neutrino physics and HEP: lecture 1

neutrinos in the landscape of particle physics

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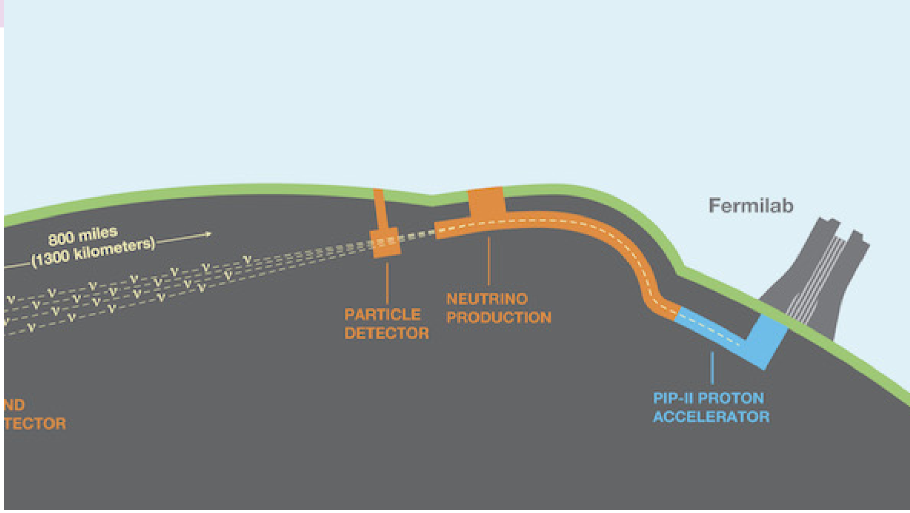
14th July 2022



Greetings, physics neighbors! It's good to be in Pittsburgh.

Special thanks to Fermilab colleagues:
Minerba Betancourt, Jorge Morfin, Steven Gardiner, … *and, of course, CTEQ colleagues*

neutrino physics: center stage for modern HEP

- these lectures – communicate excitement of contempoary neutrino pheno

→ at the crux of the quest to test the standard model

↕

→ vital to the dream of a complete understanding of the strong interaction

- shall see, neutrinos combine a many open challenges in…

…electroweak pheno; (non)perturbative QCD; numerical analysis [AIML]; …

natural follow-on to previous lectures at this school!

what you've heard over the past few days...

- the modern QCD+EW standard model has been remarkably successful

→ collider phenomenology at LHC makes clear: can compute and measure detailed spectra for Higgs, gauge-boson, ttbar, …, production

Boughezal, Mistlberger, Sterman

→ ever more stringent SM tests rest high perturbative accuracy, high statistics, maturity in controlling experimental systematics

Gellersen, Ilten, Isaacson

→ hybrid of perturbative/nonperturbative approaches to determine essential nucleon, nuclear-structure inputs

Nadolsky, Reimer, Yuan

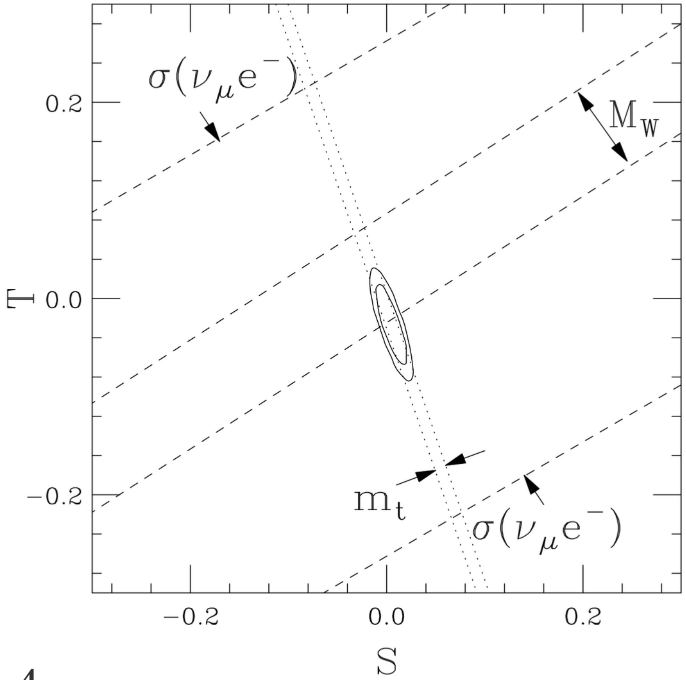
more needed to lengthen reach of SM tests, BSM searches

neutrino physics combines many of these threads

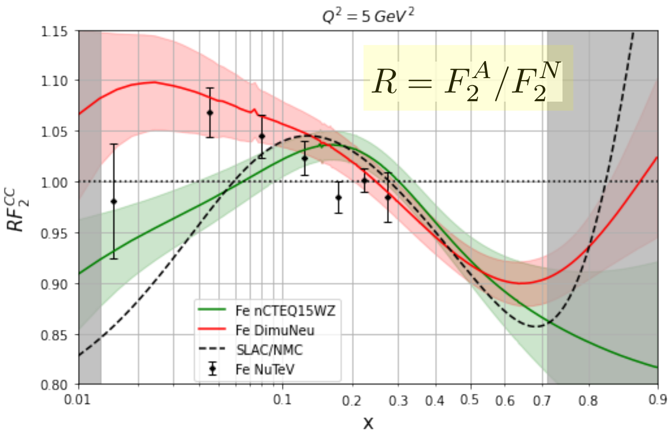
a ‘preview’

- previous ‘lessons’ all relevant to neutrino phenomenology
  - → ν scattering: essential portal to BSM models, nonstandard interactions
  - → unique probe of QCD matter: implications **to and from** ν experiments
  - → strong interplay with big data methods: MCs, tuning, Bayesian methods, AIML

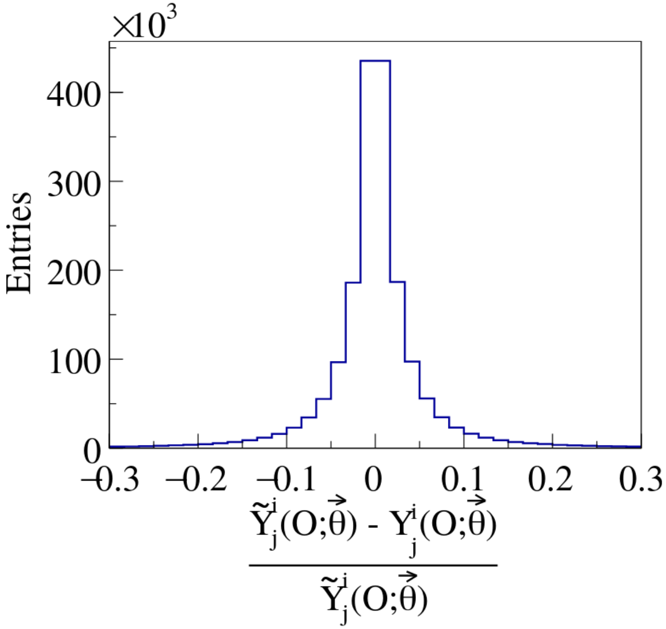
BSM constraints



QCD and nuclear DIS



Monte Carlo, ‘Big Data’



today: neutrino physics in HEP – place, key questions, history, expts

- numerous fundamental **HEP motivations** for ν physics
- field has long **history**, from dawn of subatomic physics
- fundamental property: theory of neutrino **flavor oscillations**
- survey of recent, upcoming neutrino **experiments** and reach

tomorrow: **νA cross section** – connections to QCD, nuclear dynamics

why care about neutrinos? the **neutrino mass**

- the Standard Model generically predicts ***massless*** neutrinos

why? …**there are no right-handed neutrinos** (more shortly)

↓

ordinary Higgs mass-generation mechanism unavailable:

$$-\mathcal{L}_{\mathrm{lep}}^{\mathrm{Yuk.}} = Y_{ij}^{\ell} \bar{L}_{Li} \phi E_{Rj} \ + \ \mathrm{h.c.}$$

$$m_{ij}^{\ell} = Y_{ij}^{\ell} \frac{v}{\sqrt{2}}$$

{ charged leptons develop Yukama mass after SSB }

→ can't construct analogous bilinear for neutrinos

- if neutrinos possess mass, as we'll see, this implies incompleteness in the SM

→ **missing degrees of freedom, or formal problems in SM**

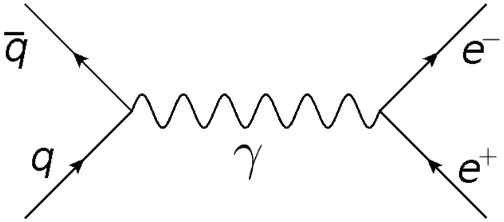
i.e., deviations from gauge invariance

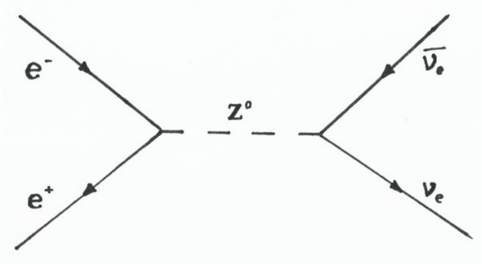
rich BSM testbed

the matter-antimatter puzzle

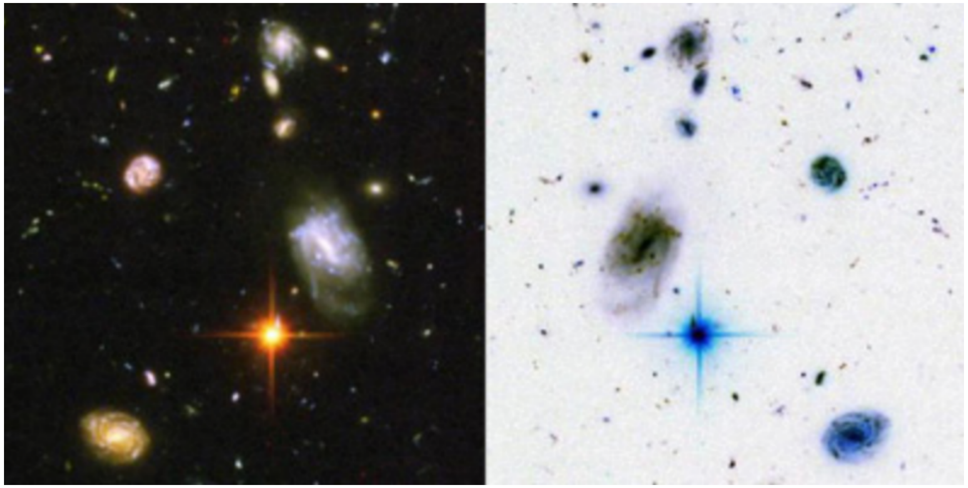
- or, why is there something, rather than (on average) nothing?

→ early universe dominated by processes that did not favor anti/matter





- might also ask: **where then is all the antimatter?**

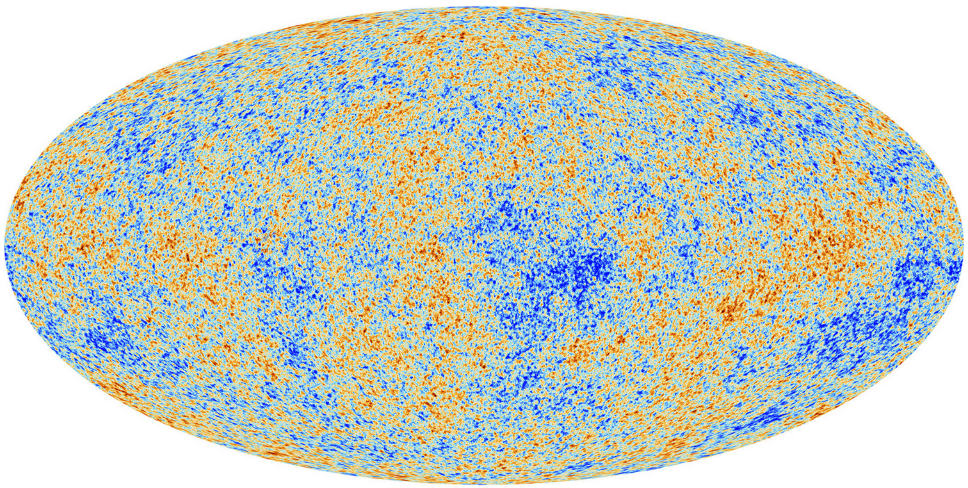


- reasons to suspect neutrinos *may* provide some mechanism to (very slightly) favor matter over antimatter

(early-universe) cosmology

- neutrinos contributed to the early evolution of the universe

  → role(s) in Big Bang Nucleosynthesis (BBN); baryo-, leptogenesis; CMB formation; seeding large-scale structure



cosmic microwave background (CMB), Planck satellite

- relic electromagnetic radiation from era of decoupling, 3.79 10^5 yrs following Big Bang

  → density variations, anisotropies carry information on structure formation

- there must be a relic neutrino radiation field as well! a 'cosmic neutrino background'

  → would be similarly informative, but w.r.t. ~1 second after Big Bang

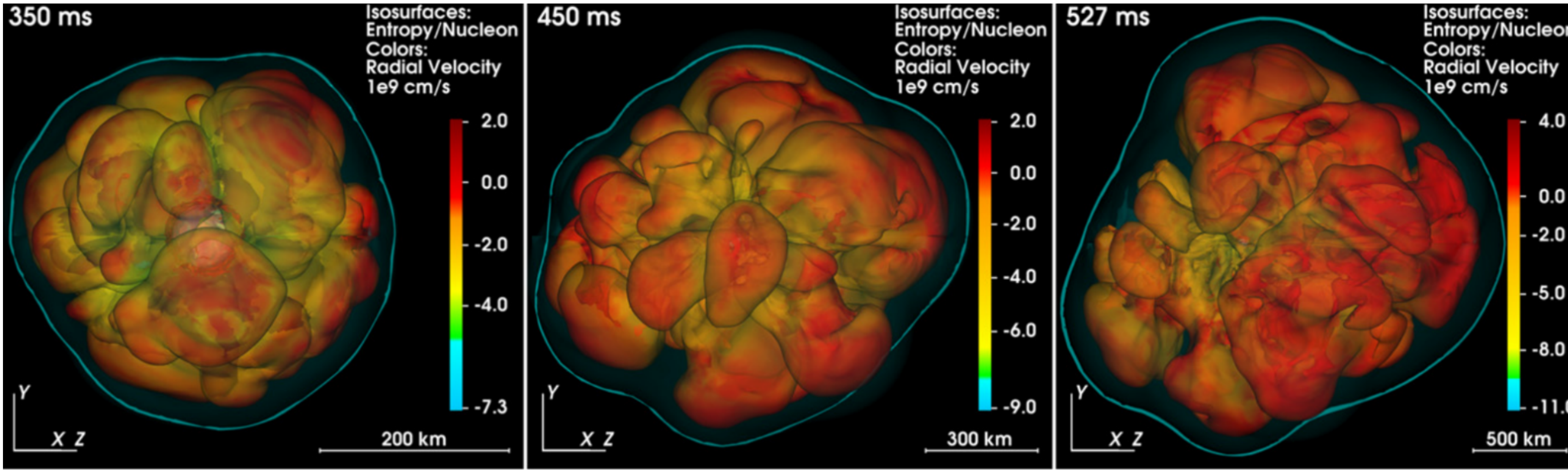
---

- critical to **supernovae** → standard candle in cosmic distance ladder; <u>must understand</u>

neutrinos and particle astrophysics

1D: **2D:** **3D:**

T. Melson et al., Astrophys.J. **808** (2015) no.2 L42.



→ neutrinos key to core-collapse supernovae (CCSNe): a driver of galactic metallicity distributions

- **delayed neutrino flux** from PNS can heat the post-shock region; re-energize shock front:

$$\sigma_i(\epsilon) = \frac{2G_F^2\epsilon^2}{3\pi}\left(c_{Vi}^2 + 5c_{Ai}^2\right)$$ elastic total cross section, $\nu N \rightarrow \nu N$

$i = (p, n)$

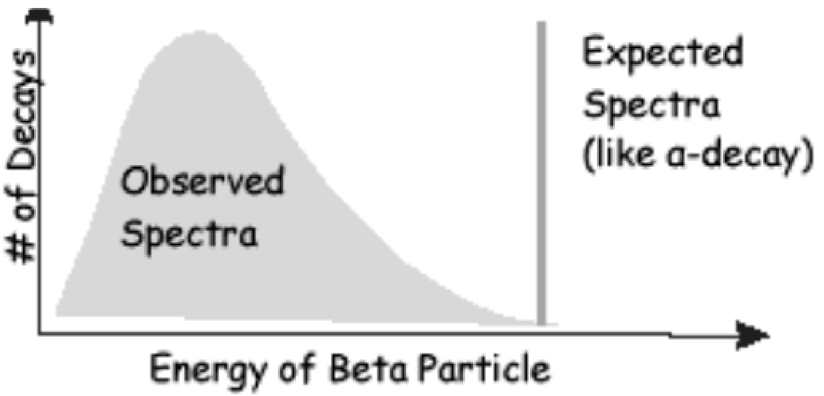
origins: Pauli, nuclear decays → must be a very light, neutral particle

- we've been grappling with neutrinos for much of the history of particle physics!
- spectra in radioactive decay of nuclei suggestive: $p \to n + e^+ + [?]$

  → interpret via Fermi's 'contact theory' (?)

W. Pauli   I.I.Rabi and... **Fermi**

- Pauli: energy conservation in **continuous** decay β-decay spectra →



requires a "desperate remedy" (1930)

- we've been grappling with neutrinos for much of the history of particle physics!
- spectra in radioactive decay of nuclei suggestive: $p \rightarrow n + e^{+} + \nu_e$

→ interpret via Fermi's 'contact theory' (?) ...yes!

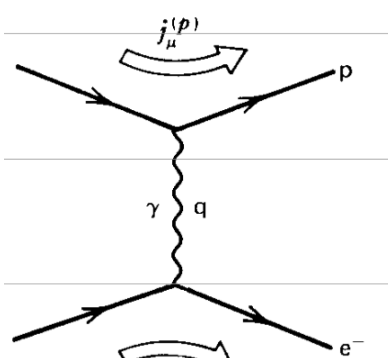
W. Pauli

I.I.Rabi and... **Fermi**

- dovetailing with Pauli's light, neutral lepton, Fermi suggested an interaction inspired by analogy with the EM

→ guess vector-like interaction

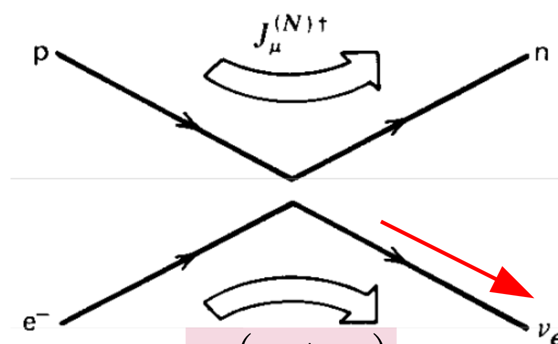
$$J_\mu^{(e\rightarrow\nu_e)} = \sqrt{G_F}\,\bar{u}_{\nu_e}\gamma_\mu u_e$$



QED

$J_\mu^{(e\rightarrow e)}$

crossed-reaction



$J_\mu^{(e\rightarrow\nu_e)}$

effective 4-fermion int.

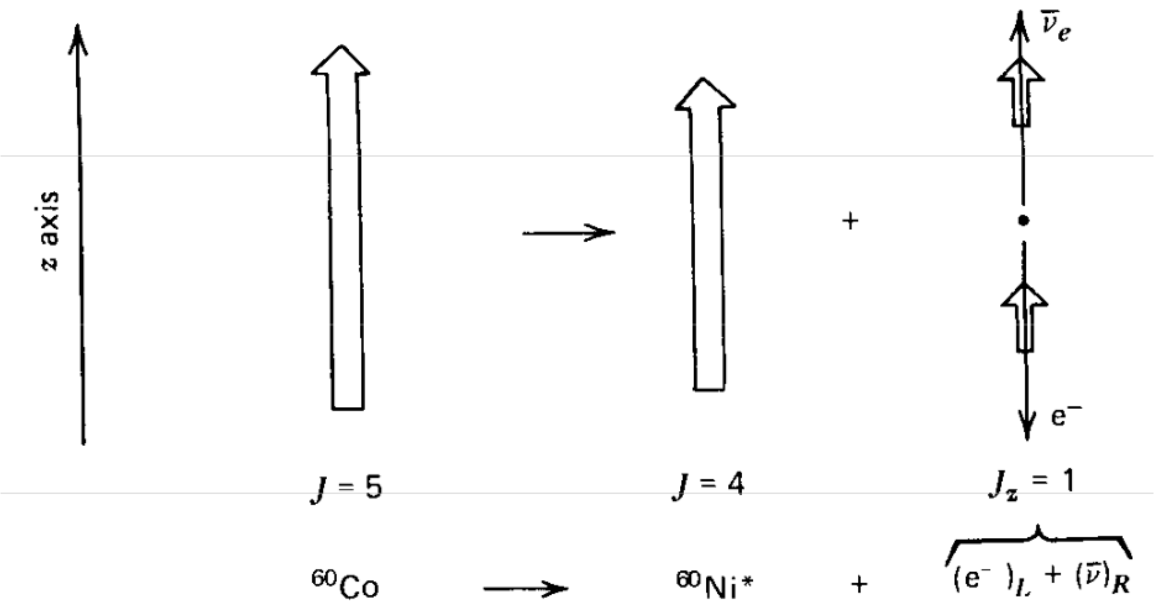
neutrinos and parity-violation from decay observations

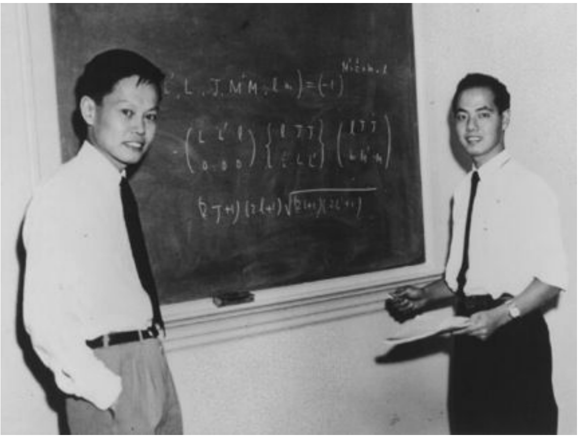
- Lee, Yang argued for parity non-conservation from semi-leptonic, had. decays

→ can be observed directly: ${}^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni}^* + e^- + \bar{\nu}_e$

- β-particle emited antiparallel to spin-polarized parent nucleus

$$J_\mu^{(e\to\nu_e)} = \sqrt{G_F}\,\bar{u}_{\nu_e}\gamma_\mu u_e \;\to\; \sqrt{G_F}\,\bar{u}_{\nu_e}\gamma_\mu(1-\gamma_5)u_e$$





- angular momentum accounted by left-handed electron, right-handed antineutrino

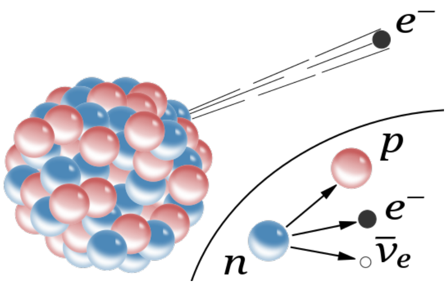
- remarkable properties; but **how about direct detection of neutrinos?**

- Bethe-Peierls predicted β-decay cross section (1934):

$$\sigma(E_\nu = 2\,\mathrm{MeV}) \approx 10^{-44}\mathrm{cm}^2$$

(very small)

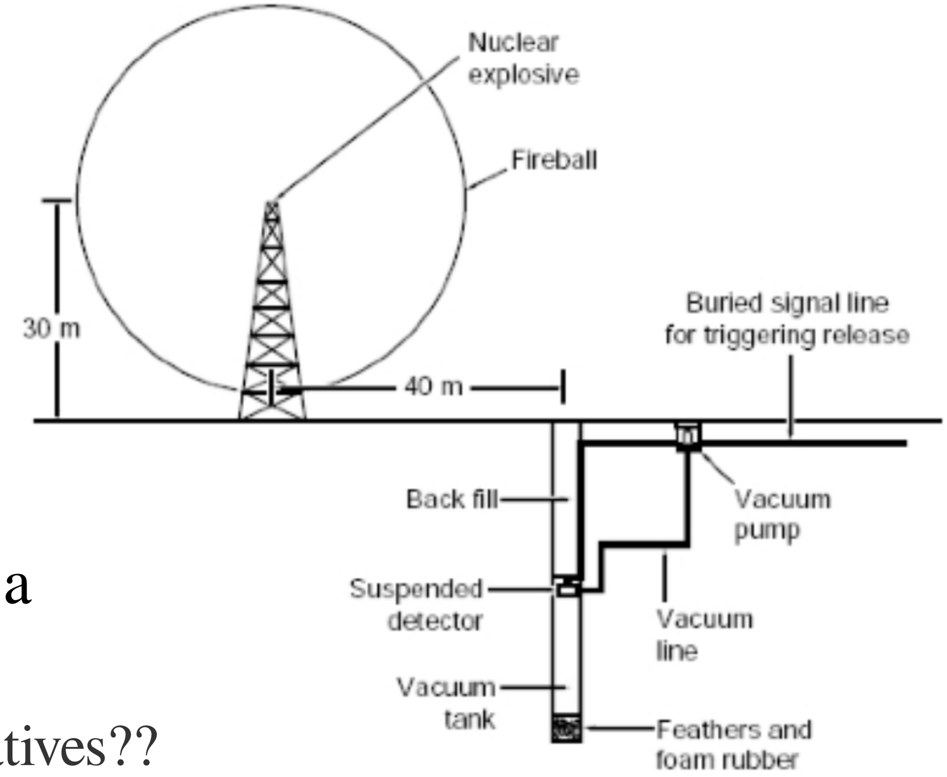
the post-War approach to neutrino detection



- (anti)neutrinos copiously produced in super-critical nuclear fission

- *Project Poltergeist* (1951): aptly named for the undetected, 'ghostly' neutrino

Clyde Cowan (far left), Fred Reines (far right) et al.



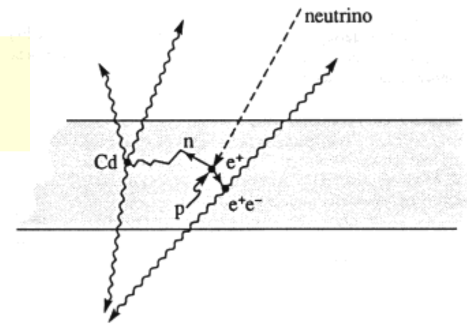
- site a detector in the Nevada desert near a nuclear test

  → this proved somewhat tricky… alternatives??

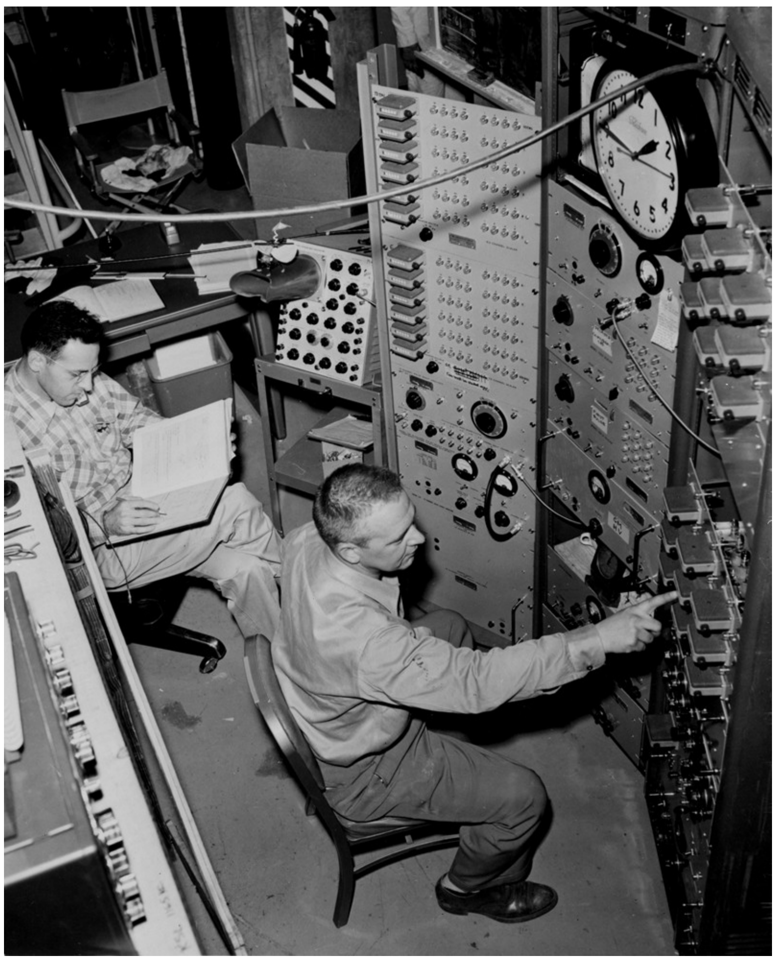
more sustainable (and ultimately successful) approach

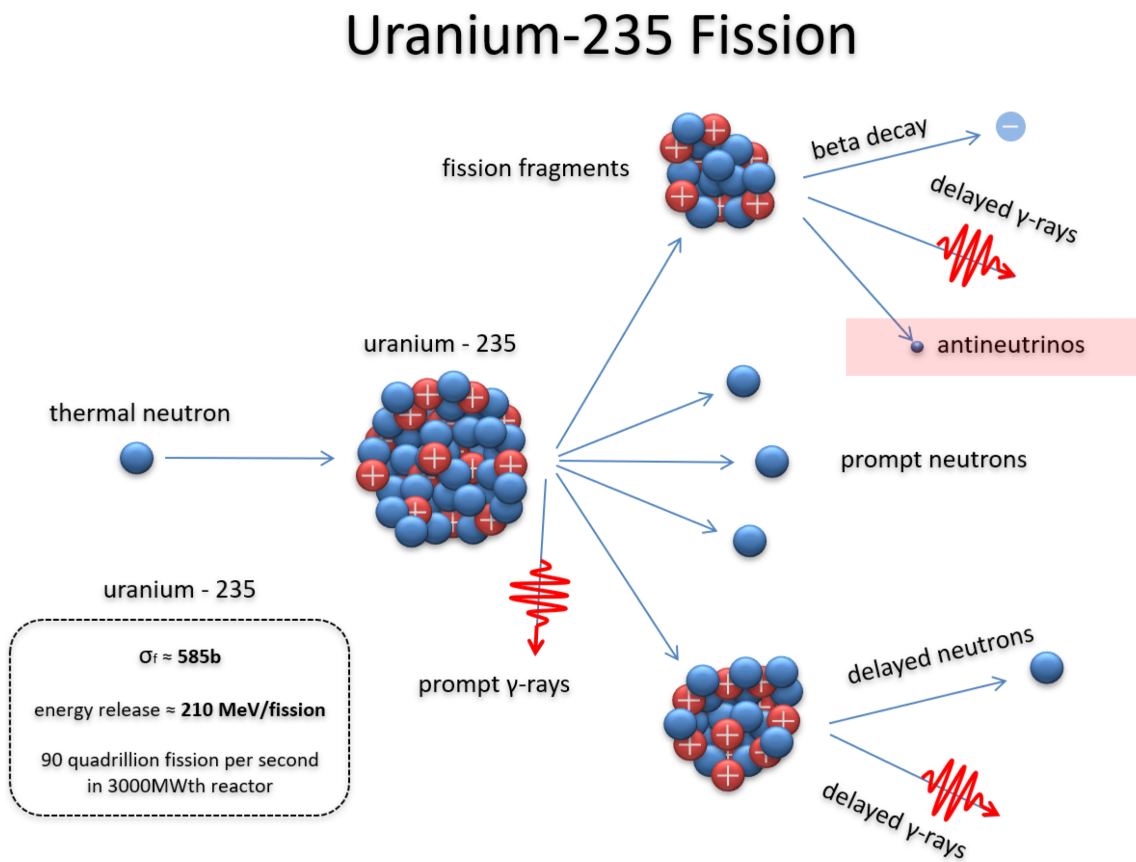
- exploit nuclear reactor and β-decay in ^{235}U fission to observe anti-ν flux
  - → first seen in Hanford, WA (1953); confirmed at Savannah River (1956)
- ½ 1995 Nobel Prize for Reines: detect anti-ν_e via inverse β-decay

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



Reines, Cowan in Savannah River control room.





consequential for coming discussion: more than 1 neutrino!

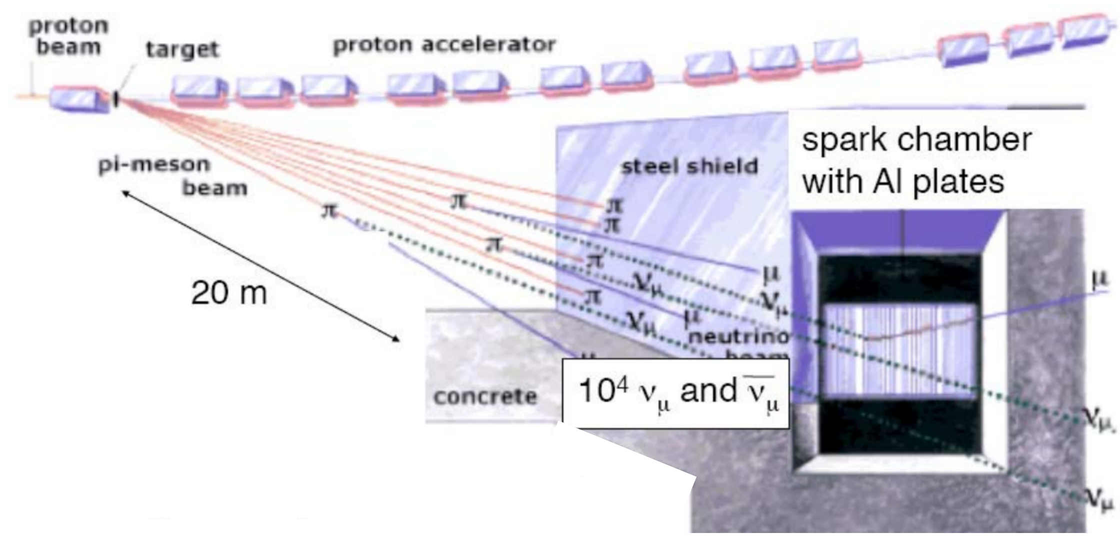
- Reines et al. discovered the electron (anti)neutrino

- in fact, leptons have ‘doublet’ structure, with >1 neutrino flavor

(1988)

→ heralded by 1962 BNL discovery of muon-neutrino, ν_μ

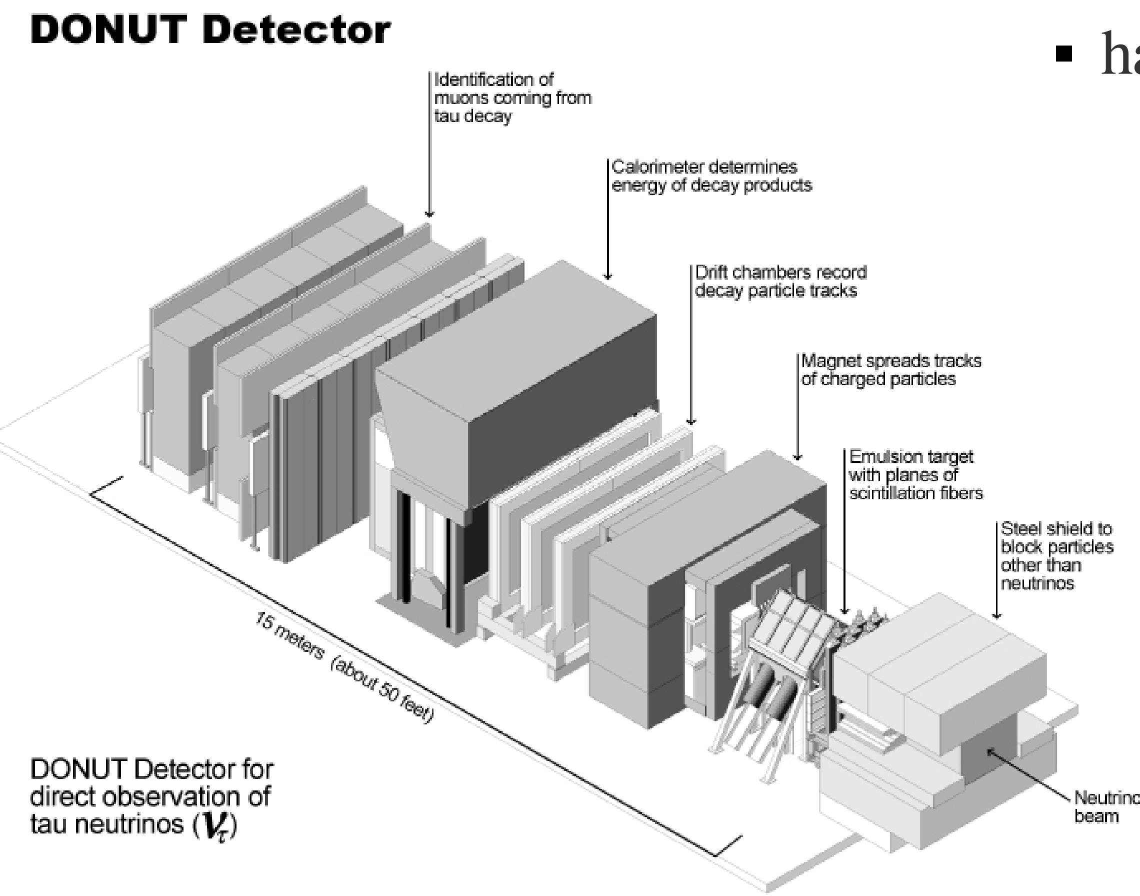
Lederman, Schwartz, Steinberger



- Melvin Schwartz with BNL 10-ton spark track cosmic-ray muon tracks visible

… so τ lepton has a neutrino partner as well (year 2000)

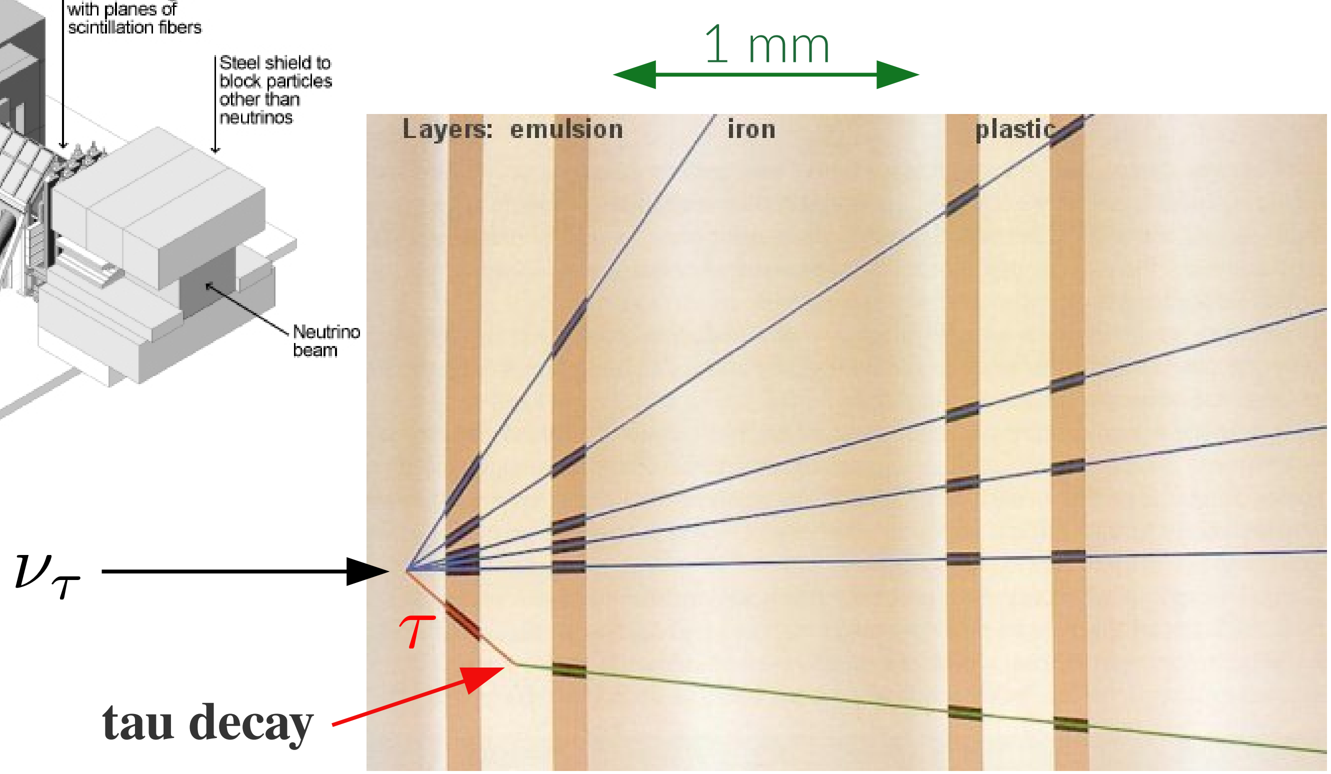
- observed at Fermilab, **DONUT**: **D**irect **o**bservation of the **nu** **t**au, (E872)



- had to confront very short τ lifetime

  → high resolution detector!

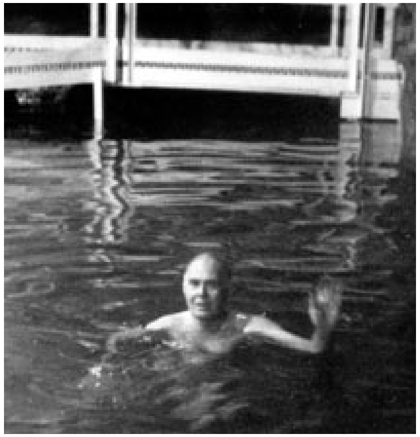
typical τ flight length: $\sim 300\mu$m



meanwhile, curious findings from astrophysical (solar) neutrinos

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

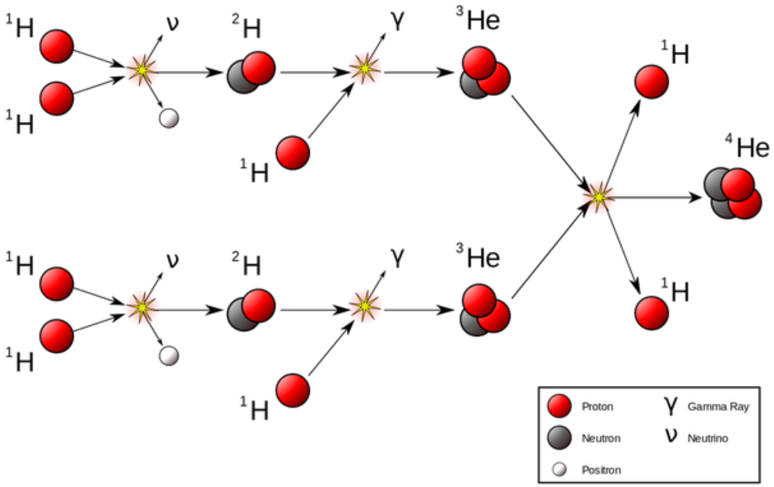
10^5-gallon tank of dry-cleaning fluid, Homestake Mine [Lead, SD]



Ray Davis, in the tank

John Bahcall

(typifying the experimentalist-theorist cultural divide...)



- Davis *et al*. observed solar ν_e flux, **but only 1/3 that predicted by theorists** (Bahcall)

→ still, proof that stars driven by nuclear fusion! [birth of ν-astro.]

(2002)

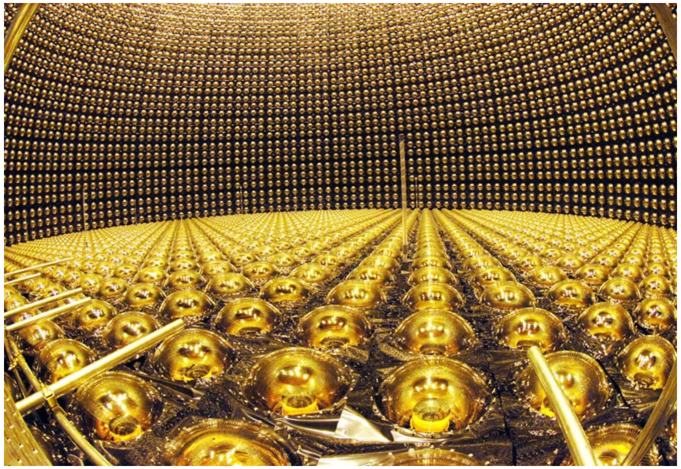
similarly, from cosmic neutrinos as well

- cosmic rays strike the earth (essentially) isotropically…

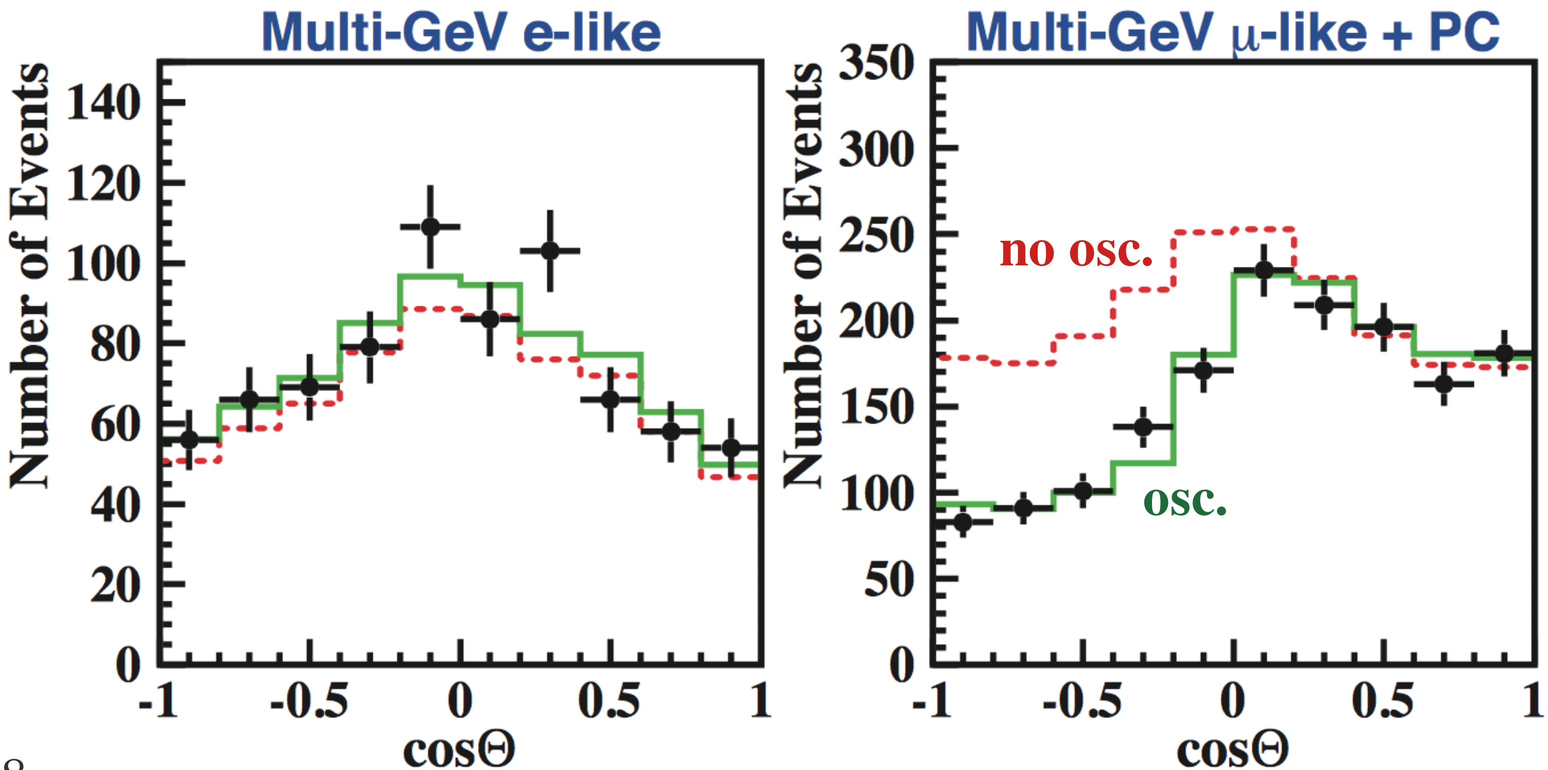
– BUT –

- pronounced up-/down- asymmetry in ν_μ flux:

$$\frac{\Phi_{\nu_\mu}(Up)}{\Phi_{\nu_\mu}(Down)} = 0.54 \pm 0.04 \quad \neq 1$$



Super Kamiokande (Japan); 50kT of water



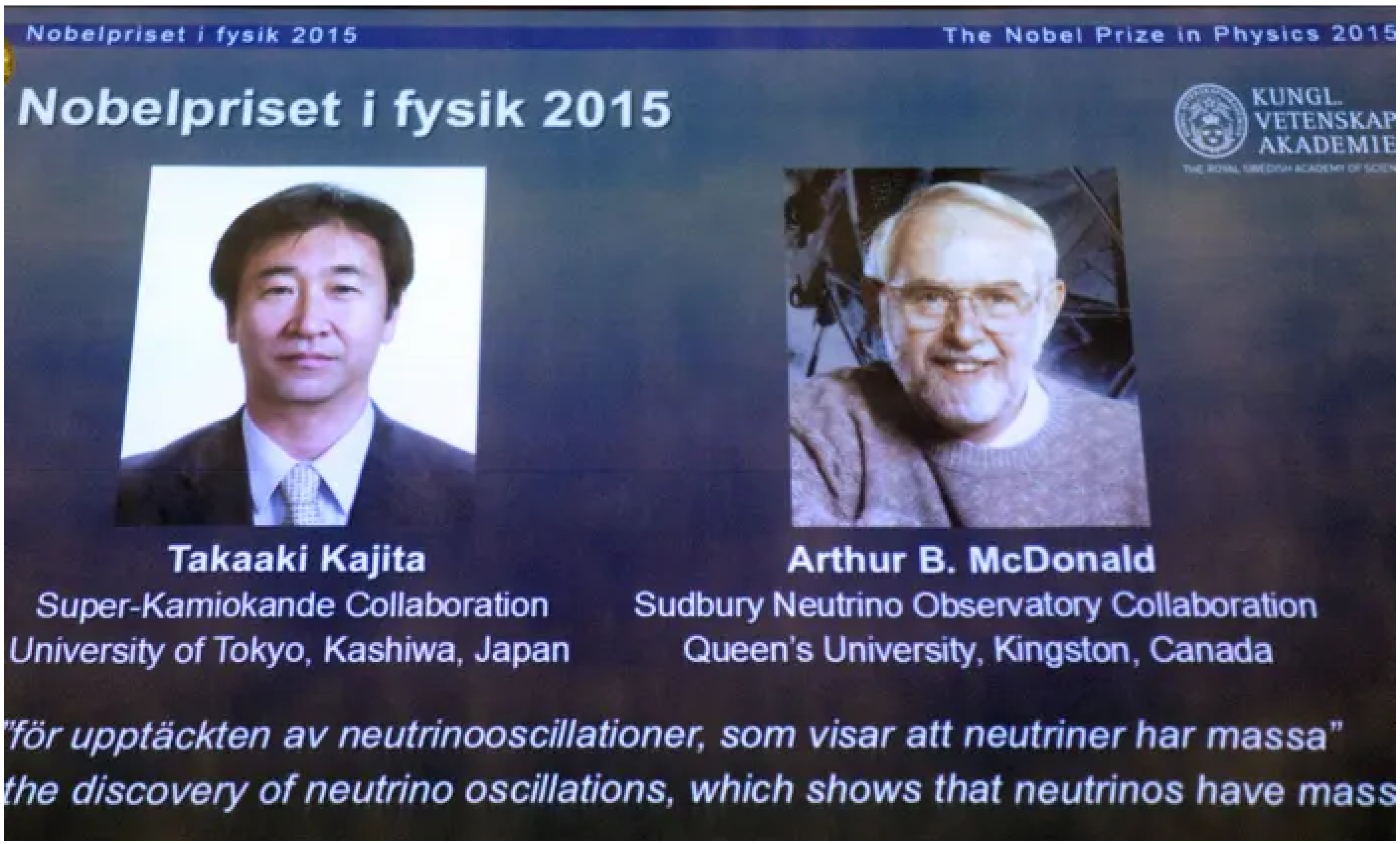
- relative reduction in ν_μ events at upward angles; vs. enhancement for ν_e

→ what's happening??

crucially, these neutrino flavors are not static – **they mix**!

- shall discuss in a moment, these neutrino flavors intermix, one into the other

i.e., there are neutrino flavor **oscillations**



(2015)

- specifically a consequence of nonzero ν mass

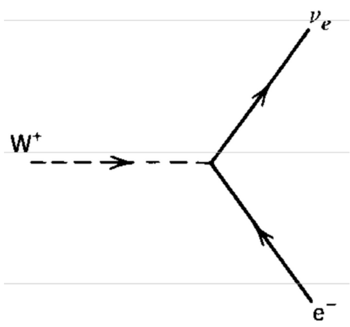
→ one of the more compelling indications of SM incompleteness

neutrinos in the standard model (SM)

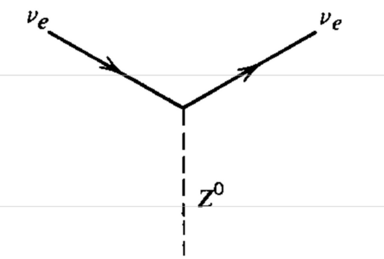
- SM gauge theory: neutrinos appear inside lepton doublets, $L_{L\ell} = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L$

$$\ell = e, \mu, \tau \qquad \leftrightarrow \qquad \nu_e, \nu_\mu, \nu_\tau$$

$$-\mathcal{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} \sum_\ell \left(\bar{\nu}_{L\ell} \gamma^\mu \ell_L^- W_\mu^+ \right) \; + \; \text{h.c.}$$



$$-\mathcal{L}_{\mathrm{NC}} = \frac{g}{2\cos\theta_W} \sum_\ell \left(\bar{\nu}_{L\ell} \gamma^\mu \nu_{L\ell} Z_\mu \right) \; + \; \text{h.c.}$$



- *W*-decay thus produces lepton pairs of definite flavor:

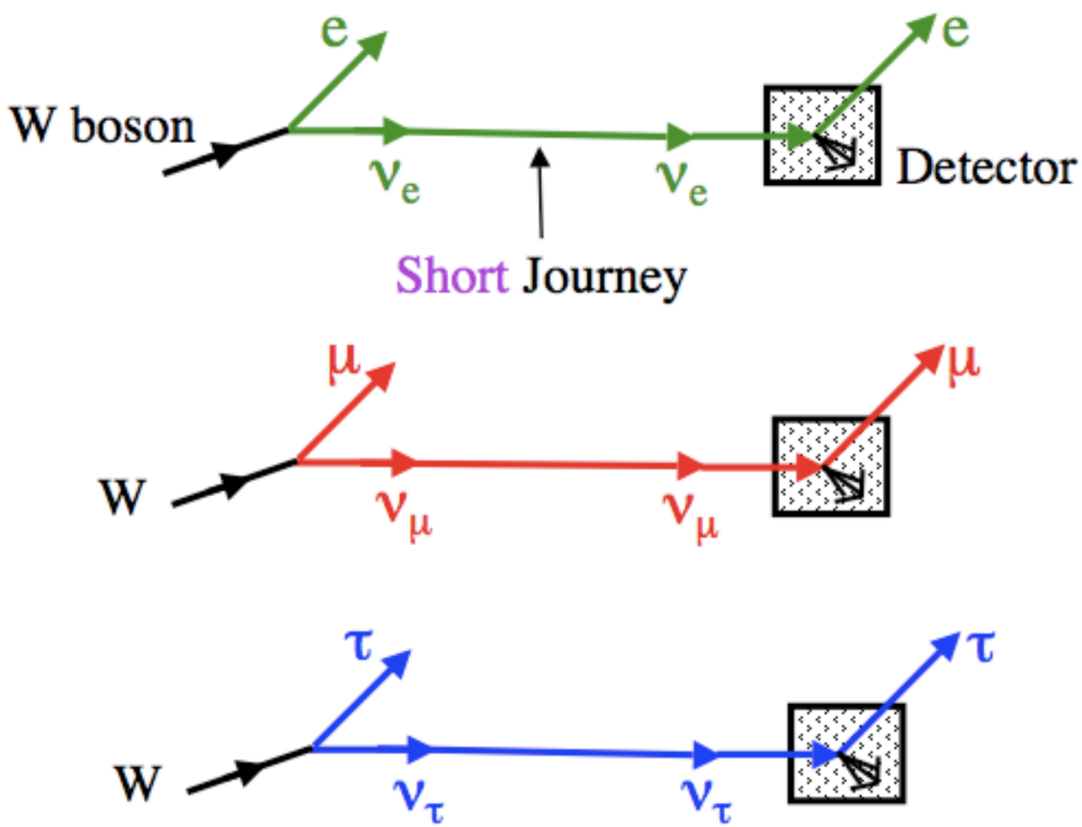
$$W^+ \to \nu_\ell + \ell^+$$

(*e.g.*, muon accompanied by muon neutrino; EM charge carried by former)

neutrinos of definite flavor

- simplest scenario, neutrinos produced in charged-current decays traverse a ‘short’ distance to nearby detector

→ reconstruct neutrino of definite flavor, corresponding to associated charged-lepton of definite flavor

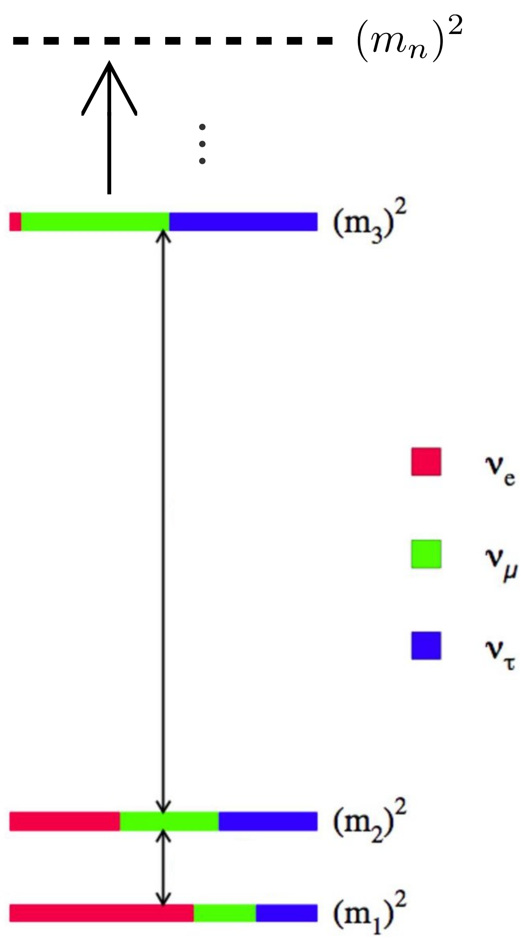


- this all seems straightforward…

- BUT remember: we noted the neutrinos are NOT massless

→ neutrino flavor states are linear combinations of mass eigenstates

for $n = (3 + m)$ mass eigenstates



in mass basis:

$$-\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}}(\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L)\gamma^\mu U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix} W^+_\mu \; + \; \text{h.c.}$$

BUT

→ flavor states are combinations of mass states; and *vice versa*

$\Downarrow$

dynamical (time-dependent) mixing of neutrino flavors!

flavor mixing

$$-\mathcal{L}_{\rm CC} = \frac{g}{\sqrt{2}}(\bar{e}_L, \bar{\mu}_L, \bar{\tau}_L)\gamma^\mu U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \\ \nu_n \end{pmatrix} W^+_\mu \ + \ \text{h.c.} \qquad \Longrightarrow \qquad U_{ij} \sim (V^\ell_{ik})^\dagger V^\nu_{kj}$$

lepton-mixing matrix

$[U$ is a $3 \times n$ matrix$]$

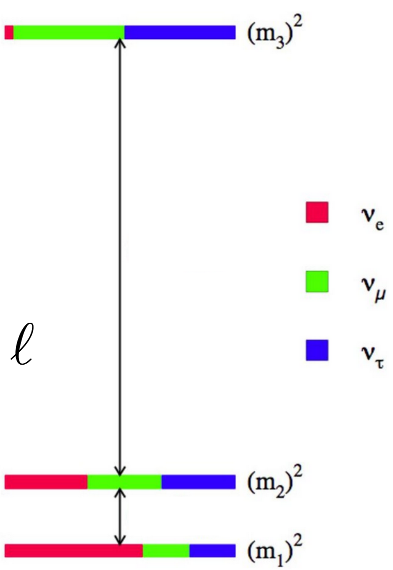
neutrino of definite flavor $\quad |\nu_\ell\rangle = \sum_i U^*_{\ell i}|\nu_i\rangle \quad$ neutrino of definite mass, m_i

- mixing matrix obeys basic unitarity, $UU^\dagger = I_3$

$$|\nu_i\rangle = \sum_\ell U_{\ell i}|\nu_\ell\rangle$$

contribution from flavor state ℓ to mass state i:

$$|\langle\nu_\ell|\nu_i\rangle|^2 = |U_{\ell i}|^2$$



mixing also suggests how to time-evolve propagating neutrinos

- similarly, take overlaps of time-dependent states; $U_{\ell i}$ governs time evolution

$$|\nu_\ell\rangle = \sum_i U^*_{\ell i}|\nu_i\rangle \longrightarrow |\nu_\ell(t)\rangle = \sum_{i=1}^{n} U^*_{\ell i}|\nu_i(t)\rangle$$

- assume neutrinos in mass basis are highly relativistic plane waves:

$$|\nu_i(t)\rangle = \exp\left(-iE_i t\right)|\nu_i(t=0)\rangle$$

$$E_i = (p_i^2 + m_i^2)^{1/2} \approx p + m_i^2/2E$$

$$[p_i \approx p_j := p \approx E;\ \text{mass eigenstates are orthogonal, } \langle\nu_i|\nu_j\rangle = \delta_{ij}]$$

- **SO**: a neutrino of definite flavor is a linear combination of contributions from mass eigenstates; these evolve with unique time dependence due to nonzero masses, nontrivial mass hierarchy

flavor oscillation probabilities become a good quantum HW problem

- unique time dependence of mass eigenstates (again, due to nonzero ν mass!) implies definite probability for neutrino mixing after finite time, *t*

$$|\nu_\ell(t)\rangle = \sum_{i=1}^{n} U^*_{\ell i}|\nu_i(t)\rangle \longrightarrow$$

- probability for oscillation, $\ell \to \ell'$, over distance L [corresponding to $t \approx L/c$]

$$P_{\ell\ell'} = |\langle\nu_{\ell'}|\nu_\ell(t)\rangle|^2 = \Big|\sum_{i=1}^{n}\sum_{j=1}^{n} U^*_{\ell i}U_{\ell' j}\langle\nu_j|\nu_i(t)\rangle\Big|^2$$

$$P_{\ell\ell'} = \delta_{\ell\ell'} - 4\sum_{i<j}^{n}\mathrm{Re}\big(U_{\ell i}U^*_{\ell' i}U^*_{\ell j}U_{\ell' j}\big)\sin^2 X_{ij} + 2\sum_{i<j}^{n}\mathrm{Im}\big(U_{\ell i}U^*_{\ell' i}U^*_{\ell j}U_{\ell' j}\big)\sin 2X_{ij}$$

$$X_{ij} \sim \Delta m^2_{ij}\left(\frac{L}{E}\right)$$

long-baseline experiments are sensitive to neutrino sector

- oscillation probability controlled by: *E*, *L*, ν mass differences; mixing matrix

$$\text{CP symmetry: odd/even under } U^*_{\ell i} \leftrightarrow U_{\ell i}$$

CP-conserving

CP-violating

$$P_{\ell\ell'} = \delta_{\ell\ell'} - 4\sum_{i<j}^{n} \mathrm{Re}\left(U_{\ell i}U^*_{\ell' i}U^*_{\ell j}U_{\ell' j}\right)\sin^2 X_{ij} + 2\sum_{i<j}^{n} \mathrm{Im}\left(U_{\ell i}U^*_{\ell' i}U^*_{\ell j}U_{\ell' j}\right)\sin 2X_{ij}$$

$$X_{ij} \sim \Delta m^2_{ij}\left(\frac{L}{E}\right)$$

- set *L* in experiment, distance between near-, far-detectors; *e.g.*, for DUNE:

flavor (dis)appearance sets limits on masses, mixing...

neutrino flavor mixing, in full glory…

- archetypal scenario: $n = 3$ Majorana neutrinos

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}; \cdots$$

→ 3 mixing angles; 1 CP-violating phase; 2 Majorana phases

– – OR – –

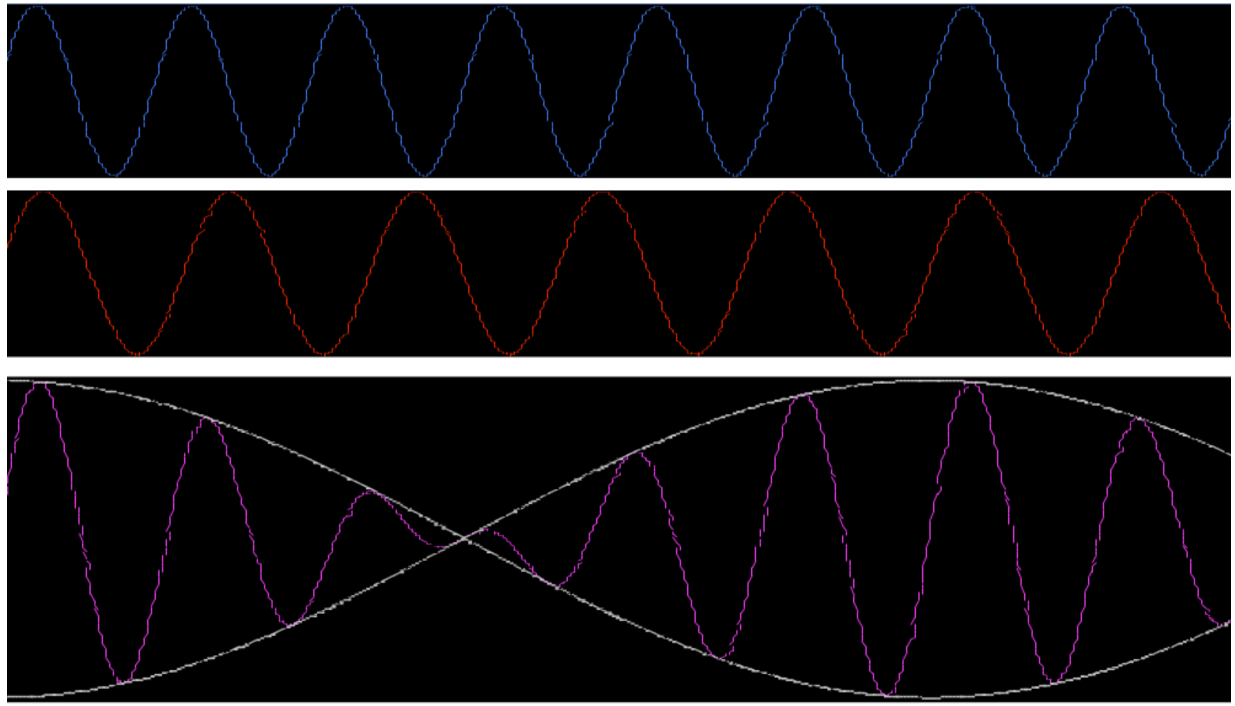
$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\rm CP}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\rm CP}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\rm CP}} & -c_{12}\,s_{23}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

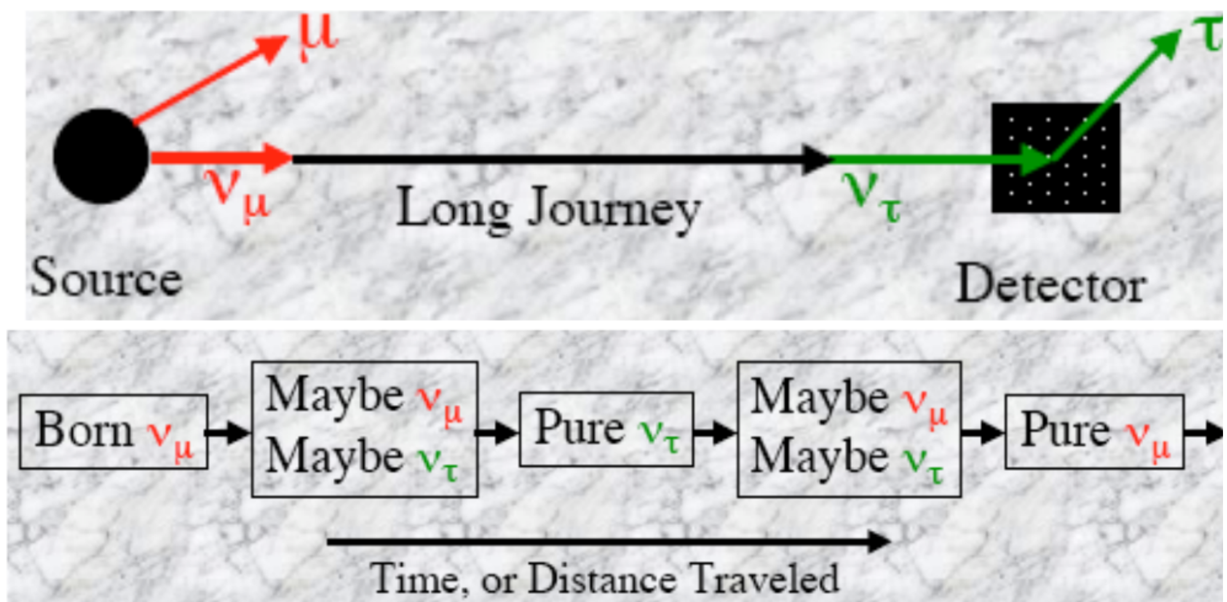
the Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) **matrix**…

→ assumes 3 Dirac neutrinos; Majorana phases absorbed into mixing

if this is complicated: simplified 2-component picture

- flavor oscillation,
- propagation,
- …,
- detection



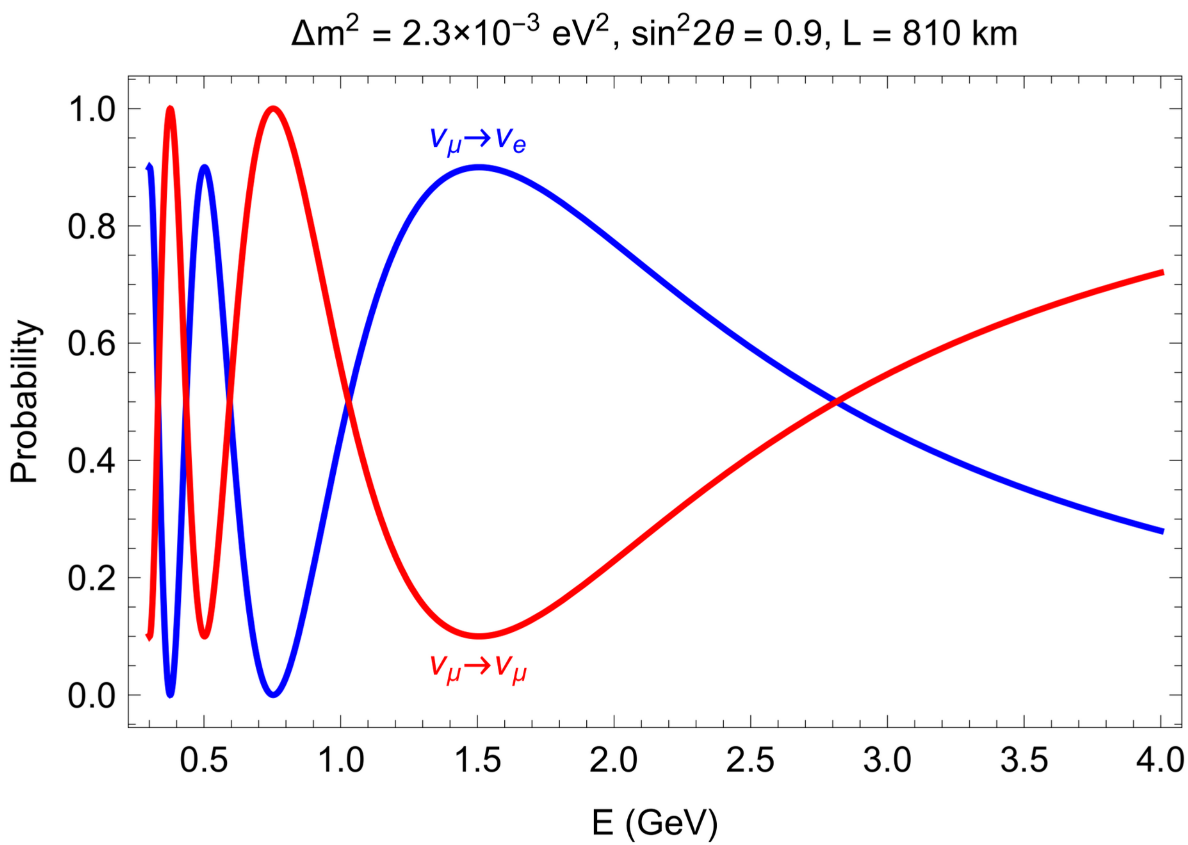


J. Morfin

2 flavor model, at fixed distance (time)

- 1 mass difference (Δm), fixed L: flavor-mixing prob. has fluctuating spectrum

$$P(\nu_\mu \to \nu_e; L) = |A_{\mu e}(L)|^2 = 4c_\theta^2 s_\theta^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



M. Betancourt

- at fixed L, specific neutrino energies suppress flavor-oscillation prob.

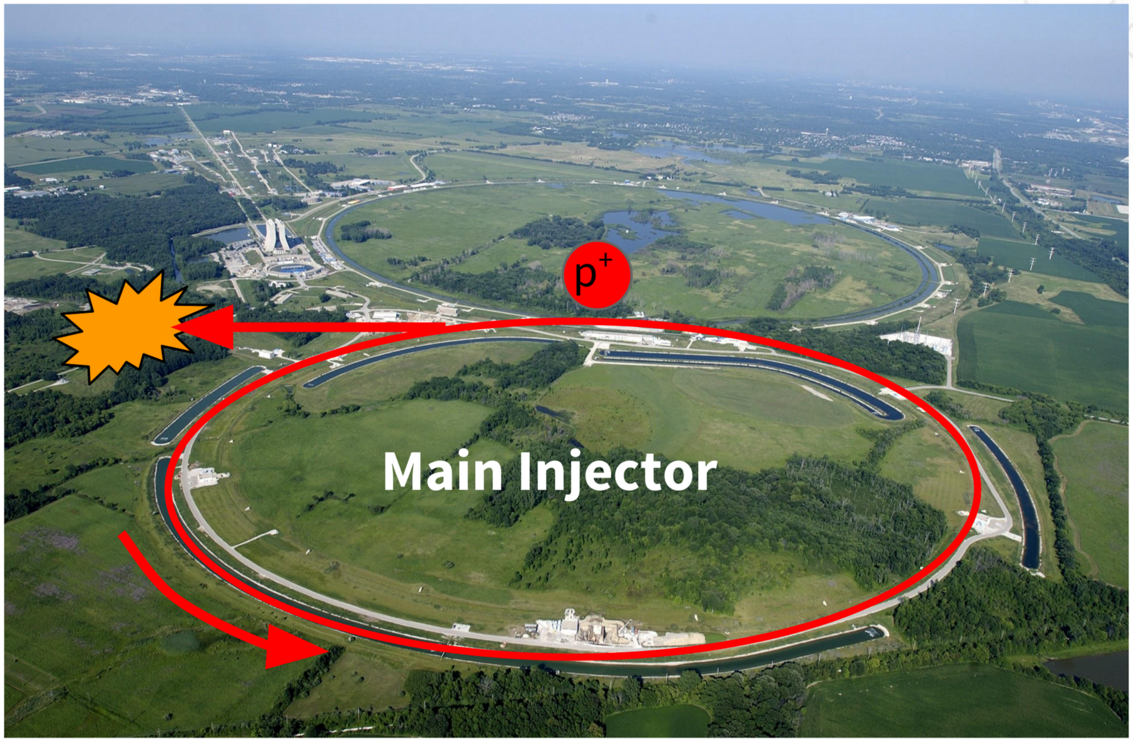
- **but** **remember**: the situation is much harder than this!

- neutrino beams are <u>NOT</u> monoenergetic – they have complicated flux distribution

→ this is schematic, in reality, neutrino parameters **unfolded** from various experiments

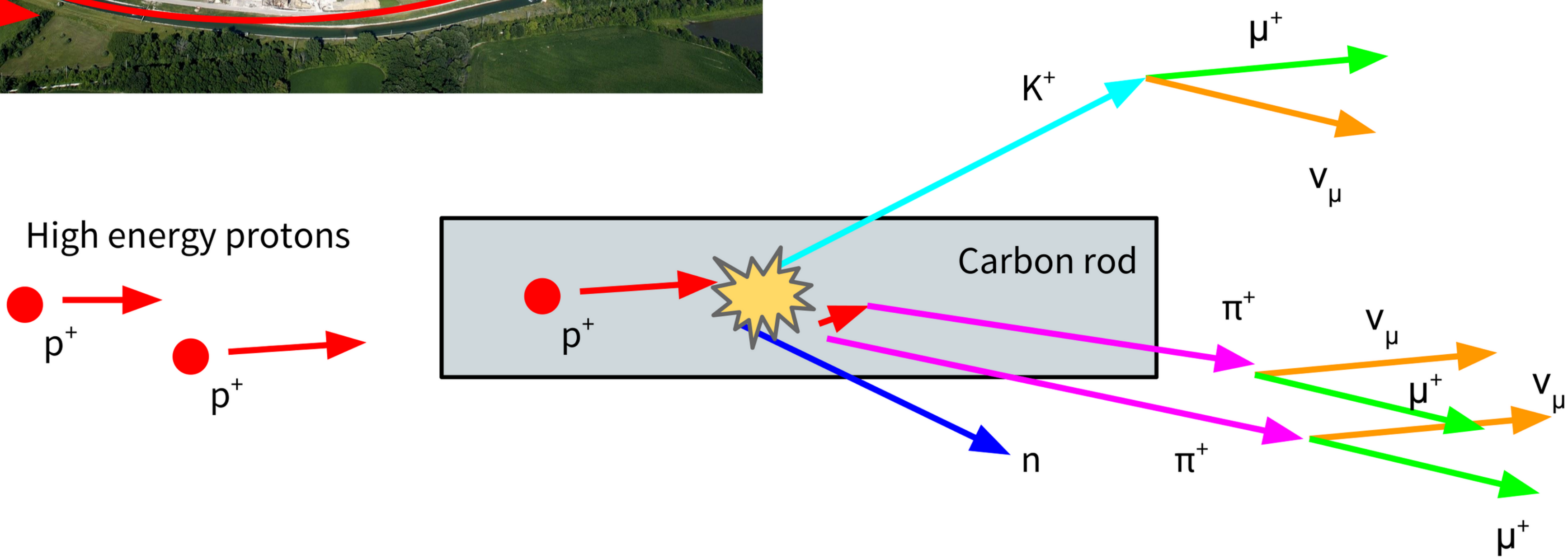
preparing a neutrino beam is a ‘messy’ business

- neutrino flux spectrum comes from complicated production process:



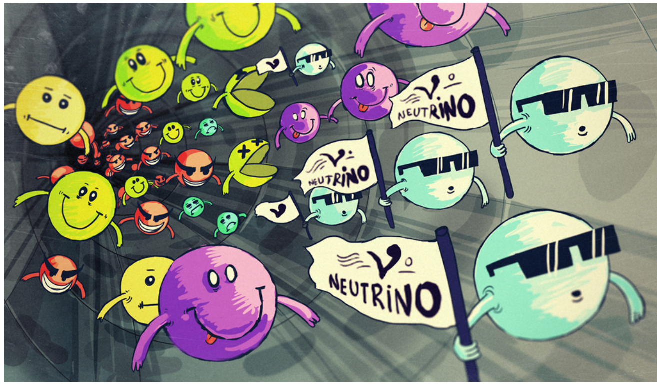
M. Betancourt

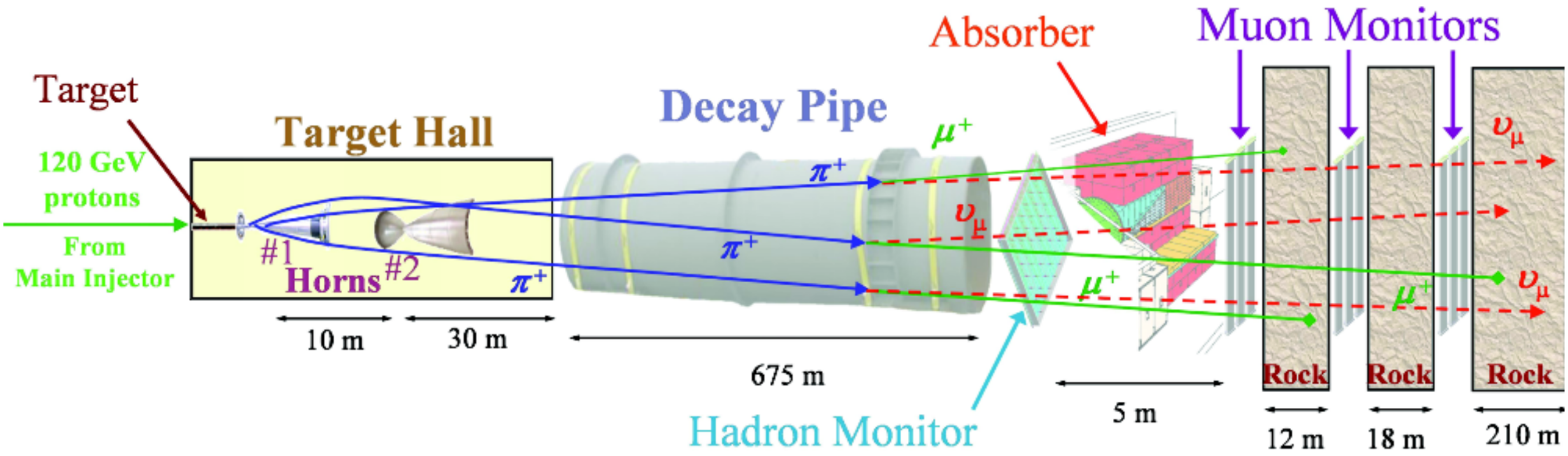
- Protons hit carbon
- Charged pions are produced
- Pions decay to neutrinos



once produced, ν beam propagates to series of detectors

- detectors are downstream of NuMI production
- relative neutrino beam purity guaranteed by chain of monitors, absorbers





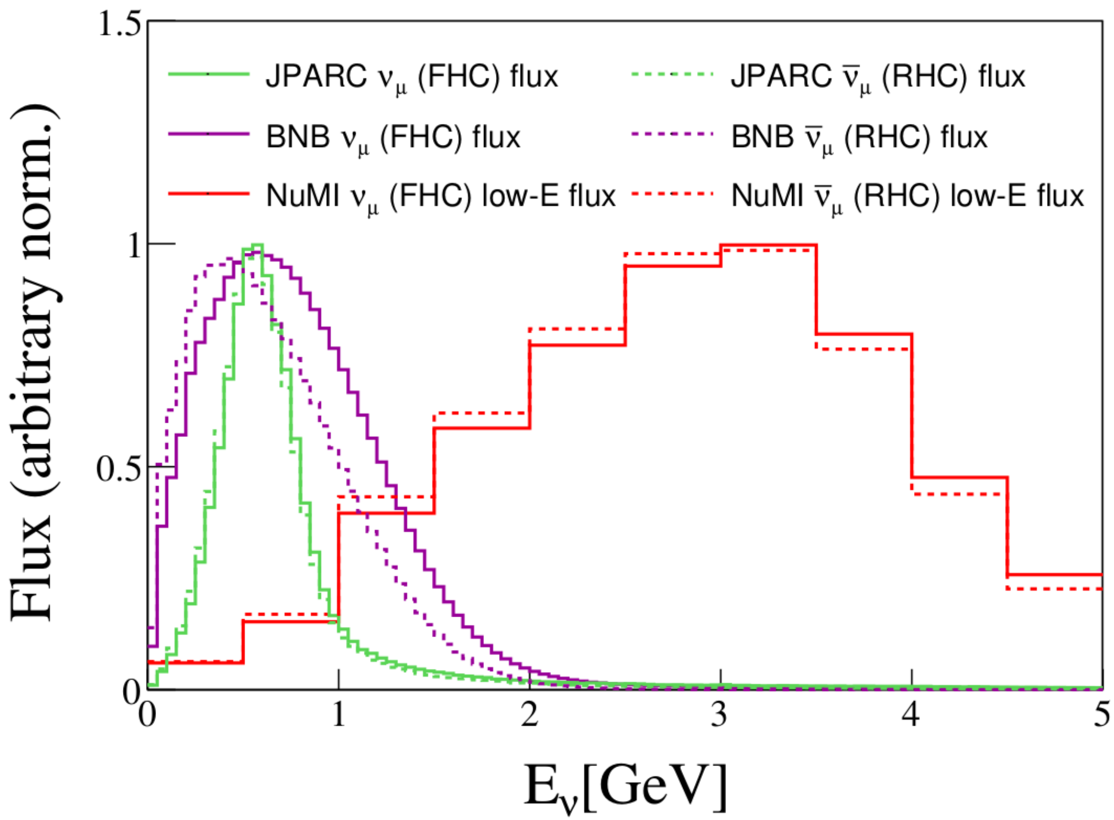
downstream experiments (MINERνA, MINOS, …)

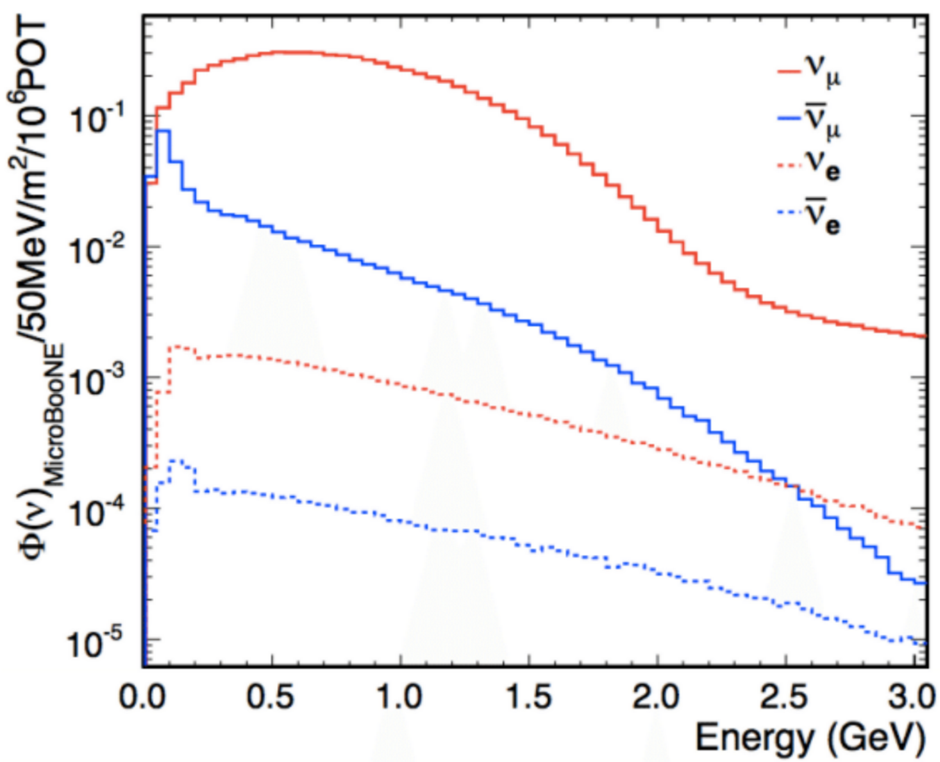
- beam dominated by ν_μ with small ν_e component

experimental configurations lead to different flux distributions

- unique beam production approaches, kinematics produce range of flux profiles
  - → for, e.g., MicroBooNE, ν_e *vs.* ν_μ suppressed by ~2 orders of magnitude (right)

JPARC (T2K); BNB (Mini/MicroBooNE); NuMI (MINERνA)

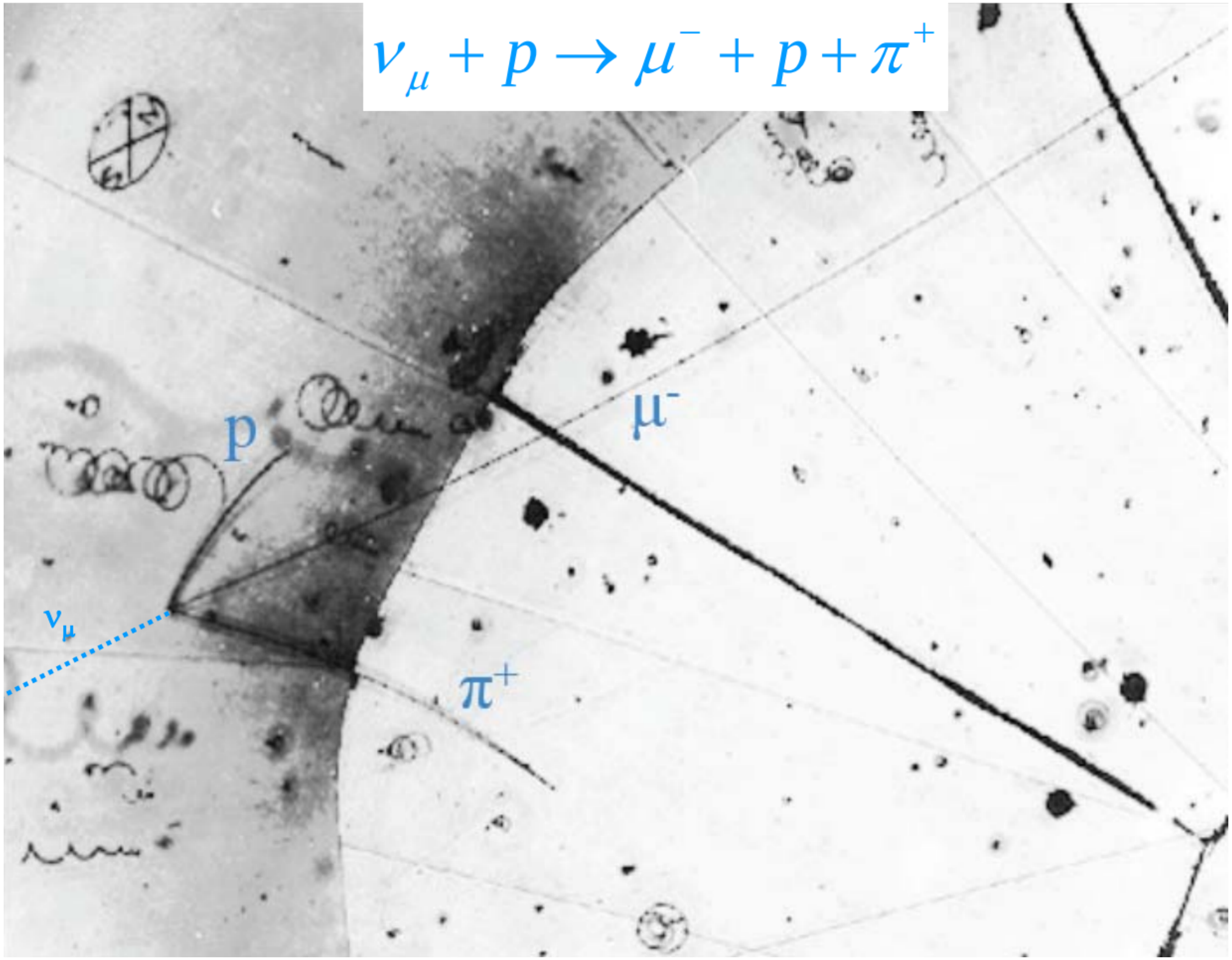




- these experiments (and many others) target different regimes, parameters…

experiments have made great strides in detection

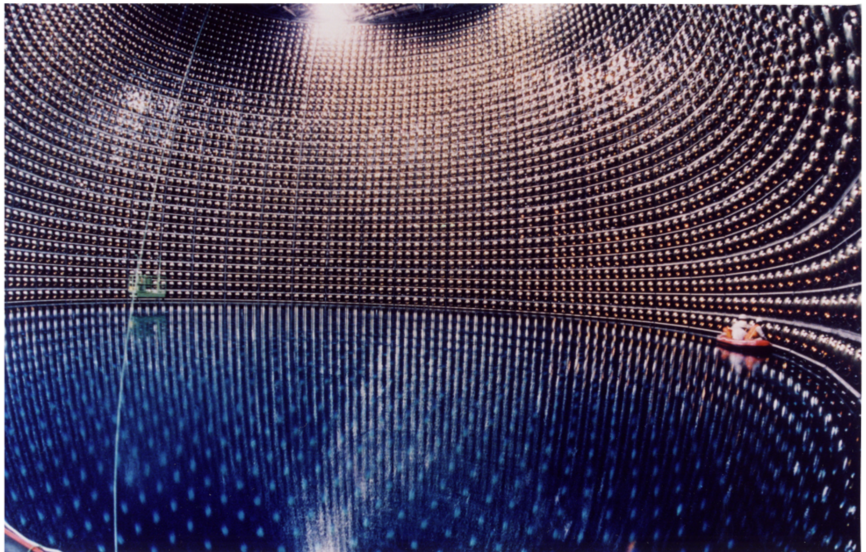
- early measurements made use of bubble chambers; *e.g.*, hydrogen target

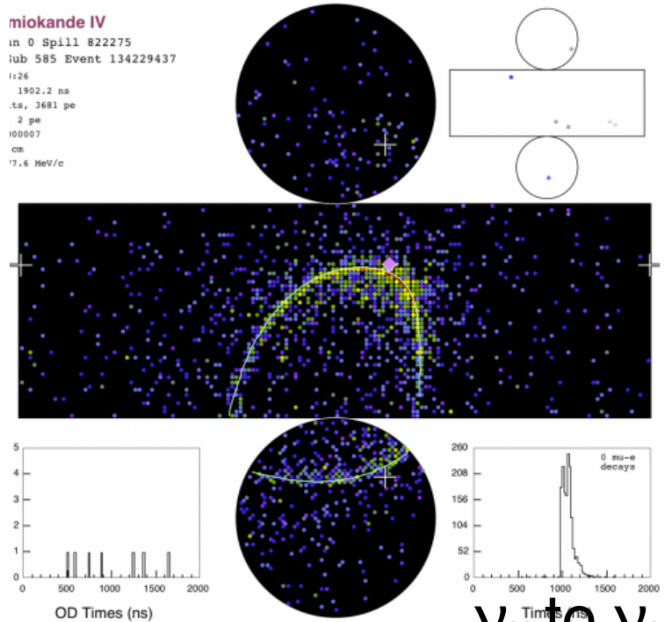


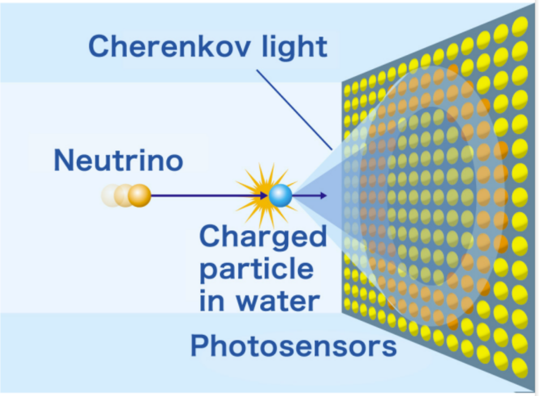
- Fermilab ('NAL') 15-foot Bubble Chamber, 1973

- in years since, wide ecosystem of detector, tracker concepts

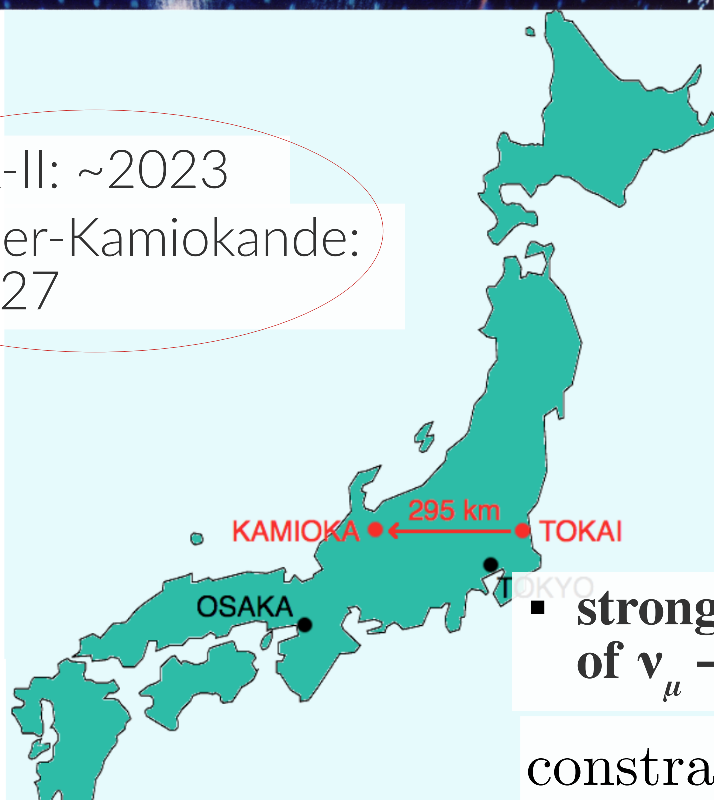
T2K (Tokai to Kamioka) neutrino experiment







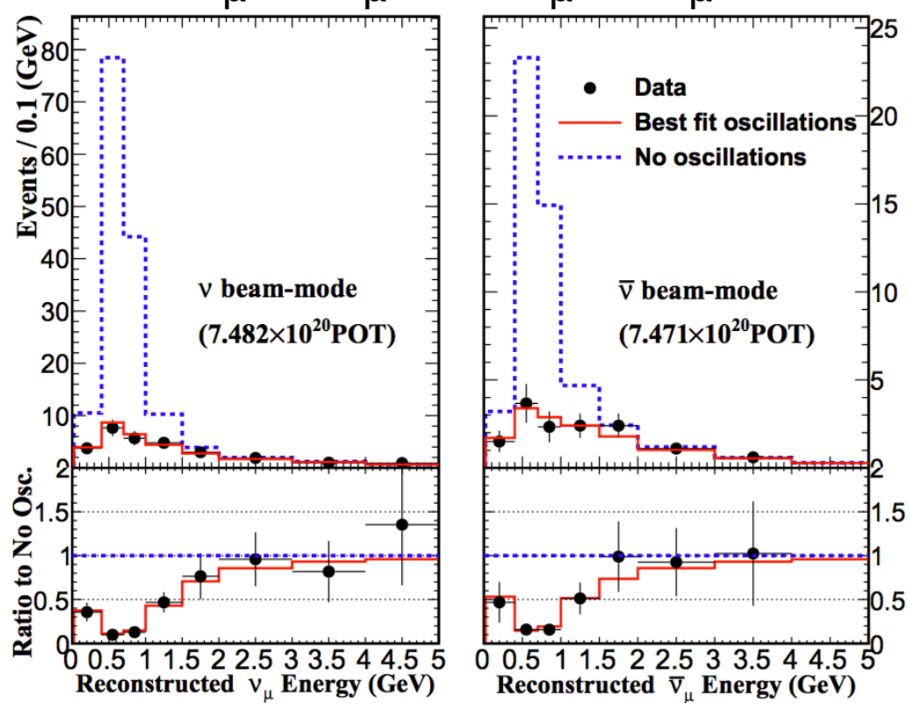
T2K-II: ~2023
Hyper-Kamiokande: ~2027



- **strong confirmation of $\nu_\mu \to \nu_e$**

constraints to δ_{CP}!

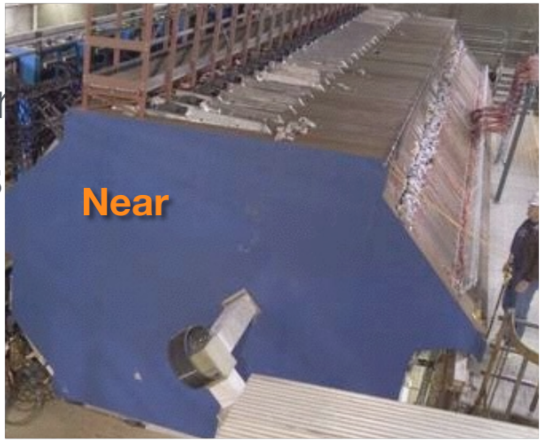
ν_μ to ν_μ and $\bar{\nu}_\mu$ to $\bar{\nu}_\mu$:

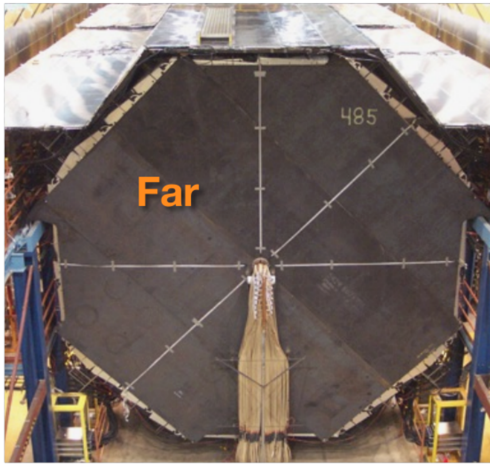


the MINOS Experiment, FNAL 2005-2016

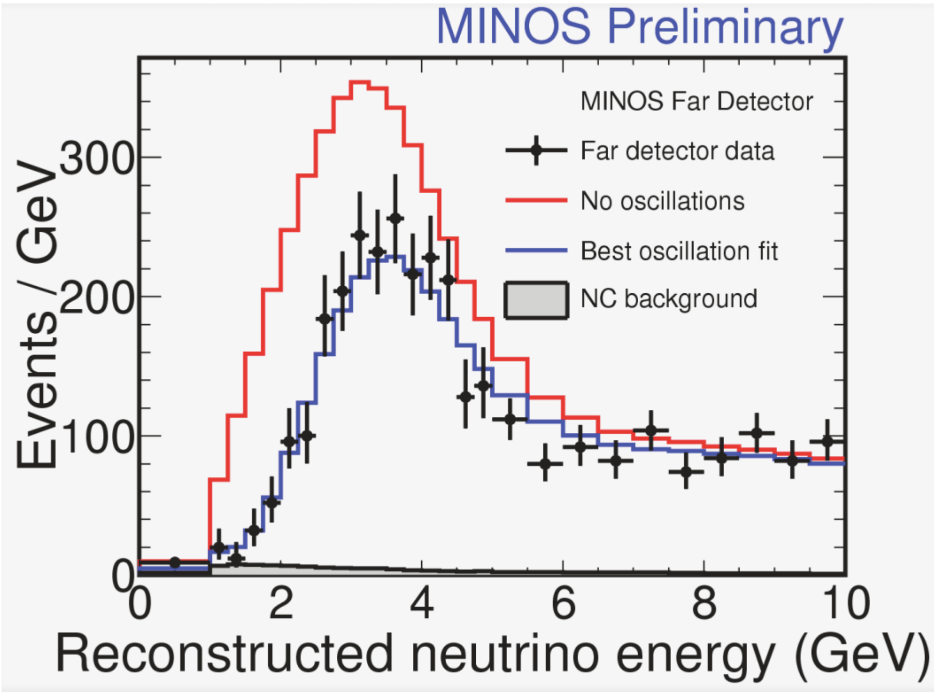
- Near and Far detectors
- Steel planes (2.54 cm), magnetized detector
- Alternating with planes of scintillator strips
  - Near detector: 1 ton
  - Far detector: 5.4 kton

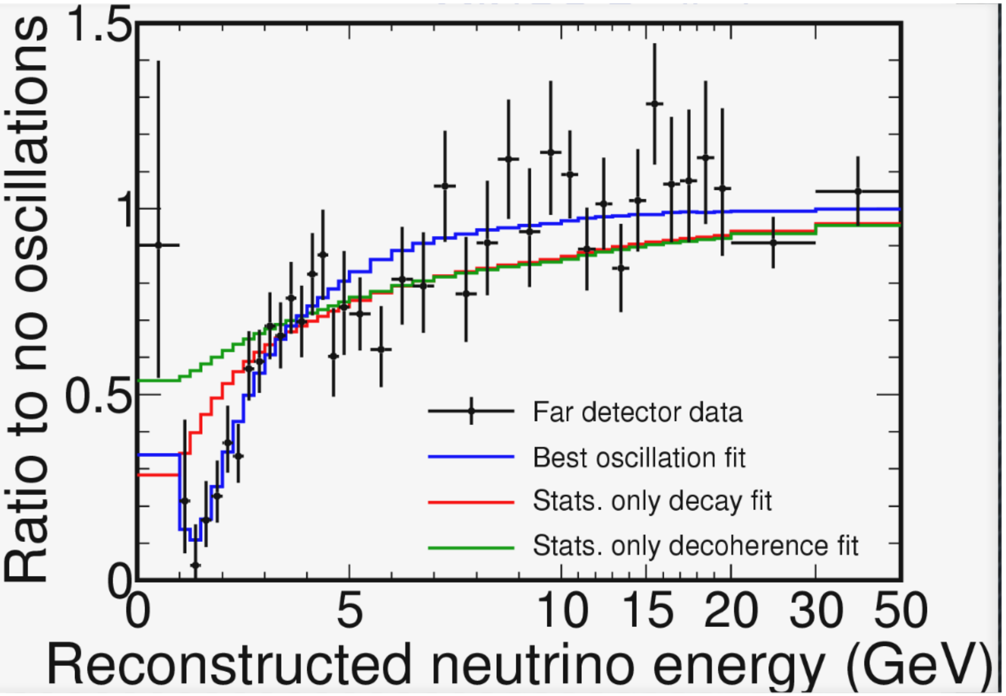
    (Soudan Mine, MN)





- confirmation of Kamiokande oscillation findings

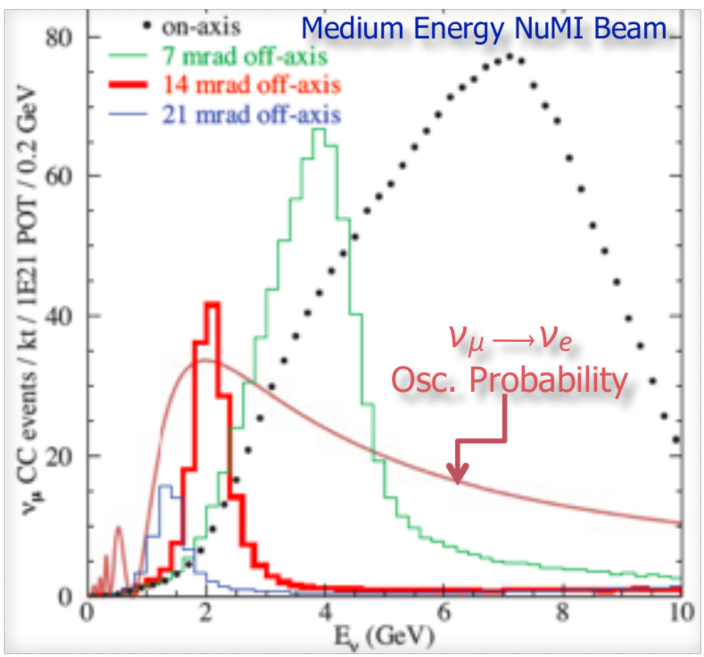


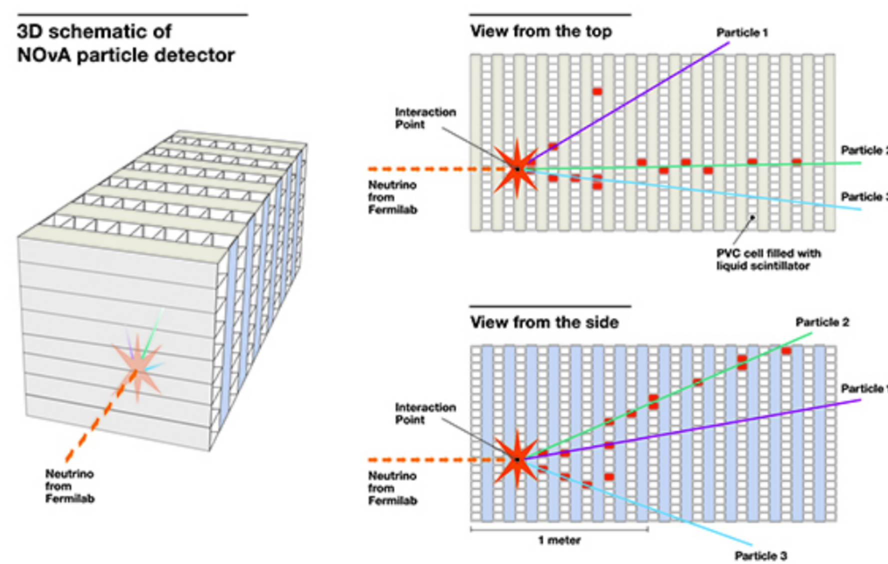


NOνA, MINOS successor

→ strong sensitivity PMNS elements; may benchmark future experiments

- Far detector is 14 ktons, sits at Minnesota
- Near Detector is 290 tons placed 300 ft underground
- Identically functionality
  - Consist of plastic cells filled with liquid scintillator
- Off axis beam neutrinos





MINERνA: neutrino-interaction experiment

- affords coverage of DIS and 'shallow-inelastic' (SIS) transition region

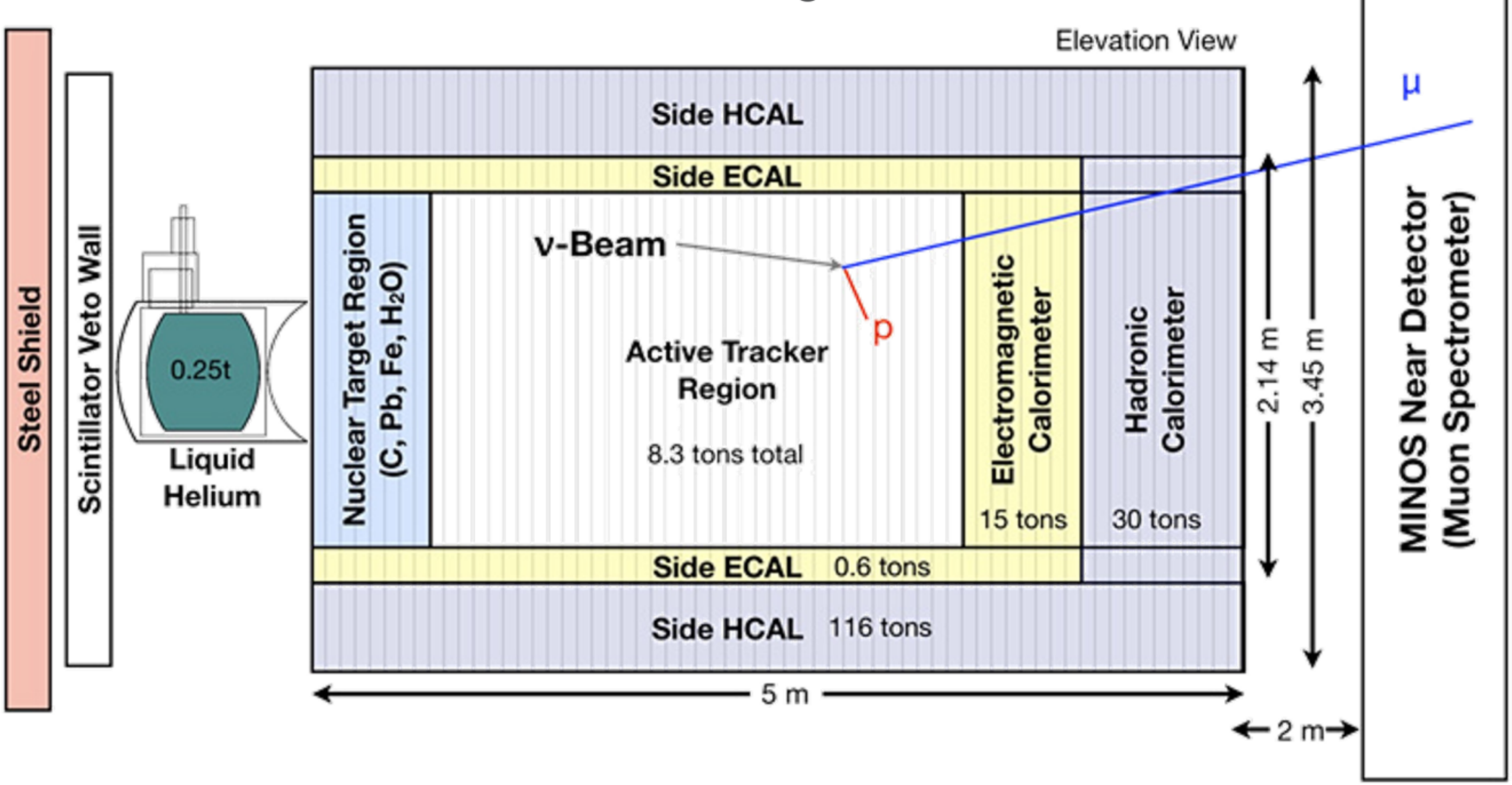
  → more on this tomorrow

- scintillator strips, photomultiplier tubes

(sometimes, theorists are allowed...)

Paul Reimer

- Massive iron region [*A* dependence]
- Additional nuclear targets!

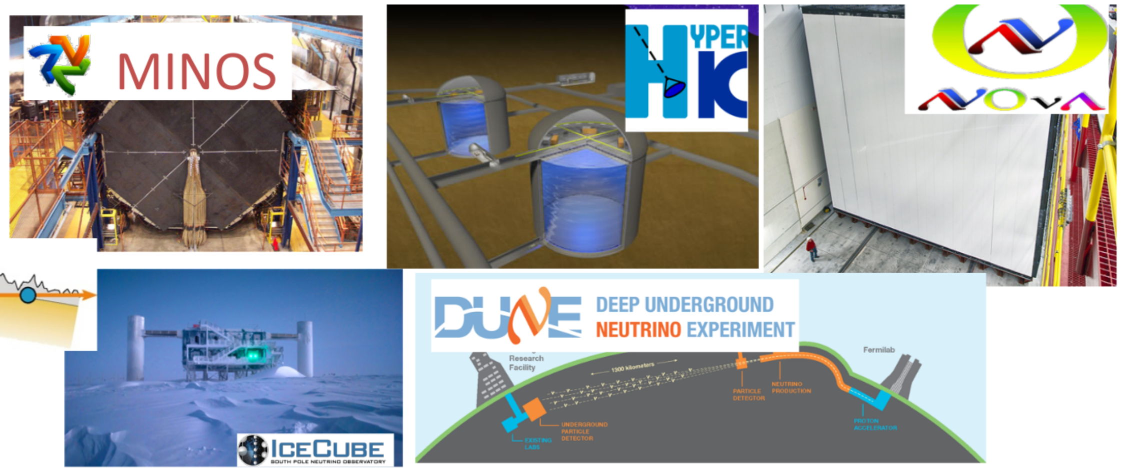


have only highlighted a small selection…

- again, wide array of detection paradigms, detector technologies

Accelerator and Atmospheric

ν ‘telescopes’



Reactor

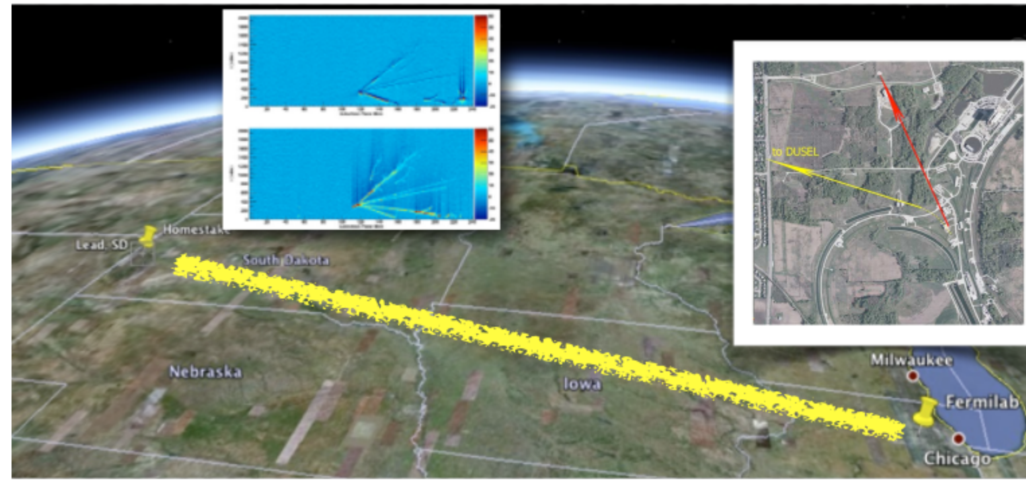
Solar

Still others: *e.g.*, $0\nu\beta\beta$ decay searches

→ Majorana vs. Dirac ?

toward the future: **DUNE**

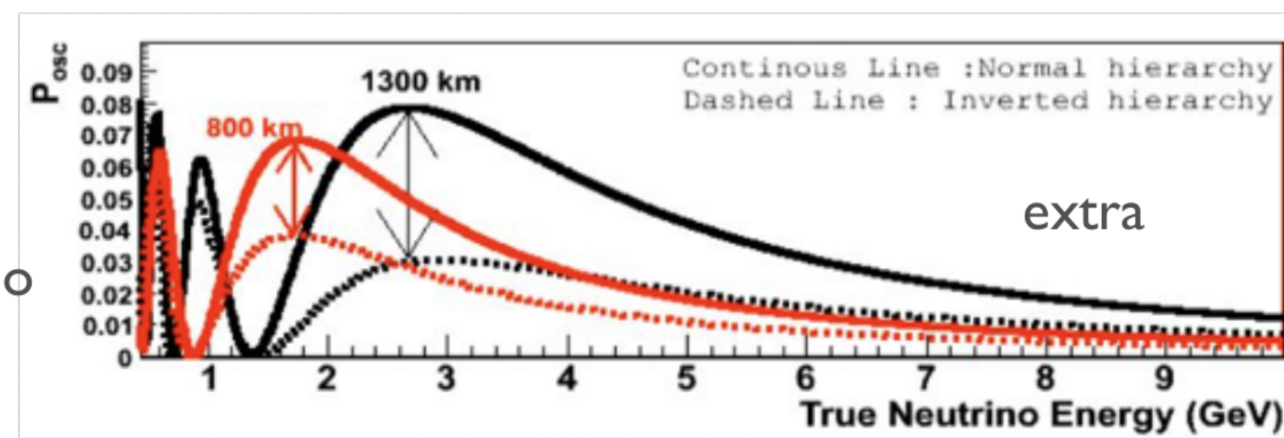
- flagship of FNAL program, completion target, ~2030



- Build new detectors farther away (1300 km) on axis
- A longer baseline provides more matter effects enhancing the asymmetry between neutrino and antineutrino appearance probabilities

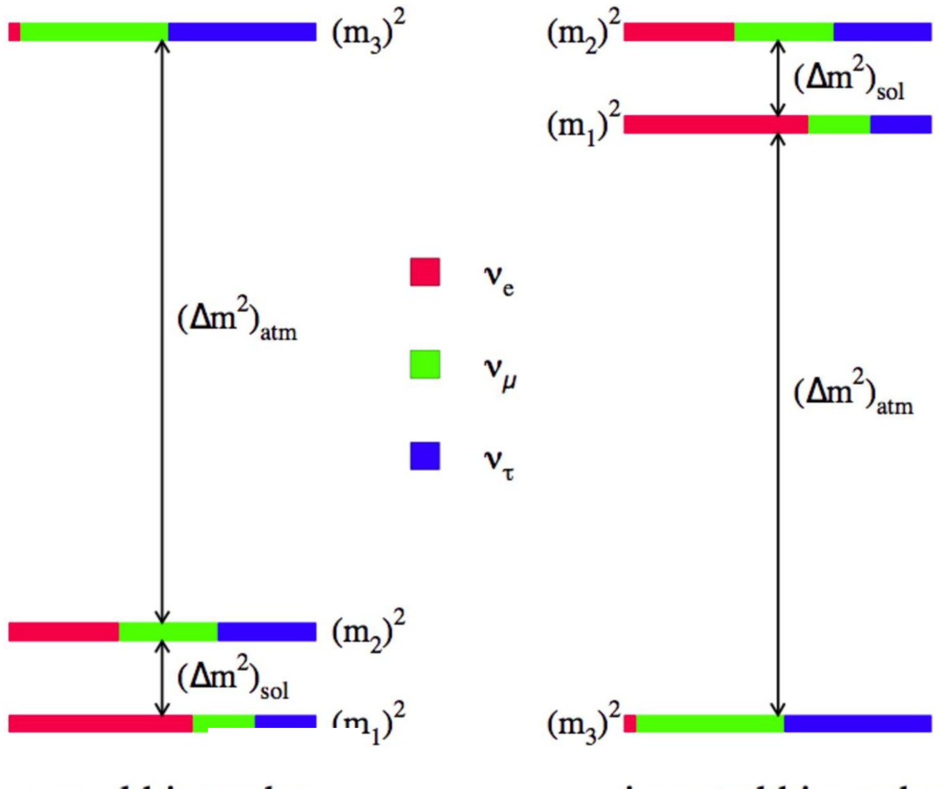
  - dramatically increased luminosity ('intensity frontier'); supported by PIP-II upgrades [800 MW SRF proton accelerator]

- Physics goals include
  - Constrain the PMNS metric
  - Search for exotic physics like NSI, CPT/Lorentz violation, extra dimensions and sterile neutrino

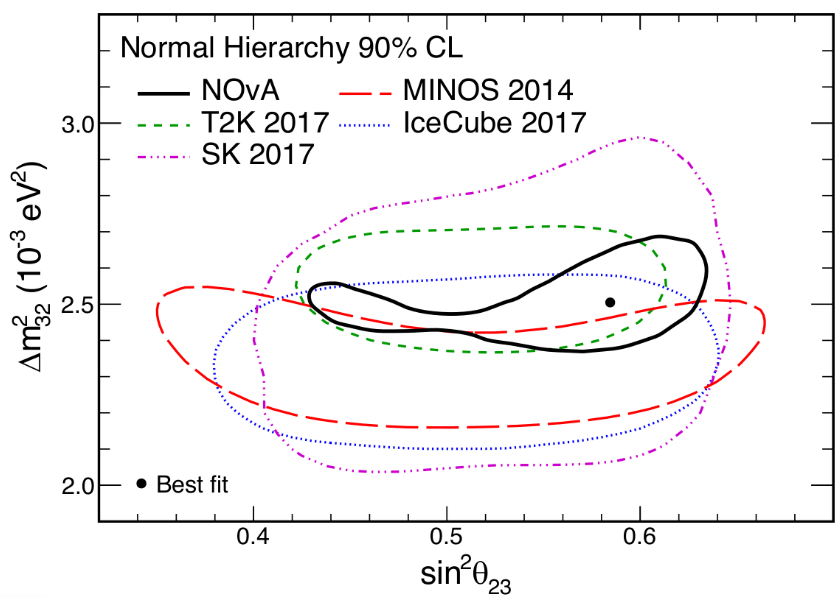


exciting puzzles await the coming data

- with DUNE, other expts, can begin to answer:
  - → is the neutrino sector responsible for the anti/matter asymmetry?
    (measure δ_{CP})
  - → might there be a fourth, sterile neutrino?
  - → what is the neutrino 'mass hierarchy' … normal *vs.* inverted?
    (determine $\text{sgn}[\Delta m^2_{23}]$)



- → is θ_{23} 'maximal'



caution! measured neutrino flux must be unfolded (tomorrow)

- oscillation searches require near/far fluxes; unfolding depends on $\sigma(E_\nu)$

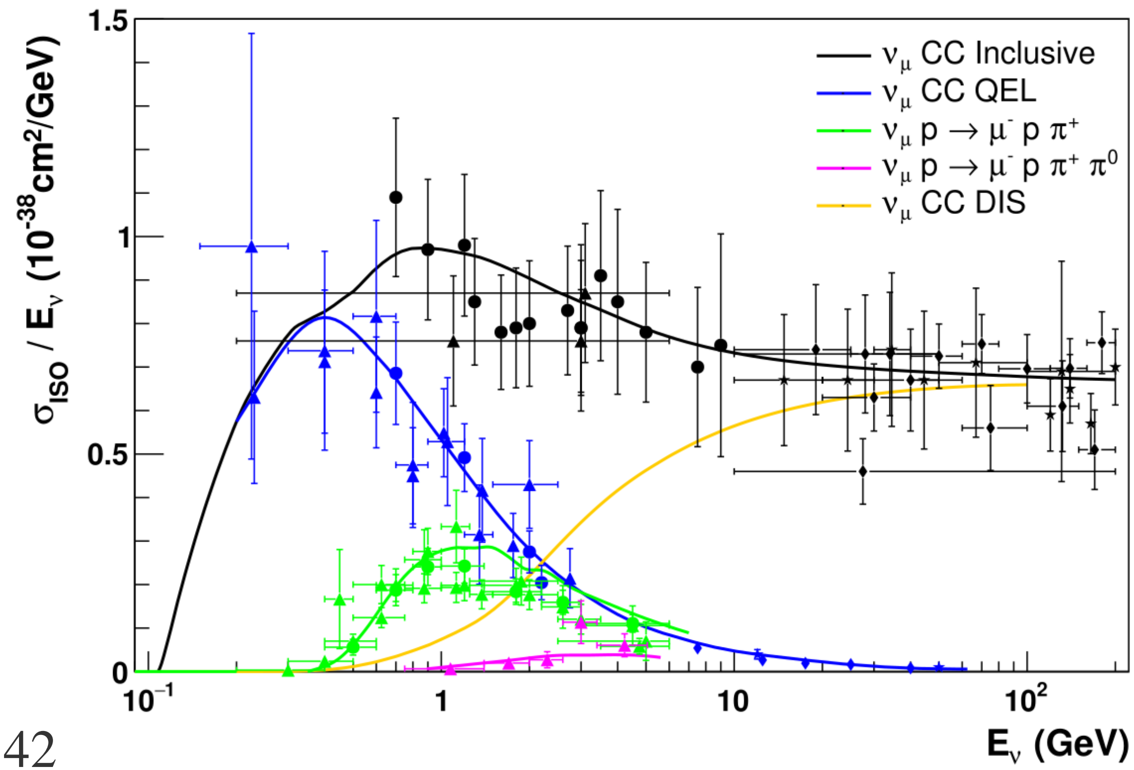
$$N_i(E_\nu^{\rm rec}, L) \sim \sum_k \int dE_\nu\, \Phi_i(E_\nu, L)\sigma_k(E_\nu) f_{\sigma_k}(E_\nu, E_\nu^{\rm rec})$$

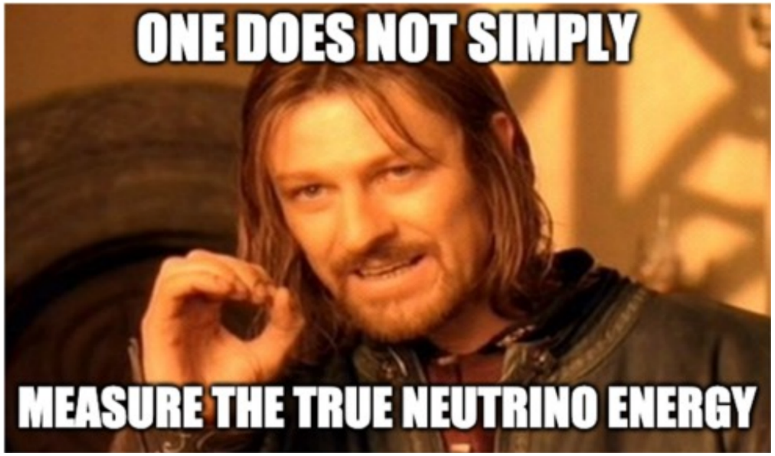
$\Phi_i(E_\nu, L)$: neutrino flux, i^{th} flavor → want this

$\sigma_k(E_\nu)$: total cross section, process k

$f_{\sigma_k}(E_\nu, E_\nu^{rec})$: smearing matrix

→ need to know these





Shirley Li

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- **tomorrow**: the νA cross section involves a complicated interplay of processes

→ QCD meets EW theory…