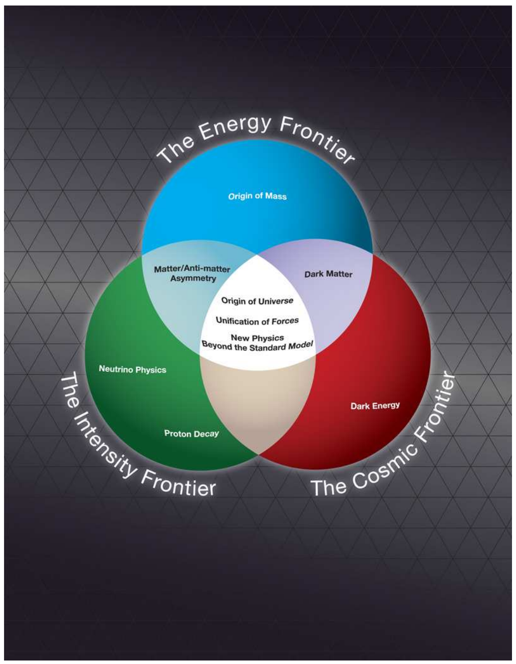
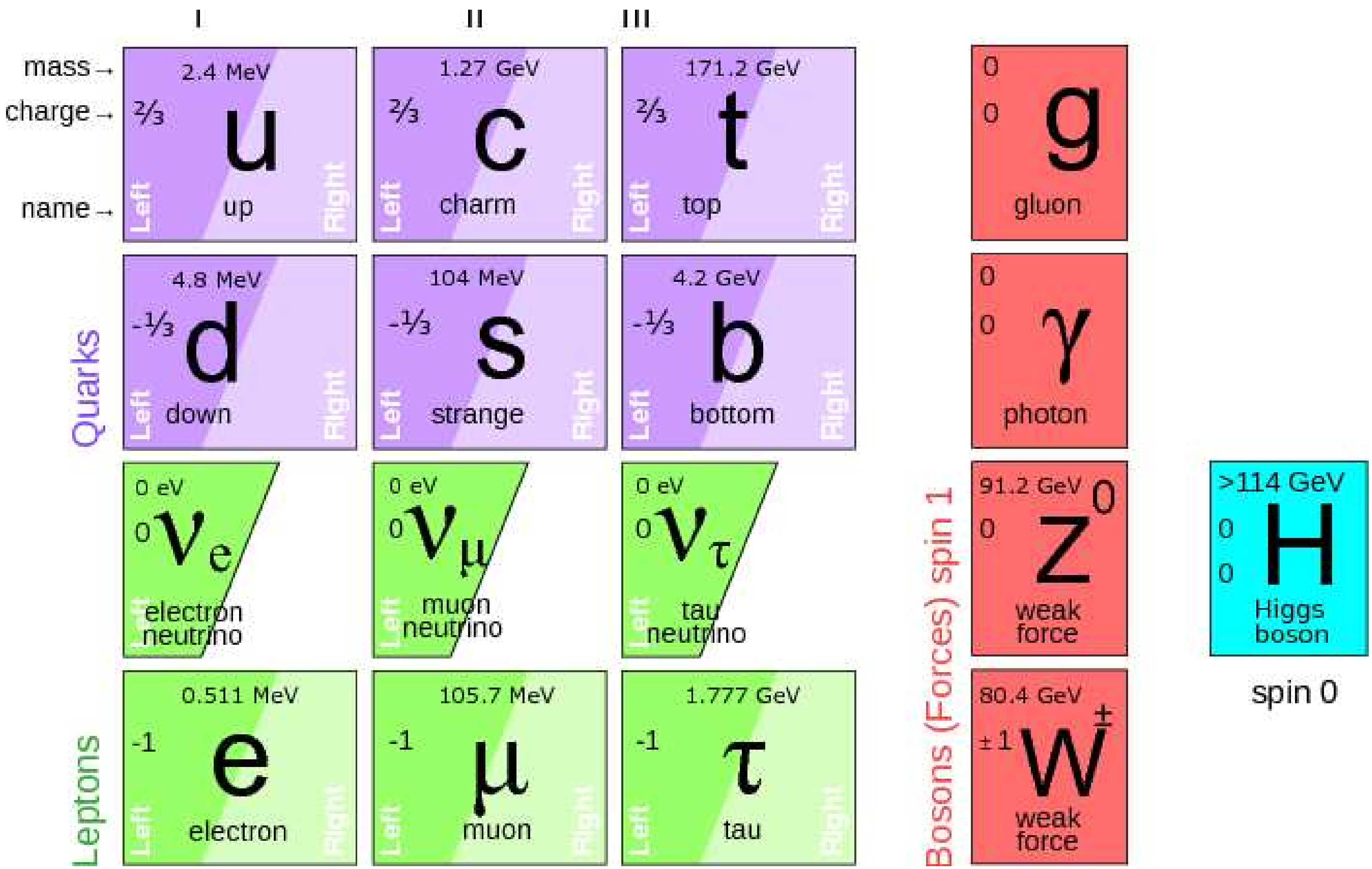
STERILE NEUTRINOS:
Baryogenesis, dark matter, primordial magnetic fields...



Oleg RUCHAYSKIY

24th Rencontres de Blois
May 31, 2012

Standard Model today



Future?

- SM Higgs gives a good fit to data.
  Reduced $gg \to h$ and enhanced $h \to \gamma\gamma$ improves the fit.
  Too good: is this just over-fitting fluctuations?

- SUSY: at the weak scale, or one loop above, or much above.

- $m_h \approx 125\,\text{GeV}$ corresponds to $\lambda = 0$ at the Planck scale? Almost, but NO.
  λ gets slightly negative and the SM vacuum is meta-stable.

Implications for European Strategy for Particle Physics:
The Higgs could be the last particle. Carpe diem.

From the talk of A. Strumia at CERN workshops "*Implication of the latest LHC results for new physics*"

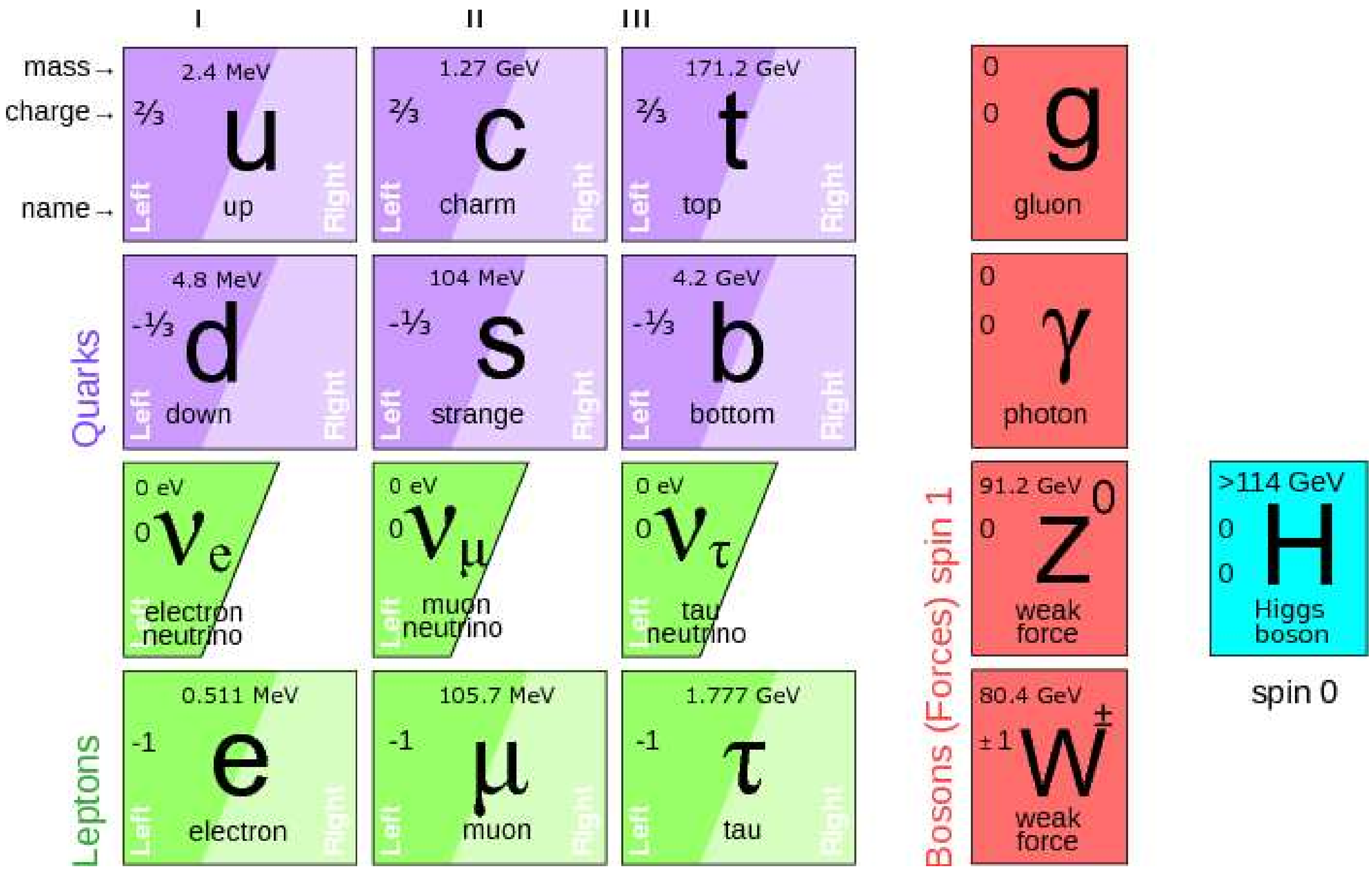
Beyond the Standard Model

BUT! already now we know a number of observational **beyond the Standard Model phenomena**:

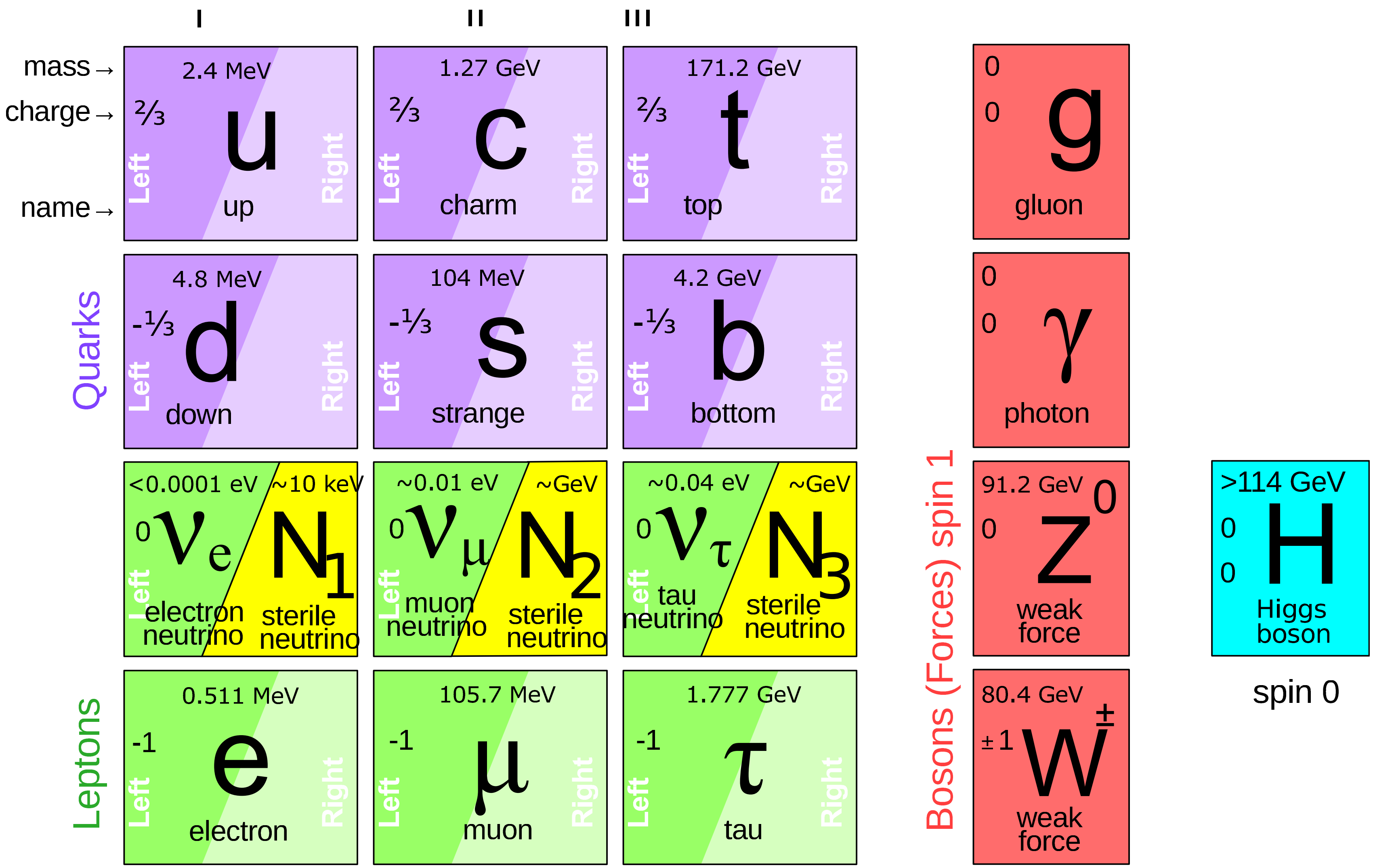
- $\longrightarrow$ **Neutrino oscillations**: transition between neutrinos of different flavours (ν_e, ν_μ, ν_τ) means violation of lepton flavour symmetries (but not total lepton number!)
- $\longrightarrow$ existence of **dark matter** (why observed gravity of galaxies and clusters is so strong?)
- $\longrightarrow$ the **absence of anti-matter** in the Universe
- $\longrightarrow$ **(Probably)** inflation (homogeneity of the observed Universe seem to require correlated initial conditions for causally non-connected regions)
- $\longrightarrow$ **(Maybe)** dark energy (**If** it will be shown that accelerated expansion of the Universe is caused not by a small cosmological constant, but by some other unknown substance – what is this substance?)

What should we do with **beyond-the-Standard-Model problems** if the “nightmare scenario” becomes true?

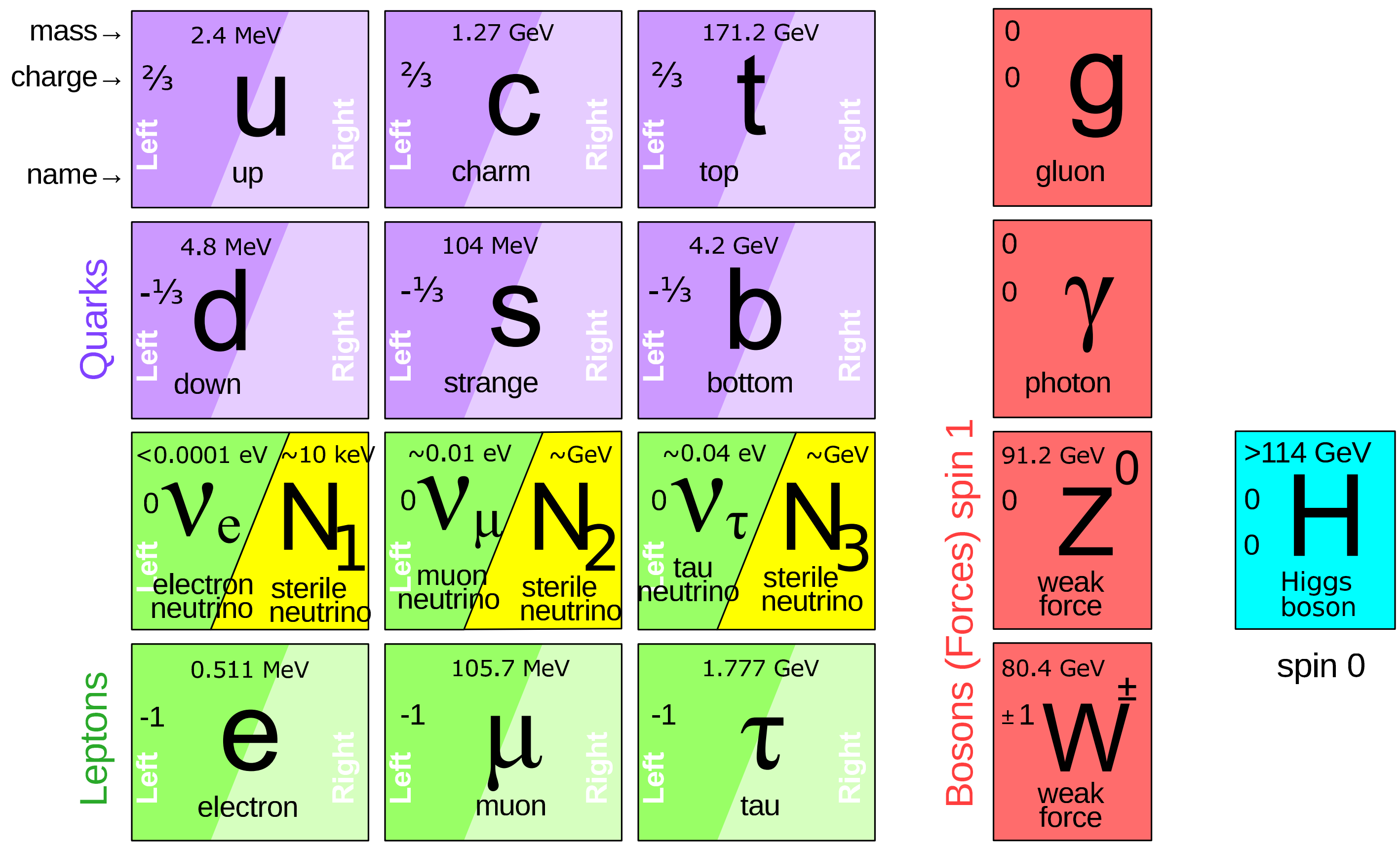
Neutrinos: left-only particles

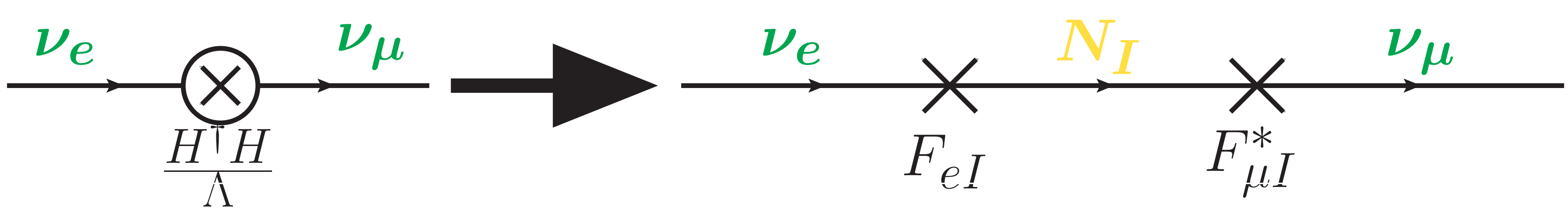


Right-handed neutrinos: sterile particles



Neutrino oscillations and sterile neutrinos





See-saw Lagrangian

- Right-chiral neutrinos N_I **carry no charge** under the Standard Model interactions $\Rightarrow$ **sterile neutrinos**

$$\mathcal{L}_{\text{see-saw}} = i\bar{N}\partial\!\!\!/ N + M_D\bar{\nu}N + \frac{M}{2}\bar{N}^c N$$

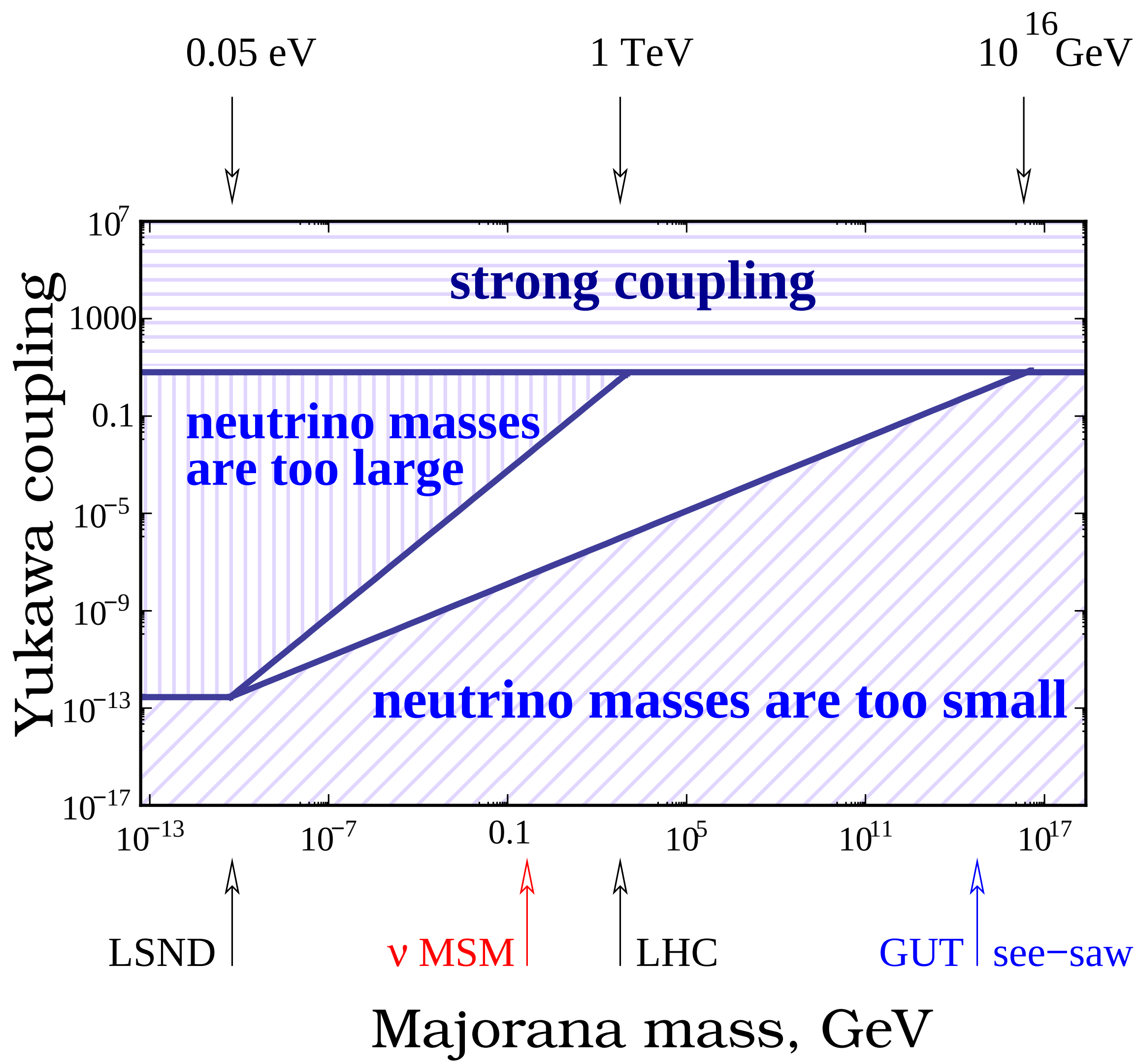
- **Dirac** mass term: $(M_D)_{\alpha I} = \left\langle \text{Higgs} \right\rangle F_{\alpha I}$

- Two mass differences mean that there are **at least two** sterile neutrinos

- Neutrino masses are given by **see-saw formula**:

$$\textbf{Neutrino mass matrix} = -M_{\text{Dirac}}\frac{1}{M_{\text{Majorana}}}M_{\text{Dirac}}^T$$

Scale of sterile neutrino masses



See the next talk by Pilar Hernandez

Neutrino Minimal Standard Model

- Alternative choice: make the masses of sterile neutrinos of the same order as those of quarks and leptons (keV–GeV) — **Neutrino Minimal Standard Model** (νMSM for short)

- The νMSM solves several beyond the Standard Model problems and **provides a complete cosmic history from inflation till today**

Asaka & Shaposhnikov (2005) and many subsequent works

✓ ...explains neutrino oscillations
✓ ...generates matter-antimatter asymmetry of the Universe
✓ ...generates cosmic magnetic fields

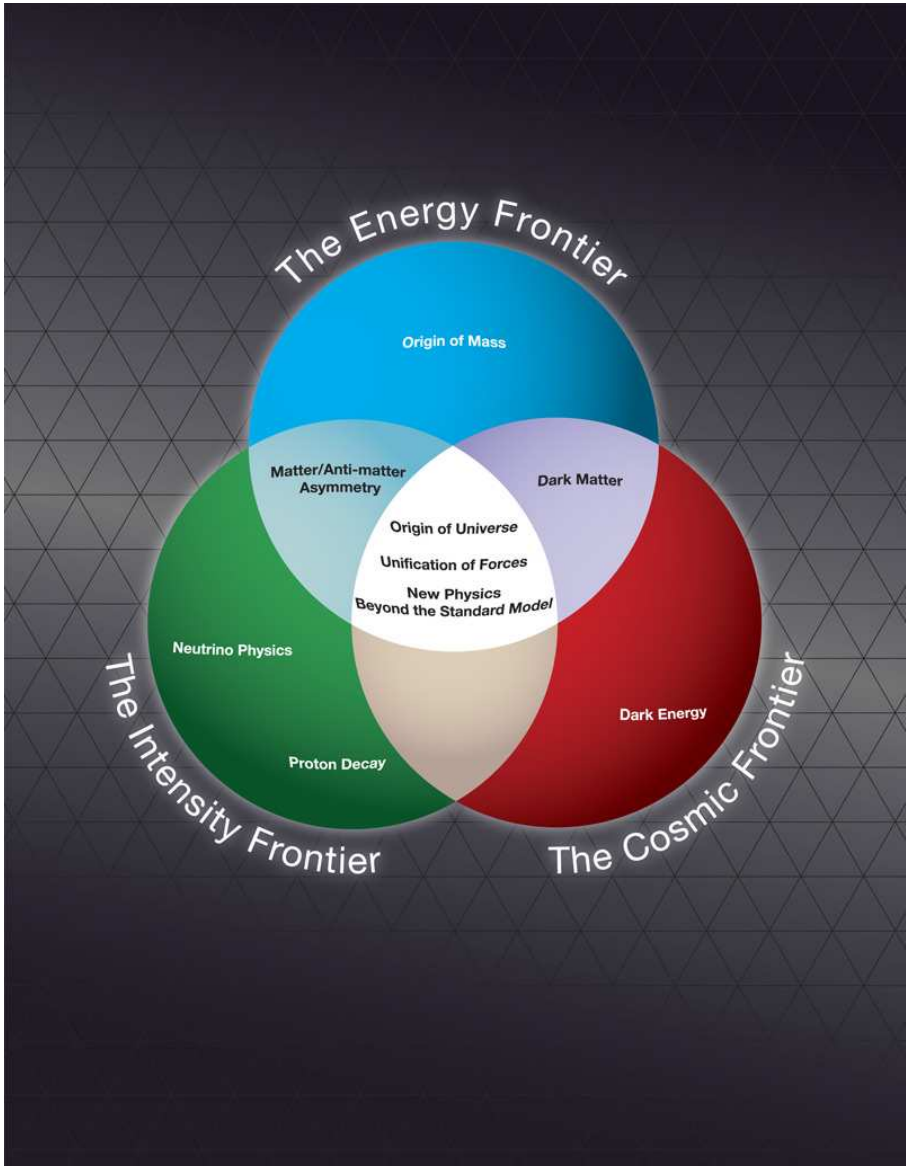
Two sterile neutrinos with MeV–GeV masses

✓ ...provides a dark matter particle (cold, **warm** or **mixed**)

Third sterile neutrino with keV mass

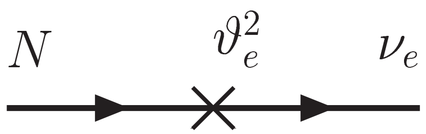
Review: Boyarsky, O.R., Shaposhnikov Ann. Rev. Nucl. Part. Sci. (2009), [0901.0011]

Sterile neutrino can be searched:

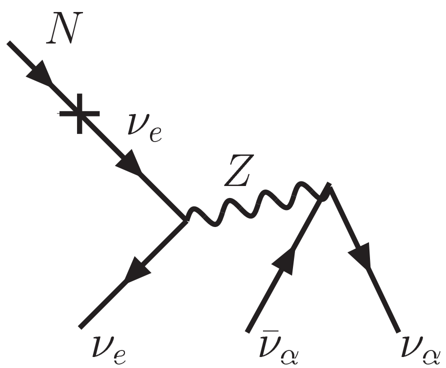


- At accelerators ("Intensity frontier experiments")
- In the spectra of galaxies and galaxy clusters ("Cosmic frontier")
- To make predictions for these searches the νMSM needs detailed early Universe computations, providing
  - correct baryon asymmetry
  - correct DM abundance
  - other early Universe signatures

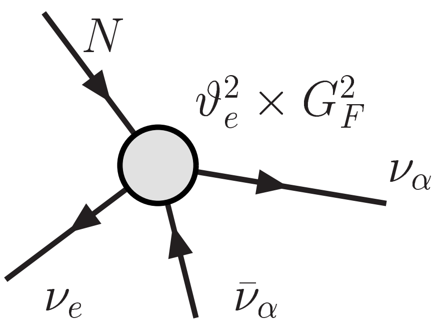
Properties of sterile neutrino



Quadratic mixing $N \leftrightarrow \nu$ of sterile neutrino to ν, $\theta^2 = \frac{|M_{\text{Dirac}}|^2}{M^2_{\text{Majorana}}}$



Decay of sterile neutrino $N \to \nu_e \nu_\alpha \bar\nu_\alpha$ through neutral current interactions



Fermi-like interaction with the "effective" Fermi constant $\vartheta_e \times G_F$

Sterile neutrinos behave as superweakly interacting heavy neutrinos with Fermi constant $G_F \longrightarrow \theta \cdot G_F$, $\theta \lll 1$

Baryo/leptogenesis in the νMSM

All three Sakharov conditions are satisfied if neutrinos are super-weakly interacting and light ($M < M_W$):

Kuzmin, Rubakov, Shaposhnikov (1985)

B-number violation: sphalerons

Farrar & Shaposhnikov (1994)

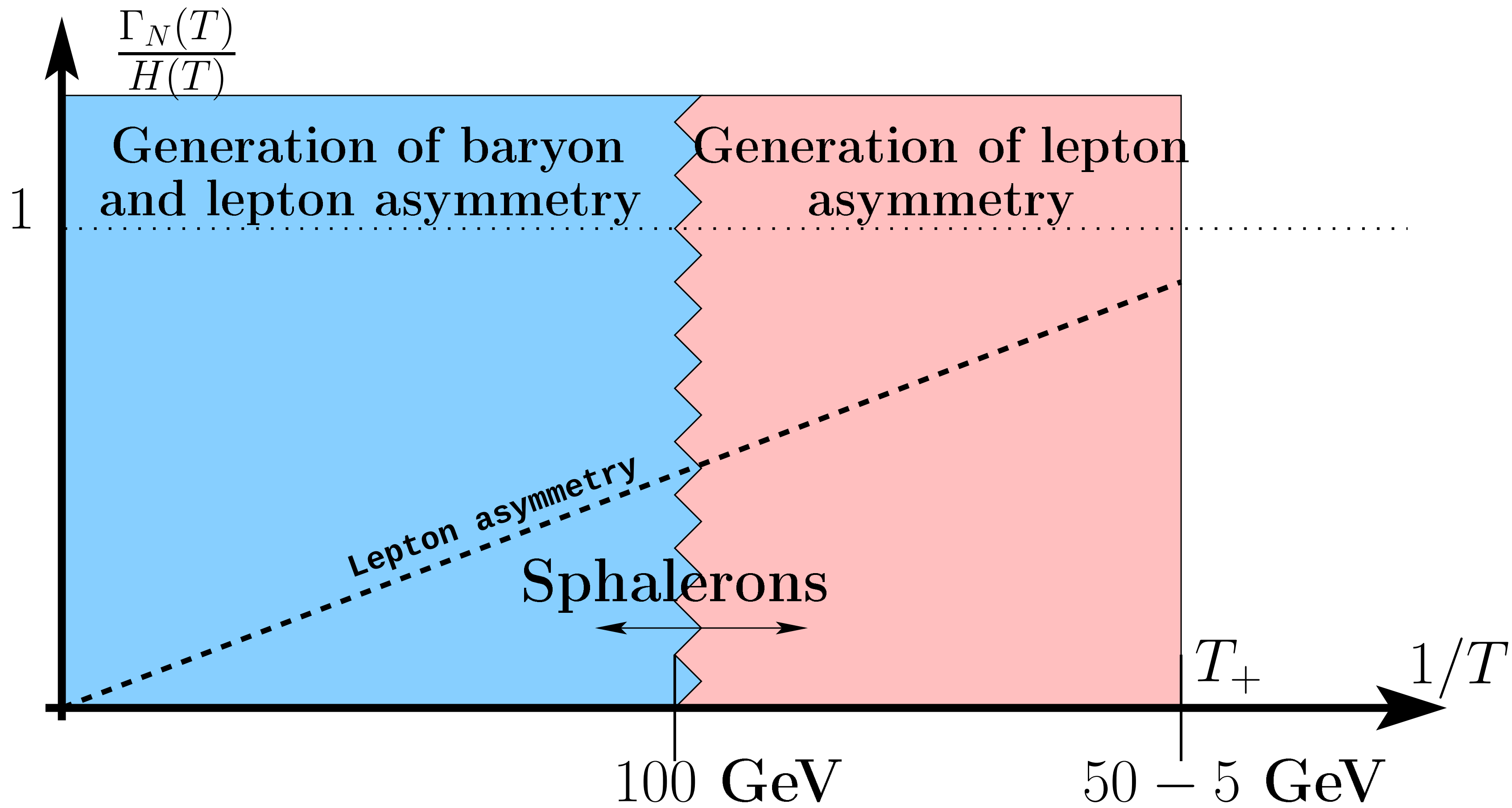
CP (and C) non-conservation: phase of the CKM matrix **plus additional CP phases in the Dirac mass matrix of sterile neutrinos**

Kajantie et al. (1996)

Asaka, Shaposhnikov (2005)

Out-of-equilibrium processes: no phase transition in the νMSM for $m_H > 72$ GeV! **but Yukawa couplings of sterile neutrinos are small enough to keep them out of thermal equilibrium at $T \sim 100$ GeV**

Baryo/leptogenesis in the νMSM



In the νMSM lepton asymmetry is **much higher** than the baryon asymmetry

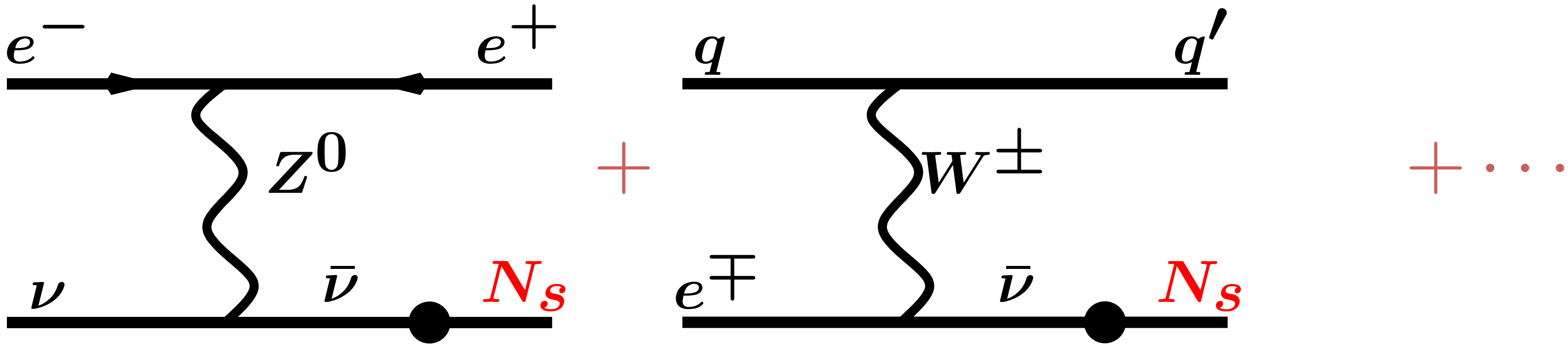
Sterile neutrino dark matter

- Two sterile neutrinos of the νMSM with the masses in MeV-GeV range are responsible for **neutrino oscillations**
- The same particle **generate baryon and lepton asymmetries of the Universe**
- The third sterile neutrino is **not required** to explain neutrino oscillations $\Rightarrow$ can couple to the usual Standard Model neutrino sector arbitrarily weakly. This is a **dark matter** particle in the νMSM

Asaka, Shaposhnikov et al. 2005-...

- Two sterile neutrinos determine the properties of the DM sterile neutrino (abundance, primordial velocities, etc.)

Production of sterile neutrino DM

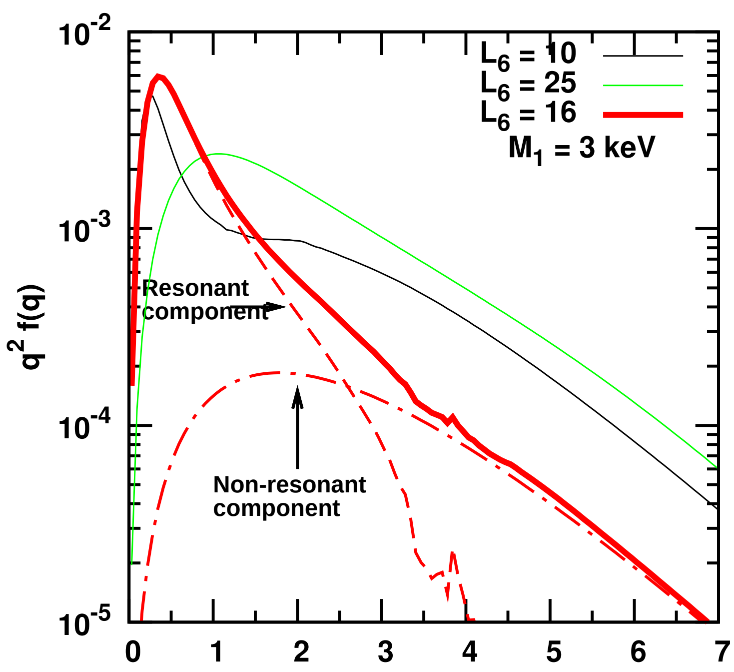


Dolgov Hansen (2000

Abazajian Fuller Tucker (2001)

In the presence of **lepton asymmetry** created by two other sterile neutrinos oscillations become **resonant**

Asaka, Shaposhnikov Laine



Boyarsky, **O.R** et al. (2006-2009)

Sterile neutrino dark matter have

- Colder (**resonant**) component with $\langle p\rangle \ll T_\nu$)
- Warmer (**non-resonant**) component with $\langle p\rangle \sim 3T_\nu$)

Shi & Fuller (1998)

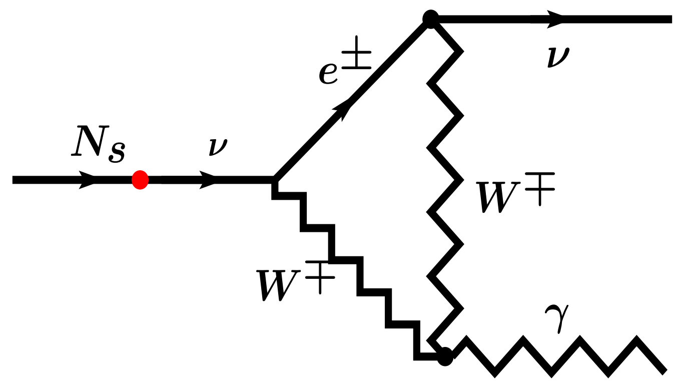
Laine & Shaposhnikov

Signatures of sterile neutrino DM

- Sterile neutrino DM is produced **relativistic** in the early Universe — **warm** dark matter

- Erases primordial density fluctuations at scales below the **free steaming scale**

- Can **decay** with cosmological lifetime

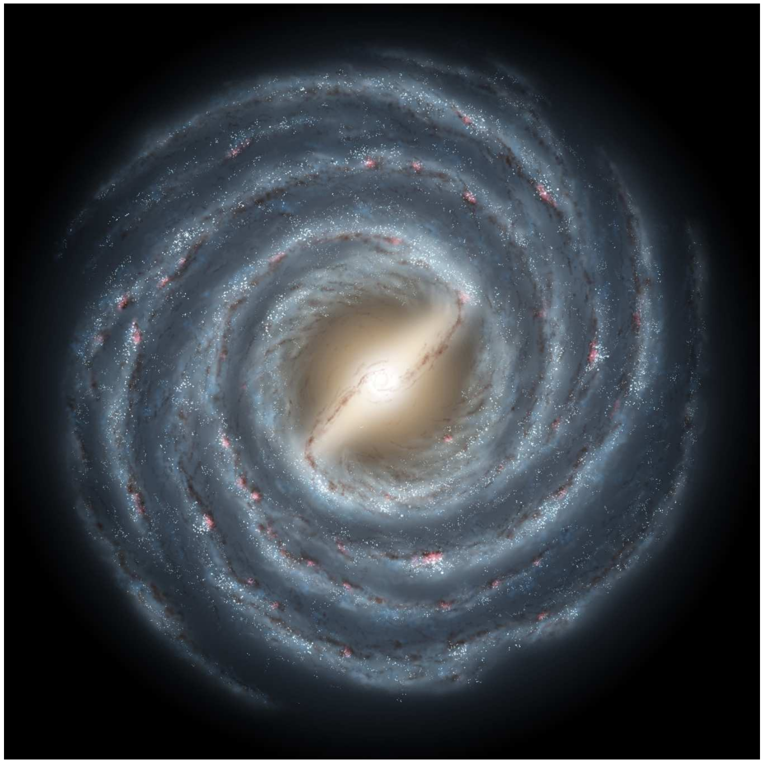


- Very characteristic signal: narrow line with $E_\gamma = \frac{1}{2} m_{\text{DM}} c^2$

- The width of the decay line due to **Doppler broadening** $\frac{\Delta E}{E_\gamma} \sim \frac{v_{\text{vir}}}{c} \sim 10^{-4} \div 10^{-3}$

Search for dark matter particles

- DM may be decaying with a cosmologically long life-time (age of the Universe or even longer). Can we detect such decay?
- **Yes!** if you multiply a small number (probability of decay) with a large number (typical amount of DM particles in a galaxy $\sim 10^{70}$–10^{100})



$$\text{Signal} \propto \int_{\text{line of sight}} \rho_{\text{DM}}(r)\,dl$$

Expected signal from the galaxy at a particular energy

Search for dark matter particles

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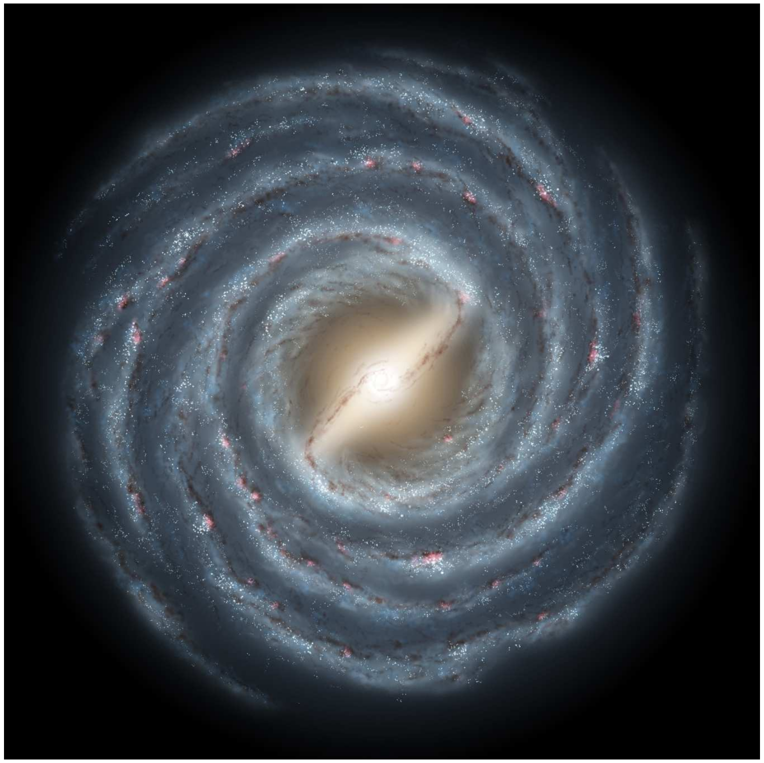
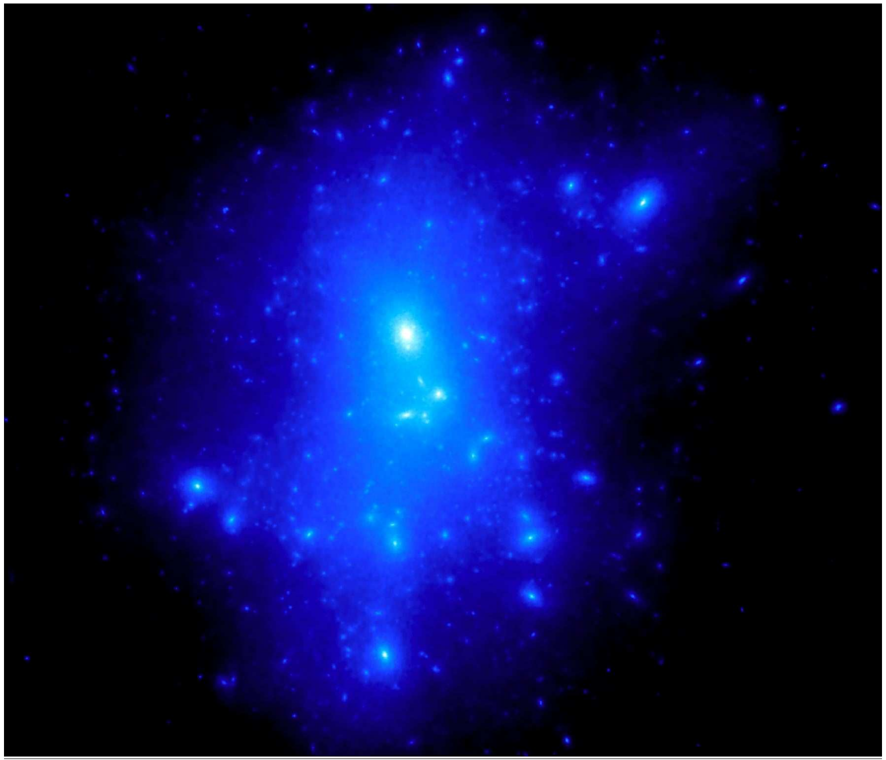
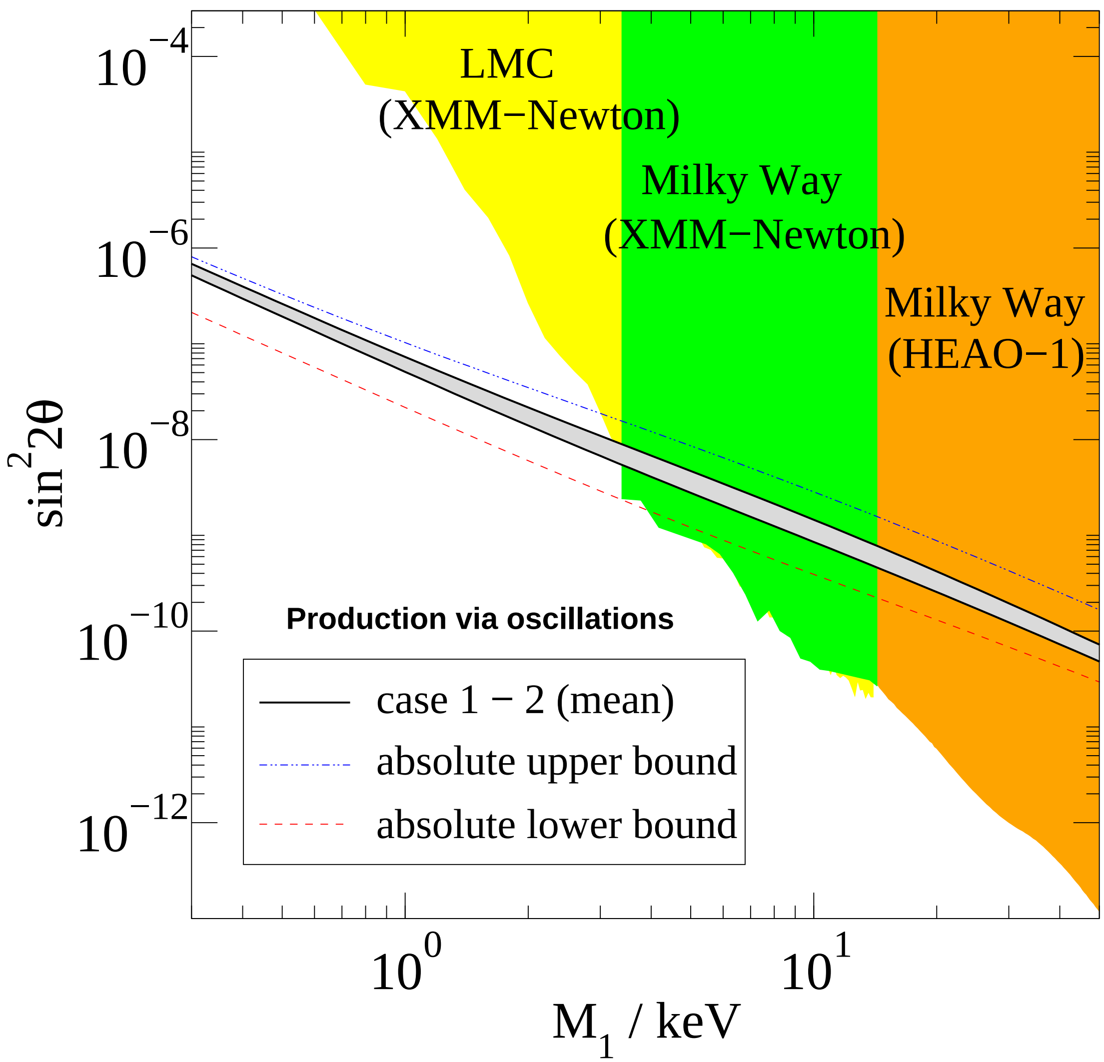




Expected signal from a galaxy at a particular energy (simulation from B. Moore)

Parameters of sterile neutrino DM



Production: Asaka, Laine, Shaposhnikov (2006)

MW (HEAO-1) Boyarsky, **O.R** et al. 2005

Coma and Virgo clusters Boyarsky, **O.R** et al.

Bullet cluster Boyarsky, **O.R** et al. 2006

LMC+MW(XM Boyarsky, **O.R** et al. 2006

MW Riemer-Sørensen et al.; Abazajian et al.

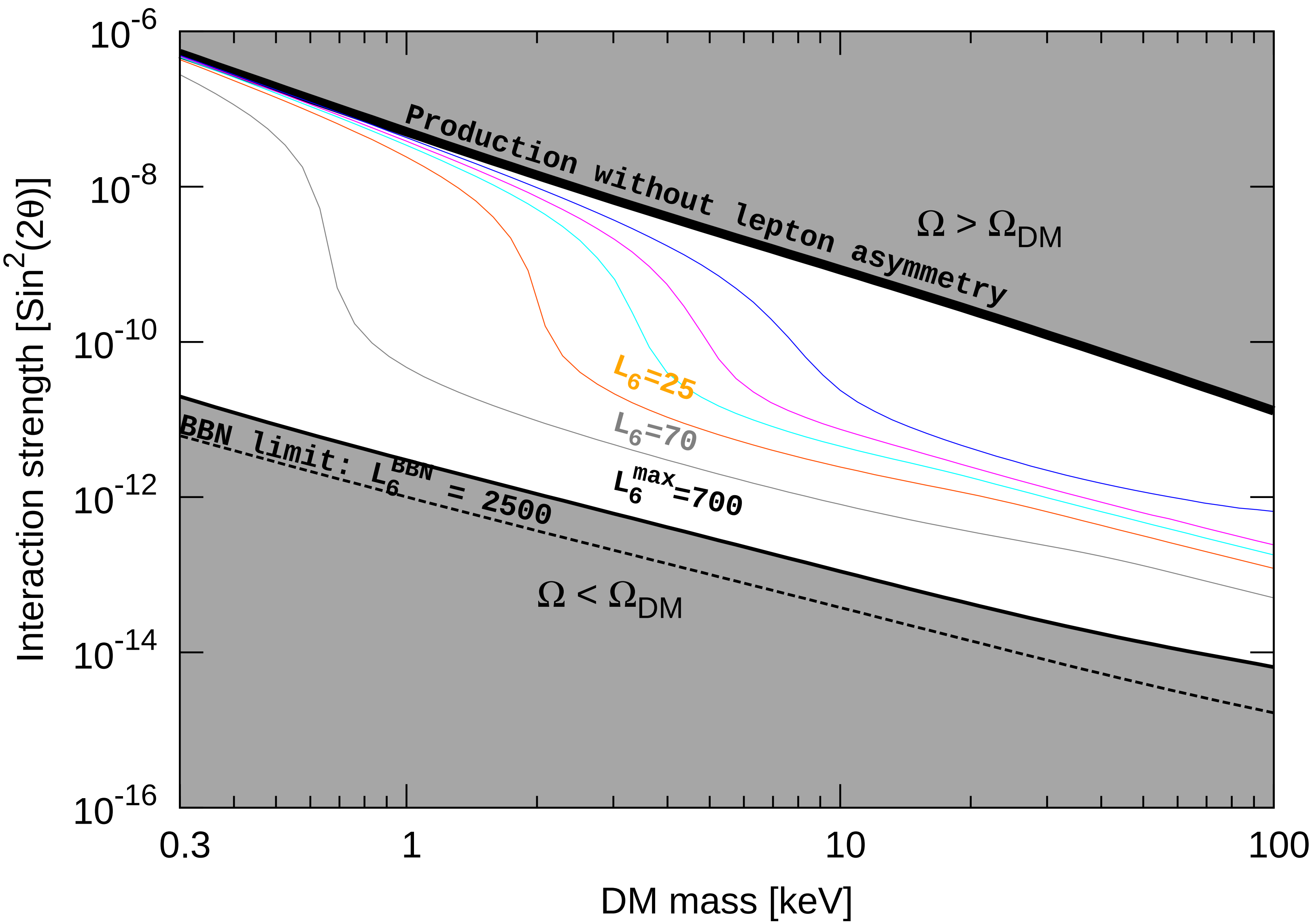
MW (XMM) Boyarsky, **O.R** et al. 2007

M31 Watson et al. 2006; Boyarsky et al 2007

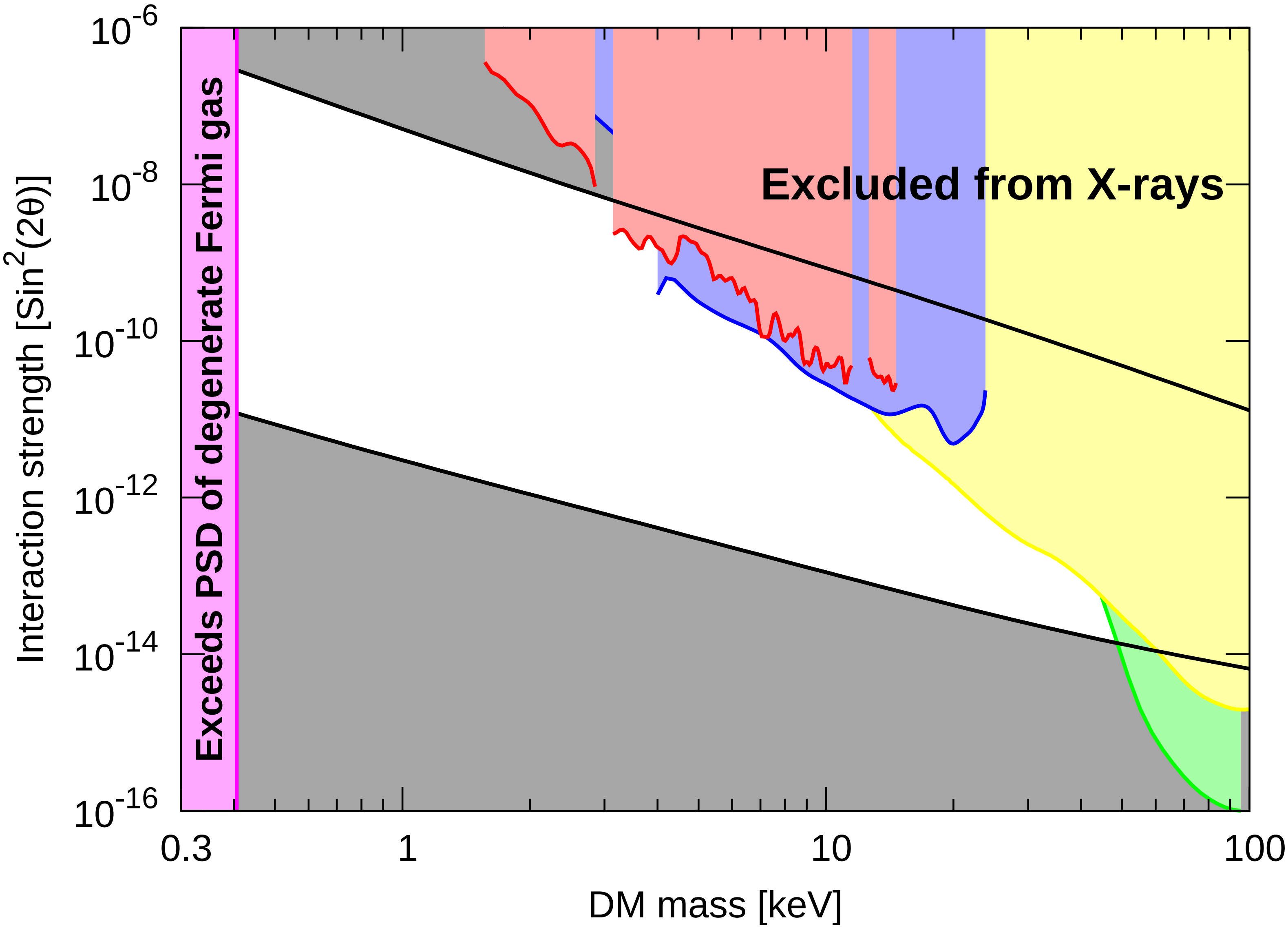
Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov



Window of parameters of sterile neutrino DM

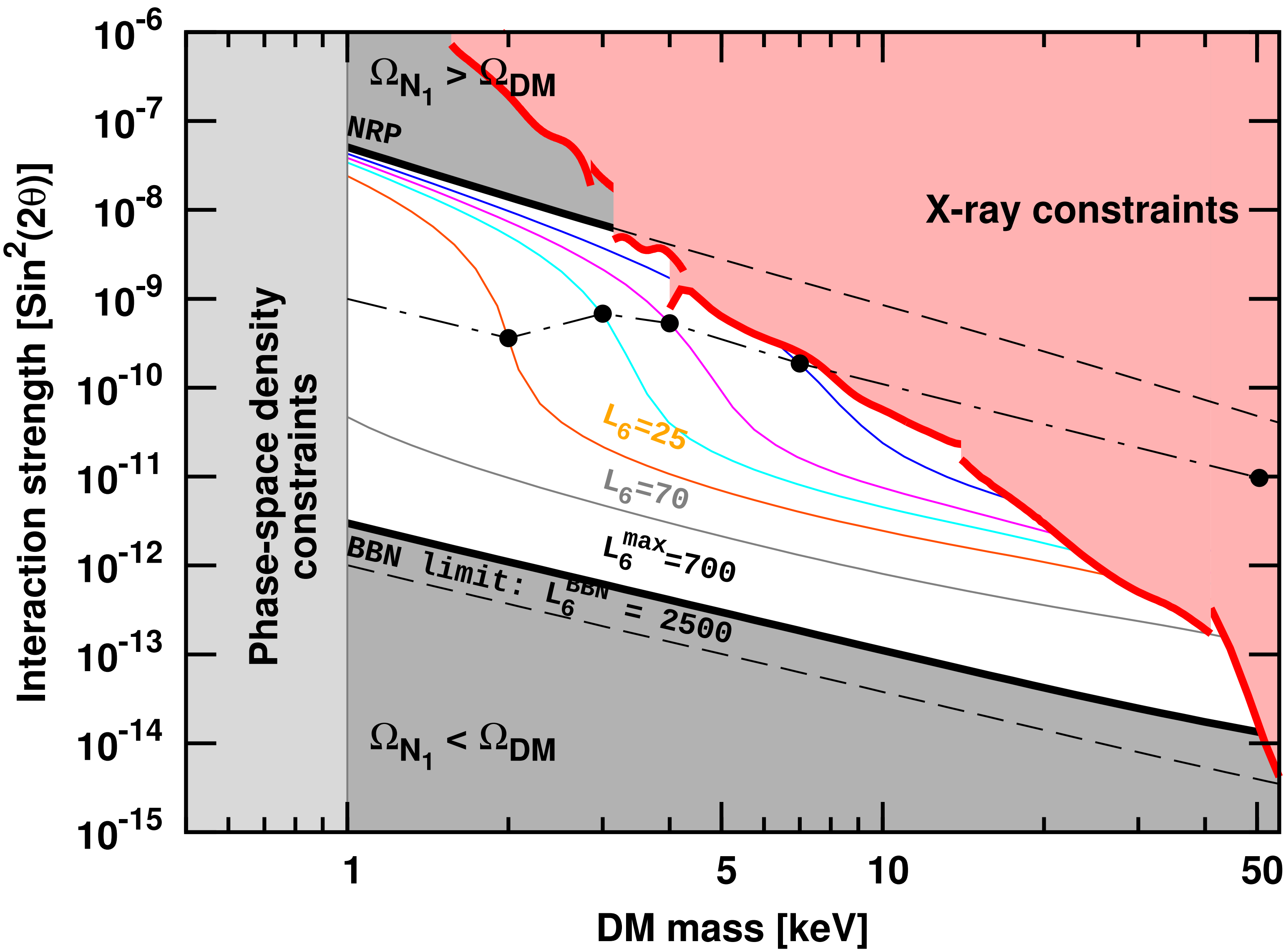


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

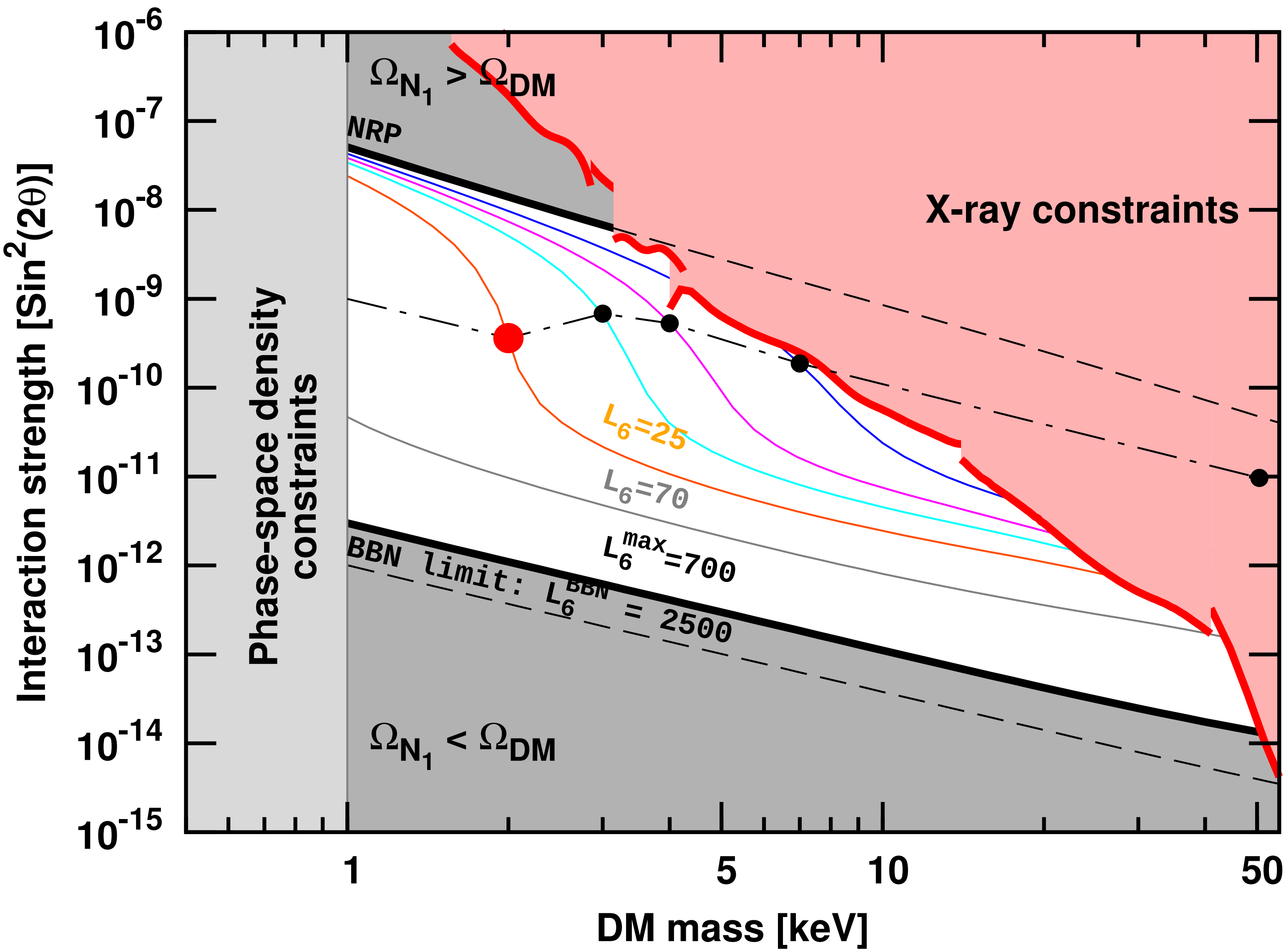
Sterile neutrino DM in the νMSM



Boyarsky, **O.R.**, Lesgourgues, Viel PRL 2009

Review: [0901.0011]

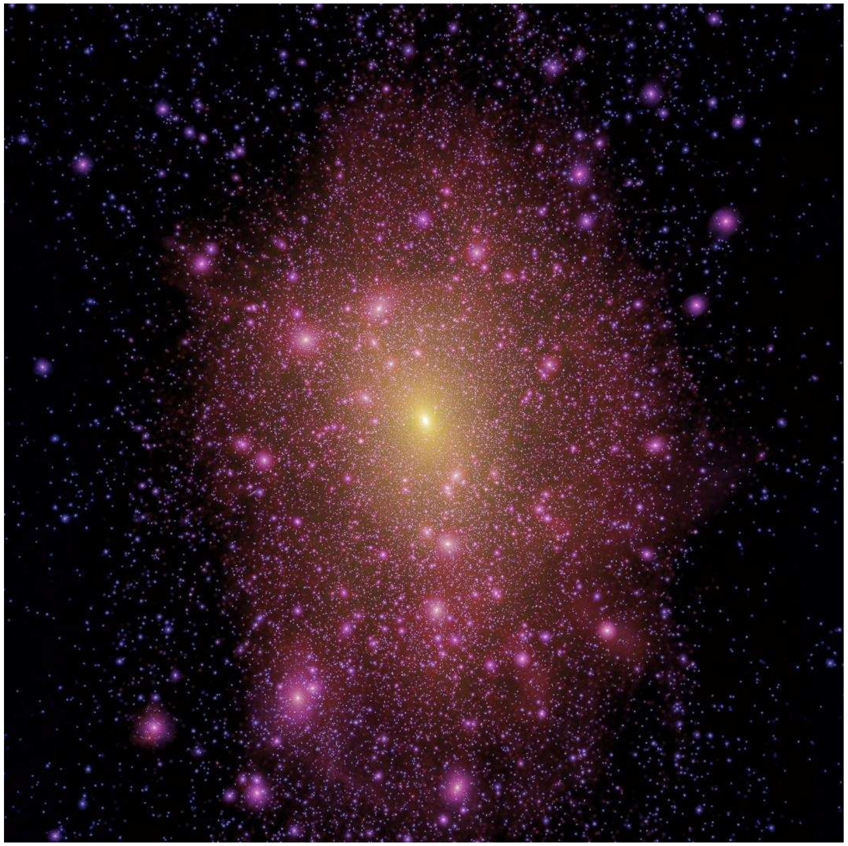
Sterile neutrino DM in the νMSM



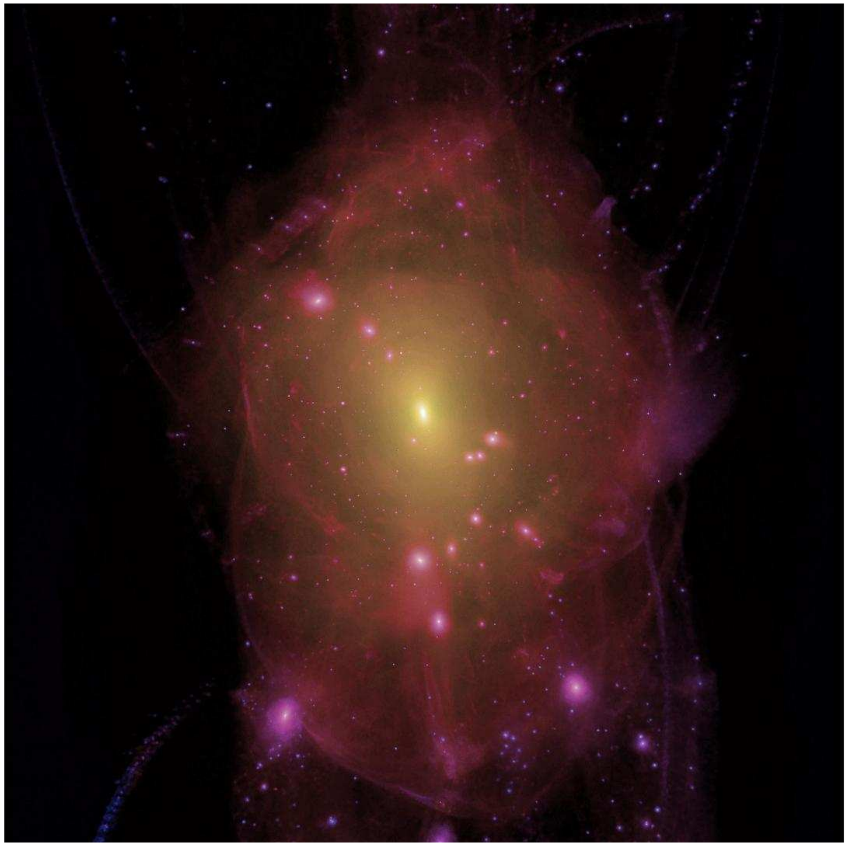
Boyarsky, **O.R.**, Lesgourgues, Viel PRL 2009

Review: [0901.0011]

Halo substructure with sterile neutrino DM



Aq-A-2 CDM halo

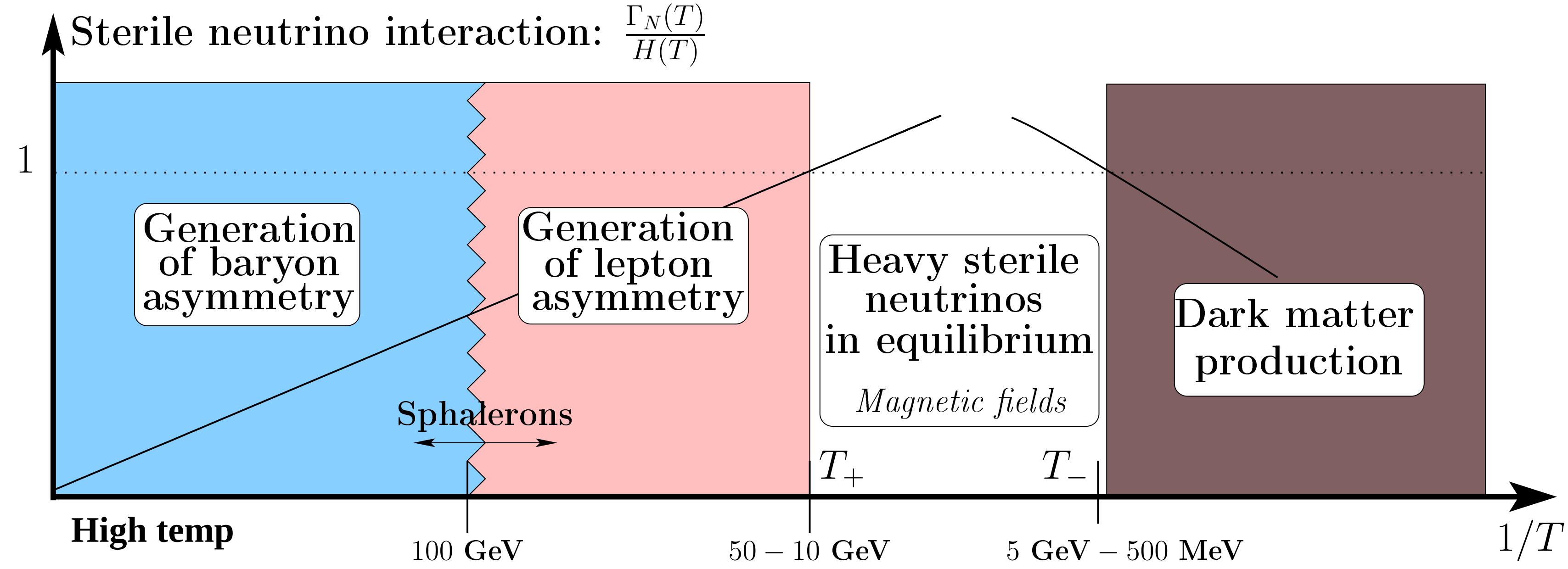


Aq-A-2 halo made of sterile neutrino DM

(C. Frenk, T. Theuns, **O.R.**, . . .)

Simulated sterile neutrino DM halo (right) is fully compatible with the Lyman-α forest data but provides a structure of Milky way-size halo different from CDM

History of the Universe in the νMSM



- Magnetic fields in the plasma **relate** baryogenesis and sterile neutrino dark matter production

work in progress

- Magnetic fields may be observable today in the intergalactic space

Magnetic fields in the νMSM

Large lepton asymmetry of the νMSM triggers **instability** in the Maxwell's equations and leads to the generation of large helical magnetic fields

- Magnetic fields, generated in the νMSM *below* 100 GeV are:
  - Maximally helical (sign of helicity determined by the sign of baryon asymmetry)
  - Energetic (magnetic energy density can be $\sim$ total radiation density)
- Their survival until today is a matter of complicated evolution, described by **chiral magneto-hydrodynamics** **work in progress**

O.R.+ Phys.Rev.Lett 2012

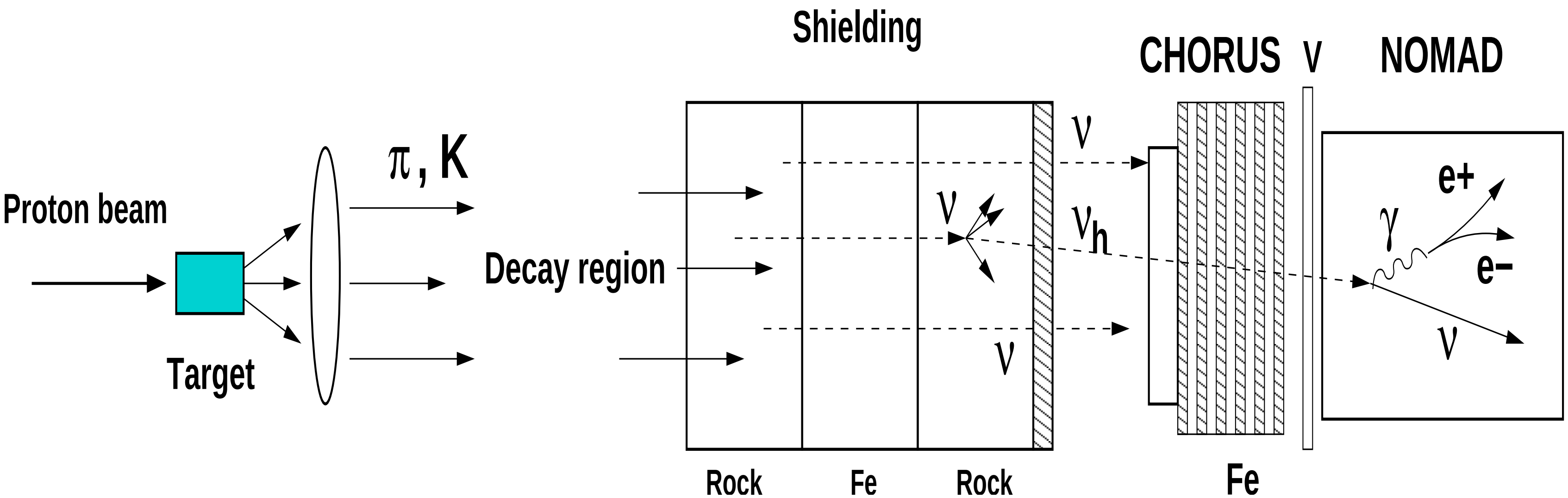
Boyarsky, **O.R.**, Shaposhnikov [1204.3604]

The leptogenesis in the νMSM leads to the **baryogenesis** and generation of **potentially observable** cosmological magnetic fields

How can we search for these particles?

Peak searches and fixed-target experiments

$M_I < 1$ MeV	$M_I \gtrsim 1$ MeV	$M_I \gtrsim 140$ MeV	...
$N_I \to \nu\nu\bar{\nu}$	$N_I \to \nu e^+ e^-$	$N_I \to \pi^\pm e^\mp$	
$N_I \to \nu\gamma$		$N_I \to \pi^0 \nu$	



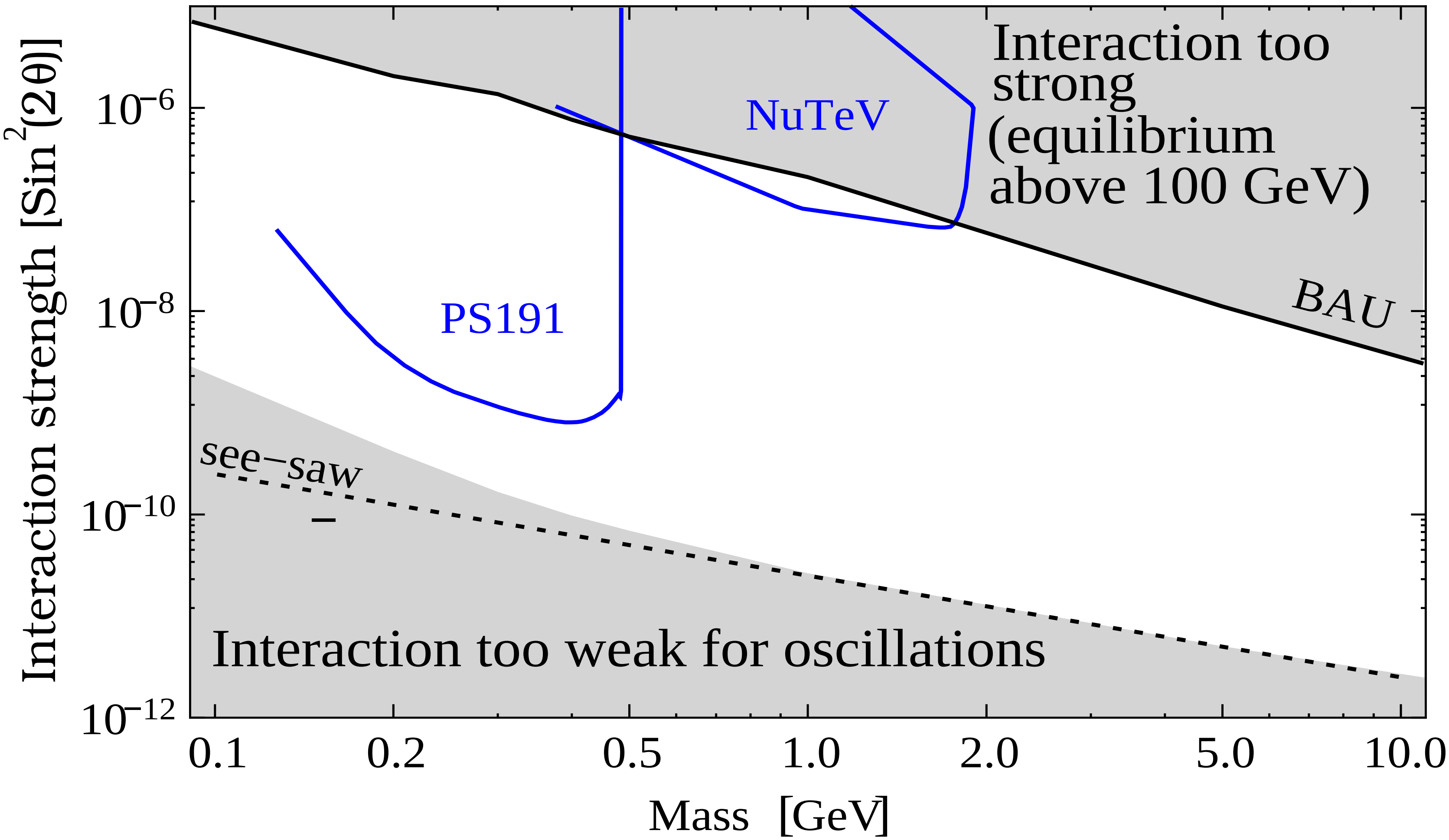
Peak searches:

- SIN $\pi M3$, Switzerland – 1981
- KEK K3, Japan, 1982
- TRIUMF M13, Canada, 1992
- TRIUMF PIENU, Canada, 2011

Fixed-target searches:

- PS191, CERN – 1984
- CHARM, CERN – 1985
- NuTeV, Fermilab – 1996-1997

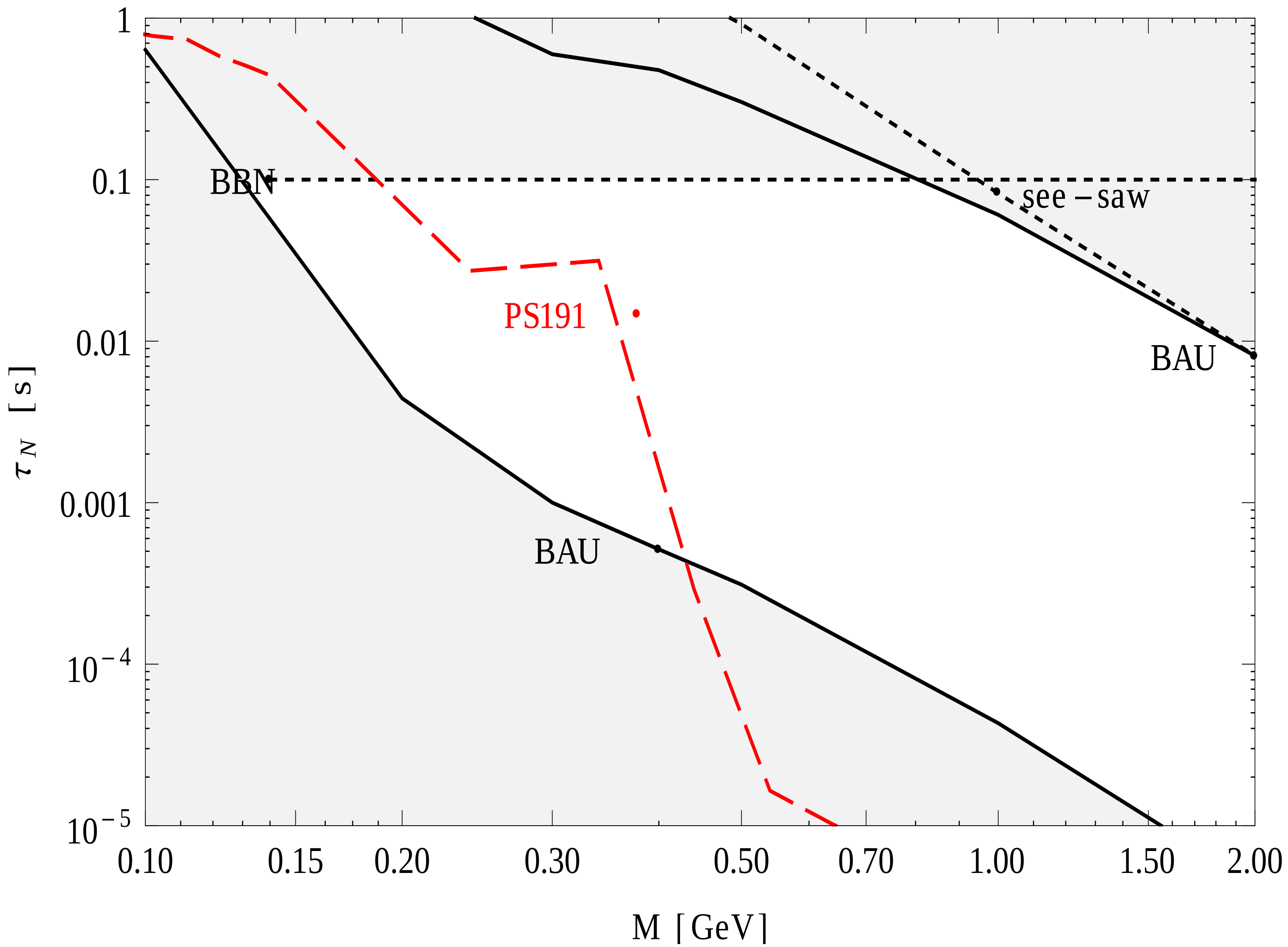
Parameter space of sterile neutrinos



Asaka, Canetti, Gorbunov, Shaposhnikov 2005–2011;

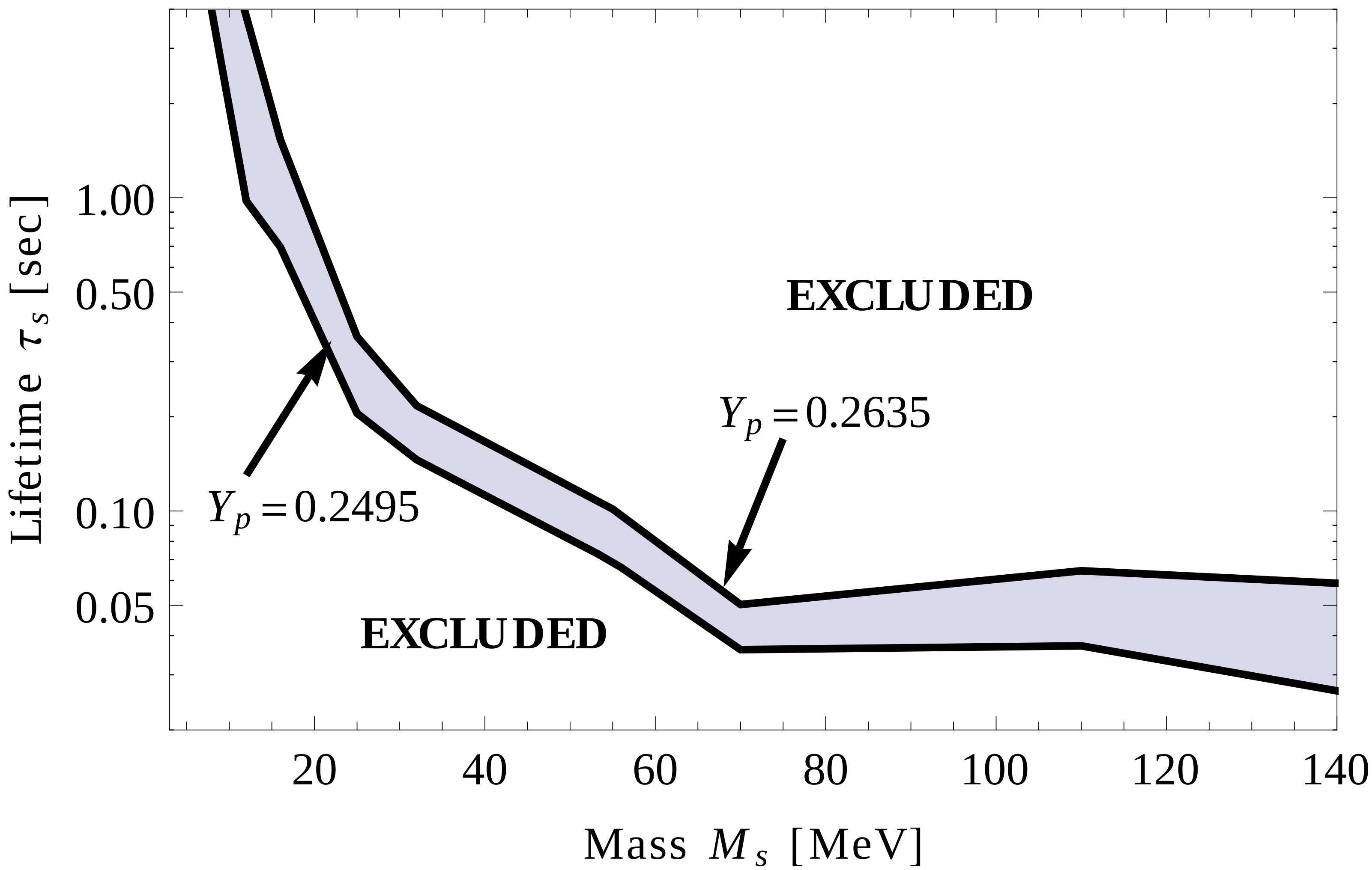
O.R & Ivashko [1112.3319] – revised accelerator bounds

Lifetime of sterile neutrinos



Canetti & Shaposhnikov (2011)

Sterile neutrinos and ^{4}He abundance

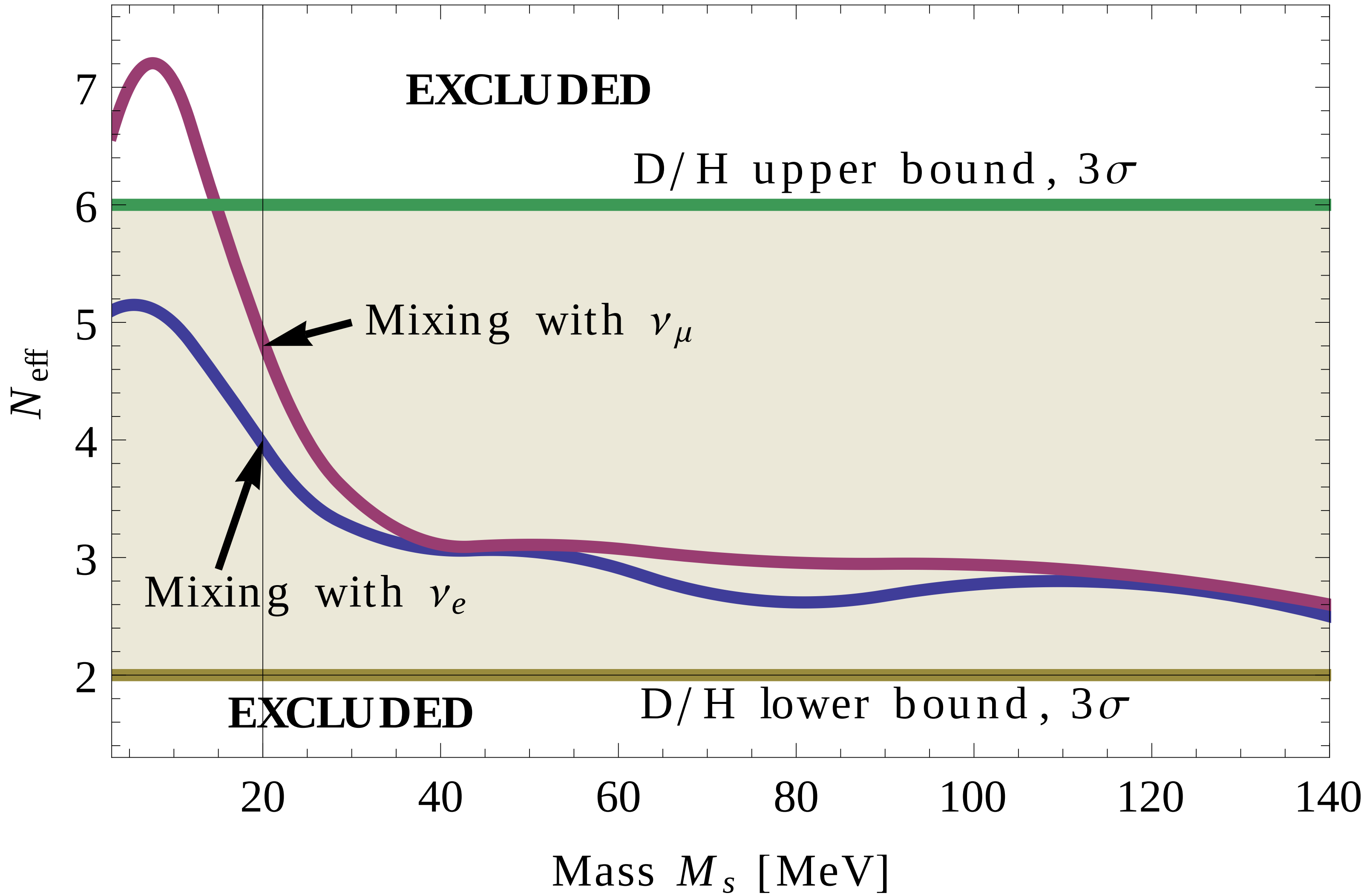


O.R. & Ivashko
[1202.2841]

2σ bounds based on Izotov & Thuan 2010

Decay of sterile neutrinos increases Helium-4 abundance

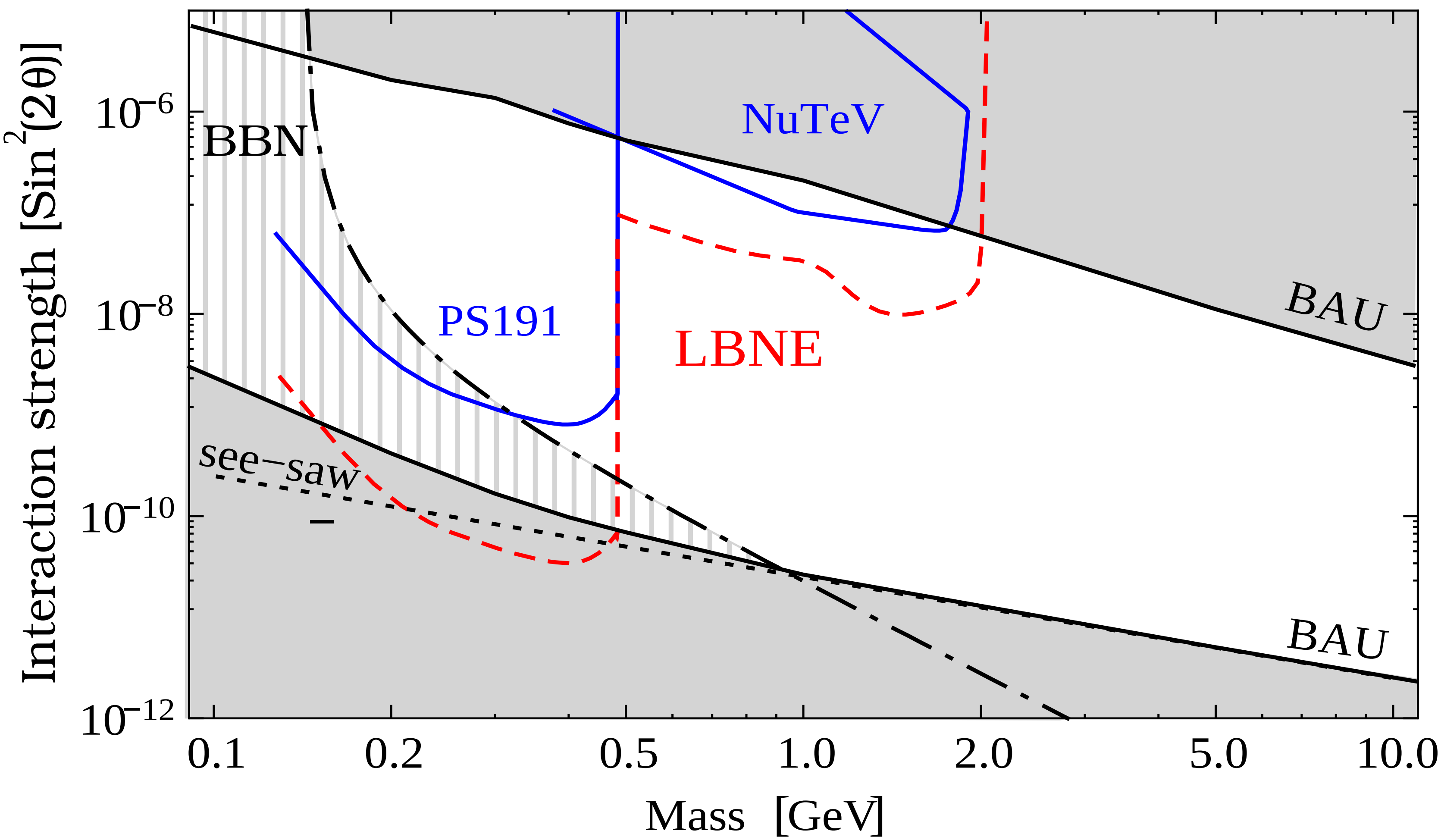
Sterile neutrinos and N_{eff}



O.R. & Ivashko
[1202.2841]

Decay of sterile neutrinos affects N_{eff}

Parameter space of sterile neutrinos



Gorbunov, Shaposhnikov (2009);

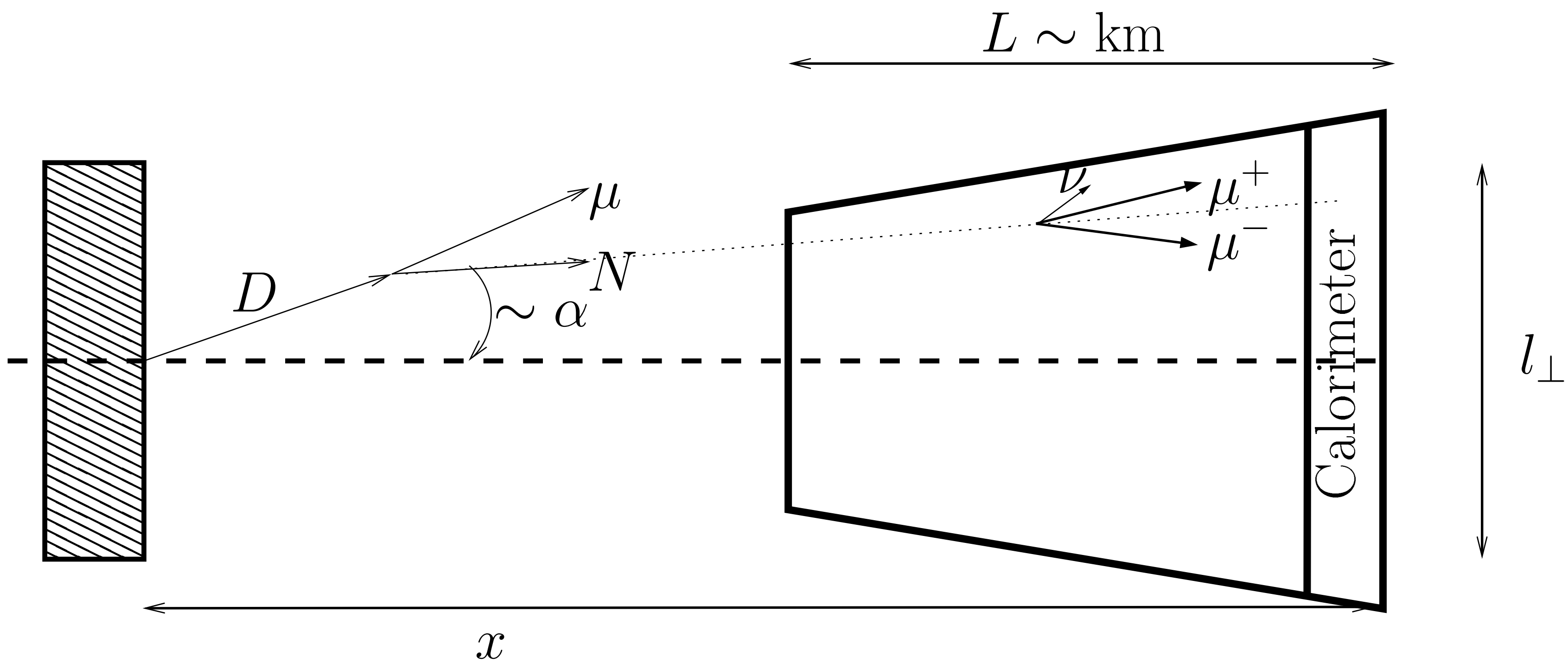
O.R & Ivashko [1112.3319] – revised accelerator bounds

O.R. & Ivashko [1202.2841] – BBN bounds

LBNE white paper [1110.6249]

White paper on sterile neutrinos [1204.5379]

Ultimate detector



To find MeV-GeV scale sterile neutrinos responsible for oscillations (and possibly playing an important role in the early Universe) we need:

- High energy/high intensity fixed-target experiments
- Large detector (length $\sim$ km)

Predictions for the nearest future

- Standard Model Higgs with the mass above ~ 125 GeV at LHC and no new physics otherwise
- Primordial spectral index $n_s = 0.96\ldots$ correlated with the Higgs mass, measured by Planck
- Non-detection of tensor modes
- Sum of neutrino masses $\sum m_\nu \approx (1-2)m_{\text{atm}}$
(hard to see it until the next generation of CMB experiments)
- In the $0\nu\beta\beta$ mass $m_{\beta\beta}$ at the level $1-10$ meV

Bright future ~~"nightmare scenario"~~

Within the next decade we can:[1]

- **Discover** two sterile neutrinos with the masses $\mathcal{O}(100)$ MeV $\div$ few GeV and mass splitting $\sim m_{\text{atm}}$ in "intensity frontier" experiments
  (**NA62 in CERN, LBNE, SLHCb**)
- **Discover** dark matter decay line with mass/lifetime consistent with the parameters of two other sterile neutrinos
  (the first X-ray spectrometer of the new generation will fly in 2014).
- **Detect** the matter power spectrum suppression at $k \sim 10$ h/Mpc
  (**next round of weak lensing/Lyman-α forest experiments**)
- **Find** the strength/correlation length of magnetic fields in voids consistent with params. of sterile neutrinos — **direct observational signature of baryogenesis**, *4th pillar of hot Big Bang*

[1] By "can" I mean "experimental technologies are available for us today"

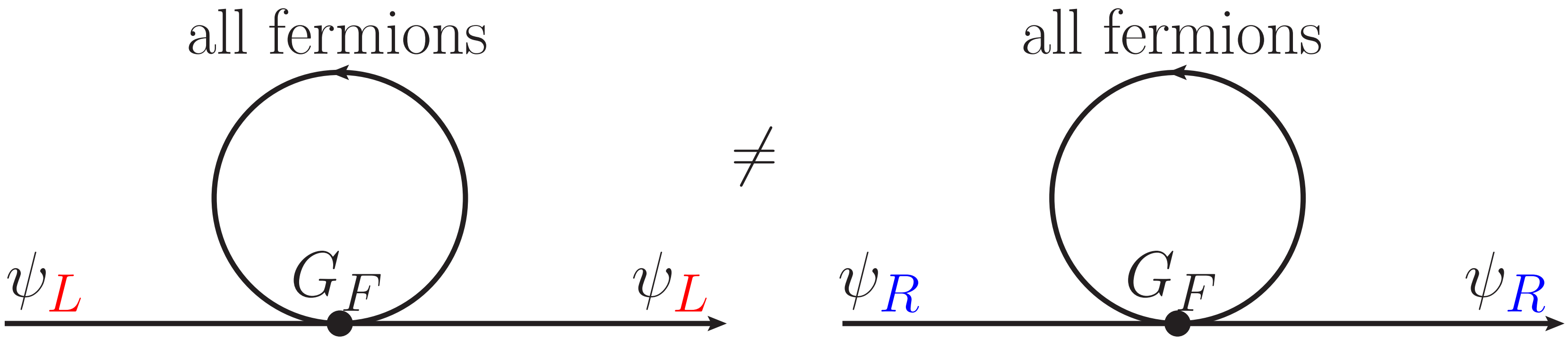
THANK YOU FOR YOUR ATTENTION

Additional slides

Weak corrections

- Chemical potentials of all left/right particles are in equilibrium at $T < 80$ TeV

- Weak corrections are proportional to the **asymmetry** of all fermions, running in the loops



Boyarsky, **O.R.**, Shaposhnikov [1204.3604]

- This diagram leads to the change of dispersion relations (shift of chemical potentials) of left/right particles

Chern-Simons term

- At finite value of baryon and lepton asymmetry effective action for magnetic fields acquires a **Chern-Simons term**:

$$\mathcal{F}[\vec{A}] = \frac{1}{2}\int d^3x \left(\vec{B}^2 + \Pi_2 \vec{A}\cdot\vec{B}\right)$$

- The Chern-Simons coefficient is given by:

Boyarsky, **O.R.**, Shaposhnikov [1204.3604]

$$\Pi_2 = \frac{\alpha}{2\pi} G_F \times (c_1 \text{ baryon number} + c_2 \text{ lepton numbers}) \neq 0$$

- Its origin is **chiral anomaly** and parity-violating nature of weak interactions

CS term and instability

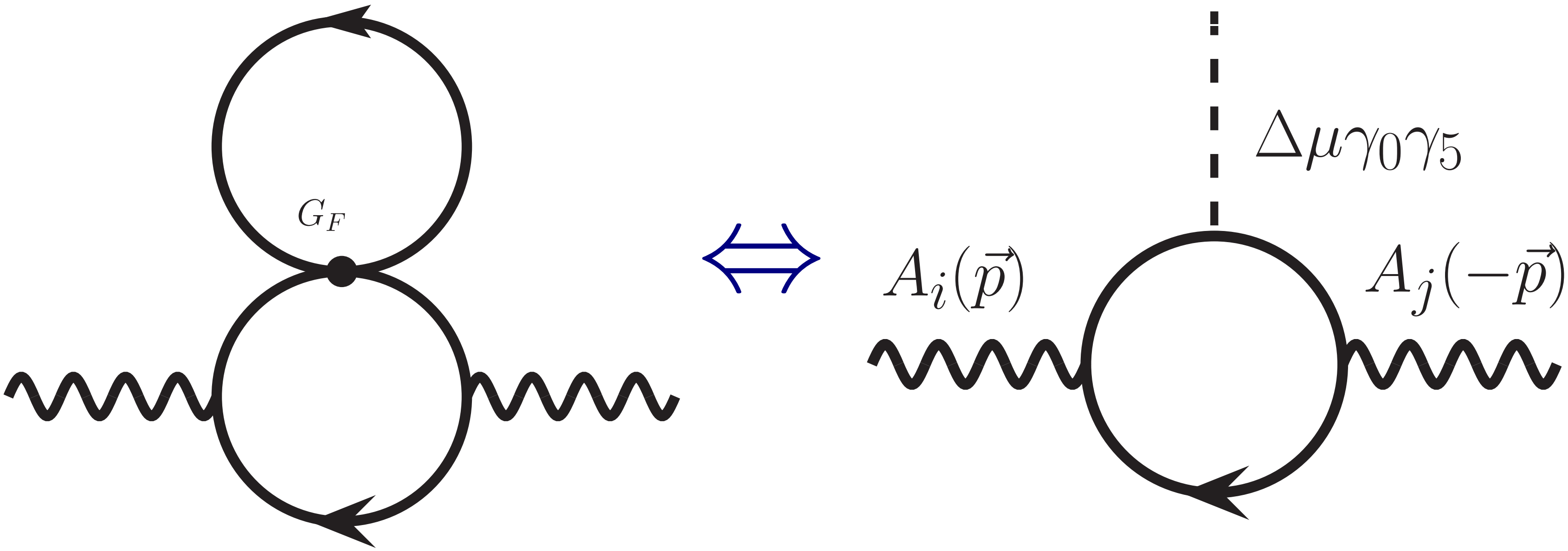
$$\mathcal{F}[\vec{A}] = \frac{1}{2}\int d^3x \left(\vec{B}^2 + \Pi_2 \vec{A}\cdot\vec{B}\right)$$

- The unstable mode will have a form $\vec{A}(\vec{x}) = A_0\Big(\cos(pz), \sin(pz), 0\Big)$
- On such a configuration $\vec{B}^2 = -p\vec{A}\cdot\vec{B}$ and are homogeneous
- The effective action is unbounded from below for $p < \Pi_2$

$$\mathcal{F}[A] = \frac{1}{2}\int d^3x \left(p^2 - p\Pi_2\right) A_0^2 < 0$$

- **Long-range magnetic fields** will be spontaneously generated in the equilibrium

Chern-Simons term



Boyarsky, **O.R.**, Shaposhnikov [1204.3604]

Weak interactions make propagators left-right asymmetric and chiral anomaly leads to the generation of parity-odd term

$$\Pi_2(0) = \frac{\alpha}{2\pi} G_F \times (c_1 \text{ baryon number} + c_2 \text{ lepton numbers}) \neq 0$$

Maximally helical configuration

- The unstable mode will have a form

$$\vec{A}(\vec{x}) = A_0\Big(\cos(pz), \sin(pz), 0\Big)$$

- The magnetic field

$$\vec{B}(\vec{x}) = -p\vec{A}(\vec{x})$$

  — is maximally helical

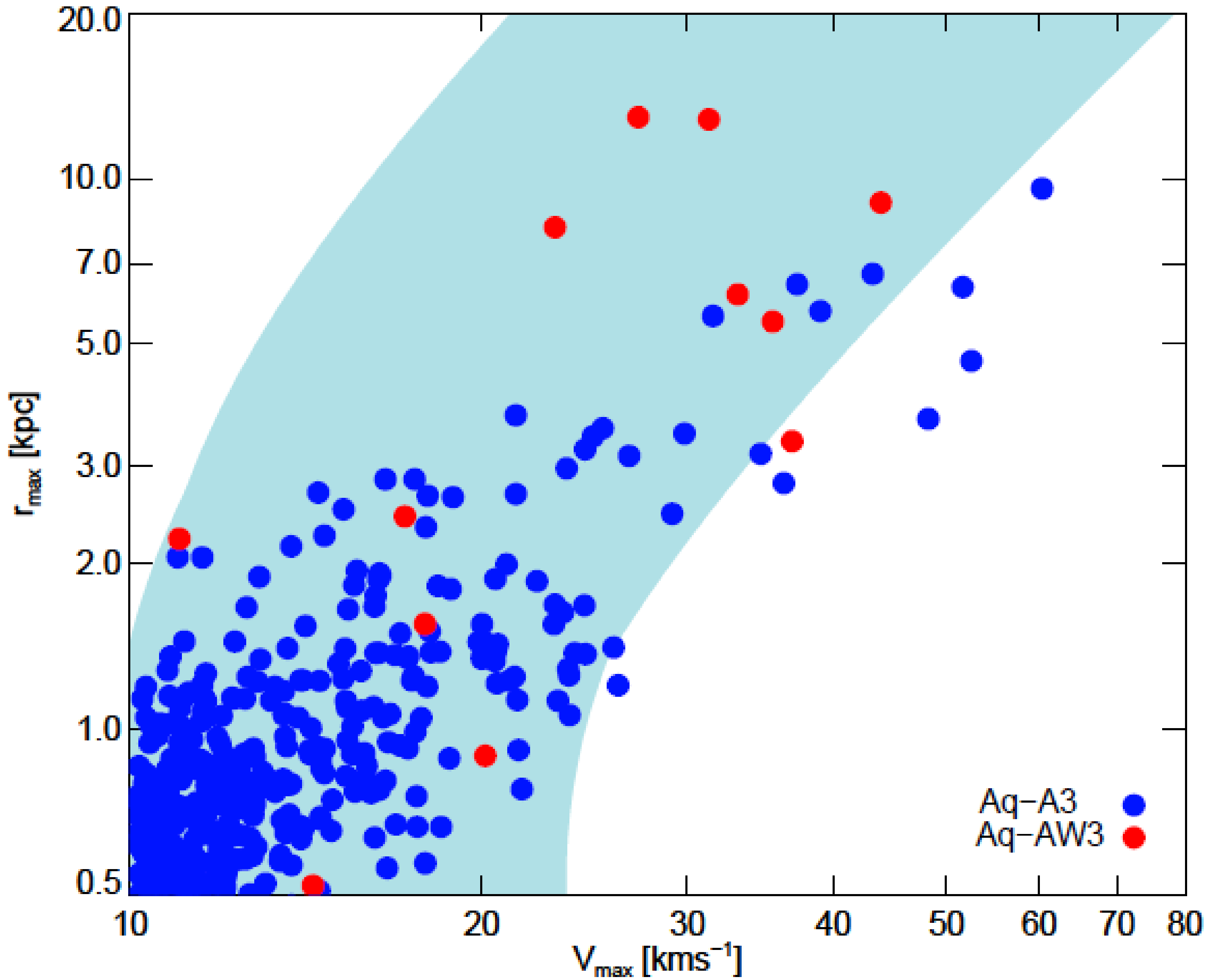
- On this configuration $\vec{B}^2 = p\vec{A}\cdot\vec{B}$ and are homogeneous

- The effective action:

$$\mathcal{F}[A] = \frac{1}{2}\int d^3x\,\Big(p^2 - p\Pi_2\Big)A_0^2 < 0$$

  for $p < \Pi_2$

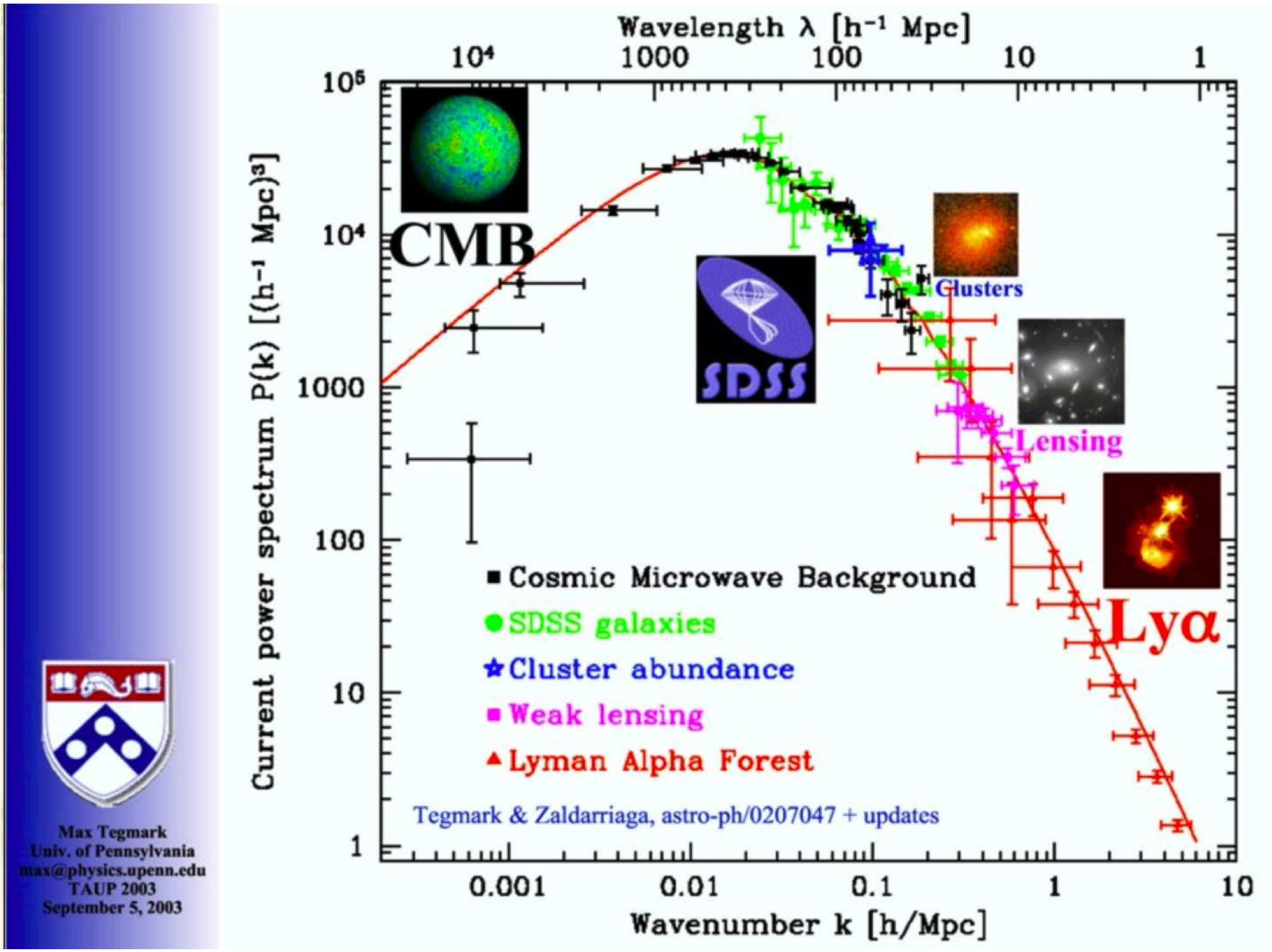
Abundance of large satellites



Strigari, Frenk
White (2011)

Lovell, Frenk,
Eke, . . . ,
Boyarsky,**O.R.**
1104.2929
[astro-ph.CO]

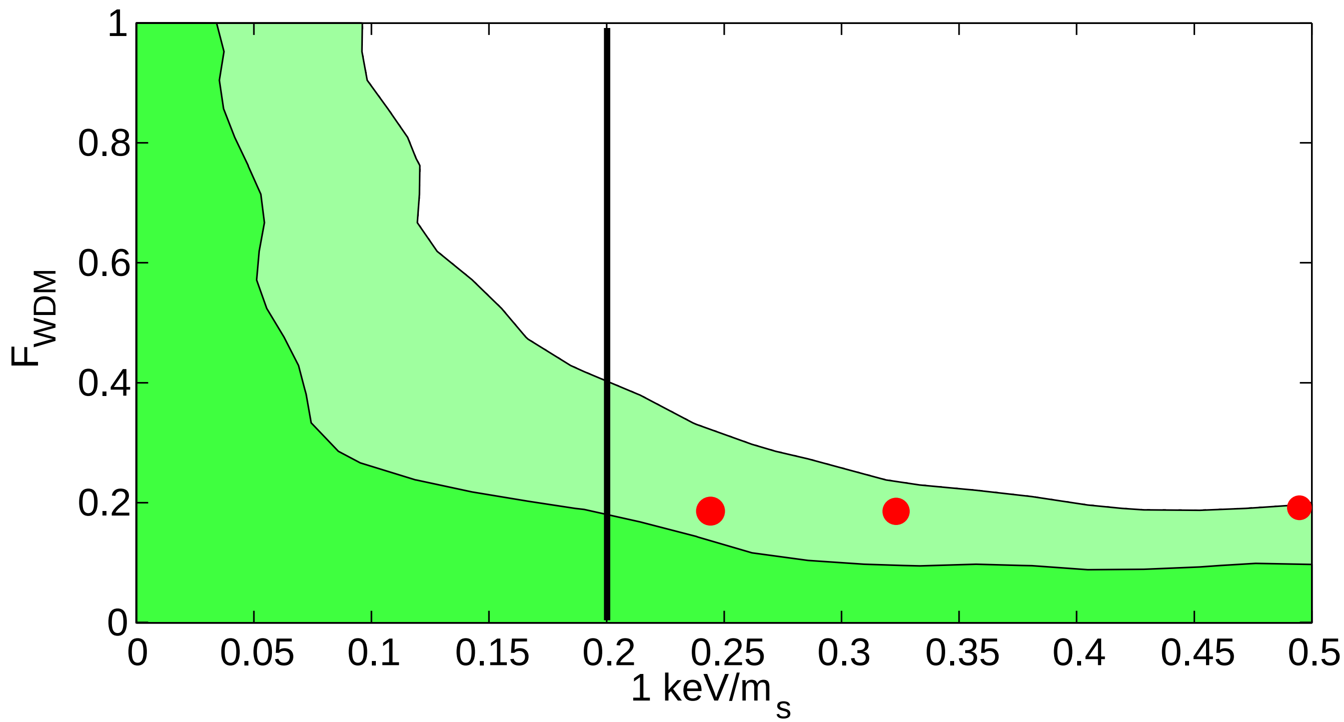
How to measure power spectrum



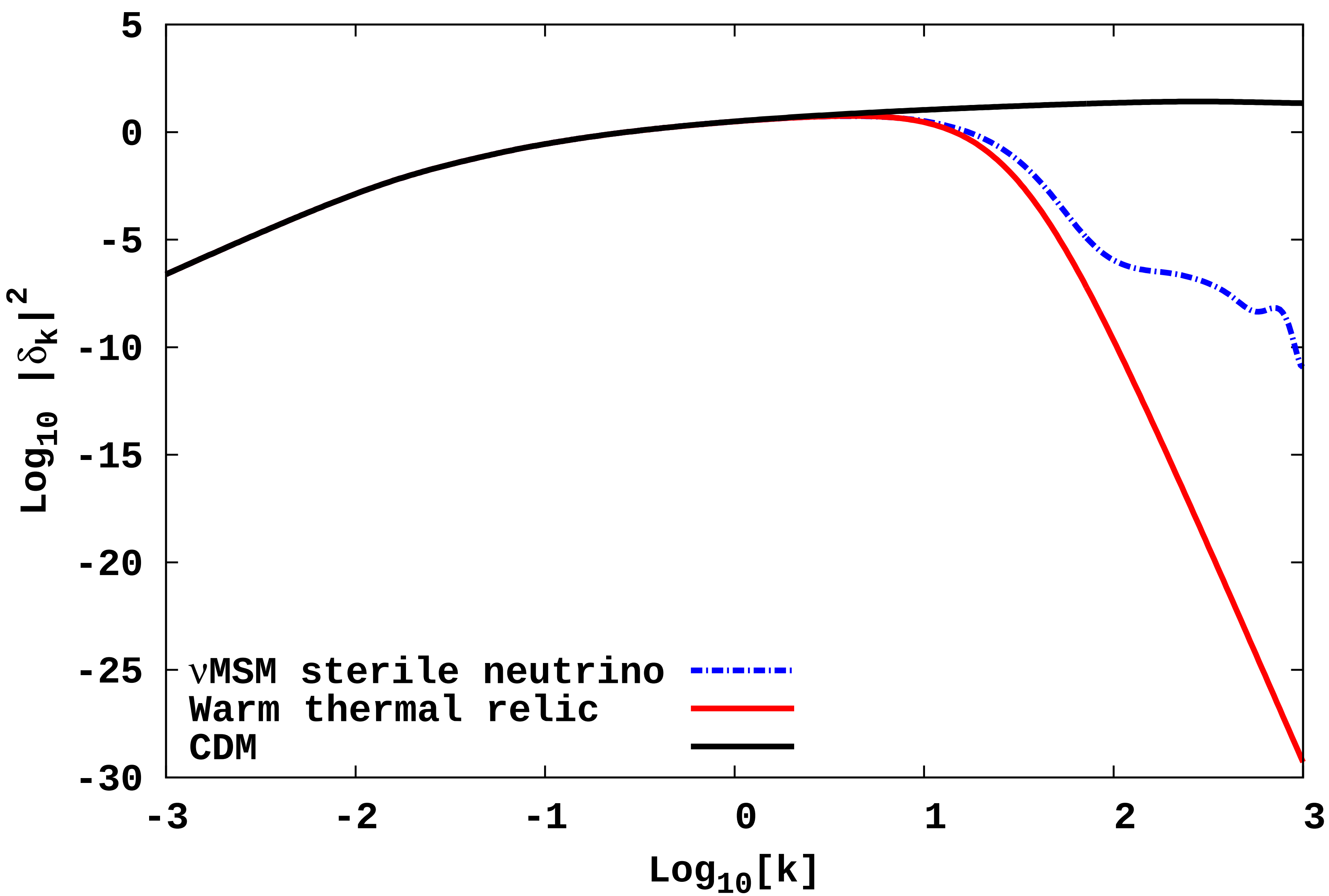
Lyman-α bounds for sterile neutrinos

- Revised version of these bounds in CDM+WDM (mixed, CWDM) models demonstrates that
  - The primordial spectra **are not described by free-streaming**
  - There exist viable sterile neutrino DM models with the masses as low as 2 keV

Boyarsky, **O.R.**, Lesgourgues, Viel JCAP & PRL (2009)

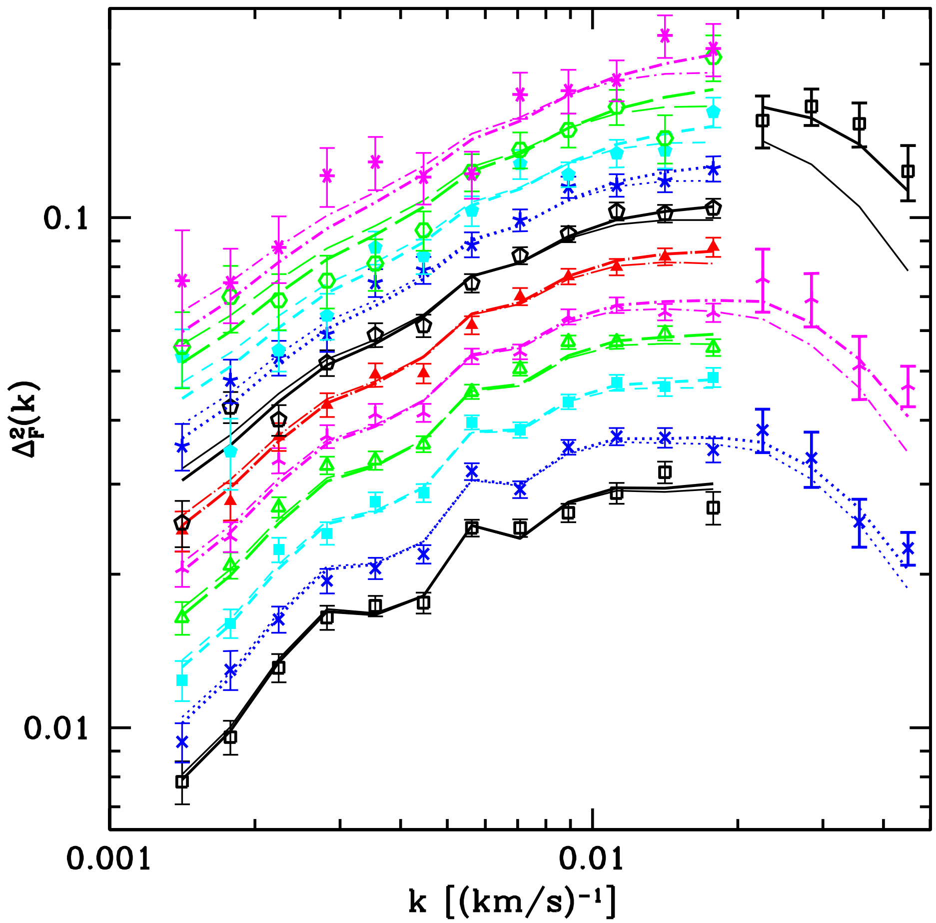


Suppression of power spectrum



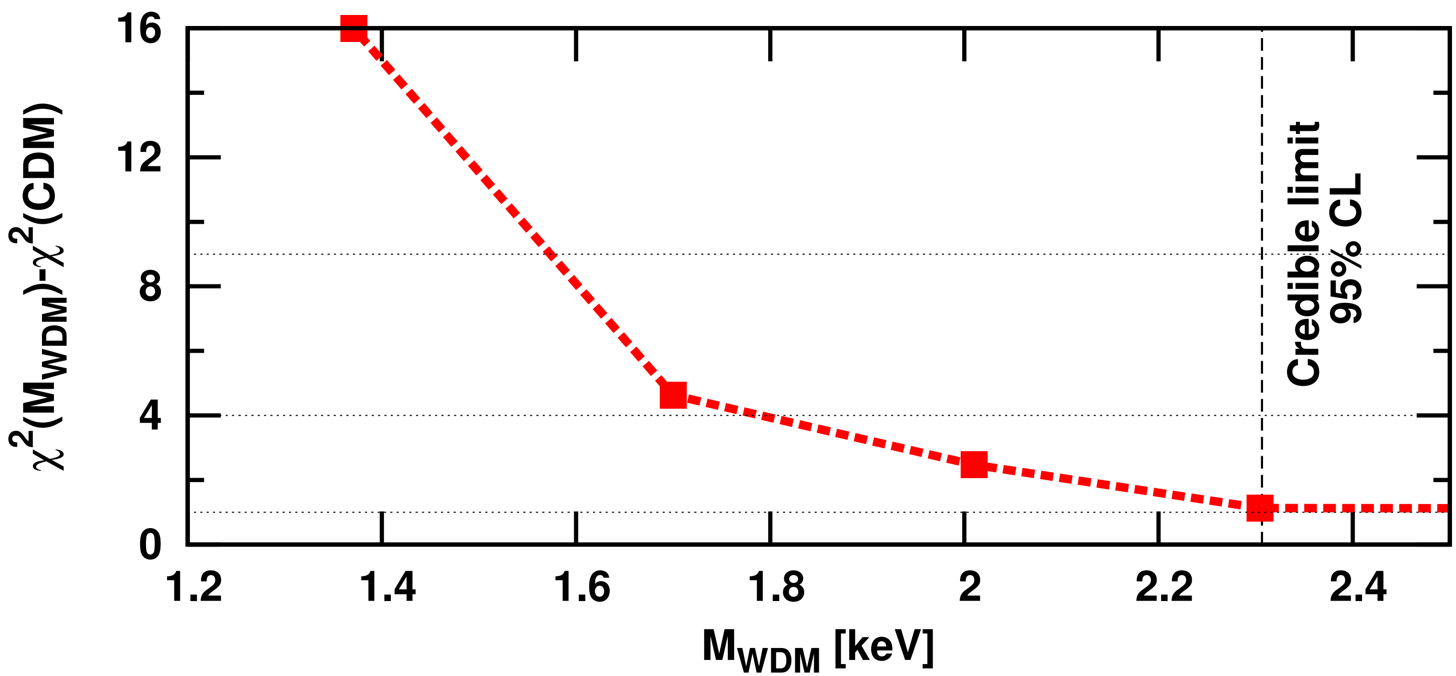
Lyman-α forest flux power spectrum

Seljak et al. '06



Measured flux power spectrum is compared against CDM and non-CDM models

Ly-α and thermal relics



Boyarsky, Lesgourgues, **O.R.**, Viel [0812.0010] (JCAP 2009)

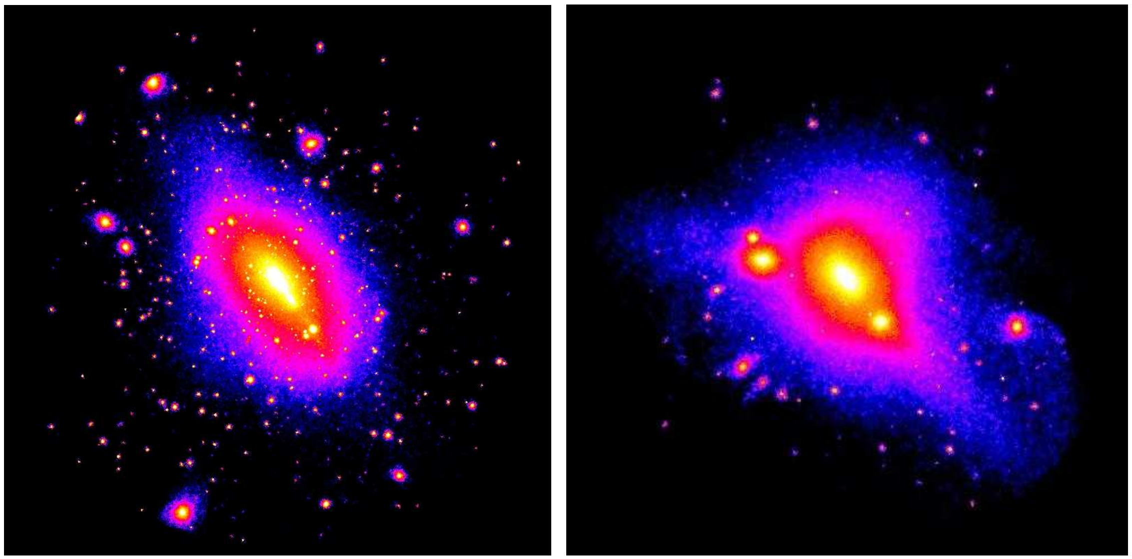
Also Viel et al. 2005-2007;

Seljak et al. (2006)

*These bounds are for **thermal relics** only!*

Lyman-α forest and warm DM

- Previous works put bounds on free-streaming $\lambda_{FS} \lesssim 150$ kpc ("WDM mass" > 2.3 keV)
- The simplest **WDM** with such a free-streaming would not modify visible substructures:



- **Thermal relic** with exponential cut-off ~ 1 Mpc would erase **too many substructures**. Anything "colder" would produce enough structures to explain observed Milky Way structures

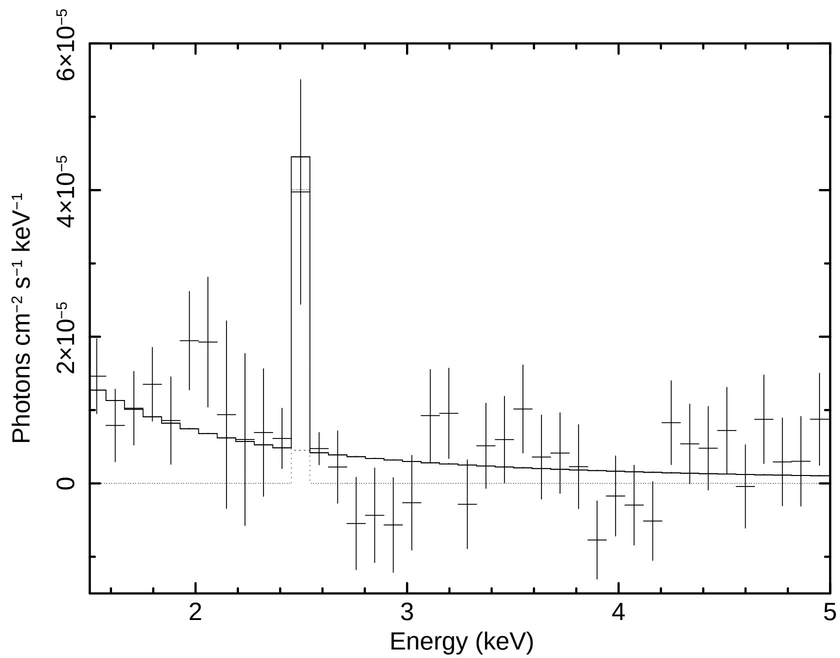
Viel et al. 2005-2007; Seljak et al.(2006)

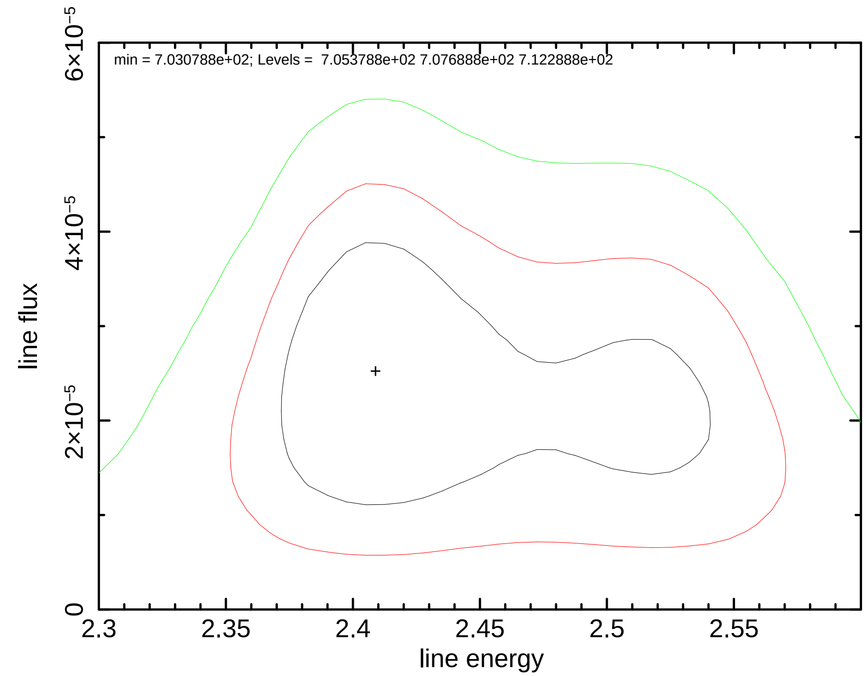
Maccio & Fontanot (2009);

Polisensky & Ricotti (2010)

Checking DM origin of a line

- *Dark Matter Search Using Chandra Observations of Willman 1, and a Spectral Feature Consistent with a Decay Line of a 5 keV Sterile Neutrino* Loewenstein & Kusenko (Dec'2009)

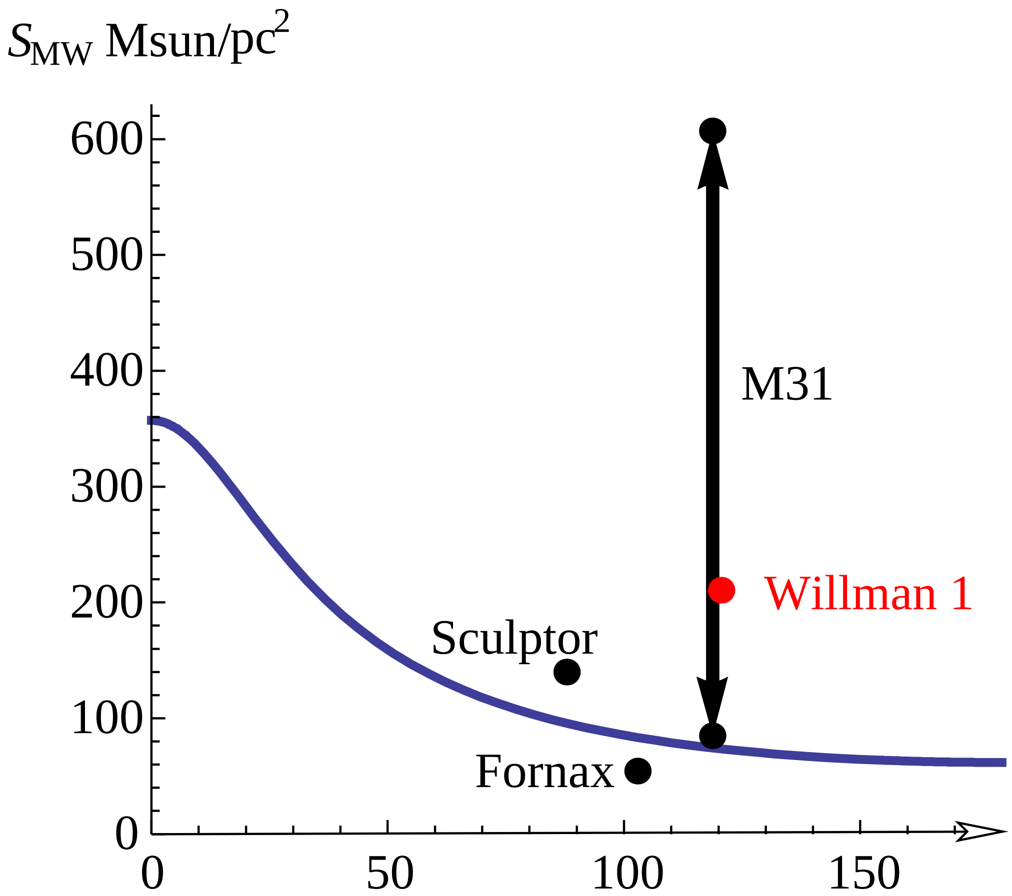




68%, 90% and 99% confidence intervals

- *Can the excess in the FeXXVI Ly gamma line from the Galactic Center provide evidence for 17 keV sterile neutrinos?* Prokhorov & Silk (Jan'2010

Do we see this line anywhere else?

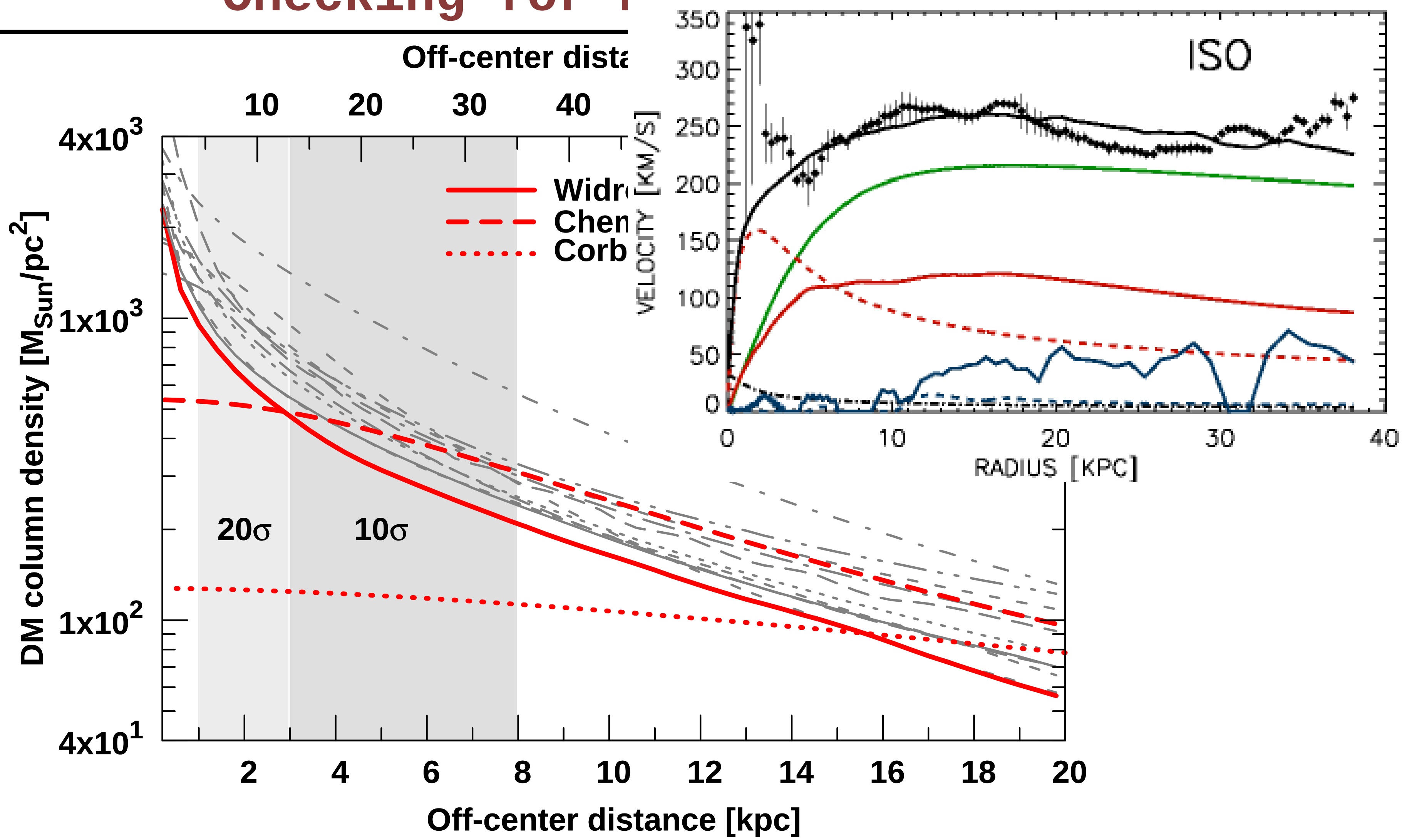


Objects with comparable expected signal for which archival data is available

- **Fornax dSph** (XMM)
  $\mathcal{S}_F = 54.4 M_\odot \text{pc}^{-2}$
- **Sculptor dSph** (Chandra)
  $\mathcal{S}_{Sc} = 140 M_\odot\ \text{pc}^{-2}$
- **Andromeda galaxy (M31)** :
  $\mathcal{S}_{M31} \sim 100 - 600 M_\odot/\text{pc}^2$

Do we see this 2.5 keV line?

Checking for DM line in M31



Willman 1 spectral feature excluded with high significance from archival observations of M31 and Fornax and Sculptor dSphs