keV scale sterile neutrino Dark Matter

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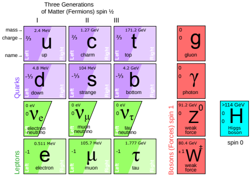
Outline

1. SM, Cosmology and sterile neutrinos
2. X-ray observations
3. Pure νMSM – just three sterile neutrinos
4. Other DM generation mechanisms
5. Laboratory searches

Standard Model – describes nearly everything



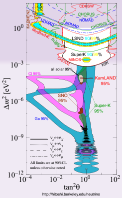
\+

Einstein gravity

Describes

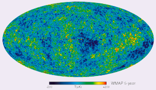
- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$ sec)

Experimental problems:



- Laboratory
  - ? Neutrino oscillations
- Cosmology
  - ? Baryon asymmetry of the Universe
  - ? Dark Matter

  - ? Inflation



  - ? Dark Energy

Sterile neutrino as DM

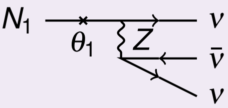
- Nearly always present in SM extensions
- Feebly interacting
- Quite stable if light (keV scale)

Outline

DM properties – Radiative decay

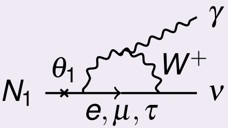
Leads to constraints from the X-ray observations

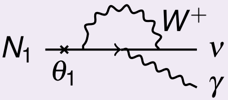
Main decay channel



- $\tau > \tau_{\text{Universe}}$ - easy:
  $$\theta^2 < 3.3 \times 10^{-4} \left(\frac{10\text{keV}}{M_1}\right)^5$$
- not visible, really...

Second decay channel: $N_1 \to \nu\gamma$

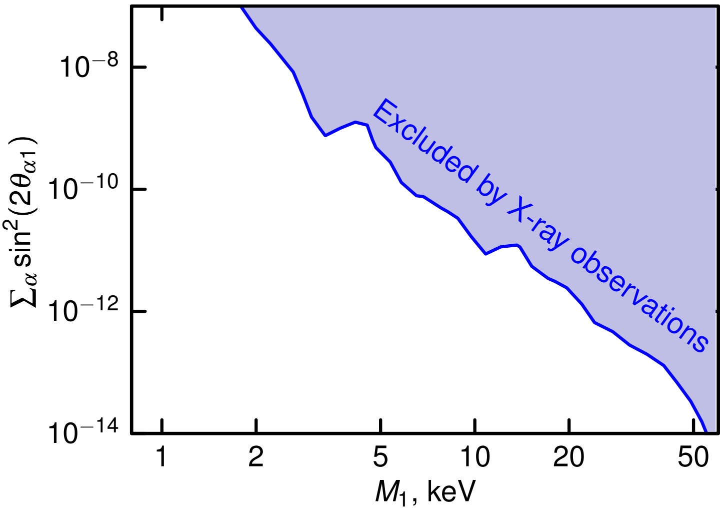




$$\Gamma \simeq 5.5 \times 10^{-27} \left(\frac{\theta_1^2}{10^{-5}}\right) \left(\frac{M_1}{1\text{keV}}\right)^5 \text{s}^{-1}$$

- Monochromatic: $E_\gamma = M_1/2$
- We should see an X-ray ($\sim$ keV) line following the DM distribution in the sky

Bounds for the N_1 – DM sterile neutrino



Universal constraint for all DM models

[Boyarsky, Ruchayskiy, Shaposhnikov'09]

Bounds from observed structure in the Universe

- Look at the compact object with DM (dwarf spheroidals)
  - Check that sterile neutrinos can "fit" there – Pauli blocking

$$M_{\mathrm{DEG}} > 0.5\mathrm{keV}$$

  - Stricter bound – phase space density arguments

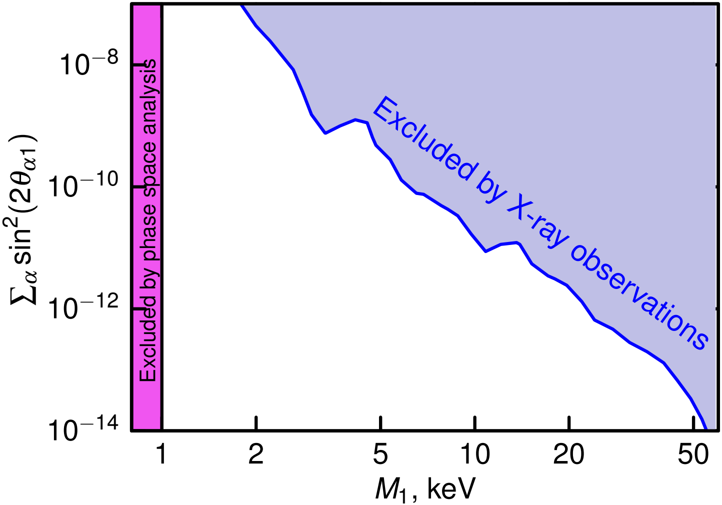
$$M > 1 - 2\,\mathrm{keV}$$

Tremaine, Gunn 79; Gorbunov, Khmelnitsky, Rubakov 08; Boyarsky, Ruchayskiy, Iakubovskyi 08

- Light sterile neutrino being relativistic after generation (warm) provides cut off in the structure formation at smaller (sub-Mpc) scales.
- Presence of this cut off can be searched by the analysis of the Lyman-α absorption line of the intergallactic hydrogen.
  - The bound depends on *velocities* of the neutrinos, not on masses – bound depends on distribution function – production mechanism

Boyarsky, Lesgourgues, Ruchayskiy, Viel'08; Viel, Becker, Bolton, Haehnelt'13; Baur et.al.17

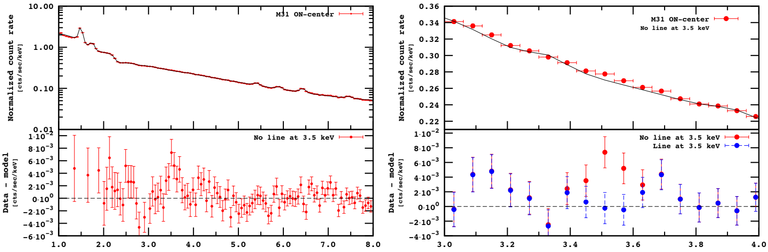
Bounds for the N_1 – DM sterile neutrino



Universal constraints for all models

Search for the line in X-rays

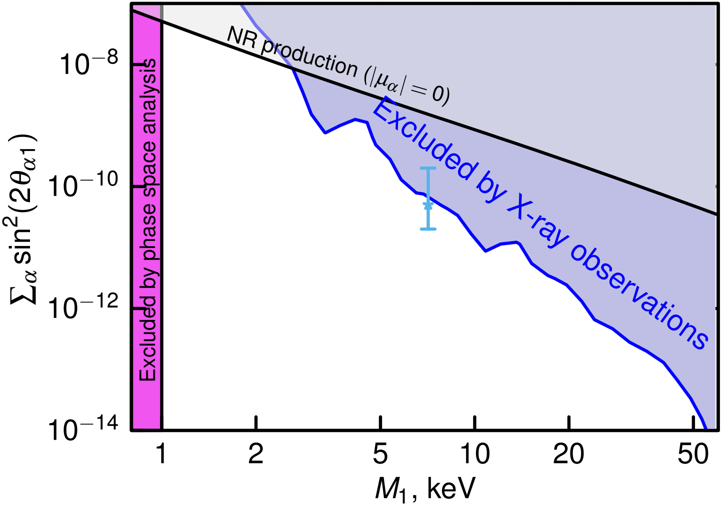
Unidentified line at 3.5 keV in X-rays



- seen by two different satellites (XMM-Newton and Chandra)
- the line has proper redshift for different sources
- the intensity is consistent the Dark Matter profiles
- the line is absent in the blanc sky observations

Bulbul, Markevitch, Foster, Smith et.al.'14, Boyarsky, Ruchayskiy, Iakubovskyi, Franse'14

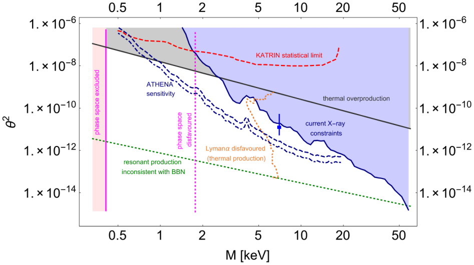
Sterile neutrino N_1 parameters would be



Current status of 3.5 keV line and future

Seen in

- Perseus, Coma, and Ophiuchus galaxy clusters
- Galaxy center
- Stacked clusters
- M31 (Adromeda galaxy)



Not seen in

- Coma, Virgo and Ophiuchus clusters
- Galaxy center
- Stacked galaxies
- Dwarf spheroidals
- Bullet cluster

Future

High resolution X-ray missions

- XARM
- LYNX
- Athena+ (2030?)

Outline

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Summary of sterile neutrino Dark Matter constraints

Dark Matter

stay like DM Decay constraints – small enough radiative decay width (X-ray observations)

always there

behave like DM Structure formation constraints

- Heavy enough to form existing structures out of fermions

  always there

- Cold enough to leave observed small scale structure intact

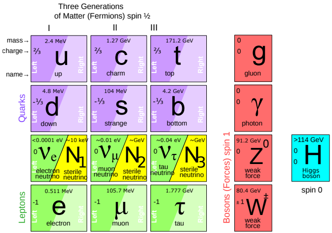
  depends on generation mechanism (spectrum)

appear like DM Production of proper DM abundance

depends on generation mechanism

Minimal Scenario – νMSM

Just three sterile neutrinos



Model action

$$\mathscr{L}_{\nu MSM} = \mathscr{L}_{SM} + i\overline{N}\partial\!\!\!/ N - \overline{L}_L F N \tilde{\Phi} - \overline{N} F^\dagger L_L \tilde{\Phi}^\dagger$$
$$- \frac{1}{2}\left(\overline{N^c} M_M N + \overline{N} M_M^\dagger N^c\right).$$

[Asaka, Shaposhnikov'05, Asaka, Blanchet, Shaposhnikov'05]

νMSM description – neutrino masses

- $M_1 \sim 1$–$50\,\text{keV}$ – Dark Matter
- $M_{2,3} \sim$ several GeV – Leptogenesys

$M_I \gg M^D = F\langle\Phi\rangle$ – "see-saw" formula is working:

Light neutrino masses $$M^\nu = -(M^D)^T \frac{1}{M_I} M^D$$

Active-sterile mixings $$\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \ll 1$$

νMSM experimental consequences (DM)

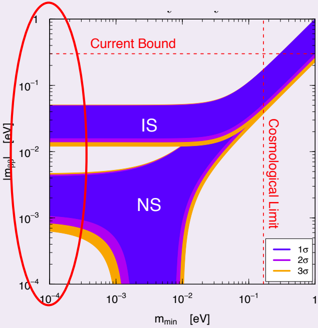
Active neutrino masses

- X-rays require very small N_1 mixing angle θ_1, so

$$m_1 < 10^{-5}\text{eV}$$

Neutrinoless double beta decay

- Additional contributions are negligible
  - N_1 – X-ray constraints
  - $N_{2,3}$ – mass $> 100\,\text{MeV}$
- Mass spectrum strongly hierarchical – X-ray constraints



$$m_{0\nu\beta\beta} < 50 \times 10^{-3}\ \text{eV}$$

[FB'05]

DM generation in the early Universe

- Because of small mixing angle (X-ray constraints!) *never* enters thermal equilibrium
  - Good – does not overclose the Universe
  - Bad (or good?) – abundance depends on initial conditions or new physics

Nowadays called

Freeze In dark Matter Particle

Feebly Interacting Massive Particle

DM generation in the early Universe

Produced in $l\bar{l} \to \nu N_1$, $q\bar{q} \to \nu N_1$, etc.

Production is proportionol to the effective active-sterile mixing angle

$$\theta_M^2(T) \simeq \frac{\theta_1^2}{\left(1 + \frac{2p}{M_1^2}\left(b(p,T) \pm c(T)\right)\right)^2 + \theta_1^2} .$$

$$b(p,T) = \frac{16 G_F^2}{\pi \alpha_W} p(2 + \cos^2\theta_W) \frac{7\pi^2 T^4}{360}$$

$$c(T) = 3\sqrt{2} G_F \left(1 + \sin^2\theta_W\right)(n_{\nu_e} - n_{\bar{\nu}_e})$$

(θ_1 – vacuum mixing angle of N_1 and active ν)

Production can be

Non-resonant (b dominates) or Resonant ($c \sim b$)

DM generation – NR production

- N_1 never enter thermal equilibrium
- Momentum distribution is not thermal

$$f_{N_1}(p) = \frac{\chi}{e^{p/T_\nu} + 1}$$

with $\chi \propto \theta_1^2$

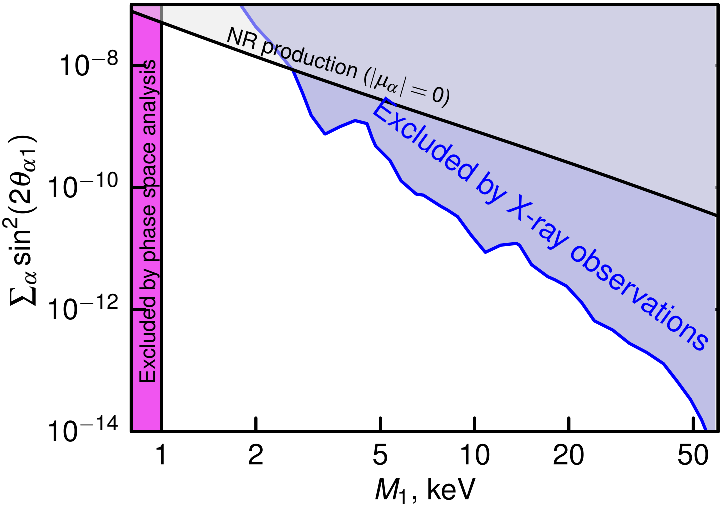
- This is much hotter, than the "Thermal Relic" with

$$f_{TR}(p) = \frac{1}{e^{p/T_{TR}} + 1}$$

of low temperature $T_{TR} < T_\nu$

- The Lyman-α constraint is quite strong $m_{NRP,min} \propto (m_{TR,min})^{4/3}$

Bounds for the N_1 – DM sterile neutrino



Nearly universal constraints

DM generation – NR production

- N_1 never enter thermal equilibrium
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with $\chi \propto \theta_1^2$

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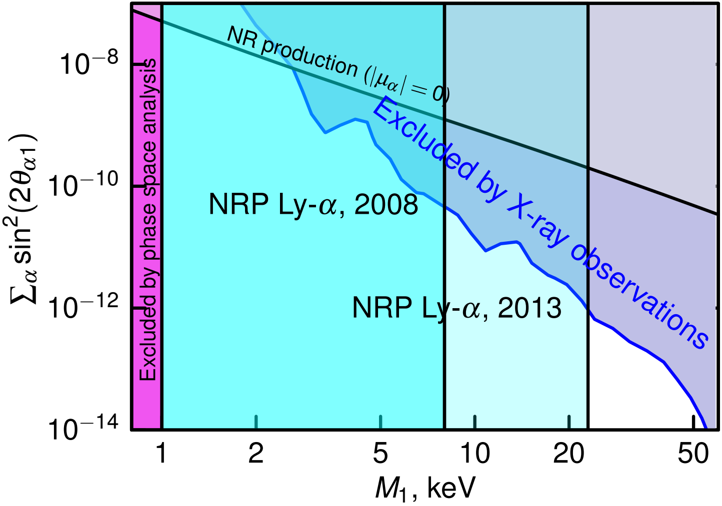
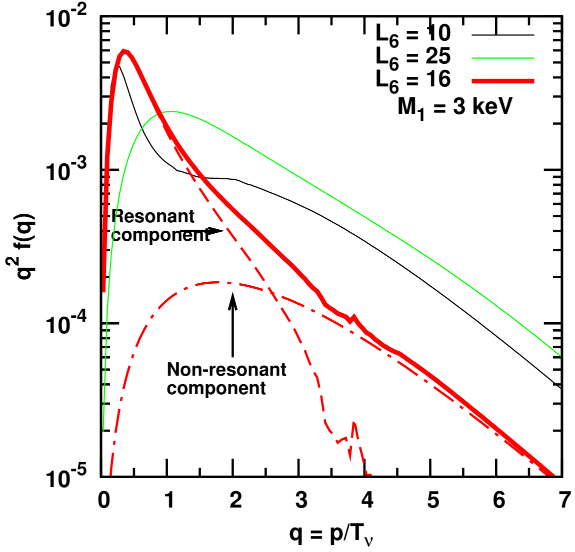


Nonresonant production is completely excluded

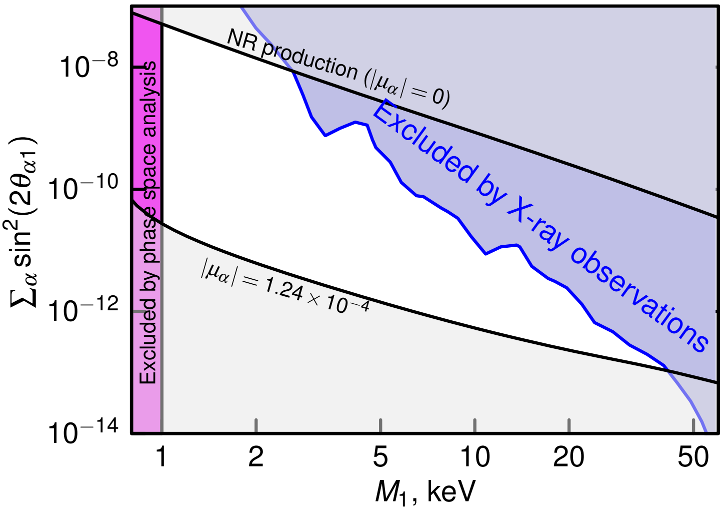
Resonant production – can provide much colder DM

Early Universe is
Lepton
asymmetric
$L = \frac{n_{\nu_e}}{n_\gamma} \neq 0$

And much more of it



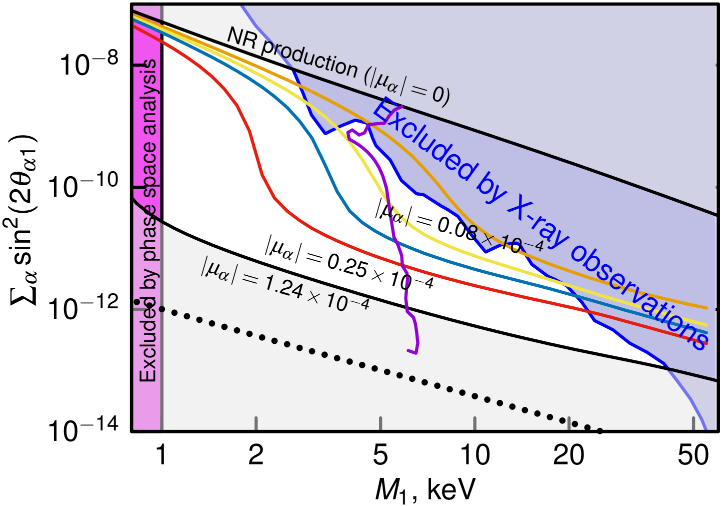
Bounds for the N_1 – DM sterile neutrino



Only for “pure νMSM” – production with lepton asymmetries

[Canetti, Drewes, Shaposhnikov'13]

Bounds for the N_1 – DM sterile neutrino



Only for "pure νMSM" – production with lepton asymmetries

[Canetti, Drewes, Shaposhnikov'13]

Low T and low M leptogenesys

CP violation present in Yukawa matrices F

non-equilibrium process are for sterile neutrino N_I

- production
- freeze-out
- decay

Note – for $M_I/T \ll 1$ the asymmetries can be generated in active and sterile sectors with opposite signs

[Asaka, Blanchet, Shaposhnikov'05, Canetti, Drewes, Shaposhnikov'13]

Thermal history of the Universe

T ↑, t ↓		
		zero abundance of $N_{1,2,3}$
		thermal production of $N_{2,3}$
		⇒ lepton asymmetry generated
		$L_\alpha \sim 10^{-10}$
200 GeV	T_{EW}	Electroweak Symmetry Breaking
		⇒ lepton asymmetry converted to baryon asymmetry
		$\Delta_B \sim 0.86 \times 10^{-10}$
	T_+	$N_{2,3}$ reach equilibrium
		⇒ lepton asymmetry washed out
few GeV	T_-	$N_{2,3}$ freeze out
		⇒ lepton asymmetry generated
	T_d	$N_{2,3}$ decay
		⇒ lepton asymmetry generated
		$L_\alpha \gtrsim 8 \times 10^{-6}$
100 MeV	T_{DM}	resonant N_1 Dark Matter production

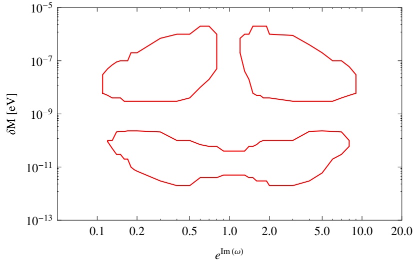
Bounds for the $N_{2,3}$ sterile neutrinos

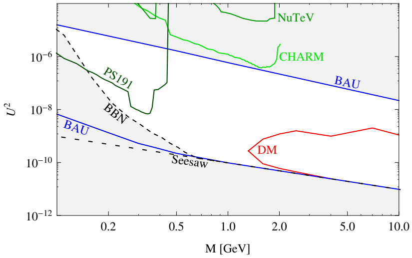
In order to generate enough lepton asymmetry for resonant DM production

$M_{1,2}$ very degenerate

$\Delta M \sim \delta m_{\text{active}}$

[Canetti, Drewes, Shaposhnikov'13]





Outline

More new physics

- Warning 1 – Can easily add/change DM production!
  - Can be nice
- Warning 2 – Can easily spoil/change everything!
  - Can be also nice, but be careful
    (c.f. talk by Andrea Caputo on Monday)

Add more stuff – νMSM + scalar

separate mechanism generates proper DM abundance of N_1

Add a scalar

$$\mathscr{L} = \mathscr{L}_{\nu\text{MSM}} + \mathscr{L}_{\text{scalar}}(X) + f_I X \bar{N}^c N$$

- νMSM – $N_{2,3}$ – leptogenesys
- Scalar
  - is an inflaton, decays in equilibrium $X \to NN$ after reheating [Shaposhnikov, Tkachev'06, FB, Gorbunov'10]
  - Some scalar decaying in or out of equilibrium [Kusenko, Petraki'07]
  - Decaying scalar which may be FIMP itself [Merle, Totzauer'15]
  - New: Coherently oscillating ultralight scalar [FB, Chudaykin, Gorbunov, soon]

DM production happens in heavy particle decays

Scalar heavier than DM neutrino

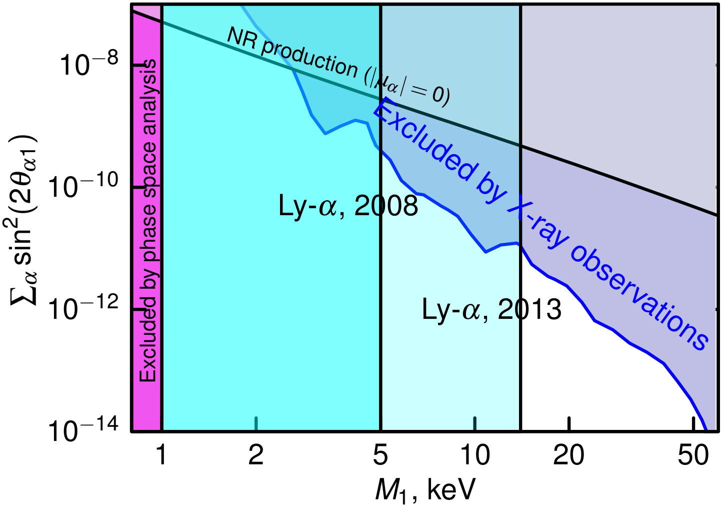
$$M_X > 2M_1$$

- Distribution is non-thermal with
$$\langle p\rangle/T_\gamma = 2.45\left(\frac{1}{S}\frac{3.9}{g_*(T_{\mathrm{prod}})}\right)^{1/3}$$
(for in equilibrium decay at T_{prod})
Colder, than non-resonant with $\langle p\rangle/T_\gamma = 3.15(4/11)^{1/3}$
- Production abundance is controlles by scalar properties (width, mass, branching) – does not depend on θ

DM neutrino mass bound from Lyman-α

$$M_1 \gtrsim 8\mathrm{keV}$$

Bounds for the N_1 – DM sterile neutrino



Production in decays of GeV scale scalar

Induced active sterile resonance

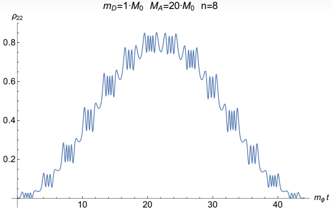
- Scalar field is light $m_X \sim 1$ eV
- X oscillates coherently
- Oscillating Majorana mass for $M_1(t) \sim M_1 + M_A \sin(m_X t)$
- Narrow resonances for $\nu \to N_1$ at $p \simeq \frac{M_A^2}{4nm_X}$
- Effective at low temperatures only

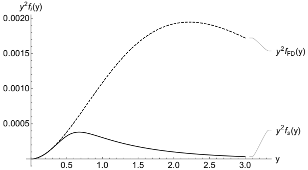
Small average memntum N_1

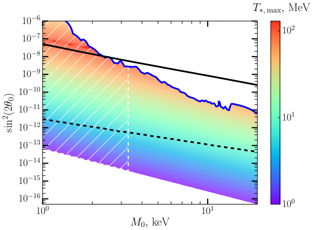
$$\frac{\langle p \rangle}{T} \sim 1.3 \left(\frac{1\text{keV}}{M_1} \right)^{2/5}$$

- Scalar field only induces the resonance

[FB, Chudaykin, Gorbunov – very soon]







Situation 3 – a lot of new physics

Assumptions

- There are three right-handed neutrinos N_1, N_2, N_3
- At low energies they have Dirac and Majorana mass terms
- They are charged under some (non-SM) gauge group, with the (right) gauge boson mass M

Thermal history

- DM Sterile neutrinos N_1 enter thermal equilibrium
- Their abundance later diluted S times by out of equilibrium decay of $N_{2,3}$
- Leptogenesys – usual (resonant) in $N_{2,3}$ decays.

Note: c.f. A.Caputo's talk on Monday – either very small g_R

[FB, Hettmansperger, Lindner'10, Nemevsek, Senjanovic, Zhang'12]

DM mass bounds (from observed DM structure)

Phase space distribution is now different, and corresponds to the *thermal relic case*

$$f(p) = \frac{1}{\exp\left(\frac{p}{T_\nu/S}\right) + 1}$$

So, N_1 are now *cooled*

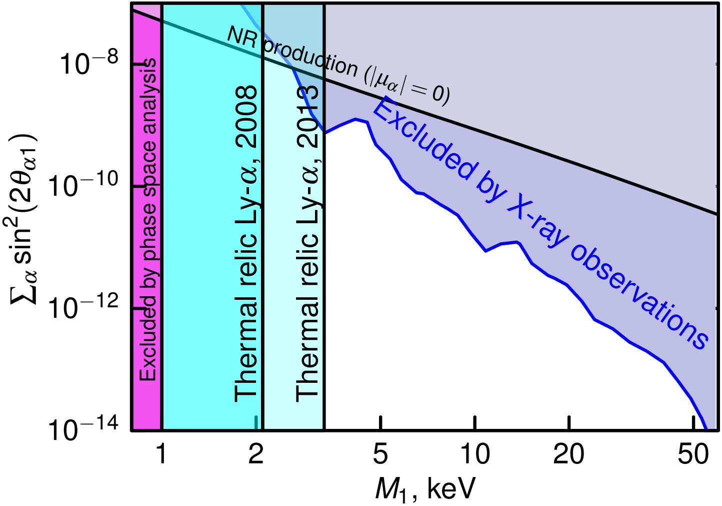
Ly-α bound – structure formation

[Boyarsky, Lesgourgues, Ruchayskiy,, Viel'09, Viel, Becker, Bolton,, Haehnelt'13]

$$M_1 > 1.5 - 3.3 \text{ keV}$$

Astrophysical constraints

Sterile neutrino in beyond SM gauge multiplets



For entropy diluted sterile neutrinos

Outline

Possibilities of (light) sterile neutrino lab search

Creation and *detection*

Suppressed by mixing angle θ^4

Detection: X-ray experiments

Sterile N in the DM clouds decay by the channel $N \to \nu\gamma$ providing the X-ray line with $E_\gamma = M/2$.
Limit on θ^2 can be deduced as far as Ω_{DM} is known

Creation only

- Forbidden decays
- Decay kinematics

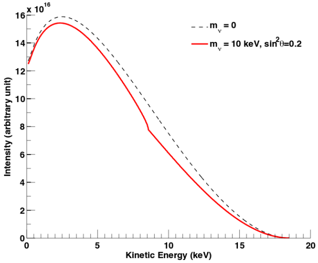
  Partial kinematics kink search in electron beta decay spectrum.

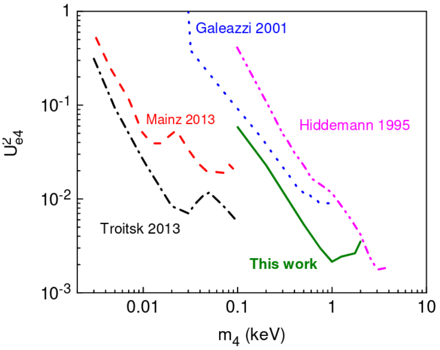
  Full kinematics event-by-event mass measurement!

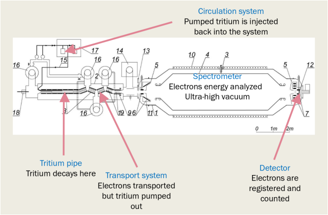
Troitsk – nu-mass

Recent best laboratory bounds. arXiv:1703.10779

beta decay spectrum for 10 keV N_1



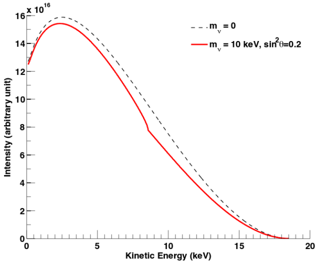


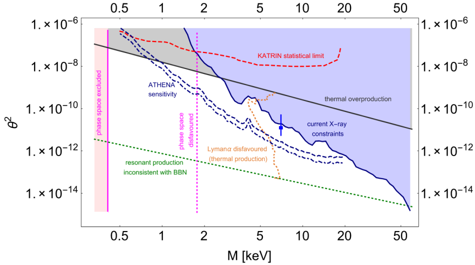


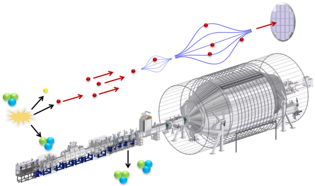
KATRIN – TRISTAN upgrade

Promised future

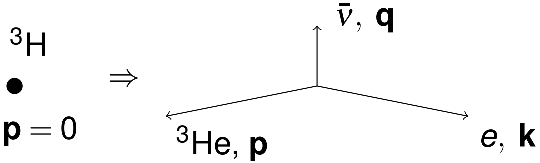
beta decay spectrum width N_1







Beta decay – Full kinematic reconstruction



Neutrino mass is reconstructed from observed momenta in each event

$$m_\nu^2 = (Q - E_p^{\text{kin}} - E_e^{\text{kin}})^2 - (\mathbf{p} + \mathbf{k})^2$$

For ^{3}H: $Q = 18.591\text{keV}$

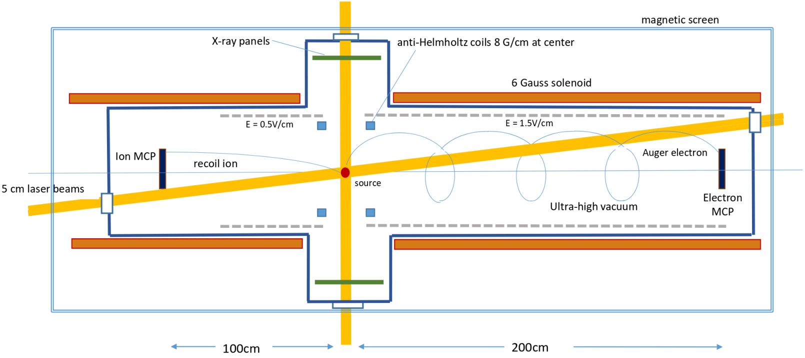
- Typical ion energy $E_p^{\text{kin}} \sim 1$ eV or $|\mathbf{p}| \sim 100\text{keV}$
- Typical electron energy $E_e^{\text{kin}} \sim 10\text{keV}$

[FB, Shaposhnikov'07]

HUNTER experiment

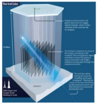
HUNTER experiment (**H**eavy **U**nseen **N**eutrinos by **T**otal **E**nergy-momentum **R**econstruction)

Phase 1 (proof of principle) funded by Keck Foundation



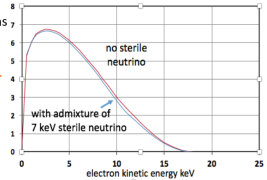
HUNTER experiment

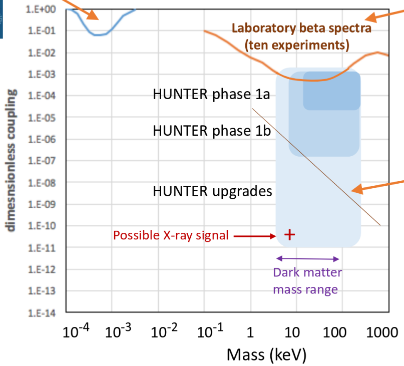
Existing limits and future coverage of HUNTER experiment



Antarctic ‘ICE CUBE’
Detector + CR muons

Sterile neutrinos would
produce minute distortions
In beta decay spectra





X-ray astronomy limits
If significant sterile ν
component of DM

Conclusions

- keV scale sterile neutrino is a great DM candidate!
- Experiment:
  - X-rays – already seen?!

    waiting for further experimens
  - Laboratory – hard. . .

    but there are attempts!
- Theory:
  - What is the best way to make them cool?

Line follows the Dark Matter halo profiles

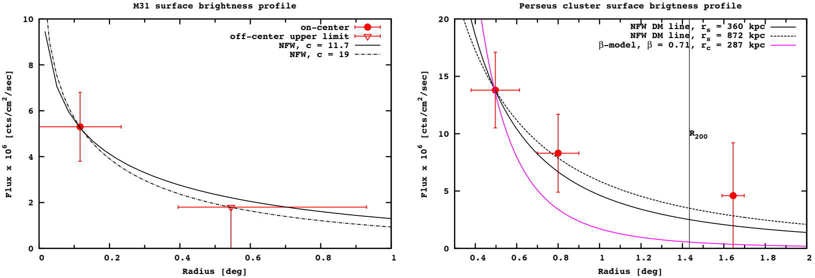


FIG. 2: The line's brightness profile in M31 (left) and the Perseus cluster (right). An NFW DM distribution is assumed, the scale r_s is fixed to its best-fit values from [22] (M31) or [23] (Perseus) and the overall normalization is adjusted to pass through the left-most point.

No line seen from the blanc sky

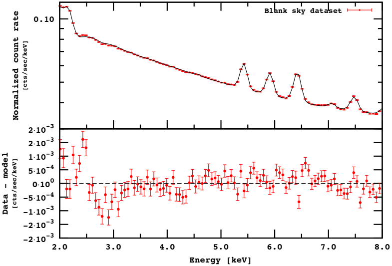


FIG. 3: Blank sky spectrum and residuals.

Constraints summary

X/γ-ray

$$\theta_1^2 \lesssim 1.8 \times 10^{-5} \left(\frac{1\text{keV}}{M_1}\right)^5$$

$$\zeta^2 \lesssim 10^{-18} \ldots (\text{keV}/M_1)^3$$

$\Omega_{N_1} = \Omega_{DM}$ if

$$\Gamma_2 \simeq 0.50 \times 10^{-6} \bar{g}_*^{1/2} \frac{M_2^2}{M_{Pl}} \left(\frac{1\text{keV}}{M_1}\right)^2$$

Ly-α bound

$$M_1 > 1.5 - 3.3\text{keV}$$

BBN $\tau_2 > 0.1 \div 2\,\text{sec}$

$$M_2 > \left(\frac{M_1}{1\text{keV}}\right)(1.7 \div 10)\ \text{GeV}$$

The entropy is effectively generated if the right-handed gauge scale is

$$M > g_{*f}^{-1/8} \left(\frac{M_2}{1\ \text{GeV}}\right)^{3/4} (10 \div 16)\ \text{TeV}$$

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