Heavy neutral leptons

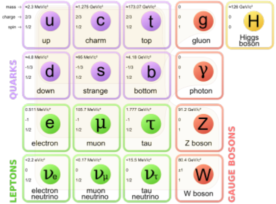
Oleg Ruchayskiy

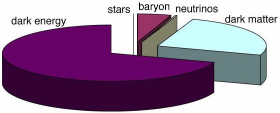
April 20, 2017

Standard Model and beyond

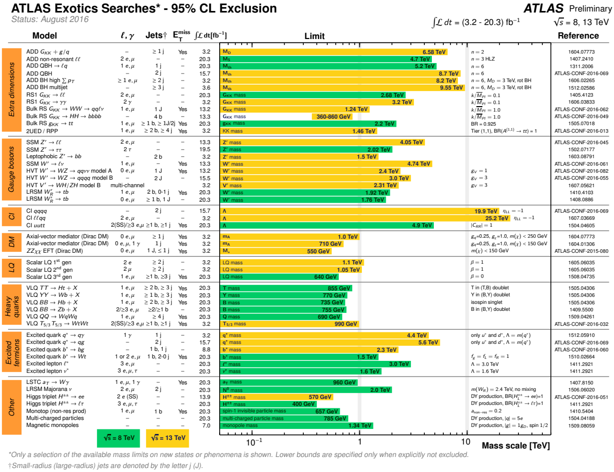
- **Standard Model of particle physics**: **17** particles to describe plethora of accelerator experiments
- **Standard Model of cosmology** – handful of numbers to describe how the Universe has started, developed and arrived to its today's state

The goal of my talk: to present to you a unified model of particle physics **and** cosmology



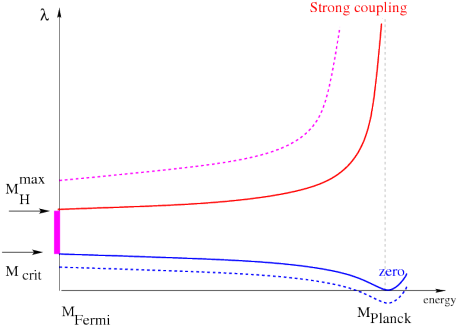


Deviations from the Standard Model?

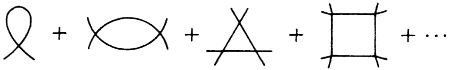


- Proton decay
- weakly interacting massive particles?
- Axions?
- Neutron electric dipole moment
- Neutrinoless double beta decay
- No $\mu \to e + \gamma$ or $\mu^+ \to e^+ e^- e^+$

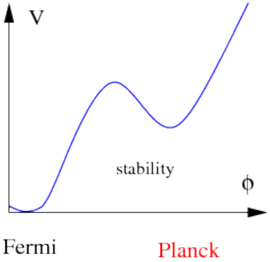
Standard Model is consistent up to very high scales

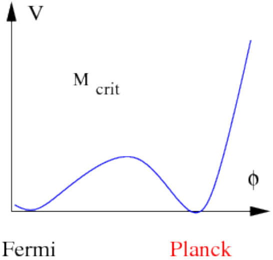


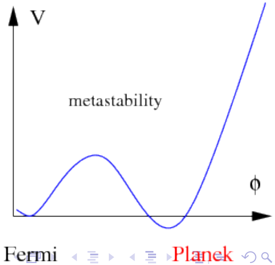
$$V(\phi) = \frac{m^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + g_6\phi^6 + g_8\phi^8 + \ldots$$



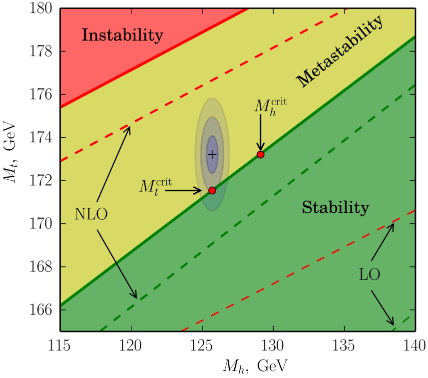
1311.4979



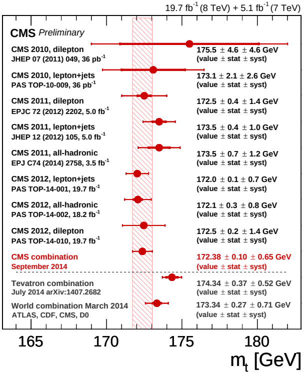




Standard Model is consistent up to very high scales



[1609.02503]



[1411.1923]

. . . It is expected that the difference between the MC mass definition and the formal pole mass of the top quark is up to the order of 1 GeV. . . (from "First combination of Tevatron and LHC measurements of the top-quark mass" **[1403.4427]**)

Bezrukov+ "Higgs boson mass and new physics" [1205.2893]

Degrassi+ [1205.6497]; Buttazzo+ [1307.3536]; Bednyakov [1609.02503]

Current status of particle physics

- ☺ All the predicted particles are discovered (Higgs was the last of such particles)
- ☺ The model is mathematically consistent. Within experimental uncertainties on the top mass, the SM can be valid quantum field theory up to the very high energy scale, possibly all the way to the Planck scale $\frac{\hbar}{M_{\text{Plank}}c} \sim \frac{GM_{\text{Plank}}}{c^2}$
- ☹ All the discovered particles/phenomena are accounted for by the model?

All the discovered phenomena are accounted for?

Why do we think that there should be any "new physics" not described by the Standard Model of particle physics? There are different motivations for that:

Particle physics

– neutrino masses and oscillations

Cosmology

Particle physics (coupled to Einstein gravity) applied to the Universe as a whole faces the challenges of

– dark matter
– matter-antimatter asymmetry of the Universe
– inflation

Deep theoretical questions

– Gauge hierarchy problem
– Strong CP-problem
– Cosmological constant problem

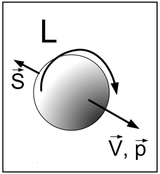
Outline

How to write neutrino mass?

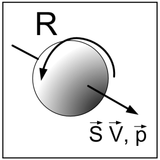
- Neutrinos are **massive**
- Mass is something that mixes left and right chirality
- Neutrinos are always left-chiral
- For **neutrino** one can write a **Majorana mass term**

$$\mathscr{L}_{\text{Majorana}} = -\frac{1}{2}\,\bar{\nu}\,M_M\,\nu^c + \text{h.c.} \qquad (1)$$

couples **left** neutrino ν and its **right** anti-particle ν^c.



Mass ⇕



- if one constructs a **Majorana spinor**:

$$\chi = \frac{\nu + \nu^c}{\sqrt{2}} \quad \text{so that} \quad \chi^c = \chi$$

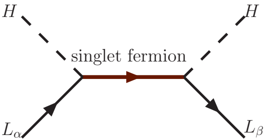
- ...then the mass term (1) is simply: $\mathscr{L}_{\text{Majorana}} = M\bar{\chi}\chi$

Neutrino Majorana mass

- Neutrino carries no electric charge, but it is **not** neutral
- ... neutrino is part of the SU(2) doublet $L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$
- ... and carries **hypercharge** $Y_L = -1$
- What we call **neutrino** is actually $\nu = (L \cdot \tilde{H})$ (where $\tilde{H}_a = \varepsilon_{ab} H_b^*$)
- Therefore neutrino Majorana mass term is (**Weinberg operator**)

$$\boxed{\text{Neutrino Majorana mass} = \frac{\boldsymbol{c}(\bar{L} \cdot \tilde{H}^\dagger)(L^c \cdot \tilde{H})}{\boldsymbol{\Lambda}}} \tag{2}$$

Introduce new gauge-singlet fermions N



Majorana mass term

$$\mathscr{L}_{\rm HNL} = \mathscr{L}_{\rm SM} + i\bar{N}\partial N + Y\,\bar{N}(\tilde{H}\cdot L) + \frac{1}{2}\bar{N}\boldsymbol{M}N^c + \text{h.c.}$$

Dirac mass term

- States that propagate (**mass eigenstates**) do not have a definite weak charges – oscillations
- Neutrinos are light because $m_{\rm Dirac} \ll \boldsymbol{M}$:

$$m_\nu \simeq \frac{(m_{\rm Dirac})^2}{\boldsymbol{M}} = U^2 \boldsymbol{M}$$

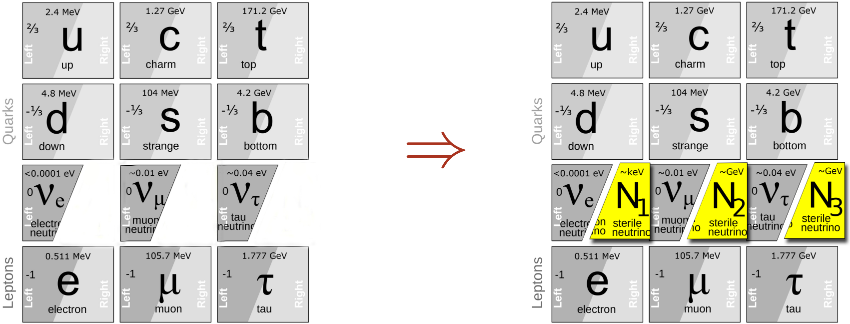
- **active-sterile mixing angle**

$$U = \frac{m_{\rm Dirac}}{\boldsymbol{M}} \ll 1$$

The new particle is called "Sterile neutrino" or "heavy neutral lepton" or **HNL**

Extension of Standard Model with heavy neutral leptons

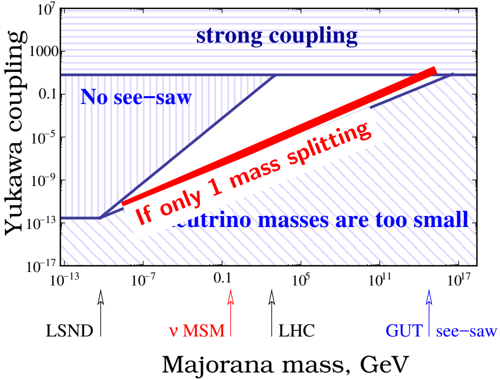
Asaka & Shaposhnikov'05. **Review:** Boyarsky+'09



Can this be a unified Standard Model of particle physics and cosmology

Sharing success of the Standard Model at accelerators and resolving major BSM problems: Neutrino masses and oscillations; Baryon asymmetry of the Universe; Dark matter

HNL parameters and neutrino oscillations



For every point in the white region, HNLs with such mass/interaction that can explain the phenomenology of neutrino oscillations

- $\mathcal{N}$ HNLs bring $7\times\mathcal{N}-3$ new parameters
- With the **full knowledge** of PMNS and active neutrino masses/phases we will be able to determine

  7 out of 11 parameters $(\mathcal{N}=2)$
  9 out of 18 parameters $(\mathcal{N}=3)$

- Undetermined parameters are: $\mathcal{N}$ Majorana masses + some ratios of Yukawas (for example, one replace $Y_{\alpha I} \leftrightarrow Y_{\alpha J}(M_I/M_J)^{1/2}$ for some pairs $I \neq J$.)

Mass of heavy neutral leptons?

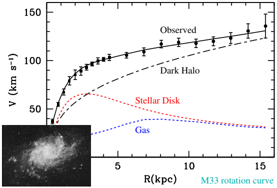
☹ No information from neutrino oscillations

- What can other BSM phenomena tell us about the HNLs mass?

Outline

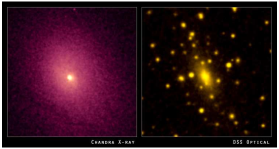
Dark Matter in the Universe

Astrophysical evidence:



Expected: $v(R) \propto \frac{1}{\sqrt{R}}$

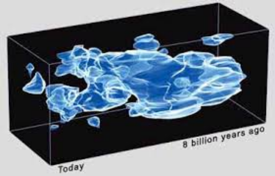
Observed: $v(R) \approx \text{const}$



Expected:

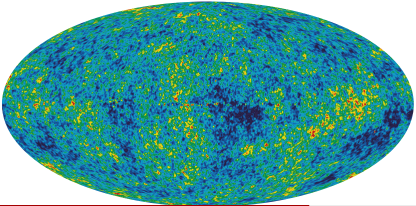
$\text{mass}_{\text{cluster}} = \sum \text{mass}_{\text{galaxies}}$

Observed: 10^2 times more mass confining ionized gas

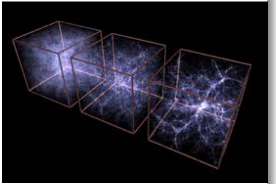


Lensing signal (direct mass measurement) **confirms** other observations

Cosmological evidence:



Jeans instability turned tiny density fluctuations into all visible structures



Neutrino dark matter

Neutrino seems to be a perfect dark matter candidate: neutral, stable, massive, abundantly produced in the early Universe

Cosmic neutrinos

- We know how neutrinos interact and we can compute their primordial number density $n_\nu = 112\,\mathrm{cm}^{-3}$ (per flavour)
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11\,\mathrm{eV}$
- Modern-day sum on neutrino masses is $\mathcal{O}(0.2\,\mathrm{eV})$ so neutrinos are only **tiny** fraction of dark matter

Neutrino dark matter I

S. Tremaine and J. Gunn (1979) Phys. Rev. Lett. *"Dynamical Role of Light Neutral Leptons in Cosmology"*

- The smaller is the mass of Dark matter particle, the larger is the number of particles in an object with the mass M_{gal}
- Average phase-space density of **any fermionic** DM should be **smaller** than density of **degenerate Fermi gas**

$$\frac{M_{\text{gal}}}{\frac{4\pi}{3}R_{\text{gal}}^3}\frac{1}{\frac{4\pi}{3}v_\infty^3} \leq \frac{2{m_{\text{DM}}}^4}{(2\pi\hbar)^3}$$

- Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass [[0808.3902]]

$$\boxed{m_{\text{DM}} \gtrsim 300 - 400\,\mathrm{eV}}$$

Two roads from neutrino dark matter

Dark matter cannot be **light** and **weakly interacting** at the same time

Alternatives:

Light and necessarily **super-weakly** interacting — **HNL**

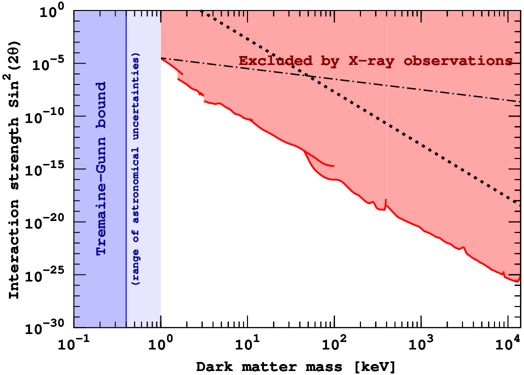
Heavy and weakly interacting — **WIMP**

. . . and of course other, completely orthogonal ideas, like axions

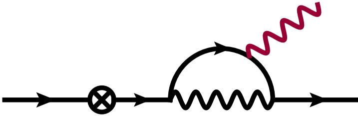
HNLs as dark matter

- **Can be light** (down to Tremaine-Gunn bound)
- **Can be warm** (born relativistic and cool down later)
- **Can be decaying** (stability is not required)
- **Can be produced** in correct amounts (via mixing with neutrinos)

Parameter space of HNL dark matter I



- Non-observation of decay line $N \to \gamma + \nu$

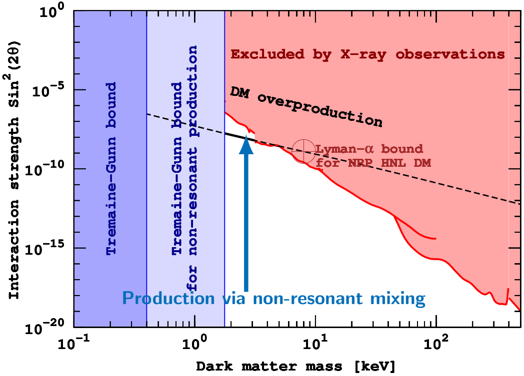


- Lifetime $\gg$ Age of the Universe (dotted line)
- Contribution to neutrino masses

$$m_\odot \sim U^2 M$$

[Asaka+'05; Boyarsky+'06]

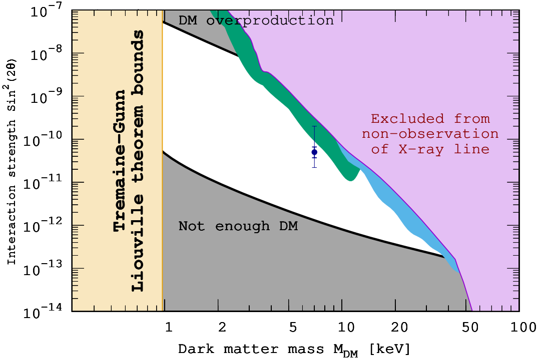
Parameter space of HNL dark matter II



– Production via non-resonant mixing
  [Dodelson & Widrow'93; Asaka, Laine, Shaposhnikov'06]
– Liouville bound (neglecting feedback from baryons)
  [Boyarsky, O.R. et al.'08; Gorbunov+'08]
– Lyman-α bound
  [Boyarsky, Lesgourgues, O.R., Viel'08]

- Production via mixing and decay signal depend on the same mixing angle U^2
- X-ray bounds grow very fast with mass (flux $\sim M_N^5$)

Parameter space of HNL dark matter III



- White region: production via **resonant** mixing **[Shi & Fuller'93; Laine & Shaposhnikov'08]**
- Requires: lepton asymmetry exceeding η_{baryon} by many orders of magnitude at $T \sim 100 - 500\,\mathrm{MeV}$

In summary

- HNL DM is **light** ($1 - 50$ keV) if there are no other particles
- Yukawa of HNL DM are tiny ($\mathcal{O}(10^{-10})$ or below)

Reminder: 3.5 keV line story

Two groups reported an identified feature in the X-ray spectra of dark matter-dominated objets

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

ApJ (2014) [1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

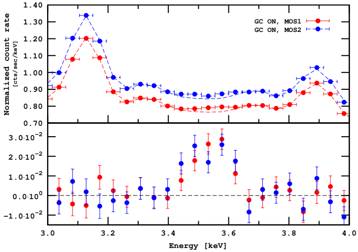
A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

PRL (2014) [1402.4119]

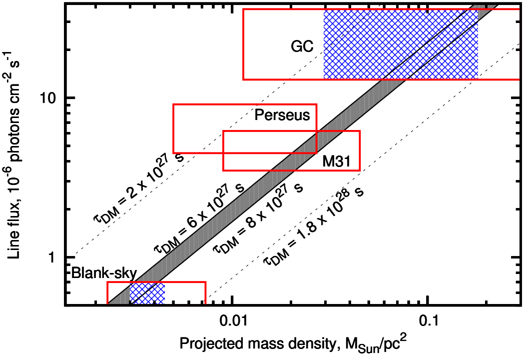
- **Energy:** 3.5 keV. Statistical error for line position $\sim 30-50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay $\mathrm{DM} \to \gamma + \nu$ (fermion) or $\mathrm{DM} \to \gamma + \gamma$ (boson)

Galactic center – a non-trivial consistency check

Boyarsky, O.R.+ PRL 115, 161301



- $4\sigma+$ statistical significance
- Also in **S. Riemer-Sorensen'14; Jeltema & Profumo'14**

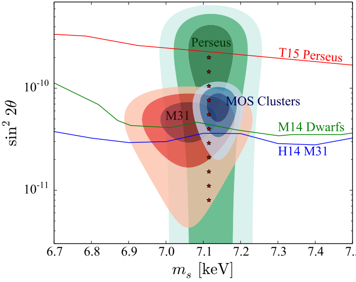


- Observation from M31 puts a **lower** bound on the GC flux
- Non-observations from the Milky Way outskirts puts an **upper** bound on the GC flux
- The observed signal fits into the range

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]

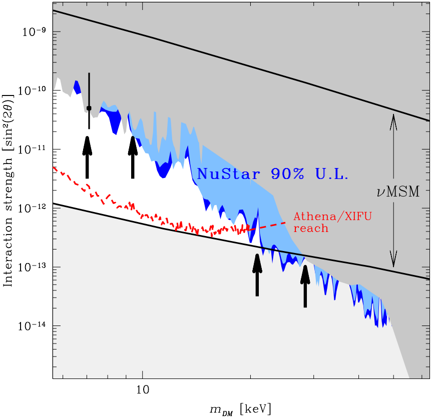
A common explanation for every detection and non-detection?

- When comparing bounds from different objects one should be careful — dark matter content in each of them uncertain by a factor $2-3$

Line in NuStar

Milky Way halo. Neronov & Malyshev [1607.07328]. Also Ng+ [1609.00667]

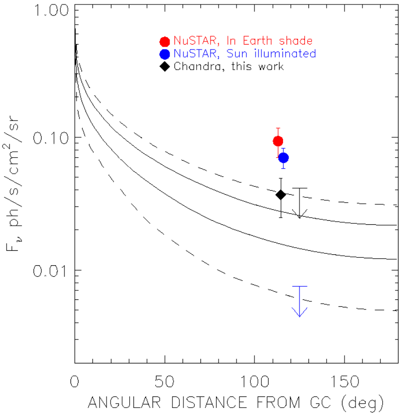
- The 3.5 keV is present in the spectrum with 11σ significance
- The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band
- The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure
- However, in the dataset when Earth shields satellite from the Sun the line is present with the same flux



Line in Chandra

Cappelluti+'17

- Most recently: 10 Msec of Chandra observation of Chandra Deep Fields
- 3σ detection of a line at ~ 3.5 keV
- If interpreted as dark matter decay – this is a signal from Galactic halo outskirts ($\sim 115^\circ$ off center)
- Chandra has mirrors made of Iridium (rather than Gold as XMM or Suzaku) – absorption edge origin becomes unlikely

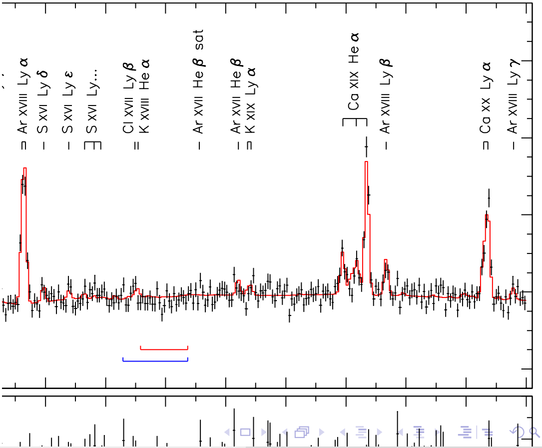


By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

Next step for 3.5 keV line: resolve the line

Perseus center spectrum [1607.07420]

- Astro-H/Hitomi – new generation X-ray spectrometer with a superb spectral resolution
- Launched February 17, 2016
- ☹ Lost few weeks later
- Before its failure observed the center of Perseus galaxy cluster
- The observations was in calibration phase (additional



What did we learn with existing Hitomi data?

- Due to its super energy resolution, *Hitomi* can distinguish between atomic line broadening (thermal velocities $\sim 10^2\,\mathrm{km/sec}$) and decaying dark matter line broadening (virial velocity $\sim 10^3\,\mathrm{km/sec}$)
- Even the short observation of Hitomi showed that Potassium, Clorium, etc. do not have super-solar abundance in Perseus cluster $\Rightarrow$ 3.5 keV line is **not** astrophysical
- Bounds much weaker for a **broad** (dark matter) line $\Rightarrow$ not at tension with previous detections

- This does not seem to be astrophysics (Hitomi spectrum)
- This does not seem to be systematics (4 different instruments)
- ???

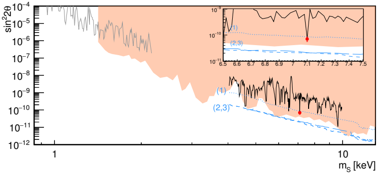
Future of decaying dark matter searches in X-rays

Another Hitomi

JAXA is planning to send a replica of Hitomi satellite (within about 2 years)

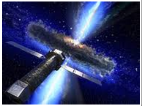
Microcalorimeter on sounding rocket (2017)

- Large field-of-view and very high spectral resolution
- Can resolve narrow lines from diffuse sources
- Flying time $\sim 10^2$ sec



Athena+

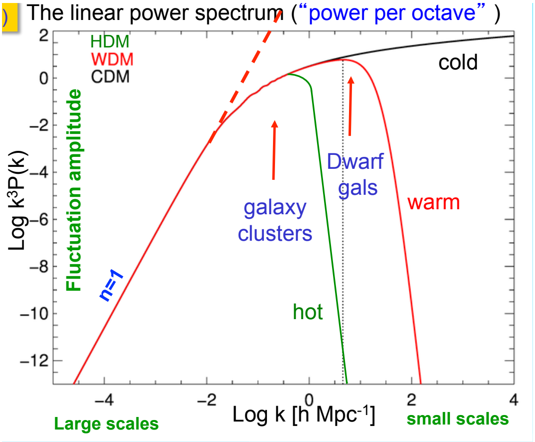
- Large ESA X-ray mission (2028) with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)

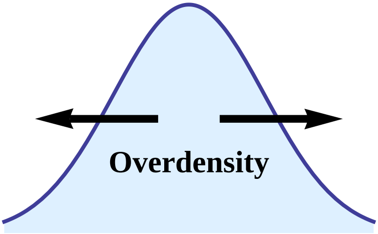


Outline

Warm dark matter

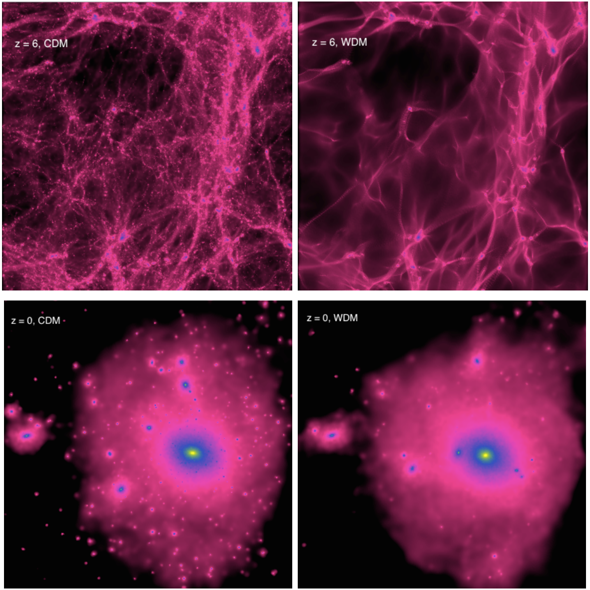
- Particles are born relativistic $\Rightarrow$ they do not cluster
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities





– Particle velocities means that warm dark matter has effective **pressure** that prevents small structure from collapsing

At non-linear scales

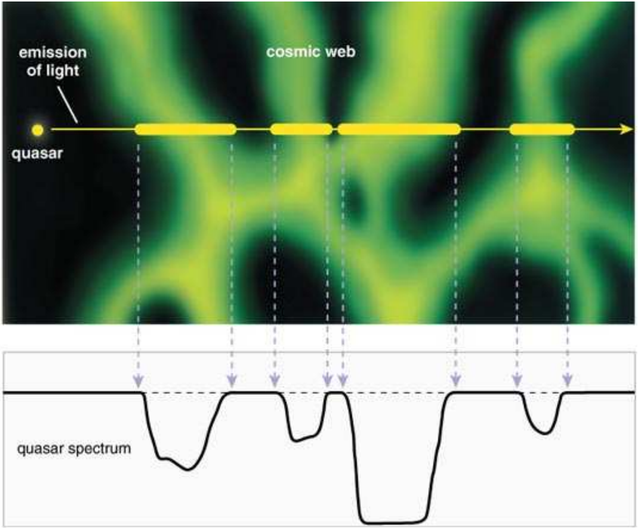


COCO Warm simulation Bose+'15

HNL dark matter:

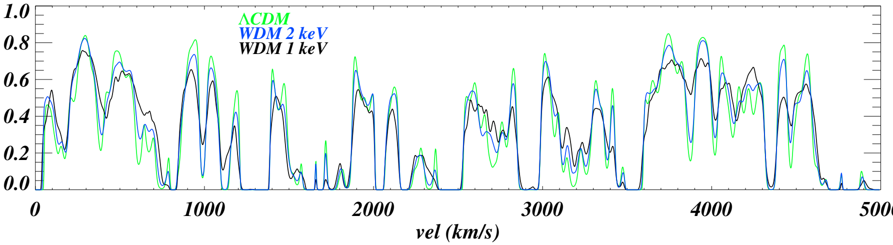
- Same structures as in **CDM** Universe at scales of Mpc and above $\Rightarrow$ no signatures in CMB or galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo
- **Can help** with "too big to fail" or "missing satellites" problems

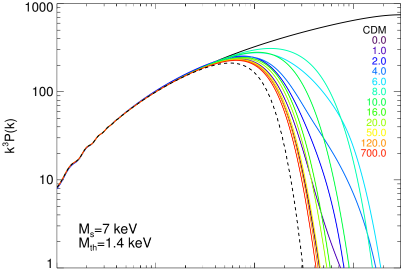
Lyman-α forest and power spectrum



Lyman-α forest data

Viel+'13

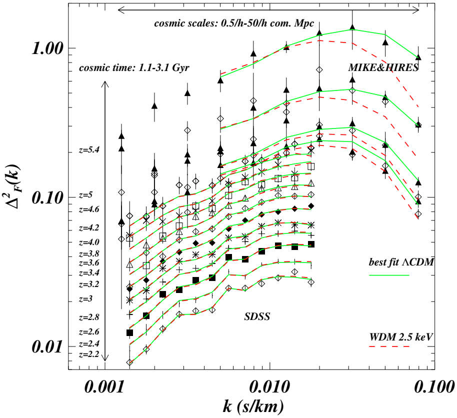




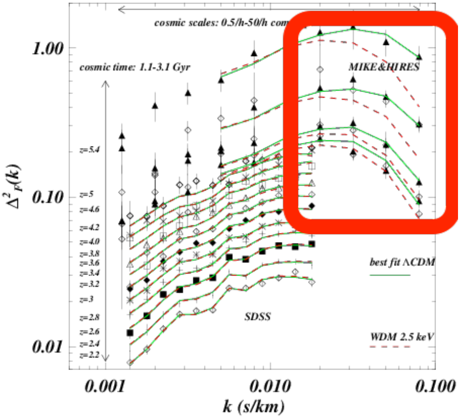
$\Rightarrow$

Warm dark matter predicts **suppression** (cut-off) in the flux power spectrum derived from the Lyman-α forest data

Suppression in the flux power spectrum



Suppression in the flux power spectrum



The suppression of the flux power spectrum is visible in high-resolution HIRES/MIKE dataset

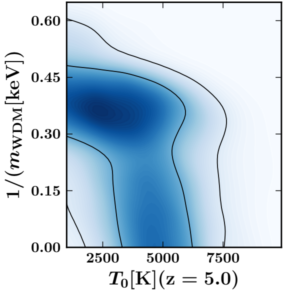
Warm dark matter or warm hydrogen?

Garzilli, Boyarsky, Ruchayskiy [1510.07006]

Suppression in the flux power spectrum may be due to

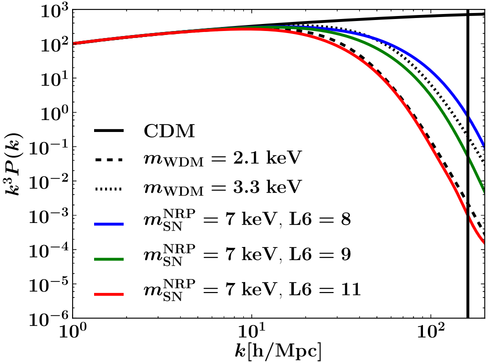
- Temperature at redshift z (Doppler broadening) – **increases hydrogen absorption line width**
- Pressure at earlier epochs (gas expands and then needs time to recollapse even if it cools)
- Warm dark matter

Data prefers cold intergalactic medium around redshift $z = 5$ $\Rightarrow$ Observed Lyman-α power spectrum suppression is due to **something else**?



High-resolution Lyman-α forest and HNL dark matter

Garzilli, Boyarsky, Ruchayskiy [1510.07006]

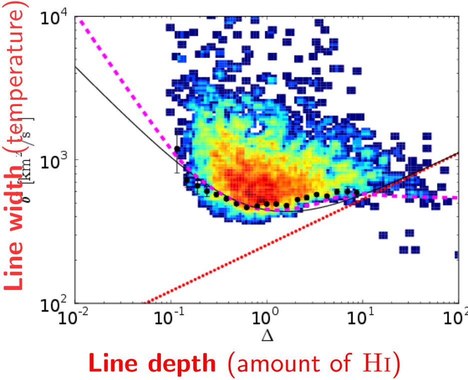


- Best fit **thermal relic** mass $= 2.1$ keV
- Corresponds to resonantly produced sterile neutrino with $M_N = 7$ keV and lepton asymmetry $L = 11 \times 10^{-6}$
- 3.5 keV line, interpreted as sterile neutrino DM, gives range of lepton asymmetries $L = 8 - 12$

By accident (or maybe not) the HNL dark matter interpretation of 3.5 keV line predicts exactly the amount of suppression of power spectrum observed in HIRES/MIKE (and fully consistent with all other structure formation bounds)

Future of Lyman-α on

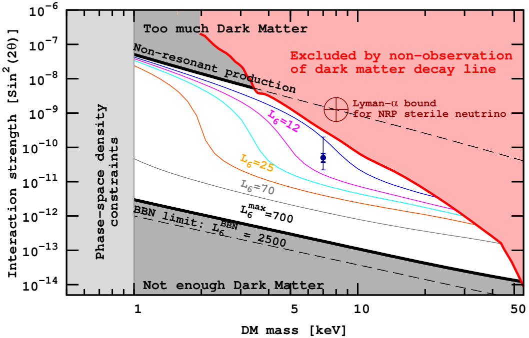
- The high-resolution Lyman-α spectra show suppression – due to thermal effects **or** due to warm dark matter
- We have only crude information about the reionization history and temperature of gas at reionization epoch
  - The measurement of gas temperatures at redshifts $z \gtrsim 5$ has high discovery potential
- This can be done **(work in progress)**



(Garzilli, Theuns, Schaye'15)

Summary: Heavy neutral leptons as dark matter

- HNL DM is **light** ($1-50$ keV)
- Yukawa of HNL DM are tiny ($\mathcal{O}(10^{-10})$) or below)
- Large ($\sim 10^6 \eta_{baryon}$) late-time lepton asymmetry is required if we want to resolve BSM problems **only** with **heavy neutral leptons**



Structure formation bounds (satellite counts / Lyman-α) have still uncontrolled systematics and no numbers from them can be taken "at face value"

Outline

Cosmology tells us

Dark matter tells us:

Need "something like neutrino", but heavier (Tremaine & Gunn bound) and even weaker interacting (not to overclose the Universe)

Baryon asymmetry tells us:

Need "something like neutrino", but even weaker interacting (not to enter thermal equilibrium in the early Universe)

Sakharov conditions

Sakharov (1967)

To generate baryon asymmetry of the Universe **3 conditions** should be satisfied

- **I.** Baryon number should not be conserved
- **II.** C-symmetry and CP-symmetry must be broken
- **III.** Deviation from thermal equilibrium in the Universe expansion

Baryogenesis with HNLs

Heavy neutral leptons provide

- Additional sources of CP-violation
- Out-of-equilibrium conditions (decays or oscillations)
- Violation of the lepton number (and $B-L$)

Wide class of scenarios known as **leptogenesis**

Thermal leptogenesis: $M_N \sim 10^{12}$ GeV

Fukugita & Yanagida'86

Resonant leptogenesis: $M_{N_1} \approx M_{N_2} > M_W$ and $|M_{N_I} - M_{N_J}| \ll M_N$

Pilaftsis, Underwood'04–'05

Leptogenesis via oscillations: 2 or 3 HNLs, $M_N < M_W$ and $|M_{N_1} - M_{N_2}| \ll M_{N_1,N_2}$

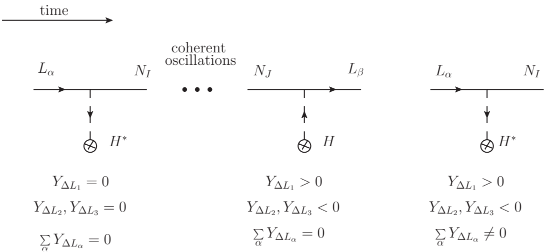
Akhmedov, Smirnov & Rubakov'98

Asaka & Shaposhnikov'05

...

Leptogenesis via oscillations

Akhmedov+'98; Asaka & Shaposhnikov'05; Canetti & Shaposhnikov'11;Asaka+'08-'16; Canetti+'12; Abada'15; Hernández+'15-'16; Drewes+'12,'15,'16; Hambye & Teresi'16
Rates: Laine+'08,'14,'15,'16

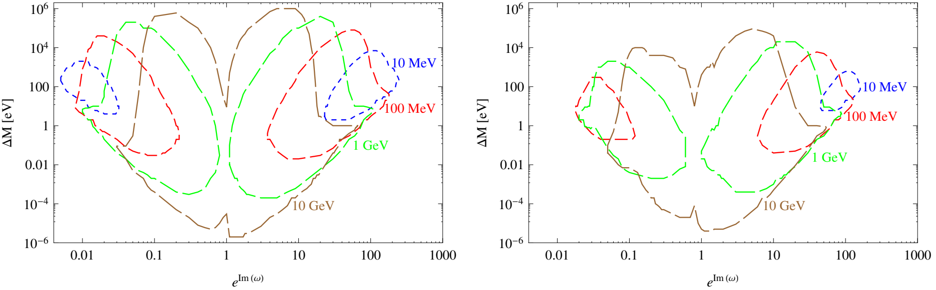


Shuve & Yavin'14

- Out-of-equilibrium CP-violating oscillations **of HNLs** allow to generate effective lepton number in the active neutrino sector
- Generation of lepton asymmetry continues down to $T \sim \mathcal{O}(10)\text{GeV}$, reaching levels $\gg \eta_{baryon}$

Shaposhnikov'08

Possible range of masses



Canetti+'12

- Leptogenesis via oscillations can occur for masses down to tens of MeV
- Requires degeneracy in masses $\Delta M/\bar{M} \ll 1$

HNL masses from leptogenesis

- HNLs responsible for neutrino masses and leptogenesis can be as light as 10 MeV or as heavy as 10^{12} GeV
- There exists only one mechanism (**leptogenesis via oscillations**) that generates significant lepton asymmetry **below** sphaleron freeze-out times
- Large lepton asymmetry is required if we want to explain dark matter, baryogenesis and neutrino oscillations **with three HNLs only**
- The evolution of lepton asymmetry in the primordial plasma is under investigation

We need to identify the parts of the parameter space where not only correct baryon asymmetry but also large lepton asymmetry is produced

Outline

Properties of sterile neutrinos

Heavy neutral lepton inherits the interactions from neutrinos

Charged current-like: $\tilde{\mathscr{L}}_{CC} = \frac{g\, U}{\sqrt{2}} \bar{e}\gamma^\mu (1-\gamma_5) \boldsymbol{N}^c W_\mu$

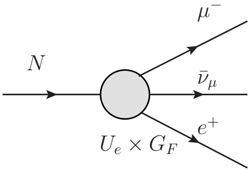
Neutral current-like: $\tilde{\mathscr{L}}_{NC} = \frac{g\, U}{\cos\theta_W} \bar{\nu}\gamma^\mu (1-\gamma_5) \boldsymbol{N}^c Z_\mu$

Typical values of parameters

$G_F \longrightarrow U \times G_F$

Yukawa coupling $\sim \left(\frac{M_N m_\nu}{\langle\Phi\rangle^2}\right)^{1/2} \approx 4\times 10^{-8} \left(\frac{M_N}{1\text{ GeV}}\right)^{1/2}$

Mixing angles $U^2 = \frac{m_\nu}{M_N} \approx 5\times 10^{-11} \left(\frac{1\text{ GeV}}{M_N}\right)$



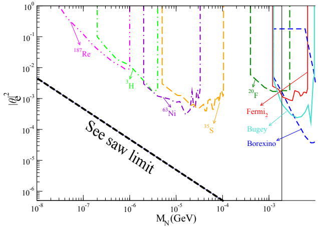
How to search for HNLs

Shrock+'80s; Gronau+'84; Gorbunov & Shaposhnikov'07; Atre et al.'09
Review: SHiP Physics Case'15

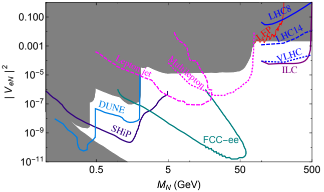
- $M_N < few\,\mathrm{MeV}$ – only U_e mixing can be probed (kink searches)
- $\mathcal{O}(10)\mathrm{MeV} \lesssim M_N \lesssim M_K$ – intensity frontier experiments (peak searches)
- $\mathcal{O}(100)\mathrm{MeV} \lesssim M_N \lesssim M_B$ – intensity frontier experiments (fixed target experiments)
- $M_N \gtrsim few\,\mathrm{GeV}$ – LHC searches (displaced vertices; multilepton final states; same sign same flavour leptons, ...)

  Helo+'15-'16; Izaguirre & Shuve'15; Ng+'15; Antush+'15-'16; Dib & Kim'15; Gado+'15; Dev+'15; Cvetic+'15-'16
- Z-factories (FCC-ee)

Blondel+'14



[0901.3589]



[1601.01658]

Challenge

- Production:

$$N_{\text{produced}} \propto |U|^2 \times N_\nu$$

typical $|U|^2 \sim 10^{-10} \div 10^{-6}$

- Decay lifetime:

$$l_N = c\tau_N \propto \frac{\dots}{G_F^2 M_N^5 |U|^2}$$

– 100s of meters for $M_N = 1$ GeV and $|U|^2 \sim 10^{-8}$

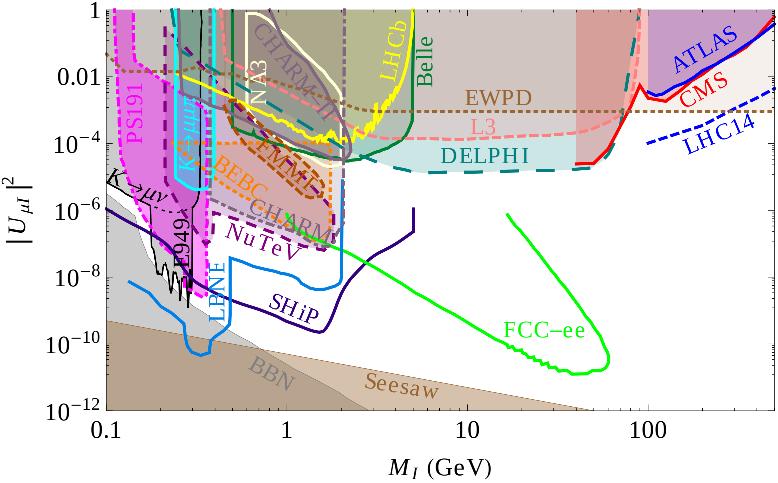
- Probability to decay over distance L: $p(L) = 1 - \exp(-L/l_N)$
- Number of events in the detector with length $L_{\text{det}} \ll l_N$

$$N_{\text{detected}} \propto \frac{L_{\text{det}}}{l_N} \propto |U|^2$$

- Probability $\propto |U|^4$ unless the particle decays $\sim 100\%$ inside the detector

Bounds on sterile neutrino coupling U_μ^2

From "SHiP Physics Paper" [1504.04855]



Outline

Finding superweakly interacting particles in lab

Proposal to Search for Heavy Neutral Leptons at the SPS

W. Bonivento (INFN, Cagliari & CERN) , A. Boyarsky (Leiden U.) , H. Dijkstra (CERN) , U. Egede (Imperial Coll., London) , M. Ferro-Luzzi, B. Goddard (CERN) , A. Golutvin (Imperial Coll., London) , D. Gorbunov (Moscow, INR) , R. Jacobsson, J. Panman (CERN) M. Patel (Imperial Coll., London) , O. Ruchayskiy (LPHE, Lausanne) , T. Ruf (CERN) , N. Serra (Zurich U.) , M. Shaposhnikov (LPHE, Lausanne) , D. Treille (CERN) Hide

Oct 7, 2013 - 21 pages

CERN-SPSC-2013-024, SPSC-EOI-010
e-Print: arXiv:1310.1762 [hep-ex] | PDF

Abstract (arXiv)
A new fixed-target experiment at the CERN SPS accelerator is proposed that will use decays of charm mesons to search for Heavy Neutral Leptons (HNLs), which are right-handed partners of the Standard Model neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations and provide a Dark Matter candidate. Cosmological constraints on the properties of HNLs now indicate that the

Several years ago an idea of a new dedicated experiment to search for steril neutrinos (aka "heavy neutral leptons") got crystallized

SHiP : Search for Hidden particles

Search for rare particles becomes **official CERN theme**

It took then 1 year to create a collaboration

A facility to Search for Hidden Particles (SHiP) at the CERN SPS

SHiP Collaboration (M. Anelli *et al.*) Show all 235 authors

Apr 20, 2015 · 234 pages

CERN-SPSC-2015-016, SPSC-P-350
e-Print: arXiv:1504.04956 [physics.ins-det] | PDF
Experiment: CERN-SPS-SHIP

- About **250** members of the SHiP collaboration from **44** institutions worldwide
- SHiP is now an official CERN project

Timeline

- Approval by CERN **2019**
- Data taking **2024**

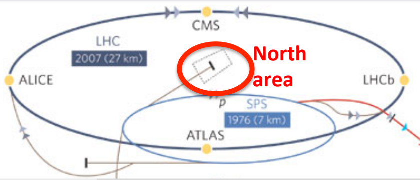
Super Proton Synchrotron (SPS)

1. Need a lot of particles, decaying to neutrinos
   - Muons? ($\mu \to e + \bar{\nu}_e + \nu_\mu$) – light
   - Pions? ($\pi \to e + \bar{\nu}_e$, $\pi \to \mu + \bar{\nu}_\mu$) – Yes! Below 140 MeV
   - Kaons? ($K \to e + \bar{\nu}_e$, $K \to \mu + \bar{\nu}_\mu$) – Yes! Below 490 MeV (NA62)
   - D-mesons ($D^+ = |c\bar{d}\rangle$, $D_s^+ = |c\bar{s}\rangle$, $D^0 = |c\bar{u}\rangle$) – Yes! Below 1.8 GeV
2. To produce D-mesons we need to produce charmed quarks. $M_c \simeq 2$ GeV

$$N_{\text{mesons}} = 2 \times X_{q\bar{q}} \times N_{PoT}$$

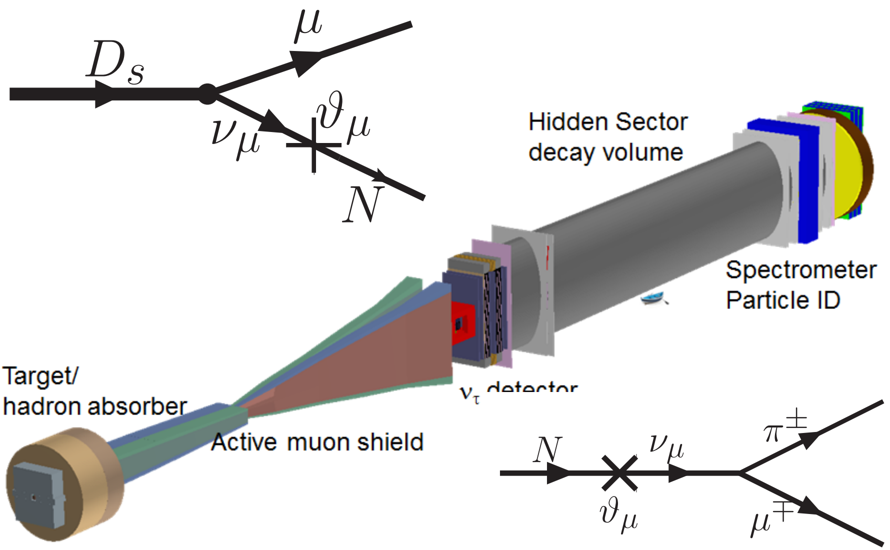
3. Want to increase N_{PoT} – high intensity proton beam
4. Want to increase $X_{q\bar{q}}$ – fraction of heavy quarks' production – high energy beam

- High energy proton beam – 400 GeV
- 4×10^{19} PoT (protons on target per year). 2×10^{20} PoT over 5 years
- Beam intensity: 4×10^{13} protons/sec
- Produces a lot of c-quarks: $X_{c\bar{c}} \sim 10^{-3}$



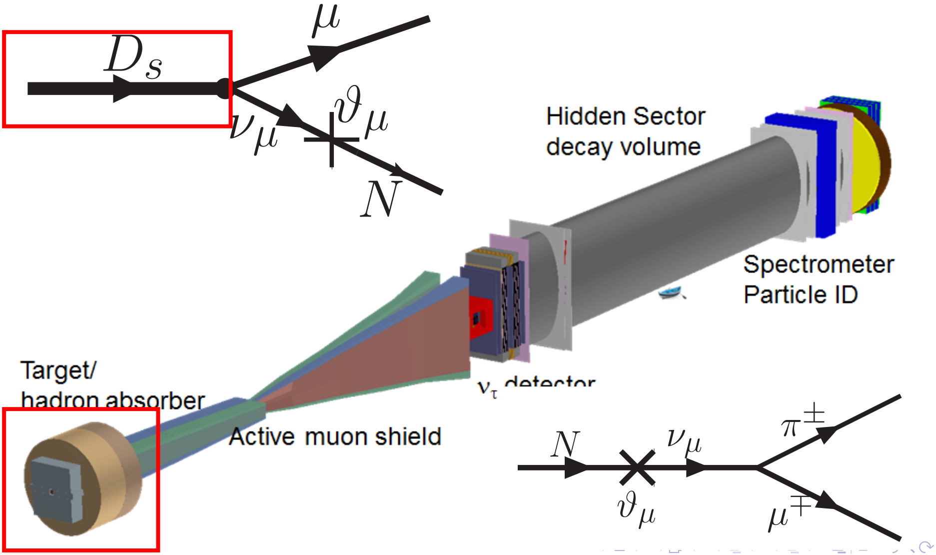
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



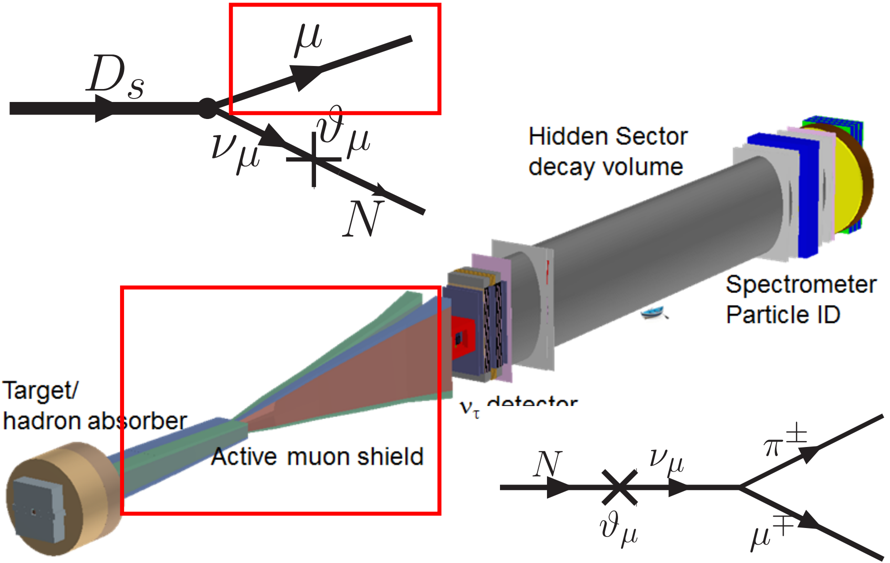
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



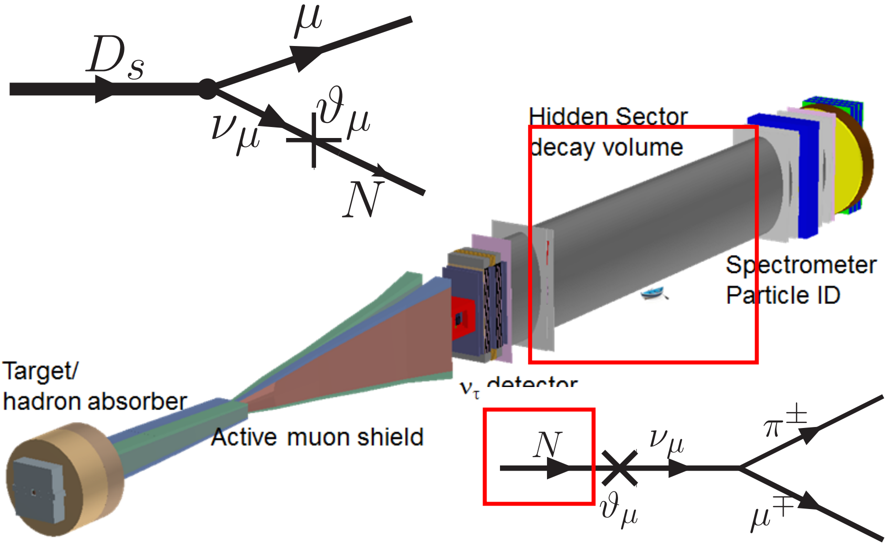
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



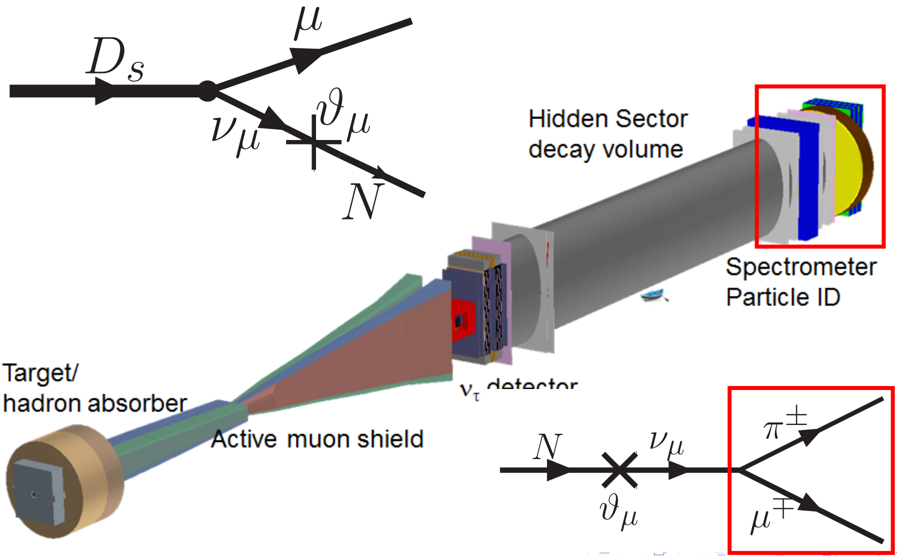
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



SHiP (*Search for Hidden Particles*) experiment

Step by step overview

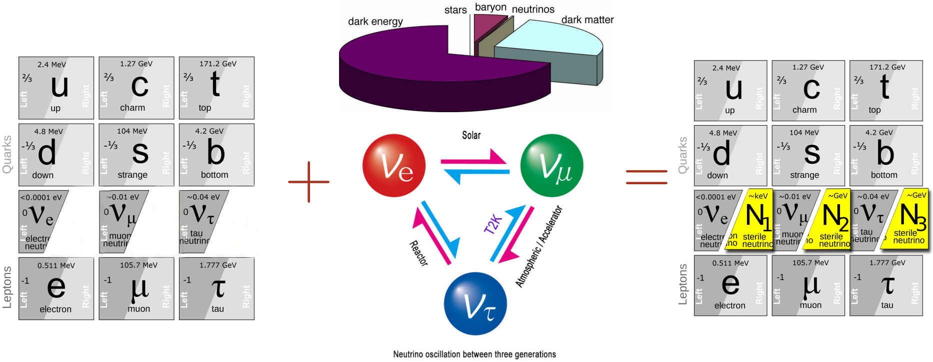


SHiP physics case paper

From: *A facility to Search for Hidden Particles at the CERN SPS: the SHiP* **physics case**

Classification of **vector portals** ; Kinetic mixing ; Anomaly-free gauge groups ($B-L$, $L_\mu - L_\tau$ etc) ; Other froms of vector portals. ; **Chern-Simons portal** ; Matter states charged under new $U(1)$; Higgs mechanism in the **dark sector** ; **Supersymmetric** $U(1)'$ models ; Self-intereaction of **dark matter via light mediators** ; Production and detection of **kinetically mixed dark photons and baryonic vectors**. **Scalar portal** ; **Hidden Valleys** ; Light scalars in supersymmetry ; **Singlet extensions** ; **Additional Abelian gauge groups**; Models with R-**parity violation** ; Linear scalar portals: Higgs-scalar mixing ; Existing experimental limits ; Probing Exotic Higgs Decays at SHiP ; Hidden sector scalars ; Hidden sector fermions and vectors ;**Pseudoscalar portals** ; Scalar portals and Dark Matter ; **Scalar as a mediator between DM and the SM** ; **Scalar as a DM candidate** ; **Dark pions** ; **Light inflatons** ; **Neutrino portal** ; **Heavy neutral leptons** ; **Left-right symmetric models** ; Left-right symmetric models with GeV-scale HNLs ; **Inverse seesaw and GeV scale singlet fermions** ; **ALPs and other PNGBs at SHiP** ; Connection to Dark Matter ; ALPs coupled to two gauge bosons ; ALPs coupled to SM fermions ; **SUSY**; **A Very Light Supersymmetric Neutralino and R-Parity Violation** ; **Light particles from the SUSY breaking sector ; Origin of light sgoldstinos** Light Dirac **gauginos** ; SUSY vector portal I: **Hidden Photinos** ; **R-parity conserving photinos** ; . . .

Conclusions

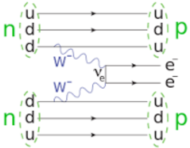


Outline

Outline

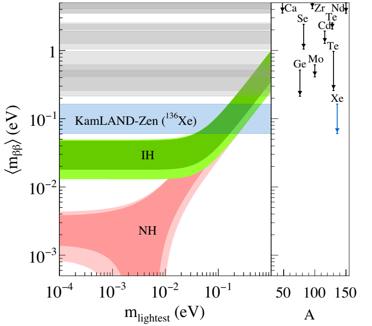
Neutrinoless double beta decay

- If neutrinos have Majorana mass, the **neutrinoless double β-decay** is possible



- Neutrino oscillations define the value of

$$m_{\beta\beta}^{(\nu)} = \left|\sum_i m_i V_{ei}^2\right|$$



[Phys. Rev. Lett. 117, 082503 (2016)]

where V_{ei} is the elements of the PMNS matrix, connecting charge (flavour) and mass (propagation) neutrino states:

$$|\nu_\alpha\rangle = \sum_i V_{\alpha i}|\nu_i\rangle$$

m_i are the masses

$0\nu\beta\beta$ and Heavy Neutral Leptons

Bezrukov'05; Benes+'05; Blennow+'10; Asaka+'11; Mitra+'12; Lopez-Pavon'12; Asaka & Eijima'13; Faessler+'14; Hernández+'16; Drewes & Eijima'16; Asaka+'16
Review: Dell'Oro+'16

- Effective Majorana mass in type-I seesaw

$$m_{\beta\beta}^{(seesaw)} = \left| \sum_i^{\nu} m_i V_{ei}^2 + \sum_{\mathrm{I}}^{HNL} f_\beta(M_{\mathrm{I}}) \frac{\langle\Phi\rangle^2 Y_{\alpha\mathrm{I}}^2}{M_{\mathrm{I}}} \right|$$

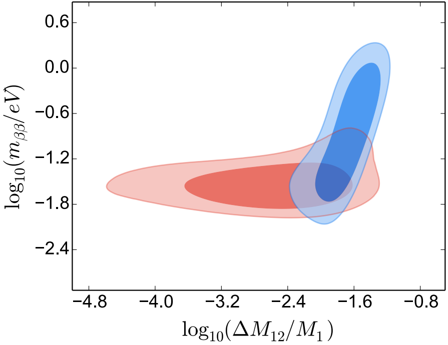
- $f(M_{\mathrm{I}})$ is the nuclear matrix element, approximately (**c.f. Faessler+'14**)

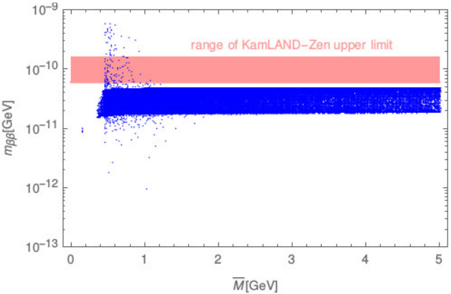
$$f(M_{\mathrm{I}}) \approx \frac{\langle p\rangle^2}{\langle p\rangle^2 + M_{\mathrm{I}}^2}, \quad \langle p\rangle \sim 100\,\mathrm{MeV}$$

- Seesaw relation in these terms

$$\sum_i^{light} m_i V_{ei}^2 + \sum_{\mathrm{I}}^{heavy} \frac{\langle\Phi\rangle^2 Y_{\alpha\mathrm{I}}^2}{M_{\mathrm{I}}} = 0$$

HNLs enhancing $0\nu\beta\beta$ signal





Drewes & Eijima'16

Hernández+'16

- Due to the freedom in active-sterile Yukawa matrix, several HNL (even close in mass) can **enhance** the rate of $0\nu\beta\beta$ decay as compared to the $m_{\beta\beta}^{(\nu)}$ while still satisfying requirements of successful baryogenesis

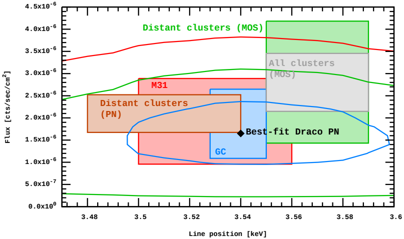
Hernández+'16. Also **Drewes & Eijima'16, Asaka+'16**

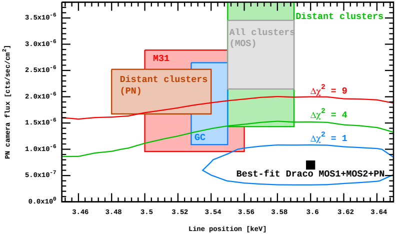
Outline

Analysis of Draco dSph

Ruchayskiy+ MNRAS (2016) [1512.07217]

- Dwarf spheroidals are "*galaxies swallowed by our Galaxy*"
- Perfect observational targets:
    - dense
    - dark ($M/L \sim 10^2 - 10^3$)
    - compact (typical sizes $5' - 30'$)
    - nearby (distances $30 - 100$ kpc)
- The line is detected in the spectrum of Draco dSph with low significance ($\Delta\chi^2 = 5.3$)
- Line flux/position are consistent with previous observations
- The data is consistent with DM interpretation for lifetime $\tau_{\rm DM} > (7-9) \times 10^{27}\,\mathrm{sec}$

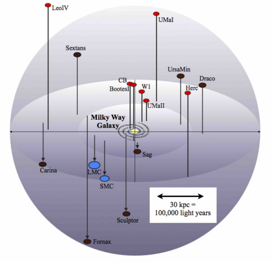


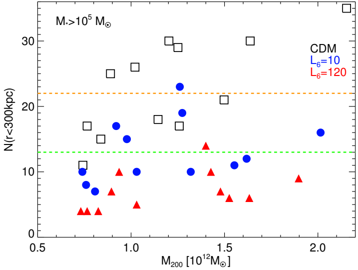


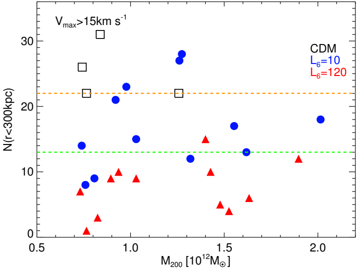
Outline

Satellite number and properties

- Warm dark matter erases substructures – compare number of dwarf galaxies inside the Milky Way with "predictions"
- **Simulations**: The answer depends **how** you "light up" satellites
- **Observations**: We do not know how typical Milky Way is





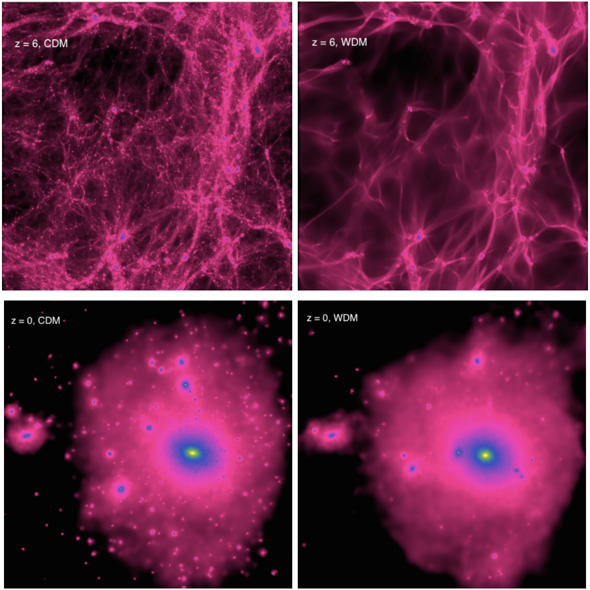


Lovell, Boyarsky, O.R.+ [1611.00010]

Current status of structure formation bounds from the Local Universe

- Connection "dark structures" $\leftrightarrow$ "visible structures" depends on (yet unknown) way to implement baryonic feedback
- Simulation to simulation (or even halo-to-halo) scatter is quite large and affects the conclusions
- We do not know how typical is our Galaxy, our Local Group, etc.
- You cannot "rule out" your warm dark matter model with these observations
- You can only **check** that your model **fits the data under "reasonable" assumptions about baryonic physics**

At non-linear scales



COCO Warm simulation Bose+'15

HNL dark matter:

- Same structures as in **CDM** Universe at scales of Mpc and above $\Rightarrow$ no signatures in CMB or galaxy counts
- Decreasing number of small galaxies around Milky Way
- Decreasing number of small satellite galaxies **within** Milky Way halo
- **Can help** with "too big to fail" or "missing satellites" problems