An Outlook on Invisibles

07 September 2018

Invisibles 2018
KIT

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Invisibles are all around us

?

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Symmetry magazine

We are extensively searching for Invisibles, to uncover them and study their properties.
The key question is what their new Physics scale/s is.

sub-eV → eV → keV → MeV → GeV → TeV → Intermediate scale → GUT scale

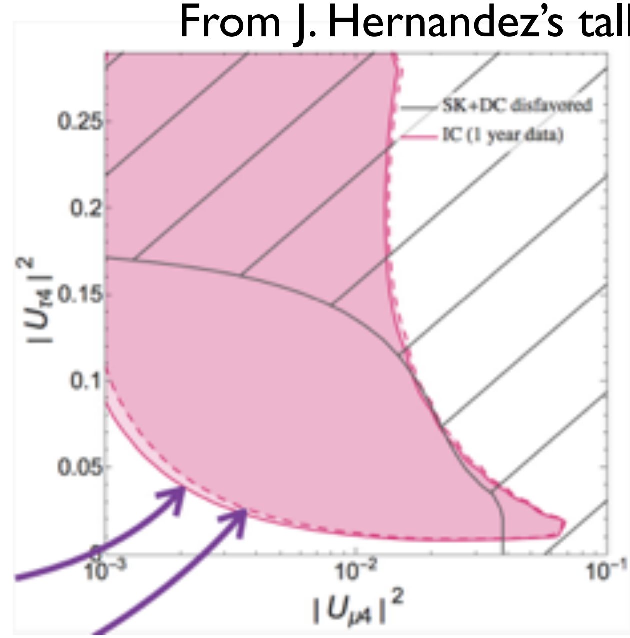
- The new invisibles could be connected to the origin of Neutrino Masses and leptonic mixing, the DM abundance, the Baryon Asymmetry, the hierarchy problem, Higgs physics, exp anomalies,… In many instances they emerge in models which are otherwise motivated.

- Or maybe not. This opens a wider range of possibilities for the mass scale and their properties.

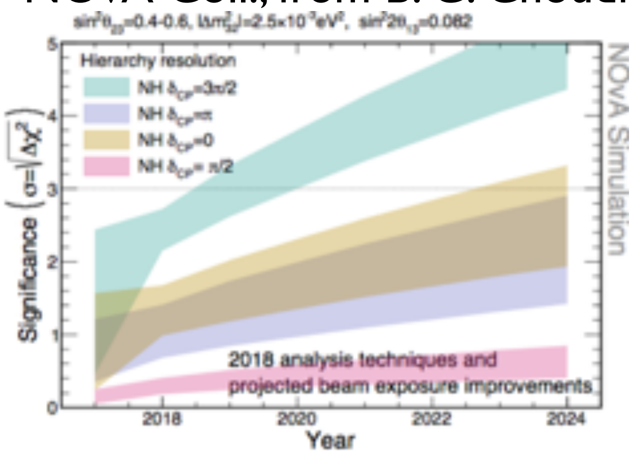
The known Invisible: the Neutrino

First of all, we need to fully establish their properties: nature, MO and masses, CPV, precise determination of the oscillation parameters and test of the 3-neutrino mixing scenario.

From J. Hernandez's talk



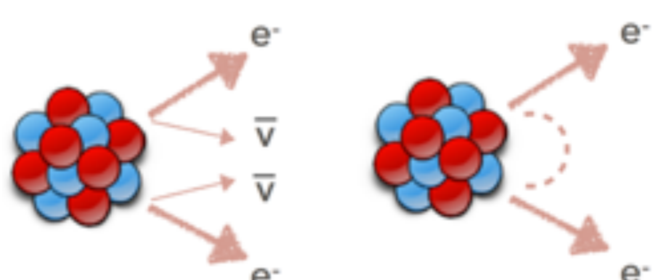
NOvA Coll., from B. C. Choudhary's talk



LBL and SBL exp: B. C. Choudhary, I. Esteban, W. Van De Pontseele

Neutrinoless double beta decay: C. Brofferio, C. Ransom

Sterile neutrino searches: S. Antusch, J. Gehrlein, Hernandez-Cabezudo, J. Hernandez, X. Marcano, D. Pramanik, Z. S. Wang,



NSIs and other exotics: Y. Farzan, M. Pandey

From C. Brofferio's talk

Direct mass searches: L. Gastaldo, A. Pollithy

Neutrinos masses and mixing

We need to understand where their masses come from and what the underlying principle behind leptonic mixing is. This calls for new Physics BSM.

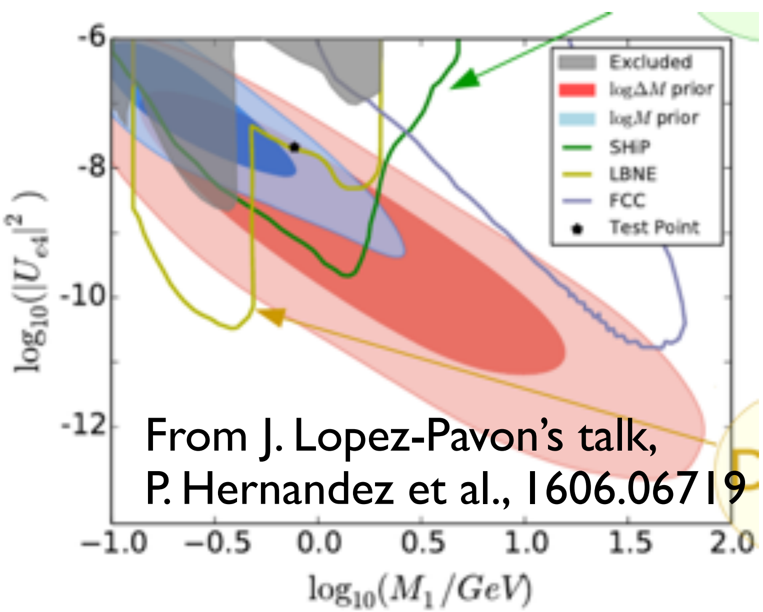
At which scale?

Recently, a lot of attention has been devoted to scales other than GUT (see-saw type I): from eV to TeV.

sub-eV eV keV MeV GeV TeV Intermediate scale GUT scale

Leptogenesis: A. Caputo, J. Harz, J. Lopez-Pavon, K. Moffat

New ideas for neutrino masses: L. Funcke, A. Ibarra



From J. Lopez-Pavon's talk, P. Hernandez et al., 1606.06719

EFTs: R. Coy

Neutrino mass/ mixing models: S. Molina Sedgwick, E. Perdomo Mendez,

Neutrinos and cosmology

Neutrinos very significantly impact the evolution of the Universe, via the imprint of the sum of masses and N_{eff}. Cosmological observations may be the most sensitive way to measure neutrino masses.

Connection to DM: A. Titov

Cosmic neutrino background: M. Arteaga Tupia

Neutrino cosmology: O. Mena

Planck TTTEEE+lowT+lowE+lensing

$$\sum m_\nu < 0.24 \text{ eV } 95\%\text{CL}$$

+ BAO

$$\sum m_\nu < 0.12 \text{ eV } 95\%\text{CL}$$

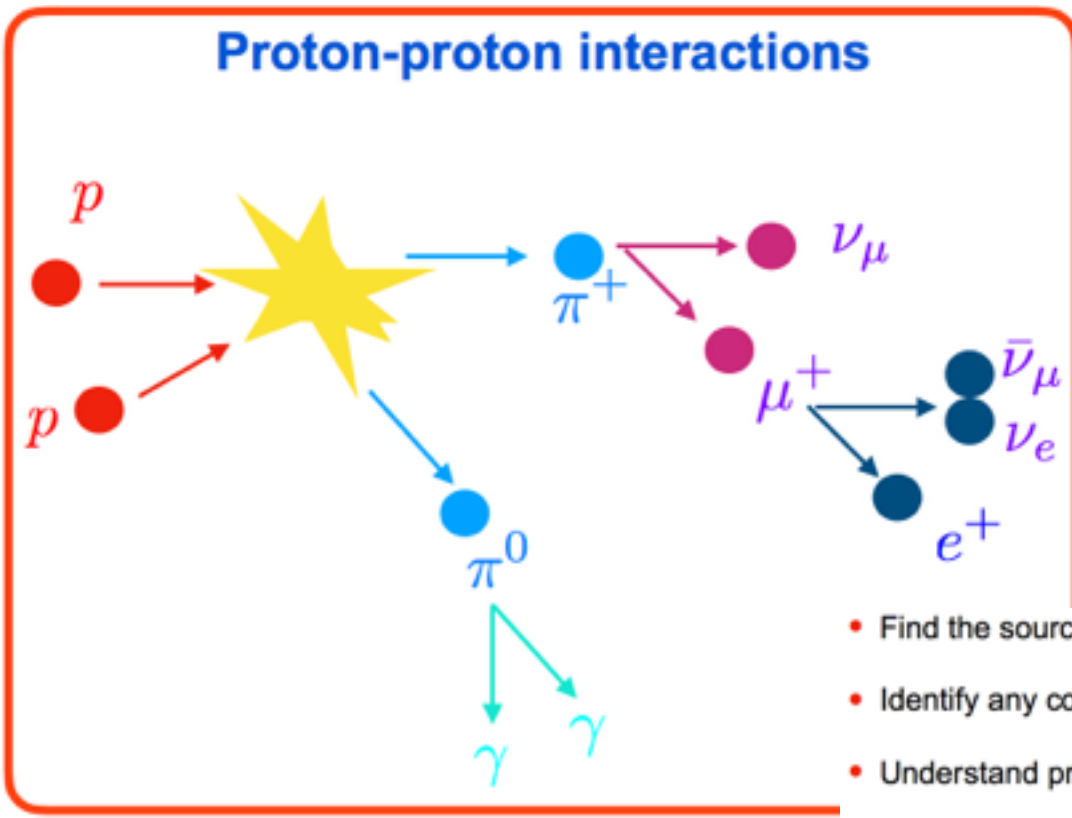
+ BAO + SNIa

$$\sum m_\nu < 0.11 \text{ eV } 95\%\text{CL}$$

From O. Mena's talk, based on 1807.06209

HE Neutrinos

With their relatively recent discovery, HE neutrinos are opening a new window on astrophysical objects and provide a complementary test of particle physics.



A. Franckowiak, I. Tamborra

- Find the sources of IceCube's high energy neutrinos.
- Identify any connection with UHECR & electromagnetic emission.
- Understand production mechanisms of high energy cosmic particles.
- Use multi-messenger data to obtain a unique view on sources.
- Test physics beyond the Standard Model.

From I. Tamborra's talk

The known unknown Invisible: Dark Matter

The particle identity of dark matter remains a mystery. In many cases, candidates have emerged in otherwise-motivated models. New ideas explore new territory for masses (light masses).

sub-eV | eV | keV | MeV | GeV | TeV | Intermediate scale | GUT scale

axions

light DM

sterile nus

WIMPs

very heavy DM

Models at low masses: K. Zurek

Heavy spin-2 field: A. Schmidt-May

FIMP DM: N. Bernal

TeV-scale DM: M. Dutra, A. Filimova, S. Khan

Light mediators: F. Kahlhofer

Dark Matter searches

DM tests: Direct and indirect searches and gravitational effects (large scale structure formation). Very exciting time: a broad ongoing and planned experimental programme and new ideas to test different mass ranges.

sub-eV | eV | keV | MeV | GeV | TeV | Intermediate scale | GUT scale

Direct searches for light DM: K. Zurek

Direct searches: A. Cheek, F. Gao, T. Edwards

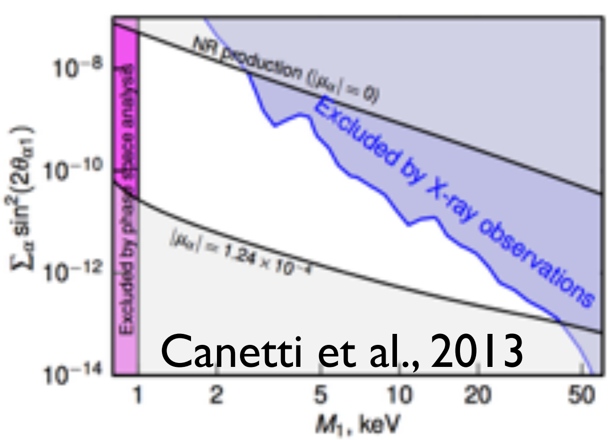
WIMP pheno: R. Catena

Indirect searches: S. Clementz, P. Sandick

DM-radiation interaction: J. Stadler,

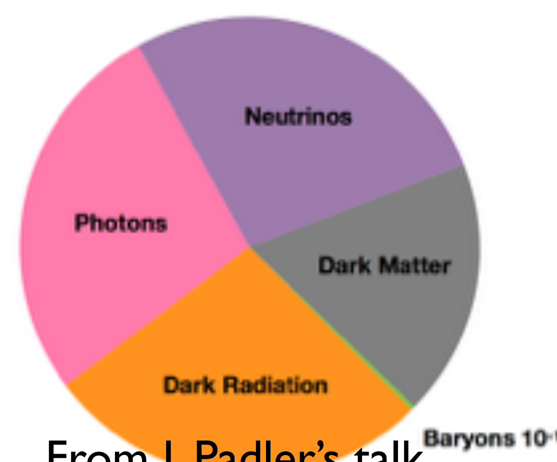
Dark radiation: J. Padler

Dwarf Spheroidal galaxies: S. Horigome



Canetti et al., 2013

Sterile neutrino searches: F. Bezrukov

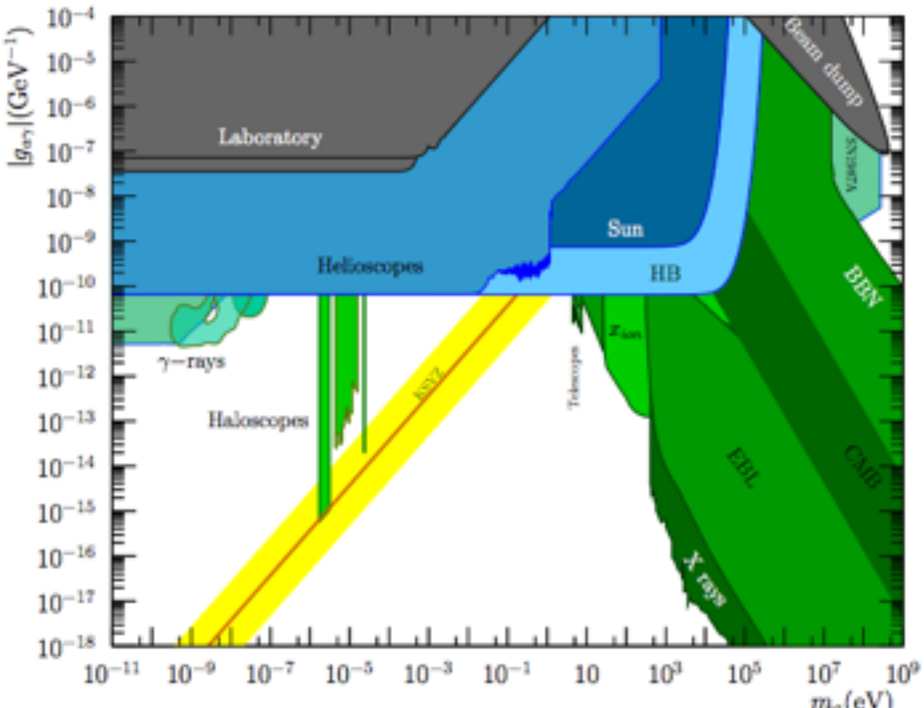


From J. Padler's talk

The well motivated unknown Invisible: Axion

Axions provide a compelling answer to the strong CP problem. Theoretical embedding and problem of naturalness as the scale is very high.
New models at different scales (extended gauge sectors, tuned models).

sub-eV | eV | keV | MeV | GeV | TeV | Intermediate scale | GUT scale



Irastorza & Redondo 1801.08127

Extended gauge sectors:
P. Agrawal, R. Houtz, P. Quilez Lasanta

Invisible axion (QCD)

$$f_a > 10^9 \text{ GeV}$$

L. di Luzio, S. Rigolin,
M. Ibe (gauge PQ)

Axions/ALPs searches

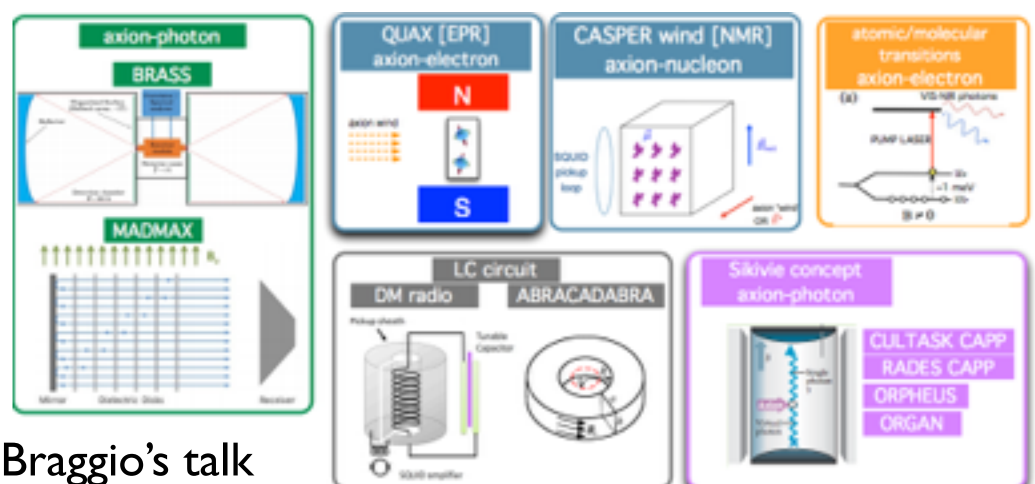
Experimental searches are expanding their reach with new experiments and new detection ideas.
Cosmological consequences are of great interest: axion DM has specific signatures (miniclusters, axion stars).

sub-mueV sub-meV sub-eV keV MeV GeV

Photophobic +astrophobic axions: L. di Luzio

ADMX

Axion experiment overview: C. Braggio



From C. Braggio's talk

Axion cosmology: A. Pargner, V. Klaer, J. Niemeyer, L. Visinelli, B. Safdi, S. Witte

Axions in cosmology: E. Vitagliano

The maybe unknown Invisible: Sterile neutrino and Other really unknown unknown Invisibles: dark photons, Z', new scalars, hidden sectors

Sterile neutrinos: neutral fermionic singlets of the Standard Model. Generically they mix with the light neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{4\times 4} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Flavour state

Massive state

Nearly-sterile neutrino, commonly called sterile neutrino

$$\mathcal{L} = \cdots + \bar{\ell}_L U_{\ell 4} \gamma_\mu \nu_{4,L} W^\mu + \mathrm{NC} + \mathrm{h.c.}$$

Adding sterile neutrinos to the Standard Model is the simplest possible extension BSM.

- Theory remains anomaly free.
- Can give origin to neutrino masses and explain their smallness (at least in some cases), provide a DM candidate (for KeV ones) and explain the baryon asymmetry.
- GUT theories embedding L-R symmetries, e.g. SU(4), SO(10),... predict their existence.

sub-eV eV keV MeV GeV TeV Intermediate scale GUT scale

There are many other Invisibles particles which can be searched for and have interesting phenomenological consequences…

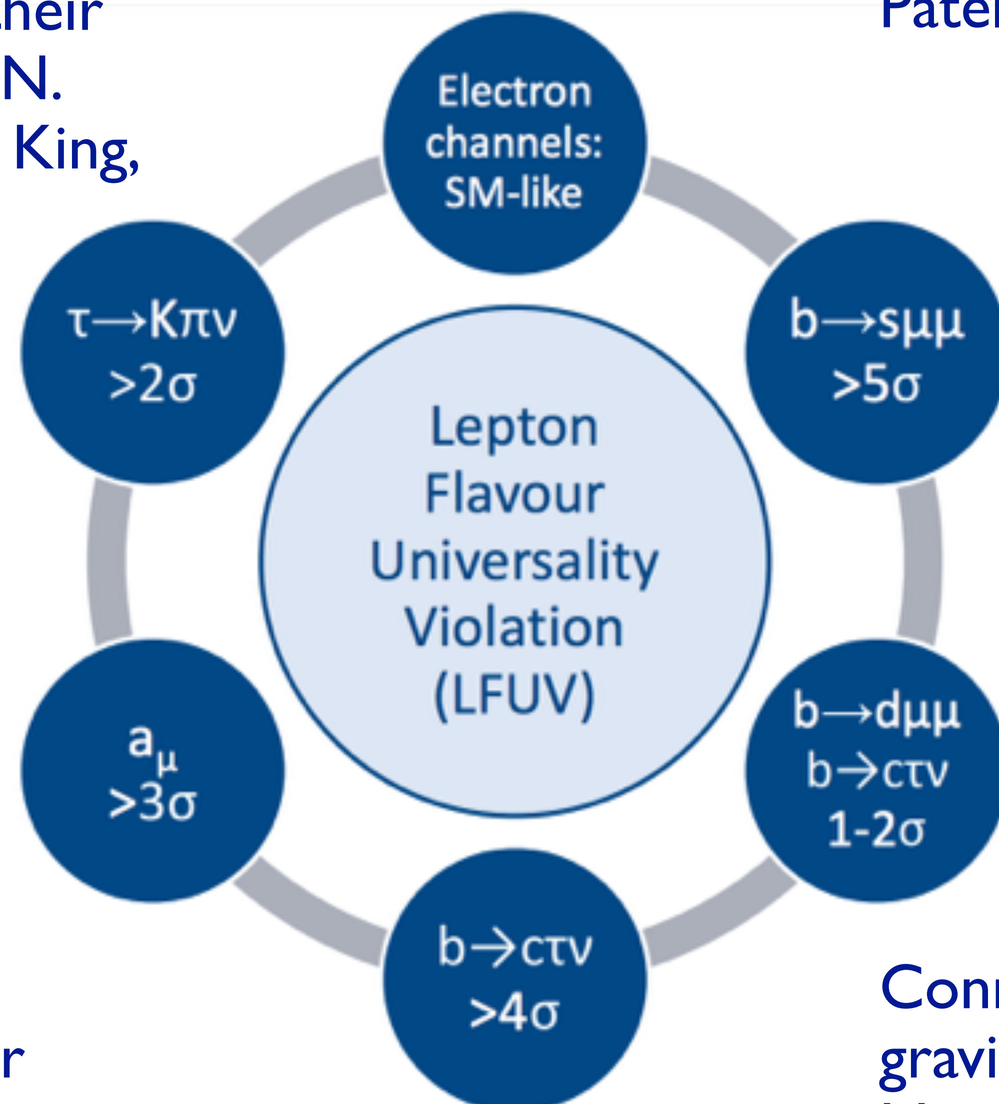
Connection to BSM and theoretical issues

BSM models and their signatures: F. Kirk, N. Rosa Agostinho, S. King,

Higgs: R. Grober, S. Patel

Hidden CFTs: K. Max

B and CLFV physics: A. Crivelin, O. Sumensari



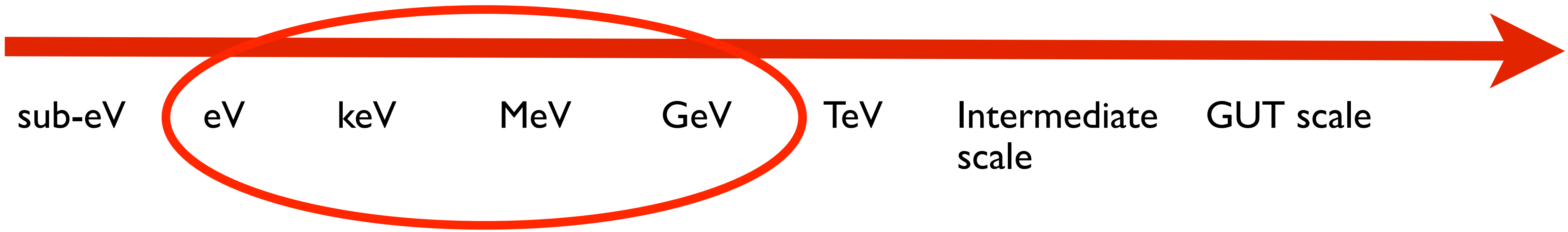
Inflation: A. Ijjas

CPV: A. Trautner

Connection with gravity: S. Gonzalez-Martin, R. Santos

From A. Crivelin's talk

Could there be a new hidden invisible sector just around the corner (below the EW scale)?



It could contain several new states (neutral fermions, gauge bosons, scalars, DM.)...

How does it "talk" to the SM?

- mixing/Yukawa couplings
- new gauge interactions
- kinetic mixing
- new scalars via the Higgs portal
- EFTs

The simplest extension introduces neutral fermions, which (unless a symmetry distinguishes them from the SM) will mix with the active neutrinos.

A coupling to the Higgs is allowed and neutrino masses can emerge. $\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{(10^{-5}\ \mathrm{GeV})^2}{1\ \mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

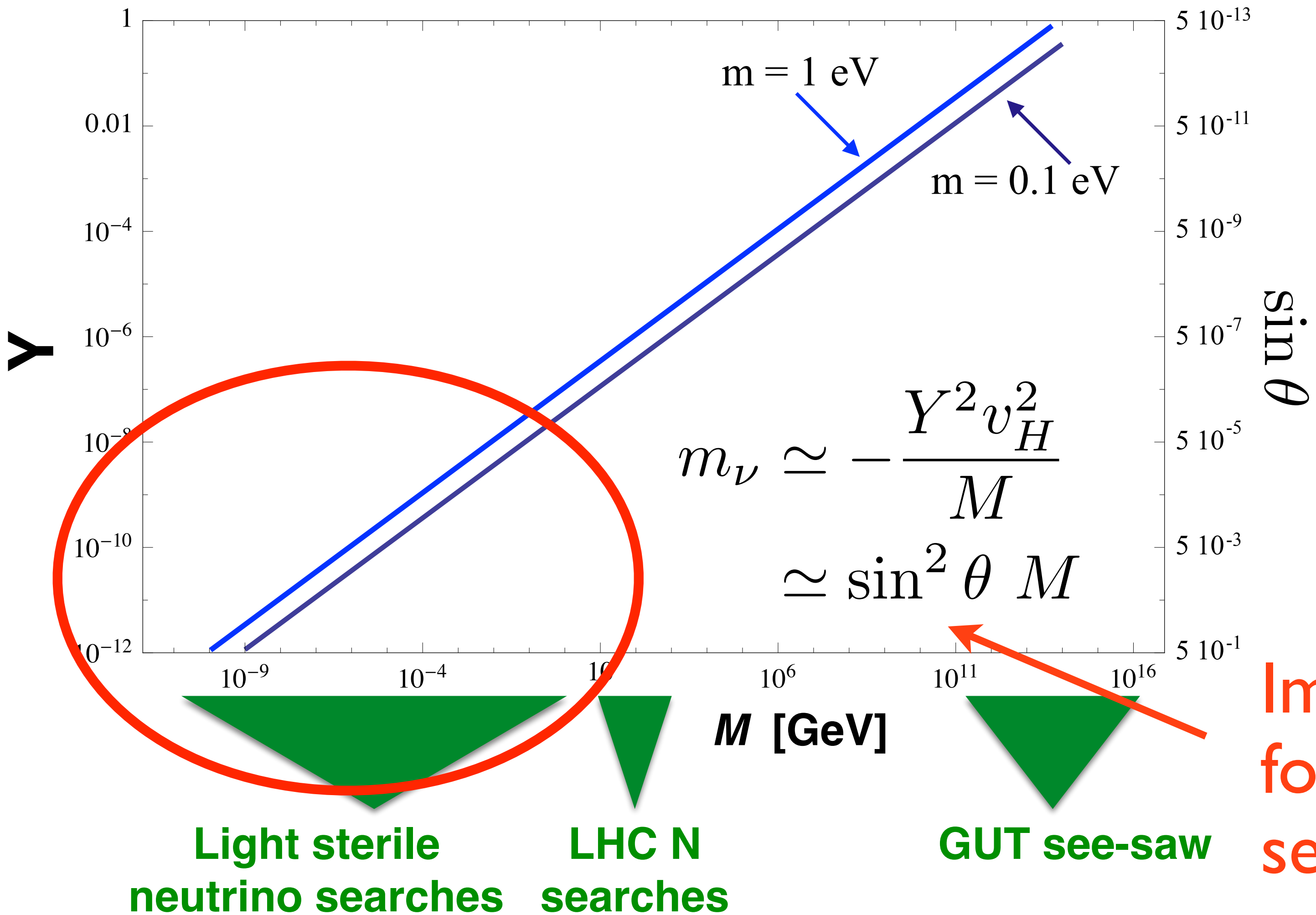
The required Yukawa couplings need to be small. Or should be forbidden altogether by a symmetry (-> radiative neutrino mass models).

The massive states are Majorana particles and

$$\nu_{\text{active}} = U_i\, n_{i,\text{light}} + U_k\, N_{k,\text{heavy}}$$

Non unitarity

Active and heavy neutrino mixing



Important for searches

Models with enhanced mixing

The mixing-mass relation can be avoided if neutrino masses are suppressed. A typical example are the inverse see-saw and extended see-saw models, in which two sterile neutrinos are introduced.

$$\mathcal{L} = Y\bar{L}\cdot HN_1 + Y_2\bar{L}\cdot HN_2^c + \Lambda\bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

The neutrino mass matrix is

$$\begin{pmatrix} 0 & Yv & Y_2 v \\ Yv & \mu' & \Lambda \\ Y_2 v & \Lambda & \mu \end{pmatrix}$$

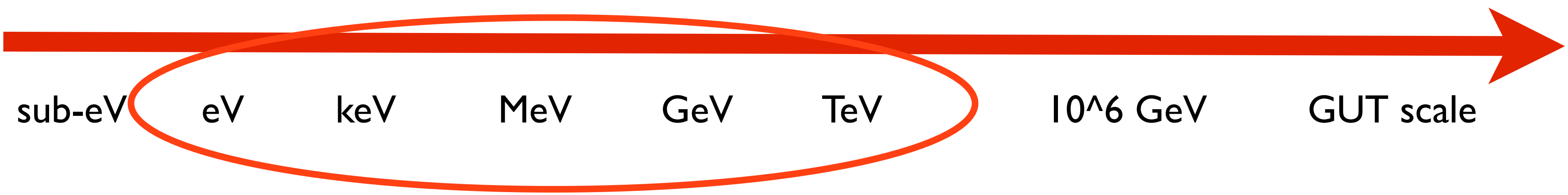
Neutrino masses are suppressed by the (small) lepton number parameters:

$$m_{tree} \simeq -m_D^T M^{-1} m_D \simeq \frac{v^2}{2(\Lambda^2 - \mu'\mu)}\left(\mu Y_1^T Y_1 + \epsilon^2 \mu' Y_2^T Y_2 - \Lambda\epsilon(Y_2^T Y_1 + Y_1^T Y_2)\right)$$

How to test the existence of these sterile neutrinos?

Signatures

They critically depend on the masses of the sterile neutrinos. Direct searches cannot go beyond TeV masses.



Neutrino masses

Peak searches

Dark Matter, WDM, HDM

Nu oscillations

Decays

Kinks in beta decay

Leptogenesis

Neutrinoless double beta decay

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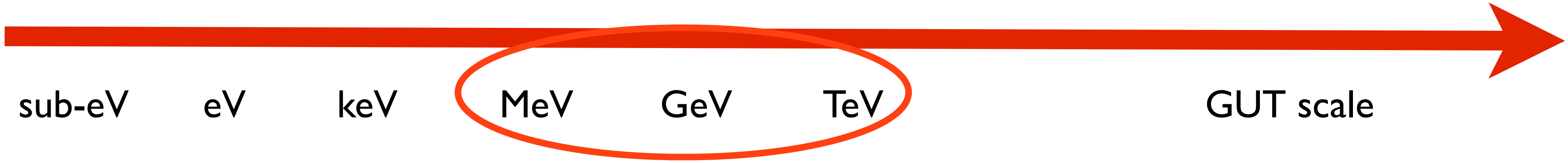
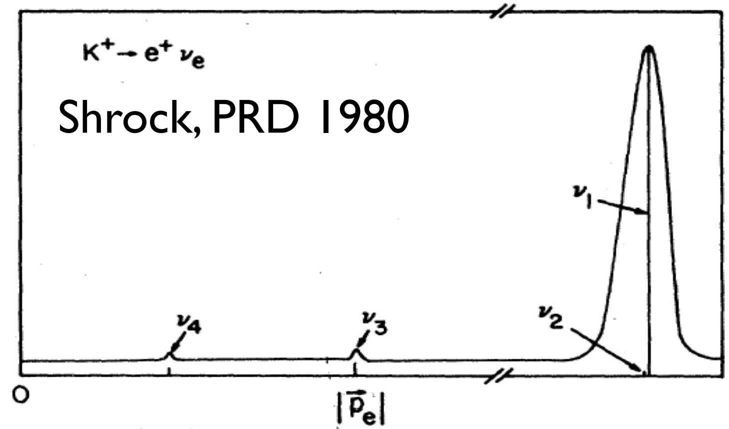
GeV-TeV scale: direct searches



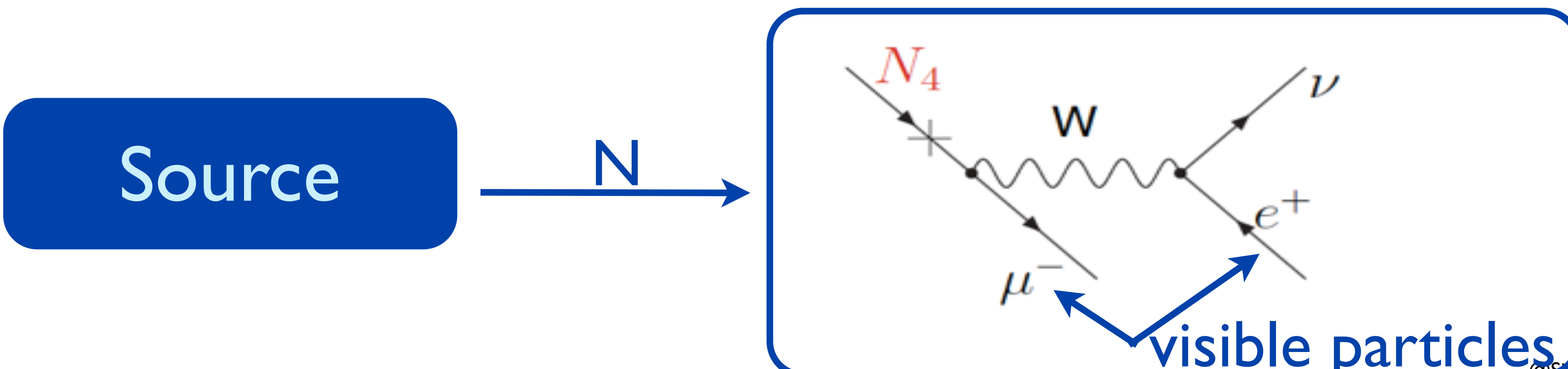
Peak Searches

If produced in pion and kaon decays, they would modify the electron and muon spectrum with a peak at lower E.



Decay Searches

Once produced, they can decay in visible particles inside the detector (electrons, muons, pions....).



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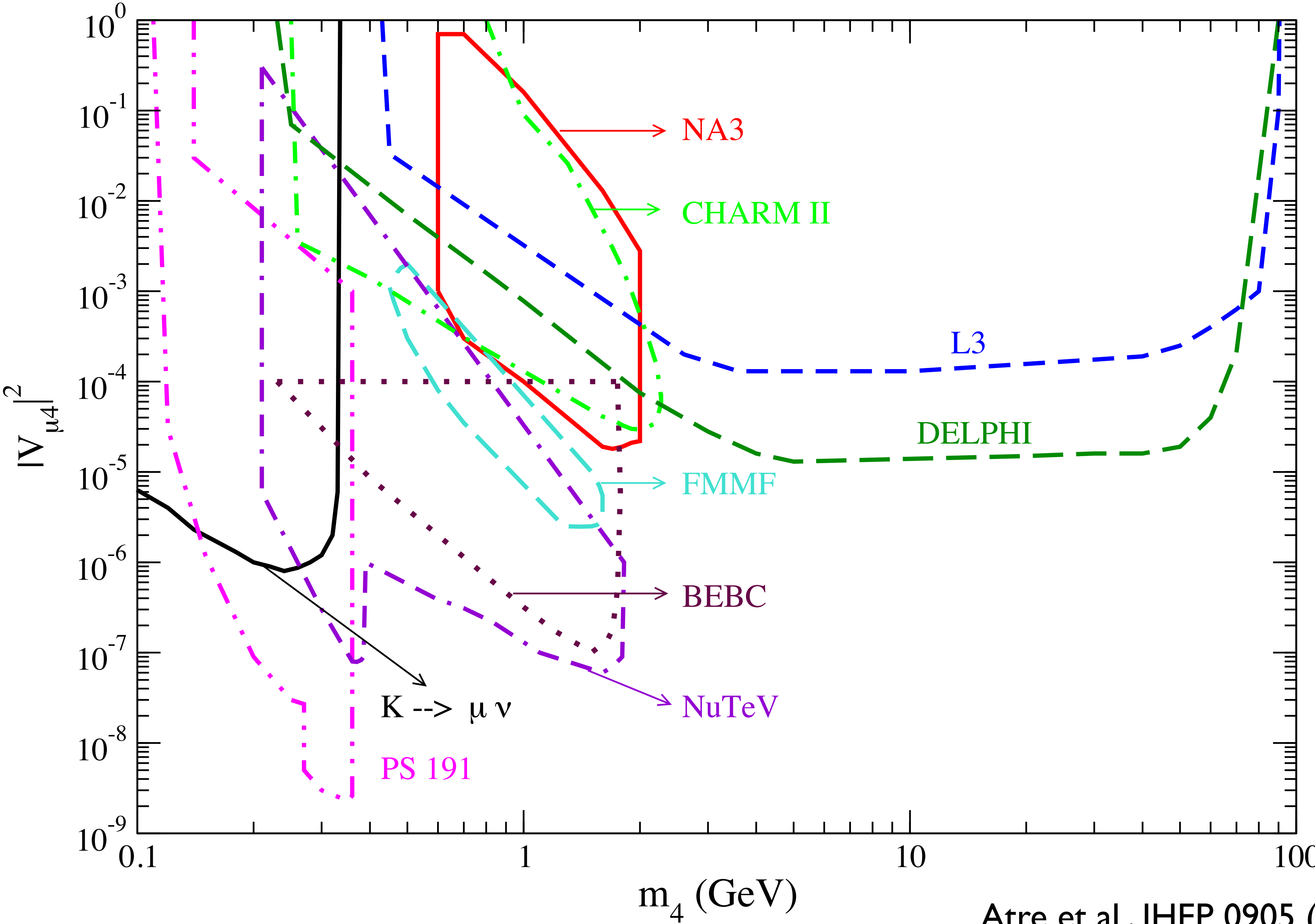

Atre et al., JHEP 0905 (2009)

Some bounds are close to the naive see-saw predictions.

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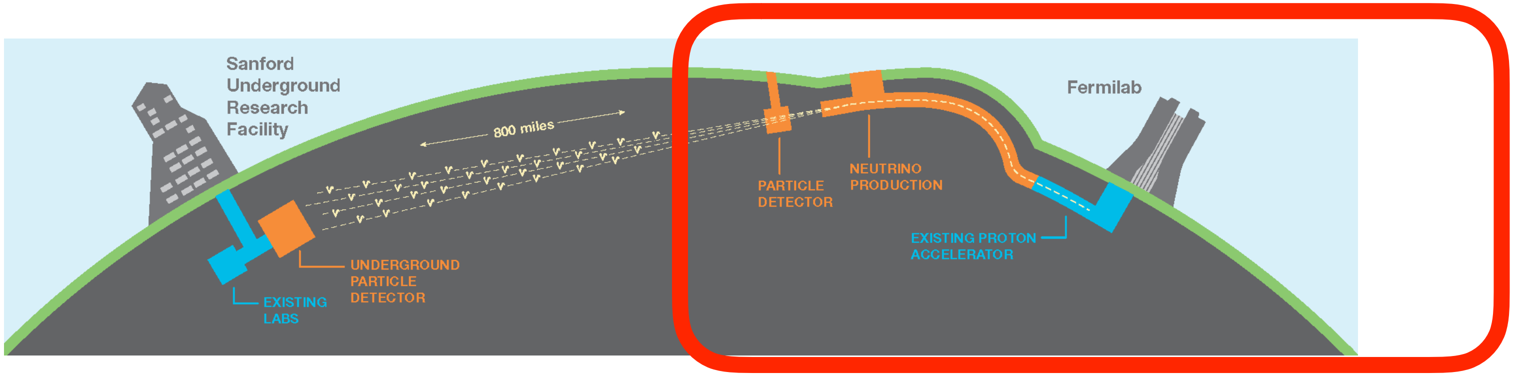
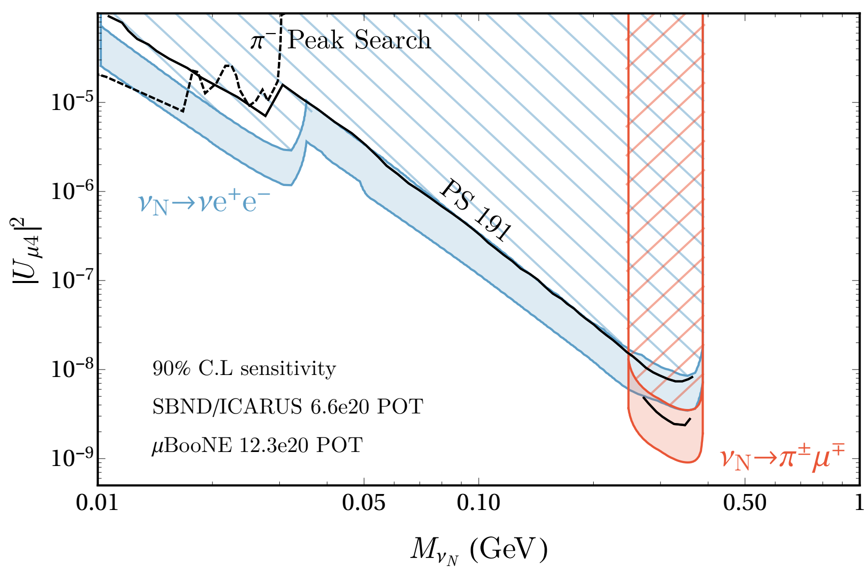
Current and future SBL/LBL experiments are effectively beam-dump experiments, with bigger exposure with respect to past searches.





Ballett, SP, Ross-Lonergan, JHEP 1704 (2017)

SBN, mainly thanks to the SBND detector, DUNE, T2K, and the specifically designed SHiP experiment can significantly improve bounds. In SBN, precise information about arrival times would provide a smoking gun signature.

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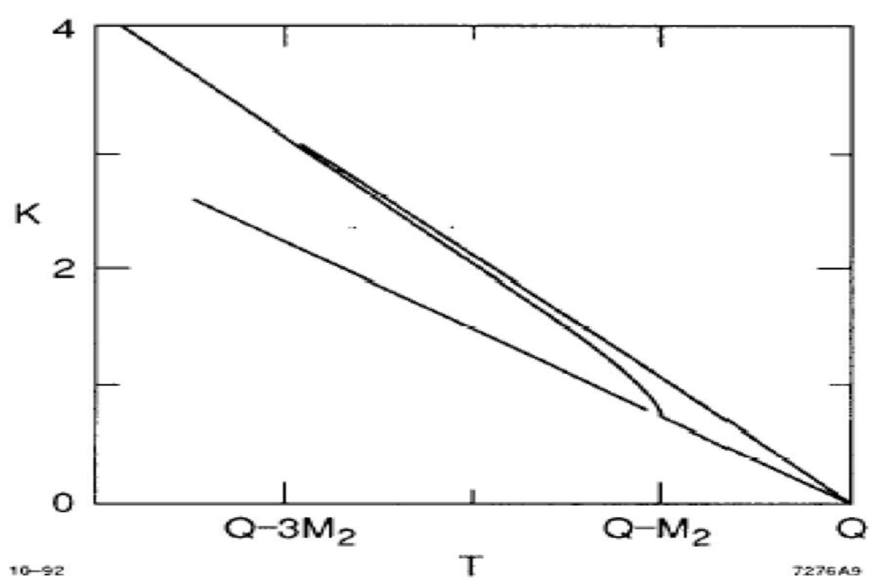
keV scale: Kinks and dark matter

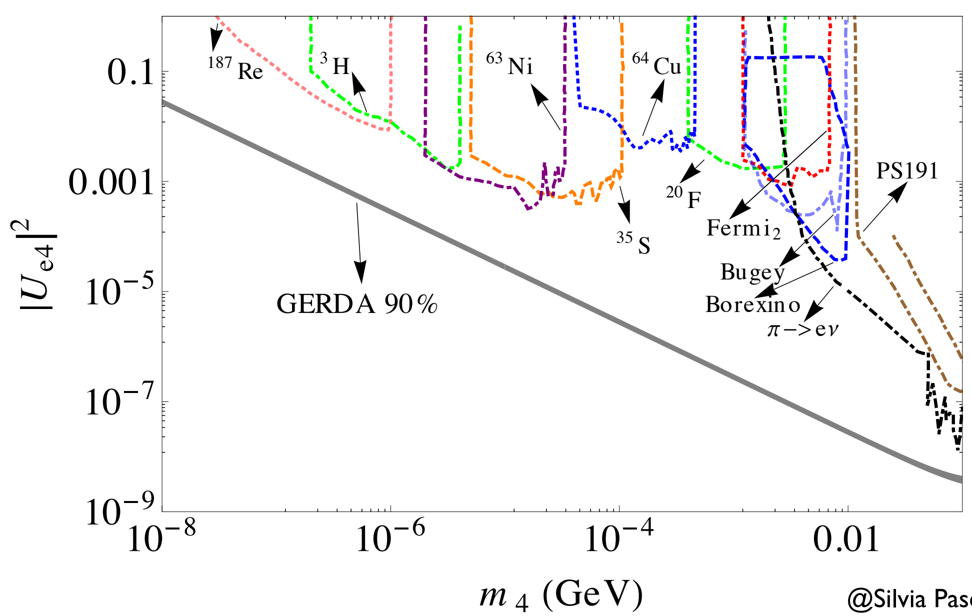
sub-eV eV keV MeV GeV TeV GUT scale

Sterile neutrinos with keV masses have attracted a lot of attention because they constitute a favoured warm dark matter candidate. Their phenomenology depends critically on the mixing angles.

- Kinks in beta decays.



Mitra, SP, Wong, 1310.6218



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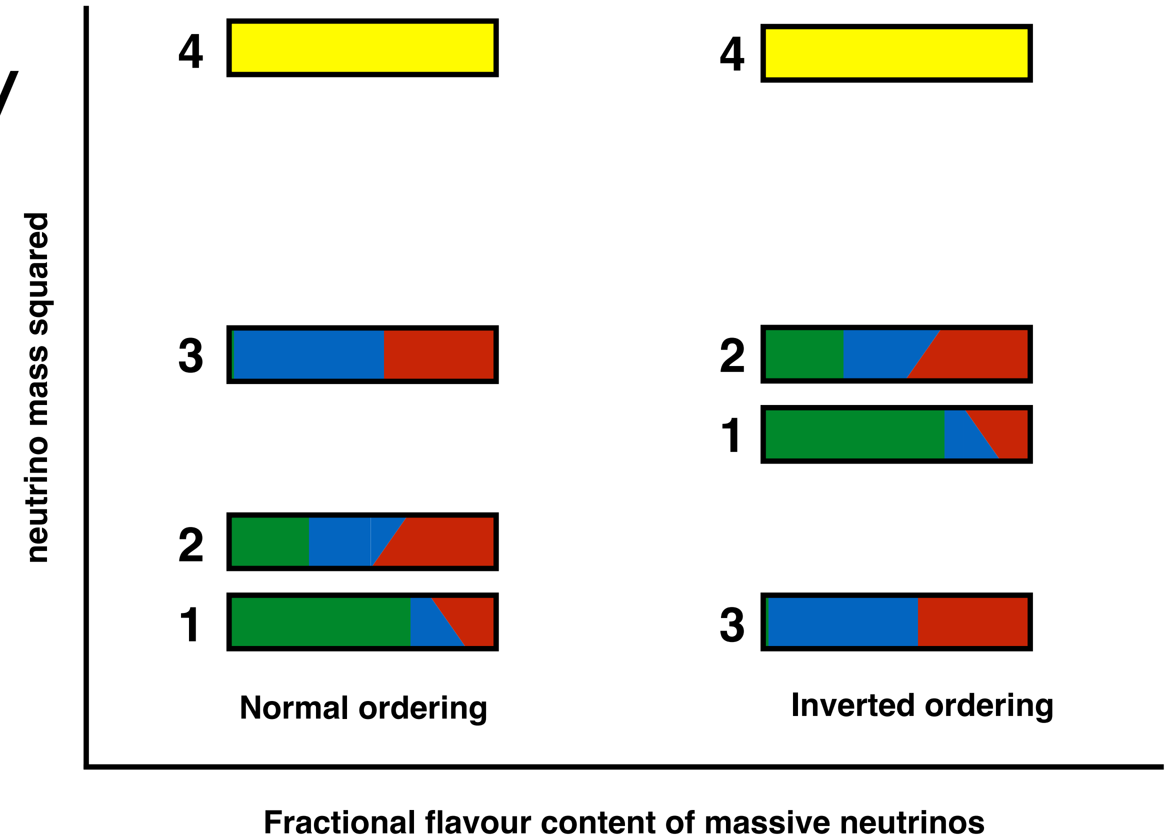
eV scale: Neutrino oscillations etc.

Sterile neutrinos with eV masses will induce neutrino oscillations at short baseline. Other signatures are present:



- Beta decays
- Neutrinoless double beta decay.
- if in equilibrium in the Early Universe, contribute to the HDM and to the number of relativistic degrees of freedom at BBN and CMB.

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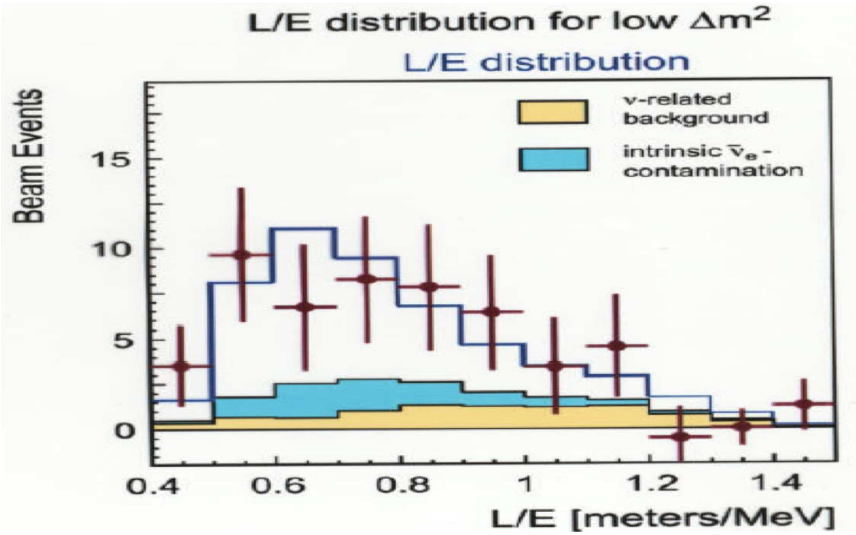
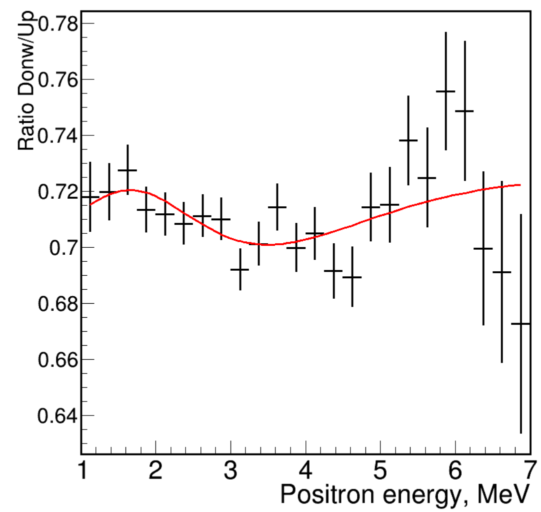
Neutrino oscillation experiments

LSND, PRL81 (1998) 1774

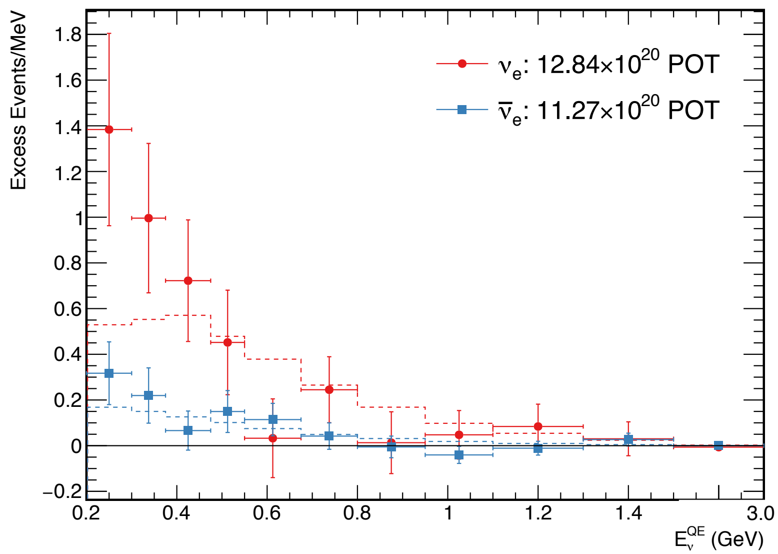


There are hints beyond standard 3 neutrino mixing. **LSND** reported the appearance of electron anti-neutrinos at short distance.



Danilov, Solvay workshop, ULB, Dec 2017

MiniBooNE Coll., 1805.12028



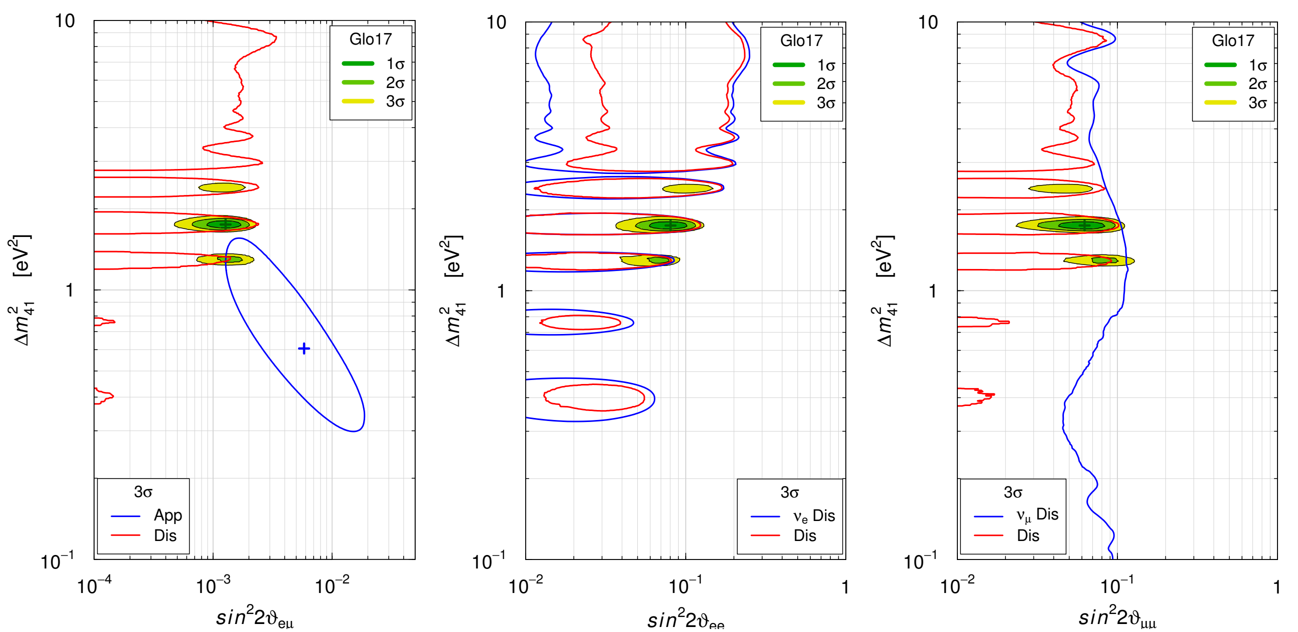
MiniBooNE was designed to test this results. It found an excess of events at low energy.

The **DANSS** reactor neutrino experiment observes some indication compatible with sterile neutrino oscillations.

Appearance experiments require mixing both with electron neutrinos and muon neutrinos: in tension with muon neutrino disappearance experiments.

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$



Gariazzo et al., JHEP 1706 (2017)

See also T. Schwetz talk at CENF workshop, A. Hernandez updated from Dentler et al., 1709.04294.

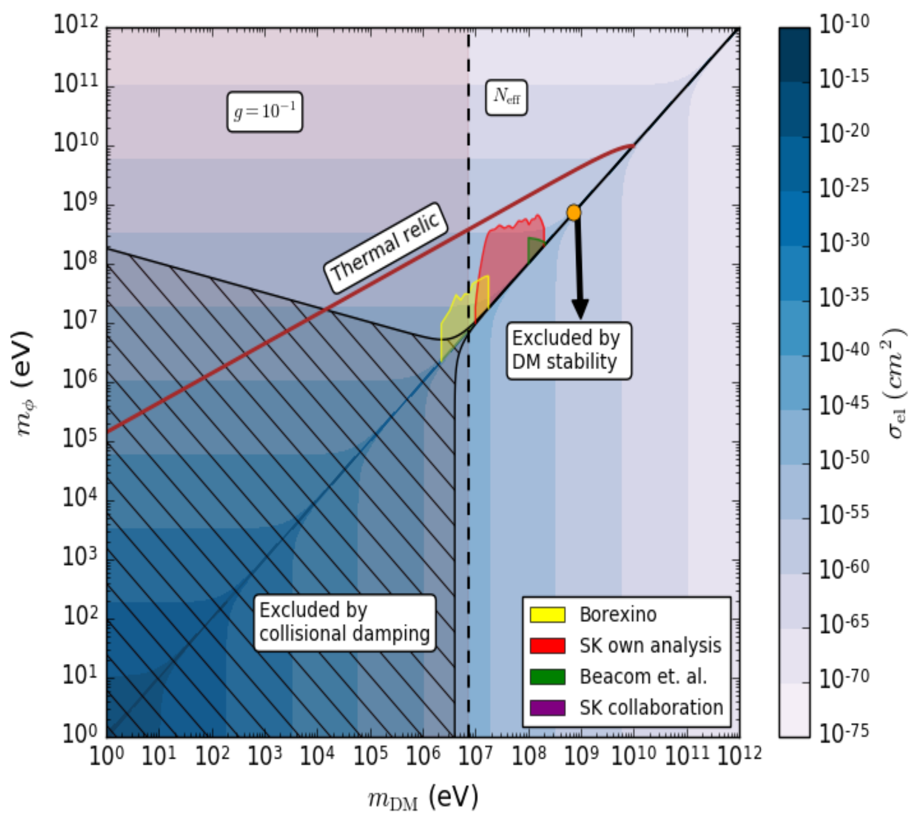
Several new experiments are starting or planned. SBN (MicroBooNE, ICARUS, SBND) will search for neutrino appearance. Beta decay experiments (KATRIN) are sensitive to eV sterile neutrinos via kink searches in positrons.

Can this sector contain other Invisibles?

Dark Matter

DM could also belong to this sector and "talk" to Ns and the SM via e.g. Neutrino, Higgs and Vector Portal:

$$\bar{L} \cdot \eta N_R \qquad \phi^\dagger \phi\, H^\dagger H \qquad g \bar{\chi}_L \gamma^\mu Z'_\mu \chi_L$$



Olivares-Del Campo et al., 1711.05283

Dirac DM, scalar mediator

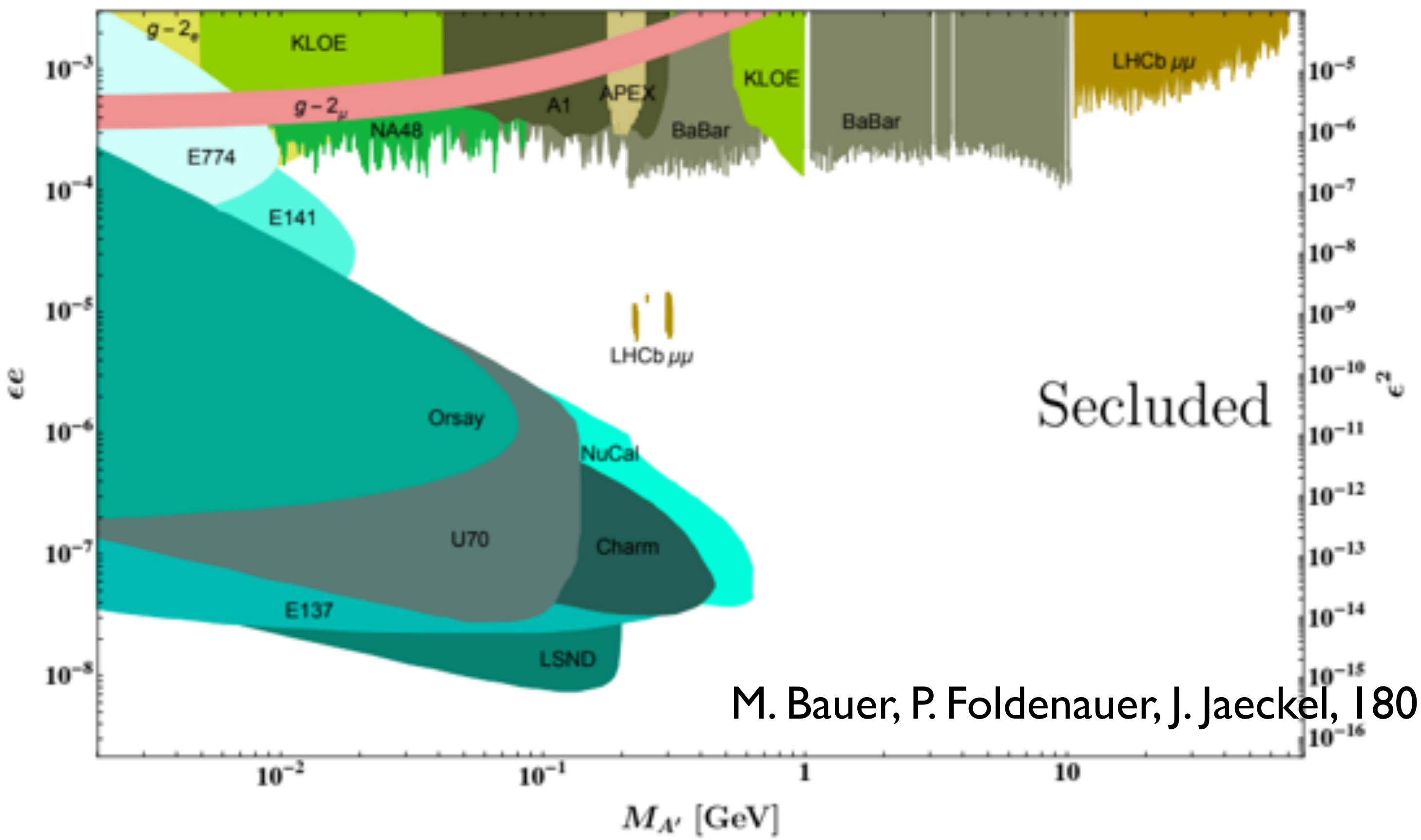
Dirac DM Scalar Mediator	$-g\overline{\chi_R}\nu_L\phi \;+\; \text{h.c.}$
Majorana DM Scalar Mediator	

$\frac{g^4}{32\,\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_\phi^2)^2}$	$\frac{g^4}{32\,\pi}\frac{m_{\rm DM}^2\,y^2}{(m_{\rm DM}^2-m_\phi^2)^2}$
$\frac{g^4}{12\,\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_\phi^2)^2}\,v_{\rm CM}^2$	$\frac{g^4}{16\,\pi}\frac{m_{\rm DM}^2\,y^2}{(m_{\rm DM}^2-m_\phi^2)^2}$

Extended gauge symmetry

It is also possible to extend the gauge sector via new U(1) and an associated Z' with light mass and very weak interactions with the SM.

New scalars are also introduced to break the symmetry and necessarily talk to the Higgs.



M. Bauer, P. Foldenauer, J. Jaeckel, 1803.05466

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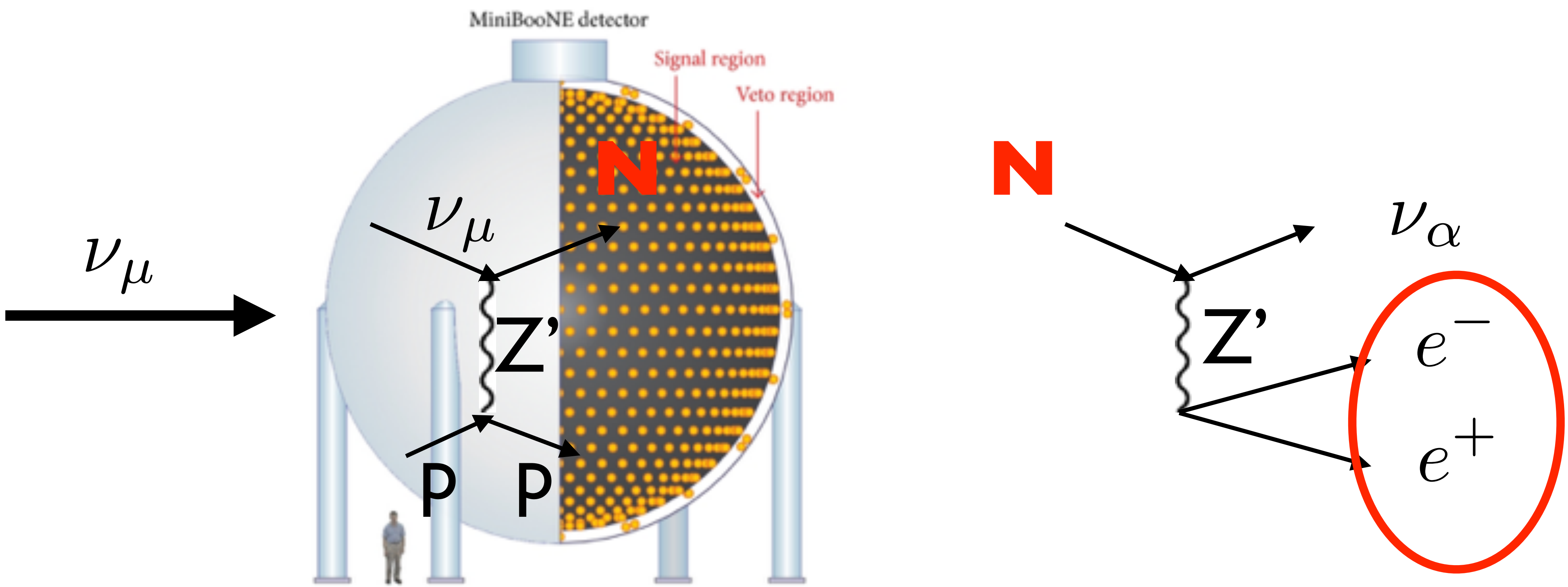
A new MiniBooNE low-E excess explanation

For a long time (>4 years) we looked for a viable explanation of the MiniBooNE low-E excess. Guided by the data, we introduce a sterile neutrino, charged under a new U(1) which mixes with the standard model neutrinos, and a light gauge boson Z'.



P. Ballett, S. Pascoli, M. Ross-Lonergan, 1808.02915

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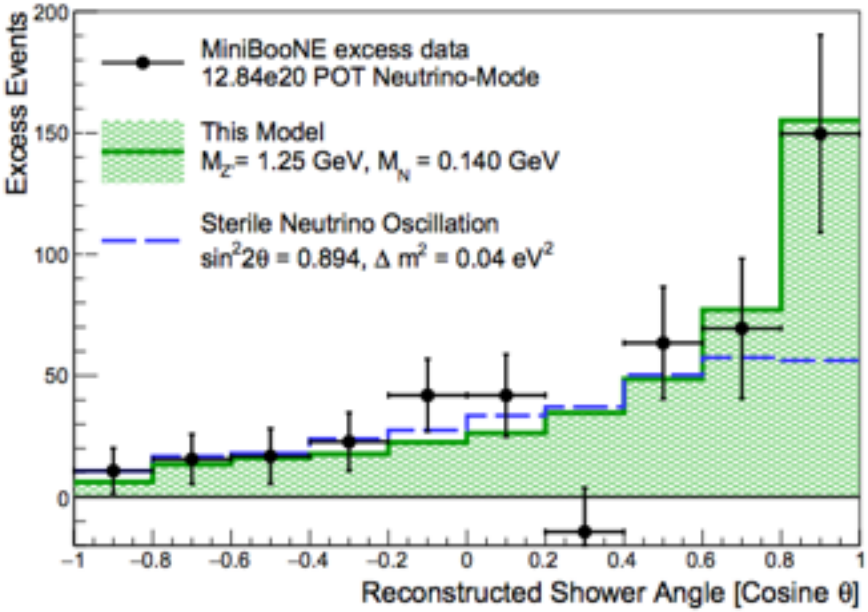
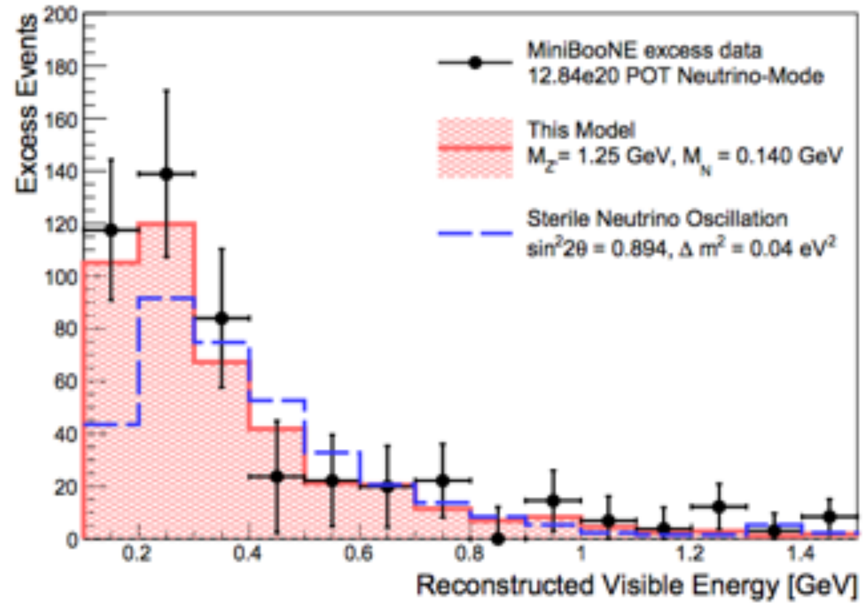
Very good angular and energy distributions can be obtained.





P. Ballett, S. Pascoli, M. Ross-Lonergan, 1808.02915

The values of the parameters are compatible with other sterile neutrino and Z' searches. The model can be made theoretically consistent.

For a similar idea see Bertuzzo et al., 1808. 02500.

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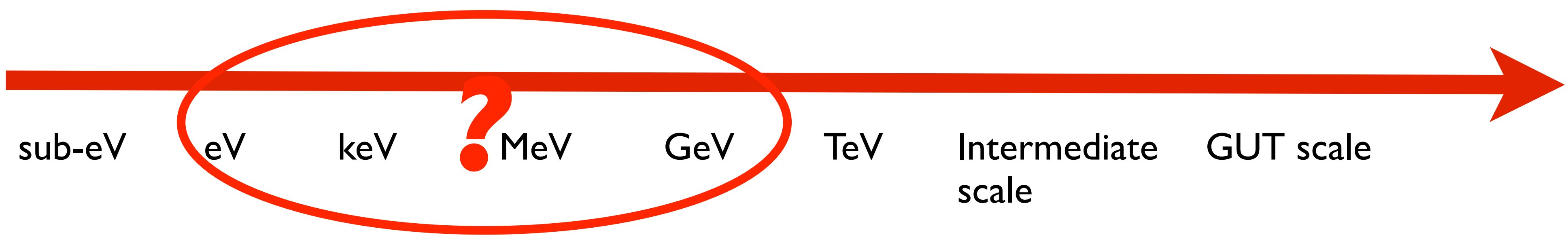
Conclusions

Invisibles are all around us and appear in many extensions of the SM.

New ideas are emerging exploring different mass scales: neutrino masses, sterile neutrinos, DM, axions, exotics… *Liberating ourselves from theoretical prejudice [B. Gavela].*



There may be more than one invisible: a new invisibles sector with multiple particles, new interactions and distinct phenomenology and cosmological consequences. Can it be just around the corner?