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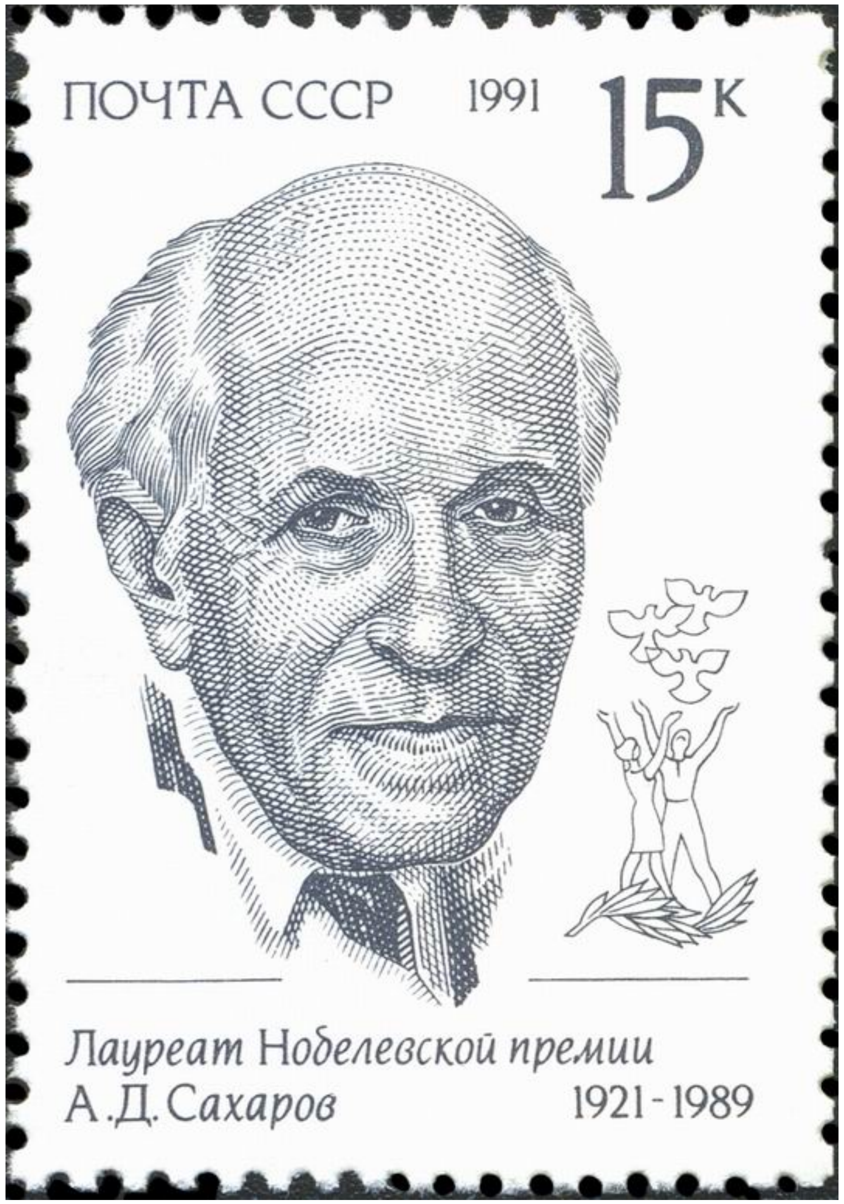
UNIVERSITY OF COPENHAGEN

Low-scale leptogenesis and the quest for heavy neutral leptons

Inar Timiryasov

Niels Bohr Institute,
University of Copenhagen

Theory seminar, Nikhef
March 10th, 2022



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."

- PhD in 1947
- Worked on thermonuclear bomb
- In 1950 with Igor Tamm proposed the idea of Tokamak
- 1963 He played a role in the Partial Nuclear Test Ban Treaty
- 1967 the paper "Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe"
- 1975 Nobel Peace Prize
- 1980 — 1986 internal exile

t-invariant.org/en/2022/02/we-are-against-war-en/

09.03.2022 18:40

Т-инвариант / T-invariant

DEUTSCH ENGLISH ESPAÑOL FRANÇAIS ITALIANO РУССКИЙ SVENSKA УКРАЇНСЬКА 中文 (中国) POLSKI SUOMI

T-INVARIANT-ONLINE

Open letter of Russian scientists and science journalists against the war with Ukraine

FEB 24, 2022

We, the undersigned Russian scientists and science journalists, declare our strong opposition to the Russian hostilities launched against the Ukrainian people. These hostilities are incurring huge human losses and undermines the foundations of the established system of international security. The responsibility for unleashing a new war in Europe lies entirely with Russia.

There is no rational justification for this war. Obviously, Ukraine poses no threat to the security of Russia. The attempts to use the situation in Donbass as a pretext for launching a military operation are totally contrived. The war against Ukraine is unjust and frankly nonsense.

Ukraine has been and remains a country close to us. Many of us have relatives, friends, and colleagues living in Ukraine

Search

Search

Свежие записи

Open letter of Russian scientists and science journalists against the war with Ukraine

Архивы

February 2022

almost 7900 people signed

Подписи продолжают приходить, добавляем по мере сил (сейчас на сайте их почти 7900)

https://t-invariant.org/2022/02/we-are-against-war/

Outline

- Introduction
  - Standard model and its problems
  - Baryon asymmetry of the Universe and Sakharov conditions
  - Seesaw mechanism
  - Leptogenesis
- Parameter space of low-scale leptogenesis
- Phenomenological implications

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

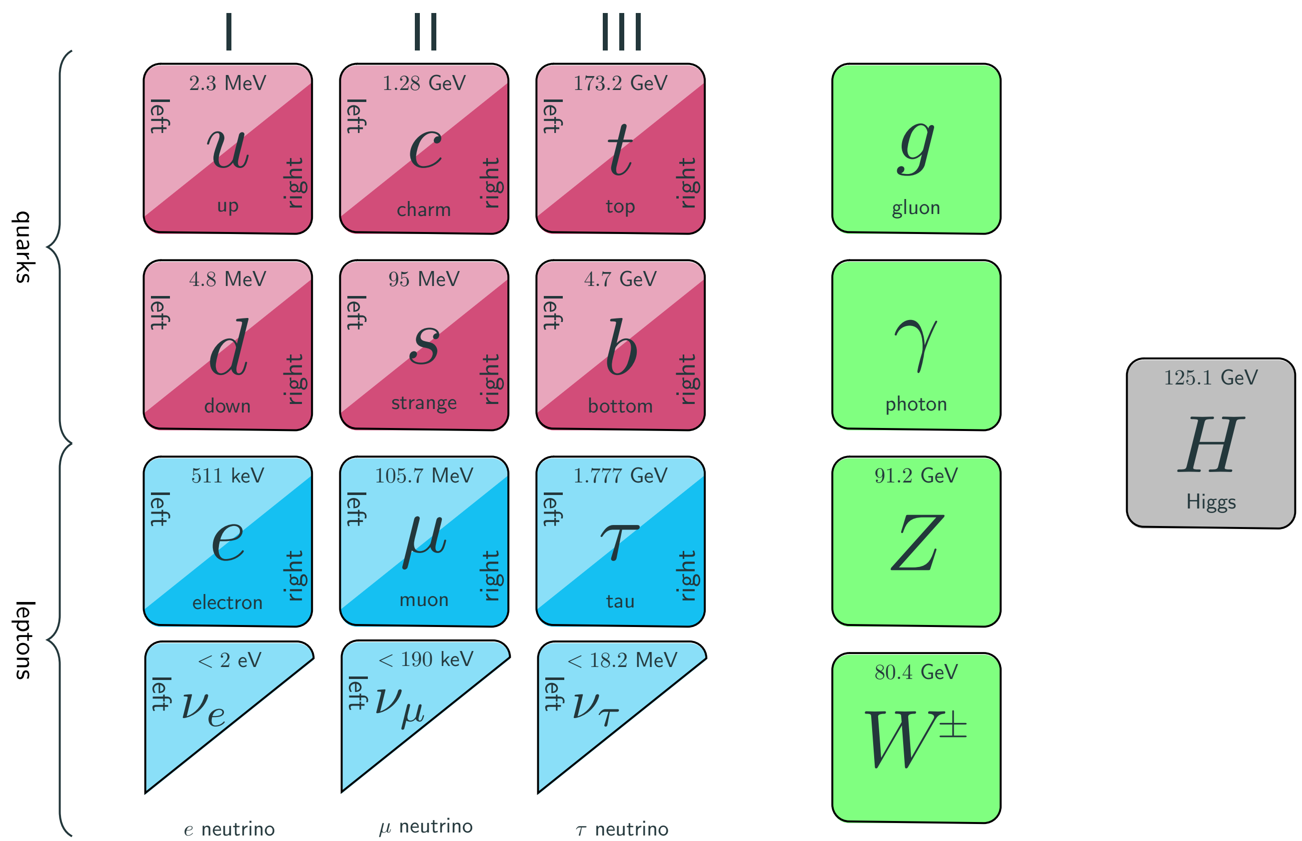
- Reconciling resonant leptogenesis and baryogenesis via neutrino oscillations
  Juraj Klarić, Mikhail Shaposhnikov, IT
  2103.16545, *Phys.Rev.D* 104 (2021) 5, 055010

- 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



- 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 after the Big Bang Nucleosynthesis (t > 1 sec)
- According to Scientific American, it led to 55 Nobels
- Are we done?

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

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

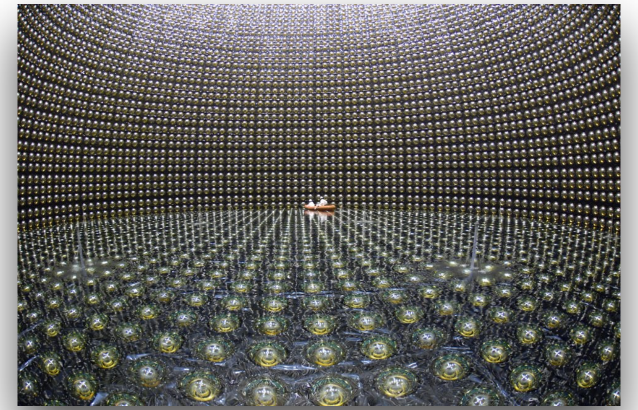
$$(\nu_e,\ e) \to \mathrm{e}^{i\beta_e}(\nu_e, e), \quad (\bar{\nu}_e,\ \bar{e}) \to \mathrm{e}^{-i\beta_e}(\bar{\nu}_e,\ \bar{e})$$
$$(\nu_\mu,\ \mu) \to \mathrm{e}^{i\beta_\mu}(\nu_\mu, \mu), \quad (\bar{\nu}_\mu, \bar{\mu}) \to \mathrm{e}^{-i\beta_\mu}(\bar{\nu}_\mu, \bar{\mu})$$
$$(\nu_\tau,\ \tau)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

Image credit: Juraj Klaric

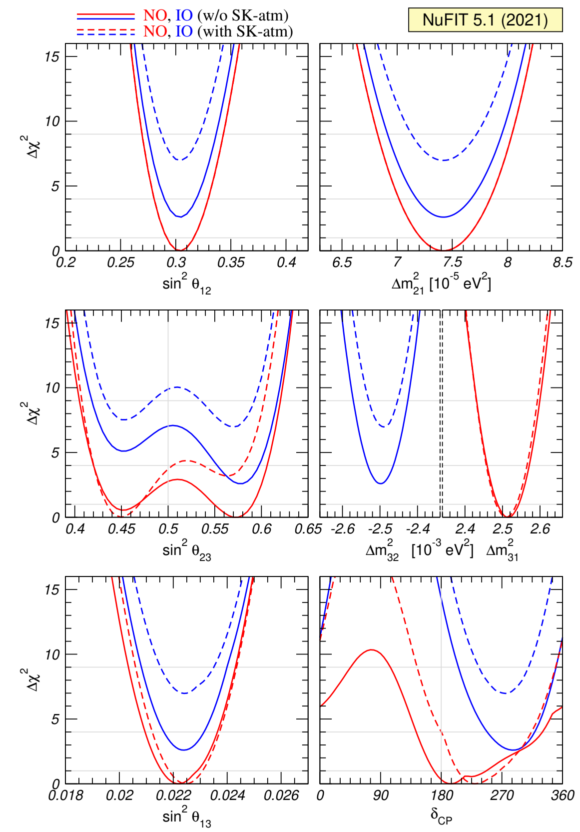
Beyond the Standard Model

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

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

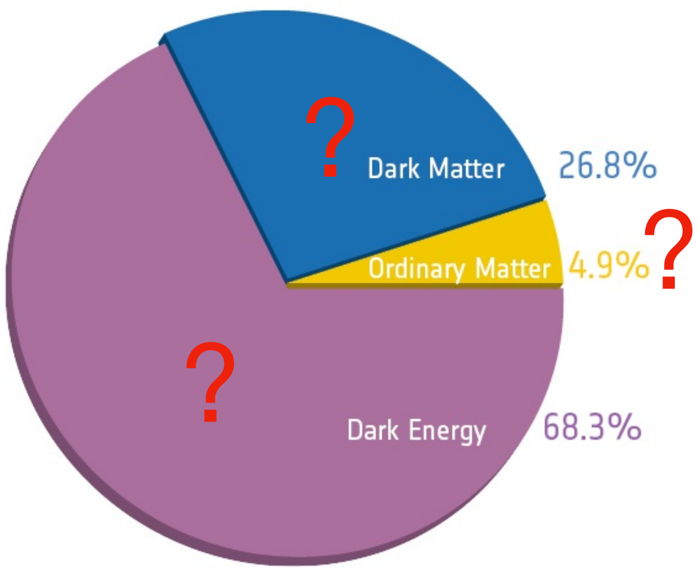


Super-Kamiokande (atmospheric oscillations $\nu_\mu \to \nu_\tau$)



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

- Cosmology



ESA and the Planck Collaboration

Baryon asymmetry of the Universe

- No antimatter in the present universe

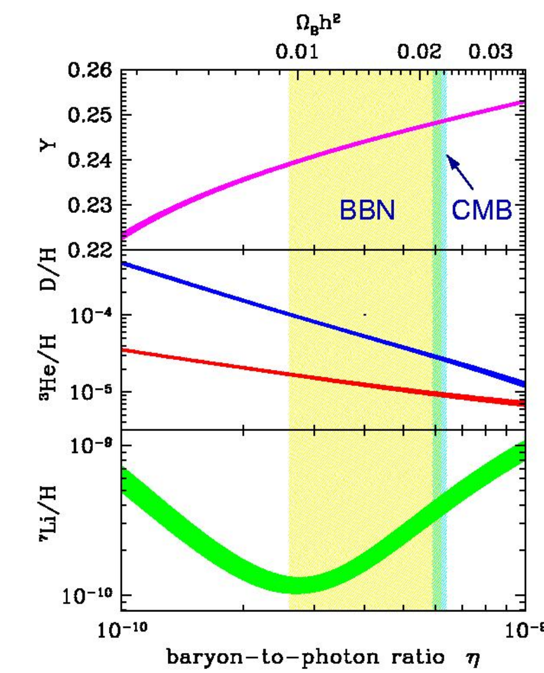
- Baryon to photon ratio

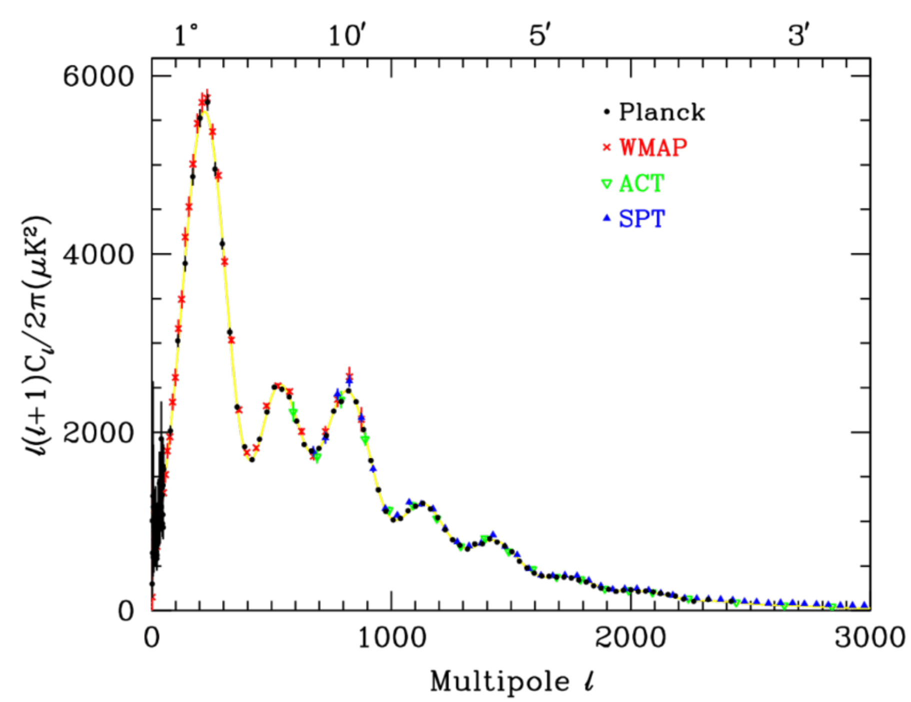
$$\Delta = \left.\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}}\right|_{\text{T}\sim 1\text{ GeV}} \simeq \left.\frac{n_B}{n_\gamma}\right|_{\text{now}} \simeq 6 \times 10^{-10}$$

- 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

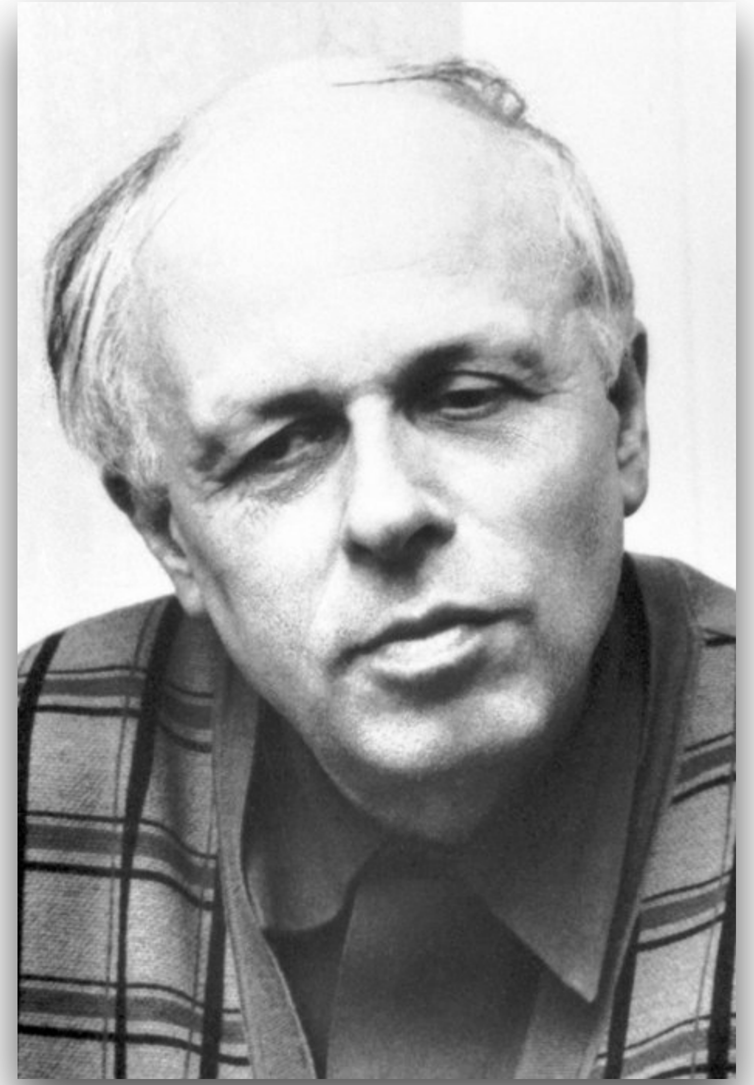




Where the asymmetry comes from?

Sakharov Conditions (1967)

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



Where the asymmetry comes from?

Sakharov Conditions (1967)

- Baryon number violation

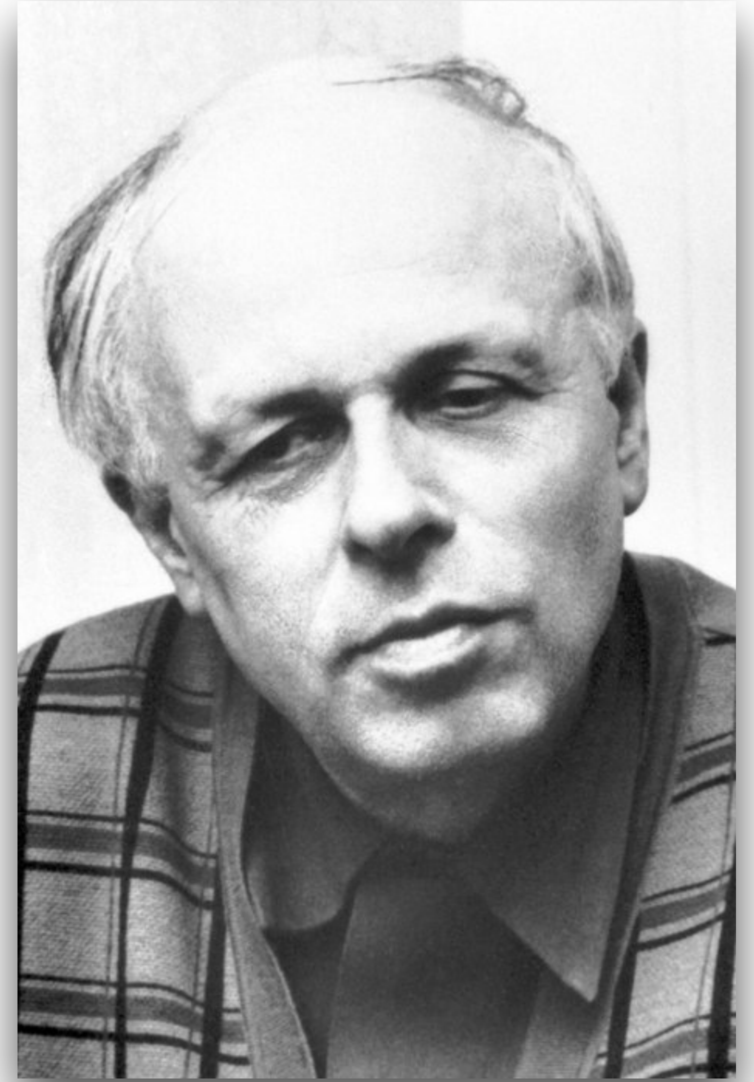
Nonperturbative sphaleron processes at T>130 GeV
[Kuzmin, Rubakov, Shaposhnikov 1985]

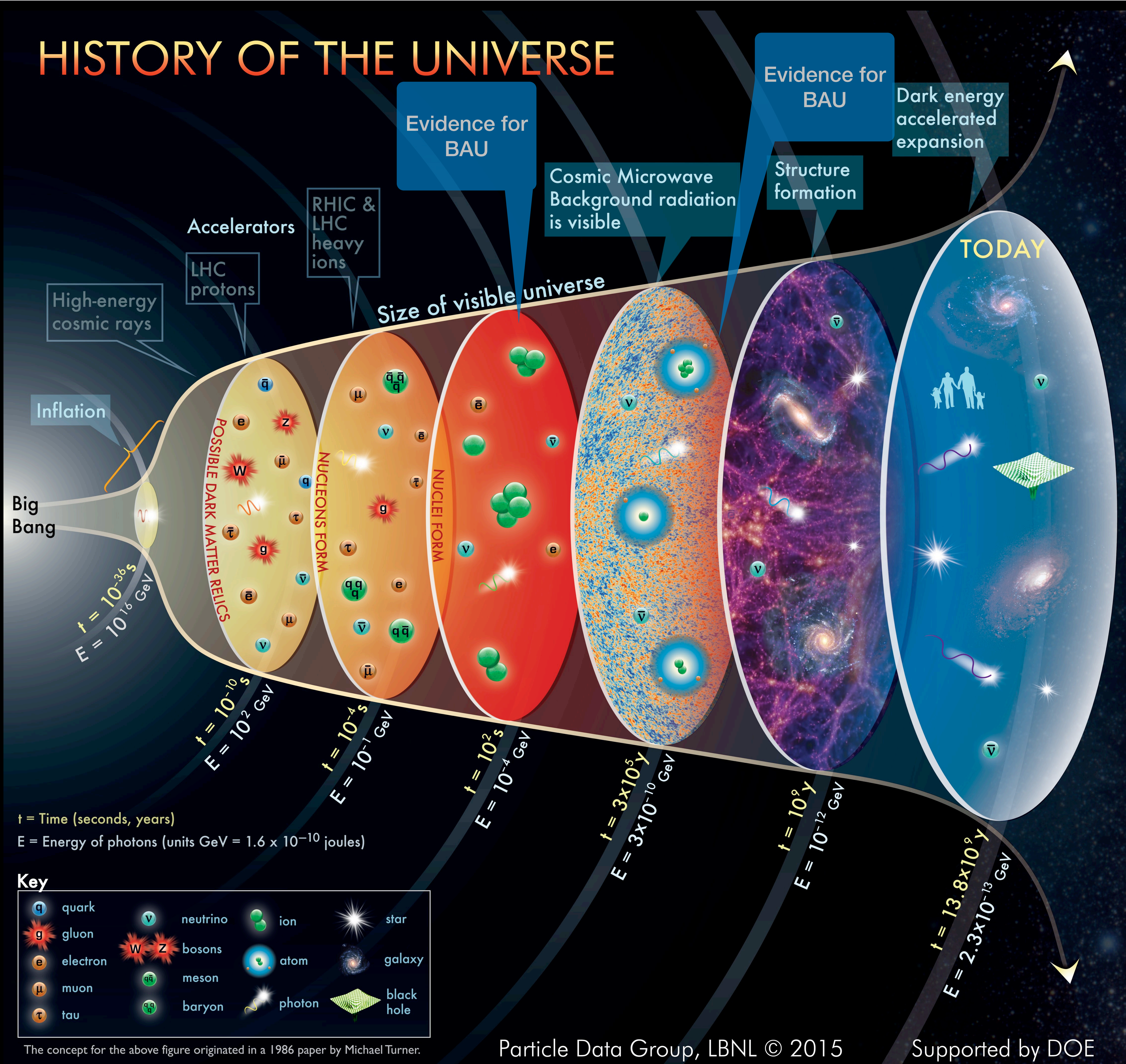
- C and CP violation

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
$E = 10^{16}$ GeV
$t = 10^{-10}$ s
$E = 10^{2}$ GeV
$t = 10^{-4}$ s
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$t = 10^{2}$ 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 = 1.6×10^{-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
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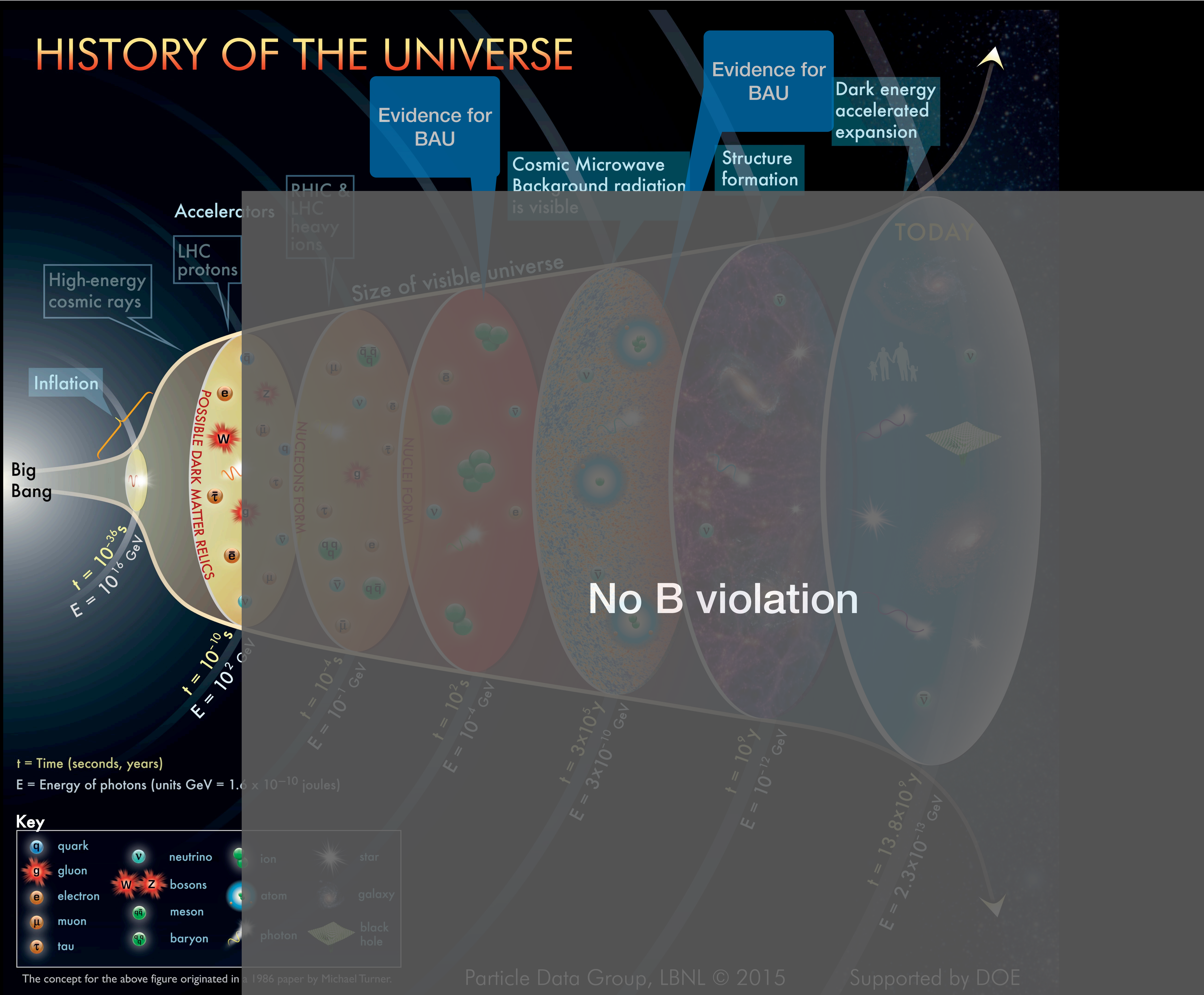
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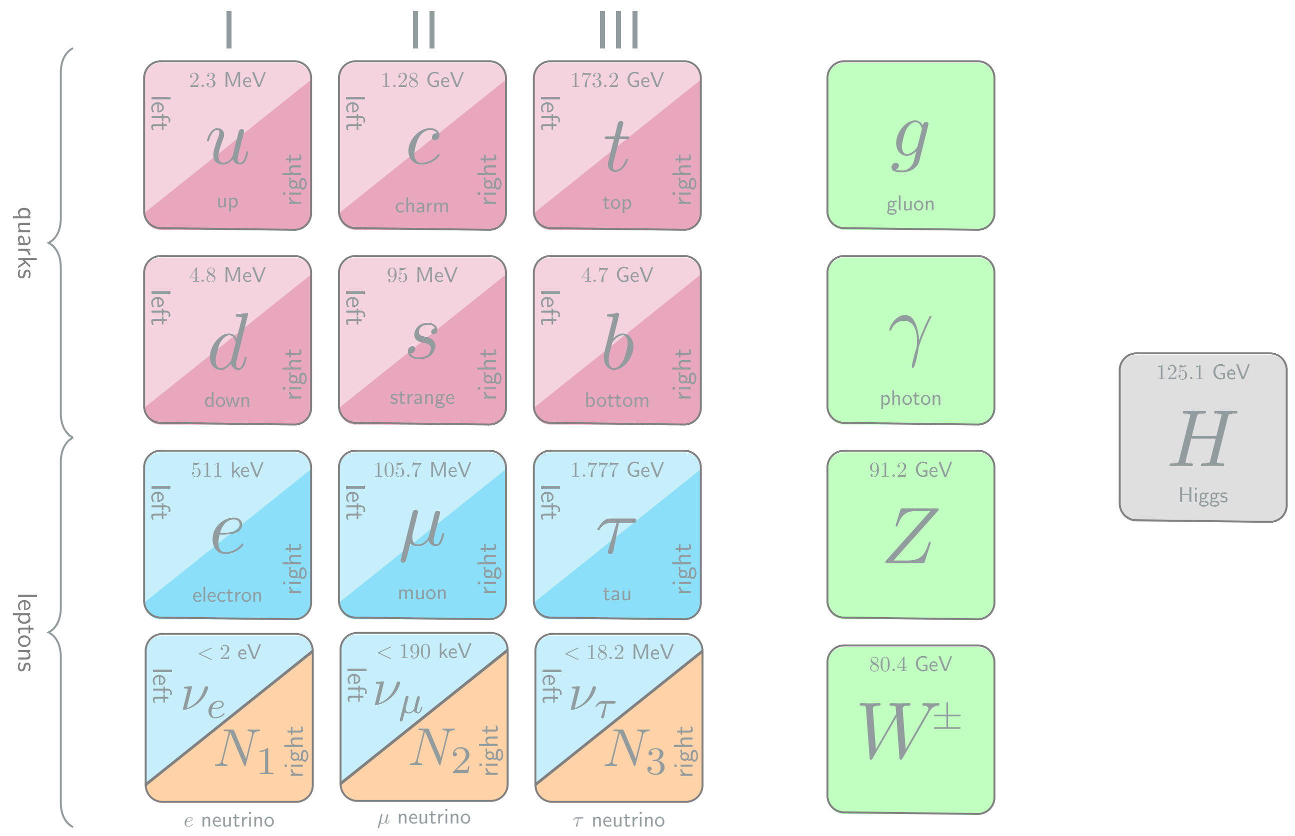
No B violation

Solving the Standard Model problems



The seesaw mechanism

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

the masses of the neutrinos are tiny $\sum m_\nu < 0.9\, eV/c^2$ [KATRIN, 2022]

$\sum m_\nu < 0.12\, eV/c^2$ Lyman-alpha

A mathematical fact:

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

the eigenvalues $\lambda_{1,2} = \frac{M}{2} \pm \sqrt{\left(\frac{M}{2}\right)^2 + m^2}$

$$m \ll M, \quad \lambda_+ \simeq M, \quad \lambda_- \simeq -\frac{m^2}{M}$$

parametrically smaller than m and M

to implement this in the SM right-handed neutrinos are needed

The seesaw mechanism

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

$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

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

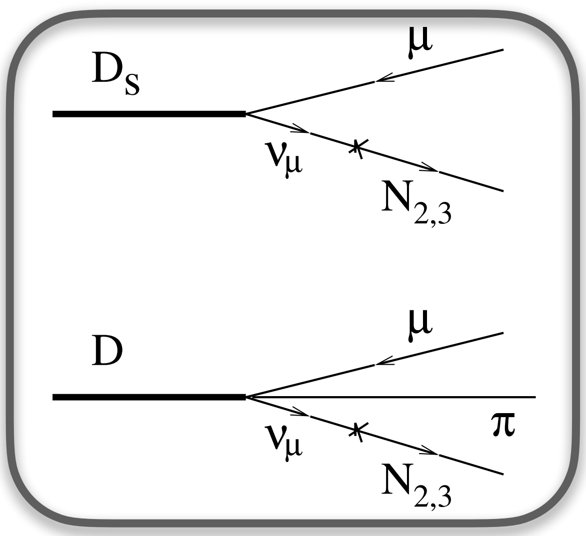
$$\nu_{L_{\alpha}} = U^{PMNS}_{\alpha i}\nu_i + \Theta_{\alpha I}N^{c}_{I}, \qquad |U_{\alpha}|^2 = |\Theta_{\alpha 2}|^2 + |\Theta_{\alpha 3}|^2$$

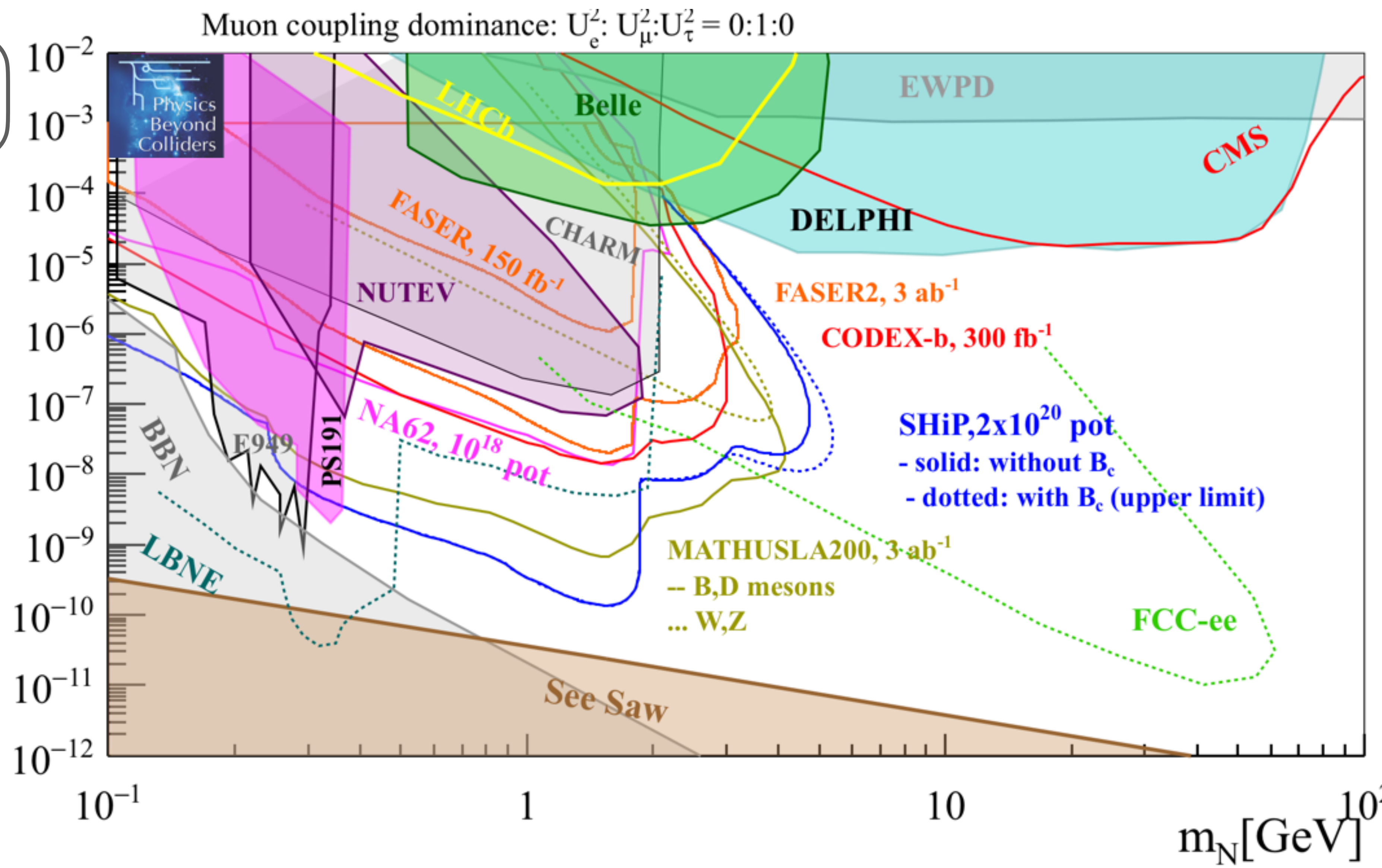
$$\Theta_{\alpha I} = \frac{\langle\Phi\rangle F_{\alpha I}}{M_I} \qquad U^2 = \Sigma_{\alpha}|U_{\alpha}|^2$$

HNLs (Heavy Neutral Leptons)

The quest for Heavy Neutral Leptons

mixing $|U_\mu|^2$





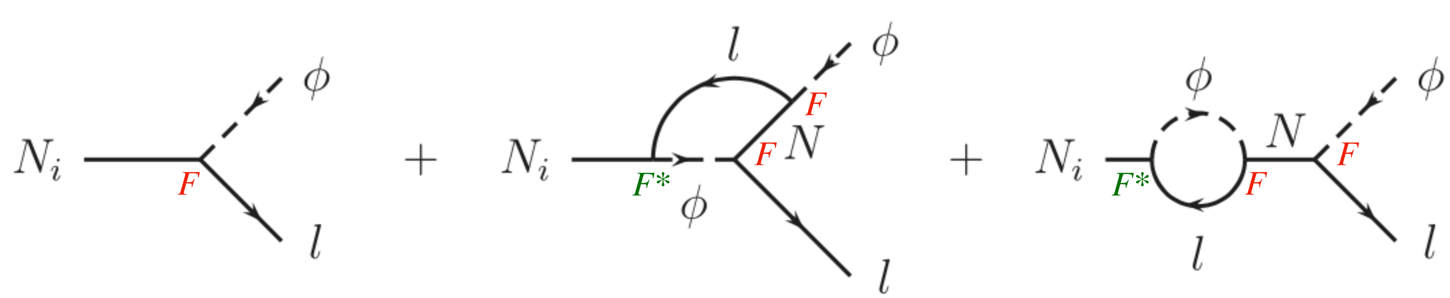
Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report. 1901.09966

Heavy Neutral Leptons: Leptogenesis

The same N can be responsible for the Baryon Asymmetry!

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

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



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

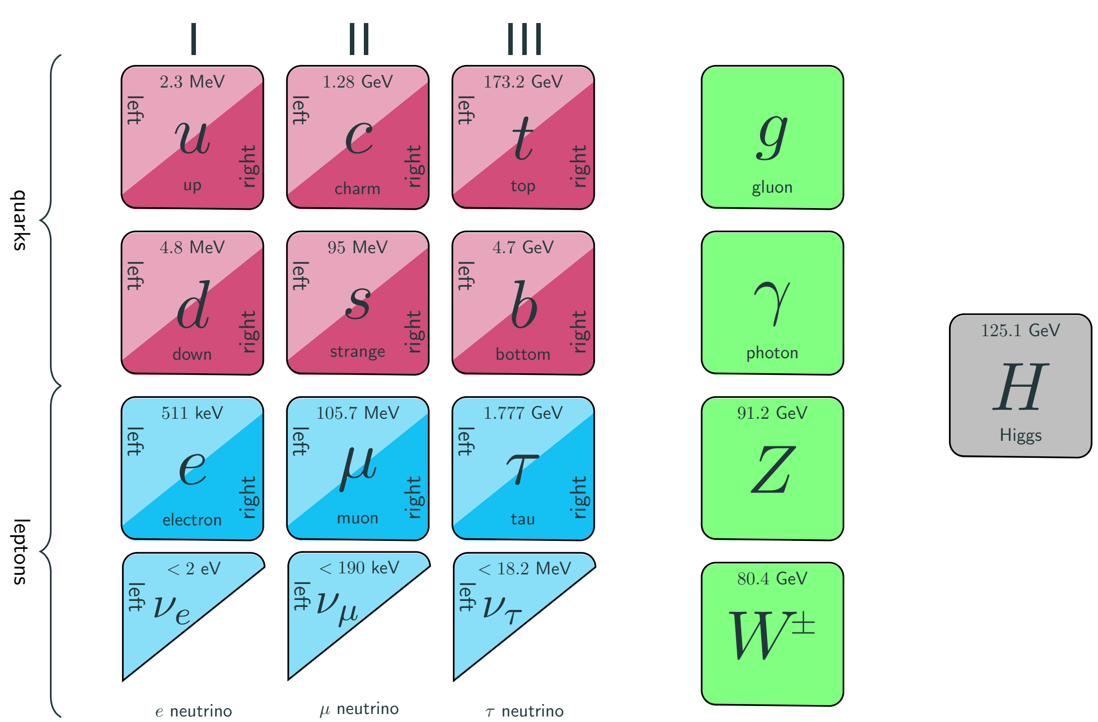
$$\varepsilon \sim \frac{\mathrm{Im}(F^\dagger F)^2}{|F|^2}$$

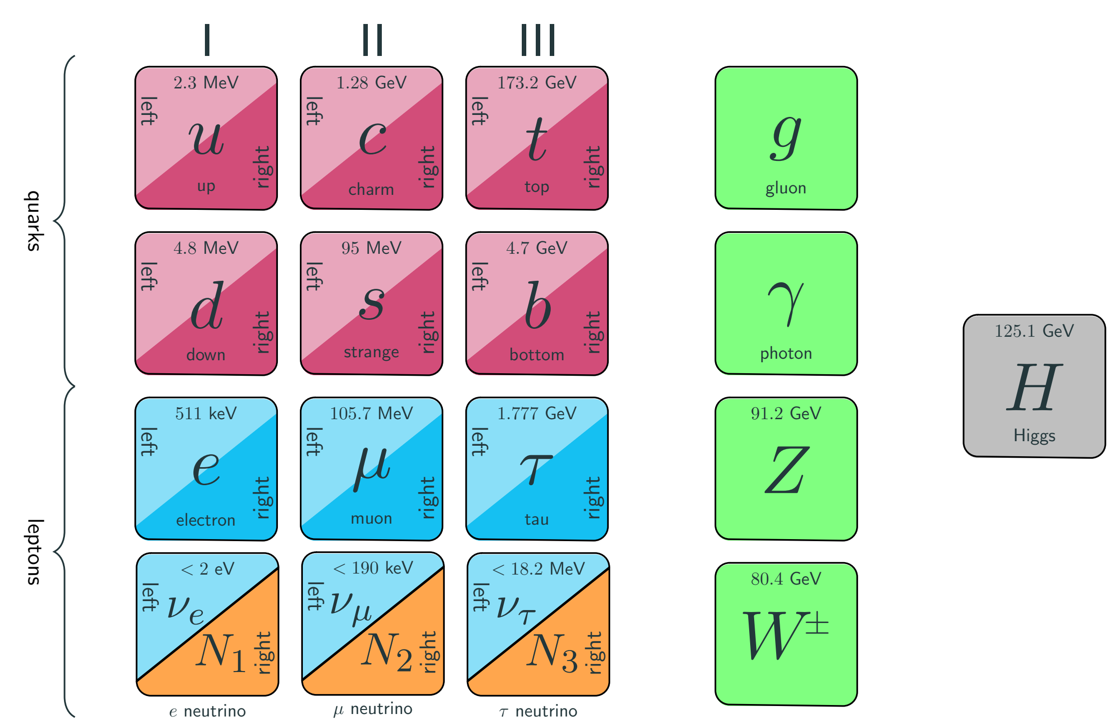
Davidson Ibarra bound, 2002
$M \gtrsim 10^9$ GeV

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

Low-scale leptogenesis and the Neutrino Minimal Standard Model (νMSM)

Asaka, Blanchet, Shaposhnikov 2005
Asaka, Shaposhnikov 2005





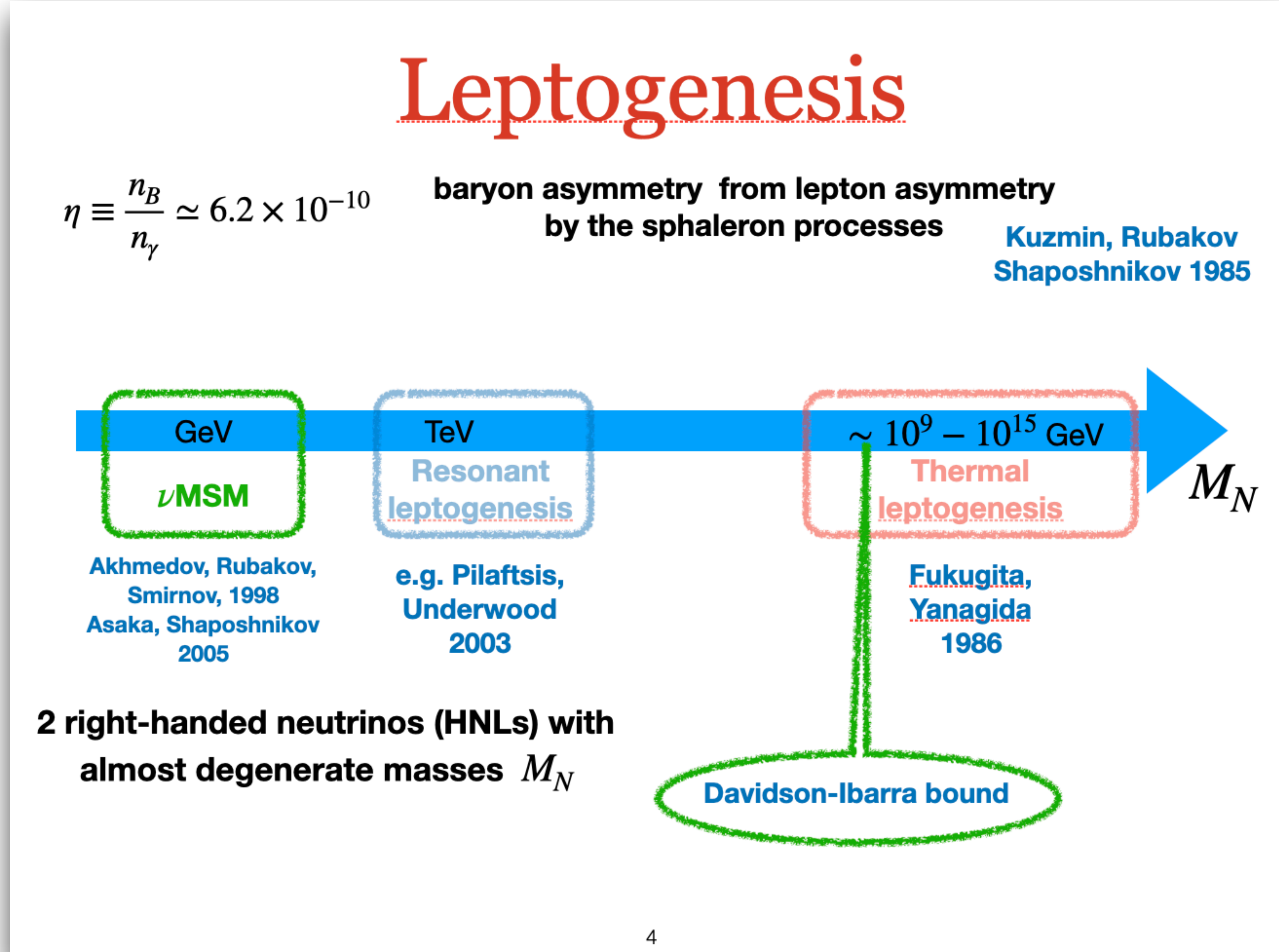
N_1	DM candidate	$m \sim keV$
N_2, N_3	ν masses via see-saw BAU (DM production)	$M_N \gtrsim 0.1\,GeV$ Nearly degenerate

Einstein-Cartan gravity? 2008.11686

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

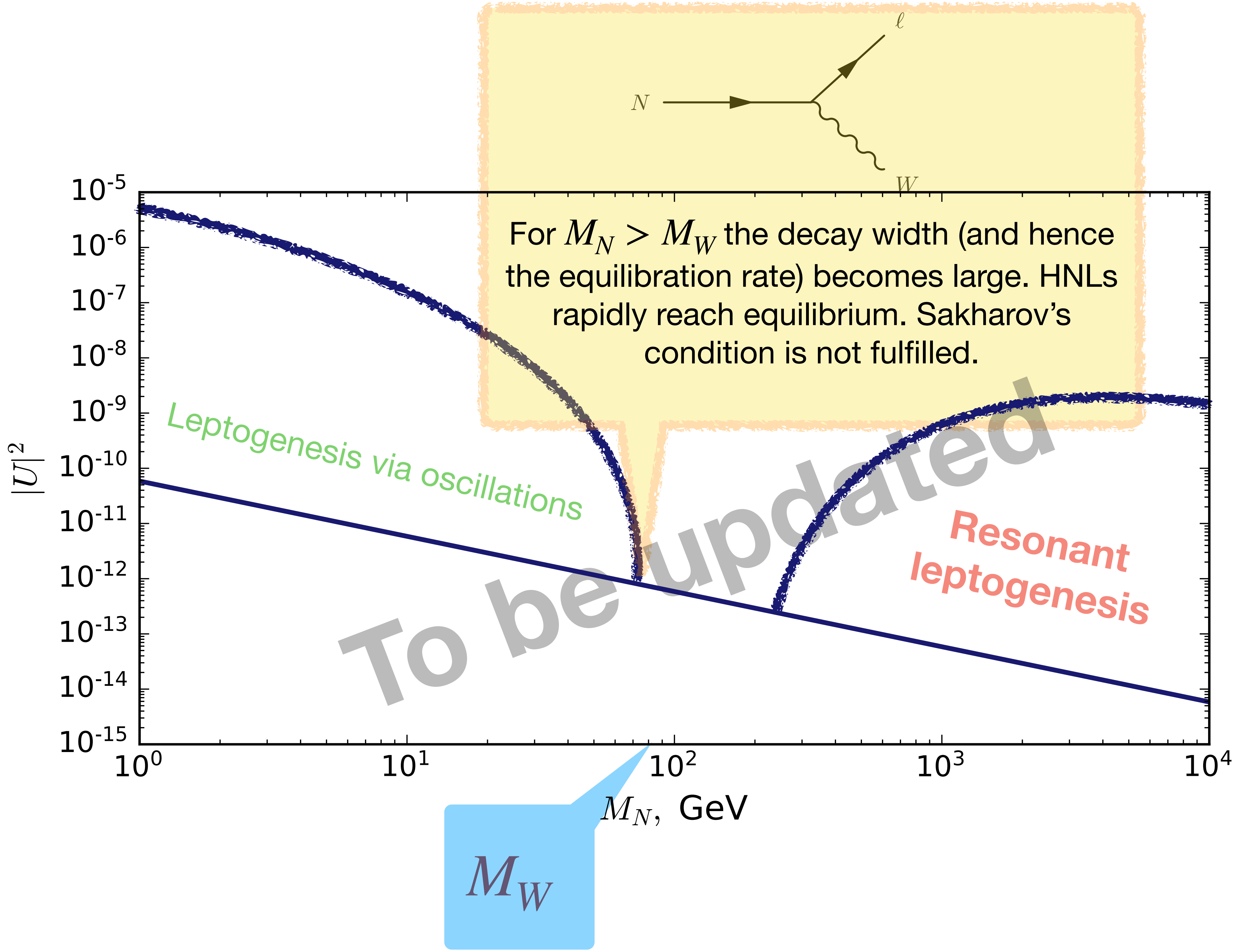
BAU in the νMSM
(model with two right-handed neutrinos)

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

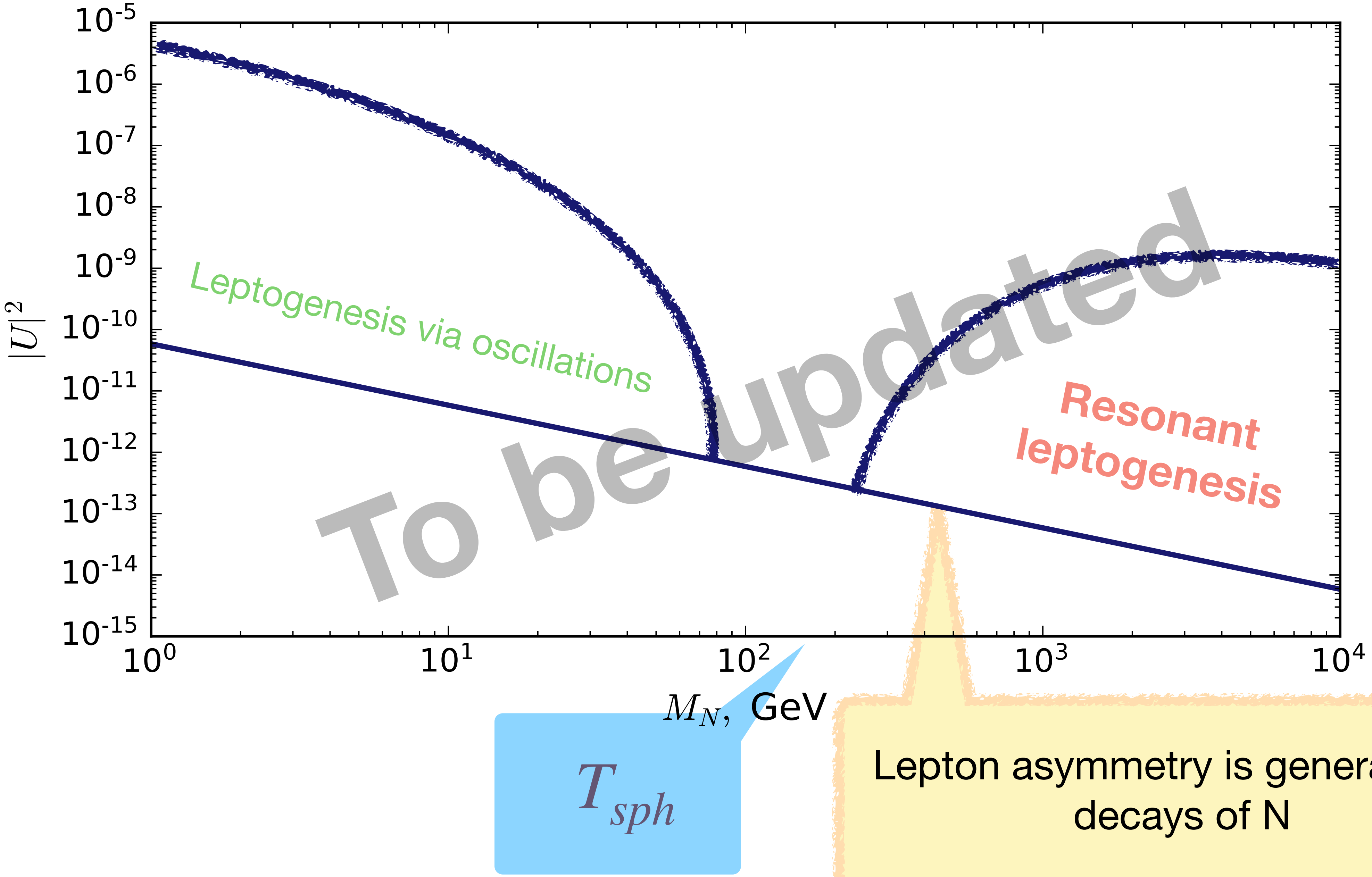


My slide from BLV 2019

Different leptogenesis mechanisms?



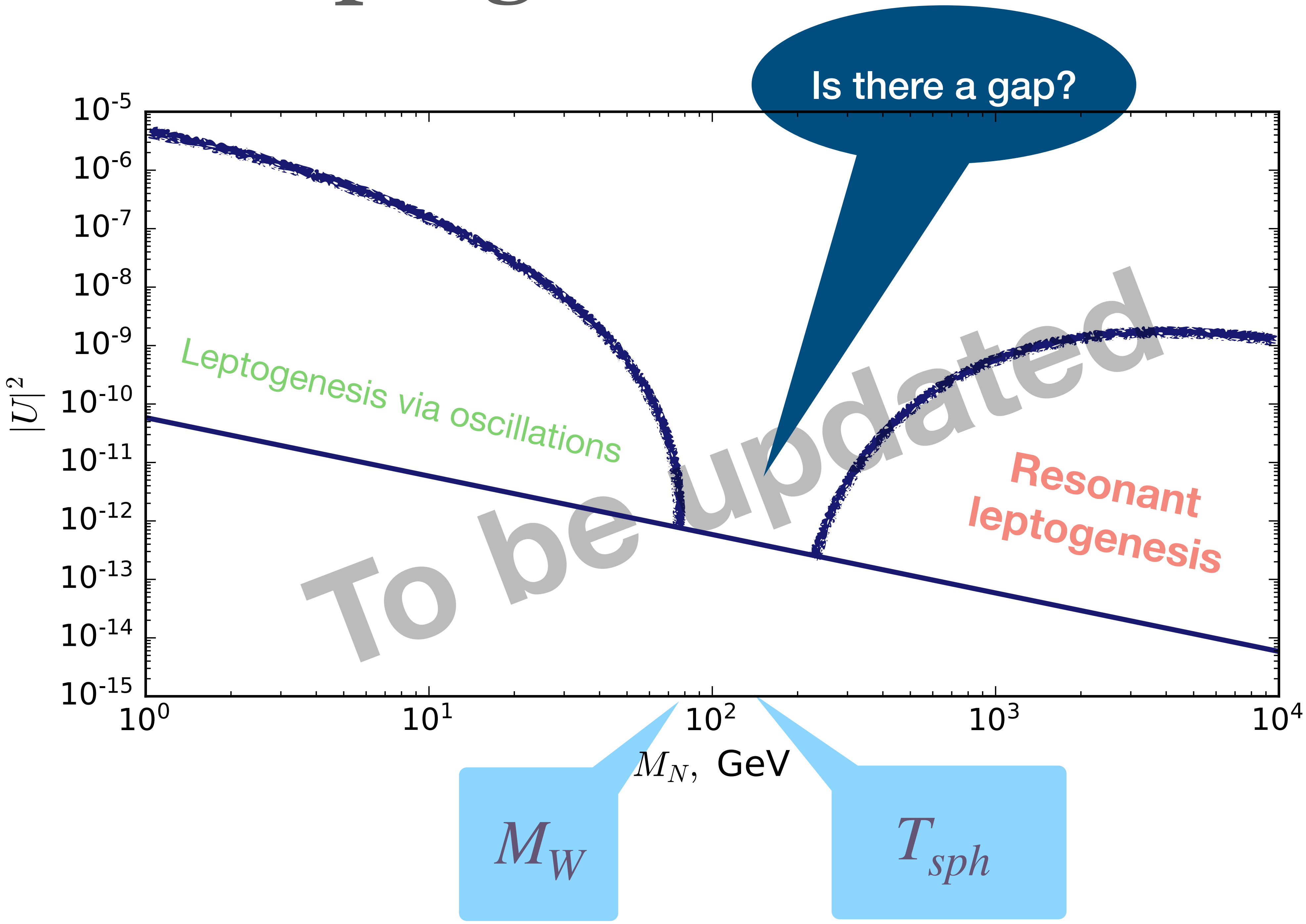
Different leptogenesis mechanisms?



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?



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

$n_{\Delta_\alpha} = L_\alpha - B/3$ $\quad$ $\mu_\beta = \omega_{\beta\alpha}\, n_{\Delta_\alpha}$ $\quad$ 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)

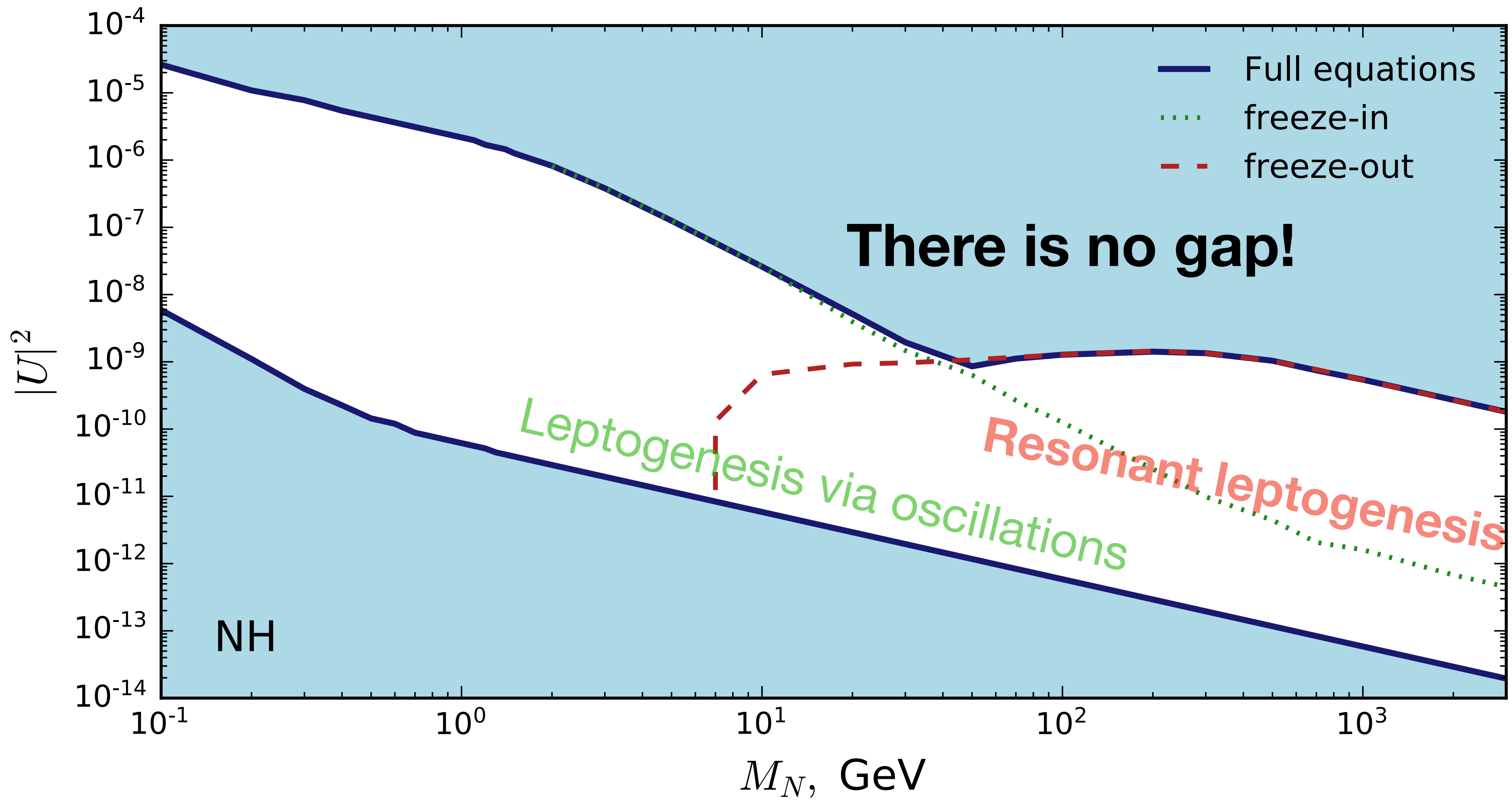
Description of low-scale leptogenesis

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

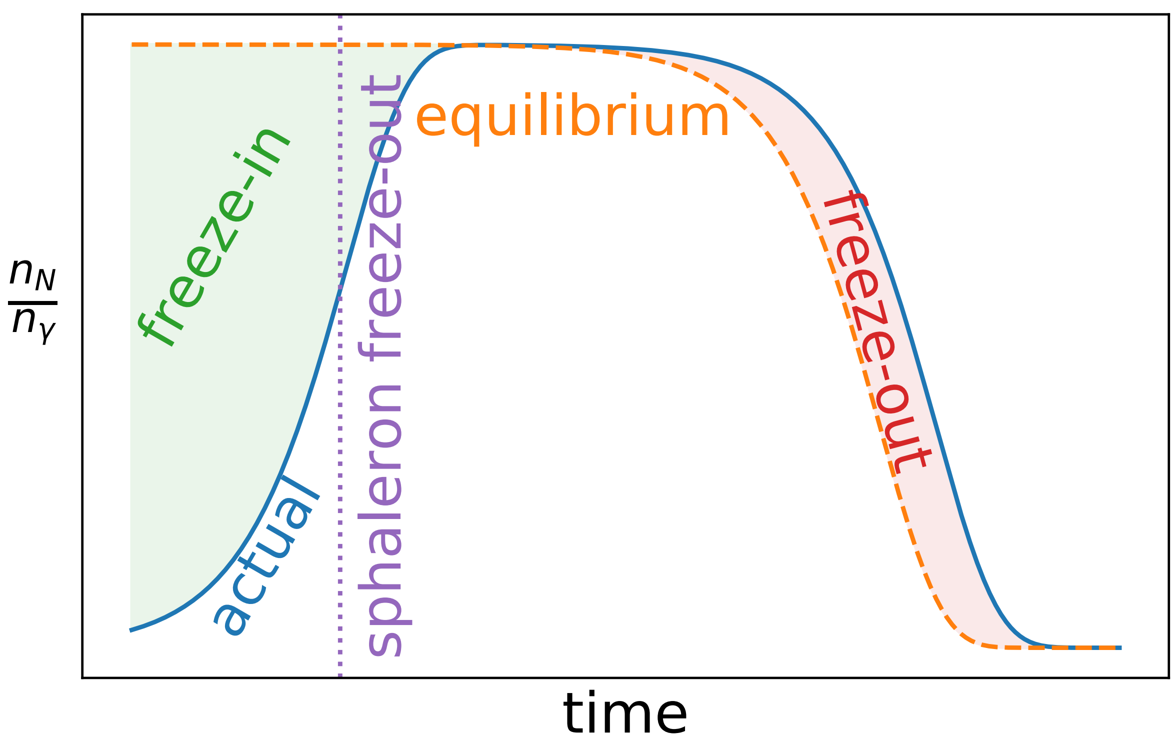
Juraj Klarić, Mikhail Shaposhnikov, IT 2008.13771



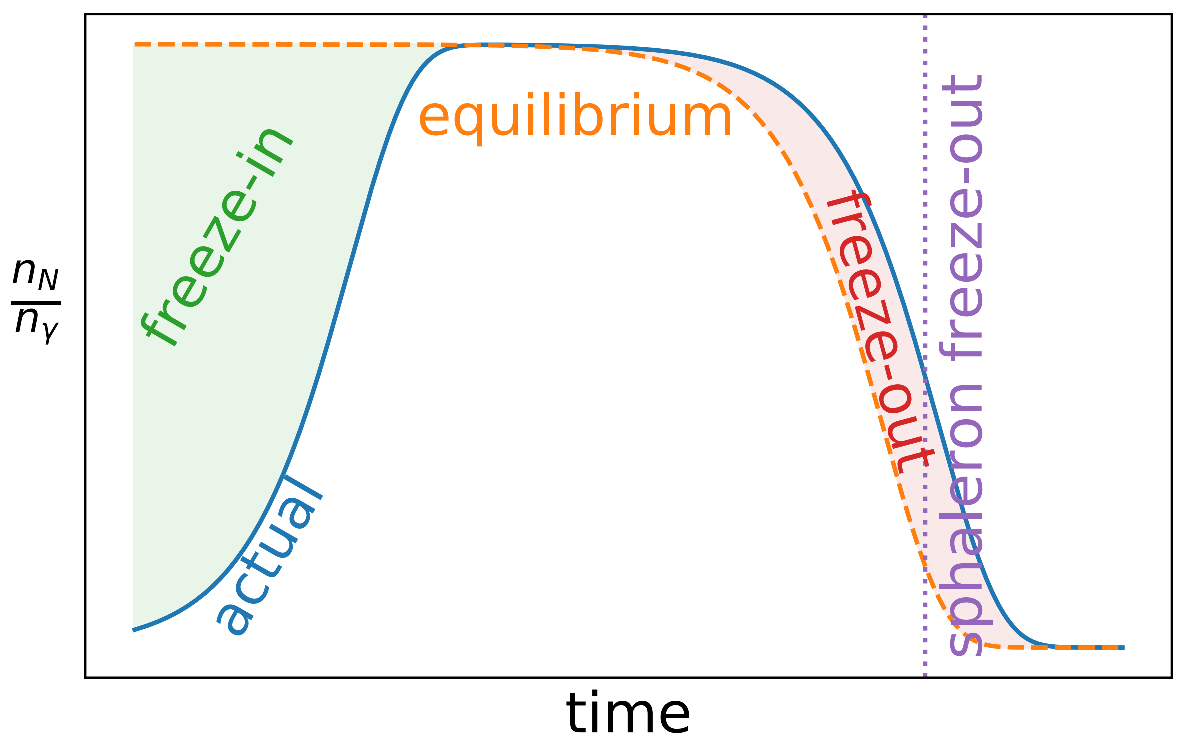
- Leptogenesis via oscillations still works for heavy HNLs because the washout of the asymmetry can vary a lot for different lepton flavours *(flavor hierarchical washout)*

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

More accurate classification of Leptogenesis mechanisms

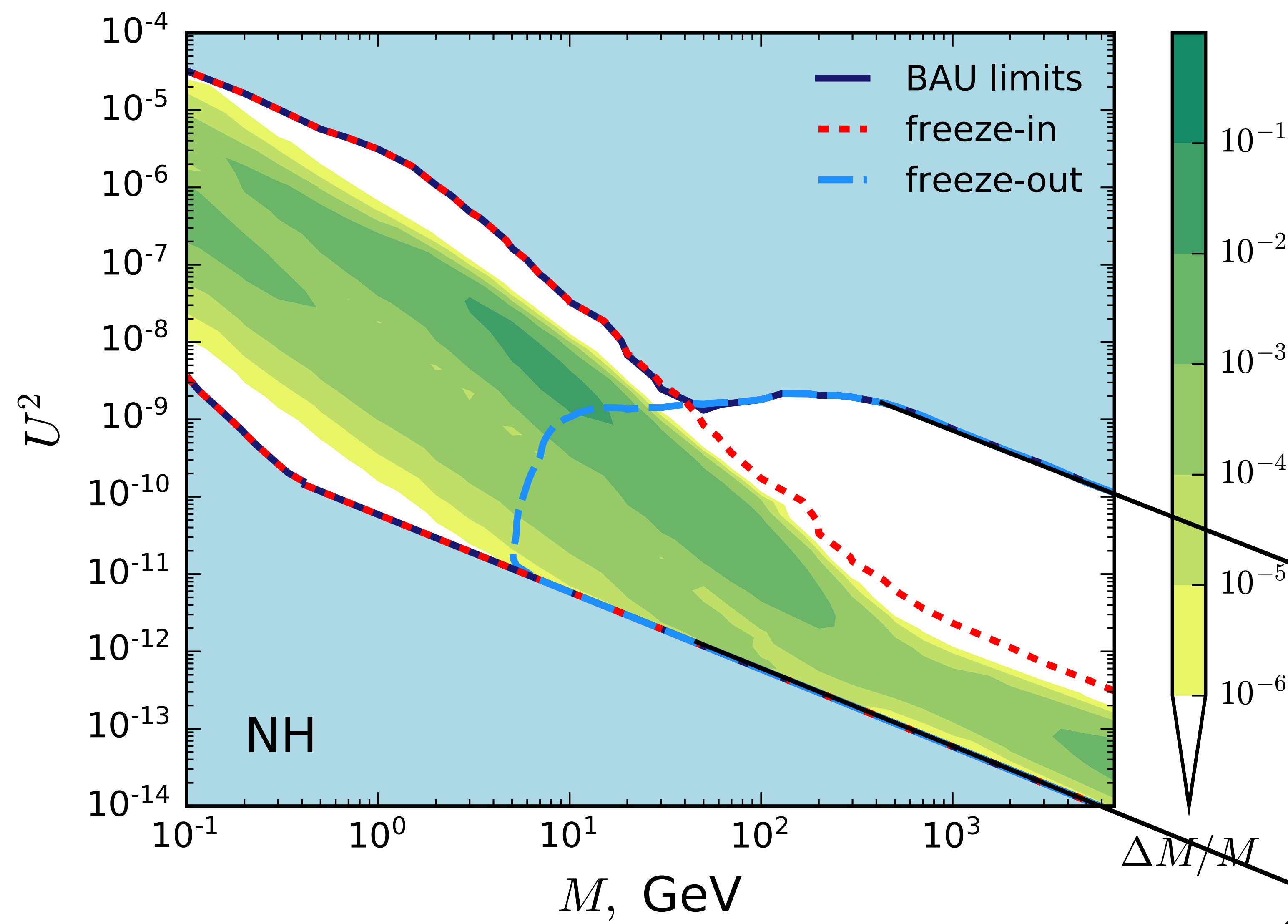


“Leptogenesis via oscillations”



“Resonant Leptogenesis”

Scaling of the right-handed neutrino masses



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

10^9 GeV -
Thermal leptogenesis

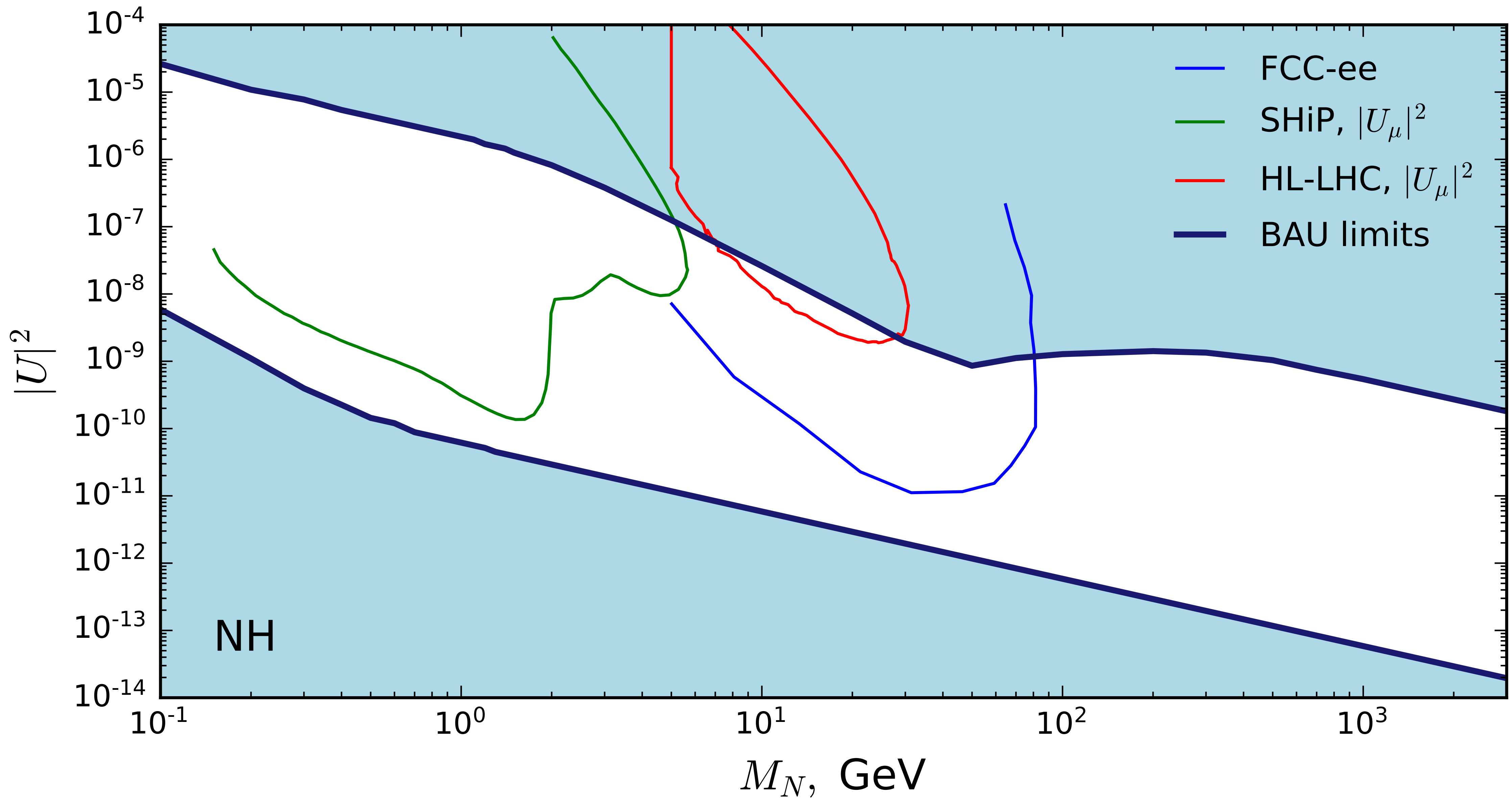
$M \to \zeta M, \quad \Delta M \to \zeta^2 \Delta M$

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

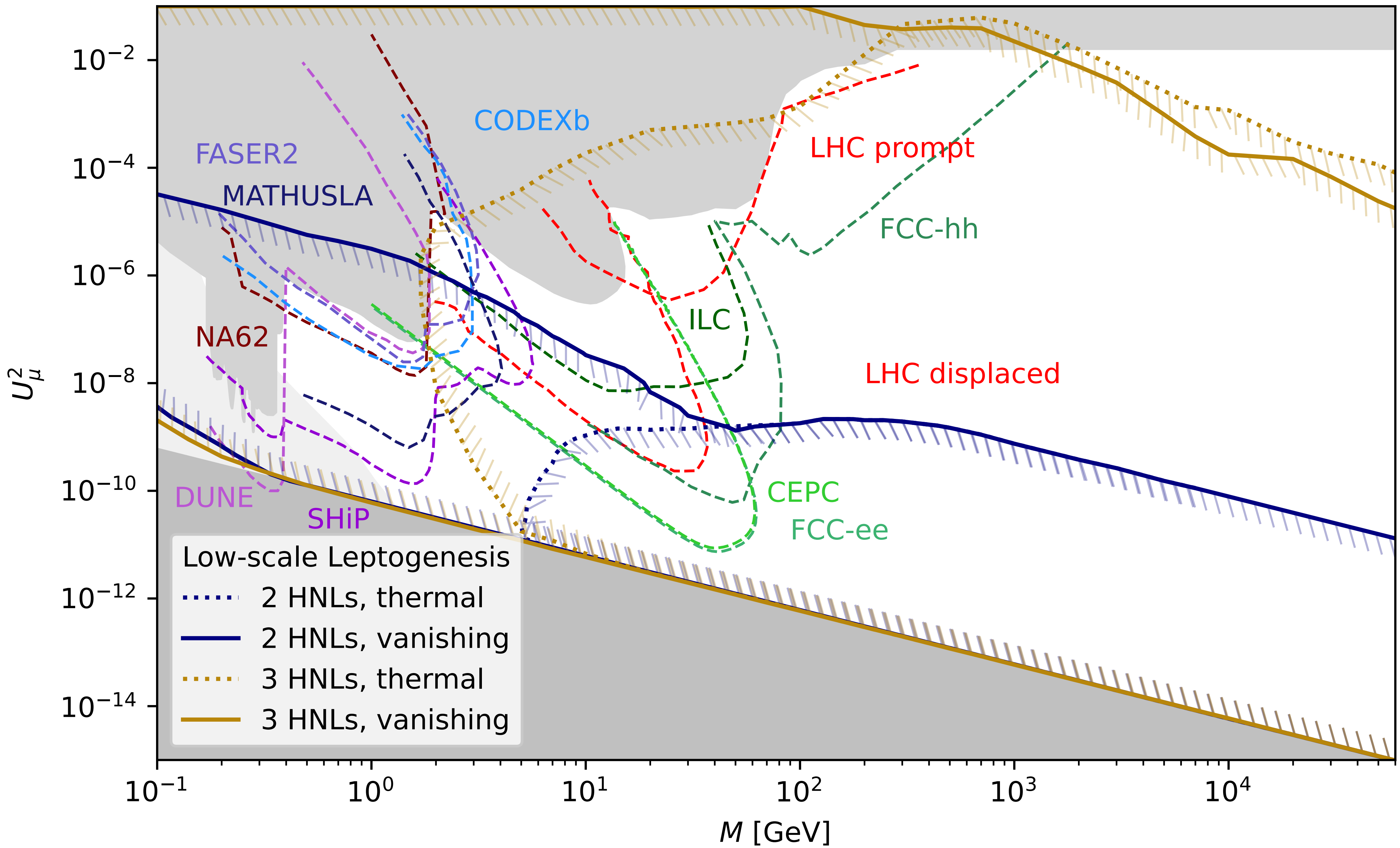
$$U^2 \sim \frac{v^2 Y^2}{M^2}$$

Y~1

Testing leptogenesis



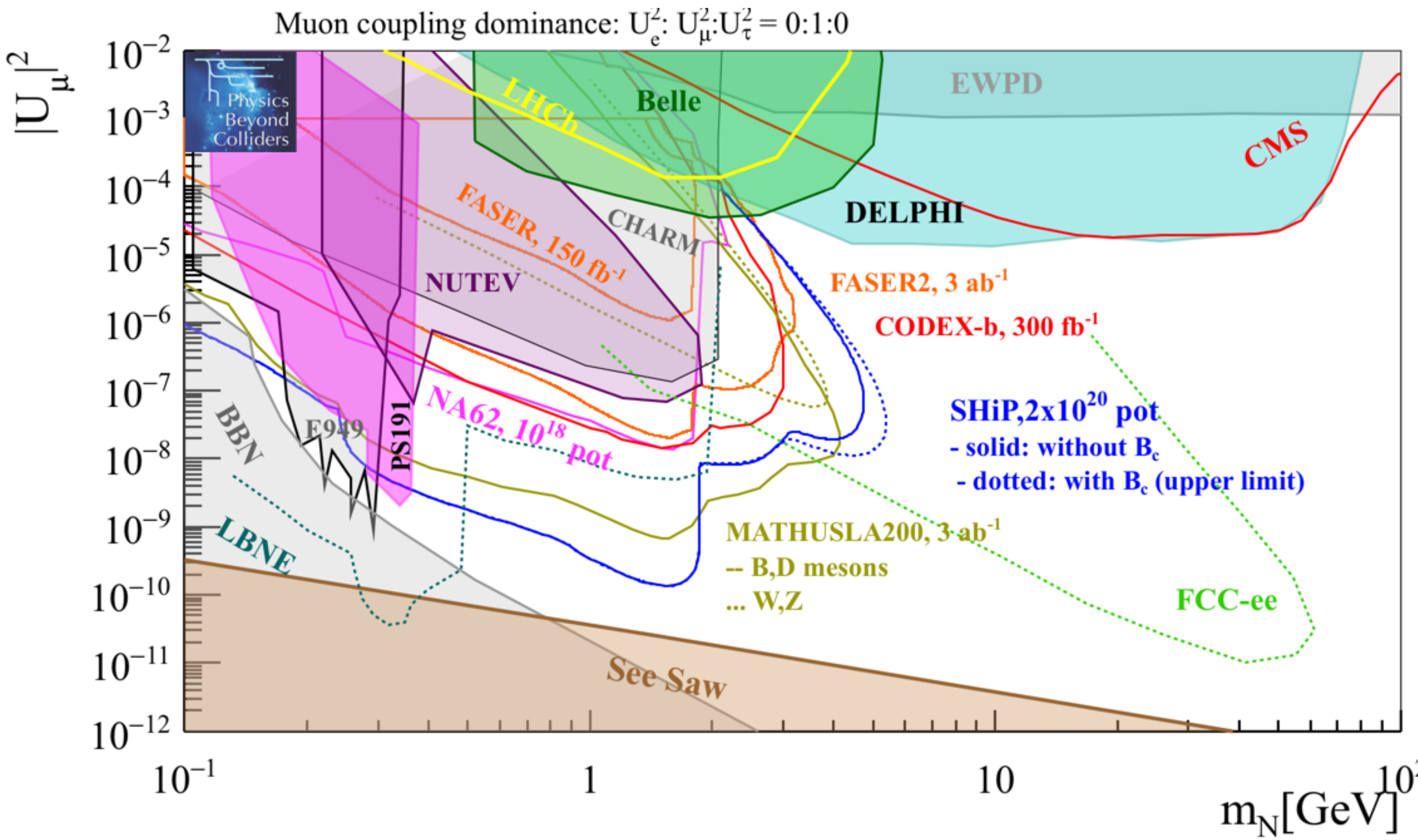
Leptogenesis with 2 and 3 right-handed neutrino



Snowmass HNL WP
Image credit: Juraj Klaric
FCC and CEPC lines: Marco Drewes

3RH case: Klaric, Georis, Drewes 2106.16226

The quest for Heavy Neutral Leptons



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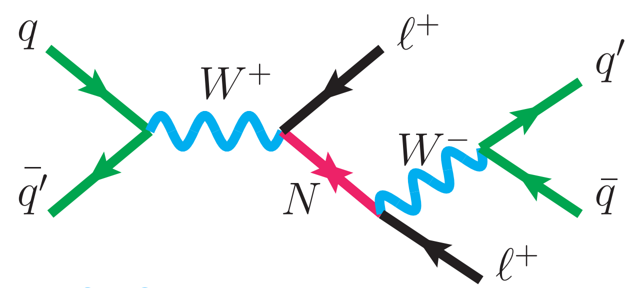
White Paper on Heavy Neutral Leptons — coming soon as a part of the Snowmass process

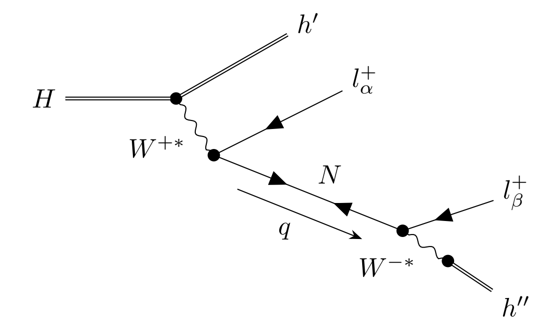
Probing lepton number violation at SHiP

Jean-Loup Tastet, IT 1912.05520

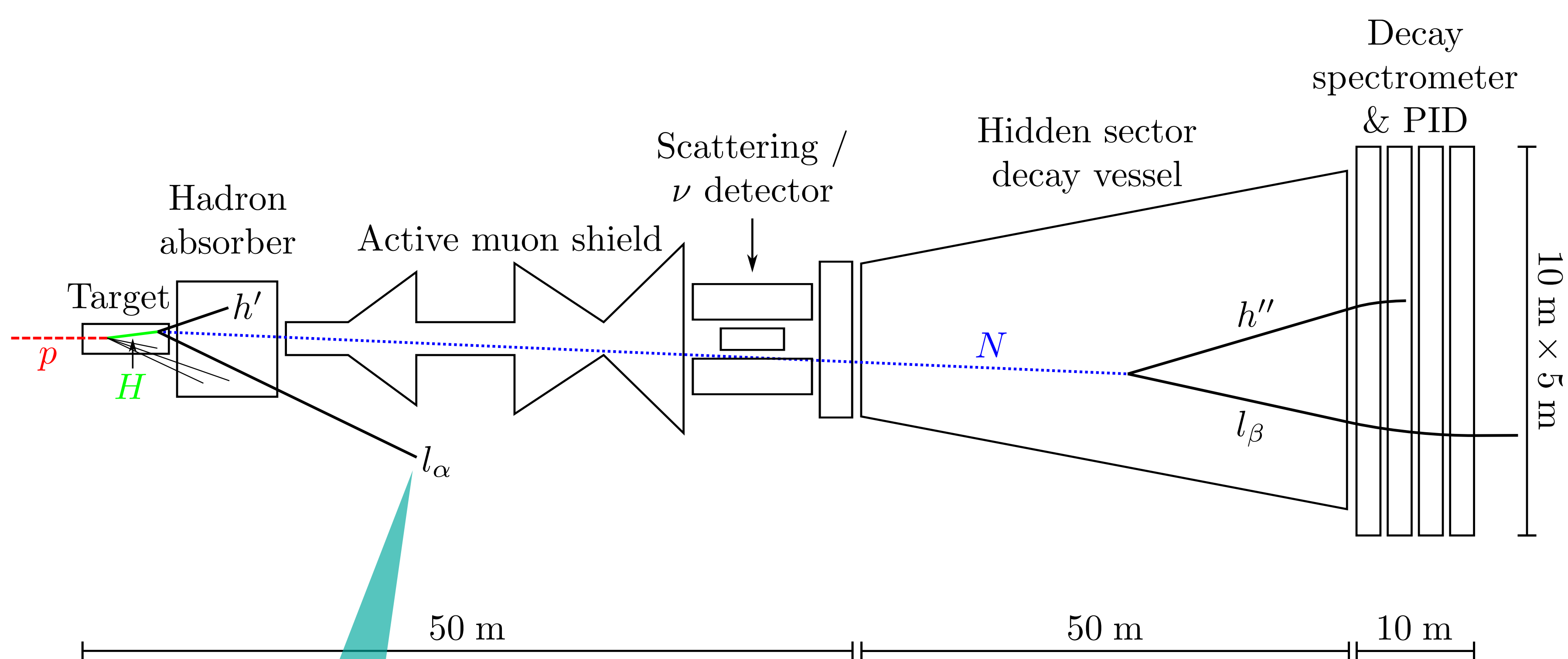
At colliders:
same-sign dileptons



e.g. CMS 1806.10905



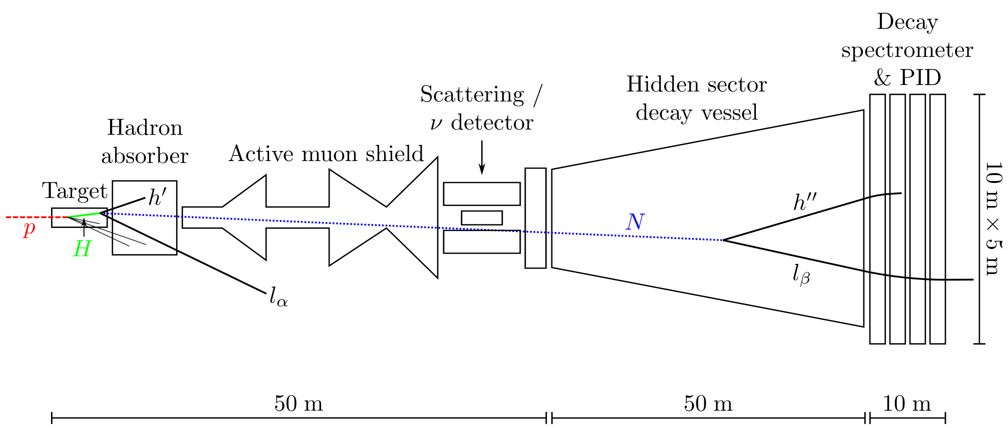
Beam dump:



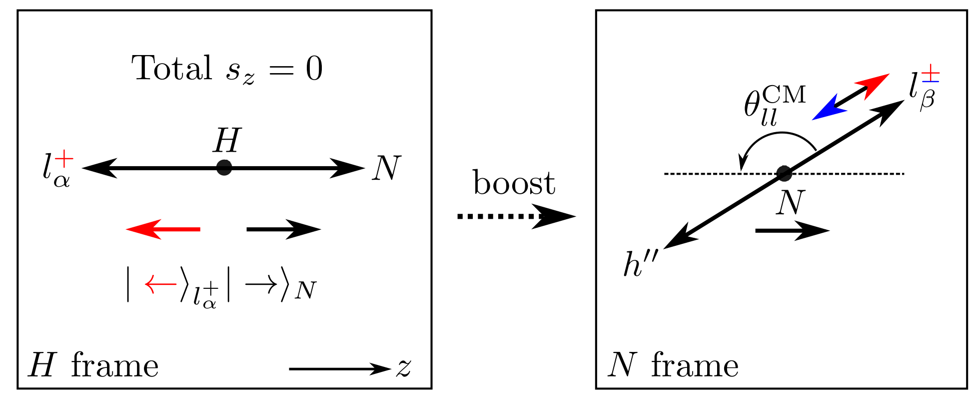
Information about the first lepton is lost

* I am a member of SHiP collaboration

Probing lepton number violation at SHiP



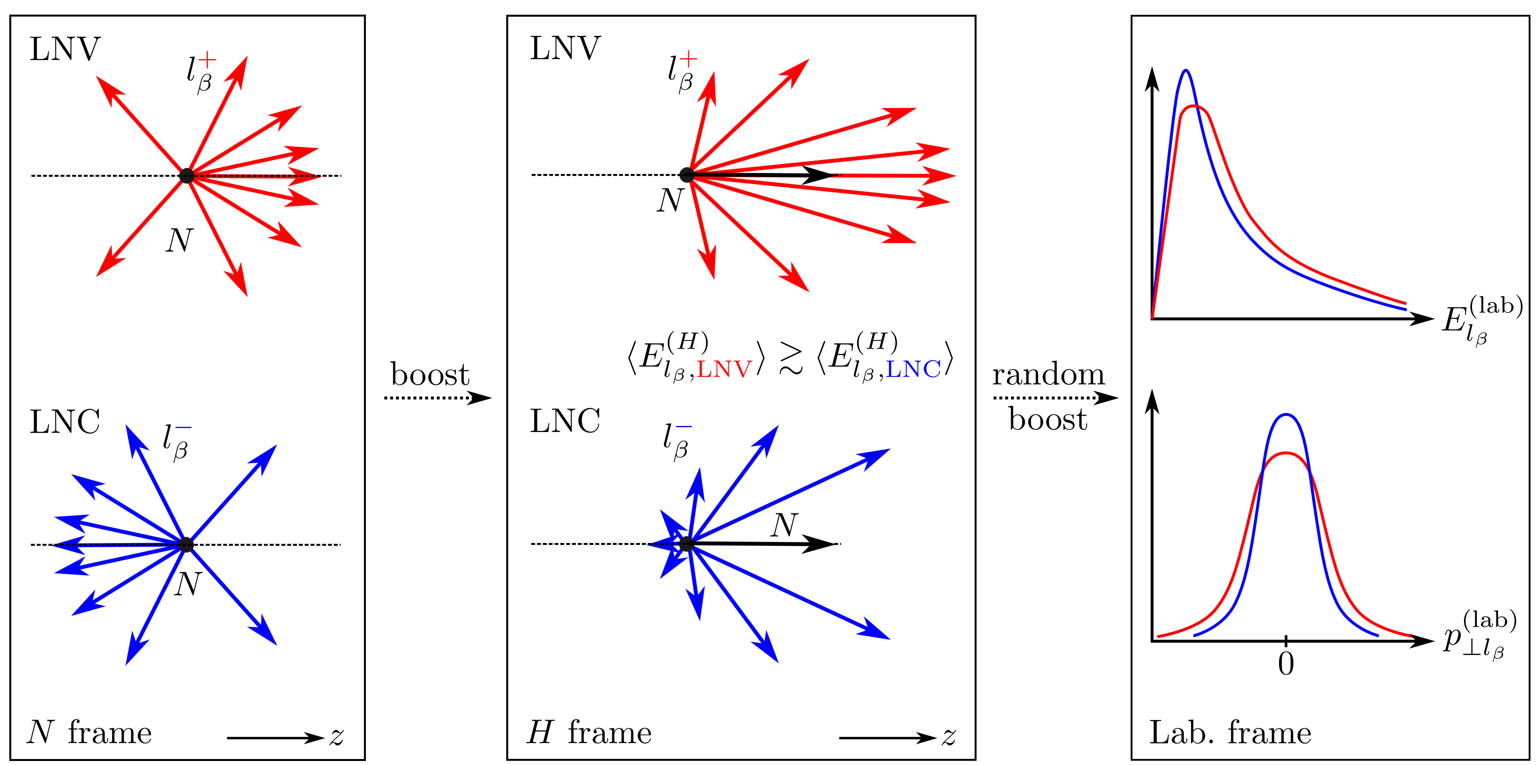
Different angular correlations for LNC and LNV processes



$l_\beta^+ \langle \nearrow | \rightarrow \rangle_N = \sin\left(\frac{\theta_{ll}^{\text{CM}}}{2}\right)$

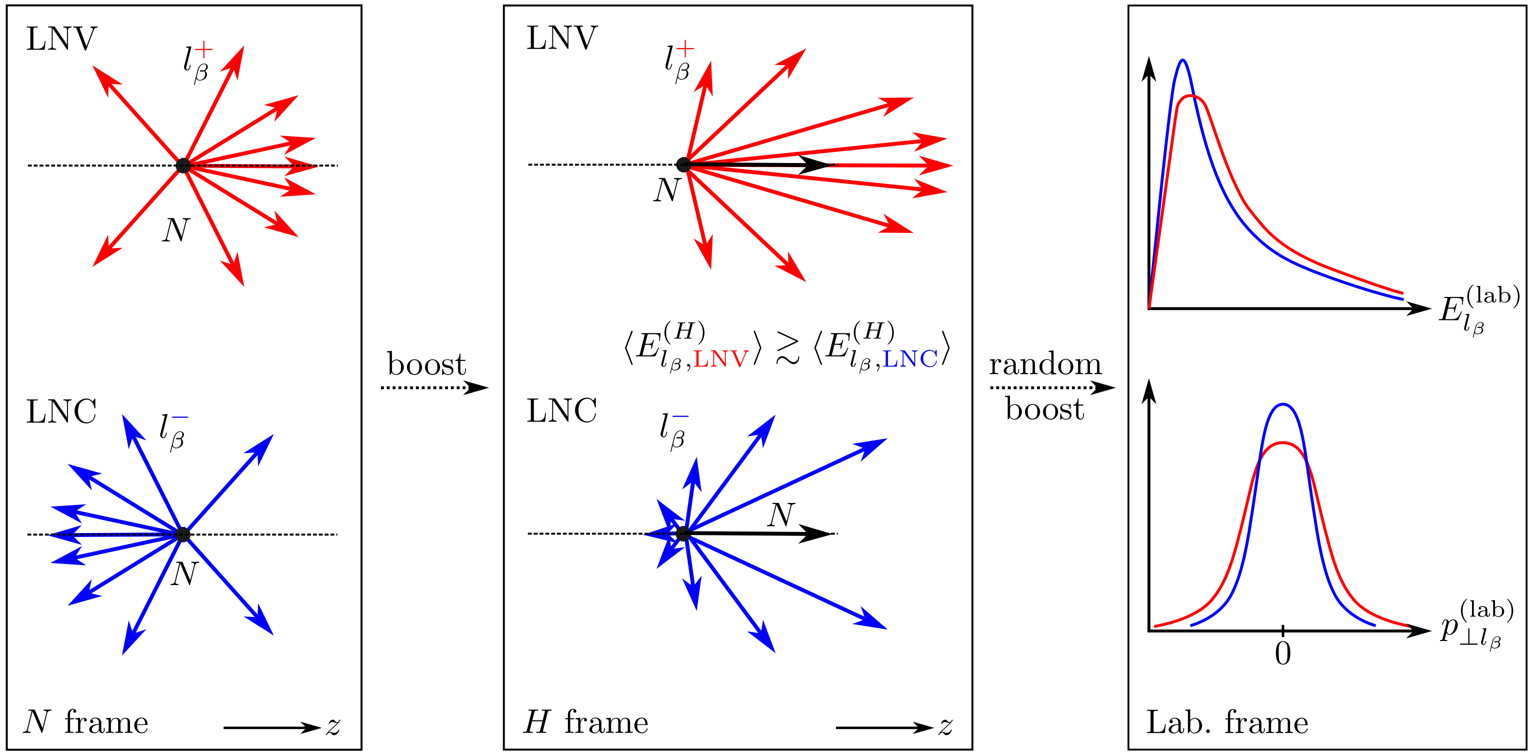
$l_\beta^- \langle \swarrow | \rightarrow \rangle_N = \cos\left(\frac{\theta_{ll}^{\text{CM}}}{2}\right)$

$\mathcal{P} \propto 1 \mp \cos\left(\theta_{ll}^{\text{CM}}\right)$



Probing lepton number violation at SHiP

Different angular correlations for LNC and LNV processes

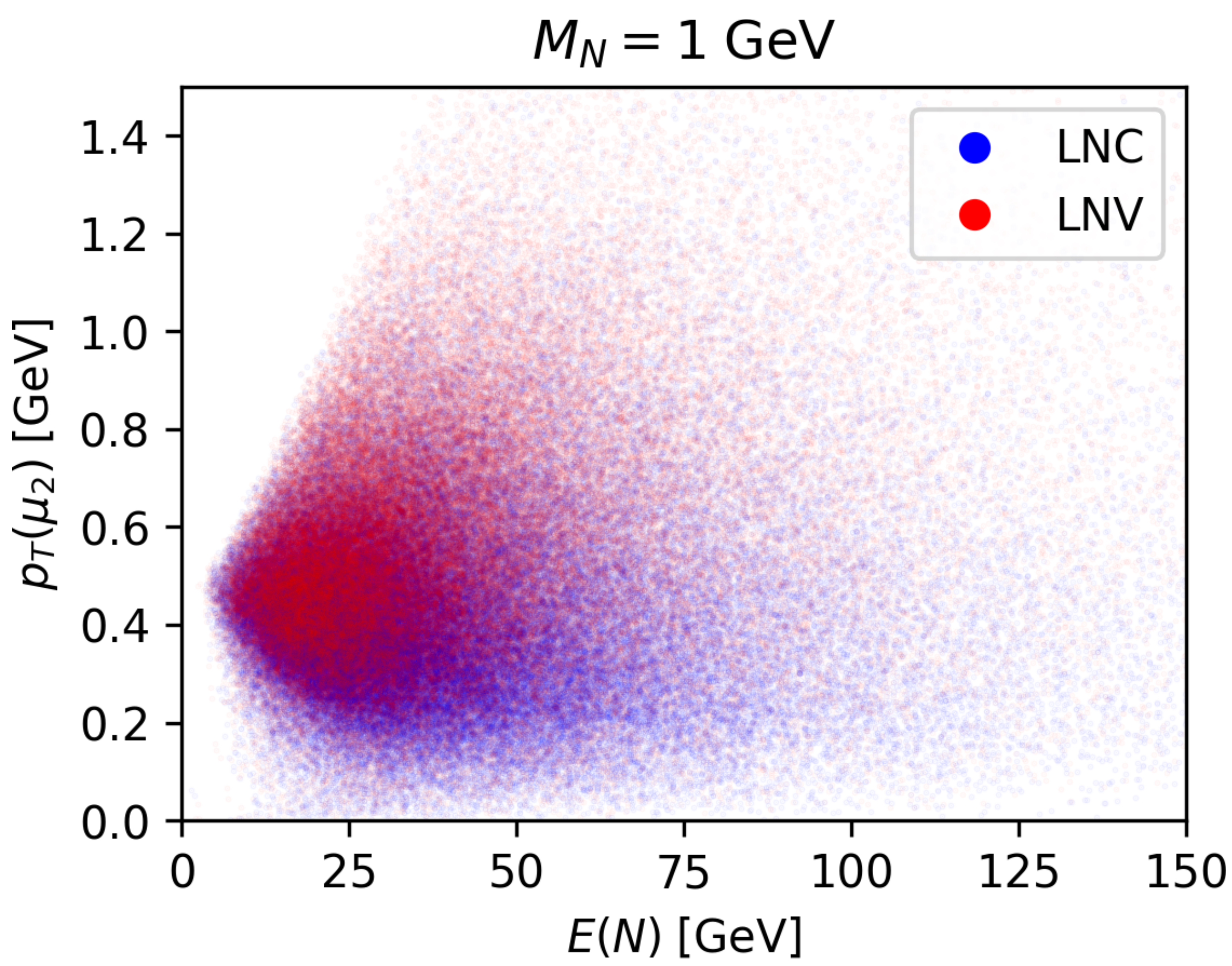


Complications

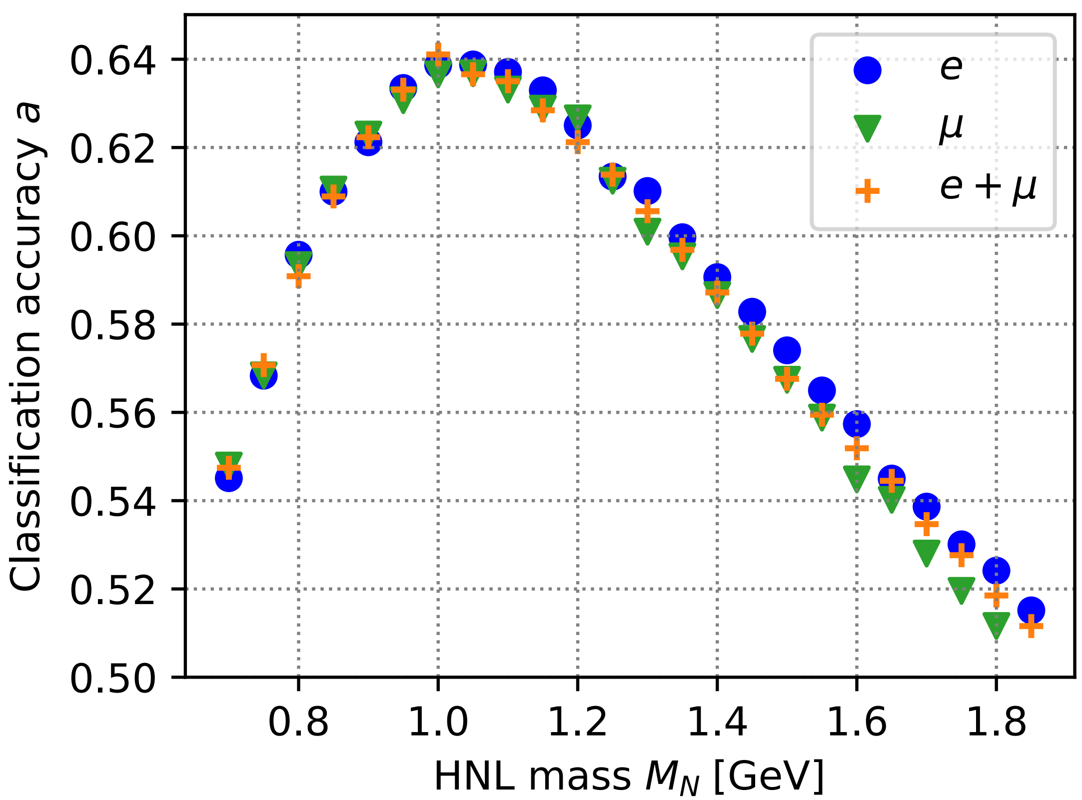
- Not all production processes are 2-body.
- Decay products (l, π) are not massless.
- Heavy mesons are not monochromatic, which smears out the effect.
- We need to take geometrical acceptance into account.

Probing lepton number violation at SHiP

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

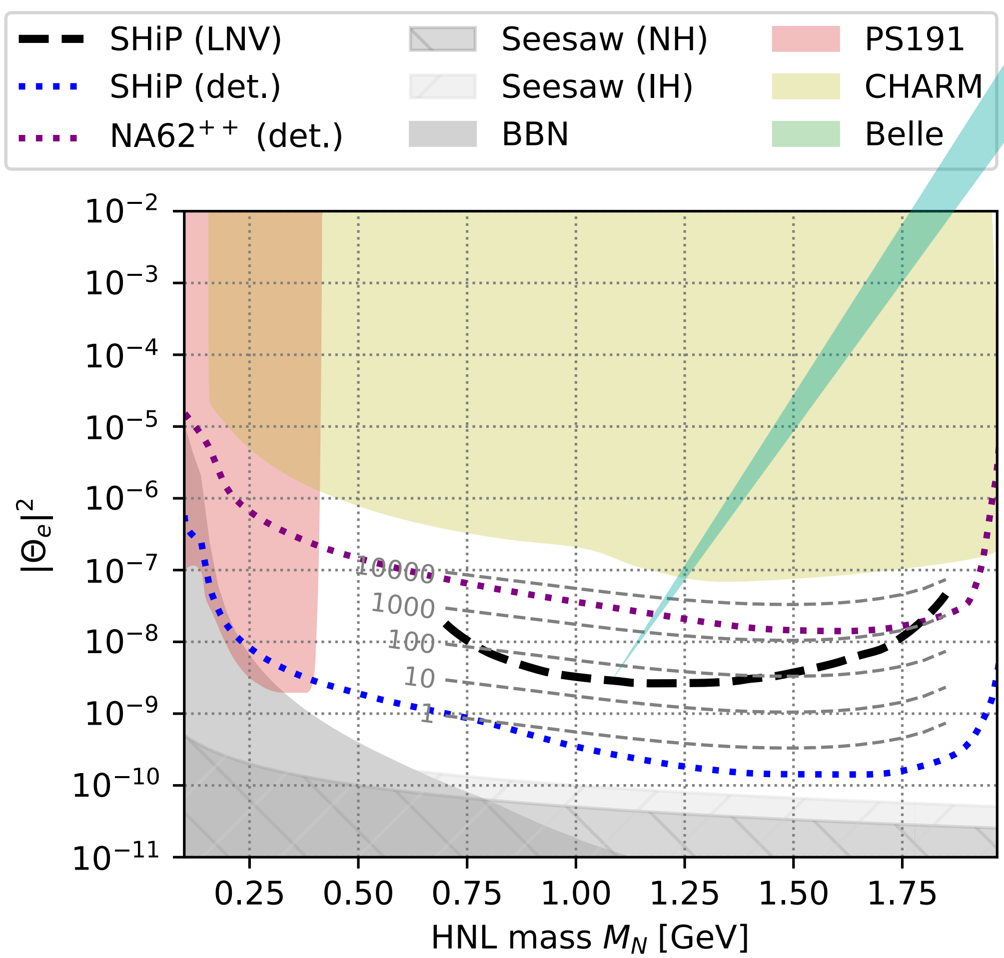


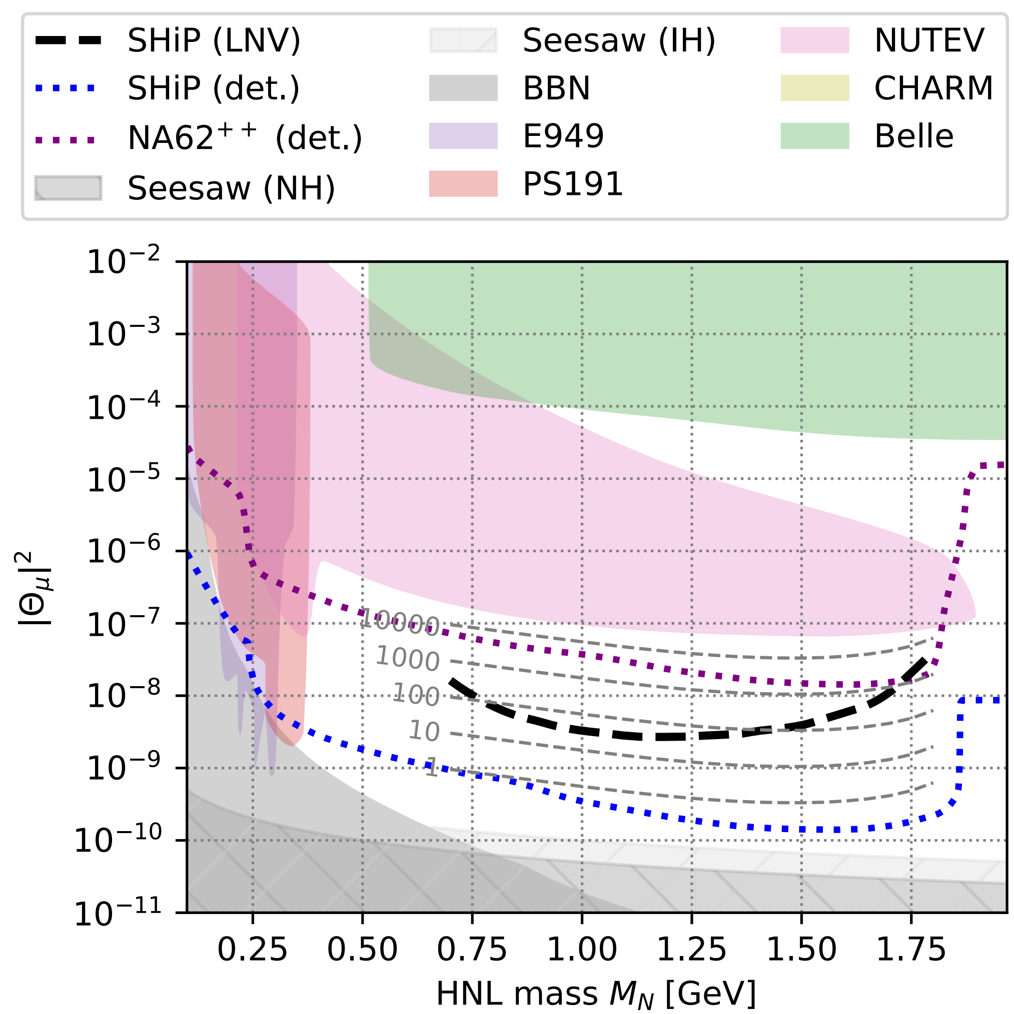
ML Classification (boosted decision trees)



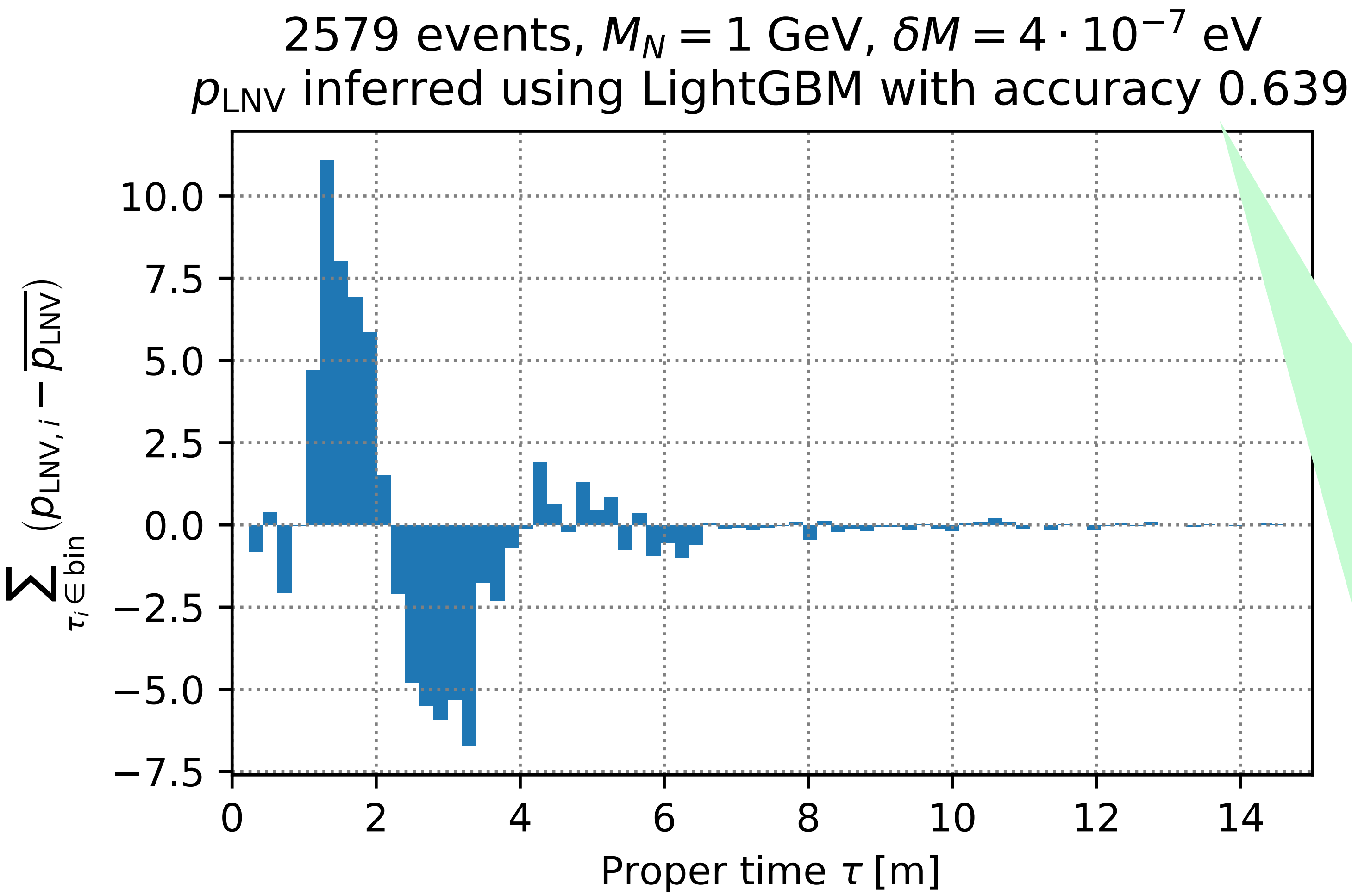
Probing lepton number violation at SHiP

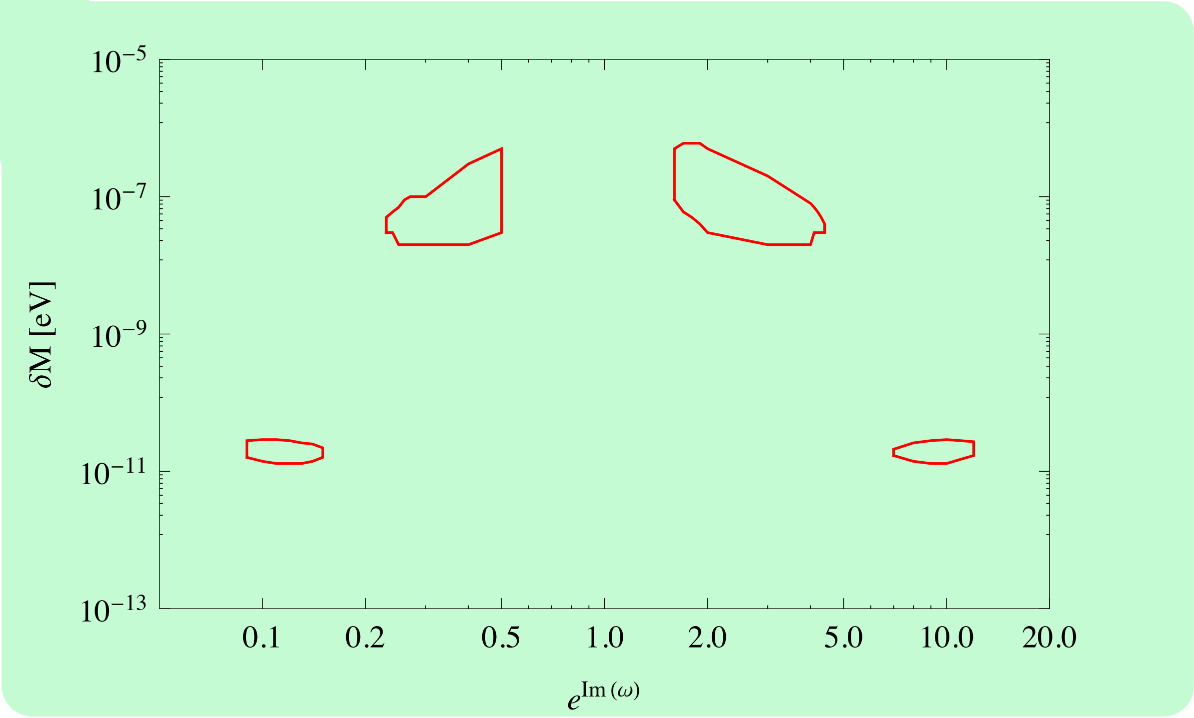
Above this line SHiP can distinguish Majorana vs Dirac





Resolvable HNL oscillations at SHiP

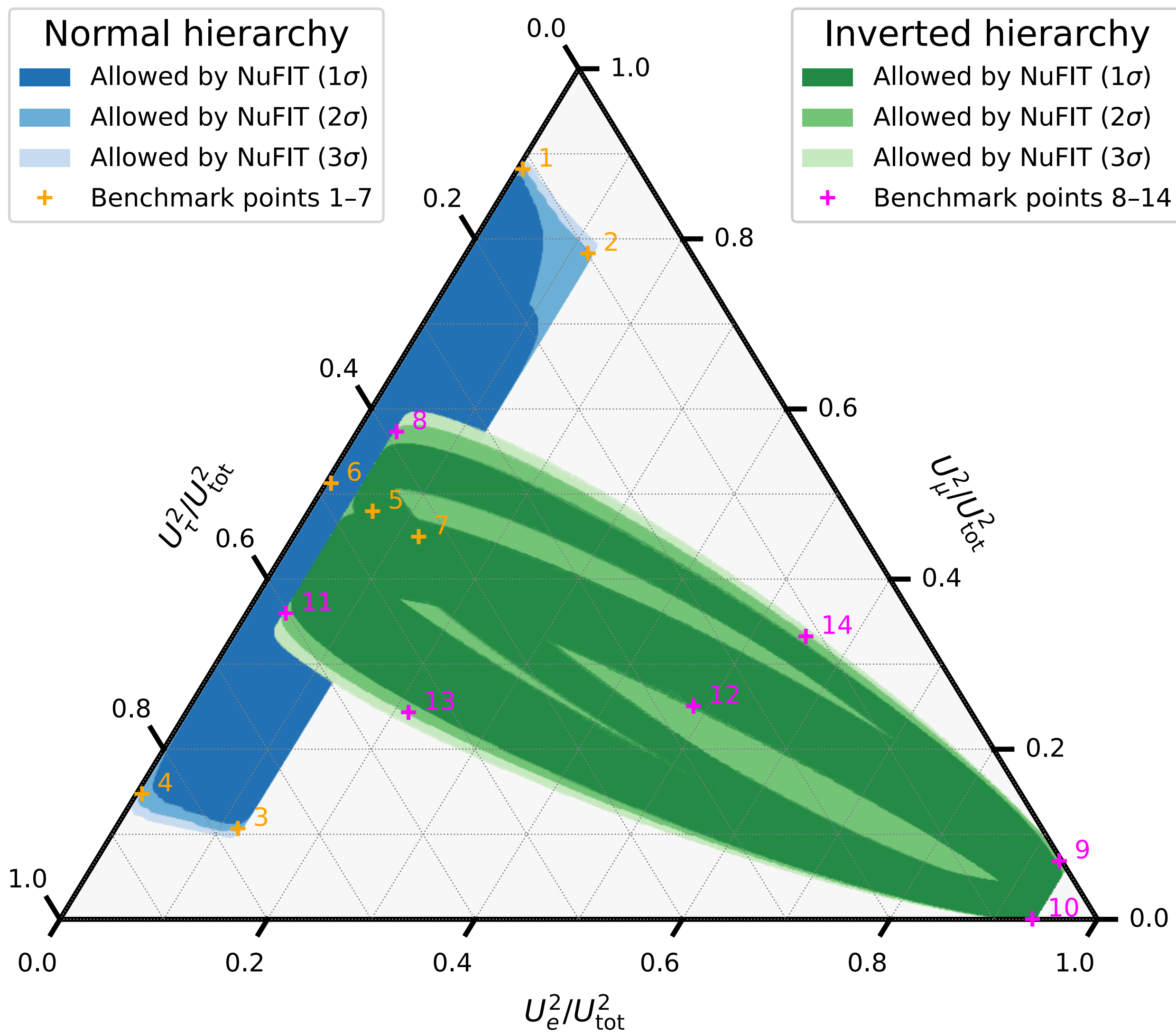




BAU and DM in the NuMSM 1208.4607

Neutrino oscillation data and reinterpretation

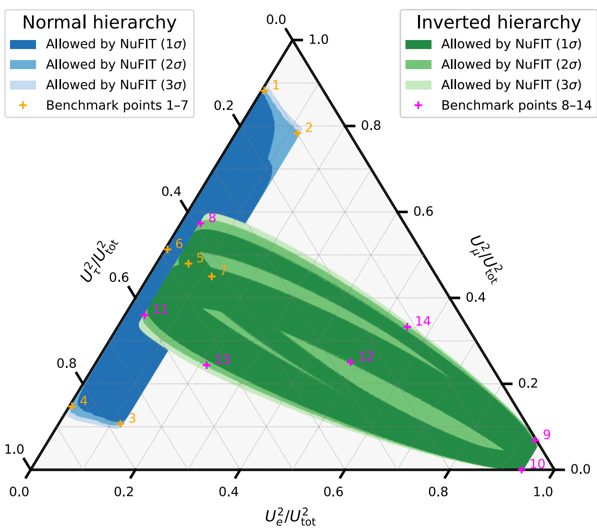
Not all mixing angles are allowed in the model with two HNLs



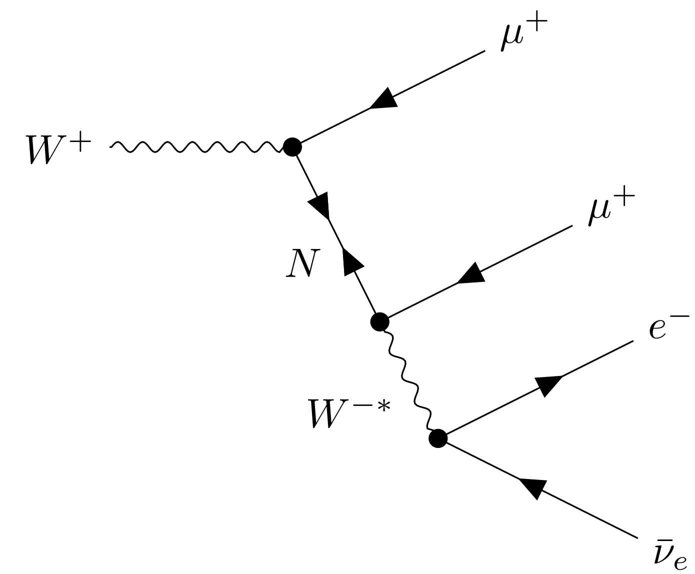
$$U_e^2/U^2_{\text{tot}} + U_\mu^2/U^2_{\text{tot}} + U_\tau^2/U^2_{\text{tot}} = 1$$

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

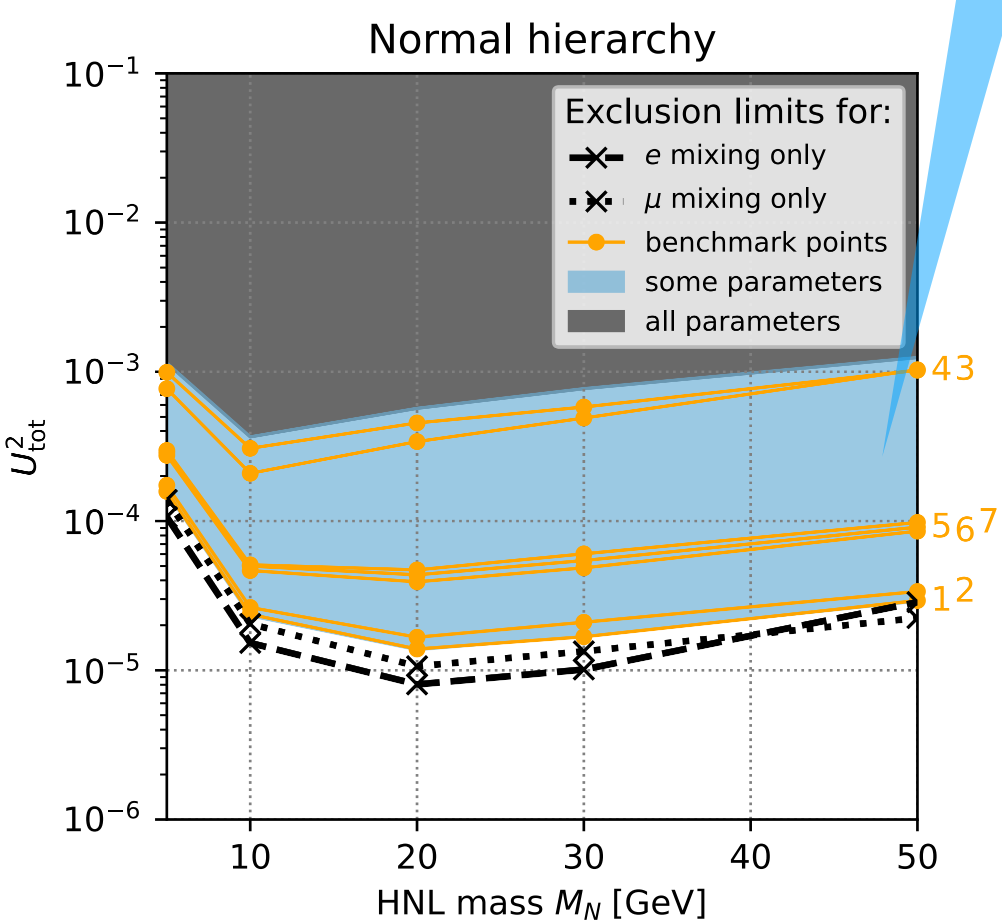
Neutrino oscillation data and reinterpretation

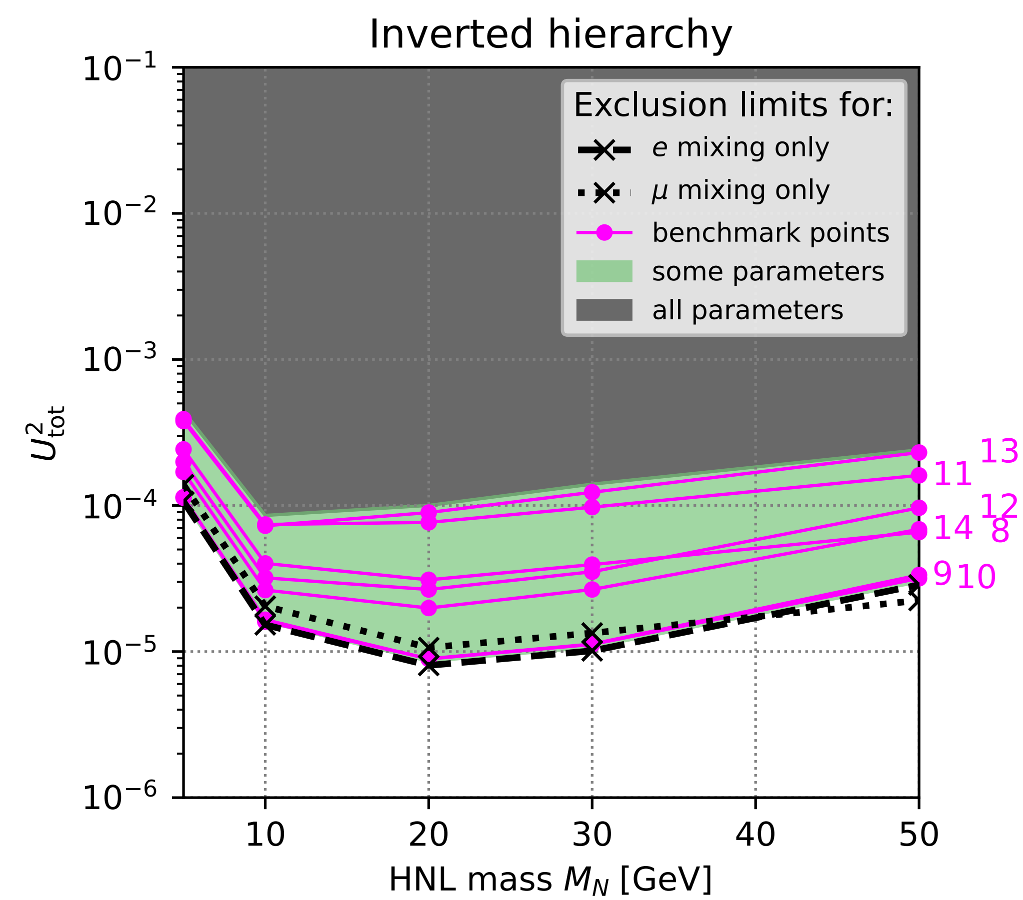


ATLAS triplepton search [1905.09787]



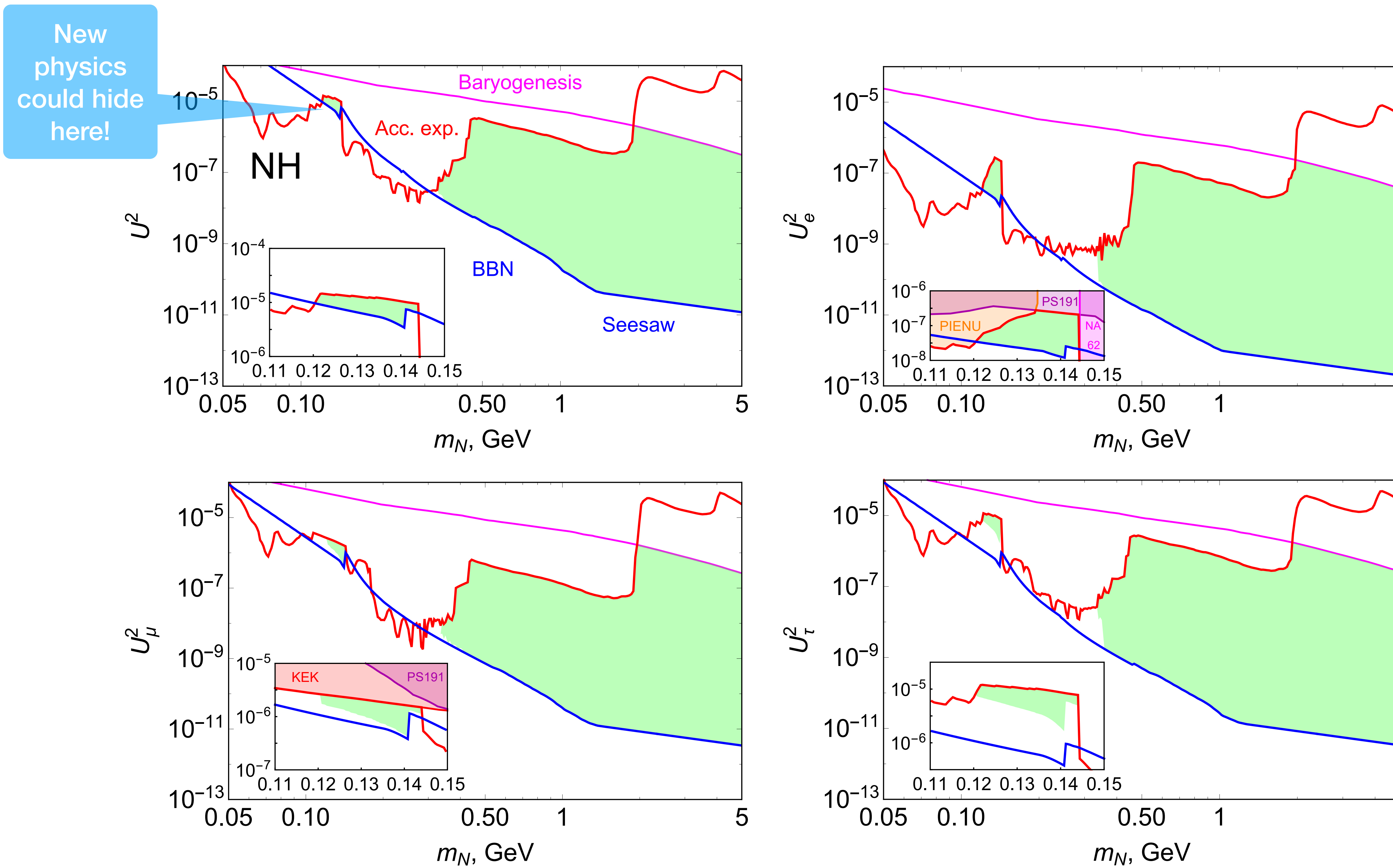
New physics could hide here!





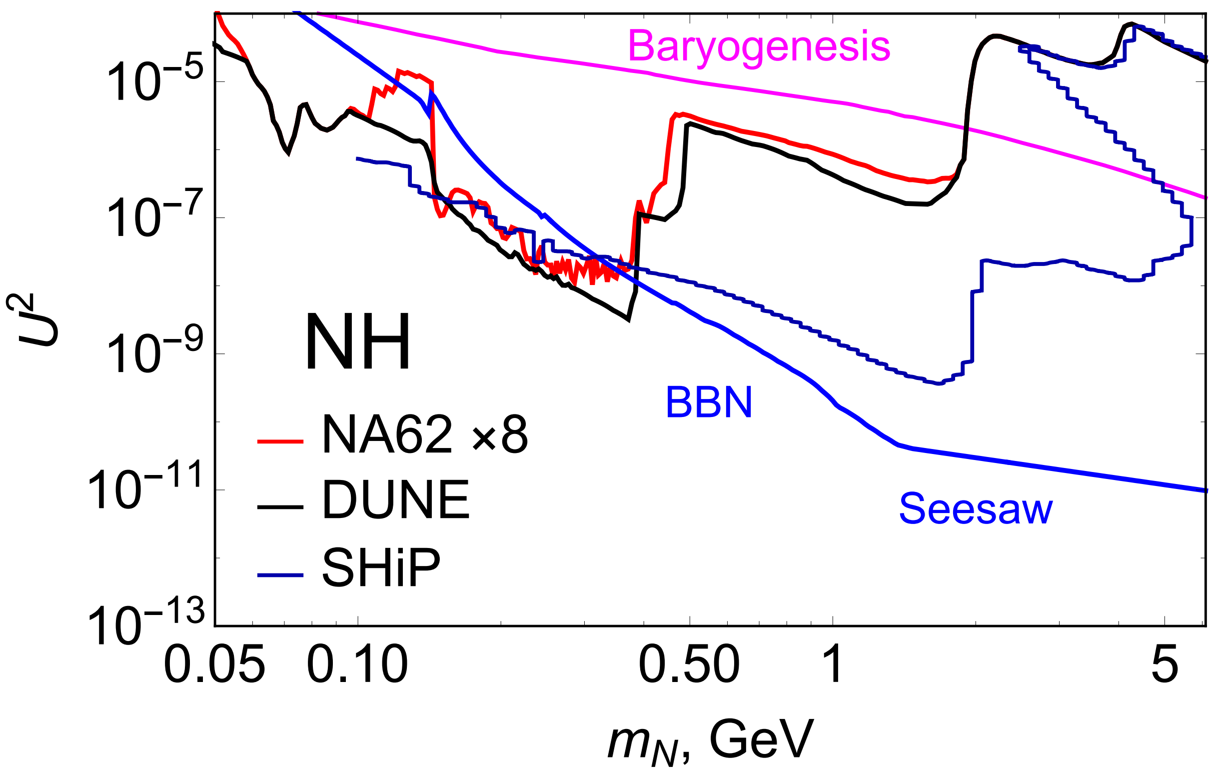
Jean-Loup Tastet, Oleg Ruchayskiy, IT 2107.12980

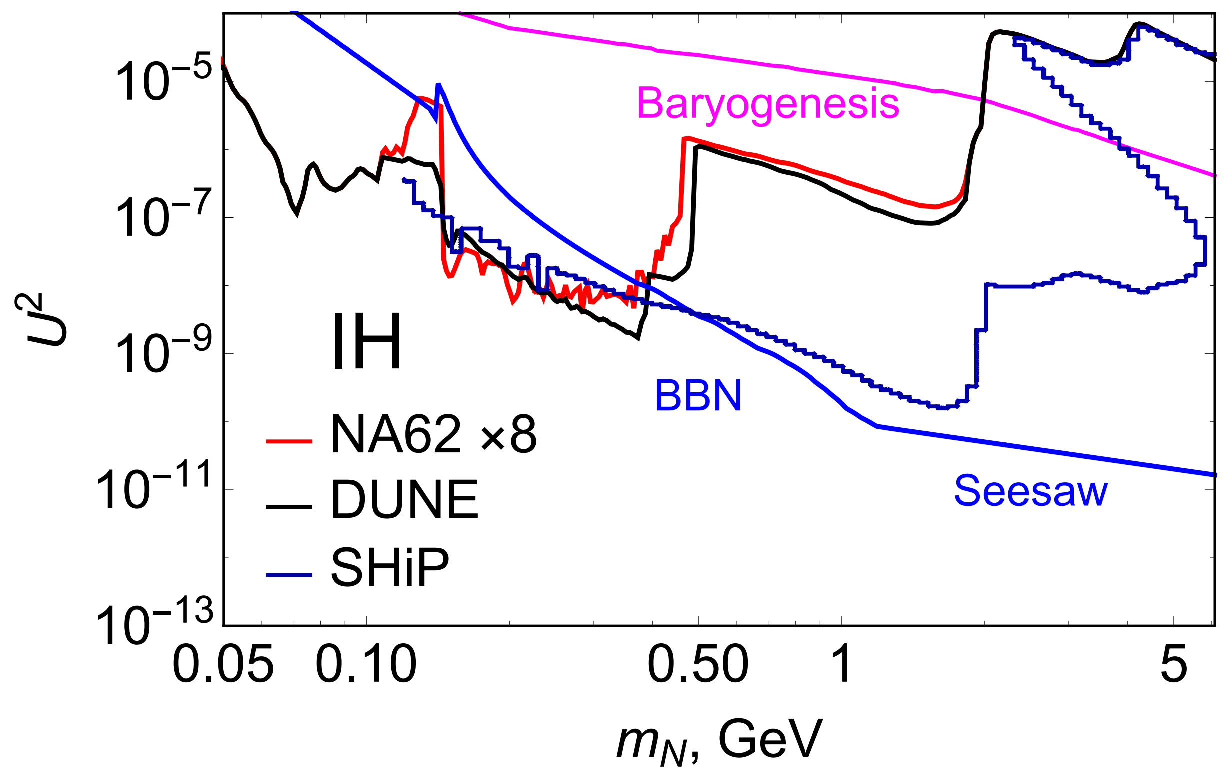
Neutrino oscillation data and reinterpretation

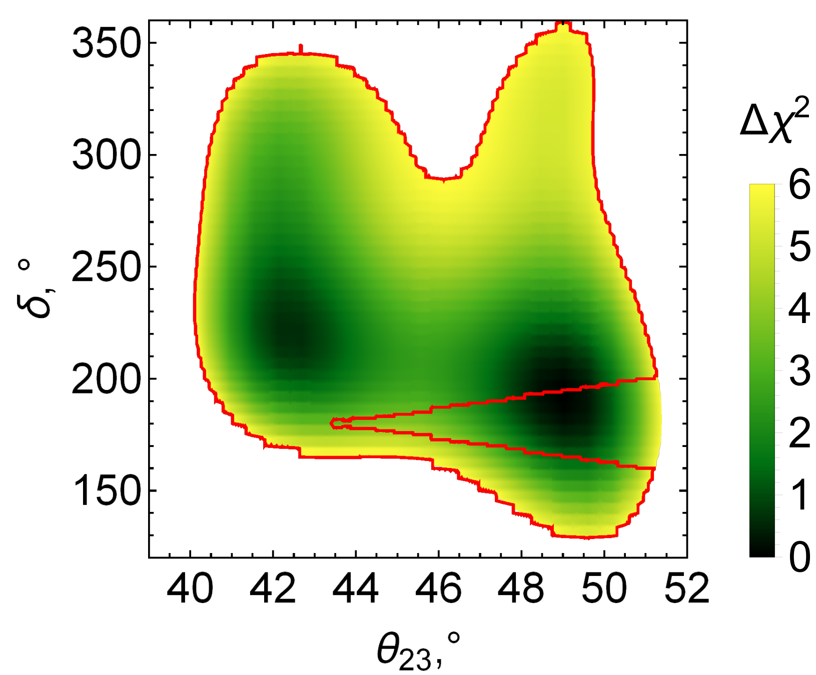


Bondarenko et al. 2101.09255

New experiments can close the window







If δ and θ_{23} are measured to be outside the red boundary,
the allowed window is excluded without a need for a dedicated search experiment.

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

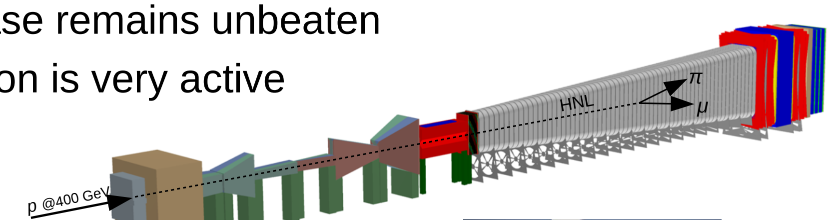
Summary and outlook

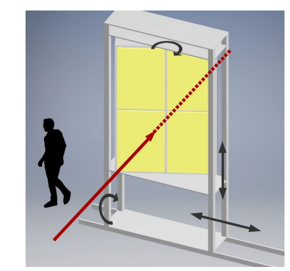
- **BDF related R&D studies have advanced well this year and will ramp up into next year**
  - These have resulted in operational improvements
- **TT90-ECN4 baseline option further solidified**
  - Higher risk items were identified and mitigated
- **A search for suitable alternative locations is underway 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

M.A. Fraser, Physics Beyond Colliders General Meeting, 2 – 3 December 2021 33

SHiP Summary

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



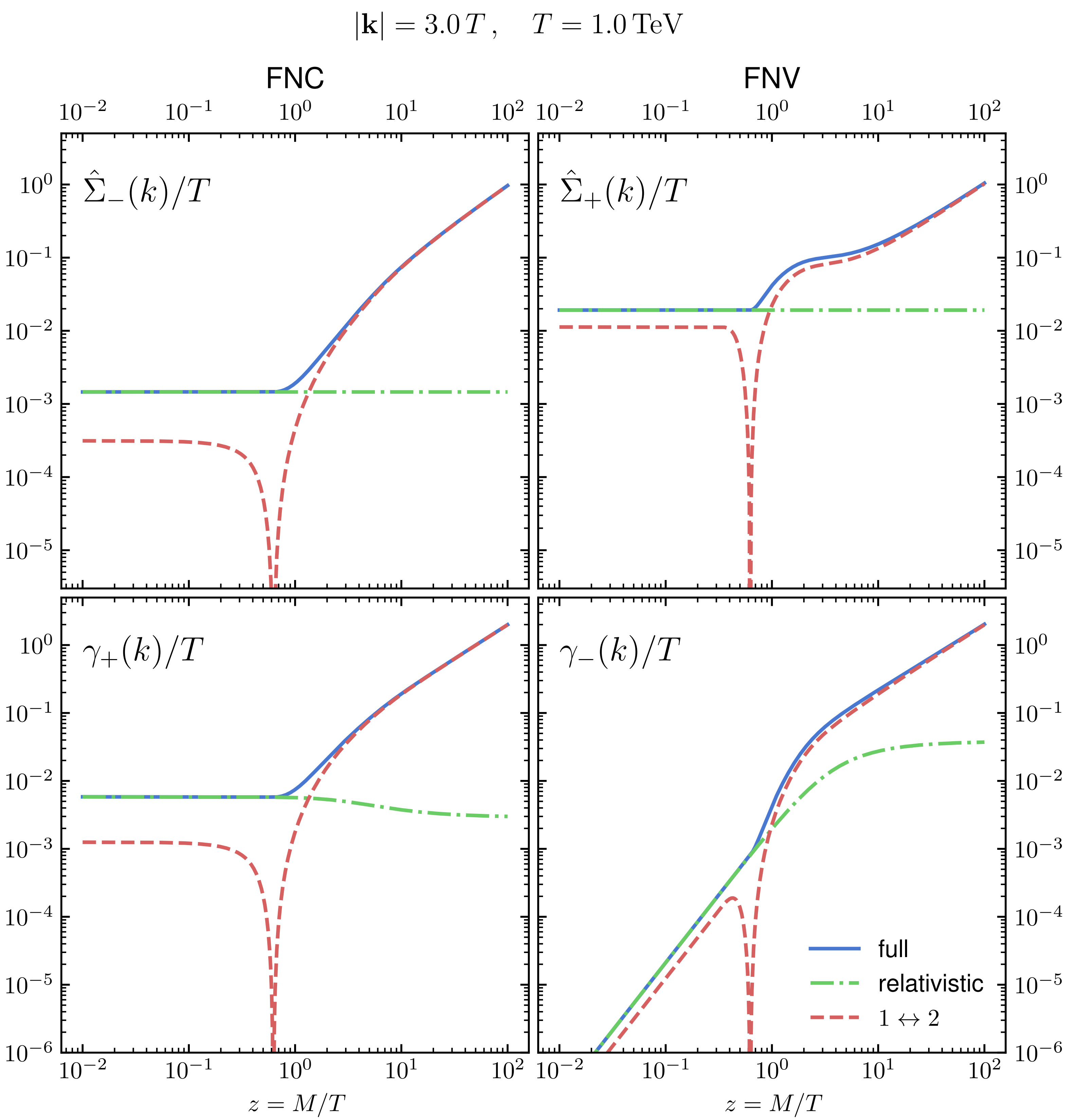


- R&D on BDF in the next 3 years
  - ► μ-shield
  - ► vacuum decay vessel + SBT
  - ► optimization of facility's performance
  - → *MoU out for signatures*
- Investigation of detector improvement + cost reduction
  - ► SND: replace emulsions by electronic Si-trackers
- SND@LHC approved, data in 2022
- New groups are embarking on SHiP

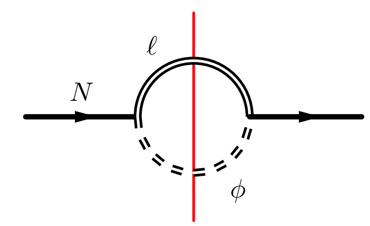
M. Schumann (Freiburg) – SHiP 16

[PBC General Meeting, December 2021]

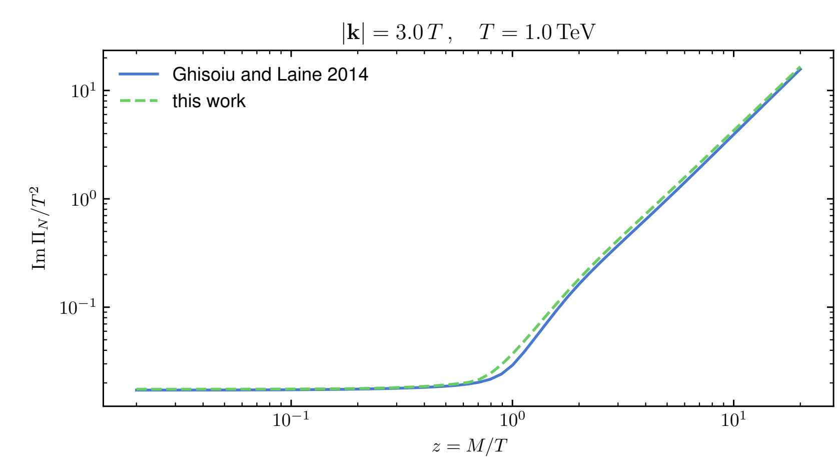
The rates



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

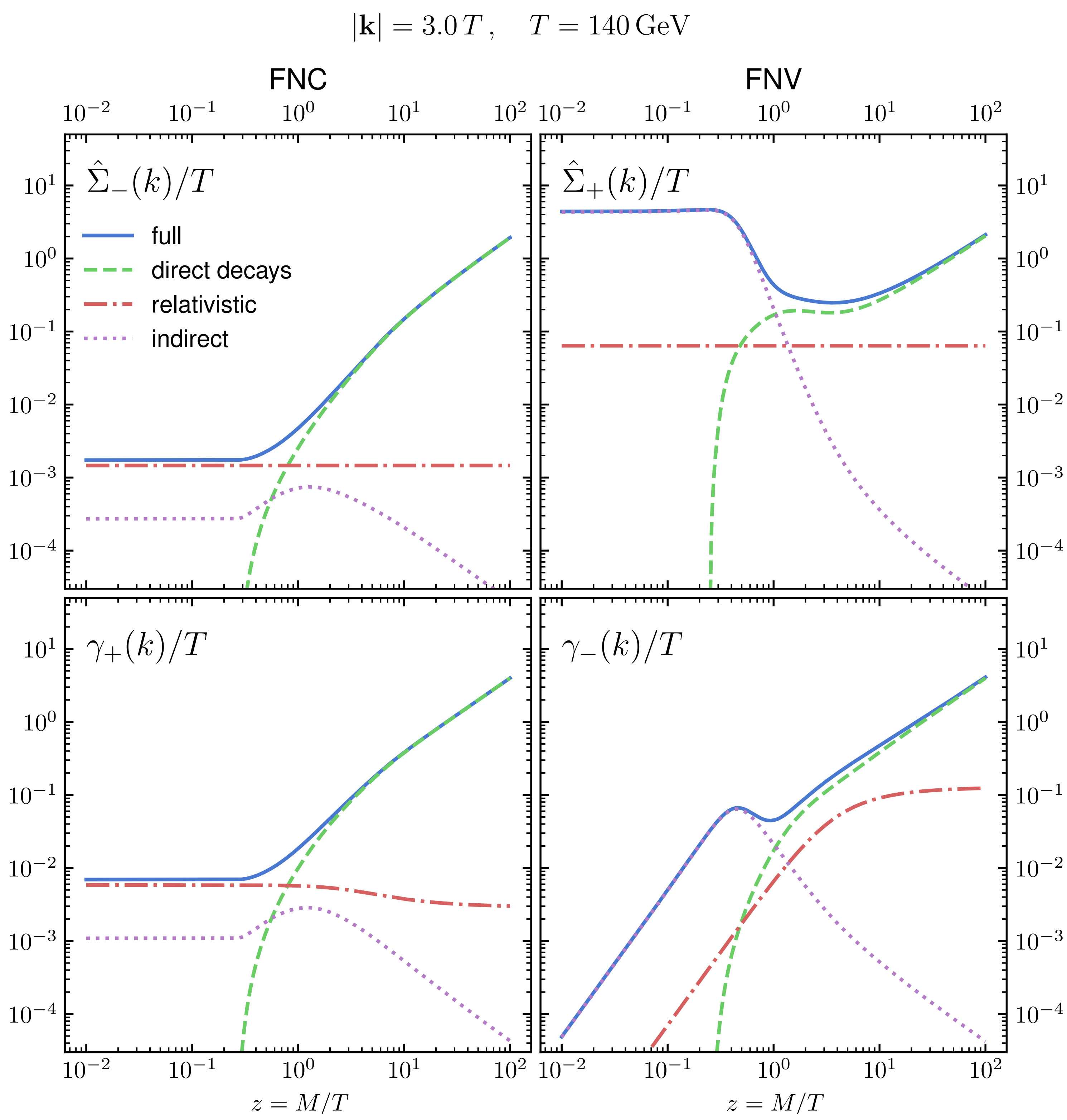


N
ℓ
ϕ

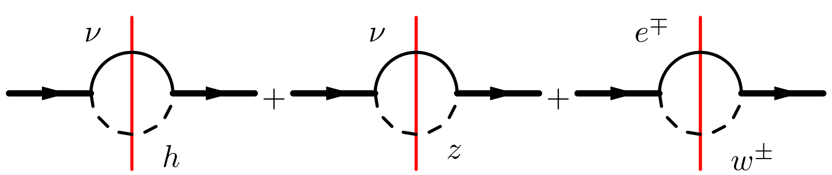


$|\mathbf{k}| = 3.0\,T\,,\quad T = 1.0\,\mathrm{TeV}$
Ghisoiu and Laine 2014
this work
$\mathrm{Im}\,\Pi_N/T^2$
$z = M/T$

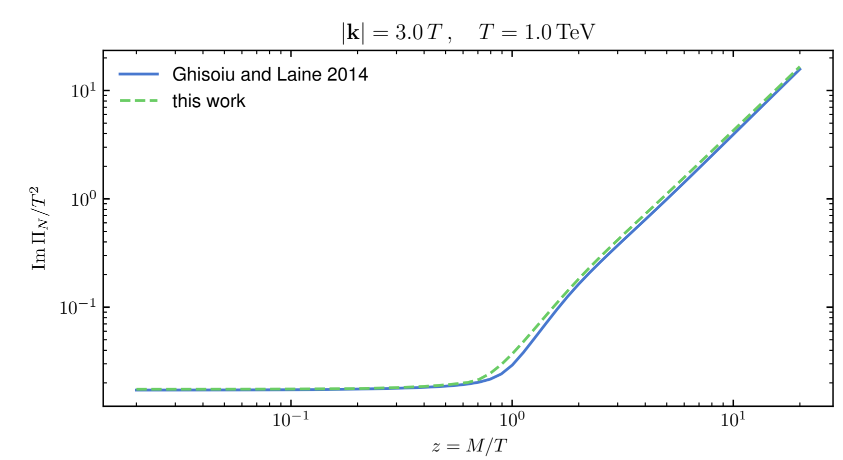
The rates



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

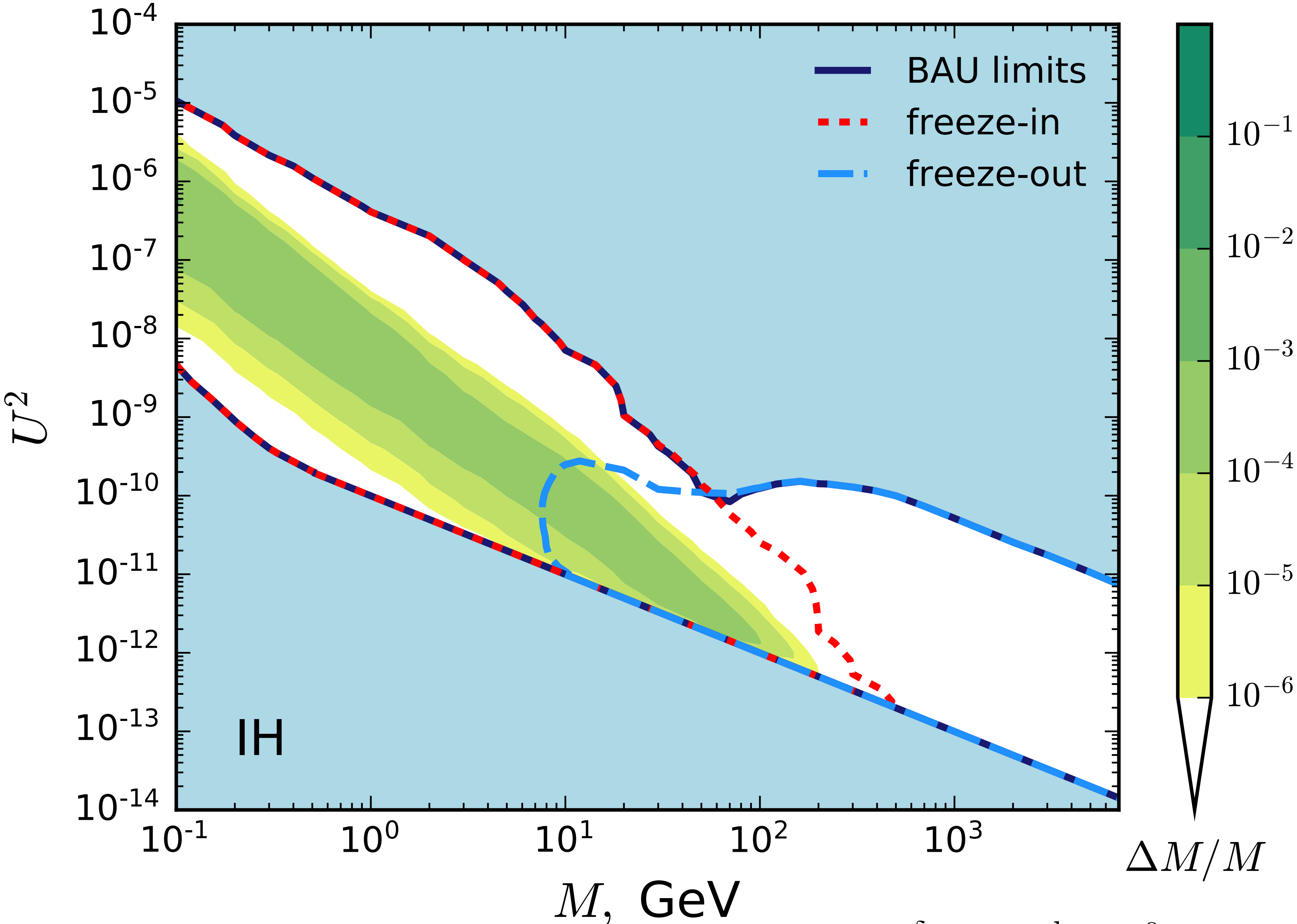


ν
h
ν
z
$e^\mp$
$w^\pm$

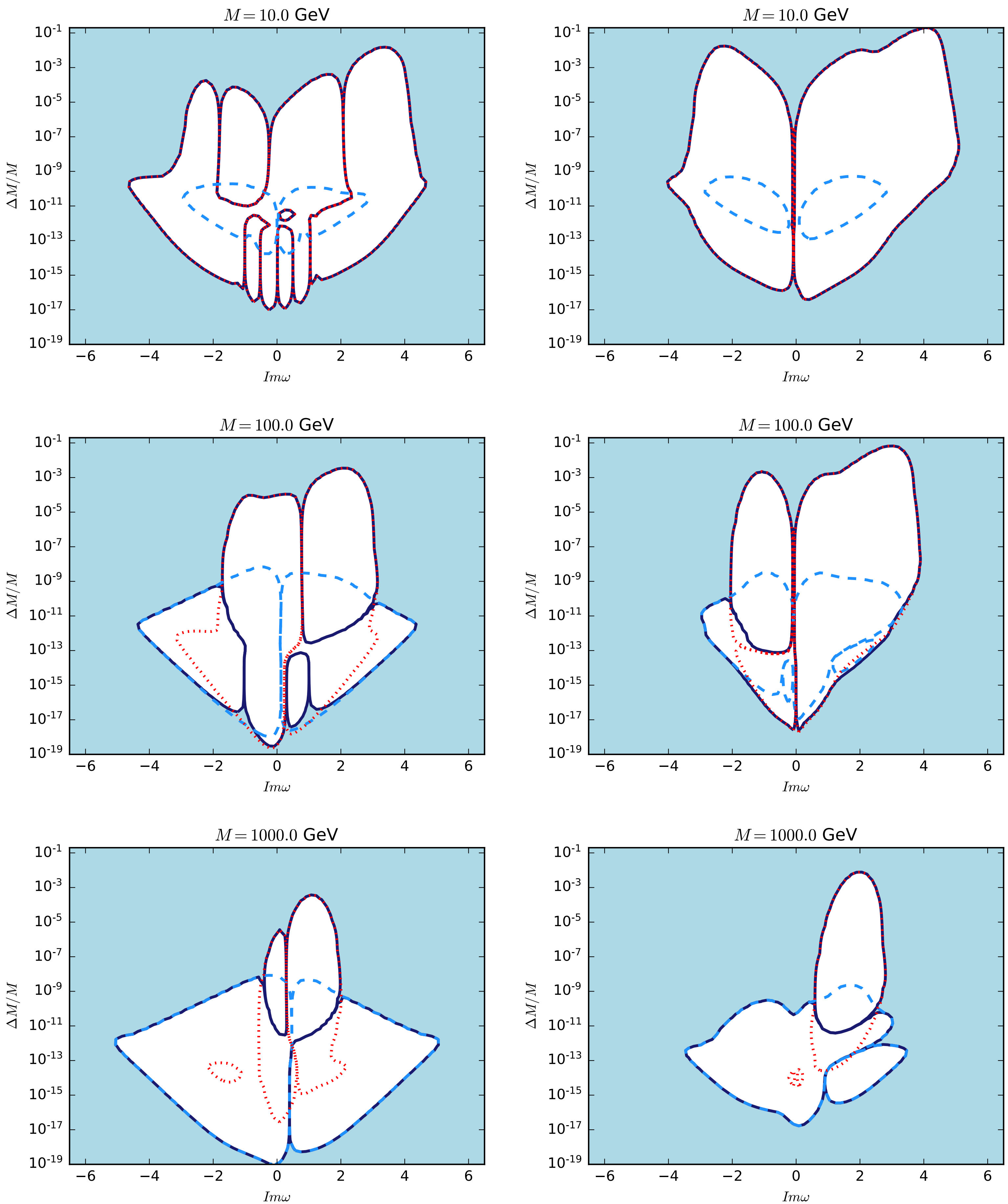


$|\mathbf{k}| = 3.0\,T\,, \quad T = 1.0\,\mathrm{TeV}$
Ghisoiu and Laine 2014
this work
$\mathrm{Im}\,\Pi_N/T^2$
$z = M/T$

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
$\Delta M/M$
$Im\omega$
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

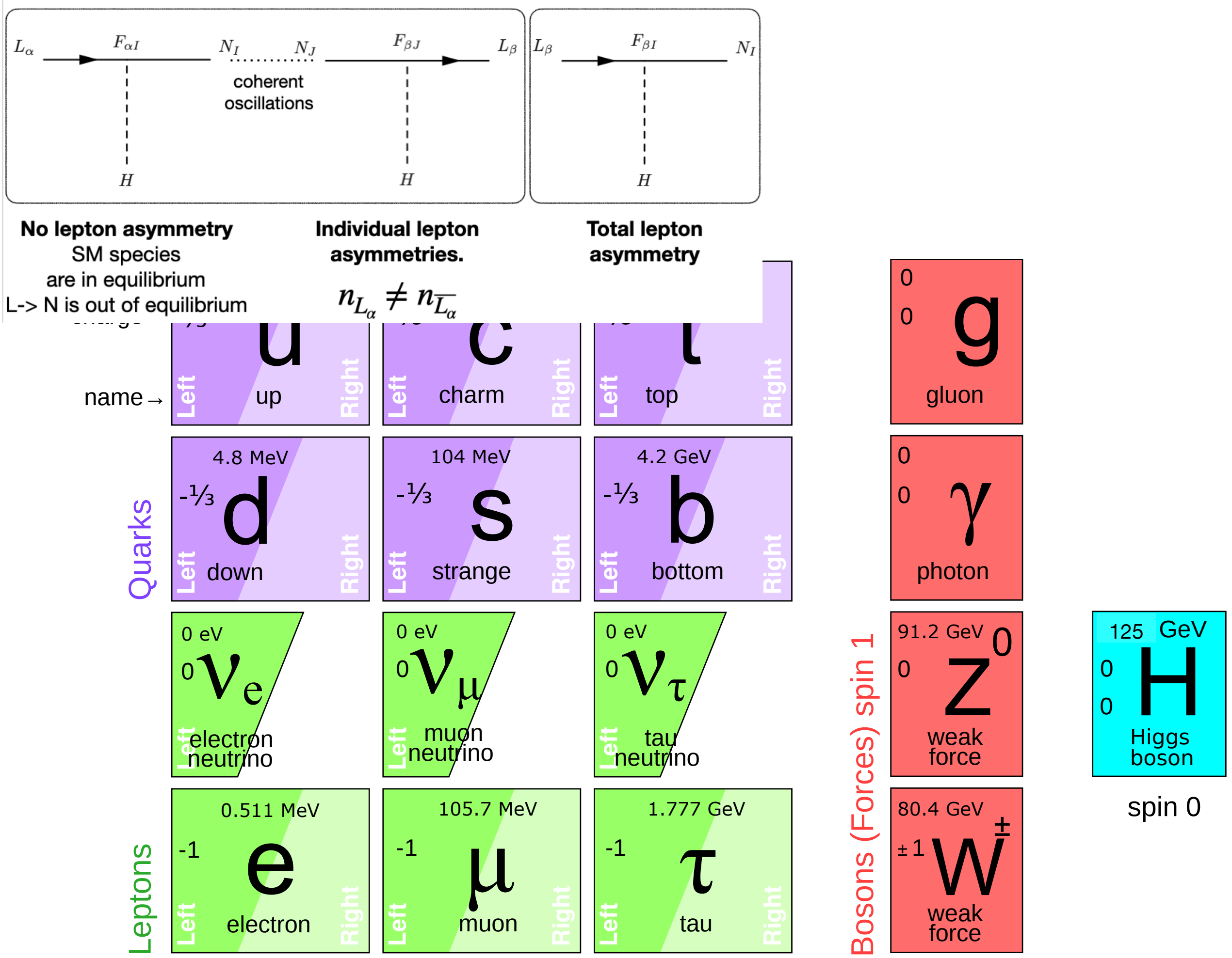
$$F = \frac{i}{v} U_\nu \sqrt{m_\nu^{\text{diag}}} \mathcal{R} \sqrt{M_M} \, ,$$

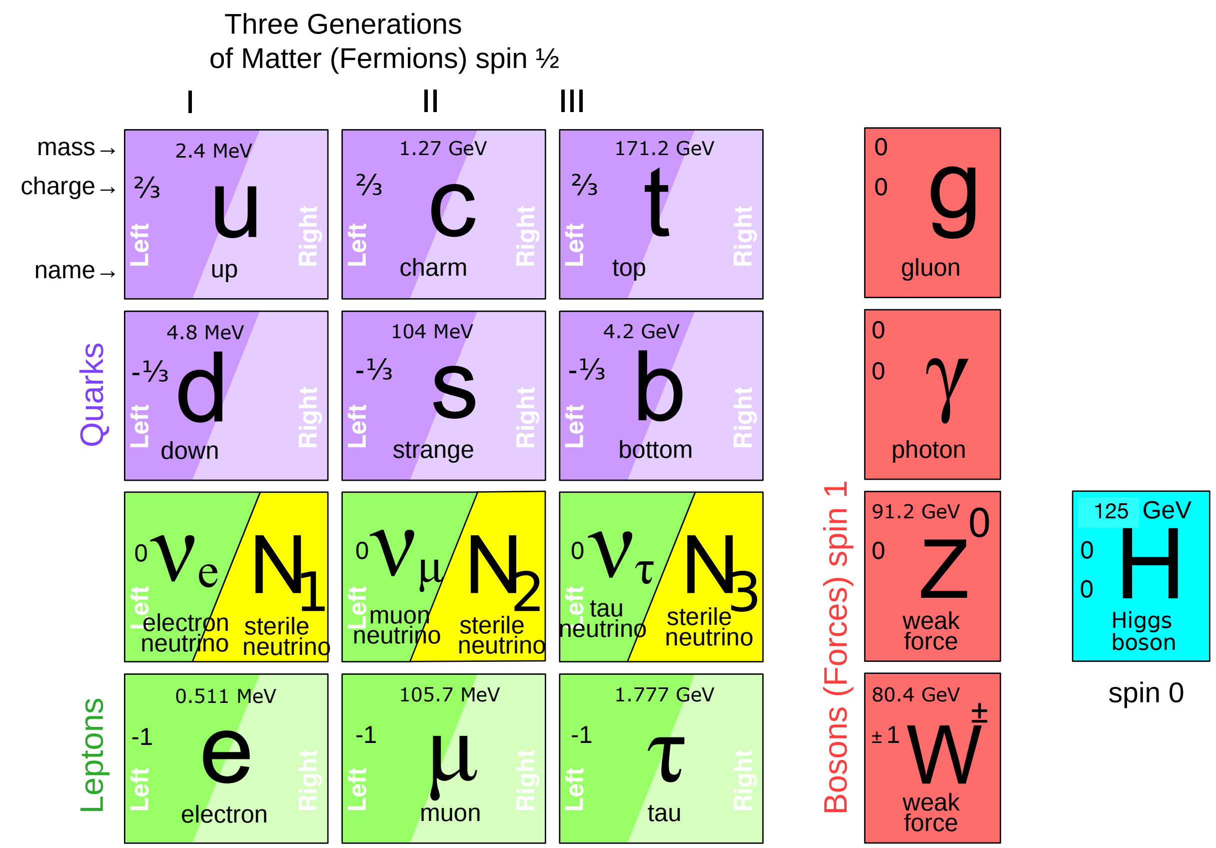
$$\mathcal{R}^{\text{NH}} = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi \sin\omega & \xi\cos\omega \end{pmatrix} , \qquad \mathcal{R}^{\text{IH}} = \begin{pmatrix} \cos\omega & \sin\omega \\ -\xi \sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$$

M, GeV	$\log_{10}(\Delta M/M)$	$\text{Im}\,\omega$	$\text{Re}\,\omega$	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





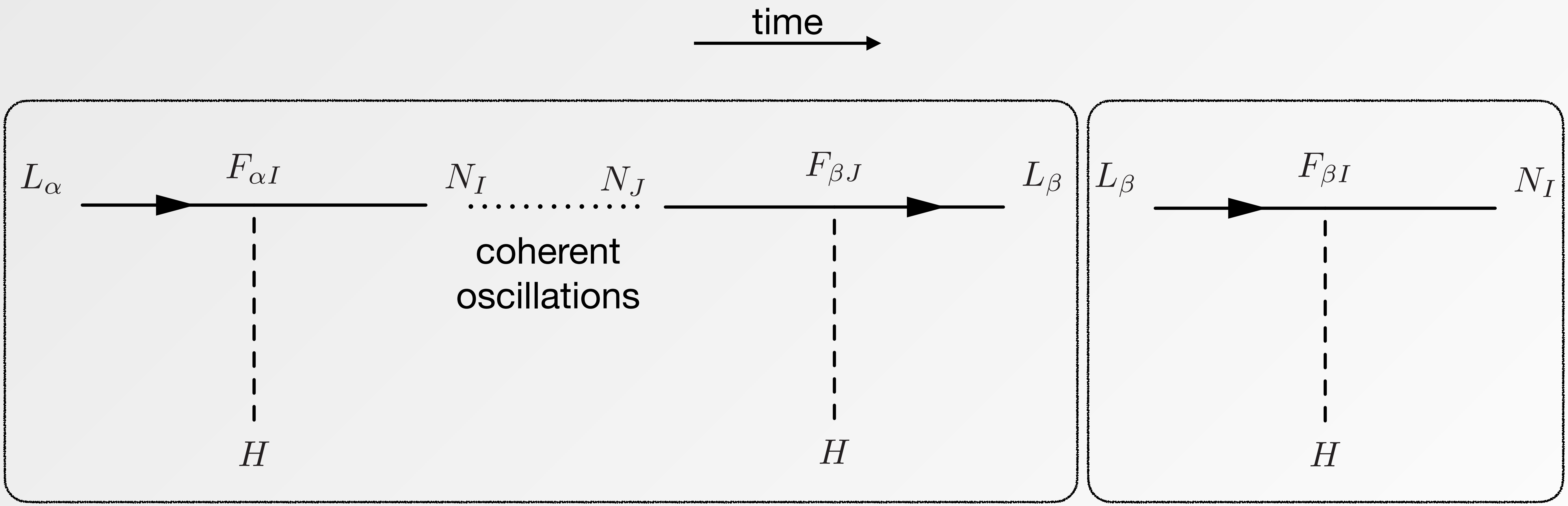
N_1 DM candidate $m \sim keV$

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

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