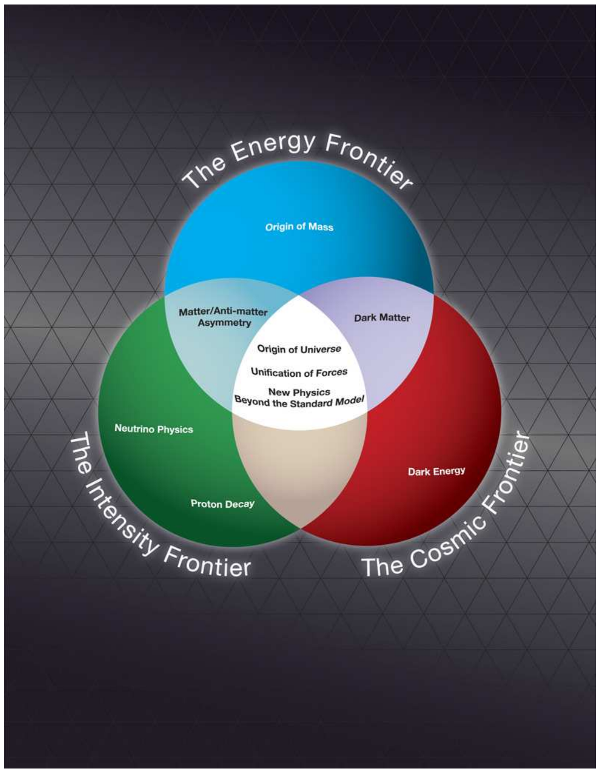
# Sterile Neutrinos: a hidden portal to physics beyond the Standard Model




**Oleg RUCHAYSKIY**

EPFL

Cosmic Frontier Workshop

**SLAC**

**March 7, 2013**

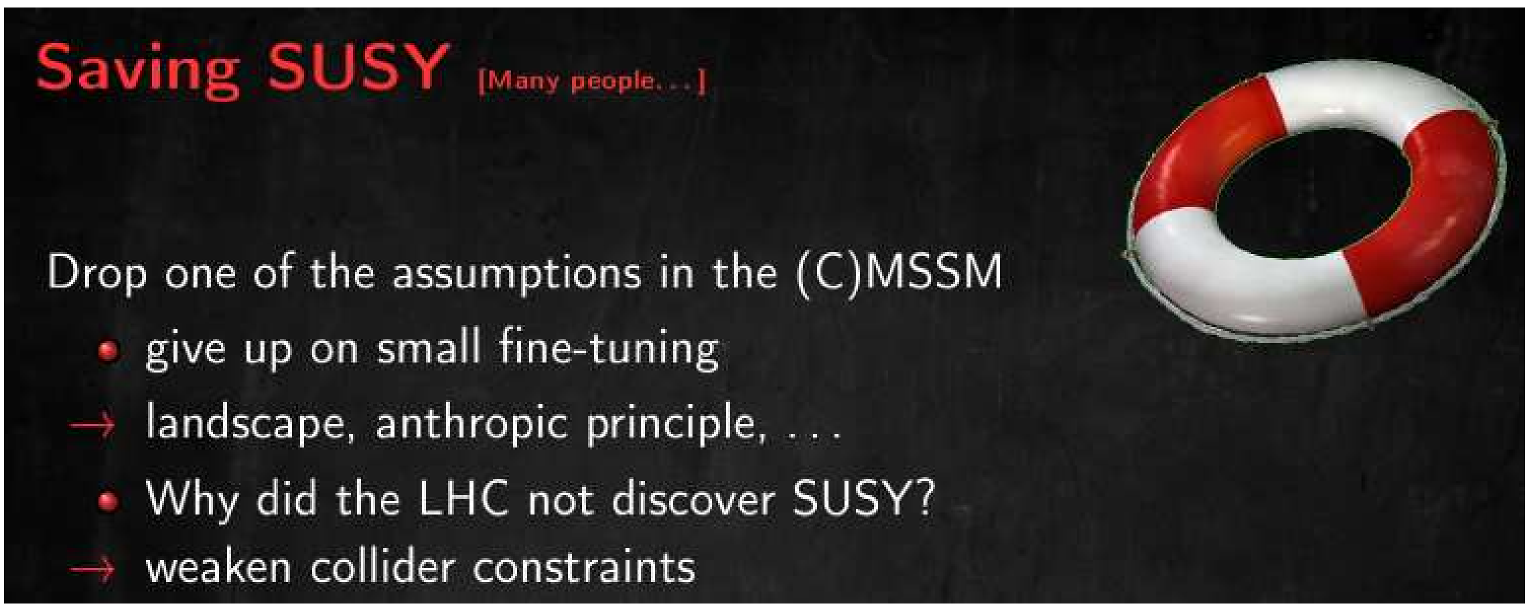
# Front page of International Herald Tribune

# New physics?

- Particle physics community strongly focused on the **new physics at the TeV scale**:
  - supersymmetry
  - extra dimensions
  - strong dynamics (“technicolor”)

## However

see e.g. many talks at ICHEP-2012



# Beyond the Standard Model

We have known for long time that some phenomena **will not find their explanation within the Standard Model** (even when Higgs if found)

→ **Neutrino oscillations**: transition between neutrinos of different flavours ($\nu_e$, $\nu_\mu$, $\nu_\tau$) 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?)

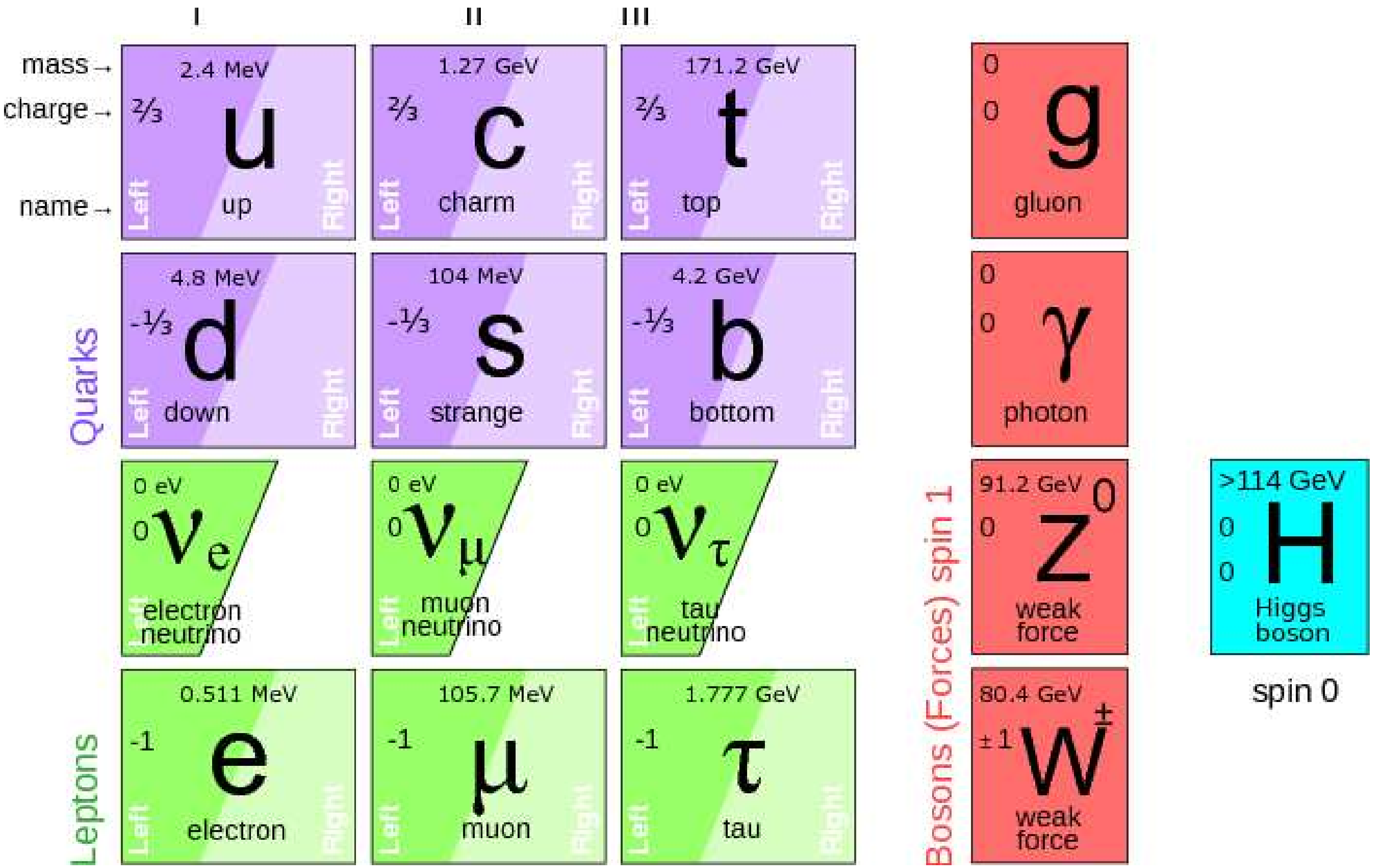
→ the **absence of anti-matter** in the Universe

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

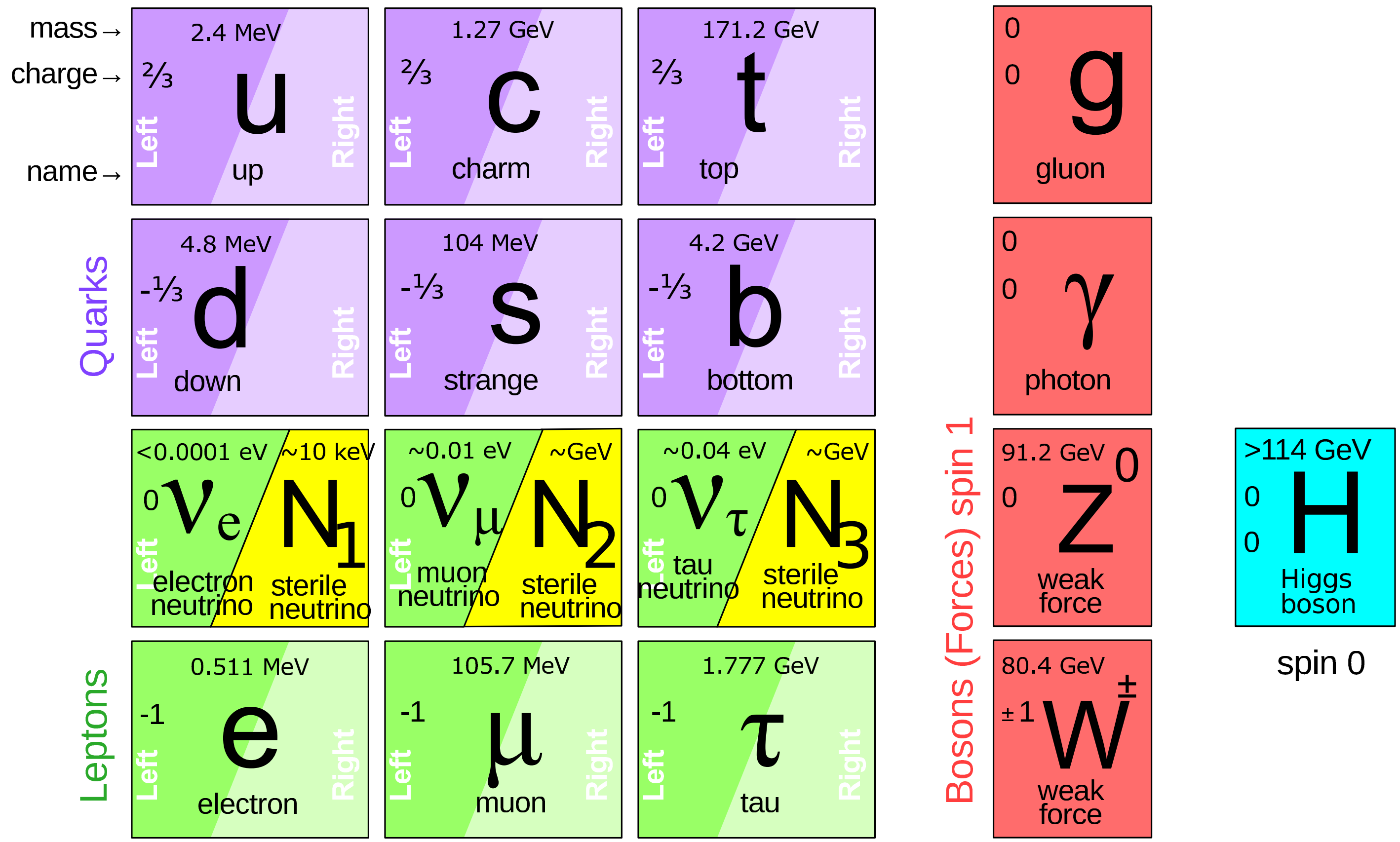
→ **(Maybe)** dark energy (**If** it will be shown that accelerated expansion of the Universe is caused not by a small cosmological constant, but by some other unknown substance – what is this substance?)

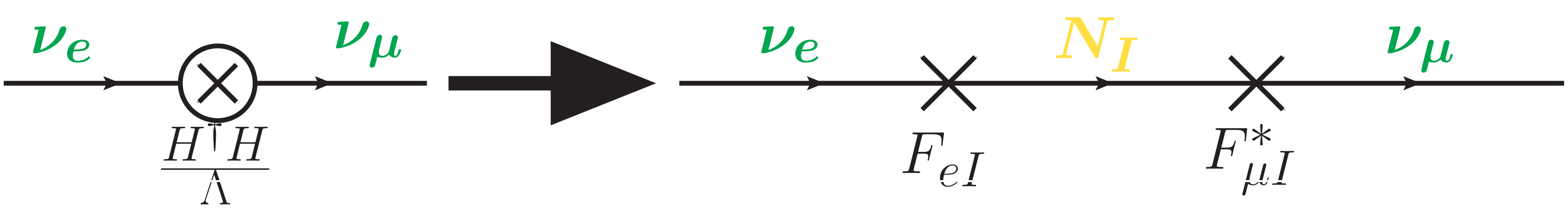
What should we do with **beyond-the-Standard-Model problems** if no new physics will be found at LHC?

# Neutrinos: left-only particles

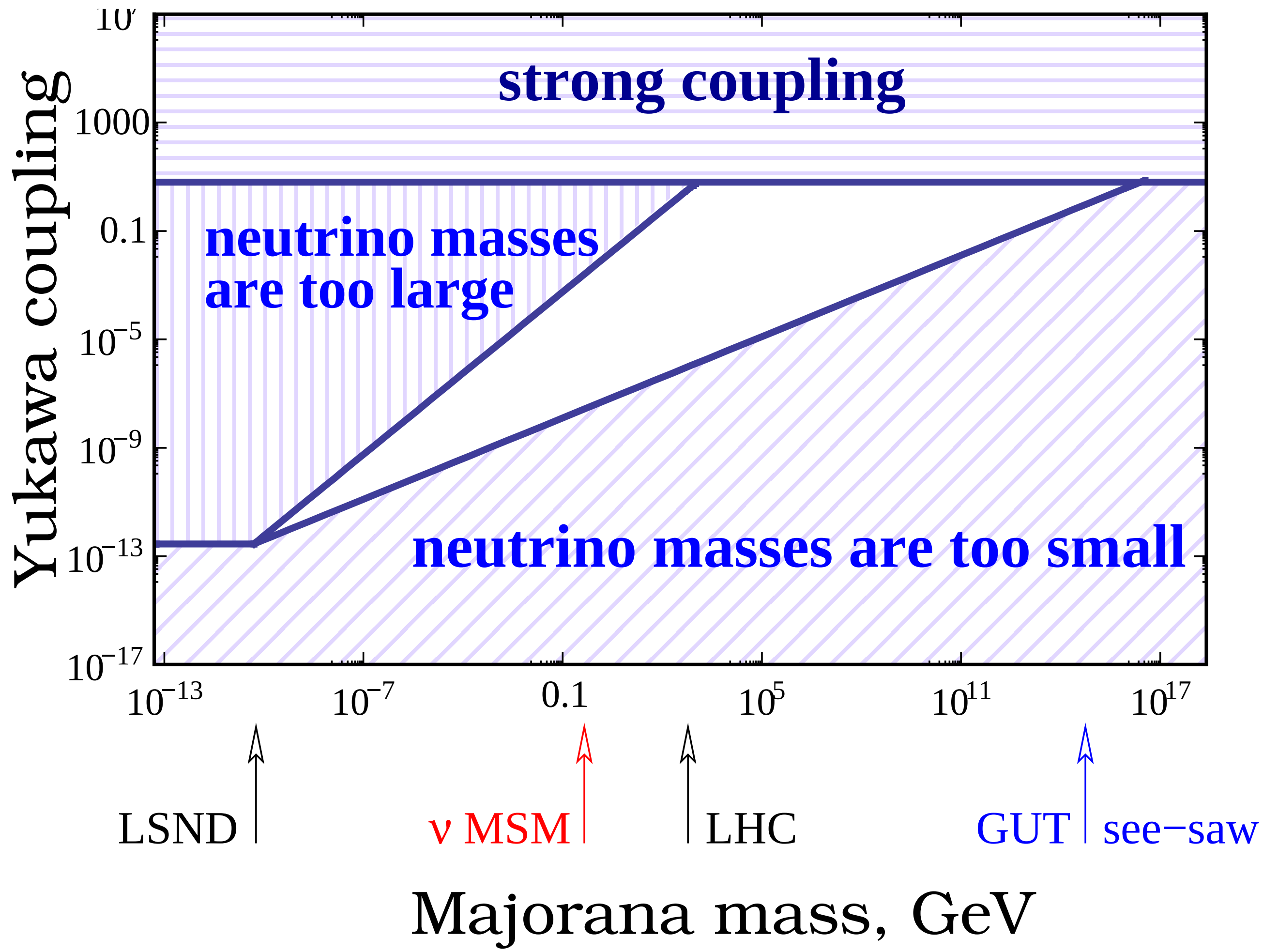


# Neutrino oscillations and sterile neutrinos



# Scale of sterile neutrino masses?




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

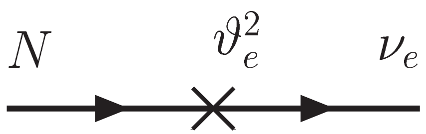
Sterile neutrino white paper [1204.5379]

# How to search for sterile neutrinos, responsible for neutrino oscillations?

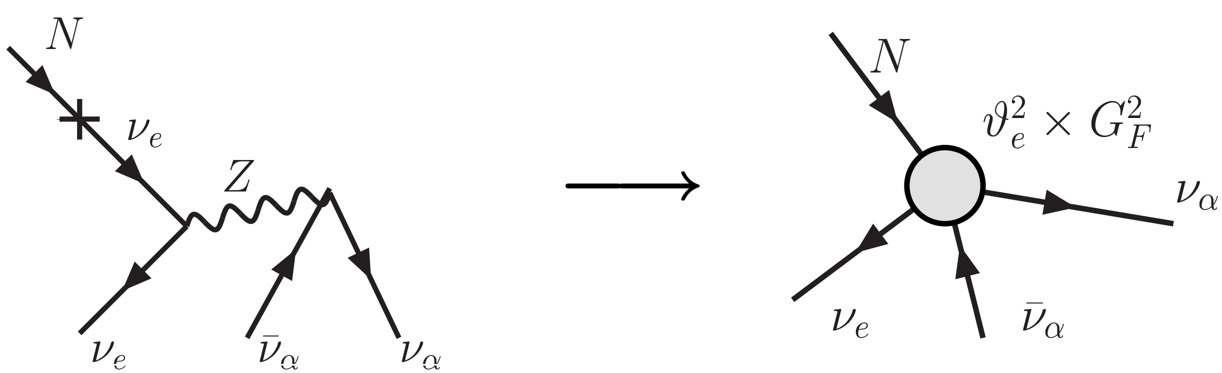
# Properties of sterile neutrino

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

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



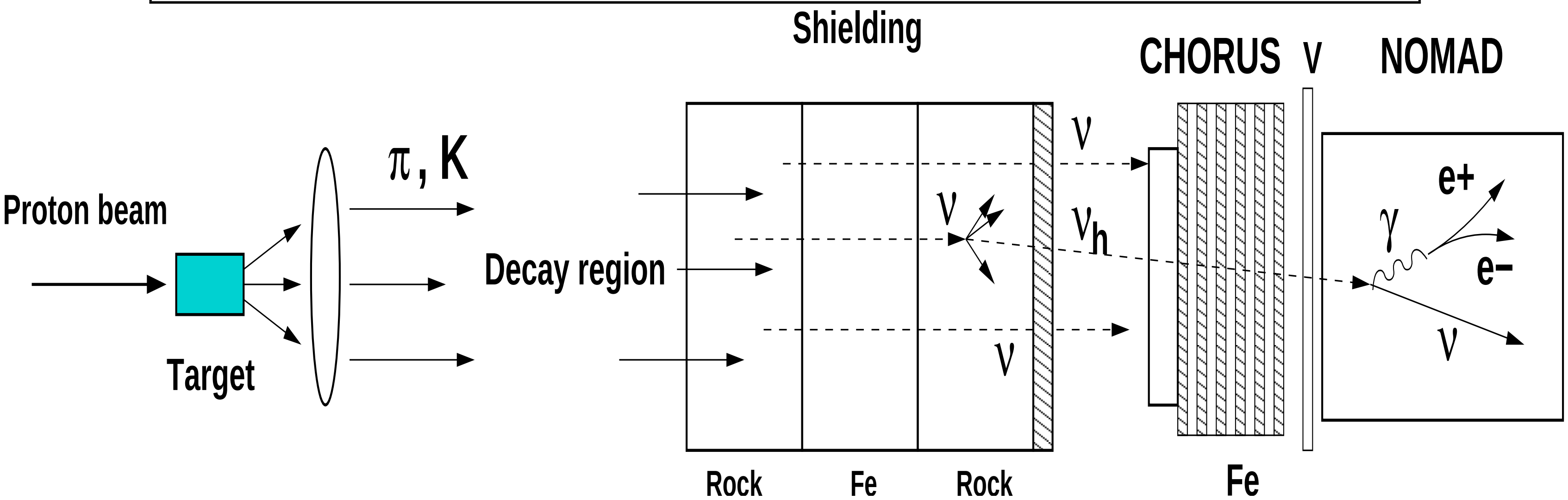

Quadratic mixing $N_s \leftrightarrow \nu$ of sterile neutrinos $N_s$ to $\nu_{e,\mu\,\tau}$




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

# Peak searches and fixed-target experiments

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




**Previous searches**

**Peak searches:**

– SIN $\pi M3$, Switzerland – 1981

– KEK K3, Japan, 1982

– TRIUMF M13, Canada, 1992

– TRIUMF PIENU, Canada, 2011

**Fixed-target searches:**

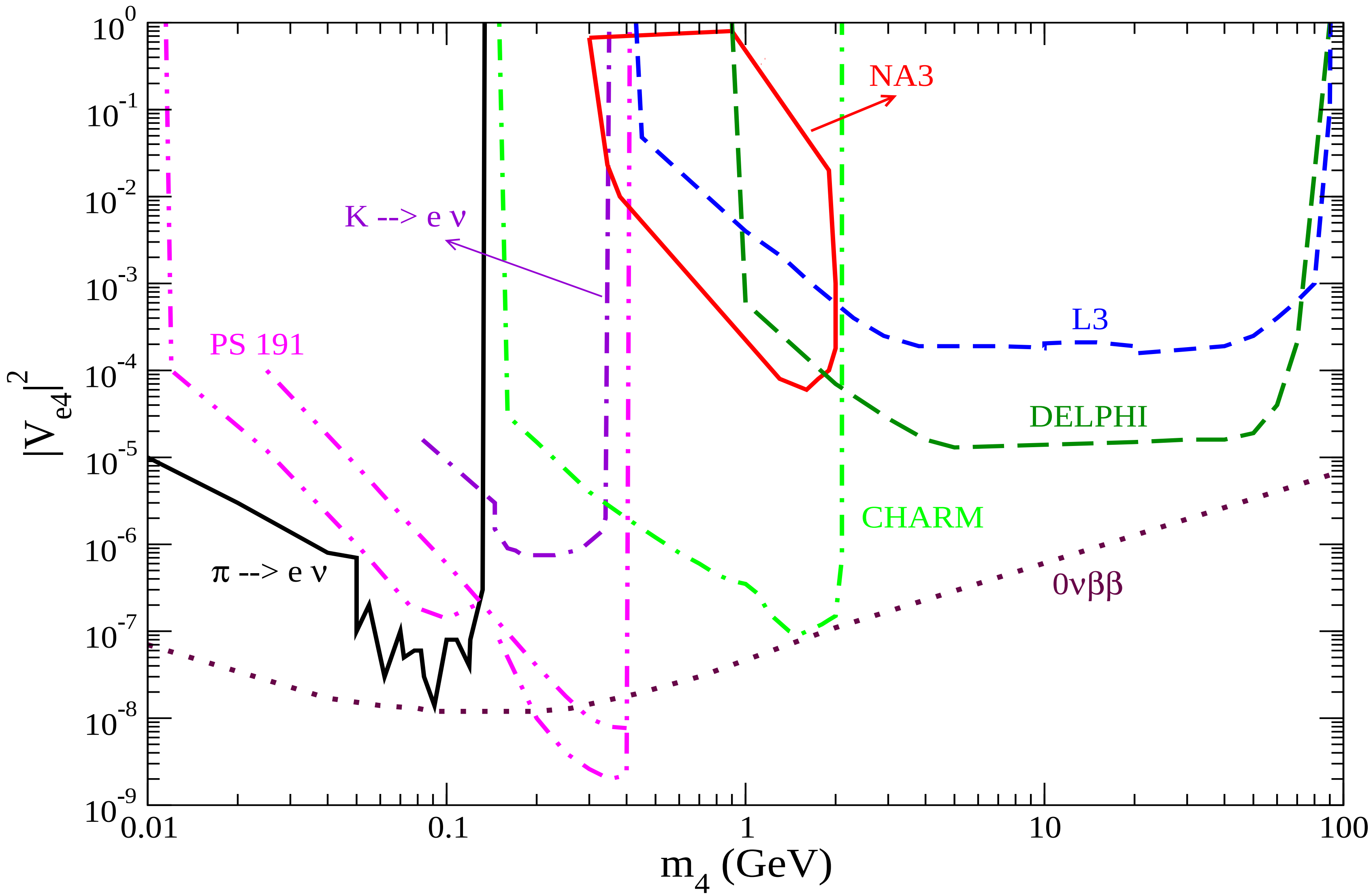
– PS191, CERN – 1984

– CHARM, CERN – 1985

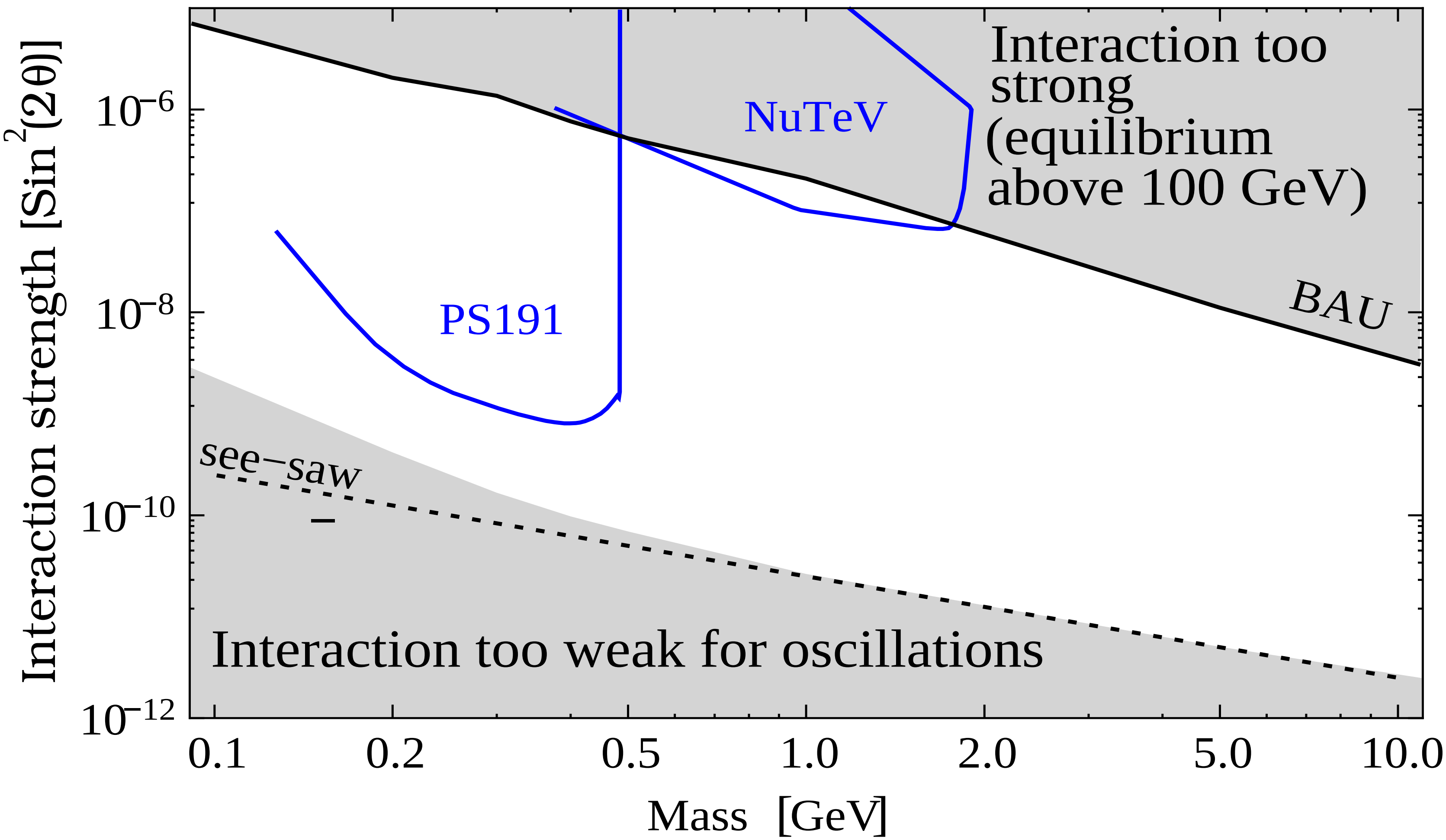
– NuTeV, Fermilab – 1996-1997

Also: LHCb [1201.5600]

# Previous sterile neutrino searches



# Probing neutrino oscillations?

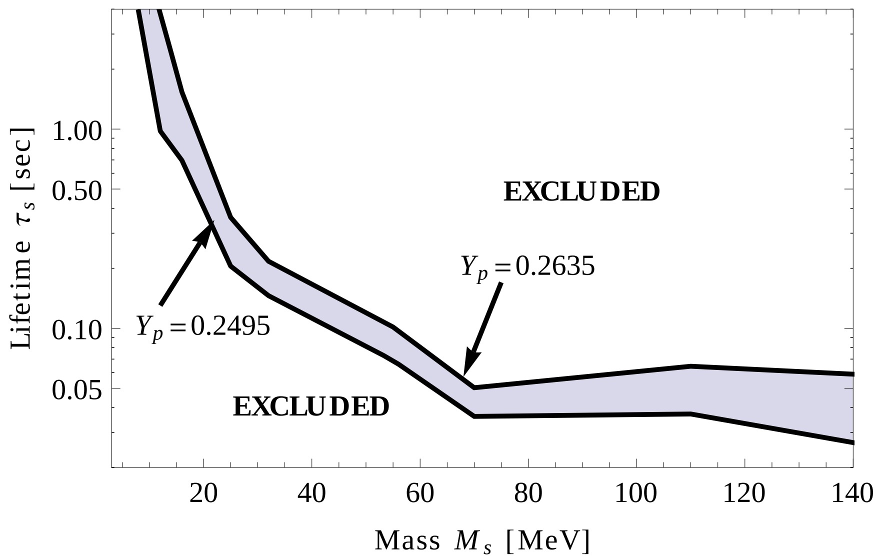



Asaka, Canetti, Gorbunov, Shaposhnikov 2005–2011;

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

**Searches so far failed to touch the "bottom line"**

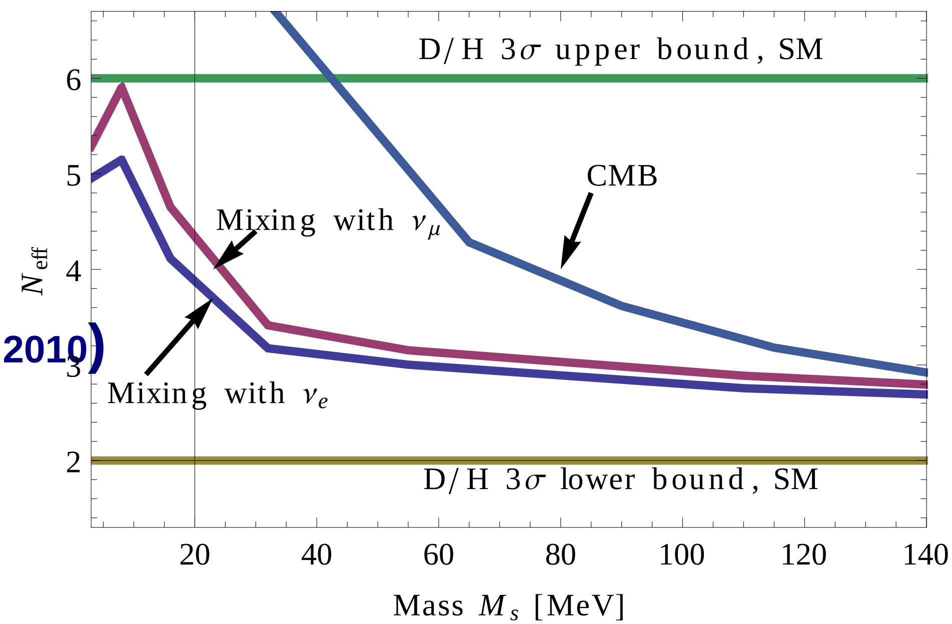
# Sterile neutrinos and the early Universe



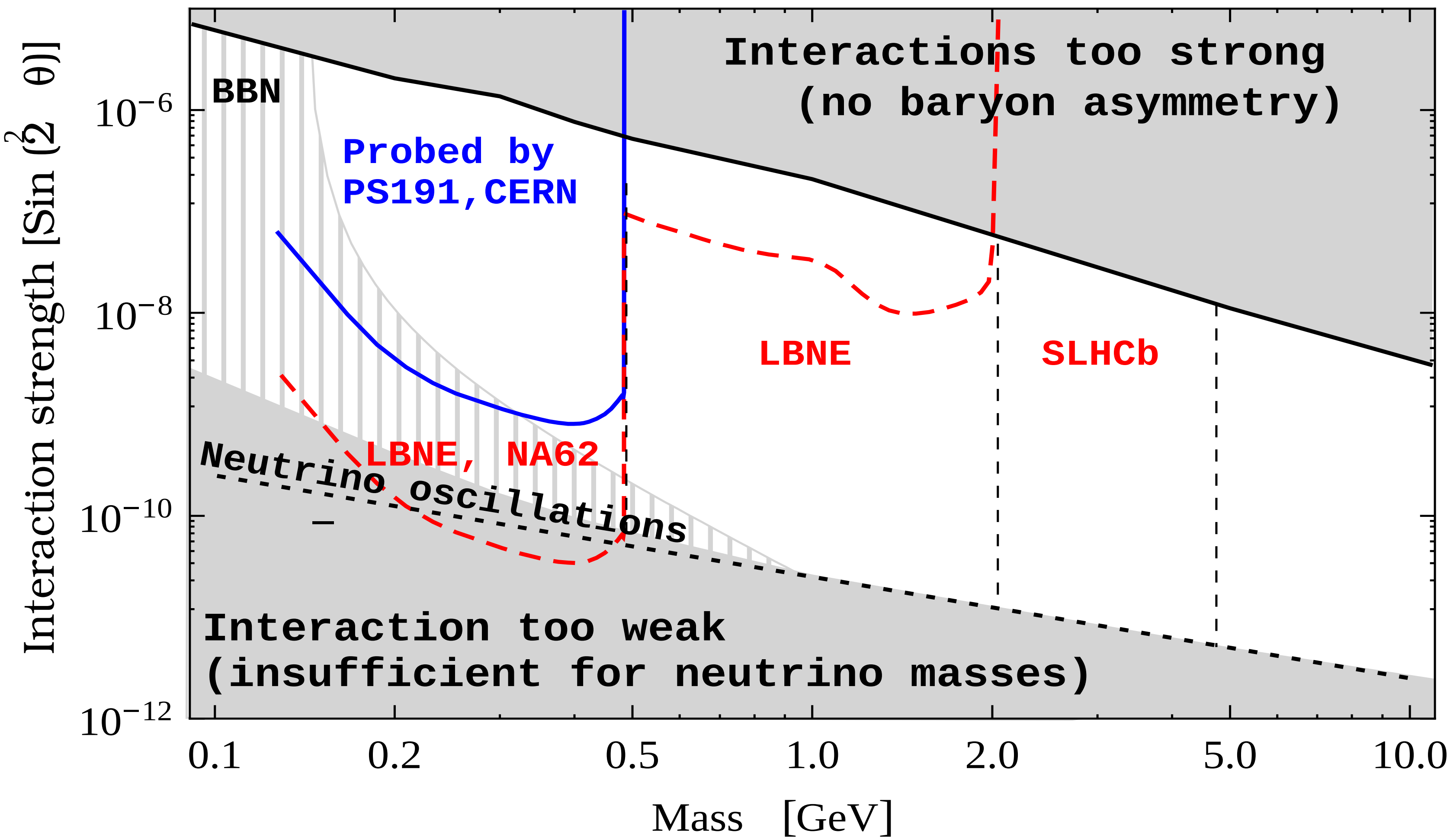

*Sterile neutrinos with the lifetime $\mathcal{O}(0.1)$ sec would affect primordial nucleosynthesis*

**O.R. & Ivashko [1202.2841]**

**($2\sigma$ bounds based on Izotov & Thuan 2010)**



# Parameter space of heavy sterile neutrinos




Dolgov et al. (2000–2001)

Canetti, Gorbunov, Shaposhnikov (2009–2012)

**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]

# Probing BAU at accelerators

– Neutrino oscillations define a **bottom-line** for searches

– Sterile neutrinos in these parameters can lead to **successful baryogenesis**

Asaka, Shaposhnikov and others, 2005–2012

– **Cosmologically interesting region** was not probed in the previous experiments

– Searches for these particles are included in the plans of

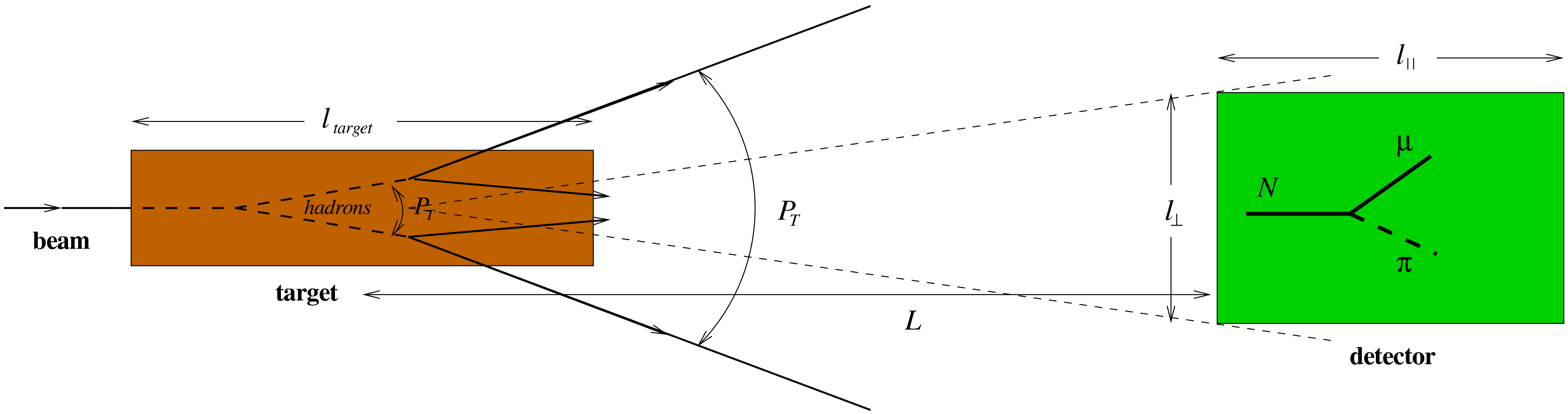
  – Upgrade of the LHCb experiment **[CERN-LHCC-2011-001]**
  – LBNE experiment (FNAL) **[arXiv:1110.6249]**
  – NA62 (CERN)
  – T2K **[arXiv:1212.1062]**

  **see also Lello & Boyanovsky (2012)**

  **searches in extended models, see e.g. Shoemaker et al. (2010); Bhupal Dev et al. (2012)**

**See a proposal to European Strategy Preparatory Group ([arXiv:1301.5516])**

# Ultimate detector (some technical details)




- To probe the mass range below $\sim 1$ 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.

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

**Details can be found in the proposal to European Strategy Preparatory Group and in the review Gninenko, Gorbunov, Shaposhnikov [arXiv:1301.5516]**

# Neutrino Minimal Standard Model

Extension of the Standard Model with 3 sterile neutrinos provides the solution to **all observational BSM problems**. This model is called *Neutrino Minimal Standard Model* or $\nu$MSM for short

### Two sterile neutrinos with MeV–GeV masses:

✓ . . . explain neutrino oscillations

✓ . . . generate matter-antimatter asymmetry of the Universe

✓ . . . generate cosmic magnetic fields

### Third sterile neutrino with keV mass:

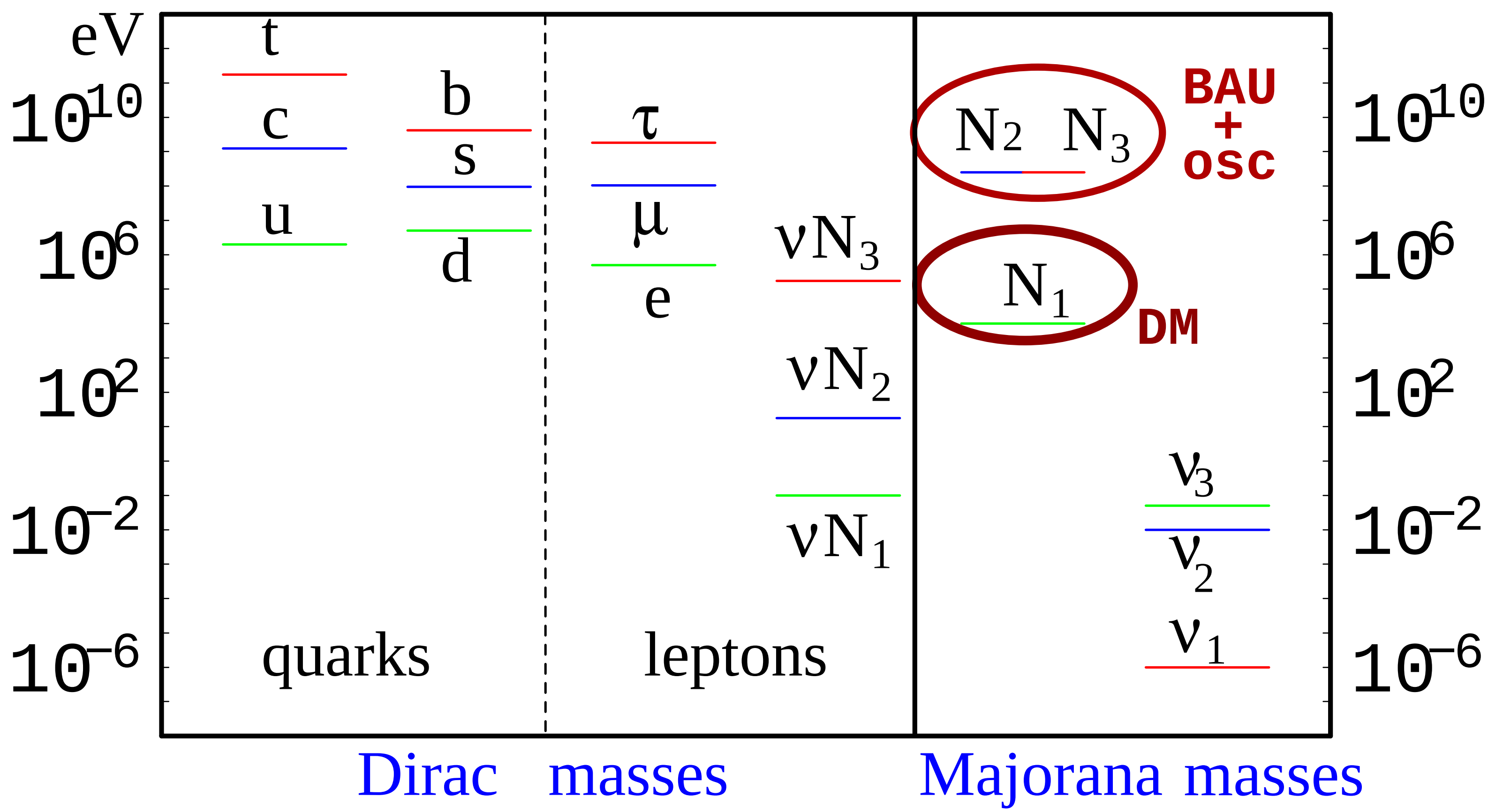
✓ . . . provides a dark matter particle (cold, **warm** or **mixed**)

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

Additionally, Higgs boson plays the role of an inflaton **making a consistent model all the way to Planck scale**

Bezrukov & Shaposhnikov (2007–present)

# Masses of sterile neutrinos in the $\nu$MSM



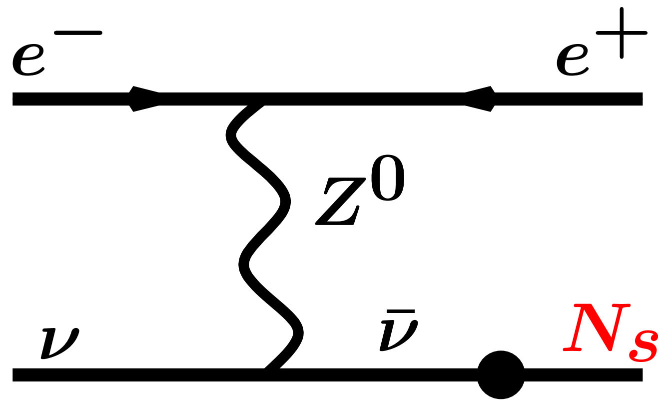

Masses of sterile neutrinos as those of other leptons
Yukawas as those of electron or smaller

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

# Sterile neutrino DM. An overview

- Sterile neutrinos: massive, neutral, super-weakly interacting ⇒ Dark matter candidate

- Can be produced in the early Universe in the correct amount through mixing with active neutrinos




Also produced in many extended models **[Shaposhnikov & Tkachev (2006); Kusenko, Petraki (2006, 2007); Boyanovsky (2007); Kusenko, Takahashi, Yanagida (2010), Fuller, Kusenko, Kishimoto. . . ]**

- Sterile neutrino DM is **never in equilibrium** in the early Universe. Its concentration is always **below** equilibrium one.

- Properties of sterile neutrino DM (abundance, primordial velocities, etc.) are **sensitive to the content of primordial plasma**

Dodelson & Widrow (1993)

Shi & Fuller (1998)

Abazajian, Fuller et al. 2001–2005

Dolgov & Hansen (2000)

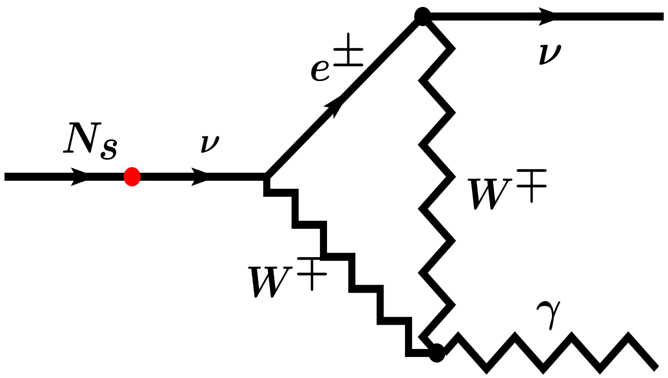
Asaka, Shaposhnikov, Laine (2005–. . . )

Boyanovsky et al. (2007–2008)

# Properties of sterile neutrino dark matter

- Can **decay** with cosmologically long lifetime (through the same interaction that led to its production)

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




Dodelson & Widrow (1993)

Shi & Fuller (1998)

Abazajian, Fuller et al. 2001–2005

Dolgov & Hansen (2000

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

Loewenstein, Kusenko (2008, 2009, 2012)

- Sterile neutrino DM is produced at temperatures $T \sim 100$ MeV (for masses $\sim$ keV – created relativistic $\Rightarrow$ **warm dark matter**

Hasen, Riemer-Søorensen (2006, 2009)

- Relativistic particles **free stream** out of overdense regions and smooth primordial inhomogeneities

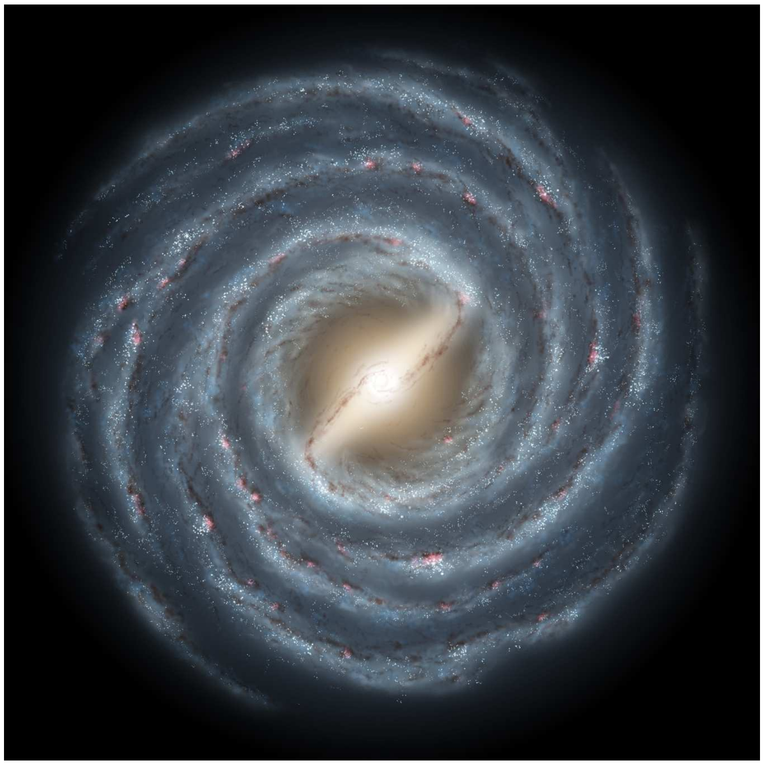
Boyarsky, **O.R** et al. (2006-2013)

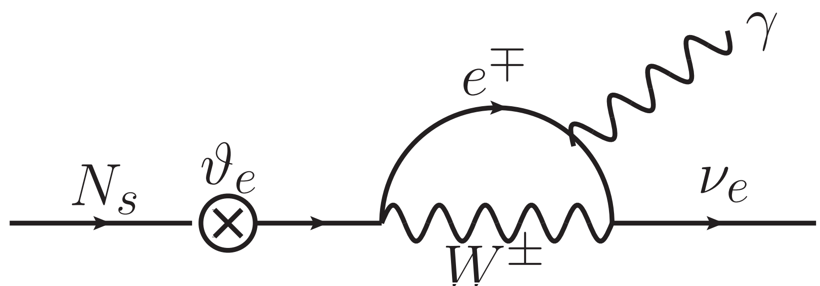
Watson et al. (2006)

# 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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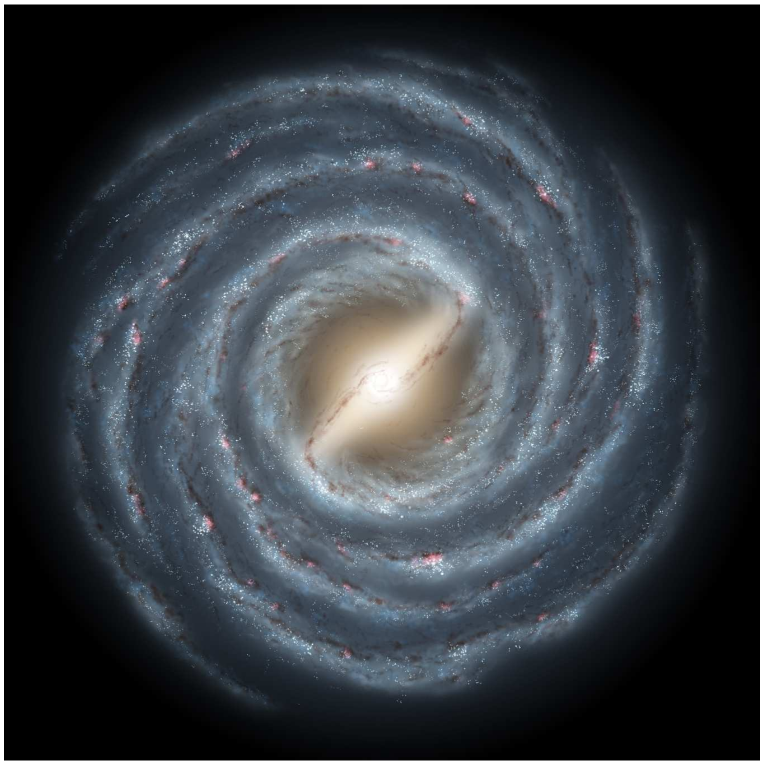
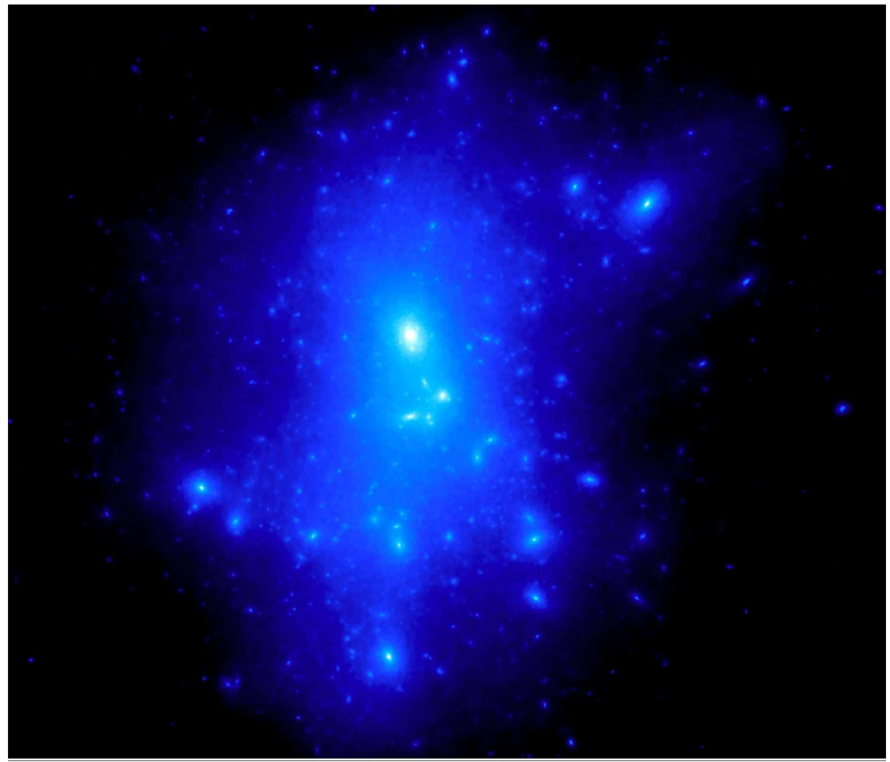
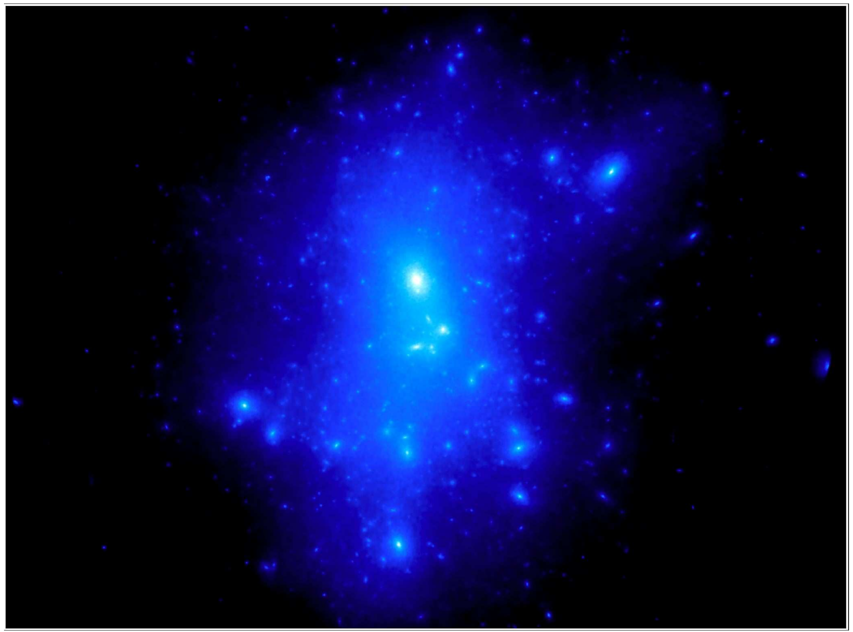


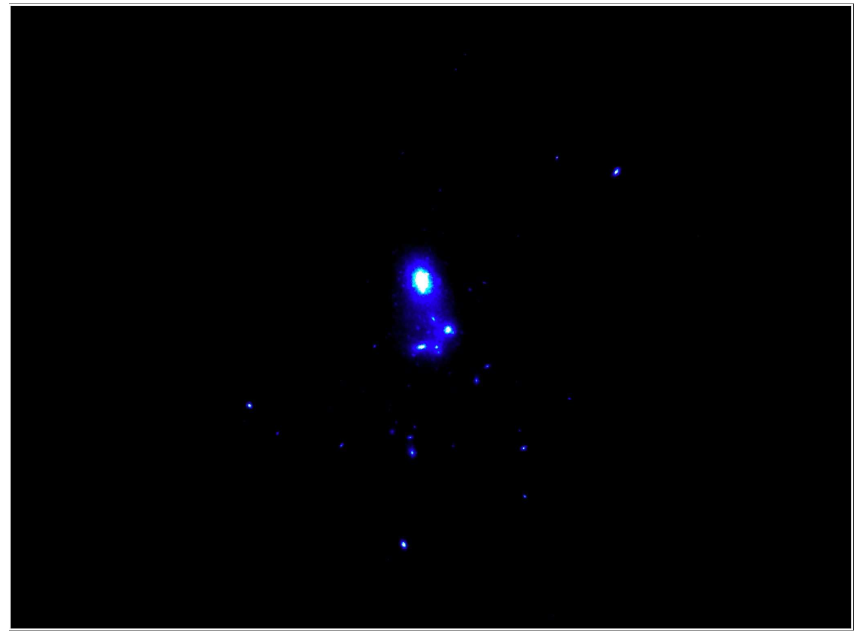


Expected signal from a galaxy at a particular energy (simulation from B. Moore)

# Search for decaying dark matter



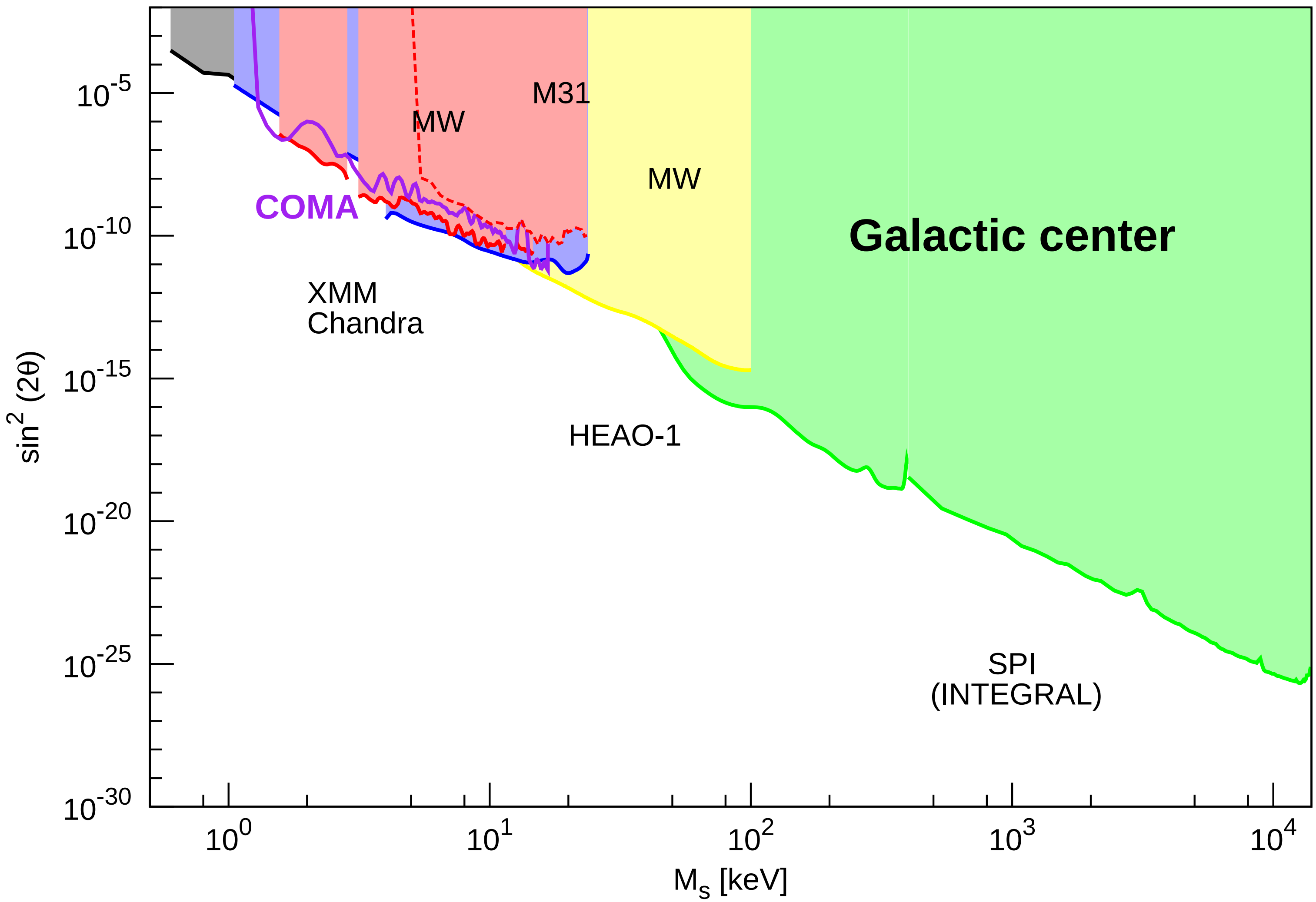
DM **decay** signal from a galaxy



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

# Bounds on decaying DM from varios objects




**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

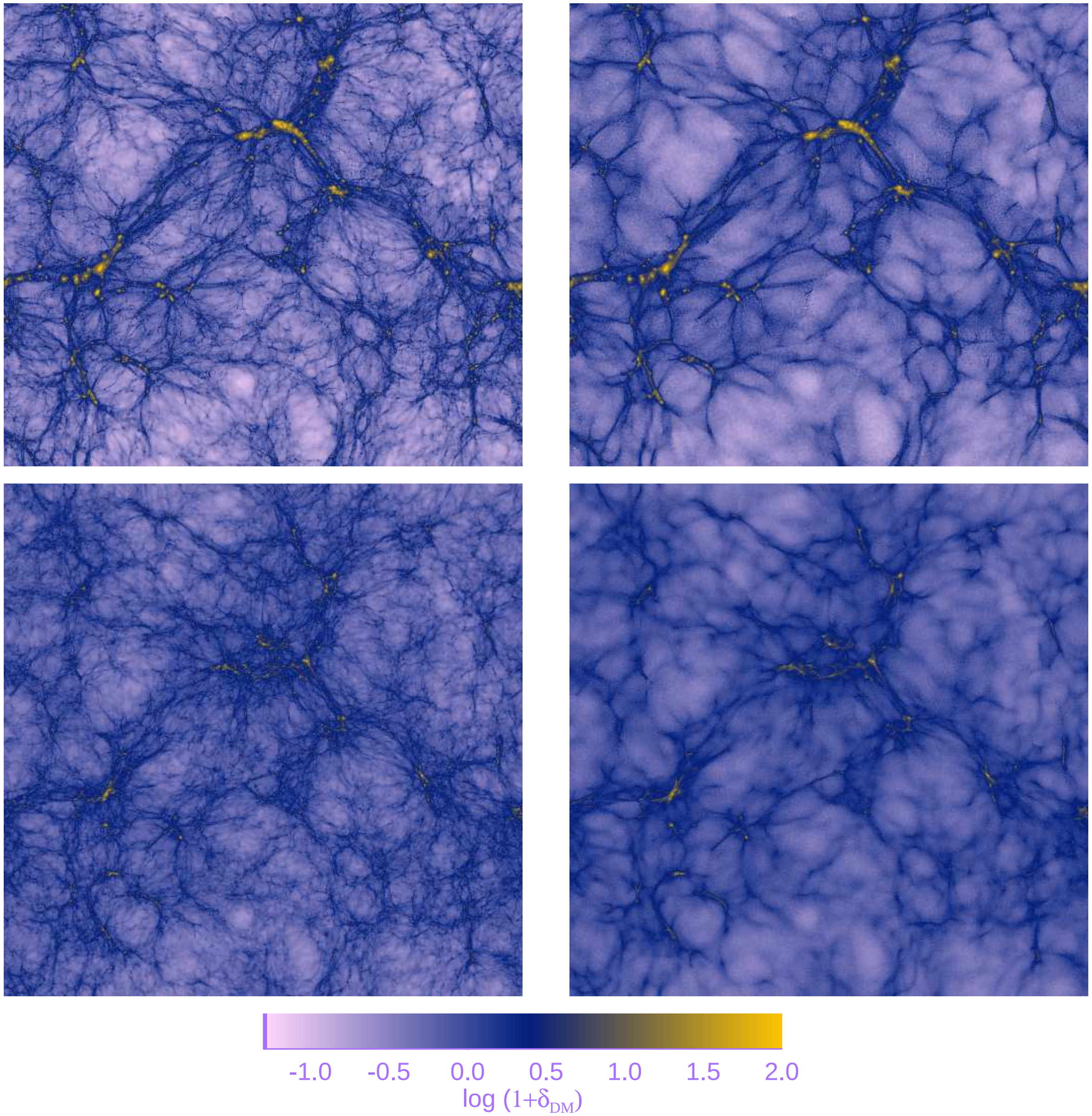
**MW** Riemer-Sørensen et al.; Abazajian et al.

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

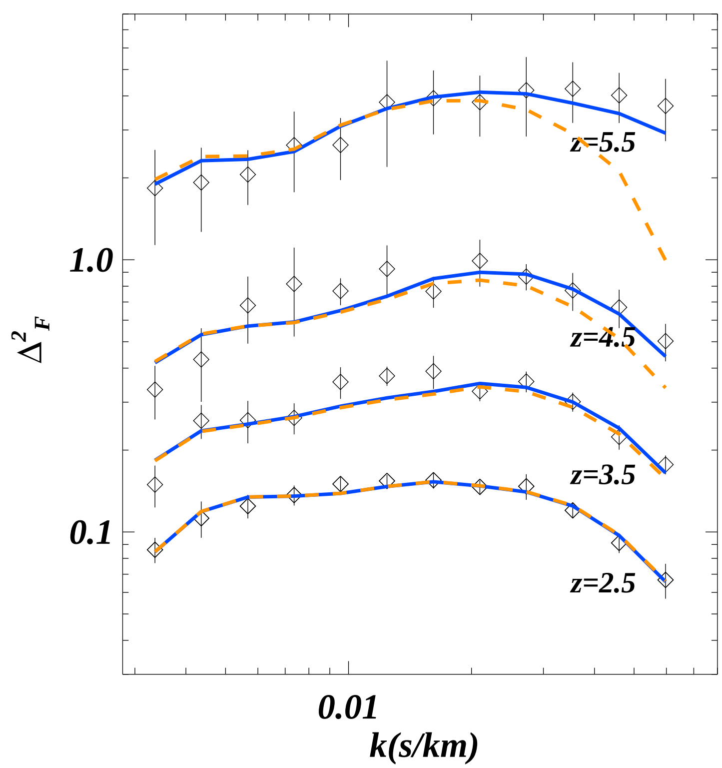
**M31** Watson et al. 2006; Boyarsky et al 2007

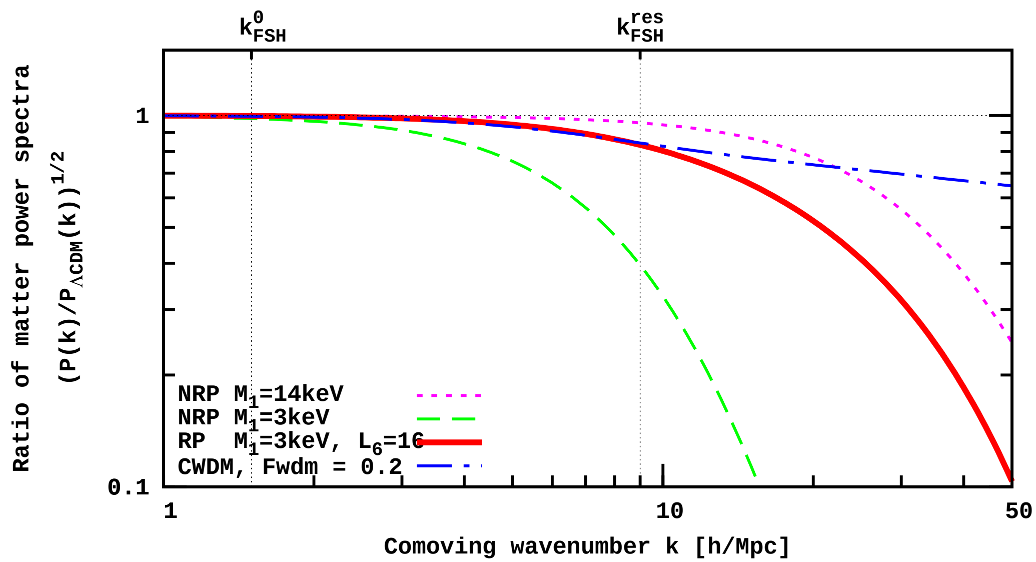
# Simulations of IGM (z = 2-5)

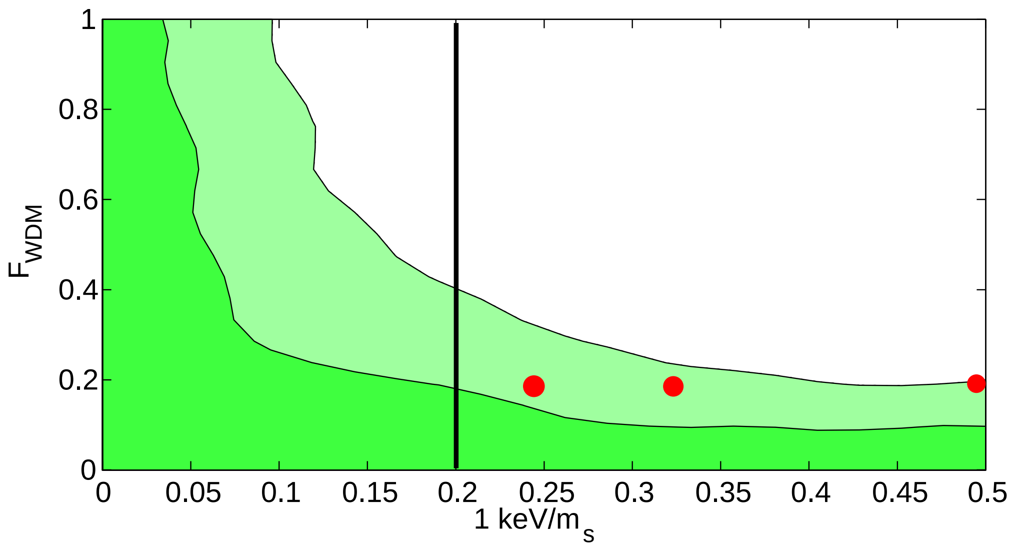
Viel et al. [1107.4094]



## Lyman-$\alpha$ forest flux power spectrum



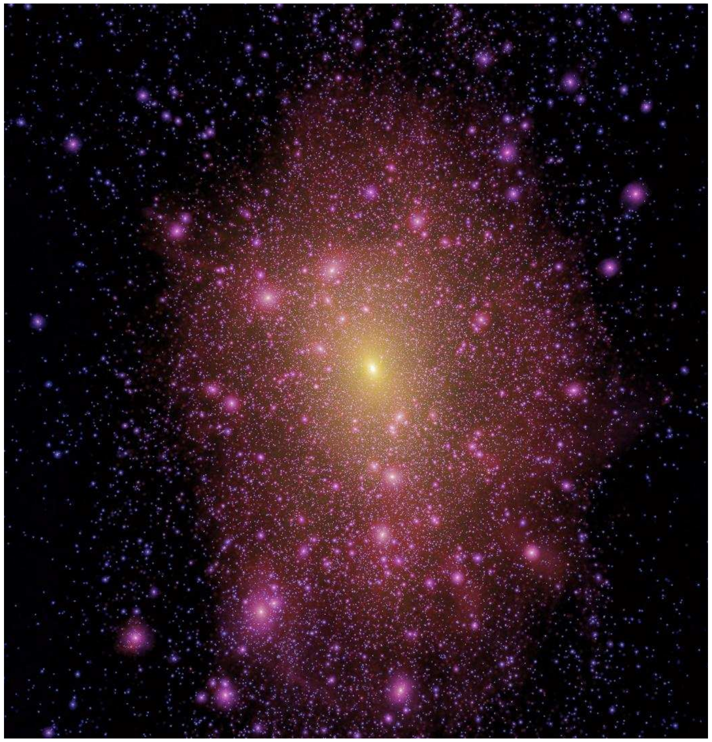



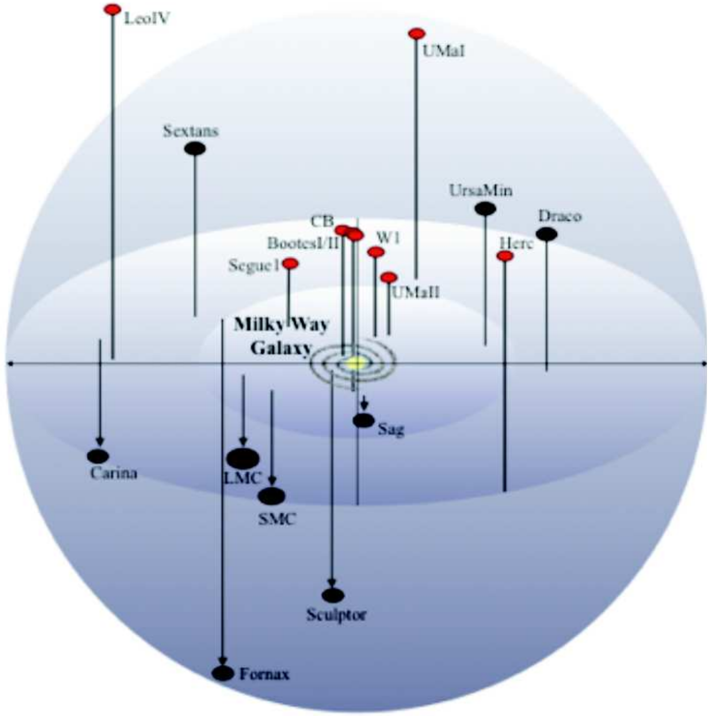




Measured flux power spectrum compared to CDM and non-CDM models **[Viel et al. (2005–2007); Abazajian et al. (2006); Seljak et al. (2006); Boyarsky et al. (2008)]**

**[Boyarsky, Lesgourgues, O.R., Viel (2008)]**

# Halo substructure in "cold" DM universe



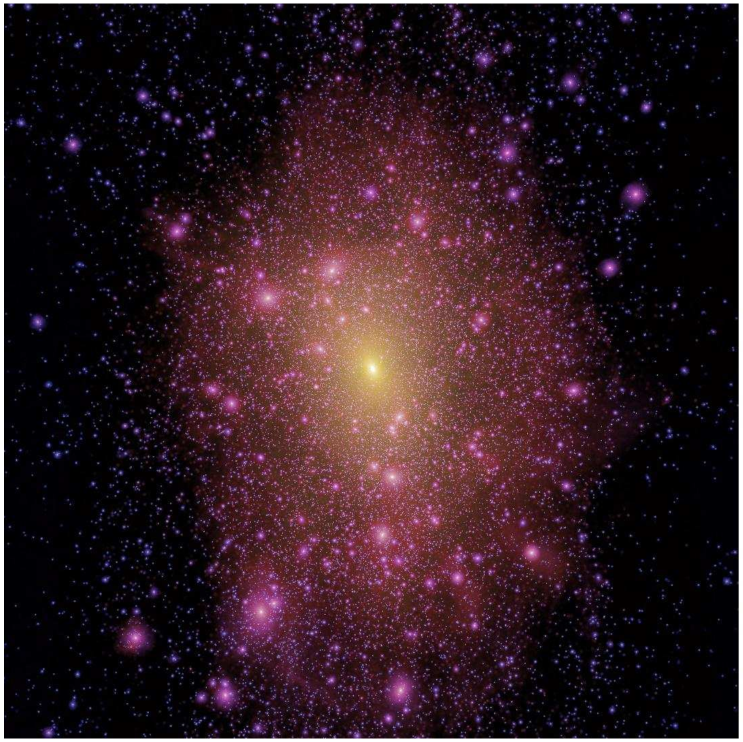



**COLD** DM models predict millions of substructures within a galaxy like Milky Way

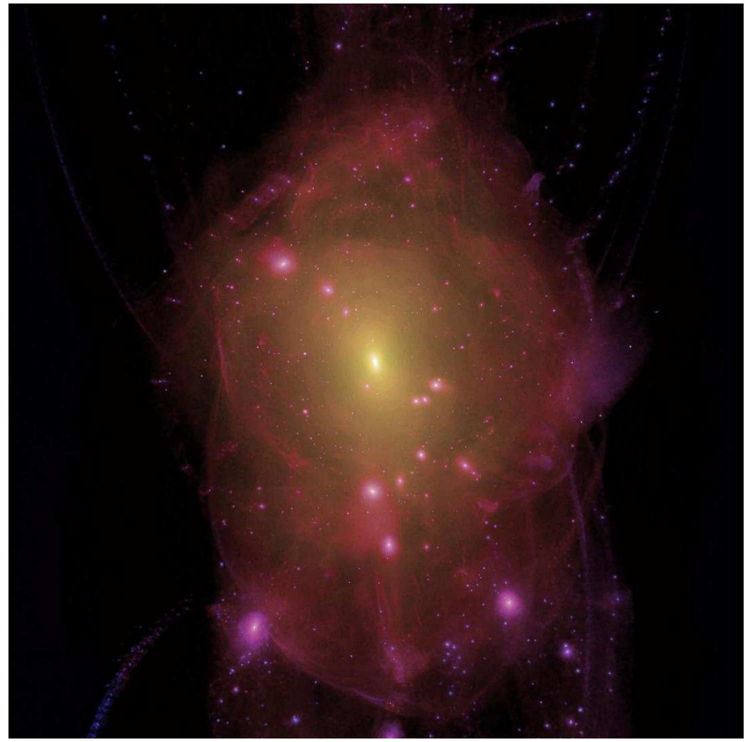
Only $\sim\ 30$ are observed within our Galaxy. M. Geha 2010

**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



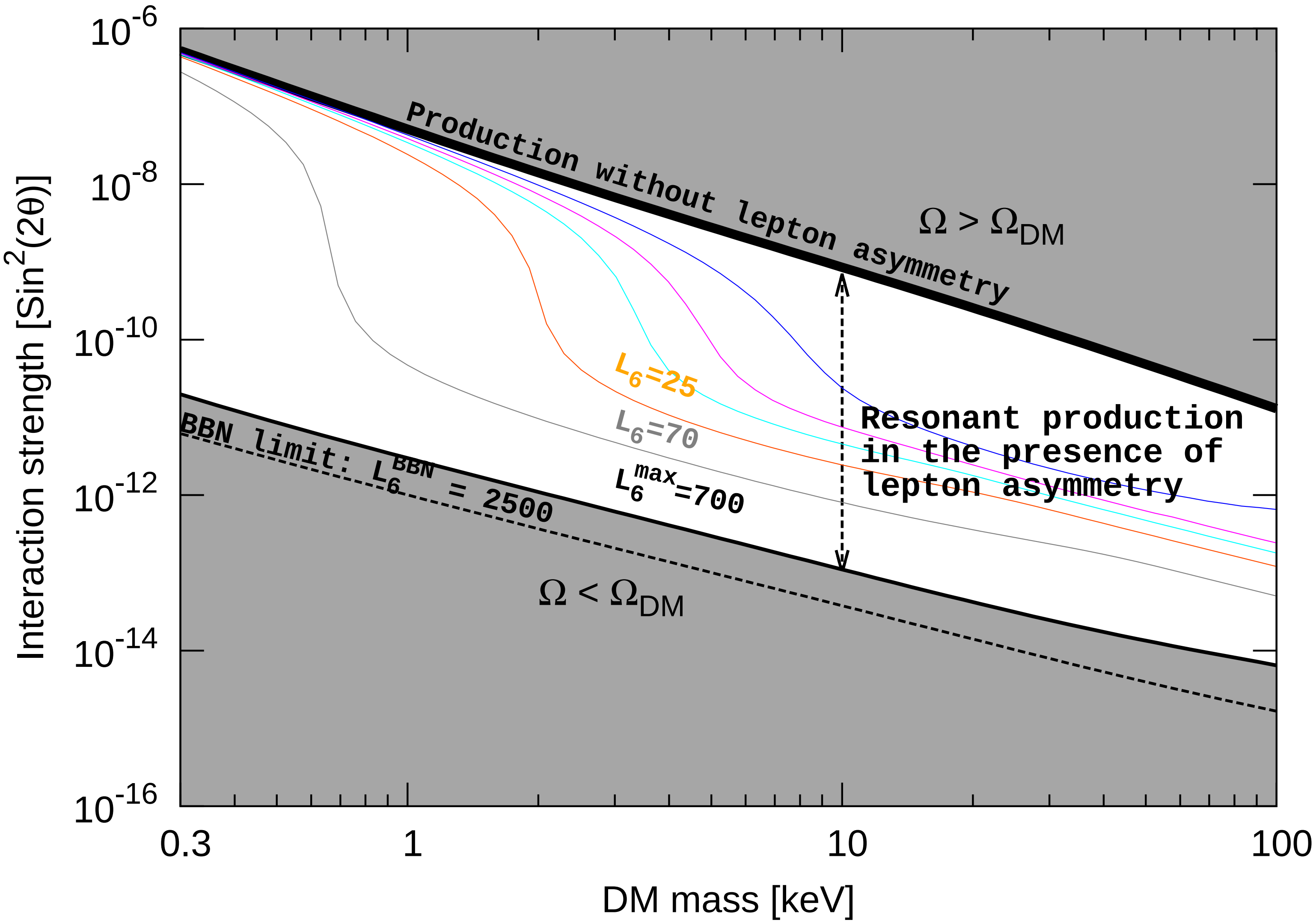
***Aq-A-2 CDM halo***



***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-$\alpha$ forest data but provides a structure of Milky way-size halo different from CDM

# Window of parameters of sterile neutrino DM

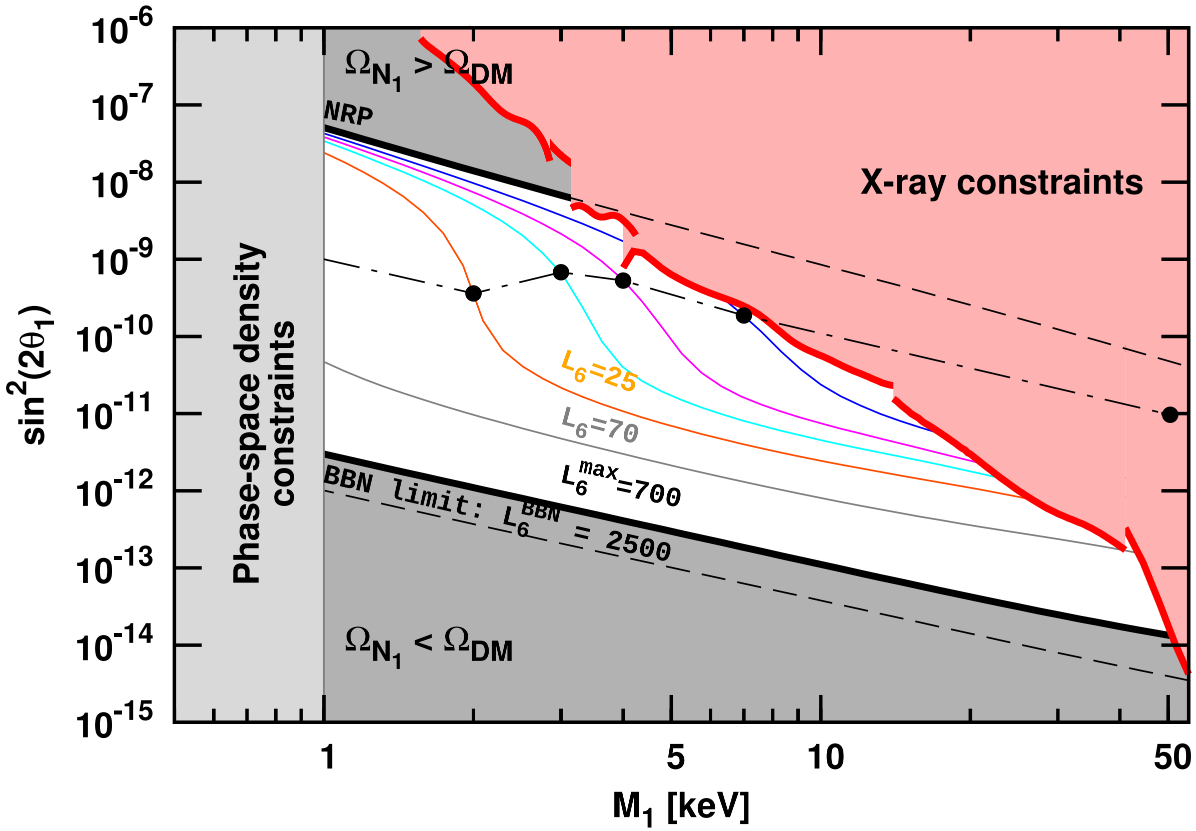



Shi & Fuller (1998)

Asaka, Laine, Shaposhnikov (2006)

Laine, Shaposhnikov (2008)

# Sterile neutrino DM in the $\nu$MSM

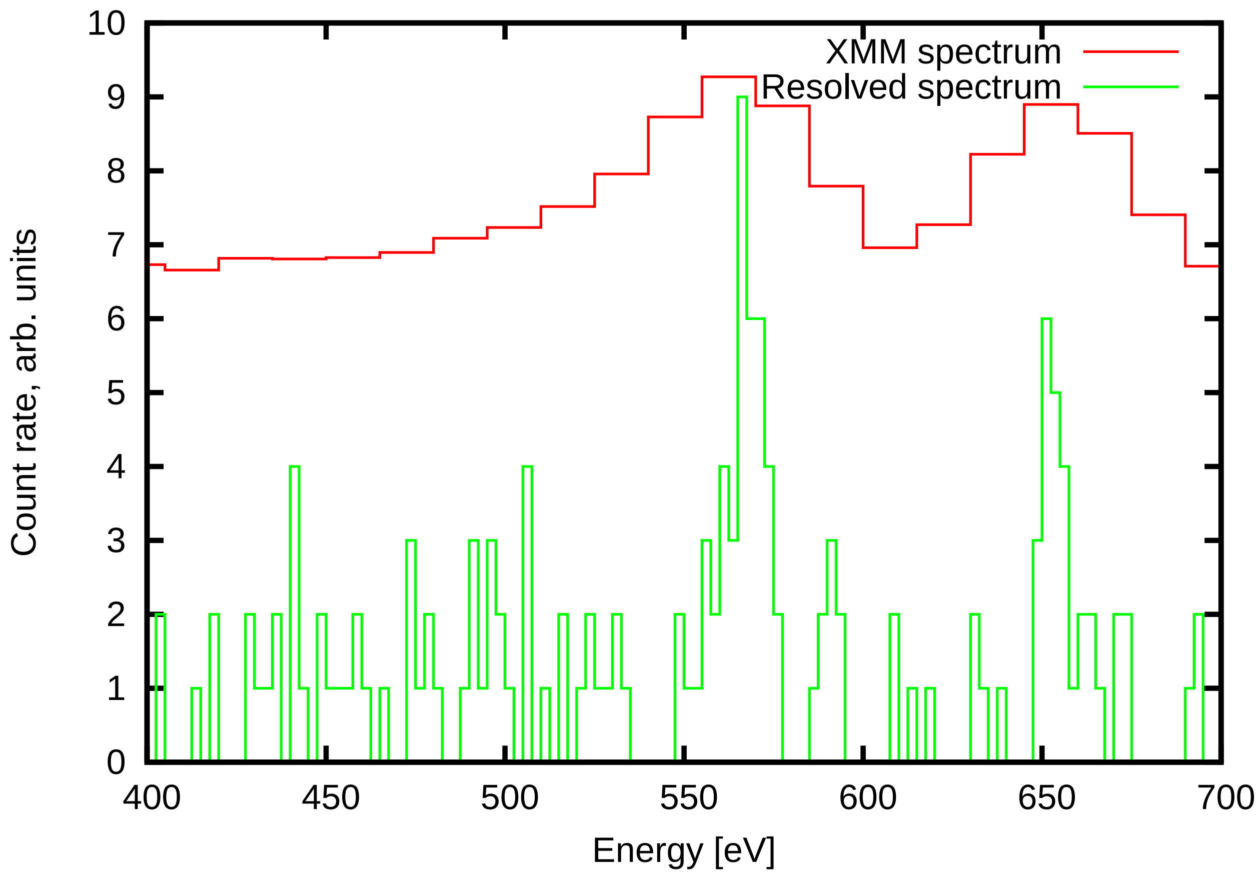



Sterile neutrino DM with $M \sim 2$ keV **are consistent with all astrophysical and cosmological observations**

Sterile neutrino dark matter **predicts** large lepton asymmetry (or requires new particles in addition to 3 sterile neutrinos)

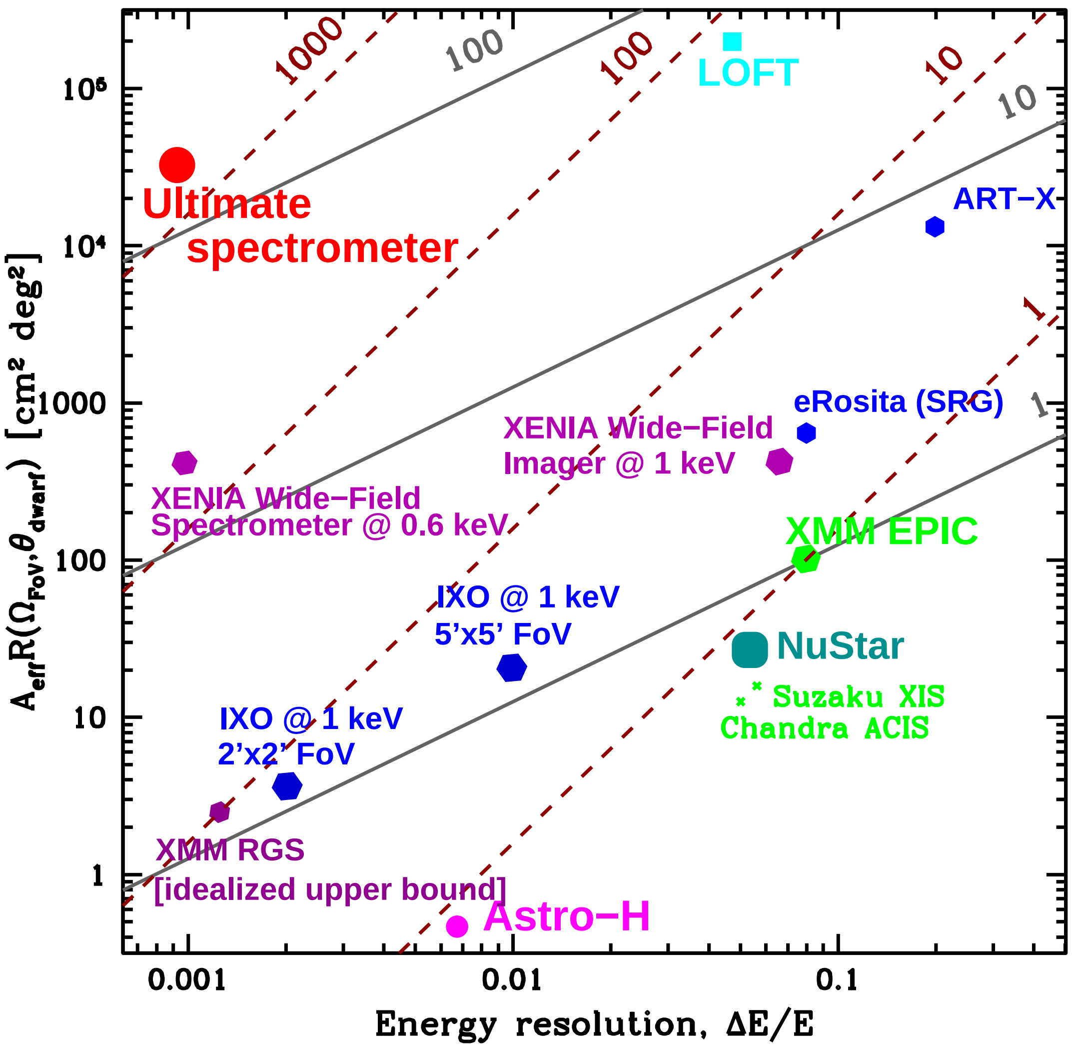
# How to search for dark matter sterile neutrinos?

# X-ray spectrometer



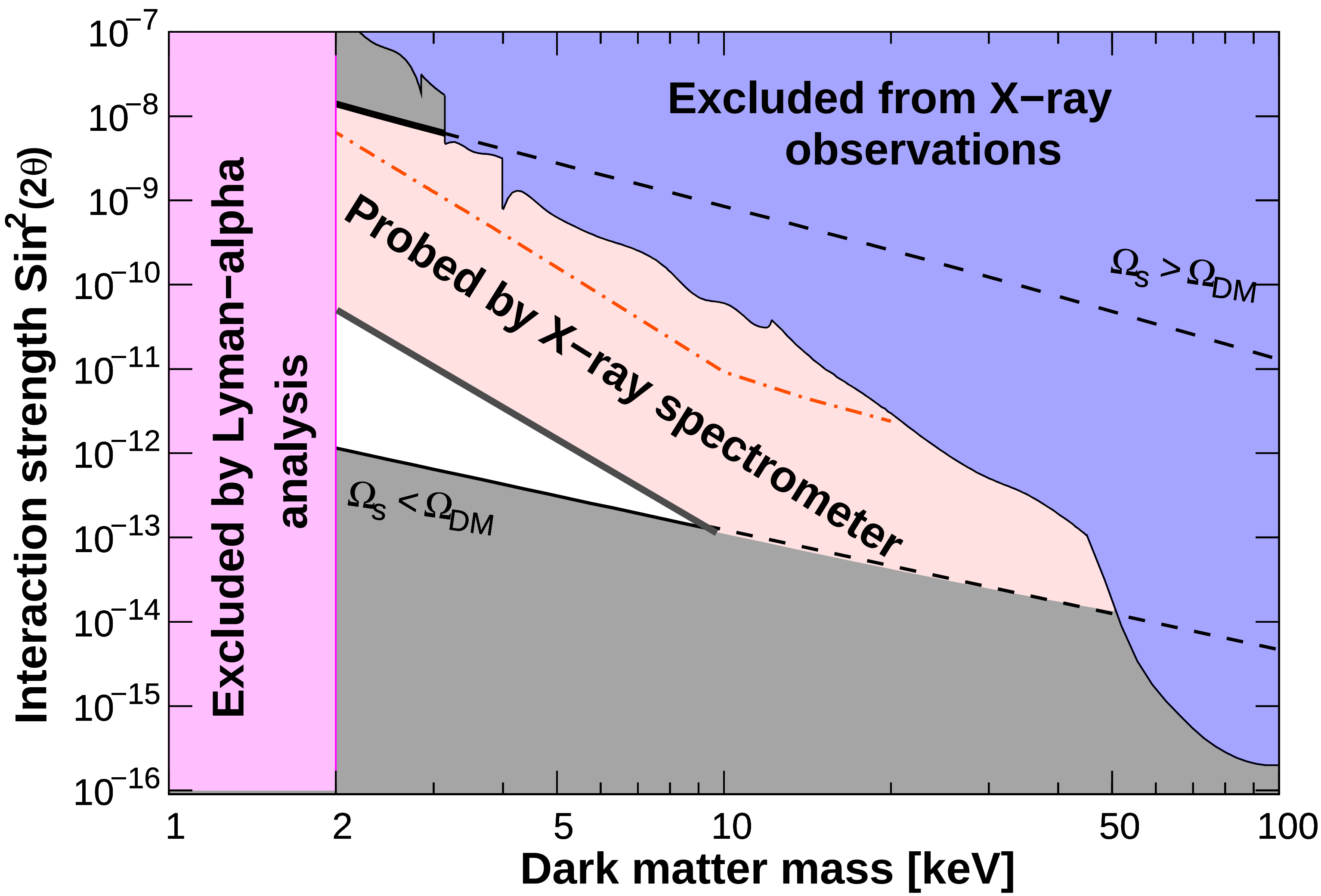

Galactic diffuse background (observed with *XMM-Newton* (red) and the same data, observed with the X-ray spectrometer (XQC project **[McCammon et al. 2002]**).

# Ultimate detector




See review *Next decade in sterile neutrino studies*, A. Boyarsky, O.R.

# Ultimate detector for DM sterile neutrino



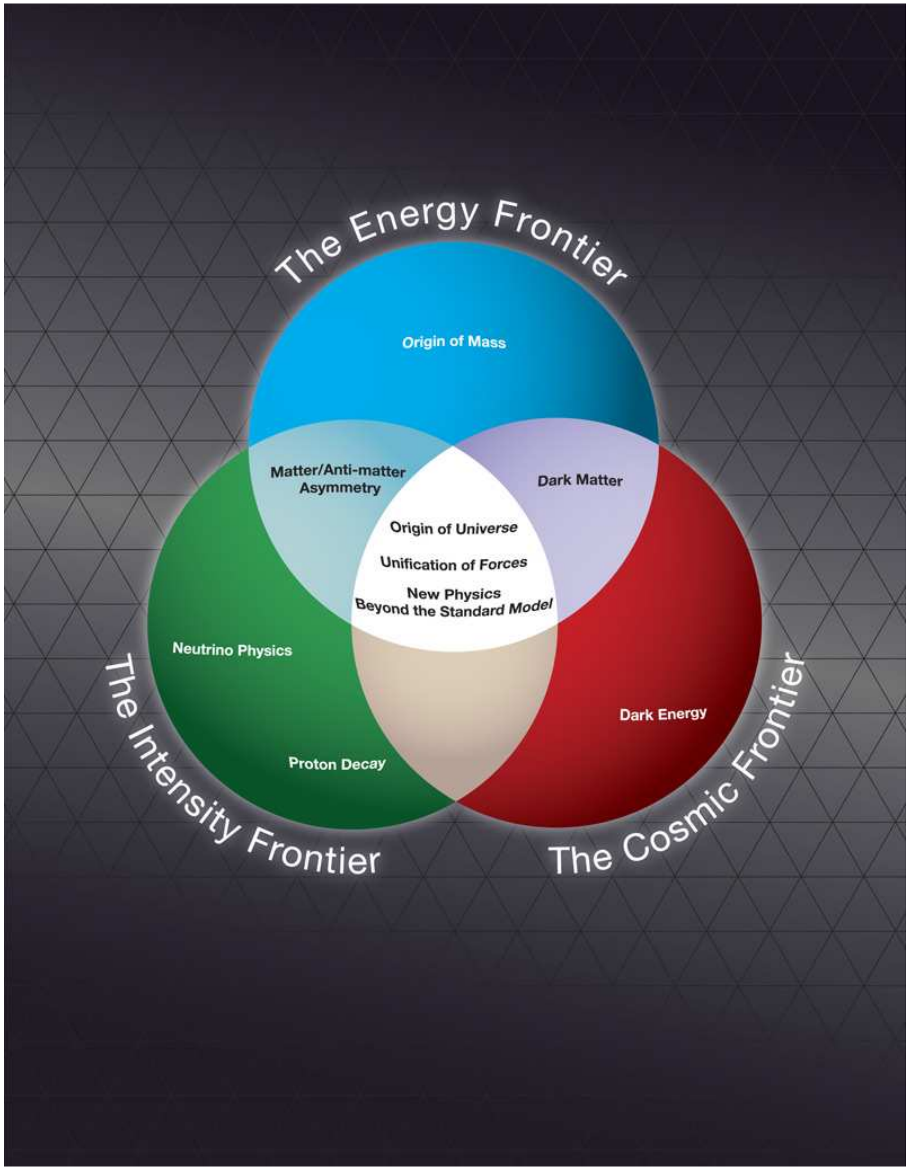

**See proposal to European Strategy Preparatory Group**

# "Nightmare scenario"

## Neutrino Minimal Standard model predicts:

- Standard Model Higgs with the mass above $\sim 125$ 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
- No signatures of dark matter annihilation in $\gamma$-rays / anti-matter
- Primordial spectral index $n_s = 0.96\ldots$ correlated with the Higgs mass
- Non-detection of tensor modes with Planck

# Complementarity of searches




Sterile neutrinos can be searched with present experimental technologies:

- ...at accelerators ("**Intensity frontier experiments**")
- ...in the high energy spectra of galaxies and galaxy clusters ("**Cosmic frontier**")

## 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-$\alpha$ forest experiments**)

THANK YOU FOR YOUR ATTENTION