Neutrino Physics: On Earth and in the Heavens

❑ The discovery of neutrino mass

❑ Challenges in the lab: double beta decay, long baseline neutrinos

❑ Challenges in the heavens: the composition of the Sun

Wick Haxton CAP Congress 17 June 2015

Introduction

A great deal of effort and expense has been consumed in recent searches for new physics at the energy frontier

But so far, the specific evidence we have that there is physics beyond the standard model has come primarily from low-energy tests

Neutrino mass and mixing: oscillations of solar and atmospheric neutrinos

Cosmological dark matter: a variety of observations showing that the amount of gravitating mass at various scales is about 7 times the baryonic mass

The former is today's theme, a story with
- exquisitely precise, clean experiments
- persistence, which will continue to be needed …

The Standard Solar Model: Davis to SNO

- ❑ Origin of solar neutrino physics: desire to test a model of low-mass, main-sequence stellar evolution
  - – local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - – hydrogen burning: pp chain, CN cycle
  - – energy transport by radiation (interior) and convection (envelope)
  - – boundary conditions: today's mass, radius, luminosity

- ❑ The implementation of this physics requires
  - – electron gas EOS
  - – low-energy nuclear cross sections
  - – radiative opacity
  - – some means of fixing the composition at ZAMS, including the ratios X:Y:Z

Model tests:

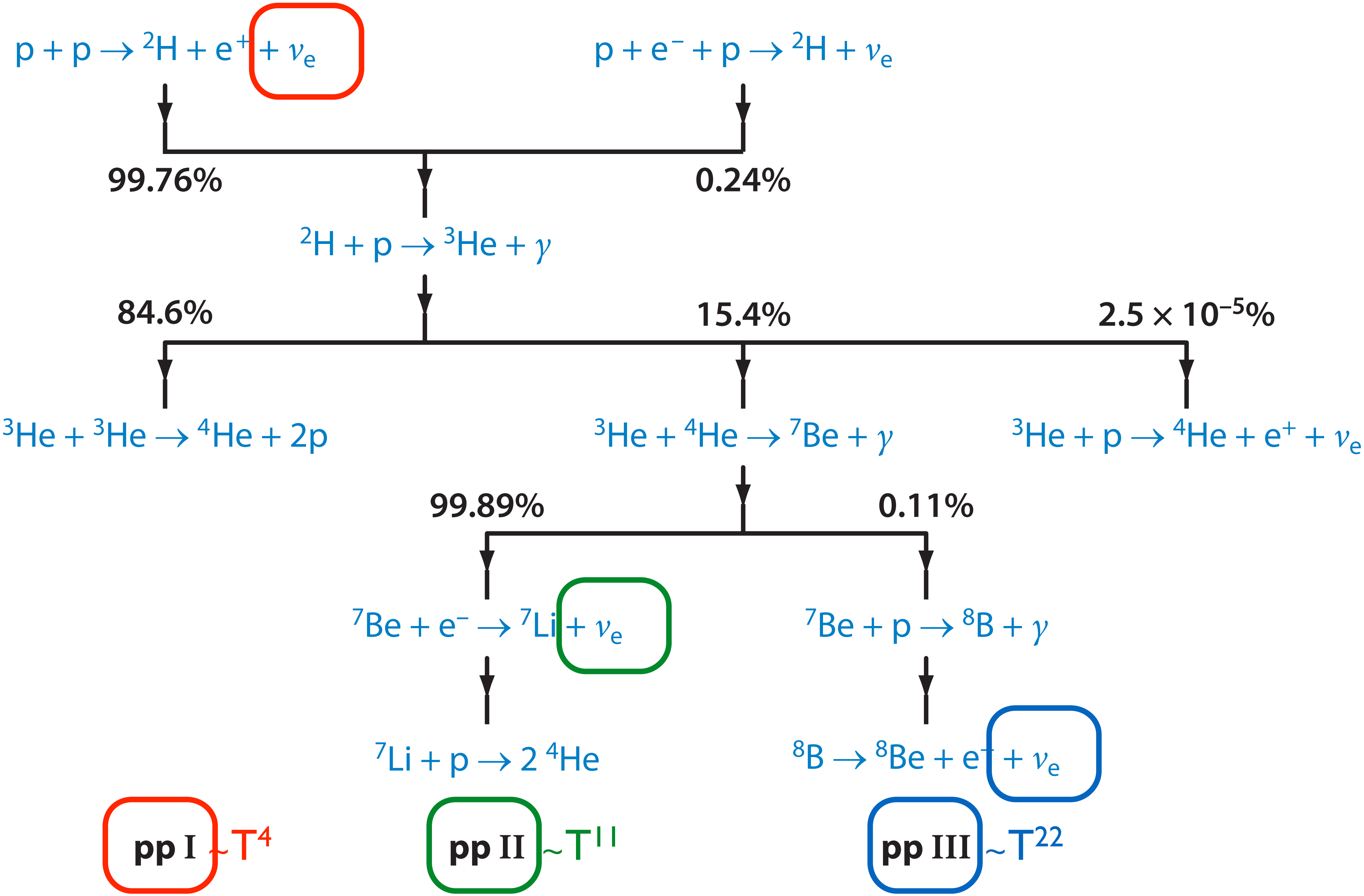
- Solar neutrinos: direct measure of core temperature to ~ 0.5%
  – once the flavor physics has been sorted out

- Helioseismology: inversions map out the local sound speed, properties of the convective zone

As sound speed measurements reached 1% in the 1990s, it became apparent that the SSM was marvelously predictive …

But the story with neutrinos was complicated

$$2e^- + 4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}$$



$\mathrm{p} + \mathrm{p} \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

$\mathrm{p} + e^- + \mathrm{p} \rightarrow {}^2\mathrm{H} + \nu_e$

99.76%

0.24%

${}^2\mathrm{H} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \gamma$

84.6%

15.4%

2.5×10^{-5}%

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\mathrm{p}$

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

${}^3\mathrm{He} + \mathrm{p} \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

99.89%

0.11%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + \mathrm{p} \rightarrow {}^8\mathrm{B} + \gamma$

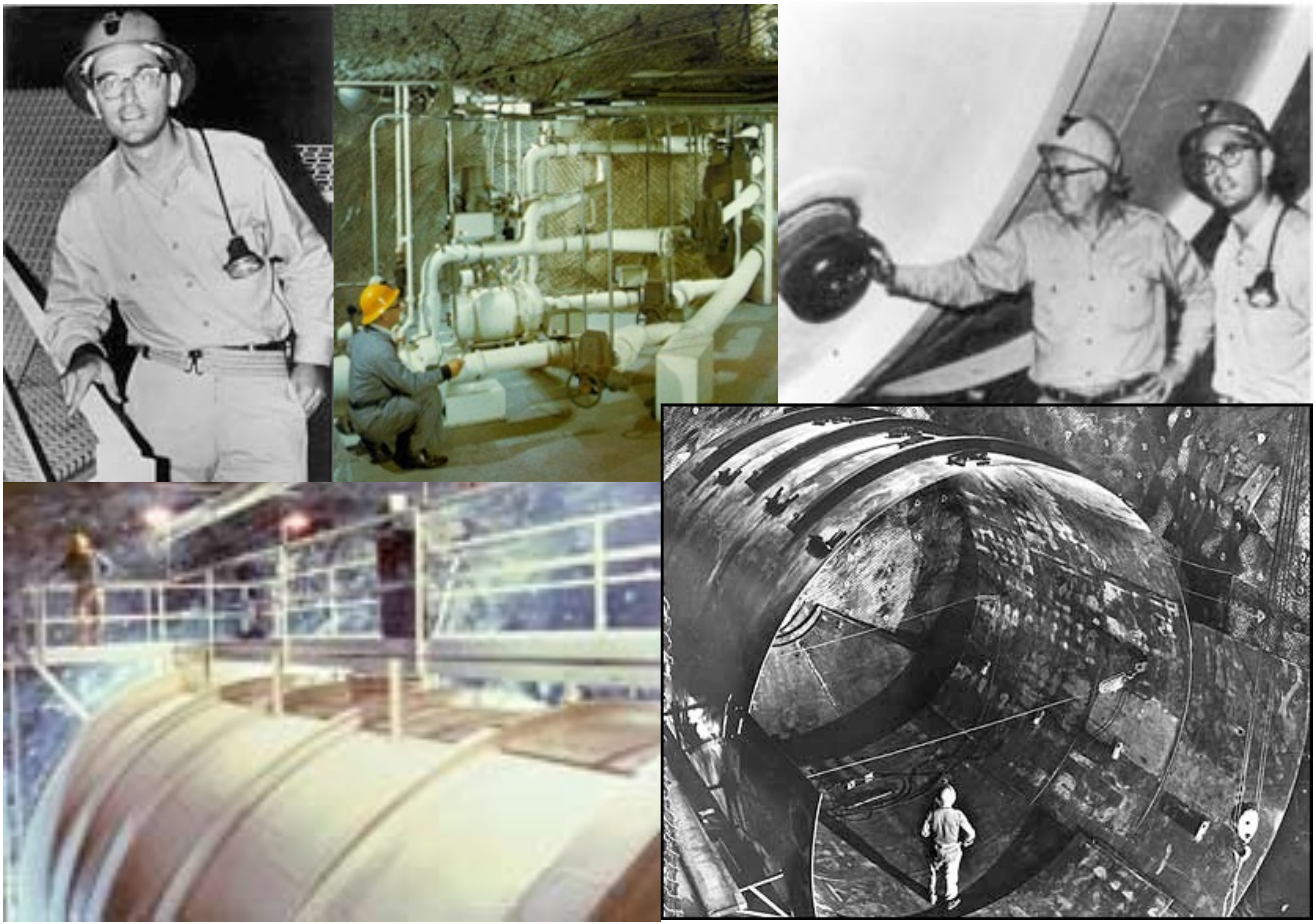
${}^7\mathrm{Li} + \mathrm{p} \rightarrow 2\,{}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + e^+ + \nu_e$

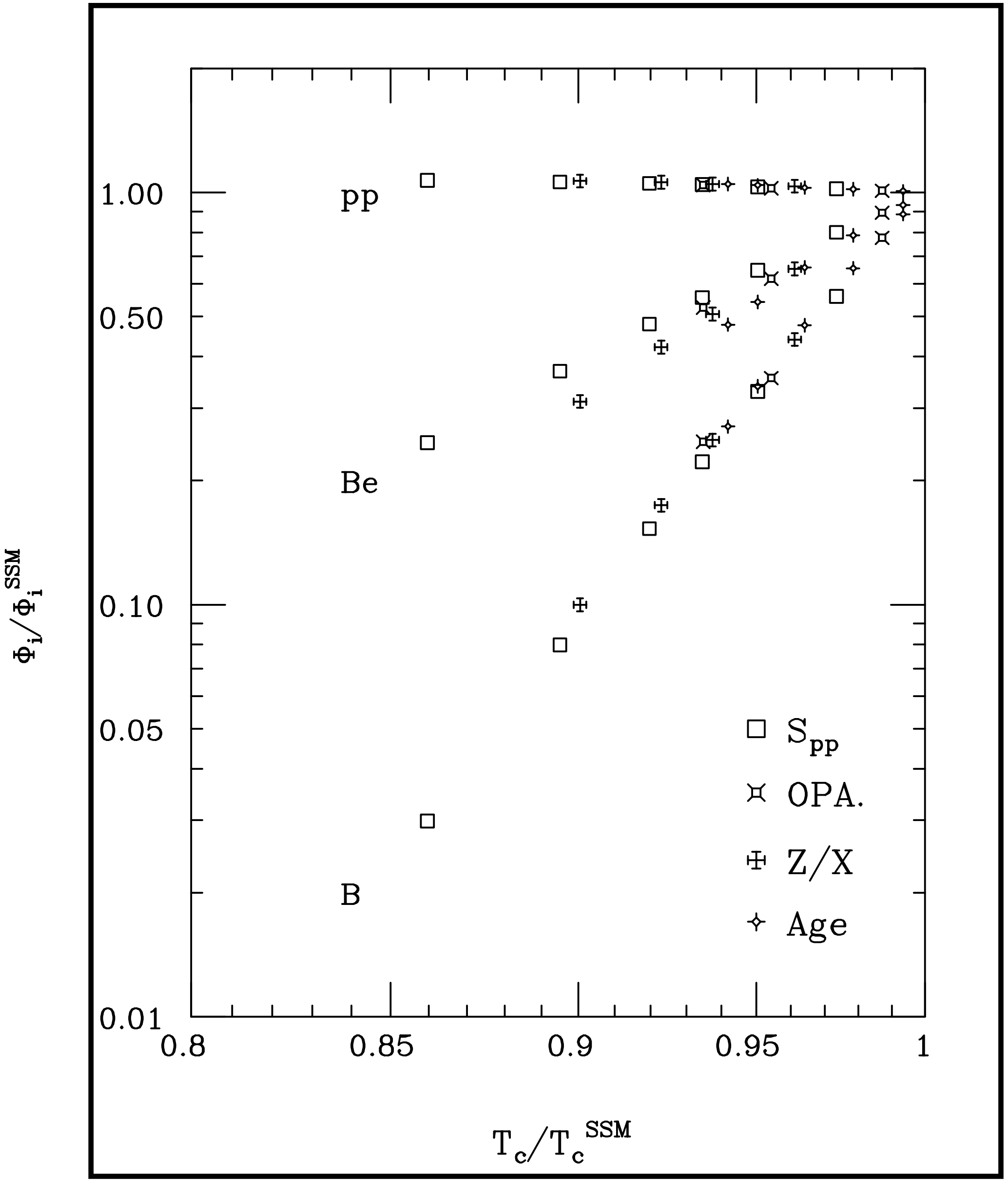
pp I $\sim T^4$

pp II $\sim T^{11}$

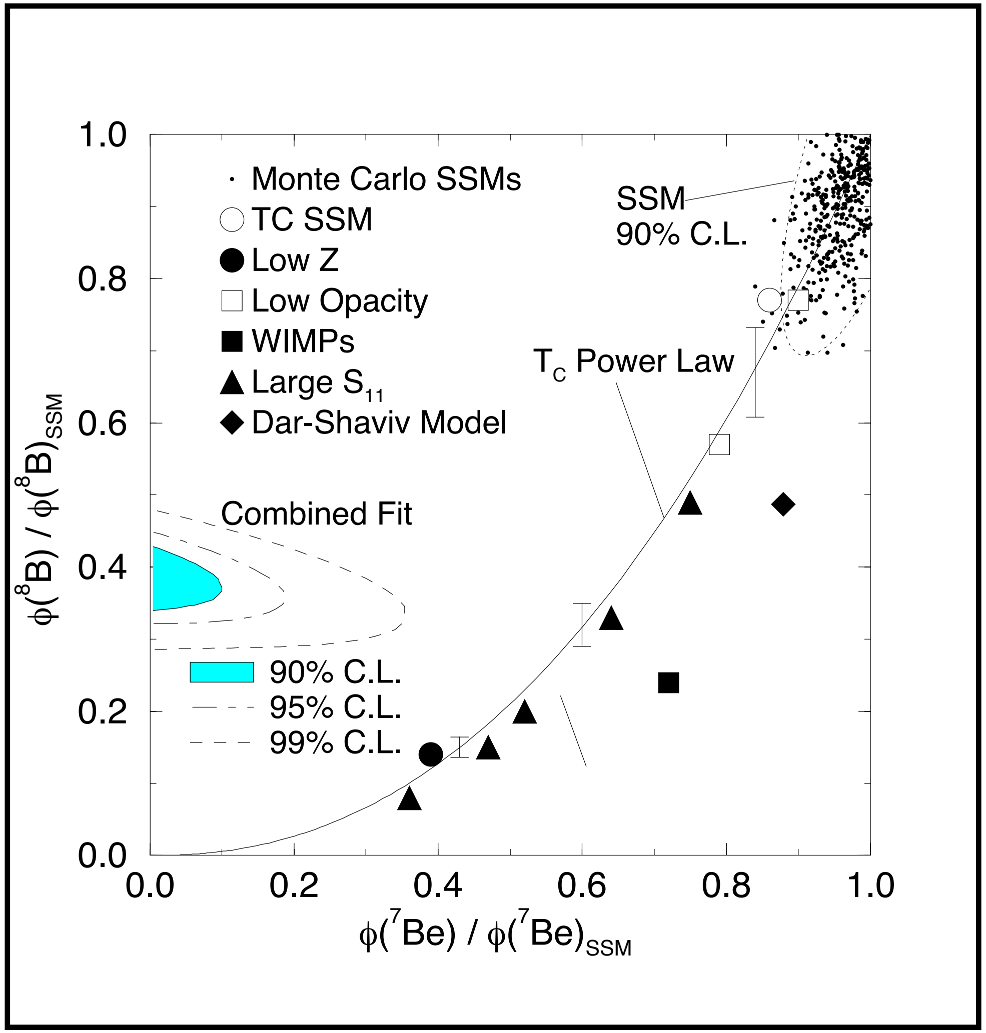
pp III $\sim T^{22}$



By mid-1990s model-independent arguments developed showing that no adjustment in the SSM could reproduce observed ν fluxes (Cl, Ga, water exps.)

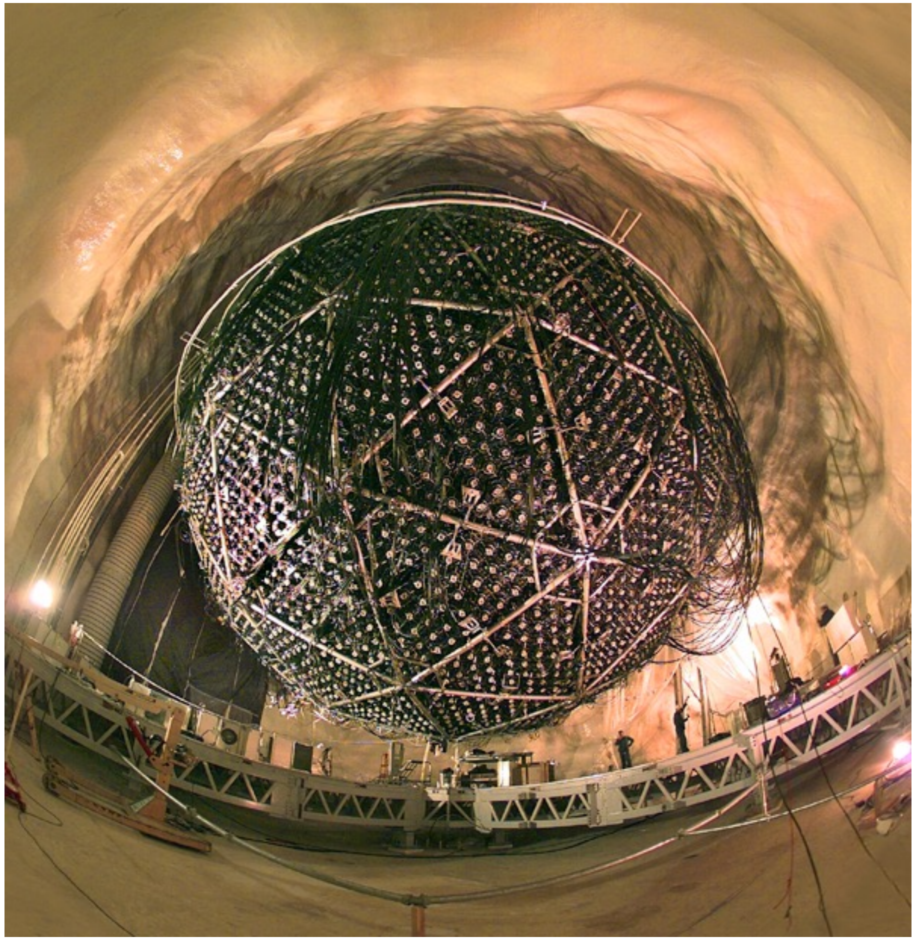


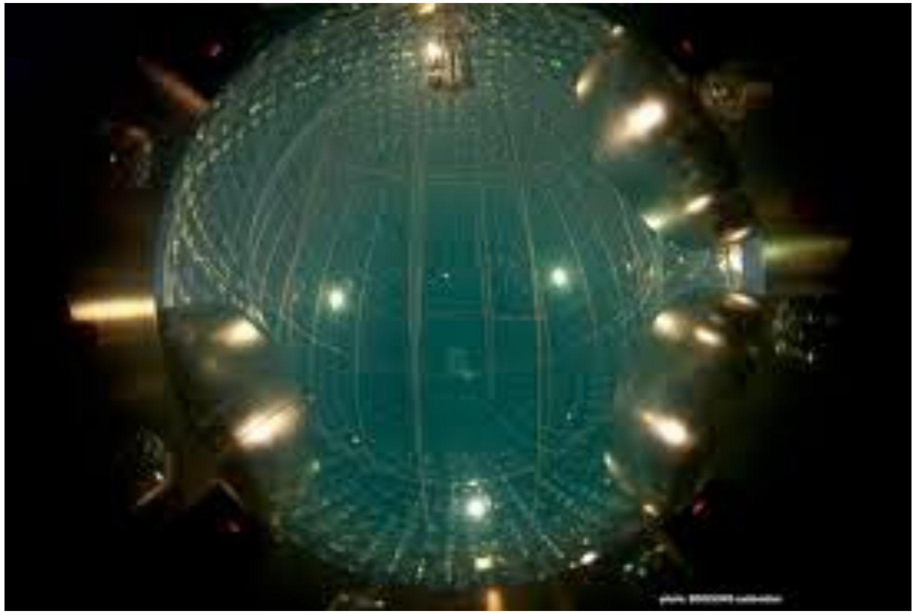
Castellani et al.

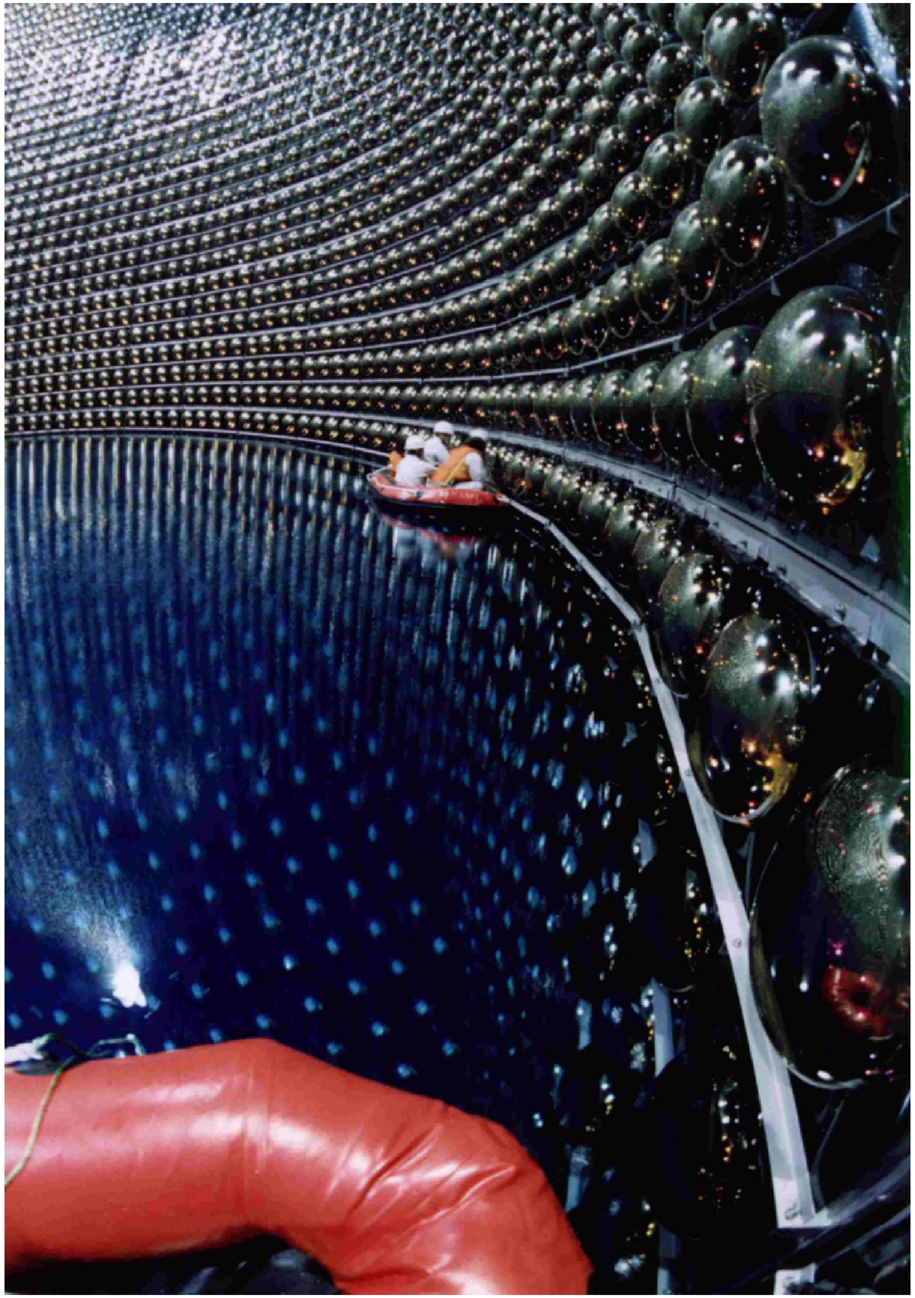


Hata et al.

(and Heeger and Robertson)

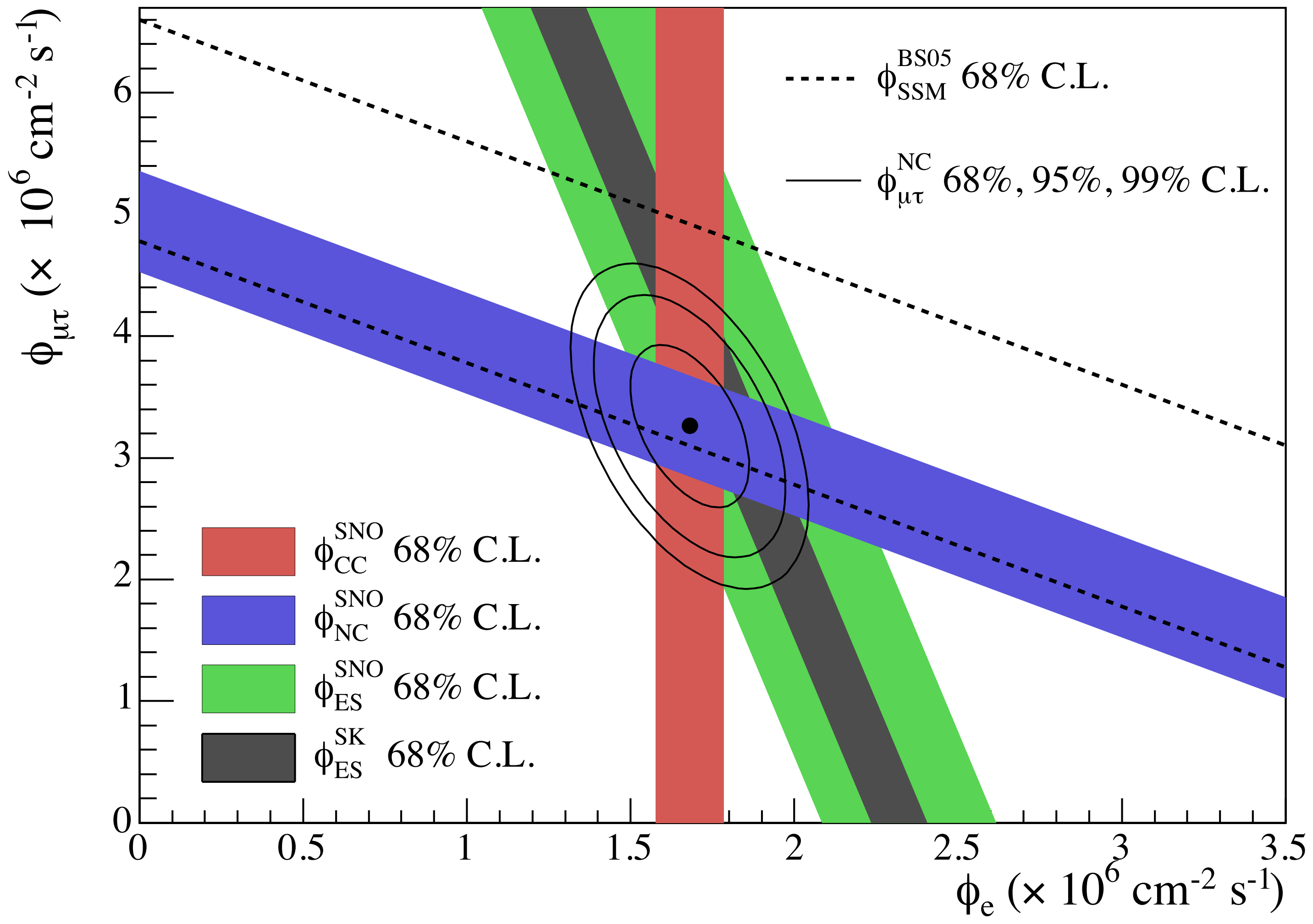






SNO, Super-Kamiokande, Borexino

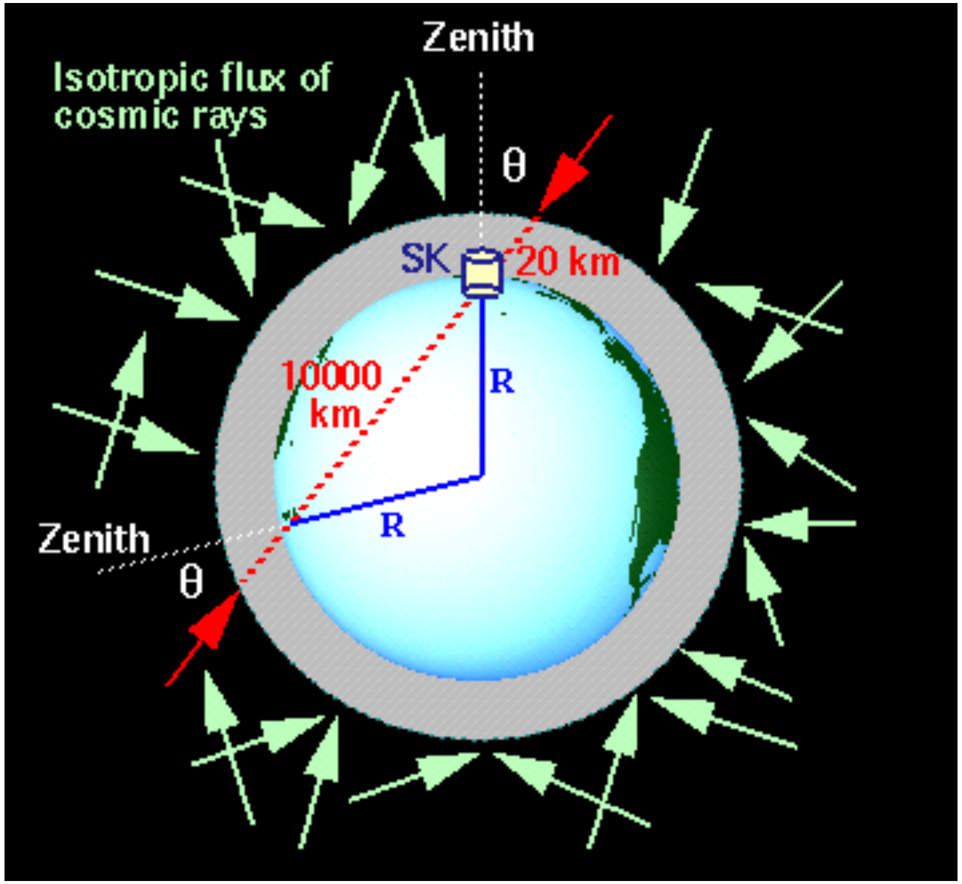
the "solar ν problem" was definitively traced to new physics by SNO flavor conversion $\nu_e \rightarrow \nu_{heavy}$



requires an extension of the SM -- Majorana masses or ν_R

… we will return to this story latter

A very similar problem arose in studies of atmospheric neutrinos — which led to discovery of a second oscillation occurring at shorter distances scales



Neutrino oscillations require a mass (massless particles travel at the speed of light and thus have no "clock")

And they require mixing

$$m_1,\ m_2,\ m_3 \qquad \neq \qquad m_{\nu_e},\ m_{\nu_\mu},\ m_{\nu_\tau}$$

mass eigenstates $\neq$ flavor eigenstates
(eigenstates of free propagation) (production eigenstates)

$$|\nu_e\rangle = \sum_i U_{ei}|\nu_i\rangle$$

e.g., for the mixing of just two flavors ,

$$\begin{aligned} |\nu_e\rangle &= \quad \cos\theta_{12}|\nu_1\rangle + \sin\theta_{12}|\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin\theta_{12}|\nu_1\rangle + \cos\theta_{12}|\nu_2\rangle \end{aligned}$$

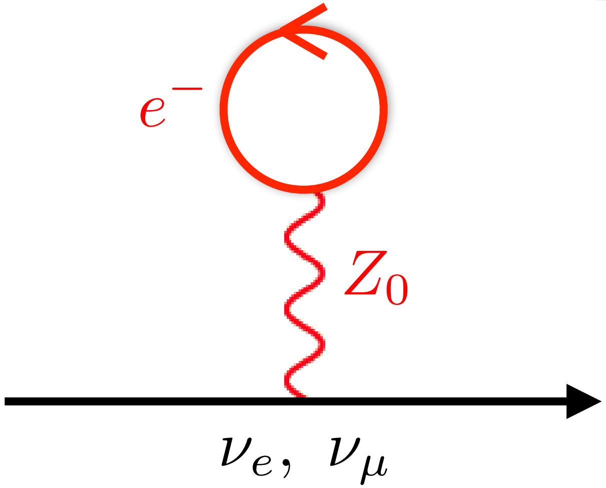
Then it is straightforward to show, for a coherent localized neutrino wave packet

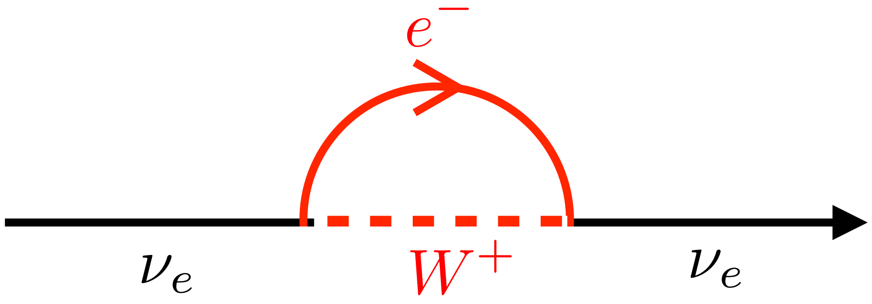
$$|\nu(t=0)\rangle = |\nu_e\rangle \quad \Rightarrow \quad P_{\nu_\mu}(t) = |\langle \nu(t)|\nu_\mu\rangle|^2 \sim \sin^2 2\theta_{12}\ \sin^2 \frac{\pi c t}{L_0}$$

$$L_0 = \frac{4\pi\ \hbar c\ E_\nu}{\delta m^2_{21} c^4} \qquad \delta m^2_{21} = m^2_2 - m^2_1$$

It was also discovered (the MSW mechanism) that in matter

$$\delta m^2_{21} \ \Rightarrow\ \delta m^2_{21}(\rho)$$





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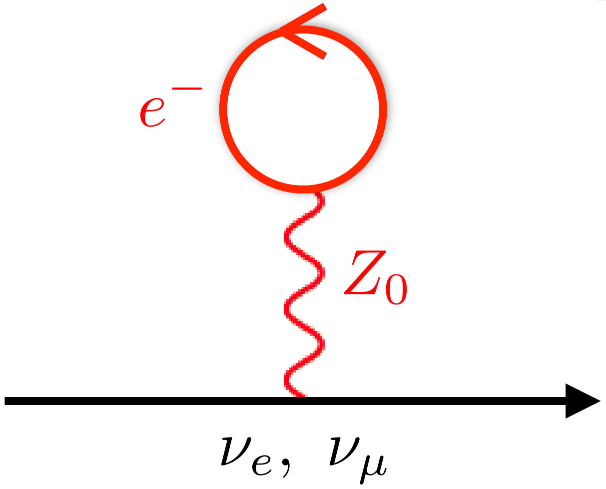
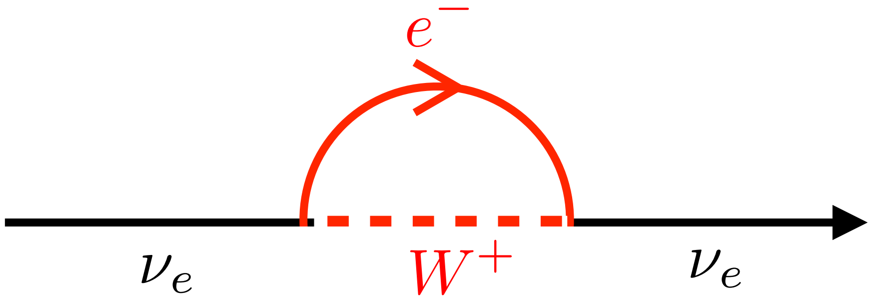
$$\delta m_{21}^2 \ \Rightarrow \ \delta m_{21}^2(\rho)$$



makes the ν_e heavier in matter



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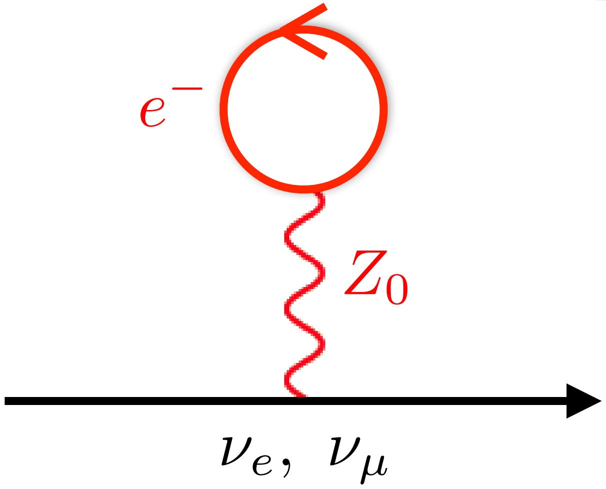
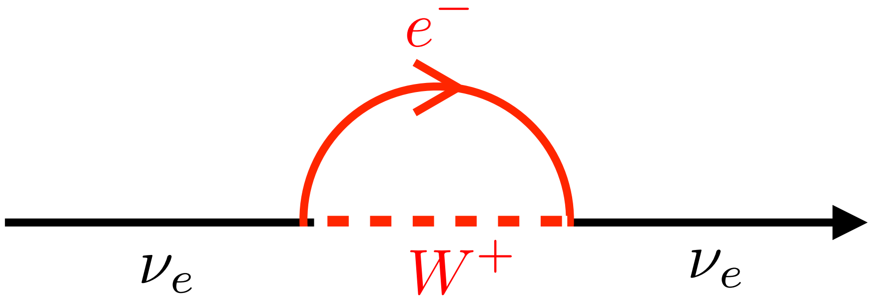
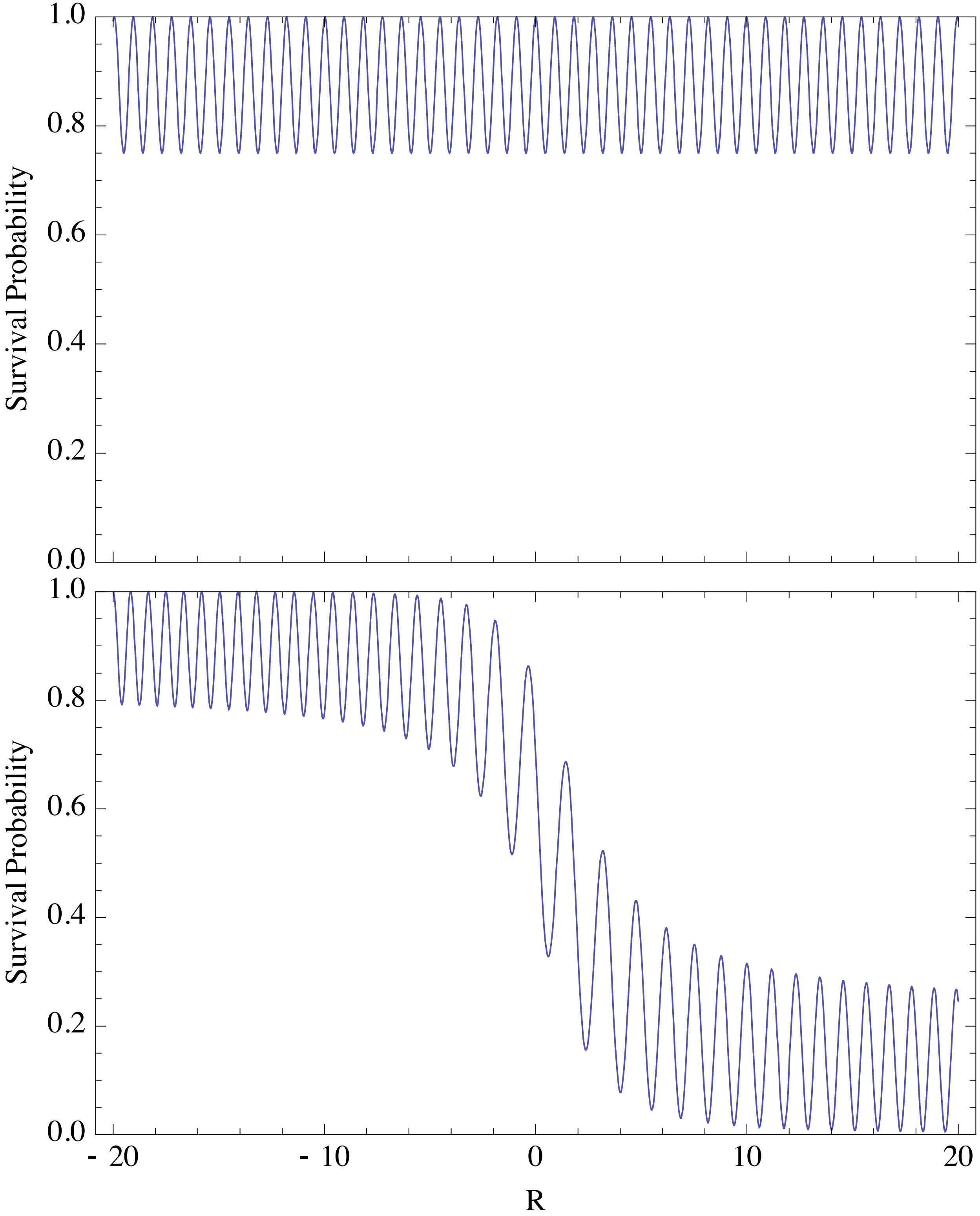


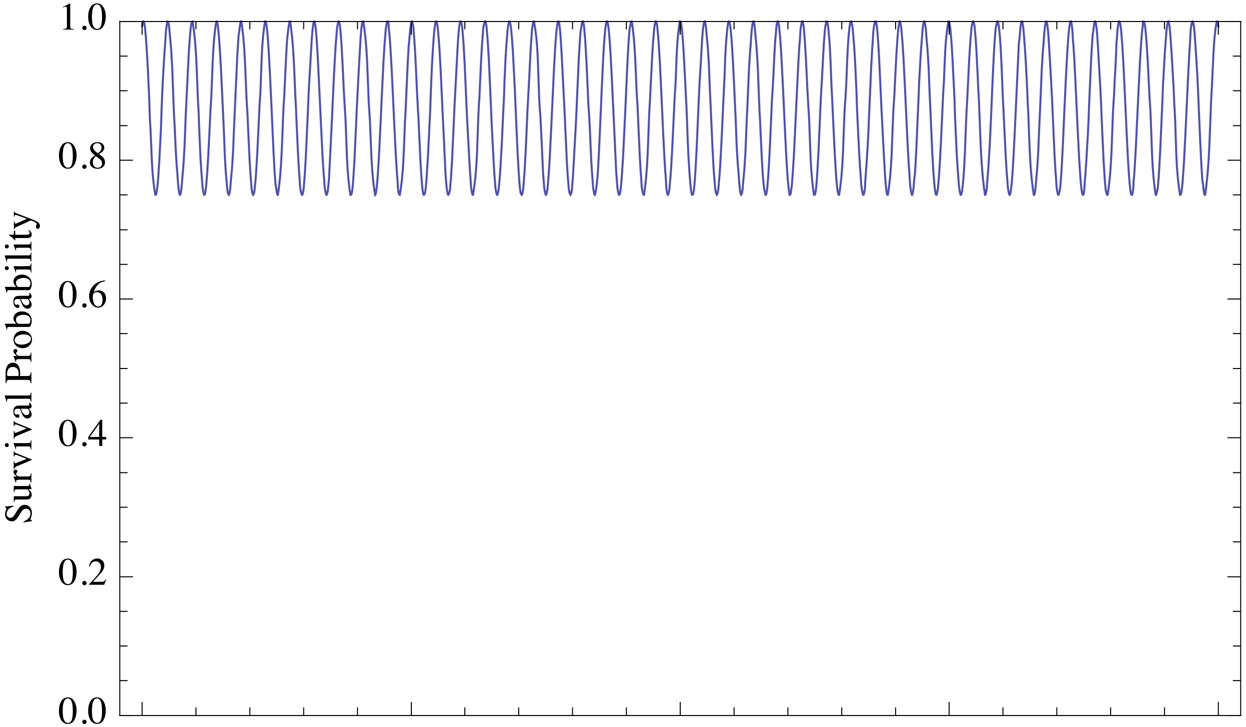
alters $\delta m^2_{12}(\rho)$





vacuum
oscillations

solar MSW
oscillations



vacuum
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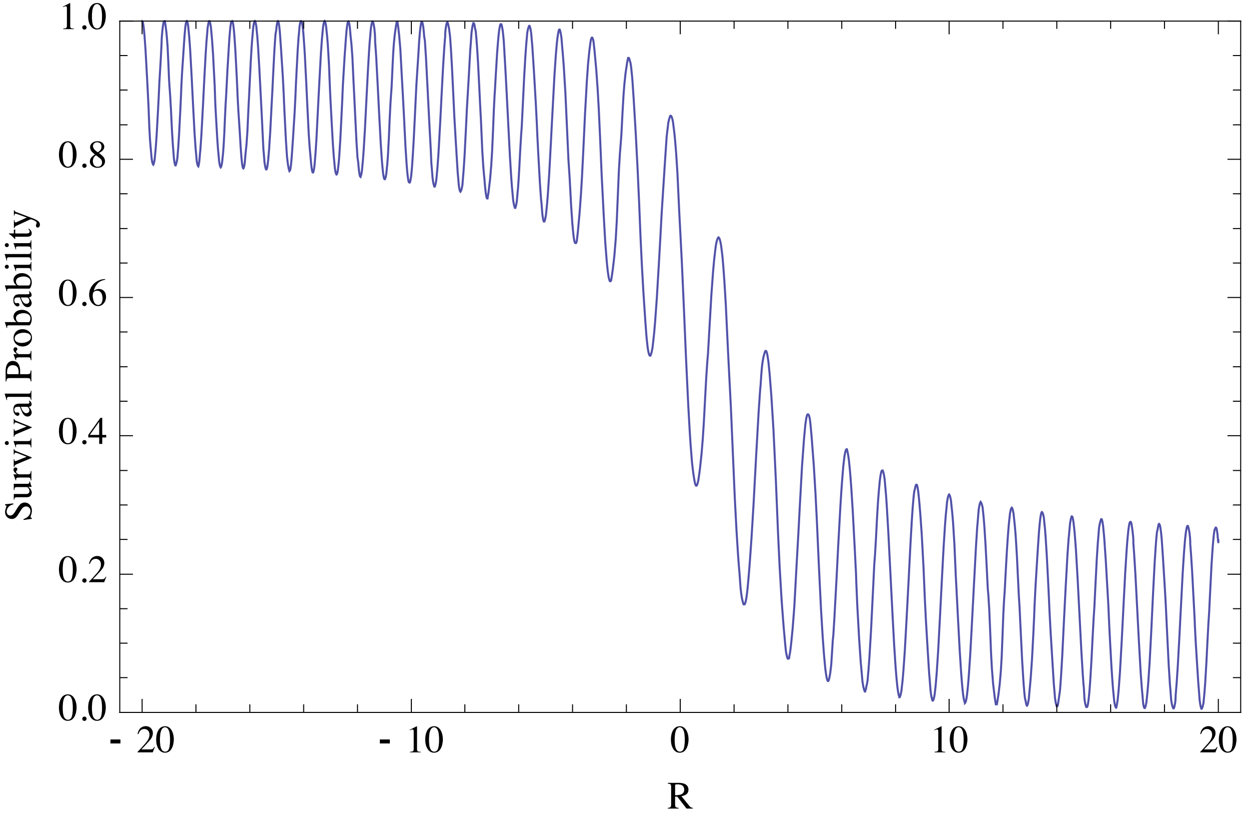


solar MSW
oscillations
altered if $m_2 > m_1$

Why is the discovery of neutrino mass important? ,

The answers weave together several issues, and a bit of history

- Neutrinos are different from other standard-model fermions in lacking a charge or other additively conserved quantum number

  what distinguishes ν from $\bar{\nu}$?

- Now that we know they have a mass, why is that mass so much smaller than other masses?

- A related long-lived nuclear decay mode, double beta decay

- 1930: Pauli's suggests a “neutrino” accompanies the electron in β decay
- 1932: Chadwick's discovery of the “neutron”
- 1934: Fermi's incorporation of both in his “effective theory” of β decay

$$n_{\text{bound}} \to p_{\text{bound}} + e^- + \bar{\nu}_e$$

- 1935: M. Goppert-Mayer describes “double β disintegration”

$$2n_{\text{bound}} \to 2p_{\text{bound}} + 2e^- + 2\bar{\nu}_e$$

- 1937: Majorana suggests that

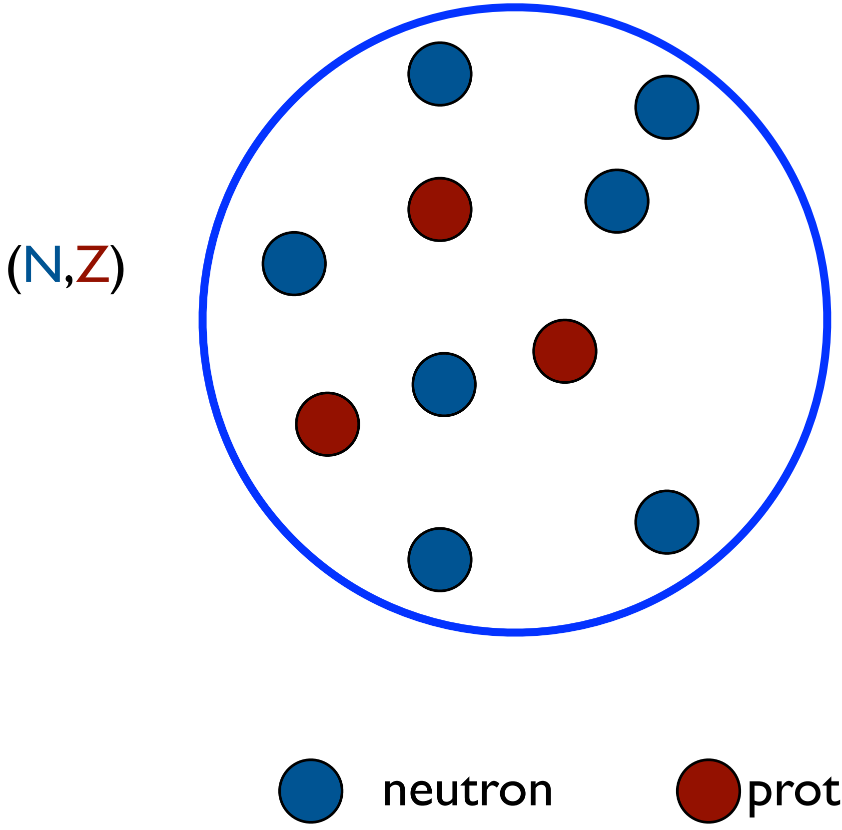
$$\nu_e \equiv \bar{\nu}_e$$





In the same year Giulio Racah pointed out that Majorana's new theory would lead to a second form of ββ decay -- a neutrinoless type

$$2n \rightarrow 2p + 2e^-$$



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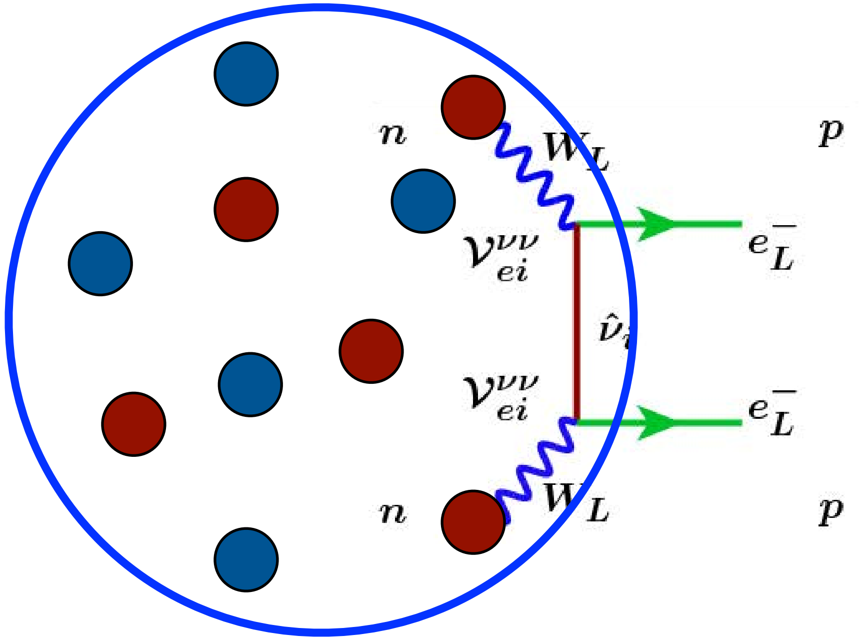
$$2n \rightarrow 2p + 2e^-$$

(N,Z)



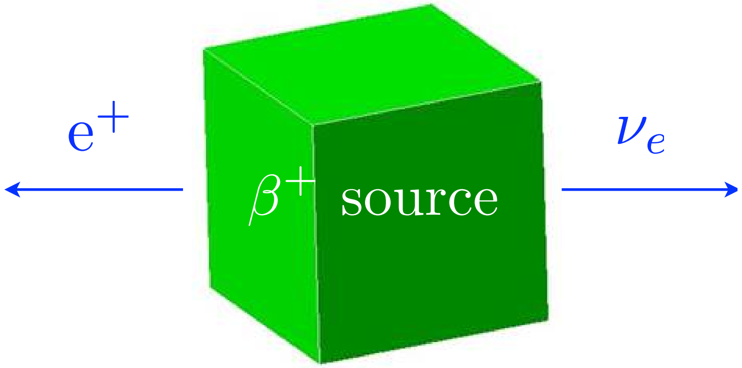
● neutron ● proton

Lepton Number: Are the Neutrino and Antineutrino distinct?

For many years it was thought that this issue was decided:

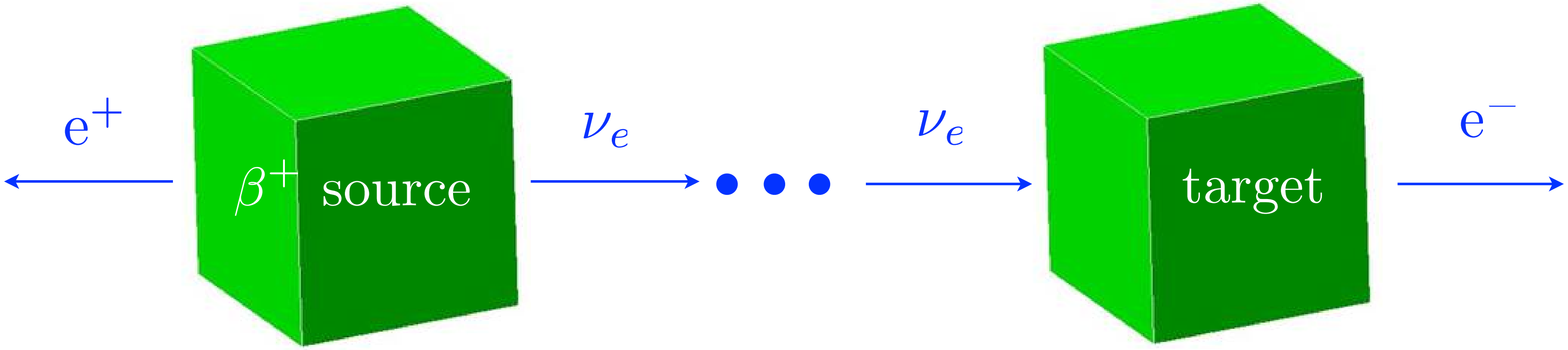
despite the lack of an obvious distinguishing quantum number, $\nu \perp \bar{\nu}$

we do a “thought” experiment (implicitly assumes a massless neutrino)



this defines the ν_e

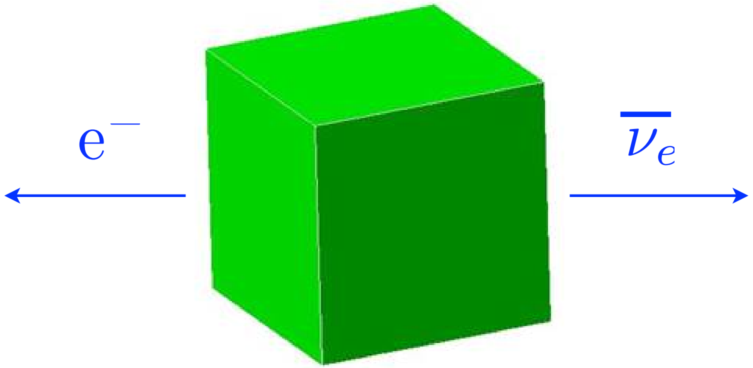
then allow it to interact in a target



this defines the ν_e

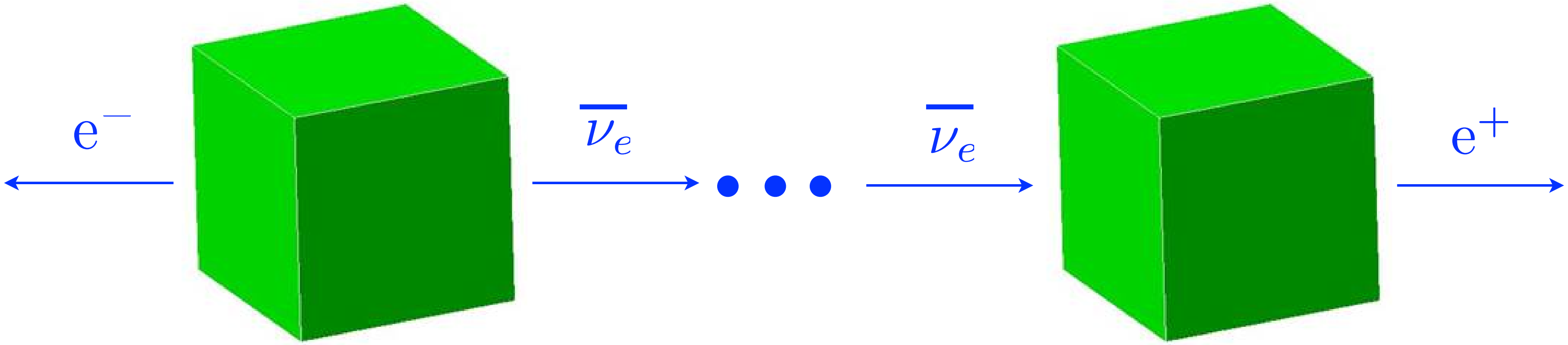
finding an e^- is produced

and then a second experiment



this defines the $\bar{\nu}_e$

allow it to interact in a target



this defines the $\bar{\nu}_e$

finding an e^+ is produced

- with these definitions of the ν_e and $\bar{\nu}_e$, they appear operationally distinct, producing different final states

- introduce a lepton “charge” to distinguish the neutrino states and to define the allowed reactions, by the additive conservation law

$$\sum_{\text{in}} \mathbf{l_e} = \sum_{\text{out}} \mathbf{l_e}$$

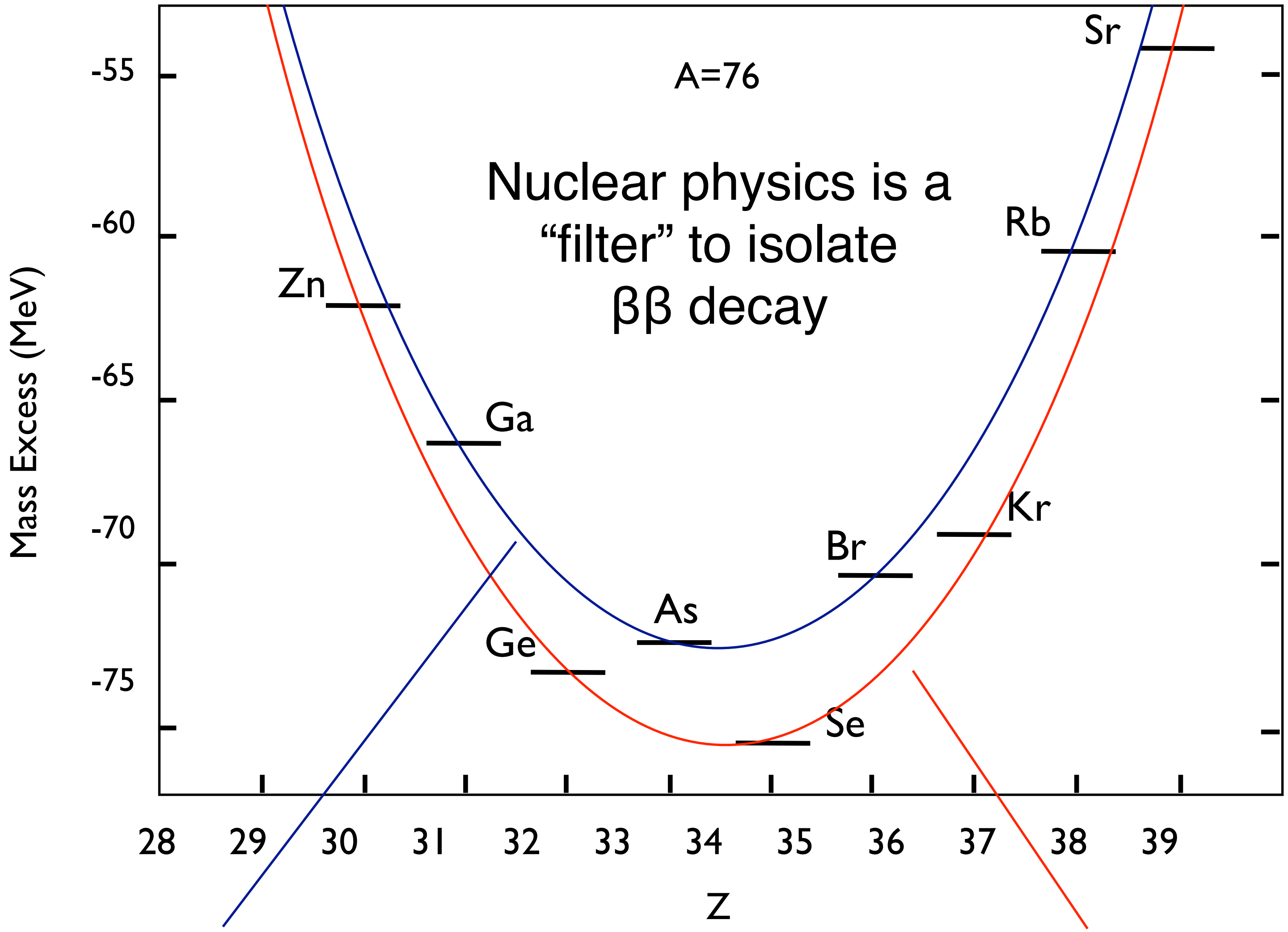
$lepton$	l_e
e^-	$+1$
e^+	-1
ν_e	$+1$
$\bar{\nu}_e$	-1

Dirac neutrino

$$\nu_e \perp \bar{\nu}_e \quad \Rightarrow \quad \text{Dirac neutrino}$$

$$\nu_e = \bar{\nu}_e \quad \Rightarrow \quad \text{Majorana neutrino}$$

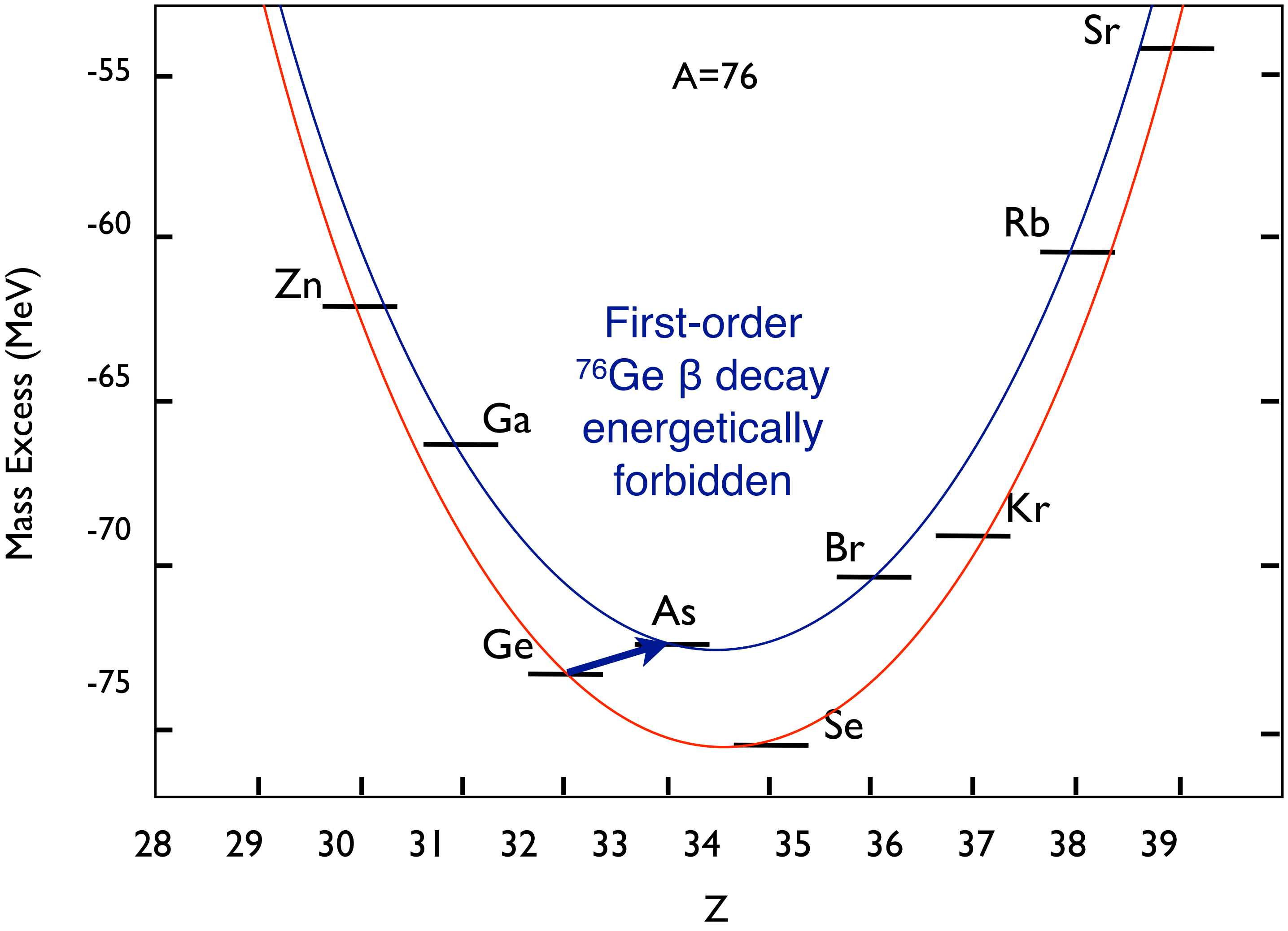
Implications for ββ decay?

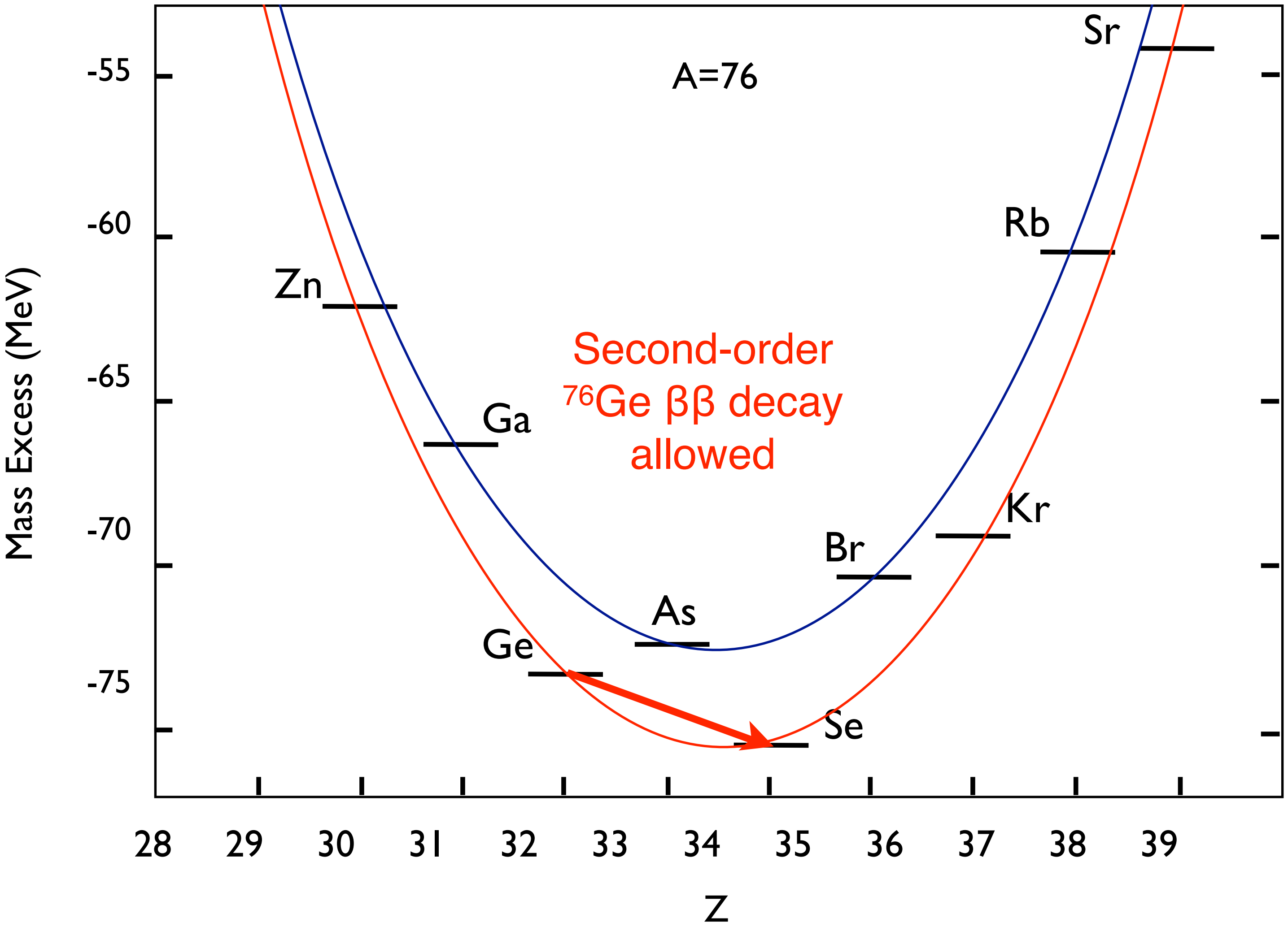


Nuclear physics is a “filter” to isolate ββ decay

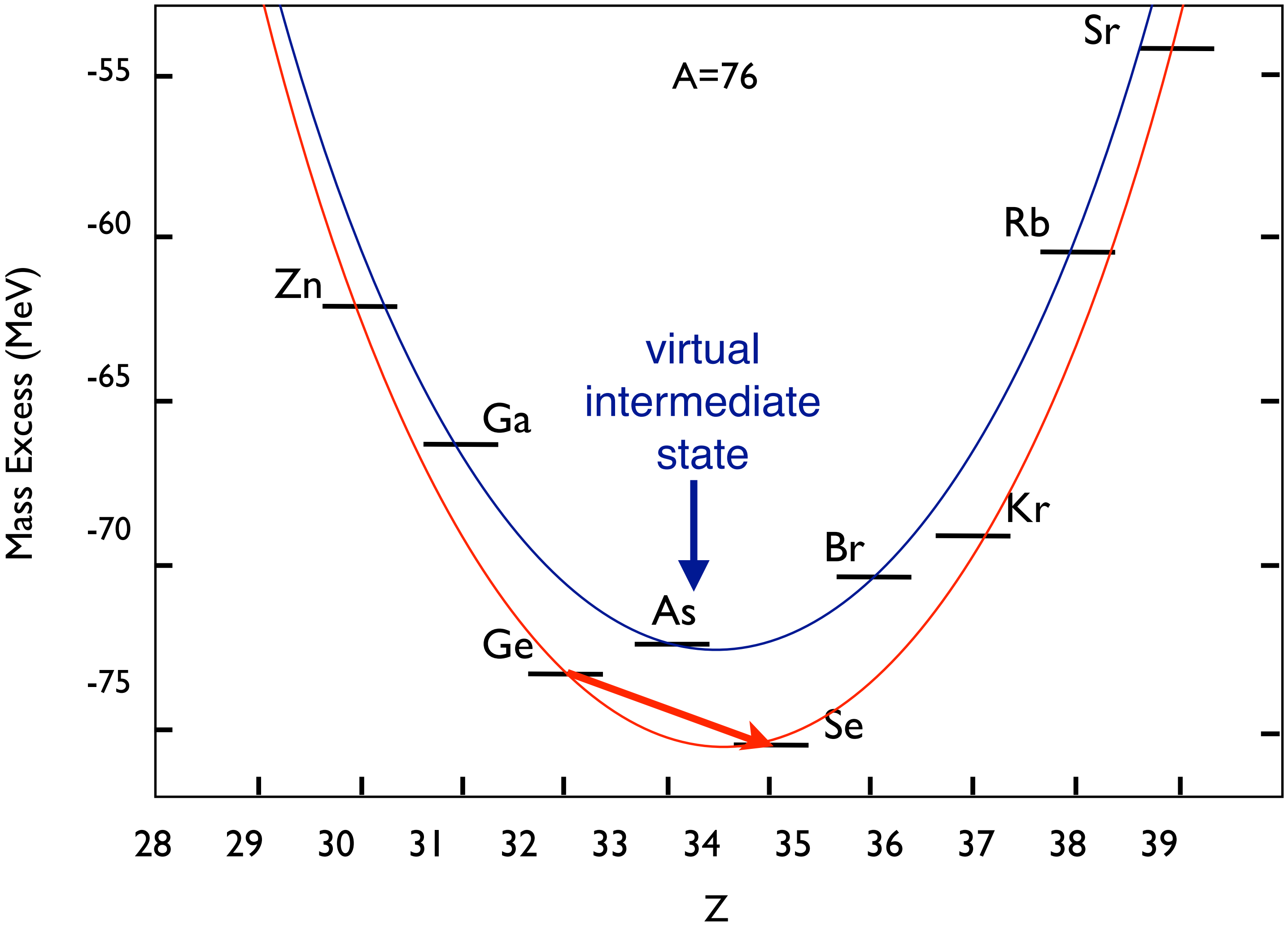
Odd N and Z nuclei:
two broken pairs

Even N and Z nuclei:
attractive pairing force


A=76
First-order
^{76}Ge β decay
energetically
forbidden
Zn
Ga
Ge
As
Se
Br
Kr
Rb
Sr
Mass Excess (MeV)
-55
-60
-65
-70
-75
28
29
30
31
32
33
34
35
36
37
38
39
Z



About 50 cases where nuclear physics isolates very rare, second-order weak interactions



About 50 cases where nuclear physics isolates very rare, second-order weak interactions

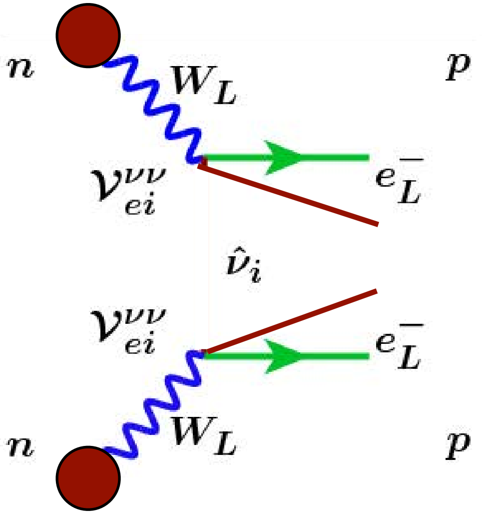
2ν ββ decay occurs regardless of whether $\nu = \bar{\nu}, \quad \nu \perp \bar{\nu}$

$$(N,Z) \to (N-1,Z+1) + e^- + \bar{\nu}_e$$

$$(N-1,Z+1) \to (N-2,Z+2) + e^- + \bar{\nu}_e \quad \Rightarrow$$

$$(N,Z) \to (N-2,Z+2) + 2e^- + 2\bar{\nu}_e$$

lepton-number conserving

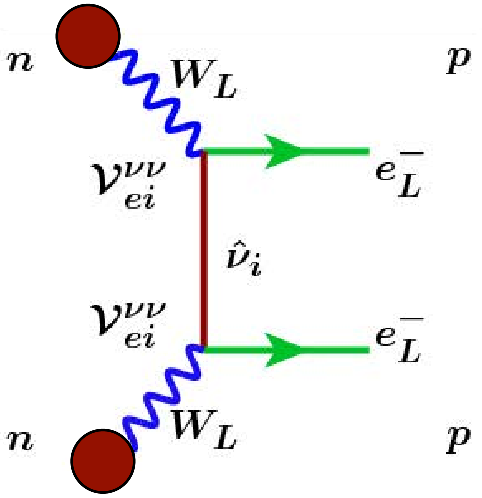


0ν ββ decay is effectively the experiment we just finished describing

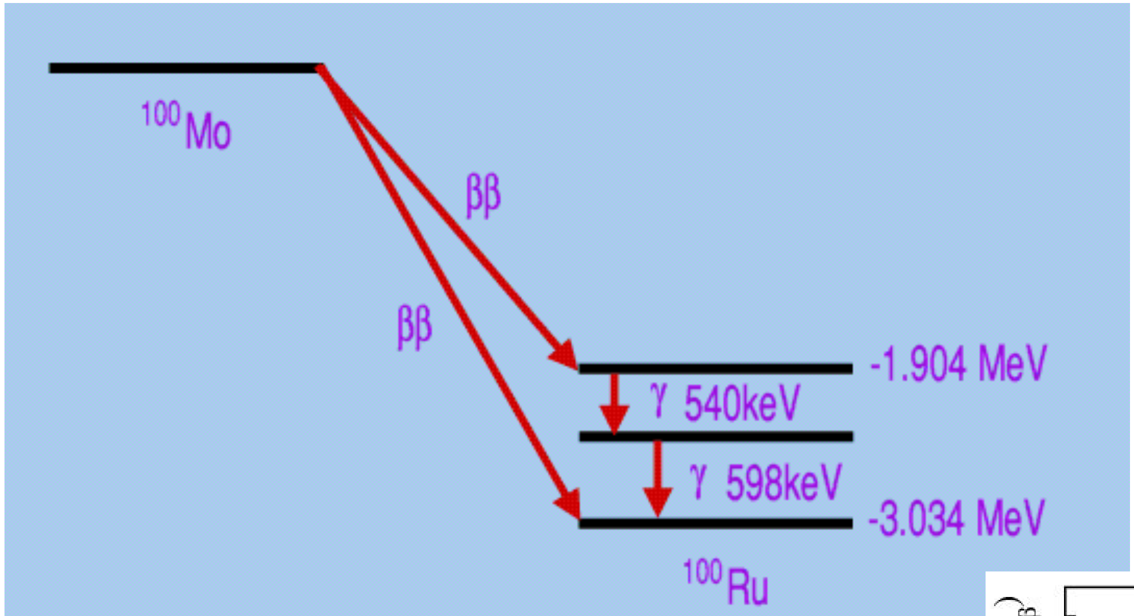
$$(N,Z) \to (N-1,Z+1) + e^- + \bar{\nu}_e$$

$$\bar{\nu}_e + (N-1,Z+1) \not\to (N-2,Z+2) + e^- \quad \Rightarrow$$

$$(N-1,Z+1) \not\to (N-2,Z+2) + 2e^-$$



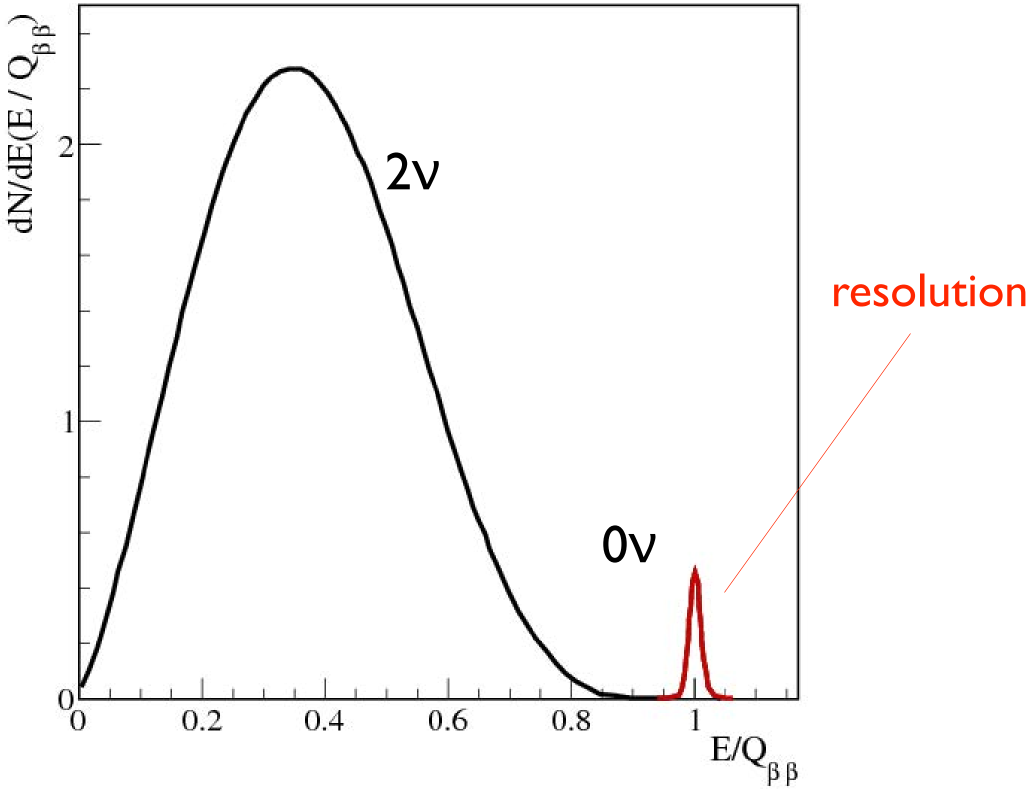
lepton-number violating - and ruled our experimental “results”



The two ββ decay modes can be distinguished in experiments

spectrum of summed energy for the two outgoing electrons:

with good detector energy resolution, the 0ν and 2ν modes can be separated



The Discovery of Parity Violation

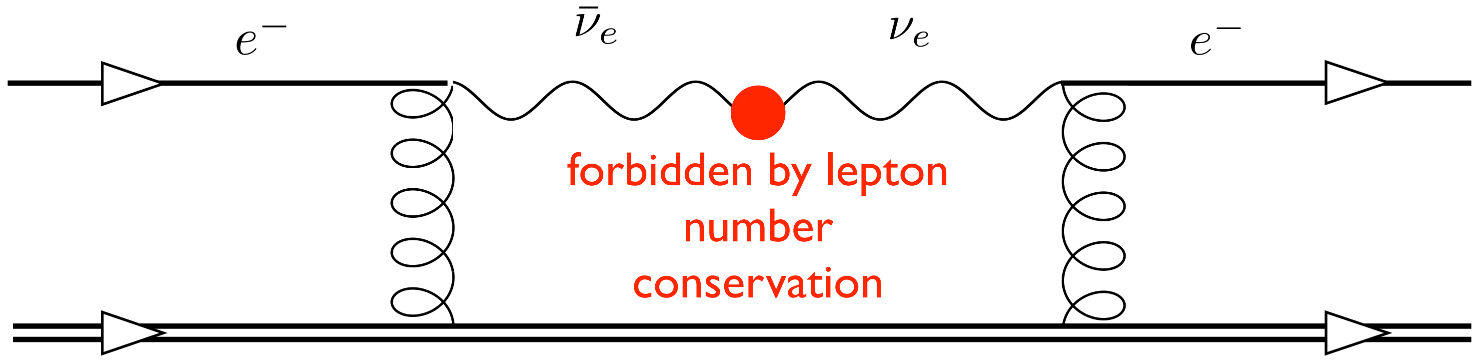
This simple picture — that the absence of neutrinoless double beta decay implies the neutrino must be Dirac — changed in 1957

Lee and Yang pointed out the likelihood that parity was violated, and that violation was quickly confirmed in experiments

In particular, Goldhaber, Grodzins, and Sunyar showed that the neutrino had a definite handedness, to the accuracy this could be measured (*maximal* parity violation)

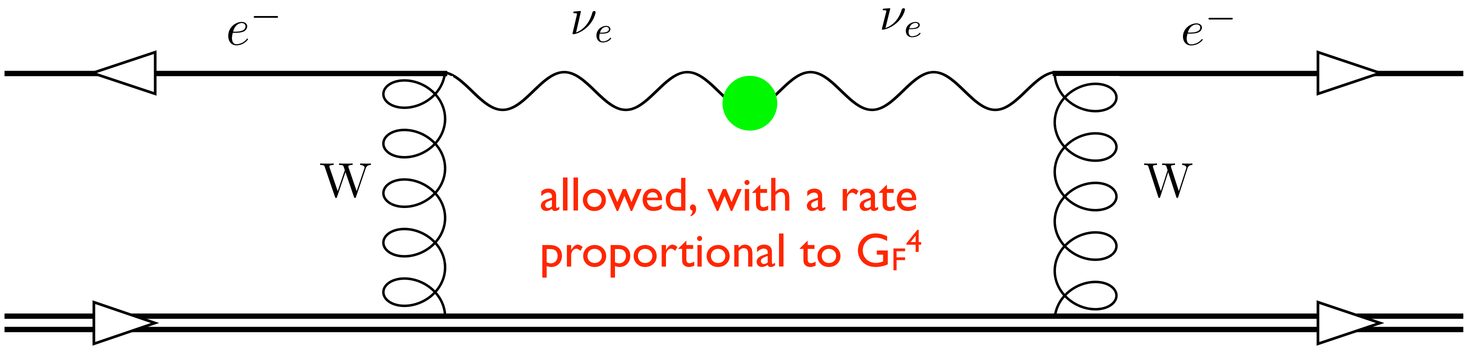
Reconsider our experiments with massless neutrinos

If there is a conserved lepton number



forbidden by lepton number conservation

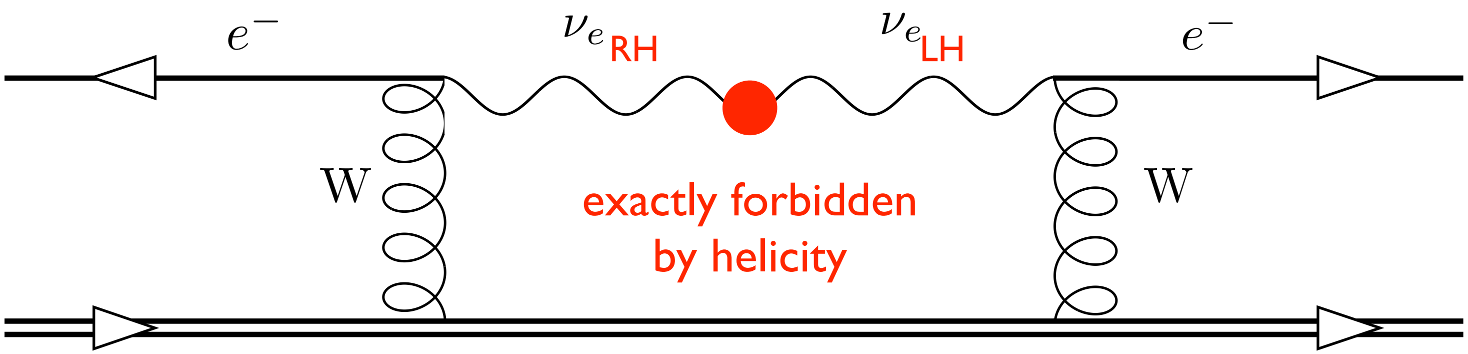
Remove the restriction of an additively conserved lepton number



allowed, with a rate proportional to G_F^4

conflicts with experimental upper bounds on rates

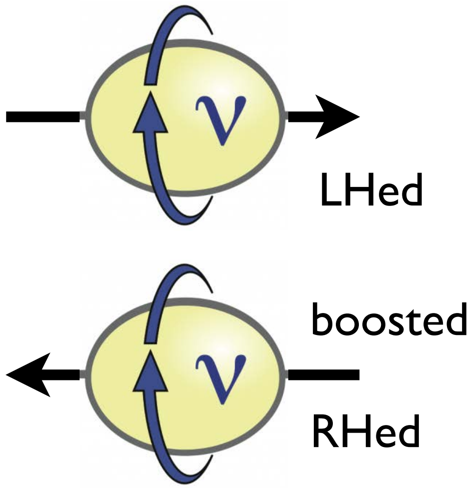
But if the ν and anti-ν have distinct handedness, nothing about lepton number can be concluded

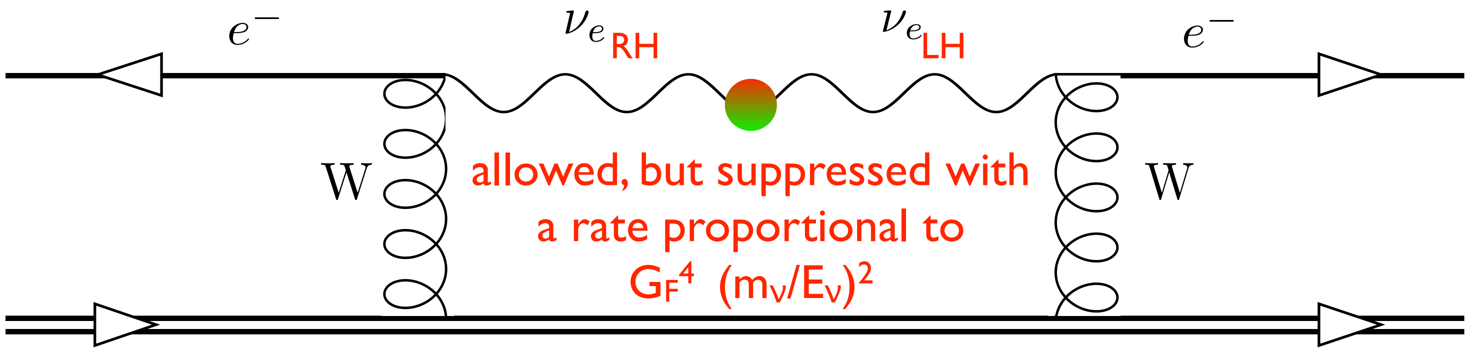


Sadly, then, this process would tell us nothing about the v's Dirac/ Majorana character

ββ Decay with Massive Neutrinos

If neutrinos have mass, helicity is not a particle label: it can be reversed by jumping to a moving frame





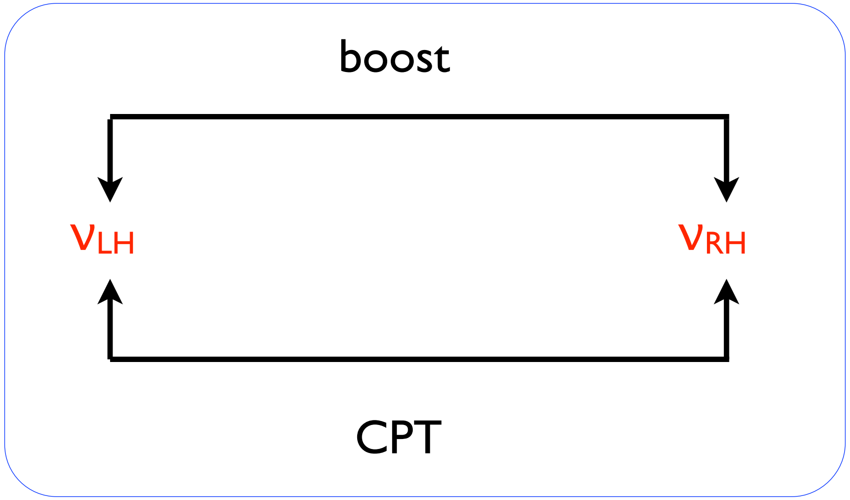
allowed, but suppressed with a rate proportional to $G_F^4\ (m_\nu/E_\nu)^2$

neutrino mass restores $\beta\beta$ decay as a definitive test of lepton number violation, though with a rate suppressed by $(m_\nu/E_\nu)^2$ where $E_\nu \sim 1/R_{\mathrm{nuclear}}$

the *Majorana ν mass* plays two roles, removing helicity as a label and providing the source of the lepton number violation

We have been discussing two limits for describing massive neutrinos

Majorana:

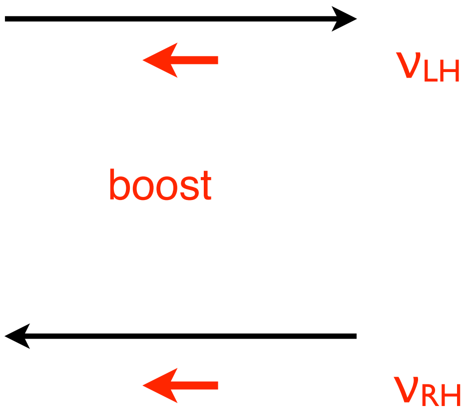


boost

ν_{LH} ν_{RH}

CPT

Lorentz invariance

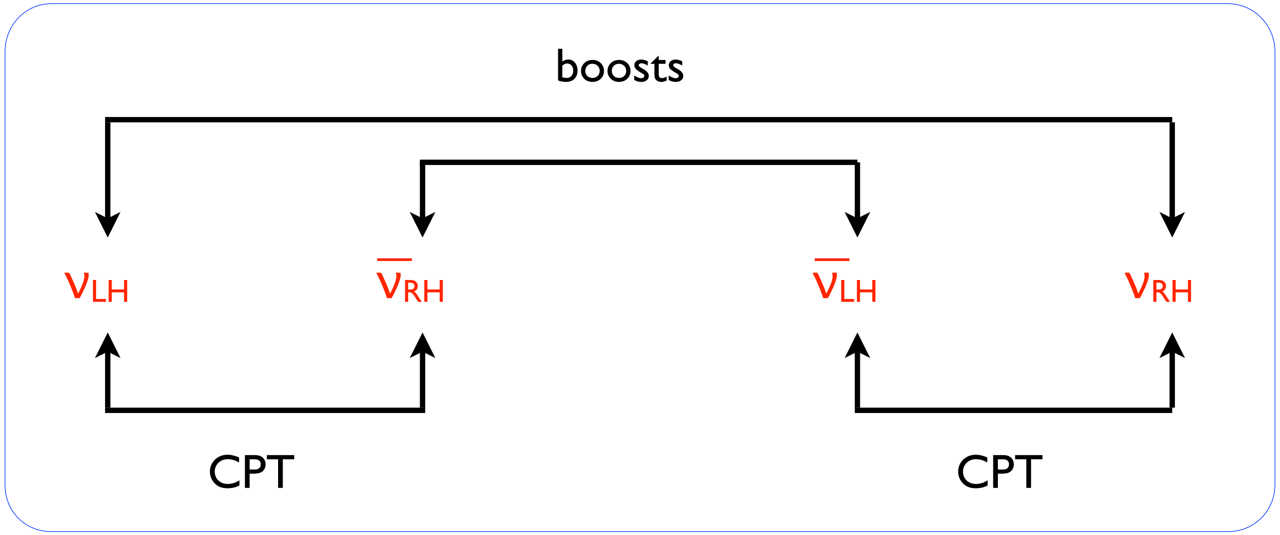


ν_{LH}

boost

ν_{RH}

Dirac:



boosts

ν_{LH} $\bar{\nu}_{RH}$ $\bar{\nu}_{LH}$ ν_{RH}

CPT CPT

We expect both kinds of mass to exist: what is not forbidden is required

Dirac equation mass term $\bar{\Psi} M_D \Psi$, project out the L/R and $\nu/\bar{\nu}$ DoFs

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M_D^T \Psi^c_R + \qquad\qquad\qquad\qquad \right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & & M_D^T \\ 0 & 0 & M_D & \\ & M_D^\dagger & 0 & 0 \\ M_D^* & & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

The Majorana mass terms complete this matrix

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M^T_D \Psi^c_R + \bar{\Psi}^c_L M_L \Psi_L + \bar{\Psi}^c_R M_R \Psi_R\right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & M_L & M^T_D \\ 0 & 0 & M_D & M^\dagger_R \\ M^\dagger_L & M^\dagger_D & 0 & 0 \\ M^*_D & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

The Majorana mass terms complete this matrix

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M^T_D \Psi^c_R + \bar{\Psi}^c_L M_L \Psi_L + \bar{\Psi}^c_R M_R \Psi_R\right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & M_L & M^T_D \\ 0 & 0 & M_D & M^\dagger_R \\ M^\dagger_L & M^\dagger_D & 0 & 0 \\ M^*_D & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

The SM: 1) has no RHed ν fields ⇒ no Dirac masses

2) assumes conserved lepton no. ⇒ no Majorana masses

so massless SM neutrinos

The Majorana mass terms complete this matrix

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M_D^T \Psi^c_R + \bar{\Psi}^c_L M_L \Psi_L + \bar{\Psi}^c_R M_R \Psi_R\right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

But 1) might anticipate $M_D \sim$ other SM Dirac masses

2) know $M_L \ll M_D$ (no ββ decay), reasonably $M_R \gg M_D$

so with these assumptions can diagonalize this matrix

The Majorana mass terms complete this matrix

$$L_M = \left[\bar{\Psi}_R M_D \Psi_L + \bar{\Psi}^c_L M_D^T \Psi^c_R + \bar{\Psi}^c_L M_L \Psi_L + \bar{\Psi}^c_R M_R \Psi_R\right] + h.c.$$

$$= \left(\bar{\Psi}^c_L, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}^c_R\right) \begin{pmatrix} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^* & M_R & 0 & 0 \end{pmatrix} \begin{pmatrix} \Psi^c_L \\ \Psi_R \\ \Psi_L \\ \Psi^c_R \end{pmatrix}$$

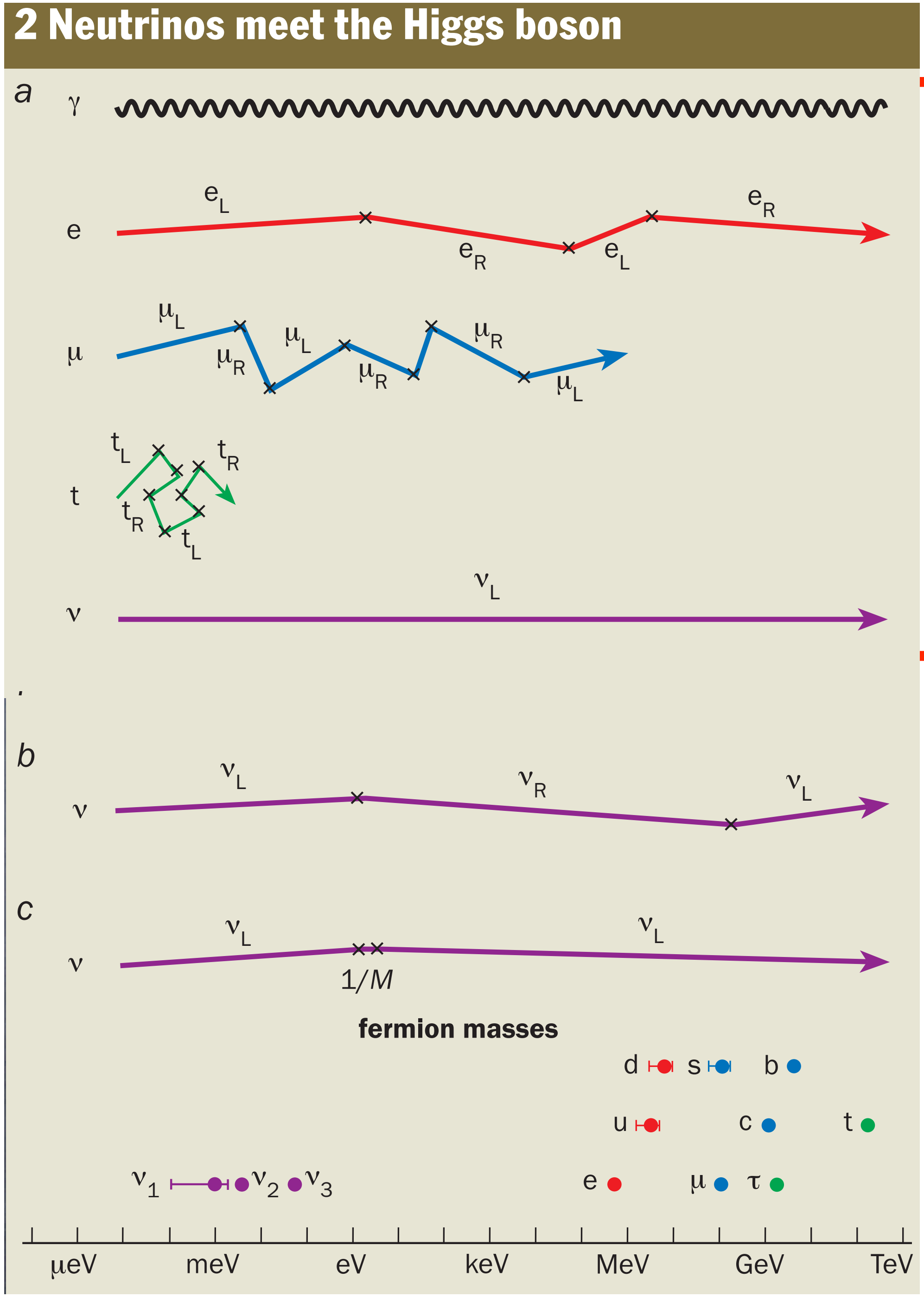
$$m_\nu^{\mathrm{light}} = M_D \left(\frac{M_D}{M_R}\right)$$

seesaw

SM fermion mass scale

needed “small parameter” specific to νs

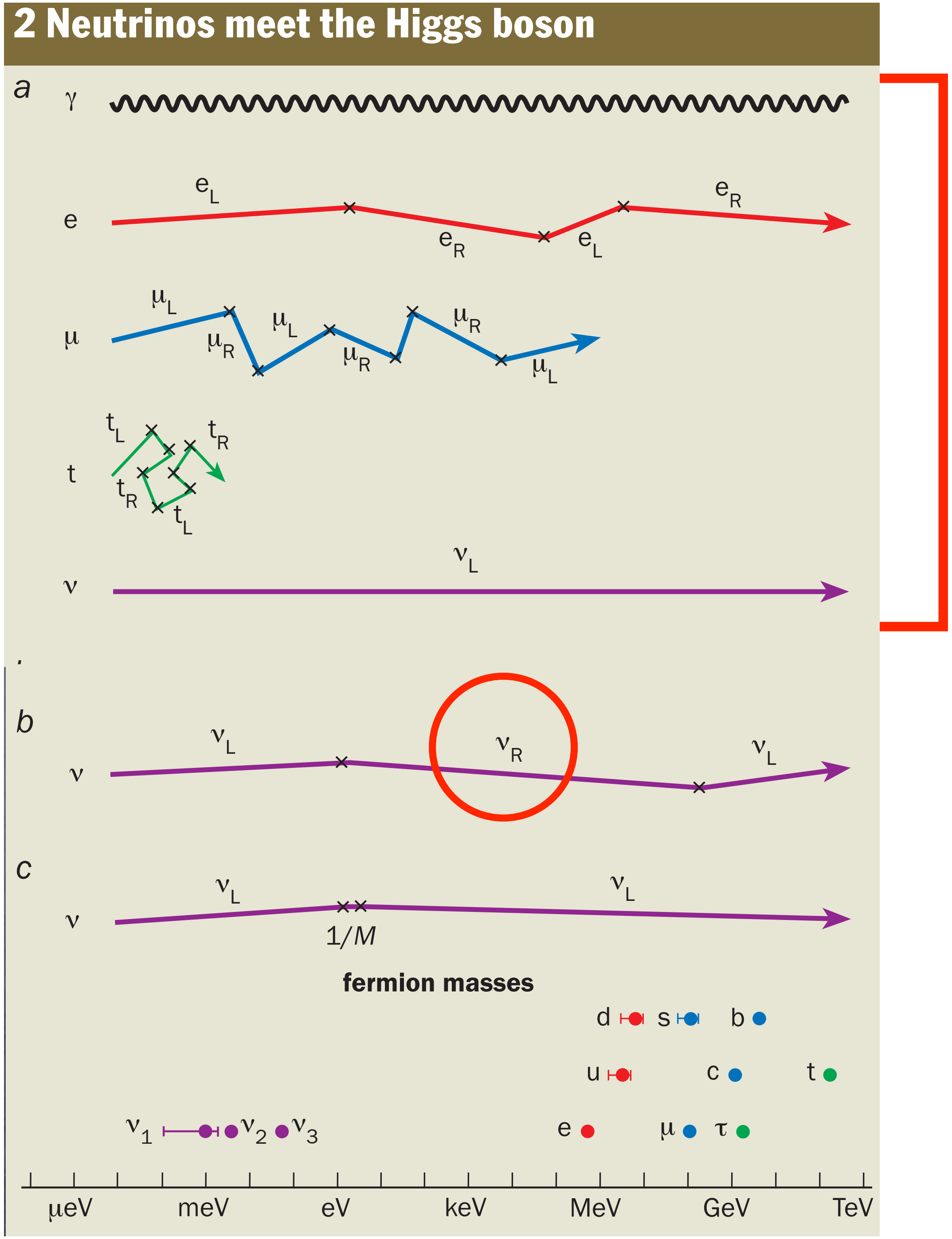
Murayama’s ν mass cartoon


2 Neutrinos meet the Higgs boson

standard model fermion masses

standard model ν and mass=0

Murayama’s ν mass cartoon

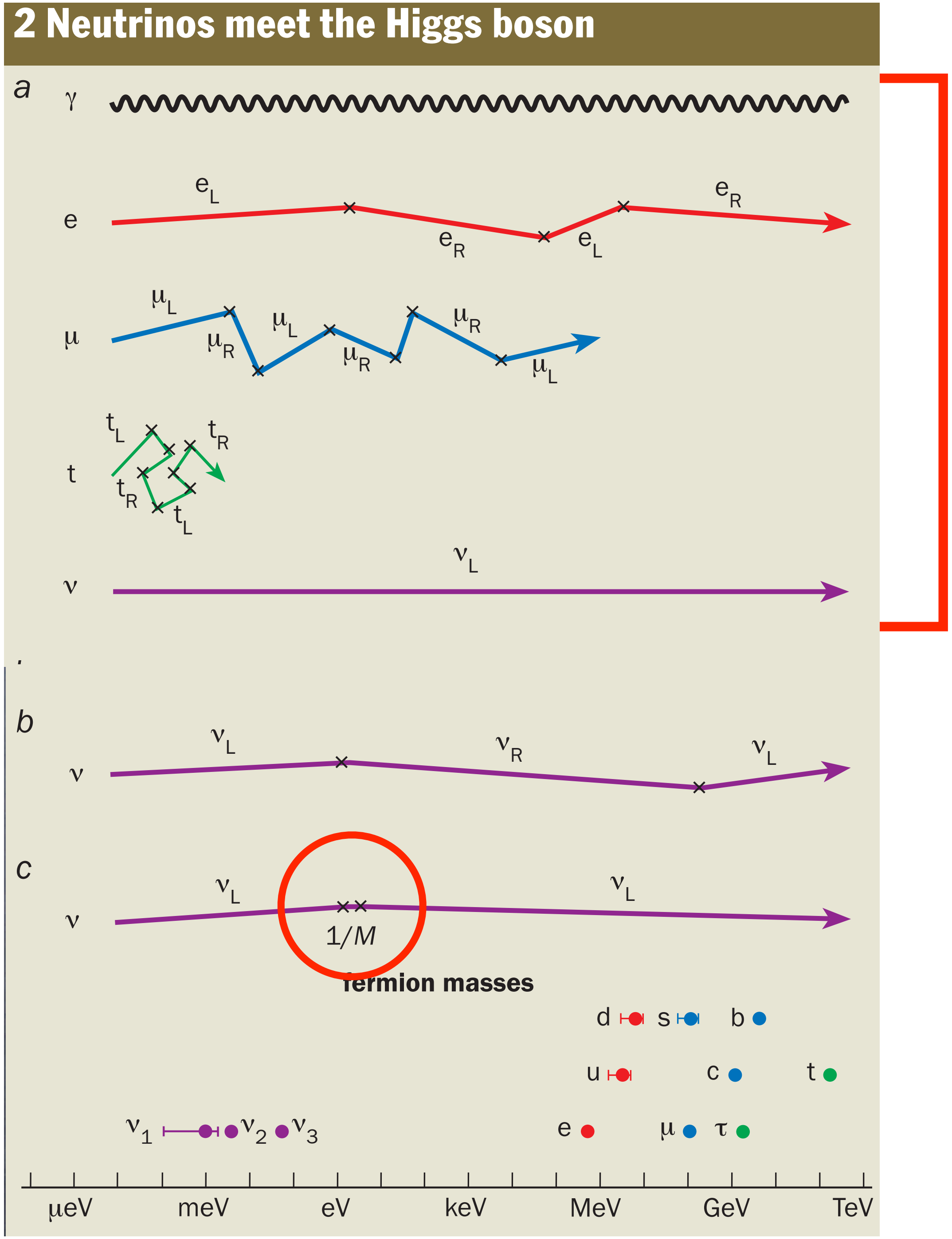


standard model fermion masses

standard model ν and mass=0

light Dirac neutrino mass

Murayama's ν mass cartoon



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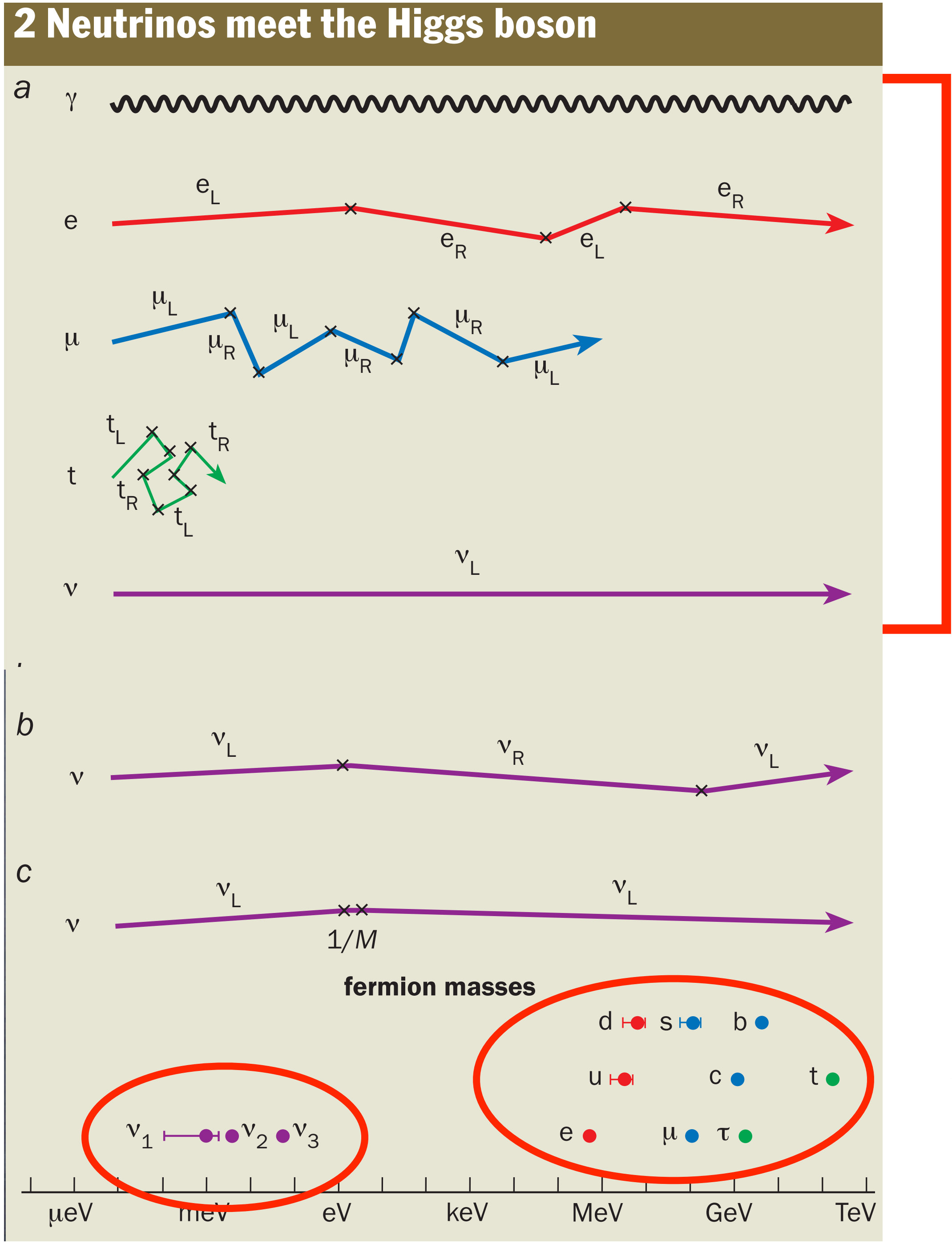
light Dirac neutrino mass

light LHed Majorana neutrino mass

Murayama’s ν mass cartoon



2 Neutrinos meet the Higgs boson

standard model fermion masses

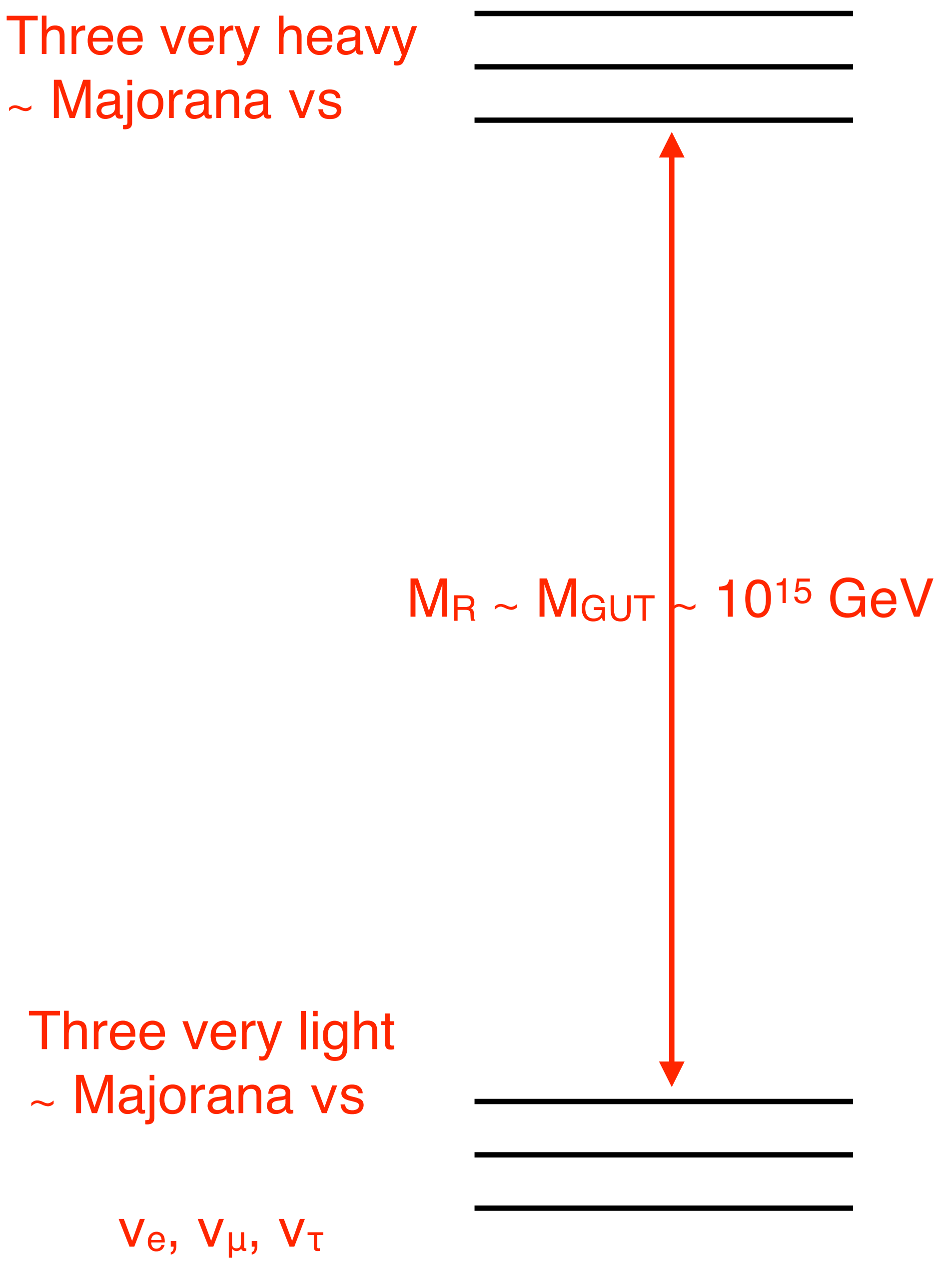
standard model ν and mass=0

light Dirac neutrino mass

light LHed Majorana neutrino mass

← the anomalous ν mass scale,
connected with the seesaw?

Has led to a “standard scenario” that is used to discuss ββ decay and other experiments

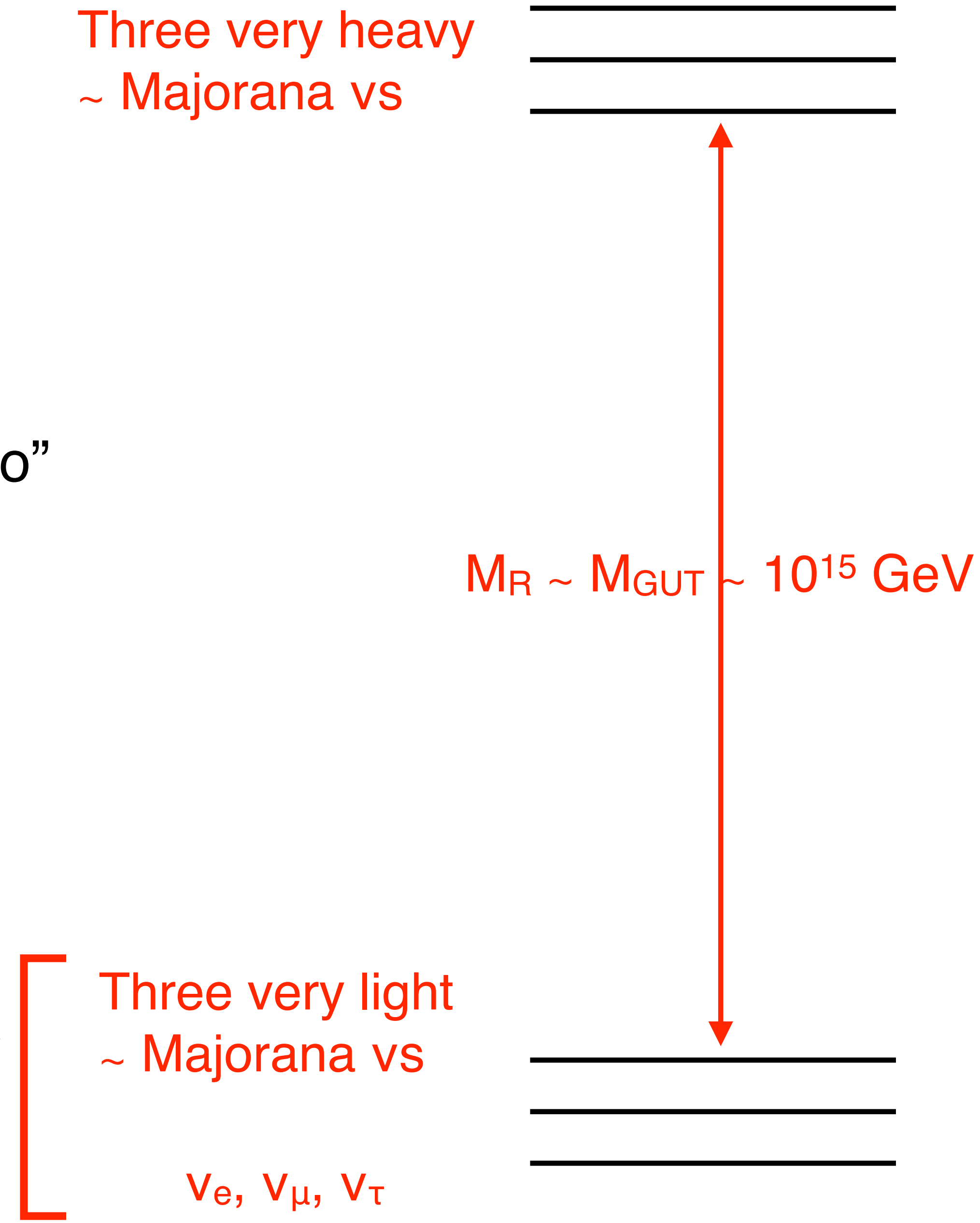


Three very heavy ~ Majorana νs

$M_R \sim M_{GUT} \sim 10^{15}$ GeV

Three very light ~ Majorana νs

ν_e, ν_μ, ν_τ



Three very heavy
~ Majorana νs

$M_R \sim M_{GUT} \sim 10^{15}$ GeV

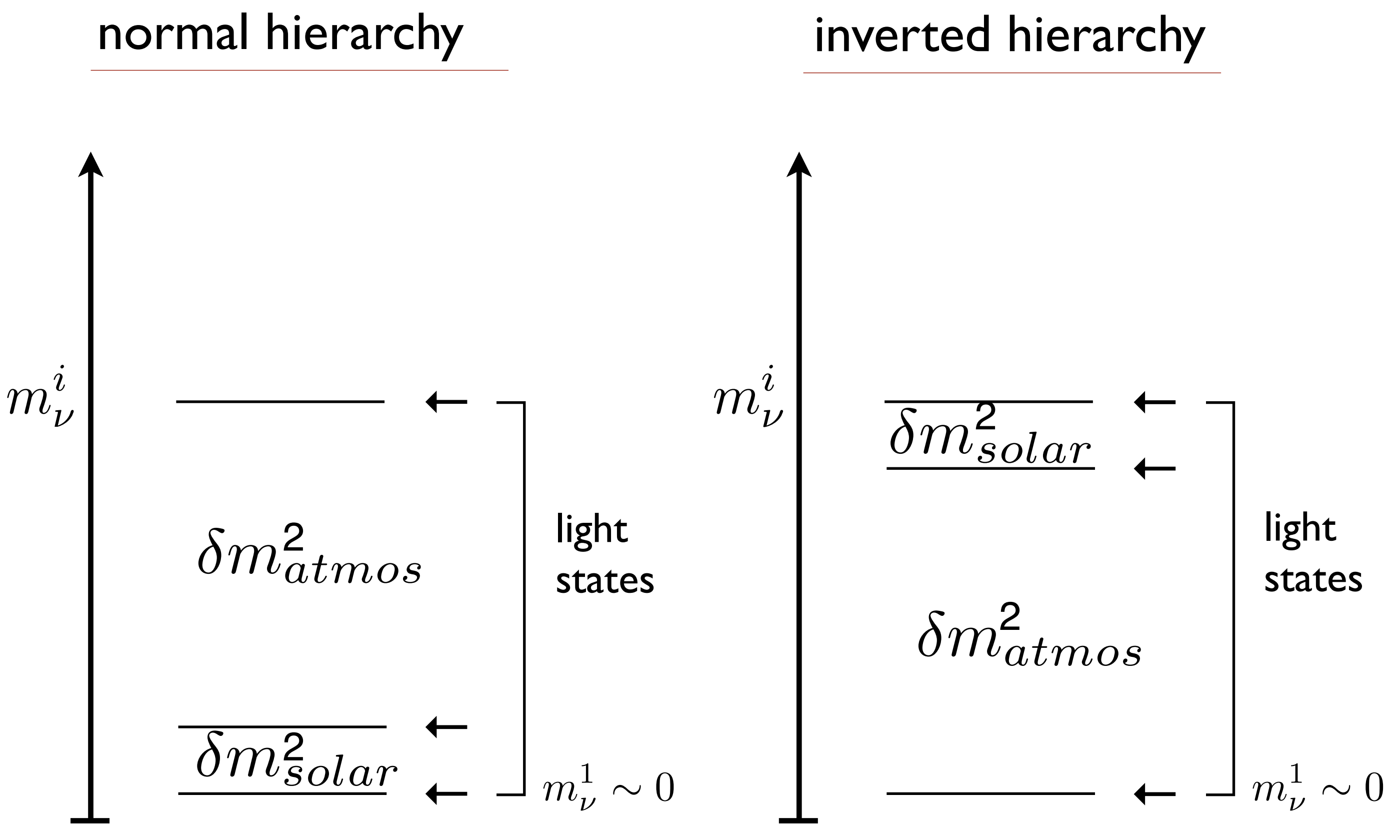
Has led to a “standard scenario” that is used to discuss ββ decay and other experiments

properties being probed in low energy experiments, cosmology

Three very light
~ Majorana νs

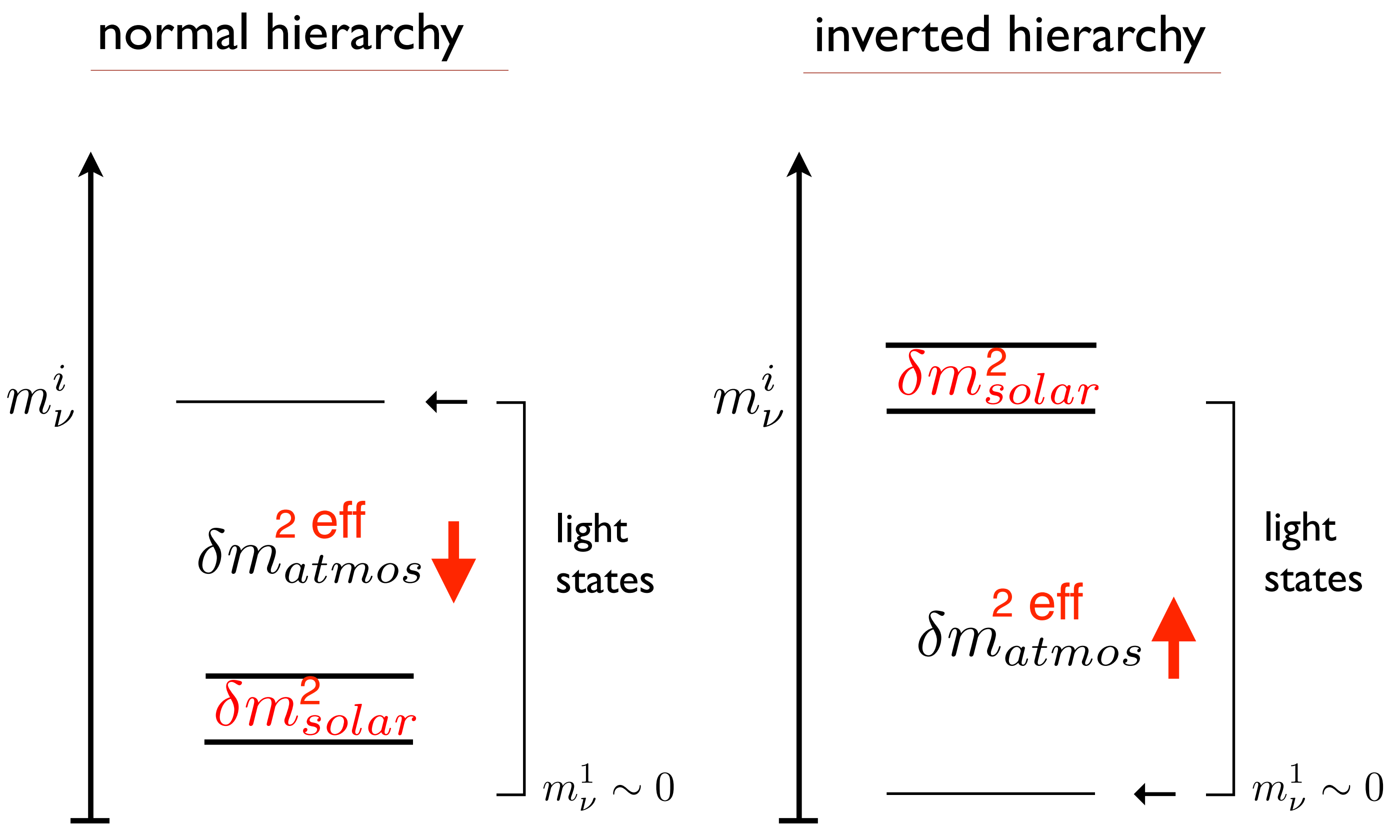
ν_e, ν_μ, ν_τ

We have learned a lot about about the pattern of the light masses from the solar, atmospheric, reactor, and accelerator experiments - but two hierarchies remain

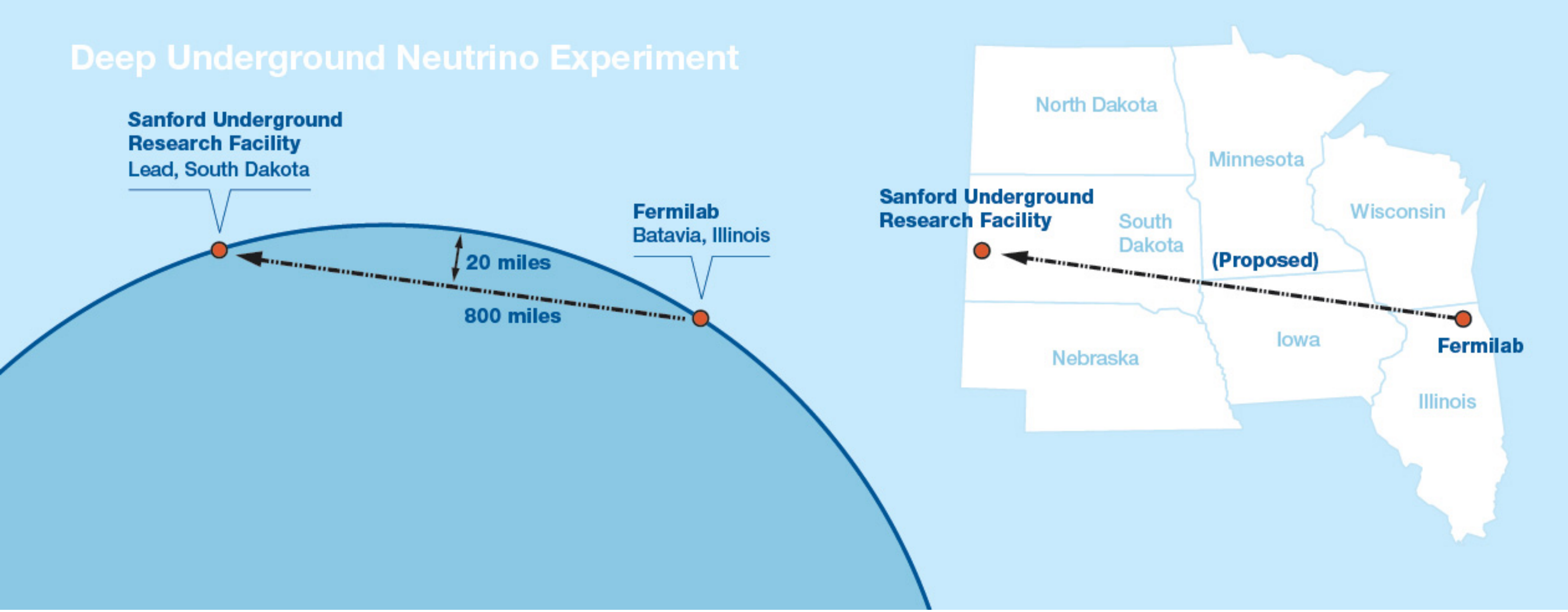


We have learned a lot about about the pattern of the light masses from the solar, atmospheric, reactor, and accelerator experiments - but two hierarchies remain

add matter, measure oscillations over δm_{atmos} scale of ~ 1000 km



LBNF: mass hierarchy (and CP violation)

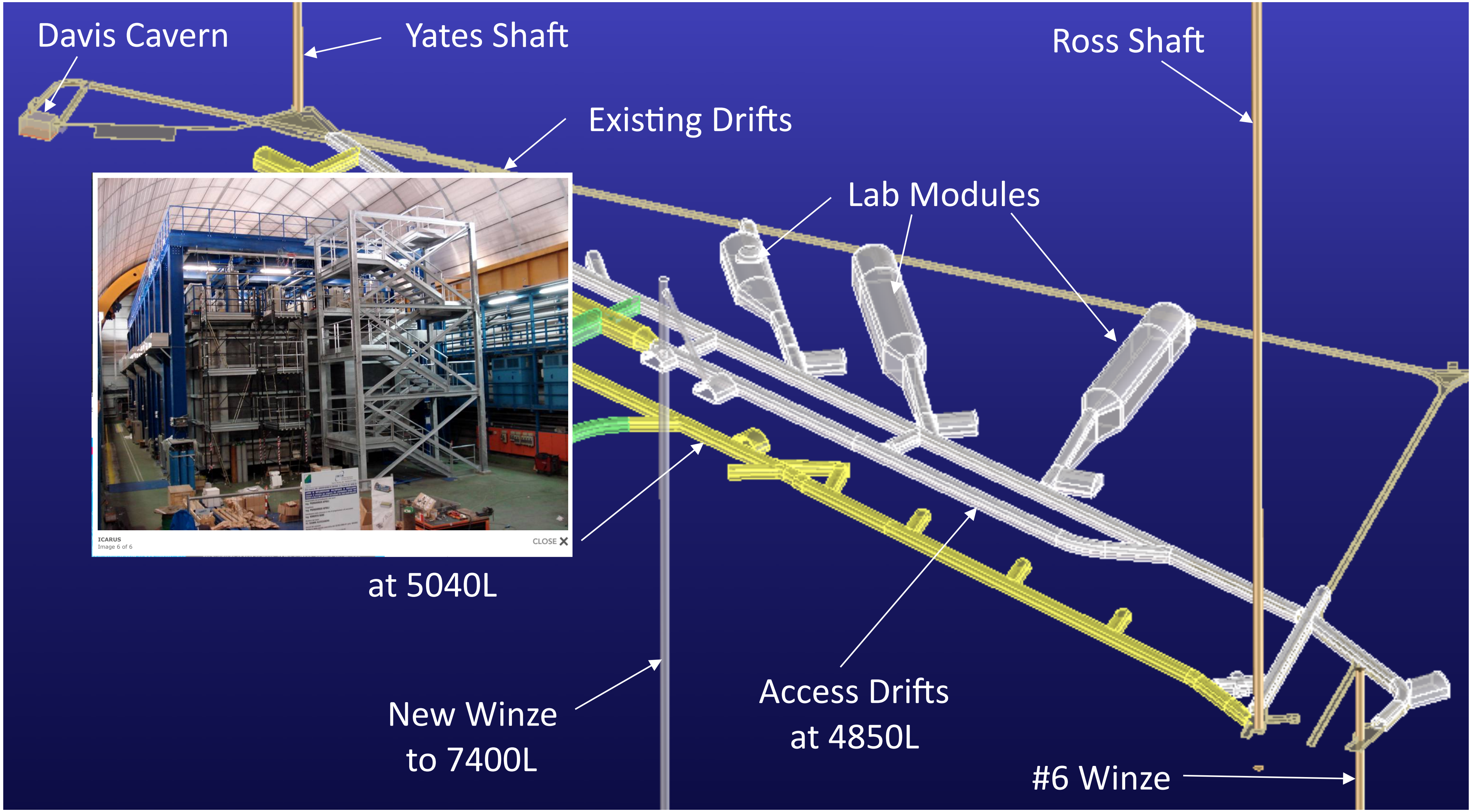


1.2 MW beam, on axis, to a 10→40 kton LiAr detector at Sanford Lab

1300 km of matter: sign of matter effects ⇔ normal/inverted;

5 years of $\nu_\mu\mathrm{s}, \bar{\nu}_\mu\mathrm{s}$ running $\nu_\mu \longrightarrow \nu_e$ vs $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ (also $\cancel{CP}$)

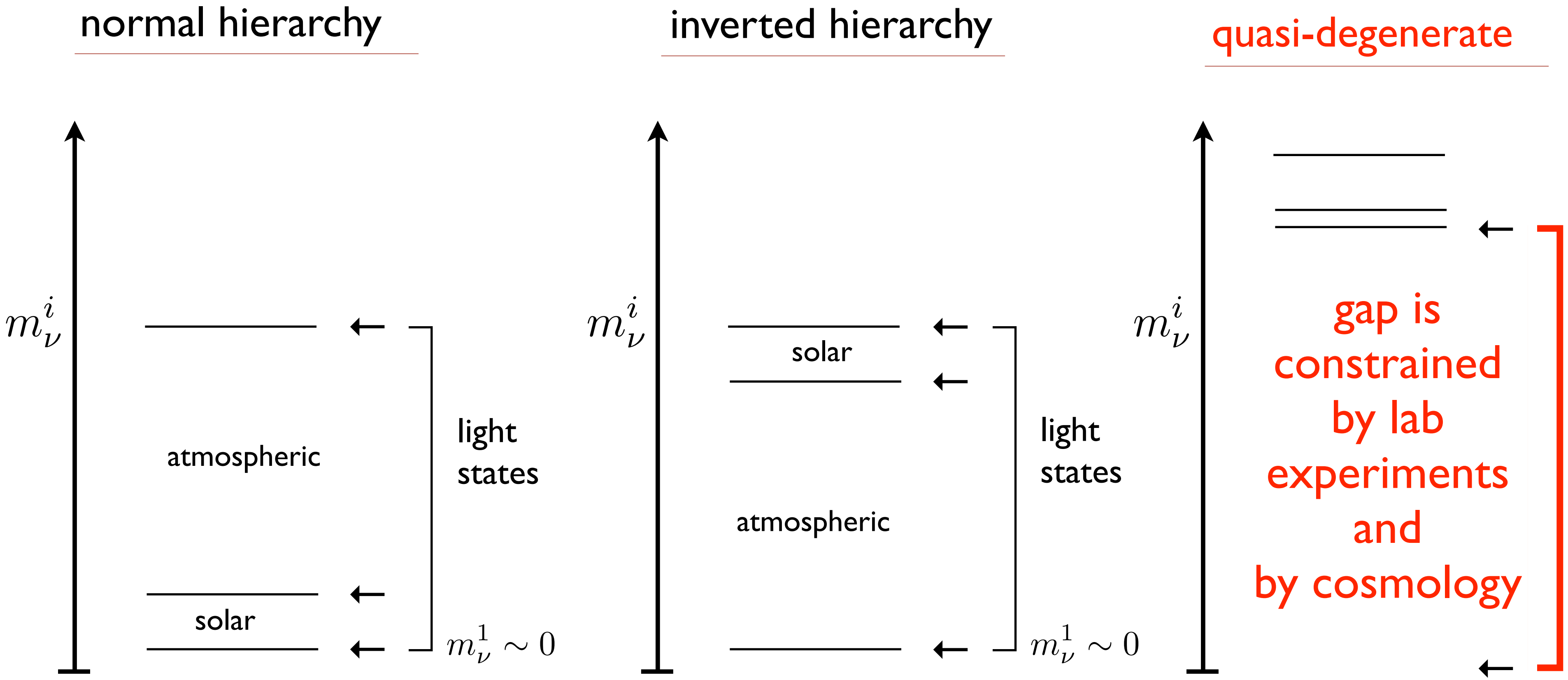
Much enlarged ICARUS-like LiAr far detector



with a near-detector at FermiLab to help characterize the initial beam

Absolute Neutrino Masses?

Oscillations measure mass differences $\delta m^2_{21} = \delta m^2_{solar}, \delta m^2_{31} = \delta m^2_{atmos}$
The absolute scale is not fixed



normal hierarchy

m^i_ν

atmospheric

solar

light states

$m^1_\nu \sim 0$

inverted hierarchy

m^i_ν

solar

atmospheric

light states

$m^1_\nu \sim 0$

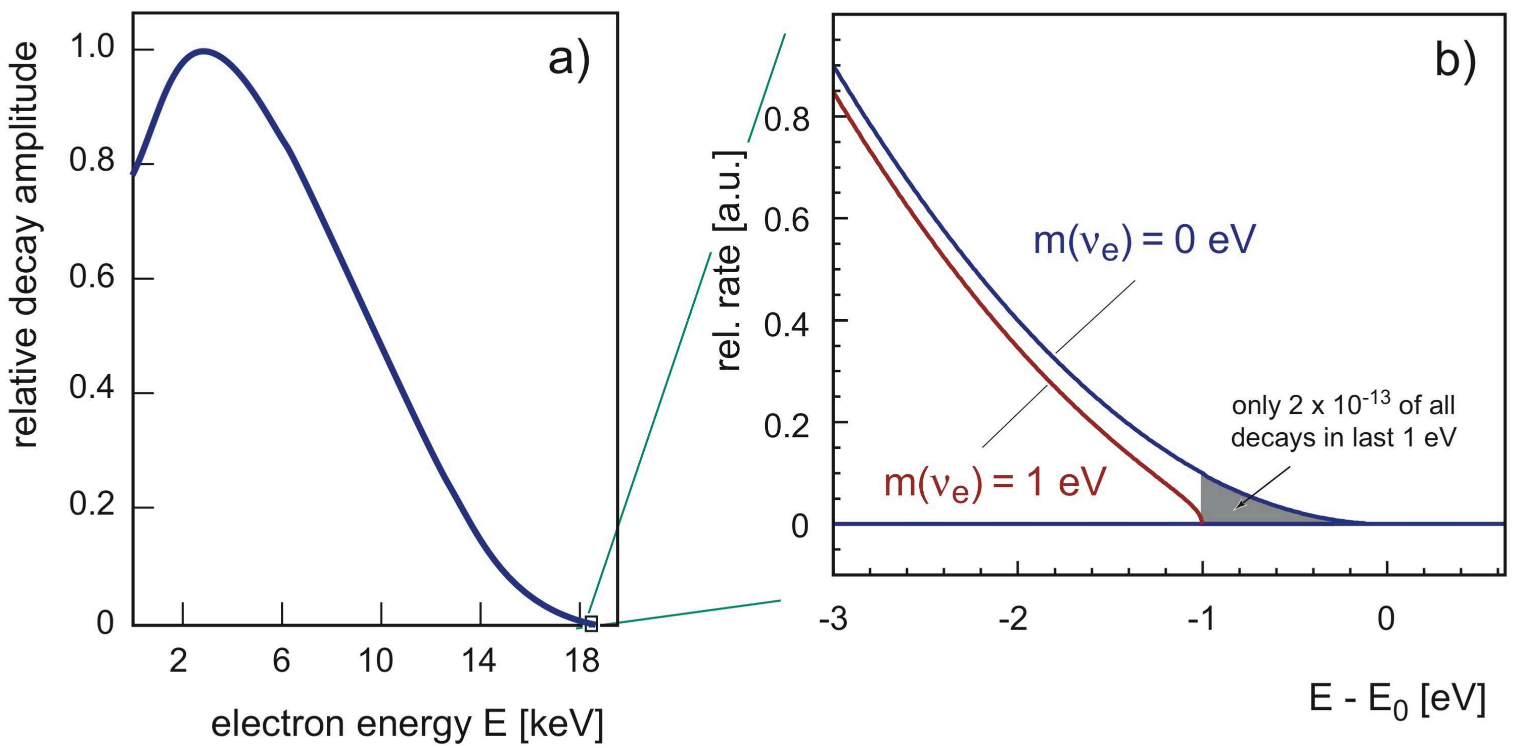
quasi-degenerate

m^i_ν

gap is constrained by lab experiments and by cosmology

how do we measure absolute masses?

From tritium β decay:



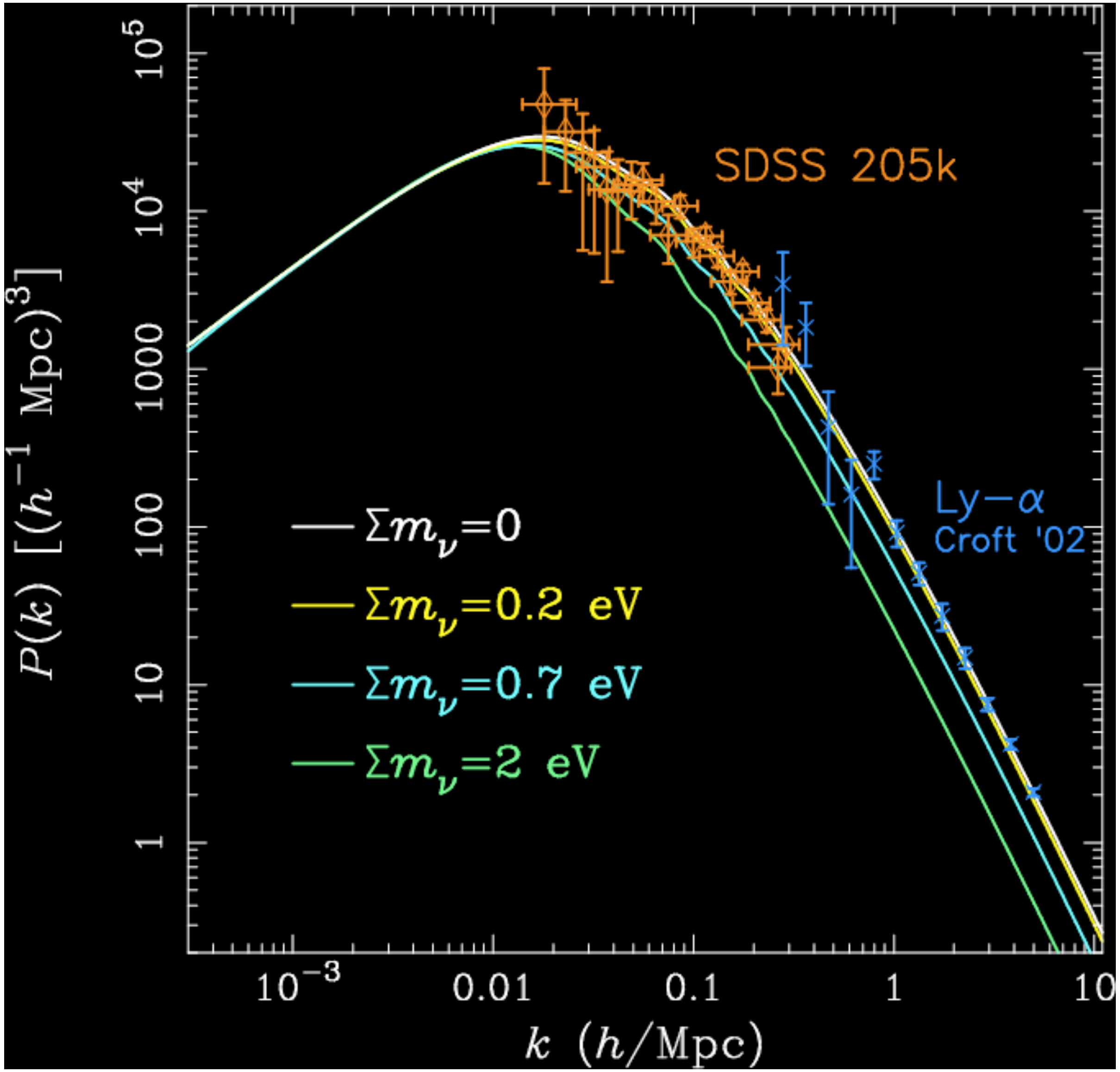
Mainz/Troitsky limit: $$\langle m_\nu \rangle_{\text{tritium}} = \sum_i |U_{ei}|^2 m_\nu^2(i) \lesssim 2.2 \text{ eV}$$

Major new effort on tritium β decay is underway, but lab experiments are running into intrinsic limits due to feasible source intensities and detector resolution

KATRIN at Karlsruhe


Leopoldshafen, 25.11.06

goal: $\langle m_v \rangle_{\text{tritium}} \lesssim 250 \text{ meV}$



Alternatively, cosmology:

Neutrinos start off relativistic in the early universe, where they suppress the growth of structure on large scales

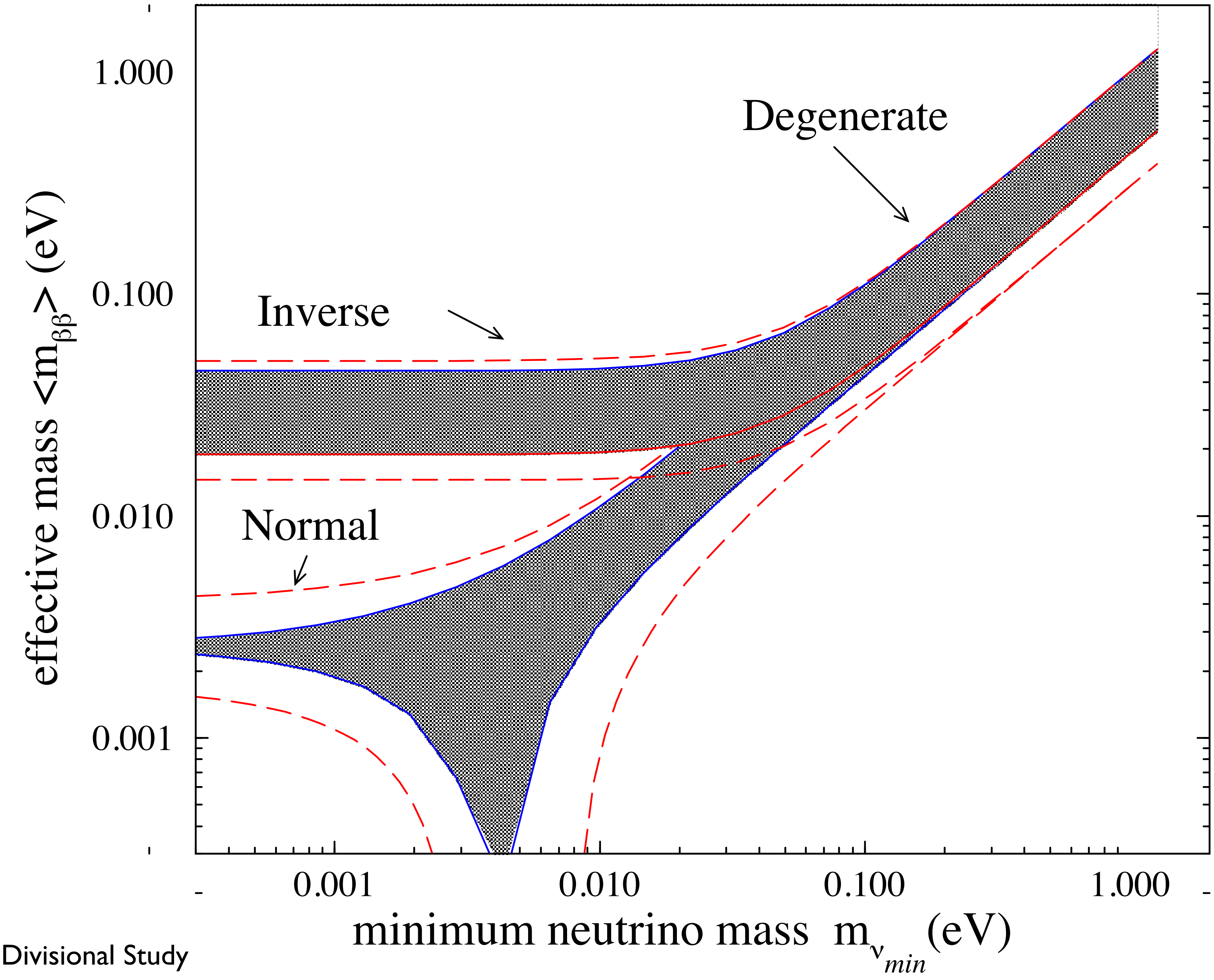
Transition to nonrelativistic

Effects scale and redshift dependent

Current limits

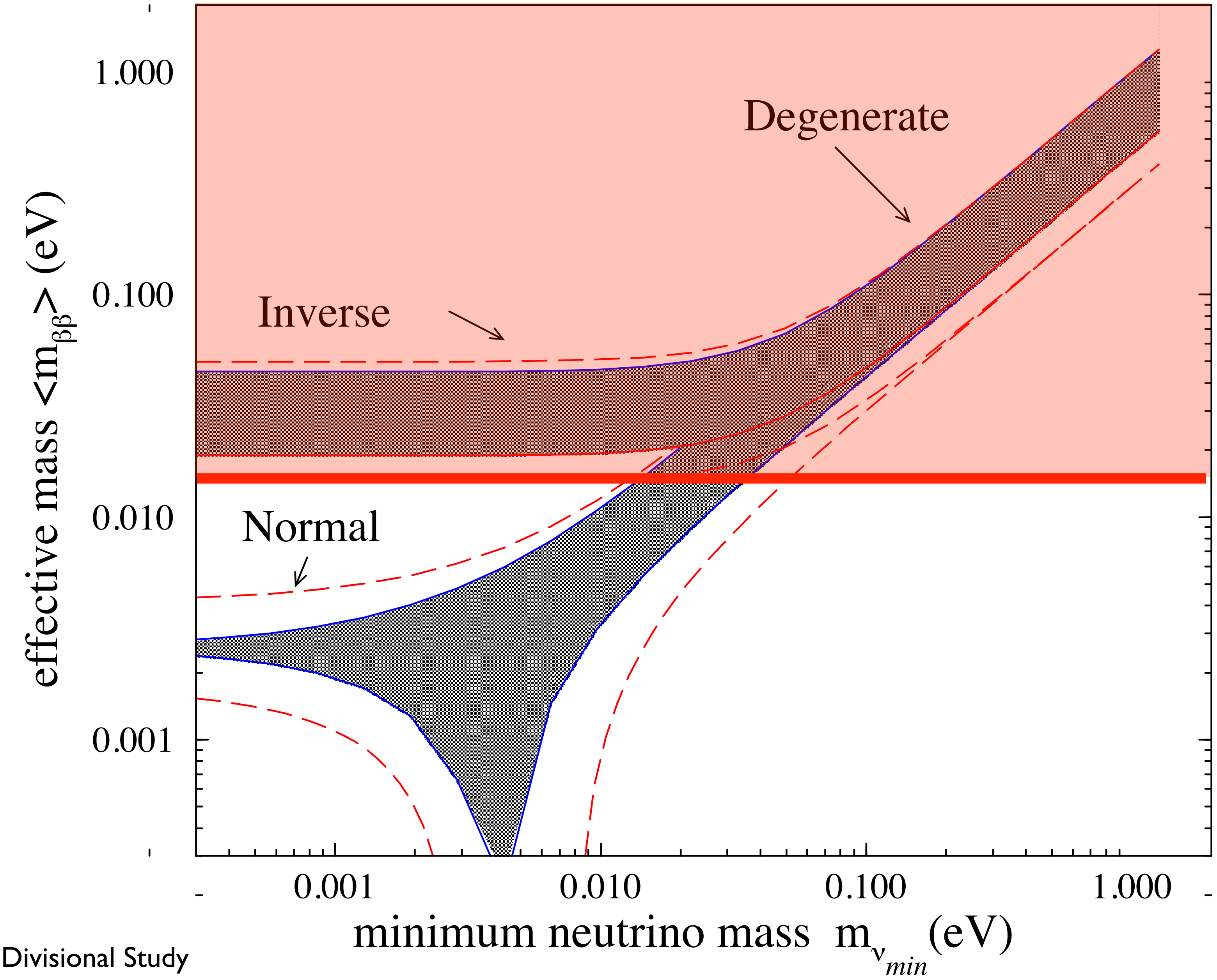
$$\frac{1}{3}\sum_i m_i \lesssim 80 \text{ meV}$$

Mass scenarios critical to next-generate ββ decay efforts



APS Multi-Divisional Study

Mass scenarios critical to next-generate ββ decay efforts

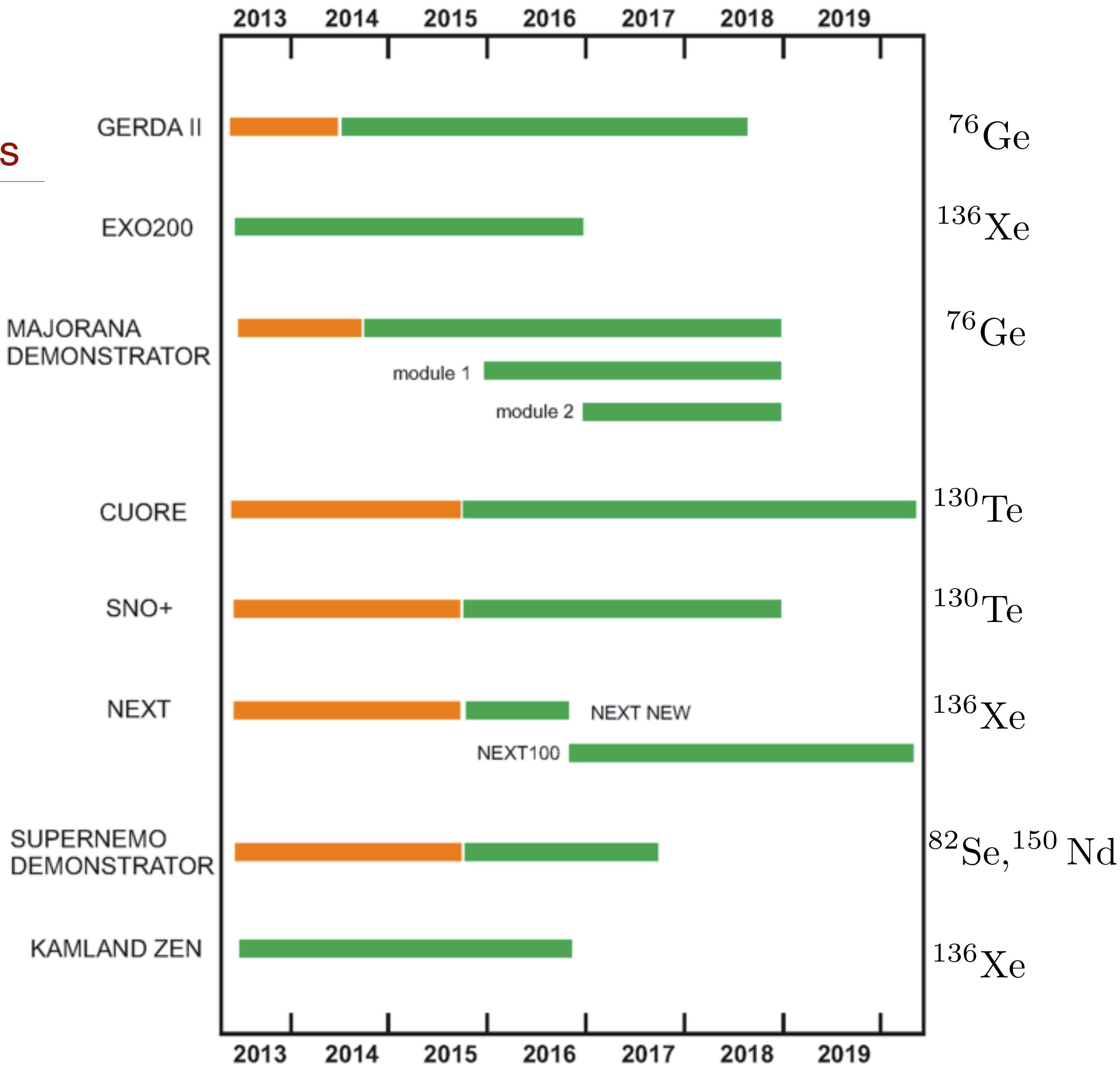


test
ββ decay
at the
inverted
hierarchy
level

APS Multi-Divisional Study

‘Demonstrator’ Experiments

Current-generation timelines for project construction and running

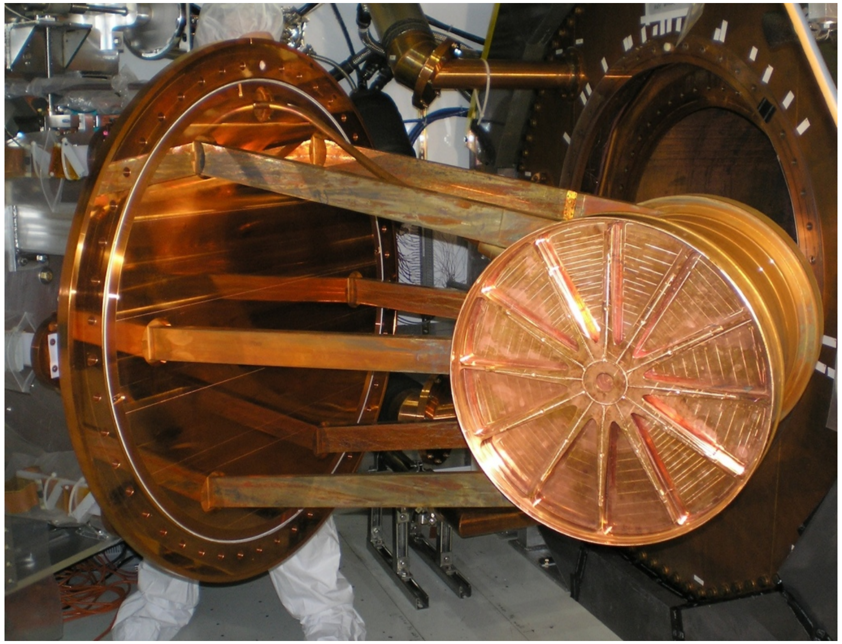


From NSAC Subcommittee on 0ν ββ decay

GERDA I, Gran Sasso; Majorana, SL

GERDA I ^{76}Ge, 21.6kg-y

$\tau_{1/2} > 2.1 \times 10^{25}$y 90% c.l.



EXO-200, WIPP

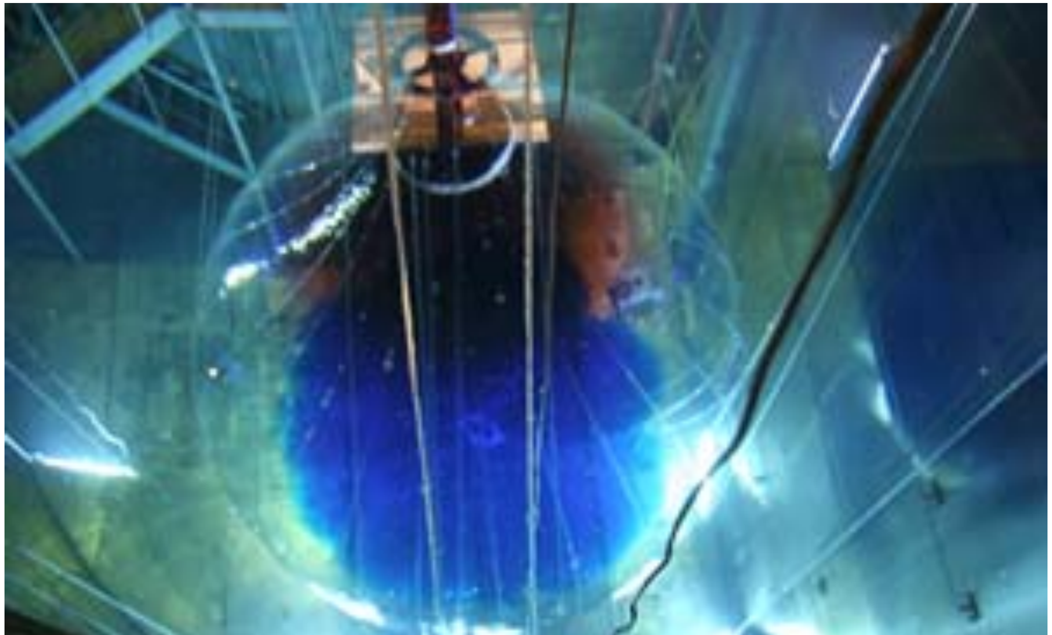
^{136}Xe, 99.8 kg-y

$\tau_{1/2} > 1.1 \times 10^{25}$y 90% c.l.

KamLAND-Zen, Kamioka

^{136}Xe, 89.5 kg-y

$\tau_{1/2} > 1.9 \times 10^{25}$y 90% c.l.



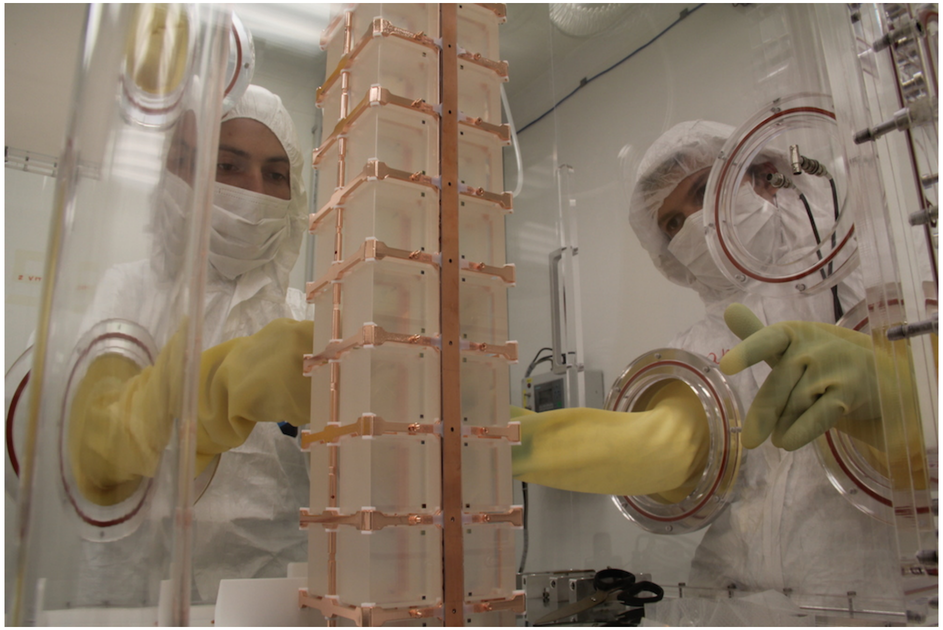
CUORE-0/Cuoricino, Gran Sasso

^{130}Te, 29.6kg-y

$\tau_{1/2} > 4.0 \times 10^{24}$y 90% c.l.

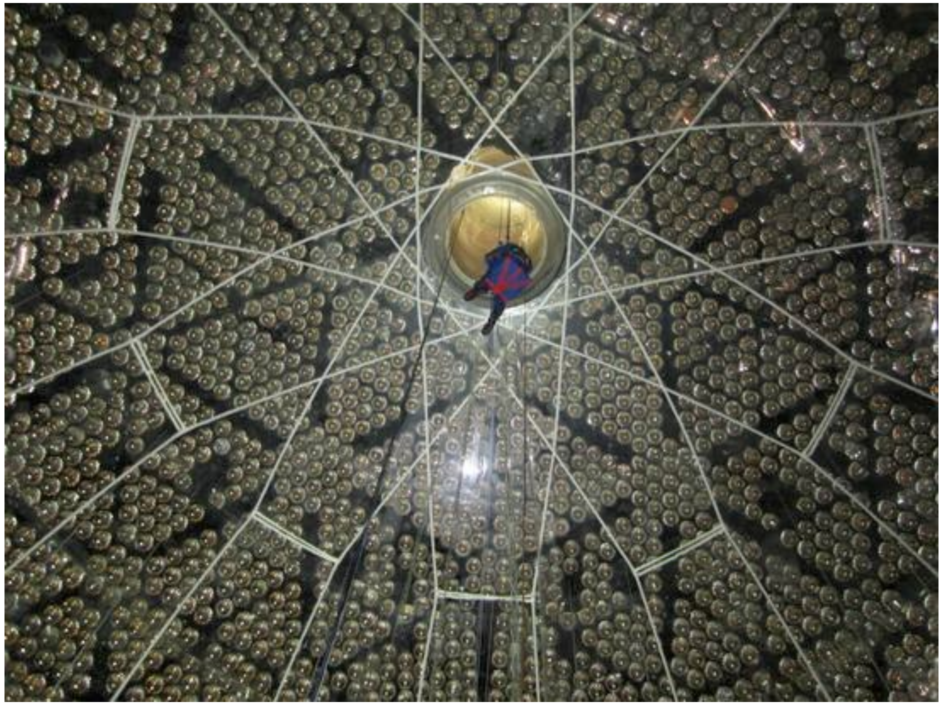
SNO+, SNOLab

^{130}Te-loaded scintillator, to begin in 2016



NEXT, Canfranc Laboratory

Gaseous ^{136}Xe TPC , final state i.d.



The benchmarks

1. where we are now

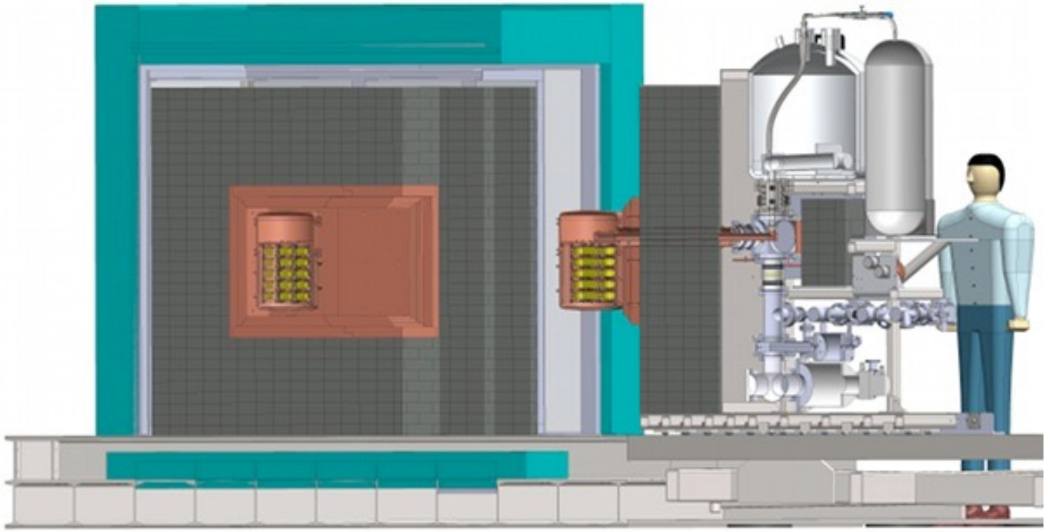
GERDA + other Ge: $\tau_{1/2} > 3.0 \times 10^{25}$y 90% c.l. $\langle m_{\beta\beta} \rangle < 460 \text{ meV}$

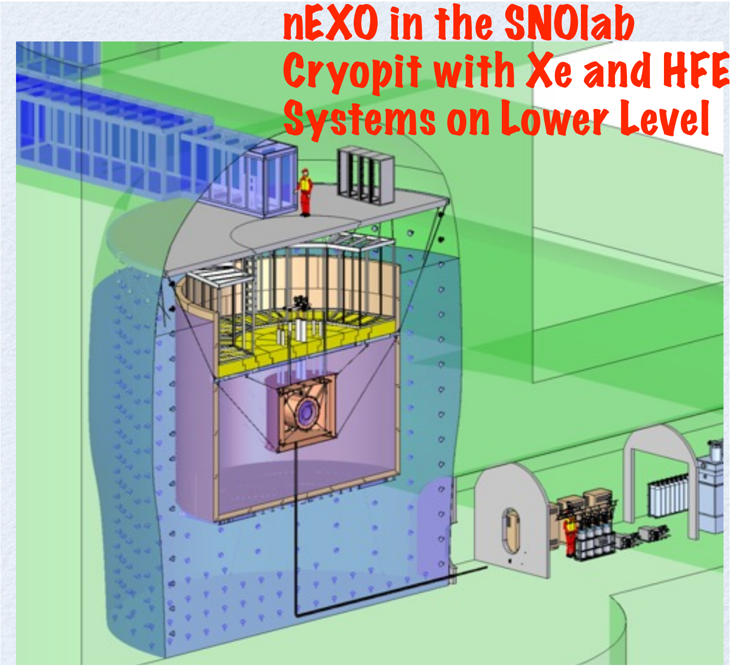
The benchmarks

2. where the demonstrator experiments will take us

5-year ‘demonstrator’ experiments: $\sim 1.6 \times 10^{26}$ y to reach 200 meV

Future: One-ton Experiments 2017→ Probing the IH





nEXO in the SNOlab
Cryopit with Xe and HFE
Systems on Lower Level

Majorana and GERDA joint effort (using the best ‘demonstrator’ technology) a 1-ton enriched ^{76}Ge detector

EXO → nEXO at the 1-ton and then 5-ton level

desirable attributes: excellent resolution, nearly free of backgrounds,
feasible costs, final-state tagging, scalability ...

The benchmarks

3. probe the inverted hierarchy mass band of 19-49 meV

ton+ experiments reaching 10^{28} y after a decade of running

Back to the Beginning: Neutrinos as a Probe of Astrophysics

Ray Davis's initial goal was to use neutrinos to determine the temperature and nuclear physics of the solar core

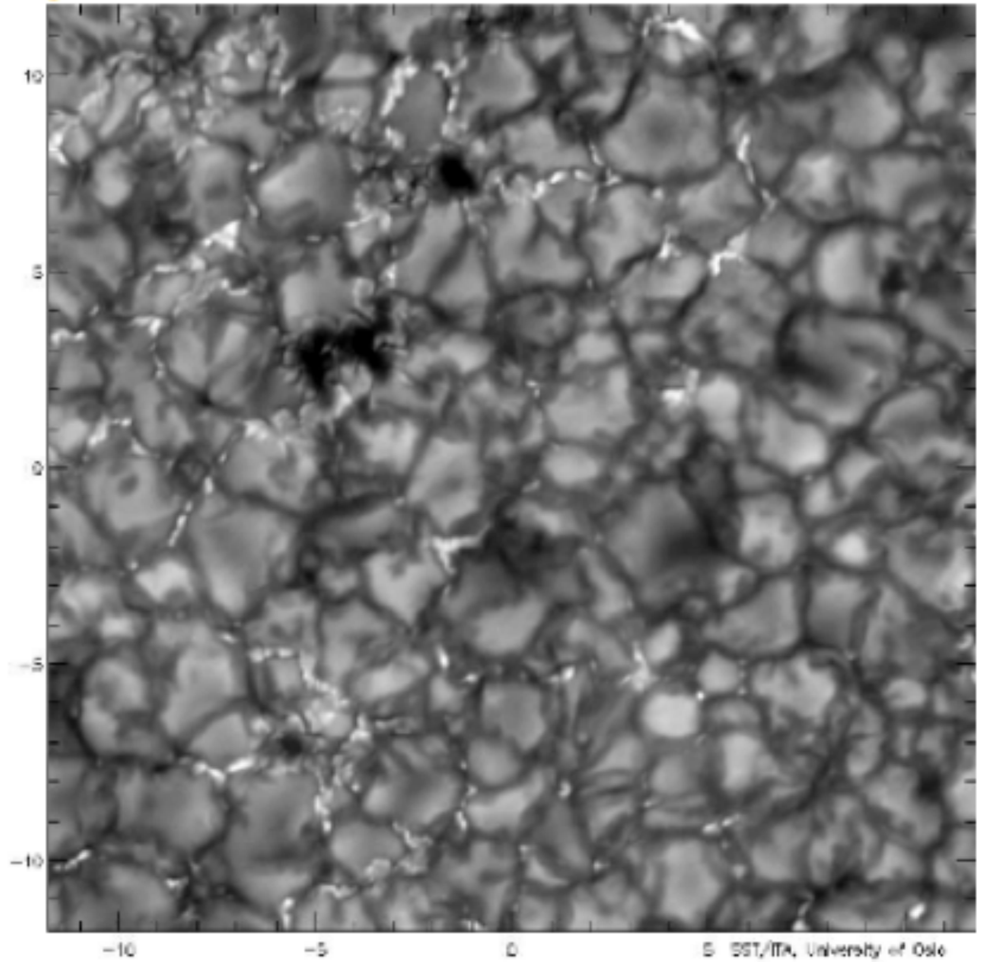
The SSM tested in these early experiments assumes the Sun was homogeneous when it first formed: gas cloud collapse

The initial conditions include the Sun's metallicity, determined in part from analyses of photo-absorption lines in the solar atmosphere

- Early analyses modeled the photosphere in 1D, without explicit treatments of stratification, velocities, inhomogenieties

- New 3D, parameter-free methods were recently introduced, significantly improving consistency of line analyses: MPI-Munich

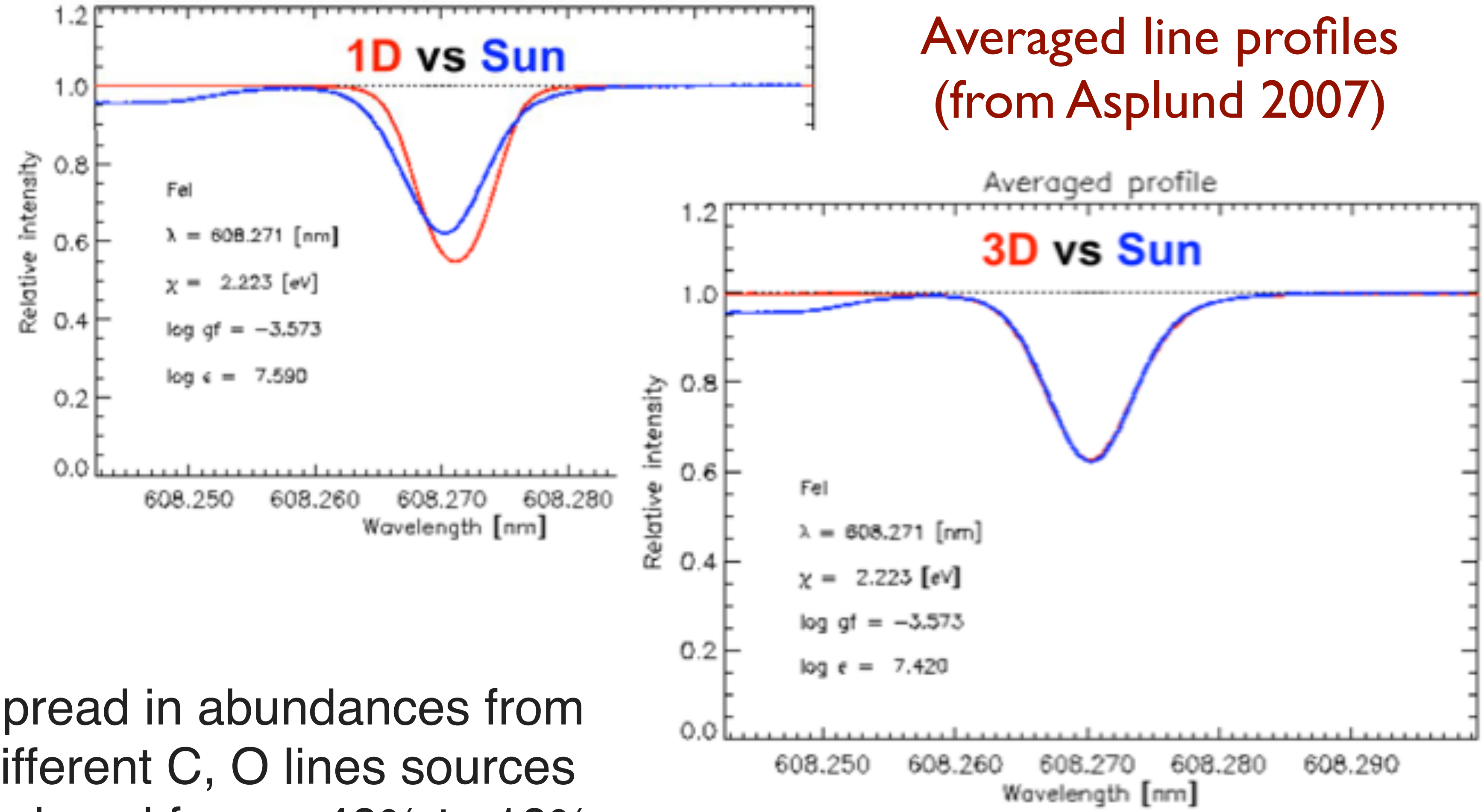
Dynamic and 3D due to convection



Mats Carlsson (Oslo)

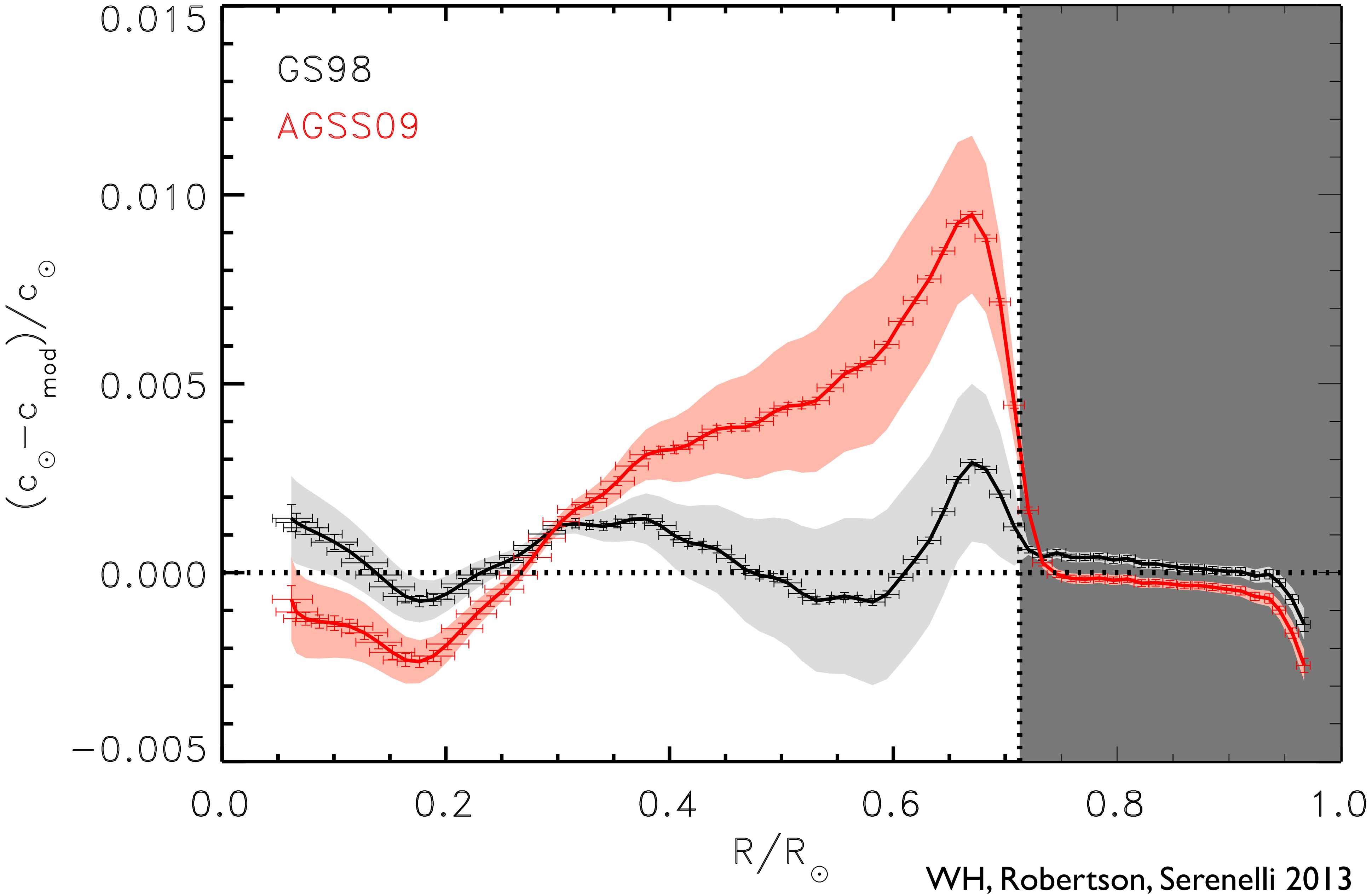
Sun

Averaged line profiles (from Asplund 2007)



- ❑ Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%
- ❑ But abundances significantly reduced Z: 0.0169 ⇒ 0.0122
- ❑ Makes sun more consistent with similar stars in local neighborhood
- ❑ Lowers SSM ^{8}B flux by 20%

But adverse consequences for helioseismology



WH, Robertson, Serenelli 2013

Table 1 Standard solar model characteristics are compared to helioseismic values, as determined by Basu & Antia (1997, 2004)

Property[a]	GS98-SFII	AGSS09-SFII	Solar
$(Z/X)_S$	0.0229	0.0178	–
Z_S	0.0170	0.0134	–
Y_S	0.2429	0.2319	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7124	0.7231	0.713 ± 0.001
$\langle \delta c/c \rangle$	0.0009	0.0037	0.0
Z_C	0.0200	0.0159	–
Y_C	0.6333	0.6222	–
Z_{ini}	0.0187	0.0149	–
Y_{ini}	0.2724	0.2620	–

old SSM

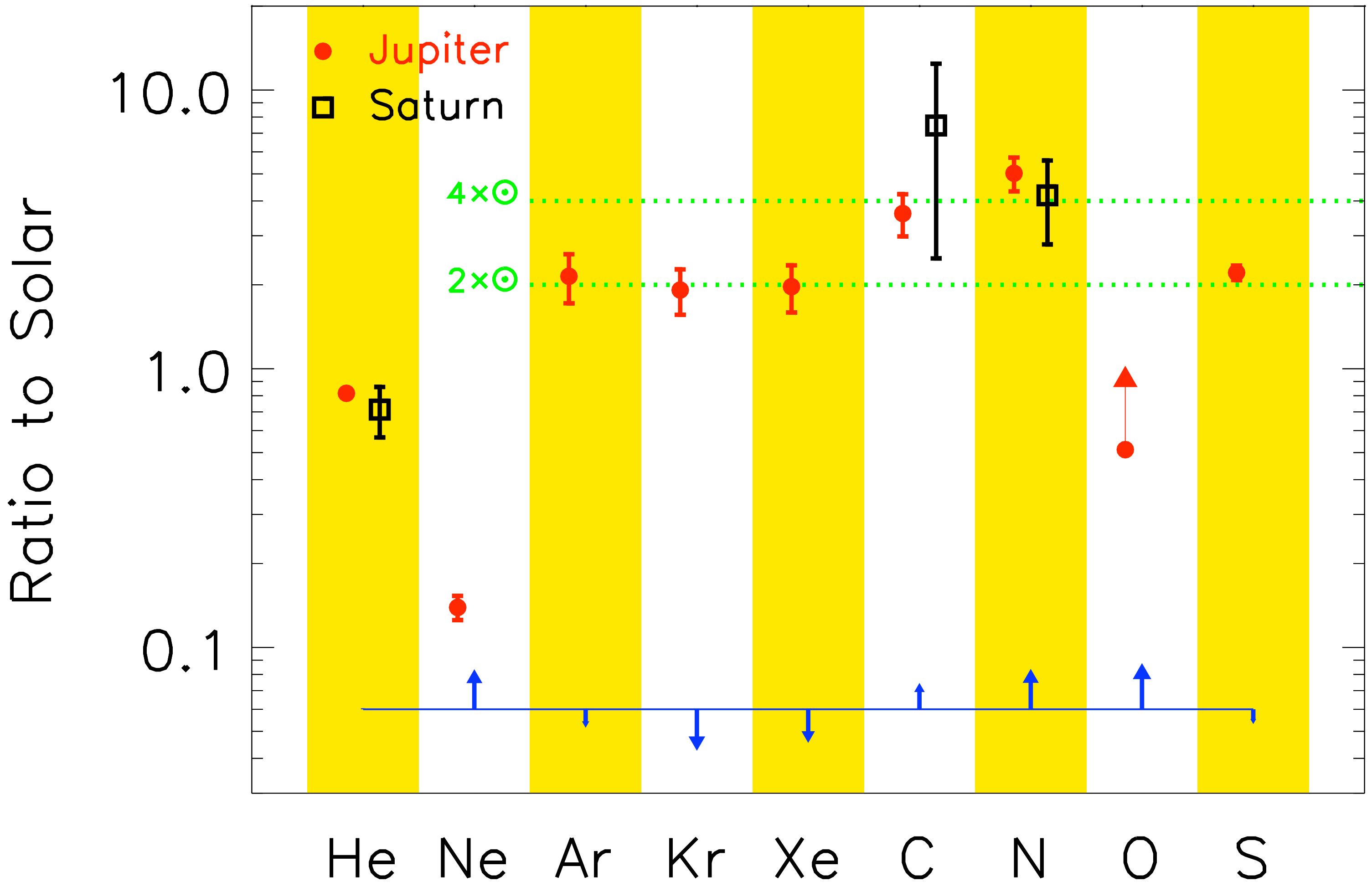
new SSM

Solar abundance problem: A disagreement between SSMs that are optimized to agree with interior properties deduced from our best analyses of helioseismology (high Z), and those optimized to agree with surface properties deduced from the most complete 3D analyses of photoabsorption lines (low Z).

Difference is a deficit of ~ 40 $M_\oplus$ of metal, integrating over the Sun's convective zone (which contains about 2.6% of the Sun's mass)

One set of measurements might be wrong…. or…

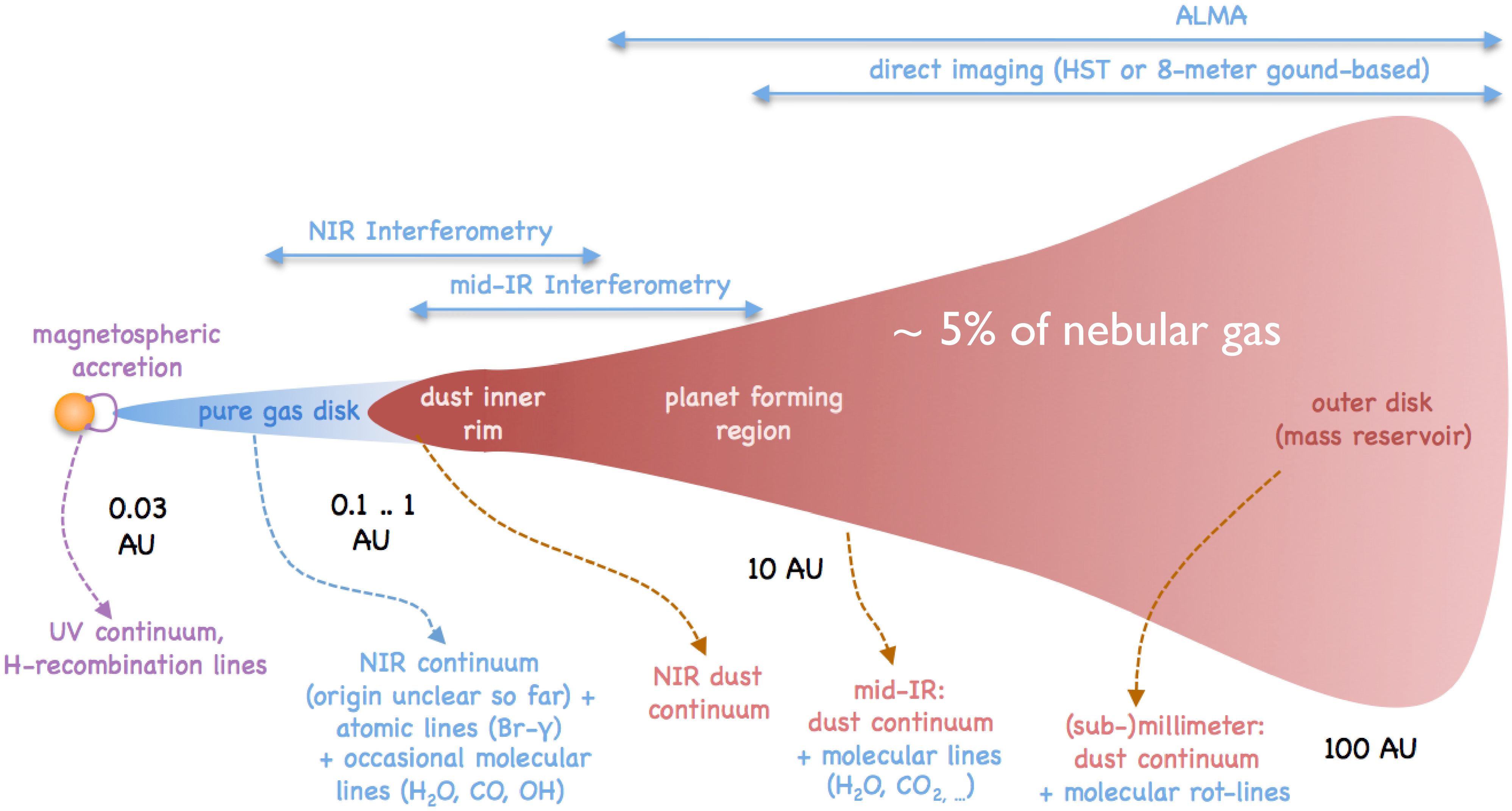
Did the Sun form from a homogeneous gas cloud?



Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

Contemporary picture of metal segregation, accretion



ALMA

direct imaging (HST or 8-meter gound-based)

NIR Interferometry

mid-IR Interferometry

magnetospheric accretion

pure gas disk

dust inner rim

planet forming region

~ 5% of nebular gas

outer disk (mass reservoir)

0.03 AU

0.1 .. 1 AU

10 AU

100 AU

UV continuum,
H-recombination lines

NIR continuum
(origin unclear so far) +
atomic lines (Br-γ)
+ occasional molecular
lines (H_2O, CO, OH)

NIR dust
continuum

mid-IR:
dust continuum
+ molecular lines
(H_2O, CO_2, ...)

(sub-)millimeter:
dust continuum
+ molecular rot-lines

Dullemond and Monnier, ARA&A 2010

This has led to the suggestion that planetary formation scrubbed metals from the last 5% of nebular gas

The depleted gas, deposited on the solar surface, would be sufficient to dilute the Sun's thin convective envelope, while leaving the interior unaltered

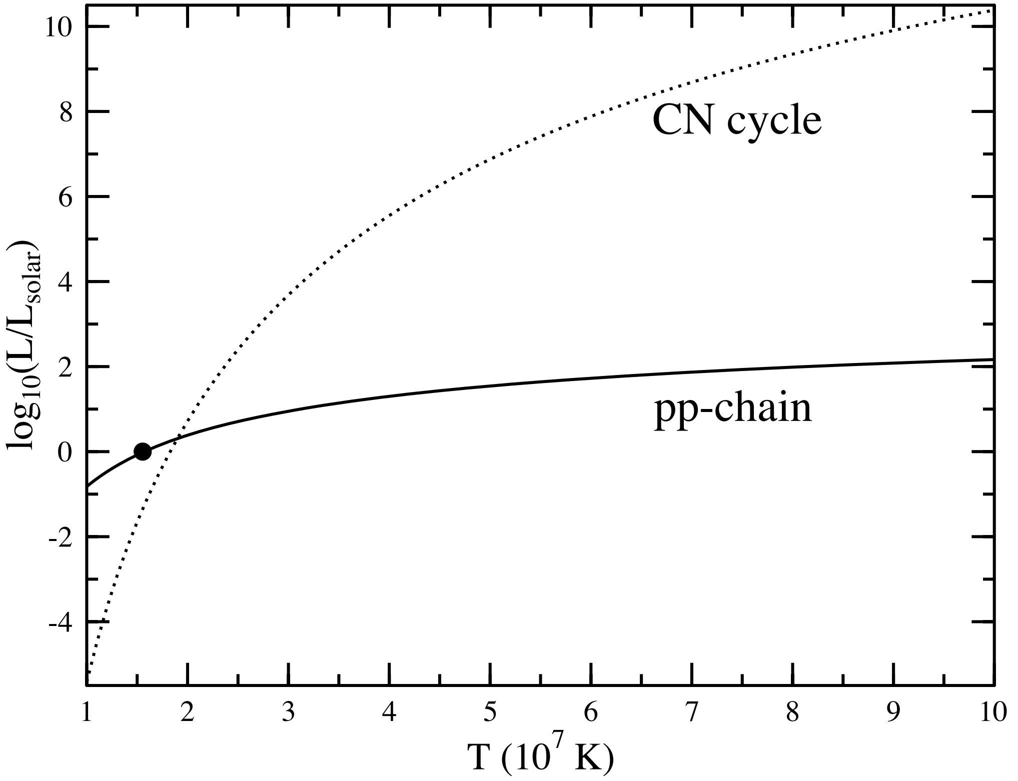
⇒ a metal-poor surface, a metal-rich interior

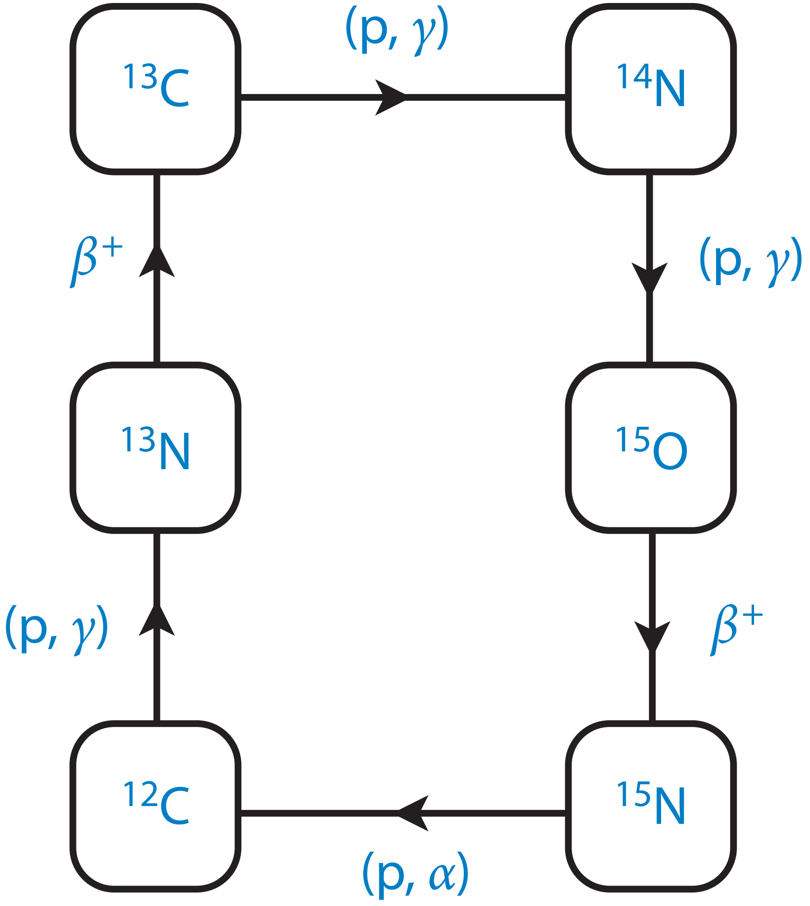
Numerically the mass of metals extracted from the protoplanetary disk (40-90 $M_\oplus$) is sufficient to account for the needed dilution

Guzik, vol. 624, ESA (2006) 17
Castro, Vauclair, Richard A&A 463 (2007) 755
WH & Serenelli, Ap. J. 687 (2008) 678
Nordlund (2009) arXiv:0908.3479
Guzik and Mussack, Ap. J. 713 (2010) 1108
Serenelli, WH, Pena-Garay, Ap. J. 743 (2011) 24

Can we use neutrinos to directly measure core metallicity?

The Sun generates 1% of its energy through the CNO cycle: catalysts for CN cycle are the primordial C, N of the solar core





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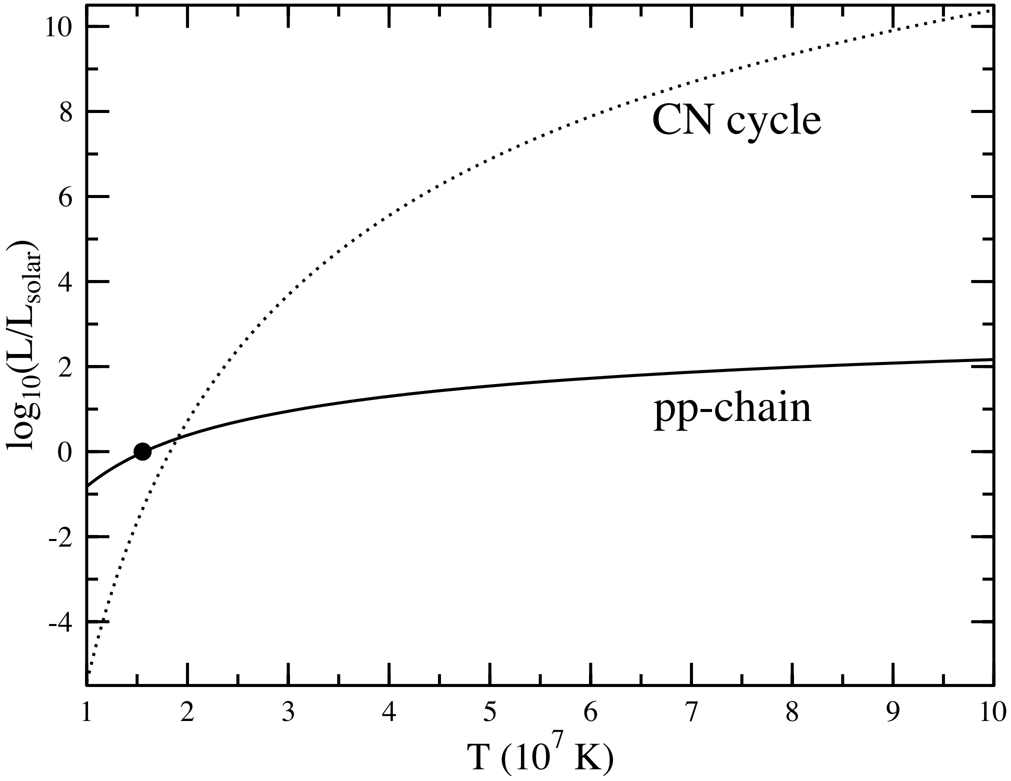

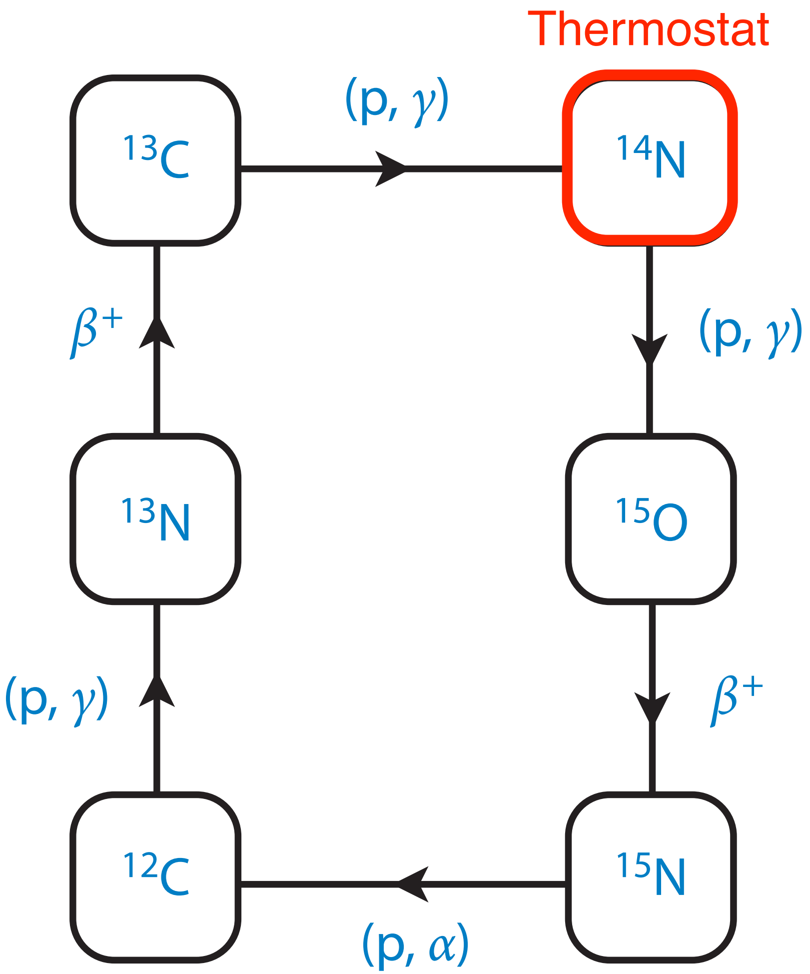

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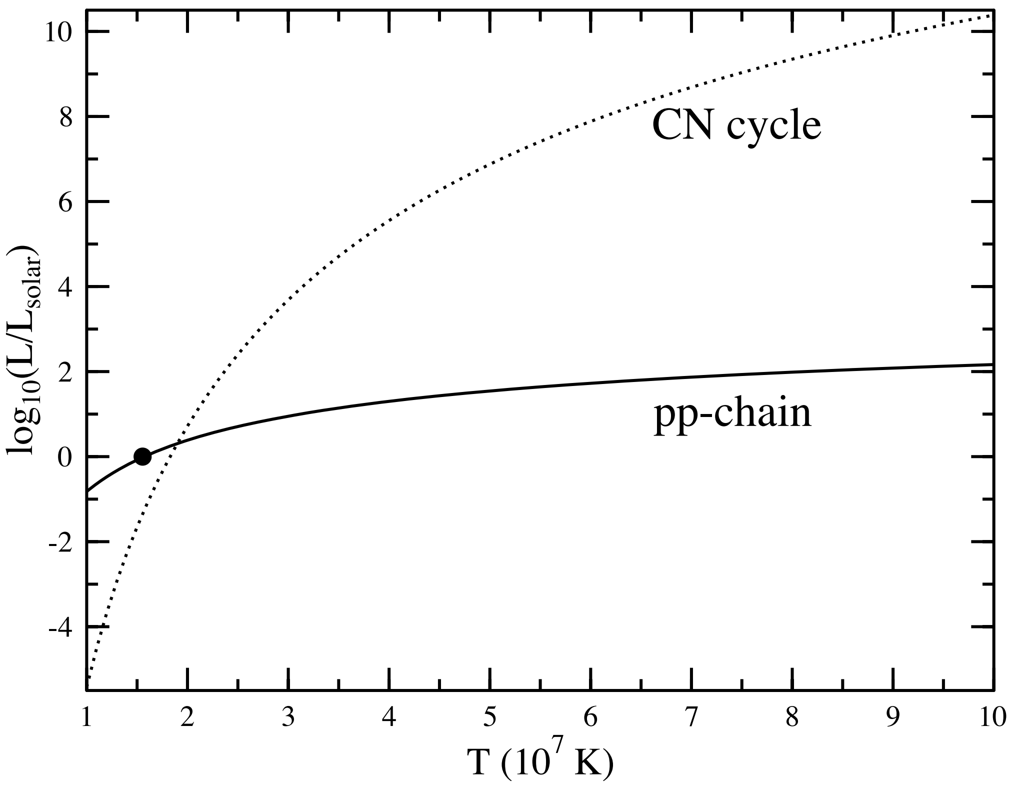

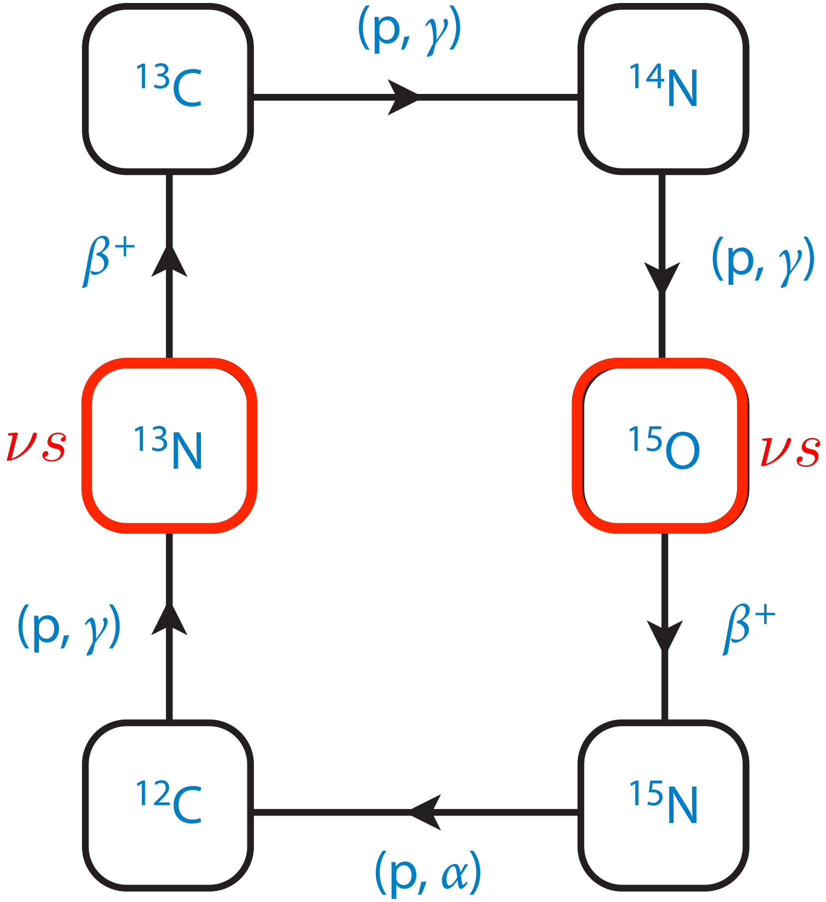

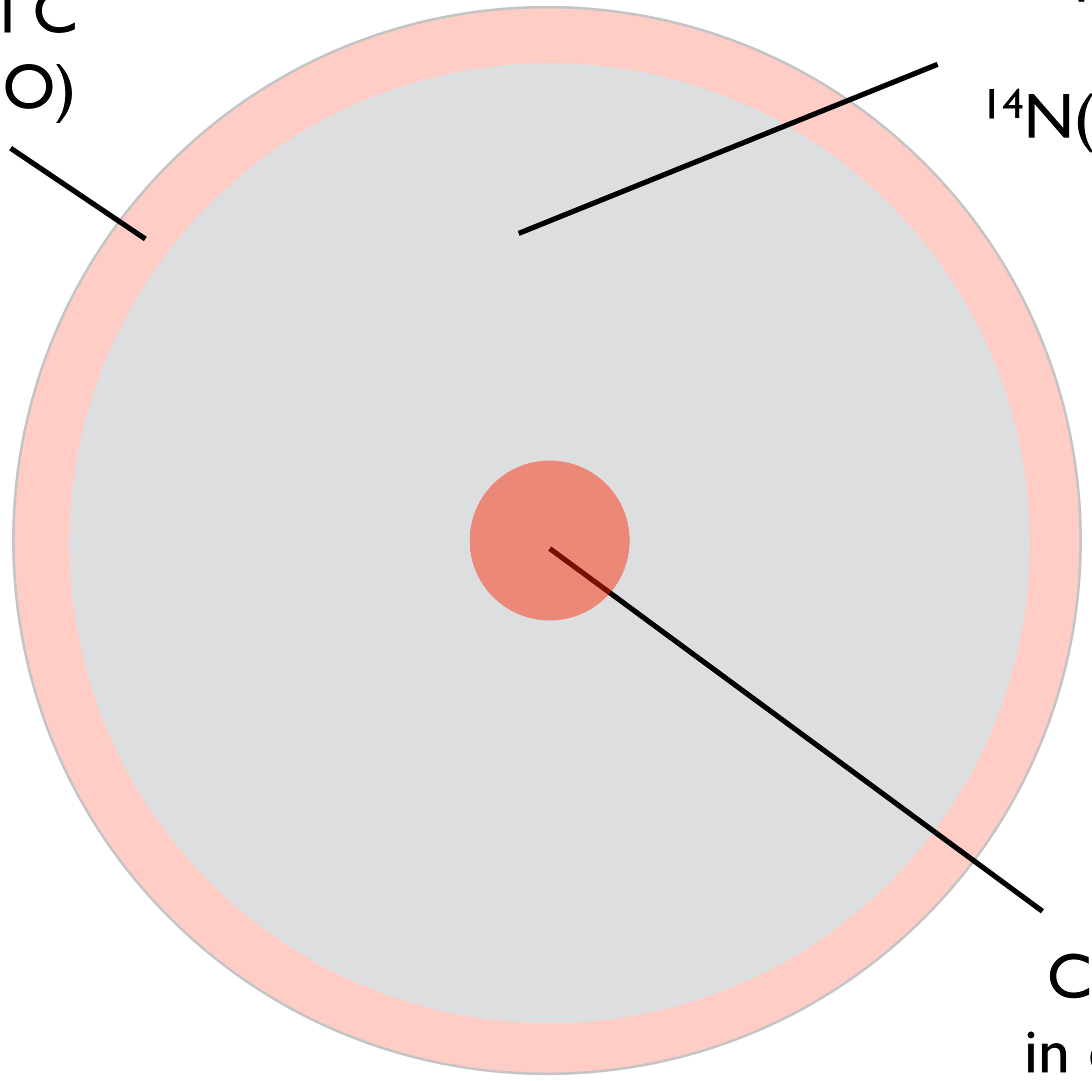

present day burning
of primordial C
$\nu(^{13}N) - \nu(^{15}O)$

primordial C
burned:
$^{14}N(p, \gamma)$ bottleneck

CN burning
in equilibrium
@ $T_7 \sim 1.5$
$\nu(^{13}N)+\nu(^{15}O)$

solar core

- measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199\ \mathrm{MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732\ \mathrm{MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

  depending on both C+N and C (the principal solar metals)

- these fluxes depend on the core temperature T (metal-dependent) but also have an additional linear dependence on core metallicity

while the Sun is complicated,
the bottom line in simple

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\left[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})\right]$$

a thermometer for the solar core:
measured to 2% by SuperKamiokande

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\left[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})\right]$$

what we want to know: the primordial core abundance of C + N (in units of SSM best value)

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

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$$\times \left[1 \underbrace{\pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D})} \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})\right]$$

the entire solar model dependence: luminosity, metalicity, solar age, etc., eliminated -- except for small residual differential effects of heavy element diffusion (necessary to relate today's neutrino measurements to core abundance 4.7 b.y. ago)

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some work needed here: $^{7}\mathrm{Be}(\mathrm{p},\gamma)$, $^{14}\mathrm{N}(\mathrm{p},\gamma)$

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SNO’s marvelous measurement
of the weak mixing angle

a future neutrino measurement: Borexino, SNO+, JinPing....?

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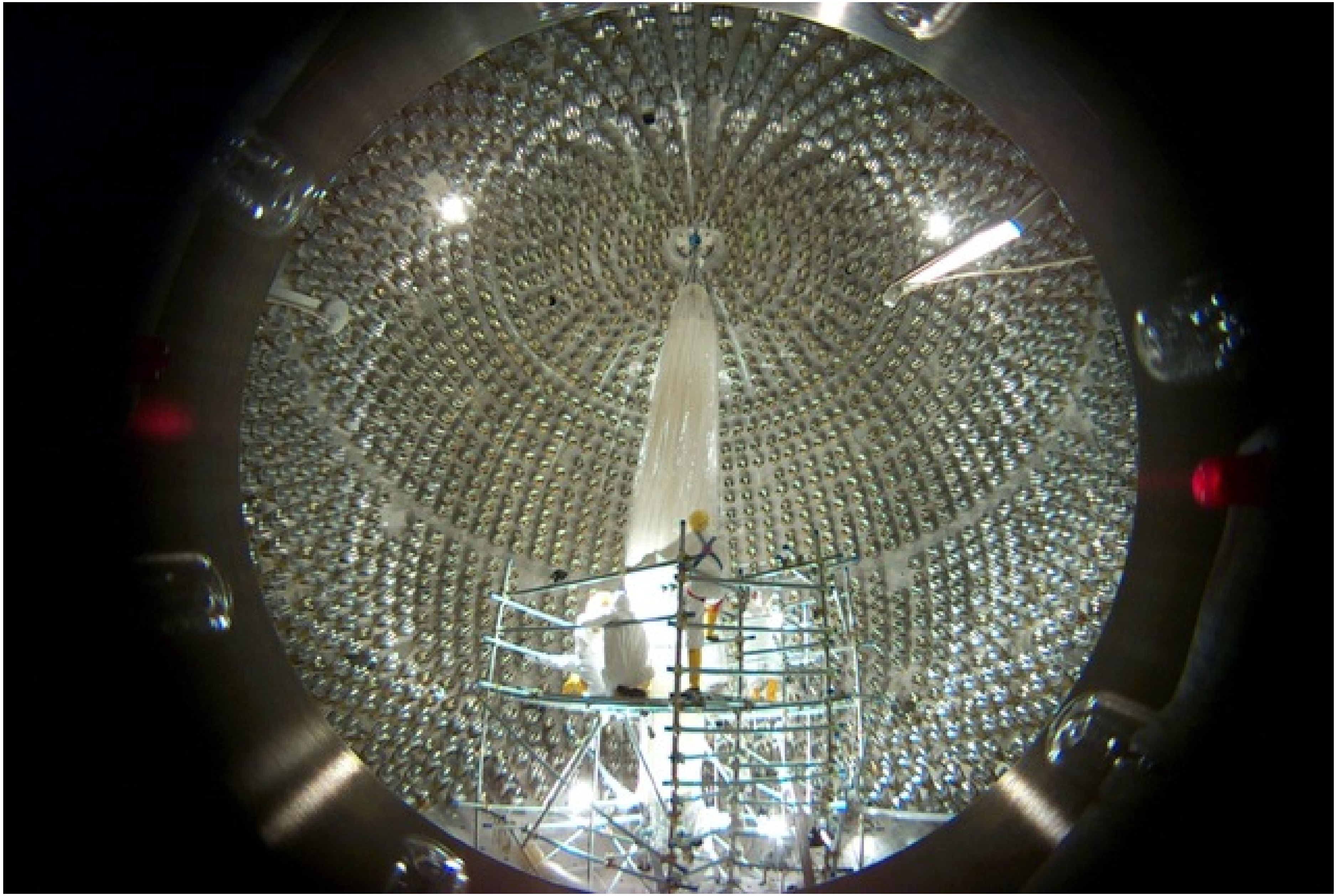
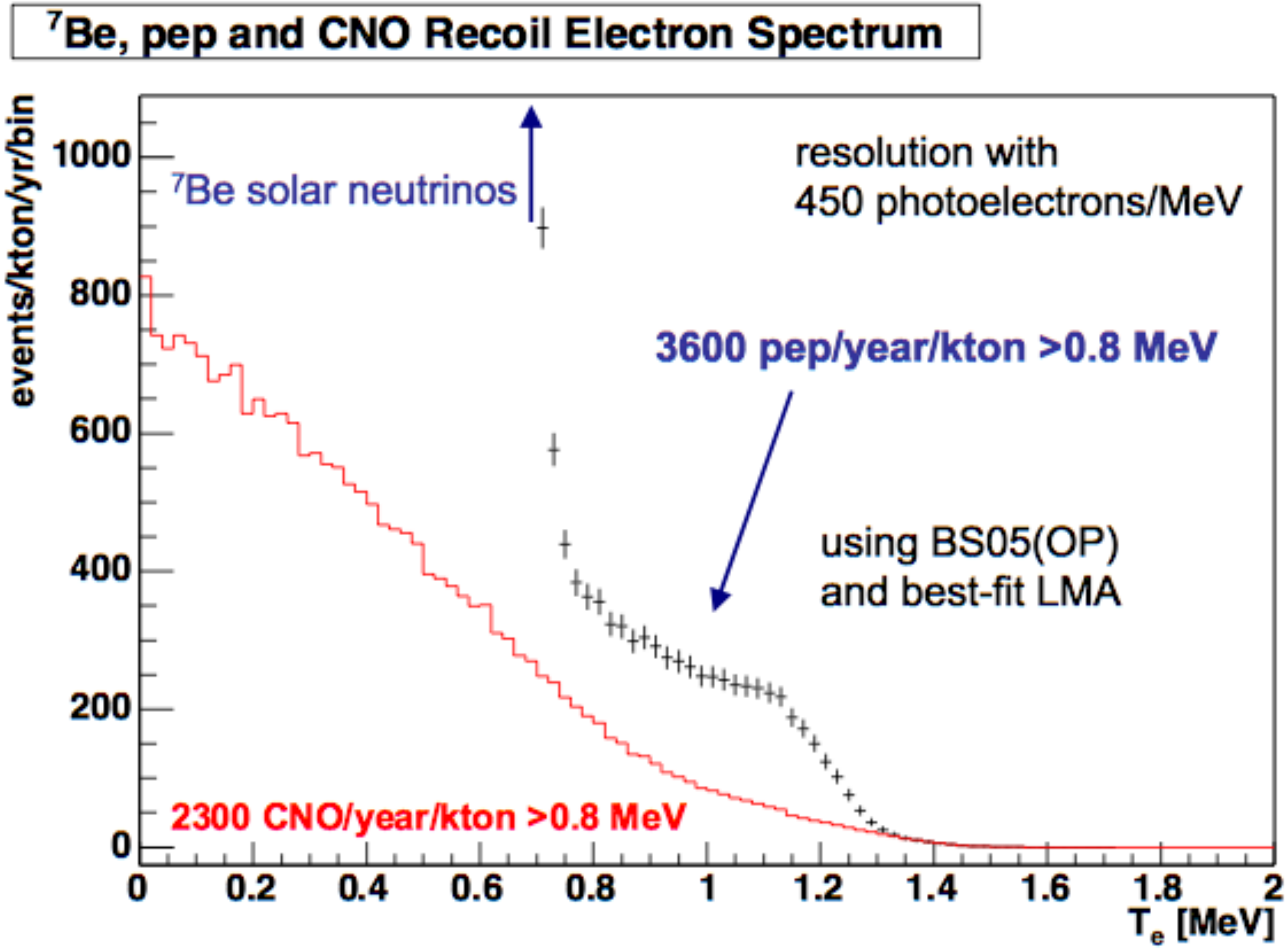


Both SNO+ and Borexino have considered such a measurement

Depth crucial: SNO+/Borexino ^{11}C ratio is 1/70

SNO+ simulation



(from Mark Chen)

this measurement is fundamental

❑ probes the most pristine primordial gas from which our solar system formed, at an interesting level of precision (10%)

❑ the first opportunity in astrophysics to directly compare surface and deep interior (primordial) compositions

❑ a first step in developing a “standard solar system model” that would link solar ν physics, solar system formation, planetary astrochemistry

summary

1960s

test the solar model: precise determination of core temperature

summary

1990s

new neutrino physics:
precise weak interaction parameters

solar
and
atmospheric
neutrinos

summary

2000s

lab verification:
KamLAND
Daya Bay, RENO
T2K, NOVA,
…

summary

2020:
challenges

Long baseline experiments to determine hierarchy, CP phase

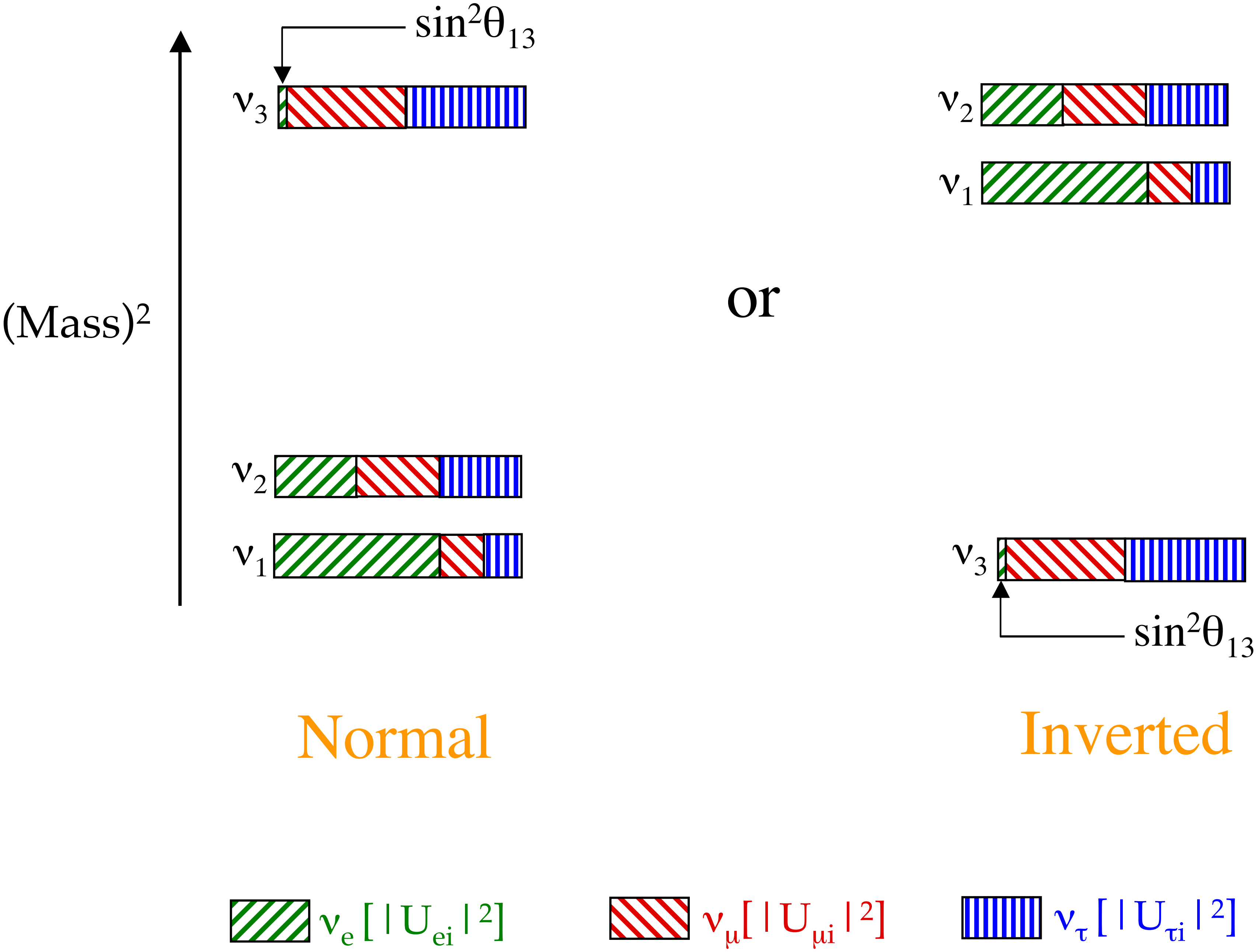
Double beta decay to test neutrino Dirac/Majorana character

Precise cosmological tests to determine absolute mass

summary

2020s

using neutrinos as a precise probe of our Sun, other astrophysics



solar, atmospheric, accelerator, reactor experiments