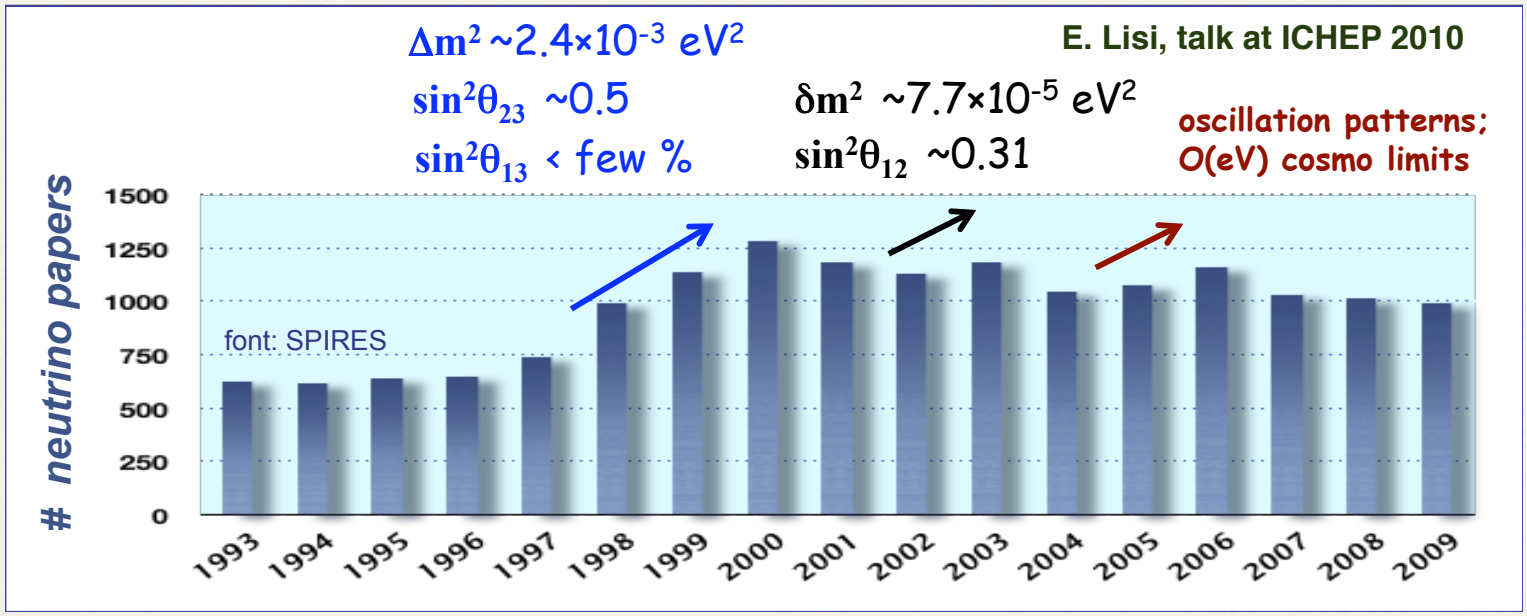
Neutrino Connections

Joseph Lykken

Fermilab

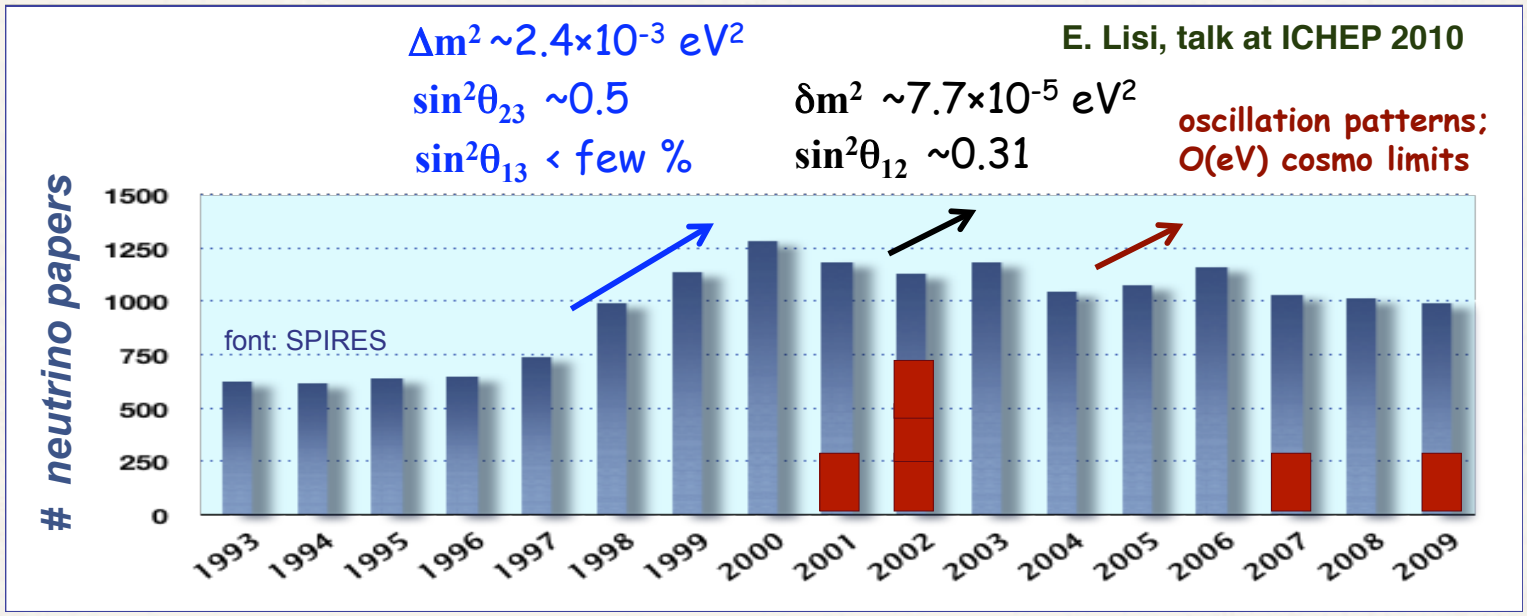
Neutrino 2014, Boston, June 7, 2014

Neutrinos are Interesting



According to the inSPIRE database, 2,900 neutrino papers were produced in 2012, compared to about 2,400 papers concerning the Higgs boson

Neutrinos are Interesting



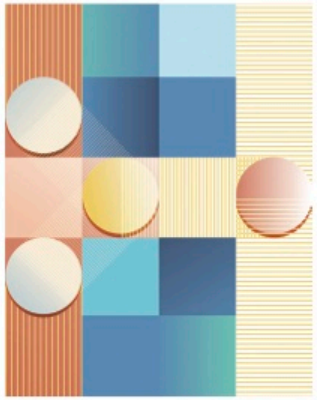
red bars = neutrino papers by J.Lykken (times 250)

According to the inSPIRE database, 2,900 neutrino papers were produced in 2012, compared to about 2,400 papers concerning the Higgs boson

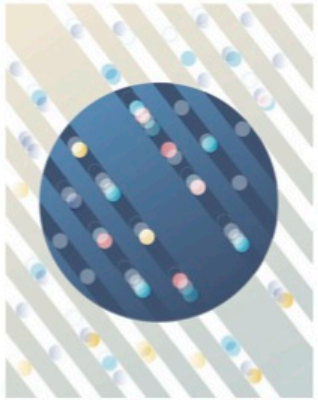
Neutrinos are one of the main science drivers of particle physics

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

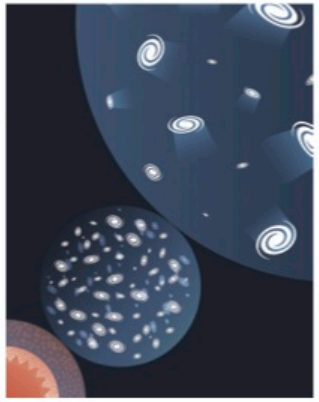


Higgs boson

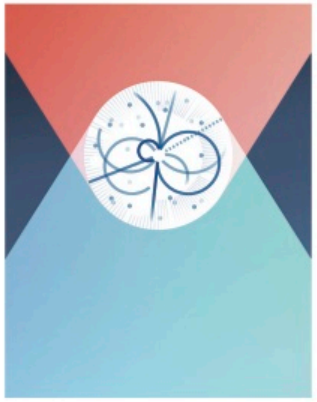


Neutrino mass

Dark matter



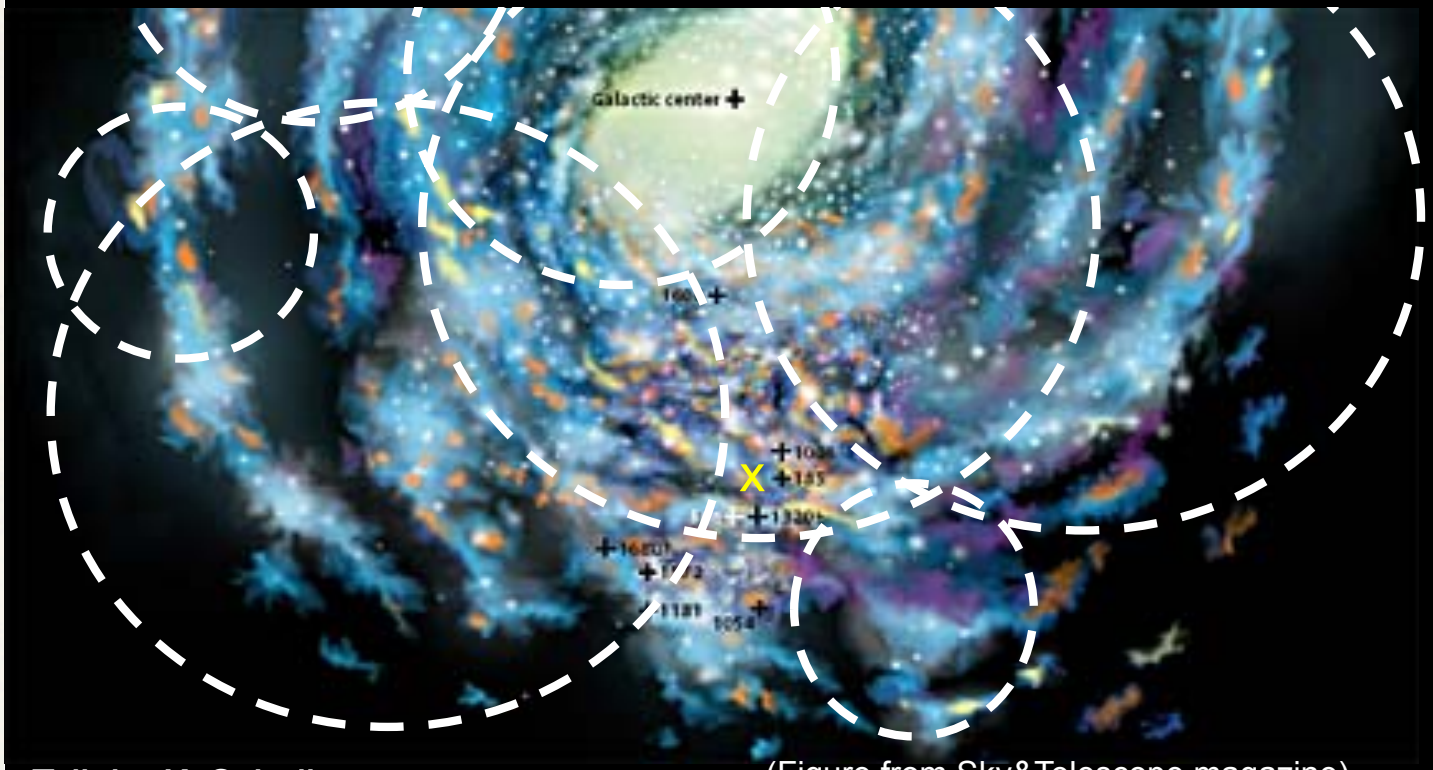
Cosmic acceleration



Explore the unknown

The neutrinos are coming!

Far side of the Milky Way is ~650 light-centuries away...
... ~2000 core collapses have happened already....

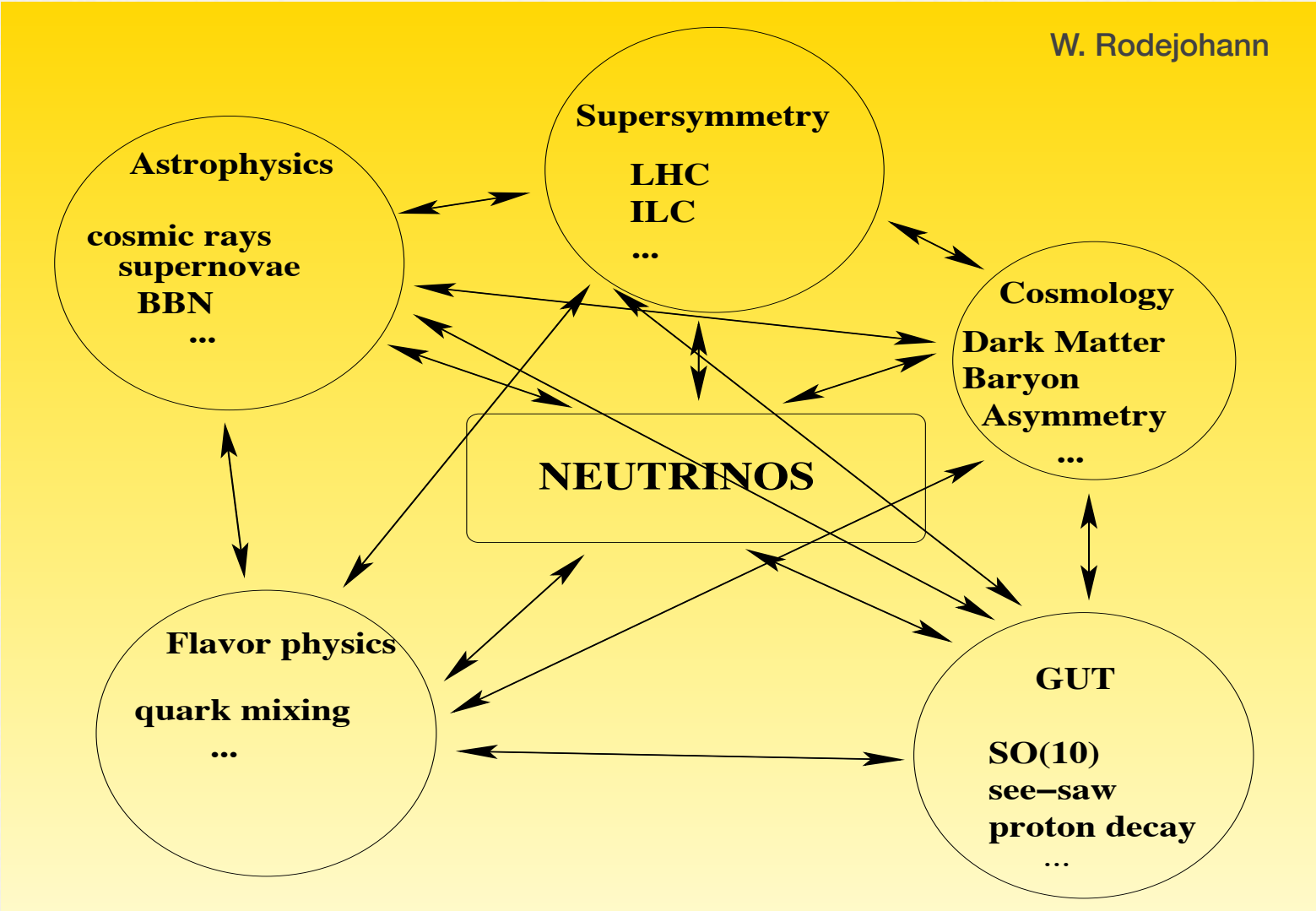


Talk by K. Scholberg

(Figure from Sky&Telescope magazine)

Neutrinos are key actors in important physical processes on Earth and out in the Universe

Neutrinos are everywhere, and related to everything

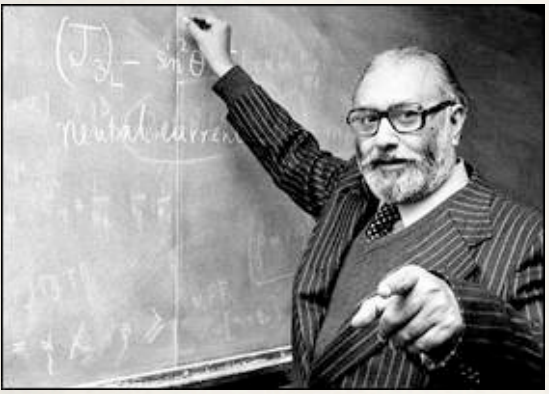


Neutrino Connections

- What are the dynamical origins of fermion masses, mixings and CP violation?
- How does the Higgs talk to neutrinos?
- Neutrinos and dark matter?
- Neutrinos and unification?
- Neutrinos and leptogenesis?
- Extra credit: Are neutrinos related to dark energy?

→ Motivates a multi-decade global experimental effort

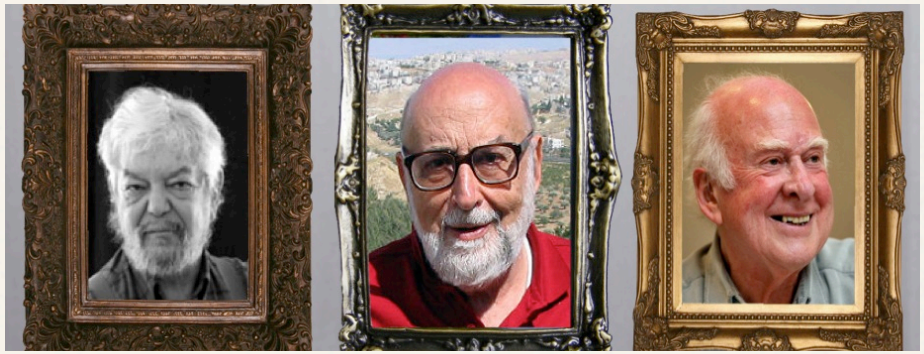
The dynamical origins of mass



- A headline of the Standard Model is that **elementary particles do not naturally have mass**,
- But they can acquire mass through dynamics
- In stark contrast to spin, the other conserved quantum number of Poincare invariance

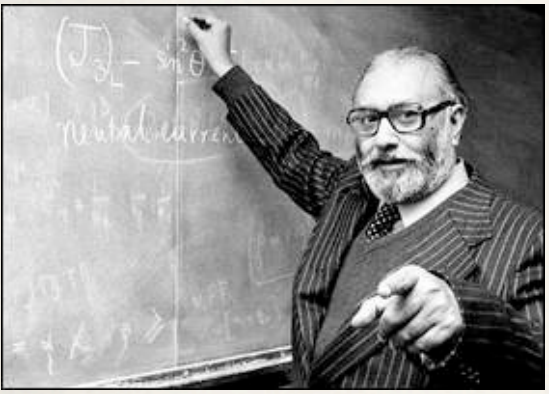
Higgs + BEGHK (1964)

- a fundamental scalar field with self-interactions
- can cause spontaneous (global) symmetry-breaking in the vacuum
- and give gauge bosons mass
- while respecting the delicate choreography of gauge symmetry with Lorentz invariance



Higgs explains: and if you started with a complex scalar field, there will be a neutral massive boson left over, and eventually you get a trip to Stockholm

The dynamical origins of mass



- ATLAS and CMS seem to have discovered a weakly self-coupled fundamental boson that couples to other heavy particles proportionally to their masses
- If this holds up, then we do in fact understand mass generation for the W and Z bosons
- **But for fermions we are just getting started...**

$$y_e \, \bar{L} \, H \, e_R + h.c. \rightarrow y_e \frac{v}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L)$$

The Particle Zoo

Fermion masses in units of m_t

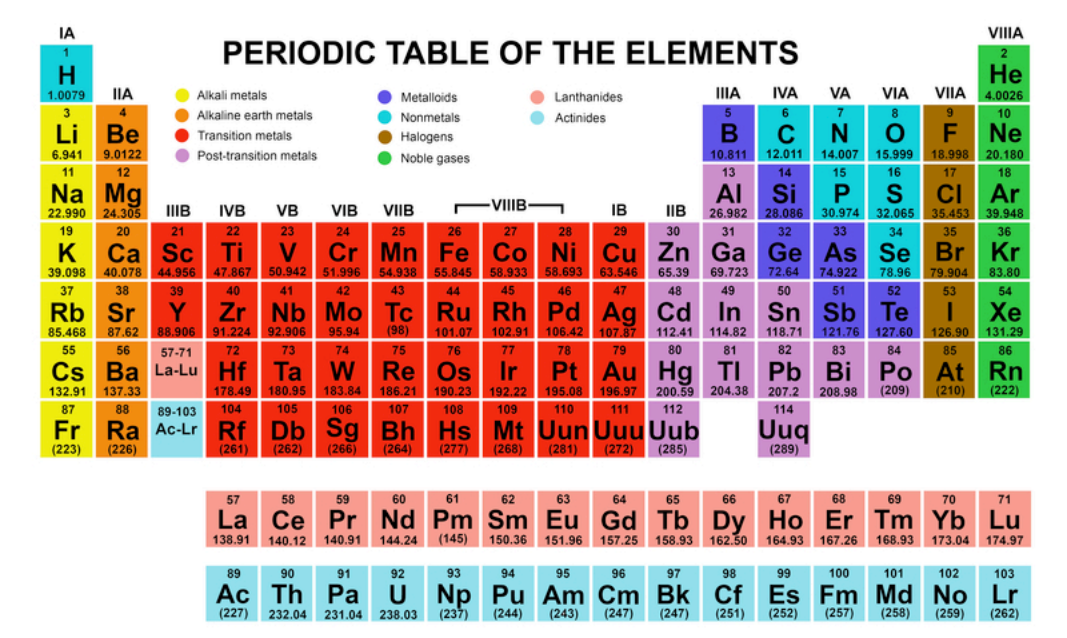
Talk by K. Babu

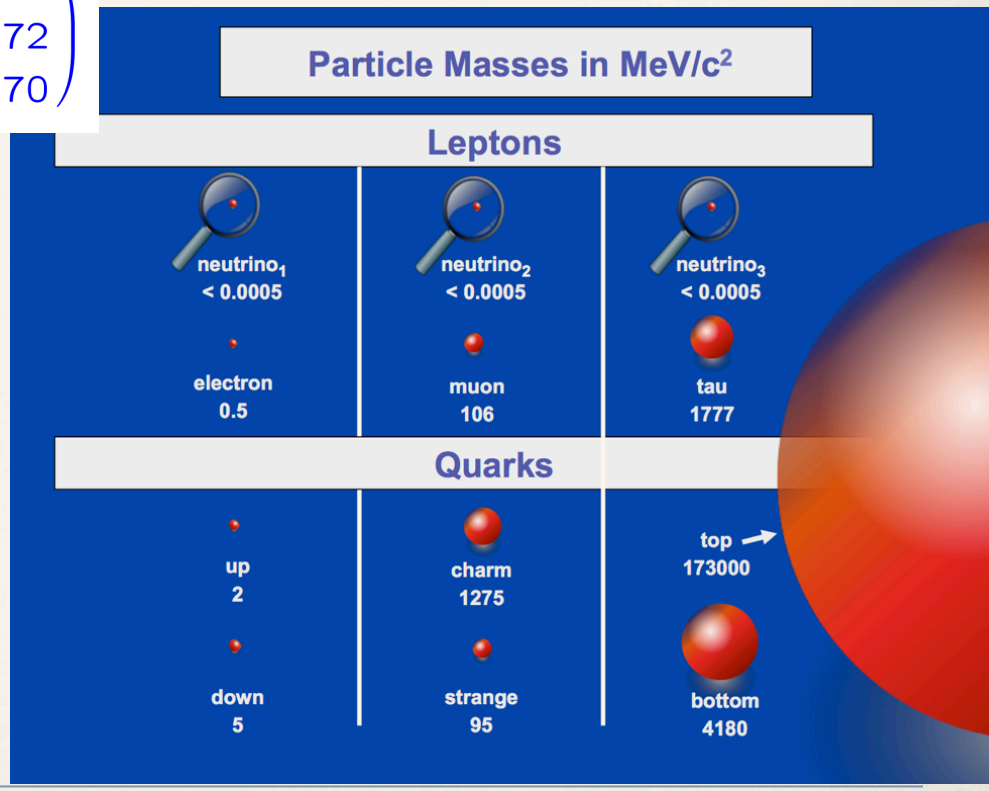
$$m_t = 1.0 \qquad m_b = 1.67 \times 10^{-2}$$
$$m_c = 3.6 \times 10^{-3} \qquad m_s = 3.1 \times 10^{-4}$$
$$m_u = 1.3 \times 10^{-5} \qquad m_d = 2.3 \times 10^{-5}$$

$$m_\tau = 1.0 \times 10^{-2} \qquad m_3 = 2.9 \times 10^{-13}$$
$$m_\mu = 6.2 \times 10^{-4} \qquad m_2 = 5.2 \times 10^{-14}$$
$$m_e = 3.0 \times 10^{-6} \qquad m_1 = < m_2$$

Normal hierarchy?

$$V_q = \begin{pmatrix} 0.976 & 0.22 & 0.004 \\ -0.22 & 0.98 & 0.04 \\ 0.007 & -0.04 & 1 \end{pmatrix} \qquad U_\ell = \begin{pmatrix} 0.85 & -0.54 & 0.16 \\ 0.33 & 0.62 & -0.72 \\ -0.40 & -0.59 & -0.70 \end{pmatrix}$$





Flavor is the big over-arching challenge of particle physics for this half of the 21st century

- What are the dynamical origins of fermion masses, mixings, and CP violation?
- What are the scales associated with this dynamics?
- What are the symmetries and symmetry-breakings?
- What is the full Higgs sector and how does it work?
- How are quark and lepton flavor related?
- What other flavor sectors are accessible, e.g.
    - superpartners?
    - dark matter?

Gathering clues from many directions

- Look for new sources of flavor-breaking/CPV in the quark sector
- Determine the flavor structure of the neutrino sector
- Determine the full Higgs sector and its flavor implications
- Look for nonconservation of lepton number, baryon number, and charged lepton flavor violation
- Find the portals to the dark sector and the dark particle content
- **Any new physics and any new scales could be relevant**

Pressing Questions for Neutrinos

Talk by K. Babu

- Are neutrinos their own antiparticles?
- Is there CP violation in neutrino oscillations?
- Is the mass hierarchy normal or inverted?
- Are there light sterile neutrinos?
- What is the scale of neutrino mass generation?
- What explains the pattern of neutrino mixings?
- Can neutrinos be unified with quarks?
- Is neutrino CP violation related to baryon asymmetry?

Can be addressed strongly with current and planned experiments

Very interesting and very important, but also very hard to address experimentally

Pursuing the origins of neutrino masses

- We studied the quark sector for 50 years and measured everything with precision, and we still have no clue where the underlying hierarchies come from, or the scale of the new physics responsible
- So studying neutrinos is hopeless, right?
- Neutrino masses probably involve the same unknown principles as quark masses, plus extra complications involving unreachable energy scales
- Why is pursuing these oddball neutrinos a good strategy?

Pursuing the origins of atomic structure

- We studied normal elements like carbon and lead for 50 years and measured everything with precision, and we still have no clue where the underlying hierarchies come from, or the principles of the new physics responsible
- So studying radium is hopeless, right?
- Radium probably involves the same unknown principles as carbon, plus extra complications
- Why is pursuing these oddball elements a good strategy?

Neutrinos point the way beyond the Standard Model

A general argument:

- Renormalizable QFTs are just stand-ins for effective field theories that flow down from some fancy UV completion associated to (at least one) actual UV energy scale **S. Weinberg, J. Polchinski, K. Wilson, ...**
- The SM at lab energies is an approximation to some effective theory with a bunch of higher dimension operators suppressed by powers of UV scales
- If you start with the UV theory, you will have to fine tune to get to something that looks like the Standard Model at lab energies
- This is the Naturalness / fine tuning / hierarchy problem

This is a good argument!

- We believed this argument so much that we have spent billions of dollars of the taxpayers money over 30 years looking for evidence of the higher dimension operators
- So far we have seen no such evidence, with the notable exception of neutrino masses
- Neutrino masses may be explained by the Weinberg operator, the unique dimension 5 operator extension of the Standard Model

$$\frac{y_\nu}{M_{\rm new}}(\bar{L}H)^2 \to \frac{y_\nu v^2}{M_{\rm new}}\bar{\nu}_L \nu_L^c$$

Neutrino imply lots of new physics

$$\frac{y_\nu}{M_{\rm new}}(\bar{L}H)^2 \to \frac{y_\nu v^2}{M_{\rm new}}\bar{\nu}_L \nu_L^c$$

- In that case, naturalness demands that the scale integrated out to get the dimension 5 operator is less than about 10^7 GeV

De Gouvea, Hernandez, Tait, arXiv:1402.2658

- So the popular Type I superheavy see-saw picture of neutrinos is fine tuned without SUSY or some other major change in the picture
- If neutrinos talk to the Higgs some other way, e.g. Higgs triplets, then at least the first step in the story may be new physics at the TeV scale
- If neutrinos are purely Dirac, there is no see-saw scale, but the tiny Yukawa couplings themselves may have a Froggatt-Nielsen type explanation involving new superheavy scales. So again you need SUSY or something to stabilize the hierarchy of energy scales

the canonical BSM paradigm

- Natural + ~minimal-flavor-violating SUSY at the weak scale
- Neutralino dark matter
- A grand desert populated at the high end by a hidden sector for dynamical SUSY breaking, some heavy Majorana neutrinos, maybe PQ axions, inflatons
- Gauge coupling unification circa 10^{16} GeV accompanied by GUT or stringy unification of matter and gauge forces
- Planck scale stringiness with lots of extra structure to explain flavor etc.

there are lots of good arguments for this picture

The Naturalness Dogma: caveat emptor

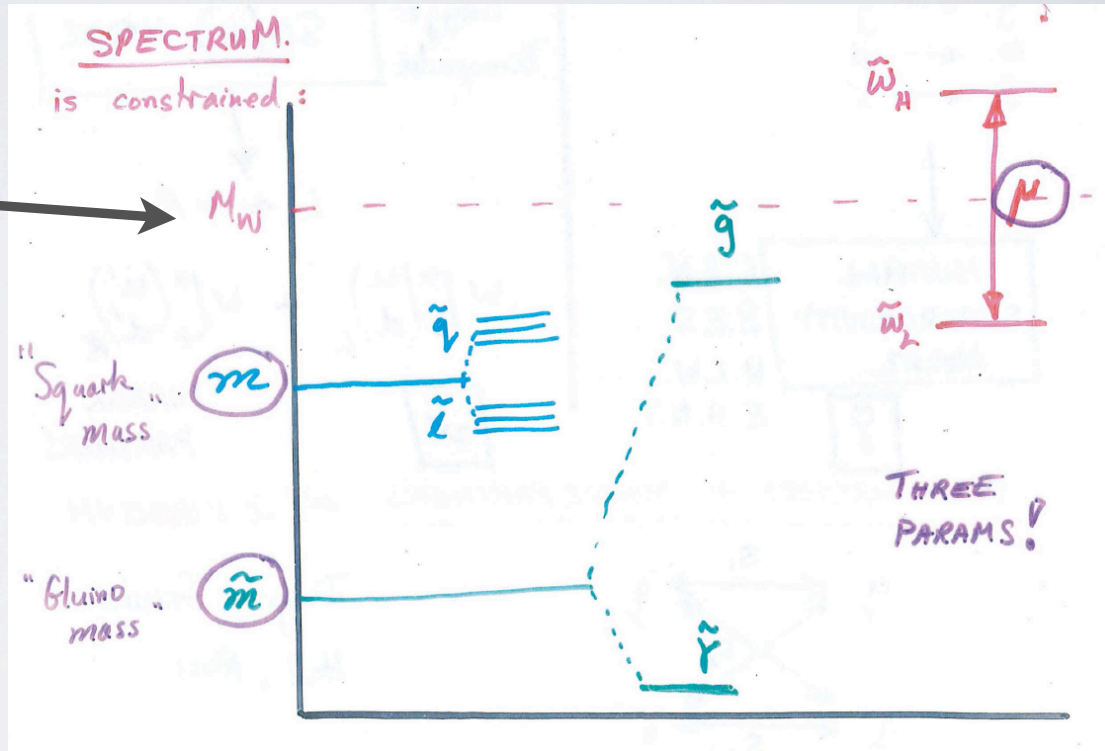
NATURAL SUSY, 1984

From Lawrence Hall's talk at SavasFest

W boson near the top of the spectrum....

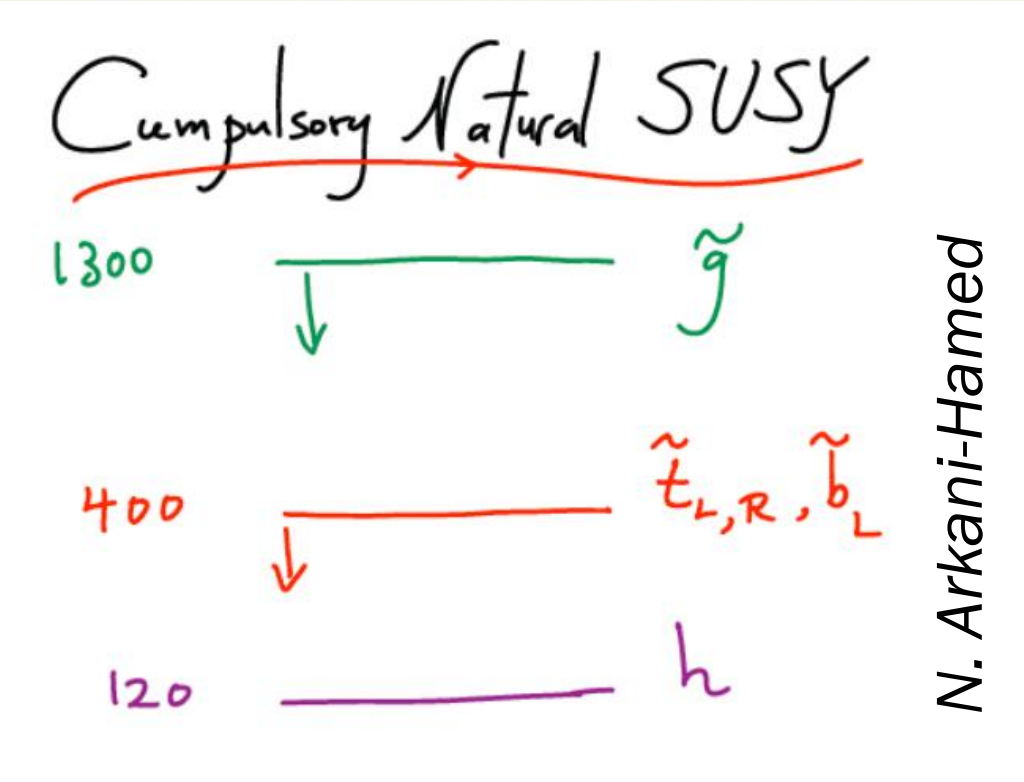
1984 was a utopian year for SUSY.

Times have changed!



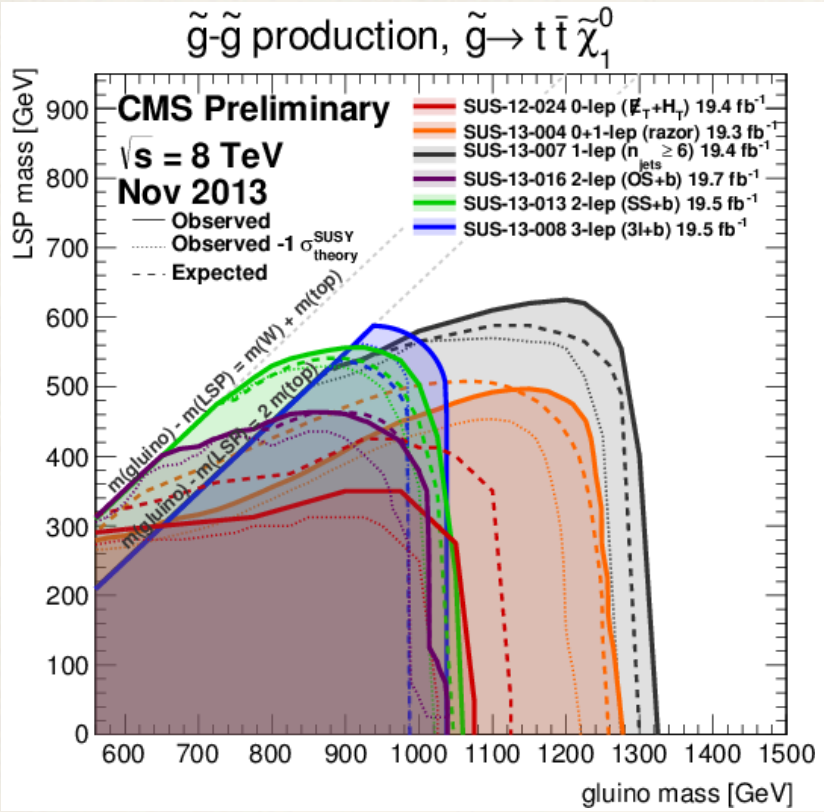
Talk by Matt Reece at LHCP 2013

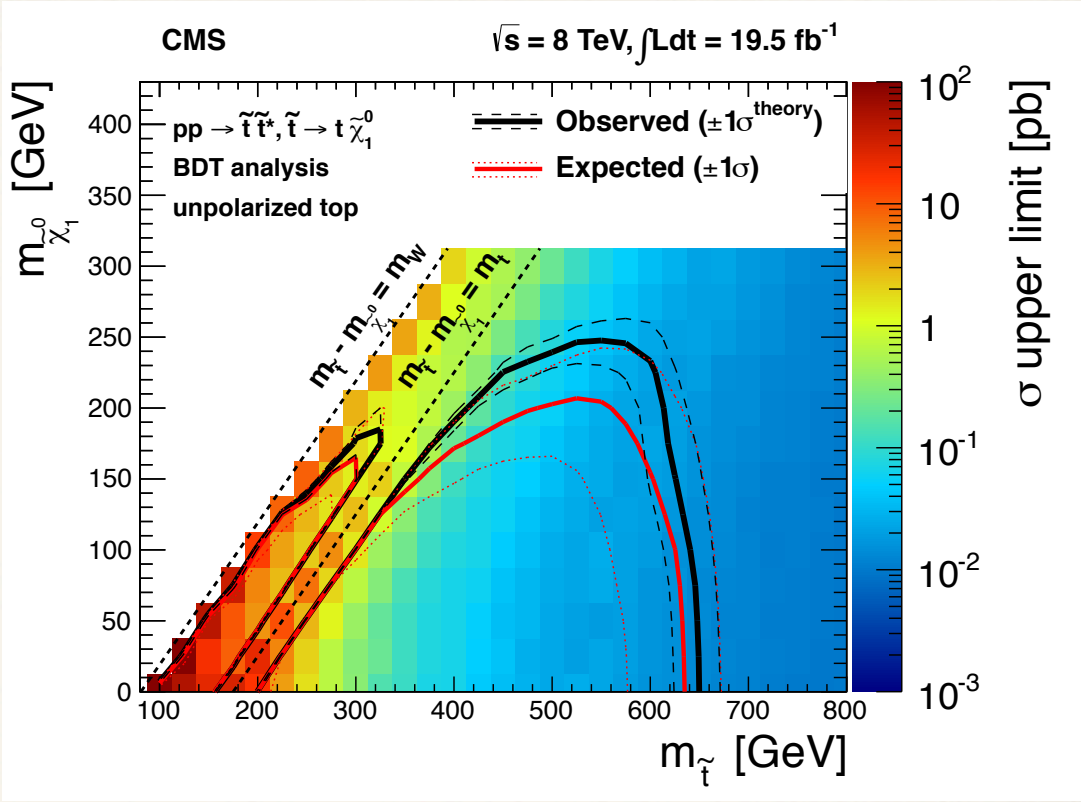
SUSY agonistes



- If you really believe in a strong naturalness argument, then we should have seen gluinos and stops already at the LHC

SUSY agonistes





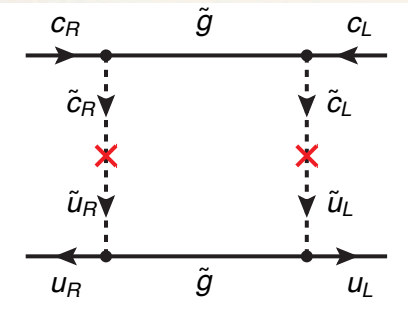
- Of course it is possible that we just missed the superpartners in the last LHC runs at 7 and 8 TeV, and they will show up quickly in the new run at 13 TeV
- Stranger things have happened: both the LEP and Tevatron collider experiments just missed discovering the Higgs boson

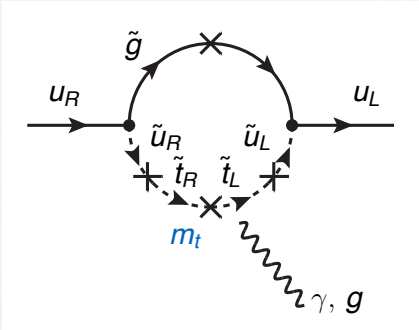
Moving SUSY to higher ground?

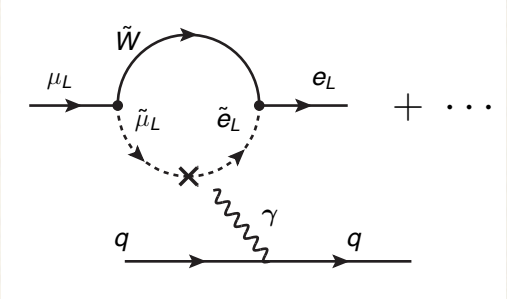
- Just in case, many theorists are busy making arguments for why it was obvious all along that superpartners should not be within reach of the LHC
- 10 TeV, 100 TeV, even 1 PeV are becoming popular mass scales for superpartners
- Moving to higher ground is very expensive...

The scales of flavor?

- Putting squark masses at 100 TeV, whatever the motivation, is a good playground for the idea that flavor-violating effects may be intrinsically O(1), but with a big mass suppression
- In such a regime it is also easier to make dynamical models of SM fermion mass hierarchies, without getting sunk by large FCNCs
- Even a 100 TeV pp collider may not probe this scale directly, so you will have to get clues from rare processes:

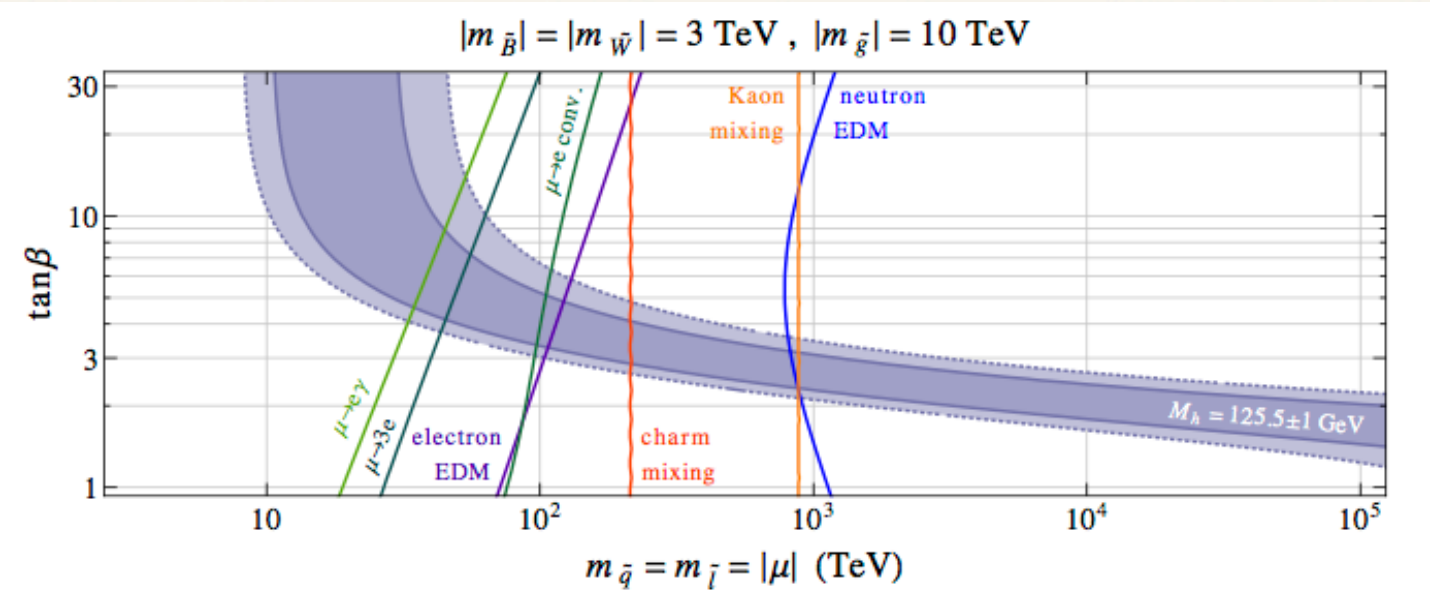






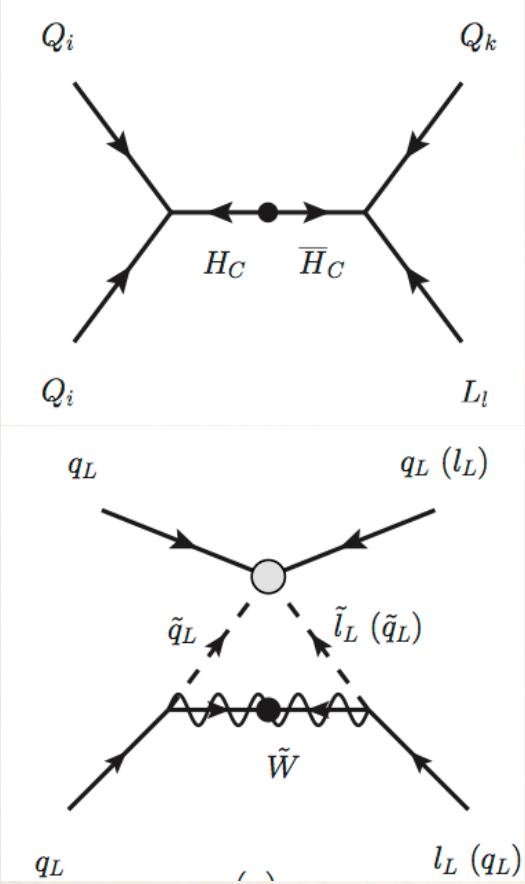
The scales of flavor?

- Heavy flavor probes up to 50 TeV (LHCb and Belle II)
- EDMs can probe up to 100 to 1000 TeV
- Kaons probe up to 1000 TeV
- MEG, Mu2e, Mu3e can probe 100 to 1000 TeV

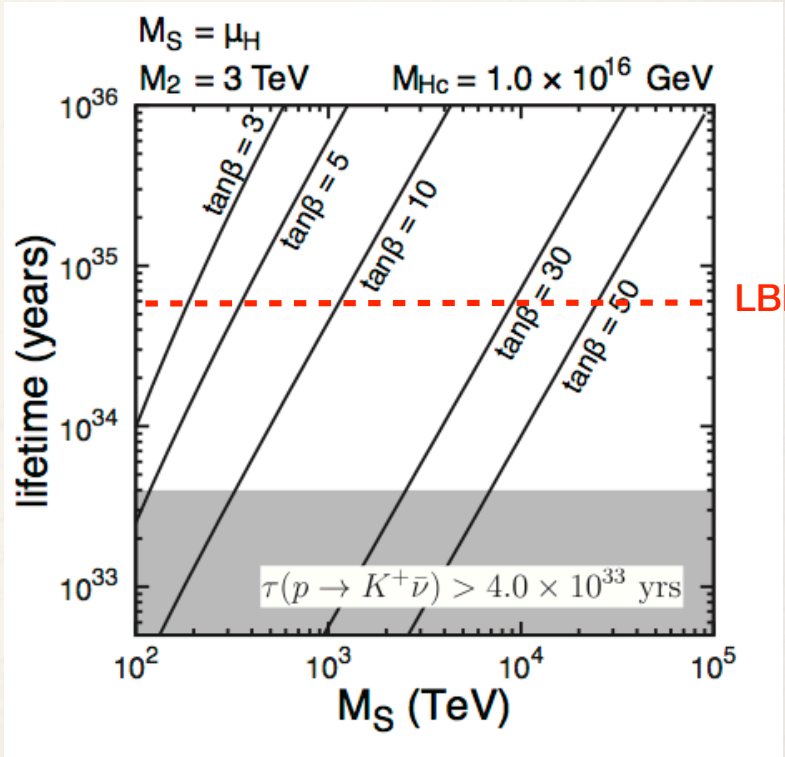


W. Altmannshofer, R. Harnik, J. Zupan, arXiv:1308.3653

Minimal SUSY SU(5) revived



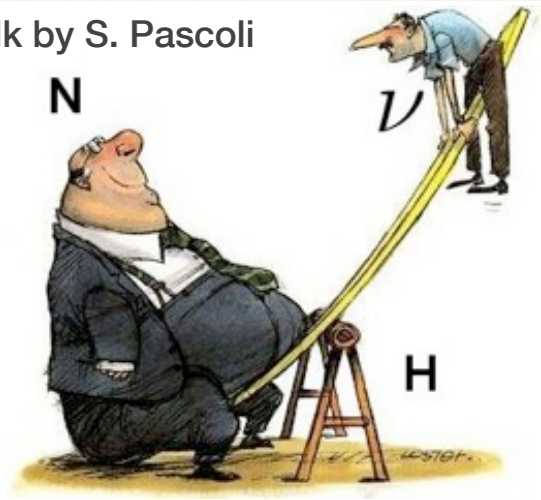
- color-triplet scalars that live in the Higgs 5-plet induce dimension five proton decay in SUSY SU(5)
- seemed to rule out the minimal scenario, since the proton lifetime was $\tau(p \to K^+\bar{\nu}) \lesssim 10^{30}$ yrs
- but with squark masses lifted to ~100 TeV, there is an extra suppression
- predicts that LBNF will see proton decay



J. Hisano et al, arXiv:1304.3651

Neutrino mass and physics at superheavy scales

Talk by S. Pascoli



See-saw mechanism type I

- Introduce a right handed neutrino **N**
- Couple it to the Higgs

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v_H}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

See-saw type I models can be embedded in GUT theories and explain the baryon asymmetry via leptogenesis.

Neutrino mass and physics at superheavy scales?

The pessimist says:

- We don't have enough ways of experimentally accessing new physics at superheavy scales
- And it is easy to write down general models, e.g. of leptogenesis, with 37 parameters invisible to any lower energy probes
- So it is hopeless to study neutrinos as a window to high scales

Neutrino mass and physics at superheavy scales?

The optimist says:

- Nature seems to have given us a number of ways of experimentally accessing new physics at superheavy scales: neutrinos, proton decay, inflation, maybe SUSY, ...
- Don't care about general models; we are looking for a very special model. Probably it has very few arbitrary parameters and some striking characteristic features
- So pursuing neutrinos and thinking about the origins of neutrino mass is a great window to high scales

Neutrino masses: what are we trying to explain?

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\lambda_2} & 0 \\ 0 & 0 & e^{i\lambda_3} \end{pmatrix}$$

$$U_{\rm TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

$$U_{\rm BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$U_{\rm LC} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{c^\nu_{23}}{\sqrt{2}} & \frac{c^\nu_{23}}{\sqrt{2}} & s^\nu_{23} \\ \frac{s^\nu_{23}}{\sqrt{2}} & -\frac{s^\nu_{23}}{\sqrt{2}} & c^\nu_{23} \end{pmatrix}$$

$$L_e - L_\mu - L_\tau$$

- Theorists making models of quark masses focus on explaining the hierarchies of masses and mixings, and ignore O(1) factors
- Theorists making models of neutrino masses do the opposite
- Usually assume that the PMNS picture is correct, and try to reproduce the numbers
- Make extra assumptions in order to make testable predictions

We really, really, need to know the mass hierarchy

Mass hierarchy as texture and model discriminator

- Typically re-covered in more complicated cases, e.g. including charged lepton mixings, θ_{13}>0 etc:

Hierarchy: normal vs. Hierarchy: inverted

$$\begin{pmatrix} \varepsilon & \varepsilon & \varepsilon \\ \varepsilon & \varepsilon & \varepsilon^2 \\ \varepsilon & \varepsilon^2 & 1 \end{pmatrix} \quad M_\nu \quad \begin{pmatrix} 1 & 0 & \varepsilon \\ 0 & 1 & \varepsilon^2 \\ \varepsilon & \varepsilon^2 & \varepsilon \end{pmatrix}$$

$$\begin{pmatrix} 1 & \varepsilon^2 & 1 \\ \varepsilon^2 & \varepsilon & \varepsilon^2 \\ 1 & \varepsilon^2 & 1 \end{pmatrix} \quad M_\nu \quad \begin{pmatrix} 1 & \varepsilon^2 & 1 \\ \varepsilon^2 & 1 & \varepsilon^2 \\ 1 & \varepsilon^2 & 1 \end{pmatrix}$$

(example from hep-ph/0612169)

- Translates into flavor symmetry models
  (Albright, Chen, hep-ph/0608137)
  See also: talk by Morimitsu Tanimoto

- Neutrino mass ordering is the prime model discriminator!

TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

Talk by W. Winter

Neutrino data is ruling out whole classes of models

In 2012

Reactor angle θ_{13} was measured by T2K, Daya Bay, MINOS, RENO, Double Chooz

$$\theta_{13} \simeq 9^\circ \simeq \theta_c/\sqrt{2}$$

Tri-bimaximal mixing was ruled out !

- Deviation from Tri-bimaximal mixing ?
- Different Anzatz ?
  Tri-maximal mixing, Tri-bimaximal Cabibbo ....

0 Neutrinos and Flavor Symmetries Morimitsu Tanimoto

Neutrino mass models make interesting predictions

Basic idea is simple: $\mathcal{U}_{MNSP} = \mathcal{U}^{\dagger}_{CKM}\,\mathcal{F}$

Datta, Everett, Ramond, hep-ph/0503222 + others

Makes a prediction that so far looks right on: $\theta_{13} = \sin\theta_C \sin\theta_{23} \simeq 9^\circ$

Predicting neutrino CP violation

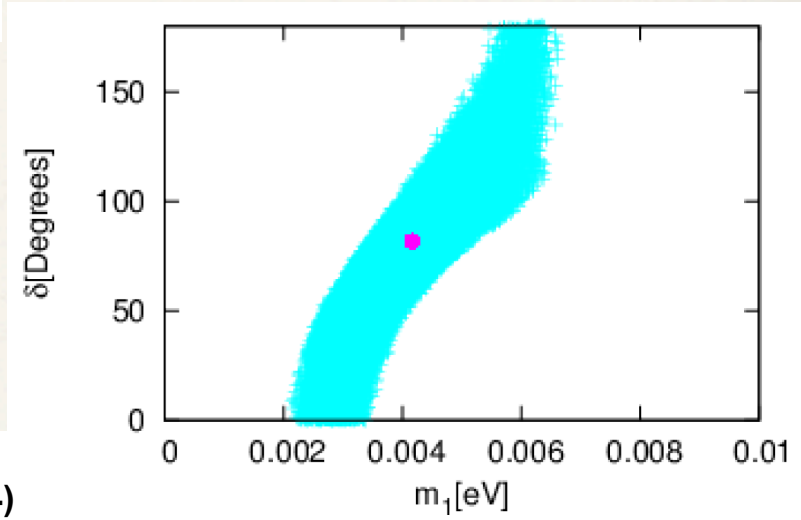
Texture zeros for neutrinos

$$A_1 : \begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix} \qquad A_2 : \begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$$

$$B_1 : \begin{pmatrix} X & X & 0 \\ X & 0 & X \\ 0 & X & X \end{pmatrix} \qquad B_2 : \begin{pmatrix} X & 0 & X \\ 0 & X & X \\ X & X & 0 \end{pmatrix}$$

Frampton, Glashow, Marfatia (2002)
Xing (2002)
Merle, Rodejohann (2006)
Goswami et. al (2006)

Talk by K. Babu



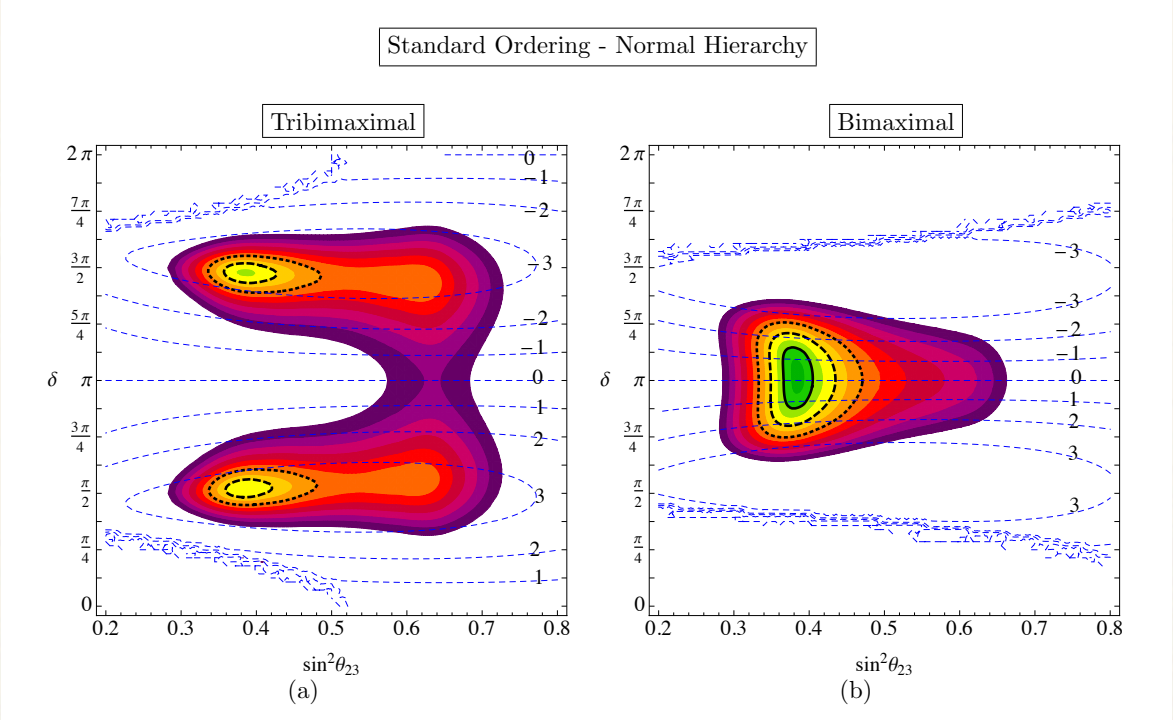
K. Babu, Z. Devi, S. Goswami (2014)
J. Liao, D. Marfatia, K. Whisnant (2014)

Predicting neutrino CP violation

$$U_{\rm PMNS} = U_e^\dagger\, U_\nu = (\tilde{U}_e)^\dagger\, \Psi \tilde{U}_\nu\, Q_0$$

$$\tilde{U}_e = R_{23}^{-1}\left(\theta_{23}^e\right) R_{12}^{-1}\left(\theta_{12}^e\right)$$

$$\cos\delta = \frac{\tan\theta_{23}}{3\sin 2\theta_{12}\sin\theta_{13}}\left[1 + \left(3\sin^2\theta_{12} - 2\right)\left(1 - \cot^2\theta_{23}\,\sin^2\theta_{13}\right)\right]$$



Marzocca, Petcov, Romanini, Sevilla, arXiv:1302.0423
Petcov, arXiv:1405.6006

Predicting neutrino CP violation

$$V_\nu = \begin{pmatrix} 2c/\sqrt{6} & 1/\sqrt{3} & 2s/\sqrt{6} \\ -c/\sqrt{6}+is/\sqrt{2} & 1/\sqrt{3} & -s/\sqrt{6}-ic/\sqrt{2} \\ -c/\sqrt{6}+is/\sqrt{2} & 1/\sqrt{3} & -s/\sqrt{6}+ic/\sqrt{2} \end{pmatrix}$$

$$c = \cos\theta, \;\; s = \sin\theta$$

$$\sin^2\theta_{13} = \tfrac{2}{3}\sin^2\theta, \;\; \sin^2\theta_{12} = \tfrac{1}{2+\cos 2\theta}, \;\; \sin^2\theta_{23} = \tfrac{1}{2}$$

$$|\sin\delta_{CP}| = 1, \quad \sin\alpha_{21} = \sin\alpha_{31} = 0$$

$$\delta_{CP} = \pm\pi/2$$

The predicton of CP phase depends on
the respected Generators of FLASY and CP symmetry.
Typically, it is simple value, 0, π, ±π/2 .

Talk by M. Tanimoto

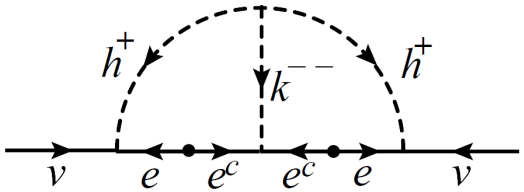
Predictions for charged lepton flavor violation

Two–loop neutrino mass generation

$$\mathcal{L} = f_{ij} L_i^a L_j^b h^+ \epsilon_{ab} + g_{ij} e_i^c e_j^c k^{--} + \mu h^+ h^+ k^{--} + \text{h.c.}$$

$$\Downarrow$$

$$\mathcal{O}_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij} \epsilon_{kl}$$

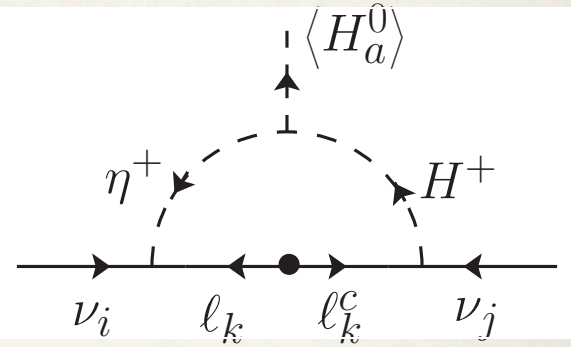


A. Zee, (1985)
Babu (1988)

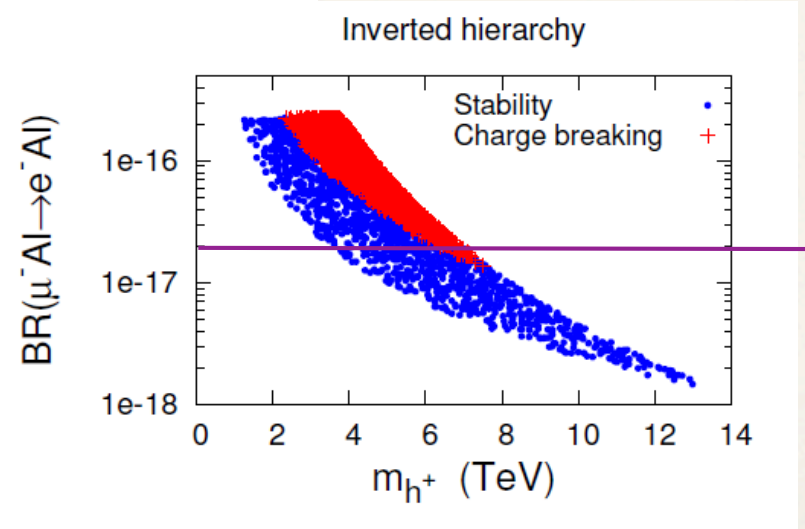
Consistent with all neutrino oscillation data

Predicts doubly charged Higgs boson with TeV mass

One neutrino is nearly massless



Talk by K. Babu



Sensitivity of Mu2e experiment

SO(10) GUT with extra family symmetry

SO(10) x (D_3 x U(1) family sym.)
Yukawa Unification for 3rd Family

	Current Limit	10 TeV	15 Te V	20 TeV	25 TeV	30 TeV
e EDM $\times 10^{28}$	$< 10.5\ e\ cm$	-0.224	-0.0408	-0.0173	-0.0113	-0.0084
μ EDM $\times 10^{28}$	$(-0.1 \pm 0.9) \times 10^9\ e\ cm$	34.6	6.23	3.04	1.77	1.20
τ EDM $\times 10^{28}$	$-0.220 - 0.45 \times 10^{12}\ e\ cm$	-2.09	-0.394	-0.185	-0.109	-0.0732
$\mathrm{BR}(\mu \to e\gamma) \times 10^{12}$	< 2.4	5.09	1.23	0.211	0.0937	0.0447
$\mathrm{BR}(\tau \to e\gamma) \times 10^{12}$	$< 3.3 \times 10^4$	58.8	13.9	2.40	1.04	0.502
$\mathrm{BR}(\tau \to \mu\gamma) \times 10^{8}$	< 4.4	1.75	0.498	0.0837	0.0385	0.0182
$\sin\delta$		-0.60	-0.87	-0.27	-0.42	-0.53

S. Raby

m_{16}	10 TeV	15 TeV	20 TeV	25 TeV	30 TeV
χ^2	49.65	31.02	26.58	27.93	29.48
M_A	2333	3662	1651	2029	2036
$m_{\tilde{t}_1}$	1681	2529	3975	4892	5914
$m_{\tilde{b}_1}$	2046	2972	5194	6353	7660
$m_{\tilde{\tau}_1}$	3851	5576	7994	9769	11620
$m_{\tilde{\chi}_1^0}$	133	134	137	149	167
$m_{\tilde{\chi}_1^+}$	260	263	279	309	351
$M_{\tilde{g}}$	853	850	851	910	1004

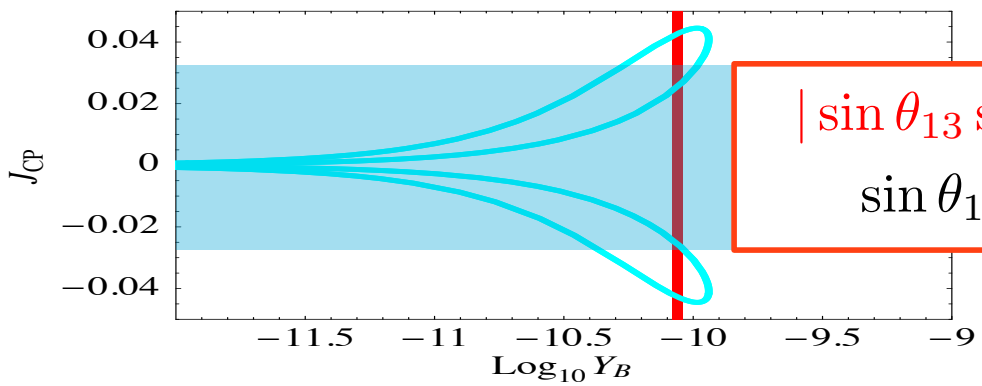
Neutrinos and leptogenesis

Does observing low energy CPV imply a baryon asymmetry?

It has been shown that, thanks to flavour effects, the low energy phases enter directly the baryon asymmetry.

Example in see-saw type I, with NH (m1<< m2 <<m3), M1<M2<M3, M1~5 10^11 GeV:

$$\epsilon_\tau \propto M_1 f(R_{ij}) \left[c_{23} s_{23} c_{12} \sin \frac{\alpha_{32}}{2} - c_{23}^2 s_{12} s_{13} \sin(\delta - \frac{\alpha_{32}}{2}) \right]$$



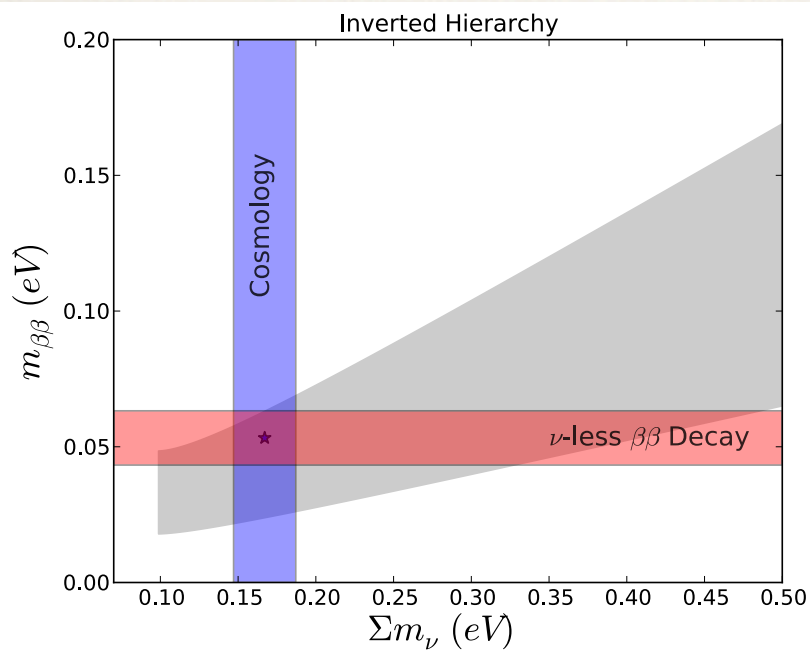
$$|\sin\theta_{13} \sin\delta| > 0.11$$

$$\sin\theta_{13}|_{\mathrm{exp}} \simeq 0.15$$

SP, Petcov, Riotto, PRD75 and NPB774

Large theta13 implies that delta can give an important (even dominant) contribution to the baryon asymmetry. Large CPV is needed and a NH spectrum. Talk by S. Pascoli

Measuring a Majorana phase using Neutrinoless Double Beta Decay and Cosmology



Assumed sensitivities: $\Delta_\beta = 10$ meV and $\Delta_S = 20$ meV.

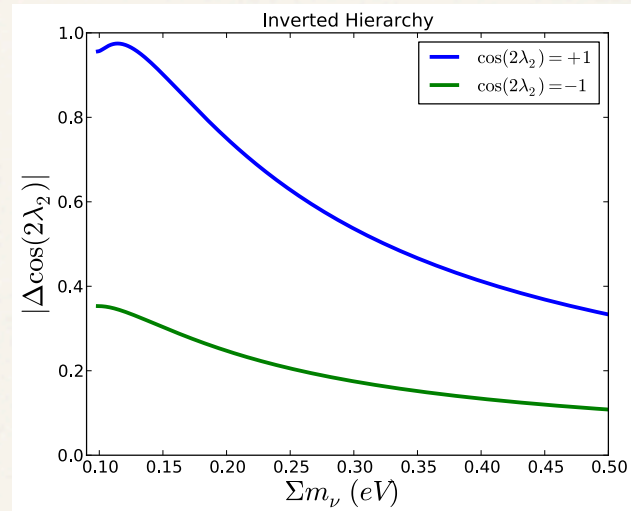


FIG. 2: Projected one-sigma constraint on the cosine of the Majorana phase from combined cosmic survey and neutrinoless double beta decay experiments. These constraints are relevant if the mass hierarchy is determined to be inverted.

$$m_{\beta\beta}^{\rm inv} \simeq c_{13}^2 \left[(m_1 c_{12}^2)^2 + (m_2 s_{12}^2)^2 + 2\cos(2\lambda_2)(m_1 c_{12}^2)(m_2 s_{12}^2) \right]^{1/2}.$$

S. Dodelson and JL, arXiv:1403.5173, and many previous works

Mixing as a window to hidden sectors

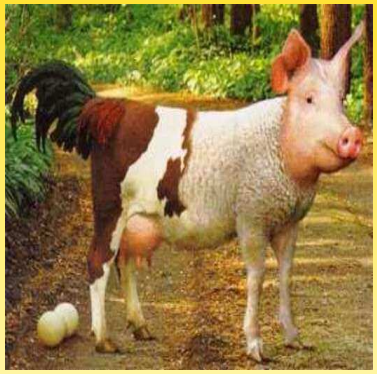
Sterile neutrinos

Talk by J. Kopp

Definition

Sterile neutrino = SM singlet fermion

- Very generic extension of the SM
  - can be leftovers of extended gauge multiplets (e.g. GUT multiplets)
- Very useful in phenomenology:
  - Can explain smallness of neutrino mass (seesaw mechanism, $m \sim$ TeV $\ldots M_{\rm Pl}$)
  - Can explain baryon asymmetry of the Universe (leptogenesis, $m \gg 100$ GeV)
  - Can explain dark matter ($m \sim$ keV)
  - Can explain various neutrino oscillation anomalies ($m \sim$ eV)



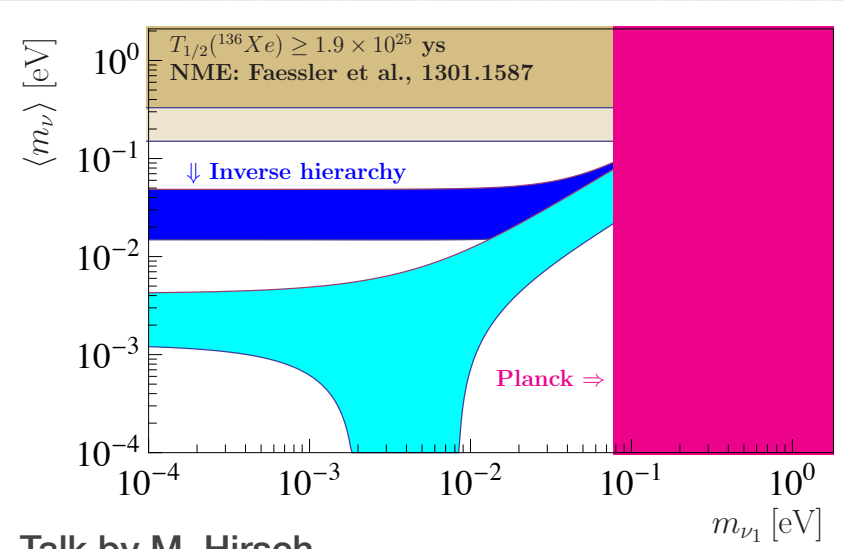
Sterile Neutrinos

- eV: SBL Anomalies
- eV: $N_{\rm eff}$ (Cosmology, BBN), r-process
- eV: BICEP-2 and Planck
- $\ll$ eV: missing upturn of $P_{ee}^{\odot}$
- keV: Warm Dark Matter
- TeV: Z-width, NuTeV
- 10^{10} GeV: Leptogenesis
- 10^{15} GeV: Seesaw Mechanism

W. Rodejohann

- Lots of good motivations for various kinds of steriles
- More generally, neutral particles like to mix with other neutrals
- So we will never ever stop looking for steriles

Sterile neutrinos and neutrinoless double beta decay

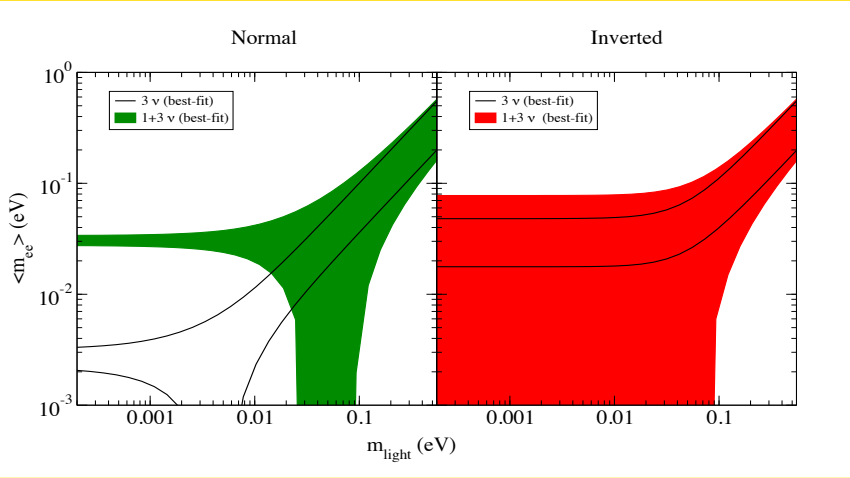


Talk by M. Hirsch

Sterile Neutrinos: the usual plot for double beta decay. . .

. . . gets completely turned around!

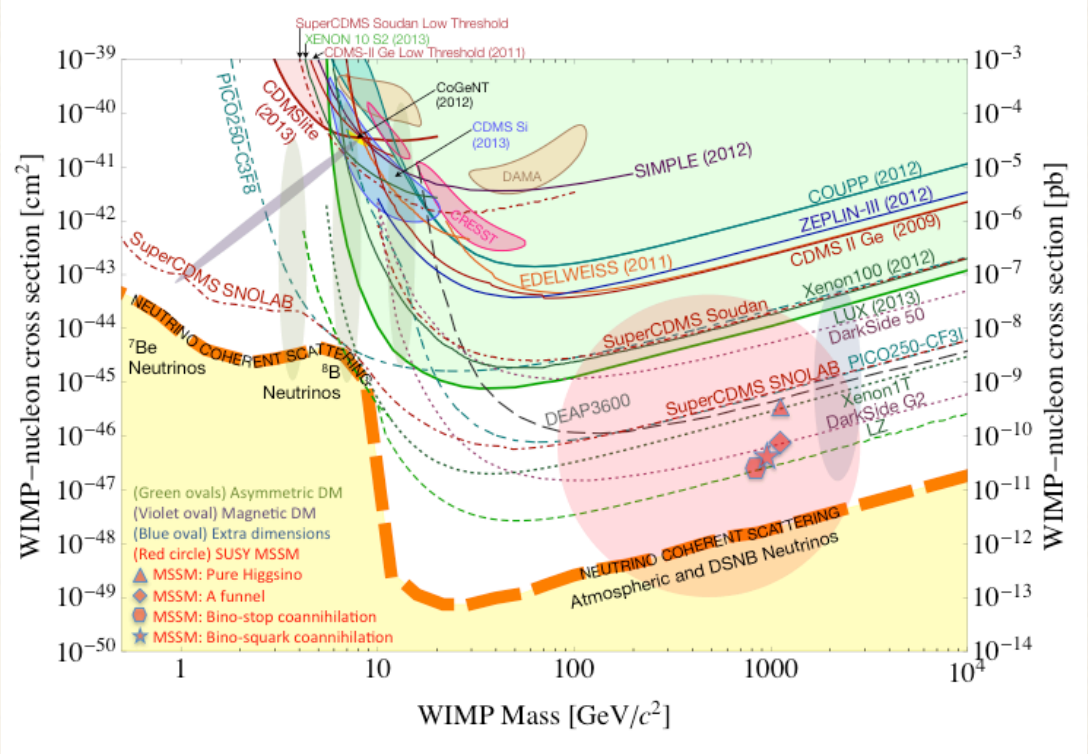
W. Rodejohann



Barry, W.R., Zhang, JHEP **1107**; Giunti *et al.*, PRD **87**; Girardi, Meroni, Petcov, 1308.5802

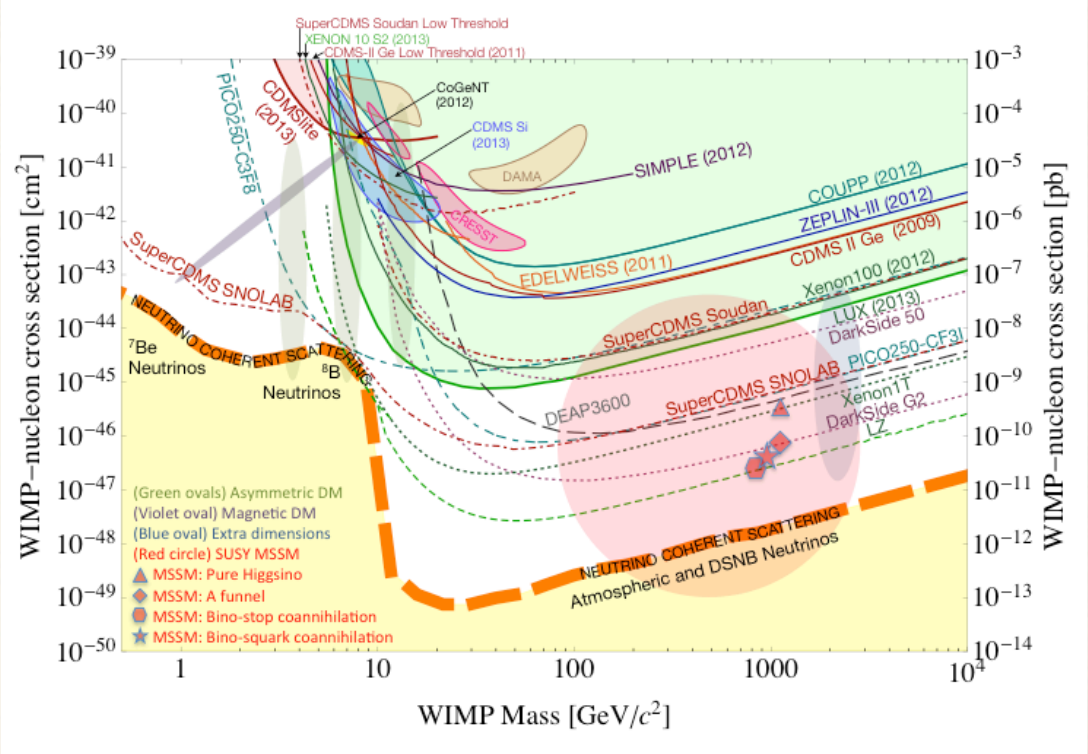
- A reminder that the 3-flavor PMNS picture is still just an assumption
- And there could be other nonstandard neutrino interactions

WIMPs getting wimpier



- the WIMP miracle is starting to look like the WIMP fairytale
- theorists may soon have to stop saying “it’s a 100 GeV neutralino, stupid”
- good news: already DAMA, CoGeNT, etc have inspired the theory community to start taking a much broader view of the dark sector

WIMPs getting wimpier



- The “Neutrino Floor” is itself interesting never-before-seen physics: coherent neutrino-nucleus scattering

Talk by G. McLaughlin

Dark matter and neutrinos

- Neutrinos are the dark matter?
- Dark matter annihilates into neutrinos?
- Dark matter decays into neutrinos?

Talk by A. Ibarra

Sterile neutrino dark matter: already discovered?

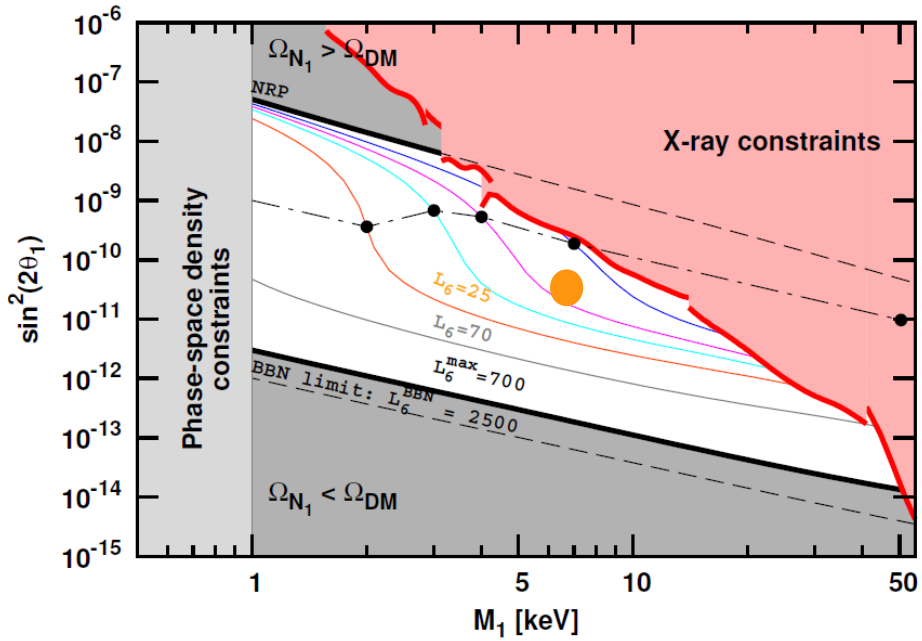
Sterile neutrinos as dark matter

Bulbul et al, 1402.2301

$$m_{\rm DM} = 7.1\,{\rm keV}$$
$$\sin^2 2\theta \approx 7\times 10^{-11}$$

Boyarsky al, 1402.4119

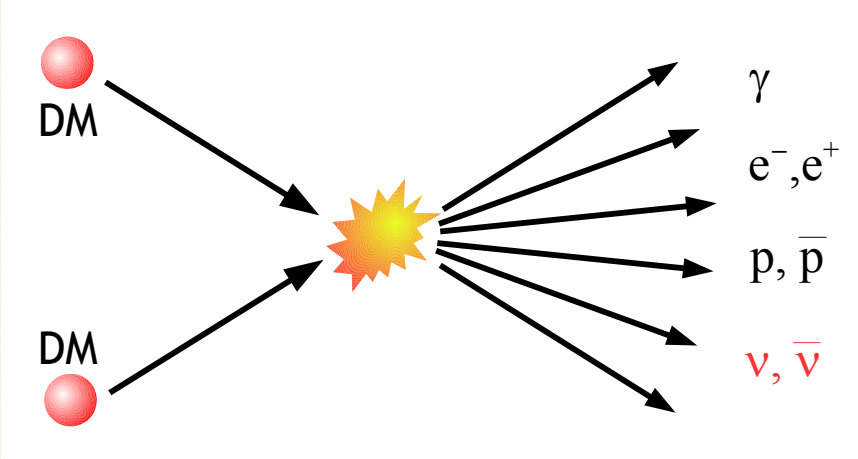
$$m_{\rm DM} = 7.06 \pm 0.05\,{\rm keV}$$
$$\sin^2 2\theta = (2.2-20)\times 10^{-11}$$

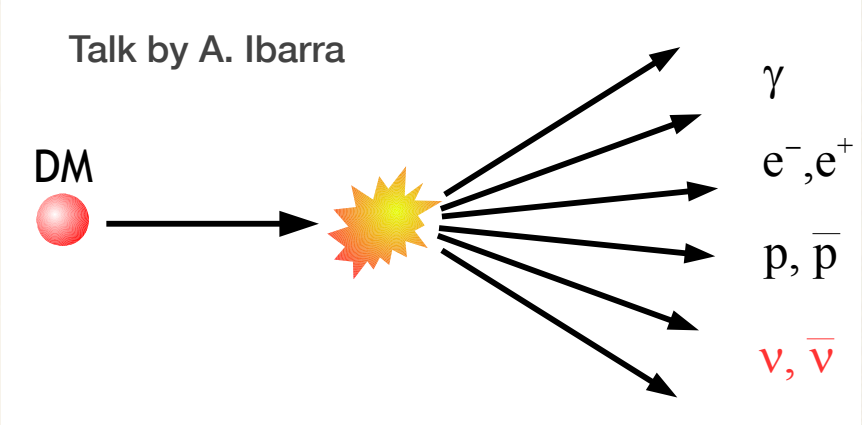


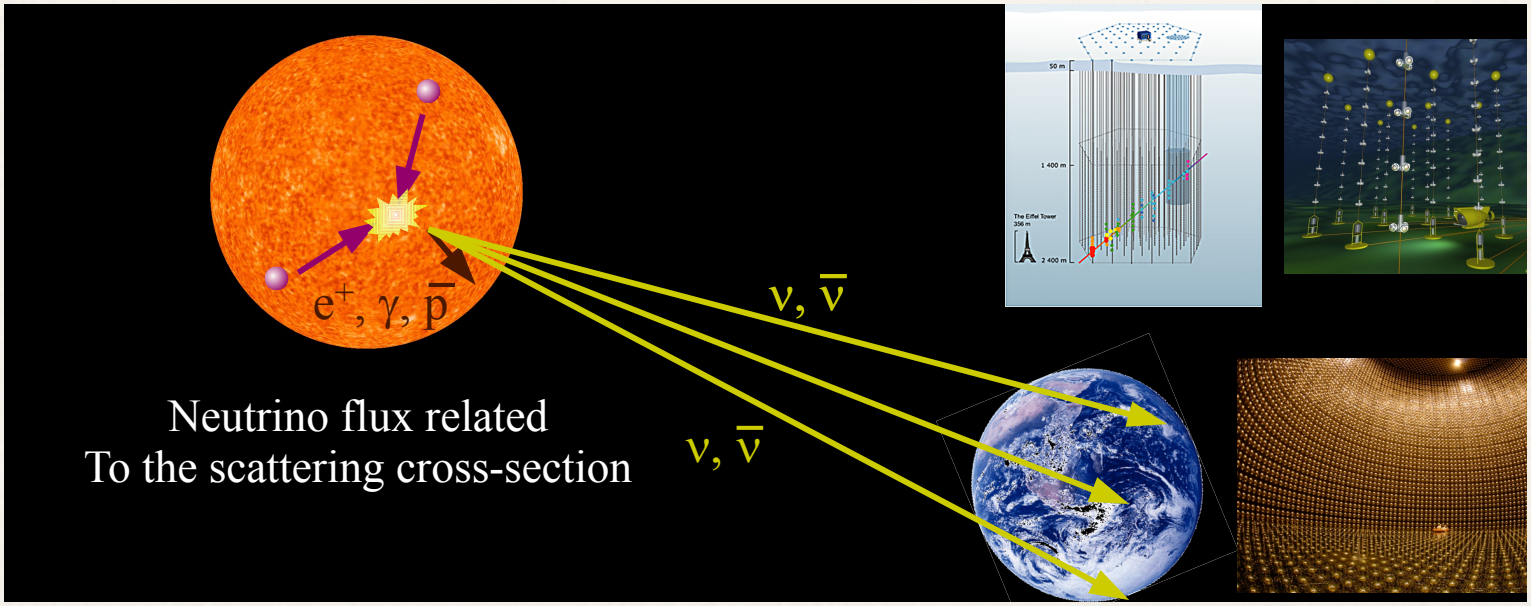
Talk by A. Ibarra

Requires $n_L/s \sim 10^{-5}$ (compared to $n_B/s \sim 10^{-10}$)

Neutrinos from dark matter annihilation or decay







~eV sterile neutrinos and dark forces?

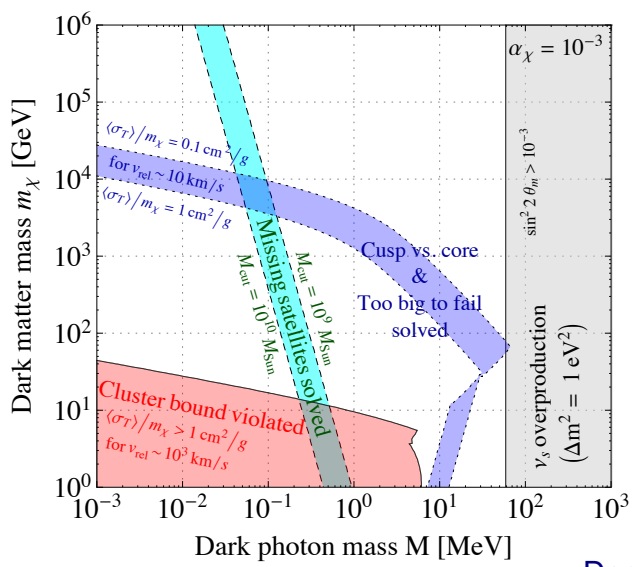
Hidden sector gauge forces and dark matter

Interesting connection to dark matter physics:

The same gauge force that suppressed sterile neutrino production can also solve small scale structure problems:

- Too big to fail problem
- Cusp vs. core problem
- Missing satellites problem

Talk by J. Kopp



Dasgupta JK arXiv:1310.6337

Outlook

- Neutrinos connect to almost all of the big questions of particle physics: pursue the oddballs!
- Anyway you cannot escape them: people doing dark matter, colliders, cosmology all are facing neutrinos
- The challenge of understanding the dynamical origins of fermion masses and mixings will require probing higher scales both directly and indirectly
- Whether canonical thinking is correct or not, we have entered a New Age

Not the End