(Underground) Neutrino Physics

Gabriel Orebi Gann
Yury Kolomensky

Physics 290E

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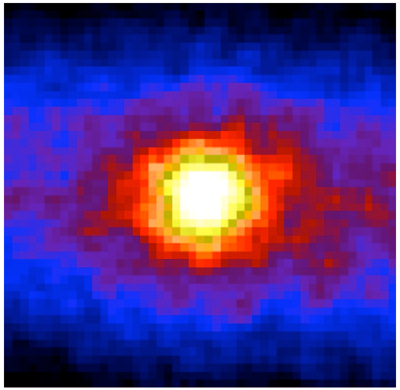
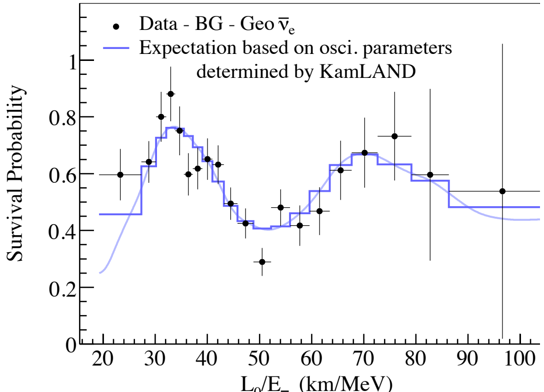
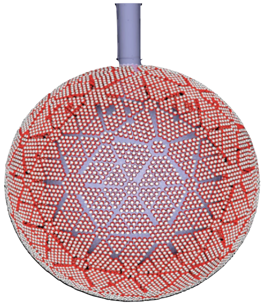
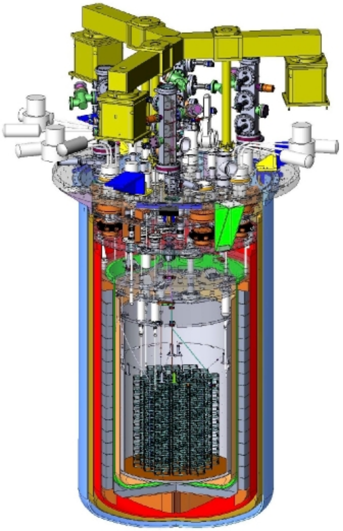








Neutrinos 101: What are neutrinos?

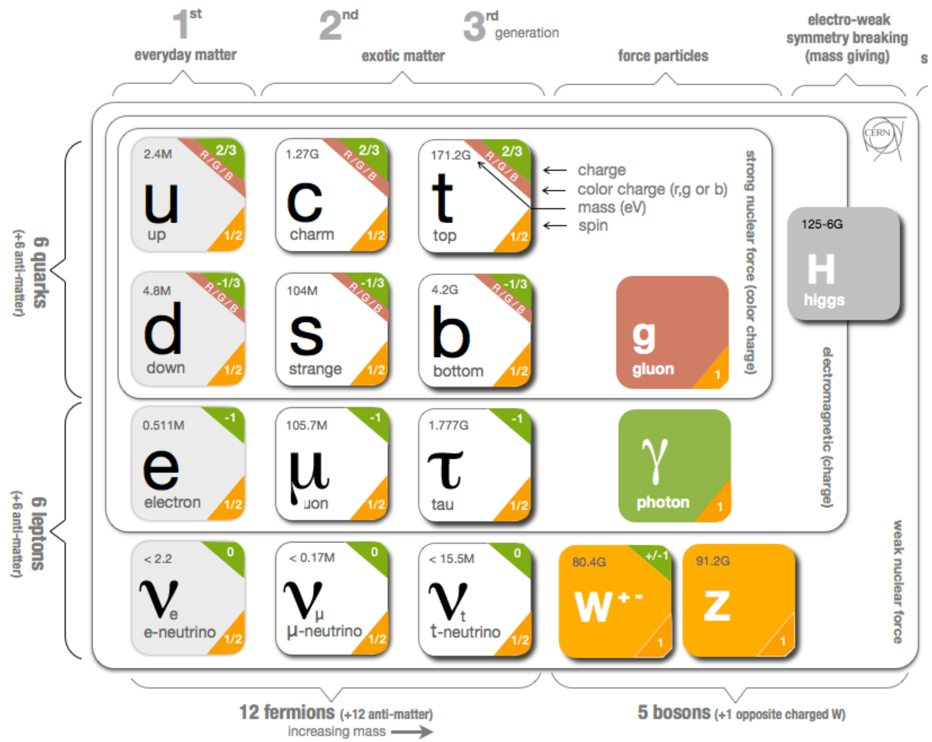
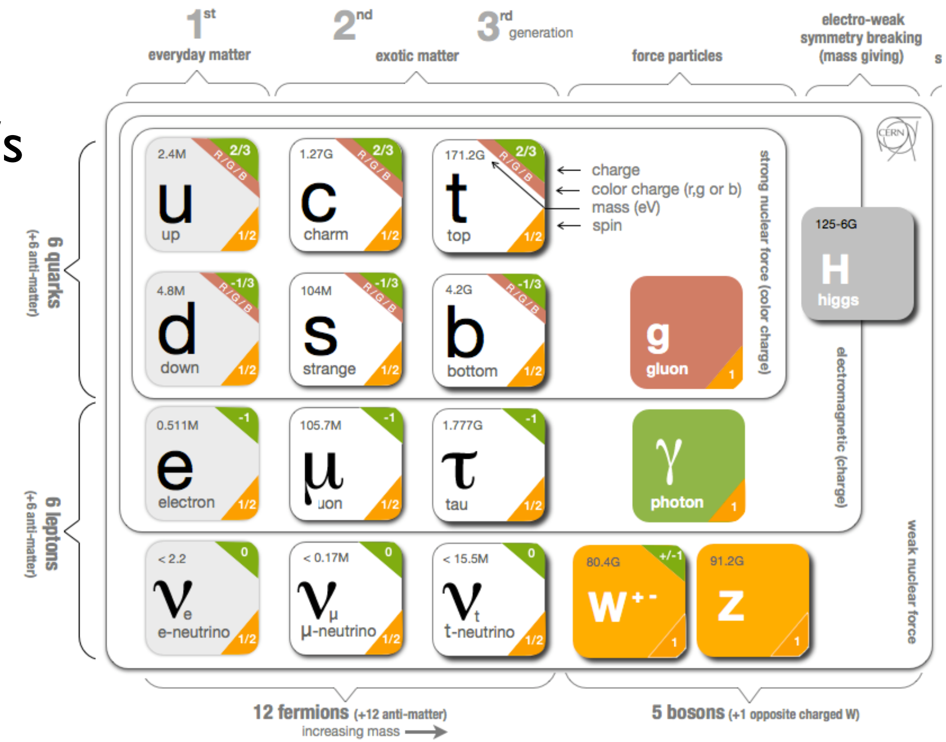


Figure: CERN

Neutrinos 101: What are neutrinos?

- Fundamental particles
- Extremely abundant (10^{11} $\nu/cm^2/s$ from the Sun @ Earth surface)



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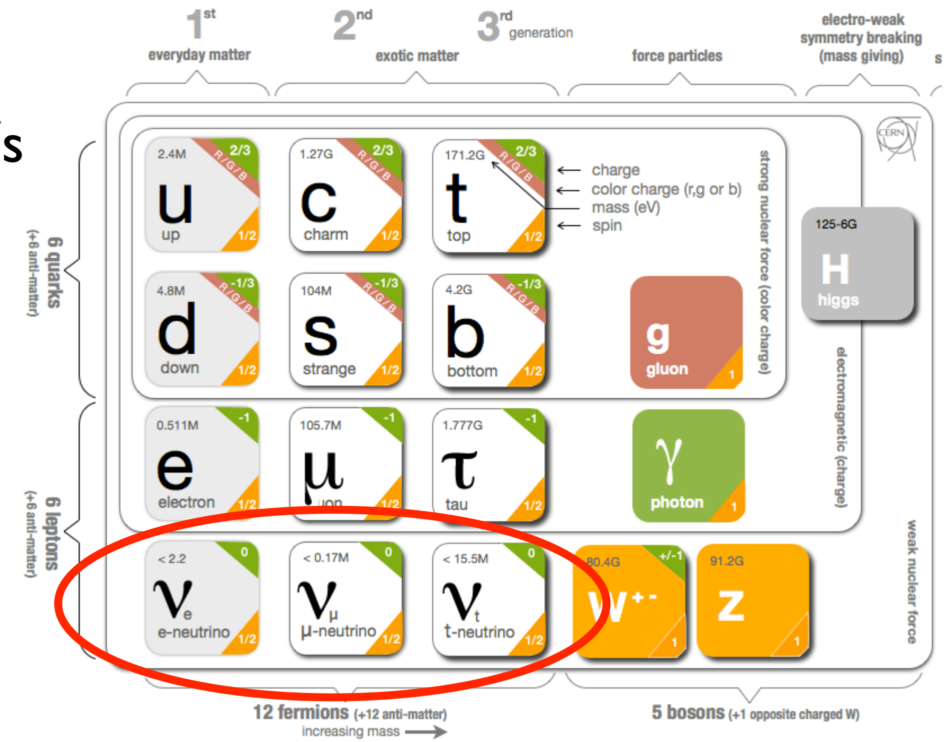

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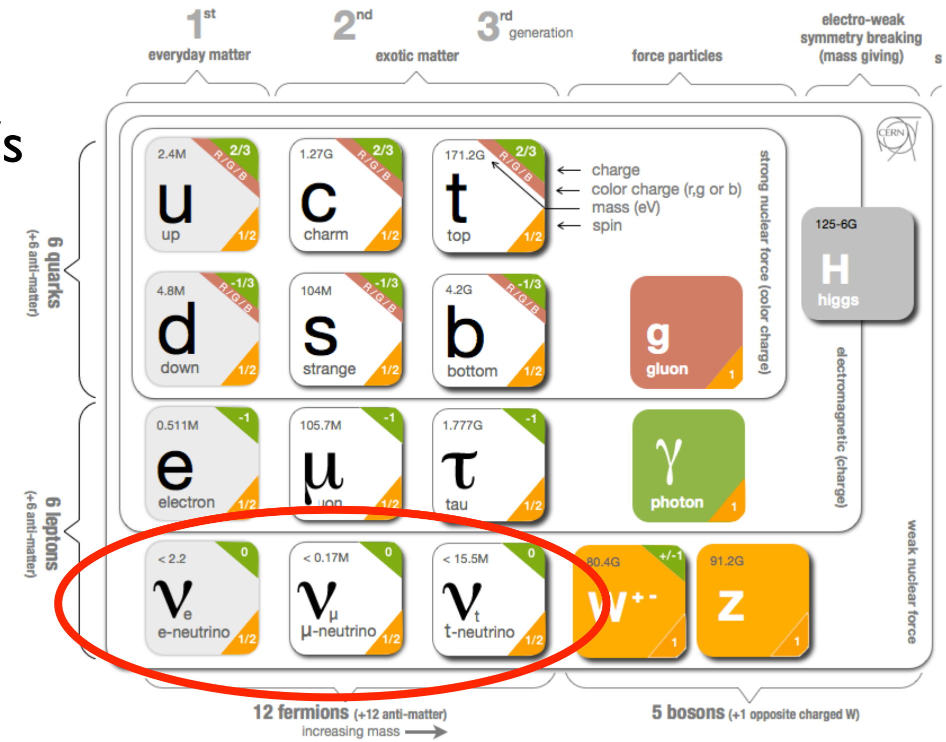

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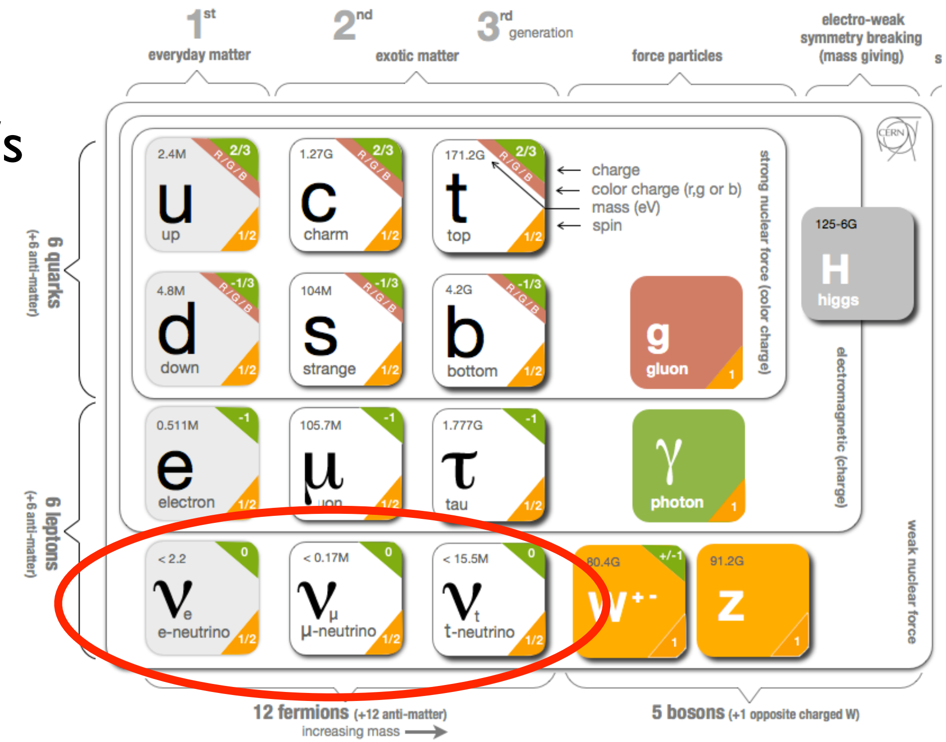

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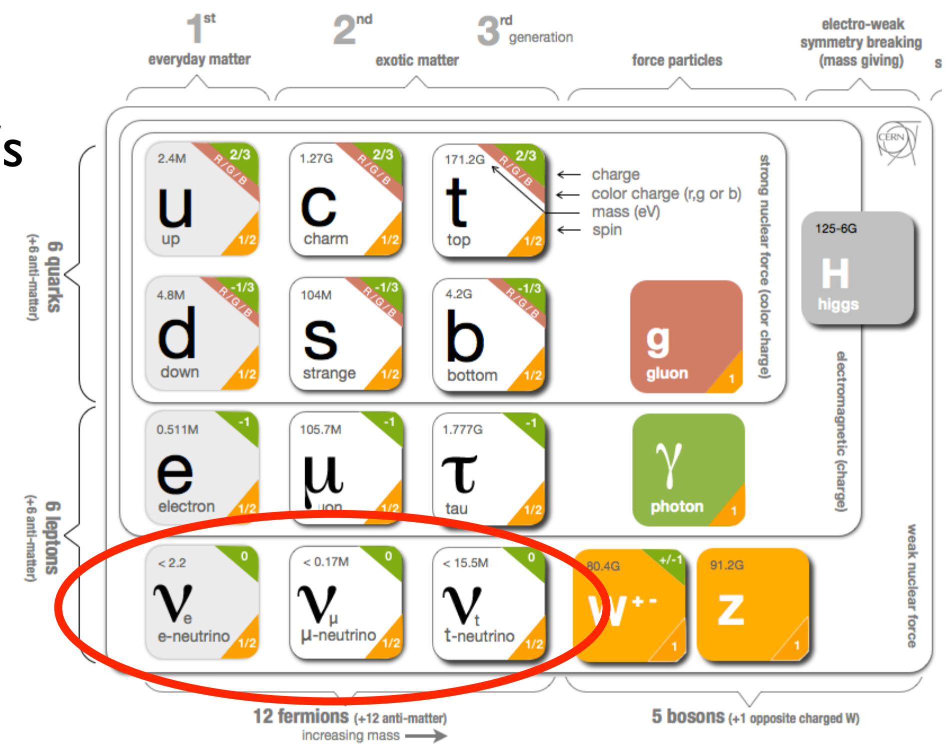

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- But not dark matter
- May hold keys to the question of matter-antimatter asymmetry in the universe

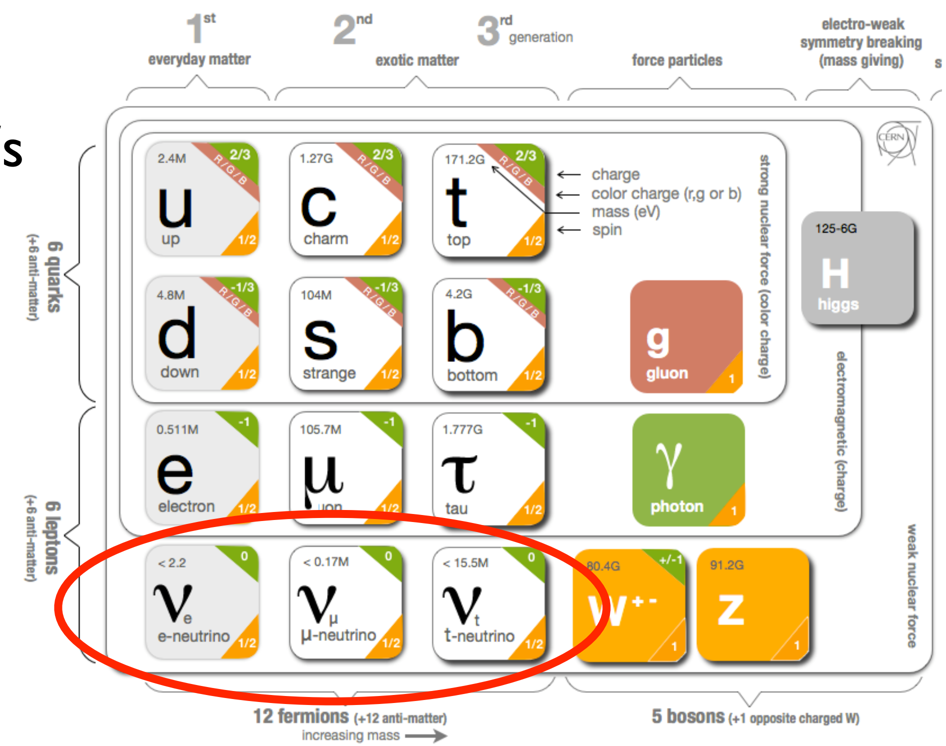
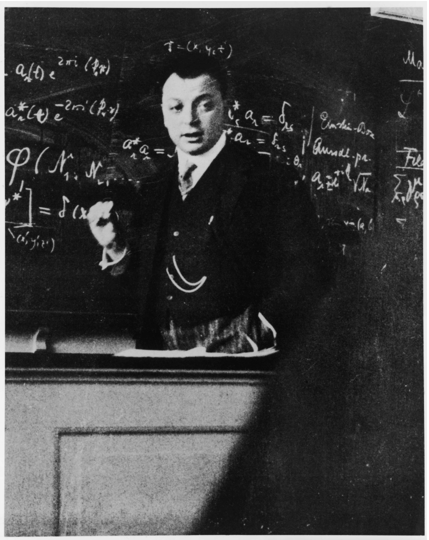


Figure: CERN

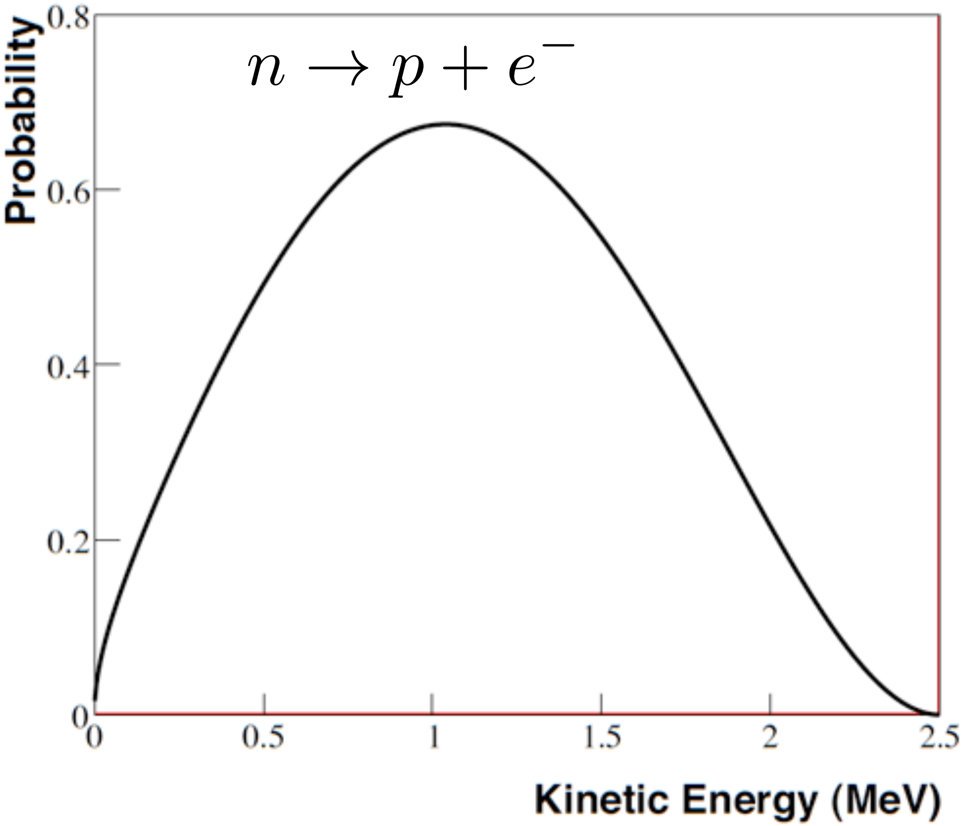
Postulating an Impossibility

1930



Wolfgang Pauli

- The continuous spectrum of β decay poses a problem...



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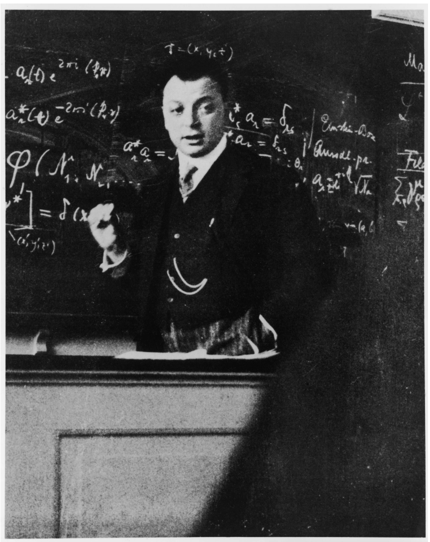

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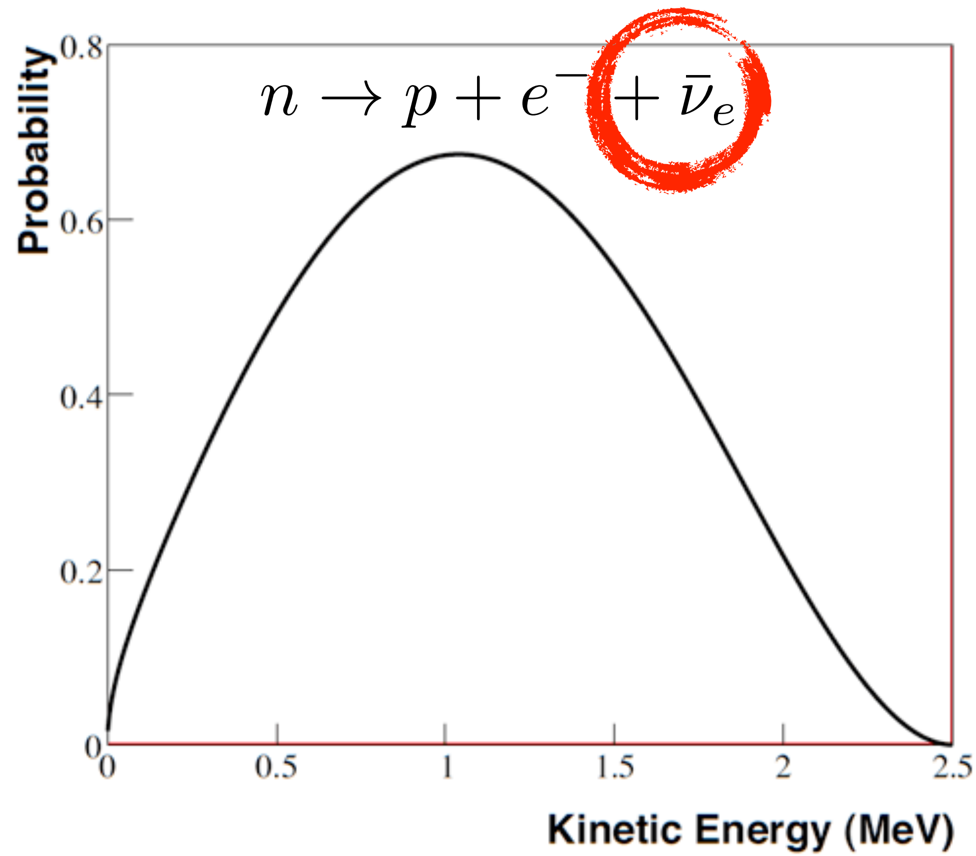

- 1930: Wolfgang Pauli proposes a new particle

Postulating an Impossibility

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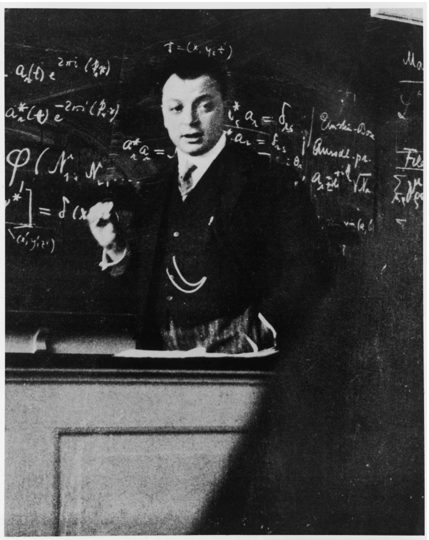


Wolfgang Pauli

Abschrift

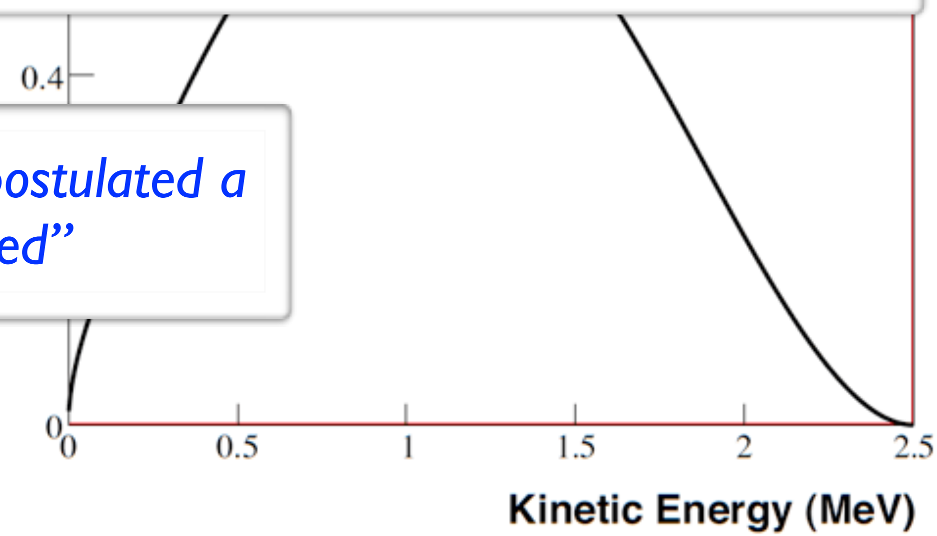
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst ansuhören bitte, Ihnen des näheren auseinandersetsen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsats" (1) der Statistik und den Energiesats zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinsip befolgen und

"I have done a terrible thing. I have postulated a particle that cannot be detected"



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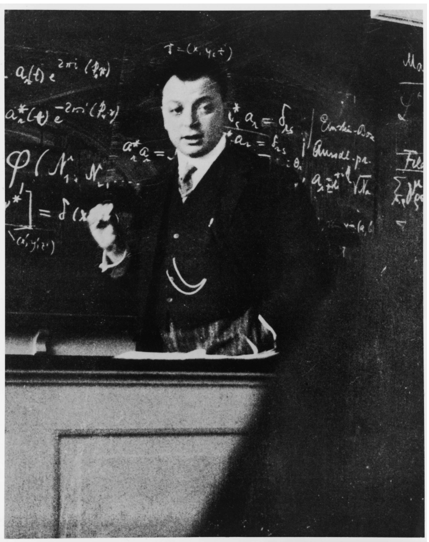

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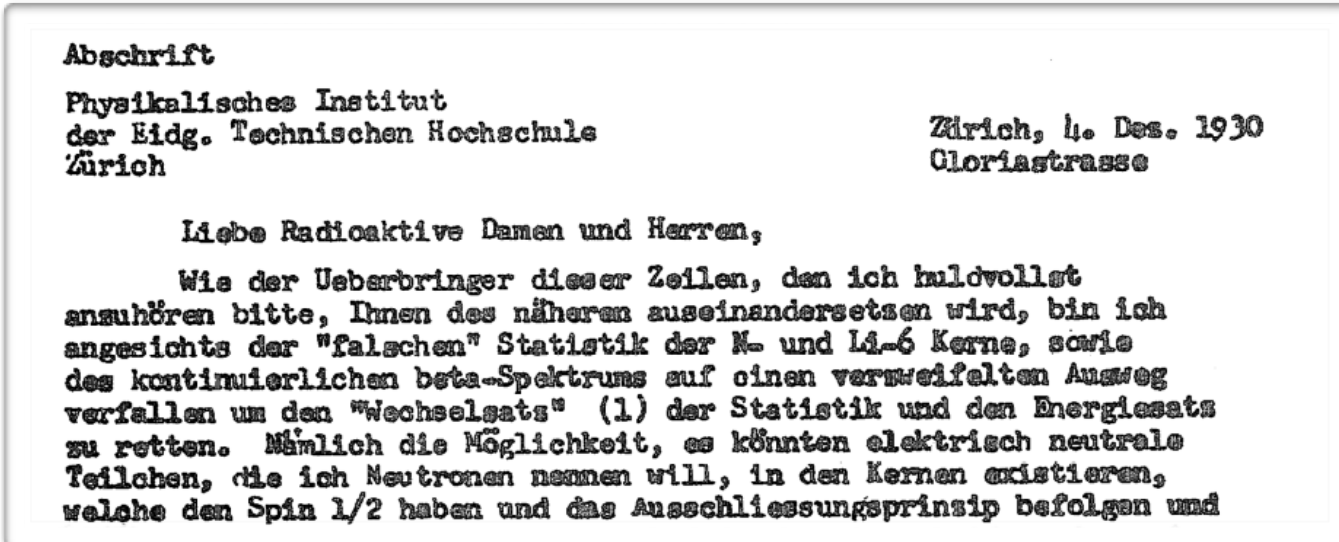

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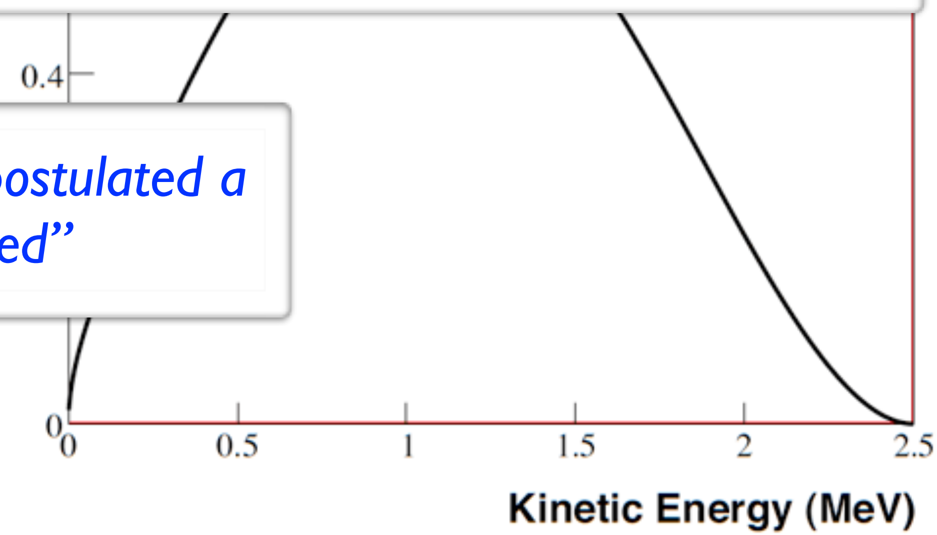

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First Detection

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IF $n \rightarrow p + e^- + \bar{\nu}_e$

THEN $\bar{\nu}_e + p \rightarrow e^+ + n$

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Prompt annihilation signal

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Delayed neutron capture

Double coincidence signal

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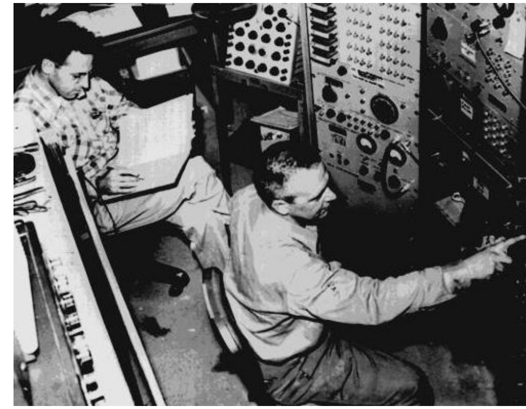
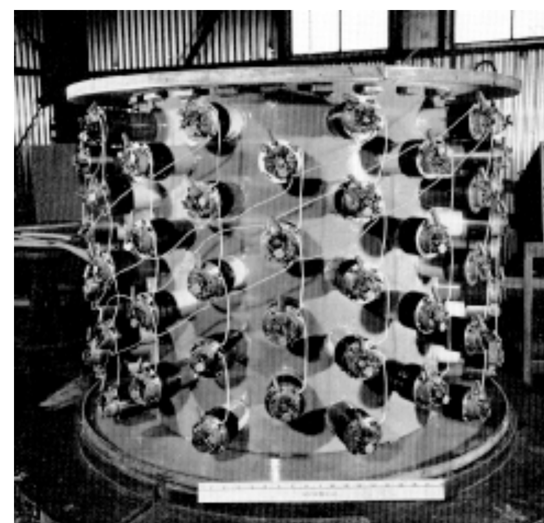
- 1956: Reines and Cowan
- Anti-neutrinos detected at Savannah River nuclear reactor

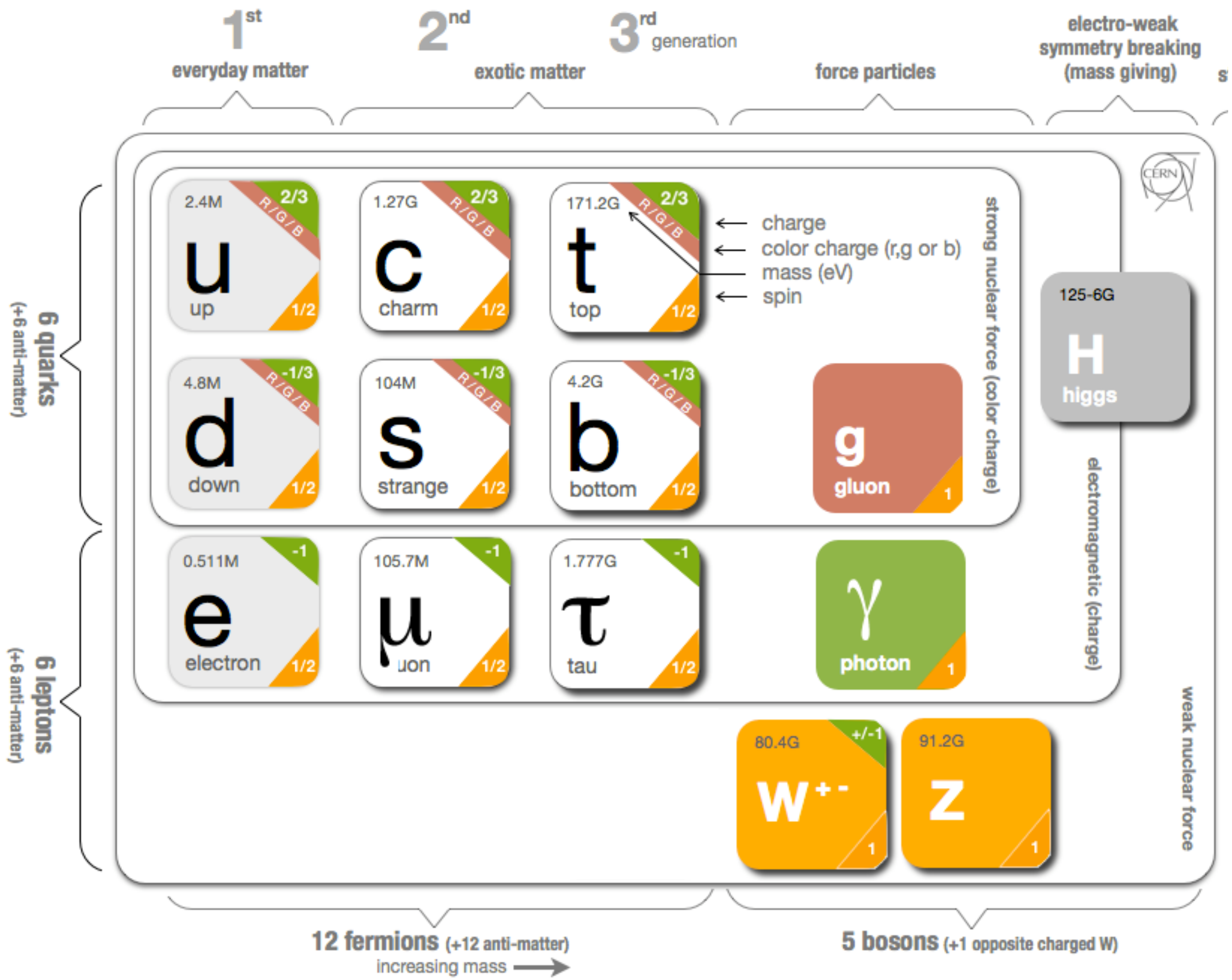
1956



Fred Reines & Clyde Cowan



Standard Model



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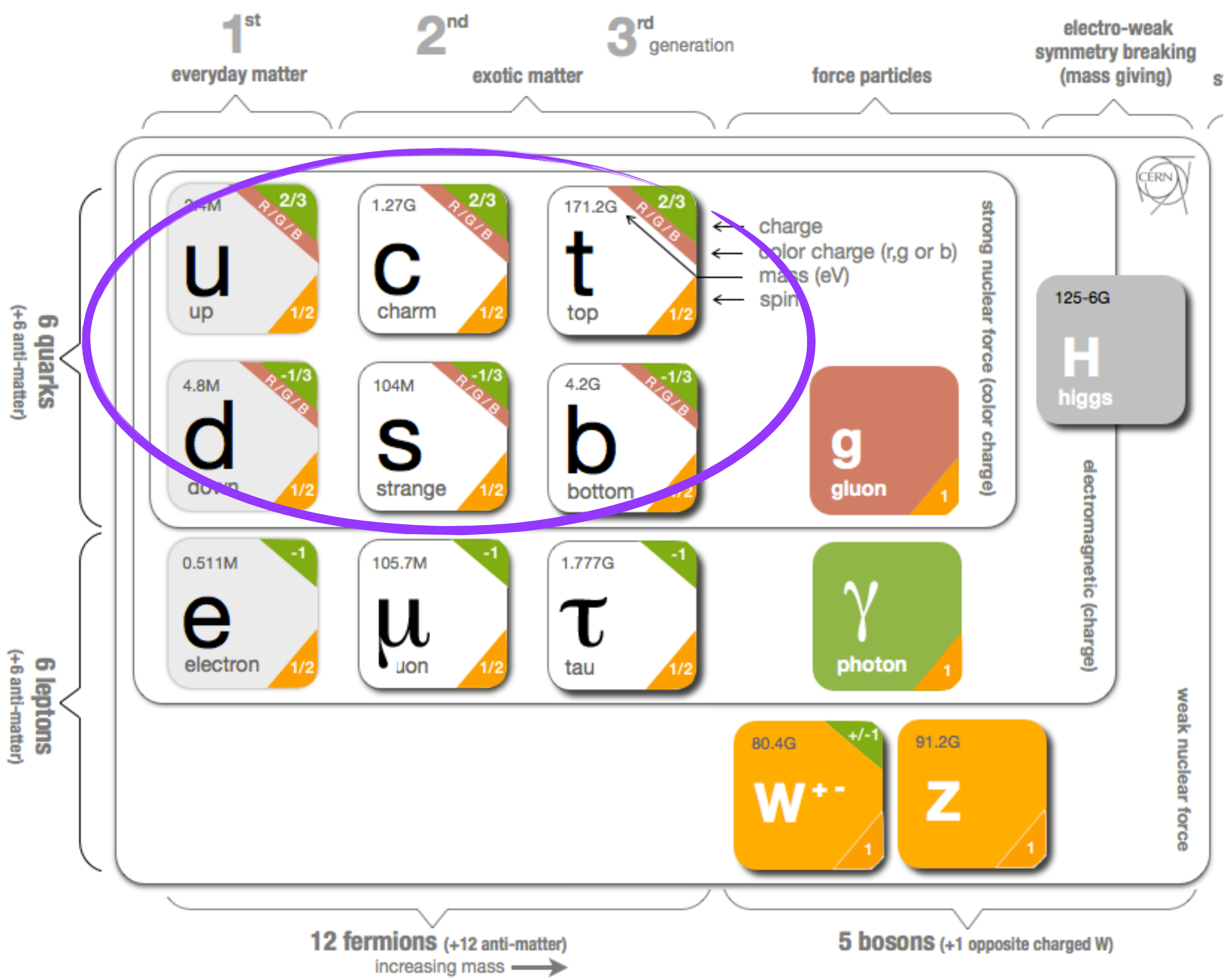
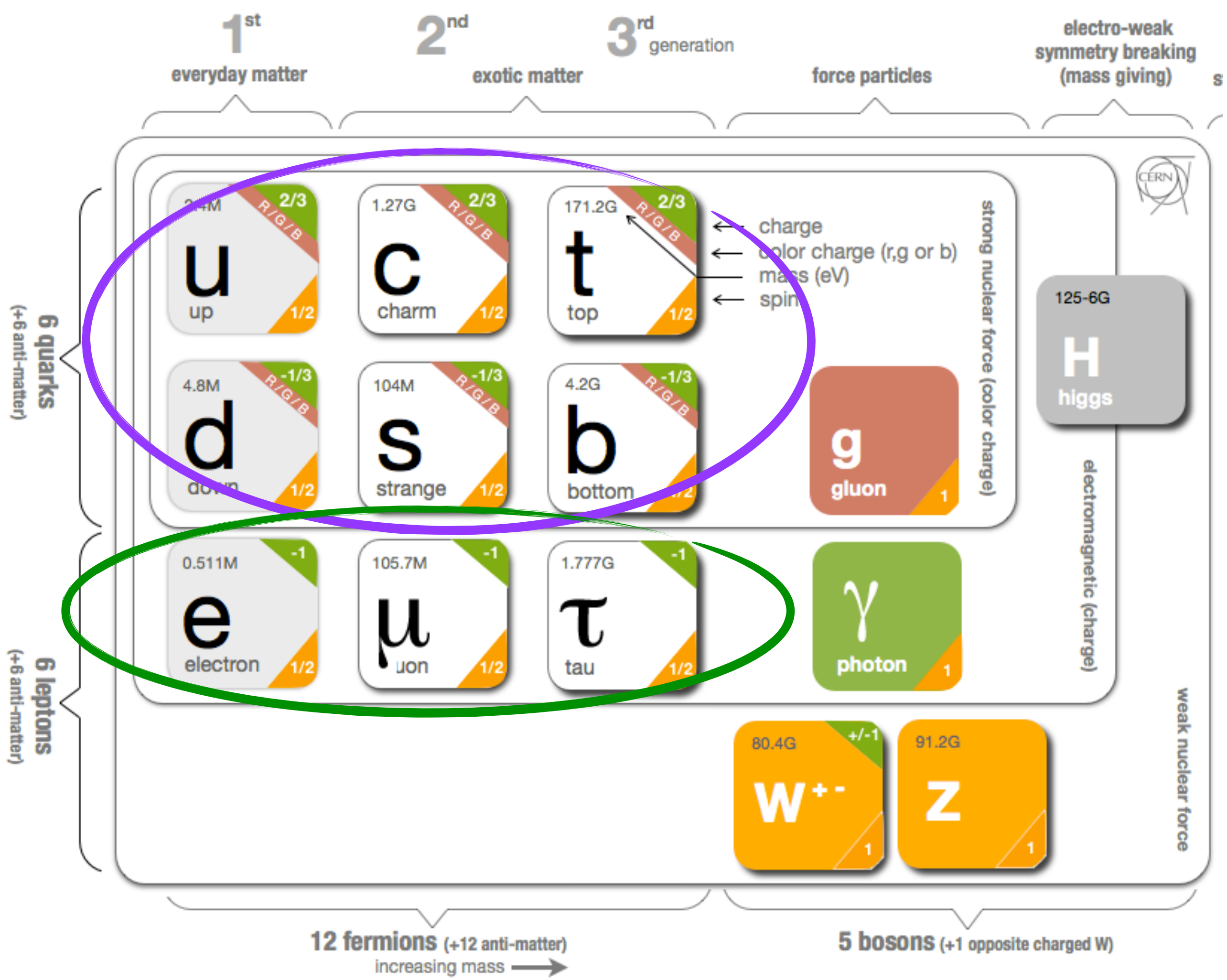


Quarks:
Fermions (spin 1/2)
Charged (+2/3, -1/3)
Massive
Colored

Standard Model



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Fermions (spin 1/2)
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Massive Leptons:
Fermions (spin 1/2)
Charged (-1)
Interact weakly / EM

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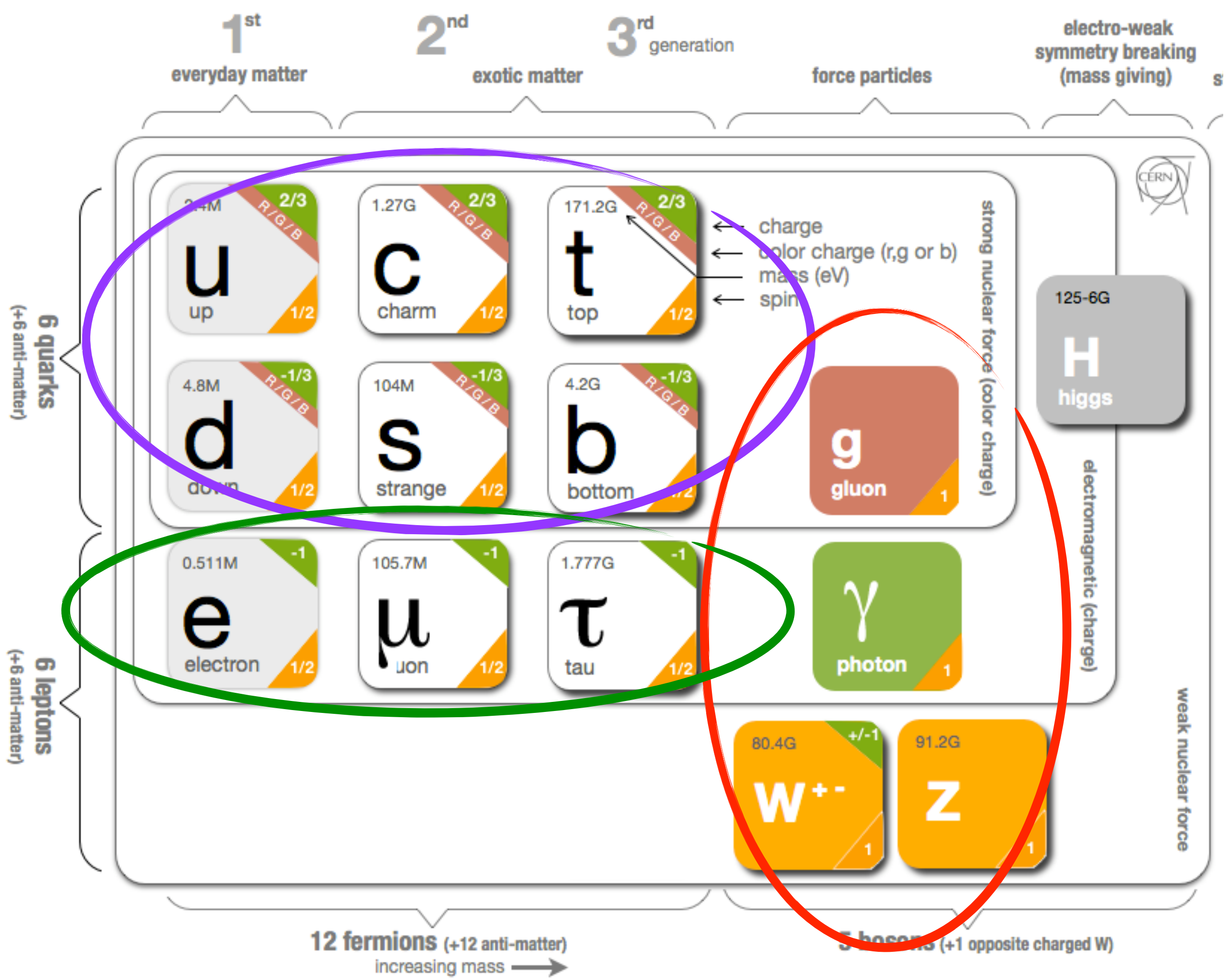

Quarks:
Fermions (spin 1/2)
Charged (+2/3, -1/3)
Massive
Colored

Force carriers:
Bosons (spin 0)

Massive Leptons:
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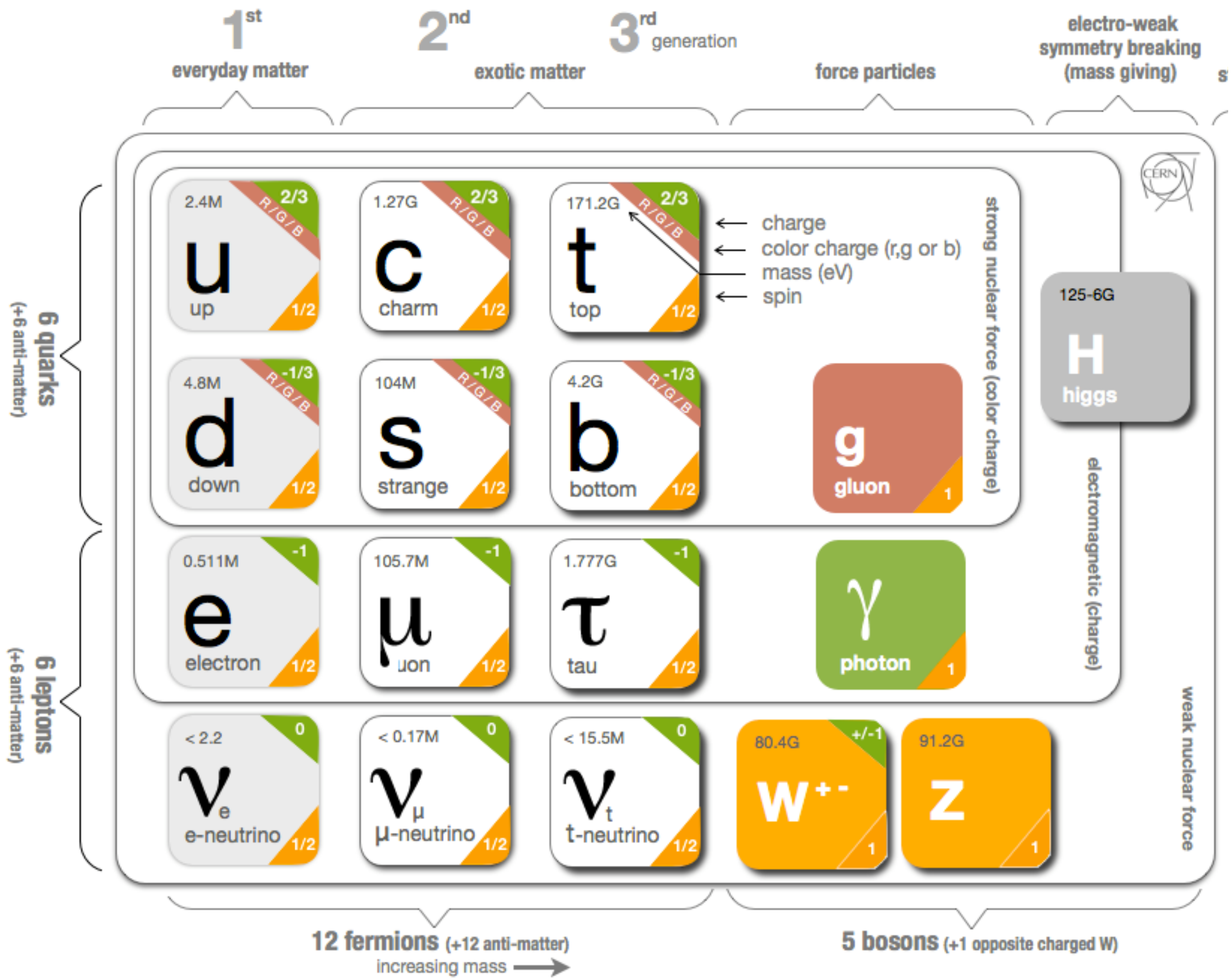
Charged (-1)
Interact weakly / EM

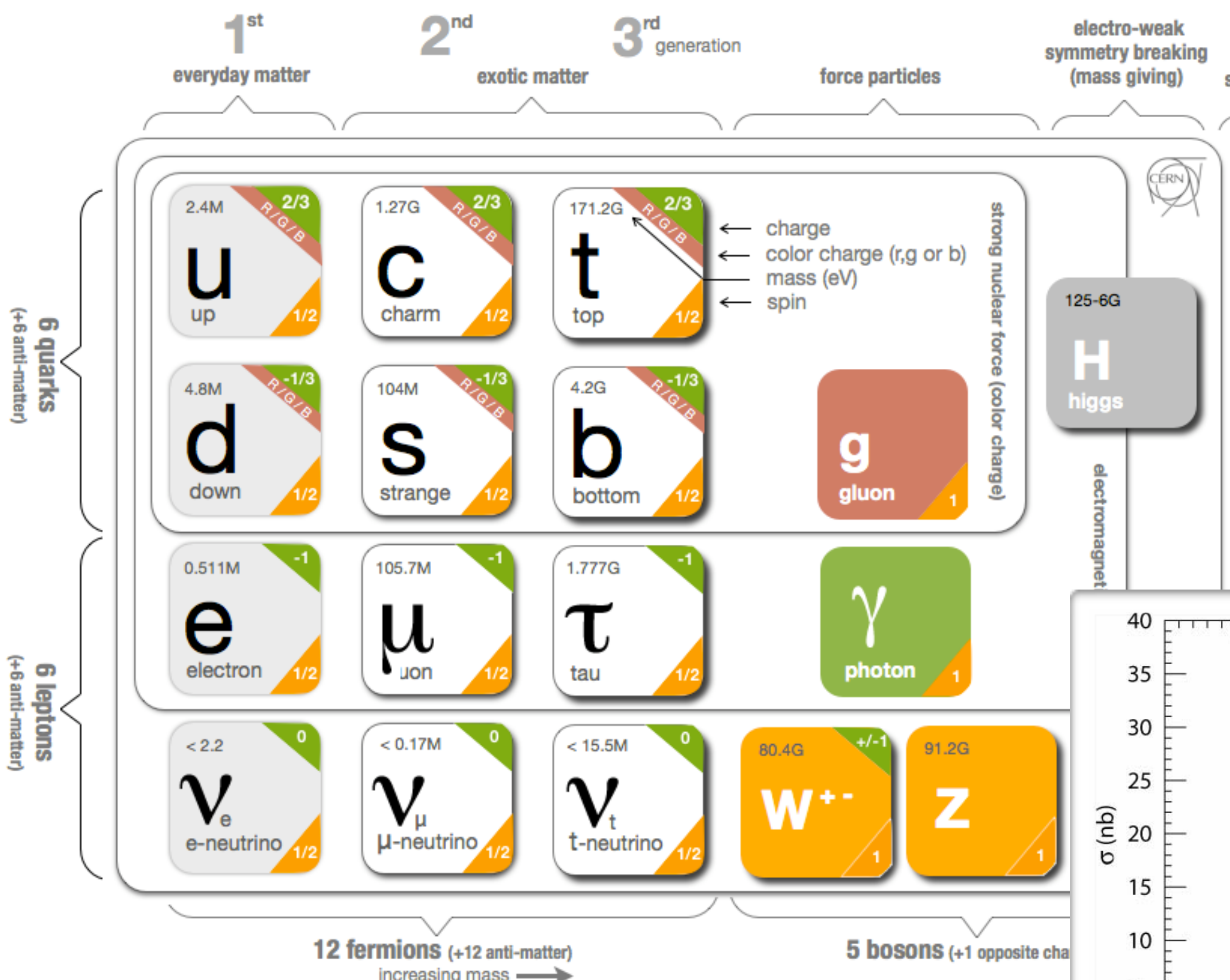
Standard Model



Neutrino properties:

1. Interact weakly
2. Massless
3. Three flavors

Standard Model



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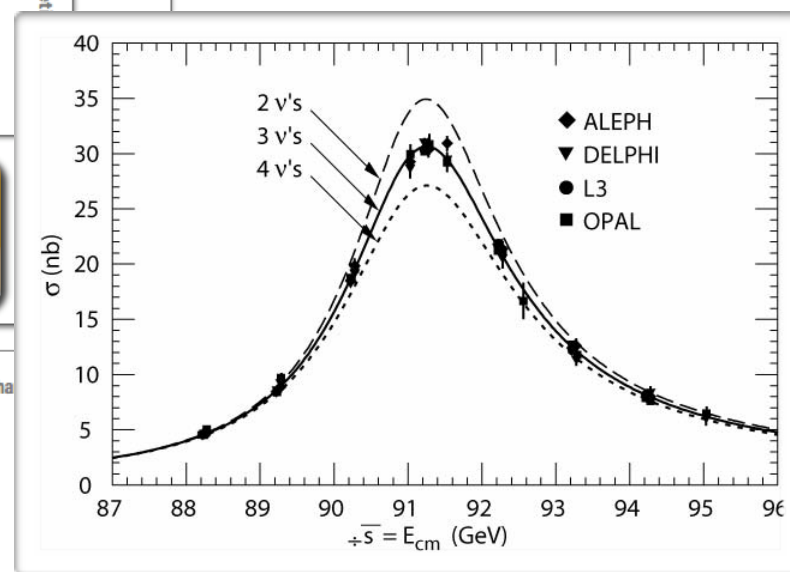

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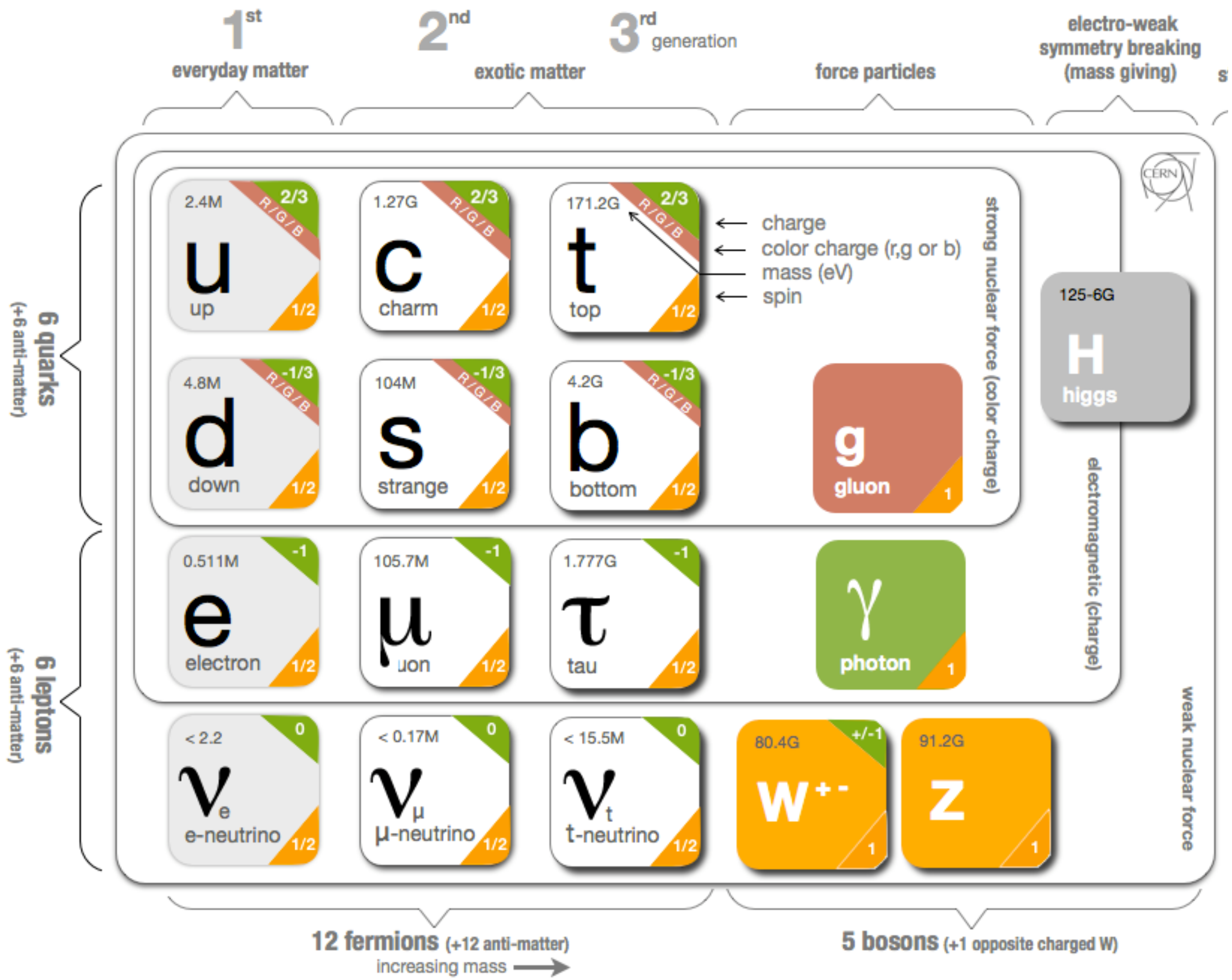

Neutrino properties:

1. Interact weakly
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3. Three flavours

ν_e - The Sun, nuclear reactors

ν_μ - Cosmic rays, man-made

ν_τ - Man-made beams First observation in 2000

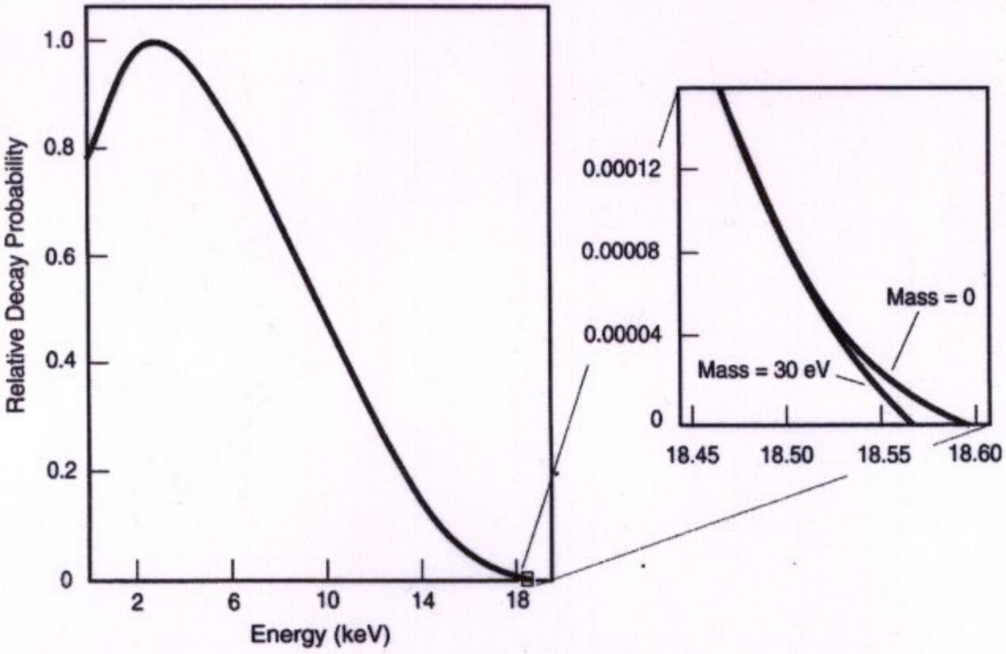
Neutrino Masses

Relativistic kinematics:

$$\sum p_i^\mu = \sum p_f^\mu \quad ; \quad E^2 = p^2 + m^2$$

Measurements of the (physical) Electron Neutrino Mass

$\Rightarrow$ Tritium decay experiments $\rightarrow He^3 + e^- + \overline{\nu}_e$



Current best limits:

ν_e : m<2.2 eV (Maintz, Troitsk)

ν_μ : m<170 keV

ν_τ : m<15.5 MeV (CLEO)

Cosmological limits:

$\Sigma m < 0.3$ eV (WMAP, 2dF, Planck)

Neutrino Detectors

- Problem: neutrino interaction cross section is *small*

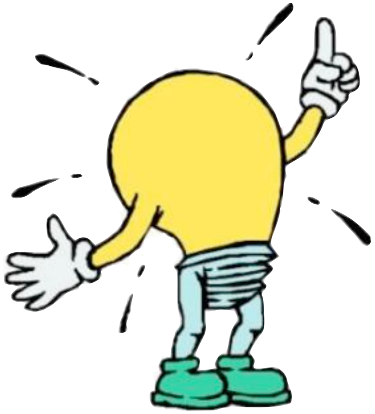
$$\sigma(\nu_\ell e^- \to \ell^- \nu_e) \approx \sigma(\nu_\ell n \to \ell^- p) \approx \sigma(\bar{\nu}_\ell p \to \ell^+ n)$$

$$= \frac{G_F s}{\pi} = \frac{G_F}{\pi} 2mE_\nu \approx 10^{-41} \frac{E_\nu}{\mathrm{GeV}} \mathrm{cm}^2 = 10^{-17} \frac{E_\nu}{\mathrm{GeV}} \mathrm{barn}$$

☞ Iff $2mE_\nu > m_l^2$, i.e. if charged current reaction is allowed kinematically

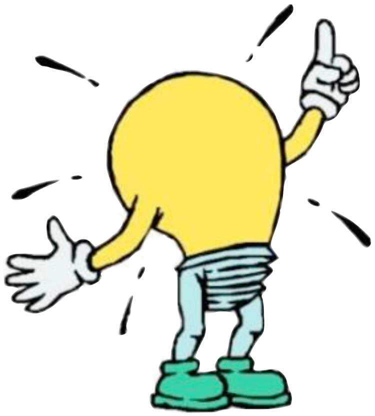
- E.g. for solar neutrinos ($E_\nu \approx 10$ MeV), interaction cross section is $9 \cdot 10^{-44}$ cm^2 ($9 \cdot 10^{-20}$ barn) !
- Mean free path in lead: $1/(\sigma n) \sim 3 \times 10^{15}$ km ~ 0.1 parsec
- Detection requires *large* detectors, *low* backgrounds

☞ Underground



Neutrino Oscillation

Produced as weak (flavor) eigenstates (ν_e, ν_μ, ν_τ)
Propagate as physical (mass) eigenstates (ν_1, ν_2, ν_3)



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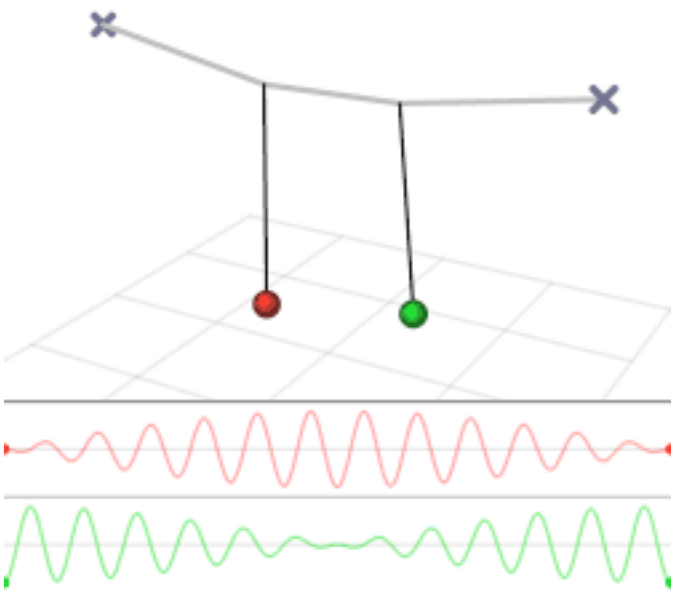
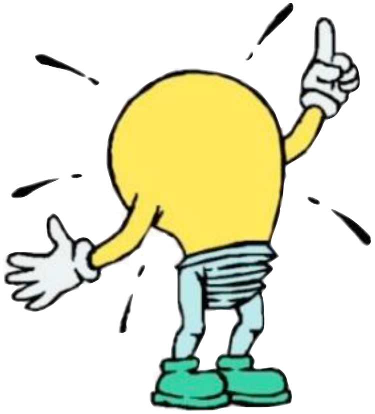
simplified 2-neutrino scenario



Source: Wikipedia



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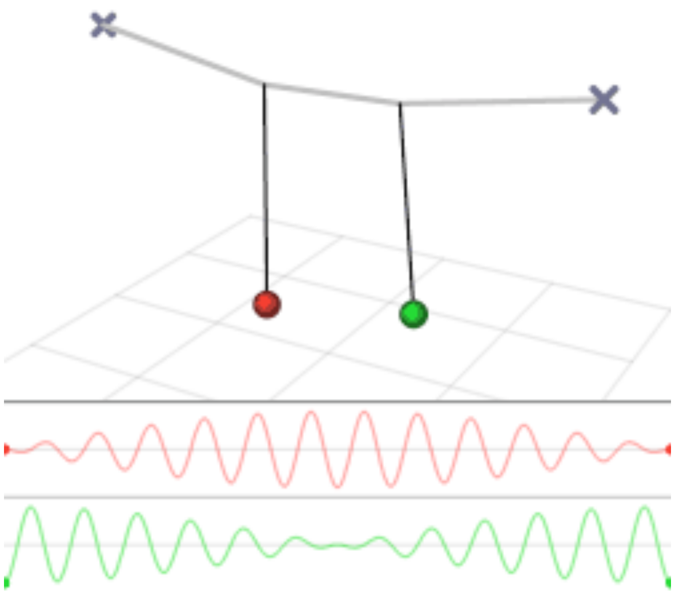

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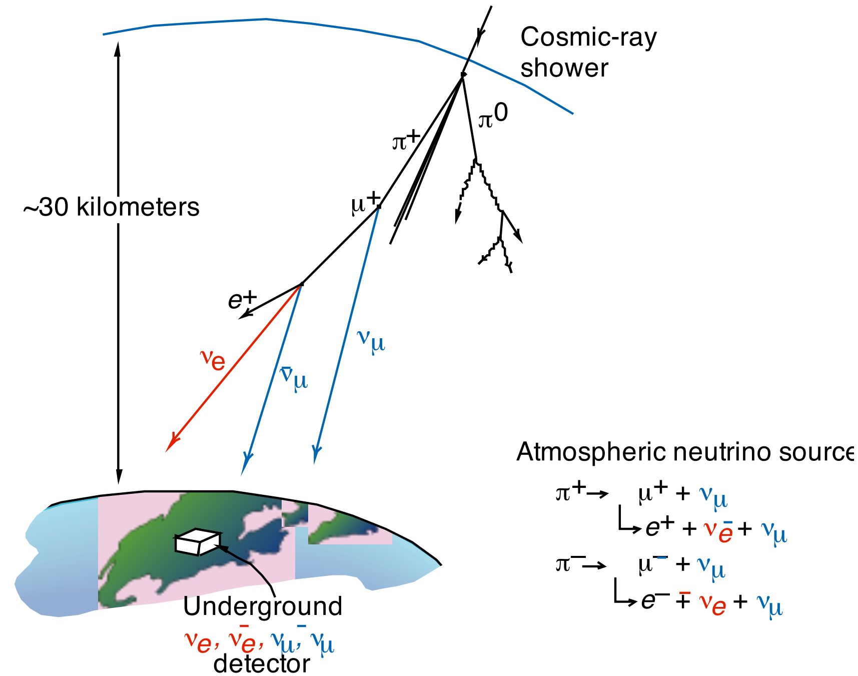
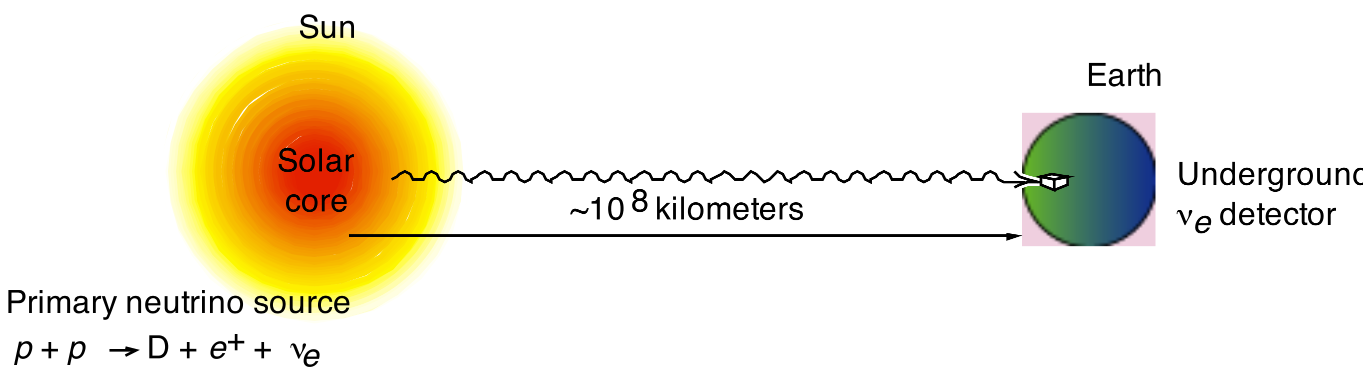
Evidence For Neutrino Oscillations



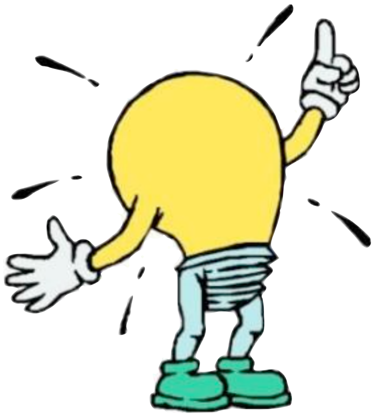
First evidence of neutrino oscillation

$$\frac{\nu_\mu}{\nu_e} \neq 2$$

Atmospheric Neutrinos
high energies



Solar Neutrinos
low energies



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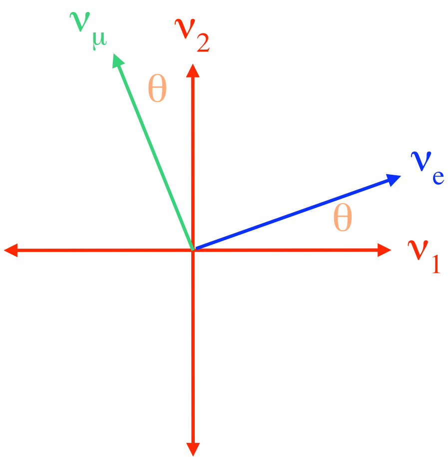

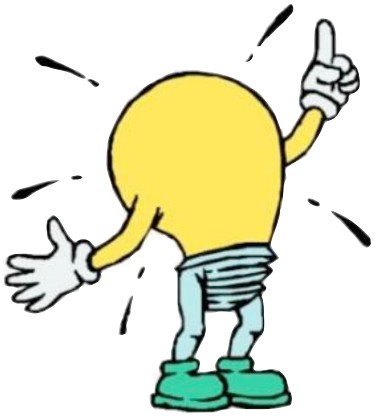

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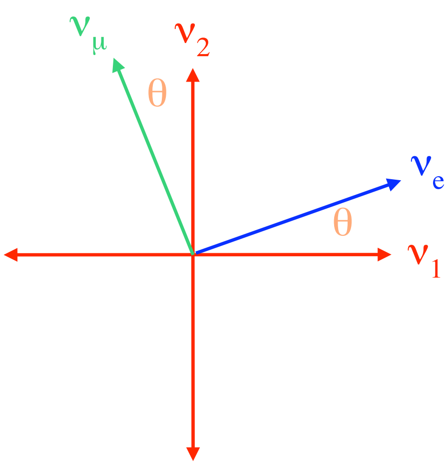

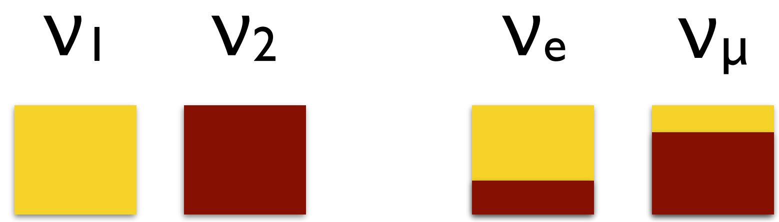

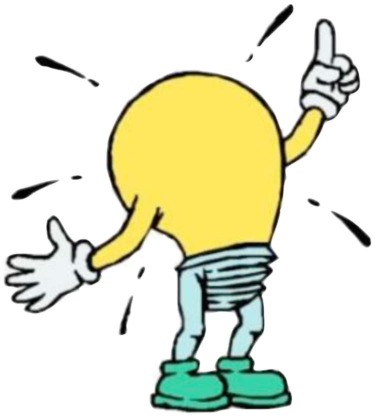

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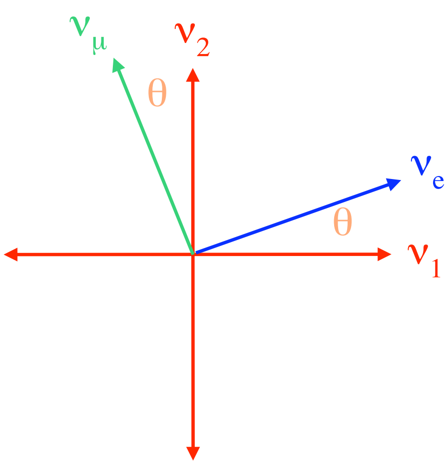

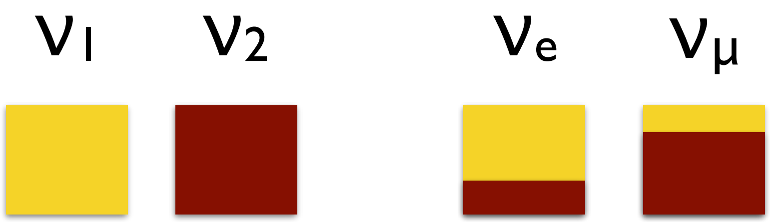

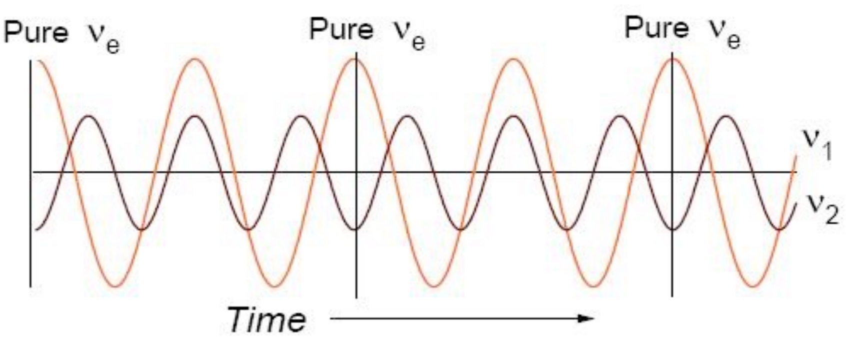

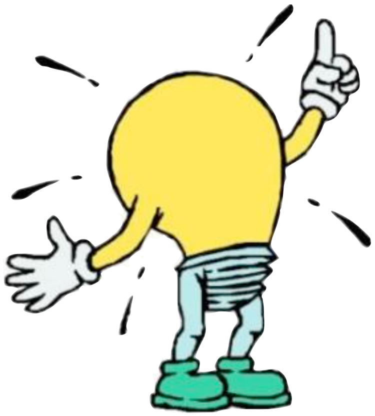

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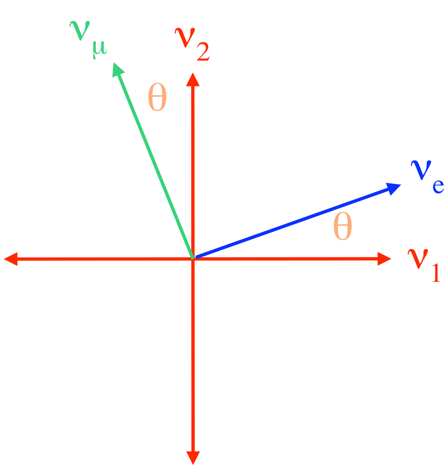
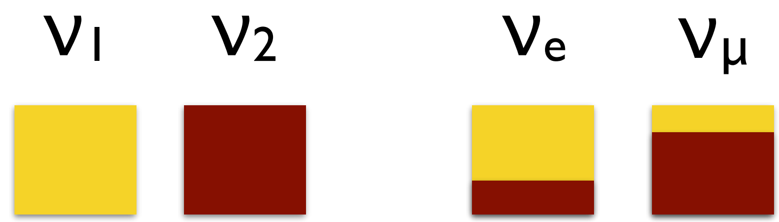
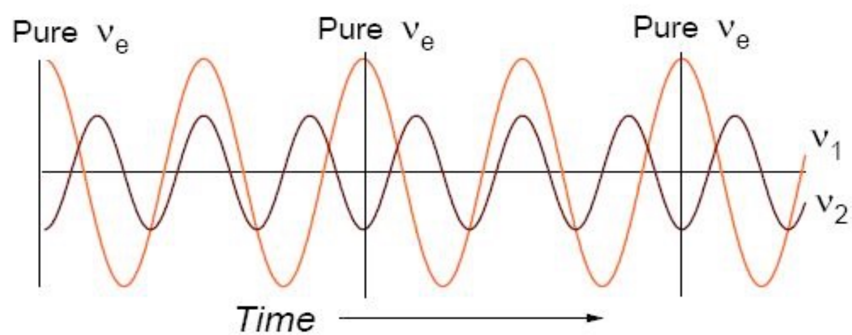
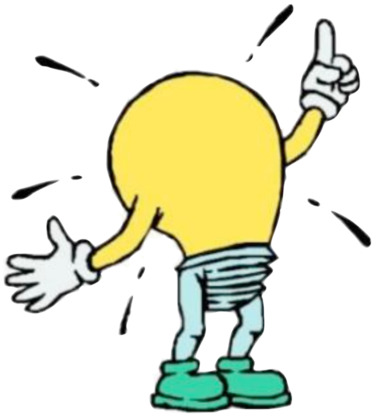






$$P_{\nu_e \to \nu_x} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right)$$



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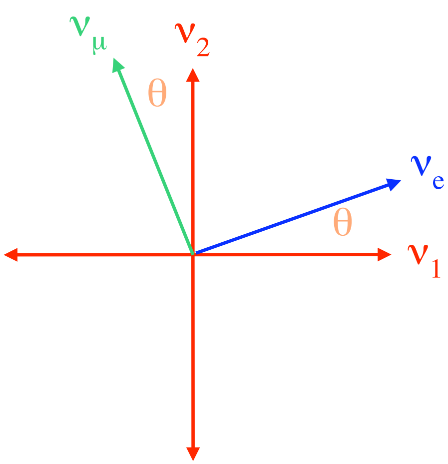
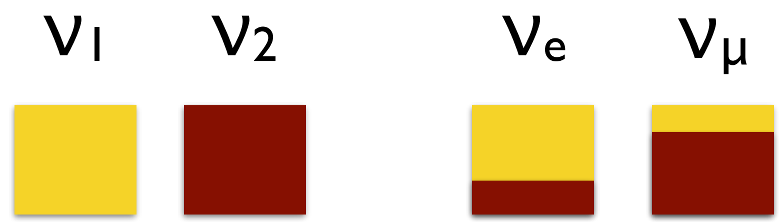
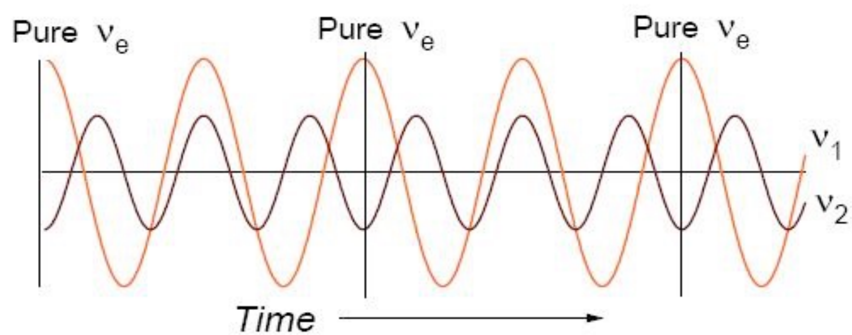
Propagate as physical (mass) eigenstates (ν_1, ν_2, ν_3)

simplified 2-neutrino scenario

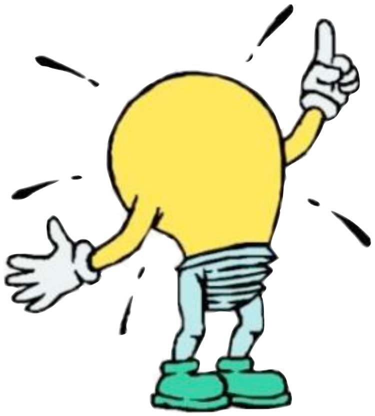






$$P_{\nu_e \to \nu_x} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right)$$

$\Delta m^2 = m_2^2 - m_1^2$: requires non-zero neutrino mass!



Neutrino Oscillation

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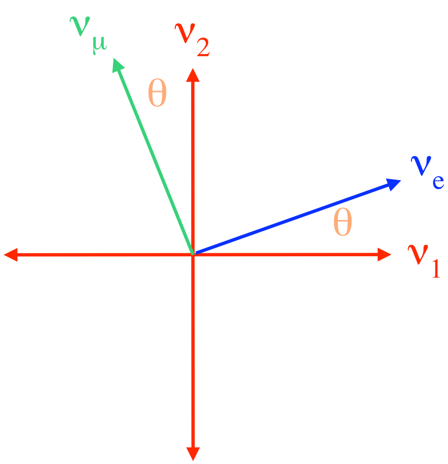

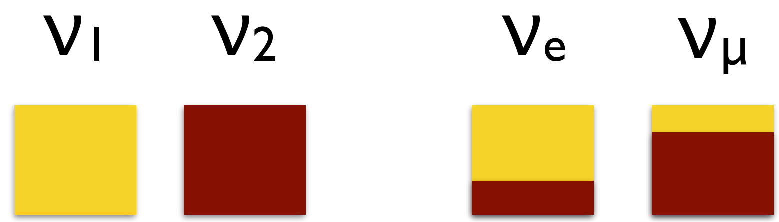

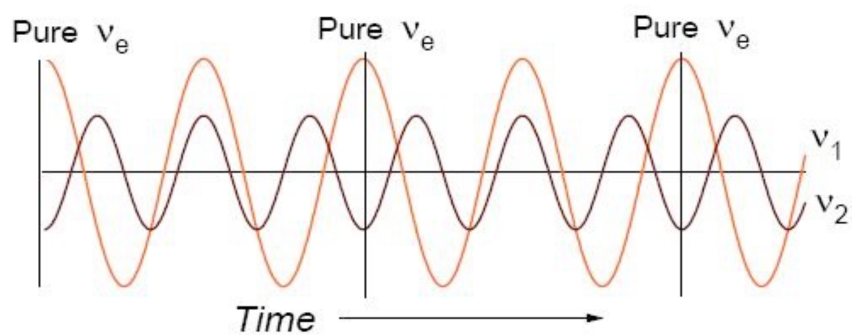

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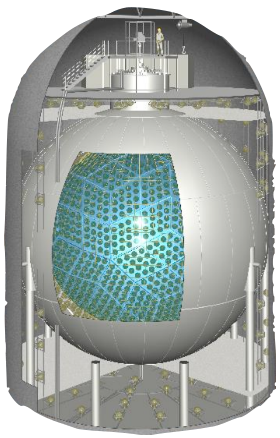
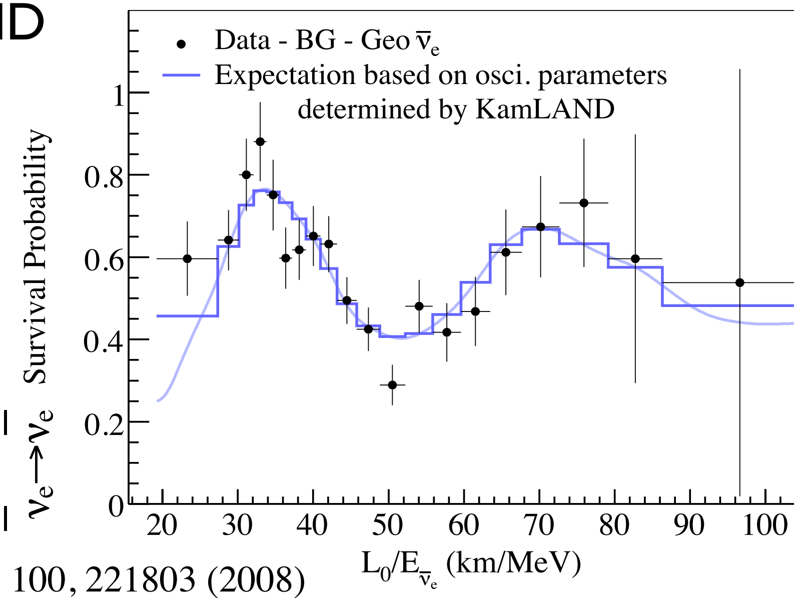
Quantum oscillations on a macroscopic scale!

Terrestrial Measurements

Reactor neutrinos:
KamLAND

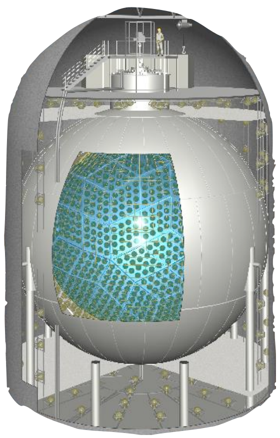


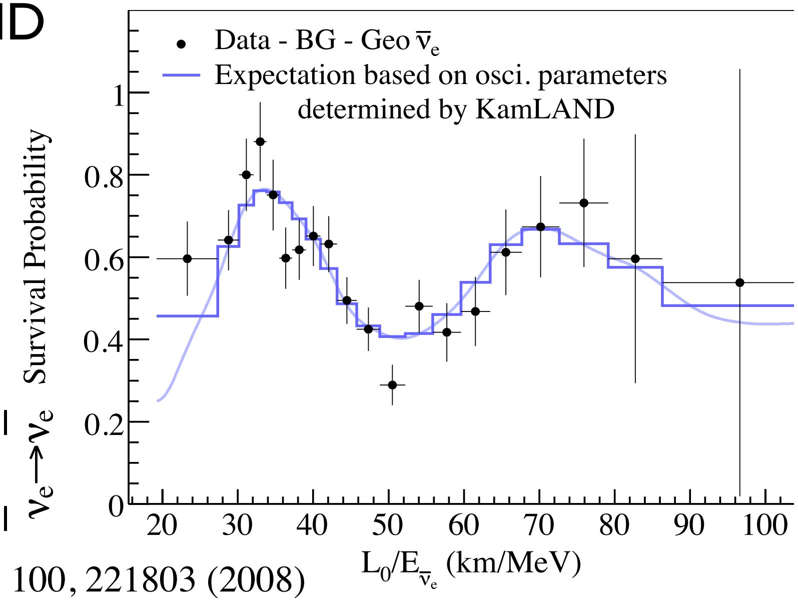


Phys. Rev. Lett. 100, 221803 (2008)

Terrestrial Measurements

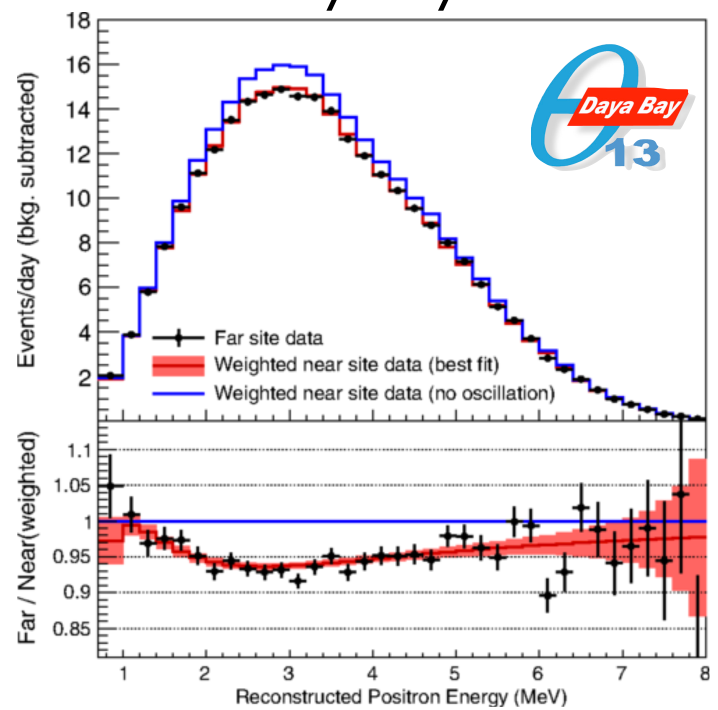
Reactor neutrinos:
KamLAND





Phys. Rev. Lett. 100, 221803 (2008)

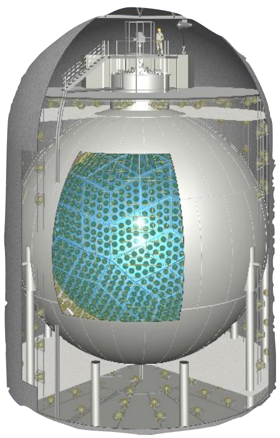
Reactor neutrinos:
Daya Bay

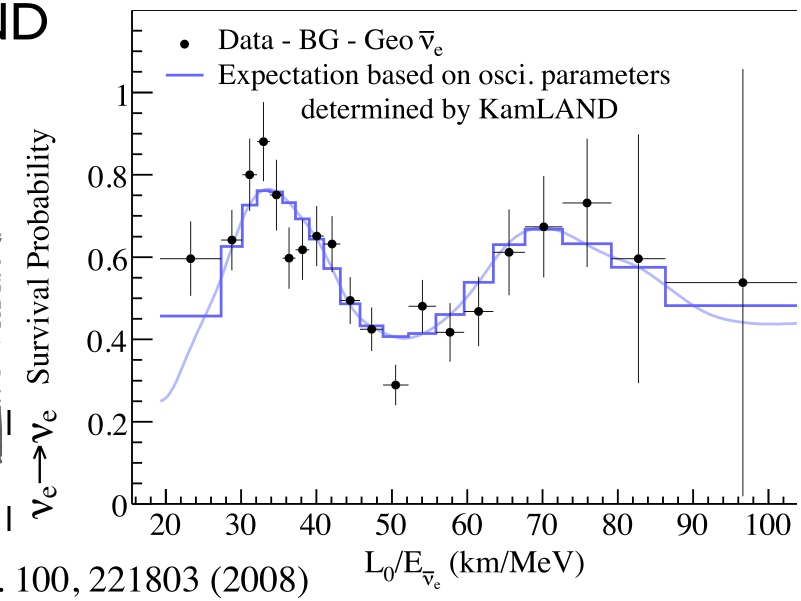


Phys. Rev. Lett. 115 (2015) 111802

Terrestrial Measurements

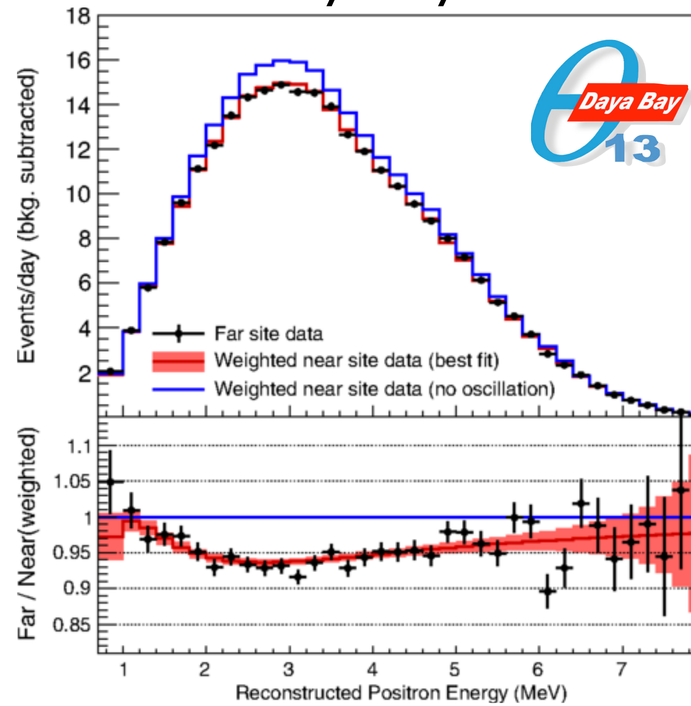
Reactor neutrinos:
KamLAND





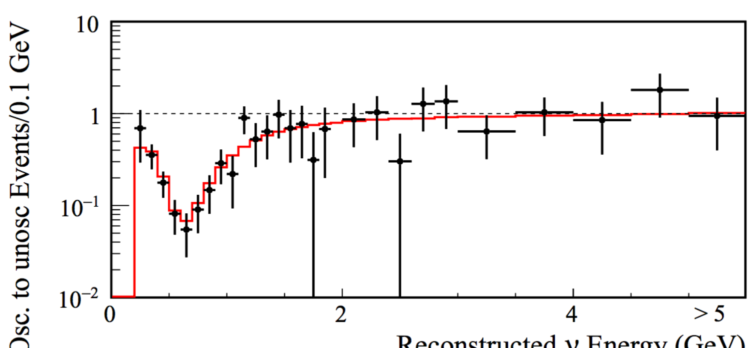
Phys. Rev. Lett. 100, 221803 (2008)

Reactor neutrinos:
Daya Bay



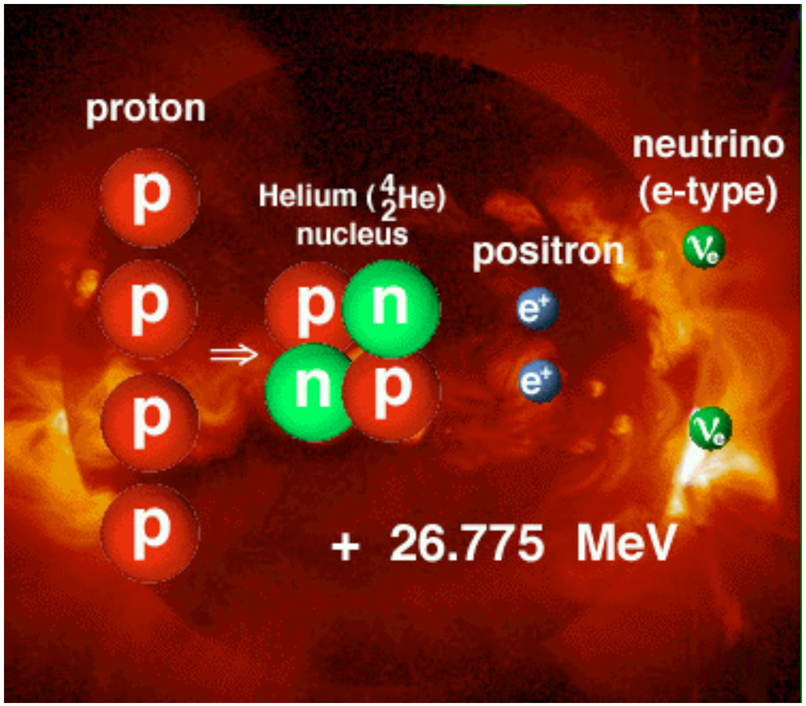
Phys. Rev. Lett. 115 (2015) 111802

Long baseline:
K2K, T2K



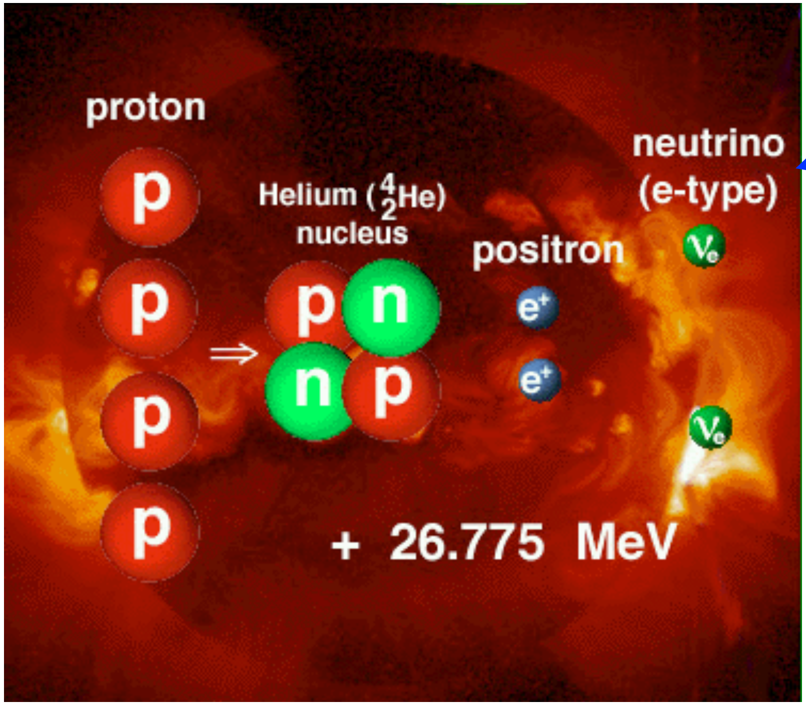
Phys. Rev. D**91** (2015) 072010

How Does the Sun Shine?



- Nuclear fusion reactions in the core produce:
  - Helium
  - Energy (heat, light)
  - Neutrinos (ν_e)

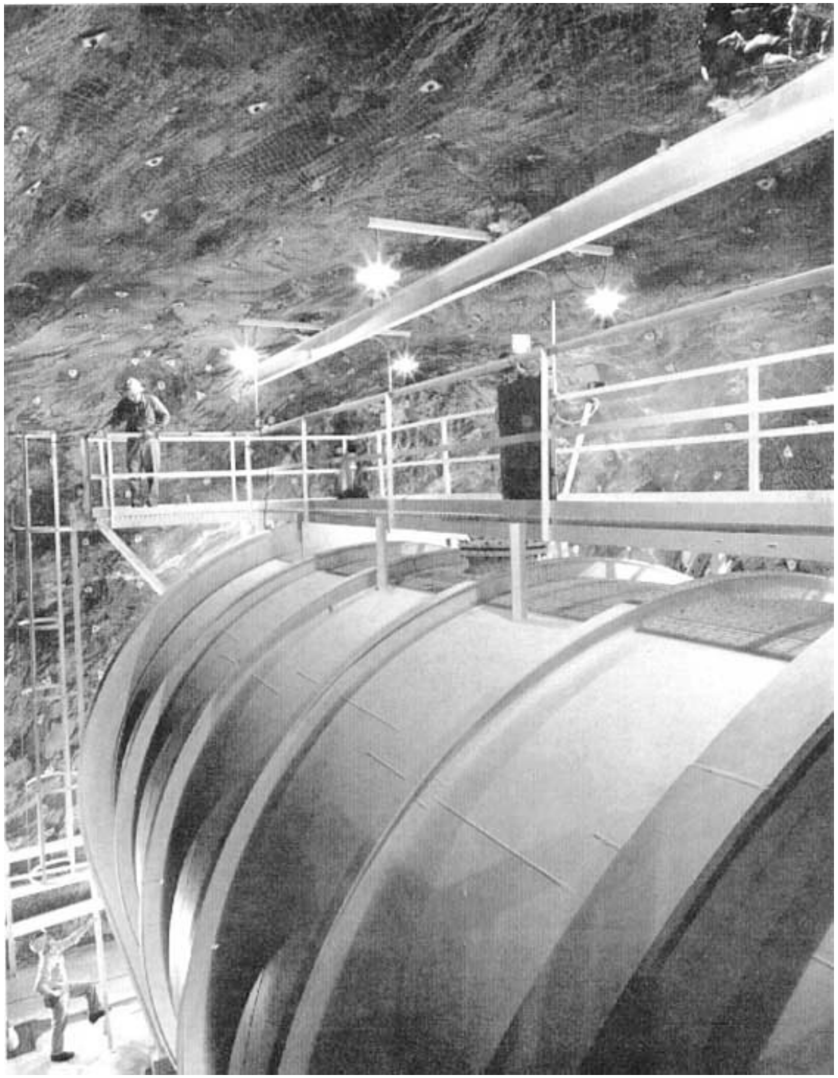
How Does the Sun Shine?



Look for these

- Nuclear fusion reactions in the core produce:
  - Helium
  - Energy (heat, light)
  - Neutrinos (ν_e)

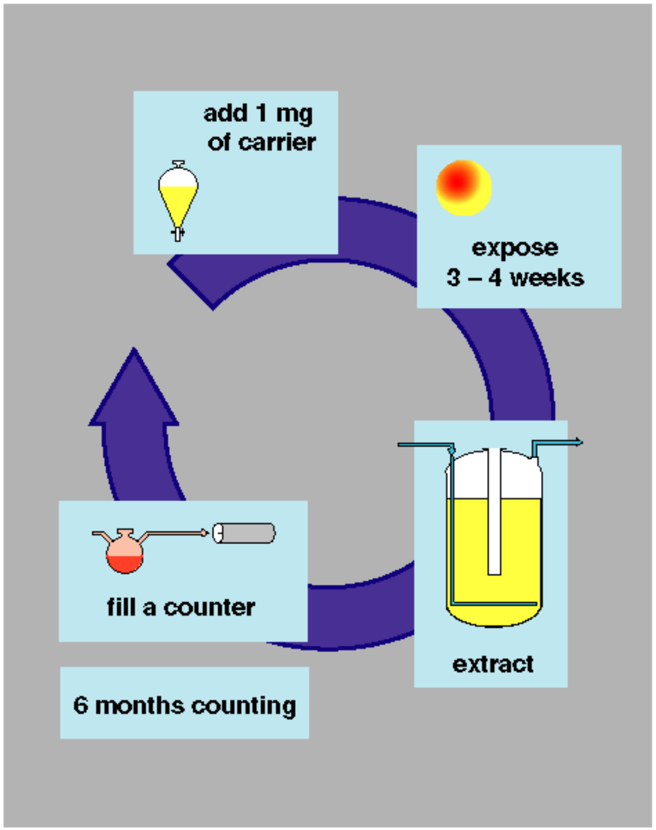
Pioneers in Solar Neutrino Physics



$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e$$

1968 First Solar Neutrino Experiment (Homestake)

Homestake Ga Experiment



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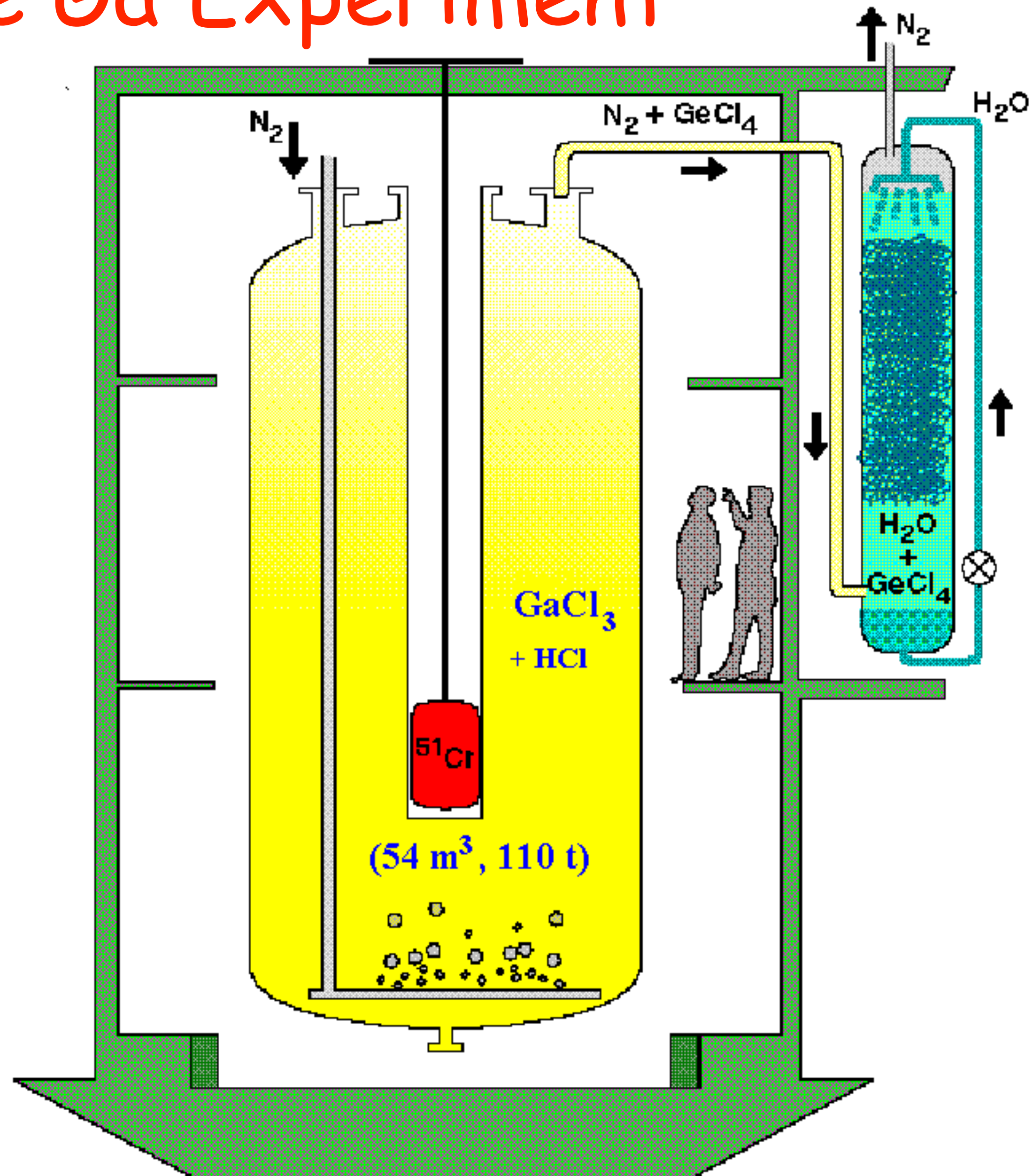


Gallium Experiment-Gallium Neutrino Observatory

Pioneer Solar Neutrino Experiments

Experiment	Depth (m.w.e.)	Target	Reaction	Threshold (MeV)
Homestake	4900	615 tons of C_2Cl_4	$\nu_e + ^{37}Cl \rightarrow ^{37}Ar + e$	0.814
SAGE	4700	60 tons metallic Ga	$\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e$	0.233
Gallex + GNO	3300	30.3 tons $GaCl_3$-HCl	$\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e$	0.233
Kamiokande	2700	3 kt H_2O 680 t fiducial volume	$\nu_x + e \rightarrow \nu_x + e$	7.5
Super-Kamiokande	2700	55 kt H_2O 22.5 kt fiducial volume	$\nu_x + e \rightarrow \nu_x + e$	5.5

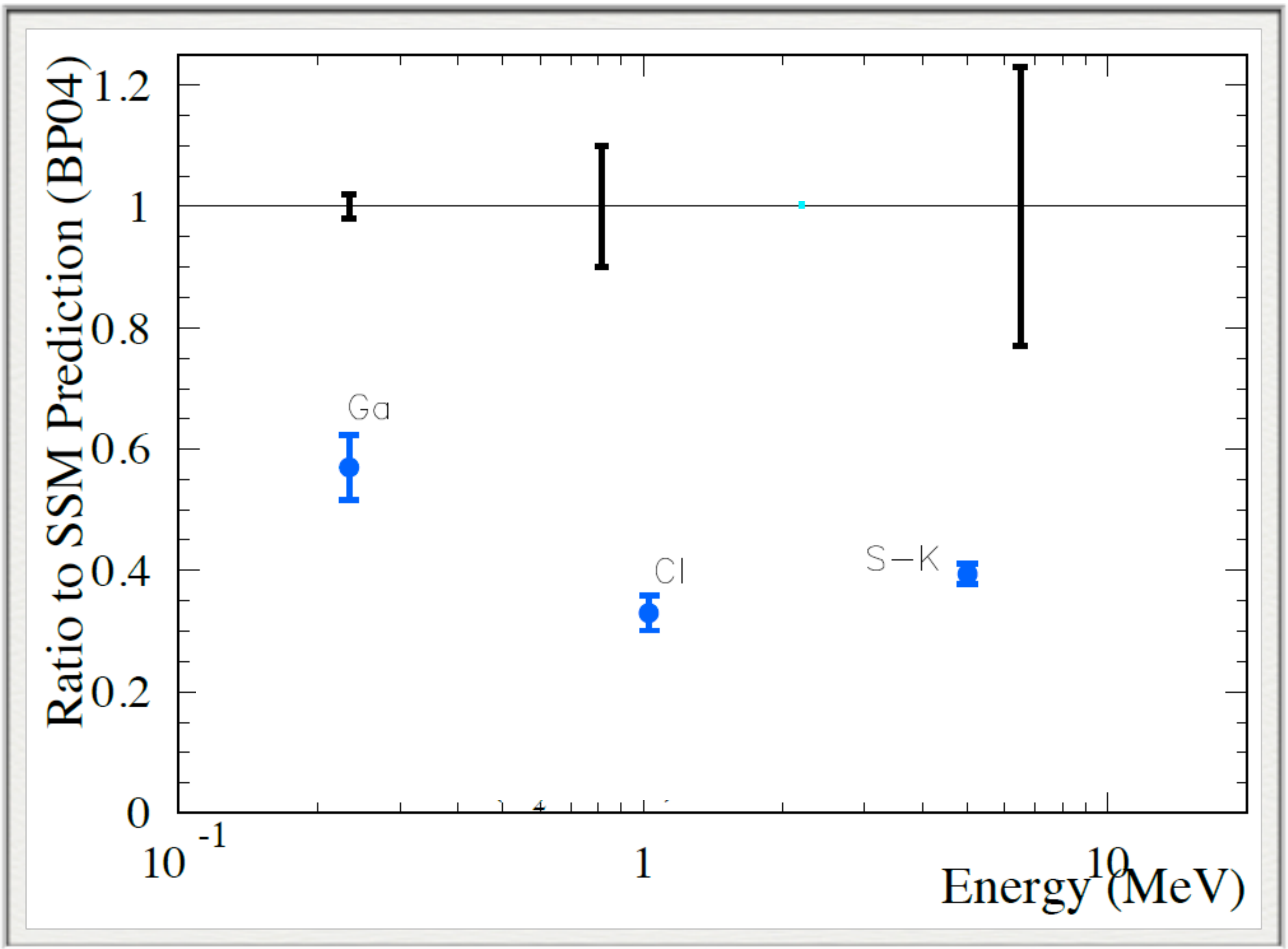
GALLEX (Gran Sasso, Italy)

SAGE (Baksan, Russia)

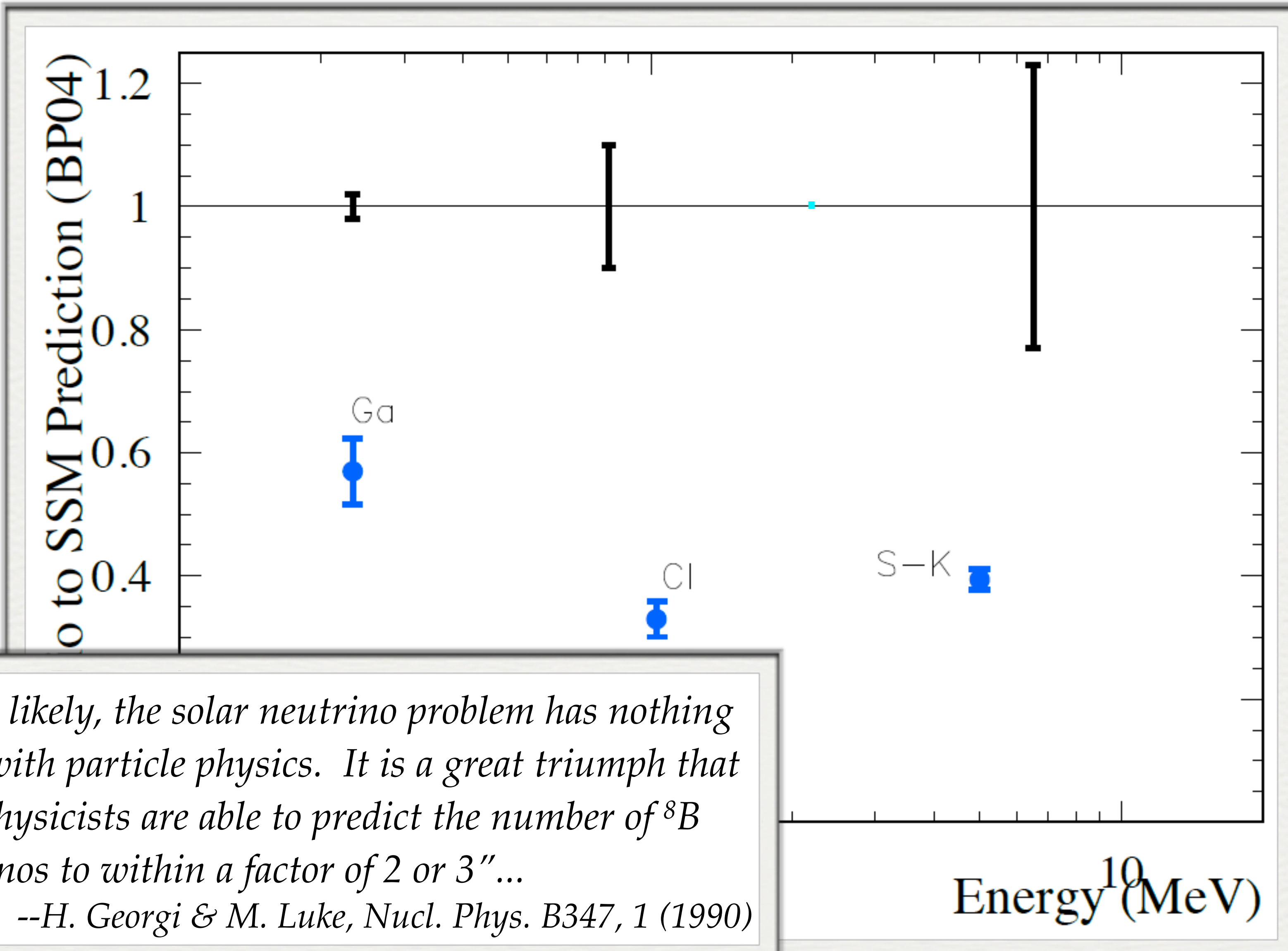
Homestake (S Dakota, USA)

Super-Kamiokande (Japan)

Solar Neutrino Problem



Solar Neutrino Problem



"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^8B neutrinos to within a factor of 2 or 3"...

--H. Georgi & M. Luke, Nucl. Phys. B347, 1 (1990)

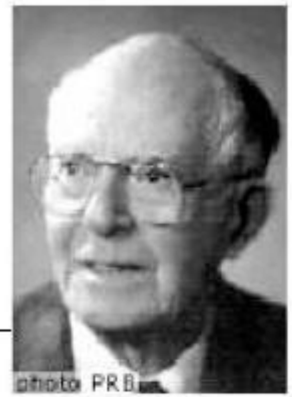
2002 Nobel Prize (1/2)

Kamiokande series

Homestake ^{37}Cl experiment

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"



Raymond Davis Jr.

1/4 of the prize

USA

University of Pennsylvania
Philadelphia, PA, USA

Masatoshi Koshiba

1/4 of the prize

Japan

University of Tokyo
Tokyo, Japan

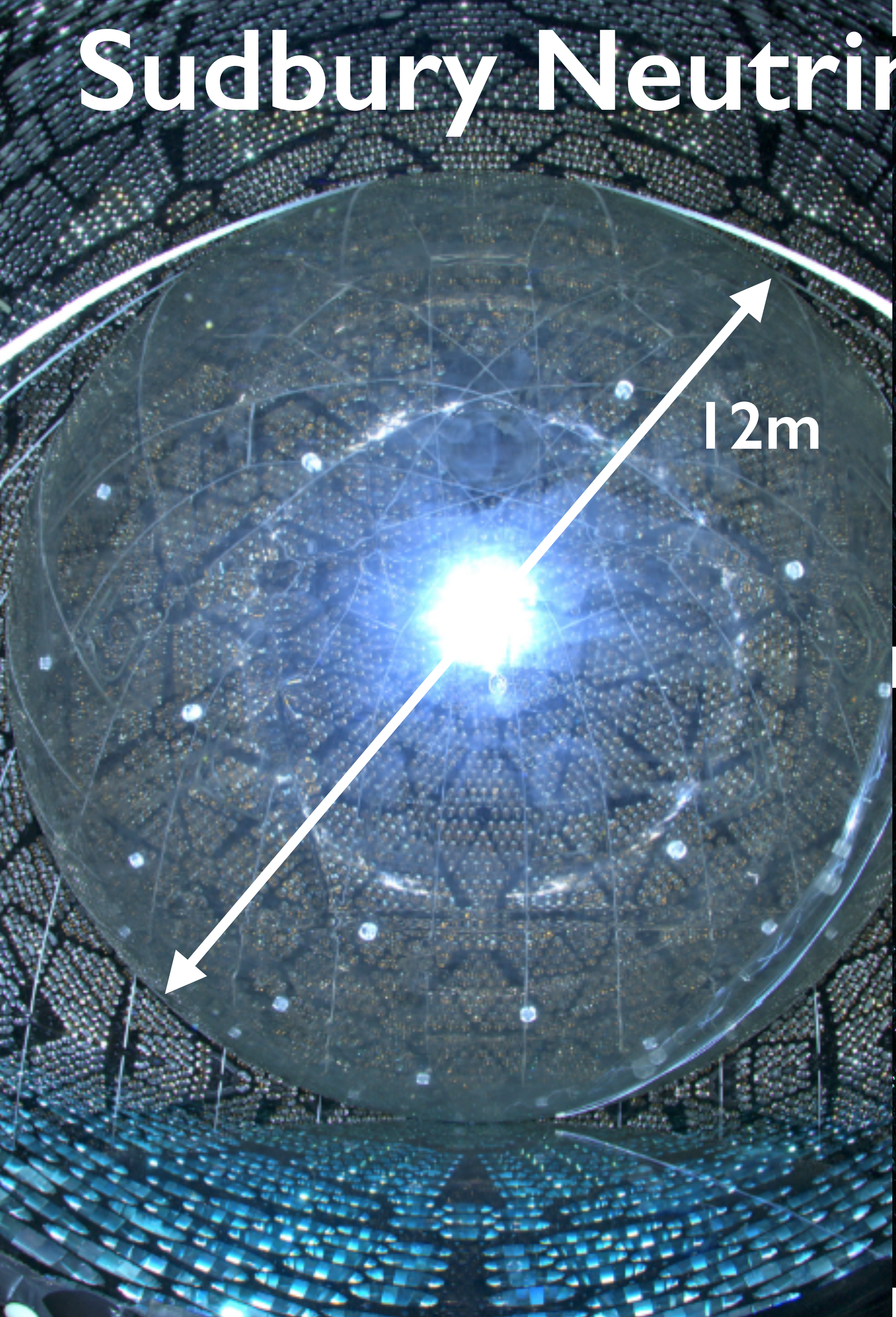
Riccardo Giacconi

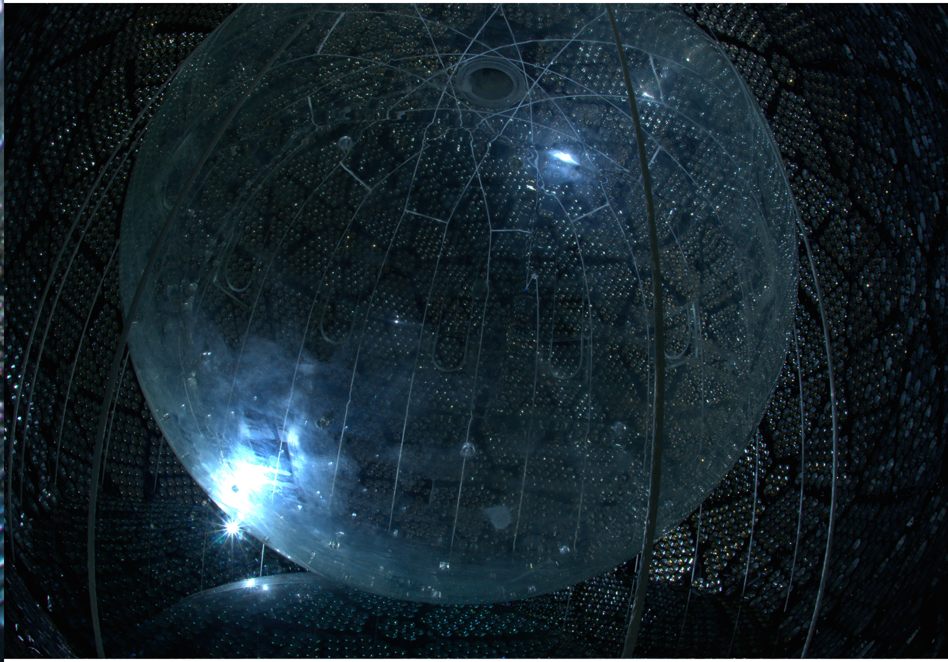
1/2 of the prize

USA

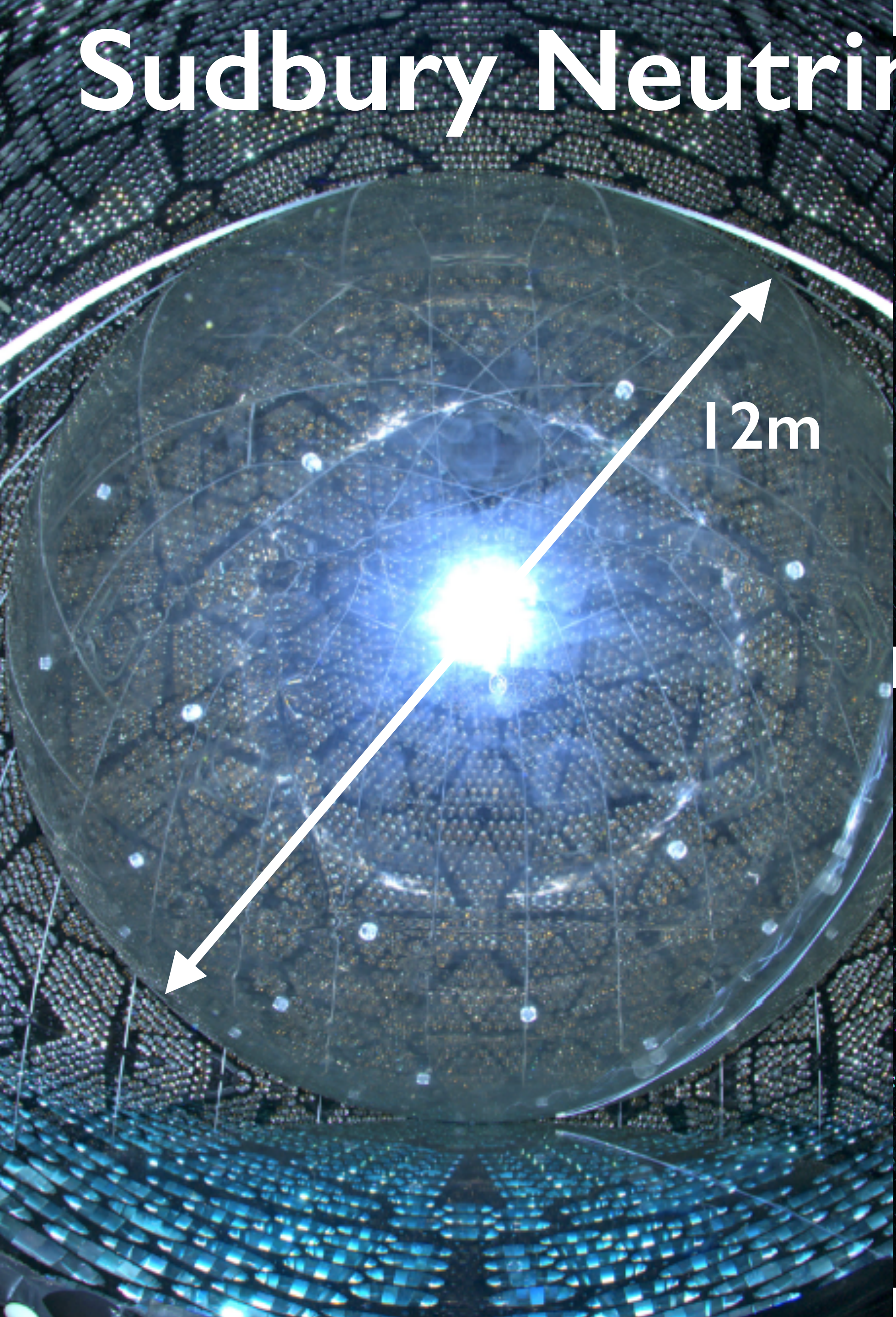
Associated Universities Inc.
Washington, DC, USA

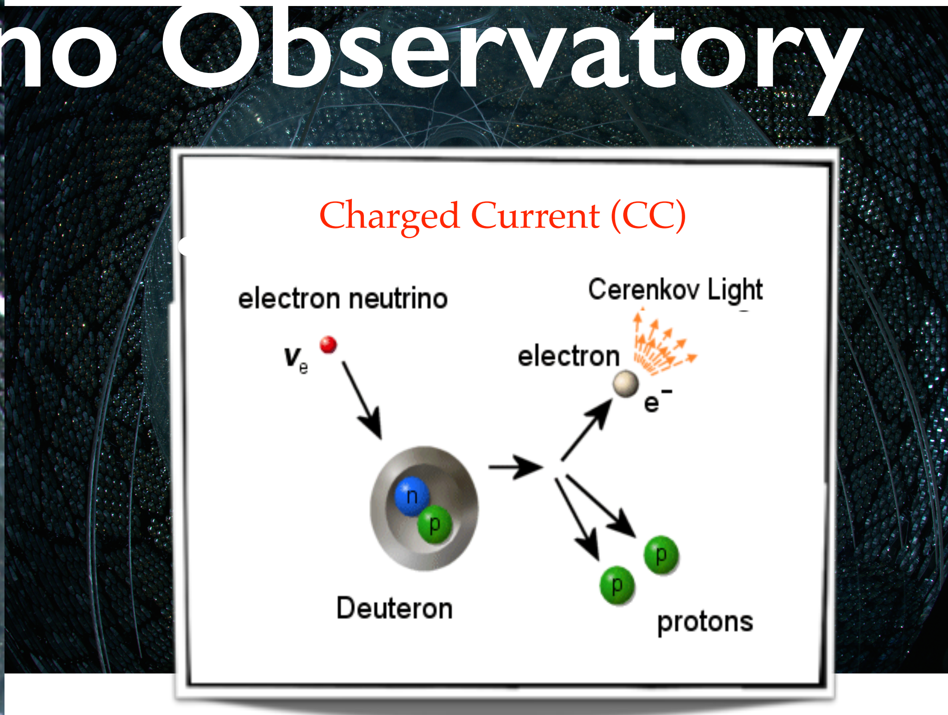
Sudbury Neutrino Observatory

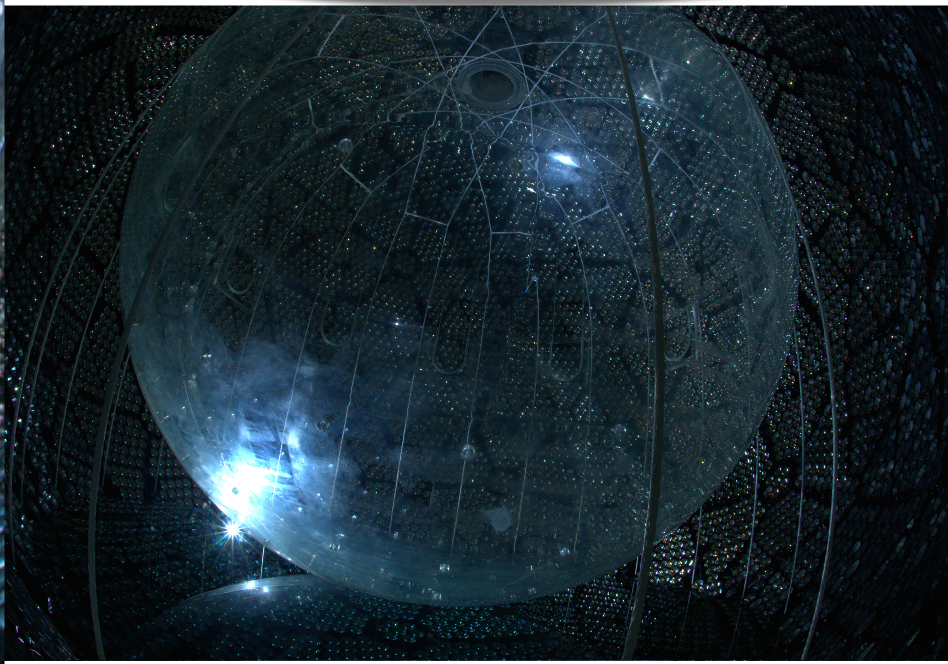




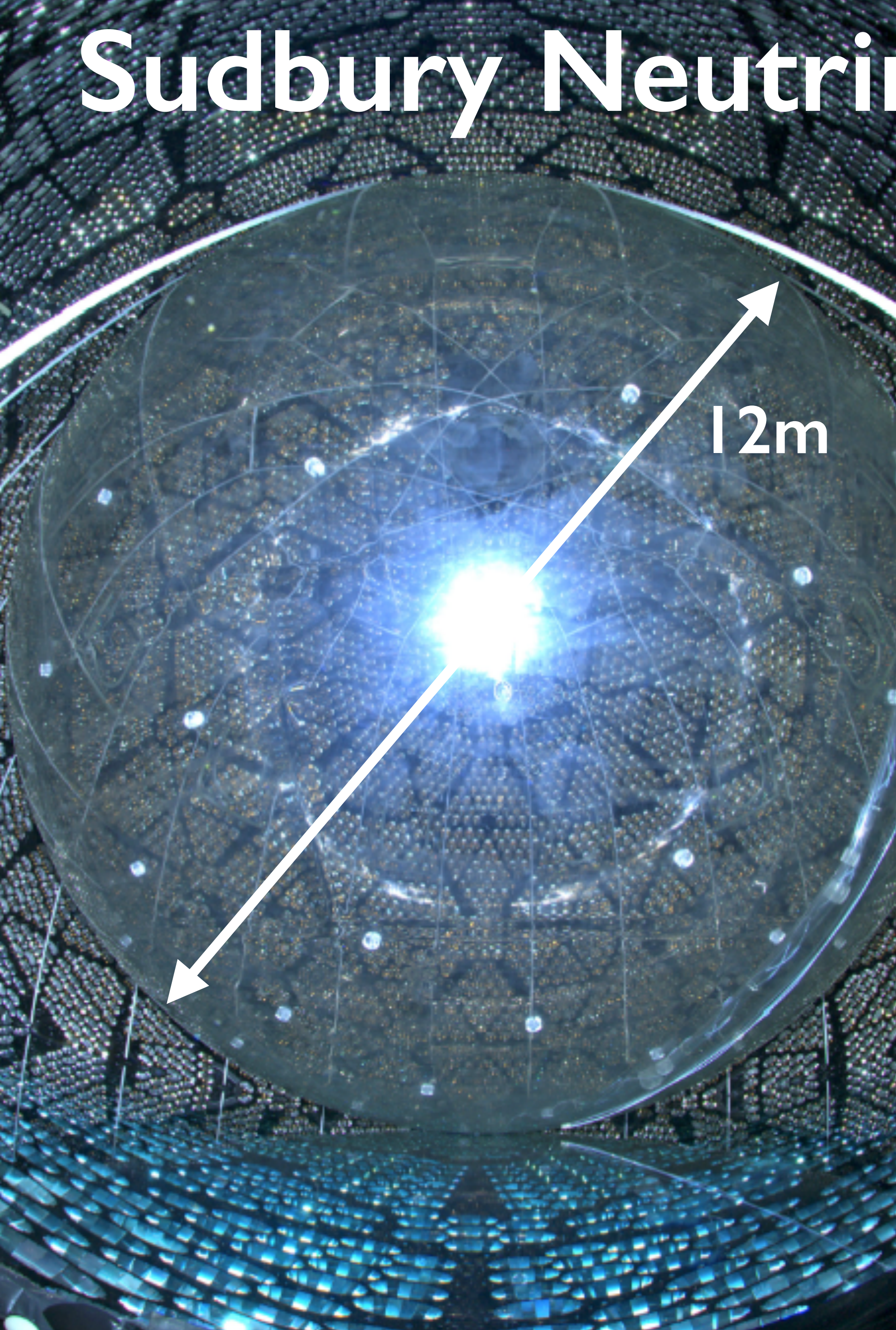
Sudbury Neutrino Observatory

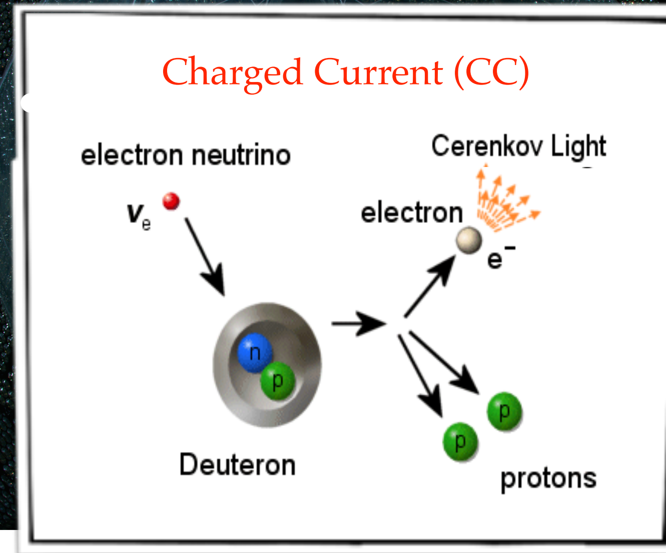


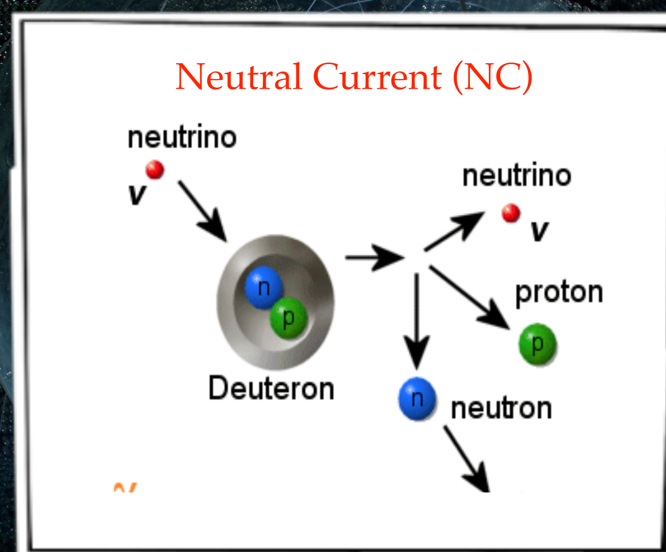


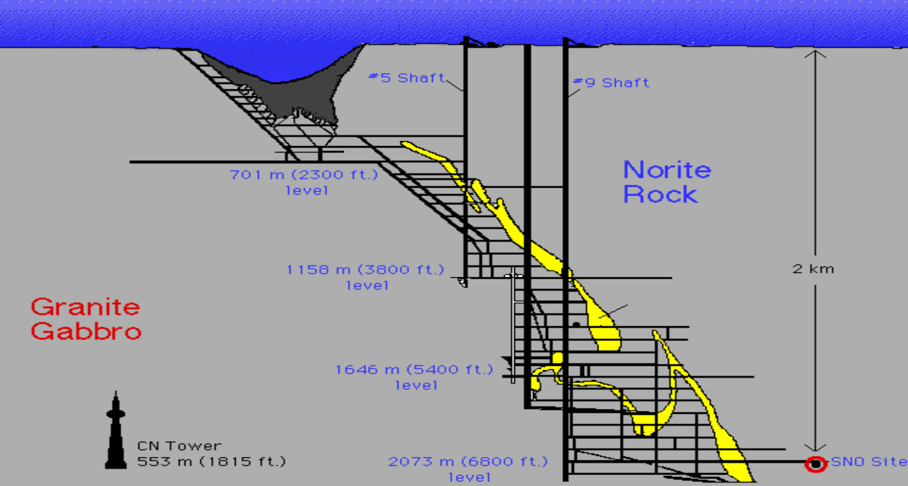


Sudbury Neutrino Observatory









Sudbury Neutrino Observatory

6000 mwe overburden

1000 tonnes D_2O

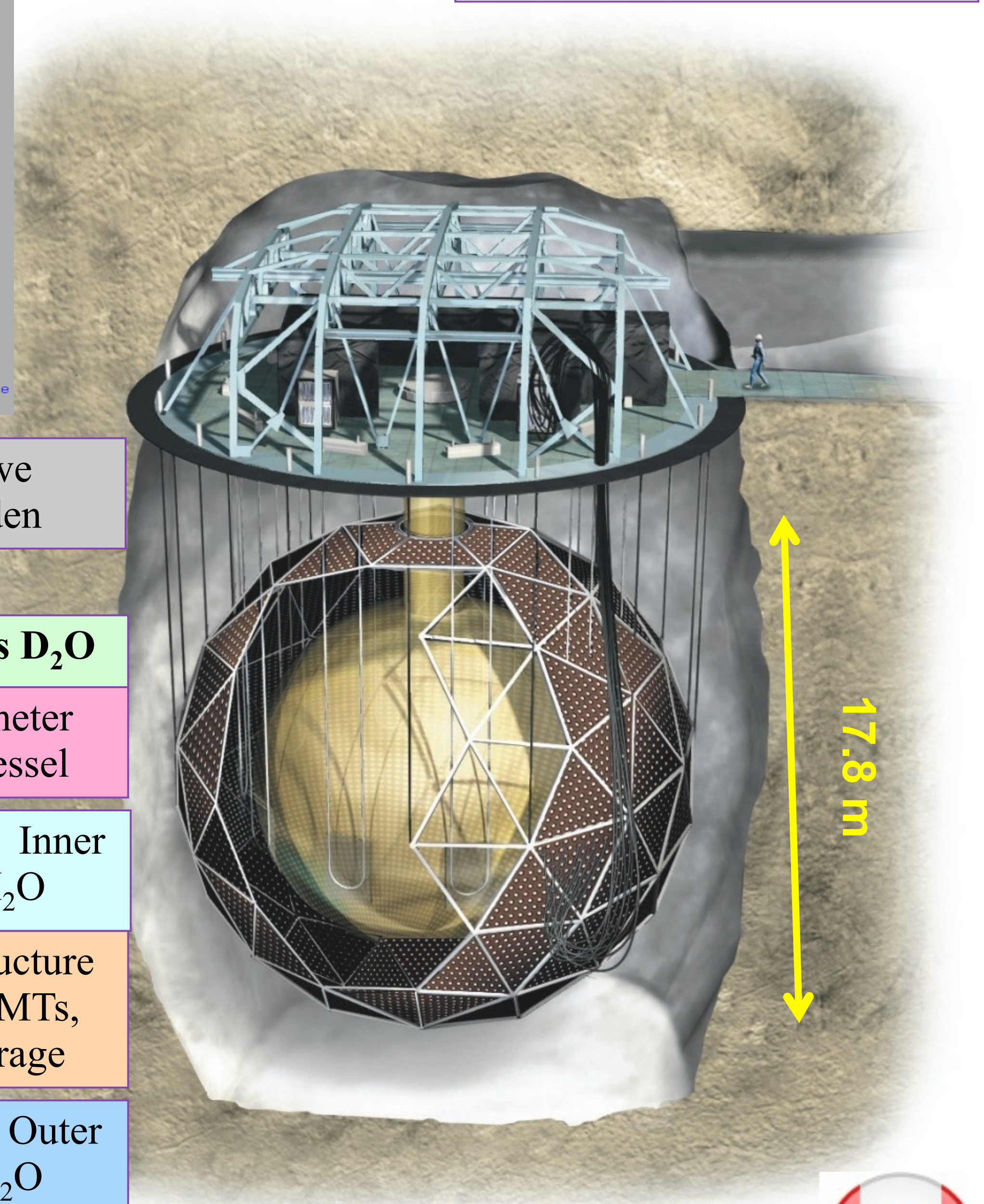
12 m Diameter Acrylic Vessel

1700 tonnes Inner Shield H_2O

Support Structure for 9500 PMTs, 60% coverage

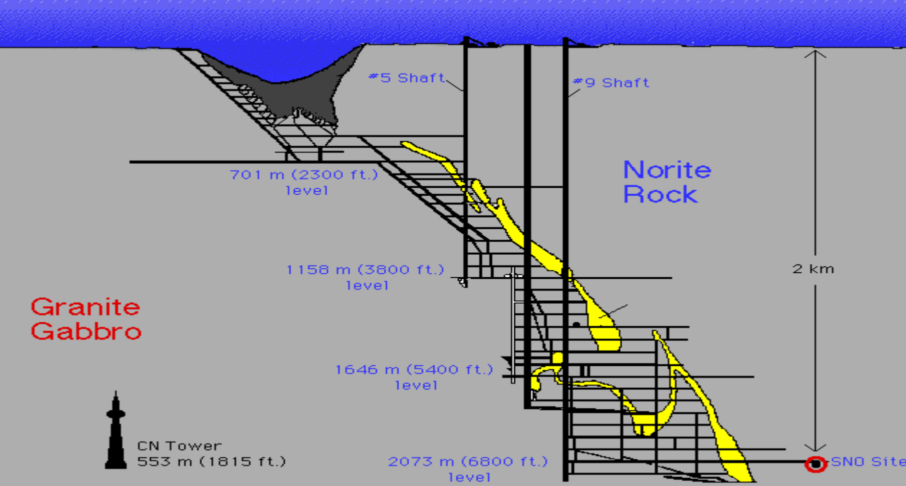
5300 tonnes Outer Shield H_2O

Image courtesy National Geographic



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

Image courtesy National Geographic



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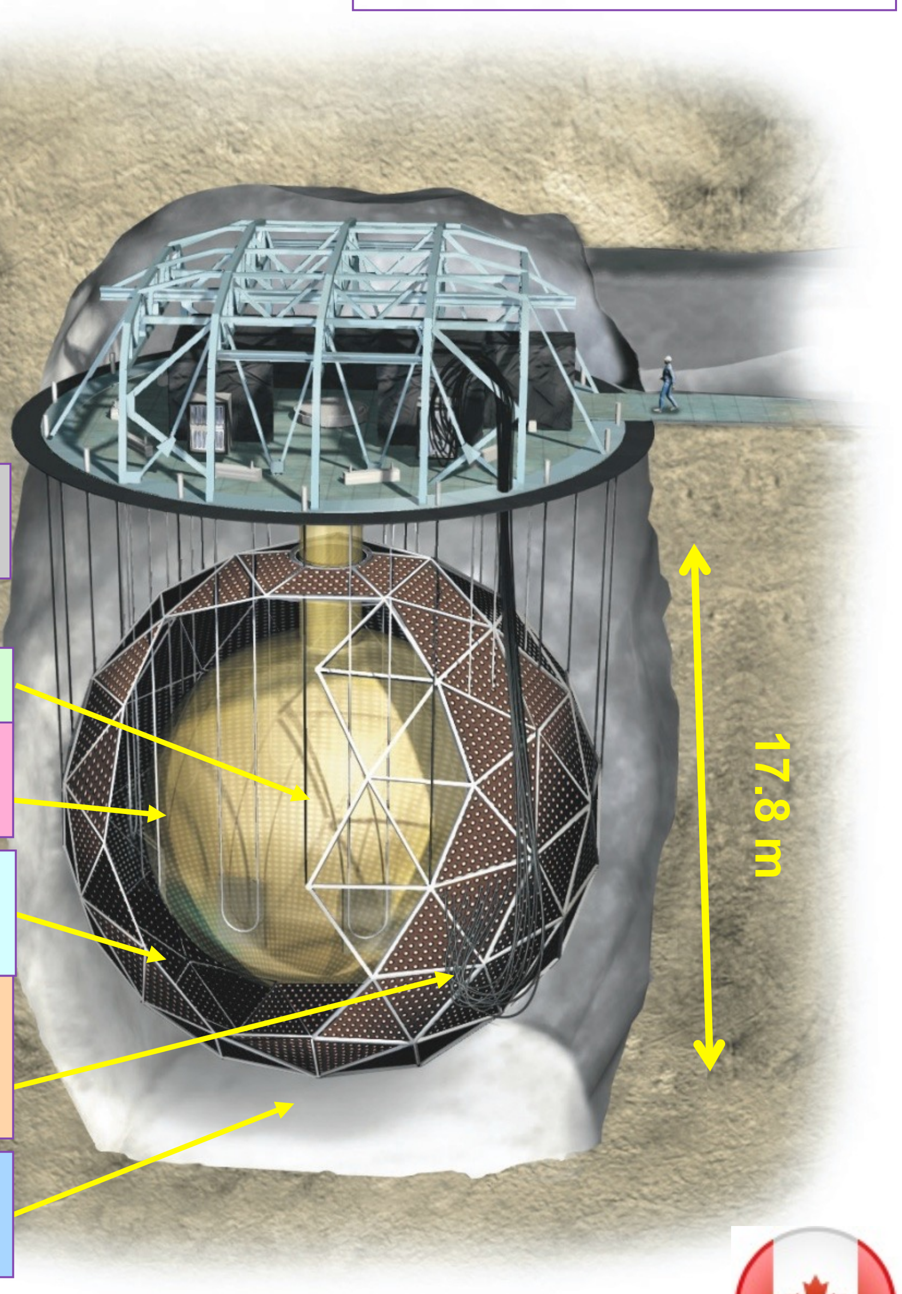

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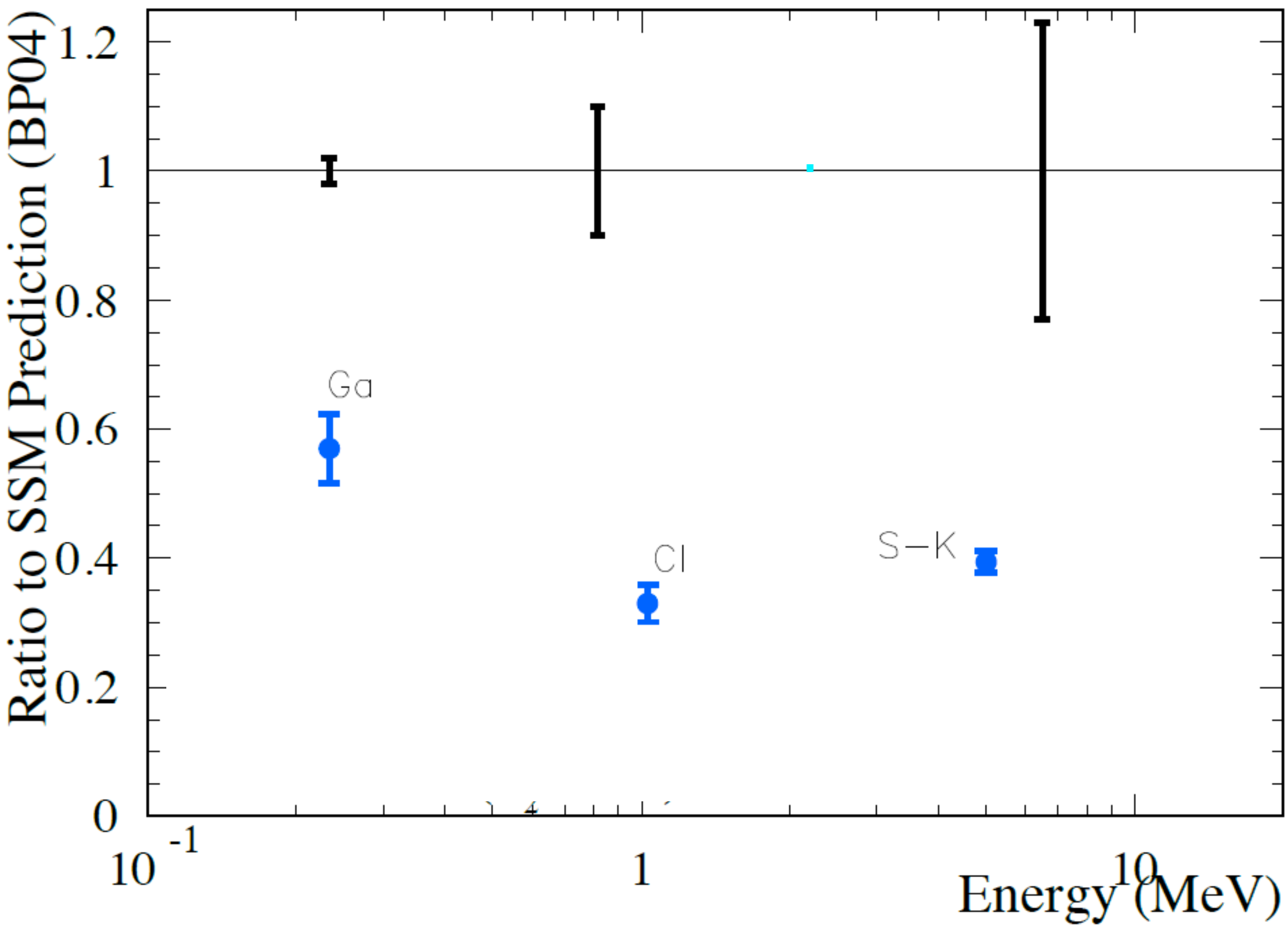
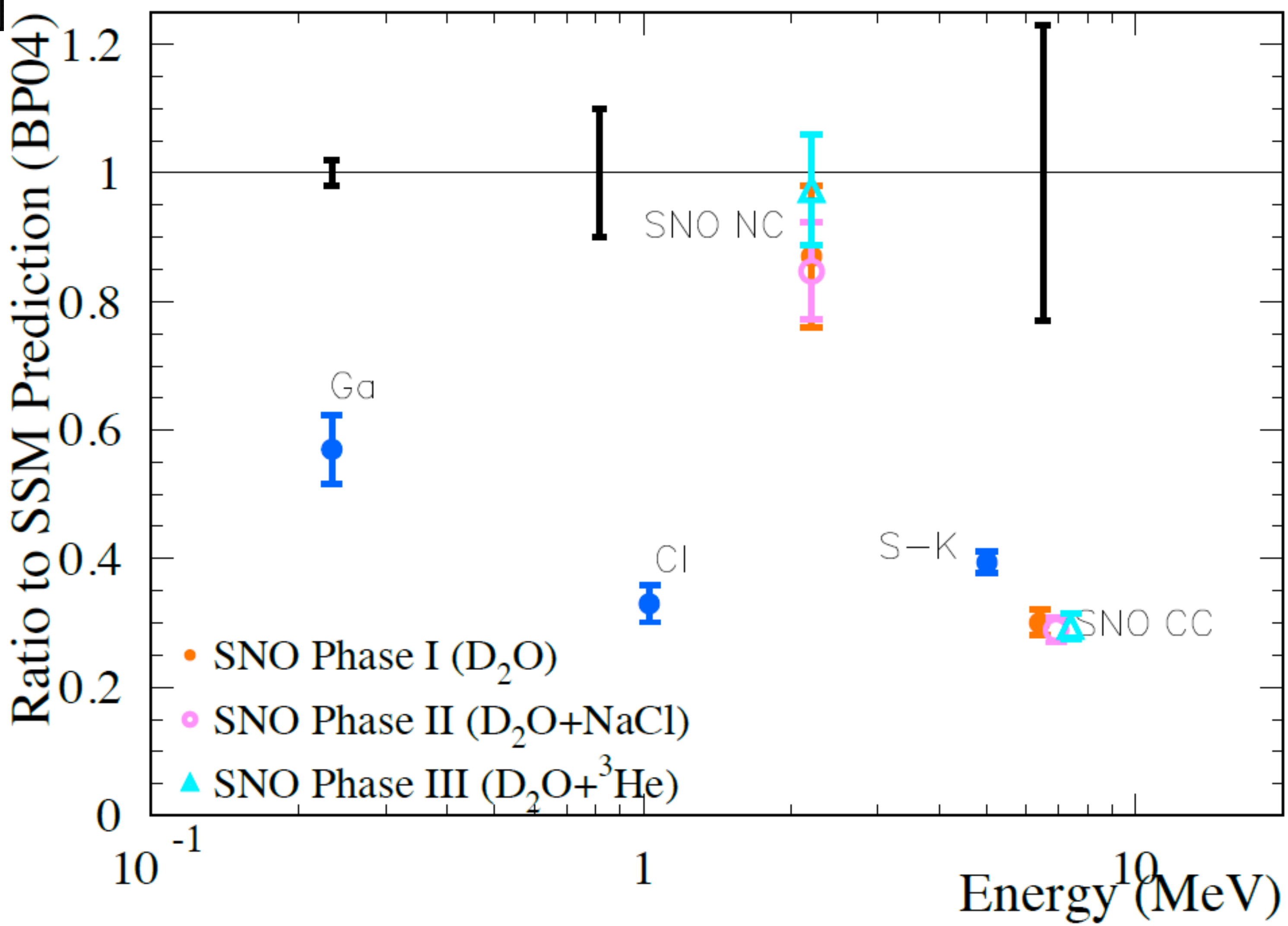
SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

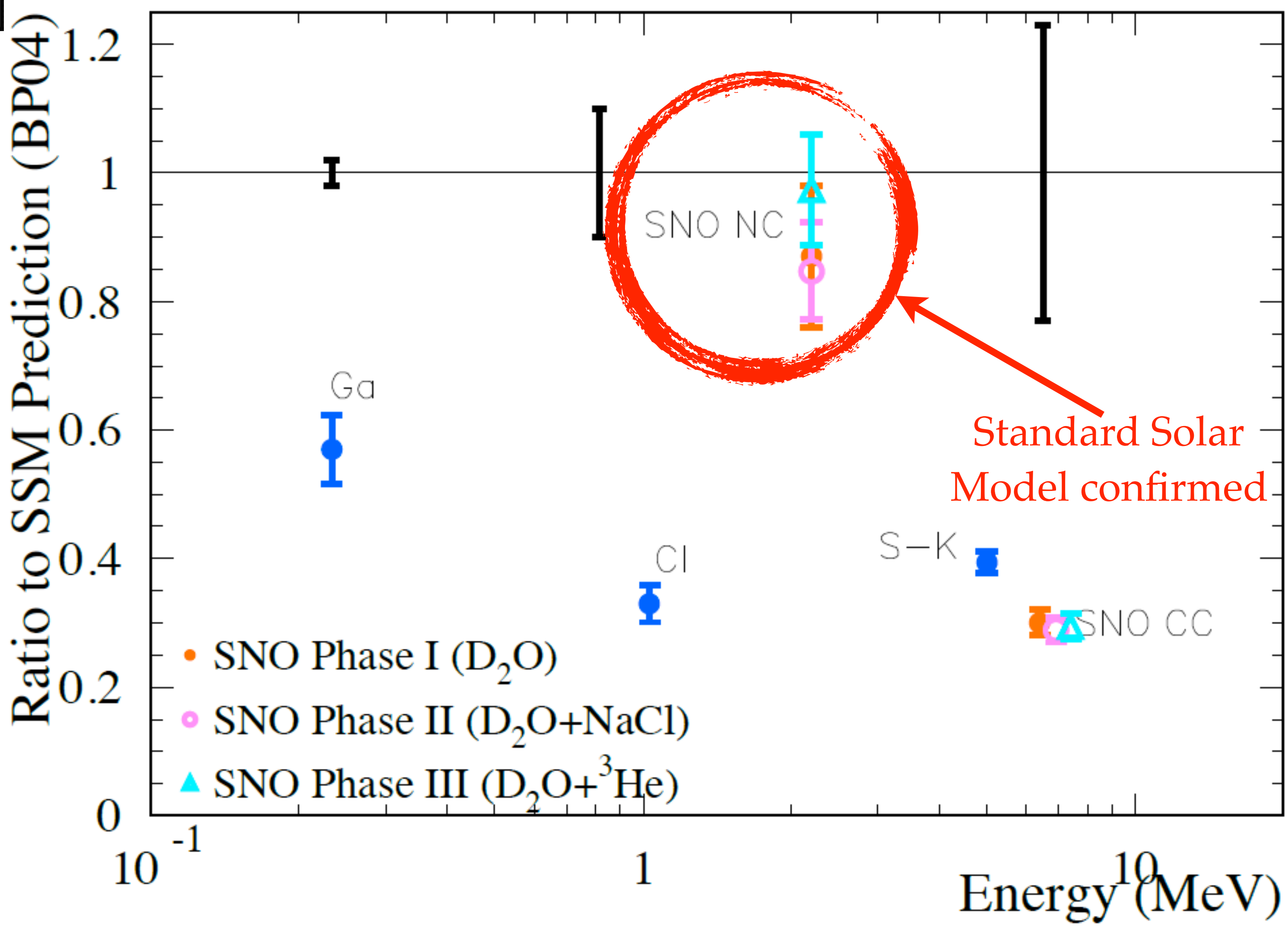
Solar Neutrino Problem



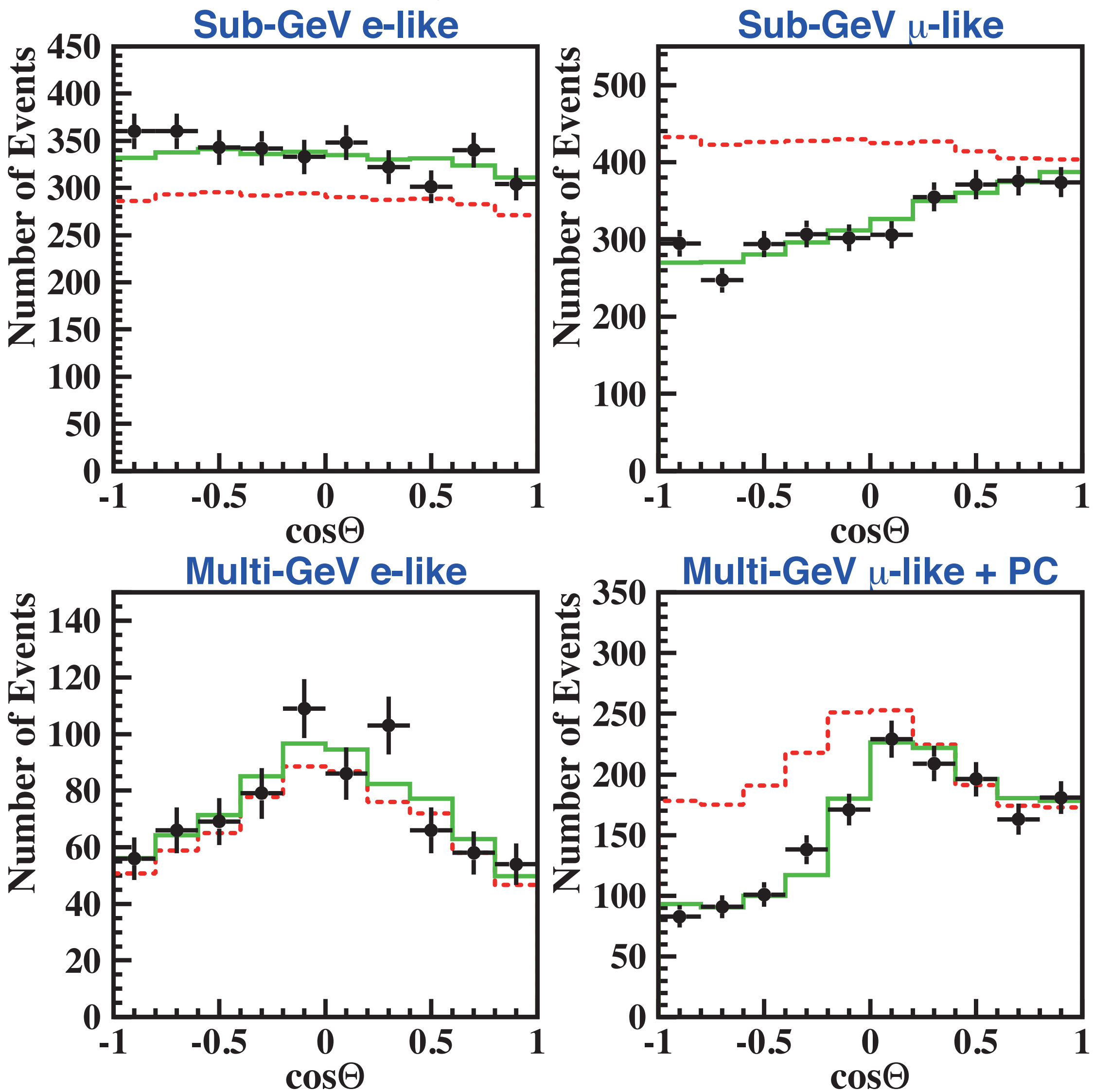
Solar Neutrino Problem Resolved

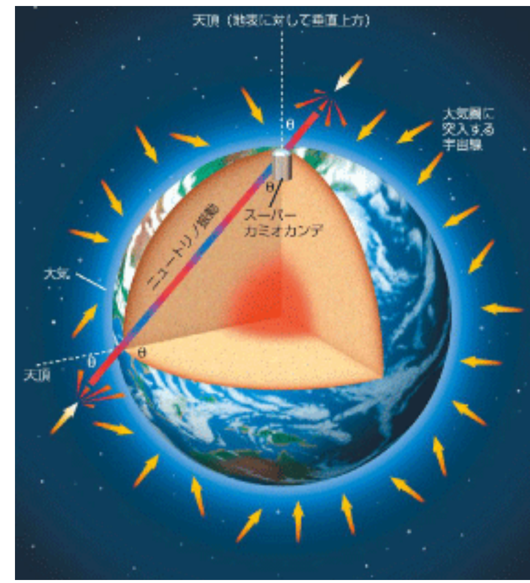


Solar Neutrino Problem Resolved

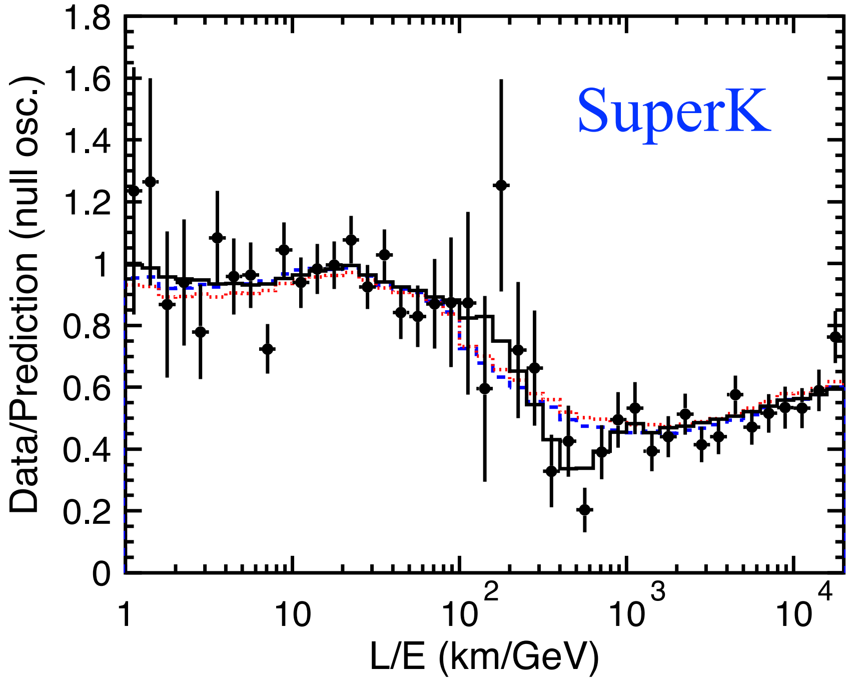


Atmospheric Neutrinos: SuperK





SuperK Results



Atmospheric neutrino data (SuperK) consistent with oscillations

2015 Nobel Prize in Physics

SuperK

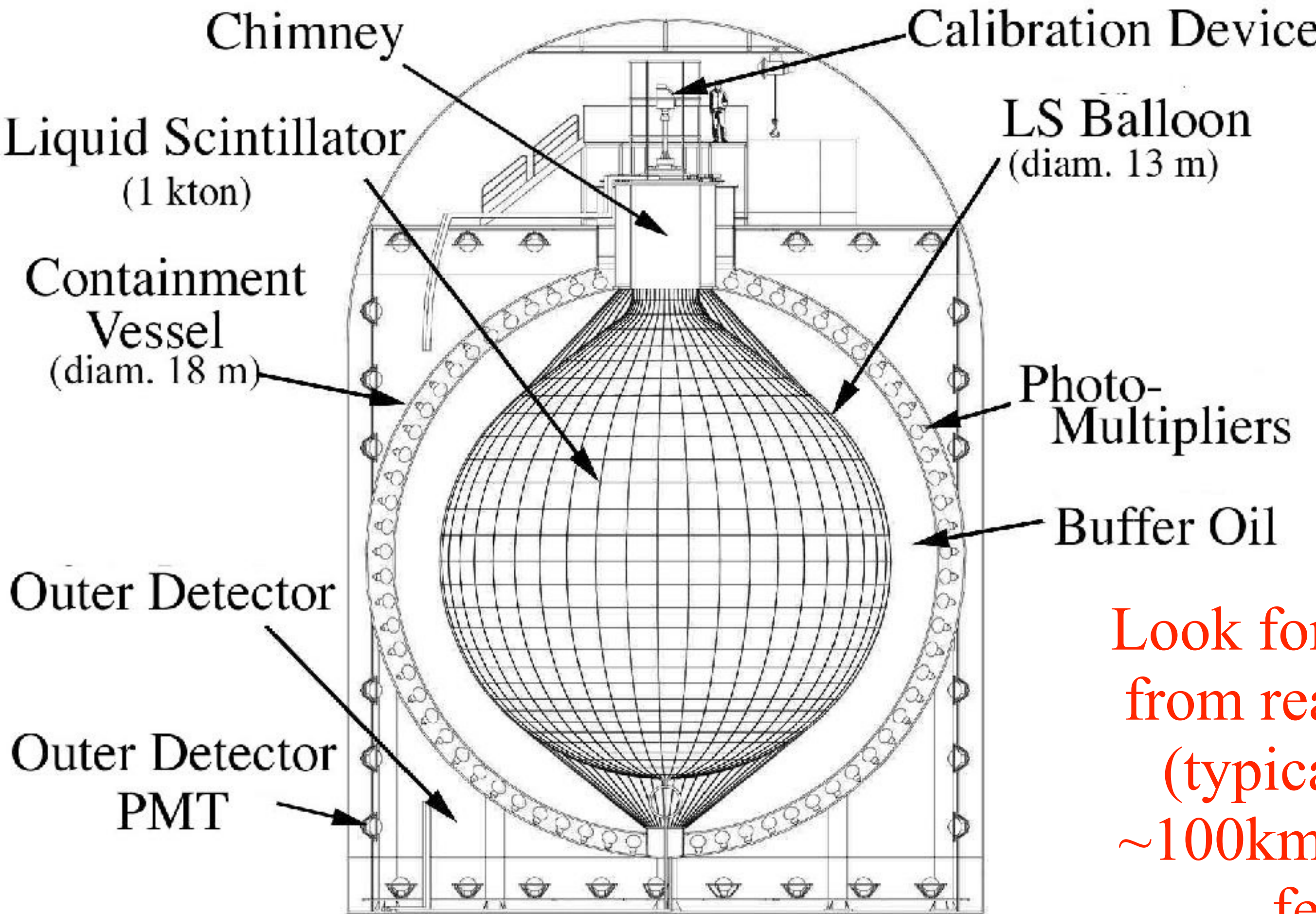
Takaaki Kajita

SNO

Arthur B. McDonald

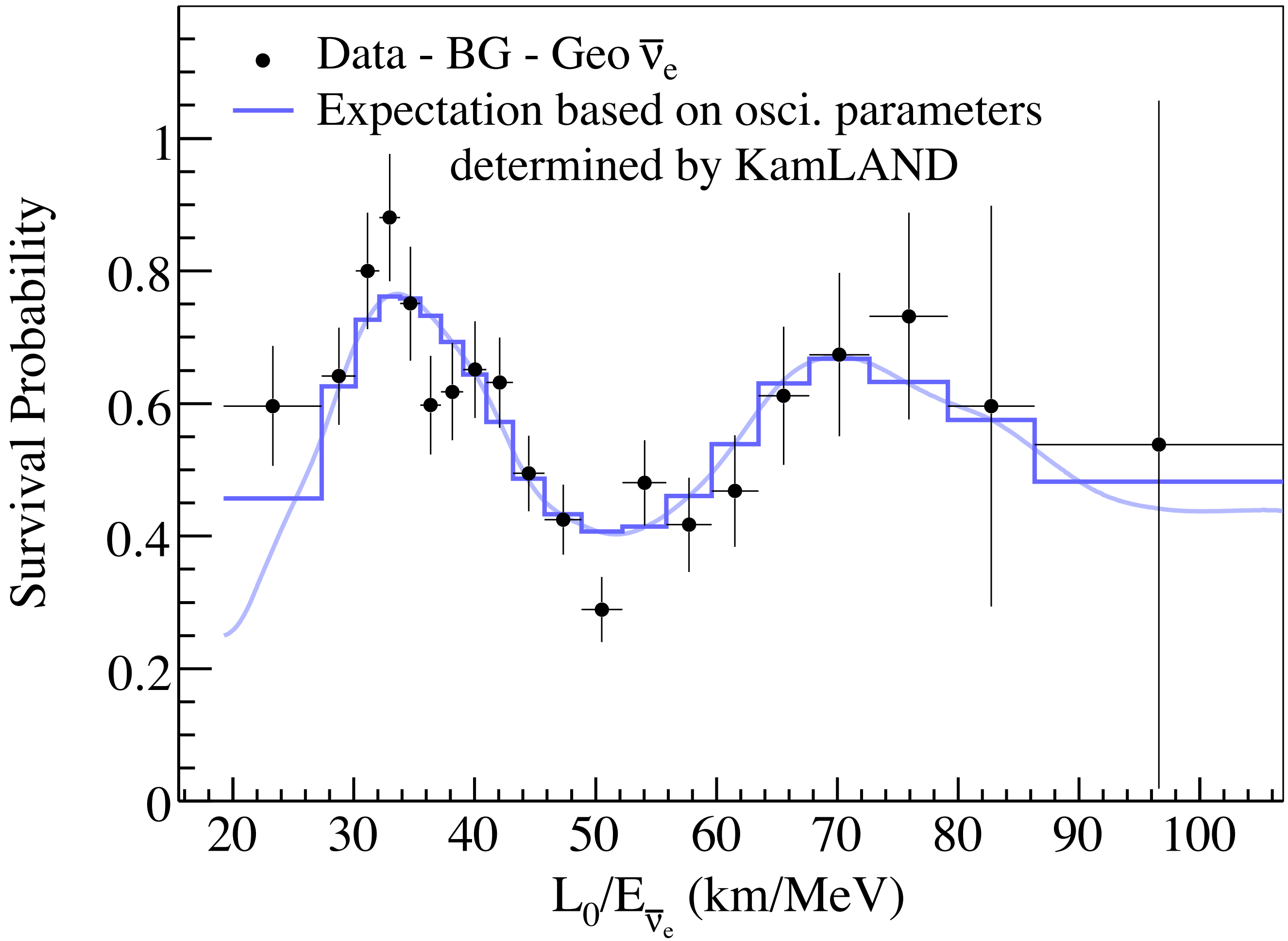
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

KamLand

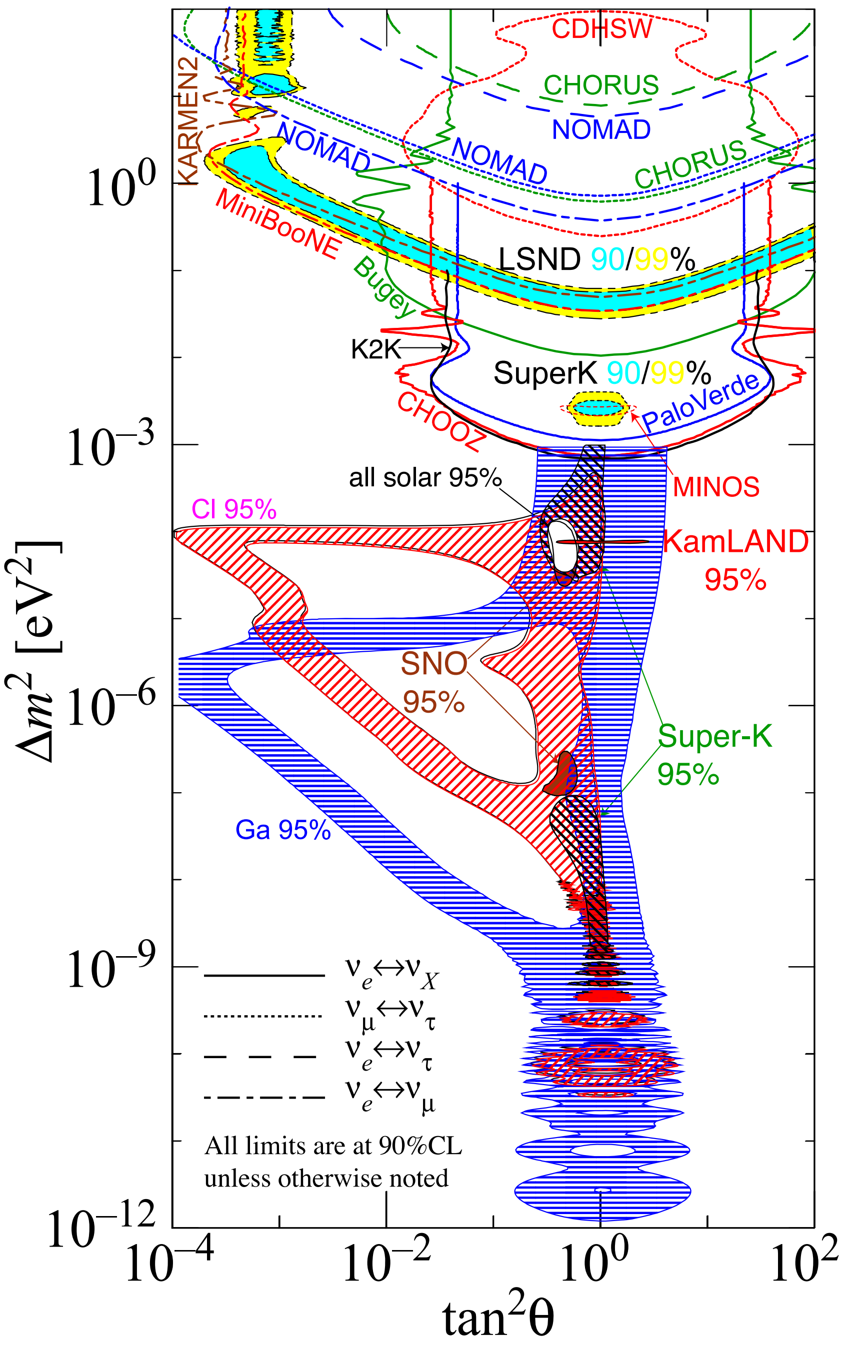


Look for anti-neutrinos from reactors in Japan (typical distance of ~100km and energy of few MeV)

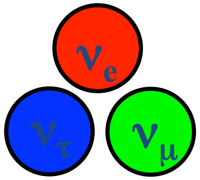
KamLAND Results

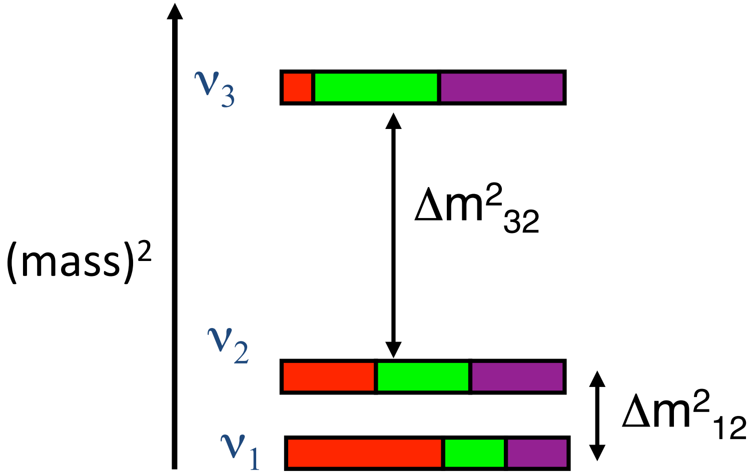


All Oscillation Data



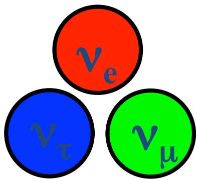
Neutrino Mixing

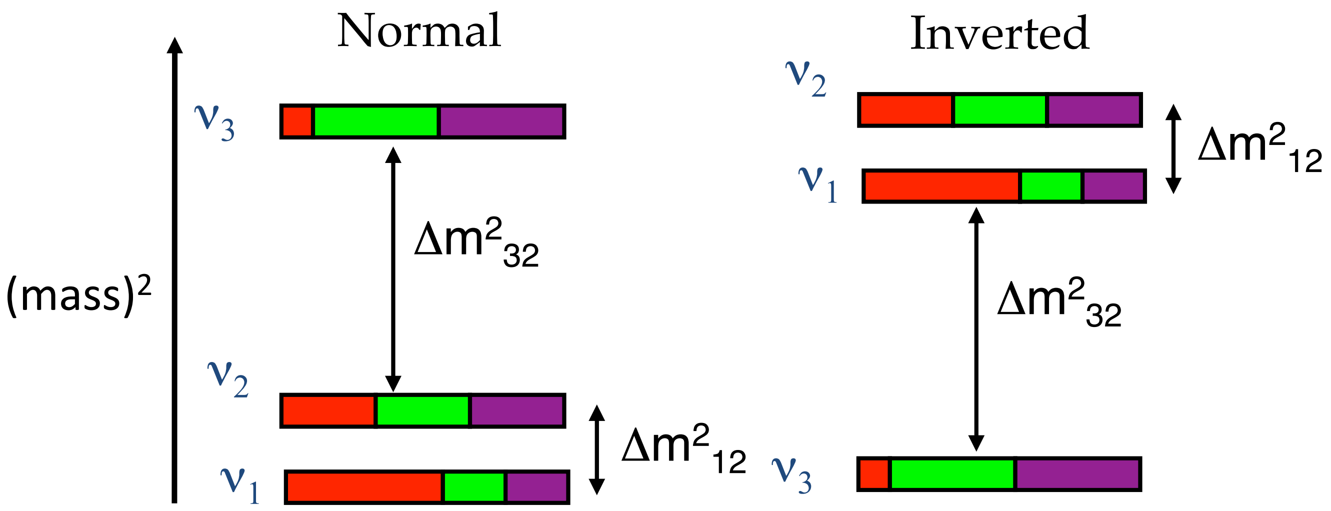




Neutrino Mixing

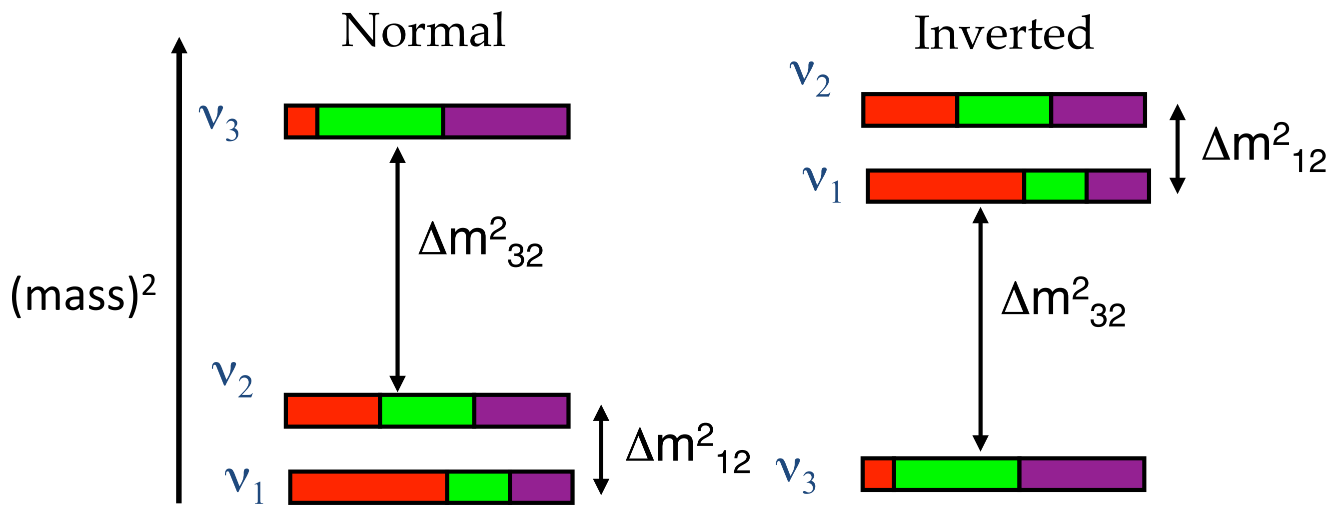
MASS HIERARCHY

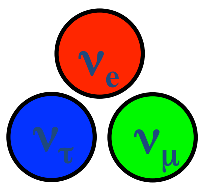




Neutrino Mixing

MASS HIERARCHY





MIXING

Parameters:

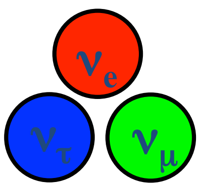
3 mixing angles

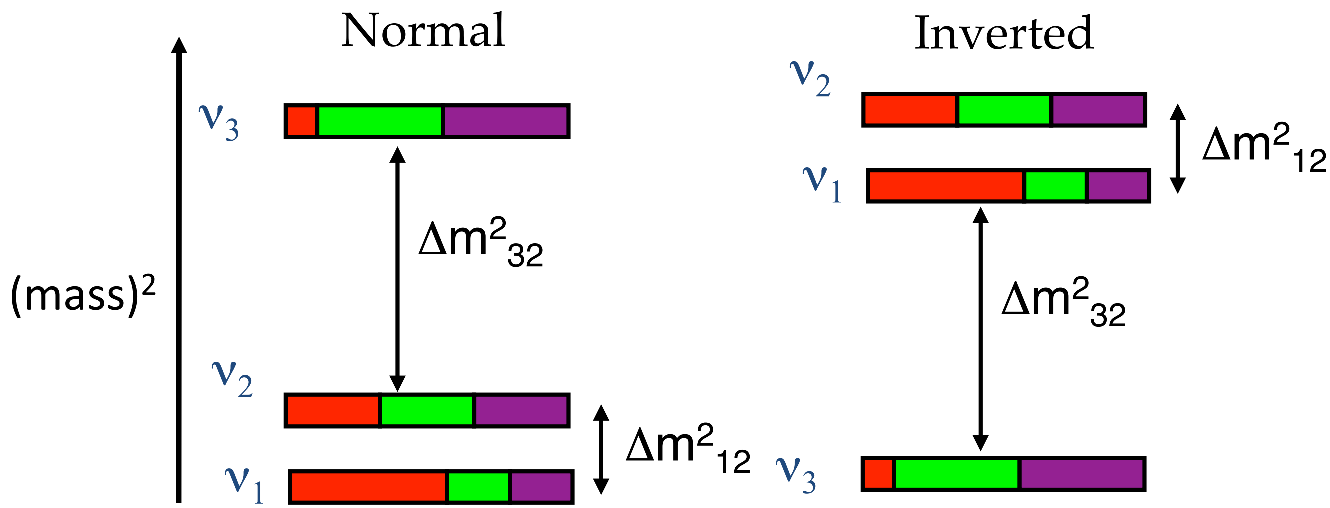
2 mass differences

1 phase

Neutrino Mixing

MASS
HIERARCHY



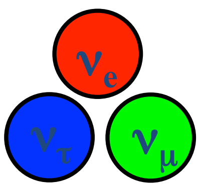


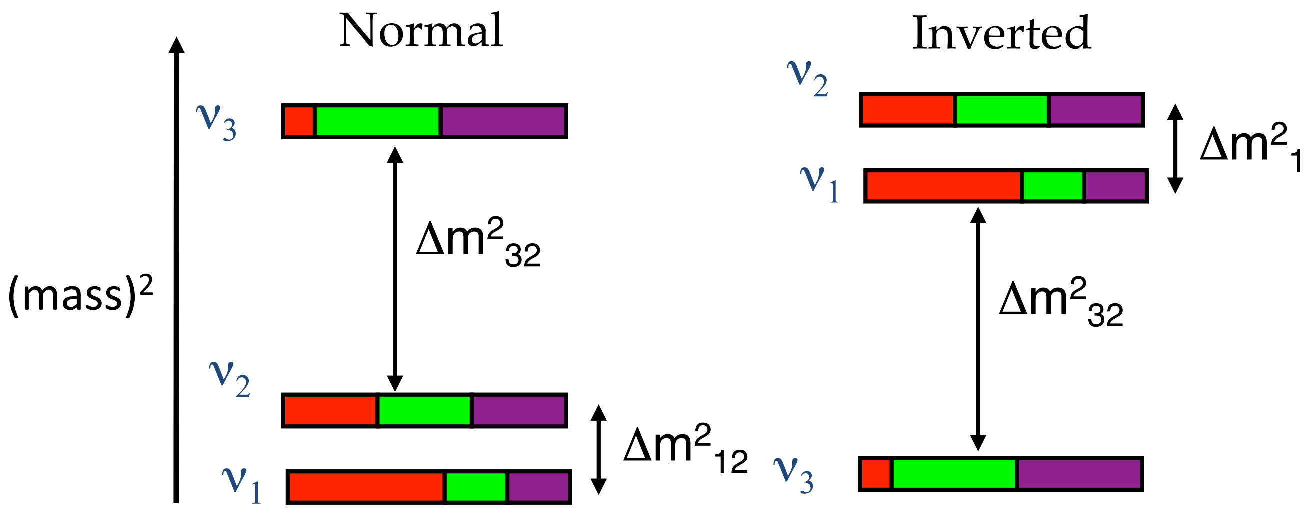
MIXING

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U^{\mathrm{diag}}_{\mathrm{Maj}}$$

Neutrino Mixing

MASS HIERARCHY





MIXING

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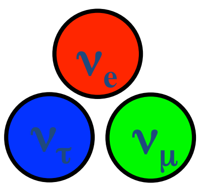
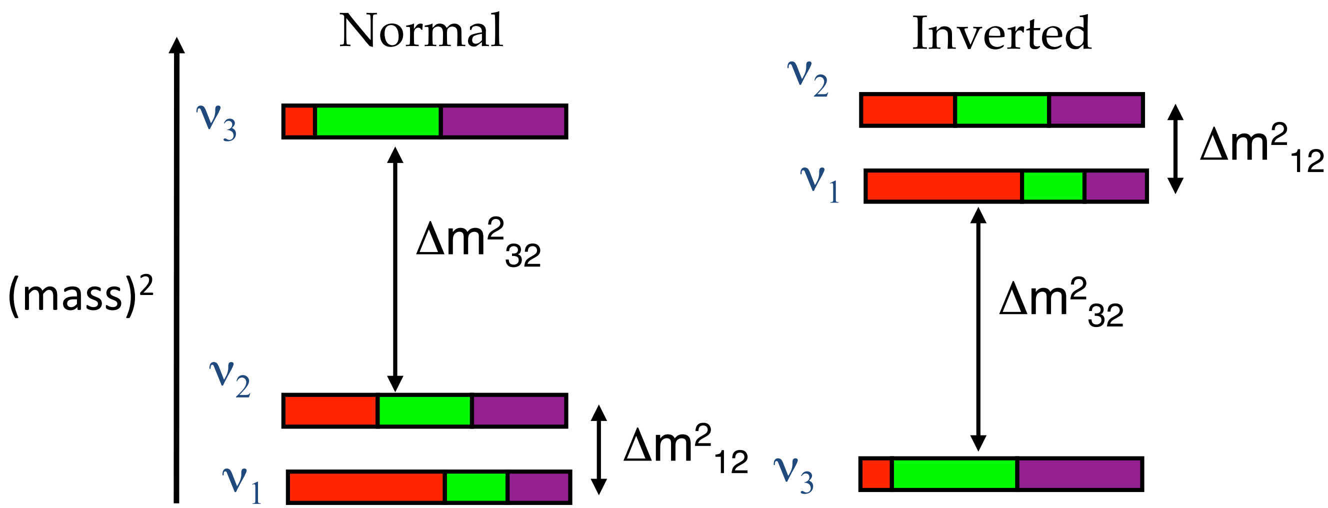
Atmospheric
well measured

Neutrino Mixing

MASS HIERARCHY





MIXING

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U^{\mathrm{diag}}_{\mathrm{Maj}}$$

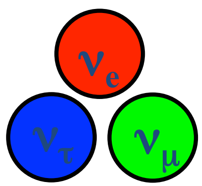
Atmospheric
well measured

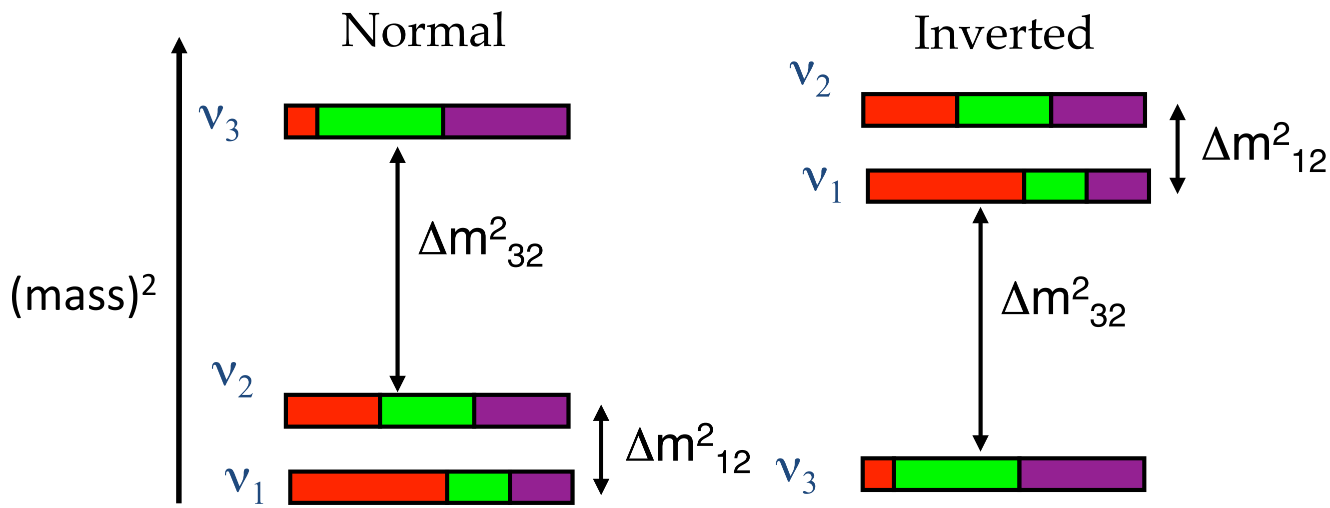
Measured as of Mar 2012!

Daya Bay θ_{13} DOUBLE CHOOZ

Neutrino Mixing

MASS HIERARCHY





MIXING

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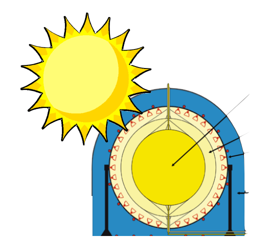
Atmospheric
well measured

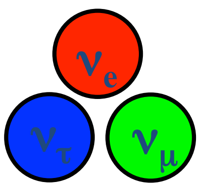
Measured as of Mar 2012!

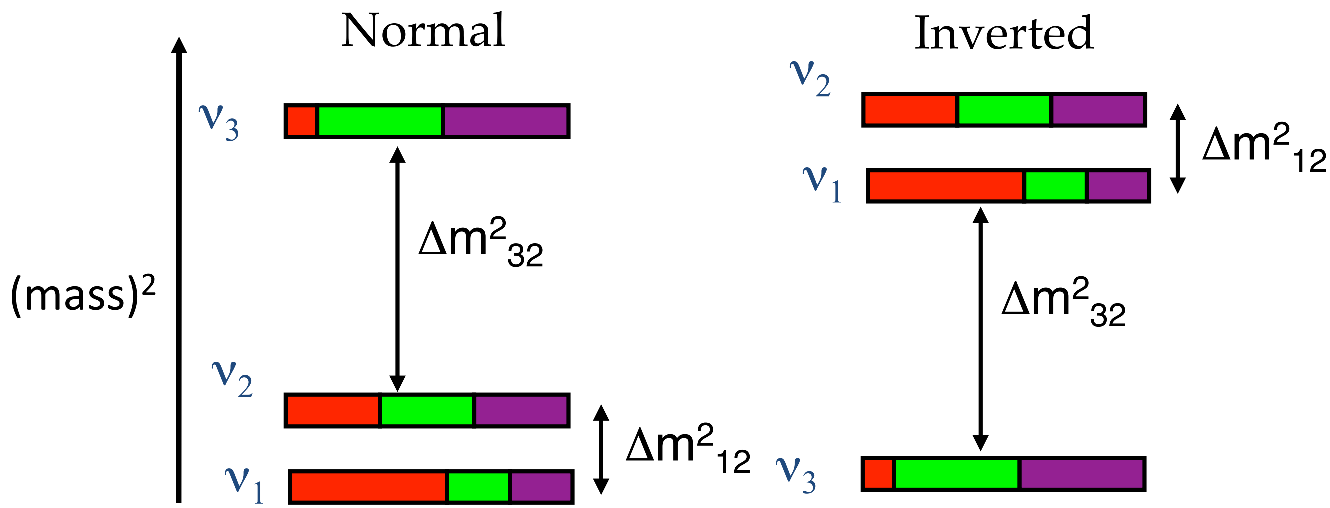
Solar
well measured



Neutrino Mixing

MASS HIERARCHY





MIXING

CP violation: ν vs $\bar{\nu}$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{\mathrm{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times U^{\mathrm{diag}}_{\mathrm{Maj}}$$

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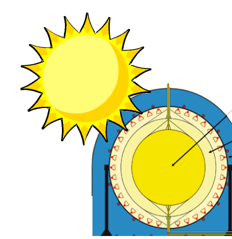


2016 Breakthrough Prize in Fundamental Physics

Kam-Biu Luk and the Daya Bay Collaboration

Yifang Wang and the Daya Bay Collaboration

Koichiro Nishikawa and the K2K and T2K Collaboration

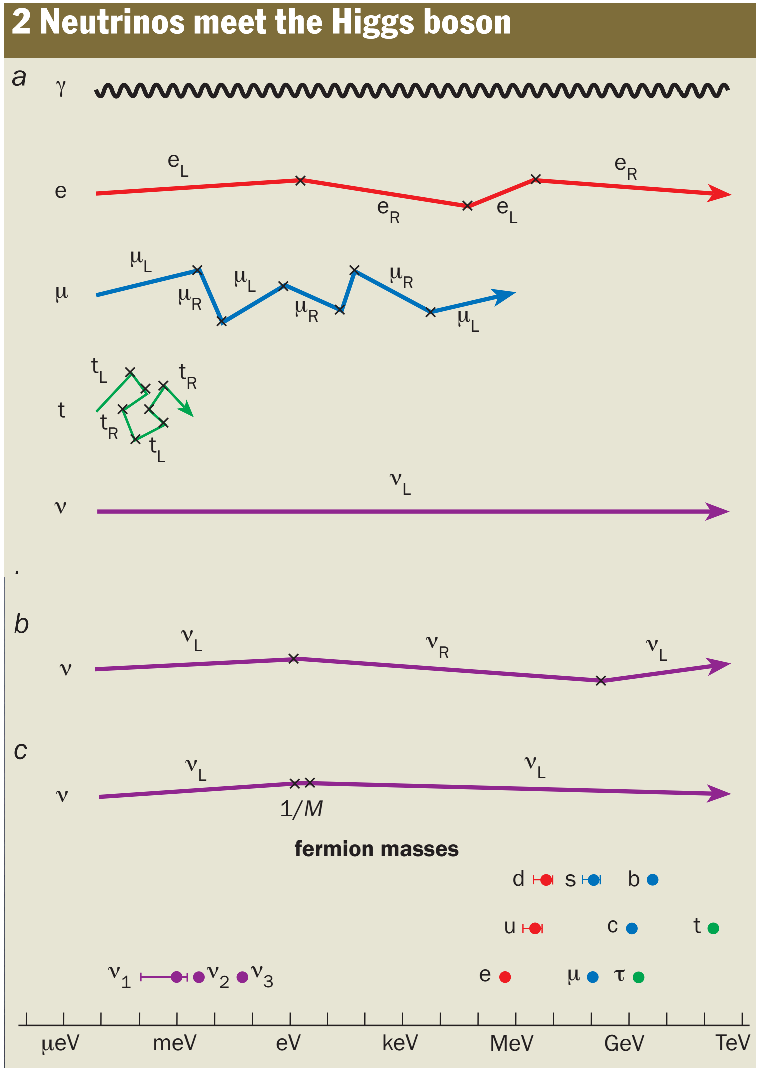
Atsuto Suzuki and the KamLAND Collaboration

Arthur B. McDonald and the SNO Collaboration

Takaaki Kajita and the Super K Collaboration

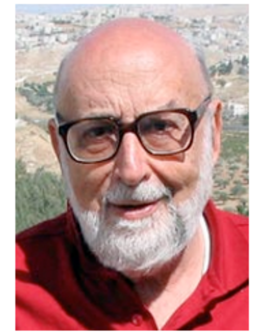
Yoichiro Suzuki and the Super K Collaboration

Mysterious Neutrinos



Standard Model masses

← the anomalous ν mass scale



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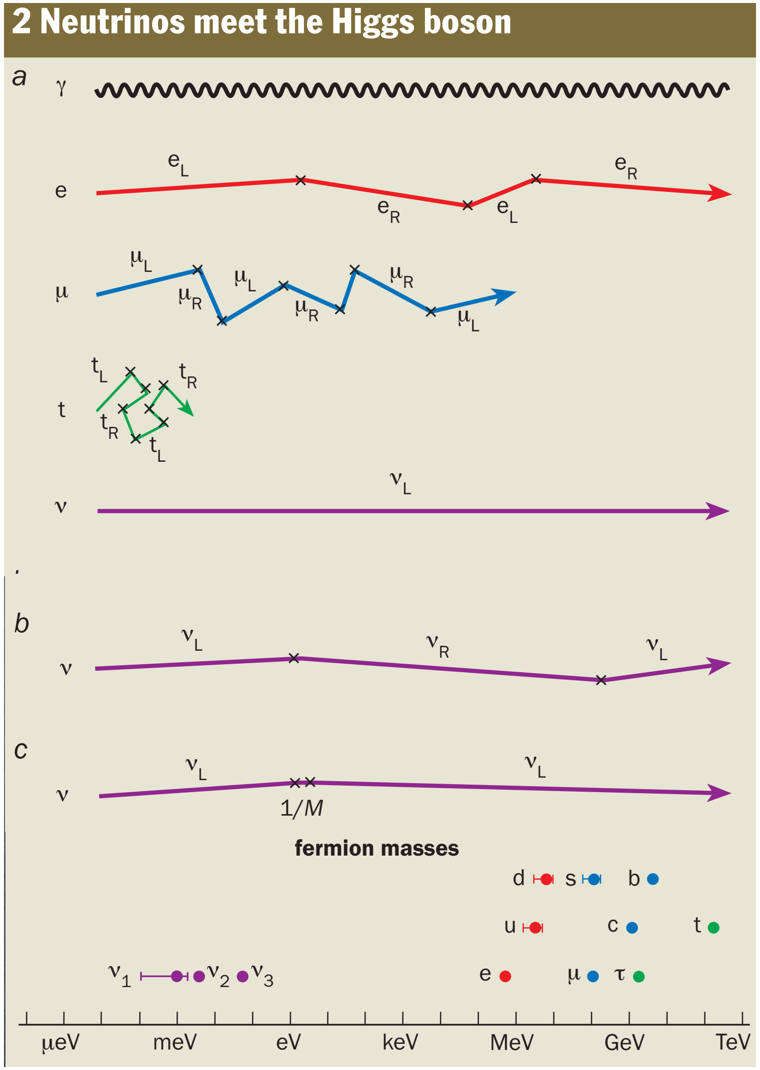
François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

H.Murayama

Mysterious Neutrinos

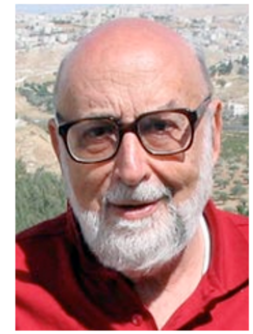


Standard Model masses

light Dirac neutrino

← the anomalous ν mass scale

H.Murayama



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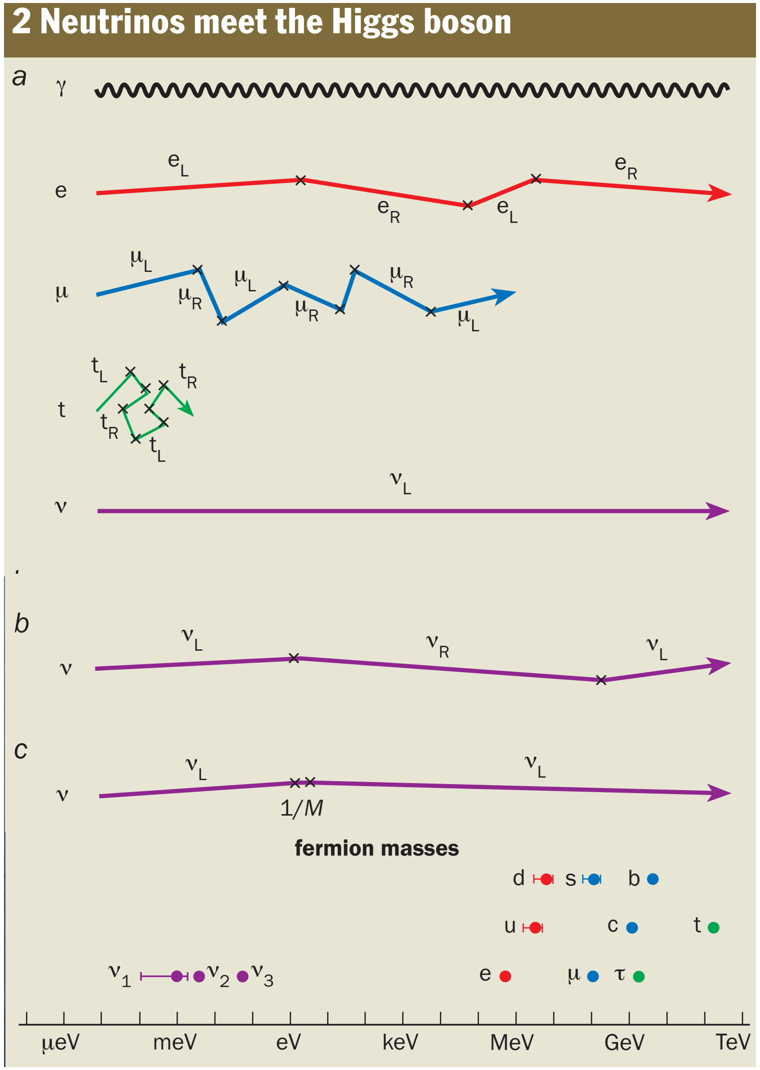
Peter W. Higgs

Mysterious Neutrinos



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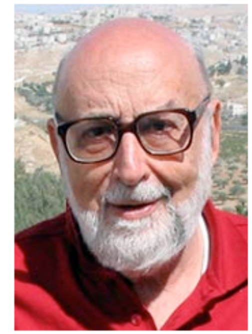

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François Englert

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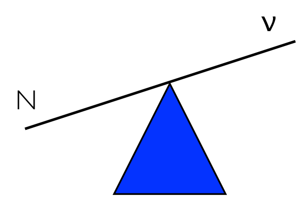
Peter W. Higgs

light Dirac neutrino

Left-Handed Majorana neutrino + see-saw mechanism



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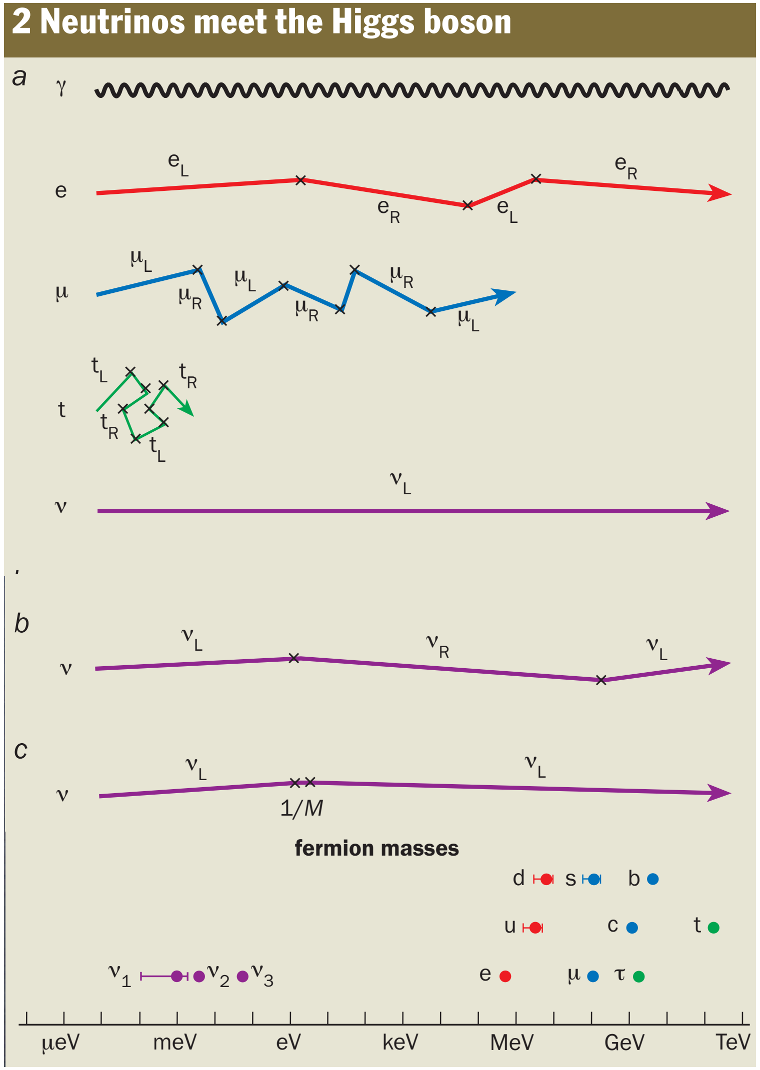
Mysterious Neutrinos



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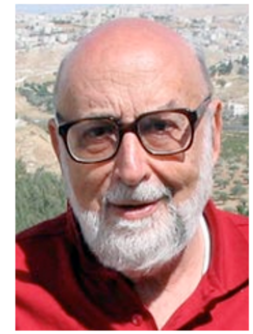

Photo: Pnicolet via Wikimedia Commons

François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

light Dirac neutrino

Left-Handed Majorana neutrino + see-saw mechanism

(Likely) requires new physics

← the anomalous ν mass scale

Key Questions

- Is neutrino its own antiparticle ?
  - ❑ Is Lepton Number conserved ?
- How light is it ?
  - ❑ Direct measurements, astrophysical constraints, neutrinoless double-beta decay
- How are the masses arranged (hierarchy)
  - ❑ Long-baseline oscillation measurements, also reactor, atmospheric neutrino experiments and cosmology
- Is there a neutrino-antineutrino asymmetry ?

☞These questions define research directions in neutrino physics for the next two decades

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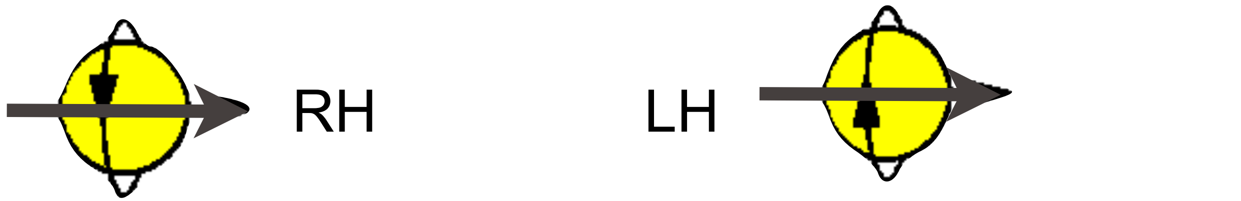
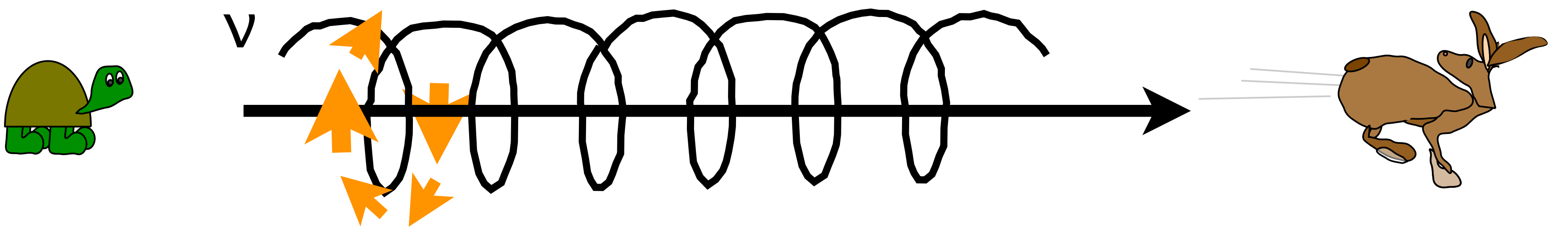
An Aside: Helicity

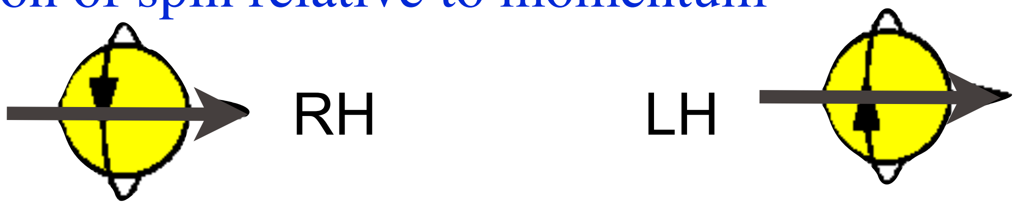


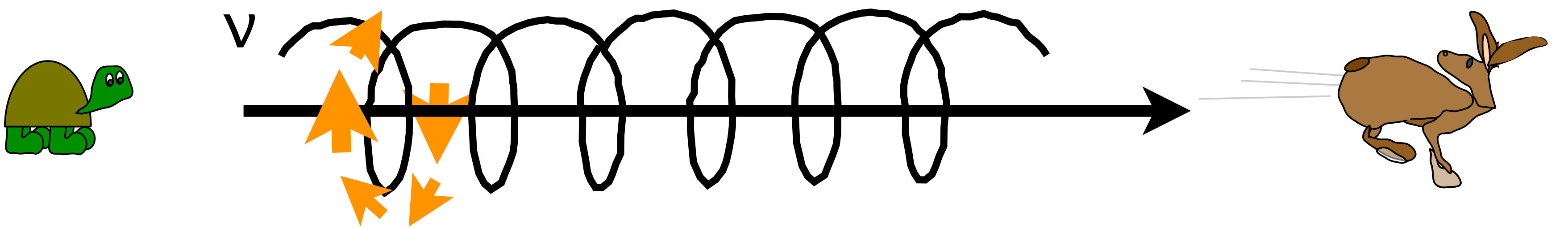


Thanks to J. Conrad, L. Winslow, G.D. Orebi Gann

An Aside: Helicity

- Orientation of spin relative to momentum





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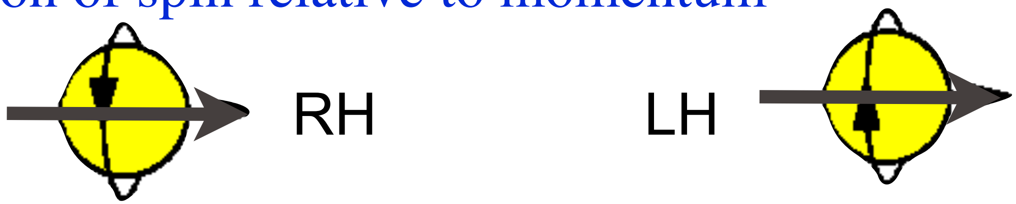
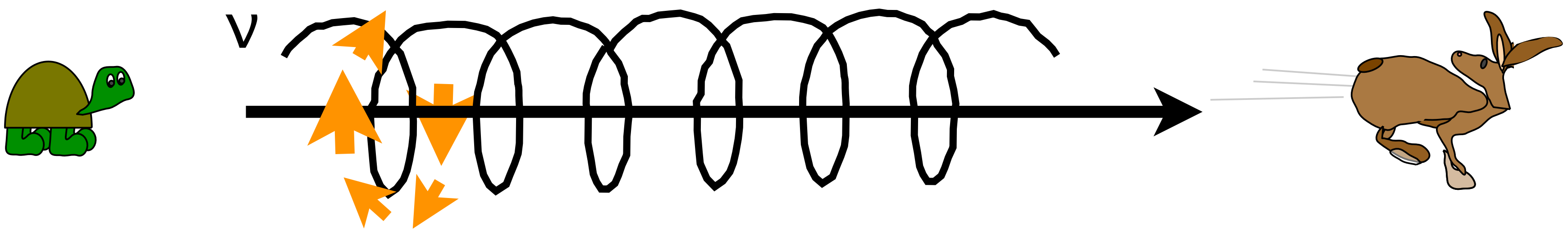


- If a particle has mass, can always boost to a frame in which helicity flips



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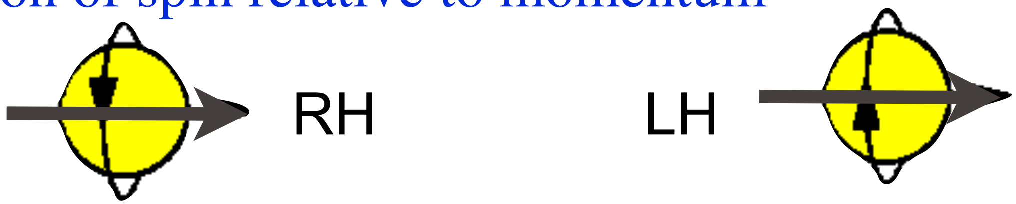

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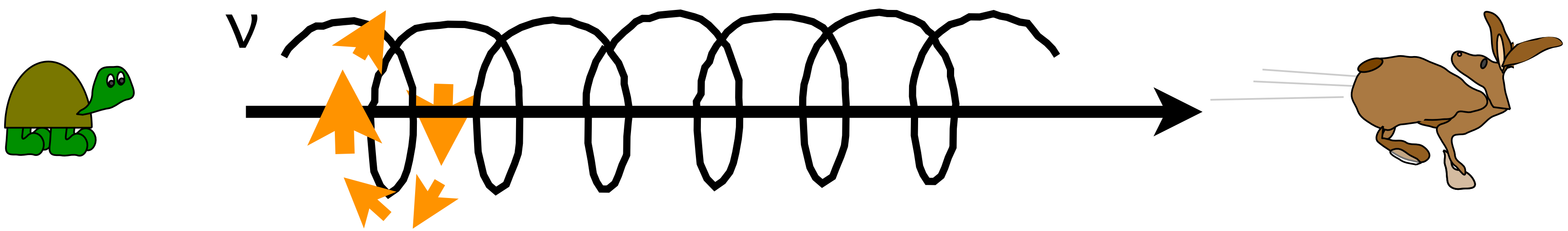

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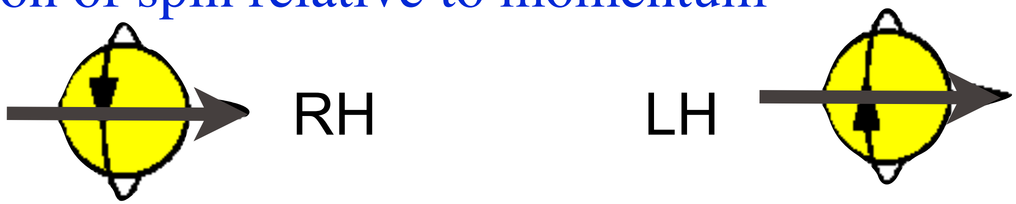

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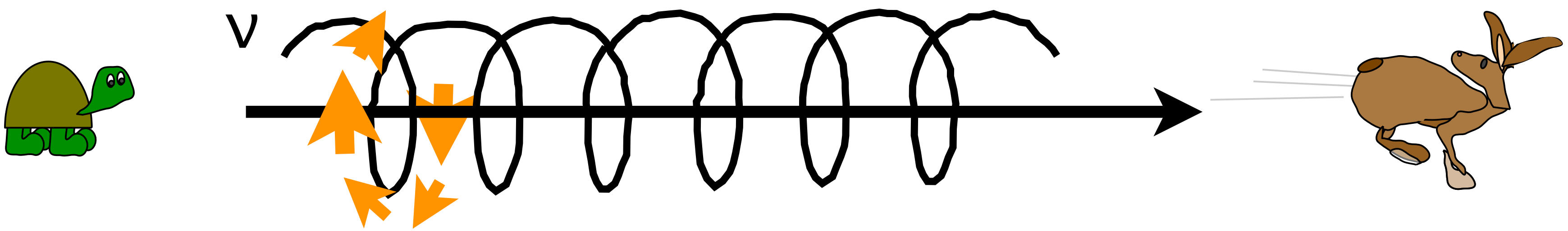


- Discovery of non-zero neutrino mass

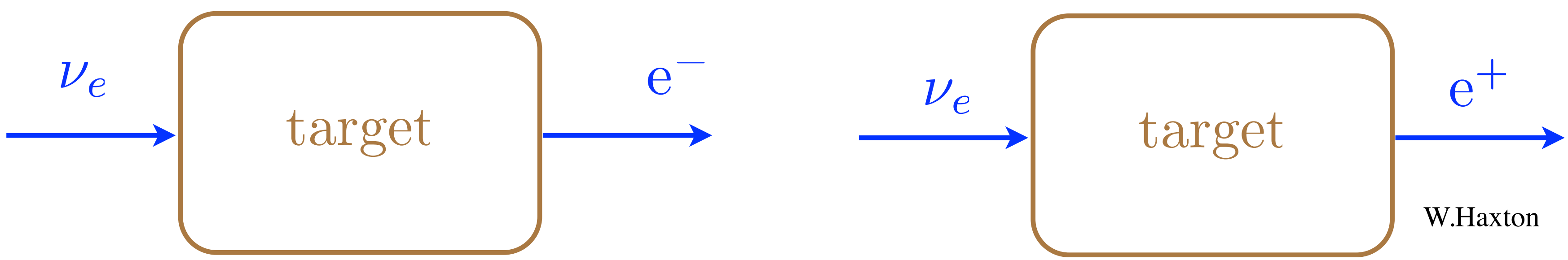
  ⇒ can have a RH ν (or LH $\overline{\nu}$)

Thanks to J. Conrad, L. Winslow, G.D. Orebi Gann

Lepton Number

- **Neutrino: only known fermion with 0 charge; could be its own antiparticle**
  - But experimentally, ν and $\bar{\nu}$ behave differently
    - ☞ $^{37}Cl + \bar{\nu}_e \nRightarrow {}^{37}Ar + e^-$ (Ray Davis @ Savanna River)
- Define ν_e and $\bar{\nu}_e$ by interaction with charged leptons ($e^{\pm}$)
- Introduce a conserved 'charge' $\Rightarrow$ lepton number

Lepton	**Lepton number**
e^-	+1
e^+	-1
ν_e	+1
$\bar{\nu}_e$	-1



W.Haxton

Dirac vs Majorana Neutrinos

- **Neutrino: only known fermion with 0 charge; could be its own antiparticle**
  - But experimentally, ν and $\bar{\nu}$ behave differently
  - Also, ν_{LH} and ν_{RH} behave differently
    - ☞ Weak interactions violate parity
    - ☞ Are these phenomena related ?

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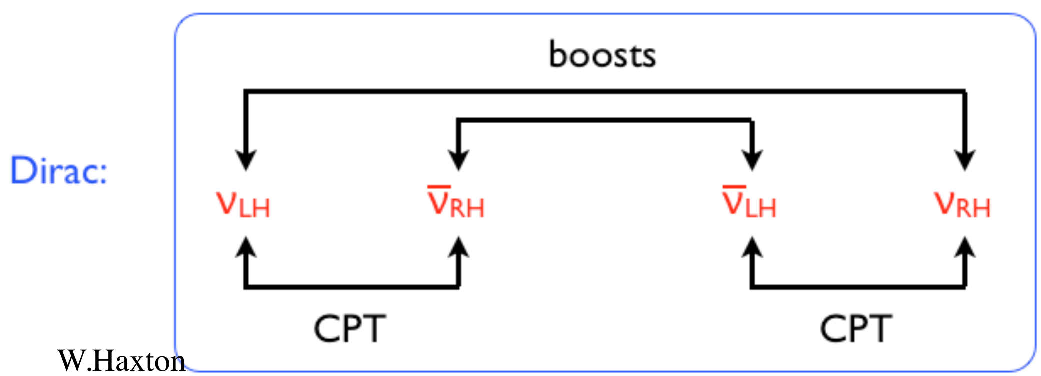
Dirac:
different particles



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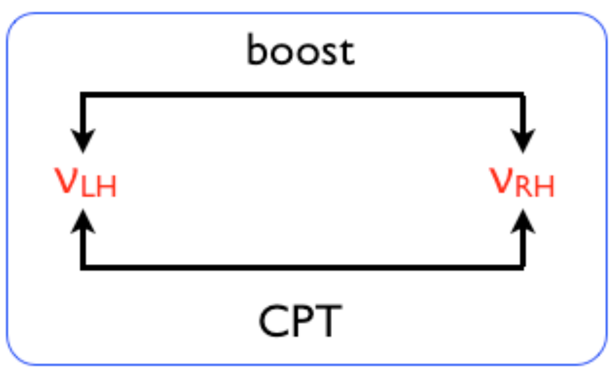
Majorana:
different helicity states

Majorana:



W.Haxton

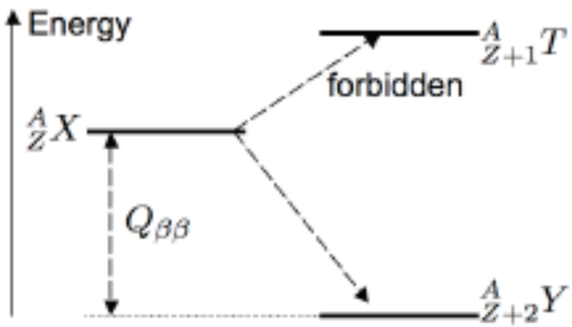
Dirac vs Majorana Neutrinos

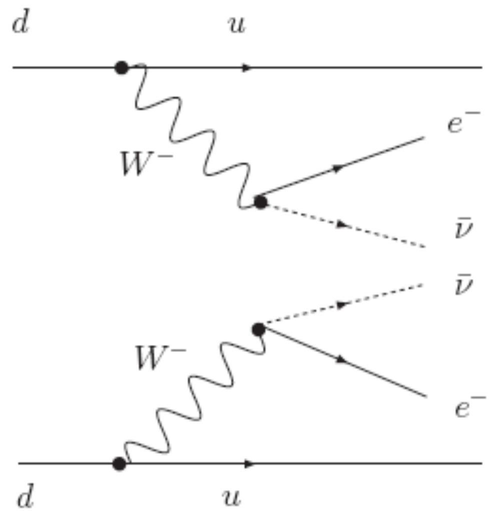
- Understand how neutrinos acquire mass is of fundamental importance

- Dirac
  - Requires new fundamental global symmetry $U(1)_{\text{lepton number}}$
    - ☞ New physics ?
    - ☞ Matter and antimatter are fundamentally different

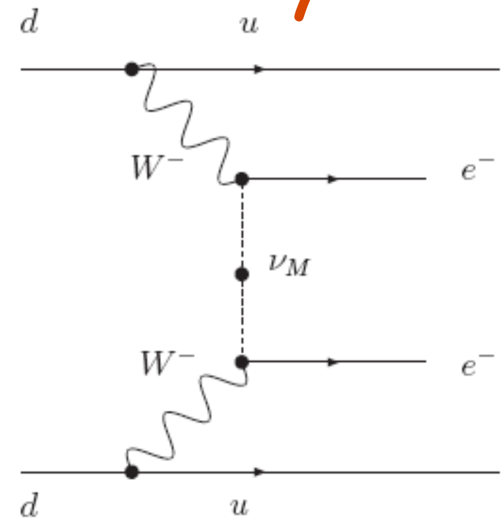
- Majorana
  - Cannot be explained by "standard" Higgs Yukawa coupling
    - ☞ New physics ?
    - ☞ Potentially sensitive to very high mass scales
    - ☞ Can generate matter⇔antimatter transitions

Neutrinoless Double-Beta Decay

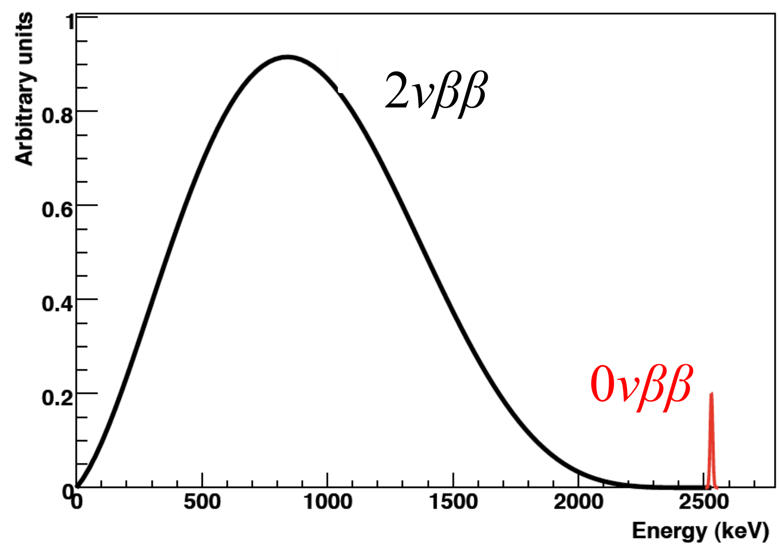




SM $2\nu\beta\beta$ decay $\tau \geq 10^{19}$ y



$0\nu\beta\beta$ $\tau \geq 10^{25}$ y



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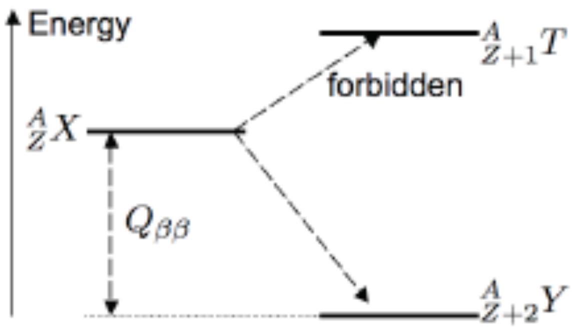

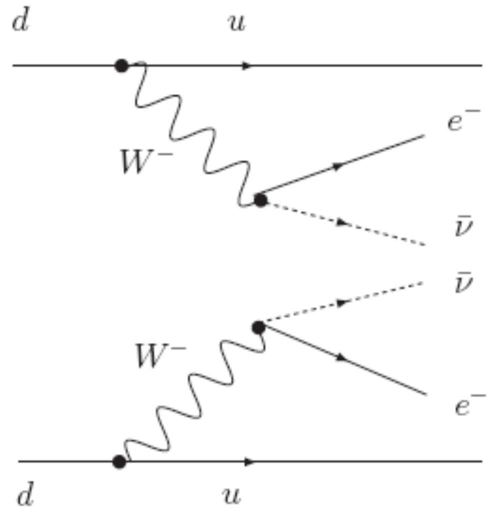

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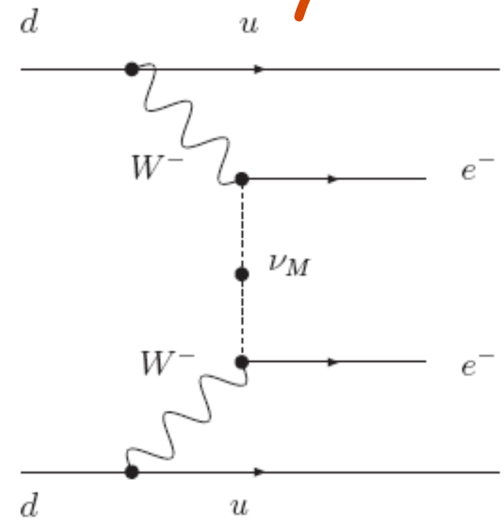

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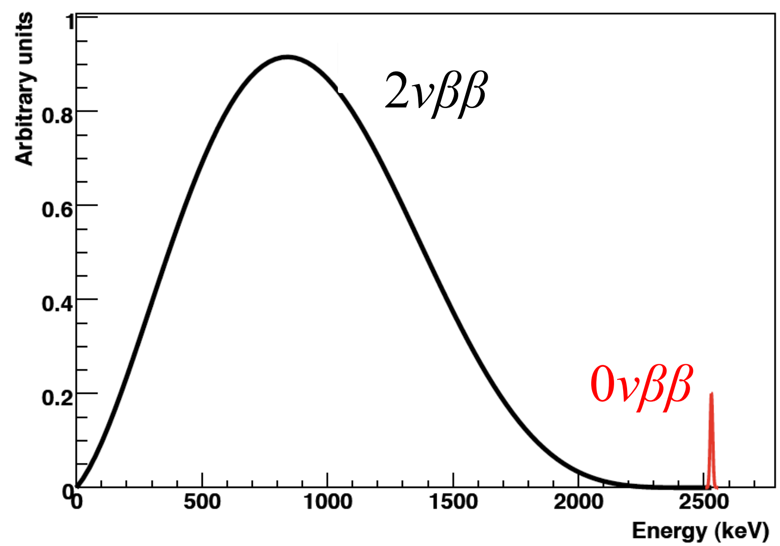

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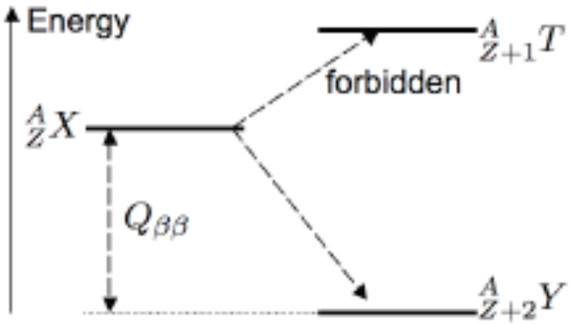
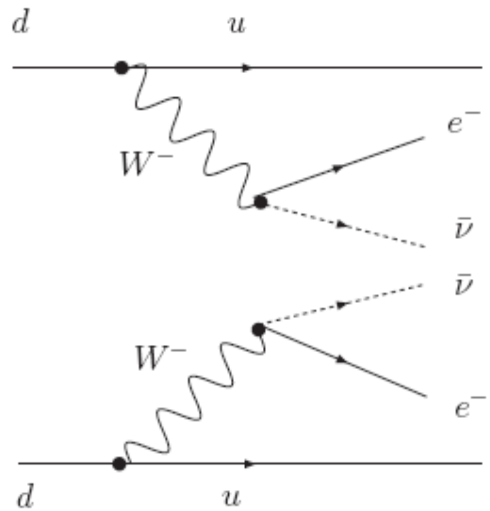
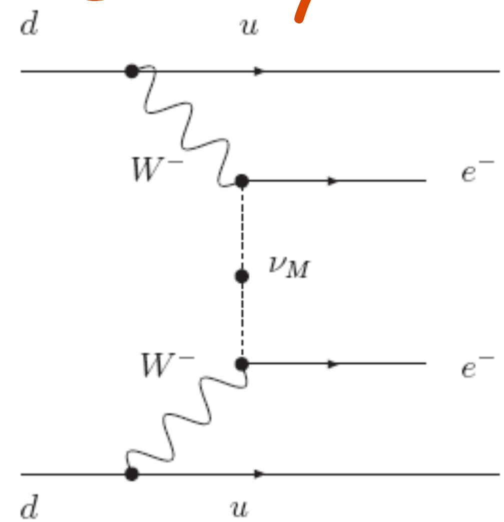
Neutrinoless Double-Beta Decay





SM 2νββ decay $\tau \geq 10^{19}$ y

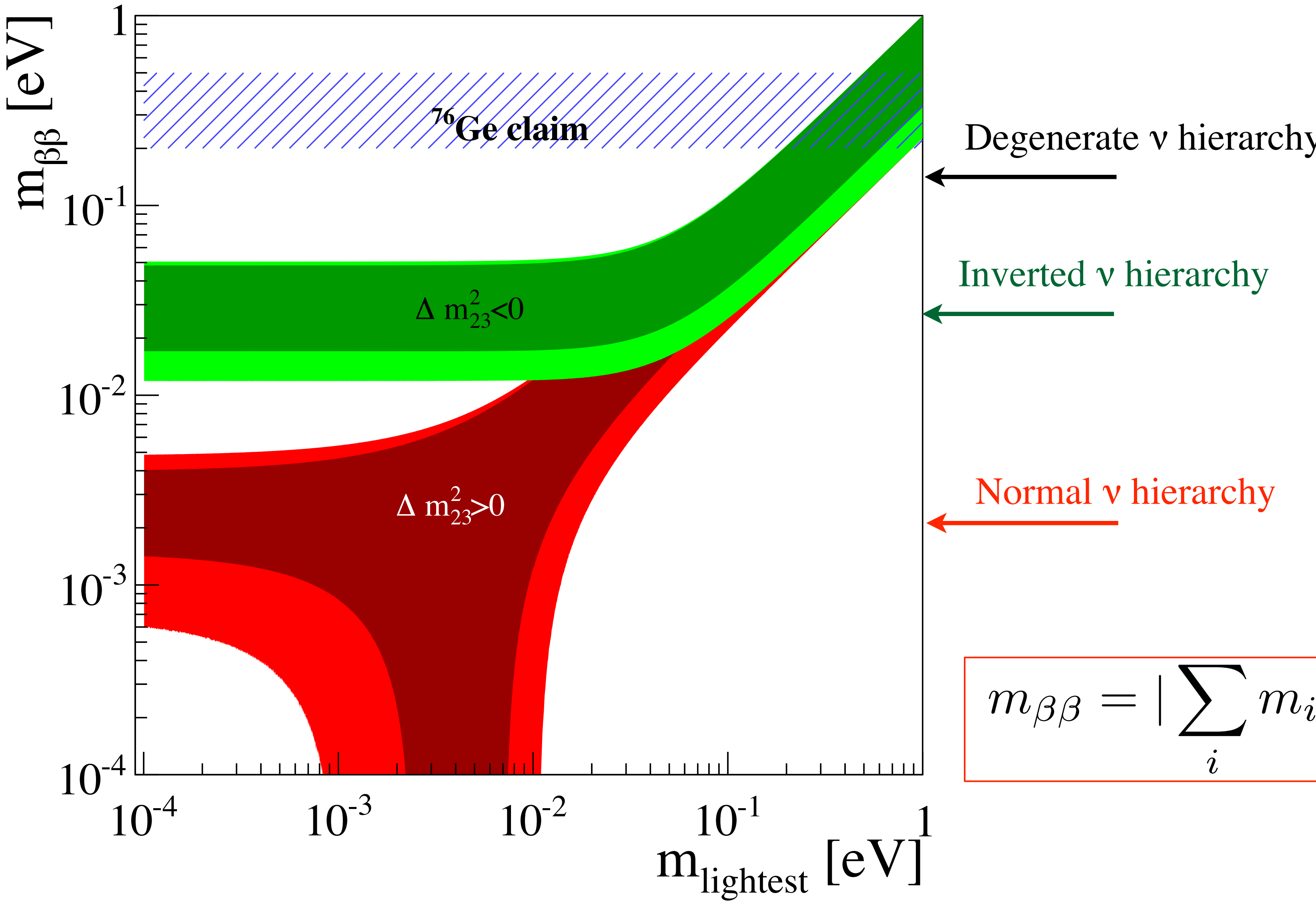


0νββ $\tau \geq 10^{25}$ y

- Observation of 0νββ would mean
  - Lepton number violation
  - Neutrinos are Majorana particles
  - Rate measures (effective) electron neutrino mass

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

DBD and Neutrino Mass



$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

0νββ Rate and Neutrino Mass

0νββ rate

Phase space $\propto Q^5$

Nuclear matrix element

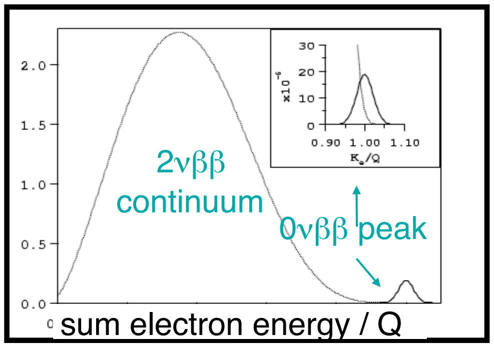
Effective neutrino mass

$$\Gamma = 1/\tau = G_F^2 \Phi(Q,Z)\, |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$

high Q candidates preferred

large phase space

low background



^{238}U γ end at 2.4 MeV

^{232}Th γ end at 2.6 MeV

[2039 keV (^{76}Ge) ⇔ 4271 keV (^{48}Ca)]

$\tau^{0\nu} \sim 10^{24}$–10^{26} years: large mass and extremely low backgrounds needed (underground labs, ultra purity materials, active rejection of backgrounds)

Experimental Sensitivity

Half-life	Expected Signal (counts/tonne-year)
5×10^{25}	~100
5×10^{26}	~10
5×10^{27}	~1
5×10^{28}	~0.1

Sensitivity scaling:

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$ (background-limited)

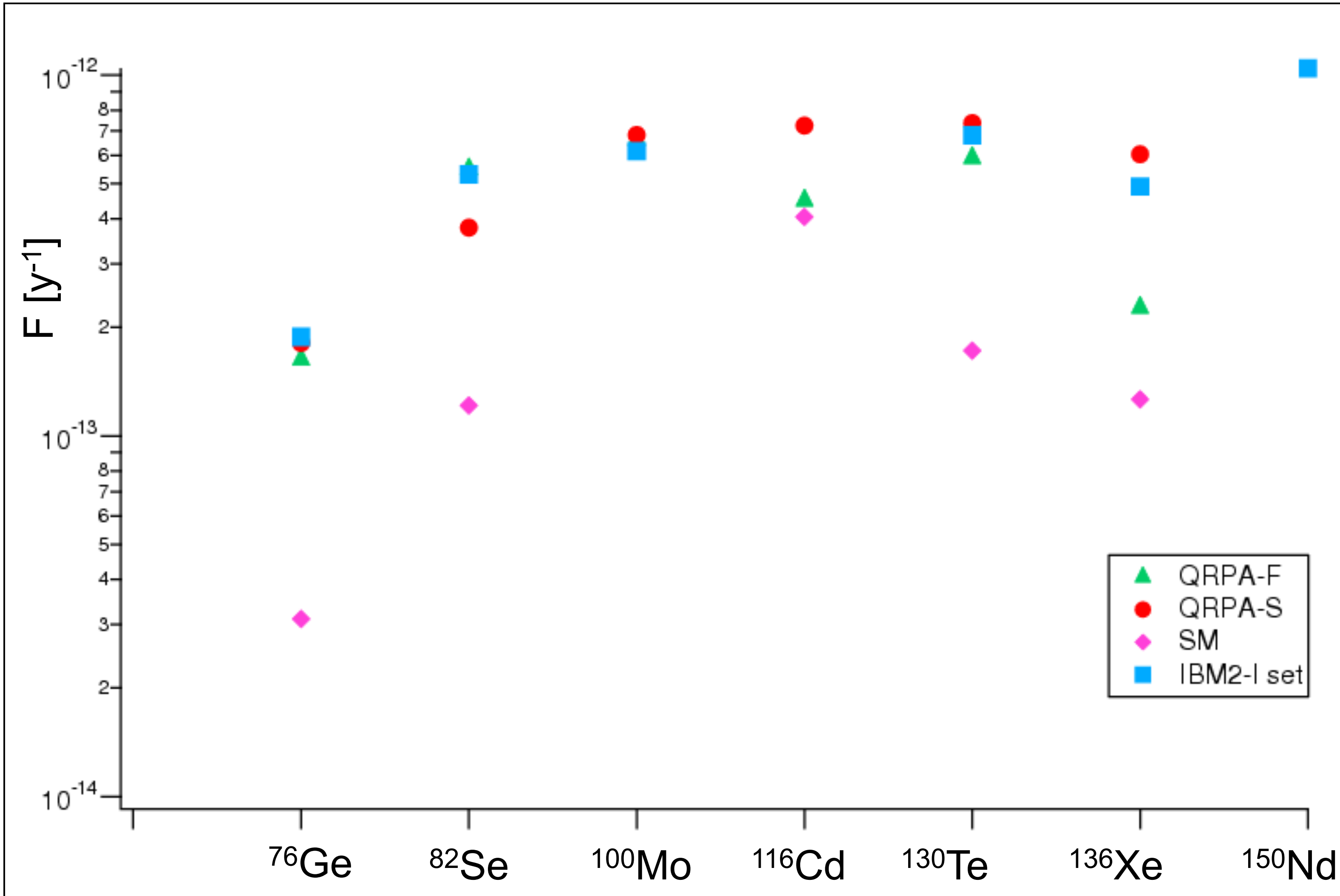
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$ (background-free)

Experimental challenge:

- ✓ Increase *Mass* (200-1000 kg for current experiments): $$, R&D
- ✓ Increase *Isotopic Abundance*: $$
- ✓ Decrease *Bkg* (ultimately to 2νββ limit): radiopurity, active rejection
- ✓ Decrease *ΔE*: technology choice

$0\nu\beta\beta$ Isotopes: Figure of Merit

$F = G_F^2 \Phi(Q,Z) |M_{0\nu}|^2 m_e^2$ [y^{-1}] (Want as high as possible)



0νββ Isotopes: Figure of Merit

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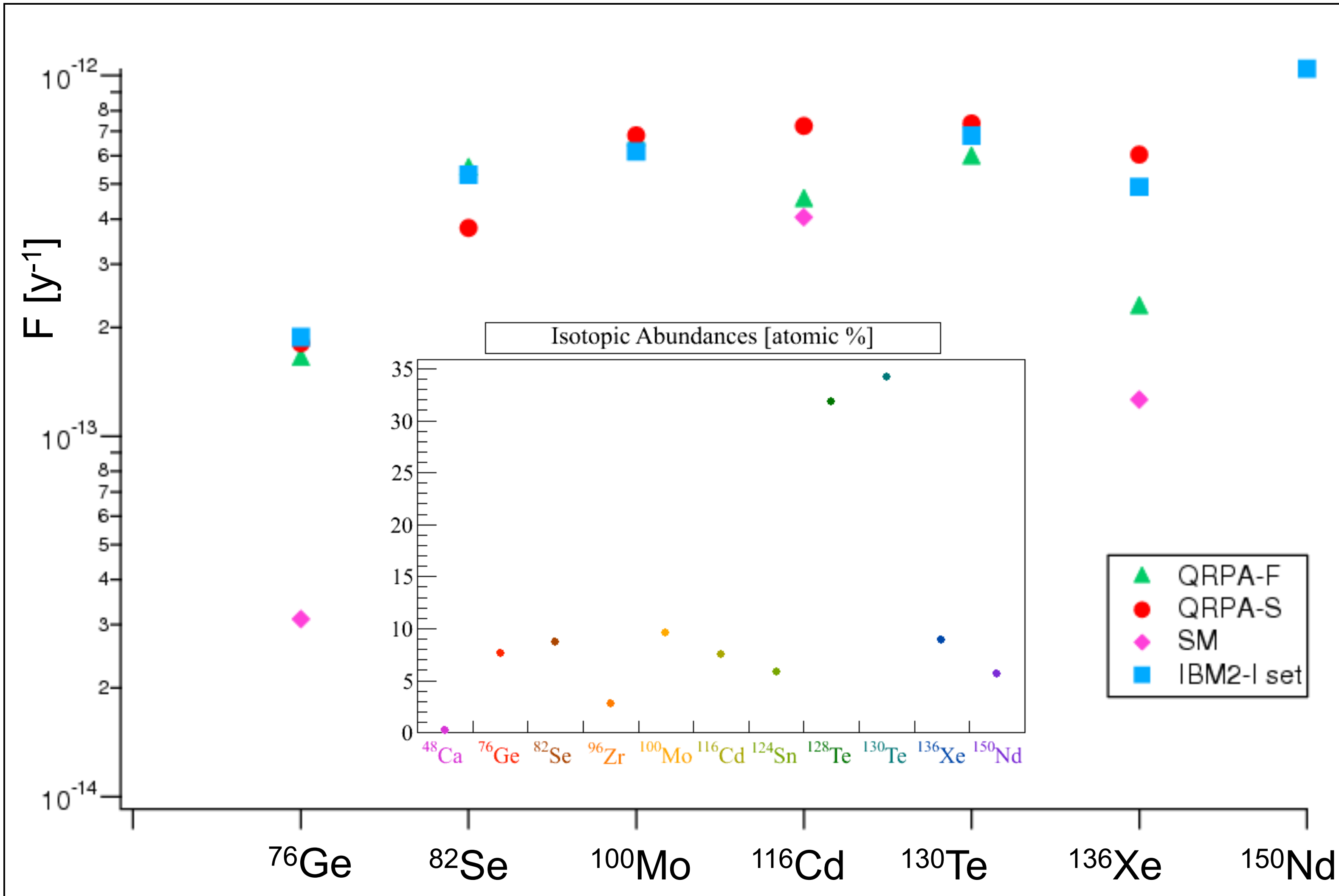
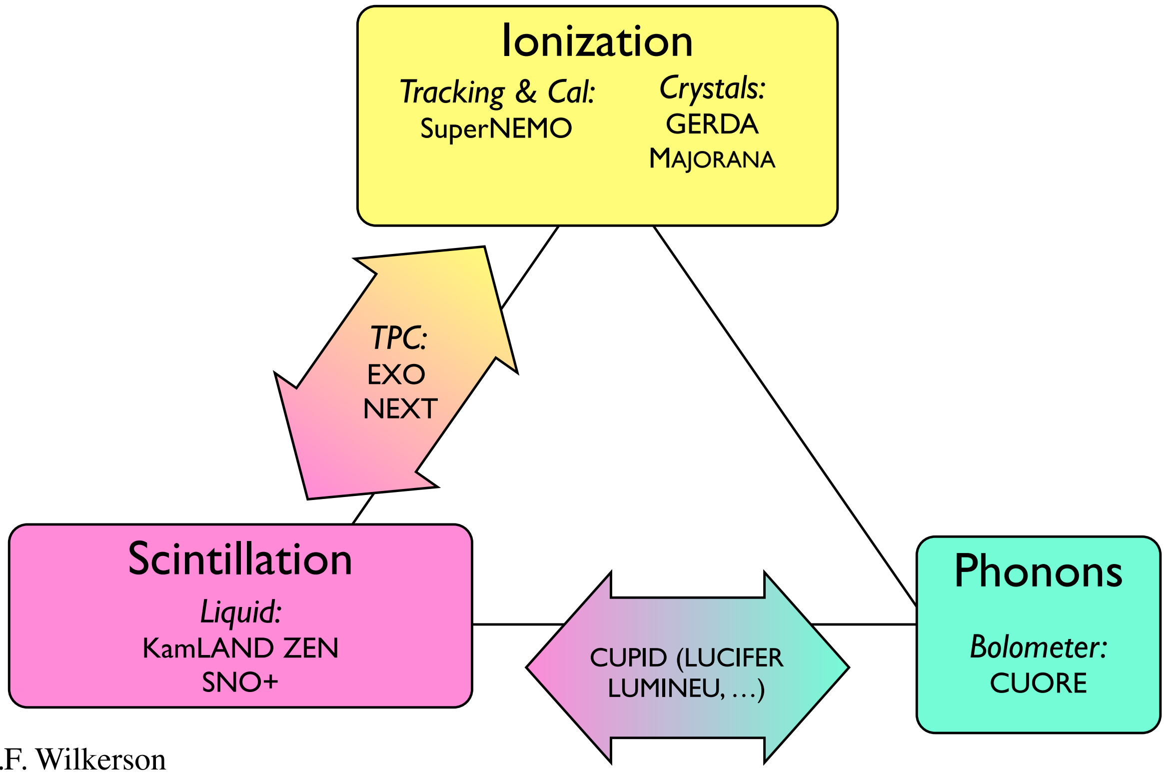
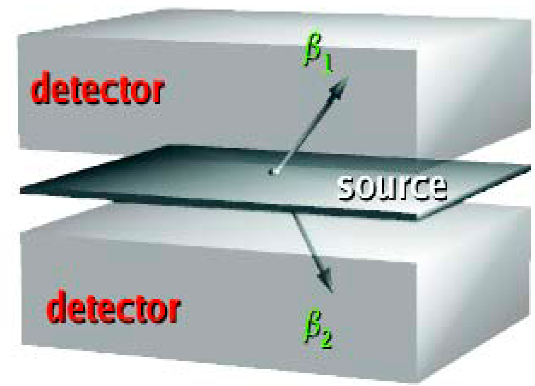


Detection Techniques

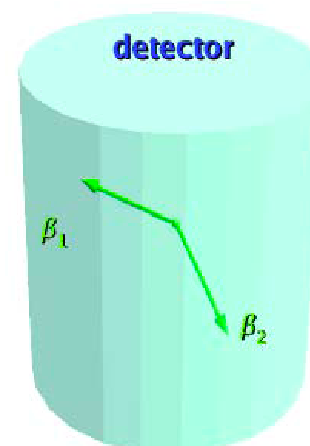


J.F. Wilkerson

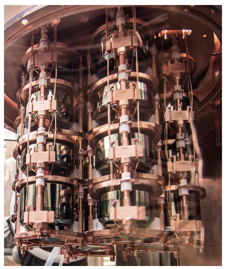
Source external to detector
(NEMO, SuperNEMO)

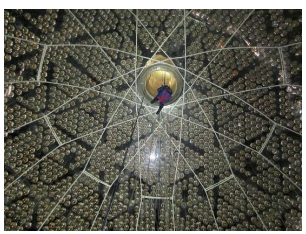


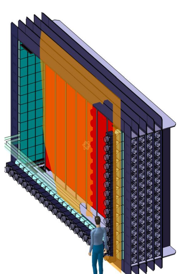
Source internal to detector
(most common)



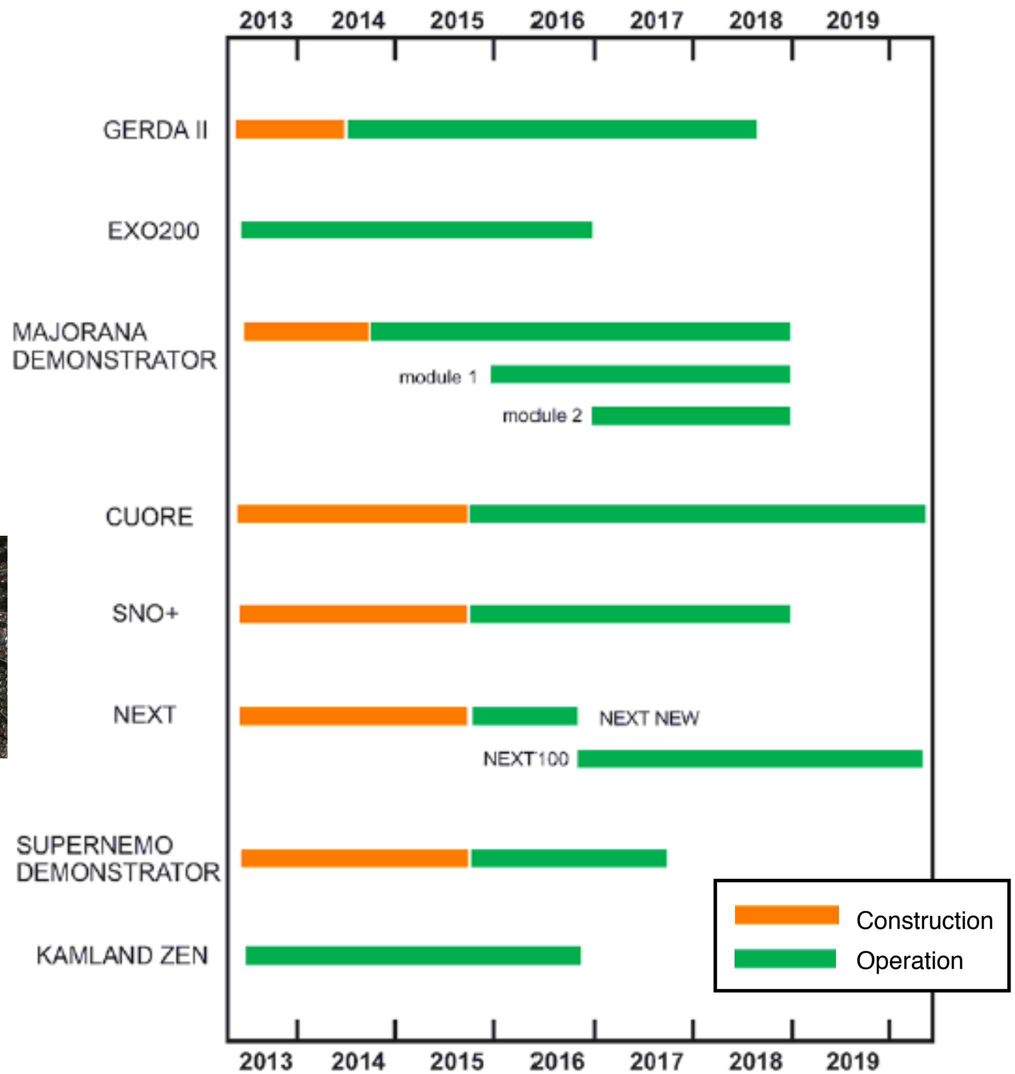
Diverse, Vibrant Program

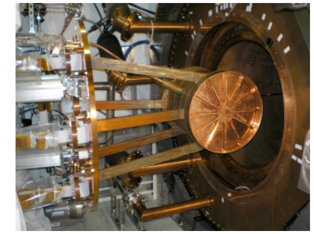


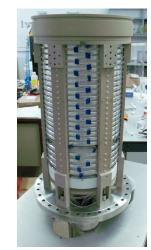




NLDBD Sub Committee Report to NSAC (2014)

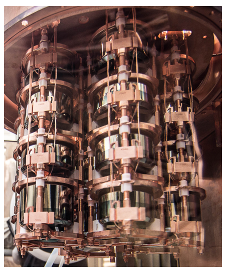


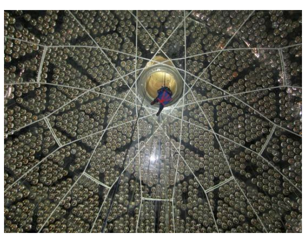


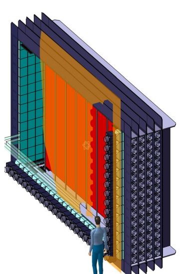


J.F. Wilkerson

Diverse, Vibrant Program







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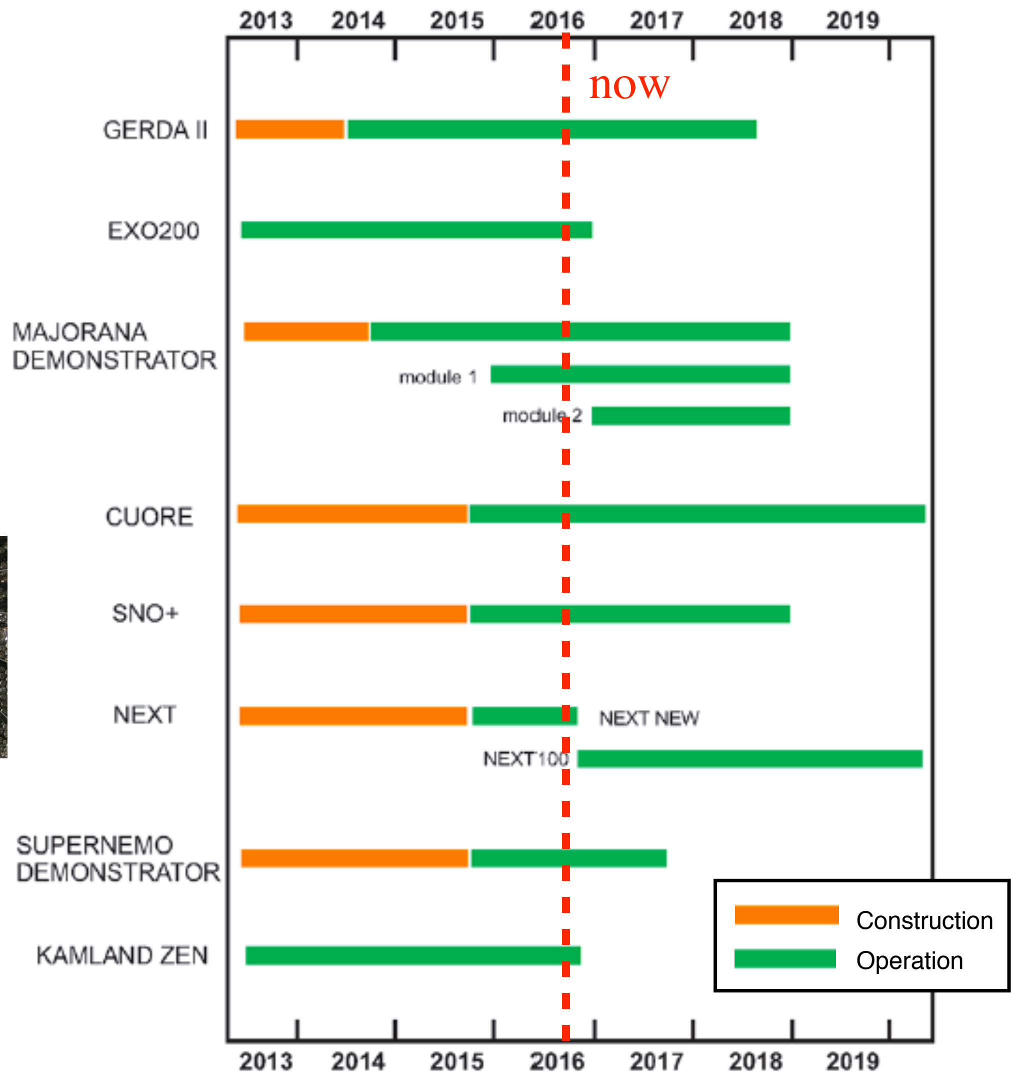
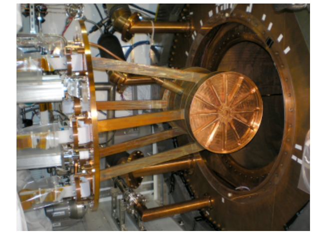




International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

1980 - 2007

2007 - 2017

2015 - 2025

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}\text{-}10^{26}$ y
(~100 meV)
30 - 200 kg
~8 expts

If $0\nu\beta\beta$ observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

200-500 kg scale

1980 - 2007

2007 - 2017

2015 - 2025

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

1980 - 2007

2007 - 2017

2015 - 2025

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

Quasi-degenerate
$T_{1/2} \sim 10^{25}\text{-}10^{26}$ y
(~100 meV)
30 - 200 kg
~8 expts

Inverted hierarchy
$T_{1/2} \sim 10^{27}\text{-}10^{28}$ y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

If $0\nu\beta\beta$ Observed

Program to study multiple $0\nu\beta\beta$ isotopes, using various techniques

~ tonne scale

1980 - 2007

2007 - 2017

2015 - 2025

International $0\nu\beta\beta$ Program

Previous Expts.
$T_{1/2} \sim 10^{24}$ y
(~ 1 eV)
~kg scale

→

Quasi-degenerate
$T_{1/2} \sim 10^{25}$-10^{26} y
(~100 meV)
30 - 200 kg
~8 expts

→

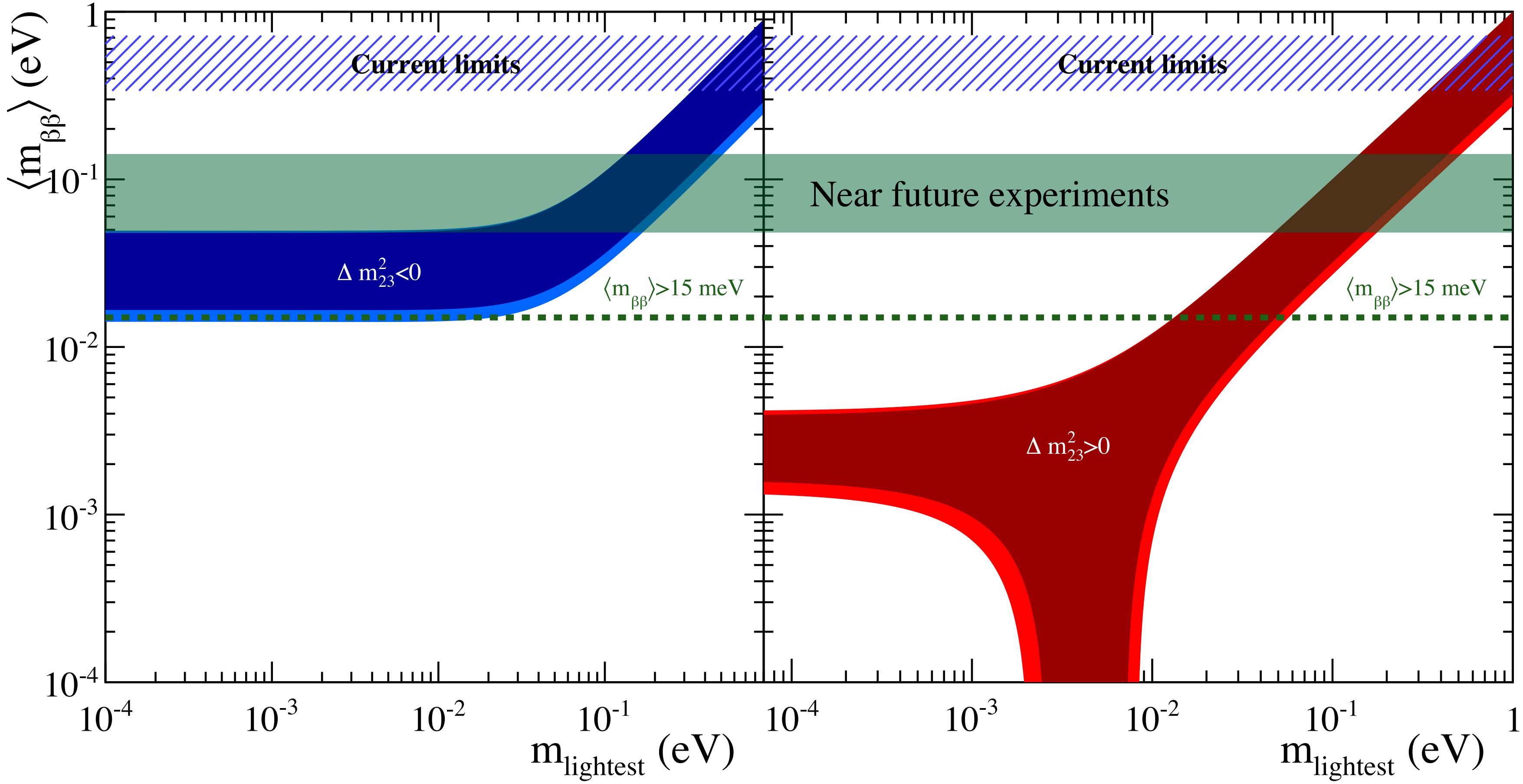
Inverted hierarchy
$T_{1/2} \sim 10^{27}$-10^{28} y
(~15 meV)
tonne (phased)
~3 experiments
All international in scope
U.S. involvement in ~2

→

Normal hierarchy
~5 meV
≥10's ton scale

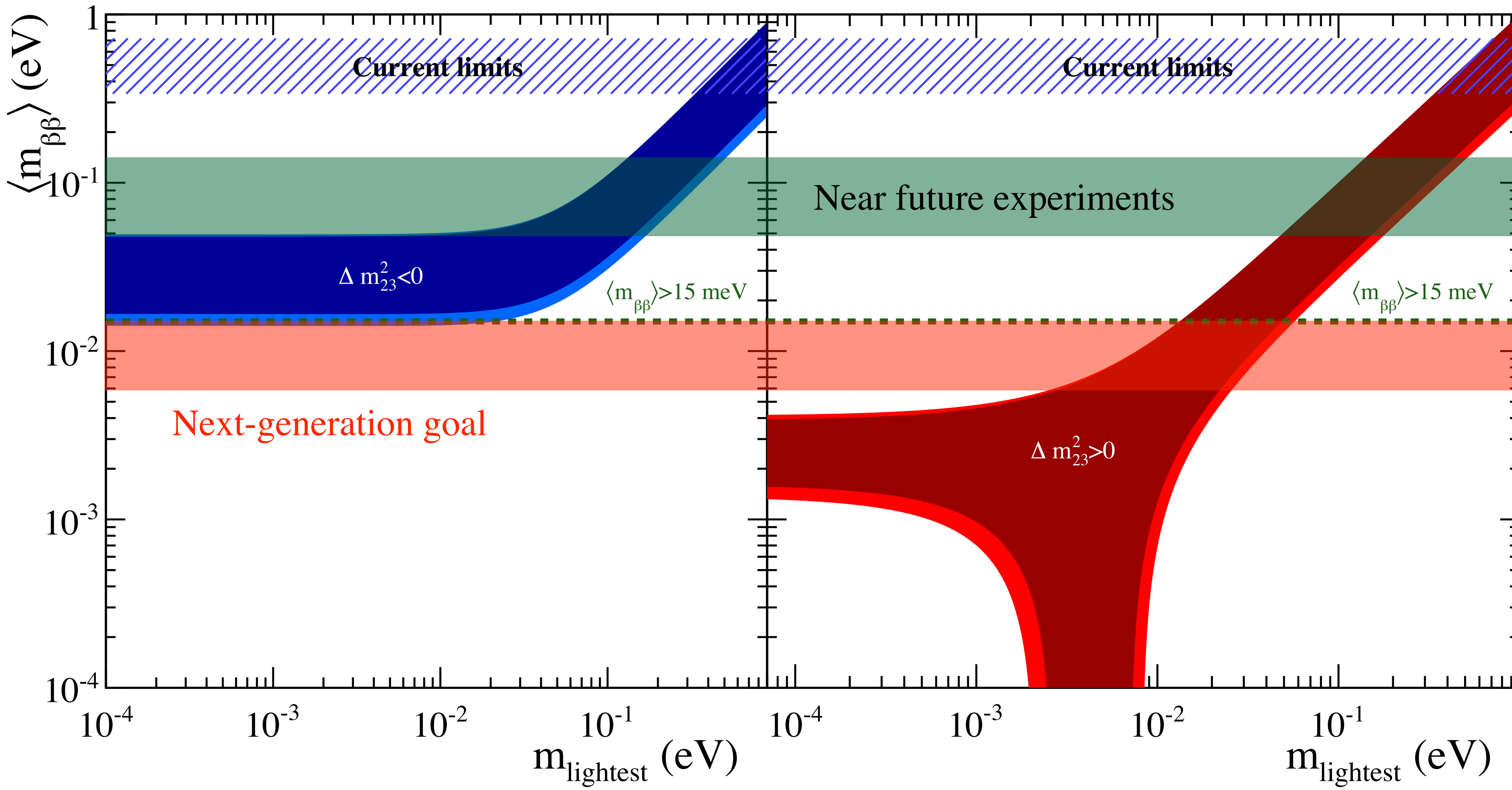
1980 - 2007 | 2007 - 2017 | 2015 - 2025

DBD and Neutrino Mass



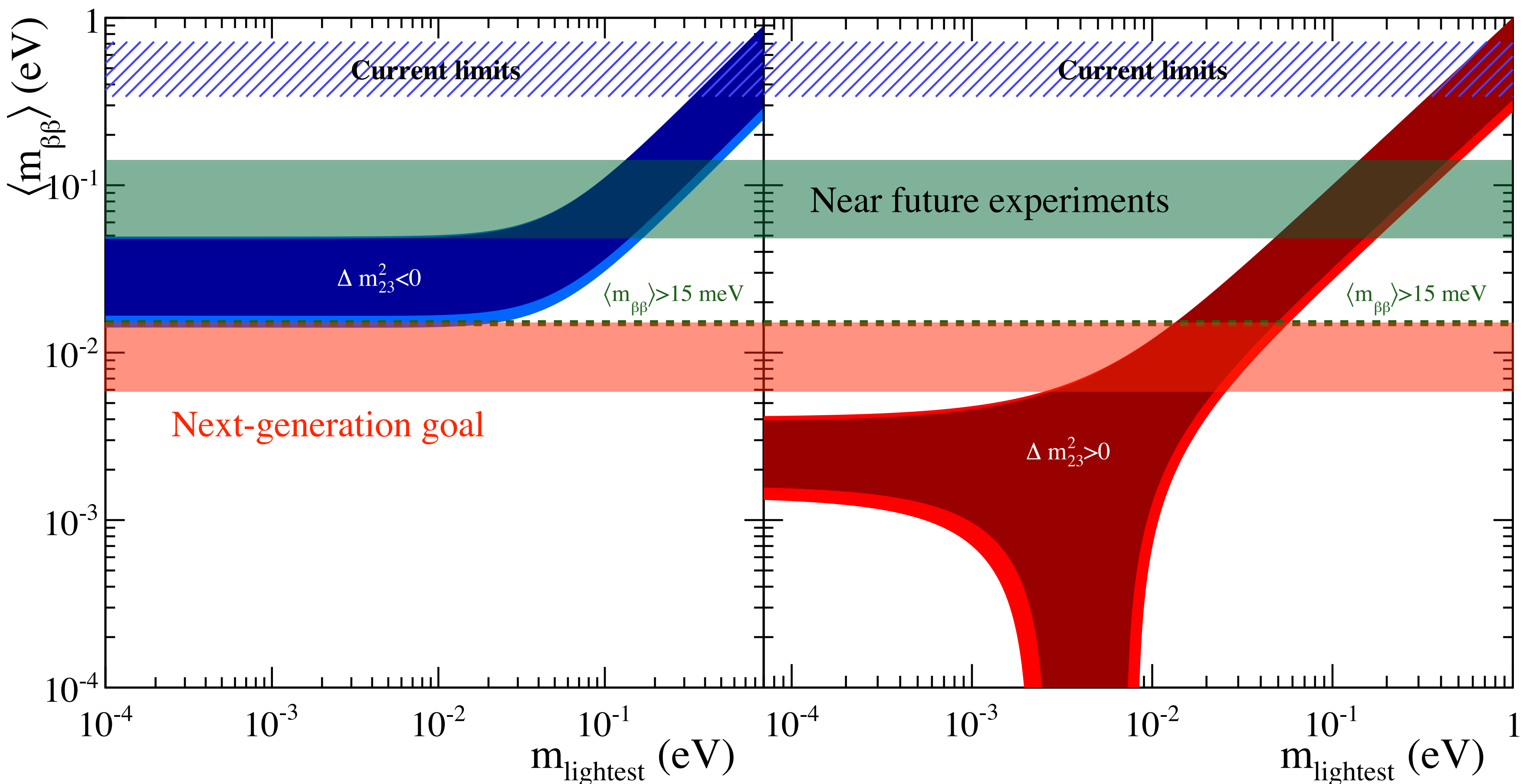
$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

DBD and Neutrino Mass



$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

DBD and Neutrino Mass



Exciting future ahead !

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$