Co-financed by the Connecting Europe Facility of the European Union

INTERACTIONS

UNIVERSITY OF COPENHAGEN

Low-scale leptogenesis via neutrino oscillations

Inar Timiryasov

Niels Bohr Institute,
University of Copenhagen

International Conference on Particle Physics and Cosmology dedicated to memory of Valery Rubakov

Yerevan, Armenia, 4th of October 2023

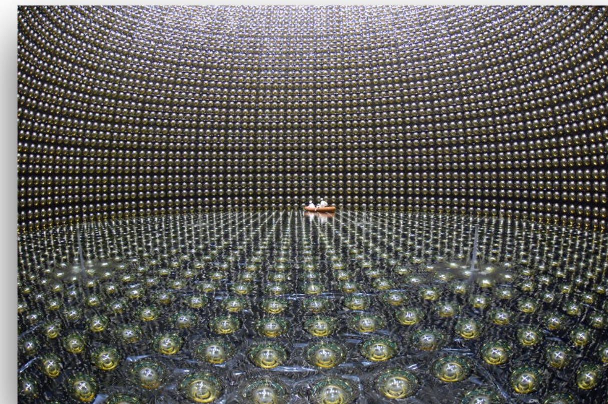
At the first meeting of
the Chair of particle
physics and cosmology
at MSU

13.11.2009

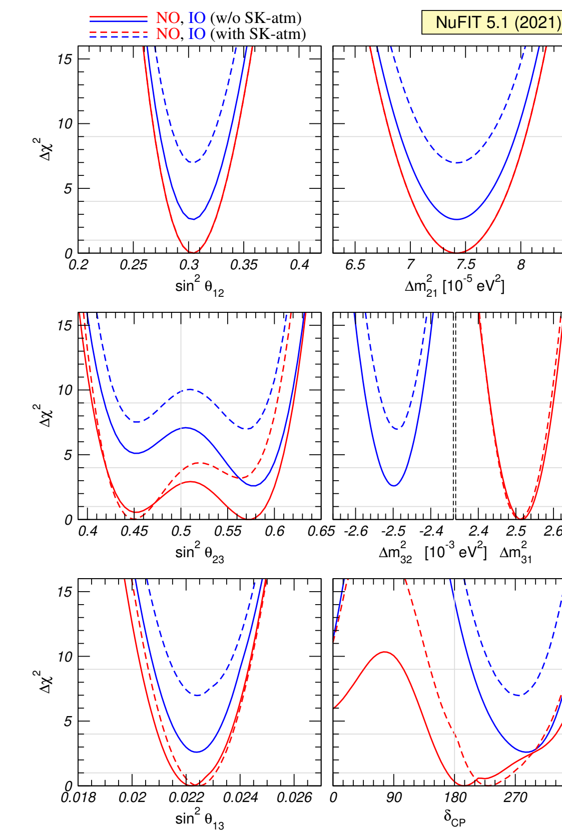
Beyond the Standard Model

- Neutrino flavour oscillations (violates L_α conservation, impossible if neutrinos are massless)

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

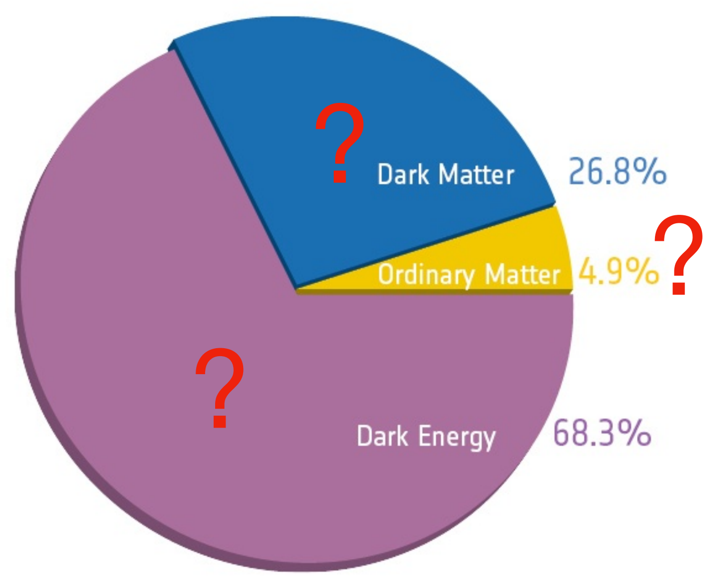


Super-Kamiokande (atmospheric oscillations $\nu_\mu \to \nu_\tau$)



NuFit collaboration http://www.nu-fit.org

- Cosmology



ESA and the Planck Collaboration

Baryon asymmetry of the Universe

- No antimatter in the present universe

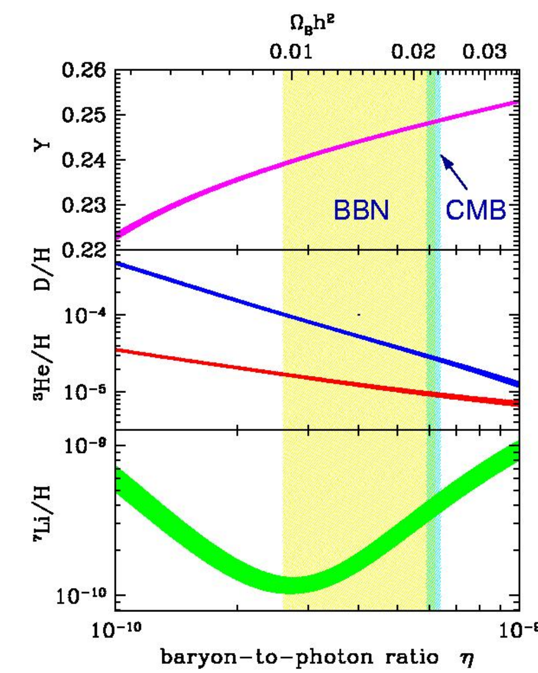
- Baryon to photon ratio

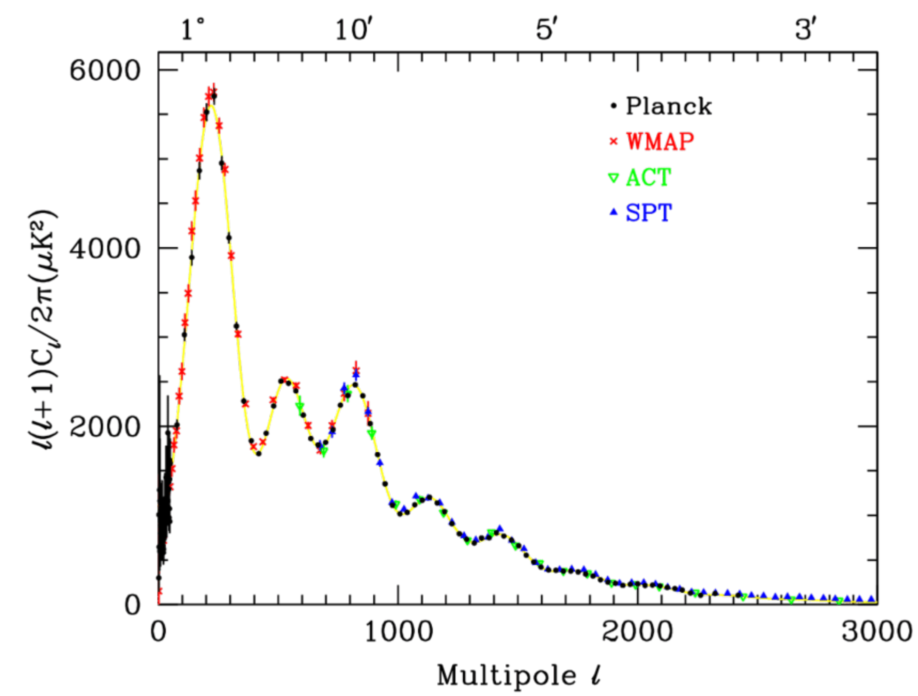
$$\Delta = \frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}\Bigg|_{\text{T}\sim 1\ \text{GeV}} \simeq \frac{n_B}{n_\gamma}\Bigg|_{\text{now}} \simeq 6 \times 10^{-10}$$

- At high T: $(10^{10} - 1)$ antiquarks per 10^{10} quarks

- Symmetric part annihilates into photons and ν

- Asymmetric part: origin of galaxies, stars, planets





Where the asymmetry comes from?

Sakharov Conditions (1967)

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

Where the asymmetry comes from?

Sakharov Conditions (1967)

- Baryon number violation

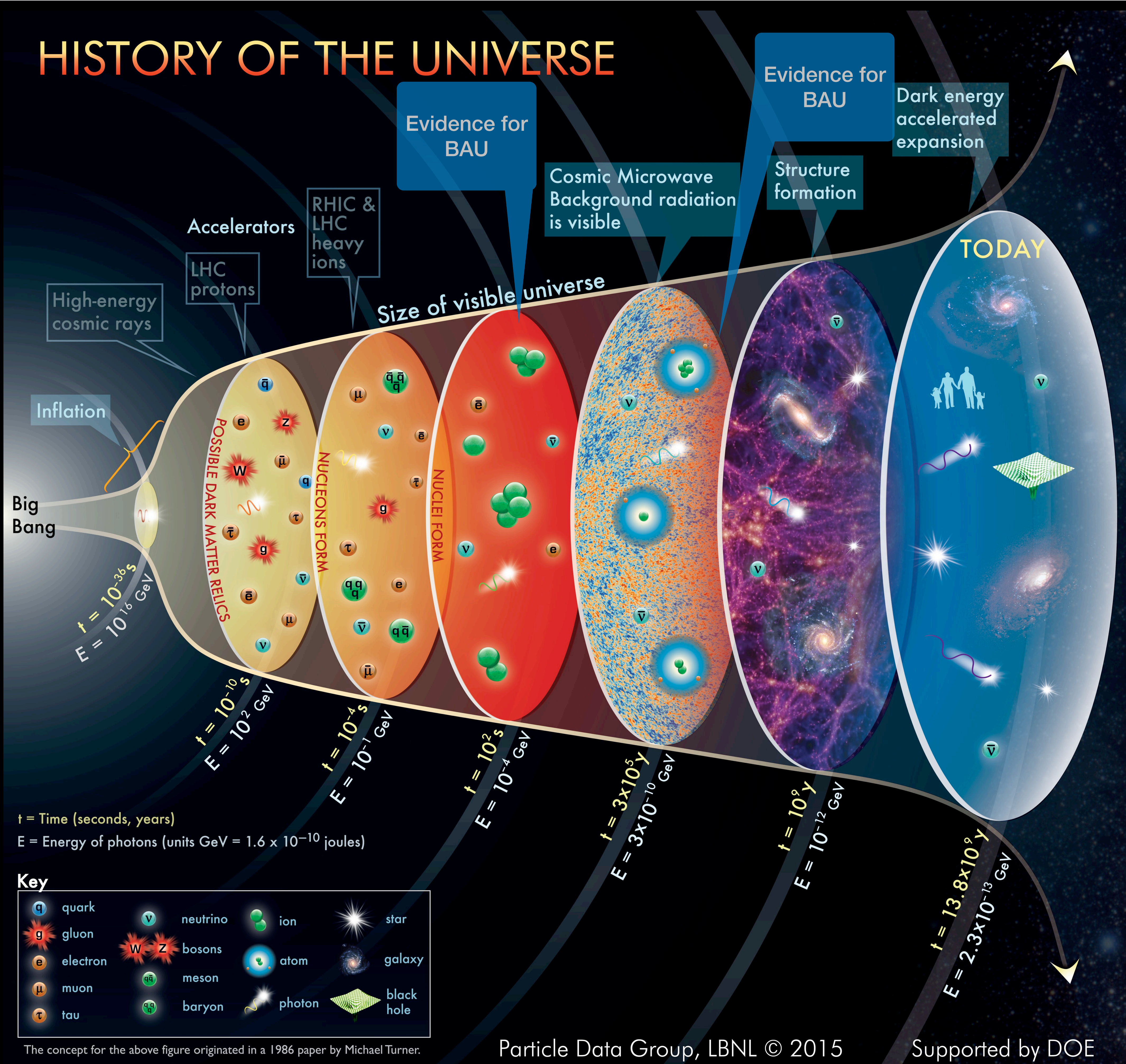
Nonperturbative sphaleron processes at T>130 GeV
[Kuzmin, Rubakov, Shaposhnikov 1985]

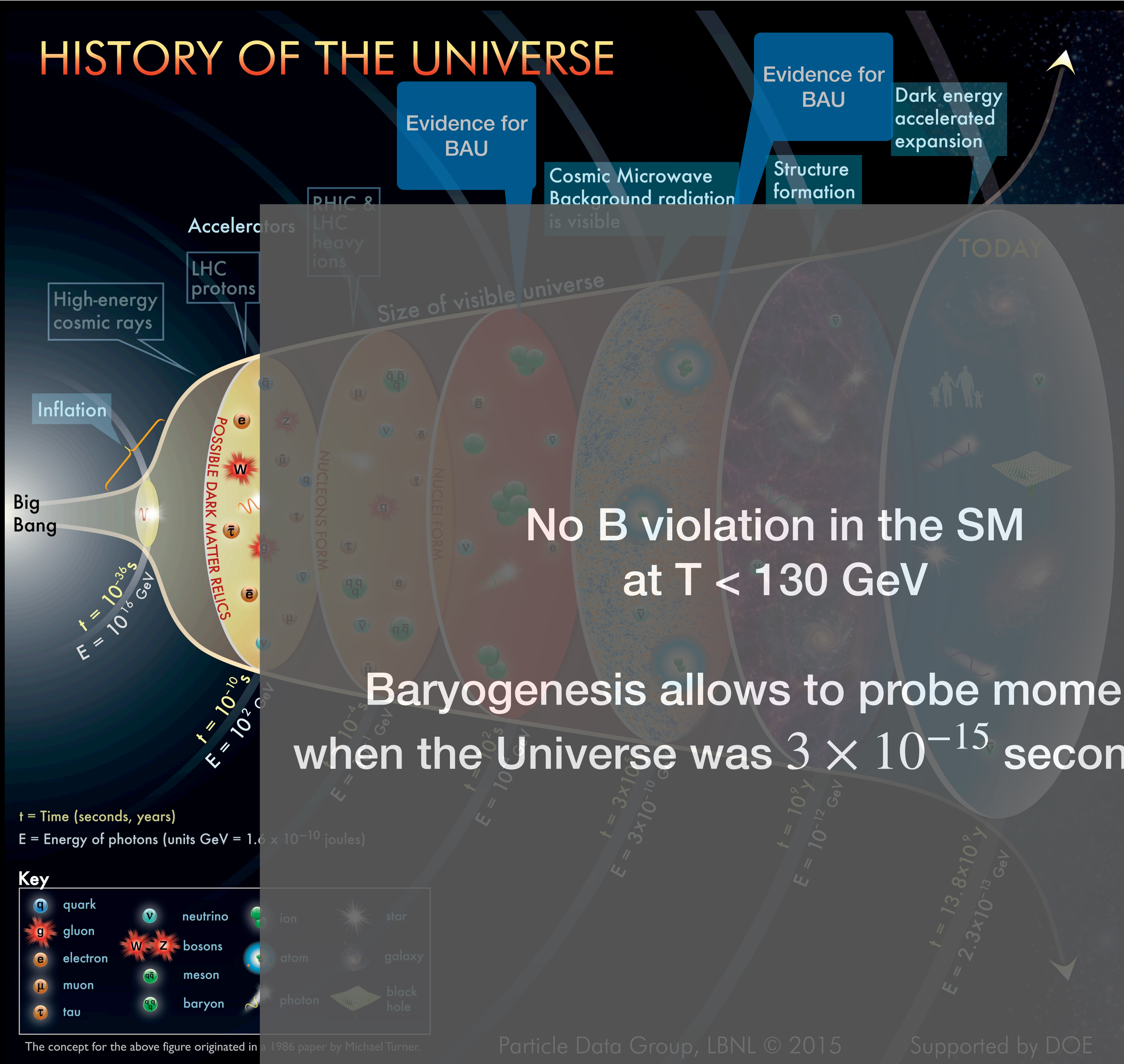
- C and CP violation

Present in the SM, but too small
$G_F^6 s_1^2 s_2 s_3 sin\delta m_t^4 m_b^4 m_c^2 m_s^2 \sim 10^{-20} \ll \Delta \sim 10^{-10}$

- Deviation from thermal equilibrium

No electroweak phase transition for $M_H > 73$ GeV
[Kajantie, Laine, Rummukainen, Shaposhnikov]


HISTORY OF THE UNIVERSE
Evidence for BAU
Evidence for BAU
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE



No B violation in the SM at $T < 130$ GeV

Baryogenesis allows to probe moments when the Universe was 3×10^{-15} seconds old

Baryogenesis via neutrino oscillations

E. Kh. Akhmedov[a,b] V. A. Rubakov[c,a,d] and A. Yu. Smirnov[a,c]
[a]The Abdus Salam International Centre for Theoretical Physics, I-34100 Trieste, Italy
[b]National Research Centre Kurchatov Institute, Moscow 123182, Russia
[c]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow 117312, Russia
[d]Institute for Cosmic Ray Research, University of Tokyo, Tanashi, Tokyo 188, Japan
(March 5, 1998)

We propose a new mechanism of leptogenesis in which the asymmetries in lepton numbers are produced through the CP-violating oscillations of "sterile" (electroweak singlet) neutrinos. The asymmetry is communicated from singlet neutrinos to ordinary leptons through their Yukawa couplings. The lepton asymmetry is then reprocessed into baryon asymmetry by electroweak sphalerons. We show that the observed value of baryon asymmetry can be generated in this way, and the masses of ordinary neutrinos induced by the seesaw mechanism are in the astrophysically and cosmologically interesting range. Except for singlet neutrinos, no physics beyond the Standard Model is required.

PACS: 98.80.Cq, 14.60.St IC/98/22, INR-98-14T hep-ph/9803255

https://arxiv.org/abs/hep-ph/9803255

The seesaw mechanism

$$\mathscr{L} = \mathscr{L}_{SM} + i\,\bar{\nu}_{R_I}\gamma^\mu\partial_\mu\nu_{R_I} - F_{\alpha I}\bar{L}_\alpha\tilde{\Phi}\nu_{R_I} - \frac{M_{IJ}}{2}\bar{\nu}^c_{R_I}\nu_{R_J} + h.c.$$

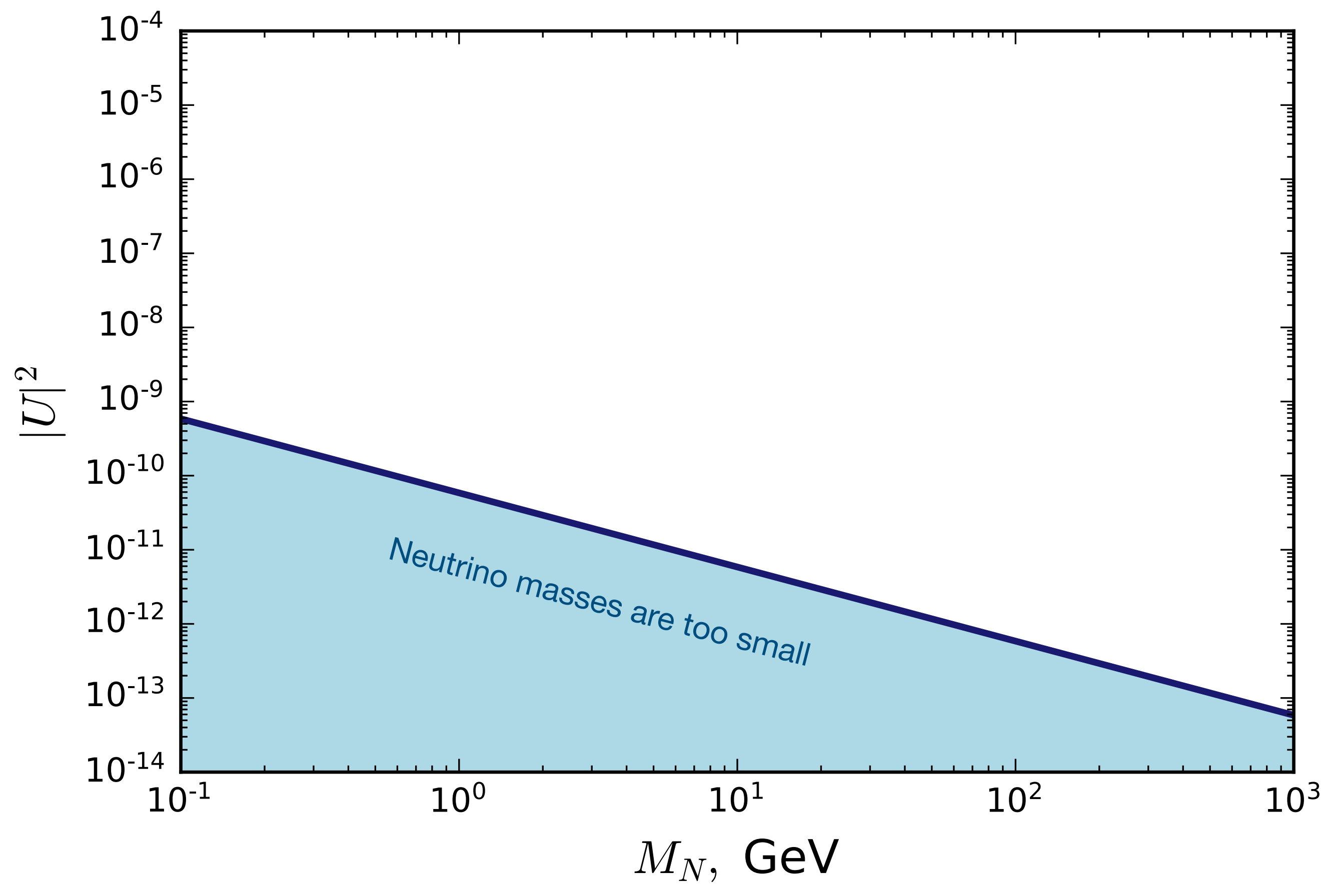
Minkowski; Yanagida; Gell-Mann, Ramond, Slansky; Glashow; Mohapatra, Senjanovic

eV sterile neutrinos are outside of this range

The plenary talk by Mikhail Danilov

- New singlet fermions
- Mixing with light neutrinos

$$\nu_{L_\alpha} = U^{PMNS}_{\alpha i}\nu_i + \Theta_{\alpha I}N^c_I$$



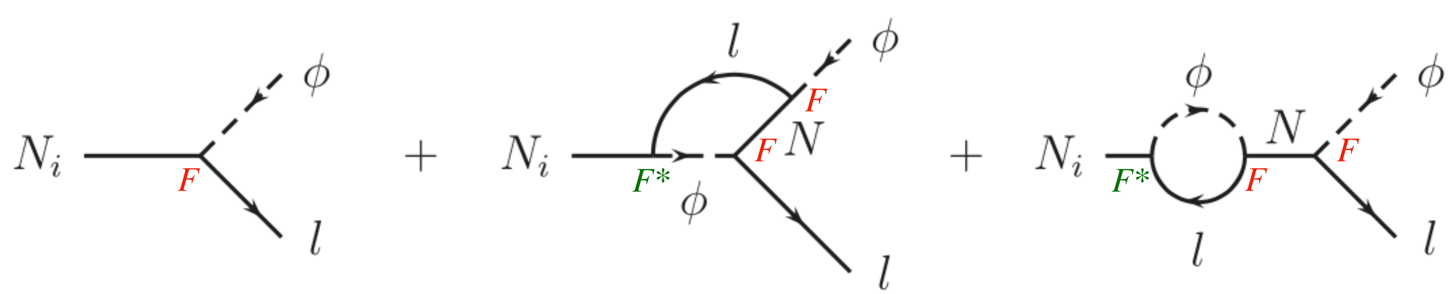
We consider nearly degenerate HNLs (Heavy Neutral Leptons)

Heavy Neutral Leptons: Leptogenesis

N can be responsible for the Baryon Asymmetry

Fukugita and Yanagida, 1986
Reviews: Buchmuller, Di Bari, Plumacher:
Leptogenesis for pedestrians, 2004
Bödeker, Buchmuller, 2009.07294

- B violated by sphaleron processes
- CP asymmetry in N decays
- Deviation from equilibrium when $\Gamma_N \sim H$



$$\varepsilon_i = \frac{\Gamma(N_i \to l\phi) - \Gamma(N_i \to \bar{l}\,\bar{\phi})}{\Gamma(N_i \to l\phi) + \Gamma(N_i \to \bar{l}\,\bar{\phi})}.$$

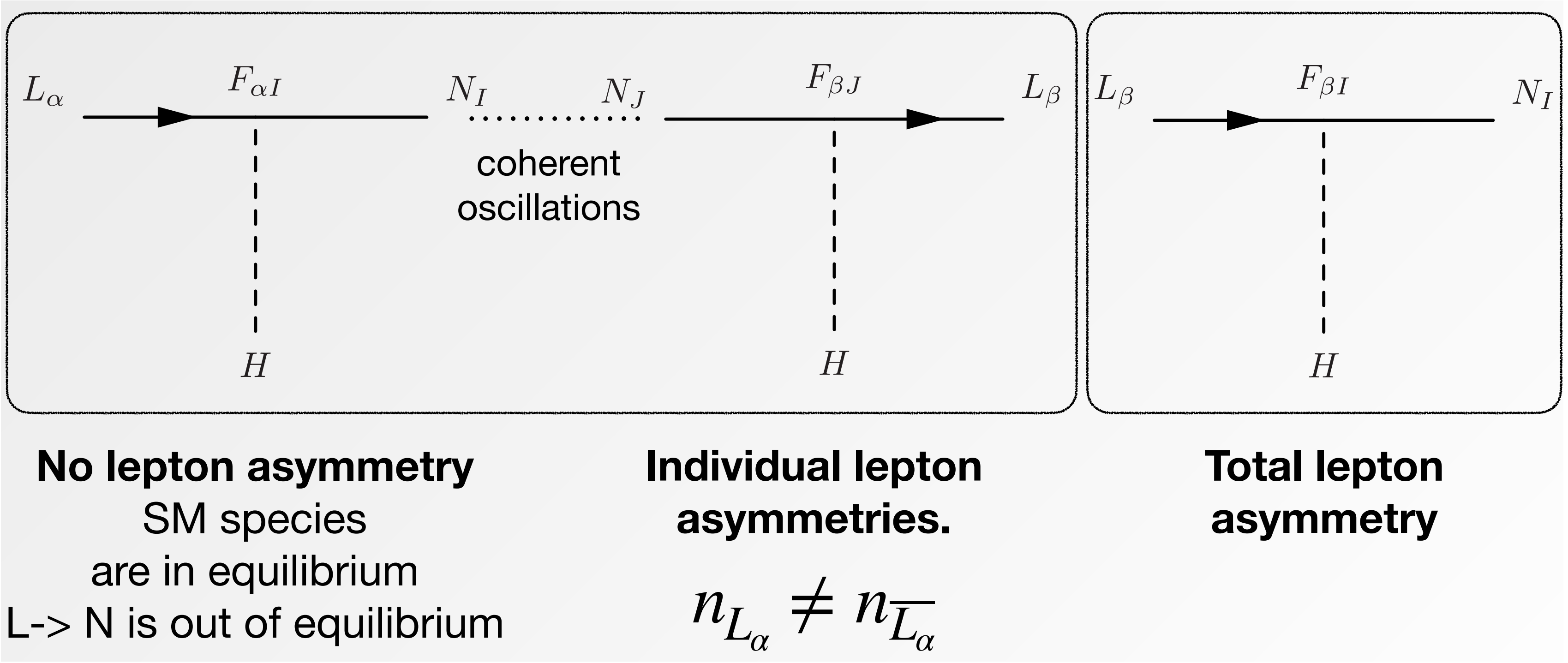
$$\varepsilon \sim \frac{\mathrm{Im}(F^\dagger F)^2}{|F|^2}$$

Davidson Ibarra bound, 2002
$M \gtrsim 10^9$ GeV

$$\varepsilon_{\max} = \frac{3}{16\pi}\frac{M m_{\rm atm}}{v^2} \simeq 10^{-6}\left(\frac{M}{10^{10}\ \mathrm{GeV}}\right)$$

Low-scale leptogenesis via neutrino oscillations

- B violated by sphaleron processes
- **CP asymmetry is enhanced by N-N oscillations**
- Deviation from equilibrium: small Yukawas
  (masses are also relatively small — "low-scale")



Akhmedov, Rubakov, Smirnov 1998
Asaka, Shaposhnikov 2005
Canetti, Drewes, Frossard; Eijima, Ishida; Shuve, Yavin; Abada, Arcadi, Domcke, Lucente; Hernández, Kekic, López-Pavón, Racker, Salvado; Drewes, Garbrecht, Gueter, Klaric; Hambye, Teresi; Ghiglieri, Laine; IT; …

Description of low-scale leptogenesis

Significant theoretical developments since 2014
[1605.07720, 1703.06085, 1703.06087, 1605.07720, 1709.07834, 1711.08469, 1208.4607, 1606.06690,1606.06719, 1609.09069, 1710.03744, 1808.10833, 1811.01971, 1905.08814, 1911.05092, 2004.10766, 2008.13771, 2203.05772]

- Fermion number violating processes (processes with and without helicity flip)
  Eijima, Shaposhnikov; Ghiglieri, Laine

- Accurate computation of the rates (including Landau-Pomeranchuk-Migdal resummation of multiple soft scatterings)
  Ghiglieri, Laine

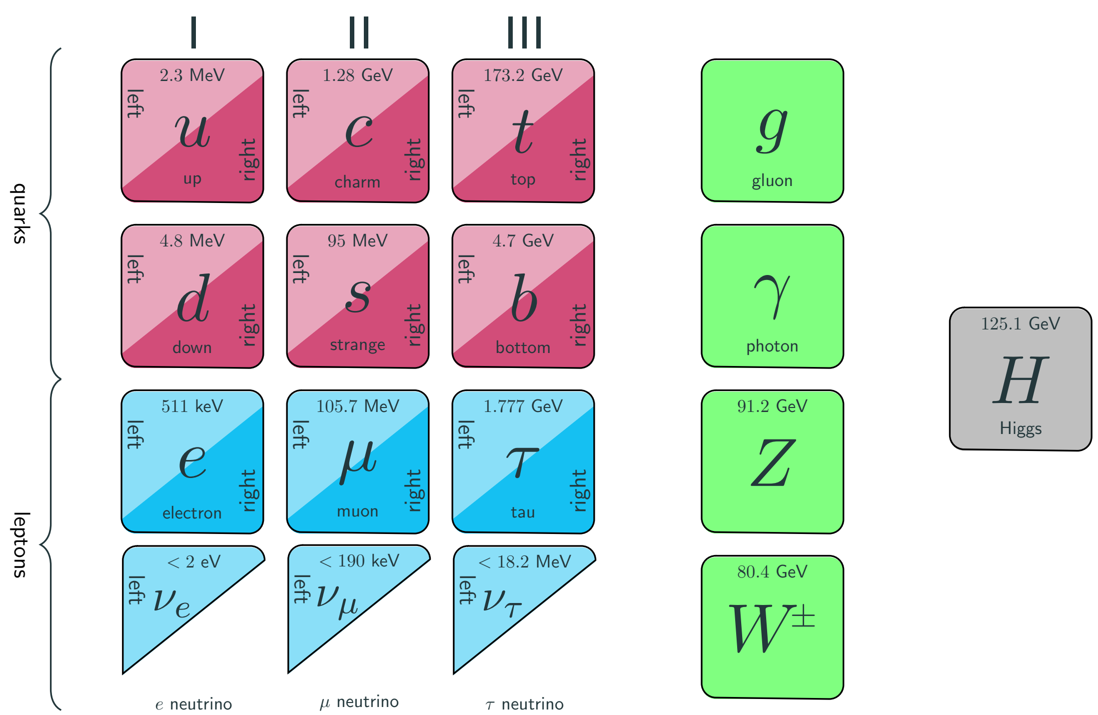
- Spectator processes
  Shuve, Yavin; Ghiglieri, Laine; Eijima, Shaposhnikov, IT

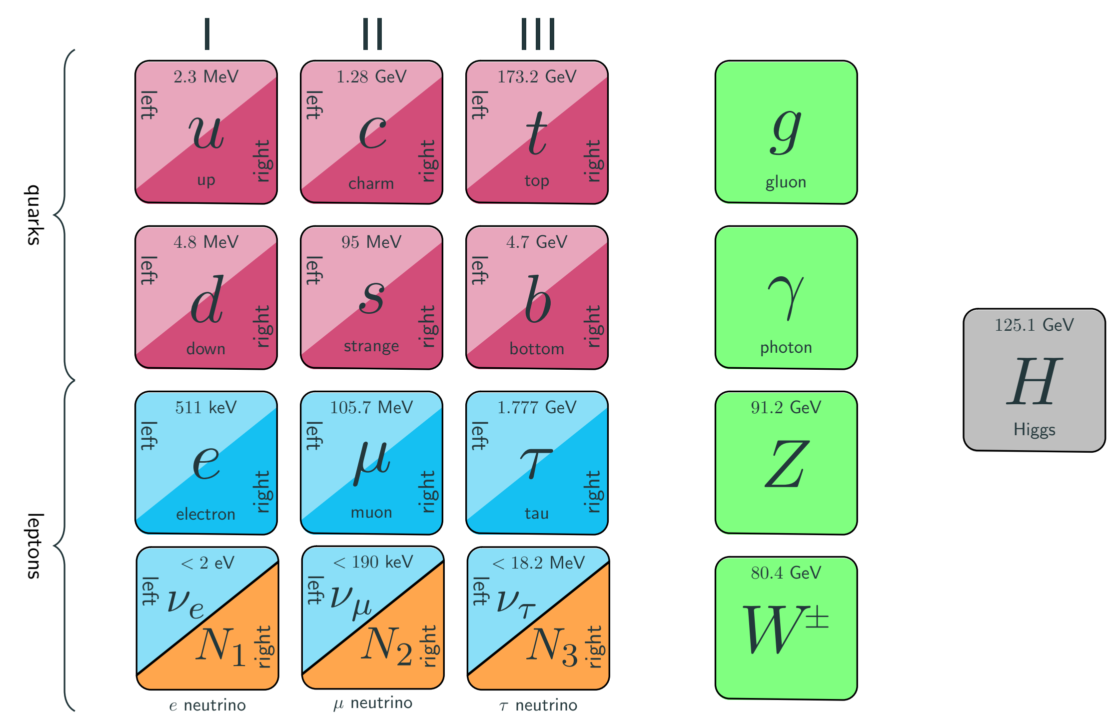
- Gradual sphaleron freeze-out
  Ghiglieri, Laine; Eijima, Shaposhnikov, IT

- Rates for HNLs with $M \sim M_W$
  Klaric, Shaposhnikov, IT

Neutrino Minimal Standard Model (νMSM)

Asaka, Blanchet, Shaposhnikov 2005
Asaka, Shaposhnikov 2005





N_1 DM candidate

Monday talk by Misha Shaposhnikov

N_2, N_3 } ν masses via see-saw
BAU
(DM production)

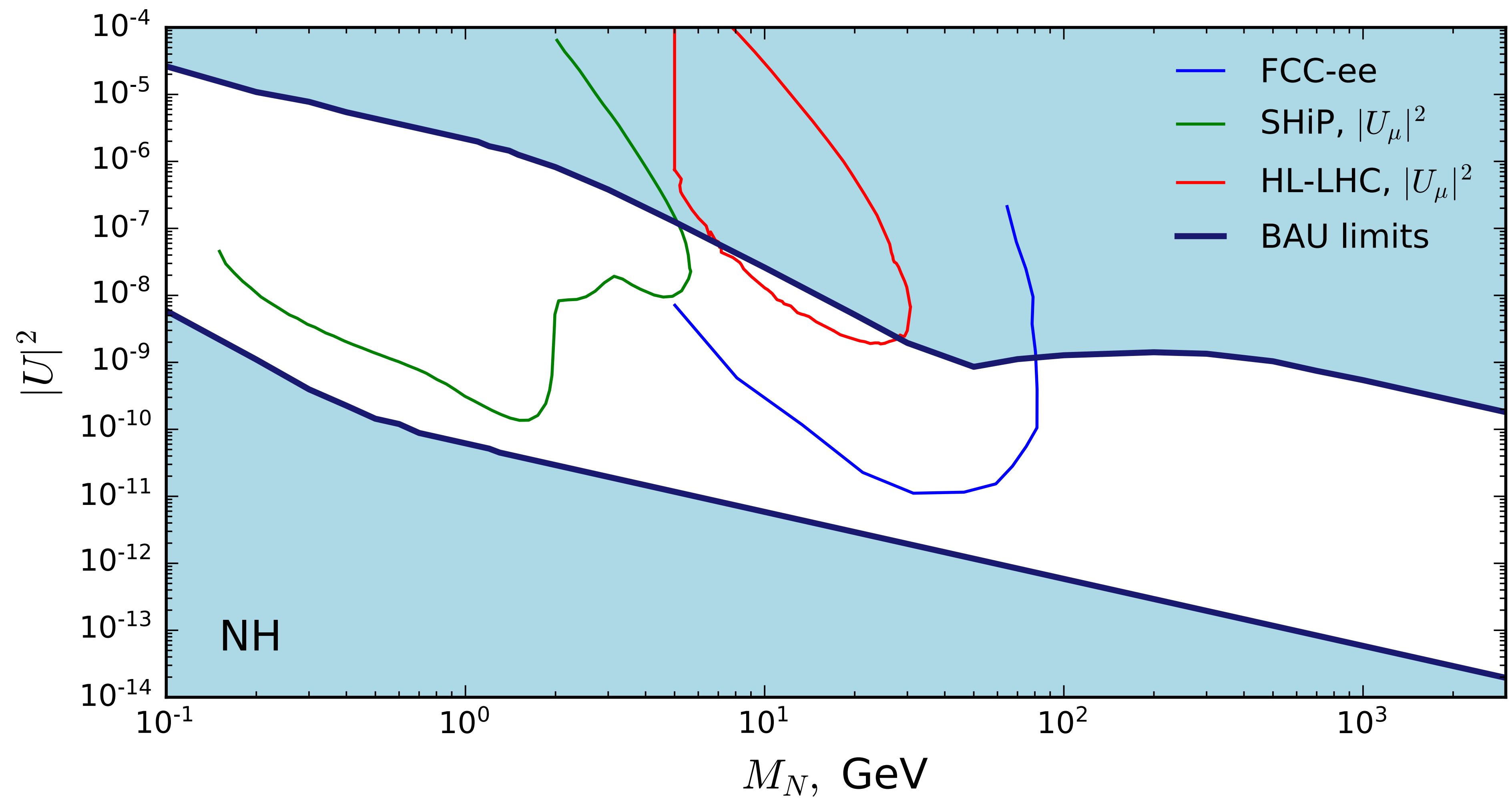
$$M_N \gtrsim 0.1\, GeV$$

Nearly degenerate

Baryogenesis via oscillations
Akhmedov, Rubakov, Smirnov, 1998
Asaka, Shaposhnikov 2005

Uniting leptogeneses

Juraj Klarić, Mikhail Shaposhnikov, IT 2008.13771, Phys.Rev.Lett. 127 (2021)

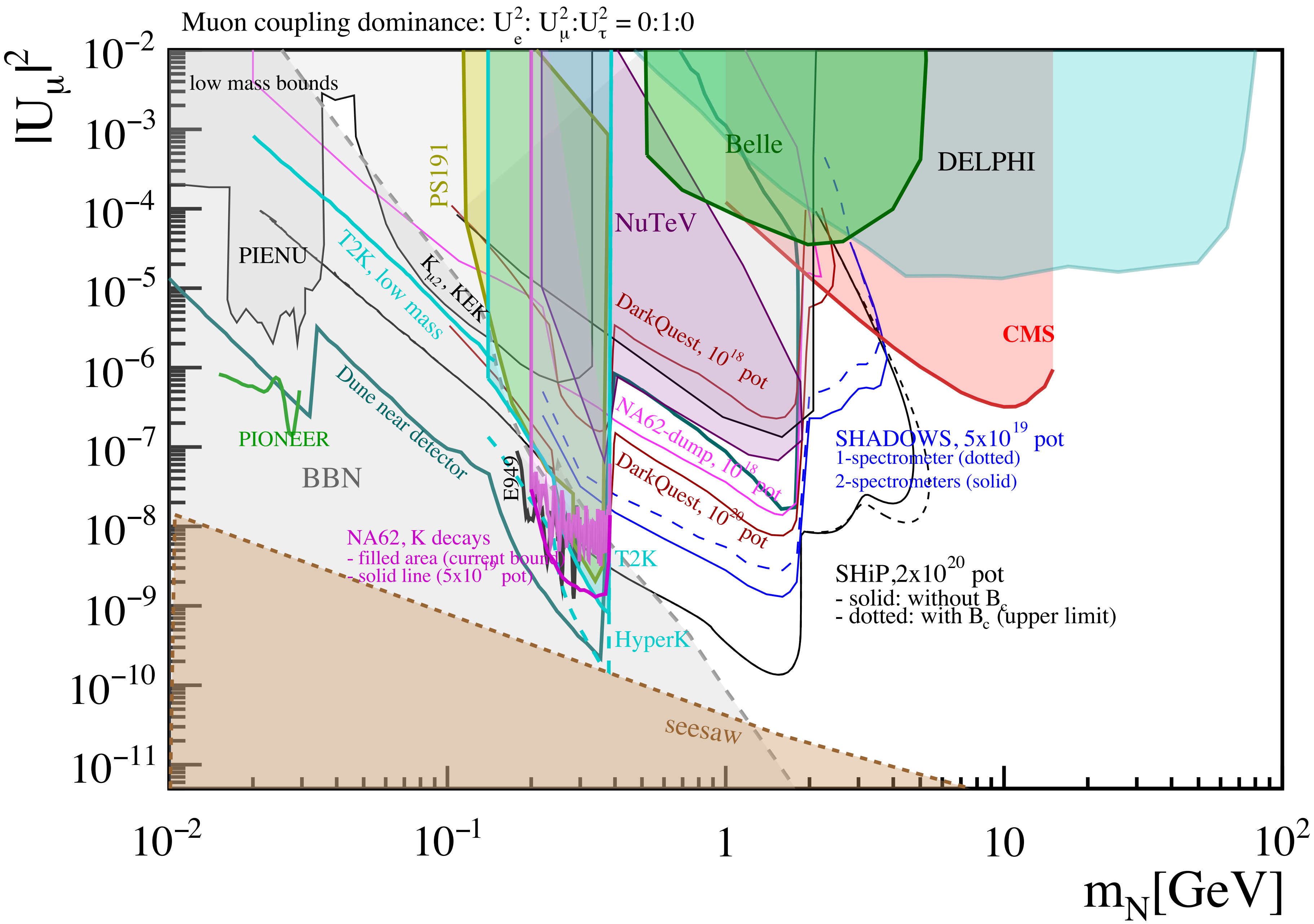


- Leptogenesis via oscillations still works for heavy HNLs because the washout of the asymmetry can vary a lot for different lepton flavours *(flavour hierarchical washout)*

- Resonant leptogenesis works for $M_N \gtrsim 5$ GeV since the asymmetry generated in HNL decays into a certain flavour can be very large

3RH case: Klaric, Georis, Drewes 2106.16226

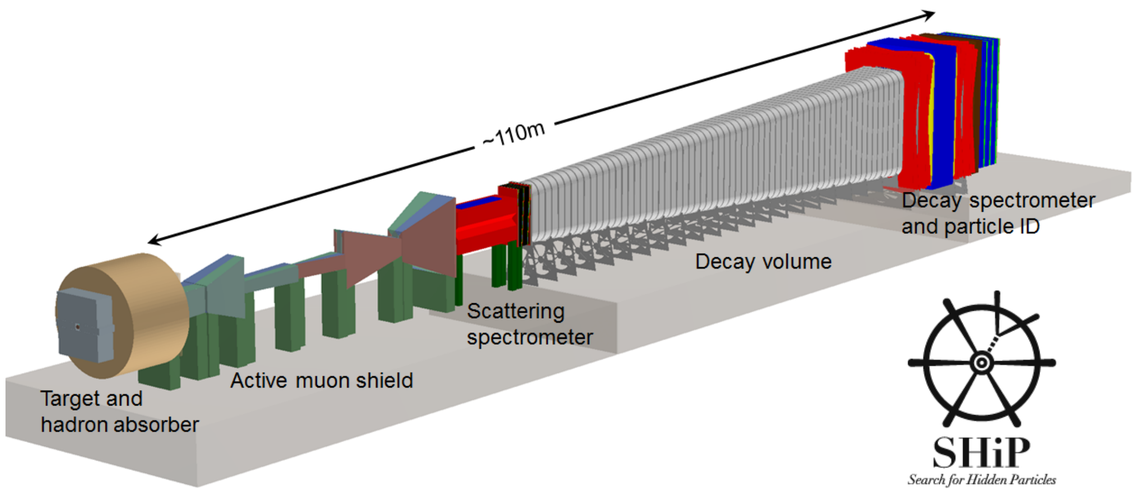
The quest for Heavy Neutral Leptons



The Present and Future Status of Heavy Neutral Leptons
2203.08039

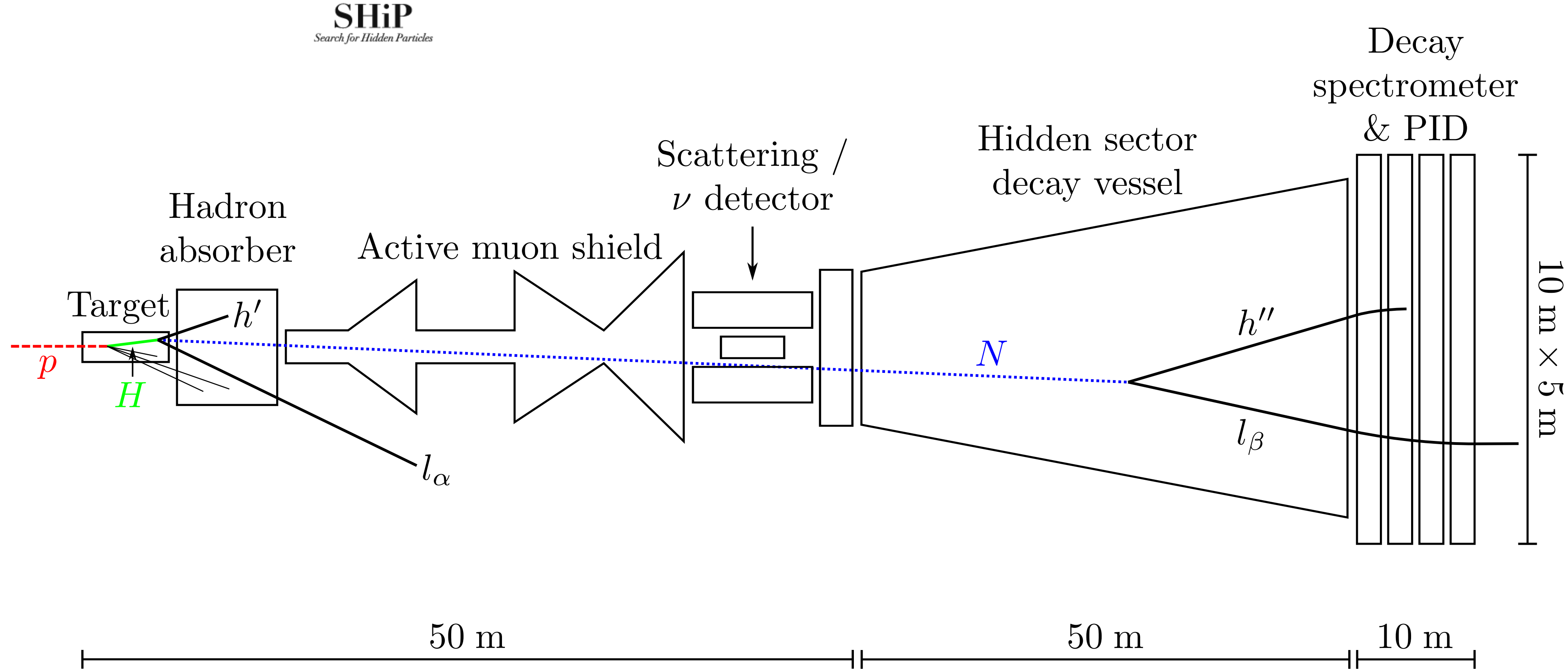
For a unified sensitivity estimation:
a new Mathematica package SensCalc
https://arxiv.org/abs/2305.13383
https://doi.org/10.5281/zenodo.7957784

How to search for HNLs?



Example: SHiP - Search for Hidden Particles

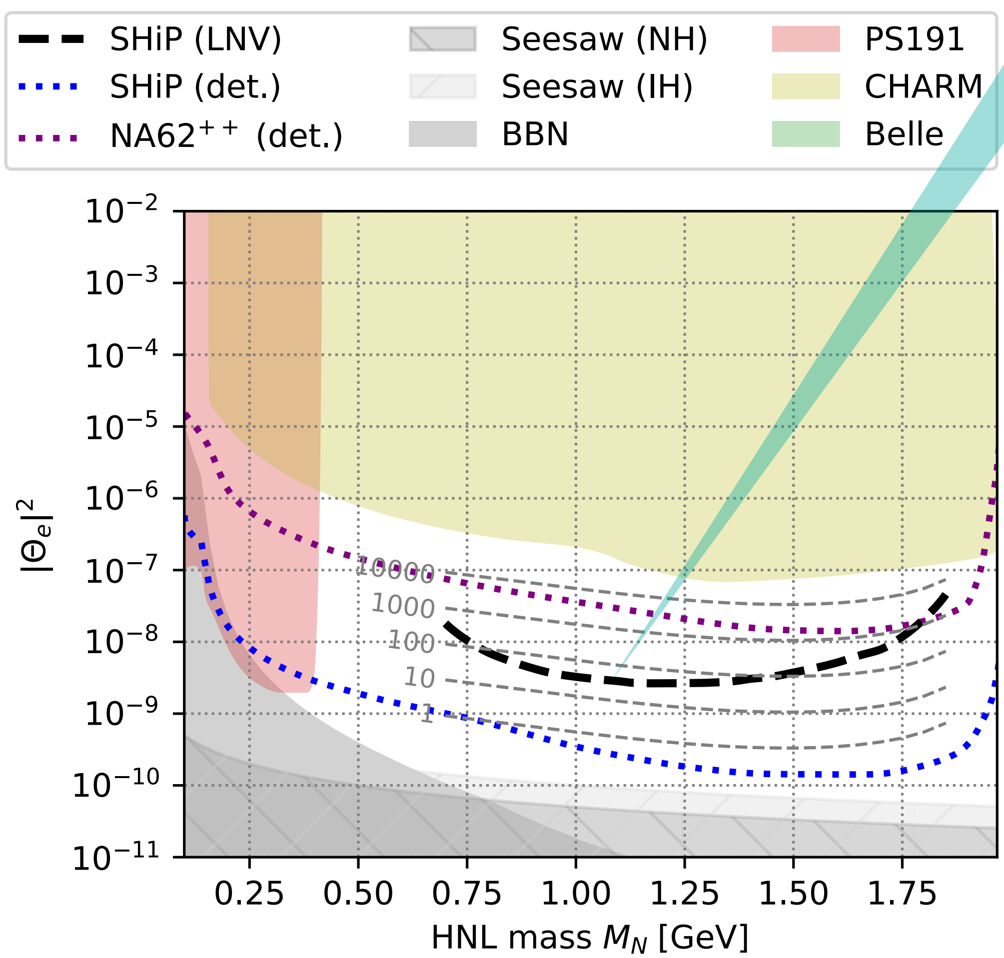
400 GeV protons from SPS
2×10^{20} POT

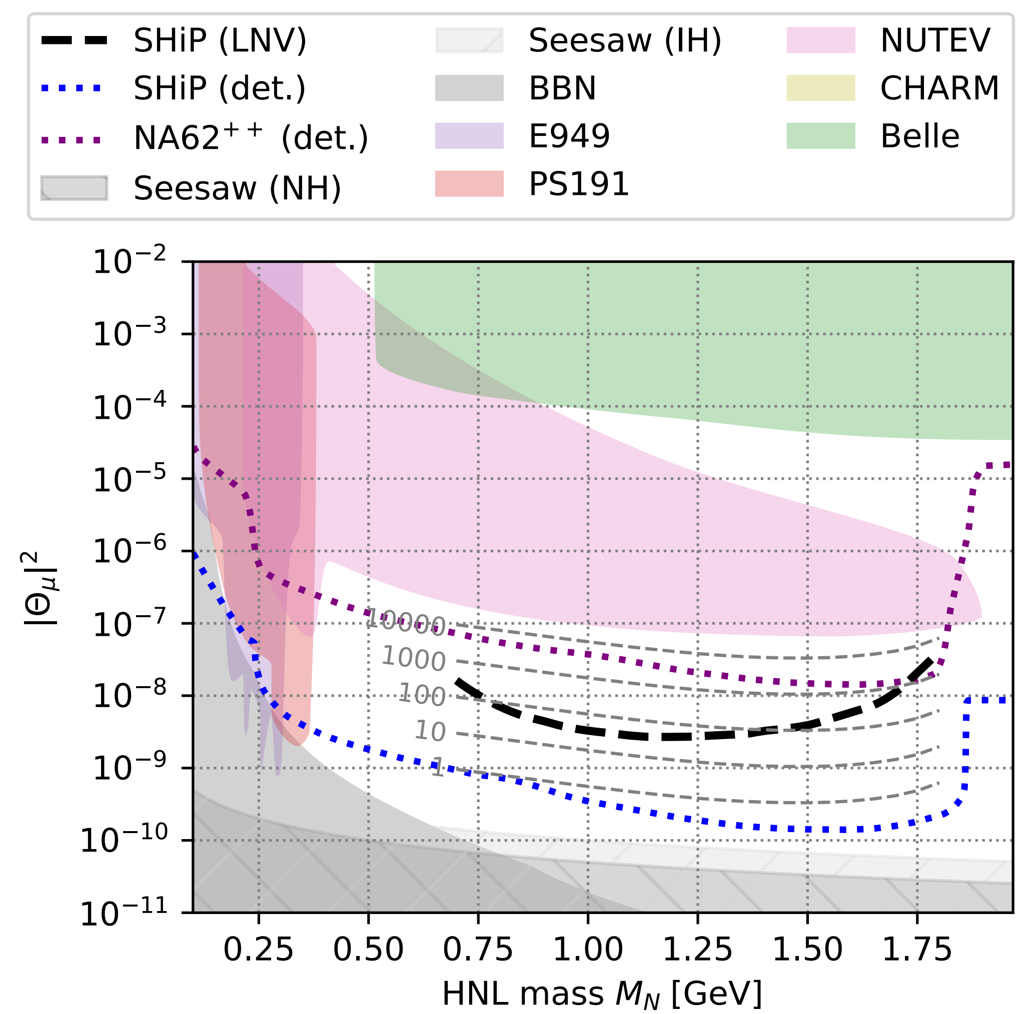


* I am a member of SHiP collaboration

Probing lepton number violation at SHiP

Above this line SHiP can distinguish Majorana vs Dirac





Jean-Loup Tastet, IT 1912.05520, JHEP

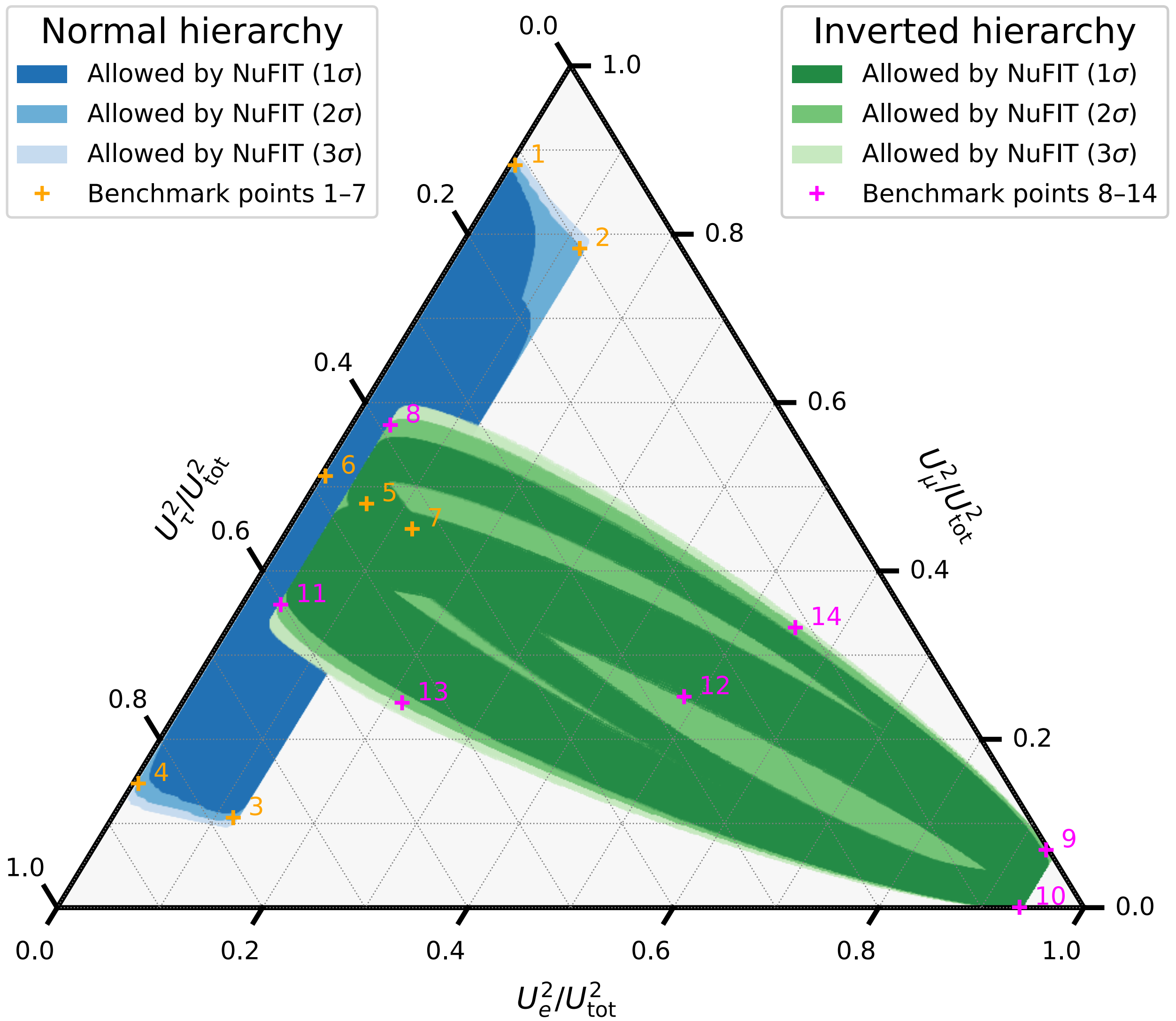
Neutrino oscillation data and mixings

Many analyses assume mixing with a single neutrino

Not all mixing angles are allowed in the model with two HNLs

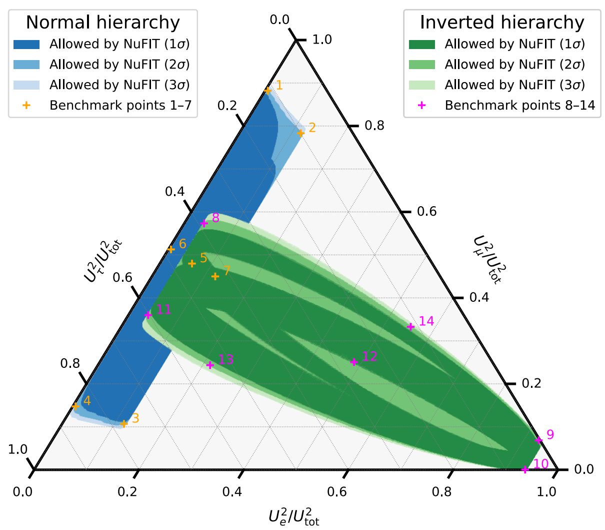
$$\nu_{L_\alpha} = U^{PMNS}_{\alpha i}\nu_i + \Theta_{\alpha I} N^c_I$$

$U^2_\alpha \equiv \sum_I |\Theta_{\alpha I}|^2$ and $U^2_{\text{tot}} \equiv \sum_{\alpha,I} |\Theta_{\alpha I}|^2$

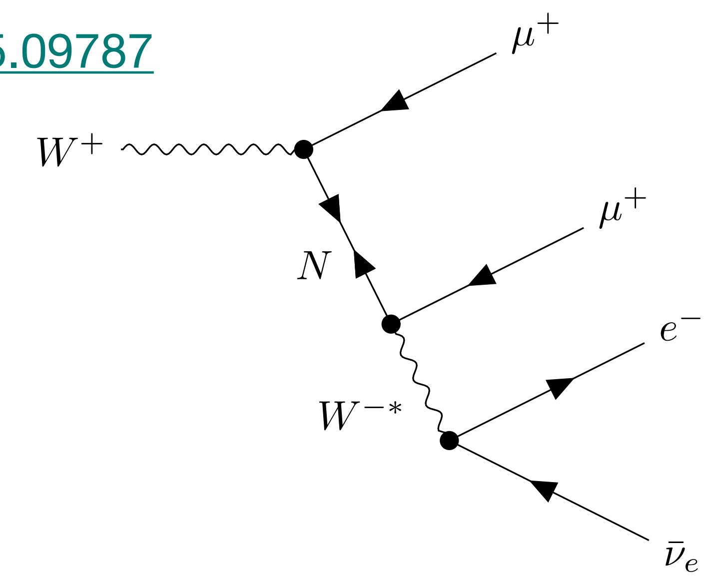


$$U^2_e/U^2_{\text{tot}} + U^2_\mu/U^2_{\text{tot}} + U^2_\tau/U^2_{\text{tot}} = 1$$

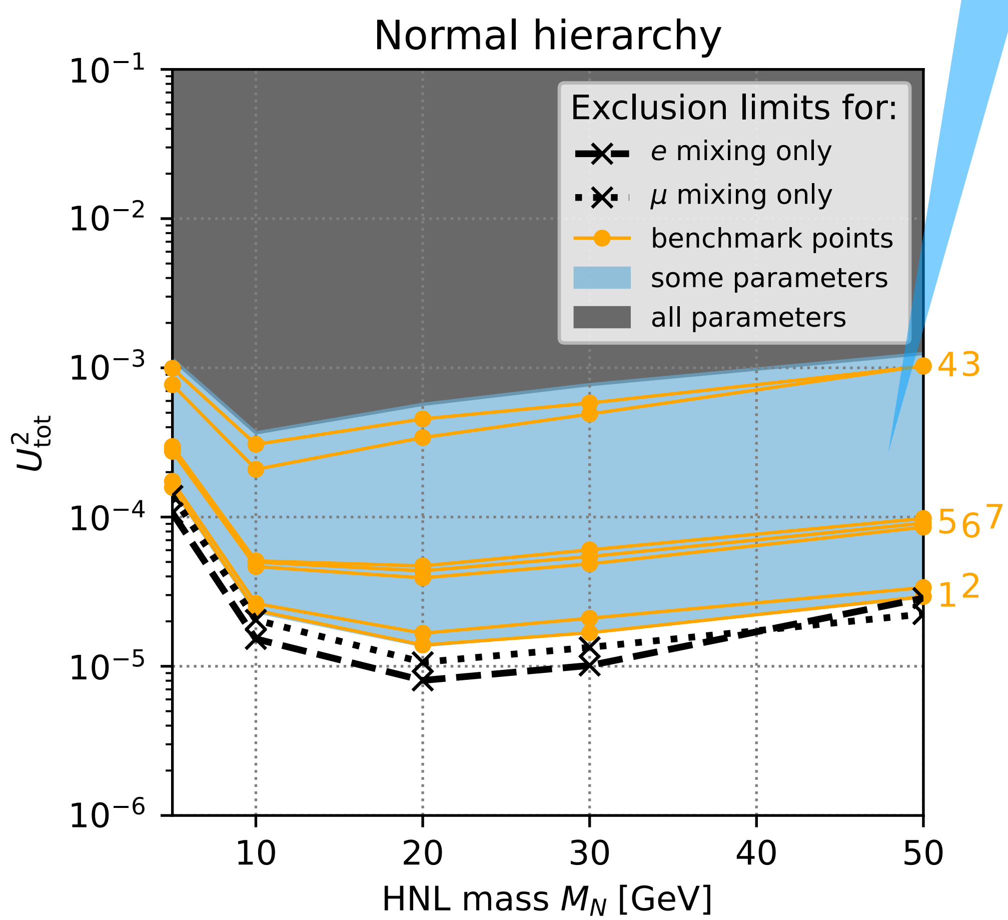
Neutrino oscillation data and reinterpretation

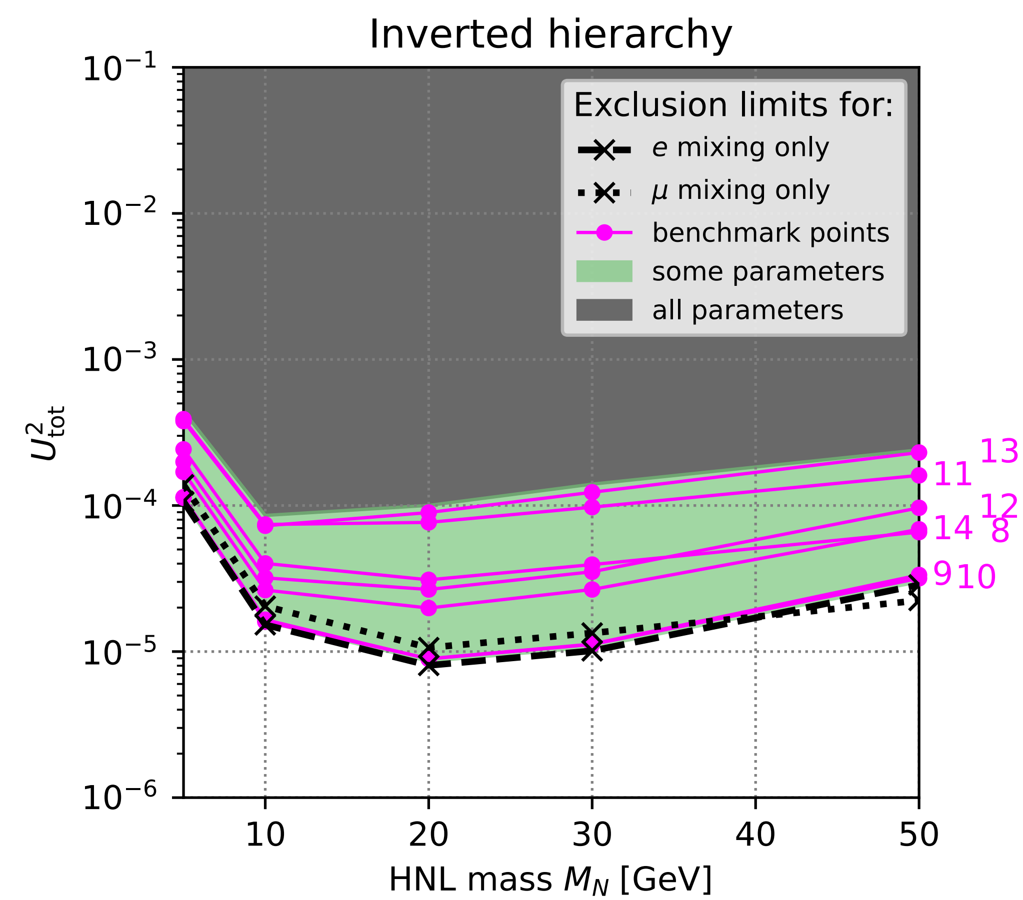


ATLAS triplepton search 1905.09787



New physics could hide here!





Jean-Loup Tastet, Oleg Ruchayskiy, IT 2107.12980 , JHEP

Summary and outlook

- Leptogenesis: relation between neutrino physics and the very early Universe
- The baryon asymmetry can be produced for masses of right-handed neutrino ranging from ~ 0.1 GeV to GUT scale
- If the masses in the range 0.1 — 100 GeV: experiment could reveal the origin of neutrino masses and the baryon asymmetry
- There are complementary search strategies for Heavy Neutral Leptons (LHC, SHiP, and FCC-ee)
- Heavy Neutral Leptons may hide even in what we think as “excluded” regions of the parameter space (140 MeV window, single mixing limits from LHC)

References

- Freeze-out of baryon number in low-scale leptogenesis
  Shintaro Eijima, Mikhail Shaposhnikov, IT
  1709.07834, *JCAP* 11 (2017) 030

- Parameter space of baryogenesis in the νMSM
  Shintaro Eijima, Mikhail Shaposhnikov, IT
  1808.10833, *JHEP* 07 (2019) 077

- Uniting Low-Scale Leptogenesis Mechanisms
  Juraj Klarić, Mikhail Shaposhnikov, IT
  2008.13771, *Phys.Rev.Lett.* 127 (2021) 11, 111802

- Reconciling resonant leptogenesis and baryogenesis via neutrino oscillations
  Juraj Klarić, Mikhail Shaposhnikov, IT
  2103.16545, *Phys.Rev.D* 104 (2021) 5, 055010

- Dirac vs. Majorana HNLs (and their oscillations) at SHiP
  Jean-Loup Tastet, IT
  1912.05520, *JHEP* 04 (2020) 005

- An allowed window for heavy neutral leptons below the kaon mass
  Bondarenko et al.
  2101.09255 *JHEP* 07 (2021) 193

- Reinterpreting the ATLAS bounds on heavy neutral leptons in a realistic neutrino oscillation model
  Jean-Loup Tastet, Oleg Ruchayskiy, IT
  2107.12980 *JHEP* 12 (2021) 182

- Heavy neutral leptons — Advancing into the PeV domain
  Kevin Urquía-Calderón, IT, Oleg Ruchayskiy
  2206.04540 *JHEP 08 (2023) 167*

Backup slides

Description of low-scale leptogenesis

- Quantum kinetic equations (to capture HNL oscillations)

$$i\frac{dn_{\Delta_\alpha}}{dt} = -2i\frac{\mu_\alpha}{T}\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}[\Gamma_\alpha]f_N(1-f_N) + i\int\frac{d^3k}{(2\pi)^3}\,\mathrm{Tr}[\tilde{\Gamma}_\alpha\,(\delta\bar{\rho}_N - \delta\rho_N)]\,,$$

$$i\,\frac{d\delta\rho_N}{dt} = -i\,\frac{d\rho_N^{eq}}{dt} + [H_N,\rho_N] - \frac{i}{2}\{\Gamma,\delta\rho_N\} - \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N(1-f_N)\right],$$

$$i\,\frac{d\delta\bar{\rho}_N}{dt} = -i\,\frac{d\rho_N^{eq}}{dt} - [H_N,\bar{\rho}_N] - \frac{i}{2}\{\Gamma,\delta\bar{\rho}_N\} + \frac{i}{2}\sum_\alpha\tilde{\Gamma}_\alpha\left[2\frac{\mu_\alpha}{T}f_N(1-f_N)\right].$$

Not affected by sphalerons

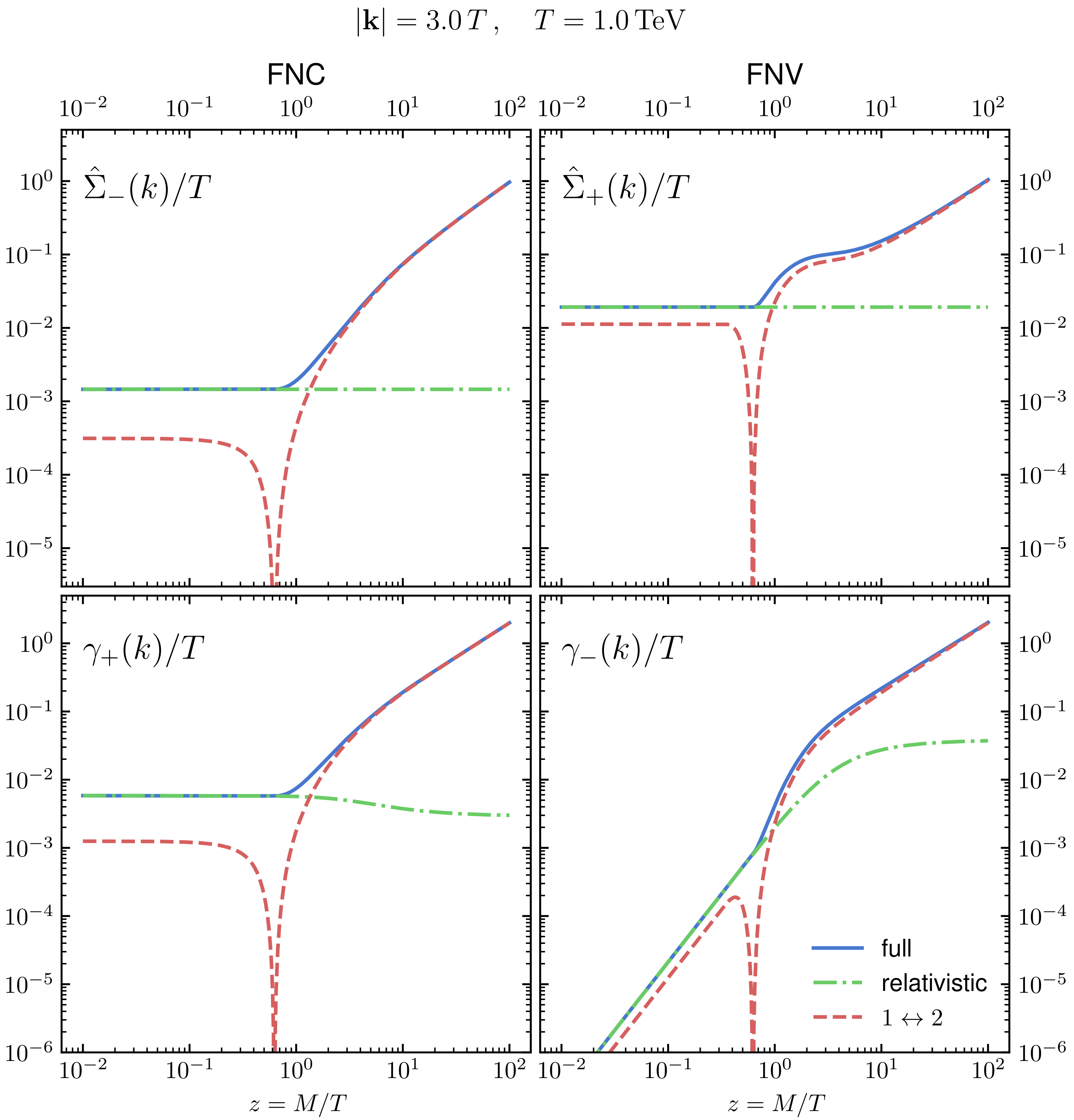
Susceptibility matrix — spectator effects

2x2 HNL matrix of densities

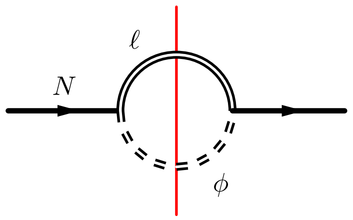
$n_{\Delta_\alpha} = L_\alpha - B/3$ $\mu_\beta = \omega_{\beta\alpha}\, n_{\Delta_\alpha}$ ρ_N $\delta\rho_N = \rho_N - \rho_N^{eq}$

- The equations must be solved numerically
- Scan over 6-dimensional parameter space (mass of N, mass splitting, phases of Yukawas)

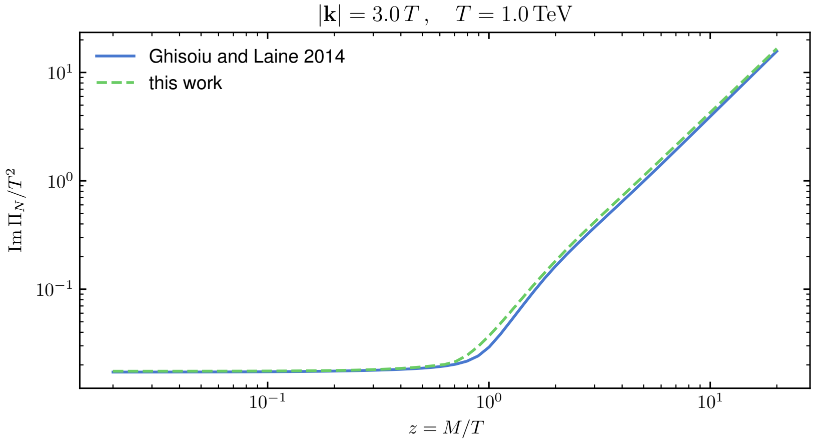
The rates



$|\mathbf{k}| = 3.0\,T\,, \quad T = 1.0\,\mathrm{TeV}$
FNC
FNV
$\hat{\Sigma}_{-}(k)/T$
$\hat{\Sigma}_{+}(k)/T$
$\gamma_{+}(k)/T$
$\gamma_{-}(k)/T$
full
relativistic
$1 \leftrightarrow 2$
$z = M/T$

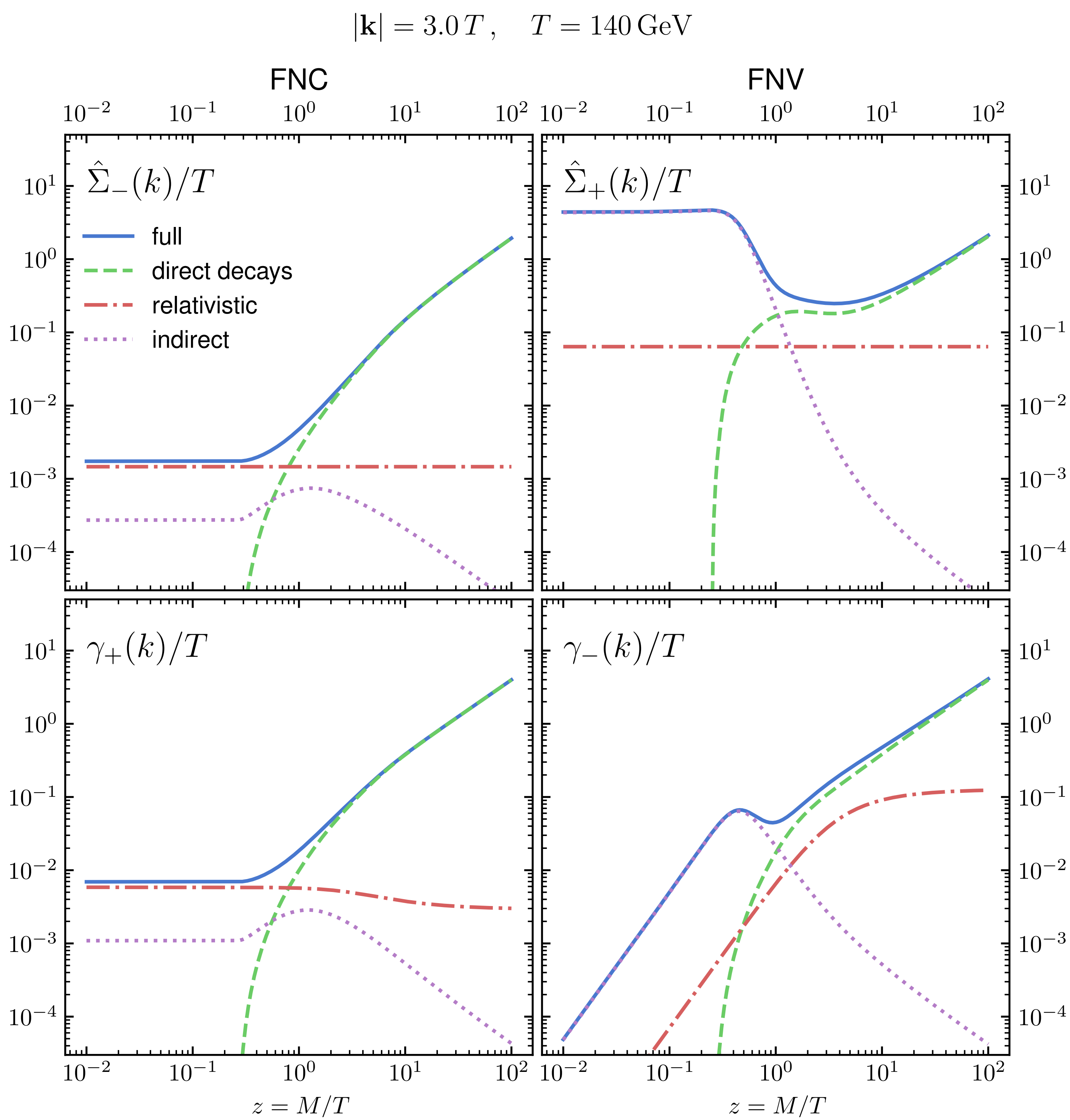


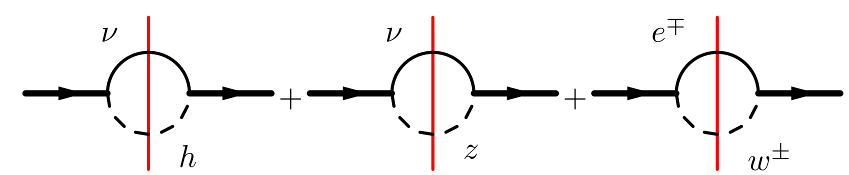
N
ℓ
ϕ

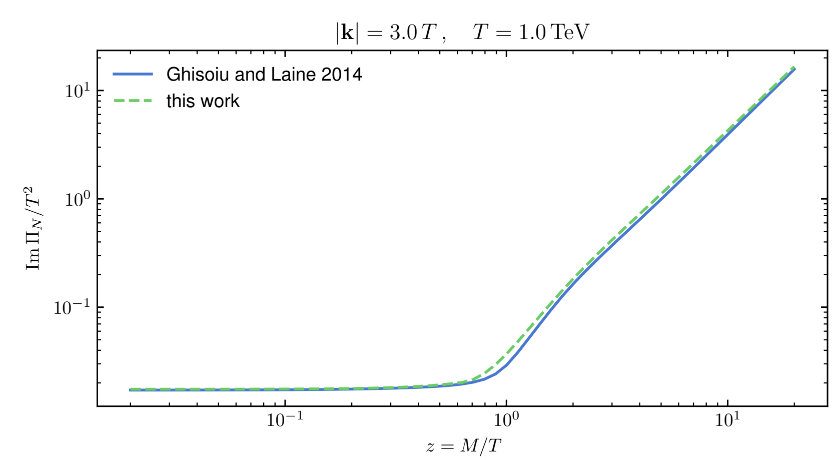


$|\mathbf{k}| = 3.0\,T\,, \quad T = 1.0\,\mathrm{TeV}$
Ghisoiu and Laine 2014
this work
$\mathrm{Im}\,\Pi_N/T^2$
$z = M/T$

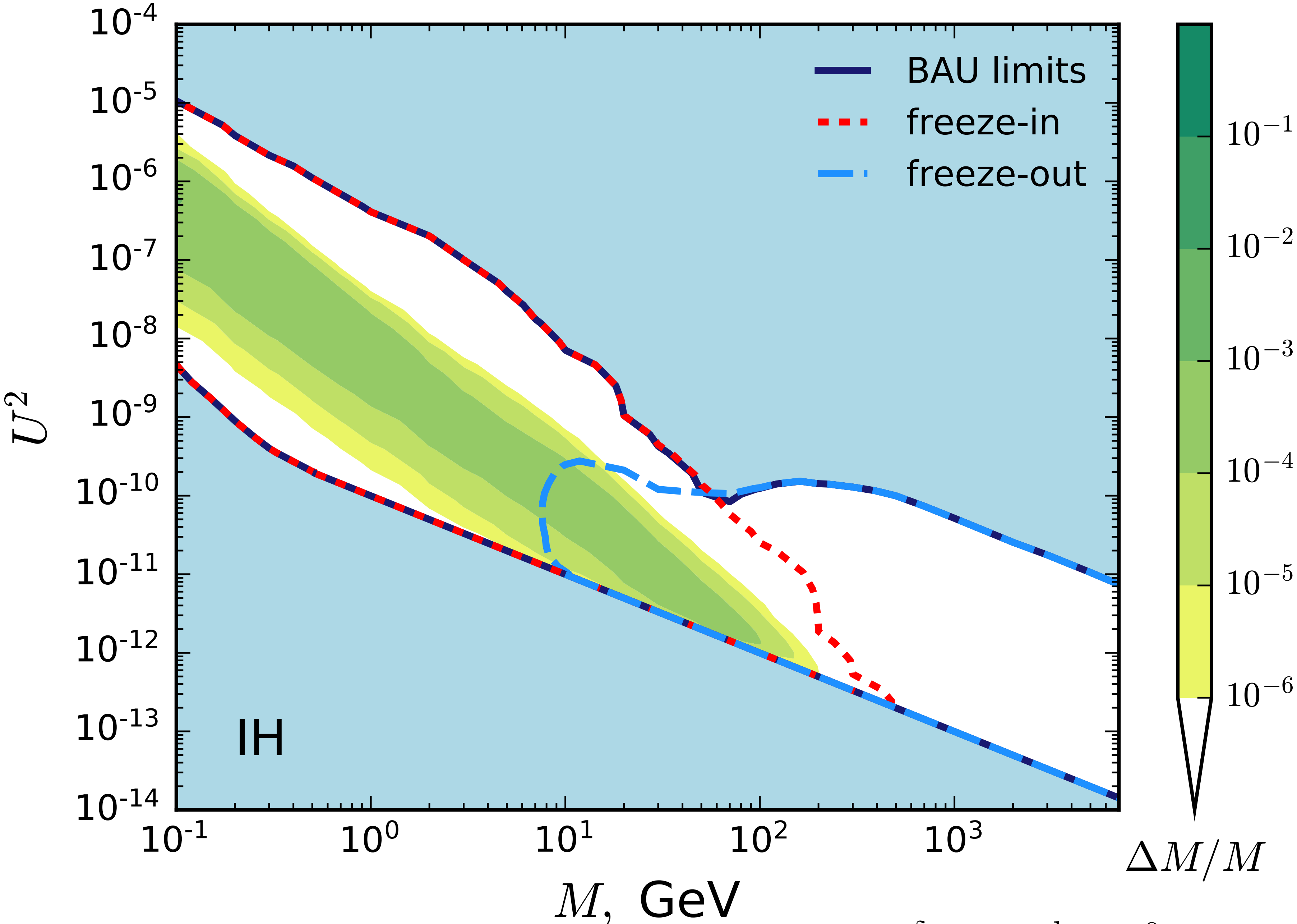
The rates


$|\mathbf{k}| = 3.0\,T\,, \quad T = 140\,\mathrm{GeV}$
FNC
FNV
$\hat{\Sigma}_-(k)/T$
$\hat{\Sigma}_+(k)/T$
$\gamma_+(k)/T$
$\gamma_-(k)/T$
full
direct decays
relativistic
indirect
$z = M/T$

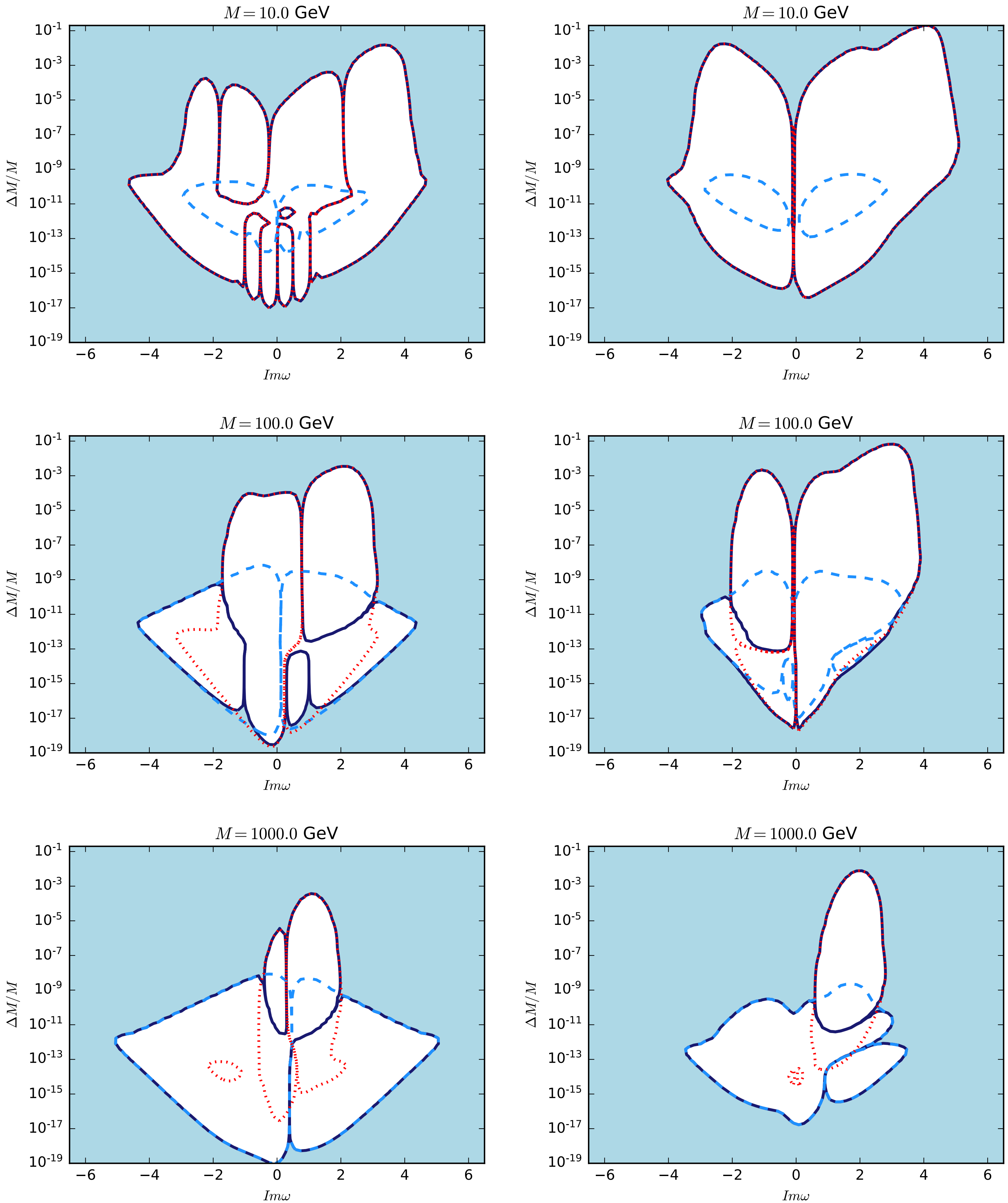

ν
h
ν
z
$e^{\mp}$
$w^{\pm}$


$|\mathbf{k}| = 3.0\,T\,, \quad T = 1.0\,\mathrm{TeV}$
Ghisoiu and Laine 2014
this work
$\mathrm{Im}\,\Pi_N/T^2$
$z = M/T$

flavour hierarchical washout



$\delta = \pi$ and $\eta = 0$


$M = 10.0$ GeV
$M = 10.0$ GeV
$M = 100.0$ GeV
$M = 100.0$ GeV
$M = 1000.0$ GeV
$M = 1000.0$ GeV
$\Delta M/M$
$Im\omega$
10^{-1} 10^{-3} 10^{-5} 10^{-7} 10^{-9} 10^{-11} 10^{-13} 10^{-15} 10^{-17} 10^{-19}
−6 −4 −2 0 2 4 6

Casas-Ibarra parametrization

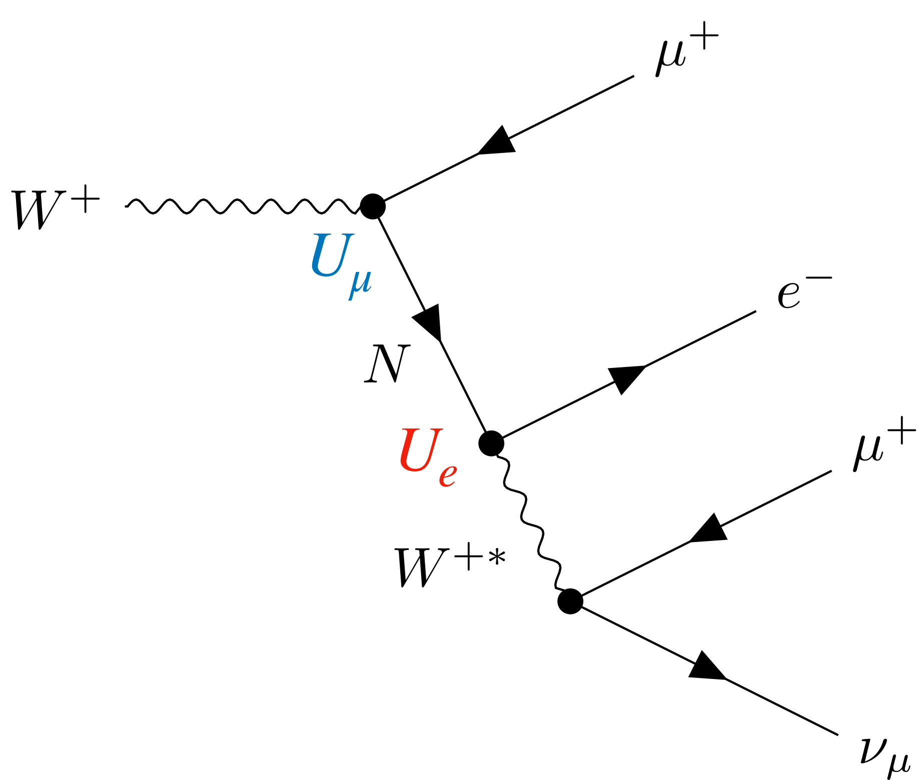
$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\rm diag}} \mathcal{R} \sqrt{M_M} \,,$$

$$\mathcal{R}^{\rm NH} = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix}, \qquad \mathcal{R}^{\rm IH} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$$

M, GeV	$\log_{10}(\Delta M/M)$	$\mathrm{Im}\,\omega$	$\mathrm{Re}\,\omega$	δ	η
$[0.1 - 7000]$	$[-19, -0.5]$	$[-7, 7]$	$[0, \pi]$	$[0, 2\pi]$	$[0, 2\pi]$

Neutrino oscillation data and reinterpretation

ATLAS triplepton search 1905.09787



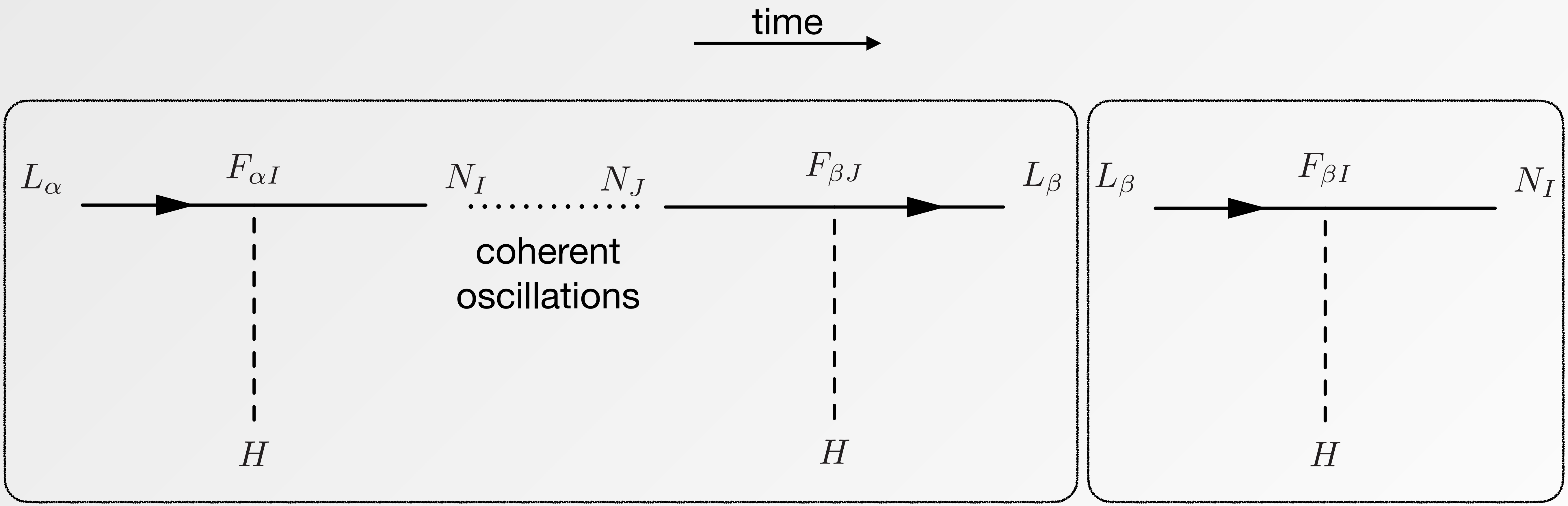
(a) LNC (b) LNV

LNC cannot be probed under single mixing assumption

Thanks to jean-Loup and Oleg
ATLAS now considers different mixing patterns!
https://arxiv.org/abs/2204.11988

$$\mathscr{L} = \mathscr{L}_{SM} + i\,\bar{\nu}_{R_I}\gamma^{\mu}\partial_{\mu}\nu_{R_I} - F_{\alpha I}\bar{L}_{\alpha}\tilde{\Phi}\nu_{R_I} - \frac{M_{IJ}}{2}\bar{\nu}^{c}_{R_I}\nu_{R_J} + h.c.$$

BAU generation



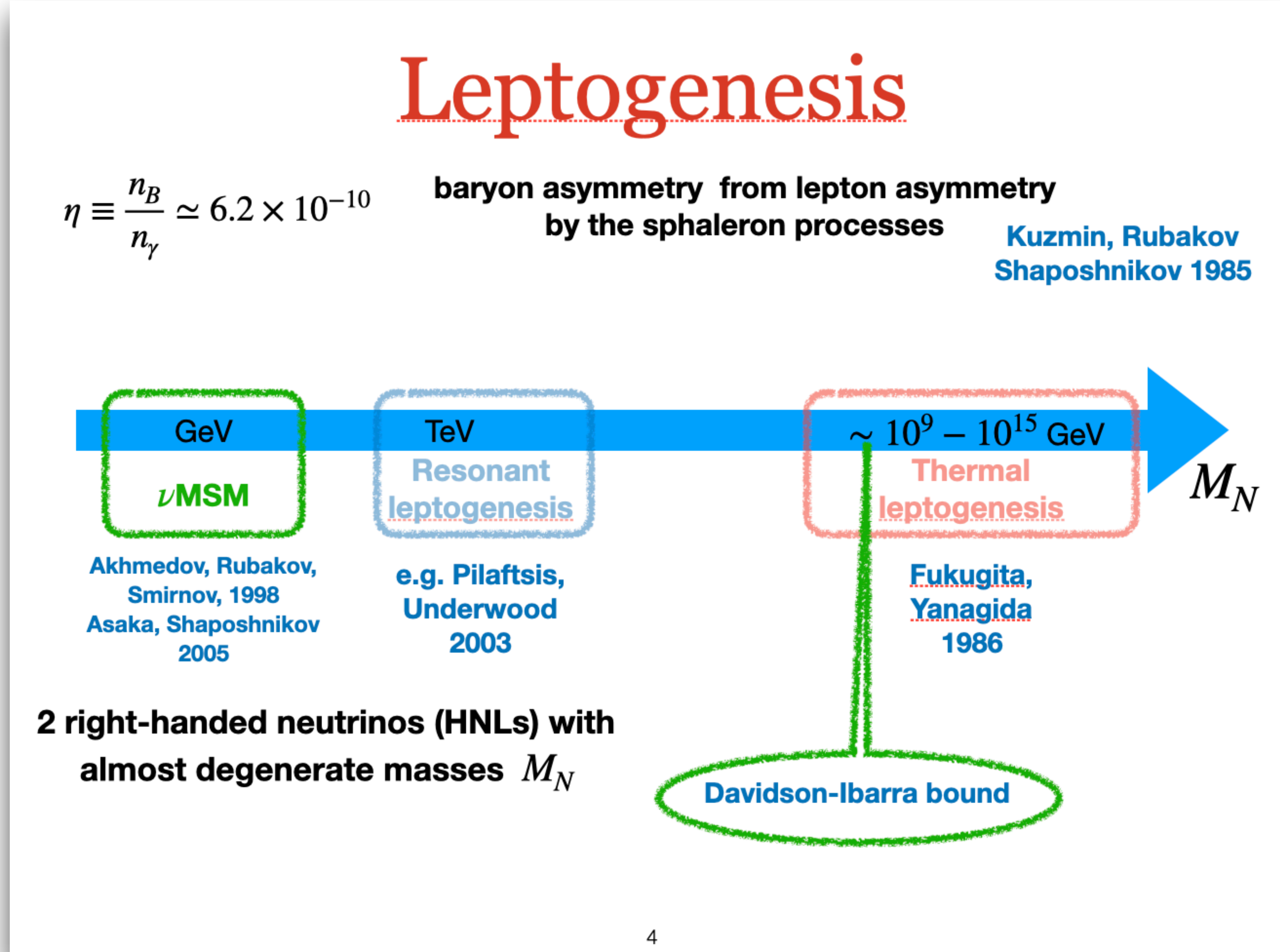
No lepton asymmetry
SM species
are in equilibrium
L-> N is out of equilibrium

Individual lepton asymmetries.

$$n_{L_\alpha} \neq n_{\overline{L_\alpha}}$$

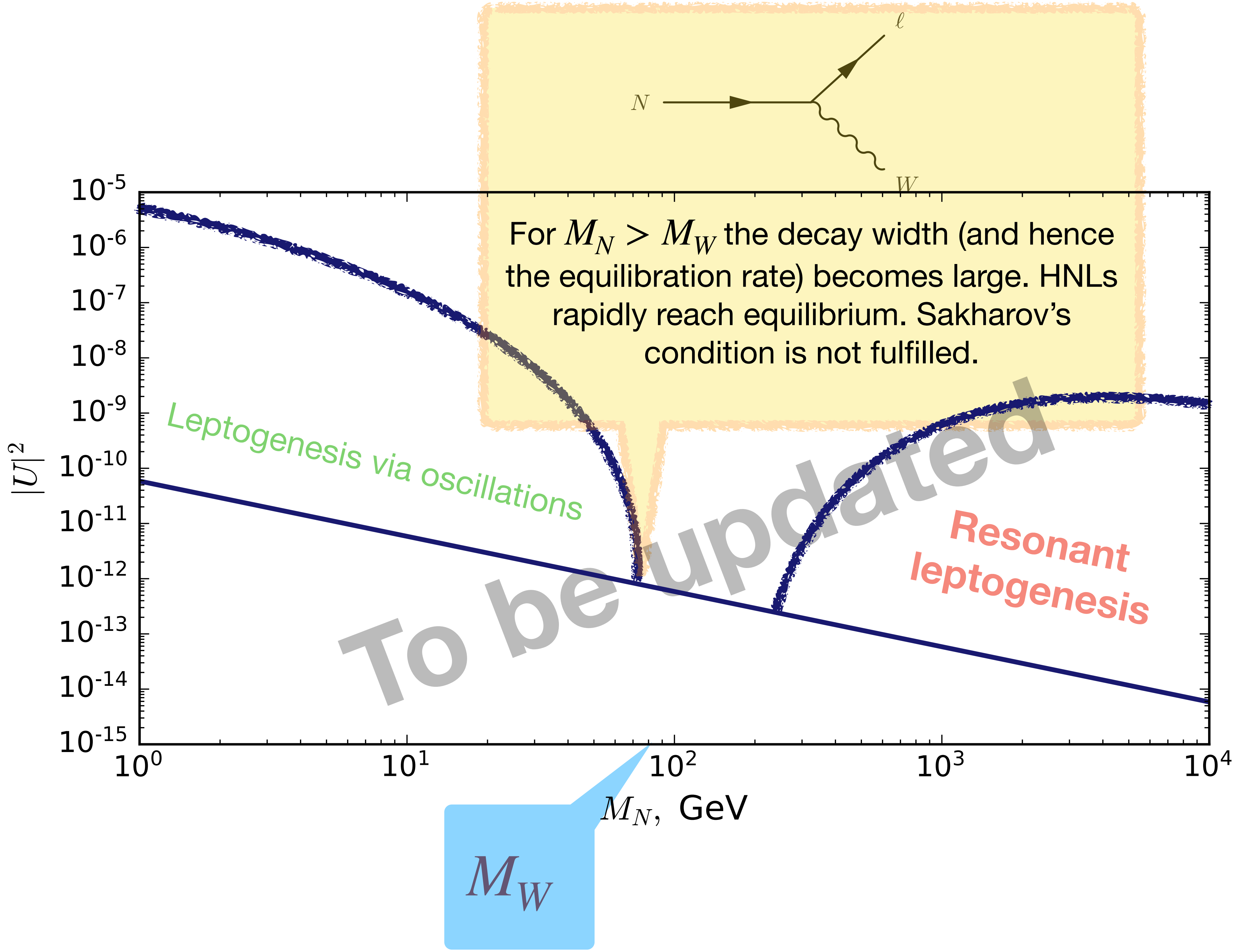
Total lepton asymmetry

$$\Gamma(L_\alpha \to L_\beta) \neq \Gamma(\overline{L_\alpha} \to \overline{L_\beta})$$

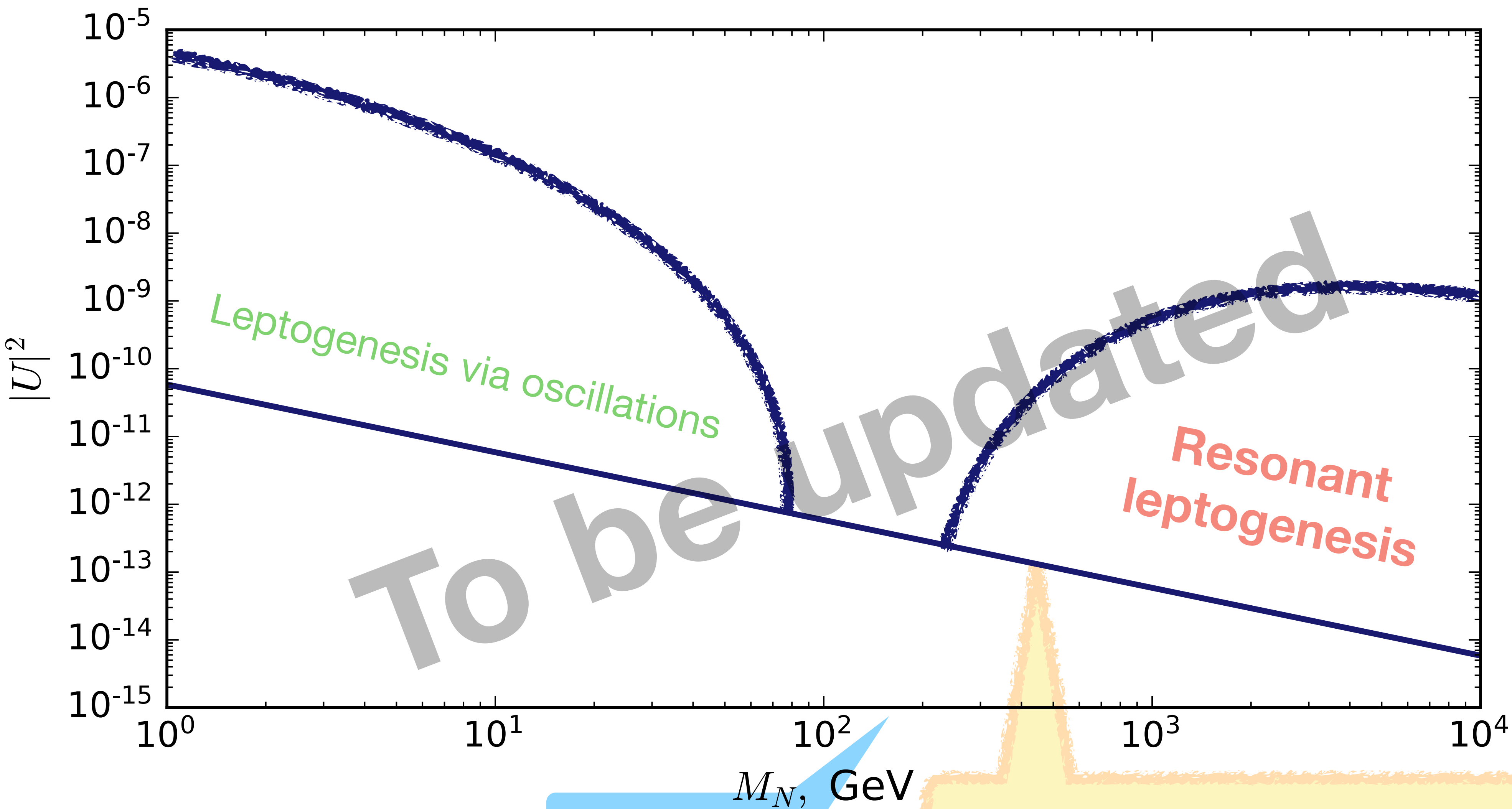


My slide from BLV 2019

Different leptogenesis mechanisms?



Different leptogenesis mechanisms?

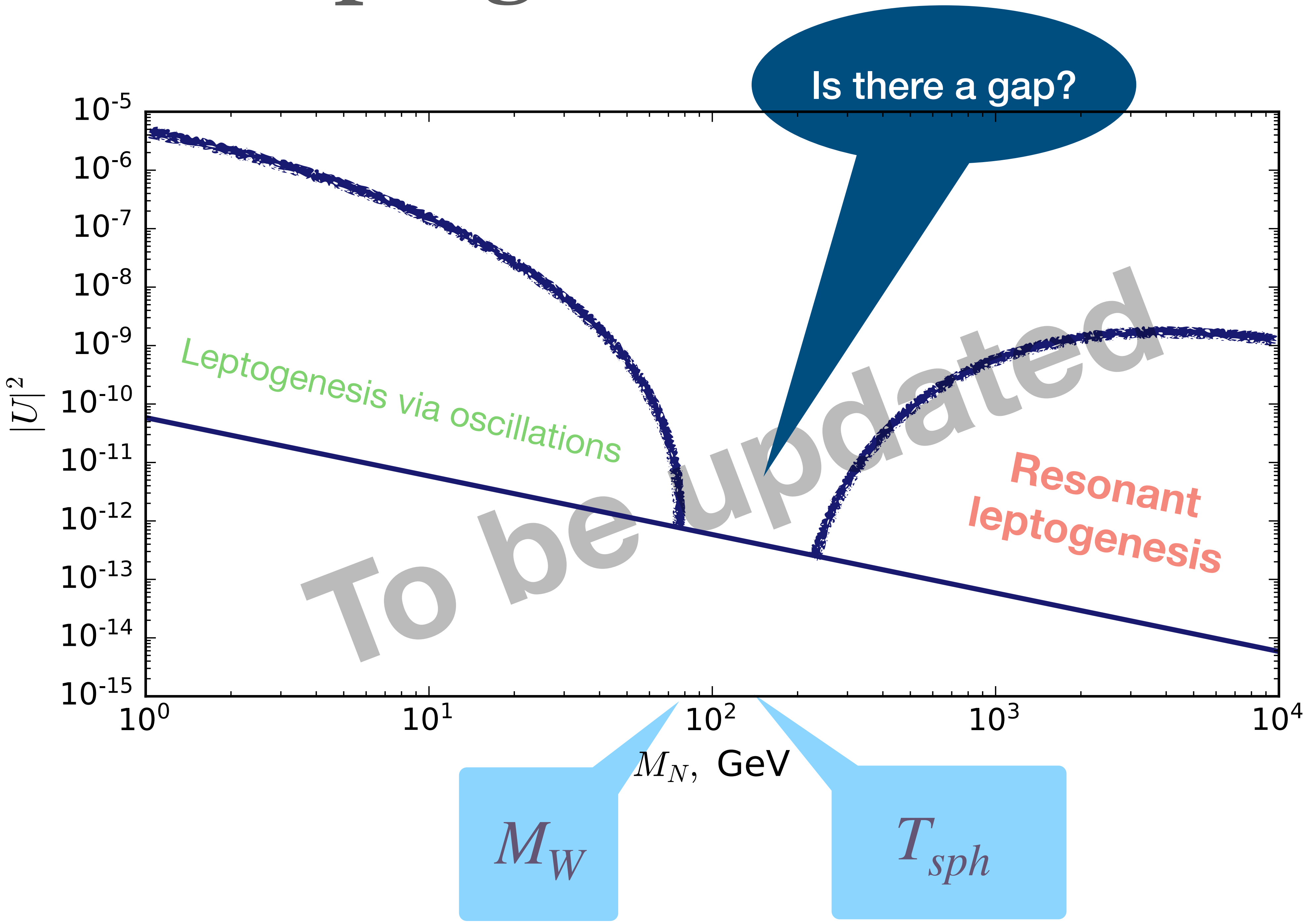


T_{sph}

Lepton asymmetry is generated in decays of N

If $M_N < 130$ GeV one can expect that this asymmetry is not transferred to BAU

Different leptogenesis mechanisms?



$$\mathrm{d}\Gamma^{\text{LNC/LNV}}_{\alpha\beta}(\tau) \cong 2\,|\Theta_{\alpha 1}|^2\,|\Theta_{\beta 1}|^2\left(1 \pm \cos\left(\Delta M \tau\right)\right) e^{-\Gamma\tau}\mathrm{d}\hat{\Gamma}^{\text{LNC/LNV}}_{\alpha\beta}$$

$$\Delta M\tau \ll 2\pi \quad \text{(Dirac-like limit)}$$

$$\Delta M\tau \gg 2\pi \quad \text{(Majorana-like limit)}$$

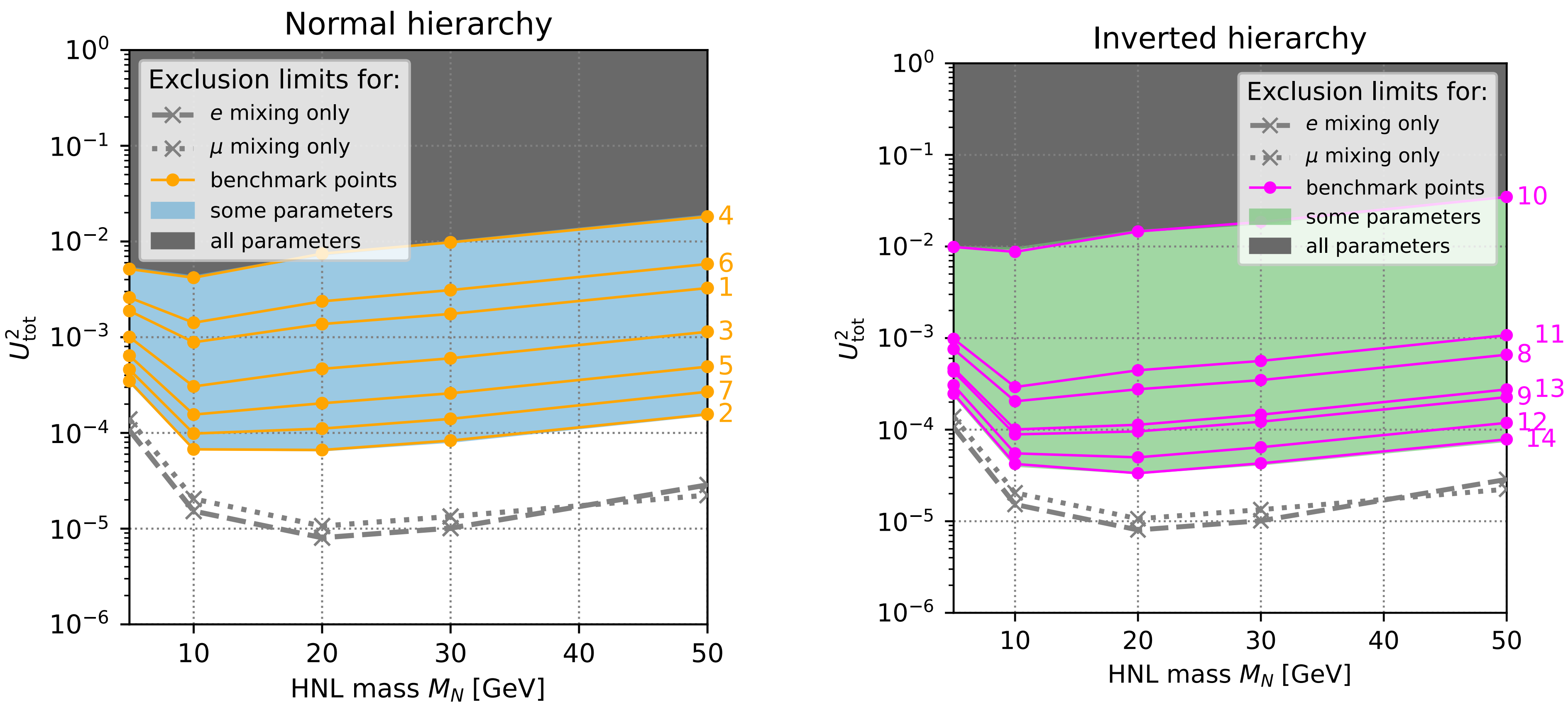
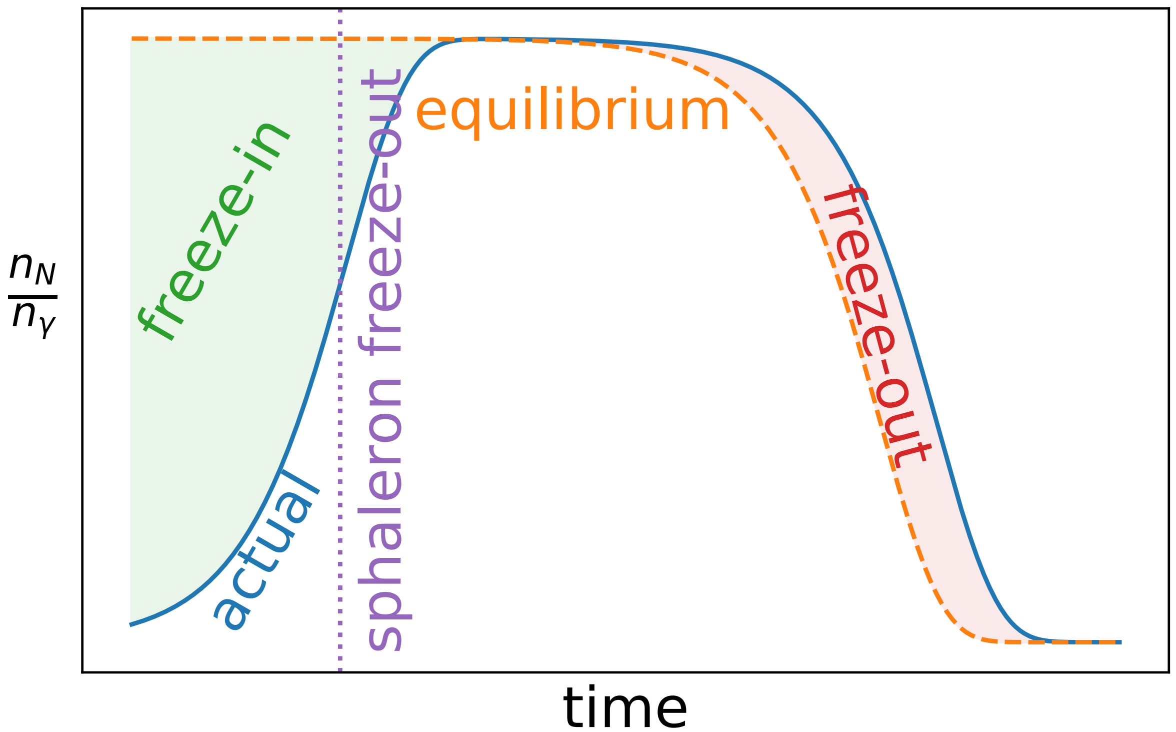
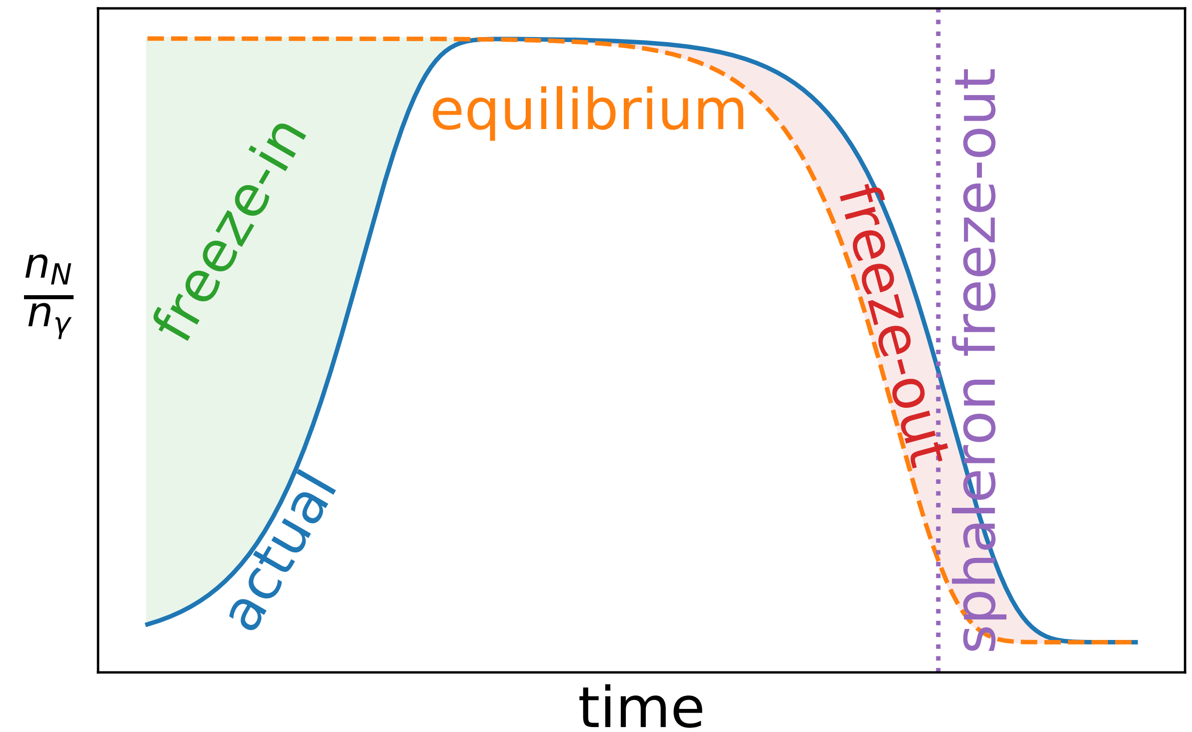


Figure 8: Same as figure 7, but for a **Dirac-like** HNL pair. The single-flavor mixing limits are grayed out because this search has *no sensitivity* to the Dirac-like case under this assumption; instead the limits for the Majorana-like case are given for comparison.

More accurate classification of Leptogenesis mechanisms



"Leptogenesis via oscillations"



"Resonant Leptogenesis"