STERILE NEUTRINO DARK MATTER - AN UPDATE

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recent review: 1602.04816

15.9.2016, TeVPA 2016, CERN, Switzerland

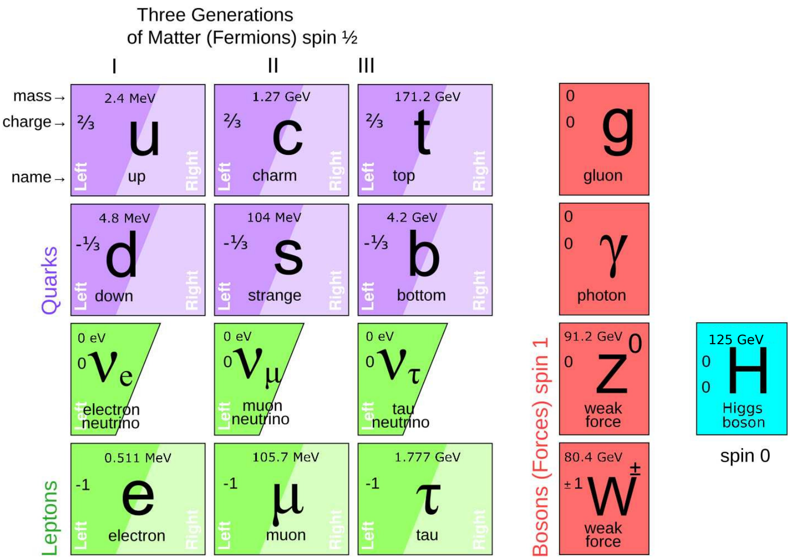
Dark Matter

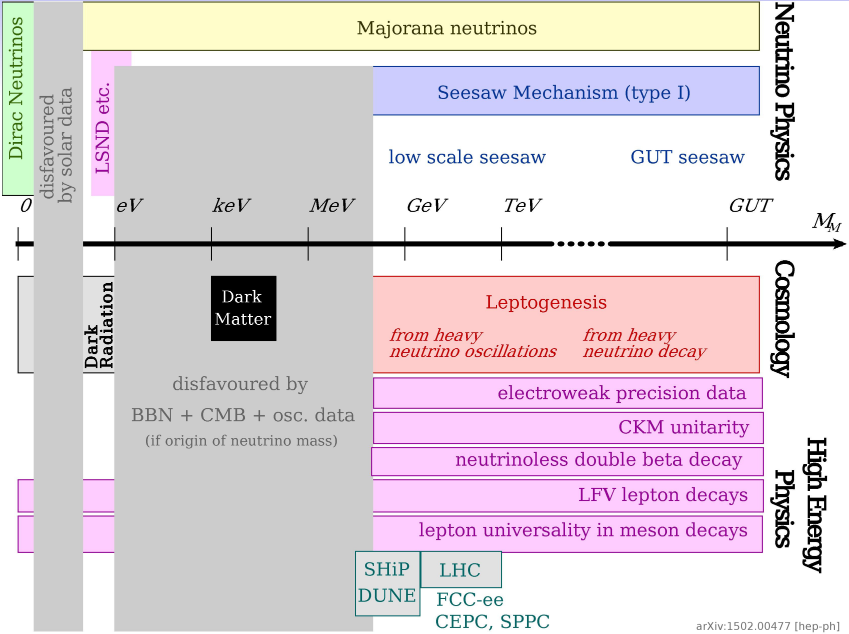
Dark Matter is

- neutral
- collisionless
- massive
- long lived

$\Rightarrow$ **massive sterile neutrinos with sufficiently small mixing angle θ are a "natural" candidate!**

Often associated with **right handed neutrinos** in the context of the seesaw mechanism
$\Rightarrow$ unknown Majorana mass M_M


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
0 eV
0
νe
electron neutrino
0 eV
0
νμ
muon neutrino
0 eV
0
ντ
tau neutrino
91.2 GeV
0
Z0
weak force
125 GeV
0
0
H
Higgs boson
spin 0
Leptons
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
80.4 GeV
±1
W±
weak force
Bosons (Forces) spin 1
Left
Right



arXiv:1502.00477 [hep-ph]

- How were they produced?
- Are they consistent with structure formation?

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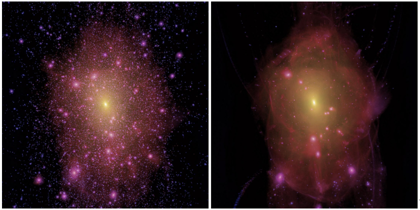
  - DM is absolutely essential to form structures in the universe
  - DM is "cold" , i.e. $\langle \mathbf{k} \rangle < M$ at freezeout



1104.2929

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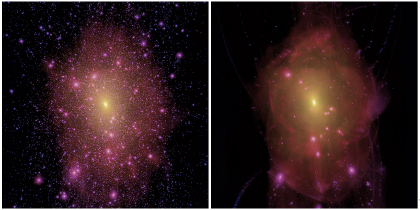
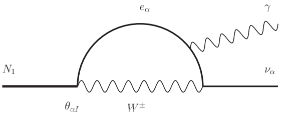


1104.2929

- Where is the decay line?
  - radiative decay $N \to \nu\gamma$
  - Search for X-ray line!



How to make sterile neutrino DM?

- **Thermal production via their mixing θ**
  - happens unavoidably for $\theta \neq 0$ Barbieri/Dolgov 91, Dodelson/Widrow 94
  - never reach equilibrium for realistic θ ("freeze in DM", "FIMP DM") $\Rightarrow$ non-thermal spectrum!
  - can be resonantly enhanced by MSW effect Shi/Fuller 99
- **Non-thermal production in the decay of heavy particles**
  - inflaton or other scalar Kusenko 06, Shaposhnikov/Tkachev 06, Bezrukov/Gorbunov 09, Kusenko/Petraki 07, ...
  - can occur when scalar is in equilibrium or during scalar production ("freeze in") see e.g. Merle/Totzauer 15
  - charged scalar Boyanovsky 08, Frigerio/Yaguna 14, leptophilic Higgs Adulpravitchai/Schmidt 15, fermion Abada 14 or vector particles Shuve/Yavin 14
- **Thermal production via (gauge) interactions at high energies**
  very difficult to dilute Bezrukov/Hettmansperger/Lindner, ...

  [I won't talk about this]

Production from active-sterile mixing

$$|\nu_\alpha\rangle = \cos\theta_m(t)\,|\nu_1(t)\rangle + \sin\theta_m(t)\,|\nu_2(t)\rangle,$$
$$|\nu_s\rangle = -\sin\theta_m(t)\,|\nu_1(t)\rangle + \cos\theta_m(t)\,|\nu_2(t)\rangle,$$

Effective mixing leads to both, coherent oscillations and decoherent scatterings .

With $\Delta(p) = \Delta m^2/(2p)$ one finds:

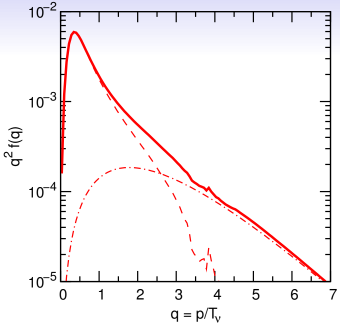
$$\sin^2(2\theta_m) = \frac{\Delta^2(p)\sin^2(2\theta)}{\Delta^2(p)\sin^2(2\theta) + [\Delta(p)\cos(2\theta) - V_D - V_T]^2},$$

production peaks at $T = 0.1 - 1$ GeV

MSW-like resonance in presence of lepton asymmetry Shi/Fuller 99
required lepton asymmetry $\sim 10^{-5}$ can be generated

Canetti/MaD/Frossard/Shaposhnikov 12

Schematically, the resulting spectrum looks like this:



- nonthermal
- effectively: warm + cold
- cold component consistent with structure formation

Boyarsky/Ruchayskiy/Shaposhnikov 2009

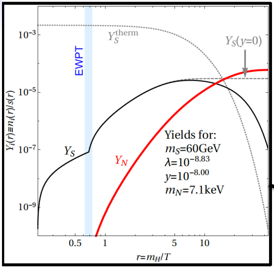
But it is rather complicated to get it quantitatively right:

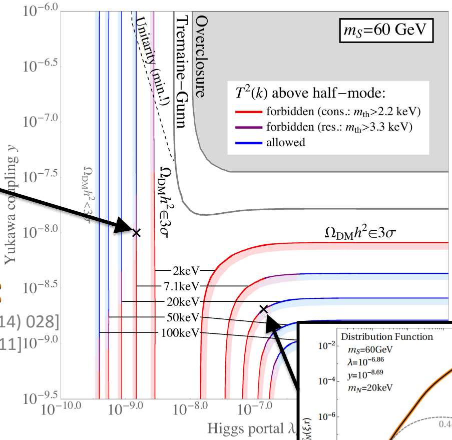
- change of g_* during QCD crossover
- hadronic corrections to neutrino propagators
- back-reaction due to depletion of asymmetries

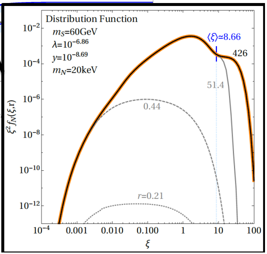
Two groups have recently made impressive progress

Venumadhav/Cyr-Racine/Abazajian/Hirata 1507.06655, Ghiglieri/Laine 1506.06752

Sterile ν Production by scalar decays







Scalar freezes in:

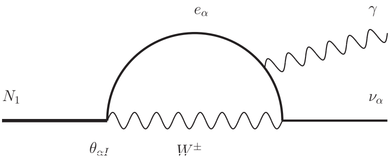
[Merle, Niro, Schmidt: JCAP **1403** (2014) 028]
[Merle, Totzauer: JCAP **1506** (2015) 011]
[König, Merle, Totzauer: 1608.XXXXX]

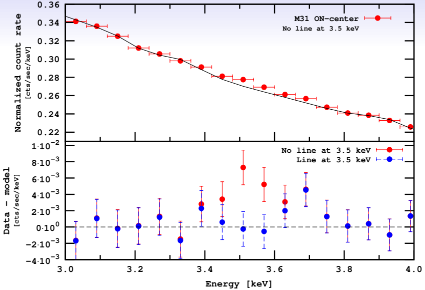
Scalar freezes out:

[Kusenko: Phys. Rev. Lett. **97** (2006) 241301]
[Kusenko & Petraki: Phys. Rev. **D77** (2008) 045016]

Slide by A. Merle

Decaying DM emission line

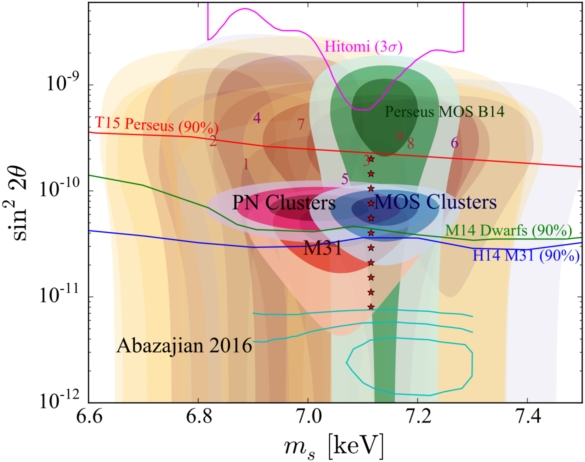




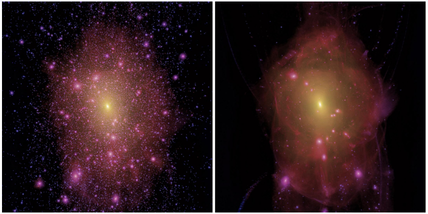
- DM decay produces a narrow emission line...
  ... but it is smeared by the instrumental resolution
- OK for exclusion, but for a discovery need better spectral resolution
- Astro-H/Hitomi satellite - unfortunately lost!
- alternatives:
  - microcalorimeter on sounding rocket
  - Athena+

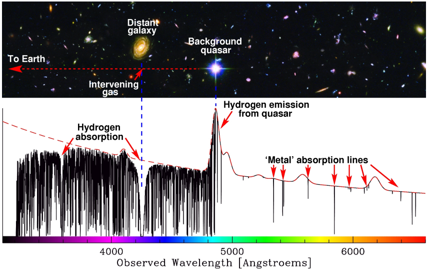
Status of te 3.5 keV line

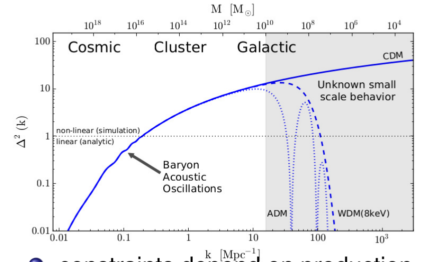
discovery by Bulbul et al 2014 and Boyarsky et al 2014
ever since: very active discussion...



Structure formation





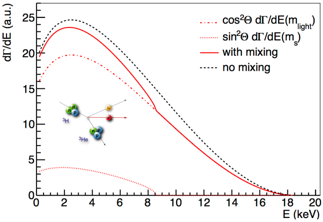


- constraints depend on production mechanism
- bounds often quote "effective thermal mass"
- non-thermal spectra are "colder"
- conversion into a physical DM-mass is non-trivial e.g. Schneider 1601.07553
- slight preference for production via decay Merle/Schneider 1409.6311

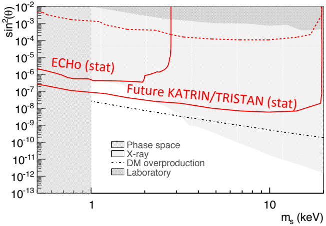
Figs.: Lovell et al 12, Kuhlen/Vogelsberger/Angulo

KATRIN/TRISTAN & keV Sterile Neutrinos

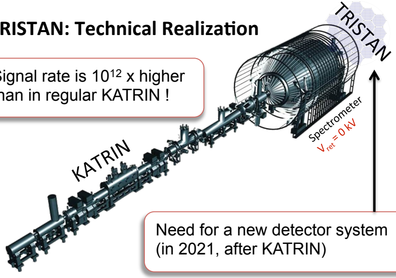
Imprint of keV Neutrinos on Tritium β-spectrum



Statistical Sensitivity



TRISTAN: Technical Realization



Signal rate is 10^{12} x higher than in regular KATRIN !

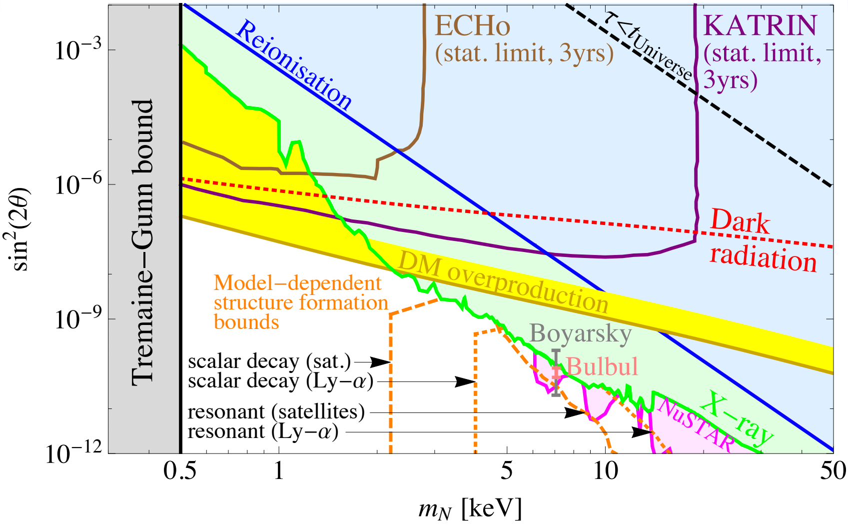
Need for a new detector system (in 2021, after KATRIN)

Novel Silicon Detector System (R&D)

- Handling high rates (10^9 cts/s)
  - >10 000 pixels
- 300 eV energy resolution & 1 keV threshold
  - Thin deadlayer (~10 nm)
- 1 mm pixels with <0.2 pF capacity
  - Multi-drift-ring design (SDD)
- Minimize systematics (ppm-level)
  - Low ADC non-linearity read-out, etc...

contact: smertens@lbl.gov

Summary



Tremaine−Gunn bound
Reionisation
ECHo
(stat. limit, 3yrs)
τ<t_Universe
KATRIN
(stat. limit,
3yrs)
Dark
radiation
DM overproduction
Model−dependent
structure formation
bounds
scalar decay (sat.)
scalar decay (Ly−α)
resonant (satellites)
resonant (Ly−α)
Boyarsky
Bulbul
NuSTAR
X−ray
10^−3
10^−6
10^−9
10^−12
0.5
1
5
10
50
m_N [keV]
sin^2(2θ)