Neutrino Results: Accelerator Experiments

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IMFP, Salamanca, April 2018

What I will cover

Knowns and unknowns in neutrino physics

Neutrino Oscillations

"Solar" sector

"Atmospheric" sector

The twist in the middle

Remaining unknowns in the 3-flavor picture:

MO and CP δ

Beyond 3-flavor?

(+xscns)

Absolute Mass

βdk endpoint, cosmology

Majorana vs Dirac?

Neutrinoless $\beta\beta$dk

The mass pattern and mixing matrix

The mass scale

The mass nature

Today

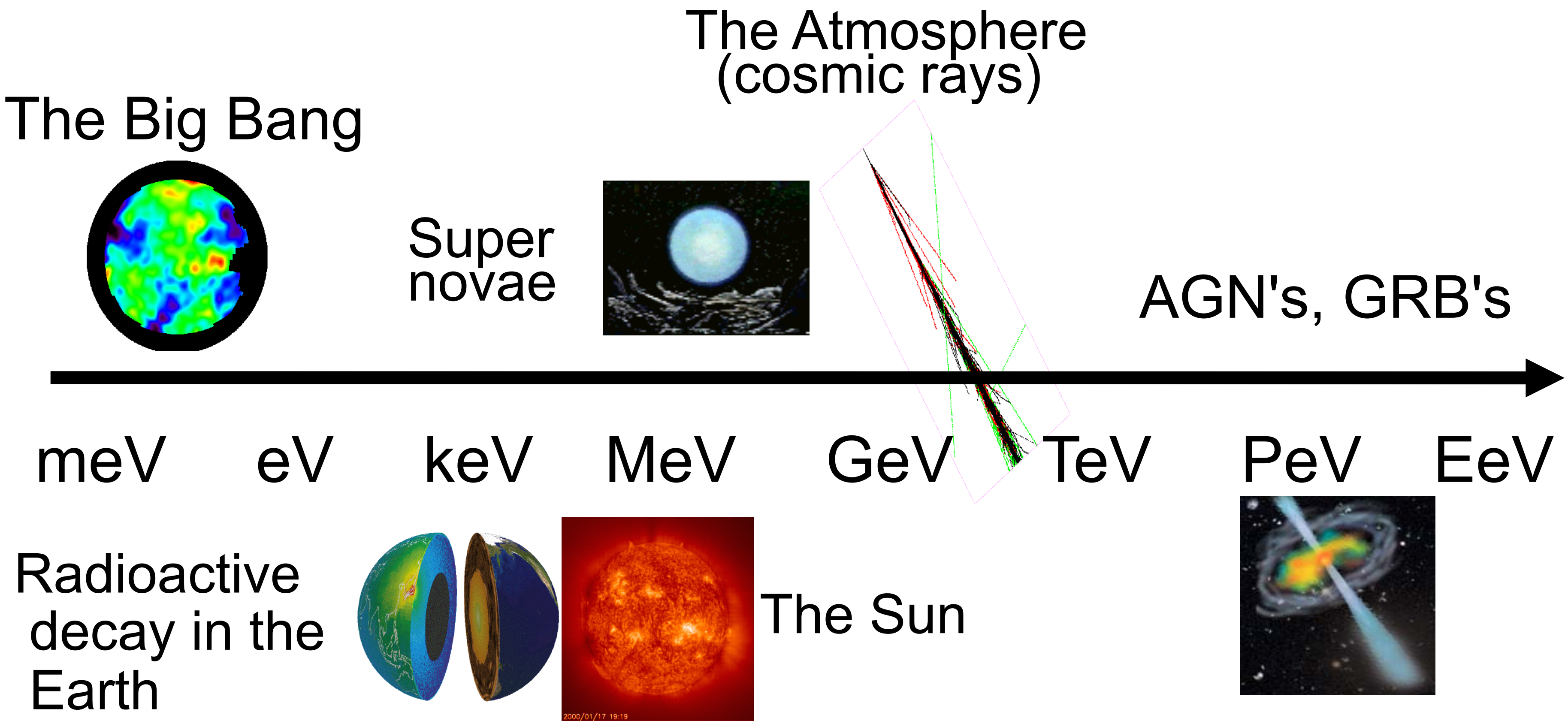
The 3-flavor picture

Accelerator experiments

Tomorrow

Non-accelerator experiments

Sources of wild neutrinos

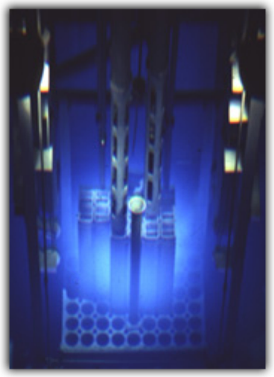


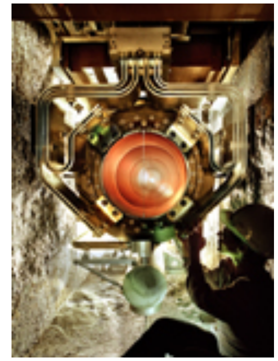
Sources of 'tame' neutrinos

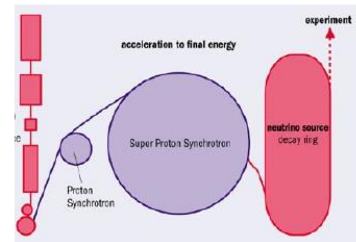
Proton accelerators

Beta beams

Nuclear reactors

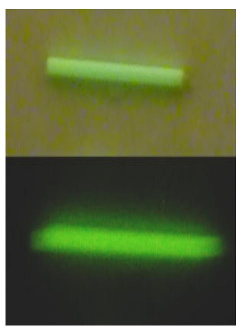


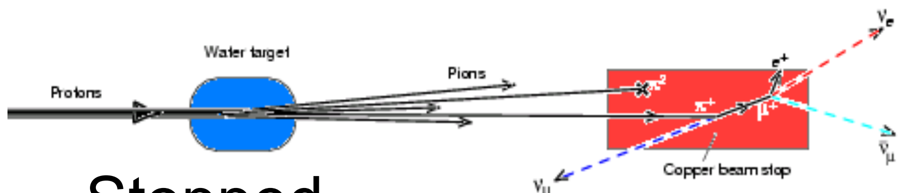




eV keV MeV GeV TeV

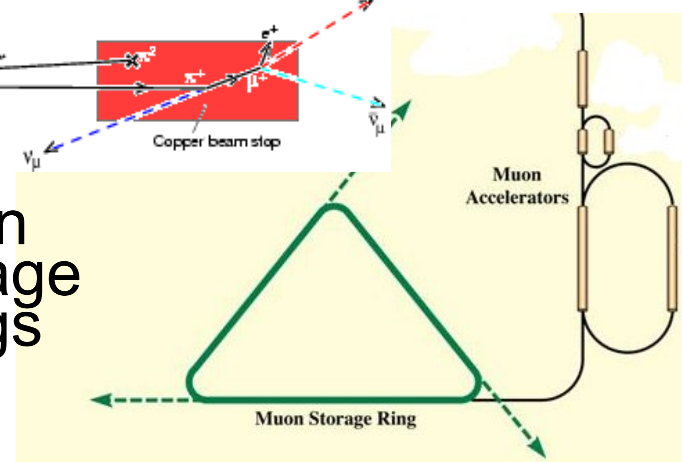
Artificial radioactive sources





Stopped pion sources

Muon storage rings

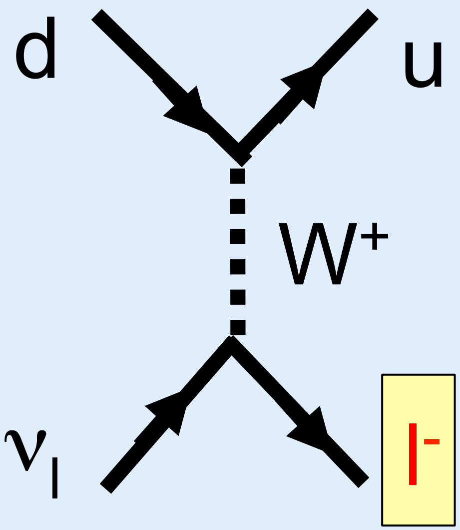


Usually (but not always) better understood...

Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

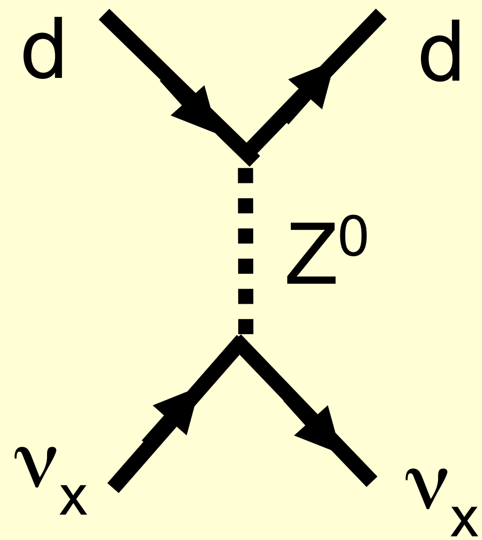


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy
to make lepton)

Neutral Current (NC)



Flavor-blind

Neutrino Mass and Oscillations

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{e1} & \mathrm{U}^*_{e2} & \mathrm{U}^*_{e3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in weak interactions

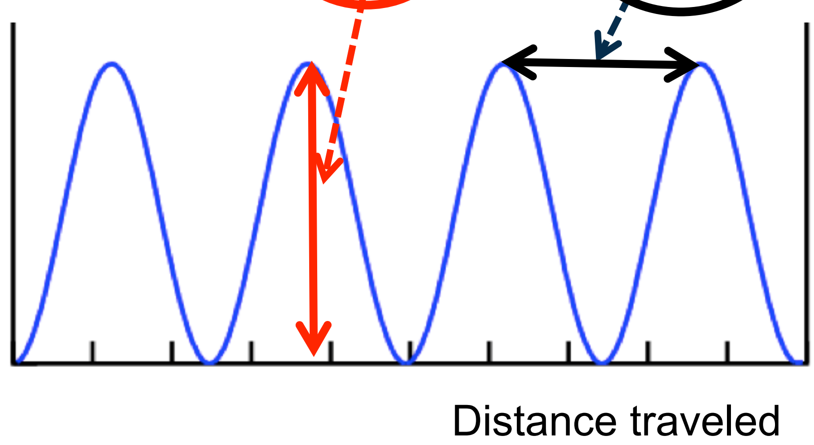
unitary mixing matrix

eigenstates of free Hamiltonian

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate (essentially, interference between mass states)

2-flavor

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$



The three-flavor paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*}|\nu_i\rangle$$

Parameterize mixing matrix U as

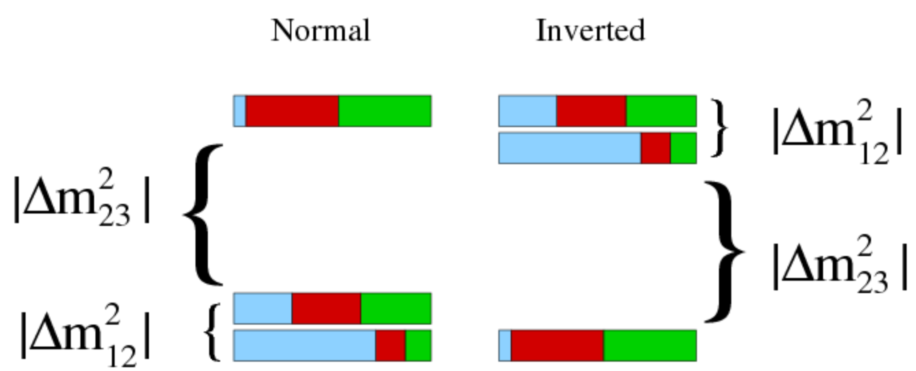
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

signs of the mass differences matter



Oscillation probabilities in a 3-flavor context

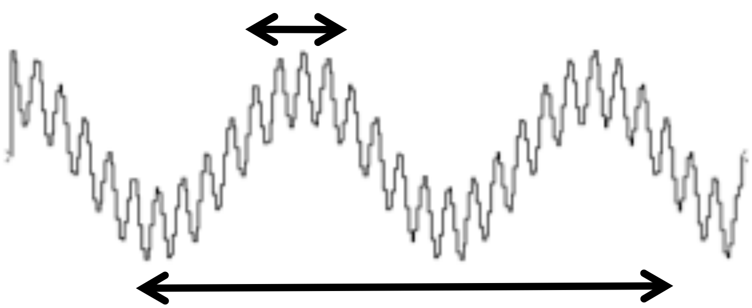
$$|\nu_f\rangle = \sum_{i=1}^{N} U_{fi}^{*}|\nu_i\rangle$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2 \qquad \text{(L in km, E in GeV, m in eV)}$$

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4\sum_{i>j} \Re(U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*}) \sin^2(1.27\Delta m_{ij}^2 L/E)$$

$$\pm 2\sum_{i>j} \Im(U_{fi}^{*}U_{gi}U_{fj}U_{gj}^{*}) \sin(2.54\Delta m_{ij}^2 L/E)$$

oscillatory behavior in L and E



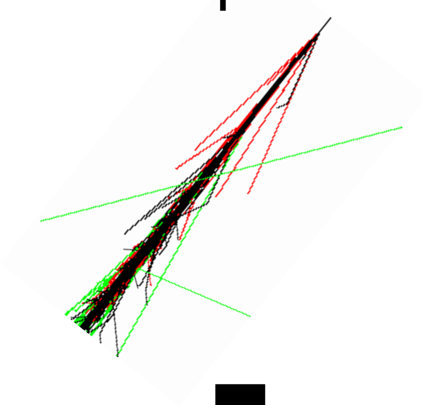
$$|\Delta m_{23}^2| >> |\Delta m_{12}^2|$$ ➔ two frequency scales

For appropriate L/E (and U_{ij}), oscillations "decouple", and probability can be described by the 2-flavor expression

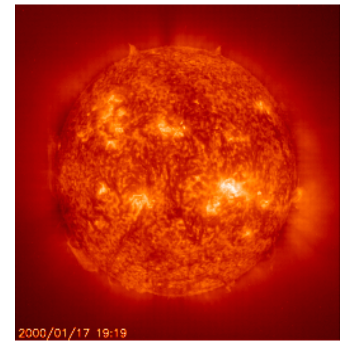
$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric

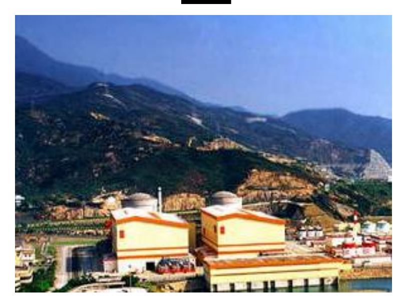


solar



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

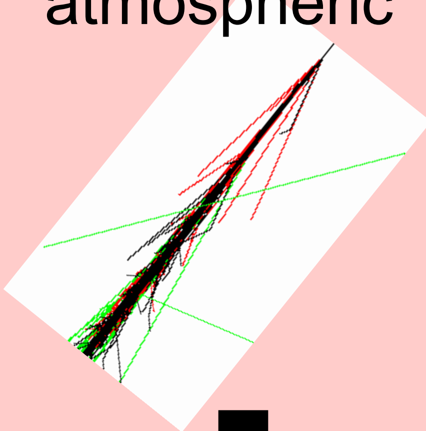
beams



reactor

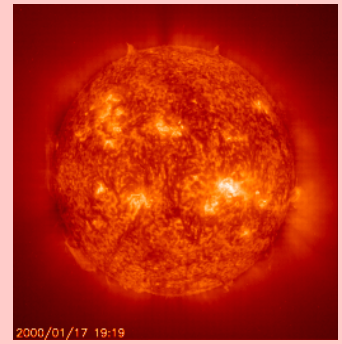
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
“wild” neutrinos...

solar



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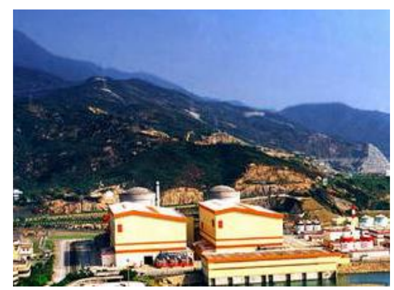
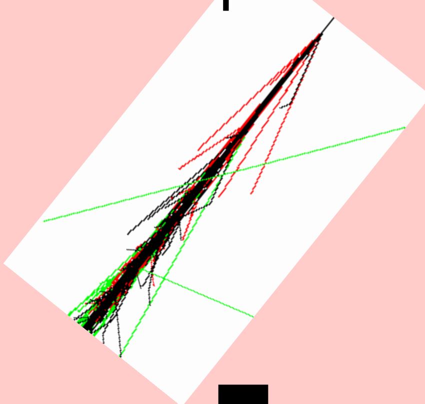
beams



reactor

We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
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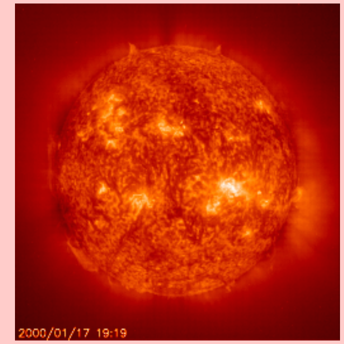
solar



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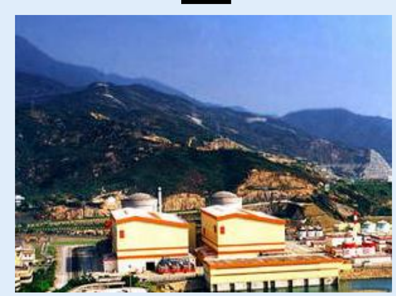
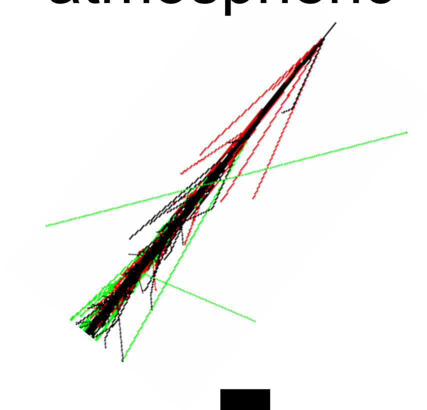
beams

confirmed with
“tame” ones...



reactor

atmospheric



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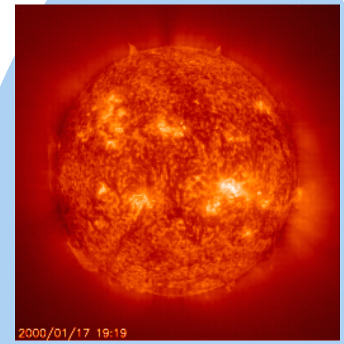
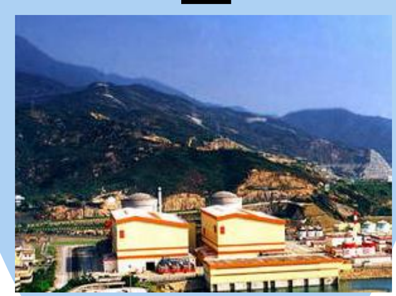
beams

solar



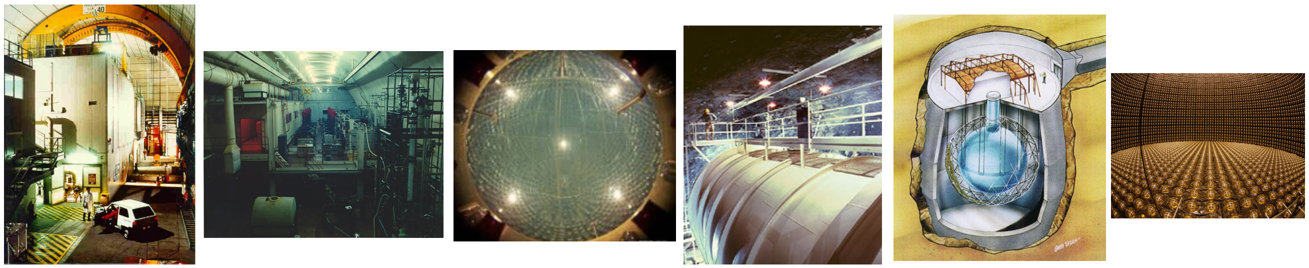


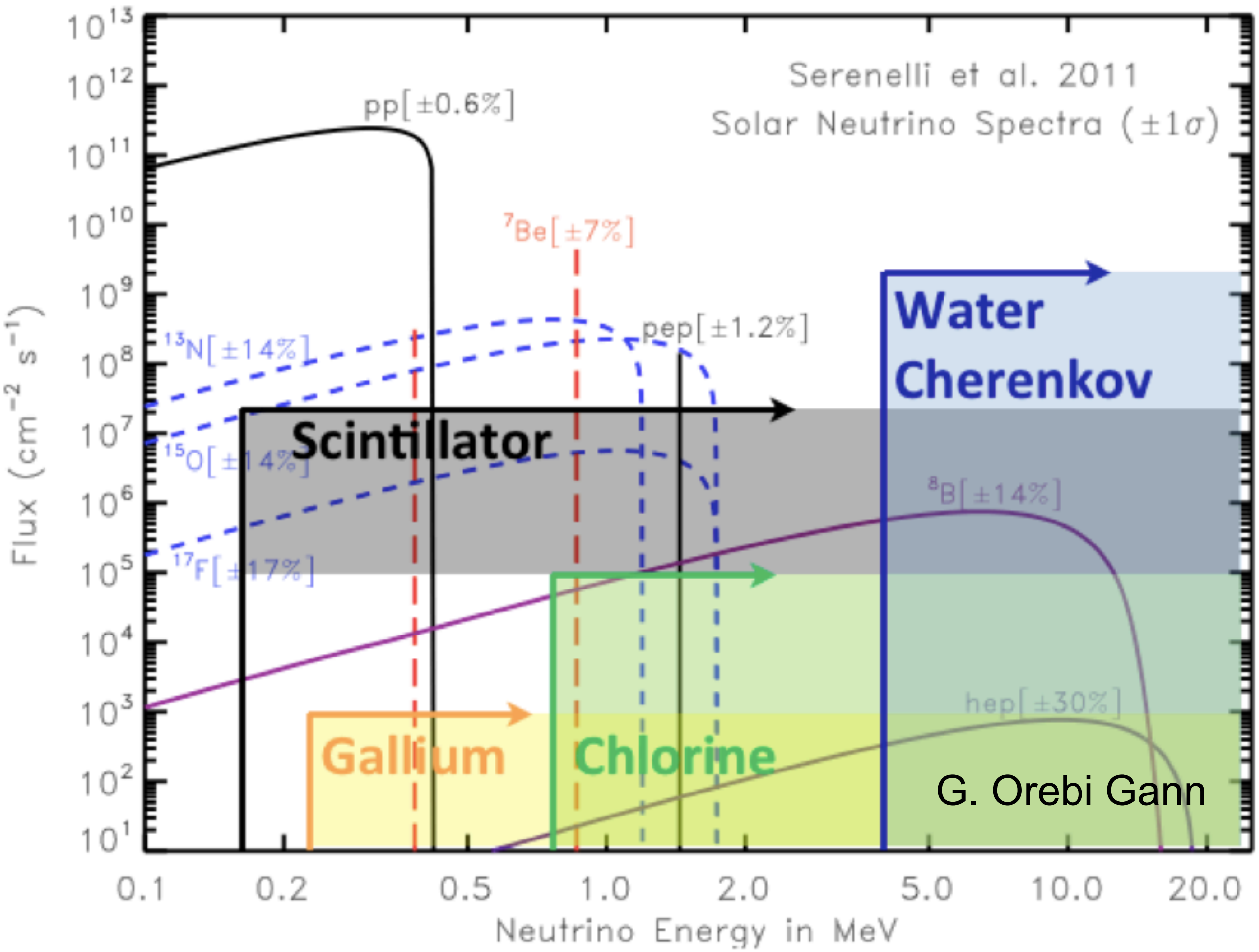
reactor

"Solar" sector: solar ν oscillations confirmed with reactors

Solar and reactor neutrinos

Multiple measurements over ~5 decades



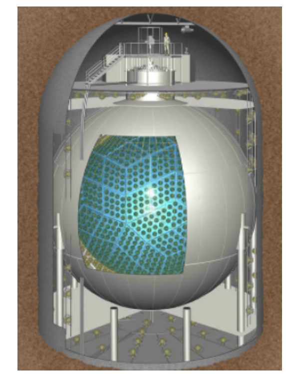


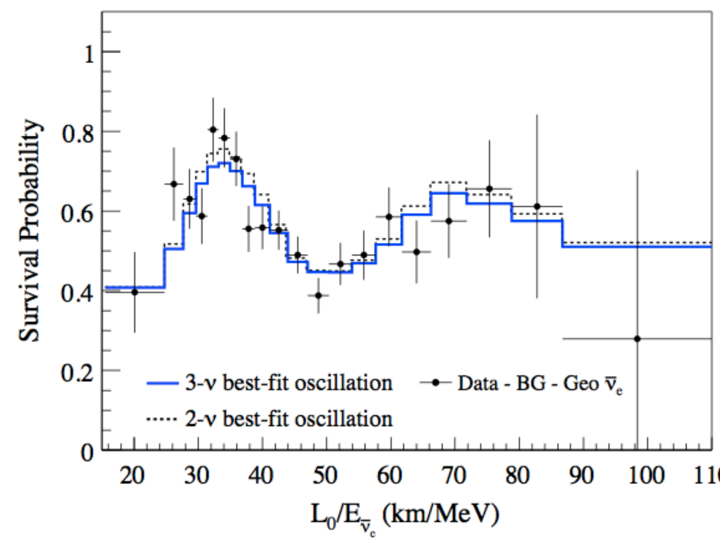
ν_e disappearance, confirmed directly as

$$\nu_e \rightarrow \nu_{\mu,\tau}$$

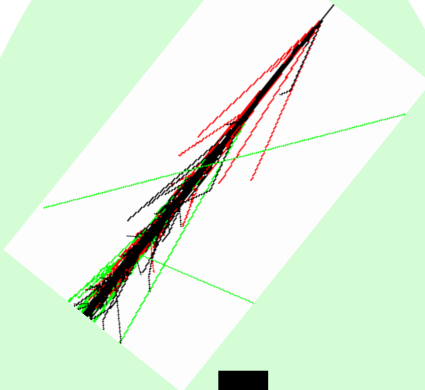
by SNO....

...and wavelength measured precisely w/ reactor $\bar{\nu}_e$ by KamLAND

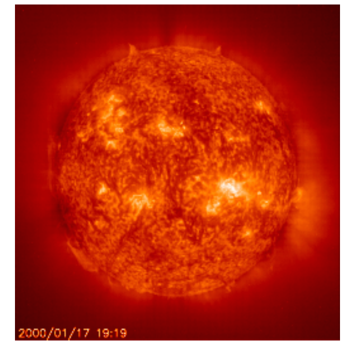




atmospheric



solar



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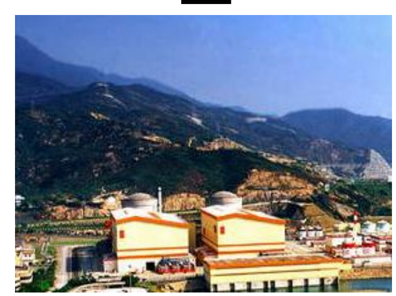
$$

beams

“Atmospheric” sector

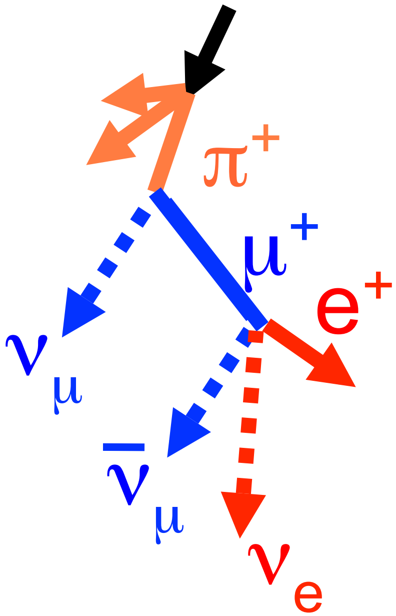


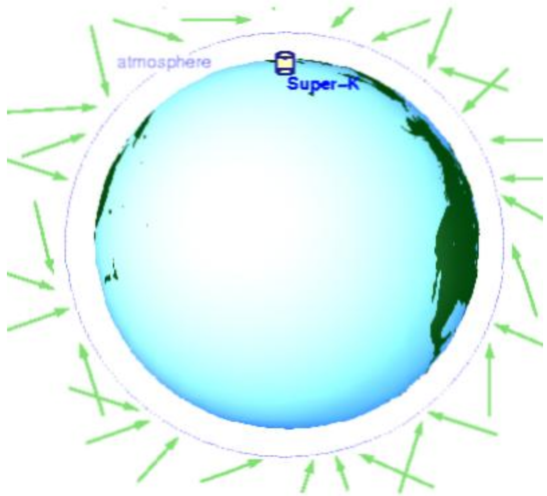
reactor

Atmospheric neutrinos

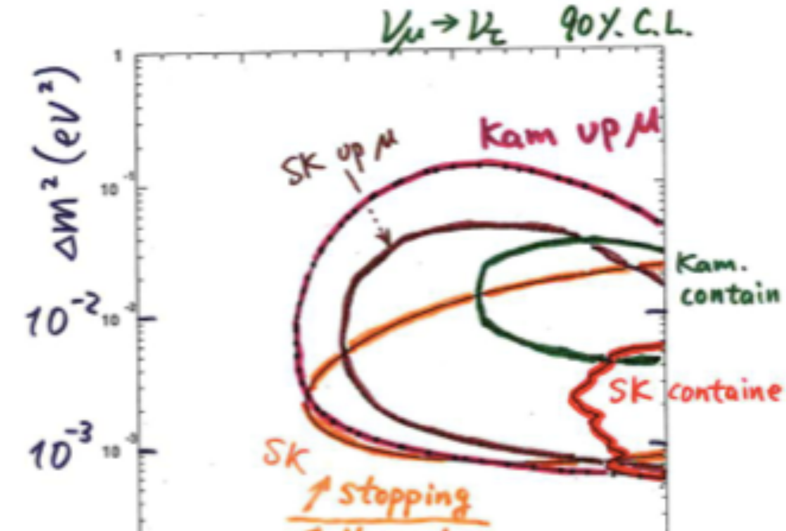
The neutrinos are free, and have a range of baselines & energies

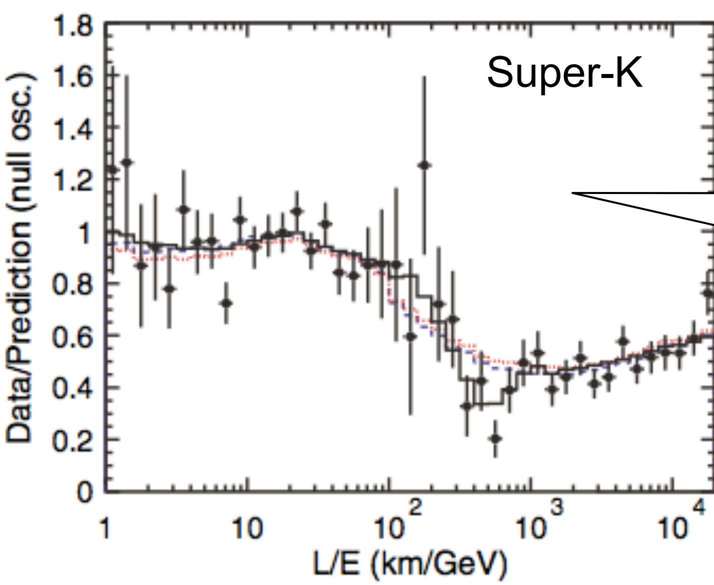
cosmic ray (p)





$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$





Clear ν_μ disappearance

Well described by 23 oscillation parameters: $|\Delta m^2_{32}| \sim 2 \times 10^{-3}$ eV^2, ~ maximal mixing

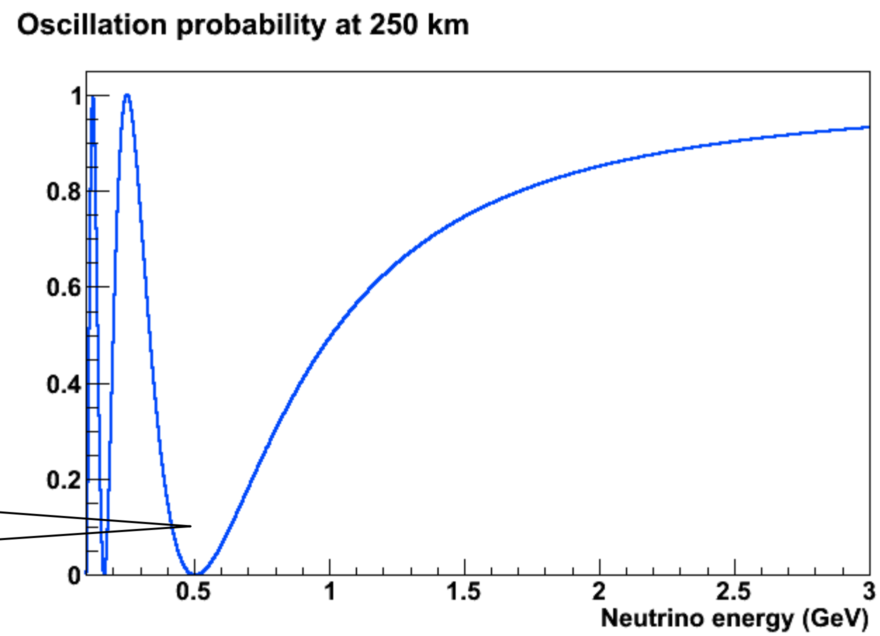
Taming the source to confirm & study oscillations with long-baseline beam experiments

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

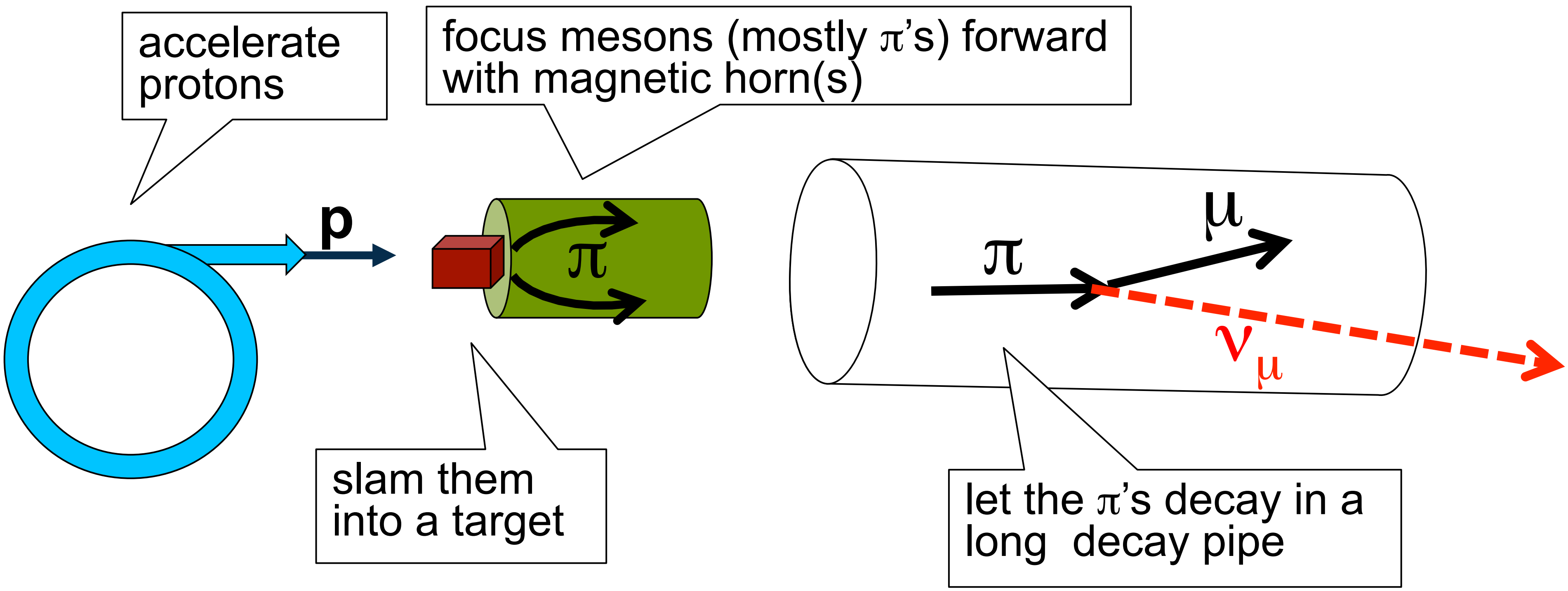
E_ν~ GeV, L~ 100's of km for same L/E

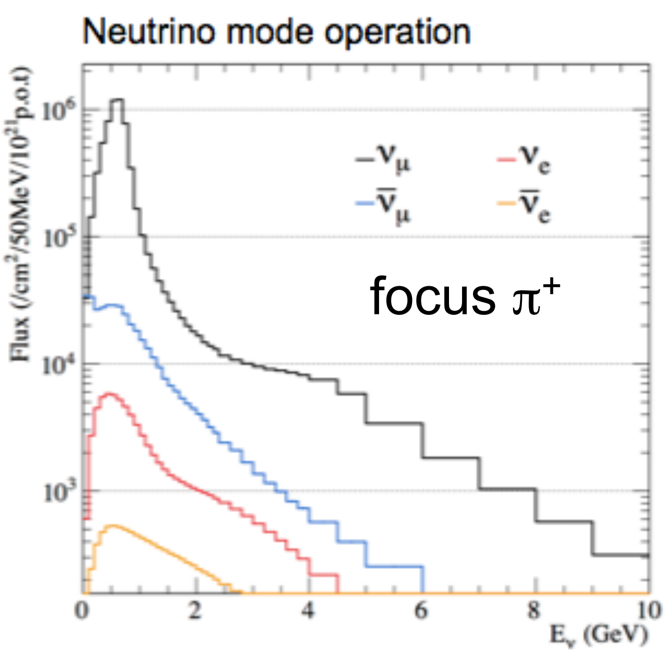
Compare flux, flavor and energy spectrum at near and far detectors

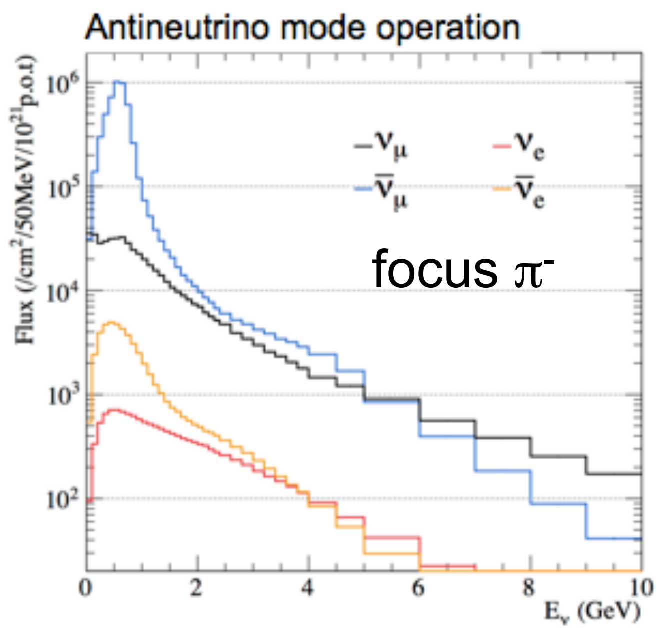
Design your beam at given baseline to cover oscillation peaks



How To Make Tame Neutrinos







T2K beam

Long-baseline beam experiments: taming the source

Past | Current | Future

K2K

KEK to Kamioka

250 km, 5 kW

Long-baseline beam experiments: taming the source

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

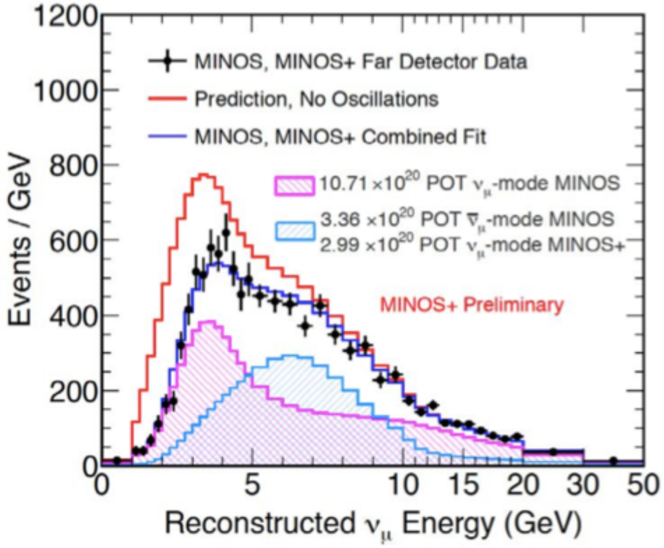
CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

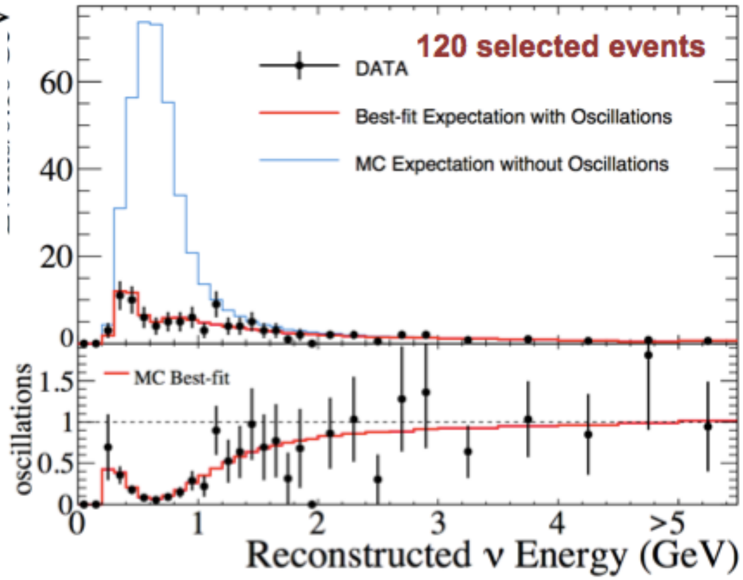
T2K
J-PARC to Kamioka
295 km, 380-750 kW

Muon neutrino disappearance

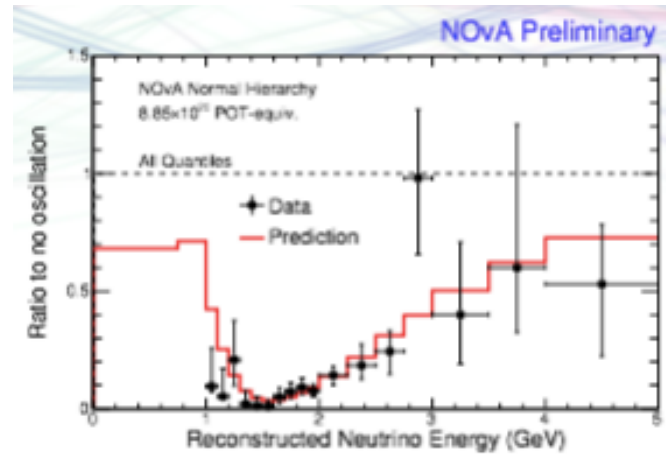
MINOS, MINOS+

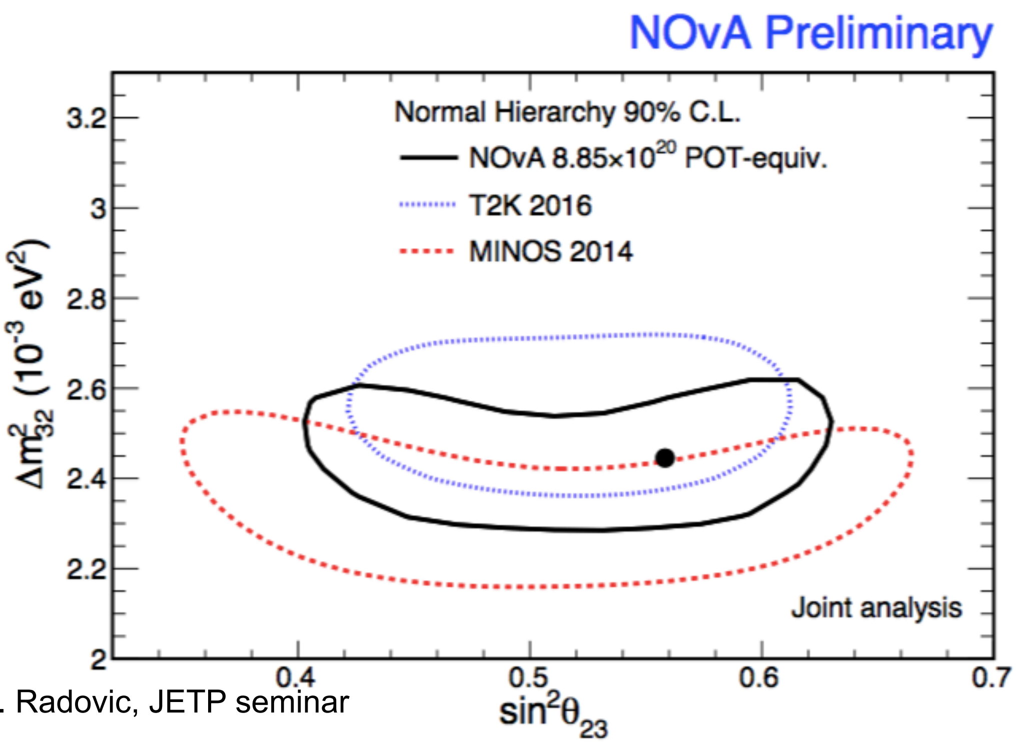


T2K



NOvA





A. Radovic, JETP seminar

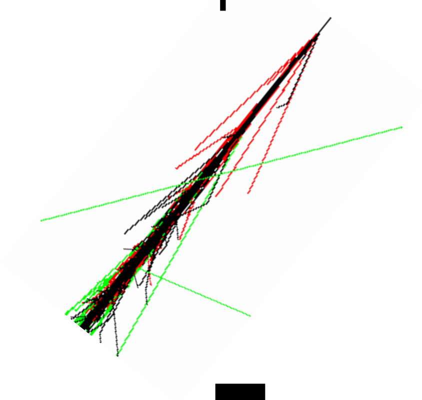
+ antinumu in MINOS, T2K

+ tau appearance in SK, OPERA

All beam & atmnus point to consistent parameters

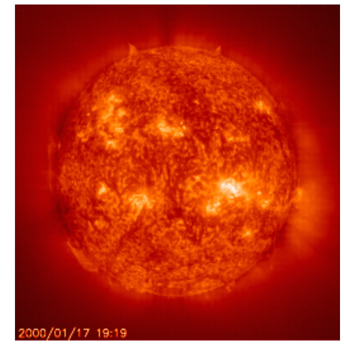
The mixing angle θ_{13}: information from beams and burns!

atmospheric



θ_{13}, the "twist in the middle"

solar



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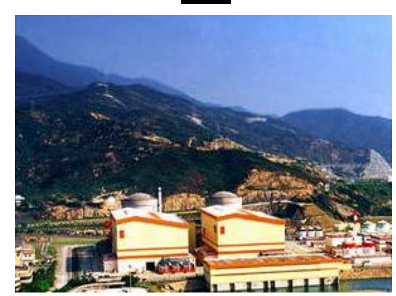
Before 2011, known to be small

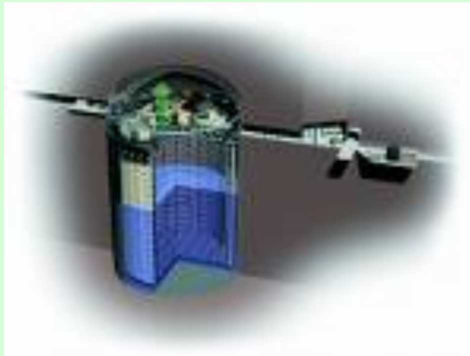
beams

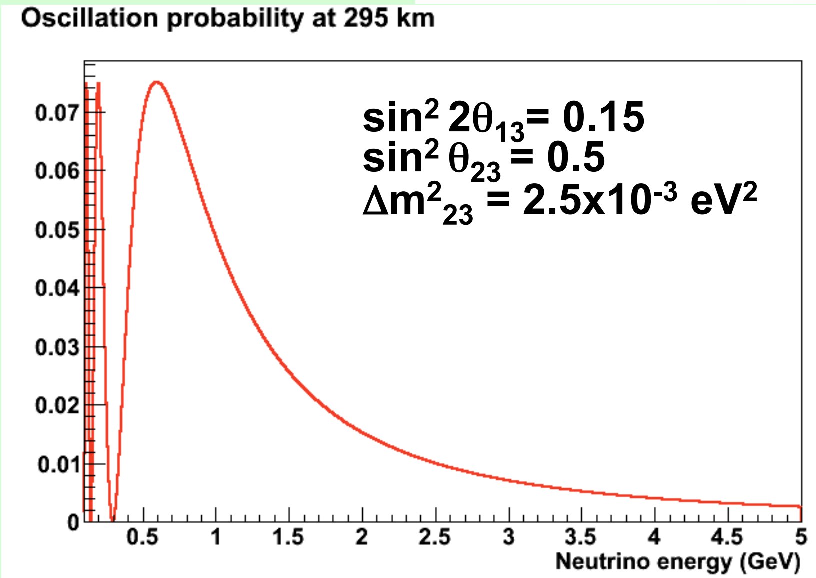


reactor

How to measure θ_{13}

Beams

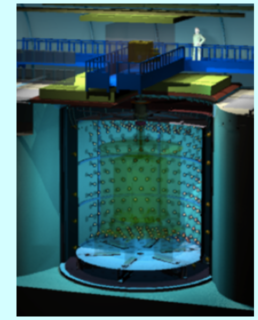


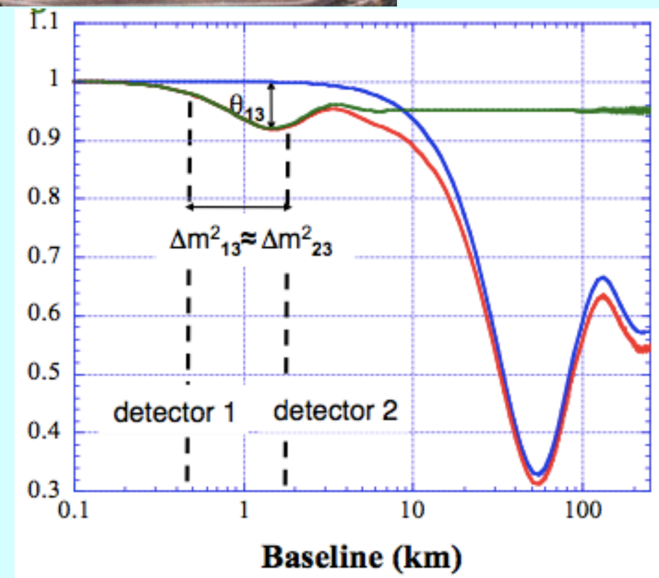


Look for *appearance*
of ~GeV ν_e in ν_μ beam
on ~300 km distance scale

K2K, MINOS, T2K, NOνA

Reactors



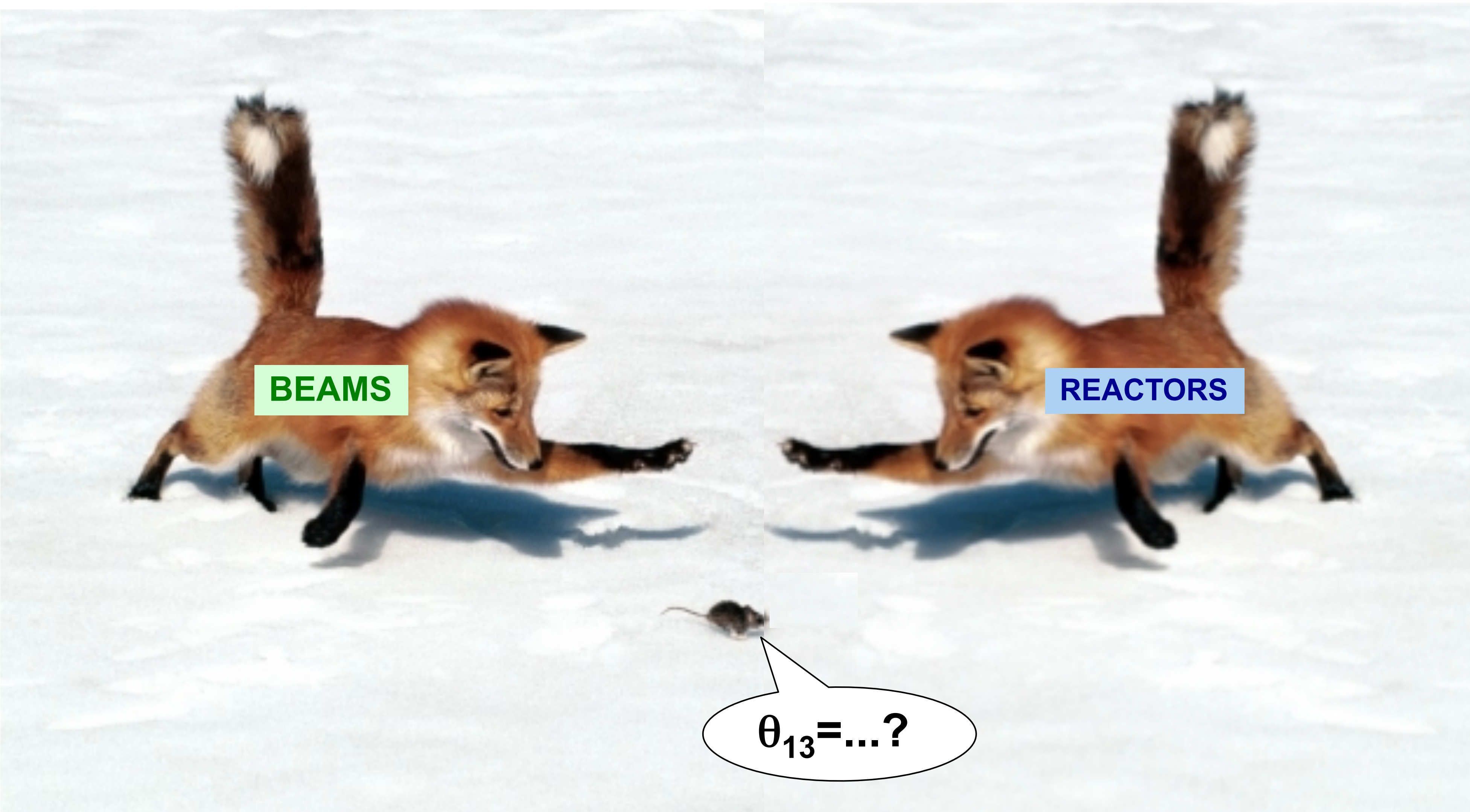


Look for *disappearance*
of ~few-MeV $\bar{\nu}_e$
on ~km distance scale

CHOOZ, Double Chooz, Daya Bay, RENO

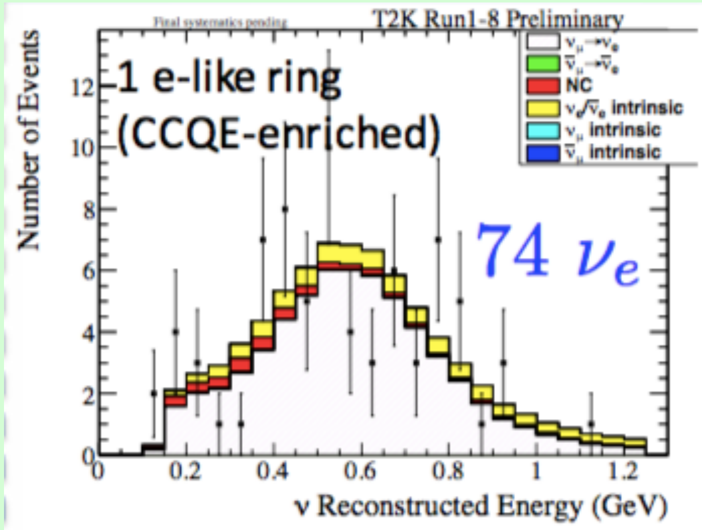
A slide from December 2011:

We're closing in on the answer...

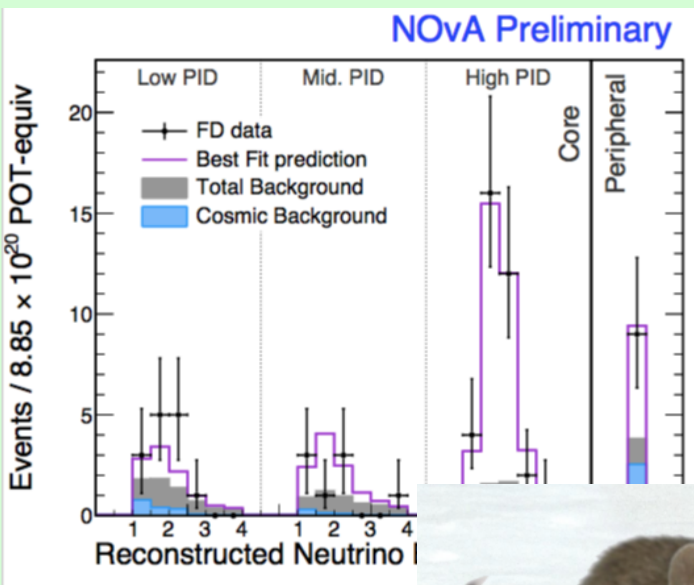


θ_{13} from beams and burns

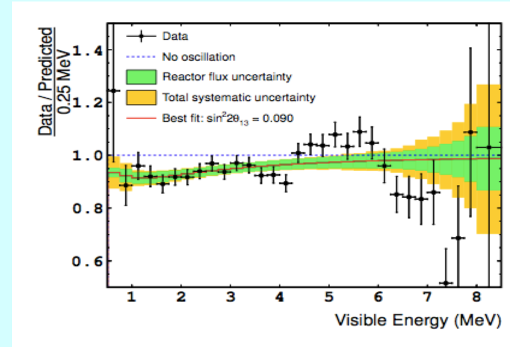
T2K



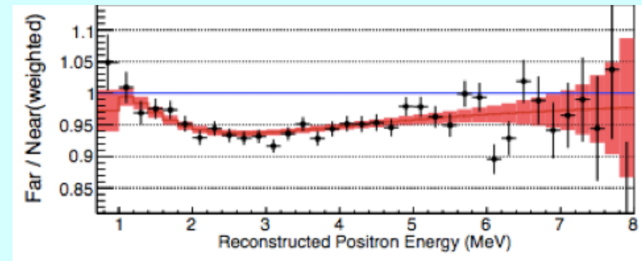
NOvA



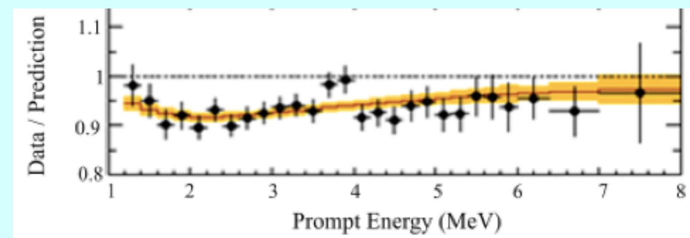
Double Chooz



Daya Bay



RENO



Appearance of
electron neutrinos i
a muon neutrino be

ppearance of reactor
ineutrinos with
aracteristic near-far
ctral distortion

But single-parameter/two-flavor fits are so 2012...

information now extracted with
joint fits to multiple oscillation channels,
neutrinos and antineutrinos

The three-flavor picture fits the data well

Global three-flavor fits to all data

parameter	best fit ± 1σ	3σ range	3σ knowledge
Δm^2_{21} [10^{-5}eV^2]	7.56±0.19	7.05–8.14	~8%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.55±0.04	2.43–2.67	~5%
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	2.49±0.04	2.37-2.61	
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.73–3.79	~10%
$\theta_{12}/°$	$34.5^{+1.1}_{-1.0}$	31.5–38.0	
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$ [a]	3.84–6.35	~9%
$\theta_{23}/°$	41.0±1.1	38.3–52.8	
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$ [b]	3.88–6.38	
$\theta_{23}/°$	50.5±1.0	38.5–53.0	
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$	1.89–2.39	~6%
$\theta_{13}/°$	$8.44^{+0.18}_{-0.15}$	7.9–8.9	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.140^{+0.082}_{-0.085}$	1.89–2.39	
$\theta_{13}/°$	$8.41^{+0.16}_{-0.17}$	7.9–8.9	
δ/π (NO)	$1.40^{+0.31}_{-0.20}$	0.00–2.00	poor info
$\delta/°$	252^{+56}_{-36}	0–360	
δ/π (IO)	$1.44^{+0.26}_{-0.23}$	0.00–0.17 & 0.79–2.00	
$\delta/°$	259^{+47}_{-41}	0–31 & 142–360	

P. F. de Salas[1], D. V. Forero [2,3],* C. A. Ternes[1], M. Tórtola [1],† and J. W. F. Valle [1‡]   arXiv:1708.01186

What do we *not* know about the three-flavor paradigm?

parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.56±0.19	7.05–8.14
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$\delta/°$	259^{+47}_{-41}	0–31 & 142–360

sign of Δm^2 unknown (ordering of masses)

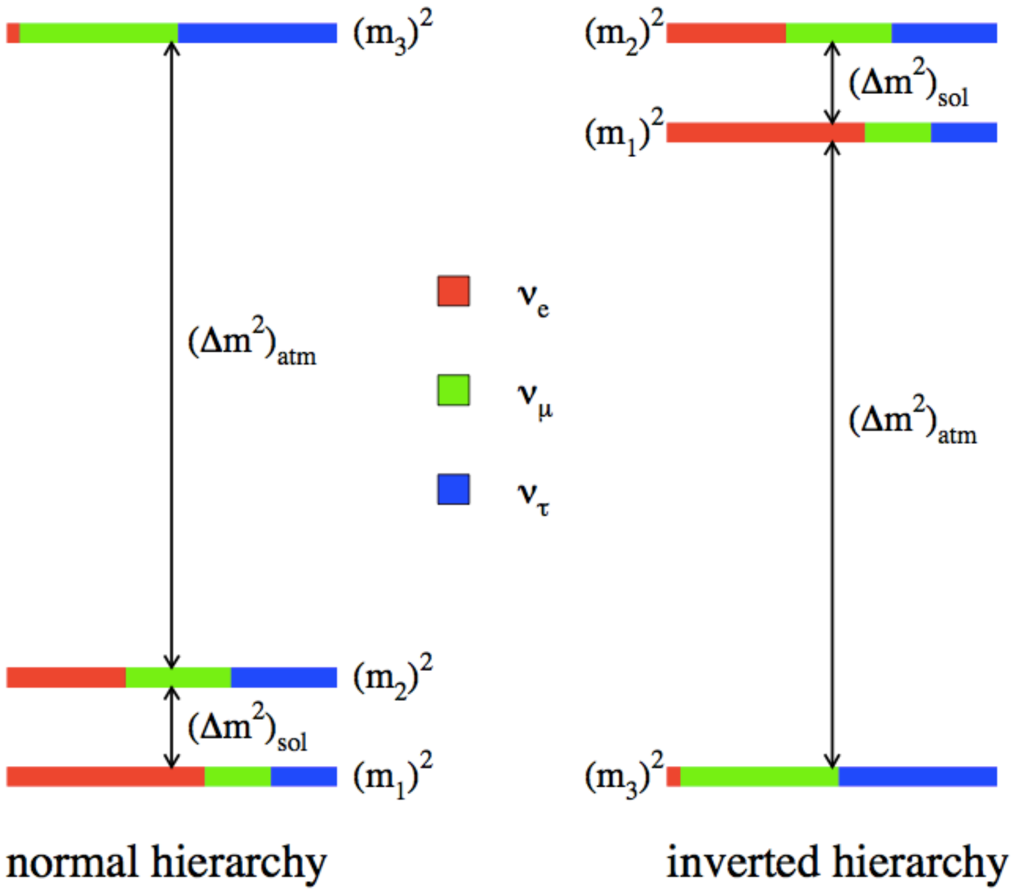
Is θ_{23} non-negligibly greater or smaller than 45 deg?

mostly unknown

Next on the list to go after experimentally:

mass ordering (sign of Δm^2_{32})

[Note: “mass hierarchy” is now uncool to say, as masses may be quasi-degenerate]



$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

There are many ways to determine the mass ordering

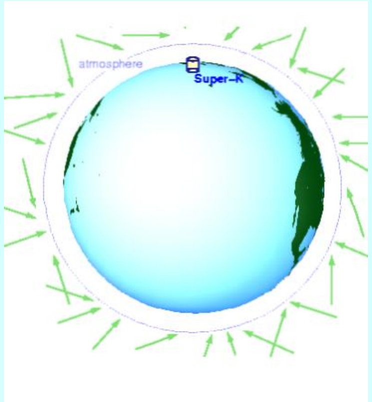
They are all challenging...

Four of the possible ways to get MO

Long-baseline beams

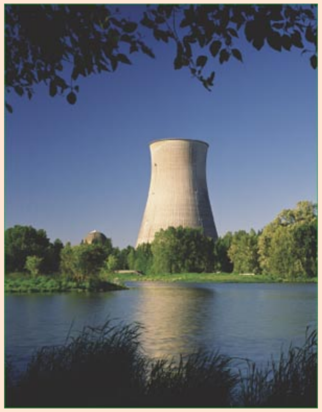
Hyper-K, LBNF/DUNE

Atmospheric neutrinos



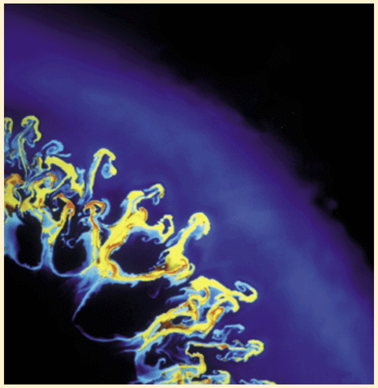
Super-K, Hyper-K, PINGU,ORCA, DUNE, INO

Reactors



JUNO

Supernovae



Many existing & future detectors

Long-baseline beams

Other methods are very promising,
but the long-baseline method
is the only one that's ***guaranteed*** with
sufficient exposure at long baseline
(...but it's tangled with CP violation)

Long-baseline approach for going after MO and CP

Measure transition probabilities for

$$\nu_\mu \rightarrow \nu_e \quad \text{and} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

through matter

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Change of sign for antineutrinos

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

A. Cervera et al., Nucl. Phys. B 579 (2000)

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

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The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again. are small

Different probabilities as a function of L& E
for neutrinos and antineutrinos, depending on:
- CP δ
- matter density (Earth has electrons, not positrons)

Where we are now with long-baseline experiments

Past | Current | Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K
J-PARC to Kamioka
295 km, 380-750 kW

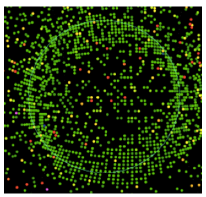
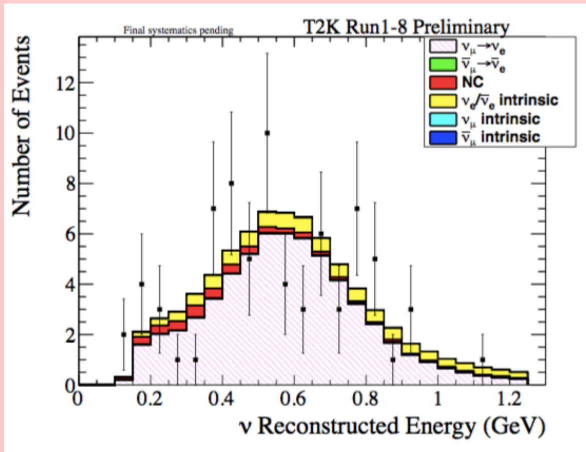
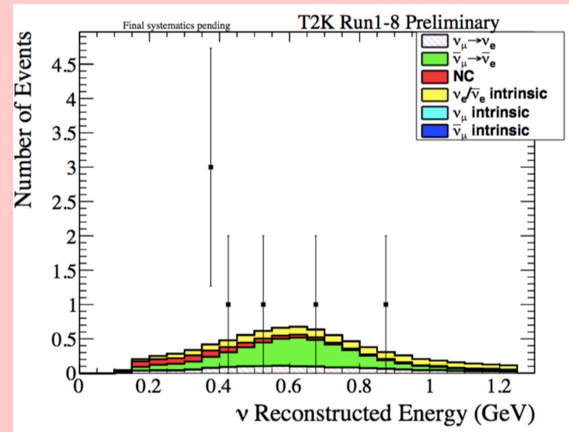
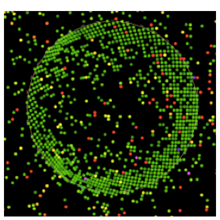
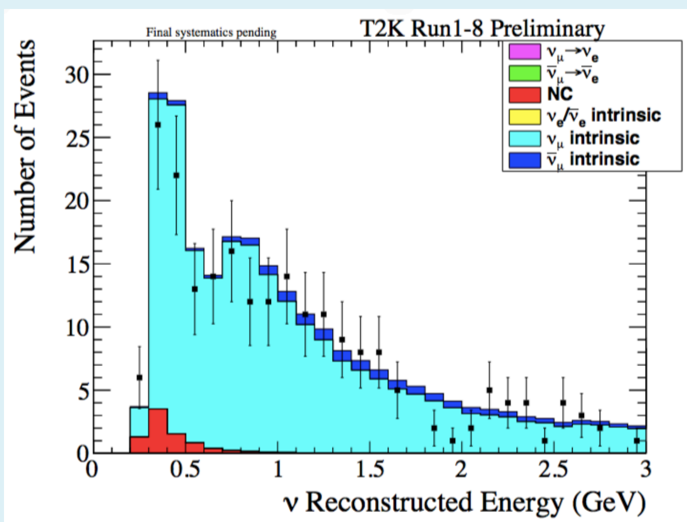
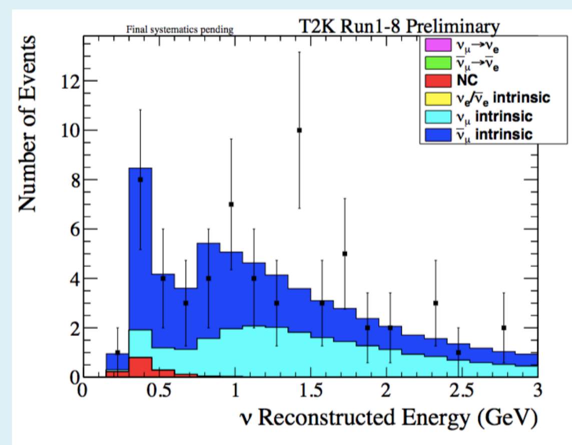
The T2K (Tokai to Kamioka) Experiment

Super-K

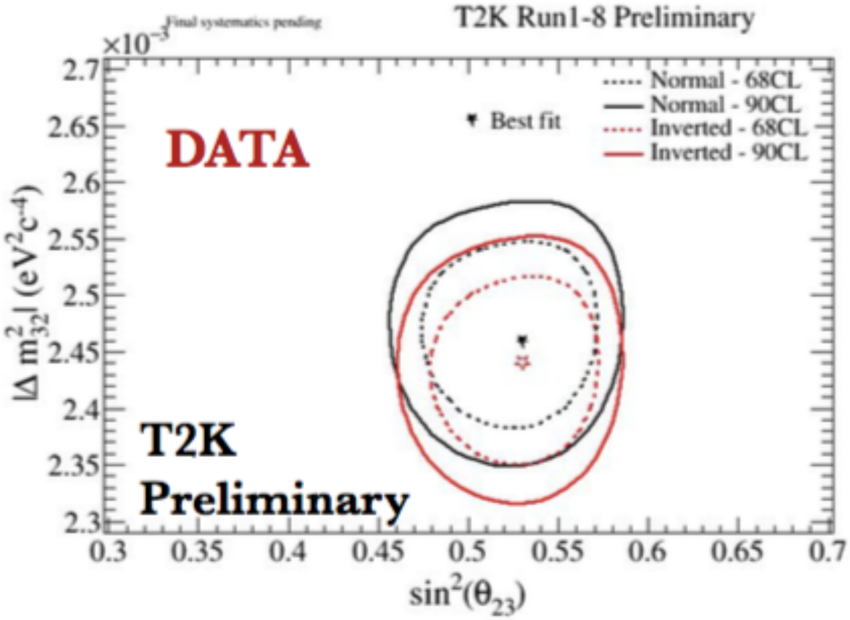
J-PARC

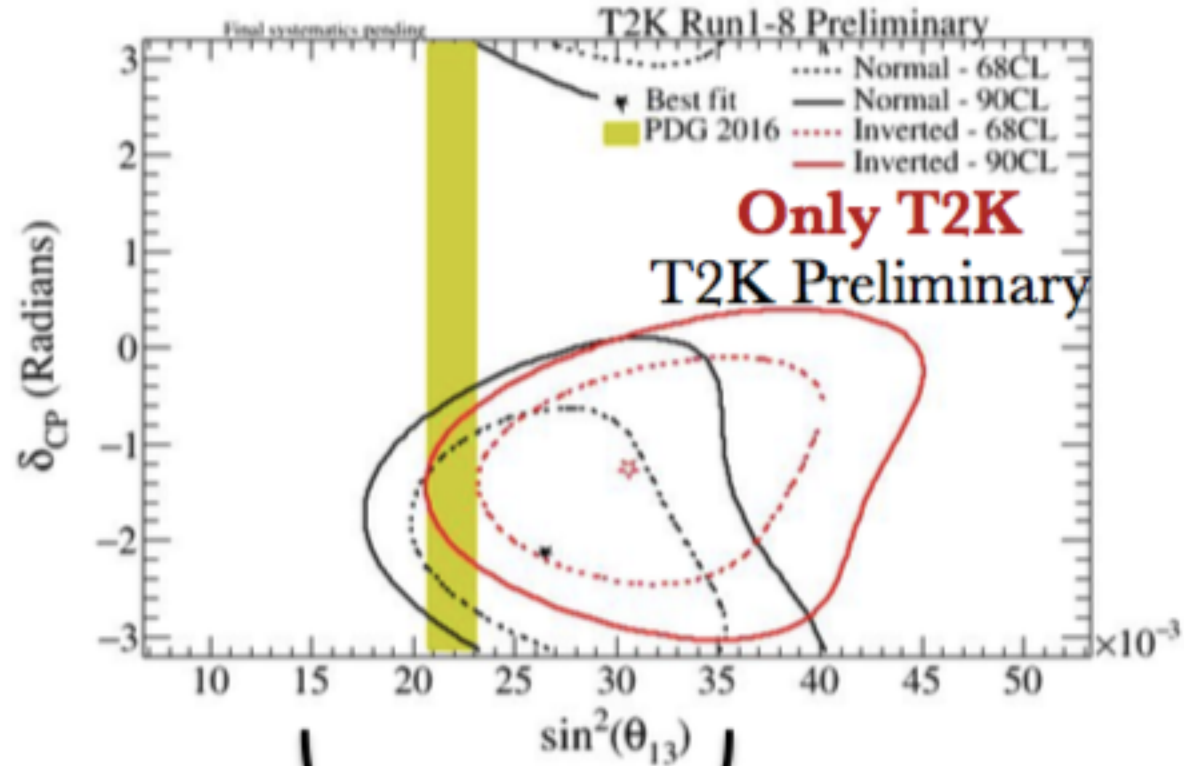
- second-generation long baseline experiment (following K2K, MINOS)
- high-intensity (750 kW) 2.5^o off-axis ν_μ beam from J-PARC 295 km to Super-K, a large water Cherenkov detector

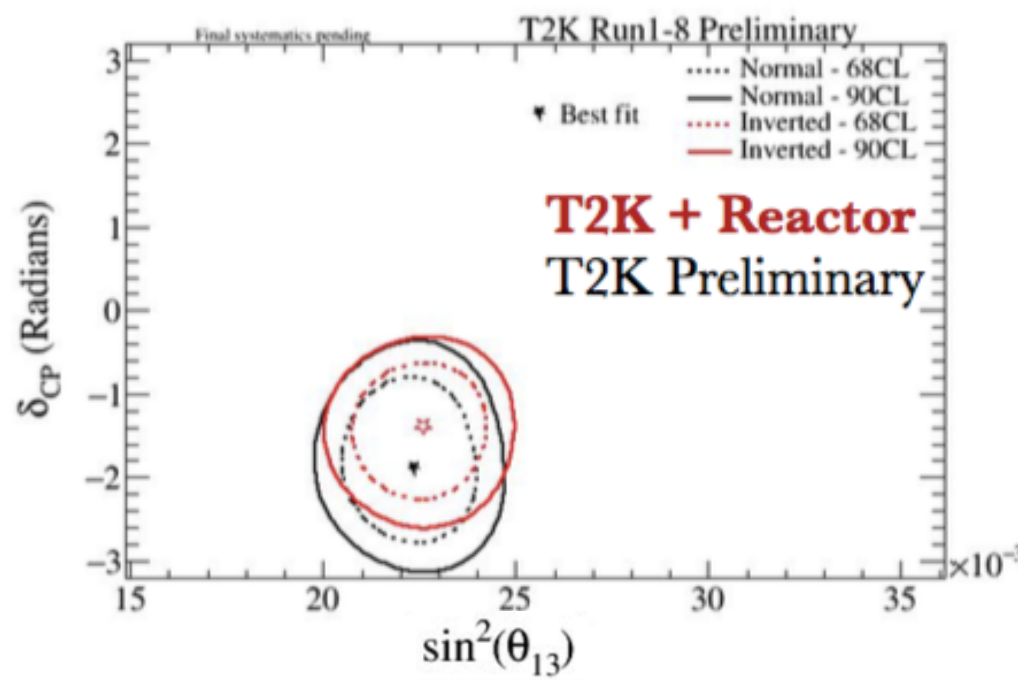
T2K appearance and disappearance

Results shown at Moriond	**Neutrinos** 1.47 x 10^{21} pot	**Antineutrinos** 0.76 x 10^{21} pot
Electron neutrino appearance 	 **74** 1-ring e-like events (**+15** in 1π sample)	 **7** 1-ring e-like events
Muon neutrino disappearance 	 **240** 1-ring μ-like events	 **68** 1-ring μ-like events

Joint fit to all T2K data

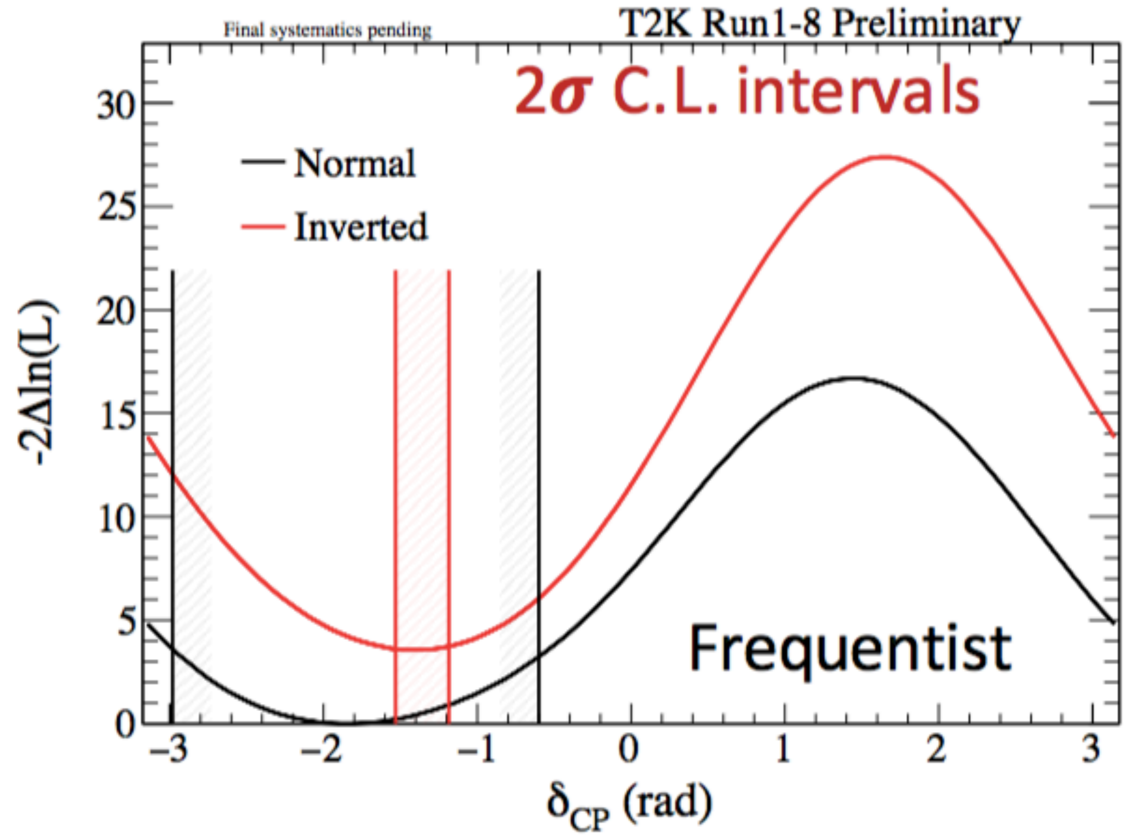






Joint fit to all T2K data

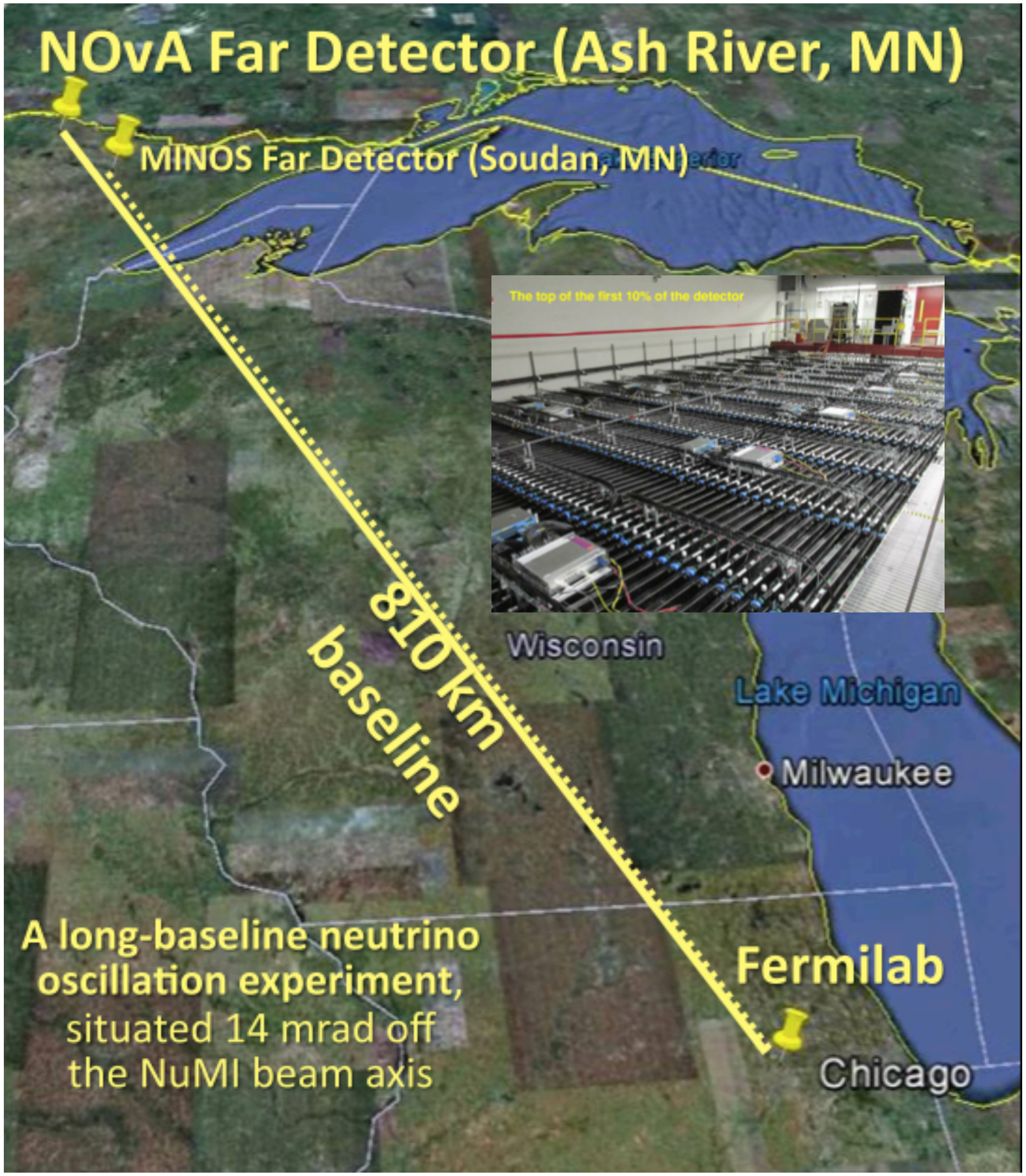
CP conserving values disfavored at 2σ



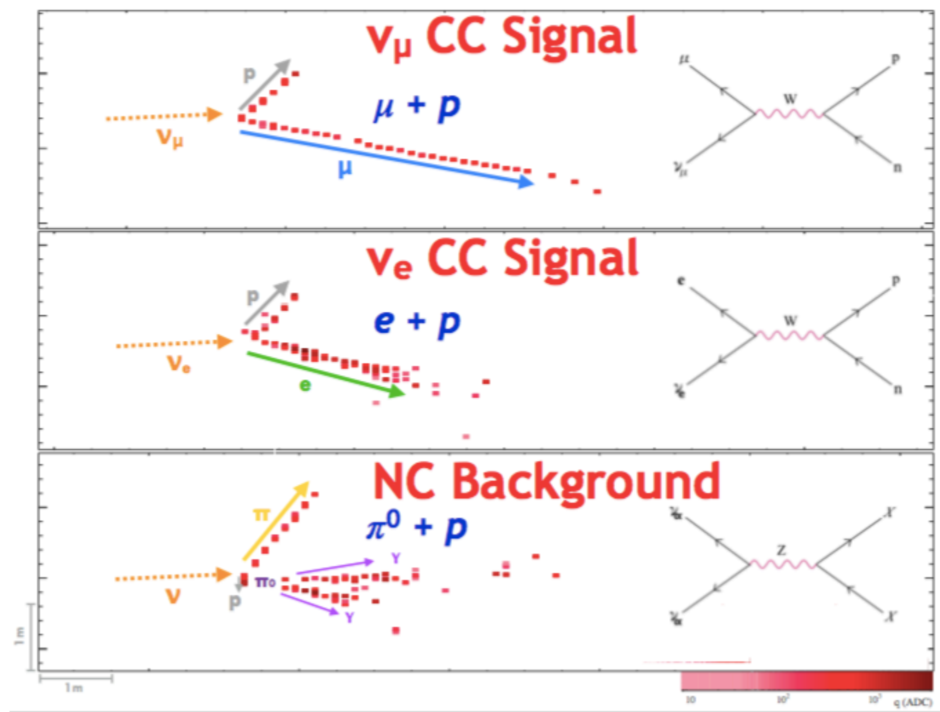
Normal Hierarchy						
Beam mode	Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$	Observed
neutrino	μ-like	267.8	267.4	267.7	268.2	240
neutrino	e-like	73.5	61.5	49.9	62	74
neutrino	e-like+1π+	6.9	6	4.9	5.8	15
anti-neutrino	μ-like	63.1	62.9	63.1	63.1	68
anti-neutrino	e-like	7.9	9	10	8.9	7

L. Magaletti, La Thuile

The NOνA long-baseline experiment



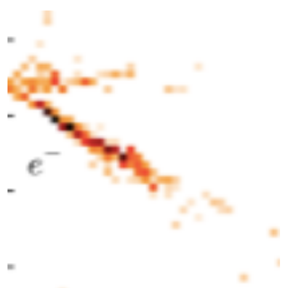
14 kt scintillator
700 kW off-axis FNAL beam
810 km baseline

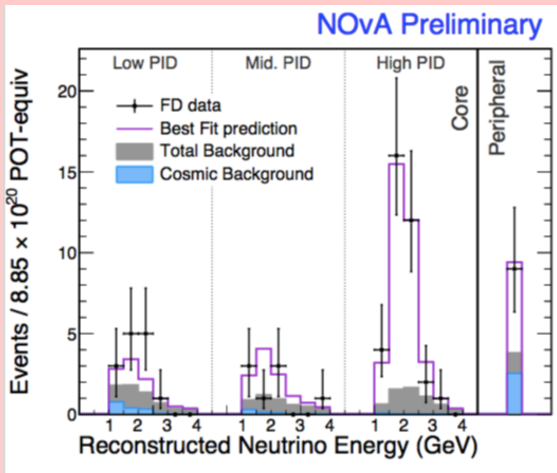


NOvA appearance and disappearance

	Neutrinos	Antineutrinos

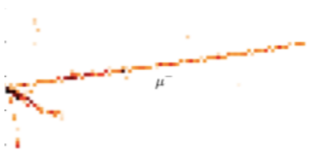
Electron neutrino appearance

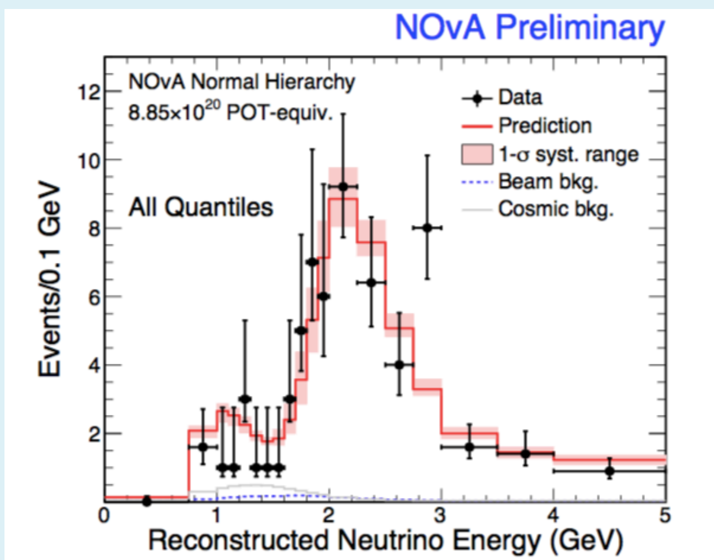




66 e-like events

Muon neutrino disappearance





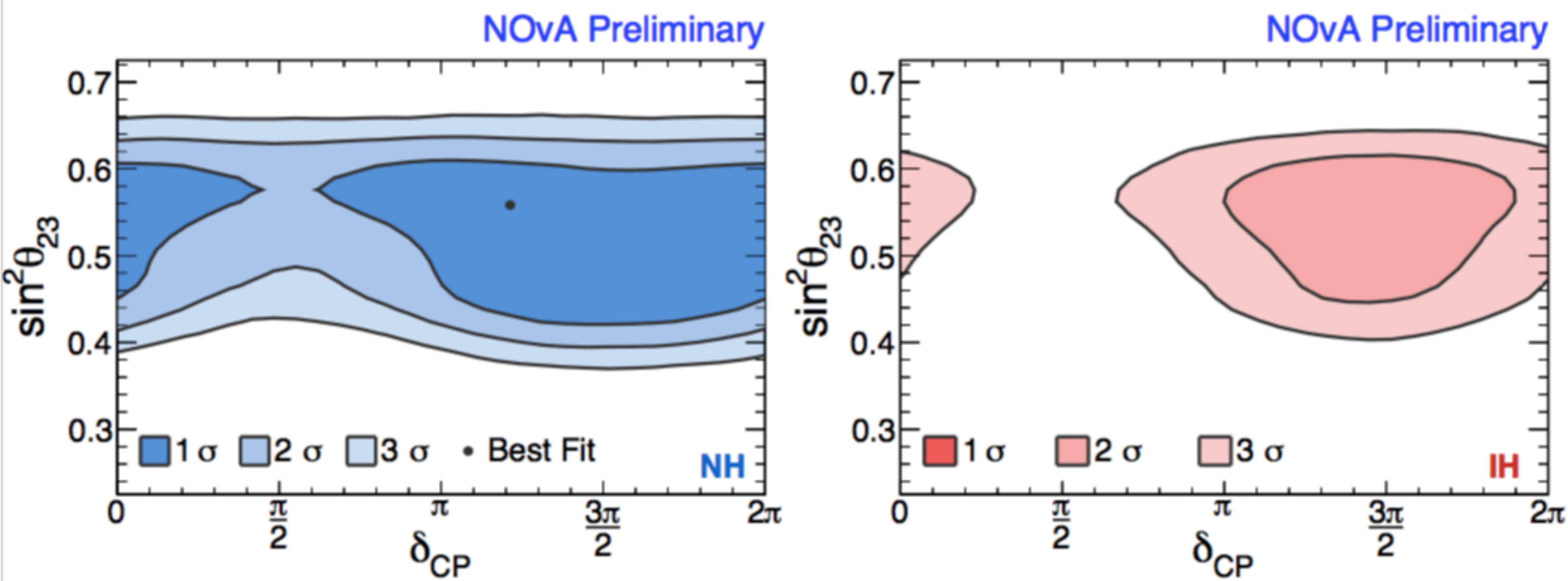
126 μ-like events

Running now

A. Radovic, FNAL JTEP talk

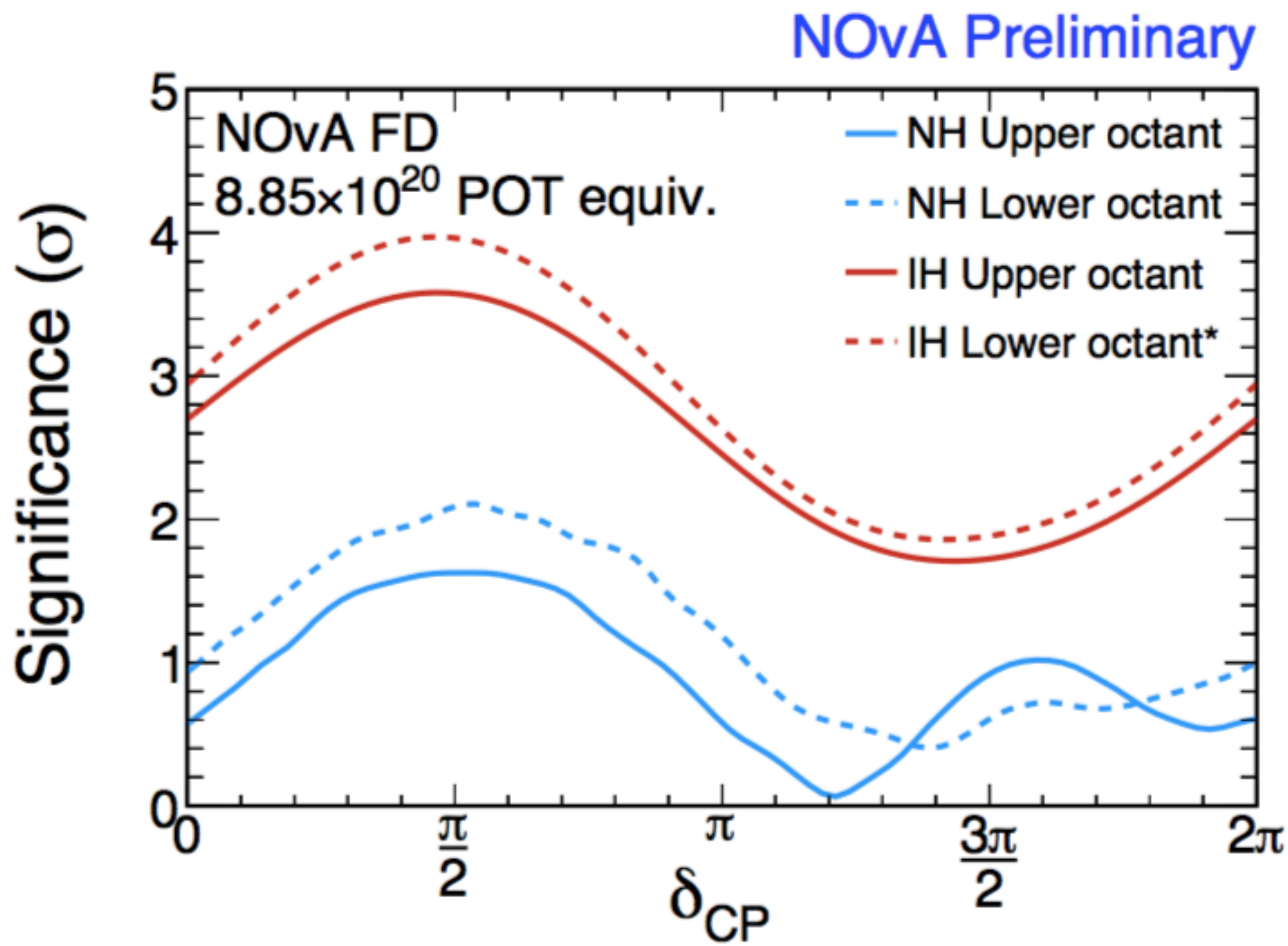
Joint fit to all NOvA data

Constrain θ_{13} using world average from PDG, $\sin^2 2\theta_{13} = 0.082$



A. Radovic, FNAL JTEP talk

Joint fit to all NOvA data

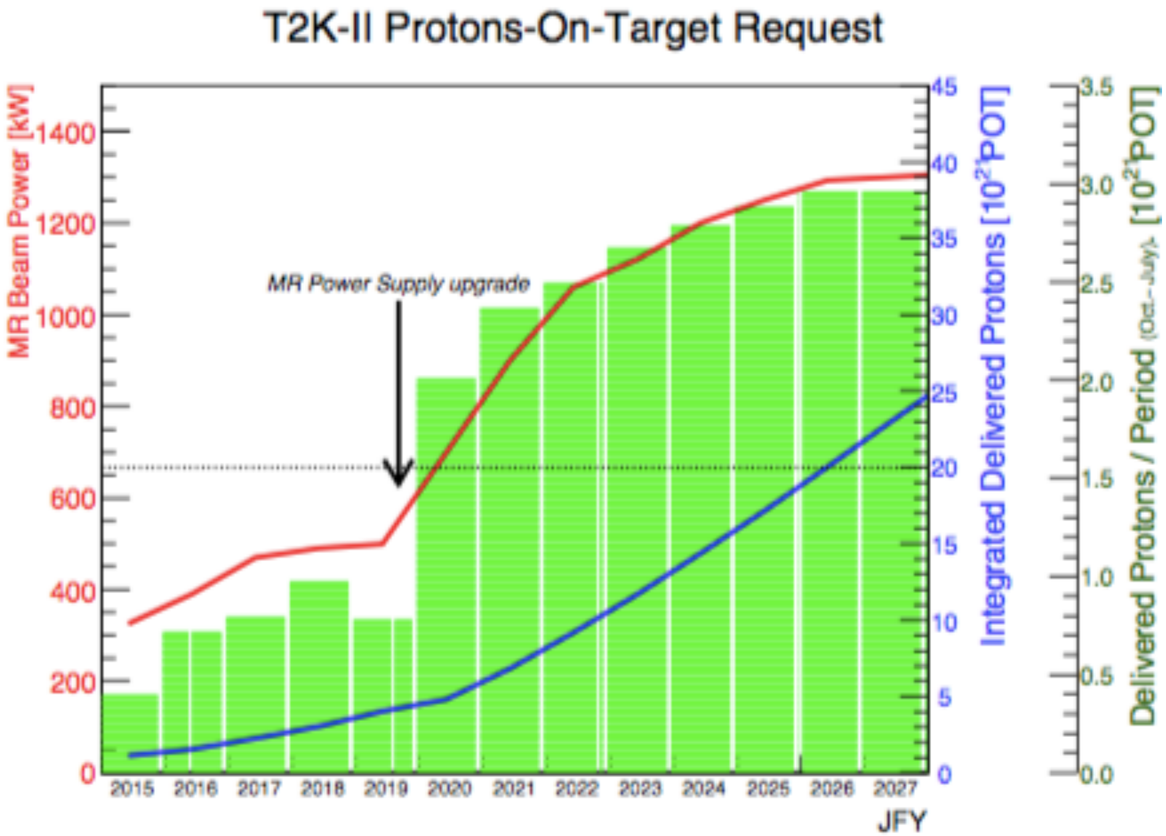


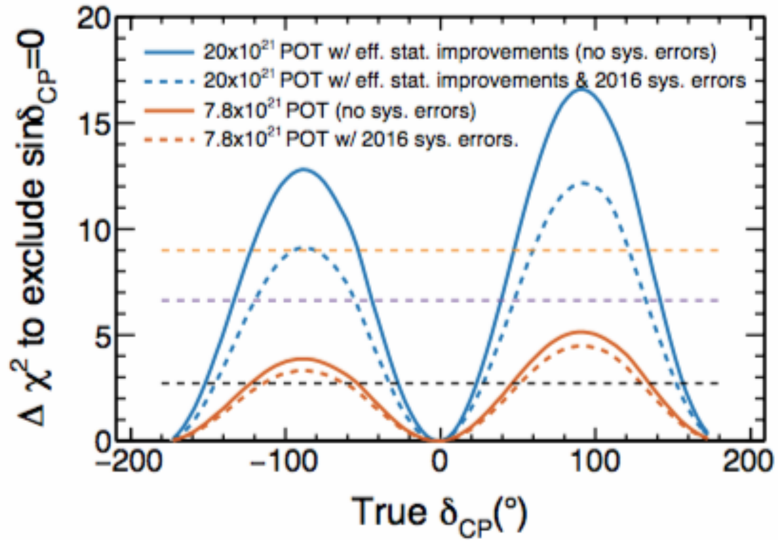
A. Radovic, FNAL JTEP talk

IH at $\delta_{CP} = \pi/2$ disfavored at $>3\sigma$

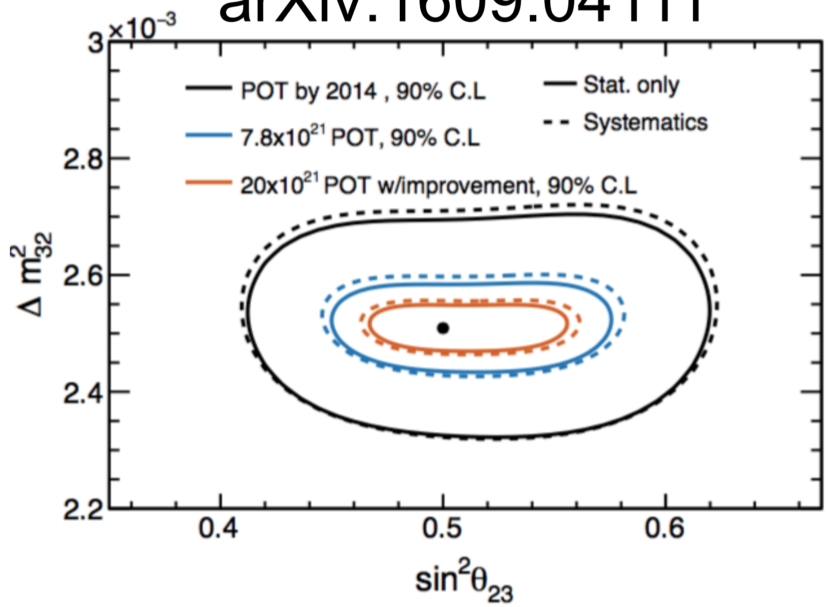
Getting close to rejection of IH at 2σ

Future Prospects for T2K



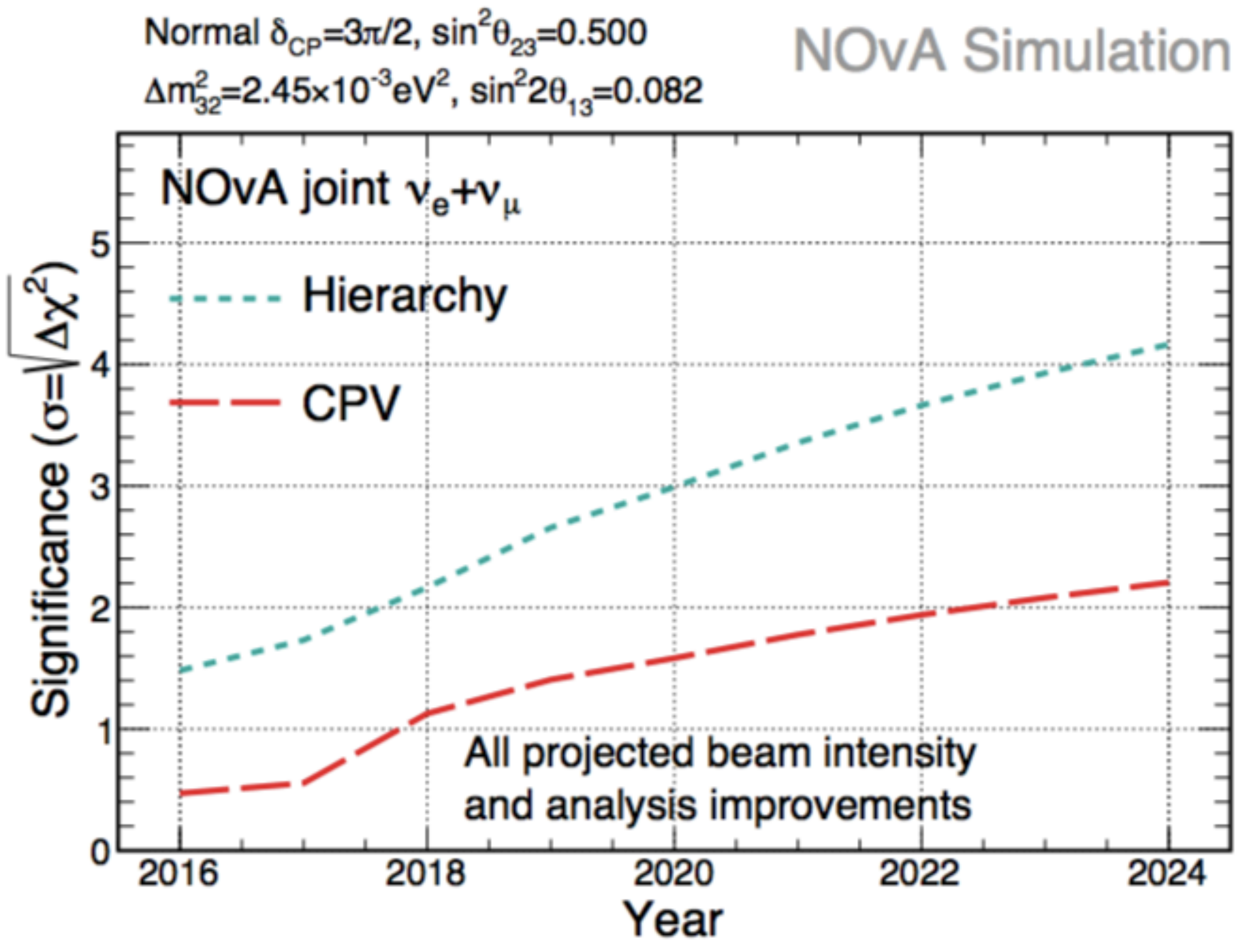


arXiv:1609.04111



- Double antinu data by summer
- Approved 7.8e21 POT by 2021
- Beam upgrade to >1 MW in 2021
- If approved T2K-II will have 20e21 POT by 2026

Future Prospects for NOvA



A. Radovic, FNAL JTEP talk

Expect antineutrino result this summer

Discussions underway for joint T2K-NOvA analysis

And the future...

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K (II)
J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW

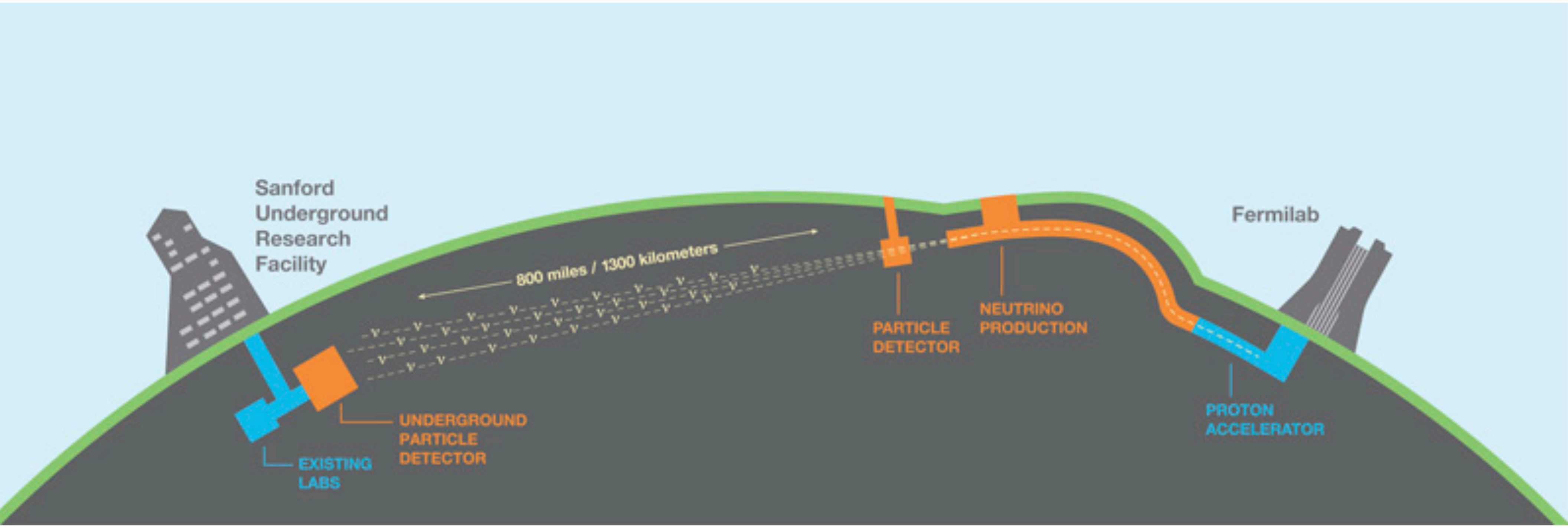
LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)

Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)




Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility

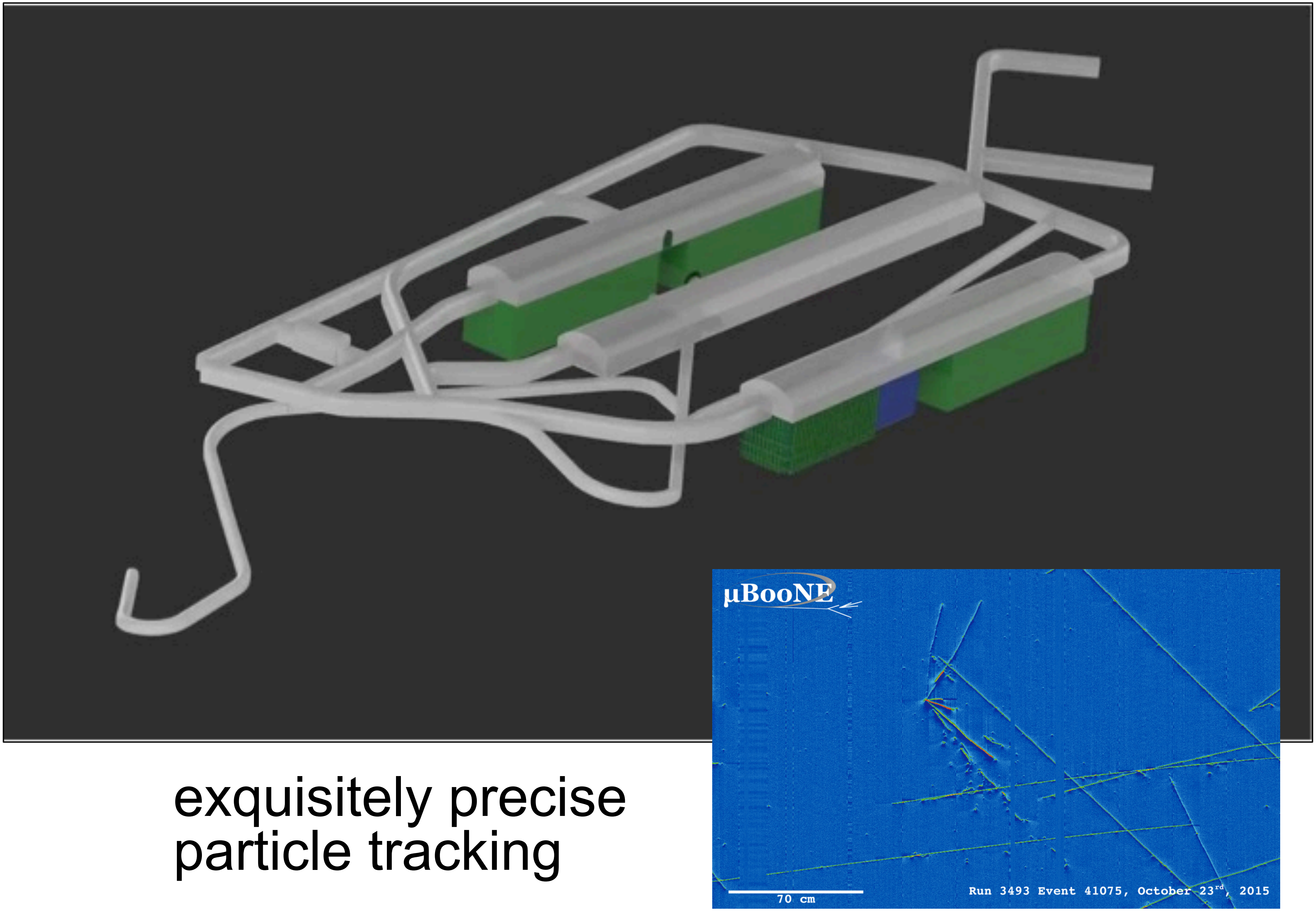
next big US-based international particle physics project



- new 1.2 MW beam, Fermilab to SD
- 1300 km baseline
- 40-kton liquid argon far detector

  (time projection chamber)

The Neutrino Detector: 70,000 tons of liquid argon



exquisitely precise particle tracking

The DUNE Collaboration

As of Jan 2018:

$\overbrace{\text{175 institutions}}^{\text{60 \% non-US}}$

1061 collaborators from 175 institutions in 31 nations

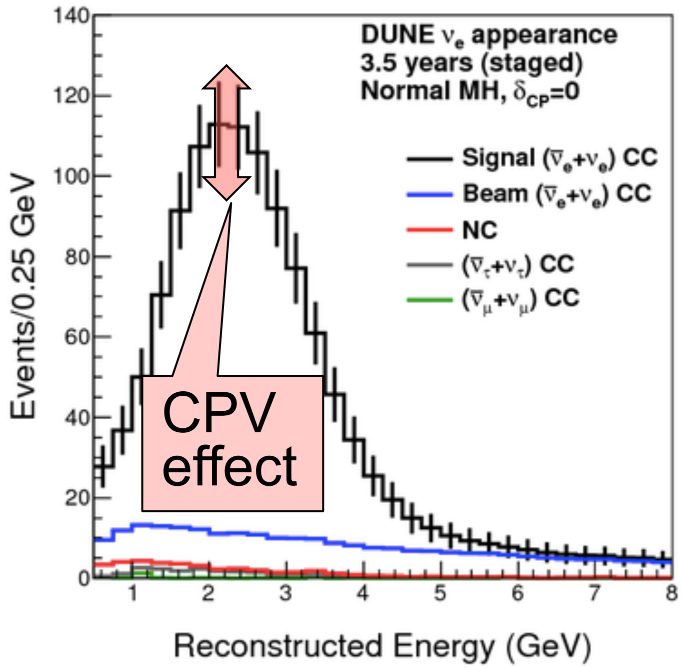
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA

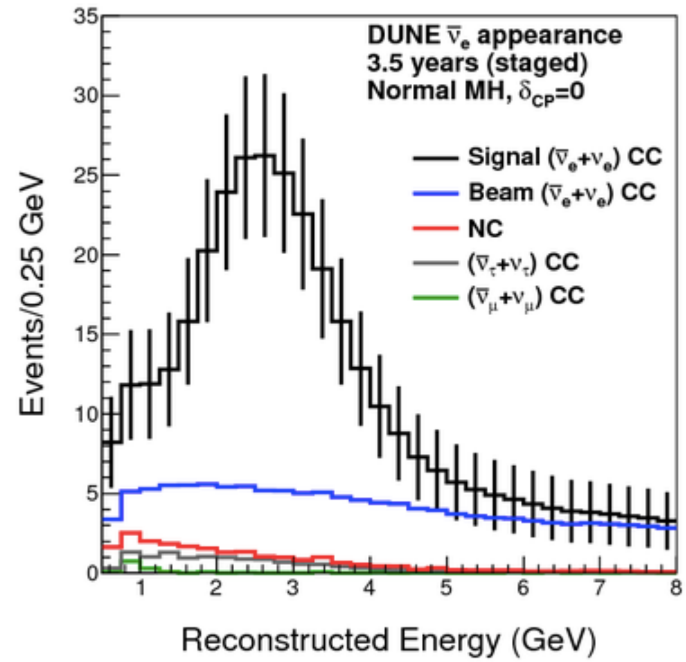
Same strategy of appearance & disappearance for MO & CPV

Neutrinos

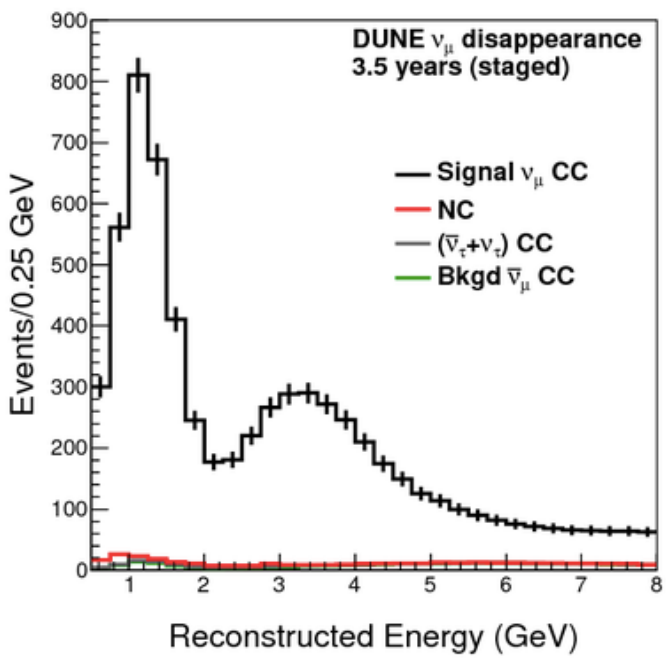
Anti neutrinos

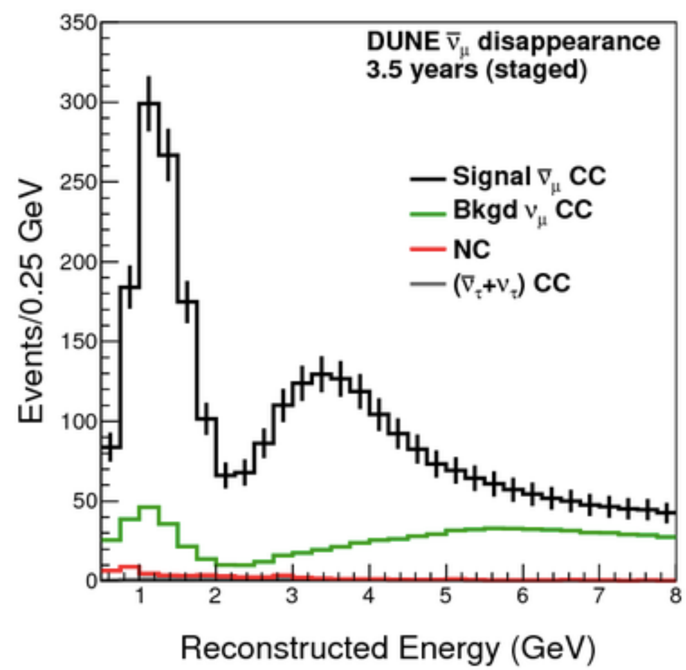
Electron flavor



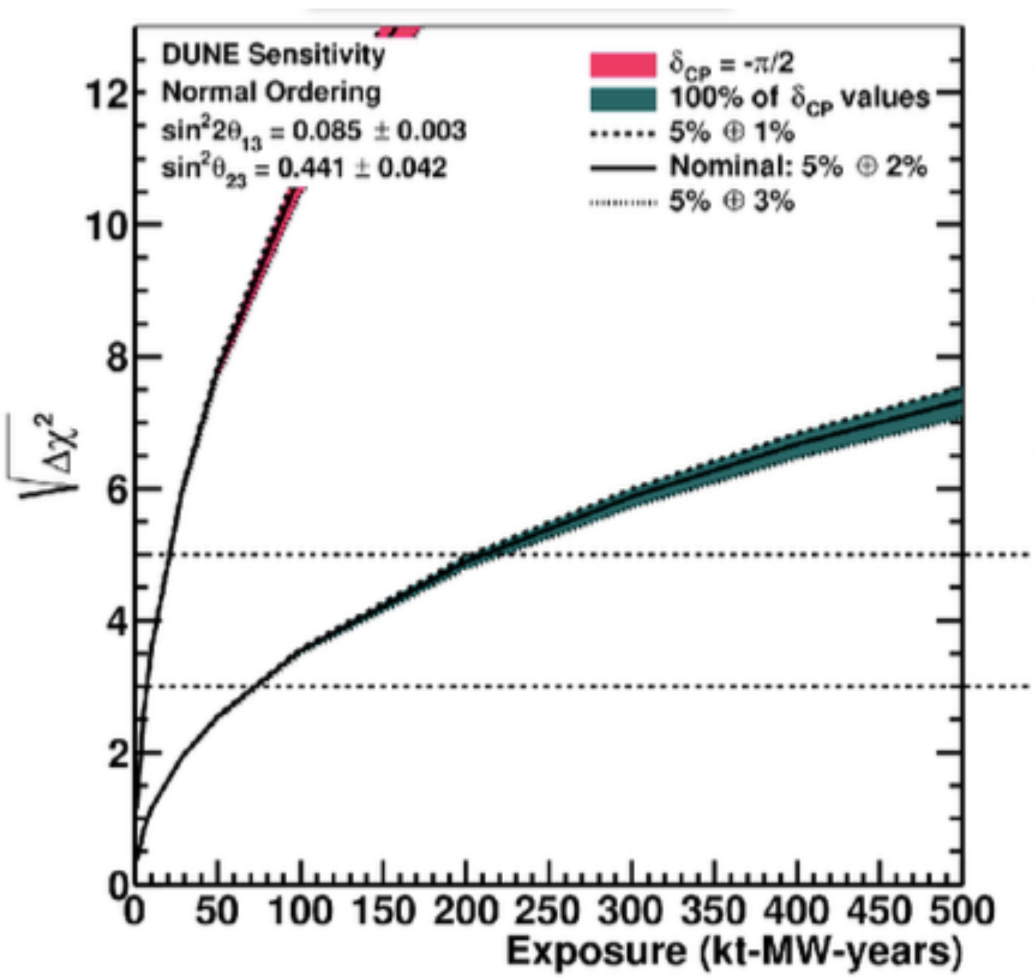


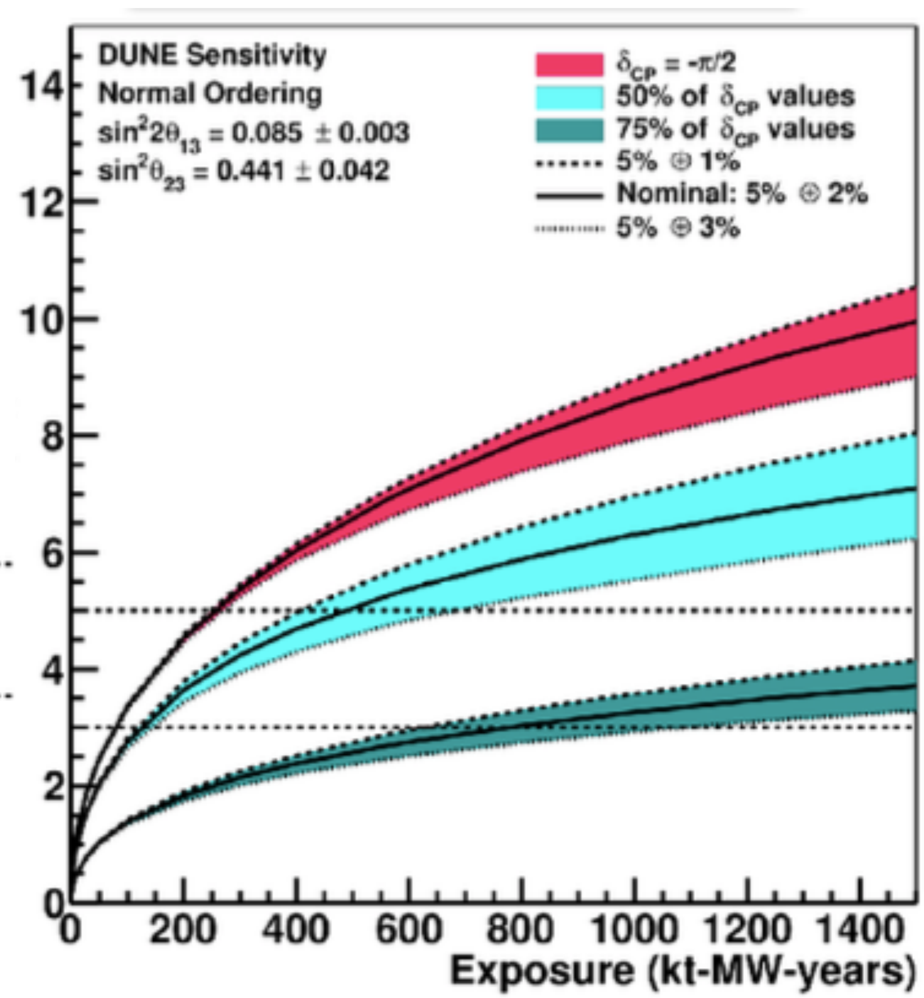
Muon flavor





DUNE sensitivity

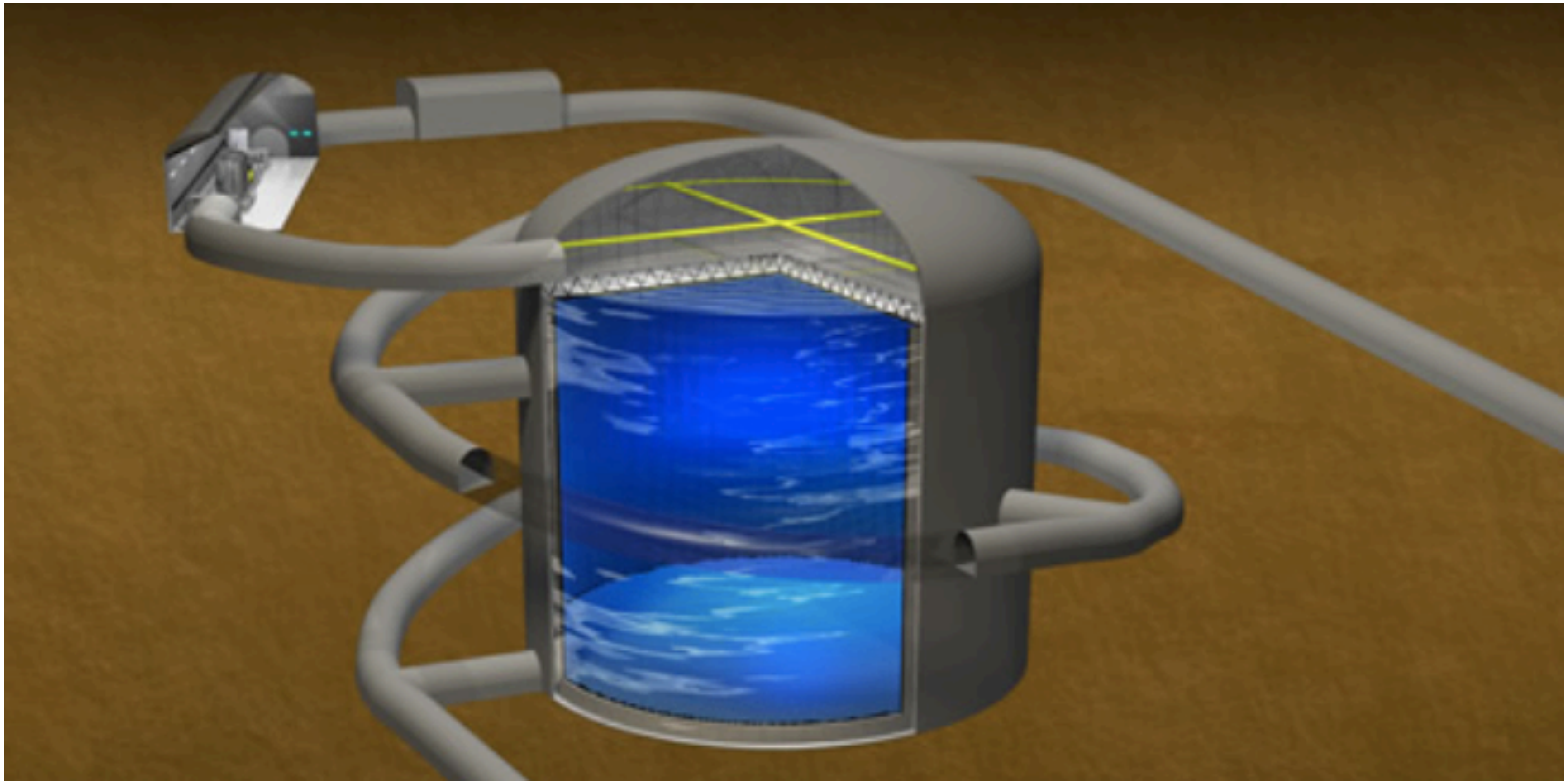




Excellent mass ordering reach for all CP values

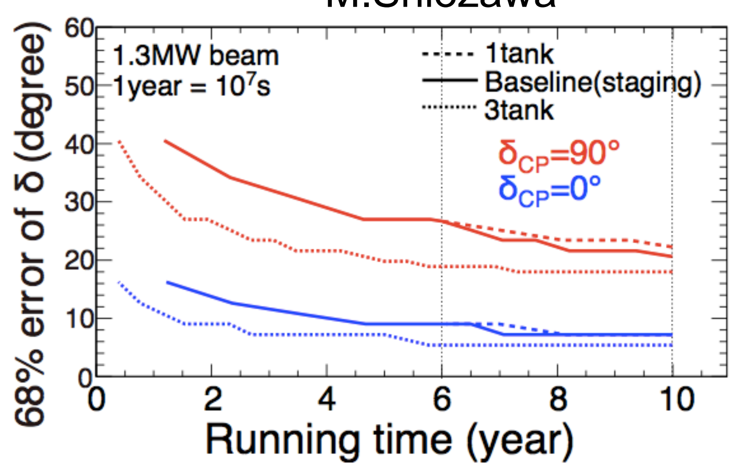
Good prospects for CPV

Hyper-Kamiokande



M.Shiozawa

- 317 kton fiducial volume in 2 staged tanks
- Beam from J-PARC 295 km away
- Discussion of 2nd detector in Korea
- CP violation, atmospheric neutrinos, supernova neutrinos, proton decay,...



Long-baseline beam experiments

Past | Current | Future

K2K
KEK to Kamioka
250 km, 5 kW

MINOS (+)
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734 km, 400+ kW

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CERN to LNGS
730 km, 400 kW

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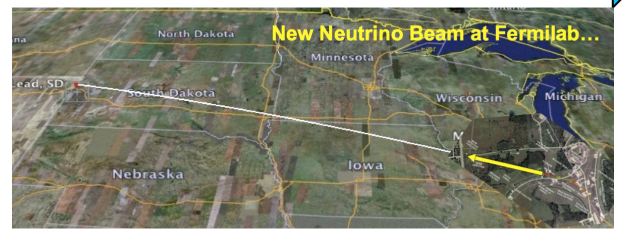
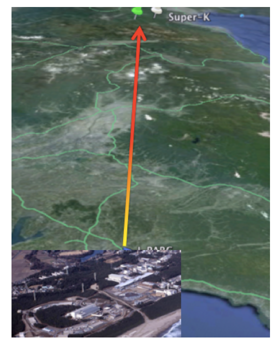
J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW



LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)



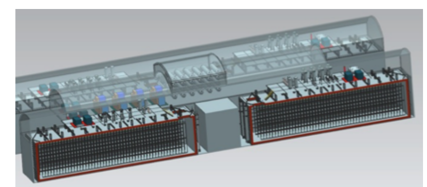
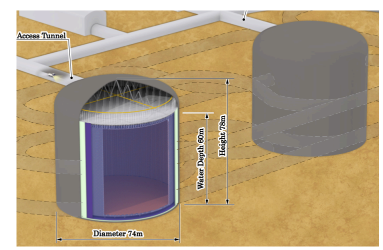
Hyper-K
J-PARC to Kamioka
295 km, 750 kW
(➔1.3 MW)

And beyond...
ESSnuB,
neutrino factories...





Summary of “3-flavor" oscillation physics

Observable	Signature	Next steps	
θ_{13}	Small appearance of ν_e in ν_μ beam; Disappearance of reactor anti-ν_e	Long-baseline beams; reactor experiments	
Mass ordering	Matter-induced ν/ anti-ν asymmetry; anti-ν_e oscillation pattern; (cosmology, 0nbbdk,...)	Long-baseline beams; reactor experiments; atmospheric neutrinos; supernova	 
CPV	ν & anti-ν oscillation	Long-baseline beams; atmospheric nus; cyclotron-based beams; neutrino factories	

Expect “indications” in coming decade; definitive measurements with next generation; could approach “CKM-level” precision with next-next+

*Note: also rich non-accelerator physics (SN, pdk, atmν,...) with different strengths for long-baseline detectors

All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

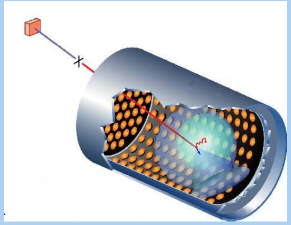
There are already some slightly uncomfortable data that **don't fit that paradigm**...

Open a parenthesis: (

Outstanding 'anomalies'

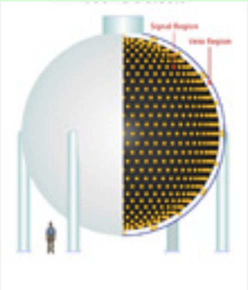
LSND @ LANL (~30 MeV, 30 m)

Excess of $\overline{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



➔ $\Delta m^2 \sim 1\ eV^2$: inconsistent with 3 ν masses

MiniBooNE @ FNAL ($\nu,\overline{\nu}$ ~1 GeV, 0.5 km)



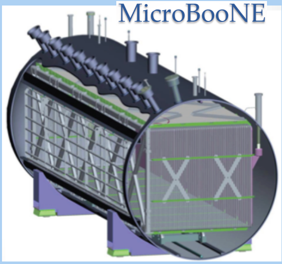
- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent w/ LSND)
- for E>200 MeV, both nu and nubar consistent with LSND

????
more data needed

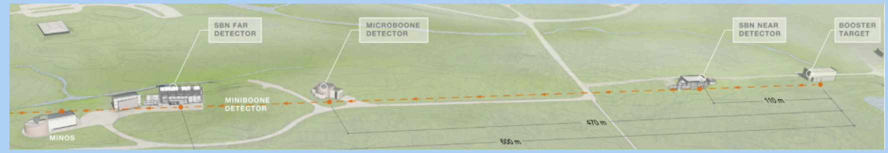
Also: possible deficits of reactor $\overline{\nu}_e$ ('reactor anomaly') and source ν_e ('gallium anomaly')

Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle & astrophysics
[cosmology w/Planck now consistent w/3 flavors... but allows 4...]
Or some other new physics??

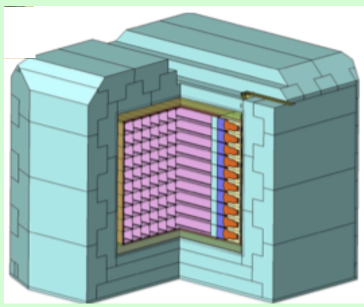
Experimental ideas to address these anomalies...



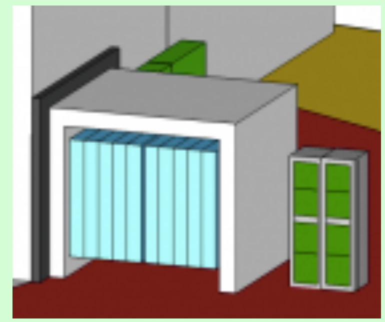
Experiments with beams
(meson decay in flight and at rest)



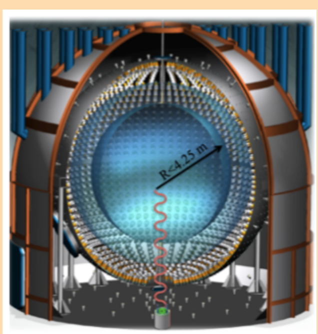
MINOS+, FNAL SBN, JSNS^2, ...



Experiments at reactors

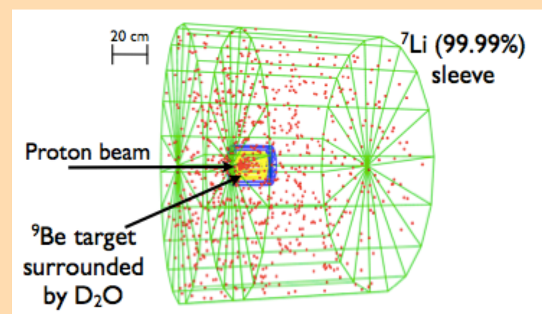


PROSPECT, SoLid, STEREO, NEOS, DANSS, CHANDLER....



Experiments with radioactive sources

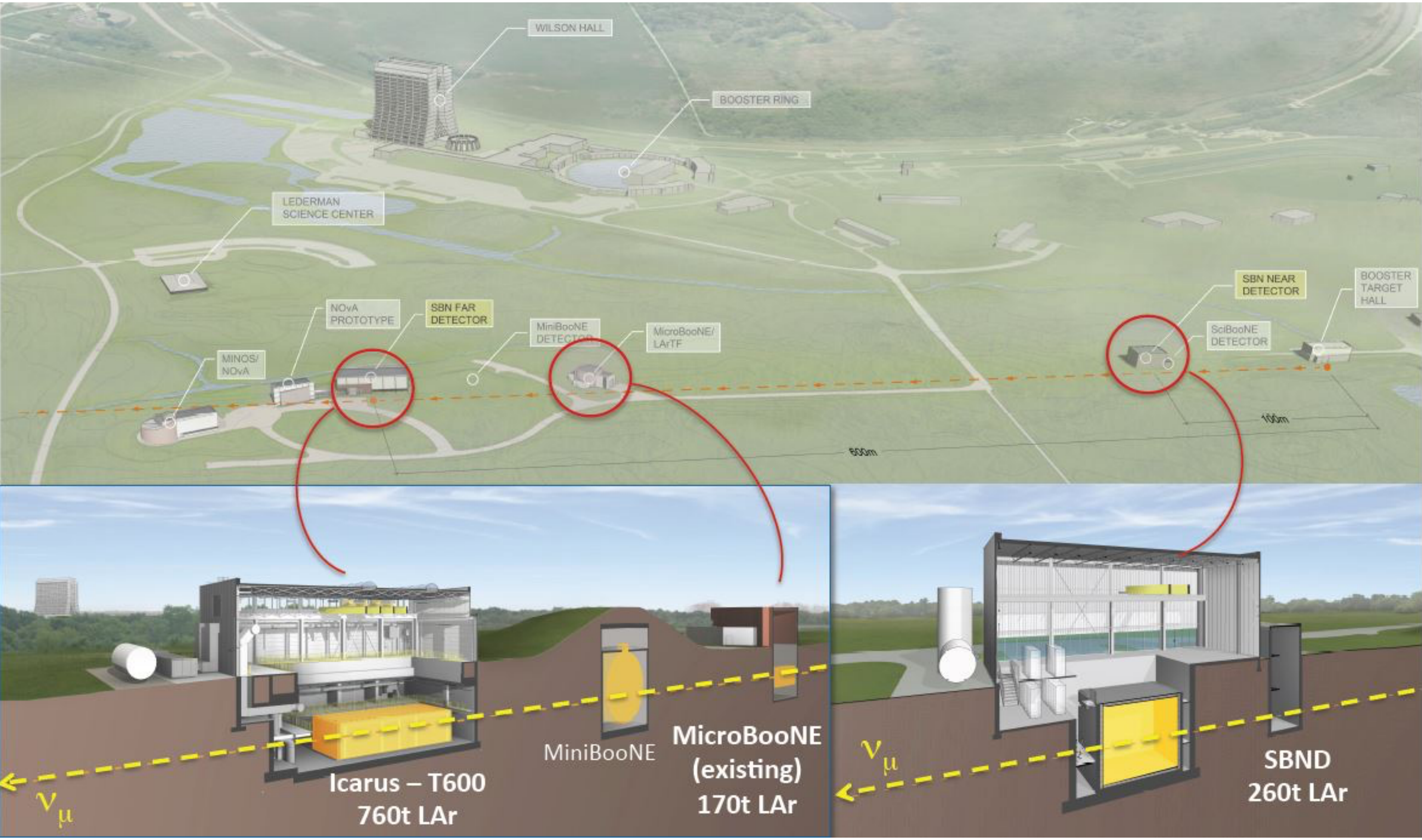
(CeSOX), IsoDAR, ...



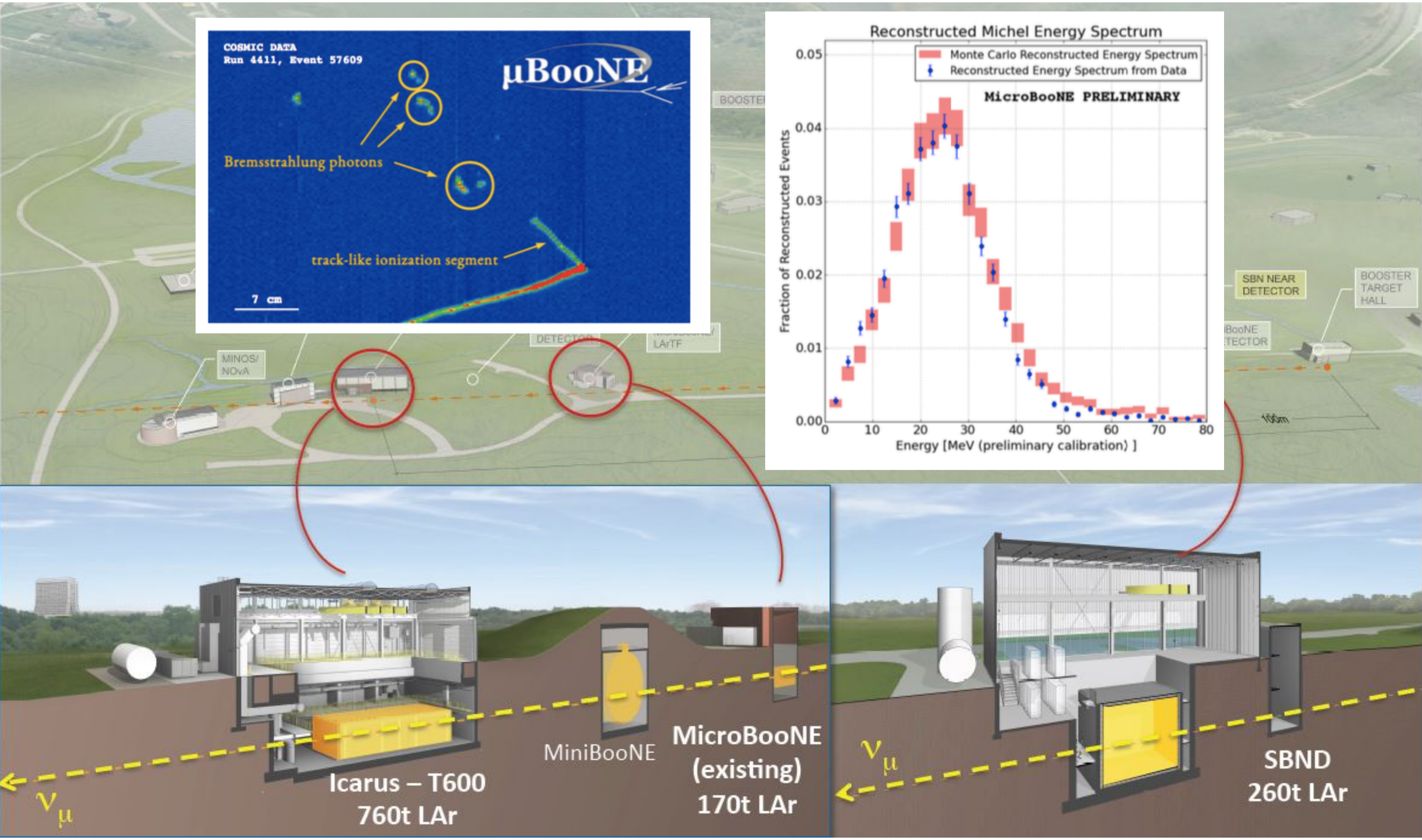
and many more...

... parenthesis not closed...

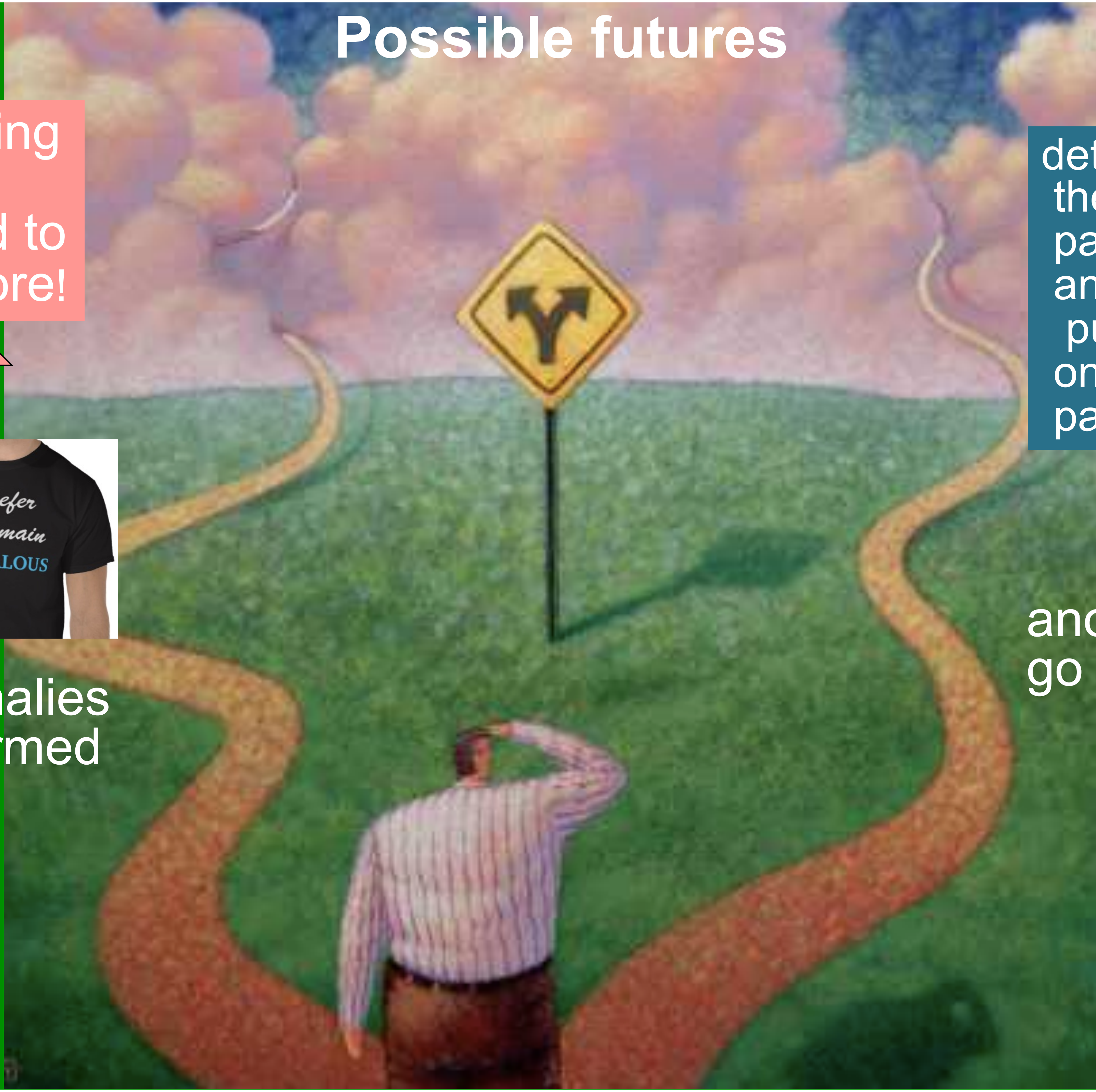
Short baseline program at FNAL



Results from MicroBooNE are starting to arrive



Possible futures



exciting new world to explore!

anomalies confirmed

determine the 3-flavor parameters and keep pushing on the paradigm

anomalies go away

Bonus topic: other accelerator-based neutrino experiments exploring cross sections

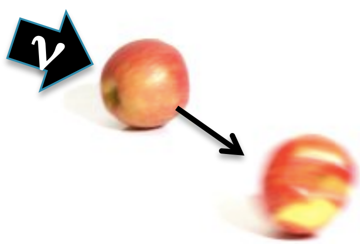
Neutrino interactions with Nuclei

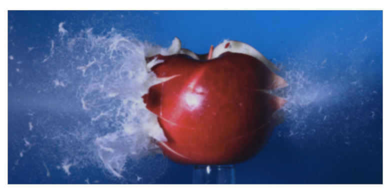
Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV



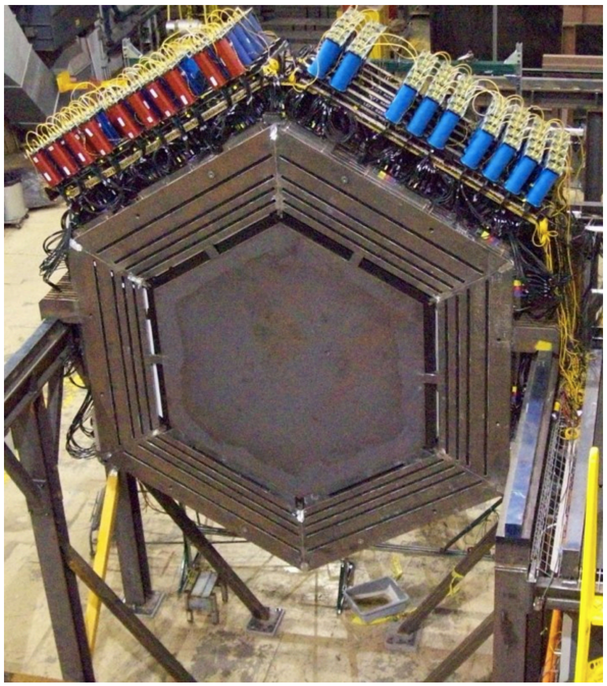


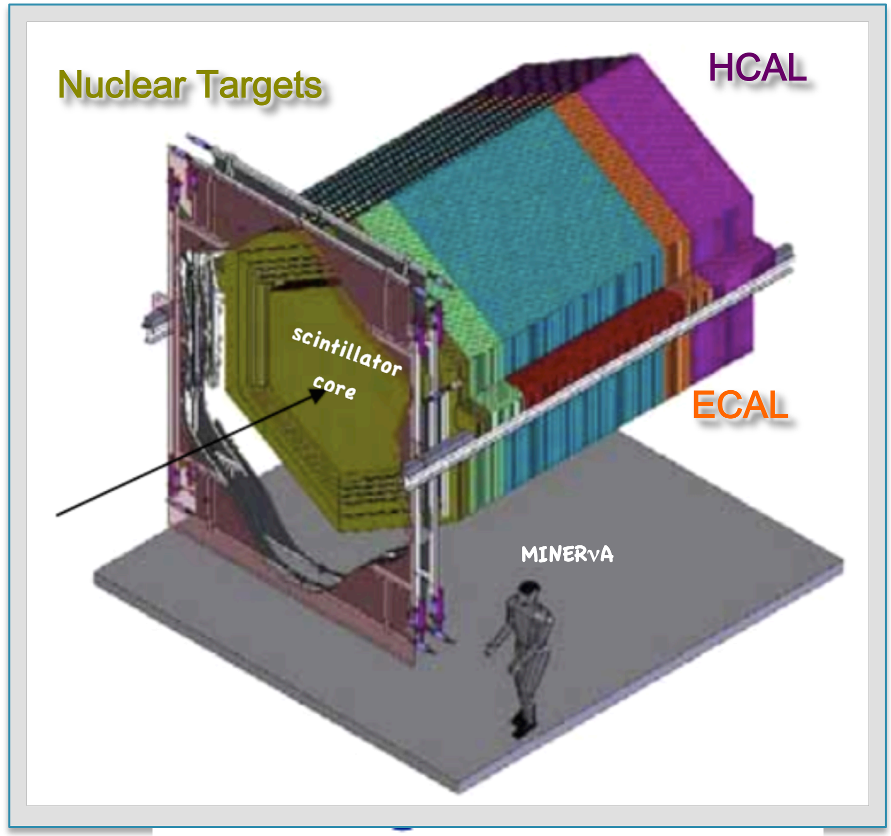
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

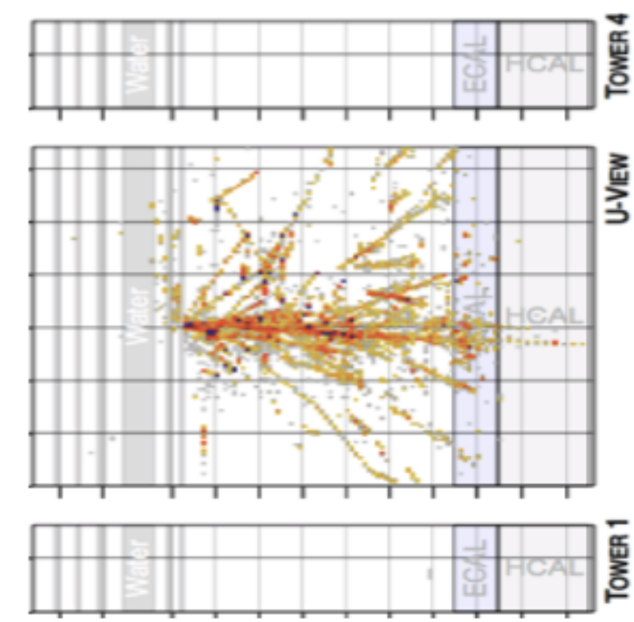
Important for oscillation expt interpretation
(and nuclear physics)

MINERνA

Detector at NuMI (Fermilab)
to measure cross-sections of
~GeV neutrinos on nuclear targets
(finely-segmented scintillator
+ em& hadronic calorimeters)

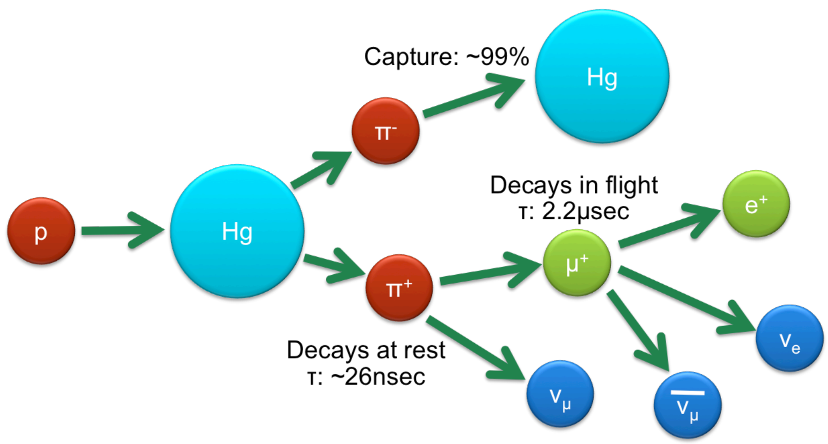


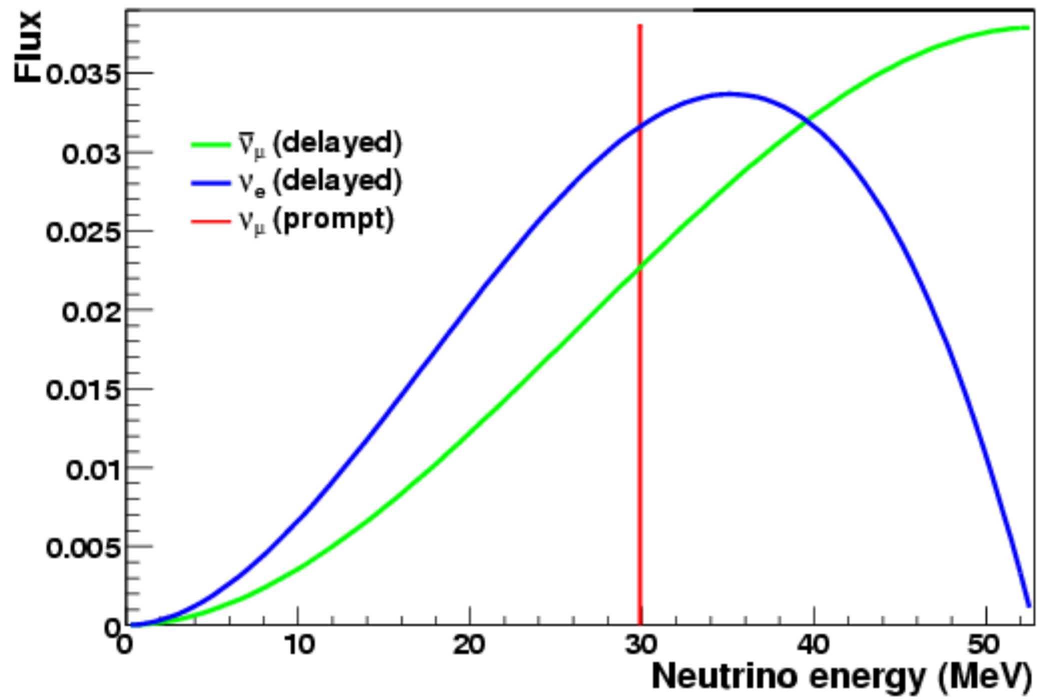




Critical to understand interactions for interpretation of long-baseline oscillation experiment backgrounds & systematics!

Stopped-Pion (πDAR) Neutrinos





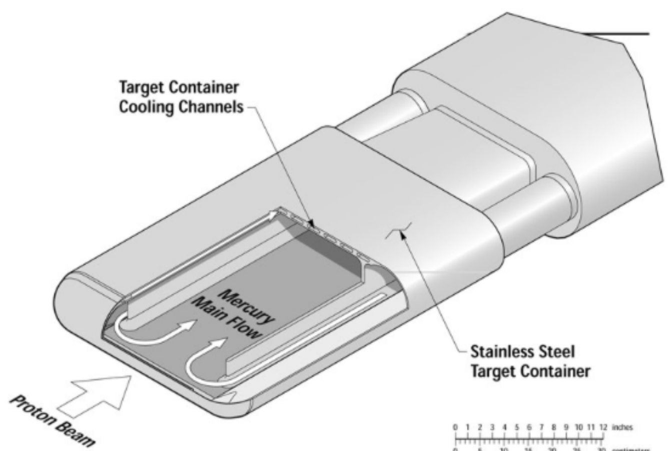
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

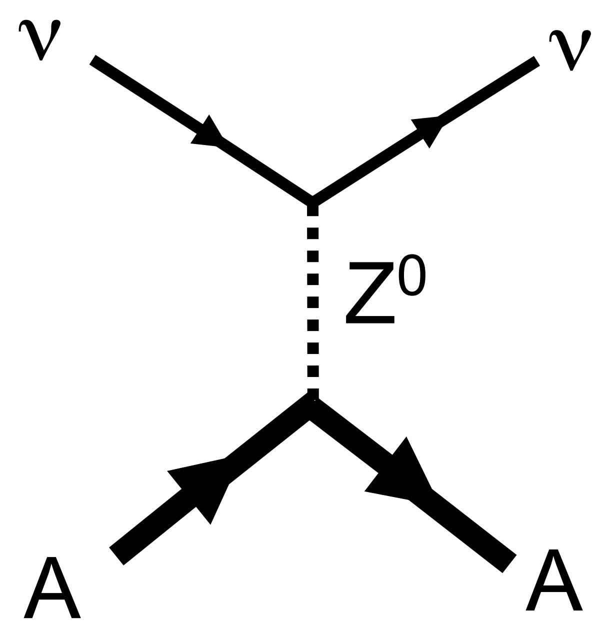
3-body decay: range of energies
between 0 and $m_\mu/2$
DELAYED (2.2 μs)



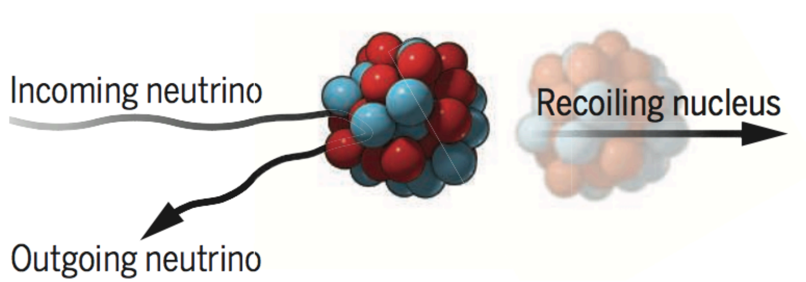
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV

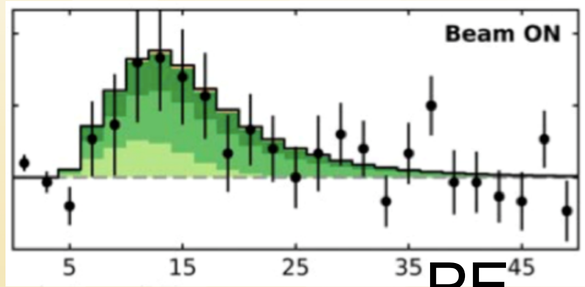


Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

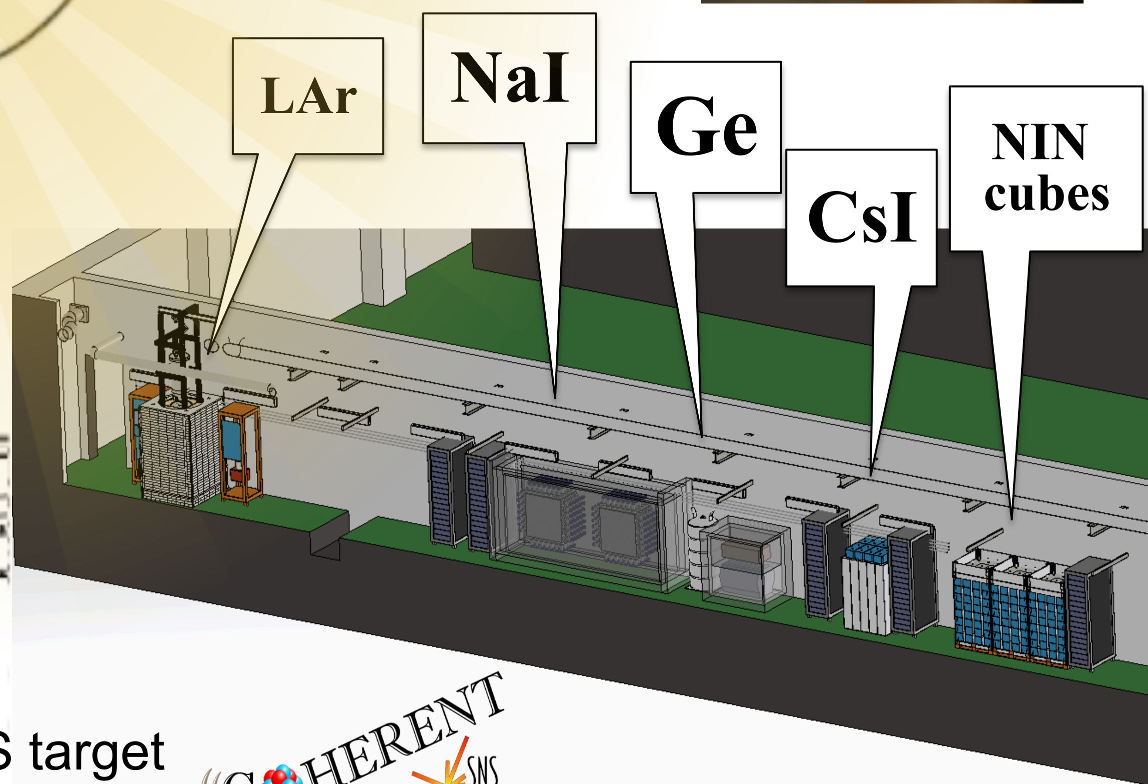
For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

Image: J. Link *Science* Perspectives

Now measured w/ stopped-π ν's



View looking down "Neutrino Alley"



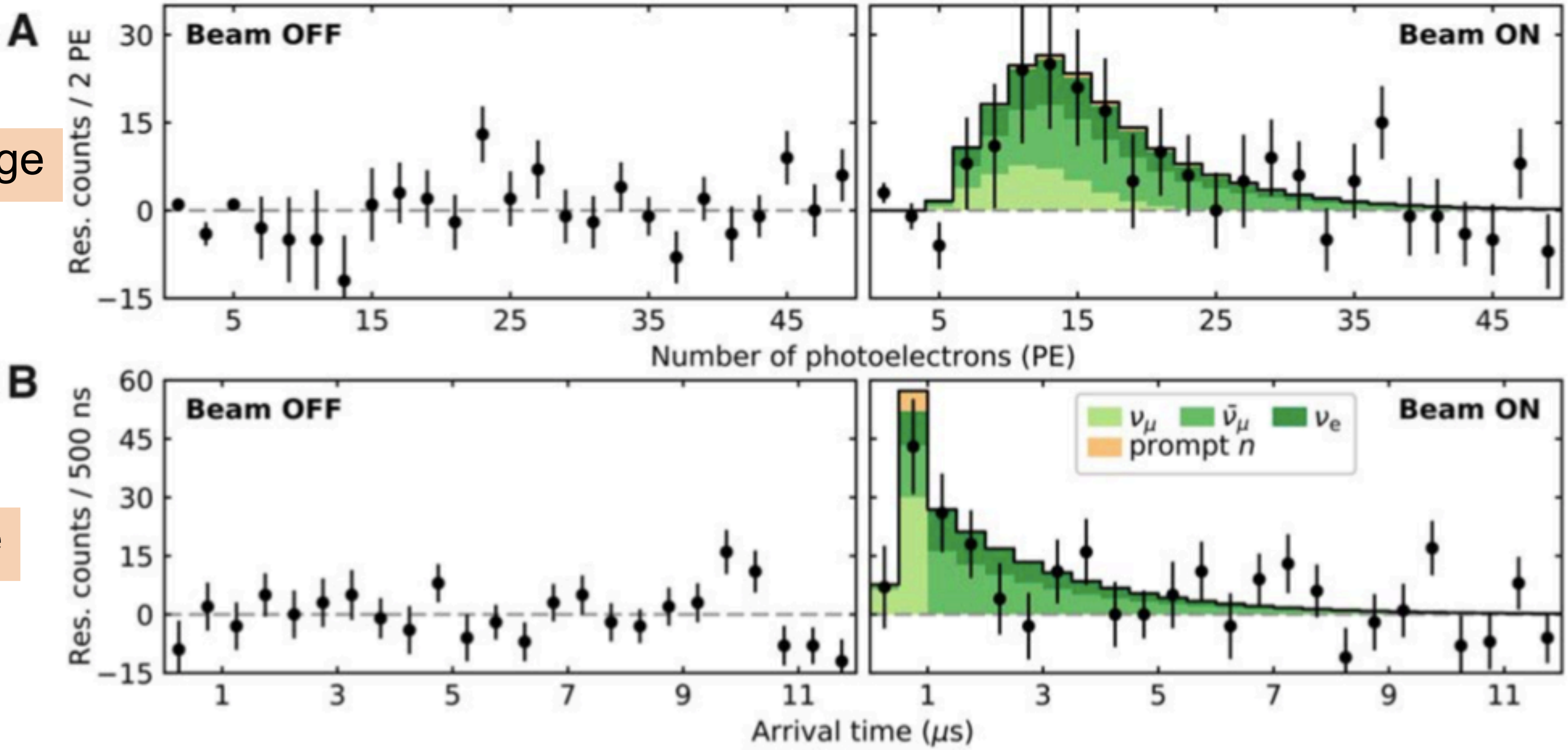
Isotropic ν glow from Hg SNS target

COHERENT SNS

First light at the SNS with 14.6-kg CsI[Na] detector

Charge

Time



Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

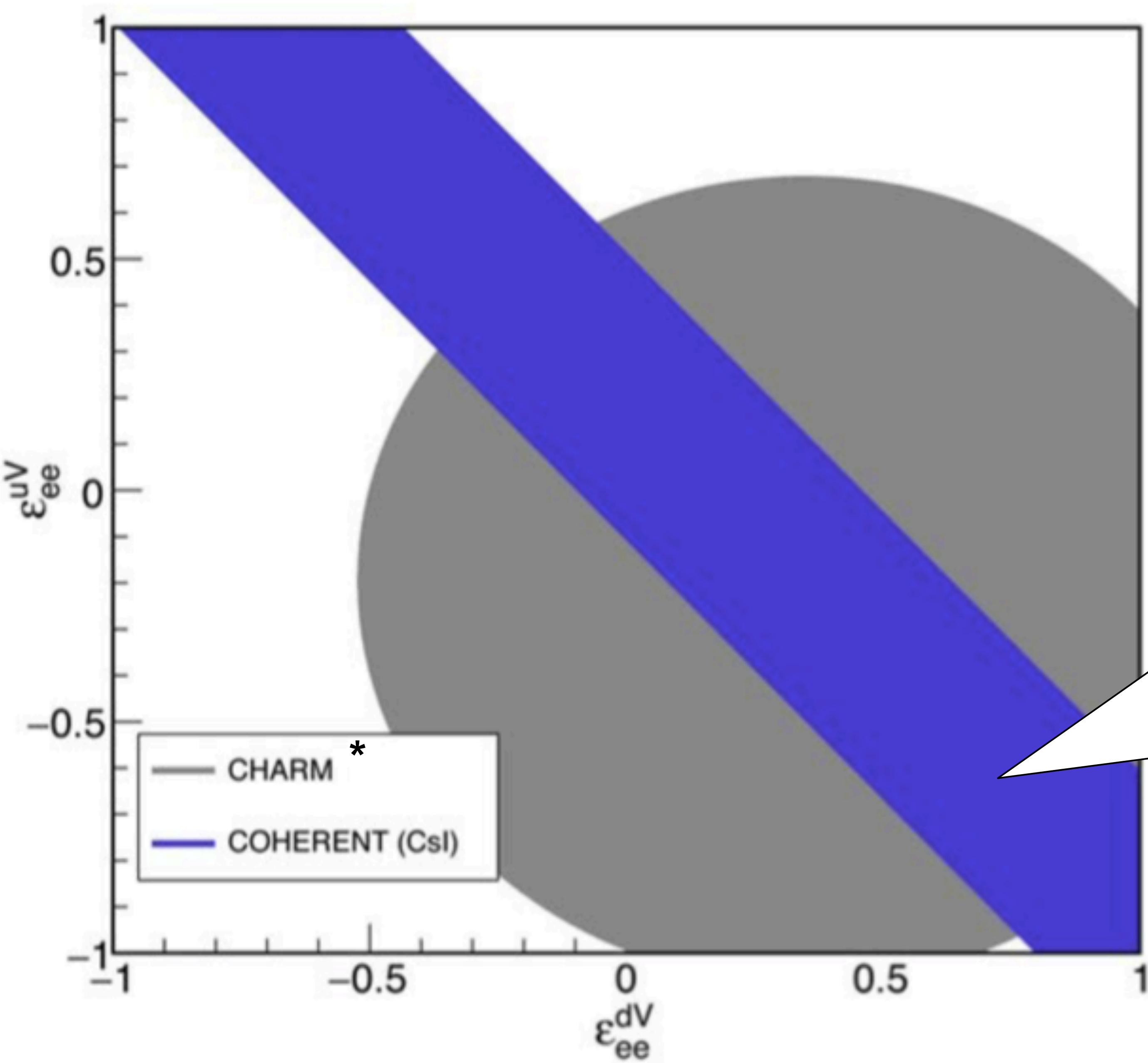
+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

Neutrino non-standard interaction constraints for current CsI data set:



- Assume all other ε's zero

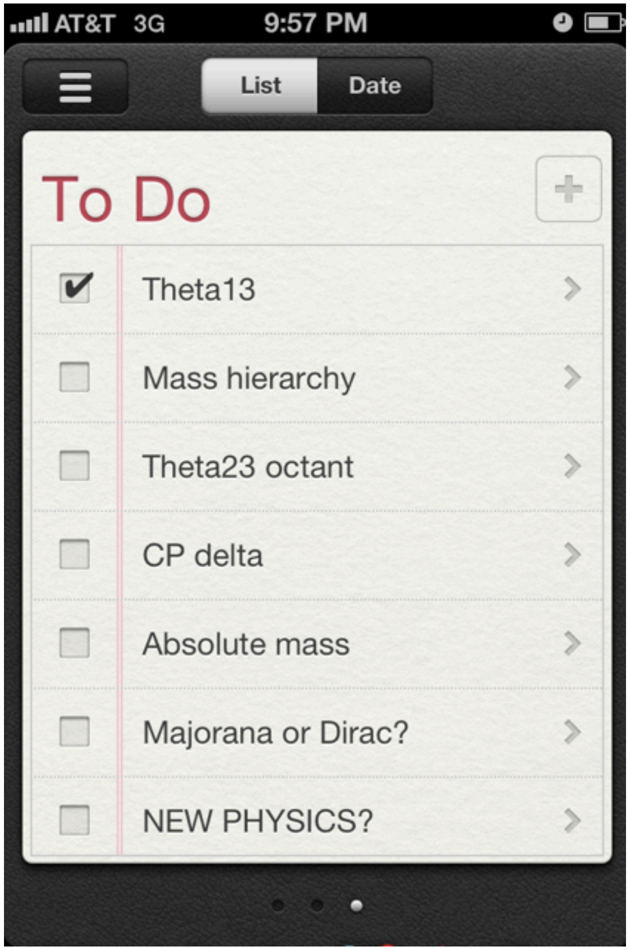
Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

See also Coloma et al., arXiv:1708.02899

*CHARM constraints apply only to heavy mediators

Overall Summary

Huge progress in understanding of neutrinos over the last 20 years, **but still many outstanding questions**



getting 2σ-ish results ... good prospects for 3σ $(+?)$ in next ~5 years
but will need DUNE/HK for 5σ

more on this tomorrow!