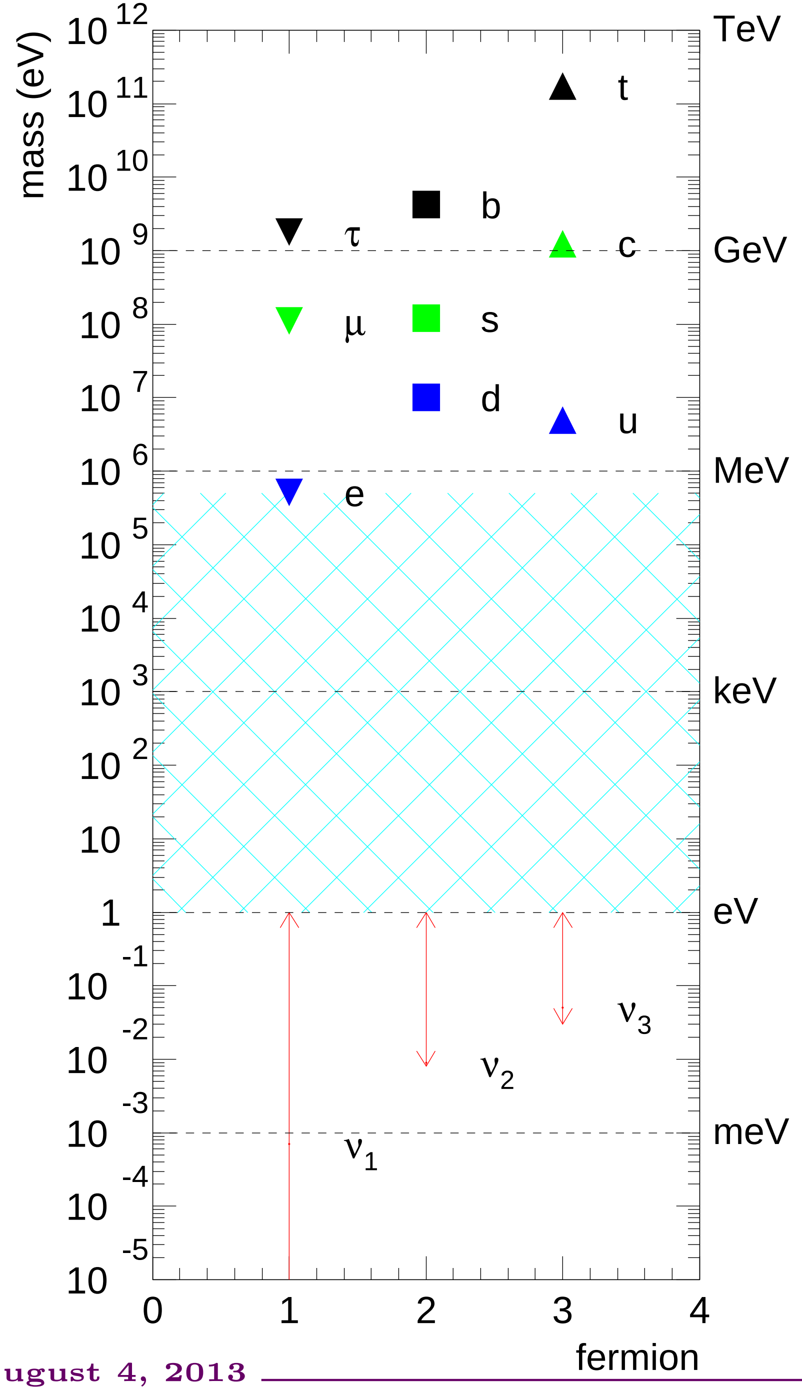
"Neutrino" Theory: Some Opportunities and Challenges

- Neutrino physics is a rapidly evolving subfield of particle physics. There are lots of data, the physics questions are compelling and challenging.
- Neutrino physics "sits" at the intersecion of particle and nuclear physics, astrophysics, and cosmology. Interdisciplinary, requires a combination of several different theoretical tools.
- Here I will briefly discuss some examples and discuss some of the challenges, concentrating to the US-based community.



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

$\Downarrow$

NEW PHYSICS

Neutrino Masses, EWSB, and a New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

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 . . .

- understanding the fate of lepton-number. Neutrinoless double beta decay!
- A comprehensive long baseline neutrino program. LBNE underground is necessary first step 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. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- Neutrino properties affect, in a significant way, the history of the universe (Cosmology). Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?

Global fits, data interpretation, connection to fundamental questions

- No single observation alone can answer all questions
- Some important measurements could take a long time to come
- Each experiment will do the best job at analyzing their own data
- Crucial to consider all data as it comes and check for consistency
  - ► well defined frameworks and global fits necessary and important
  - ► difficult, time consuming task:

    many types of observables, different types of uncertainties,

    non-trivial statistical treatment, non-trivial correlations,

    non-trivial parameter degeneracies
- Use results to optimize next steps and better phrase questions of interest
- Find potential inconsistencies hiding new physics!

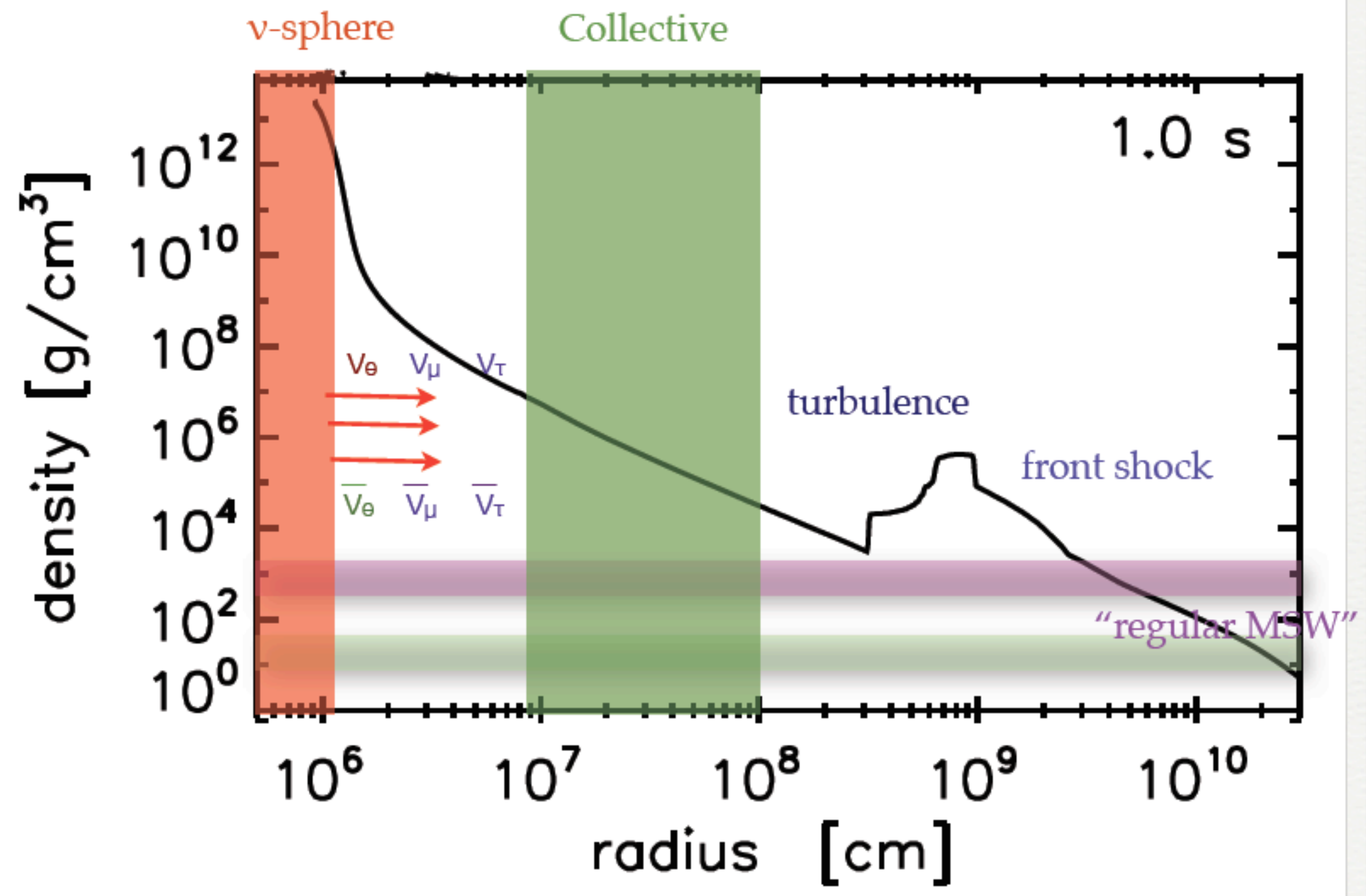
Present effort: in US 0 to ½ FTE

a few groups in Europe

SN neutrino oscillations

- By far the richest oscillation problem known to mankind
  - two MSW transitions
  - time-varying spectra and matter profile
  - evolution in the turbulent background -- effect of stochastic fluctuations
  - streaming neutrinos are so dense, they enter each other's oscillation Hamiltonian
    - this neutrino "self-refraction" leads to collective effects, a novel many-body phenomenon

SN ν oscillations: physics cartoon



Urgent questions right now

- What are the signature that could be imprinted on the neutrino spectra?
  - How to read the signal
- What detector characteristics are necessary?
  - Energy resolution, size, depth, threshold, etc
- Connect detector modeling to primary physics effects
  - From numerical calculations of collective oscillations to LArsoft

Understanding Neutrino Scattering On Nuclei

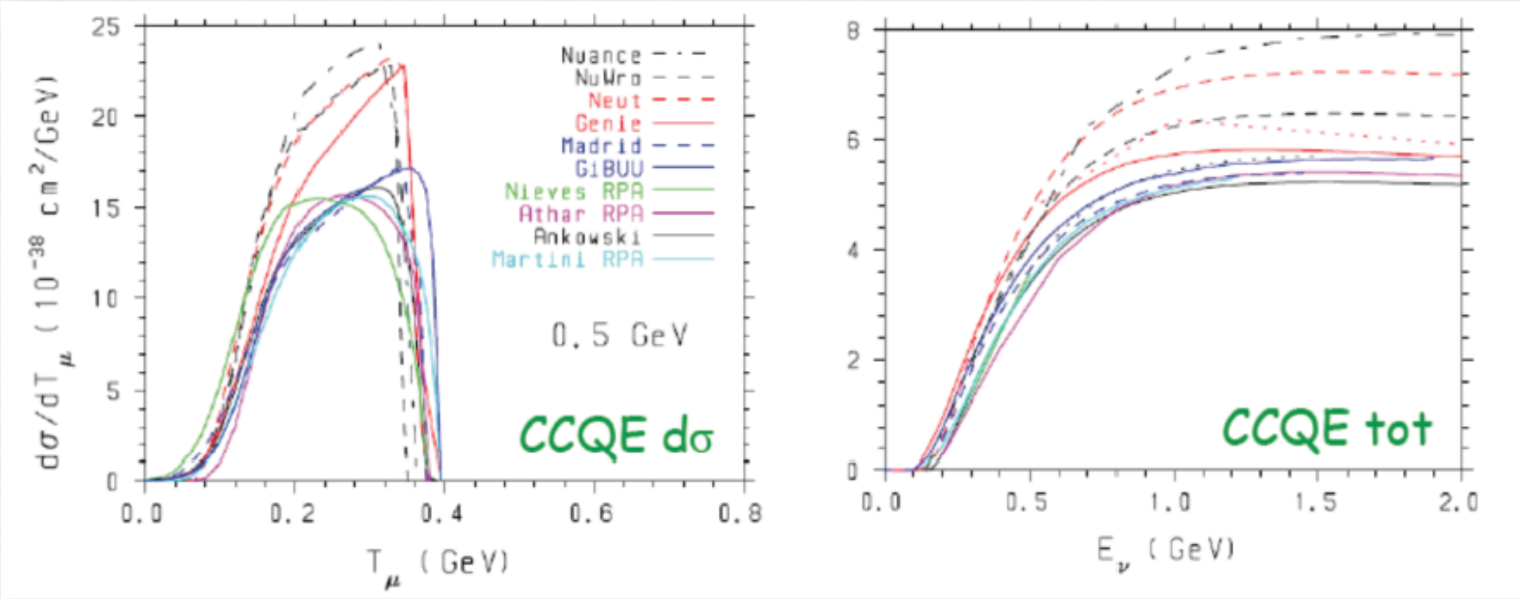
- Neutrino-beam experiments are entering the precision era and will attempt to measure the appearance of a new flavor, ν_e, in the beam. They also will attempt to compare results in the neutrino and anti-neutrino channels – flavor effects, neutrino vs antineutrino systematics.

- Neutrino detectors are made of materials like iron, scintillator, argon etc. and NOT out of free nucleons – nuclear effects.

- In experiments employing pion decay as neutrino source, the beam itself is not well characterized in terms of flux, spectrum and flavor composition.

The "theory"

- As far as experiments are concerned the theory of neutrino nucleus interactions is contained in event generators – example QE CC on carbon



Dytman, 2009

- Many generators use wrong physics models (e.g. Fermi-gas) and use (unphysical) tuning of parameters to fit existing data

How would theorists help?

- There is a lot of known and understood x-section theory which currently is not implemented in the generators, e.g. spectral functions
- Large discrepancies in pion production models – reasons not understood
- Argon is a case which basically has not been studied at all
- No studies for neutrino / antineutrino differences exist
- No quantitative studies in terms of impact on oscillation parameters exist
- No studies for LBNE exist

"Non-physics" challenges, and efforts

- The US-based community is very small. Not enough critical mass to attach all of these problems. Same complaint applies, with different degrees of intensity to other topics in particle physics phenomenology (e.g., perturbative QCD, quark and charged-lepton flavor physics, etc).
- On-going efforts: 'Neutrino Theory Task Force', part of the IF Neutrino Subgroup (AdG, Huber, Link, Lunardini, Morfin).
- Neutrino Theory Meeting (AdG, Friedland, Huber, Mocioiu) on May 20 at Fermilab.
- Informal discussion with DOE on June 2 in D.C.
- Informal discussion with NSF (Dienes).
- Working on next steps. Stay tuned!

The European Strategy for Particle Physics, May 30, 2013

- “Theory is a strong driver of particle physics and provides essential input to experiments, [..] from the foundations of the Standard Model to detailed calculations guiding the experimental searches.
- Europe should support a diverse, vibrant theoretical physics programme, ranging from abstract to applied topics, in close collaboration with experiments and extending to neighbouring fields such as astroparticle physics and cosmology. Such support should extend also to high-performance computing and software development.”