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INTERACTIONS

UNIVERSITY OF COPENHAGEN

Low-scale leptogenesis and the quest for heavy neutral leptons

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Niels Bohr Institute,
University of Copenhagen

NuTS workshop, Madrid
May 25, 2022

Outline

- Introduction
  - Baryon asymmetry of the Universe and Sakharov conditions
  - Seesaw mechanism
  - Leptogenesis
- Parameter space of low-scale leptogenesis
- Phenomenological implications
  - Direct searches at SHiP
  - Dirac vs Majorana HNLs and their oscillations at SHiP
  - Reinterpretation

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

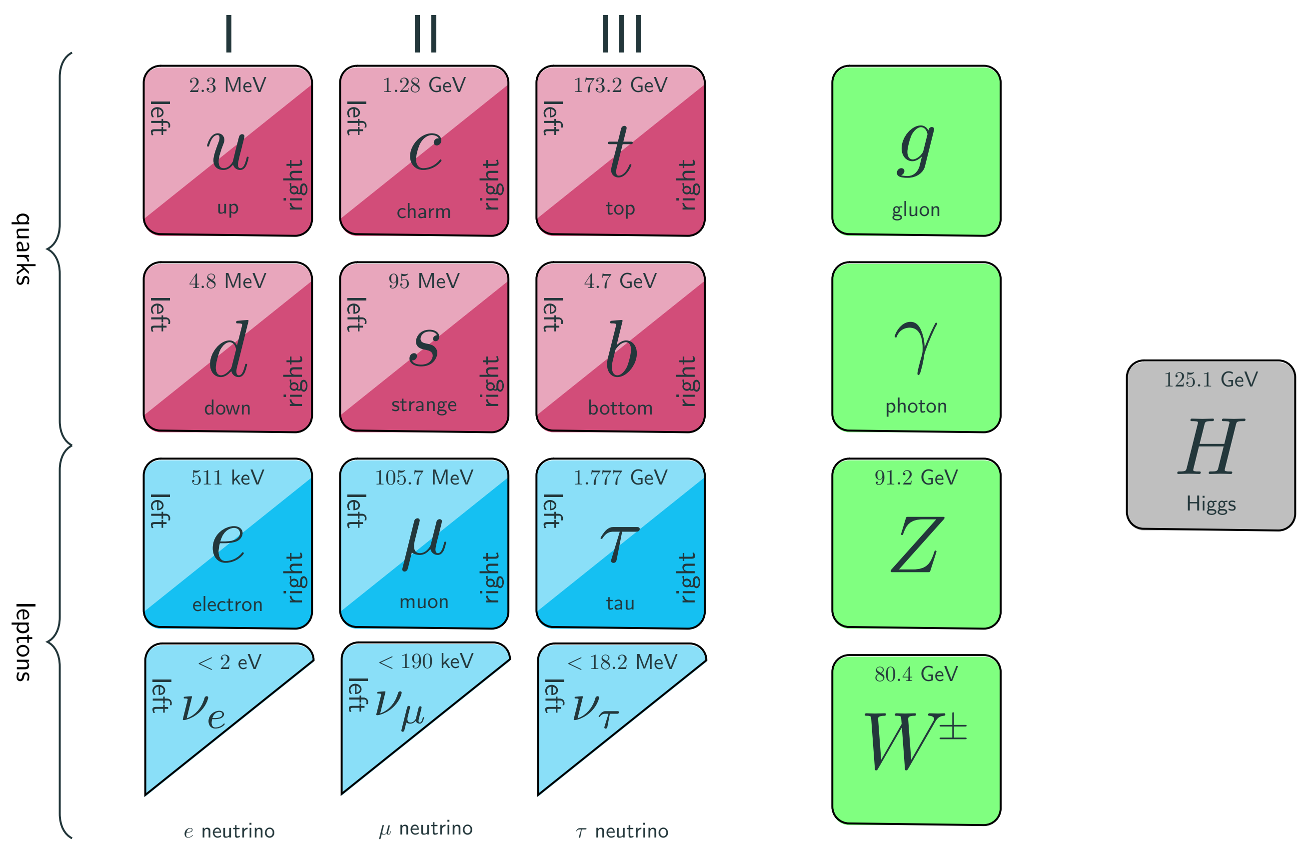
- Reconciling resonant leptogenesis and baryogenesis via neutrino oscillations
  Juraj Klarić, Mikhail Shaposhnikov, IT
  2103.16545, *Phys.Rev.D* 104 (2021) 5, 055010

- 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

The Standard Model



Global symmetries:
baryon and lepton numbers are conserved (classically)

$$q \to \mathrm{e}^{i\beta/3} q, \quad \bar{q} \to \mathrm{e}^{-i\beta/3} \bar{q}$$

$$(\nu_e,\ e) \to \mathrm{e}^{i\beta_e}(\nu_e, e), \quad (\bar{\nu}_e,\ \bar{e}) \to \mathrm{e}^{-i\beta_e}(\bar{\nu}_e,\ \bar{e})$$

$$(\nu_\mu,\ \mu) \to \mathrm{e}^{i\beta_\mu}(\nu_\mu, \mu), \quad (\bar{\nu}_\mu, \bar{\mu}) \to \mathrm{e}^{-i\beta_\mu}(\bar{\nu}_\mu, \bar{\mu})$$

$$(\nu_\tau,\ \tau) \to \mathrm{e}^{i\beta_\tau}(\nu_\tau, \tau), \quad (\bar{\nu}_\tau, \bar{\tau}) \to \mathrm{e}^{-i\beta_\tau}(\bar{\nu}_\tau, \bar{\tau})$$

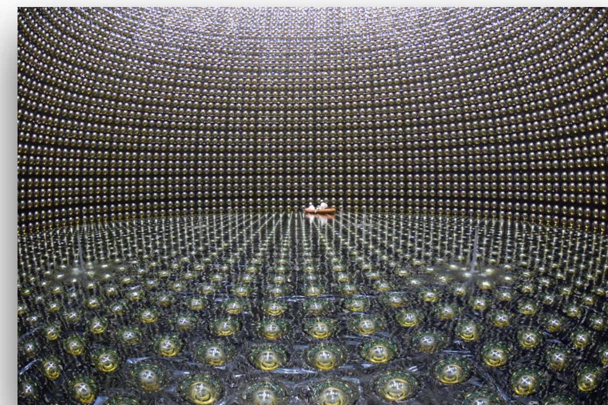
- Gauge theory
  $SU(3) \times SU(2) \times U(1)$
- Explains all laboratory experiments
- Together with General Relativity (or, e.g. Einstein-Cartan theory) explains the evolution of the universe from Big Bang Nucleosynthesis (t > 0.1 sec)
- According to Scientific American, it led to 55 Nobels
- Are we done?

Image credit: Juraj Klaric

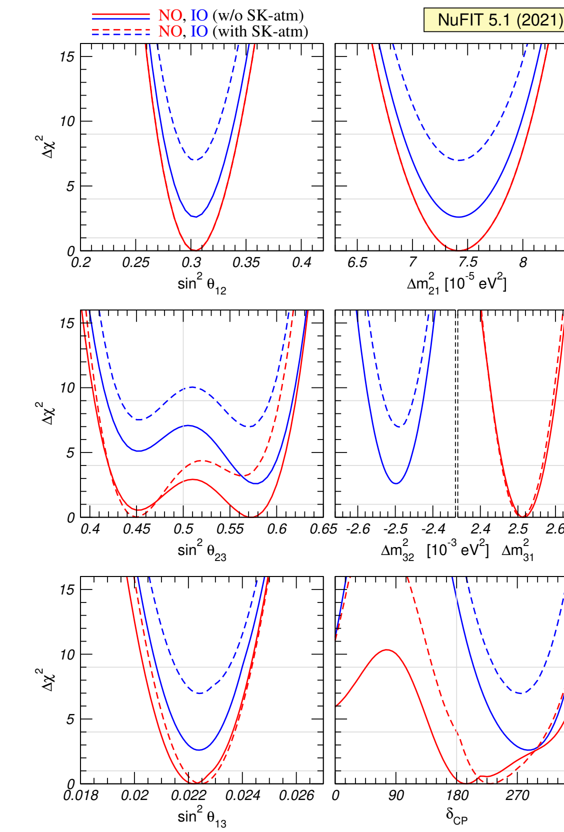
Beyond the Standard Model

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

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

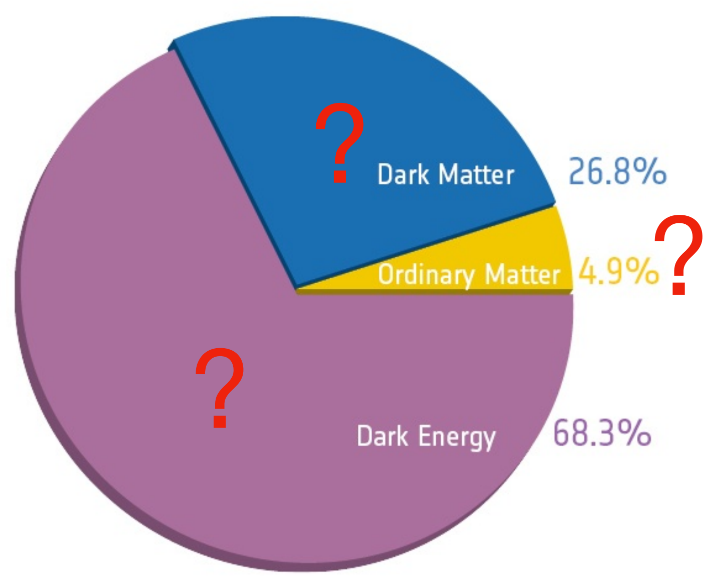


Super-Kamiokande (atmospheric oscillations $\nu_\mu \to \nu_\tau$)



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

- Cosmology



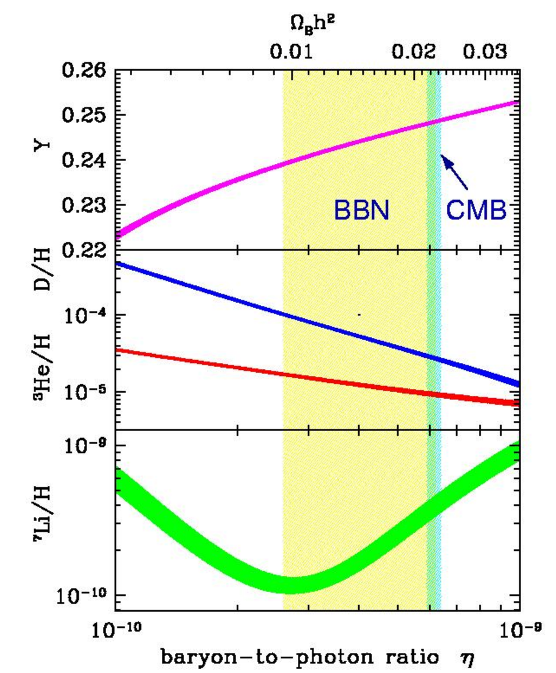
ESA and the Planck Collaboration

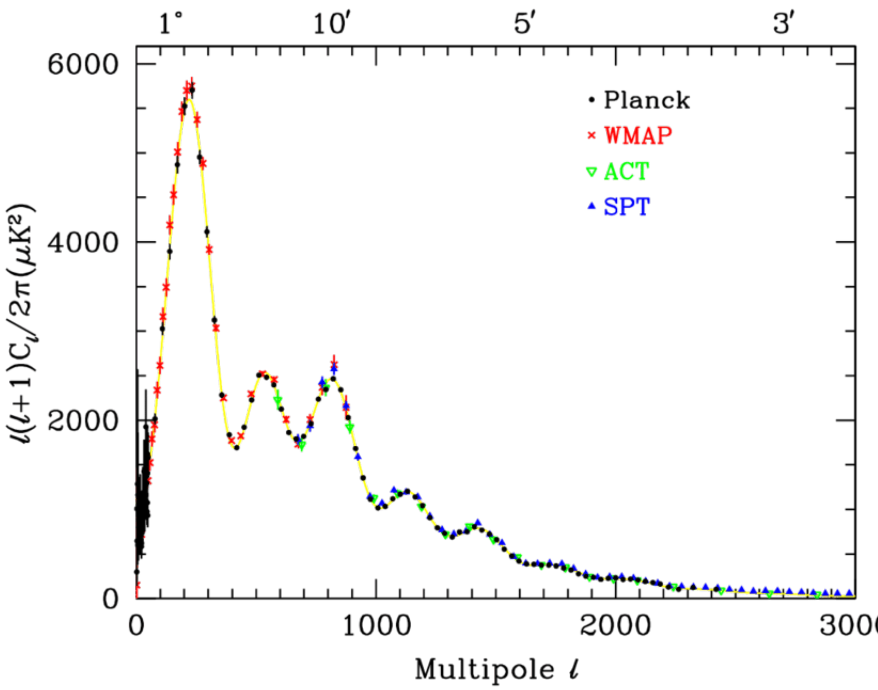
Baryon asymmetry of the Universe

- No antimatter in the present universe
- Baryon to photon ratio

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

- 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

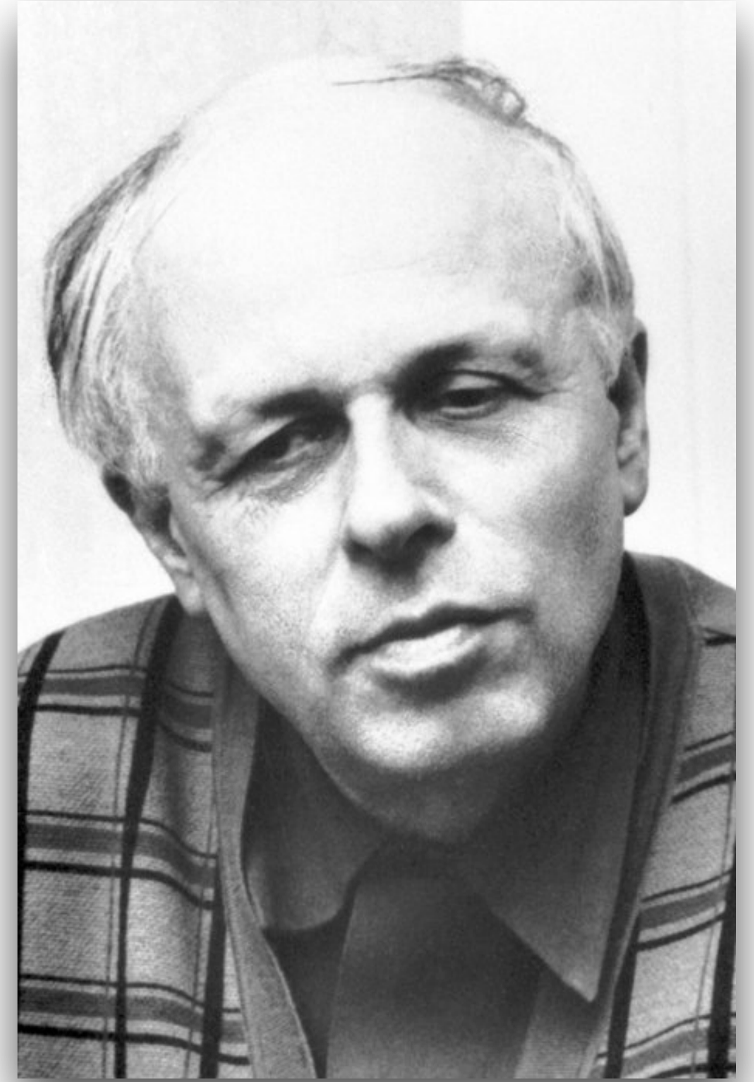




Where the asymmetry comes from?

Sakharov Conditions (1967)

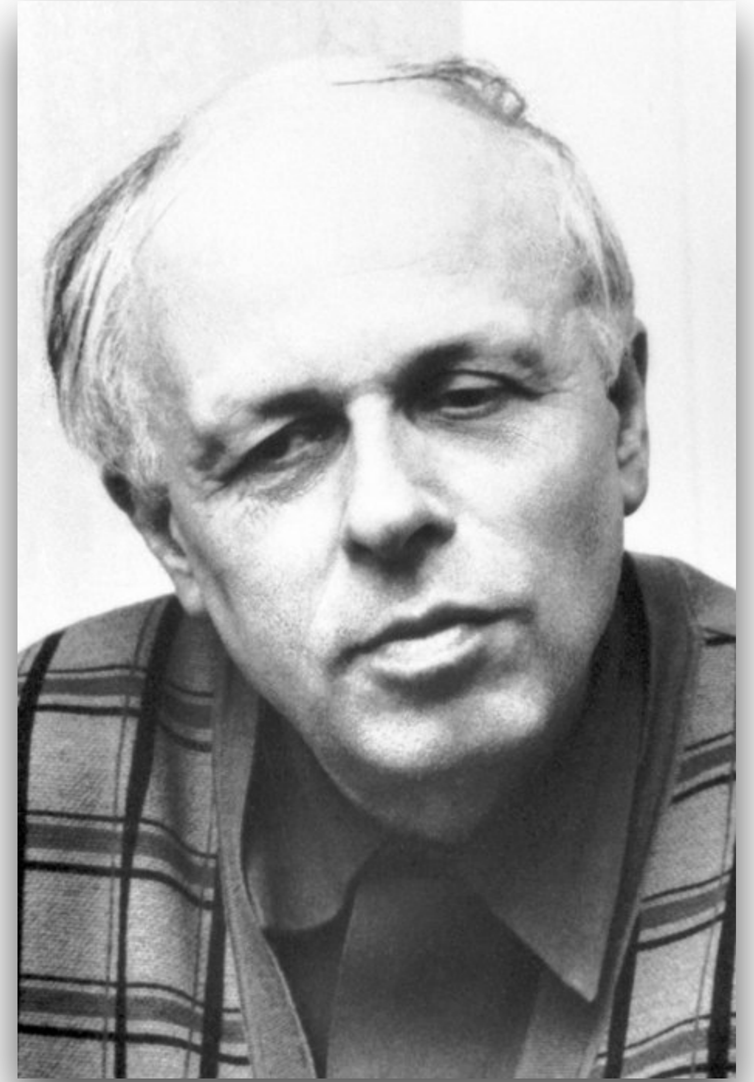
- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium



The *Nobel Peace Prize* 1975 was awarded to Andrei Dmitrievich Sakharov
"for his struggle for human rights in the Soviet Union, for disarmament and cooperation between all nations."

Where the asymmetry comes from?

Sakharov Conditions (1967)



- Baryon number violation

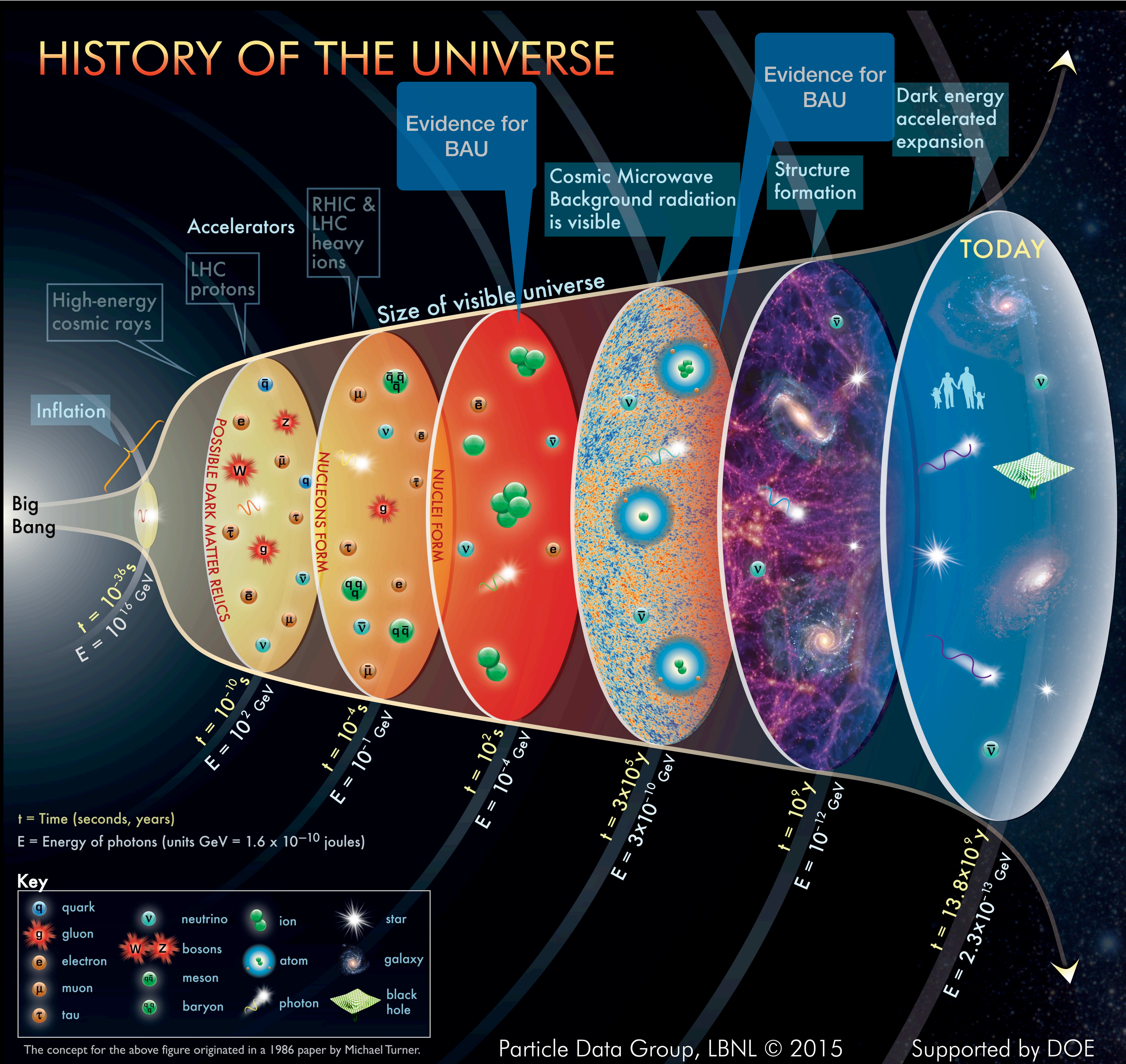
Nonperturbative sphaleron processes at T>130 GeV
[Kuzmin, Rubakov, Shaposhnikov 1985]

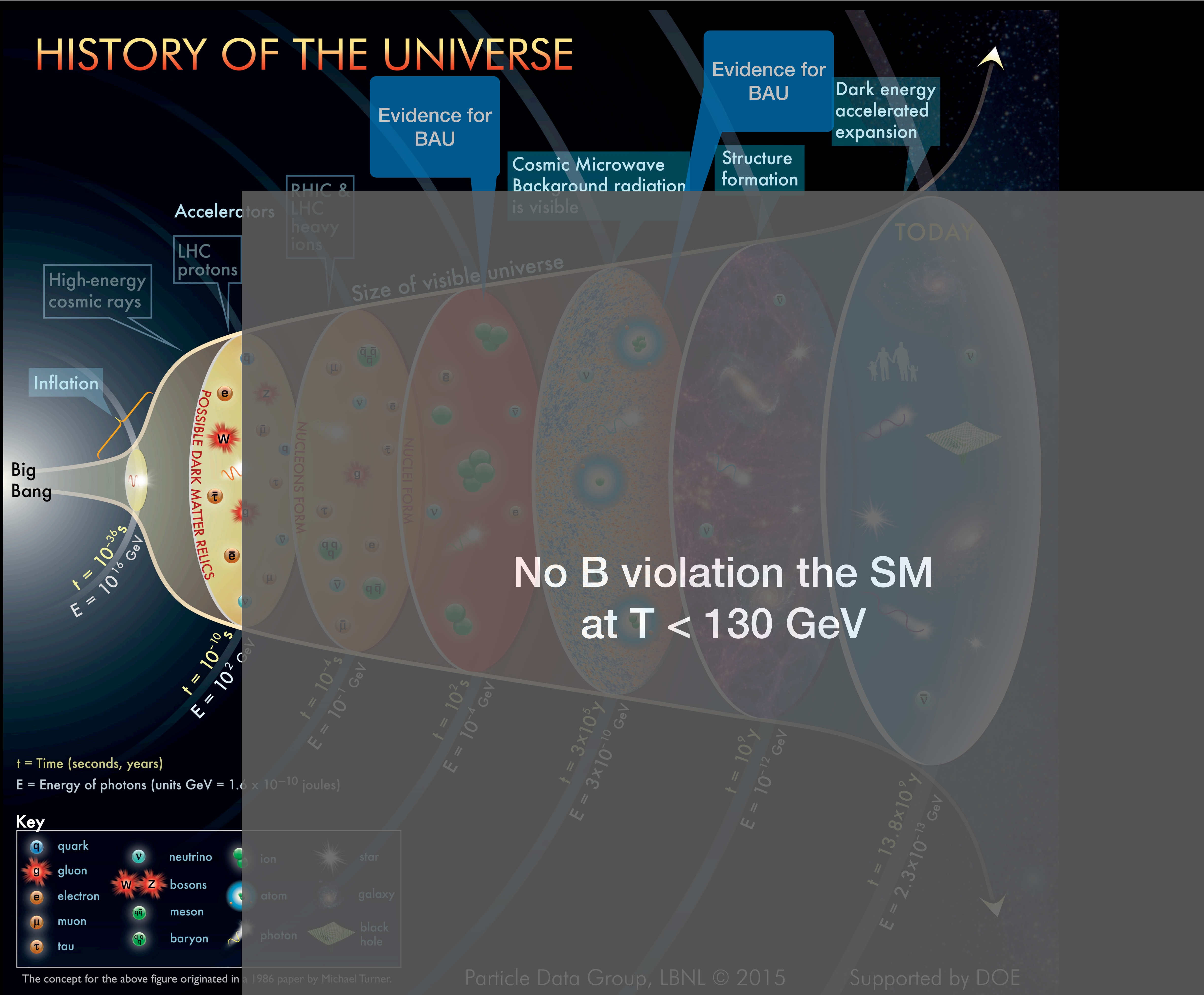
- C and CP violation

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
Accelerators
RHIC & LHC heavy ions
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 = 10¹⁶ GeV
t = 10⁻¹⁰ s
E = 10² GeV
t = 10⁻⁴ s
E = 10⁻¹ GeV
t = 10² s
E = 10⁻⁴ GeV
t = 3x10⁵ y
E = 3x10⁻¹⁰ GeV
t = 10⁹ y
E = 10⁻¹² GeV
t = 13.8x10⁹ 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



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Particle Data Group, LBNL © 2015
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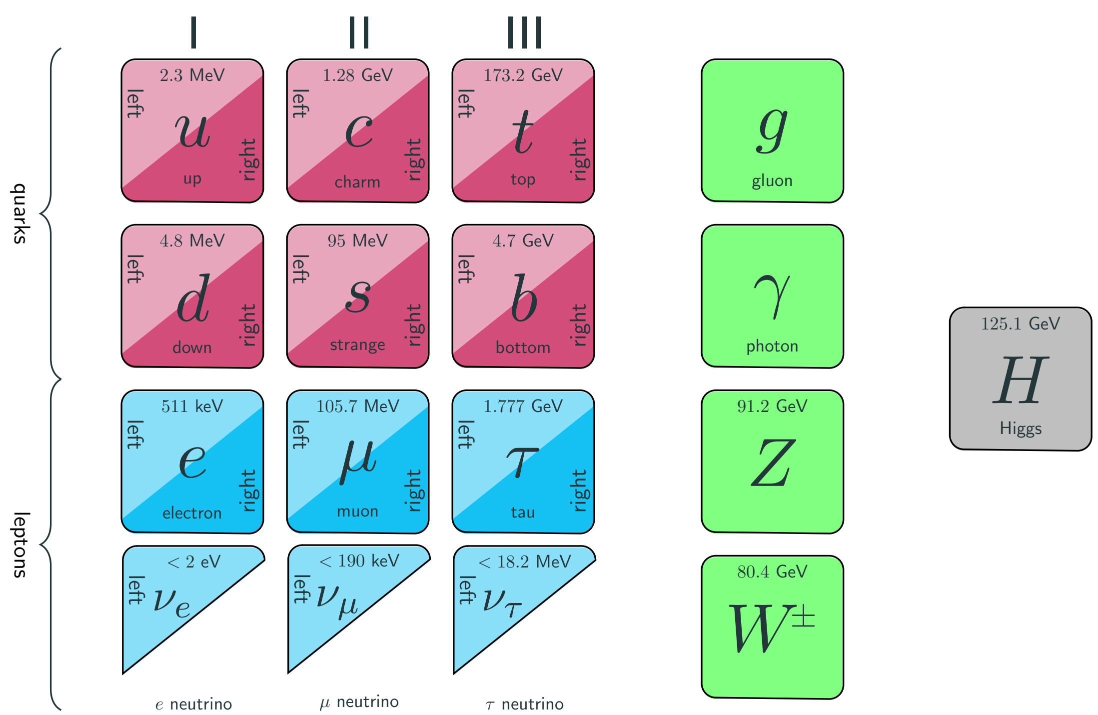
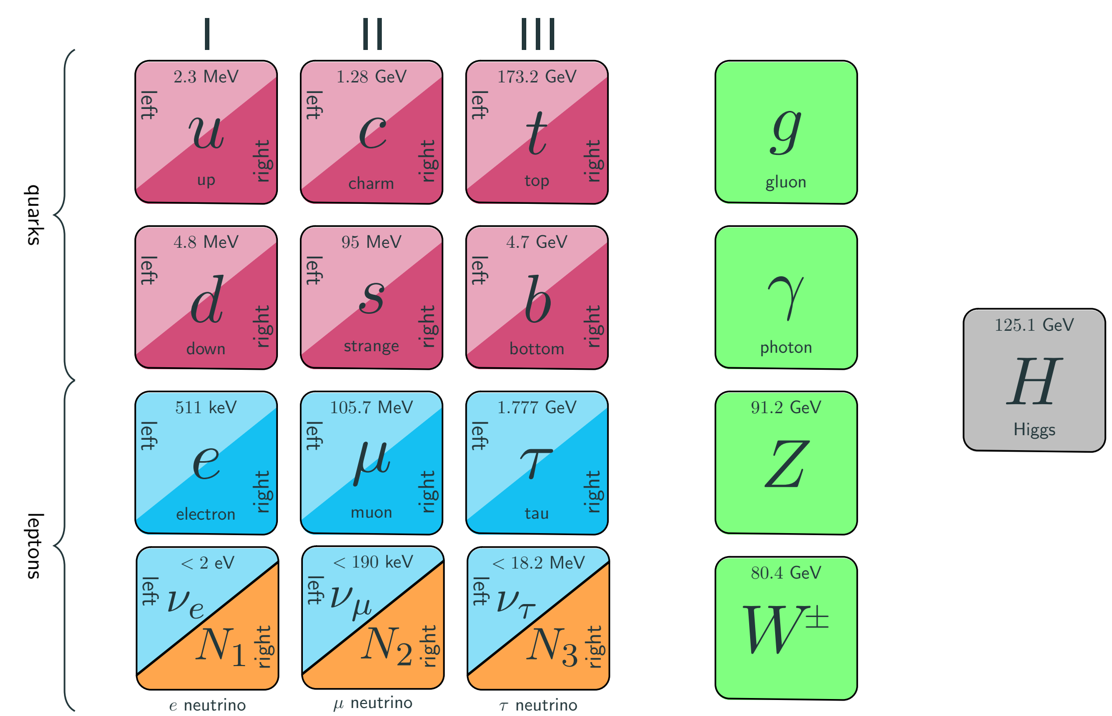
No B violation the SM
at T < 130 GeV

Neutrino Minimal Standard Model (νMSM)

Asaka, Blanchet, Shaposhnikov 2005
Asaka, Shaposhnikov 2005





N_1 DM candidate

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

Dark matter in the νMSM

talk by Misha Shaposhnikov

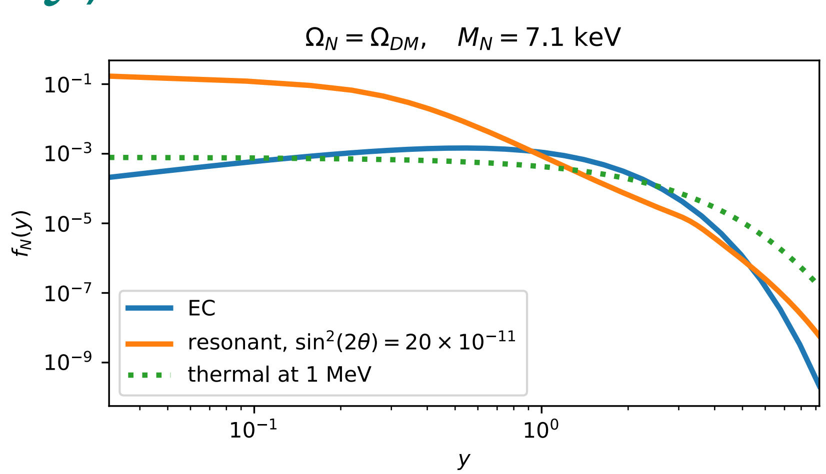
- Resonant production [Shi and Fuller]

  Requires large lepton asymmetry $L/s \sim 10^{-5}$
  Possible in the νMSM
  [Shaposhnikov, Canetti, Drewes, Frossard 1208.4607; Ghiglieri, Laine 2004.10766]

- Thermal production via four-fermion interaction in Einstein-Cartan gravity

  No assumption about the symmetry of the connection $\Gamma^{\lambda}_{\mu\nu}$
  Without matter — equivalent to GR
  Integrating out torsion: $\frac{\xi}{M_P^2}\bar{N}\gamma^{\mu}N\,\bar{\Psi}\gamma_{\mu}\Psi$
  Fermionic DM with mass keV — 10^8 GeV (depending on ξ)
  [Shaposhnikov, Shkerin, IT, and Zell 2008.11686, Phys.Rev.Lett. 126 (2021)]

New constraints: https://arxiv.org/abs/2205.09777



The seesaw mechanism

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

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

At least 2 HNLs to be compatible with oscillation data

Mass states N_I (~HNLs), $I = 1,2,...$

Φ is the SM Higgs doublet, L_α are the SM lepton doublets

$F_{\alpha I}$ are new Yukawa couplings, M_{IJ} is the mass matrix of RH neutrinos

Mixing with N_I

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

$$|U_\alpha|^2 = |\Theta_{\alpha 2}|^2 + |\Theta_{\alpha 3}|^2$$

$$\Theta_{\alpha I} = \frac{\langle\Phi\rangle F_{\alpha I}}{M_I}$$

$$U^2 = \Sigma_\alpha |U_\alpha|^2$$

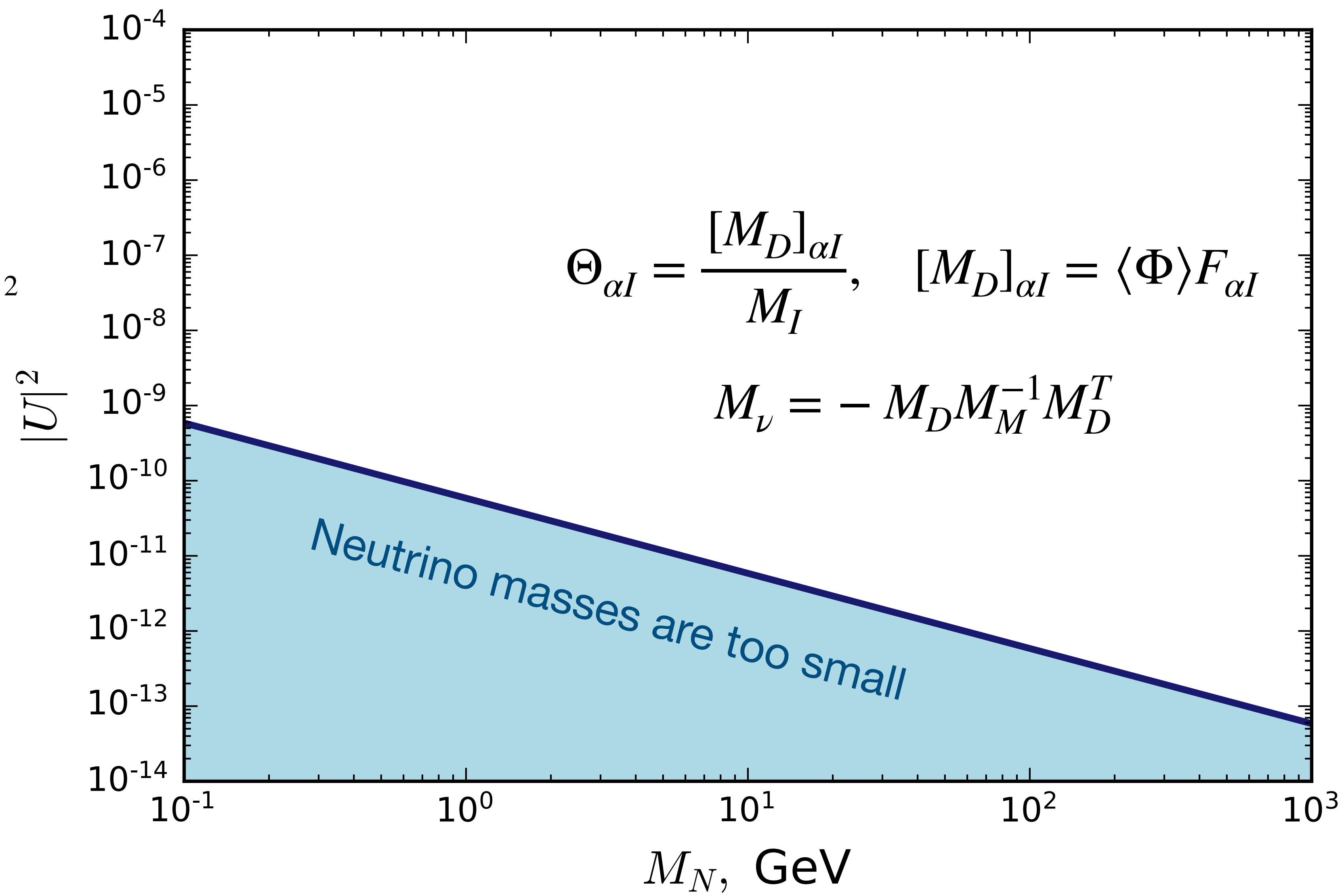
HNLs (Heavy Neutral Leptons)

Mixing with light neutrinos

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

$$|U_\alpha|^2 = |\Theta_{\alpha 2}|^2 + |\Theta_{\alpha 3}|^2$$

$$|U|^2 = \Sigma_\alpha |U_\alpha|^2$$



We consider nearly degenerate HNLs (Heavy Neutral Leptons)

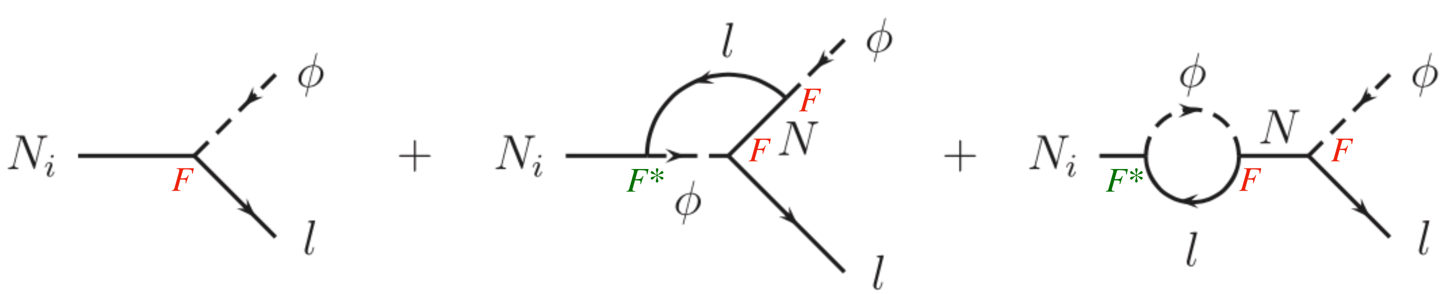
Heavy Neutral Leptons: Leptogenesis

talk by Juraj Klarić

The same 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 $\Gamma_N \sim H$



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

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

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

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

BAU in the νMSM (model with two right-handed neutrinos)

- Initial idea: Akhmedov, Rubakov, Smirnov
- Formulation of kinetic theory: Asaka, Shaposhnikov.
- Analysis of the baryon asymmetry generation in the vMSM: Asaka, Shaposhnikov, Canetti, Drewes, Frossard; Eijima, Ishida; Shuve, Yavin; Abada, Arcadi, Domcke, Lucente; Hernández, Kekic, J. López-Pavón, J. Racker, J. Salvado; Drewes, Garbrecht, Gueter, Klaric; Hambye, Teresi; Ghiglieri, Laine; IT; …

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

$n_{\Delta_\alpha} = L_\alpha - B/3$

Susceptibility matrix — spectator effects

$\mu_\beta = \omega_{\beta\alpha}\, n_{\Delta_\alpha}$

2x2 HNL matrix of densities

ρ_N $\quad \delta\rho_N = \rho_N - \rho_N^{eq}$

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

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, …]

- 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

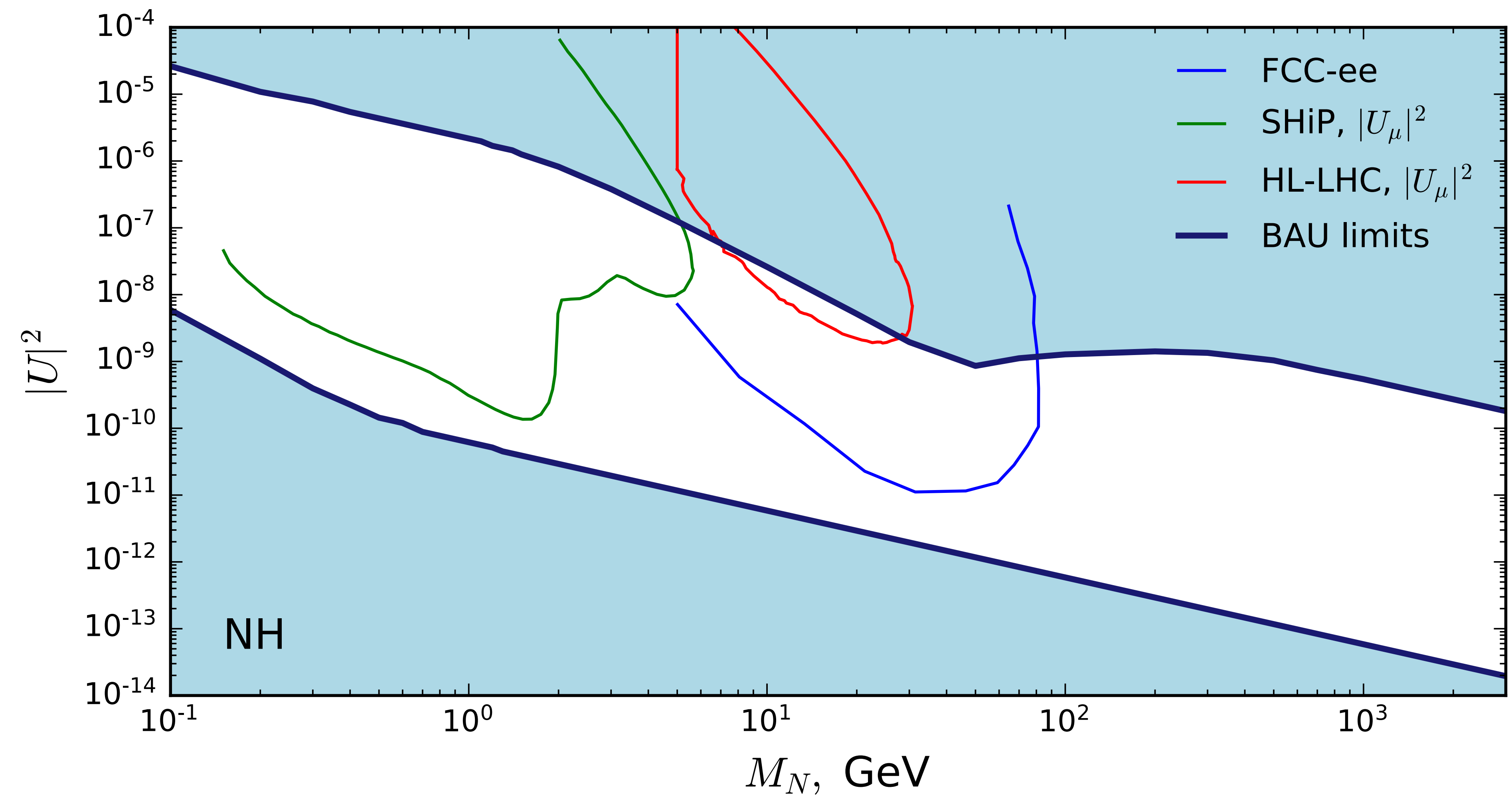
- Spectator processes
  Shuve, Yavin; Ghiglieri, Laine; Eijima, Shaposhnikov, IT

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

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

Uniting leptogeneses

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

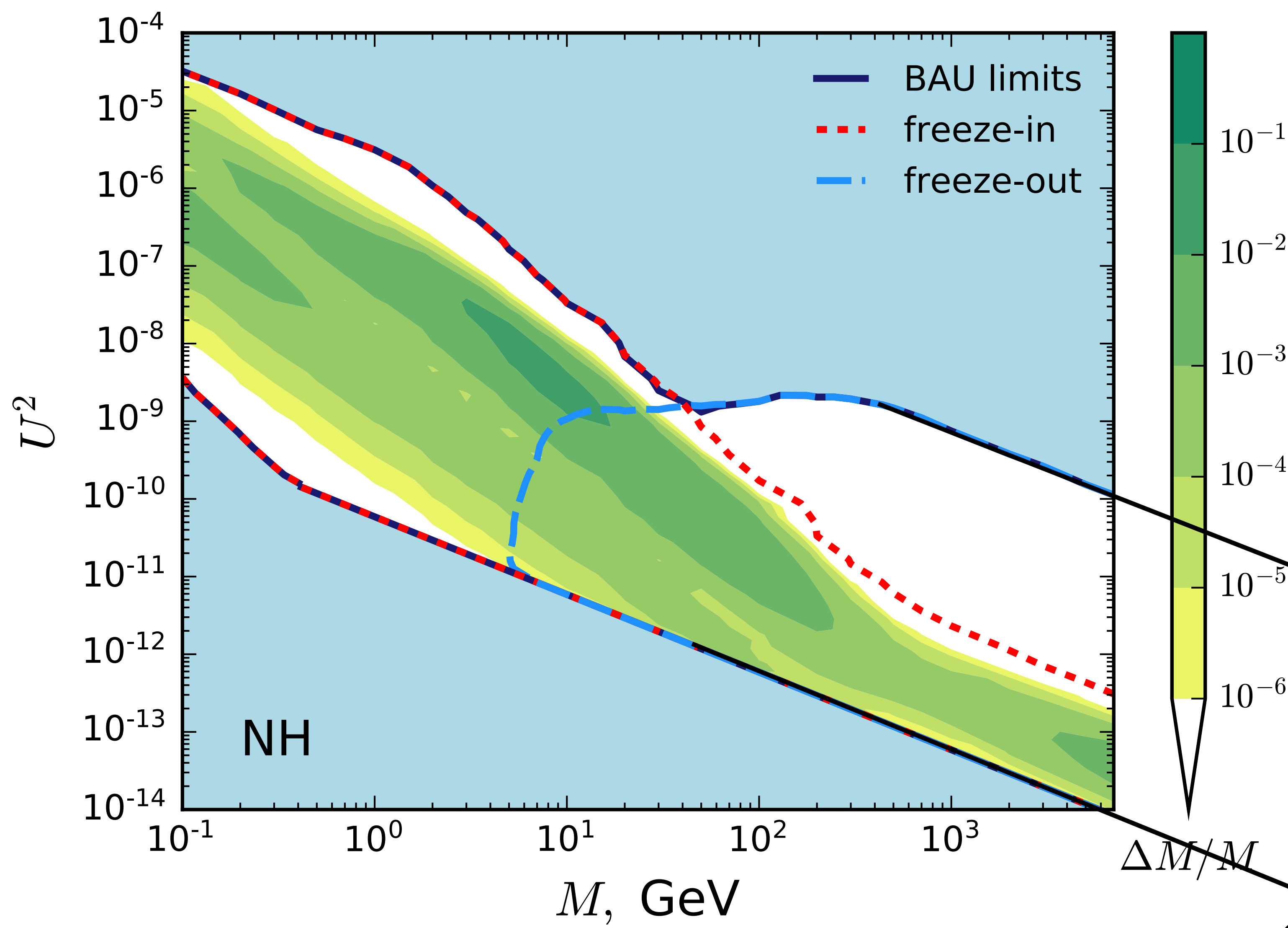


- Leptogenesis via oscillations still works for heavy HNLs because the washout of the asymmetry can vary a lot for different lepton flavours *(flavour hierarchical washout)*

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

Scaling of the right-handed neutrino masses

Juraj Klarić, Mikhail Shaposhnikov, IT 2103.16545, PRD



10^6 GeV
Change of susceptibility matrices (up quark in equilibrium)

10^9 GeV - Thermal leptogenesis

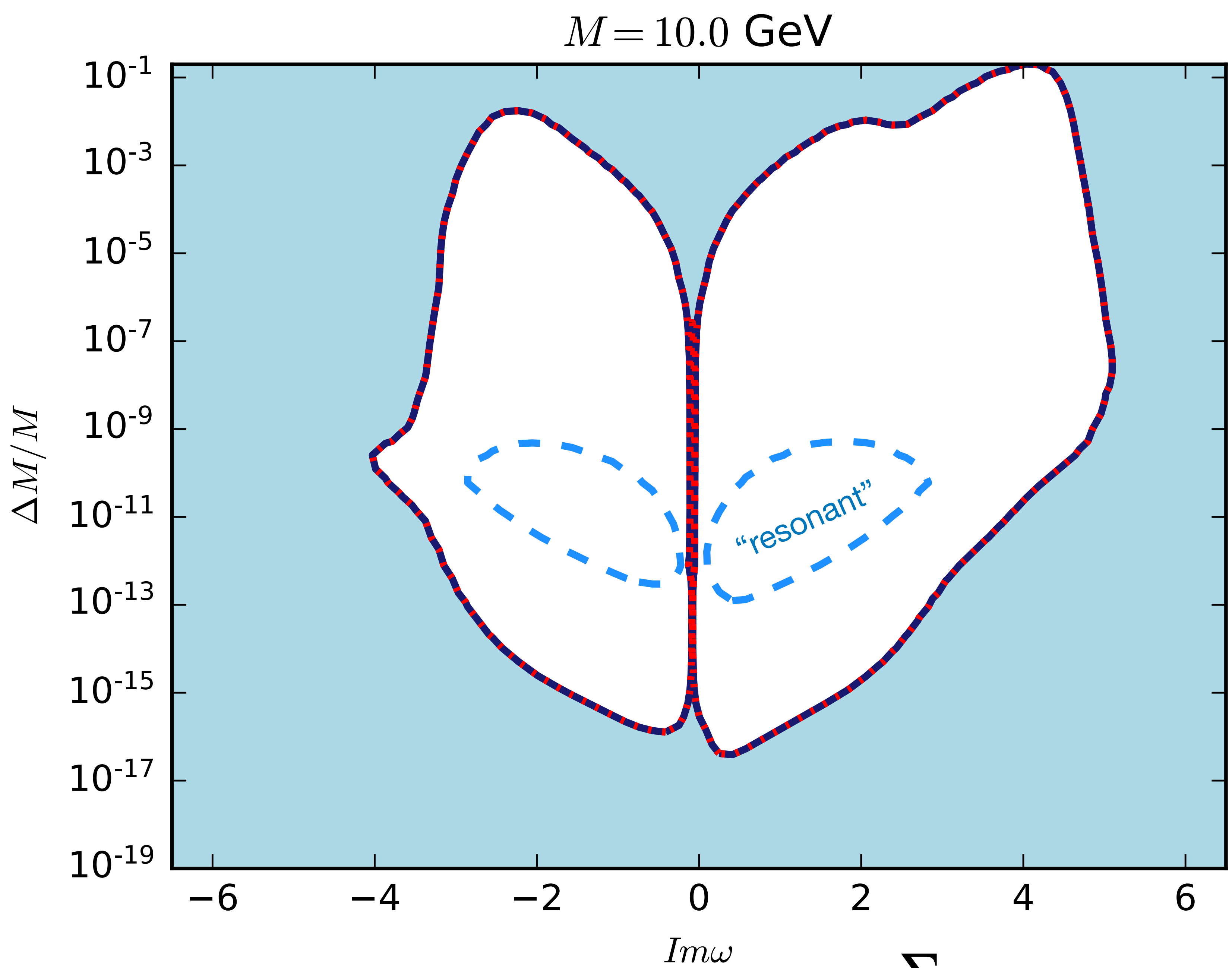
$M \to \zeta M, \quad \Delta M \to \zeta^2 \Delta M$

$$U^2 = \frac{\sum m_\nu}{M}$$

$$U^2 \sim \frac{v^2 Y^2}{M^2}$$

Y~1

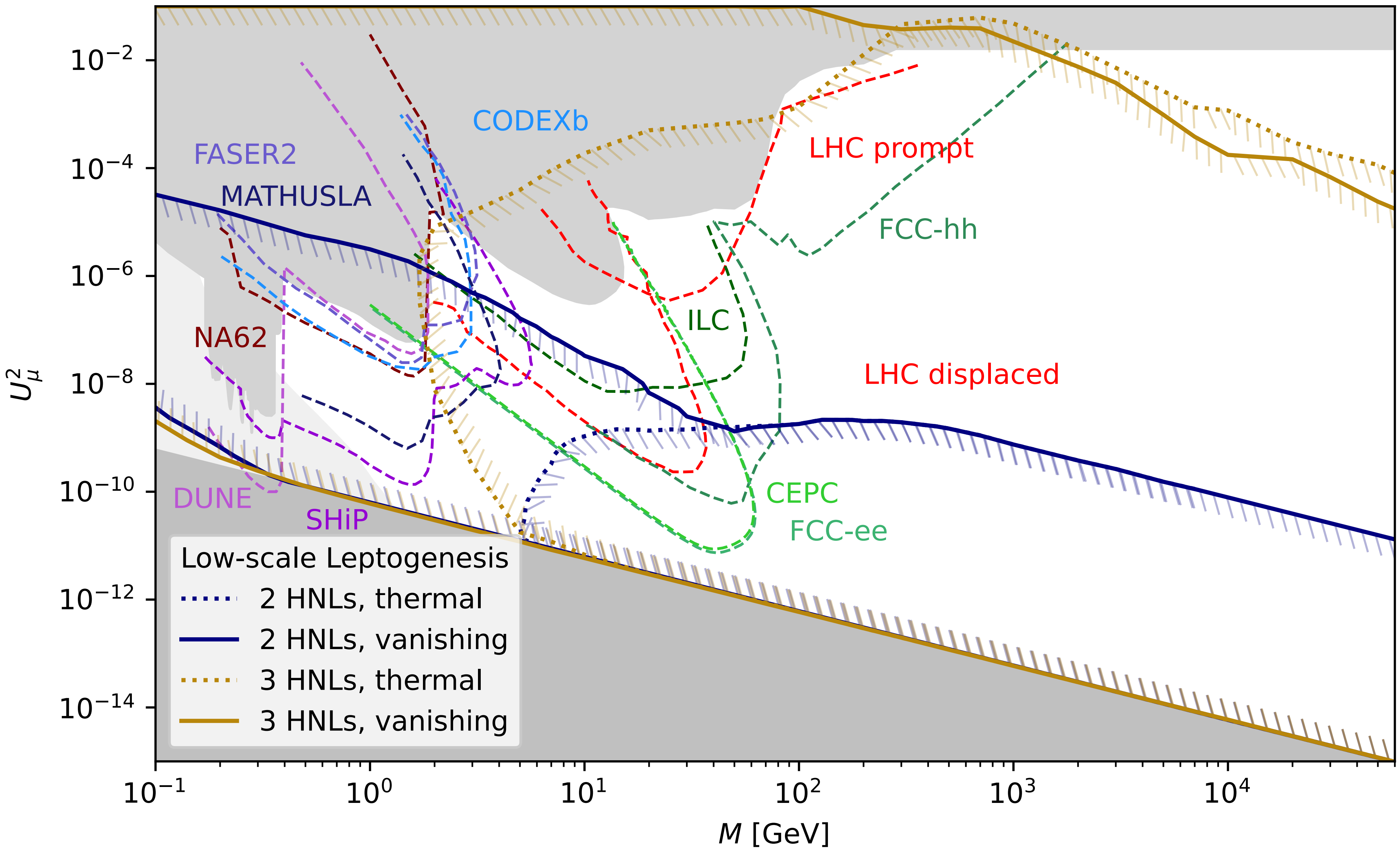
How degenerate are the HNLs?



$$U^2 = \frac{\sum m_\nu}{M_N} \cosh(2\, Im\omega)$$

Leptogenesis with 2 and 3 right-handed neutrino

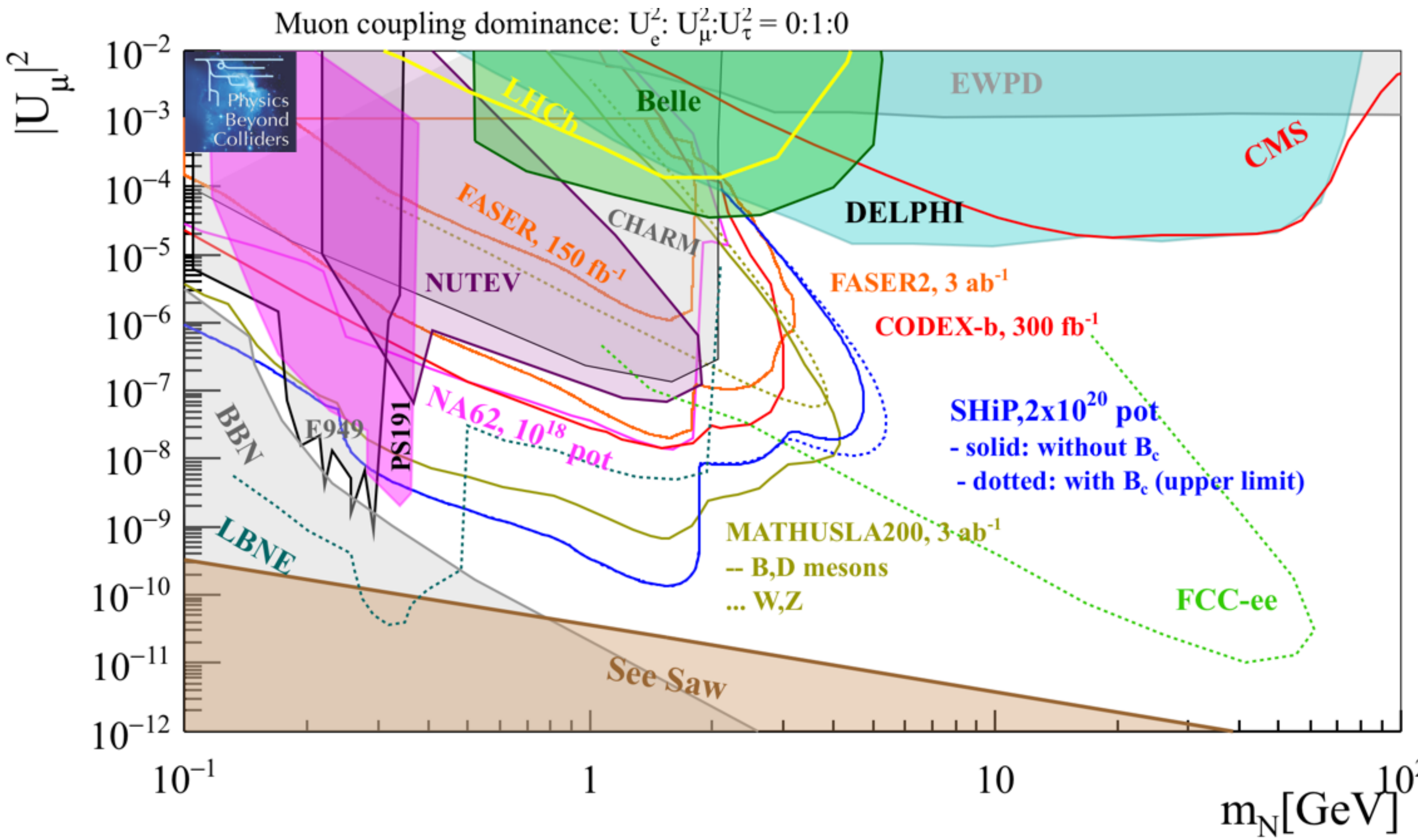
talk by Juraj Klarić



Snowmass HNL WP
2203.08039

3RH case: Klaric, Georis, Drewes 2106.16226

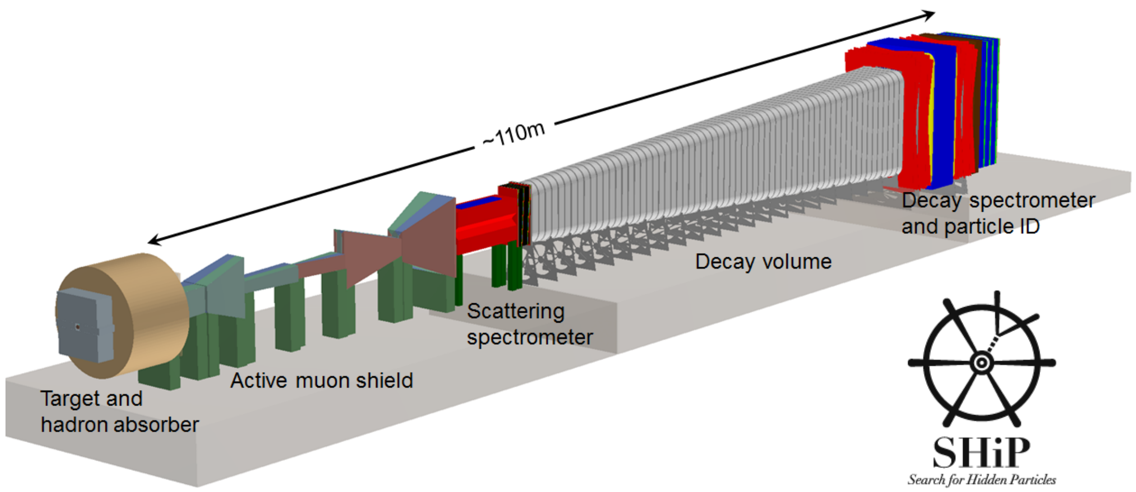
The quest for Heavy Neutral Leptons



Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report. 1901.09966

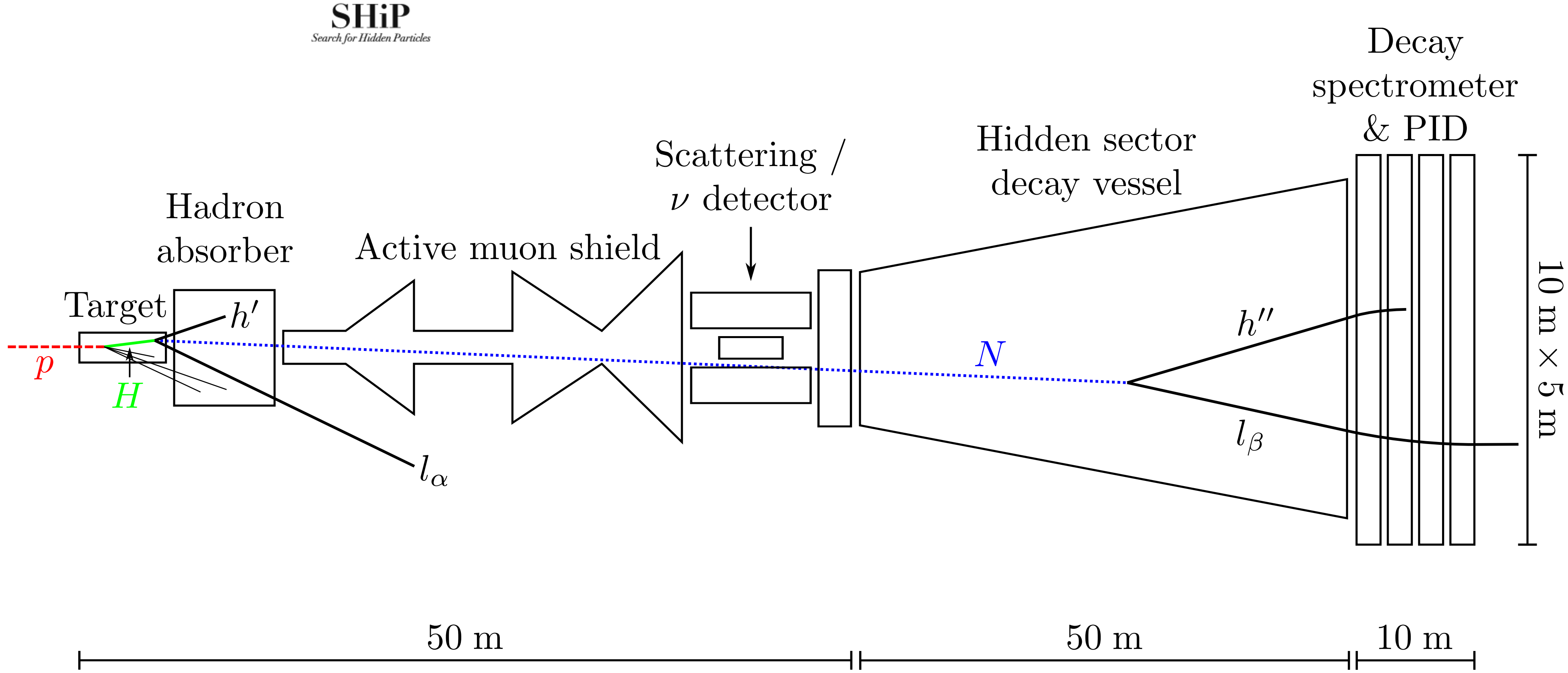
How to search for HNLs?

Example: SHiP - Search for Hidden Particles



SHiP
Search for Hidden Particles

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

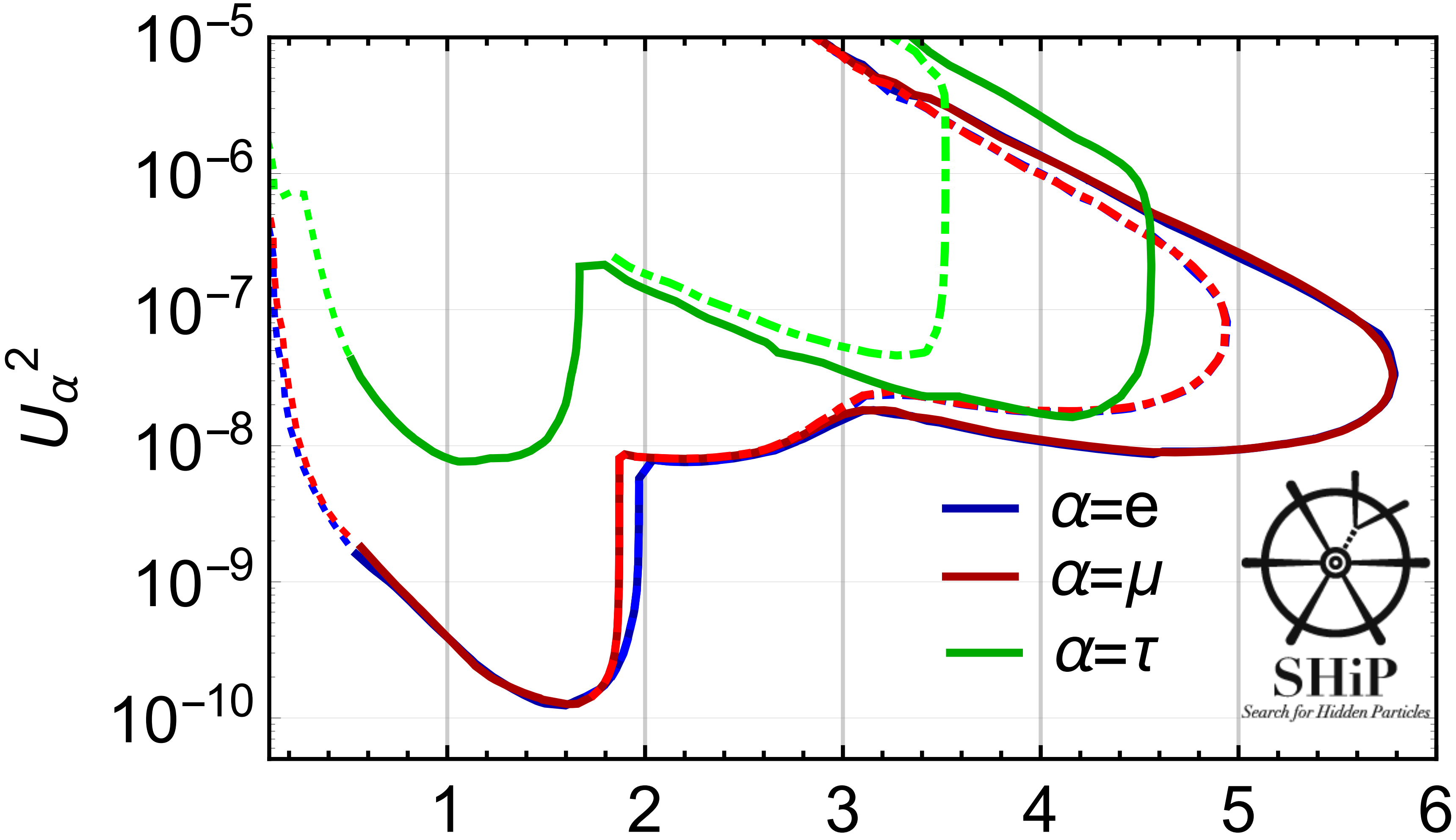


Last week: SHiP Open Session
https://indico.cern.ch/event/1151104/sessions/441492/#20220519

* I am a member of SHiP collaboration

SHiP sensitivity

JHEP 04 (2019) 077 1811.00930

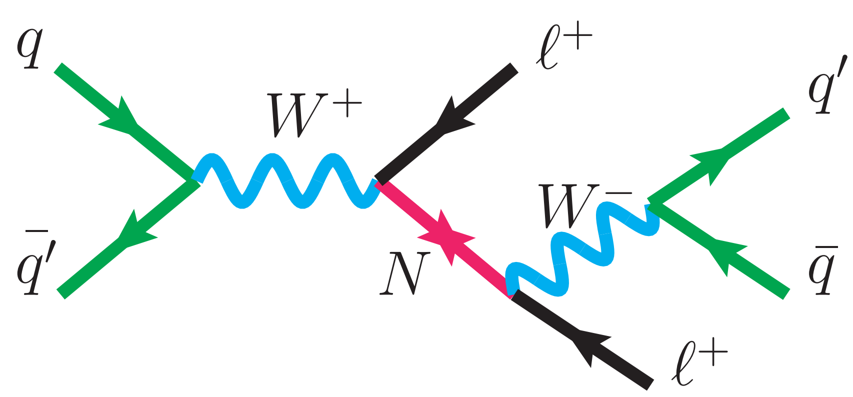


A tool to calculate SHiP sensitivity to arbitrary mixings
https://zenodo.org/record/1472071

Majorana vs Dirac HNLs

- If HNLs are found, are they responsible for neutrino masses and BAU?
- In the seesaw mechanism, HNLs are Majorana

At colliders:
same-sign dileptons
LNV processes

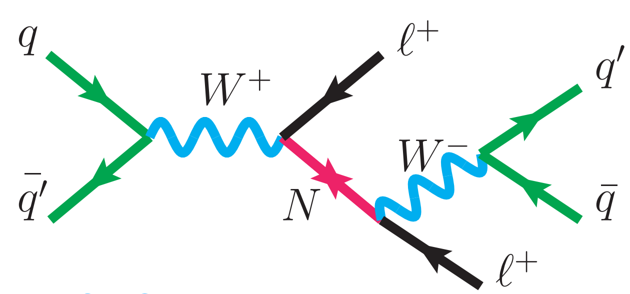


e.g. CMS 1806.10905

Probing lepton number violation at SHiP

Jean-Loup Tastet, IT 1912.05520, JHEP

At colliders:
same-sign dileptons



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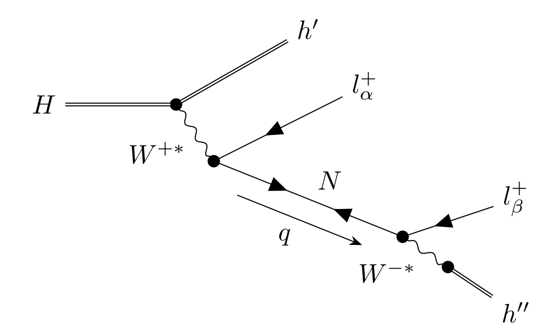
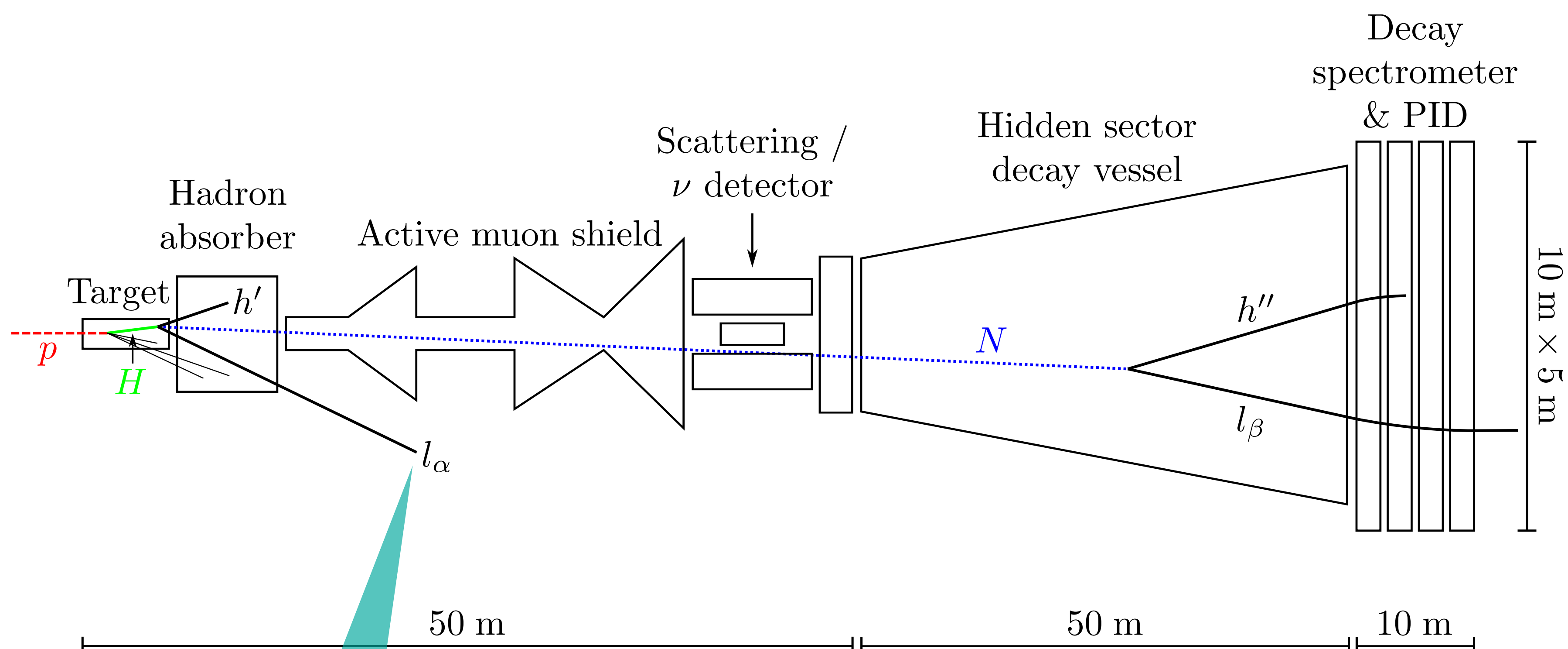
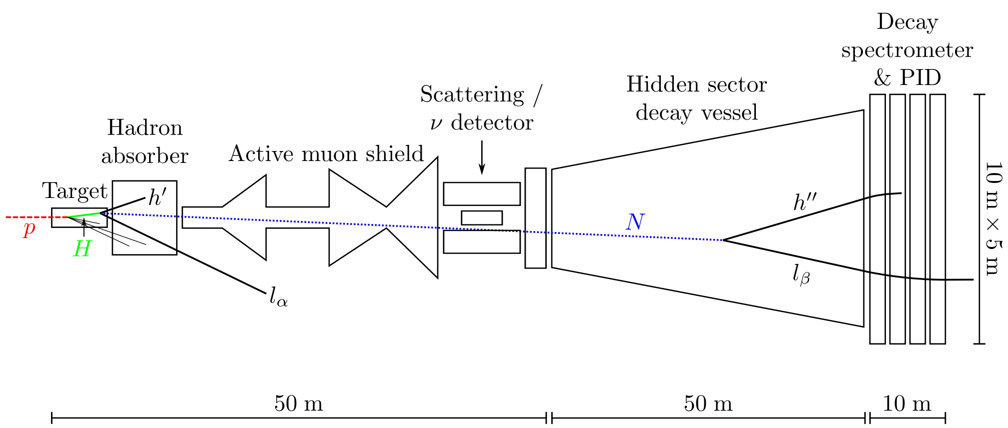


Beam dump:

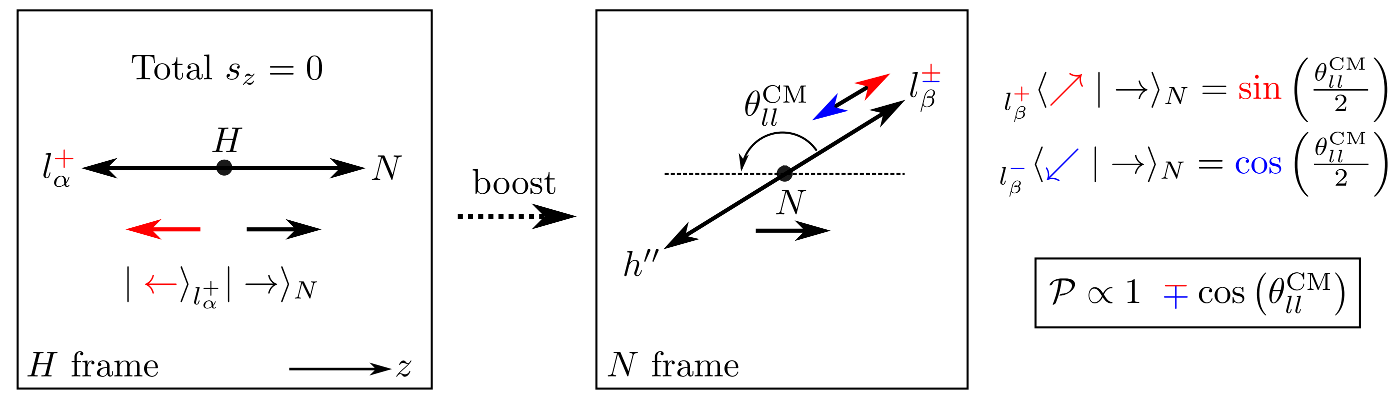


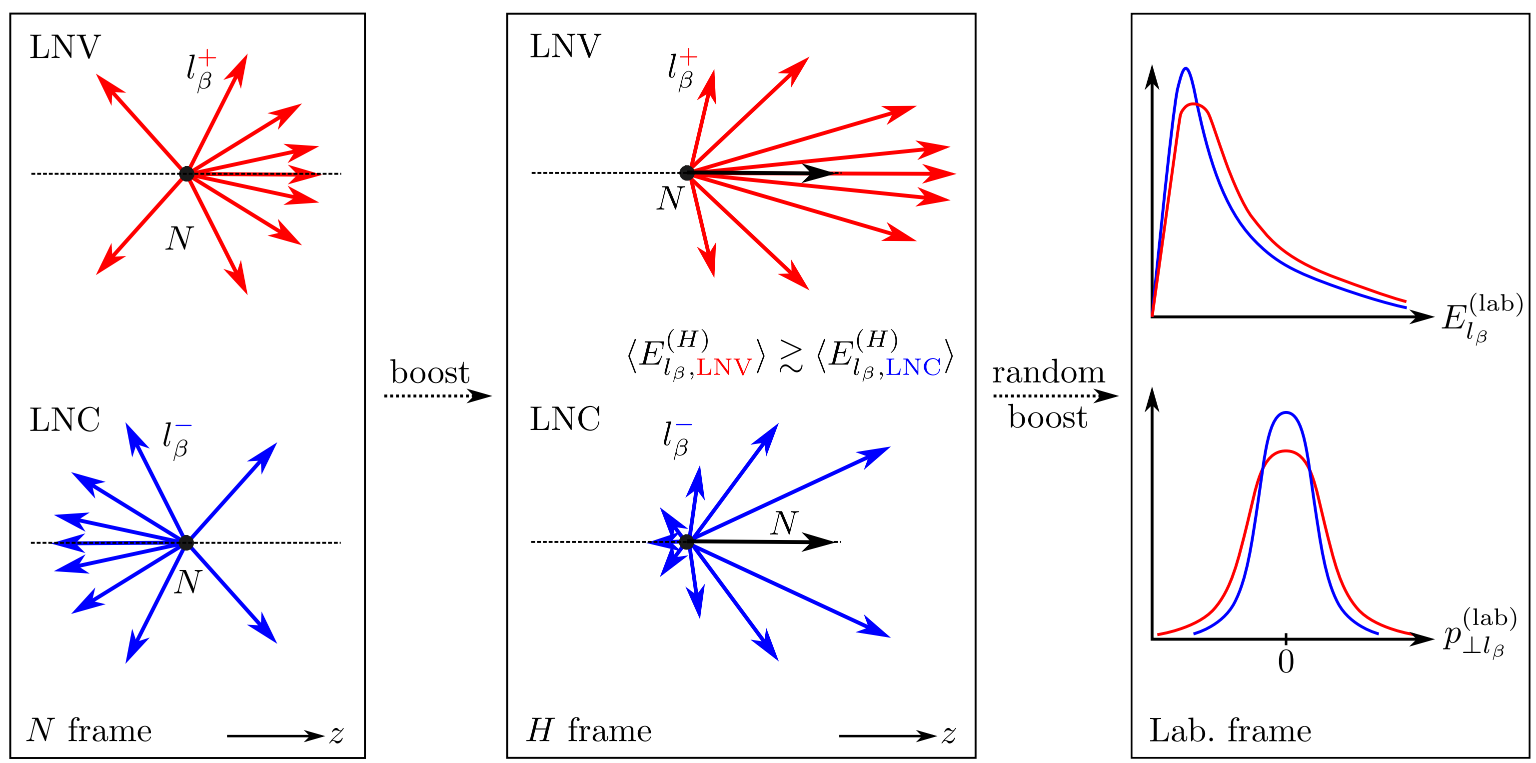
Information about the first lepton is lost

Probing lepton number violation at SHiP



Different angular correlations for LNC and LNV processes





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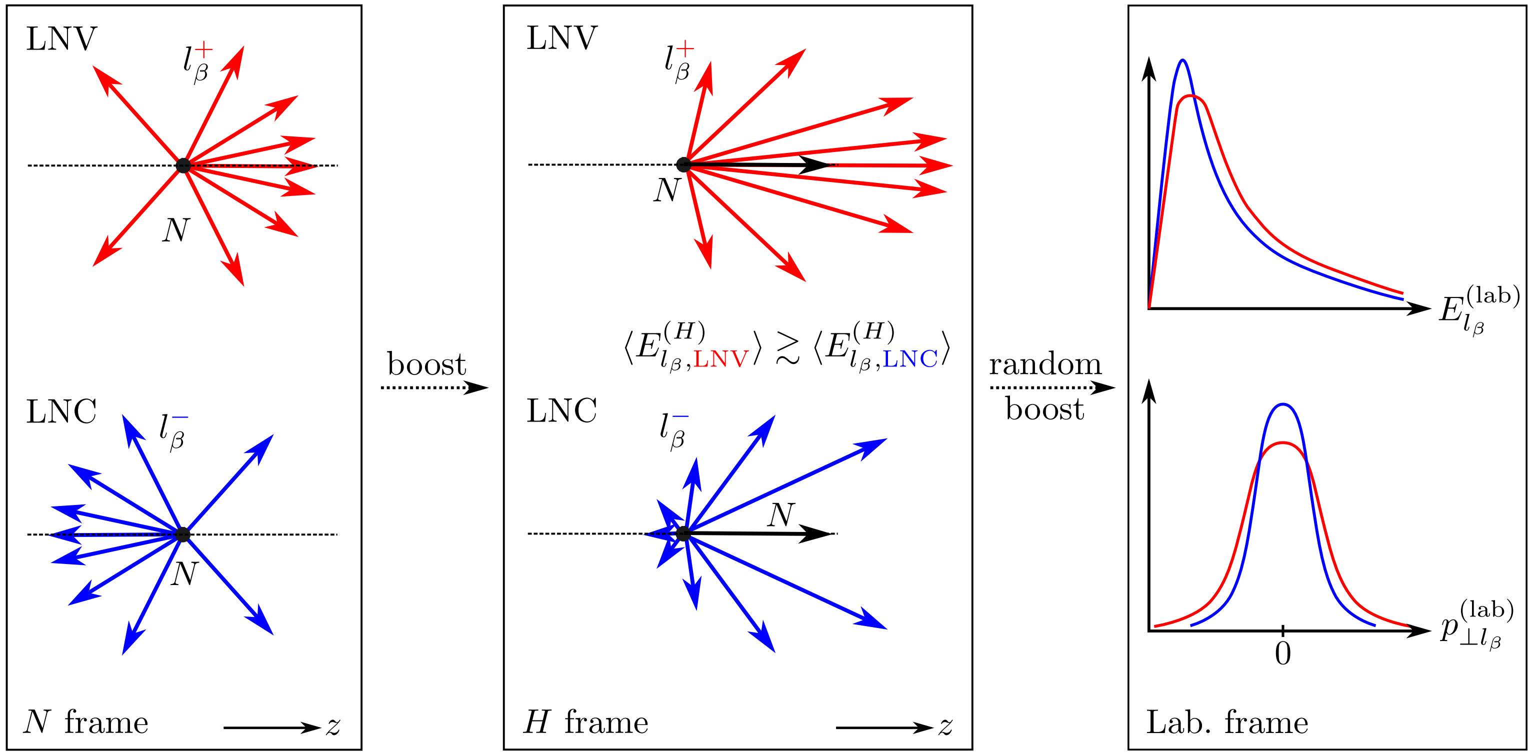


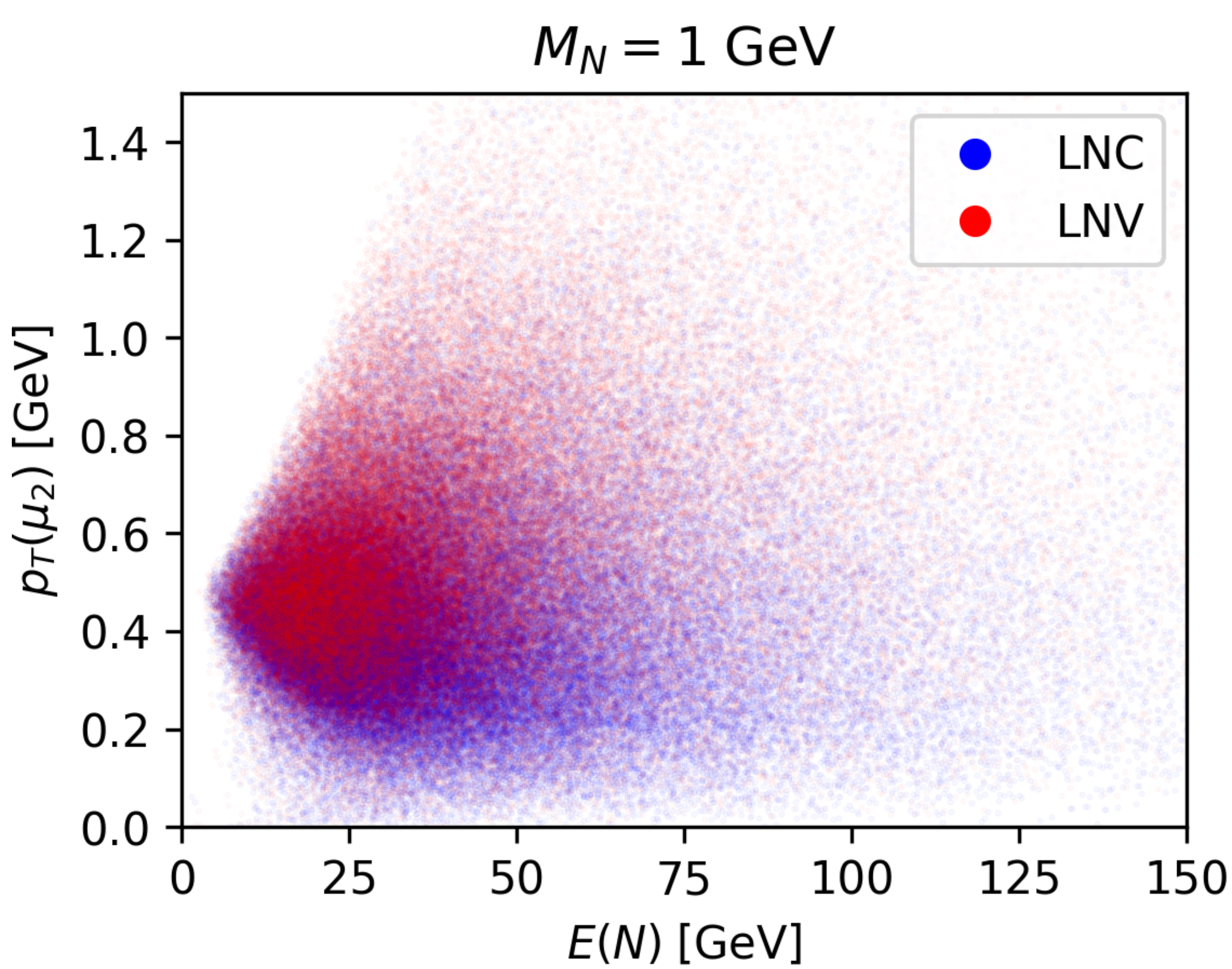
Complications

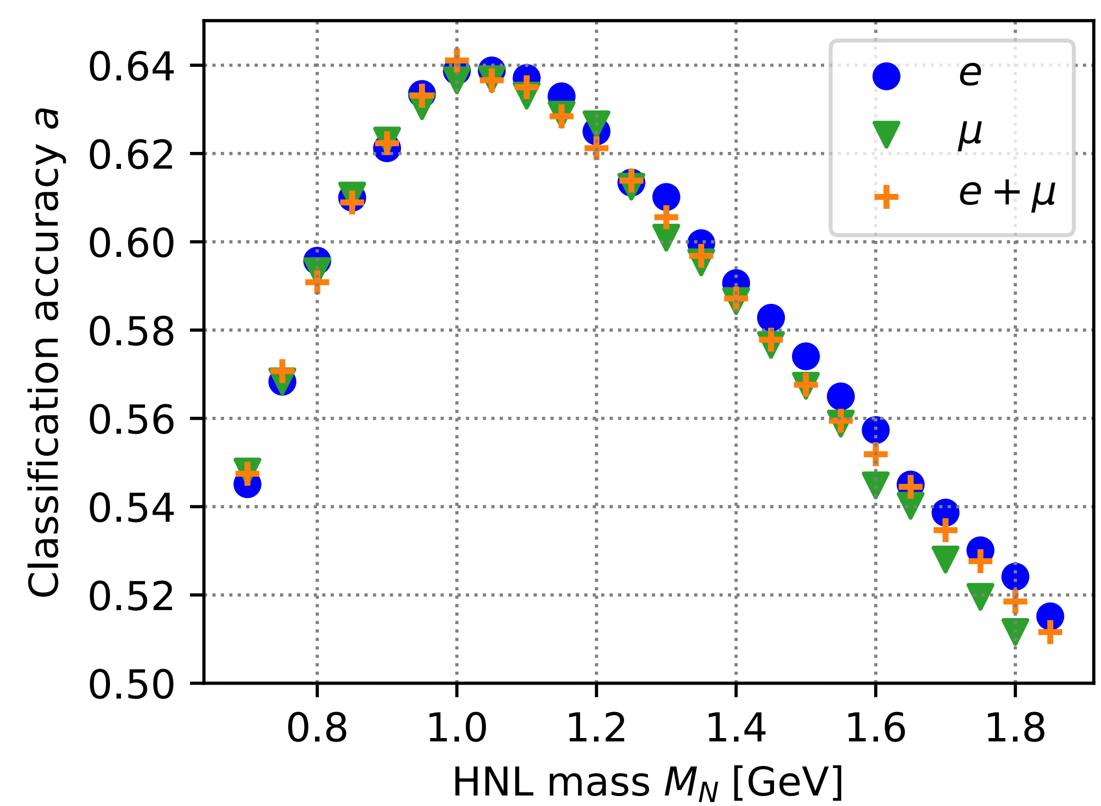
- Not all production processes are 2-body.
- Decay products (l, π) are not massless.
- Heavy mesons are not monochromatic, which smears out the effect.
- We need to take geometrical acceptance into account.

Probing lepton number violation at SHiP

our own MC analysis
-correct matrix elements
-angular correlations
-in Julia language

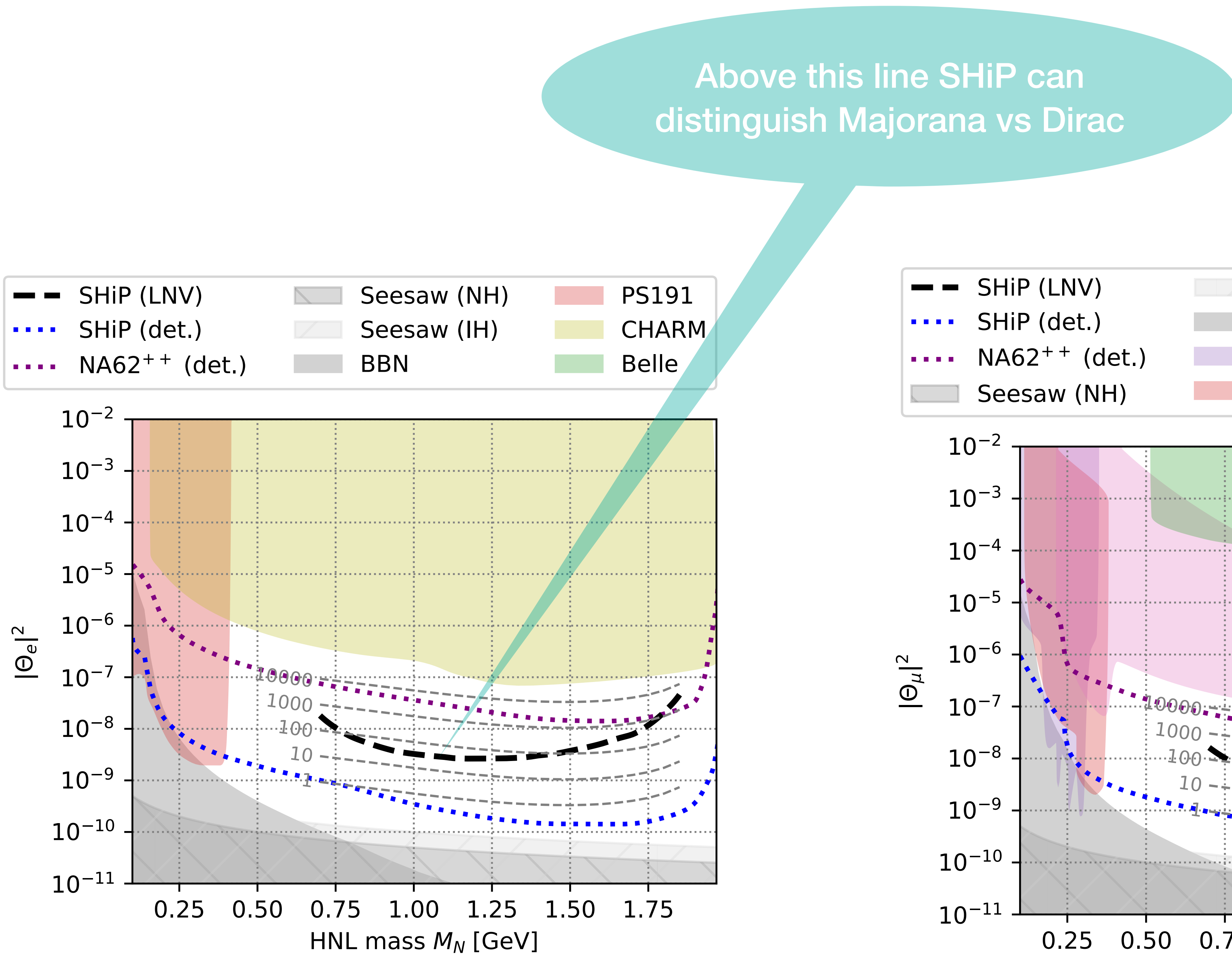
ML Classification (boosted decision trees)

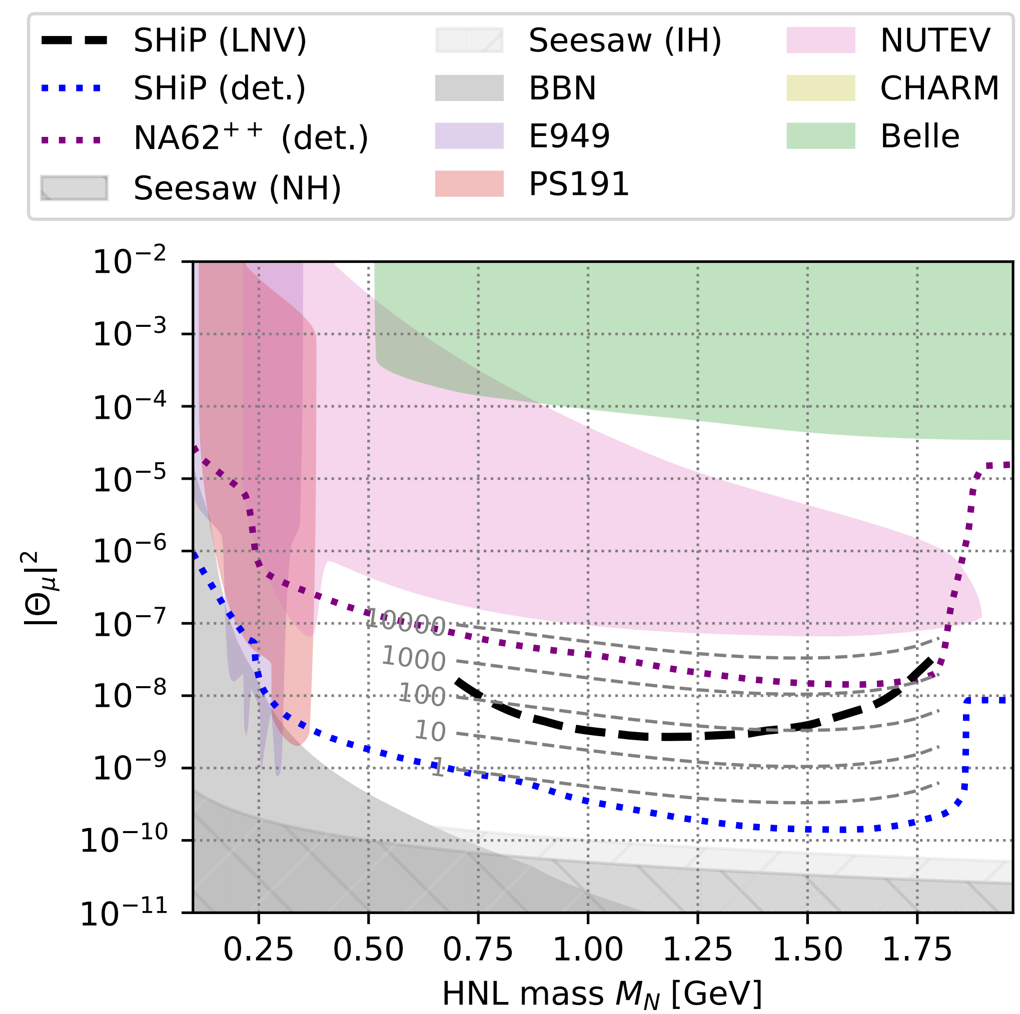




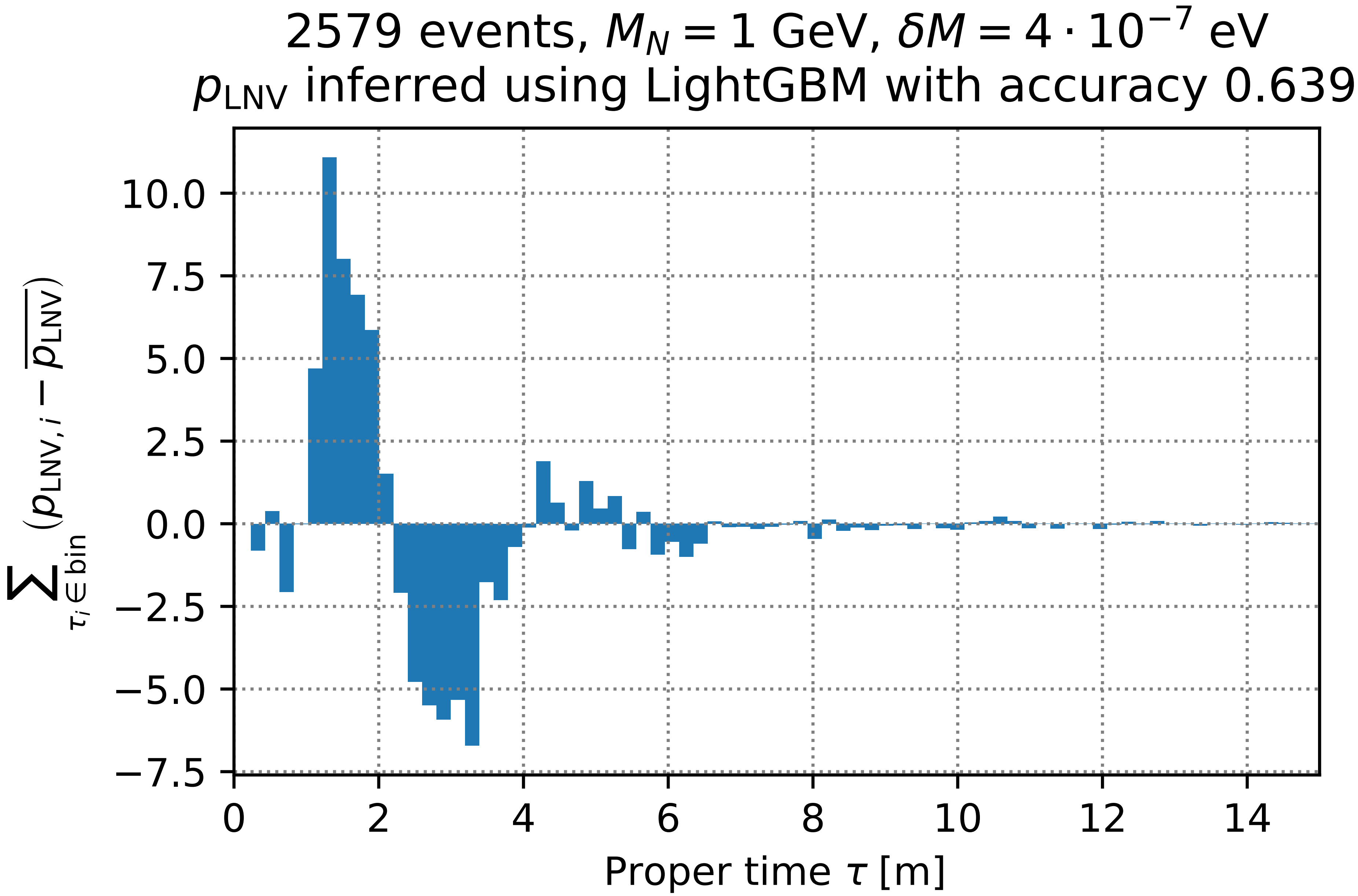
MG model: Coloma, Fernández-Martínez, González-López, Hernández-García, Pavlovic 2007.03701

Probing lepton number violation at SHiP





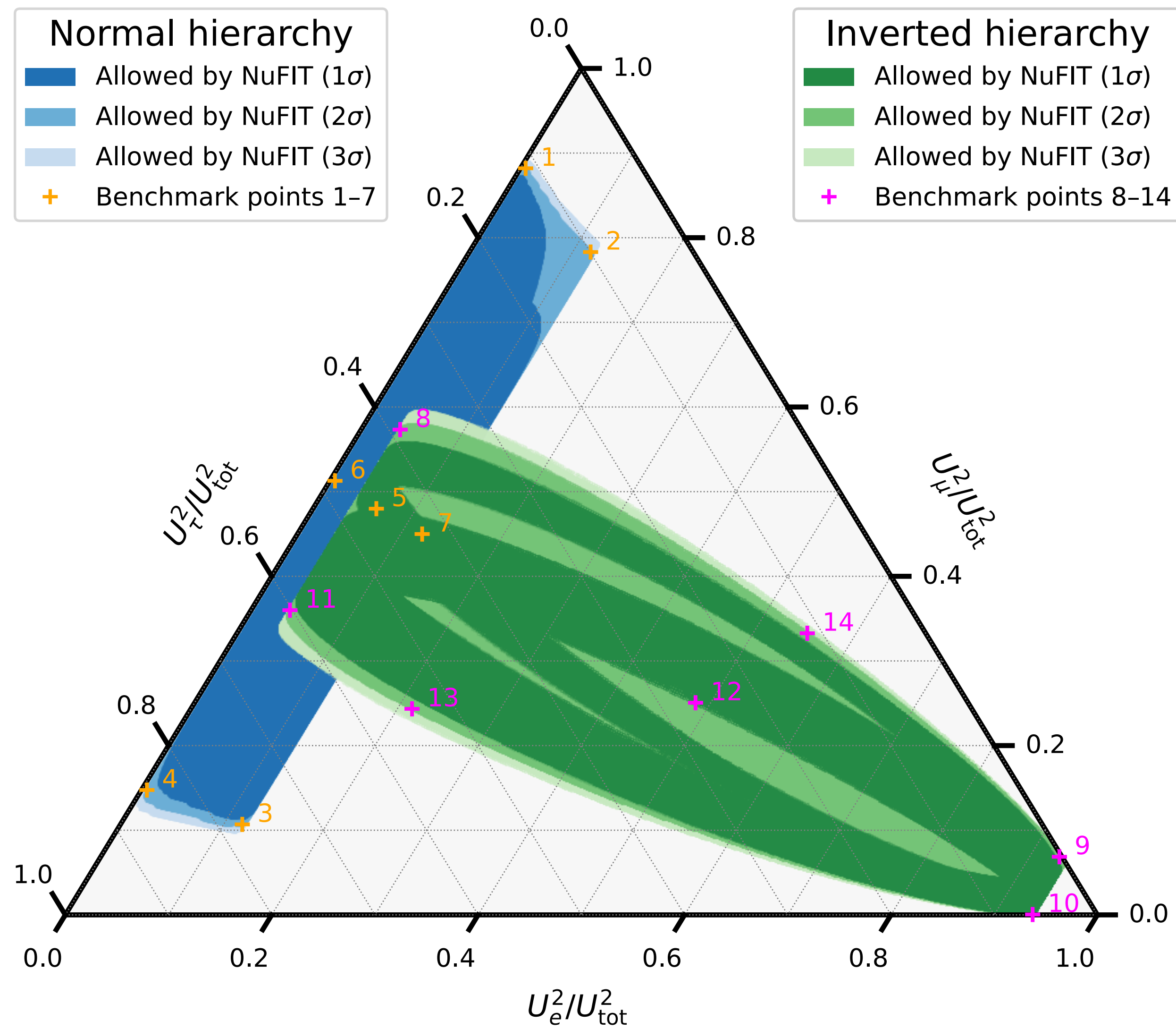
Resolvable HNL oscillations at SHiP



δM **corresponds to BAU and DM in the** ν**MSM (1208.4607)**

Neutrino oscillation data and mixings

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



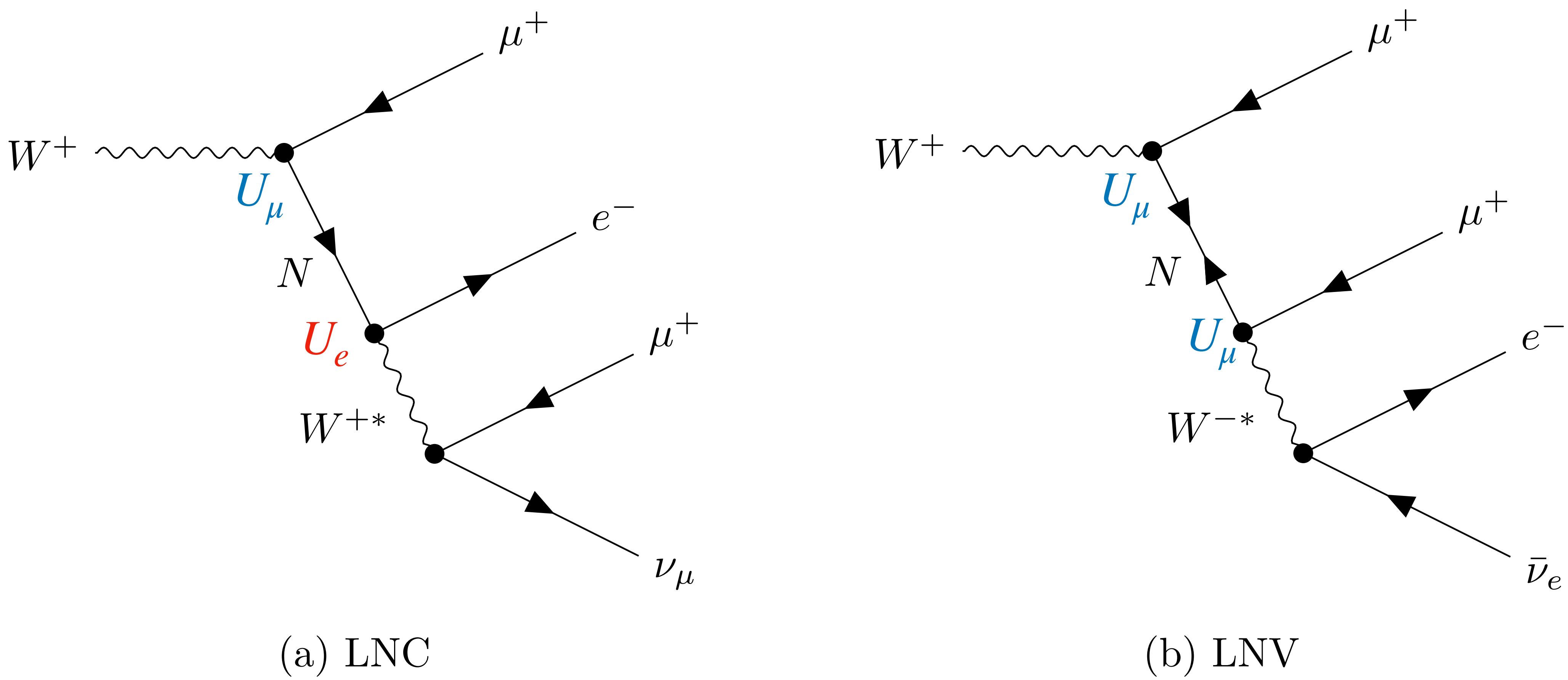
$$U_e^2/U_{\text{tot}}^2 + U_\mu^2/U_{\text{tot}}^2 + U_\tau^2/U_{\text{tot}}^2 = 1$$

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

Neutrino oscillation data and reinterpretation

Talk by Jean-Loup Tastet

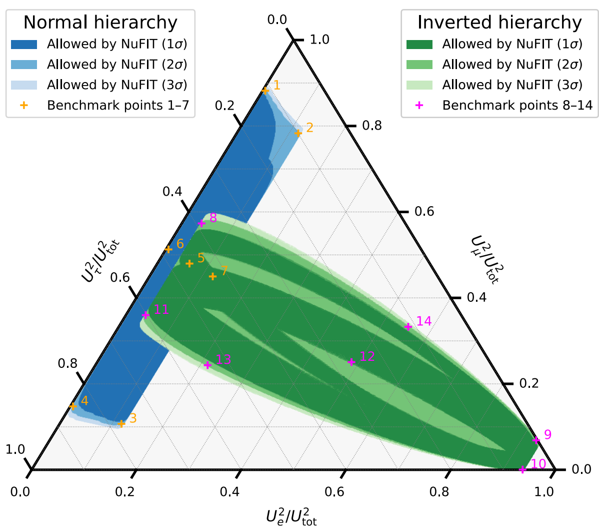
ATLAS triplepton search 1905.09787



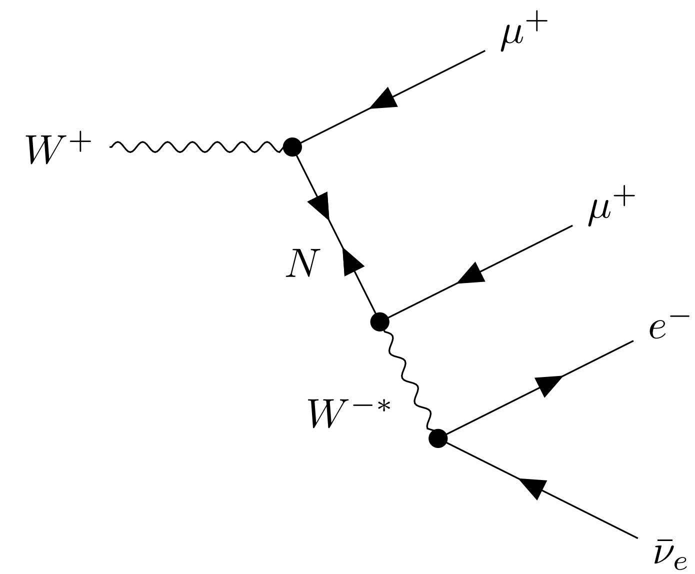
LNC cannot be probed under single mixing assumption

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

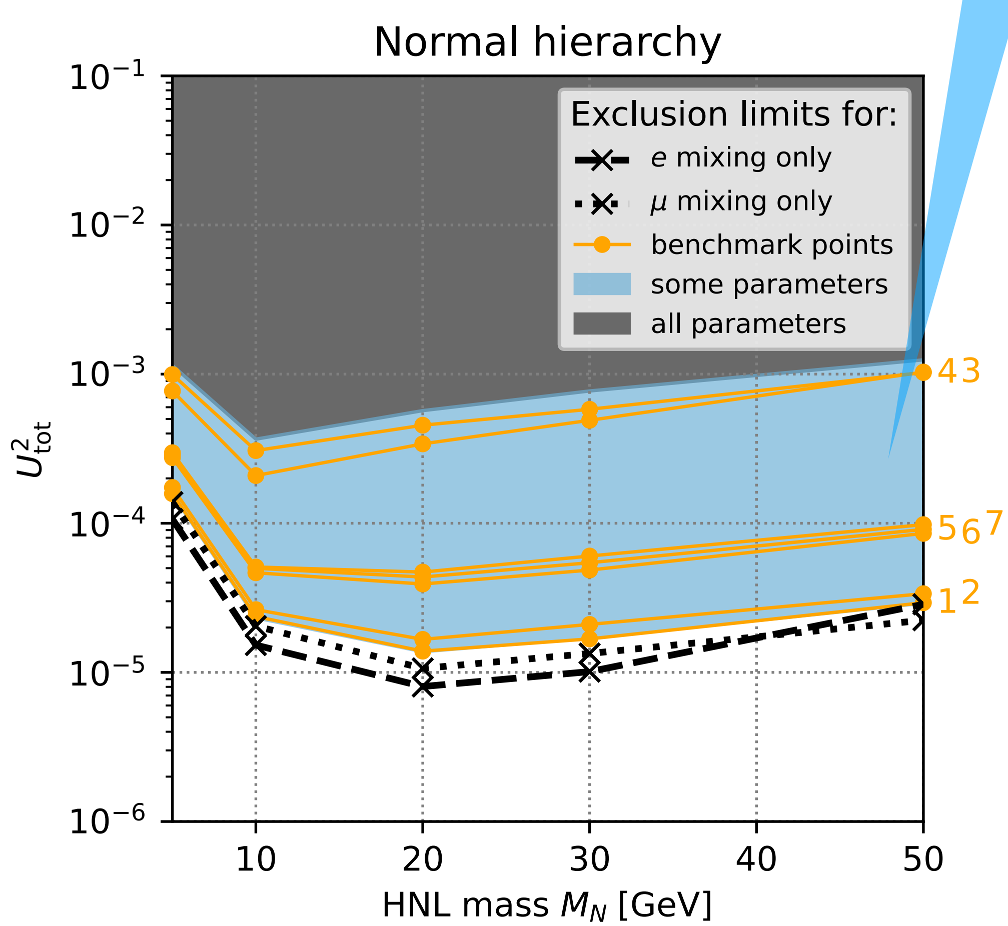
Neutrino oscillation data and reinterpretation

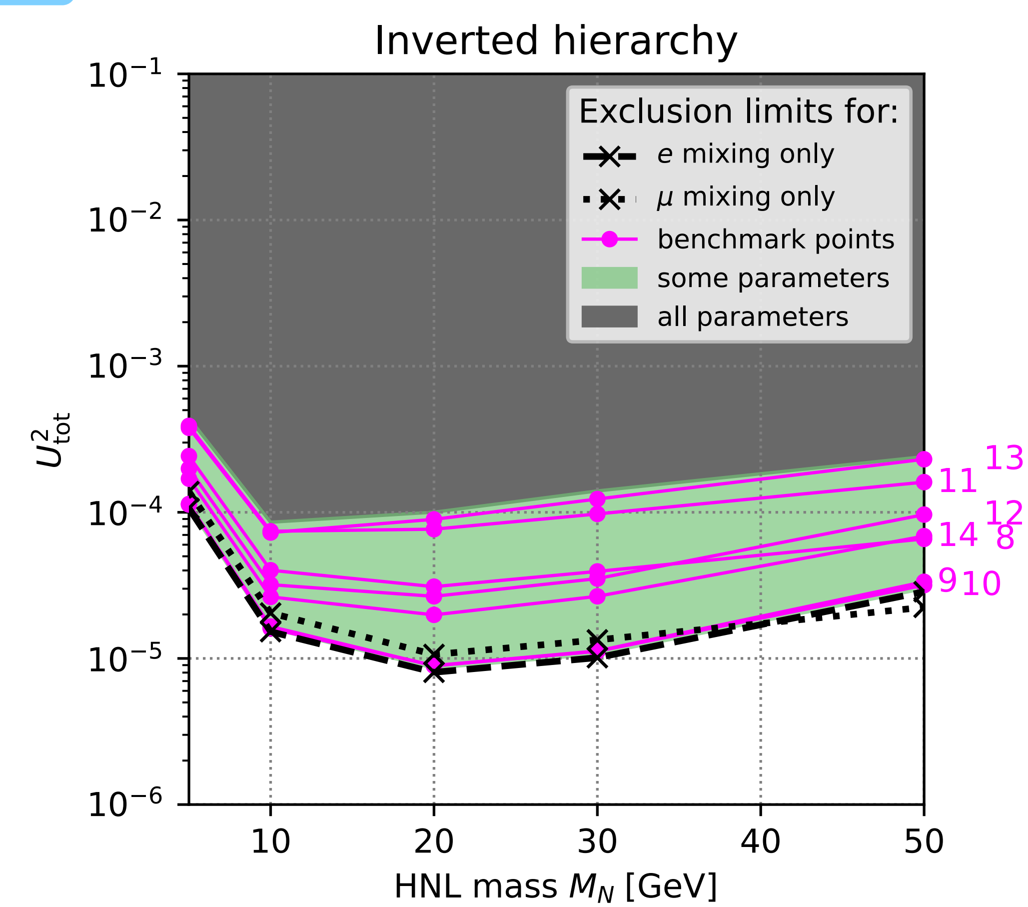


ATLAS triplepton search [1905.09787](1905.09787)



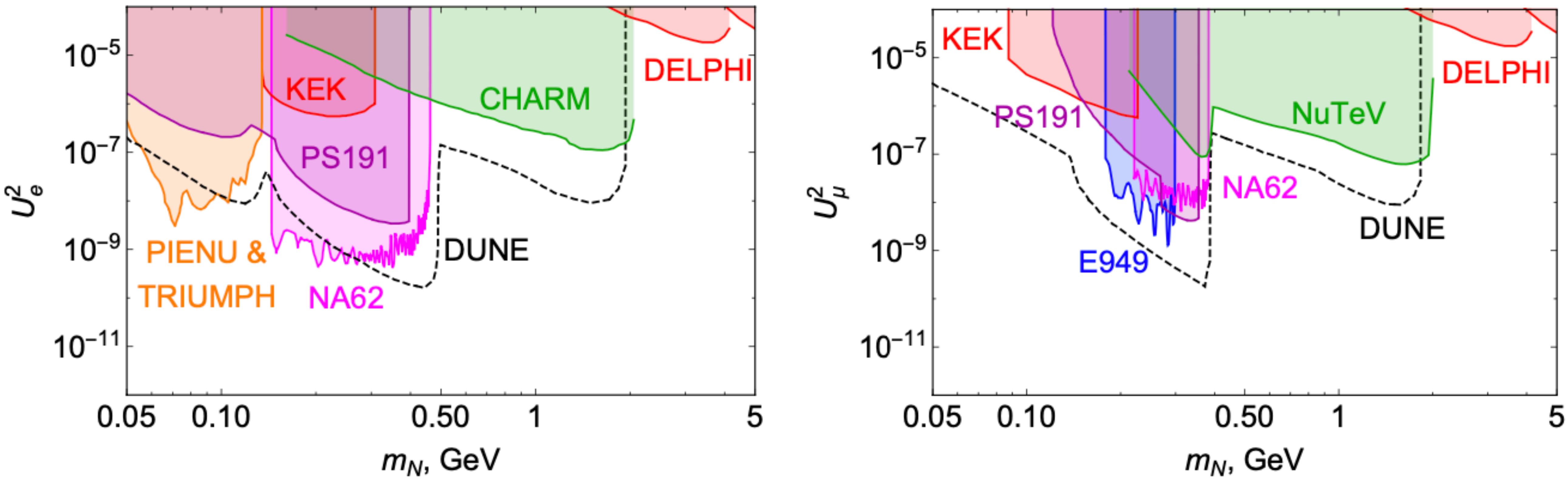
New physics could hide here!





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

An allowed window for HNLs below the kaon mass



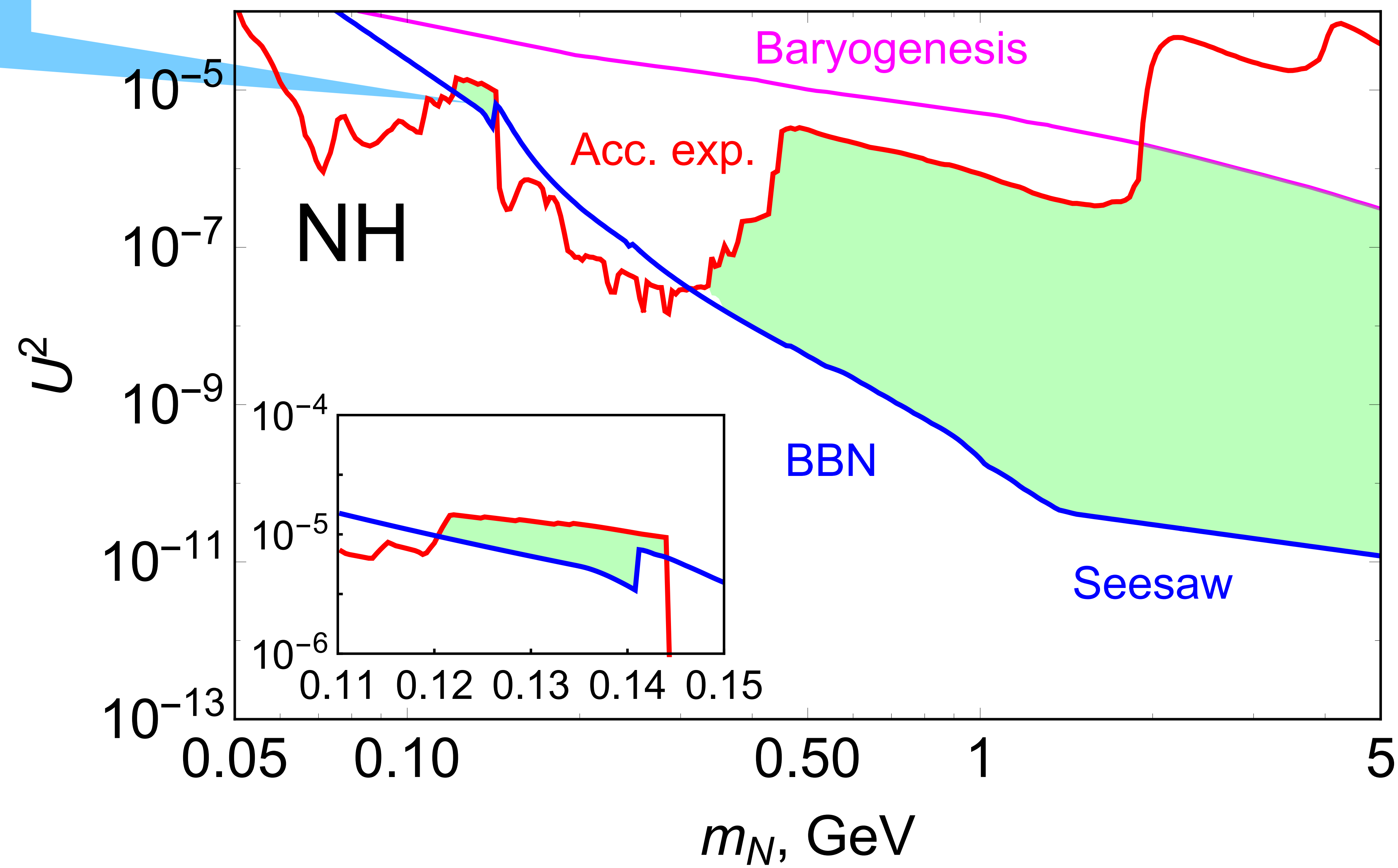
Existing limits are obtained under the single flavour mixing assumption

Bondarenko et al. 2101.09255 , JHEP

An allowed window for HNLs below the kaon mass

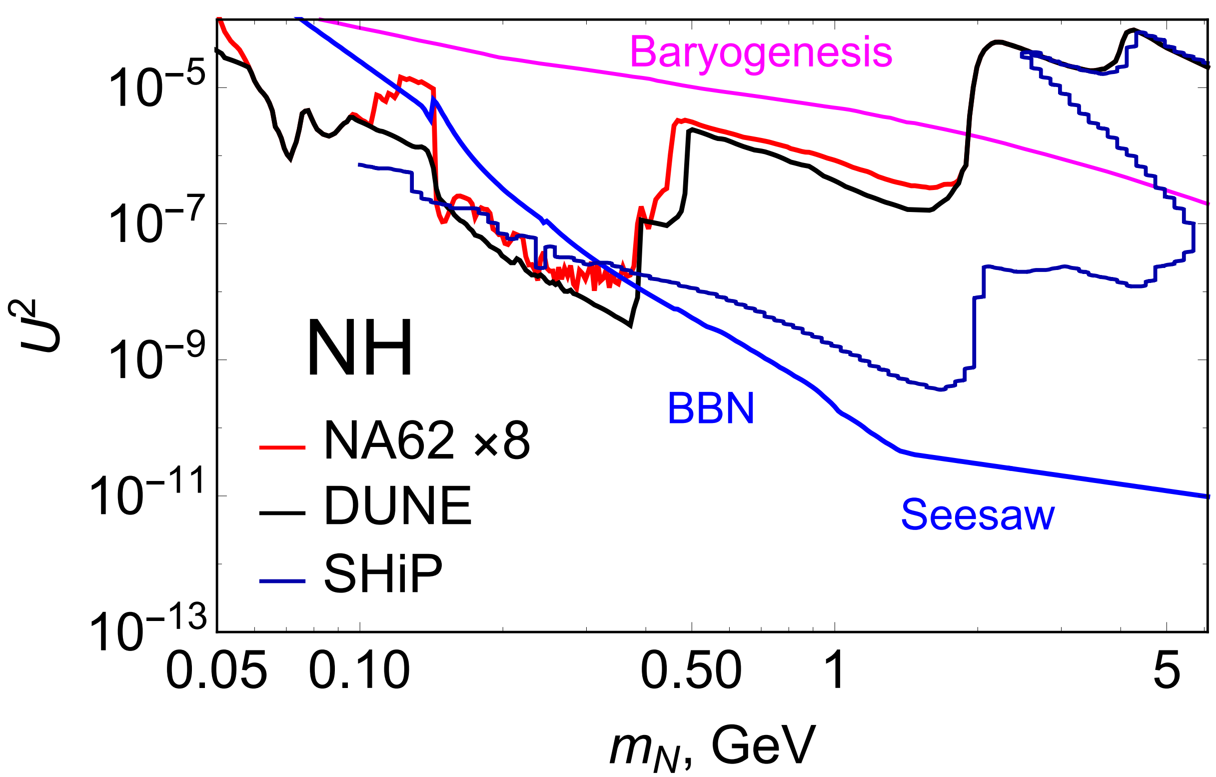
Bondarenko et al. 2101.09255 , JHEP

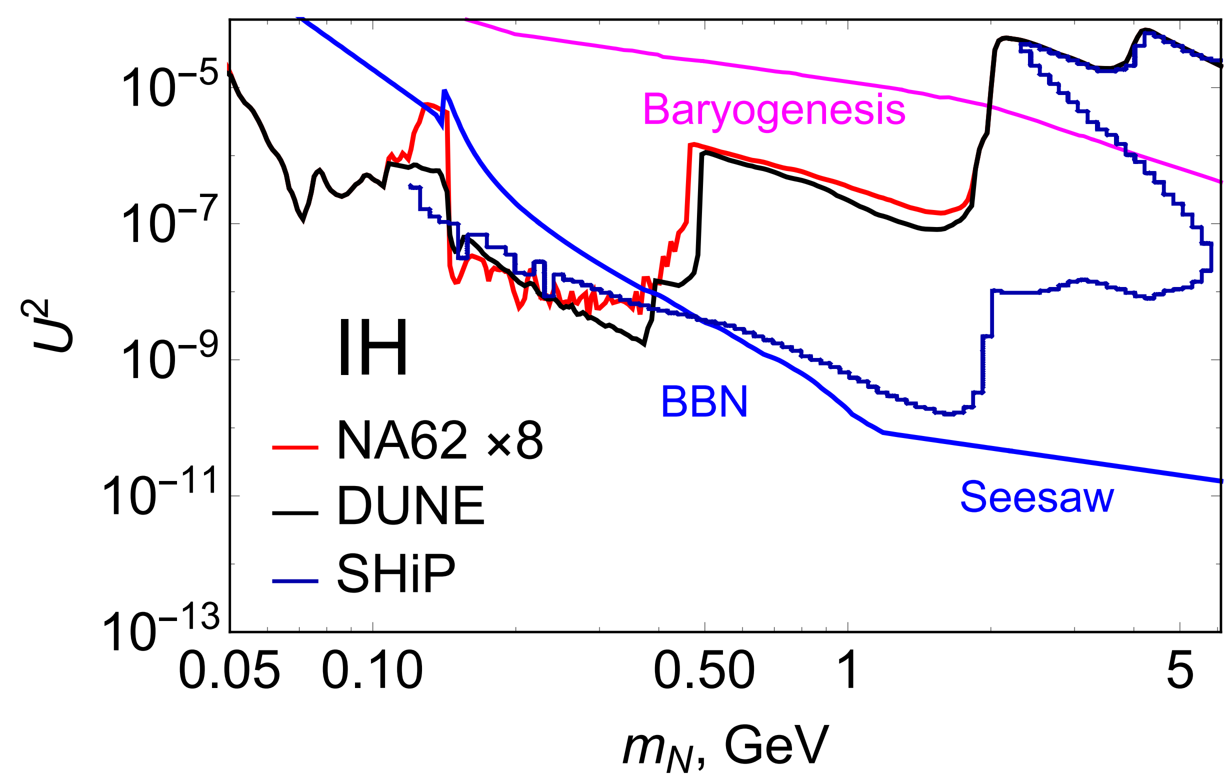
New physics could hide here!

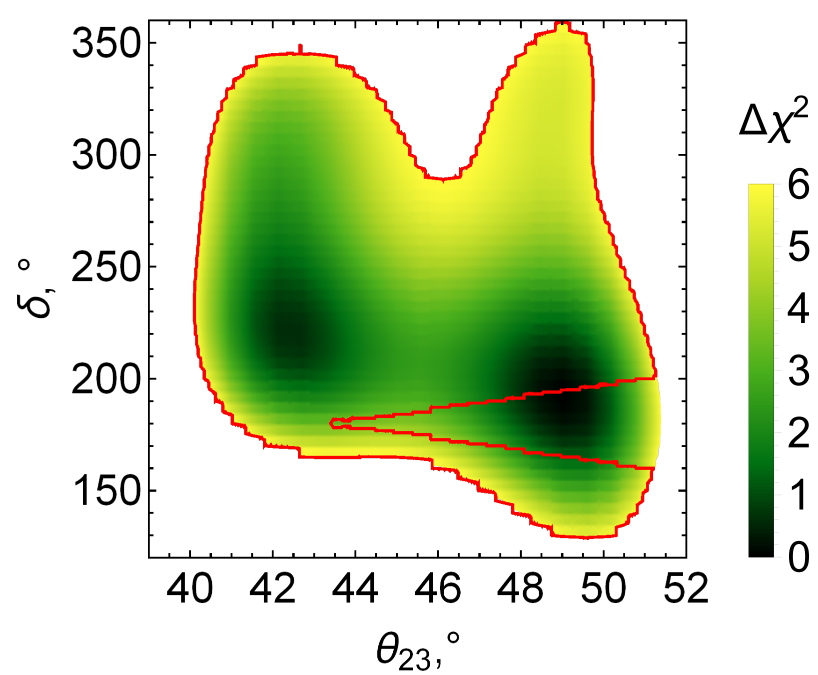


New BBN bound:
Boyarsky, Ovchynnikov, Ruchayskiy, Syvolap 2008.00749, *Phys.Rev.D* 104 (2021)

New experiments can close the window







If δ and θ_{23} are measured to be outside the red boundary, the allowed window will be excluded

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)
- 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)

Backup slides

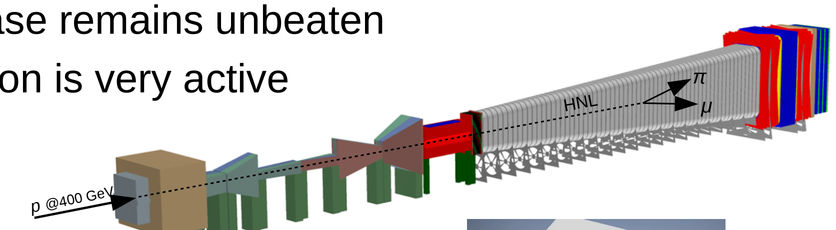
SHiP and BDF

Summary and outlook

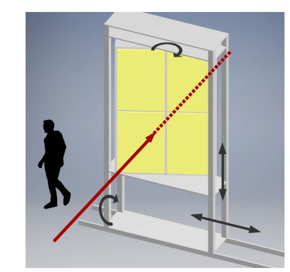
- **BDF related R&D studies have advanced well this year and will ramp up into next year**
  - These have resulted in operational improvements
- **TT90-ECN4 baseline option further solidified**
  - Higher risk items were identified and mitigated
- **A search for suitable alternative locations is underway and optimisation of the baseline:**
  - Significant potential for cost-reduction identified
  - BDF WG is well on track to focus on the most promising option(s) for detailed studies in the coming years

SHiP Summary

- SHiP science case remains unbeaten
- SHiP collaboration is very active



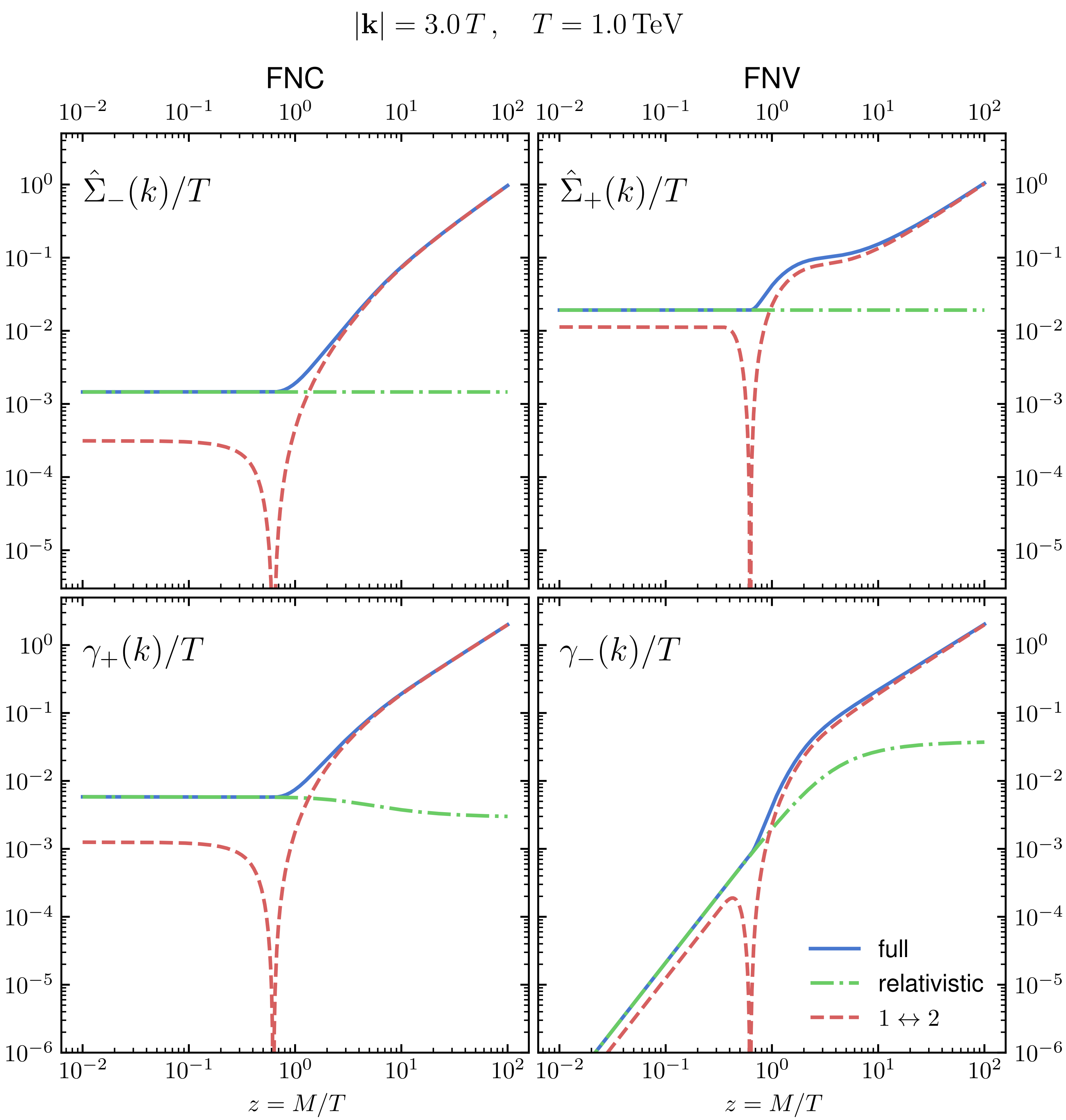
- R&D on BDF in the next 3 years
  - ► μ-shield
  - ► vacuum decay vessel + SBT
  - ► optimization of facility's performance
  - → *MoU out for signatures*



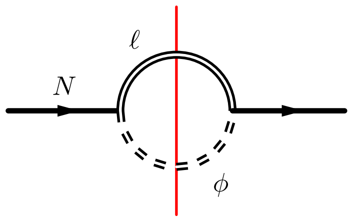
- Investigation of detector improvement + cost reduction
  - ► SND: replace emulsions by electronic Si-trackers
- SND@LHC approved, data in 2022
- New groups are embarking on SHiP

PBC General Meeting, December 2021

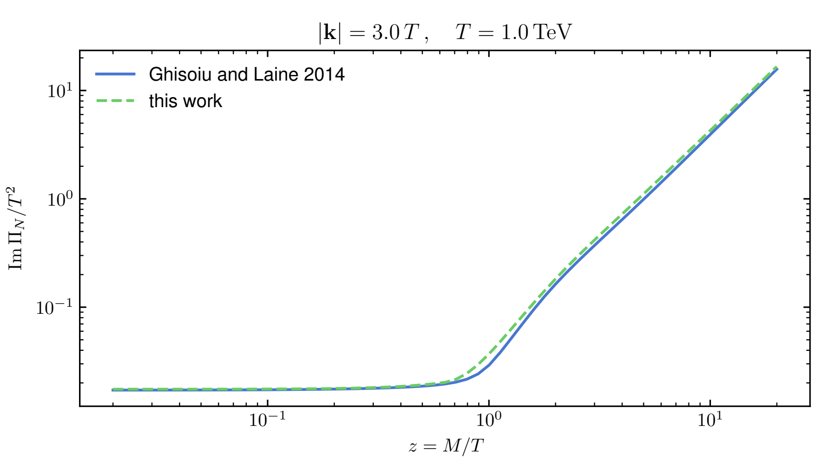
The rates



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

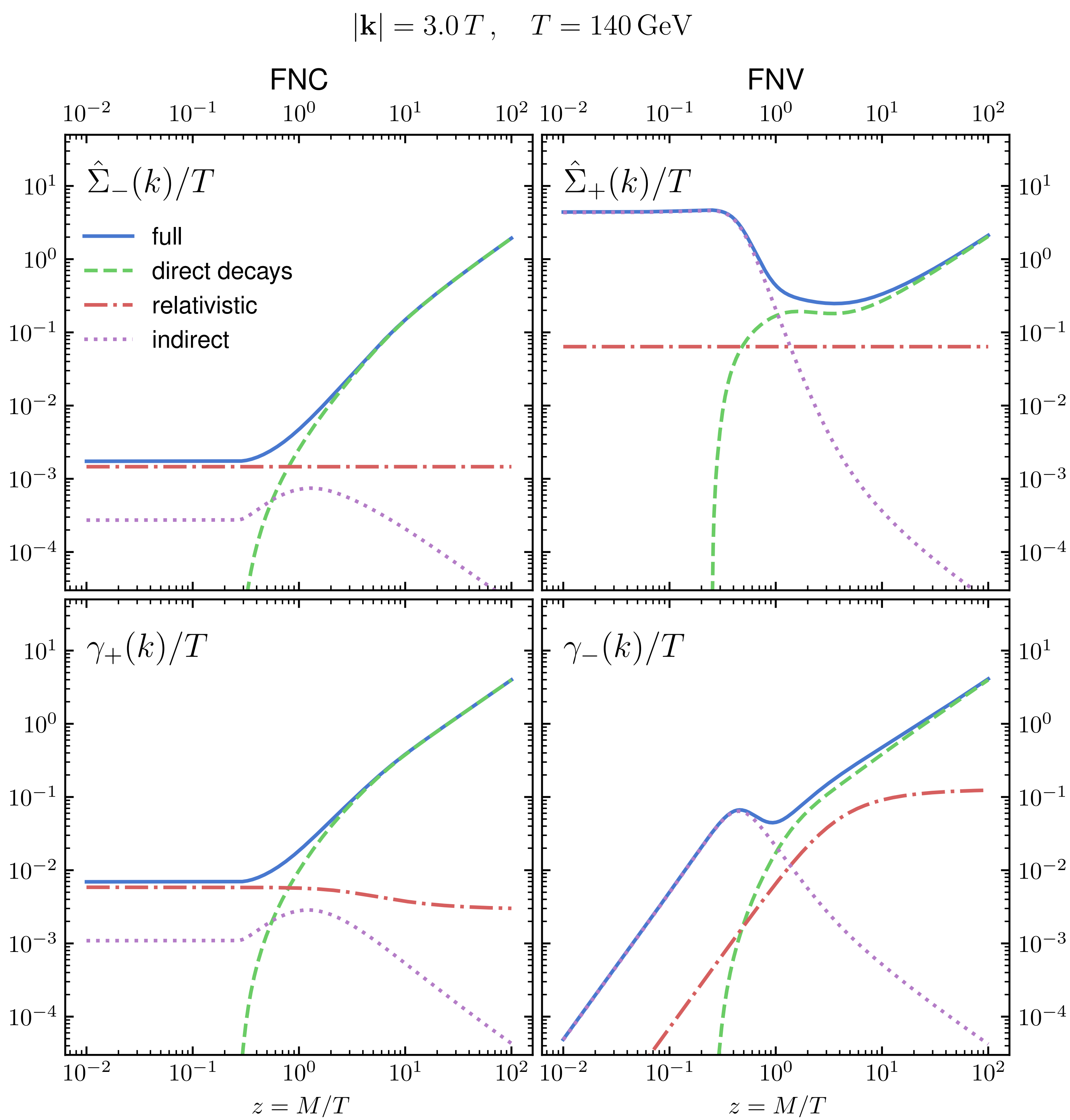


N
ℓ
ϕ

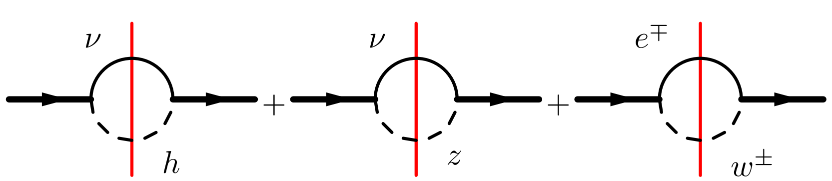


$|\mathbf{k}| = 3.0\,T\,,\quad T = 1.0\,\mathrm{TeV}$
Ghisoiu and Laine 2014
this work
$\mathrm{Im}\,\Pi_N/T^2$
$z = M/T$

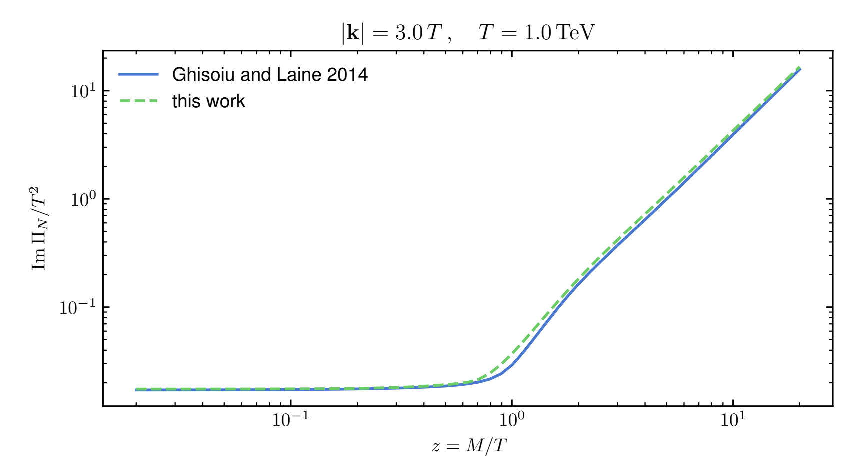
The rates



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

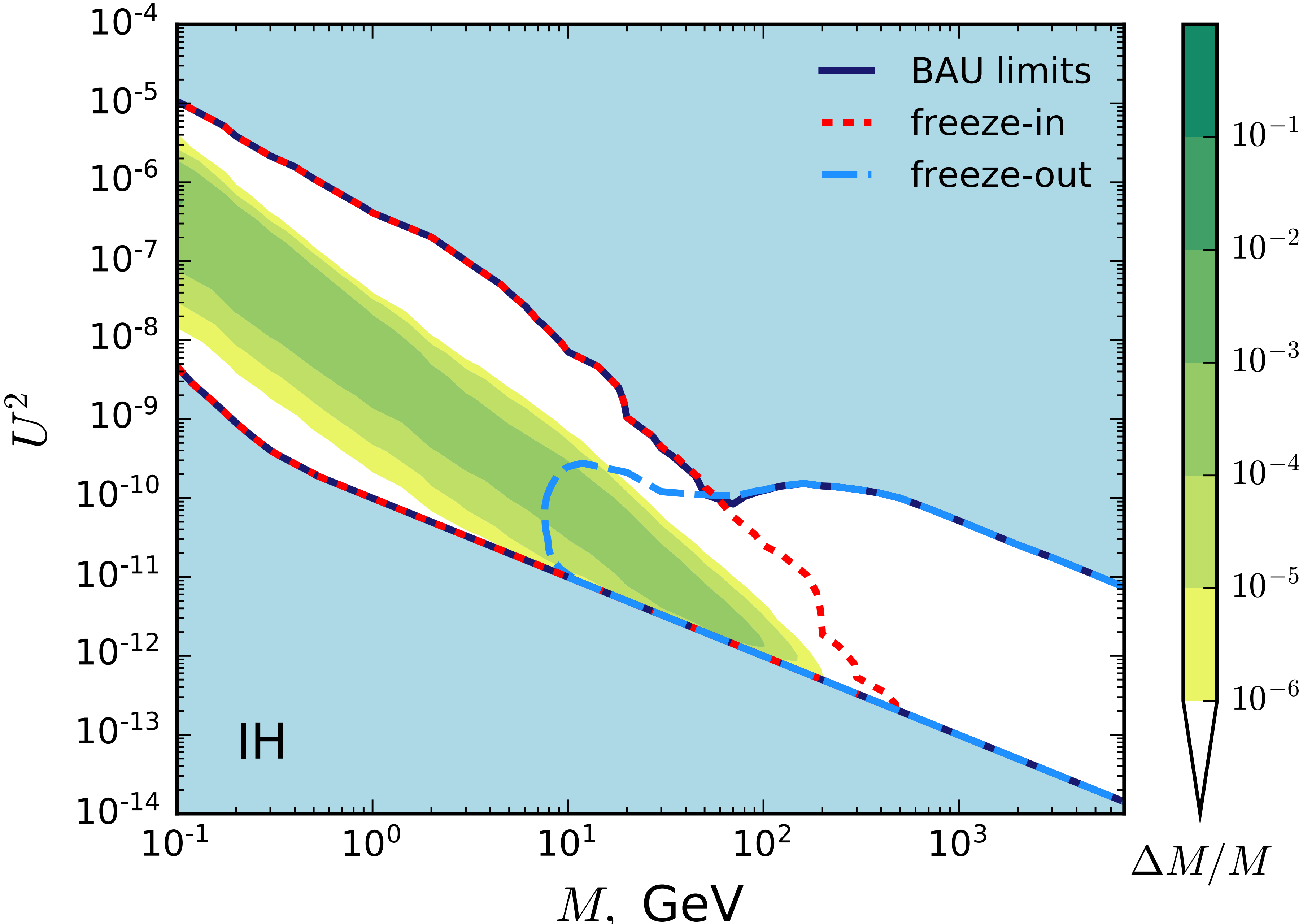


ν
h
ν
z
$e^{\mp}$
$w^{\pm}$

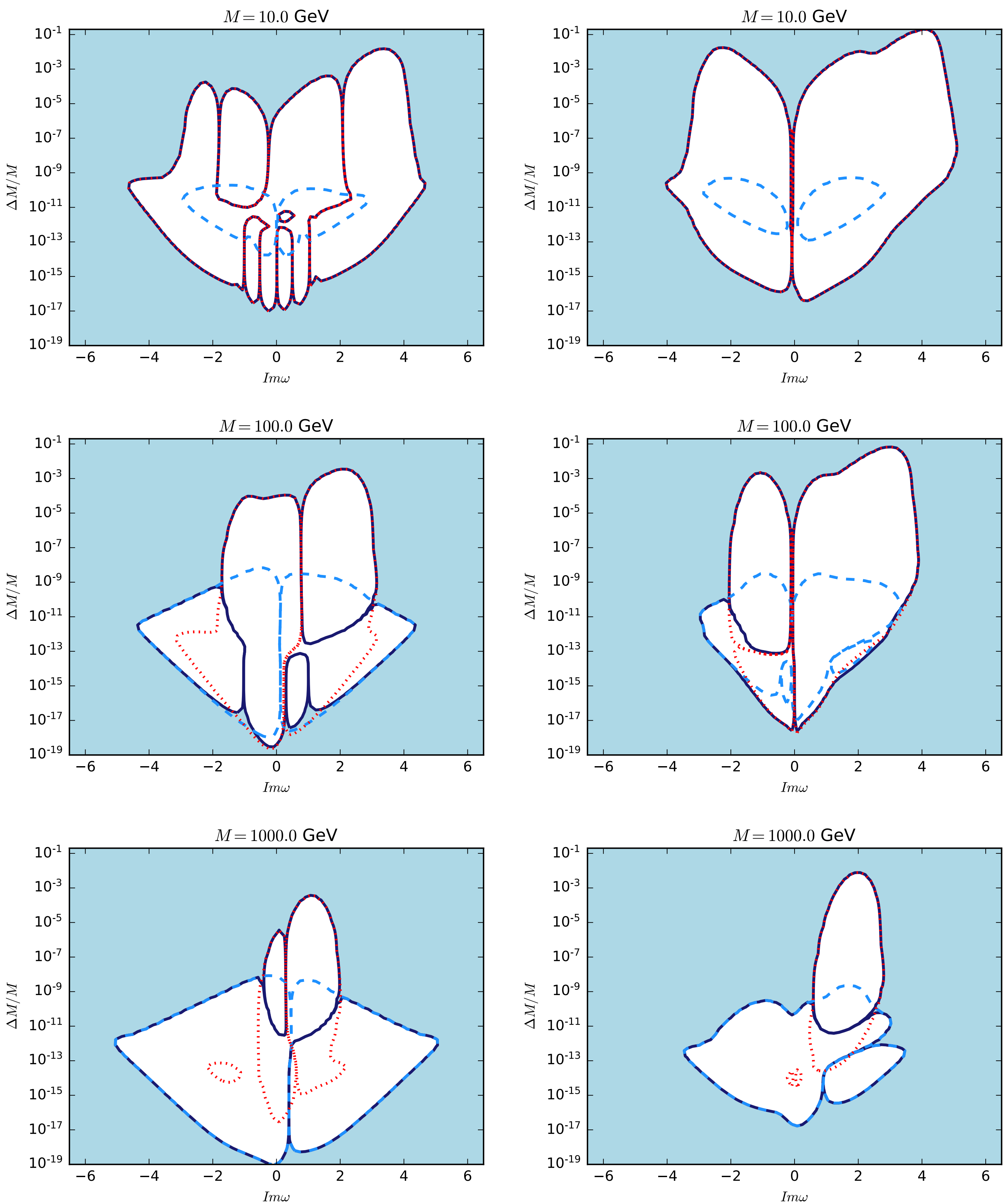


$|\mathbf{k}| = 3.0\,T\,,\quad T = 1.0\,\mathrm{TeV}$
Ghisoiu and Laine 2014
this work
$\mathrm{Im}\,\Pi_N/T^2$
$z = M/T$

flavor 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
ΔM/M
10^-1
10^-3
10^-5
10^-7
10^-9
10^-11
10^-13
10^-15
10^-17
10^-19
Imω
−6
−4
−2
0
2
4
6

Casas-Ibarra parametrization

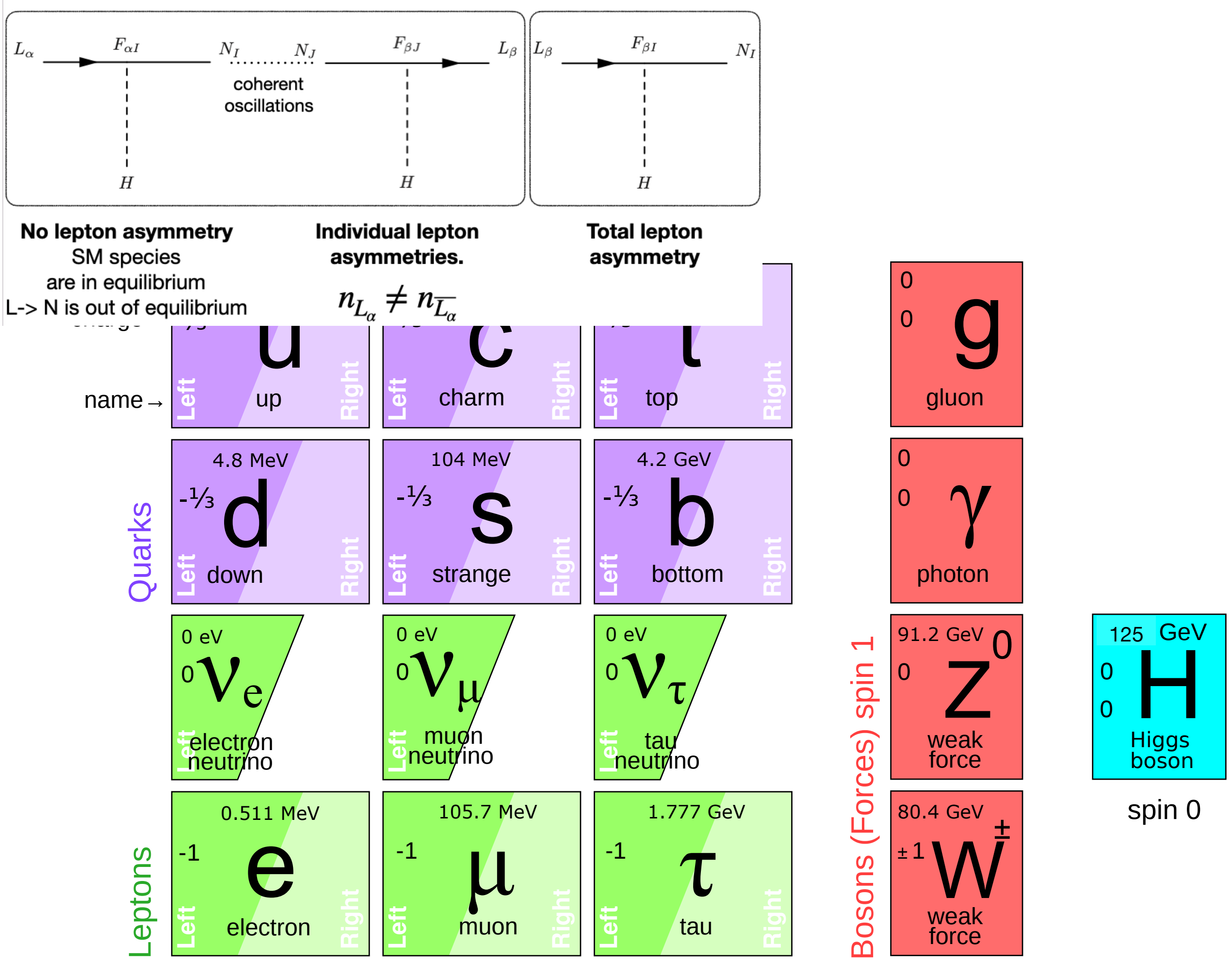
$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\rm diag}} \mathcal{R} \sqrt{M_M} \, ,$$

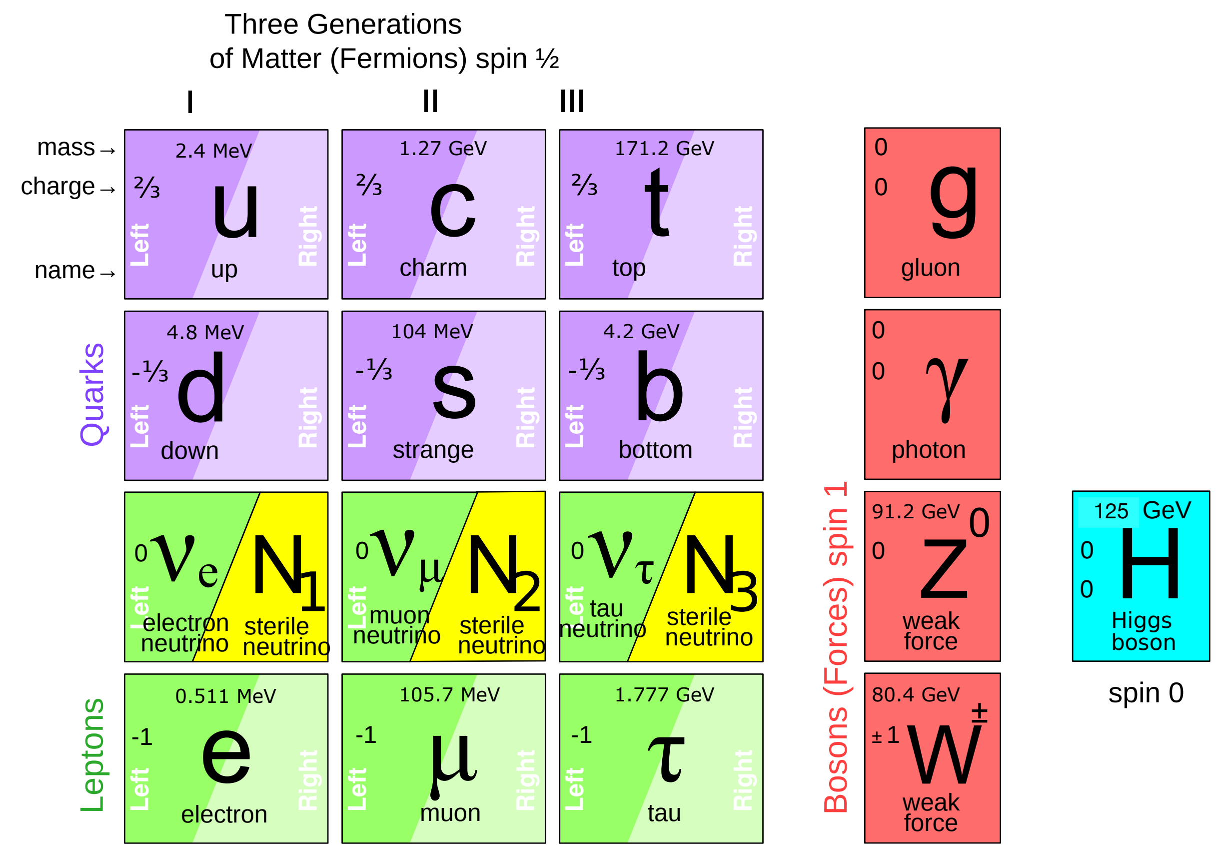
$$\mathcal{R}^{\rm NH} = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix} , \qquad \mathcal{R}^{\rm IH} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$$

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 Minimal Standard Model

Asaka, Blanchet, Shaposhnikov 2005
Asaka, Shaposhnikov 2005



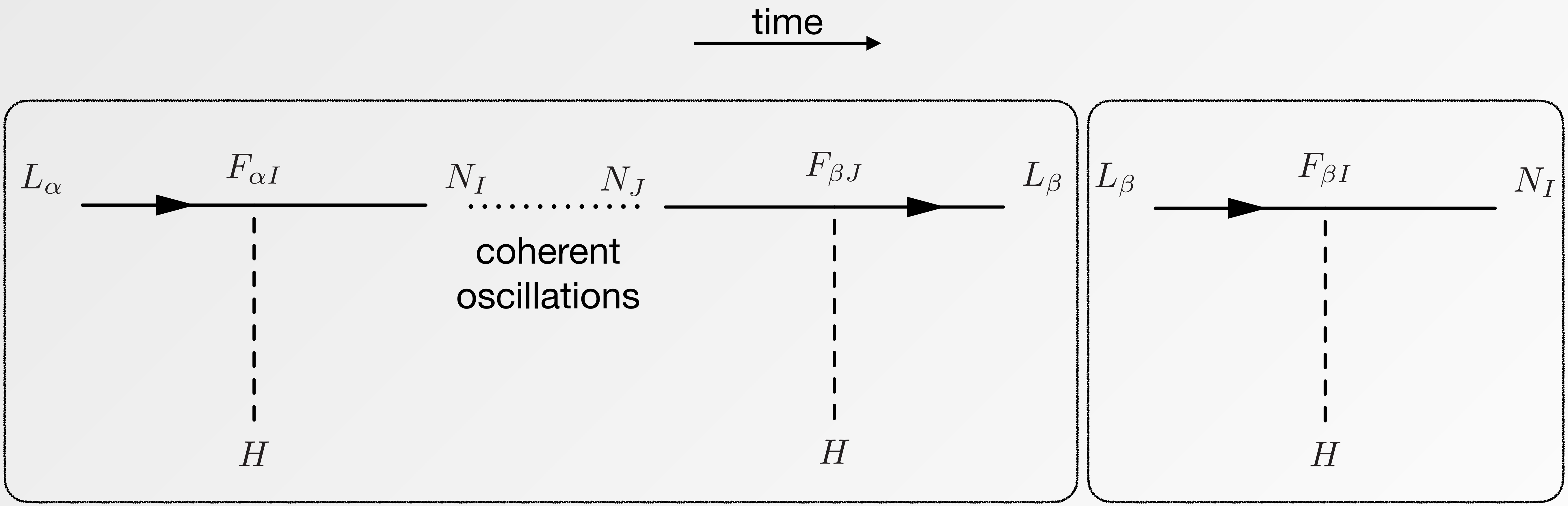


N_1	DM candidate	$m \sim keV$
N_2, N_3	ν masses via see-saw BAU (DM production)	$M_N \gtrsim 0.1\, GeV$ Nearly degenerate

Akhmedov, Rubakov, Smirnov, 1998
Asaka,Shaposhnikov 2005

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

BAU generation



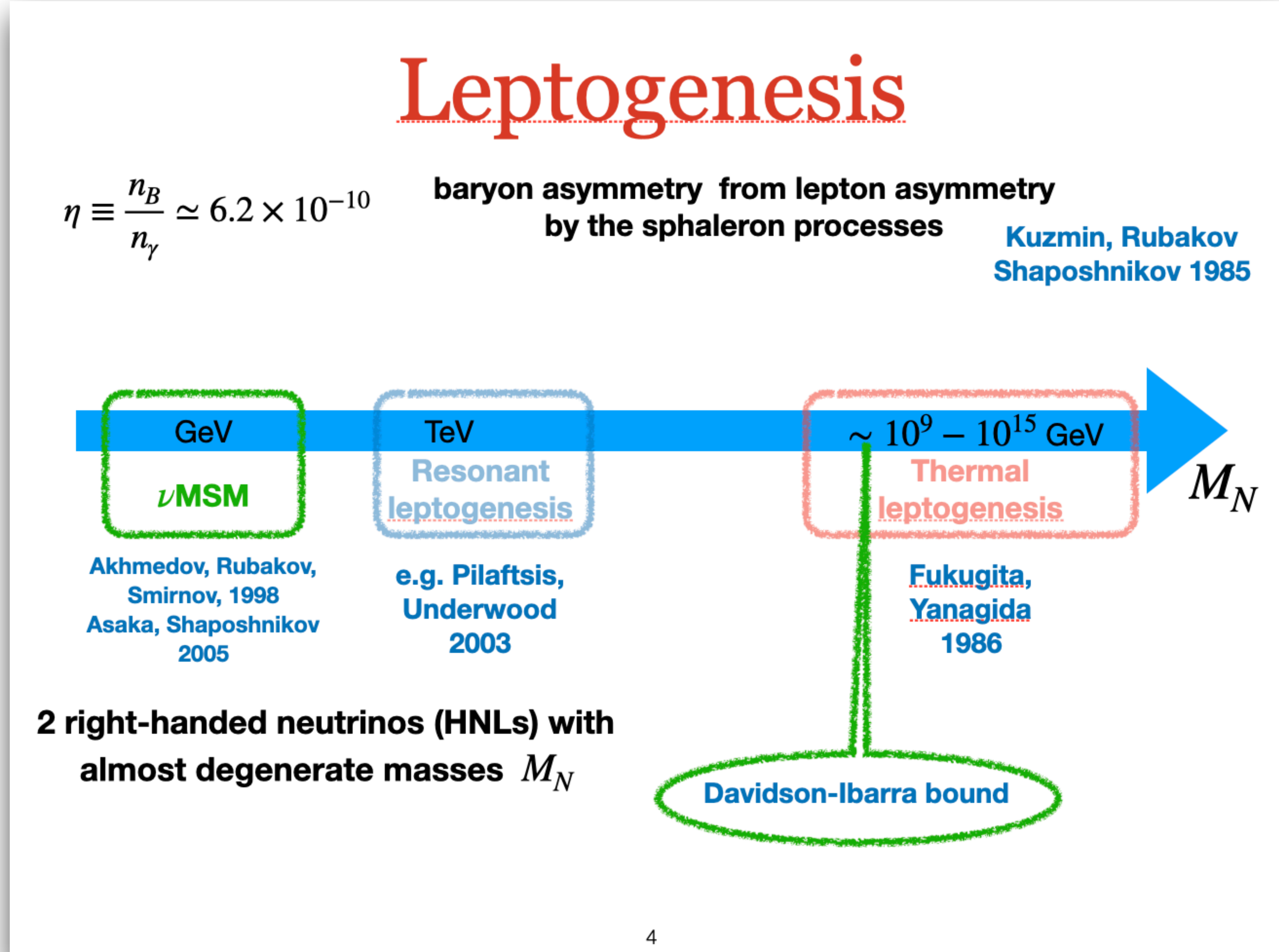
No lepton asymmetry
SM species
are in equilibrium
L-> N is out of equilibrium

Individual lepton asymmetries.

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

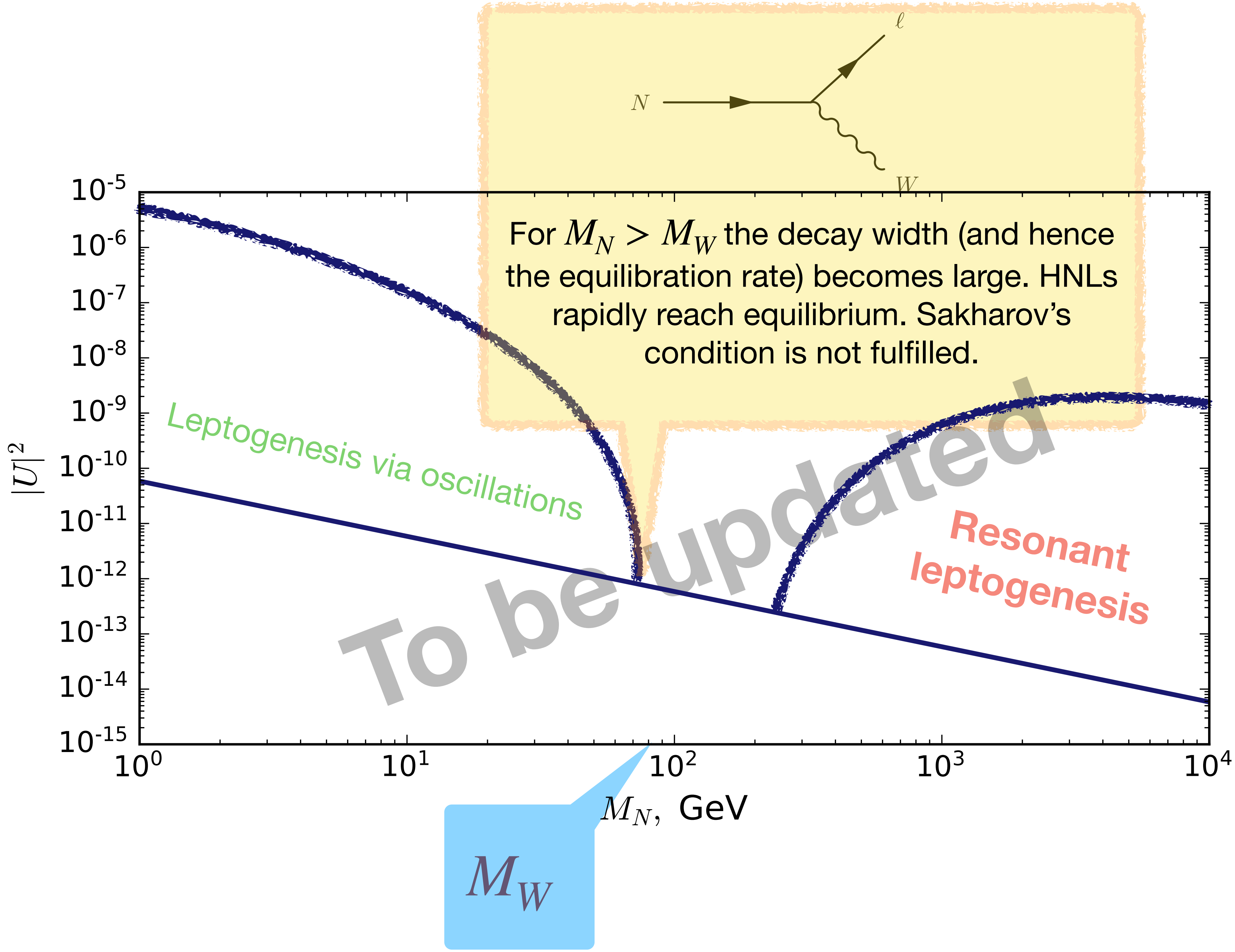
Total lepton asymmetry

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

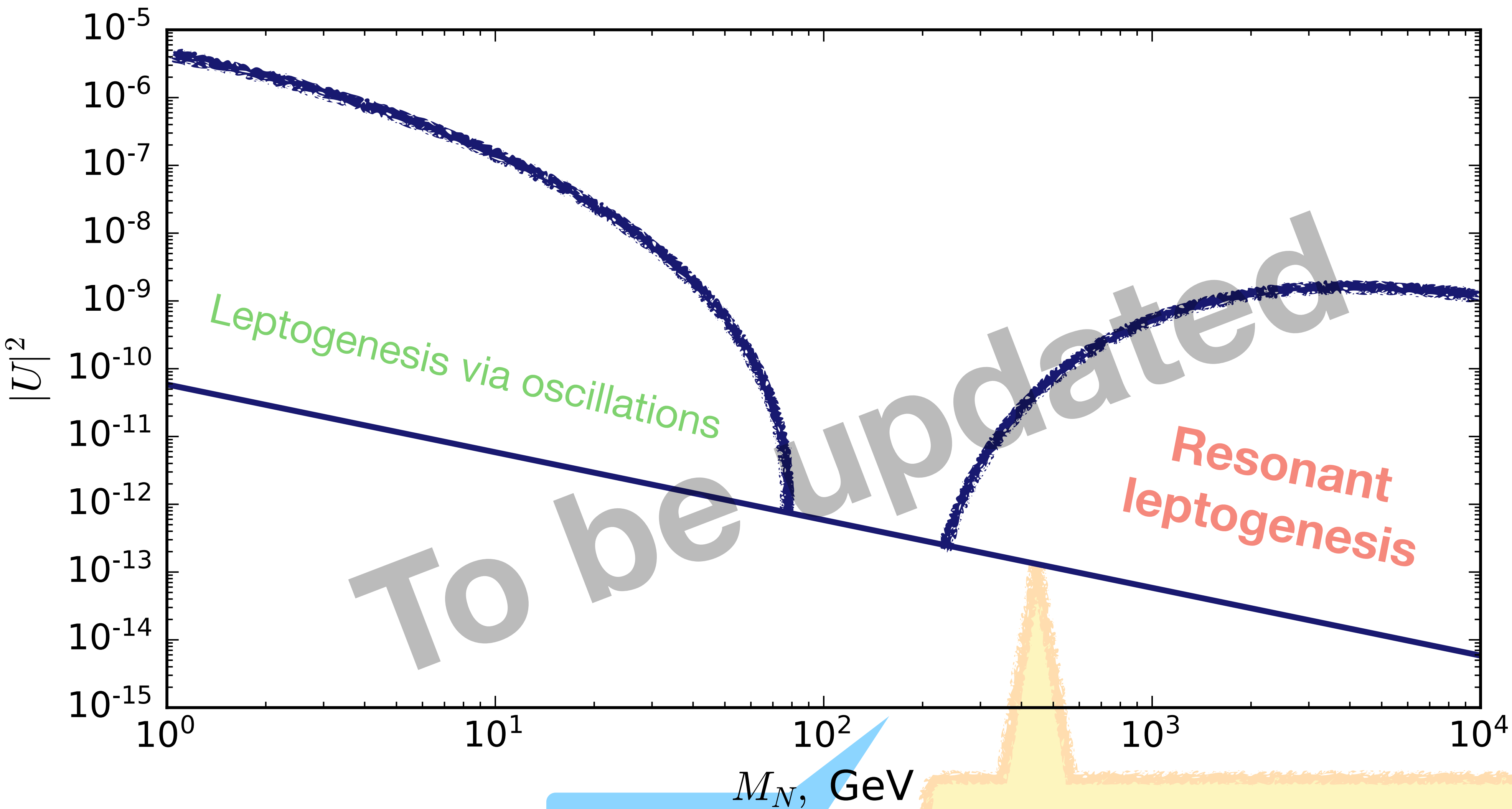


My slide from BLV 2019

Different leptogenesis mechanisms?



Different leptogenesis mechanisms?

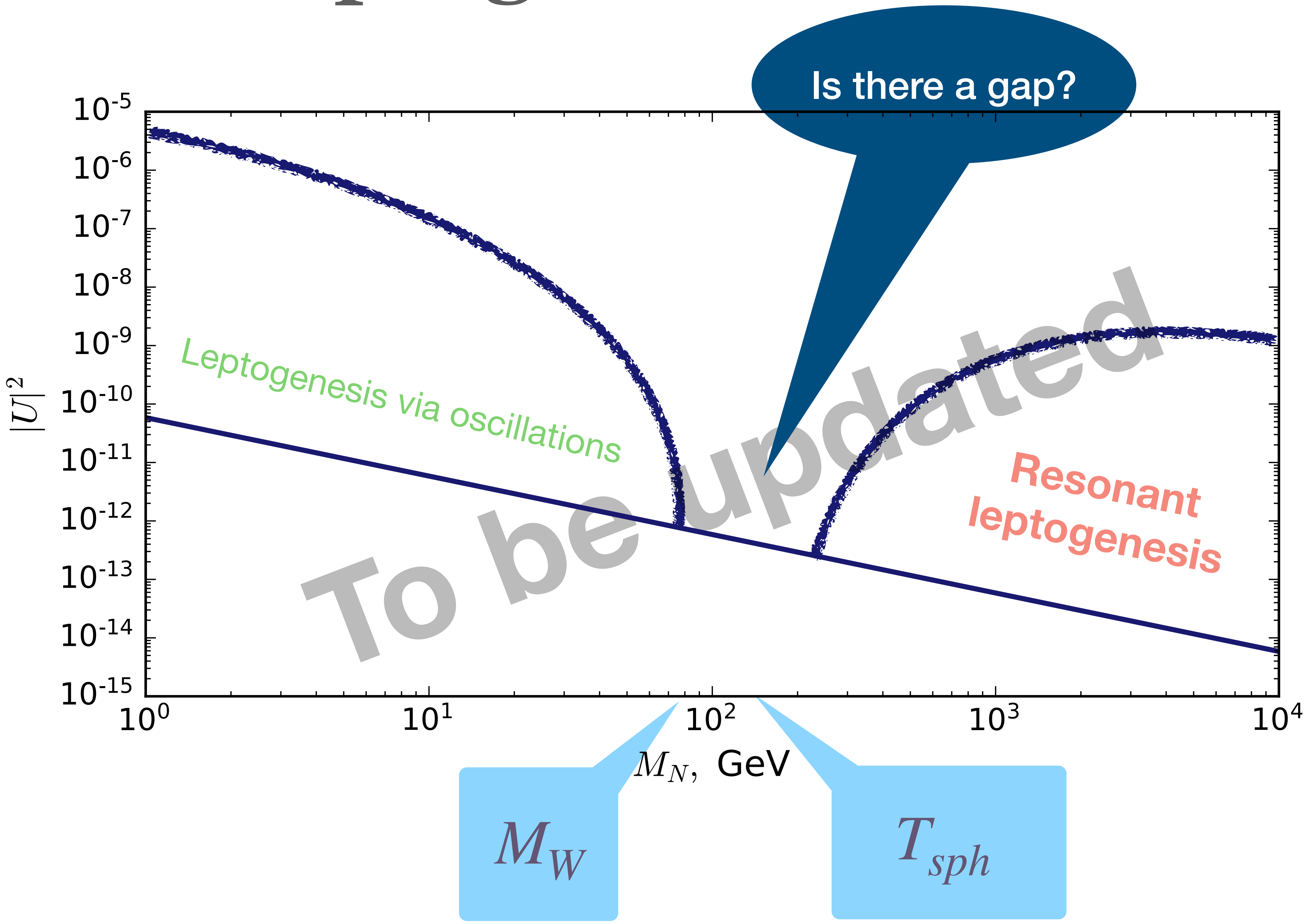


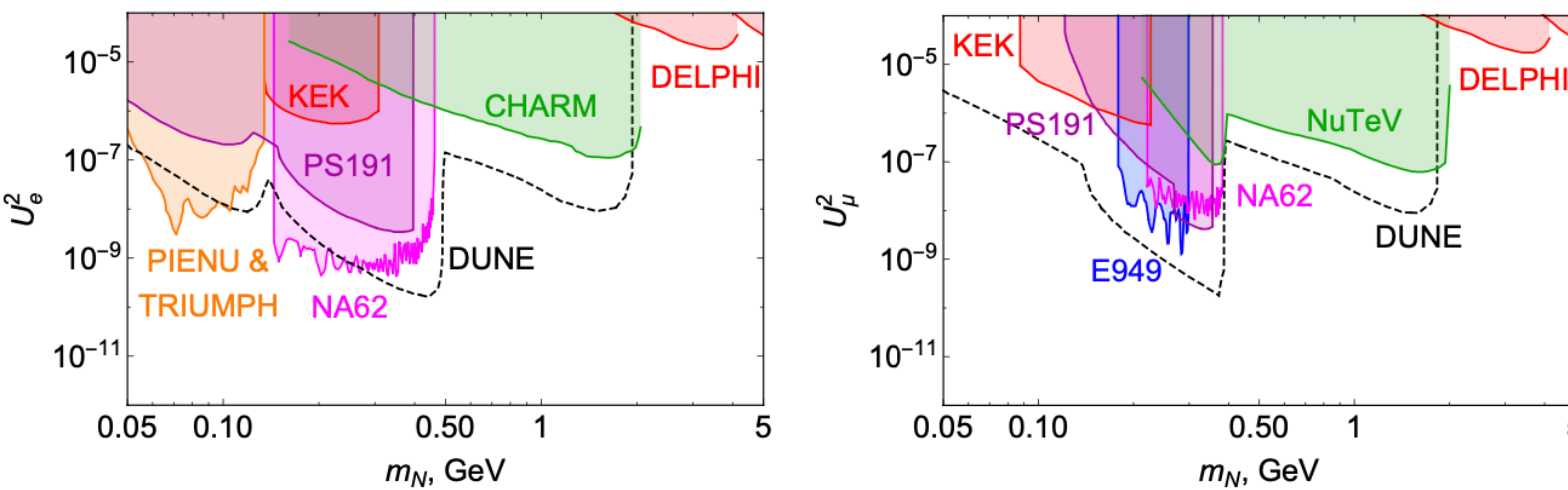
T_{sph}

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?





KEK
DELPHI
CHARM
PS191
PIENU &
TRIUMPH
NA62
DUNE
10^{-5}
10^{-7}
10^{-9}
10^{-11}
U_e^2
0.05
0.10
0.50
1
5
m_N, GeV
KEK
DELPHI
NuTeV
PS191
NA62
DUNE
E949
10^{-5}
10^{-7}
10^{-9}
10^{-11}
U_μ^2
0.05
0.10
0.50
1
5
m_N, GeV

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

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

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

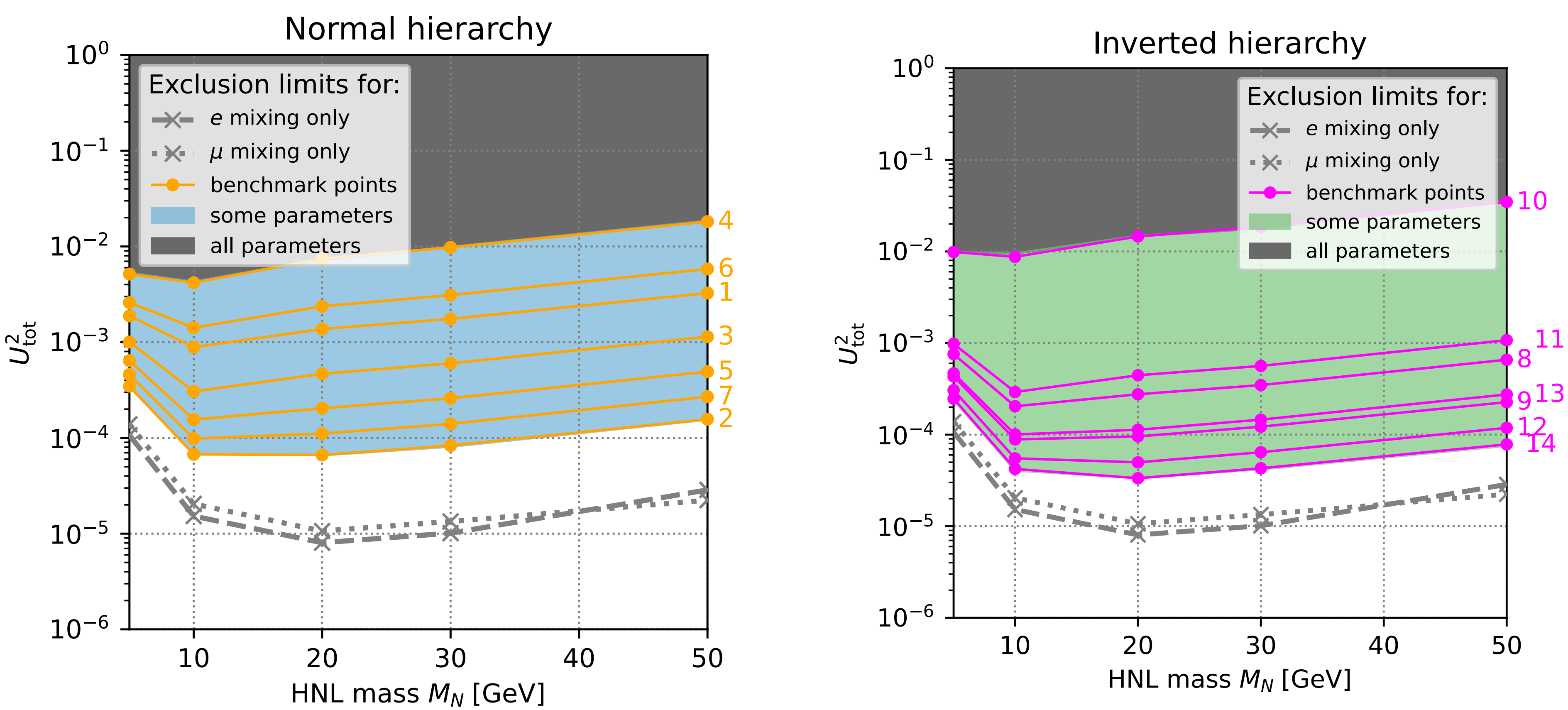
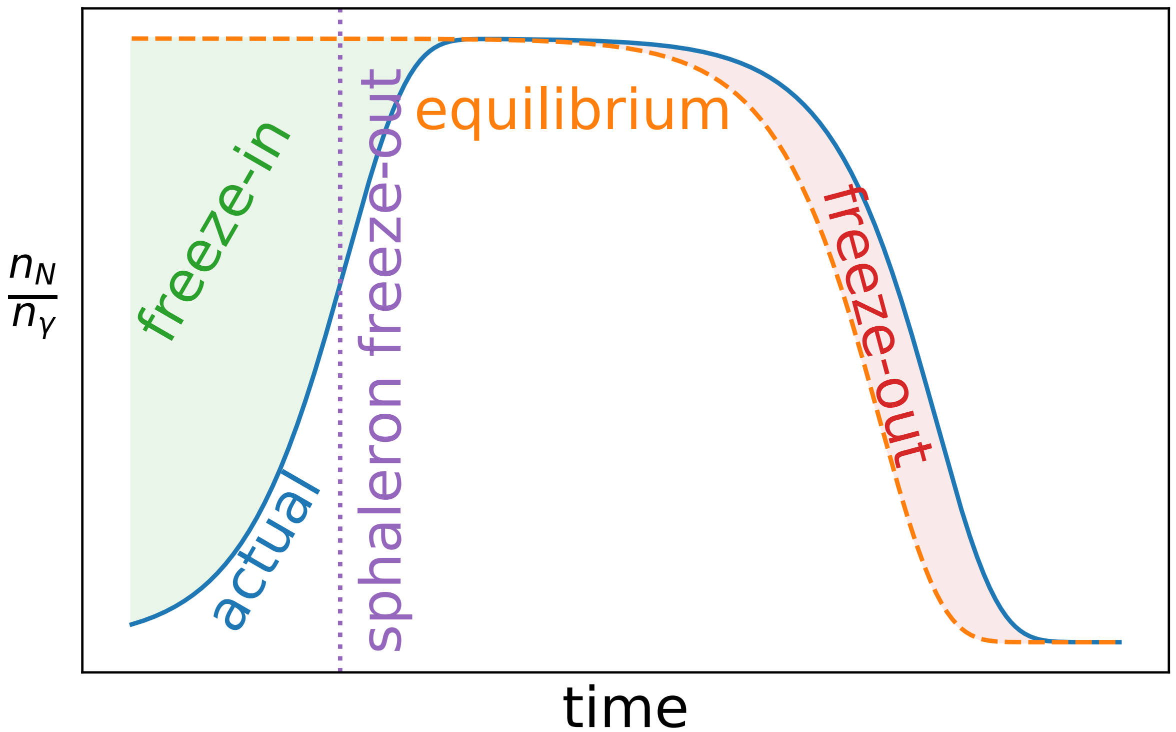
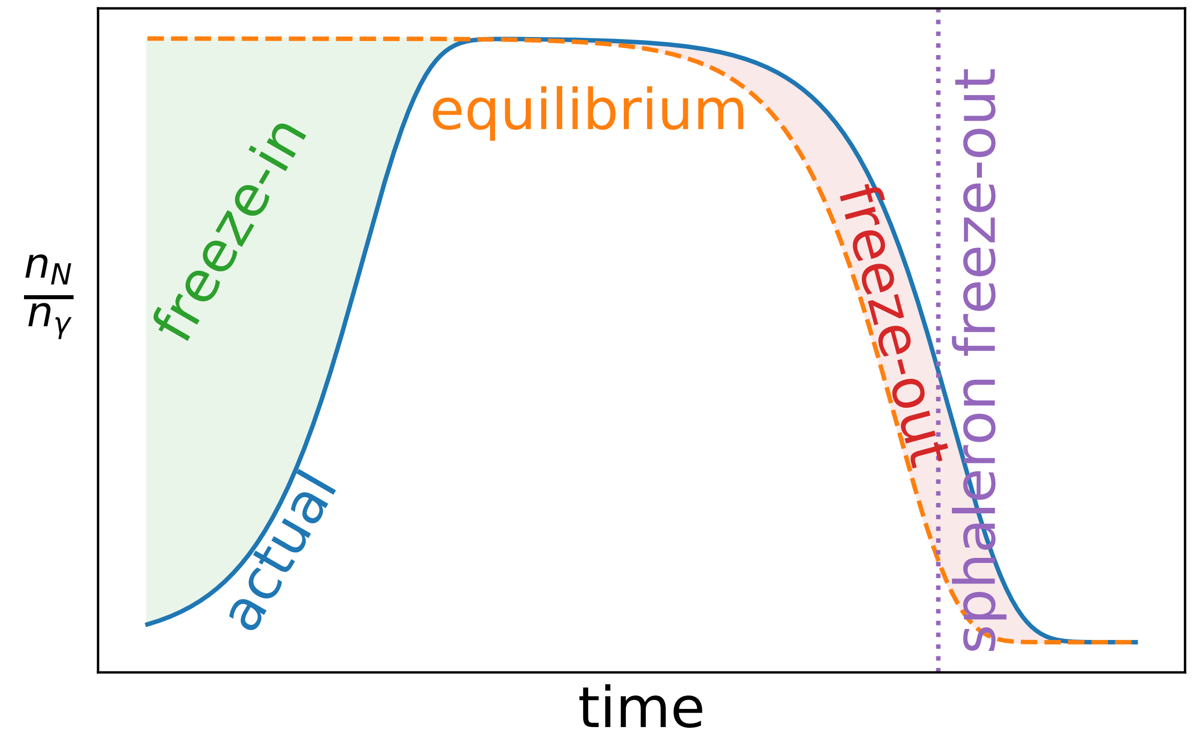


Figure 8: Same as figure 7, but for a **Dirac-like** HNL pair. The single-flavor mixing limits are grayed out because this search has *no sensitivity* to the Dirac-like case under this assumption; instead the limits for the Majorana-like case are given for comparison.

More accurate classification of Leptogenesis mechanisms



“Leptogenesis via oscillations”



“Resonant Leptogenesis”