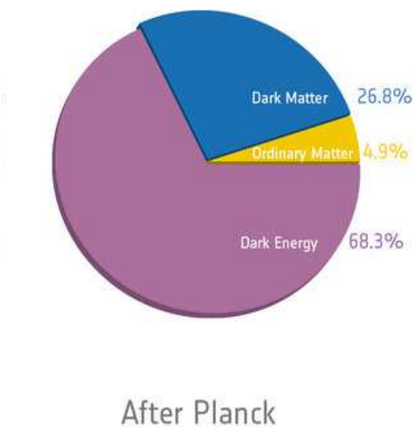
Cosmology and particle physics after Higgs



Oleg RUCHAYSKIY

EPS HEP 2013

July 19, 2013

The whole talk in one slide

In these talk I will argue that on the one hand...

particle physics **strongly suggests** the existence of new massive neutral super-weakly interacting particles

...while on the other hand,

cosmology **asks** for massive, neutral, weaker-than-neutrino-interacting particles

The two can be happily "married" which results in the theory **free of all the observational "beyond-the-Standard-Model" problems**

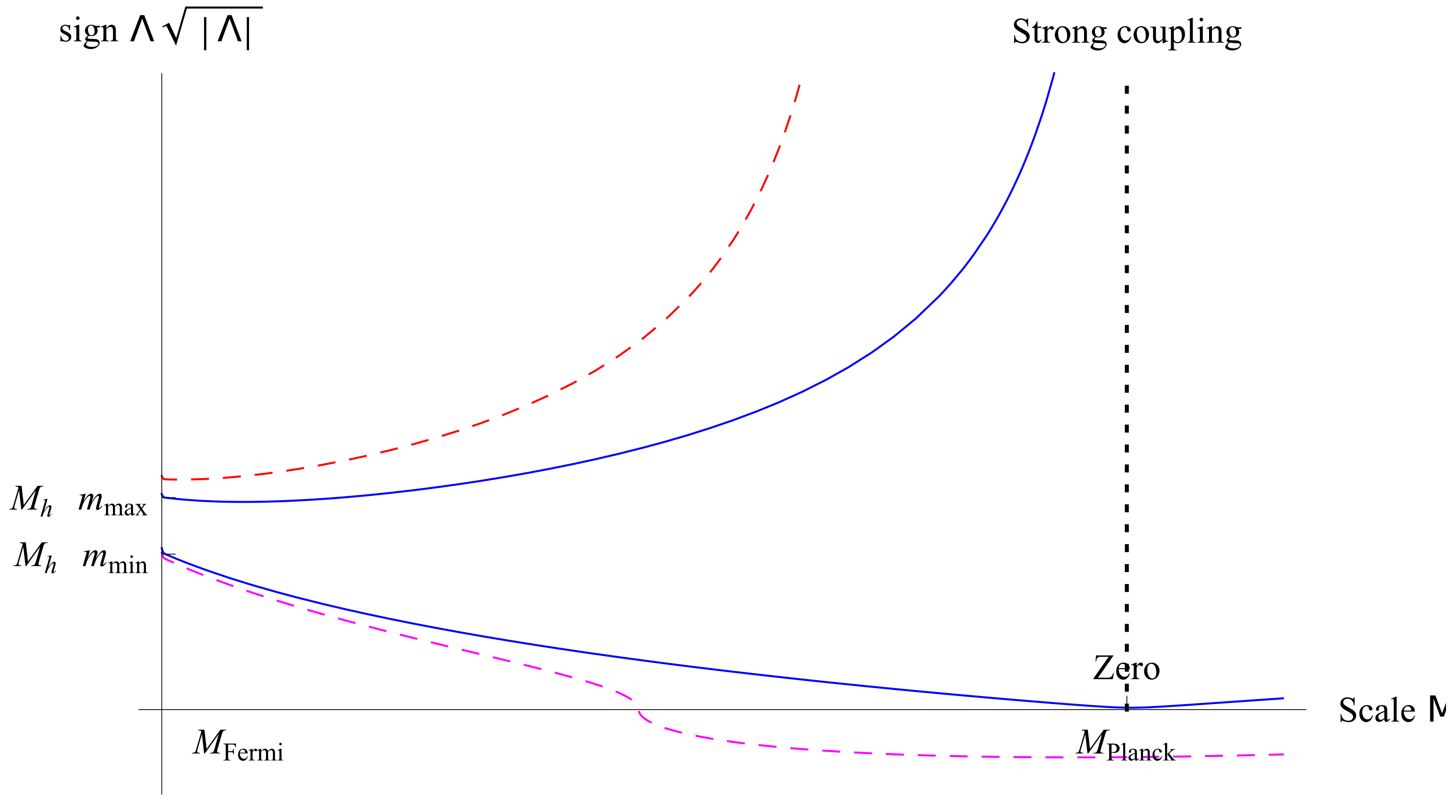
Predictions "how to search" follow

All predicted particles are found! ☺

– Higgs was the last such particle

– Its **non**-discovery would mean that the century-long quest took the wrong trail

The theory is mathematically consistent! ☺



If the mass of the Higgs boson is $125 - 126$ GeV the Standard Model is a consistent weakly-coupled theory up to very high scales (probably up to the Planck scale)

Talk by Fedor Bezrukov in this session in the afternoon.
Plenary talk by Mikhail Shaposhnikov next week

All discovered phenomena are explained? ☹

Particle physics: neutrino oscillations

Cosmology: particle physics (coupled to Einstein gravity) applied to the Universe as a whole faces the challenges of

- dark matter
- matter-antimatter asymmetry of the Universe
- inflation

Theory: some parameters of the Standard Model Lagrangian are "unnaturally" small

- Gauge hierarchy problem
- Strong CP-problem
- Cosmological constant problem

What did we expect to discover?

- **Pre-LHC** particle physics community using "gauge hierarchy problem" as the guiding principle, strongly focused on the idea that **new physics should show up at the TeV scale**
  - supersymmetry
  - extra dimensions
  - strong dynamics ("technicolor")

  dozens of new papers **daily** hep-ph/hep-th for many years

- **Pre-Planck** community strongly focused on
  - non-Gaussianity
  - dark radiation
  - dark energy with $w \neq -1$

  dozens of new papers **daily** astro-ph for many years

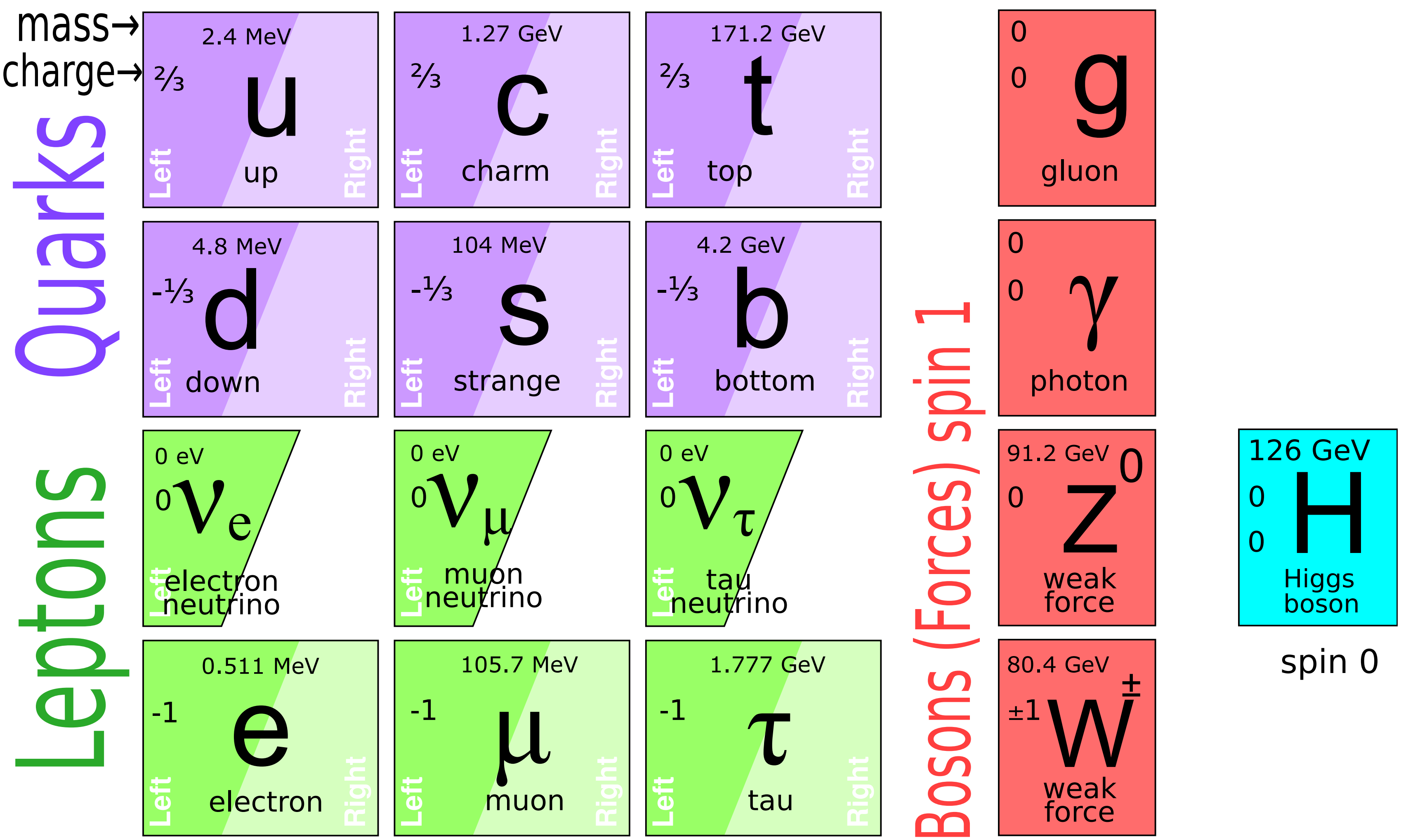
Future of particle physics and cosmology?

What should we do with **beyond-the-Standard-Model problems** if

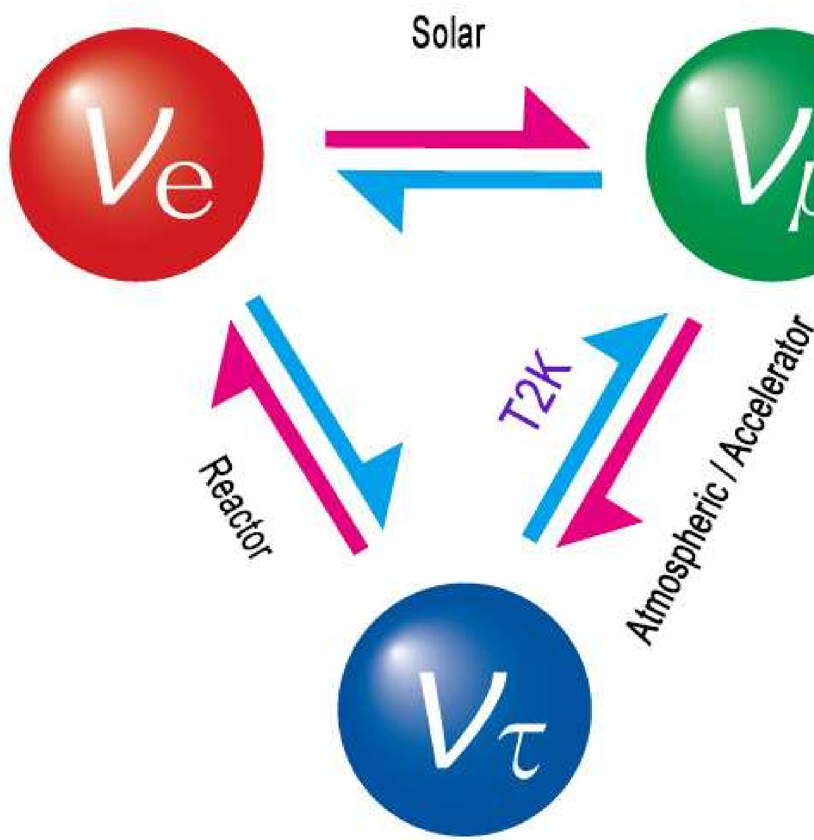
– no new physics will be found at the LHC

– no deviations from "vanilla" ΛCDM model will come from cosmological experiments?

Standard Model of particle physics



Neutrino oscillations



Neutrino oscillation between three generations

From `http://j-parc.jp`

Neutrino mass term

- Recall that neutrino is a part of an SU(2)-doublet $L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$

- Therefore

left lepton doublet

Higgs doublet

$$\text{Neutrino mass term} = \frac{c_{\alpha\beta}(\bar{L} \cdot \tilde{H}^\dagger)(L \cdot \tilde{H})}{\Lambda}$$

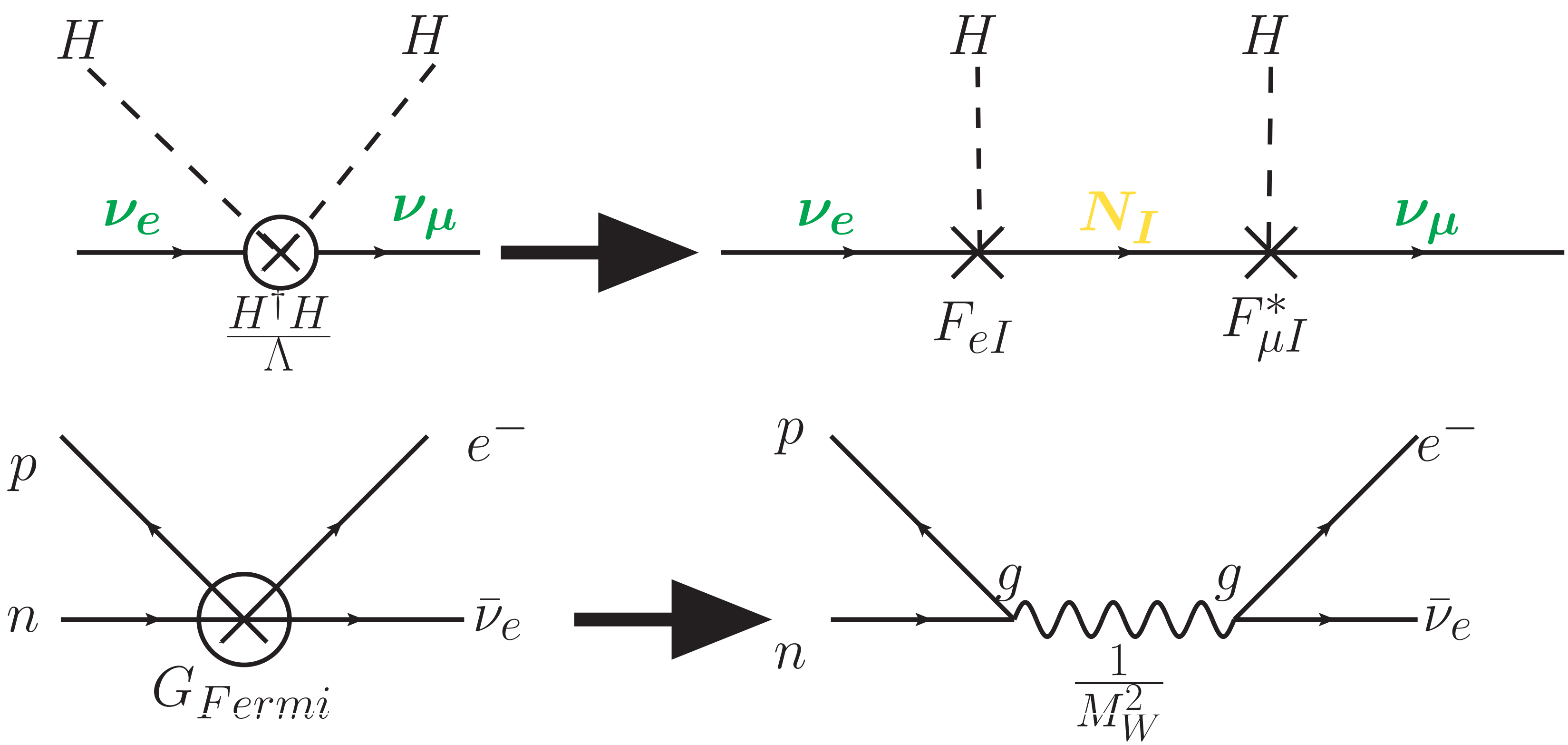
constant with dimension of energy

- For electron we could write a different mass term:

$$\text{Electron mass term} = f_e \, \bar{e}_R (L_\alpha \cdot H)$$

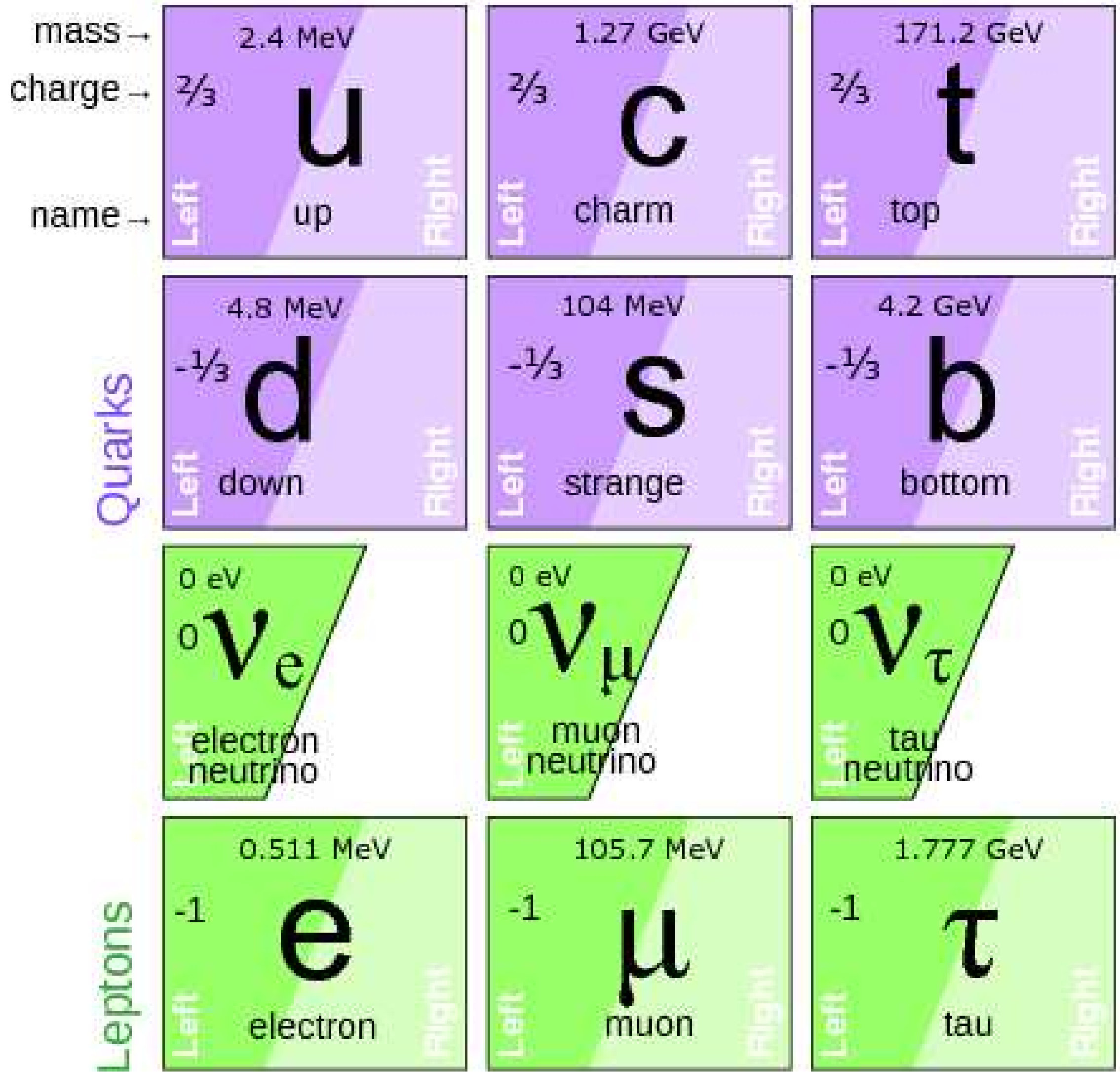
because **right-handed** (SU(2) singlet) electron e_R exists!

"Resolving" neutrino mass term

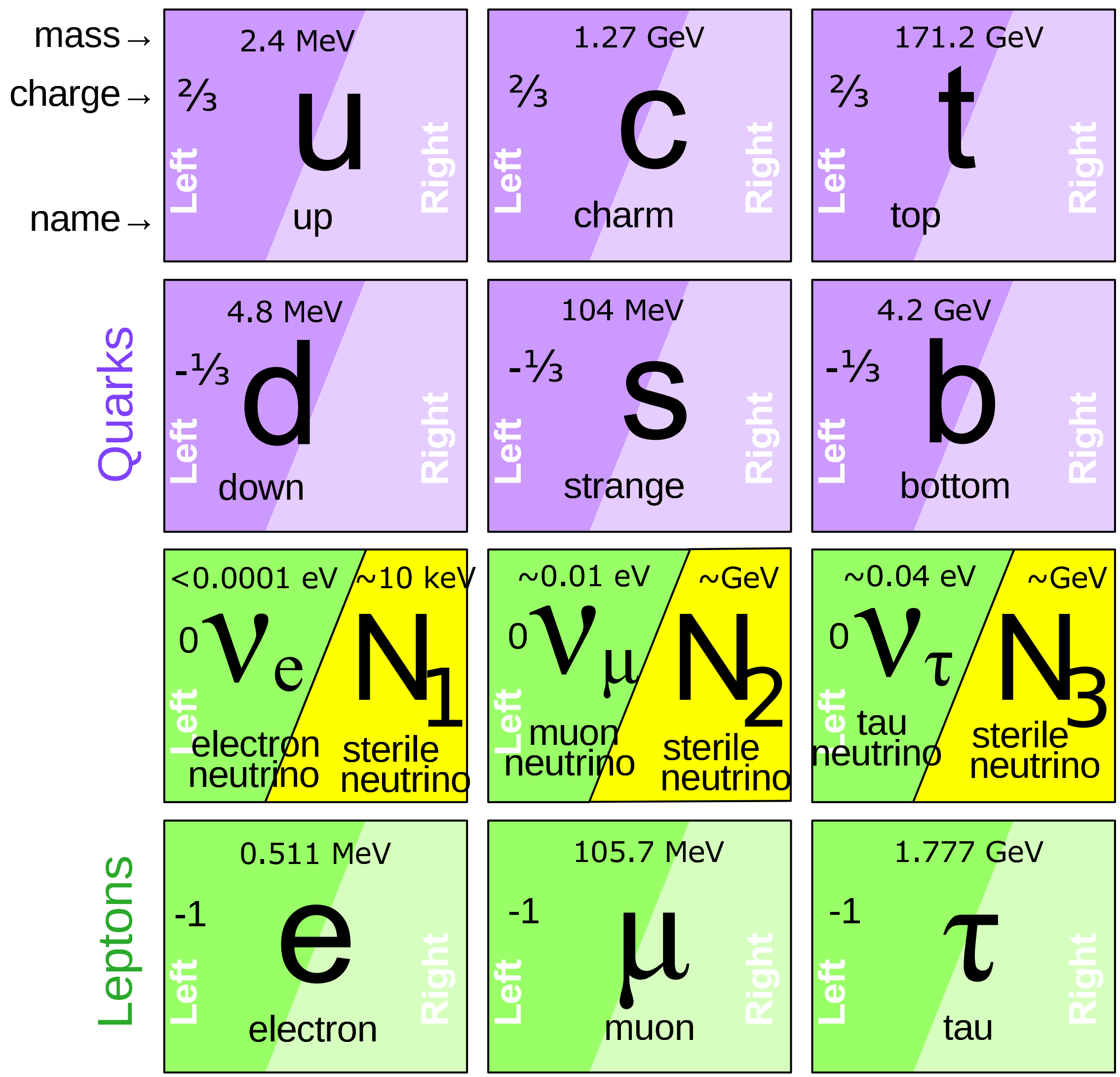


Neutrino oscillations mean that there exist new particles!

Neutrino oscillations ...



...and right-handed neutrinos



Right-handed neutrinos?

- If we added right-handed counterpart of the ordinary (left) neutrinos, we can write the usual Dirac mass term (as for electron)

- In the Standard Model weak charges of left and right components are different (but strong and electric are the same)
  - $\nu_{e,\mu,\tau}$: upper component of the SU(2) doublet, U(1)$_Y$ charge = -1
  - Higgs boson: SU(2) doublet, U(1)$_Y$ charge = 1

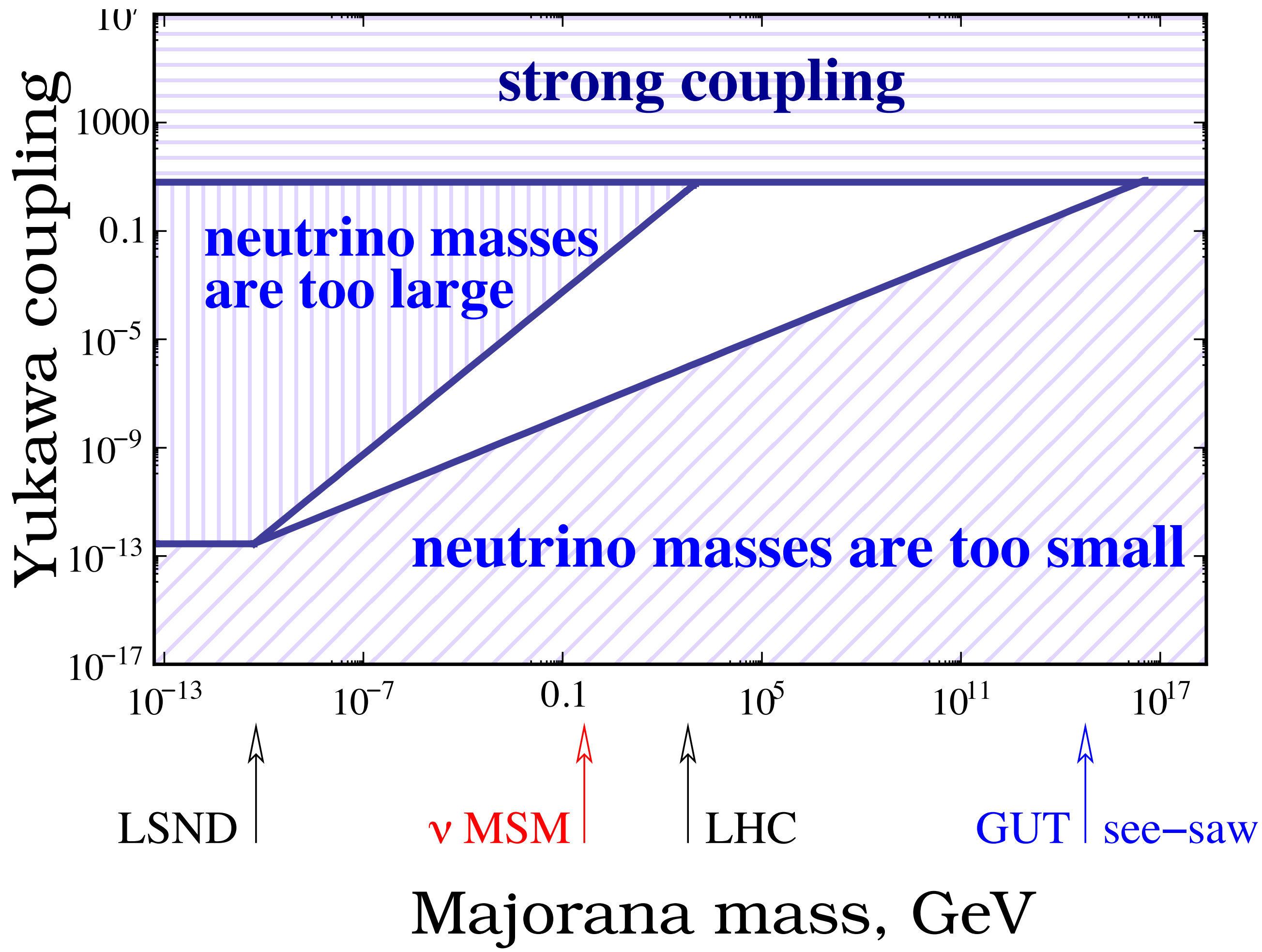
- Right-chiral neutrinos N_I **carry no charge** under the SM interactions (**"sterile neutrinos"**)

- Neutral leptons can have their own **Majorana mass term**, not generated via Higgs mechanism:

$$\text{Majorana mass } = M_N \bar{N}^c N$$

Scale of sterile neutrino masses?

1204.5379



See-saw formula

Neutrino Yukawa interaction

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

Neutrino Majorana mass

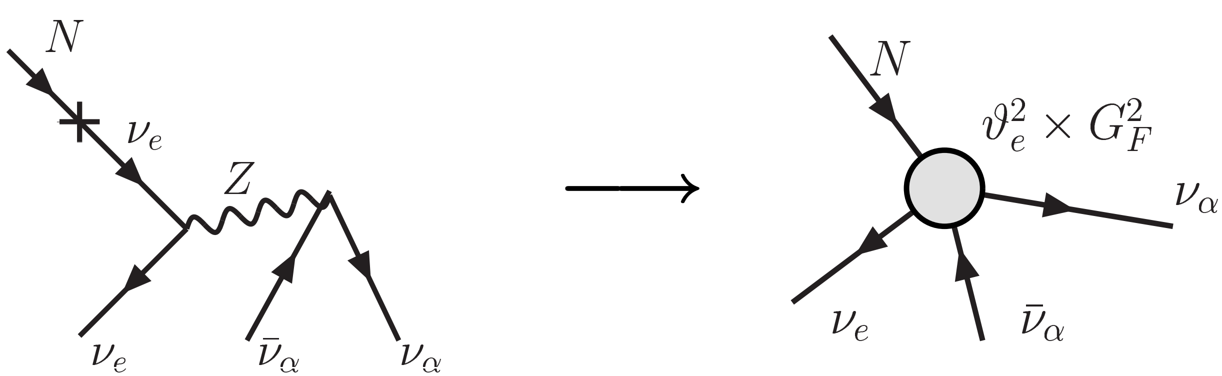
Mass of sterile neutrinos is not determined by neutrino oscillations!

Properties of sterile neutrino

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

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

Mixing angles $\vartheta^2_{e,\mu,\tau} \equiv \frac{|M_{\text{Dirac}}|^2}{M^2_{\text{Majorana}}} = \frac{\mathcal{M}_{\text{active}}}{M_{\text{sterile}}} \approx 5 \times 10^{-11} \left(\frac{1\text{ GeV}}{M_{\text{sterile}}}\right)$



For example, 0.5 GeV sterile neutrino has its interaction cross-section suppressed by 10^{-10} as compared with ordinary neutrino

Sterile neutrinos -- what are they

- Sterile neutrinos behave as massive neutral particles, interacting **weaker than neutrinos** (suppression of interaction strength $\vartheta^2 \sim \frac{matm}{M_{\text{sterile}}}$)

- **Their masses cannot be fixed** and can be anything from m_{atm} to 10^{15} GeV

- These particle has been searched in the range up to $\mathcal{O}(1)$ eV $\lesssim M_N \lesssim \mathcal{O}(10^2)$ GeV, but **searches never approached the bottom line determined by neutrino oscillation**

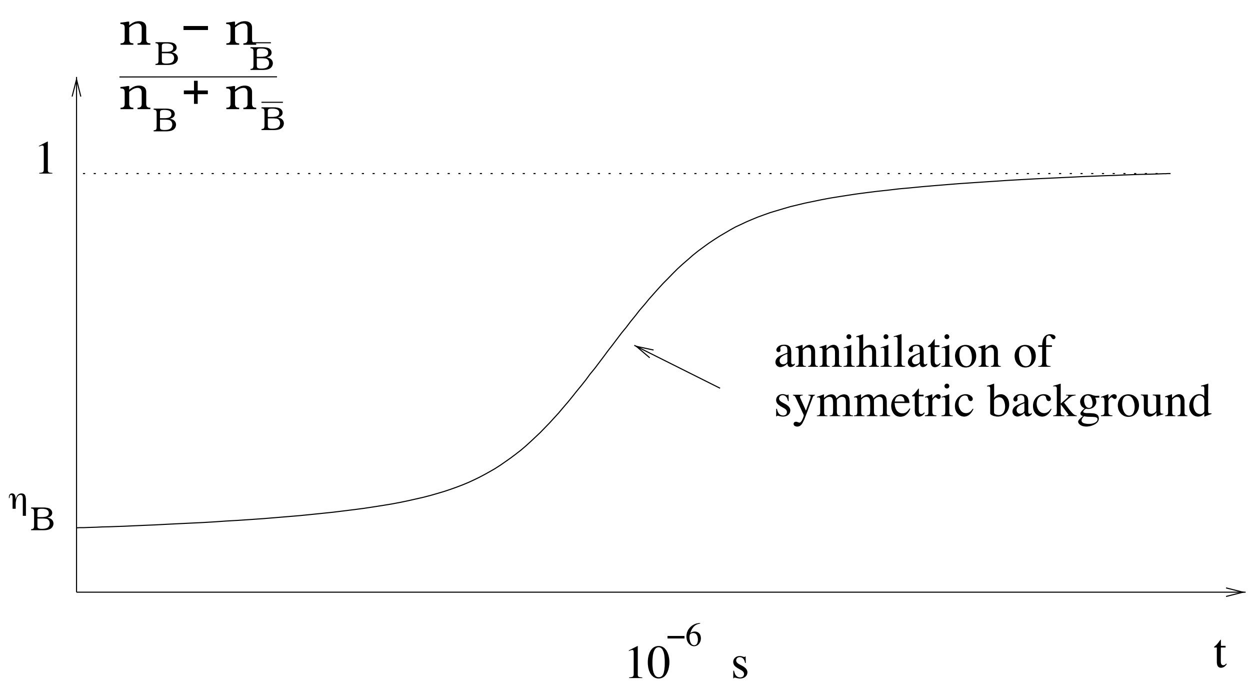
Can these particles by interesting for cosmology?

What does this mean for cosmology?

Matter-antimatter asymmetry of the Universe

Shaposhnikov

$$\eta_B = \frac{n_B}{n_\gamma} \sim 10^{-10}$$



What created tiny initial asymmetry between baryons and anti-baryons in the early Universe?

Sakharov conditions for BAU

It is possible to generate baryon–anti-baryon asymmetry, starting from symmetric initial conditions, provided that you satisfy three conditions ("**Sakharov conditions**") Sakharov'67

- **I.** Baryon number is not conserved
- **II.** C- and CP-symmetries are broken
  (actually, any symmetry that commutes with Hamiltonian and anti-commutes with baryon number should be broken)
- **III.** These processes are out-of-equilibrium (otherwise any potential asymmetry will be washed out)

In the Standard Model only first of these conditions is satisfied!

through a non-perturbative process known as *sphaleron*

Sakharov condition-III

- In thermal equilibrium any quantity is defined in a unique way as a function of **temperature** and possibly a number of some **conserved charges** Q (or corresponding **chemical potentials**)

- All SM processes (including those that violate CP) are deeply in thermal equilibrium at temperatures around **100 GeV**

- The first-order phase transition does not take place in the SM for Higgs mass greater than **72 GeV**

Baryogenesis is not possible in the Standard Model!

Enter sterile neutrinos

Sterile neutrinos may provide all conditions necessary for successful baryogenesis:

- Their "weaker-than-weak" interaction (ϑG_F) means that they go out of equilibrium much earlier than even neutrinos
- Their mass matrix may contain additional CP-violating phases (*a la* CP violating phases of CKM matrix)
- Their Majorana masses violate lepton number

This class of scenarios is called LEPTOGENESIS

Sterile neutrinos and leptogenesis

There exist three classes of leptogenesis scenario related to sterile neutrinos:

Thermal leptogenesis: **Fukugita & Yanagida'86**

Works for $M_N \sim 10^{12}$ GeV

Resonant leptogenesis: **Pilaftsis, Underwood'04–'05**

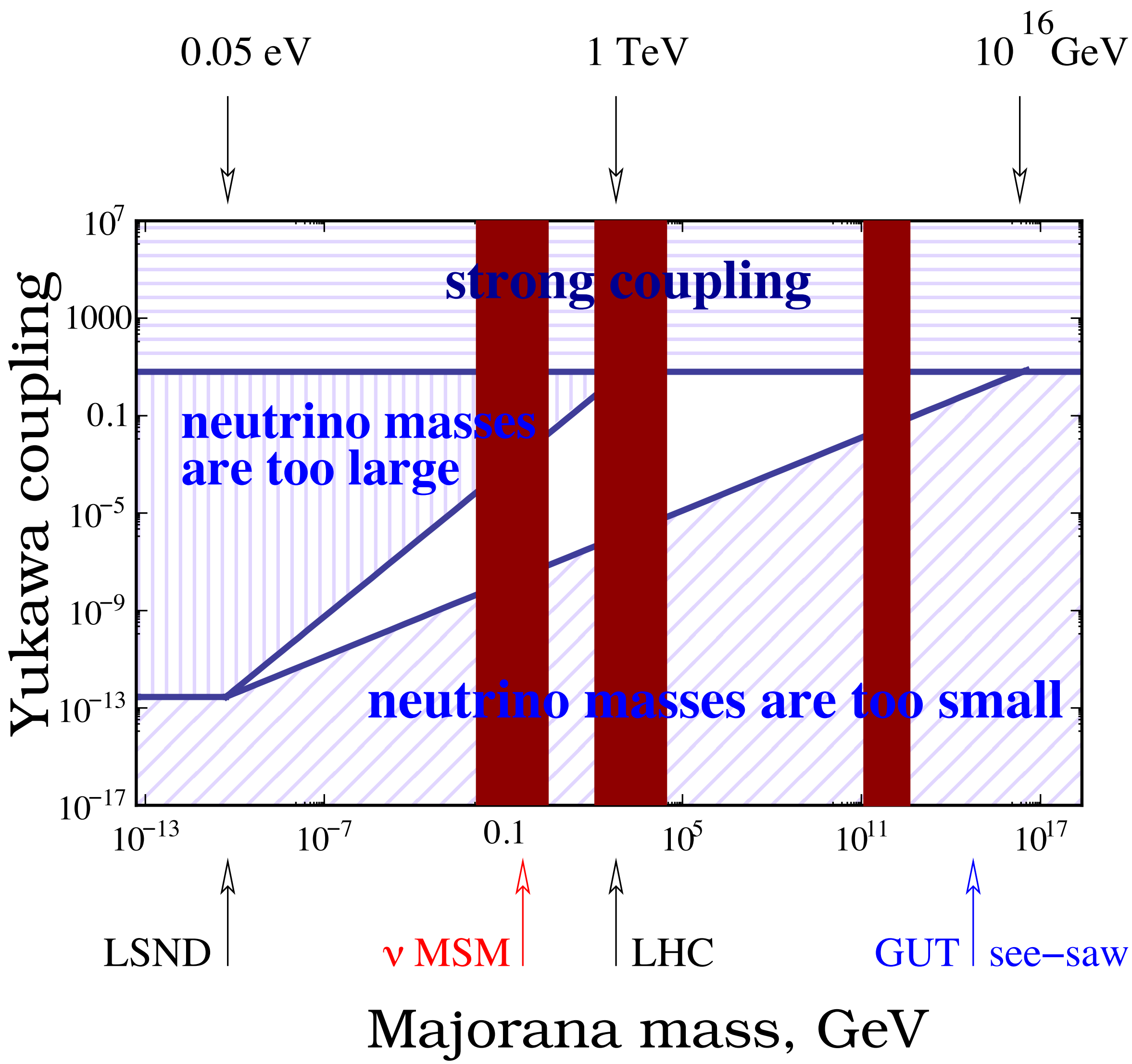
Works for $M_{N_1} \approx M_{N_2} \sim \mathcal{O}(\mathrm{TeV})$ and $|M_{N_1} - M_{N_2}| \ll M_{N_1,N_2}$

Leptogenesis via oscillations: **Akhmedov, Smirnov & Rubakov'98**

Asaka &Shaposhnikov'05

Works for $M_{N_1} \approx M_{N_2} \lesssim M_W$ and $|M_{N_1} - M_{N_2}| \ll M_{N_1,N_2}$

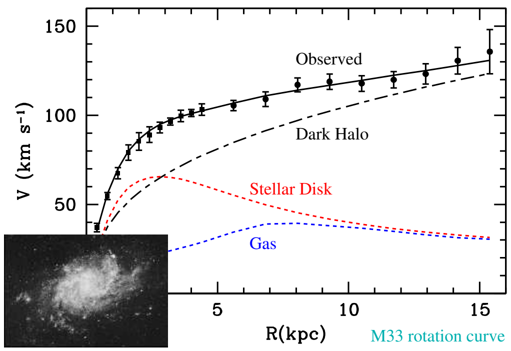
Baryon asymmetry in the Universe

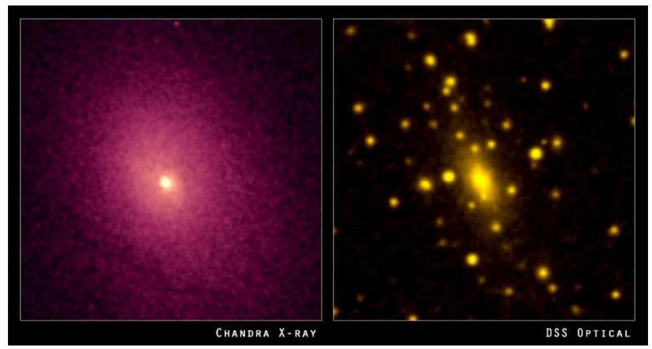


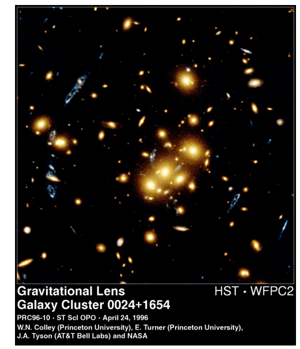
Widths of baryogenesis stripes are not up to scale!

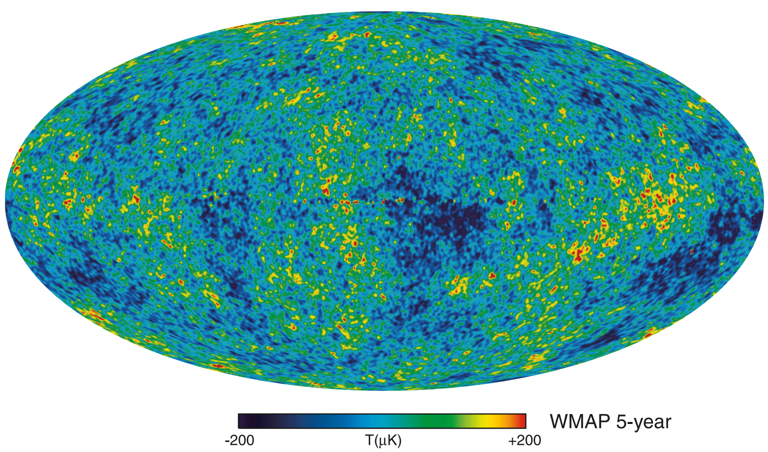
Dark matter

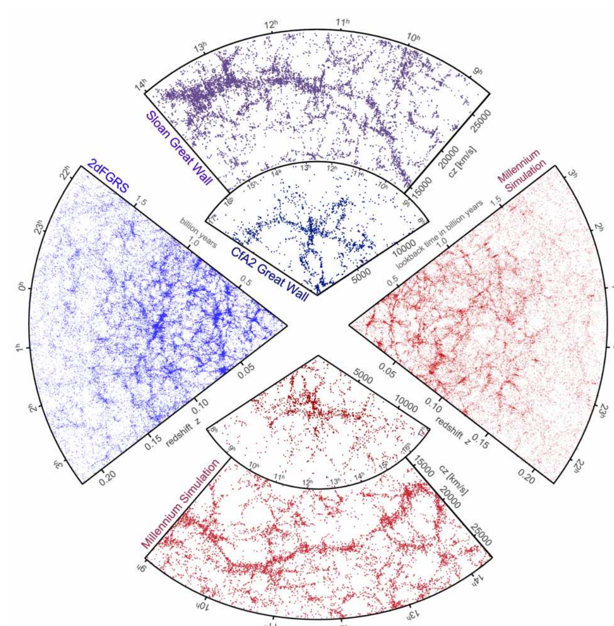
Extensive evidence for the presence of **dark, non-baryonic** matter, dominating the mass balance of the Universe at scales above 100 pc.











Neutrino dark matter

S. Tremaine & J. Gunn *"Dynamical Role of Light Neutral Leptons in Cosmology"* Phys. Rev. Lett. (1979)

– The smaller is the mass of Dark matter particle, the larger is the number of particles in an object with the mass M_{gal}

– Average phase-space density of neutrino (**any fermionic**) DM should be **smaller** than density of **degenerate Fermi gas**

$$\frac{M_{\text{gal}}}{\frac{4\pi}{3}R_{\text{gal}}^3}\frac{1}{\frac{4\pi}{3}v_\infty^2} \leq \frac{2{m_{\text{DM}}}^4}{(2\pi\hbar)^3}$$

galactic scale measurements **microscopic physics**

O.R. with Boyarsky *et al* [0808.3902]

– Objects with highest phase-space density – dwarf spheroidal galaxies – lead to the **lower bound** on the fermionic DM mass

$m_{\text{DM}} \gtrsim 300 - 400$ **eV** – **"Tremaine-Gunn bound"**

Neutrino dark matter

– **However**, if you compute contribution to DM density from massive active neutrinos ($\mathcal{M}_\nu \lesssim$ MeV), you get

$$\Omega_{\nu\,\text{DM}} h^2 = \sum \mathcal{M}_\nu \int \frac{d^3k}{(2\pi)^3} \frac{1}{e^{\frac{k}{T}} + 1} = \boxed{\frac{\sum \mathcal{M}_\nu[\text{eV}]}{94\ \text{eV}}}$$

– Using minimal mass of 300 eV you get $\Omega_{\text{DM}} h^2 \sim 3$ (**wrong by about a factor of 30!**)

– Sum of masses to have the correct abundance $\sum \mathcal{M}_\nu \approx 11$ eV

Massive Standard Model neutrinos cannot be simultaneously “astrophysical” and “cosmological” dark matter: to account for the missing mass in galaxies **and** to contribute to the cosmological expansion

Two obvious generalizations of neutrino DM:

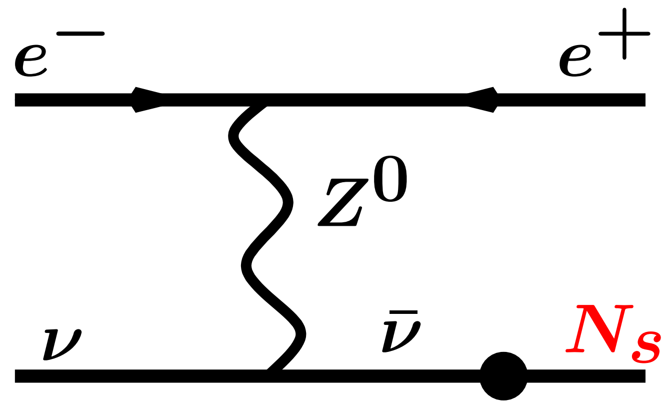
1) Make the "neutrino" heavier so that it decouples non-relativistic (and therefore the expression $\Omega_{DM}h^2 = \frac{\sum \mathcal{M}_\nu[\text{eV}]}{94\text{ eV}}$ is not applicable anymore) but keep the interaction of the same order.

2) Make the "neutrino" interact weaker-than-weak, so that it never enters the equilibrium with the plasma in the first place (and therefore the expression $\Omega_{DM}h^2 = \frac{\sum \mathcal{M}_\nu[\text{eV}]}{94\text{ eV}}$ is not applicable anymore)

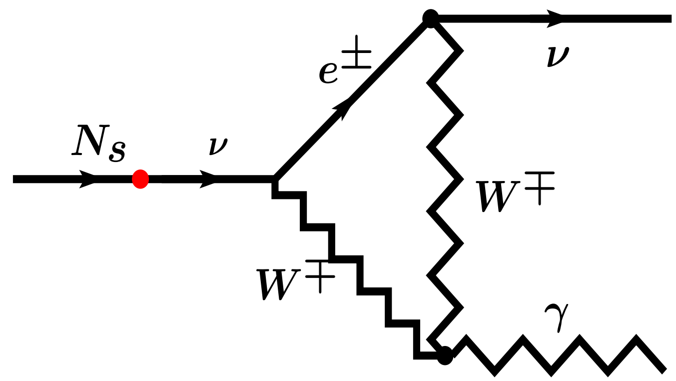
- First modification is called . . . . **WIMP**
  large mass and interaction strength of such a particle means that it will be unstable unless there is an exact symmetry, protecting it from decay
- Second modification is called . . . . **sterile neutrino**
  mass that can be rather small ($\mathcal{O}(0.5$ keV) and super-weak interaction strength of such a particle means that it can be unstable but still provide a correct phenomenology

Sterile neutrino dark matter

- Can be produced in the early Universe in correct amounts



- Can **decay** with cosmologically long 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** $\frac{\Delta E}{E_\gamma} \sim \frac{v_{\text{vir}}}{c} \sim 10^{-4} \div 10^{-3}$

Dolgov Hansen (2000

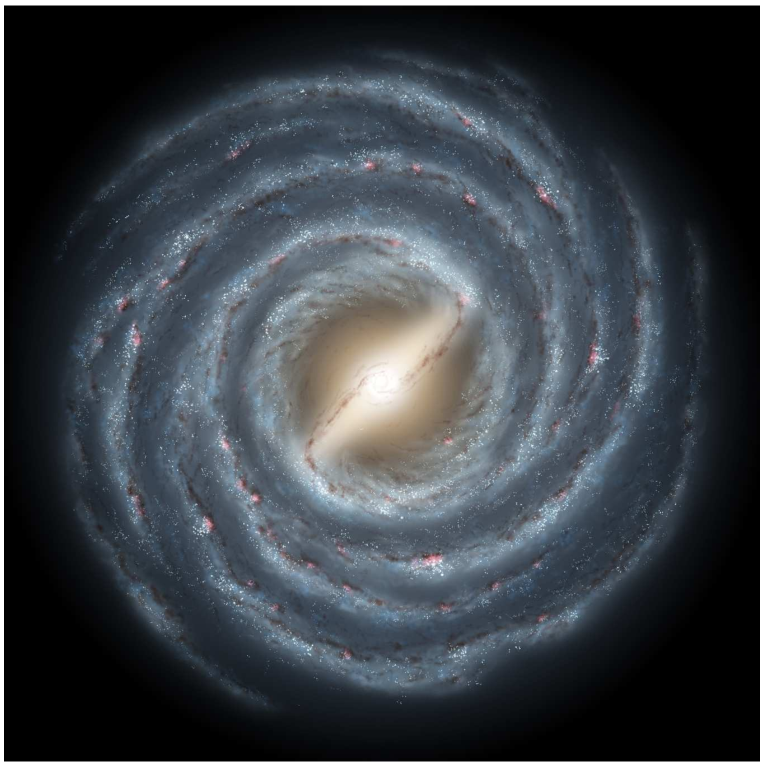
Abazajian Fuller Tucker (2001)

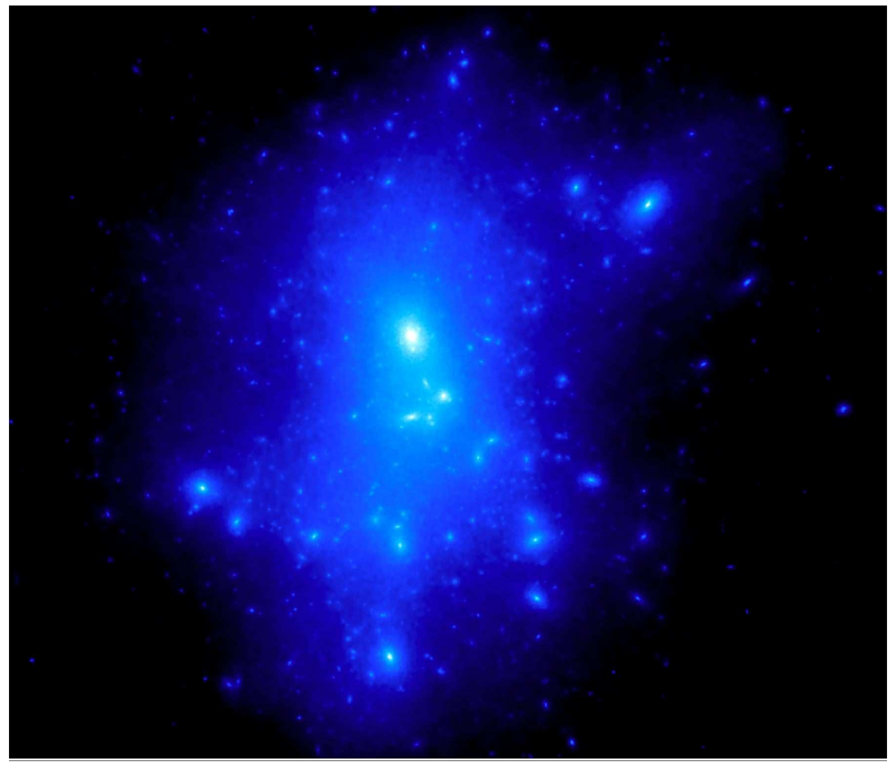
Asaka, Shaposhnikov, Laine

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

Search for DM decay

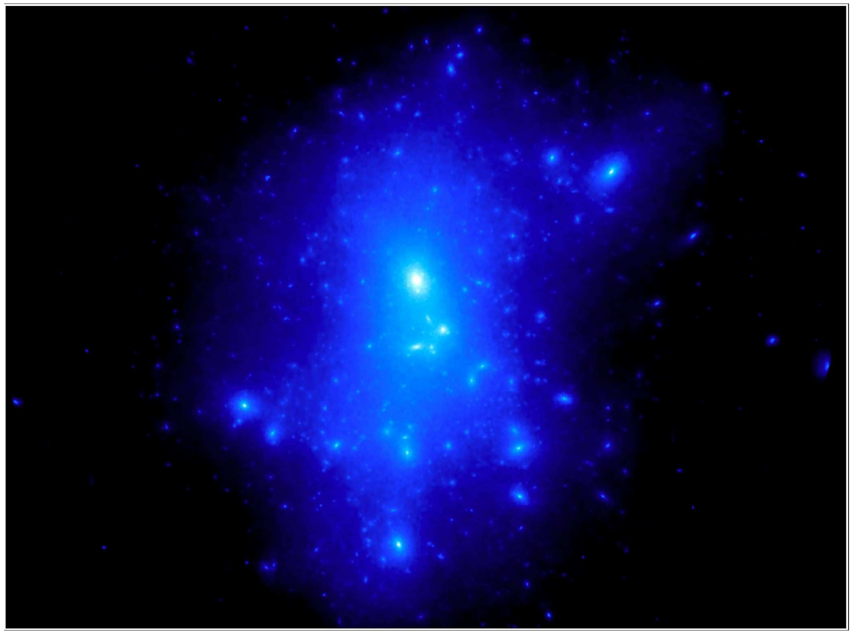
- Sterile neutrino DM is **decaying** with a cosmologically long life-time. Can we detect such decay?
- **Yes!** if you multiply a small number (probability of decay) with a large number (typical amount of DM particles in a galaxy $\sim 10^{70}$–10^{100})



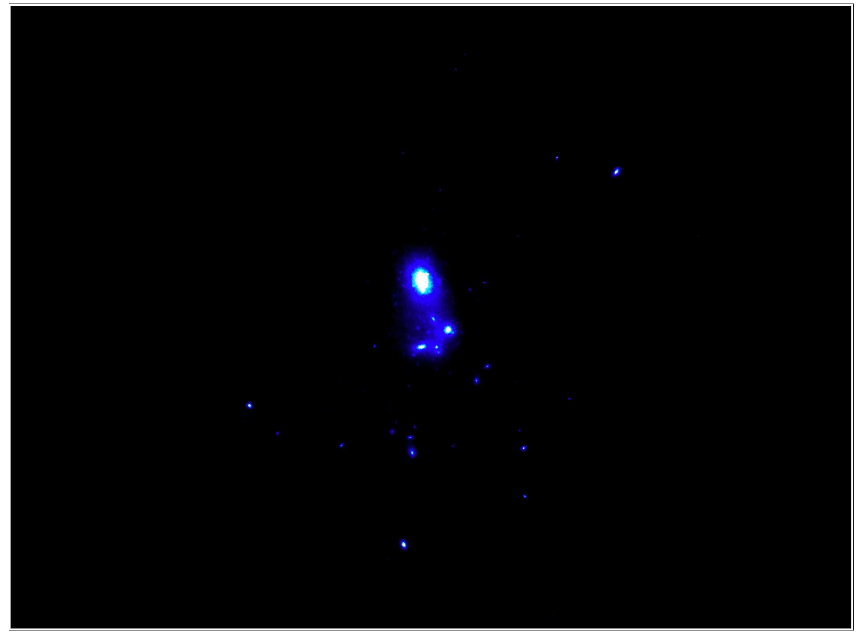


Expected signal from a galaxy at a particular energy (simulation from B. Moore)

Search for decaying dark matter



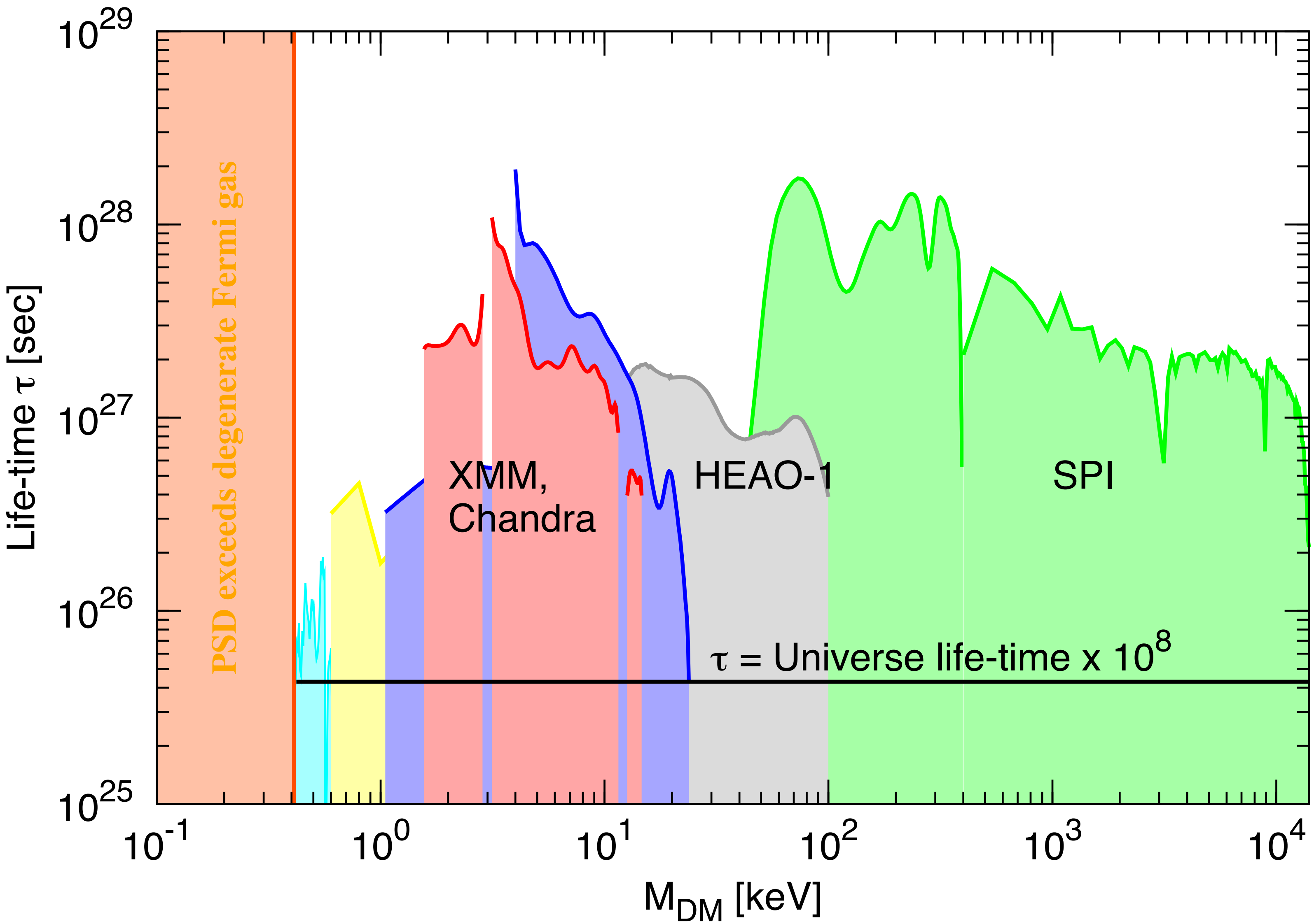
DM **decay** signal from a galaxy



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

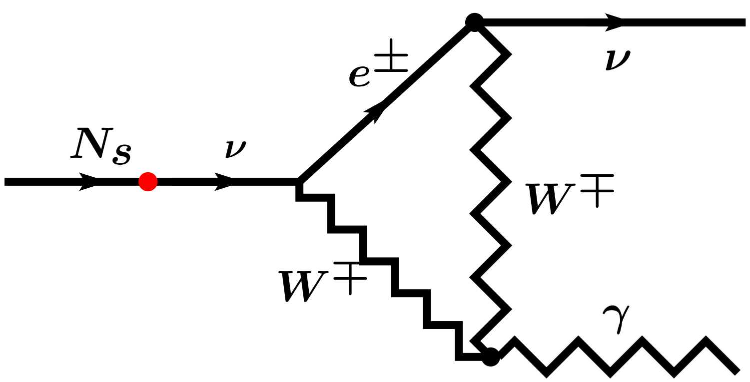
MW Riemer-Sørensen et al.; Abazajian et al.

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

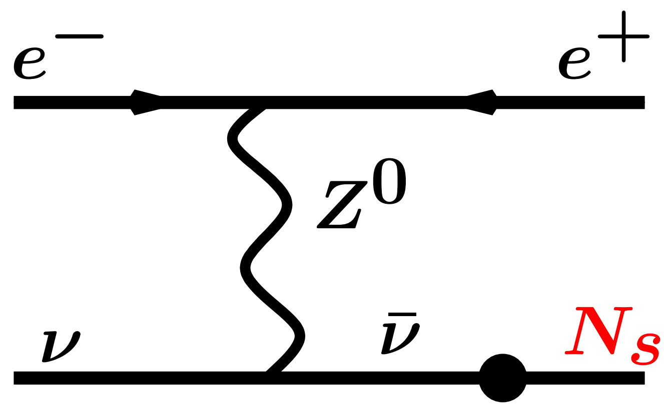
M31 Watson et al. 2006; Boyarsky et al

Properties of sterile neutrino DM

- The same interaction that is responsible for decay is responsible for production
- Sterile neutrino is **produced through mixing** with the thermal bath of active neutrinos in the primordial plasma



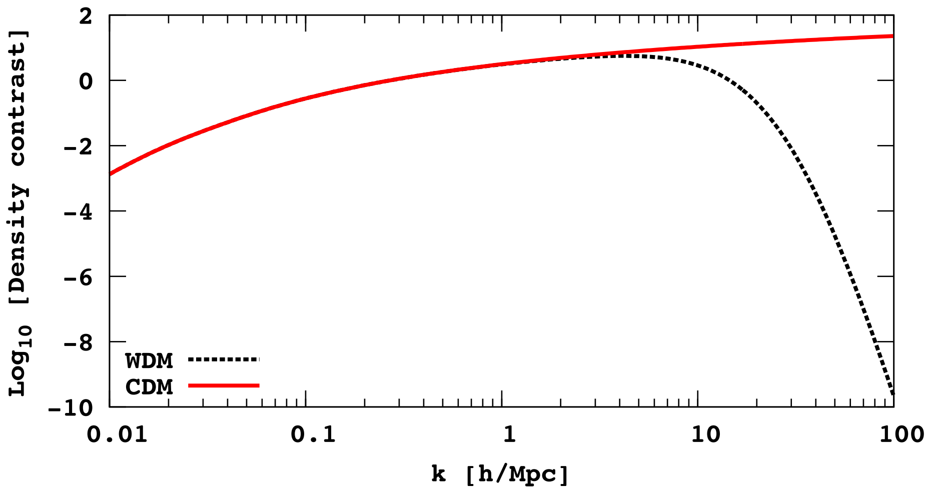
Decay of sterile neutrinos



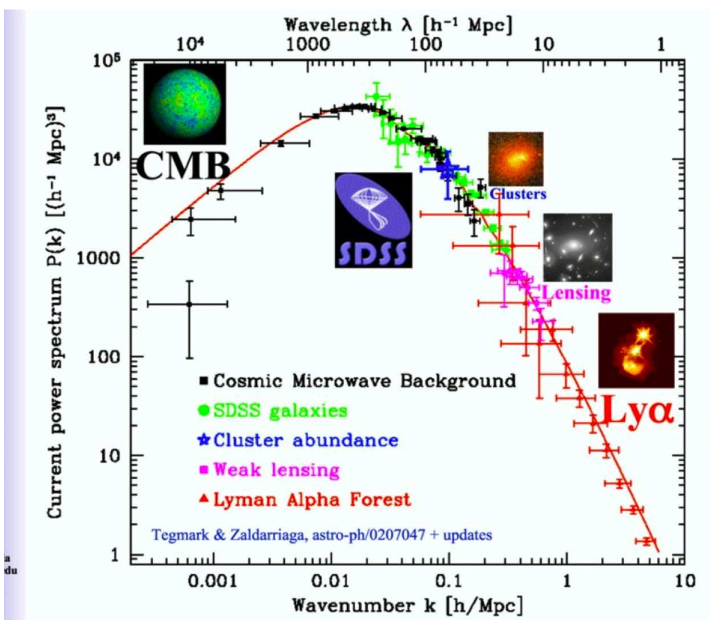
Production of sterile neutrinos

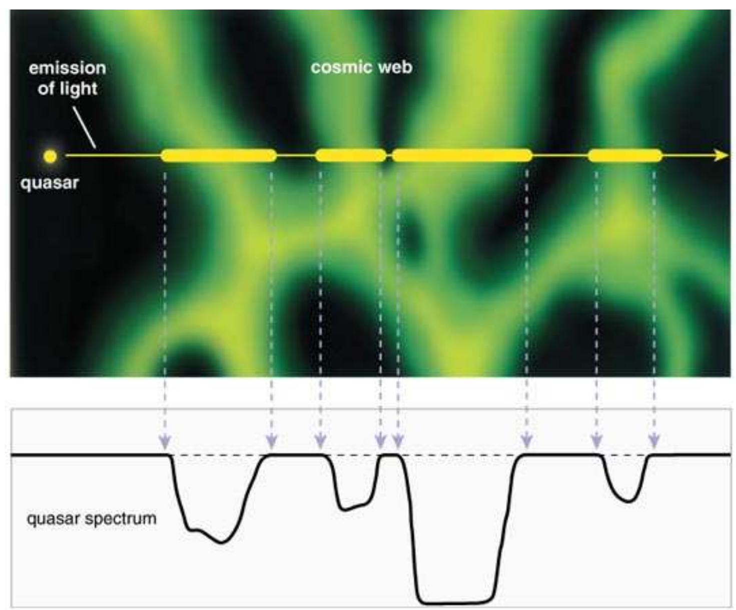
- Sterile neutrinos **are produced relativistic** and "cool down" in the radiation-dominated epoch. Such type of dark matter is called **warm dark matter**

What is WARM dark matter?



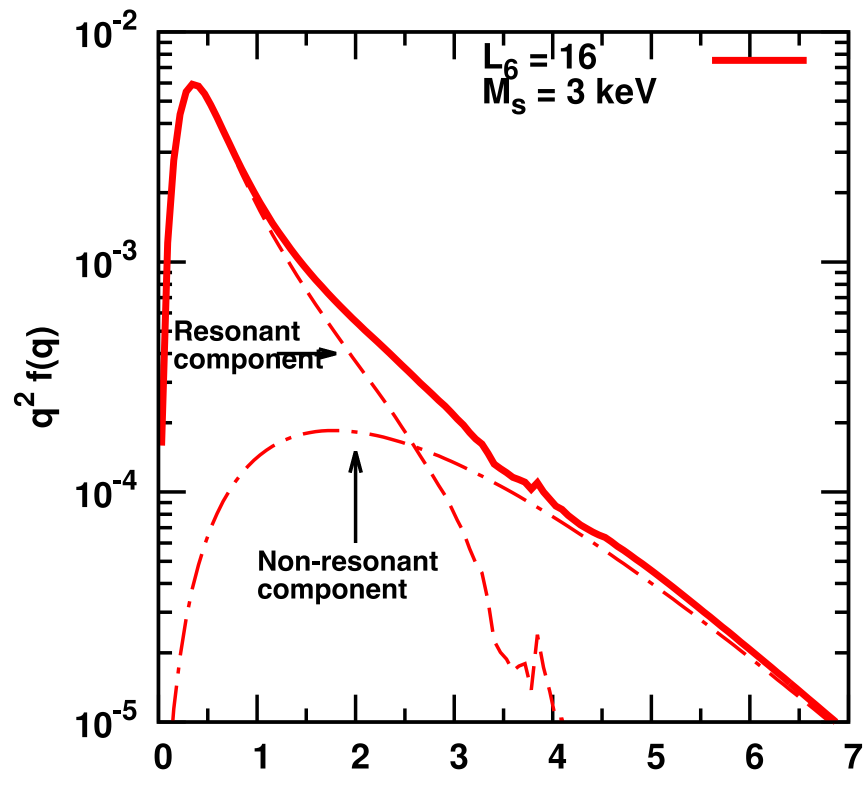
– Sterile neutrino suppression scale – below $\mathcal{O}(1\,\mathrm{Mpc})$
– Such scales can at the moment be probed by Lyman-α forest data





Sterile neutrino in the early Universe

- Sterile neutrino DM is produced via mixing with active neutrinos
- They are always **out-of-equilibrium** and are therefore sensitive to the content of the plasma
- In the presence of **large lepton asymmetry** the **MSW resonance** can take place and production of sterile neutrinos becomes much more effective
- Such sterile neutrinos are "colder" than their "non-resonant" counterparts



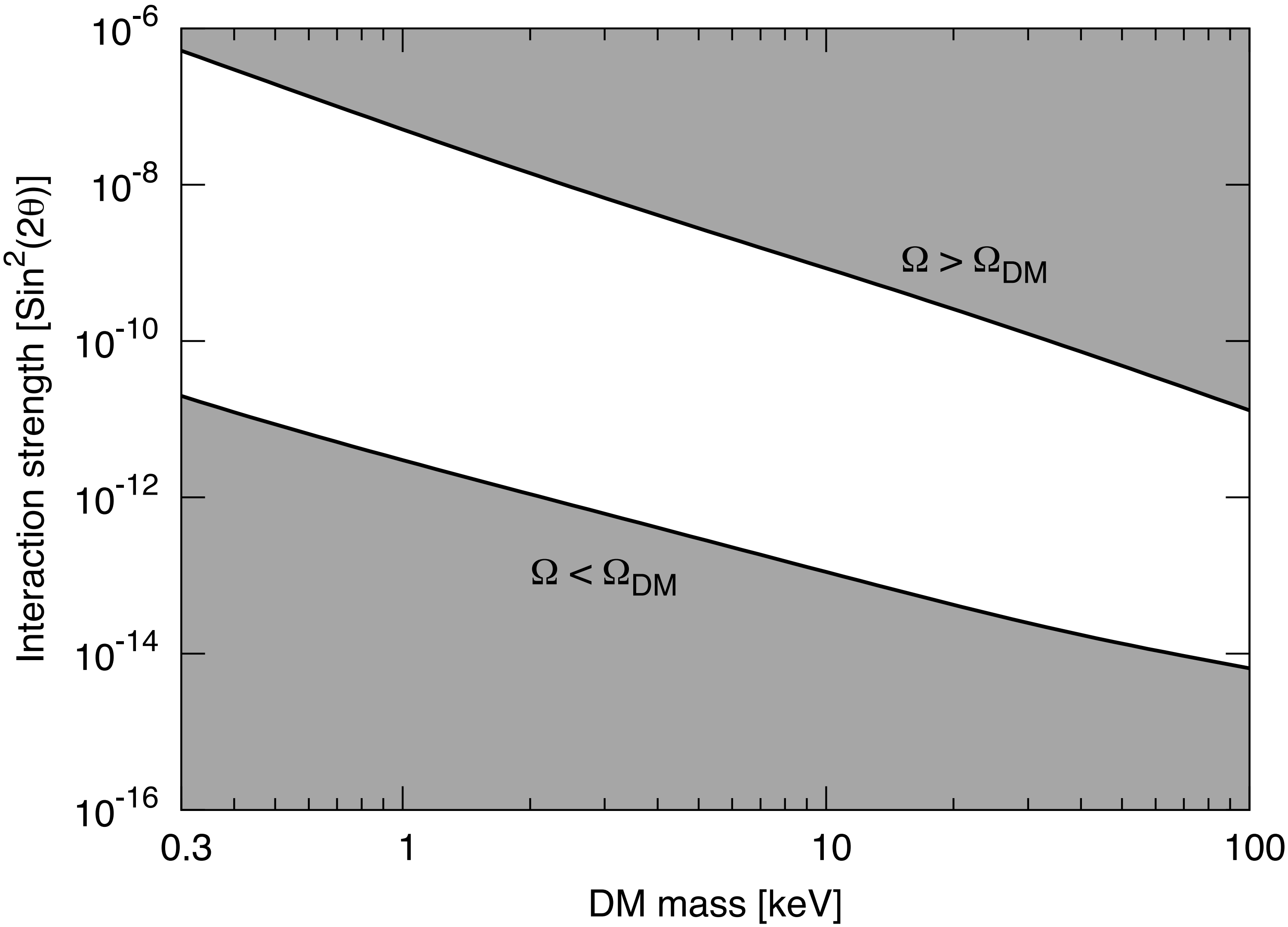
Shi & Fuller [astro-ph/9810076]

Laine & Shaposhnikov [0804.4543]

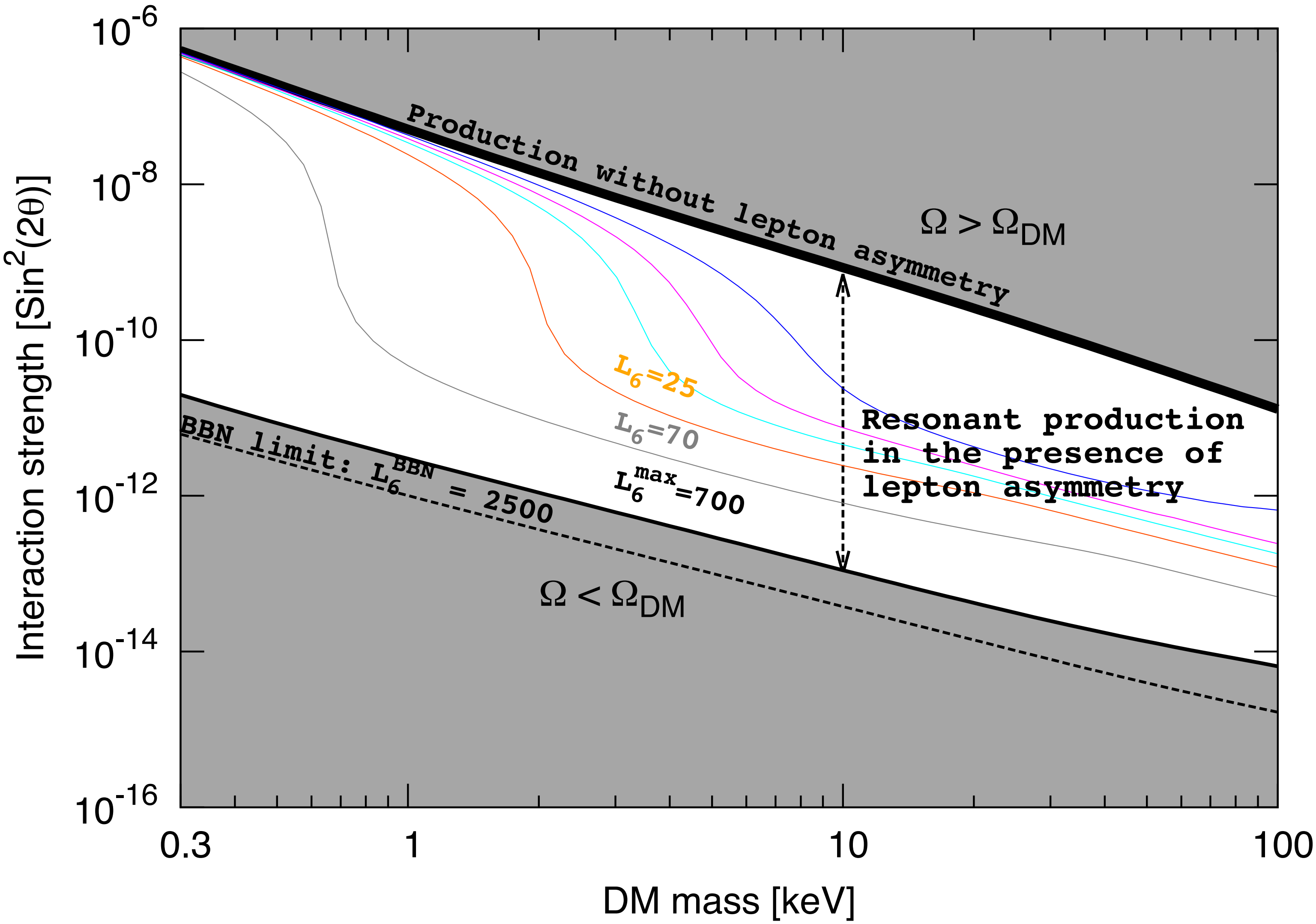
Window of parameters of sterile neutrino DM

Asaka, Laine, Shaposhnikov (2006)

Laine, Shaposhnikov (2008)



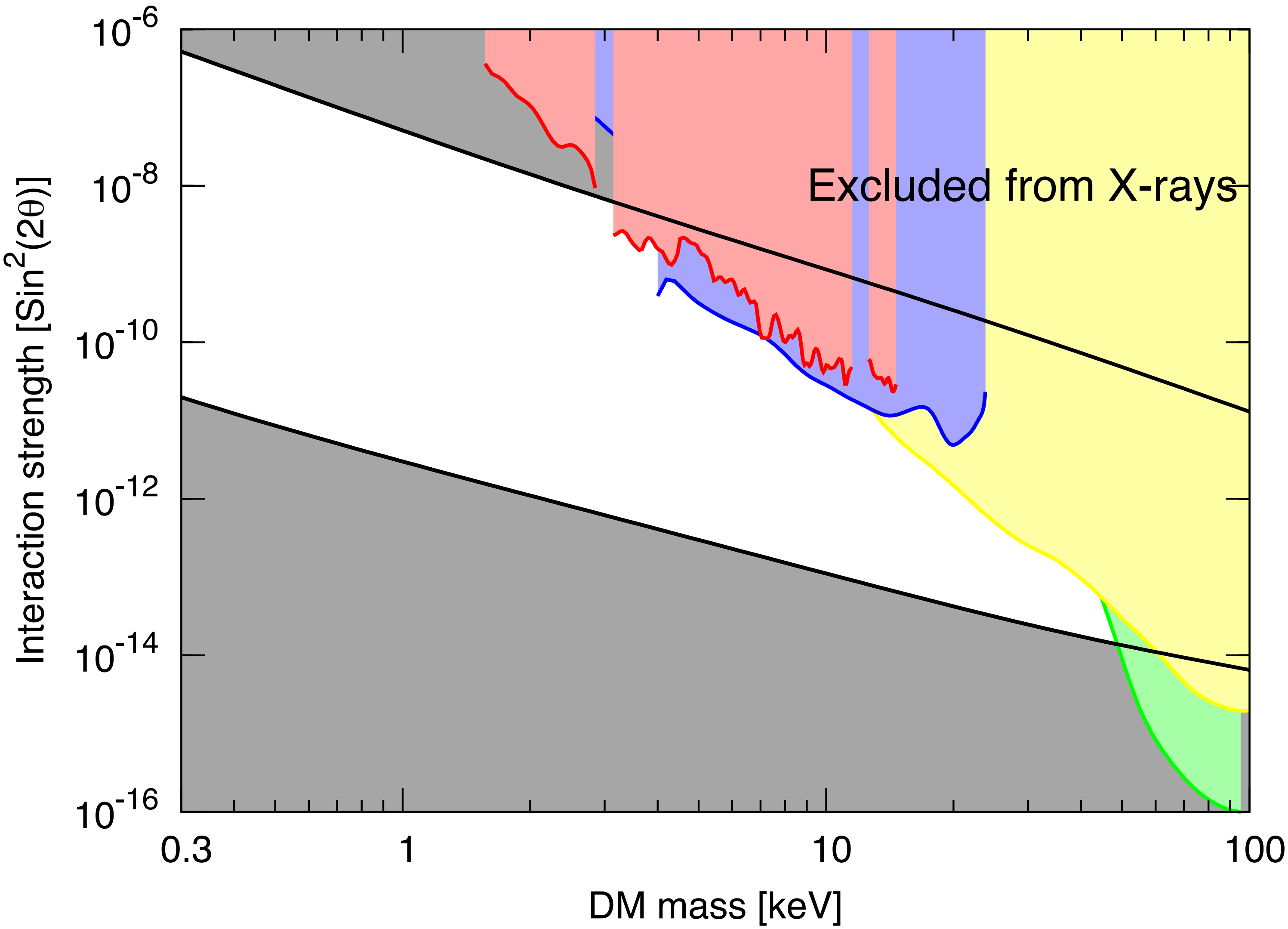
Window of parameters of sterile neutrino DM



Asaka, Laine, Shaposhnikov (2006)

Laine, Shaposhnikov (2008)

Window of parameters of sterile neutrino DM

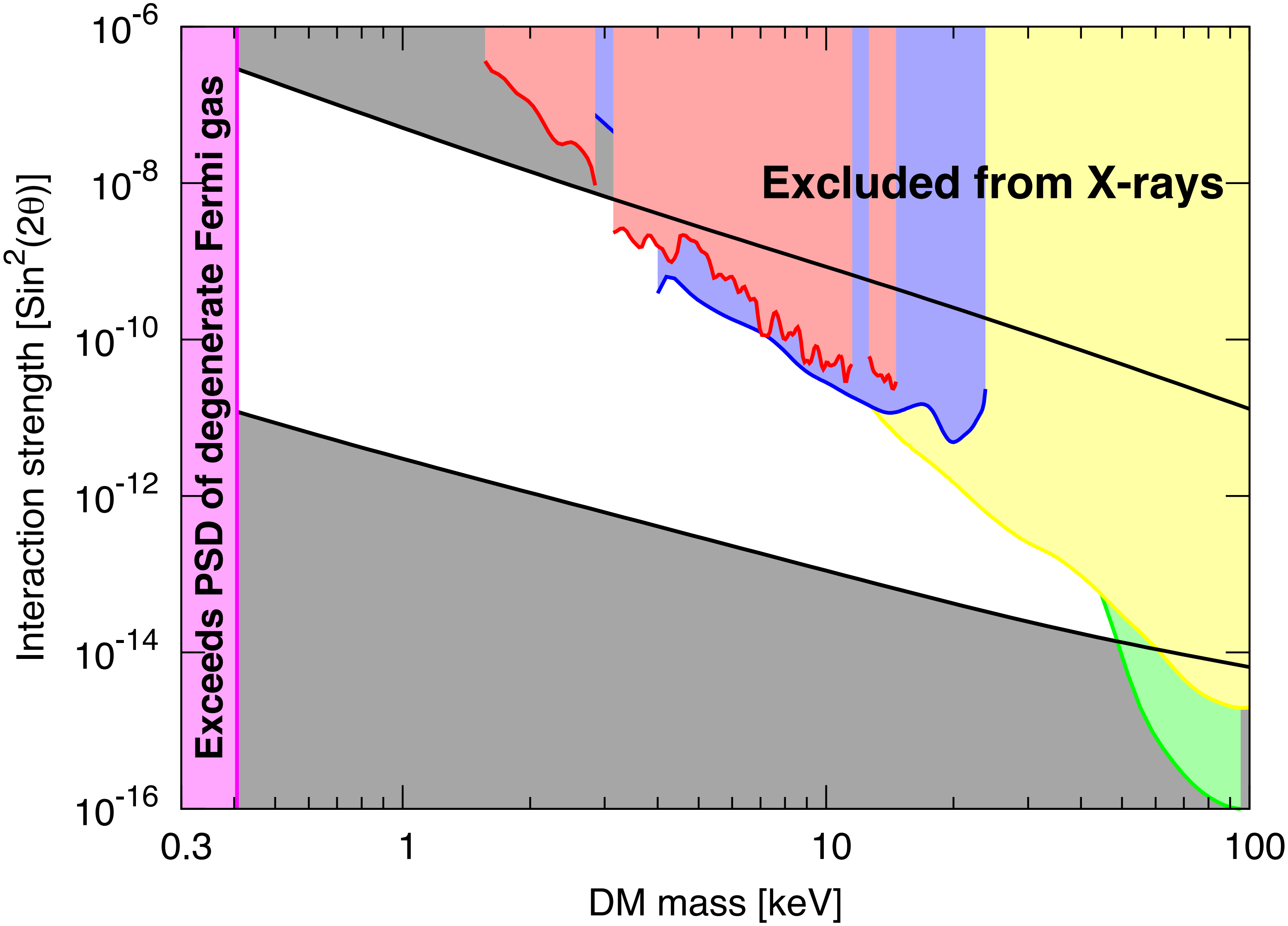


Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

Window of parameters of sterile neutrino DM



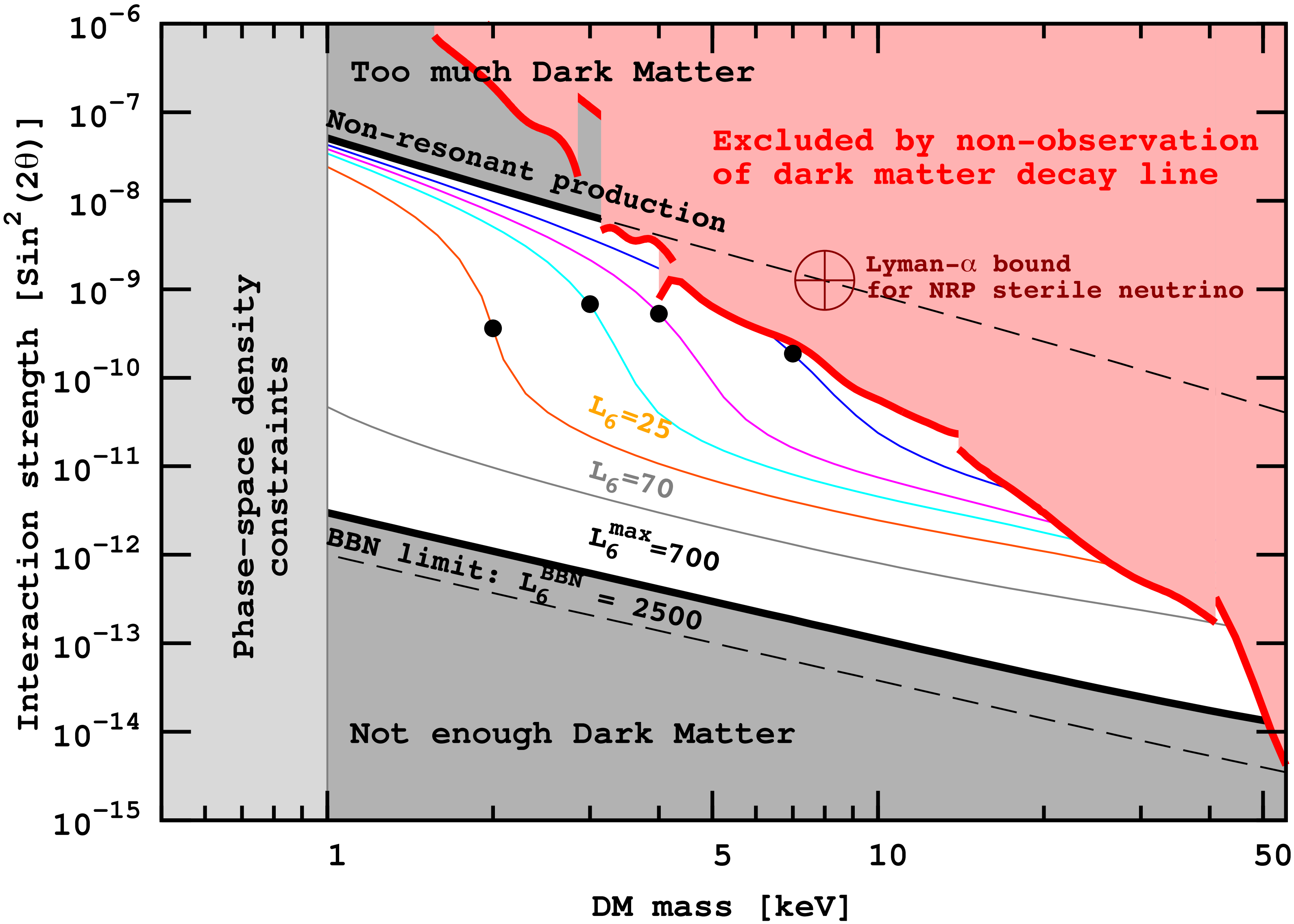
Asaka, Laine, Shaposhnikov

Laine, Shaposhnikov

O.R. and many others 2005-2010

Parameter space is bounded on all sides!

Sterile neutrino DM status



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

Review: [0901.0011]

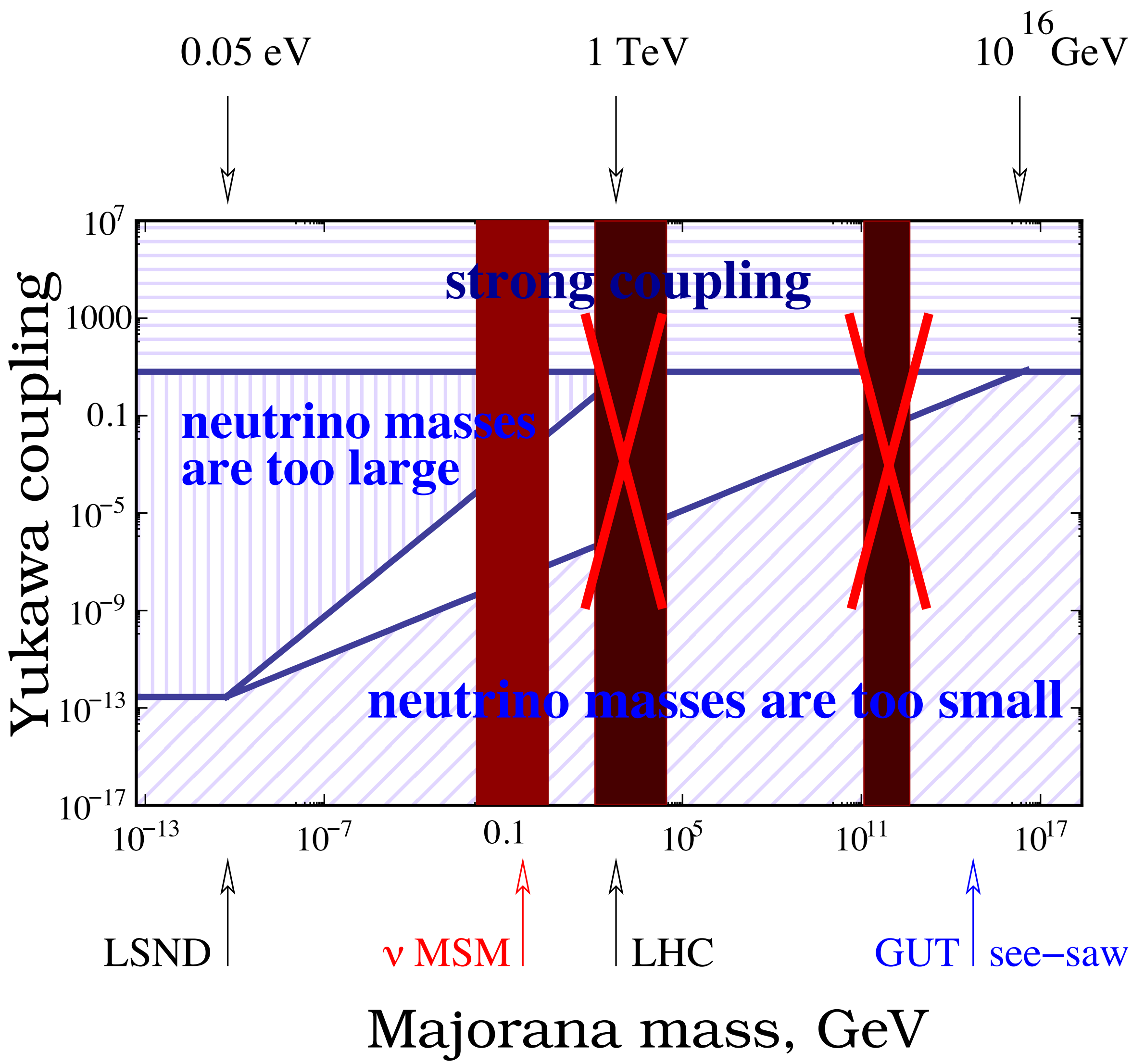
Black points – allowed by Ly-α forest data

Status of sterile neutrino DM

- Non-observation of X-ray from DM decay put strong limits on the possible mass of sterile neutrino DM (although for resonant production this limit is higher than 4 keV
- Production in the presence of large lepton asymmetry (MSW-like resonance) is perfectly consistent with both Lyman-α and X-ray data. Non-resonant only production is at tension at the moment.[1]
- The **only known mechanism** of generation of large lepton asymmetry at temperatures $\mathcal{O}(1\,\mathrm{GeV})$ is provided via decay of sterile neutrinos with the masses in the MeV–GeV range
- **The same sterile neutrinos** can be simultaneously responsible for neutrino oscillations and generation of **baryon** asymmetry of the Universe

[1] It is hard to determine the actual value of systematic errors in the Lyman-α method. It is possible that for different data and different data analysis this number could change

Large lepton asymmetry selects one mass region



Widths of baryogenesis stripes are not up to scale!

Sterile neutrinos can ...

	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

- The idea that neutrino masses are explained by the type I see-saw leads to the hypothesis of the existence of massive neutral super-weakly interacting particles
- Cosmology (DM and BAU) require for something like this – heavy particles, long-lived, neutral, interacting weaker than neutrinos

...resolve all BSM puzzles

	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

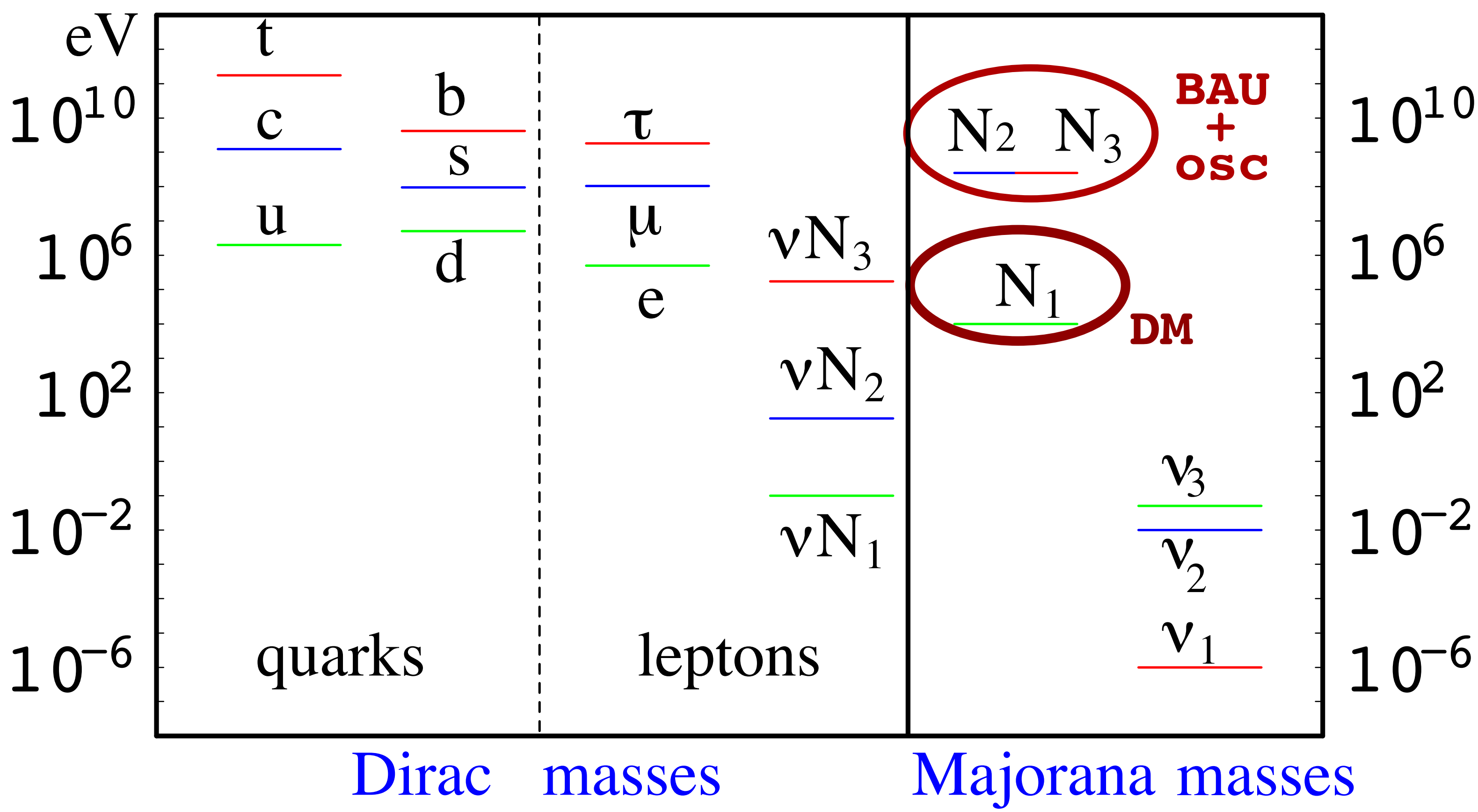
Neutrino Minimal Standard Model

(νMSM for short)

Asaka & Shaposhnikov (2005) and many subsequent works

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]

CONCLUSIONS

"Nightmare scenario"

The νMSM is possibly the only model today that predicts as new physics should be probed in the case of negative results for all these experiments

This slide has been written several years ago and remains up-to-date

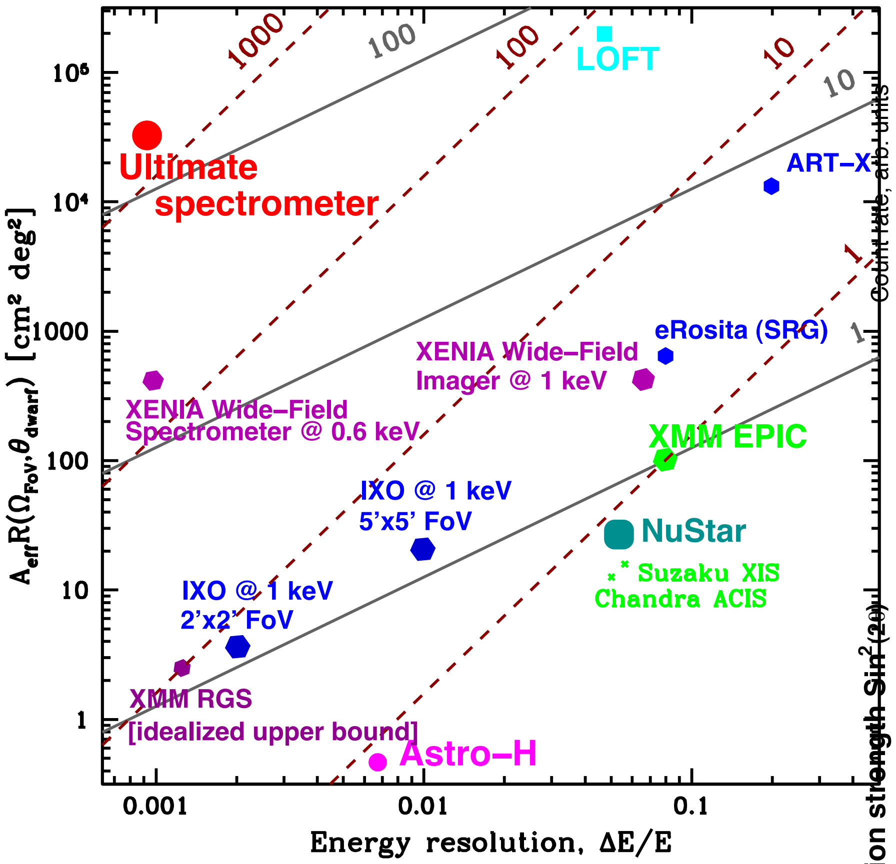
- Standard Model Higgs with the mass above ~ 125 GeV and **no other particles discovered** at the LHC
- Sum of neutrino masses $\sum m_\nu \approx (1-2) m_{\text{atm}}$
- In the $0\nu\beta\beta$ mass $m_{\beta\beta}$ at the level $1-10$ meV
- Negative results of all dark matter direct detection experiments and no signatures of dark matter annihilation in γ-rays / anti-matter
- Primordial spectral index $n_s = 0.96\ldots$, Gaussian perturbations and no tensor modes as seen by Planck
- No "dark radiation"

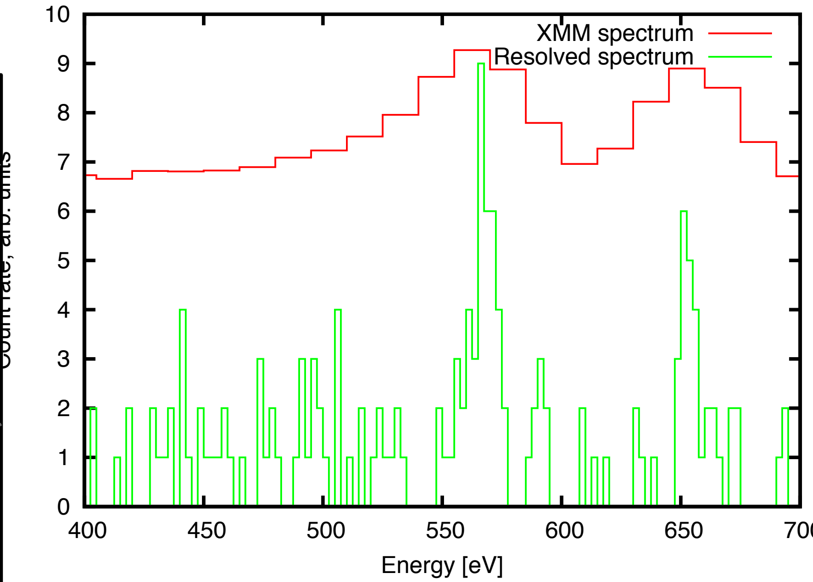
Verifying the νMSM

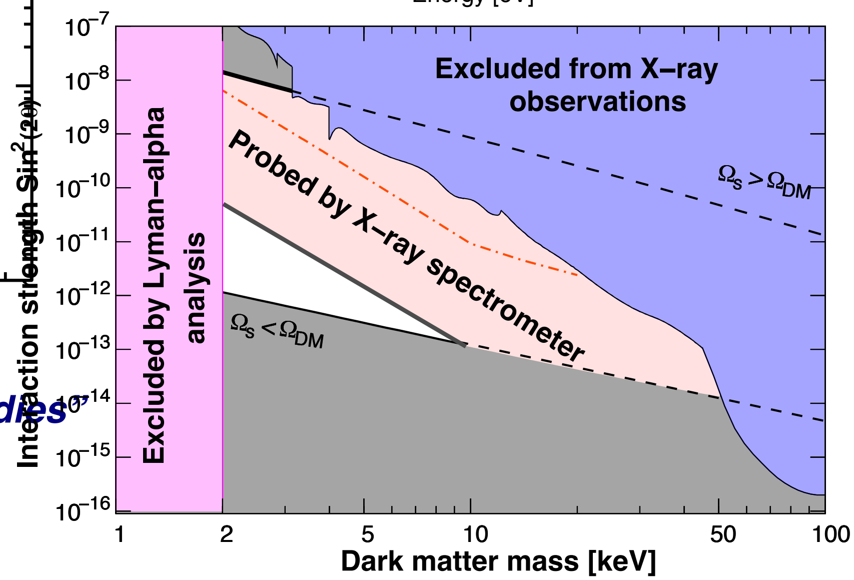
Neutrino Minimal Standard model predicts can be verified in "intensity" and "cosmic" frontier experiments

- 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 (such as **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**).
- Sterile neutrino warm (actually COLD+WARM) dark matter affects the matter power spectrum at $k \sim 1 - 10$ h/Mpc (**next round of weak lensing/Lyman-α forest experiments**)
- Parameters of two heavier particles (measured intensity frontier experiments) and the dark matter (measured at cosmic frontier) are **correlated**

X-ray spectrometer to search for decaying Dark Matter

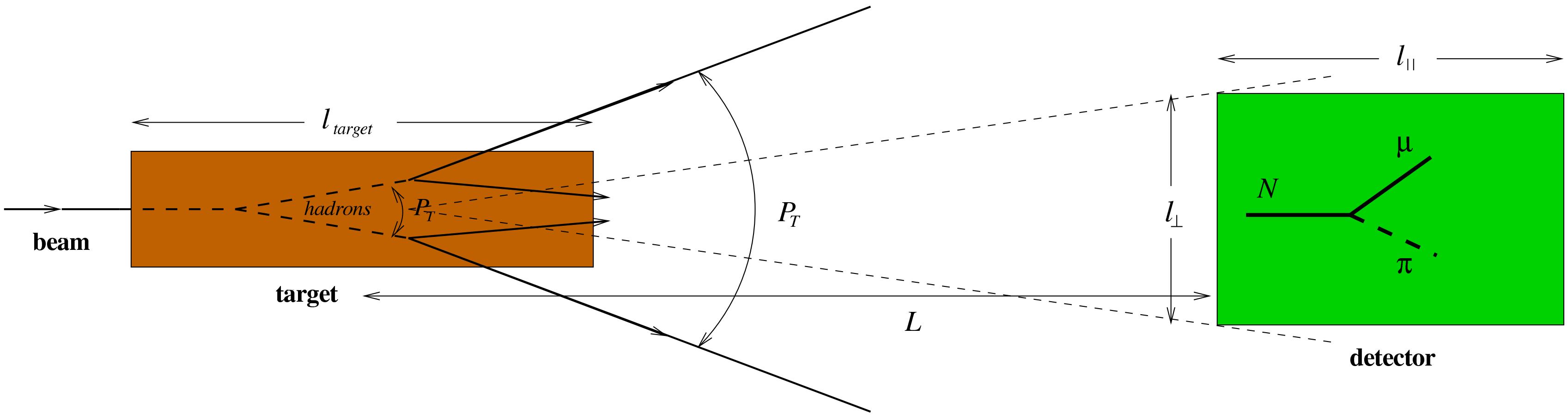






See review *"Next decade in sterile neutrino studies"* [1306.4954]

Ultimate detector for BAU sterile neutrinos



– 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 hundred meters.

See proposal to European Strategy Preparatory Group

A theory of everything?

- The νMSM is based on a new paradigm: **no new physics between Electroweak and Planck scales**. Within this paradigm a consistent quantum field theory valid up to Planck scale and resolving all major BSM problem can be built
- Coupled with Higgs inflation, the νMSM provides the resolution of all **observable BSM puzzles** (neutrinos masses, BAU, DM, inflation)
- No hierarchy problem (Higgs mass is stable as there are no new heavy particles)
- Hierarchy between Fermi and Planck scale is natural (in the 't Hooft's sense – putting $M_W/M_{\text{Pl}} \to 0$ increases symmetry)
- When coupled to gravity this theory is asymptotically safe

Shaposhnikov & Wetterich'09

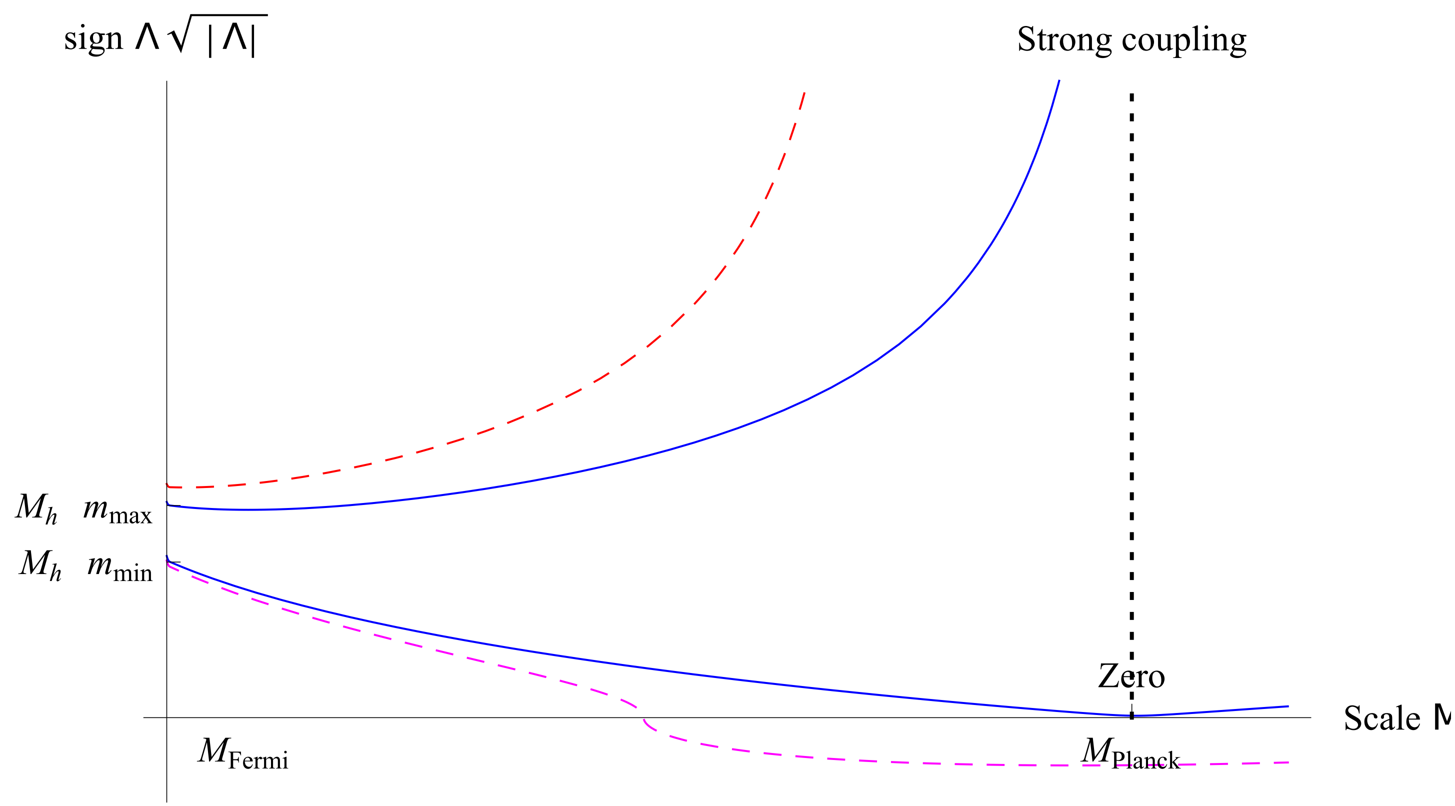
To summarize:

Can νMSM be the next “standard model of particle physics”?

THANK YOU FOR YOUR ATTENTION!

BACKUP SLIDES

Can SM be valid till Planck scale?



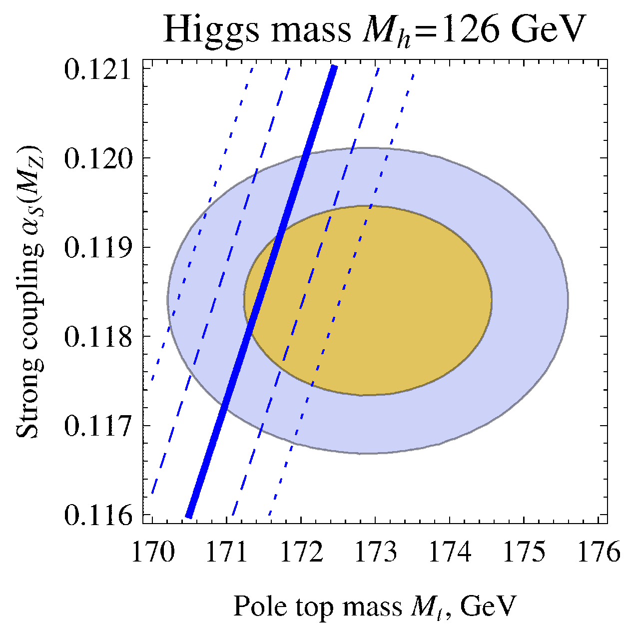
– **Yes!** if the Higgs boson is above 129 ± 6 GeV (uncertainty comes from existing experimental uncertainties in the mass of the top quark and α_s)

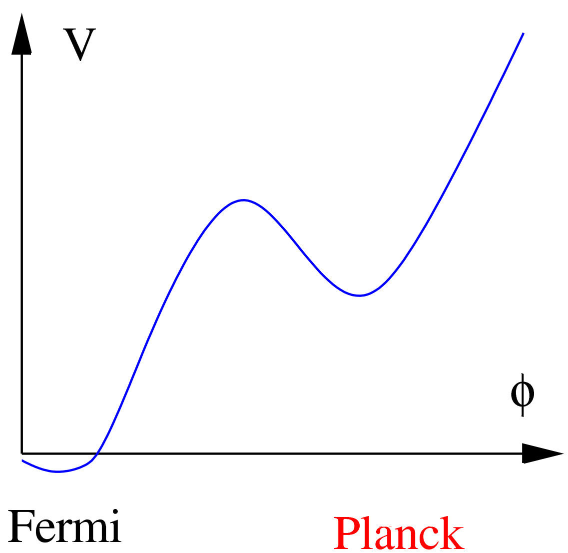
Bezrukov et al. "*Higgs boson mass and new physics*" [1205.2893]

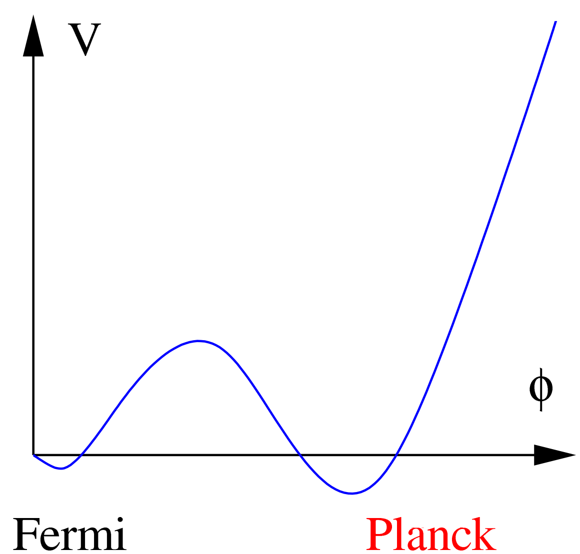
– Difference in conclusion with **Degrassi et al. [1205.6497]** comes from different treatment of experimental uncertainties on top mass

Can SM be valid till Planck scale?

[1205.2893]

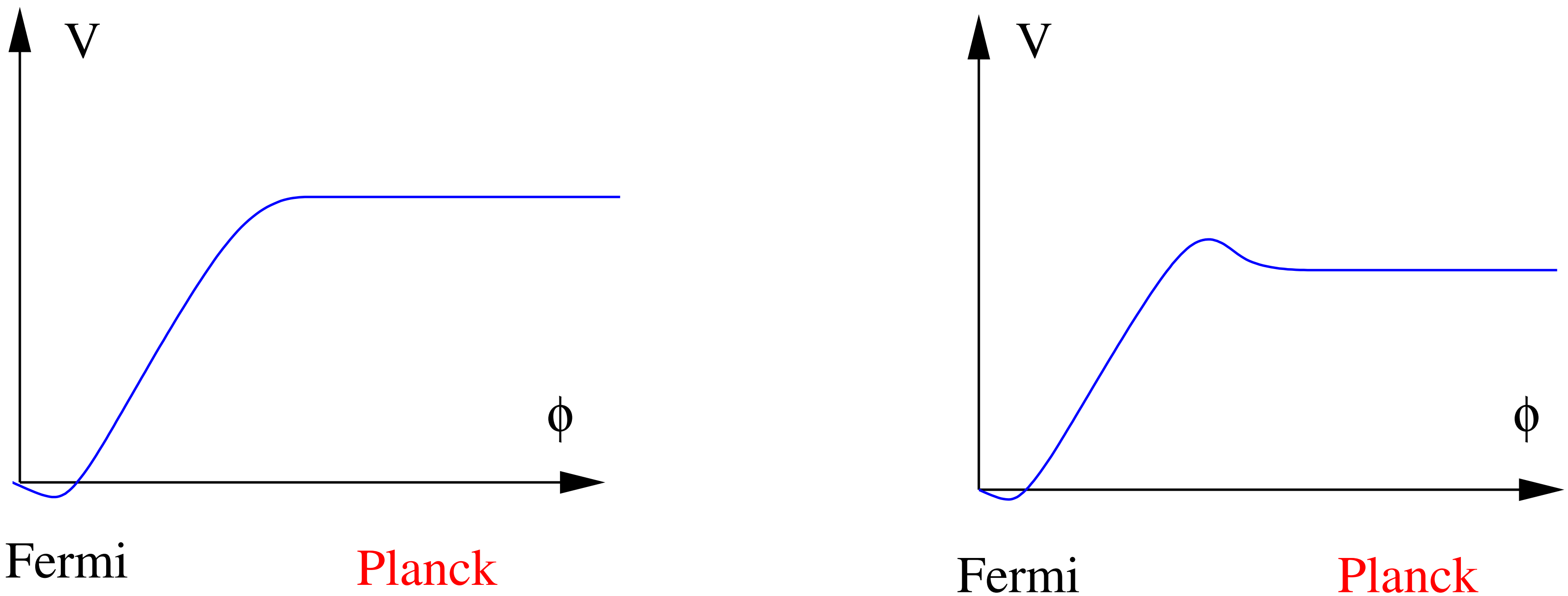






SM valid up to Planck scale and inflation

[1205.2893]



- Non-minimal Higgs coupling to gravity ($\xi_1 H^\dagger H R$) gives a slow-roll perfectly consistent with the Planck results

- Consistency of the SM is valid up to the Planck scale is required in order not to spoil the slow-roll potential

Let's take this seriously

- Ok, let us accept that the Standard Model is valid up to the Planck scale. What do we give up/gain?
- You need **something like νMSM** to solve your BSM problems (neutrino masses, DM, BAU)
- The νMSM is a testable and falsifiable model (Parameter space is bounded on all sides)
- Adding dilaton scalar generates all dimensionful couplings in the theory: Higgs mass, Majorana masses, Planck scale
- Theory can be made scale-invariant at quantum level but would become non-renormalizable and lose predictability around Planck scale
- Hierarchy problem (stability of Higgs mass)? $\Rightarrow$ Gone (no heavy particles)

Let's take this seriously

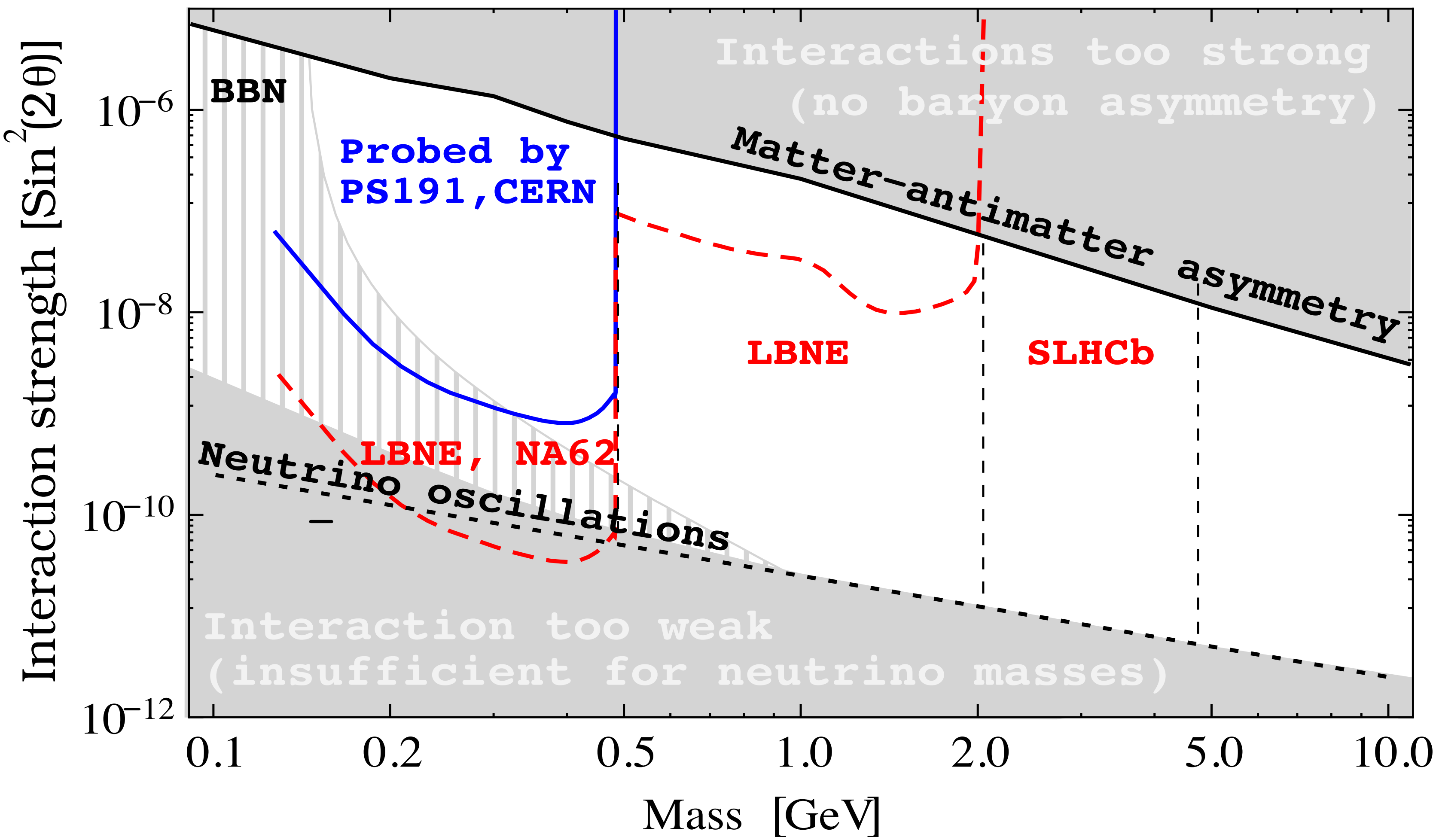
- Hierarchy between Fermi and Planck scale? ⇒ Natural (in the 't Hooft's sense – putting $M_W/M_{\mathsf{Pl}} \to 0$ increases symmetry)

- Grand Unification is gone?
  ⇒ Not necessarily. For example, adding some Planck suppressed higher-dimensional operators you can still get GUT (but at Planck scale)
  Shafi & Wetterich '88

- Explanation of charge quantization is gone if there will be no GUT?
  ⇒ No. In any model with Majorana right-handed neutrinos charges of particles are quantized as a consequence of gauge anomaly cancellation
  Babu & Mohapatra '90

- Dilaton – new massless degree of freedom

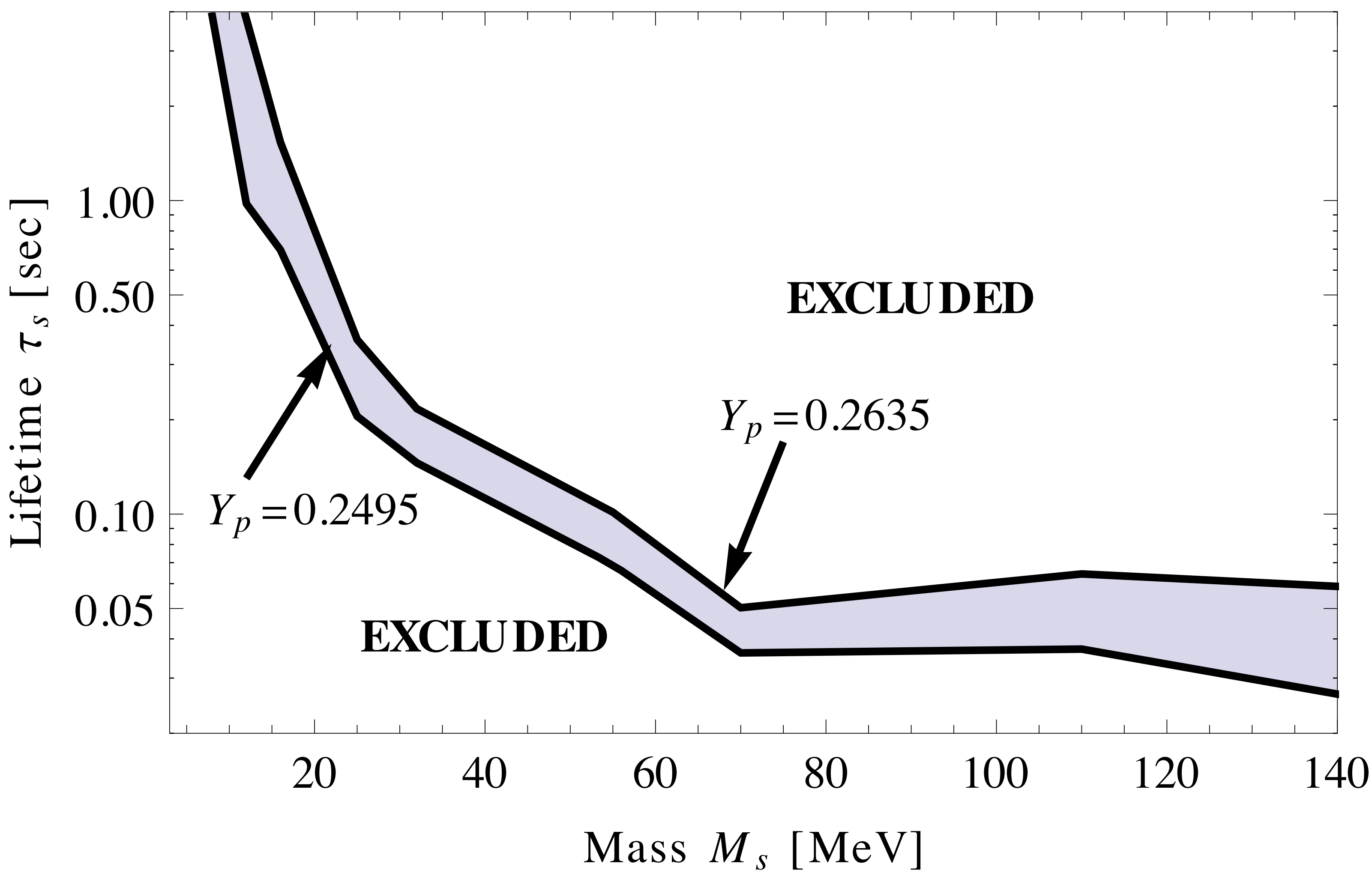
Parameter space of heavy sterile neutrinos



Asaka, Canetti, Gorbunov, Shaposhnikov, 2005–2011;

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

Sterile neutrinos and ^{4}He abundance

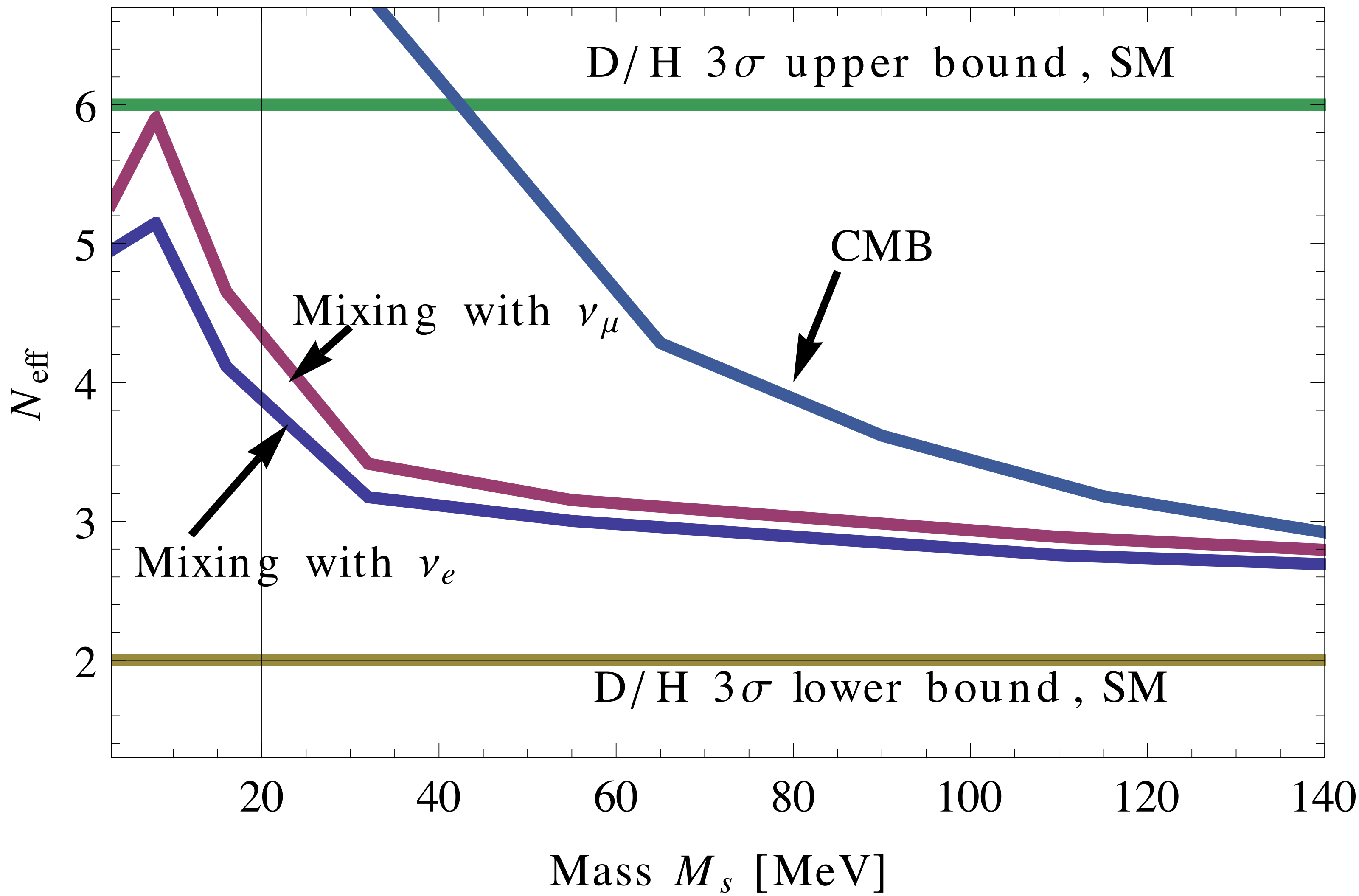


O.R. & Ivashko
[1202.2841]

2σ bounds based on Izotov & Thuan 2010

Decay of sterile neutrinos increases Helium-4 abundance

Sterile neutrinos and N_{eff}

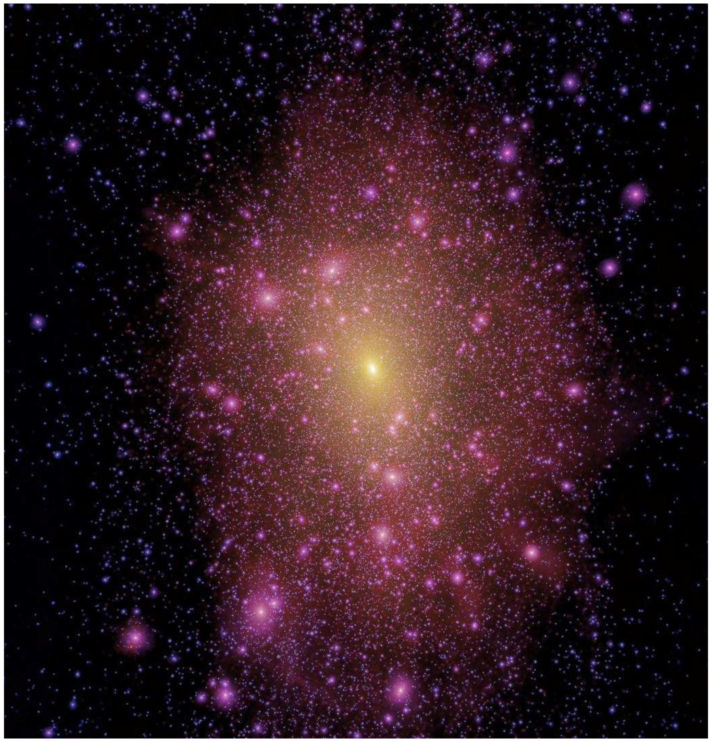


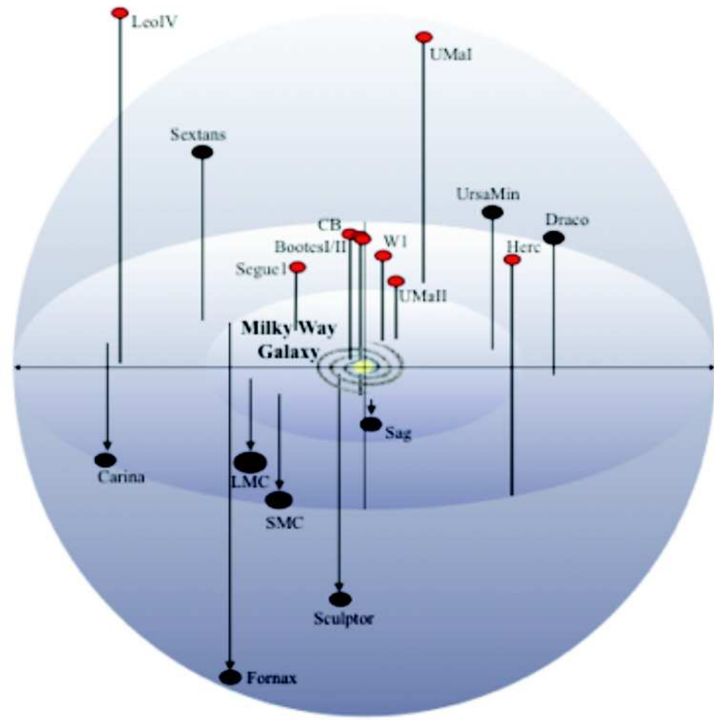
O.R. & Ivashko
[1202.2841]

Decay of sterile neutrinos affects N_{eff}

Dark matter at galactic scales

Halo substructure in "cold" DM universe



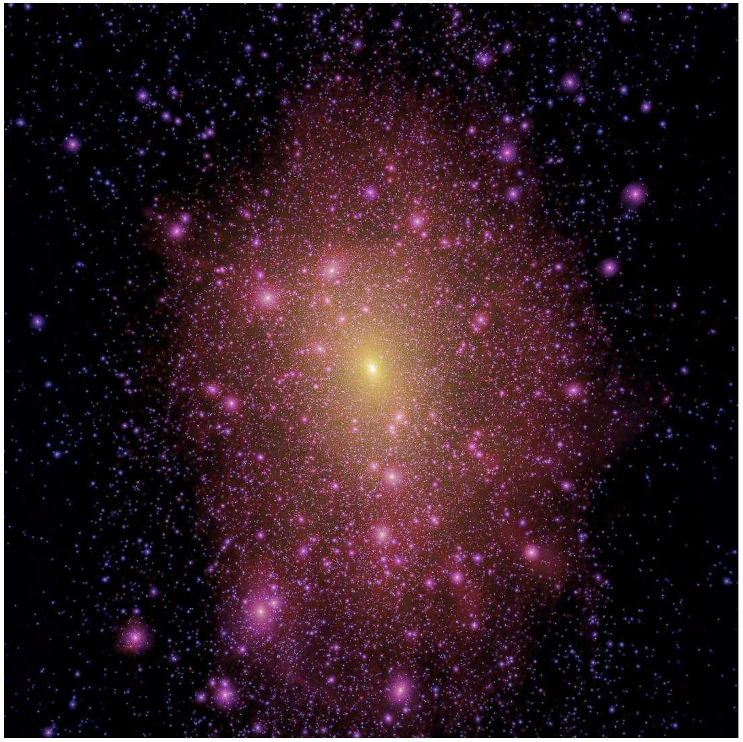


COLD DM models predict millions of substructures within a galaxy like Milky Way

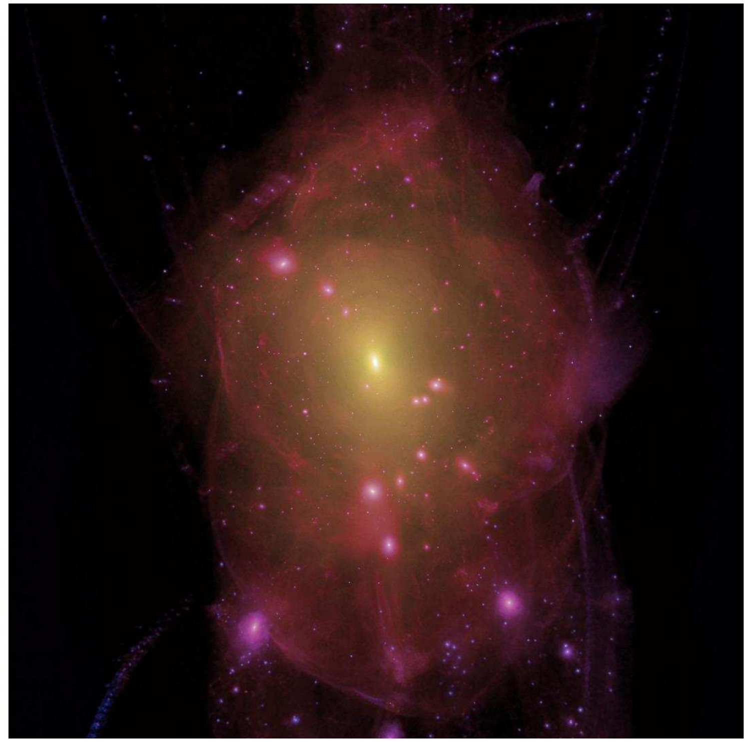
Only $\sim$ 30 are observed within our Galaxy. M. Geha 2010

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 "warm" DM universe



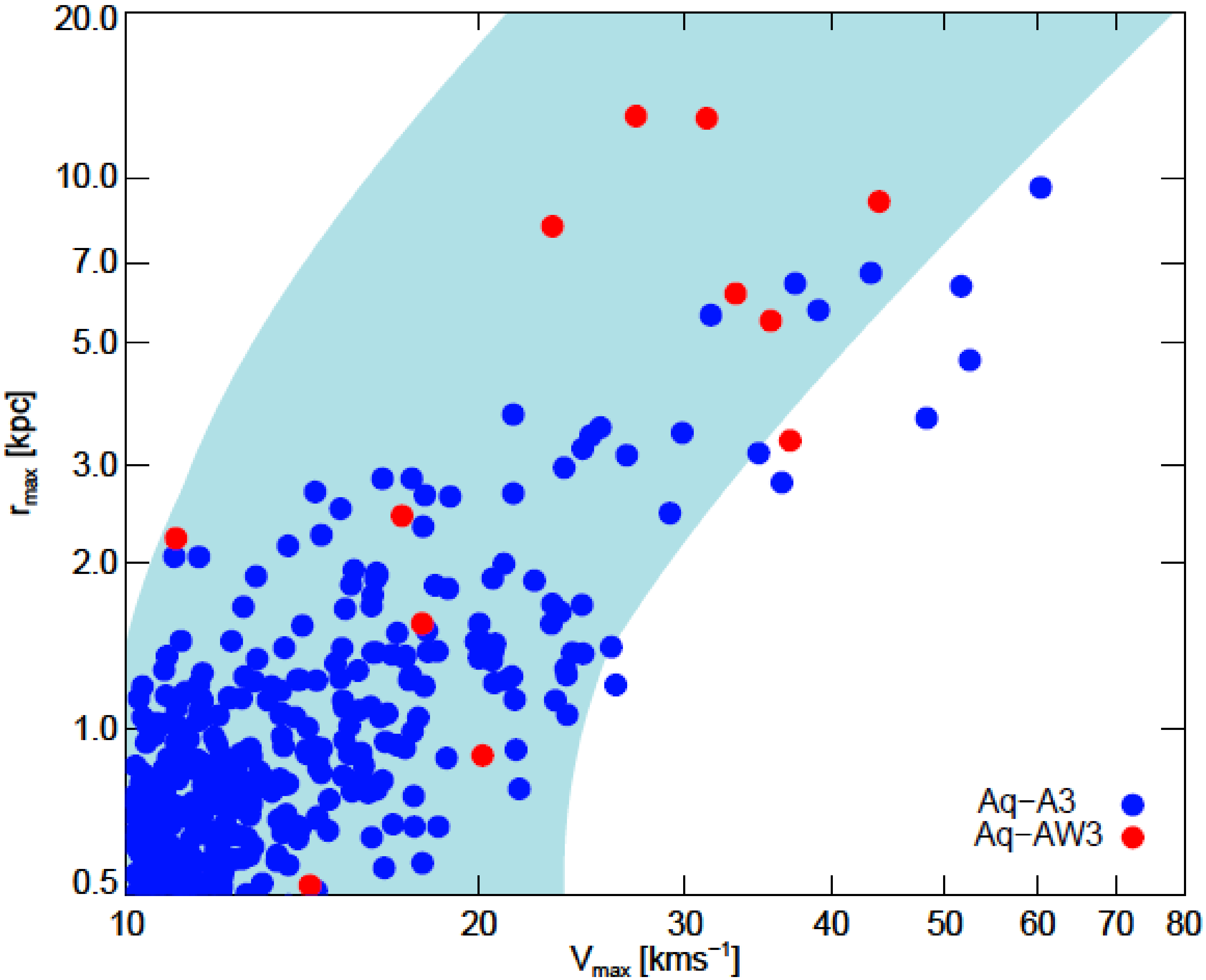
Aq-A-2 CDM halo



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

Abundance of large satellites

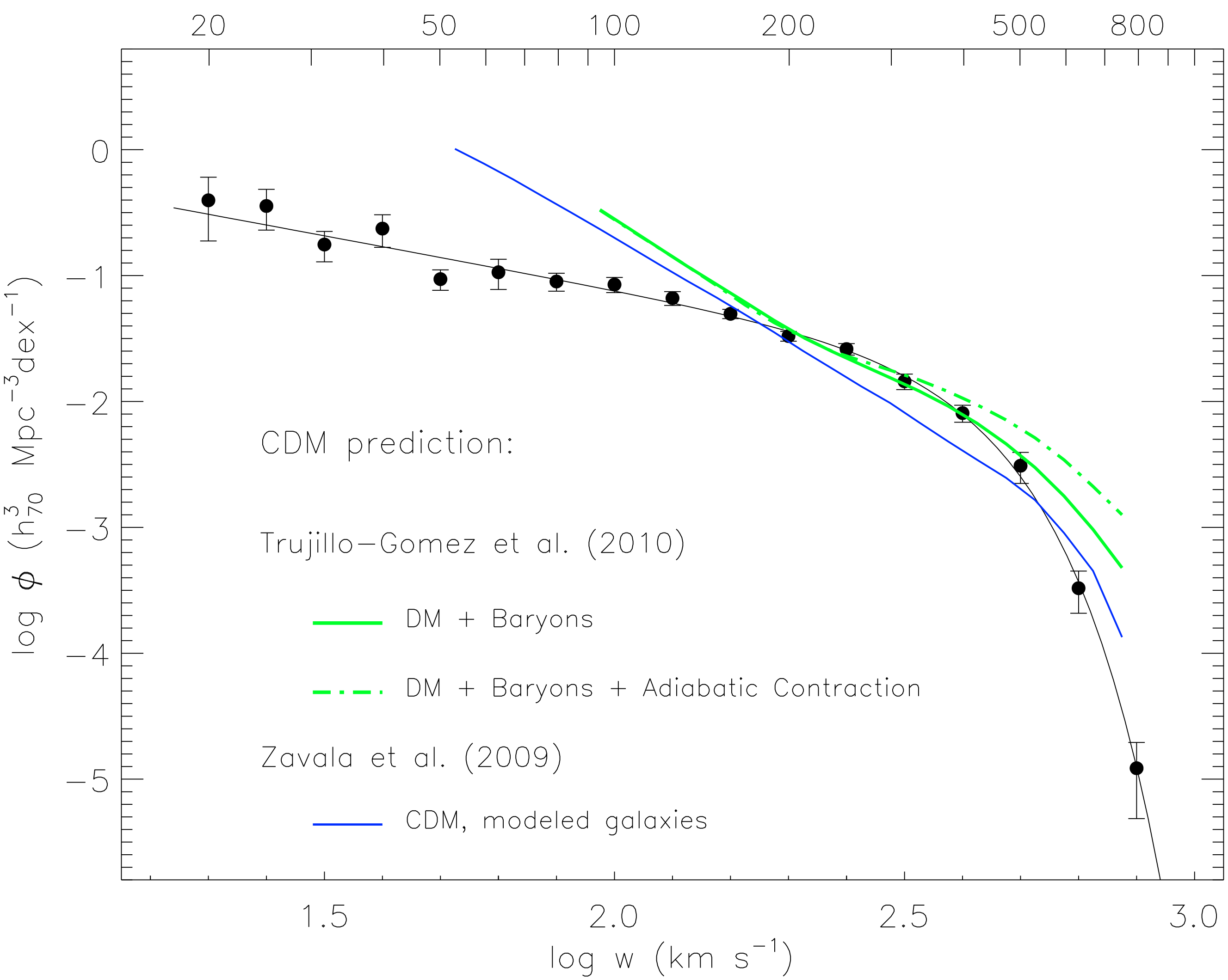


Strigari, Frenk, White (2011)

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

ALFALFA Velocity width function vs. CDM

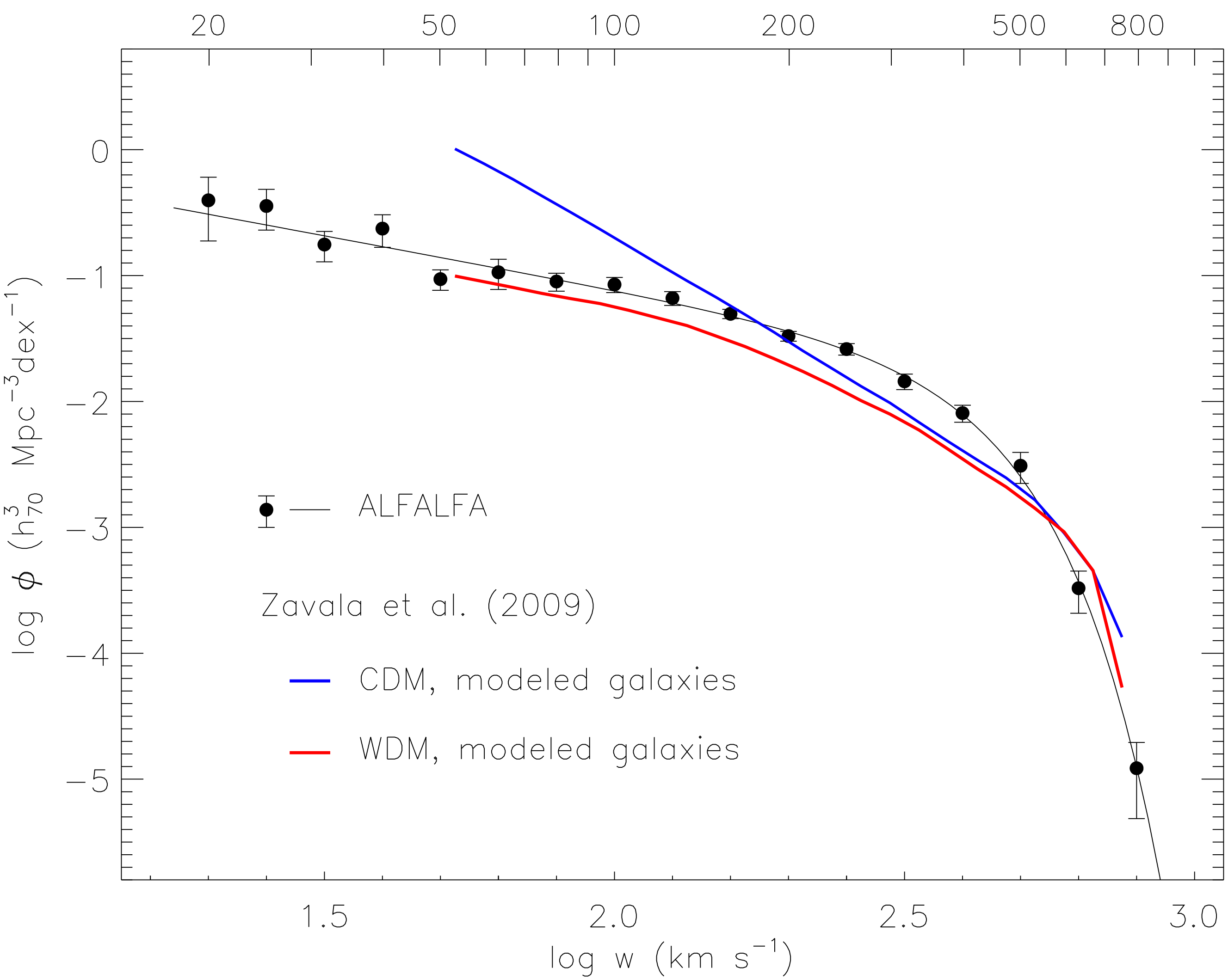
Papastergis+ [1106.0710]



ALFALFA (HI) survey. Deviations from ΛCDM predictions for $v_{rot} \lesssim 100$ km/sec

Velocity width function vs. WDM

Papastergis+
[1106.0710]



ALFALFA (HI) survey. Deviations from ΛCDM predictions for $v_{rot} \lesssim 100$ km/sec

Leptogenesis in the νMSM

Leptogenesis via oscillations

Akhmedov, Smirnov, Rubakov'98

1) Need to choose **at least two** sterile neutrinos that **do not thermalize** until T_{sph}

- At $T > m_t$ thermalization goes via Higgs exchange $N + t \leftrightarrow \nu + t$ or $H \leftrightarrow N + \nu$, dots
- $\Gamma_{therm} \sim \frac{9|F|^2 f_t^2}{64\pi^3}$ compares to $H(T)$ at $T_{eq} \sim 5 M_N$.
- Therefore, if $M_N < M_W$ – particles not thermalized until sphalerons freeze-out

2) Sterile neutrinos are produced (e.g. via $H \to N + \nu$)
no lepton number is any sectors so far!

3) Sterile neutrinos **oscillate into each other** in the CP-violating way
recall, that we can have CP-phases in the Yukawa matrix of sterile neutrinos!

4) This generate some effective "lepton number" in sterile (and, therefore, in active) sectors

Leptogenesis via oscillations

- The frequency oscillation between two neutrinos with masses $M_1 \approx M_2$ is given by

$$\omega_{\text{osc}} \sim \frac{M_1^2 - M_2^2}{E_N} \approx \frac{M_N \Delta M(T)}{T}$$

- If $\omega_{\text{osc}} \gg H(T_{\text{sph}})$ – many oscillations had occurred by the time of sphaleron freeze-out and lepton number is "washed out"

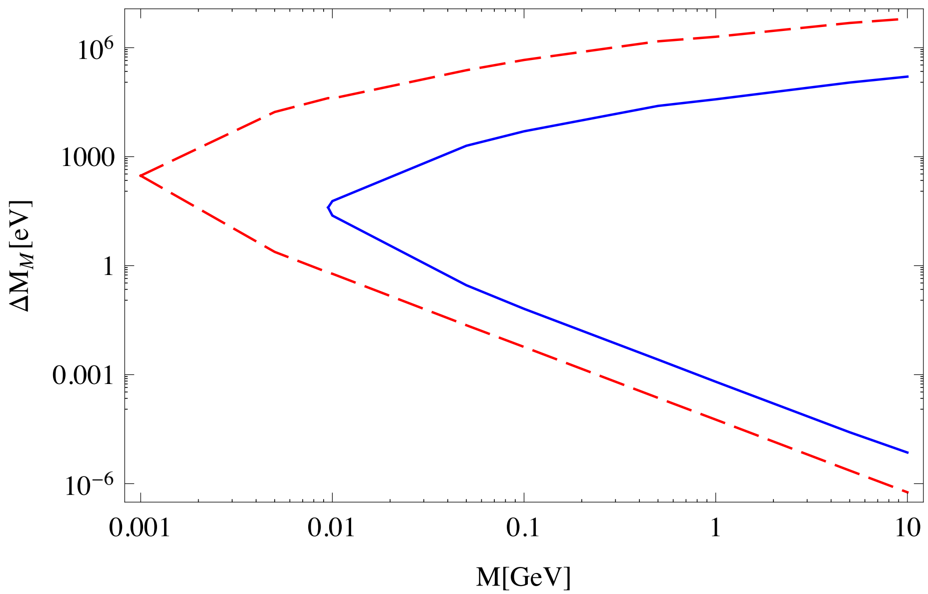
- If $\omega_{\text{osc}} \ll H(T_{\text{sph}})$ – essentially no oscillations had occurred and lepton number in the sterile sector did not have time to develop

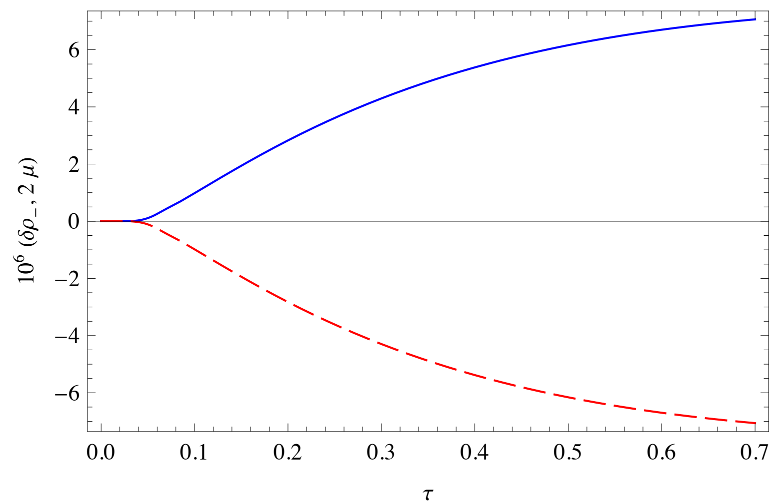
- Optimal condition:

$$\omega_{\text{osc}} \sim \frac{T_{\text{sph}}^2}{M_*} \Longrightarrow \big(M_* M_N \Delta M(T)\big)^{1/3} \sim T_{\text{sph}}$$

Leptogenesis via oscillations

Canetti & Shaposhnikov [1006.0133]





- Mechanism works down to $M_N \sim 1$ MeV
- Roughly $\Delta M(T_{\text{sph}}) \sim m_{\text{atm}} \left(\frac{1\text{ GeV}}{M_N}\right)$
- This leptogenesis do no have to stop at $T \sim T_{\text{sph}}$. Lepton asymmetry continues to be generated **below sphaleron freeze-out**