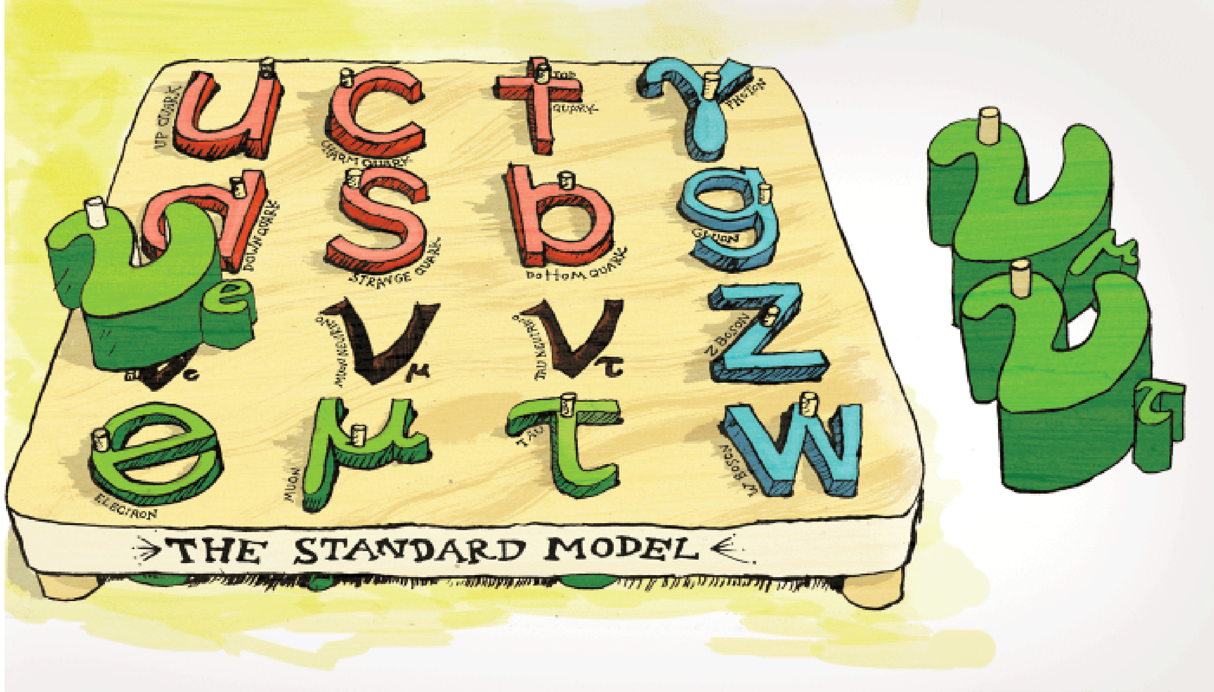
Some Physics with High Energy Neutrinos



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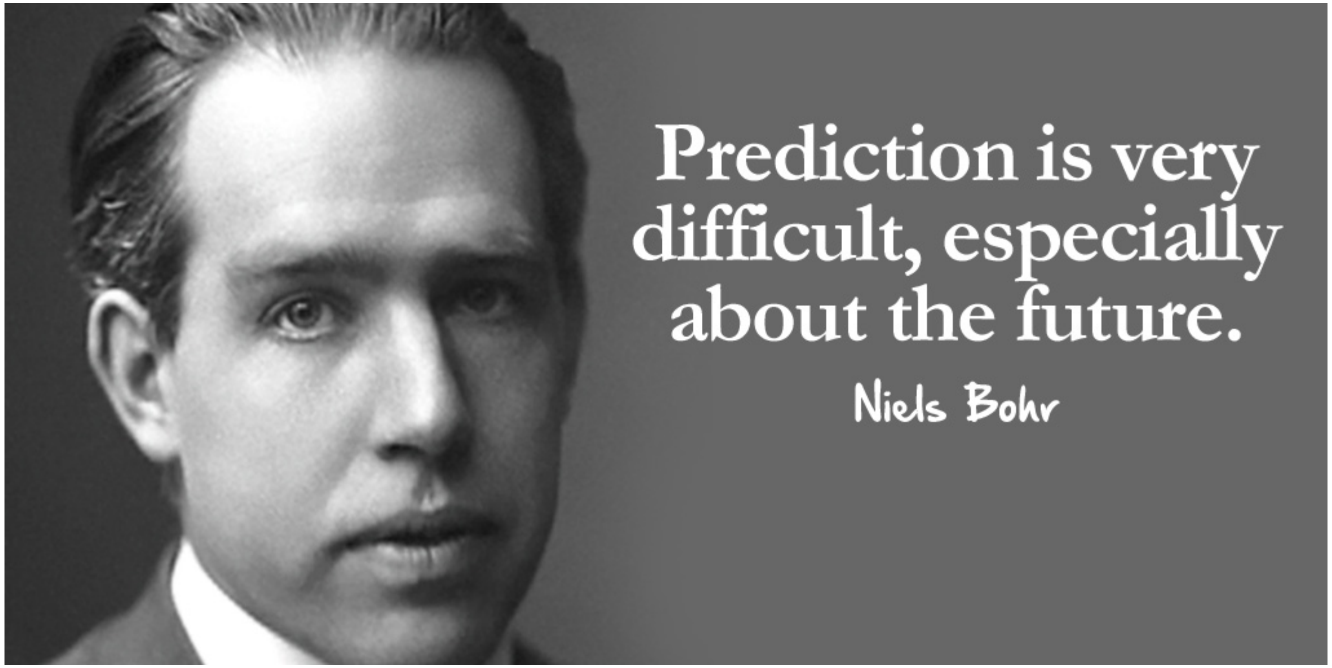
Snowmass Muon Collider Forum– Virtual World

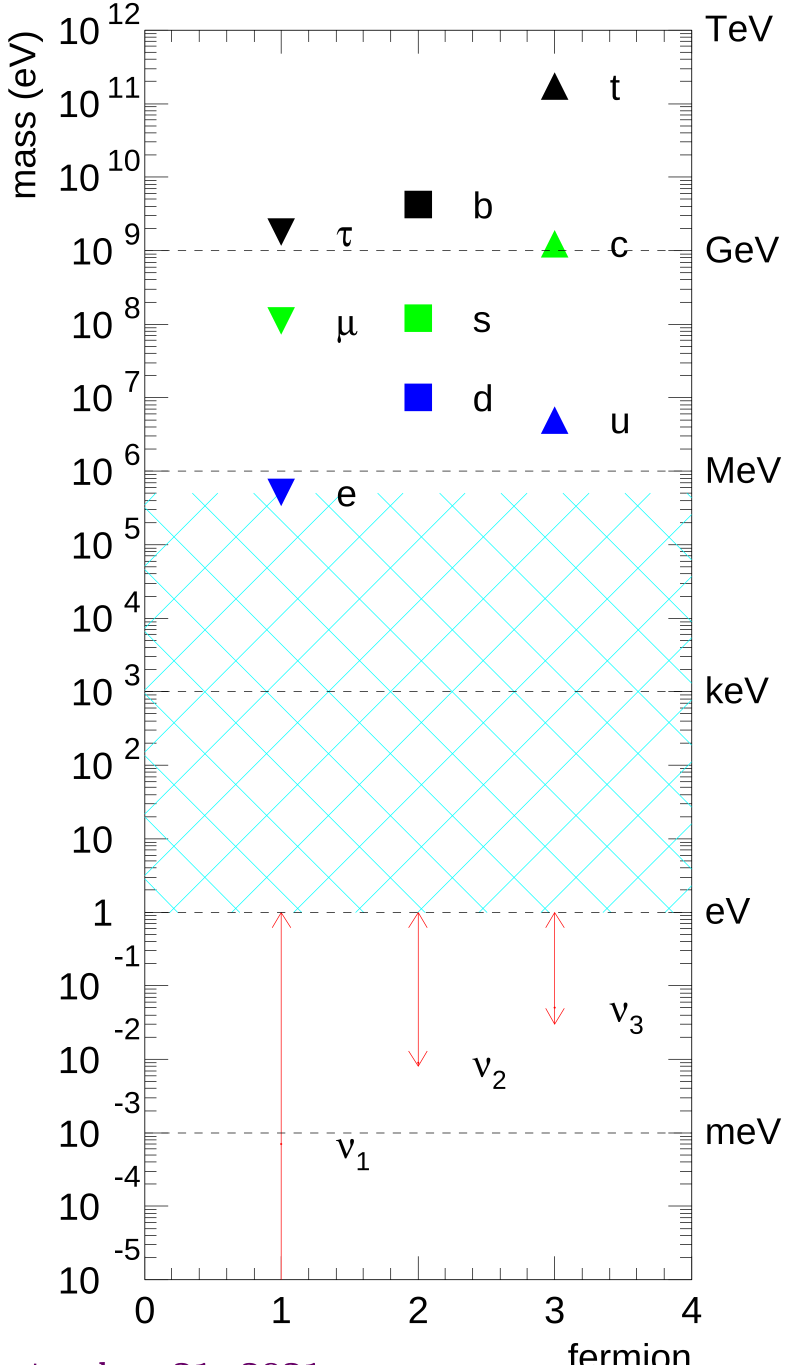
September 21, 2021

WARNING: Use at own risk. The contents of this talk reflect the personal opinions of the author and not those of the experimental or theoretical neutrino communities. Ideas are rather speculative and seriously underdeveloped. The lack of references to detailed studies reflects the author's ignorance and not the absence of those in the literature.



Outline

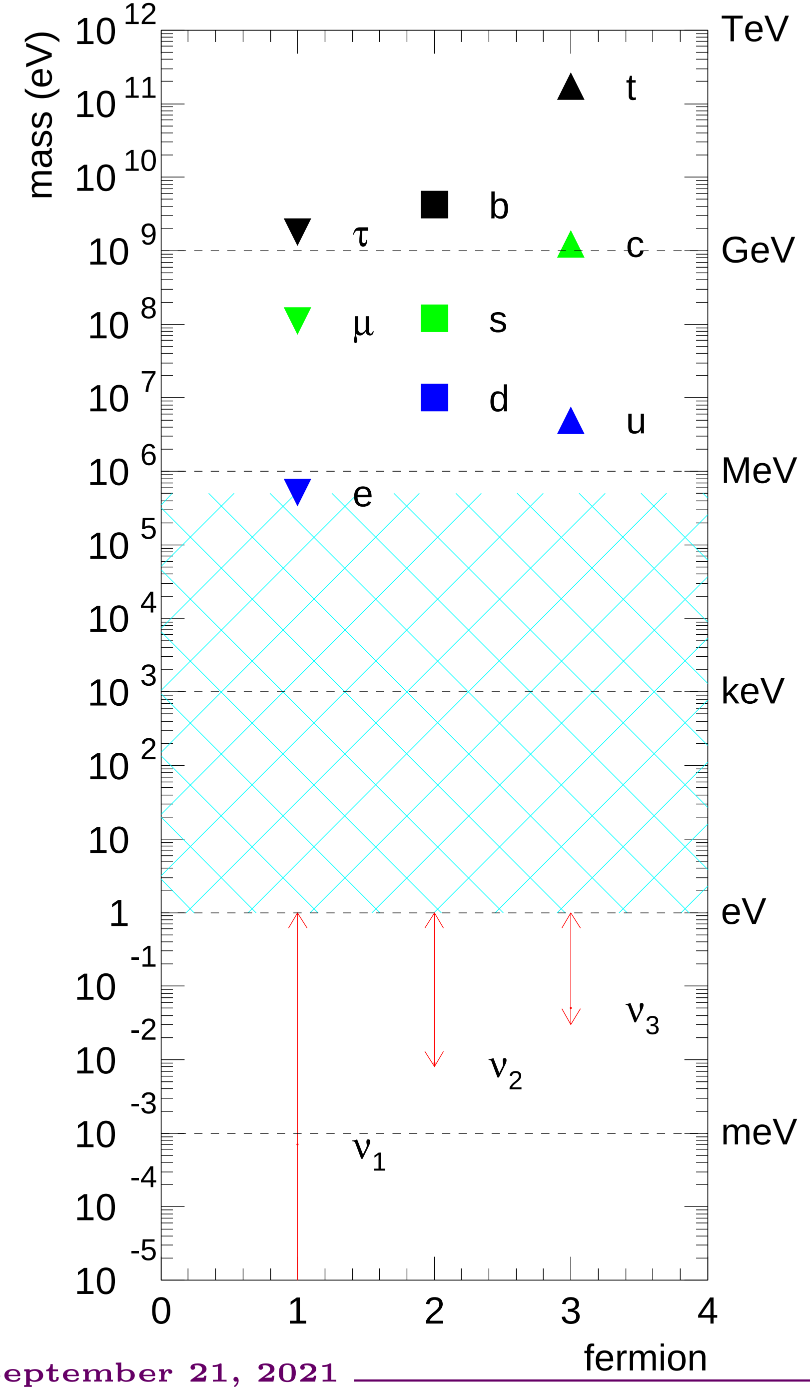
1. The Neutrino Mass Puzzle;
2. A Neutrino-Oscillation Detour on the Way to the Muon Collider?;
3. Your Neutrino-Radiation Problem is Our Neutrino-Beam Solution?;
4. High-Energy Neutrino Scattering?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

⇓

NEW PHYSICS

Nonzero neutrino masses imply the existence of new fundamental fields ⇒ New Particles*

We know nothing about these new particles. They can be bosons or fermions, very light or very heavy, they can be charged or neutral, experimentally accessible or hopelessly out of reach…

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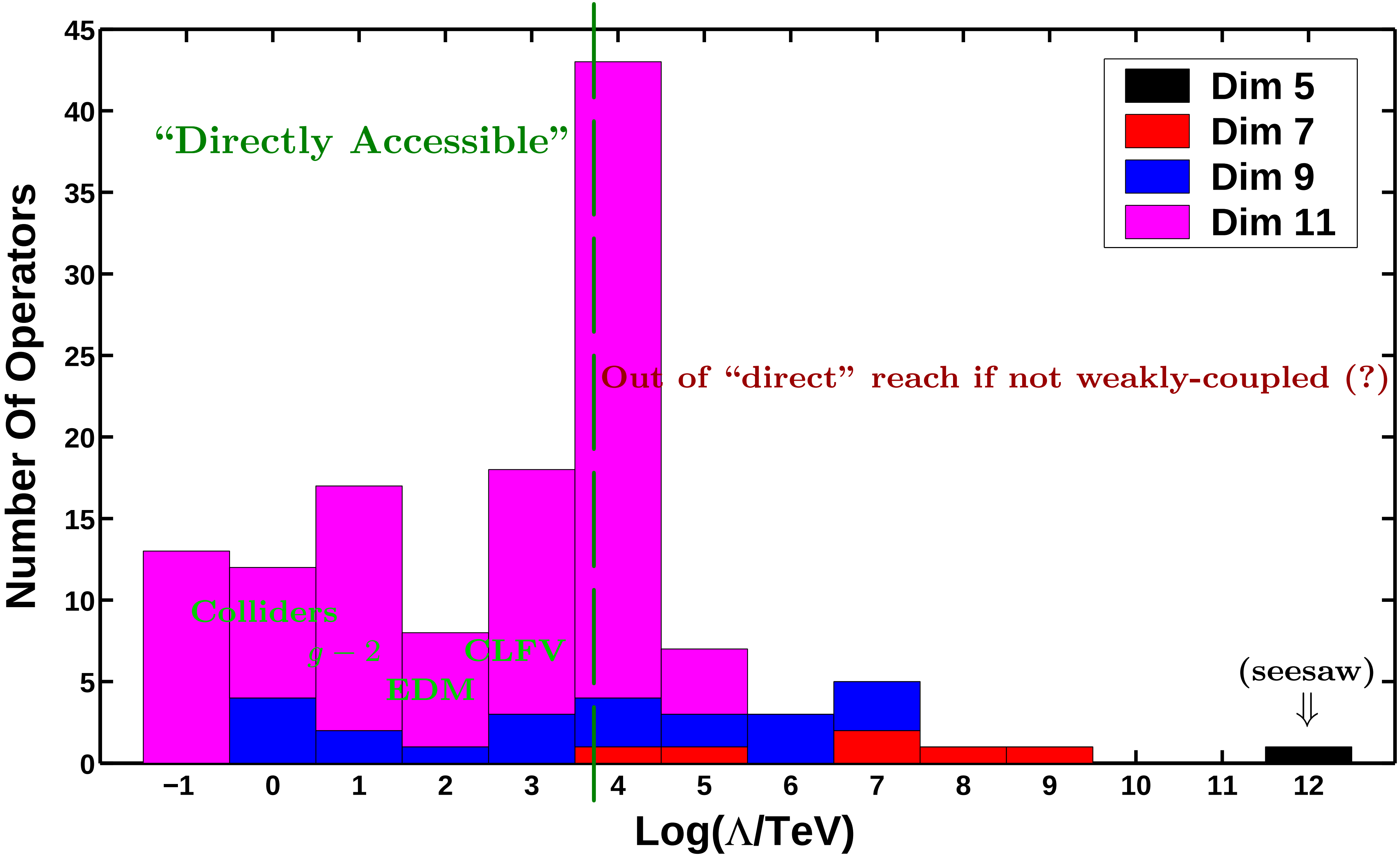
*There is only a handful of questions our model for fundamental physics cannot explain (these are personal. Feel free to complain).

- What is the physics behind electroweak symmetry breaking? (Higgs ✓).
- What is the dark matter? (not in SM).
- Why is there so much ordinary matter in the Universe? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM).

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts ...

- Uncover the nature of neutrinos. Neutrinoless double beta decay! What else?
- A comprehensive long baseline neutrino program. (On-going T2K and NOνA. DUNE and HyperK next steps towards the ultimate "superbeam" experiment.)
- The next-step is to develop a qualitatively better neutrino beam – e.g. muon storage rings (neutrino factories).
- Different baselines and detector technologies a must for both over-constraining the system and looking for new phenomena.
- Probes of neutrino properties, including neutrino scattering experiments.
- Precision measurements of charged-lepton properties ($g-2$, edm) and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- **Collider experiments. Including a Muon Collider, if they discover new particles. [Bonus: muons and neutrinos are cousins]**
- Cosmology: neutrino properties impact the history of the universe.
- ...



Number Of Operators
Log(Λ/TeV)
Dim 5
Dim 7
Dim 9
Dim 11
"Directly Accessible"
Out of "direct" reach if not weakly-coupled (?)
Colliders
g − 2
EDM
CLFV
(seesaw)
0
5
10
15
20
25
30
35
40
45
−1
0
1
2
3
4
5
6
7
8
9
10
11
12

The Muon Path to the Energy Frontier is Intense

If we are ever to build a weak-scale(+) muon collider, we will need to learn how to build, for a finite amount of money, ...

...a multi MW proton source

...muon beams

...muon storage rings

...etc.

The physics case for every one of these components is quite strong in its own right. [IMHO]

Long-Baseline Experiments, Present and Future (Not Exhaustive, Dates Illustrative!)

- [NOW] T2K (Japan), NOνA (USA) – $\nu_\mu \to \nu_e$ appearance, ν_μ disappearance – precision measurements of “atmospheric parameters” $(\Delta m^2_{13}, \sin^2\theta_{23})$. Pursue mass hierarchy via matter effects. Nontrivial tests of paradigm. First step towards CP-invariance violation.

- [$\sim$2022] JUNO (China) – $\bar{\nu}_e$ disappearance – precision measurements of “solar parameters” $(\Delta m^2_{12}, \sin^2\theta_{12})$. Pursue the mass hierarchy via precision measurements of oscillations.

- [$\sim$2023] IceCube Gen-2 (South Pole) – atmospheric neutrinos – pursue mass hierarchy via matter effects.

- [$\sim$2028] HyperK (Japan), DUNE (USA) – Second step towards CP-invariance violation. More nontrivial tests of the paradigm. Ultimate “super-beam” experiments.

Neutrino Oscillations After DUNE and HyperK (2040s)

More likely, we are going to need a better beam.

Ideas include:

- Decay-at-rest beams (π, K, nuclei);
- Nucleus-decay-in-flight beams (β-beams);
- Muon-decay-in-flight beams (neutrino factories).

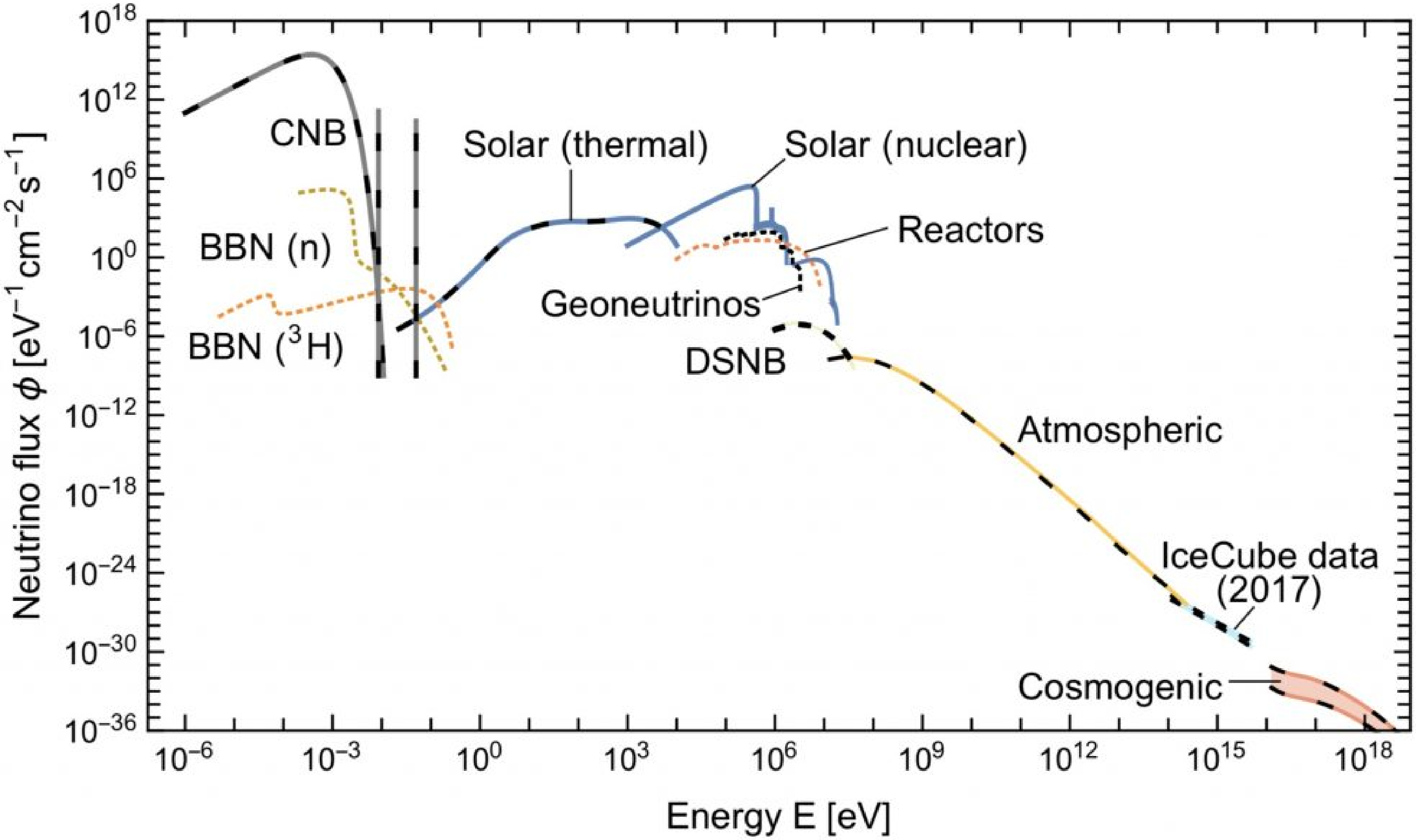
$$\mu^- \to e^- \nu_\mu \bar{\nu}_e \quad \text{and} \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

- Muon energy and charge known very well → neutrino energy spectra known very well and neutrino beams very clean!
- Detectors with charge-ID allow one to kill the beam-background.
- High-energy ν_e and $\bar{\nu}_e$-beams allow for $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ oscillation measurements!
- $$\phi_{\rm osc} \sim 3.6 \left(\frac{\Delta m^2}{3\times 10^{-3}~\text{eV}^2}\right)\left(\frac{L}{10^5~\text{km}}\right)\left(\frac{100\text{GeV}}{E}\right)$$
- We are going to need a bigger planet! Or lower neutrino energies...
- Life could be very different if there were new light neutrino degrees of freedom (e.g., a new mass-squared difference).

Muon-Collider High-Energy Neutrino–Nucleus Scattering

- Neutrino Radiation can be exploited for a high-energy neutrino fixed-target experiment.
- Similar in spirit to FASERν (arXiv:1908.02310) with several advantages:
  - Neutrino energy spectrum very well known;
  - Beam has a well-defined flavor (ν_μ and $\bar{\nu}_e$ or vice-versa);
  - Perhaps very narrow beam. Is this good for something? Perhaps different, better targets and detectors?
  - May be an excellent place to do "short-baseline" oscillations. E.g., ν_τ appearance. Could be a very hot topic.
- Neutrino DIS.

Competition & Cooperation



Nature provides us with her own neutrino beams!

Neutrino Physics at the $\mu^+\mu^-$ Collision Point

- As already mentioned, direct test of neutrino mass models. Neutral heavy leptons, etc.
- How much of a "Neutrino Collider" is a Muon Collider? Any luminosity from the decay-daughter-neutrinos to collide? $\nu_\mu + \bar{\nu}_\mu$, and $\nu_\mu + \nu_e$ collisions. Would be amazingly cool, is it semi-realistic once luminosities and backgrounds are taken into account?
- Perhaps more realistic (?), there is the possibility to study $\mu^+ + \nu_\mu$ collisions from W^+ radiation off the muon beam and $\nu_\mu + \bar{\nu}_\mu$ from double $W^+ + W^-$ radiation (i.e., $\mu^+ + \mu^- \to W^+ + W^- + (\nu_\mu + \bar{\nu}_\mu)$).
- While we are at it, it is interesting to think about a $\mu^+ + \mu^+$ collider ($L = 2$ initial state). The LHC already has a $B = 2$ collision, how hard can it be? Unique (?) ability to search for lepton-number violation (e.g. $\mu^+ + \mu^+ \to W^+ + W^+$) unrelated to electrons.

What Could We Learn About?

- Neutrino–neutrino interactions;
- Neutrino interactions with a Dark Sector (LH-portal);
- New channels to look for lepton-number violation. E.g. Type-II Seesaw (Higgs triplet $T = (t^{+}+, t^{+}, t^{0})$, $\mu^{+}\mu^{+} \rightarrow t^{++} \rightarrow W^{+}W^{+}$);
- Many more interesting things I haven't thought about. There is a lot of work to do.

New neutrino self-interactions, quick example

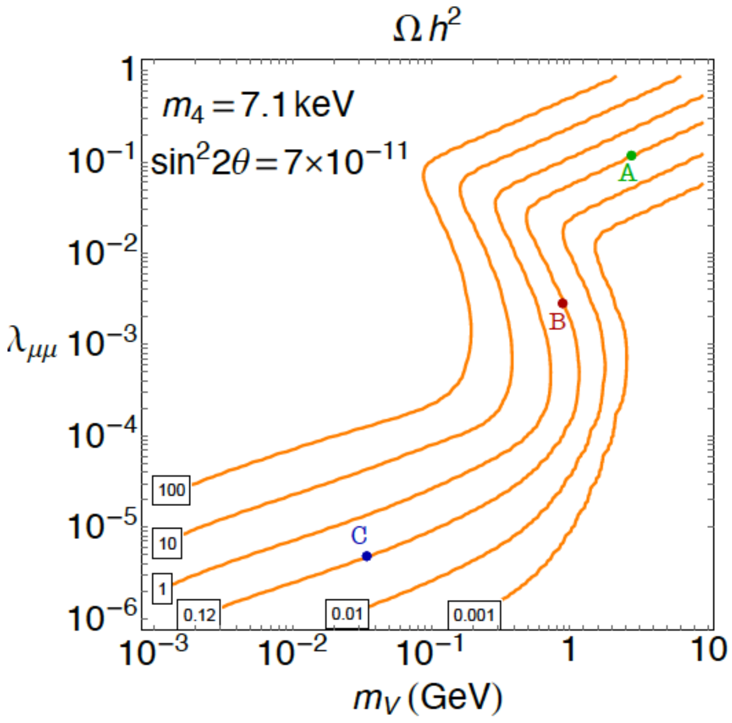


FIG. 4. Contours of Ωh^2 for $m_4 = 7.1\,\text{keV}$, $\sin^2 2\theta = 7 \times 10^{-11}$, showing regions of over and under-abundance. The values of the relic density are labeled on the contours. Three benchmark points on the contour corresponding to the observed relic density are chosen: A ($\lambda_{\mu\mu} = 0.11$, $m_V = 2.77\,\text{GeV}$), B ($\lambda_{\mu\mu} = 0.003$, $m_V = 0.88\,\text{GeV}$) and C ($\lambda_{\mu\mu} = 4.8 \times 10^{-6}$, $m_V = 0.03\,\text{GeV}$).

[K.J. Kelly et al, arXiv:2005.03681]

$\mathcal{L} \supset \lambda_{\mu\mu}\bar{\nu}_\mu\gamma_\alpha\nu_\mu V^\alpha$ [neutrinophilic Z'], sterile neutrinos are dark matter.

Conclusions

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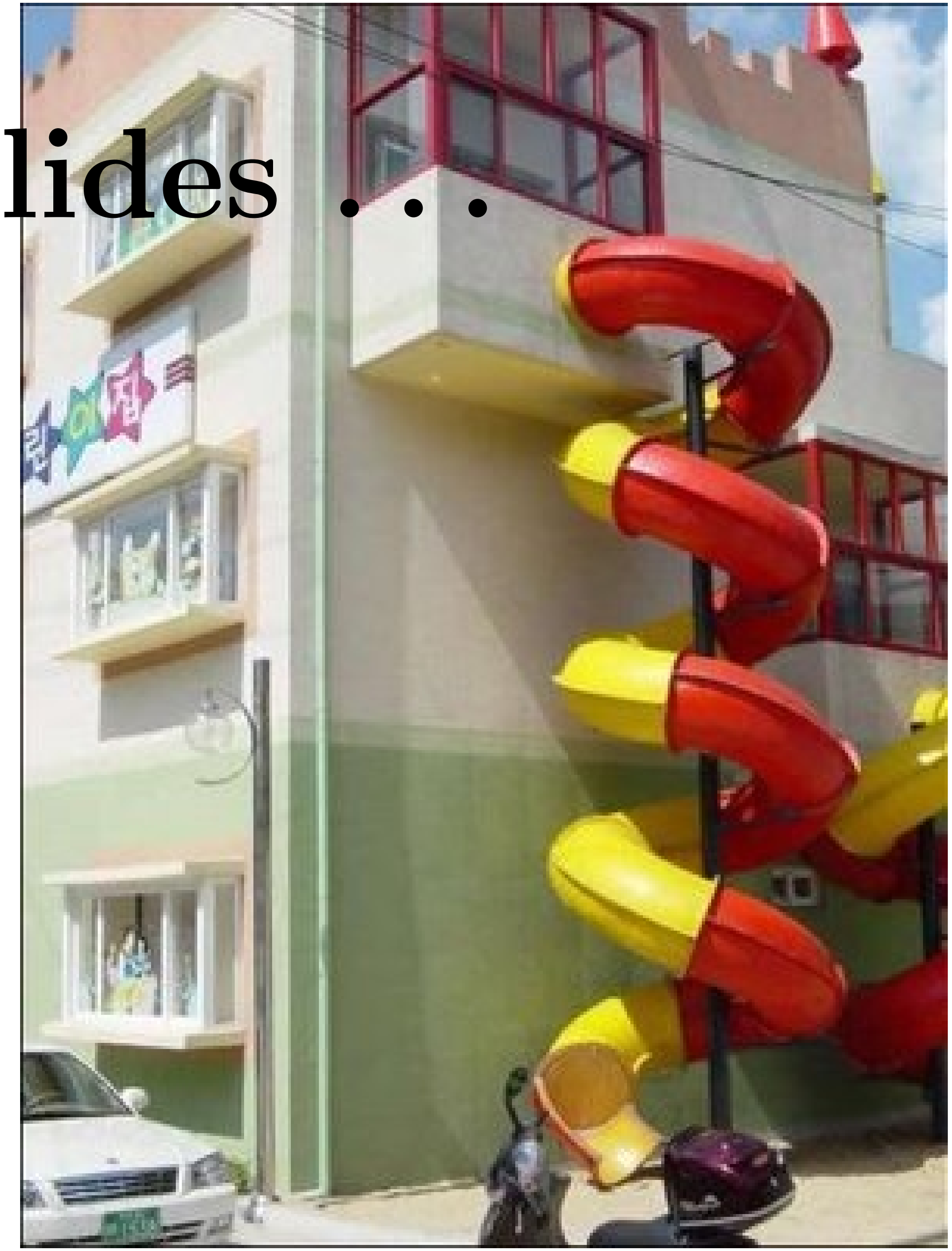
Backup Slides . . .



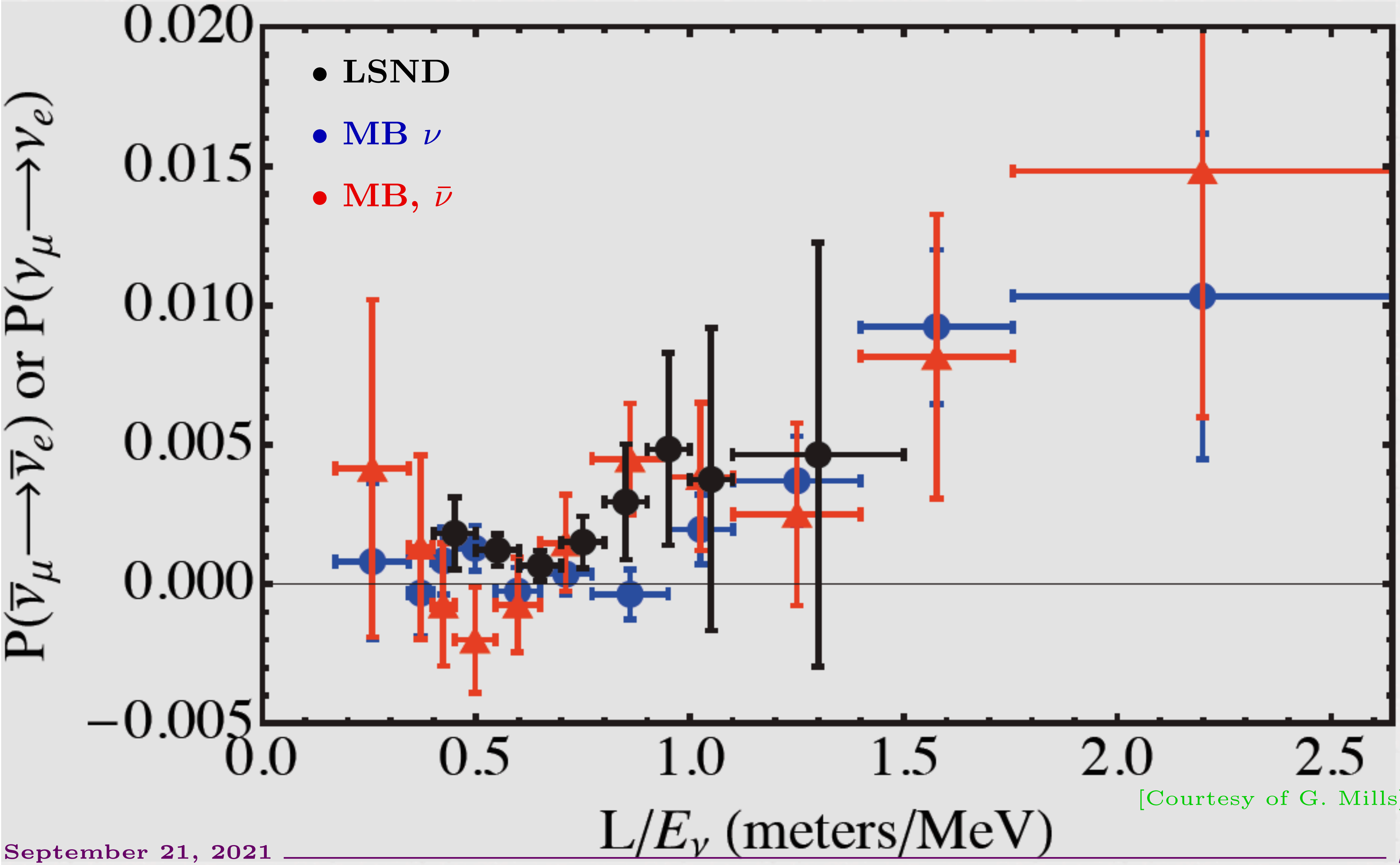
Not all is well(?): The Short Baseline Anomalies

Different data sets, sensitive to L/E values small enough that the known oscillation frequencies do not have "time" to operate, point to unexpected neutrino behavior. These include

- $\nu_\mu \to \nu_e$ appearance — LSND, MiniBooNE;
- $\nu_e \to \nu_{\rm other}$ disappearance — radioactive sources;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ disappearance — reactor experiments.

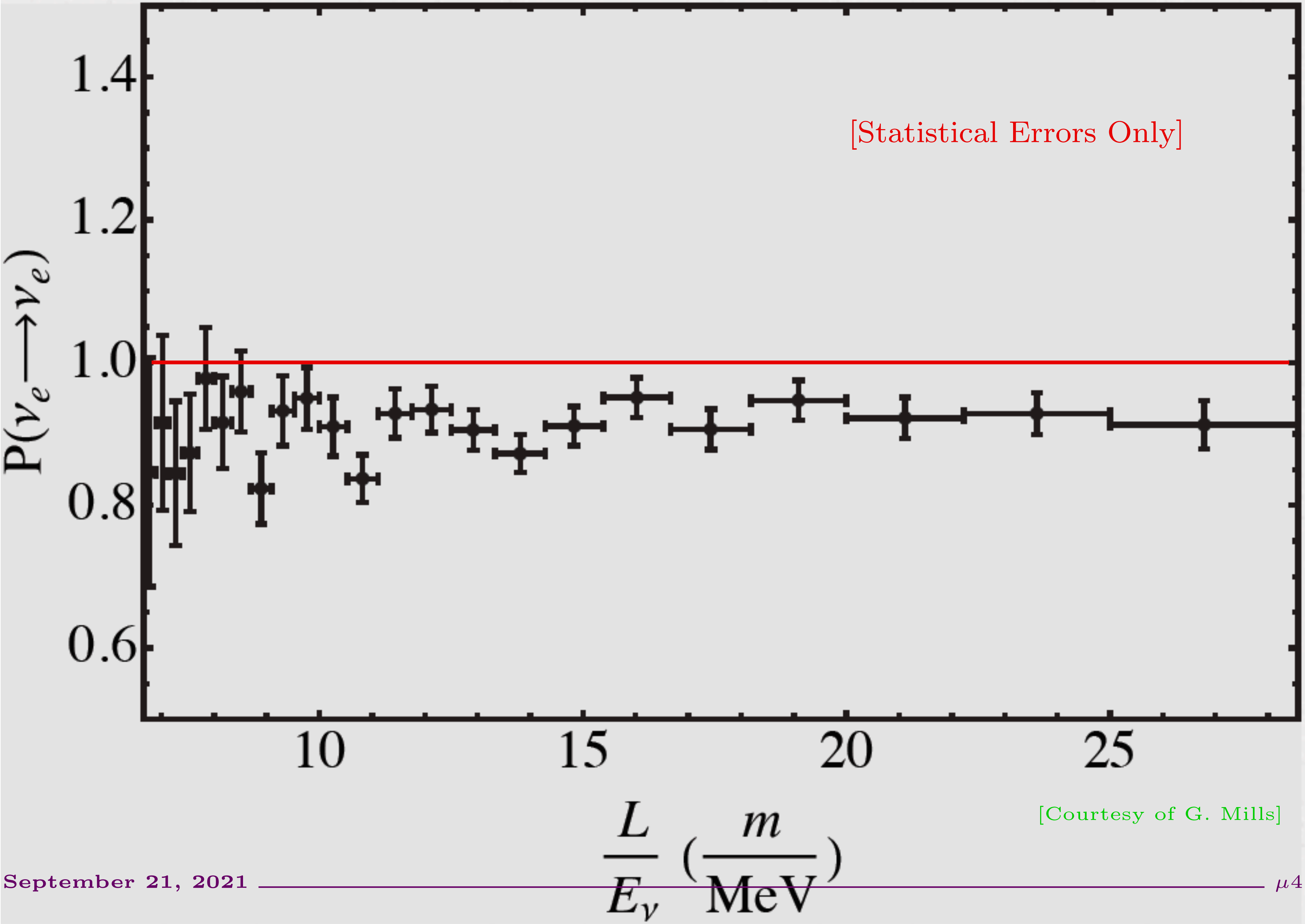
None are entirely convincing, either individually or combined. However, there may be something very very interesting going on here…

MiniBooNE & LSND

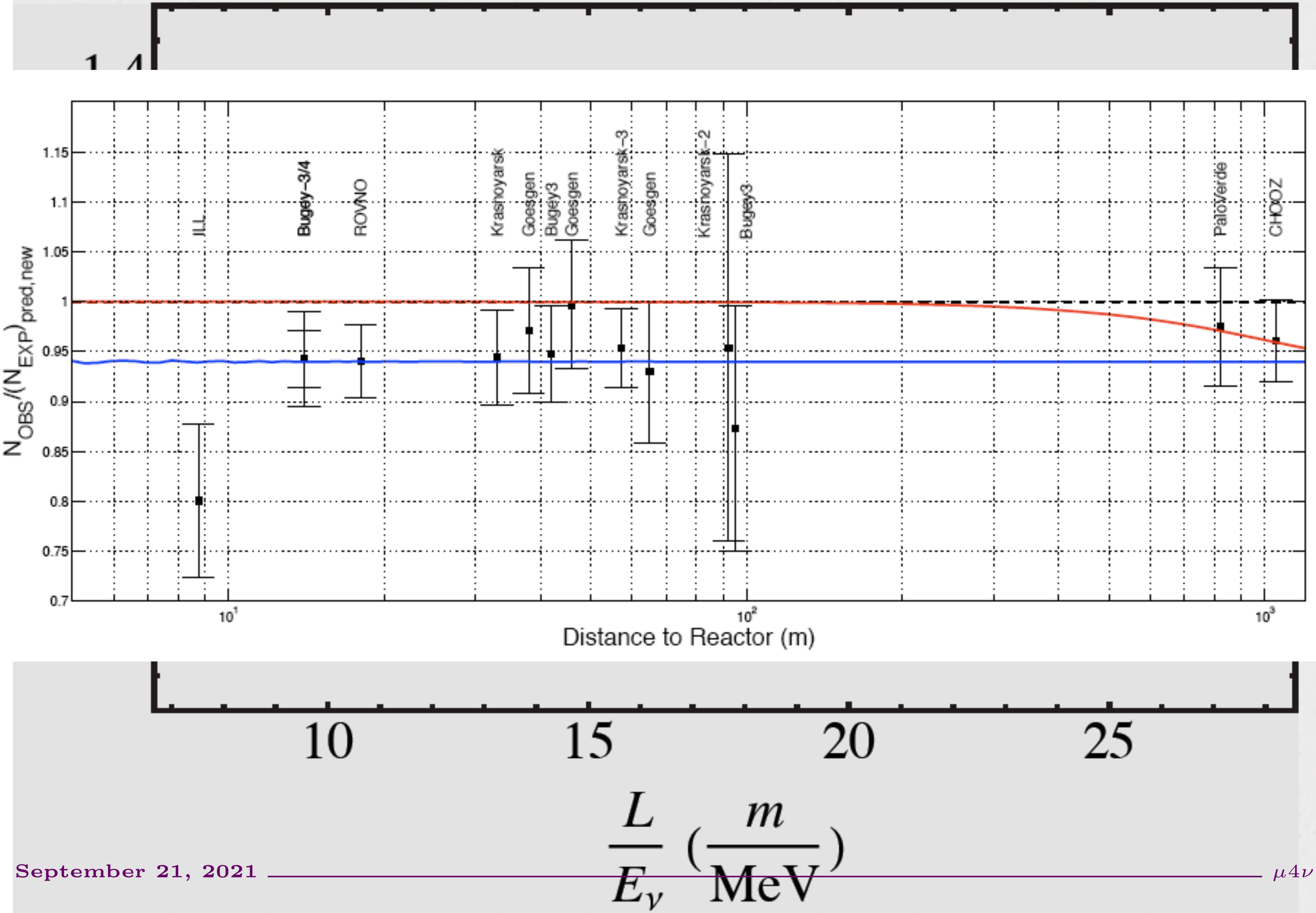


[Courtesy of G. Mills]

Bugey 40 m


[Statistical Errors Only]
$P(\nu_e \longrightarrow \nu_e)$
1.4
1.2
1.0
0.8
0.6
10
15
20
25
$\frac{L}{E_\nu}\ (\frac{m}{\mathrm{MeV}})$
[Courtesy of G. Mills]

Bugey 40 m



ILL
Bugey-3/4
ROVNO
Krasnoyarsk
Goesgen
Bugey3
Goesgen
Krasnoyarsk-3
Goesgen
Krasnoyarsk-2
Bugey3
PaloVerde
CHOOZ
$N_{OBS}/(N_{EXP})_{pred,new}$
1.15
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
10^1
10^2
10^3
Distance to Reactor (m)
10
15
20
25
$\frac{L}{E_\nu}\ (\frac{m}{\mathrm{MeV}})$

What is Going on Here?

- Are these "anomalies" related?
- Is this neutrino oscillations, other new physics, or something else?
- Are these related to the origin of neutrino masses and lepton mixing?
- How do clear this up **definitively**?

Need new clever experiments, of the short-baseline type!

Observable wish list:

- ν_μ disappearance (and antineutrino);
- ν_e disappearance (and antineutrino);
- $\nu_\mu \leftrightarrow \nu_e$ appearance;
- $\nu_{\mu,e} \to \nu_\tau$ appearance.

High-energy seesaw has no other observable consequences, except, perhaps, ...

Baryogenesis via Leptogenesis

One of the most basic questions we are allowed to ask (with any real hope of getting an answer) is whether the observed baryon asymmetry of the Universe can be obtained from a baryon–antibaryon symmetric initial condition plus well understood dynamics. [Baryogenesis]

This isn't just for aesthetic reasons. If the early Universe undergoes a period of inflation, baryogenesis is required, as inflation would wipe out any pre-existing baryon asymmetry.

It turns out that massive neutrinos can help solve this puzzle!

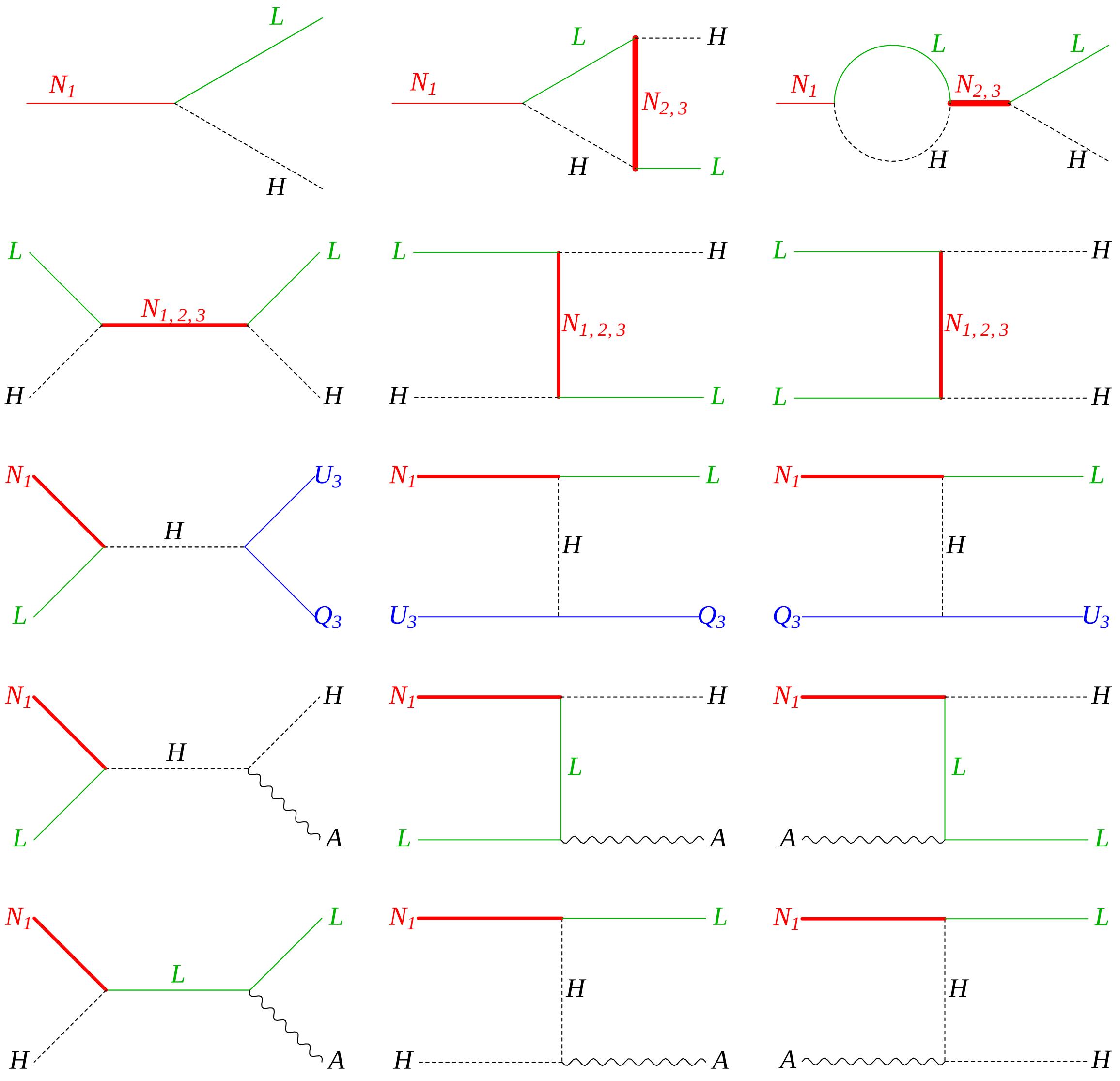
In the old SM, (electroweak) baryogenesis does not work – not enough CP-invariance violation, Higgs boson too light.

Neutrinos help by providing all the necessary ingredients for successful baryogenesis via leptogenesis.

- Violation of lepton number, which later on is transformed into baryon number by nonperturbative, finite temperature electroweak effects (in one version of the νSM, lepton number is broken at a high energy scale M).
- Violation of C-invariance and CP-invariance (weak interactions, plus new CP-odd phases).
- Deviation from thermal equilibrium (depending on the strength of the relevant interactions).

E.g. – thermal, seesaw leptogenesis, $\boxed{\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.}$

[Fukugita, Yanagida]

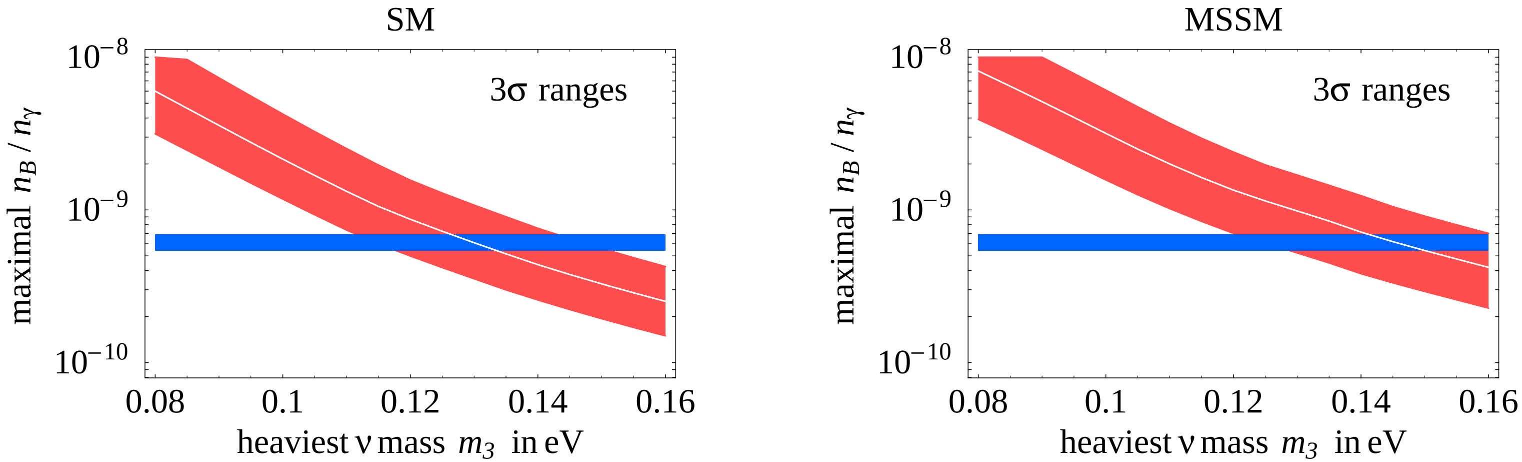


- L-violating processes
- $y \Rightarrow$ CP-violation
- deviation from thermal eq. constrains combinations of M_N and y.
- need to yield correct m_ν

not trivial!

[G. Giudice *et al*, hep-ph/0310123]

E.g. – thermal, seesaw leptogenesis, $\boxed{\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.}$



[G. Giudice *et al*, hep-ph/0310123]

It did not have to work – but it does

MSSM picture does not quite work – gravitino problem

(there are ways around it, of course...)

Relationship to Low Energy Observables?

In general ... no. This is very easy to understand. The baryon asymmetry depends on the (high energy) physics responsible for lepton-number violation. Neutrino masses are a (small) consequence of this physics, albeit the only observable one at the low-energy experiments we can perform nowadays.

see-saw: y, M_N have more physical parameters than $m_\nu = y^{\rm t} M_N^{-1} y$.

There could be a relationship, but it requires that we know more about the high energy Lagrangian (model depent). The day will come when we have enough evidence to refute leptogenesis (or strongly suspect that it is correct) - but more information of the kind I mentioned earlier is really necessary (charged-lepton flavor violation, collider data on EWSB, lepton-number violation, etc).