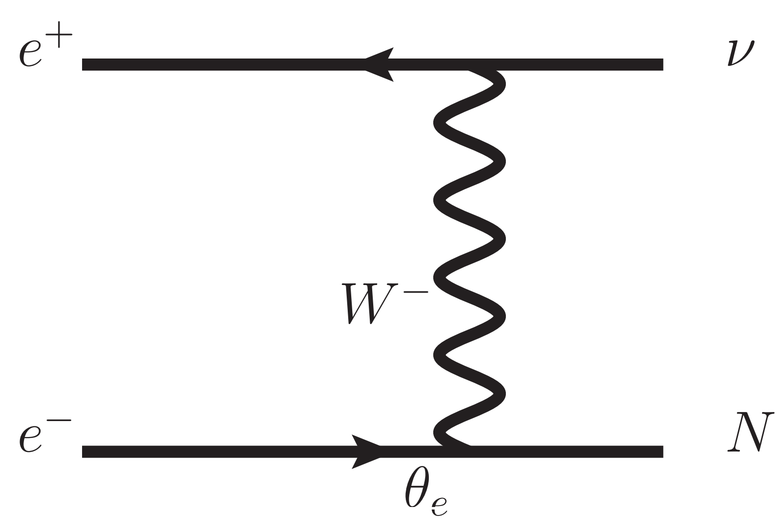
coupling to electron maximal 12%!

[for normal neutrino mass ordering]

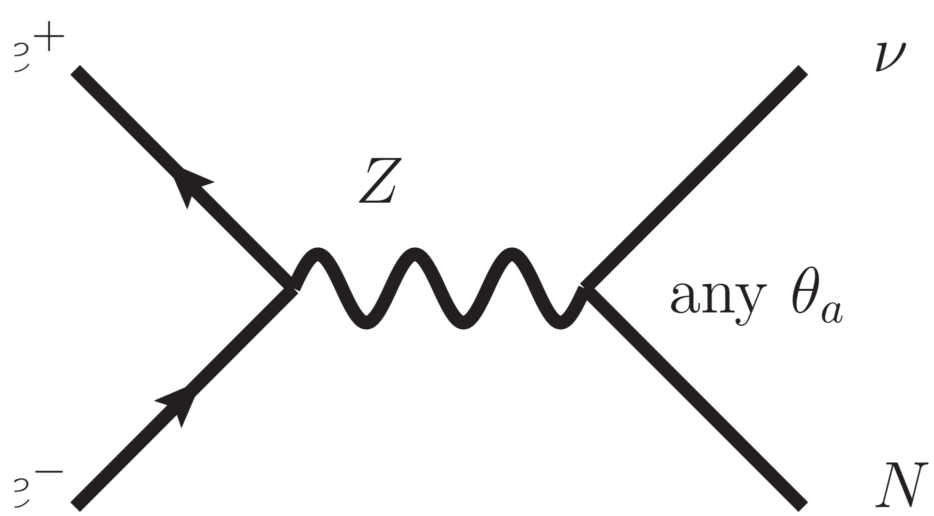
Neutrino Mixing vs Collider Searches



Effect on production at lepton colliders:



suppressed compared to



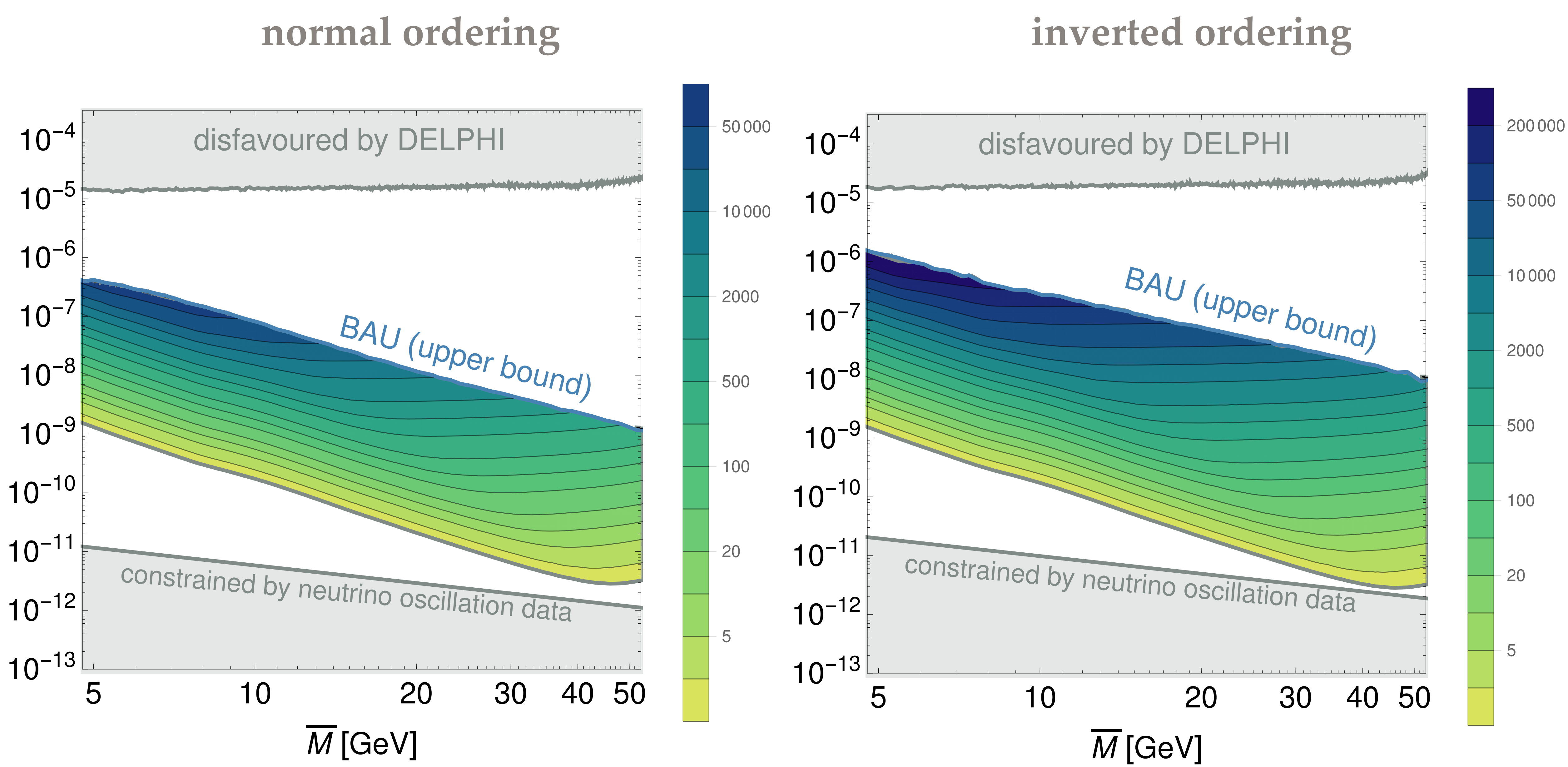
Area within black line:

allowed by neutrino oscillation data

coupling to electron maximal 12%!

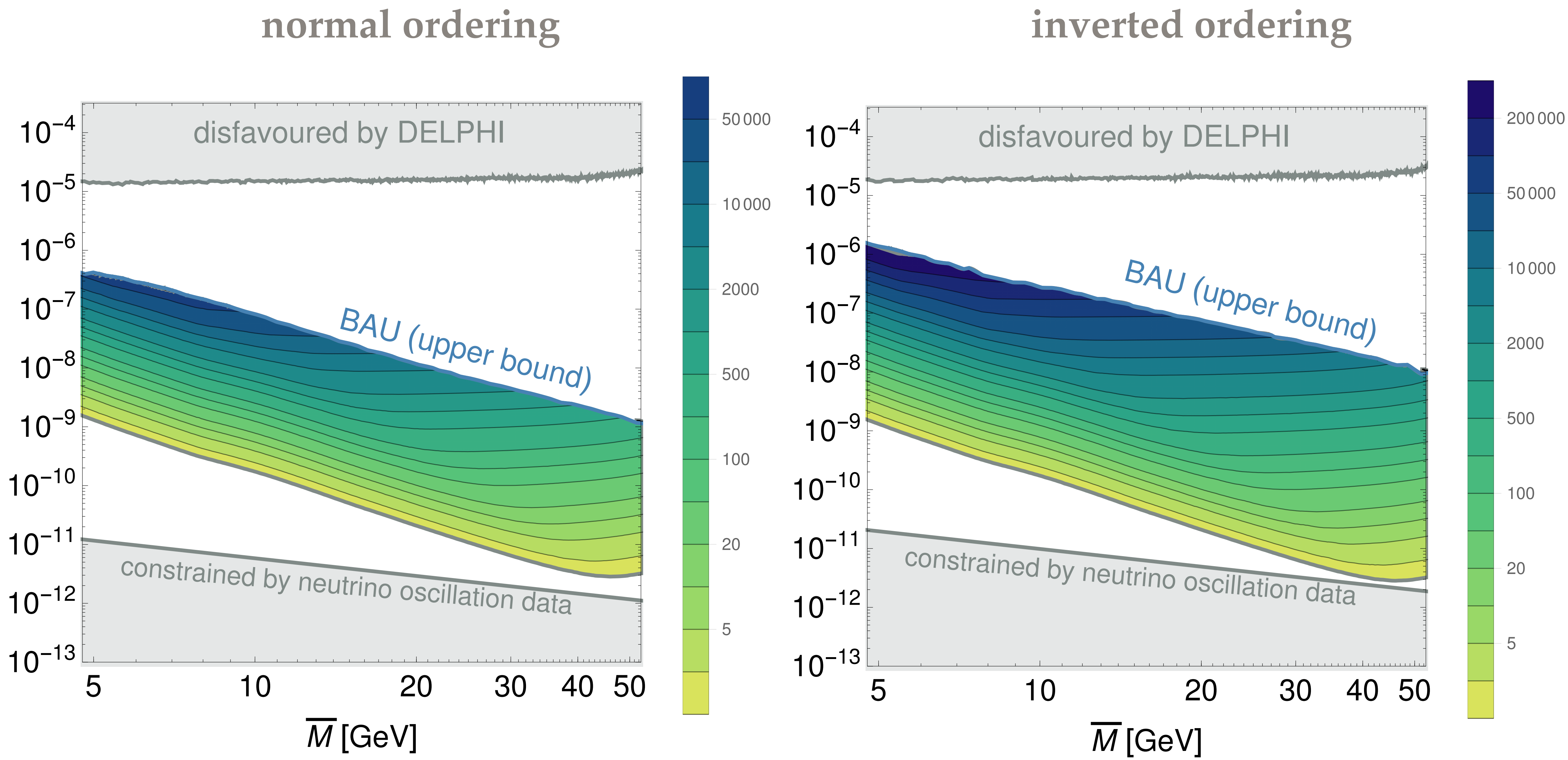
[for normal neutrino mass ordering]

Number of Events



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

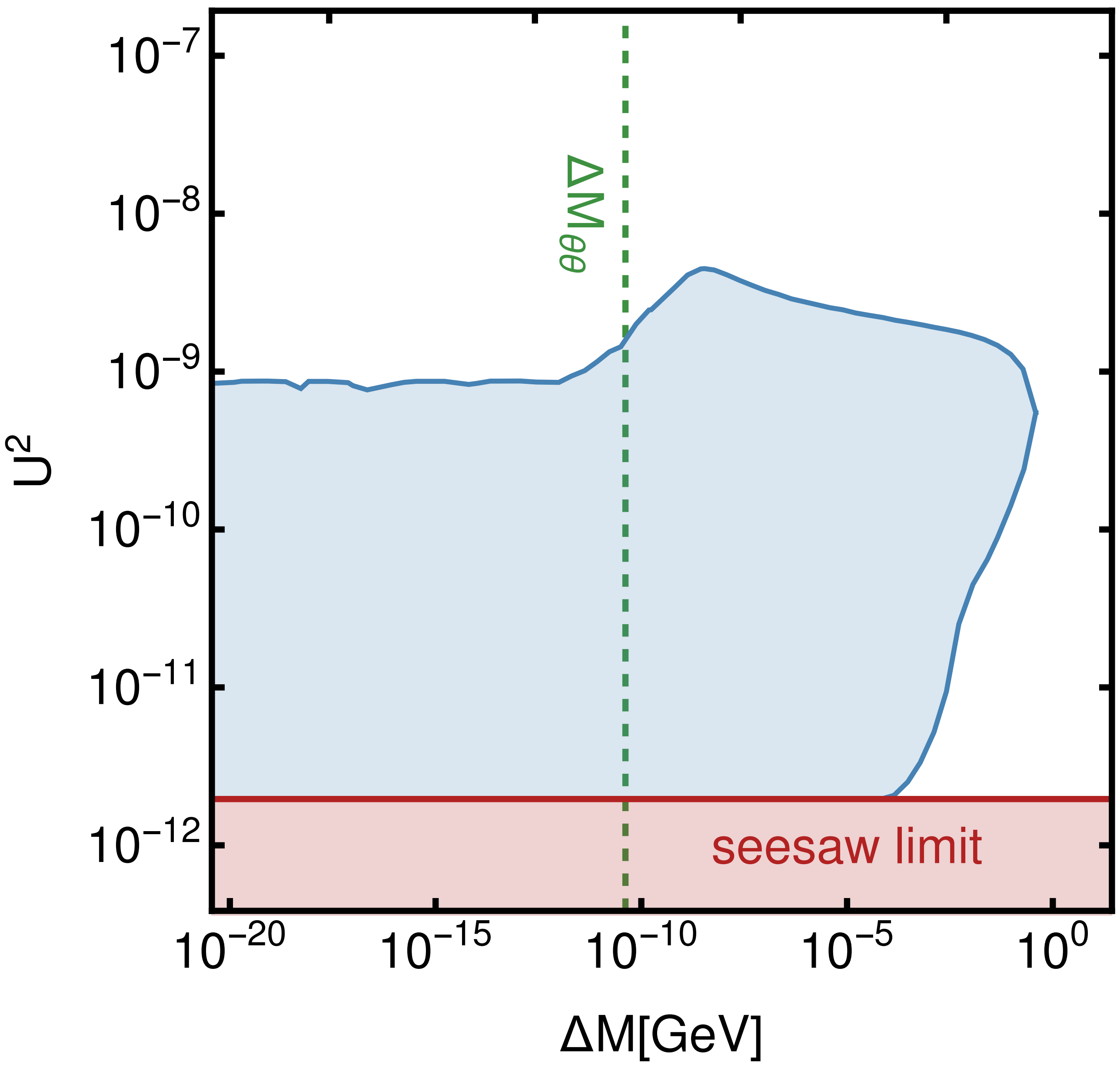
Number of Events



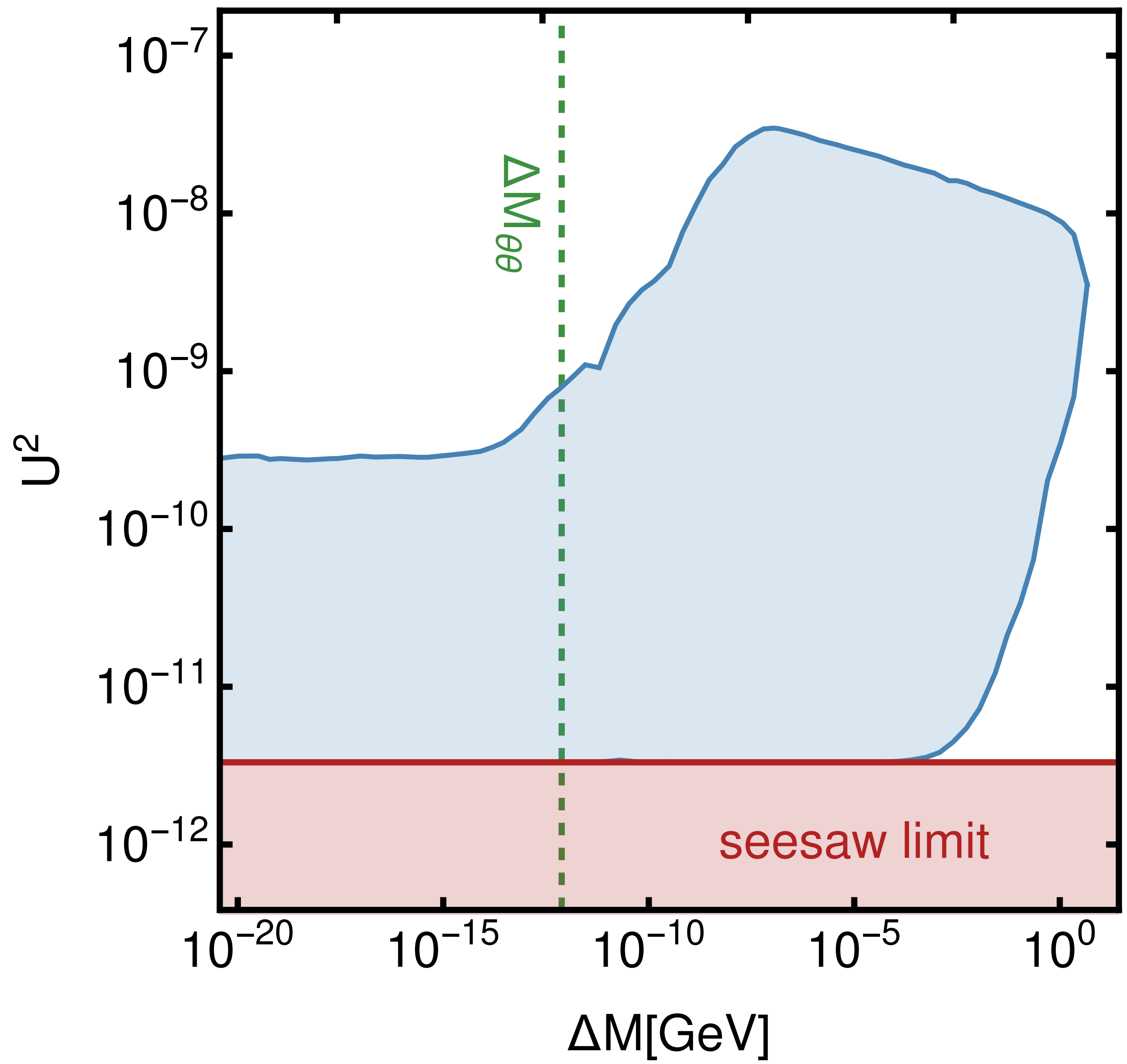
percent level measurement of flavour structure!

Leptogenesis and Heavy Neutrino Mass Splitting

normal ordering

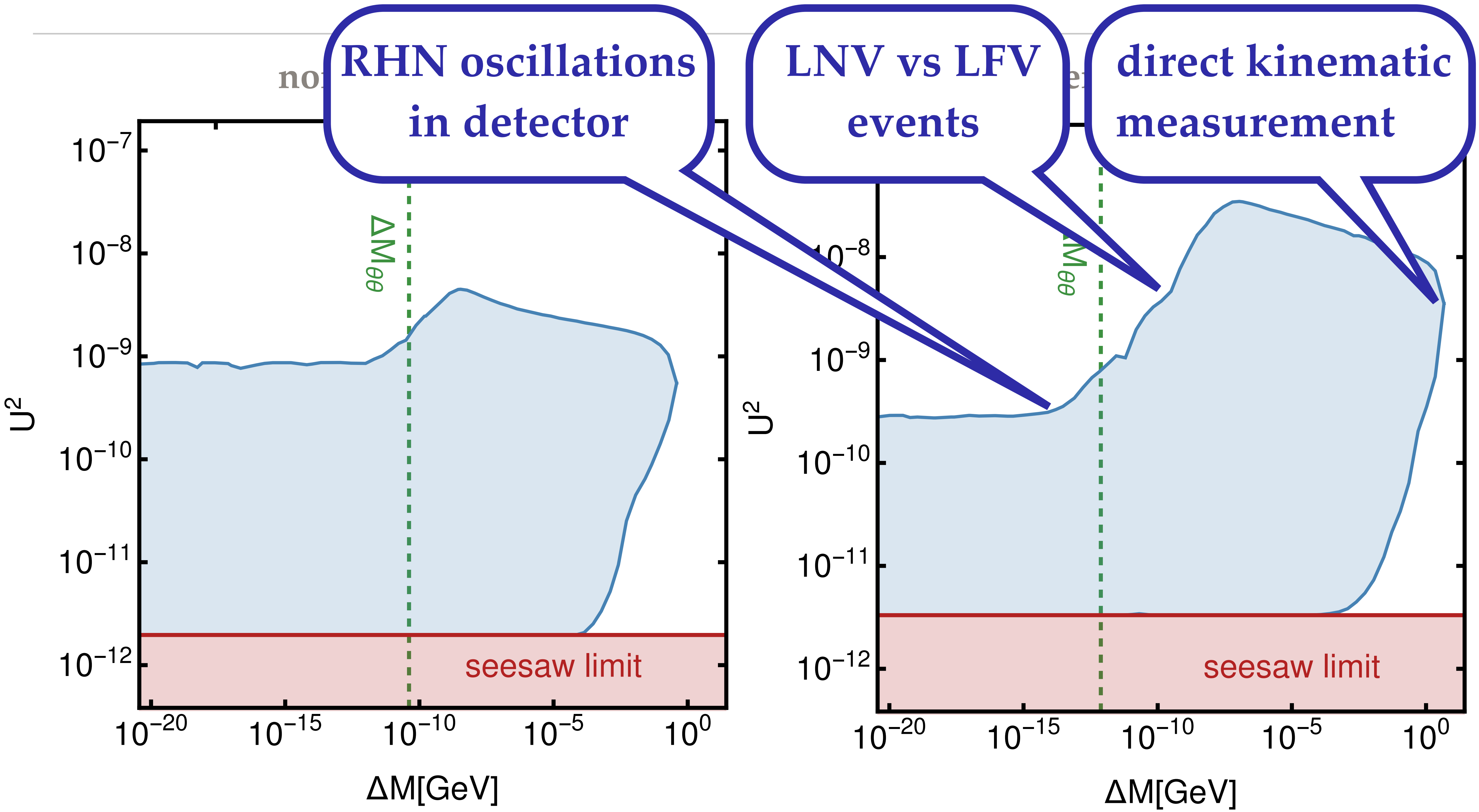


inverted ordering



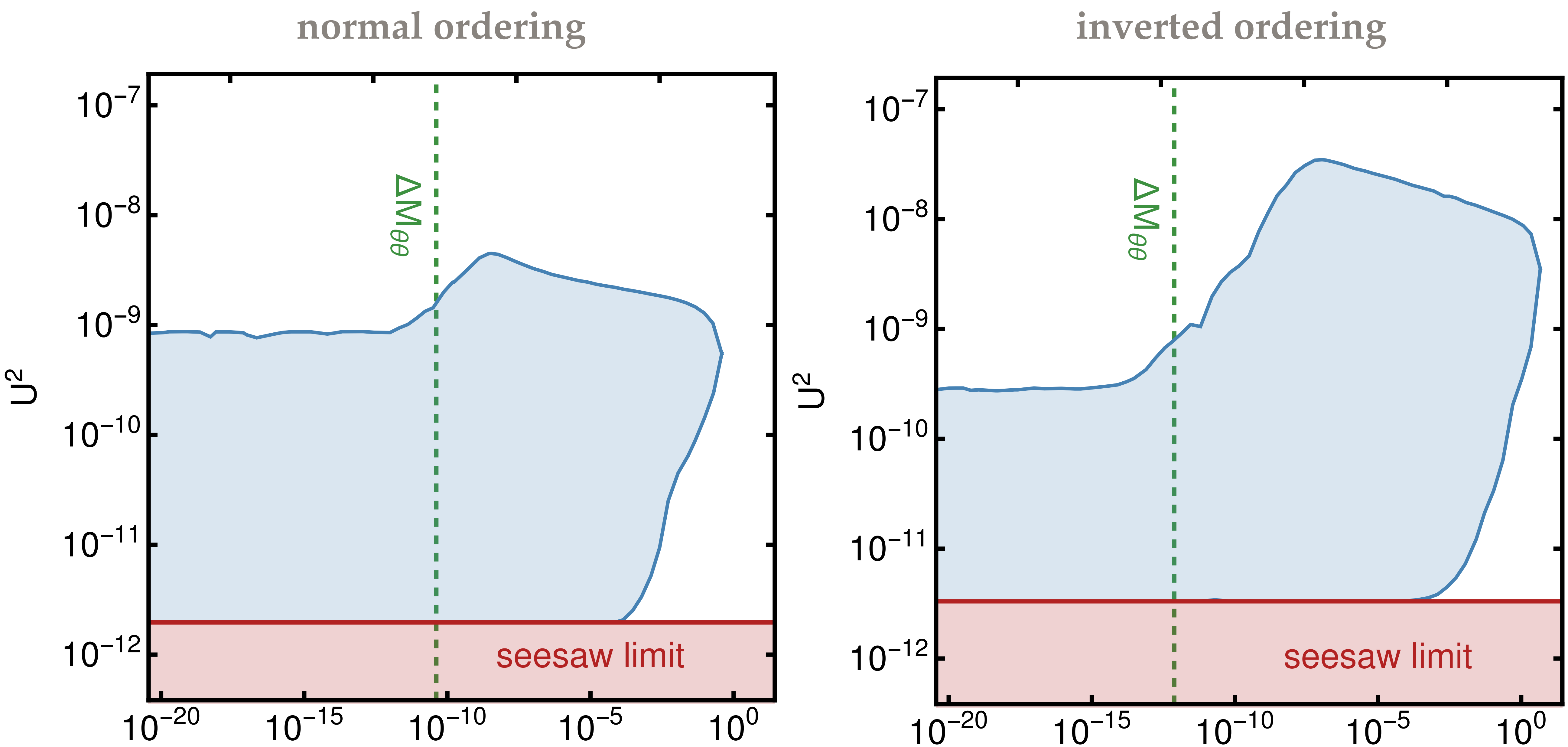
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Leptogenesis and Heavy Neutrino Mass Splitting



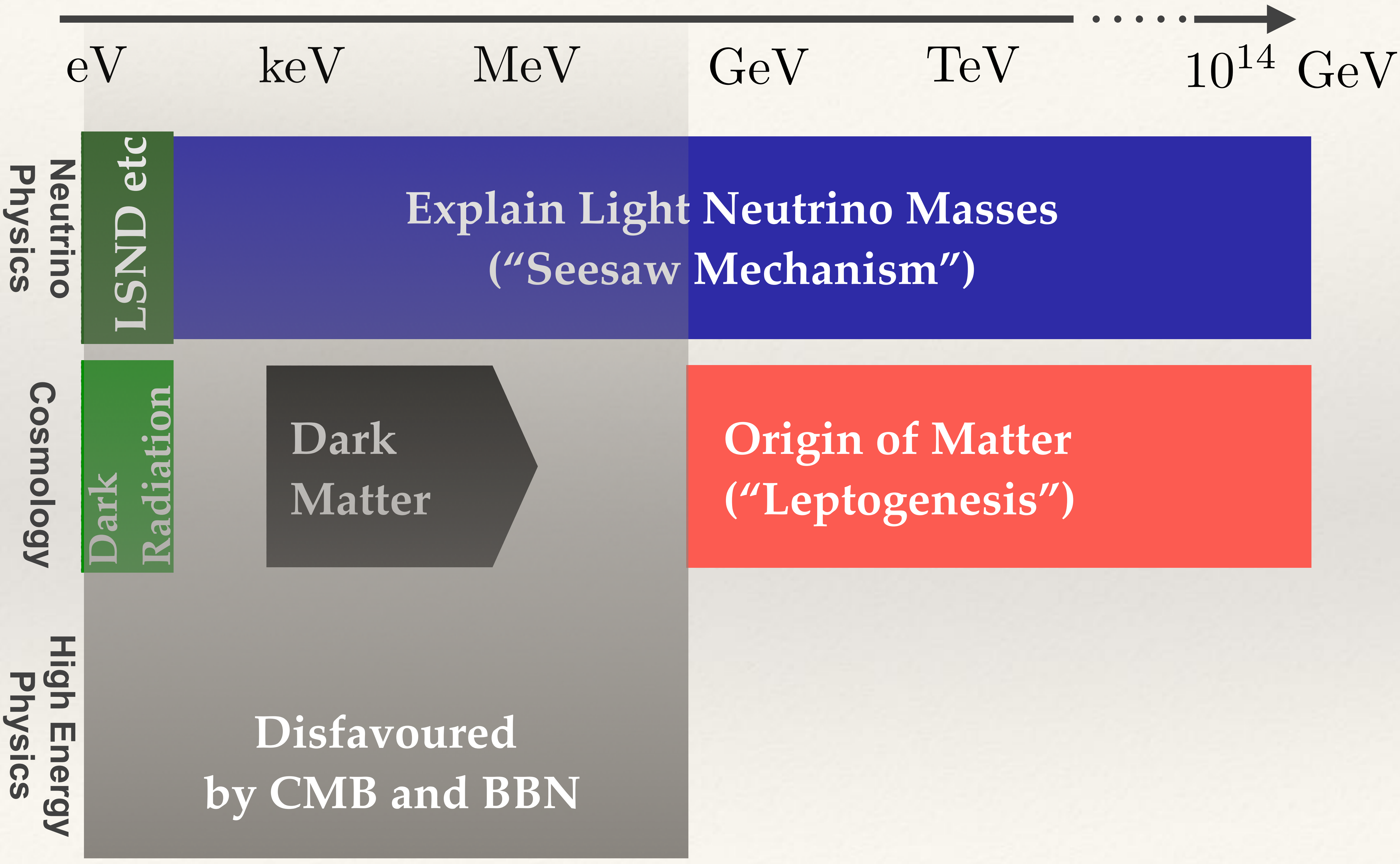
Antusch/Cazzato/MaD/Fischer/Garbrecht/Gueter/Klaric 1710.03744

Leptogenesis and Heavy Neutrino Mass Splitting

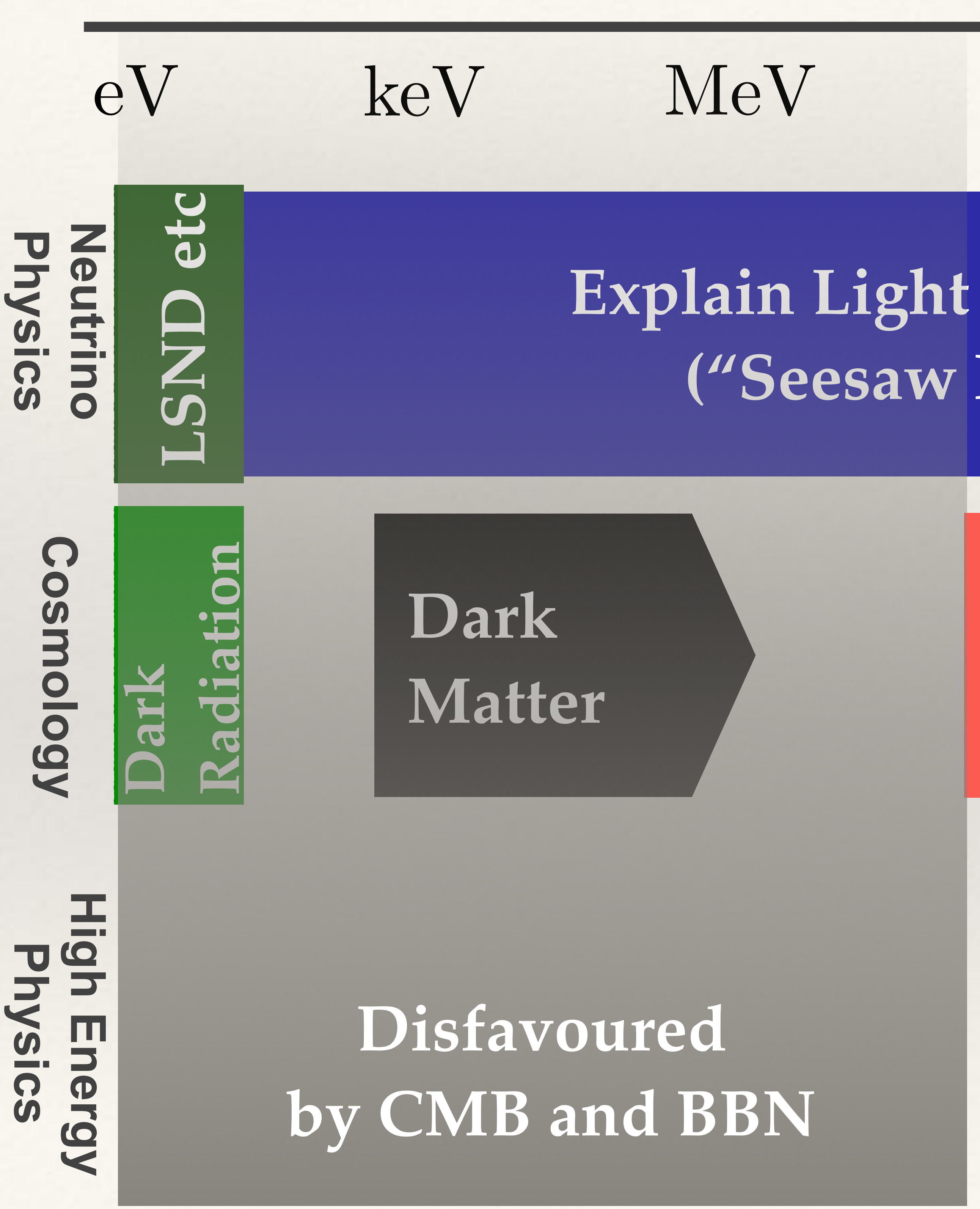


with three RH neutrinos:
no need for mass degeneracy for leptogenesis MaD/Garbrecht 12

Right Handed Neutrinos and the Light Neutrino Masses

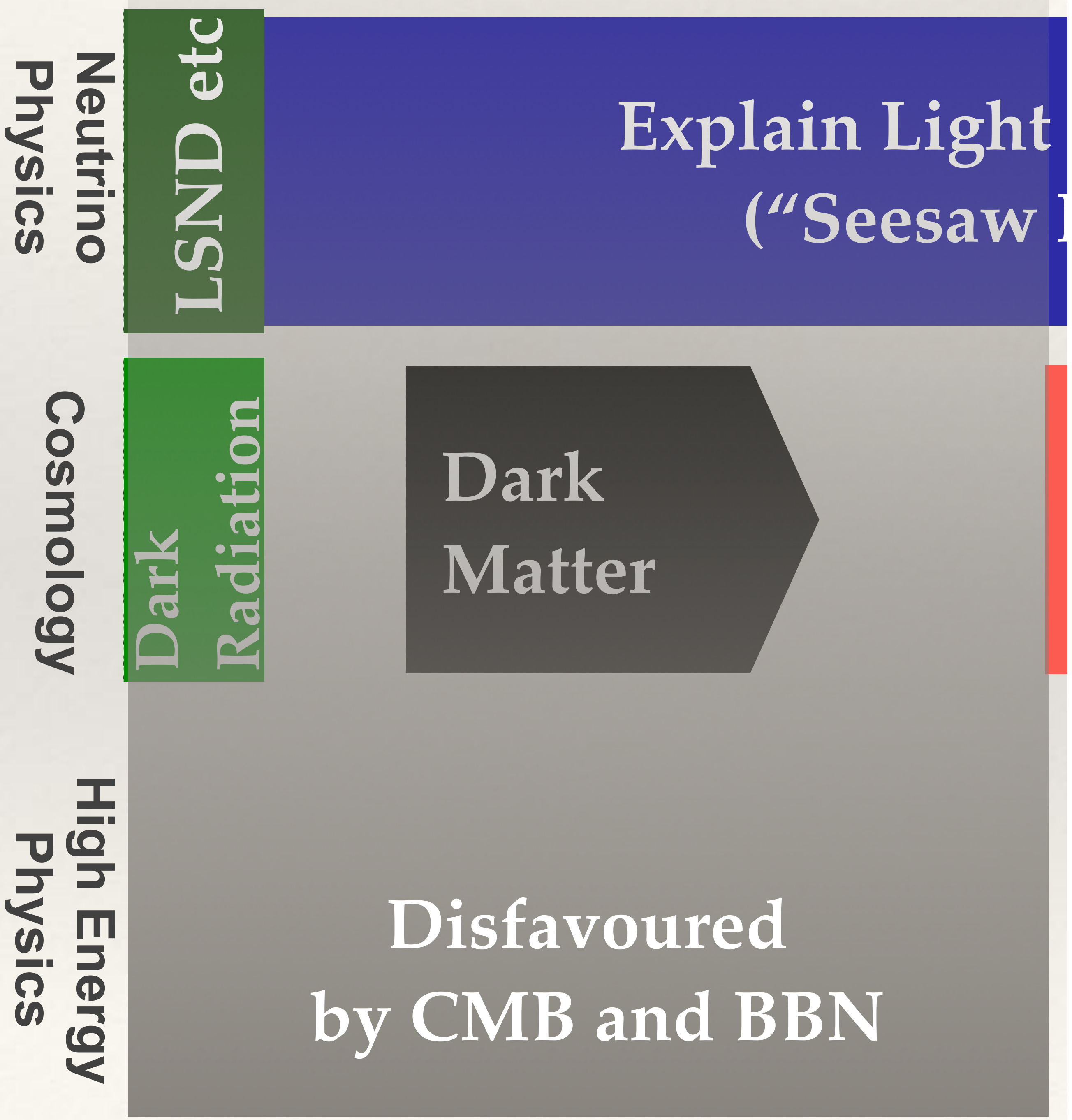


Right Handed Neutrinos and the Light Neutrino Masses

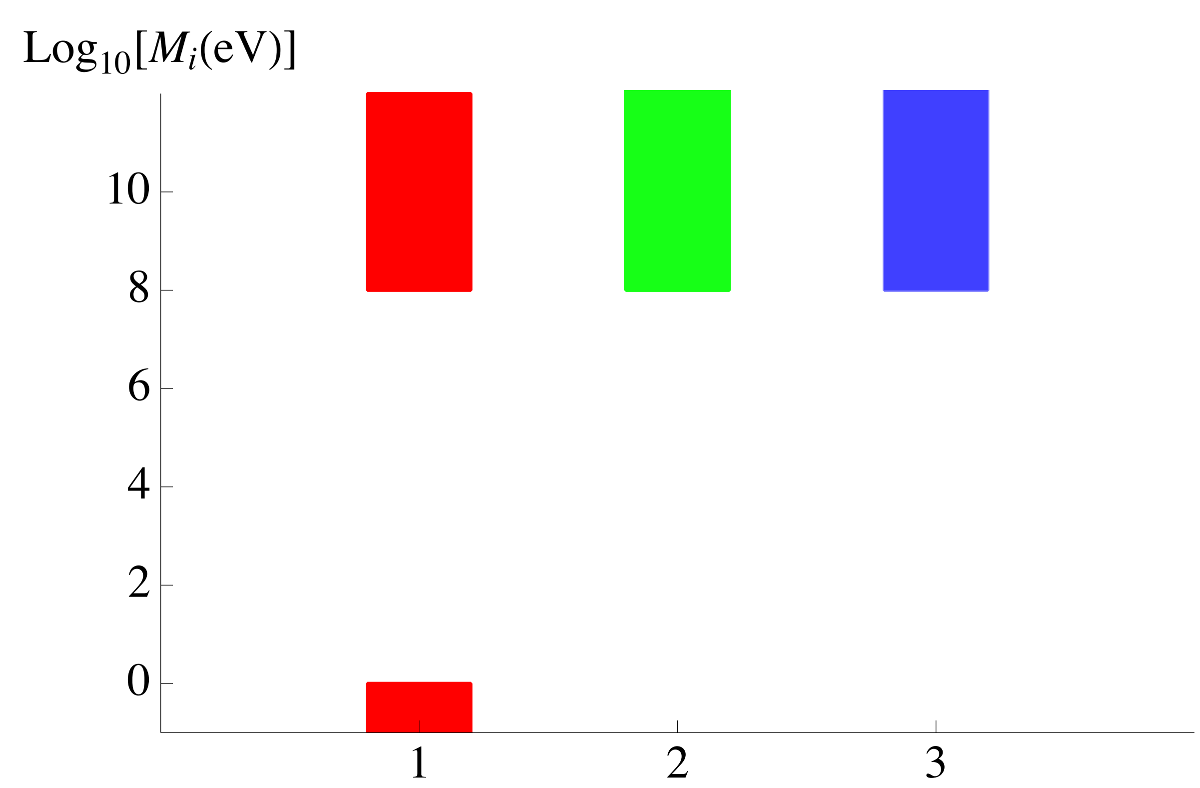


- RH neutrinos **must mix** to generate light neutrino mass
- Mixing leads to **production in the early universe**
- For masses below 100 MeV, RH neutrinos **do not decay before BBN**
- Their decay either **disturbs BBN** or **affects the CMB**

Right Handed Neutrinos and the Light Neutrino Masses

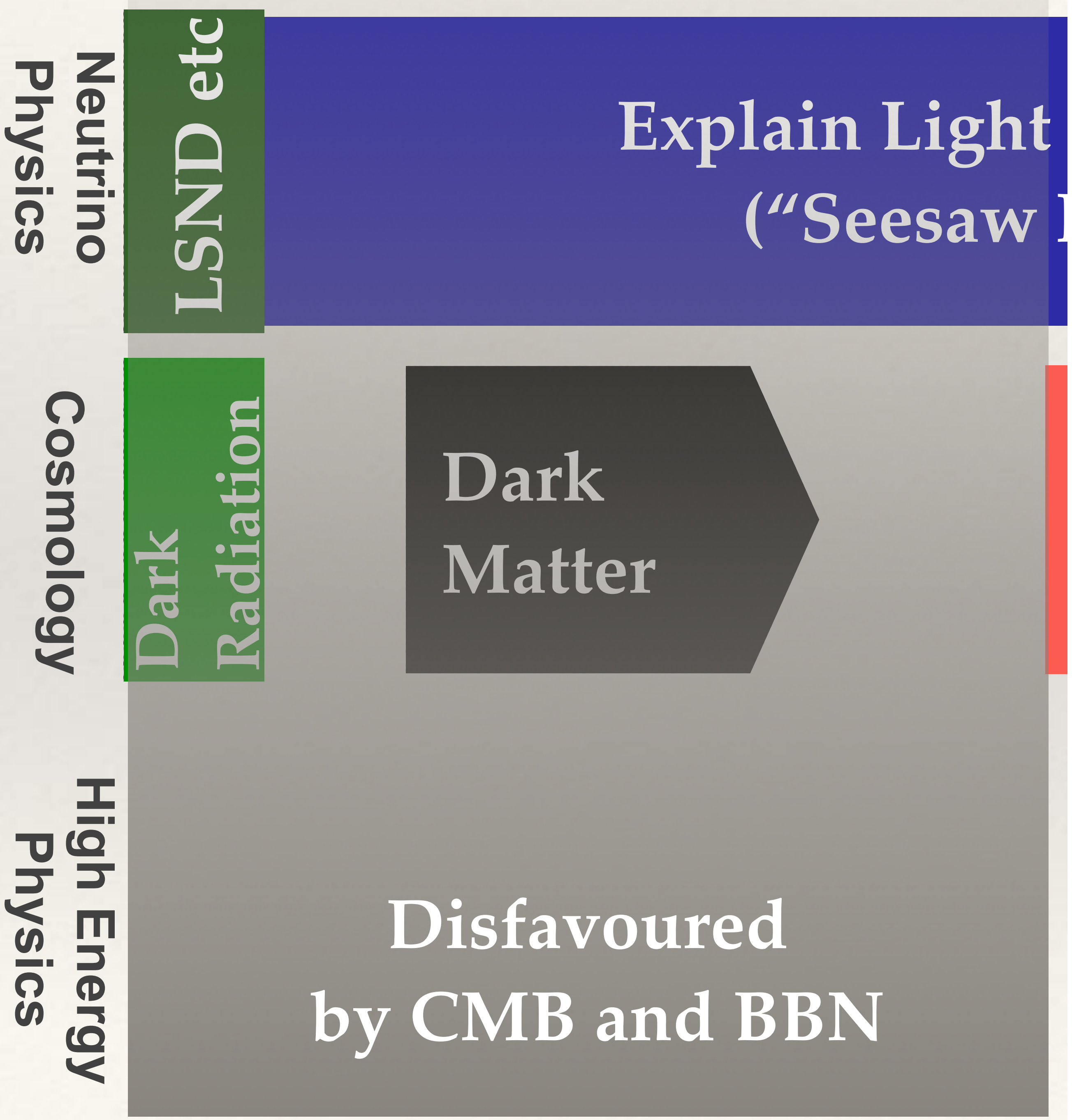


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} > 10^{-3}$ eV, three RHN reach equilibrium

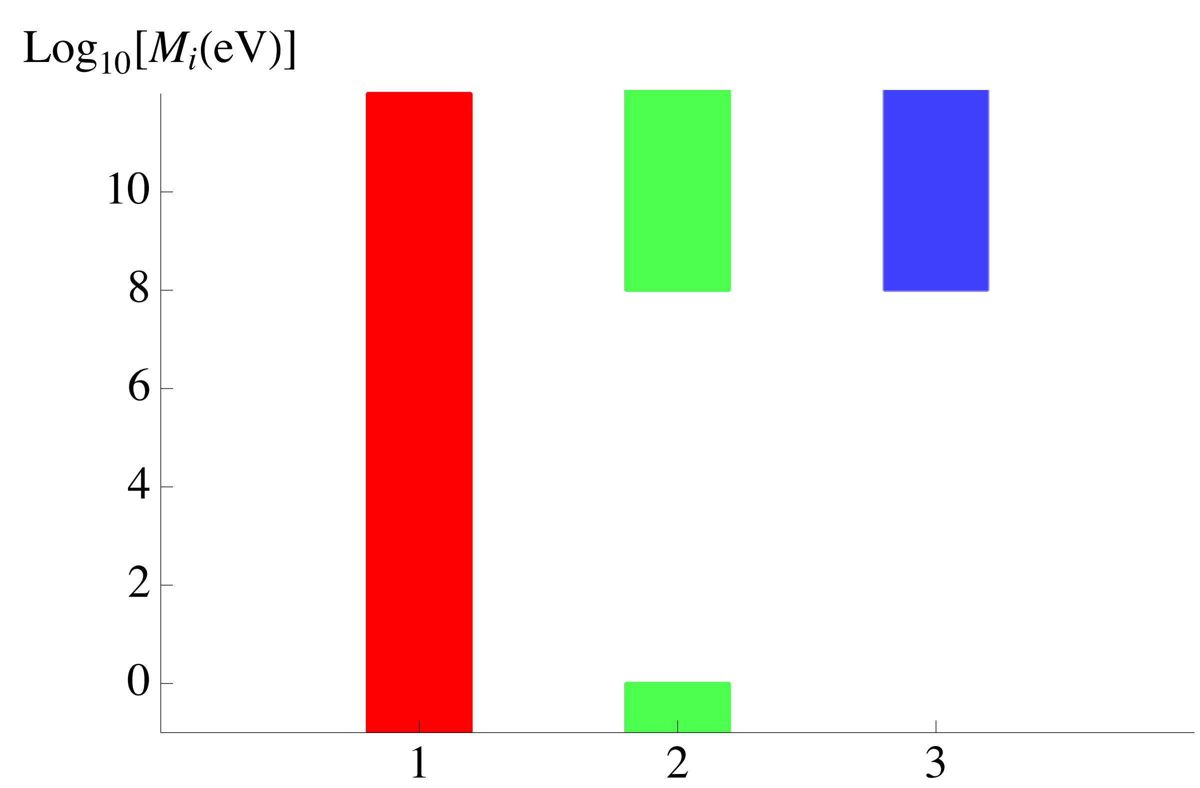


Hernandez/Kekic/Lopez-Pavon 1406.2961

Right Handed Neutrinos and the Light Neutrino Masses

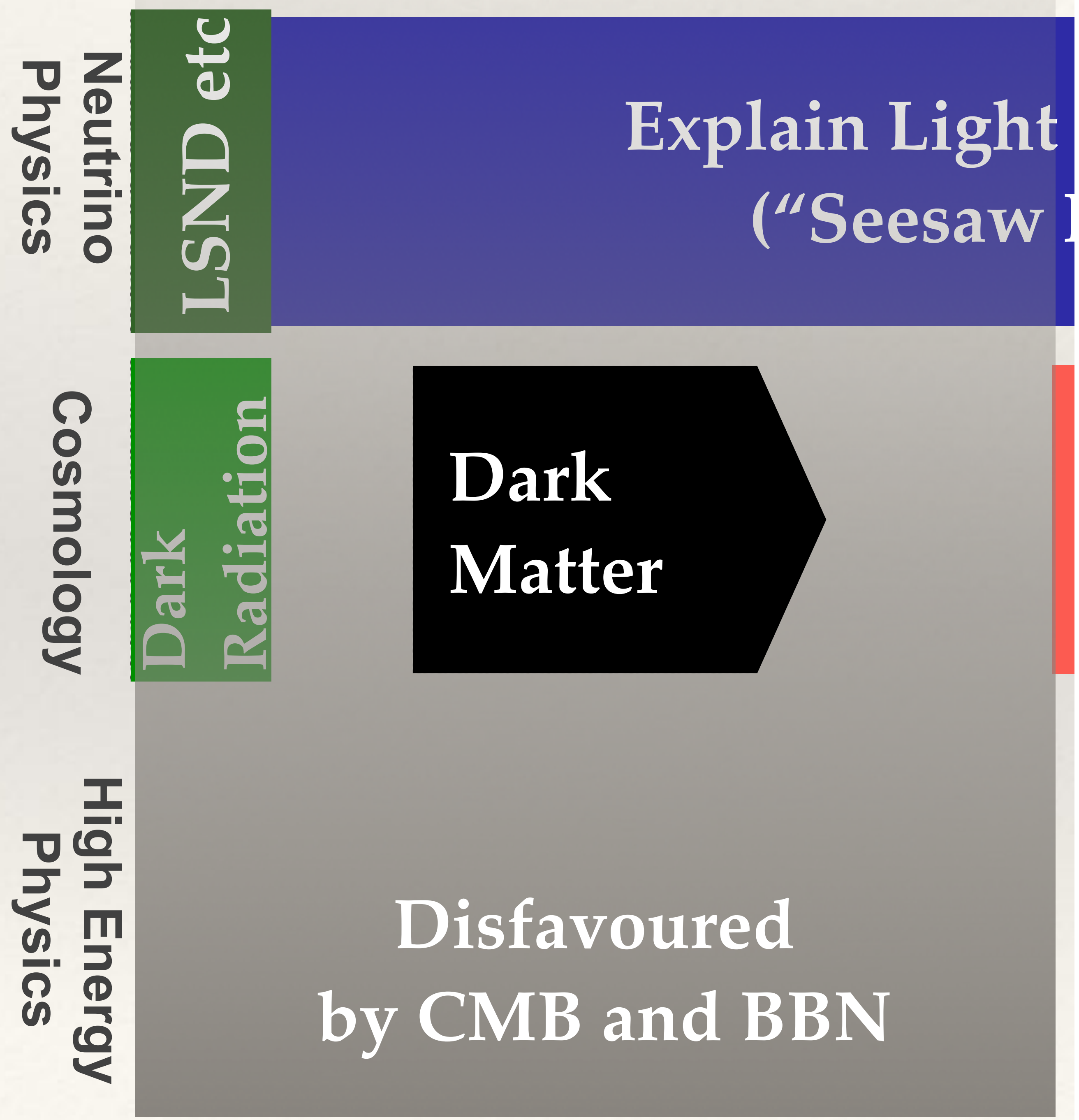


- Seesaw: Need one RHN for each $m_i \neq 0$
- For $m_{lightest} < 10^{-3}$ eV, one RHN almost decouples

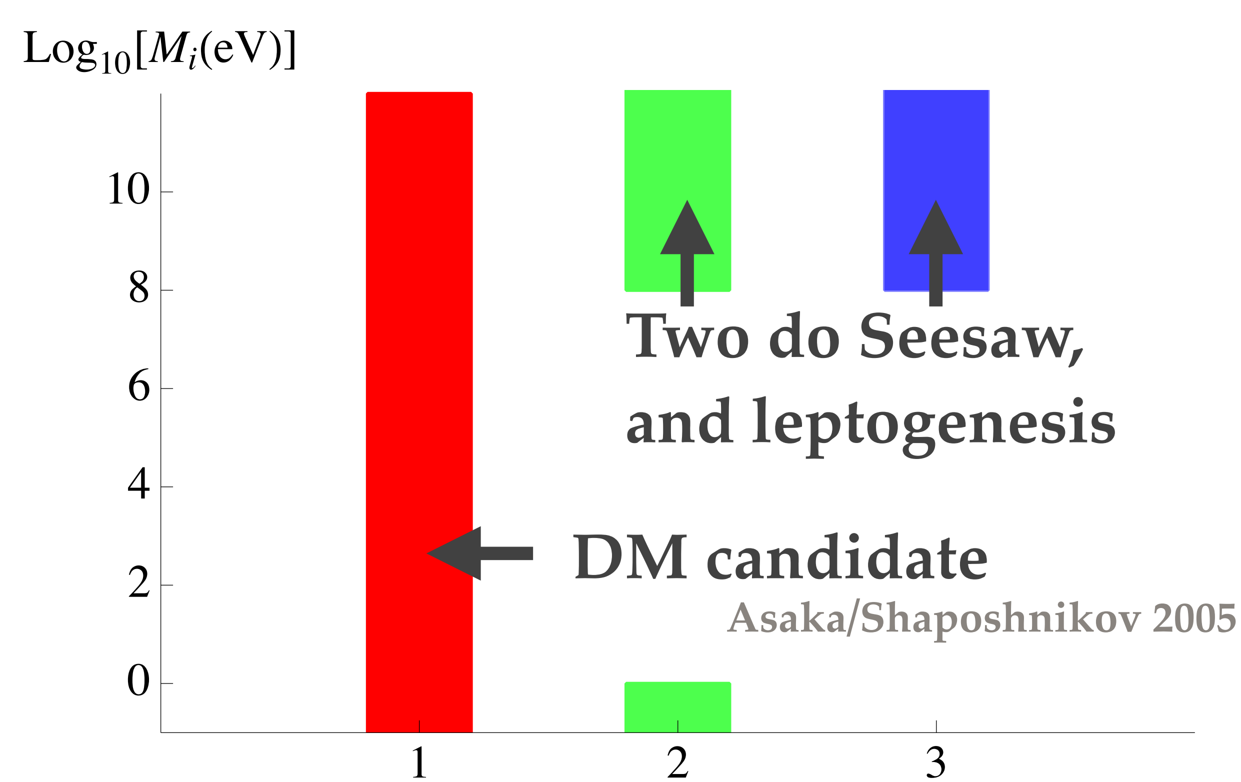


Hernandez/Kekic/Lopez-Pavon 1406.2961

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