Marco Drewes, Université catholique de Louvain

A Global View on Heavy Neutrinos

05. 03. 2020

1st Joint Nikhef+Grappa Neutrino Meeting

Nikef, Amsterdam, Holland

Content

I) Motivation

II) Global Constraints on Heavy Neutrinos

- ν

- two heavy neutrinos or νMSM
- three heavy neutrinos

III) Examples for Complementarity

- Example 1): collider predictions from ν oscillation data
- Example 2): full testability of the νMSM

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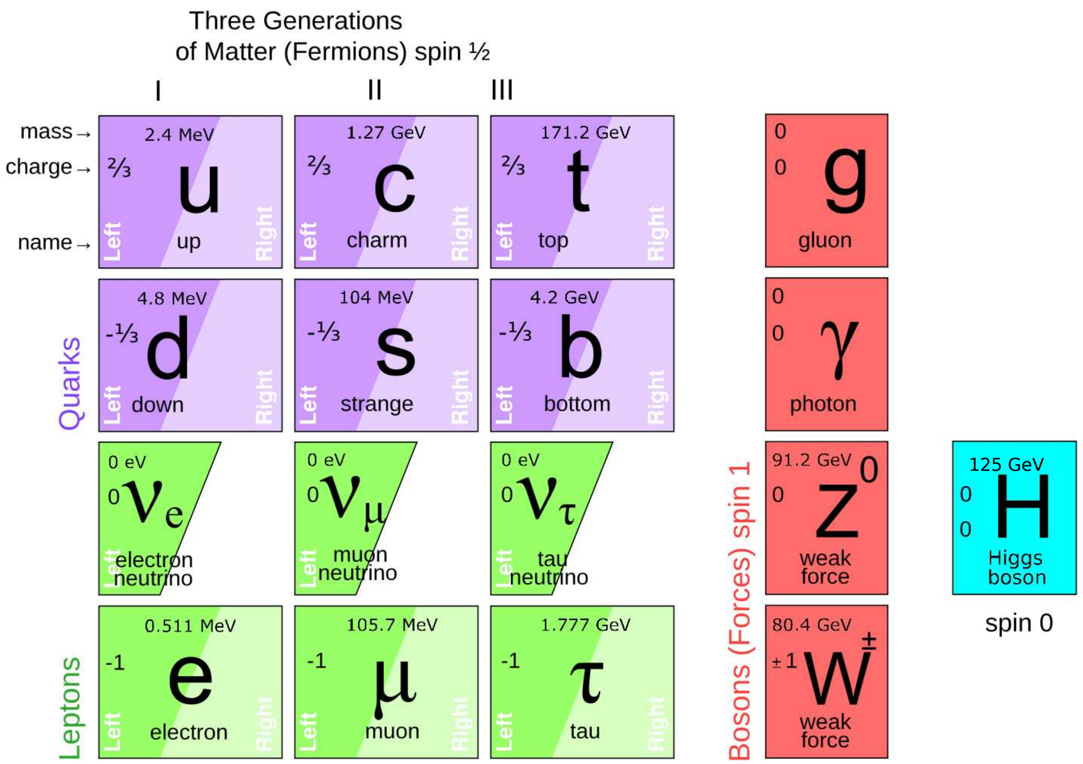
The Seesaw Mechanism (type I)

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

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

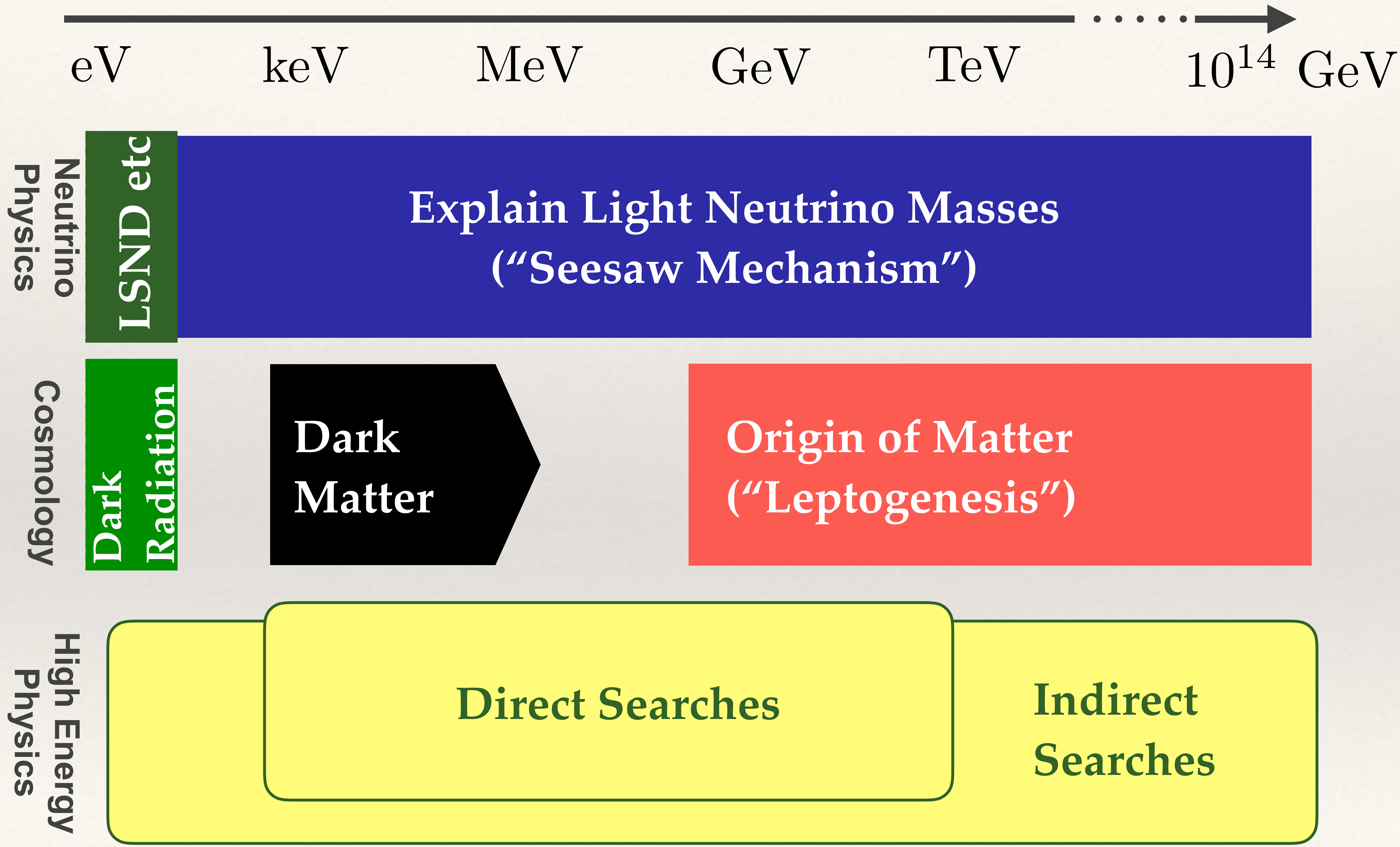


three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

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



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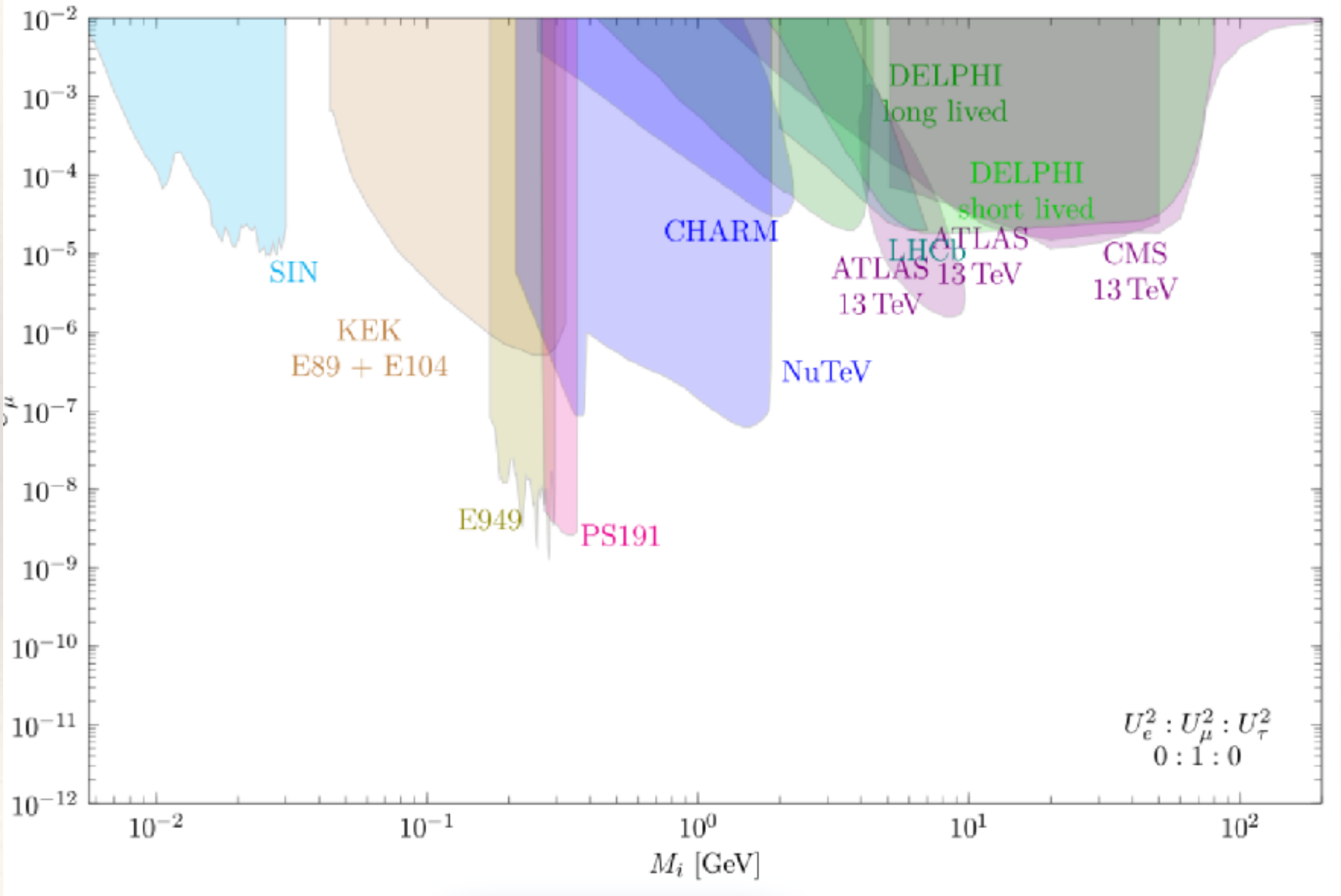
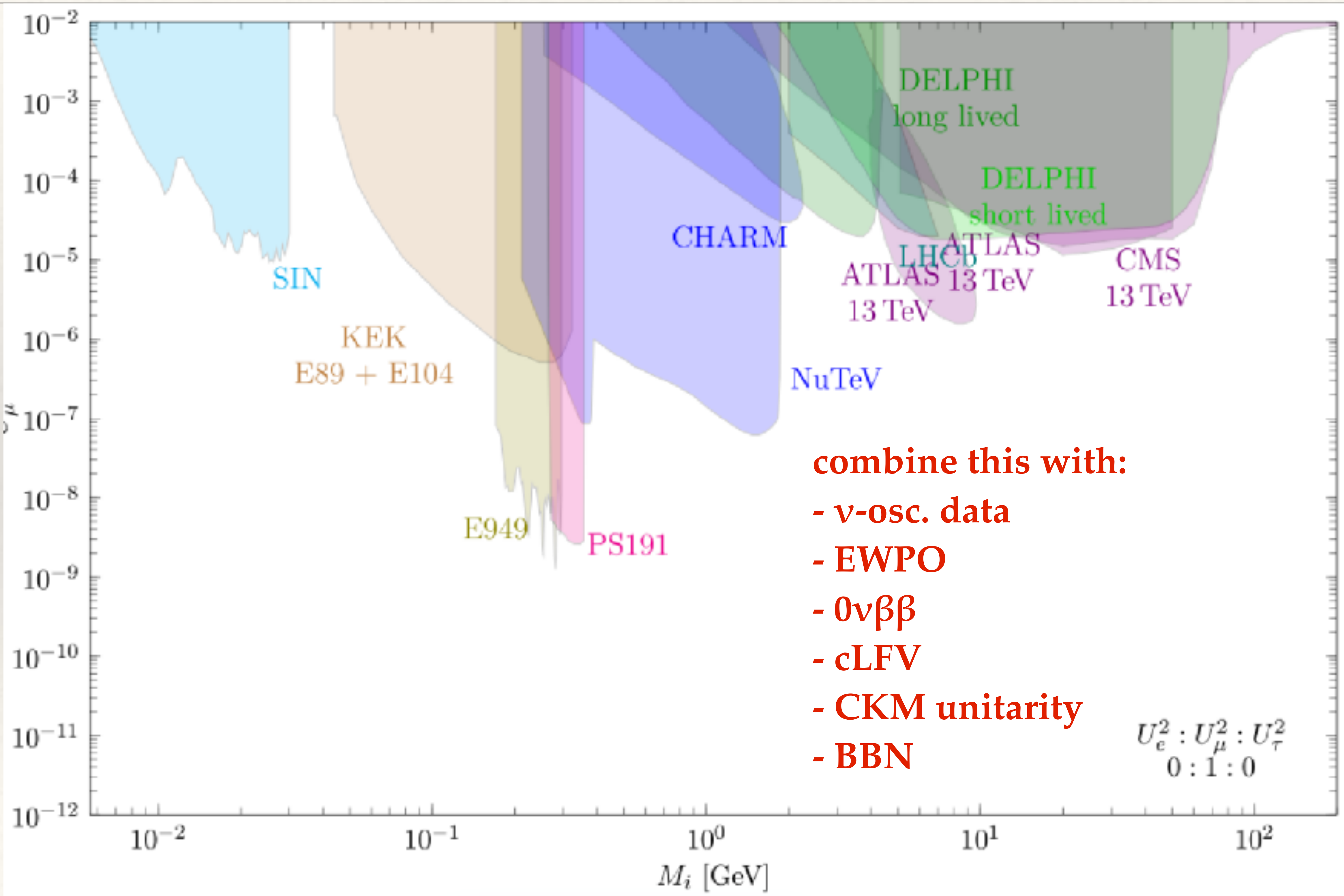
Current Direct Search Constraints



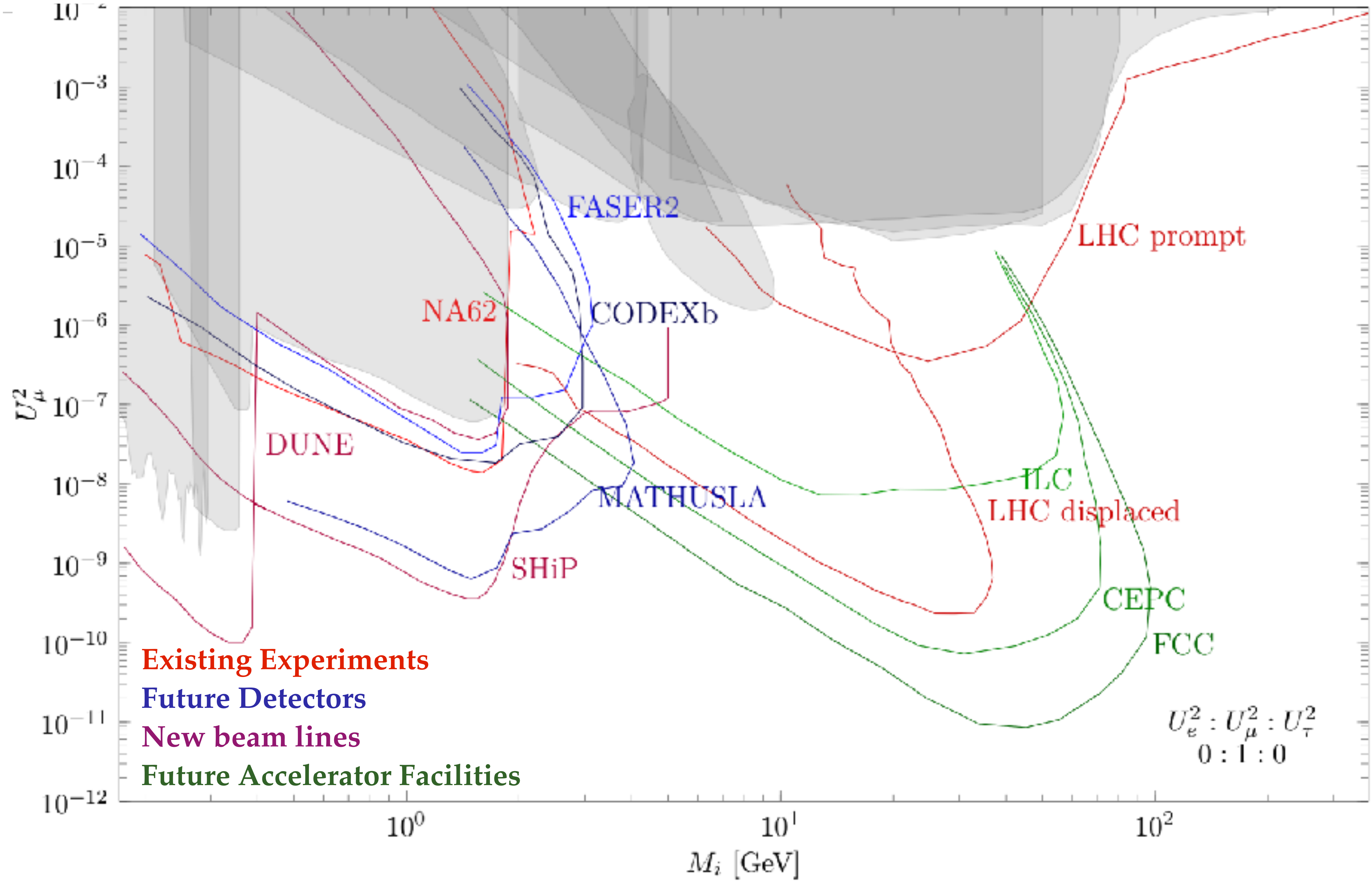
Current Direct Search Constraints



combine this with:

- **ν-osc. data**
- **EWPO**
- **0νββ**
- **cLFV**
- **CKM unitarity**
- **BBN**

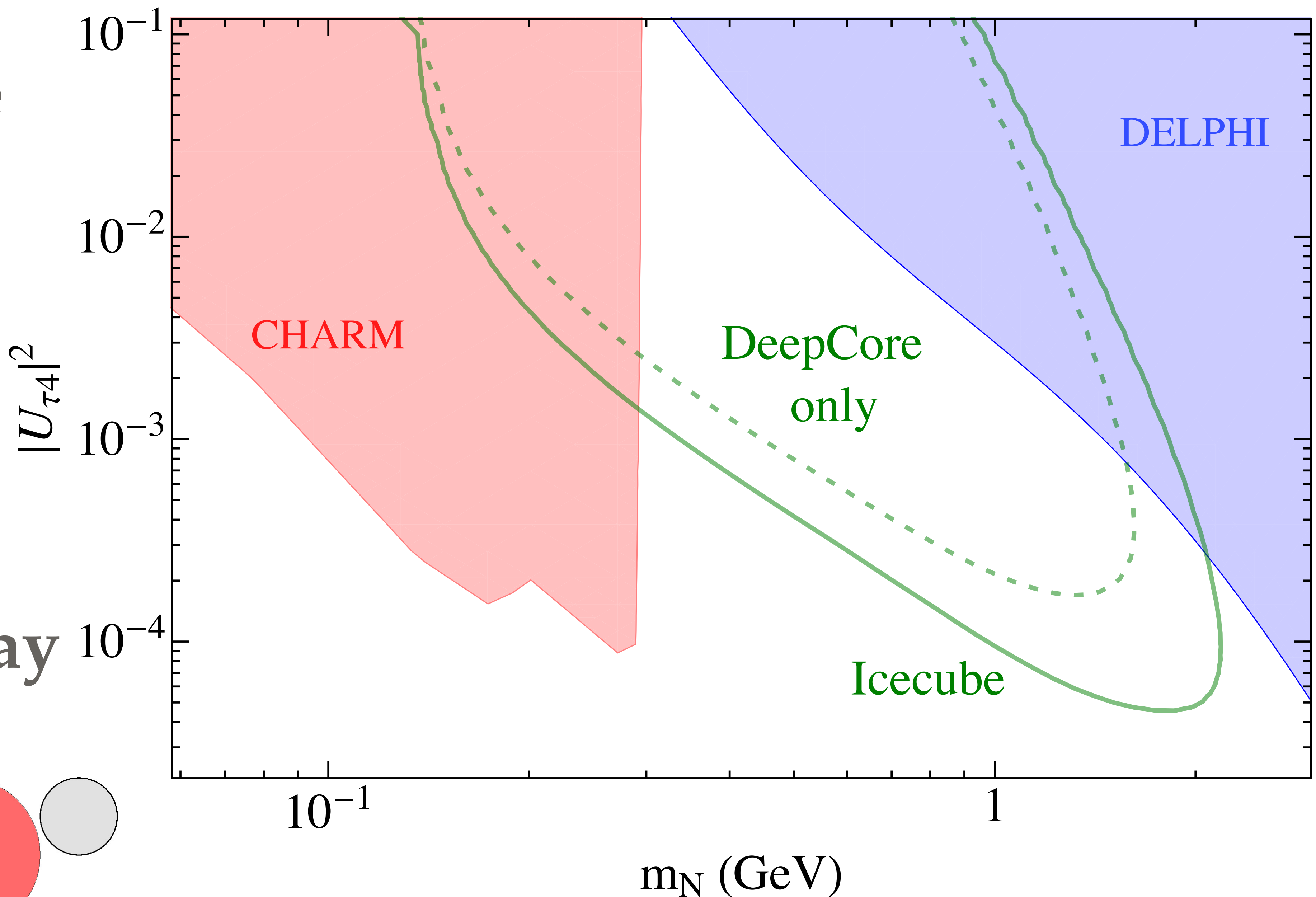
Heavy Neutrino Searches

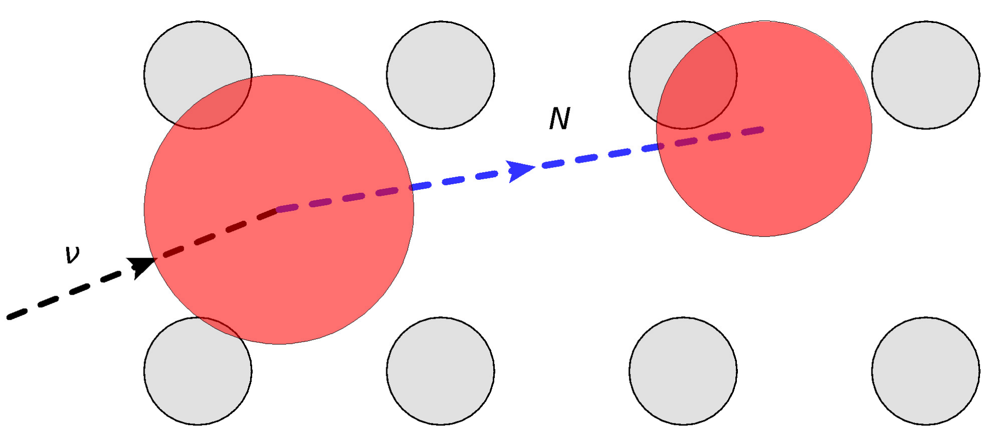


Searching for HNLs with Ice Cube… and KM3NeT?

search for "double cascade" events:

- **one in HNL production**
- **one in HNL decay**





Coloma et al 1707.08573

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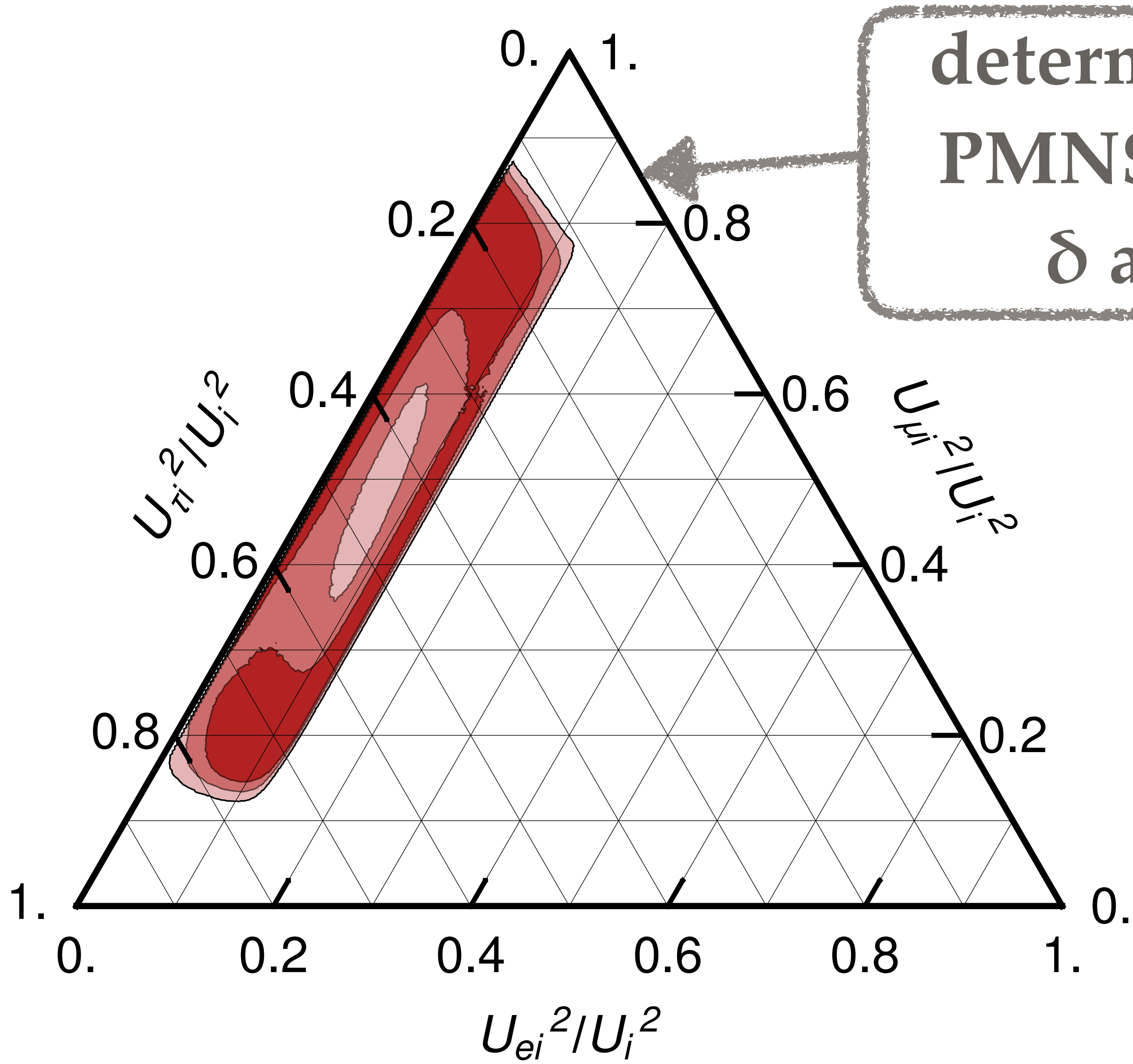
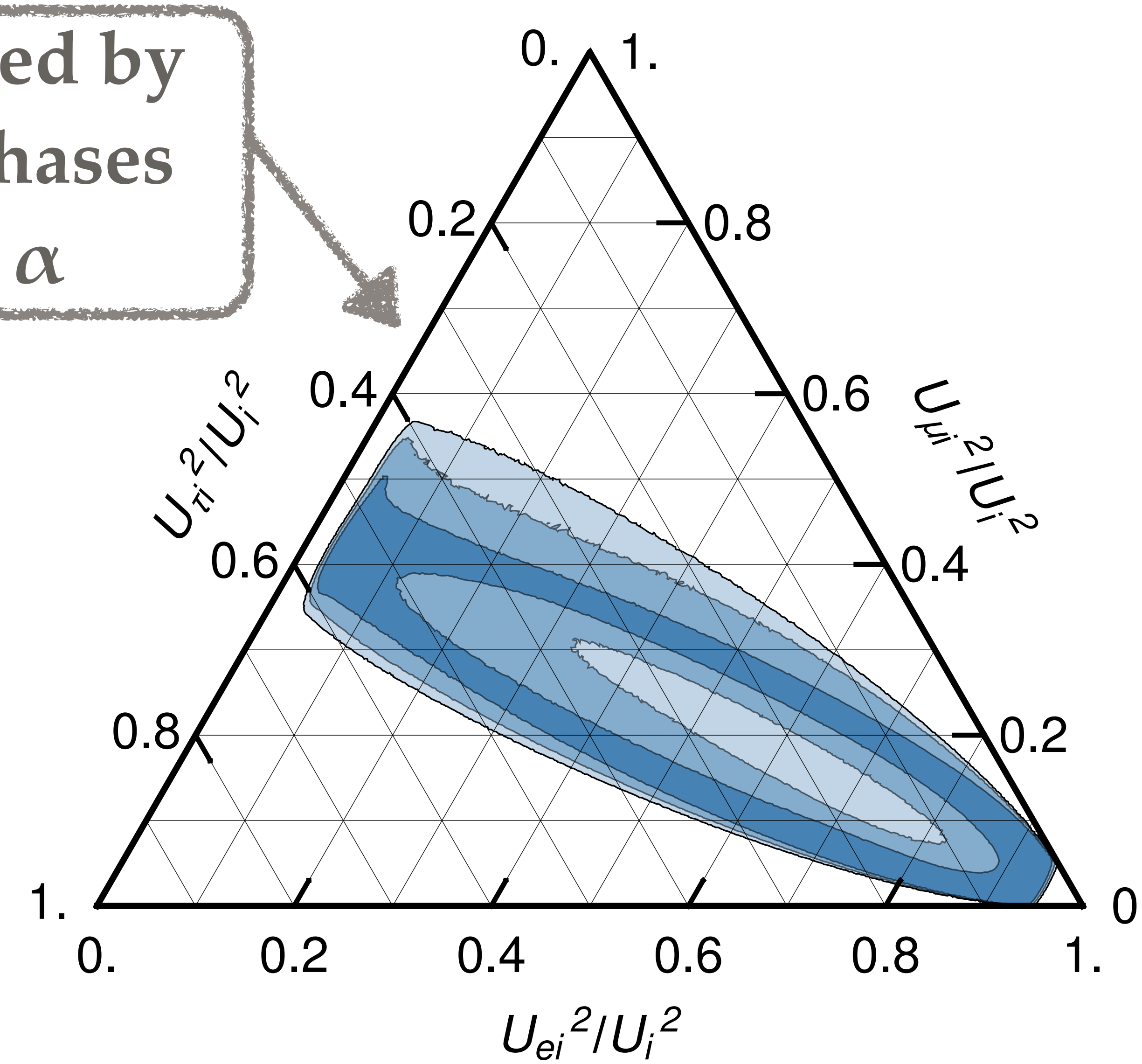
Constraints from ν-Oscillation Data in Model with 2 Heavy Neutrinos

determined by PMNS phases δ and α



normal neutrino mass ordering

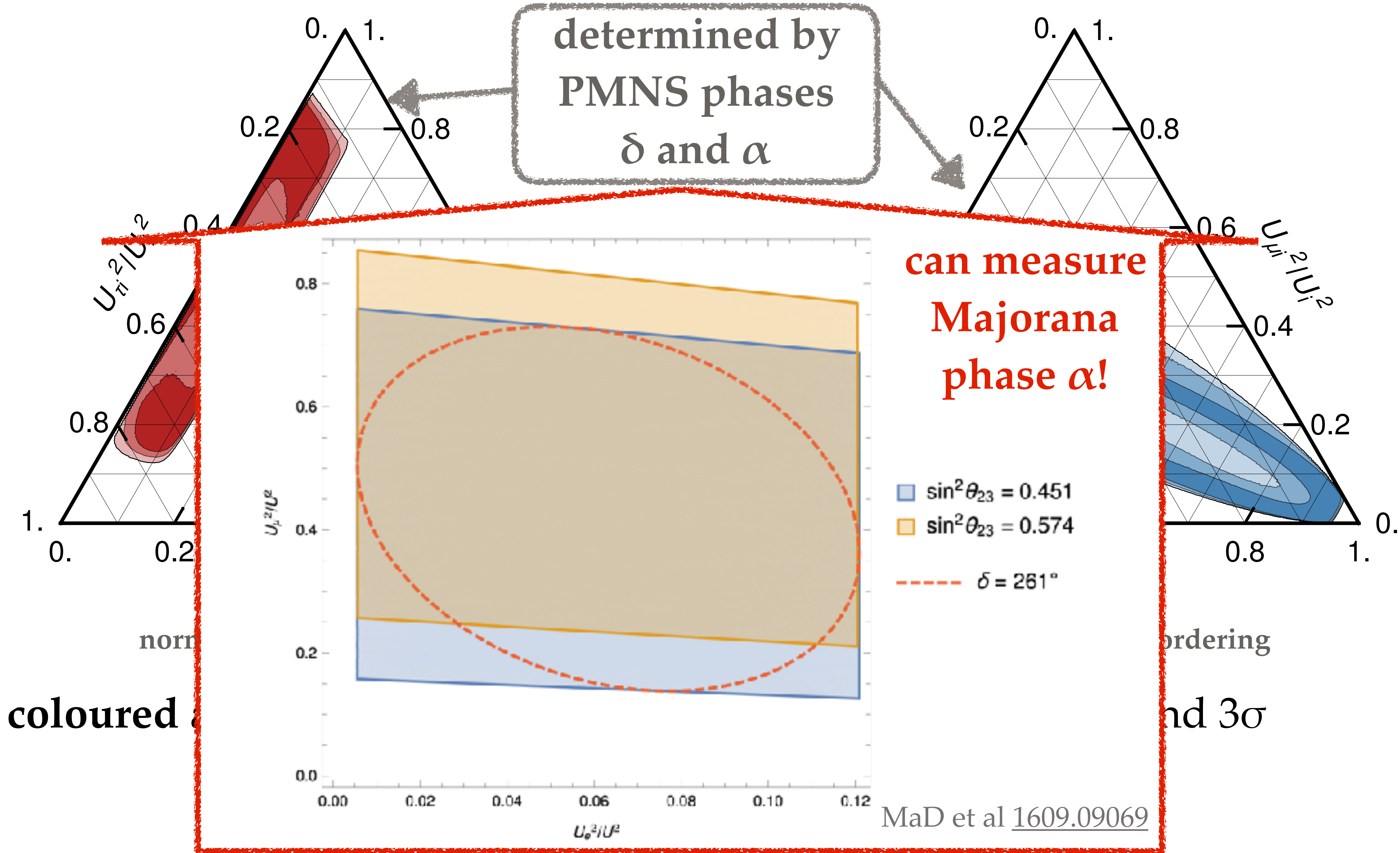


inverted neutrino mass ordering

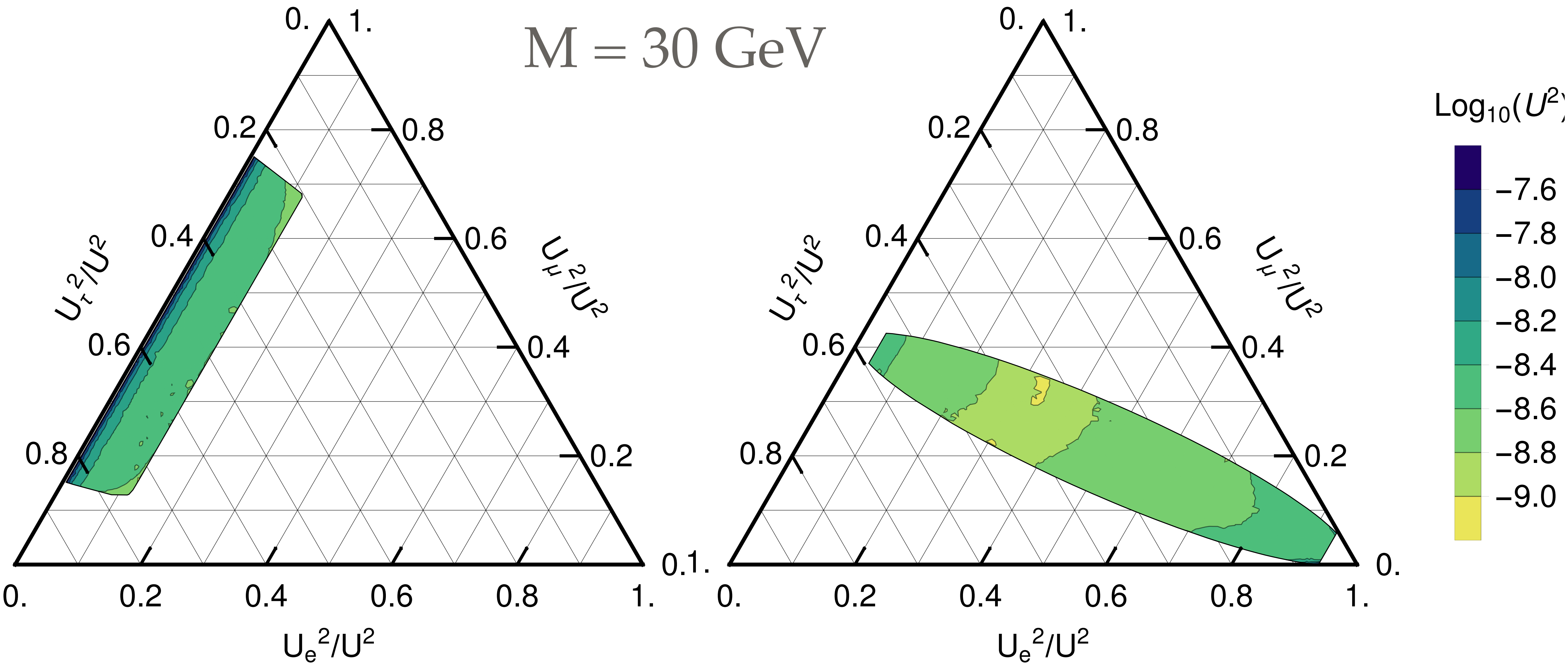
coloured areas: consistent with ν-oscillation data at 1σ, 2σ and 3σ

from MaD / Hajer / Klaric / Lafranchi 1801.04207

Constraints from ν-Oscillation Data in Model with 2 Heavy Neutrinos



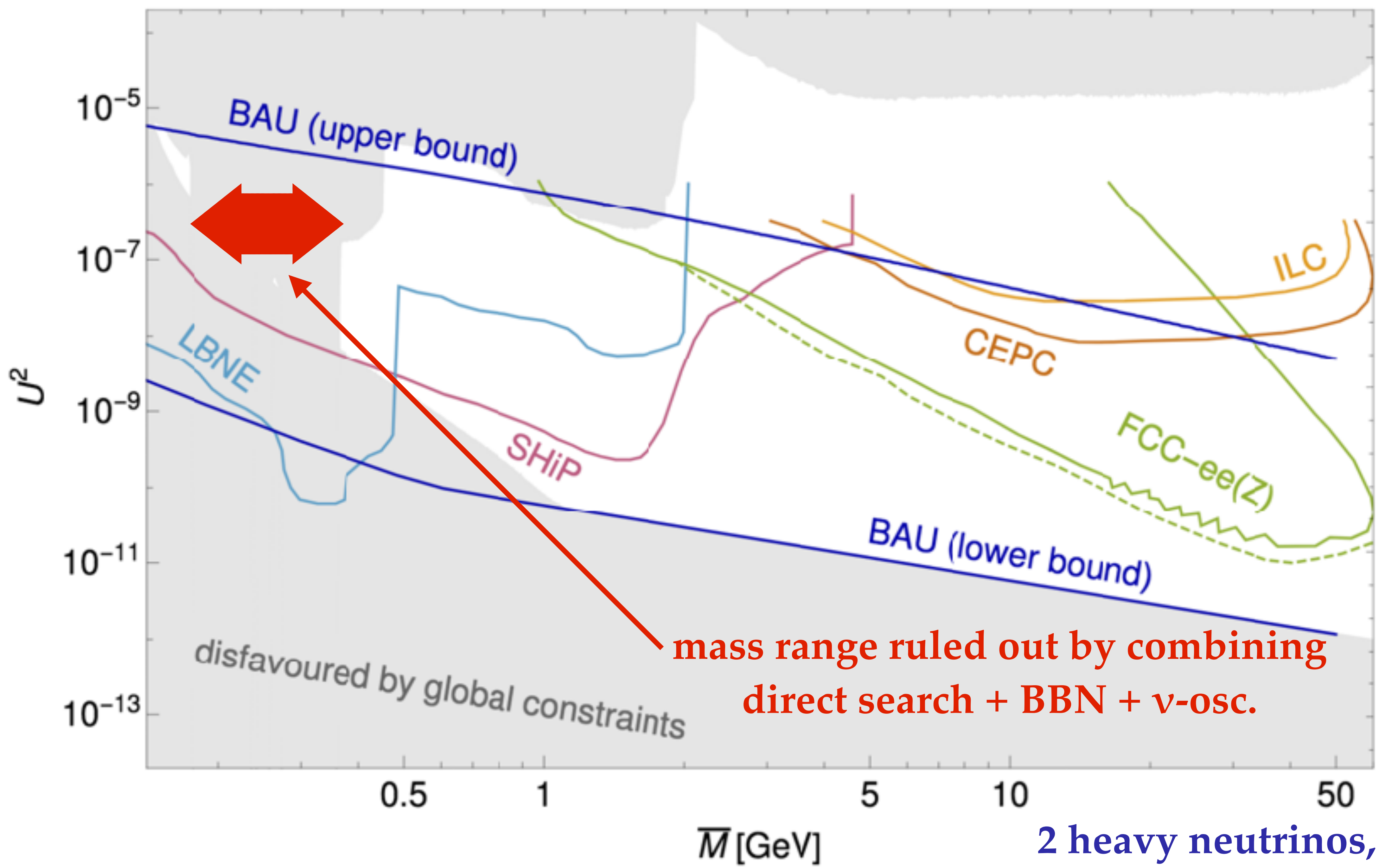
Constraints from Leptogenesis in Model with 2 Heavy Neutrinos



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

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

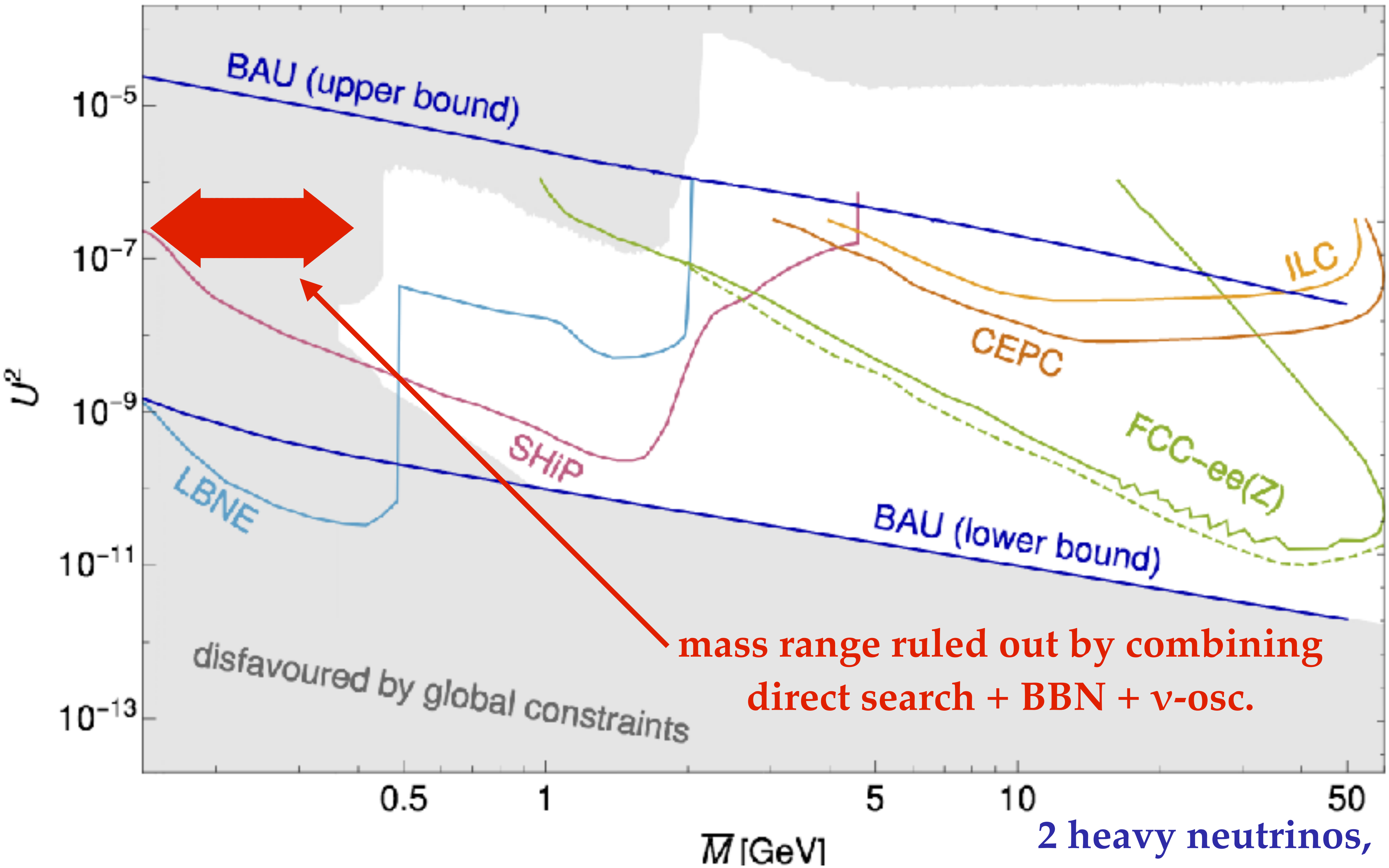
Global Constraints: Total Mixing



MaD / Garbrecht / Gueter / Klaric 1609.09069

2 heavy neutrinos, normal ordering of light neutrino masses

Global Constraints: Total Mixing



MaD / Garbrecht / Gueter / Klaric 1609.09069

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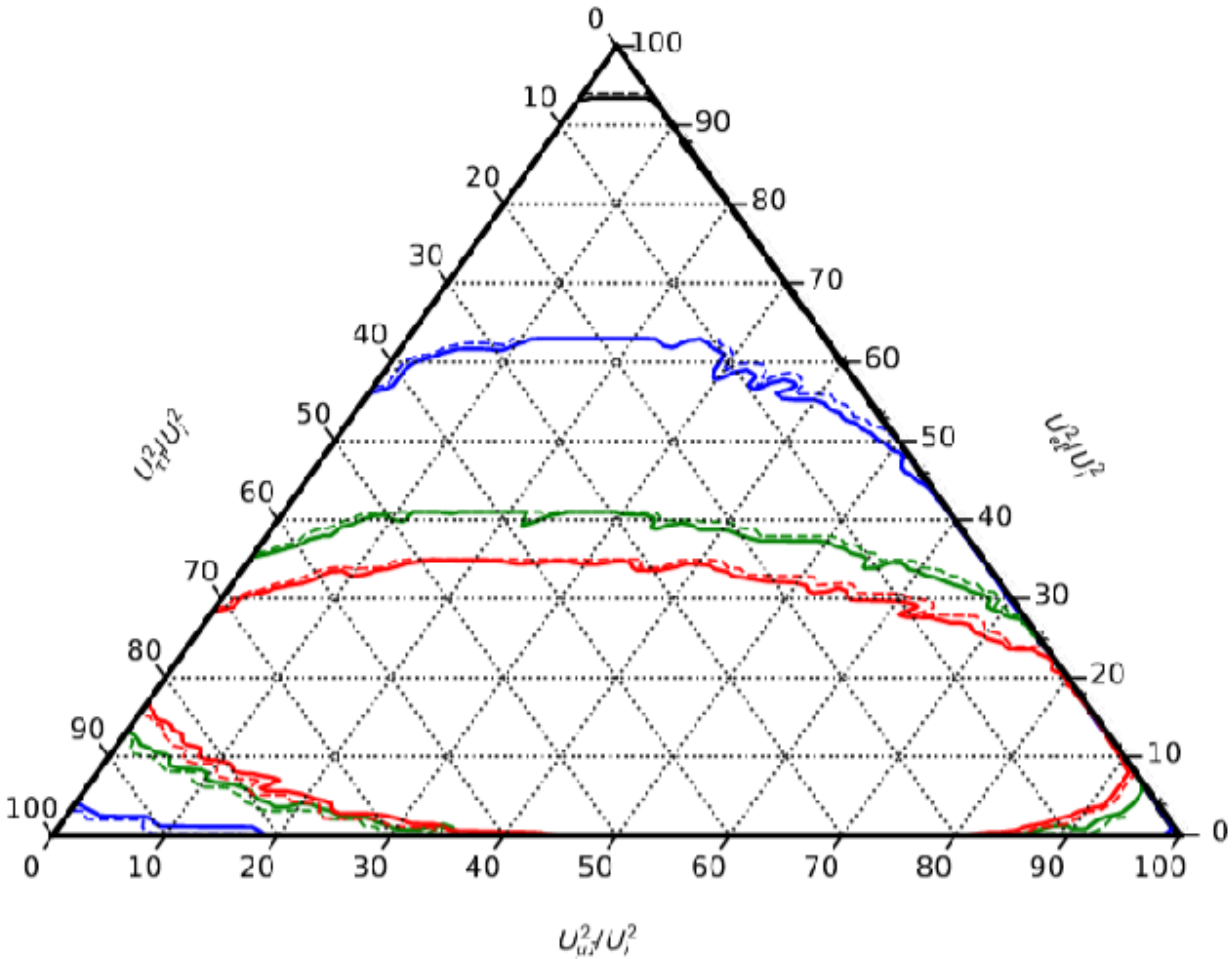
Constraints from ν-Oscillation Data in Model with 3 Heavy Neutrinos



normal ordering

$m_{lightest} < 10$ meV

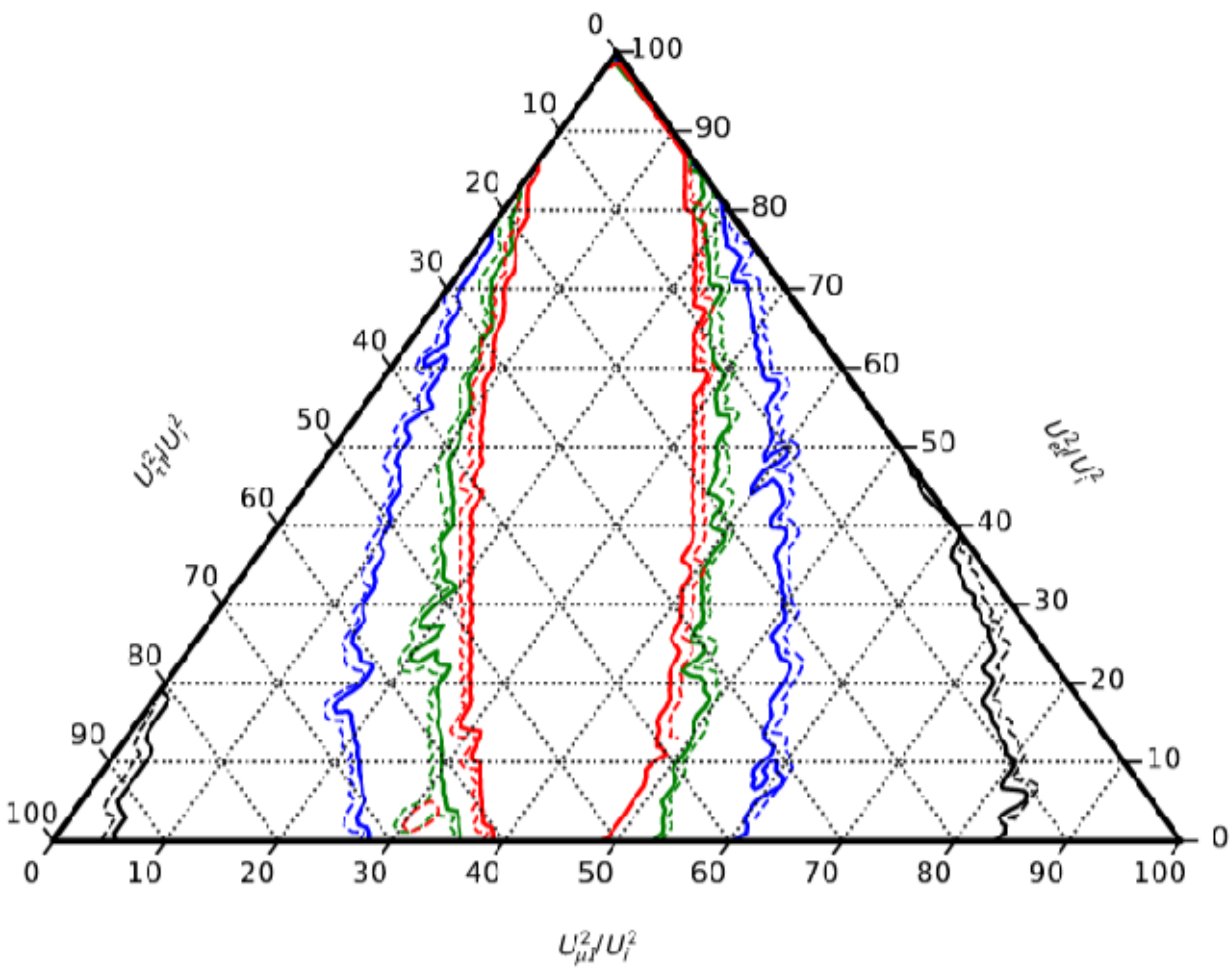
$m_{lightest} < 1$ meV

$m_{lightest} < 0.1$ meV

$m_{lightest} < 0.01$ meV

Chrzaszcz et al 1908.02302

Constraints from ν-Oscillation Data in Model with 3 Heavy Neutrinos



inverted ordering

$m_{lightest}$ < 10 meV

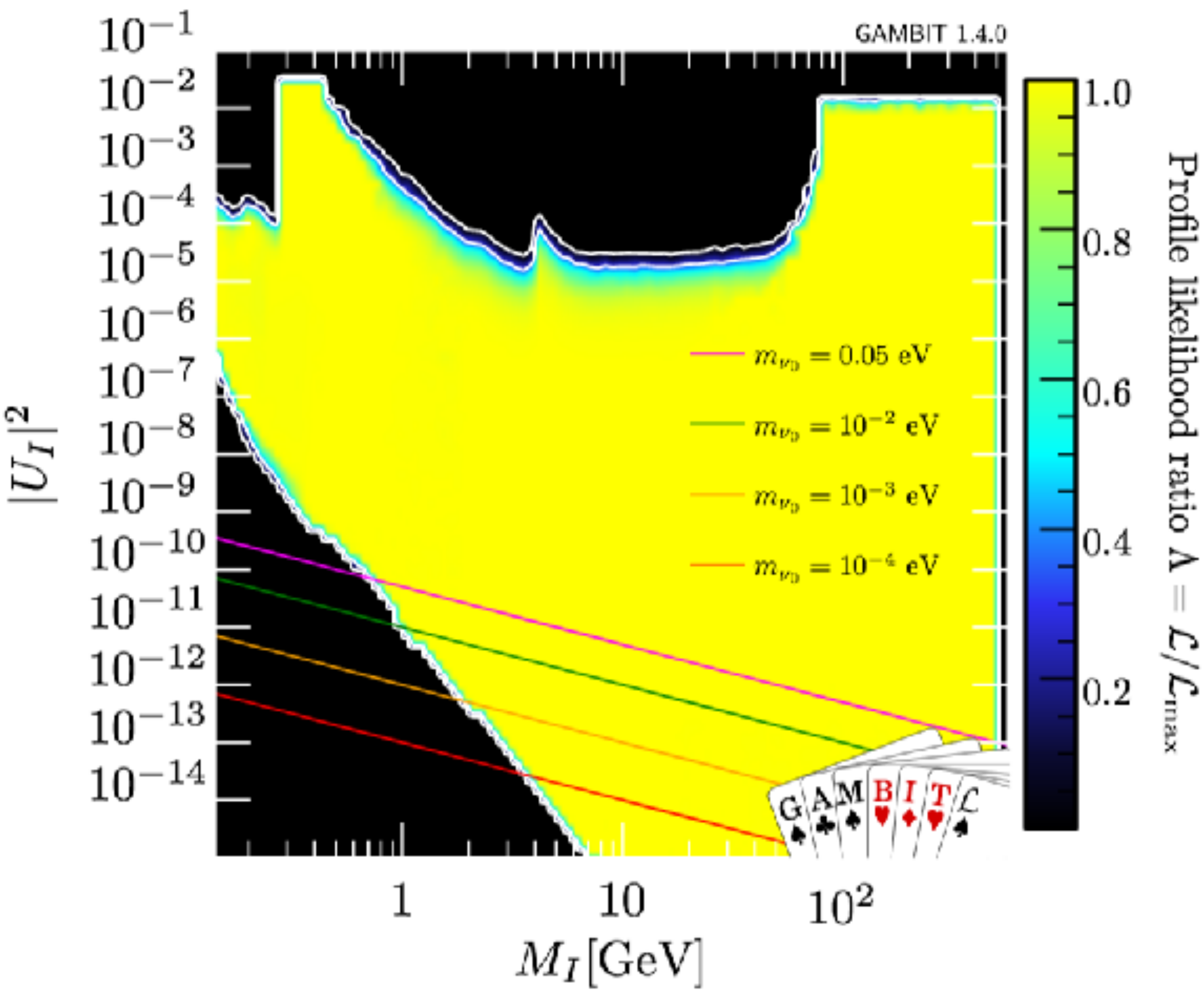
$m_{lightest}$ < 1 meV

$m_{lightest}$ < 0.1 meV

$m_{lightest}$ < 0.01 meV

Chrzaszcz et al 1908.02302

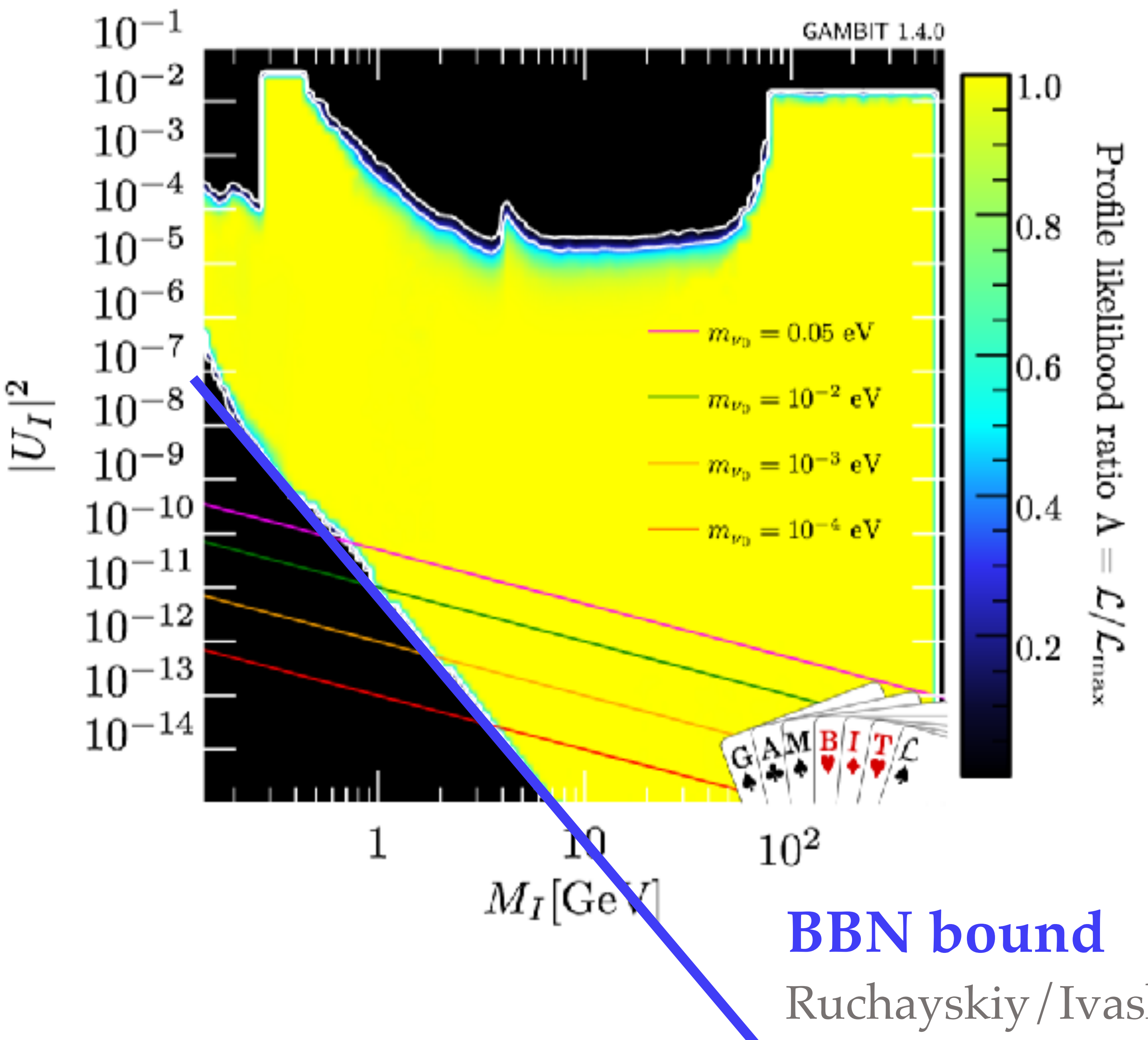
Global Constraints: Total Mixing



3 heavy neutrinos, normal ordering of light neutrino masses

Chrzaszcz et al 1908.02302

Global Constraints: Total Mixing



3 heavy neutrinos, normal ordering of light neutrino masses

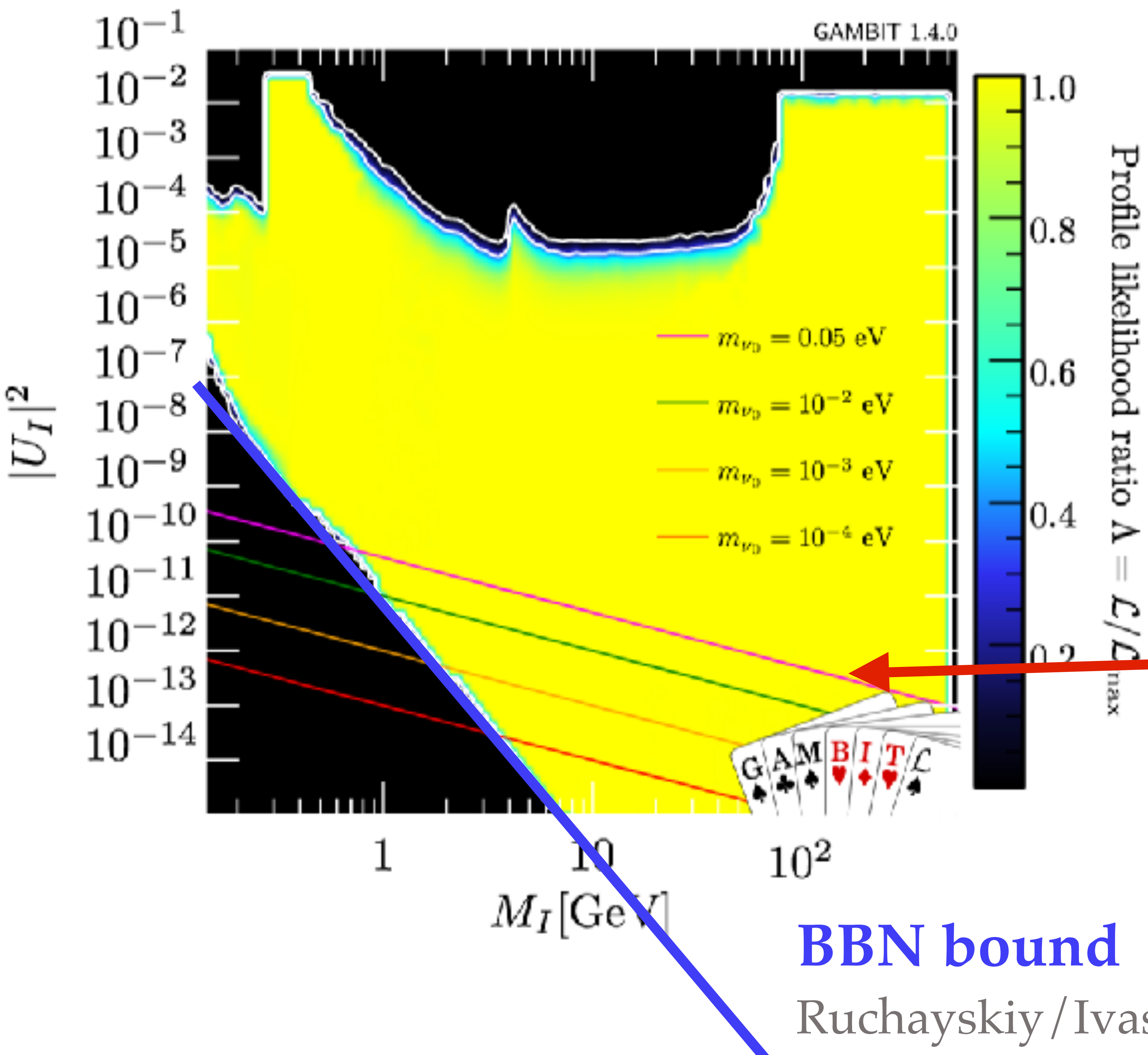
Chrzaszcz et al 1908.02302

BBN bound

Ruchayskiy/Ivashko 1202.2841

Hernandez/Lopez-Pavon 1406.2961

Global Constraints: Total Mixing



3 heavy neutrinos, normal ordering of light neutrino masses

Seesaw bounds

MaD 1904.11959

Chrzaszcz et al 1908.02302

BBN bound

Ruchayskiy / Ivashko 1202.2841

Hernandez / Lopez-Pavon 1406.2961

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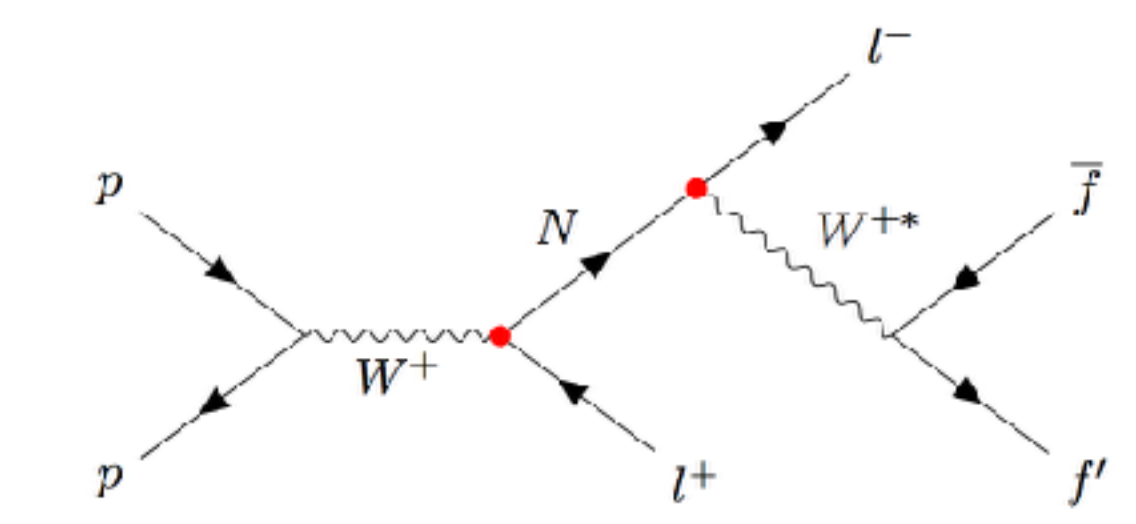
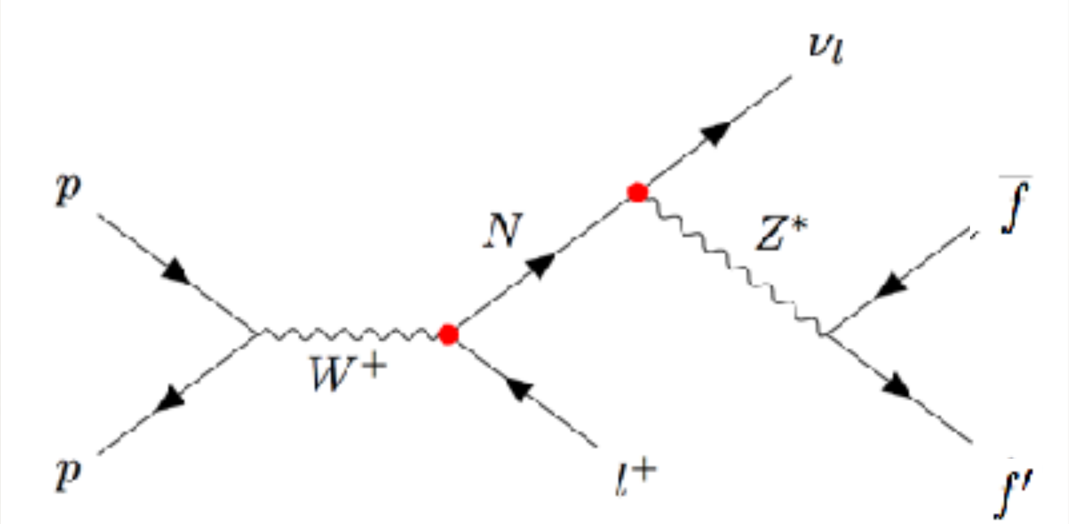
LHC Signatures

- Most searches to date focus on production via s-channel exchange go weak gauge bosons
- At higher energies t-channel Wγ-fusion becomes important

Dev et al 1308.2209



(a) Charged current decay



(b) Neutral current decay

Many final states:

The heavy neutrino can decay **leptonically or semileptonically**, into **mesons or jets**, **prompt or displaced**, with **LFV** and/or **LNV**

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

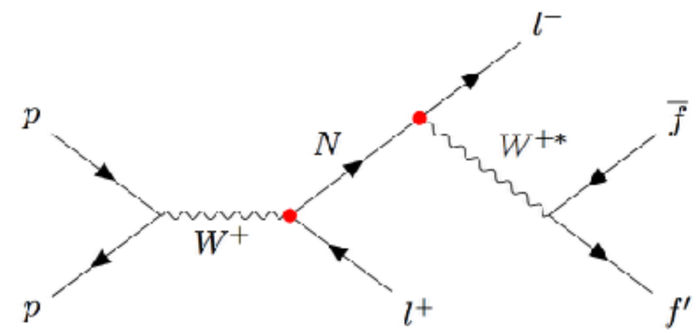
Shaposhnikov 0605047
Kersten/Smirnov 0705.3221

colliders rely on branching ratio

→ **active-sterile mixing angle θ must be large**

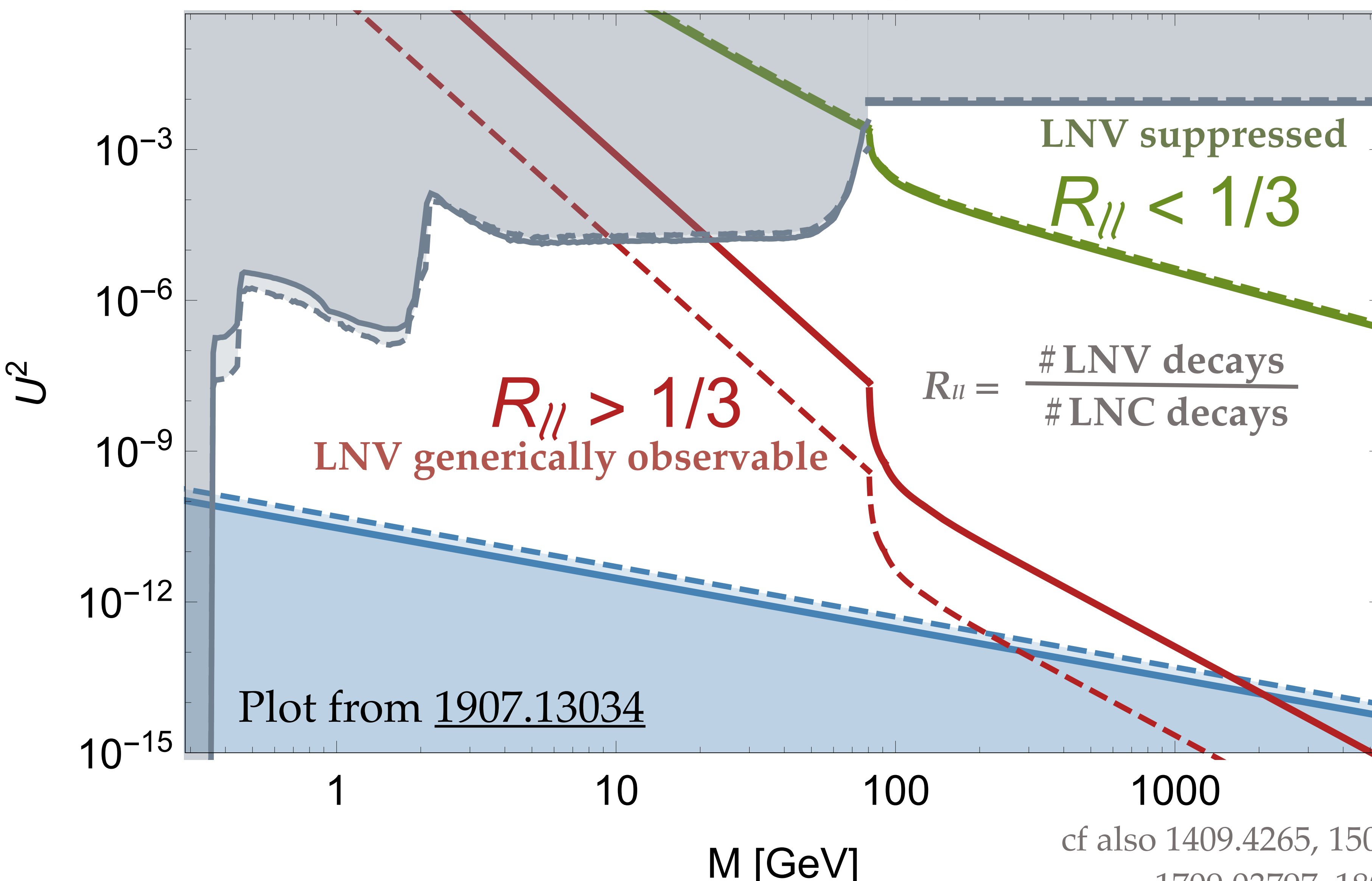
Can LNV be observed?

B-L symmetry: destructive interference amongst contributions from different HNL flavour



(a) Charged current decay

But: B-L is broken to generate neutrino mass.
Is this enough???



HNL oscillations destroy coherence and make LNV observable!

Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma^2_N + \Delta M^2_{\text{phys}}}$$

Does neutrino osc. data allow for this without fine tuning? It depends

MaD / Klaric / Klose 1907.13034

cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367

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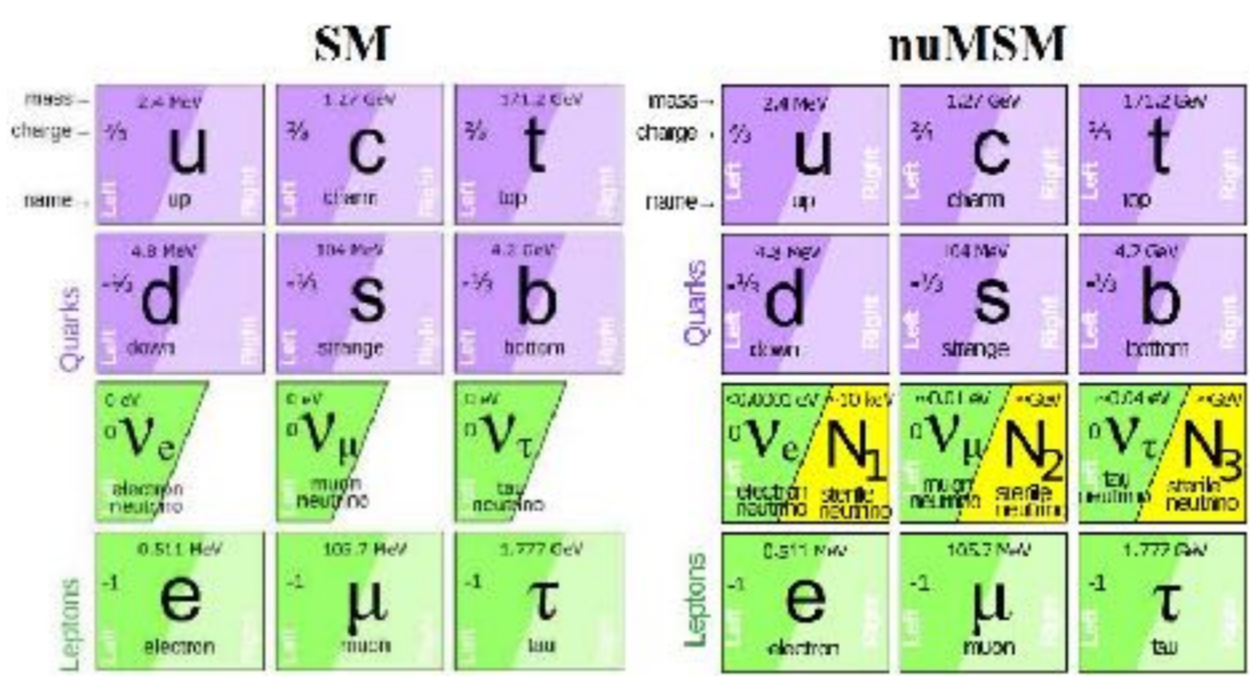
A minimal realisation: The νMSM

- **No sew scale.** Majorana mass is near the electroweak scale
- **No new gauge group.**
- **Same # families for RH and LH fermions.**
- **Yukawas similar to charged leptons.**
- **Approximately respect approximate B-L symmetry.**
  One RH neutrinos almost decouples: Dark Matter!
  the other two have degenerate masses: Seesaw + leptogenesis!



Shaposhnikov / Askaka 0505013

Full Testability of 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]

Minimality makes the model fully testable!

cf. Hernandez et al 1606.06719, MaD et al 1609.09069

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

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Higgs vev v

light neutrino mixing angles

light neutrino mass splittings

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

Casas/Ibarra 01

Dirac phase δ
Majorana phase α

lightest ν mass (almost) vanishes

complex angle ω

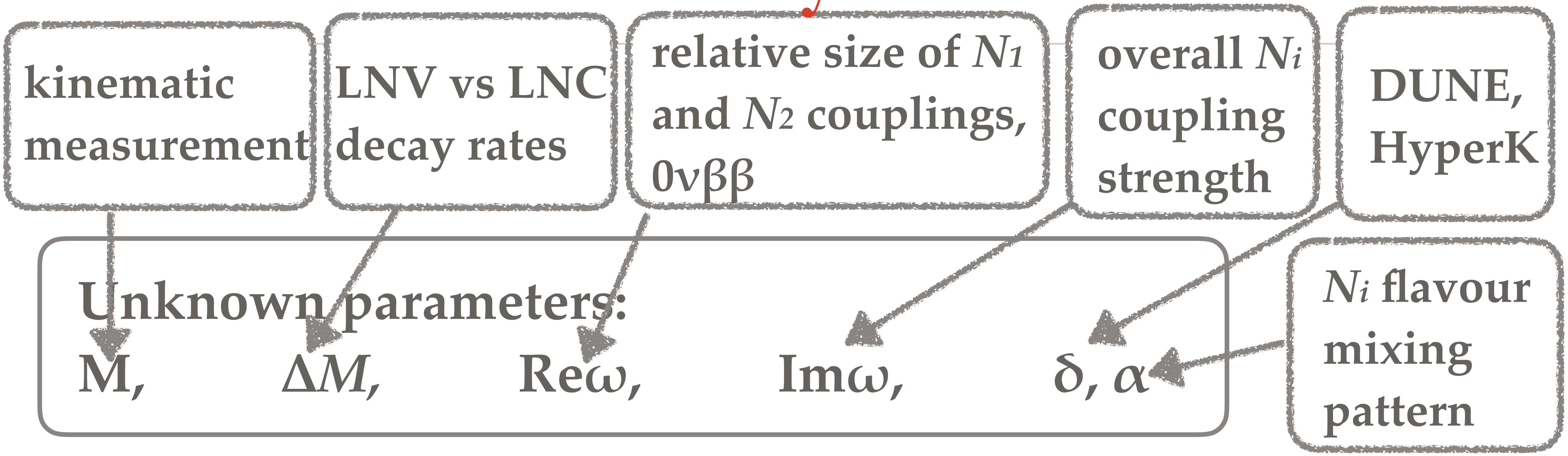
N-mass M and splitting ΔM

Full Testability of the νMSM

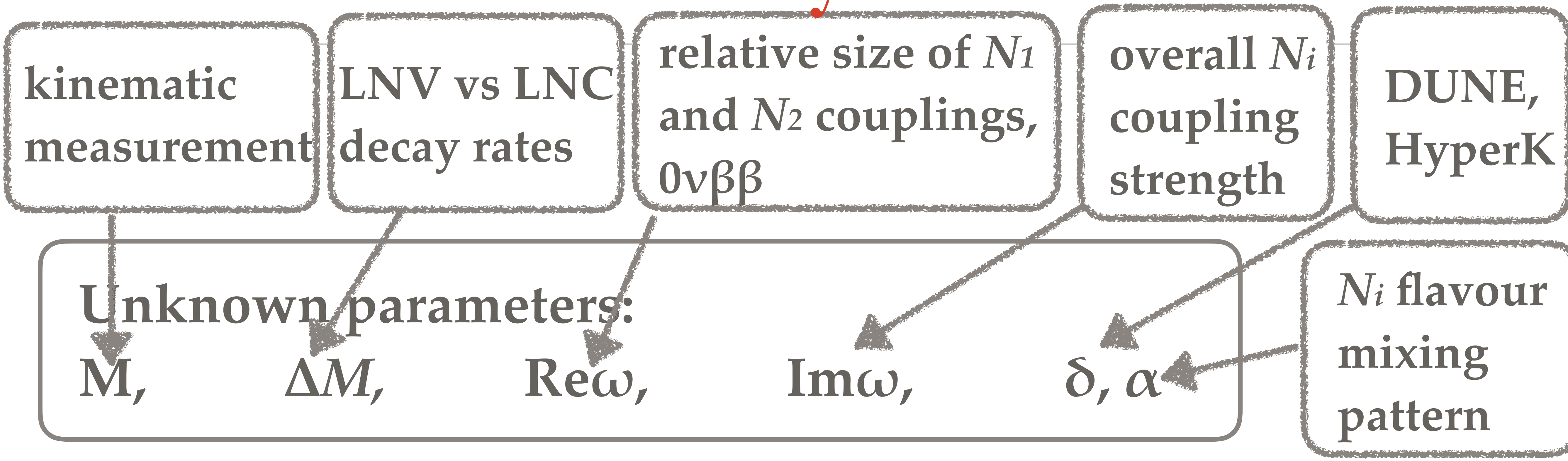
Unknown parameters:

M, ΔM**,** **Re**ω**,** **Im**ω**,** δ**,** α

Full Testability of the νMSM



Full Testability of the νMSM



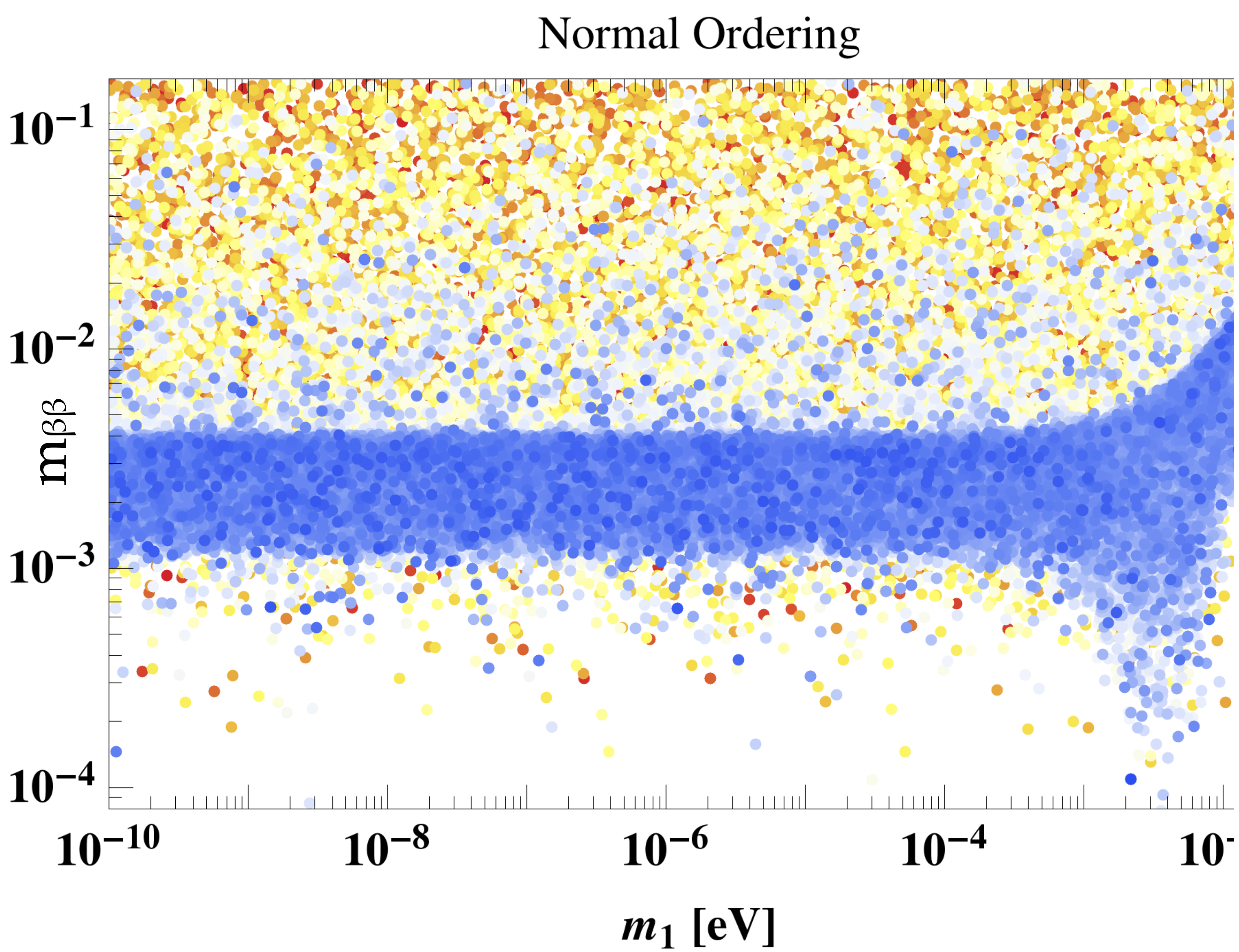
- In principle all parameters can be measured
 ⇒ fully testable model of neutrino masses and baryogenesis
- This requires a combination of collider/fixed target experiment data and ν-osc. data (and possibly $0\nu\beta\beta$)
 ⇒ poster child example for synergy between collider and long baseline programs! cf. Hernandez et al 1606.06719, MaD et al 1609.09069

The $0\nu\beta\beta$ Connection

Heavy neutrino exchange can dominate $0\nu\beta\beta$…

…even in the leptogenesis region

$\Rightarrow$ additional probe of $\text{Re}\,\omega$!



plot from Abada et al 1810.12463

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

Dekens et al 2002.07182

A Multi-Frontier Problem

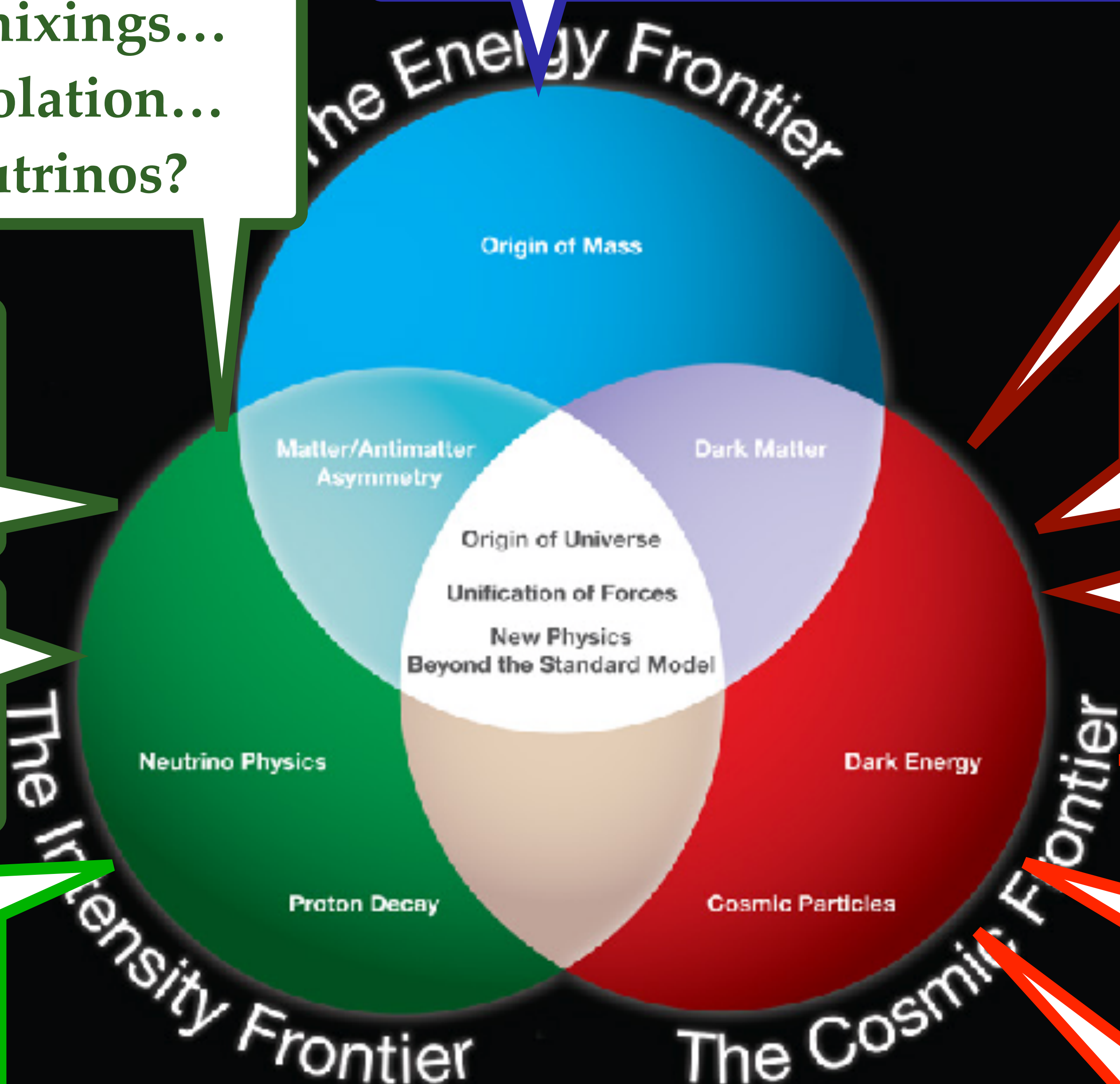
Collider Probes of the origin of neutrino mass

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?

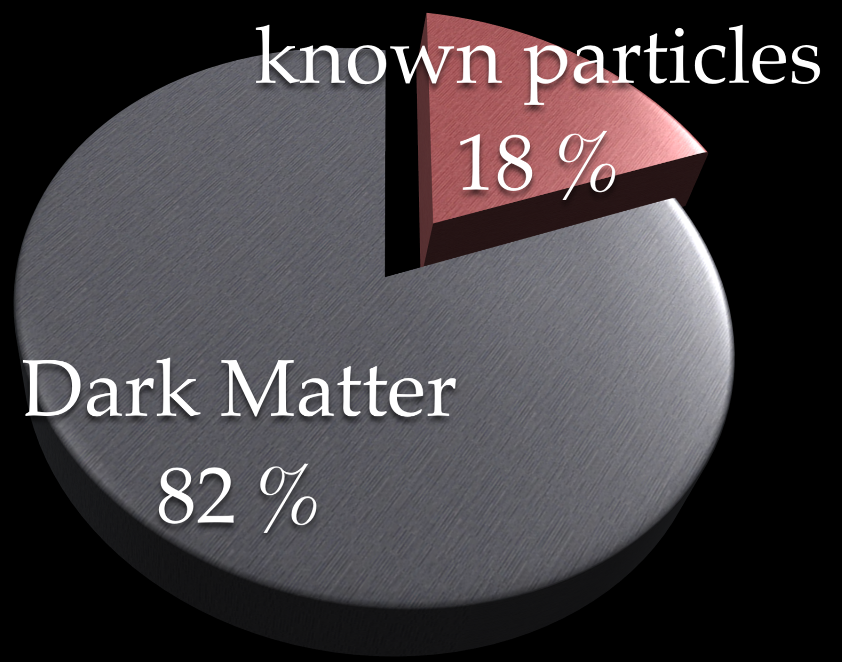
Sterile Neutrino
Dark Matter?

Backup Slides

Sterile Neutrino Dark Matter

- **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

- heavy
- long lived
- neutral
- feebly interacting

Neutrinos are the only known particles that fulfil three conditions…

…but they are too light

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

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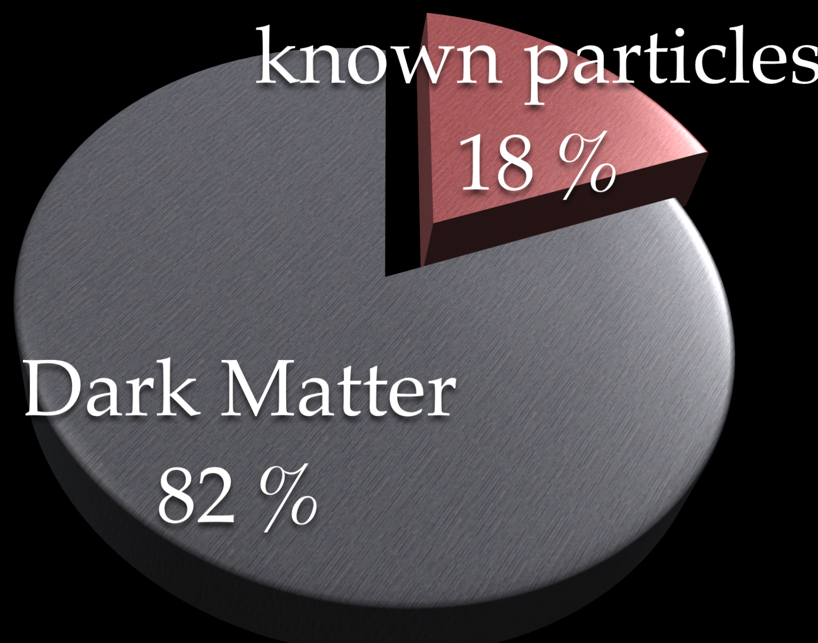

Heavy “Sterile” Neutrino Dark Matter

Dark Matter Particles are

- heavy
- long lived
- neutral
- feebly interacting

} heavy sterile neutrinos can fulfil all conditions!

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

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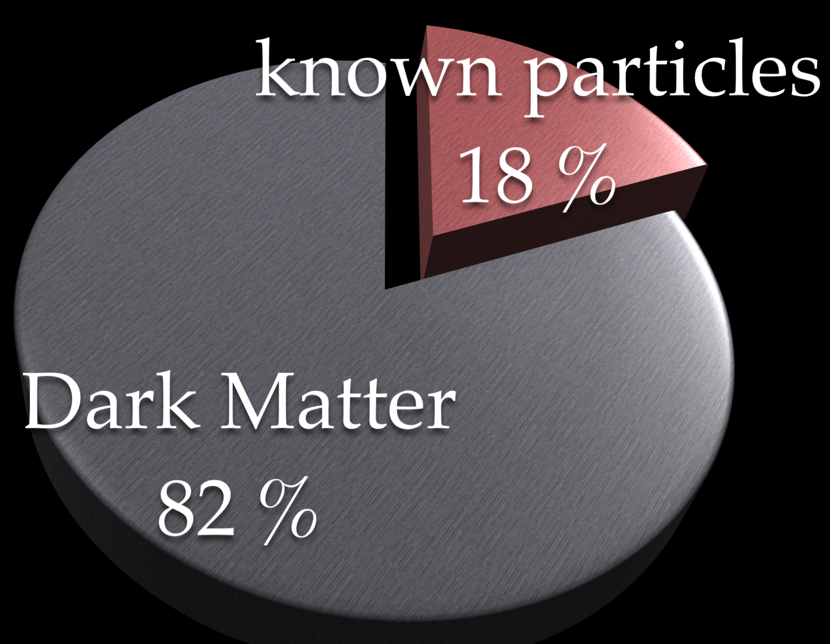
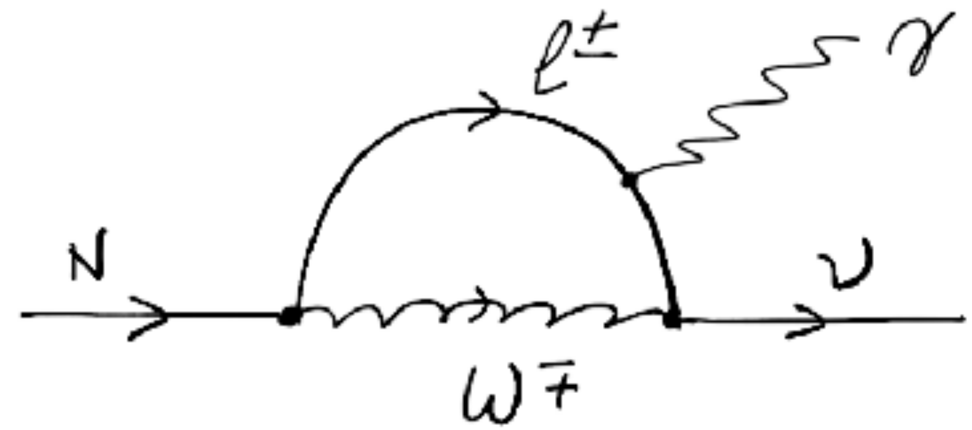


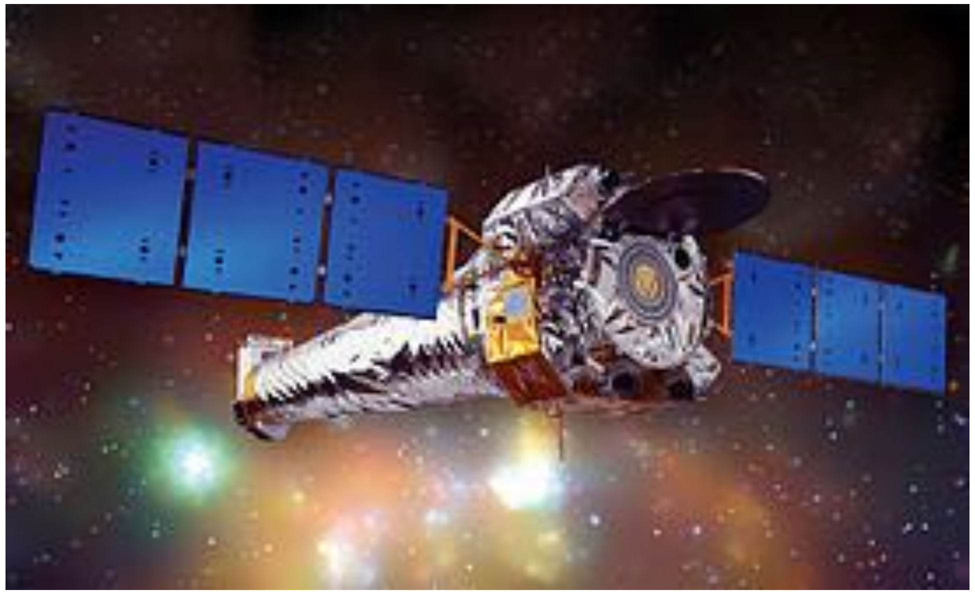
Indirect Dark Matter Searches

loop level decay into photons

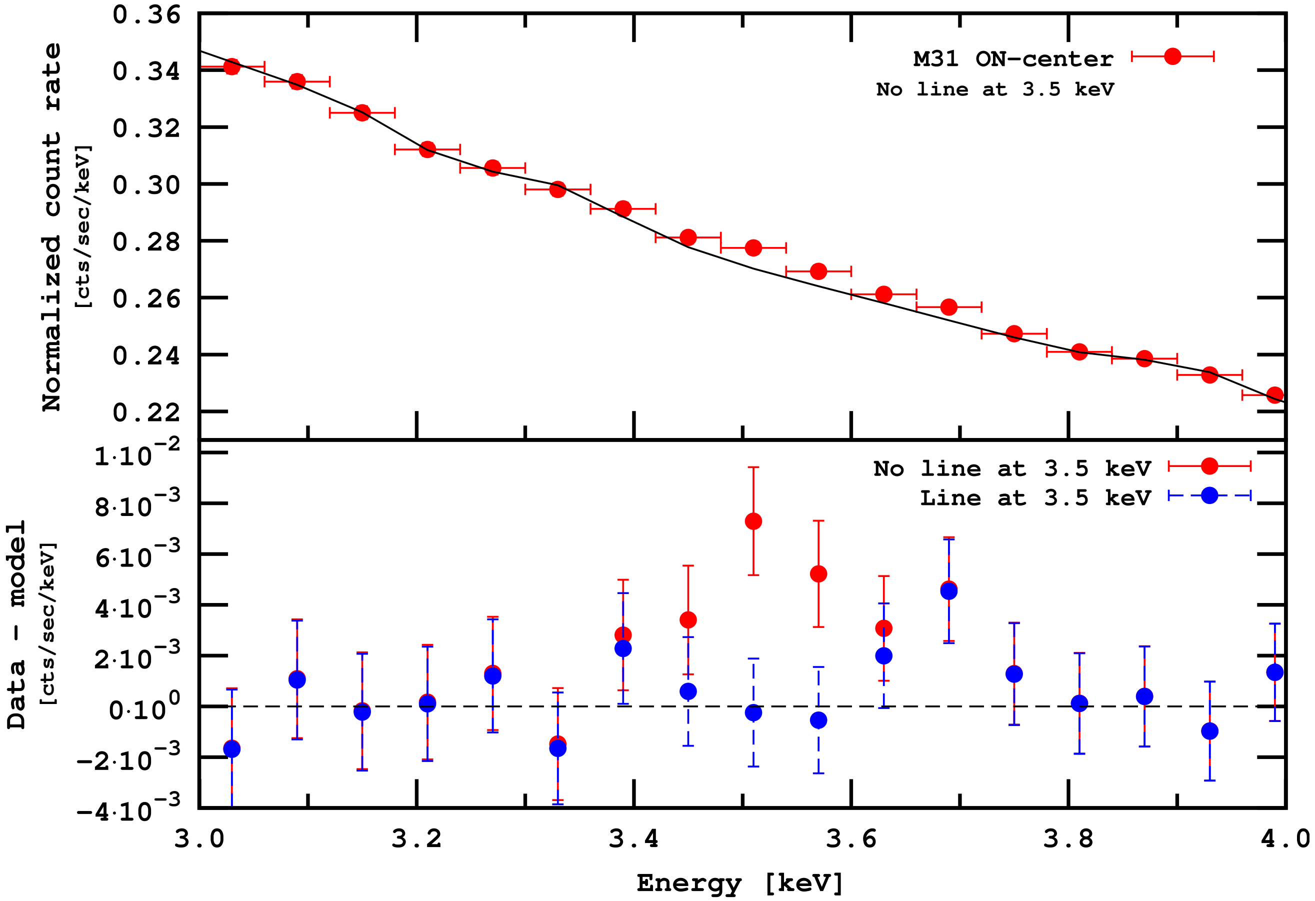


$$\Gamma_{N\to\gamma\nu} = \frac{9\,\alpha\,G_F^2}{256\pi^4}\theta^2 M^5 = 5.5\times10^{-22}\theta^2\left[\frac{M}{1\,\mathrm{keV}}\right]^5 \mathrm{sec}^{-1}\,.$$

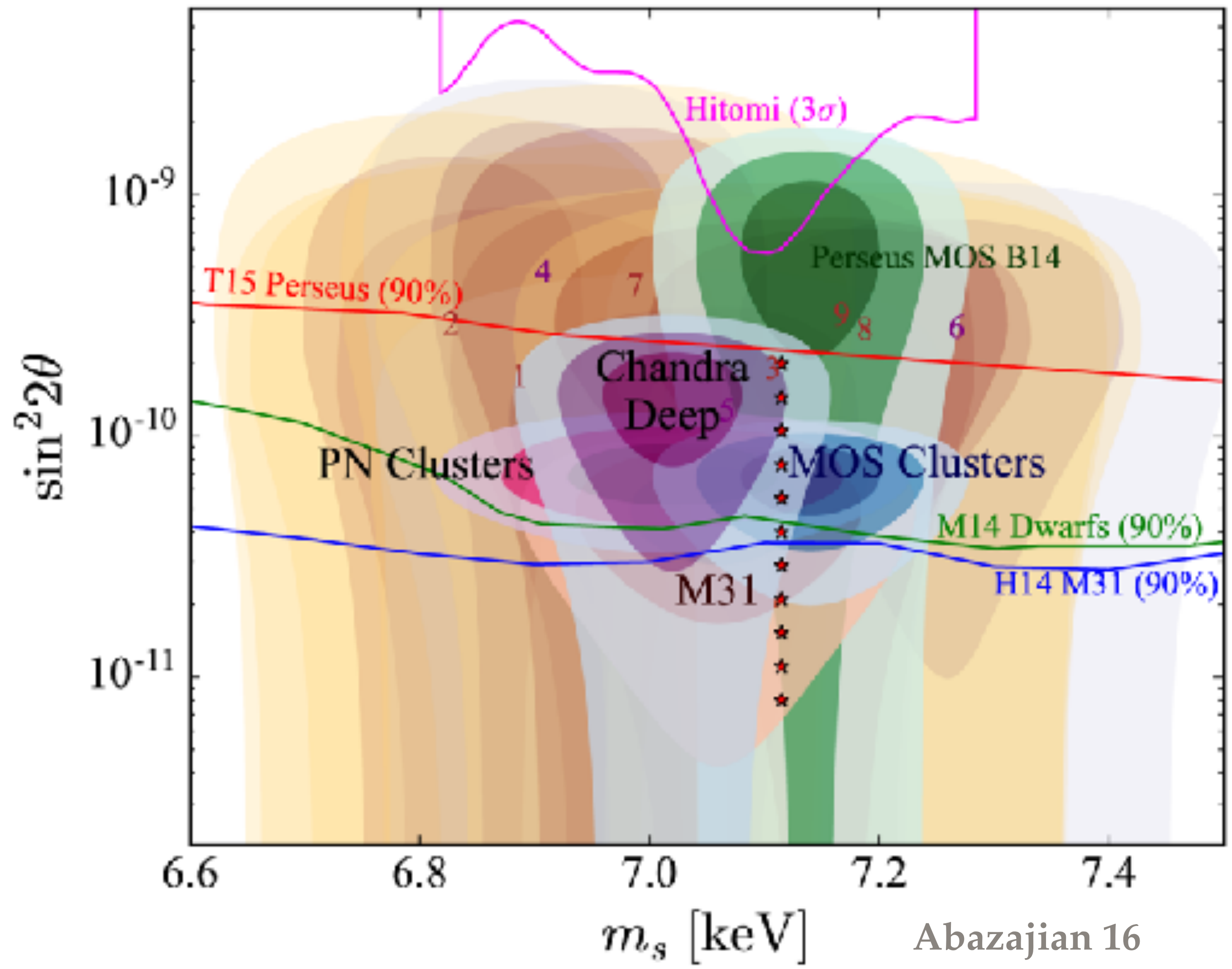
One can search for an emission line!



Has the line been seen?



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



Abazajian 16

Situation unclear…

need better spectral resolution (XARM and ATHENA will help)

How to make Sterile Neutrino DM?

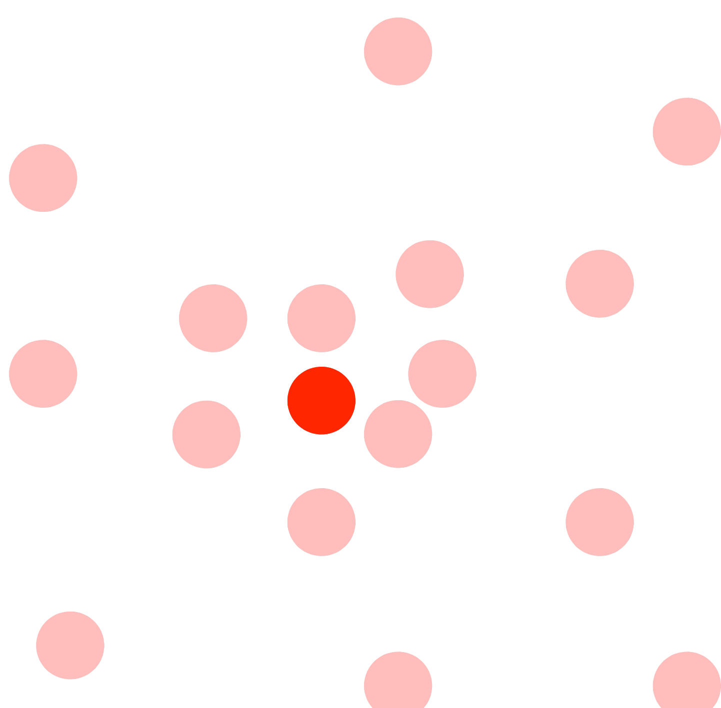
1. thermal production through mixing

2. thermal production through new interactions at high energy

3. non-thermal production in decay of heavy particles

Quasiparticles in the Primordial Plasma

- Neutrinos in early universe are screened by the weak interactions with the primordial plasma
  $\Rightarrow$ quasiparticles with modified dispersion relations and mixing angle
- The effect is similar to diffraction of photons in transparent media
  $\Rightarrow$ can be parameterised by effective mass and effective mixing angle

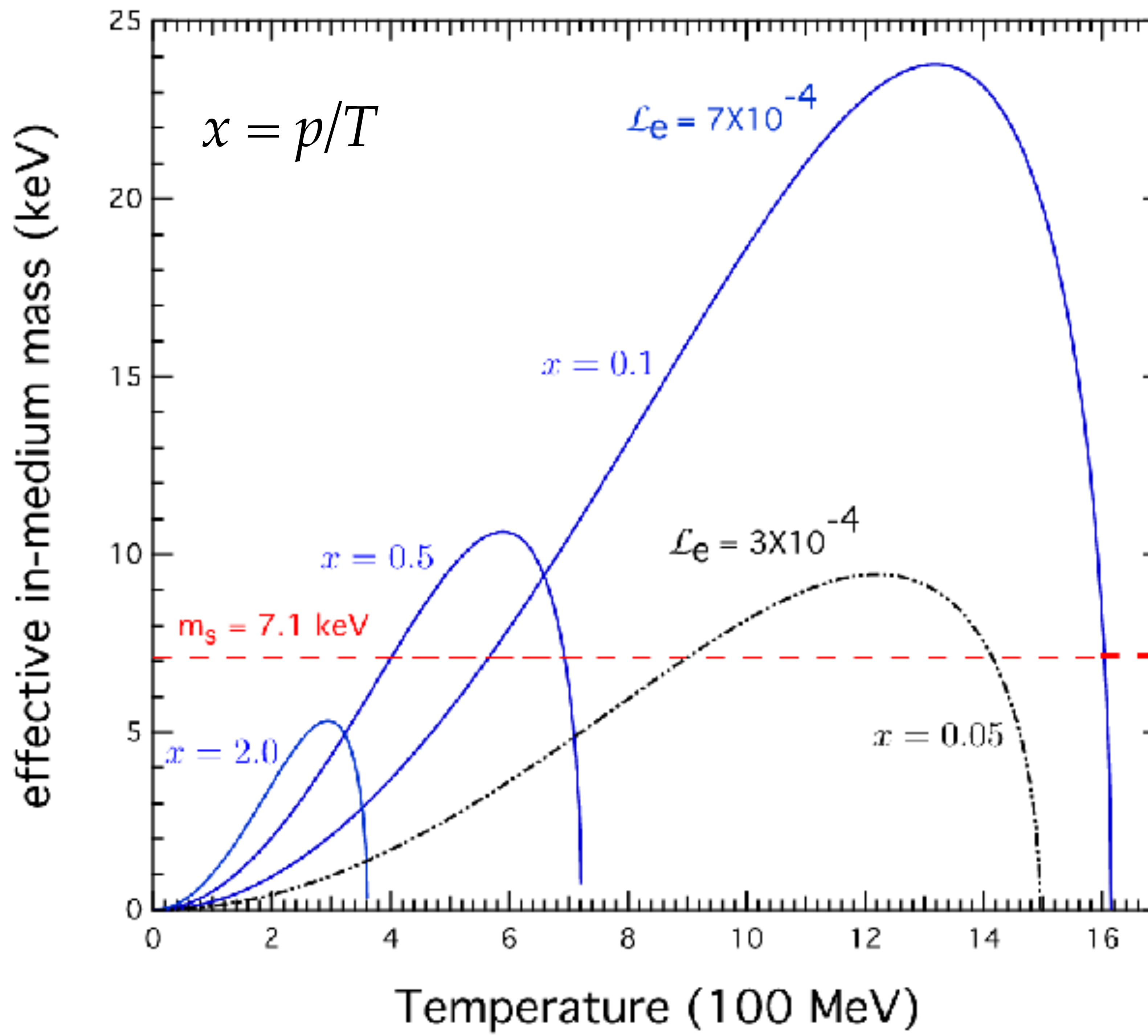


- If the medium properties change adiabatically, the quantum state stays coherent
- If the medium changes non-adiabatically or the particles scatter, decoherence occurs

.

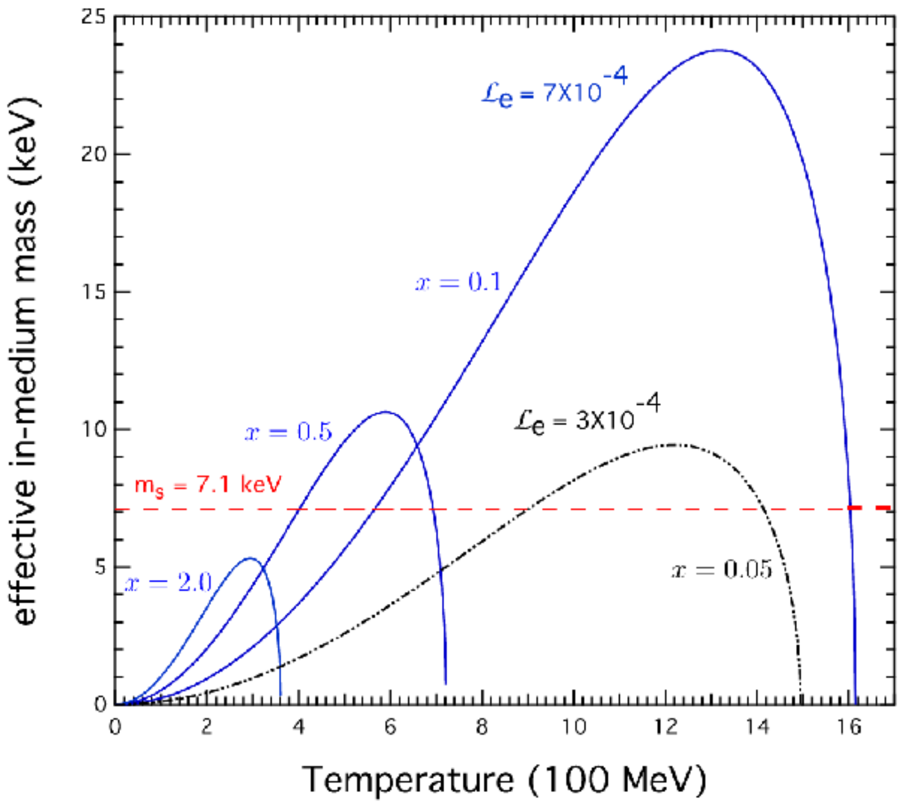
Level Crossing and Resonant DM Production

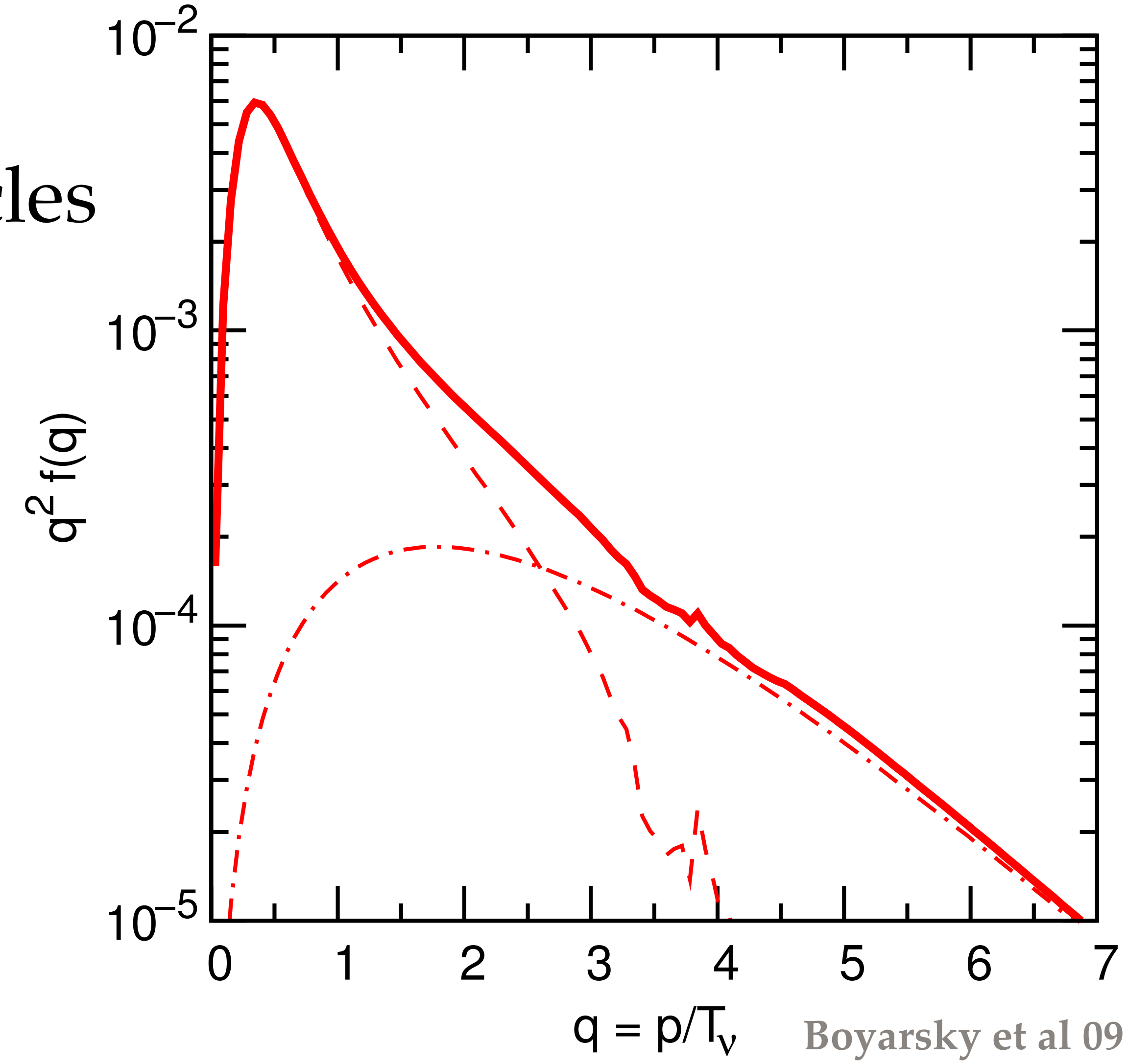
- effective mass of ordinary neutrinos depends on temperature T, momentum p and lepton chemical potential $\mathcal{L}$
- effective masses of ordinary and sterile neutrinos can become equal for some parameters
- "level crossing" leads to resonant production of DM



Level Crossing and Resonant DM Production

resonance generates non-thermal momentum distribution of DM particles



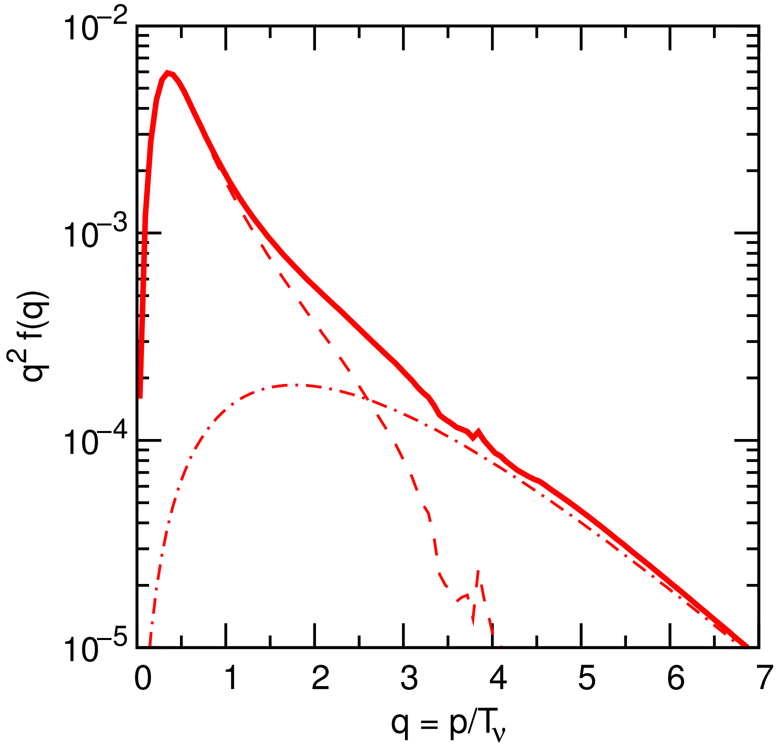


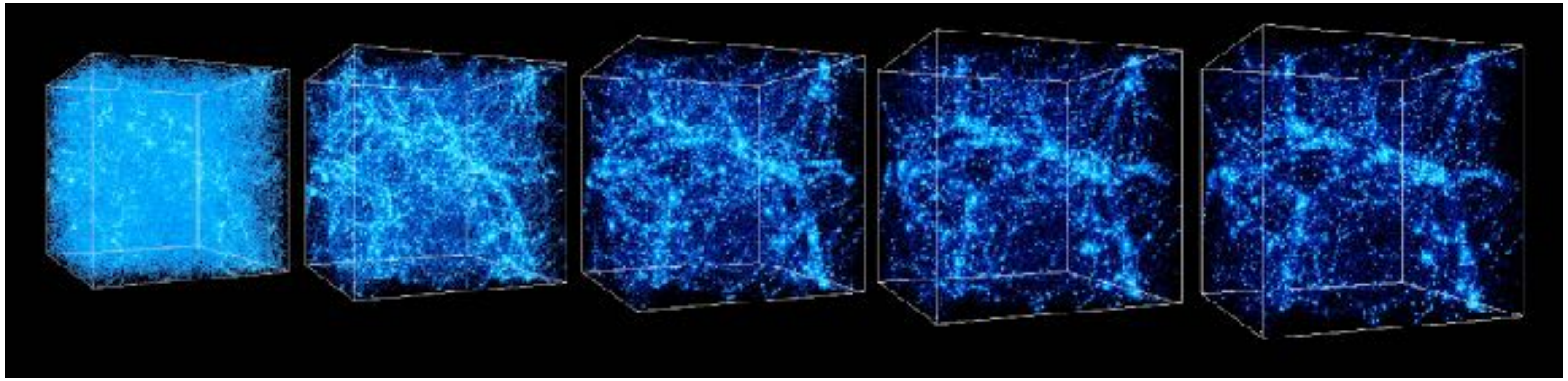
Boyarsky et al 09

This affects the Dark Matter free streaming length

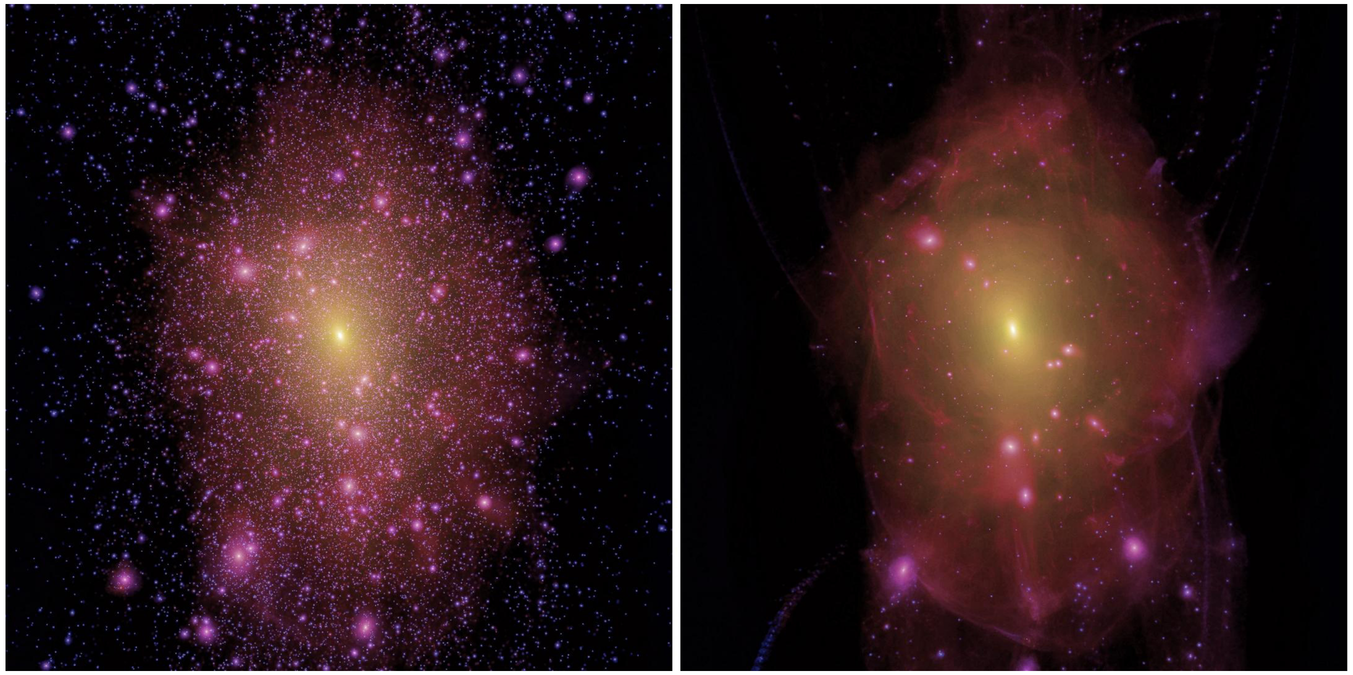
$$\lambda_{\rm fs}(t) \equiv a(t) \int_{t_i}^{t} dt' \, \frac{v(t')}{a(t')} \approx 1\,{\rm Mpc} \frac{\rm keV}{M} \frac{\langle p_{\rm DM} \rangle}{\langle p_\nu \rangle}$$

Impact on Structure Formation





This affects the formation of structures in the universe…



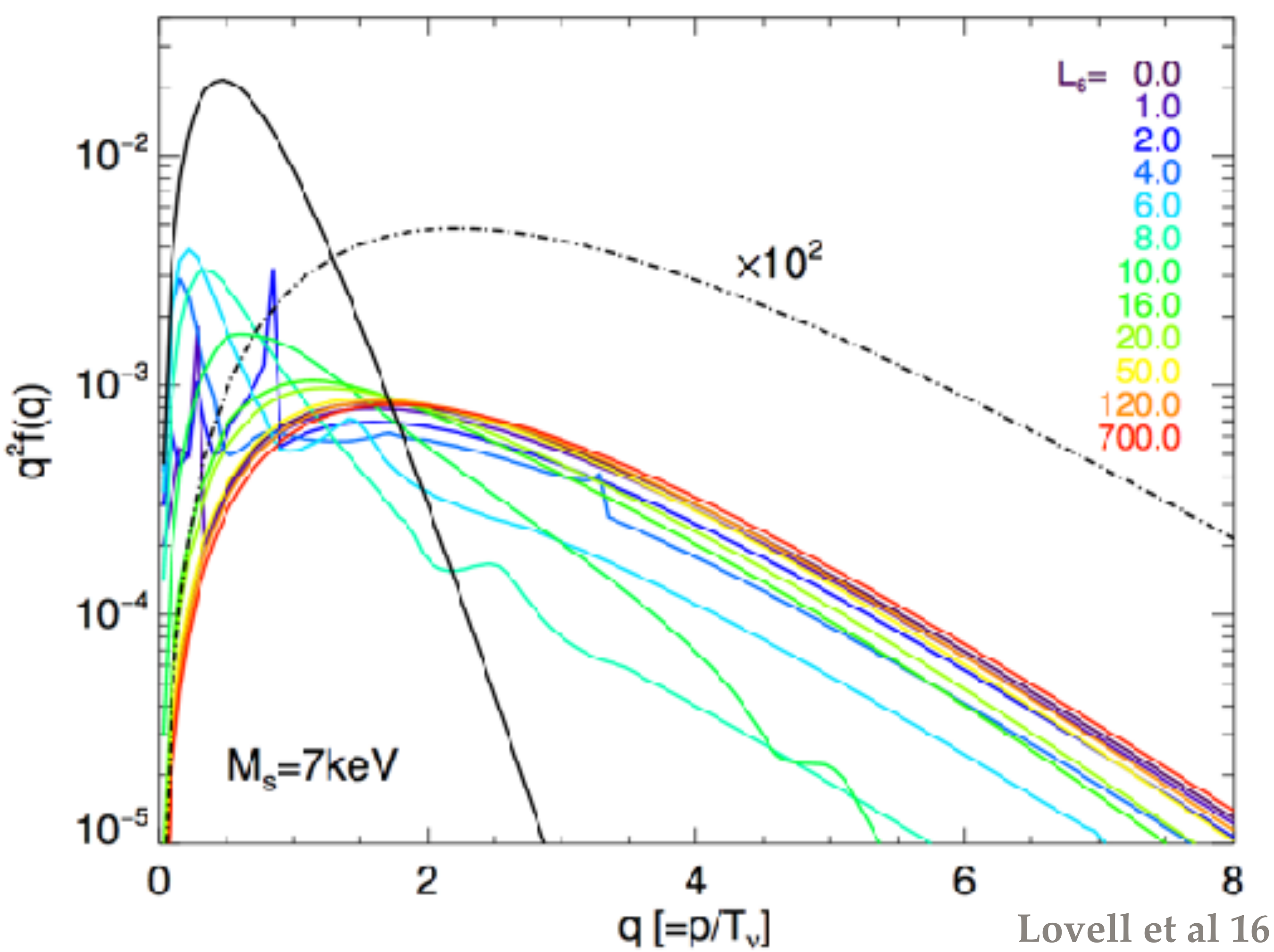
"cold" DM

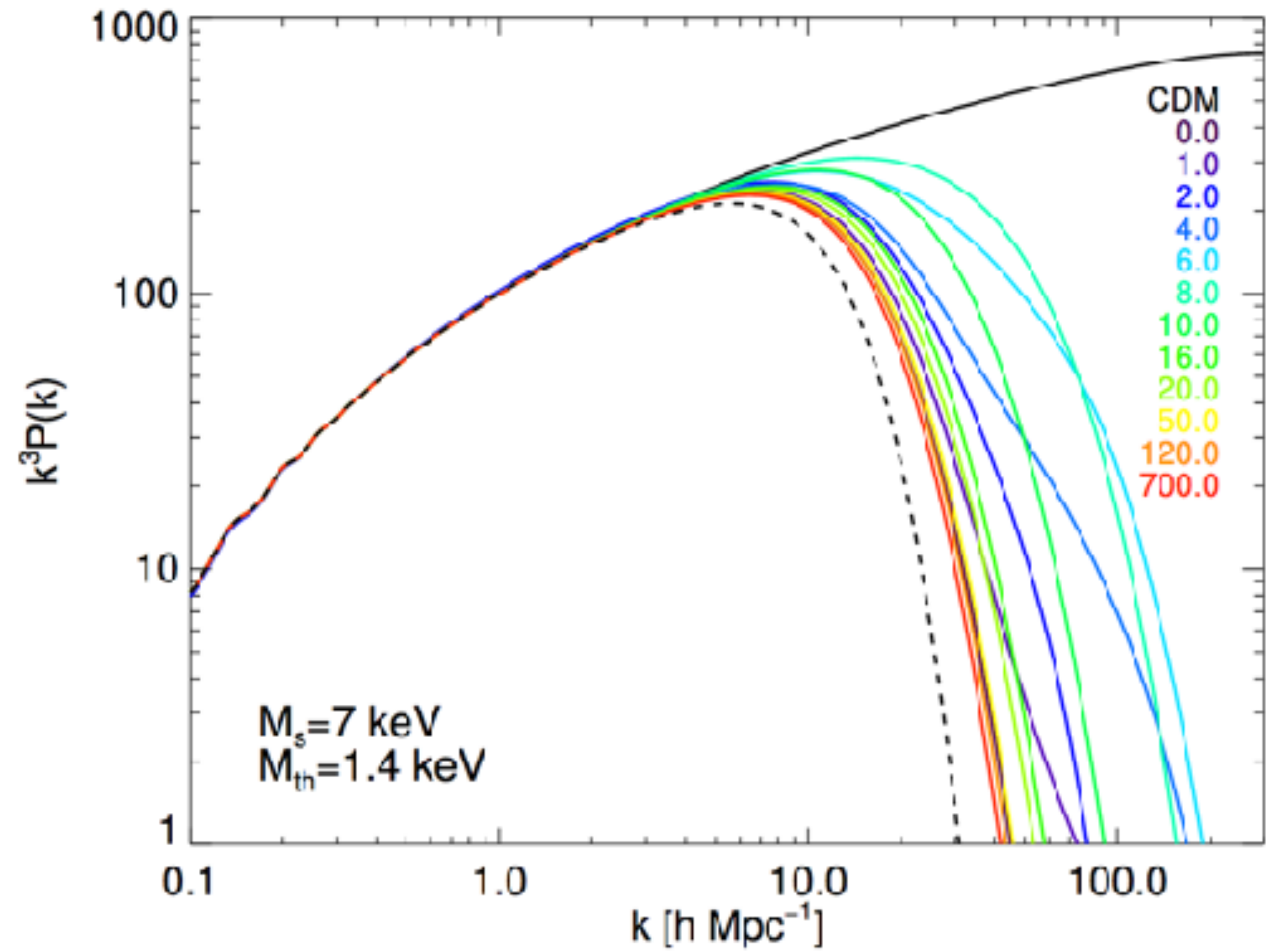
"warm" DM

…leading to observable differences in the matter distribution on small scales (below Mpc)

Lovell 12

Impact on Matter Power Spectrum



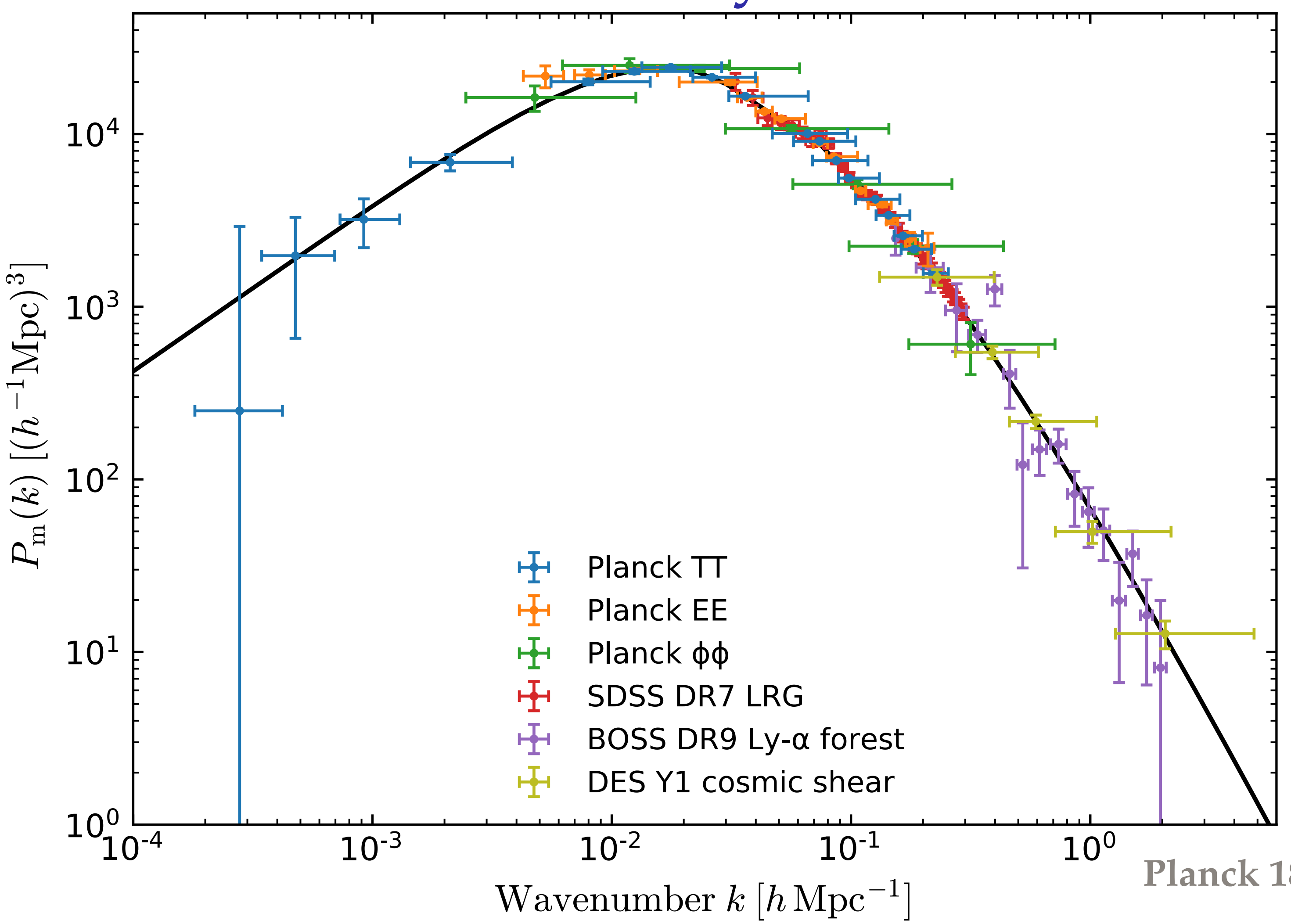


Dark Matter
momentum distribution

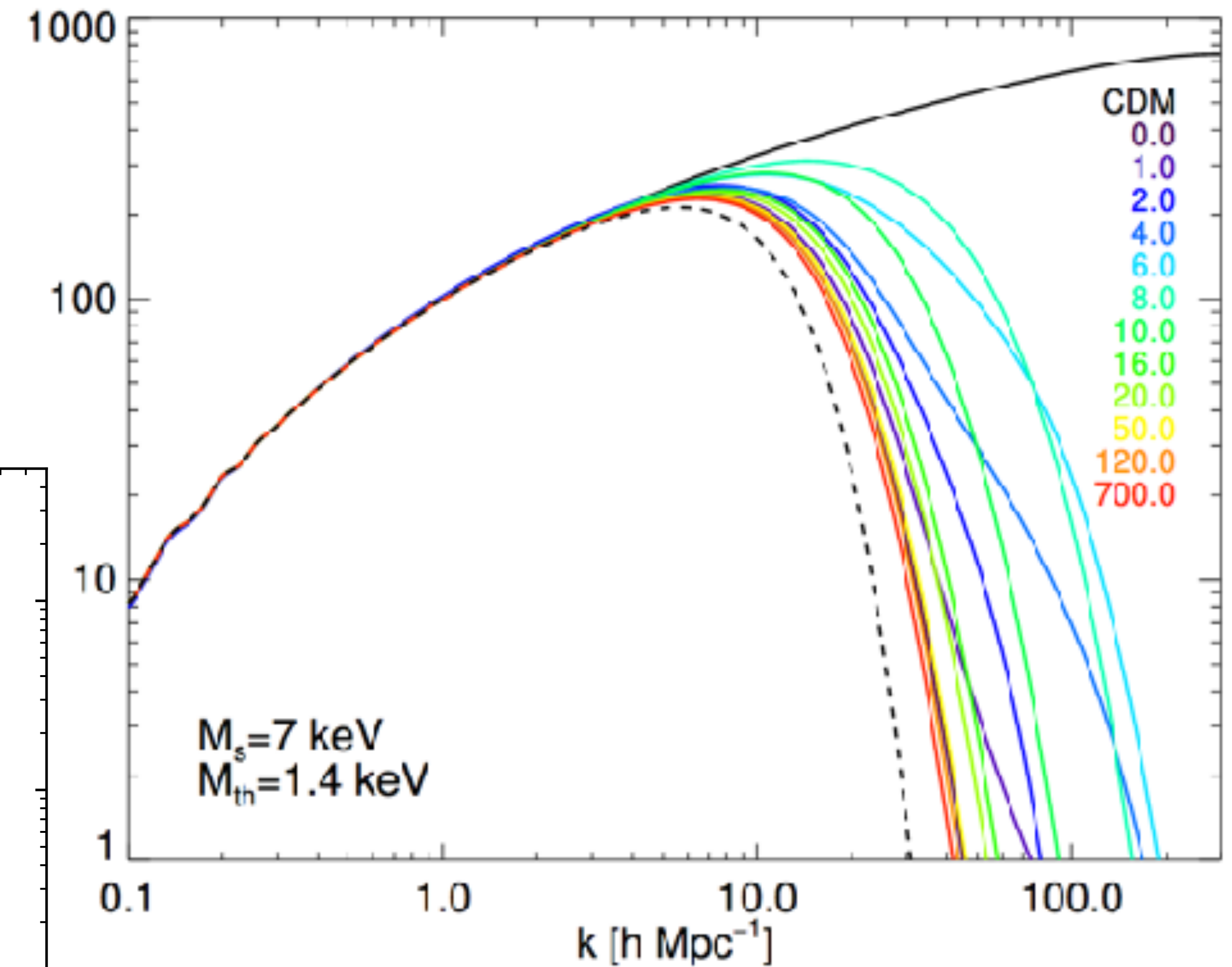
Matter Power Spectrum

Observational Probes

- These scales are primarily constrained by Lymanα forest, weak lensing, 21cm line
- also: dwarf galaxy counts, reionisation history, substructures

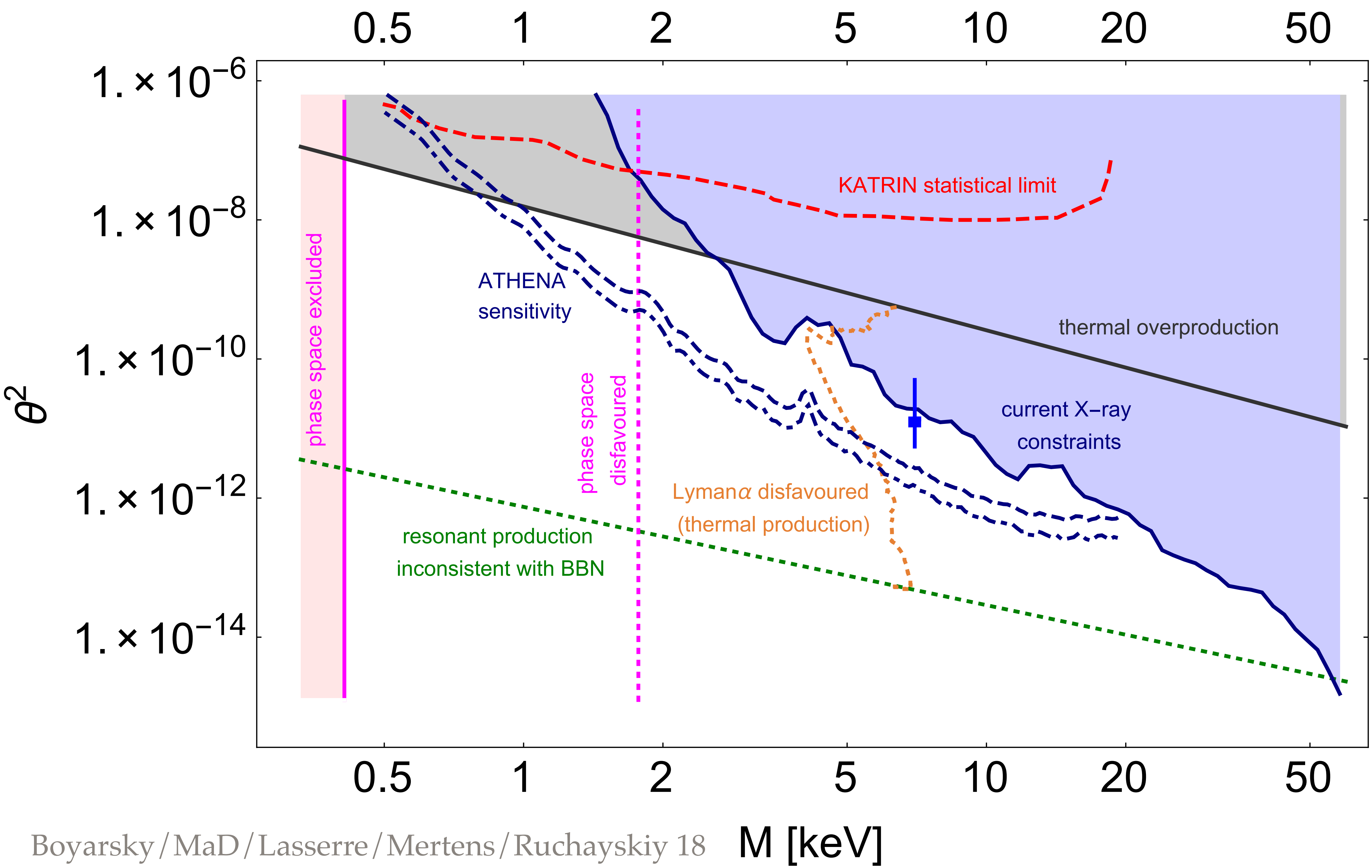


Planck 18



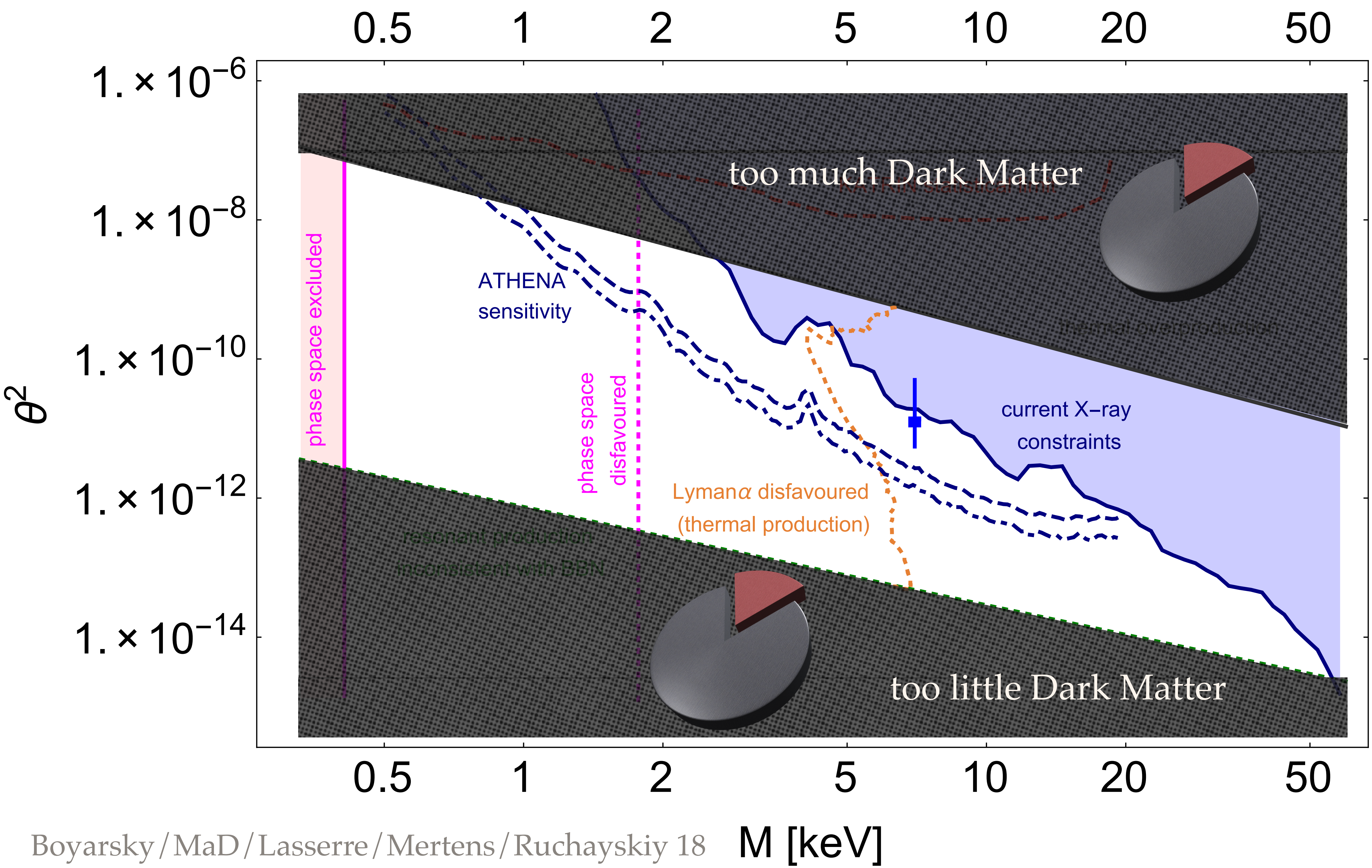
Matter Power Spectrum

Sterile Neutrino Dark Matter



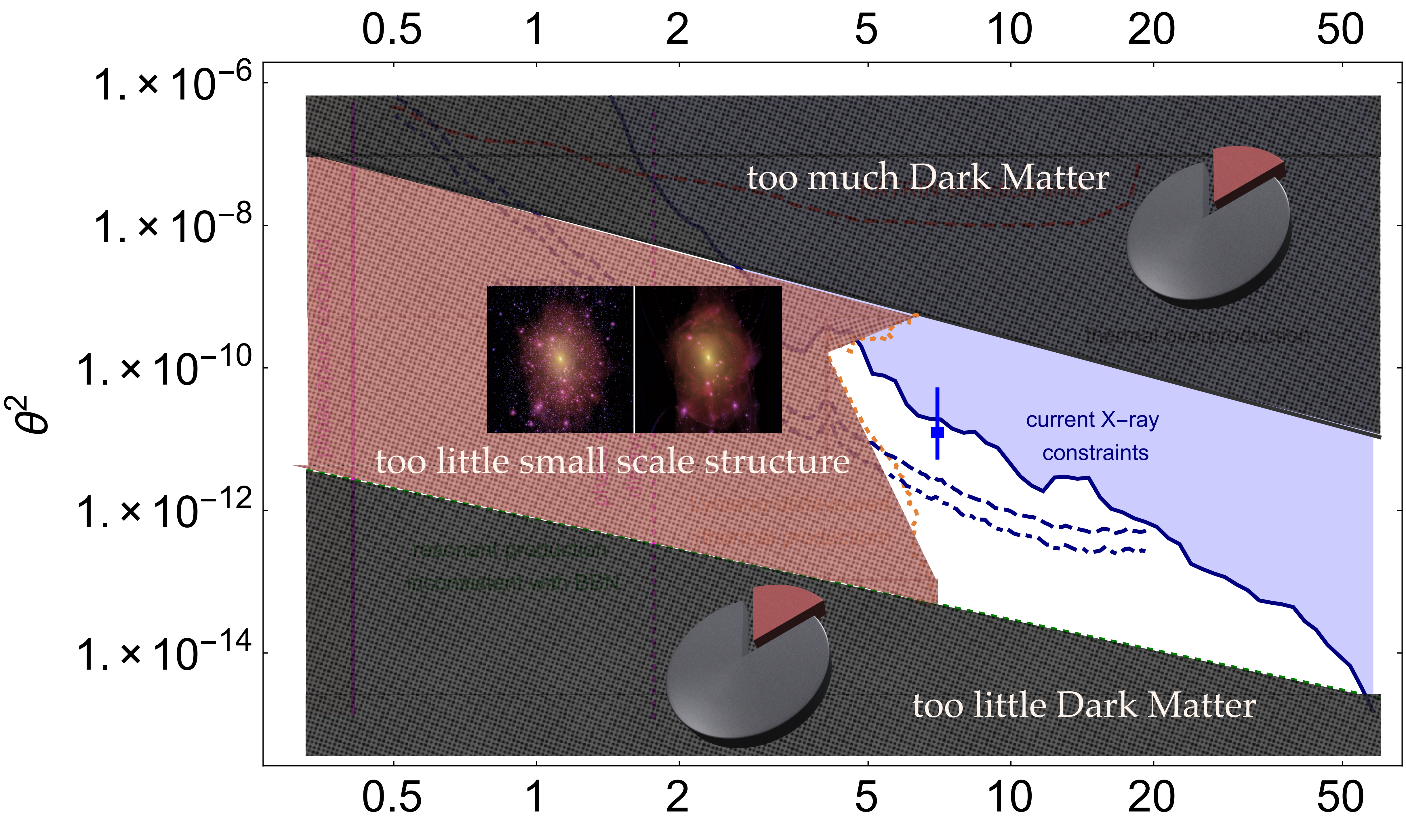
Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



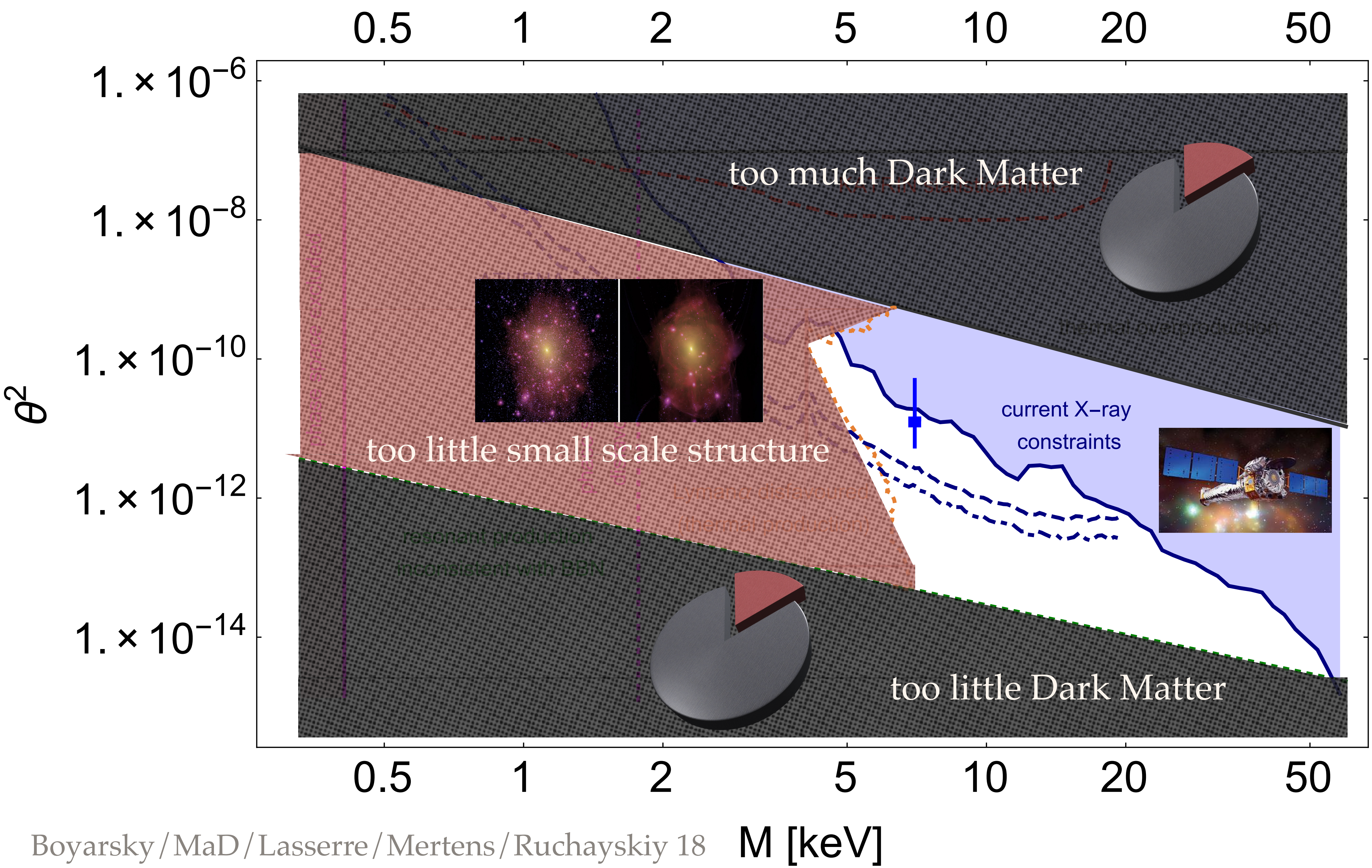
Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

Sterile Neutrino Dark Matter



Boyarsky/MaD/Lasserre/Mertens/Ruchayskiy 18

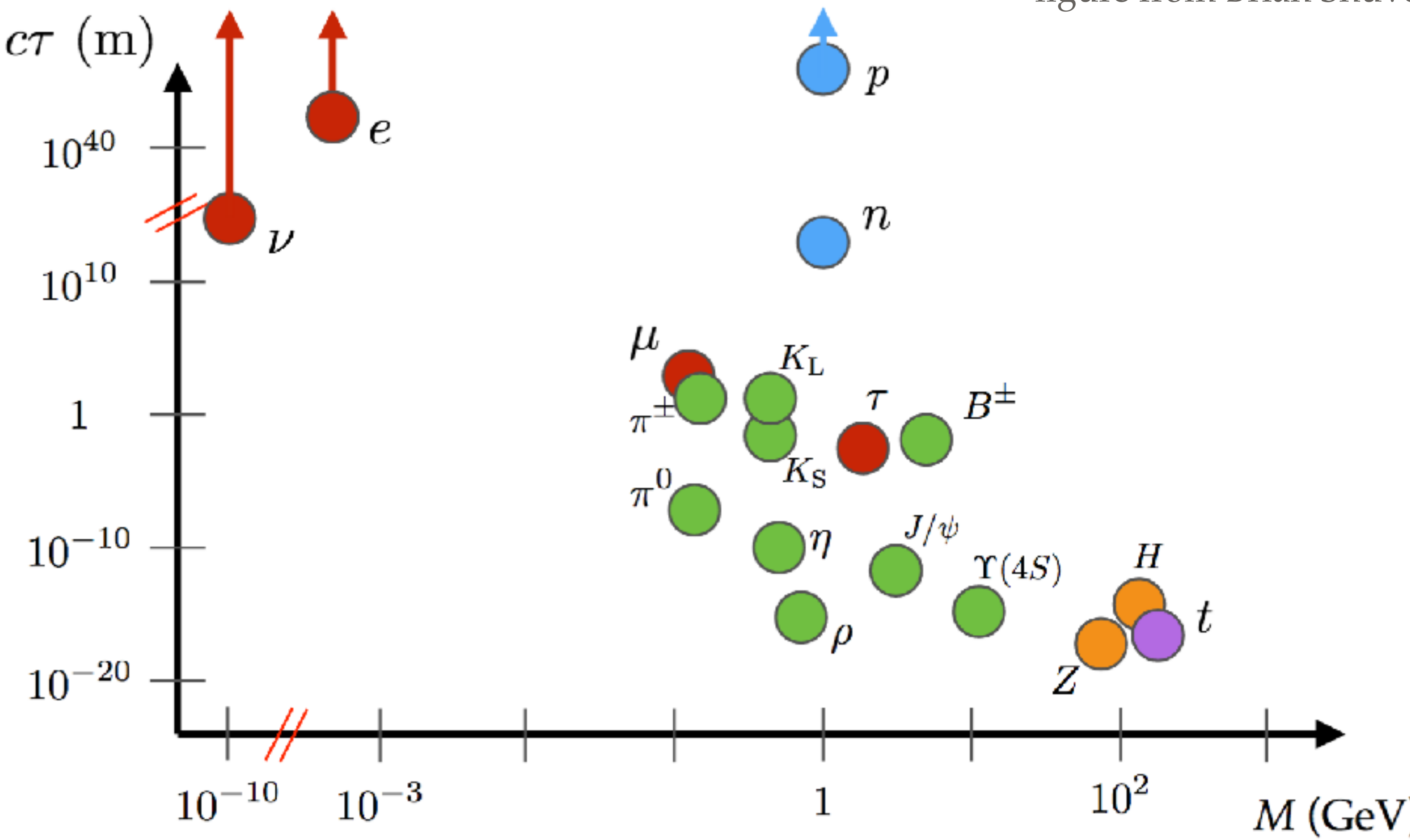
Lifetime Constraint on HNLs

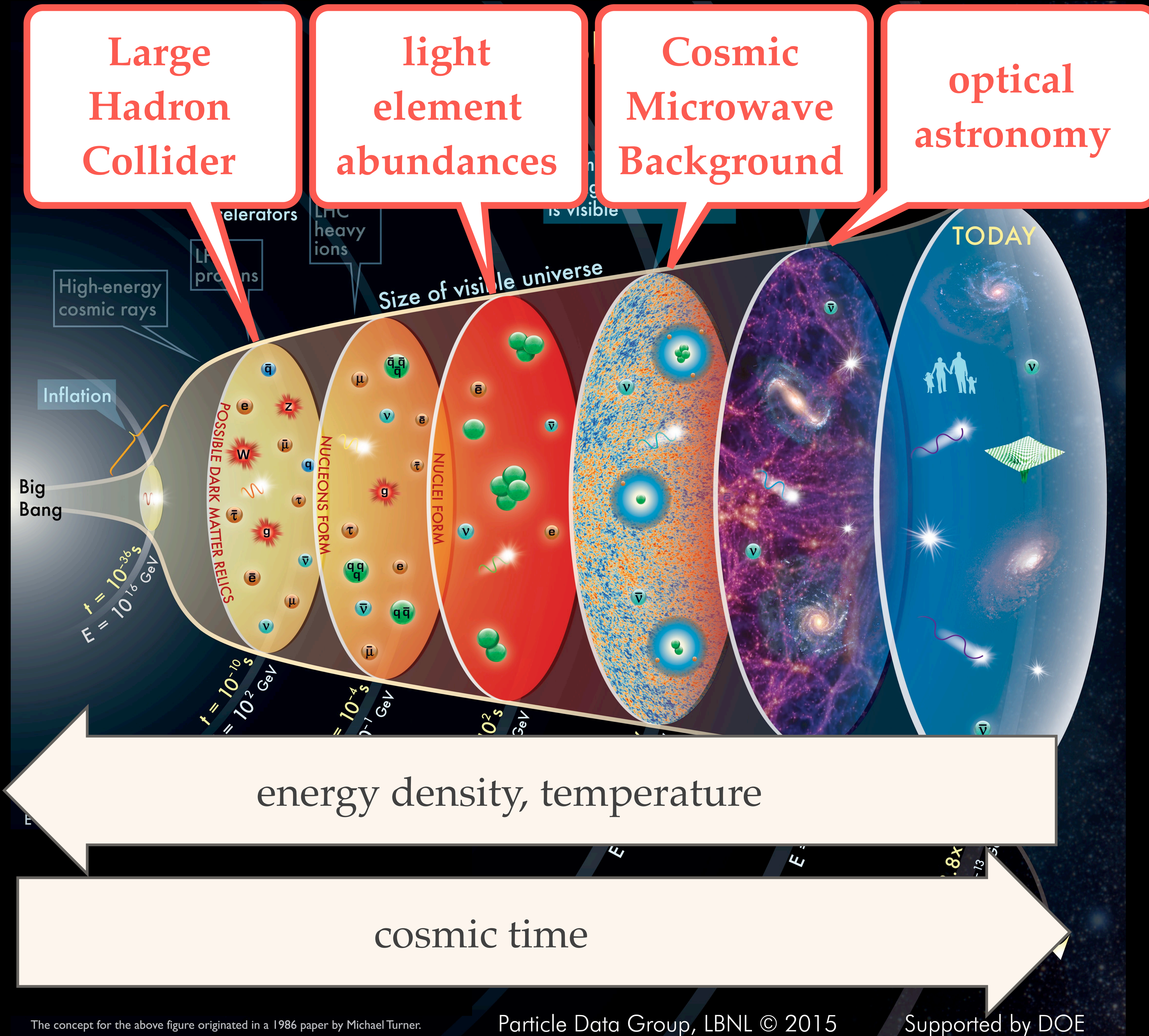
Keys to Longevity

	muon	pion	B meson	neutron
small coupling				
heavy mediator	W boson	W boson	W boson	W boson
symmetry			flavour	isospin
kinematics				phase space suppression

Longevity in the Standard Model

figure from Brian Shuve




Large Hadron Collider
light element abundances
Cosmic Microwave Background
optical astronomy
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
LHC heavy ions
energy density, temperature
cosmic time
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
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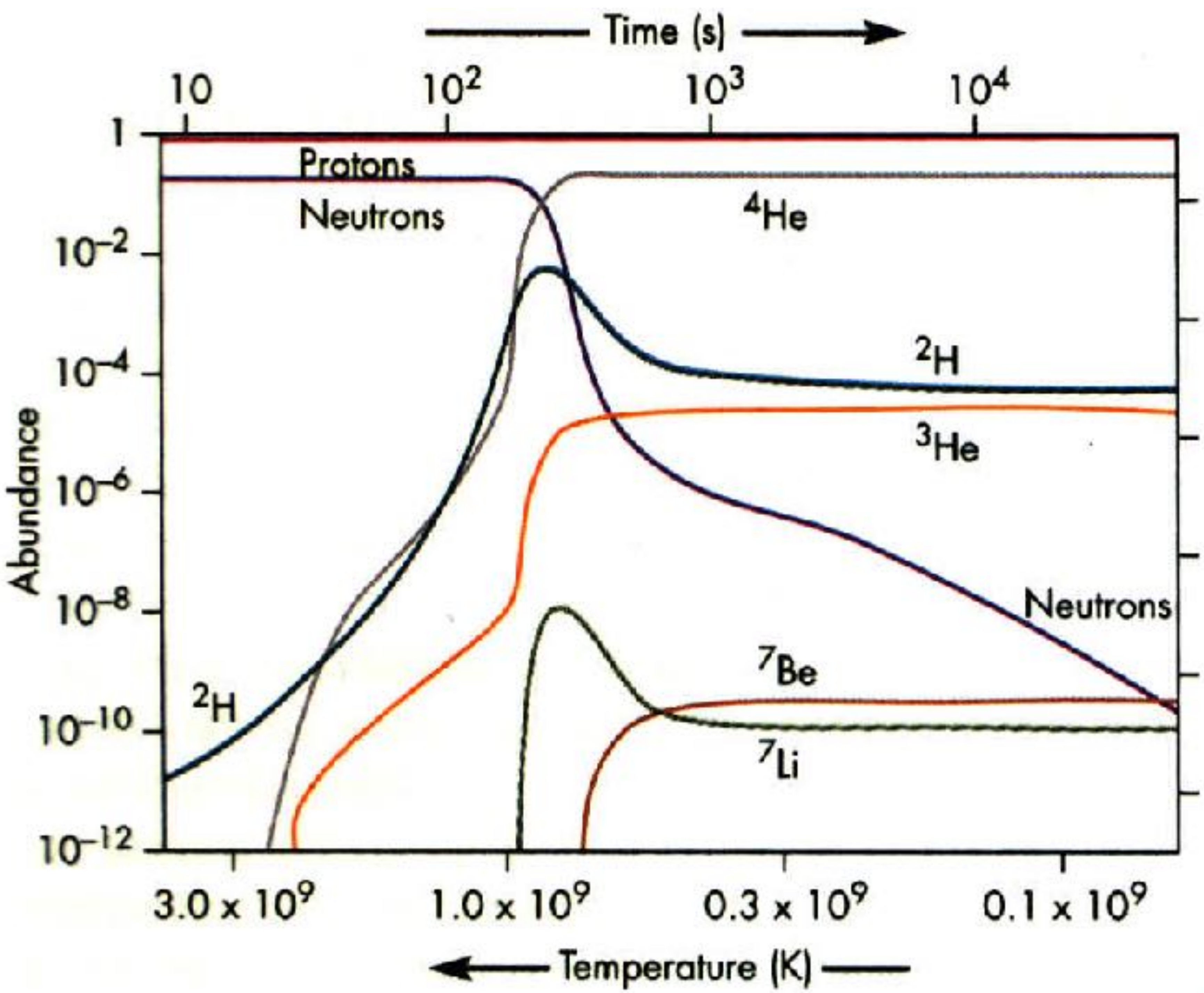
Big Bang Nucleosynthesis



Light elements are produced in a chain of nuclear reactions.

Theory is in good agreement with observed abundances in IGM

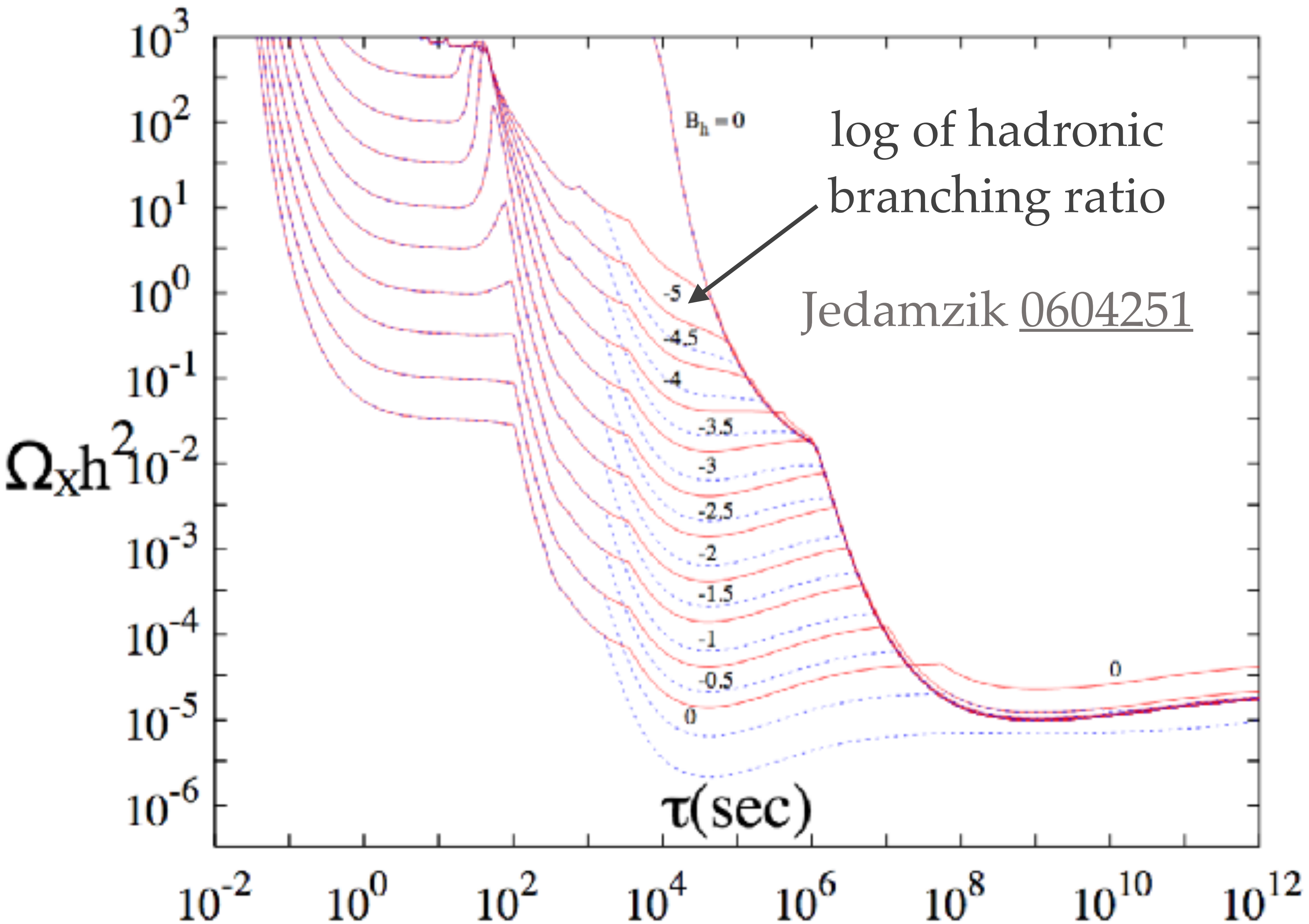
Decay of LLPs would disturb BBN

⇒ LLP must not decay during BBN!

Big Bang Nucleosynthesis

What exactly goes wrong? recent update: Hufnagel et al 1808.09324

- **Decay products can dissociate nuclei**



Big Bang Nucleosynthesis

What exactly goes wrong? recent update: Hufnagel et al 1808.09324

- **Decay products can dissociate nuclei**

- **Decay modifies relation between temperature and energy density…**

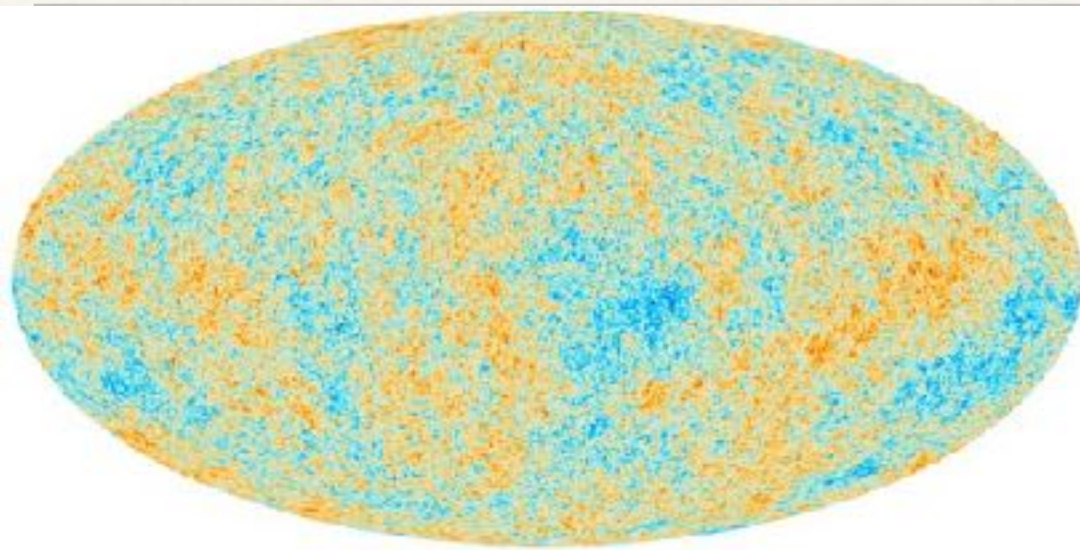
$$\rho_\gamma + \rho_{\text{neutrinos}} + [\text{new physics effects}] \equiv \rho_\gamma + N_{\text{eff}}\rho_\nu = \frac{\pi^2}{15}T_\gamma^4\left[1 + N_{\text{eff}}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$$

…and thereby the Hubble rate

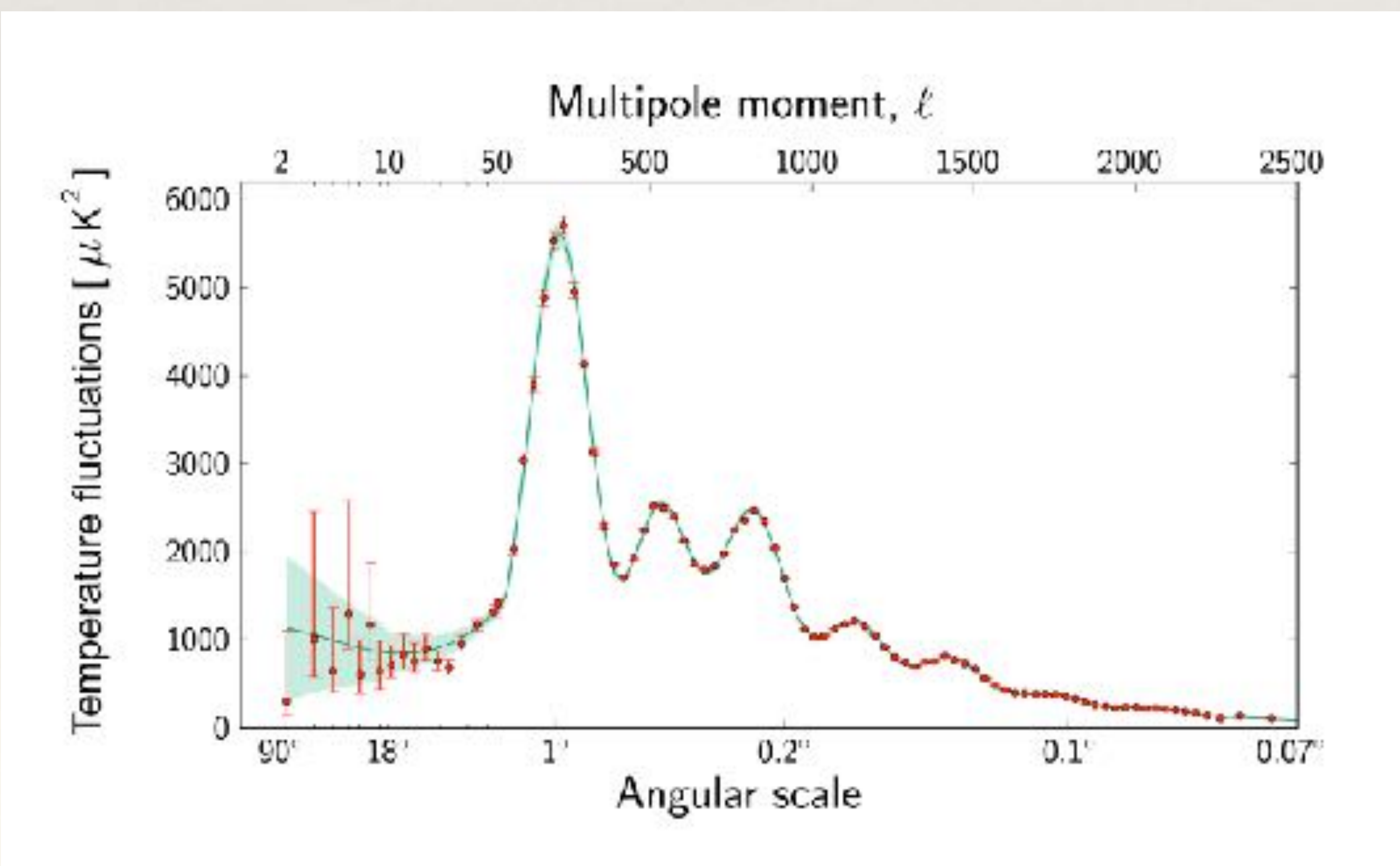
$$H^2 = \frac{8\pi}{3}G\rho$$

- **Entropy injection modifies baryon to photon ratio**

Cosmic Microwave Background



CMB is sensitive to the number of relativistic particle species in the primordial plasma



SM predicts 3 neutrinos (in addition to photons). This prediction **assumes thermal distributions with single T**.

Observed value:

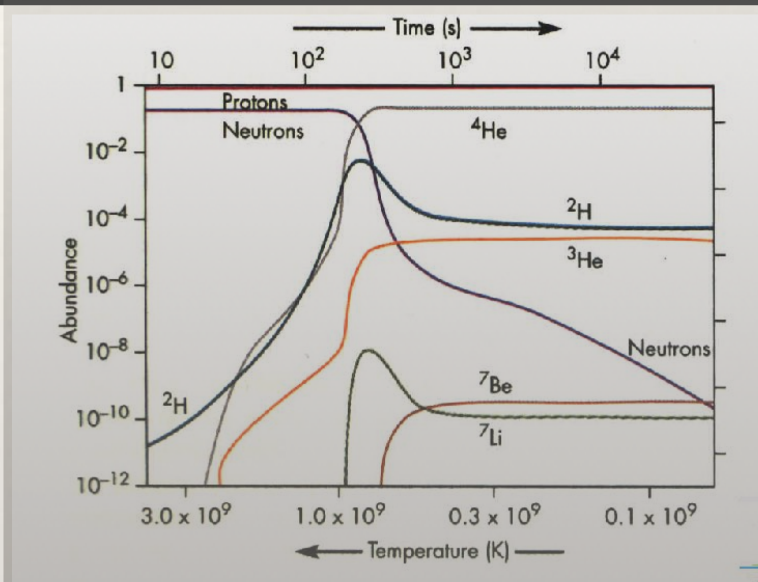
$N_{eff} = 2.99 \pm 0.17$ Planck 1807.06209

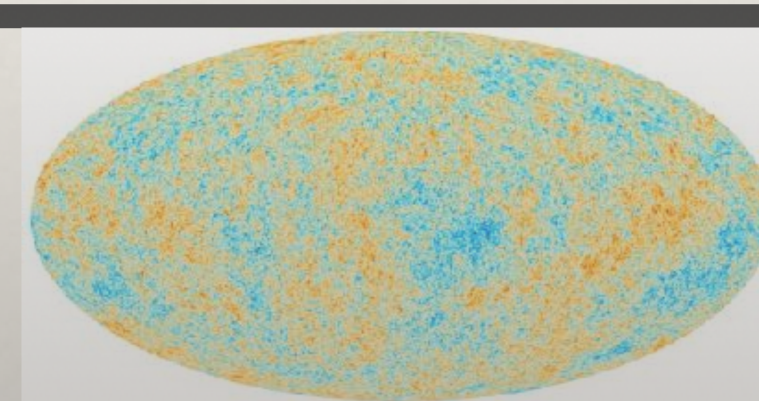
LLP decay would disturb spectra and ruin this agreement

How long lived can new particles be?

0.1s

300.000 yrs





hot plasma

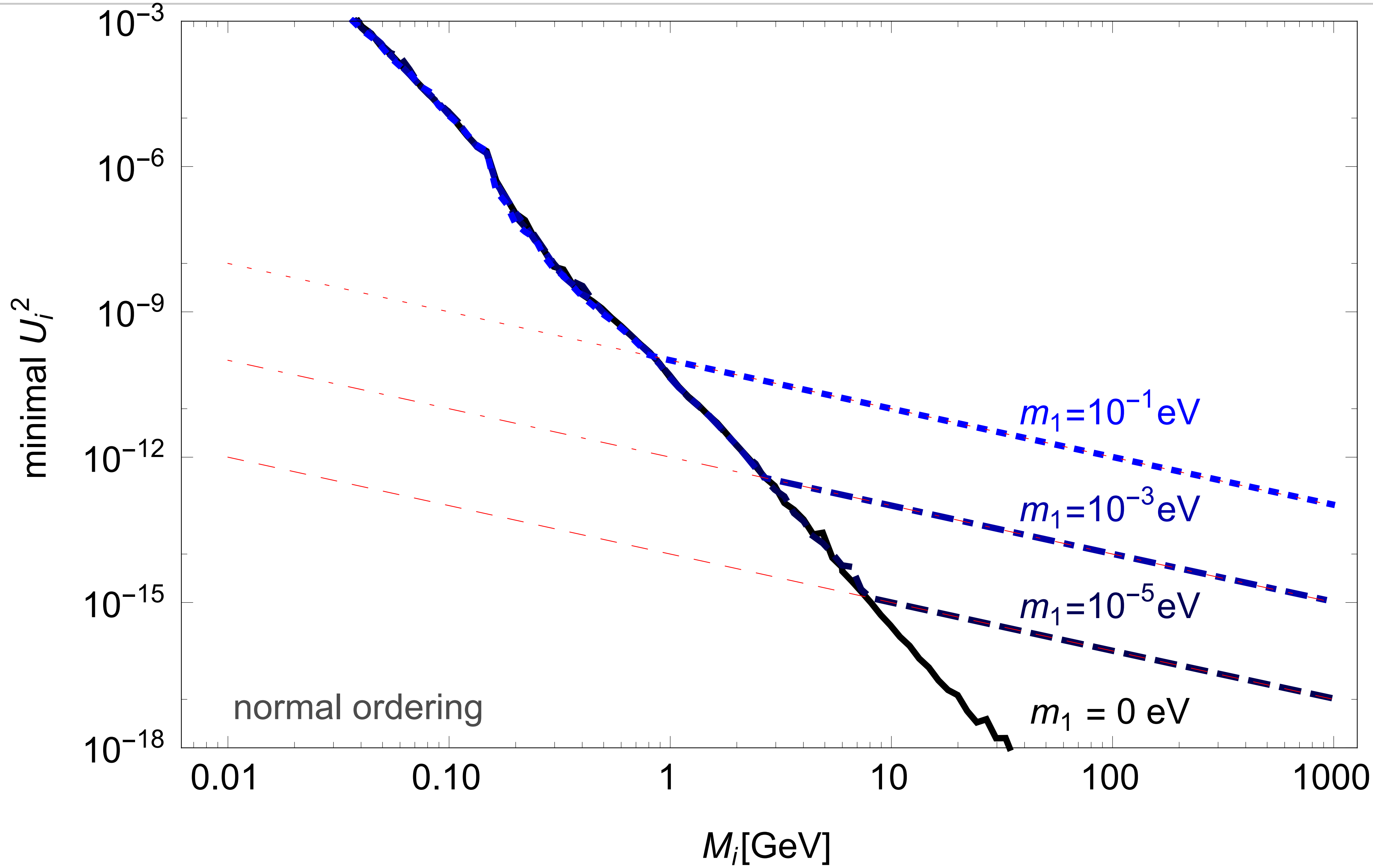
galaxy formation

⇐ must decay before 0.1s …

…or after more than 300.000 yrs ⟹

(e.g. Dark Matter)

A lower limit?



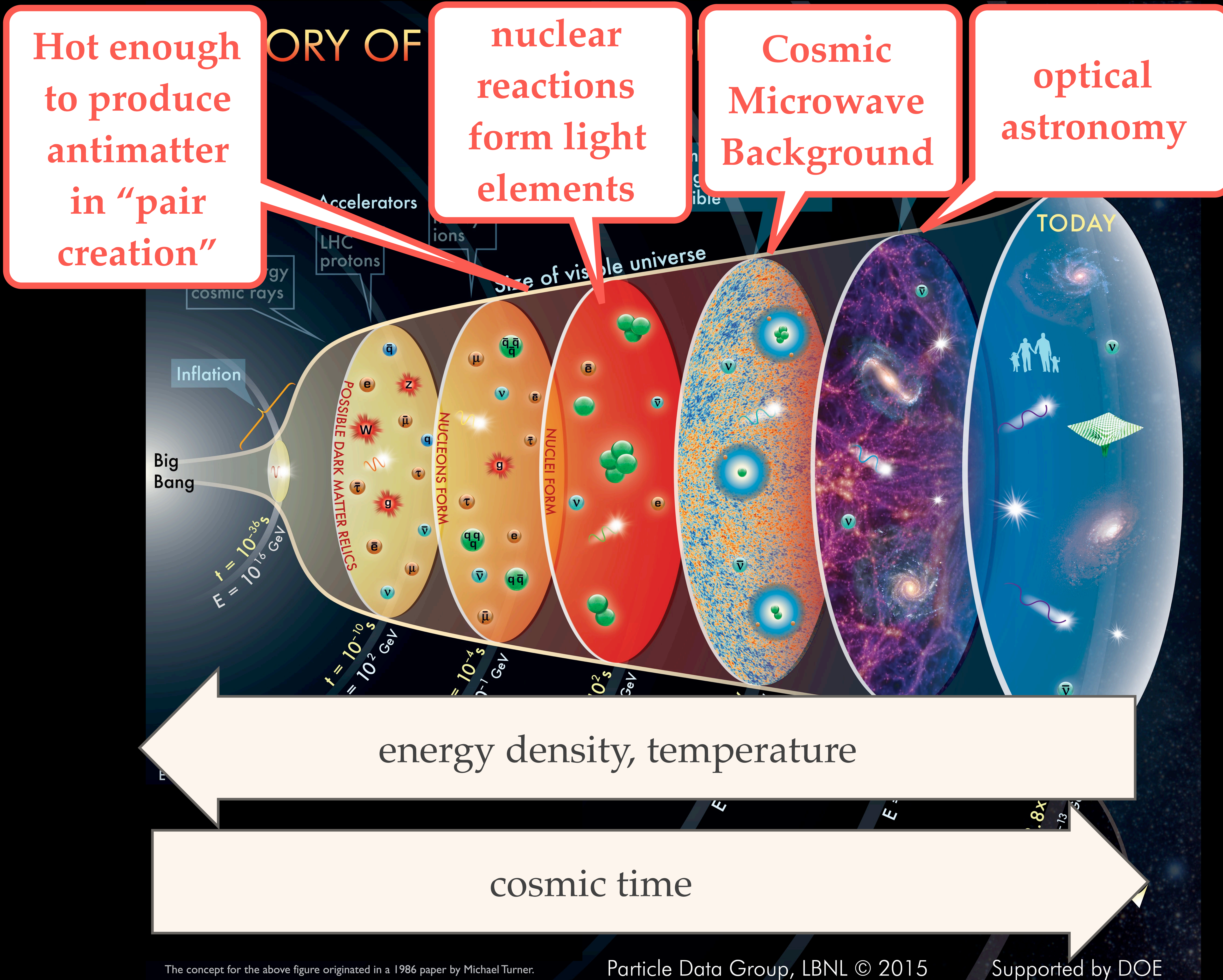
lower limits from neutrino data+BBN

strongly depend on #RHN and mass of the lightest neutrino MaD 1904.11959

Leptogenesis

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

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


Hot enough to produce antimatter in "pair creation"
nuclear reactions form light elements
Cosmic Microwave Background
optical astronomy
Accelerators
LHC protons
ions
cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
t = 10⁻³⁶ s
E = 10¹⁶ GeV
t = 10⁻¹⁰ s
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
energy density, temperature
cosmic time
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
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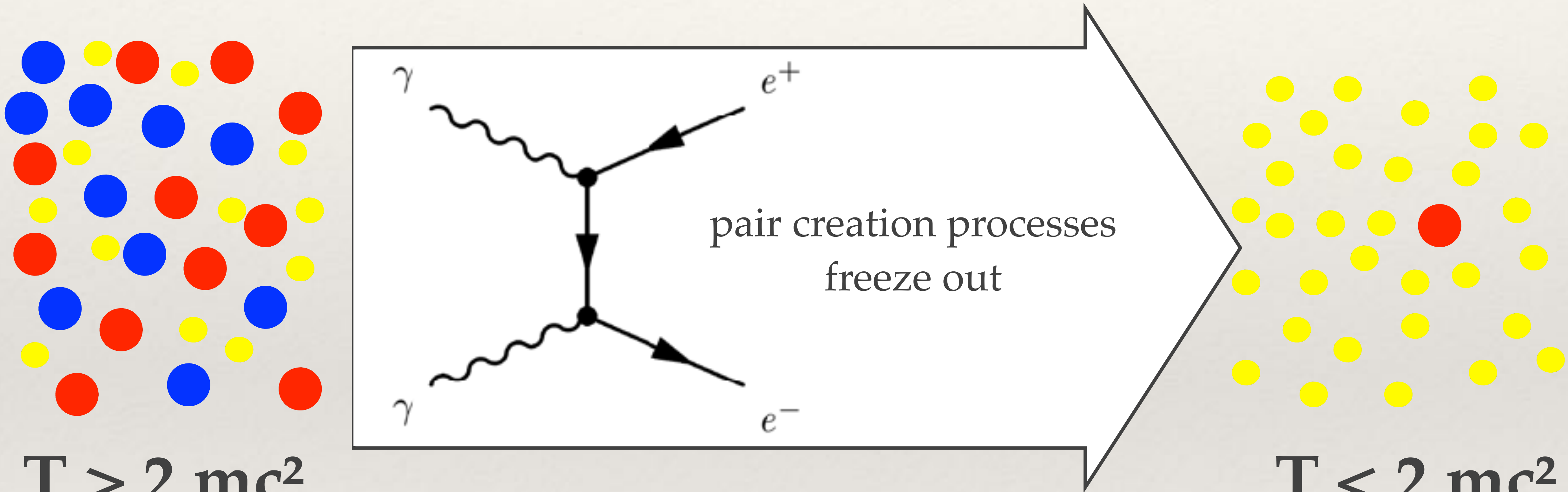
Baryon Asymmetry of the Universe

The observable universe contains almost no antimatter and a lot more photons than baryons.



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

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:

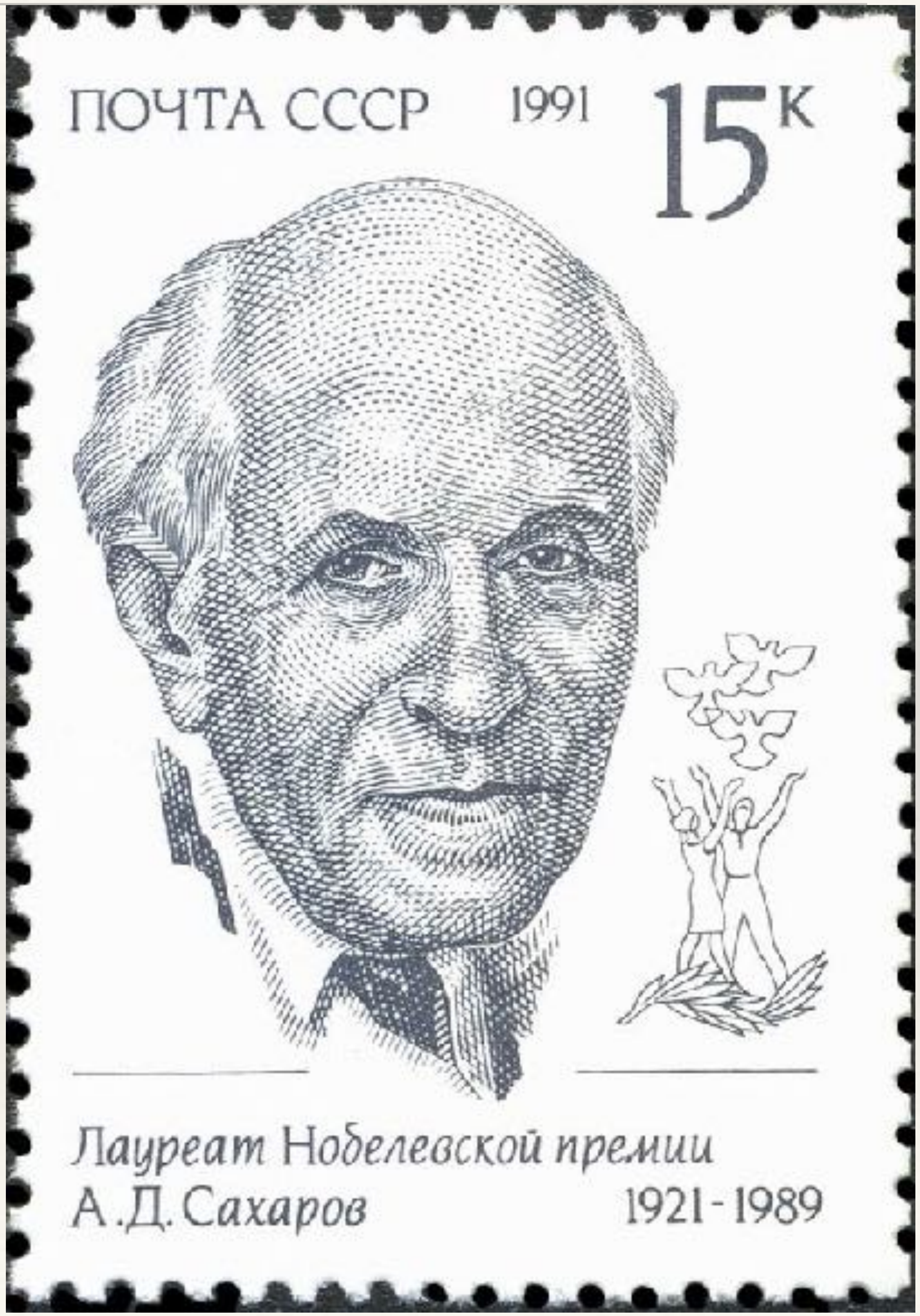
$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

(PDG)

Where does the asymmetry come from?

Sakharov Conditions (1967)

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



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Exists in Standard Model (sphaleron)

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- Baryon number violation
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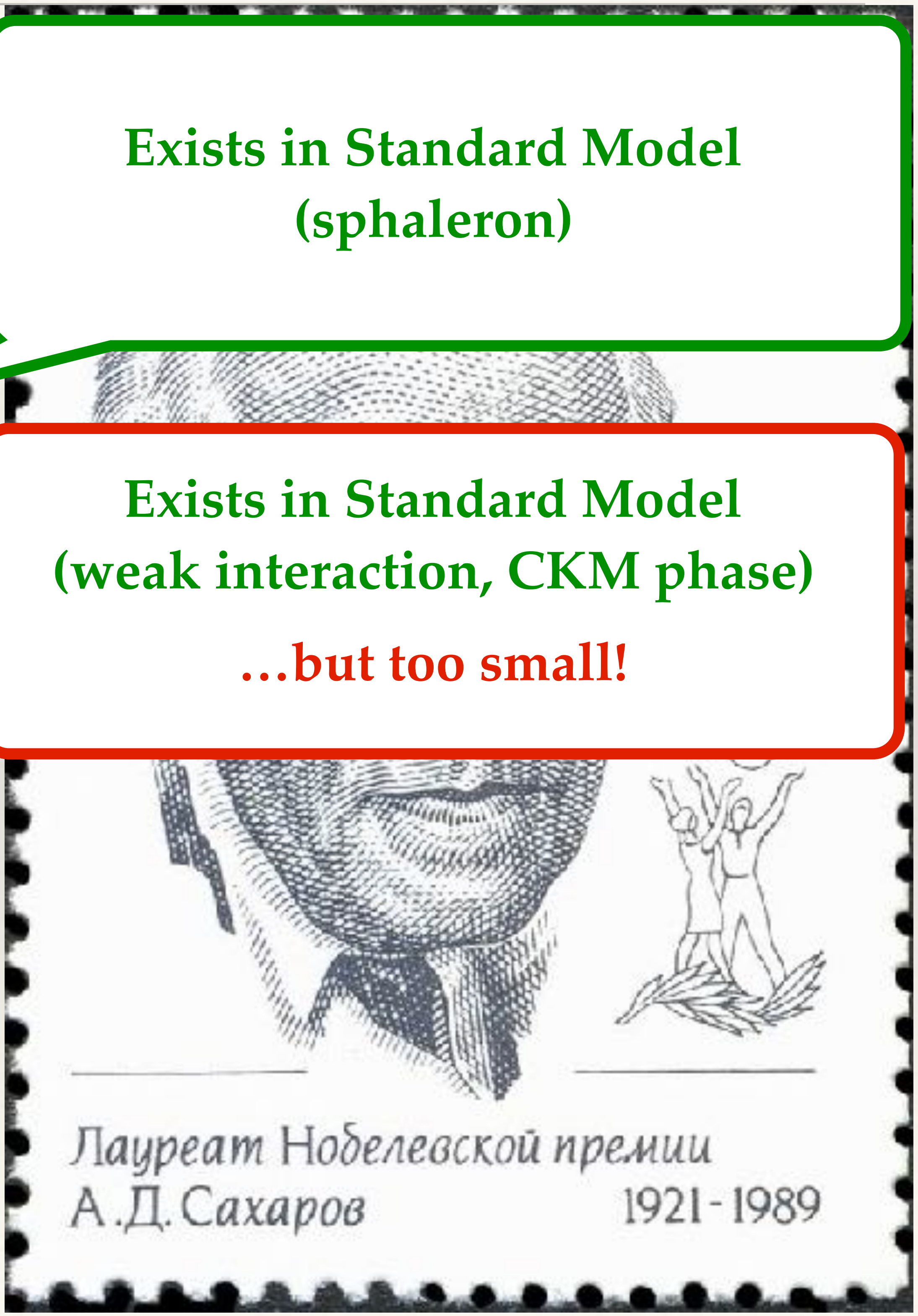
- Deviation from thermal equilibrium

Exists in Standard Model
(sphaleron)

Exists in Standard Model
(weak interaction, CKM phase)

…but too small!



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Sakharov Conditions (1967)

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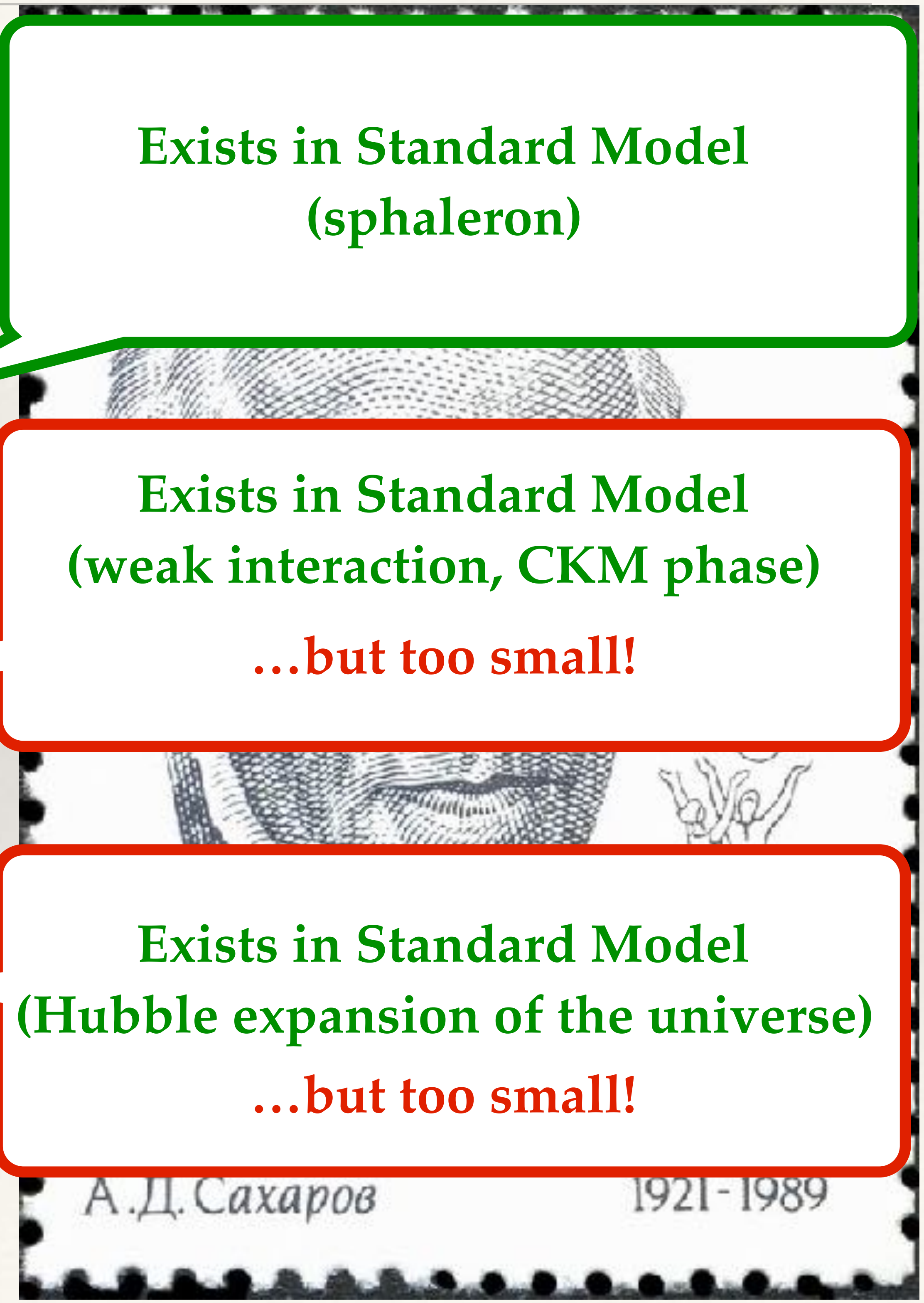
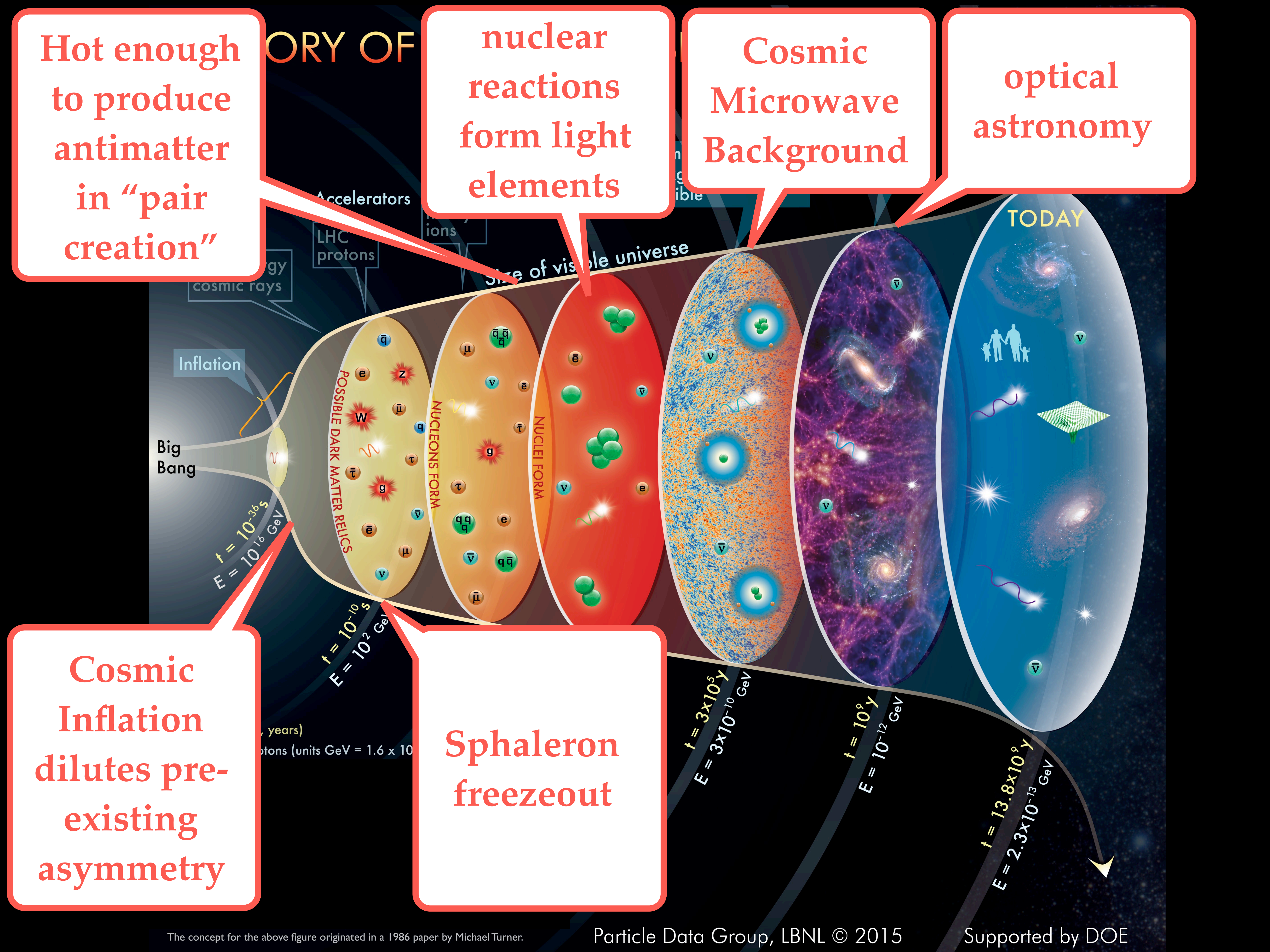


Exists in Standard Model (sphaleron)

Exists in Standard Model (weak interaction, CKM phase)
…but too small!

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



Hot enough to produce antimatter in “pair creation”
nuclear reactions form light elements
Cosmic Microwave Background
optical astronomy
Cosmic Inflation dilutes pre-existing asymmetry
Sphaleron freezeout
Accelerators
LHC protons
ions
cosmic rays
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
TODAY
$t = 10^{-36}$ s
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 3\times10^{5}$ y
$E = 3\times10^{-10}$ GeV
$t = 10^{9}$ y
$E = 10^{-12}$ GeV
$t = 13.8\times10^{9}$ y
$E = 2.3\times10^{-13}$ GeV
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
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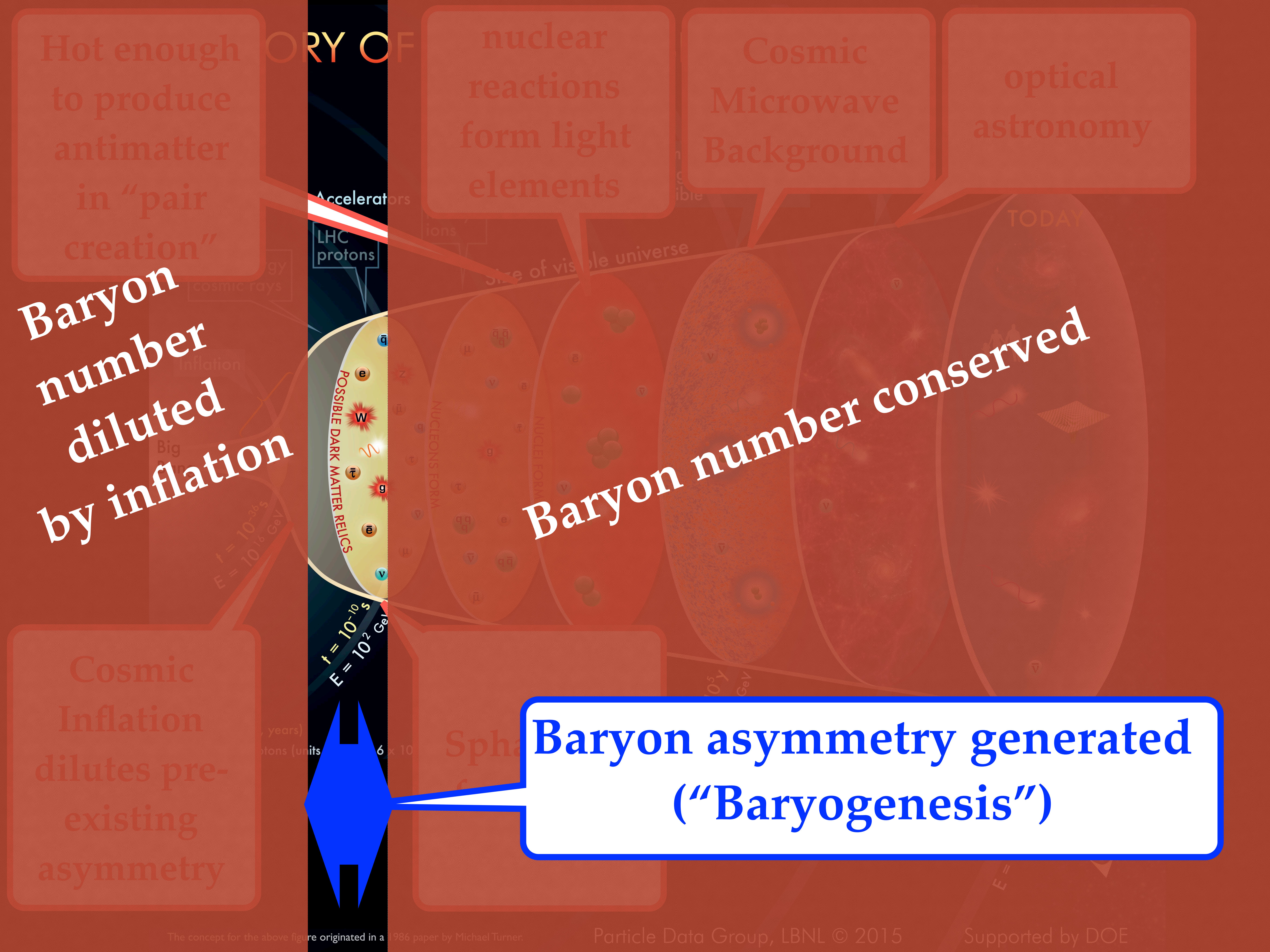

Hot enough to produce antimatter in "pair creation"
nuclear reactions form light elements
Cosmic Microwave Background
optical astronomy
Baryon number diluted by inflation
Baryon number conserved
Cosmic Inflation dilutes pre-existing asymmetry
Baryon asymmetry generated ("Baryogenesis")
Accelerators
LHC protons
POSSIBLE DARK MATTER RELICS
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
TODAY
Size of visible universe
Particle Data Group, LBNL © 2015
Supported by DOE
The concept for the above figure originated in a 1986 paper by Michael Turner.

Thermal Leptogenesis

Basic idea

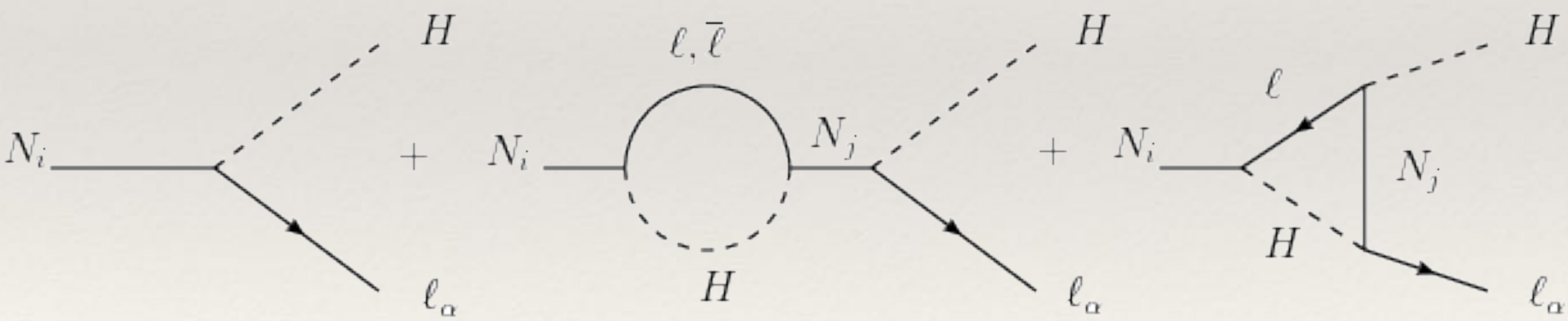
- ***N* are around in the early universe**
- ***N* interactions are CP violating**
- ***N* may preferably decay into matter**

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

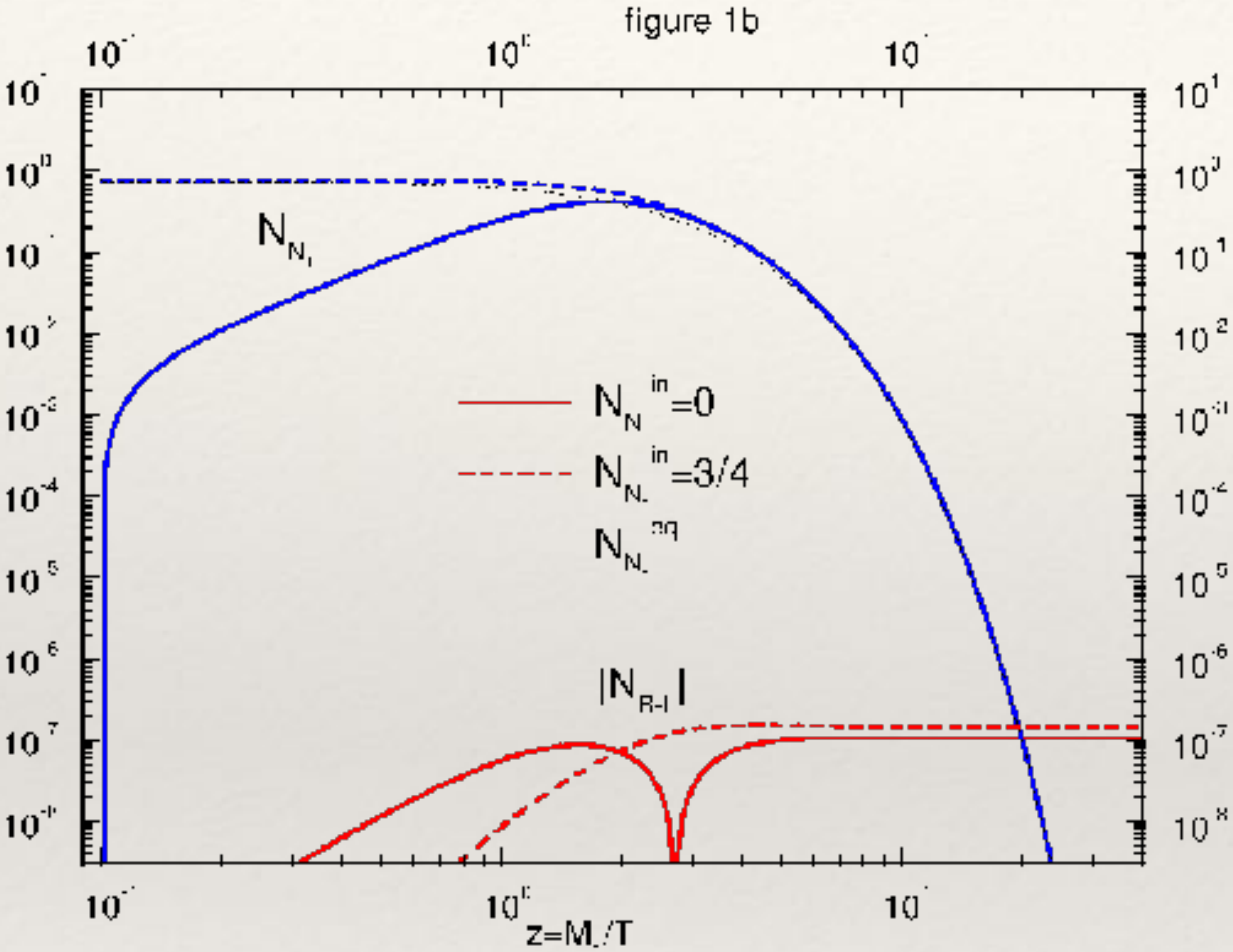
$$Y_{B-L} \propto \epsilon/g_*$$



asymmetry arises from quantum interference in the plasma

⇒ we derive quantum kinetic equations from first principles

Leptogenesis with small M?



Buchmuller / Di Bari / Plumacher 0205349

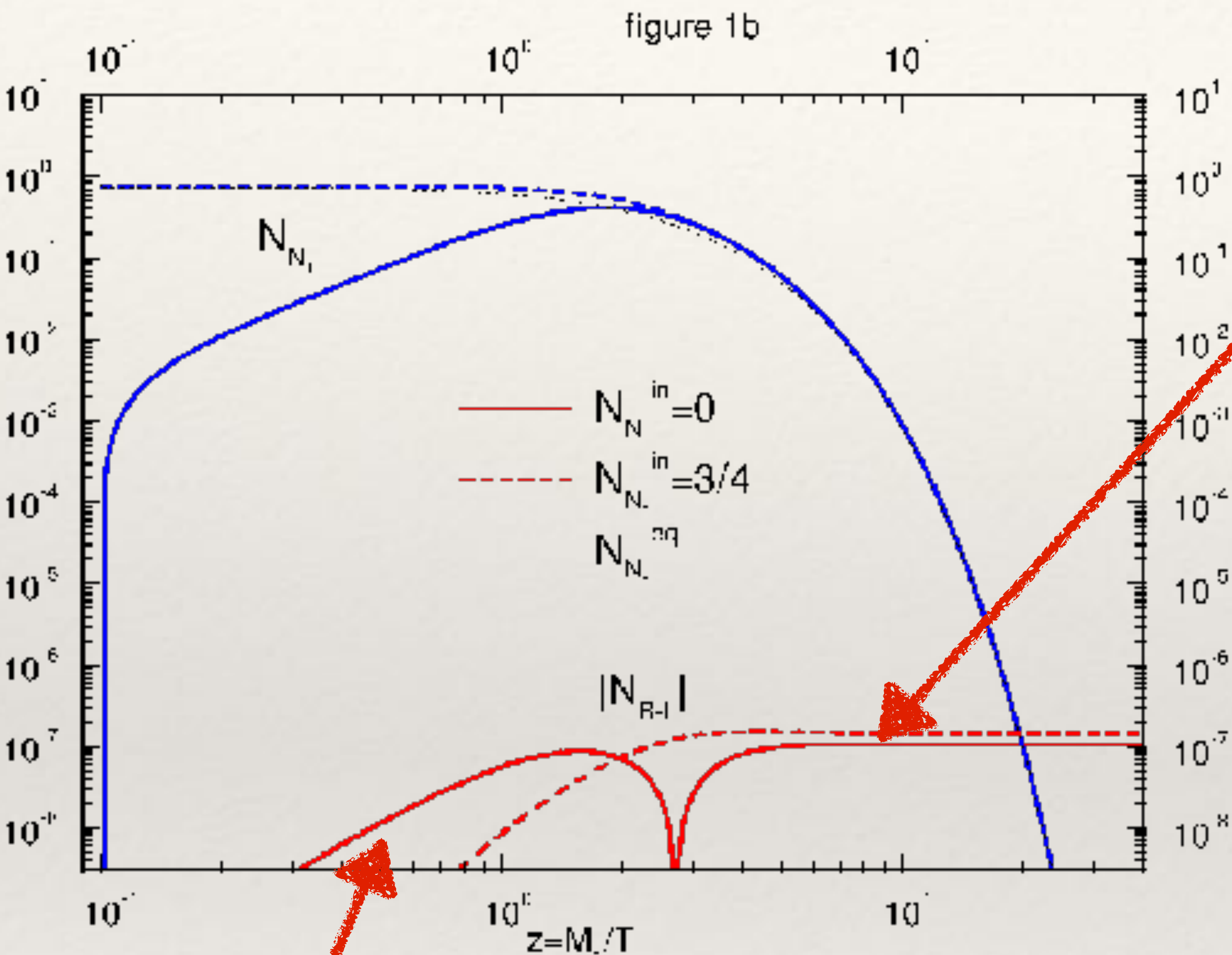
What about the famous Davidson-Ibarra bound M > 10 ^{9} GeV? 0202239

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

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

"source" "washout"

Leptogenesis with small M?



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

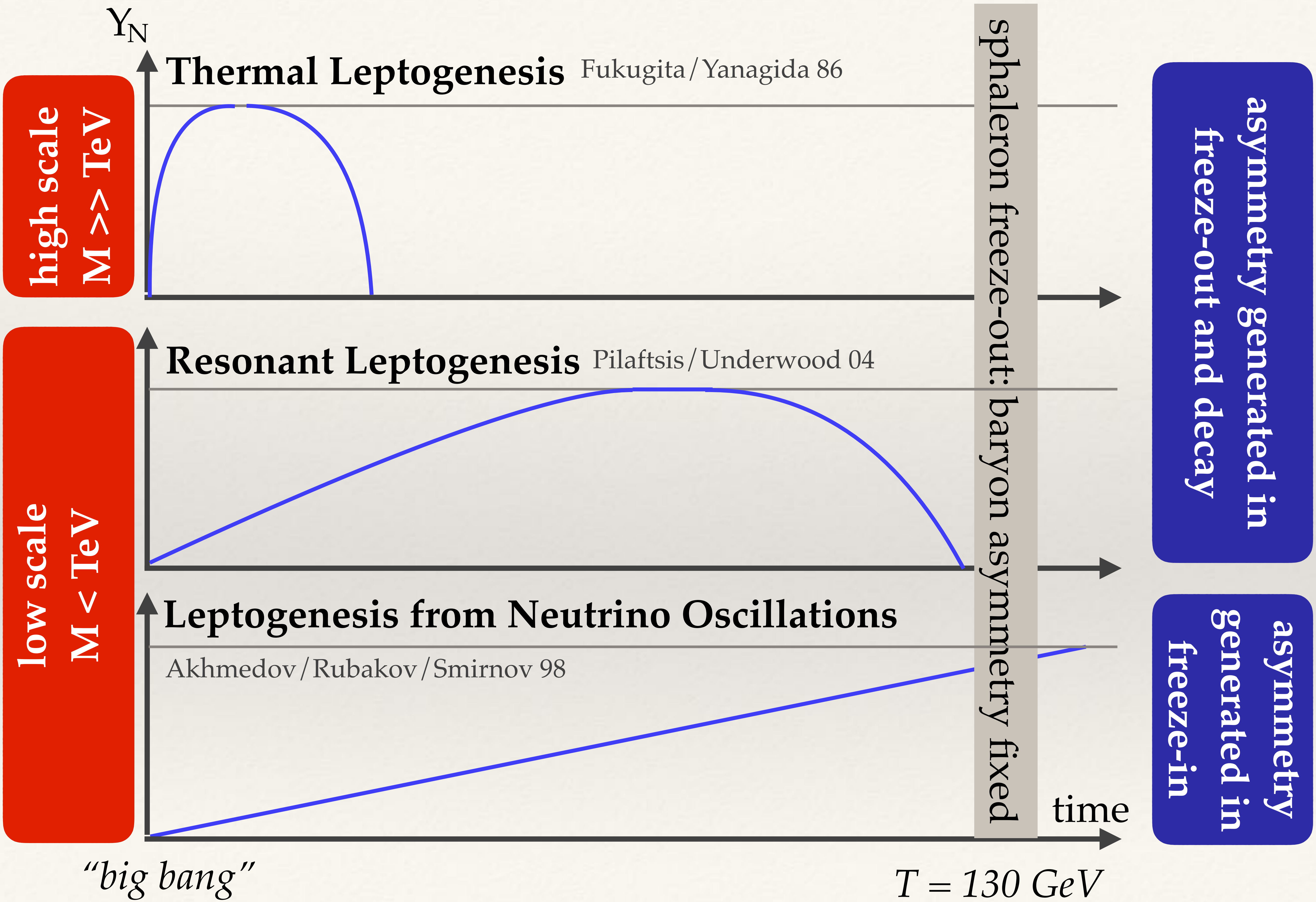
Sakharov's nonequilibrium condition can be fulfilled in two ways.

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

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

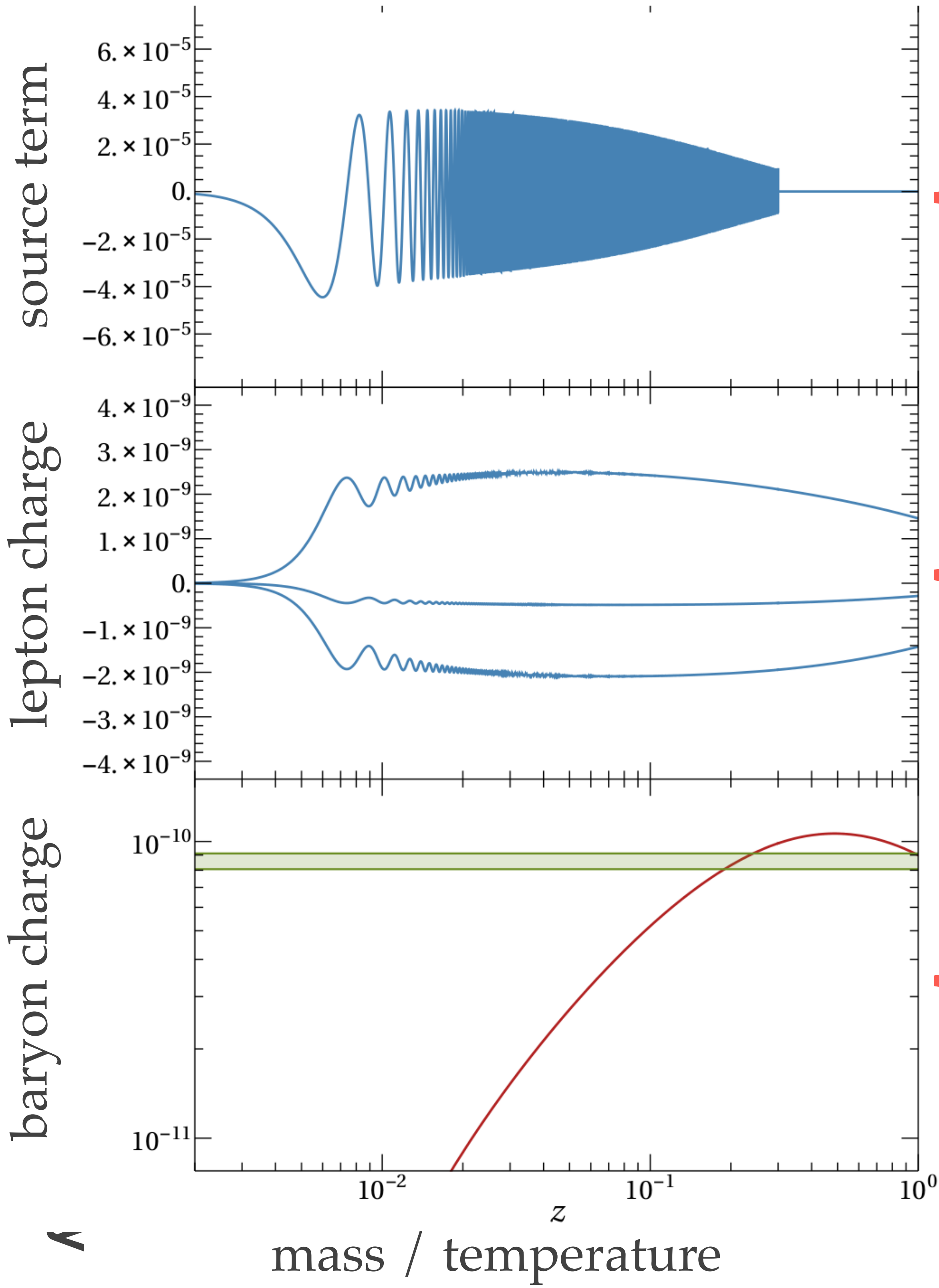
$$xH\frac{dY_{B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{eq}) - c_W\Gamma_N Y_{B-L}$$

"source" "washout"



Y_N
Thermal Leptogenesis
Fukugita/Yanagida 86
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

Freeze-In Leptogenesis

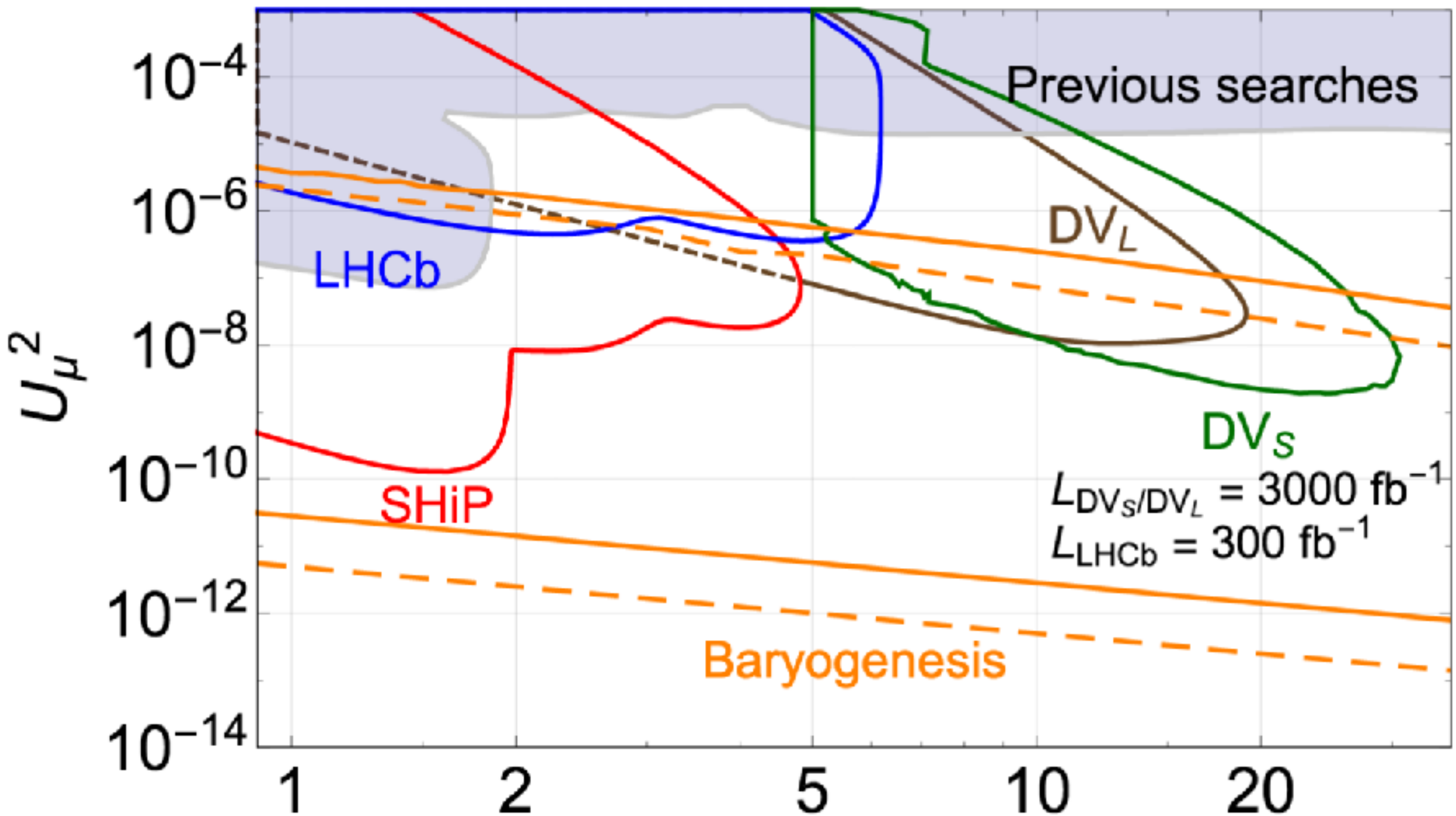


Heavy Neutrinos undergo CP violating oscillations during heat production.

This induces asymmetries in the SM lepton flavours.

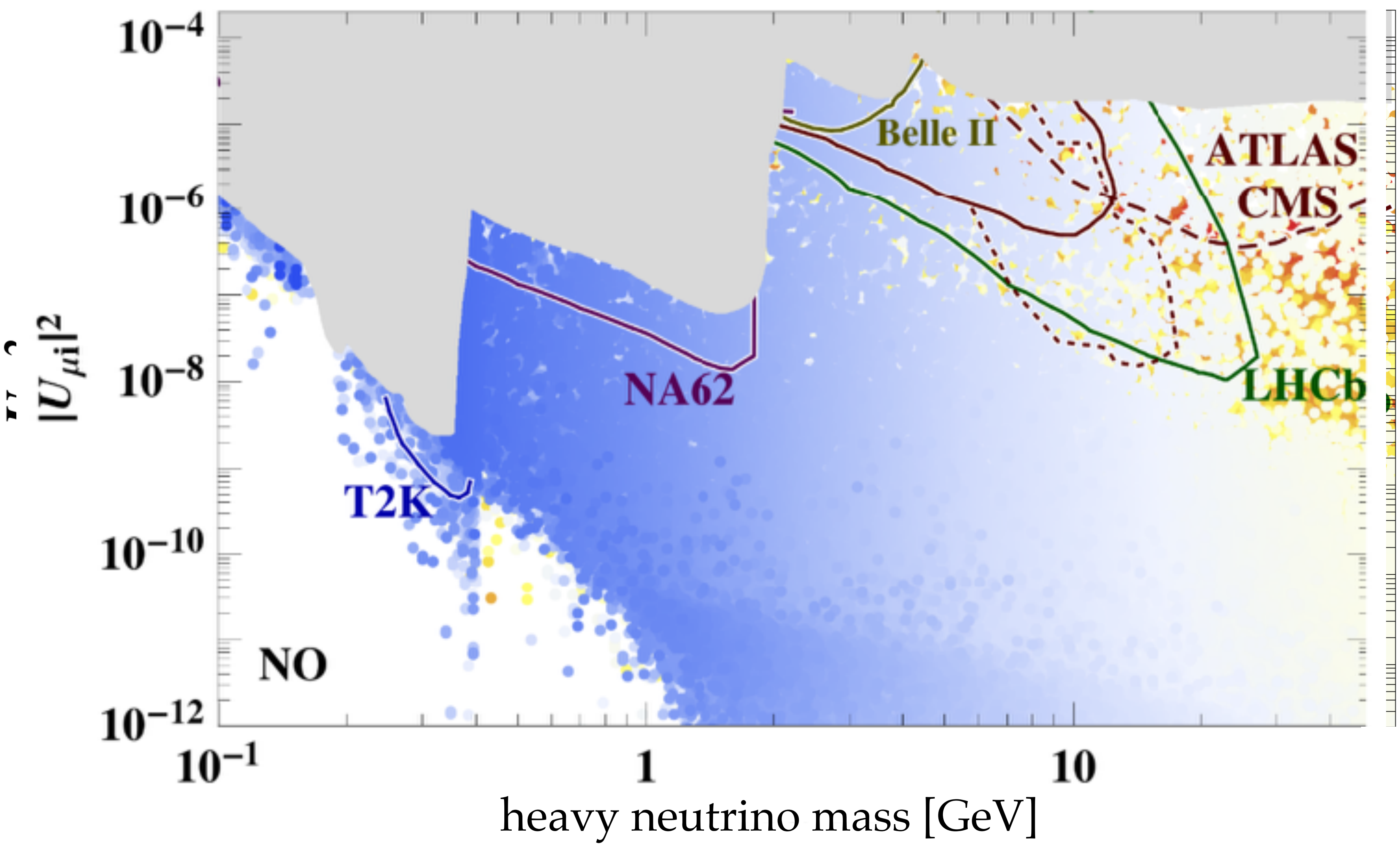
Sphalerons partly transfer the asymmetries into a baryon number.

Leptogenesis in the νMSM



Plot from Boiarska et al 1902.04535 , leptogenesis computation used on Eijima et al 1808.10833

Leptogenesis with three HNLs



plot from
Abada et al 1810.12463

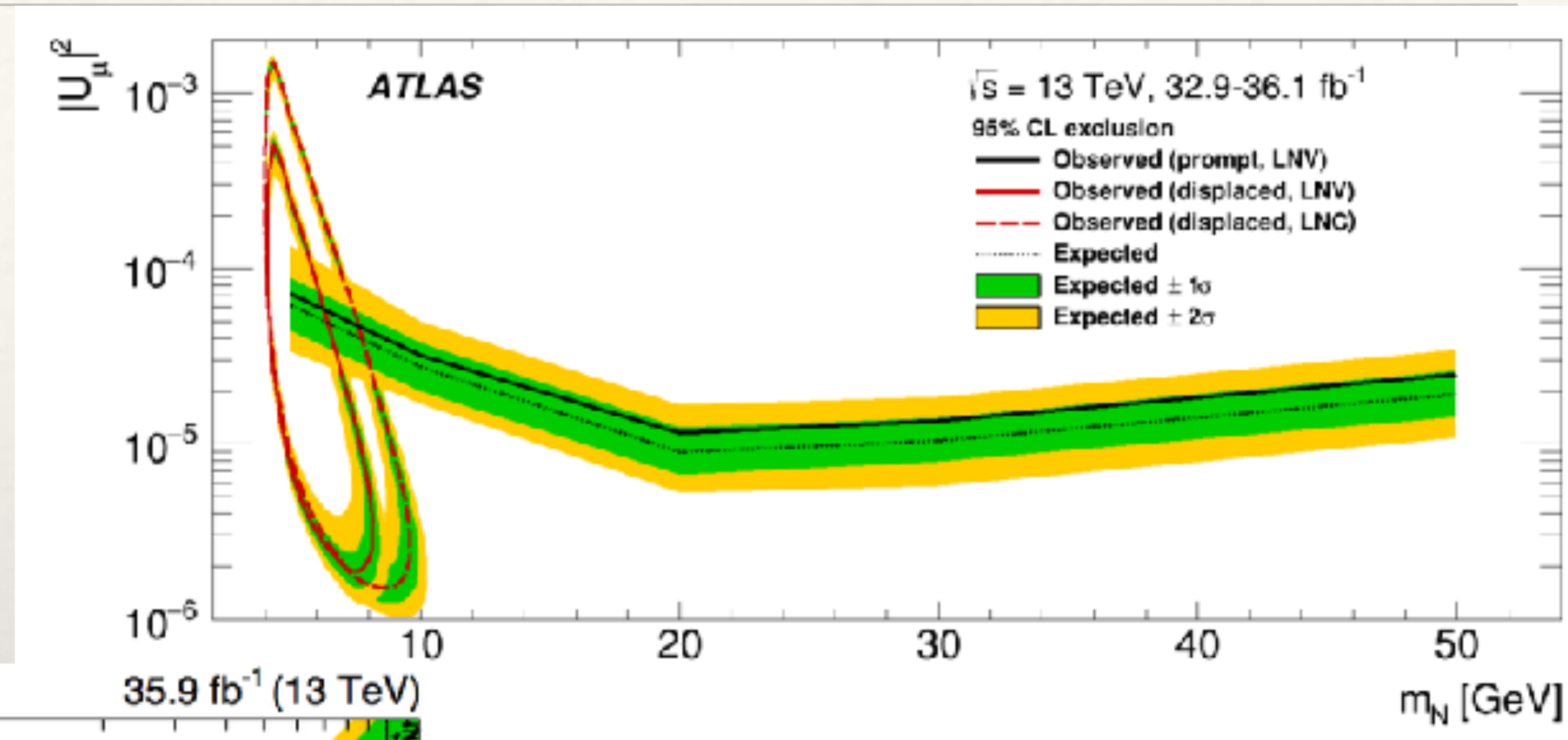
Parameter space grows in all directions!

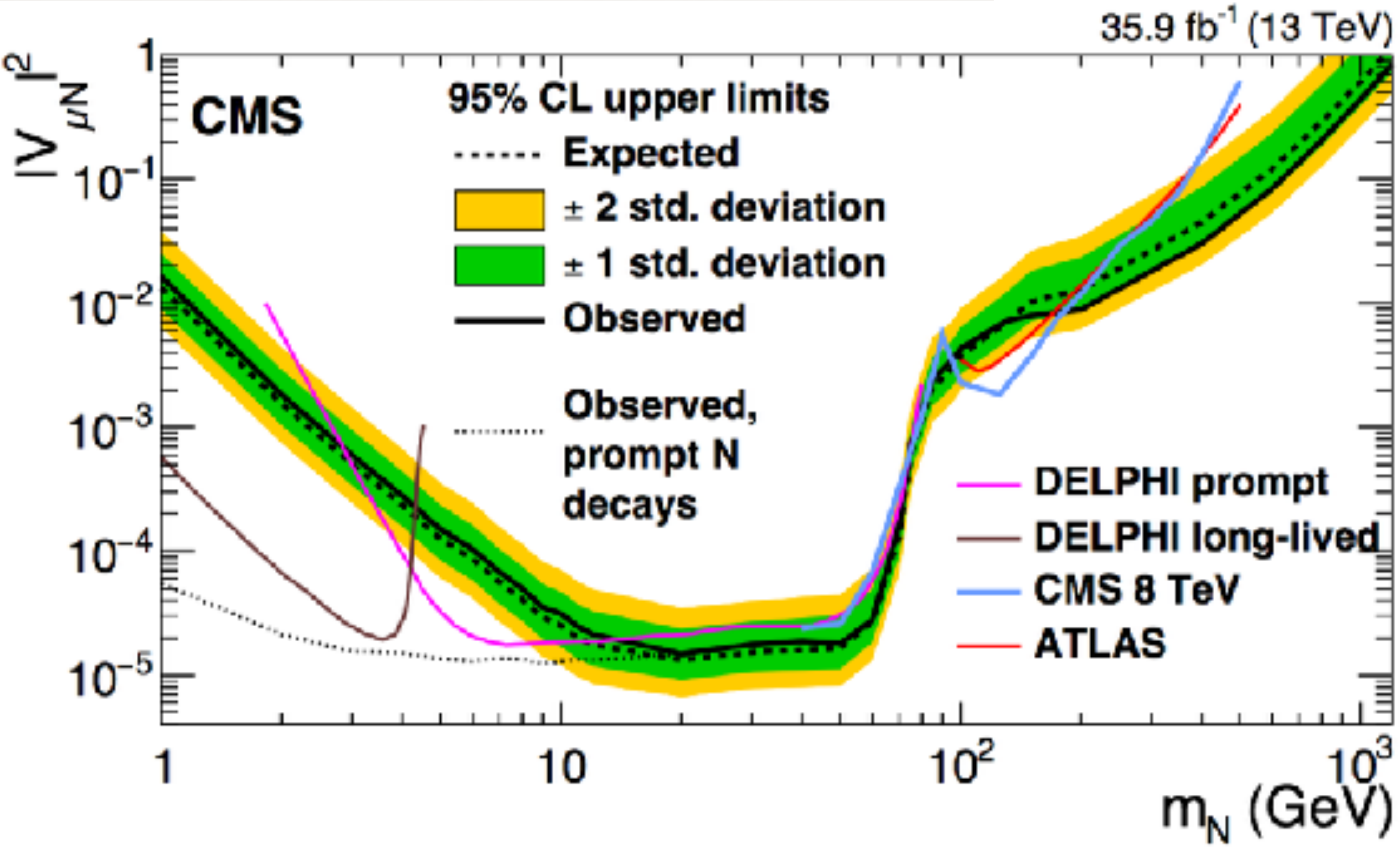
- **colourful points: leptogenesis + neutrino masses with three HNLs**
- **colour code measures the degree of fine tuning**

LHC Displaced Searches

Recent LHC Results

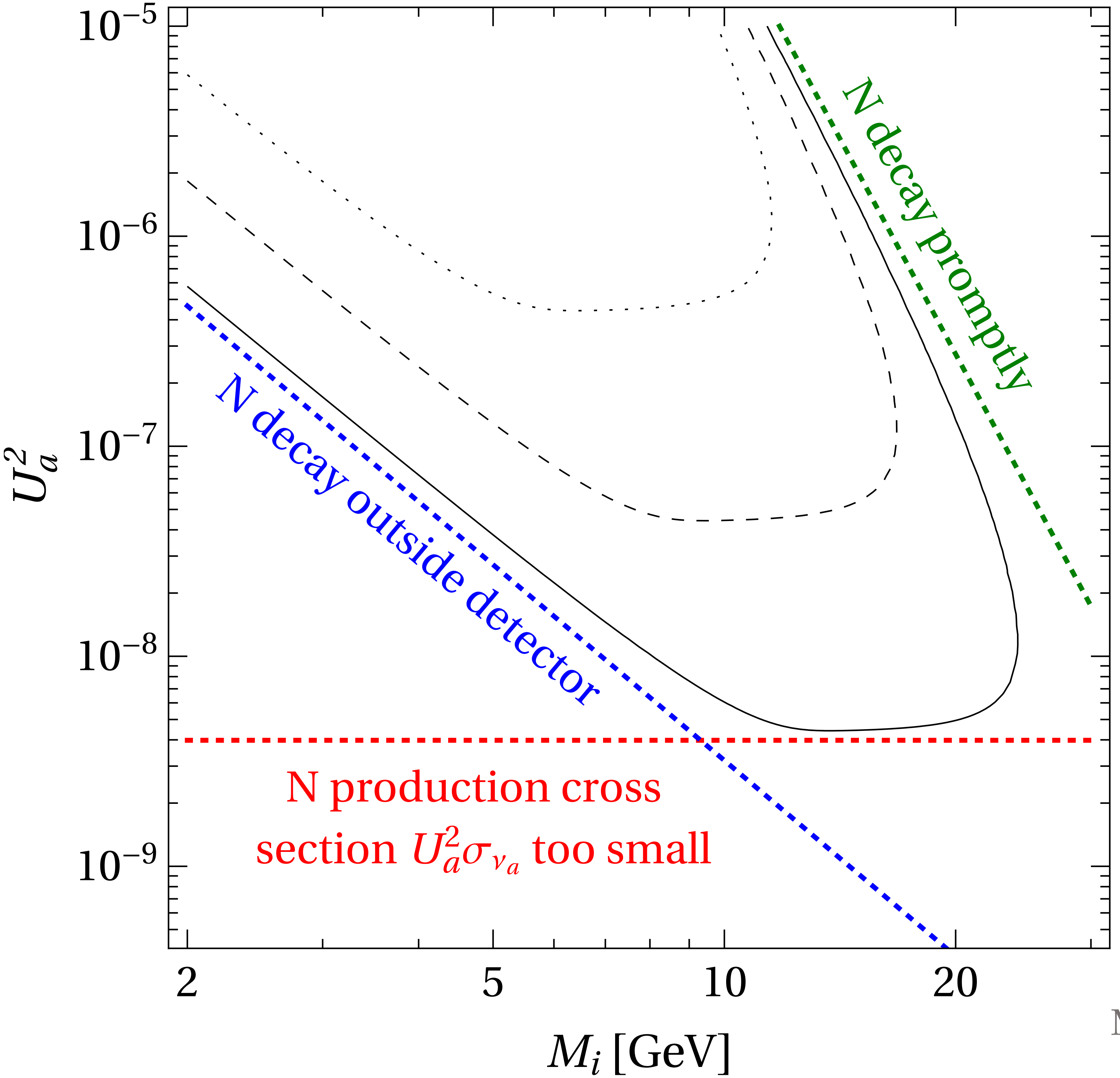
ATLAS trilepton search
prompt and displaced
LNV or LNC
1905.09787





CMS trilepton search
prompt decays only
LNV or LNC
1802.02965

Displaced Vertex Sensitivity Region



MaD / Hajer 1903.06100

Future LHC Searches

prompt decays at the LHC

Izaguirre / Shuve 1504.02470

Pascoli / Ruiz / Weiland 1812.08750

displaced vertices at the LHC

MaD / Hajer 1903.06100

see also

Helo et al 1312.2900

Izaguirre / Shuve 1504.02470

Gago et al 1505.05880

Dib / Kim 1509.05981

Cottin et al 1806.05191

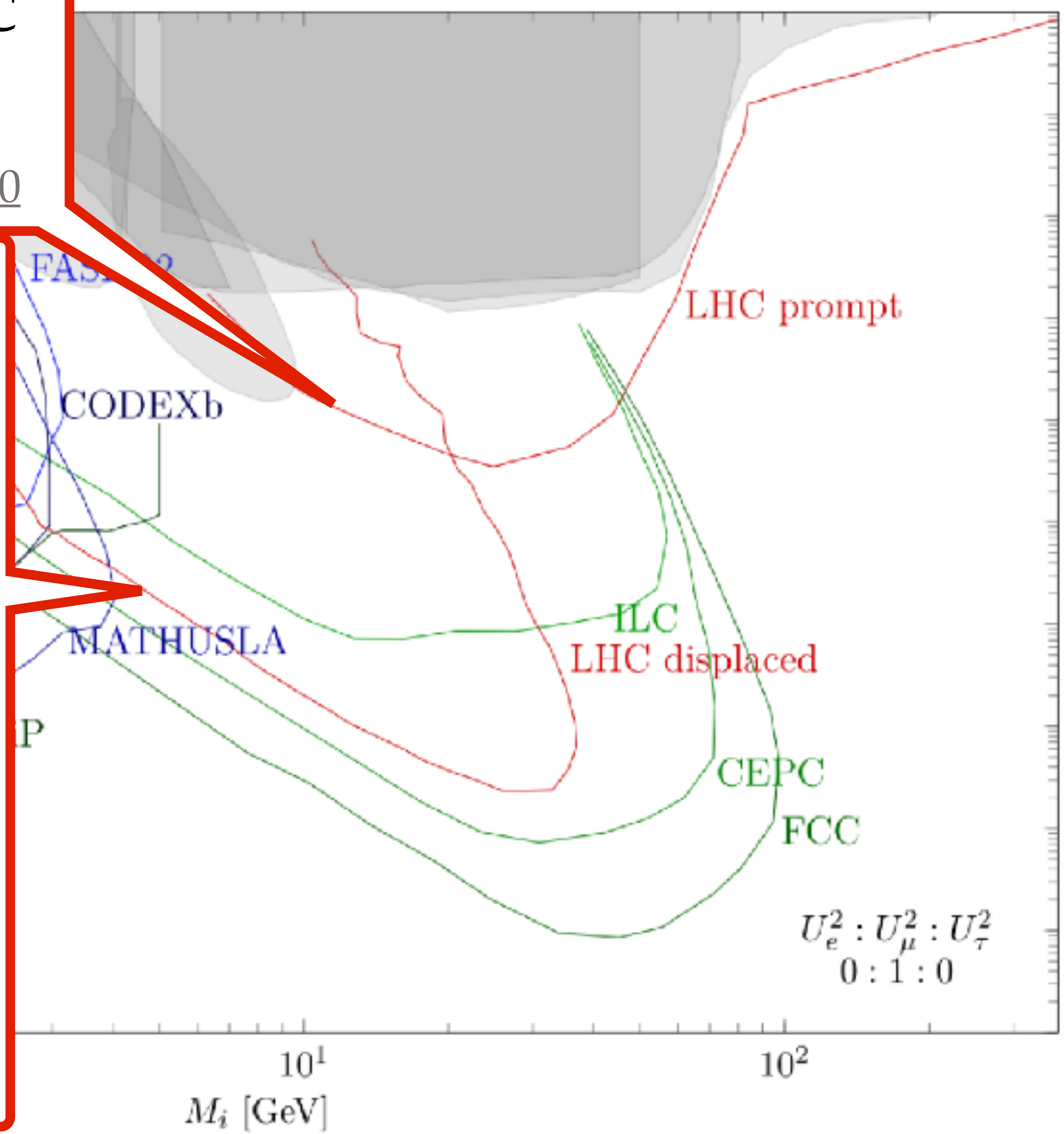
Abada et al 1807.10024

Boiarska et al 1902.04535

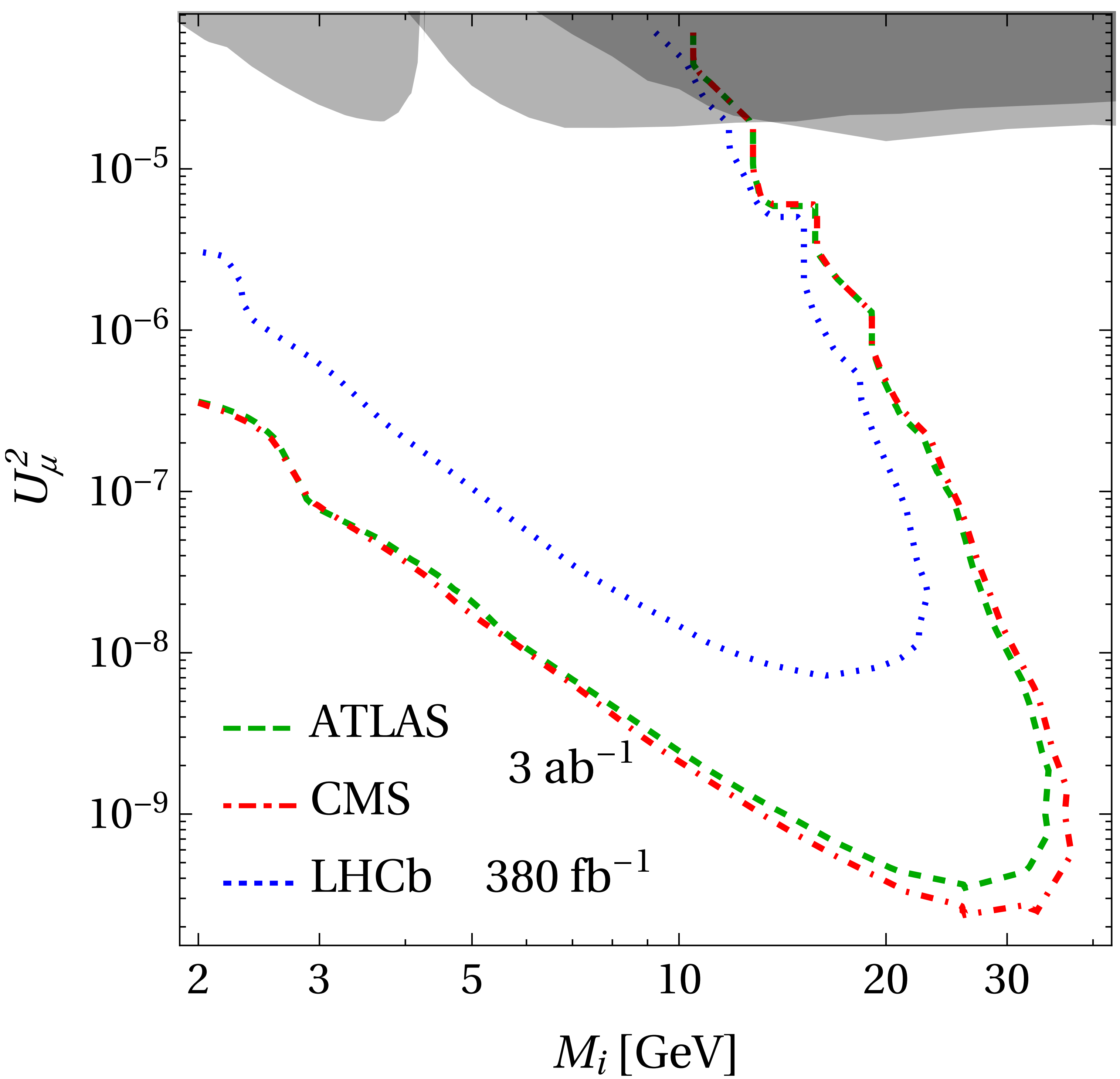
Liu et al 1904.01020

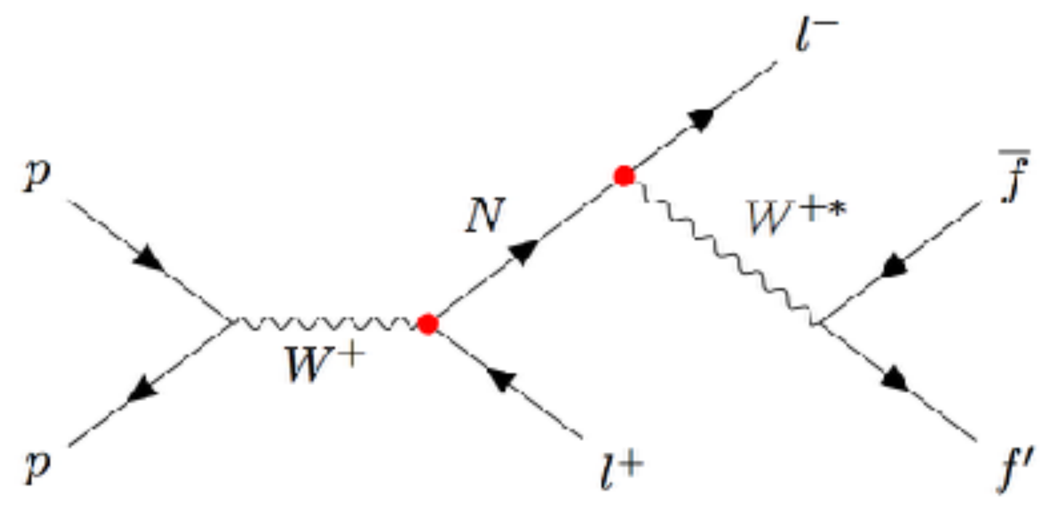
Dib et al 1903.04905

Cvetic et al 1805.00070, 1905.03097

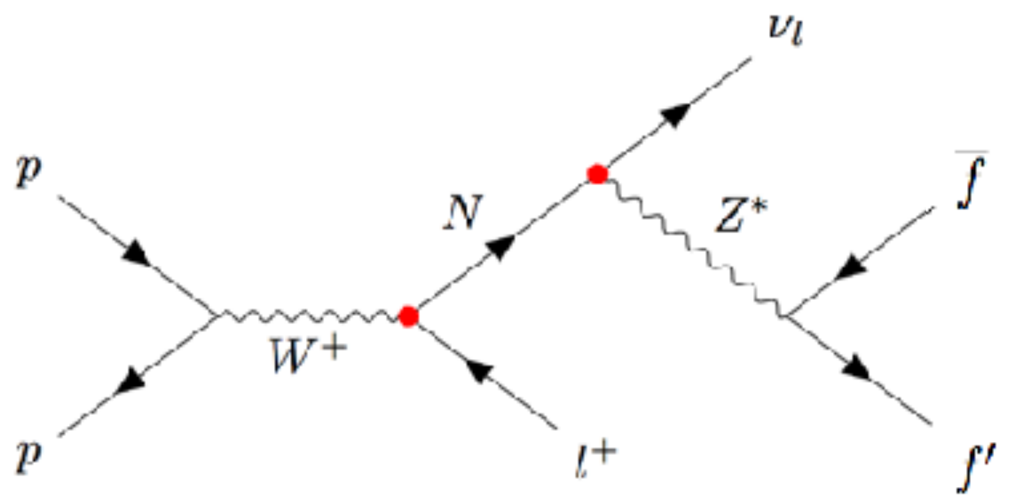


HL-LHC Displaced Vertex Search





(a) Charged current decay



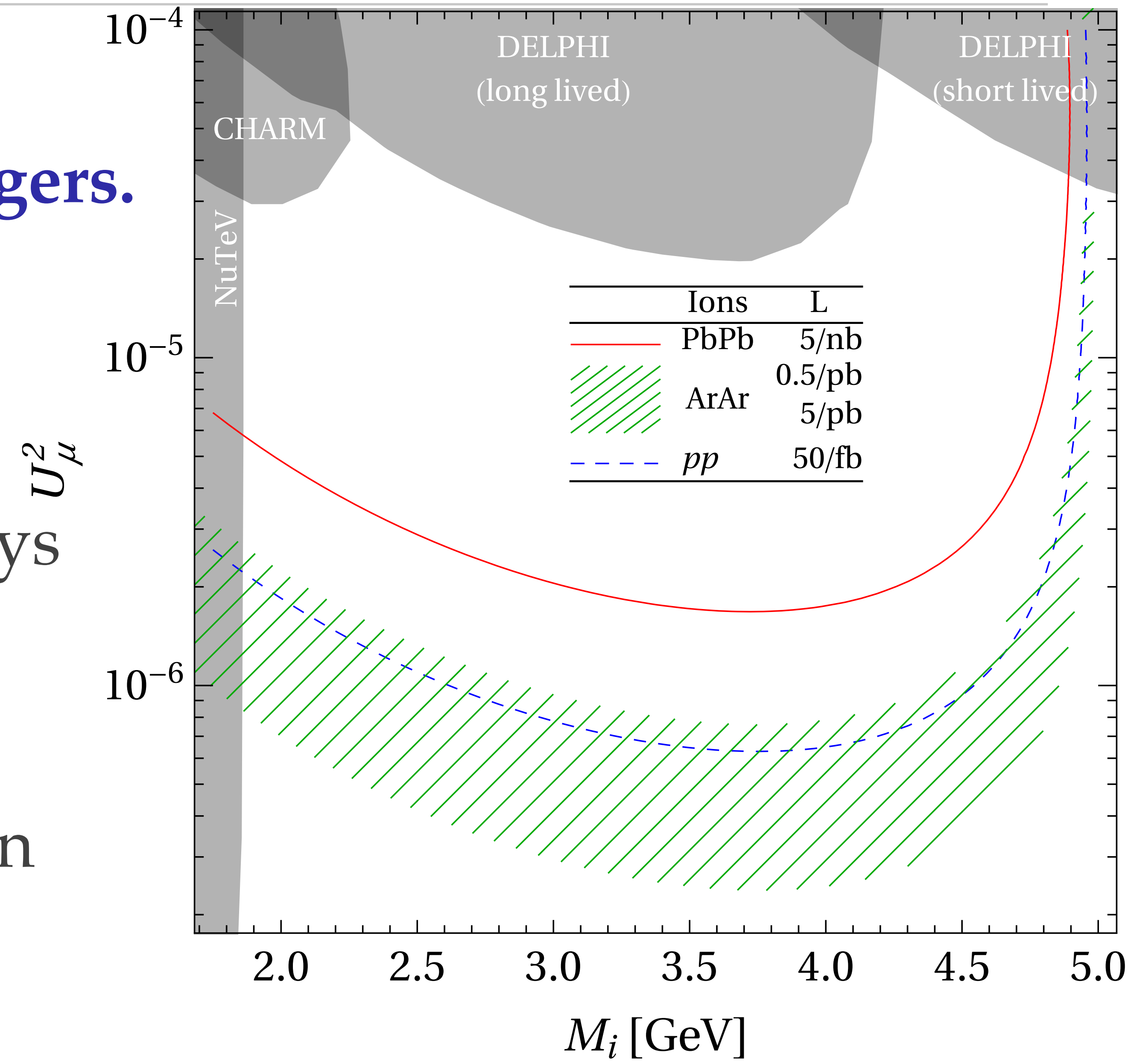
(b) Neutral current decay

MaD / Hajer 1903.06100

A Heavy Metal Path to New Physics

In heavy ion runs: use very low triggers. Allows to search for low p_T events!

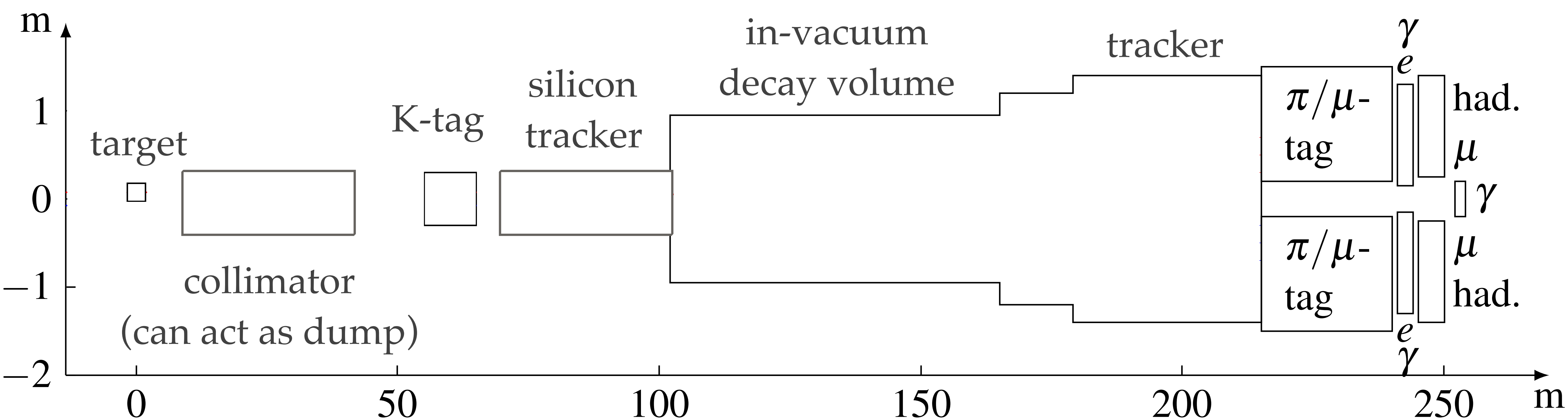
- HNLs with masses below 5 GeV can be produced in B meson decays
- Searches at CMS and ATLAS are difficult because of the low transverse momentum (more than 99% of them have below 25 GeV)
- Low triggers in heavy ion runs allow to collect this data



MaD / Giammanco / Hajer / Lucente 1905.09828

Fixed Target Experiments

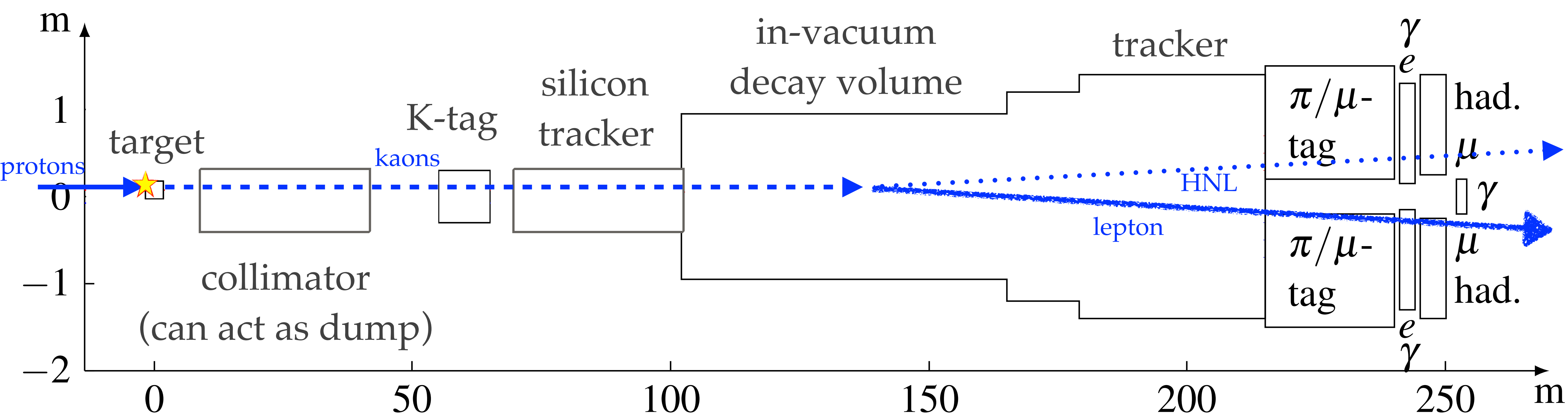
The NA62 Experiment



- **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

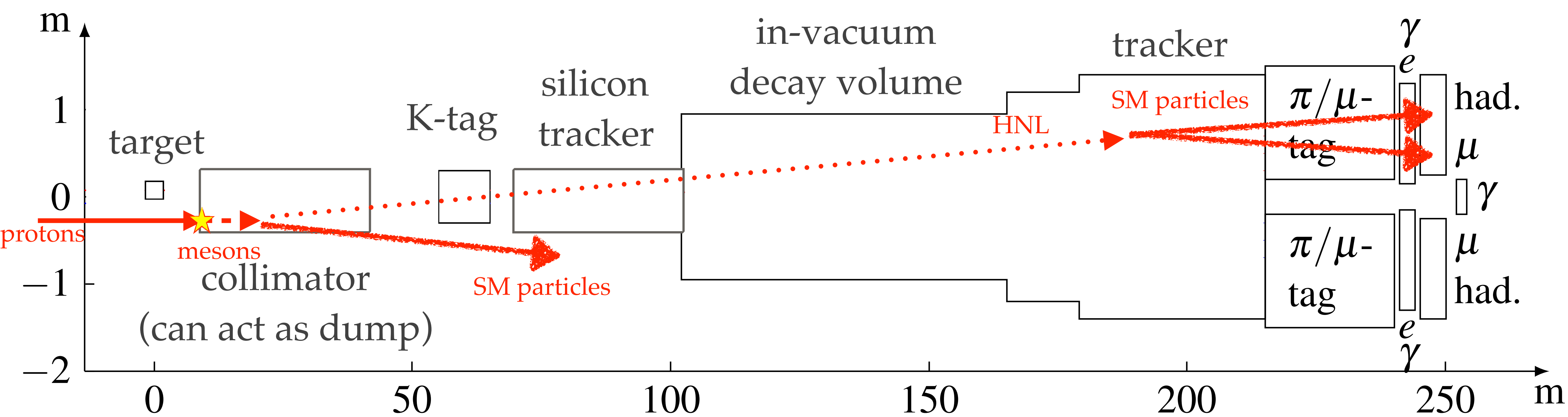


Target Mode:

- 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 Dump Mode

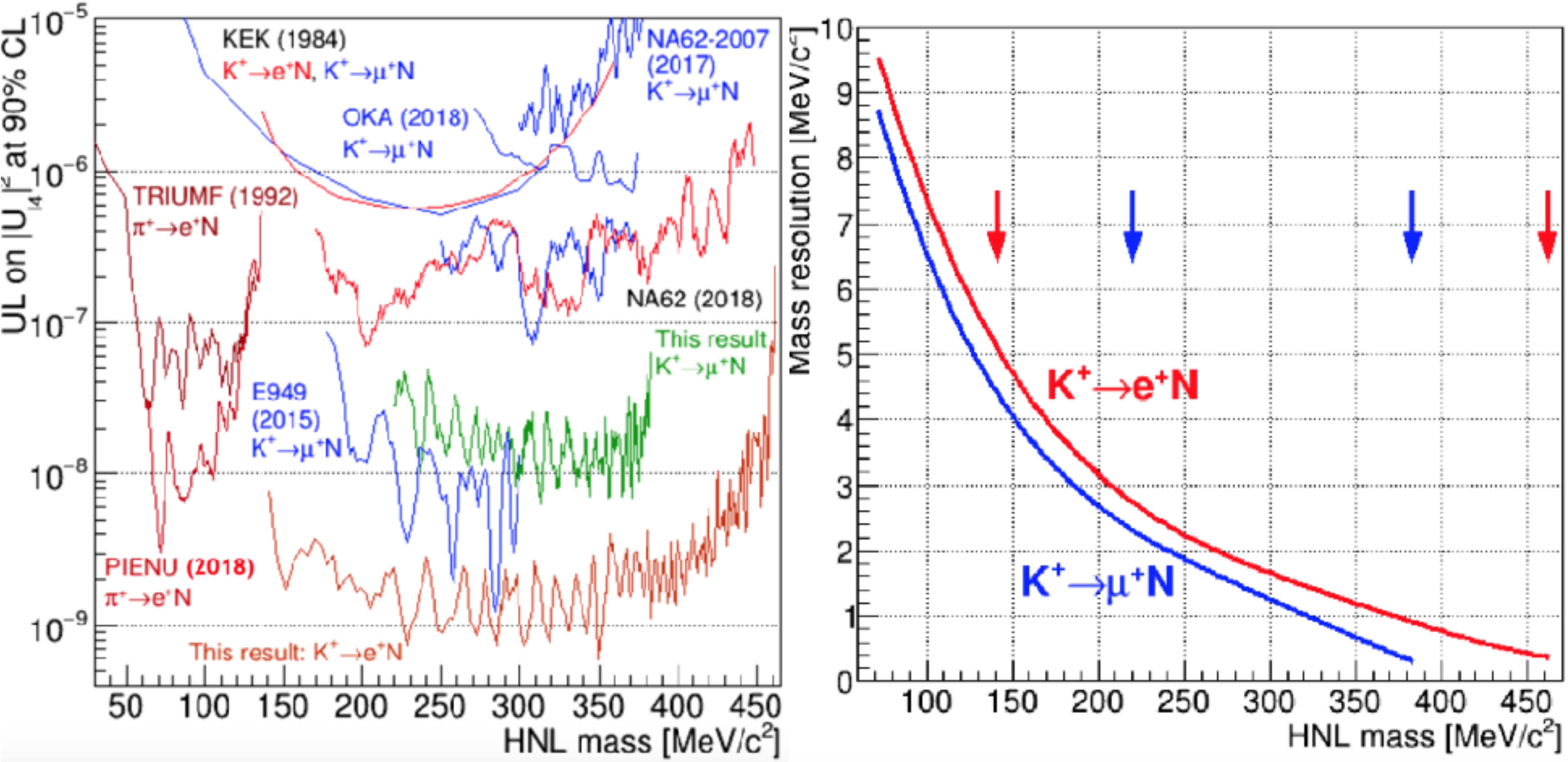


Dump mode

- 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**

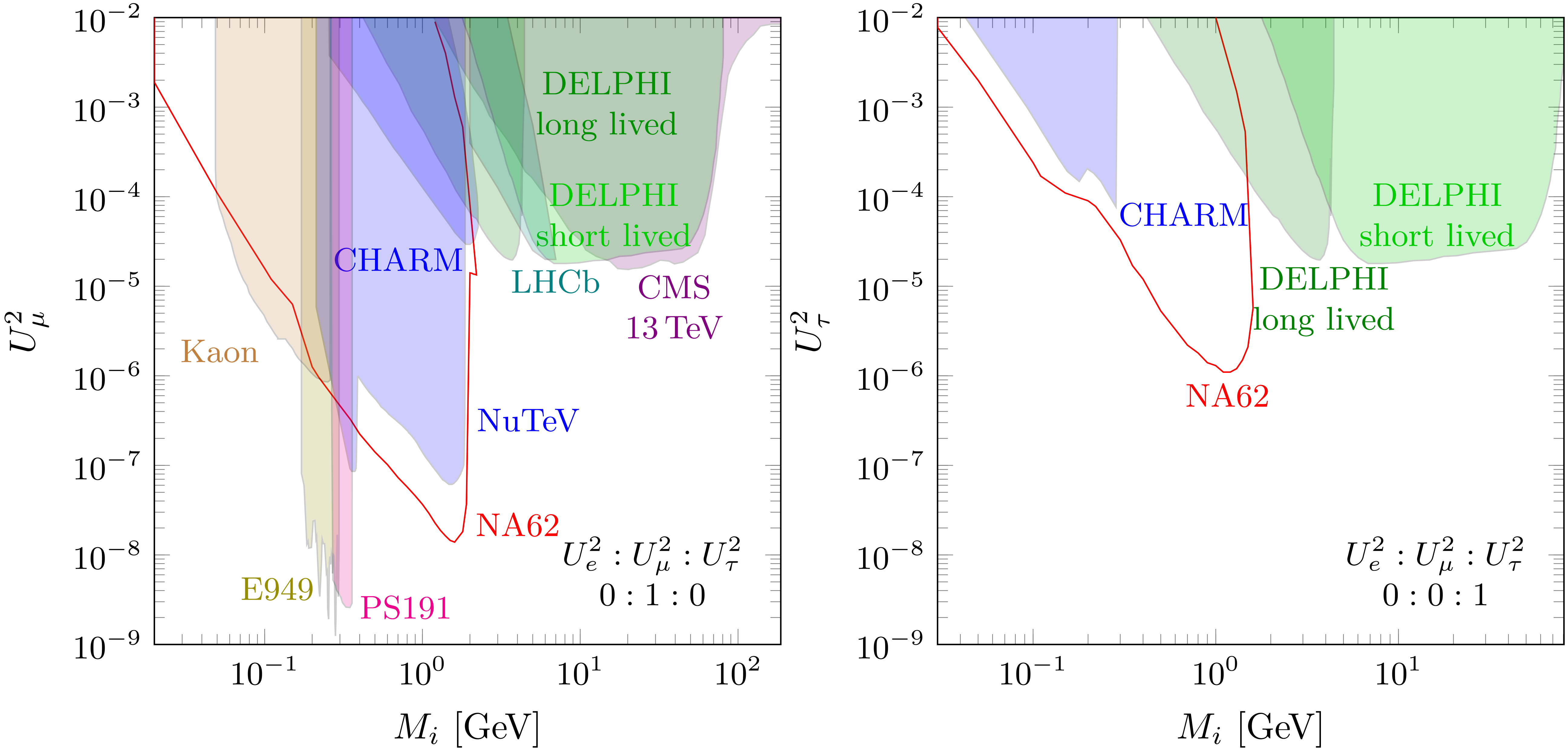
NA62 Kaon Mode: First Results



from Evgueni Goudzovski's talk at Kaon 2019, see also talk by Artur Shaikhiev here

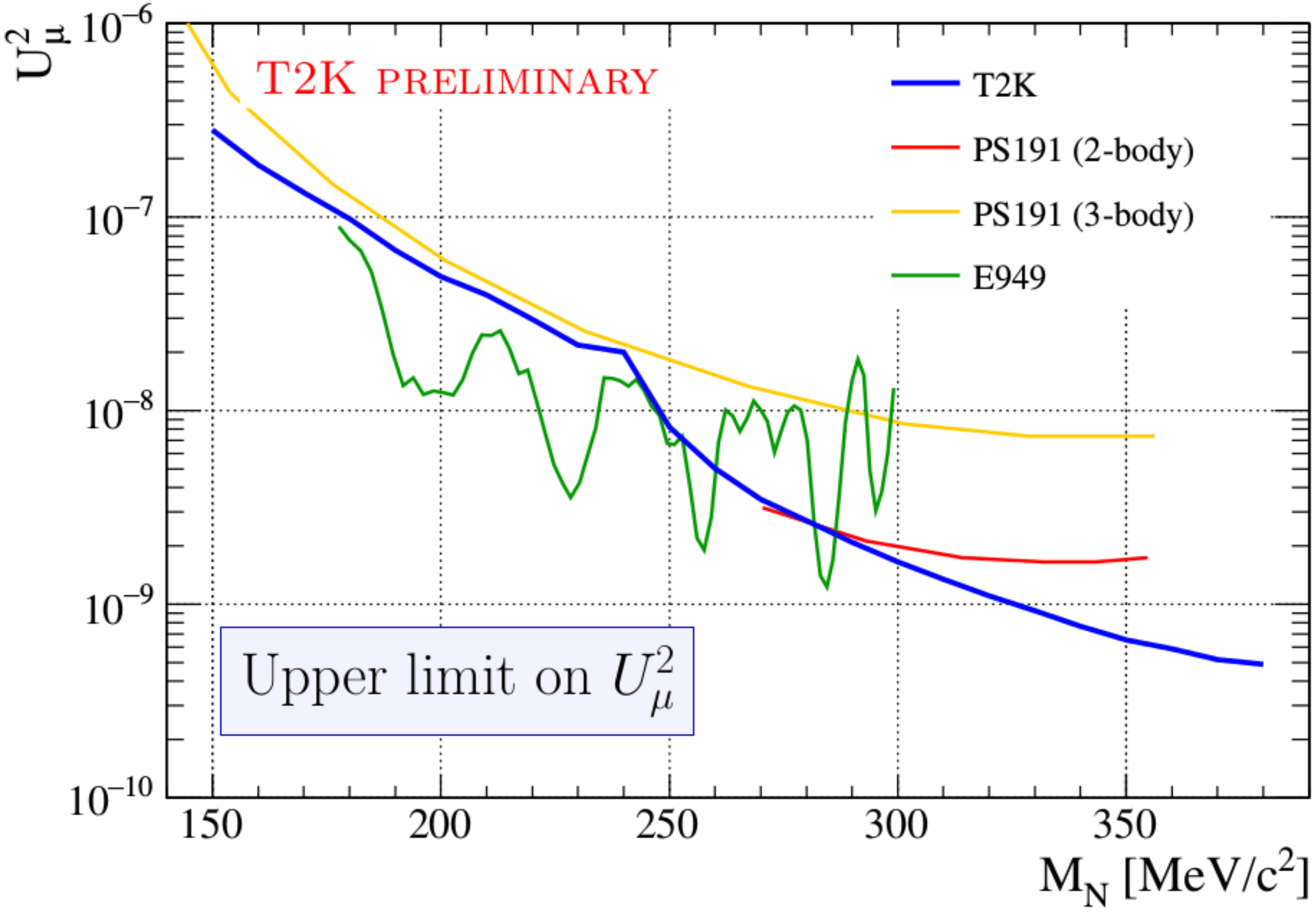
see also Cortina-Gil et al 1712.00297

NA62 Dump Mode Sensitivity



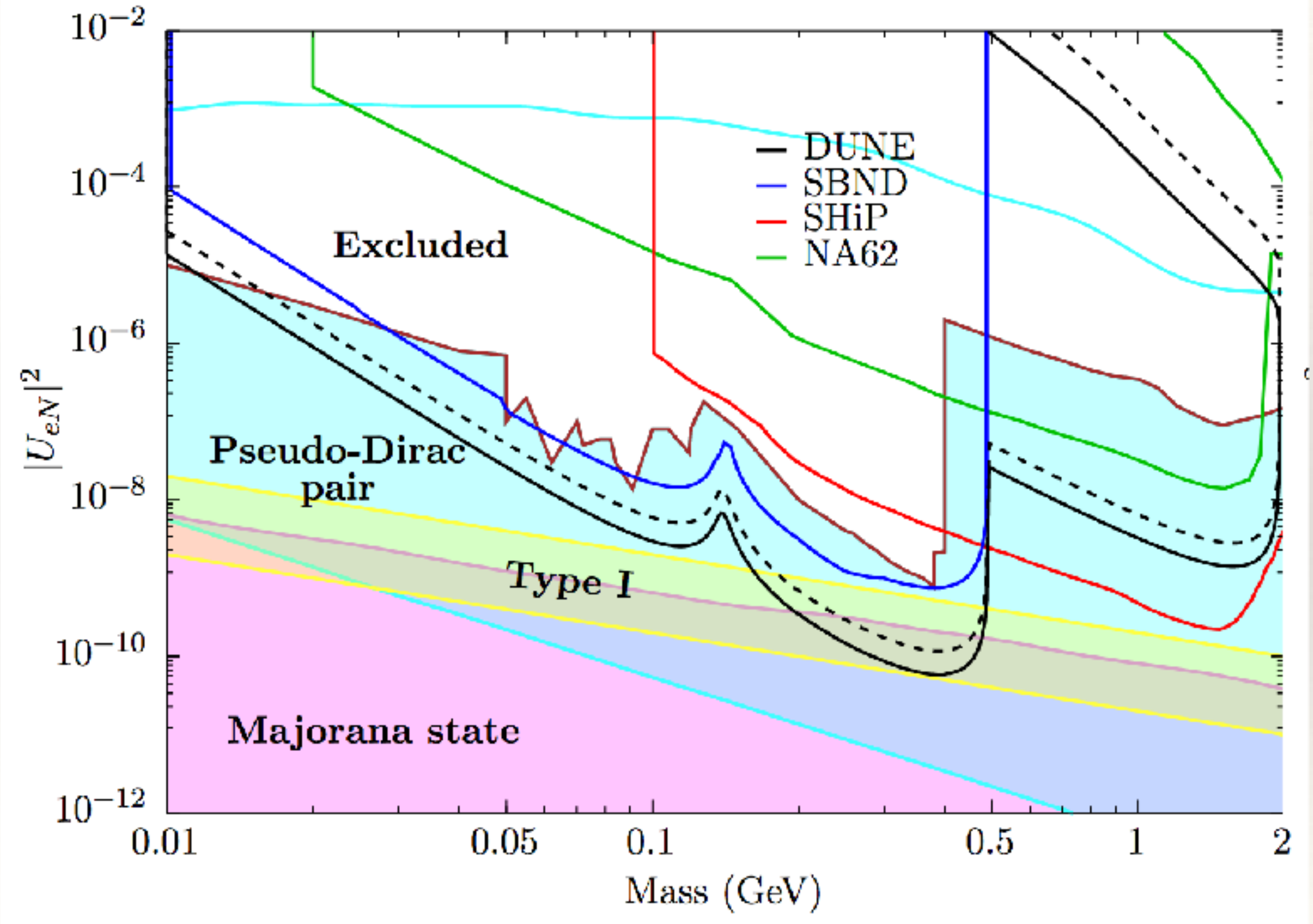
MaD / Hajer / Klaric / Lafranchi 1801.04207

T2K



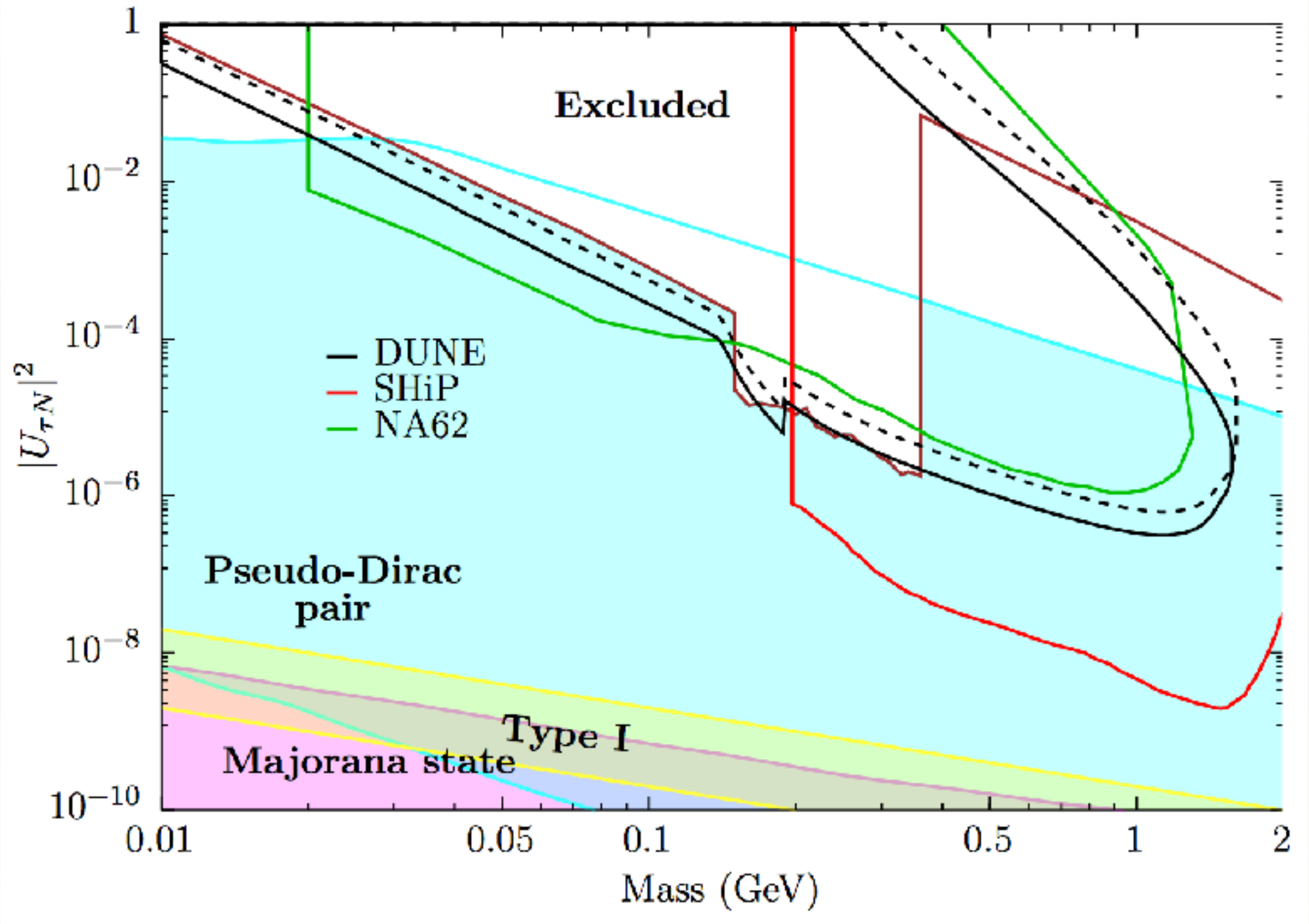
Abe et al 1902.07598

DUNE Near Detector



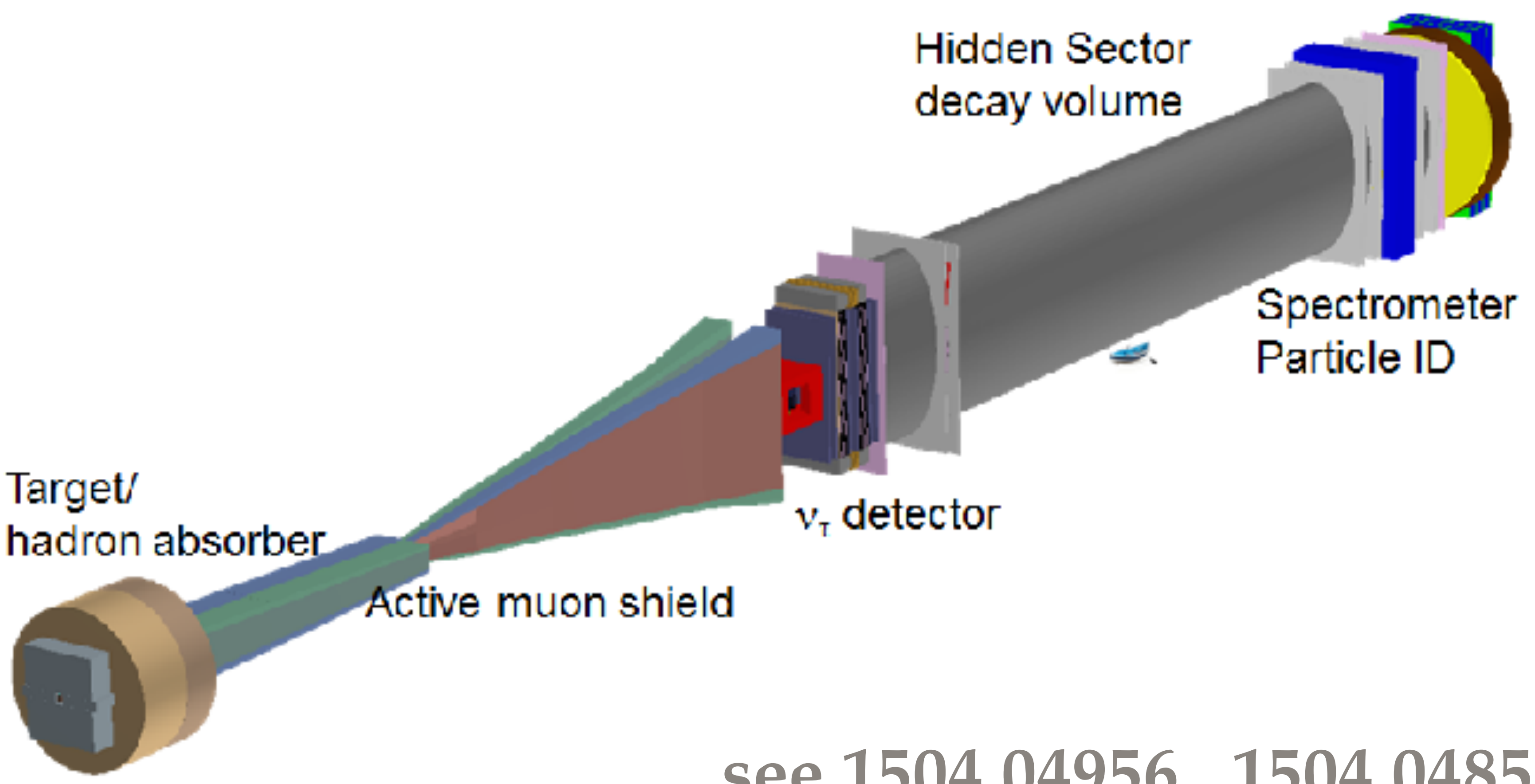
Plot from 1905.00284, see also Krasnov 1902.06099

DUNE Near Detector



Plot from 1905.00284, see also Krasnov 1902.06099

The SHiP Proposal



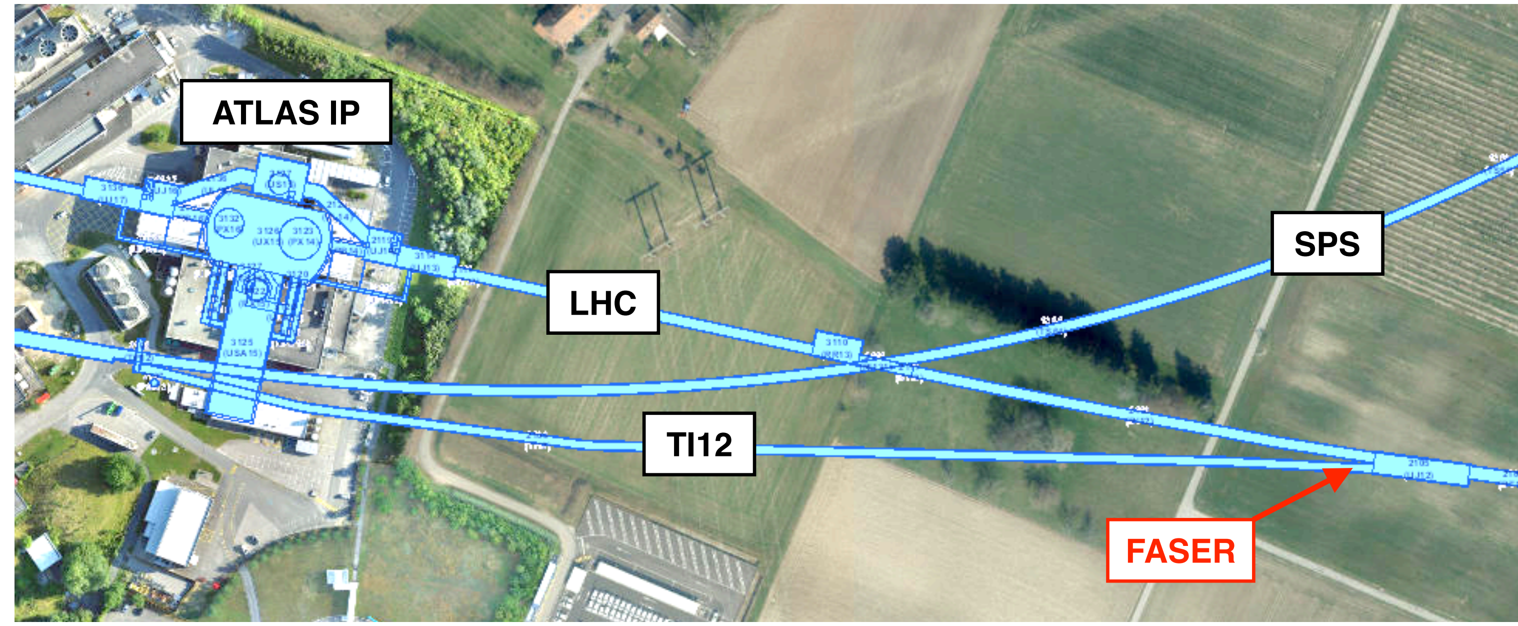
see 1504.04956 , 1504.04855

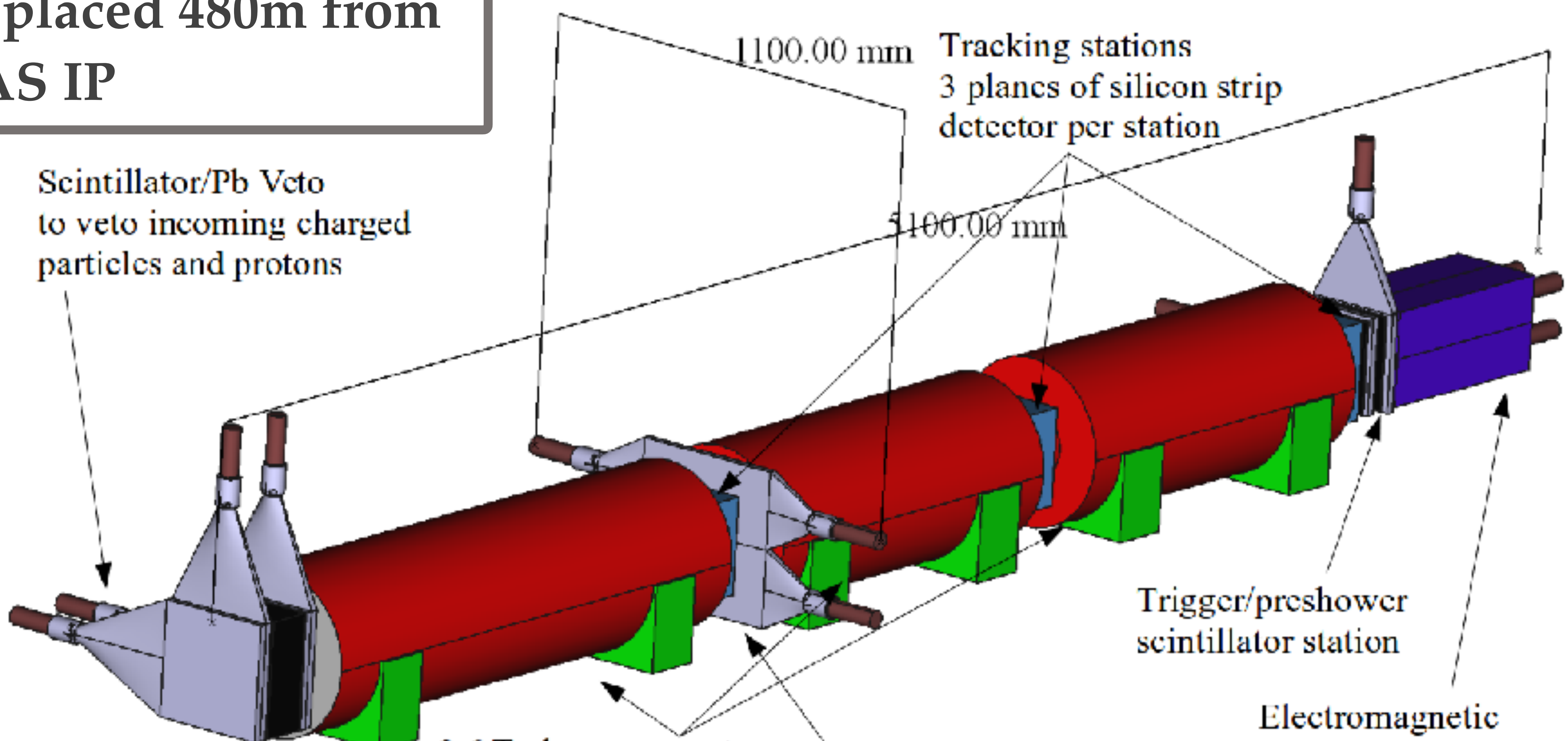
Search for Hidden Particles

- new fixed target experiment using SPS beam with 10^{20} protons on target
- would be world's most sensitive fixed target experiment

Future Detectors

- dedicated LLP detector
- size: 20cm x 5m
- to be placed 480m from ATLAS IP

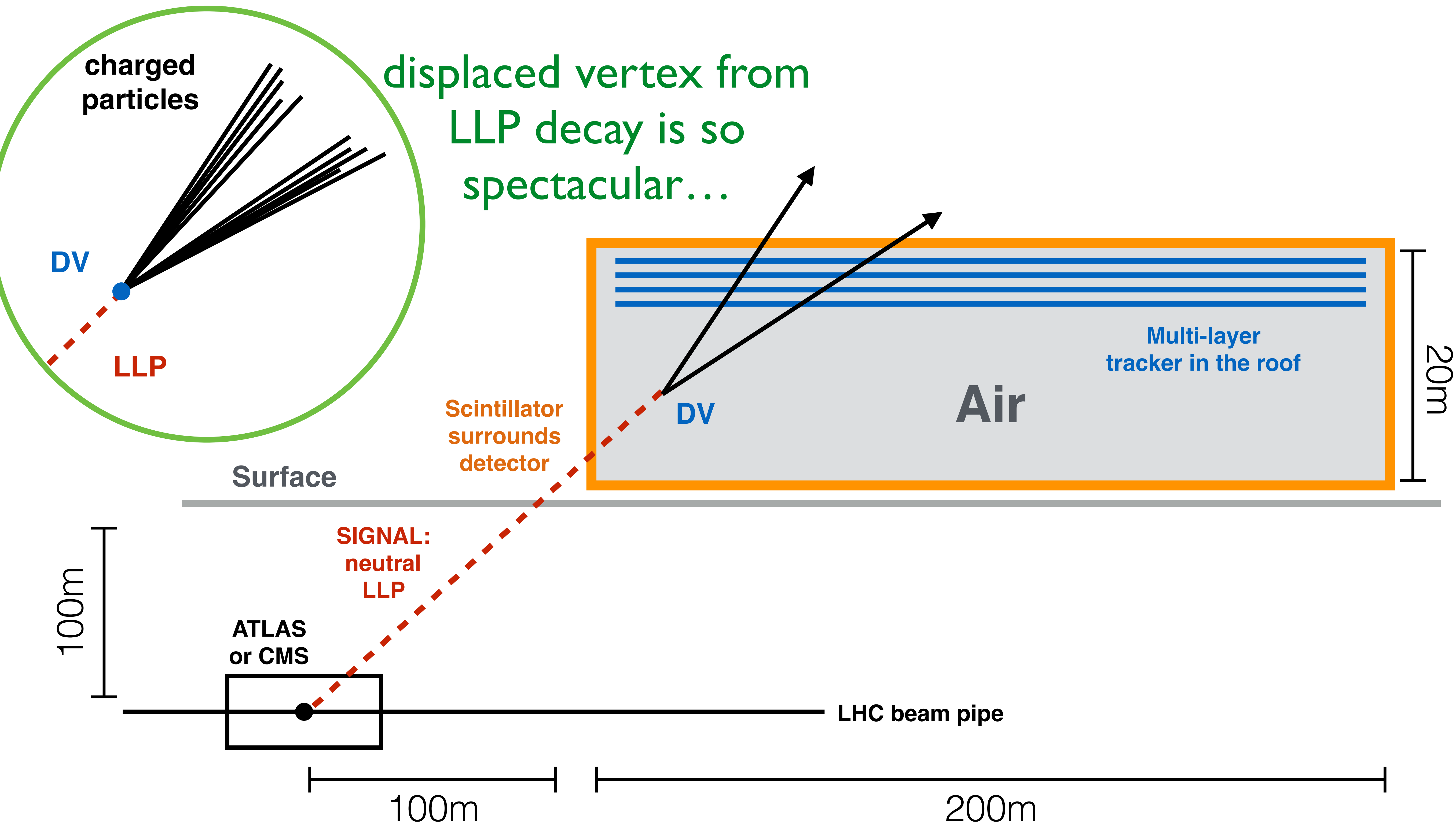




FASER 1812.09139

MATHUSLA

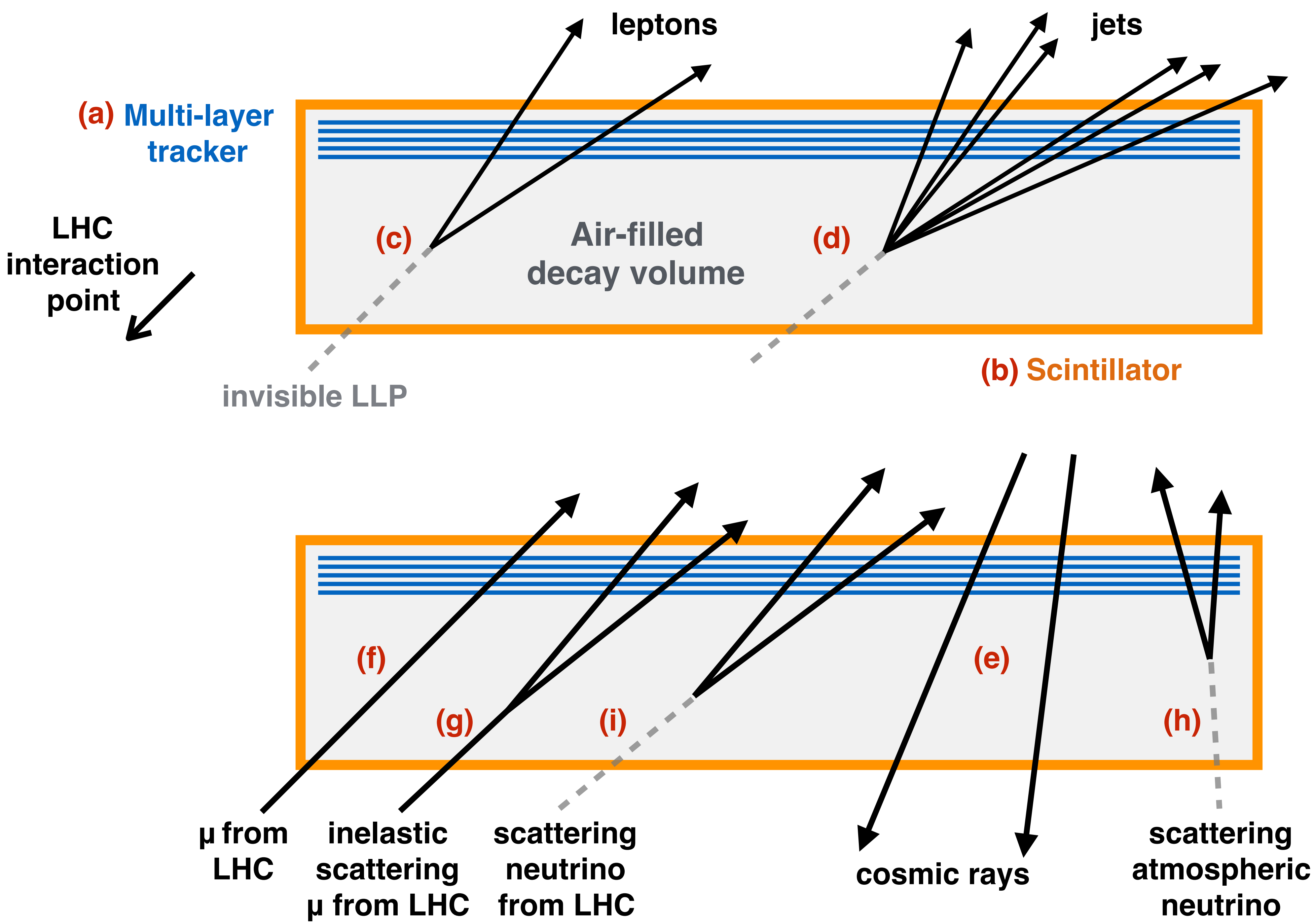
MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles



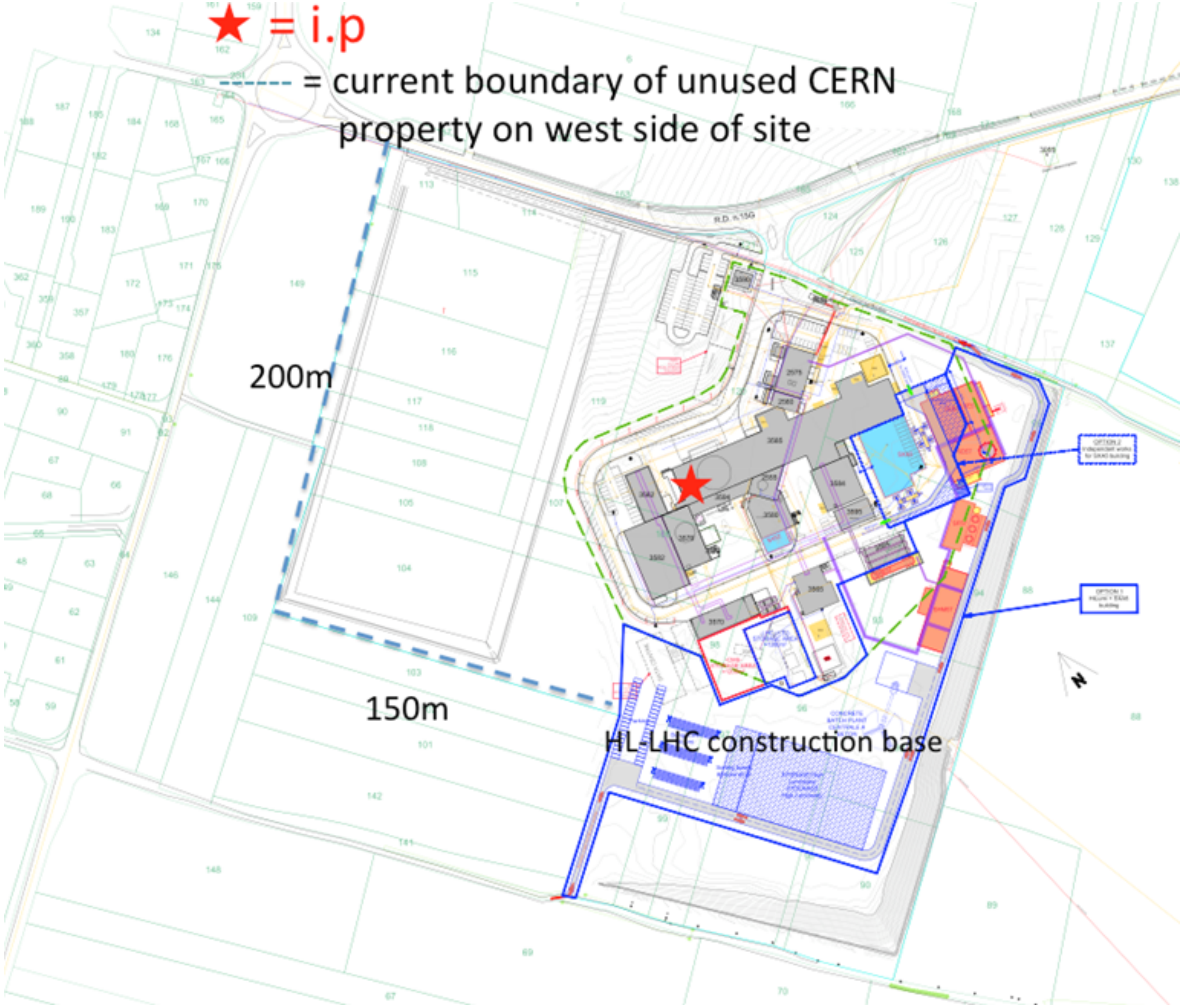
MATHUSLA physics case 1806.07396

slide by David Curtin

Schematic Design



Where to put this?



MATHUSLA Test Stand

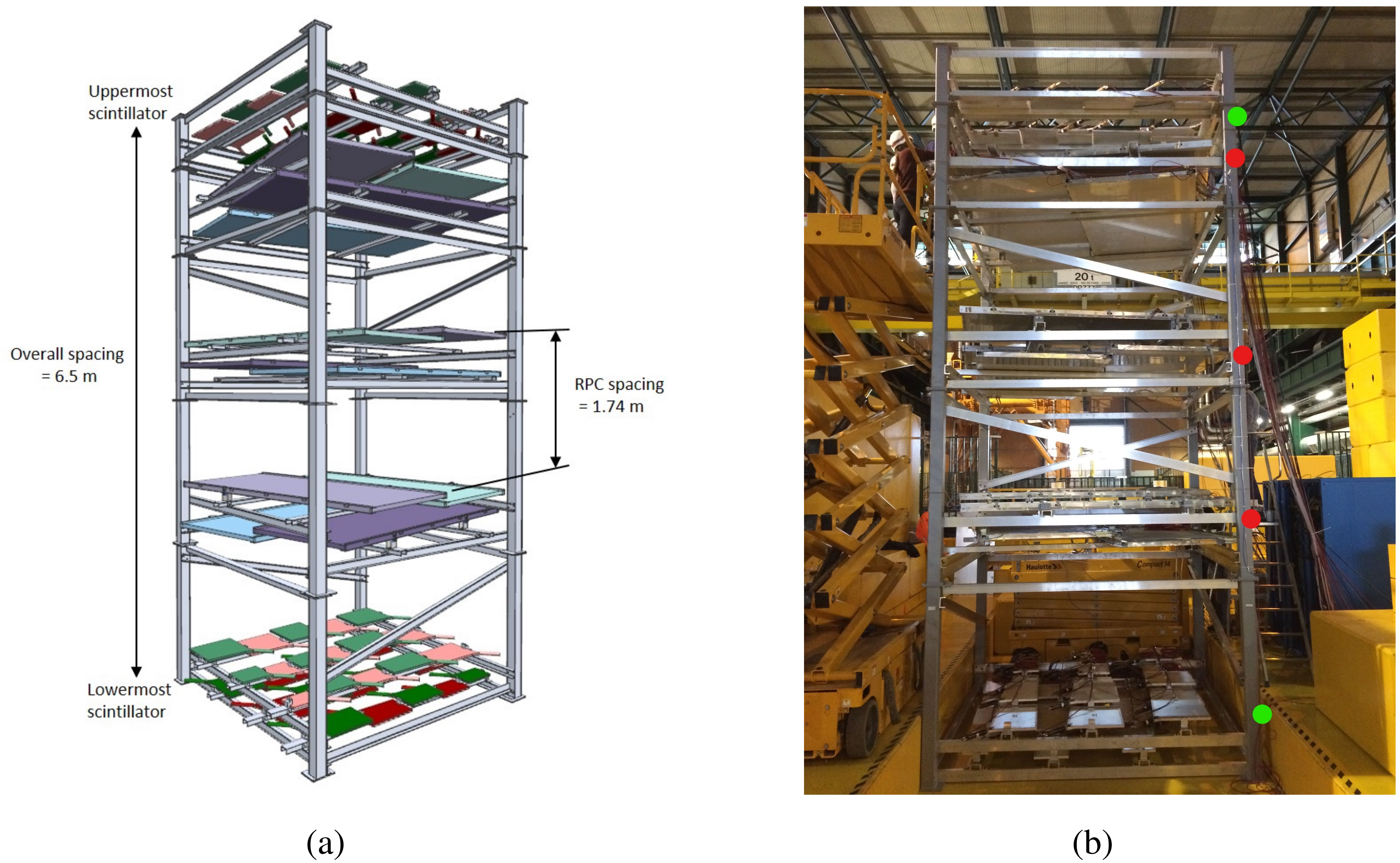
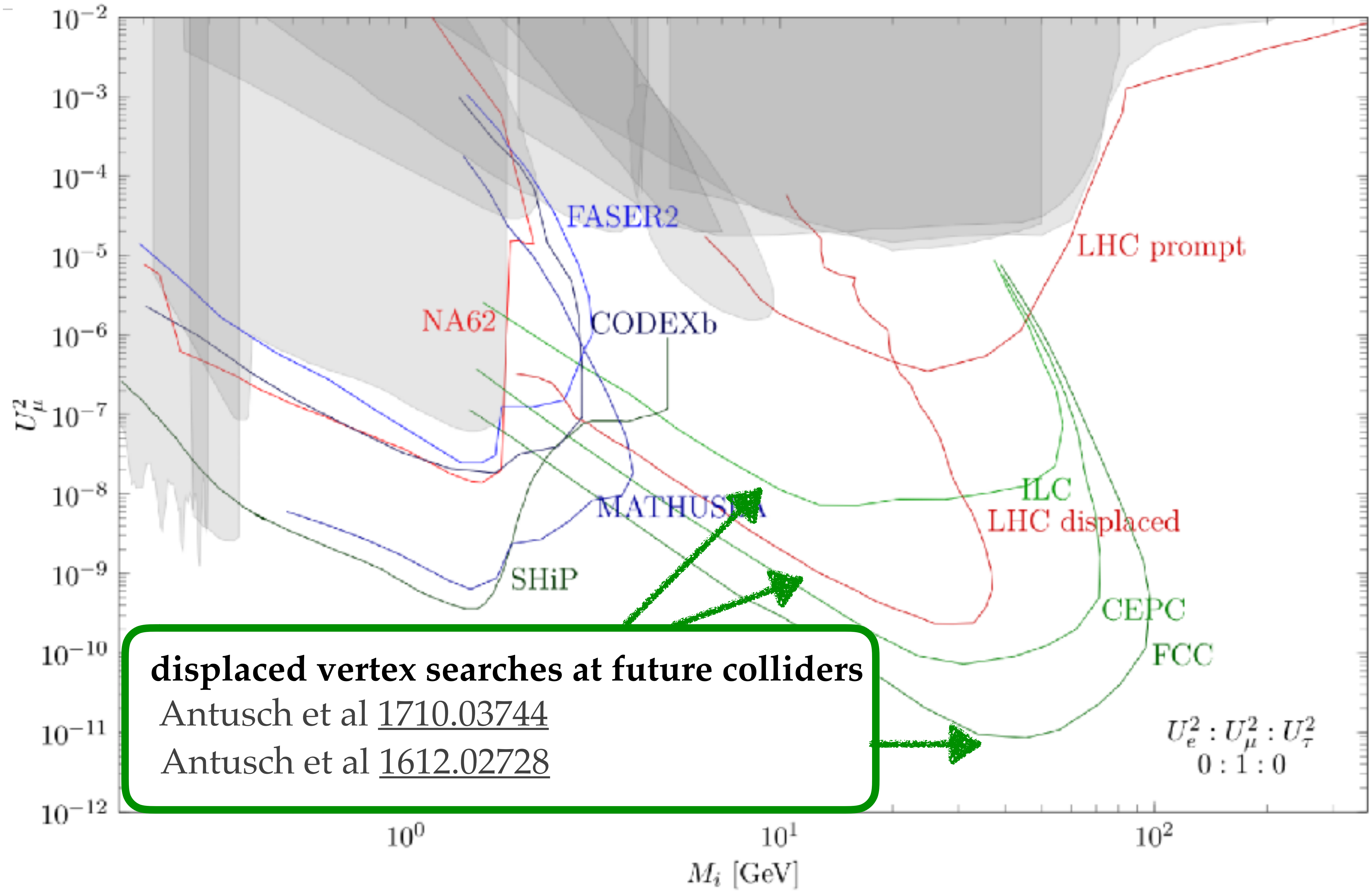


Figure 20. (a): schematic view of the MATHUSLA test stand. (b): picture of the final assembled structure in his test area in the ATLAS SX1 building at CERN. The green dots identify the two scintillator layers used for triggering, while the red dots the three RPC layers used for tracking.

Future Colliders

Future Colliders



displaced vertex searches at future colliders

Antusch et al 1710.03744

Antusch et al 1612.02728

νMSM from B-L Symmetry

The Hierarchy Problem

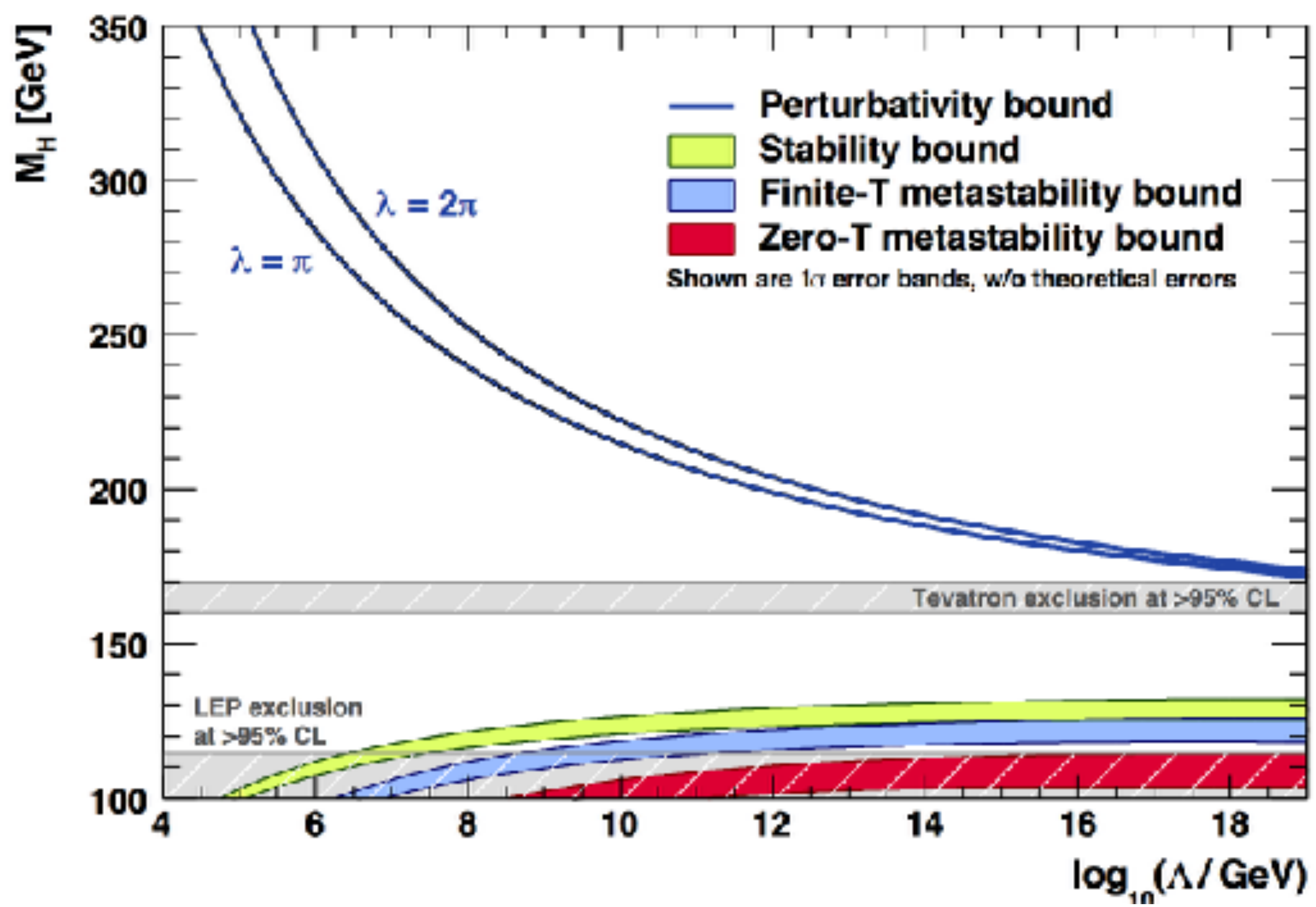
Hierarchy Problem

- Adding heavy states leads to electroweak hierarchy problem
- No problem if all masses below electroweak scale

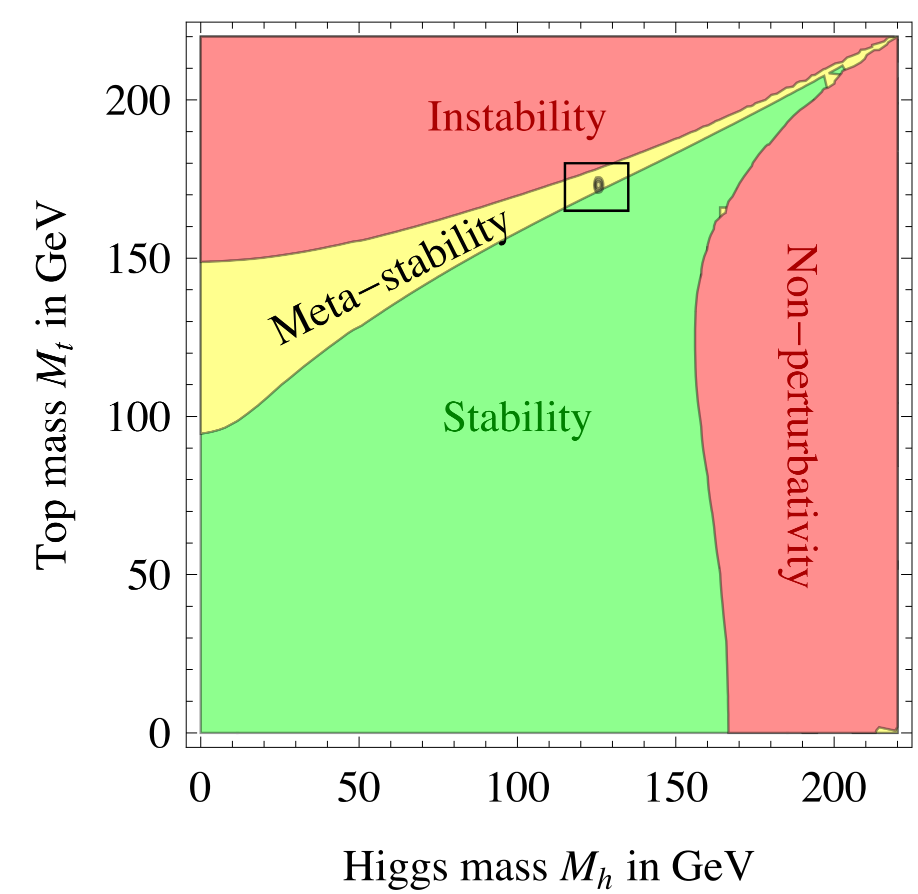
Bardeen 95,
Shaposhnikov 07

Higgs properties / vacuum stability

- SM could e valid EFT to Planck scale!



Ellis et et al 09



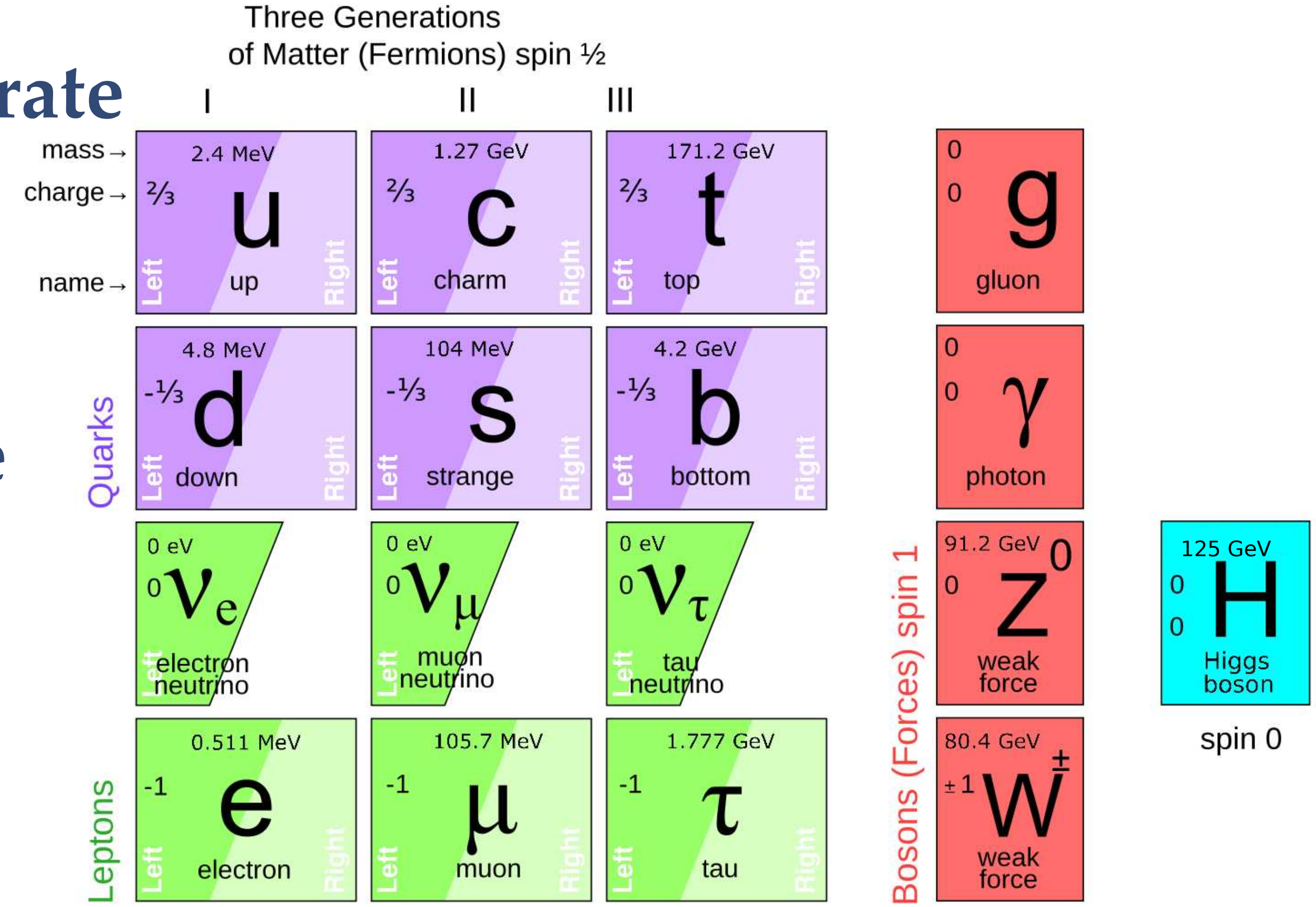
Degrassi et al 1205.6497

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



DM candidate must have very feeble couplings (cf. e.g. 1602.04816, 1807.07938)

⇒ Effective theory for νMSM collider/fixed target pheno:

Type I seesaw with two RH Neutrinos below EW scale

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

Dark Matter:
lighter (keV) mass
feeble coupling

No hierarchy problem
Vacuum metastable

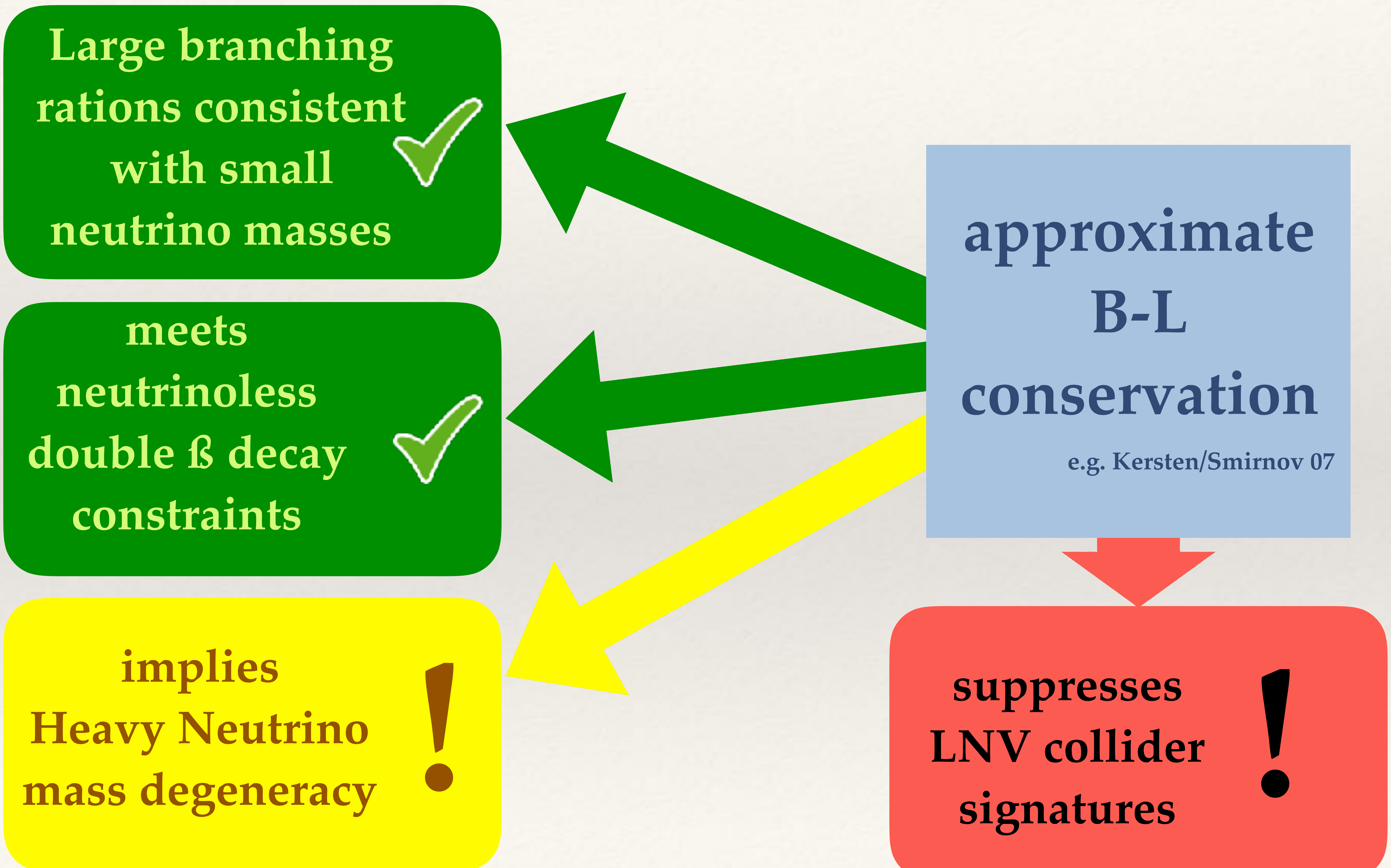
Shaposhnikov 06
Kersten/Smirnov 07

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

***B-L* violating parameters**

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

Neutrino masses vs collider searches



Neutrino masses vs collider searches

hard to distinguish signatures kinematically

cannot study heavy "flavours" individually

may observe CP violation in Heavy Neutrino decay

Cvetic/Kim/Saa 14

leptogenesis in the νMSM works

Asaka/Shaposhnikov 05

"golden channels" suppressed

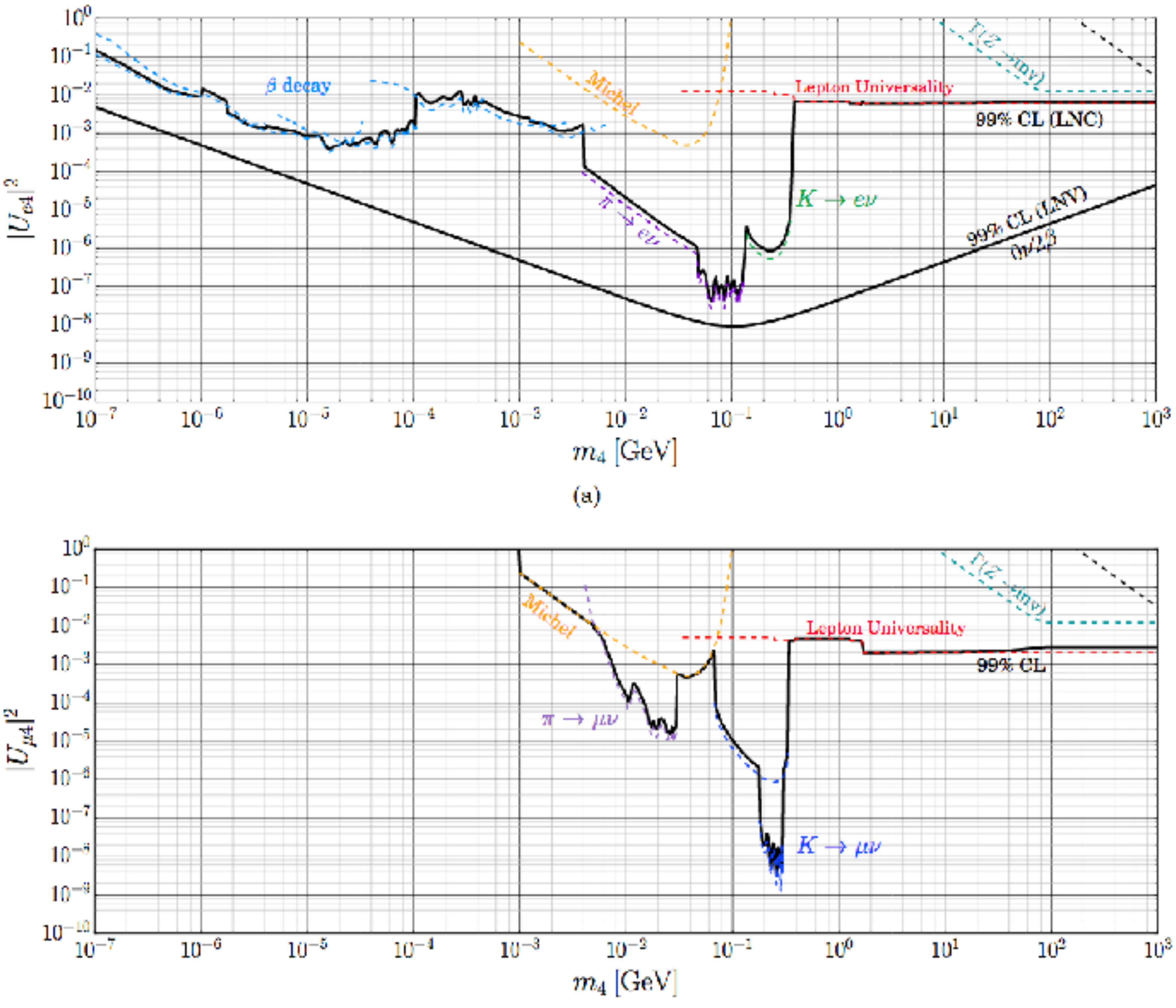
need to use other channels (LFV, displaced vertices)

implies Heavy Neutrino mass degeneracy !

suppresses LNV collider signatures !

Beyond the Minimal Model

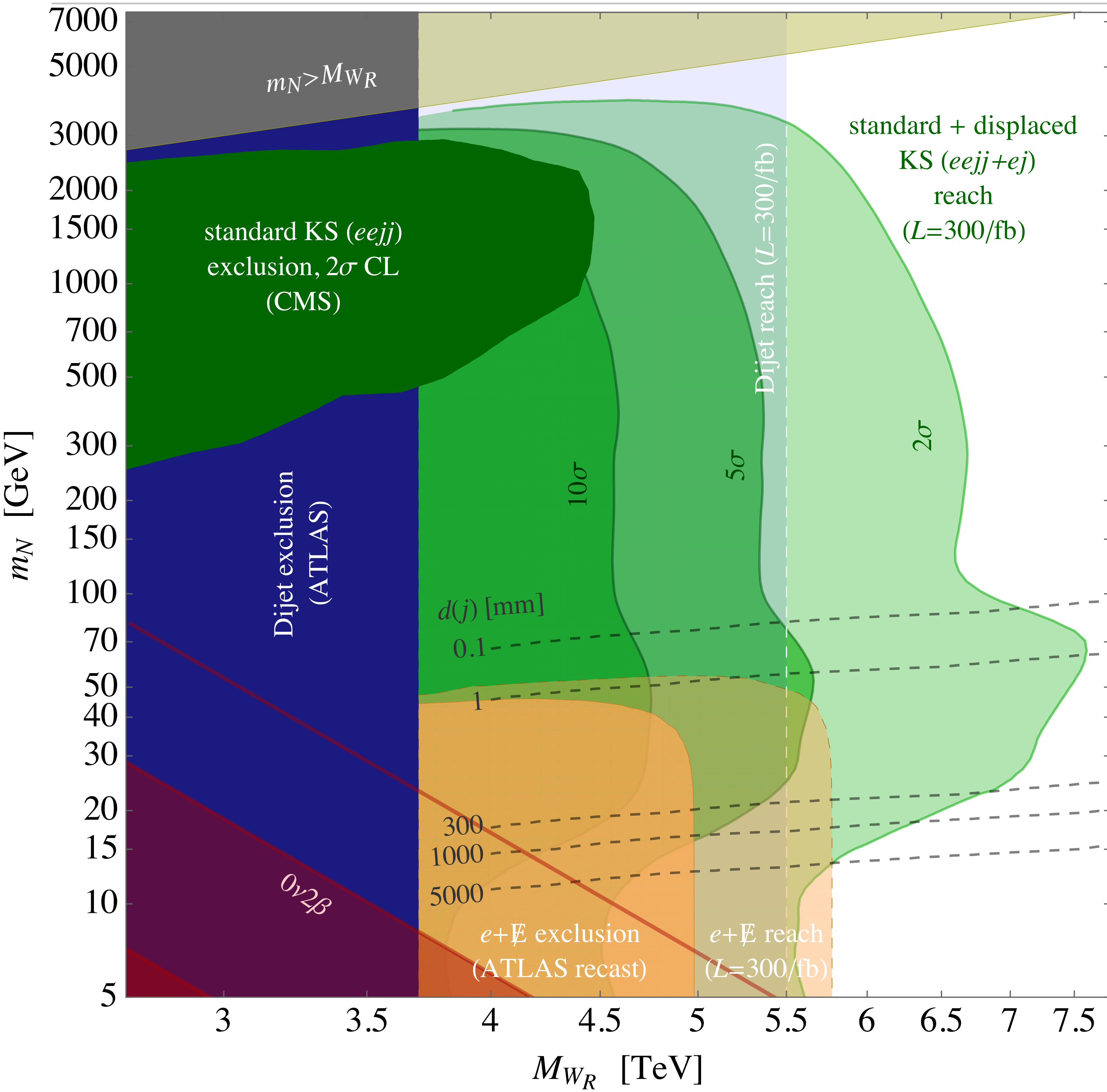
HNLs in a Dark Sector

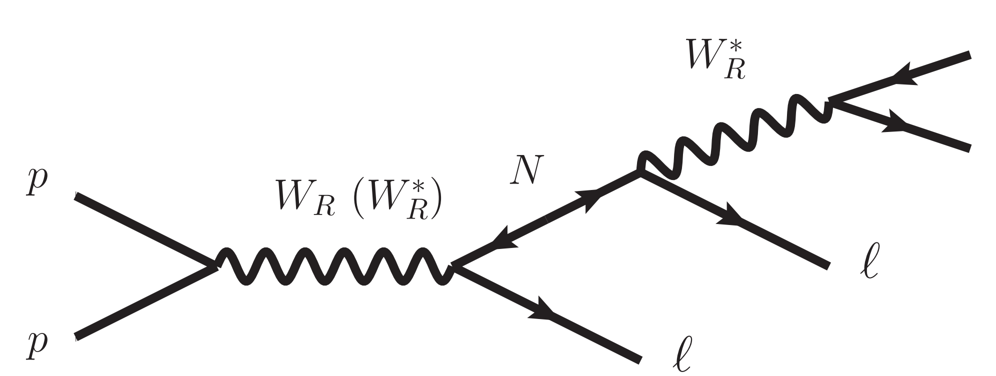


constraints weaken if HNL can decay into hidden particles

Gouvea / Kobach 1511.00683

Beyond the Minimal Model: Gauge Extensions





- discovery potential is much better in models with extra gauge interaction (e.g. L-R symmetric model)

plot from Nemevšek/Nesti/Popara 1801.05813

cf. Cai et al 1711.02180