ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Sterile Neutrinos as the Origin of Dark and Baryonic Matter

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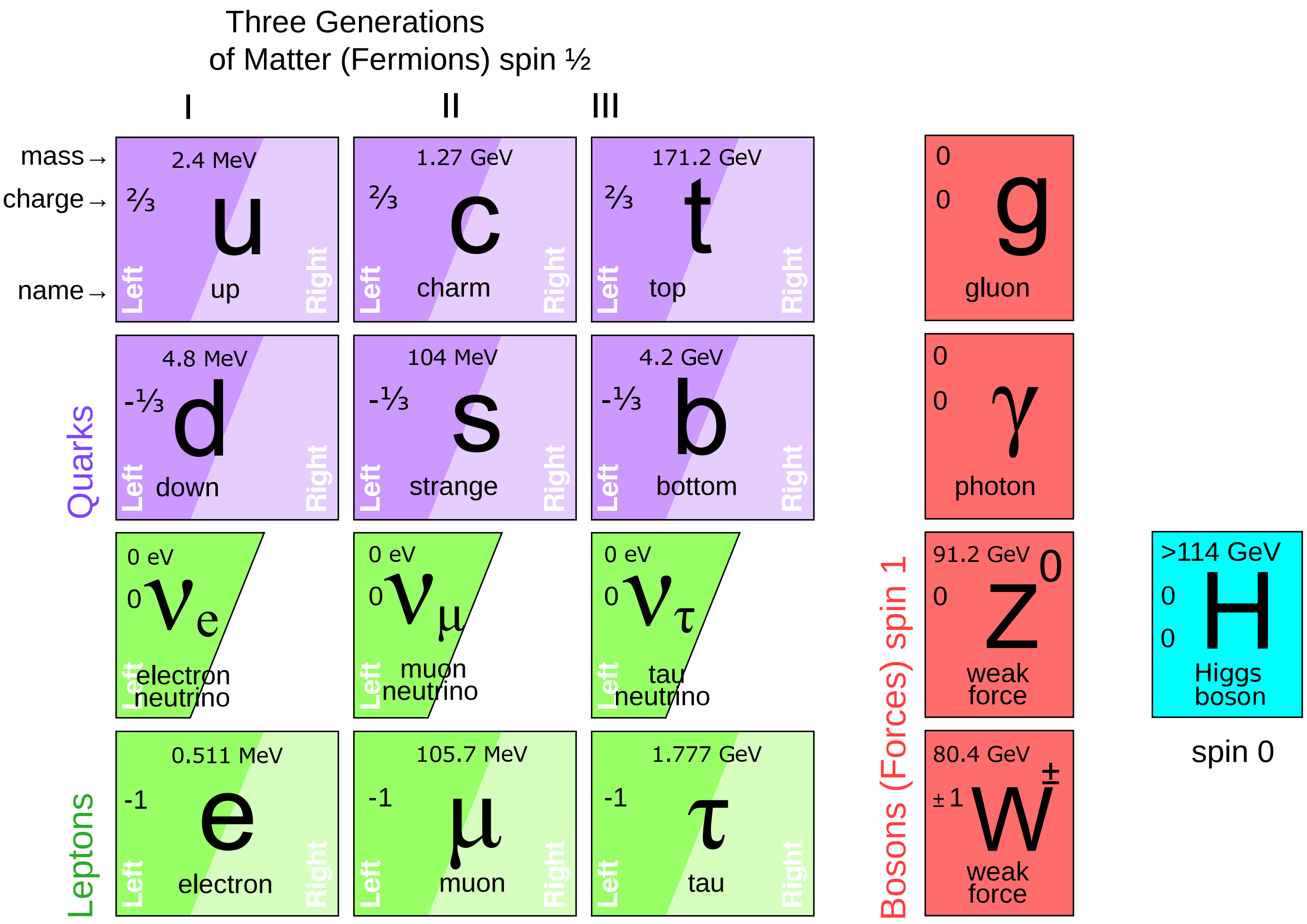
CEA-Saclay, 6 October, 2014

Problem: How to explain all confirmed experimental evidence for physics beyond the Standard Model

- Neutrino masses and oscillations
- Baryon asymmetry of the Universe
- Dark Matter

by minimal means?

the SM



Three Generations
of Matter (Fermions) spin ½

	I	II	III	Bosons (Forces) spin 1	
mass → charge → name →	2.4 MeV ⅔ u up Left Right	1.27 GeV ⅔ c charm Left Right	171.2 GeV ⅔ t top Left Right	0 0 g gluon	
Quarks	4.8 MeV -⅓ d down Left Right	104 MeV -⅓ s strange Left Right	4.2 GeV -⅓ b bottom Left Right	0 0 γ photon	
	0 eV 0 ν_e electron neutrino Left	0 eV 0 ν_μ muon neutrino Left	0 eV 0 ν_τ tau neutrino Left	91.2 GeV 0 Z^0 weak force	>114 GeV 0 0 H Higgs boson
Leptons	0.511 MeV -1 e electron Left Right	105.7 MeV -1 μ muon Left Right	1.777 GeV -1 τ tau Left Right	80.4 GeV ±1 $W^\pm$ weak force	spin 0

The missing piece: sterile neutrinos

Most general renormalizable (see-saw) Lagrangian

$$L_{see-saw} = L_{SM} + \bar{N}_I i\partial_\mu \gamma^\mu N_I - F_{\alpha I}\, \bar{L}_\alpha N_I \Phi - \frac{M_I}{2}\, \bar{N}_I^c N_I + h.c.,$$

Assumption: all Yukawa couplings with different leptonic generations are allowed.

$I \leq \mathcal{N}$ - number of new particles - HNLs - cannot be fixed by the symmetries of the theory.

Let us play with $\mathcal{N}$ to see if having some number of HNLs is good for something

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- $\mathcal{N} = \mathbf{3}$: All active neutrinos get masses: all neutrino experiments, can be explained (LSND with known tensions). The theory contains 6 new CP-violating phases: baryon asymmetry of the Universe can be understood. If LSND is dropped, dark matter in the Universe can be explained. The quantisation of electric charges follows from the requirement of anomaly cancellations (1-3-3, 1-2-2, 1-1-1, 1-graviton-graviton).

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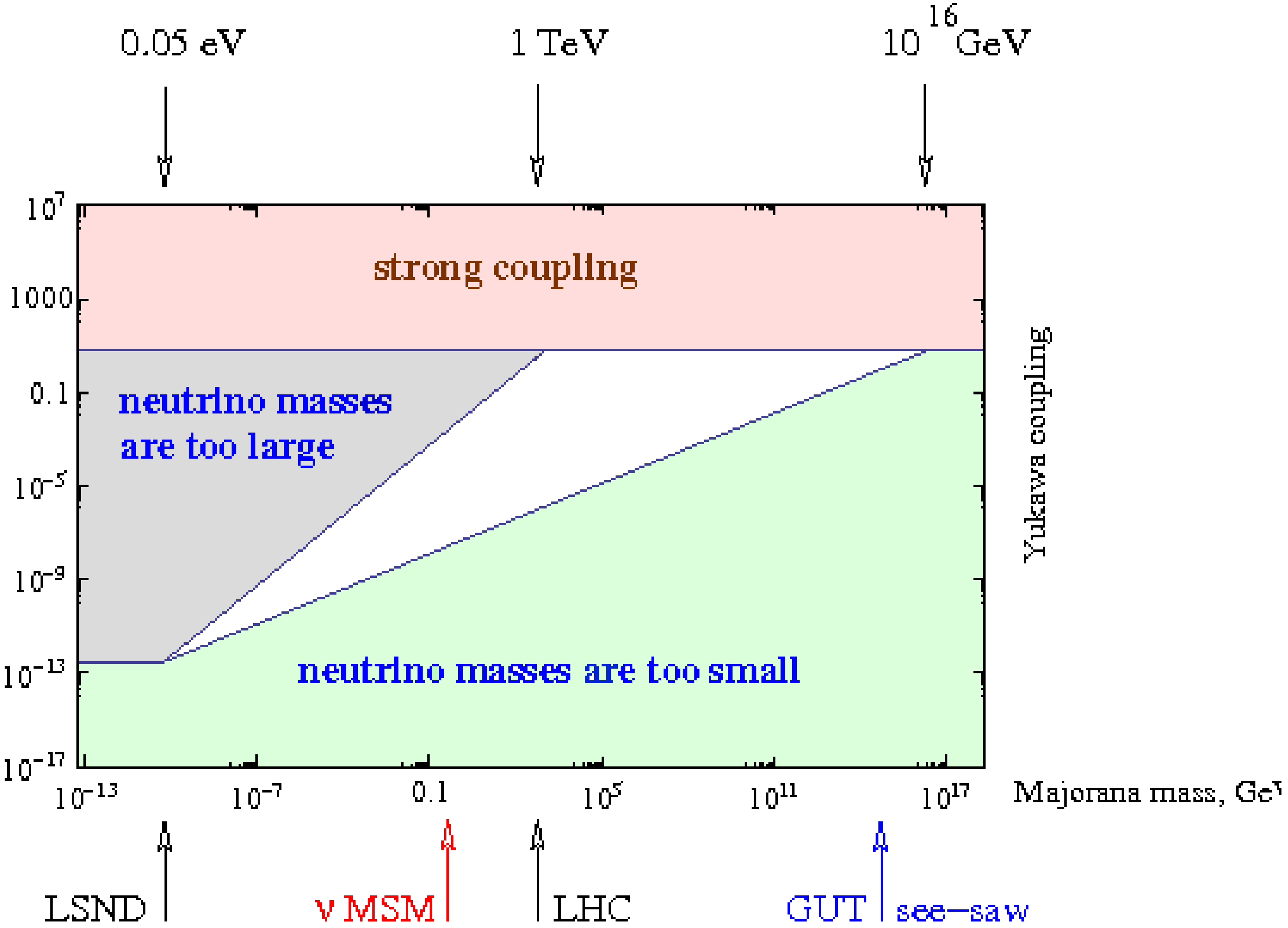
- $\mathcal{N} = 2$: Two of the active neutrinos get masses: all neutrino experiments, except LSND-like, can be explained. The theory contains 3 new CP-violating phases: baryon asymmetry of the Universe can be understood
- $\mathcal{N} = 3$: All active neutrinos get masses: all neutrino experiments, can be explained (LSND with known tensions). The theory contains 6 new CP-violating phases: baryon asymmetry of the Universe can be understood. If LSND is dropped, dark matter in the Universe can be explained. The quantisation of electric charges follows from the requirement of anomaly cancellations (1-3-3, 1-2-2, 1-1-1, 1-graviton-graviton).
- $\mathcal{N} > 3$: Now you can do many things, depending on your taste - extra relativistic degrees of freedom in cosmology, neutrino anomalies, dark matter, different scenarios for baryogenesis, and different combinations of the above.

New mass scale and Yukawas

$$Y^2 = Trace[F^\dagger F]$$



Physics of large mixing angles

Consider SM + one extra massive Dirac spinor Ψ, which is singlet with respect to SM.

$$L = L_{SM} + \bar{\Psi} i \partial_\mu \gamma^\mu \Psi - F_\alpha \, \bar{L}_\alpha \Psi H - M \, \bar{\Psi}\Psi + h.c.,$$

Symmetry: lepton number conservation. For any F_α and M all active neutrinos are massless.

Small symmetry breaking terms $\Longrightarrow$ small active neutrino masses :

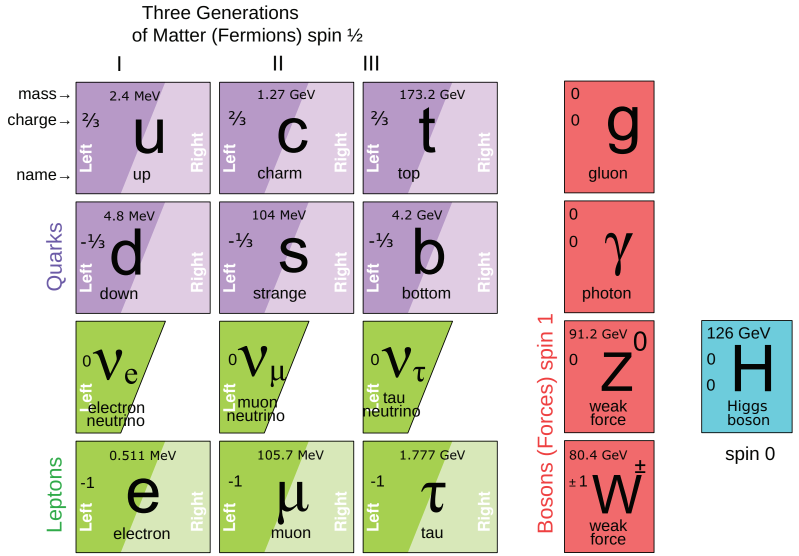
$$\Delta L = f_\alpha \, \bar{L}_\alpha \Psi^c H - m \, \bar{\Psi}\Psi^c + h.c.,$$

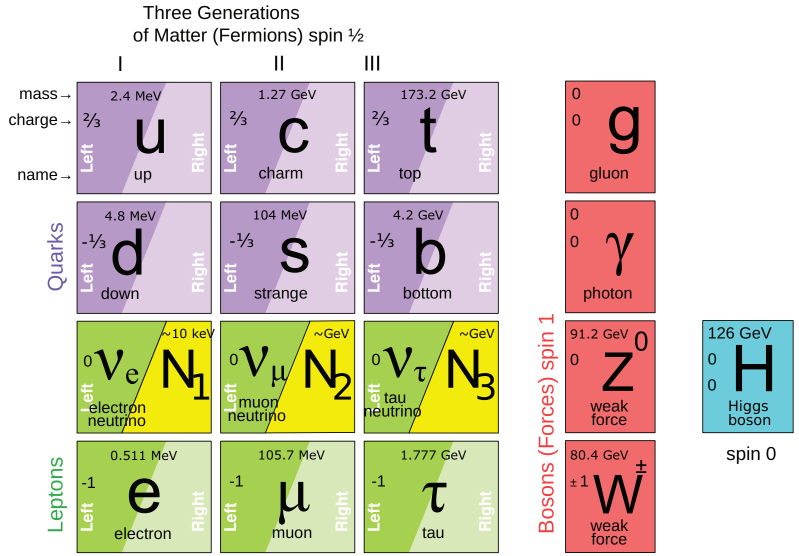
Active neutrino masses:

$$m_\nu \simeq \frac{F v^2 \times f}{M} + \frac{F^2 v^2 \times m}{M^2}$$

Consequence: any increase of experimental sensitivity may lead to discovery of HNL responsible for active neutrino masses!

$\mathcal{N} = 3$ with $M_I < M_W$: the νMSM





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

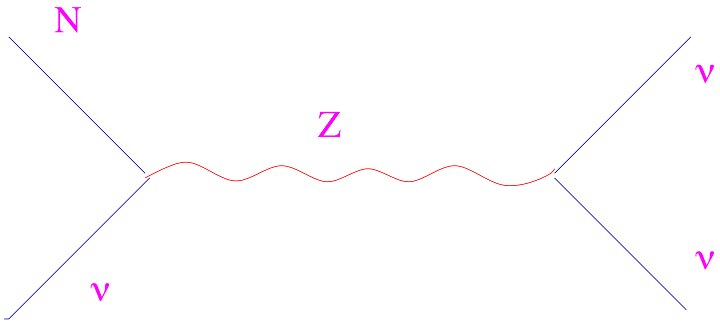
Role of $N_2, \; N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

What should be the properties of $\boldsymbol{N_{1,2,3}}$ in the minimal setup - no any type of new physics between the Fermi and Planck scales ?

How to search for them experimentally?

DM candidate: the lightest Majorana ν, N_1

Yukawa couplings are small → sterile N can be very stable.



Main decay mode: $N \to 3\nu$.

For one flavour:

$$\tau_{N_1} = 5\times 10^{26}\,\text{sec}\left(\frac{1\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\Theta^2}\right)$$

$$\Theta = \frac{m_D}{M_I}$$

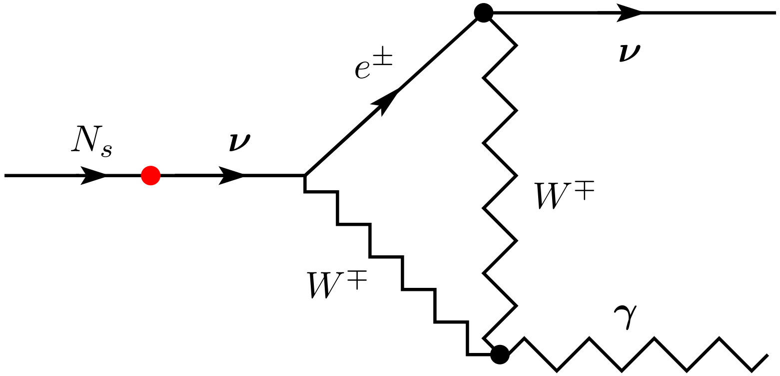
Dark Matter candidate: N_1

DM particle is not stable. Main decay mode $N_1 \to 3\nu$ is not observable.

Subdominant radiative decay channel: $N \to \nu\gamma$.

Photon energy:

$$E_\gamma = \frac{M}{2}$$



Radiative decay width:

$$\Gamma_{\rm rad} = \frac{9\,\alpha_{\rm EM}\,G_F^2}{256 \cdot 4\pi^4}\,\sin^2(2\theta)\,M_s^5$$

Dark Matter production

Cosmological production of sterile neutrinos

Sterile neutrino never equilibrates, since their interactions are very weak

$$\Omega_N h^2 \sim 0.1 \sum_I \sum_{\alpha=e,\mu,\tau} \left(\frac{|\Theta_{\alpha I}|^2}{10^{-8}}\right)\left(\frac{M_I}{1\ \mathrm{keV}}\right)^2 .$$

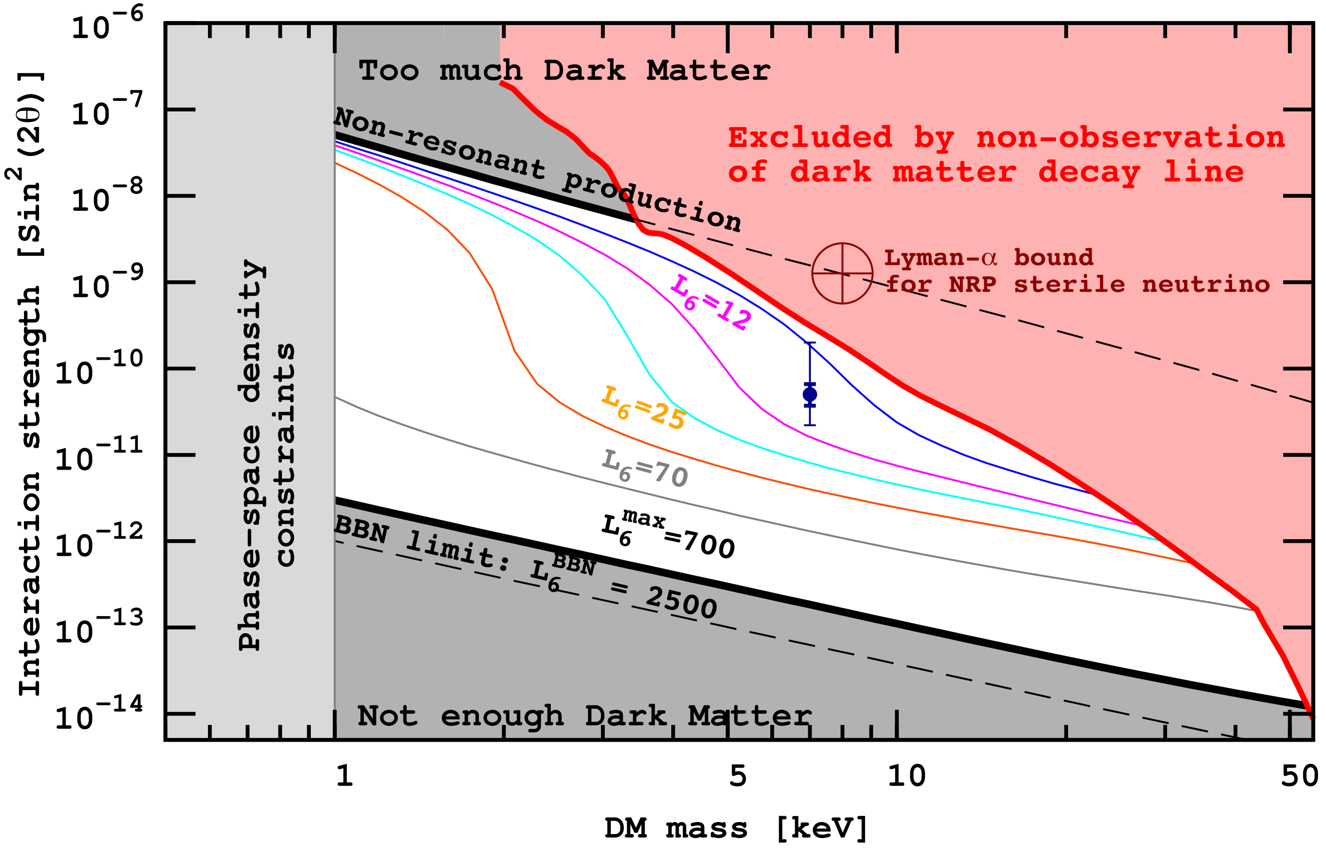
Production temperature $\sim 130 \left(\frac{M_I}{1\ \mathrm{keV}}\right)^{1/3}$ MeV

Production rate depends on Yukawa couplings and on lepton asymmetry.

Note: DM sterile neutrino does not contribute to the number of relativistic species! Perfect agreement with Planck measurements.

Constraints on DM sterile neutrino N_1

- Stability. N_1 must have a lifetime larger than that of the Universe
- Production. N_1 are created in the early Universe in reactions $l\bar{l} \to \nu N_1, \;\; q\bar{q} \to \nu N_1$ etc. We should get correct DM abundance
- Structure formation. If N_1 is too light it may have considerable free streaming length and erase fluctuations on small scales. This can be checked by the study of Lyman-α forest spectra of distant quasars and structure of dwarf galaxies
- X-rays. N_1 decays radiatively, $N_1 \to \gamma\nu$, producing a narrow line which can be detected by X-ray telescopes (such as Chandra or XMM-Newton).

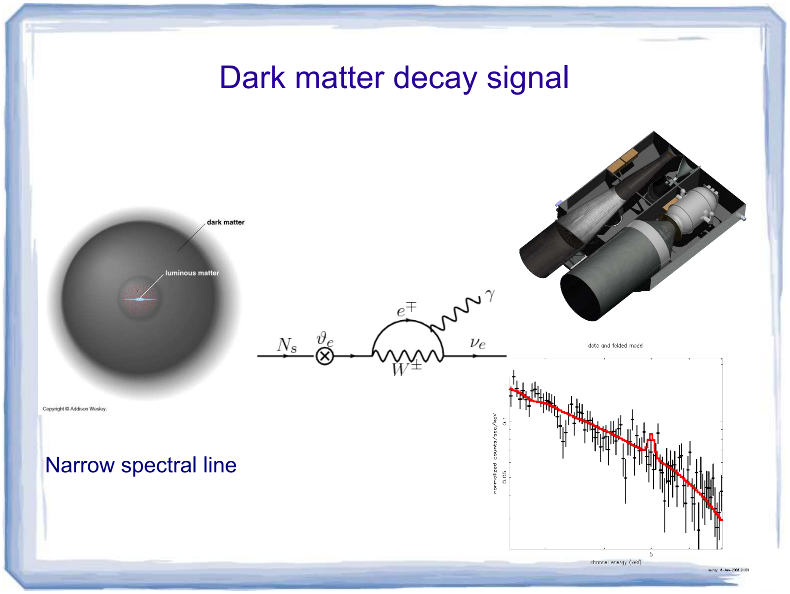


Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster. A. Boyarsky , O. Ruchayskiy, D. Iakubovskyi, J. Franse. e-Print: arXiv:1402.4119

Search for N_1

X-ray telescopes similar to *Chandra* or *XMM-Newton* but with better energy resolution: narrow X-ray line from decay $N_e \to \nu\gamma$



Dark matter decay signal

Narrow spectral line

One needs:

- Improvement of spectral resolution up to the natural line width ($\Delta E/E \sim 10^{-3}$).
- FoV $\sim 1^\circ$ (size of a dwarf galaxies).
- Wide energy scan, from $\mathcal{O}(100)$ eV to $\mathcal{O}(50)$ keV.

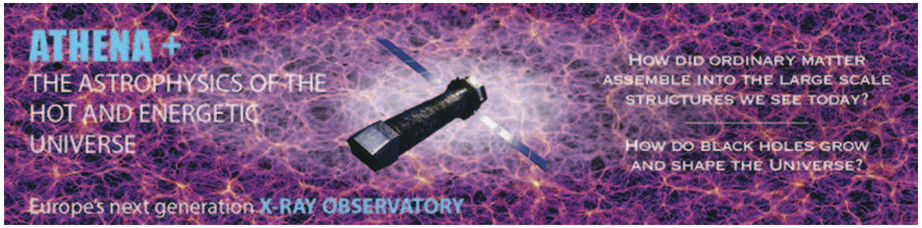
Searches for HNL in space

- Has been previously searched with *XMM-Newton, Chandra, Suzaku, INTEGRAL*
- Spectral resolution is not enough (required $\Delta E/E \sim 10^{-3}$)
- Proposed/planned X-ray missions with sufficient spectral resolution:

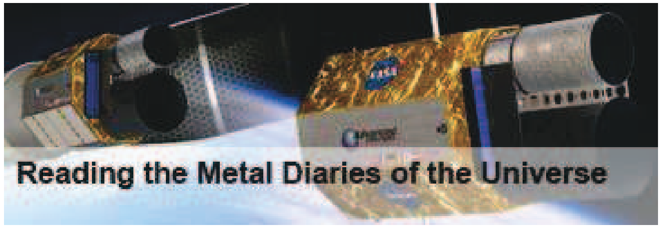
Astro-H

LOFT

Athena+



Origin/Xenia



Baryon asymmetry

- CP-violation - OK due to new complex phases in Yukawa couplings
- Lepton number violation - OK due to HNL couplings and due to Majorana masses
- Deviations from thermal equilibrium: OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Note:

- there is no electroweak phase transition for the Higgs mass 126 GeV
- For masses of N in the GeV region they decay at temperatures ~ 1 GeV. These decays cannot be used for baryogenesis, as they occur below the sphaleron freeze-out temperature

Baryon asymmetry

Akhmedov, Rubakov, Smirnov; Asaka, MS

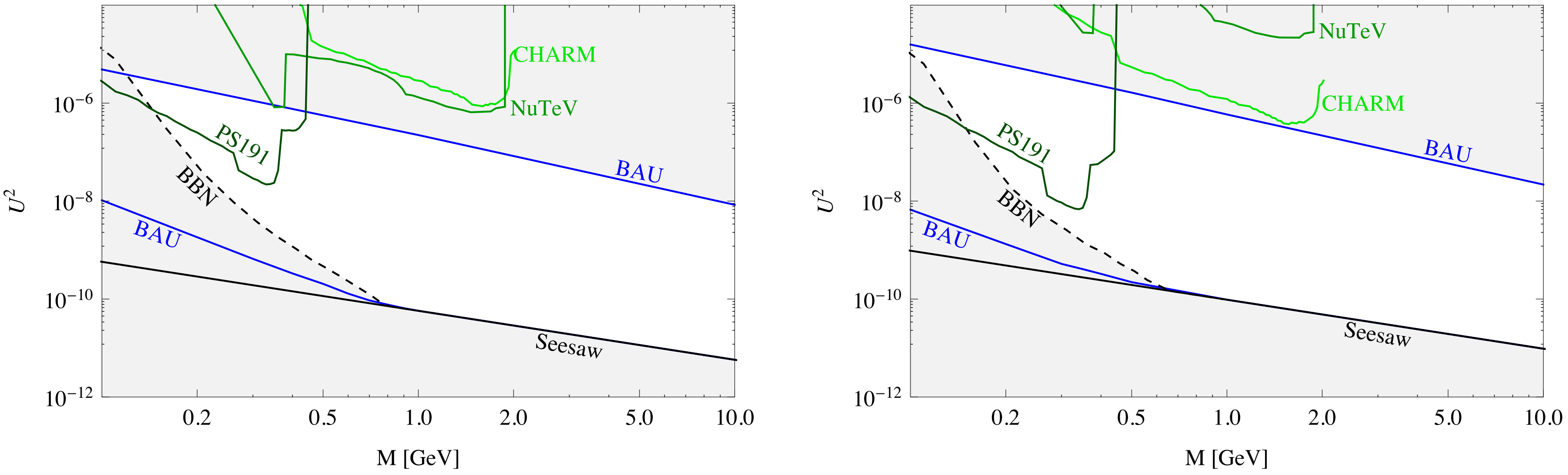
Idea - $N_{2,3}$ HNL oscillations as a source of baryon asymmetry.
Qualitatively:

- HNL are created in the early universe and oscillate in a coherent way with CP-breaking.
- Lepton number from HNL can go to active neutrinos.
- The lepton number of active left-handed neutrinos is transferred to baryons due to equilibrium sphaleron processes.

Constraints on BAU HNL $N_{2,3}$

Baryon asymmetry generation: CP-violation in neutrino sector+singlet fermion oscillations+sphalerons

- BAU generation requires out of equilibrium: mixing angle of $N_{2,3}$ to active neutrinos cannot be too large
- Neutrino masses. Mixing angle of $N_{2,3}$ to active neutrinos cannot be too small
- BBN. Decays of $N_{2,3}$ must not spoil Big Bang Nucleosynthesis
- Experiment. $N_{2,3}$ have not been seen



Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS).

Sakharov condition

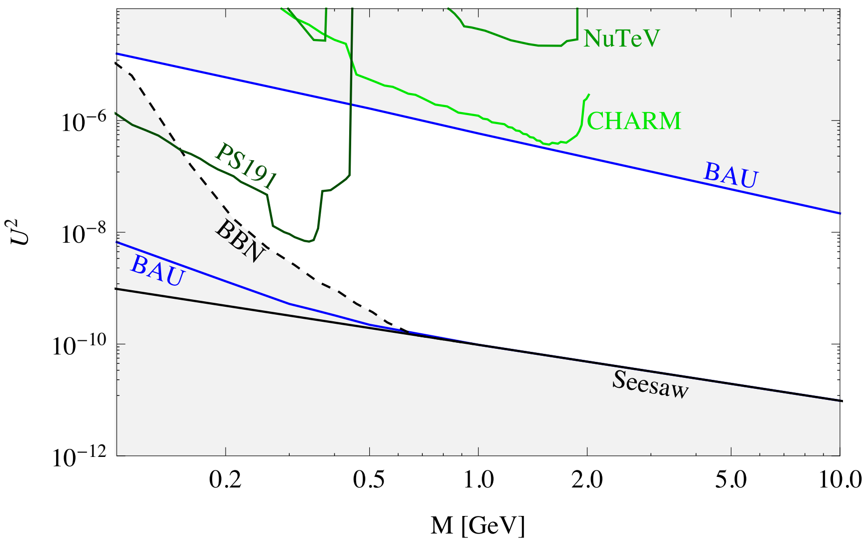
Rate of HNL equilibration $\Gamma \simeq \kappa F^2 T$ must be smaller than the rate of the Universe expansion at the sphaleron freeze-out $T = T_{sph} \simeq 130$ GeV, $H \simeq T^2/M_0$, $M_0 \sim M_{Pl}$ ($\kappa \simeq 3 \times 10^{-6}$ - some number following from solution of kinetic equations in the early universe):

$$\kappa F^2 \left(1 - \frac{M^2}{M_W^2}\right)^2 T_{sph} < \frac{T_{sph}^2}{M_0}$$

Numerically, $F < 8 \times 10^{-6}$, and

$$U^2 < 2 \times 10^{-6} \left(\frac{GeV}{M}\right)^2 \left(1 - \frac{M^2}{M_W^2}\right)^2$$

Sakharov condition



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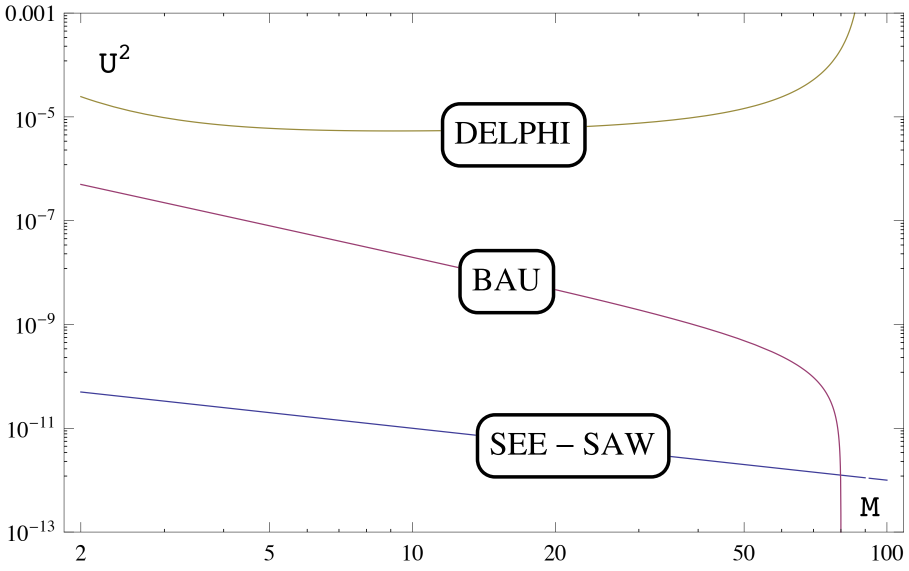
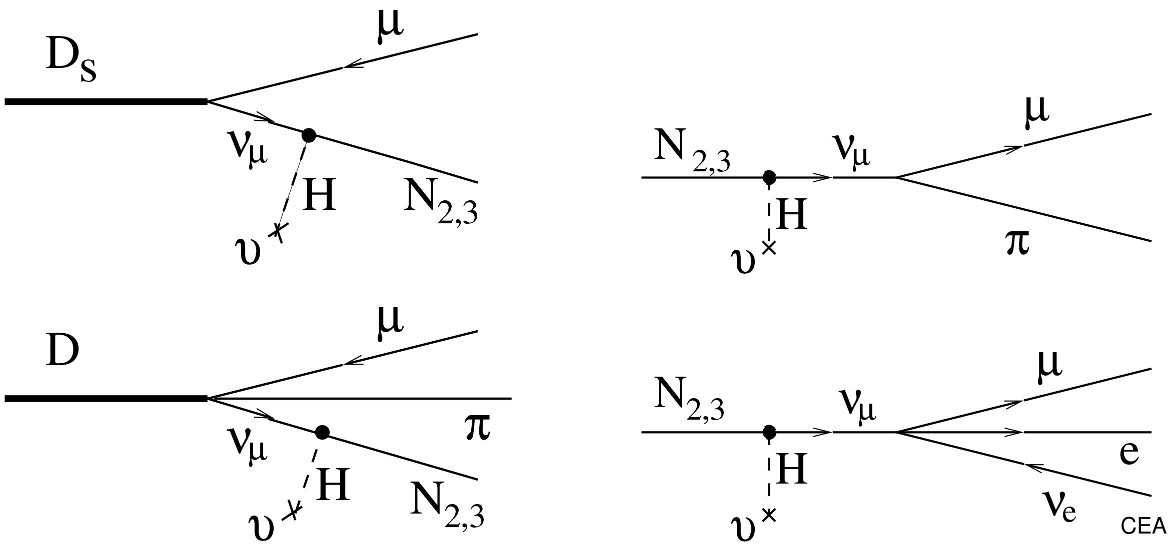


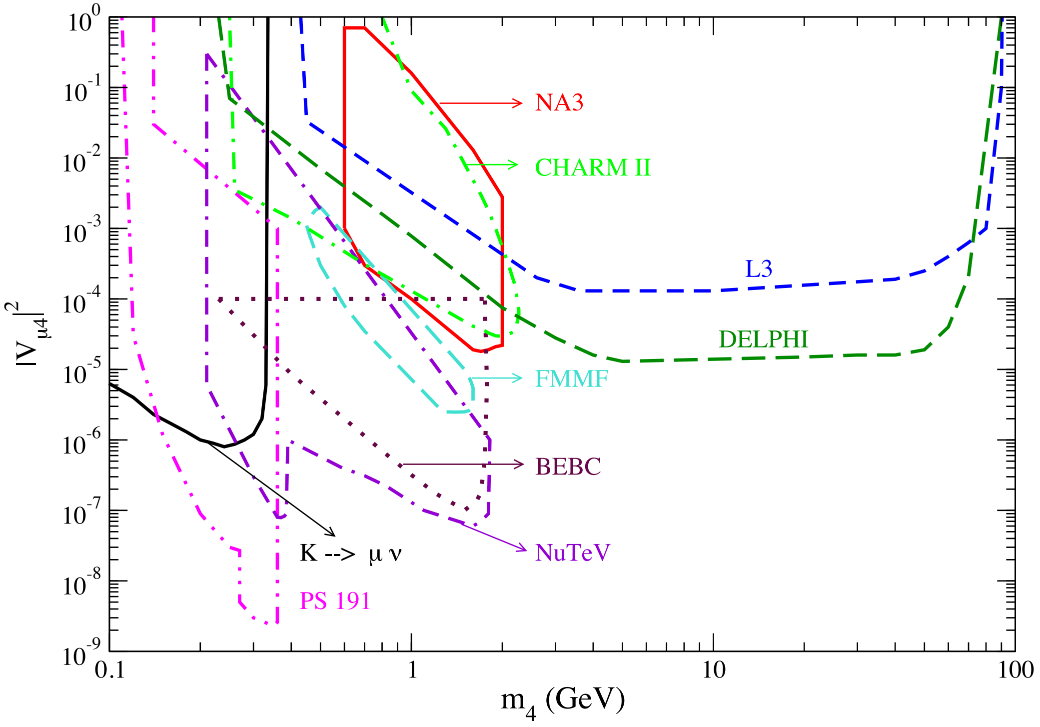
Experimental search for HNL

- Production
  - via intermediate (hadronic) state

    $\boldsymbol{p + \text{target} \to \text{mesons} + ...}$, and then hadron$\to$ $\boldsymbol{N + ...}$.
  - via $\boldsymbol{Z}$-boson decays: $\boldsymbol{e^+e^- \to Z \to \nu N}$
- Detection
  - Subsequent decay of $\boldsymbol{N}$ to SM particles



Survey of constraints



From arXiv:0901.3589, Atre et al

How to improve the bounds or to discover light very weakly interacting HNL’s?

Dedicated experiments

Common features of all relatively light feebly interacting particles :

- Can be produced in decays of different mesons (π, K, charm, beauty)
- Can decay to SM particles (l^+l^-, $\gamma\gamma$, $l\pi$, etc)
- Can be long lived

Requirements to experiment:

- Produce as many mesons as you can
- Study their decays for a missing energy signal: charm or B-factories, NA62
- Search for decays of hidden sector particles - fixed target experiments
  - Have as many pot as you can, with the energy enough to produce charmed (or beauty) mesons
  - Put the detector as close to the target as possible, in order to catch all hidden particles from meson decays (to evade $1/R^2$ dilution of the flux)
  - Have the detector as large as possible to increase the probability of hidden particle decay inside the detector
  - Have the detector as empty as possible to decrease neutrino and other backgrounds

Most recent dedicated experiment - 1986, Vannucci et al

Volume 166B, number 4 PHYSICS LETTERS 23 January 1986

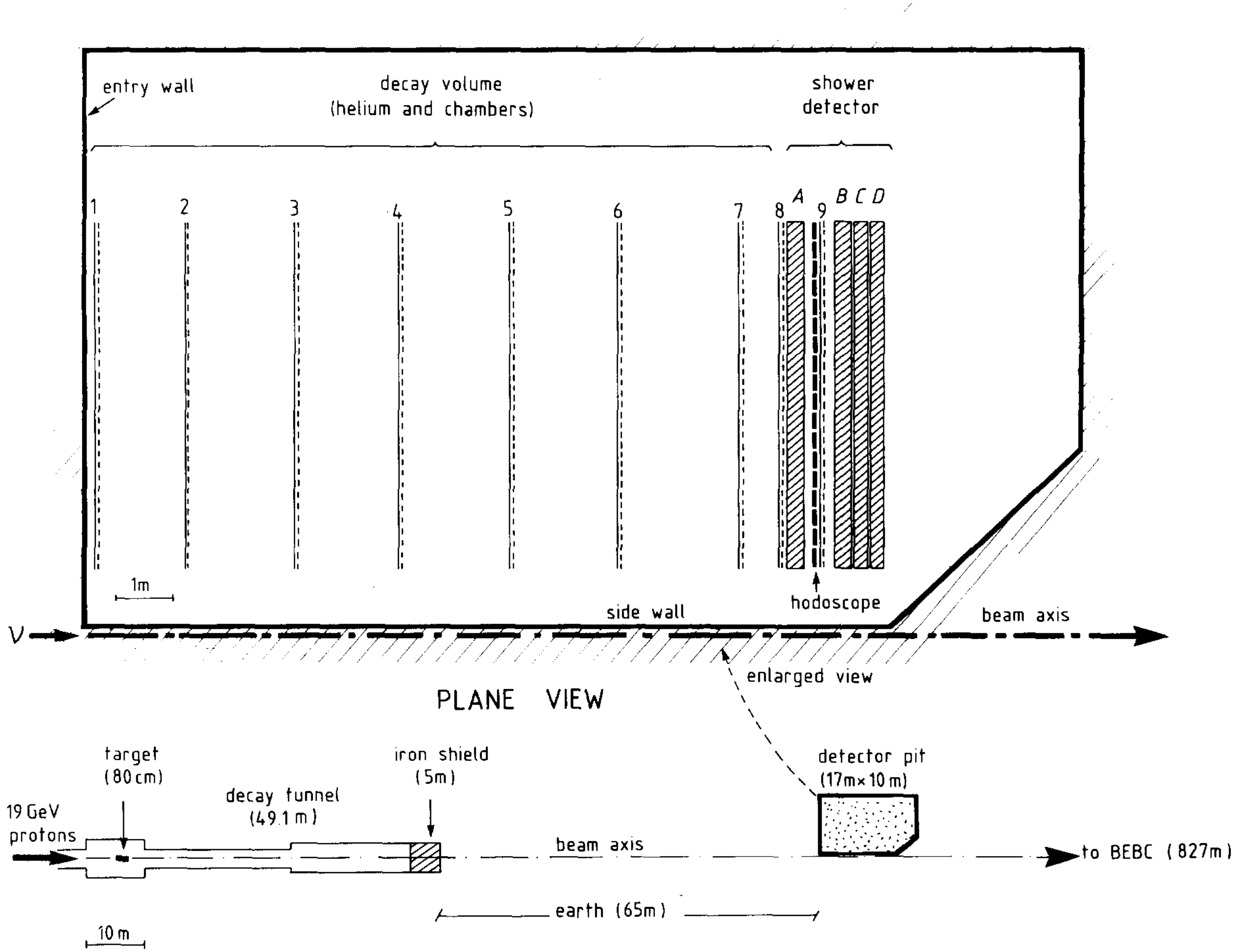


Fig. 1. Beam and layout of the detector.

No new particles are found with mass below K-meson, the best constraints are derived

Proposal to Search for Heavy Neutral Leptons at the SPS arXiv:1310.1762

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, O. Ruchayskiy, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

⇓

General beam dump facility: Search for Hidden Particles

SHiP

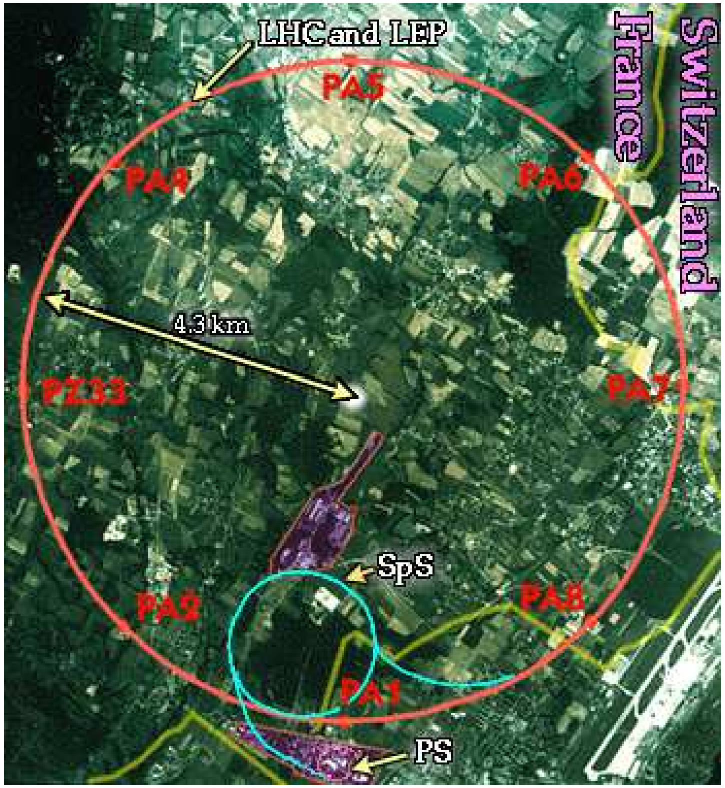
Search for Hidden Particles

SHiP is currently a (proto) collaboration of 41 institutes from 14 countries

web-site: http://ship.web.cern.ch/ship/

1st SHiP Workshop: Zurich, 10-12 June 2014
2nd SHiP Workshop: CERN, 24-26 September, 2014
3rd SHiP Workshop: CERN, 15 December, 2014

CEA Saclay participation – contact person: Maxim Titov

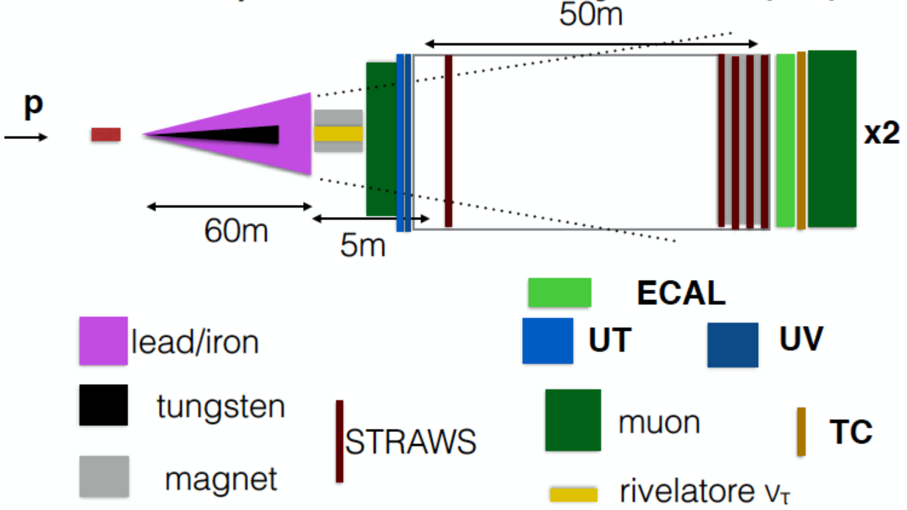


Energy: 400 GeV, power: 750 kW

$\mathbf{4.5 \times 10^{13}}$ protons per pulse (upgrade to $\mathbf{7 \times 10^{13}}$), every 6 s

CNGS: $\mathbf{4.5 \times 10^{19}}$ protons on target per year (200 days, 55% machine availability, 60% of the SPS supercycle

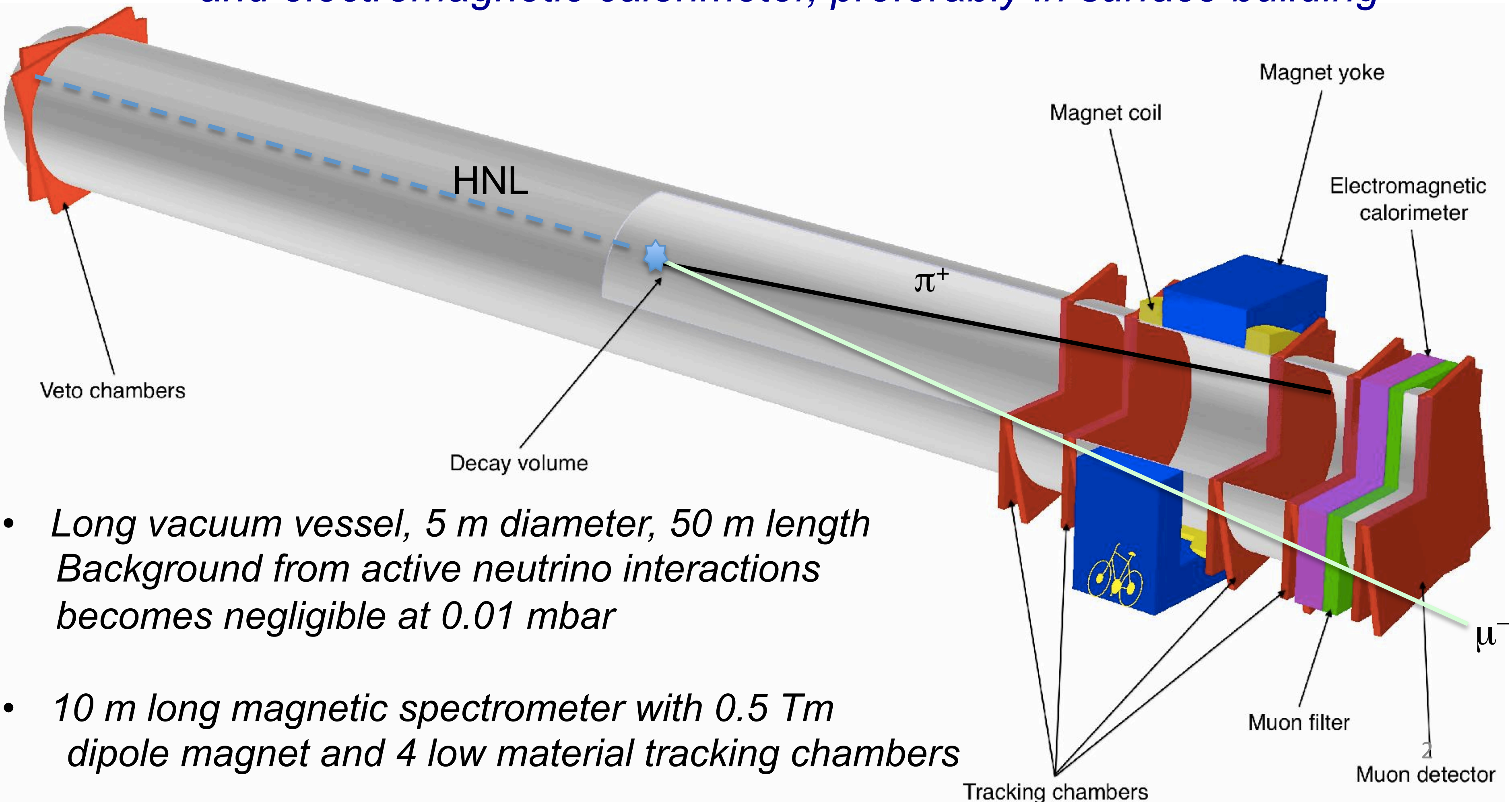
New possible layout (iii)



Initial detector concept for EOI

- *Reconstruction of the HNL decays in the final states: $\mu^-\pi^+$, $\mu^-\rho^+$ & $e^-\pi^+$*

→ *Requires long decay volume, magnetic spectrometer, muon detector and electromagnetic calorimeter, preferably in surface building*

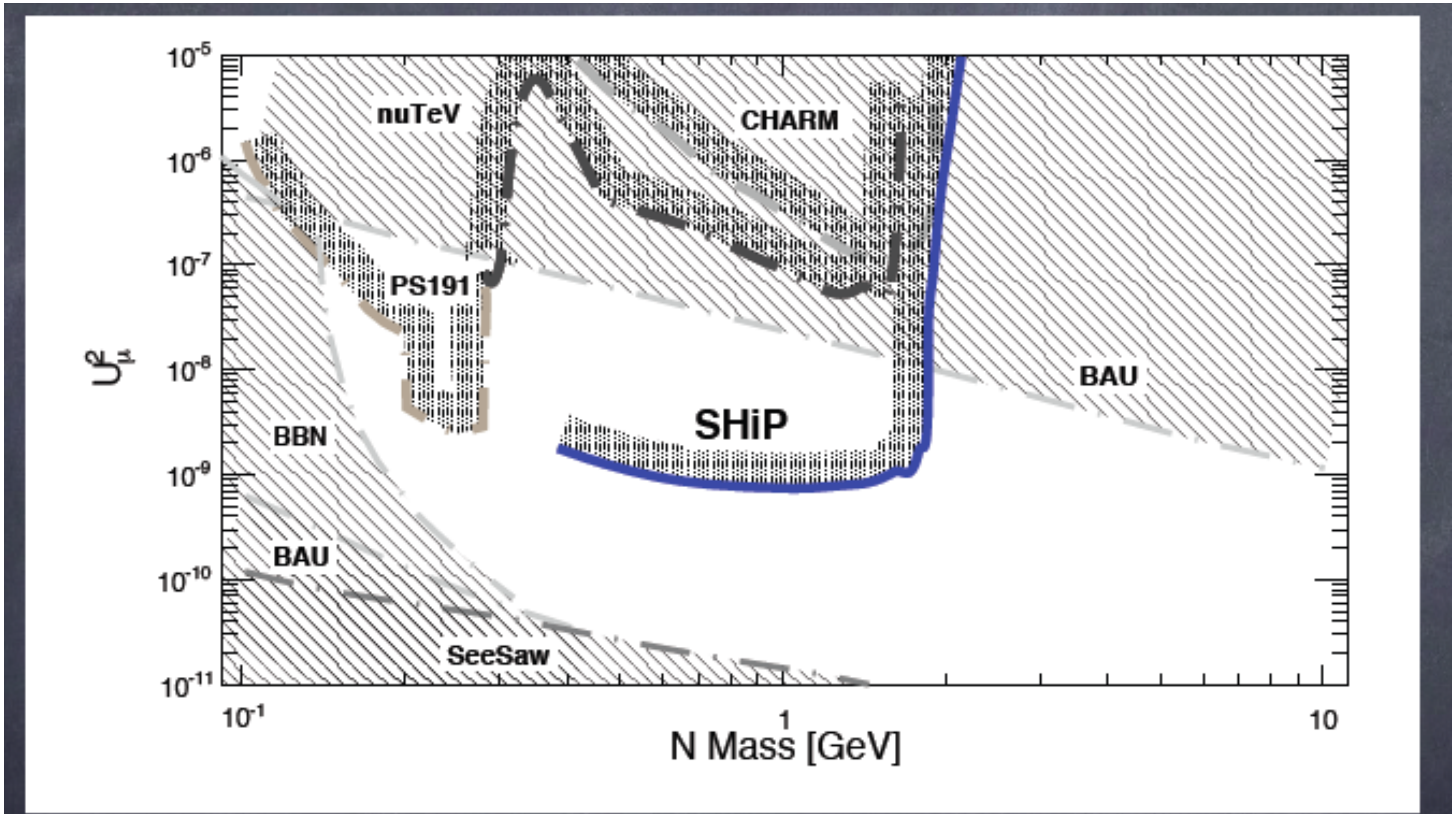


- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*

- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

Sensitivity to HNL: U_μ

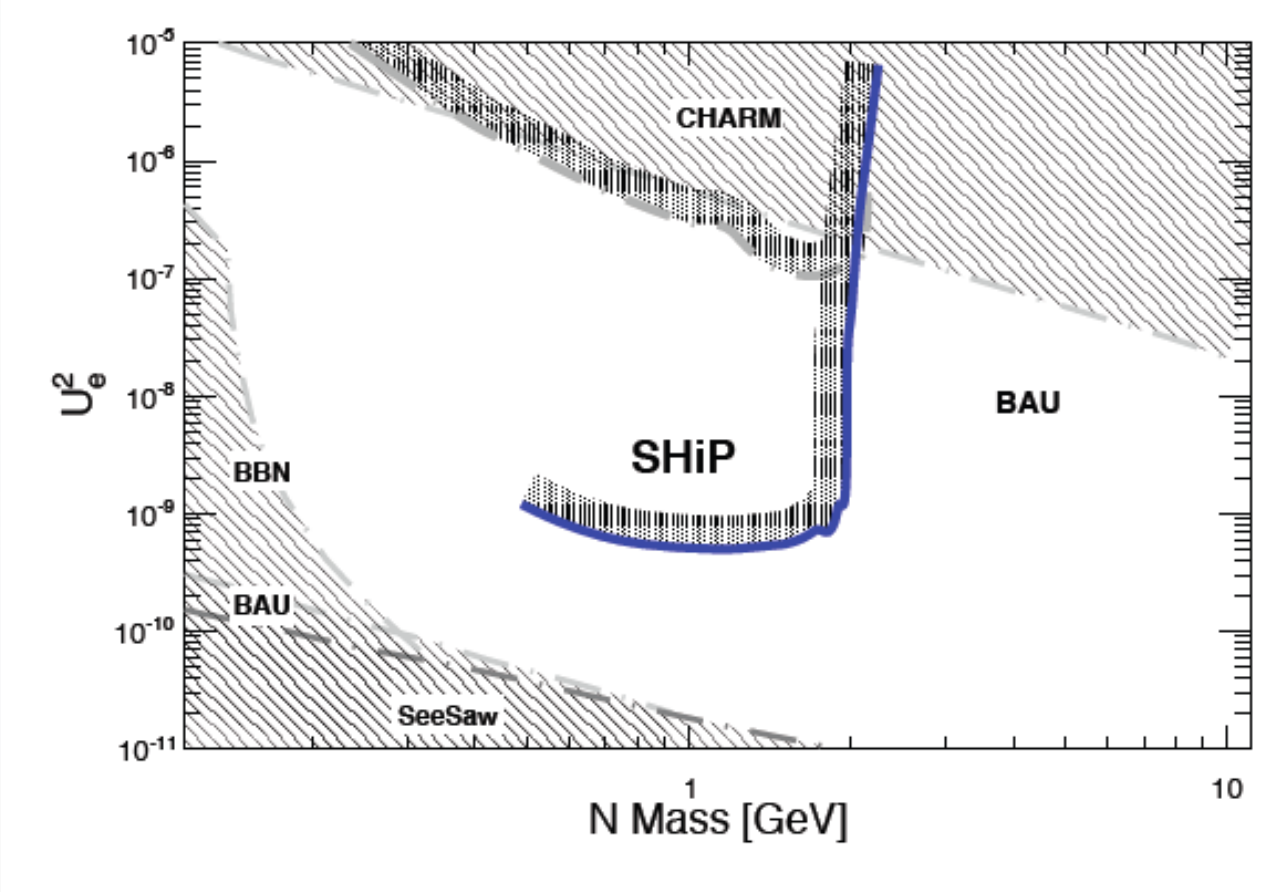
$U^2 = U_e^2 + U_\mu^2 + U_\tau^2$



Normal Hierarchy $U_\mu^2 = 0.8$

Decay Channels: $N \to \pi\mu$ and $N \to \mu\rho$

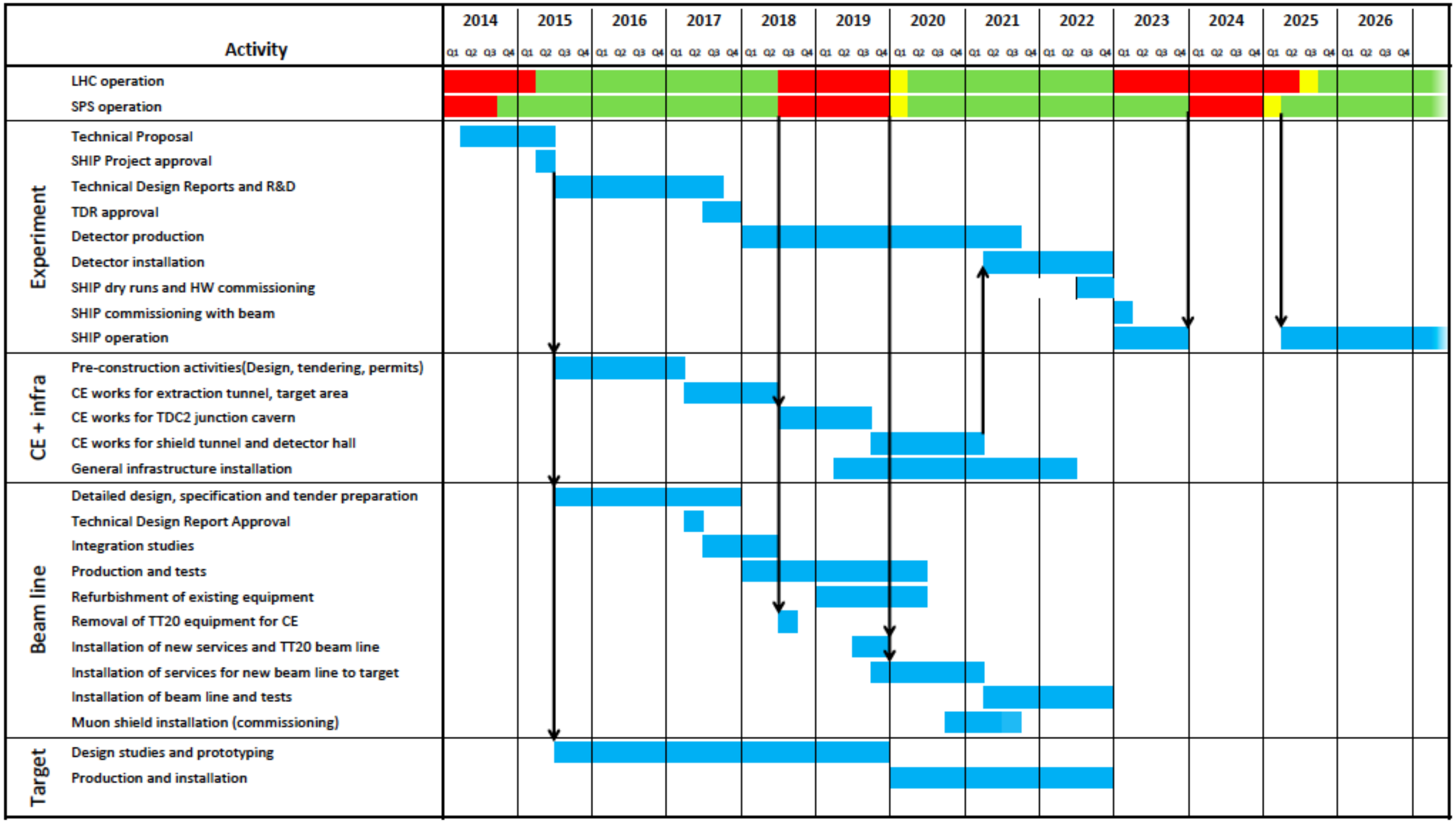
Sensitivity to HNL: U_e



Inverted Hierarchy $U_e^2 = 0.9$

Decay Channels: $N \to \pi e$ and $N \to e\rho$

Planning schedule of the SHIP facility



LHC operation
SPS operation

Technical Proposal
SHIP Project approval
Technical Design Reports and R&D
TDR approval
Detector production
Detector installation
SHIP dry runs and HW commissioning
SHIP commissioning with beam
SHIP operation

Pre-construction activities(Design, tendering, permits)
CE works for extraction tunnel, target area
CE works for TDC2 junction cavern
CE works for shield tunnel and detector hall
General infrastructure installation

Detailed design, specification and tender preparation
Technical Design Report Approval
Integration studies
Production and tests
Refurbishment of existing equipment
Removal of TT20 equipment for CE
Installation of new services and TT20 beam line
Installation of services for new beam line to target
Installation of beam line and tests
Muon shield installation (commissioning)

Design studies and prototyping
Production and installation

A few milestones:

- ✓ ***Form SHIP collaboration*** → ***June-September 2014***
- ✓ ***Technical proposal*** → ***2015***
- ✓ *Technical Design Report* → *2018*
- ✓ *Construction and installation* → *2018 – 2022*
- ✓ *Commissioning* → *2022*
- ✓ *Data taking and analysis of 2×10^{20} pot* → *2023 - 2027*

Expectations for TLEP

Processes: $Z \to N\nu, \quad N \to l q \bar{q}$ (lepton + meson, lepton + 2 quark jets),

$$BR(Z \to \nu N) \simeq BR(Z \to \nu\nu) U^2, \qquad \Gamma_N \simeq \frac{G_F^2 M^5}{192\pi^3} U^2 A$$

Coefficient A counts the number of open channels, $A \sim 10$ for $M > 10$ GeV

Assumptions: 10^{12} Z-decays in 3 m detector.

- “short lived” N: decay length < 3 m $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 10^{-10}$ as the sensitivity will grow as the number of Z-decays! This works for $M \gtrsim 20$ GeV.
- “long lived” N: decay length exceeds the size of the detector $\Longrightarrow$ constraint on U^2 may go down to $U^2 < 4 \times 10^{-8}$ as the sensitivity will grow as the square root of the number of Z-decays. This works for lighter HNL.

FCC-ee for 10^{12} Z

very preliminary

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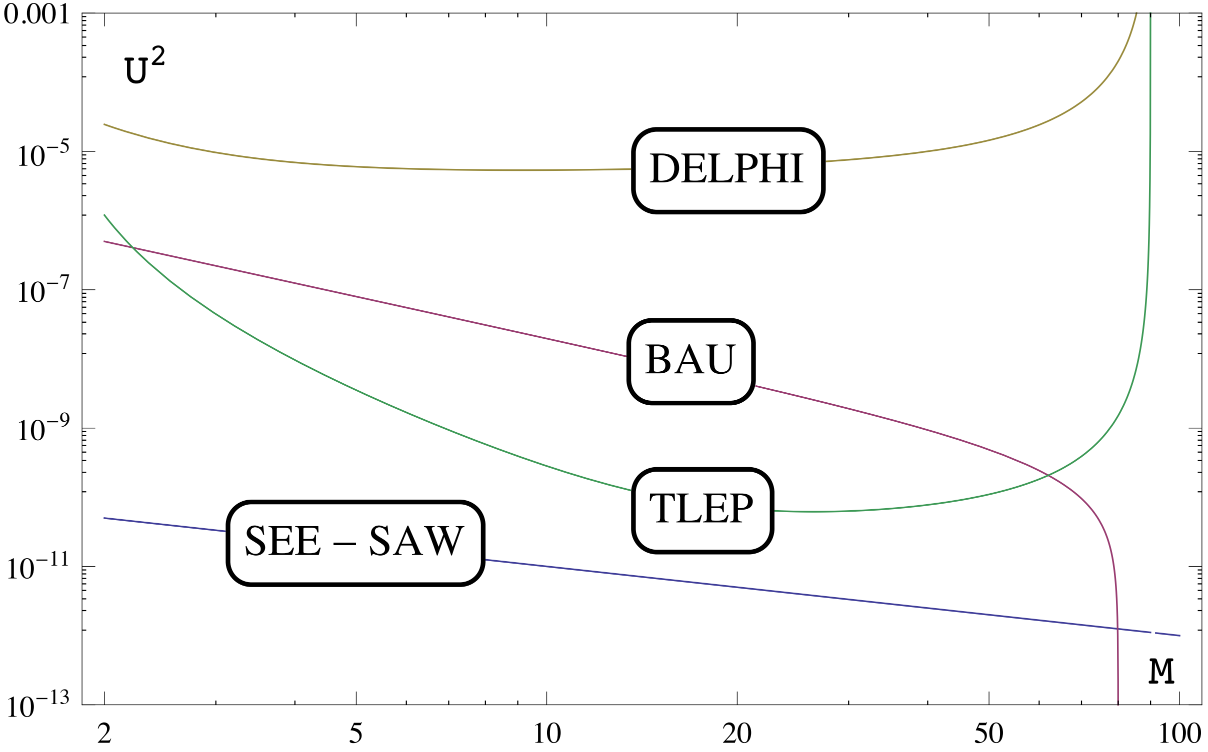

Conclusions

- Heavy neutral leptons can be a key to (almost all) BSM problems:
  - neutrino masses and oscillations
  - dark matter
  - baryon asymmetry of the universe
- They can be found in Space and on the Earth
  - X-ray satellites - Astro H
  - proton fixed target experiment - SHIP, $M \lesssim 2$ GeV
  - collider experiments at FCC-ee in Z-peak, $M \gtrsim 2$ GeV

νMSM and observations

No deviations from SM at LHC@8 TeV	structure of νMSM	OK
No deviations from SM at LHC@14 TeV	structure of νMSM	?
SM Higgs boson with $M_H > 129 \pm 2$ GeV	Higgs inflation	OK within 2σ
SM Higgs boson with $M_H = 129 \pm 2$ GeV	asymptotic safety	OK within 2σ
No WIMPS	structure of νMSM	OK, (DAMA ?)
Unitarity of PMNS matrix	structure of νMSM	OK
no light sterile ν	structure of νMSM	LSND (?)
neutrino mass $m_1 \lesssim 10^{-5}$ eV	dark matter	OK (K-K?)
$1.3~\mathrm{meV} < m_{\beta\beta} < 50~\mathrm{meV}$	dark matter	OK (K-K?)
No visible $\mu \to e\gamma,~\mu \to 3e, etc$	BAU	OK
$N_\nu = 3$	structure of νMSM	OK, Planck
spectral index $n_s = 0.967$	Higgs inflation	OK, Planck
small tensor to scalar ratio	Higgs inflation	OK, Planck
no non-Gaussianities	Higgs inflation	OK, Planck

(Critical Higgs Inflation - r can be large, Bezrukov, MS)