Summary of Snowmass 2013

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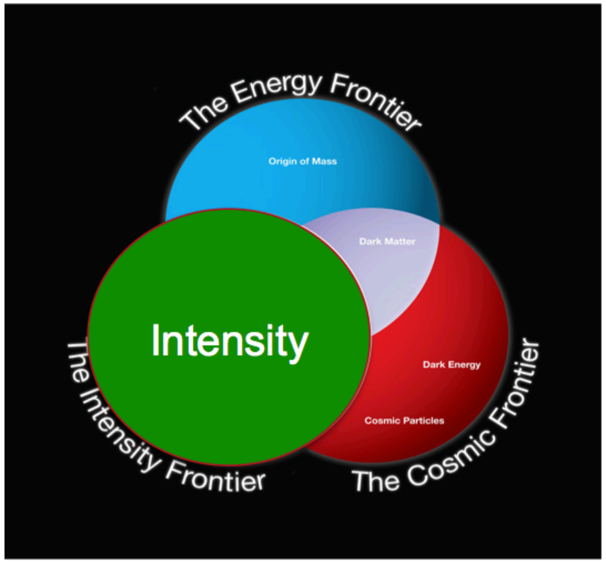
Snowmass 2013 refers to the Community Summer Study, led by the Division of Particles and Fields of the American Physical Society. It took place in the US over the past 10 months or so.

- Kick-off meeting in at Fermilab, October 11–13, 2012.
- 9 day meeting in Minneapolis (July 29 to August 6).
- Lots of small, targeted meetings in between.

'The American Physical Society's Division of Particles and Fields is pursuing a long-term planning exercise for the high-energy physics community. Its goal is to develop the community's long-term physics aspirations. Its narrative will communicate the opportunities for discovery in high-energy physics to the broader scientific community and to the government.'

HEP and the Frontiers

The Frontiers represent experimental approaches

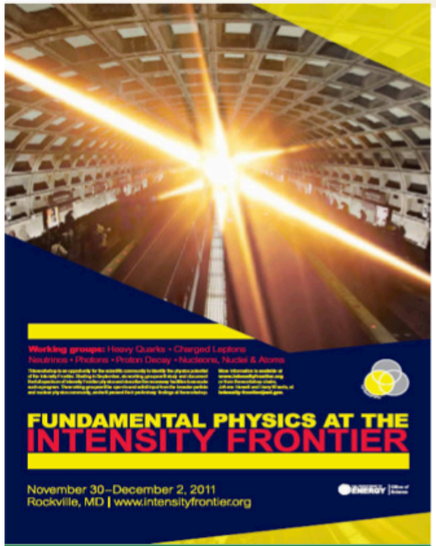


Shows multi-pronged approach to search for new physics

- **Direct Searches**
- **Precision Measurements**
- **Rare and Forbidden Processes**
- **Fundamental Properties of Particles and Interactions**
- **Cosmological observations**

For NuFact: Neutrinos and Charged Leptons are part of the INTENSITY FRONTIER. [Conveners J. Hewett and H. Weerts]

Intensity Frontier Workshop



Fundamental Physics at the Intensity Frontier : Rockville, MD
Nov 30–Dec 2, 2011

Charge:
Document the science opportunities at the Intensity Frontier, Identify experiments and facilities needed for components of program

arXiv:1205.2671
Defines Intensity Frontier
Focus mainly on opportunities for this decade

All–hands Intensity Frontier meeting, Argonne National Lab, April 2013
Numerous subgroup meetings during the last year

Here, only NEUTRINOS (sincere apologies to charged-leptons!) . . .

Subgroup of the Intensity Frontier Working Group for the 2013 Community Summer Study, “Snowmass on the Mississippi” (conveners: André de Gouvêa, Kevin Pitts, Kate Scholberg, Sam Zeller)

Organized into seven subsubgroups:

- Nu1: Neutrino Oscillations and the Three-Flavor Paradigm (Mary Bishai, Karsten Heeger, Patrick Huber);
- Nu2: The Nature of the Neutrino: Majorana vs. Dirac (Steve Elliott, Lisa Kaufman);
- Nu3: Absolute Neutrino Mass (Hamish Robertson, Ben Monreal);
- Nu4: Neutrino Interactions (Jorge Morfin, Rex Tayloe);
- Nu5: Anomalies and New New Physics (Boris Kayser, Jon Link);
- Nu6: Astrophysical and Cosmological Neutrinos (Kara Hoffman, Cecilia Lunardini, Nikolai Tolich);
- Nu7: Neutrinos and Society (José Alonso, Adam Bernstein).

Aside: discussion of status of "neutrino theory"

- The US-based community is very small. Not enough critical mass to attach all of the relevant qestions.
- 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 and NSF
- Working on next steps. Stay tuned!
- Suggestions, recommendations, moral support welcome!

Goals

Describe the research opportunities in Neutrino Physics for this and the coming decade.

This is aimed at the neutrino community, the intensity frontier community, the particle physics community at large, the funding agencies, and, ideally, society as a whole. (We clearly won't achieve this, but it is important to worry about it)

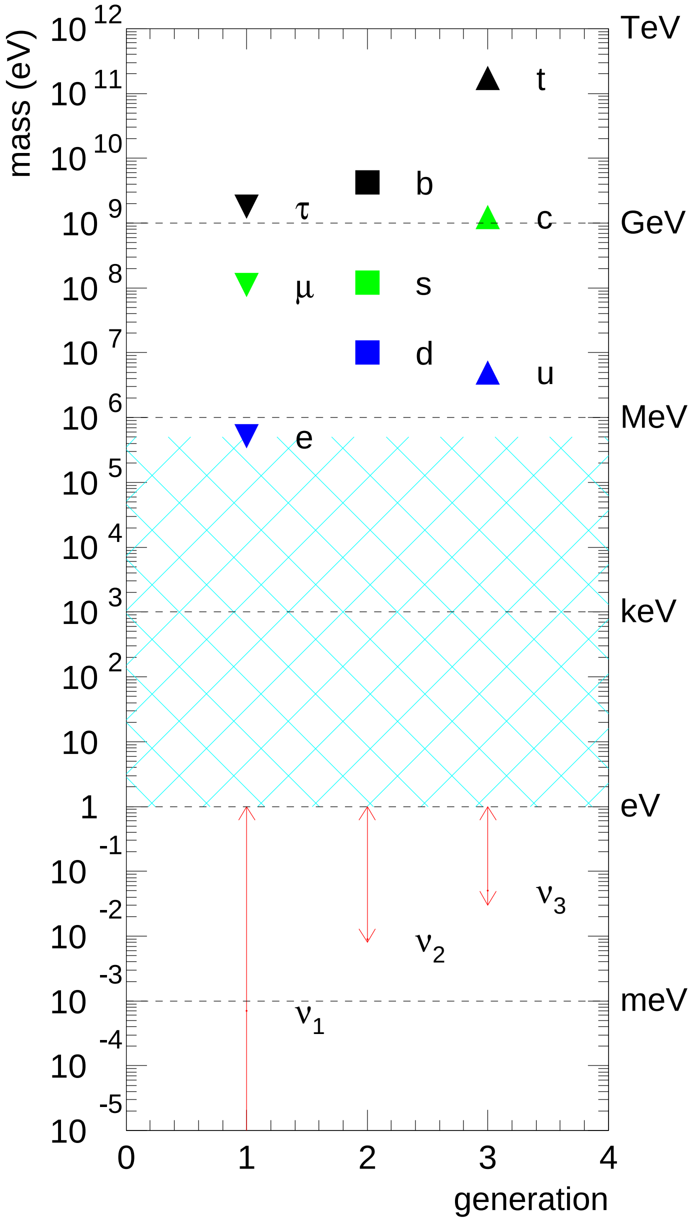
Very important: make the **physics case** for a broad, comprehensive neutrino research program. How does it fit within the Intensity Frontier, and how does it fit in the overall goals of nuclear and particle physics?

Deliverables:

1. 60-page writeup with contributions from all working groups.
2. 6–8-page summary, part of the Intensity Frontier ∼30 page document.

Input:

- Intensity Frontier 2011 Rockville Workshop, and 2012 Intensity Frontier Report,
- 83 one-page white papers received from the community, plus several Snowmass white papers,
- Workshops (SLAC, ANL, Snowmass),
- Comments on drafts of documents. Important in order to, somehow, represent the community.



What We Are Trying To Understand:

⇐ **NEUTRINOS HAVE TINY MASSES**

⇓ **LEPTON MIXING IS "WEIRD"** ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Hence, massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

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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 more matter than antimatter? (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).

CP-Violation in the Lepton Sector – Why Bother?

The SM with massive Majorana neutrinos accommodates **five** irreducible CP-invariance violating phases.

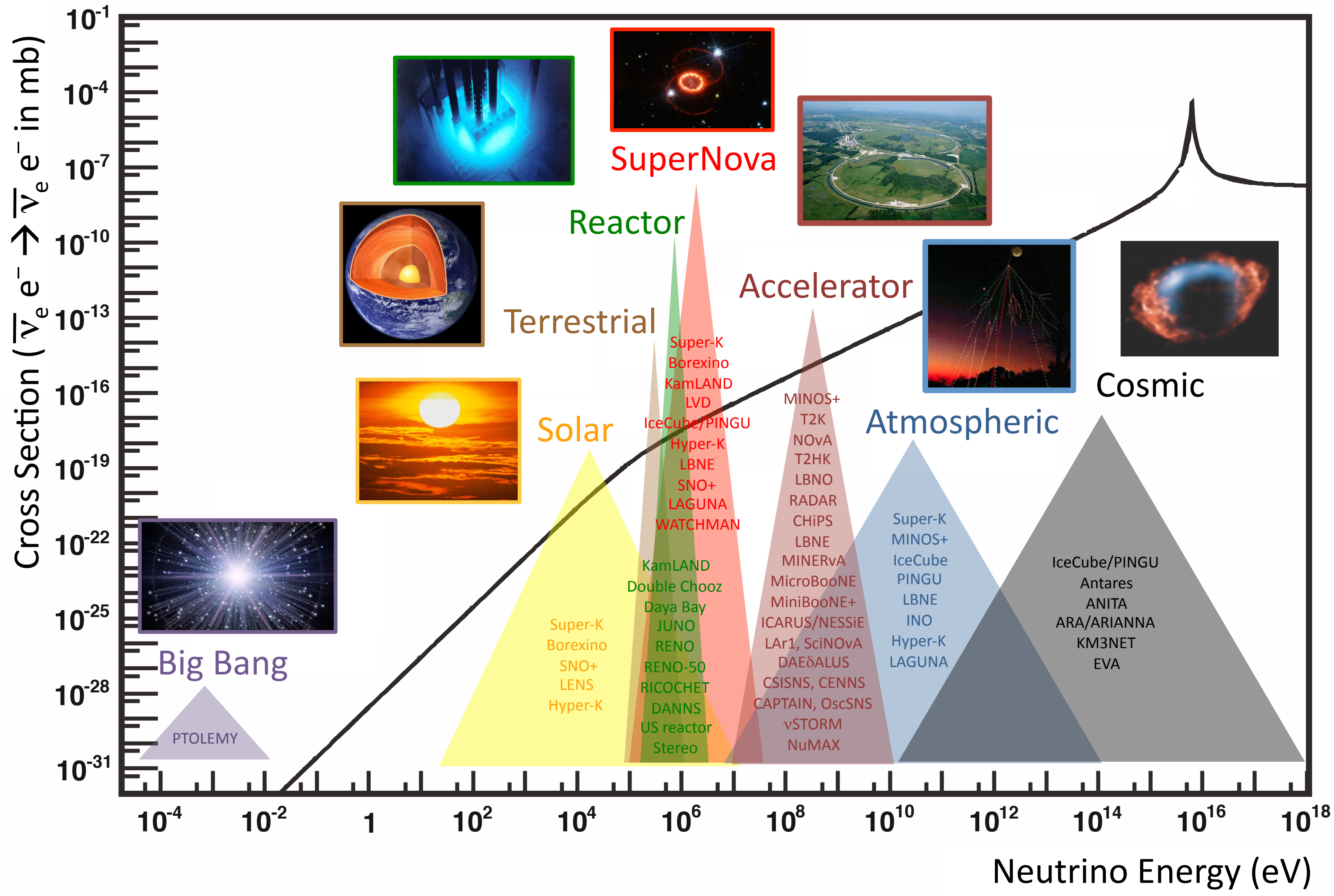
- One is the phase in the CKM phase. We have measured it, it is large, and we don't understand its value. At all.
- One is θ_{QCD} term ($\theta G\tilde{G}$). We don't know its value but t is only constrained to be very small. We don't know why (there are some good ideas, however).
- Three are in the neutrino sector. One can be measured via neutrino oscillations. 50% increase on the amount of information.

We don't know much about CP-invariance violation. Is it really fair to presume that CP-invariance is generically violated in the neutrino sector solely based on the fact that it is violated in the quark sector? Why? Cautionary tale: "Mixing angles are small"

And that is not all!... a somewhat personal list

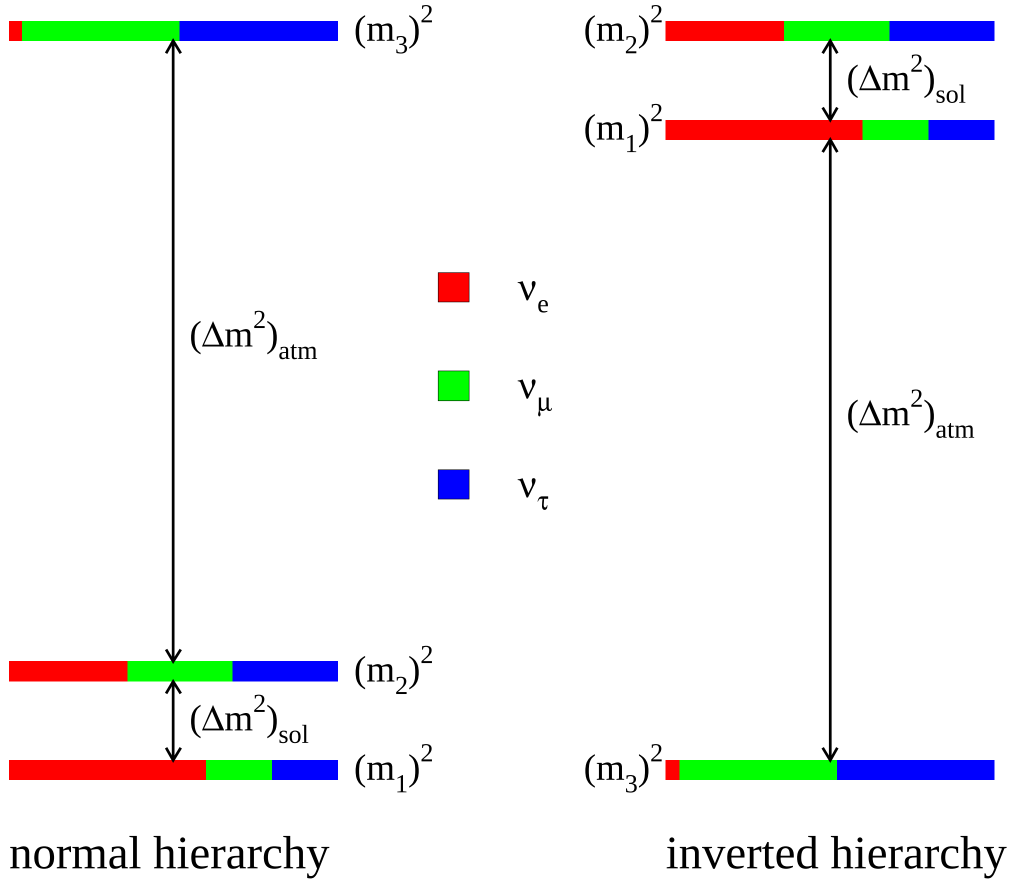
Neutrinos are unique probes of several different physics phenomena from vastly different scales, including...

- Dark Matter;
- Weak Interactions;
- Nucleons;
- Nuclei;
- the Earth;
- the Sun;
- Supernova explosions;
- The Origin of Ultra-High Energy Cosmic Rays;
- The Universe.



Opportunities for SMALL, MEDIUM, and LARGE efforts. Broad, healthy program!

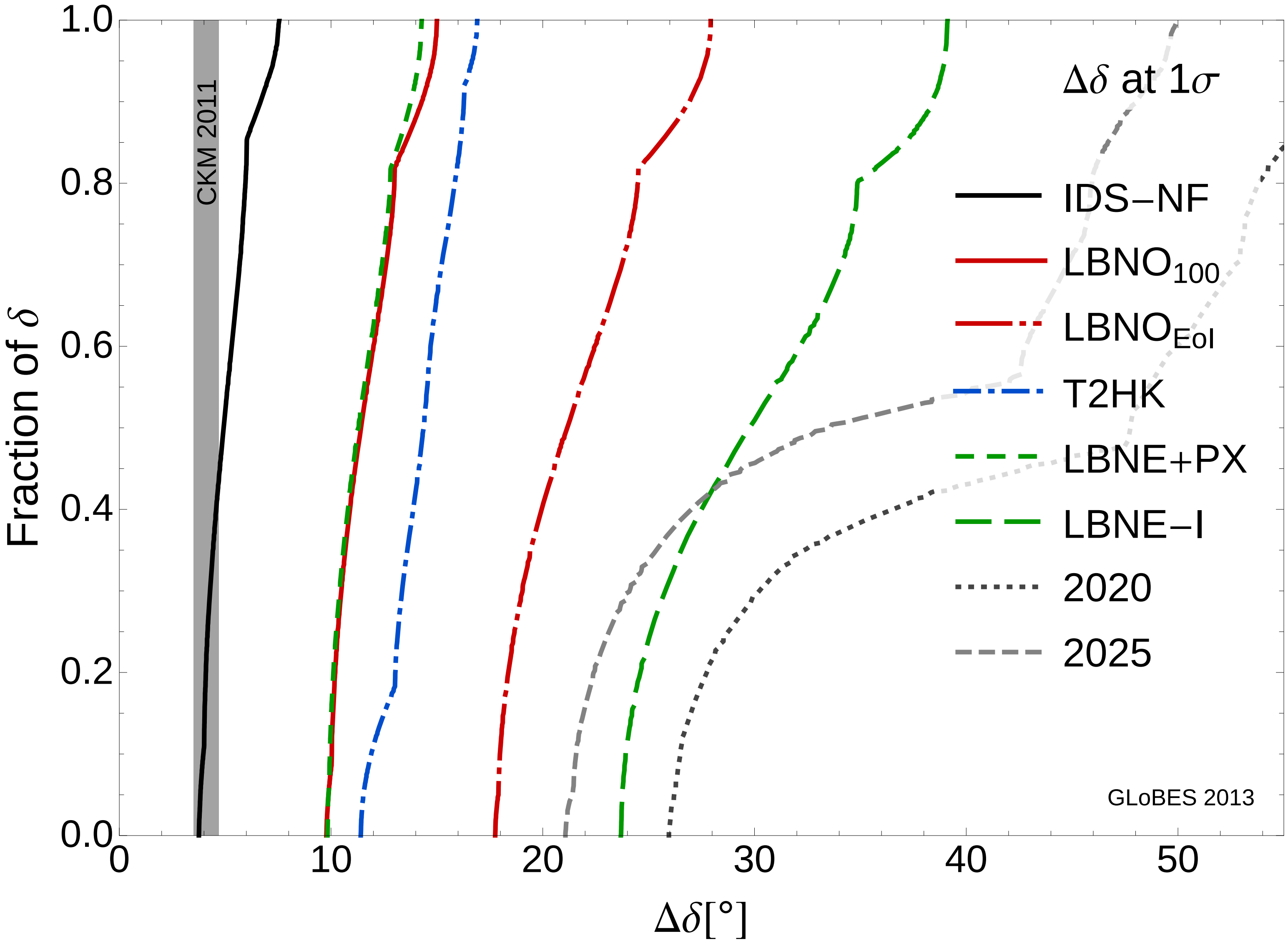
Nu1: TESTING THE 3-FLAVOR PARADIGM + SM INTERACTIONS



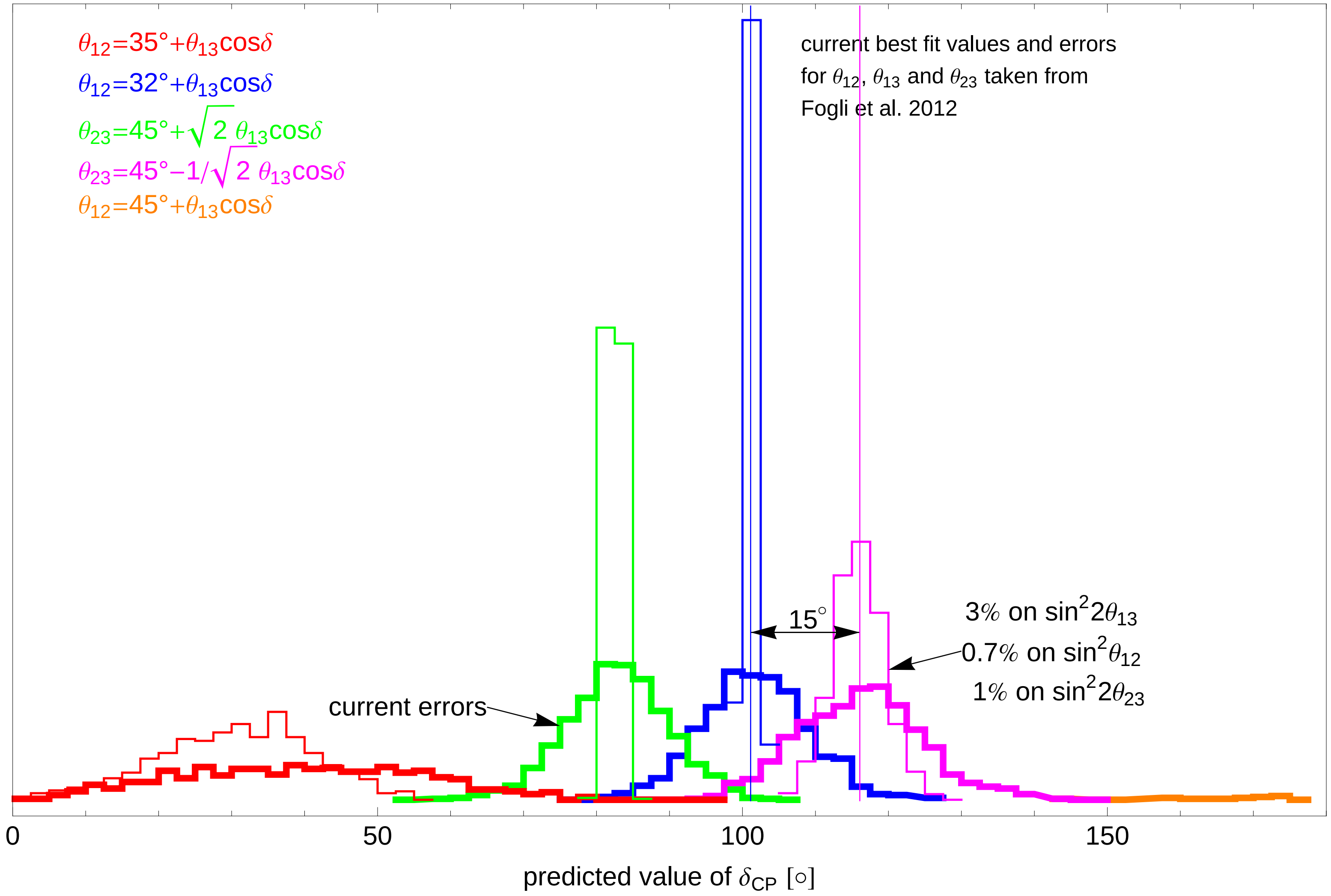
- ~~What is the ν_e component of ν_3?~~ ($\theta_{13} \neq 0$!)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

$\Rightarrow$ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)


Δδ at 1σ
IDS−NF
LBNO100
LBNOEoI
T2HK
LBNE+PX
LBNE−I
2020
2025
CKM 2011
GLoBES 2013
Fraction of δ
Δδ[°]
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40
50

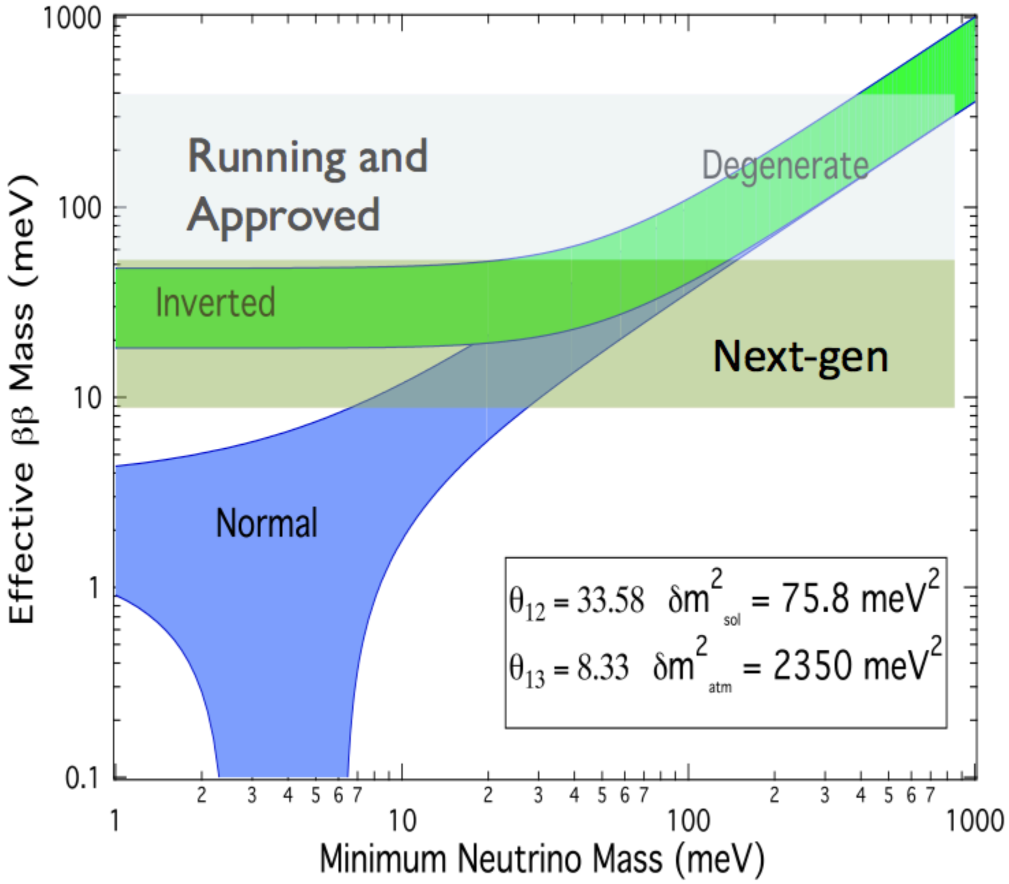
[Nu1]



θ12=35°+θ13cosδ
θ12=32°+θ13cosδ
θ23=45°+√2 θ13cosδ
θ23=45°−1/√2 θ13cosδ
θ12=45°+θ13cosδ
current best fit values and errors
for θ12, θ13 and θ23 taken from
Fogli et al. 2012
15°
3% on sin²2θ13
0.7% on sin²θ12
1% on sin²2θ23
current errors
0
50
100
150
predicted value of δCP [○]

[Nu1]

Goals for Next-Generation $0\nu\beta\beta$

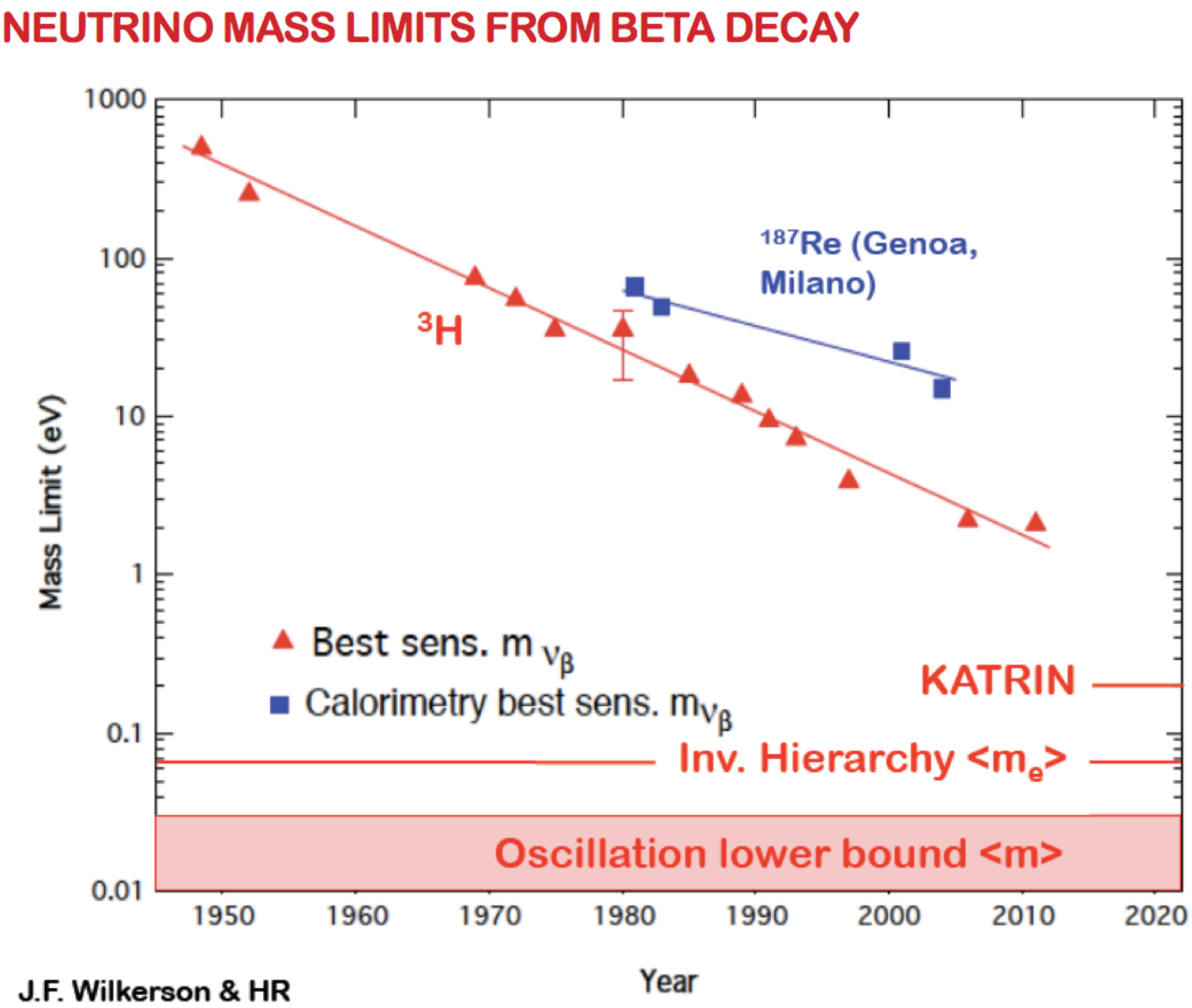


- Majorana vs Dirac
- Absolute Neutrino Mass
- Lepton Number Violation

- Next-generation $\beta\beta$ experiments must cover the entire allowed region of the inverted hierarchy

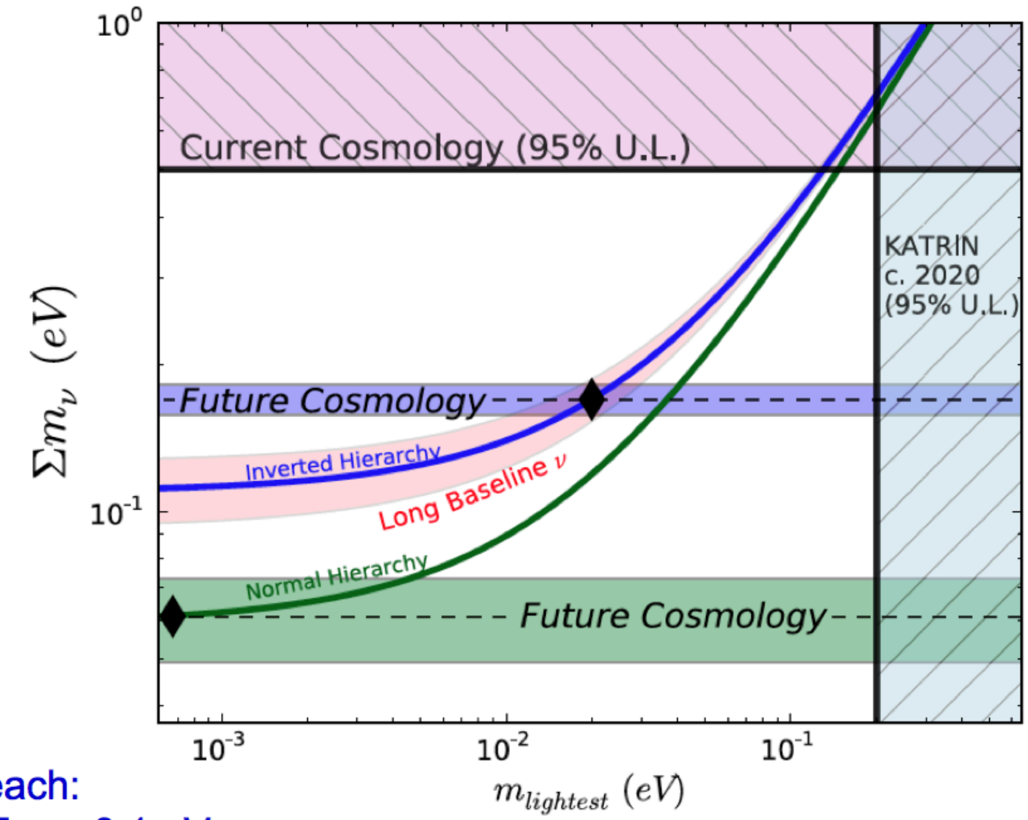
- Ideas for probing the normal hierarchy exist

[L.J. Kaufman, Nu2]



[H. Robertson, Nu3]

Neutrinos and Cosmology



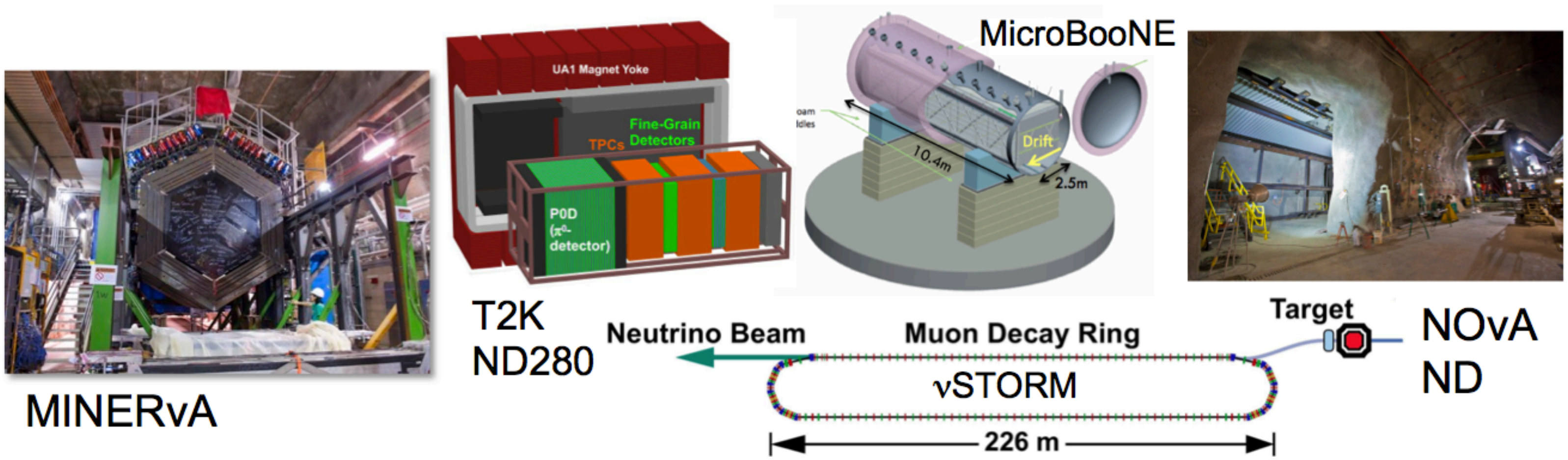
Projected Reach:
2013-2016: Σm_ν ~0.1 eV
2016-2020: Σm_ν ~ 0.06 eV
2020-2025: Σm_ν ~ 16 meV

(S. Dodelson, Wednesday session)
See talk by S. Ritz

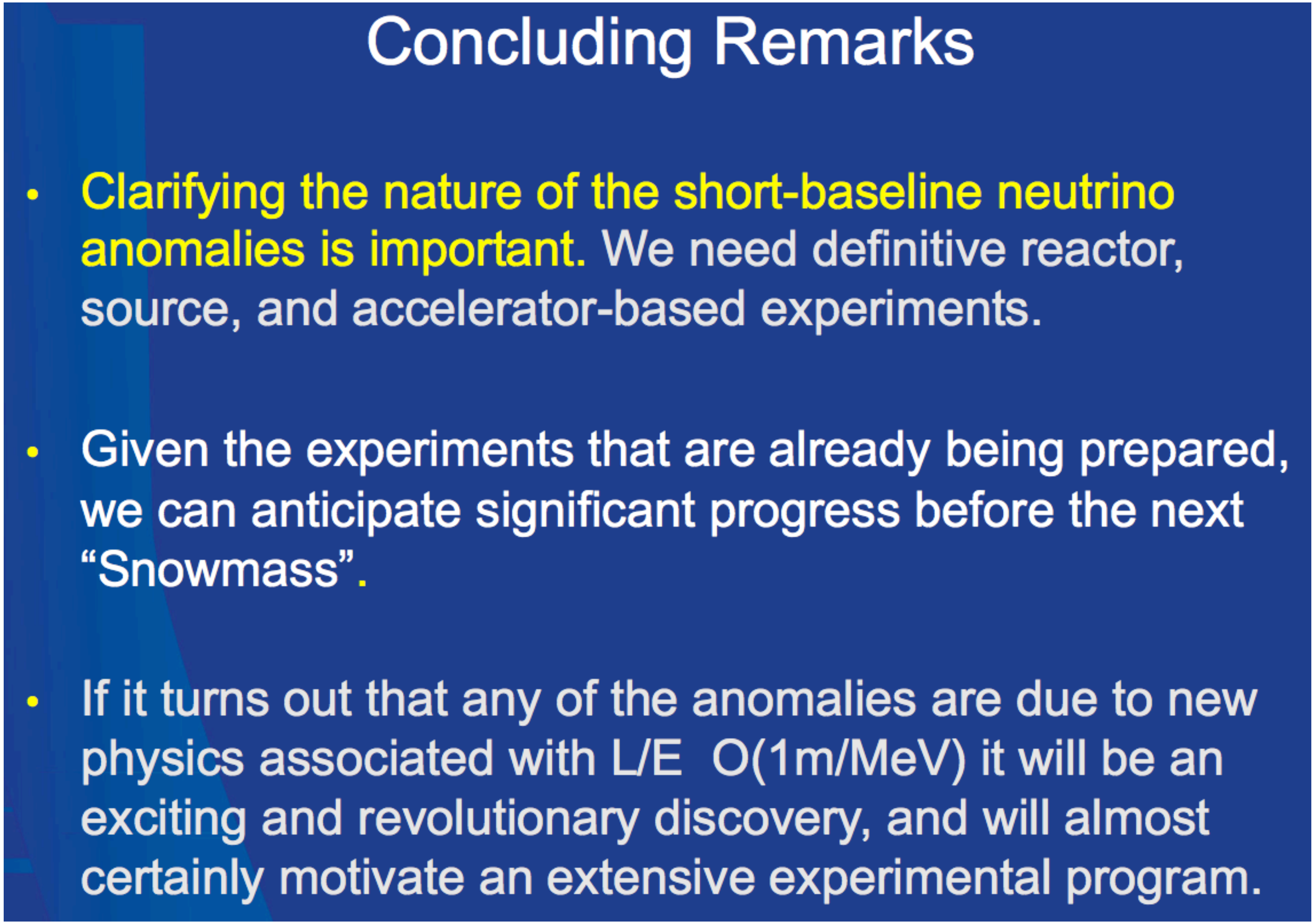
[Nu3/Nu6]

Study of Neutrino Interactions

- We need to fully characterize neutrino-matter interactions to enable deeper understanding of ν oscillations, supernova dynamics, and dark matter searches. Studies of ν interactions in themselves also serve as standard model tests and as important probes of nuclear structure.
- These activities can be pursued in "near detectors" associated with large long-baseline projects or alongside R&D projects related to next-next generation neutrino beams.



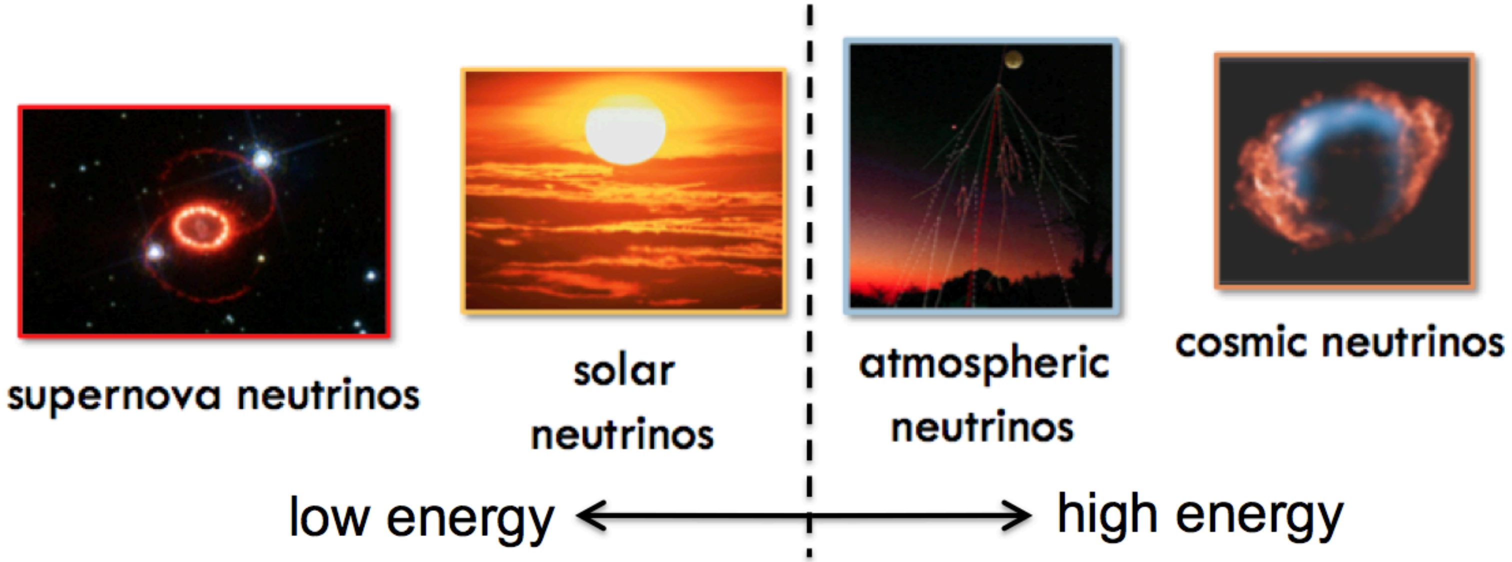
[Nu4]


Concluding Remarks
• Clarifying the nature of the short-baseline neutrino anomalies is important. We need definitive reactor, source, and accelerator-based experiments.
• Given the experiments that are already being prepared, we can anticipate significant progress before the next “Snowmass”.
• If it turns out that any of the anomalies are due to new physics associated with L/E O(1m/MeV) it will be an exciting and revolutionary discovery, and will almost certainly motivate an extensive experimental program.

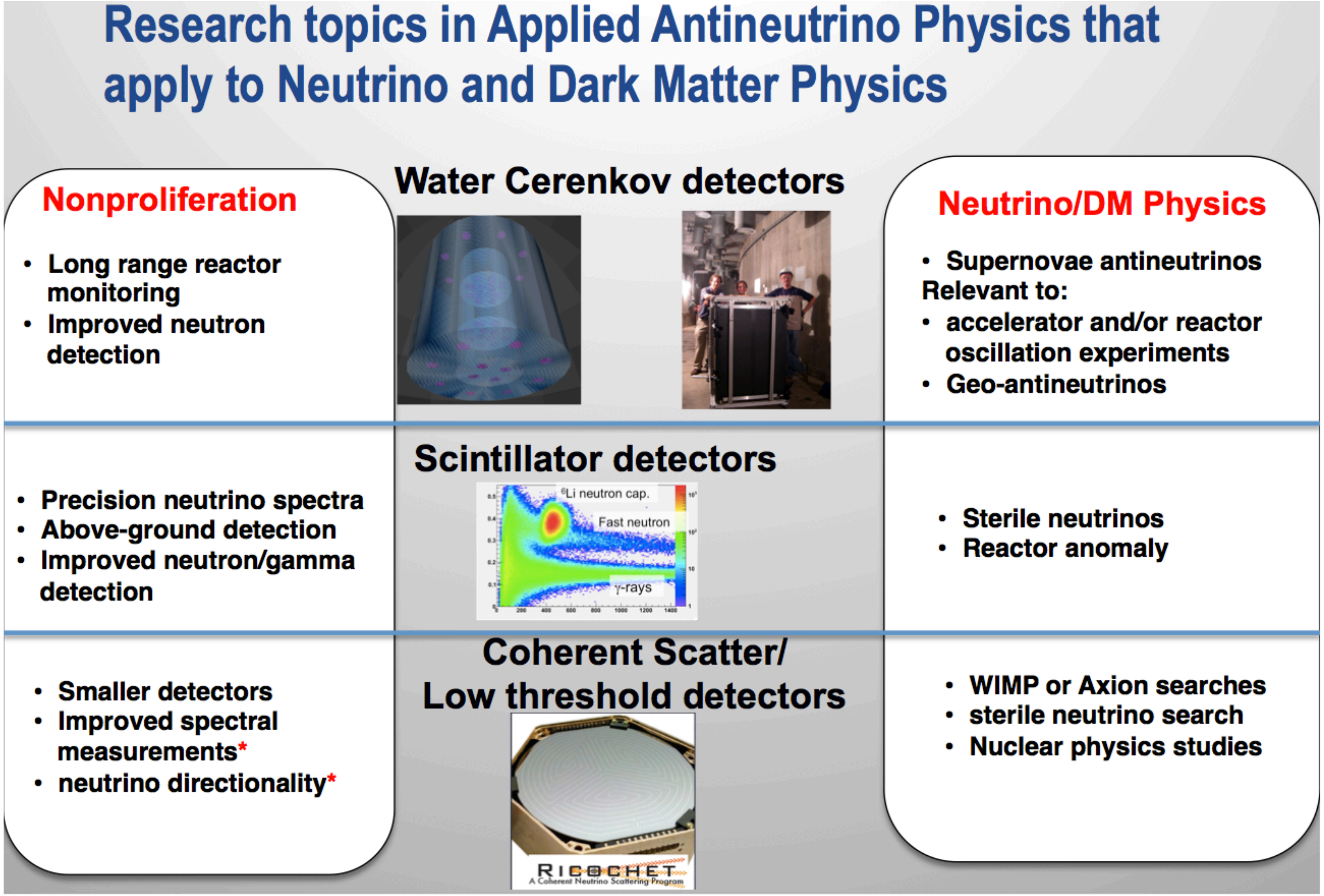
[S. Geer, Nu5]

Astrophysical Neutrinos

Neutrinos come from natural sources as close as the Earth and Sun, to as far away as distant galaxies, and even as remnants from the Big Bang. They range in kinetic energy from less than one meV to greater than one PeV, and can be used to study properties of the astrophysical sources they come from, the nature of neutrinos themselves, and cosmology.



[Nu6]



[A. Bernstein, Nu7]

For the sake of both fields, neutrino/DM physicists should learn about nonproliferation

- Despite many common elements, neutrino applications differ from fundamental science in important ways

  1. Policy context matters as much or more than the technology
  2. Detectors have to be robust, safe, and easy to deploy
  3. Outputs must be easy to interpret

IAEA
International Atomic Energy Agency
Atoms For Peace

- For neutrino physics to have an impact on nonproliferation, physicists need an education in the history and practice of nonproliferation, and the coming challenges – Nuclear Science and Security Consortium a highly effective example at UCB, UCD, UCI, USCD

  - Many schools - mostly nuclear engineering but also some physics departments (e.g. Virginia Tech and UC Davis) provide training in nonproliferation

NSSC7
Training the Next Generation

[A. Bernstein, Nu7]

Table 1-1. *Summary of the very many current and proposed experiments, in the U.S. and abroad, designed to address various physics questions. The intent is not to give a "laundry list", but to give a sense of the activity and breadth of the field. Some multipurpose experiments appear under more than one physics category. Experiments based in the U.S. (or initiated and primarily led by U.S. collaborators) are shown in blue and underlined (note that many others have substantial U.S. participation or leadership). Proposed and future experiments are in bold; current experiments (running or with construction well underway) are in regular font. More details and references can be found in the subsections of the Neutrino Working Group report.*

Source	3-flavor osc.	Maj. vs Dirac	Abs. Mass	Interactions	Anomalies	Astro/Cosmo
Reactor	KamLAND, Double Chooz, Daya Bay, **JUNO**, RENO, **RENO-50**			**RICOCHET**	**DANNS**, **Stereo**, **US Reactor**	
Solar	Super-K, Borexino, SNO+, **Hyper-K**, **LENS**					Super-K, Borexino, SNO+, **Hyper-K**, **LENS**
Supernova[1]	Super-K, Borexino, KamLAND, LVD, IceCube/**PINGU**, **Hyper-K**, **LBNE**, SNO+, **LAGUNA**, **WATCHMAN**					Super-K, Borexino, KamLAND, LVD IceCube/**PINGU**, **Hyper-K**, **LBNE**, SNO+, **LAGUNA**, **WATCHMAN**
Atmospheric	Super-K, MINOS+ , IceCube/**PINGU**, **LBNE**, **INO**, **Hyper-K**, **LAGUNA**					
Pion DAR	**DAEδALUS**			**CSISNS**, **CENNS**, **CAPTAIN**	**OscSNS**	
Pion DIF	MINOS+, T2K, NOνA, **T2HK**, **LAGUNA-LBNO**, **RADAR**, **CHIPS**, **LBNE**			MINERνA, **SciNOνA**	MicroBooNE, **MiniBooNE+/II**, **Icarus/NESSiE**, **LAr1**	
μDIF	**NuMAX**			**nuSTORM**	**nuSTORM**	
Radioactive Isotopes		Many: see Nu2 report for table	KATRIN, **Project 8**, **ECHo**, **PTOLEMY**		**SOX**, **CeLAND**, **Daya Bay Source**, **IsoDAR**	
Cosmic						IceCube/**PINGU**, ANTARES/**ORCA**, **ARA**,**ARIANNA**, ANITA, **EVA**, **KM3NET**

[1]Included are only kton-class underground detectors; many others would also record events. [2]We note that nearly all experiments can address anomalies at some level; we include in this column only those with this as a primary physics goal.

A Path Forward (goal NOT to prioritize!)

Multi-pronged approach to address all the outstanding questions and fully explore the new physics revealed by neutrino oscillation.

- *Comprehensive test of the three-flavor paradigm, via long-baseline, precision neutrino oscillation experiments.* The next-generation: super beams. Start to over-constrain the parameter space, and seriously explore CP-violating phenomena in the lepton sector.

  LBNE (underground!), later with Project X to lead international campaign to observe CP violation and test the three-flavor paradigm.

  Complementary experiments with different energies, baselines and detector technologies (e.g. T2HK in Japan) required.

  Very-large detectors, underground → atmospheric neutrinos, nucleon decay, and precision measurements of neutrinos from supernovae.

  Next-next generation experiments: better (both more intense, and better understood) neutrino beams. Possibilities: **NuFact**, or neutrinos from pion decay at rest (e.g. DAEδALUS). Muon-based neutrino beams: strong synergies with Project X, Step in the R&D for a high-energy muon collider.

Also required

- *Precision measurements of neutrino cross sections and a detailed understanding of the neutrino flux from pion-decay-in-flight neutrino beams.* Along with dedicated theory effort!
- *Definite resolution of the current short-baseline anomalies.* Require neutrino sources other than pion-decay-in-flight and pursuit of different flavor-changing channels ($\nu_{e,\mu}$ disappearance and $\nu_\mu \to \nu_e$) from reactor, radioactive source and accelerators.
- *Vigorous pursuit of R&D projects related to the development of next-next generation neutrino-beam experiments.*

- *Searches for neutrinoless double-beta decay.* Must. Clear plan in progress.
- *Determination of the absolute values of the neutrino masses.* Beta decay still most promising model-independent probe. KATRIN, along with vigorous R&D efforts for next-generation probes required to identify if sensitivities to $m_{\nu_e} < 0.05$ eV possible. Nontrivial information from different cosmological probes. Measurement of "neutrino masses" from cosmology would make the case for terrestrial measurements strong!

What is Next?

- Deliverables going to appear online in the next couple of weeks. Several "layers": White Papers (most already out), Neutrino Subgroup Report (∼60 pages), Intensity Frontier Report (∼ 30 pages), Snowmass Report (∼ 30 pages).

- P5 will start meeting in the next couple of months. Prioritize, set the path forward for US particle physics within realistic budgetary constraints.

- Perhaps most important: need for coordinated INTERNATIONAL plan. Not just for neutrinos, but for particle physics as a whole!