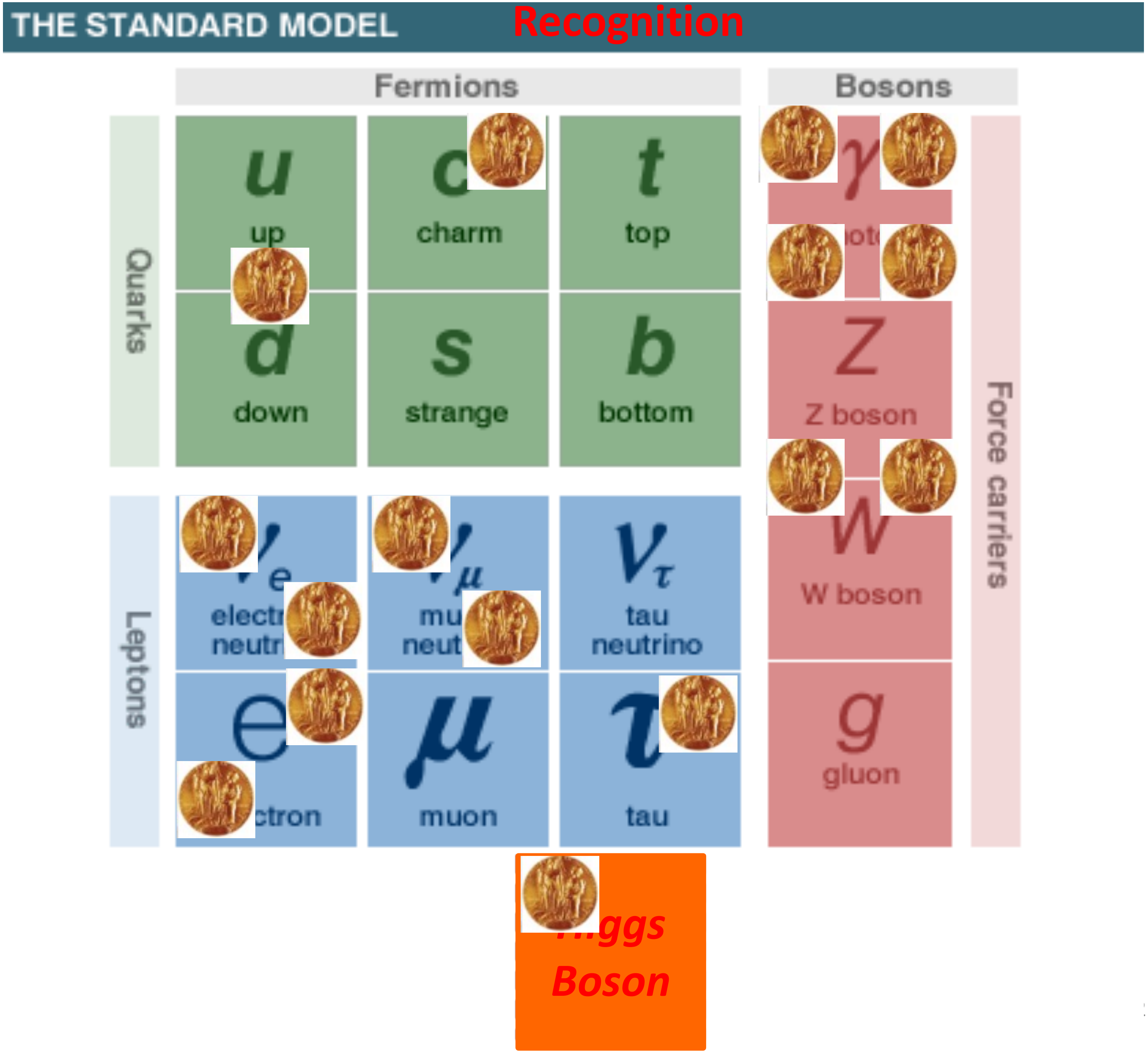
Neutrinos, ORNL, and Nuclear Physics

Yuri Efremenko

EBSS-2019

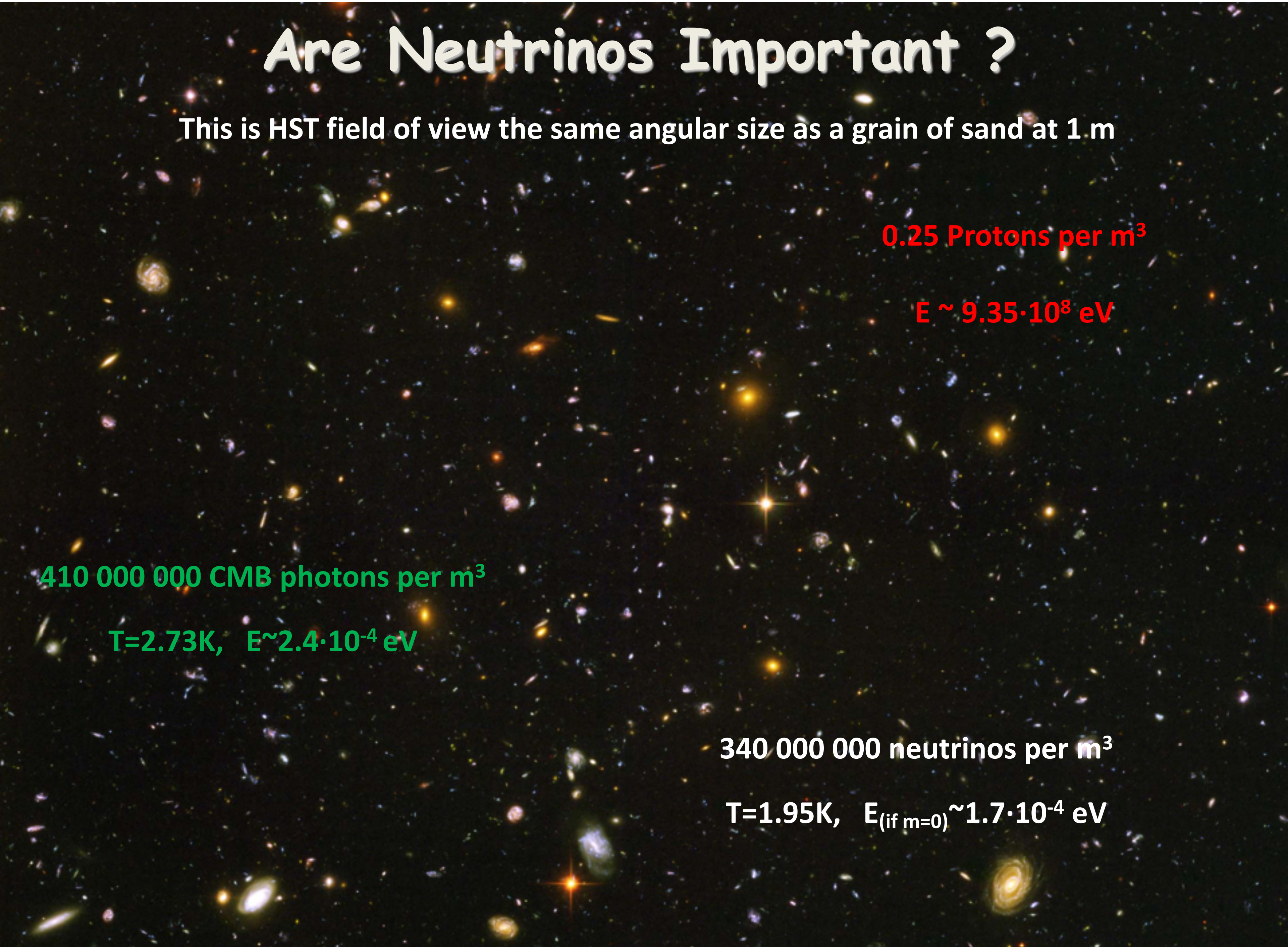
June 28th



THE STANDARD MODEL
Recognition
Fermions
Bosons
Quarks
Leptons
Force carriers
u
up
c
charm
t
top
d
down
s
strange
b
bottom
ν_τ
tau
neutrino
μ
muon
τ
tau
Z
Z boson
W
W boson
g
gluon
Boson

Are Neutrinos Important ?

This is HST field of view the same angular size as a grain of sand at 1 m



0.25 Protons per m^3

$E \sim 9.35 \cdot 10^8$ eV

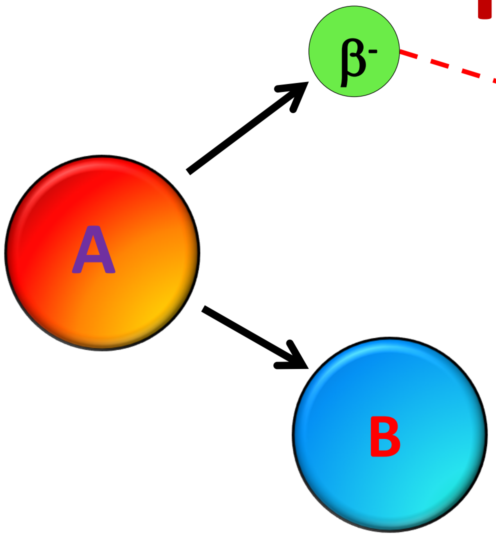
410 000 000 CMB photons per m^3

$T = 2.73K$, $E \sim 2.4 \cdot 10^{-4}$ eV

340 000 000 neutrinos per m^3

$T = 1.95K$, $E_{(if\ m=0)} \sim 1.7 \cdot 10^{-4}$ eV

Neutrino Discovery



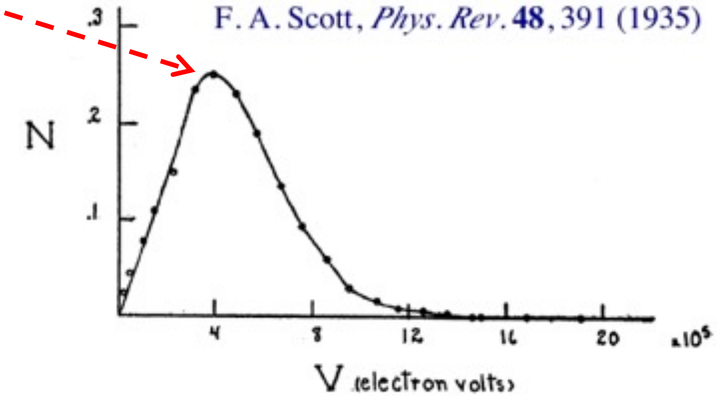
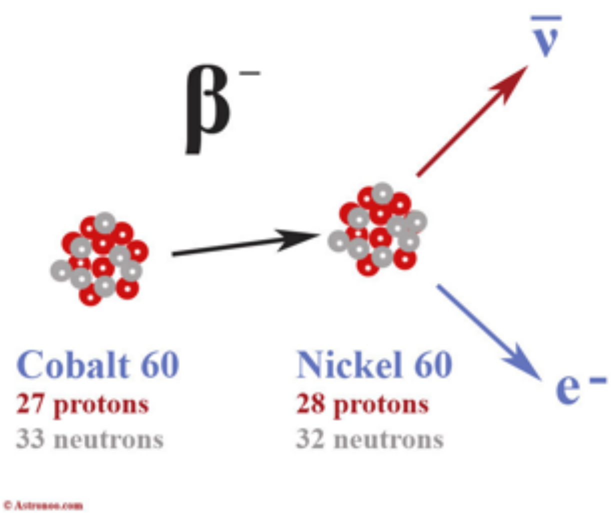
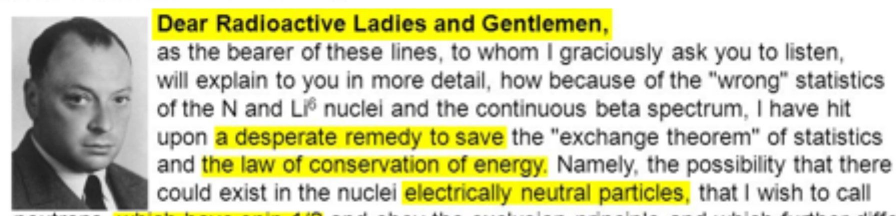


Fig. 5. Energy distribution curve of the beta-rays.

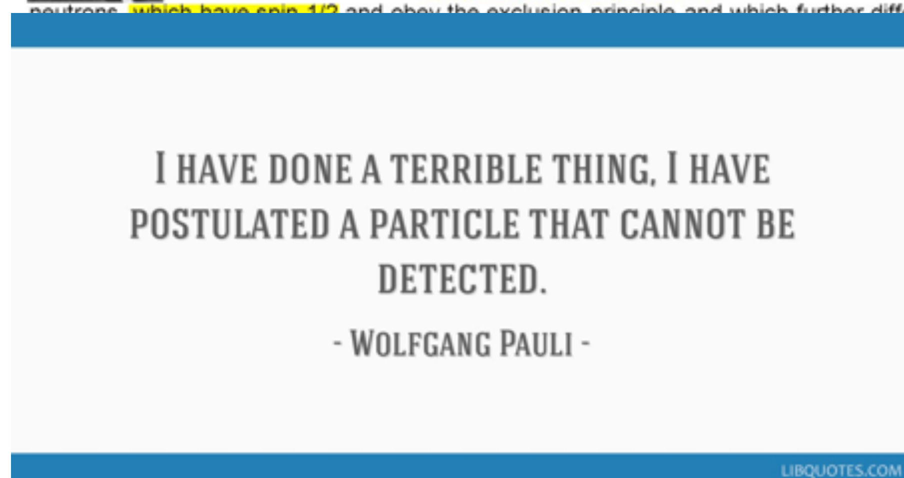
Niels Bohr suggested that perhaps energy conservation did not hold inside the nucleus





Dear Radioactive Ladies and Gentlemen,

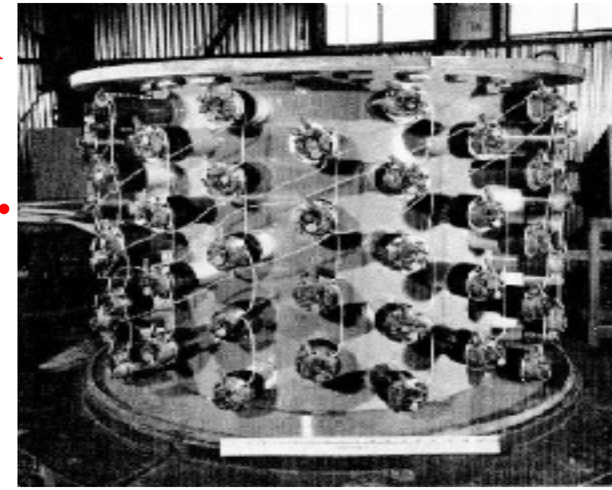
as the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call



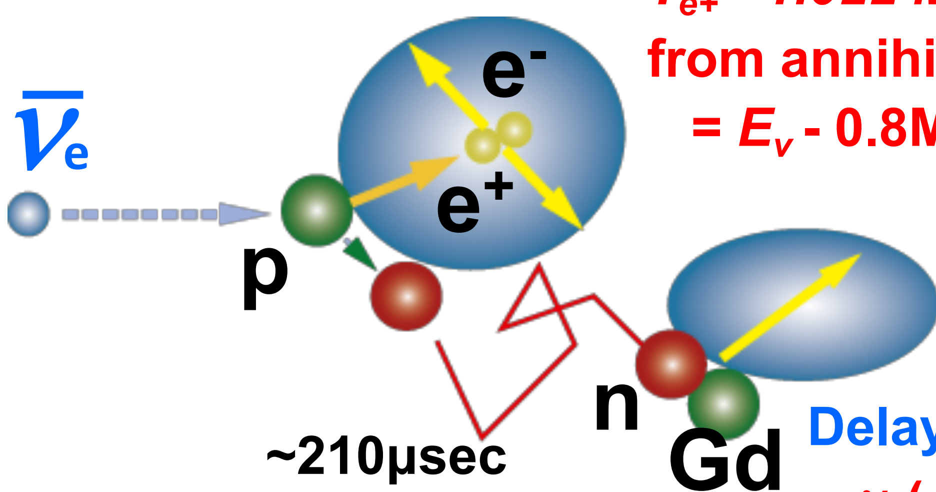
First Detection of Neutrinos

First neutrino detection from nuclear reactor Reines and Cowan 1956.

(took 25 years since prediction)



Inverse beta decay



Prompt signal

T_{e+} + 1.022 MeV from annihilation = E_ν - 0.8MeV

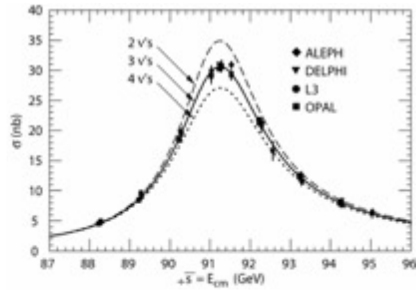
Delayed signal

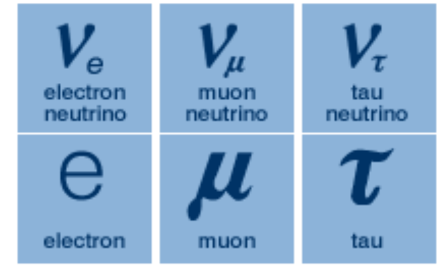
γ (~8 MeV)

Two correlated light flashes In liquid scintillator

What do we Know About Neutrinos?

There are only three light neutrinos





Neutrinos can oscillate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 3} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

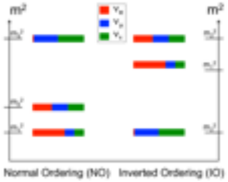
Neutrinos have non zero mass

We do not have any indications that neutrinos are not stable

What we do not know about neutrinos?

Exact mass value and why it is so small?

Neutrino Mass Ordering?

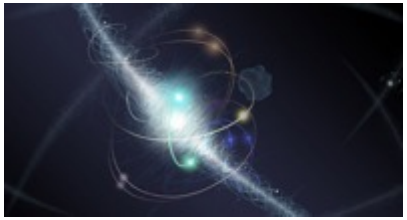


Is neutrino its own antiparticle?

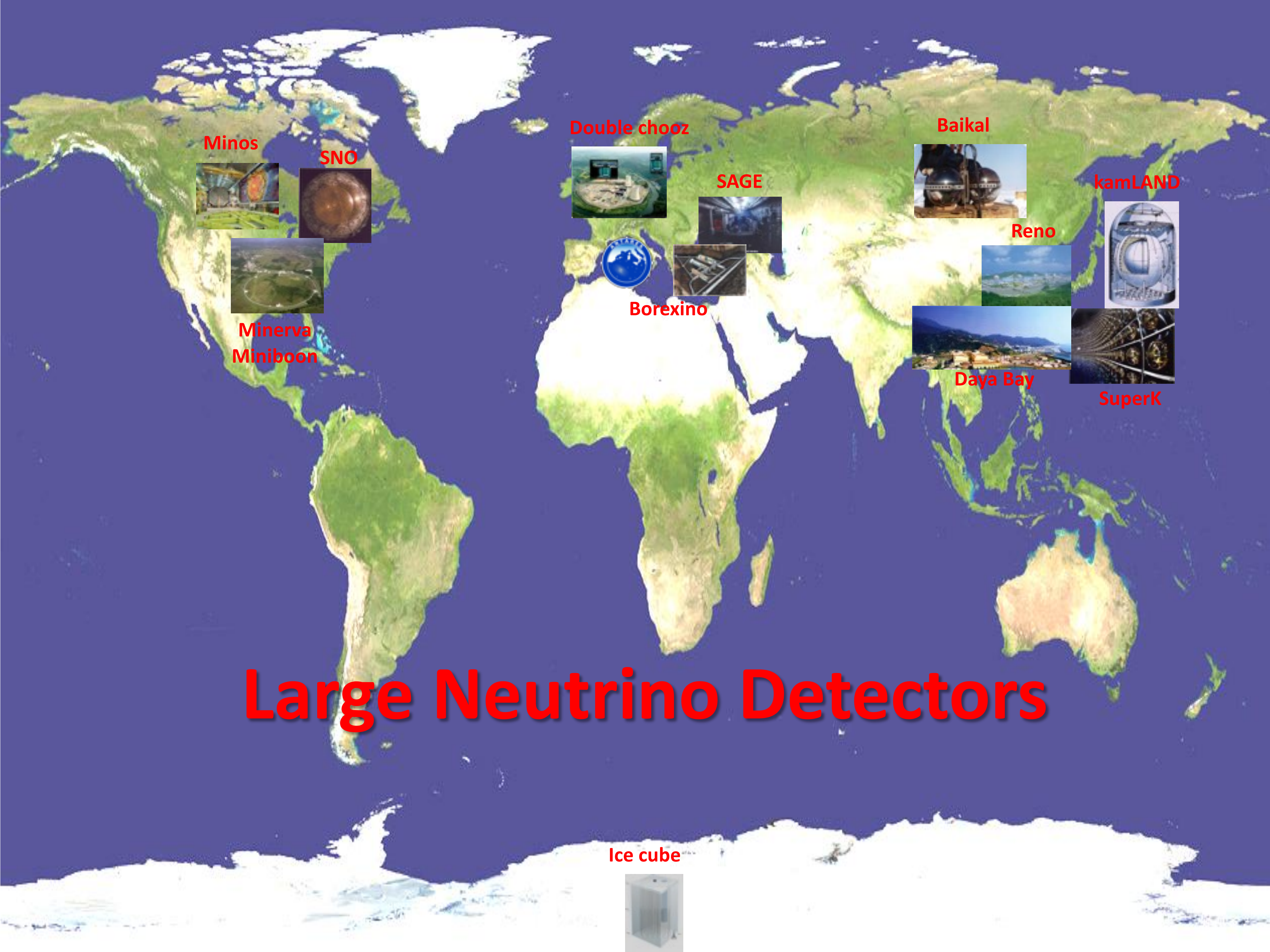
Can neutrino help to explain baryon asymmetry of the Universe

How neutrinos affect evolution of the universe?

Are neutrinos messengers of a new physics?

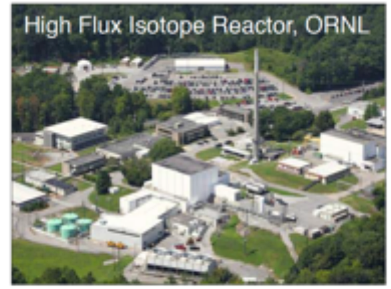


Large Neutrino Detectors

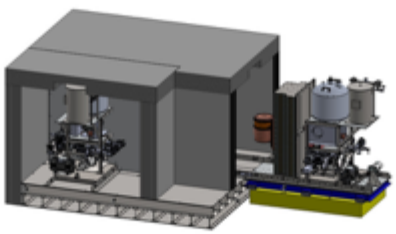


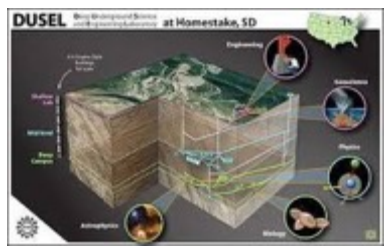
Neutrino Program at the ORNL

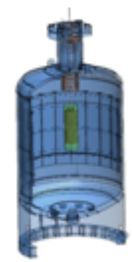
I. Study of Reactor Antineutrinos → PROSPECT experiment at HFIR

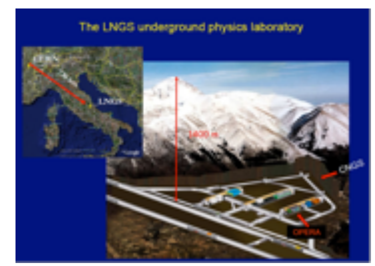


II. Search for Neutrino Mass → MAJORANA and LEGEND-200 experiments

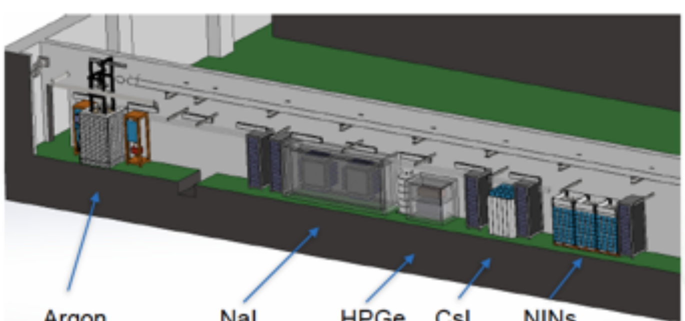








III. Search for New physics → COHERENT experiment at the SNS



Part I

Reactor Antineutrinos

Neutrino Oscillations

The idea of neutrino oscillations existed long before Davis experiment: Pontecorvo (1958), Maki, Nakagawa, and Sakata (1962), and Pontecorvo and Gribov (1969)

If m_ν is non-zero, then mixing between different neutrino flavors is possible

$$|\nu_j\rangle = \sum_j U_{jl} |\nu_l\rangle$$

What is produced and detected is weak eigenstate $|\nu_j\rangle$

U_{jl} is a 3 x 3 unitary matrix (like the CKM matrix for quarks)

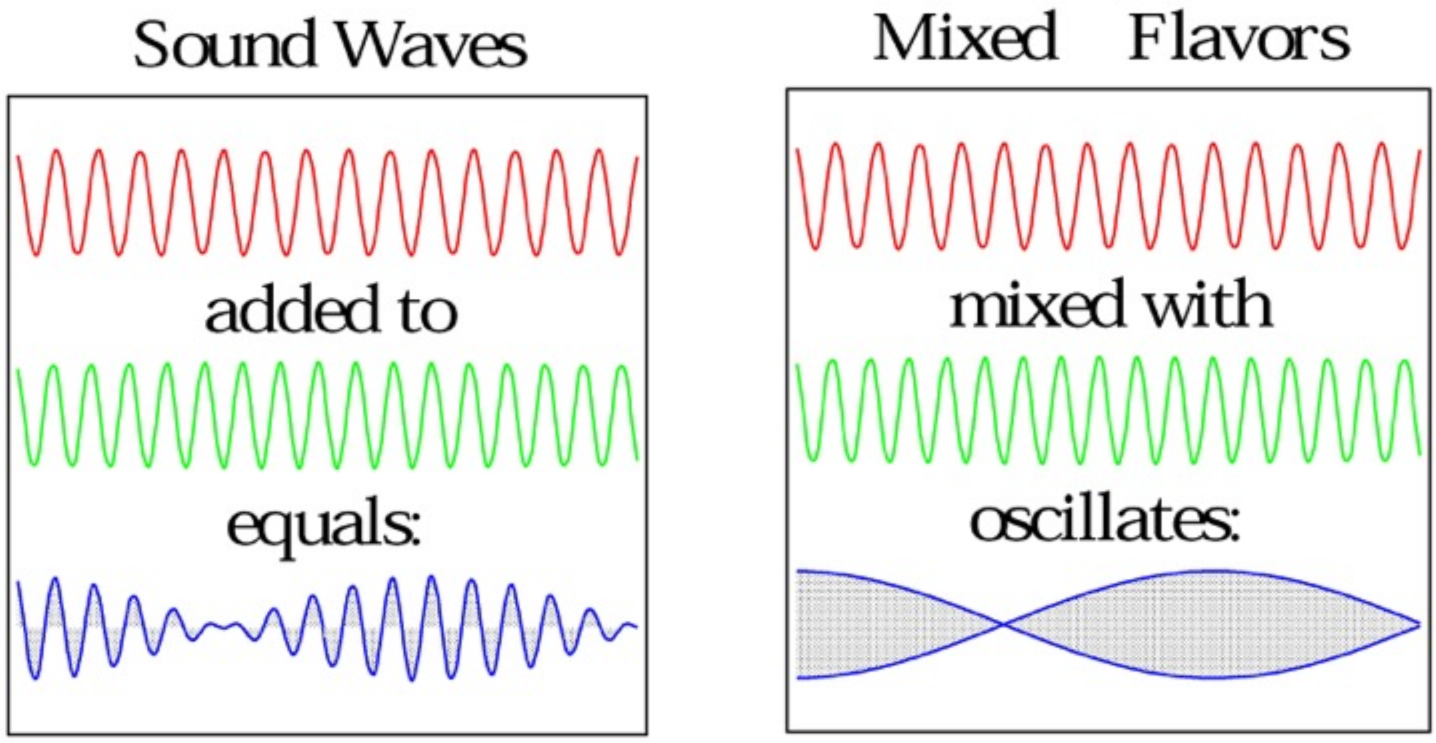
What propagates is the mass eigenstate $|\nu_l\rangle$

$$U_{jl} = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Simplified expression for two flavor oscillations in a vacuum:

$$P(\nu_l \rightarrow \nu_{l'}) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 (\mathrm{eV}^2) L(\mathrm{m}) / E_\nu (\mathrm{MeV}))$$

Neutrino oscillations are analogous to "beatings" in the sound waves



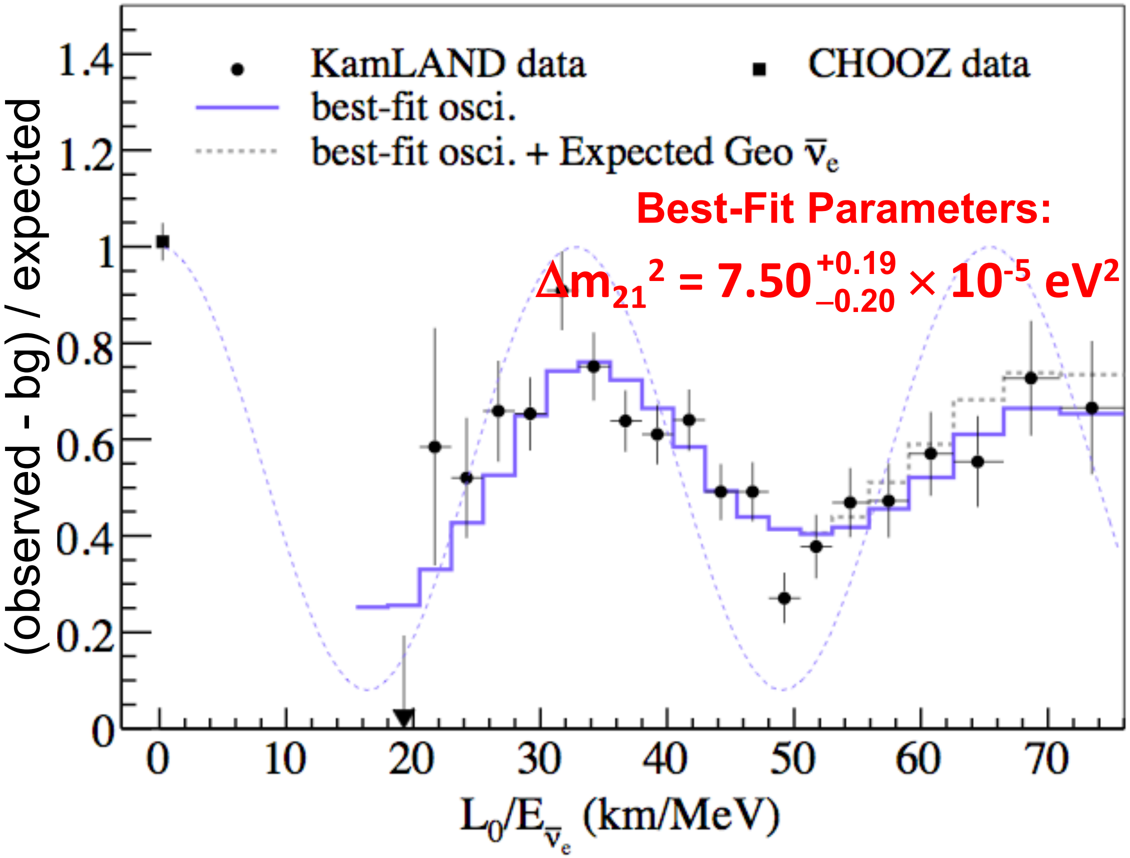
ν_1 wave-function

ν_2 wave-function

ν_e neutrino flux

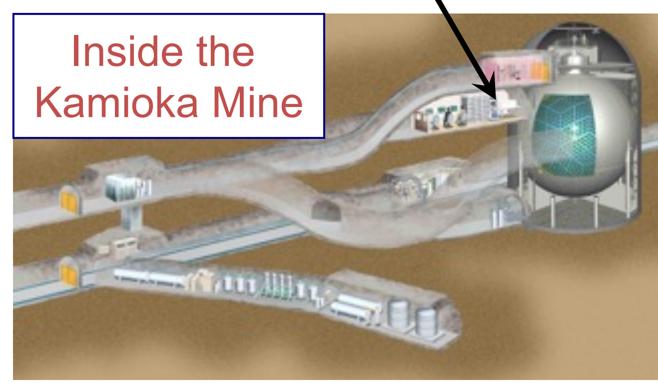
Long Baseline Oscillations

Data from March 2002 till November 2009



L = 180km flux-weighted average reactor distance

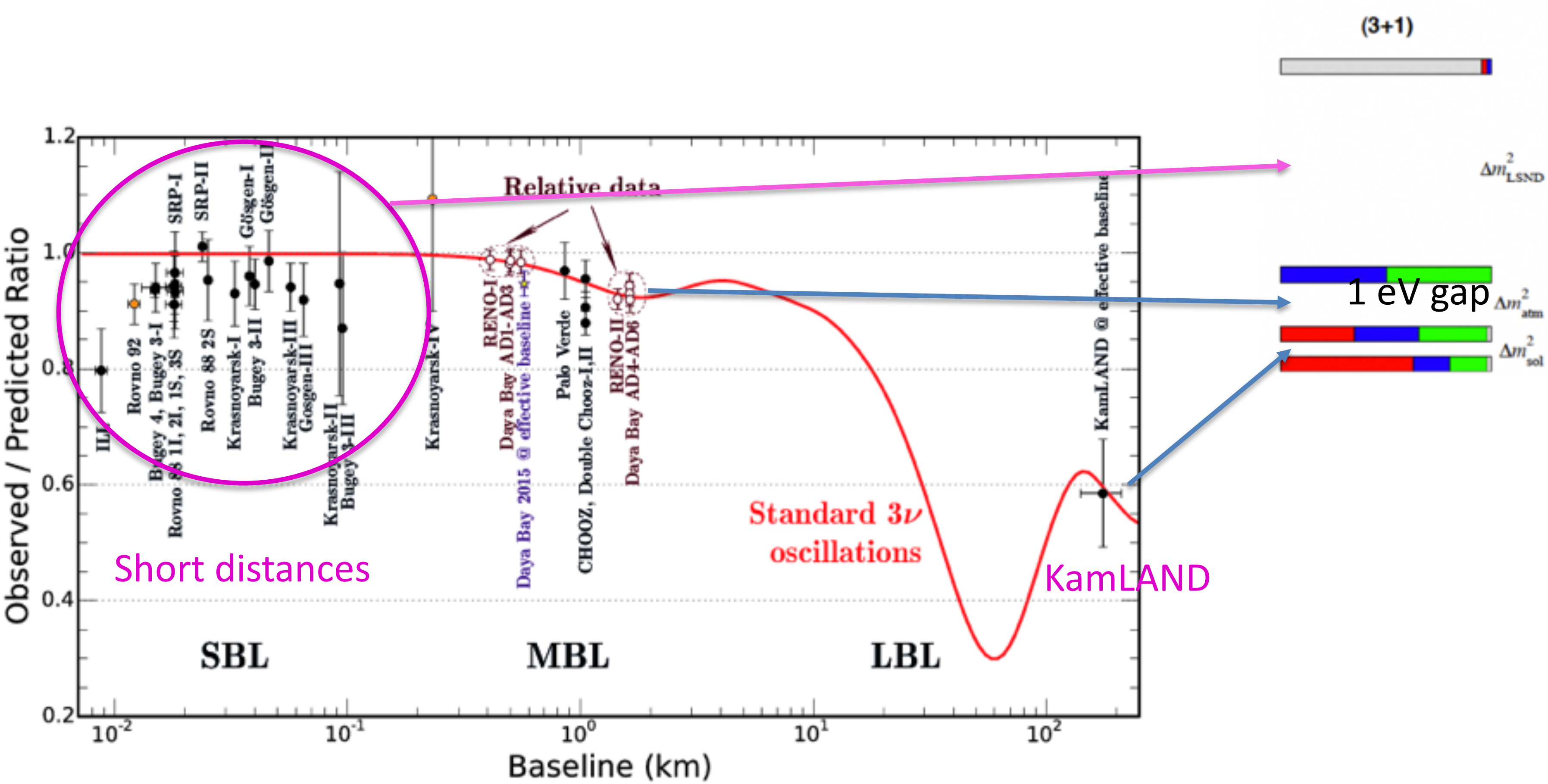
$$P(\nu_e \rightarrow \nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{1.27 \Delta m^2 L}{E}$$



KamLAND – 1 kt liquid scintillator detector

Reactor Antineutrino Anomaly (RAA)

Deficit of antineutrinos at a very short distances relative to predictions

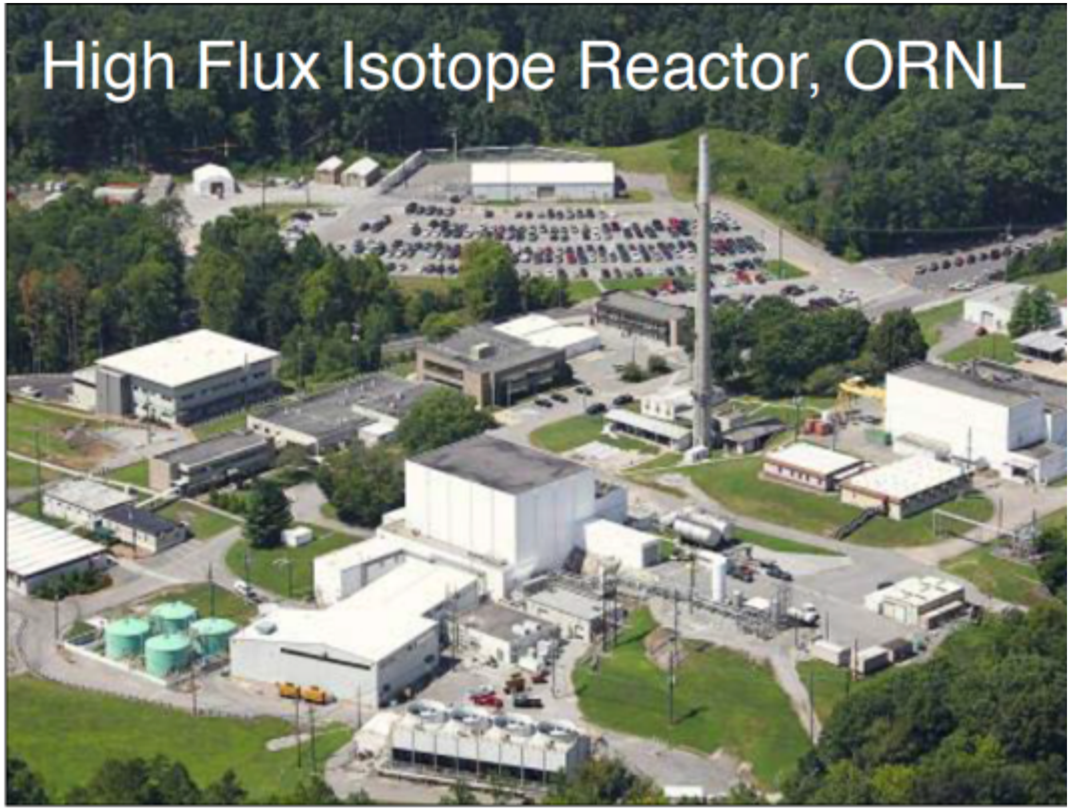


[Phys. Rev. D 83, 073006 (2011)]

$$P(\nu_e \to \nu_\mu, L) = \sin^2 2\theta \ \sin^2 \frac{1.27\Delta m^2 L}{E}$$

To explain RAA need one more type neutrino (sterile), or something is wrong with predictions

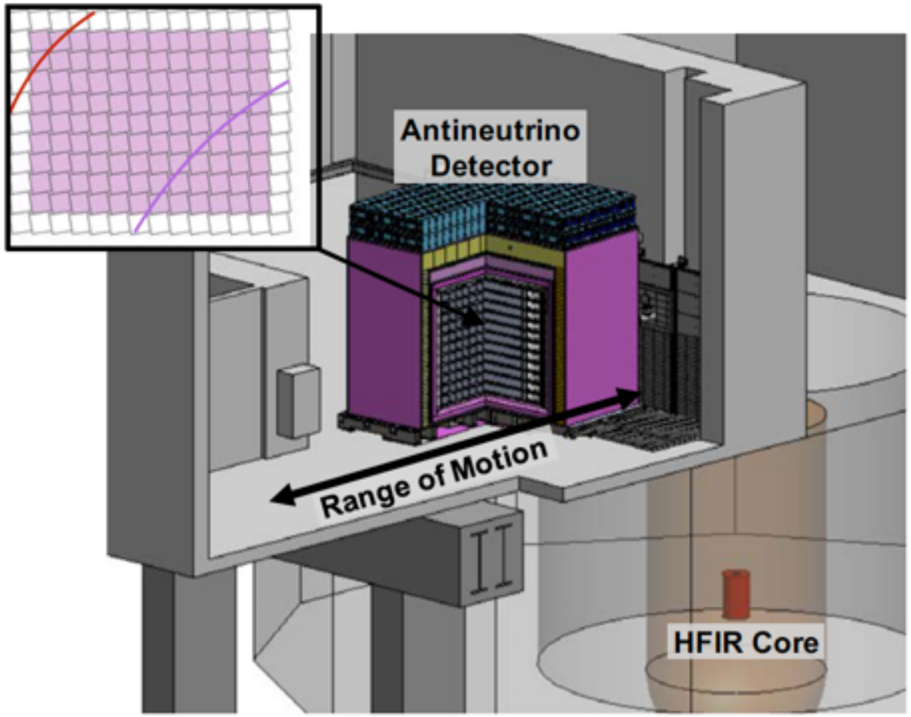
ORNL PROSPECT Experiment aim to resolve RAA

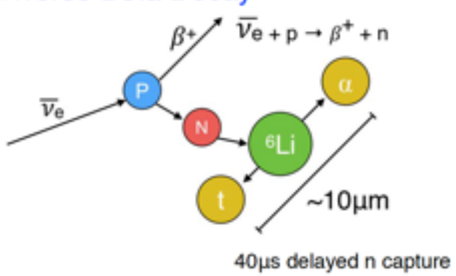


HFIR compact core (h=0.5m r=0.2m) served as a point like source of neutrinos

Use highly segmented detector to accumulate statistics for several distances at the same time

ORNL PROSPECT Experiment

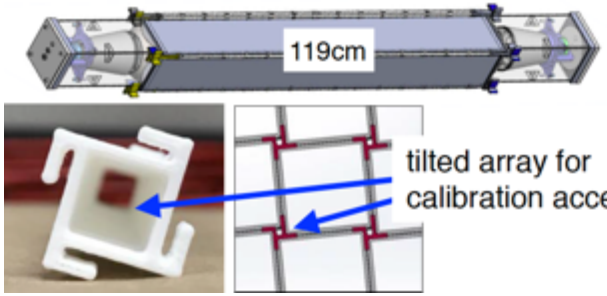




signal

inverse beta decay (IBD)

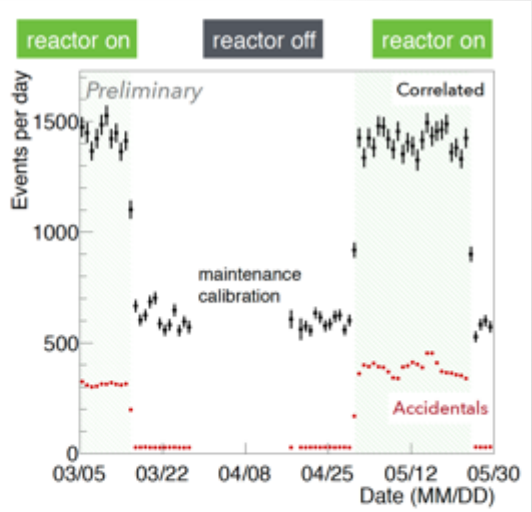
γ-like prompt, n-like delay

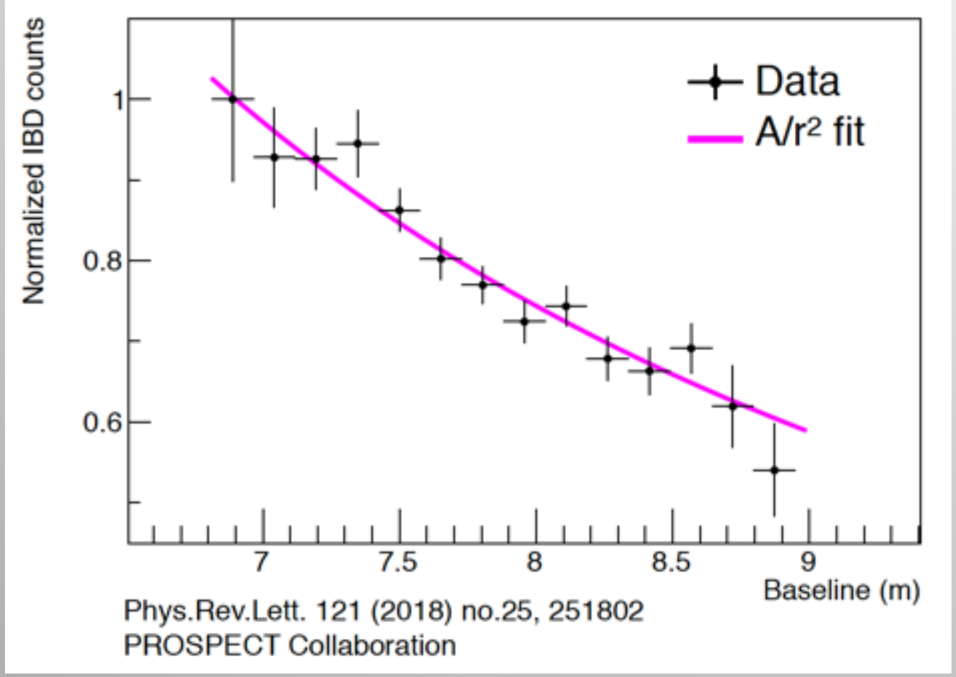


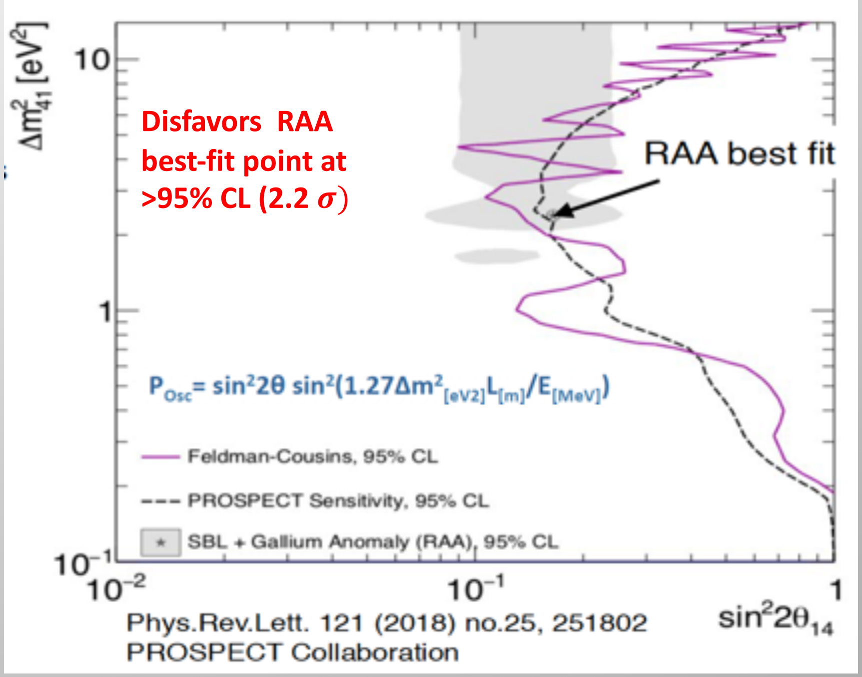
tilted array for calibration access

Prospect First Result

24 608 IBD events detected, average 750/day





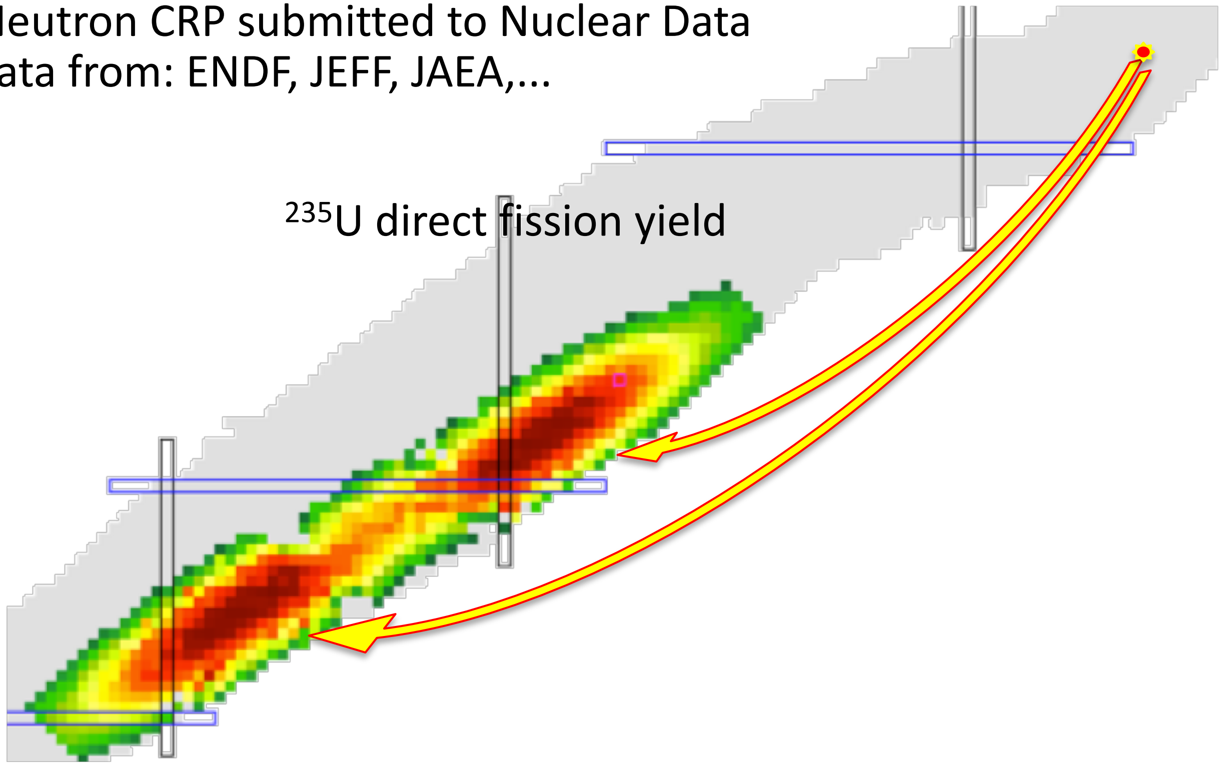


What nuclear data influence the reactor antineutrino flux prediction?

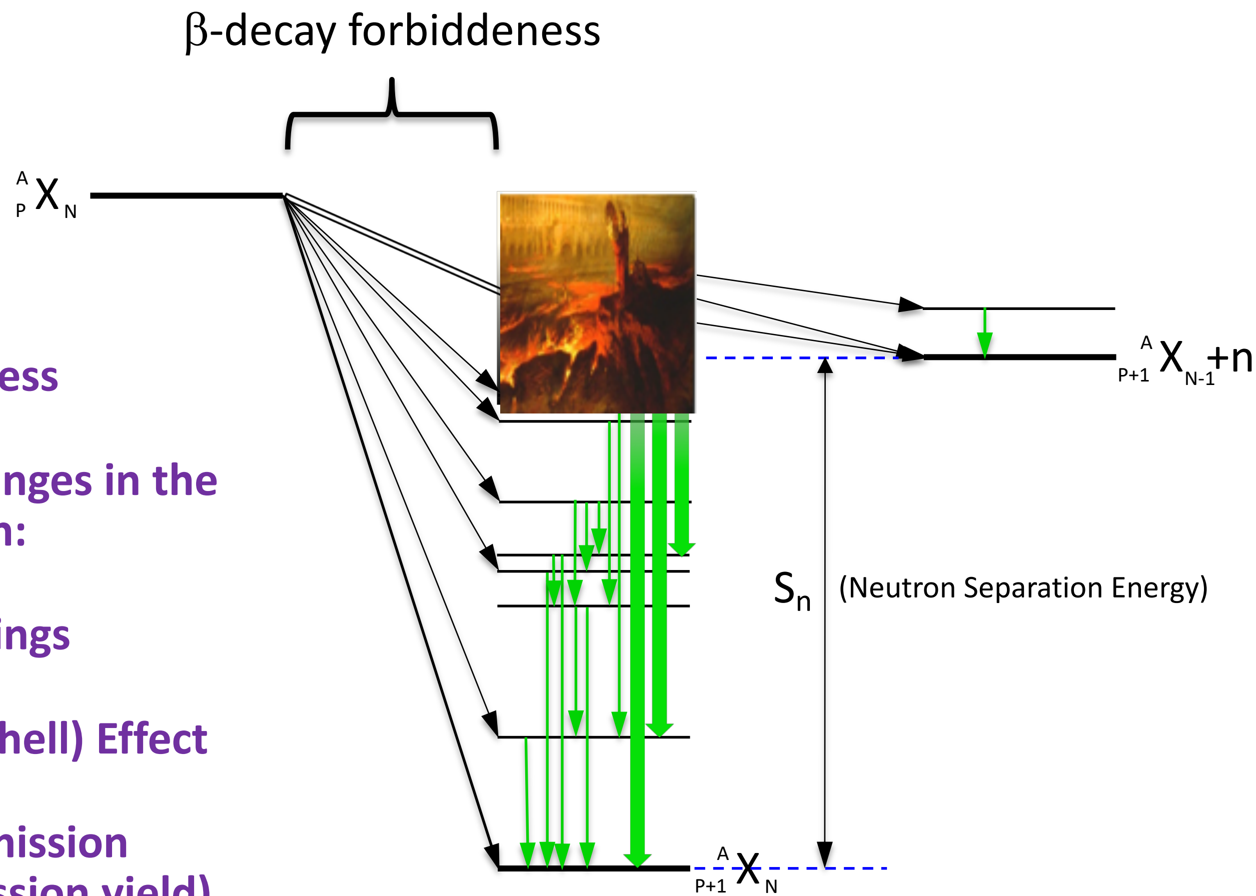
Changes in the fission yield, direct and cumulative

See β-Delayed Neutron CRP submitted to Nuclear Data
See Data from: ENDF, JEFF, JAEA,...

^{235}U direct fission yield



Need to Know all Decays into Excited States



β-decay forbiddeness

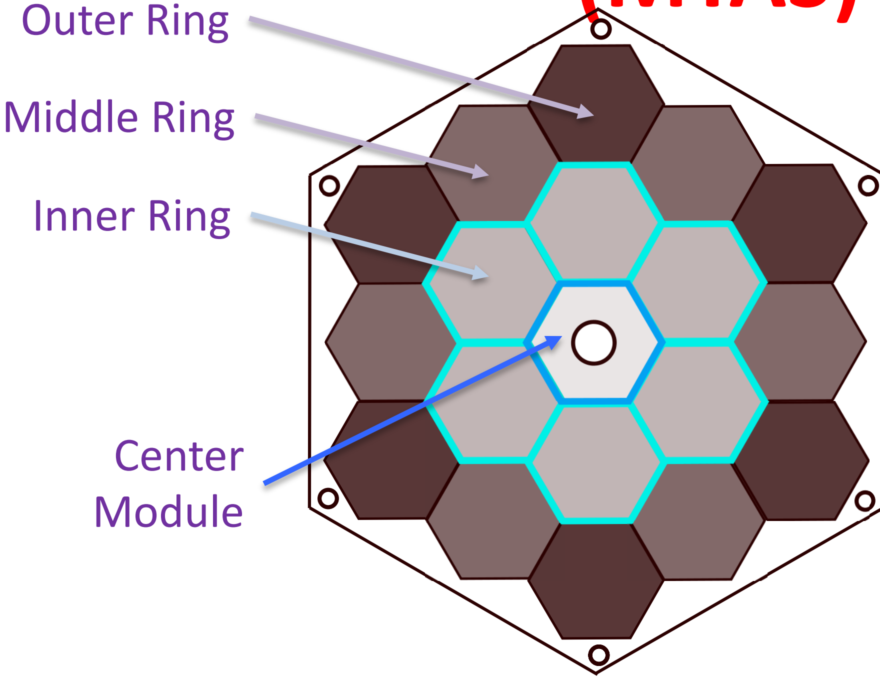
What can lead to large changes in the β-feeding pattern:

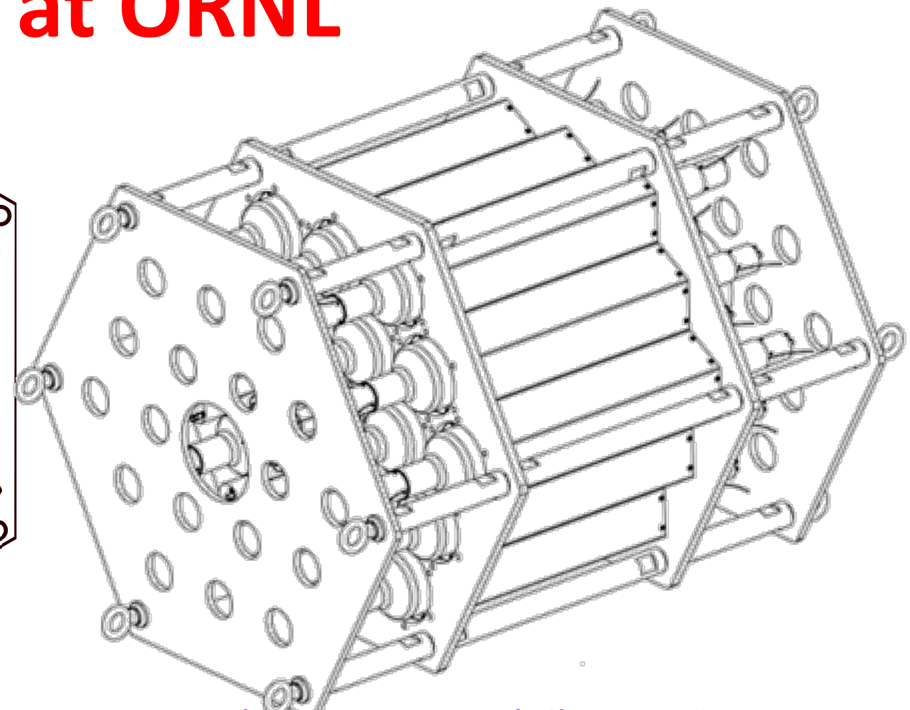
Ground State Feedings

Pandemonium (capital of hell) Effect

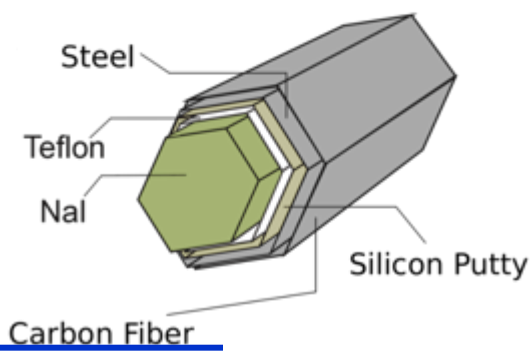
β-Delayed Neutron Emission (also affects cumulative fission yield)

Modular Total Absorption Spectrometer (MTAS) at ORNL





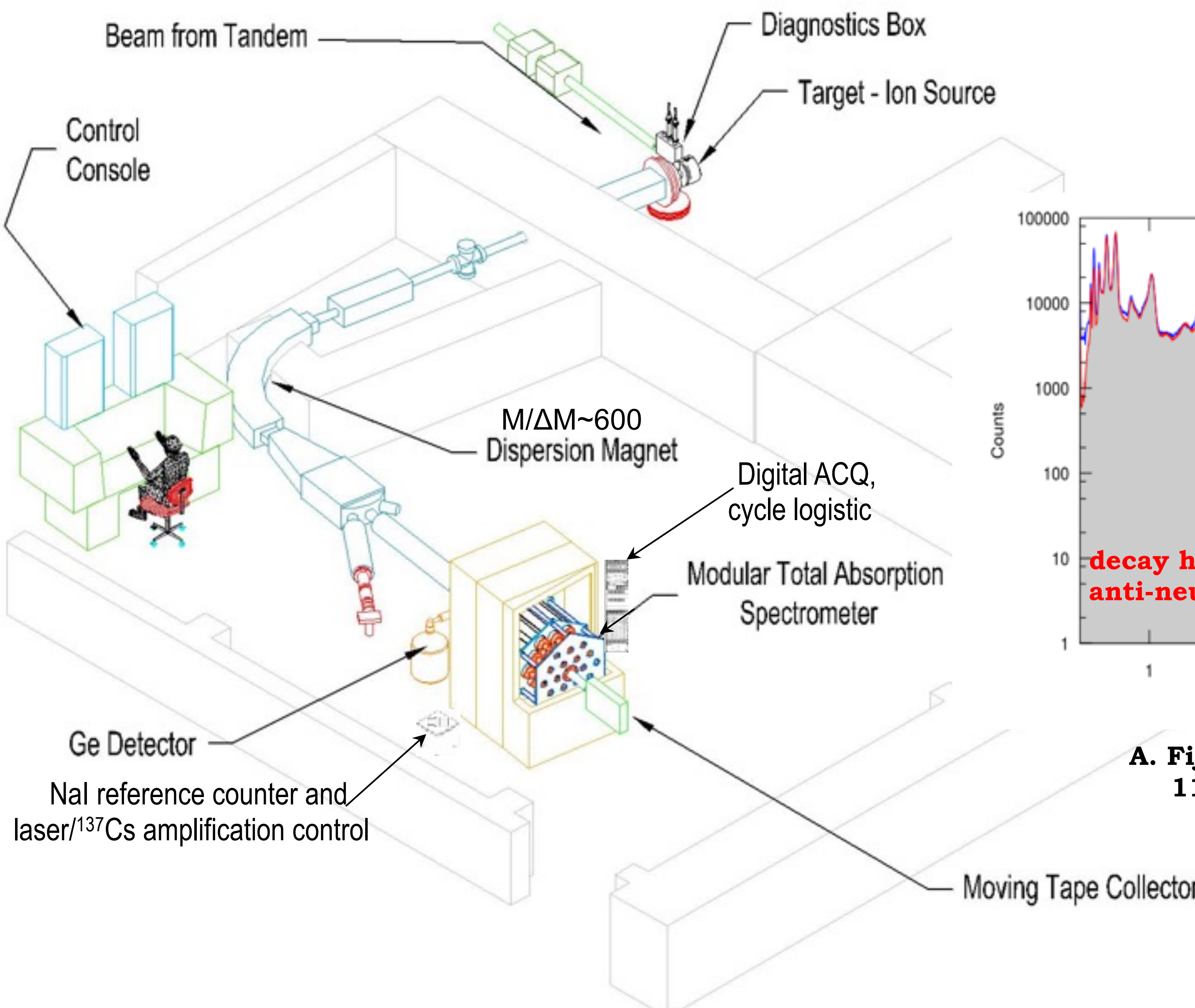
MTAS: 18 - 8”x 7”x 21” (20cm x 17.8cm x 53.3cm) hexagon NaI(Tl) modules

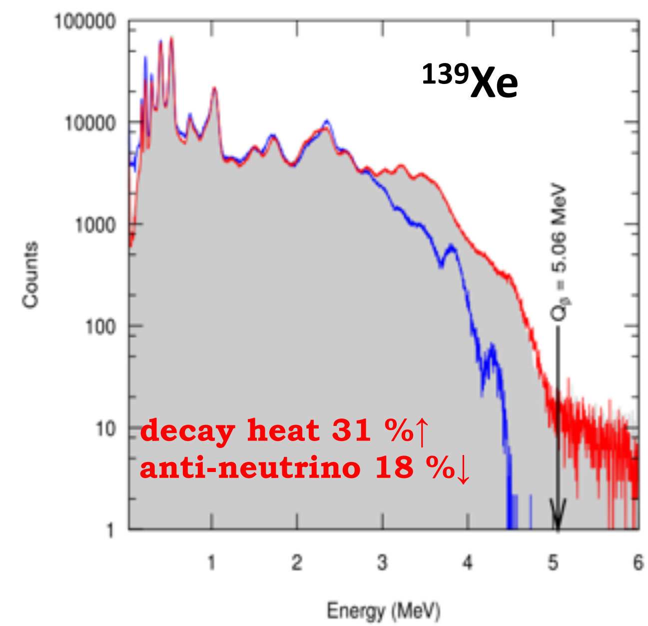


Organized in 3 Rings of 6 modules each (Inner, Middle, and Outer)
1 - Center module, same dimensions but with a 2.5” diameter hole
About 1 ton of NaI(Tl)!
Over 5 tons of lead shielding + neutron shielding
(even more at ANL!)

Other total absorption spectrometers include the Lucrecia, DTAS (Valencia, Jyvaskyla), SuN (MSU).

ORNL's Tandem, on-line mass separator and MTAS





A. Fijałkowska et al, PRL 119, 052503 (2017)

MTAS - higher mass fission peak ***(38 decays measured)***

January 2012, March, October-December 2015, January 2016

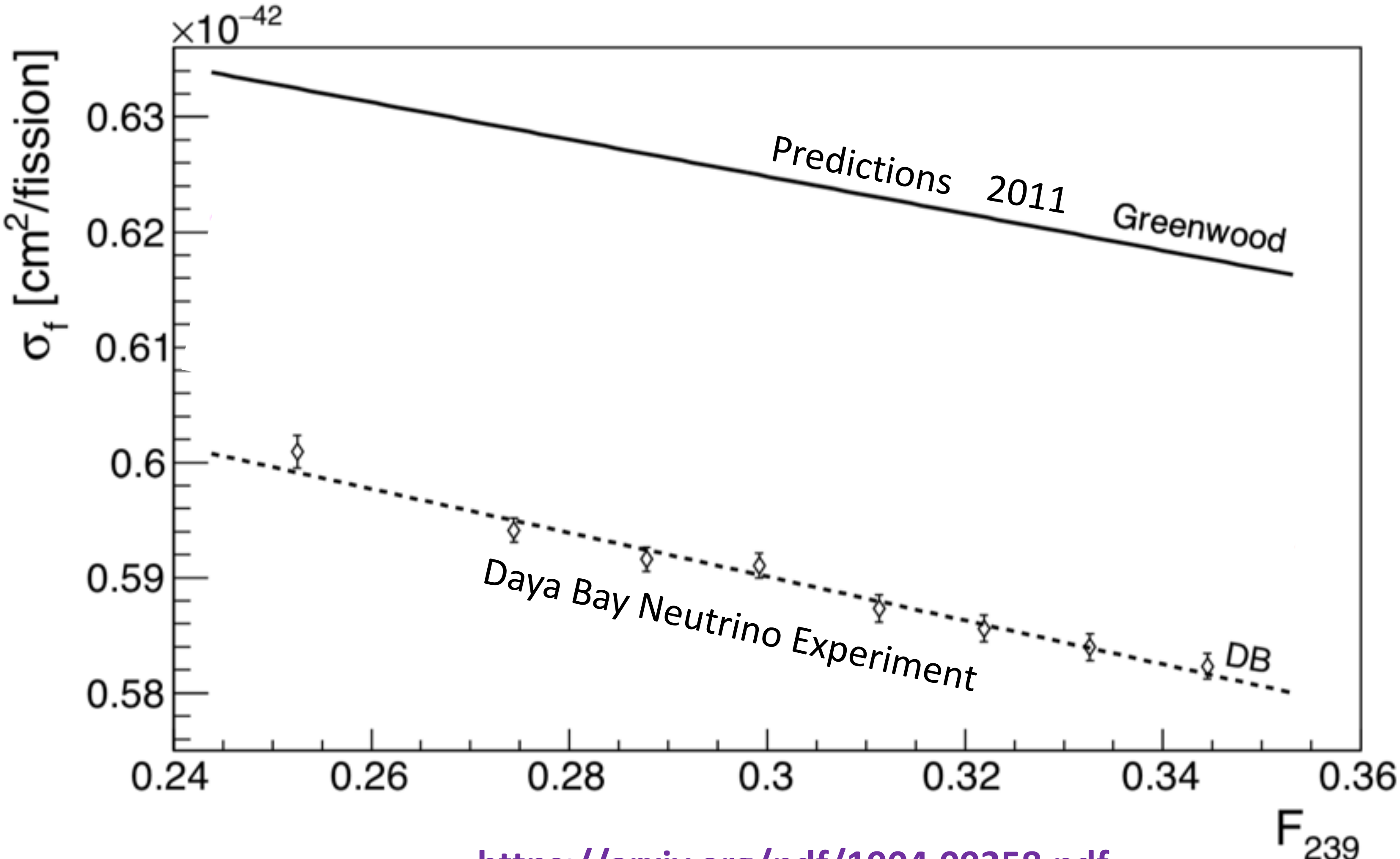
Ce 139 137.641 d	Ce 140 88.450	Ce 141 32.508 d	Ce 142 11.114	Ce 143 33.039 h	Ce 144 284.8 d	Ce 145 2.98 m	Ce 146 13.52 m	Ce 147 56.4 s	Ce 148 56 s	Ce 149 5.3 s
La 138 0.090	La 139 99.910	La 140 1.6781 d	La 141 3.92 h	La 142 92.6 m	La 143 2 14.3 m	La 144 40.9 s	La 145 2 24.8 s	La 146 ν 6.27 s	La 147 4.015 s	La 148 1.26 s
Ba 137 11.232	Ba 138 71.698	Ba 139 83.06 m	Ba 140 12.752 d	Ba 141 18.27 m	Ba 142 10.7 m	Ba 143 14.5 s	Ba 144 11.5 s	Ba 145 2 4.31 s	Ba 146 ν 2.22 s	Ba 147 893 ms
Cs 136 13.16 d	Cs 137 30.1671 y	Cs 138 32.2 m	Cs 139 9.27 m	Cs 140 ν 63.7 s	Cs 141 24.94 s	Cs 142 3 ν 1.689 s	Cs 143 ν 1.791 s	Cs 144 994 ms	Cs 145 582 ms	Cs 146 323 ms
Xe 135 9.10 h	Xe 136 8.87	Xe 137 1 3.83 m	Xe 138 ν 14.08 m	Xe 139 1 39.68 s	Xe 140 1 13.60 s	Xe 141 1.73 s	Xe 142 1.22 s	Xe 143 511 ms	Xe 144 388 ms	Xe 145 188 ms
I 134 52.0 m	I 135 6.61 h	I 136 1 45s 1 84 s	I 137 1 24.2 s	I 138 ν 6.4 s	I 139 2.29 s	I 140 860 ms	I 141 430 ms	I 142 ~200 ms	I 143 100 ms	I 144 50 ms
Te 133 12.5 m	Te 134 41.8 m	Te 135 2 ν 18.6 s	Te 136 17.5 s	Te 137 2.49 s	Te 138 1.4 s	Te 139 >300 ns	Te 140 300 ms	Te 141 100 ms	Te 142 50 ms	
Sb 132 1 2.79 m	Sb 133 2.5 m	Sb 134 780 ms	Sb 135 1.68 s	Sb 136 923 ms	Sb 137 450 ms	Sb 138 500 ms	Sb 139 300 ms			
Sn 131 56.0 s	Sn 132 39.7 s	Sn 133 1.45 s	Sn 134 1.12 s	Sn 135 530 ms	Sn 136 250 ms	Sn 137 190 ms				

*Priority **1**,**2** ,**3** : 12 decays*

reactor high-energy $\bar{\nu}$ (8)

OAK RIDGE National Laboratory

Nuclear Physics and RAA



https://arxiv.org/pdf/1904.09358.pdf

Part II

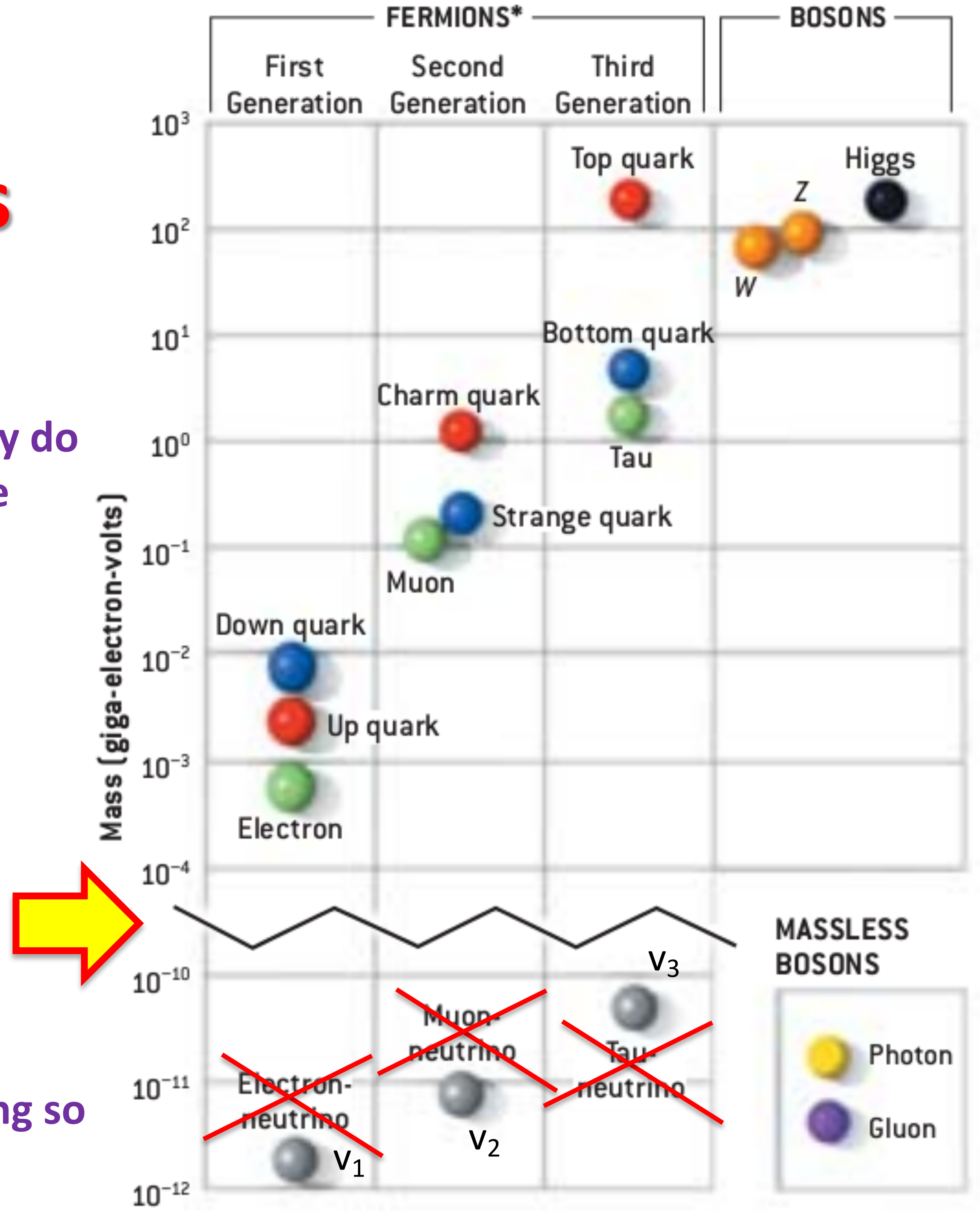
Neutrino Mass

Neutrino Mass

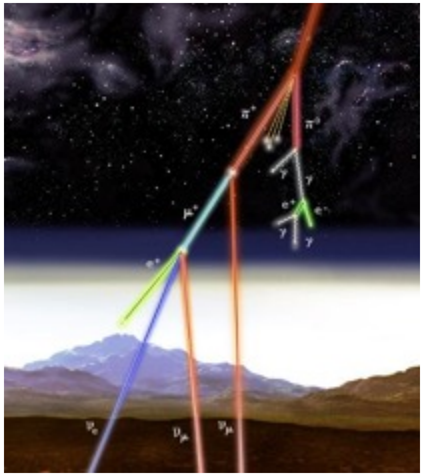
Because Neutrinos Oscillates they do have a mass, a very small one

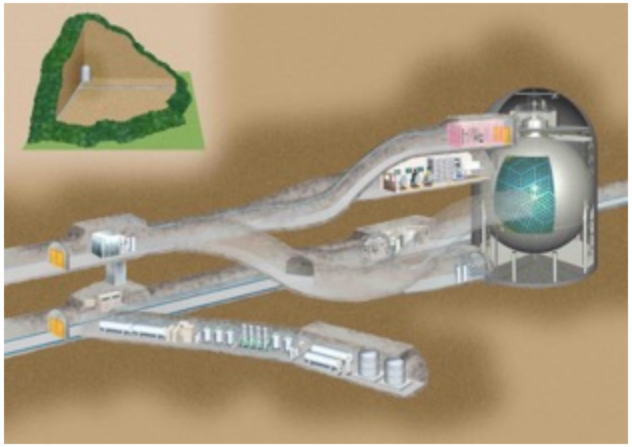
Here is a gap for 6 orders of magnitude

How we can measure something so small?



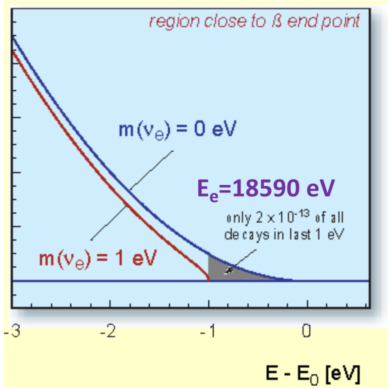
Neutrino Mass

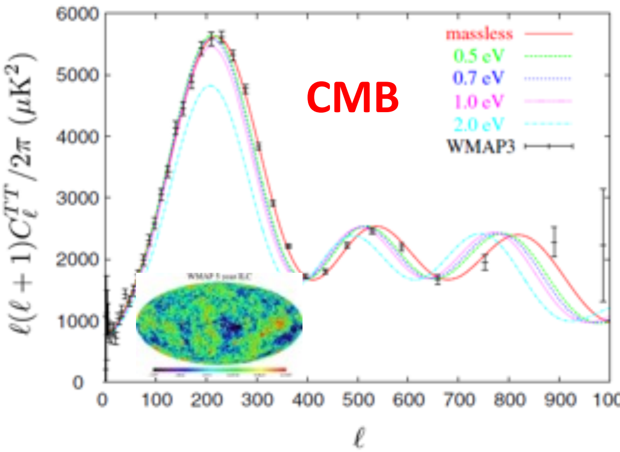


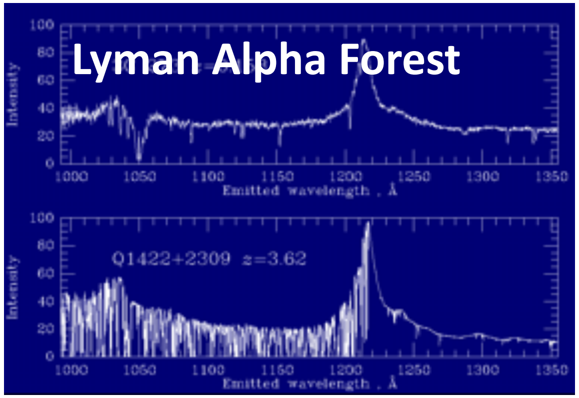


$0.0 < \Sigma m_\nu < 1$ eV

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$





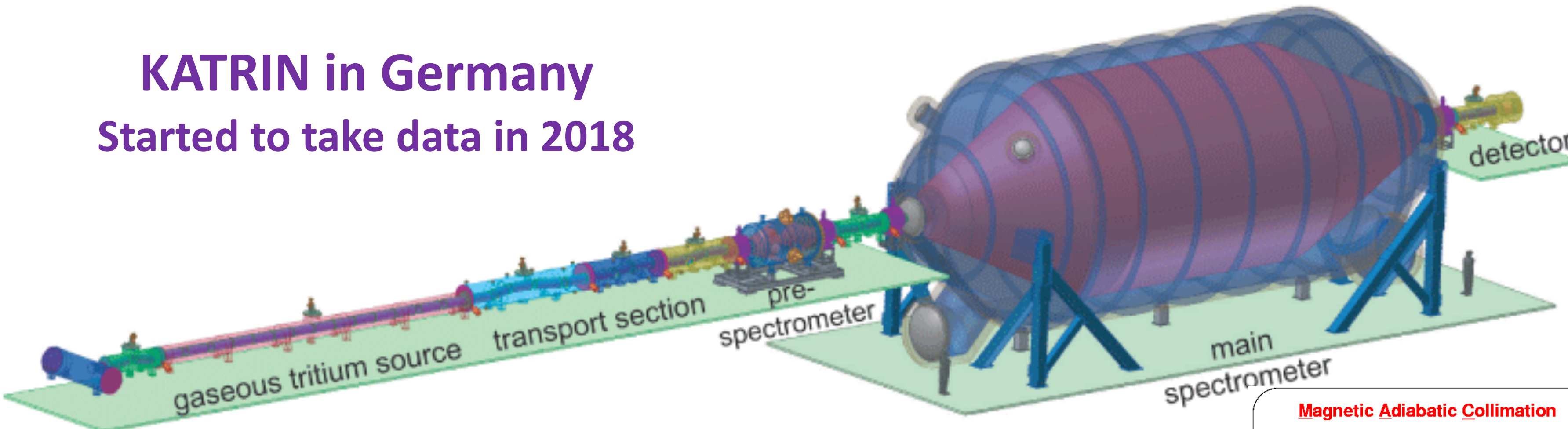


Possible Advance in Direct Search for Neutrino mass

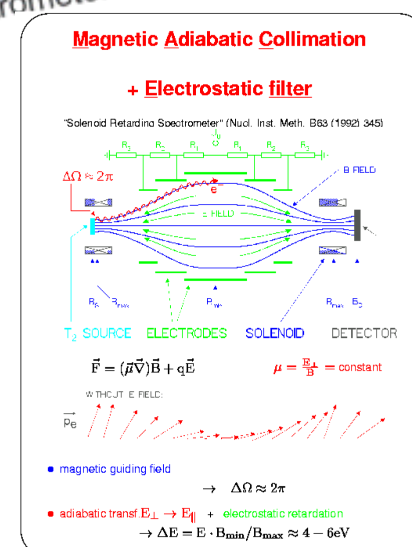
Ultra high quality vacuum vessel

KATRIN in Germany

Started to take data in 2018



$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$



Look for the ν_e mass. Similar idea as before, but BIGGER

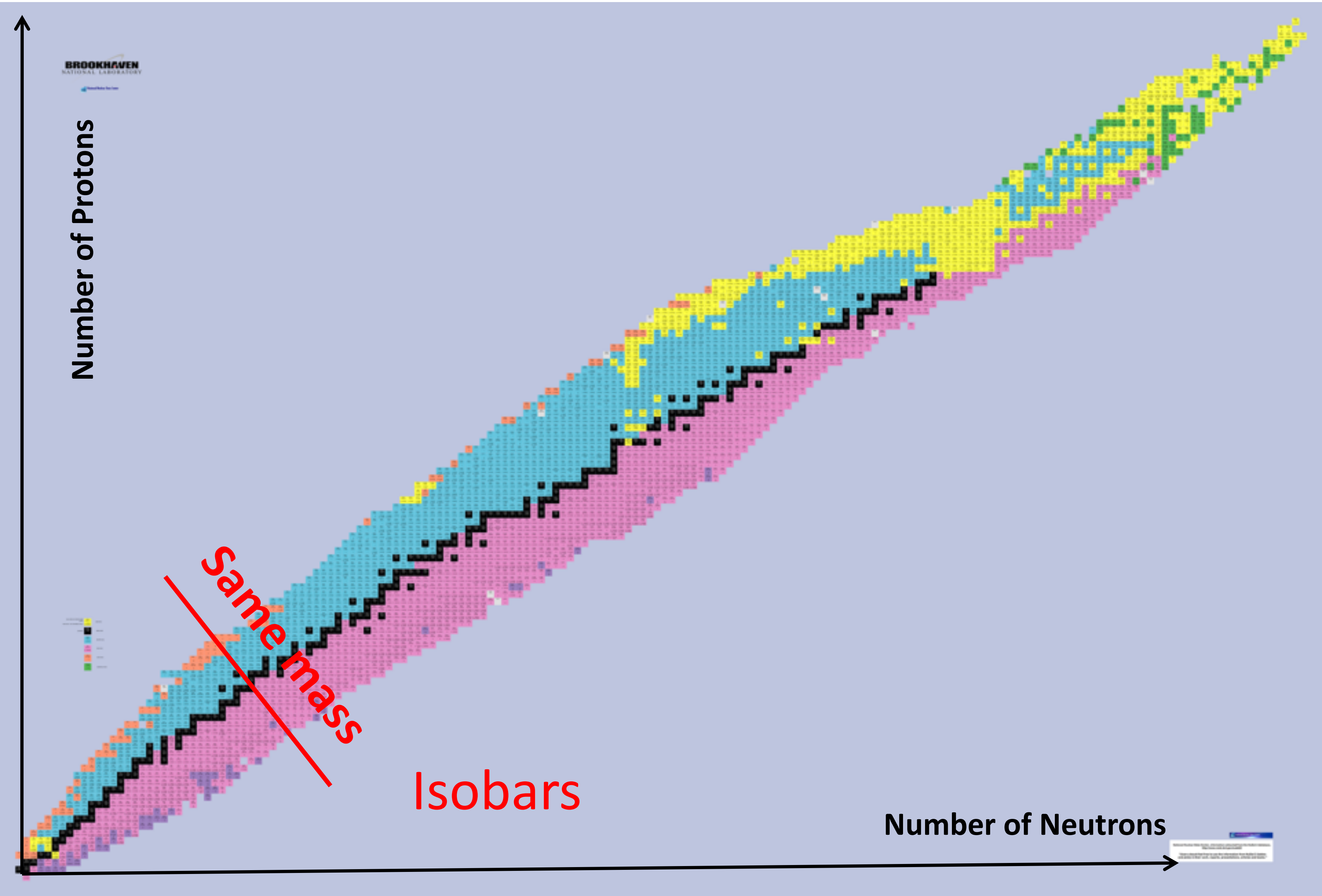
Aim is to reach 0.2 eV sensitivity

Katrin experiment started to take data last year

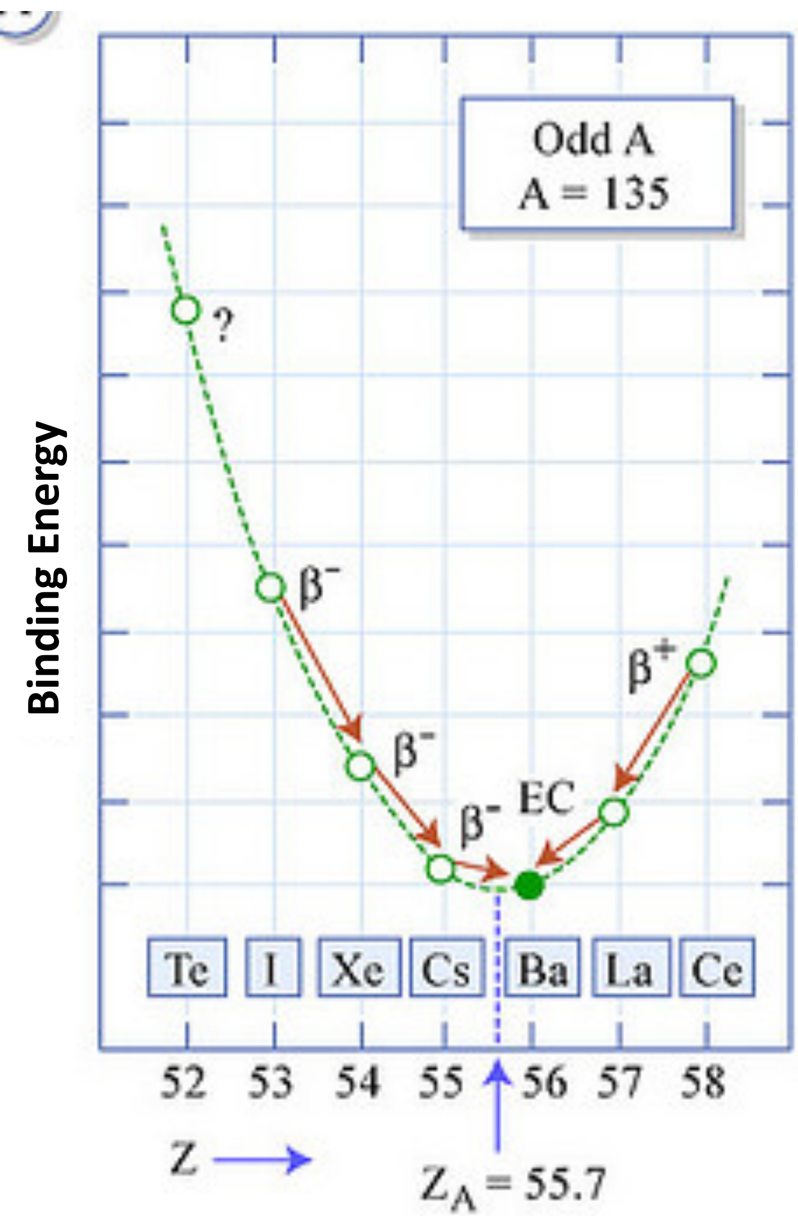
Need to wait for a first result a few years

Are there any alternative methods?

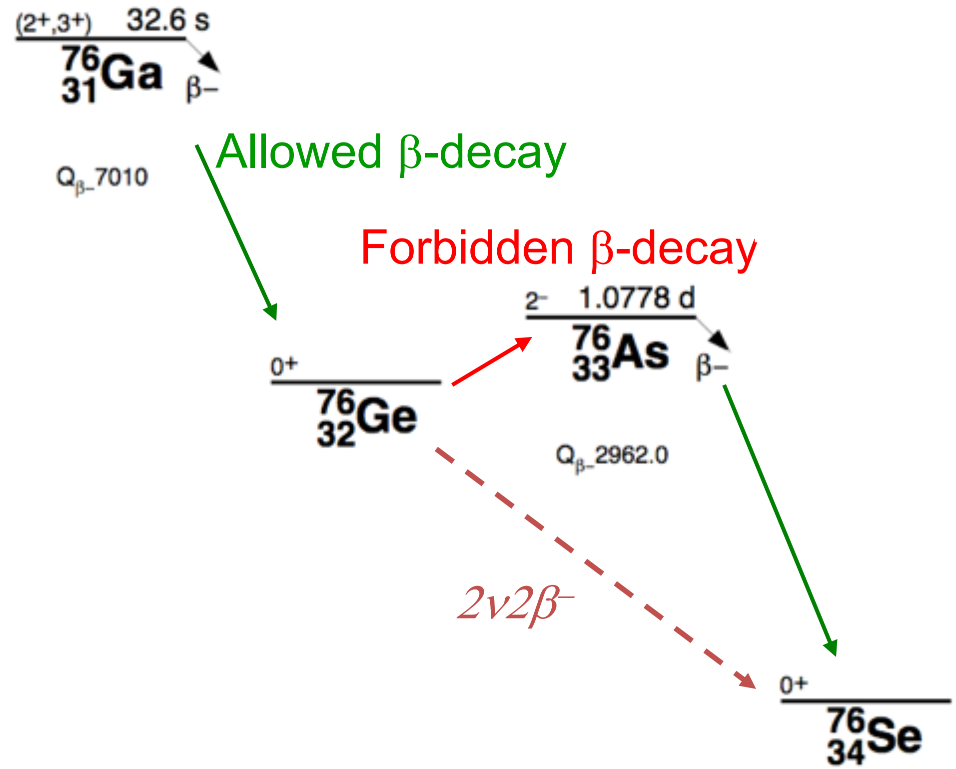
Chart Of Isotopes



Mass Parabola



However for some isotopes



$2\upsilon 2\beta$: decay second order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-} + 2\overline{\nu}_e$$

Double Beta Isotopes

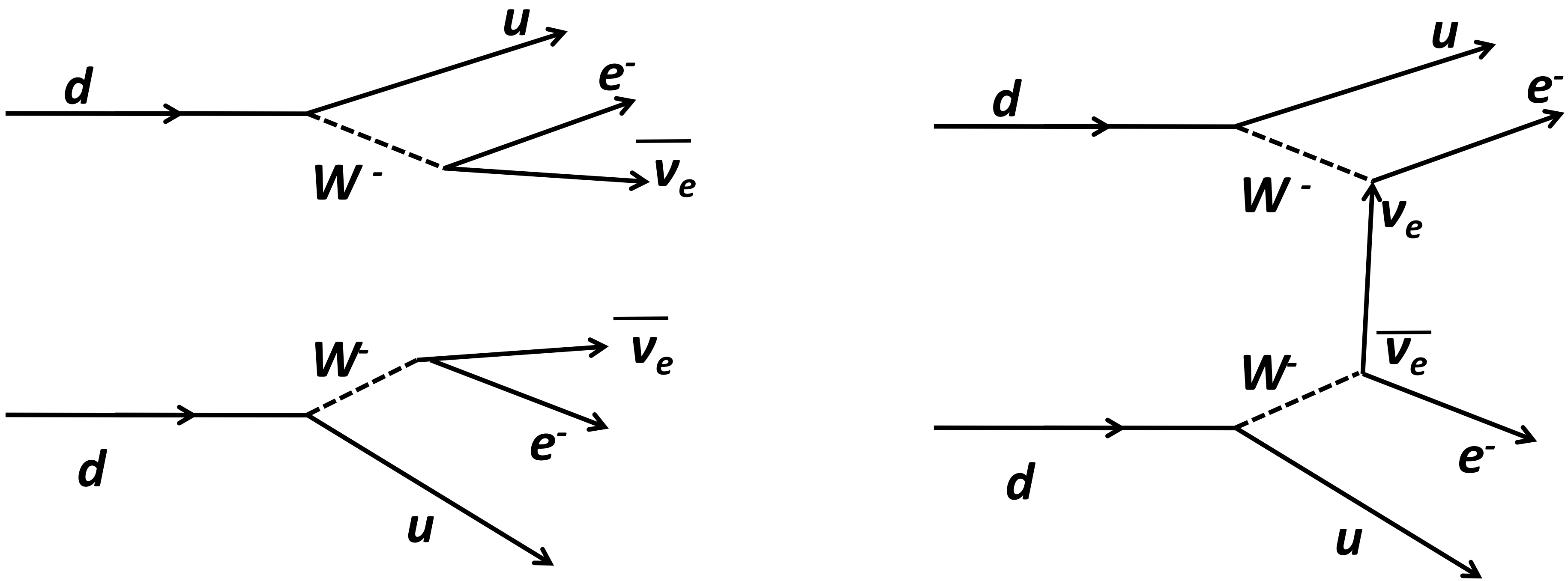
ββ2ν-mode:

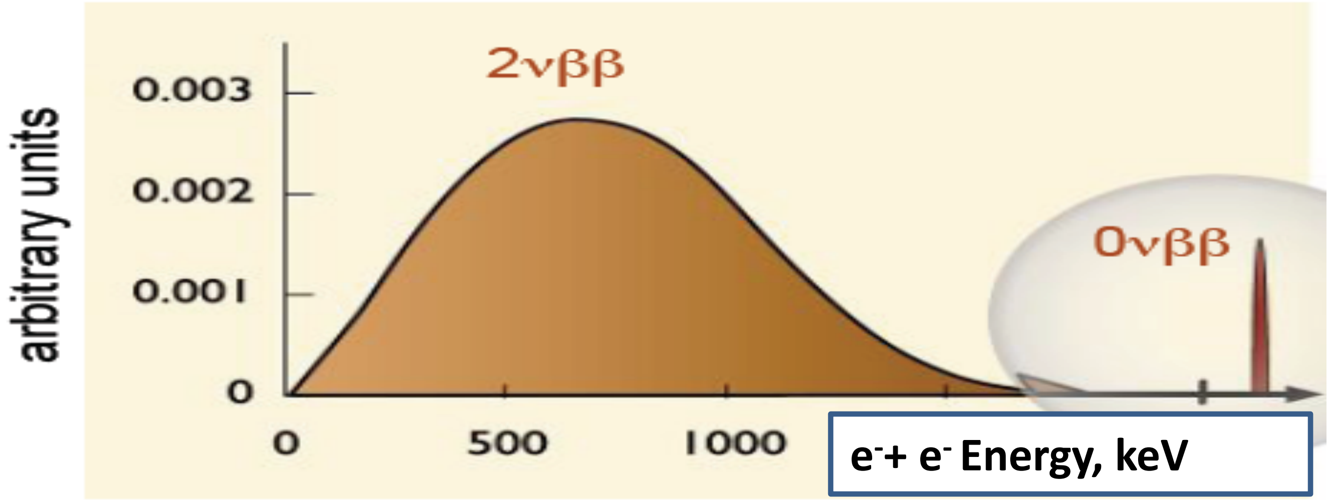
Isotope	$T^{2\nu}_{1/2}$ (y)	References	$M^{2\nu}_{GT}$ (MeV^{-1})
^{48}Ca	$(4.2 \pm 1.2) \times 10^{19}$	(55, 56)	0.05
^{76}Ge	$(1.3 \pm 0.1) \times 10^{21}$	(57, 58, 59)	0.15
^{82}Se	$(9.2 \pm 1.0) \times 10^{19}$	(60, 61)	0.10
^{96}Zr†	$(1.4^{+3.5}_{-0.5}) \times 10^{19}$	(62, 63, 64)	0.12
^{100}Mo	$(8.0 \pm 0.6) \times 10^{18}$	(65, 66, 67, 68, 69, 70), (71)†	0.22
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$	(72, 73, 74)	0.12
^{128}Te$^{(1)}$	$(7.2 \pm 0.3) \times 10^{24}$	(75, 76)	0.025
^{130}Te$^{(2)}$	$(2.7 \pm 0.1) \times 10^{21}$	(75)	0.017
^{136}Xe	$> 8.1 \times 10^{20}$ (90% CL)	(77)	<0.03
^{150}Nd†	$7.0^{+11.8}_{-0.3} \times 10^{18}$	(68, 78)	0.07
^{238}U$^{(3)}$	$(2.0 \pm 0.6) \times 10^{21}$	(79)	0.05

Phase space **Nuclear Matrix Element**

$$\left(T^{2\nu}_{1/2}\right)^{-1} = G_{2\nu}(Q_{\beta\beta}, Z)\,|M^{2\nu}_{GT}|^2$$

Two neutrinos or zero neutrinos?

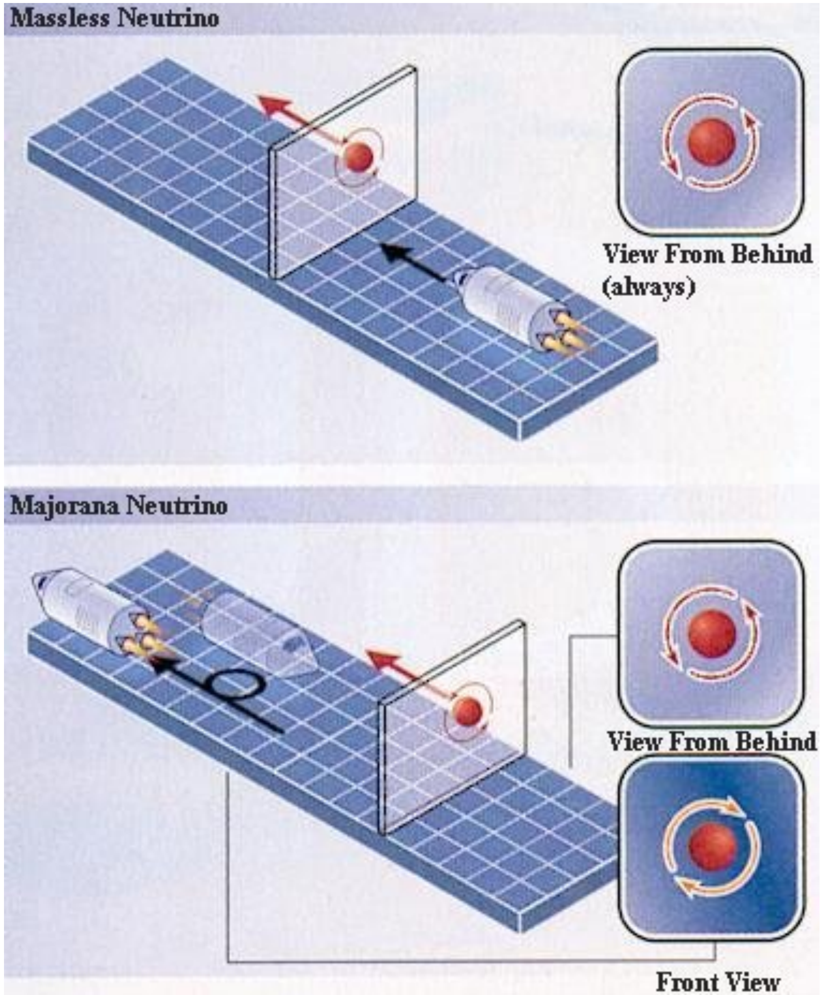




Neutrino nature

Dirac

Particles and antiparticles are different



Majorana

Particle is identical to its own antiparticle

Neutrino – Left Handed
Anti Neutrino - Right handed

Mixing between neutrinos and anti neutrinos is possible. Probability of mixing is proportional to the neutrino mass

If this is correct there are huge implications → lepton number violation

Neutrino Less Double beta decay

ββ0ν-mode:

Nuclear Matrix Element

Phase space

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|M^{0\nu}|^2 < m_\nu >^2$$

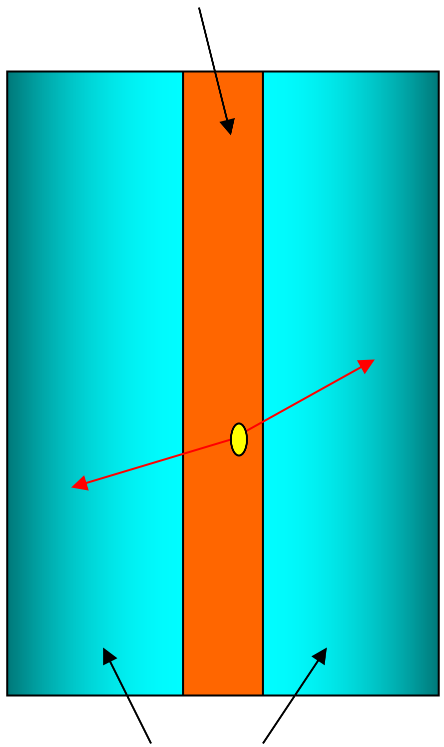
Effective Neutrino Mass

$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right| \approx \left| (0.87)^2 \cdot m_1 + (0.5)^2 \cdot \sqrt{m_1^2 + \Delta m_{21}^2} \cdot e^{2i\beta} + s_{13}^2 \cdot m_3 \cdot e^{-2i(\gamma-\delta)} \right|$$

Detector = Target Ideology

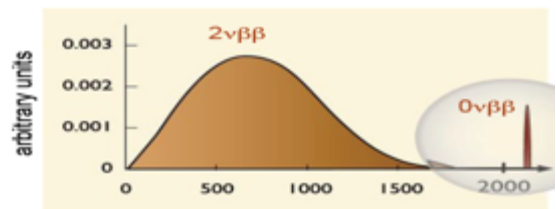
I

2β Isotope



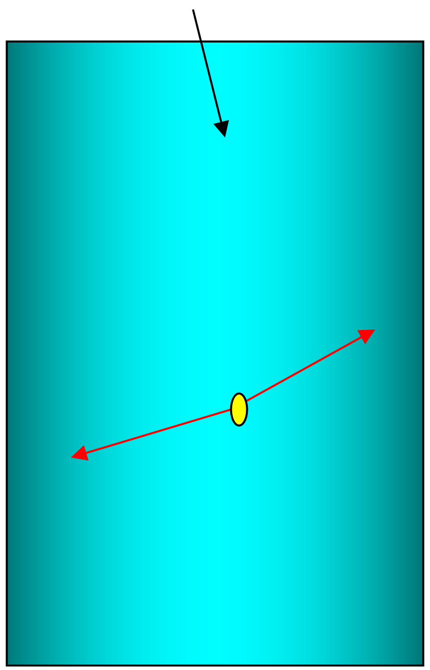
Detector

There is always uncontrolled energy losses in the non sensitive part of setup



II

2β Isotope and detector



Detector and target are the same media.

No energy losses in the passive material.

^{76}Germanium was custom made by "Mother Nature" for 2β0ν search

- This is a great opportunity to have the same atoms for target and for detector

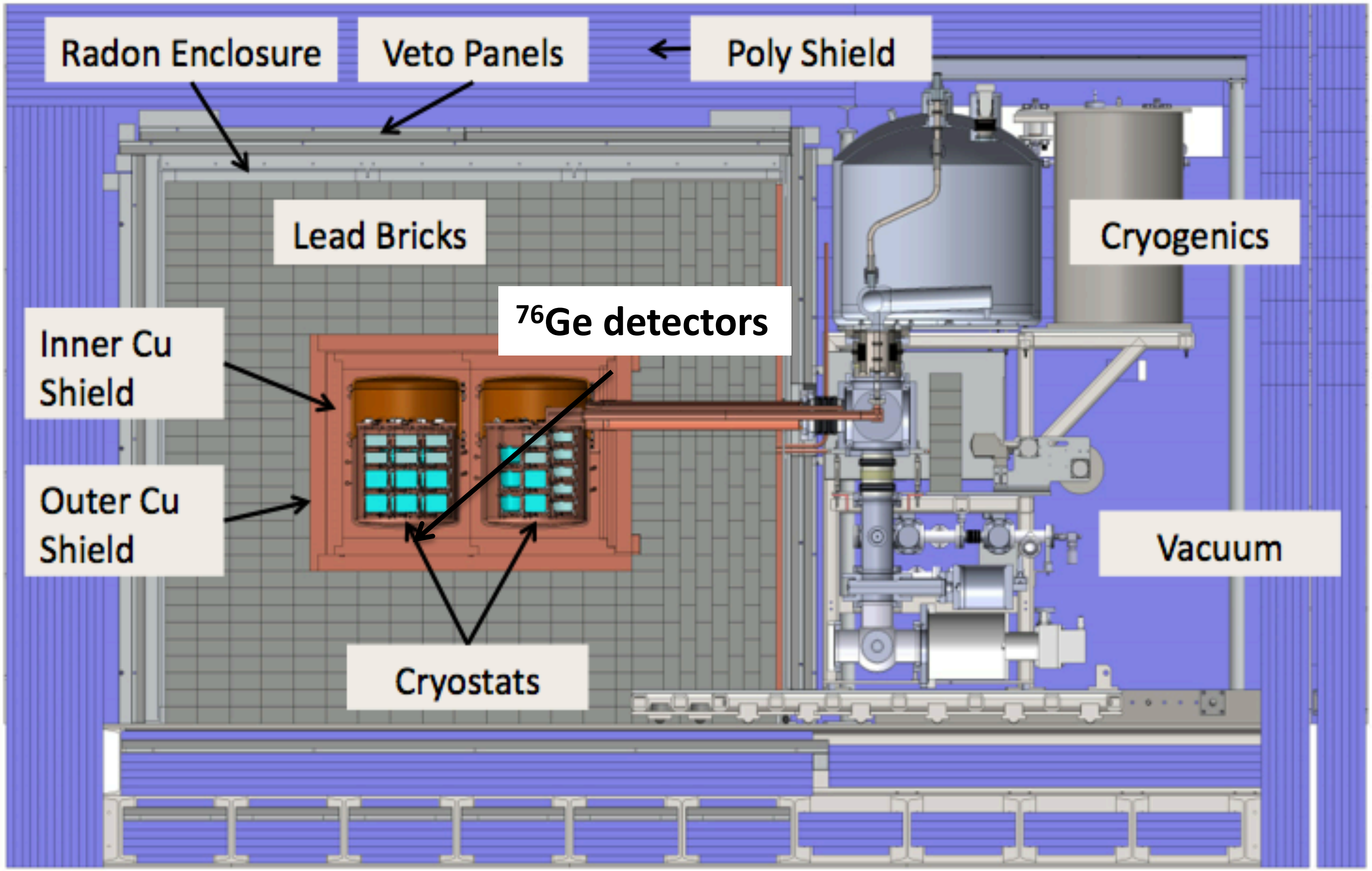
- No any other atoms need to be in the detector (almost correct)

- Intrinsically Germanium detectors are very clean

- High Ge density makes detectors very compact

- Ge detector has the best energy resolution

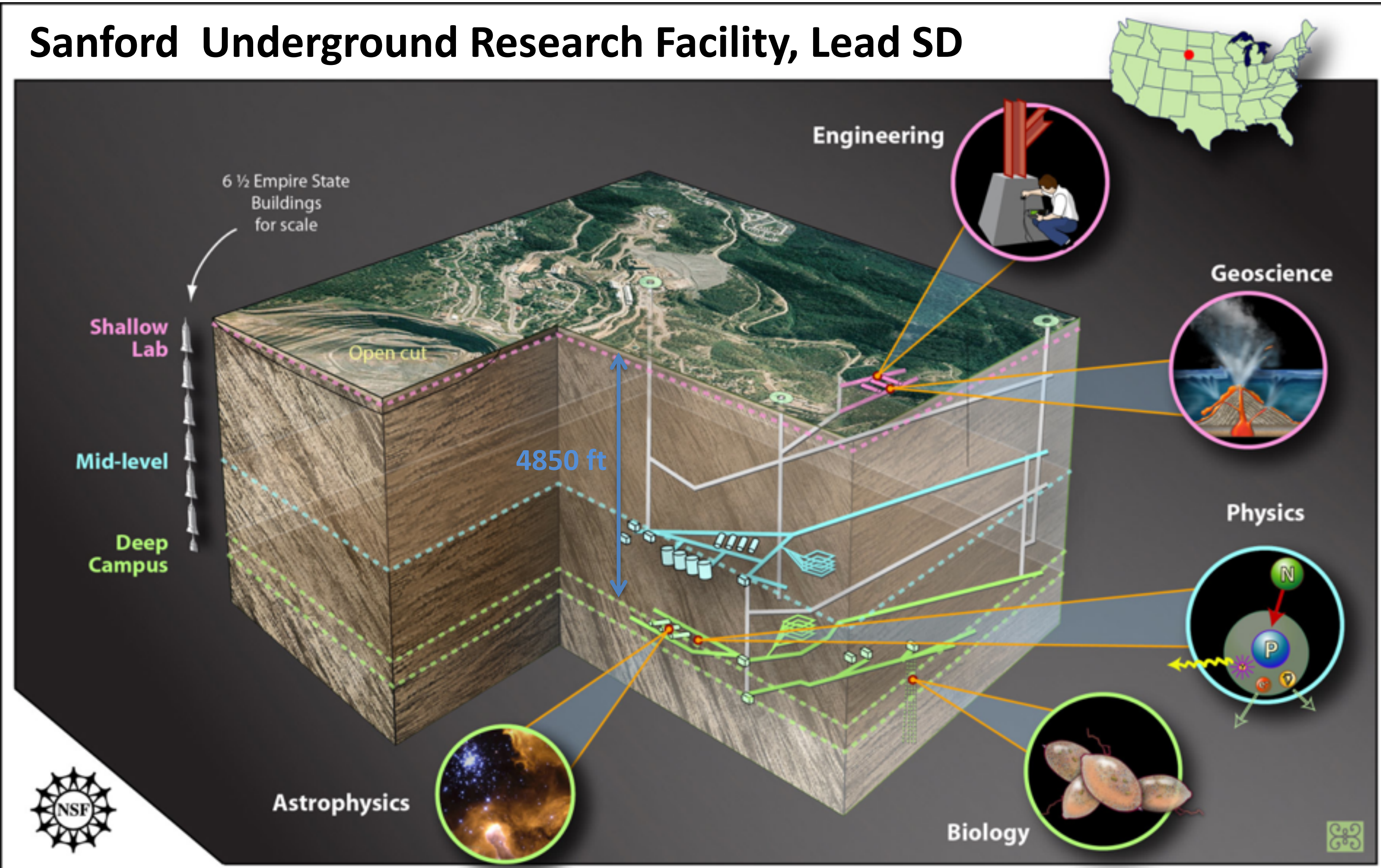
The Majorana Demonstrator



~ 30 kg of Isotopically Enriched ^{76}Ge detectors located at ultra quiet conditions with minimum radioactive background.

Natural ^{76}Ge is 7.5%

Majorana Demonstrator Location



The Majorana Collaboration

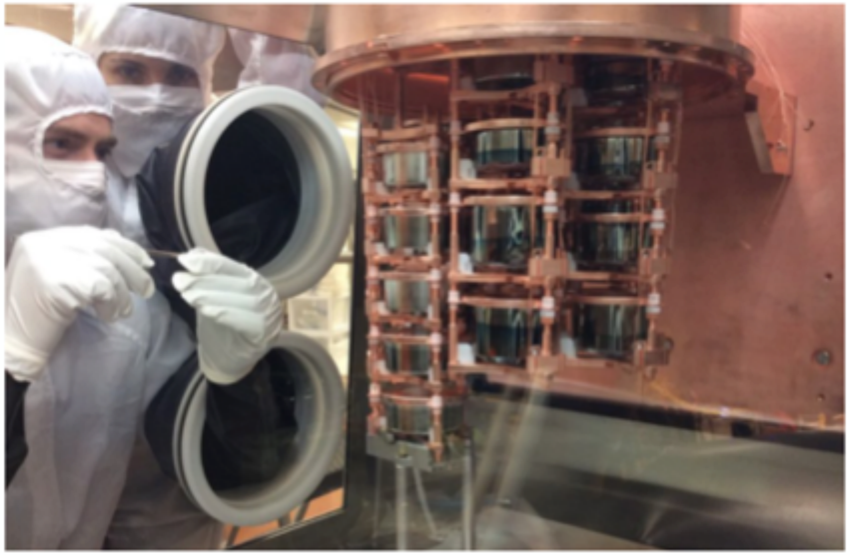
Controls Of Backgrounds

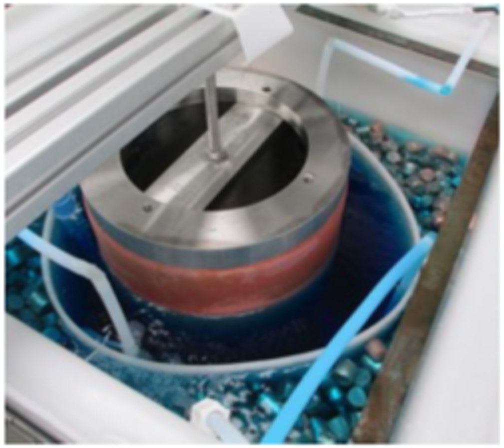
Ultra-pure materials

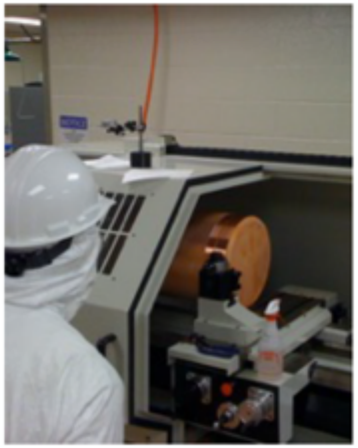
- Low mass design
- Custom cable connectors and front-end boards
- Selected plastics & fine Cu coax cables
- Underground Electro-formed Cu
  - Th decay chain (ave) ≤ 0.1 μBq/kg
  - U decay chain (ave) ≤ 0.1 μBq/kg

Detector assembly

- Dedicated glove boxes with a purged N_2 environment





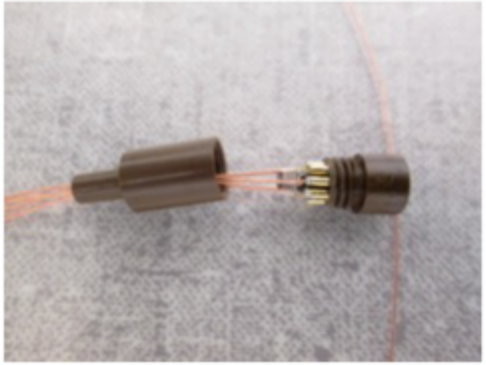


Machining and Cleaning

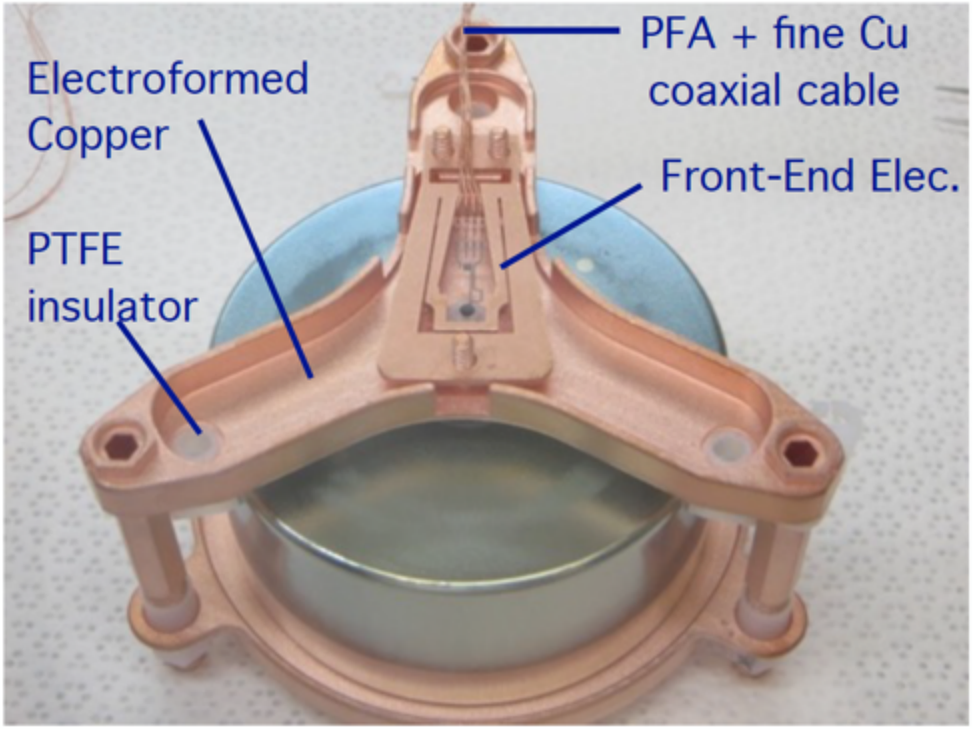
- Cu machining in an underground clean room
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts

Detector Readout Components

Fine Cu coaxial cable and clean connectors



Connectors reside on top of cold plate.
In-house machined from Vespel.
Axon' pico co-ax cable.
Low background solder and flux.



String Assembly

Detector Module and Shield

Two independent modules are deployed:

- A self-contained vacuum and cryogenic vessel housing the detector cryostat
- Contains a portion of the shielding
- Can be transported for assembly and deployment

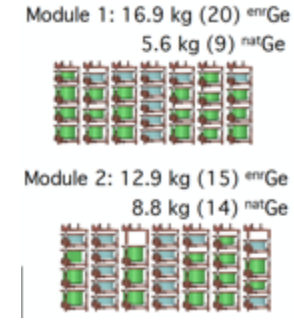
Cryostat loading

Pb and outer Cu shield

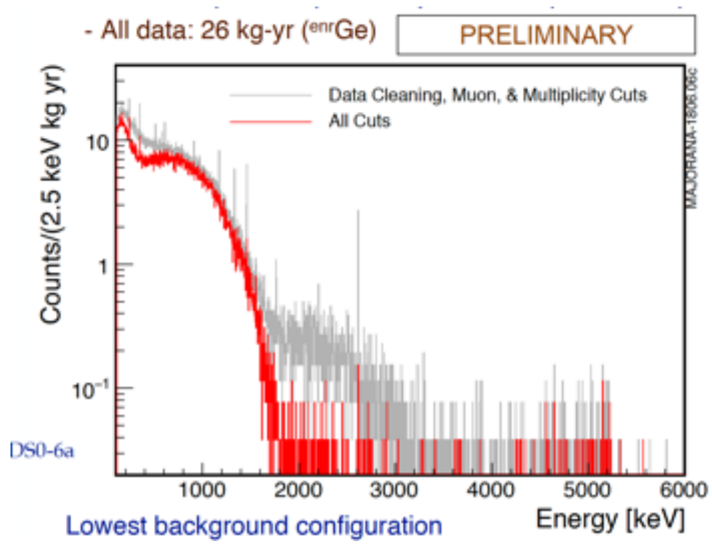
Module deployment

Muon active shield

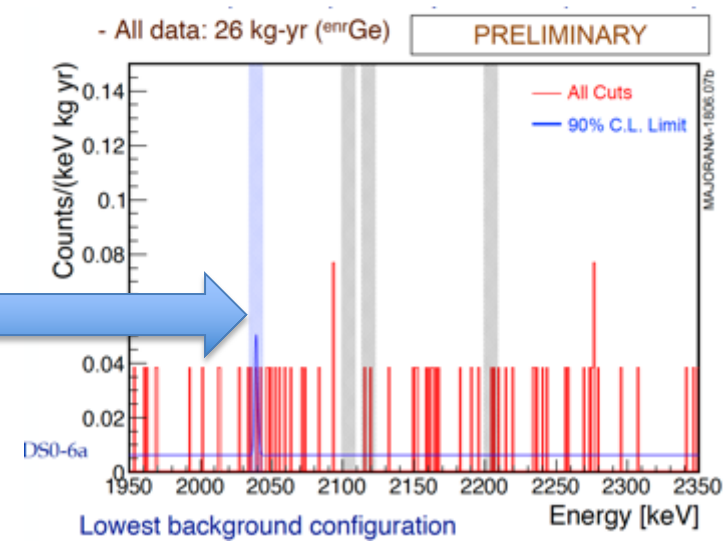
First Results from MJD



Summer 2018



Zoom into R.O.I.



Limit on the half Live time < 2.5 * 10^{25} yr

Imply that m_ν < (200-433) meV

$M^{0\nu}$ = 2.81 - 6.13 $\quad$ $G_{0\nu}$ = 2.365 * 10^{-15} yr^{-1} $\quad$ g_A =1.27

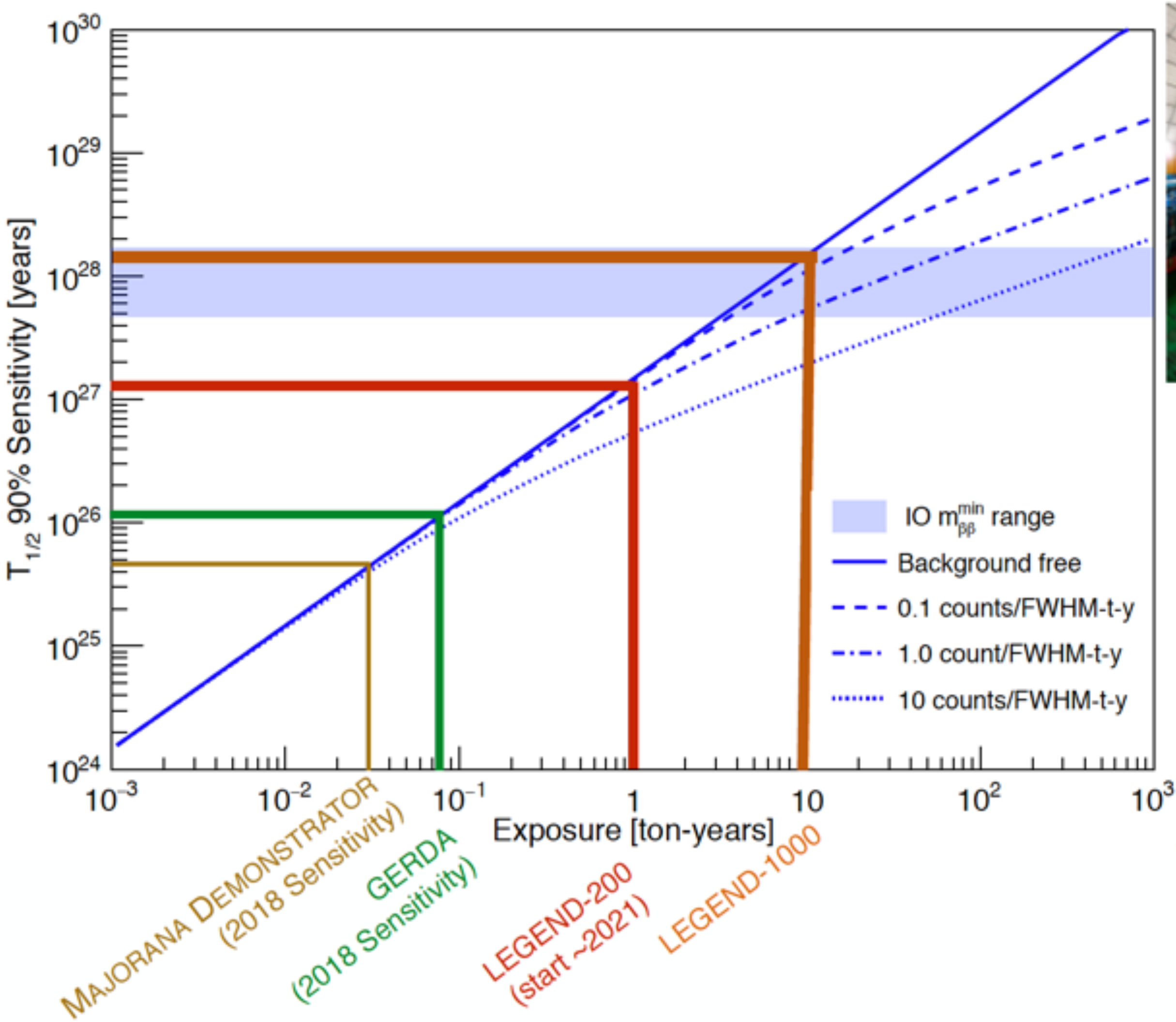
$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta},Z)\,|M^{0\nu}|^2 < m_\nu >^2$$

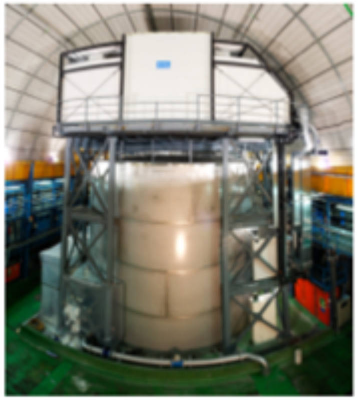
Need to better understand nuclear matrix elements

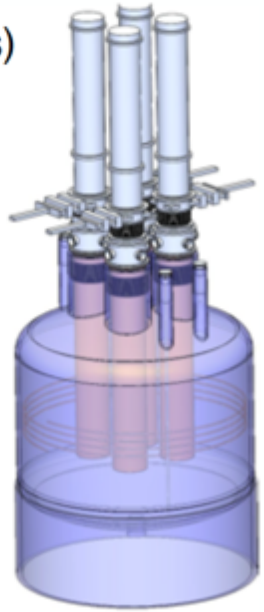
MJD and Gerda joining efforts → LEGEND-200

Next Generation ^{76}Ge: LEGEND — Large Enriched Germanium Experiment for Neutrinoless ββ Decay (52 Institutions, ~250 Members)

^{76}Ge (87% enr.)







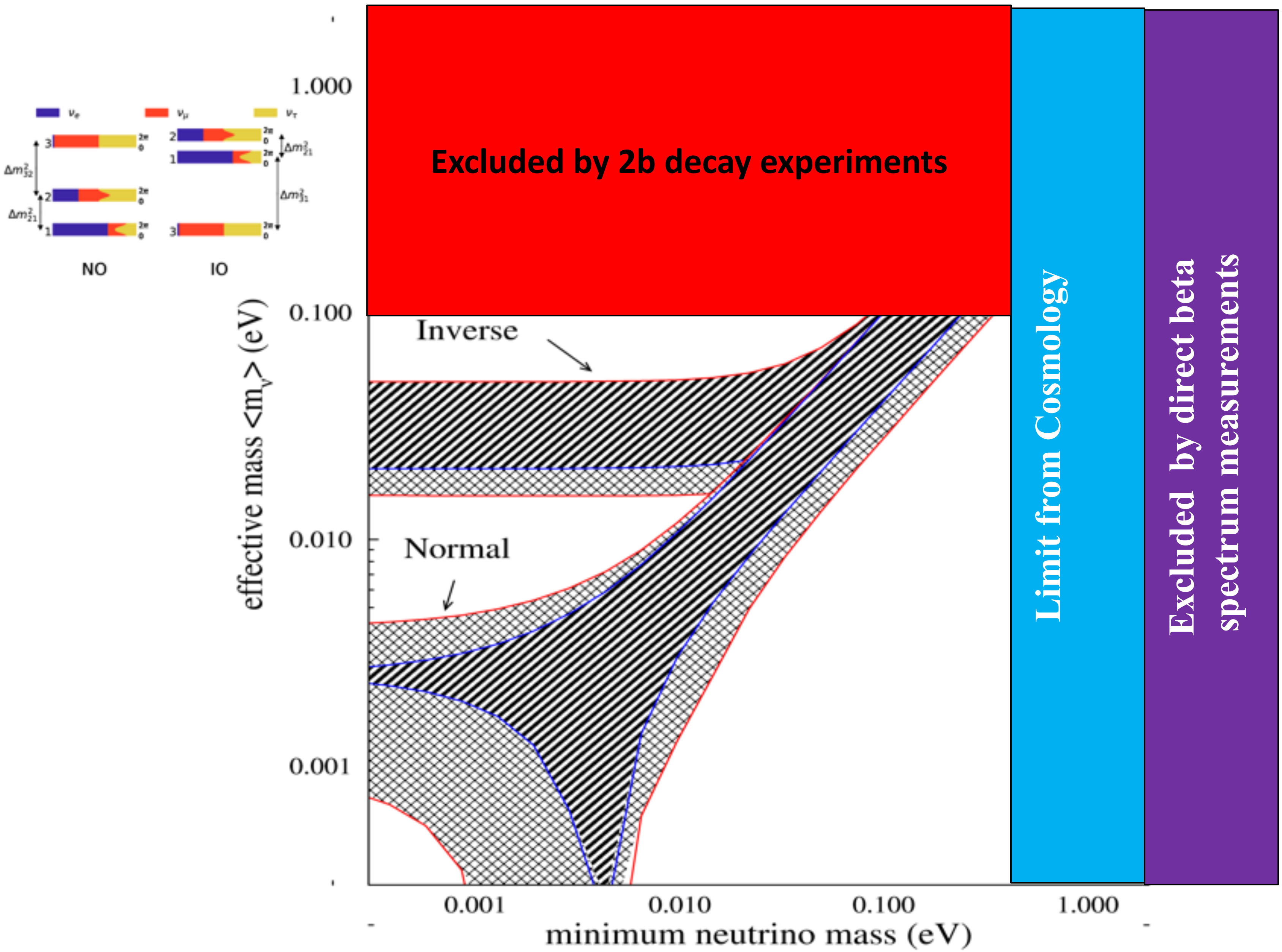
First Stage:

- (up to) 200 kg ^{76}Ge in upgrade of existing infrastructure at LNGS
- BG goal 0.6 cts/(FWHM t yr)
- Data start ~2021
- Will use existing MAJORANA & GERDA detectors (65 kg), plus new detectors (135 kg)

Subsequent Stages:

- 1000 kg ^{76}Ge (staged)
- BG goal: 0.1 cts/(FWHM t yr)
- Location: TBD

Global Neutrino Mass Status



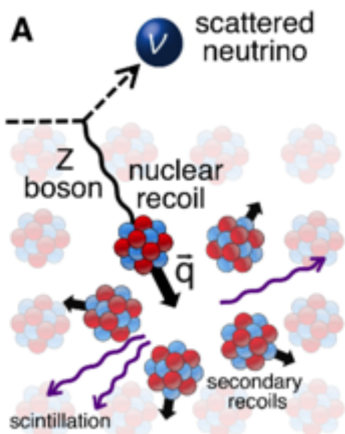
Part III

Something Very New and Absolutely Unique to ORNL

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a virtual Z boson, and the nucleus recoils as a whole;

coherent up to E_ν~ 50 MeV



D.Z. Freedman PRD 9 (1974)

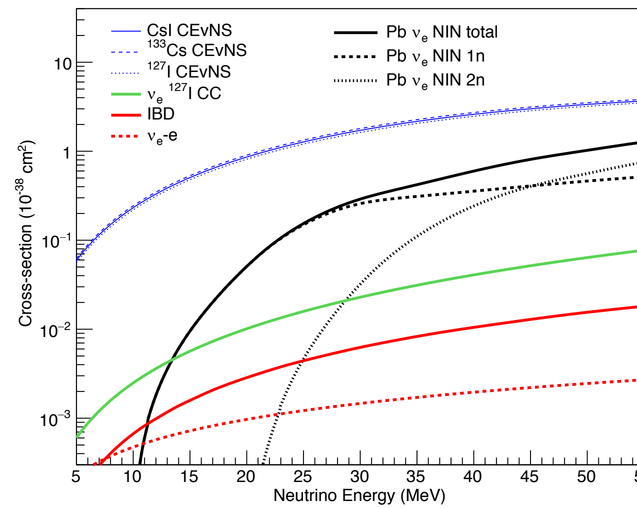
Submitted Oct 15, 1973

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering.

V.B.Kopeliovich & L.L.Frankfurt

JETP Lett. 19 (1974)

Submitted Jan 7, 1974

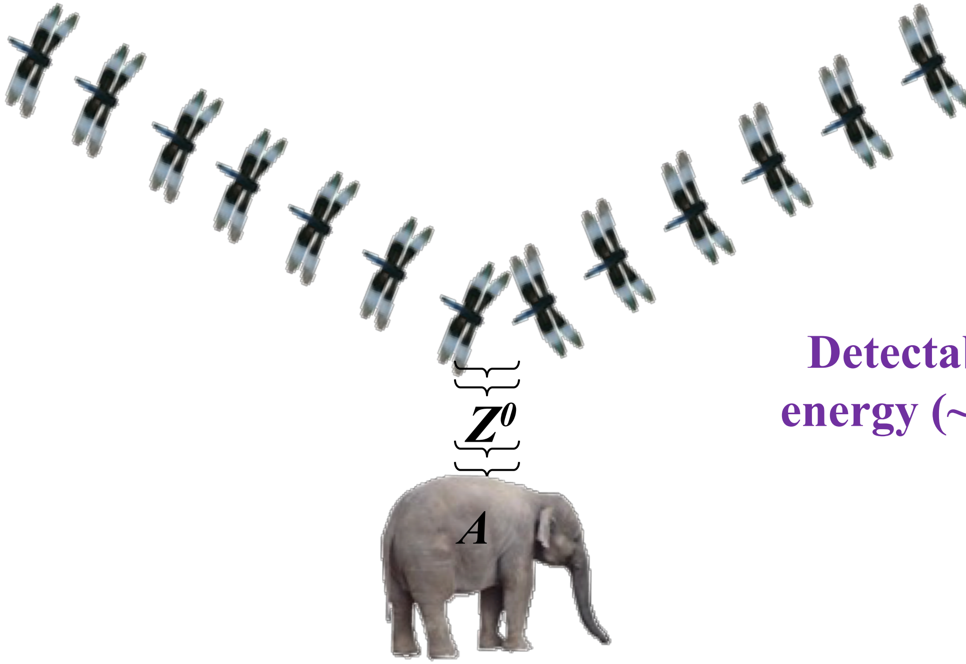


CEvNS cross-section is large!

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{(N-(1-4\sin^2\theta_W)Z)^2}{4}F^2(Q^2) \qquad \propto N^2$$

CEvNS cross section is accurately predicted by the Standard Model

CEvNS Eluded Detection for 43 Years



Detectable only via very low energy (~10keV) nuclear recoil

Straight-forward to calculate

“Huge” cross section > 10^{-39} cm^2

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

First Observation in 2017

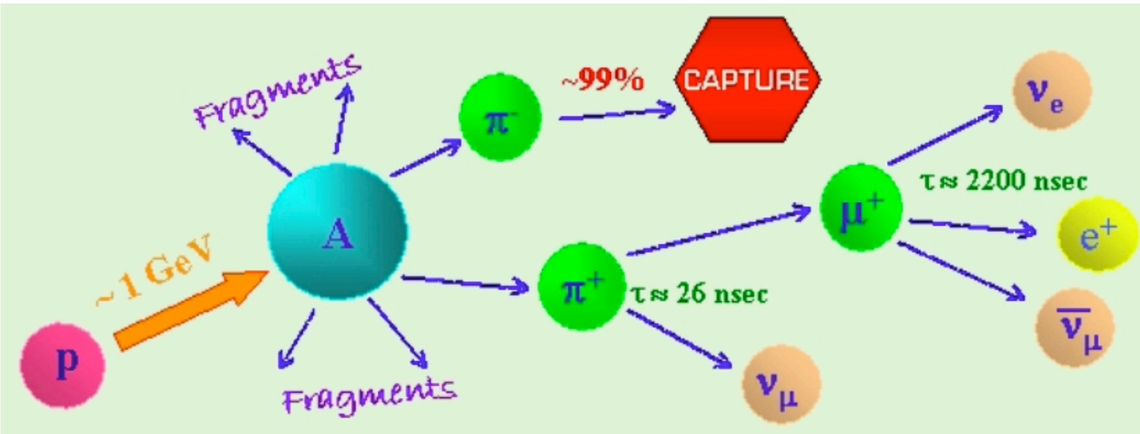
World Wide Efforts to Detect CEvNS

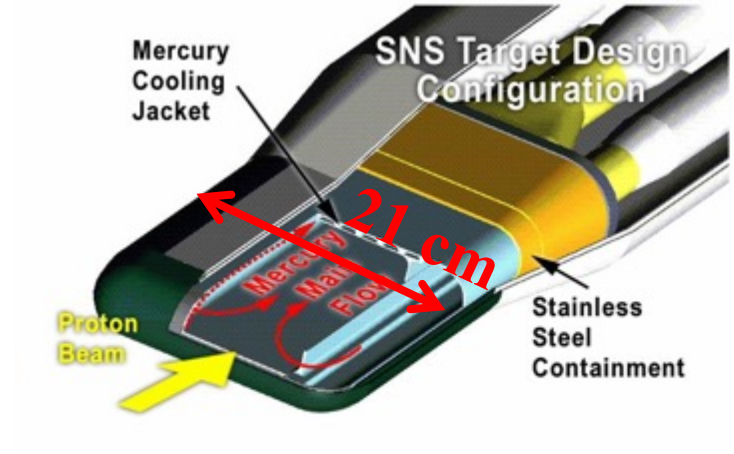
Except COHERENT, all other collaboration attempt to use nuclear reactors as a neutrino source

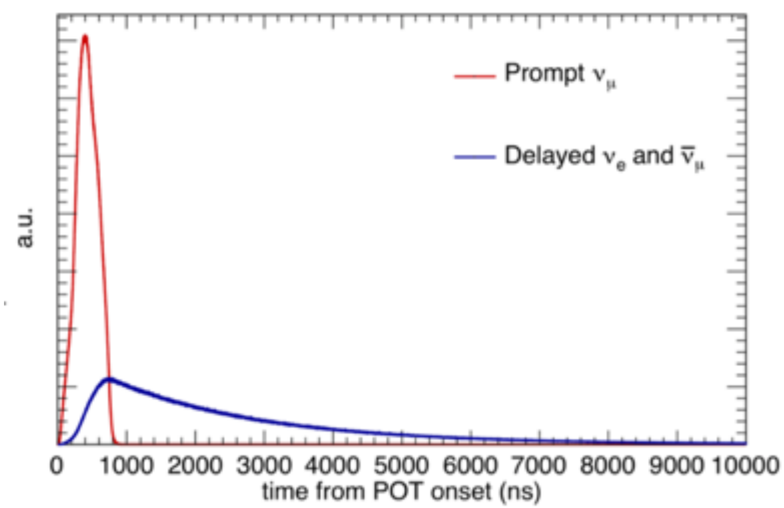
Nuclear reactors give large flux, but low energy neutrinos with a constant flux

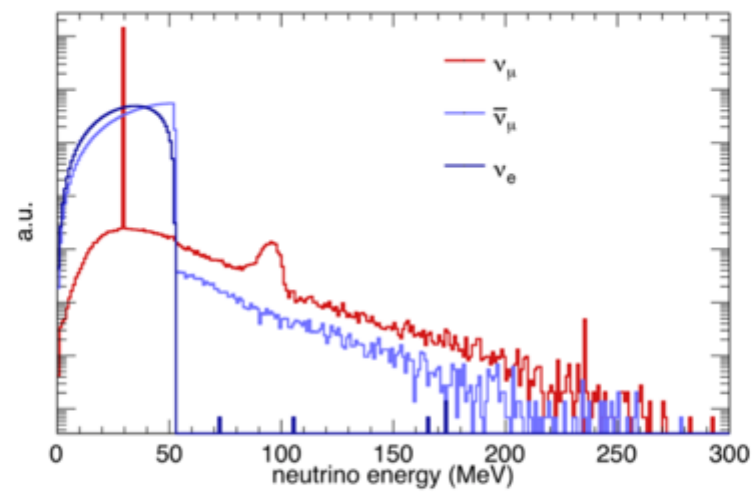

SNS-Spallation
Neutrino Source
Proton beam energy – 1.0 GeV
Intensity - 10^{16} protons/sec
Pulse duration - 380ns(FWHM)
Repetition rate - 60Hz
Total power – 1.4 MW
Liquid Mercury target
My Car

Neutrino Production at the SNS









World most powerful pulsed neutrino source

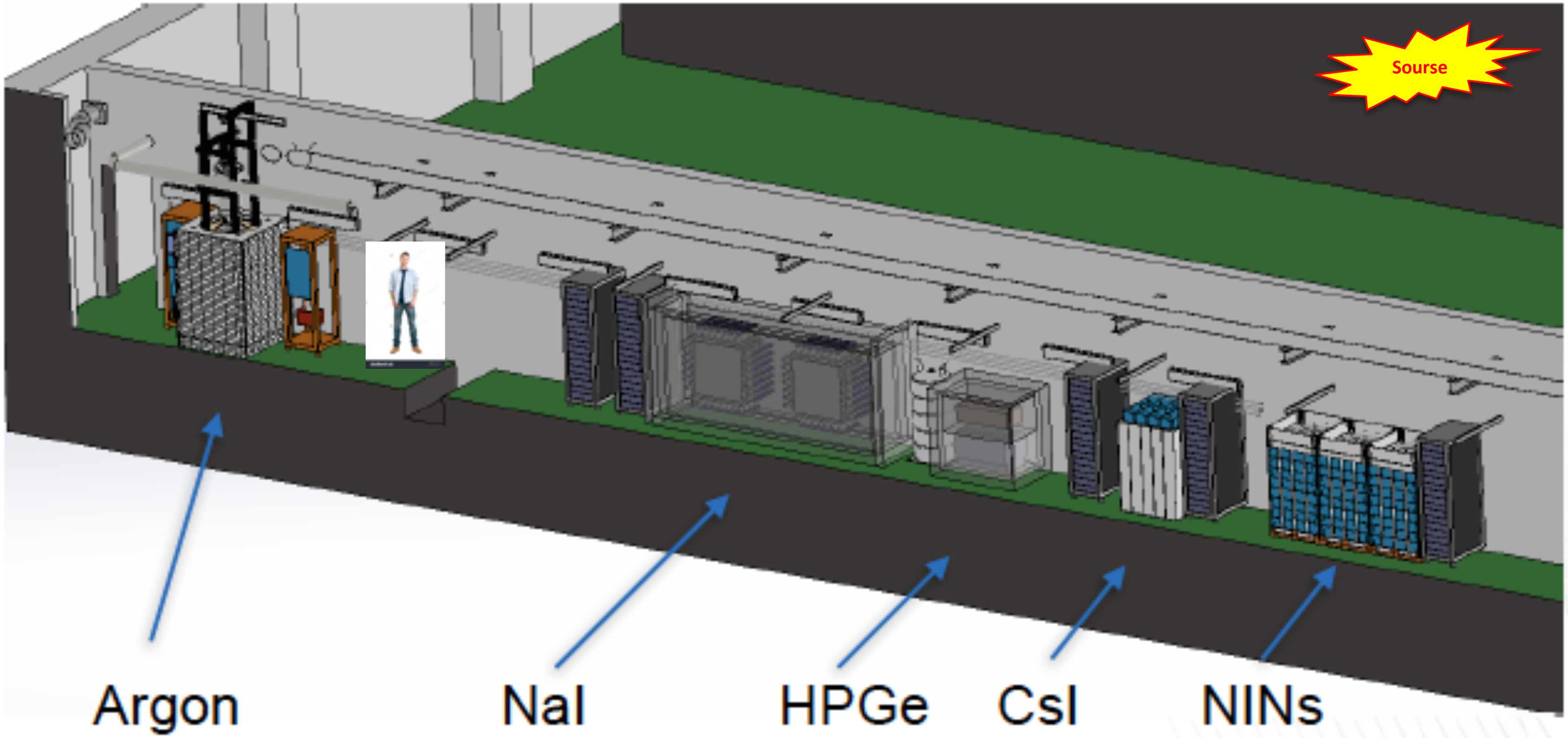
Number of each flavor of neutrinos produced at SNS is $1.9 \cdot 10^{22}$ year^{-1}

COHERENT Collaboration

COHERENT SNS

THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
LaurentianUniversity UniversitéLaurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
BERKELEY LAB
NORTH CAROLINA CENTRAL UNIVERSITY
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE UT KNOXVILLE
TUNL
W UNIVERSITY of WASHINGTON

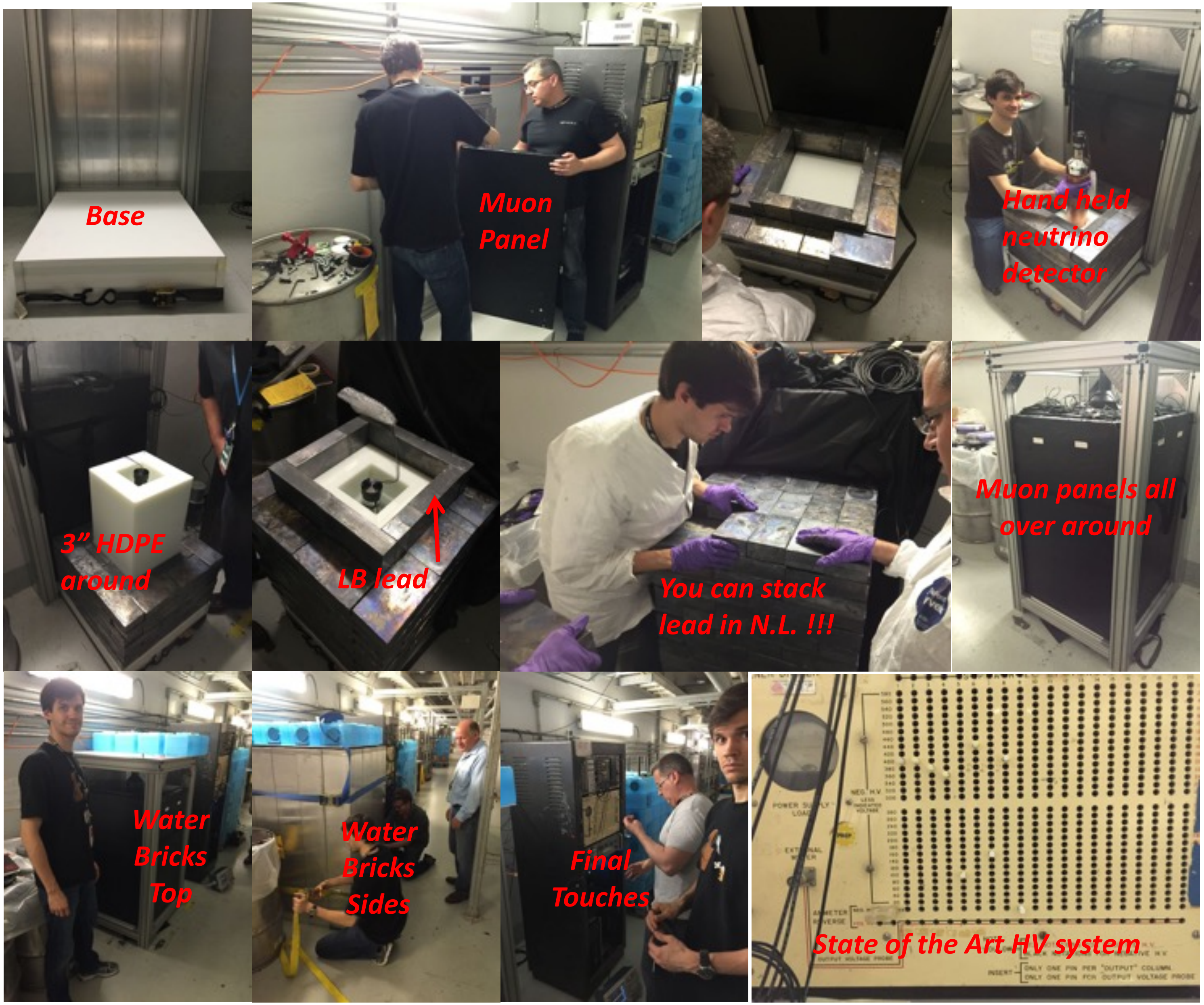
Neutrino Alley at the SNS



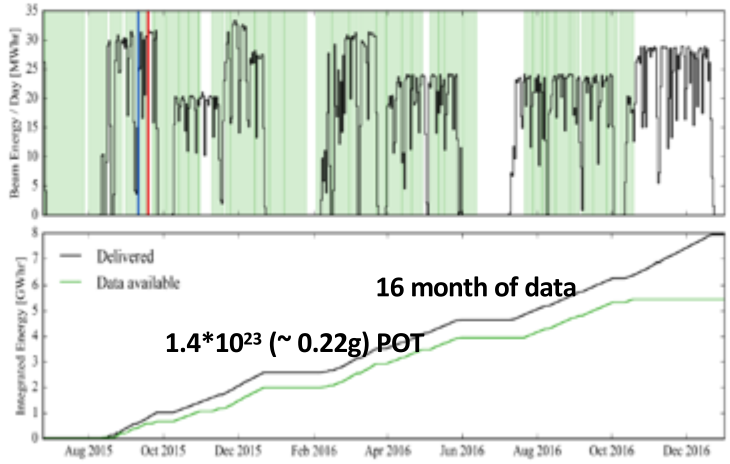
Target station basement location is isolated from neutron beam lines
There are no voids between SSN target and Neutrino Alley
There is extra protection from cosmic rays by
neutron beam lines shielding

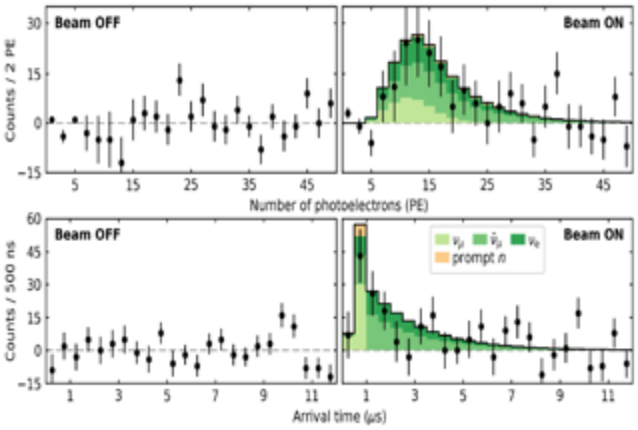
But neutrinos freely reaching this place

CsI detector Installation (August 2015)



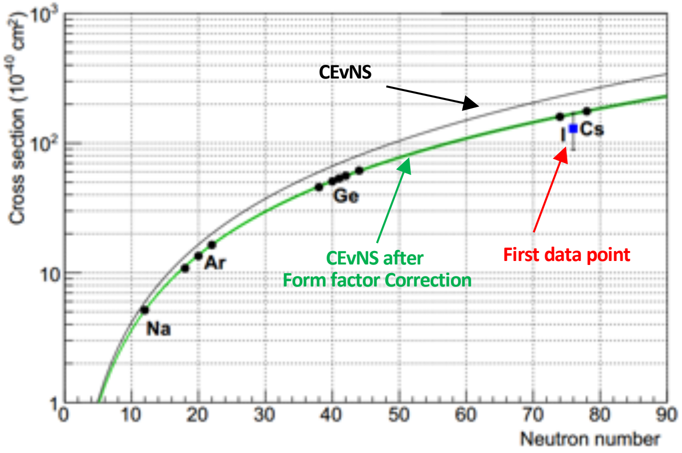
First Detection of CEvNS with CsI detector



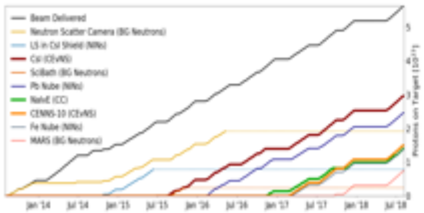


First working hand held neutrino detector -14kg!!!

Now we have 2.5 times statistics compare to the first publication

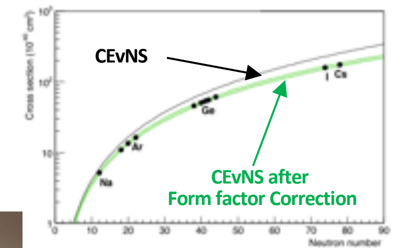


Next is Liquid Argon Target



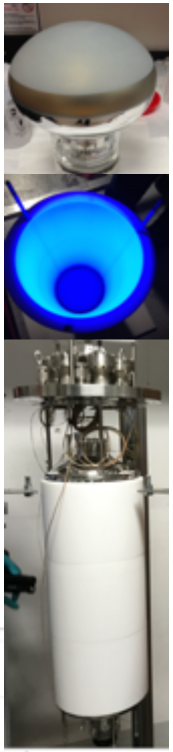
Single Phase Liquid Argon Detector CENNS-10

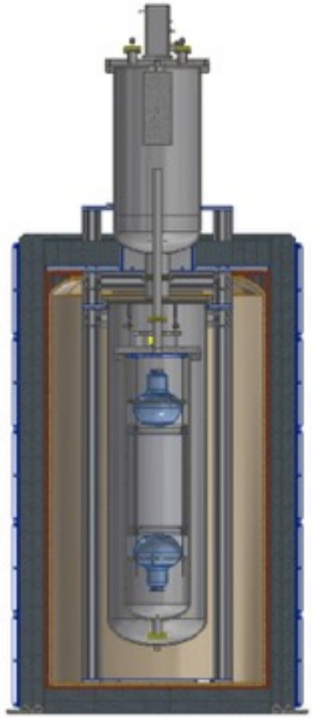
Aim is to detect CEvNS for very different target

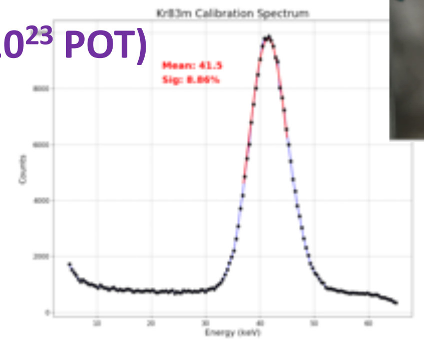


CENNS-10 SNS timeline:

- 10-12/2016: (re)build, commission and deployed detector at SNS
- 12/16 - 5/17: "Run -0". Poor light collection, E_{thresh}~100keVnr
  Test of hardware.
- 7/17- now: "Run 1" Rebuild detector. Light collection increase by a factor of 10! It should be enough to see CEvNS. E_{thresh}~20keVnr
  Presently accumulated statistics is ~4.1 GWhr (~$1*10^{23}$ POT)
- We implemented blind analysis by looking on the data between beam spills only.
  Planning to open box soon!!!!

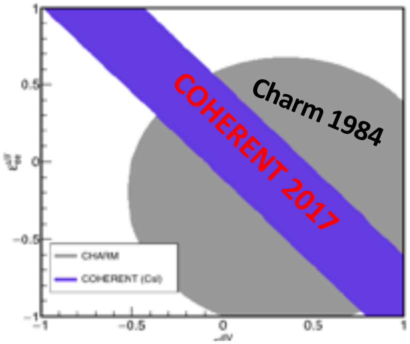






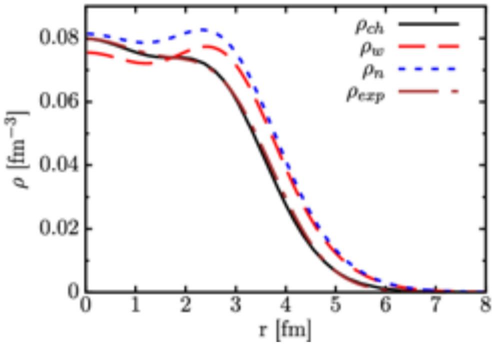
Future Physics for COHERENT – looking for anomalies

Non-Standard ν Interactions: Test of the SM, DM

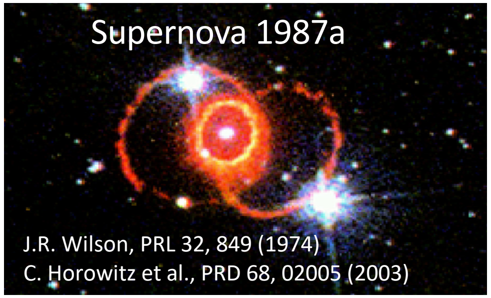


$$\left(\frac{d\sigma}{dE}\right)_{\nu_\alpha A} = \frac{G_F^2 M}{\pi} F^2(2ME)\left[1 - \frac{ME}{2k^2}\right] \times \quad (4)$$
$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$
$$+ \sum_{\alpha\neq\beta} [Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\},$$

Nuclear Physics Form Factors, Axial Currents



Supernovae Cross Sections and E_W Measurements

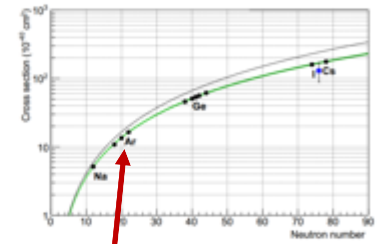


Those studies become significant if we do measurements with a very good accuracy

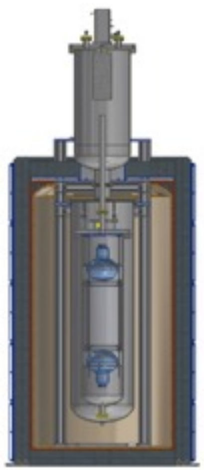
To do so we need multiple detectors able to accumulate large statistics with accurate measurements of recoil spectra

Second Generation – ton scale detectors and SNS neutrino flux normalization

Next Step - 1 ton LAr detector



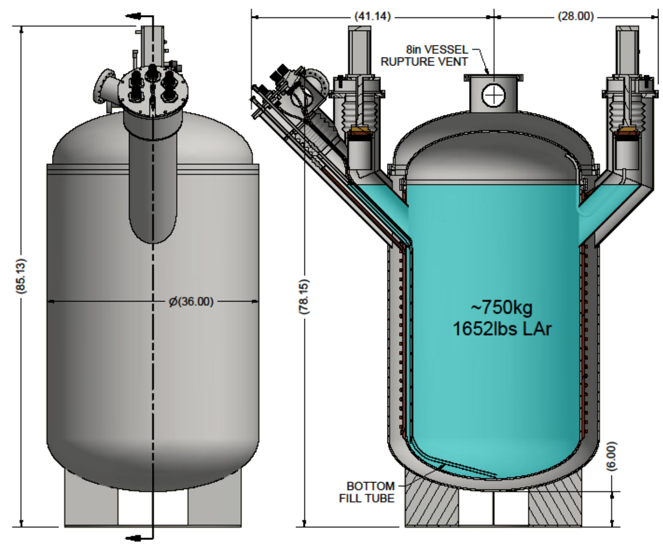
Need high statistics low background measurements of CEvNS



Transition from 22 kg to 1 ton LAr detector.

Can fit at the same place where presently 22 kg detector is sitting

Will see ~3 000 of CEvNS events per year



Important Next Step – SNS Neutrino Flux Normalization

Presently we assume that neutrino flux at SNS is known within 10%

Cross sections of neutrino interaction with Deuterium are known with 2-3% accuracy

S.Nakamura et. al. Nucl.Phys. A721(2003) 549

Prompt NC ν_μ +d → $1.8*10^{-41}$ cm^2
Delayed NC $\nu_{e\mu\text{-bar}}$+ d → $6.0*10^{-41}$ cm^2
Delayed CC ν_e + d → $5.5*10^{-41}$ cm^2

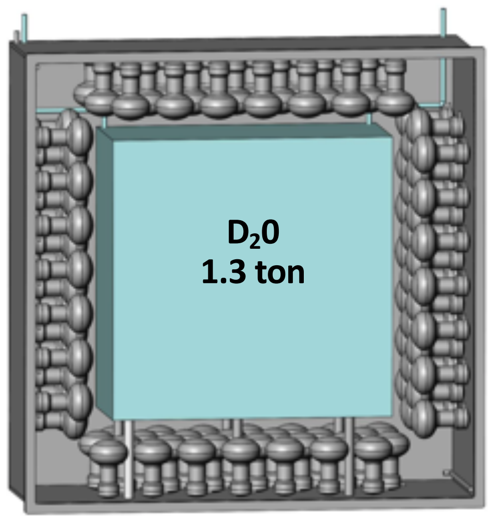
For 1 t fiducial mass detector ~ thousand interactions per year

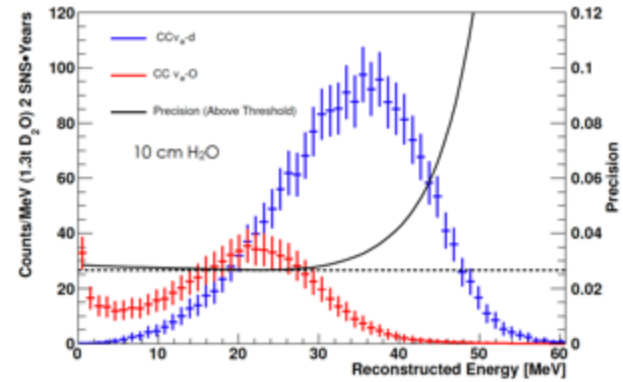
Detector calibration with Michel Electrons from cosmic muons (same energy range)

Well defined D_2O mass constrained by acrylic tank

10 cm of light water tail catcher

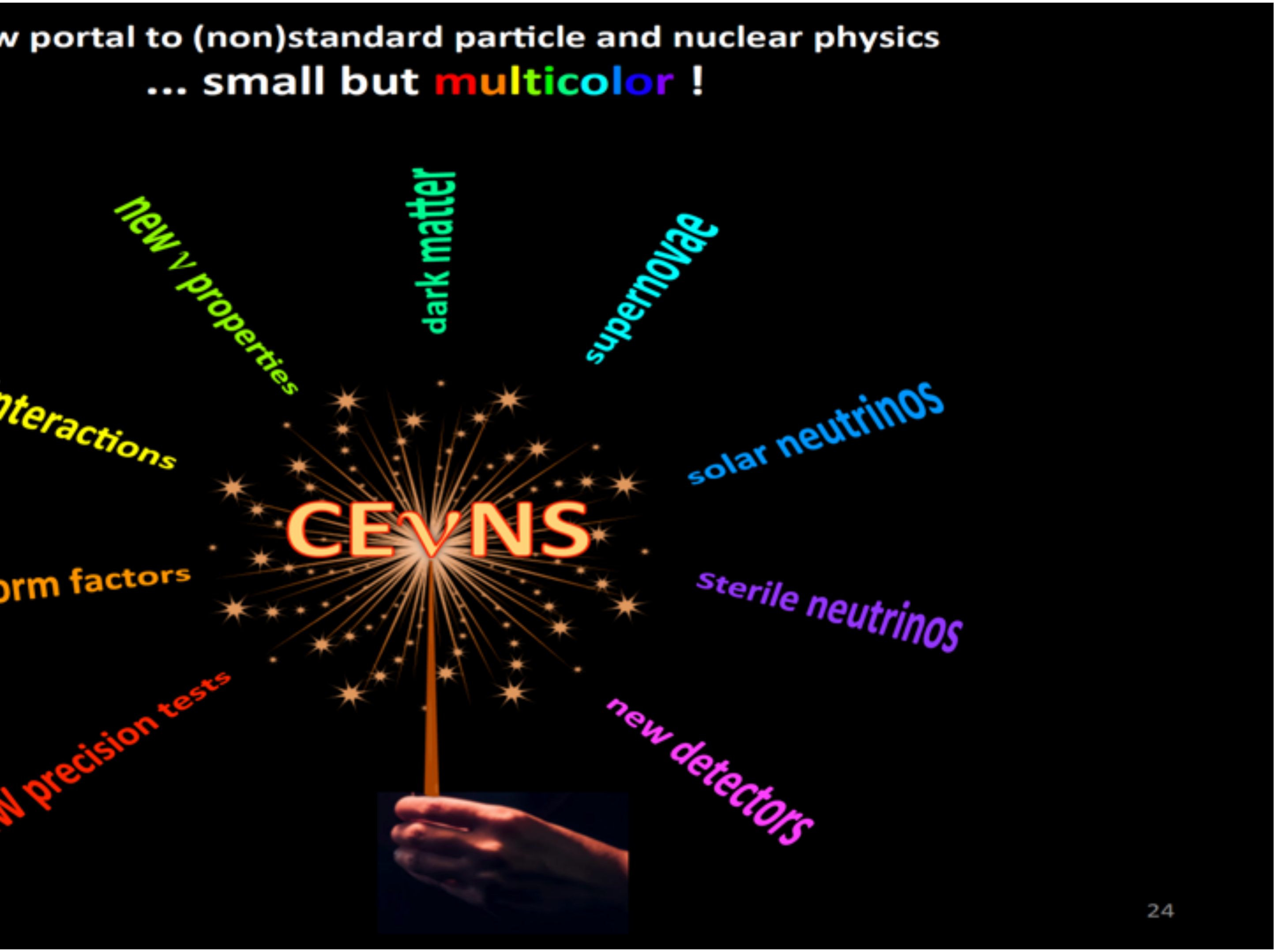
Outer dimensions 2.3 * 2.3 * 1.0 m^3





SNS calibration and CC measurements on Oxygen

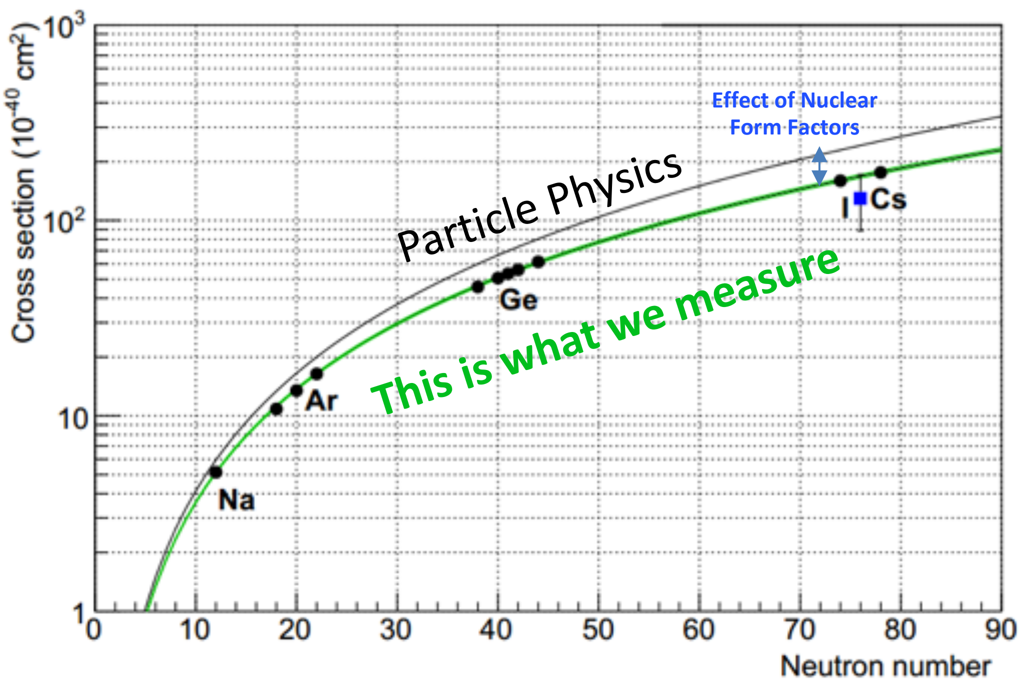
Slide from the opening talk at the Neutrino 2018 by Prof. Eligio Lisi, INFN



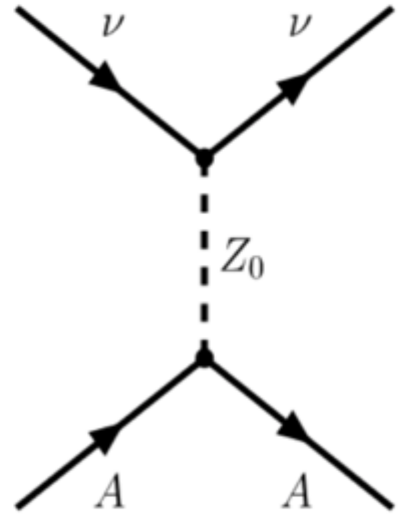
We Will Deploy Various Detectors with wide range of Nuclear Targets

Why Nuclear Form Factors are cool?

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$



Origin of Nuclear Form Factor



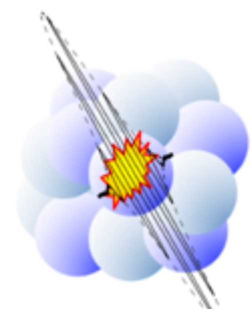
- Neutrino (v) interacts with entire nucleus (A), not just individual nucleons and quarks

- For large nuclei, E_v < 50 MeV to meet coherence condition

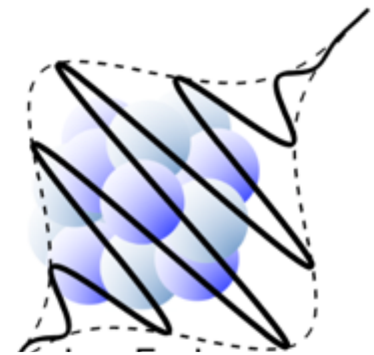
- De Broglie wavelength for 50 MeV v

$$\lambda = \frac{h}{p} = \frac{hc}{E} = \frac{1200 \text{ eV fm}}{50 \text{ MeV}} \sim 25 \text{ fm}$$

- Compare to ~fm (10^{-15} m) nuclear radius

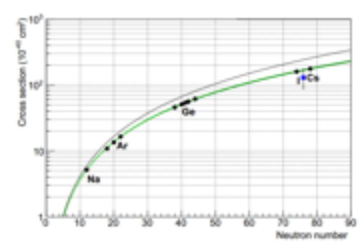


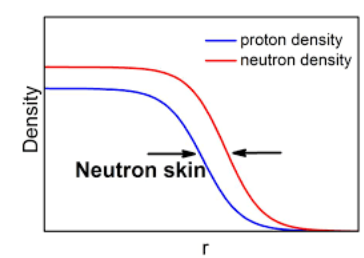
High Q = short
de Broglie wavelength



Low Q = long
de Broglie wavelength

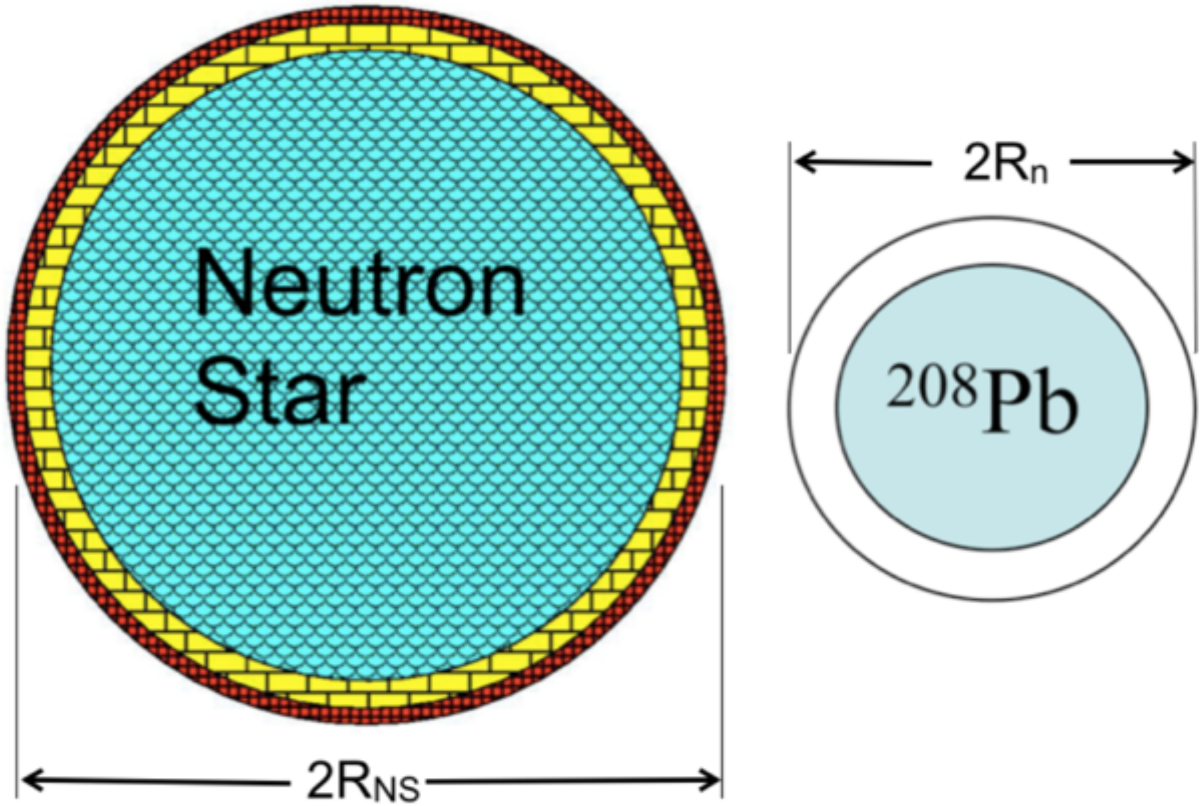
Measuring Form Factors we can extract what is nucleus neutron radius





Radii of ^{208}Pb and Neutron Stars

- Pressure of neutron matter pushes neutrons out against surface tension ==> R_n-R_p of ^{208}Pb correlated with P of neutron matter.
- Radius of a neutron star also depends on P of neutron matter.
- Measurement of R_n (^{208}Pb) in laboratory has important implications for the structure of neutron stars.



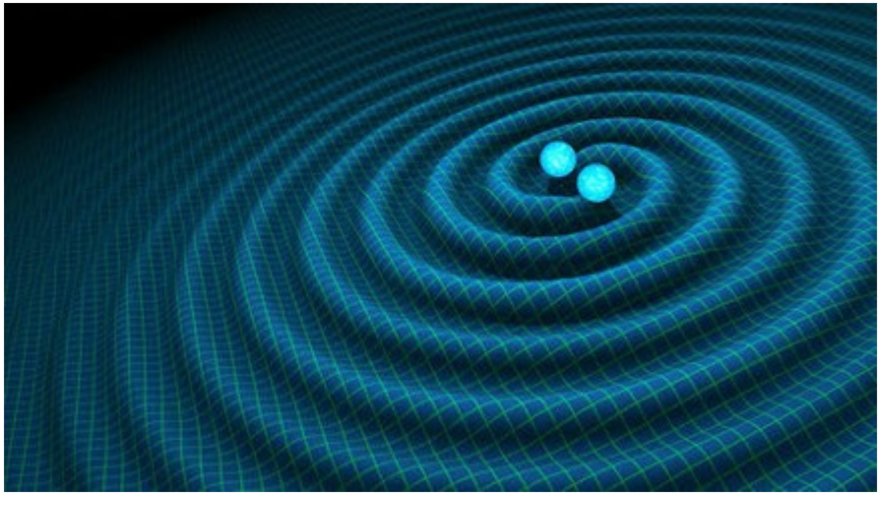
Neutron star is 18 orders of magnitude larger than Pb nucleus but has same neutrons, strong interactions, and equation of state.

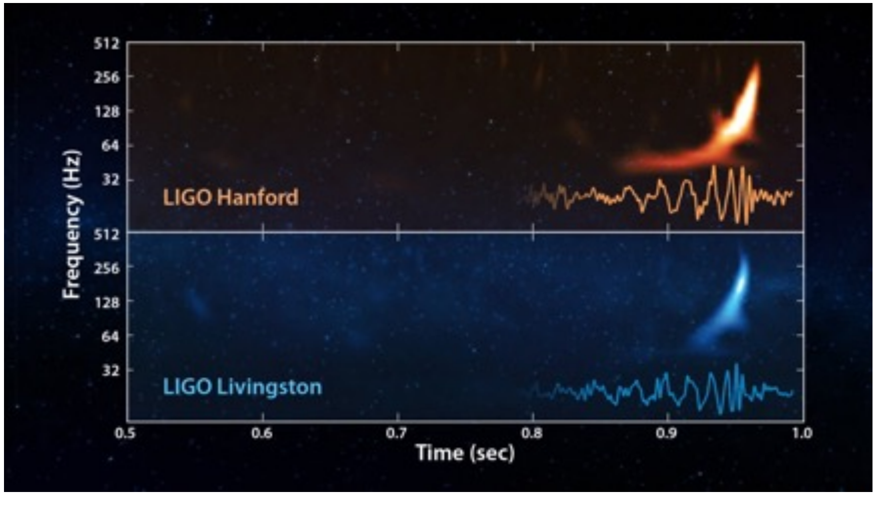
C.Horowitz

Gravitational Waves

Historic detection of Gravitational Waves in 2015 from merger of two black holes

Measure chirp signal as two bodies radiate gravitational waves and spiral in to higher frequencies



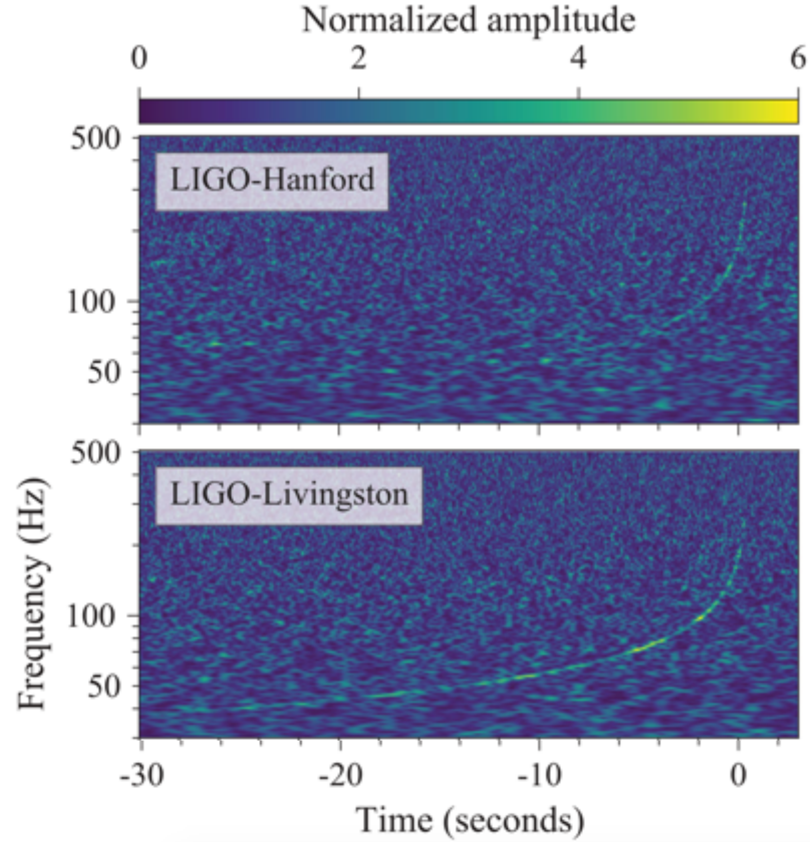


GW170817

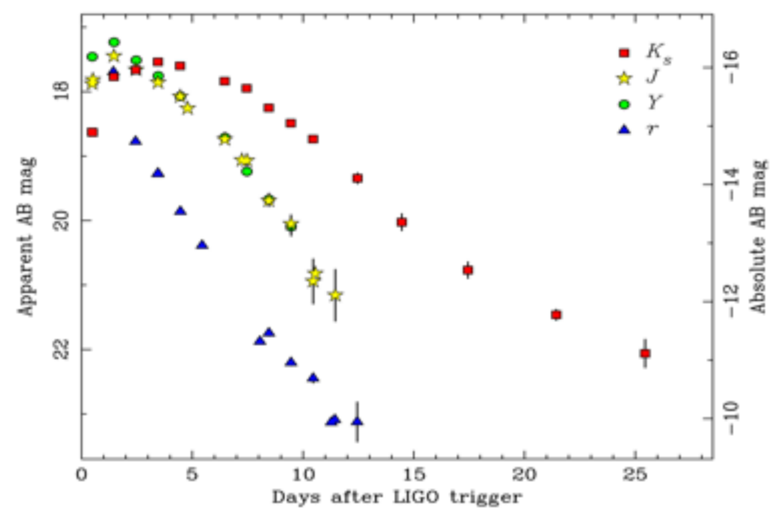
On August 17, 2017 GW were detected with independent observation y Fermi and Integral spacecrafts of a short gamma ray burst observation

Extensive follow up observe this event at X-ray, ultra violet, visible, infrared and radio waves.

This event was a merger of two neutron stars



Black holes are perfectly spherical objects, but neutron stars can be deformed



Merger GW170817: deformability of NS

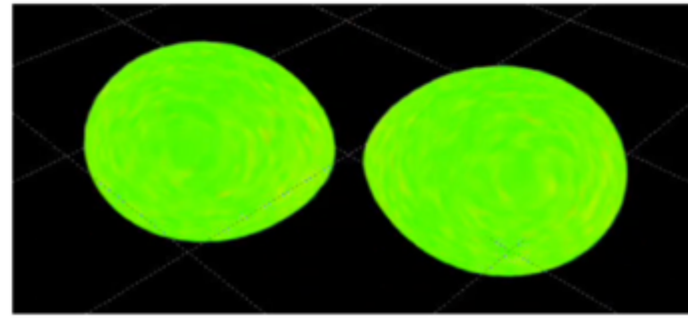
- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom ~ R^3.

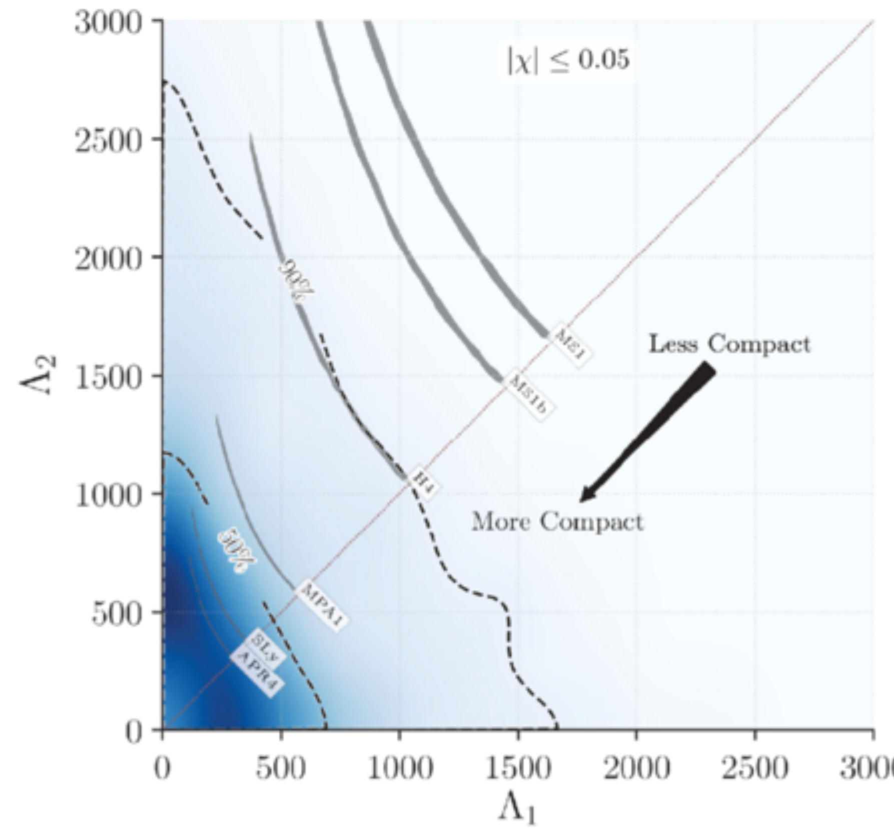
$$\kappa = \Sigma_f \frac{|\langle f|rY_{10}|i\rangle|^2}{E_f - E_i} \quad \propto R^3$$

- Tidal deformability (or mass quadrupole polarizability) of a neutron star scales as R^5.

$$\Lambda \propto \Sigma_f \frac{|\langle f|r^2Y_{20}|i\rangle|^2}{E_f - E_i} \quad \propto \quad R^5$$

- GW170817 observations set upper limits on Λ_1 and Λ_2.





C.Horowitz

Neutrino and Gravitational Waves

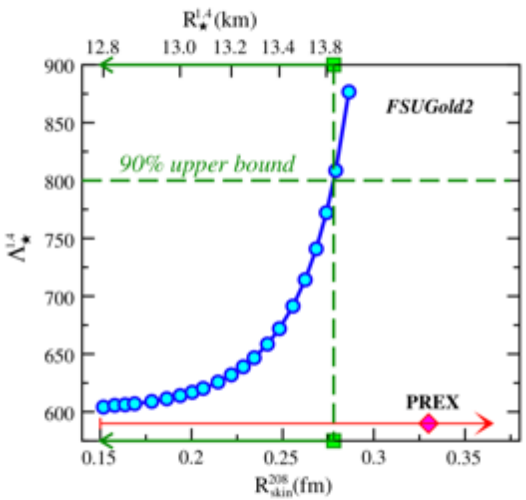


FIG. 1. The dimensionless tidal polarizability $\Lambda_{\star}^{1.4}$ of a $1.4M_{\odot}$ neutron star as a function of the neutron-skin thickness of ^{208}Pb (lower abscissa) and the radius of a $1.4M_{\odot}$ neutron star (upper abscissa) as predicted by the FSUGold2 family of relativistic interactions. Constraints on $R_{\rm skin}^{208}$ and $R_{\star}^{1.4}$ are inferred from adopting the $\Lambda_{\star}^{1.4} \leq 800$ limit deduced from GW170817 [2].

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Featured in Physics

Neutron Skins and Neutron Stars in the Multimessenger Era

F. J. Fattoyev,[1,*] J. Piekarewicz,[2,†] and C. J. Horowitz[1,‡]

Detect two neutron stars merge via gravitational waves

From merger time calculate NS masses

From tidal deformability measure NS radius

Detect CEvNS on heavy nucleus at the SNS

From nuclear form factor, extract pressure of neutron matter

Calculate NS radius for given mass

Compare !!!

Conclusion

Neutrinos are cool

They are belong to domain which has overlap between particle physics, nuclear physics and astrophysics

There is extensive neutrino program at the ORNL