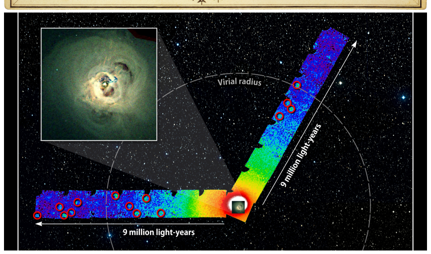
QUEST FOR NEW PHYSICS DRIVEN BY EXPERIMENT AND SIMPLICITY



Oleg Ruchayskiy

SEWM

July 18, 2014

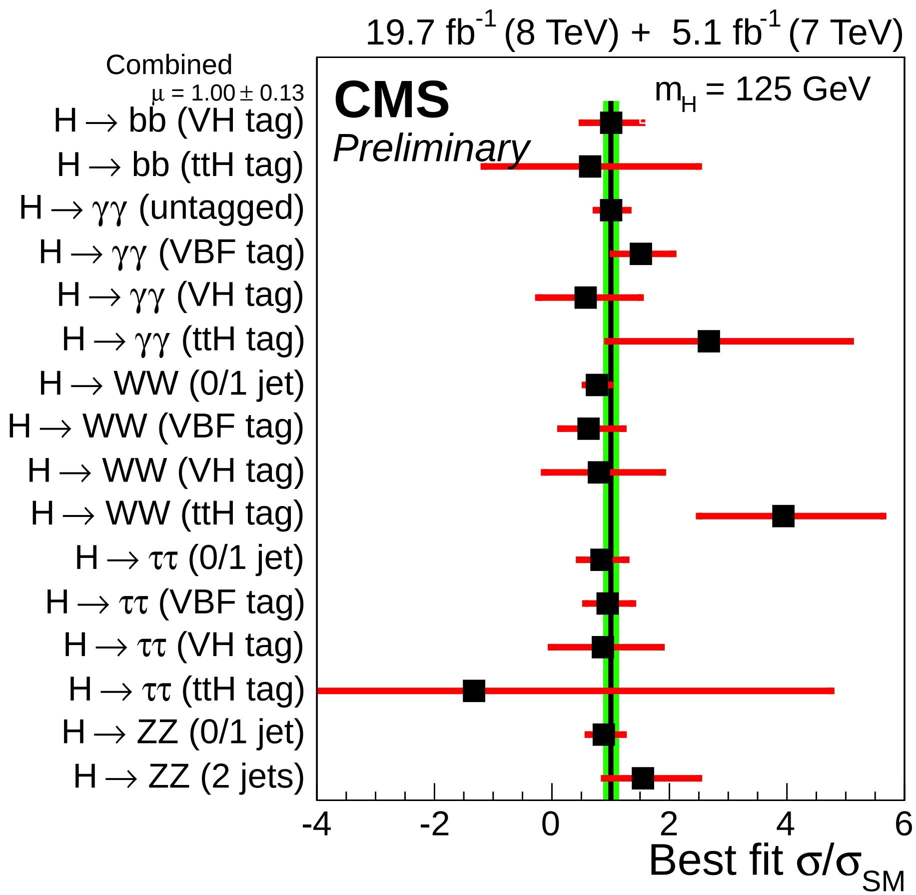
What do we want?

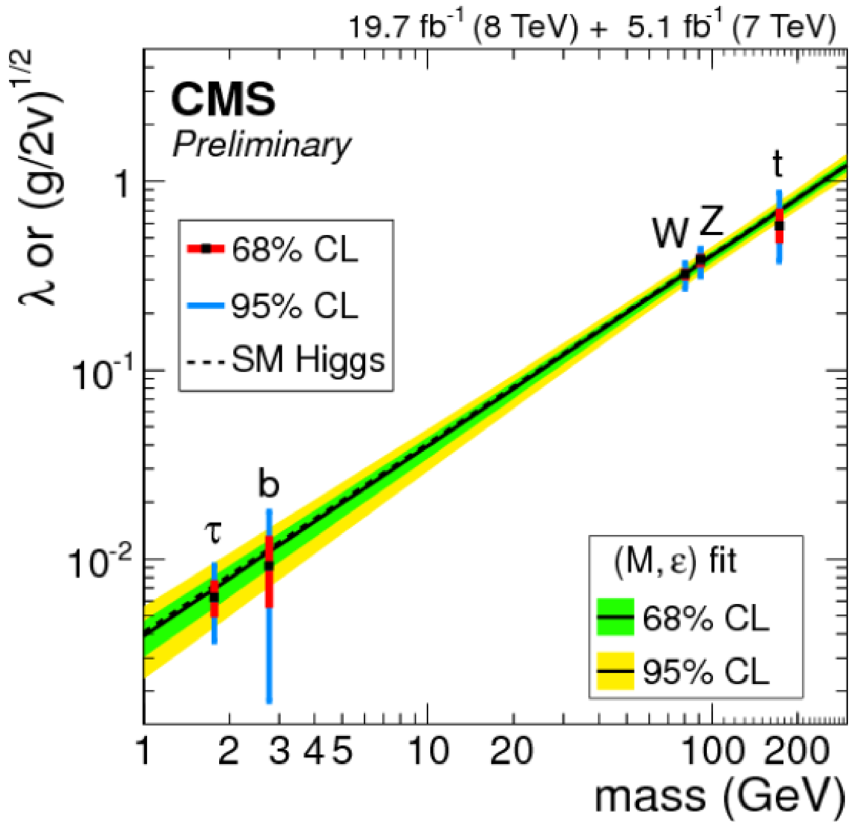
As a particle physicists we want to build "**The Theory**" such that

- ▷ All observed phenomena are explained
- ▷ All predicted particles are discovered
- ▷ The resulting theory is mathematical self-consistent

Are we there yet?

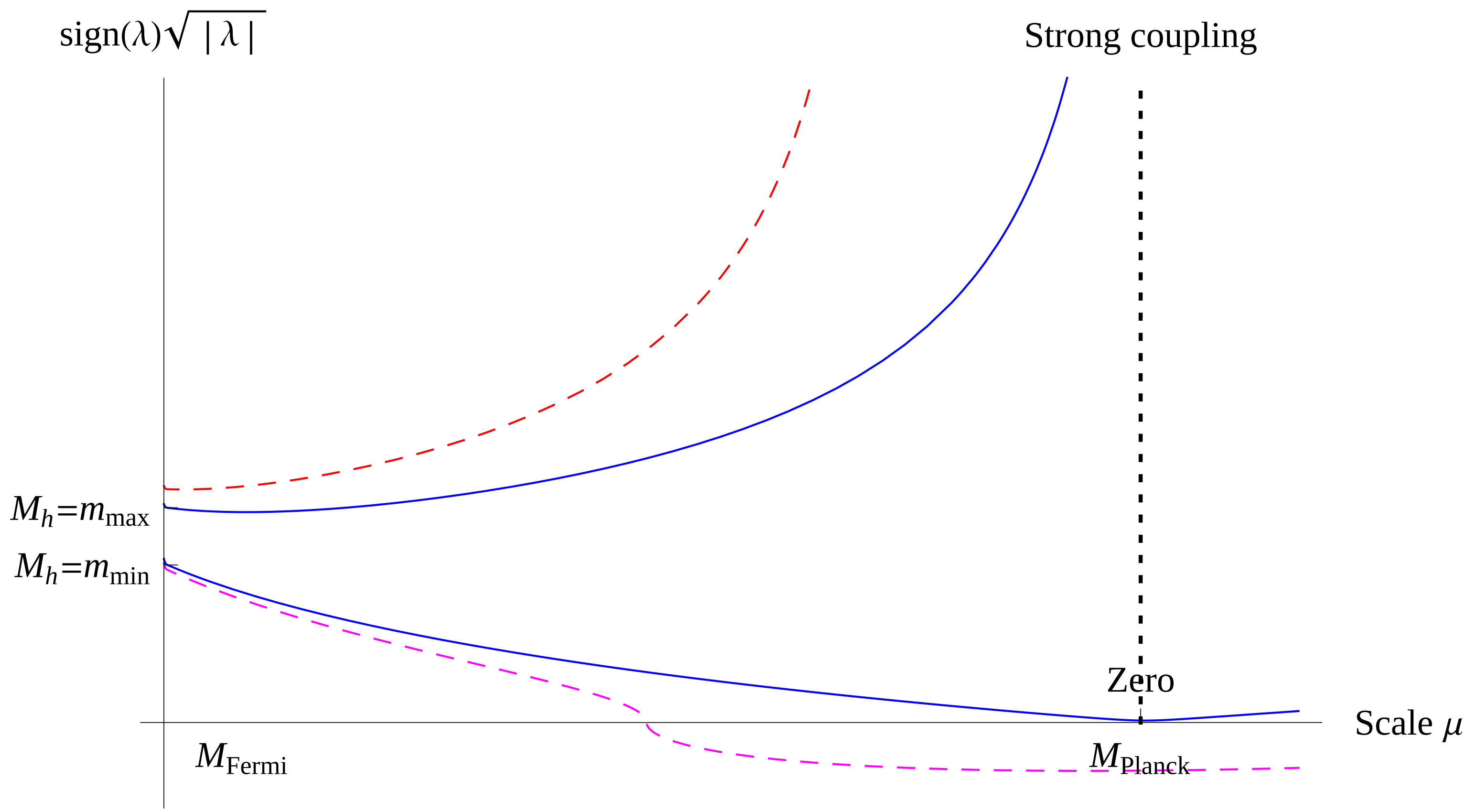
All predicted particles are found!





Century long quest came to its end – all predicted particles have been found!

Theory is mathematically consistent!



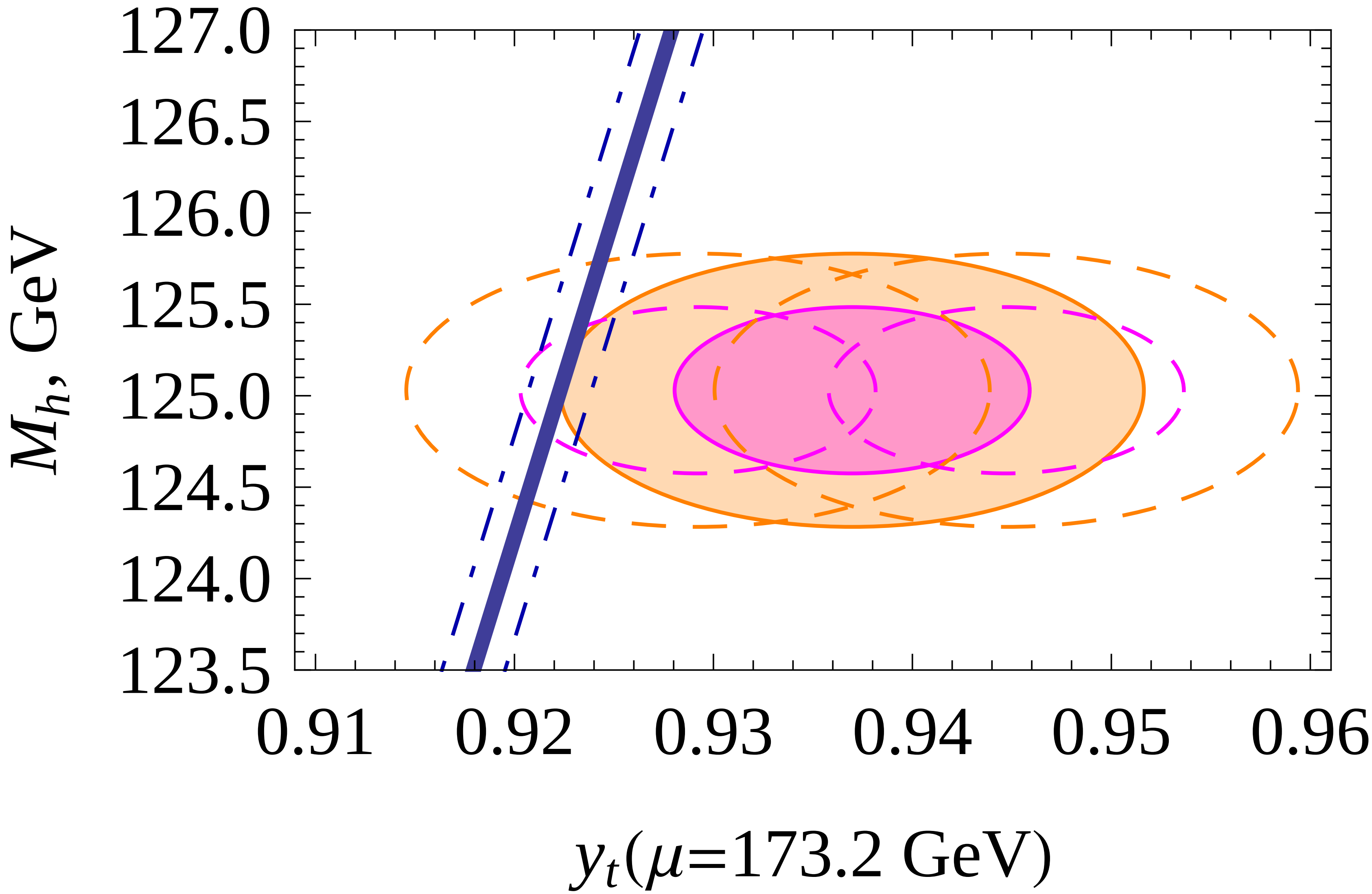
Mass of the Higgs boson ~ 126 GeV means that the Standard Model is a consistent weakly-coupled theory up to very high scales (probably to the Planck scale)

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

Also **Degrassi et al. [1205.6497]**

SM valid up to the Planck scale?

Bezrukov et al.'14



- ✓ All predicted particles of the Standard Model have been found ☺
- ✓ The theory behind these particles and their interactions stays **mathematically consistent** to very high energies ☺

Did we just had the last Nobel Prize in particle physics?

All discovered phenomen explained? ☹

Particle physics: neutrino oscillations

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

- dynamics of gravitating objects at scales from galactic to cosmological (**dark matter**?)
- absence of primordial asymmetry of the Universe

Possibly

- initial conditions for the Universe (**inflation**?)
- accelerated expansion of the Universe (**dark energy**?)

Expectations for new physics?

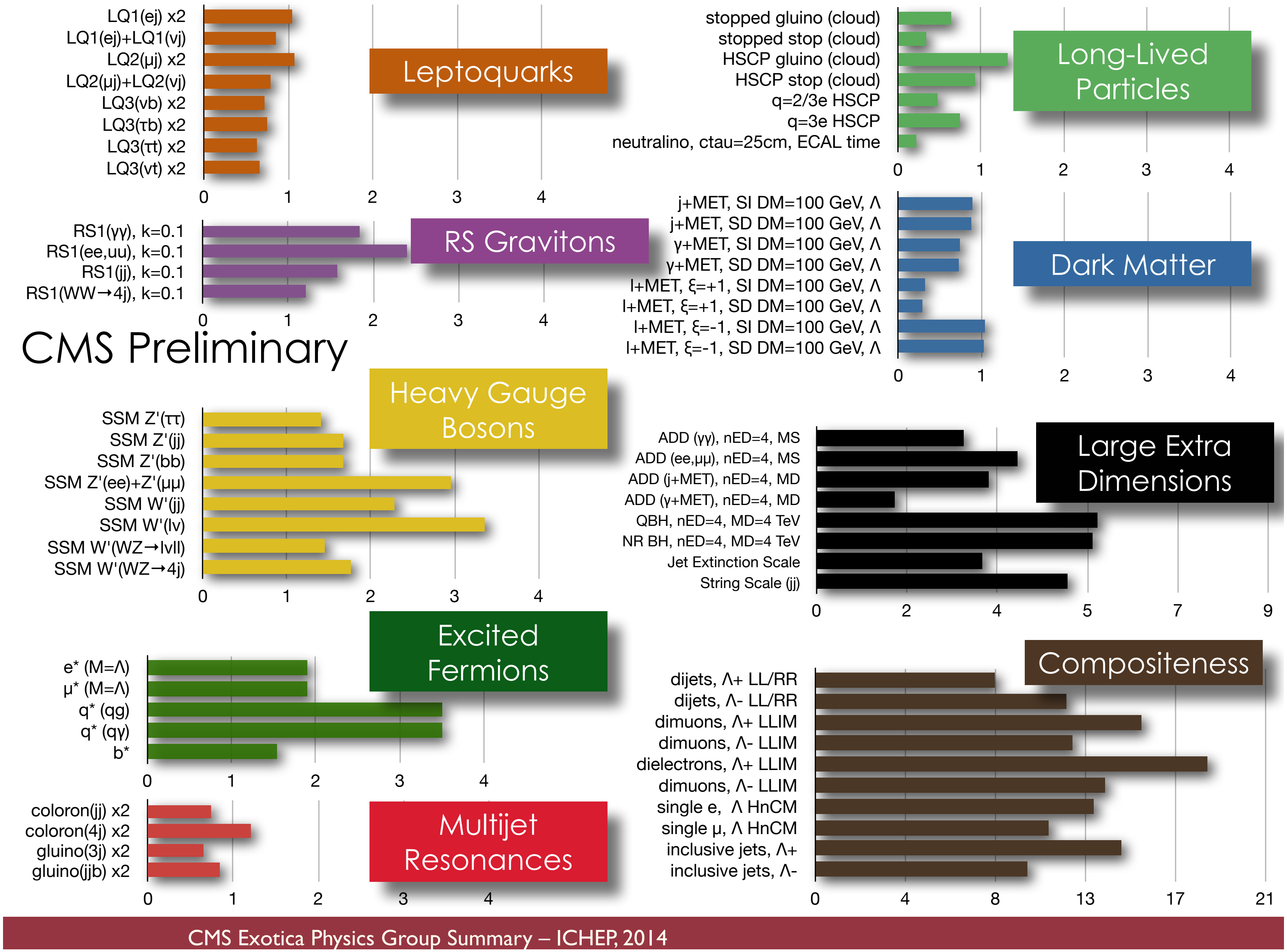
- Unsolved problems $\Rightarrow$ **new particles should exist**
- We did not detect them $\Rightarrow$ they are **heavy**
- How heavy can they be? – Not too much!
- Indeed, Higgs mechanism gives mass to all the particles

heavy particle $\Leftrightarrow$ Strong interaction with Higgs boson $\Longrightarrow$ Large quantum corrections to the Higgs boson mass

this is known as "gauge hierarchy problem"

- $\Rightarrow$ New physics should be about electroweak scale?

Searches for new physics at LHC



Heavy or light?

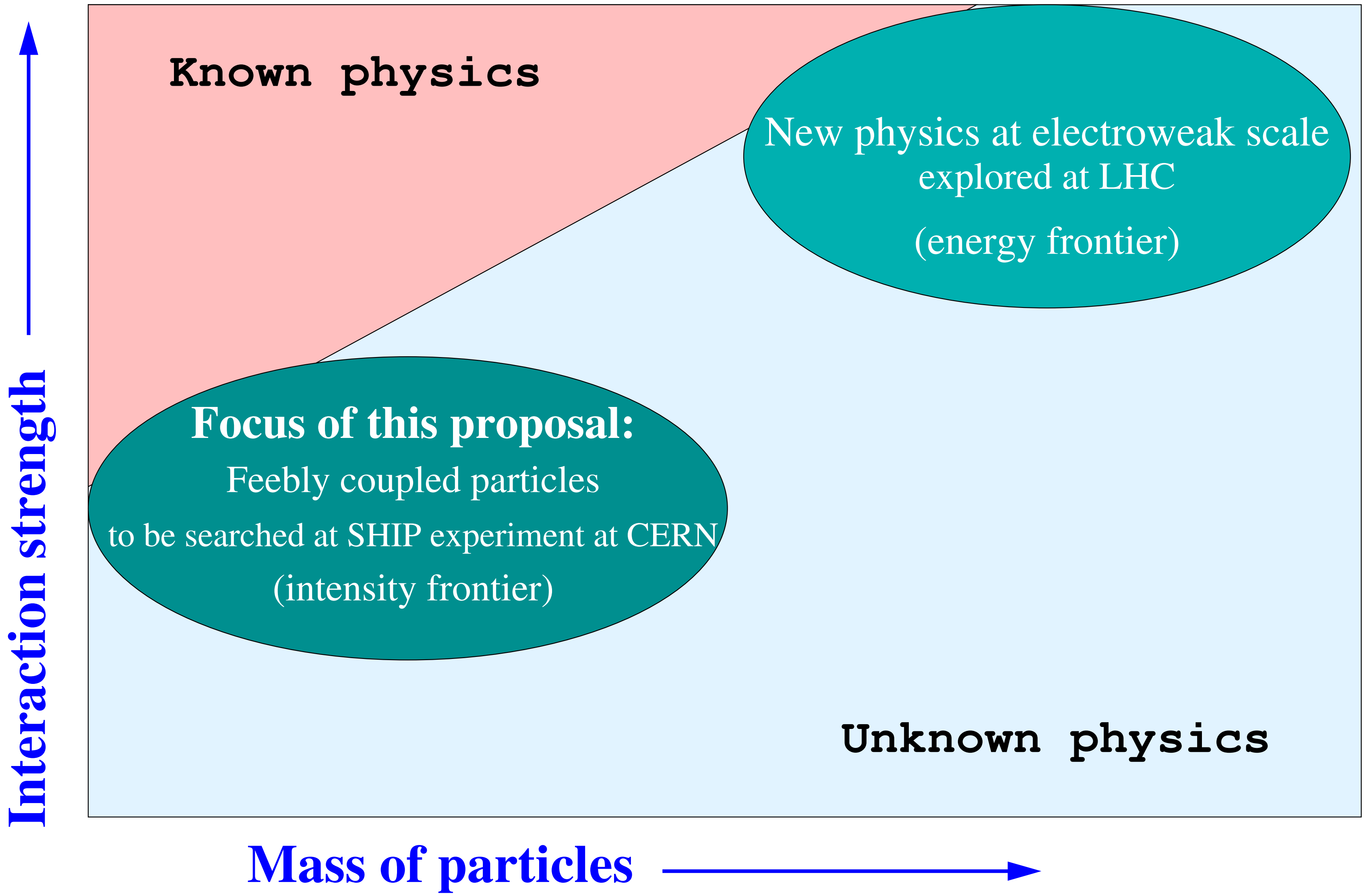
- Unsolved problems $\Rightarrow$ **new particles should exist** ✓
- We did not detect them $\Rightarrow$ they are ~~heavy~~ light but **very weakly interacting**
- Higgs mechanism gives mass to all the particles

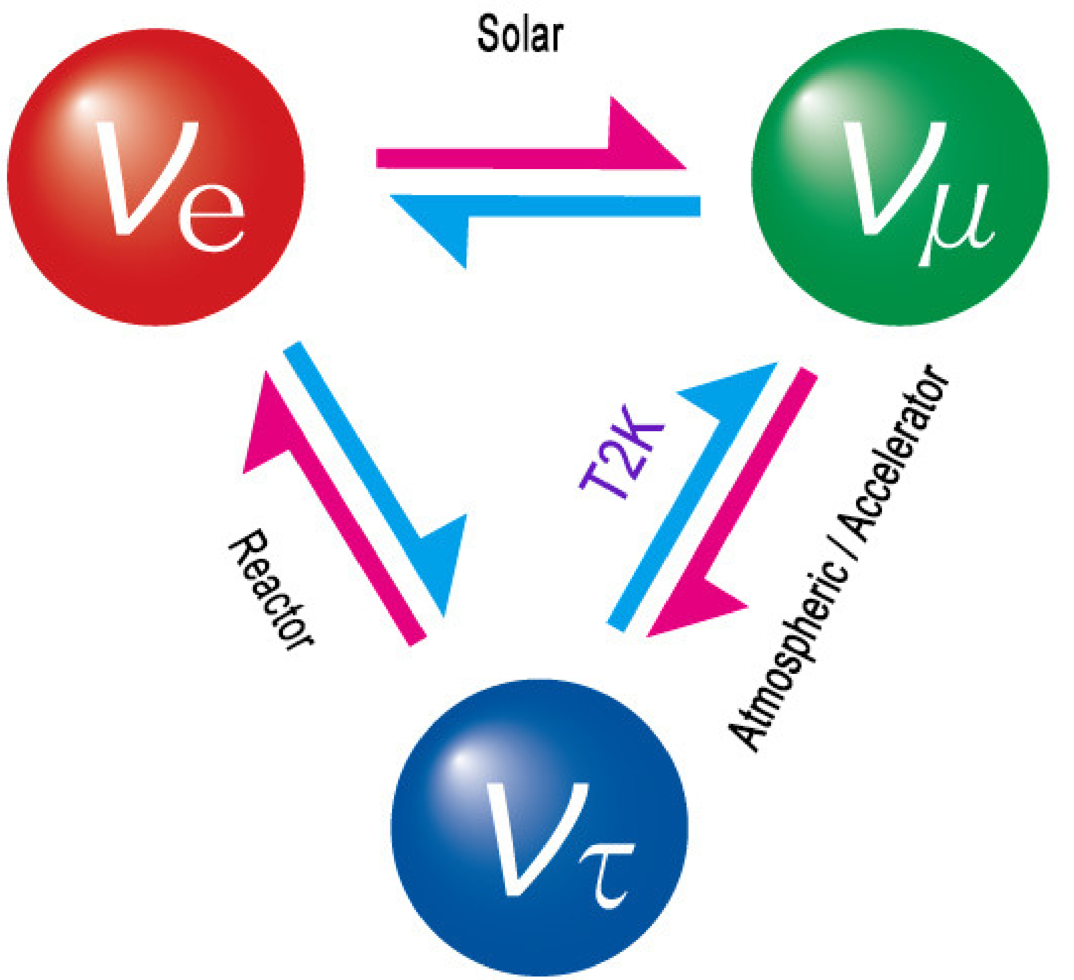
  No heavy particle $\Longrightarrow$ **No** corrections to the Higgs boson mass

Is it possible to resolve the BSM problems with light very weakly interacting particles?

▷ Complete *(testable?)* theory, valid up to Planck scale?

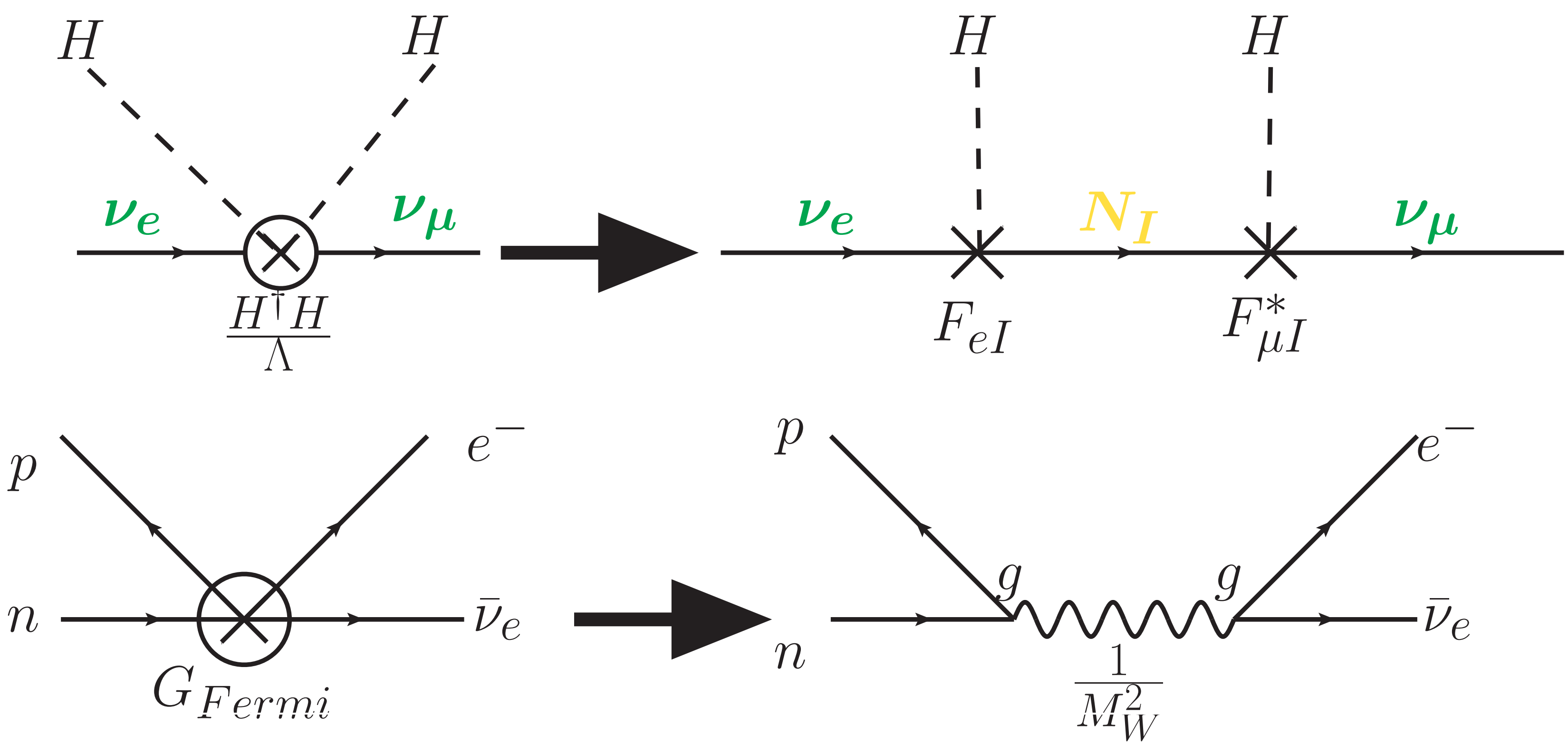
Two directions



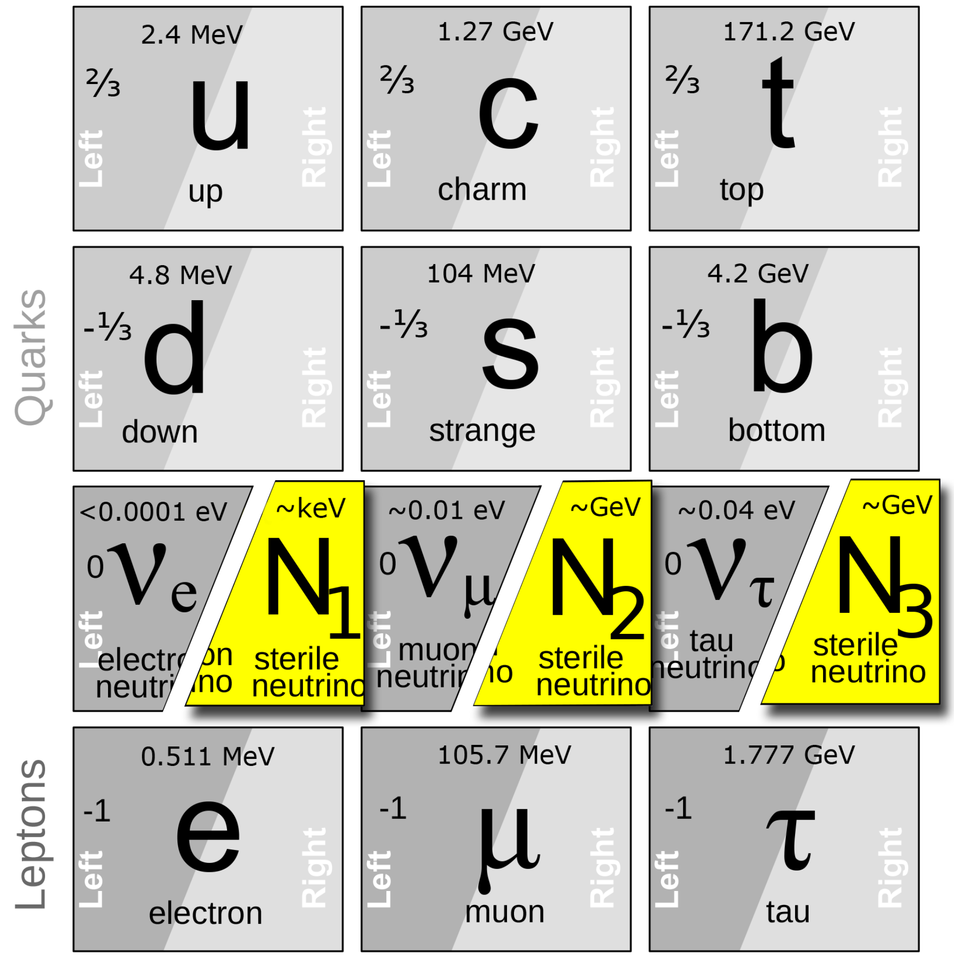


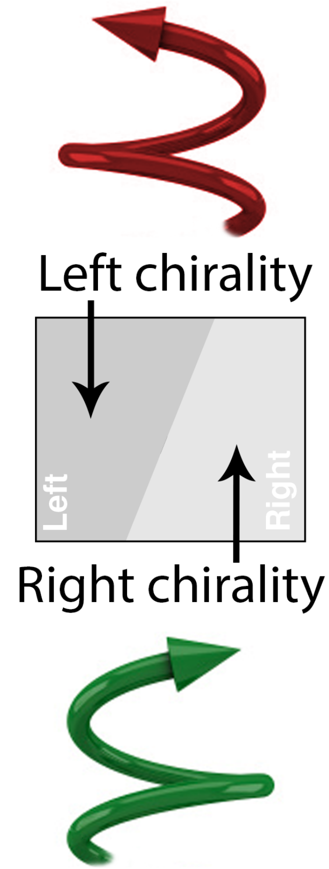
Neutrino oscillation between three generations

"Resolving" neutrino mass term



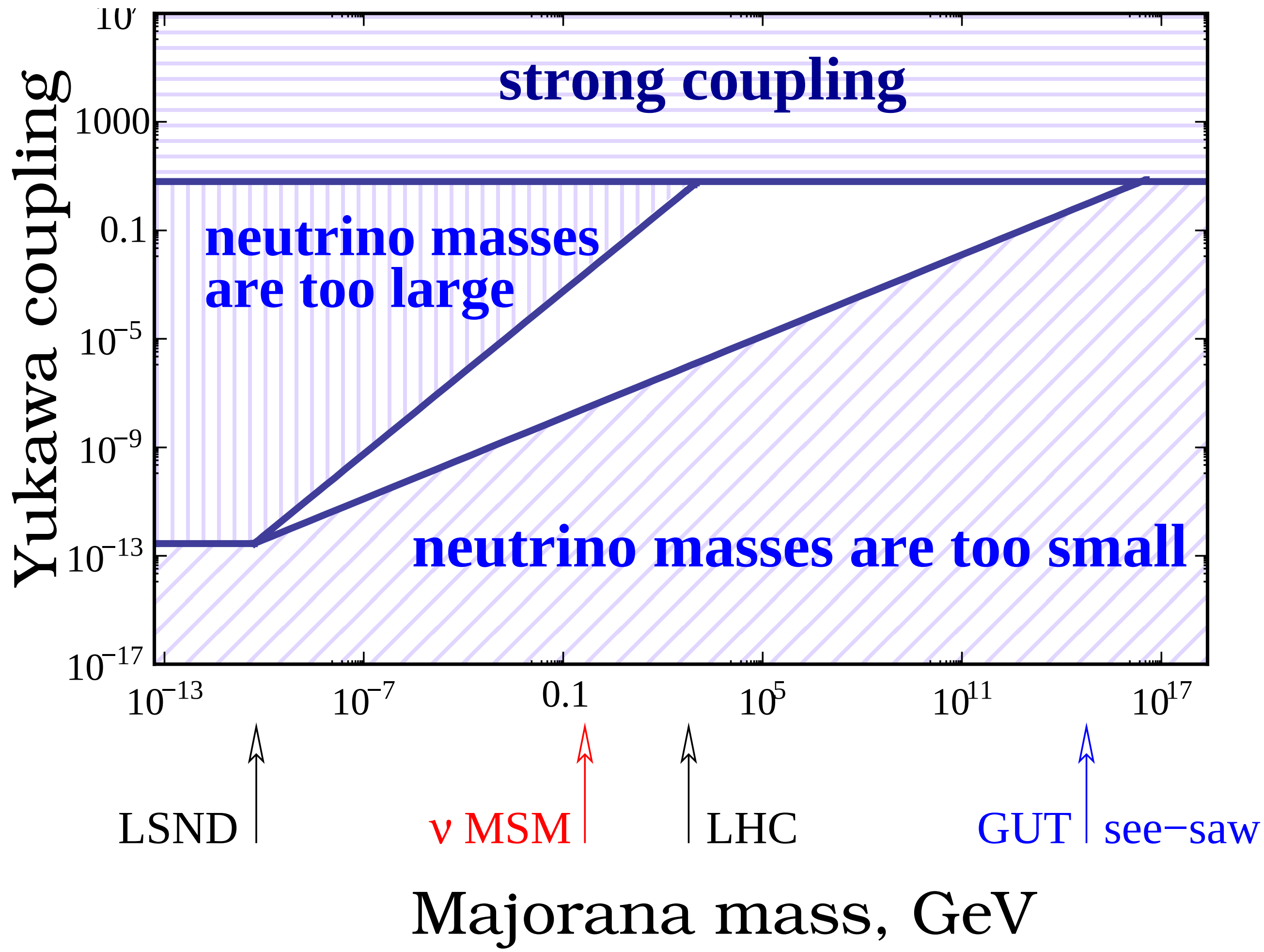
Neutrino oscillations mean that there exist new particles!





Right components of neutrinos?!

Scale of sterile neutrino masses?



1204.5379

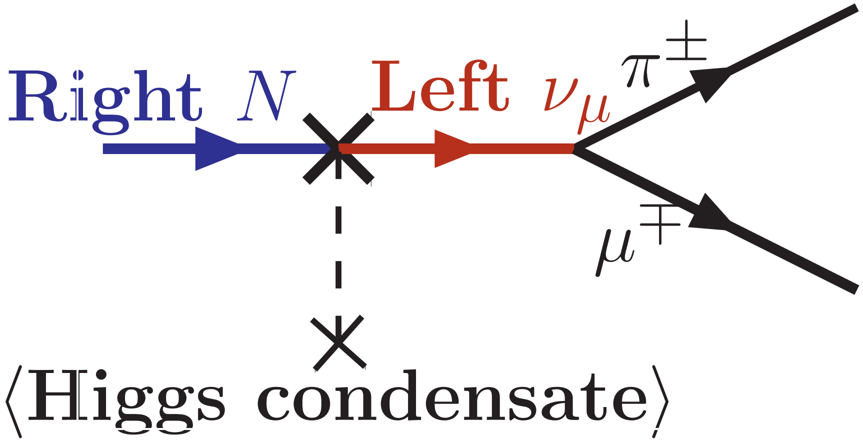
See-saw formula

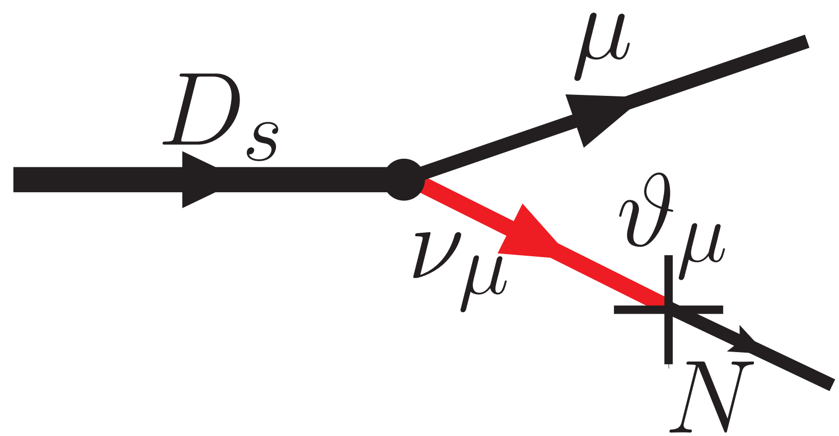
$|F|$ – Neutrino Yukawa interaction

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

M_N – Neutrino Majorana mass

Mass of sterile neutrinos is not determined by neutrino oscillations!





Sterile neutrinos behave as **superweakly interacting** massive neutrinos with a smaller Fermi constant $\vartheta \times G_F$

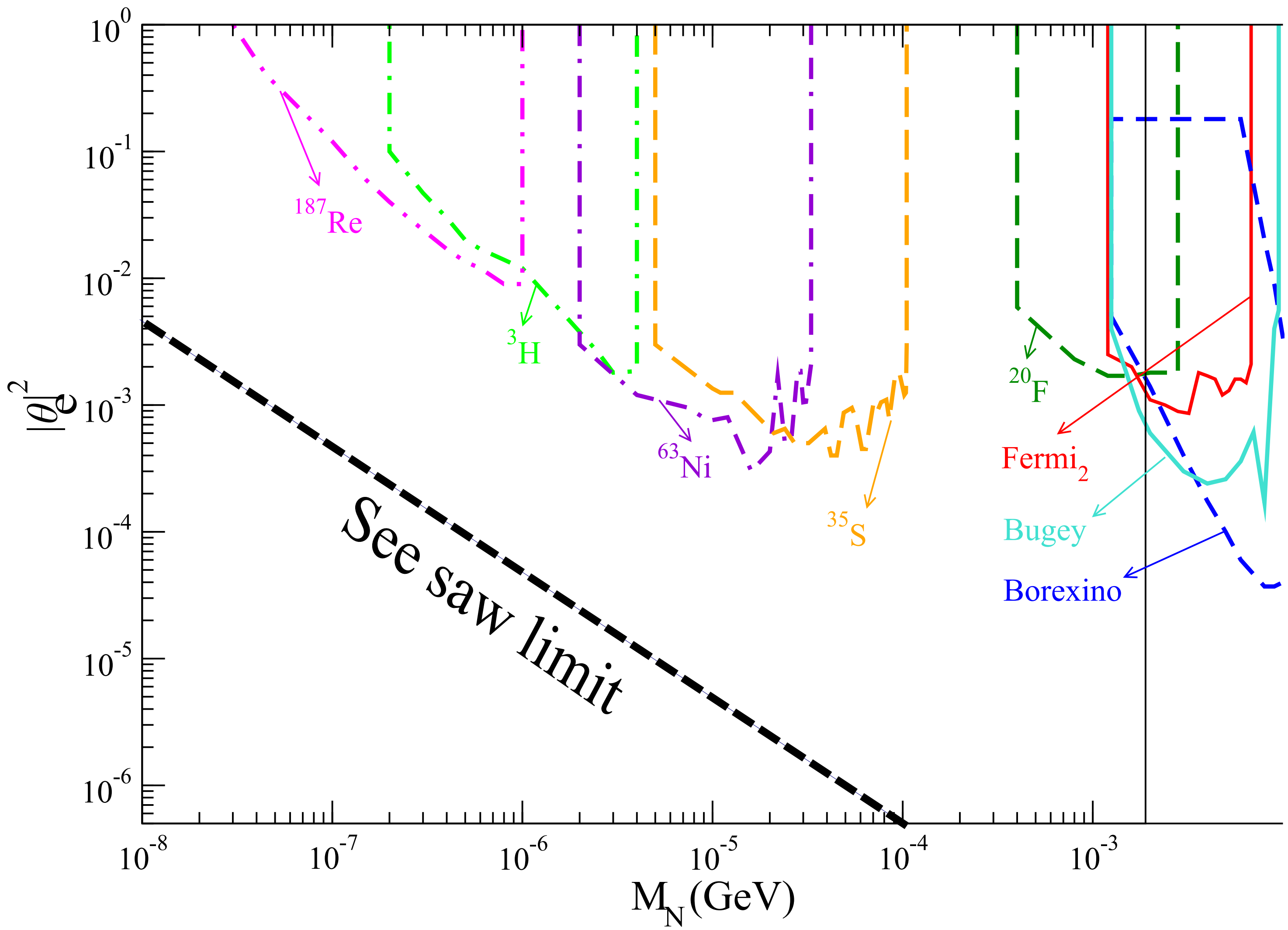
- This **mixing strength** or **mixing angle** is

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

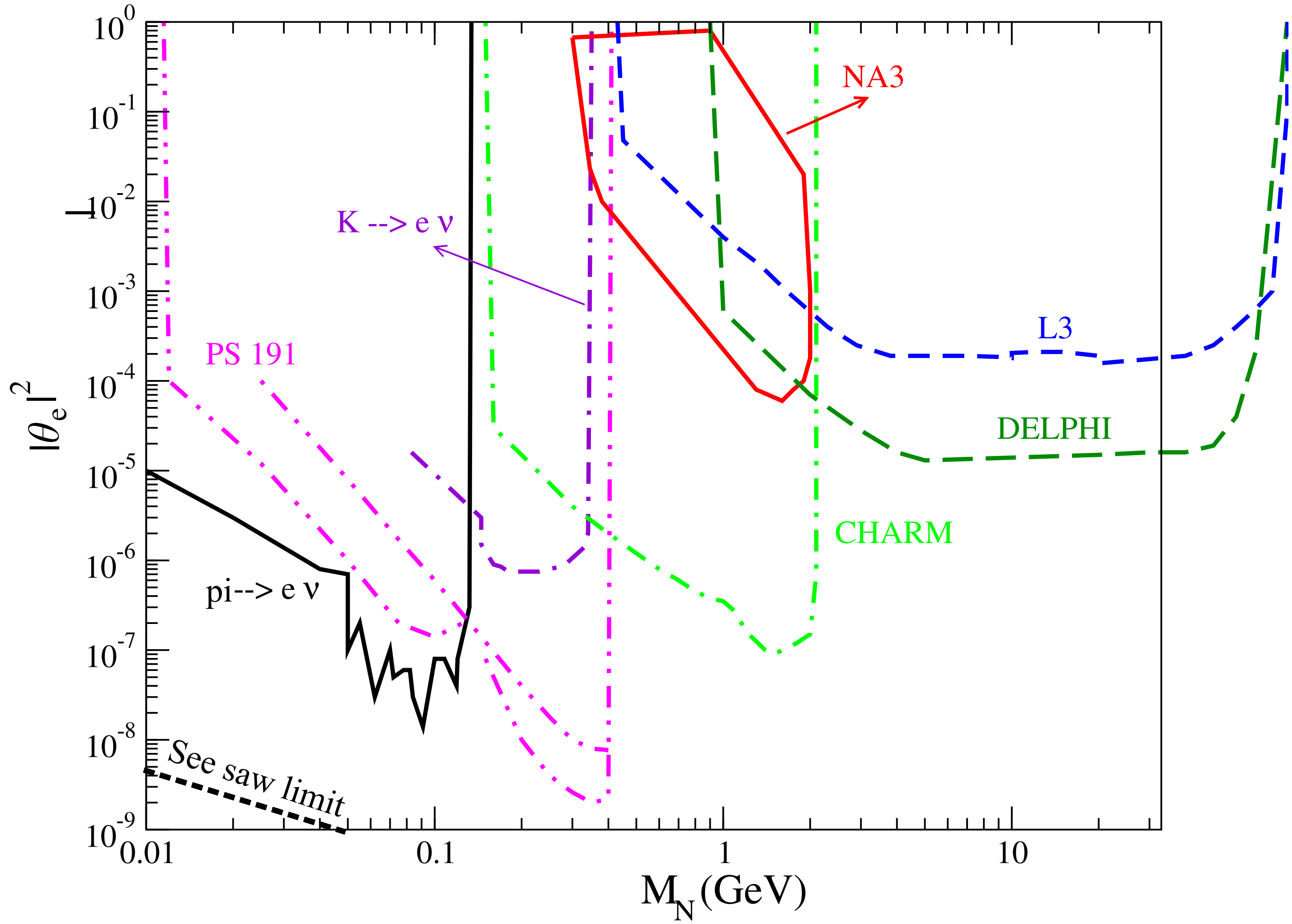
- Another name $\Rightarrow$ **heavy neutral leptons** (or **HNL**)

If sterile neutrinos exist – how to find them?

Bounds on sterile neutrinos



Bounds on sterile neutrinos



> **Ya. Zel'dovich:** *The Universe is the poor man's accelerator: experiments don't need to be funded, and all we have to do is to collect the experimental data and interpret them properly*

Why?

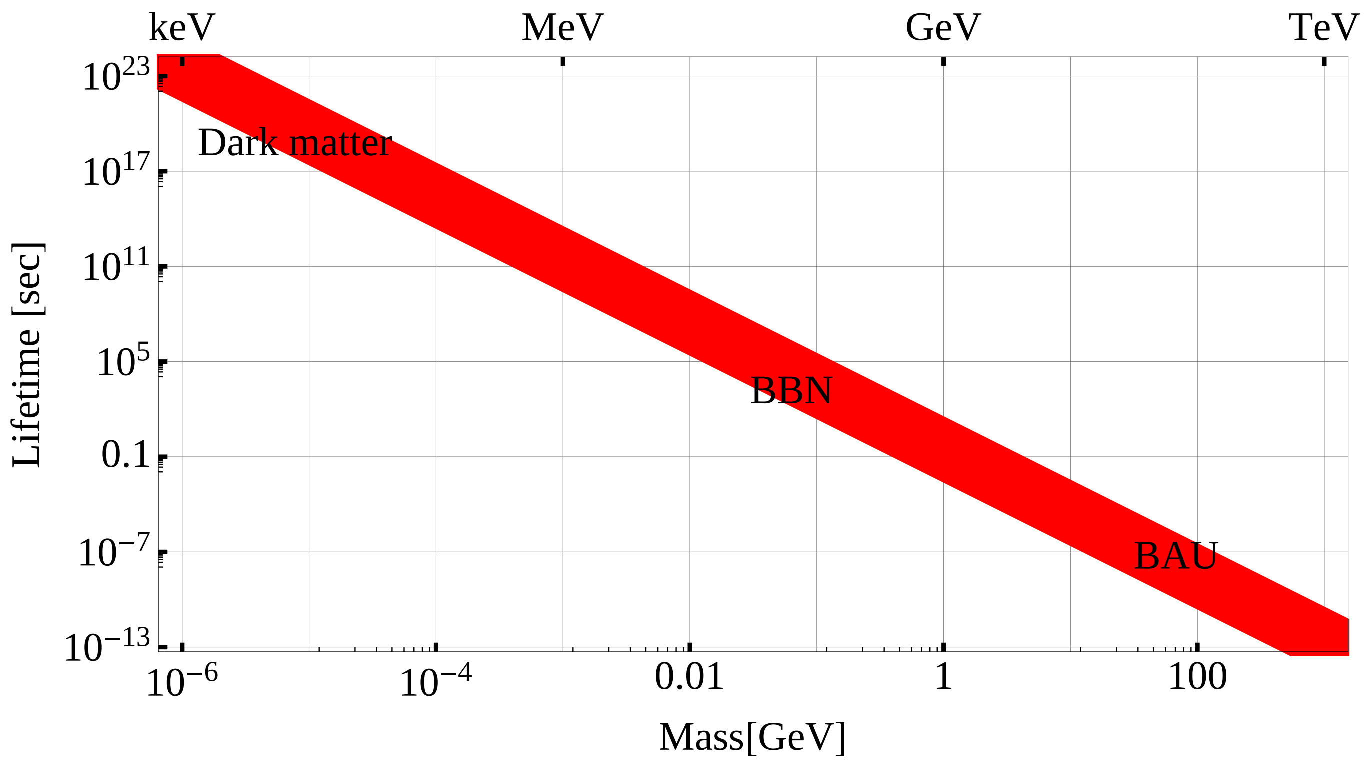
⇒ Primordial plasma could have reached the densities and temperatures unachievable in the lab for the longest possible times

⇒ Especially relevant if we are after some effects due to very-weakly-interacting particles/rare processes

Lifetime of HNLs

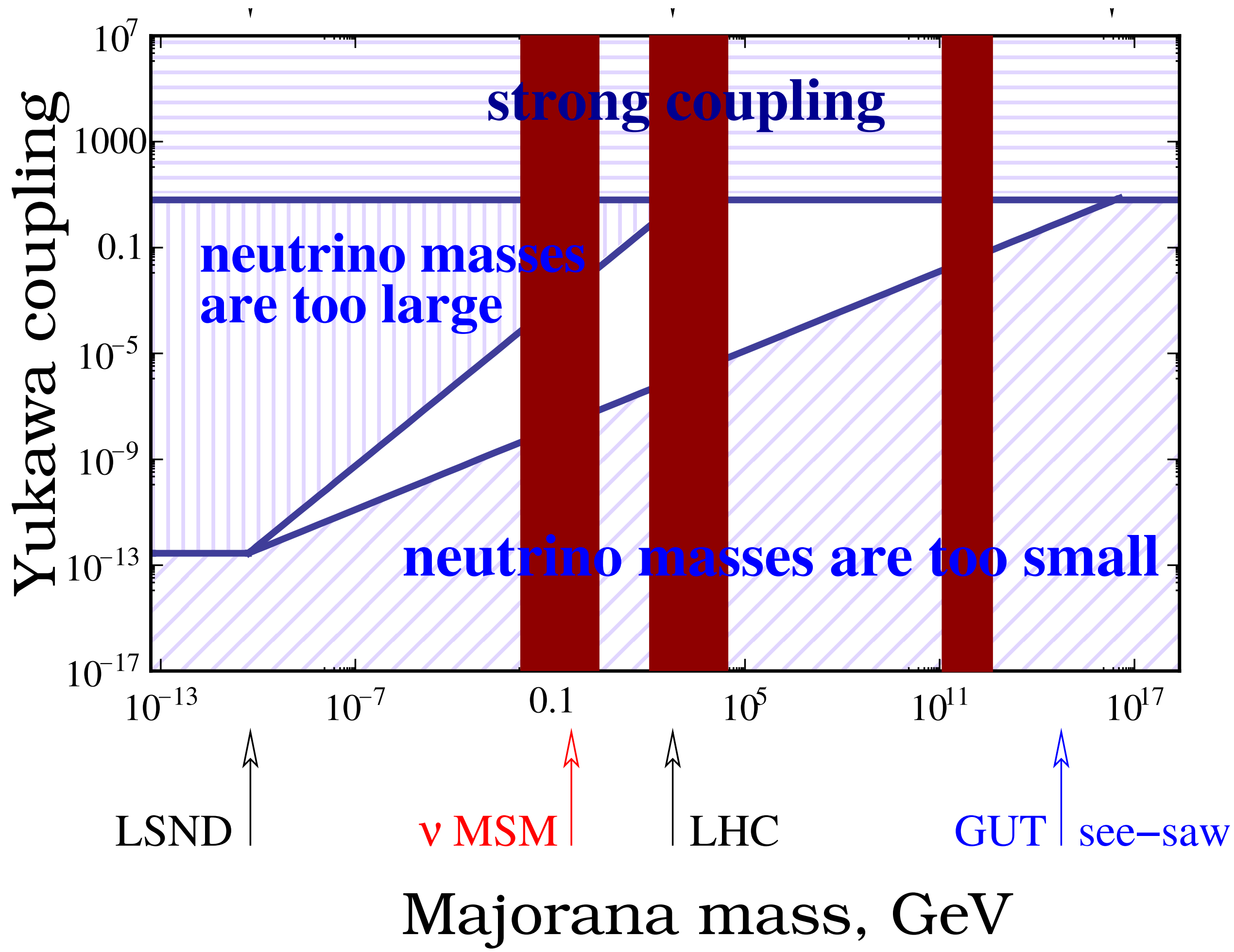
- Mode that always exists $N \to \nu\bar{\nu}\nu$

$$\text{Lifetime}_N = \left(\frac{\vartheta^2 G_F^2 M_N^5}{86\pi^3}\right)^{-1} \approx 0.3\,\text{sec}\left(\frac{1\ \text{GeV}}{M_N}\right)^4$$



For illustration only! The width of the line can be even larger

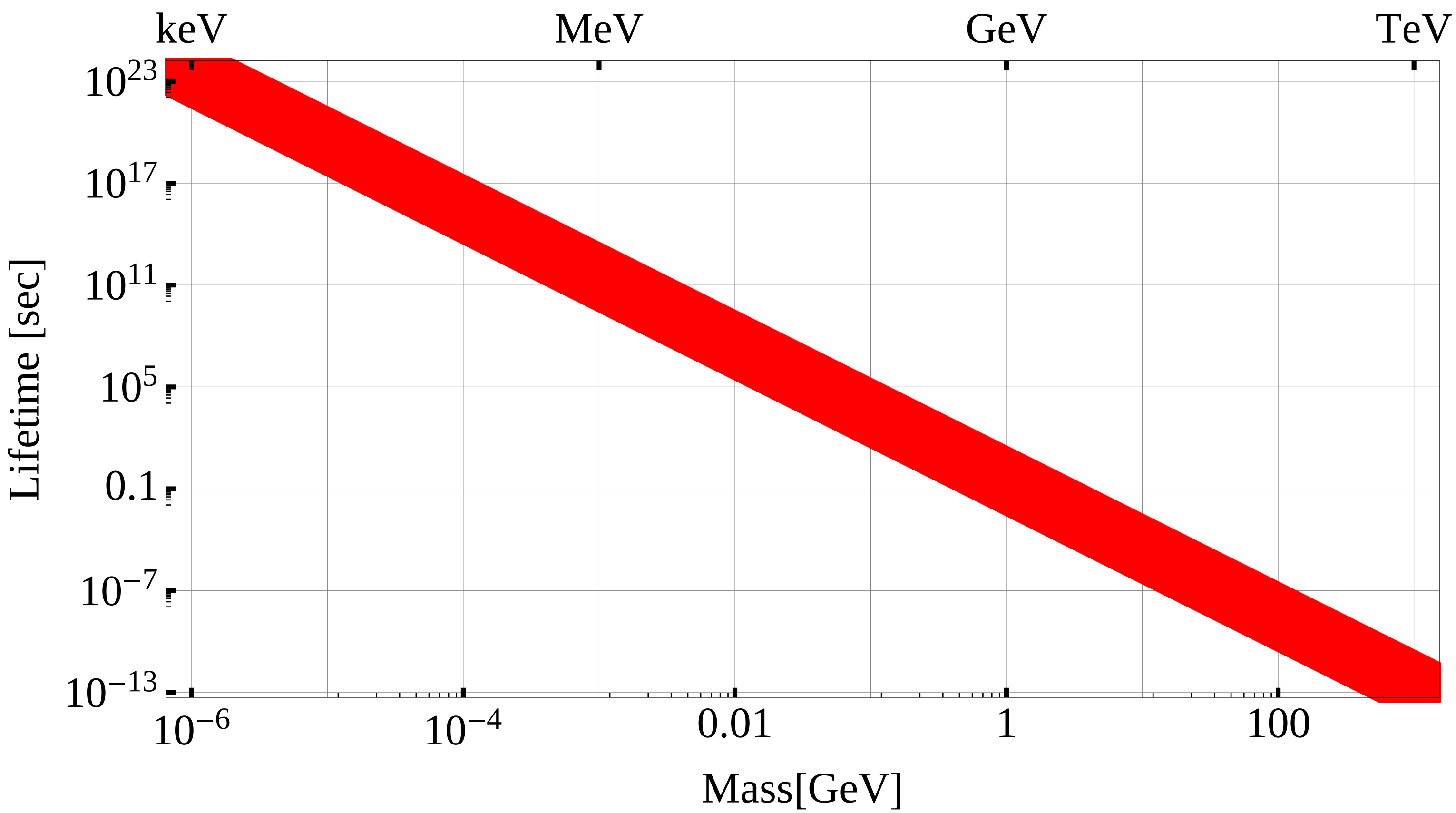
Sterile neutrino and BAU



Red stripes: ranges of masses where generation of BAU is possible (approximate)

Sterile neutrinos with their Majorana masses + CP phases in the Yukawa matrix satisfy all three Sakharov conditions and generate baryon asymmetry of the Universe (via **leptogenesis**)

Lifetime of τ_N

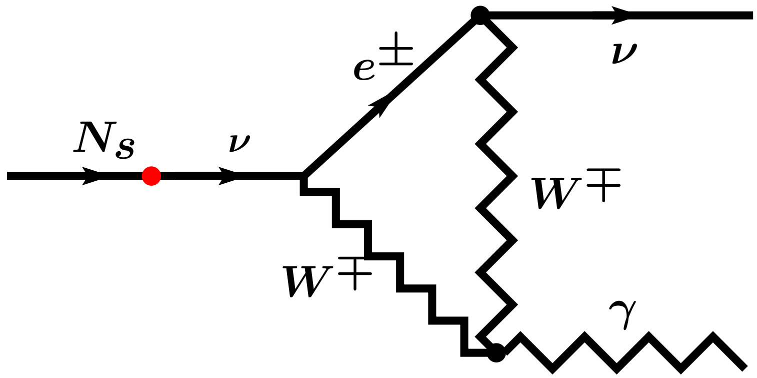


- Very long-lived particles $\Rightarrow$ dark matter?
- Take $M_N \sim 1$ keV. Lifetime $\tau_N \sim 10^{24}\,\mathrm{sec}$ — is this long enough?
- Fraction of decayed DM particles: $\dfrac{\text{Age of the Universe}}{\tau_N} \sim 10^{-6}$

Lifetime of τ_N

- **But!** in a galaxy like Andromeda or Milky Way (total mass $M_{\text{gal}} \sim 10^{12} M_\odot$) there would be 10^{75} **DM particles** with the mass 1 keV

- **Subdominant** (Br$\sim \frac{1}{123}$) decay channel: $N \to \nu + \gamma$



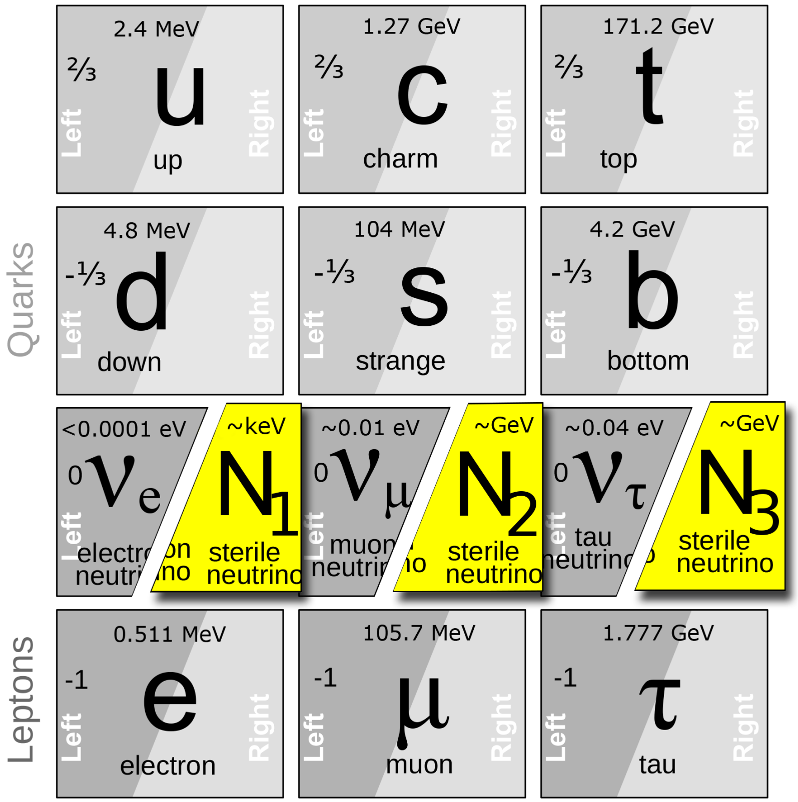
$$\Gamma_{N\to\nu\gamma} = \frac{9\alpha G_F^2}{256\pi^4}\vartheta^2 M_N^5$$

$$E_\gamma = \frac{1}{2} M_N$$

- Therefore, decay of a small fraction of 10^{75} particles releases $\sim 10^{40}\,\mathrm{erg/sec}$ in 0.5 keV photons

- **The entire X-ray luminosity of Andromeda galaxy** in the range $0.1 - 2.4$ keV is $L_X \sim$ **few** $\times 10^{39}\,\mathrm{erg/sec}$ (90% of which is coming from point sources)

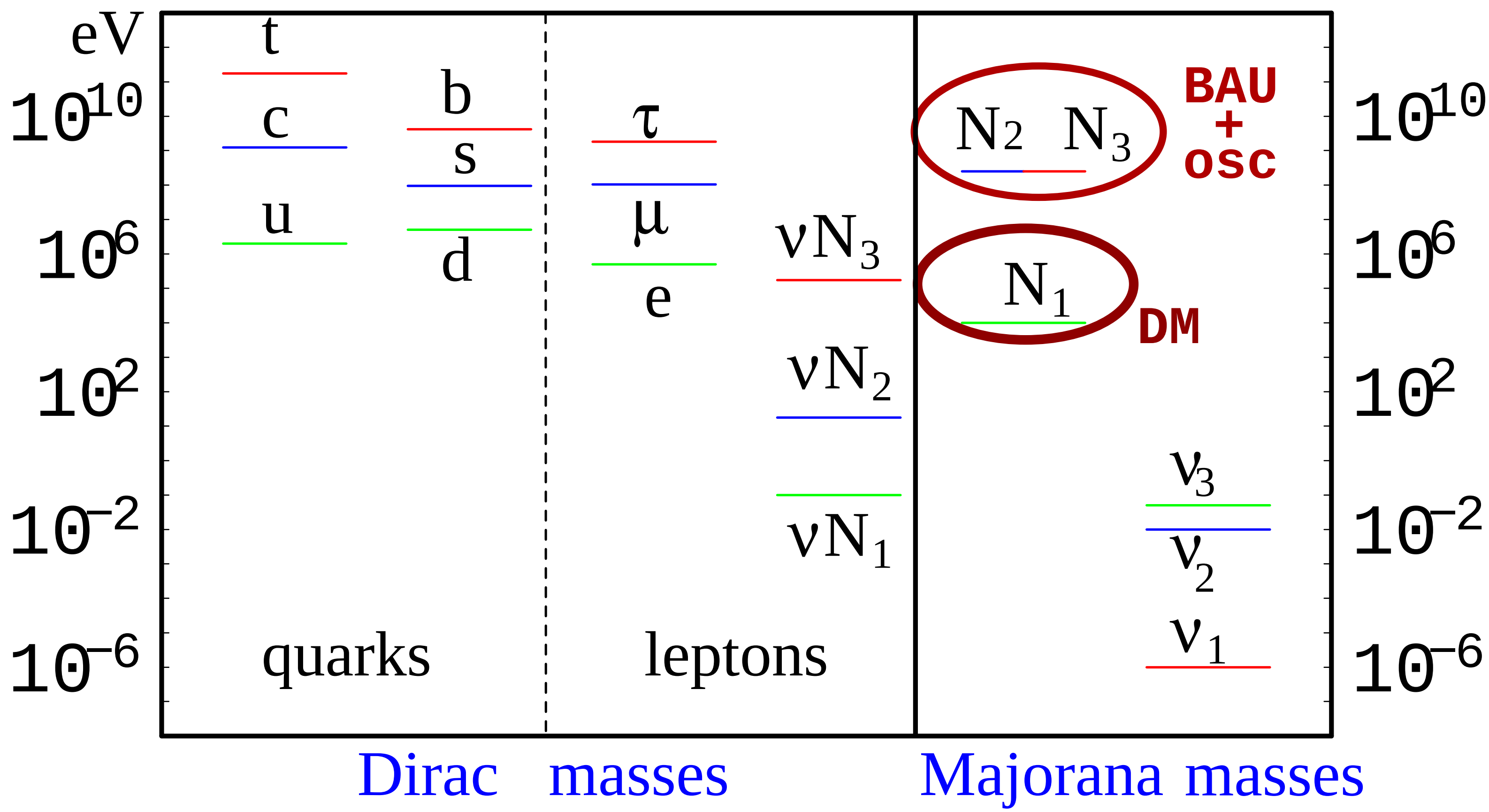
Dark matter and neutrino oscillations



- Two neutrino mass splitting $\Rightarrow$ need (at least) two sterile neutrino
- Are they Dark matter? $\Rightarrow$ No way! Very short lifetime
- Third sterile neutrino? $\Rightarrow$ Yes! Great DM (its exact properties depend on two other sterile neutrinos)

Sterile neutrino is a viable dark matter candidate in a model with at least two other sterile neutrinos

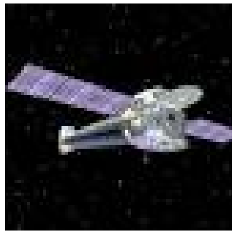
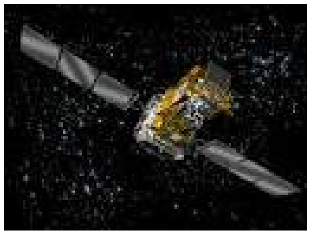
Neutrino Minimal Standard Model (νMSM)



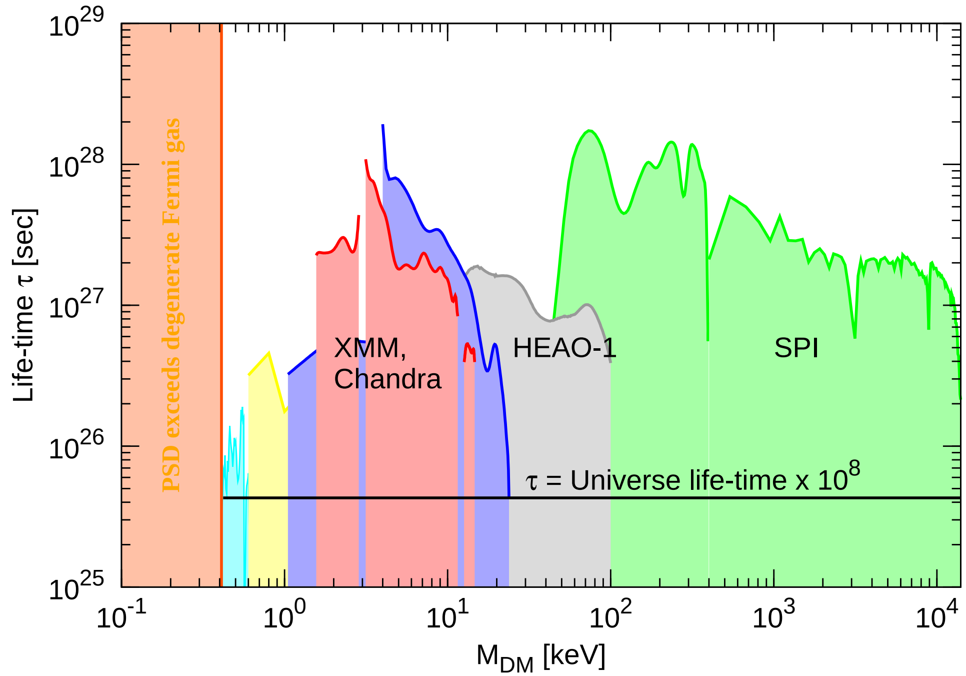
Masses of sterile neutrinos as those of other leptons
Yukawas as those of electron or smaller

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

Search for Dark Matter decays in X-rays


Available X-ray satellites: Suzaku, XMM-Newton, Chandra, INTEGRAL



MW (HEAO-1) 2005

Coma and Virgo clusters 2006

Bullet cluster 2006

LMC (XMM) 2006

MW (XMM) 2006–2007

M31 (XMM) 2007, 2010

$$\text{Signal-to-noise} \propto \mathcal{S}\sqrt{t_{\text{exp}} \cdot \Omega_{\text{fov}} \cdot A_{\text{EFF}} \cdot \Delta E}$$

All types of individual objects/observations have been tried: galaxies (LMC, Ursa Minor, Draco, Milky Way, M31, M33,...); galaxy clusters (Bullet cluster; Coma, Virgo, ...) with all the X-ray instruments

Detection of An Unidentified Emission Line

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

ESRA BULBUL[1,2], MAXIM MARKEVITCH[2], ADAM FOSTER[1], RANDALL K. SMITH[1] MICHAEL LOEWENSTEIN[2], AND SCOTT W. RANDALL[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.
Submitted to ApJ, 2014 February 10

[1402.2301]

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]
[1]Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2]Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland

[1402.4119]

Unidentified spectral line at $E \sim 3.5$ keV

[1402.4119]

Boyarsky et al. 2014

M31 galaxy	XMM-Newton, center & outskirts
Perseus cluster	XMM-Newton, outskirts only
Blank sky	XMM-Newton

[1402.2301]

Bulbul et al. 2014

73 clusters	XMM-Newton, central regions of clusters only. Up to $z = 0.35$, including Coma, Perseus
Perseus cluster	Chandra, center only
Virgo cluster	Chandra, center only

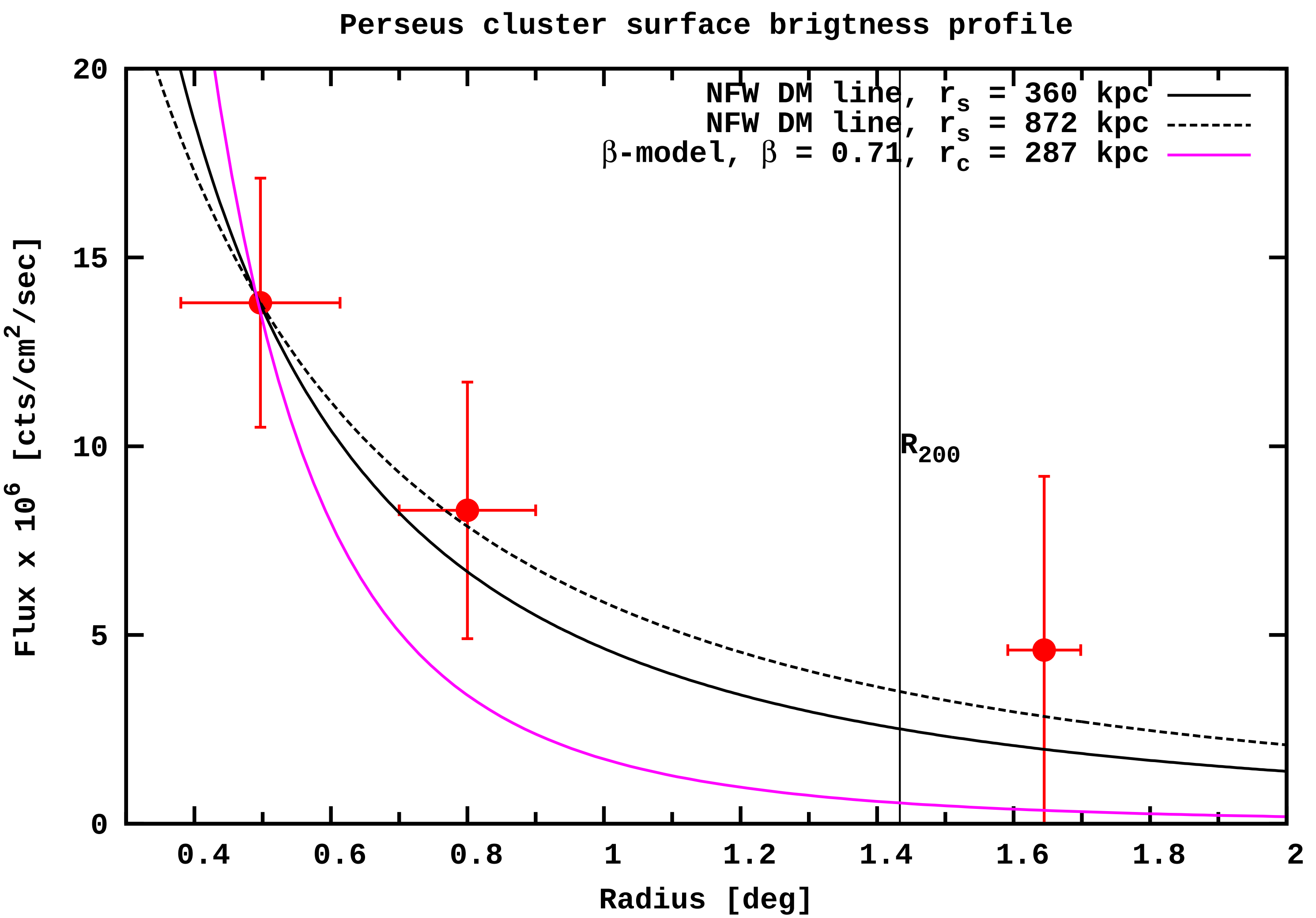
Position: 3.52 ± 0.02 keV.

Lifetime: $\sim 10^{28}$ sec (uncertainty $\mathcal{O}(10)$)

Significance: Between 4σ and 5σ (global, taking into account trial factors)

Surface brightness profile (Perseus)

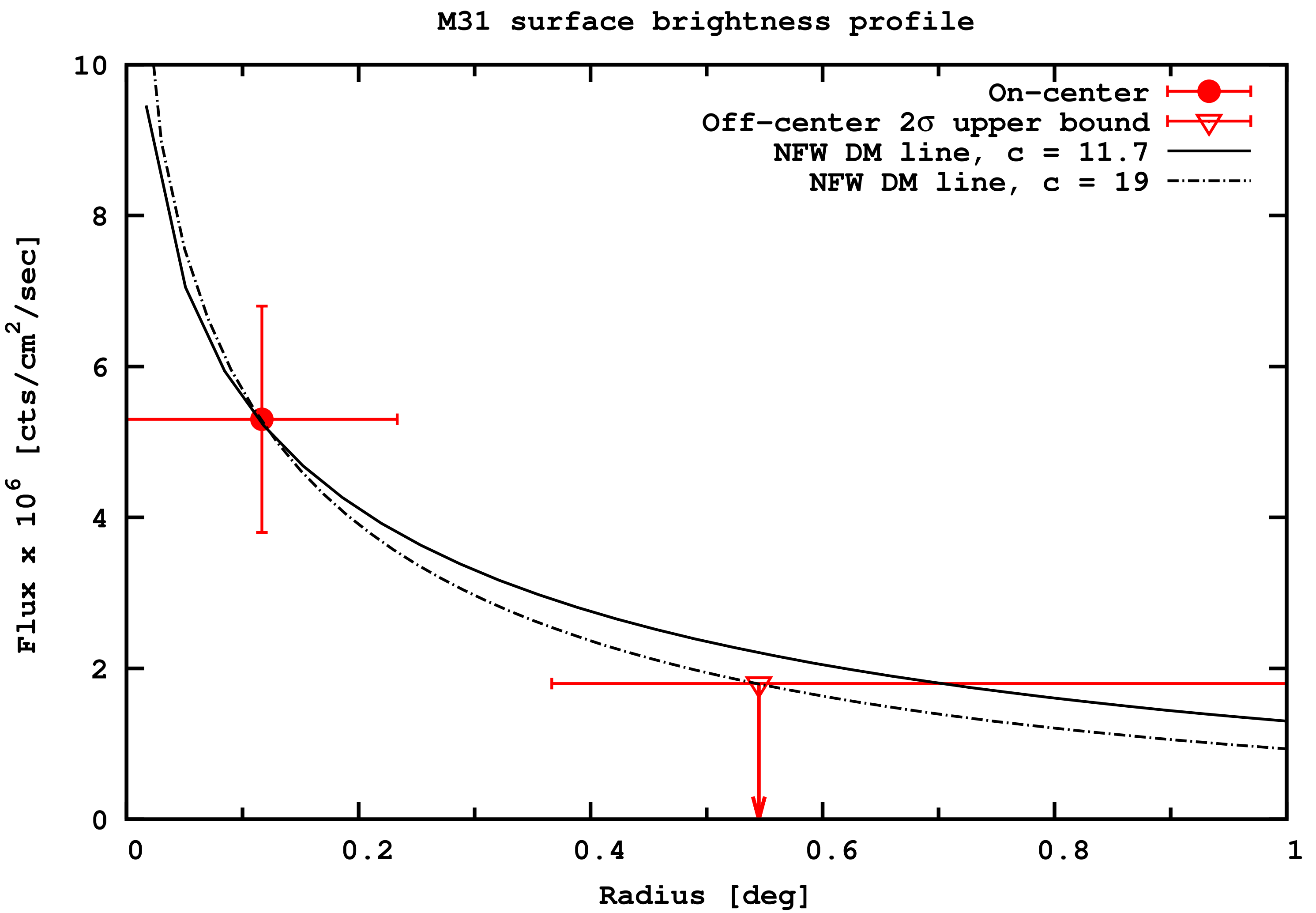
[1402.4119]



This is not a fit!

Surface brightness profile (M31)

[1402.4119]

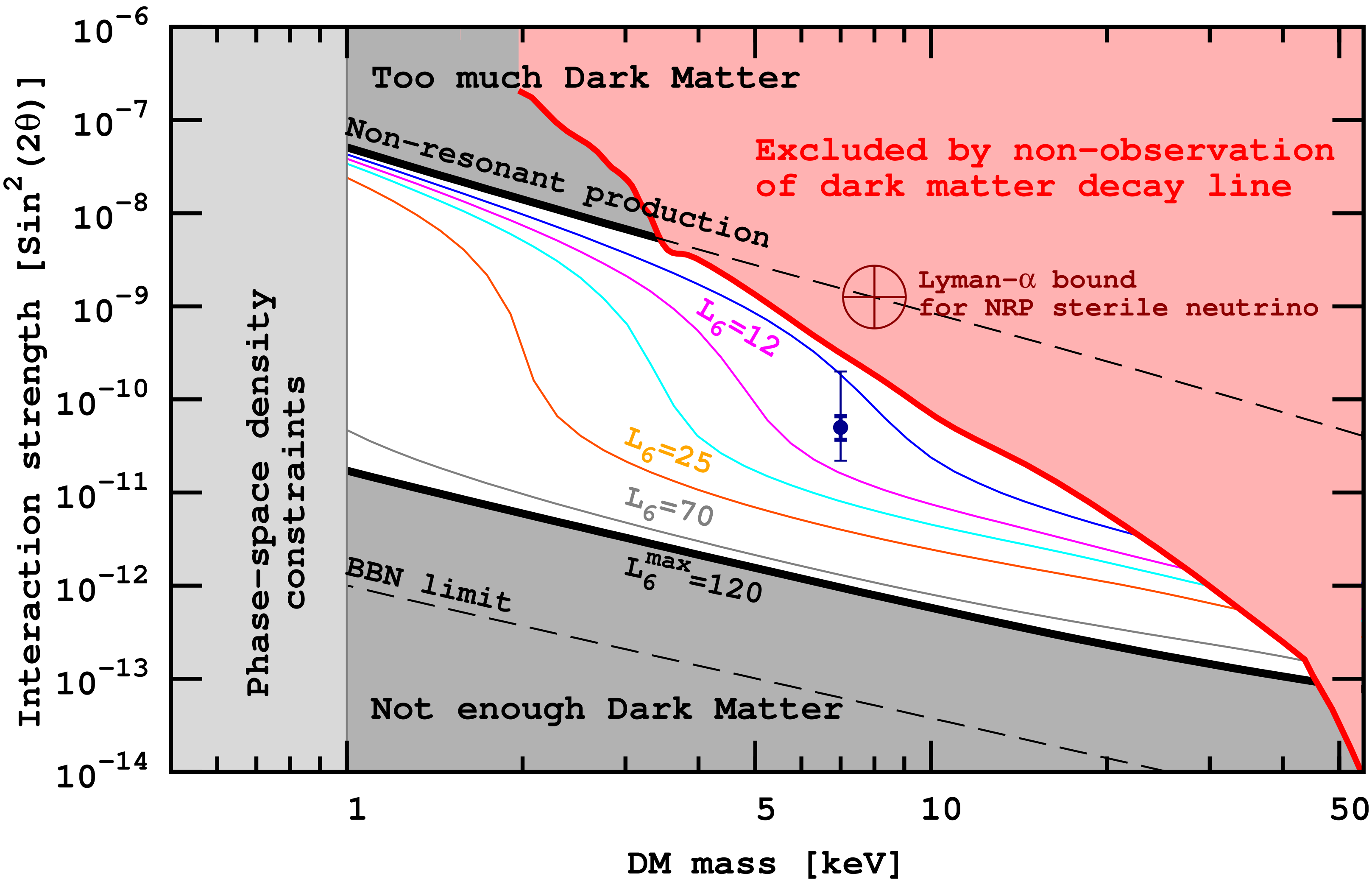


This is not a fit!

This can be anything

The 3.5 keV X-ray line from decaying **gravitino** dark matter. **Axino** dark matter in light of an anomalous X-ray line. The Quest for an Intermediate-Scale Accidental **Axion** and Further **ALPs**. keV Photon Emission from Light **Nonthermal Dark Matter**. X-ray lines from R-parity violating decays of keV **sparticles**. Neutrino masses, leptogenesis, and **sterile neutrino** dark matter. A Dark Matter Progenitor: **Light Vector Boson Decay** into (Sterile) Neutrinos. A 3.55 keV Photon Line and its Morphology from a 3.55 keV ALP Line. 7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model. X-ray line signal from decaying **axino** warm dark matter. The 3.5 keV X-ray line signal from **decaying moduli** with low cutoff scale. X-ray line signal from 7 keV **axino** dark matter decay. Can a **millicharged dark matter** particle emit an observable gamma-ray line?. Effective field theory and keV lines from dark matter. Resonantly-Produced 7 keV **Sterile Neutrino Dark Matter** Models and the Properties of Milky Way Satellites. Cluster X-ray line at $3.5\,\mathrm{keV}$ from axion-like dark matter. Axion Hilltop Inflation in Supergravity. A 3.55 keV hint for decaying axion-like particle dark matter. The 7 keV axion dark matter and the X-ray line signal. An X-Ray Line from **eXciting Dark Matter**. 7 keV sterile neutrino dark matter from split flavor mechanism.

Sterile neutrino and 3.5 keV line



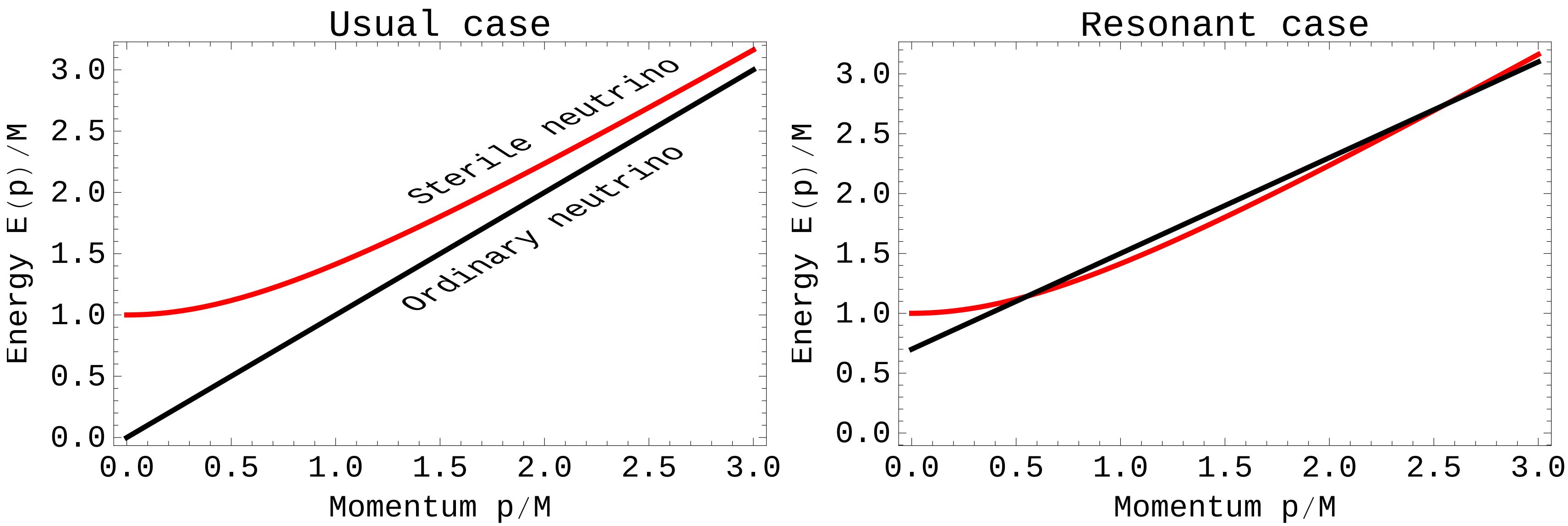
X-rays: Boyarsky, **O.R** et al.

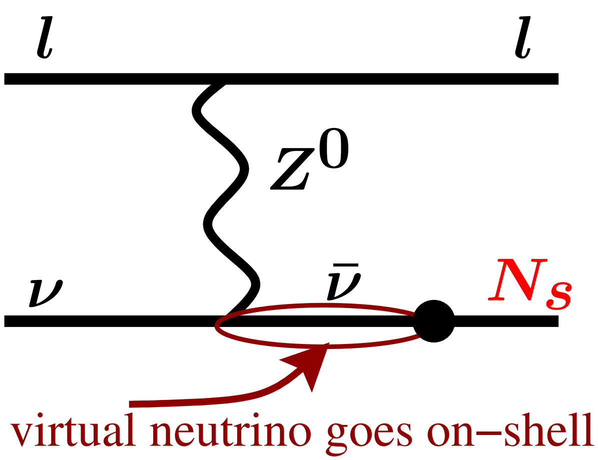
Production: Laine & Shaposhnikov (2008)

Lyman-α: Boyarsky, Lesgourgues, **O.R.** et al.

Sterile neutrino DM with such parameters is not completely cold and would leave its imprints in the formations of structures

Resonant enhancement



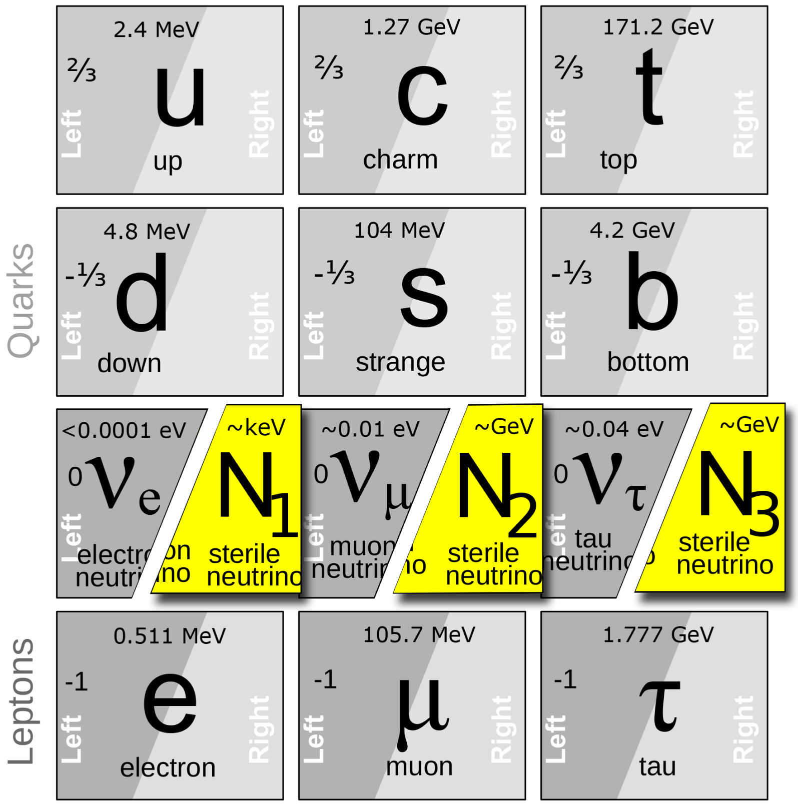


Conversion of ν to N is enhanced whenever "levels" cross and virtual neutrino goes "on-shell" (analog of MSW effect but for active-sterile mixing)

Shi & Fuller [astro-ph/9810076]

Laine & Shaposhnikov [0804.4543]

Dark matter and neutrino oscillations



– Two neutrino mass splitting $\Rightarrow$ need (at least) two sterile neutrino

– Are they Dark matter? $\Rightarrow$ No way! Very short lifetime

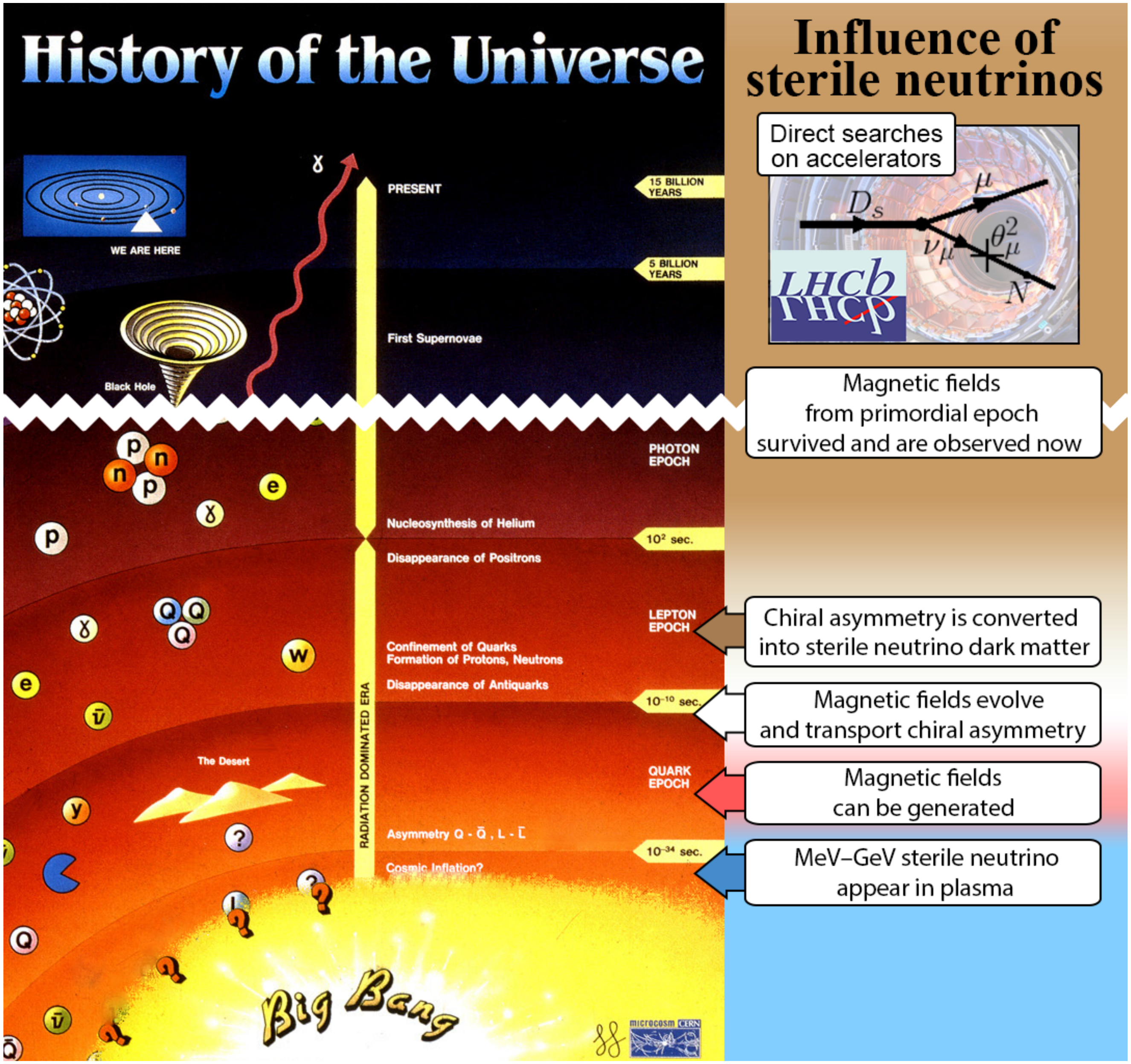
$$\text{Lifetime}_N = \left(\frac{\vartheta^2 G_F^2 M_N^5}{86\pi^3}\right)^{-1}$$

$$\approx 0.3\,\text{sec}\left(\frac{1\text{ GeV}}{M_N}\right)^4$$

– Third sterile neutrino? $\Rightarrow$ Can be dark matter

– **Lepton asymmetry** needed for its production can be created by two other sterile neutrinos

Early Universe with heavy neutral leptons

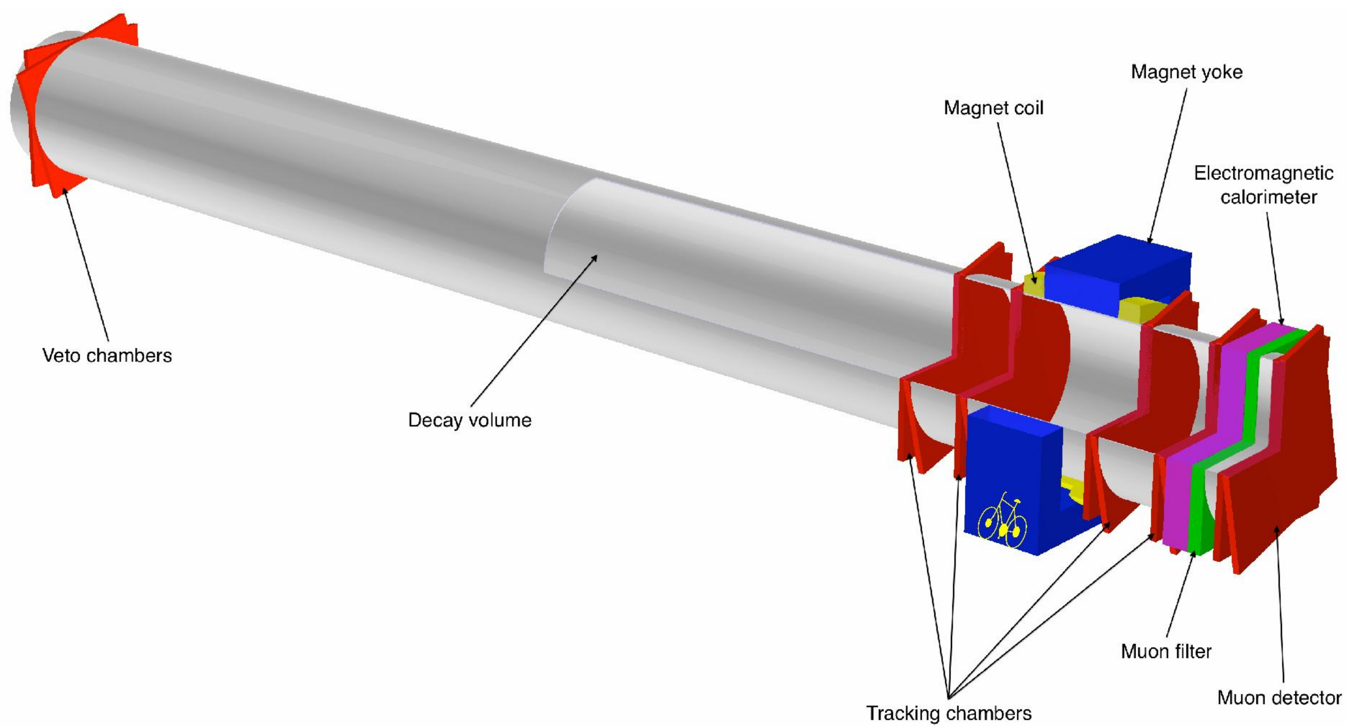


[arXiv:1310.17

W. Bonivento, A. Boyarsky, H. Dijkstra, U. Egede, M. Ferro-Luzzi, B. Goddard, A. Golutvin, D. Gorbunov, R. Jacobsson, J. Panman, M. Patel, **O. Ruchayskiy**, T. Ruf, N. Serra, M. Shaposhnikov, D. Treille

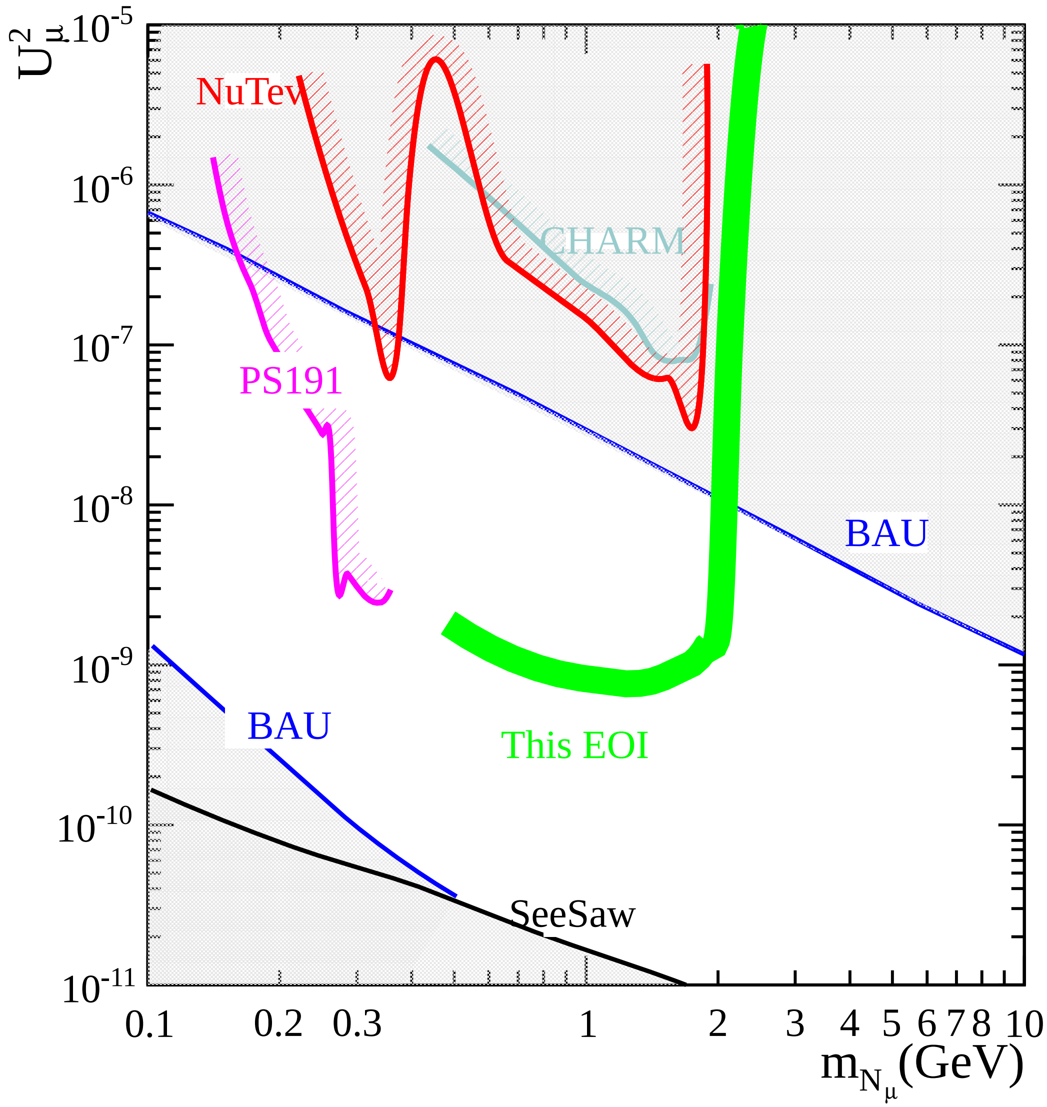
Proposal to Search for Heavy Neutral Leptons at the SPS

Expression of Interest. Endorsed by the CERN SPS council



Open collaboration meeting

Expected sensitivity

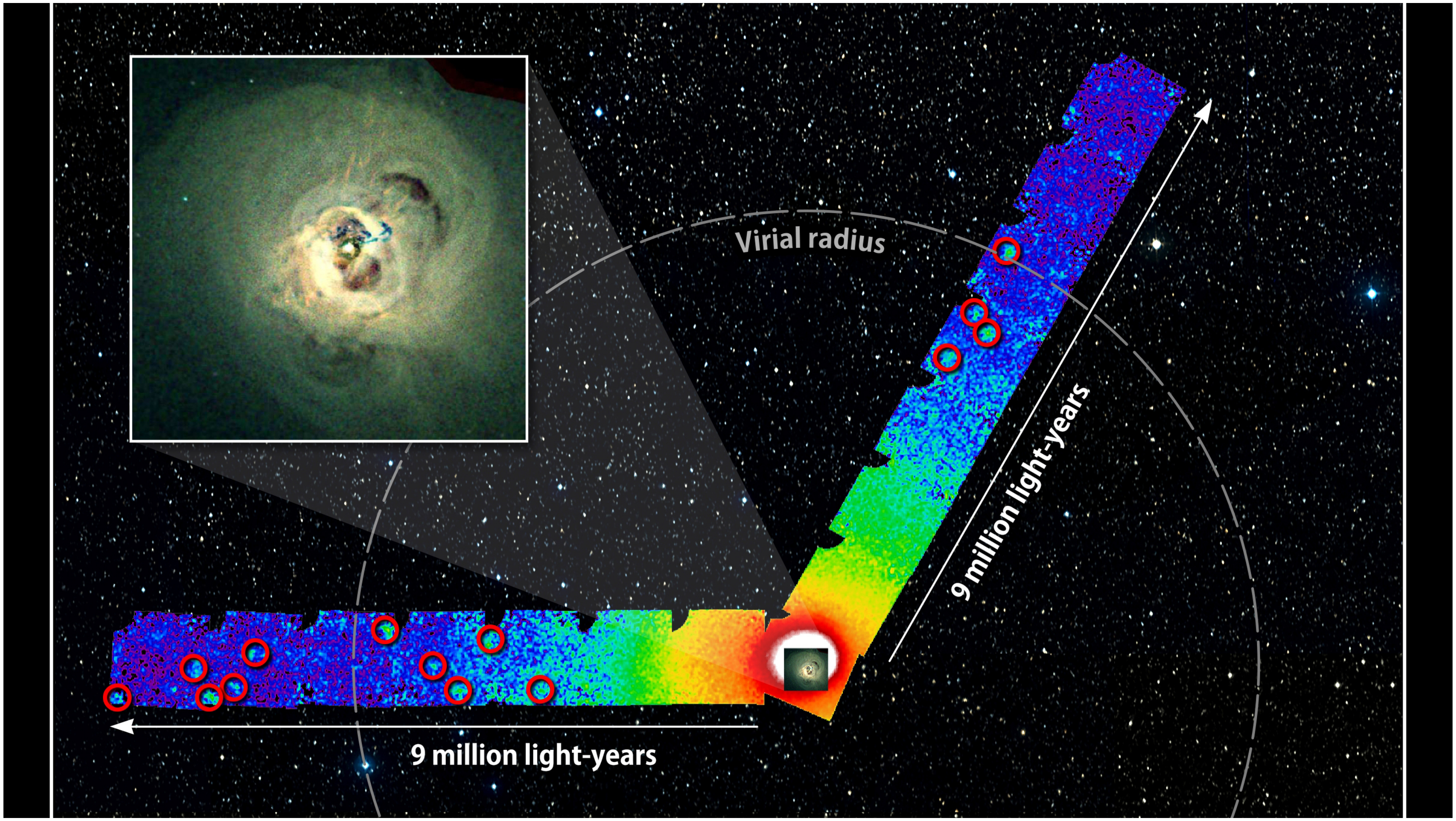


Conclusions

- ▷ Observable beyond-the-Standard-Model puzzles mean that new particles should exist
- ▷ These particles can be either **heavy** or **super-weakly interacting**
- ▷ Neutrino oscillations suggest that sterile neutrinos (heavy neutral leptons) can exist
- ▷ Such particles can explain baryon asymmetry of the Universe, provide dark matter candidate and explain neutrino oscillations
- ▷ The resulting model (the νMSM) looks like Standard Model from the point of view of todays' experiments
- ▷ To distinguish $\Rightarrow$ intensity frontier experiments and "poor man's accelerator"

Thank you for your attention

Perseus galaxy cluster

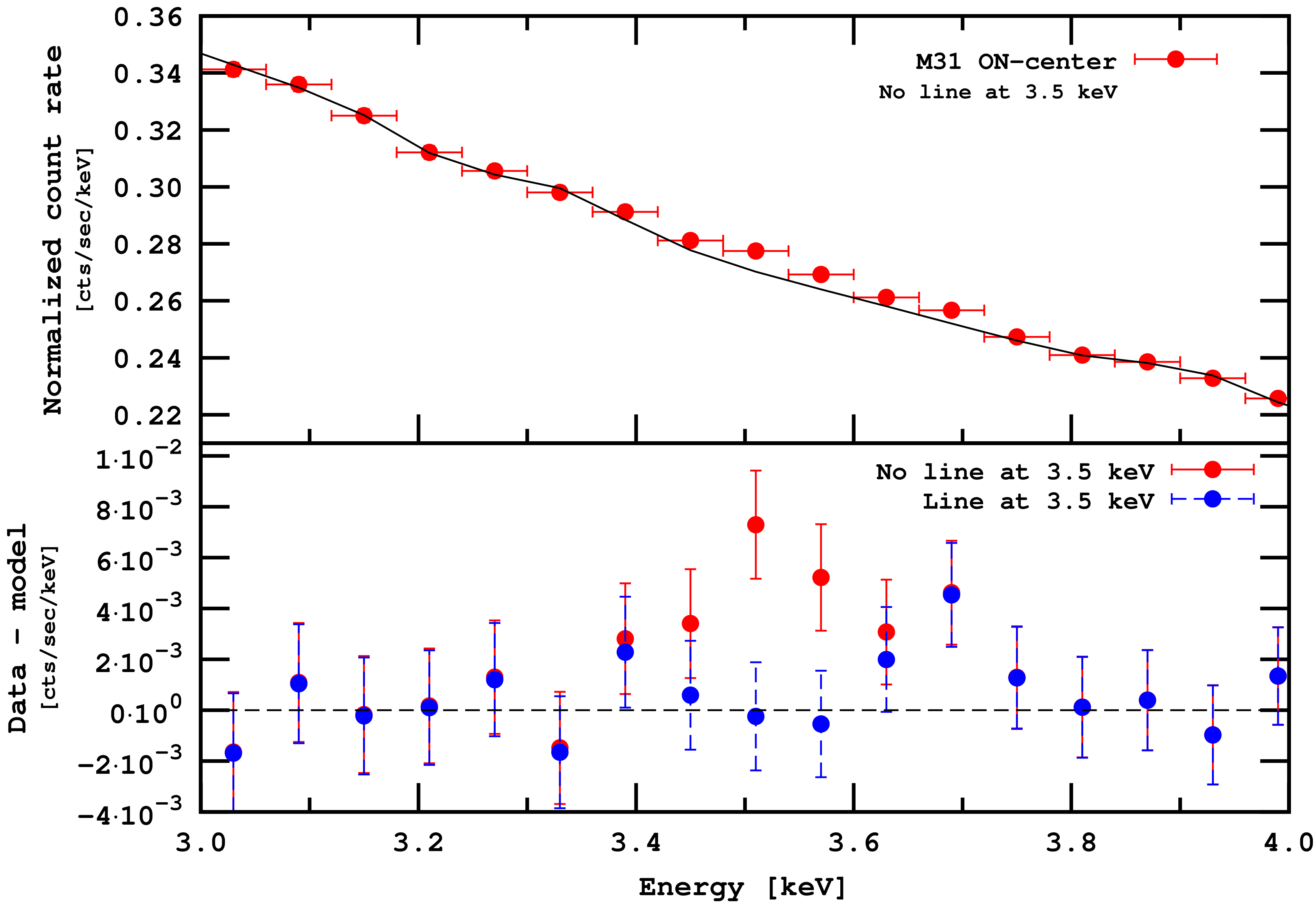


Bulbul et al. took only 2 central XMM observation – $14'$ around the cluster's center

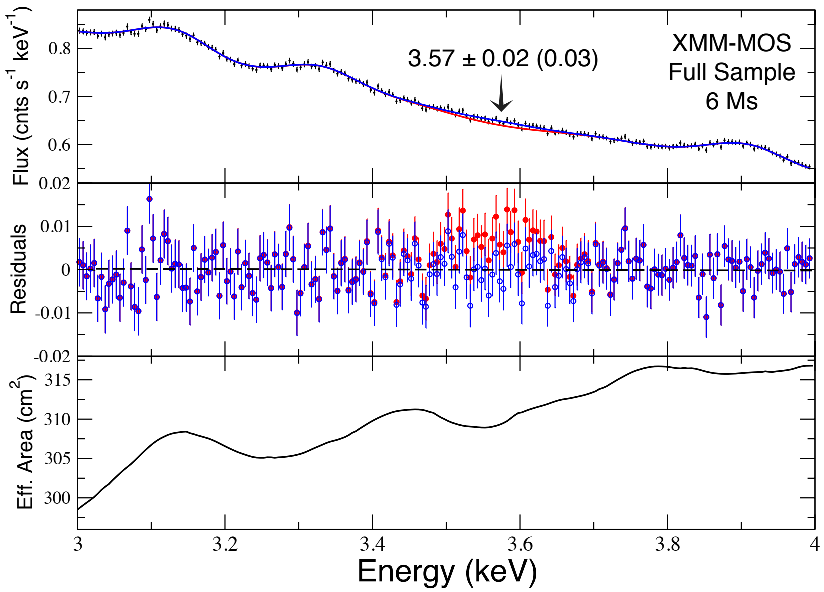
We took 16 observations **excluding** 2 central XMM observations to avoid modeling complicated central emission

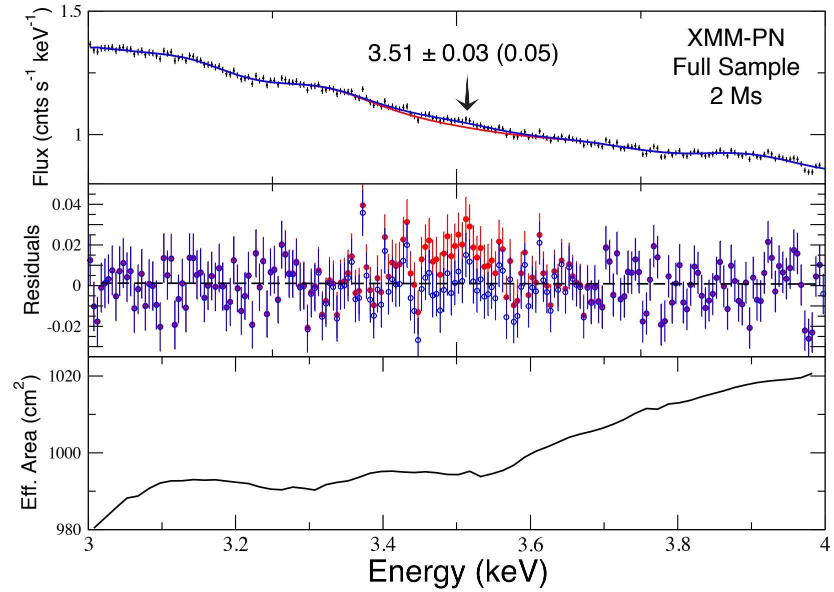
Andromeda galaxy (zoom 3-4 keV)

[1402.4119]

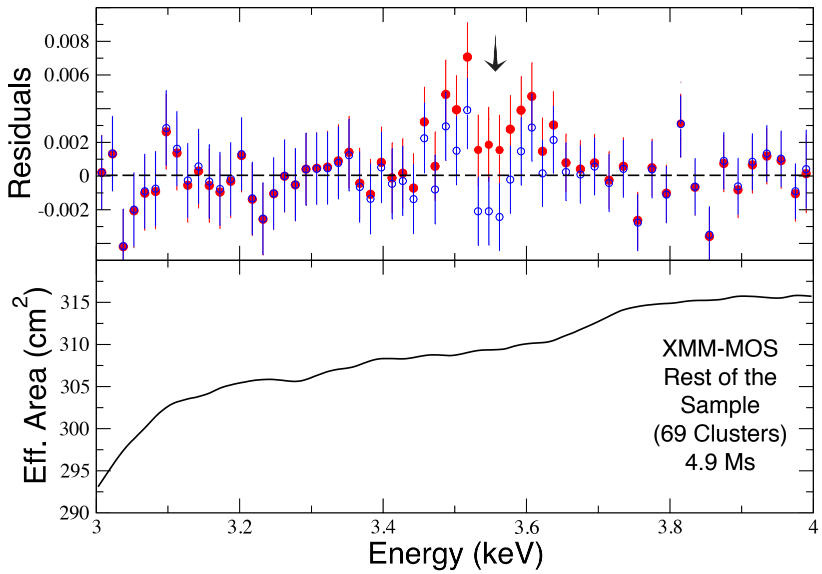


Full stacked spectra



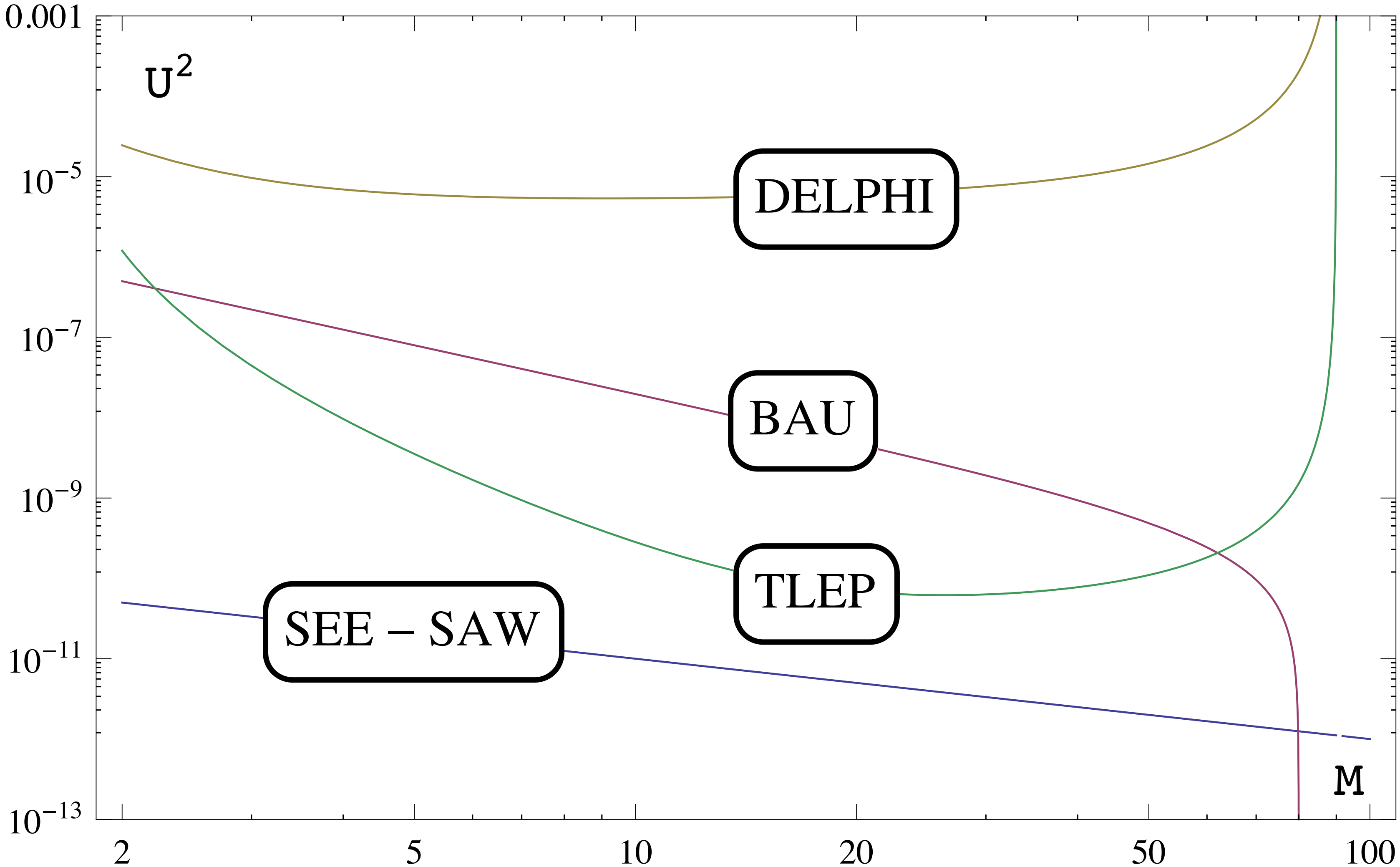


Bulbul et al. [1402.2301]



- All spectra blue-shifted in the reference frame of clusters
- Instrumental background processed similarly and **subtracted**

Higher masses (PRELIMINARY!)



From M. Shaposhnikov's talk at TLEP-7 workshop