Sterile neutrinos: unifying **cosmology** with **particle physics**

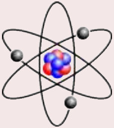
Oleg Ruchayskiy
Oleg.Ruchayskiy @ nbi.ku.dk

KØBENHAVNS UNIVERSITET

Live Theoretical Physics Colloquium

Once upon a time . . .

. . . the model of particles and interactions was simple



1. Proton
2. Electron
3. Photon
4. Neutron

} Atom

. . . atoms could transform into each other

. . . physicists built quantum theory of radioactivity

. . . the theory described experiments really well but **predicted** existence of additional heavy particles

- these particles were eventually discovered
- but the structure of the theory dictated existence of yet other particles
- . . .

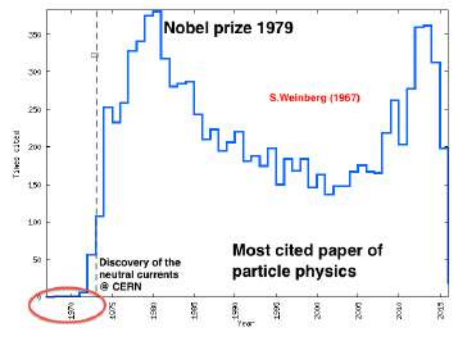
Once upon a time . . .

. . . the Standard Model was deemed complicated

. . . Of course our model has too many arbitrary features for these predictions to be taken very seriously. . .

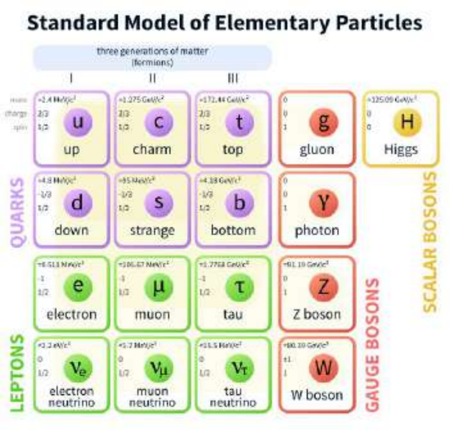
S. Weinberg (1967) "A model of leptons"

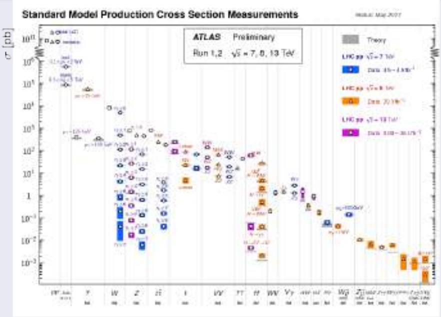
12'400 citations at the time of writing



Once upon a time . . .

. . . all major predictions of the Standard Model were confirmed

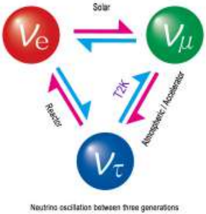




ATLAS collaboration (2018)

BSM problem I: Neutrino oscillations

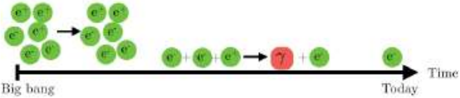
What makes neutrinos disappear and then re-appear in a different form? Why they have mass?



- Predicted by **Pontekorvko 1957** soon after the kaon oscillation story (why - because neutrinos are **neutral**)
- Observed in the 1960s as solar neutrino deficit
- Verified by many experiments both in **appearance** and **disappearance**

What mediates neutrino oscillations?

BSM problem II: Baryon asymmetry of the Universe

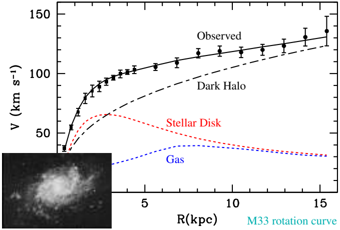


- Space around us consists of matter with no evidence of primordial antimatter
- Standard cosmological scenario predicts symmetrical initial conditions
- Physics is (mostly) symmetric w.r.t. particles $\leftrightarrow$ antiparticles
- Matter-antimatter symmetric universe would be filled predominantly with photons and neutrinos
- Observed CP-violations would lead to many billion times smaller asymmetry

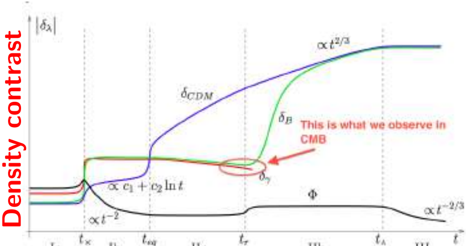
> What particles/processes created tiny matter-antimatter disbalance in the early Universe?

BSM problem III: Dark matter

What is the most prevalent kind of matter in our Universe?



- Gives mass to galaxies
- Does not emit or absorb light



$z \simeq 1100$

- Drives cosmological expansion
- Drives formation of structures

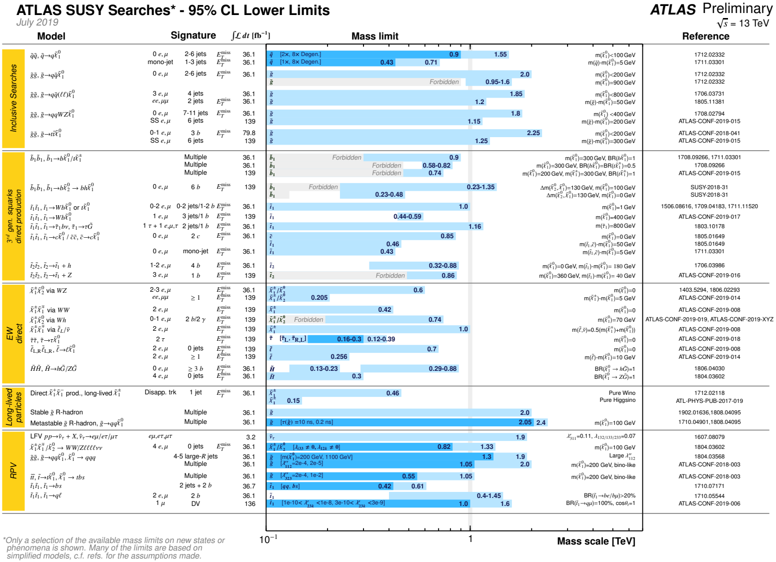
> What particles is dark matter made of?

Once upon a time . . .

. . . we thought we knew where to look for BSM phenomena

- We ambitiously wanted to discover new physics alongside the Higgs boson
- Some even thought we have a compeling reason for that

...Yet our expectations were proven to be wrong



So, although we know that new particles exist . . .

. . . we do not know what they are

Pre-LHC expectations

Post-LHC expectations

- There are no definitive predictions what kind of new physics we are looking for (although there is no shortage of ideas)
- The absence of definite theoretical guidance is our "**new normal**"
- It is the **experimental community** that guides our forward development

How many particles are needed to solve all BSM problems?

Scale of new particles?

Rough range of theoretical predictions

- Neutrino masses and oscillations

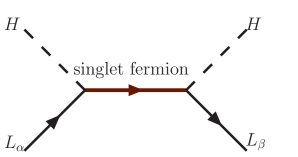
  Scale of new physics: from $10^{\equiv 9}$ GeV to 10^{15} GeV
- Dark matter

  Scale of new physics: from $10^{\equiv 30}$ GeV to 10^{64} GeV
- Baryon asymmetry of the Universe

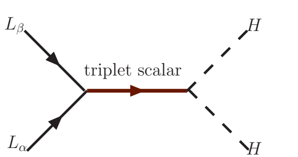
  Scale of new physics: from $10^{\equiv 3}$ GeV to 10^{15} GeV

Neutrino oscillations and new particles

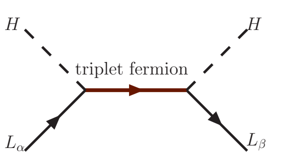
Neutrino oscillations imply new particles



Type I see-saw
extra singlet fermion



Type II see-saw
extra SU(2) triplet scalar



Type III see-saw
extra SU(2) triplet fermion

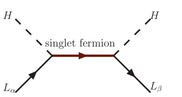
- Operator of dimension > 4 implies new particles
- Naively the masses of these new particles are

$$M_{\text{new states}} \lesssim \Lambda = \frac{v^2}{m_{\text{atm}}}$$

where $v = \langle H \rangle$ – Higgs VEV

Neutrino oscillations and Heavy Neutral Leptons

- Assume one extra fermion N
- It couples to the "neutrino" combination $\nu = (\tilde{H} \cdot L)$
- This combination is $SU(3) \times SU(2) \times U(1)$ gauge singlet
- **N carries no Standard Model gauge charges!**



$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + F\bar{N}(\tilde{H} \cdot L) + \mathscr{L}_{\text{Majorana}}(N) \tag{1}$$

- Majorana mass term $\mathscr{L}_{\text{Majorana}}(N) = \frac{1}{2}\bar{N}\boldsymbol{M}N^c + \text{h.c}$ is possible for N
- In terms of ν and N we get ($m_{\text{Dirac}} = F\nu$ – Dirac mass)

$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + \frac{1}{2}\begin{pmatrix}\bar{\nu} \\ \bar{N}^c\end{pmatrix}\begin{pmatrix}0 & m_{\text{Dirac}} \\ m_{\text{Dirac}} & \boldsymbol{M}\end{pmatrix}\begin{pmatrix}\nu^c \\ N\end{pmatrix} \tag{2}$$

Neutrino oscillations and Heavy Neutral Leptons

Particle content

- If $M \gg m_{\text{Dirac}}$ this theory describes two particles:
  - Light **neutrino** with mass $\boxed{m_\nu \simeq m_{\text{Dirac}} \dfrac{m_{\text{Dirac}}}{M}}$ — **seesaw formula**
  - Heavier particle with mass $\approx M$
- Neutrinos are light because $m_{\text{Dirac}} \ll M$
- Mixture between states ν and N (difference between weak eigenstate ν and massive state $\tilde{\nu}$) is parametrized by **active-sterile mixing angle**

$$\boxed{\sin U \approx U = \frac{m_{\text{Dirac}}}{M} \ll 1} \qquad (3)$$

Neutrino oscillations and Heavy Neutral Leptons

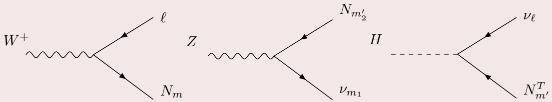
We call this new particle

"Sterile neutrino" or "heavy neutral lepton" or **HNL**

also "Majorana fermion", "heavy Majorana neutrino", "right-handed neutrino", etc.

Interactions of HNLs

Interactions



$$\mathscr{L}_{int} = \frac{g}{2\sqrt{2}} W^+_\mu \overline{N}\, U^*\, \gamma^\mu (1 \equiv \gamma_5) \ell^{\equiv}_\alpha + \frac{g}{2\cos\theta_W} Z_\mu \overline{N}\, U^*\, \gamma^\mu (1 \equiv \gamma_5) \nu + \dots \quad (4)$$

- In every process where neutrino appears and where kinematics allows we expect an HNL with probability $\propto |U|^2$. For example,

$$\Gamma(W^+ \to \mu^+ + N) = |U_\mu|^2\, \Gamma(W^+ \to \mu^+ + \nu_\mu) \quad (5)$$

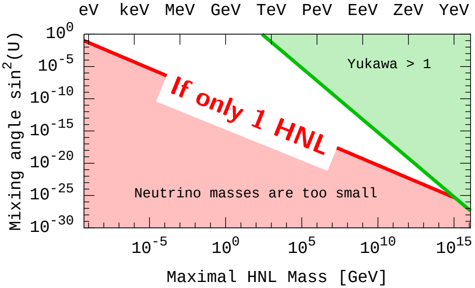
Feebly interacting HNLs

- HNLs are thus interacting "weaker-than-neutrinos" (by a factor $|U_\alpha|^2$). However, these particles can be detected via other means, thanks to their larger mass [1805.08567]
- Naive seesaw formula tells us

$$U^2 \sim \frac{m_{\rm atm}}{M} \sim 10^{-12}\frac{100\,\mathrm{GeV}}{M} \quad (6)$$

- Fortunately, we need **more than 1 HNL** to explain both $\Delta m^2_{\rm atm}$ and $\Delta m^2_{\rm sun}$
- All neutrino experiments would allow to determine

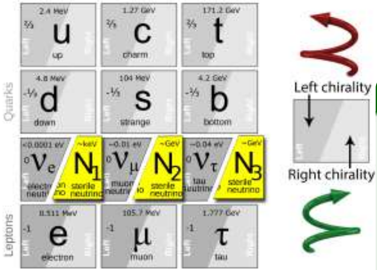
  7 out of 11 parameters (2HNL)
  9 out of 18 parameters (3HNL)

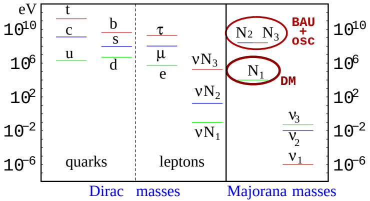


Seesaw formula (6) provides a **bottom line for values of the coupling**

Within a model with 2 HNLs any pattern of neutrino oscillations can be snuggly accomodated

How many light particles are needed to solve all BSM problems?





HNL can explain . . .

- . . . **neutrino oscillations**

  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

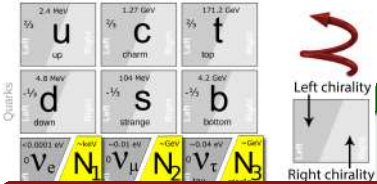
- . . . **Baryon asymmetry**

  Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05–

- . . . **Dark matter**

  Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+; Asaka, Shaposhnikov, Laine'06 –

How many light particles are needed to solve all BSM problems?



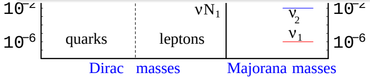
HNL can explain . . .

- . . . **neutrino oscillations**

  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79;

HNL can explain all of it

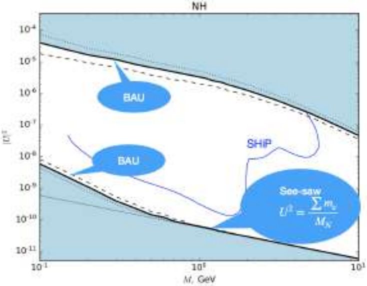
- **Neutrino Minimal Standard Model (νMSM)**
  Asaka & Shaposhnikov'05 + . . . hundreds of subsequent works
- Masses of HNL are of the order of masses of other leptons
- **Reviews: Boyarsky, Ruchayskiy, Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]**

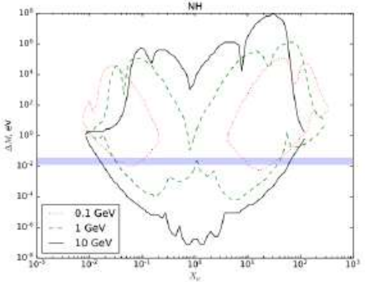


Baryogenesis in the νMSM

- Two HNLs with GeV masses ($\mathcal{O}(100\,\mathrm{MeV})$ up to $\mathcal{O}(80\,\mathrm{GeV})$)
- Degeneracy in mass $\Delta M/M \ll 1$
- Lepton asymmetry is generated in CP-violating **oscillations** of two HNLs
- Recent results and comparison with previous works **Eijima, Shaposhnikov, Timiryasov** **[1808.10833]**

$$|U|^2 \simeq \frac{m_2+m_3}{2M_N}\left(X_\omega^2 + X_\omega^{-2}\right)$$





- Initial idea: Akhmedov+'98
- Kinetic theory including back-reaction: Asaka, Shaposhnikov'05
- Analysis: Asaka, Shaposhnikov, Canetti, Drewes, Frossard; Abada, Arcadi, Domcke, Lucente; Hernndez, Kekic, Lpez-Pavn, Racker, Salvado; Drewes, Garbrech, Guetera, Klari; Hambye, Teresi; Eijima, Timiryasov; Ghiglieri, Laine
- Recent refs: [1208.4607], [1606.06690] ,

Can these particles be discovered?

What do we have and what do we need ?

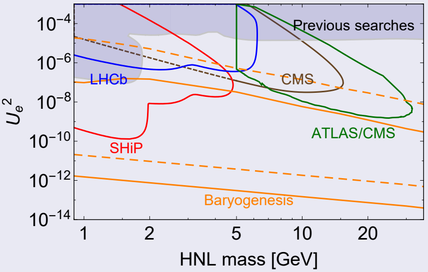
Theoretical predictions

1. Two heavy neutral lepton of $\mathcal{O}(GeV)$ scale
2. Nearly degenerate in mass
3. Possibly CP violation in the active-steirle mixing

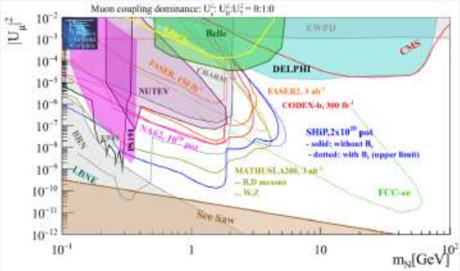
Experimental program

1. Discover new particle
2. Measure its properties (Mass, spin, branching fractions, flavour structures)
3. Confront with theoretical predictions (from seesaw, BAU, etc)

What experiments can discover HNLs?



LHC searches (Boiarska+ [1902.04535])

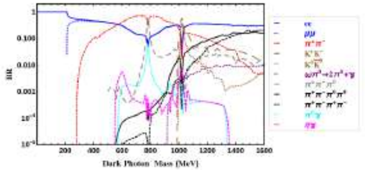


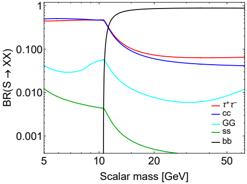
Beyond LHC (PBC report [1901.09966])

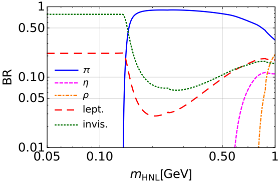
- HNLs are part of the search program of all major particle physics experiments

What did we discover?

- Boson or fermion?
- If invariant mass $m_{\mu\mu}$ or even M_{jj} has a peak – boson – or is broadly distributed (HNL)
  $\gamma' \to \ell^+\ell^\equiv$ vs. $N \to \mu^+\mu^\equiv\nu$ or $N \to \ell^+ + \pi^\equiv$, etc







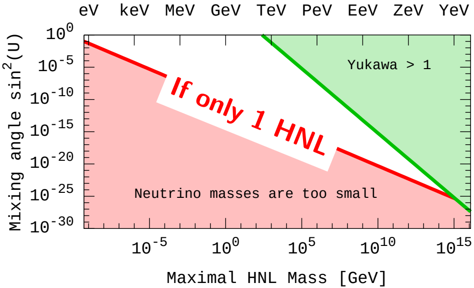
Plots from [1608.08632; 1805.08567; 1908.04635]

How many of them?

- We discovered HNLs  How many of them?
- If you discovered an HNL signal – you actually discovered **two or more particles** ☺
- Naive seesaw formula

$$U^2_{bottom} \sim \frac{m_{atm}}{M} \sim 10^{-11}\frac{10\,\text{GeV}}{M}$$

- In order to have HNLs with mixings $U^2 \gg U^2_{bottom}$ you need several HNLs that "**conspire**" to cancel each other's contribution to neutrino masses



Shaposhnikov'06; Kersten & Smirnov'07

Do they fit predictions?

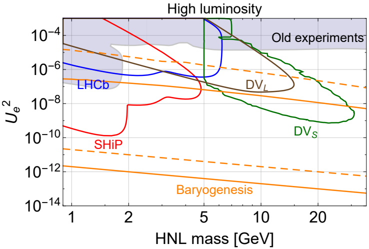
- Once HNL parameters are determined, you can check whether they fall into the theory predictions
- And whether different measurements agree with each other

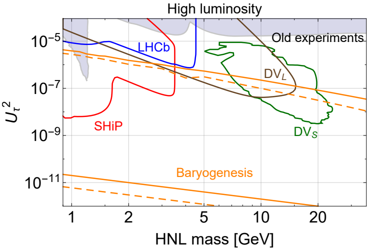
Boiarska+ [1902.04535]

BAU contours: Eijima+ [1808.10833];

Short DV: Cottin+ [1806.05191];

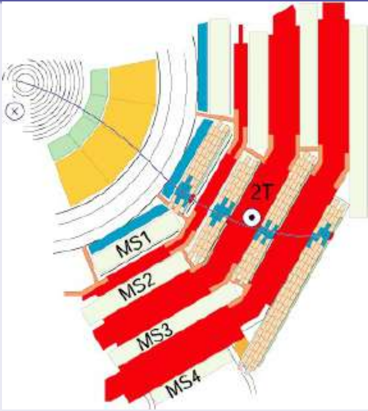
Long DV: Bondarenko+ [1903.11918]

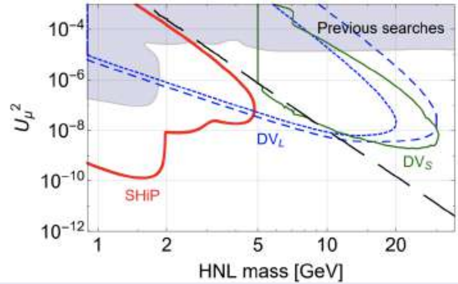




Probing other decay channels

Displaced vertices with the muon tracker



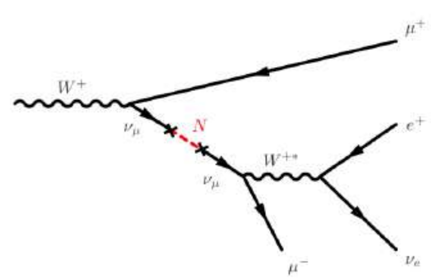


Boiarksa+ [1902.04535]; Bondarenko+ [1903.11918]

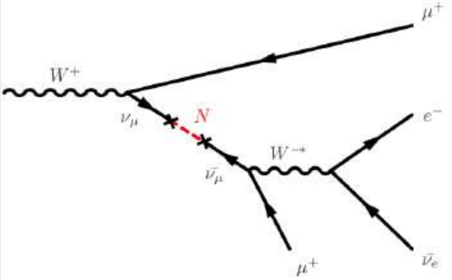
Dashed line: Drewes & Hajer [1903.06100]

Lepton number violation in HNL decays?

HNLs are Majorana particles and therefore can violate lepton number



Lepton number **conserving** (**LNC**) decay, mediated by HNL $W^+ \to \mu^+\mu^{\equiv}e^+\nu_e$



Lepton number **violating** (**LNV**) decay, mediated by HNL $W^+ \to \mu^+\mu^+e^{\equiv}\bar{\nu}_e$

Many works, see *e.g.* [1502.05915], [1505.01934], [1509.05981], [1805.11400], [1907.13034]

Can we measure HNL mass splitting at LHC?

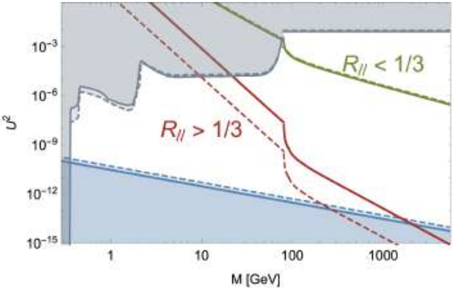
- Two HNLs with couplings well above seesaw line[a] **suppress** LNV effects
- However, two HNLs if sufficiently long-lived can oscillate and **undo** the suppression

[a]Only those we can probe

- If we measure both LNV and LNC events as well as the total lifetime – we can hope to determine the **mass splitting**

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\text{phys}}}{2\Gamma_N^2 + \Delta M^2_{\text{phys}}}.$$

R_{ll} — ratio of same-sign to opposite-sign leptons **Anamiati+ [1607.05641]**

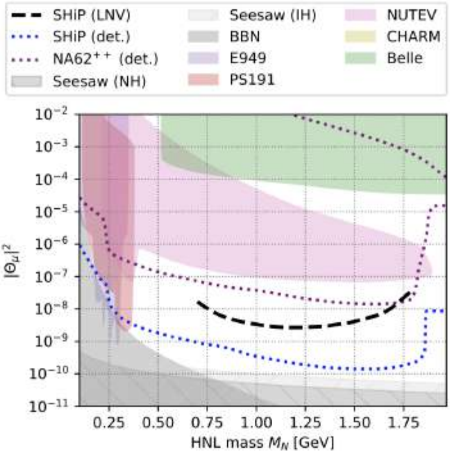


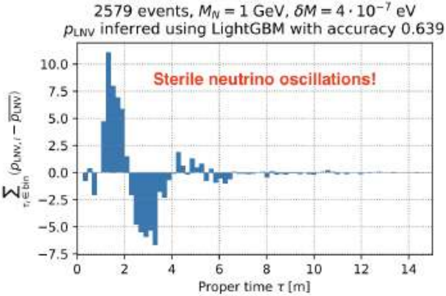
Drewes+ [1907.13034]

- ΔM can also be measured in SHiP [1912.05520]

Majorana nature of HNLs and sterile neutrino oscillations

Jean-Loup Tastet & Inar Timiryasov [1912.05520]



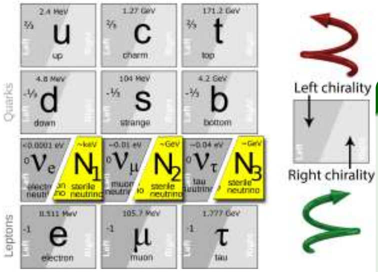


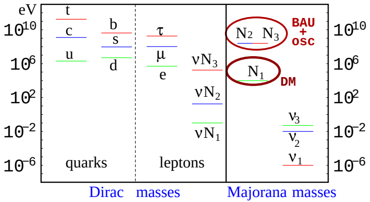
- In some region of parameter space it is even possible to measure ΔM
- Binning events in proper time τ we can determine ΔM via $\Delta M \tau = 2\pi$

Holistic view

Accelerator measurements can be confronted with results of other experiments

What about dark matter?





HNL can explain ...

- ...neutrino oscillations

  Bilenky & Pontecorvo'76; Minkowski'77; Yanagida'79; Gell-Mann et al.'79; Mohapatra & Senjanovic'80; Schechter & Valle'80

- ...Baryon asymmetry

  Fukugita & Yanagida'86; Akhmedov, Smirnov & Rubakov'98; Pilaftsis & Underwood'04-05; Shaposhnikov+'05–

- ...Dark matter

  Dodelson & Widrow'93; Shi & Fuller'99; Dolgov & Hansen'00; Abazajian+; Asaka, Shaposhnikov, Laine'06 –

Neutrino dark matter

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

Cosmic neutrinos

- We know how neutrinos interact and we can compute their primordial number density $n_\nu = 112\,\mathrm{cm}^{\equiv 3}$ (per flavour)
- To give correct dark matter abundance the sum of neutrino masses, $\sum m_\nu$, should be $\sum m_\nu \sim 11\,\mathrm{eV}$

Tremaine-Gunn bound (1979)

- Such light neutrinos cannot form small galaxies – one would have to put too many of them and violated Pauli exclusion principle
- Minimal mass for fermion dark matter $\sim 300 \equiv 400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would **overclose the Universe**

Two generalizations of neutrino dark matter

- Dark matter cannot be both **light** and **weakly interacting** at the same time
- To satisfy **Tremaine-Gunn bound** the number density of any dark matter made of fermions should be **less** than that of neutrinos
- Neutrinos are light, therefore they decouple relativistic and their equilibrium number density is $\propto T^3$ at freeze-out

First alternative: WIMP

Heavy but **weakly**-interacting dark matter – its number density is Boltzmann-suppressed ($n \propto e^{\equiv m/T}$) at freeze-out

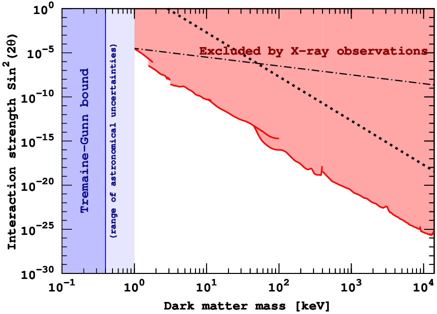
Second alternative: sterile neutrino

Light but **super-weakly**-interacting dark matter so that their number density never reaches equilibrium value

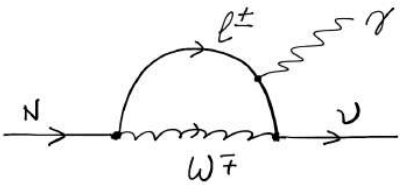
In particle physics one usually speaks of heavy neutral lepton but in cosmology the same particle is known as sterile neutrino

Properties of sterile neutrino dark matter

- Can be **light** (down to Tremaine-Gunn bound of 0.5 keV or so)
- Can be **decaying** (with lifetime exceeding the age of the Universe)



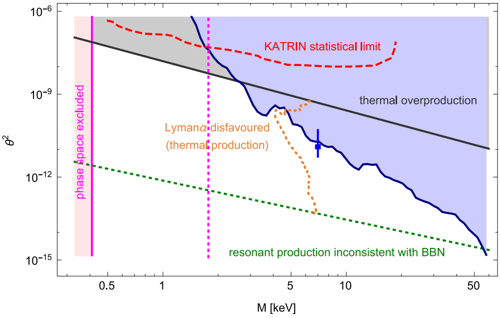
- Non-observation of decay line $N \to \gamma + \nu$

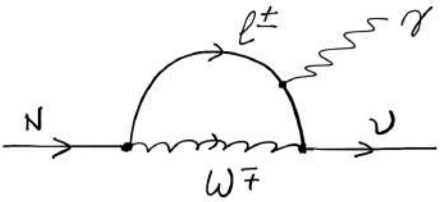


- Lifetime $\gg$ Age of the Universe (dotted line)
- Contribution to neutrino masses below $m_{\odot}$ [Asaka+'05; Boyarsky+'06]

Searching for keV-scale sterile neutrinos

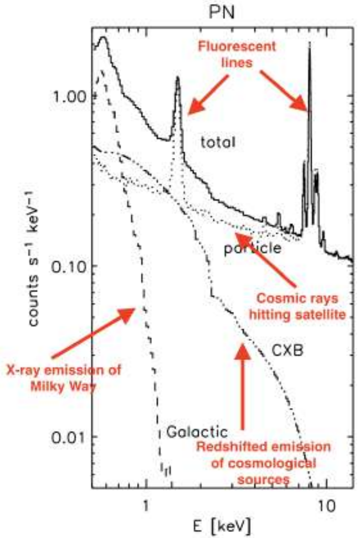
See our review **"Sterile neutrino dark matter"** [1807.07938]

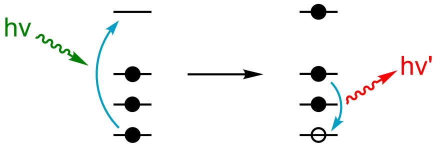


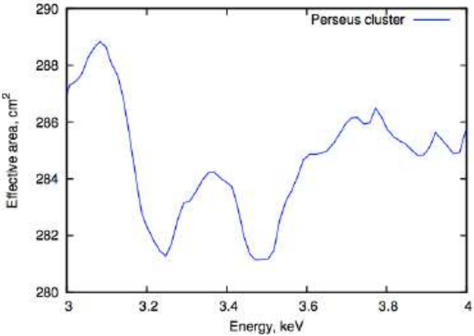


We can search for monochromatic X-ray line originating from sterile neutrinos dark matter decays

Challenges: X-ray sky is never "empty"







Detection of An Unidentified Emission Line

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

Bulbul et al. 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

Boyarsky, Ruchayskiy et al. Phys. Rev. Lett. (2014) [1402.4119]

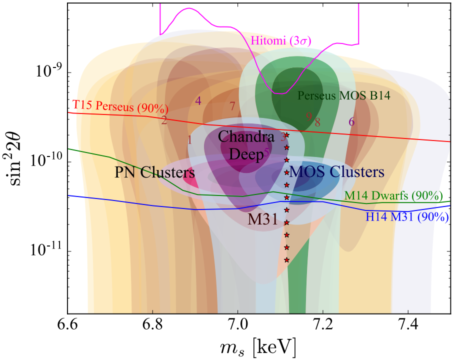
- **Energy:** 3.5 keV. Statistical error for line position $\sim 30 \equiv 50$ eV.
- **Lifetime:** $\sim 10^{27} \equiv 10^{28}$ sec

Can this be...

- ...(sterile neutrino) decaying dark matter?

Subsequent works

- 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+



[1705.01837]

for reviews see

- *"Sterile neutrinos in cosmology"* [1705.01837]
- *"Sterile Neutrino Dark Matter"* [1807.07938]

What can this be?

Statistical fluctuation? – Detections in many objects

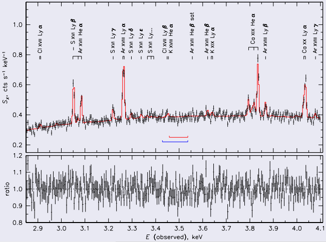
Milky way & Andromeda galaxies, Perseus cluster, Draco dSph, distant clusters. COSMOS & Chandra deep fields

Systematics? – Detection with 4 different telescopes

- Different mirror coating (Au vs. Ir)
- Different detector technologies (CCD vs. Cadmium-Zinc-Telluride)

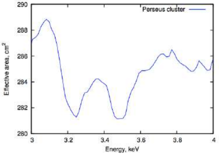
Astronomical line?

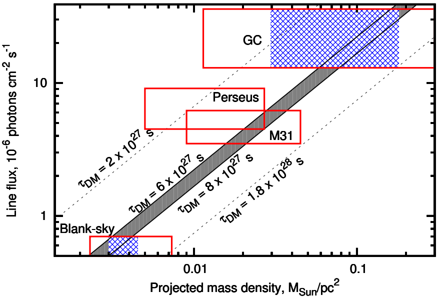
Hitomi observation of the Perseus galaxy cluster ruled out the interpretation as Potassium or any other narrow atomic line. Sulphur ion charge exchange? (Gu+ 2015 & 2017)

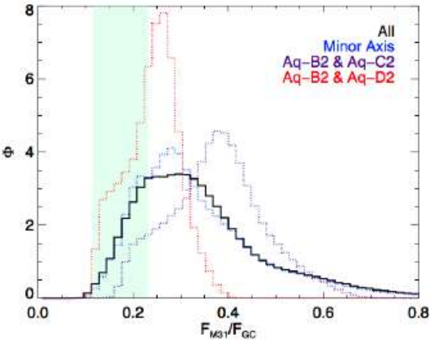


Dark matter is universal. . . but uncertain

- The line is few percents of background
- Challenging to rule out all **systematics** at this level
- But! Dark matter hypothesis means that signal should be present in **all** galaxies and clusters
- . . . and scale accordingly

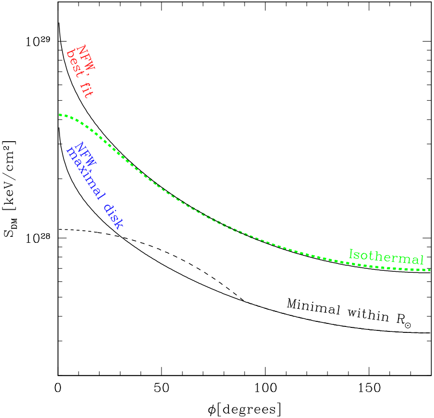






Signal from the Milky Way outskirts

- We are surrounded by the Milky Way halo on all sides
- Expect signal from any direction. Intensity drops with off-center angle
- Surface brightness profile of the Milky Way would be a "smoking gun"



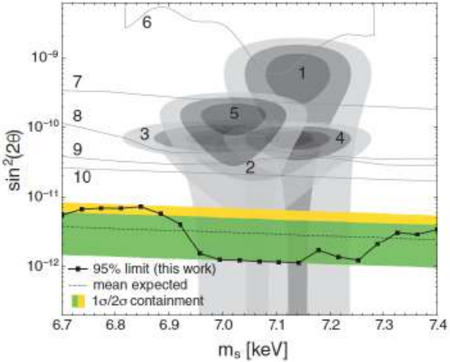
As usual two independent groups got the idea:

- *The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations* C. Dessert, N. Rodd, B. Safdi [1812.06976]
  Submitted on 17 Dec 2018
- *Surface brightness profile of the 3.5 keV line in the Milky Way halo* A. Boyarsky, D. Iakubovskyi, O. Ruchayskiy, D. Savchenko Submitted [1812.10488]
  Submitted on 26 Dec 2018

Dessert et al. Science (March 2020) [1812.06976]

- Quantity $\sin^2(2\theta)$ – sterile neutrino DM mixing angle – is proportional to dark matter decay width
- This mixes physical limit (flux) with their assumptions about DM distribution in the Galaxy ☹
- Ignoring all this, dark matter interpretation has $\sin^2(2\theta) \gtrsim 2\times 10^{=11}$ **give or take a factor of few**

- Deep exposure dataset (30 Msec) of Milky Way regions $5^\circ \equiv 45^\circ$
- Self-invented complicated statistical analysis instead of a standard fitting approach, used by the X-ray community
- **At face value** this rules out dark matter interpretation by a factor ~ 10



Strong line in the Milky Way

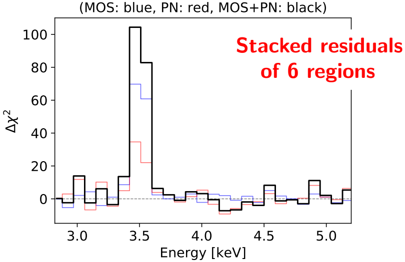
Boyarsky, Ruchayskiy, et al. [1812.10488] + update

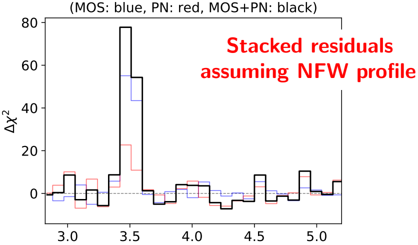
- 49 Msec of quiescent Milky Way regions ($10'$ to 45°)
- The data split into **6 radial bin**
- Line is detected in 4 bins with $> 3\sigma$ and in 2 bins with $> 2\sigma$ significance
- Good background model in the interval $2.8 \equiv 6$ keV plus $10 \equiv 11$ keV

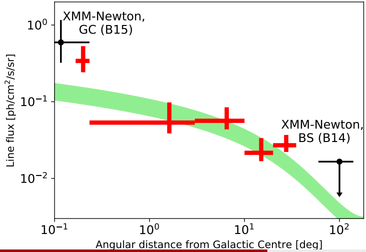
Region	$10' - 14'$ **(Reg1)**	$14' - 3^\circ$ **(Reg2)**	$3^\circ - 10^\circ$ **(Reg3)**	$10^\circ - 20^\circ$ **(Reg4)**	$20^\circ - 35^\circ$ **(Reg5)**	$35^\circ - 45^\circ$ **(Reg6)**
MOS/PN exp.	3.1/1.1	3.0/0.8	2.2/0.7	6.2/2.3	17.0/4.1	5.5/2.5
MOS/PN FoV	205/197	398/421	461/518	493/533	481/542	468/561
χ^2/d.o.f.	179/161	184/174	193/184	171/145	139/131	131/128
p-values	0.14	0.29	0.32	0.07	0.31	0.41
3.5 keV position	$3.52^{+0.01}_{-0.01}$	$3.48^{+0.02}_{-0.03}$	$3.51^{+0.02}_{-0.01}$	$3.56^{+0.03}_{-0.02}$	$3.46^{+0.02}_{-0.01}$	$3.48^{+0.03}_{-0.03}$
3.5 keV flux	$0.37^{+0.05}_{-0.08}$	$0.05^{+0.03}_{-0.02}$	$0.06^{+0.02}_{-0.01}$	$0.022^{+0.007}_{-0.004}$	$0.028^{+0.004}_{-0.005}$	$0.016^{+0.006}_{-0.006}$
3.5 keV $\Delta\chi^2$	19.4	4.5	12.4	15.6	25.1	8.1
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Dark matter profile of the line

Boyarsky, Ruchayskiy, et al. [1812.10488] + update





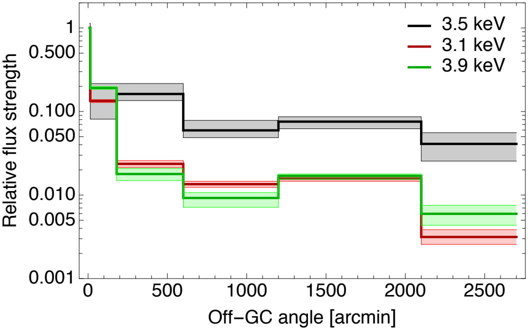


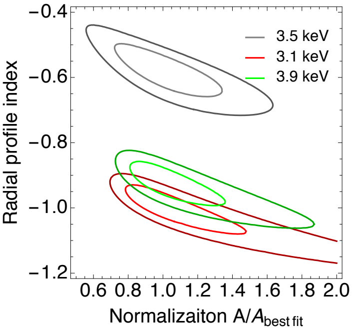
Profile	Significance in σ	Line position [keV]	Decay width Γ [10^{-28} sec^{-1}]
NFW [19] $r_s = 20$ kpc	7σ	$3.494^{+0.002}_{-0.010}$	0.39 ± 0.04
Burkert $r_B = 9$ kpc	6.4σ	$3.494^{+0.003}_{-0.014}$	$0.57^{+0.05}_{-0.08}$
Einasto $r_s = 14.8$ kpc $\alpha = 0.2$	6.9σ	$3.494^{+0.002}_{-0.009}$	$0.40^{+0.04}_{-0.06}$

TABLE II. Combined spectral modeling of spatial regions Reg1–Reg5 with the same position of the line and relative normalizations in different regions fixed in accordance with a DM density profile. Two parameters of the line fit are: the energy and the intrinsic decay width, Γ. As intrinsic line width and the normalization of DM den-

The signal is not astrophysical

Boyarsky, Ruchayskiy, et al. [1812.10488] + update

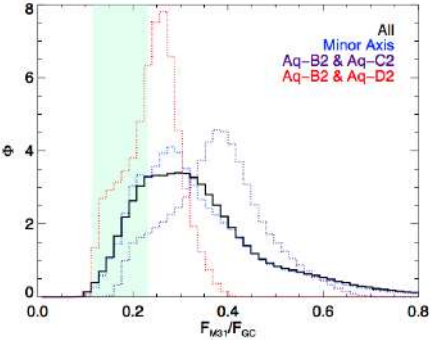




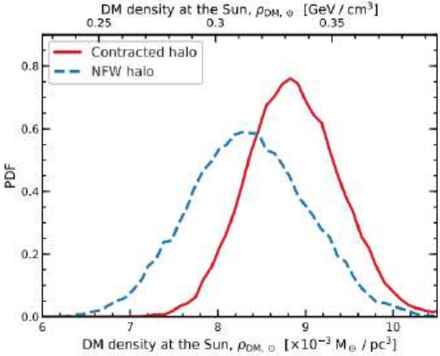
The radial profile of the 3.5 keV line is significantly more shallow than radial profiles of nearby astrophysical lines

Dark matter content

[1411.0311]



[1911.04557]

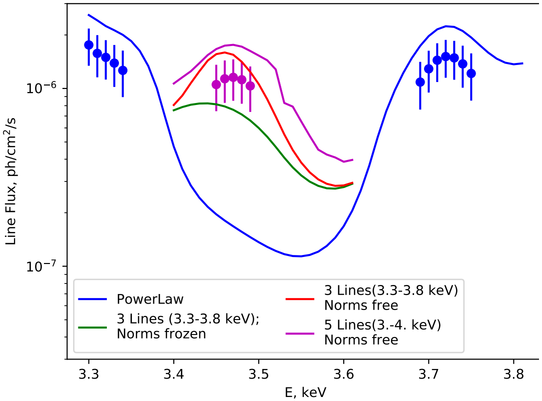


Dessert et al. assumes $\rho_\odot = 0.4\,\mathrm{GeV}/\mathrm{cm}^3$

- To rule out "mixing angle" as inferred in our work from the center of M31 you should **marginalize** over uncertainties in DM densities of M31 vs. Milky Way

Proper modeling at narrow interval

Boyarsky et al. [2004.06601]; also Abazajian [2004.06170]



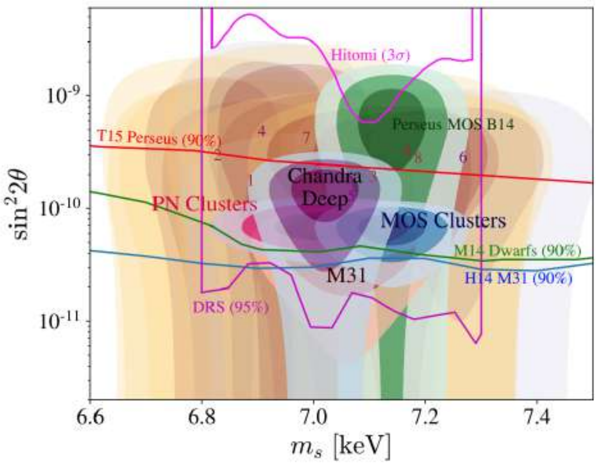
- The background is **non-monotonic** at the interval of energies 3.3-3.8 keV where they perform search
- There are other lines in this interval
- Not including them into the model **artificially raises the continuum** $\Rightarrow$ reduce any line

Blue data points: lines with $\geq 3\sigma$ significance

Magenta data points: lines with $\geq 3\sigma$ significance (4σ for $E = 3.48$ keV)

Bounds are consistent with previous detections

Abazajian [2004.06170]



- Does not include proper modeling of effective area
- Does not account for wider interval of energies
- Should be correct within a factor of few

Future: X-ray spectrometers

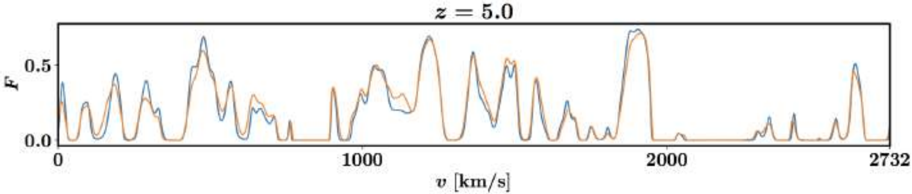
- Short flight of **Hitomi** demonstrated that the origin of the line can be quickly checked with spectrometers
- **Hitomi** replacement – XRISM is scheduled to be launched in 2021–2022

With X-ray spectrometer one can

- Check the width of the line (for Perseus cluster the difference in line broadening between atomic lines ($v \sim 180$ km/sec) and DM line ($v \sim 1000$ km/sec) is visible)
- See the structure (doublets/triplets) of lines (if atomic)
- Check exact position of the line (Redshift of the line is Perseus was detected at 2σ with XMM – easily seen by **XRISM**)
- Confirm the presence of the line with known intensity from all the previous detection targets: Milky Way, M31, Perseus, etc.

Structure formation and sterile neutrino dark matter

- Sterile neutrinos are born relativistic in the early Universe
- While they cool down with expansion – they **homogenize** primordial density perturbations
- This translates into the small-scale lack of power that can be observed in the correlation of the Lyman-α absorption lines

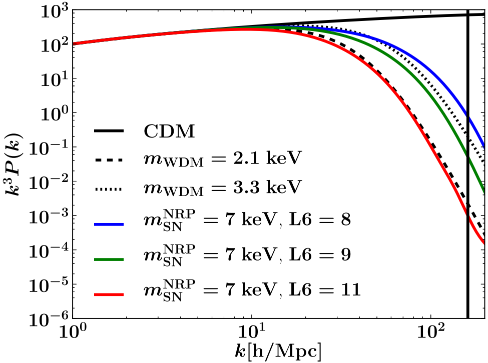


Garzilli, Magalich, Theuns, Frenk, Weniger, Ruchayskiy, Boyarsky [1809.06585]

Blue: CDM, Orange: 7 keV sterile neutrino

High-resolution Lyman-α forest and HNL dark matter

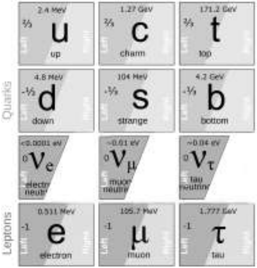
Garzilli, Boyarsky, Ruchayskiy et al. [1510.07006], and then [1809.06585] [1912.09397]



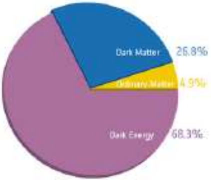
- Best fit **thermal relic** mass $= 2.1$ keV
- Corresponds to resonantly produced sterile neutrino with $M_N = 7$ keV and lepton asymmetry $L = 11 \times 10^{\equiv 6}$
- 3.5 keV line, interpreted as sterile neutrino DM, gives range of lepton asymmetries $L = 8 \equiv 12$

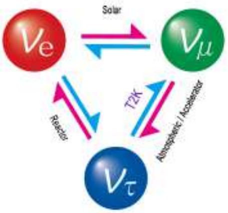
By accident (or maybe not) the HNL dark matter interpretation of 3.5 keV line predicts exactly the amount of suppression of power spectrum observed in HIRES/MIKE (and fully consistent with all other structure formation bounds)

Conclusions



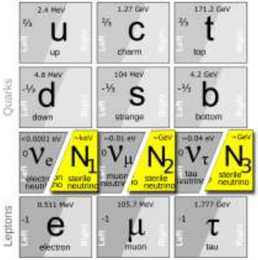
+





Neutrino oscillation between three generations

=



Backup slides

Outline

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 $B \equiv L$)

Wide class of scenarios known as **leptogenesis**

Thermal leptogenesis: $M_N \sim 10^9 \equiv\equiv 10^{12}$ GeV

Fukugita & Yanagida'86

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

Pilaftsis, Underwood'04–'05

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

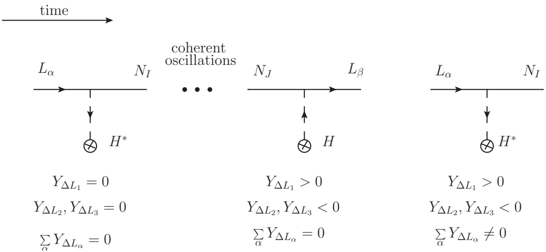
Akhmedov, Smirnov & Rubakov'98

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



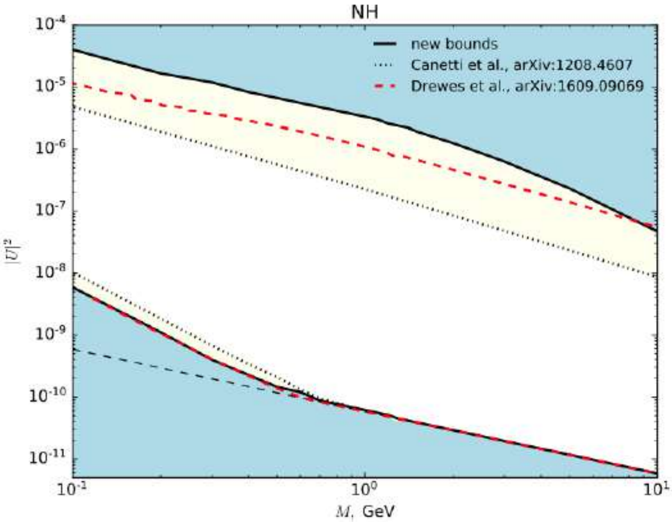
Shuve & Yavin'14

- 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 $T \sim \mathcal{O}(10)\mathrm{GeV}$, reaching levels $\gg \eta_{baryon}$

Shaposhnikov'08

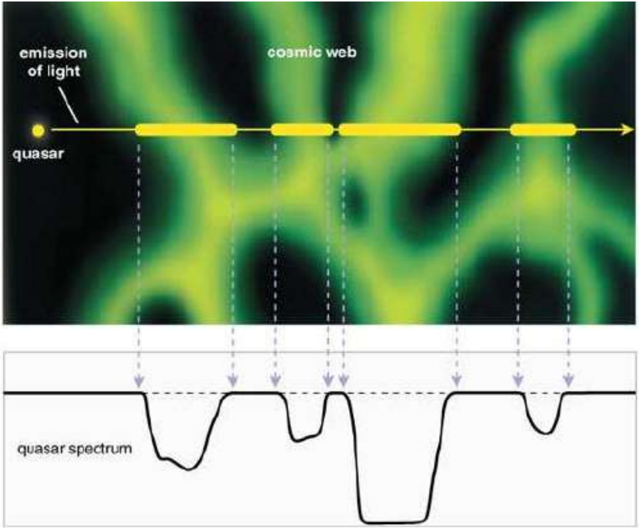
Comparison between works

From Eijima, Shaposhnikov, Timiryasov [1808.10833]



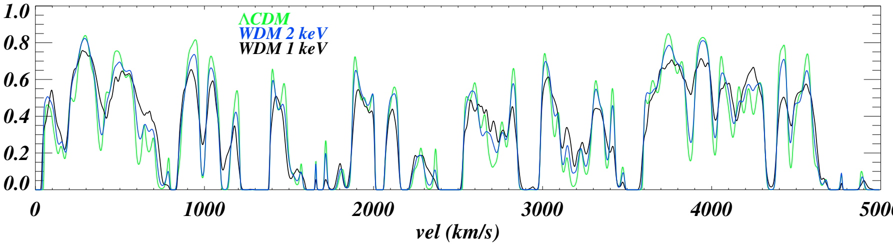
Outline

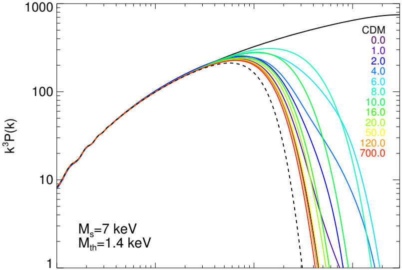
Lyman-α forest and power spectrum



Lyman-α forest data

Viel+'13

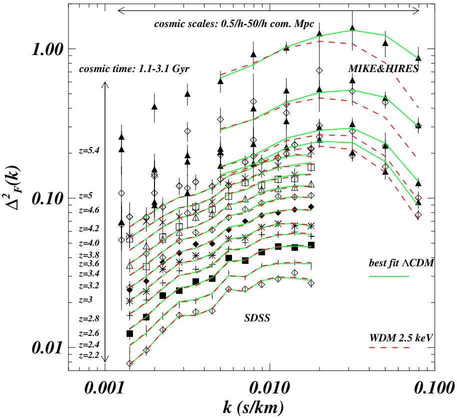


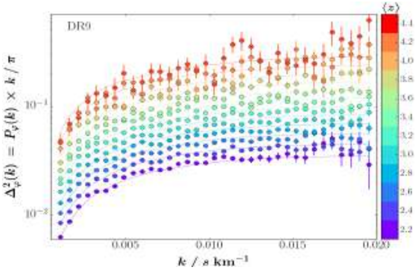


$\Rightarrow$

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



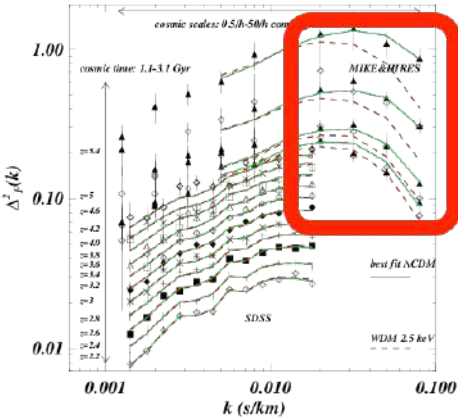


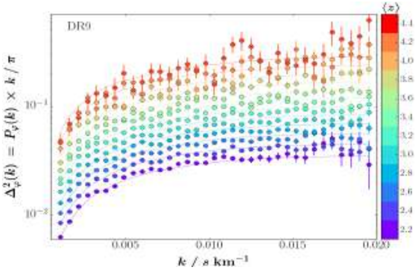
BOSS Ly-α [1512.01981]

In Lyman-α spectra higher spectral resolution means **smaller scales**

No suppression of flux power spectrum in SDSS/BOSS datasets $\Rightarrow$ only lower bound on WDM mass have been put **Seljak+'06;Viel+'06;Boyarsky+'08**

Suppression in the flux power spectrum





BOSS Ly-α [1512.01981]

In Lyman-α spectra higher spectral resolution means **smaller scales**

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

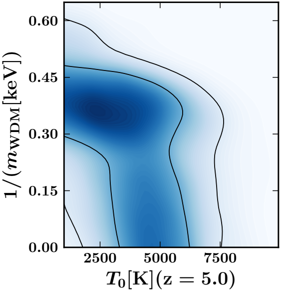
Warm dark matter or warm hydrogen?

Garzilli, Boyarsky, Ruchayskiy [1510.07006]

Suppression in the flux power spectrum may be due to

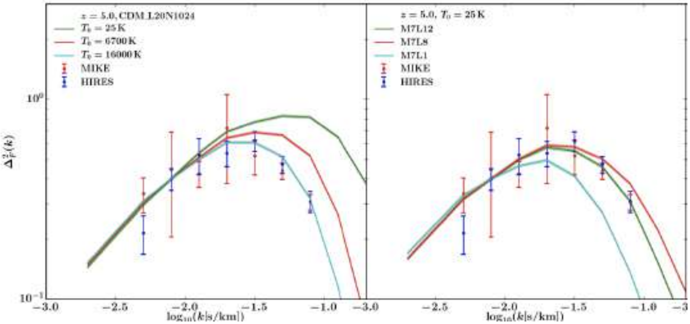
- Temperature at redshift z (Doppler broadening) – **increases hydrogen absorption line width**
- Pressure at earlier epochs (gas expands and then needs time to recollapse even if it cools)
- Warm dark matter

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



Warm dark matter or warm intergalactic medium?

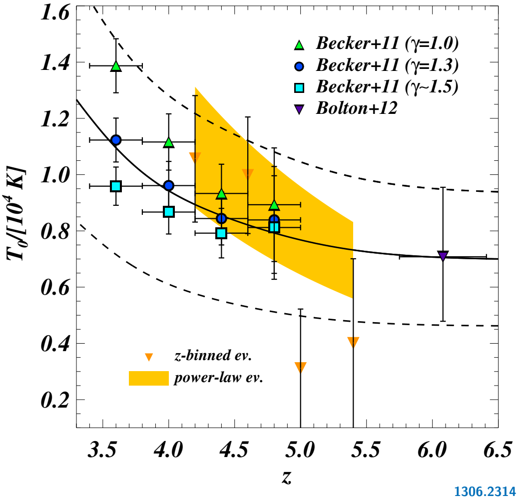
Garzilli et al. (2015, 2018)

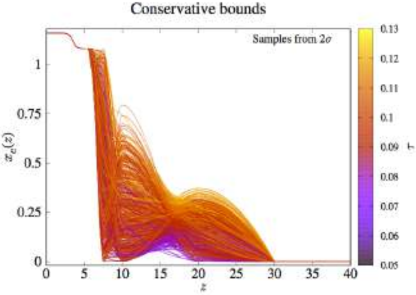


- HIRES flux power spectrum **exhibits suppression at small scales**
- This suppression can be explained equally well by thermal history of the Universe (unconstrained at these redshifts) or by **warm dark matter**

What is known about the IGM thermal history?

Current measurements of IGM temperature

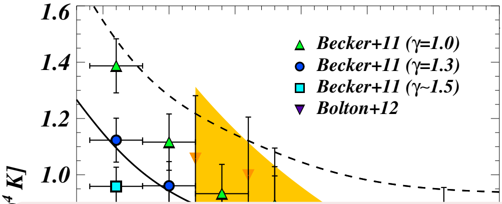


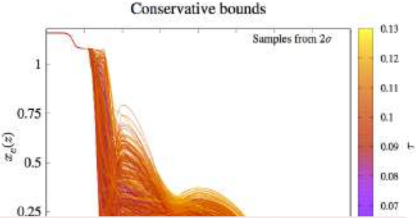


- There are many measurements at $z < 5$
- There is a single measurement **above** $z = 6$
- History of reionization at higher redshifts is poorly constrained

What is known about the IGM thermal history?

Current measurements of IGM temperature





- We need to know **when** the Universe was reionized
- We need to know **to what temperature** the gas was heated

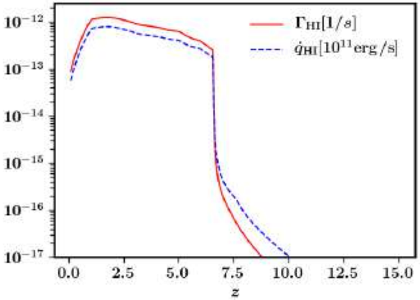
z

1306.2314

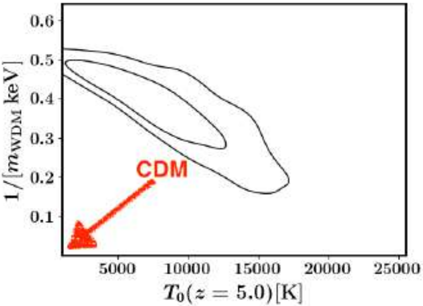
- History of reionization at higher redshifts is poorly constrained

Warm dark matter may have been discovered

Garzilli 2015, 2018, 2019 with O.R. and A. Boyarsky



Onorbe et al. 2016



Garzilli et al. [1912.09397]

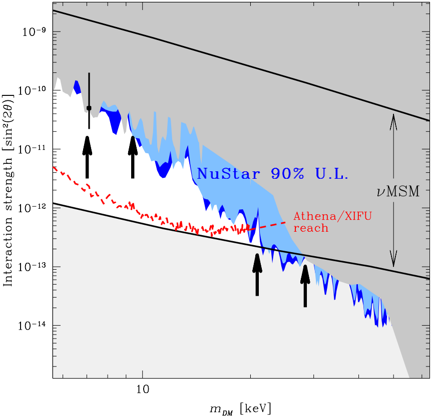
- Universe reionizes late
- CDM is ruled out for such reionization scenario (even if instantaneous temperature is varied)

Outline

Line in NuStar

Milky Way halo. [1607.07328]

- 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

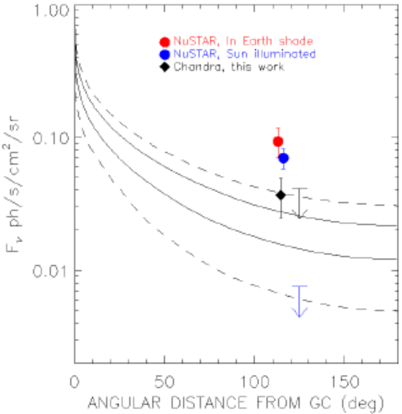


See also discussions in Roach+ [1908.09037], Perez+ [1609.00667]

Line in Chandra

Cappelluti+'17 [1701.07932]

- 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

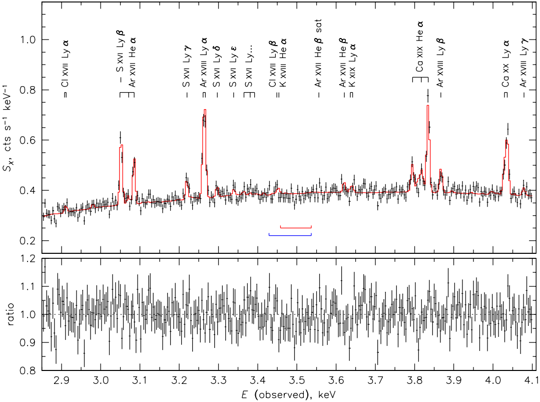


By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

Next step for 3.5 keV line: resolve the line

- 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 filters block most of X-ray below 3 keV)

Perseus center spectrum **[1607.07420]**



What did we learn with existing Hitomi data?

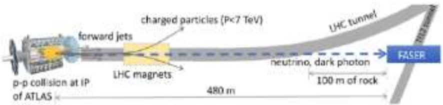
- Due to its super energy resolution, *Hitomi* can distinguish between atomic line broadening (thermal velocities $\sim 10^2\,\mathrm{km/sec}$) and decaying dark matter line broadening (virial velocity $\sim 10^3\,\mathrm{km/sec}$)
- Even the short observation of Hitomi showed that Potassium, Clorium, 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

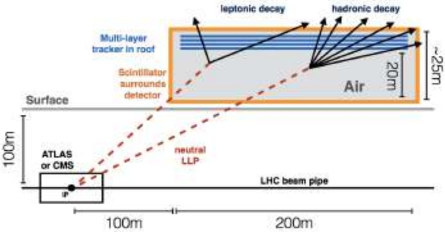
- This does not seem to be astrophysics (Hitomi spectrum)
- This does not seem to be systematics (4 different instruments)
- ???

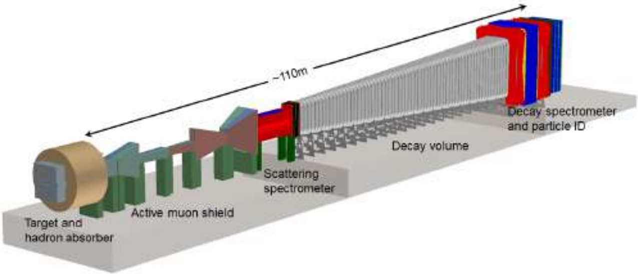
Outline

What we are discussing today

See PBC report [1901.09966] or *"Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020"* [1910.11775]







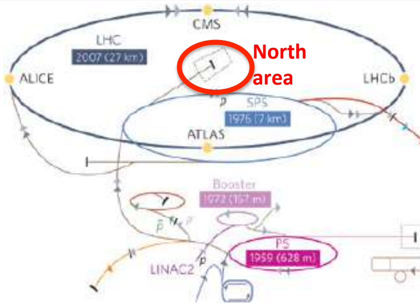
- FASER: ATLAS
- MATHUSLA: CMS or ATLAS
- Codex-b: LHCb
- SHiP: SPS
- NA62++: SPS
- . . . (actually, many more)

Outline

1. Baryogenesis with HNLs
2. Lyman-α forest and sterile neutrino dark matter
3. 3.5 keV line
4. SHiP and other Intensity Frontier experiments
5. SHiP experiment
6. The end

Super Proton Synchrotron (SPS)

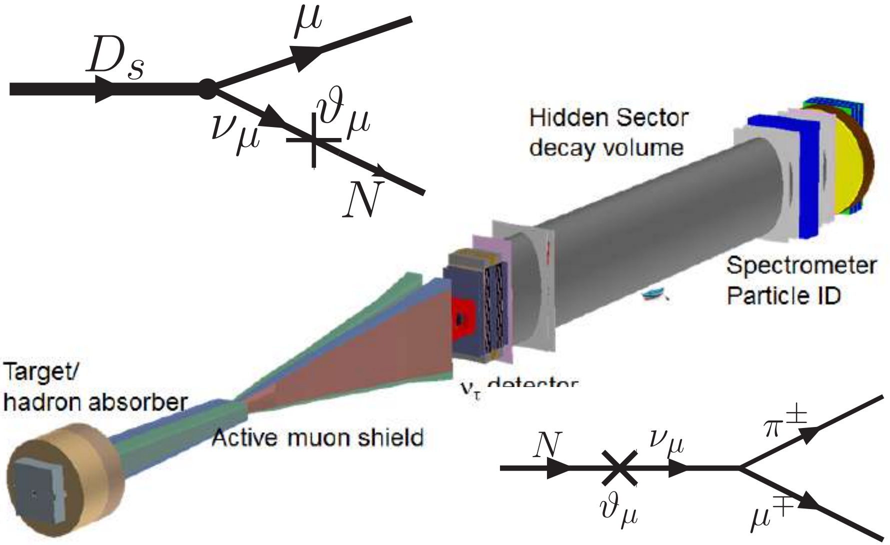
$$N_{D\equiv\text{mesons}} = 2 \times X_{c\bar{c}} \times N_{PoT}$$



- 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: $X_{c\bar{c}} \sim 10^{\equiv 3}$

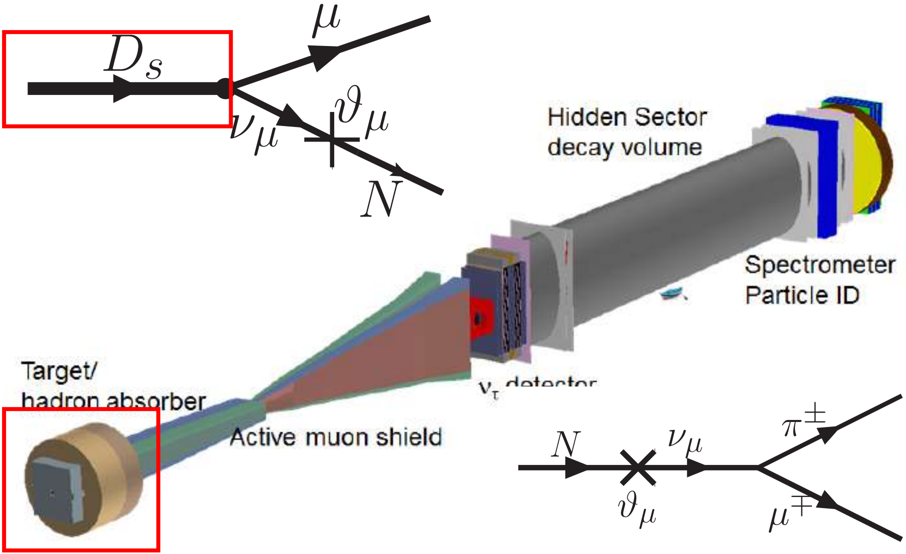
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



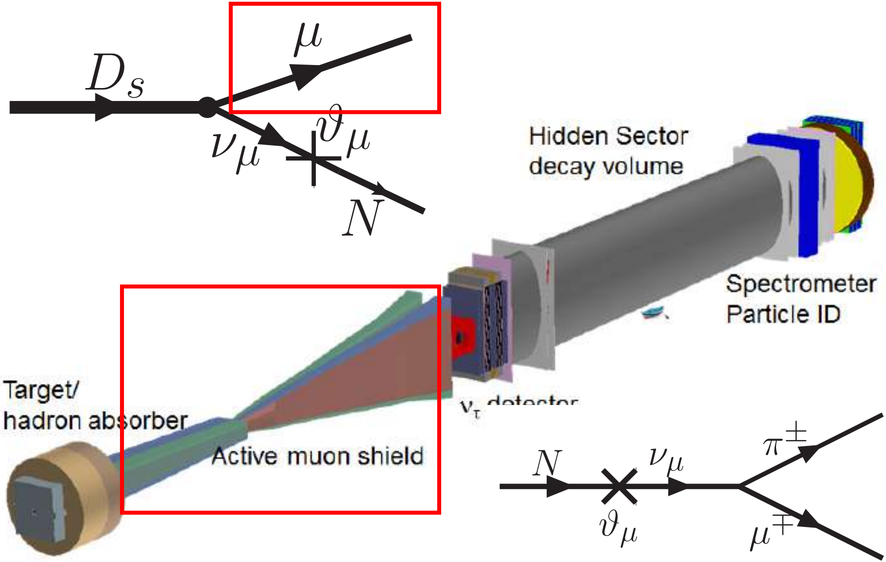
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



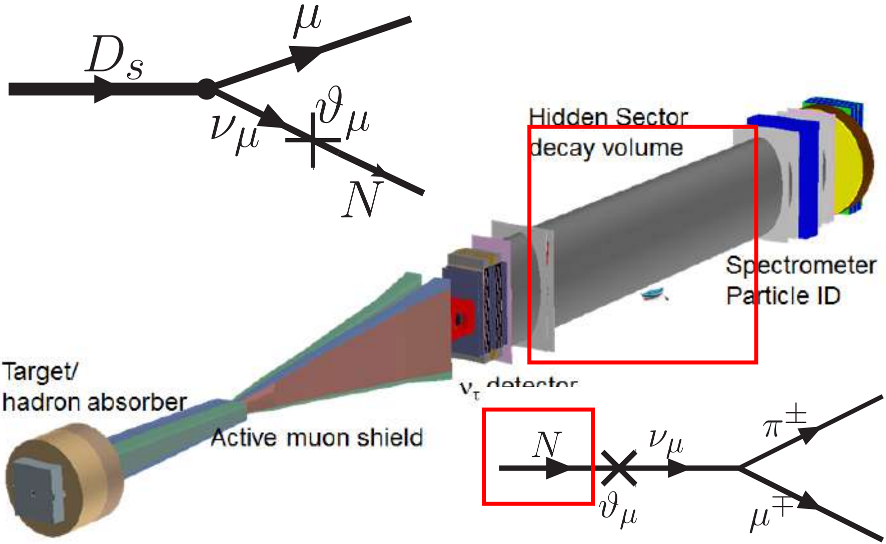
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



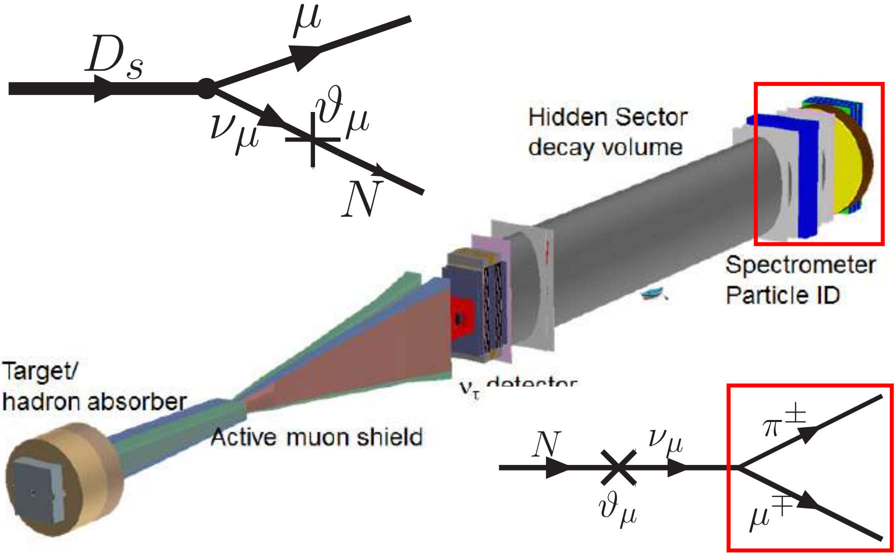
SHiP (*Search for Hidden Particles*) experiment

Step by step overview



SHiP (*Search for Hidden Particles*) experiment

Step by step overview



Challenges

- **Background** – many intensity frontier experiments are background free. Many but not all and knowing the background is crucial
- **PID** – can you identify particles that were produced? Are they only "charged particles", "hadrons" or something more specific
- **Mass reconstruction** – if you have a signal, what was the mass particle that decayed? If you have N signal candidate events - do they all reconstruct to the same mass?

Take home messages

- All major predictions of the Standard Model have been spectacularly confirmed
- Yet, there are "beyond-the-Standard-model" puzzles of **observational** nature that lack their explanation
- Particles that are responsible for it are either too heavy (beyond the LHC reach) or too feebly interacting
- There are no theoretical predictions and therefore we need to **explore all possible options**
- **Feebly Interacting Particle**s can be searched during next LHC runs (or alongside LHC) – results within next decade

Outline