What's the Matter Here?
Experimental Neutrino Probes of Matter/Antimatter Differences

- Conceptual View of Matter vs. Antimatter
- Neutrinoless Double Beta Decay Searches
- Searching of CP violation with Neutrinos
- Future Opportunities

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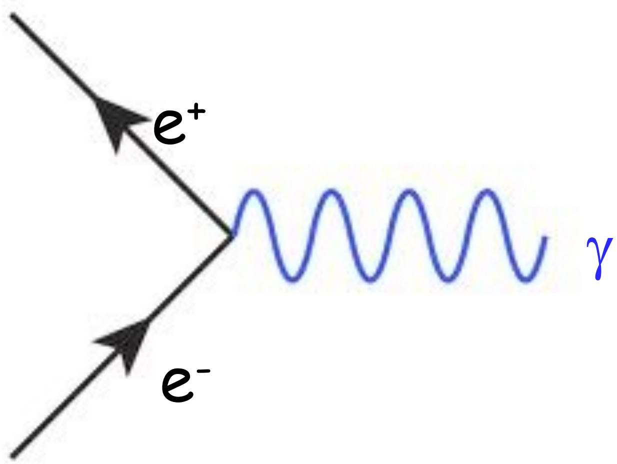
SLAC Summer Institute 2022

Matter and Antimatter

How is e^+ different from e^-?

Opposite charges, but otherwise identical.

When e^+ meets e^- …



Annihilation!

Matter and Antimatter

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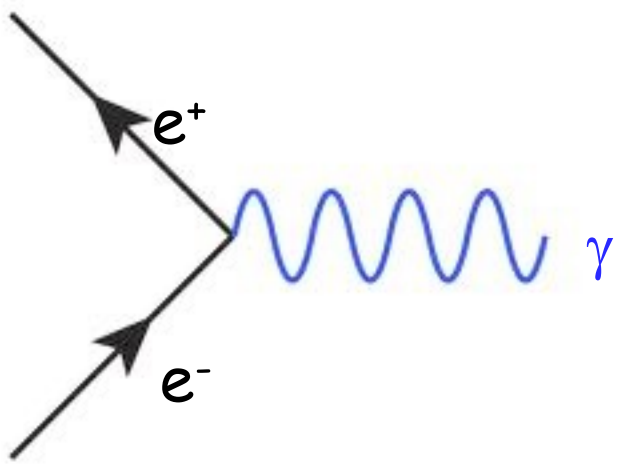
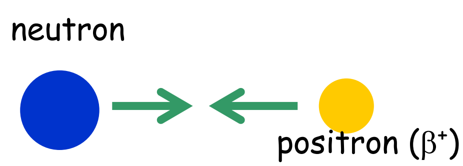


Annihilation!

But!



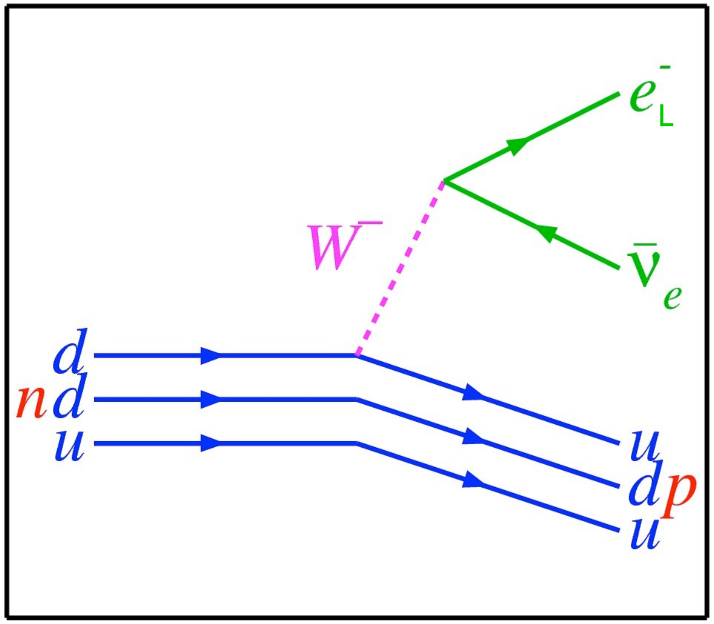
No big deal

Nothing really "anti" about antimatter….

Matter and Antimatter

OK, an important detail

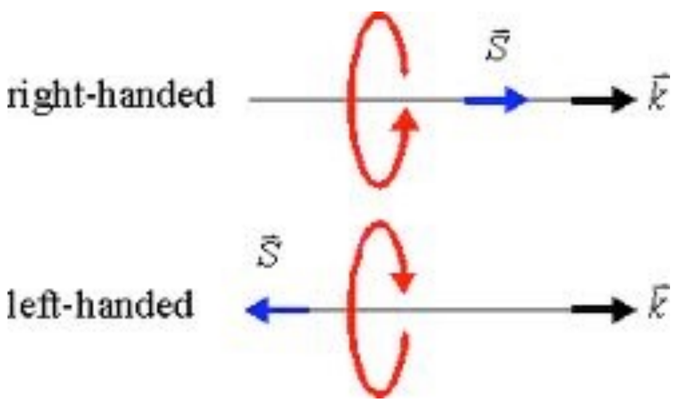
Modern view of β decay



The weak interaction violates parity--it only couples to particles of a particular "handedness" (chirality):

In this reaction, the electron must be left-handed.

If the electron were massless, this handedness is the same as "helicity:"

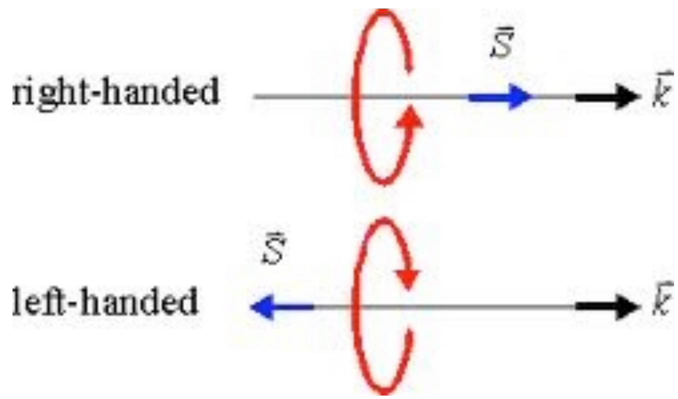


spin clockwise viewed along direction of motion (like a screw)

Matter and Antimatter

OK, an important detail

Weak interaction makes only left-handed electrons and right-handed positrons.



But the electromagnetic interaction doesn't care about handedness, and so we have in Nature four kinds of "electron"

$$e^-_L, e^-_R, e^+_L, e^+_R$$

Weak+EM

EM only

Weak+EM

Matter and Antimatter

Do They Behave Differently?

Obvious answer---Yes:

Universe is made entirely from matter:

- Protons and neutrons (up quarks and down quarks)
- Electrons

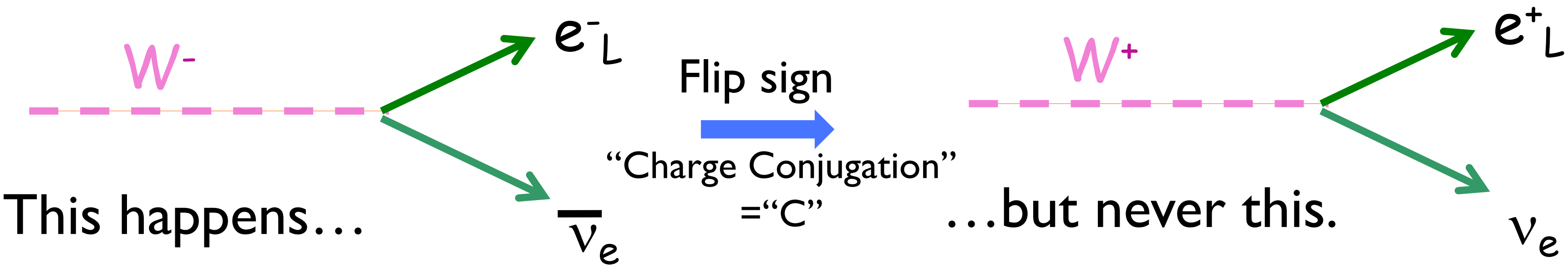
Somewhere along the line, they must have behaved differently.

Do we see any processes in which they do behave differently?

Matter and Antimatter

Do They Behave Differently?

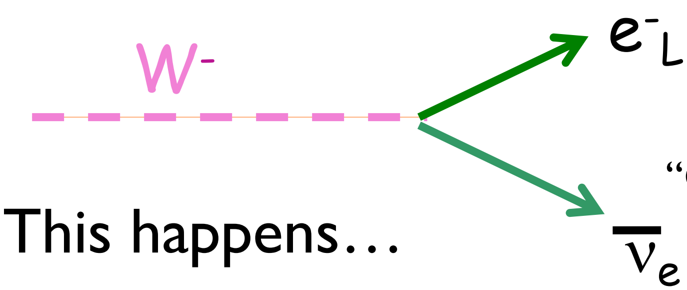
Simple answer---Yes:



Matter and Antimatter

Do They Behave Differently?

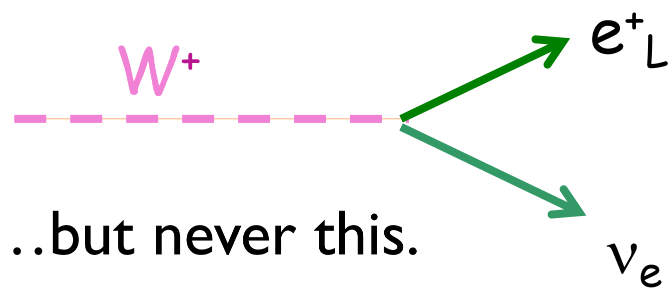
Simple answer---Yes:



This happens…

Flip sign

“Charge Conjugation”
=“C”

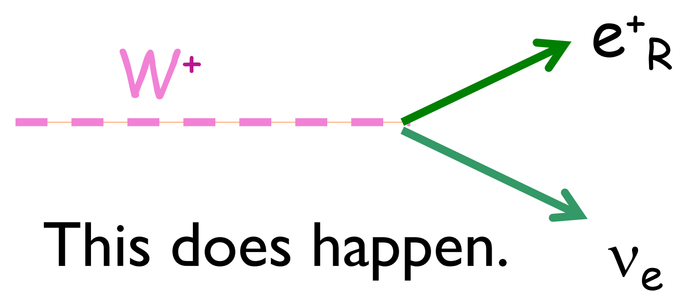


…but never this.

Reflect Parity = “P”

Slightly more complex answer---No:

Once we account for parity violation by weak interaction (C*P=CP) we expect matter and antimatter to do the same thing.

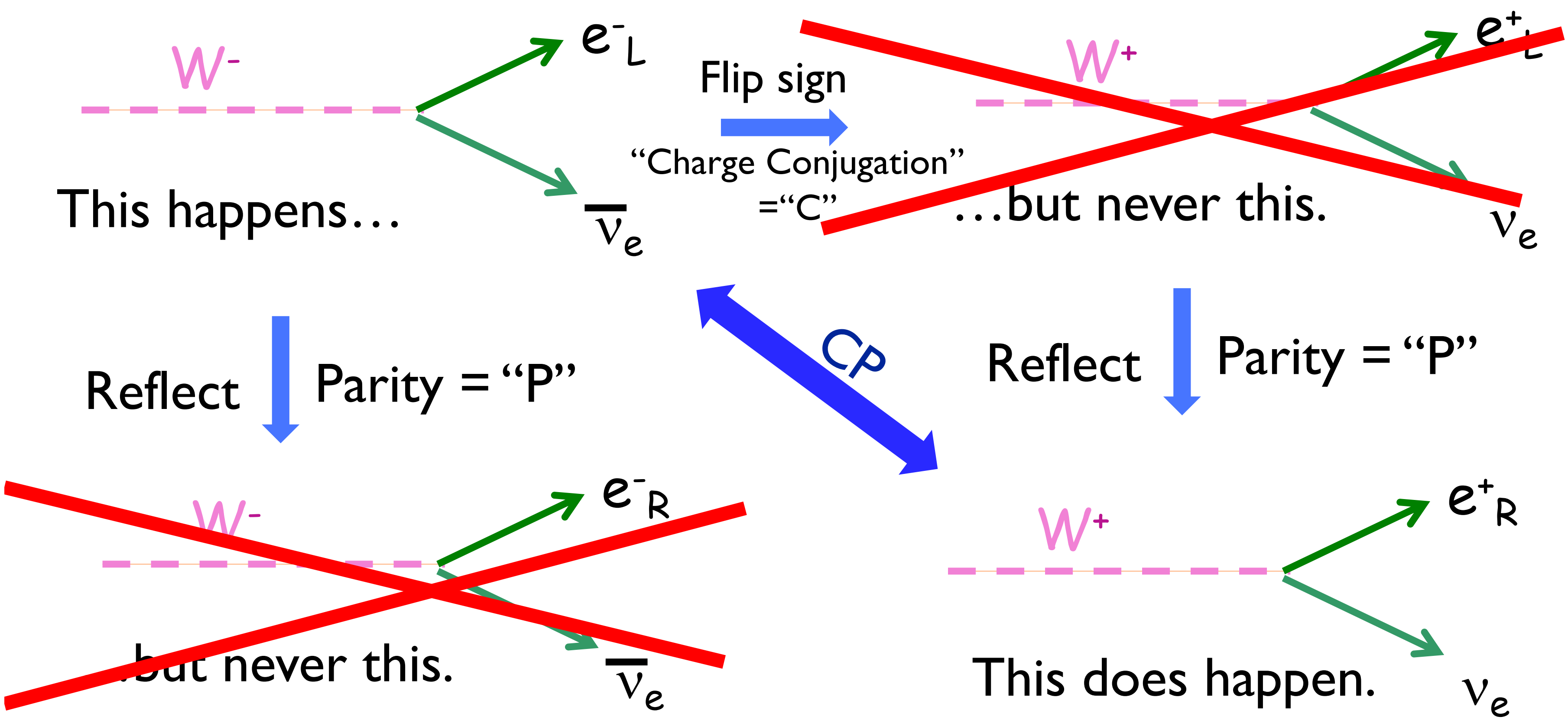


This does happen.

Matter and Antimatter

Do They Behave Differently?

Slightly more complex answer---No:



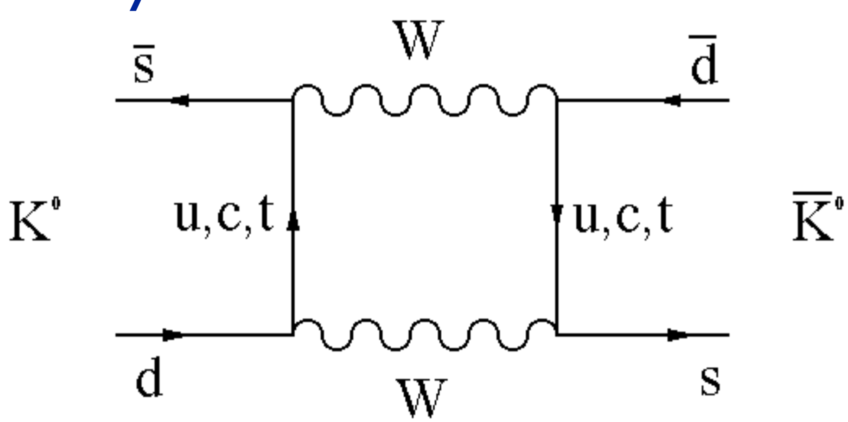
Matter and Antimatter

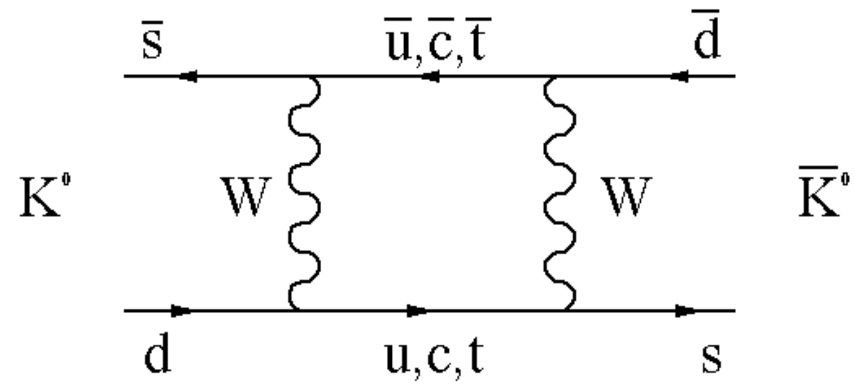
Do They Behave Differently?

Even more complex answer---Yes:

Neutral kaons are produced in eigenstates of strong interaction—

But they can mix via weak interaction





So eigentstates of weak interaction (and CP) are actually

$$K_1 = \tfrac{1}{\sqrt{2}}\left(K^0 - \overline{K}^0\right) \quad \Rightarrow \quad CP\left(K_1\right) = \tfrac{1}{\sqrt{2}}\left(-\overline{K}^0 + K^0\right) = K_1 \quad \left\langle CP \right\rangle = +1$$

$$K_2 = \tfrac{1}{\sqrt{2}}\left(K^0 + \overline{K}^0\right) \quad \Rightarrow \quad CP\left(K_2\right) = \tfrac{-1}{\sqrt{2}}\left(\overline{K}^0 + K^0\right) = -K_2 \quad \left\langle CP \right\rangle = -1$$

Matter and Antimatter

Do They Behave Differently?

Even more complex answer---Yes:

$$K_1 \rightarrow 2\pi \quad \langle CP \rangle_{2\pi} = +1$$

$$K_2 \rightarrow 3\pi \quad \langle CP \rangle_{3\pi} = -1$$

But sometimes (~0.2%): $K_2 \rightarrow 2\pi \quad \langle CP \rangle: \quad -1 \rightarrow +1$

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

Modern explanation

$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{td} = |V_{td}|e^{-i\beta}$$

Quarks and antiquarks have different sign for complex phase---confirmed by observing CP violation for B^0 mesons. It is a tiny effect.

Matter and Antimatter

CP Violation and the Universe

"Sakharov Conditions":

Observed asymmetry between matter and antimatter happens if:

- Interactions outside of thermal equilibrium
- At least one process that violates "baryon number"
- CP Violation

But degree of CP violation observed in the quark sector not large enough to generate observed asymmetry.

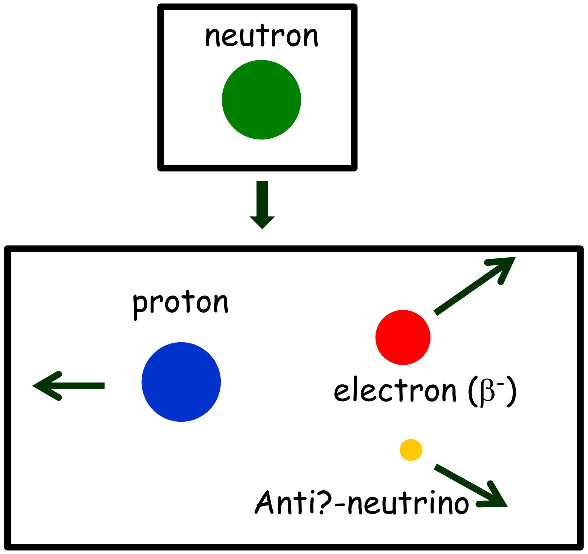
Matter and Antimatter

The Story So Far

- Antimatter is perhaps not so exotic---nothing "anti" about it
- It behaves differently than matter (CPV) but mechanism is simple
- Not enough of a difference to explain why the Universe is matter

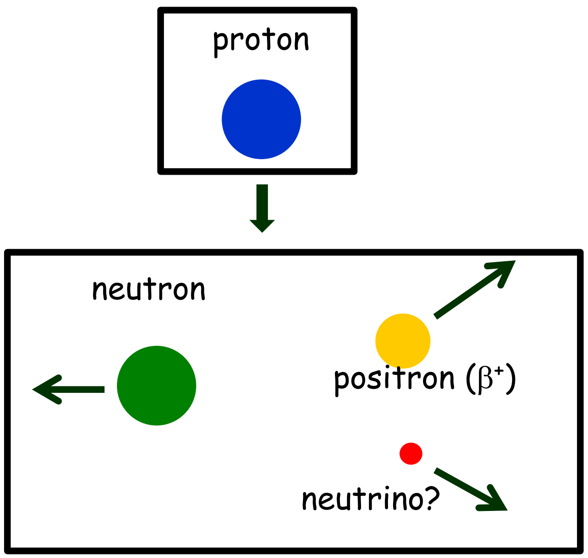
So how about neutrinos and antineutrinos…?

Beta Decay and Anti-Beta Decay



$$\underset{\uparrow \atop \text{particle}}{n} \longrightarrow \underset{\uparrow \atop \text{particle}}{p} + \underset{\uparrow \atop \text{particle}}{e^{-}} + \underset{\uparrow \atop \text{Anti?particle}}{\overline{\nu}}$$

If electrons are matter and positrons antimatter, makes sense to "balance" reaction with another antiparticle or particle.



$$\underset{\uparrow \atop \text{particle}}{p} \longrightarrow \underset{\uparrow \atop \text{particle}}{n} + \underset{\uparrow \atop \text{antiparticle}}{e^{+}} + \underset{\uparrow \atop \text{particle?}}{\nu}$$

Neutrino and Antineutrino Interactions

Inverse Beta Decay

$$n \rightarrow p + e^{-} + \overline{\nu} \qquad \nu + n \rightarrow p + e^{-}$$

If this happens… …then this also happens.

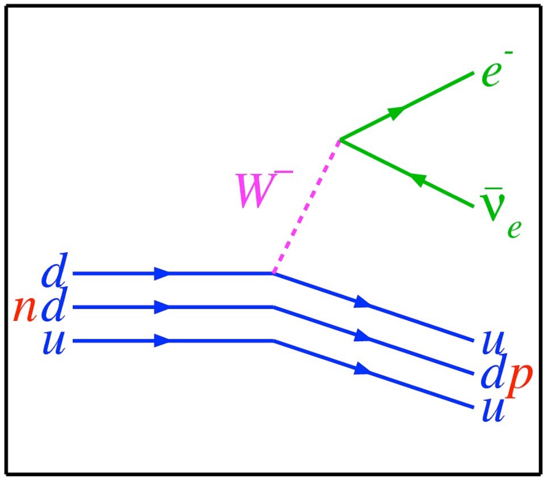
$$p \rightarrow n + e^{+} + \nu \qquad \underbrace{\overline{\nu}}_{\text{antiparticle}} + \underbrace{p}_{\text{particle}} \rightarrow \underbrace{n}_{\text{particle}} + \underbrace{e^{+}}_{\text{antiparticle}}$$

If this happens… …then this also happens.

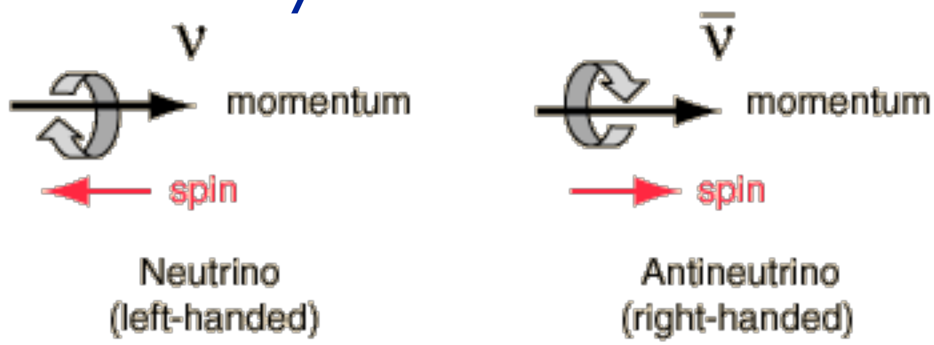
But because neutrinos are massless…

Standard Model Neutrinos

Why massless?



Beta decay experiments all consistent with antineutrinos being always right-handed, and neutrinos always left-handed.



Massless neutrinos travel at the speed of light, but…

If νs have mass, they can be outrun—this changes helicity:

Momentum direction flips but spin is the same…

A left-handed neutrino becomes a right-handed neutrino

We never “see” the right-handed guy, so m_ν=0.

Standard Model Neutrinos

So, unlike electrons with four states

$$e^-_L, e^-_R, e^+_L, e^+_R$$

Neutrinos have just two: $\nu_L, \overline{\nu}_R$

And since: $\nu_L + n \rightarrow p + e^-_L \qquad \overline{\nu}_R + p \rightarrow n + e^+_R$

$$\nu_L + \underset{\substack{\uparrow \\ \text{particle}}}{n} \rightarrow \underset{\substack{\uparrow \\ \text{particle}}}{p} + \underset{\substack{\uparrow \\ \text{particle}}}{e^-_L} \qquad \overline{\nu}_R + \underset{\substack{\uparrow \\ \text{particle}}}{p} \rightarrow \underset{\substack{\uparrow \\ \text{particle}}}{n} + \underset{\substack{\uparrow \\ \text{antiparticle}}}{e^+_R}$$

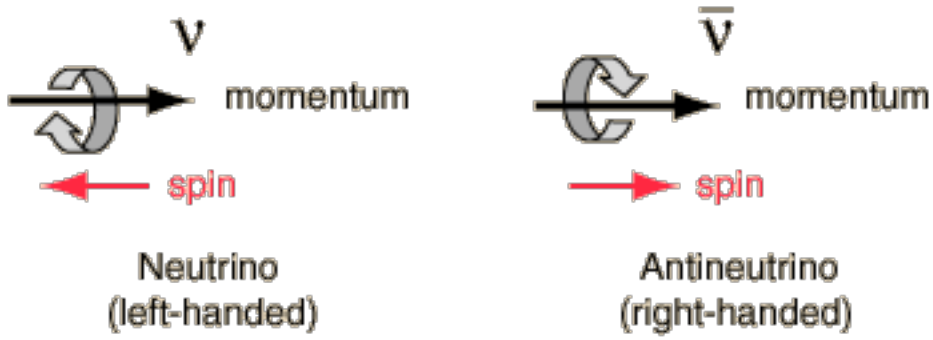
we called ν_R the "antineutrino:"

And it's all good.

But because of discovery of neutrino oscillations, this all got messed up.

ν mass and Chirality

- ν mass messes up our simple picture of νs and anti-νs



Now neutrinos don't have to move at the speed of light;
we can move faster than a ν---looks like it is going backwards

This changes a ν_L into a ν_R, or an anti-ν_R into an anti-ν_L

So What?

Doesn't this make neutrinos just like the other fundamental particles?

So now we can have four neutrino states ("Dirac" neutrinos):

	"Old"		"New" (Have no weak interactions)
"Dirac neutrinos"	ν_L	How are these different?	ν_R
	$\bar{\nu}_R$		$\bar{\nu}_L$

But what's the ***physical*** difference between $\bar{\nu}_R$ and ν_R?

They have:

Same charge (0)
Same mass
Same handedness

They differ only in their "anti"-ness…

So What?

Doesn't this make neutrinos just like the other fundamental particles?

Also strange:

$$\nu_{eL} + n \longrightarrow p + e^- \qquad \cancel{\nu_{eR} + n \longrightarrow p + e^-}$$

$$\bar{\nu}_{eR} + p \longrightarrow n + e^+ \qquad \cancel{\bar{\nu}_{eL} + p \longrightarrow n + e^+}$$

Weak interaction completely ignores ν_R and $\bar{\nu}_L$!

There is another option.

So What?

Doesn't this make neutrinos just like the other fundamental particles?

Maybe there really are only two states:

$$\nu_L , \nu_R$$

So that actually:

$$\nu_{eL} + n \rightarrow p + e^-$$

$$\nu_{eR} + p \rightarrow n + e^+$$

In other words, $\nu = \bar{\nu}$ (the neutrino is its own antiparticle)

"Majorana Neutrinos"

Only way this is *not* true is if "anti-ness" (Lepton Number) is a fundamentally conserved property

So What?

Doesn't this make neutrinos just like the other fundamental fermions?

Not quite:

Majorana neutrinos allow new CP-violating phases:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\textit{Dirac phase}} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\textit{Majorana phases}}$$

Majorana CP + HEAVY ν_R + … = Origin of matter/antimatter asymmetry?

"Leptogenesis"

Majorana or Dirac?

Which way does Ockham's razor cut?

• Neutrinos are Dirac: Look like very other fermion, same higgs mechanism, at the cost of two new (electroweak-immune) states and probably a new global symmetry (or property).

• Neutrinos are Majorana particles: Fewer states, no new gauge symmetry needed, at the cost of two new phases, a nifty new mass-generating mechanism, and possibly renormalizability.

Today, there is no `Standard' Model until this question is resolved

The Model

Neutrinos and Antineutrinos

You often find statements like,
"Neutrinos are unique in that they may be their own antiparticles…"

But let's be clear:
Lepton number conservation is an ***observation*** about the (old) SM Lagrangian, not a fundamental symmetry that is required or enforced.

Lepton flavor number was the same thing, before neutrino mixing.

Majorana vs. Dirac

- How to Decide?

Majorana vs. Dirac

- Idea 1: Colliding Neutrino Beams!

Do they annihilate??

Majorana vs. Dirac

➢Idea 1: Colliding Neutrino Beams!

Do they annihilate??

Good luck with that.

The physics case for neutrino neutrino collisions

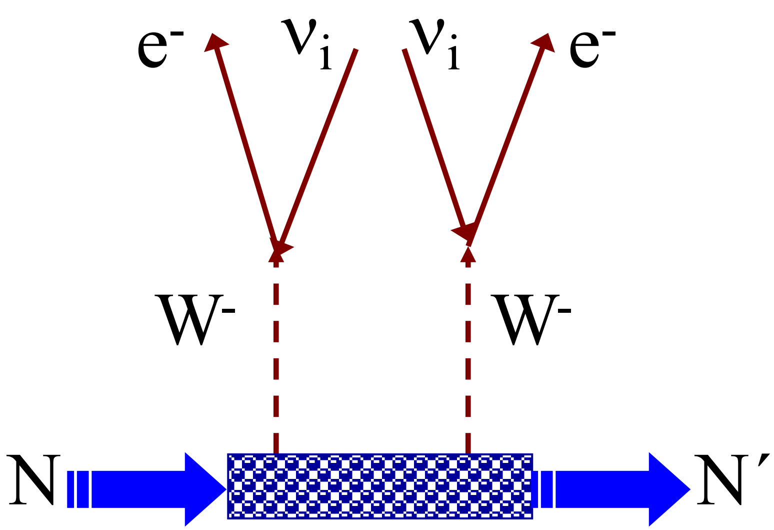
Sitian Qian,[*] Tianyi Yang,[†] Sen Deng, Jie Xiao, Leyun Gao, Andrew Michael Levin,[‡] and Qiang Li[§]
State Key Laboratory of Nuclear Physics and Technology,
School of Physics, Peking University, Beijing, 100871, China

Meng Lu and Zhengyun You
School of Physics, Sun Yat-Sen University, Guangzhou 510275, China

Majorana vs. Dirac

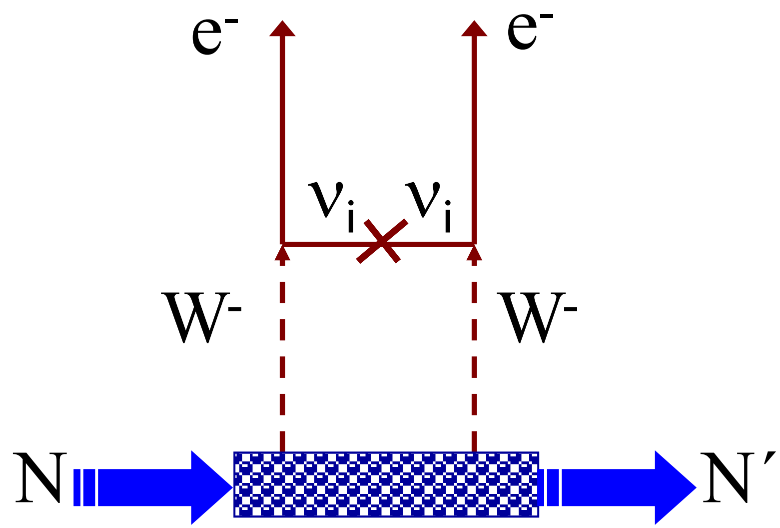
➢Idea 2: 2νββ vs. 0νββ

Two-neutrino double beta decay



Rare process with half-lives of ~10^{21} years

Neutrinoless double beta decay



$$T_{1/2} \propto m_{\beta\beta}^2 \sim 10^{27} \text{ years}$$

Mass is <u>mixed</u> average, including phases

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

$$m_{\beta\beta} = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha_1} + s_{13}^2 m_3 e^{i\alpha_2}|$$

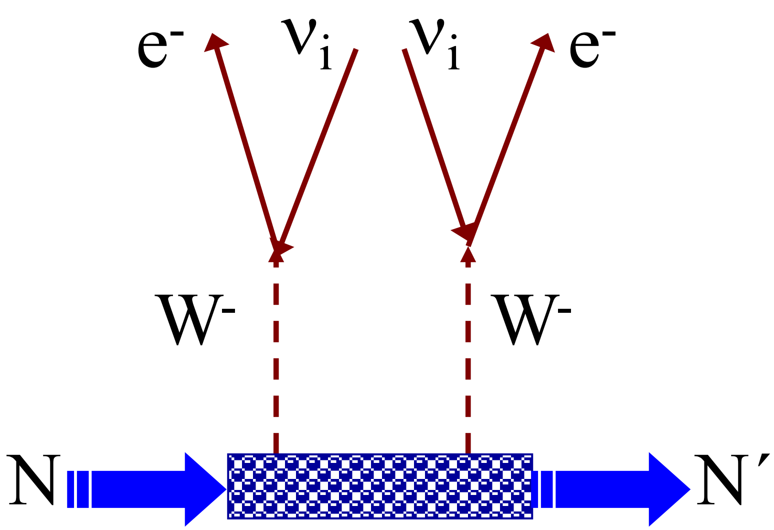
Large coeffs. *Small coeff.*

Fortunately, Avogadro's number is very big.
Unfortunately, one mixing angle is very small.

Majorana vs. Dirac

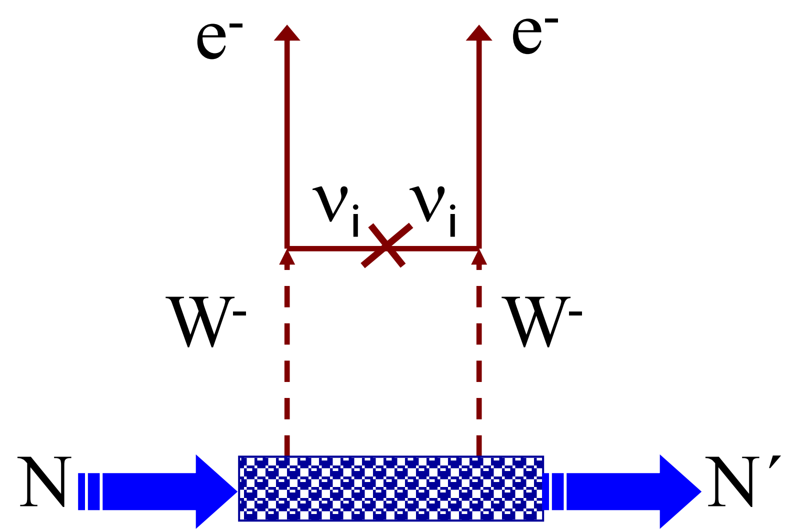
➢Idea 2: 2νββ vs. 0νββ

Two-neutrino double beta decay



Rare process with half-lives of ~10[21] years

Neutrinoless double beta decay



$$T_{1/2} \propto m_{\beta\beta}^2 \sim 10^{27}\ \text{years}$$

Mass is <u>mixed</u> average, including phases

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

$$m_{\beta\beta} = 0.69 m_1 + 0.72 m_2 e^{2i\lambda_2} + 0.02 m_3 e^{2i(\lambda_3 - \delta_{CP})}$$

Large coeffs.

Small coeff.

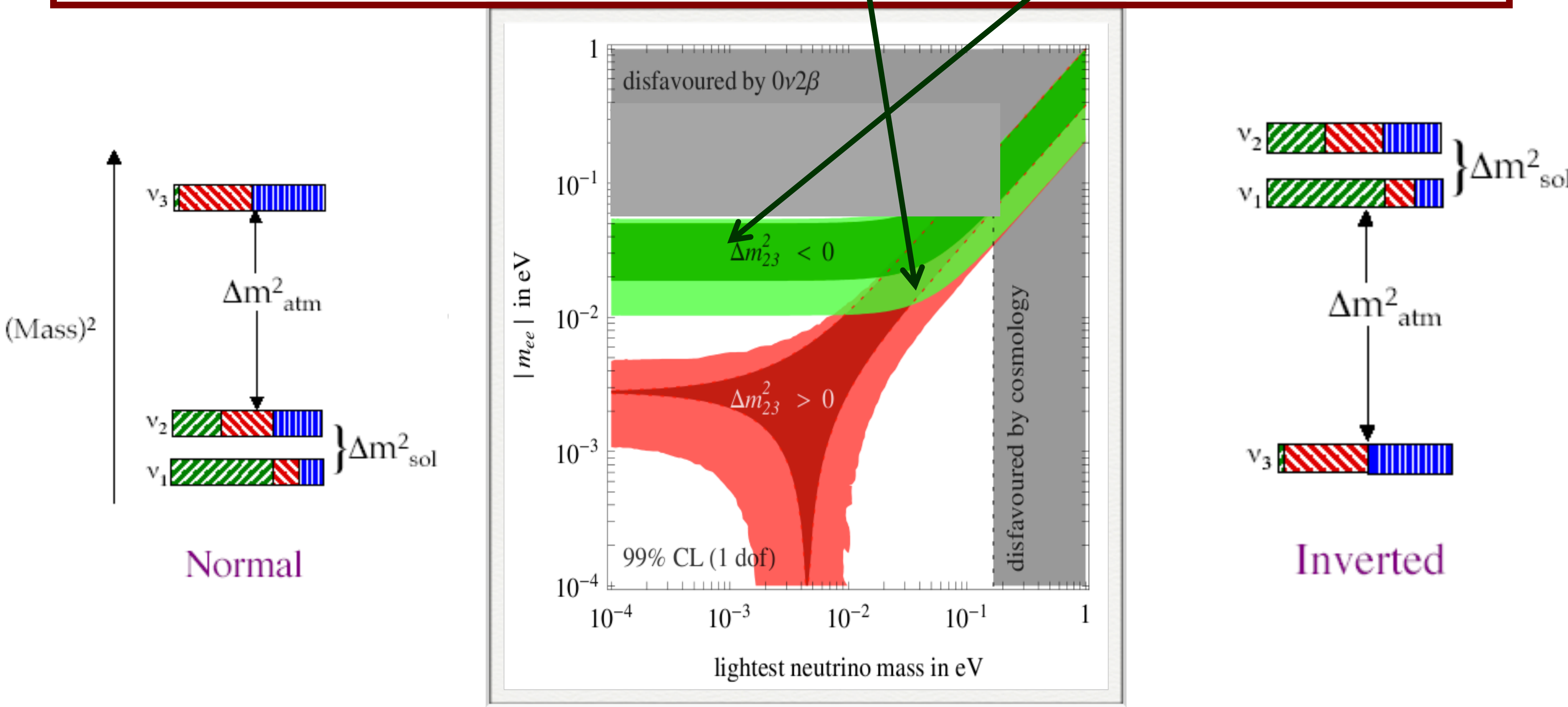
Fortunately, Avogadro's number is very big.

Unfortunately, one mixing angle is very small.

0νββ:Majorana Nature and m_ν

➢Desired Sensitivity

We `hope' that either mass ordering is "inverted" or masses are somewhat degenerate.



$$(m_{\beta\beta} \equiv m_{ee} \equiv \langle m_\nu \rangle \equiv m_\nu)$$

$0\nu\beta\beta$ Experiments

$$m_{\beta\beta} = |c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha_1} + s_{13}^2 m_3 e^{i\alpha_2}|$$

m_1, m_2, m_3 and phases unknown

Axial vector coupling---Somewhat uncertain

We measure this

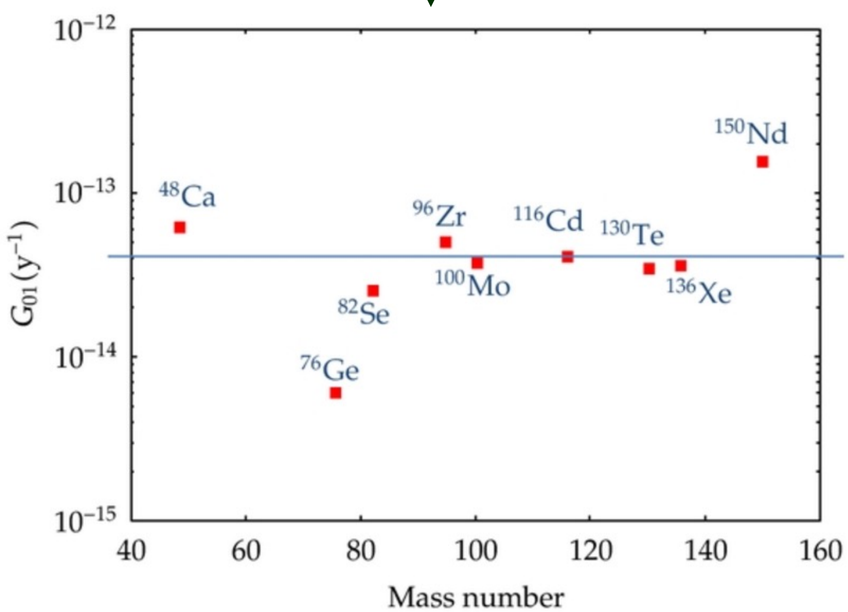
$$\frac{1}{T_{1/2}} = G\, g_A^4\, \mathcal{M}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

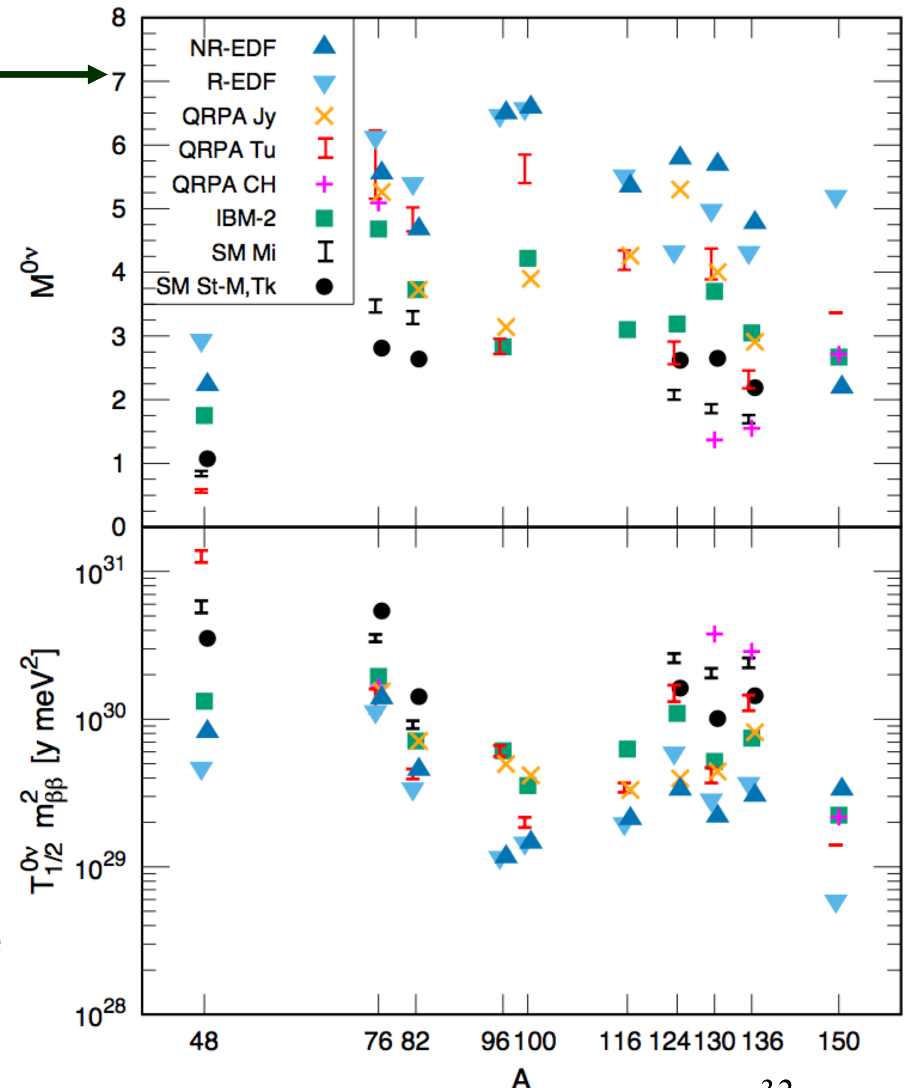
Calculable phase space

Nuclear matrix element---
Very hard to calculate!

$0\nu\beta\beta$ Experiments

$$\frac{1}{T_{1/2}} = G\, g_A^4\, \mathcal{M}^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$





Top of inverted ordering has $m_{\beta\beta}$~50 meV
So need to measure
$T_{1/2}$>1x10^{25} to 3x10^{27} depending on isotope

$0\nu\beta\beta$ Experiments

To see a signal in 1 year when half-life is 10^{27} y,

$$t_{1/2}^{0\nu} = \ln 2 \, T \, \varepsilon \, \frac{N_{\beta\beta}}{N_{\text{peak}}}$$

You need ~ 1.4 x 10^{27} atoms ~ 2400 moles of isotope (~ 200 kg ^{76}Ge)

If you have **zero background** and perfect efficiency

Otherwise…

$$t_{1/2}^{0\nu} = \ln 2 \ \mathrm{T} \ \epsilon \ \frac{N_{\beta\beta}}{n_\sigma \sqrt{B}}$$

Where n_σ is "significance of desired detection" in gaussian σ
and B = expected background counts.
For 10 expected background counts in T, and 3σ, you need ~10x more

And isotopic enrichment is not cheap.

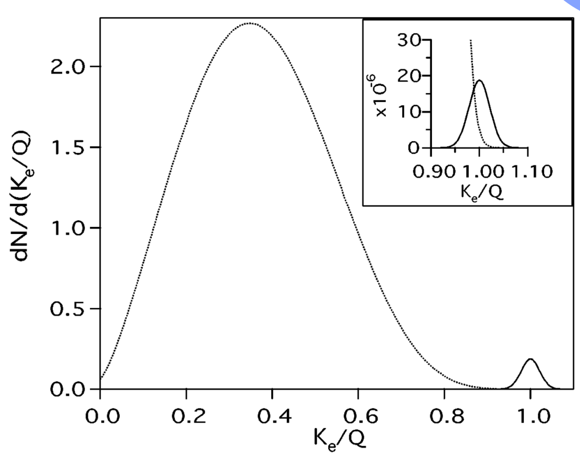
0νββ Experiments

Backgrounds

A “perfect” ββ experiment

Pure isotope

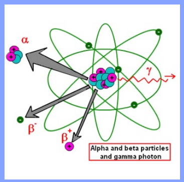
Elliot and Vogel
Annu. Rev. Nucl. Part. Sci. 2002. 52:115–51



Only background from 2νββ decays—Depends on resolution and 2νββ matrix element (2νββ NME not the same as 0νββ NME)

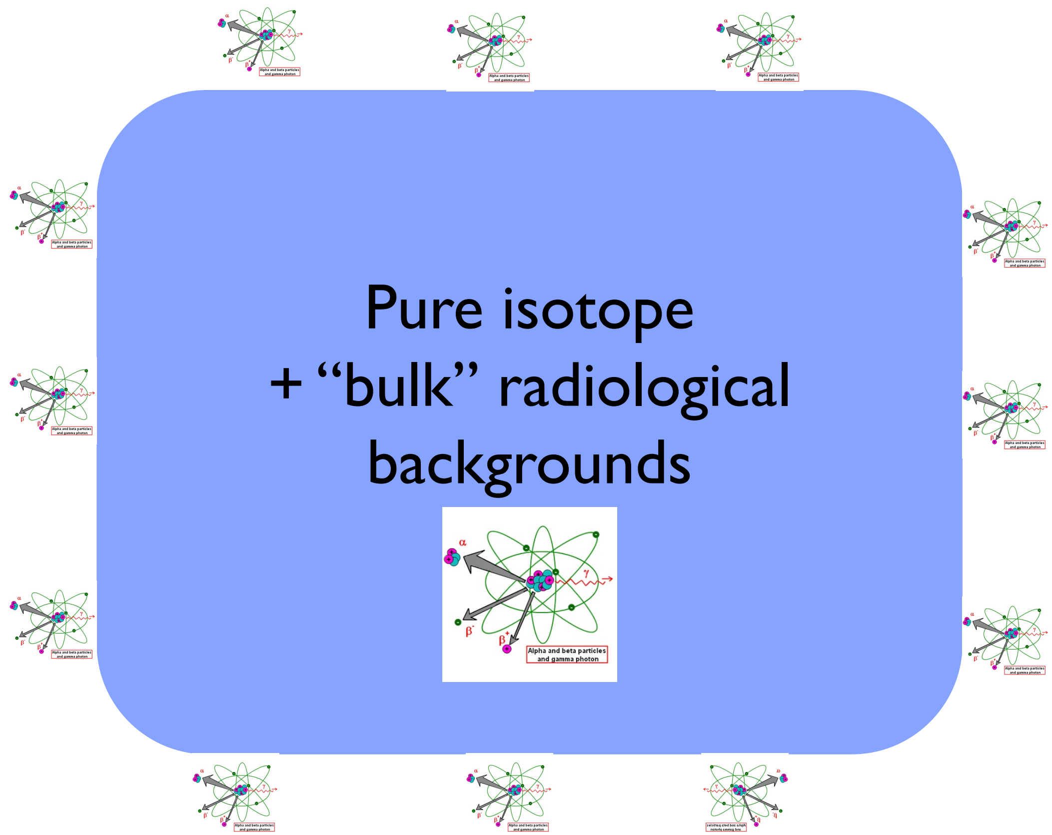
$0\nu\beta\beta$ Experiments
Backgrounds

Pure isotope
+ “bulk” radiological
backgrounds



0νββ Experiments

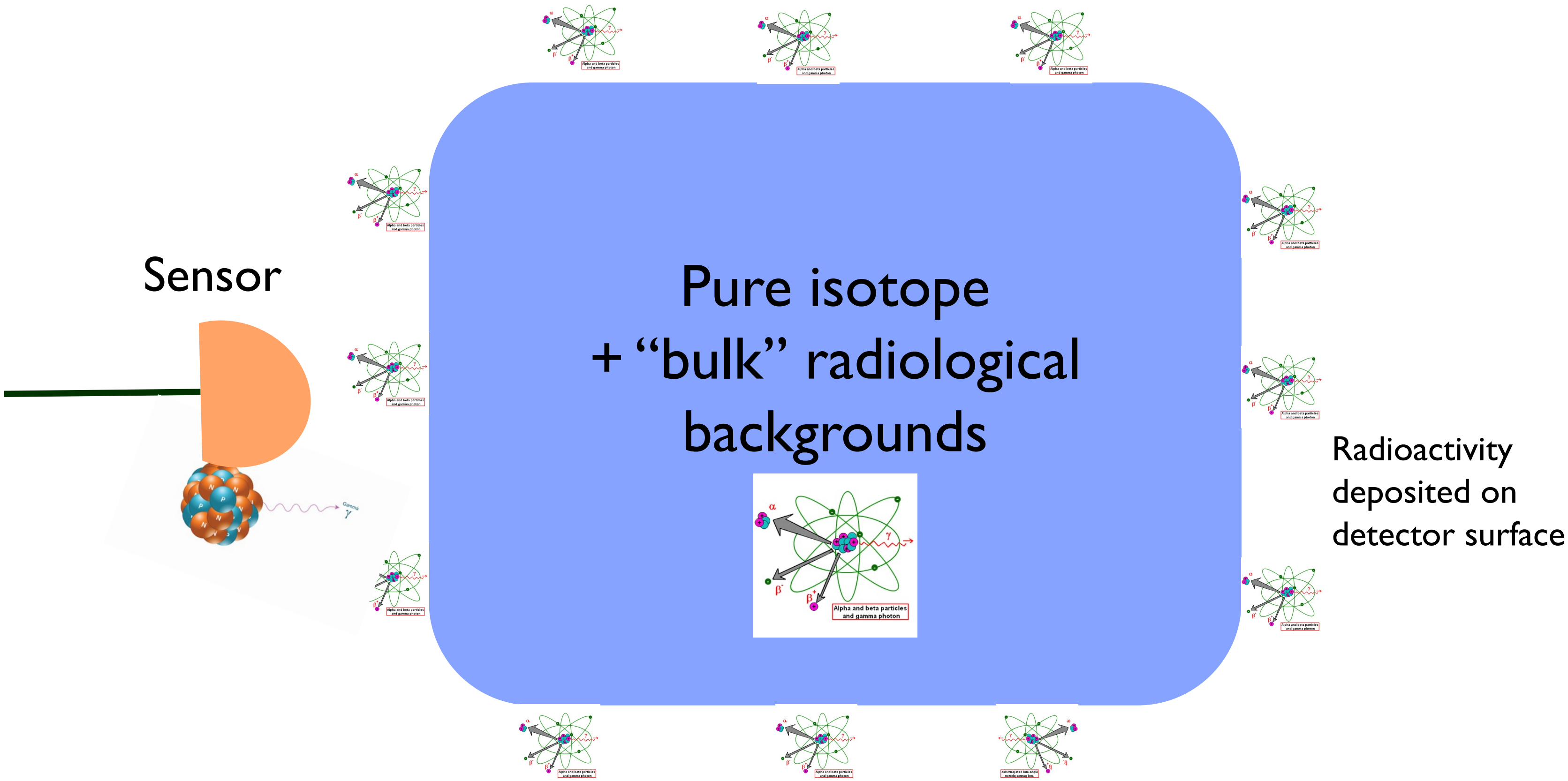
Backgrounds



Radioactivity
deposited on
detector surface

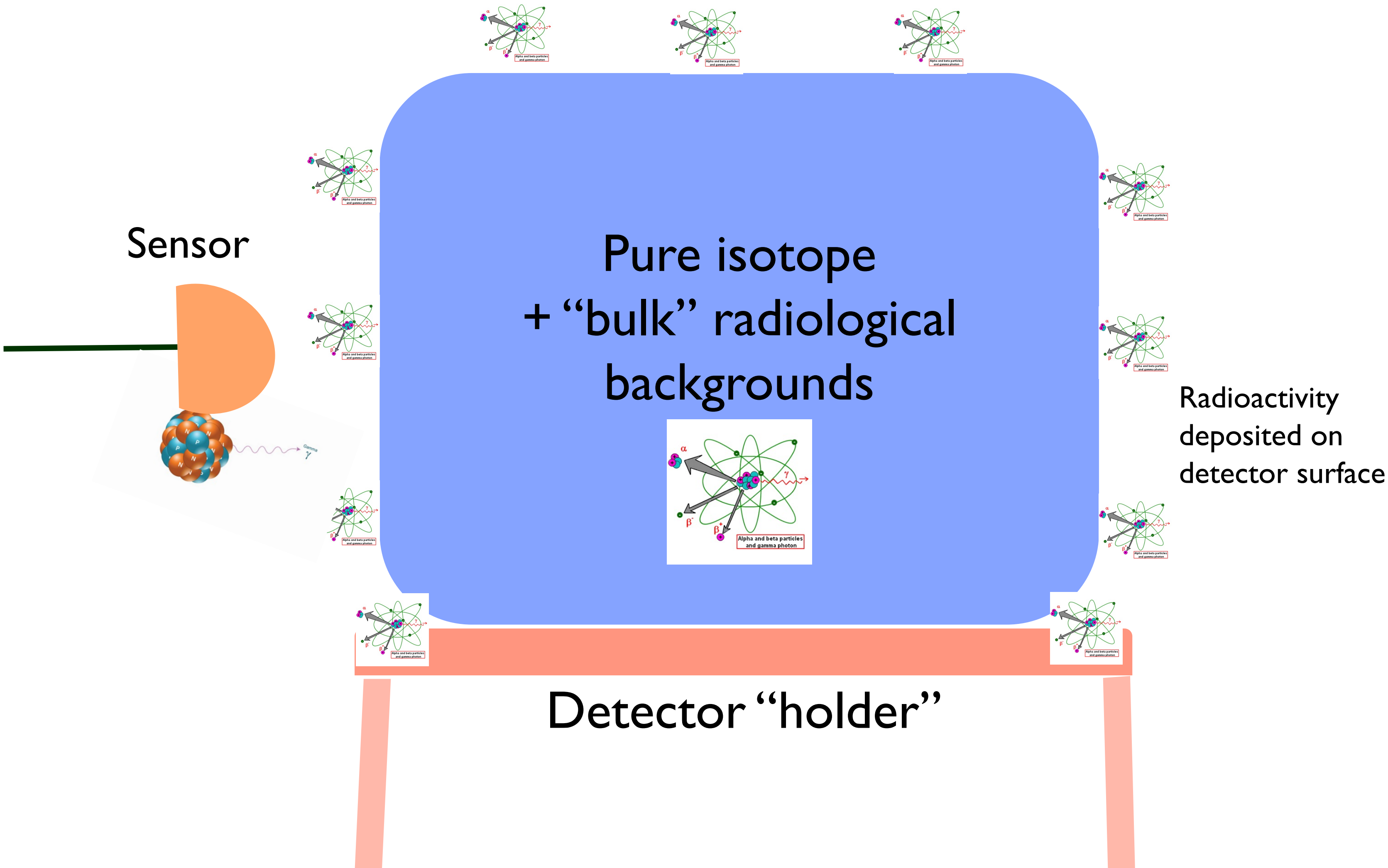
0νββ Experiments

Backgrounds



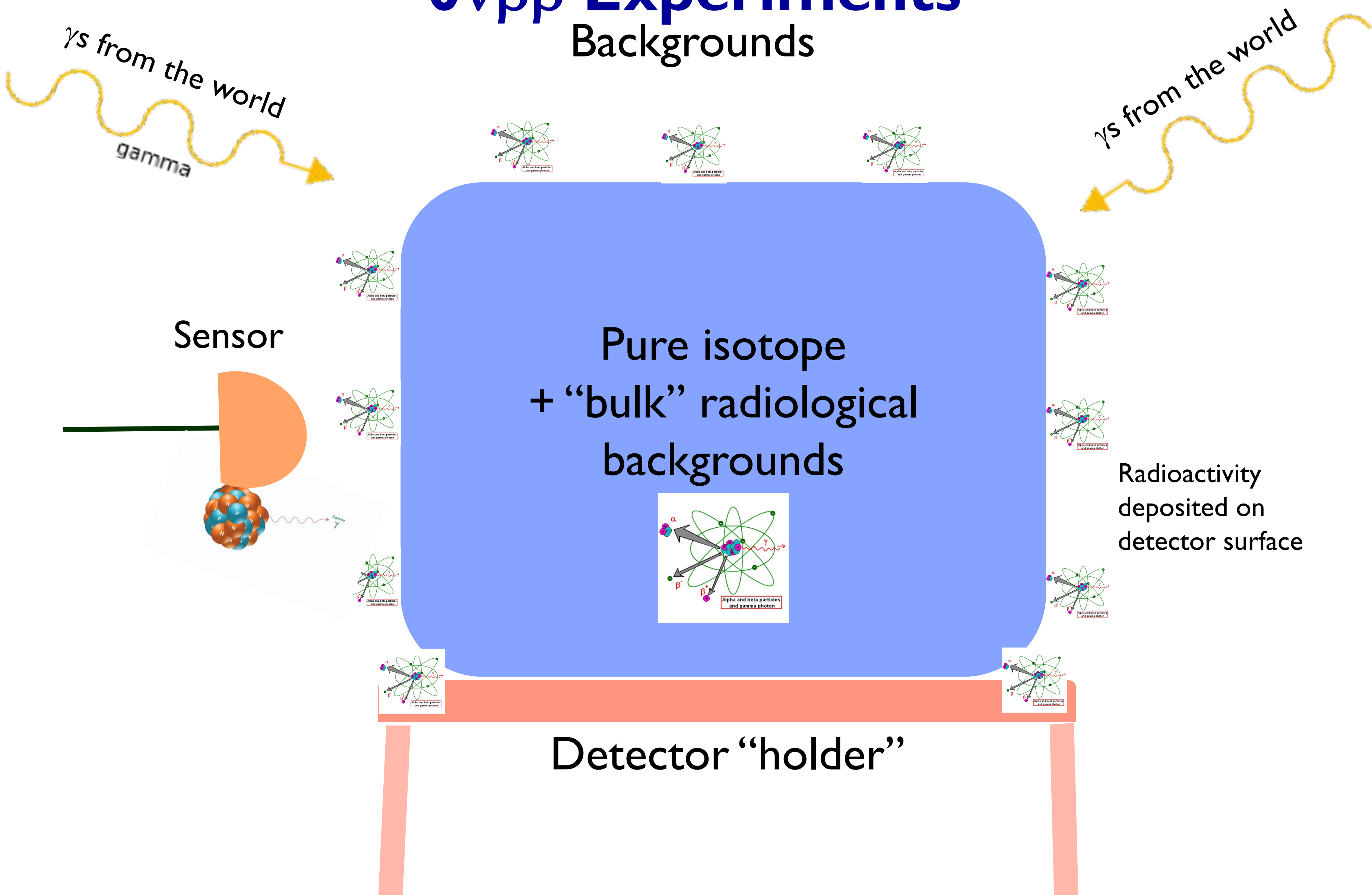
0νββ Experiments

Backgrounds



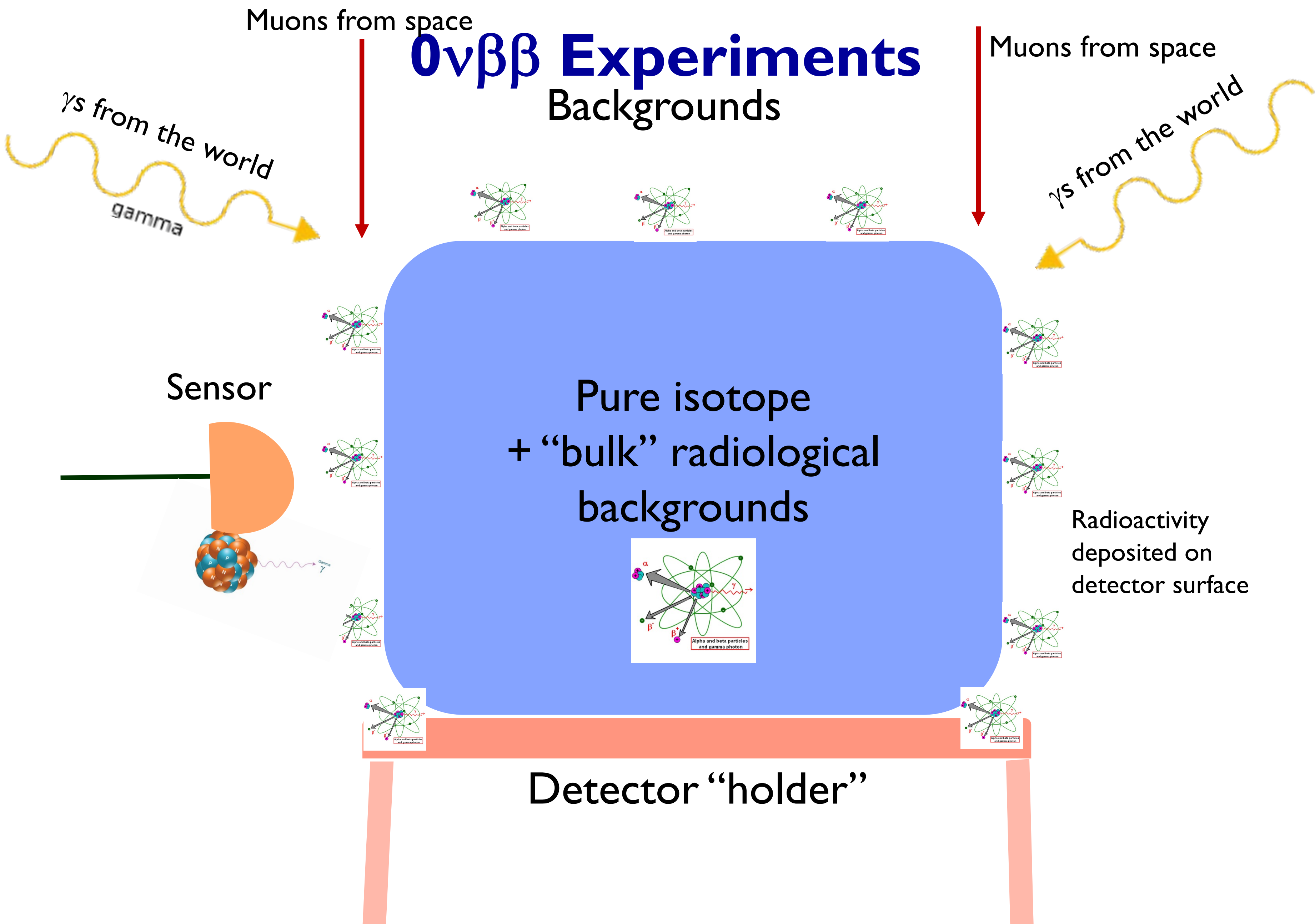
$0\nu\beta\beta$ Experiments

Backgrounds



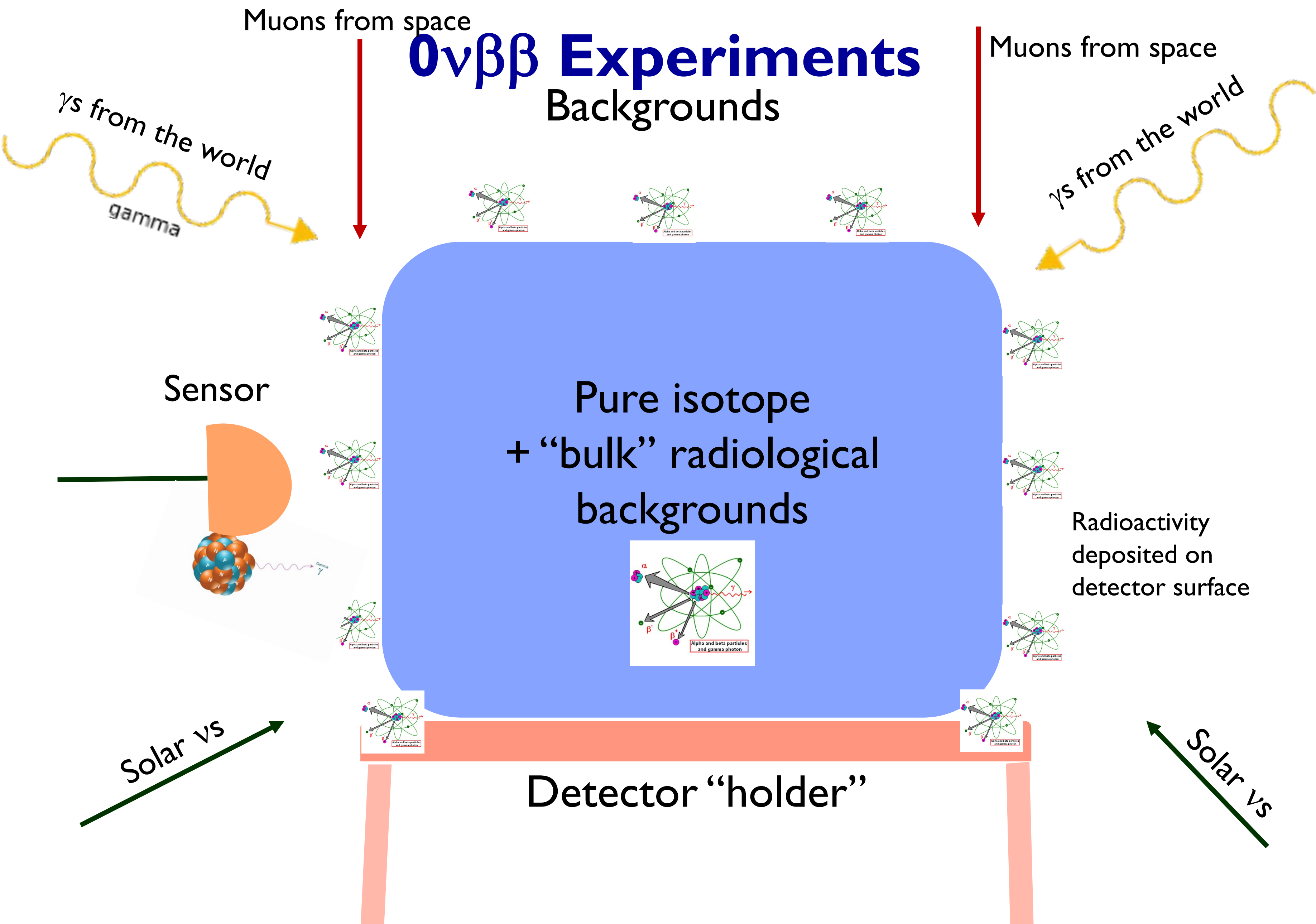
0νββ Experiments

Backgrounds



0νββ Experiments

Backgrounds



$0\nu\beta\beta$ Experiments

Designing an experiment:

- Pick an isotope with
  - Large $0\nu\beta\beta$ matrix element and phase space
  - Small $2\nu\beta\beta$ decay rate
  - Large isotopic abundance or able to be enriched inexpensively
  - High $\beta\beta$ endpoint
  - (Not too expensive)
- Purify isotope (enrichment helps but $$)
- Detector with very narrow energy resolution to minimize $2\nu\beta\beta$ bkd
- Push "edges" and "holder" as far away as possible from bulk
- Place sensors as far away as possible and/or make low-mass
- Have shielding, preferably active
- Locate deep underground
- Use as much isotope as possible for highest sensitivity
- Make bulk as small as possible to reduce solar ν background
- Detector with great reco/particle ID to reduce residual backgrounds

$0\nu\beta\beta$ Experiments

Option that satisfies all of these best:

$0\nu\beta\beta$ Experiments

Option that satisfies all of these best:

NONE!

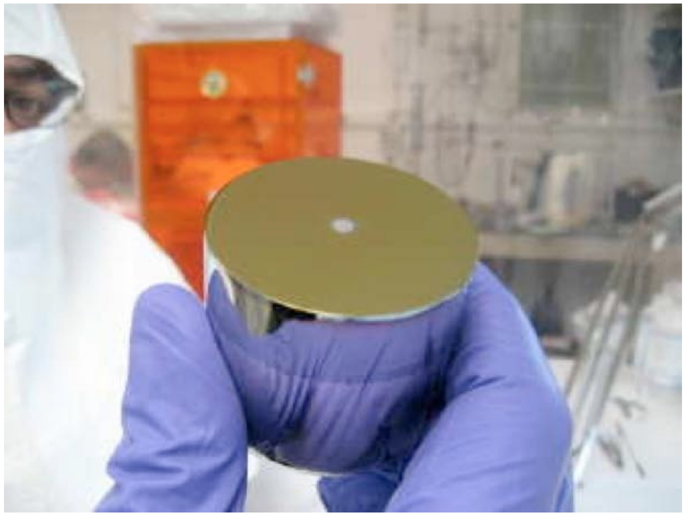
$0\nu\beta\beta$ Experiments

Option that satisfies all of these best:

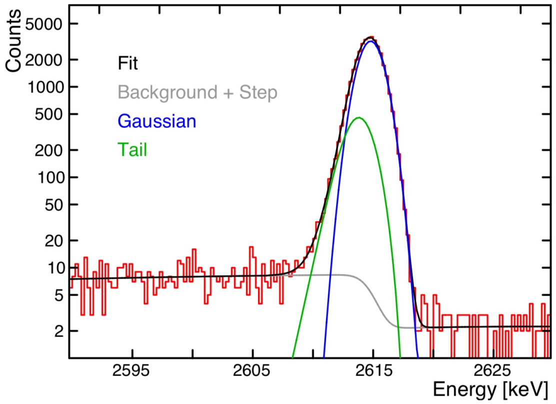
NONE!

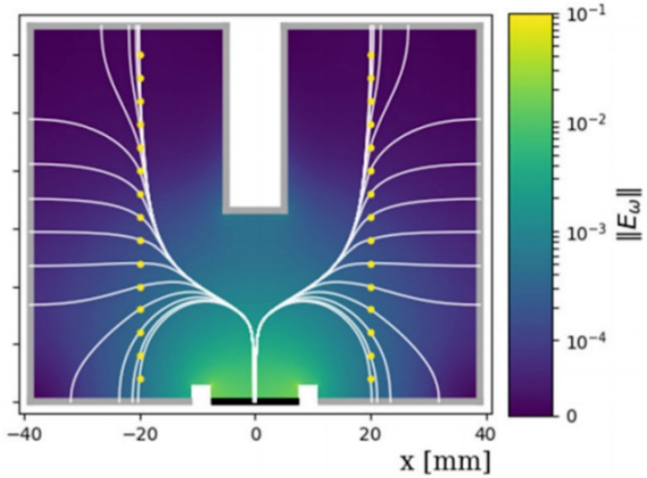
Every experiment is a compromise.

Germanium



- Can be made very pure
- Enrichable in ^{76}Ge (for $$)
- Excellent energy resolution



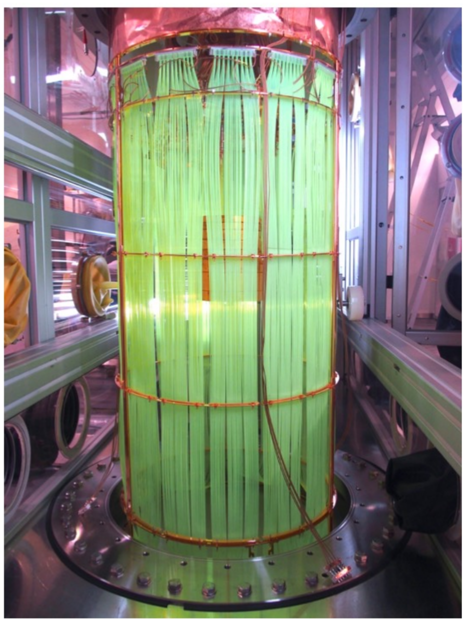


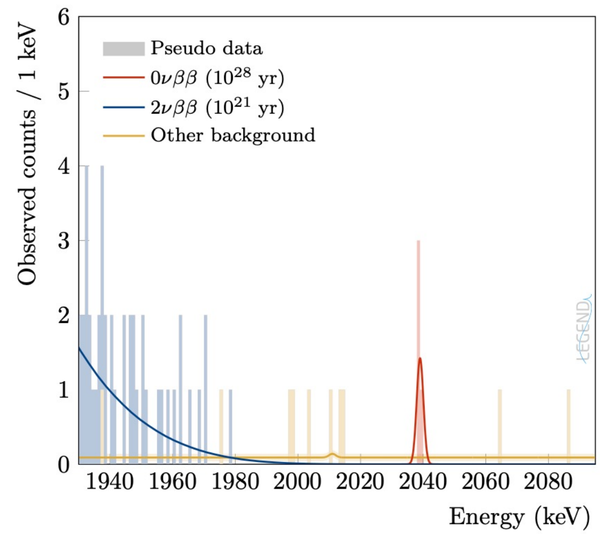
- Small size/detector
- Bulk is "all" isotope
- Very good Particle ID
- Small 0ν phase space
- Low ββ endpoint

Germanium

LEGEND-200 and LEGEND-1000

- Use Ge in-hand to reduce costs
- Shield with active LAr to reduce impact of small detector size
- Use multi-detector rejection to exclude multi-size γs
- Move to SNOLAB for tonne-scale (LEGEND-1000) for depth
- New detector configuration to further improve particle ID

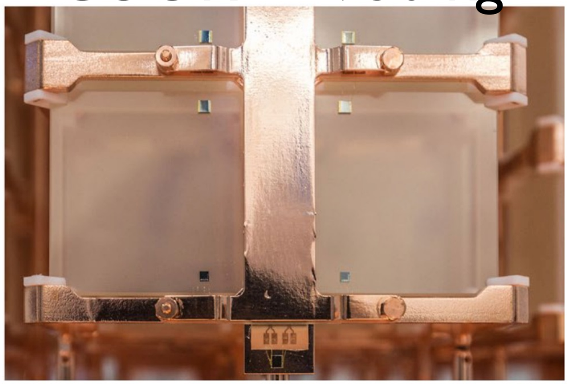


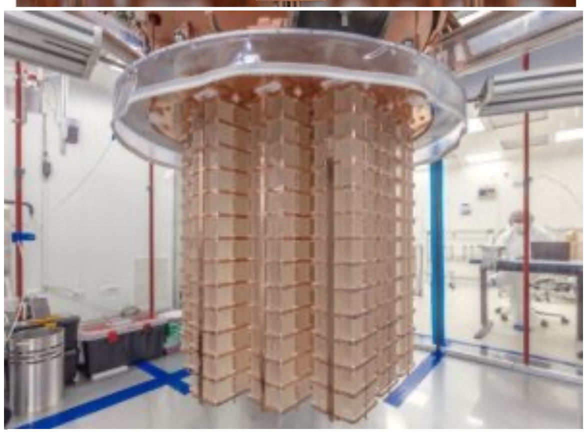


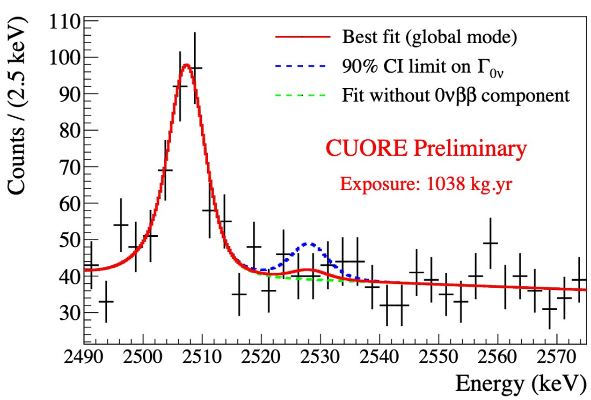
Expect near-zero background

Bolometers--^{nat}Te

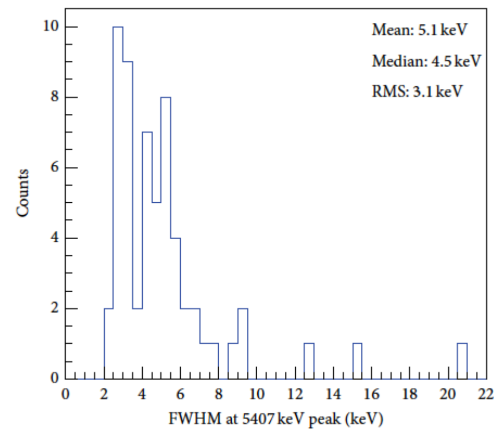
CUORE---750 kg







- Can be made very pure
- High isotopic abundance (34%)
- Very good energy resolution

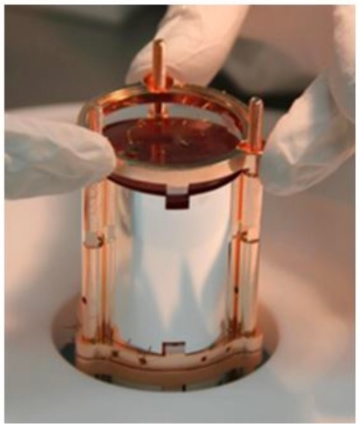


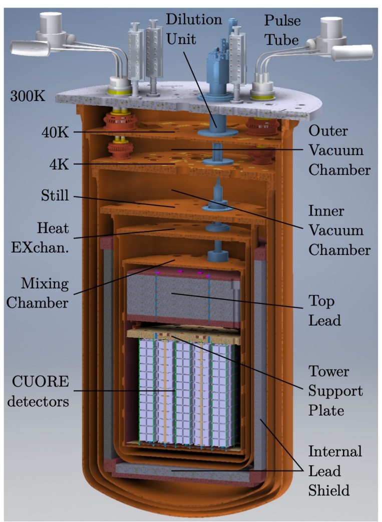
- Small size/detector
- Bulk is "all" isotope
- OK Particle ID
- Large 0ν phase space
- Very slow (pileup can matter)

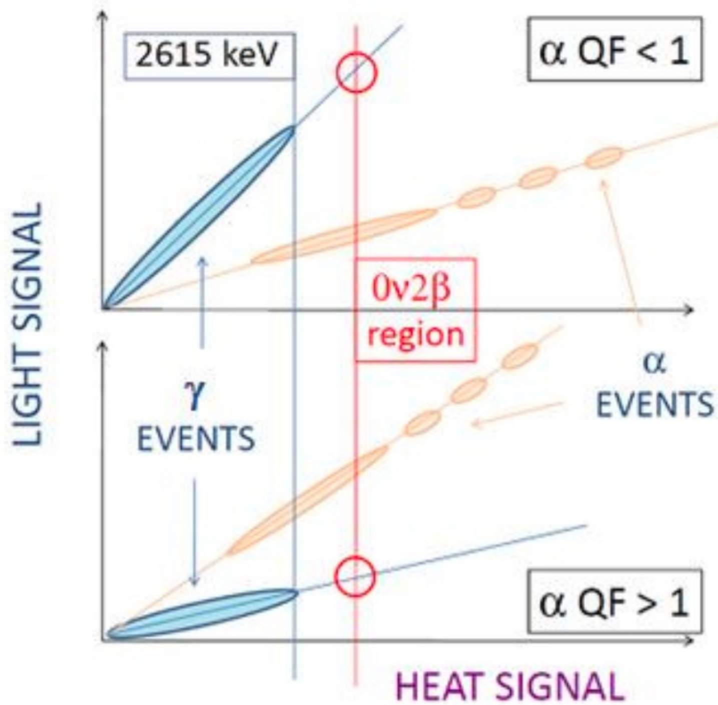
Bolometers—^{100}Mo

CUPID (=CUORE + PID)

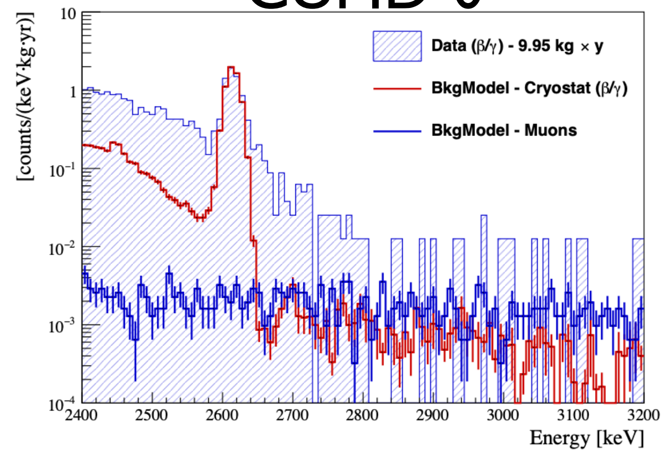
- Use existing CUORE cryostate to reduce costs
- Use ^{100}Mo with very high endpoint for ββ (~3 MeV)
- Look for scintillation light in crystals to improve PID





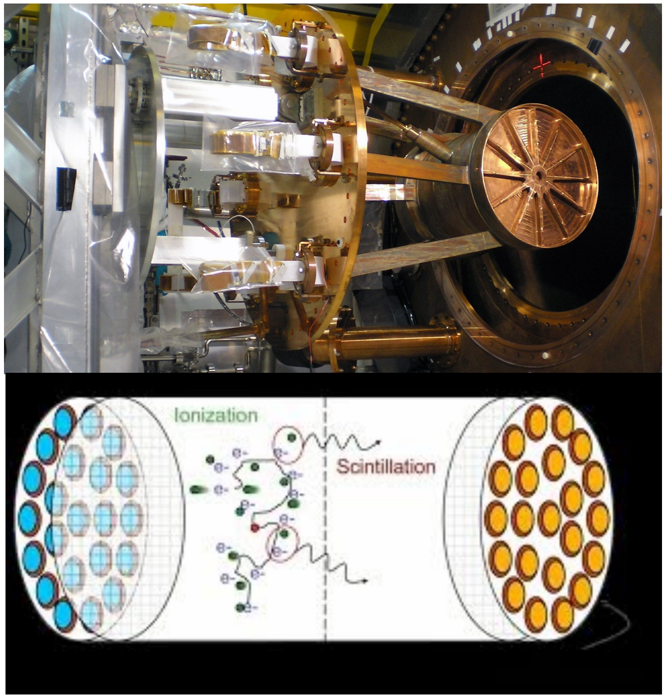


CUPID-0

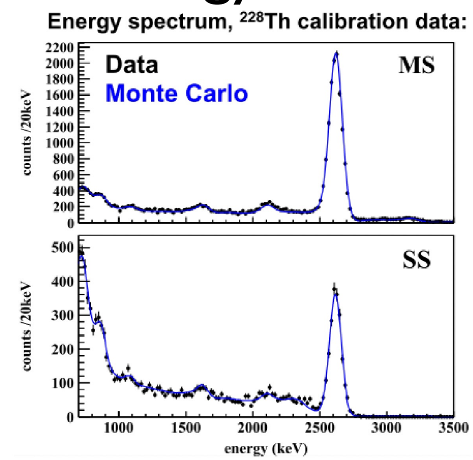


Liquid ^{136}Xe TPC

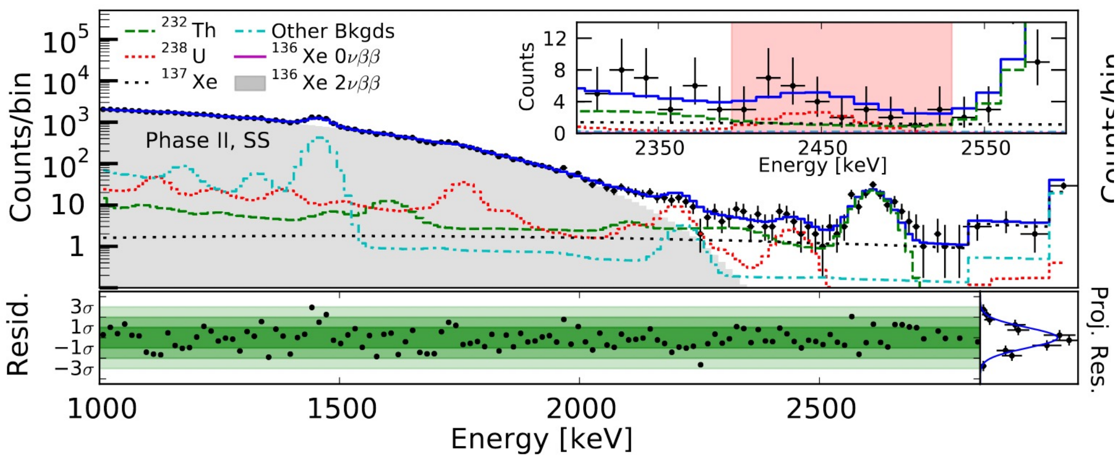
EXO-200



- Can be made very pure
- Enrichable for $$
- Poor energy resolution



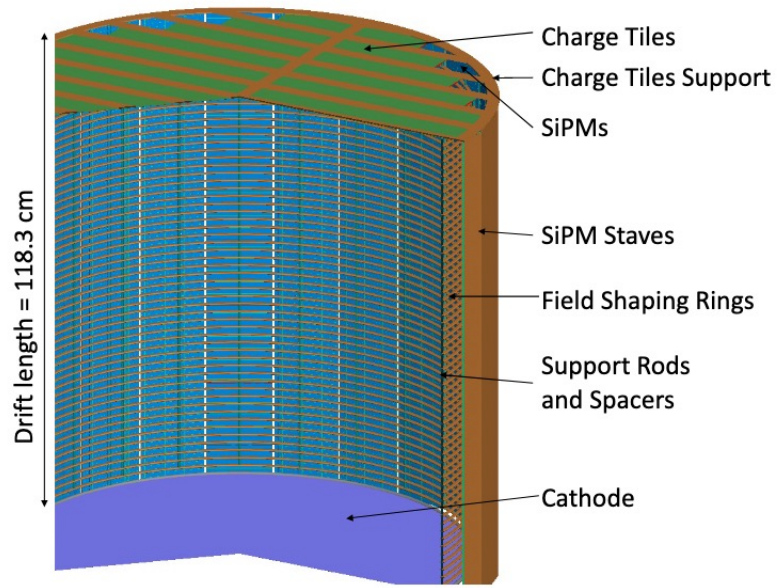
- Big detector size
- Bulk is "all" isotope
- Very good Particle ID
- Large 0ν phase space

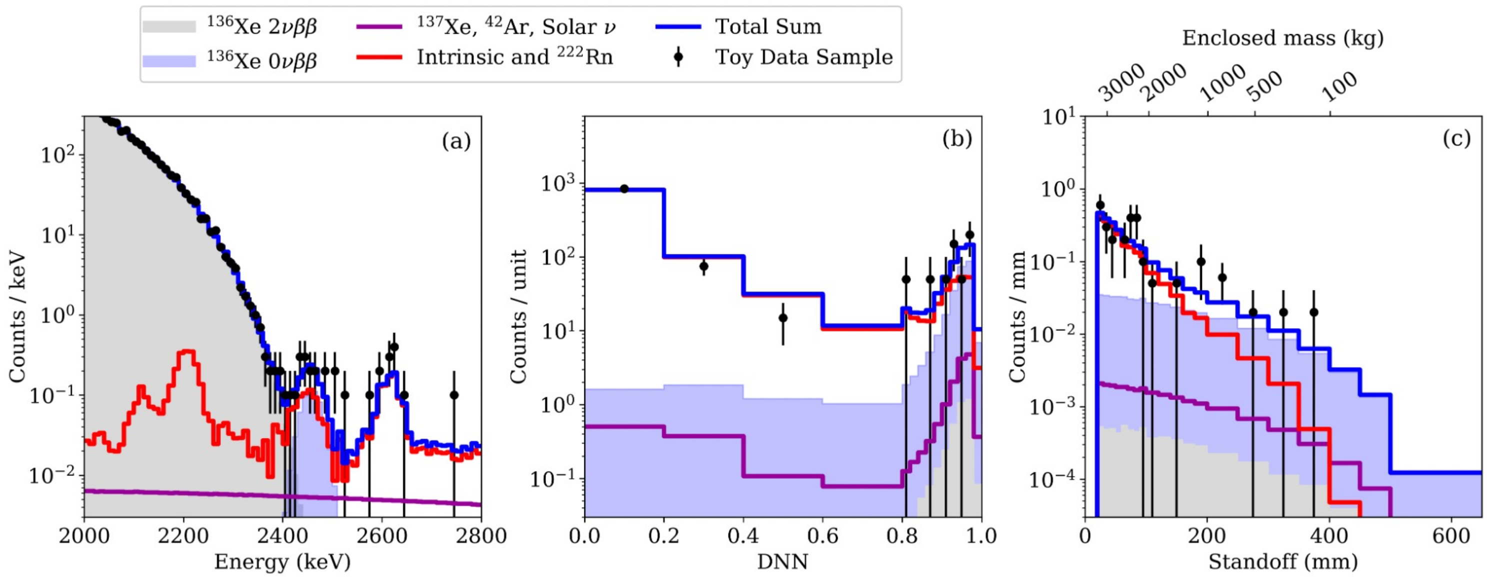


Liquid ^{136}Xe TPC

nEXO

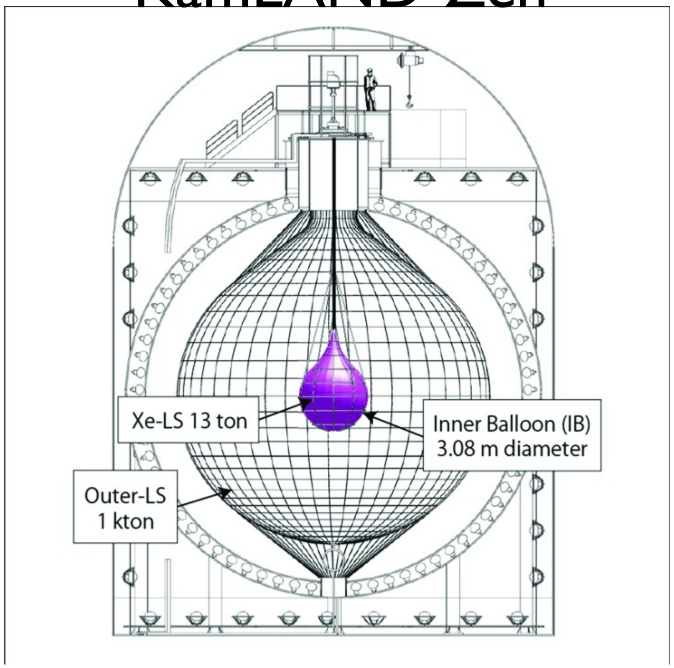
- Increase detector mass to 5 tonnes of ^{136}Xe
- Narrow energy resolution to < 1%
- Improve particle ID
- Cleaner materials



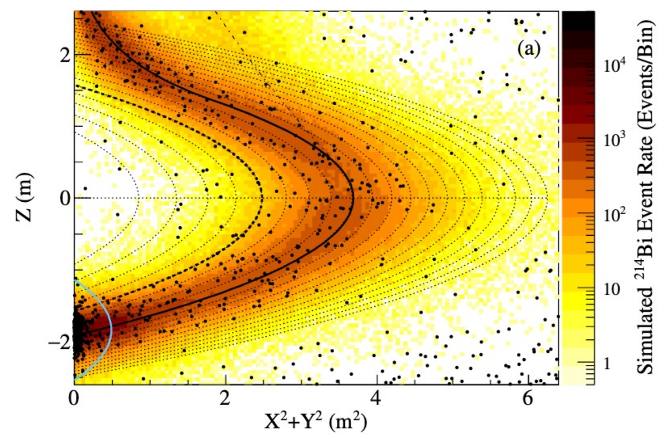


Liquid Scintillator Loading: ^{136}Xe

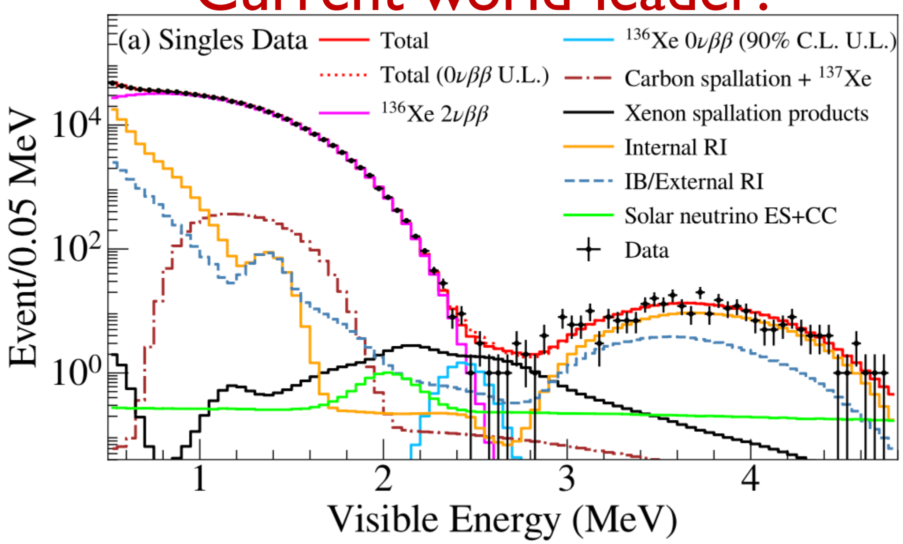
KamLAND-Zen



- Isotope can be made very pure ⬆
- Scintillator can be made clean ⬆⬇
- Enrichable for $$ ⬇⬇
- Very poor energy resolution ⬇⬇
- Big detector size ⬆



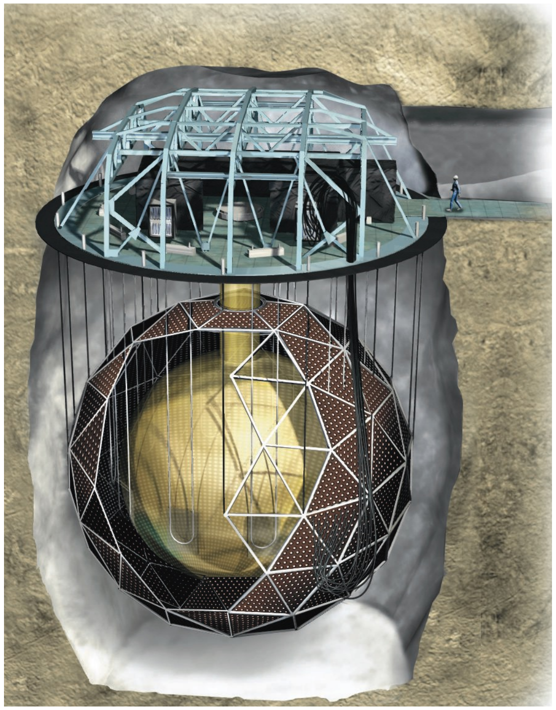
Current world-leader!



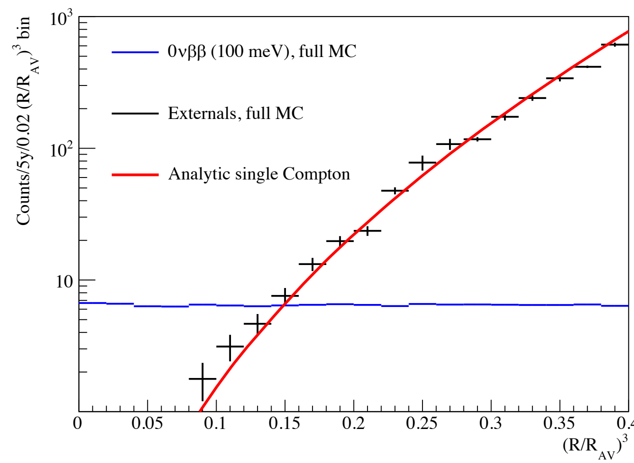
- Bulk is not all isotope ⬇
- Good Particle ID ⬆
- Large 0ν phase space ⬆

Liquid Scintillator Loading: ^{130}Te

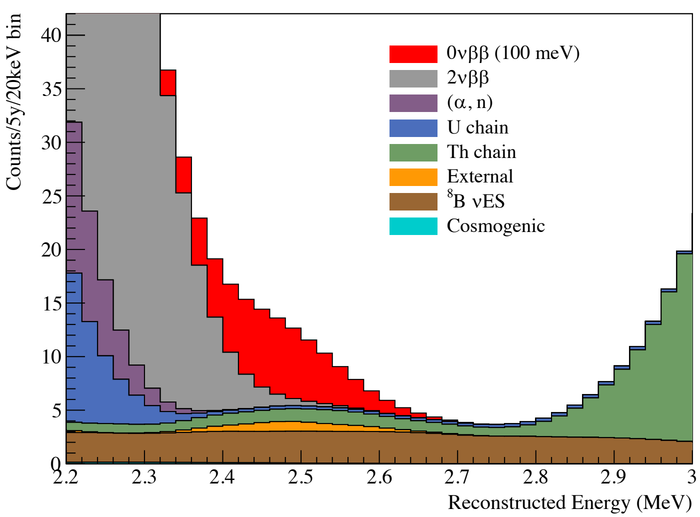
SNO+



- Isotope can be made very pure ⬆
- Scintillator can be made clean ⬆⬇
- High isotopic abundance ⬆
- Very poor energy resolution ⬇⬇
- Big detector size ⬆⬆



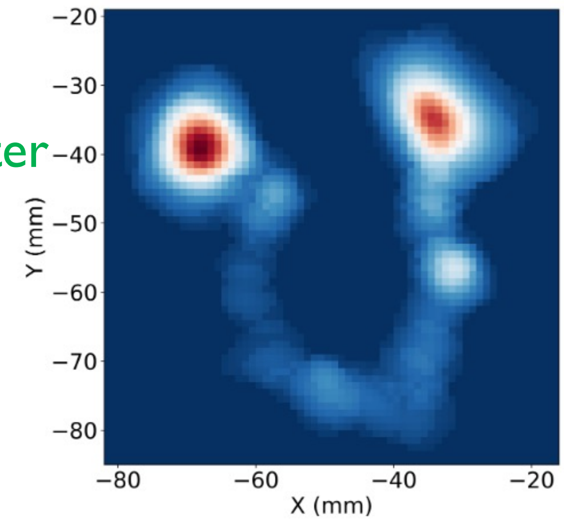
- Bulk is not all isotope ⬇
- Good Particle ID ⬆
- Large 0ν phase space ⬆



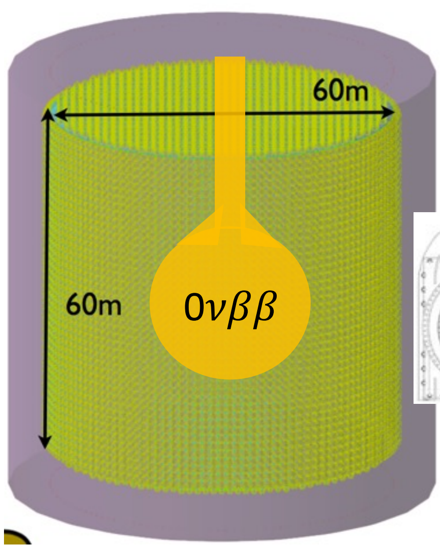
Beyond the "tonne scale"

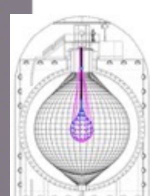
NEXT---High-pressure GXe TPC

- Distinctive topology!
- Possibility to tag Ba daughter
- Bkd subtraction with depleted Xe
- 100 kg prototype built

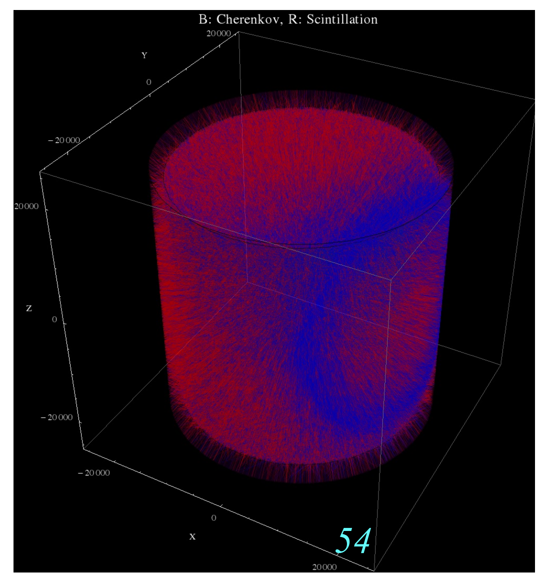


Theia

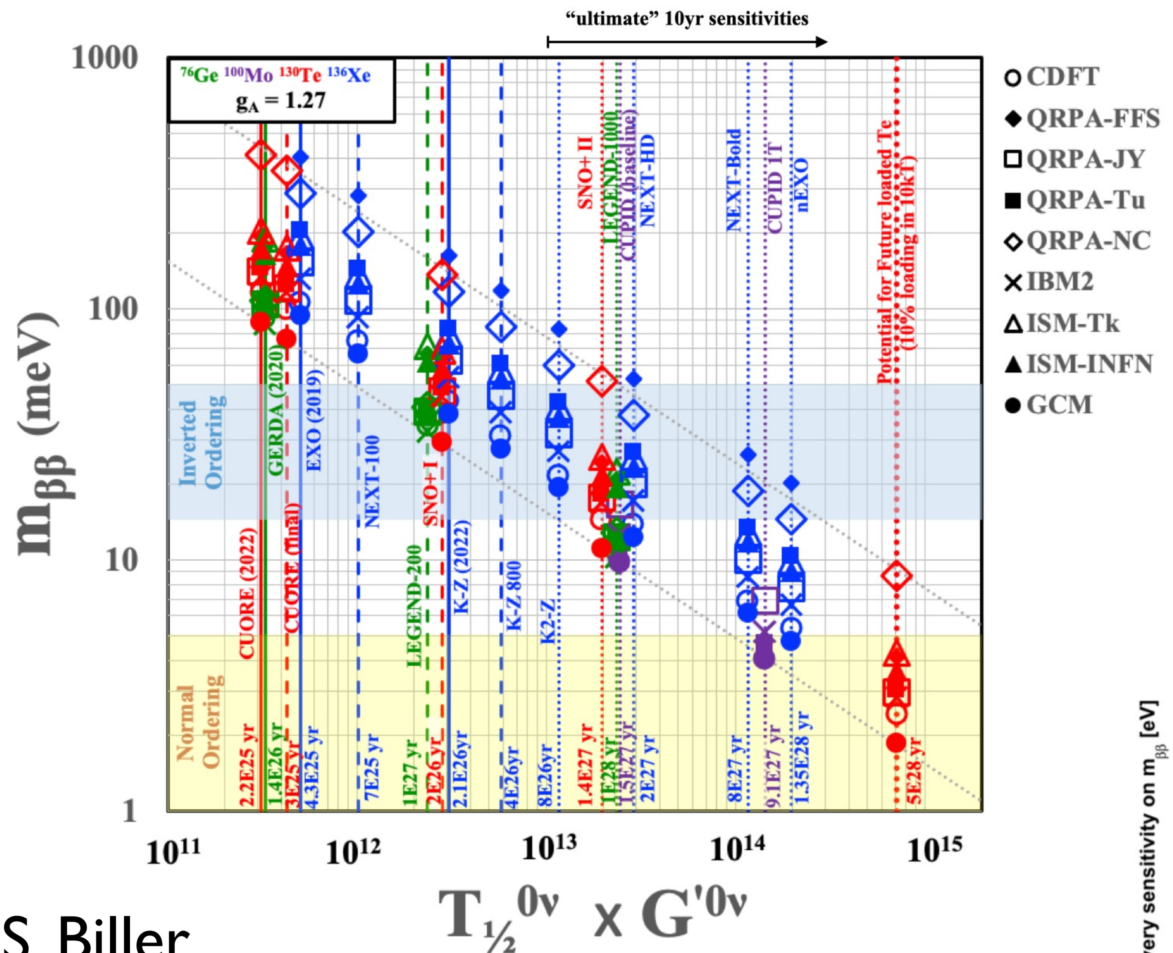




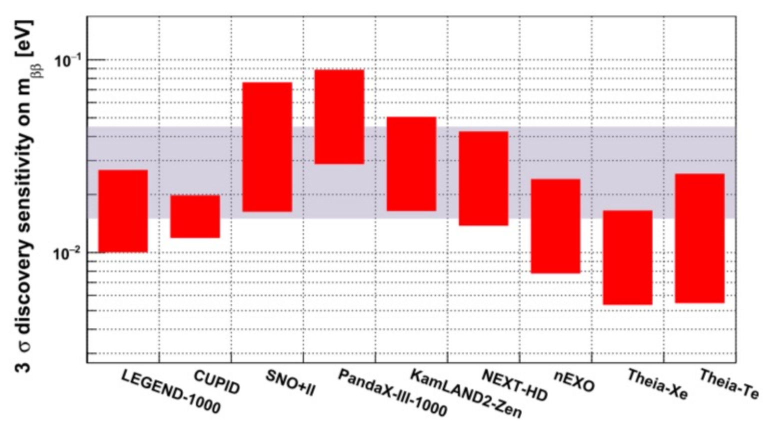
- Hybrid Cherenkov/scintillation
- Direction reduces ^{8}B solar bkd
- Large mass for 50 t ^{nat}Te loading
- Broad program of other physics
- Several prototypes built or under construction



Sensitivity Comparisons



S. Biller

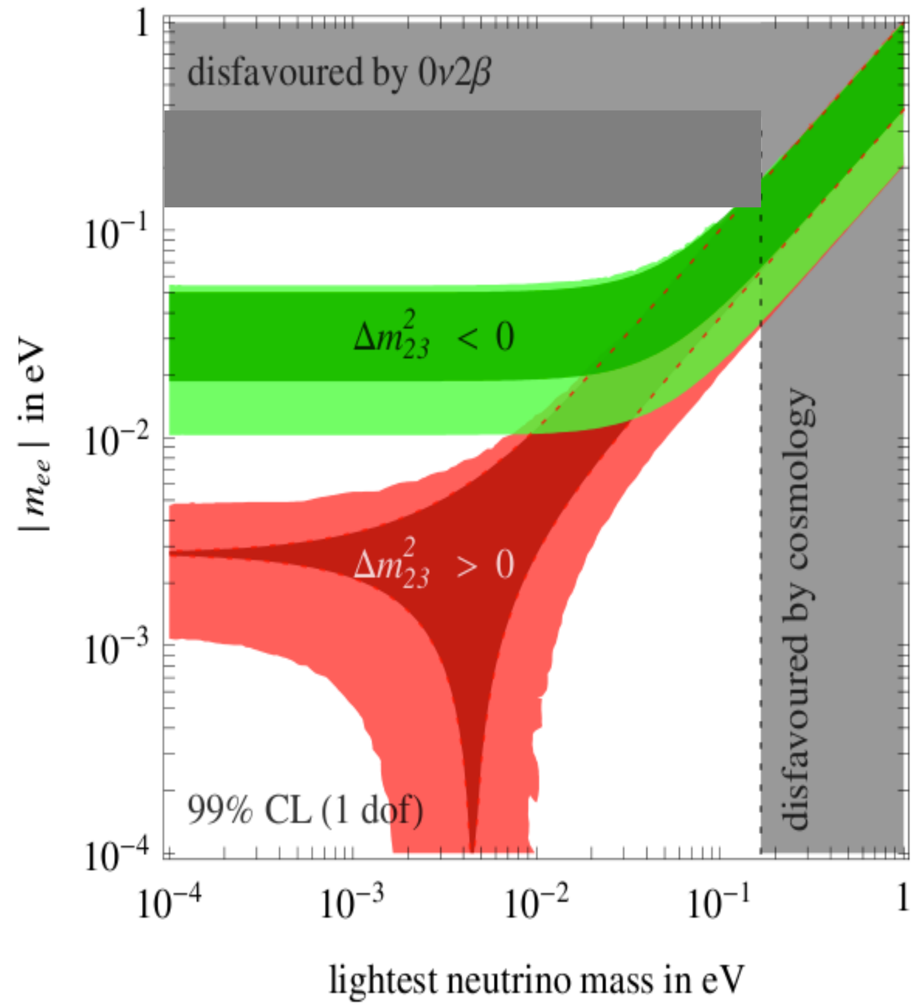


Majorana vs. Dirac

What if no experiments see 0νββ?

Are neutrinos Dirac particles?

Depends on the mass ordering,
the absolute mass,
and the Majorana CP Phases.



Measuring the mass ordering is an active topic…
And…what about CP violation, anyway…?

Long Baseline Neutrino Oscillation Experiments

Two-flavor oscillations are so simple: $P_{\upsilon_\mu \to \upsilon_\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$

Three-flavor oscillations are rich and complex:

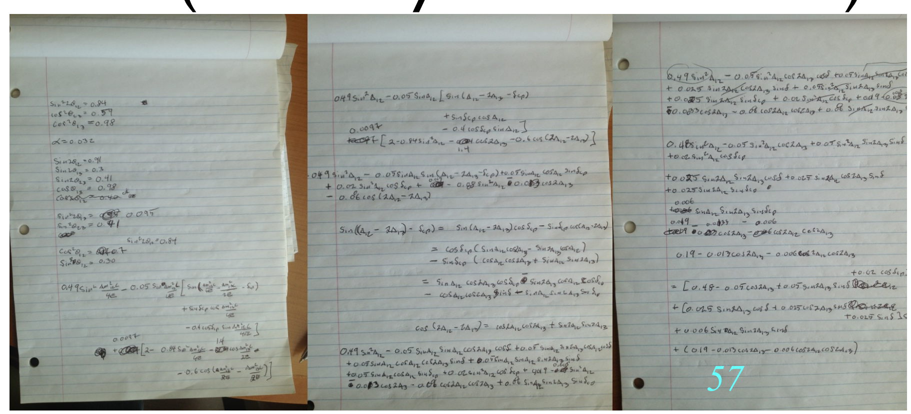
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2\Delta_{31} \\ & +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\ & +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2\Delta_{21} \\ & -8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\ & +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2\Delta_{31}, \end{aligned}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

$$a = 2\sqrt{2} G_F n_e E$$
$$= 7.6 \times 10^{-5} \rho\left[g/cm^3\right] \times E_\nu \left[GeV\right]$$

(Don't try this at home…)



Long Baseline Neutrino Oscillation Experiments

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31}$$ "θ_{13} term"

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

"CP term" $$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21}$$

"solar term" $$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta) \cdot \sin^2\Delta_{21}$$

"matter terms" $$-8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31}$$

$$+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{31}^2}(1 - 2S_{13}^2) \cdot \sin^2\Delta_{31},$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E_\nu}$$

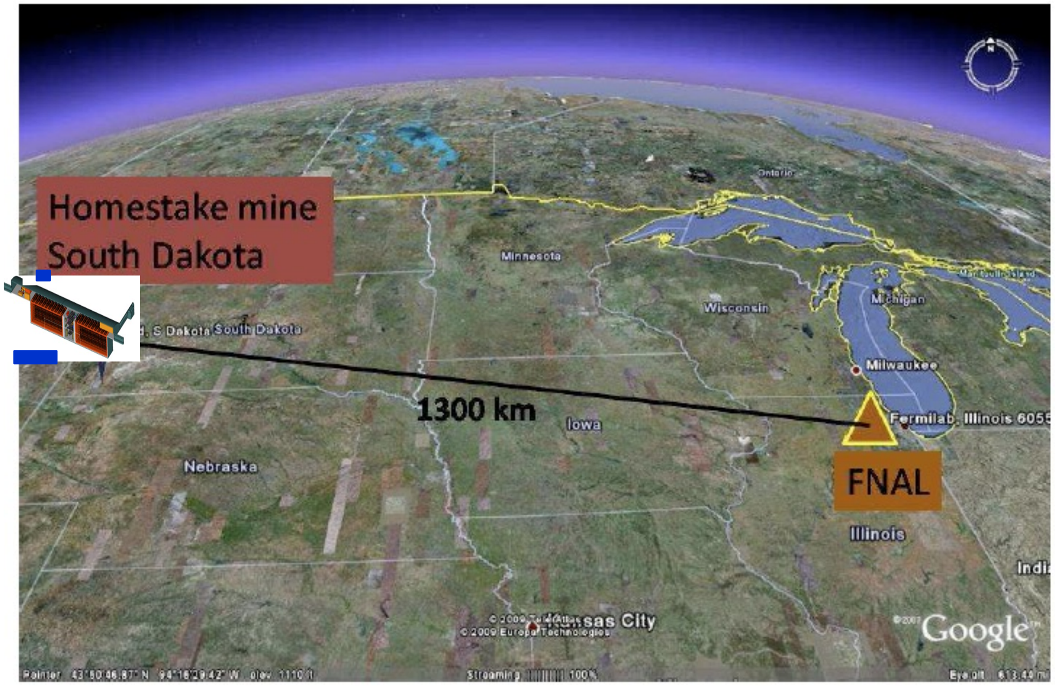
$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m_{12}^2 L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

Lots of signs that matter:

- Δ: $\Delta m_{13}^2<0$?
- δ: ν vs. anti-ν
- a: ν vs. anti-ν

$\longrightarrow$ "Appearance" probability changes for ν and anti-ν even if $\delta=0$…
…and that depends on sign of Δm_{13}^2

Future Long Baseline Neutrino Oscillation Experiments



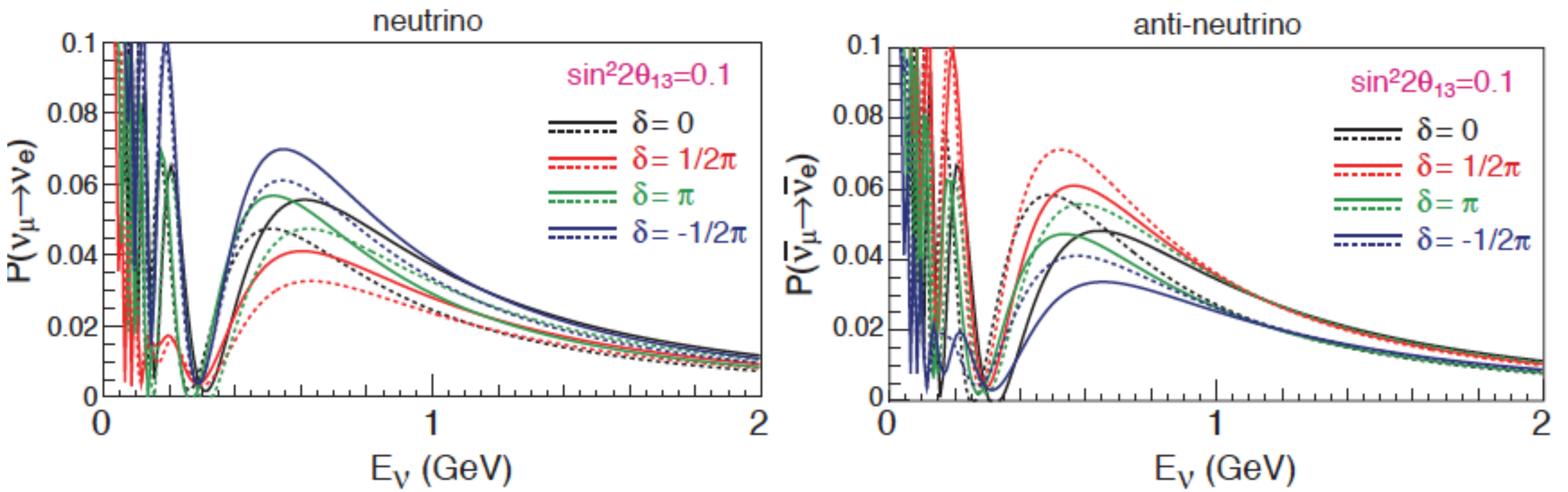
LBNF-DUNE

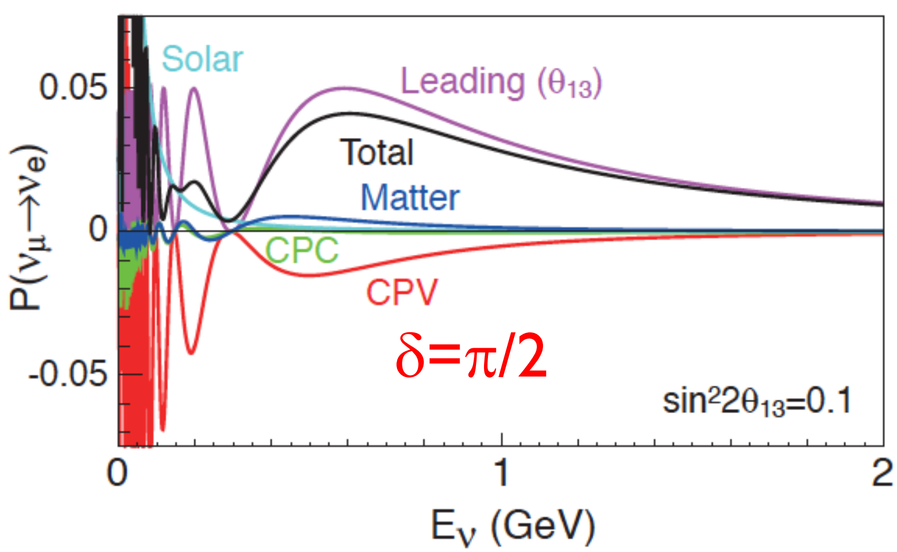
Tokai-Hyper-K
(T2HK)

CP Violation

Different baselines have different sensitivities

For L=239 km (T2-HyperKamiokande)



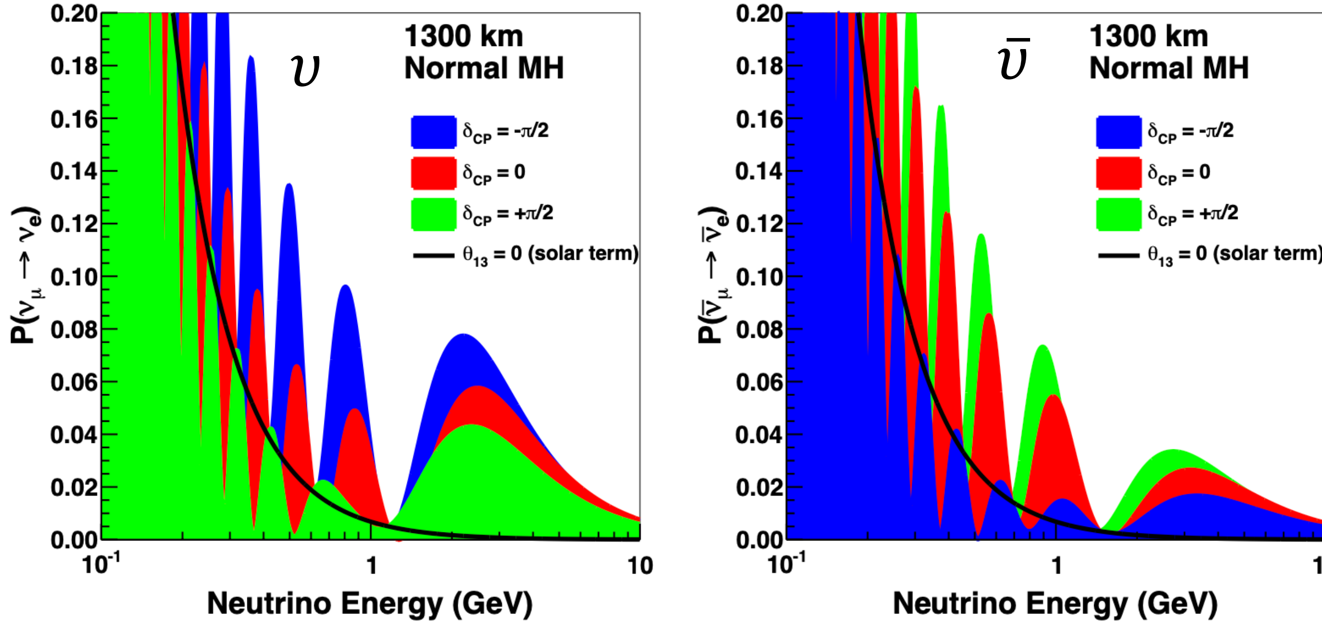


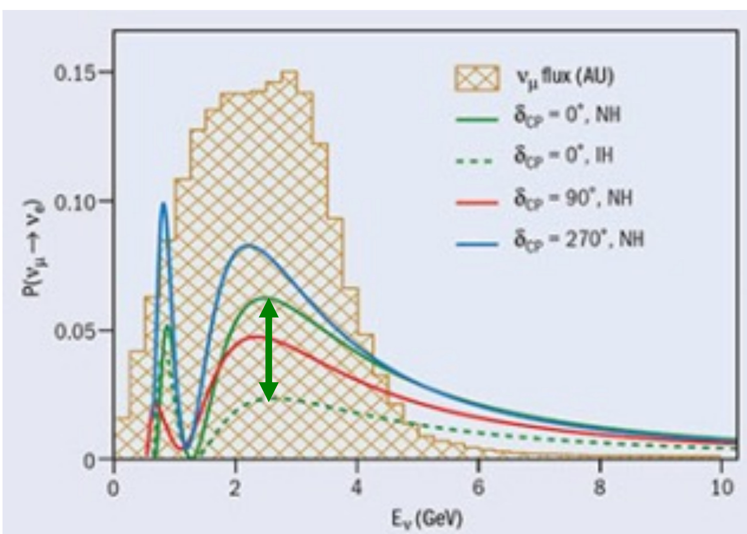
- "Short" baseline make matter effect small
- Less dependence on sign of Δm^2
- So little to no sensitivity to sign of Δm^2
- δ also affects oscillation ***pattern!***

CP Violation

Different baselines have different sensitivities

For L=1300 km (LBNF-DUNE)

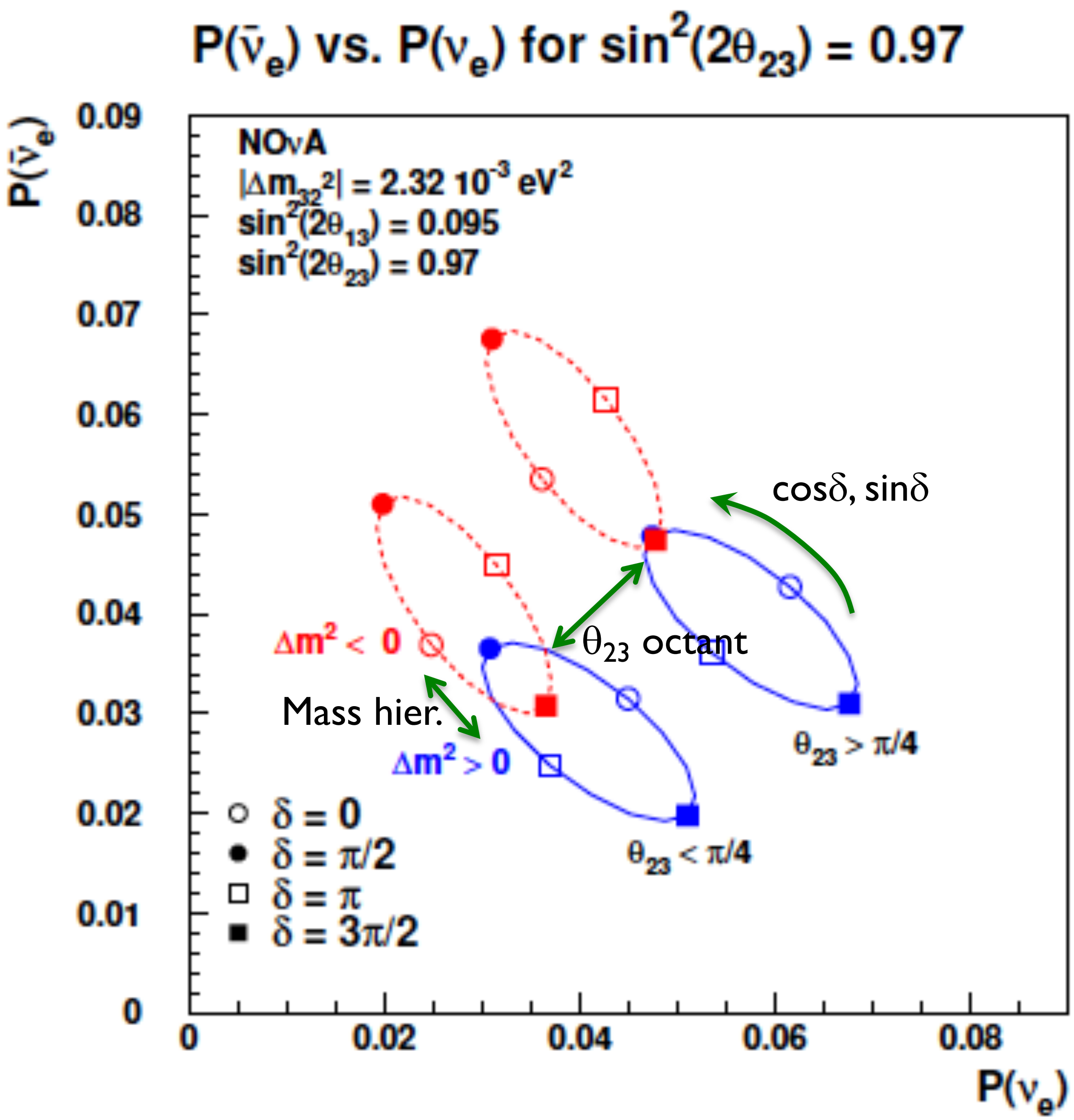




- Difference of ν/anti-ν even for δ=0
- Difference depending on sign of Δm_{13}^2
- So sensitivity to measuring sign of Δm_{13}^2
- δ still effects oscillation pattern

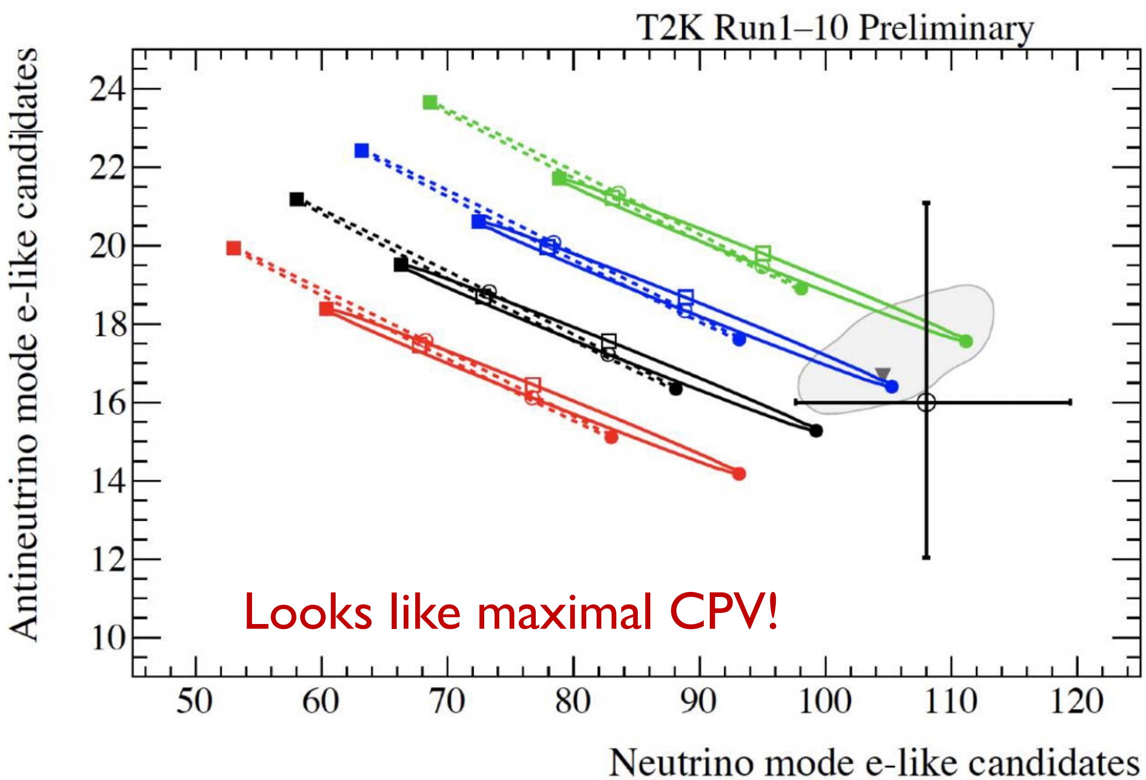
Existing Measurements

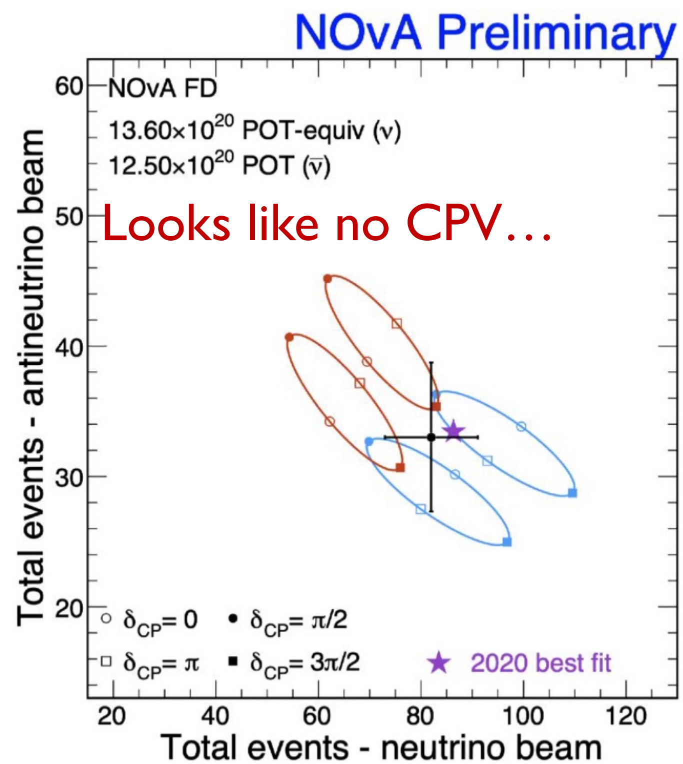
“Bi-probability” plot



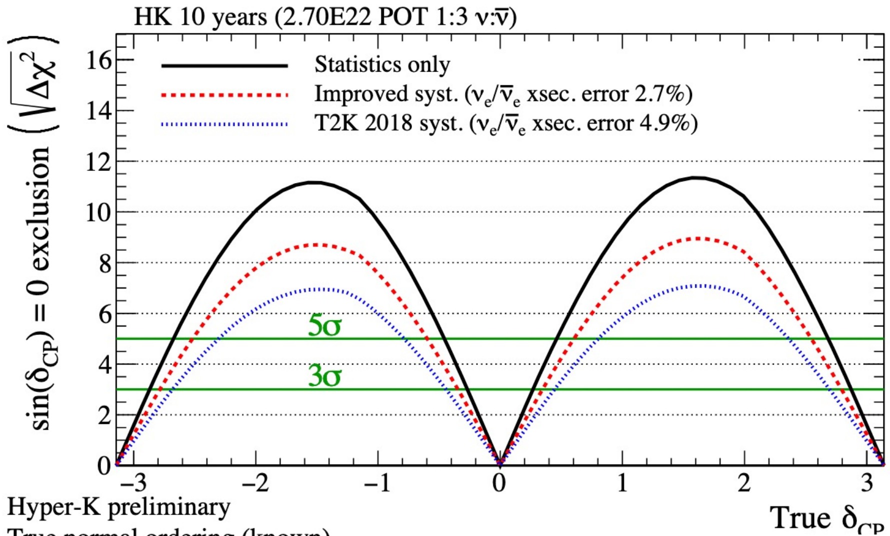
Existing Measurements

"Bi-probability" plot



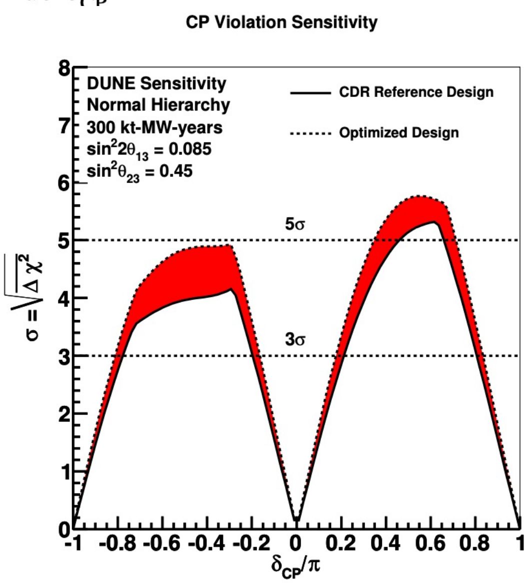


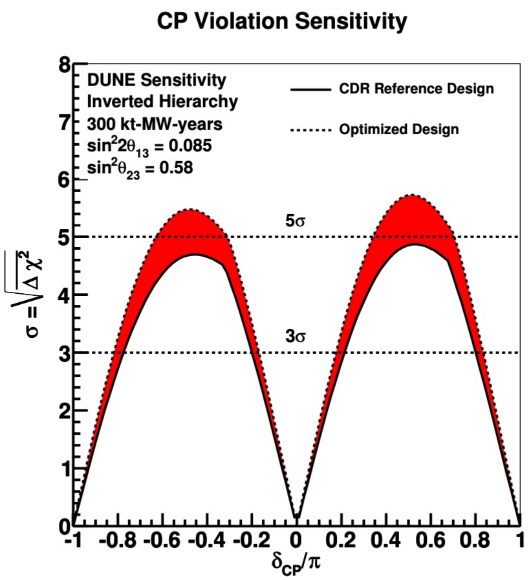
Future Measurements



Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-3}$

Hyper-K does very well once mass ordering is assumed to be known





DUNE will resolve both mass hierarchy and measure CP

CP Violation

Best neutrino question at Snowmass (Plenary):

Q: What do we learn about the Universe by knowing the value of δ?

My answer:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\textit{Dirac phase}} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{\textit{Majorana phases}}$$

This is a **MODEL.**

With 3 angles + 3 Δm^2s + 1 absolute mass scale + 3 phases it does a great job of describing the dozen or so independent experimental results.

CP Violation

Best neutrino question at Snowmass (Plenary):

Q: What do we learn about the Universe by knowing the value of δ?

- "Models can be built…" and "arguments can be made" that connect δ to Majorana CP violation and leptogenesis.

$|\sin\theta_{13}\sin\delta| \gtrsim 0.11$ (Pascoli, Petcov, Riotto, Nuc. Phys. B 774, (2007))

- But we should remember that this

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

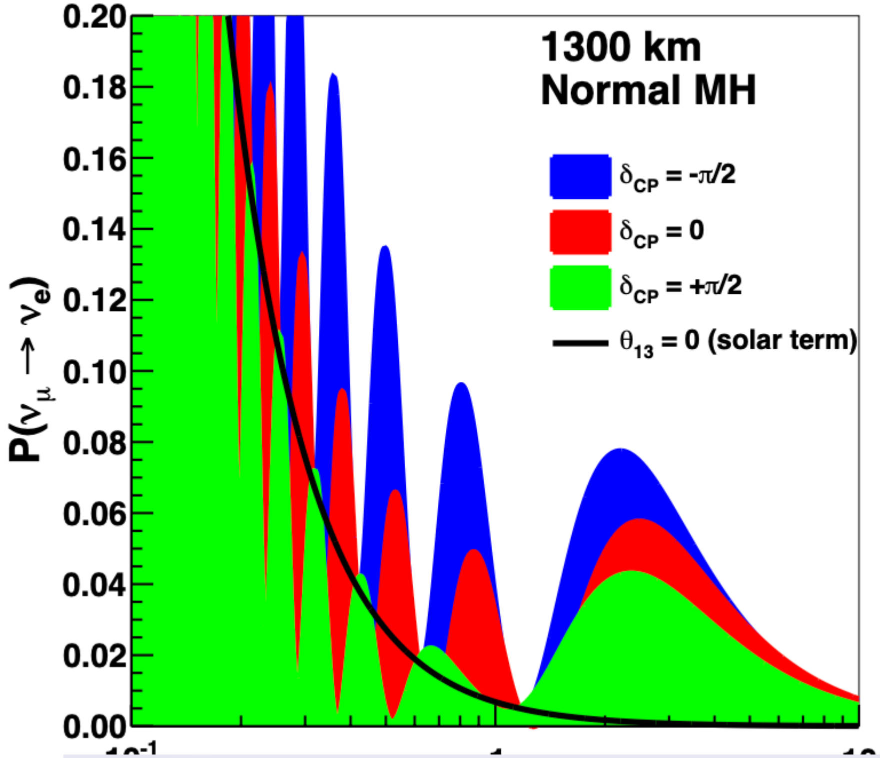
is a *prediction* of the 3-flavor model. δ can (in principle) be measured independently of A_{CP} using just the oscillation patterns. With such a measurement, we predict the oscillation probabilities for anti-ν_μs into anti-ν_es and ask:

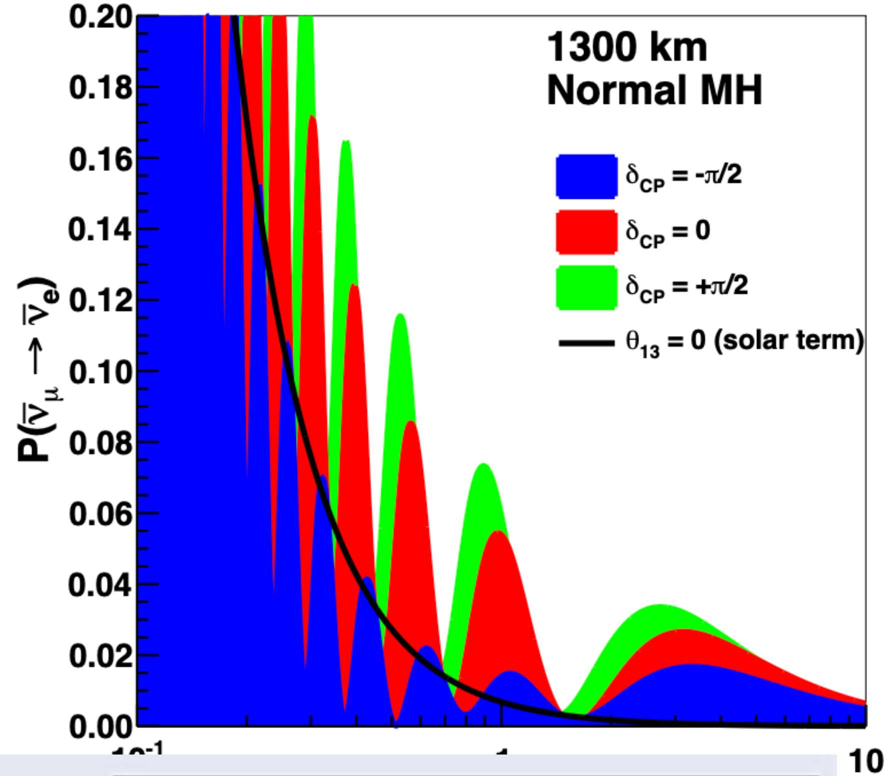
$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \overset{?}{\simeq} \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

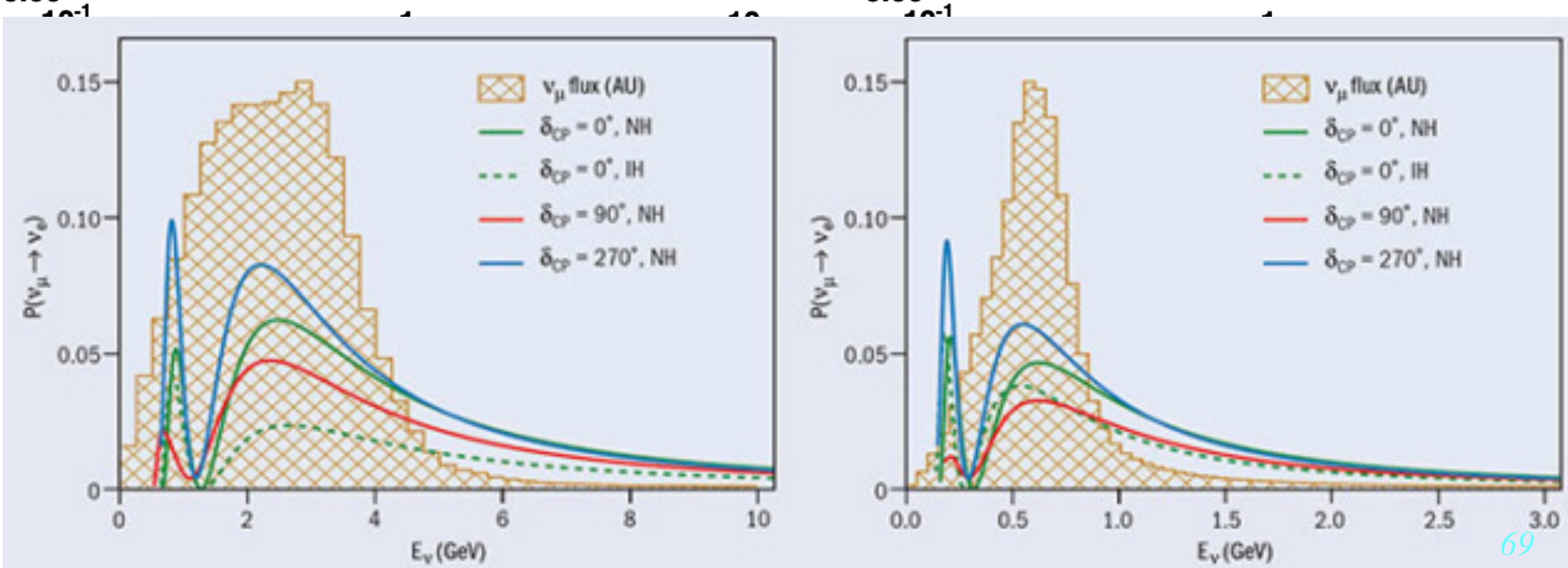
Questions and Opportunities

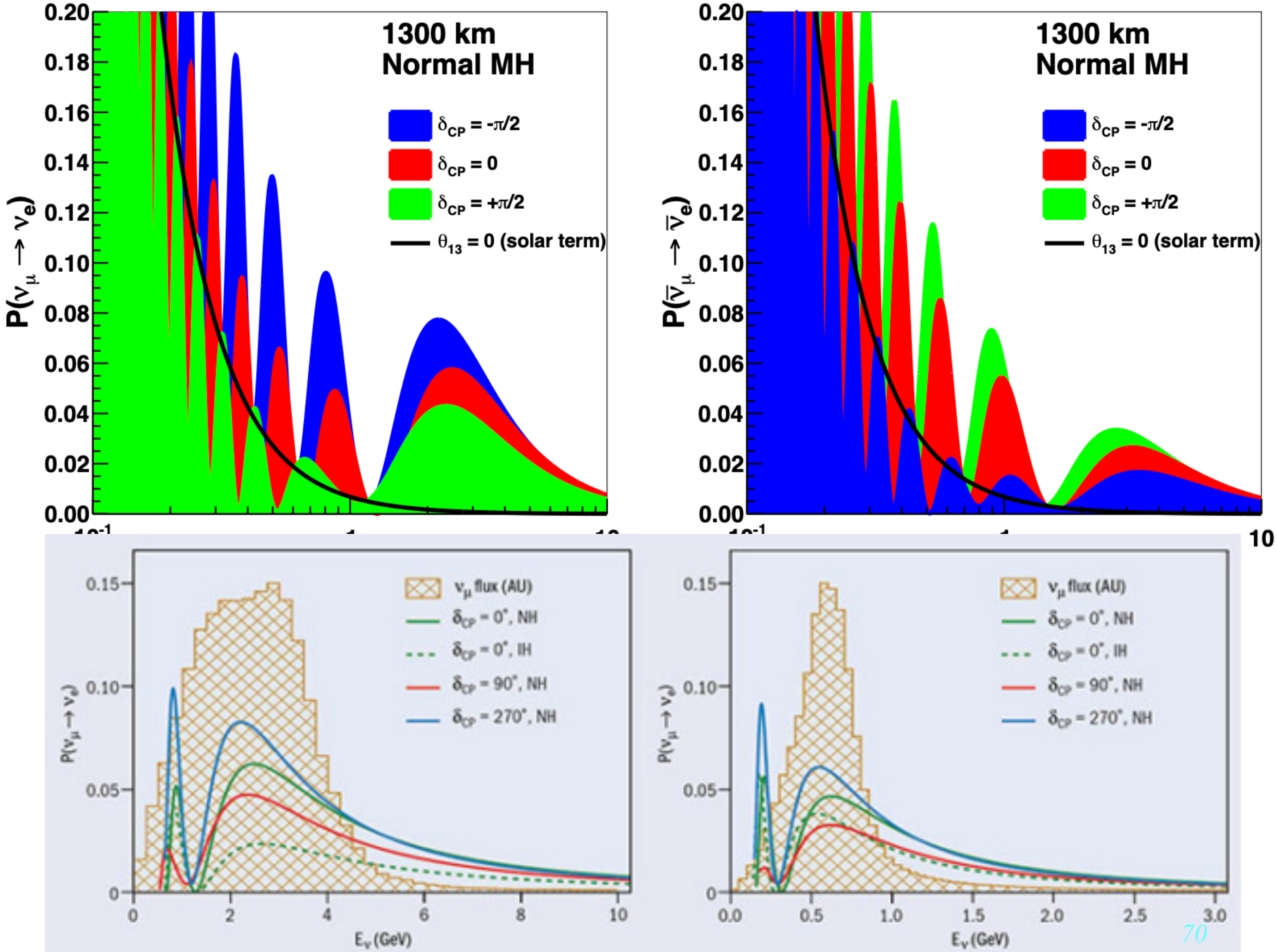
- Can neutrinos be Majorana and $\upsilon - \bar{\upsilon}$ oscillate differently? (Yes)
- How might we measure the Majorana CP phases?
  - Idea 1: $0\nu\beta\beta$ experiment with 10 tonnes of anti-^{136}Xe!
  - Idea 2: ?
- What precision is reasonable to test whether δ explains all CPV?
  - And are DUNE and Hyper-K enough?
- What about experiment for T violation, as distinct from CP…?
- If neutrinos are Dirac particles, what makes $\bar{\upsilon}_R$ and υ_R different?
  - And can we ever detect (even indirectly!) the ν_R?
- How about CPT violation---what sensitivity is meaningful?
  - And then what experiment would we need to do?

[redacted]


1300 km
Normal MH
δCP = -π/2
δCP = 0
δCP = +π/2
θ13 = 0 (solar term)
P(νμ → νe)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00


1300 km
Normal MH
δCP = -π/2
δCP = 0
δCP = +π/2
θ13 = 0 (solar term)
P(ν̄μ → ν̄e)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10


νμ flux (AU)
δCP = 0°, NH
δCP = 0°, IH
δCP = 90°, NH
δCP = 270°, NH
P(νμ → νe)
Eν (GeV)
0.15
0.10
0.05
0
0
2
4
6
8
10
0.0
0.5
1.0
1.5
2.0
2.5
3.0


1300 km
Normal MH
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = +\pi/2$
$\theta_{13} = 0$ (solar term)
$P(\nu_\mu \to \nu_e)$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
1300 km
Normal MH
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = +\pi/2$
$\theta_{13} = 0$ (solar term)
ν_μ flux (AU)
$\delta_{CP} = 0°$, NH
$\delta_{CP} = 0°$, IH
$\delta_{CP} = 90°$, NH
$\delta_{CP} = 270°$, NH
$P(\nu_\mu \to \nu_e)$
E_ν (GeV)
ν_μ flux (AU)
$\delta_{CP} = 0°$, NH
$\delta_{CP} = 0°$, IH
$\delta_{CP} = 90°$, NH
$\delta_{CP} = 270°$, NH
$P(\nu_\mu \to \nu_e)$
E_ν (GeV)

3-flavor Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

For the three known flavors of neutrinos, this is generalized in analogy with the quark sector:

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

As in quark sector, "phase" δ leads to differences in processes for matter and antimatter (CP Violation):

$$P(\nu_\mu \to \nu_e) \neq P(\overline{\nu}_\mu \to \overline{\nu}_e)$$

Long Baseline Neutrino Oscillation Experiments

Full 3-flavor survival/appearance probability more complex (and richer) than 2-flavor:

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) = & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31} \\ & +8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\cdot\sin\Phi_{31}\cdot\sin\Phi_{21} \\ & -8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\cdot\sin\Phi_{31}\cdot\sin\Phi_{21} \\ & +4S_{12}^2 C_{13}^2\left(C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\right)\sin^2\Phi_{21} \\ & -8C_{13}^2 S_{13}^2 S_{23}^2\left(1-2S_{13}^2\right)\frac{aL}{4E_\nu}\cos\Phi_{32}\sin\Phi_{31}. \end{aligned}$$

CP violating term → third term

`Solar term' → fourth term

Matter term → fifth term

$$\Phi_{ij} \equiv \Delta m_{ij}^2 L/4E_\nu \qquad c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$$

Matter term depends on sign of $m_3^2 - m_1^2$

CP-violating term tells us if $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$

1 and 2 σ Contours for Starred Point