Dark Sectors

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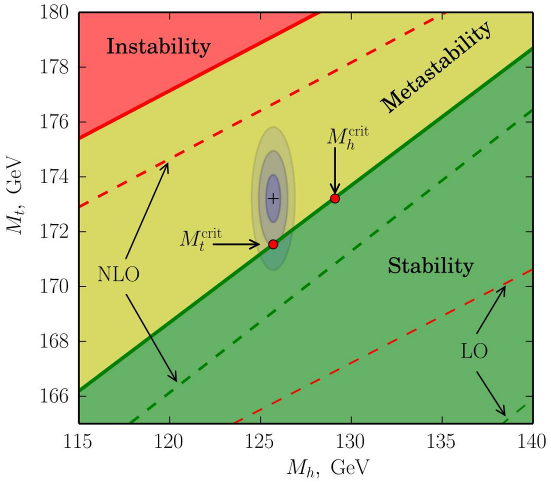
The theory is mathematically consistent and does not lose predictability up to very high energies $M_P \sim 10^{19}$ GeV

1609.02503



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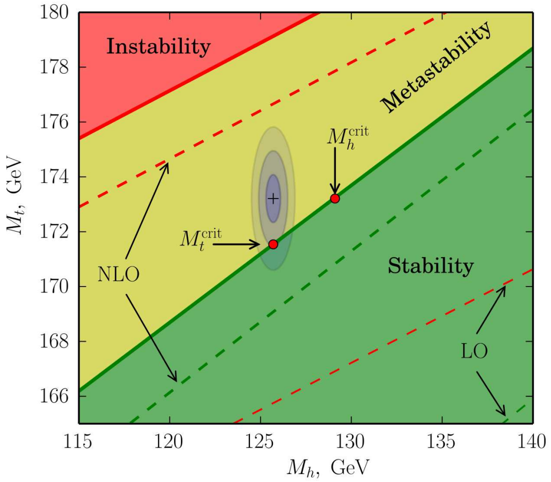


How to reconsile this with evidence for new physics?

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

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

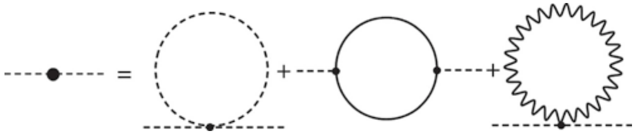
suppressed by the Planck scale are too small, $m_\nu < 10^{-5}$ eV.

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

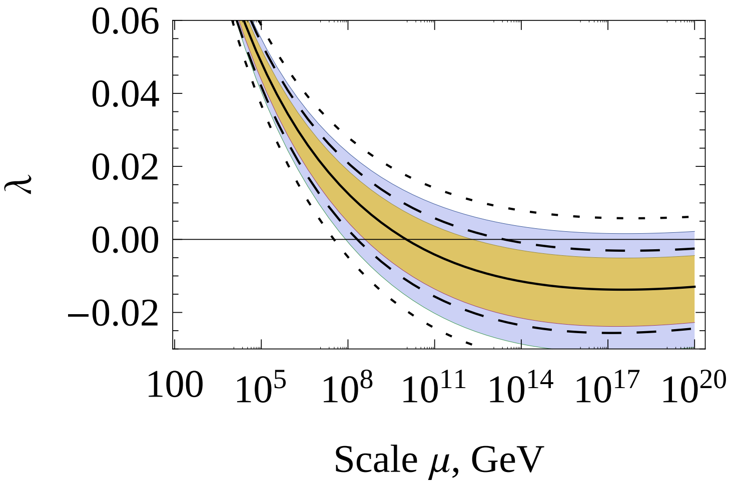


$$\delta m_H^2 \simeq \alpha_{GUT}^n M_{heavy}^2$$

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: DARK SECTORS!

Naturalness:

“Physics at the electroweak scale or right above it should be organised in such a way that quadratic divergencies in the Higgs boson mass are eliminated”.

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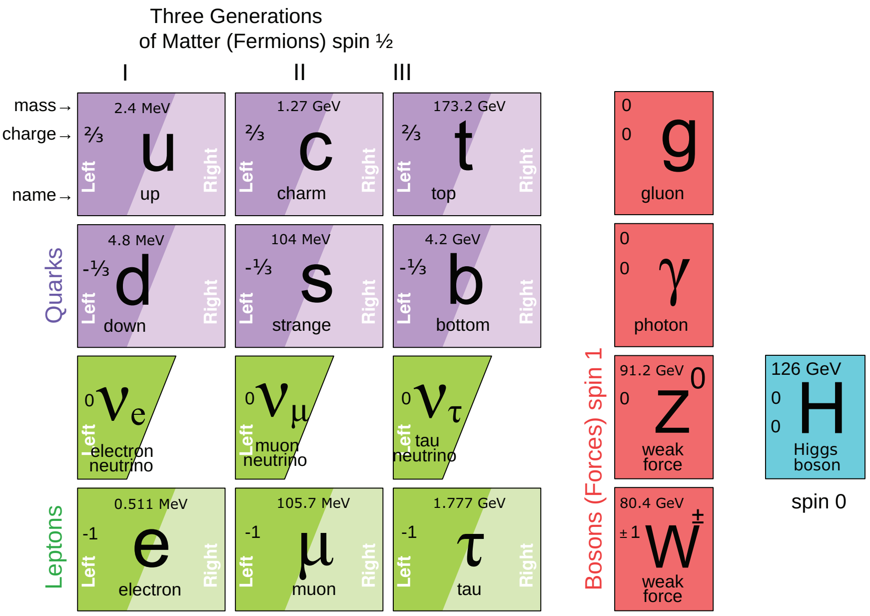
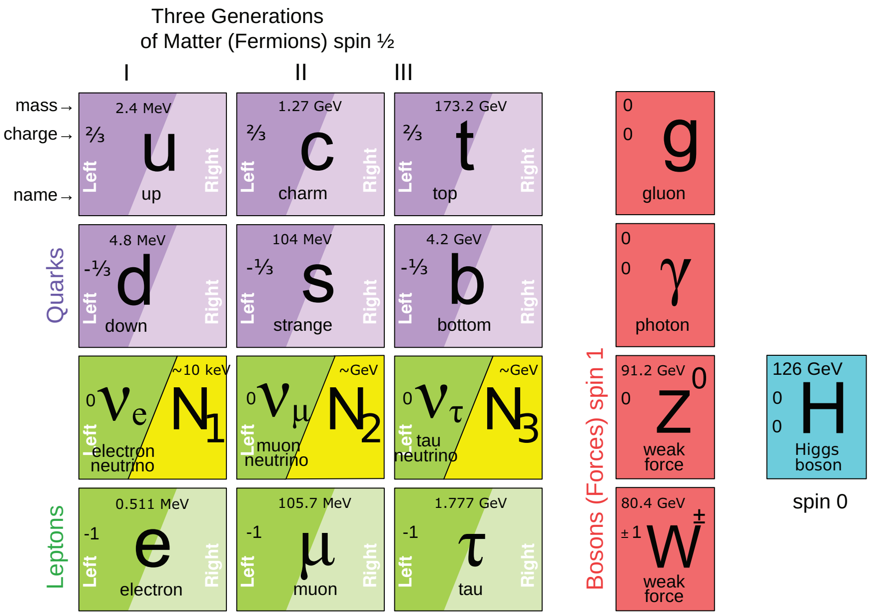
Change of paradigm?

UV physics (gravity?) should be organised in such a way that the Fermi scale is much smaller than the Planck scale

Possible consequences: Dark sectors – light very weakly interacting particles addressing BSM problems (dark matter, neutrinos, baryon asymmetry of the Universe)

Example of “complete” theory: the νMSM





νMSM $\equiv$ Neutrino minimal Standard Model

$\equiv$ Minimal low scale see-saw model with 3 singlet fermions

Role of the Higgs boson: break the symmetry and inflate the Universe

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.

HNLs are just an example of Dark (Hidden) Sector particles, which appear in models with or without new physics above the Fermi scale. They can couple to SM via different “portals” - gauge-invariant operators:

$B_{\mu\nu}$ - vector portal, dimension 2: dark photon

$H^\dagger H$ - scalar portal, dimension 2: new scalars

$H^T L$ - neutrino portal, dimension 5/2: new leptons, HNLs

$G_{\mu\nu}\tilde{G}^{\mu\nu}$ - axion portal, dimension 4, new pseudo-scalars

...

B-hypercharge field, H - Higgs field, L- leptonic doublet

Common feature: relatively light and very weakly interacting

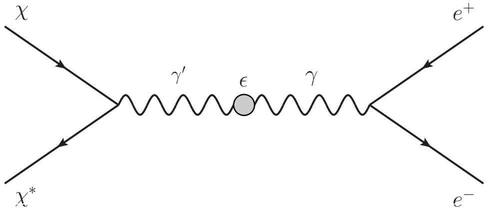
Vector portal

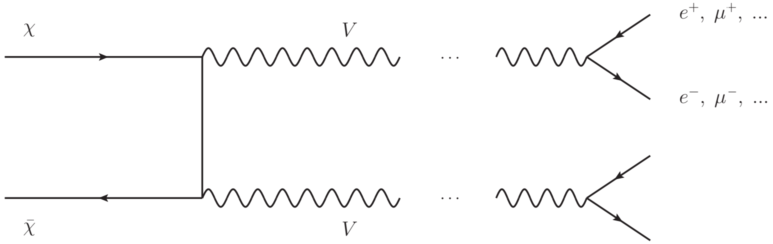
Okun, Voloshin, Holdom, Ellis, Schwarz, Tyupkin, Kolb, Seckel, Turner, Georgi, Ginsparg, Glashow, Foot, Volkas, Blinnikov, Khlopov, Gninenko, Ignatiev, ...

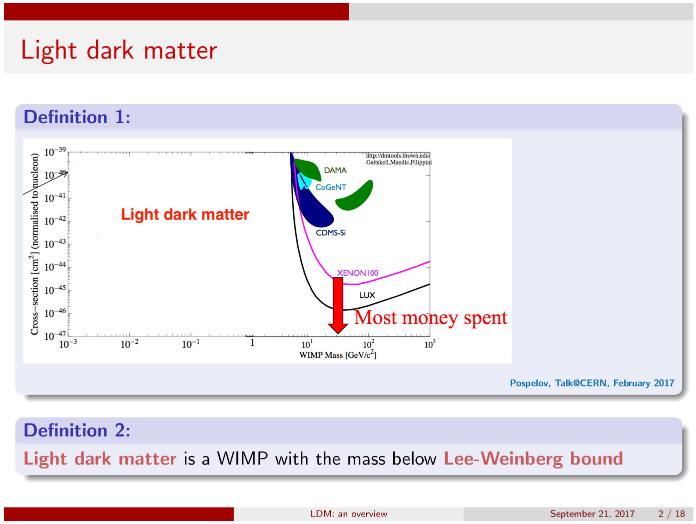
New vector particles: motivations

- Structure of the SM gauge group SU(3)×SU(2)×U(1) may descend from a larger (e.g. GUT) group, and low energy theory symmetric under SU(3)×SU(2)×$[\mathrm{U}(1)]^n$ is possible. Examples: gauging of the $B - L$ “accidental” global symmetry of the SM;
- Left-right symmetric models $[SU(3) \times SU(2) \times U(1)]_{our} \times [SU(3)' \times SU(2)' \times U(1)']_{mirror}$: spontaneous parity violation. Messenger between left and right mirror particles .
- Dark matter hidden sector may have complicated structure, not associated with ideas of mirror symmetry. A possible bridge between hidden and and our world can be the vector portal.

- Mediator of interaction with Dark matter
  - Light dark matter with M as small as few MeV: increase of annihilation cross-section of DM particles.







Light dark matter

Definition 1:

Pospelov, Talk@CERN, February 2017

Definition 2:

Light dark matter is a WIMP with the mass below Lee-Weinberg bound

LDM: an overview September 21, 2017 2 / 18

  - Self-interacting dark matter: core-cusp problem in dwarf galaxies, too-big-to-fail problem (excess of massive sub-halos in N-body simulations of Milky Way type galaxies)

Scalar portal

Patt, Wilczek, Schabinger, Wells, No, Ramsey-Musolf, Walker, Khoze, Ro, Choi, Englert, Zerwas, Lebedev, Mambrini, Lee, Everett, Djouadi, Falkowski, Schwetz, Zupan, Tytgat, Gunion, Haber, Kane, Dawson,...

New scalars: motivations

- LHC: fundamental scalar boson exists in nature. There are many quarks, leptons, vector bosons. Why the Higgs boson should be unique?
- Hierarchy problem: SUSY and extended SUSY, mirror world with twin Higgs, neutral naturalness
- Composite Higgs boson: extra scalar states
- Large extra dimensions: KK scalar modes
- Pseudo-Nambu-Goldstone bosons (PNGB) of a spontaneously broken symmetry
- Flavour problem: familons

- Hidden Valley scenario: low mass hidden sector coupled to the SM through mediators of different nature
- Inflation is most probably driven by a scalar field
- Candidate for dark matter
- Messenger between the visible and dark matter sectors
- Electroweak baryogenesis (new scalar can make the EW phase transition of the first order, resulting in thermal non-equilibrium)
- Neutrino masses: type II see-saw

Axion portal

Weinberg, Wilczek, Witten, Conlon, Arvanitaki, Dimopoulos, Dubovsky,
Kaloper, March-Russell, Cicoli, Goodsell, Lazarides, Shafi, Choi,
Harnik, Kaplan, Espinoza, Quiros, Hooper, Feng...

Axion-like particles and PNGB: motivations

Well known example: axion to solve strong CP-problem

- String theory compactifications: axiverse with ALPs with masses taking values distributed across every scale of energy
- Pseudoscalars in extended Higgs sectors (e.g. NMSSM)
- Large extra dimensions with relatively small fundamental Planck scale
- PNGBs of spontaneously broken global flavour symmetries : familons
- Dark matter - mediation of interactions between SM and DM particles

Typical interaction:

$$\frac{a}{f_A} G_{\mu\nu}\tilde{G}^{\mu\nu}, \quad \frac{\partial_\mu a}{f_A}\bar{\psi}\gamma_\mu\gamma_5\psi, \quad etc$$

Light SUSY particles: motivations

SUSY: general framework for addressing hierarchy problem and Grand Unification. The prejudice that SUSY particles are heavy comes from the minimal models such as MSSM or CMSSM

- Unstable neutralino in models with R-parity breaking (then DM candidates - axino or axion)
- Scalar and pseudoscalar sgoldstinos coming from SUSY breaking (e.g. no-scale SUGRA)
- Pseudo Dirac gauginos χ_1, χ_2: dark matter candidate χ_1
- SUSY partners of axion: axino and saxion
- SUSY partners of dark photons: hidden photinos $\tilde{\gamma}, \tilde{\gamma}', \ldots$ (string theory compactifications)

Common features of hidden particles

Production

- Meson decays
  - Dark photon A': $\eta,\ \rho,\ \pi, \ldots \rightarrow \gamma A'$
  - HNL, neutralino, axino N: $K, D, B \rightarrow N + lepton$
  - scalars, light inflaton, pseudoscalars, sgoldstino X: $K, D, B \rightarrow X + meson$
  - photino $\tilde{\gamma}$: $B \rightarrow K\tilde{\gamma}\tilde{\gamma}$
- Direct production, bremsstrahlung
  - Dark photon A': $q\,\bar{q} \rightarrow A',\ q\,g \rightarrow A'\,q$, $pp \rightarrow ppA'$
  - scalars S: $p + \mathrm{target} \rightarrow S + \ldots$
  - ALPs, saxions a: Drell-Yan $q\bar{q} \rightarrow \gamma^*$, followed by Primakoff $\gamma^* \rightarrow a\gamma$

Common features of hidden particles

Detection

- Hidden particle decays
  - Dark photon A': $A' \to l^+l^-, \;\; A' \to \mathbf{hadrons}$
  - HNL, neutralino, axino N: $N \to meson + lepton, \; \ldots$
  - scalars, light inflaton, pseudoscalars, sgoldstino X: $X \to \gamma\gamma, \; l^+l^-, \; \ldots$
  - hidden photino $\tilde{\gamma}$: $\tilde{\gamma} \to \tilde{\gamma}' + l^+l^-$

Searches for dark sectors

P326 NA62

SHiP
Search for Hidden Particles

DARKLIGHT

Belle II

CMS

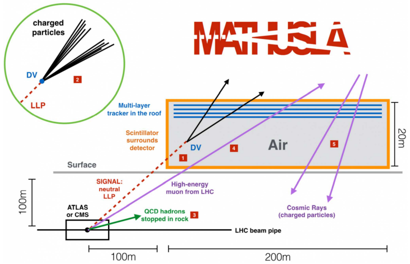
T2K

LHCb

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

ATLAS EXPERIMENT

NA64 Search for dark sectors in missing energy events



FCC hh ee he

Conclusions

The search for new very weakly interacting particles with masses below the Fermi scale, can

- find particles that lead to neutrino masses and oscillations
- find particles that lead to baryon asymmetry of the Universe
- find particles that could inflate the Universe
- shed new light on the properties of dark matter

Conclusions

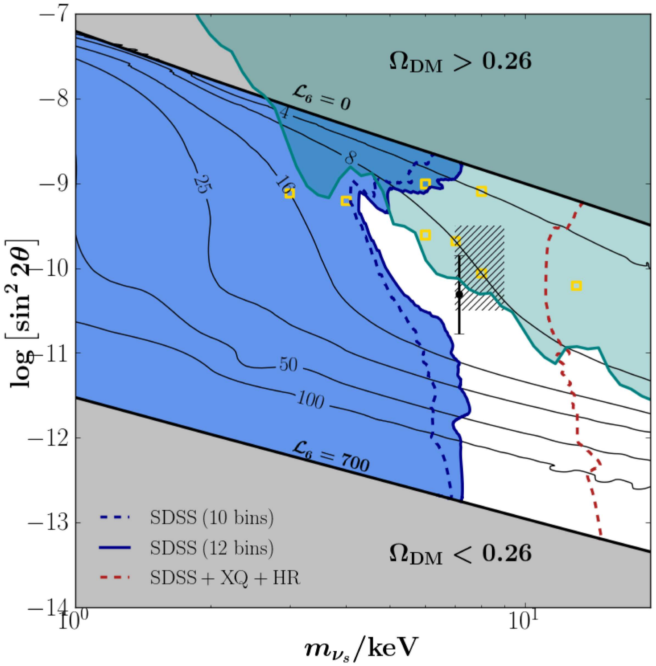
- High energy and high intensity frontier are complimentary:
    - High energy: search for new heavy particles with $\mathcal{O}(1)$ couplings. Low energy SUSY, composite Higgs, large extra dimensions, ... LHC, FCC in hh mode
    - High intensity: indirect search for new heavy particles with couplings $\ll 1$ leading to deviations from the SM through the loops. LHCb, NA62, BELLE, flavour physics experiments,...
    - High intensity: search new light particles with couplings $\ll 1$. Heavy neutral leptons, dark photon, ALPs, ... SHiP, NA62, NA64, FCC in ee mode, ...

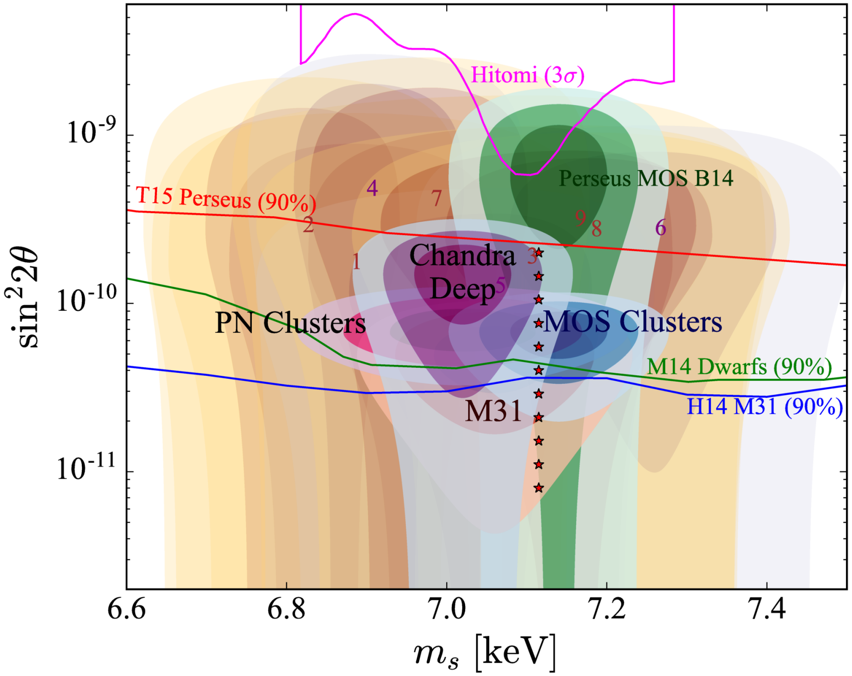
Backup slides

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

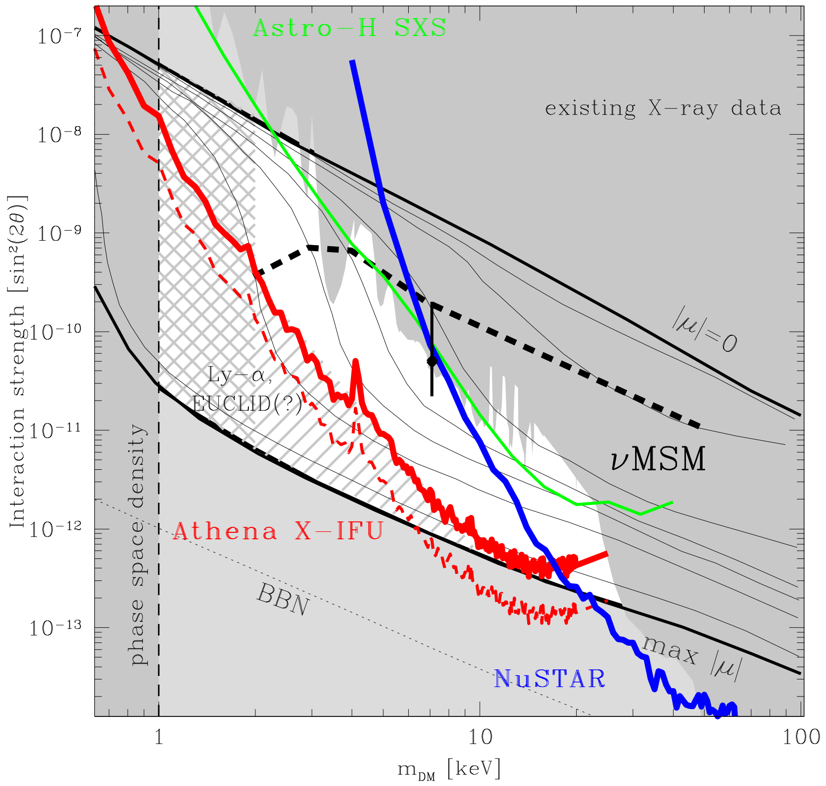




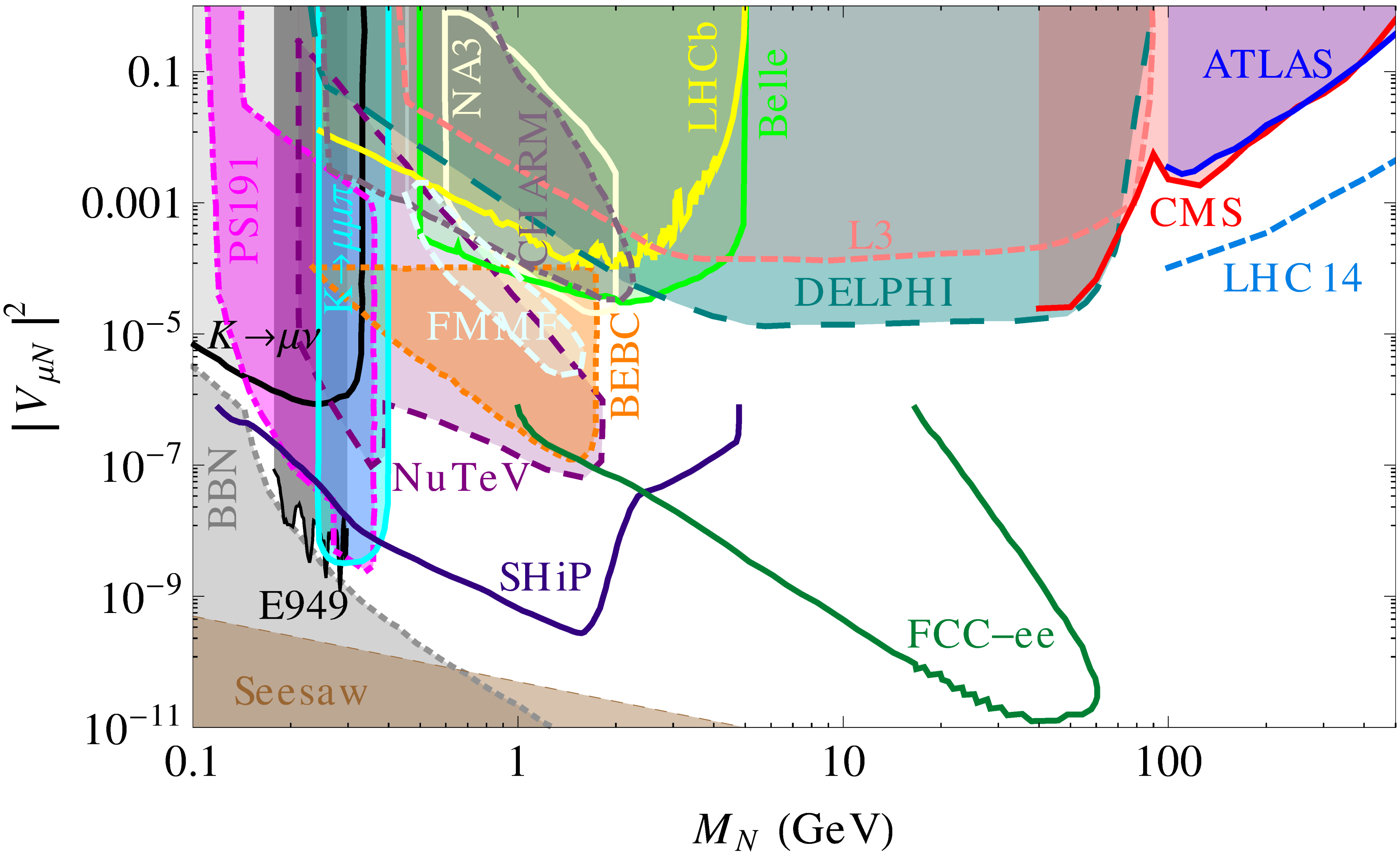
1706.03118, Baur et al.

1705.01837 Abazajian

- HNL (N_1) dark matter searches in X-rays, future after Astro-H (Hitomi) failure
  - Micro-calorimeter on sounding rocket (2018?): instrument with large field-of-view and very high spectral resolution
  - Hitomi 2: X-ray Astronomy Recovery Mission (XARM) (2020?)
  - Large ESA X-ray mission (2028) – Athena + , X-ray spectrometer (X-IFU) with unprecedented spectral resolution



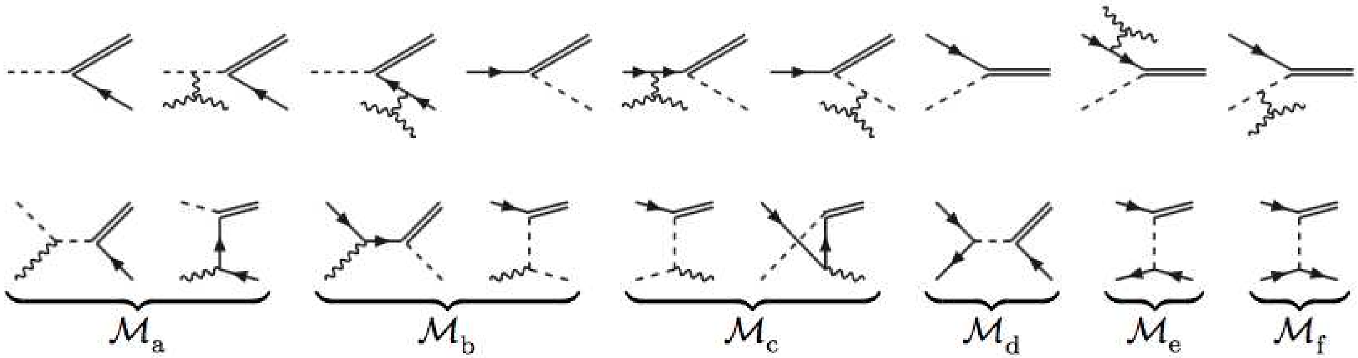
Survey of constraints, $N_{2,3}$



Baryon asymmetry

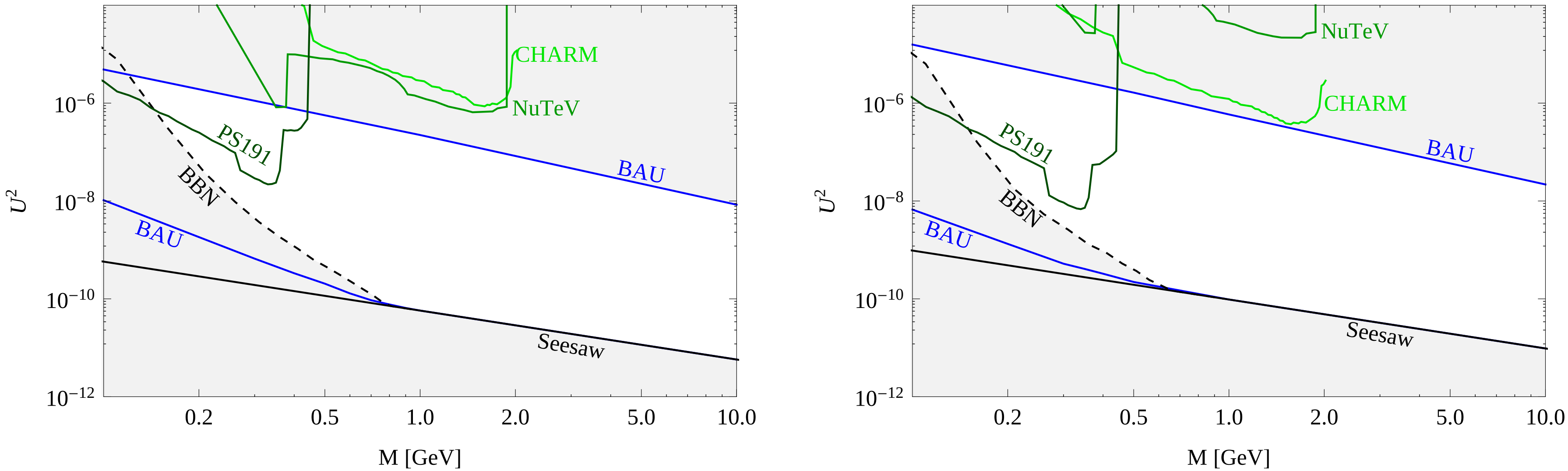
Creation of baryon asymmetry - a complicated process involving creation of HNLs in the early universe and their coherent CP-violating oscillations, interaction of HNLs with SM fermions, sphaleron processes with lepton and baryon number non-conservation

Akhmedov, Rubakov, Smirnov; Asaka, MS



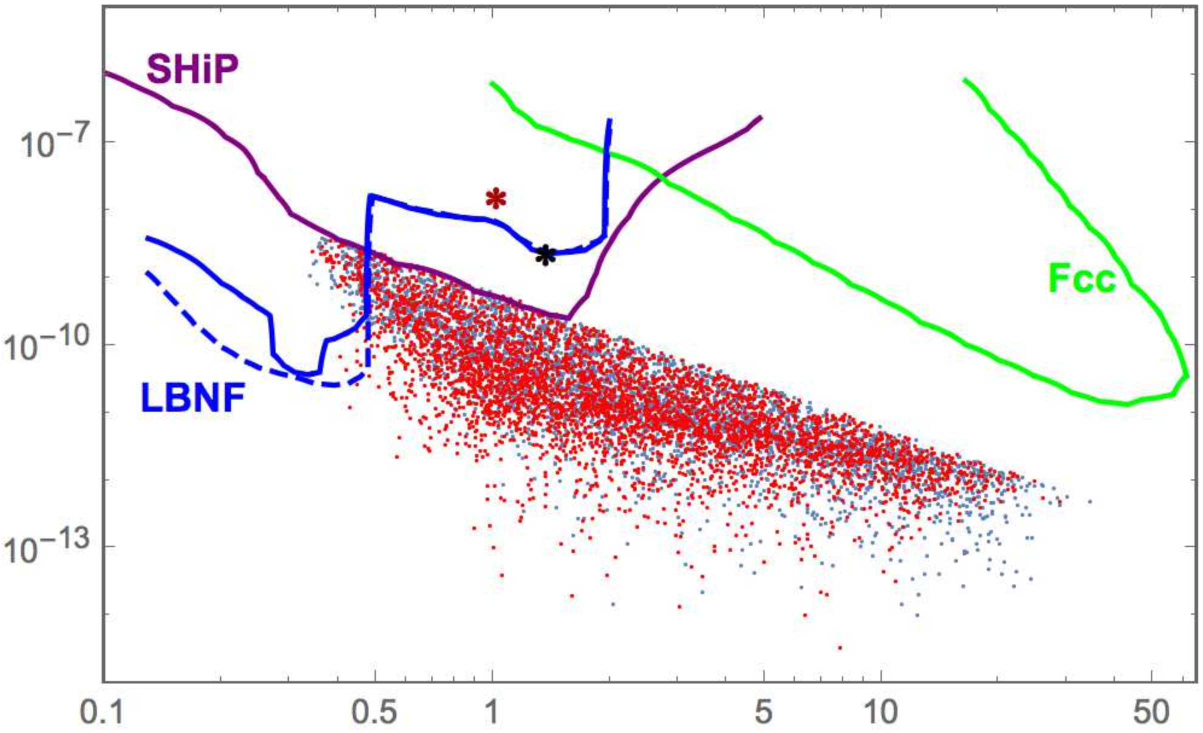
Resummation, hard thermal loops, Landau-Pomeranchuk-Migdal effect, etc. Ghiglieri, Laine. How to describe these processes is still under debate, but the consensus is that it works and is testable at SHiP.

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



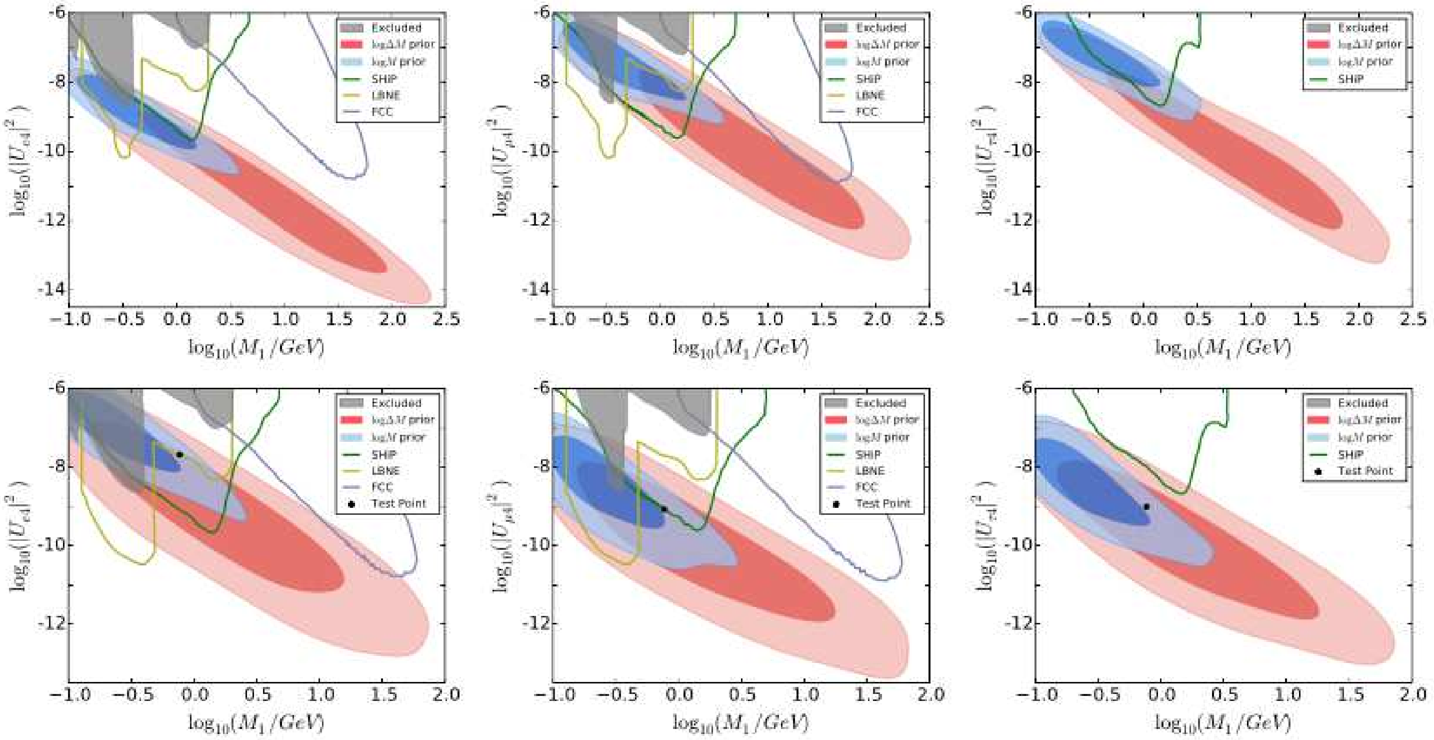
Constraints on U^2 coming from the baryon asymmetry of the Universe, from the see-saw formula, from the big bang nucleosynthesis and experimental searches. Left panel - normal hierarchy, right panel - inverted hierarchy (Canetti, Drewes, Frossard, MS ’12).

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



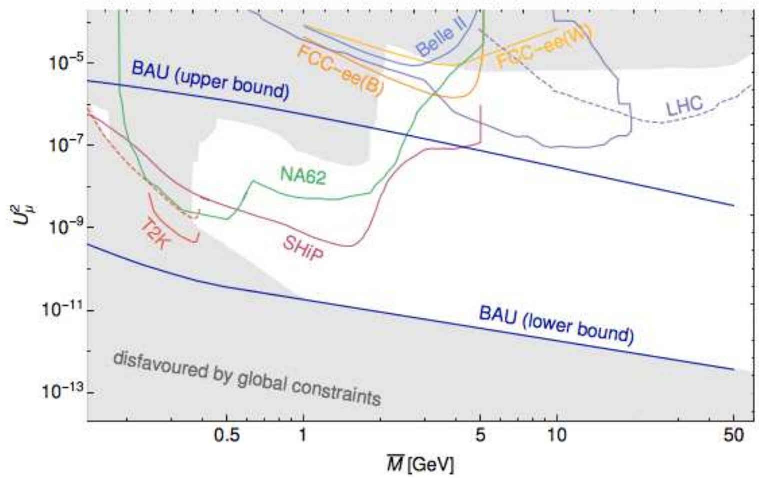
weak washout regime (Abada, Arcadia, Domcke, Lucente ’ 15).

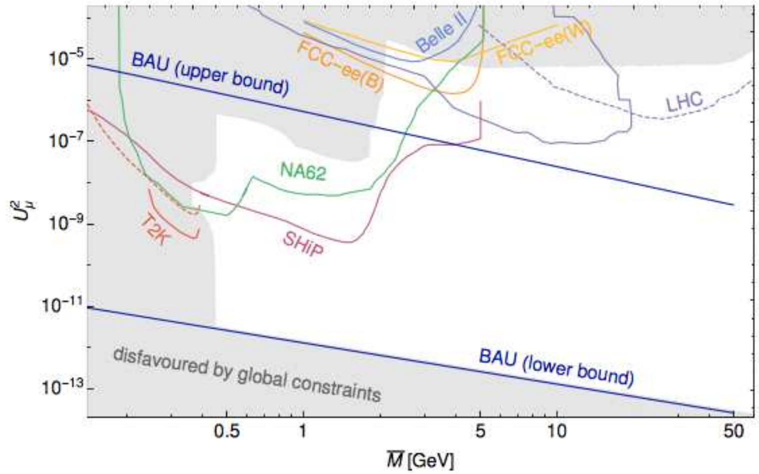
Baryon asymmetry: HNLs $N_{2,3}$



Comparison of the posterior probability contours at 68% and 90% on the planes mixings with e, μ, τ versus masses, with the present (shaded region) and future constraints from DUNE, FCC and SHiP for NH (up) and IH (down) Hernández, Kekic, J. López-Pavón, Racker, J. Salvado '16.

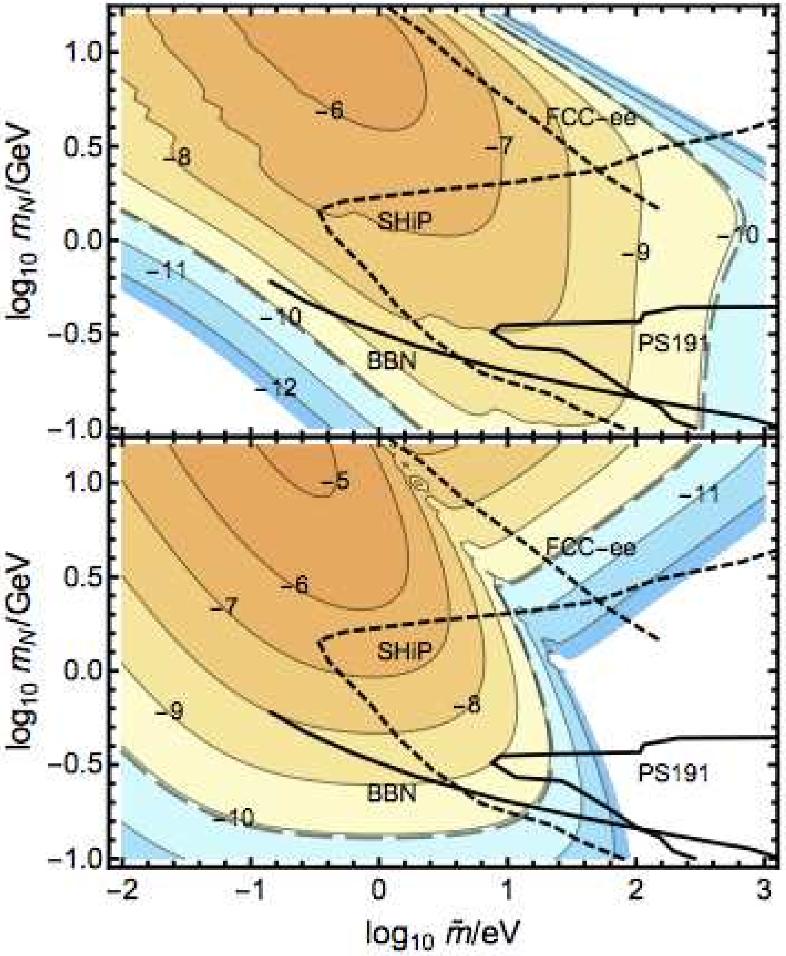
Baryon asymmetry: HNLs $N_{2,3}$





Drewes, Garbrech, Guetera, Klarić ’16.

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



Hambye, Teresi '17.