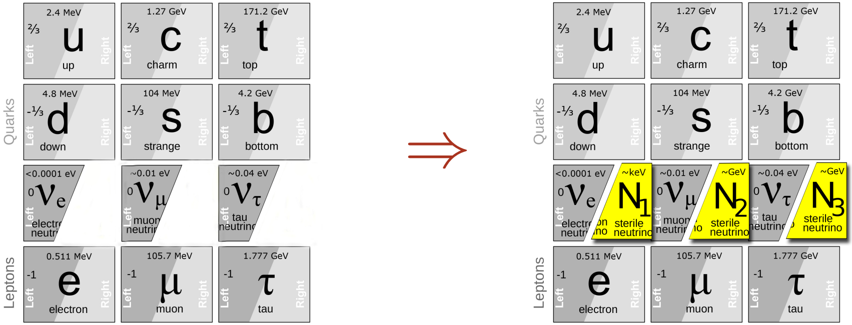
News about heavy neutral leptons

Oleg Ruchayskiy

March 1, 2017

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

Type I seesaw model

Majorana mass term

$$\mathscr{L}_{\text{Seesaw Type I}} = \mathscr{L}_{\text{SM}} + i\bar{N}\partial\!\!\!/ N + Y\,\bar{N}(\tilde{H}\cdot L) + \frac{1}{2}\bar{N}MN^c + \text{h.c.}$$

Dirac mass term

- Neutrinos are light because $m_{\text{Dirac}} \ll \boldsymbol{M}$:

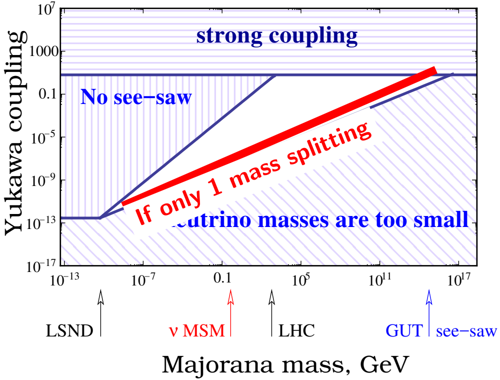
$$m_\nu \simeq \frac{(m_{\text{Dirac}})^2}{\boldsymbol{M}} = U^2\boldsymbol{M}$$

- **active-sterile mixing angle**

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

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

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 $I\neq J$.)

Properties of sterile neutrinos

Heavy neutral lepton inherits the interactions from neutrinos

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

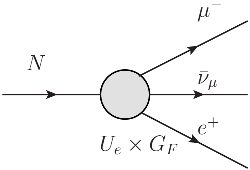
Neutral current-like: $\tilde{\mathscr{L}}_{\rm NC} = \frac{g\, U}{\cos\theta_W}\, \bar{\nu}\gamma^\mu(1-\gamma_5)\boldsymbol{N}^c Z_\mu$

Typical values of parameters

$$G_F \longrightarrow U \times G_F$$

Yukawa coupling $\sim \left(\frac{M_N m_\nu}{\langle\Phi\rangle^2}\right)^{1/2} \approx 4\times10^{-8}\left(\frac{M_N}{1\ \text{GeV}}\right)^{1/2}$

Mixing angles $U^2 = \frac{m_\nu}{M_N} \approx 5\times10^{-11}\left(\frac{1\ \text{GeV}}{M_N}\right)$



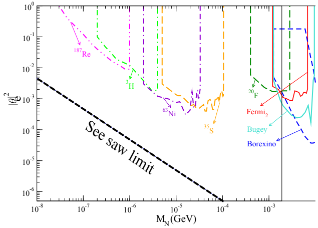
How to search for HNLs

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

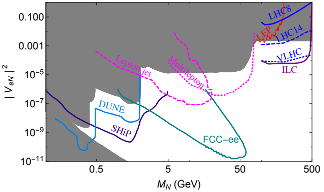
- $M_N < \textit{few}\,\mathrm{MeV}$ – only U_e mixing can be probed (kink searches)
- $\mathcal{O}(10)\mathrm{MeV} \lesssim M_N \lesssim M_K$ – intensity frontier experiments (peak searches)
- $\mathcal{O}(100)\mathrm{MeV} \lesssim M_N \lesssim M_B$ – intensity frontier experiments (fixed target experiments)
- $M_N \gtrsim \textit{few}\,\mathrm{GeV}$ – 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]

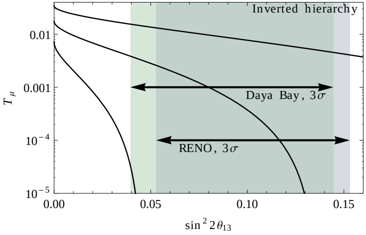


[1601.01658]

Accidental suppression of mixing angles

Shaposnikov'06; Asaka et al.'11; Ruchayskiy & Ivashko'11; Drewes et al.'16

- Already with **two** HNLs accidental **suppression** of some of the flavour mixing angles is possible, given unknown phases in PMNS matrix
- Therefore it is important to target channels, governed by different mixing angles U_α (at SHiP, NA62, LHC, ...)



Ruchayskiy&Ivashko'11

$$T_\mu \equiv \frac{U_\mu^2}{\sum_\alpha U_\alpha^2}$$

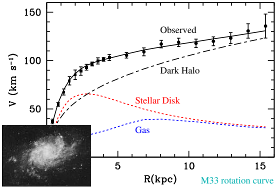
Mass of heavy neutral leptons?

☹ No information from neutrino oscillations

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

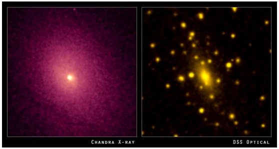
Dark Matter in the Universe

Astrophysical evidence:



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

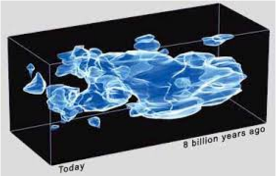
Observed: $v(R) \approx \mathrm{const}$



Expected:

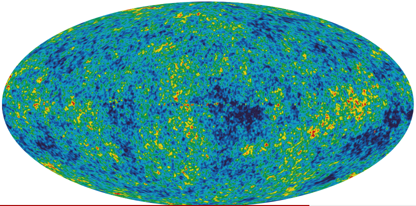
$\mathrm{mass}_{\mathrm{cluster}} = \sum \mathrm{mass}_{\mathrm{galaxies}}$

Observed: 10^2 times more mass confining ionized gas

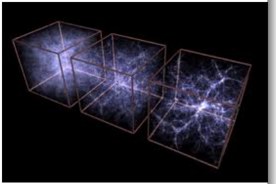


Lensing signal (direct mass measurement) **confirms** other observations

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 $\sum m_\nu \sim 11\,\mathrm{eV}$

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 $\sim 300 - 400\,\mathrm{eV}$
- If particles with such mass were **weakly interacting** (like neutrino) – they would oveclose the Universe ($\Omega \sim 3\,!$)

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**

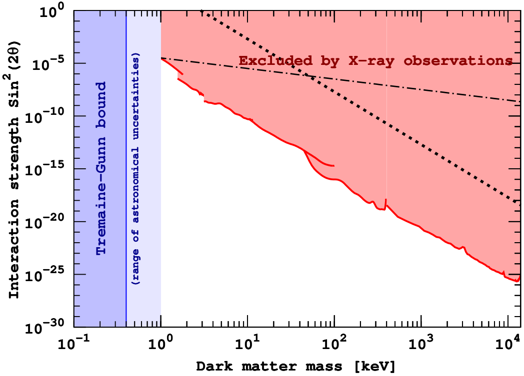
Heavy and weakly interacting — **WIMP**

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

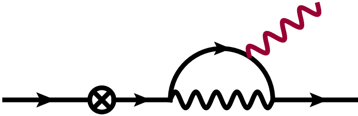
HNLs as dark matter

- **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 $N \to \gamma + \nu$

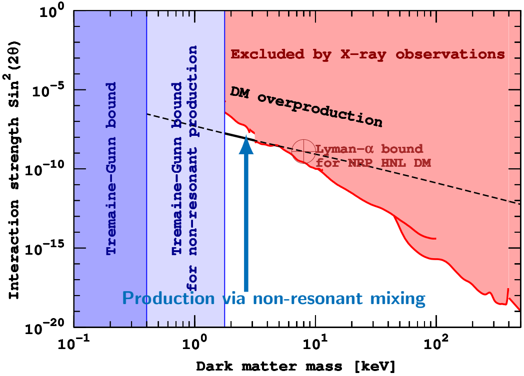


- Lifetime $\gg$ Age of the Universe (dotted line)
- Contribution to neutrino masses

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

[Asaka+'05; Boyarsky+'06]

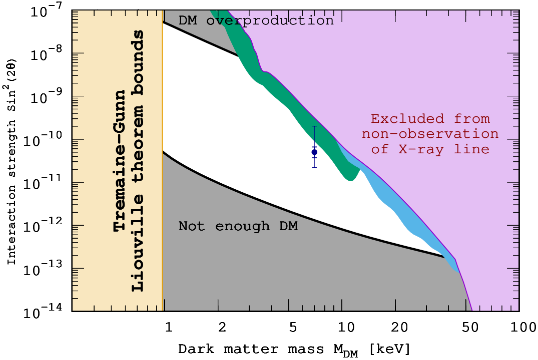
Parameter space of HNL dark matter II



– 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



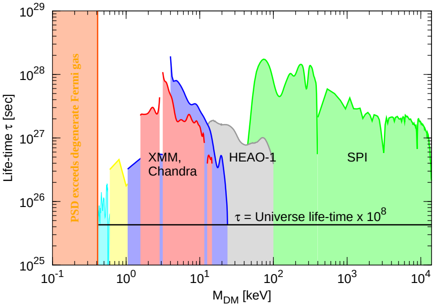
- White region: production via **resonant** mixing **[Shi & Fuller'93; Laine & Shaposhnikov'08]**
- Requires: lepton asymmetry exceeding η_{baryon} by many orders of magnitude at $T \sim 100 - 500\,\text{MeV}$

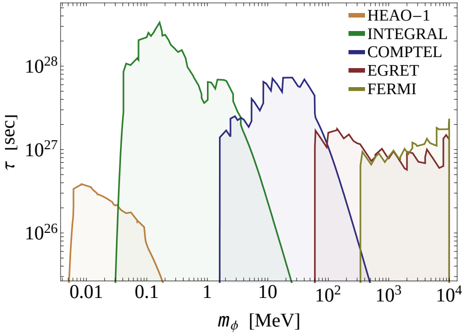
In summary

- 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)

Searches for radiatively decaying dark matter

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





Essig+'13

"Next decade of sterile neutrino studies"

MW (HEAO-1) Boyarsky+'05; Coma and Virgo clusters Boyarsky+'06; Bullet cluster Boyarsky+'06; LMC+MW(XMM) Boyarsky+'06 MW Riemer-Sørensen+'06; Abazajian+'06; MW (XMM) Boyarsky+'07 MW (INTEGRAL) Yuksel+'07; Boyarsky+'07; M31 Watson+'06; Boyarsky+'07; Horiuchi+'13; dSph Loewenstein+'08,'09,'12; Malyshev+'15,. . .

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

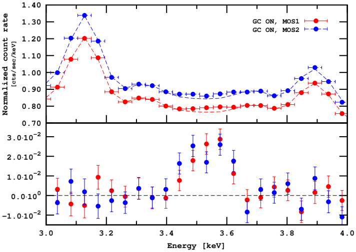
A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

PRL (2014) [1402.4119]

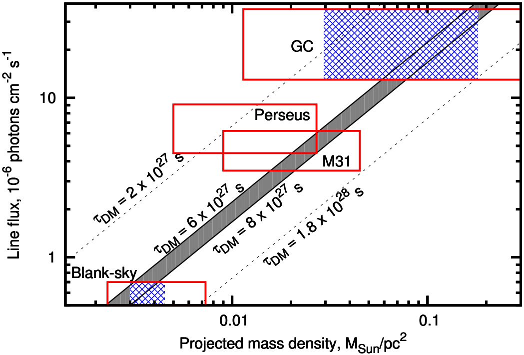
- **Energy:** 3.5 keV. Statistical error for line position $\sim 30-50$ eV.
- **Lifetime:** $\sim 10^{28}$ sec (uncertainty: factor ~ 3)
- **Possible origin:** decay $\mathrm{DM} \to \gamma + \nu$ (fermion) or $\mathrm{DM} \to \gamma + \gamma$ (boson)

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**

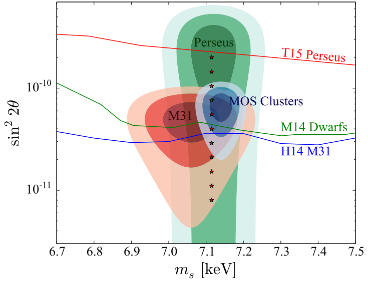


- Observation from M31 puts a **lower** bound on the GC flux
- Non-observations from the Milky Way outskirts puts an **upper** bound on the GC flux
- The observed signal fits into the range

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]

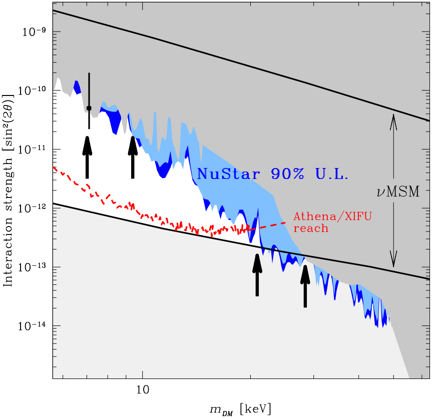
A common explanation for every detection and non-detection?

- 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]

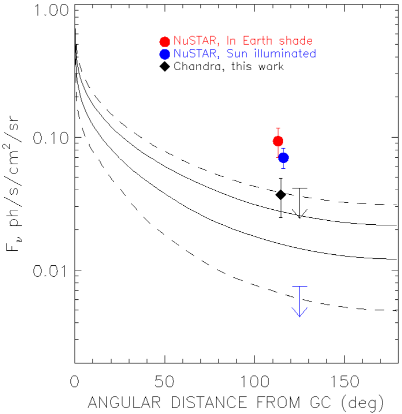
- The 3.5 keV is present in the spectrum with 11σ significance
- The spectrum of NuStar ends at 3 keV, so this is a lower edge of sensitivity band
- The 3.5 keV line has been previously attributed to reflection of the sunlight on the telescope structure
- However, in the dataset when Earth shields satellite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

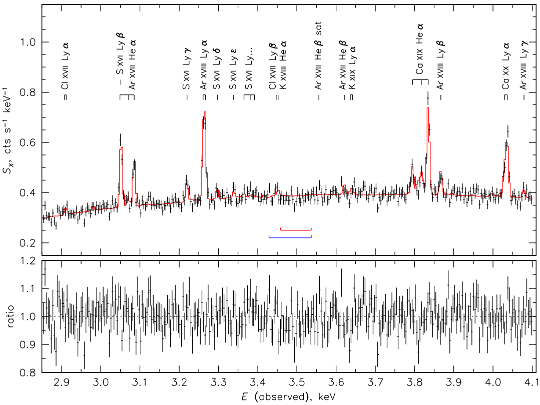


By now the 3.5 keV line has been observed with 4 existing X-ray telescopes, making the systematic (calibration uncertainty) origin of the line highly unlikely

Next step for 3.5 keV line: resolve the line

- 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)
> - ???

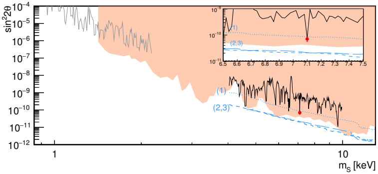
Future of decaying dark matter searches in X-rays

Another Hitomi

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

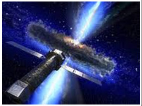
Microcalorimeter on sounding rocket (2017)

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



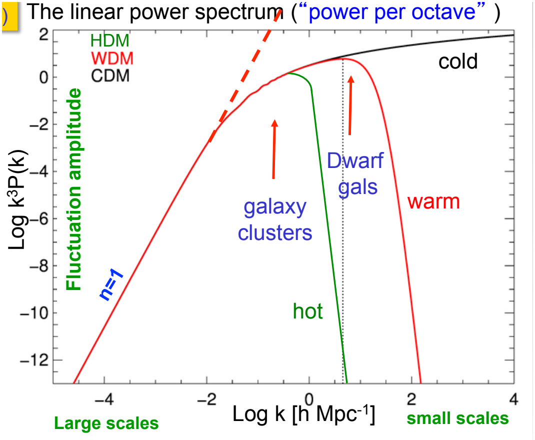
Athena+

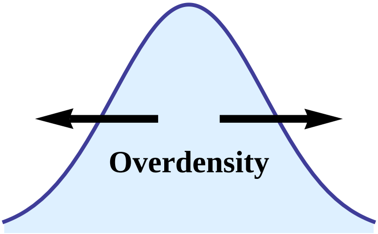
- Large ESA X-ray mission (2028) with X-ray spectrometer (X-IFU)
- Very large collecting area ($10\times$ that of XMM)



Warm dark matter

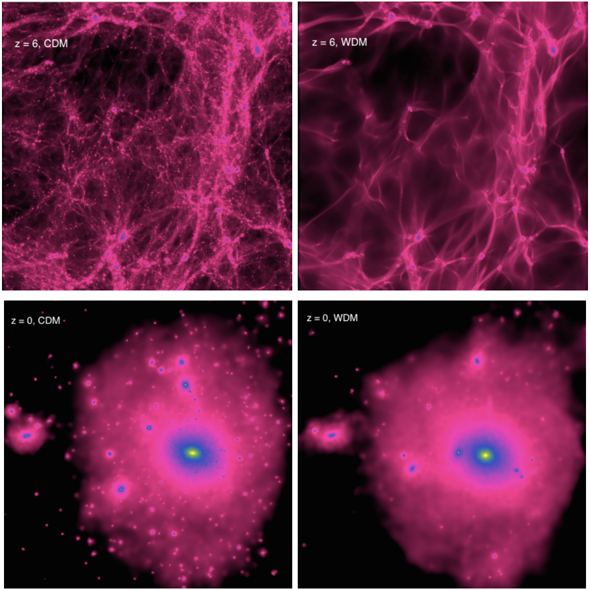
- Particles are born relativistic $\Rightarrow$ they do not cluster
- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities





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

At non-linear scales



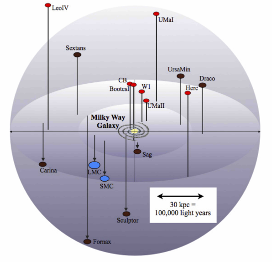
COCO Warm simulation Bose+'15

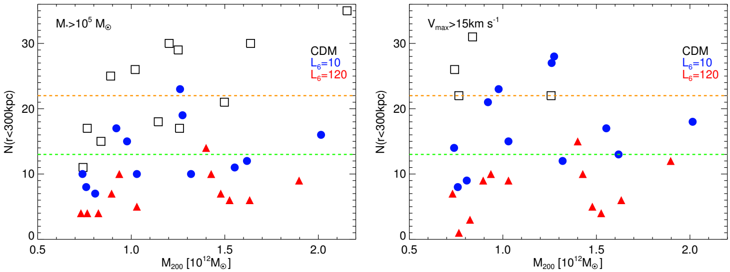
HNL dark matter:

- Same structures as in **CDM** Universe at scales of Mpc and above ⇒ 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

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



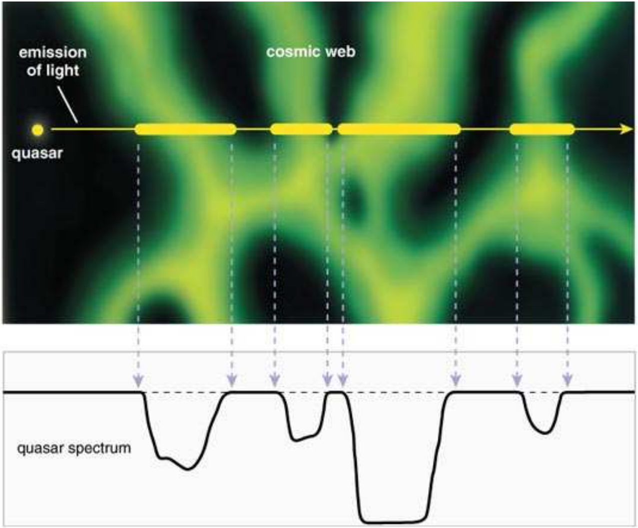


Lovell, Boyarsky, O.R.+ [1611.00010]

Current status of structure formation bounds from the Local Universe

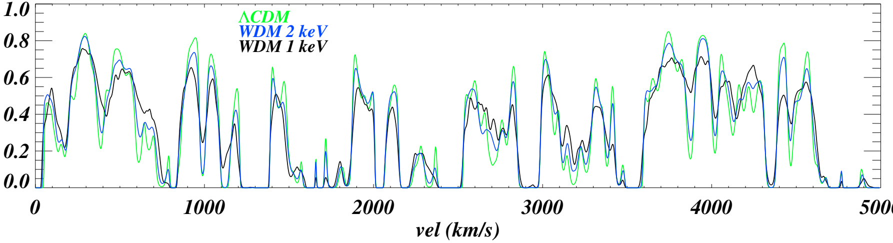
- Connection "dark structures" $\leftrightarrow$ "visible structures" depends on (yet unknown) way to implement baryonic feedback
- Simulation to simulation (or even halo-to-halo) scatter is quite large and affects the conclusions
- We do not know how typical is our Galaxy, our Local Group, etc.
- You 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**

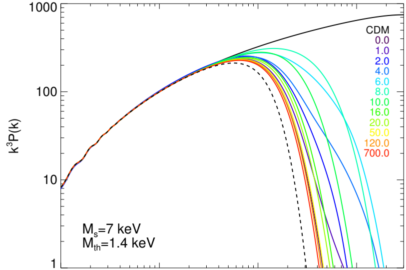
Lyman-α forest and power spectrum



Lyman-α forest data

Viel+'13

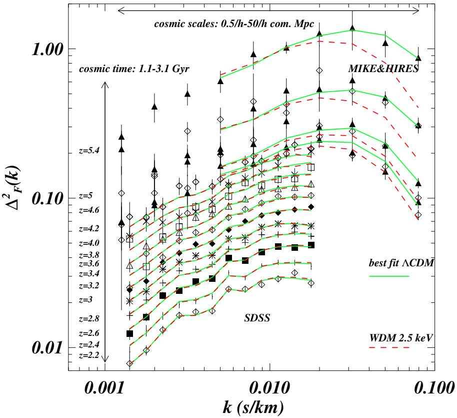


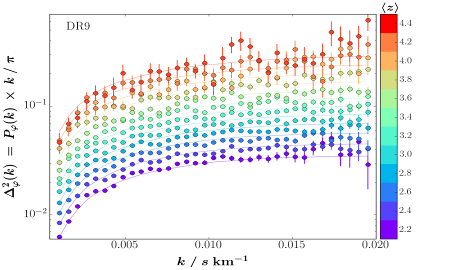


⇒

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



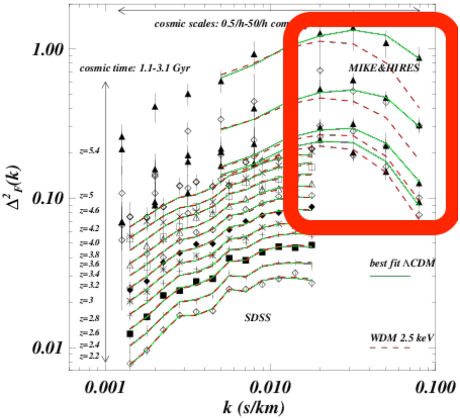


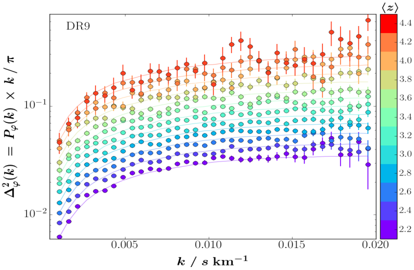
BOSS Ly-α [1512.01981]

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

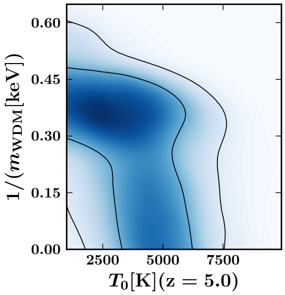
Warm dark matter or warm hydrogen?

Garzilli, Boyarsky, Ruchayskiy [1510.07006]

Suppression in the flux power spectrum may be due to

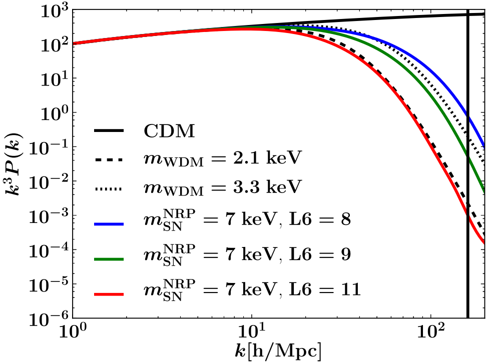
- Temperature at redshift z (Doppler broadening) – **increases hydrogen absorption line width**
- Pressure at earlier epochs (gas expands and then needs time to recollapse even if it cools)
- Warm dark matter

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



High-resolution Lyman-α forest and HNL dark matter

Garzilli, Boyarsky, Ruchayskiy [1510.07006]

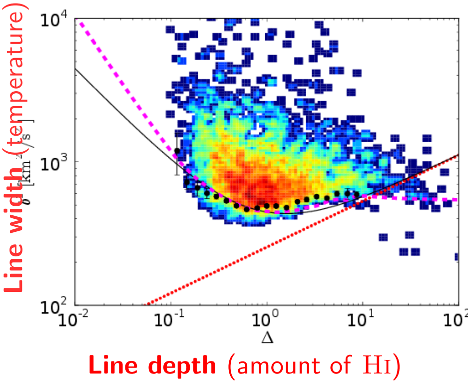


- Best fit **thermal relic** mass $= 2.1$ keV
- Corresponds to resonantly produced sterile neutrino with $M_N = 7$ keV and lepton asymmetry $L = 11 \times 10^{-6}$
- 3.5 keV line, interpreted as sterile neutrino DM, gives range of lepton asymmetries $L = 8 - 12$

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

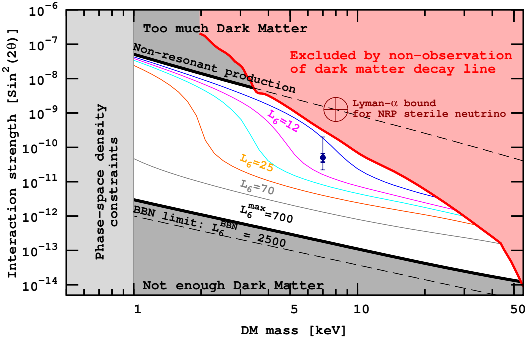
- The high-resolution Lyman-α spectra show suppression – due to thermal effects **or** due to warm dark matter
- We have only crude information about the reionization history and temperature of gas at reionization epoch
    - The measurement of gas temperatures at redshifts $z \gtrsim 5$ has high discovery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

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

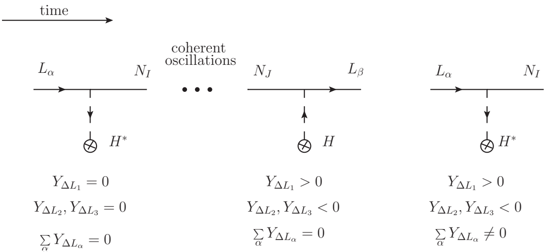
Asaka & Shaposhnikov'05

...

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

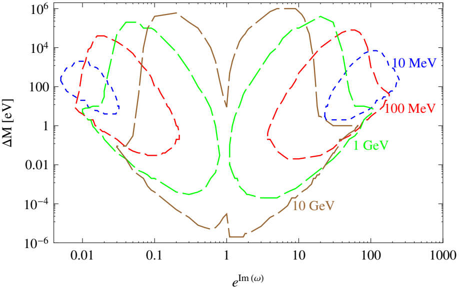


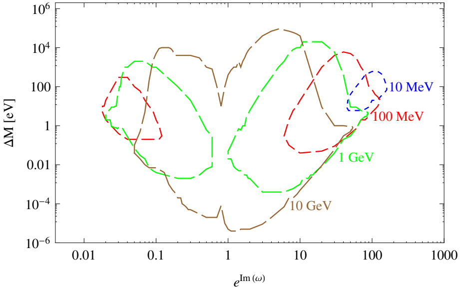
Shuve & Yavin'14

- 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

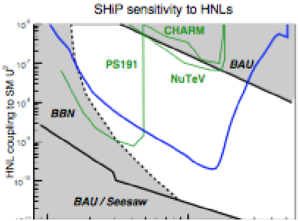
- Leptogenesis via oscillations can occur for masses down to tens of MeV
- Requires degeneracy in masses $\Delta M/\bar{M} \ll 1$

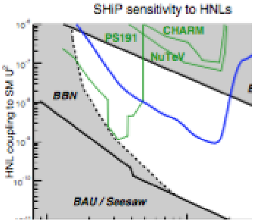
HNL masses from leptogenesis

- 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

SHiP sensitivity to HNL models





- Different baryogenesis models require different patterns of $U_e : U_\mu : U_\tau$
- Existing sensitivity curves (SHiP TP) assumed certain patterns of $U_e : U_\mu : U_\tau$ and cannot be translated to other models

We will generate a grid of simulations and interface that would allow to estimate SHiP sensitivity for any HNL model

A project run by SHiP Theory group (K. Bondarenko, A. Boyarsky, D. Gorbunov, M. Shaposhnikov, O. Ruchayskiy) together with SHiP Physics group (Nico Serra)

How many simulations do we need?

- A model with **2** HNLs has **8 relevant phenomenological parameters** (M_1, M_2, $|U_{\alpha 1}|, |U_{\alpha 2}|$)
- For **most of the cases** production via different flavours $|U_{\alpha I}|^2$ is **independent**
- Number of events in the detector are proportional to $|U_{\alpha I}|^2$ but never to $U_{\alpha I} U_{\alpha J}$ (no coherent effects):
- So, for **2** HNLs with $M_1 \approx M_2$...

$$\begin{aligned} D^- &\to N_{1,2} + e^- \\ &\quad\quad \hookrightarrow \pi^+ + \mu^- \end{aligned}$$

- ...total number of events in the detector is proportional to

$$\begin{aligned} N_{obs} &\propto |U_{\mu 1}|^2 |U_{e 1}|^2 + |U_{\mu 2}|^2 |U_{e 2}|^2 \\ &= N_{obs,1} + N_{obs,2} \end{aligned}$$

holds when $c\tau\gamma \gg L_{SHiP}$!

We can simulate **1 HNL** and translate the results to all HNL models

HNL@SHiP project

Summary

if $\Delta M > 10^{-8}\,\mathrm{eV}$

- Number of events in the decay volume scales with $|U_\alpha|^2$ as following

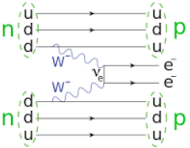
$$N_{events}[M|U_e^2, U_\mu^2, U_\tau^2] = \sum_{\alpha,\beta} P_{\alpha\beta}(M)|U_\alpha|^2|U_\beta|^2$$

  holds when $c\tau\gamma \gg L_{SHiP}$!

- **Grid** $P_{\alpha\beta}\left(M^{(i)}\right)$ contains all the necessary information
  (scan over $\mathcal{O}(100)\,\mathrm{MeV} \leq M^{(i)} \leq 5$ GeV)
- Interpolate for other sets of HNL parameters $(M_N, U_{\alpha I})$

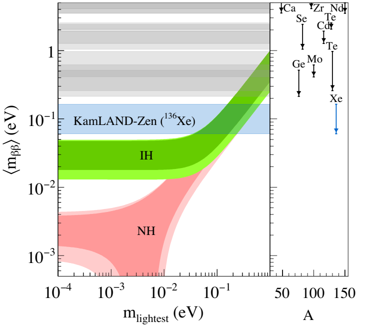
Neutrinoless double beta decay

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



- Neutrino oscillations define the value of

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



[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

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

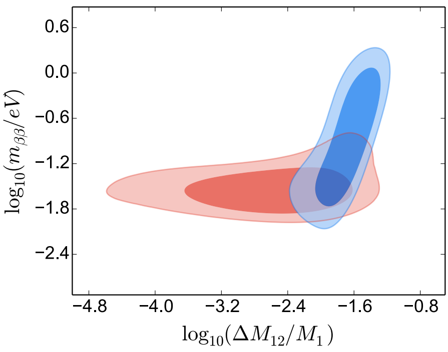
- $f(M_\mathrm{I})$ is the nuclear matrix element, approximately (c.f. Faessler+'14)

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

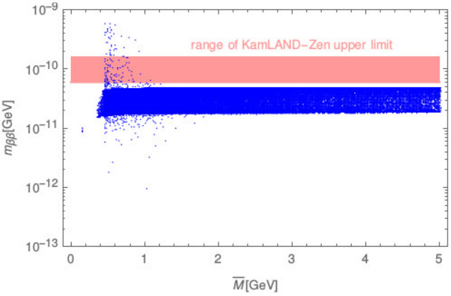
- Seesaw relation in these terms

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

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



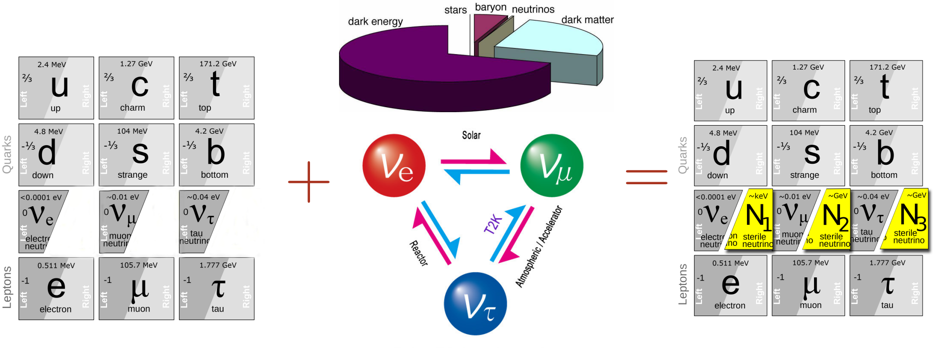
Hernández+'16



Drewes & Eijima'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



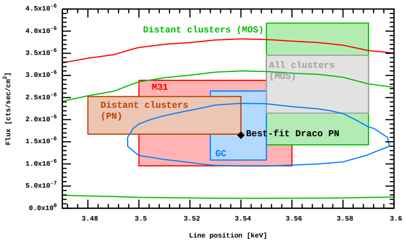
Neutrino oscillation between three generations

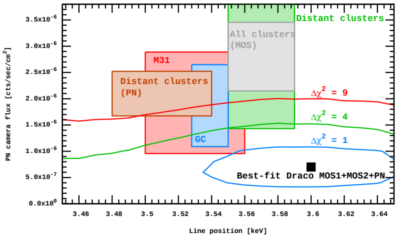
Outline

Analysis of Draco dSph

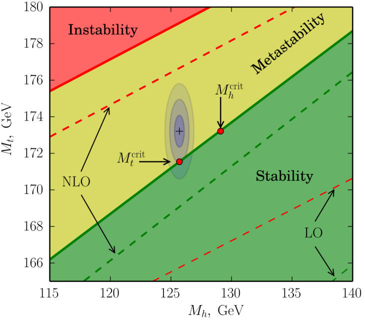
Ruchayskiy+ MNRAS (2016) [1512.07217]

- 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 $\tau_{\rm DM} > (7-9) \times 10^{27}\,\mathrm{sec}$

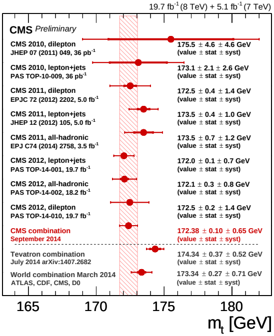




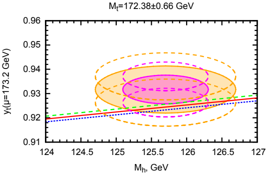
Standard Model is consistent up to very high scales



[1609.02503]



[1411.1923]



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]