Nuclear Physics Connections

Alan Poon
Lawrence Berkeley National Laboratory

Outline

- Scientific questions
- Major scientific discoveries since the last Nuclear Physics Long Range Plan (2007)
- Compelling and unique science to be done in the next 5 years and through 2020

Scientific Questions

Fundamental Symmetries and Neutrinos (FS&N)

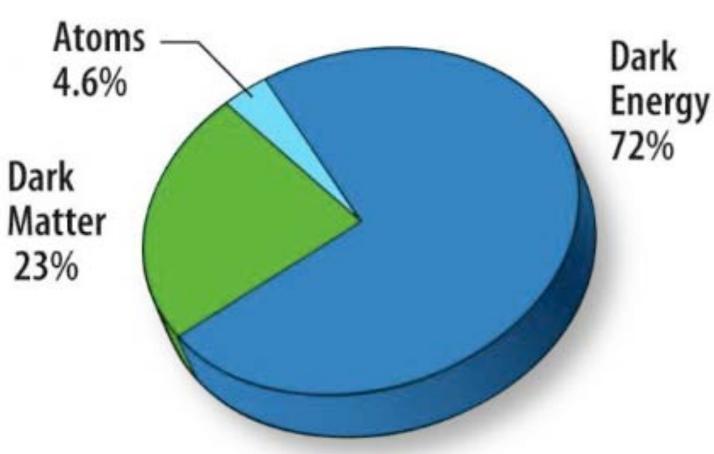
- What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?
- Why is there now more visible matter than antimatter in the universe?
- What are the unseen forces that were present at the dawn of the universe but disappeared from view as the universe evolved?

Nuclear Physics Long Range Plan 2007

Neutrino mass and hierarchy, Dirac vs Majorana neutrino, lepton mixing, evolution of astrophysical structures...

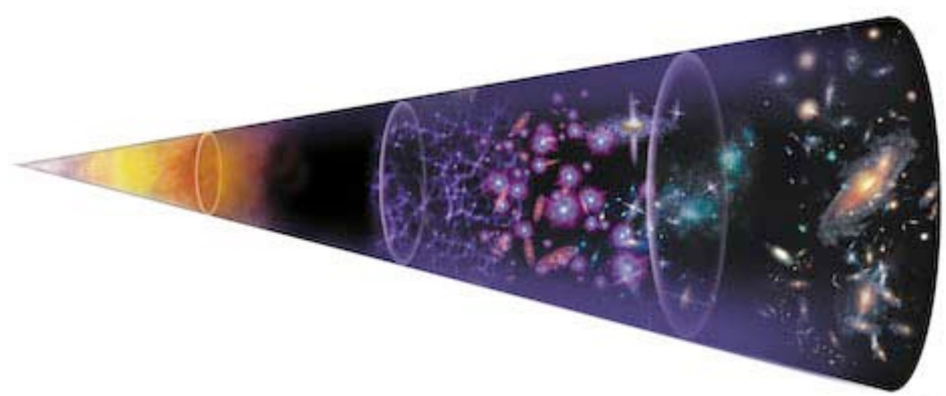
CP violation, lepton and baryon number violation (electroweak baryogenesis, leptogenesis)...

SM masses, couplings, structure of interactions, completeness and extensions...



NASA

TODAY



Scientific America

US Nuclear Physics
Long Range Plan 2007

RECOMMENDATION III

We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the New Standard Model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.

Major Accomplishments in FS&N since 2007

- ✳ Improved understanding of θ_{12} and Δm_{12}^2 and solar neutrinos: **Borexino, SNO, KamLAND**
- ✳ Establishment of **Sanford Underground Research Facility**
- ★ Results on ^{136}Xe $\tau_{2\nu\beta\beta}$ and $\tau_{0\nu\beta\beta}$: **EXO, KamLAND-Zen**
- ★ Determination of θ_{13}: **Daya Bay, RENO, Double Chooz**

neutrinos

- ✳ β-asymmetry "Big A" : **UCNA @ LANL**
- ✳ Completion and first result of QWeak: **JLab**
- ✳ New determination of τ_{μ}, g_p : **MuLan, MuCap @ PSI**
- ✳ T-violation limit in neutron beta decay: **emiT**
- ✳ Muon Michel parameters: **TWIST @ TRIUMF**
- ✳ Results from **MiniBooNE**
- ✳ Many advances in theory: ***0νββ* matrix elements, loop corrections...**

★ Nuclear Physics participation

Four Components in FS&N

EDM searches: *Origin of matter* *New forces* Exp'ts: nEDM	***0νββ decay searches:*** *Nature of neutrinos* *Origin of matter* Exp'ts: CUORE, MAJORANA, EXO → Tonne
Electron & muon properties & interactions: *New forces* *New subatomic particles* Exp'ts: MOLLER, SoLID, Muon g-2	***Radioactive decays and other tests:*** *New forces* *Neutrino mass* Exp'ts: KATRIN, Nab

From Report on the Implementation of LRP 2007 (2013)

Four Components in FS&N

EDM searches: *Origin of matter* *New forces* Exp'ts: nEDM	***$0\nu\beta\beta$ decay searches:*** *Nature of neutrinos* *Origin of matter* Exp'ts: CUORE, MAJORANA, EXO → Tonne	Search for new phenomena beyond SM
Electron & muon properties & interactions: *New forces* *New subatomic particles* Exp'ts: MOLLER, SoLID, Muon g-2	***Radioactive decays and other tests:*** *New forces* *Neutrino mass* Exp'ts: KATRIN, Nab	Precision tests of SM

• • • • • •

From Report on the Implementation of LRP 2007 (2013)

Four Components in FS&N

EDM searches:

Origin of matter
New forces

Exp'ts: nEDM

0νββ decay searches:

Nature of neutrinos
Origin of matter

Exp'ts: CUORE, MAJORANA, EXO → Tonne

Electron & muon properties & interactions:

New forces
New subatomic particles

Exp'ts: MOLLER, SoLID, Muon g-2

Radioactive decays and other tests:

New forces
Neutrino mass

Exp'ts: KATRIN, Nab

Search for new phenomena beyond SM

• • • • • •

Precision tests of SM

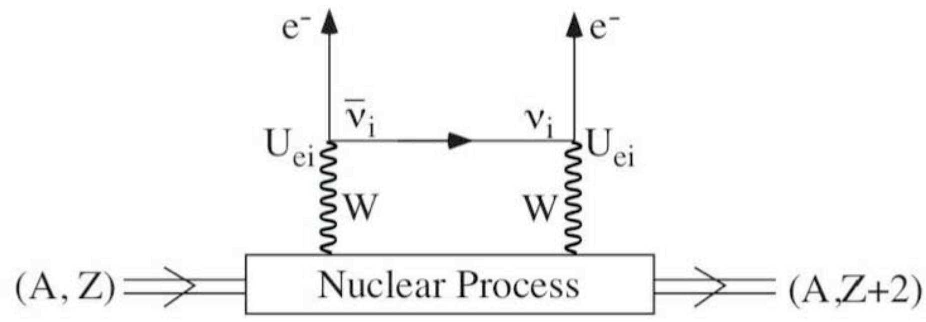
From Report on the Implementation of LRP 2007 (2013)

The US Neutrino Program in Nuclear Physics

- Search for lepton number violation (via $0\nu\beta\beta$ decays)
- Investigate neutrino mass nature (Dirac vs Majorana)
- Model-independent probe of neutrino mass scale $< \sim 200$ meV in kinematic measurements (via β decays)
- Solar neutrinos

Neutrinoless Double Beta Decays

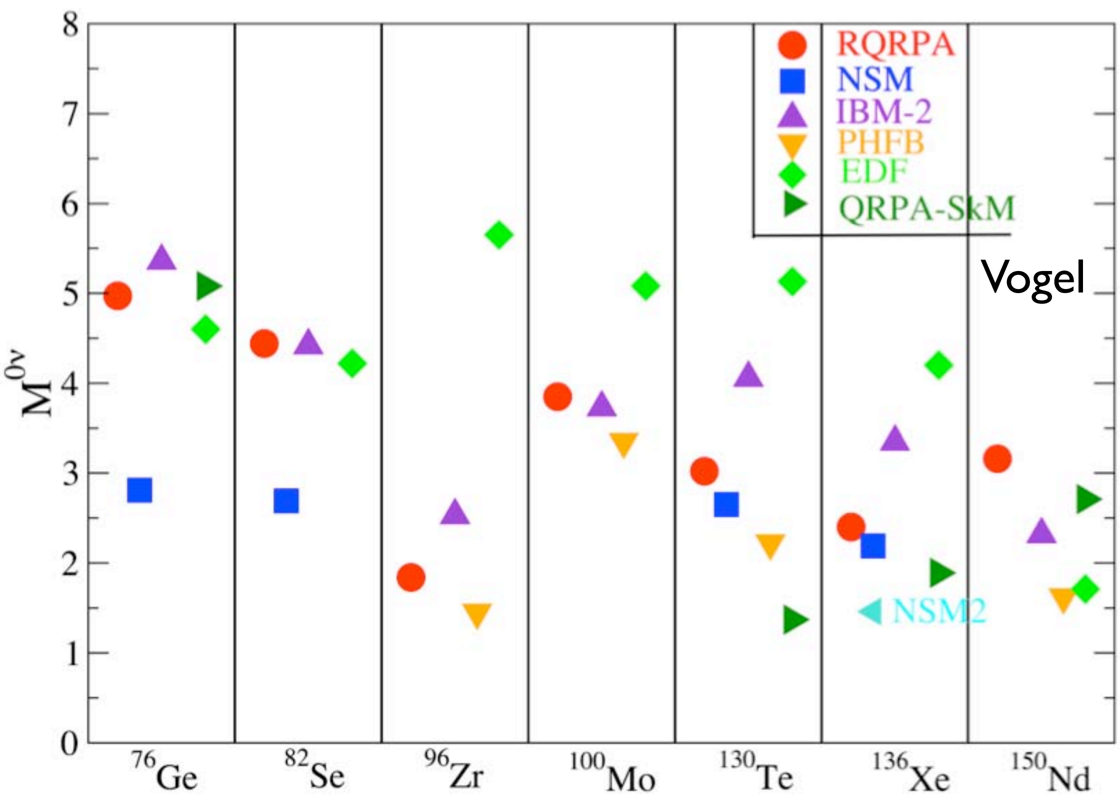
- If observed:
  - Lepton number violation: ΔL=2
  - Neutrinos are Majorana particles



- Decay rate:

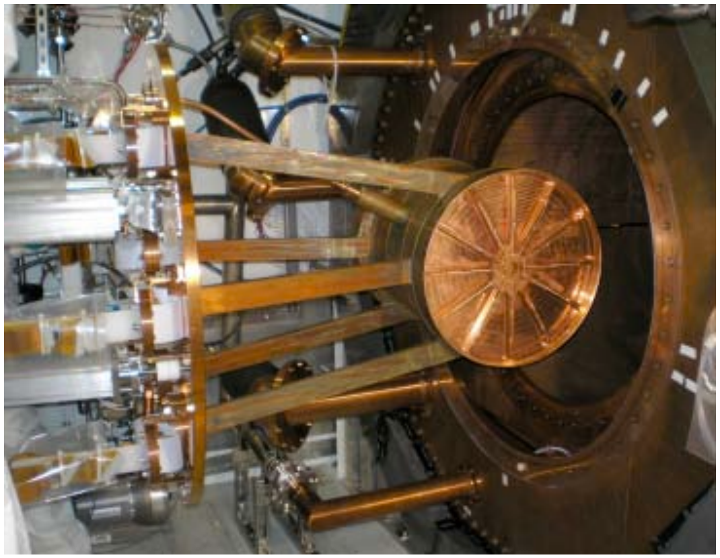
$$\left[T^{0\nu}_{\frac{1}{2}}\right]^{-1} \propto g_A^4\, G_{0\nu}\, |M_{0\nu}|^2\, |\langle m_{\beta\beta}\rangle|^2$$

$G_{0\nu}$	Phase space (calculable)
$\|M_{0\nu}\|^2$	Nuclear matrix element
$\langle m_{\beta\beta}\rangle$	Effective neutrino mass



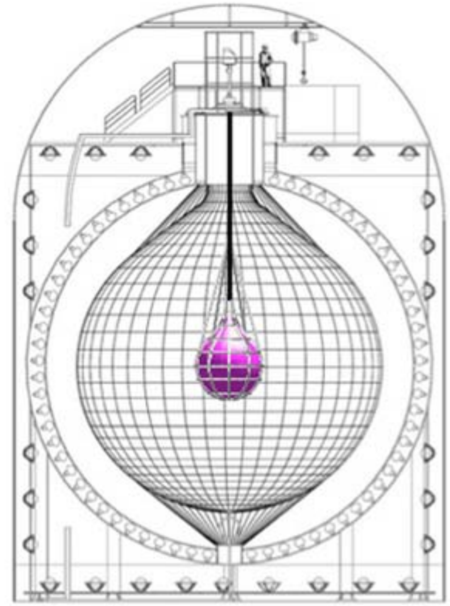
Recent ^{136}Xe results

EXO-200*



- Located at WIPP in NM
- Liquid phase time projection chamber
- Large-area avalanche photodiodes allowed for detection of scintillation in LXe
- 200 kg enriched Xe (~81% ^{136}Xe) total
- First observation of ^{136}Xe $2\nu\beta\beta$

KamLAND-Zen*



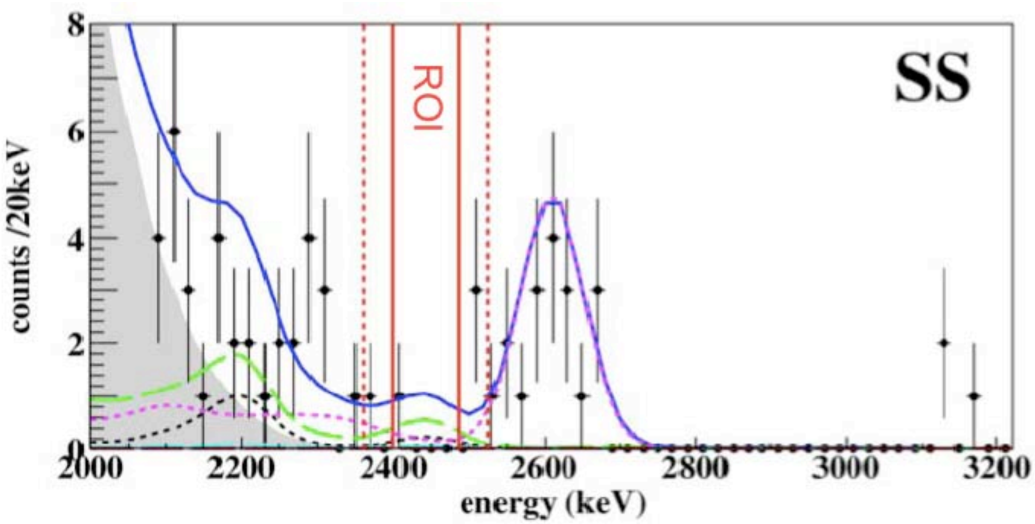
- Located at Kamioka mine in Japan
- ~320 kg enriched Xe (~91% ^{136}Xe) installed.
- ^{enr}Xe dissolved in liquid scintillator, contained in a thin-wall (nylon) inner balloon

* Nuclear Physics participation in both experiments

Recent ^{136}Xe results

EXO-200

32.5 kg-y exposure

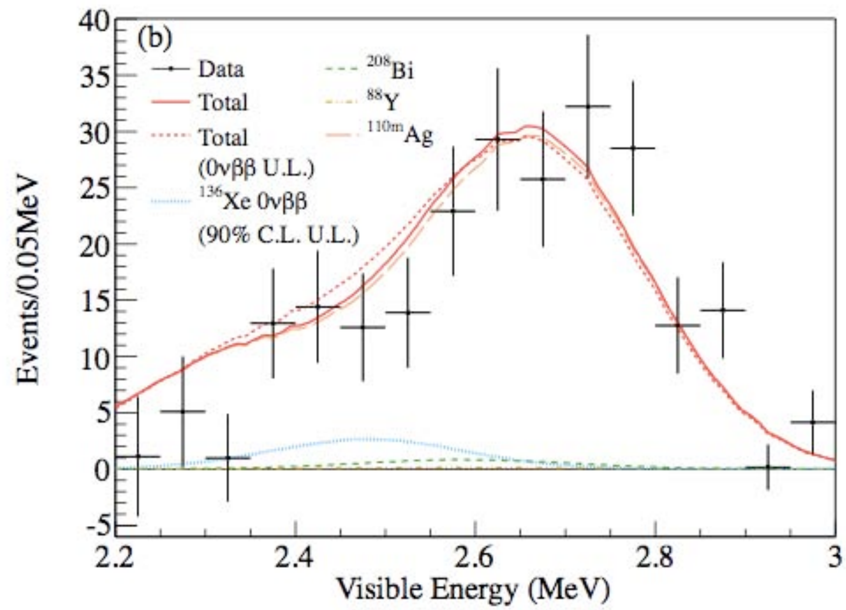


$$T^{0\nu}_{1/2} > 1.6 \times 10^{25}\,\text{year}\,(90\%\text{C.L.})$$

PRL 109 032505 (2012)

KamLAND-Zen

89.5 kg-y exposure



$$T^{0\nu}_{1/2} > 2.0 \times 10^{25}\,\text{year}\,(90\%\text{C.L.})$$

arXiv:1211.3863 (2012)

Combined:

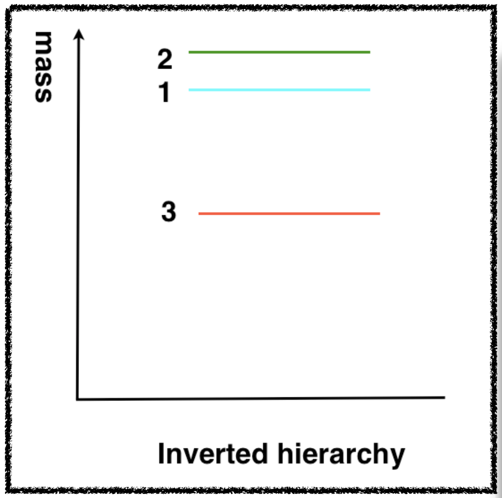
$$T^{0\nu}_{1/2} > 3.4 \times 10^{25}\,\text{year}\,(90\%\text{C.L.})$$

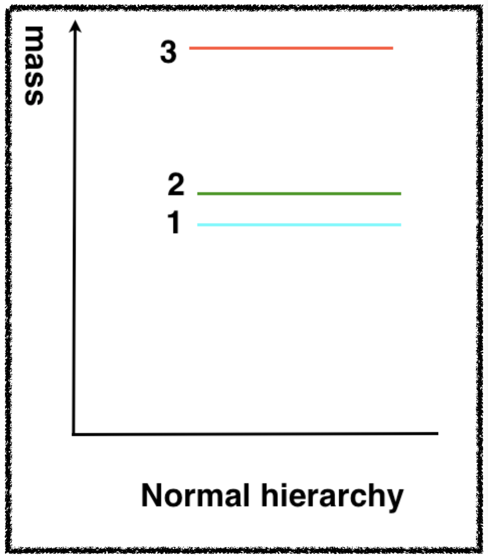
$$\langle m_{\beta\beta} \rangle < (120 - 250)\,\text{meV}$$

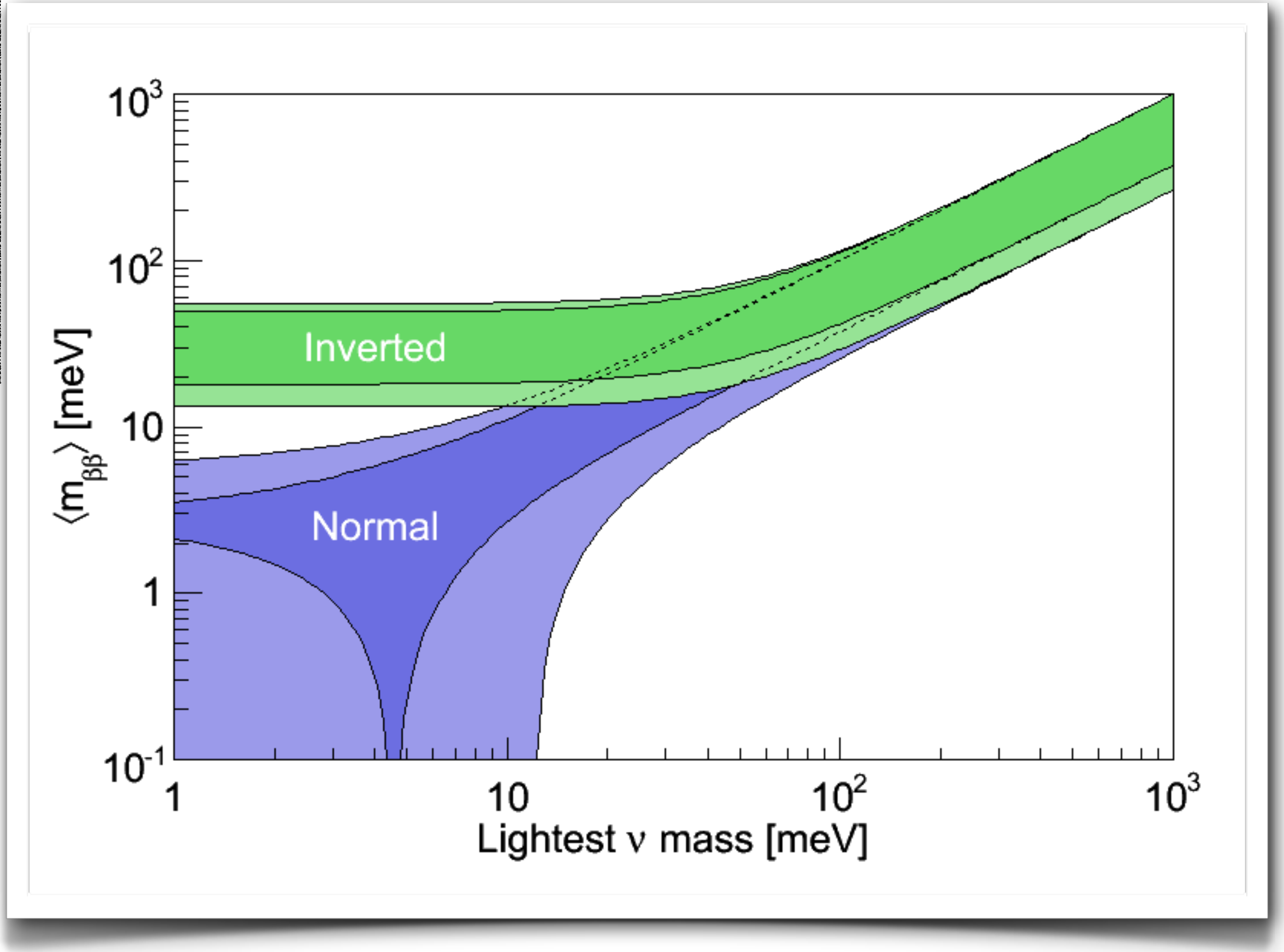
arXiv:1211.3863 (2012)

Sensitivity - Current and Future

$$\langle m_{\beta\beta}\rangle = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2\, e^{2i\phi_{12}} + s_{13}^2 m_3\, e^{2i\phi_{13}} \right|$$

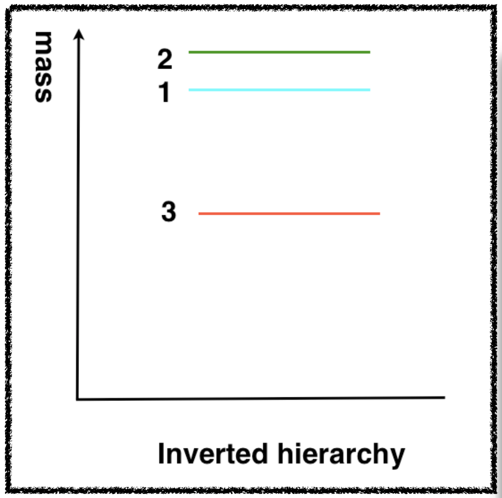


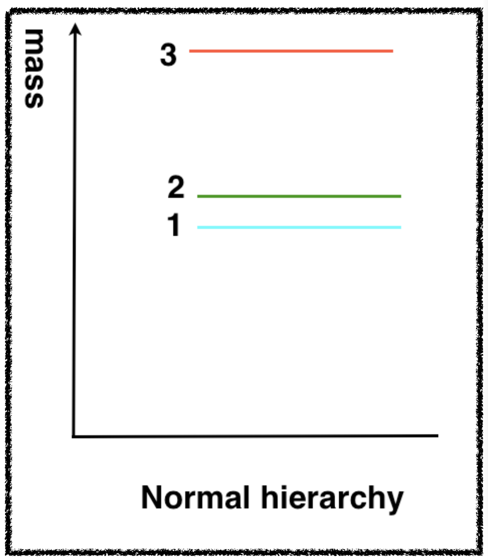


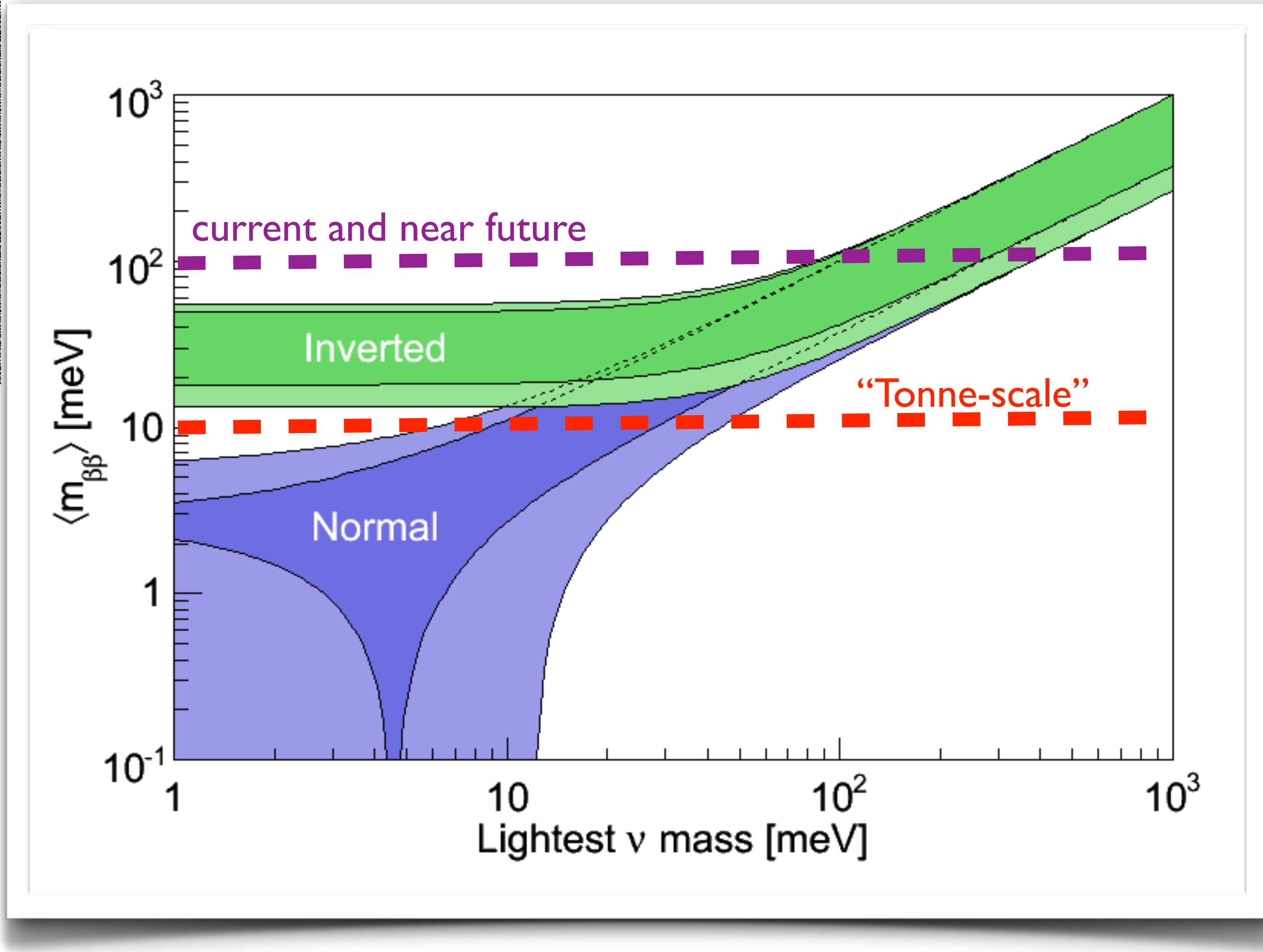


Sensitivity - Current and Future

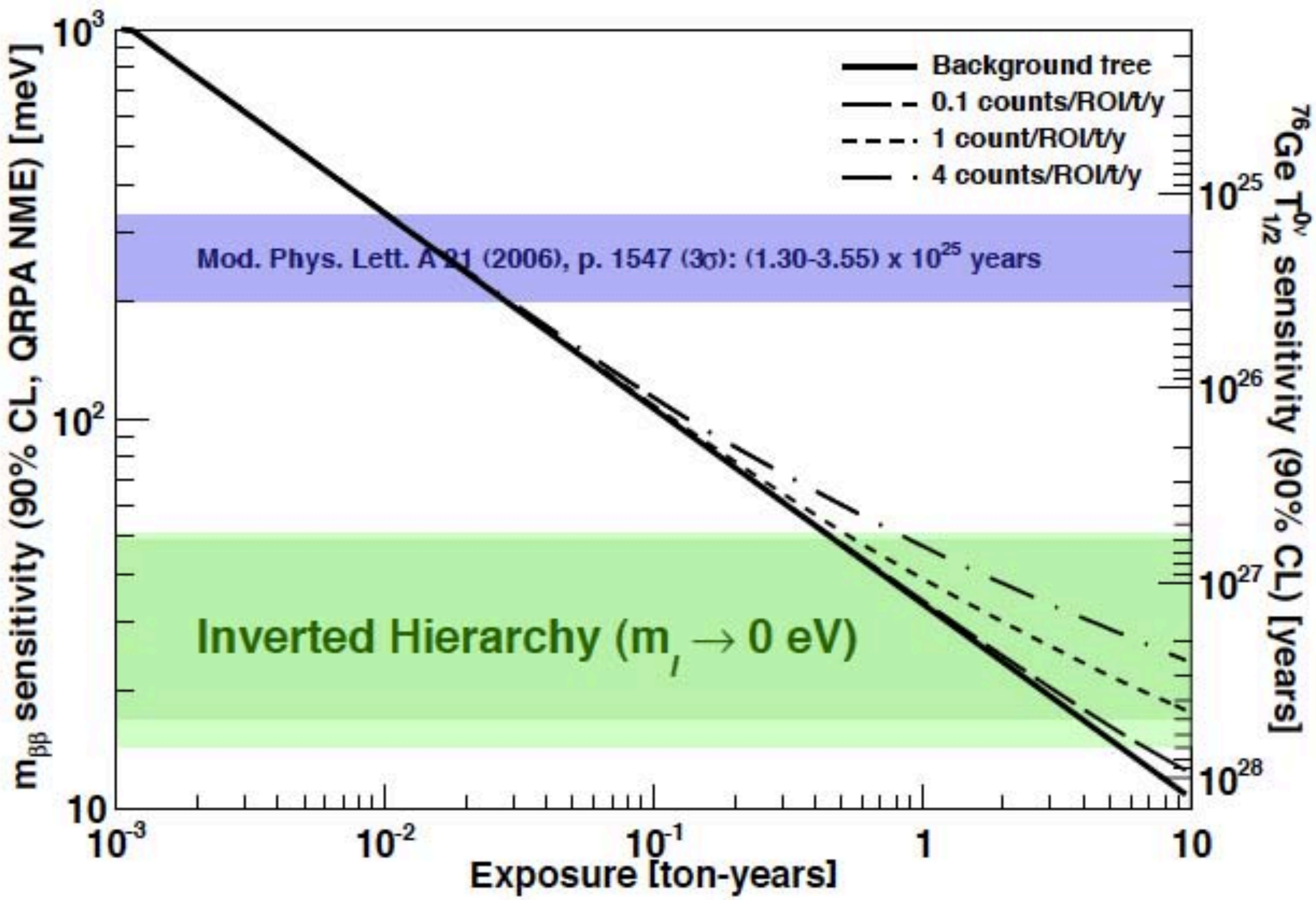
$$\langle m_{\beta\beta} \rangle = \left| c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 \, e^{2i\phi_{12}} + s_{13}^2 m_3 \, e^{2i\phi_{13}} \right|$$







Backgrounds and Sensitivity



$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\,\Delta E}{M\,t_{live}} \right)^{1/4}$$

b :	Background rate
ΔE :	Detector energy resolution
M :	Target mass
t_{live} :	Live time

⇒ low background,

large target mass

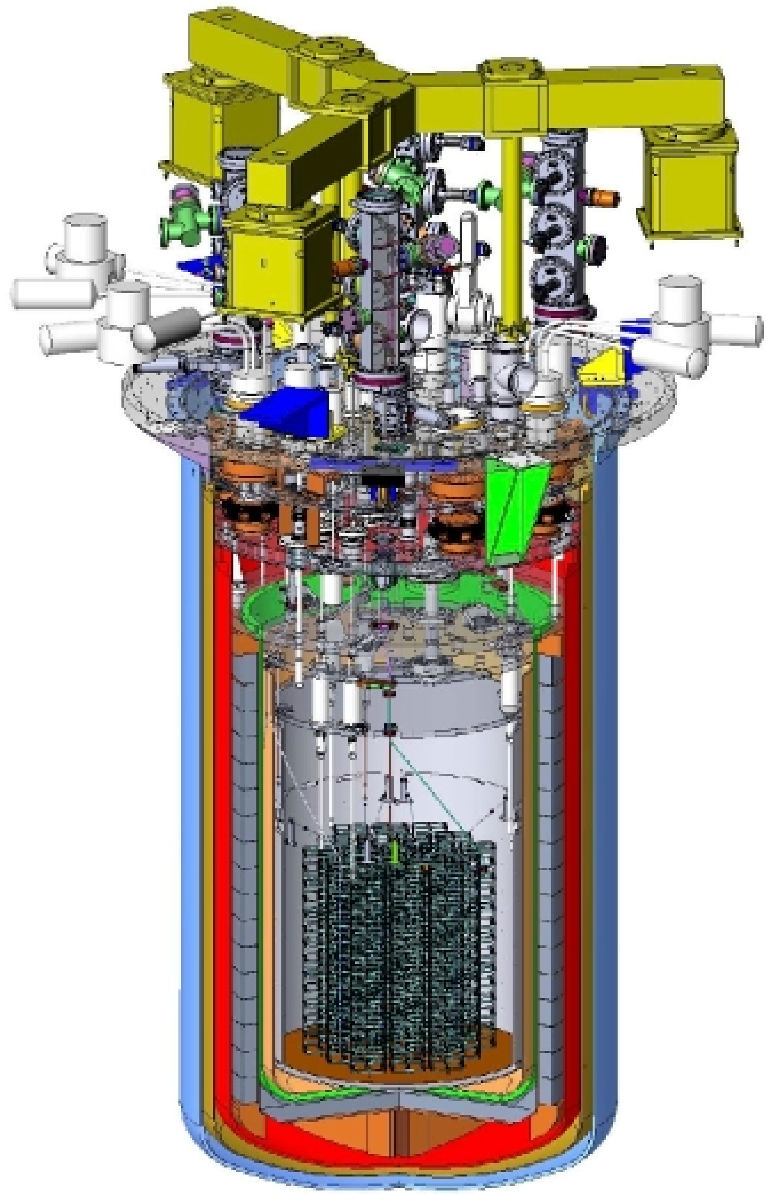
CUORE

Array of 988 TeO_2 crystals

- **19** towers suspended in a cylindrical structure
- **13** levels, **4** crystals each
- 5x5x5 cm^3 (750g each)
- ^{130}Te: 33.8% natural isotope abundance

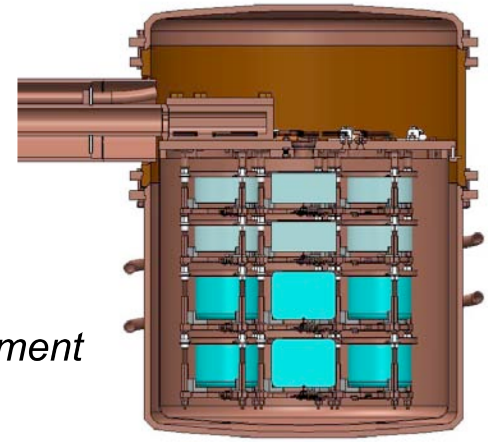
750 kg TeO_2 => 200 kg ^{130}Te

- New pulse tube refrigerator and cryostat
- Radio-purity techniques and high resolution achieve low backgrounds
- Joint venture between Italy (INFN) and US (DOE-NP, NSF)
- Under construction (expected start of operations by end of 2014)
- Expect energy resolution of 5 keV FWHM and background of ~0.01 counts/(kg*keV*year) in ROI

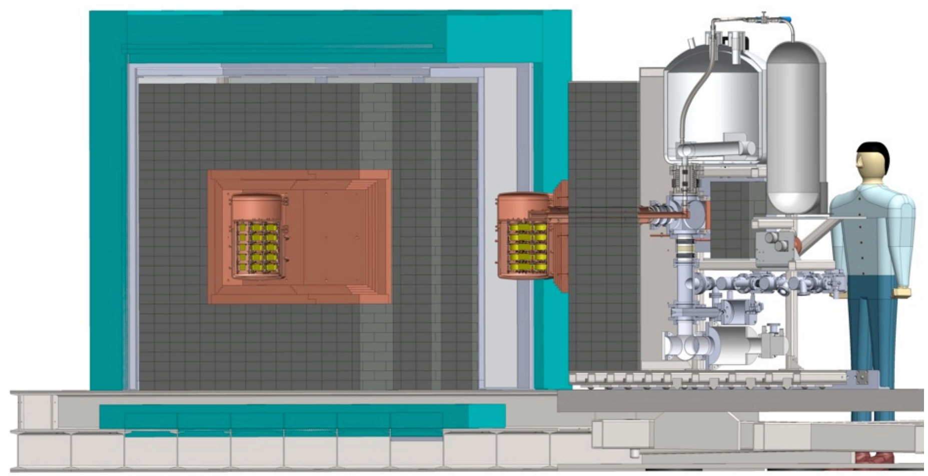


The MAJORANA DEMONSTRATOR (MJD)

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Test Klapdor-Kleingrothaus claim.
- Low-energy dark matter (light WIMPs) search.



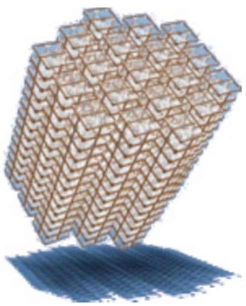
- **Located underground at 4850' Sanford Underground Research Facility**
- **Funded by DOE-NP, NSF and international partners**
- **Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV):**
  3 counts/ROI/t/y (after analysis cuts) *scales to 1 count/ROI/t/y for a 1-t experiment*
- **40-kg of P-type Point-Contact Ge detectors**
  - 30 kg of 86% enriched ^{76}Ge crystals & 10 kg of ^{nat}Ge
- **2 independent cryostats**
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
- **Compact Shield**
  - low-background passive Cu and Pb shield with active muon veto
- **Three steps**
  - Prototype Cryostat** (2 strings, ^{nat}Ge) [Spring 2013]
  - Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge) [Late 2013]
  - Cryostat 2 (7 strings ^{enr}Ge) [Fall 2014]



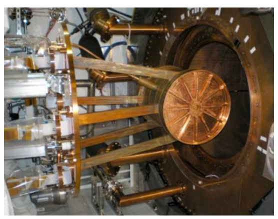
** Same design as Cryostats 1 & 2, but fabricated using OFHC Cu (non-electroformed) components.

0νββ - Efforts Underway Internationally

CUORE



EXO200



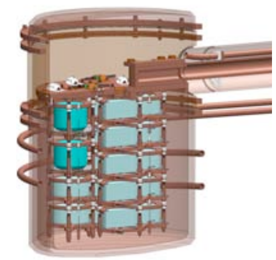
NEMO

Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ tonne	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
II		Point contact Ge in LAr	30-35 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	30 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	CaMoO4 scint. bolometer	50 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
COBRA	Cd-116	CdZnTe detectors	10 kg 183 kg	R&D
CUORICINO	Te-130	TeO_2 Bolometer	10 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Commissioning
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	380 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	Construction
EXO200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	~ tonne	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
SNO+	Nd-150	0.1% ^{nat}Nd suspended in Scint	55 kg	Construction

Wilkerson, NuMass 2013

GERDA

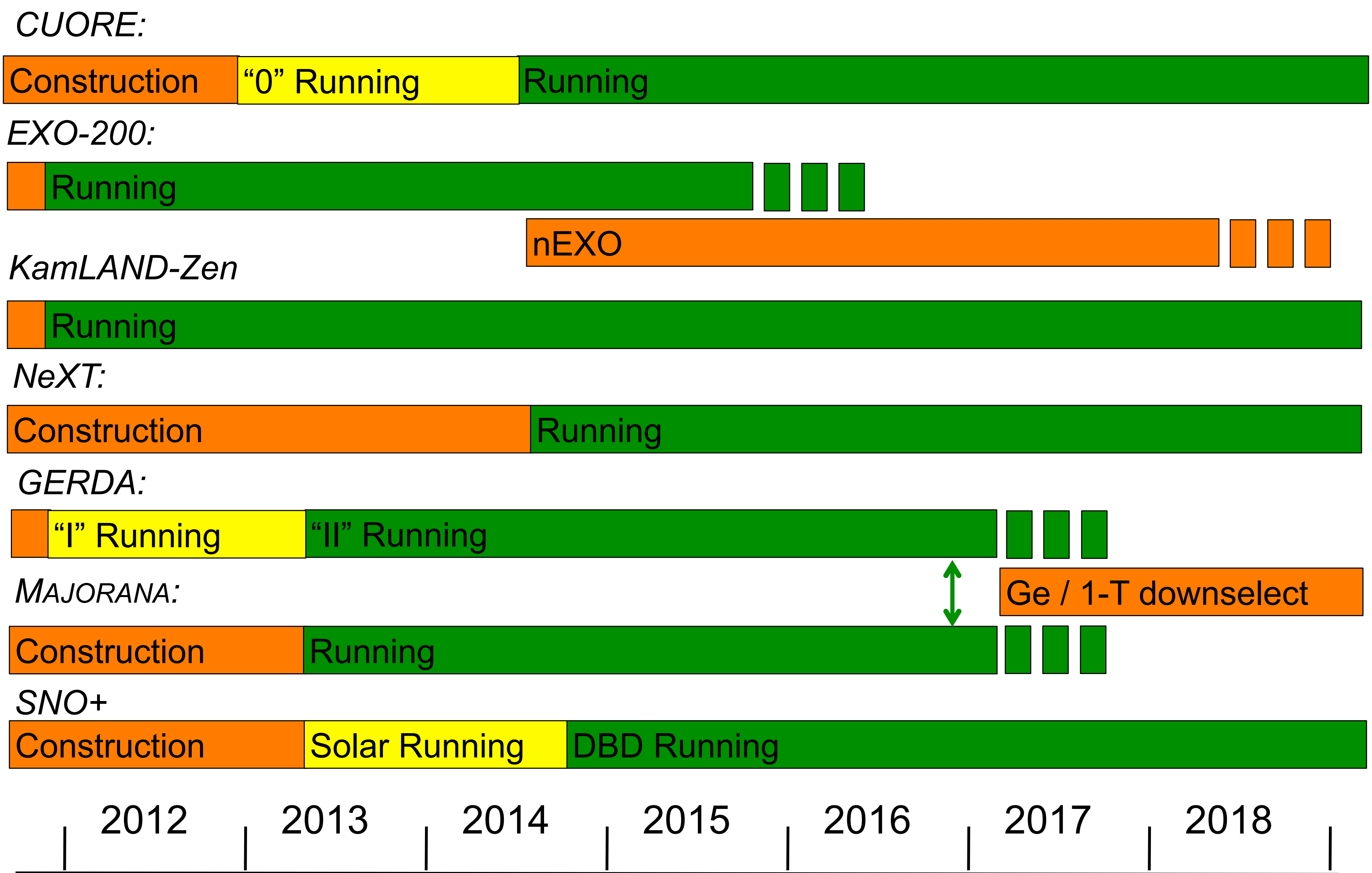
MAJORANA



CANDLES

Future “tonne-scale” neutrinoless double beta decay program to be stewarded by DOE-NP. Current R&D supported by DOE-NP, DOE-HEP and NSF.

Double Beta Decay: some milestones



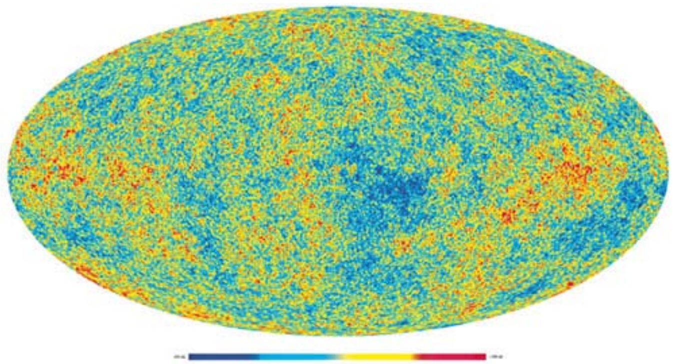
Compiled by Robertson for NSAC LRP 2007 implementation report (2012)

Four Components in FS&N

EDM searches: *Origin of matter* *New forces* Exp'ts: nEDM	***$0\nu\beta\beta$ decay searches:*** *Nature of neutrinos* *Origin of matter* Exp'ts: CUORE, MAJORANA, EXO → Tonne
Electron & muon properties & interactions: *New forces* *New subatomic particles* Exp'ts: MOLLER, SoLID, Muon g-2	***Radioactive decays and other tests:*** *New forces* *Neutrino mass* Exp'ts: KATRIN, Nab

From Report on the Implementation of LRP 2007 (2013)

Three tracks to neutrino mass

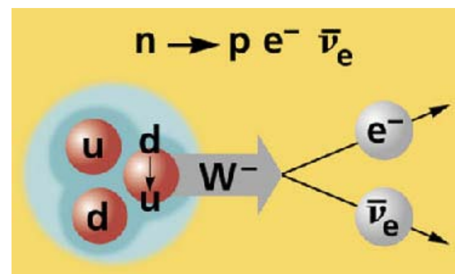


- Cosmology:
  - Model / data set dependent
  - Current limit $\sum m_\nu < \sim 1\ \mathrm{eV}$

Heaven

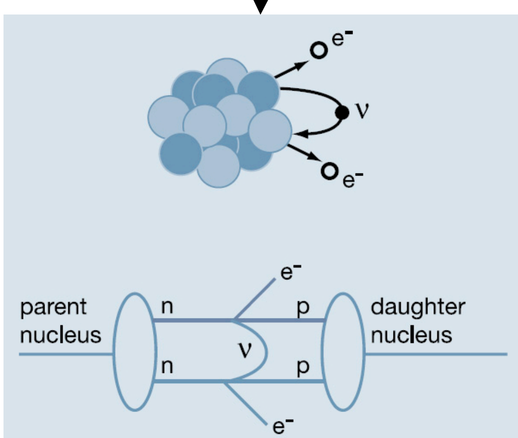
Mass Measurements

Surface



- Kinematics of β decays:
  - Model independent
  - Current limit $m_\nu < 2.1\ \mathrm{eV}$

Underground



- ββ decays:
  - Model dependent (matrix elements)
  - Current limit $m_{\beta\beta} < \sim (0.1 - 0.4)\ \mathrm{eV}$

What do they measure?

- Cosmology: $\sum m = \sum_{i=1}^{3} m_i = m_1 + m_2 + m_3 \quad (\text{and } N_{\text{eff}}\,?)$

- β decays:

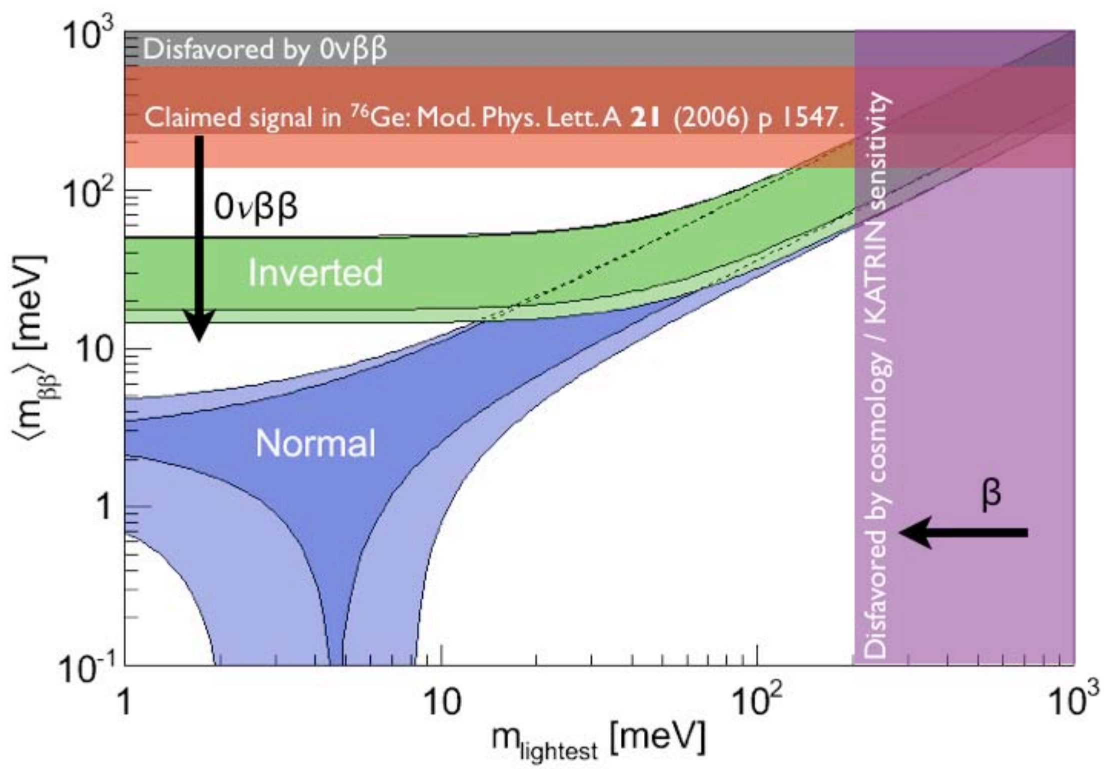
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

- 0νββ decays:

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

- Oscillations:

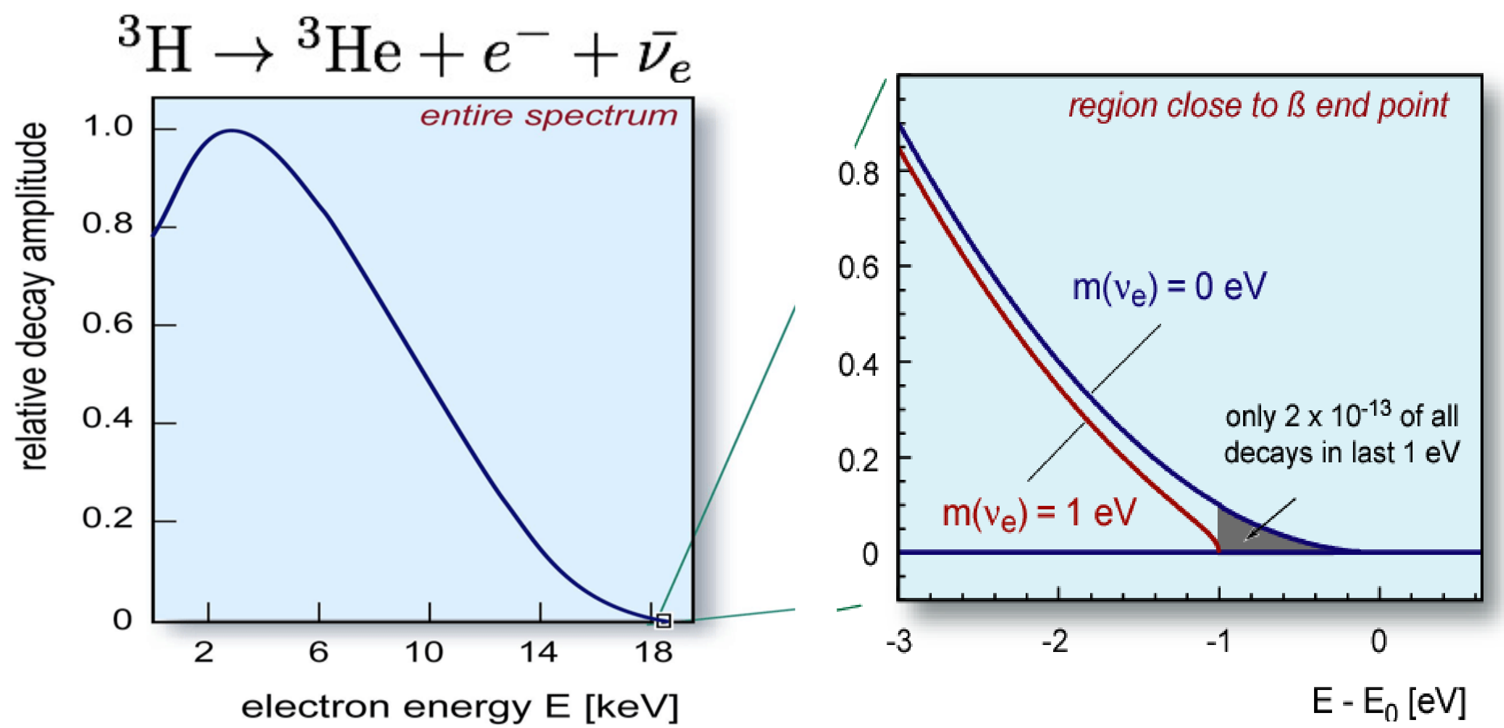
$$\Delta m_{ij}^2 = m_j^2 - m_i^2$$



Complementary measurements

Determining the neutrino mass from β endpoint

- Original idea from Fermi [Z. Physik 88 (1934)]
- The shape of the β spectrum near the end point depends on m(ν$_e$).



$$\frac{dN}{dE} \propto F(E,Z)\, p\,(E+m_e)(E_o - E_e) \sum |U_{ei}|^2 \sqrt{(E_o - E_e)^2 - m_i^2}$$

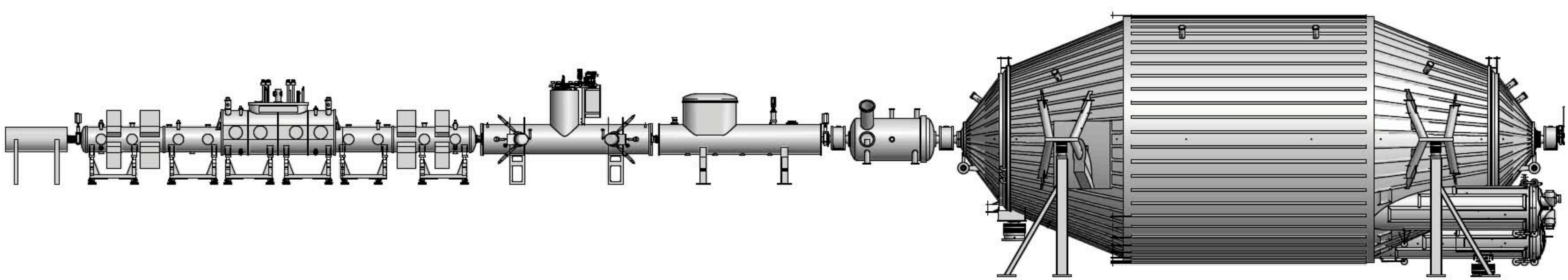
Karlsruhe **Tri**tium **N**eutrino Experiment (KATRIN)

KATRIN is being mounted at Karlsruhe Institute of Technology, where the European Tritium Laboratory Karlsruhe (TLK) is a unique facility for closed loop tritium cycling.

US DOE-NP funds the detector subsystem.

Tritium data taking: ~2015.

Sensitivity: < 200 meV



~ 75 m long with 40 superconducting solenoids

Project 8

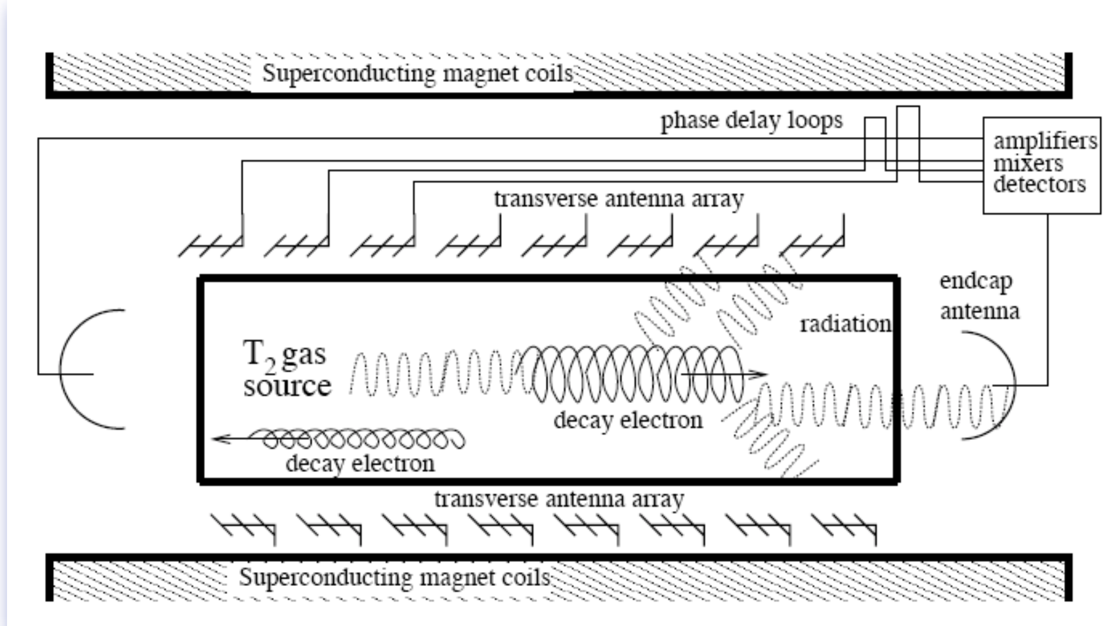
- Coherent radiation emitted can be collected and used to measure the energy of the electron in a non-destructive manner:
  - uniform B field
  - low pressure tritium gas
  - antenna array

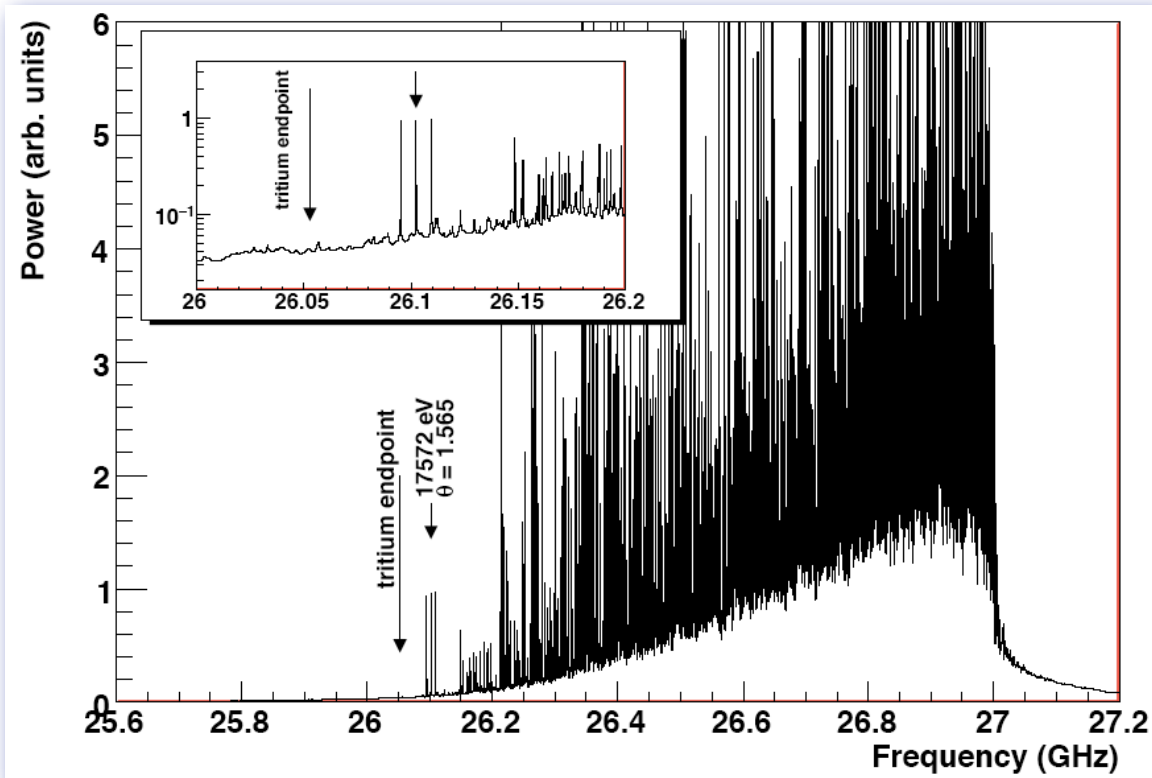
- Cyclotron frequency:

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

- Radiated power ~ 1 fW

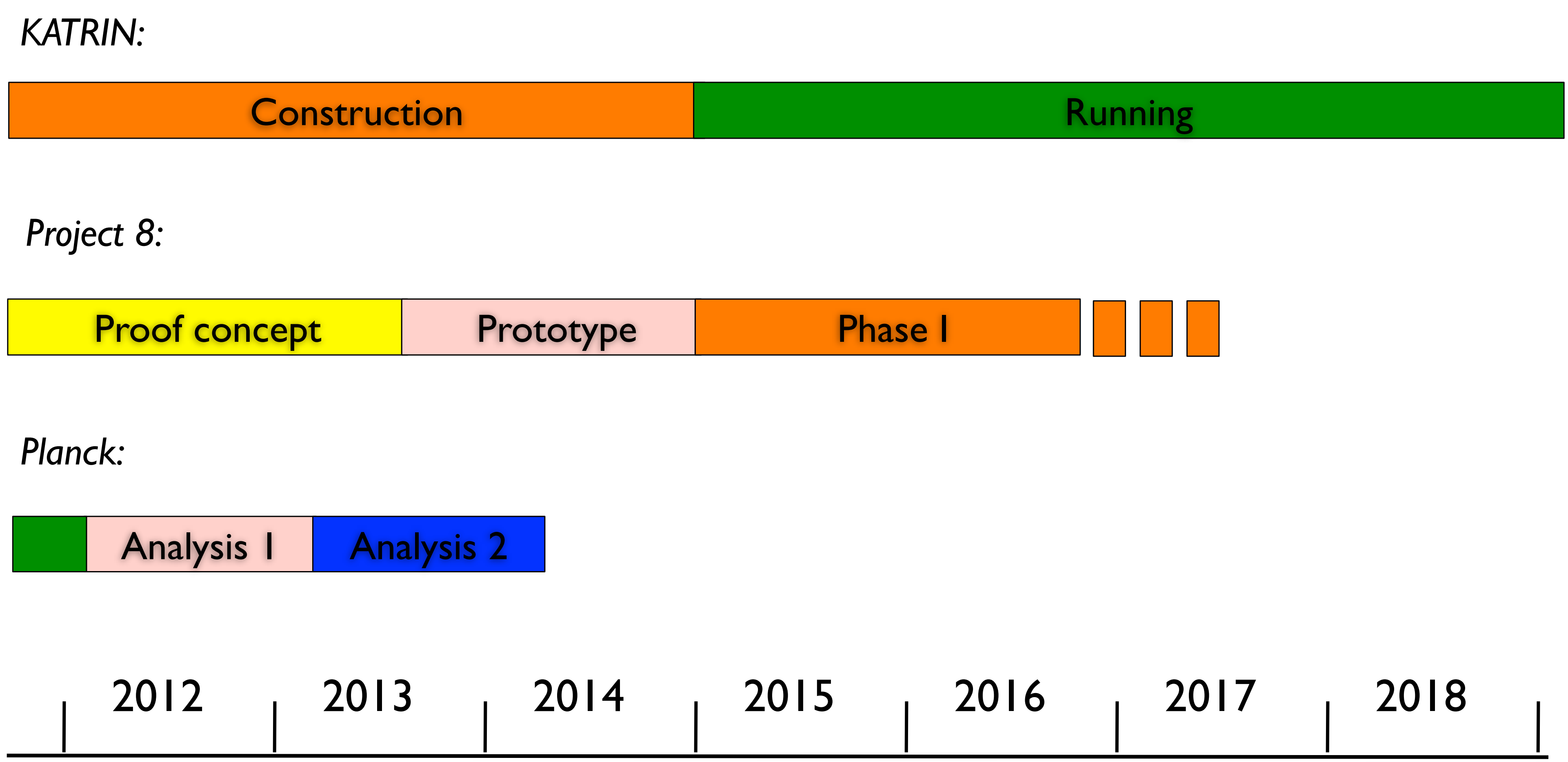
- Proof-of-concept stage





Monreal & Formaggio, Phys. Rev. D80:051301 (2009)

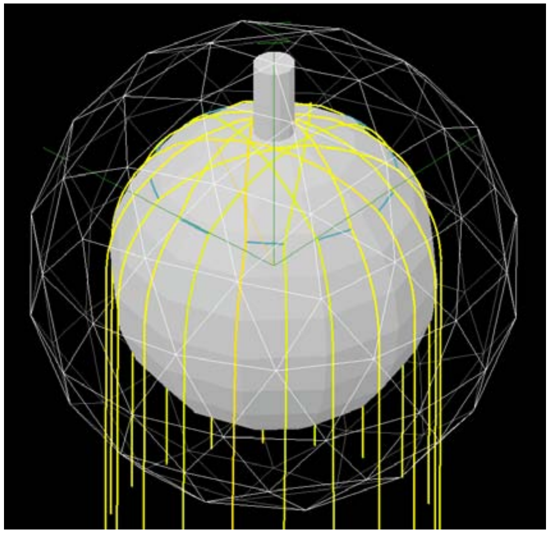
Direct Neutrino Mass Measurement Timeline



Compiled by Robertson for NSAC LRP 2007 implementation report (2012)

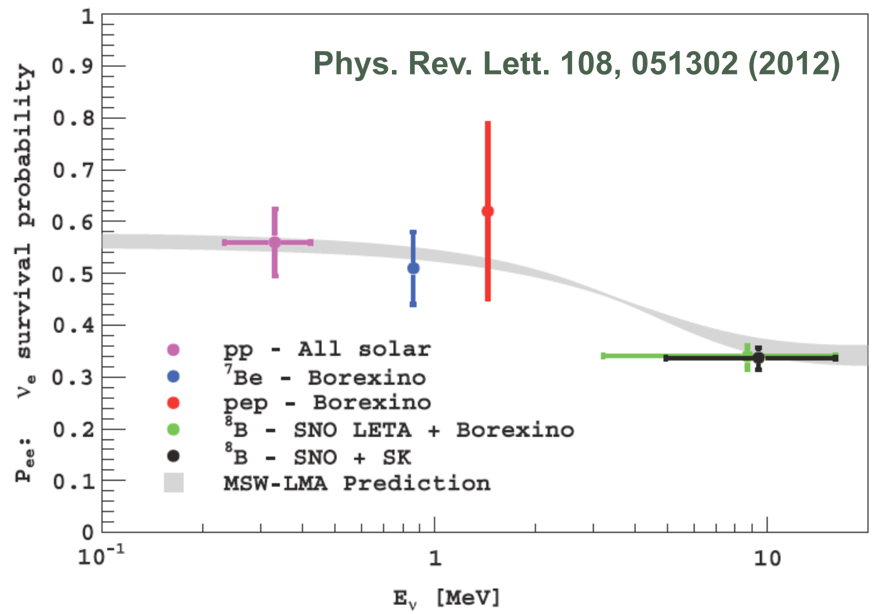
Solar neutrinos

SNO+ @ SNOLAB

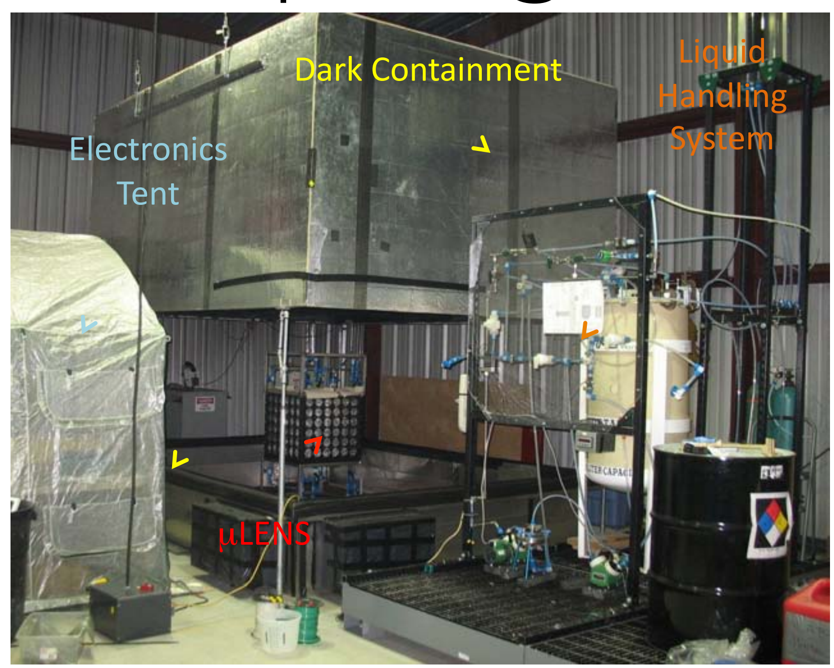


- pep solar neutrinos:
  - known flux (±1.2%), known ν-e elastic scattering cross section
  - probe survival probability at low energy with a few % precision
- CNO neutrinos
  - goal: ±10% after 3 years.
  - differentiate high-Z / low-Z core metallicity

Borexino @ LNGS



LENS / μLENS @ KURF



Underground Laboratory

Who needs an underground lab?

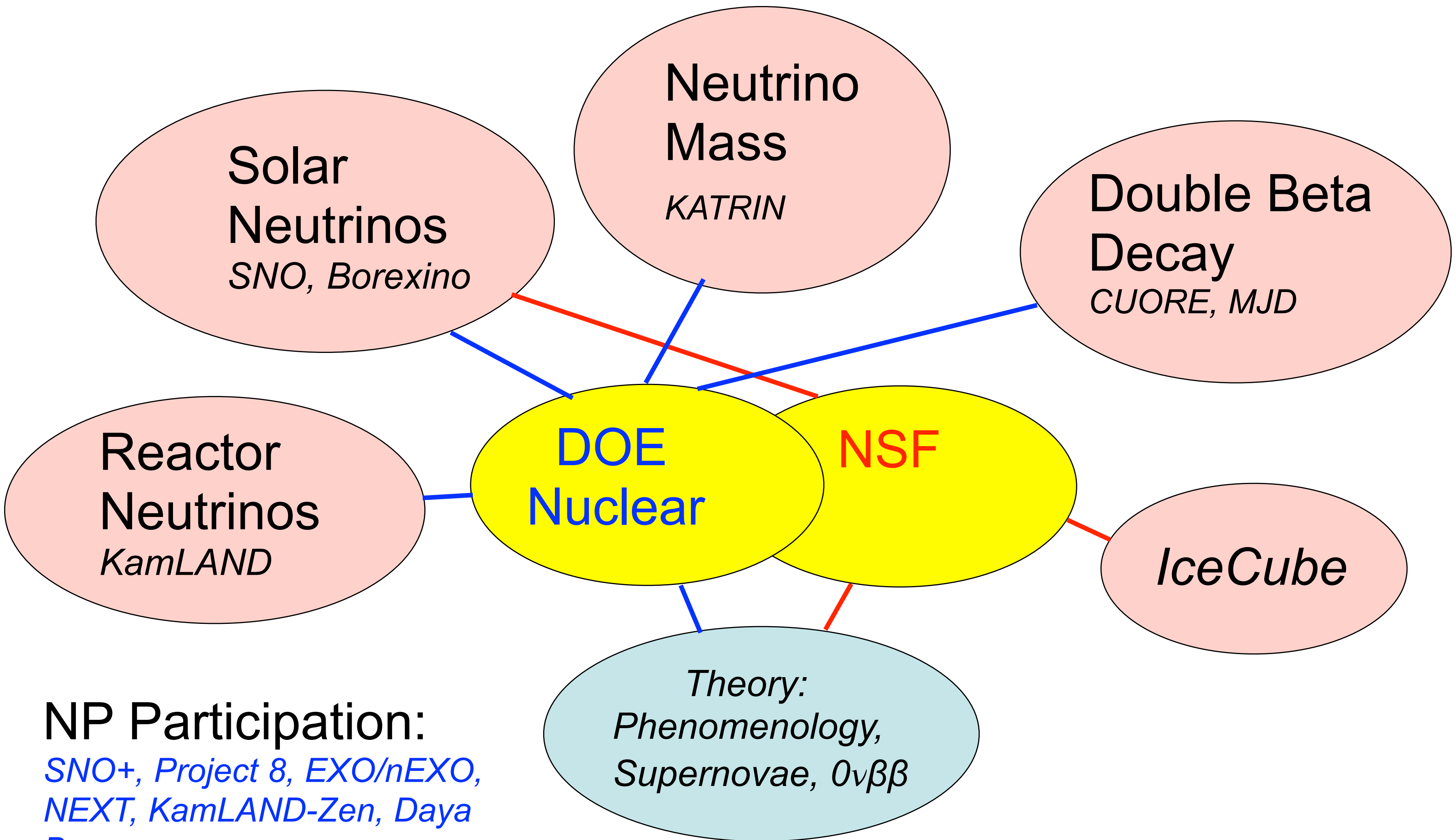
We do!

- The recommendation on underground laboratory from LRP 2007 has been realized (although not exactly as originally envisioned). Its importance was reaffirmed in the recent LRP 2007 implementation review

- Sanford Underground Research Facility (SURF) is a new asset for the scientific community:
  - Deepest underground laboratory in the US
  - Attracted $75M in private funding
  - Hosting MAJORANA DEMONSTRATOR (NP), LUX (HEP), and experiments from other fields

- Other facilities are also playing important roles in the field.

The Neutrino Portfolio in DOE-NP and NSF



NP Participation:

SNO+, Project 8, EXO/nEXO, NEXT, KamLAND-Zen, Daya Bay.

Future "tonne-scale" neutrinoless double beta decay program to be stewarded by DOE-NP. Current R&D supported by DOE-NP, DOE-HEP and NSF.

Recent studies/reviews

- Report to NSAC on Implementation of 2007 LRP ("Tribble subommittee", 2013.01):

  "The subcommittee is **unanimous** in reaffirming the LRP vision for the field. Each of the recommendations is supported by an extremely compelling science case. If any one part is excised, it will be a significant loss to the U.S. in terms of scientific accomplishments, scientific leadership, development of important new applications, and education of a technically skilled workforce to support homeland security and economic development."

- DOE Office of Science "Facilities" Prioritization:

  Goal Statement: Prioritization of scientific facilities to ensure optimal benefit from Federal investments. By September 30, 2013, formulate a 10-year prioritization of scientific facilities across the Office of Science based on (1) the ability of the facility to contribute to world-leading science, (2) the readiness of the facility for construction, and (3) an estimated construction and operations cost of the facility.

  - "Tonne-scale" NDBD experiment is considered in this exercise.

Summary: The FS&N program in Nuclear Physics is

- **Discovery-oriented**
- **Diverse, vibrant and active**
- **Directing larger investments to efforts with significant potential payoff:**
  - $0\nu\beta\beta$ and other neutrino experiments
  - Fundamental symmetries (not discussed in this talk): nEDM, MOLLER, SoLID, Nab, equipment request for muon g-2...etc
- **Incompletely summarized. My apologies to those whose projects could not be mentioned due to the time constraint.**

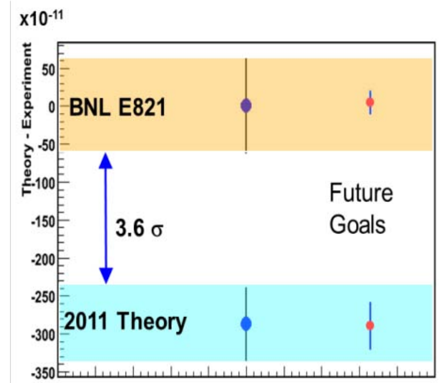
Backup slides

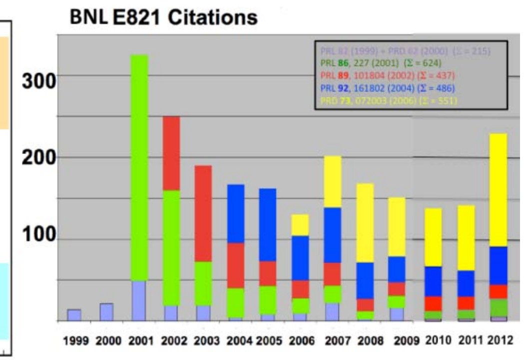
DOE Double Beta Decay: Comments

- DOE/Nuclear Physics is the steward for next-generation double beta decay experiments at DOE.
- DOE/HEP, however, is supporting EXO-200 for historical reasons, along with DOE/NP research and NSF support
- DOE/HEP (along with NSF) also is supporting all the R&D activities for the proposed 1-tonne scale next generation EXO, "nEXO."
- DOE/HEP and NP will establish a joint process to determine a selection process that involves both HEP and NP communities.
- After the time of selection, DOE/NP will become the sole DOE office supporting next-generation DBD projects.

The Muon g-2 Experiment http://dev.xenomedia.com:13089//

soon to be http://muon-g-2.fnal.gov/

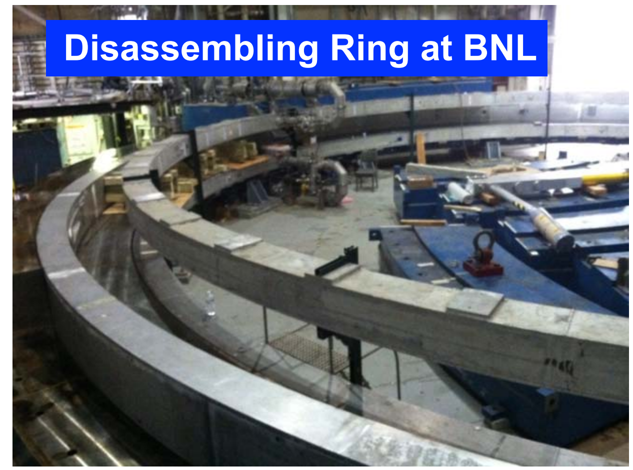




- **Goal: To definitively determine whether**

$$a_\mu = \frac{(g-2)_\mu}{2}, \text{ where } \vec{\mu}_\mu = g_\mu \left(\frac{Qe}{2m}\right) \vec{s},$$

is inside or outside of the Standard Model



- **a_μ is sensitive to: SUSY, the dark photon (secluded U(1)), anomalous couplings, Randal Sundrum type SM extensions, etc.**

- **CD0 in September 2012, preparing CDR**
- **Ring being disassembled at BNL**
- **Relocate storage ring to FNAL**
  - **Coils move in June 2013**
- **New detectors & electronics**
- **Magnet shimming in 2015**
- **First data in 2016**

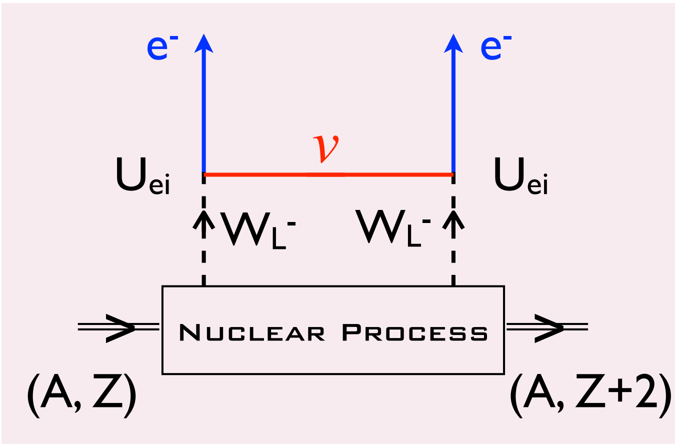
D. Hertzog & L. Roberts

0νββ and LNV Mechanisms

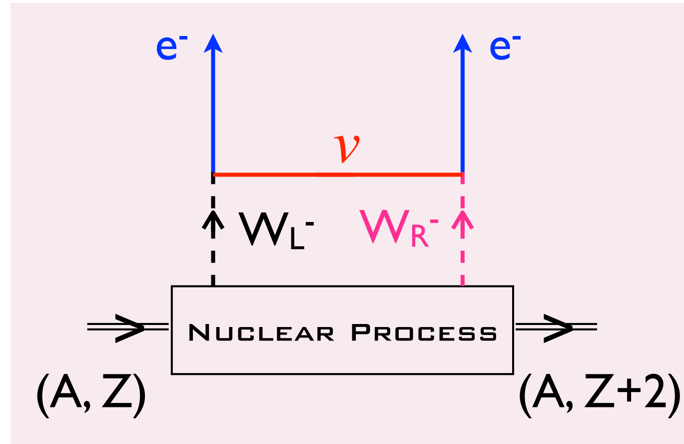
P. Vogel

A number of underlying mechanisms are possible, all could contribute.

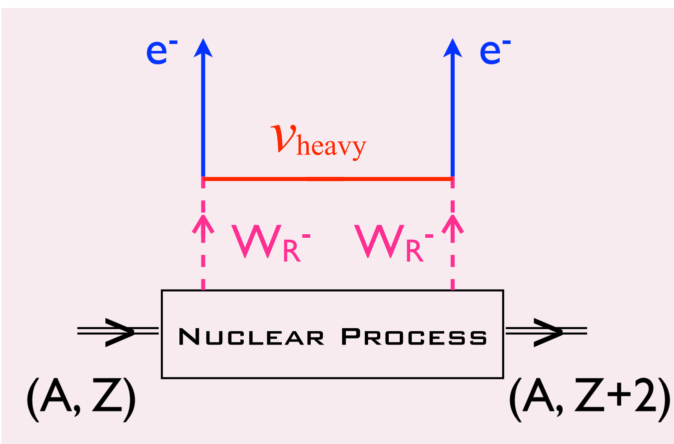
- light Majorana neutrino exchange, SM



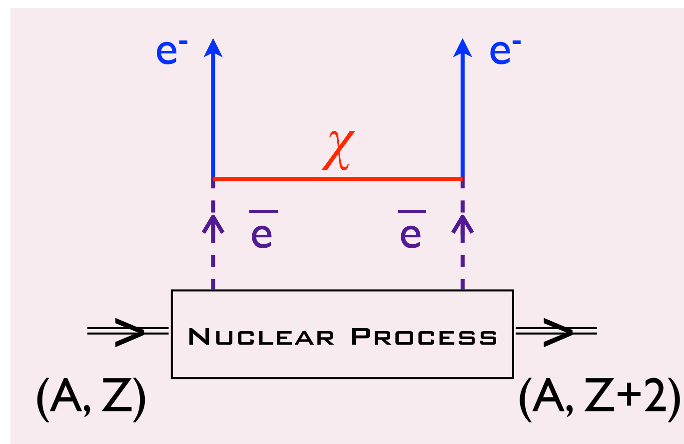
- light or heavy Majorana neutrino exchange, extension to include RH W



- Heavy Majorana neutrino with RH W, extension to include right handed currents



- Supersymmetry, with R parity violation, (selectron and neutralino exchange)



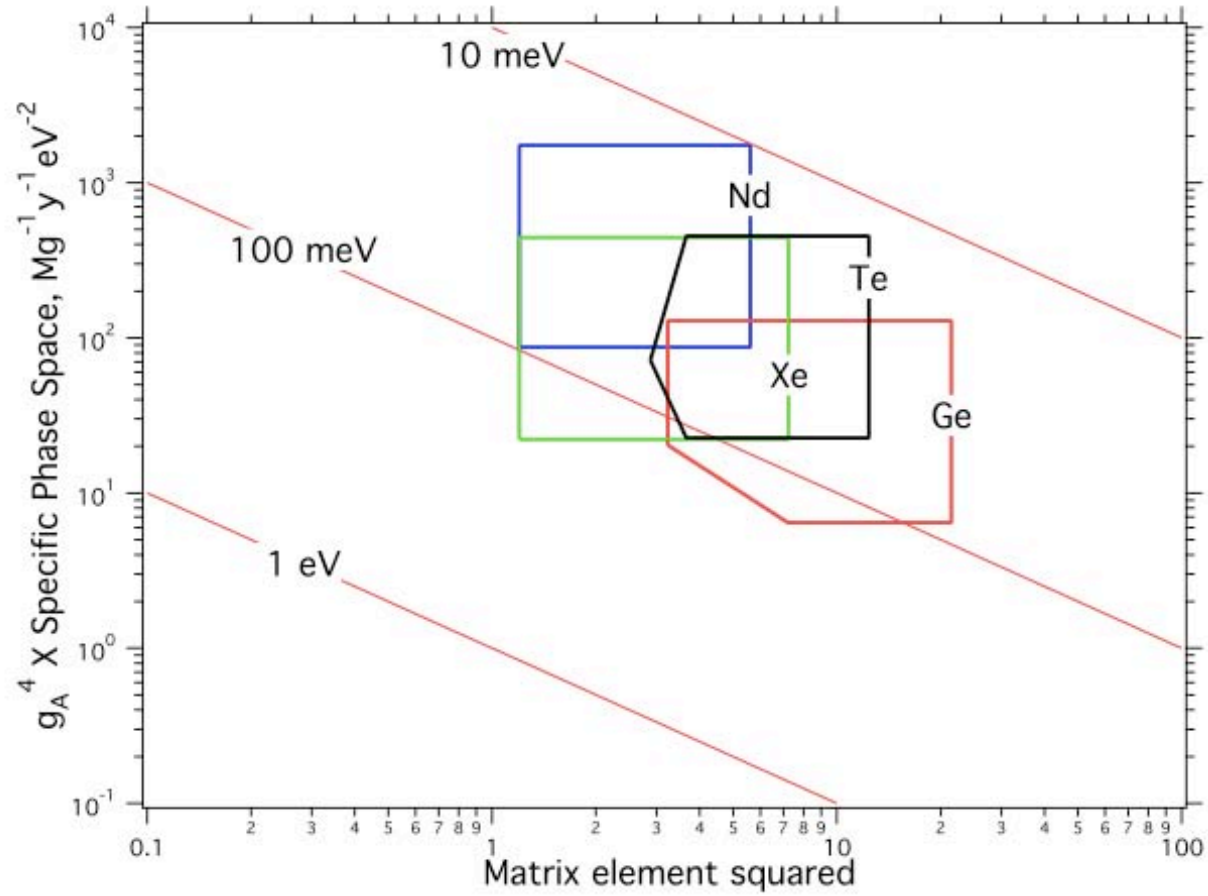
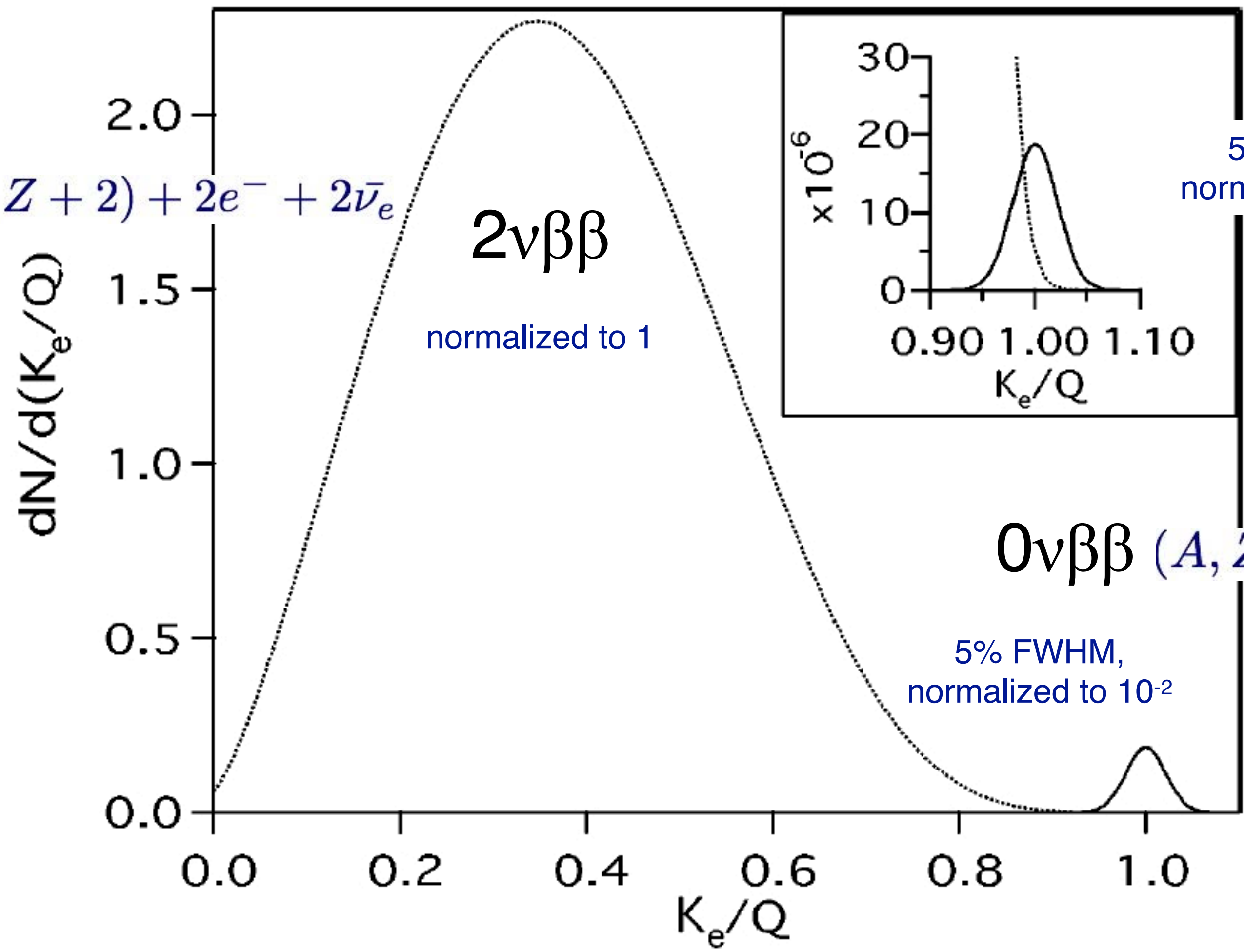


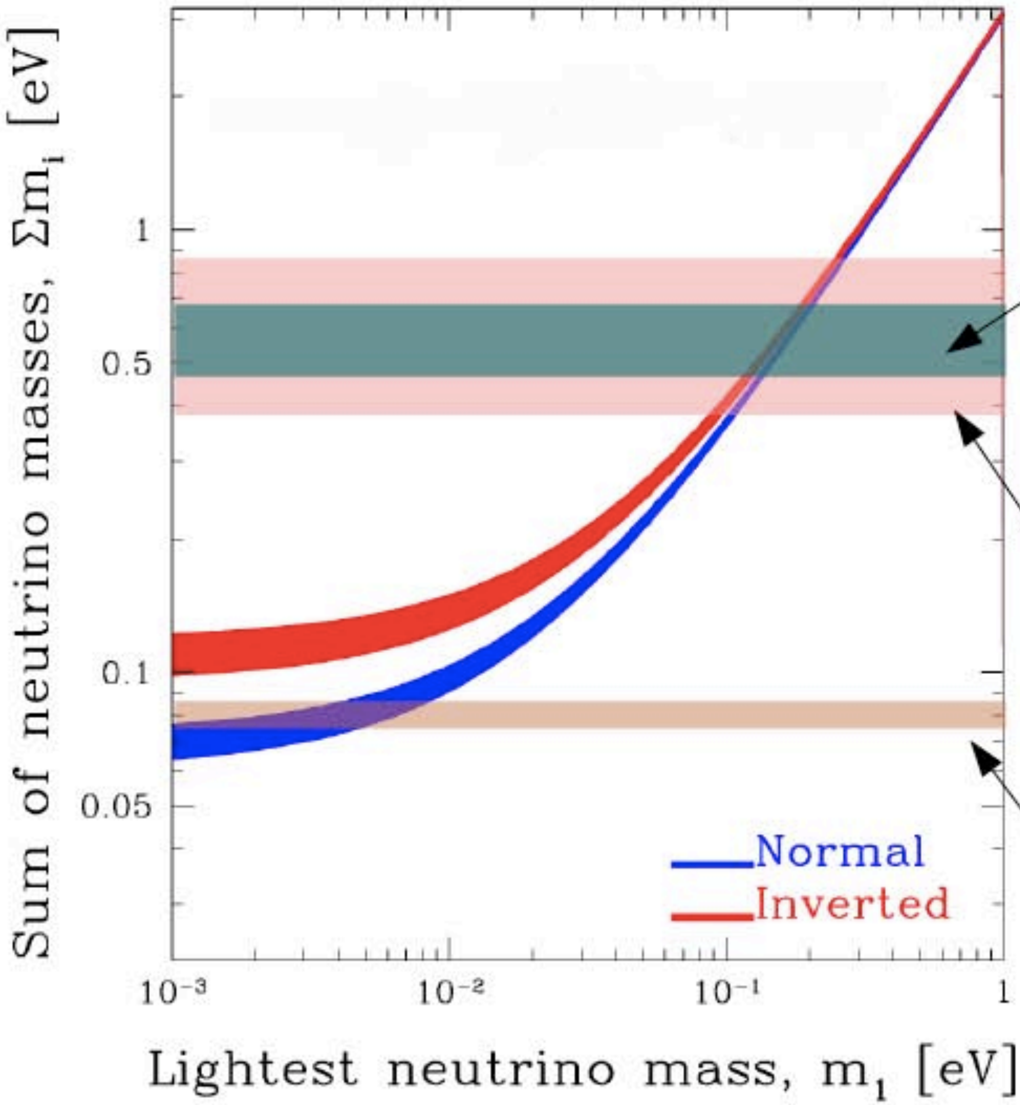
Fig. 1. Regions in the renormalized specific phase space $g_A^4 H_{0\nu} = g_A^4 \ln(2) \frac{N_A}{A m_e^2} G_{0\nu}^{(0)}$ and matrix element squared $|M_{0\nu}|^2$ that encompass modern theoretical calculations, for the candidate neutrinoless double beta decay isotopes ^{76}Ge, ^{130}Te, ^{136}Xe, and ^{150}Nd. The vertical span reflects the range of g_A, which differs for the shell model and other models, leading to non-rectangular boundaries. The matrix-element calculational methods are shell model (SM), generator-coordinate method (GCM), quasiparticle random-phase approximation (QRPA), interacting boson model (IBM), and Projected Hartree-Fock Bogoliubov method (PHFB), as given in Table 1. The lines indicate the effective Majorana mass that would correspond to a count rate of 1 event per tonne per year.

arXiv:1301.1323v1

Double Beta Decay Signal



Present constraints and future sensitivities...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ HST+SNIa

$$\sum m_\nu < 0.44 \rightarrow 0.76\,\text{eV} \quad (95\%\,\text{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y[3]W 2010
Gonzalez-Garcia et al. 2010, etc.

Planck alone (1 year)

$$\sum m_\nu < 0.38 \rightarrow 0.84\,\text{eV} \quad (95\%\,\text{CI})$$

Perotto et al. 2006

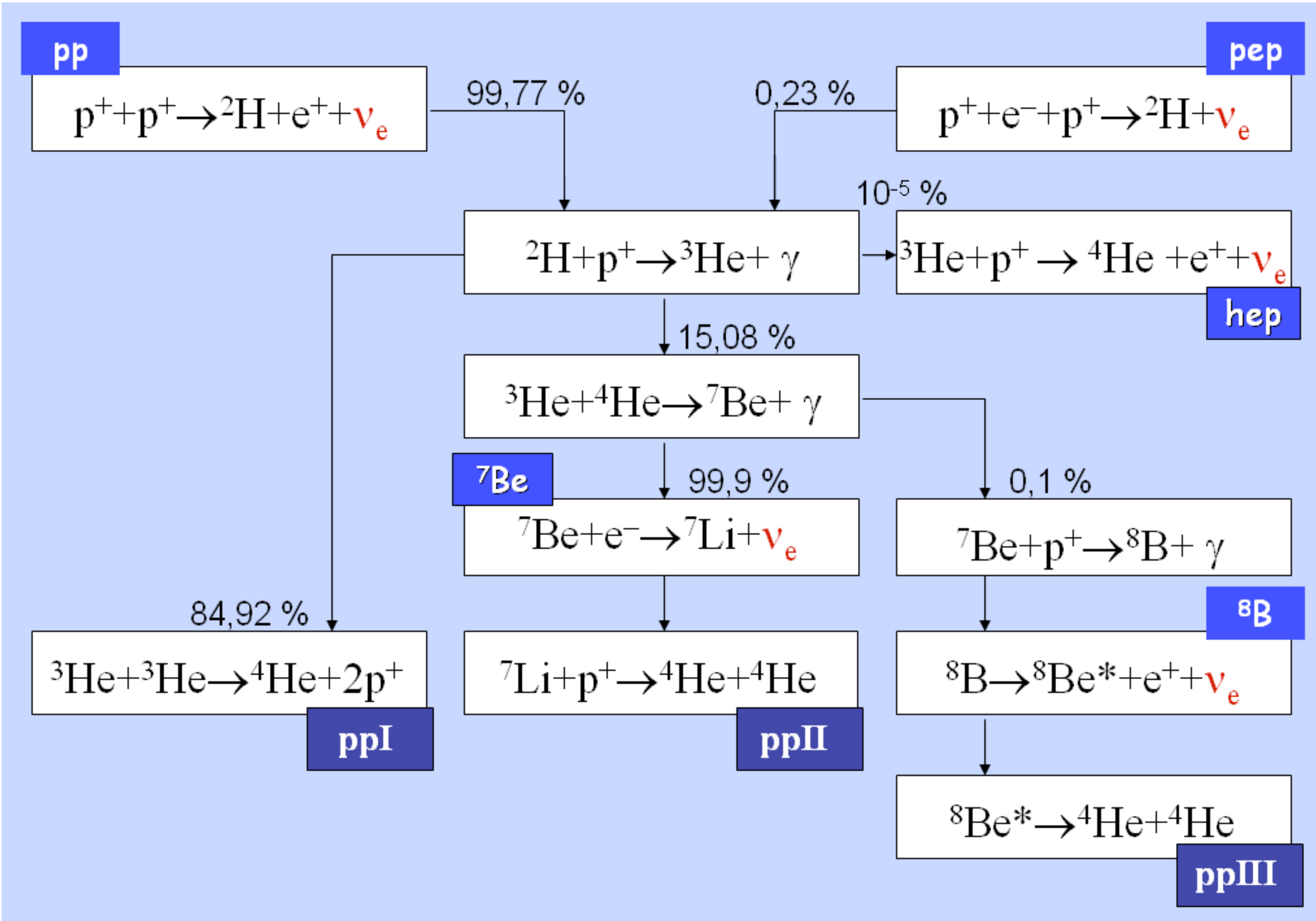
Planck+Weak lensing (LSST)

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\text{eV} \quad (95\%\,\text{CI})$$

Hannestad, Tu & Y[3]W 2006

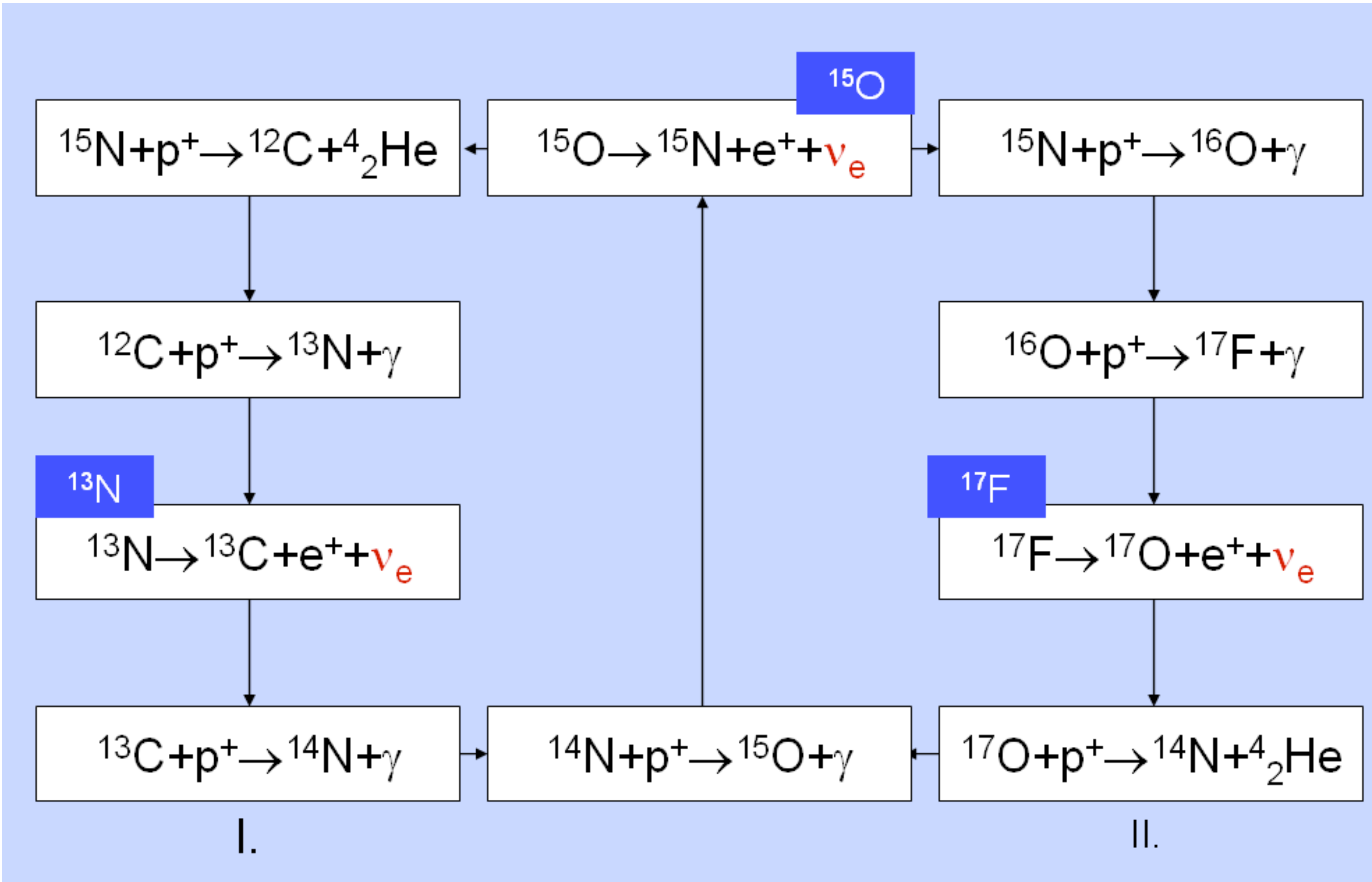
Yvonne Wong

The *pp* chain



graphics from Wikicommons

CNO cycle



graphics from Wikicommons