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Sterile Neutrinos as the Origin of Dark and Baryonic Matter

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ON PARTICLE PHYSICS AND QUANTUM FIELD THEORY

Indirect Searches for New Physics:
Fifth Forces, Scalars and Massive Neutrinos

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- The Standard Model in now complete: the last particle - Higgs boson, predicted by the SM, has been found

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The theory is mathematically consistent and does not lose predictability up to very high energies $M_P \sim 10^{19}$ GeV

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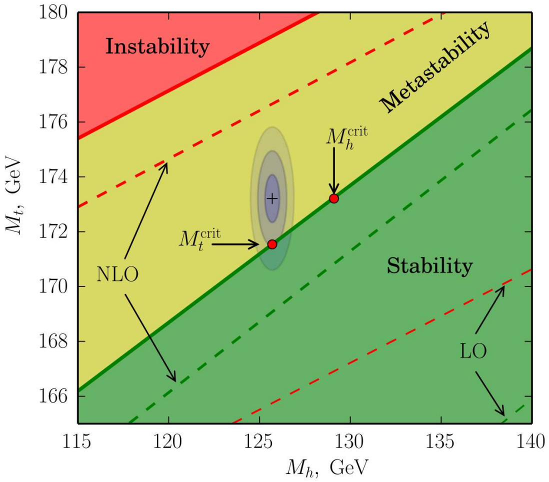

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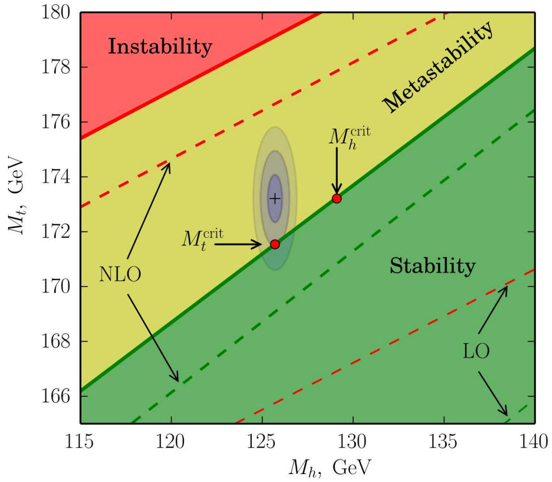


How to reconsile this with evidence for new physics?

Experimental evidence for new physics beyond the Standard Model:

- Observations of neutrino oscillations (in the SM neutrinos are massless and do not oscillate)
- Evidence for Dark Matter (SM does not have particle physics candidate for DM).
- No antimatter in the Universe in amounts comparable with matter (baryon asymmetry of the Universe is too small in the SM)
- Cosmological inflation is absent in canonical variant of the SM
- Accelerated expansion of the Universe (?) - though can be "explained" by a cosmological constant.

Theoretical prejudice for new physics beyond the Standard Model: WHY questions

- Cosmological constant problem: Why $\epsilon_{vac}/M_{Pl}^4 \lll 1$?
- Hierarchy problem: Why $M_W/M_{Pl} \ll 1$?
- Stability of the Higgs mass against radiative corrections.
- Strong CP-problem: Why $\theta_{QCD} \ll 1$?
- Fermion mass matrix: Why $m_e \ll m_t$?
- ...

Where is new physics?

Only at the Planck scale?

Does not work: neutrino masses from five-dimensional operator

$$\frac{1}{M_P} A_{\alpha\beta} \left(\bar{L}_\alpha \tilde{\phi}\right) \left(\phi^\dagger L^c_\beta\right)$$

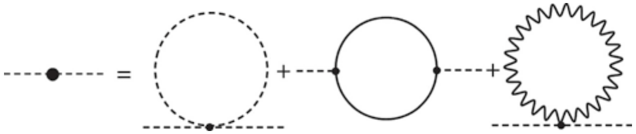
suppressed by the Planck scale are too small, $m_\nu < 10^{-5}$ eV.

Below the Planck scale, but where?

- Neutrino masses and oscillations: the masses of right-handed see-saw neutrinos can vary from $\mathcal{O}(1)$ eV to $\mathcal{O}(10^{15})$ GeV
- Dark matter, absent in the SM: the masses of DM particles can be as small as $\mathcal{O}(10^{-22})$ eV (super-light scalar fields) or as large as $\mathcal{O}(10^{20})$ GeV (wimpzillas, Q-balls).
- Baryogenesis, absent in the SM: the masses of new particles, responsible for baryogenesis (e.g. right-handed neutrinos), can be as small as $\mathcal{O}(10)$ MeV or as large as $\mathcal{O}(10^{15})$ GeV
- Higgs mass hierarchy : models related to SUSY, composite Higgs, large extra dimensions require the presence of new physics right above the Fermi scale, whereas the models based on scale invariance (quantum or classical) may require the absence of new physics between the Fermi and Planck scales

Arguments for absence of new heavy particles above the Fermi scale

- Stability of the Higgs mass against radiative corrections

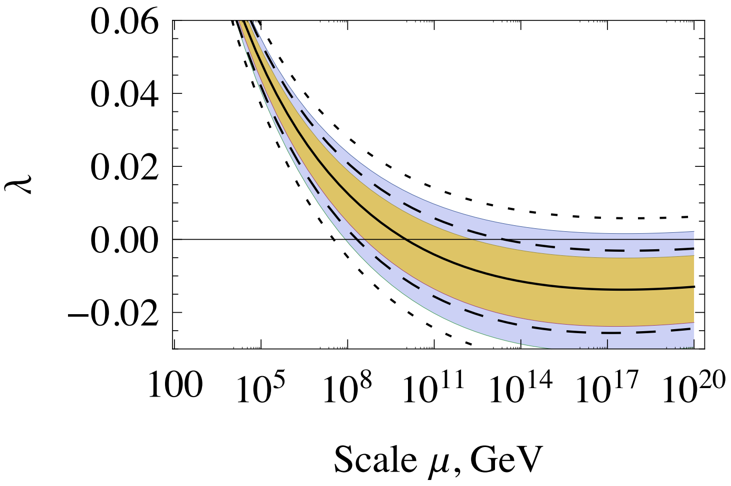


$$\delta m_H^2 \simeq \alpha_{GUT}^n M_{heavy}^2$$

No heavy particles - no large contributions - no fine tuning

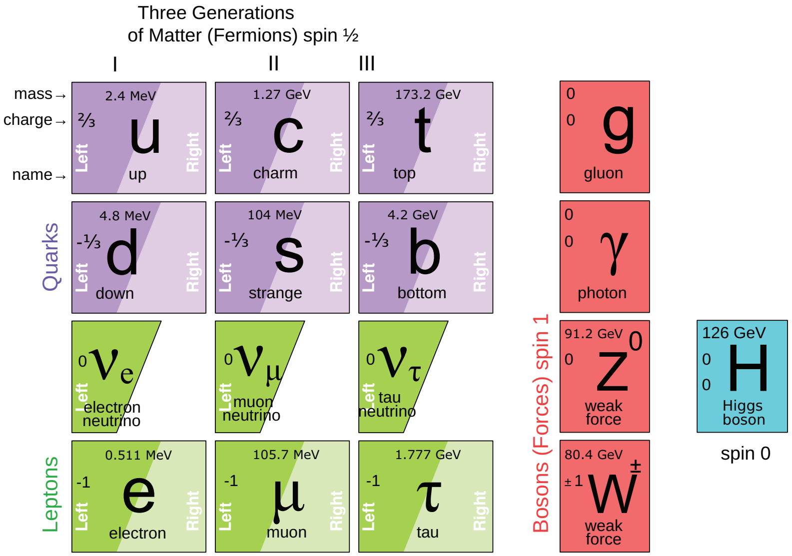
- Higgs self coupling $\lambda \approx 0$ at the Planck scale (criticality of the SM - asymptotic safety?). This is violated if new particles contribute to the evolution of the SM couplings.

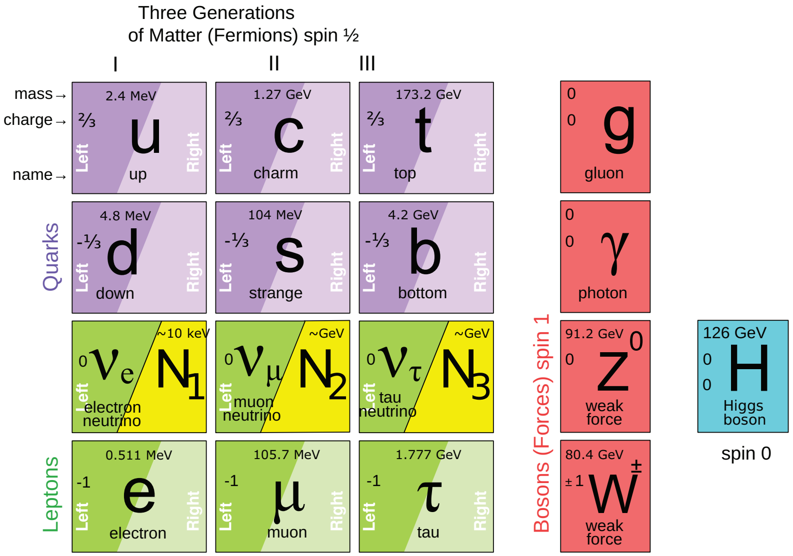
Higgs mass M_h=125.3±0.6 GeV



Then all the experimental BSM problems should be explained by light particles!

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





N = Heavy Neutral Lepton - HNL

Role of N_1 with mass in keV region: dark matter

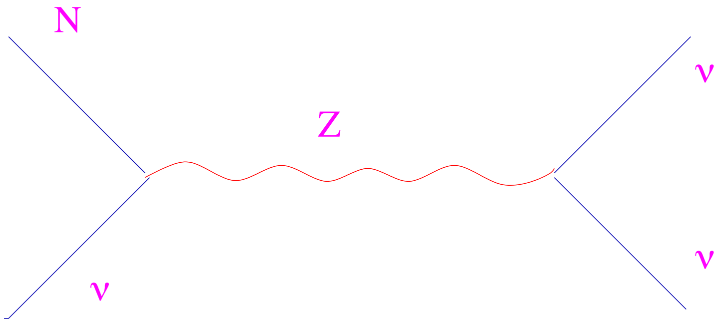
Role of $N_2,\ N_3$ with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

What should be the properties of $N_{1,2,3}$ 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:

$$\tau_{N_1} = 5\times10^{26}\,\text{sec}\left(\frac{1\text{keV}}{M_1}\right)^5\left(\frac{10^{-8}}{\Theta^2}\right)$$

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

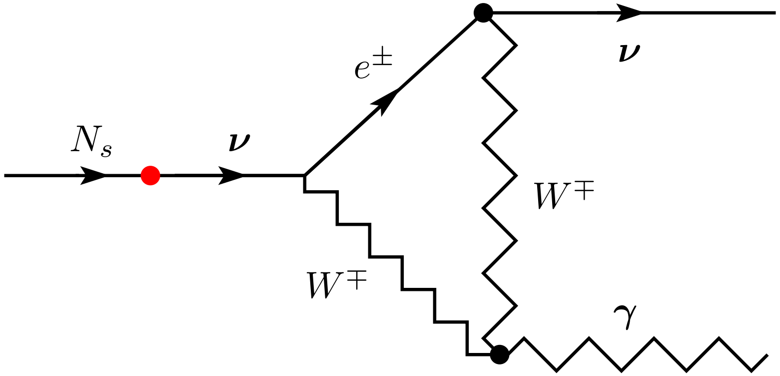
Dark Matter candidate: N_1

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

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

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

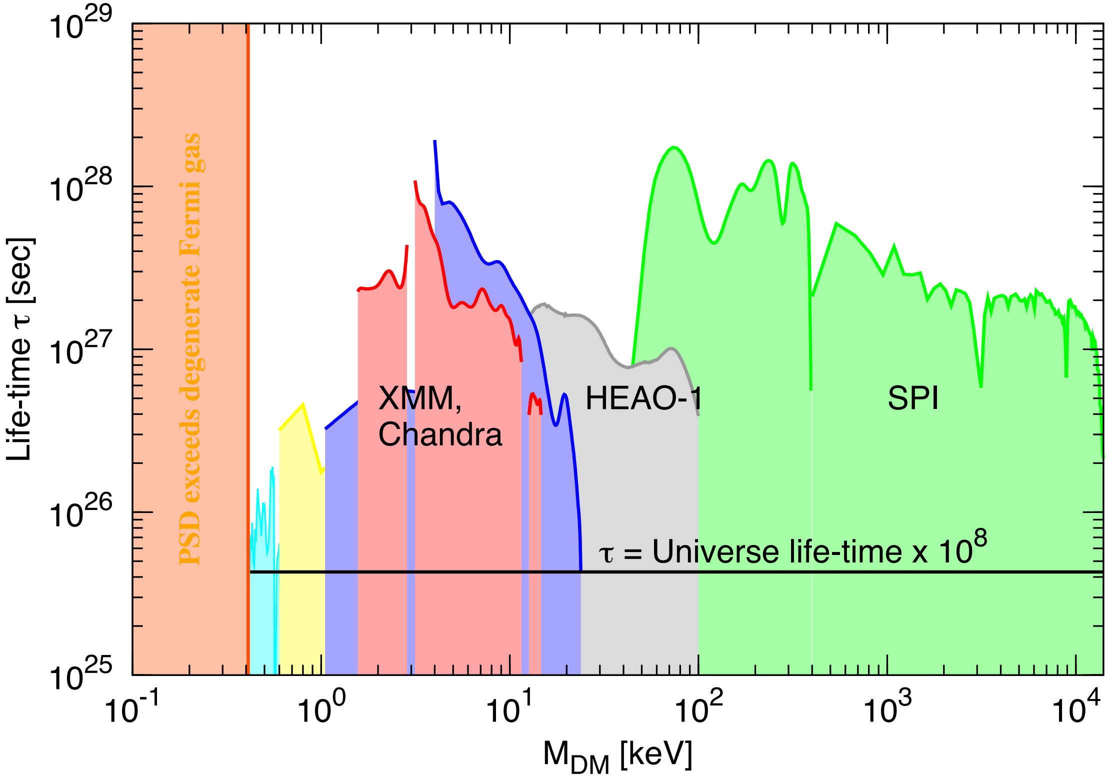
Production rate depends on Yukawa couplings and on lepton asymmetry.

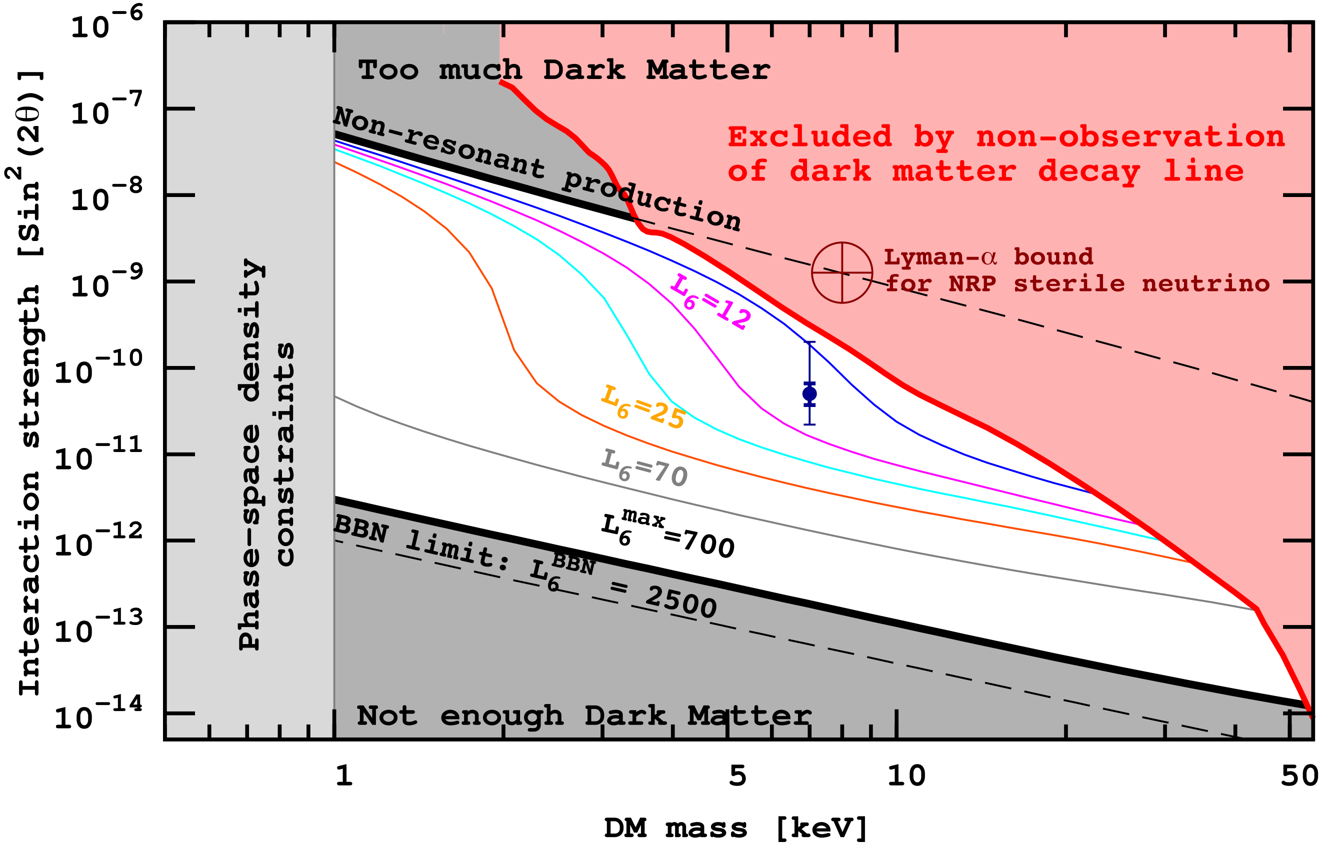
Note: DM sterile neutrino does not contribute to the number of relativistic species! Perfect agreement with Planck measurements.

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 $l\bar{l} \to \nu N_1, \quad q\bar{q} \to \nu N_1$ 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).

Available X-ray satellites:
Suzaku, XMM-Newton, Chandra,
INTEGRAL, NuStar





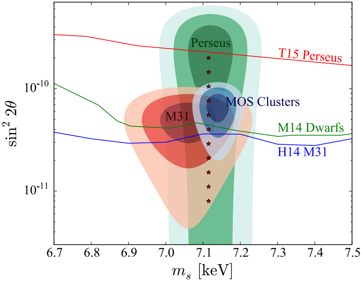
Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters. E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein, S. W. Randall. e-Print: arXiv:1402.2301

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

Subsequent works

For overview see e.g. [1602.04816] “A White Paper on keV Sterile Neutrino Dark Matter”

- Subsequent works confirmed the presence of the 3.5 keV line in some of the objects
  Boyarsky O.R.+, Iakubovskyi+; Franse+; Bulbul+; Urban+; Cappelluti+
- challenged it existence in other objects
  Malyshev+; Anderson+; Tamura+; Sekiya+
- argued astrophysical origin of the line
  Gu+; Carlson+; Jeltema & Profumo; Riemer-Sørensen; Phillips+



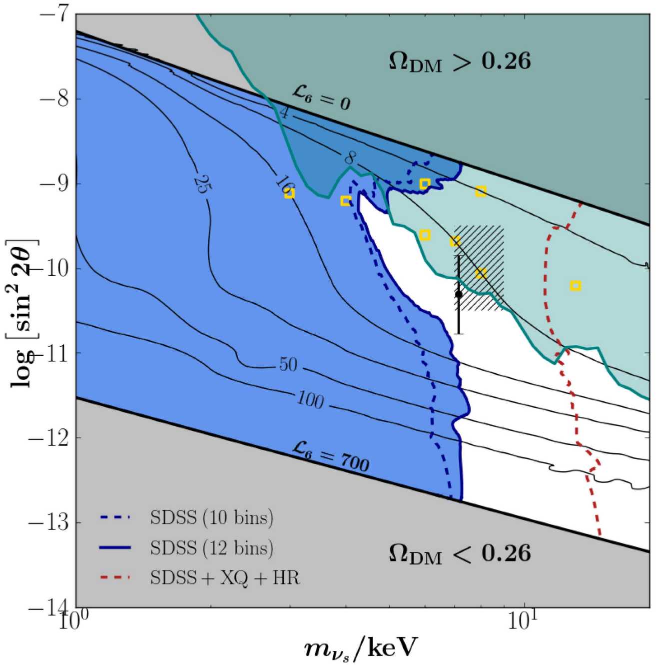
[1507.06655]

- No common explanation for every detection and non-detection
- . . . apart from decaying dark matter signal
  - . . . given uncertainties of our knowledge of the Dark Matter content in individual objects

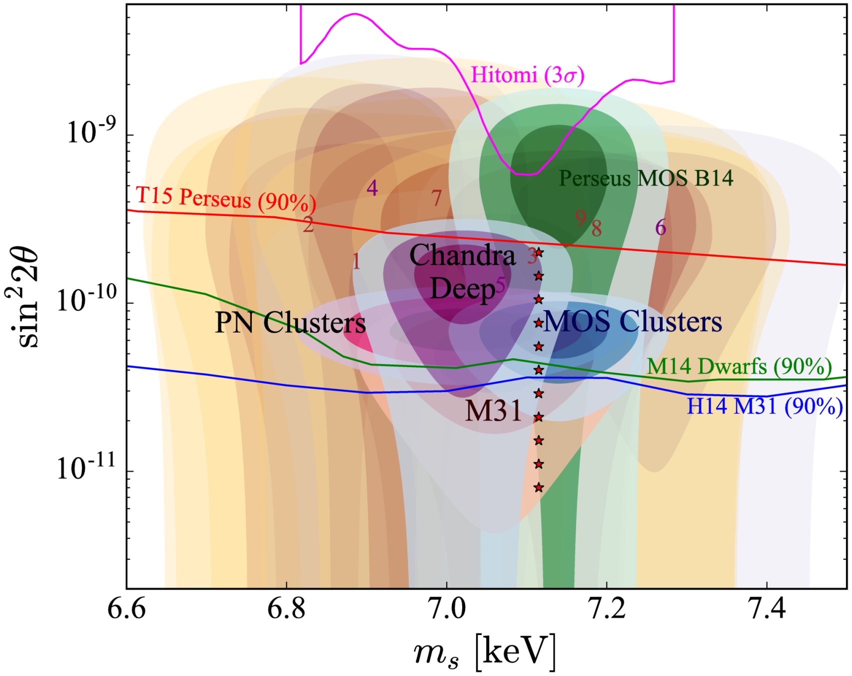
Status of sterile neutrino dark matter N_1

Decaying DM: $N_1 \to \gamma\nu$

3.5 keV line: E. Bulbul et al, Boyarsky et al



1706.03118, Baur et al.



1705.01837 Abazajian

Future of decaying dark matter searches in X-rays

Another Hitomi (around 2020)

It is planned to send a replacement of the Hitomi satellite

Microcalorimeter on sounding rocket (2019)

- Flying time $\sim 10^2$ sec. Pointed at GC only
- Can determine line's position and width

Athena+ (around 2028)

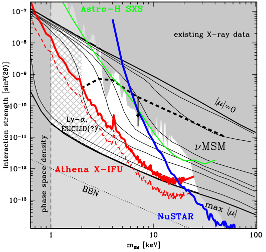
- Large ESA X-ray mission with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)
- Super spectral resolution

"Dark matter astronomy era" begins?

Spaceflight Now
@SpaceflightNow

JAXA, NASA approve replacement mission for Japan's failed Hitomi X-ray astronomy satellite. spaceflightnow.com/2017/07/06/jax …

4:34 PM - 7 Jul 2017



Baryon asymmetry

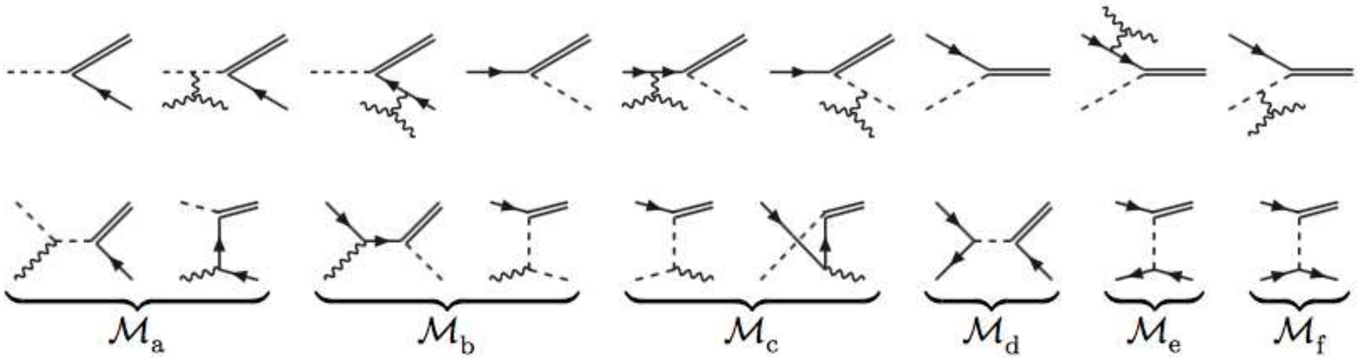
Sakharov conditions:

- Baryon number violation - OK due co complex vacuum structure in the SM and chiral anomaly
- CP-violation - OK due to new complex phases in Yukawa couplings
- Deviations from thermal equilibrium - OK as HNL are out of thermal equilibrium for $T > \mathcal{O}(100)$ GeV

Baryon asymmetry

Creation of baryon asymmetry - a complicated process involving creation of HNLs in the early universe and their coherent CP-violating oscillations, interaction of HNLs with SM fermions, sphaleron processes with lepton and baryon number non-conservation

Akhmedov, Rubakov, Smirnov; Asaka, MS



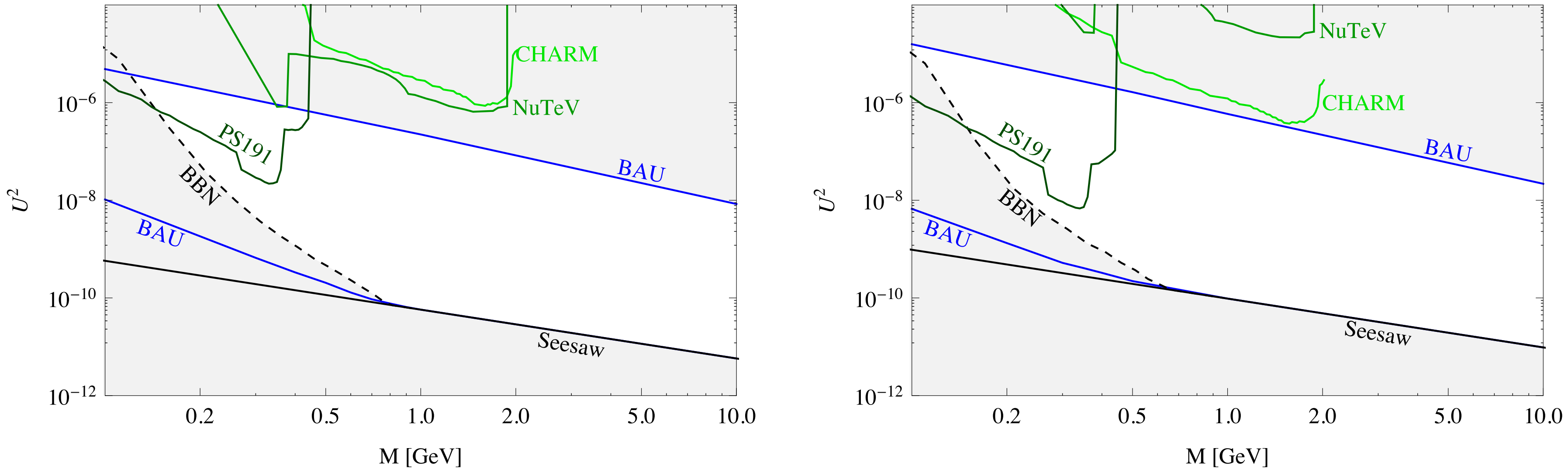
Resummation, hard thermal loops, Landau-Pomeranchuk-Migdal effect, etc. Ghiglieri, Laine. How to describe these processes is still under debate, but the consensus is that it works and is testable.

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

Baryon asymmetry: HNLs $N_{2,3}$



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 '12).

Baryon asymmetry: HNLs $N_{2,3}$

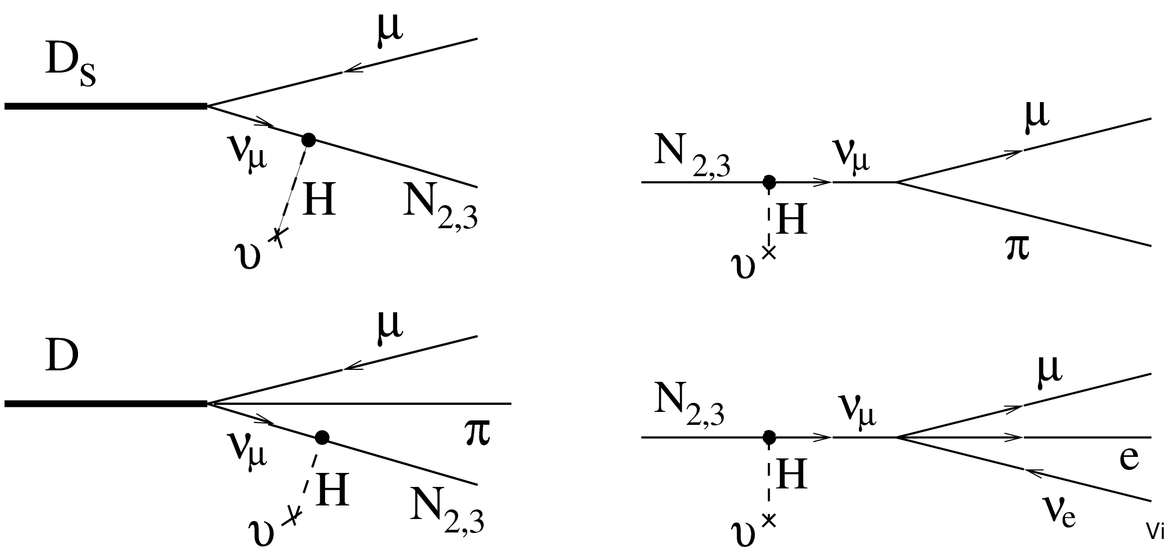
Similar results: recent works by

- Abada, Arcadia, Domcke, Lucente ’ 15
- Hernández, Kekic, J. López-Pavón, Racker, J. Salvado ’16
- Drewes, Garbrech, Guetera, Klarić ’16
- Hambye, Teresi ’17

Experimental search for HNL

- Production
  - via intermediate (hadronic) state

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



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

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

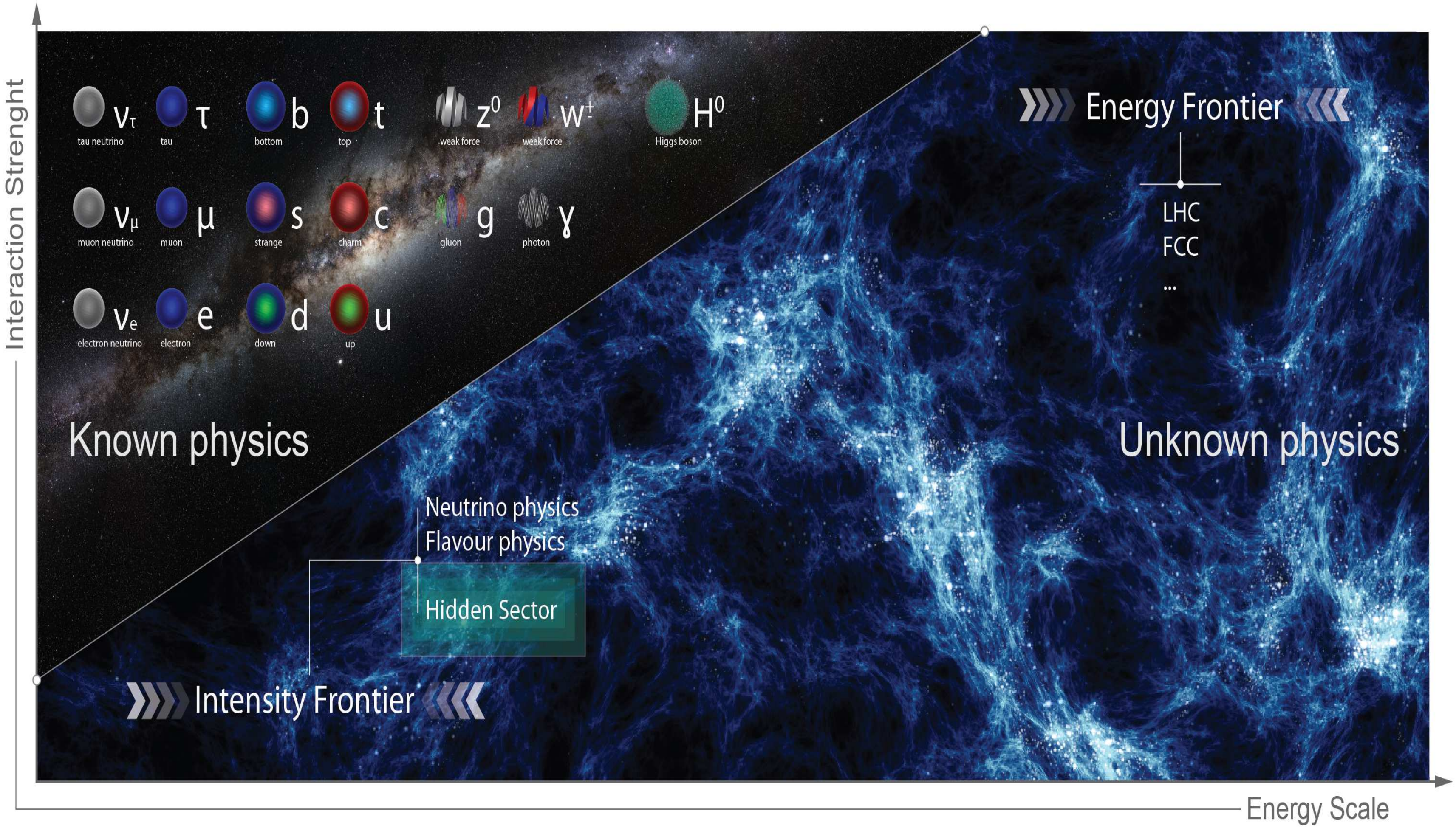
⇓

General beam dump facility: Search for Hidden Particles

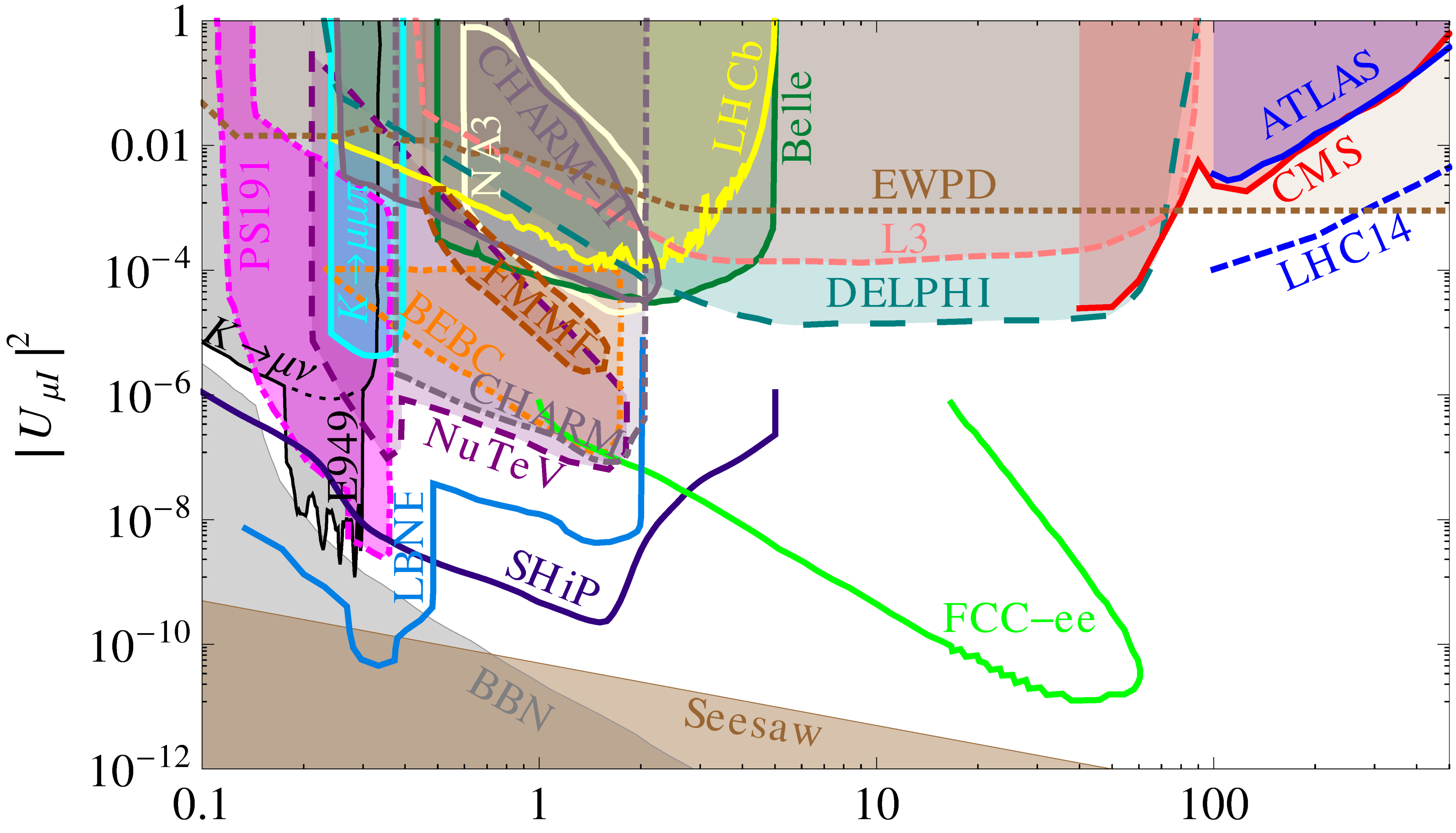
SHiP is currently a collaboration of 46 institutes from 15 countries

SHiP

Hidden sector: very weakly interacting relatively light particles: HNL, dark photon, scalars, ALPS, etc



Current and future sensitivities



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
  - proton fixed target experiment - SHiP, $M \lesssim 2$ GeV
  - collider experiments at LHC, and FCC-ee in Z-peak, $M \gtrsim 2$ GeV