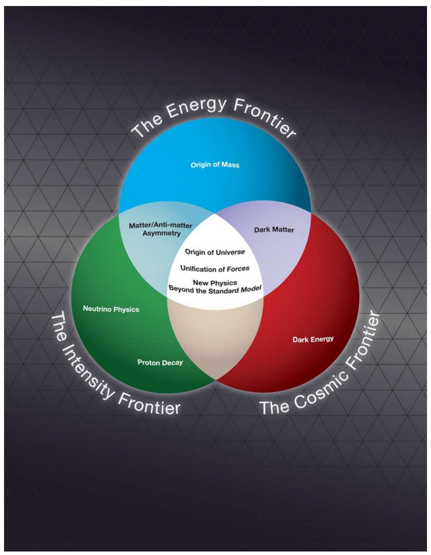
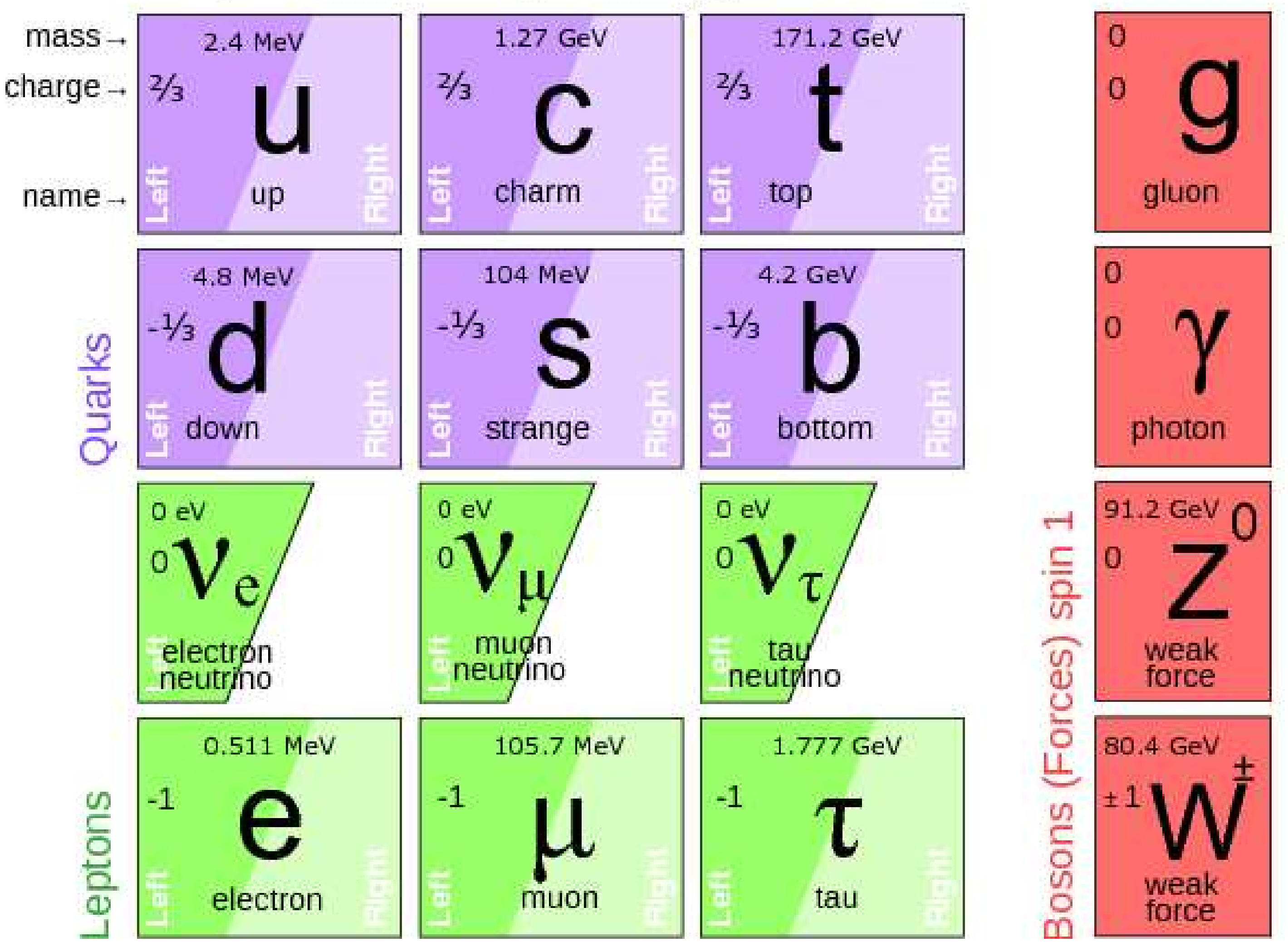
STERILE NEUTRINOS ~~AND~~ AS BSM PHYSICS:
Neutrino Masses, Dark Matter, Baryon Asymmetry and more. . .



Oleg RUCHAYSKIY

Rencontres du Vietnam
July 16, 2012

Particle physics today



. . . And a 5σ detection of a boson at 125–126 GeV . . .

Particle physics tomorrow?

- 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**:

→ **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!)

→ existence of **dark matter** (why observed gravity of galaxies and clusters is so strong?)

→ the **absence of anti-matter** in the Universe

→ **(Probably)** inflation (homogeneity of the observed Universe seem to require correlated initial conditions for causally non-connected regions)

→ **(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?)

Where can we expect new physics?

- **Neutrino oscillations** $m_\nu \sim \sqrt{\Delta m^2_{\rm atm}} \sim 10^{-2}$ eV.
  See-saw mechanism $m_\nu \sim v^2/\Lambda$, where $v = \langle H \rangle = 174$ GeV and **new scale** $\Lambda \sim 10^{12\div 15}$ GeV

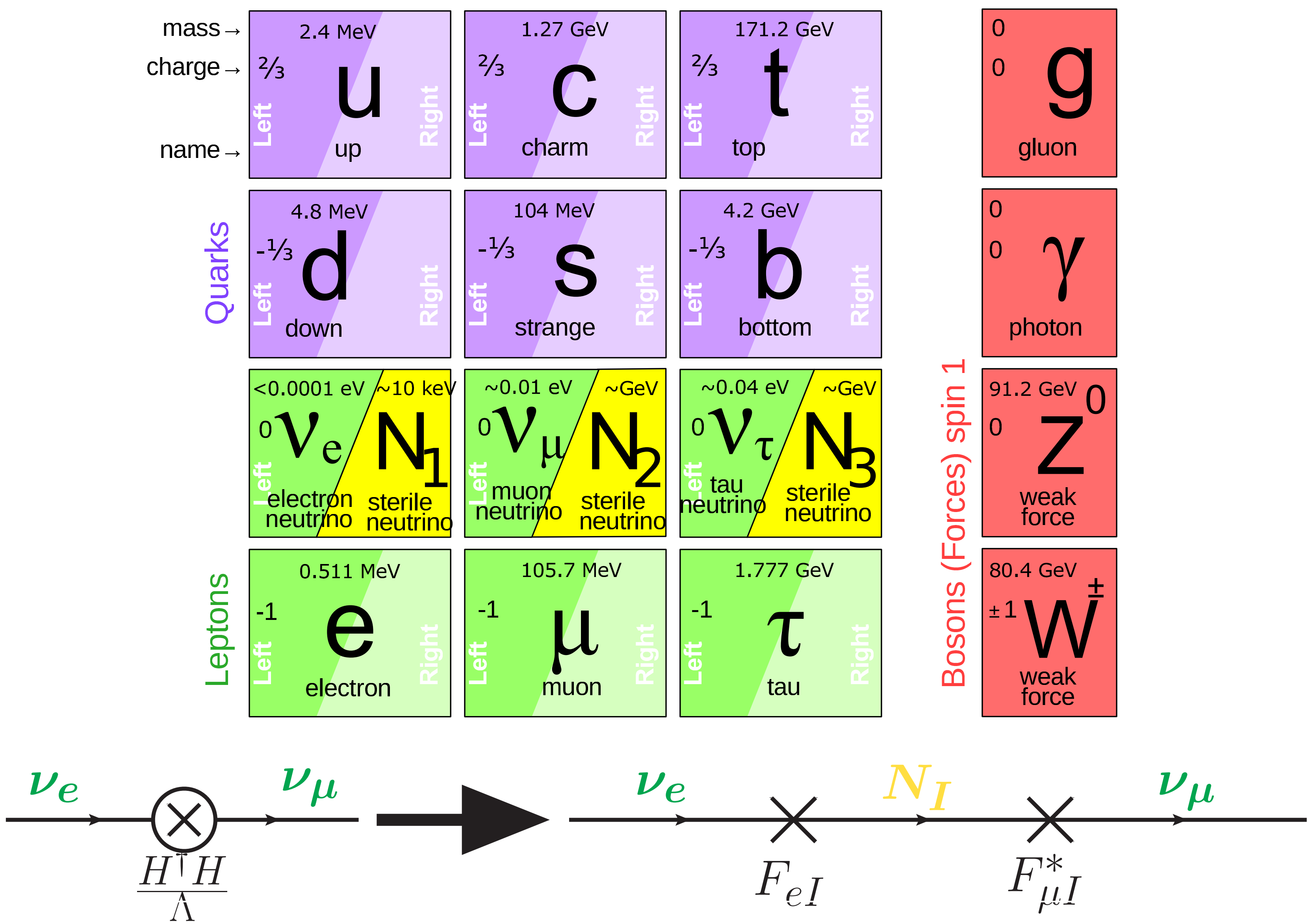
- **Dark matter**
  - particles with weak cross-section will have correct abundance $\Omega_{\rm DM}$ ("WIMP miracle"). **New scale** ~ 1 TeV
  - Axions. **New scale** $10^{10} - 10^{12}$ GeV.

- **Fine-tuning problems:**
  - gauge hierarchy problem: ~ 1 TeV
  - grand unification: $\sim 10^{15}$ GeV
  - CP-problem: $10^{10} - 10^{12}$ GeV (if provided by axion)

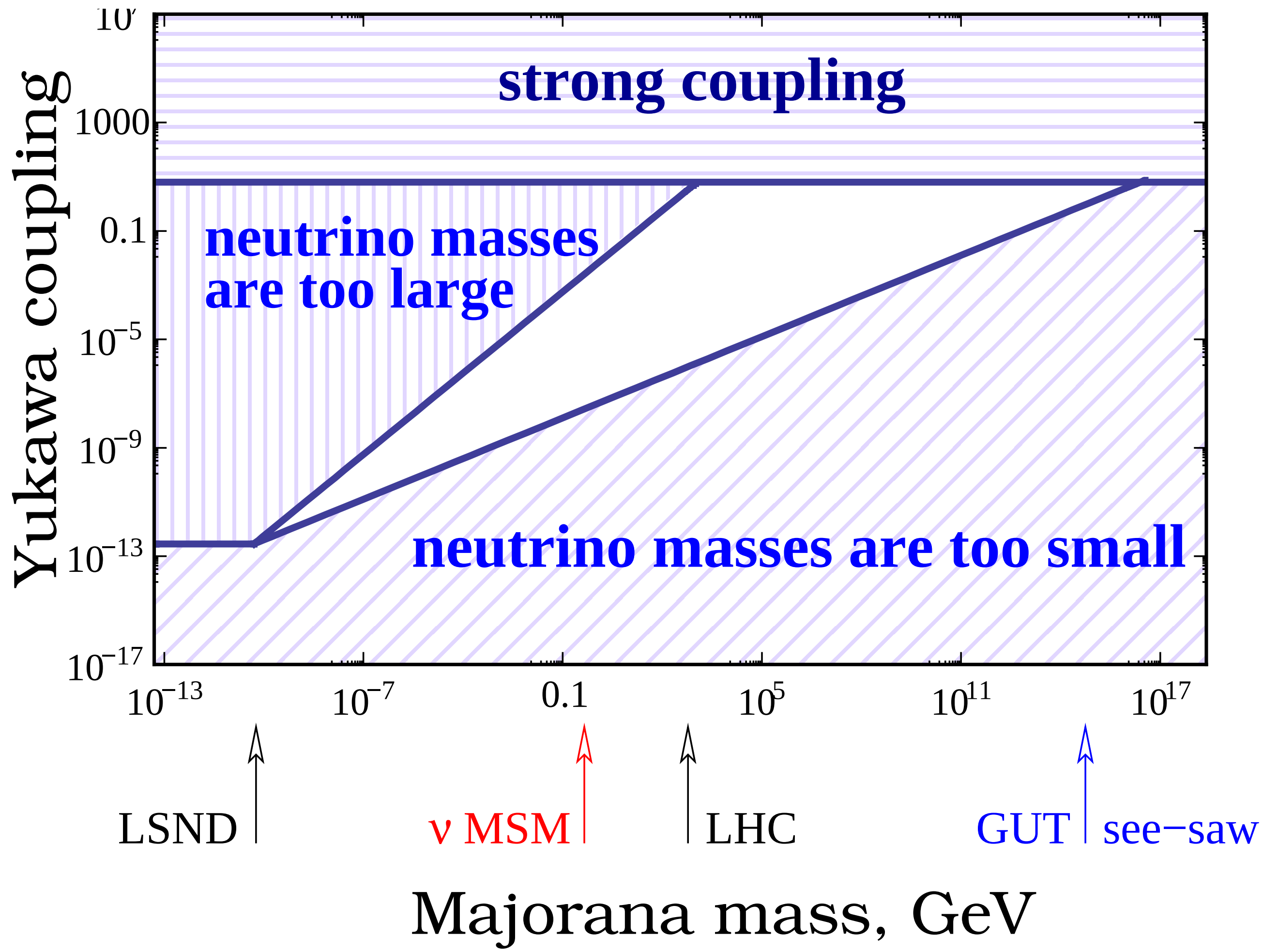
- Particle physics community focuses on TeV BSM: SUSY, extra dimensions, strong dynamics, . . .

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

Right-handed neutrinos: sterile particles



Scale of sterile neutrino masses?



$$M_{\text{active}} \sim \frac{v^2 |F|^2}{M_{\text{sterile}}}$$

Sterile neutrino white paper [1204.5379]

Sterile neutrinos can ...

	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

- See-saw mechanism does not fix mass scale of sterile neutrinos
- A simplest model to explain oscillations (*two sterile neutrinos*) brings in **11** new parameters (of which only **7** can be fixed by neutrino oscillation experiments)

Sterile neutrinos can ... do it all

	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

A possible choice: make the masses of sterile neutrinos of the same order as those of quarks and leptons (keV–GeV) —

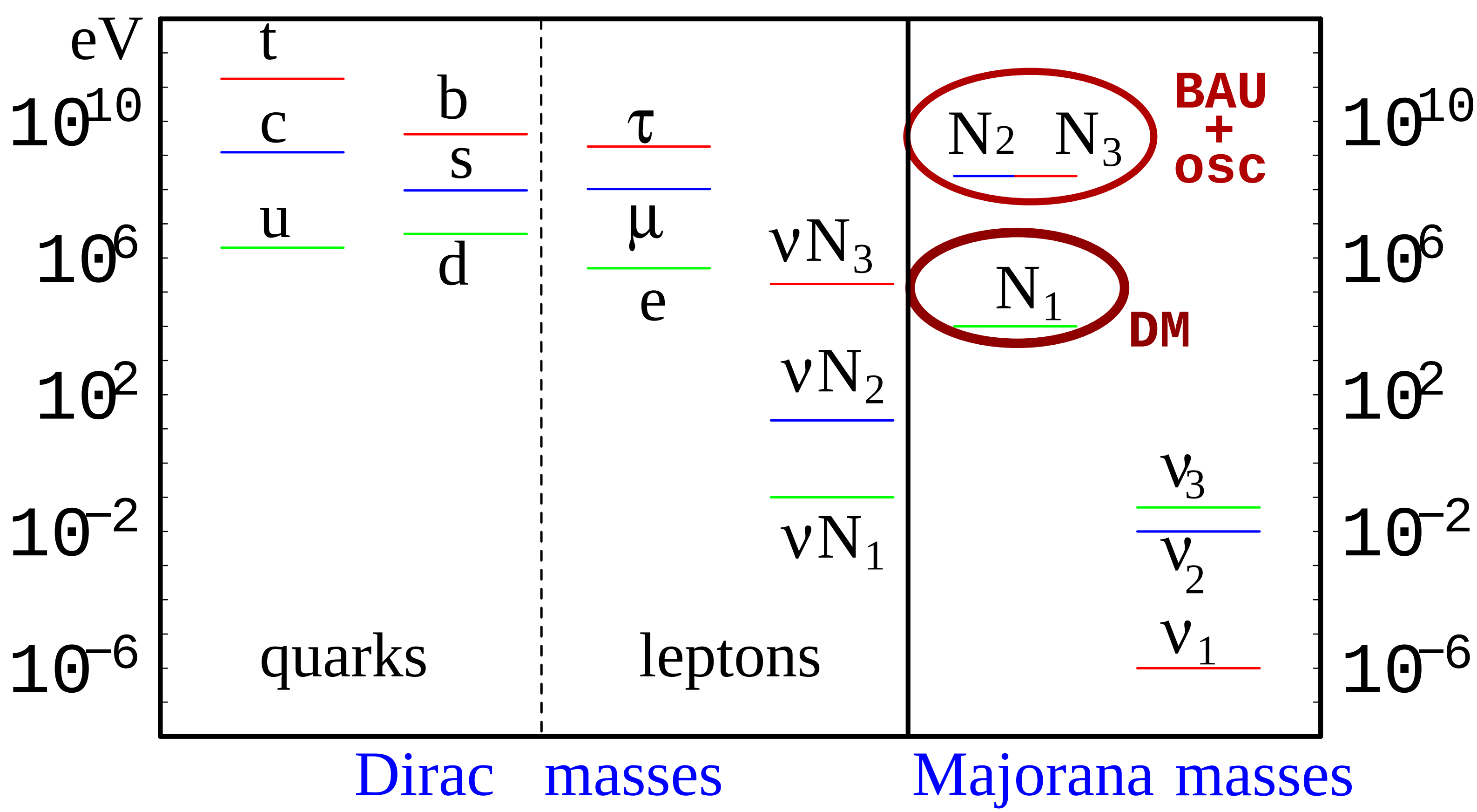
Asaka & Shaposhnikov (2005) and many subsequent works

Neutrino Minimal Standard Model

(νMSM for short)

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

Masses of sterile neutrinos in the νMSM



Masses of sterile neutrinos as those of other leptons
Yukawas as those of electron or smaller

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

Neutrino Minimal Standard Model

The νMSM solves BSM problems and **provides a complete cosmic history from inflation till today** without introducing new particles above electroweak scale

- ✓ . . . 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**)

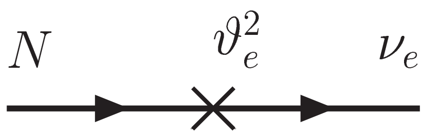
Third sterile neutrino with keV mass

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

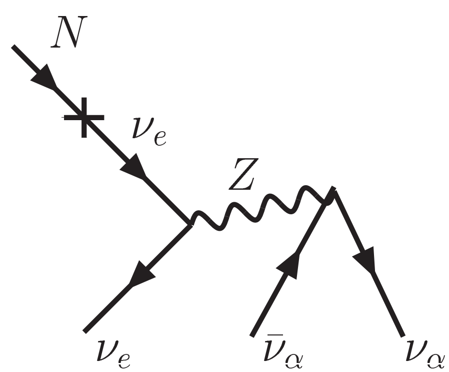
Additionally, Higgs boson plays the role of an inflaton

Bezrukov & Shaposhnikov (2007)

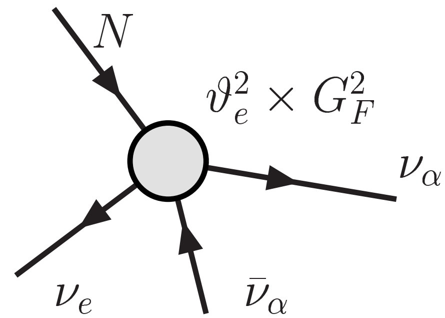
Properties of sterile neutrino



Quadratic mixing $N_s \leftrightarrow \nu$ of sterile neutrinos N_s to $\nu_{e,\mu\,\tau}$



$\longrightarrow$



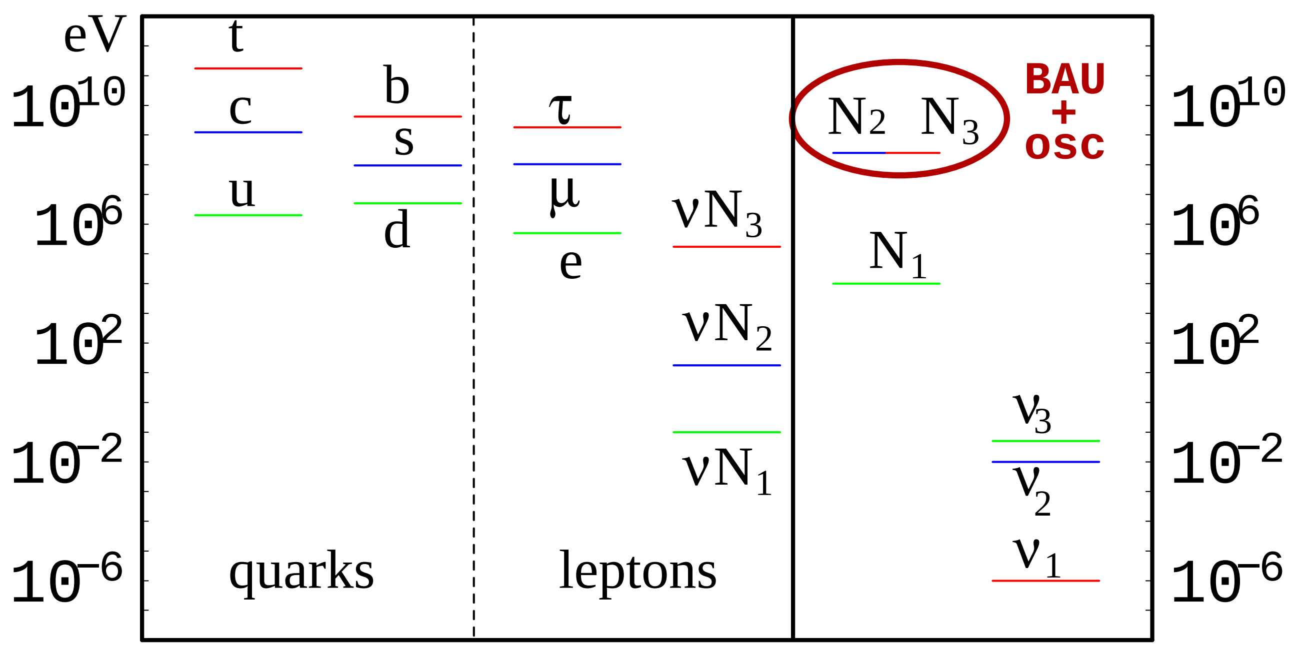
Fermi-like interaction with the "effective" Fermi constant $\vartheta_e \times G_F$

Sterile neutrinos behave as ***superweakly interacting* heavy neutrinos with a smaller Fermi constant**

$$G_F \longrightarrow \vartheta \times G_F$$

Mixing angles $\vartheta^2_{e,\mu,\tau} = \dfrac{|M_{\text{Dirac}}|^2}{M^2_{\text{Majorana}}}$

STERILE NEUTRINOS AND BARYON ASYMMETRY OF THE UNIVERSE



Baryogenesis in the νMSM

All three Sakharov conditions are satisfied if neutrinos are **super-weakly interacting and light**

Kuzmin, Rubakov, Shaposhnikov (1985)

B-number violation: sphalerons

Farrar & Shaposhnikov (1994)

CP (and C) non-conservation: **CP phases in the Yukawa matrix of sterile neutrinos** (phase of the CKM matrix)

Kajantie et al. (1996)

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

Asaka, Shaposhnikov (2005)

Leptogenesis in the νMSM

- About **50** baryogenesis scenarios are known . . .

  See the list in: Shaposhnikov, "Baryogenesis" JoP 171 (2009)

- . . . and yet the νMSM is **unlike any of them**

- It generates **large lepton asymmetry** below sphaleron freeze-out

  Baryon asymmetry is well-measured $\eta_B \sim 10^{-10}$. For **lepton** asymmetry we know a rough appear bound at the BBN epoch $\eta_L \lesssim$ few $\times\ 10^{-2}$

  Shaposhnikov (2008)

- Two observational consequences:

  Shi & Fuller (1998); Laine & Shaposhnikov (2008)

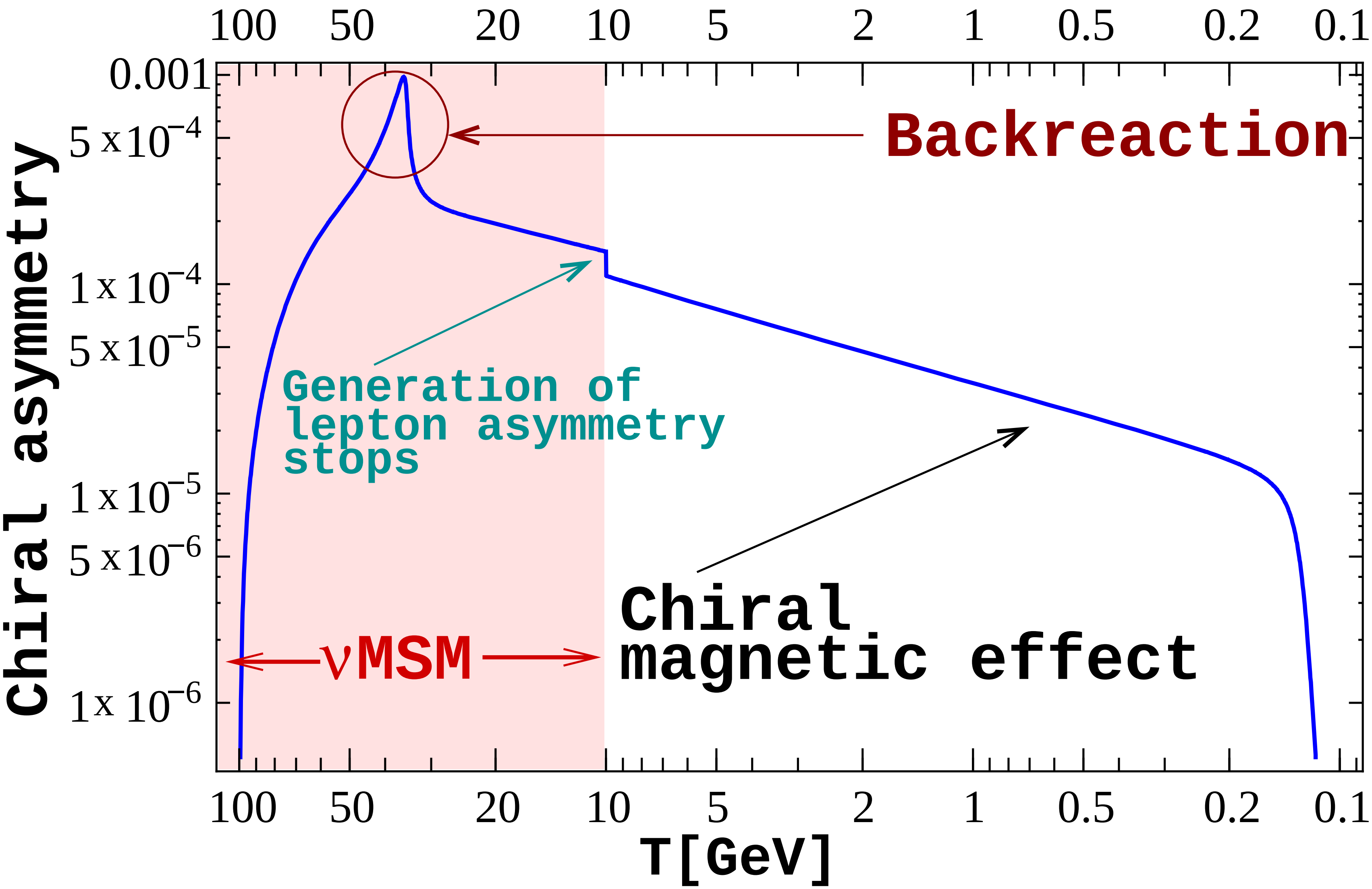
  – Affects properties of dark matter particles
  – Triggers instability in primordial plasma and generates cosmic magnetic field

    Boyarsky, Fröhlich, **O.R.** Phys. Rev. Lett. (2012)

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

    work in progress

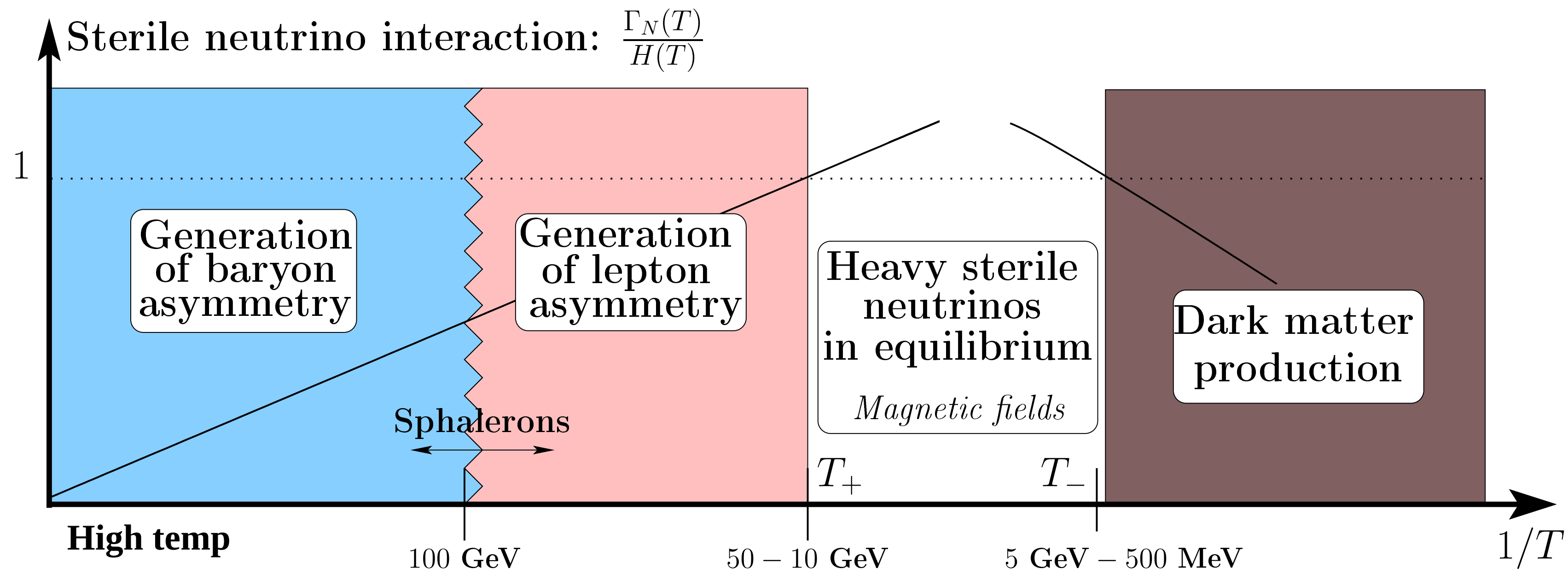
Evolution of chiral asymmetry in νMSM



O.R. with J. Fröhlich & A. Boyarsky Phys. Rev. Lett. (2012)

work in progress

History of the Universe in the νMSM



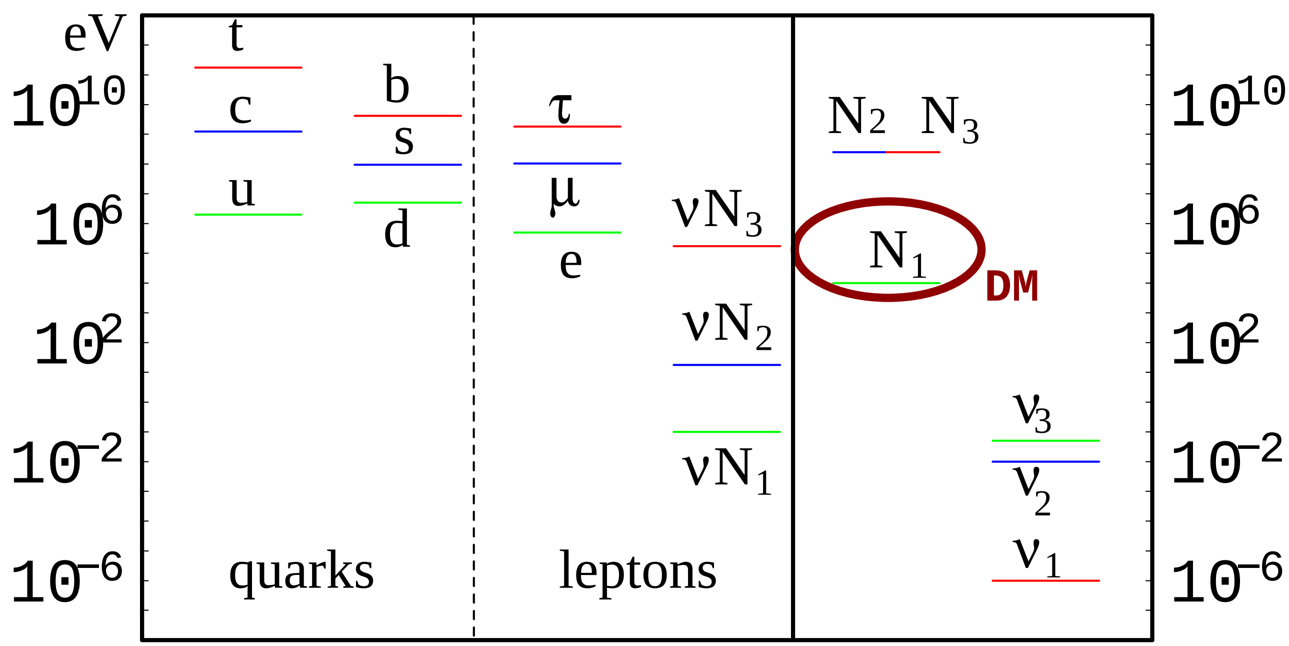
- Magnetic fields in the plasma **relate** baryogenesis and sterile neutrino dark matter production

work in progress

- Magnetic fields may be **observable** today in the intergalactic space

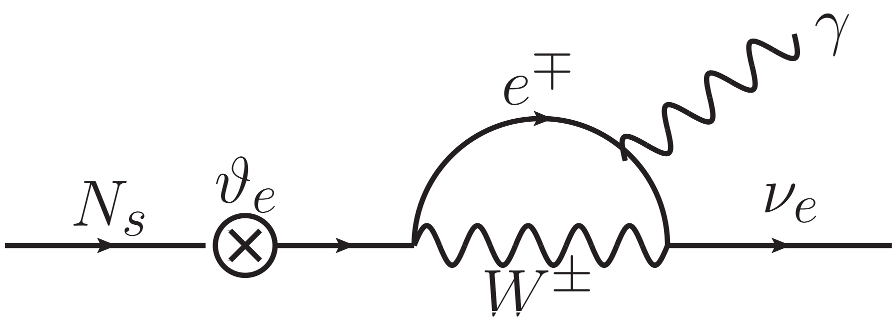
Neronov & Vovk Science, 2010

STERILE NEUTRINOS AND DARK MATTER IN THE UNIVERSE



Sterile neutrino: promising DM candidate

- Sterile neutrino DM should be heavier than ~ 0.3 keV (as any fermionic DM)
- Sterile neutrino is **produced through mixing** with the thermal bath of active neutrinos in the early Universe
- Sterile neutrino **decays**
- Decay rate grows as m_{DM}^5



- Two body decay produces a very characteristic signal: narrow line with $E_\gamma = \frac{1}{2} m_{\mathrm{DM}} c^2$
- Sterile neutrino DM is produced **relativistic** in the early Universe — **warm dark matter**. Erases primordial density fluctuations at scales below the **free steaming horizon**

Tremaine & Gunn (1979)

Dodelson & Widrow (1993)

Shi & Fuller (1998)

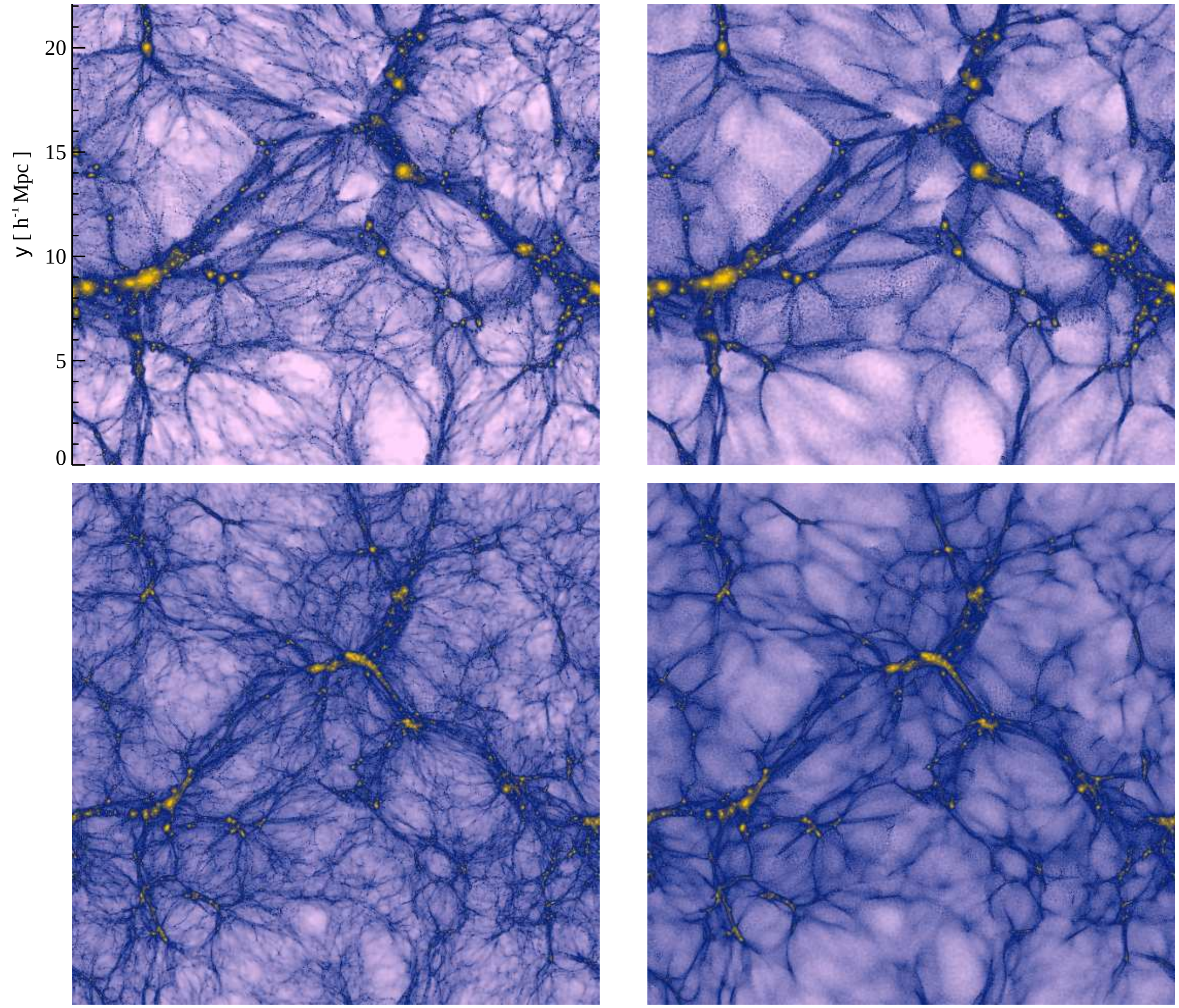
Abazajian et al. 2001-2005

Asaka, Laine, Shaposhnikov 2005–2008;

Boyarsky, **O.R** and many others 2005–present

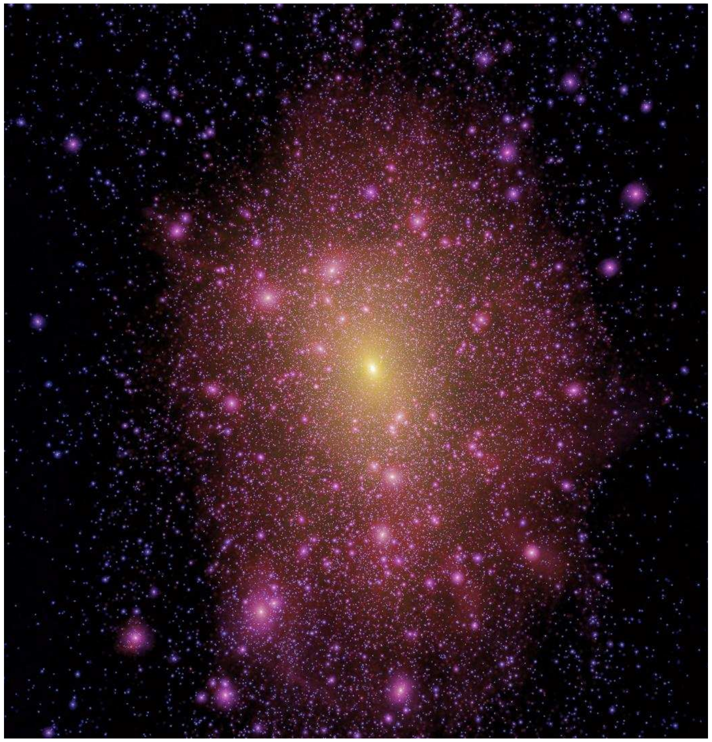
Sterile neutrino large scale structure

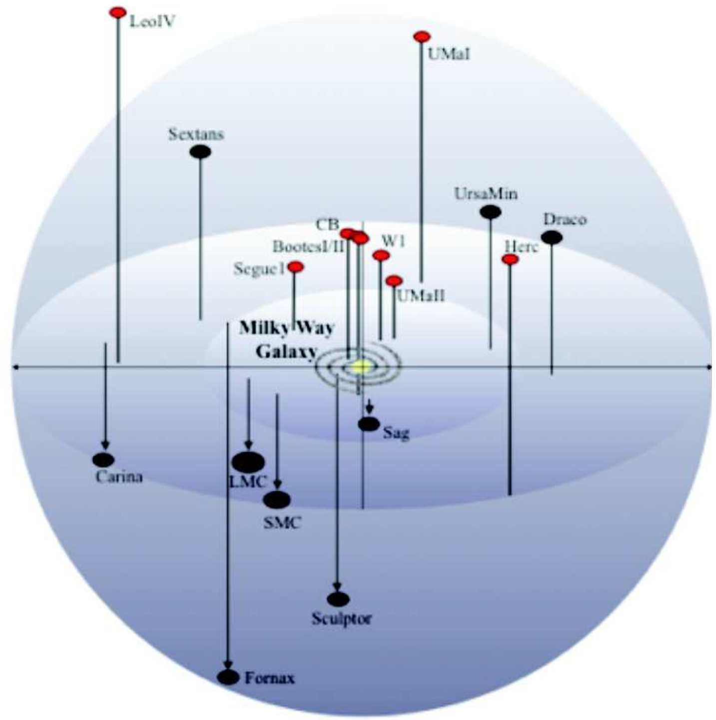
Viel et al. [1107.4094]



Probed by weak lensing and Lyman-α

Halo substructure in "cold" DM universe



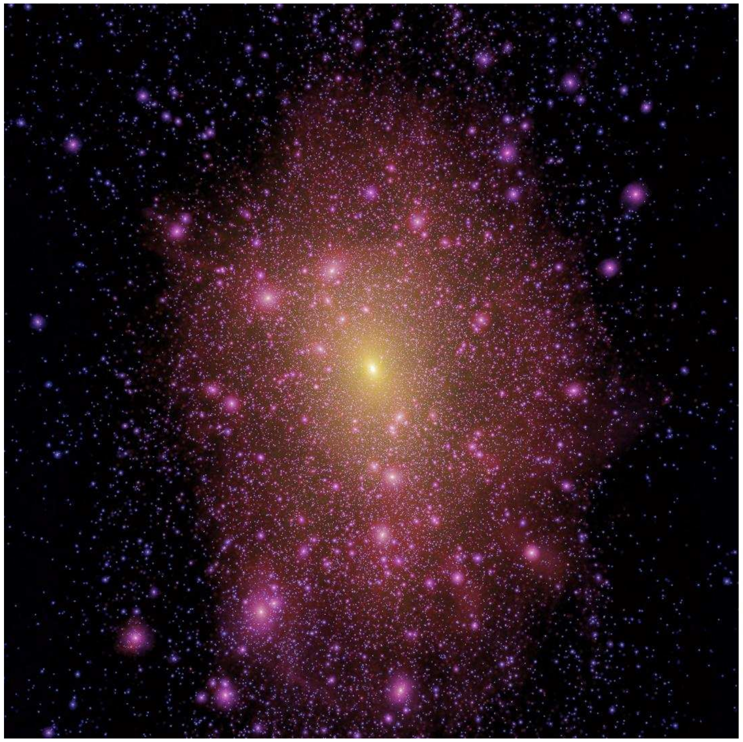


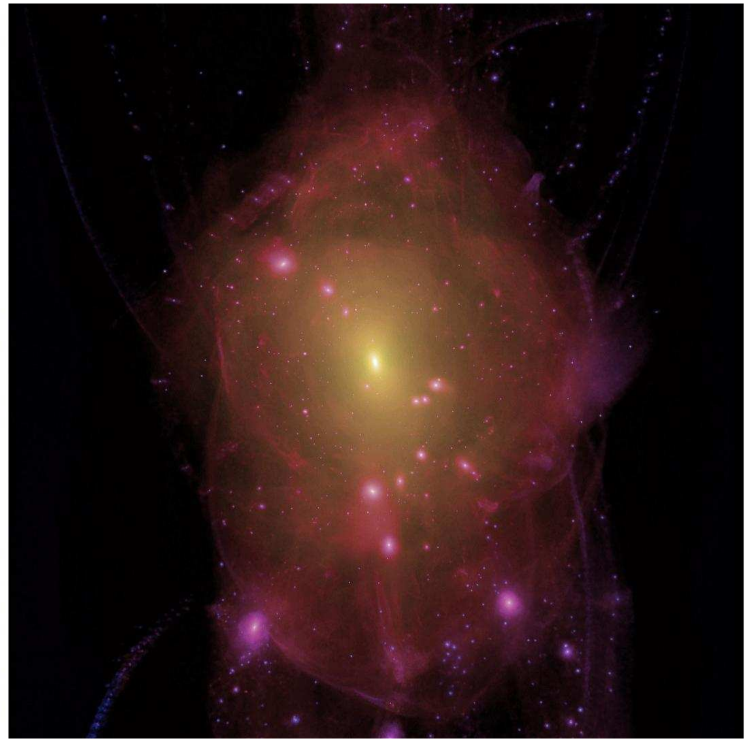
COLD DM models predict millions of substructures within a galaxy like Milky Way

Only $\sim$ 30 are observed within our Galaxy. M. Geha 2010

Is small number of observed substructures due to dark matter free-streaming? Moore et al. (1999), Klypin et al. (1999) and many others

Halo substructure in "cold" DM universe





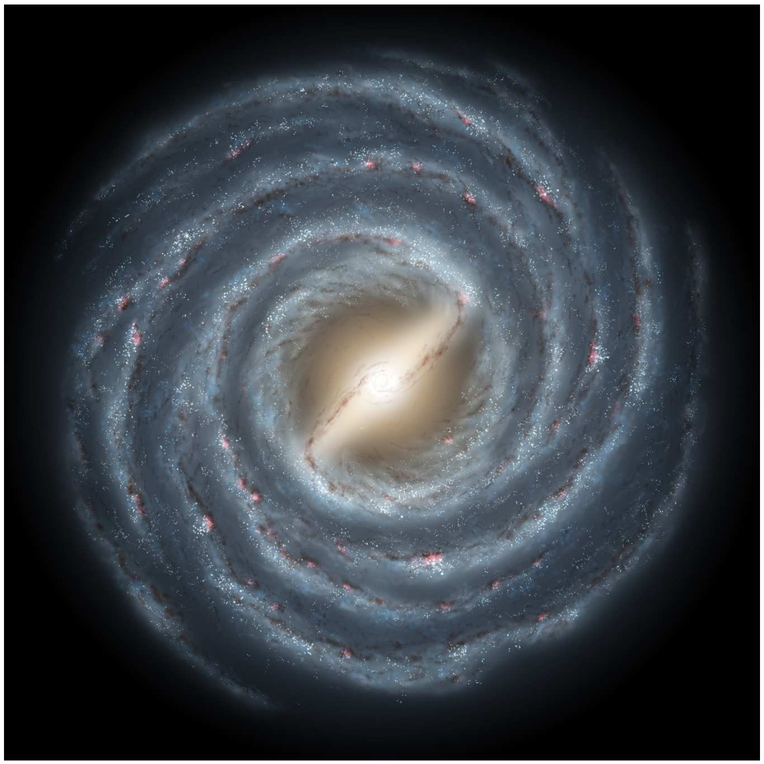
Aq-A-2 CDM halo

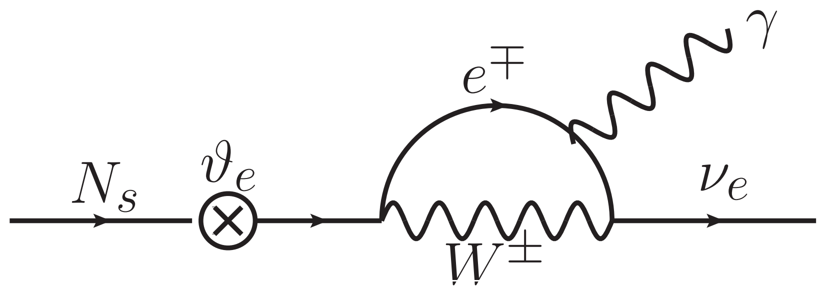
Aq-A-2 halo made of sterile neutrino DM (C. Frenk, T. Theuns, **O.R.**, . . .)

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

Search for DM decay

- Sterile neutrino DM is decaying with a cosmologically long life-time. 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})





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

Expected signal from the galaxy at a particular energy

Search for DM decay

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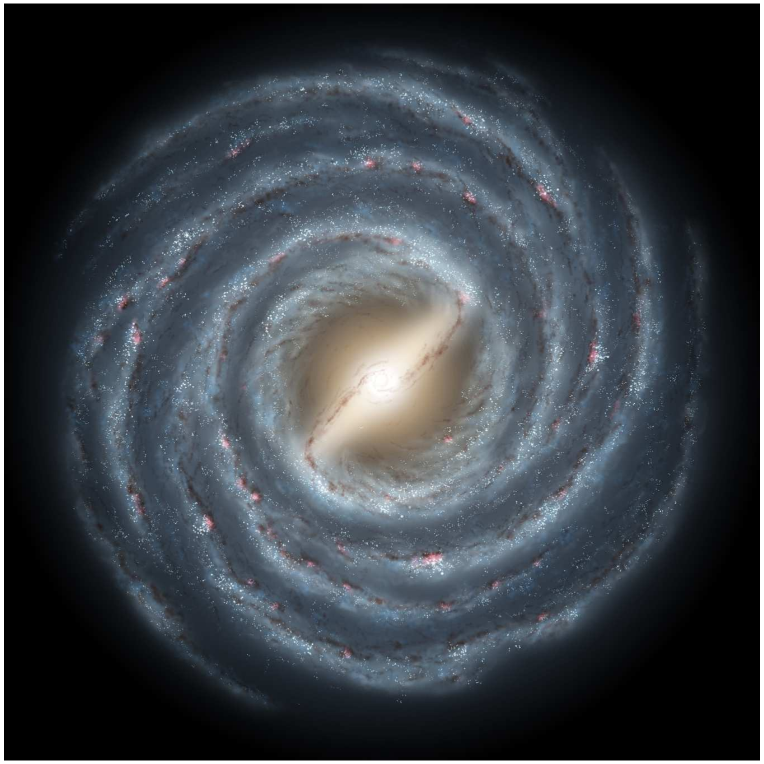
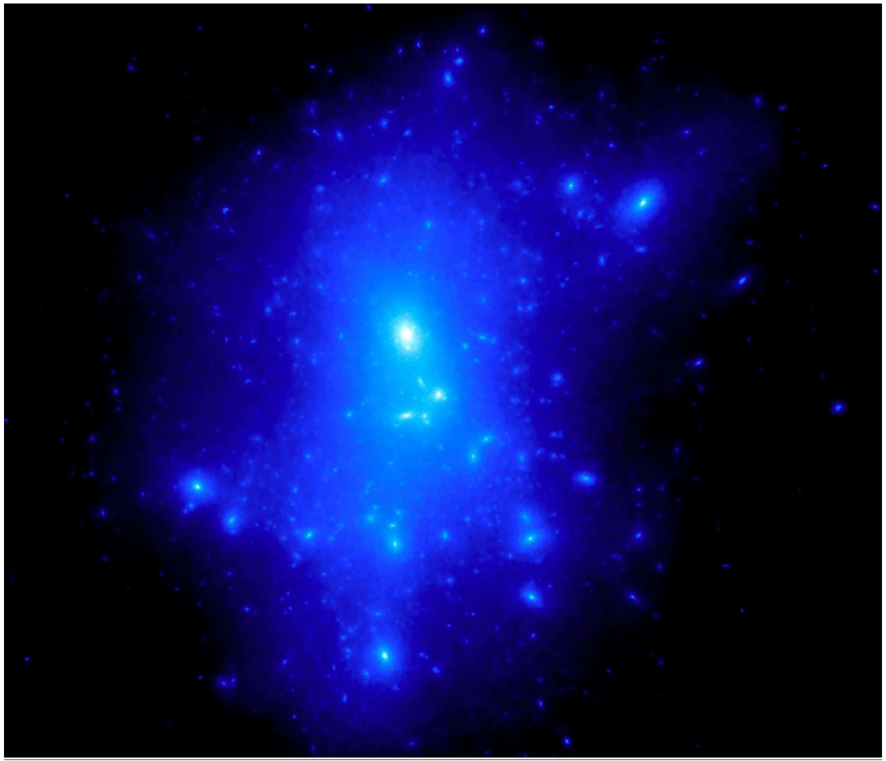
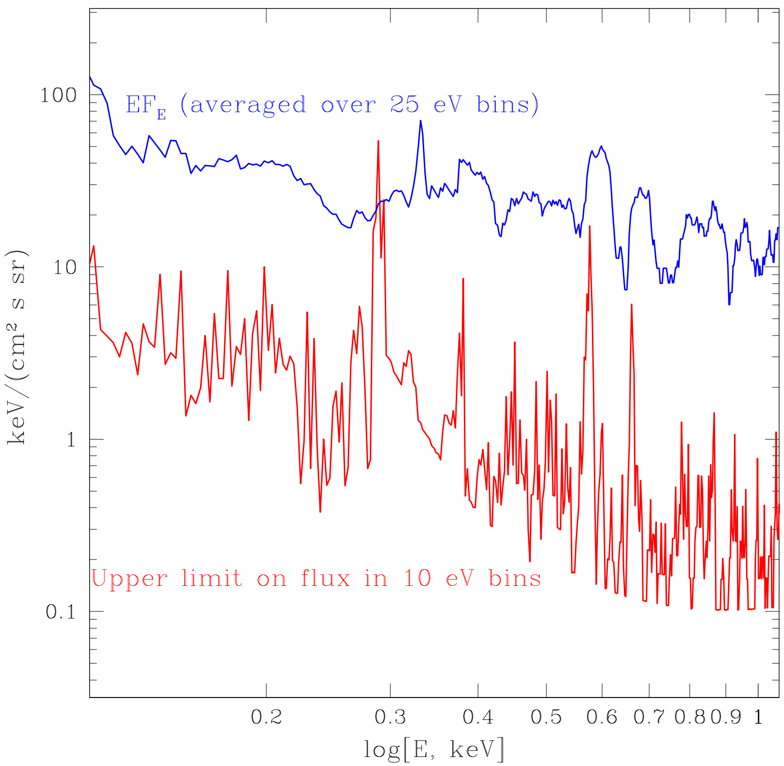




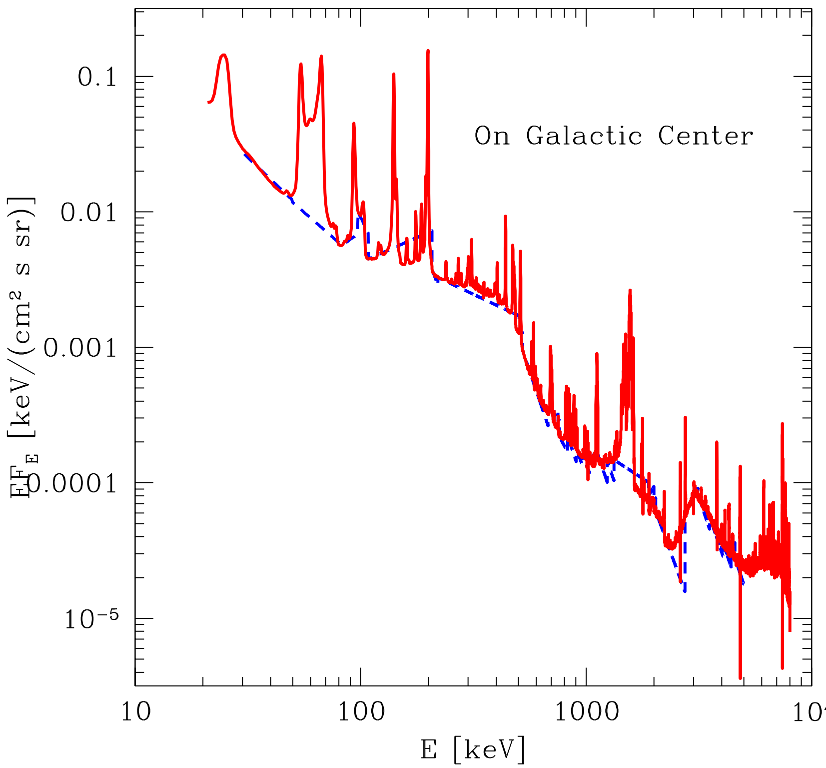
Expected signal from a galaxy at a particular energy (simulation from B. Moore)

Search for dark matter particles

Finding a decaying DM line is not an easy task – most DM-dominated objects have X-ray emission (**are massive enough to confine keV-temperature gas**)

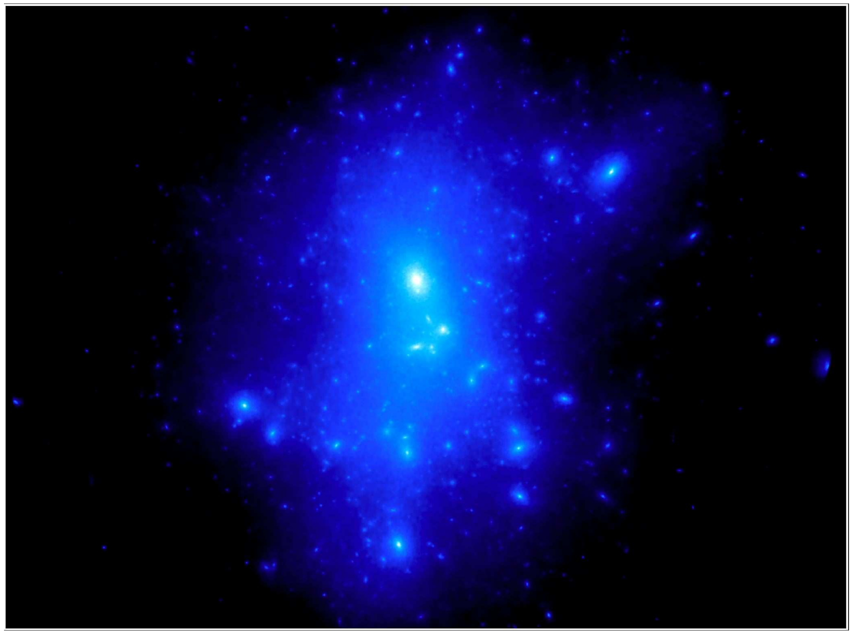


Milky Way in soft X-rays

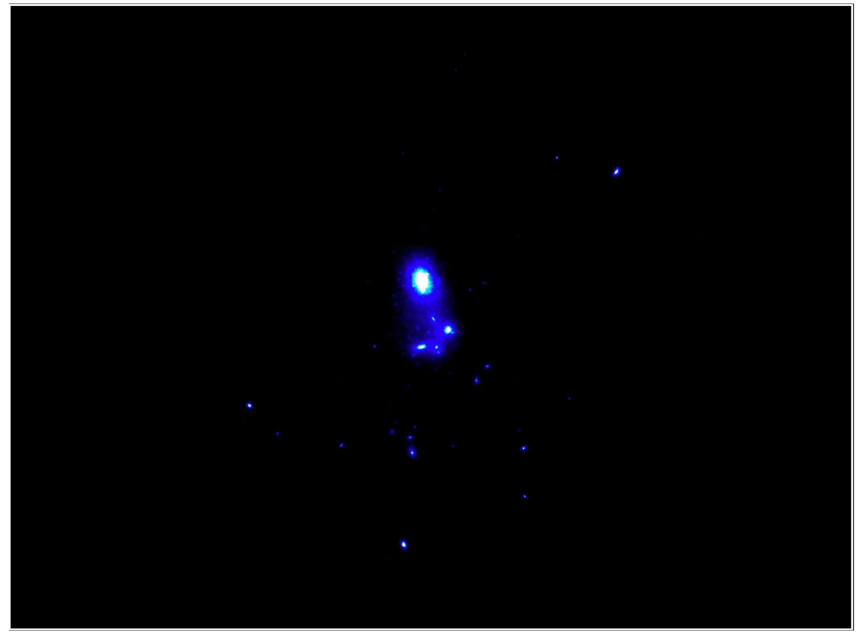


Milky Way in hard X-rays/γ-rays

Search for decaying dark matter



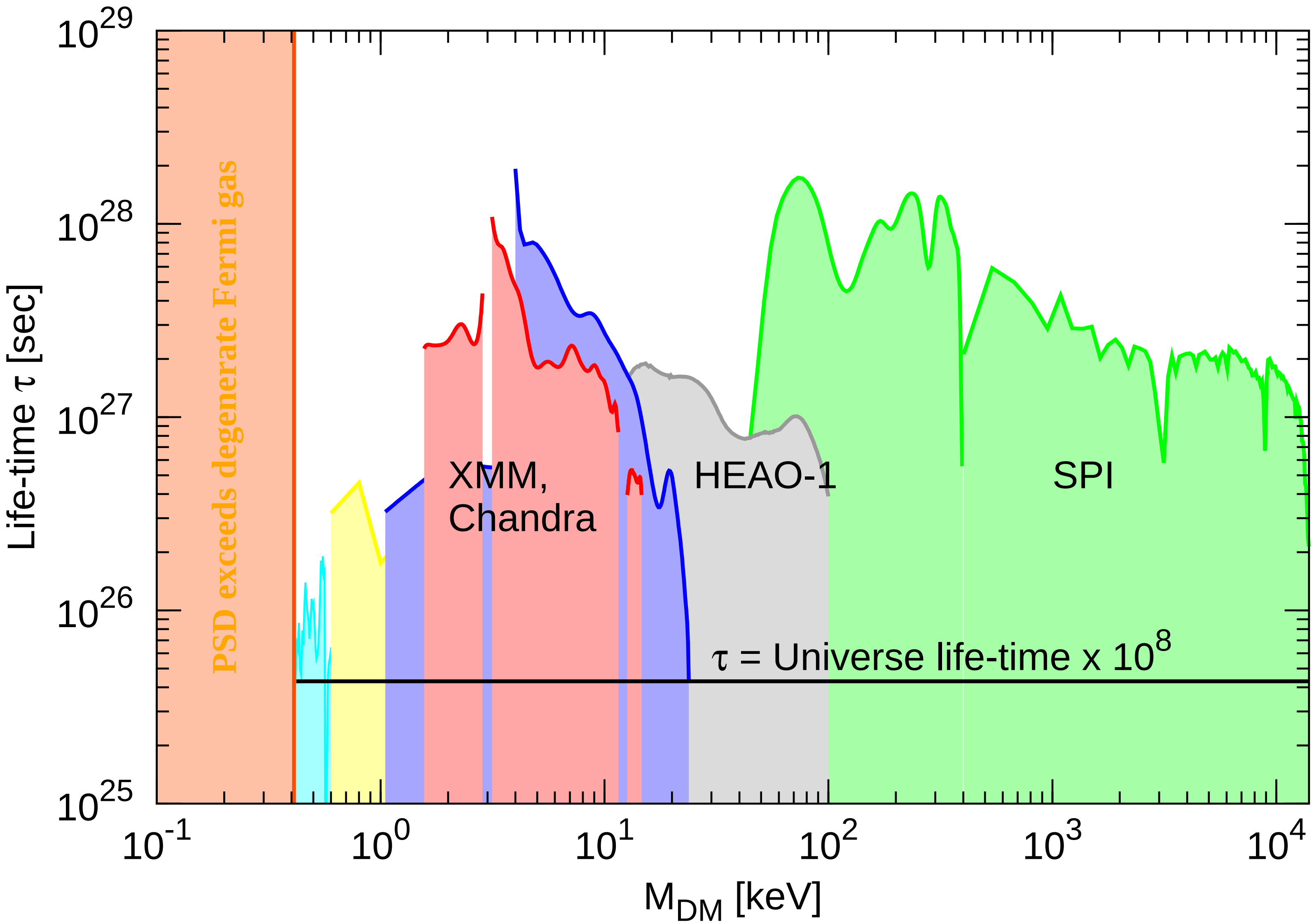
DM **decay** signal from a galaxy



DM **annihilation** signal from a galaxy

For decaying dark matter astrophysical search is (almost) "**direct detection**" as any candidate line can be unambiguously checked (confirmed or ruled out) as DM decay line

Restrictions on life-time of decaying DM



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

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

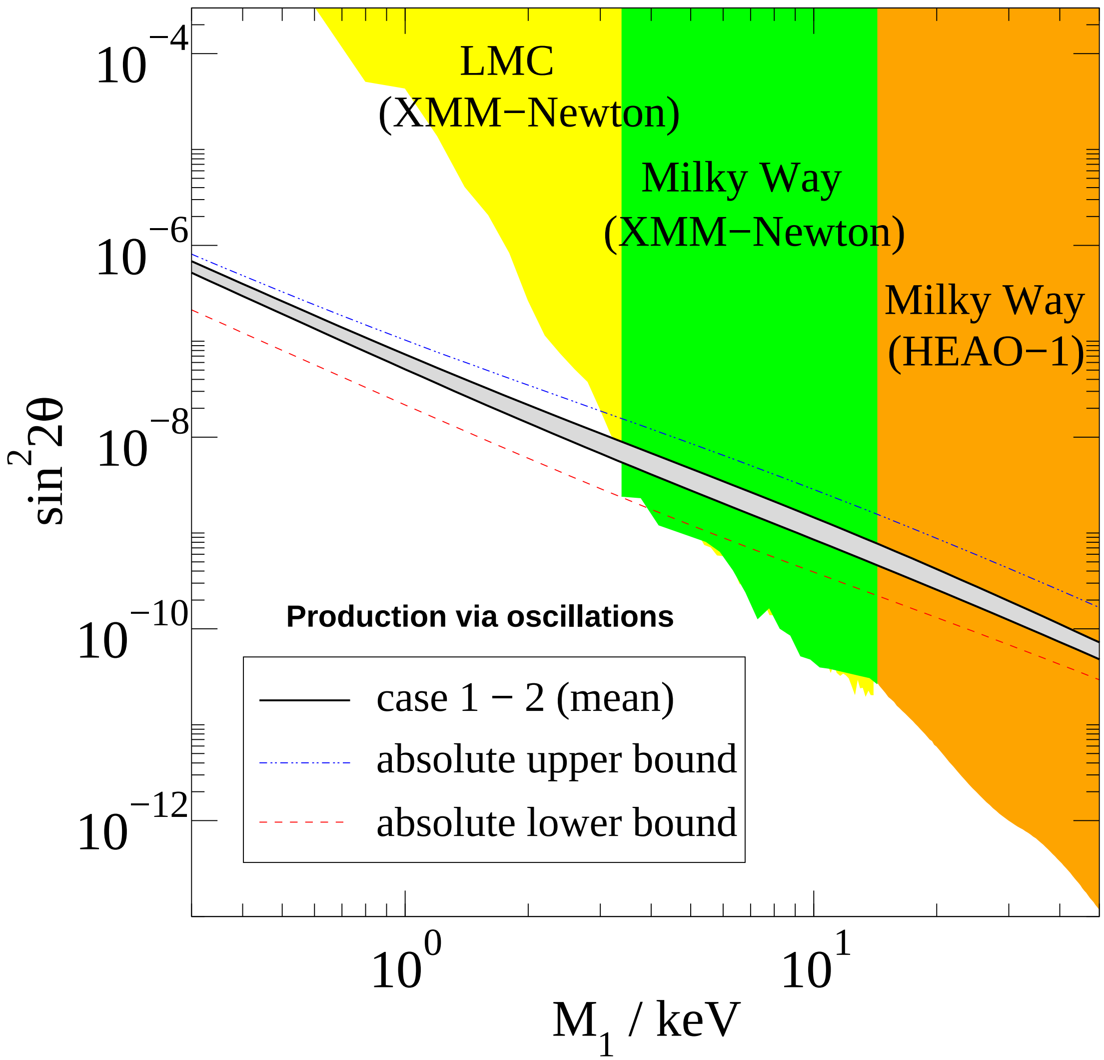
Bullet cluster Boyarsky, **O.R** et al. 2006

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



Production: Asaka, Laine, Shaposhnikov (2006)

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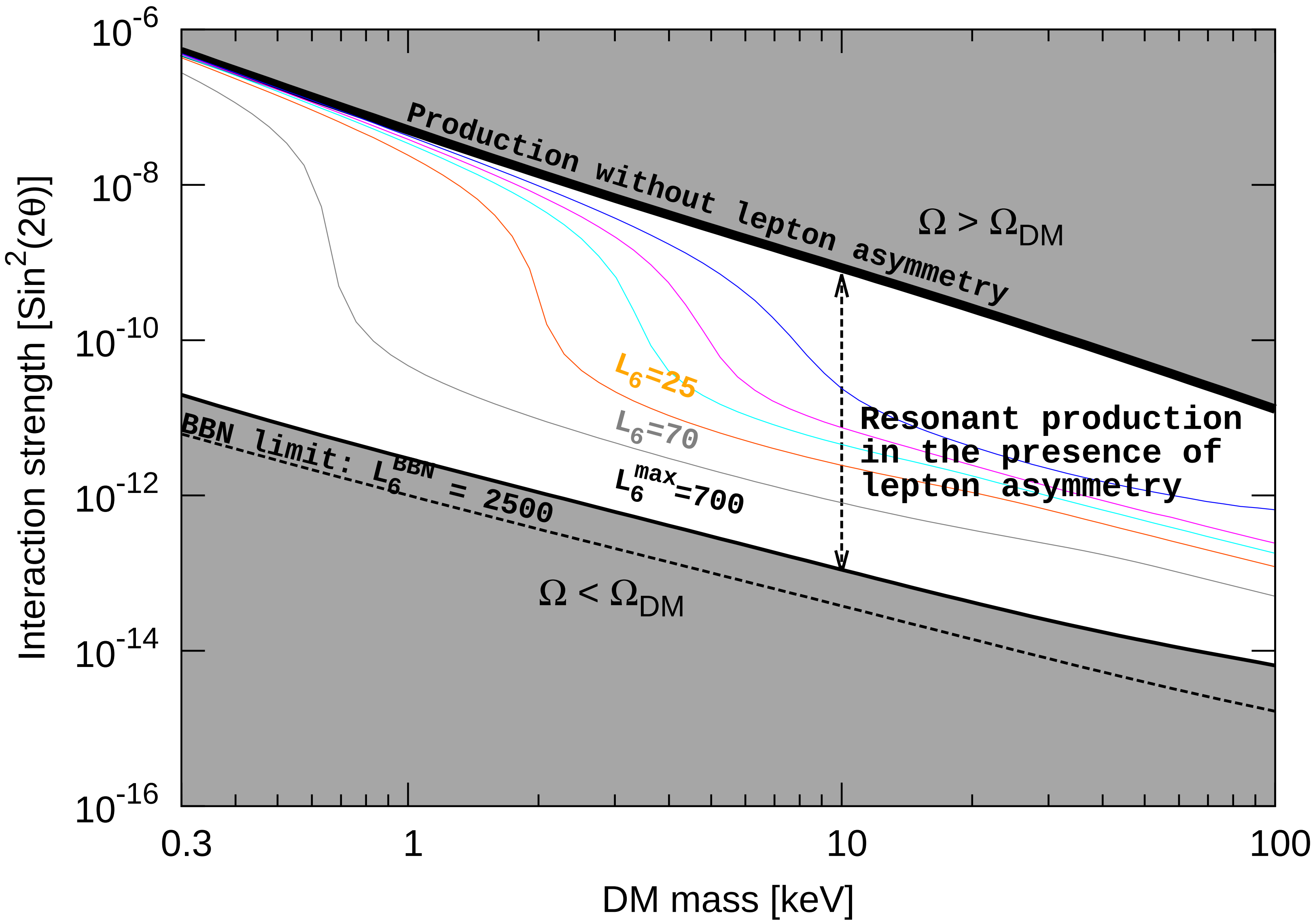
M31 Watson et al. 2006; Boyarsky et al. 2007

Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov (2006)

Laine, Shaposhnikov (2008)



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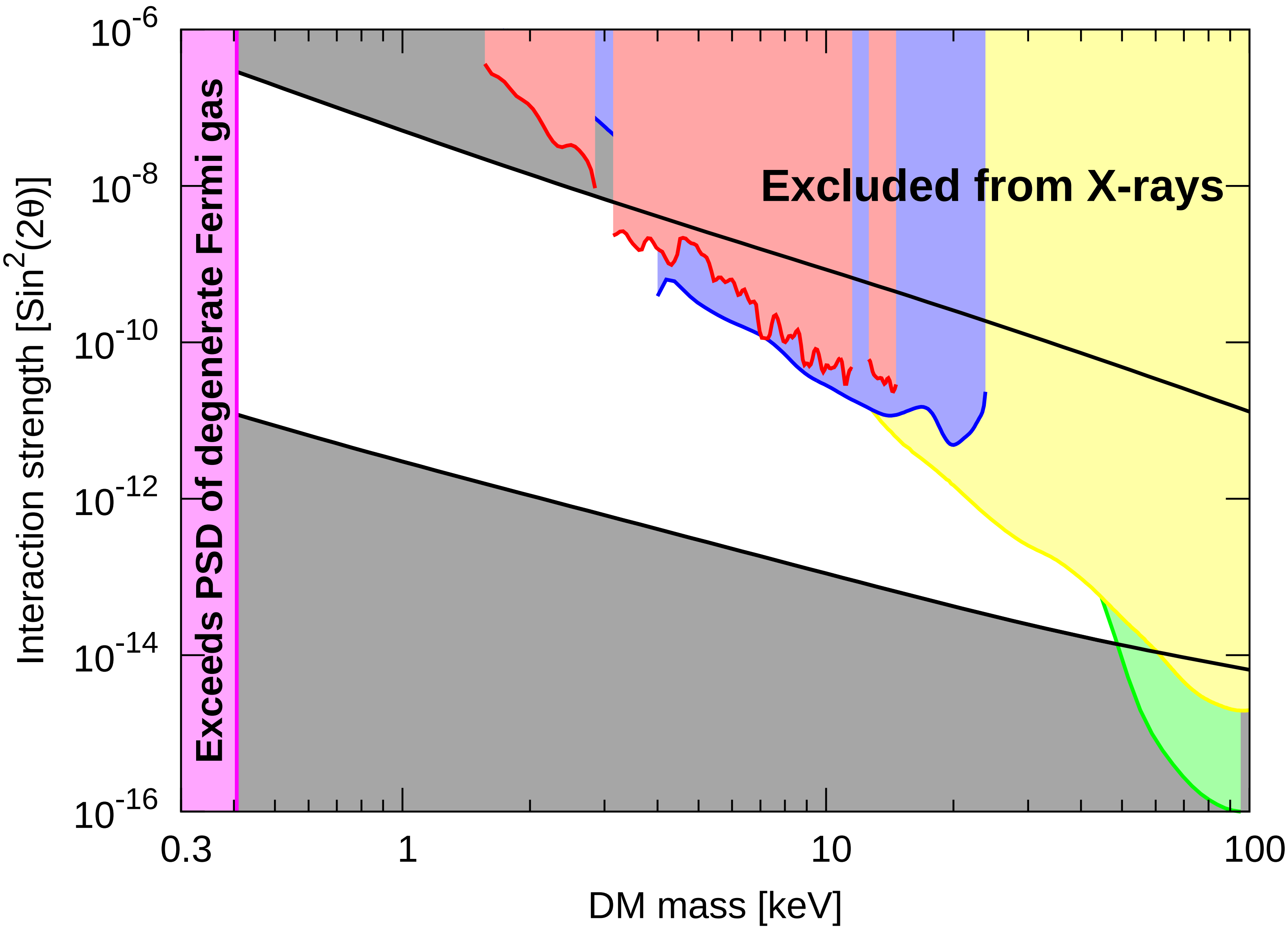
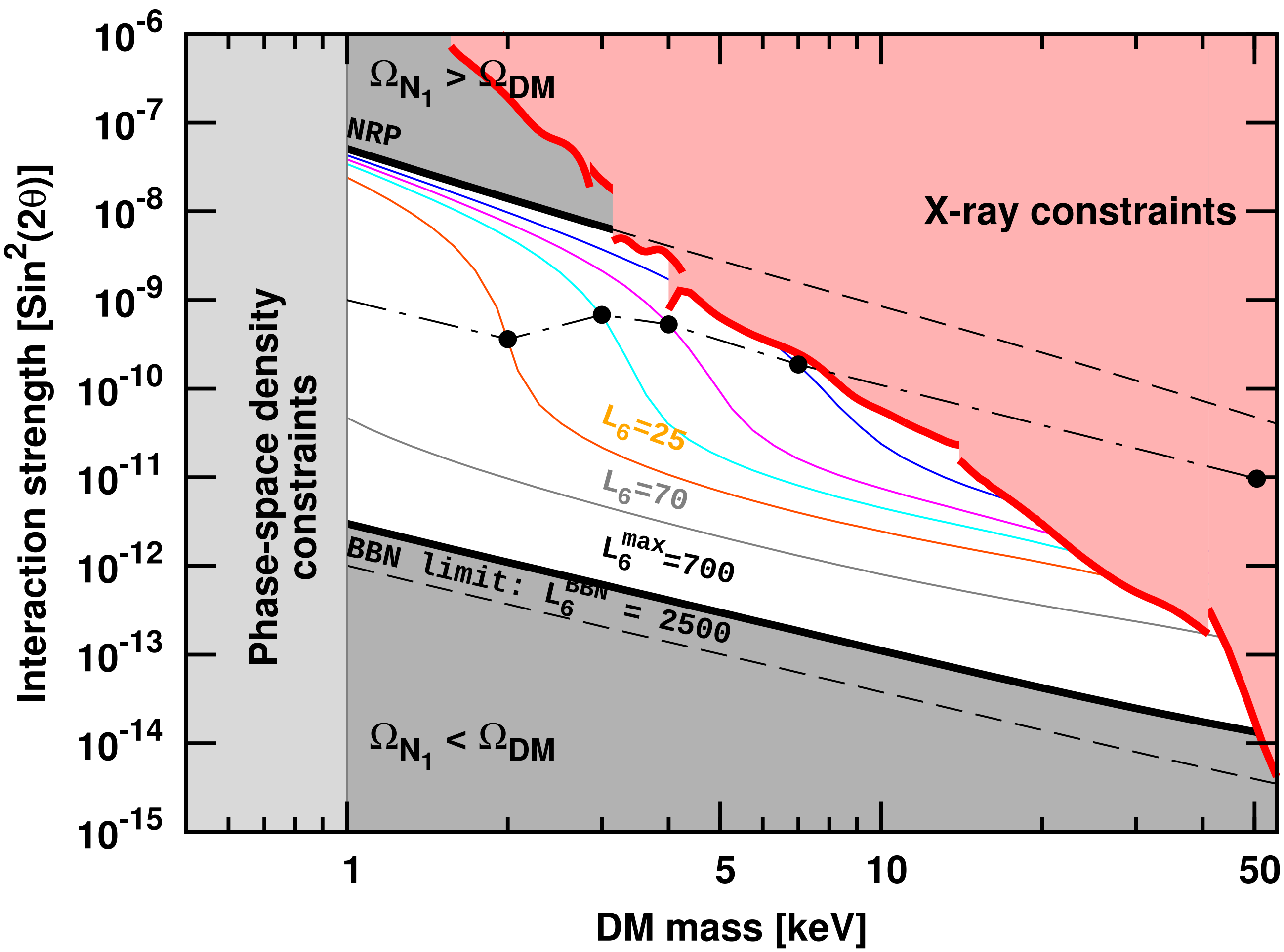


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

Sterile neutrino DM in the νMSM



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

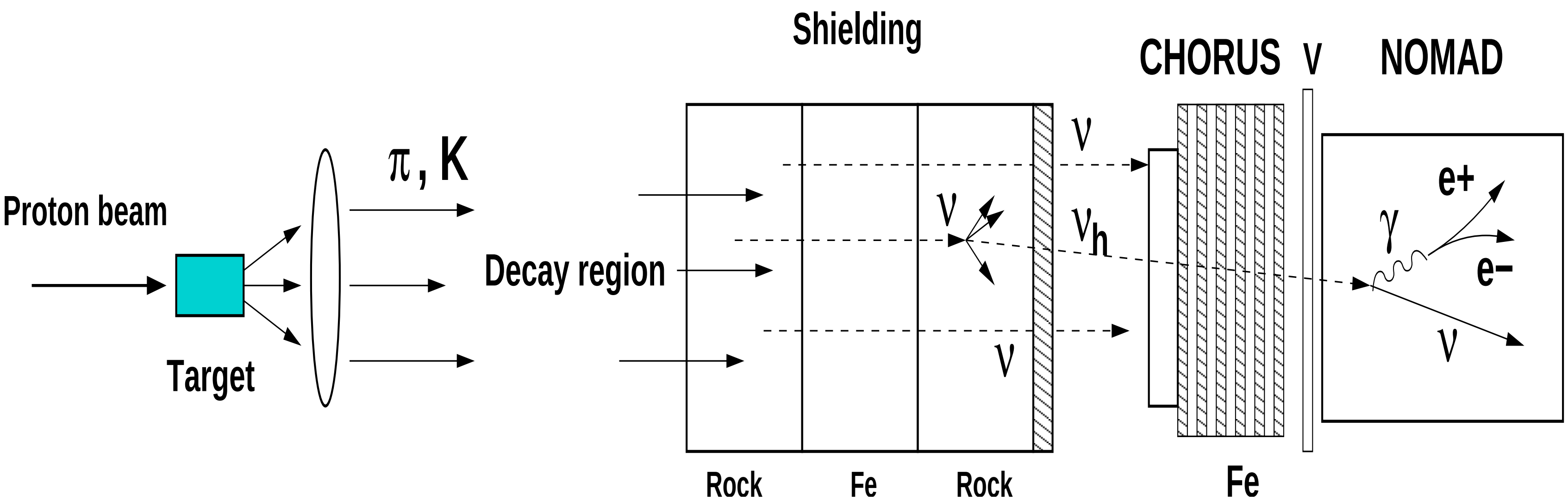
Review: [0901.0011]

- Parameter space of sterile neutrino DM is bounded on all sides
- Models as light as 2 keV are consistent with all existing astrophysical and cosmological observations

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	...
$N_I \to \nu\nu\bar{\nu}$	$N_I \to \nu e^+ e^-$	$N_I \to \pi^\pm e^\mp$	
$N_I \to \nu\gamma$		$N_I \to \pi^0 \nu$	



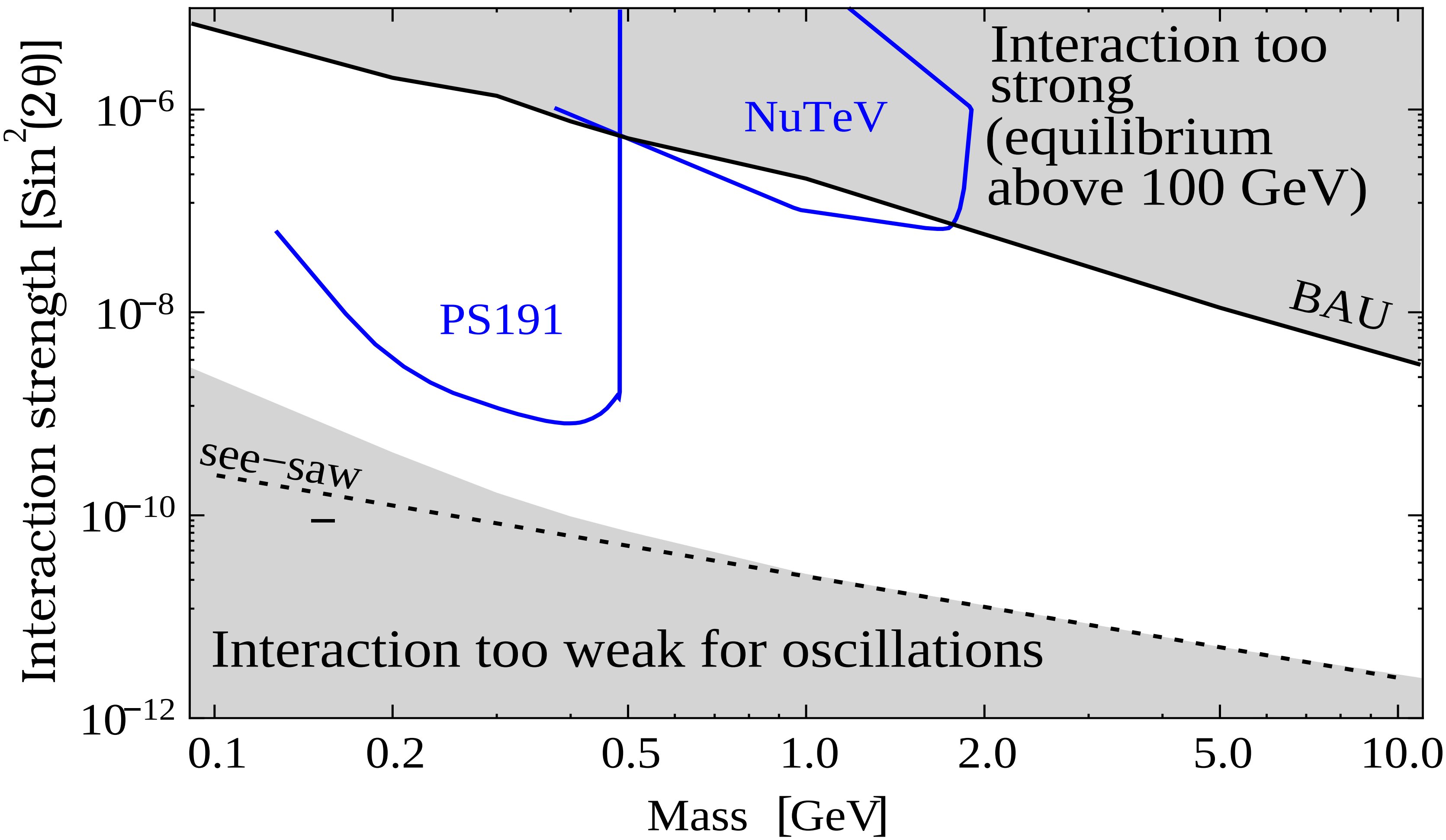
Peak searches:

- 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

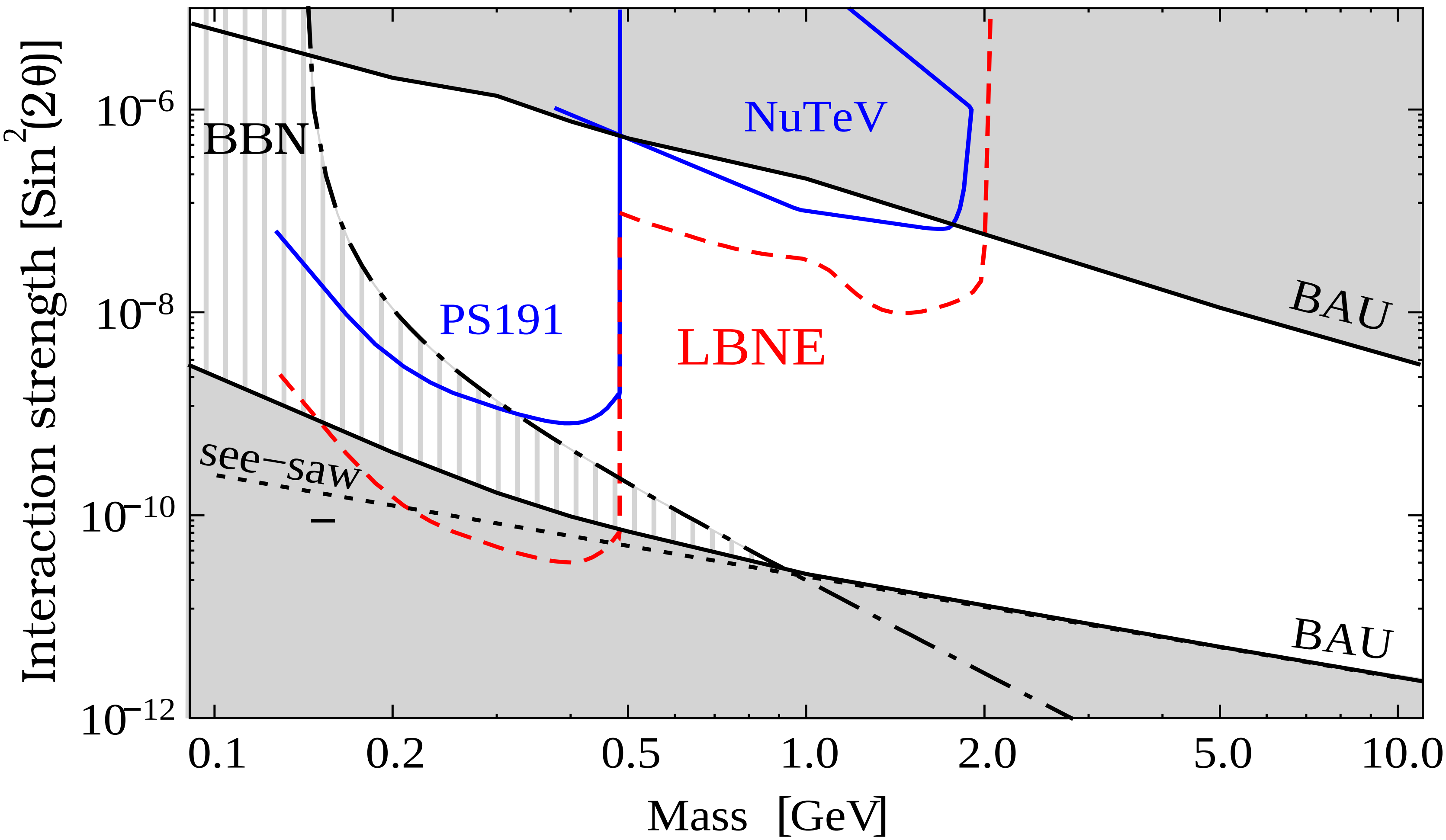
Parameter space of sterile neutrinos



Asaka, Canetti, Gorbunov, Shaposhnikov 2005–2011;

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

Parameter space of sterile neutrinos



Gorbunov, Shaposhnikov (2009);

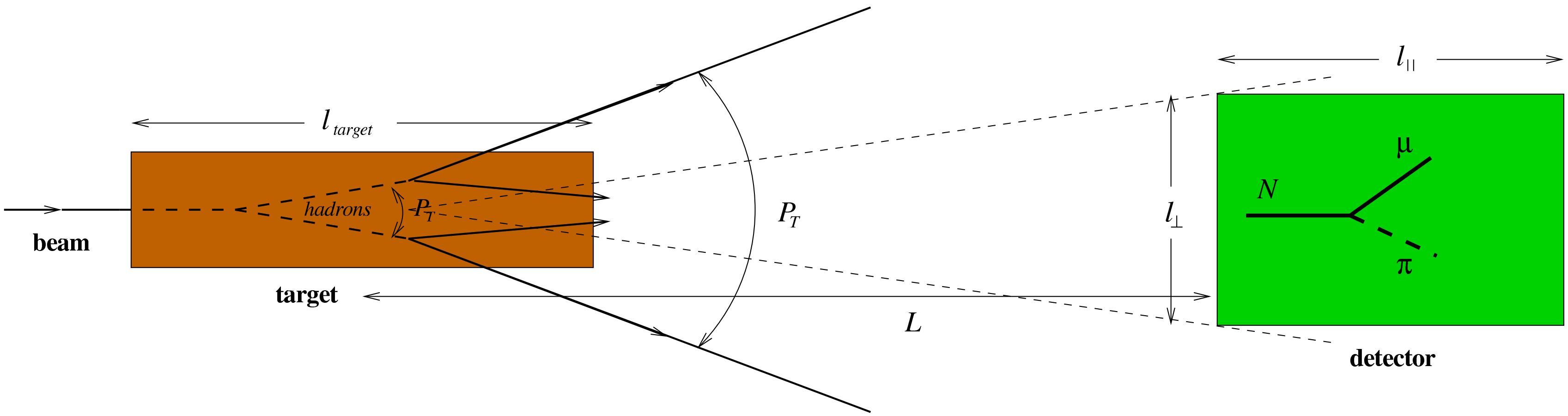
O.R & Ivashko [1112.3319] – revised accelerator bounds

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

LBNE white paper [1110.6249]

White paper on sterile neutrinos [1204.5379]

Ultimate detector



– Neutrino oscillations define a bottom-line for searches

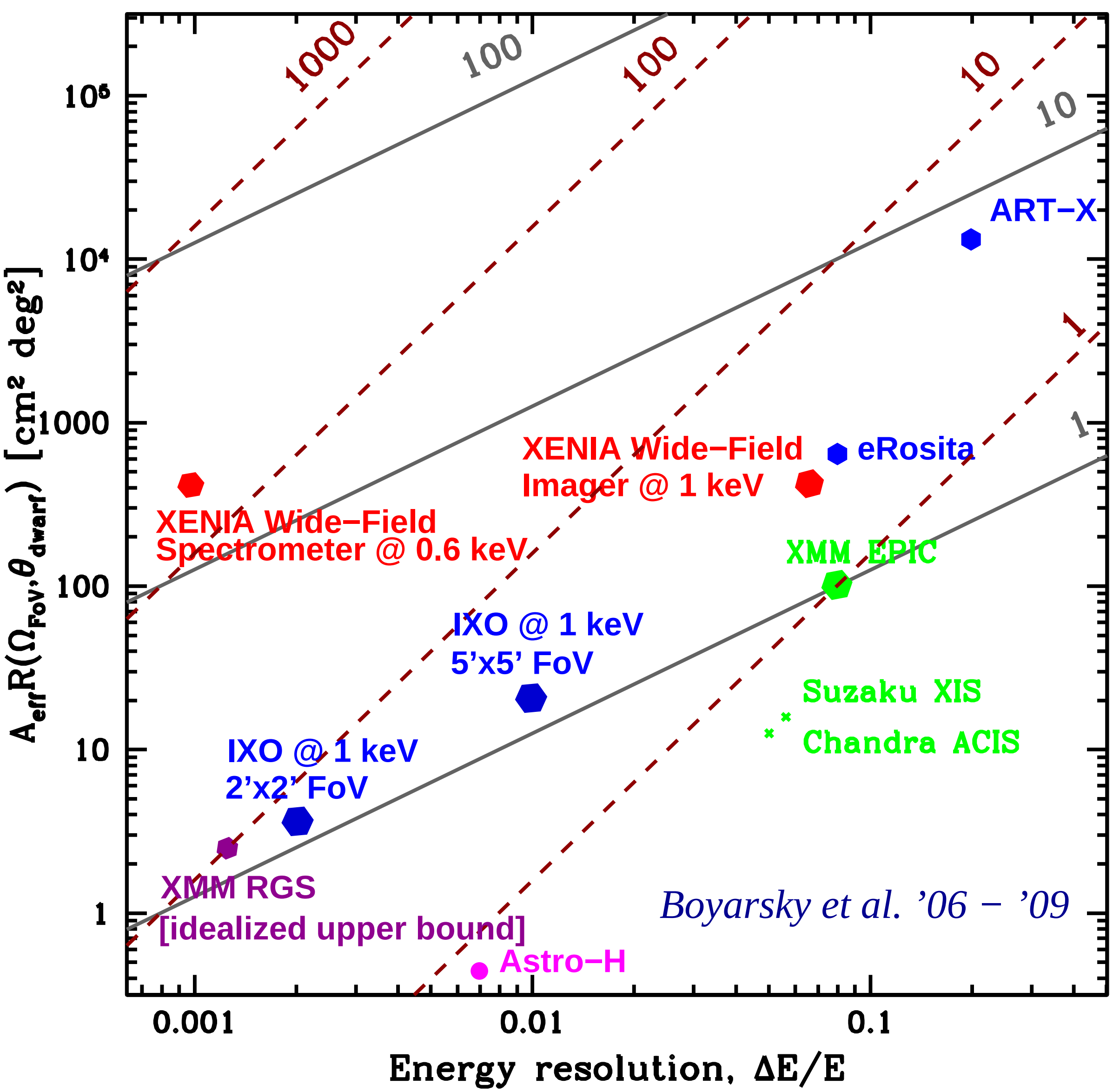
– Cosmologically interesting region (BAU) was not probed in the previous experiments

– Admixture at the level 10^{-6}–10^{-10} of sterile neutrinos in the neutrino beams

– To probe the mass range below ~ 1 GeV with 400 GeV beam and 10^{20} incident protons on target (SPS at CERN) one needs a detector constructed from sections similar to previous experiments (PS191, CHARM) but with a total length of a few kilometers.

See proposal to European Strategy Preparatory Group

Ultimate sterile neutrino DM detector



Conclusion

Neutrino Minimal Standard Model (ν**MSM**) provides resolution of all major observational BSM problems and gives a **complete history of the Universe** from inflationary era till today **without introducing new particles above the electroweak scale**

	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

Tested at **intensity** and **cosmic** frontiers

"Nightmare scenario"

Neutrino Minimal Standard model predicts:

- Standard Model Higgs with the mass above ~ 125 GeV at LHC and no new physics otherwise
- Primordial spectral index $n_s = 0.96\dots$ correlated with the Higgs mass
- Non-detection of tensor modes
- Sum of neutrino masses $\sum m_\nu \approx (1-2)m_{\text{atm}}$
- In the $0\nu\beta\beta$ mass $m_{\beta\beta}$ at the level $1-10$ meV

Bright future ~~"nightmare scenario"~~

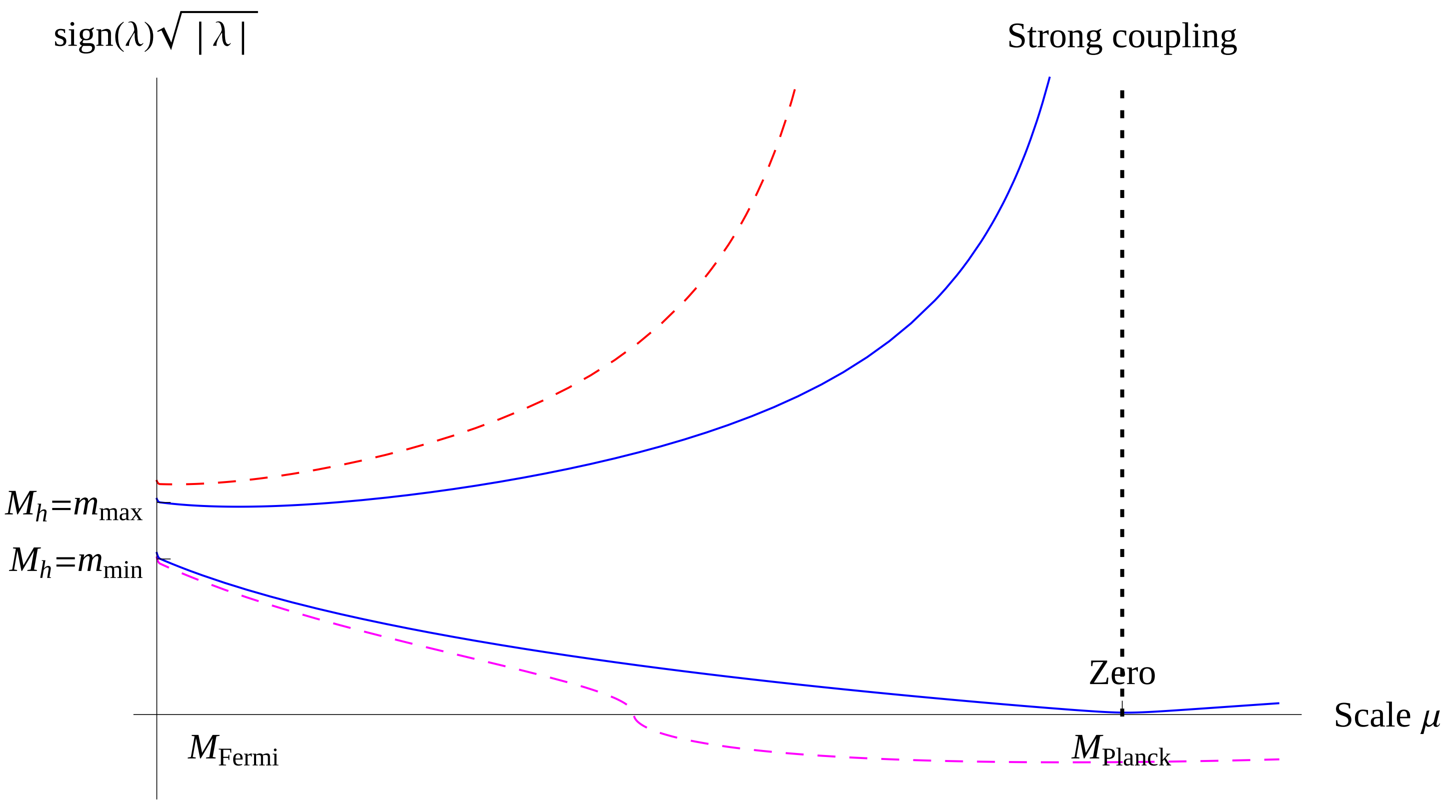
Neutrino Minimal Standard model also predicts:

- Two sterile neutrinos with the masses $\mathcal{O}(100)$ MeV $\div$ few GeV and mass splitting $\sim\ m_{\text{atm}}$ **discoverable** in “intensity frontier” experiments (**NA62 in CERN, LBNE, SLHCb** or **dedicated experiment** *a la* CHARM or PS191)
- Decaying dark matter 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**).
- Warm (actually COLD+WARM) dark matter affecting the matter power spectrum at $k \sim 1 - 10$ 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*

THANK YOU FOR YOUR ATTENTION

Additional slides

Can SM be valid till Planck scale?



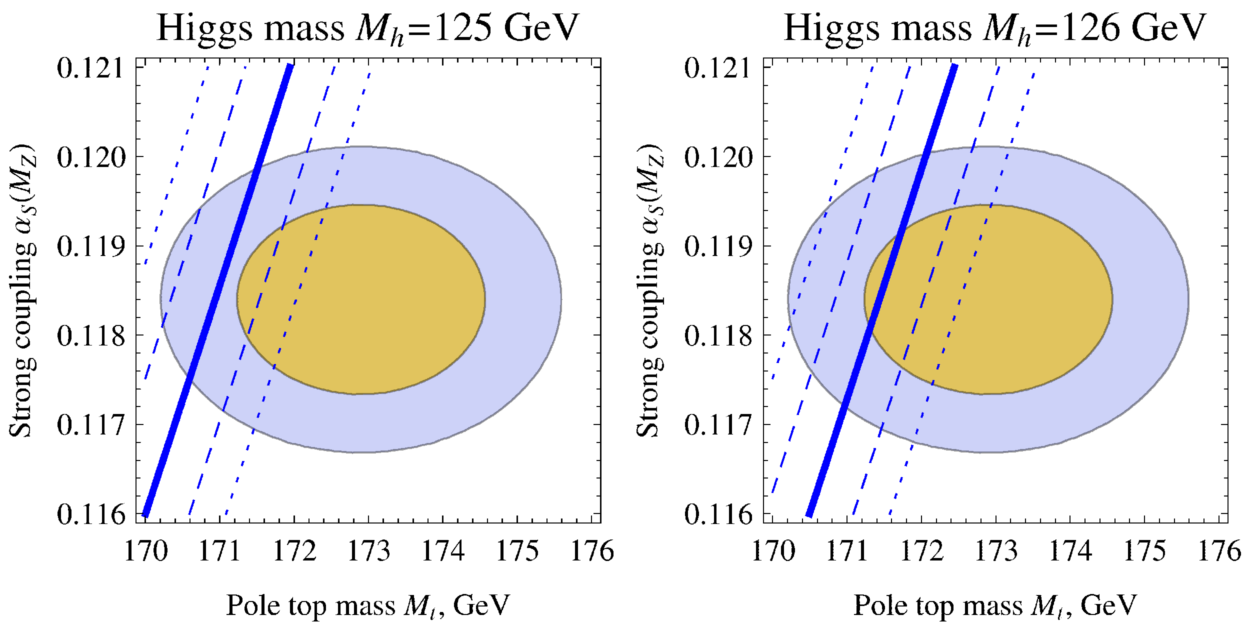
– **Yes!** if the Higgs boson is above 129 ± 6 GeV (uncertainty comes from existing experimental uncertainties in the mass of the top quark and α_s)

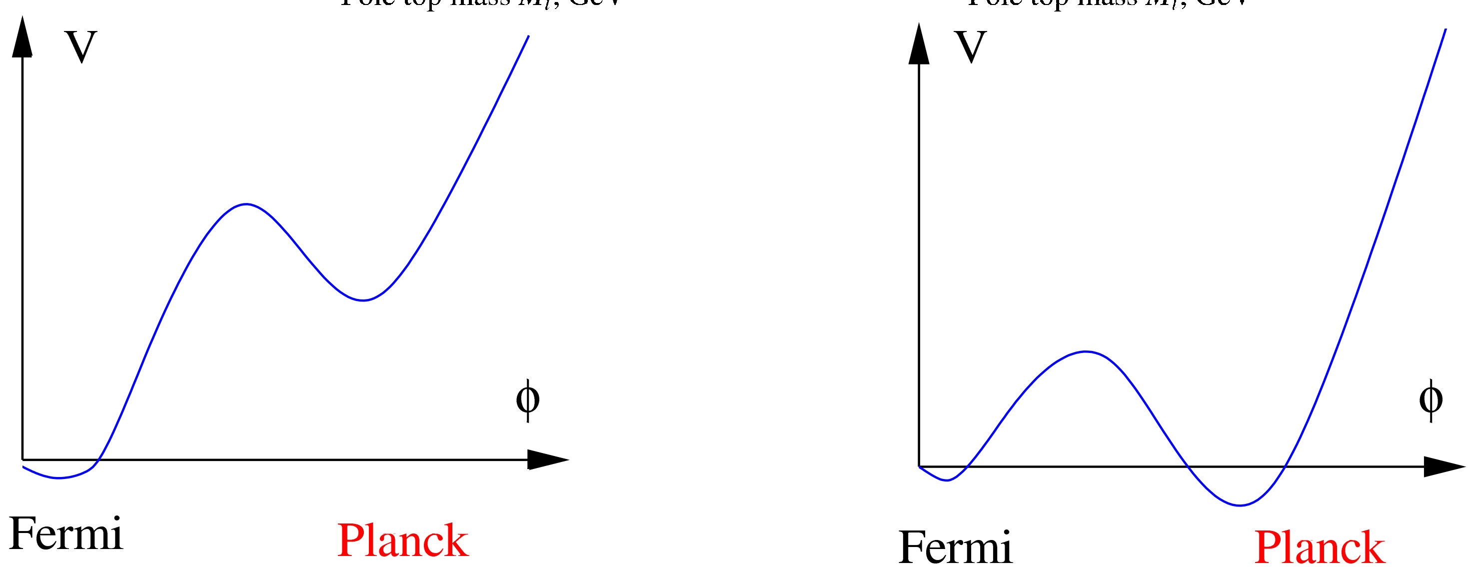
Bezrukov et al. "*Higgs boson mass and new physics*" [1205.2893]

– Difference in conclusion with **Degrassi et al. [1205.6497]** comes from different treatment of experimental uncertainties on top mass

Can SM be valid till Planck scale?

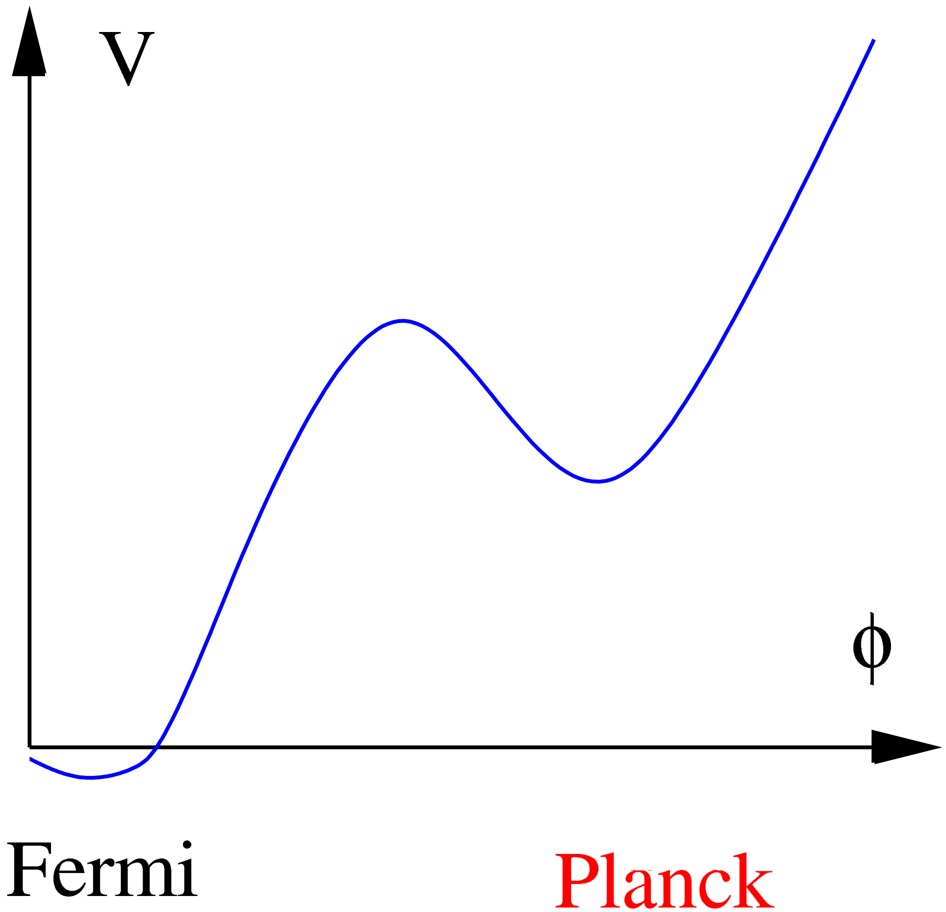
[1205.2893]

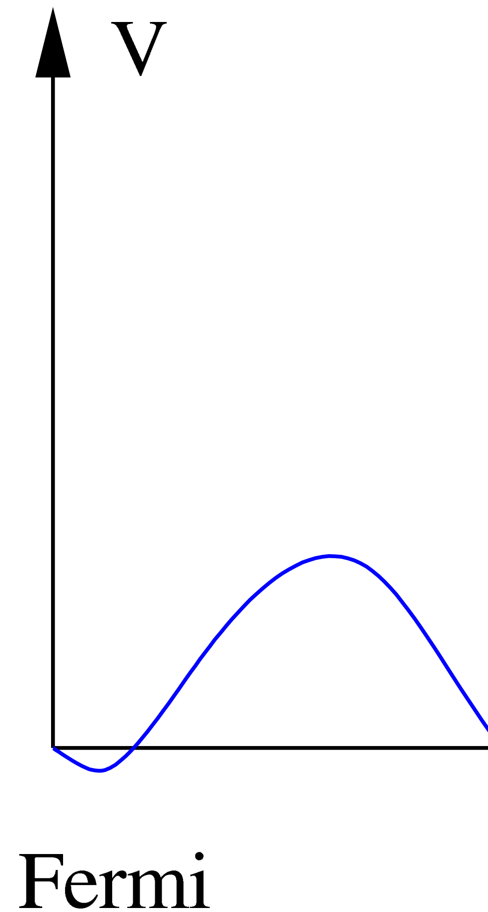




SM valid up to Planck scale and inflation

[1205.2893]

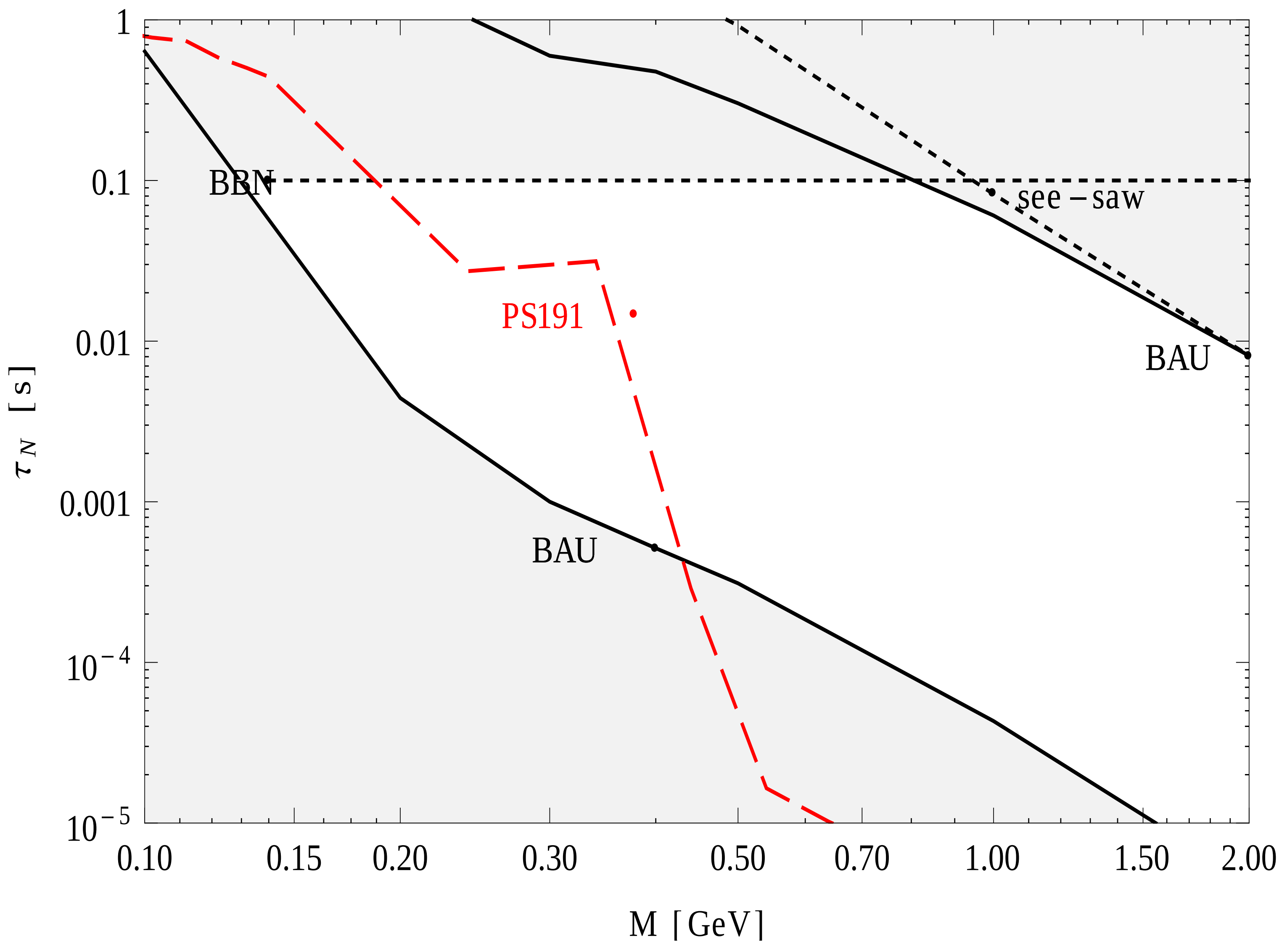




Non-minimal Higgs coupling to gravity ($\xi H^\dagger H R$) gives a slow-roll potential if SM is valid up to the Planck scale.

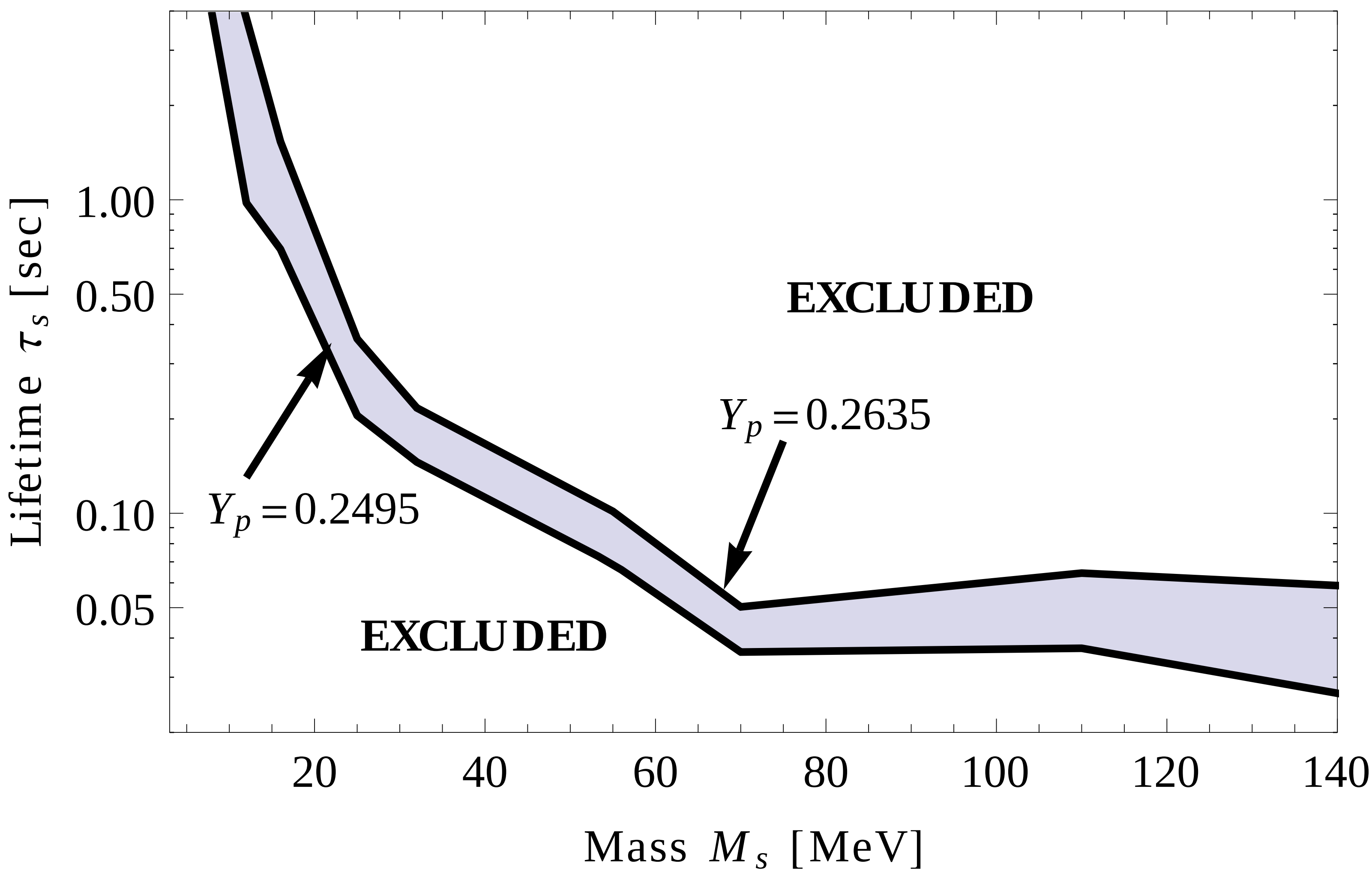
BBN EPOCH

Lifetime of sterile neutrinos



Canetti & Shaposhnikov (2011)

Sterile neutrinos and ^{4}He abundance

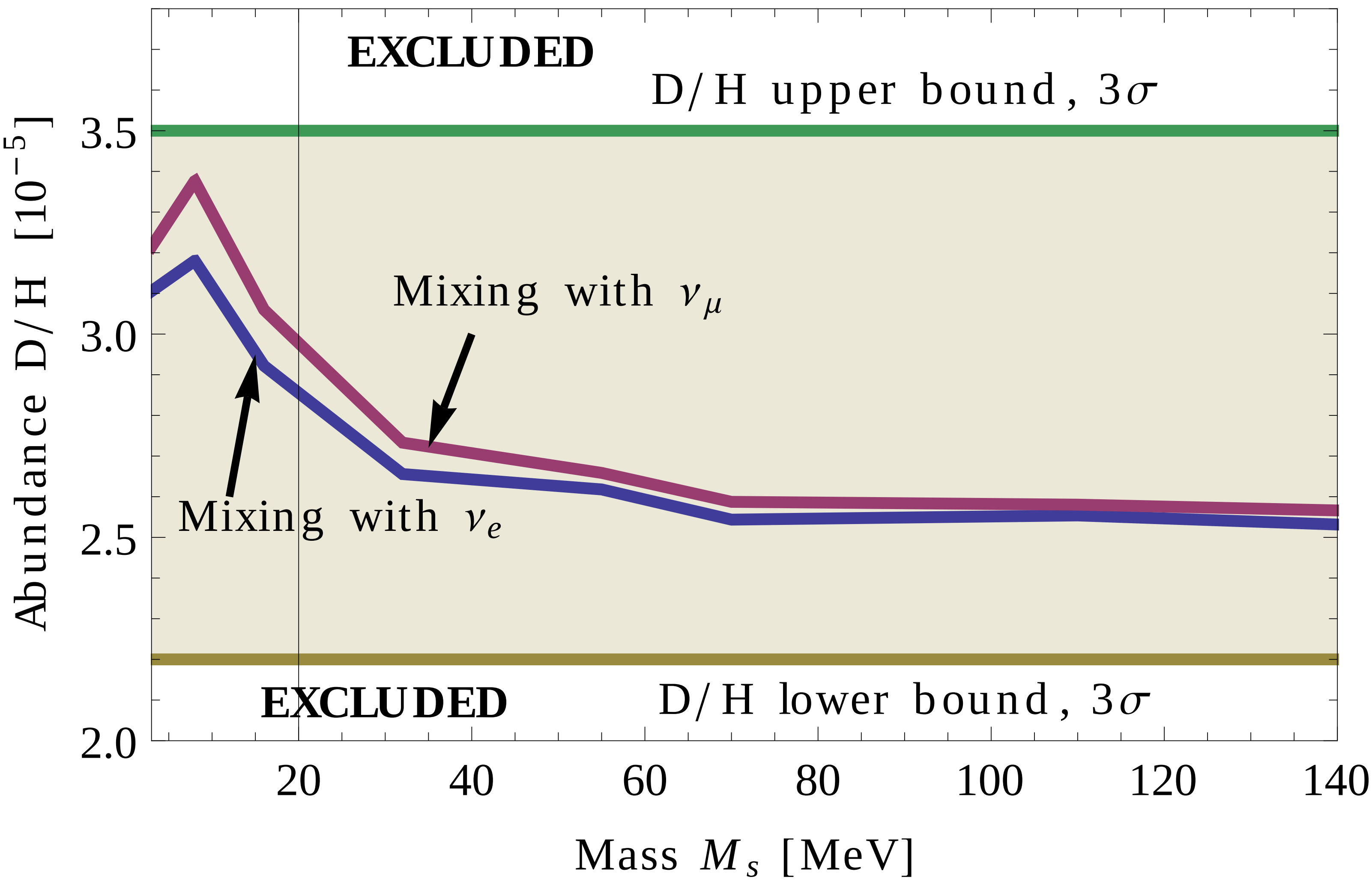


O.R. & Ivashko
[1202.2841]

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}

Lepton asymmetry and magnetic fields

Reminder: equilibrium plasma

- Properties of the equilibrium system are characterized by its temperature and **the values of conserved charges**
- In the Standard Model at $T < 100$ GeV (when electroweak symmetry is broken) there are **4 conserved charges**:
  - **Baryon number** B
  - Three **flavour lepton numbers** L_e, L_μ, L_τ

  Additionally the plasma is electrically neutral
- Plasma breaks Lorentz invariance down to 3-dimensional symmetry

Static magnetic fields in plasma

- Effective action of the **static** electromagnetic fields has the form

$$\mathcal{F}[A] = \frac{1}{2}\int d^3p\, A_i(\vec{p})\Pi_{ij}(p)A_j(-\vec{p}) + \mathcal{O}(A^3) \qquad (1)$$

(magnetic field $\vec{B} = \nabla \times \vec{A}$)

- **Polarization operator** Π_{ij} should be rotation invariant and gauge invariant (i.e. transversal: $p_i\Pi_{ij} = 0$). The most general form:

$$\Pi_{ij}(\vec{p}) = (p^2\delta_{ij} - p_ip_j)\Pi_1(p^2) \quad + \quad i\epsilon_{ijk}p^k\Pi_2(p^2)$$

parity-even part   parity-odd part

  - Π_1 is a renormalization of the electric charge, we will forget about it from now on ($\Pi_1 = 1$)
  - here and below we will speak only about $\Pi_2(0)$ that we denote simply by Π_2

Chern-Simons term

- In coordinate space $\Pi_2 \neq 0$ this leads to a **Chern-Simons term**:

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

- The Chern-Simons term
  - contains less derivatives than $(\nabla \times A)^2$
  - can be both positive and negative

- The matrix Π_{ij} has a negative eigenvalue for

$$p < \Pi_2$$

- **Long-range magnetic fields** with $p < \Pi_2$ will be generated

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:

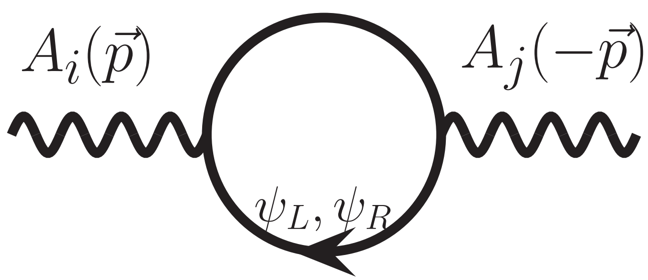
$$\mathcal{F}[A] = \frac{1}{2}\int d^3x\,\Big(p^2 - p\Pi_2\Big)A_0^2 < 0$$

for $p < \Pi_2$

Origin of Chern-Simons term

- Chern-Simons terms are usually prohibited by discrete symmetries (P, CP, CPT)
- The origin of this term?
- P, CP, CPT are broken by non-zero chiral charges of chiral fermions (by non-zero chemical potentials μ_L and μ_R)
- If number of **left particles** $\neq$ the number of **right particles** (i.e. they have **different chemical potentials** $\mu_R \neq \mu_L$) then

$$\Pi_2 = \frac{\alpha}{\pi}\Delta\mu$$



Vilenkin (1978)

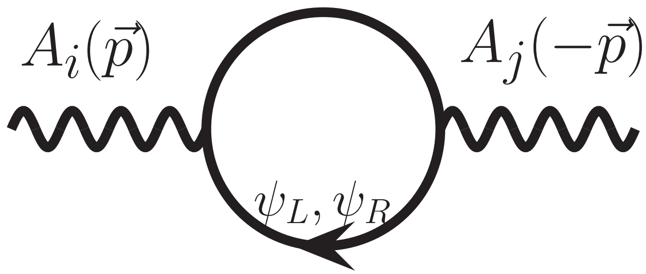
Redlich & Wijewardhana (1985);

Fröhlich et al. (1998–2001)

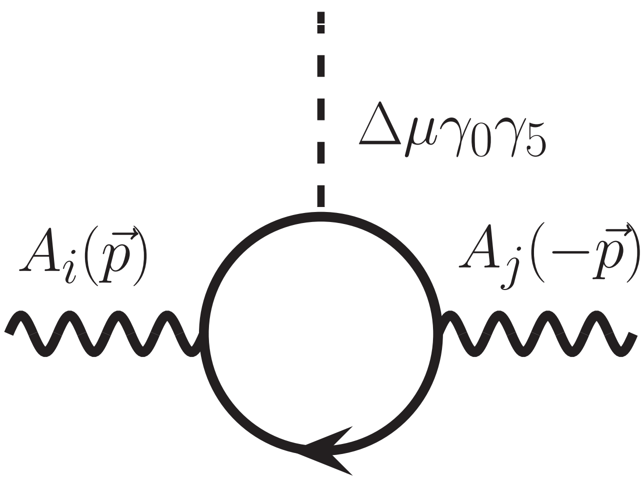
Joyce & Shaposhnikov (1997)

- In plasma with the different number of left and right particles

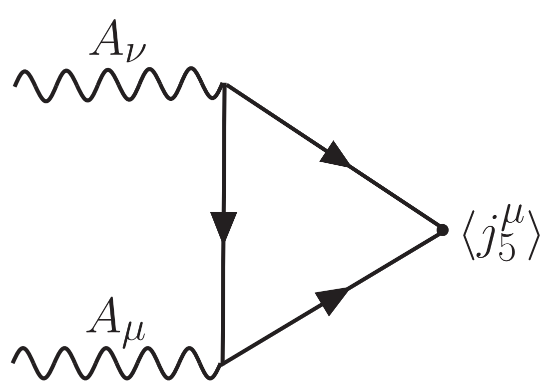
$$\Pi_2 = \frac{\alpha}{\pi}\Delta\mu$$



- This diagram is related to axial anomaly



$\Leftrightarrow$



Left-right equilibration rates

- **Chirality flipping processes** are related to fermion' Yukawa (or mass).
- Although $T \gg m$ and these reactions are suppressed as $(m/T)^2$ as compared to chirality-preserving reactions after long time they will wash out $\Delta\mu$:

$$\frac{\Delta\mu}{dt} = -\Gamma_f \Delta\mu$$

Equilibrium vs. non-equilibrium $\Delta\mu$

? Although $\left(\frac{m_e}{80\ \text{TeV}}\right)^2 \sim 10^{-17}$ chirality flipping reactions are in thermal equilibrium for $T < 80$ TeV and drive $\mu_L - \mu_R$ to zero **exponentially fast** (suppression of at least e^{-1000} over one Hubble time)

Joyce & Shaposhnikov

? Only **non-equilibrium relaxation** of initial $\Delta\mu(t)$ is possible? This relaxation can be “slow”...

Laine’05

...

? Equilibrium state is always $\mu_L = \mu_R$?

No!

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

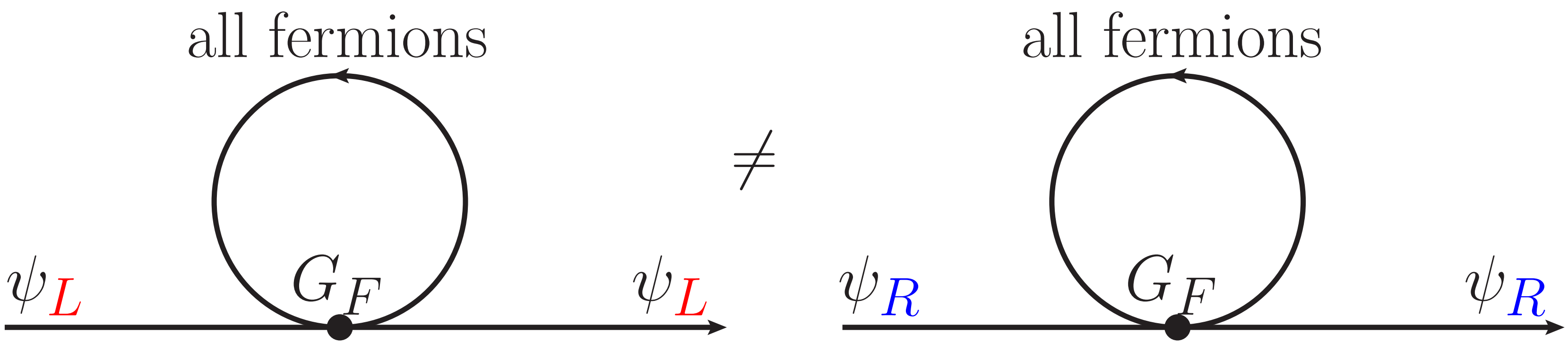
! It is possible to have **equilibrium** difference of chemical potentials!

! This **does not require** super-high temperatures (can even happen at zero temperature but finite density!)

Weak corrections

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

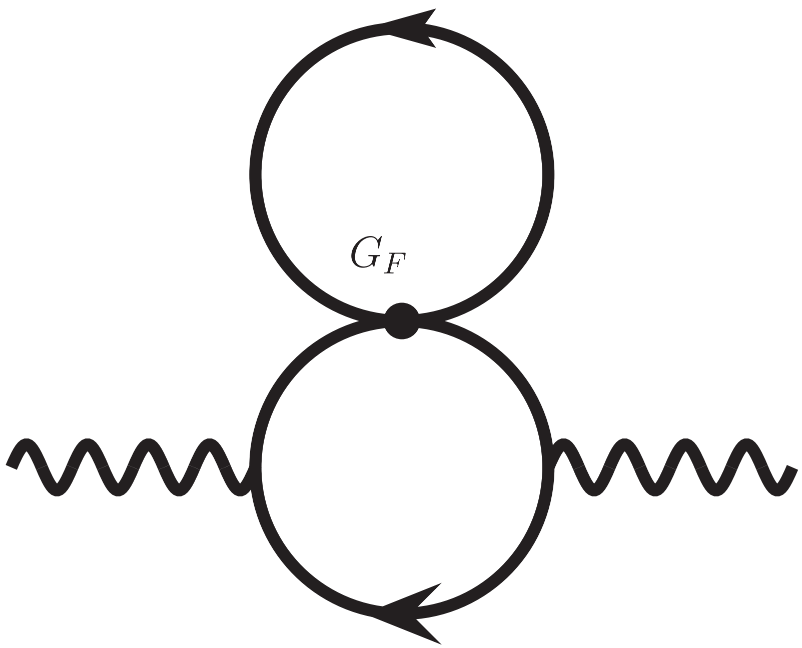
- Weak corrections lead to the **change of dispersion relations** (shift of chemical potentials) of left/right particles
  it is crucial that chirality flipping processes are in equilibrium



- The resulting $\mu_L - \mu_R$ is proportional to the **asymmetry** of all fermions, running in the loops

- Asymmetry $n_\psi - n_{\bar\psi} \propto$ global charges(B, L_e, L_μ, L_τ)

Chern-Simons term

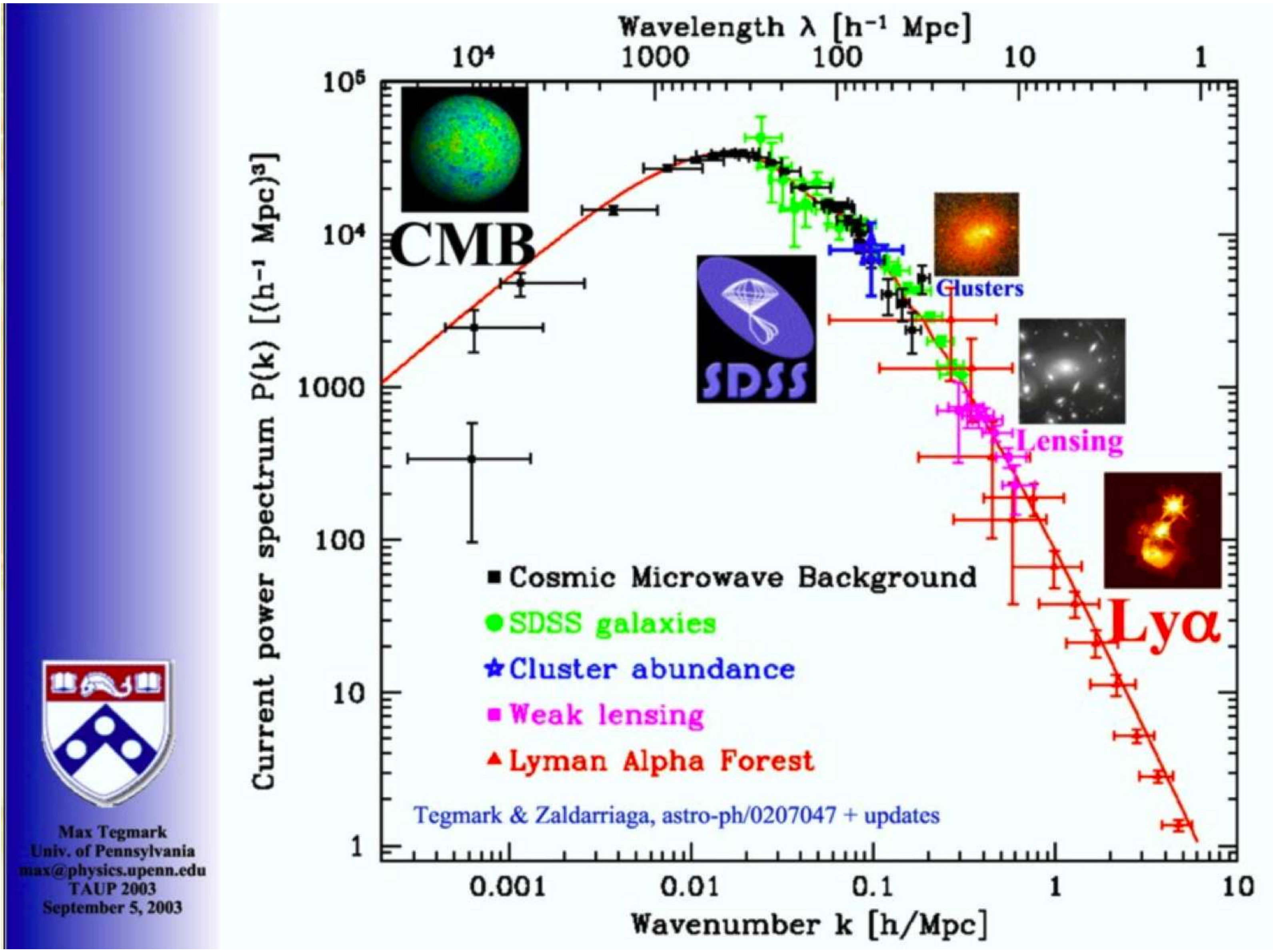


Boyarsky,
Shaposhnikov,
O.R.
[1204.3604]

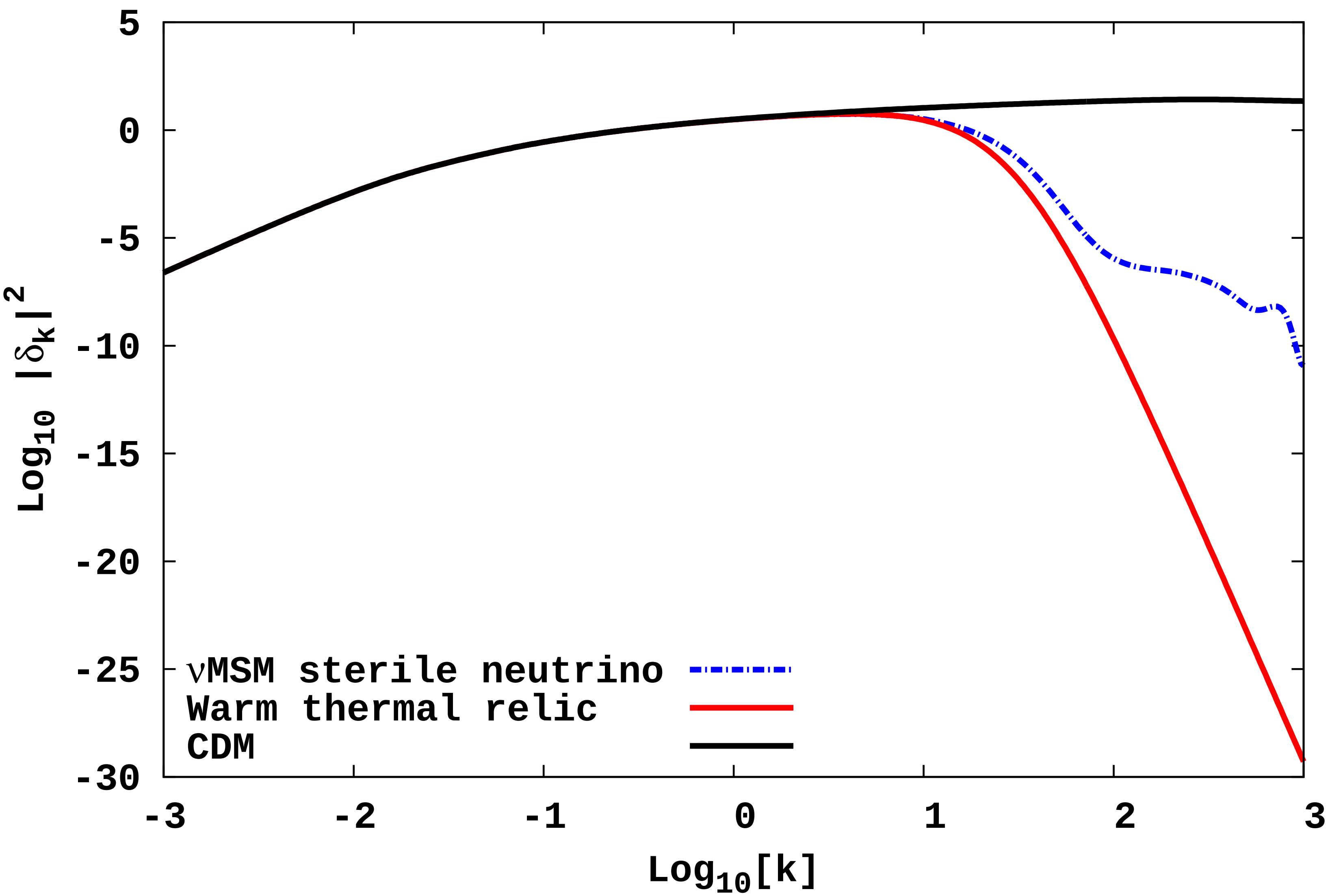
$$\Pi_2 = \frac{\alpha}{2\pi} G_F \times (c_1 \text{ baryon number} + c_2 \text{ lepton numbers}) \neq 0$$

Sterile neutrino dark matter and structure formation

How to measure power spectrum



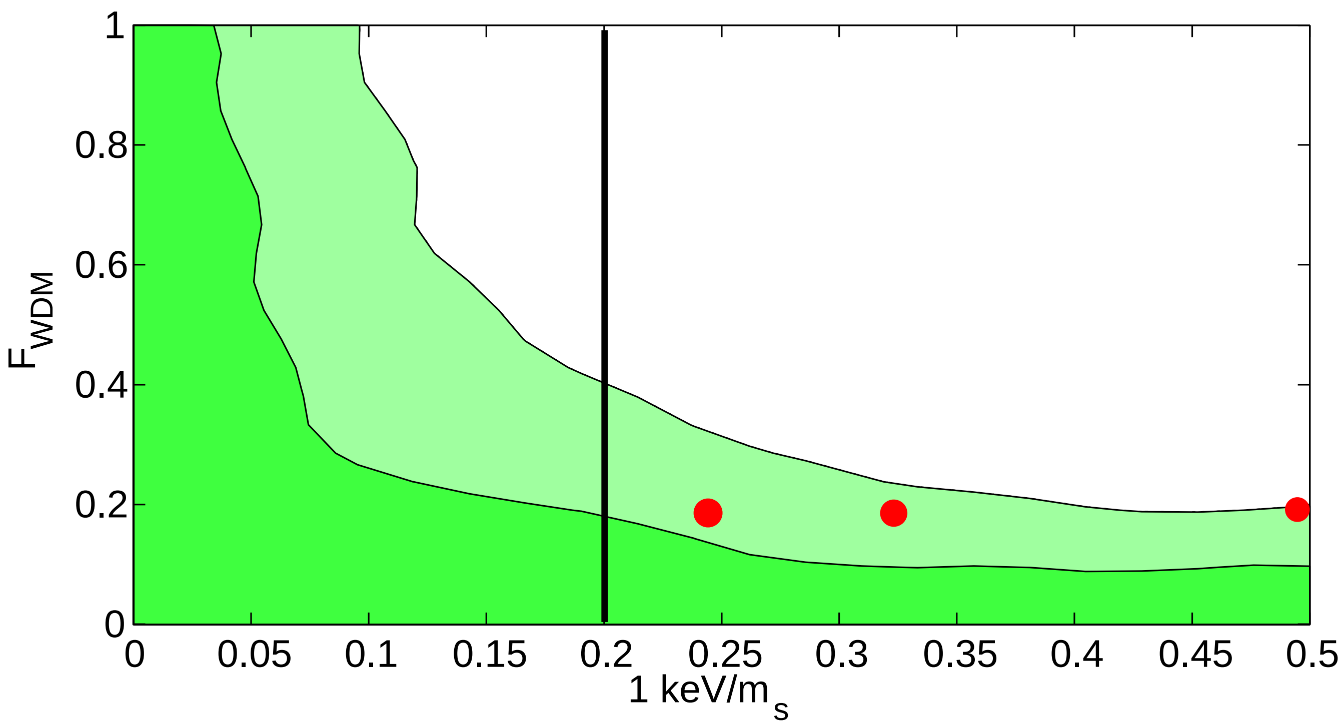
Suppression of power spectrum



Lyman-α bounds for sterile neutrinos

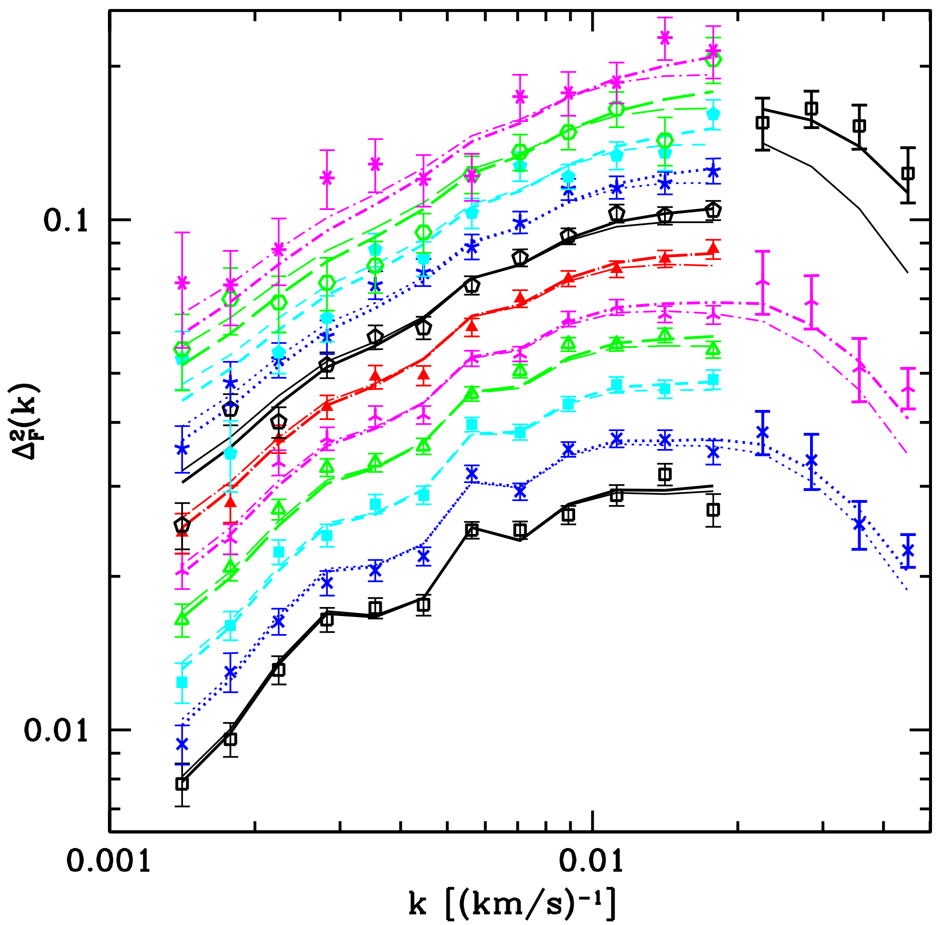
- Revised version of these bounds in CDM+WDM (mixed, CWDM) models demonstrates that
  - The primordial spectra **are not described by free-streaming**
  - There exist viable sterile neutrino DM models with the masses as low as 2 keV

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



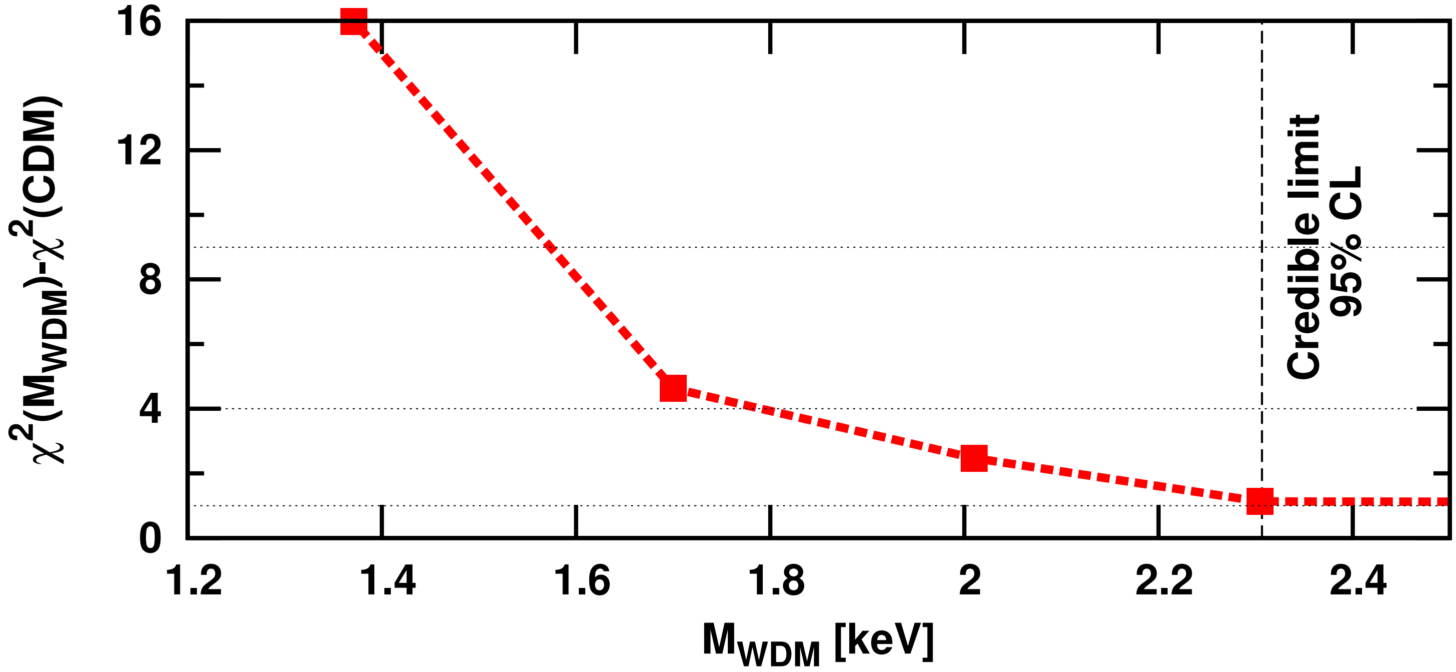
Lyman-α forest flux power spectrum

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)

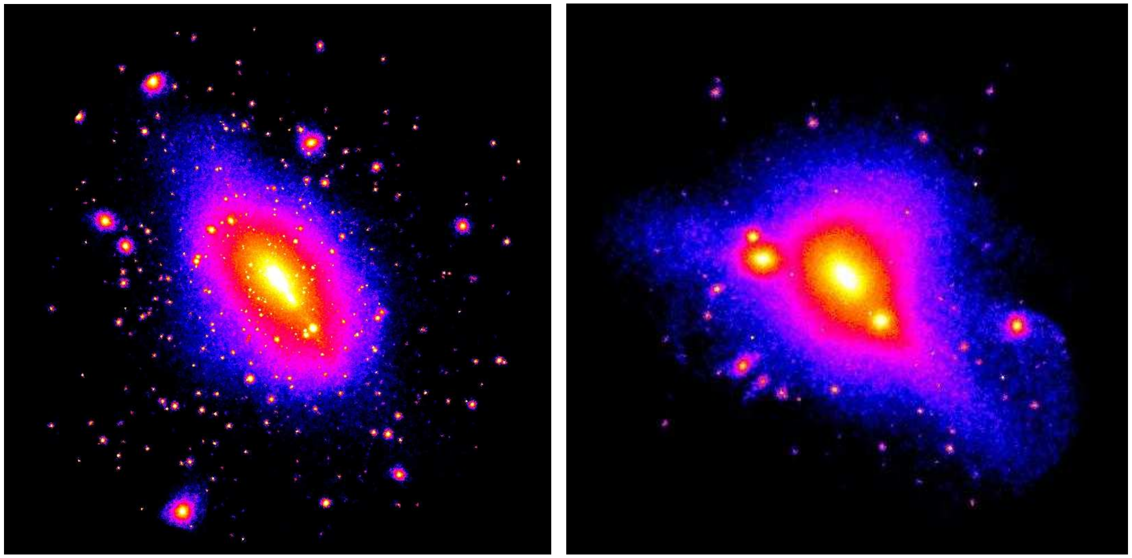
Also Viel et al. 2005-2007;

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

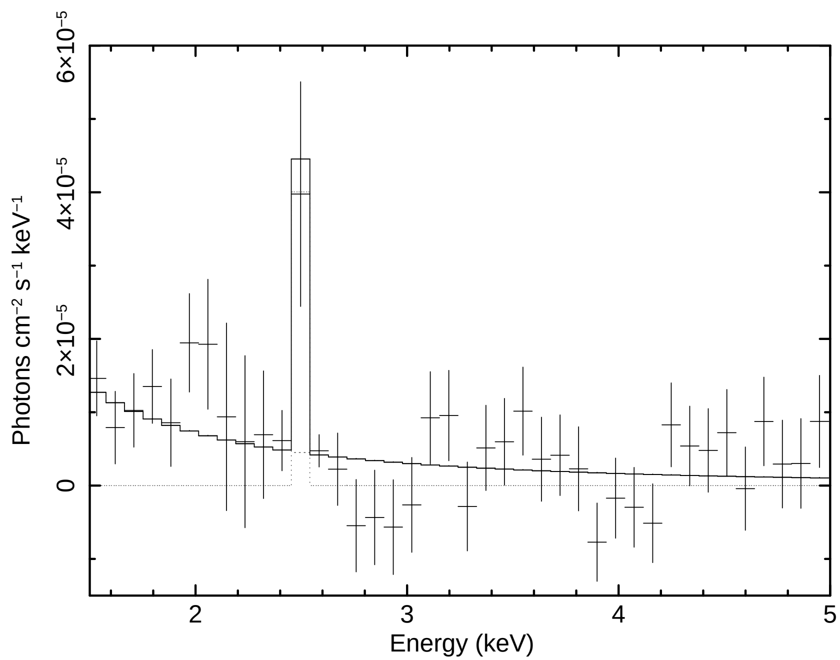
Viel et al. 2005-2007; Seljak et al.(2006)

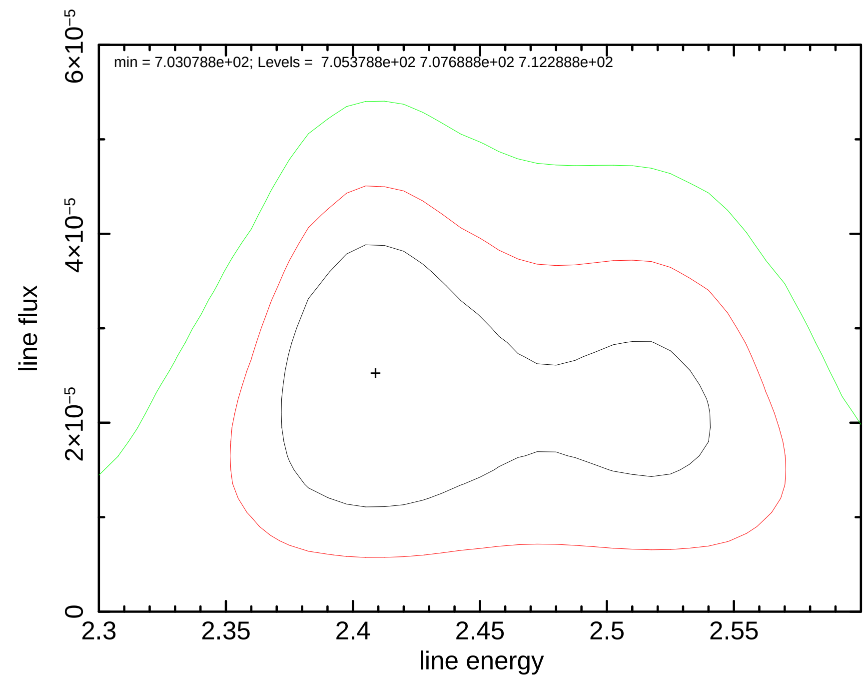
Maccio & Fontanot (2009);

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)

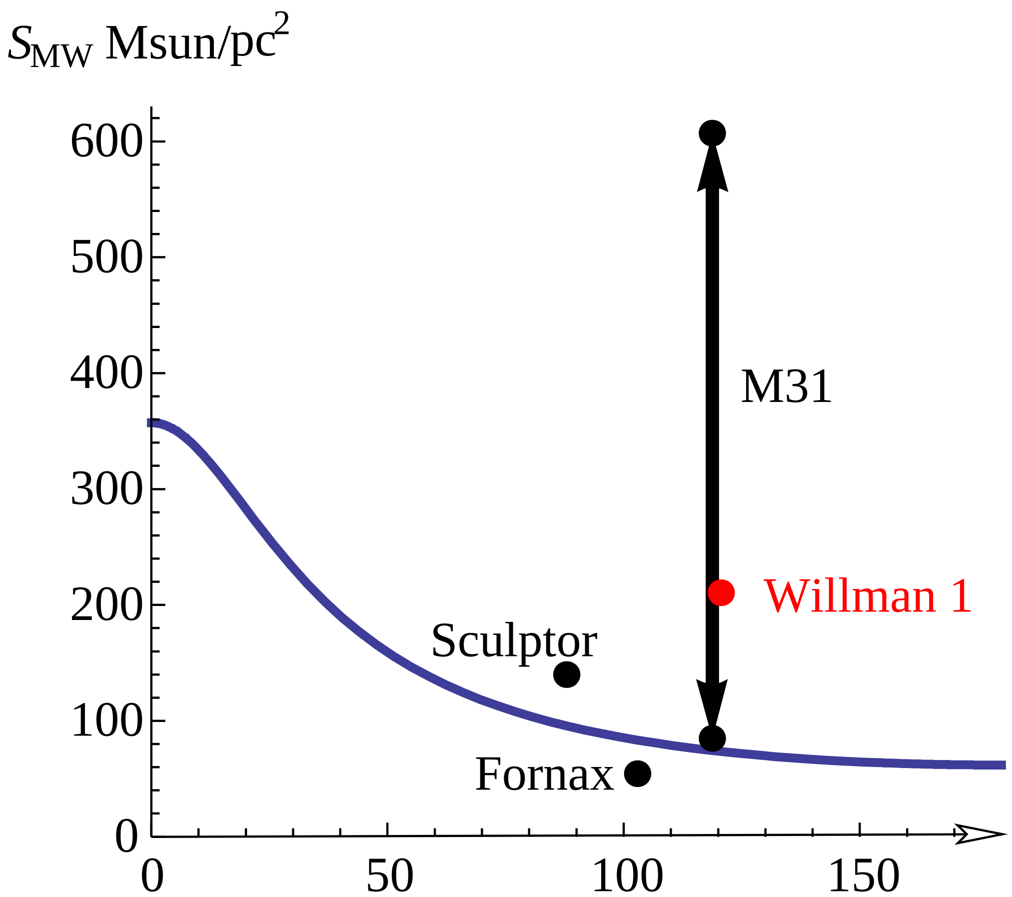




68%, 90% and 99% confidence intervals

- *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?

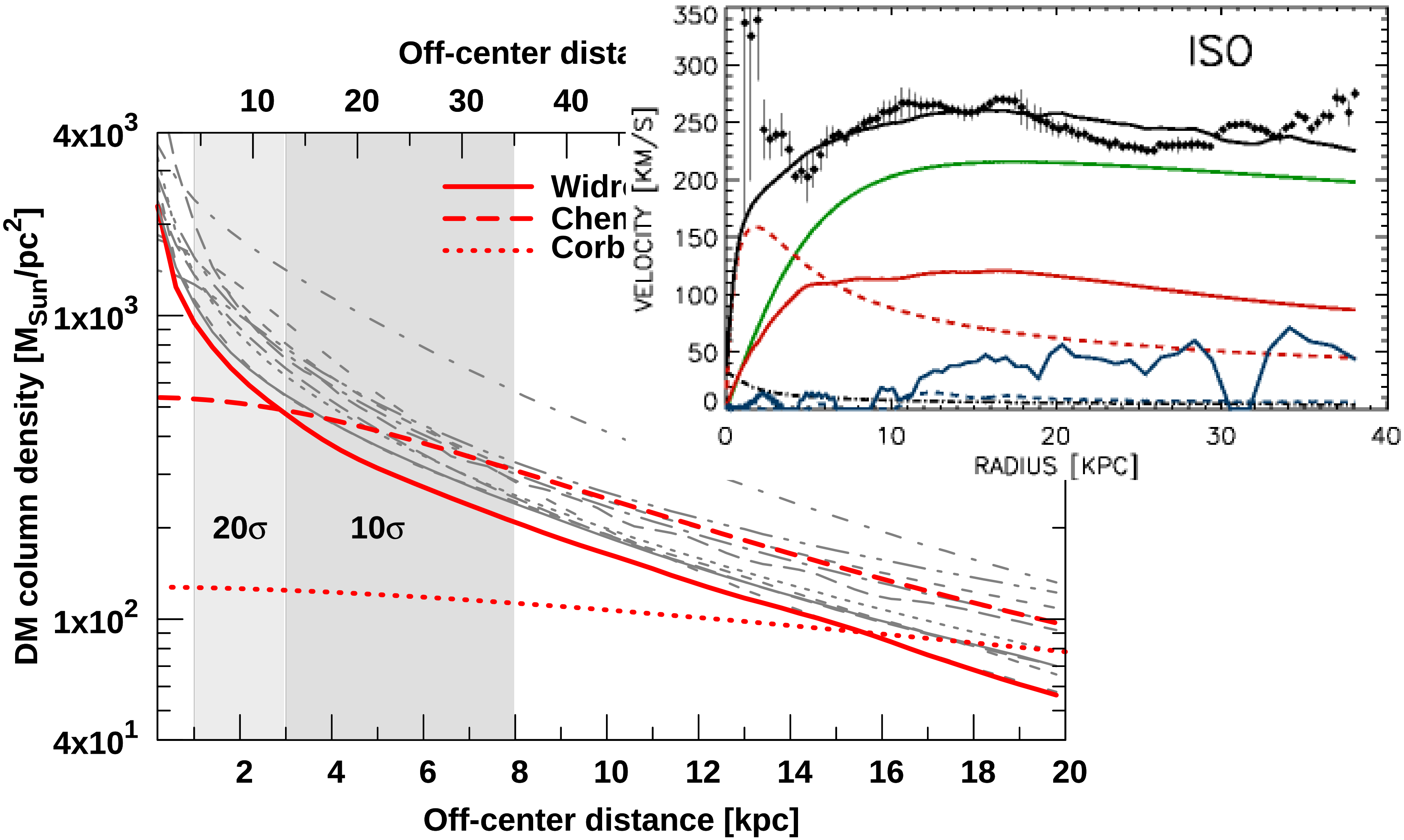


Objects with comparable expected signal for which archival data is available

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

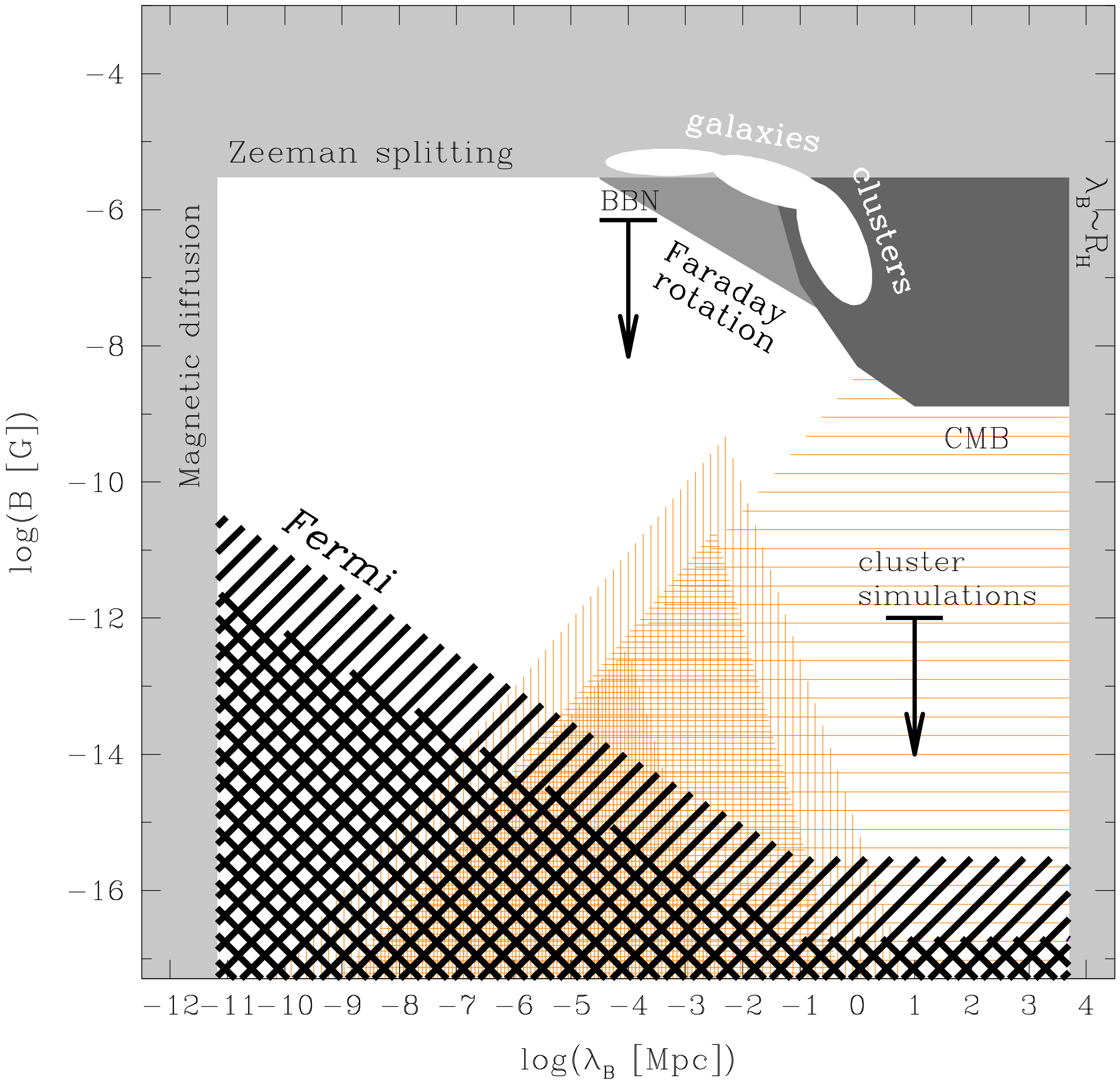
Do we see this 2.5 keV line?

Checking for DM line in M31



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

Evidence for magnetic fields in voids?



Neronov & Vovk, Science (2010);

Dolag et al. (2010);

Tavecchio et al. (2011)

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