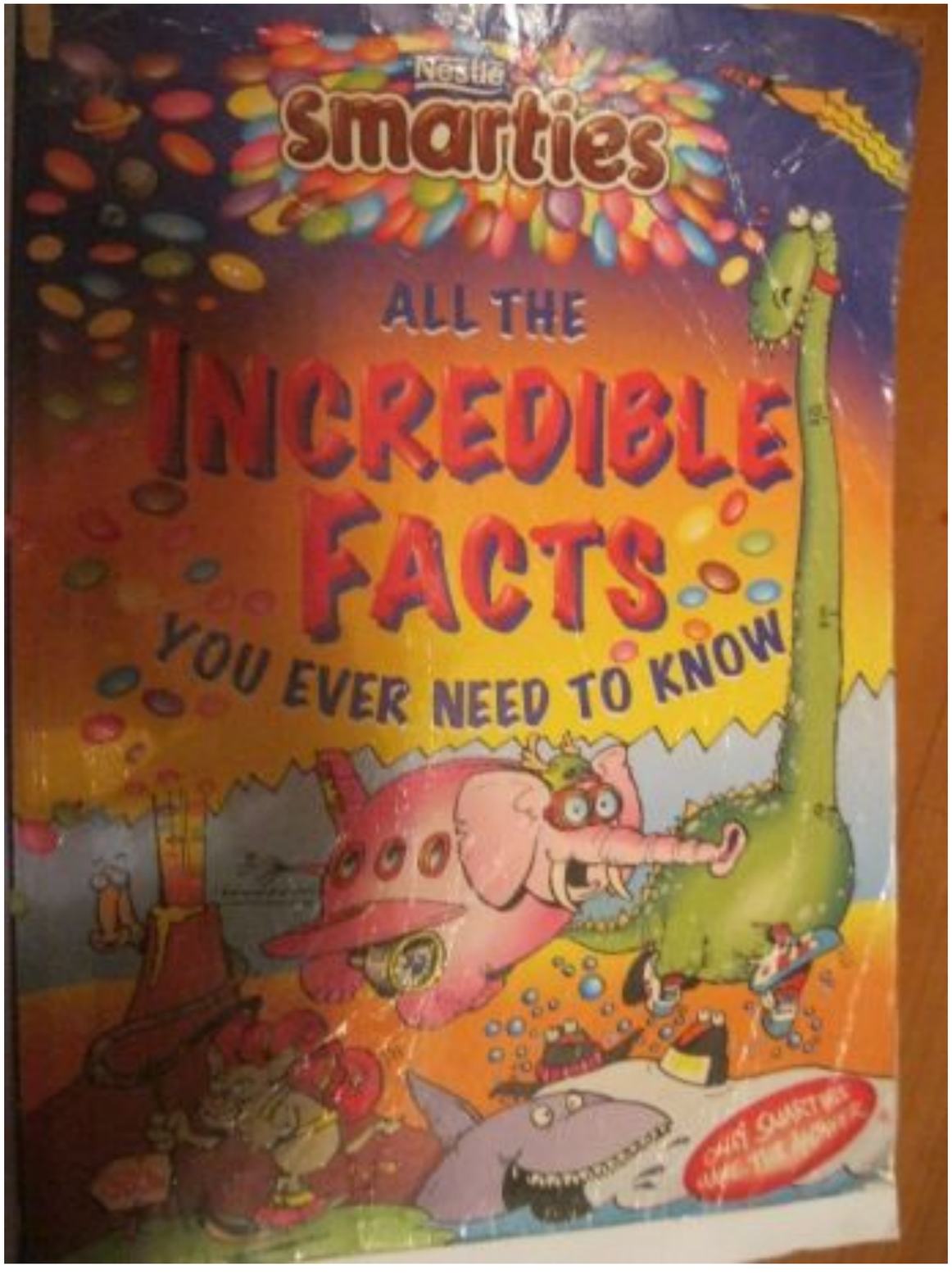
CHANGING FLAVOR: THE UNIVERSE'S WEIRDEST PARTICLE

Kirsty Duffy, Fermilab

BNL Colloquium

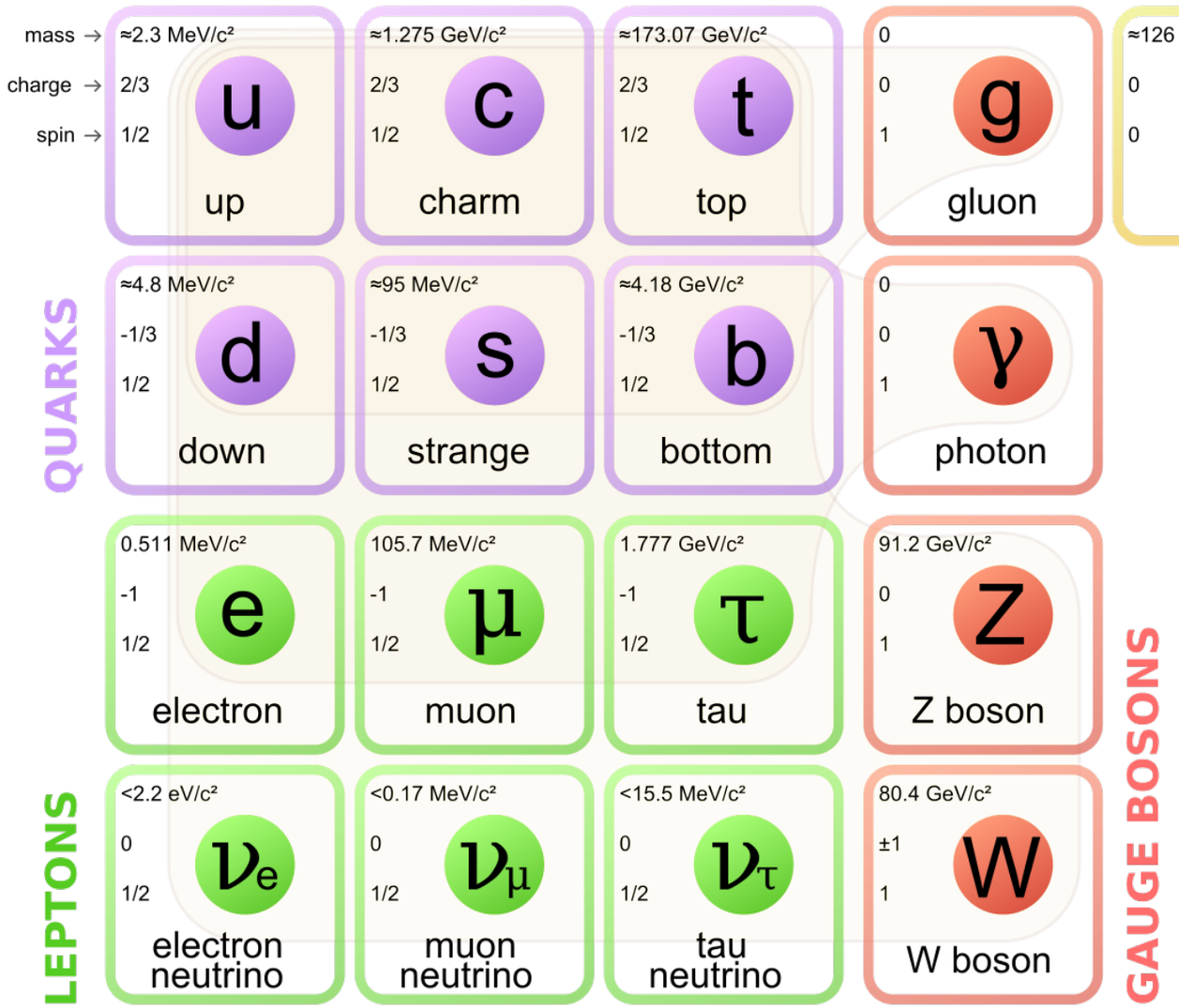
Tuesday 5th November, 2019

Fermilab


Nestlé
Smarties
ALL THE
INCREDIBLE
FACTS
YOU EVER NEED TO KNOW

Everything we see is made out of **protons**, **neutrons**, and **electrons**

THE STANDARD MODEL



- **12 matter particles** that make up all the "stuff" in our universe
  - 6 quarks
  - 6 leptons
- **4 fundamental forces:**
  - Gravity
  - Electromagnetism
  - Strong force
  - Weak force

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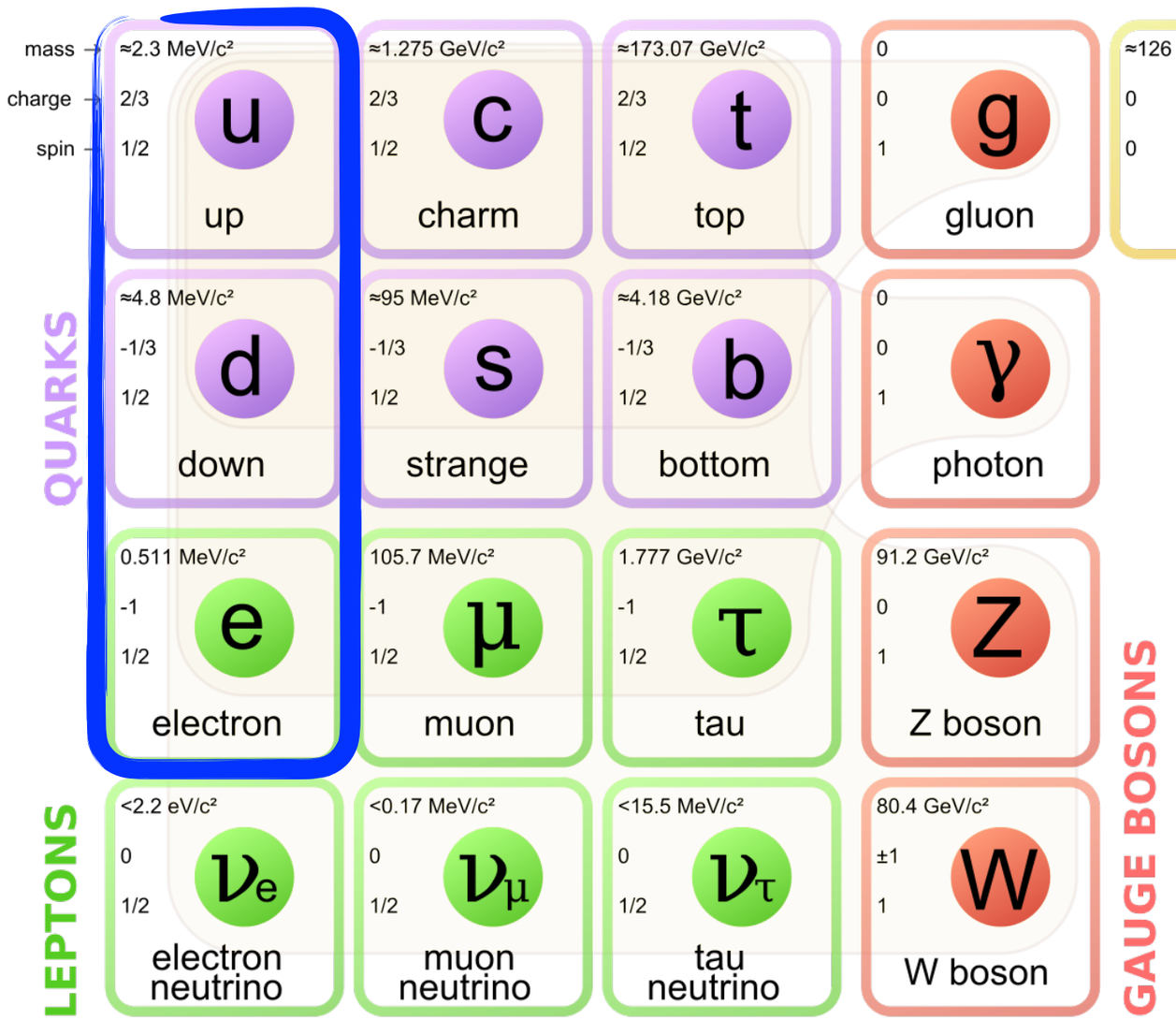

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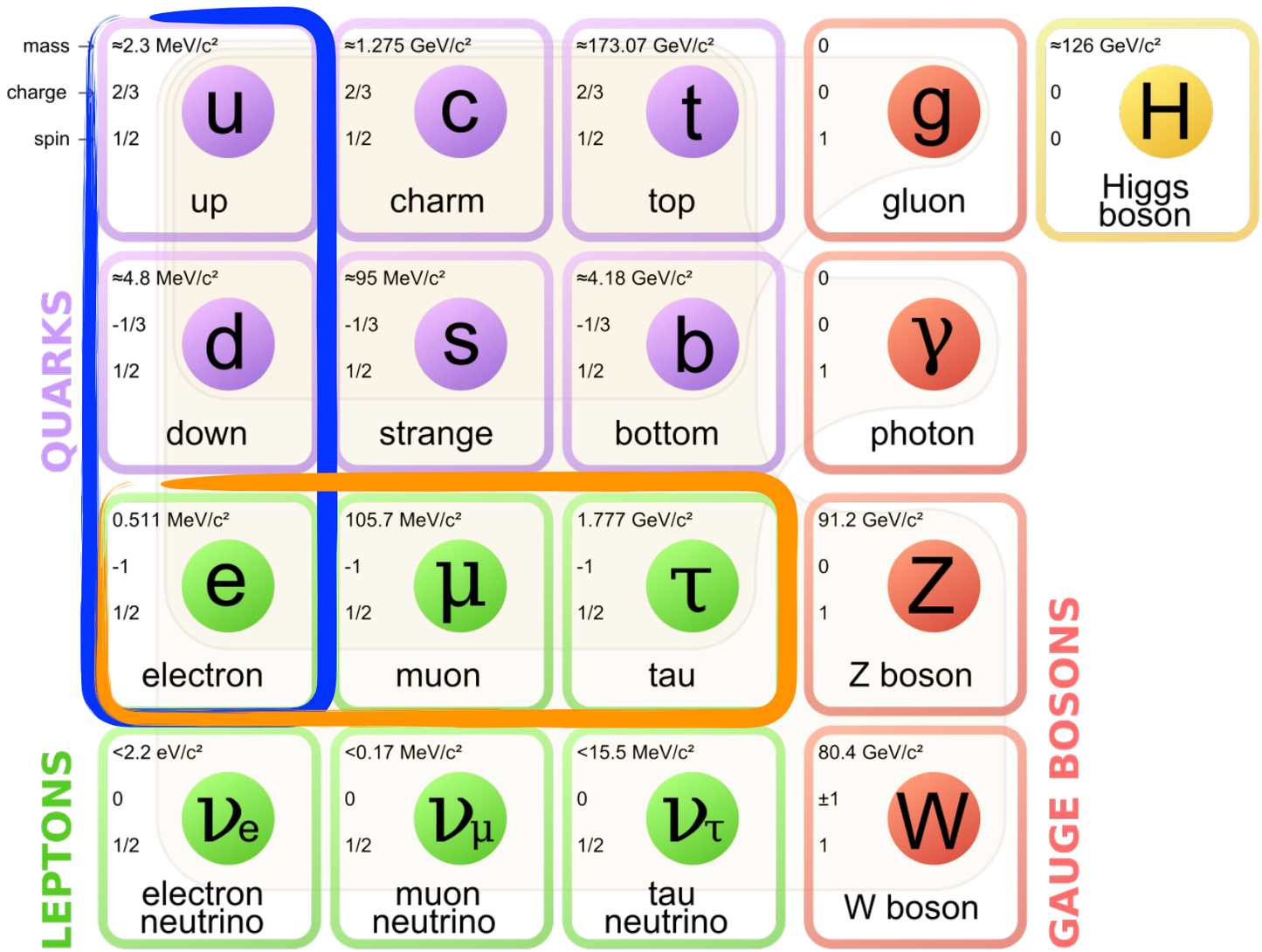

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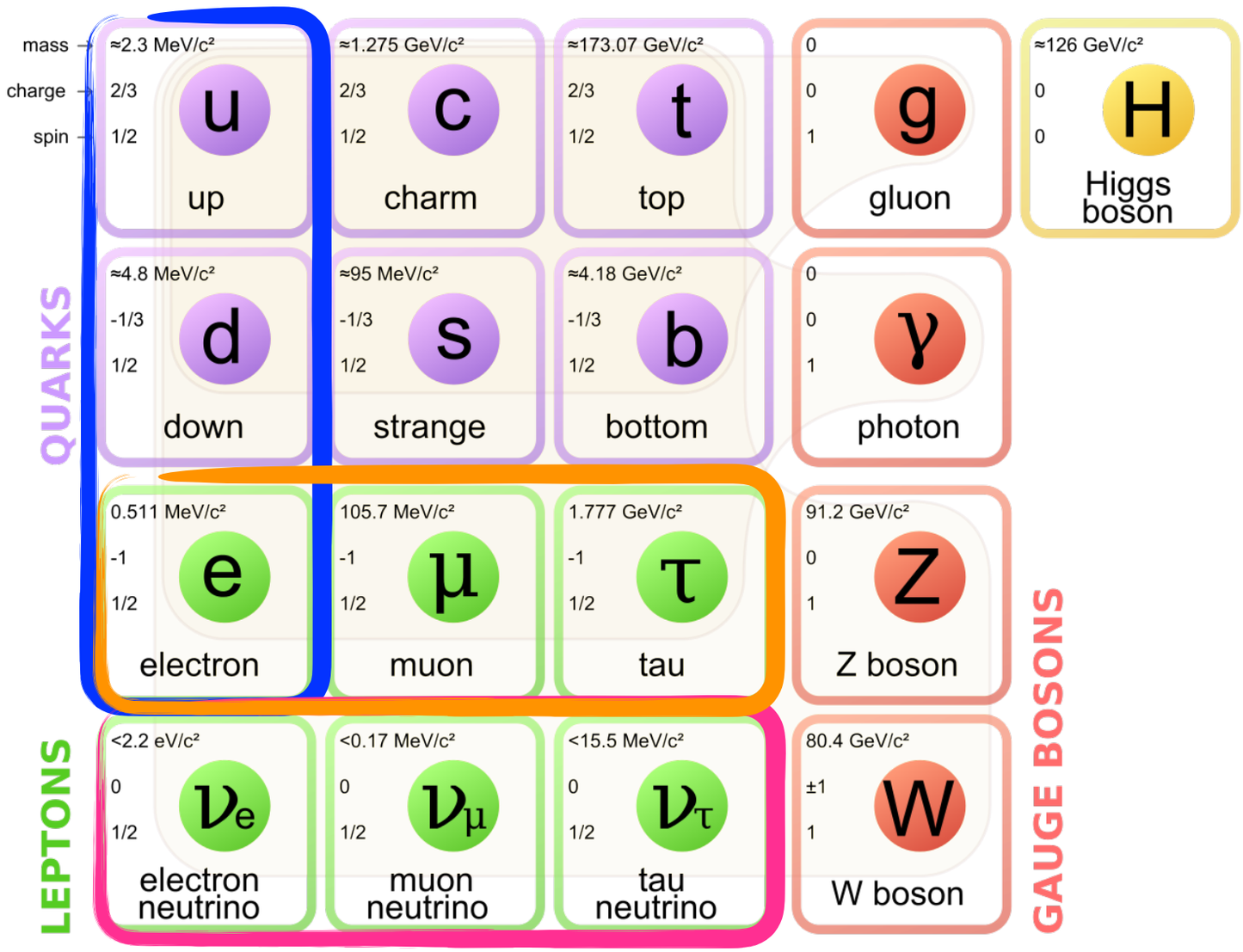

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NEUTRINOS ARE EVERYWHERE

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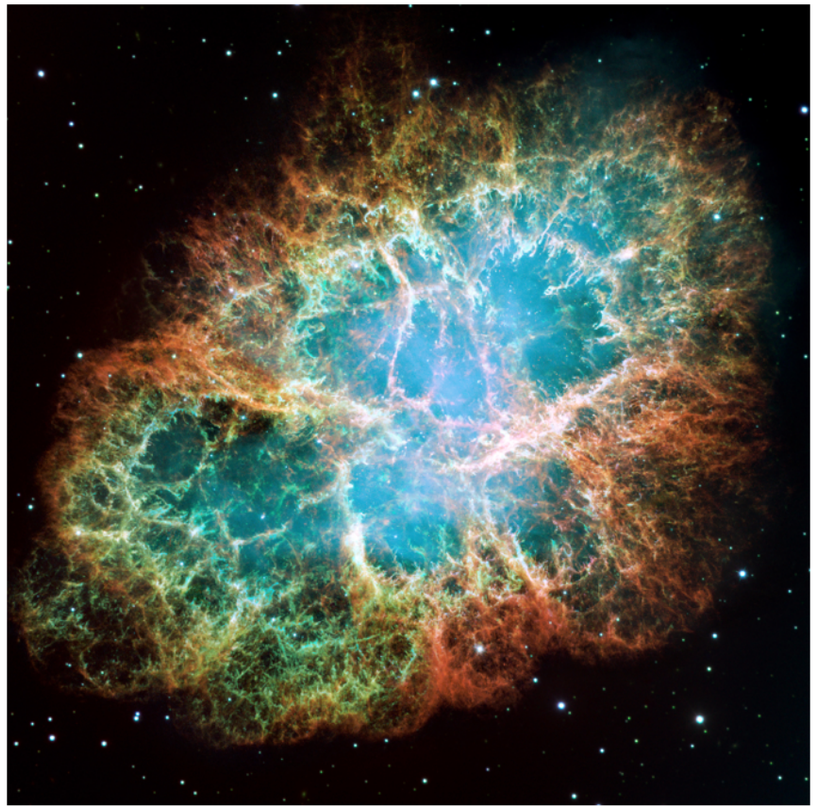

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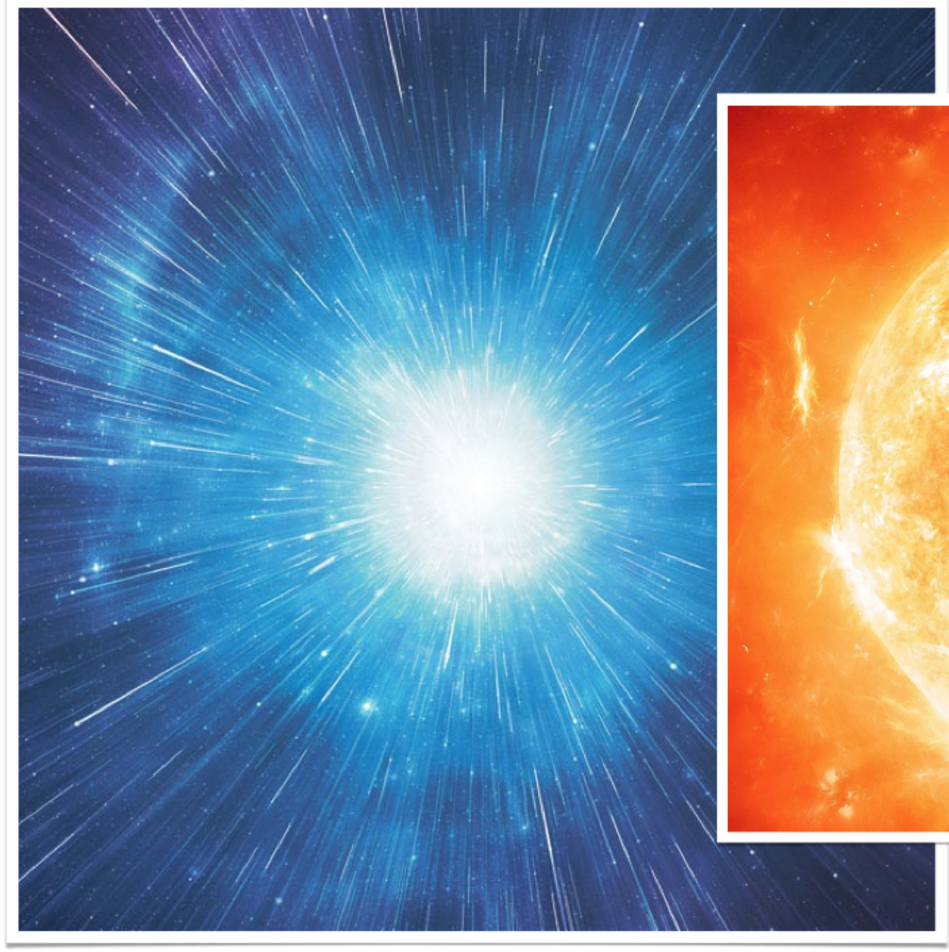

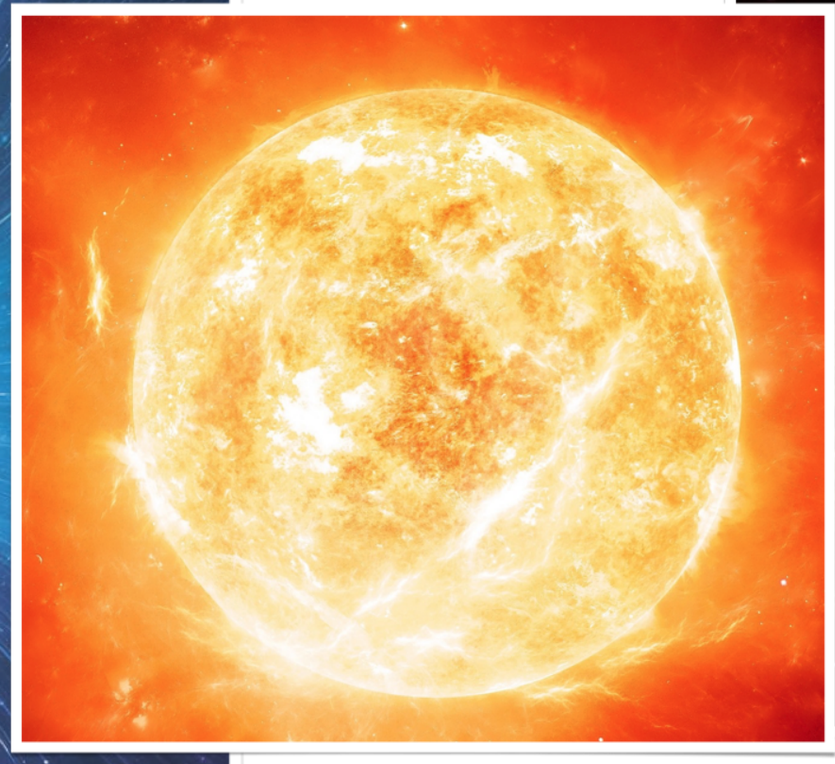

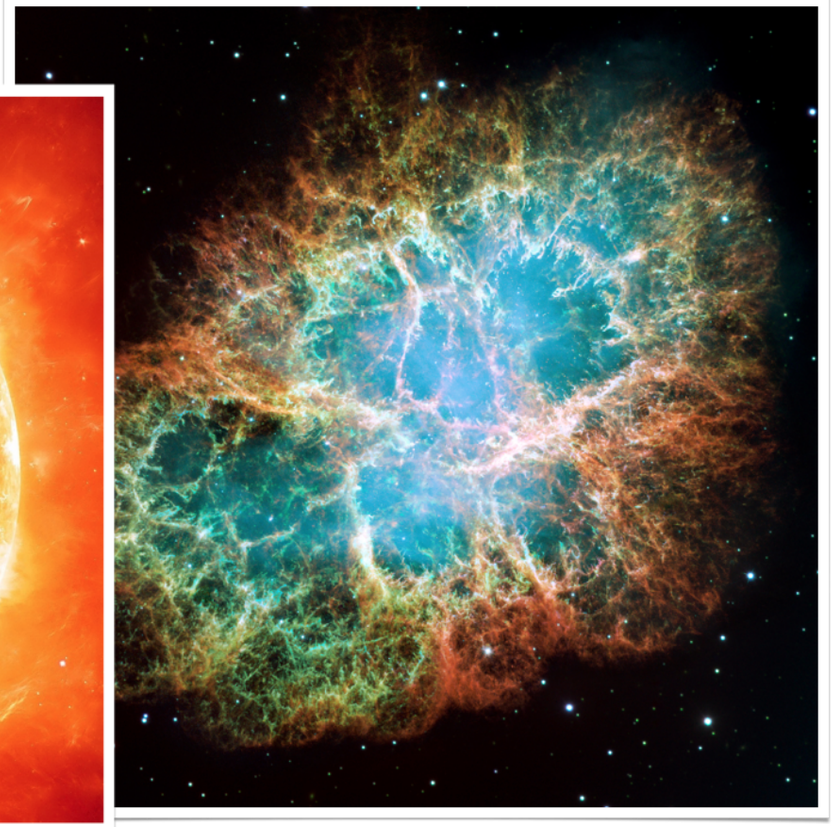

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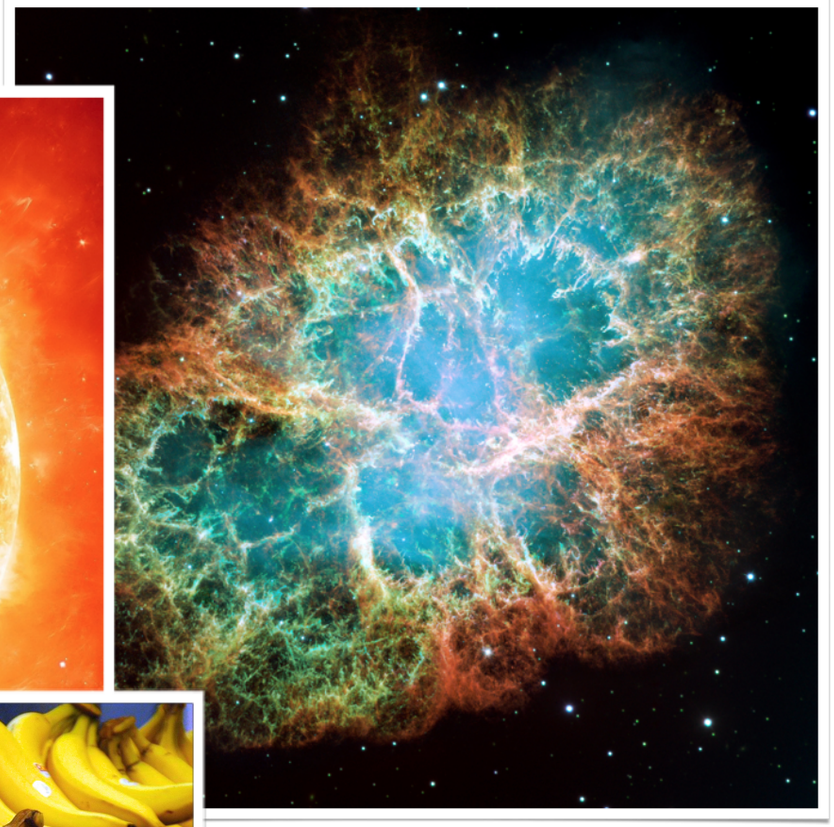

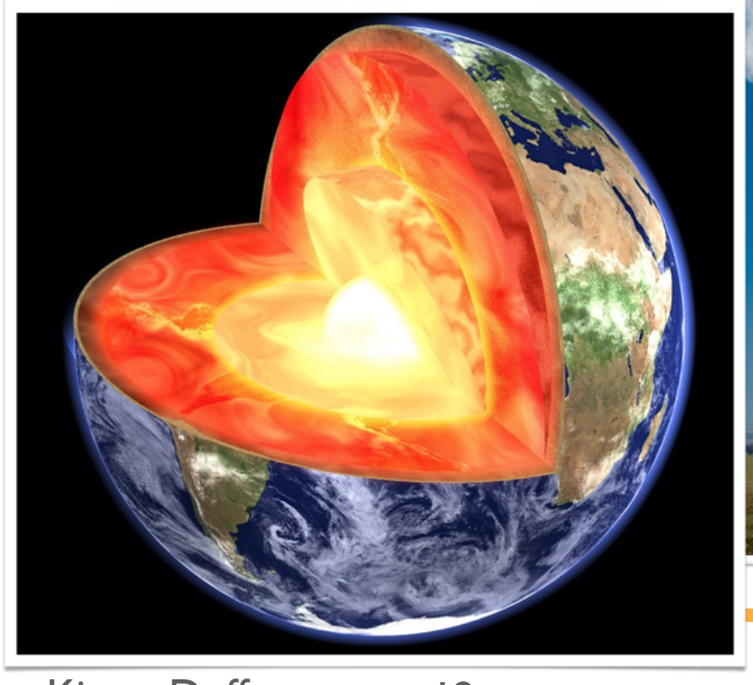

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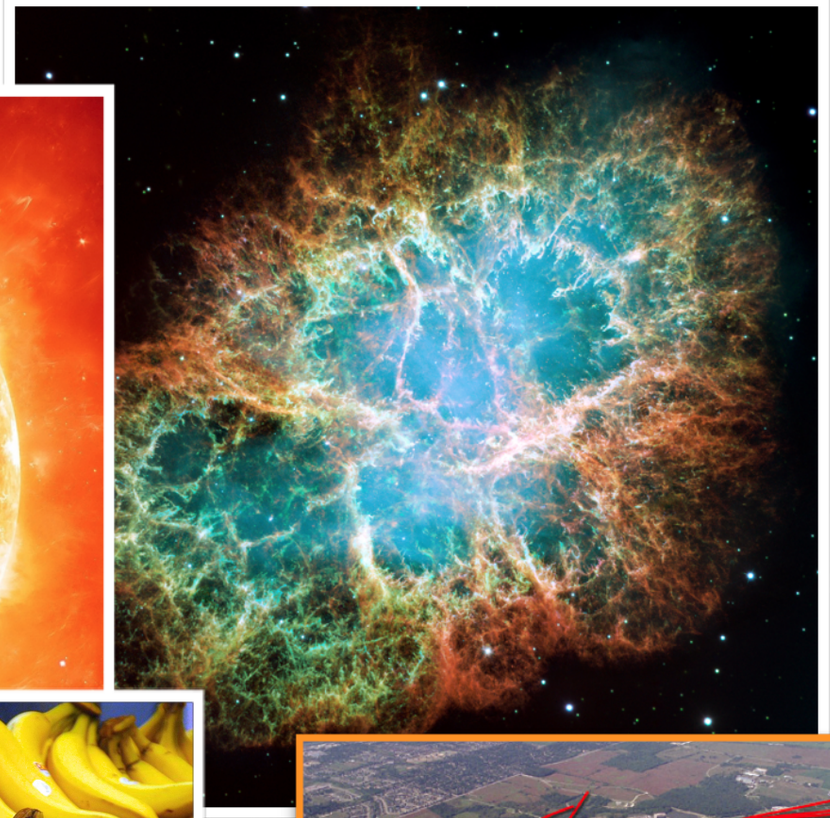
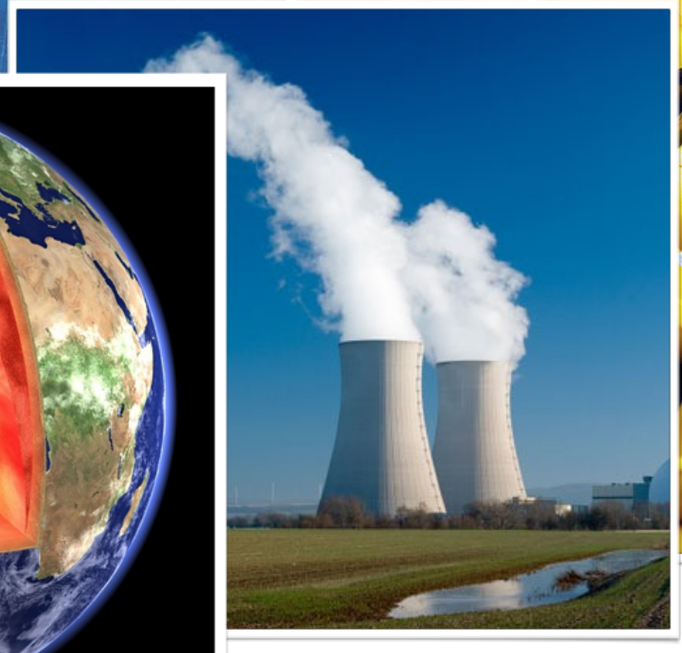
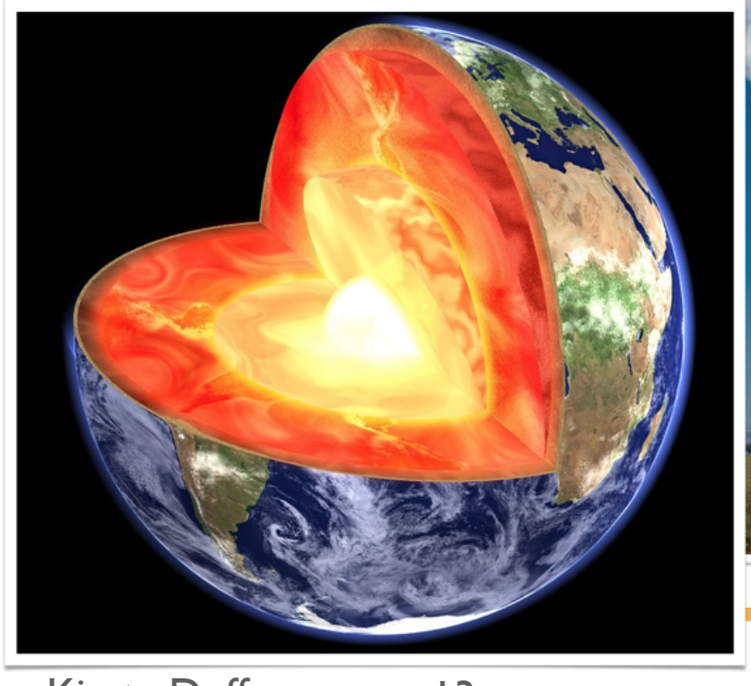
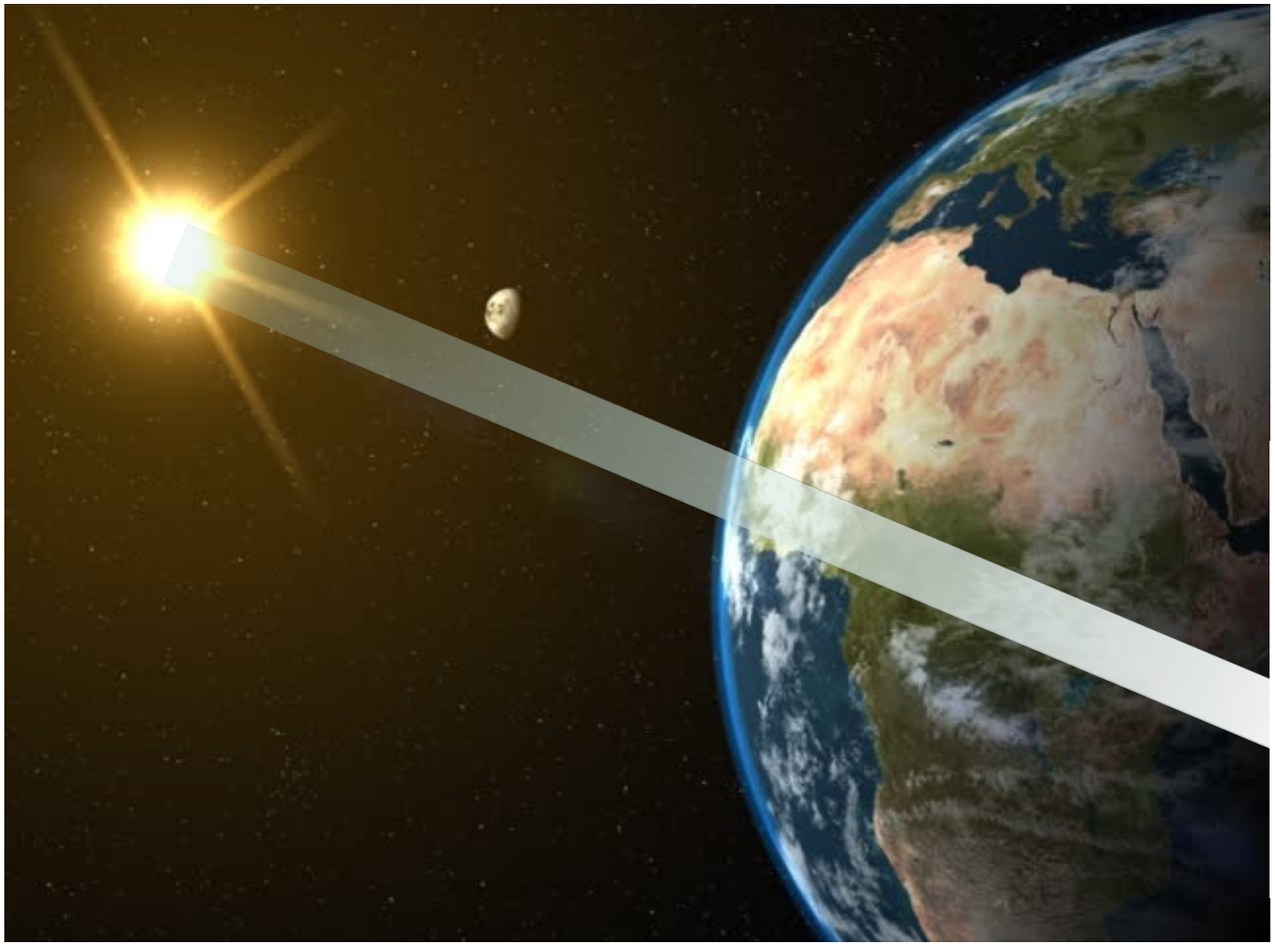






…BUT THEY ALMOST NEVER INTERACT



SOME HISTORY

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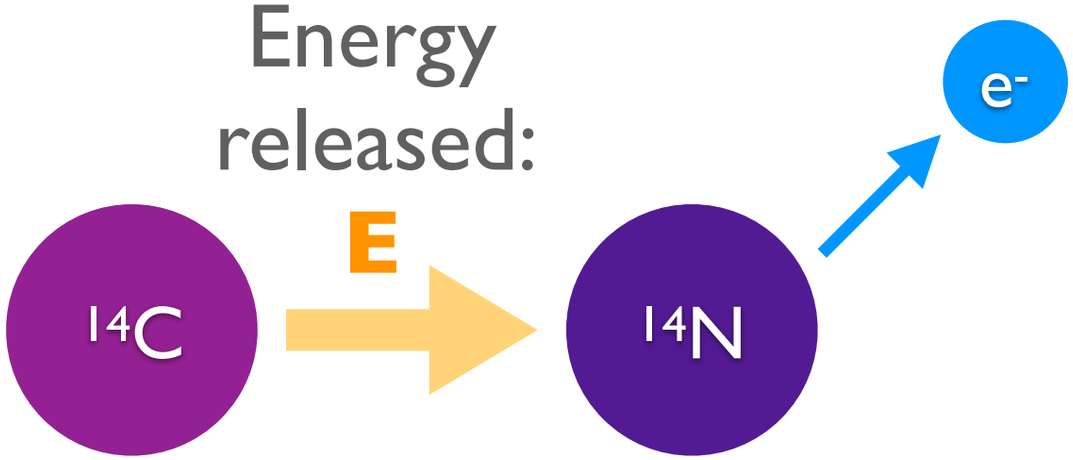
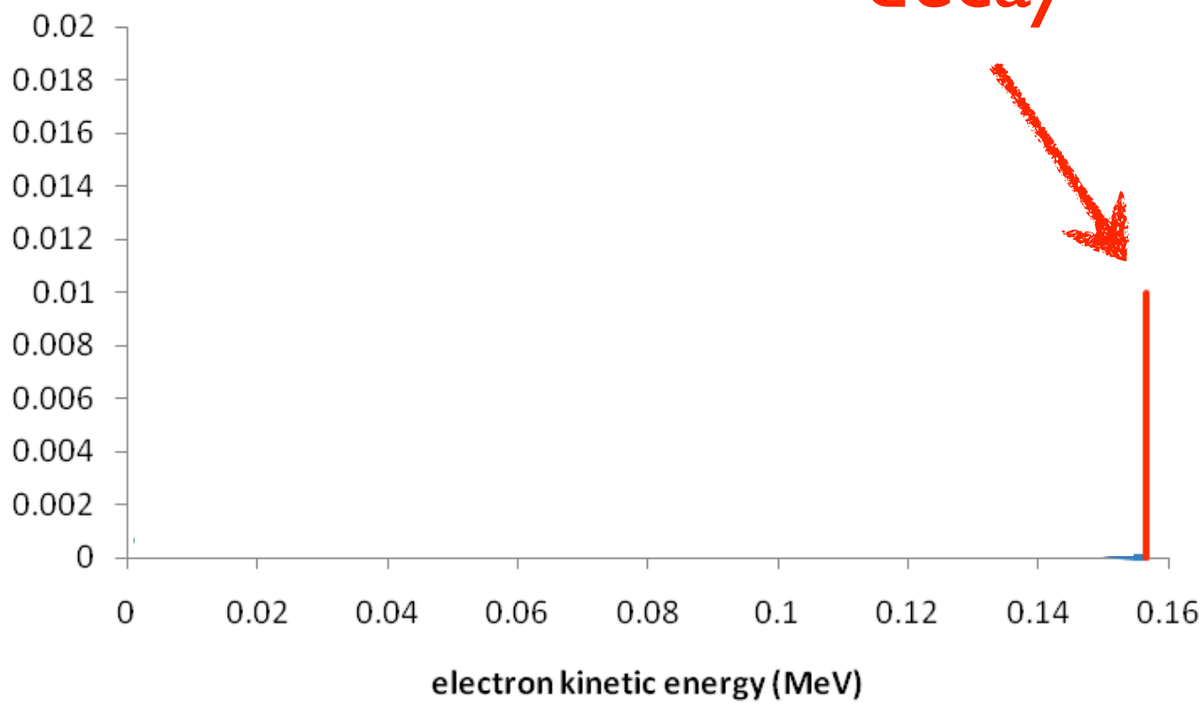
Energy released: **E**



Conservation of energy and momentum predict all e^- produced with same energy in a two-body decay

Expected from 2-body decay



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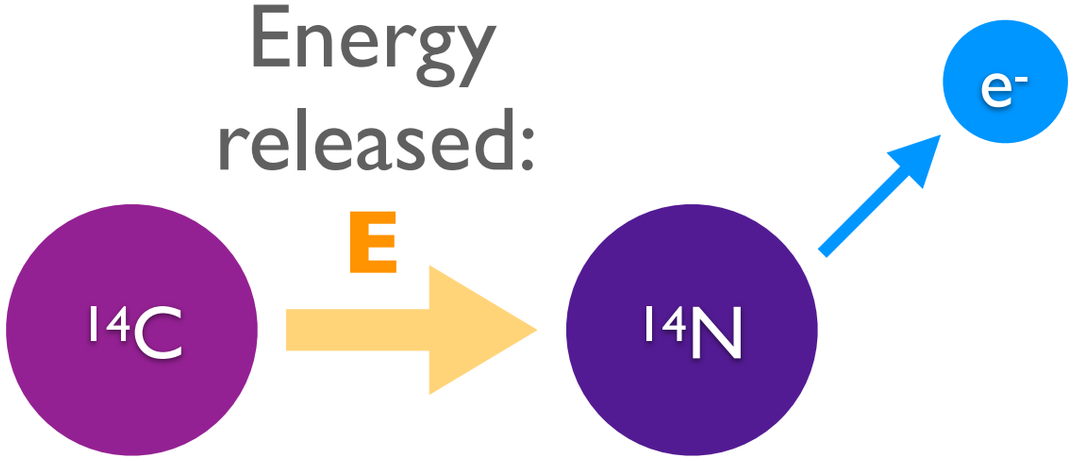
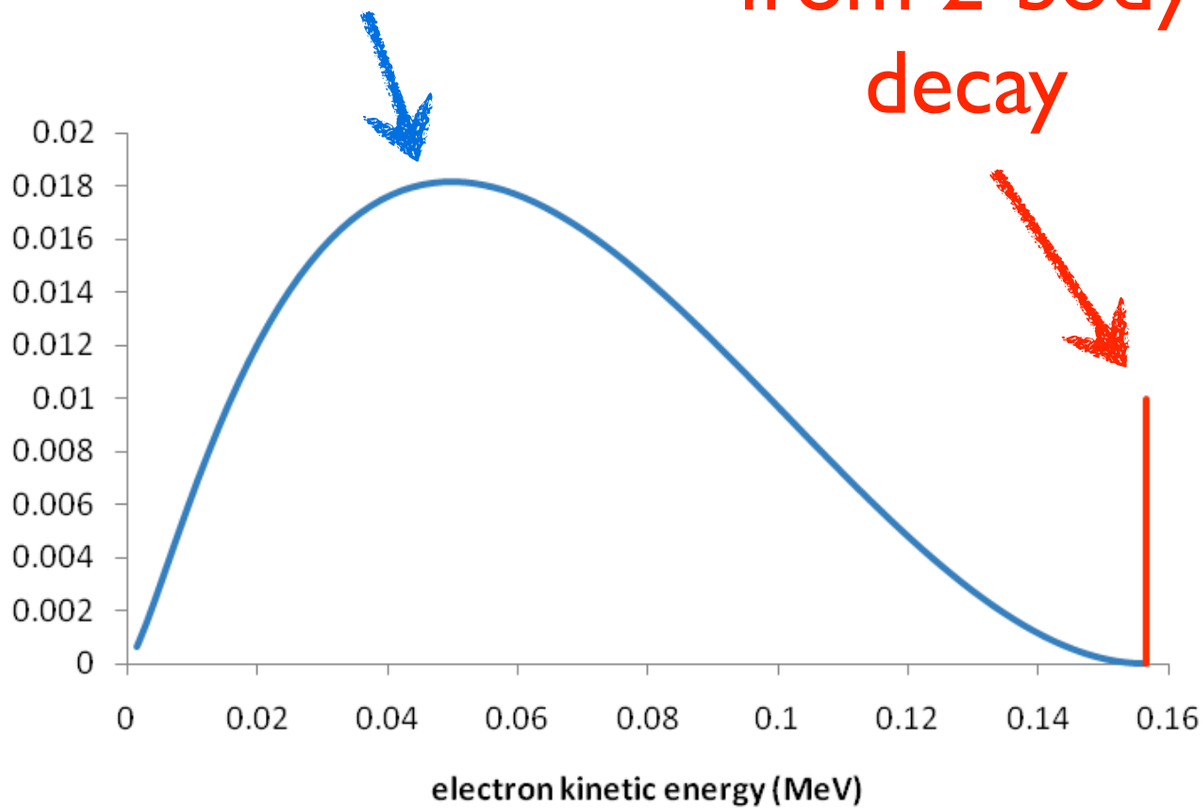




- **BIG PROBLEM**
- Energy not conserved?

PAULI'S "DESPERATE REMEDY"

Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the Gauverein meeting in Tübingen.

Copy

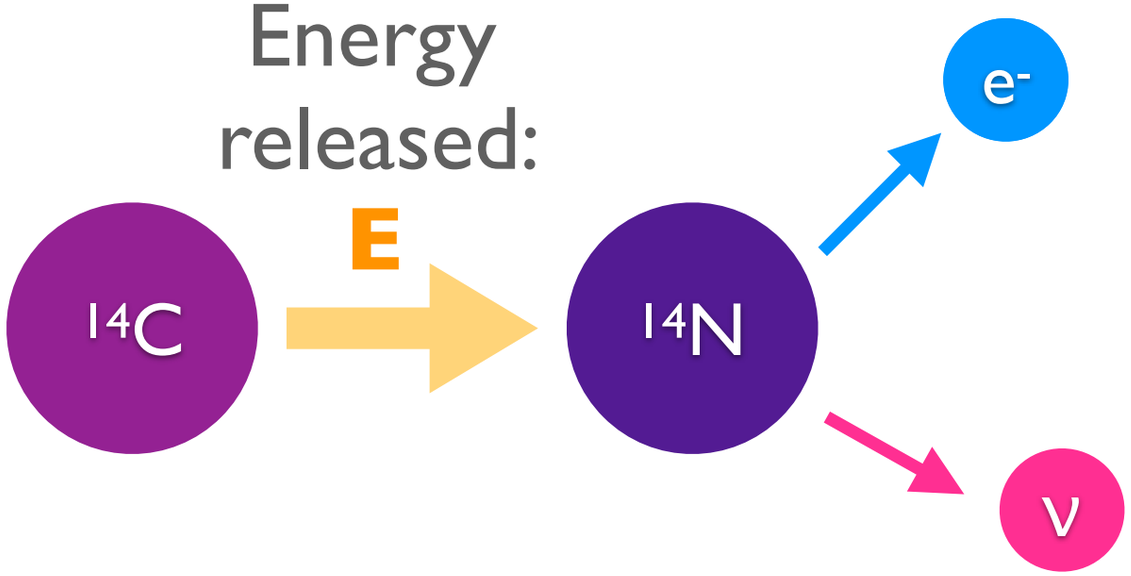
Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

PAULI'S "DESPERATE REMEDY"



- Pauli suggested that β-decay is actually a three-body process, including a new particle:
  - Light
  - Electrically neutral
  - So far unobserved

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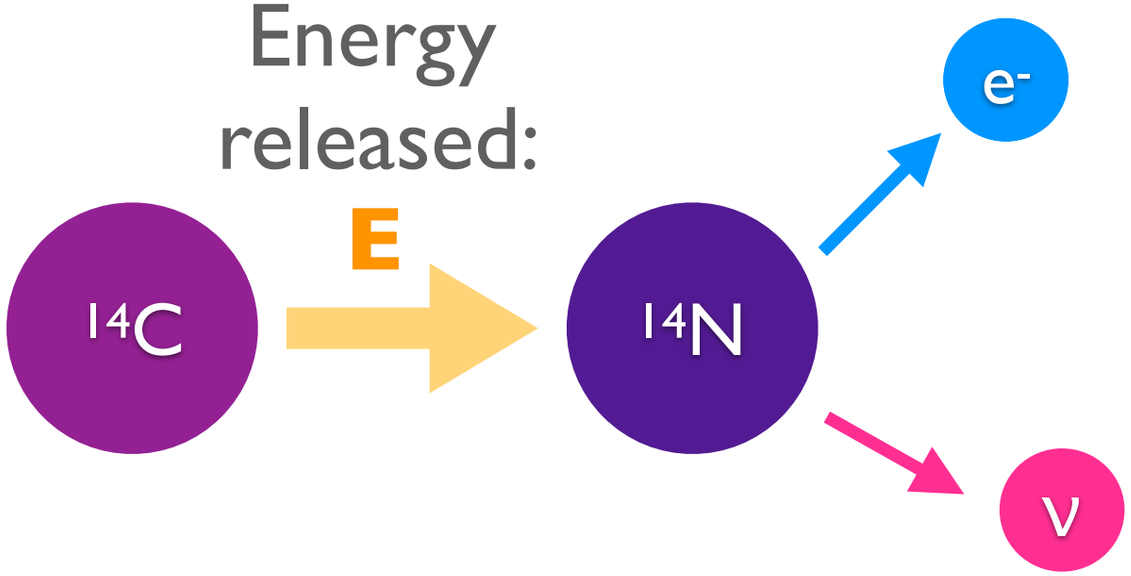

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  - Light
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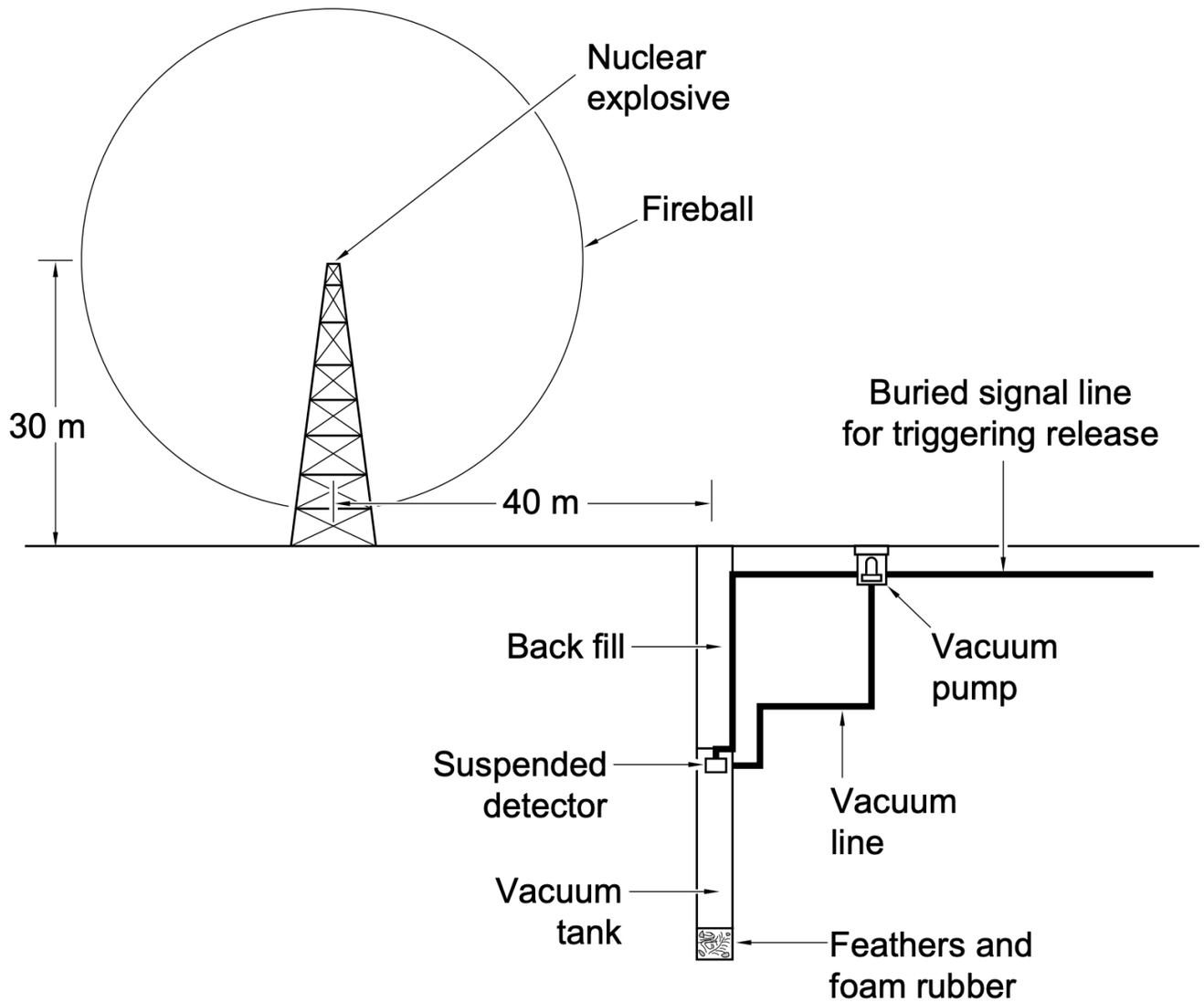
"I have done a terrible thing, I have postulated a particle that cannot be detected"

Not impossible — just requires intense neutrino source and very sensitive (and large) detectors!

PROJECT POLTERGEIST

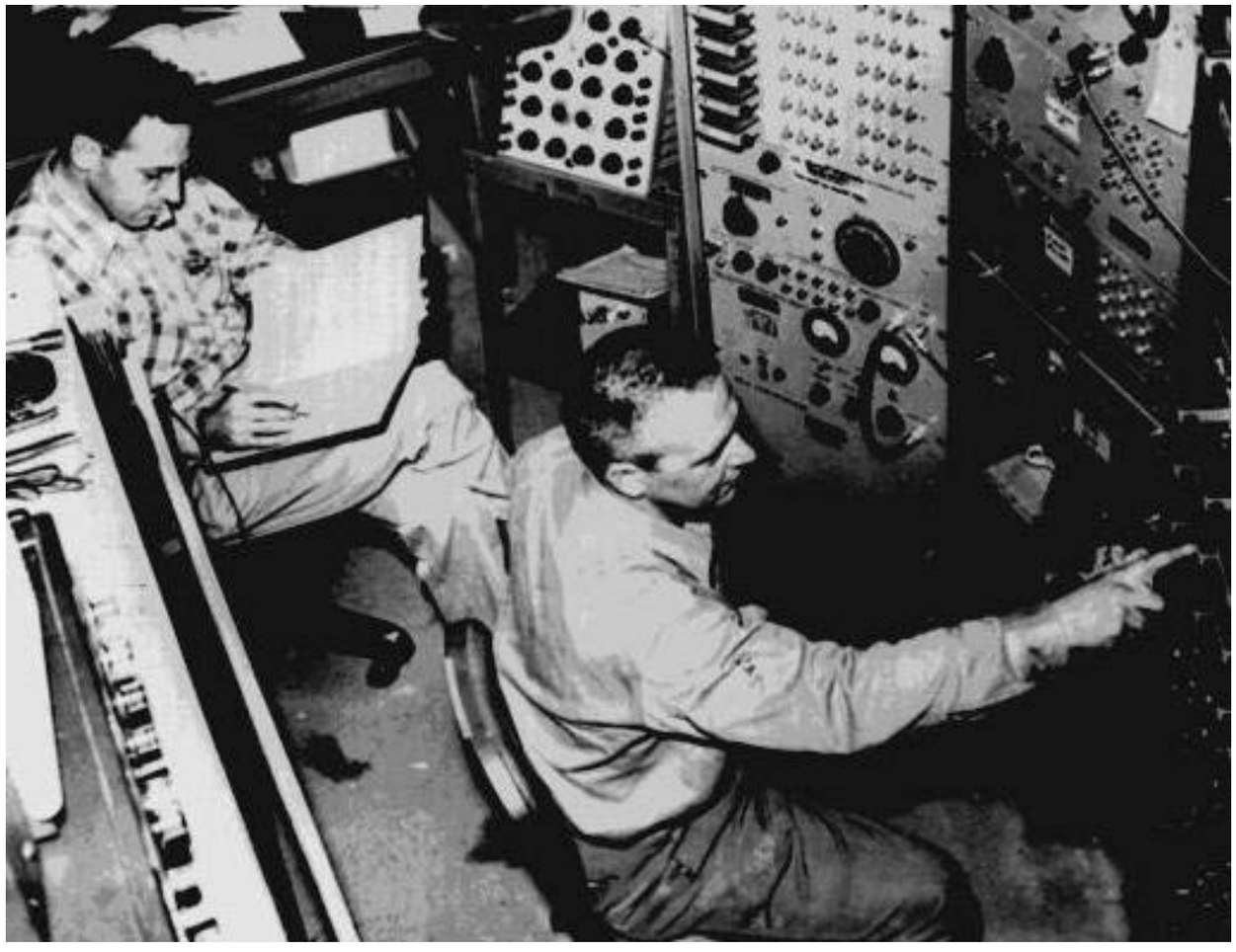
Simple plan:

1. Explode a nuclear bomb
2. At the same time, drop a neutrino detector down a shaft (to protect it from the ground shaking) onto a bed of feathers
3. Detect neutrinos
4. Wait until the radiation dies down to recover the detector
5. …repeat?



DETECTING THE NEUTRINO

Fred Reines and Clyde Cowan eventually **detected the neutrino in 1956** in an experiment at the Savannah River nuclear power plant



Telegram to Pauli, 14th June 1956:

"We are happy to inform you that we have definitely detected neutrinos from fission fragments."

AND MORE NEUTRINOS!

- Leon Lederman, Melvin Schwartz, and Jack Steinberger conducted an experiment at Brookhaven in 1962
- Took a beam of neutrinos and sent it into a detector
- → found that almost all neutrinos (107/113) produced muons, not electrons
- **A new neutrino that prefers muons?**

AND MORE NEUTRINOS!

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  and Jack Steinberge
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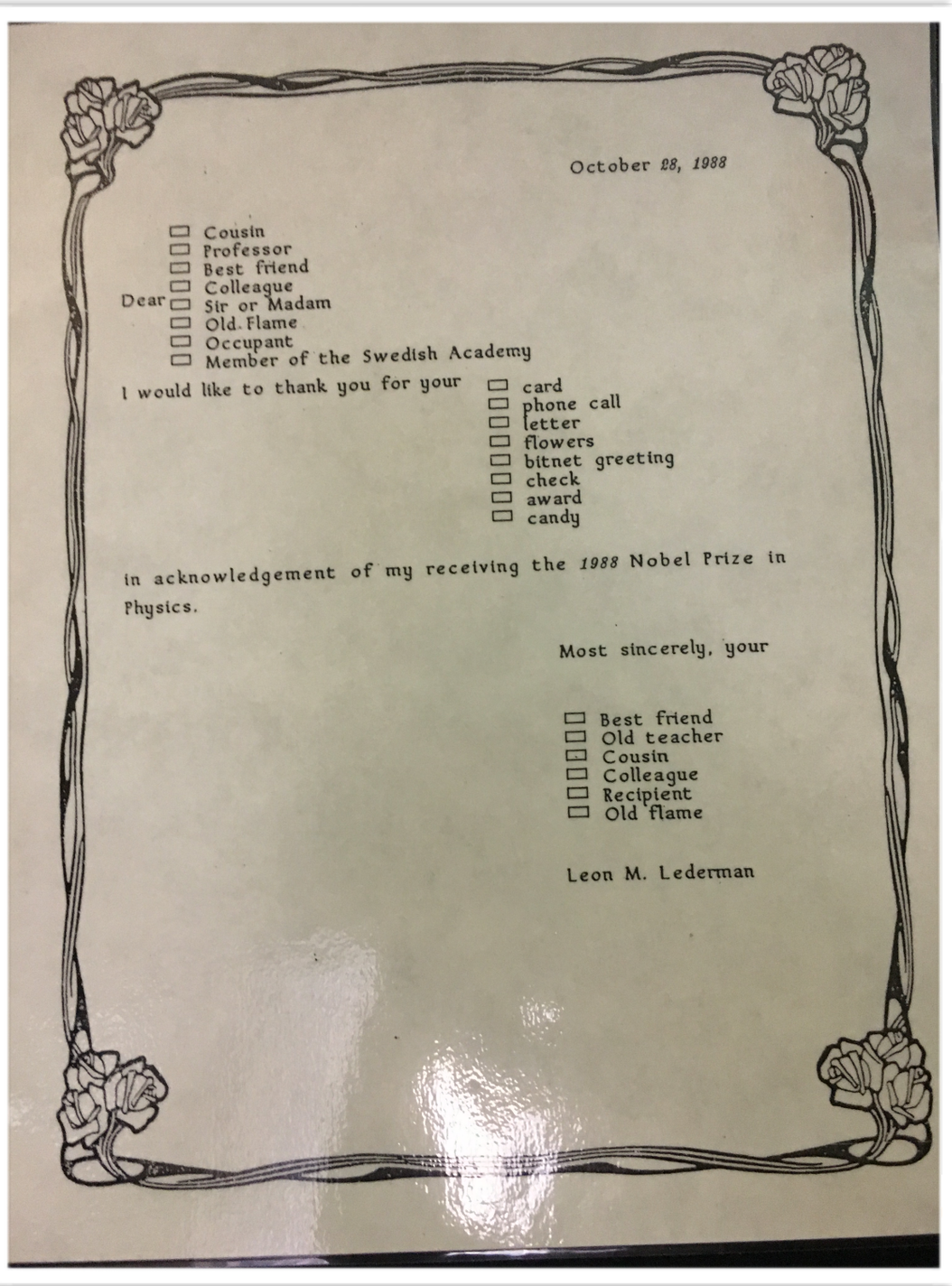


October 28, 1988

Dear
- ☐ Cousin
- ☐ Professor
- ☐ Best friend
- ☐ Colleague
- ☐ Sir or Madam
- ☐ Old Flame
- ☐ Occupant
- ☐ Member of the Swedish Academy

I would like to thank you for your
- ☐ card
- ☐ phone call
- ☐ letter
- ☐ flowers
- ☐ bitnet greeting
- ☐ check
- ☐ award
- ☐ candy

in acknowledgement of my receiving the *1988* Nobel Prize in Physics.

Most sincerely, your

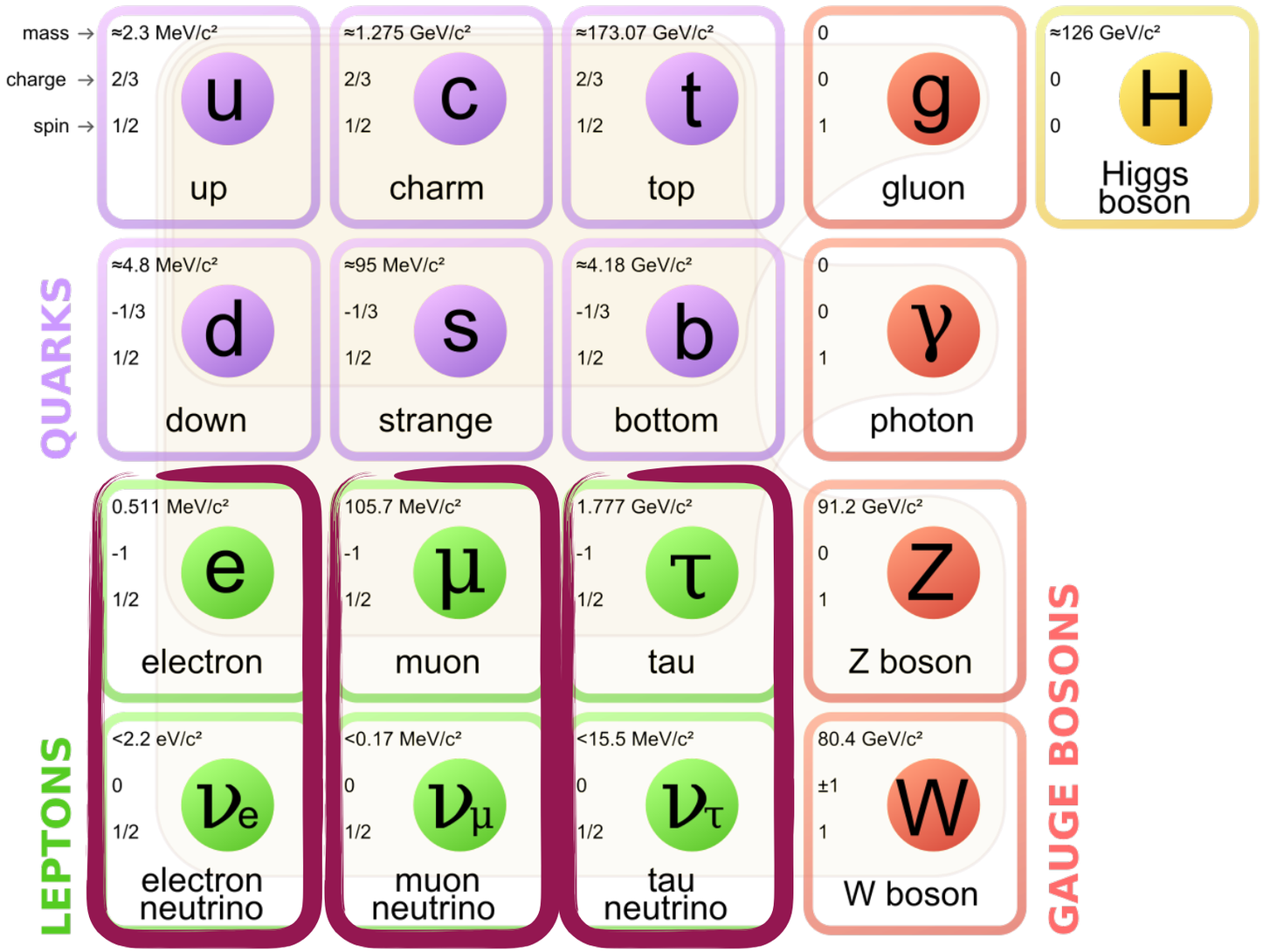
- ☐ Best friend
- ☐ Old teacher
- ☐ Cousin
- ☐ Colleague
- ☐ Recipient
- ☐ Old flame

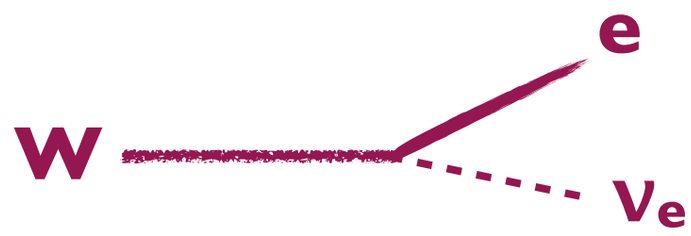
Leon M. Lederman

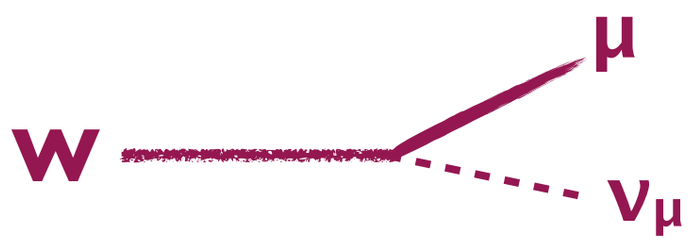
AND MORE NEUTRINOS!

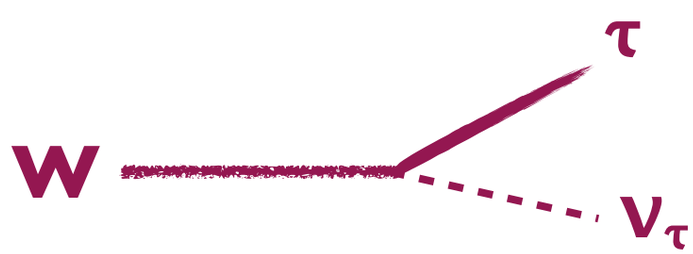
- In 1974 the existence of a new particle was confirmed
- The tau lepton: similar to electron or muon but heavier
- Is there also a tau neutrino?
- Yes! Discovered in 2000 by DONuT collaboration at Fermilab

THREE FLAVOURS OF NEUTRINO









THE SOLAR NEUTRINO PROBLEM

- Ray Davis (a Brookhaven chemist) devised an experiment to measure neutrinos from the sun in the late 1960s

- 615 tonnes of cleaning fluid

- Look for Ar from
  $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

- Expect **~36 Ar atoms** per month

THE SOLAR NEUTRINO PROBLEM

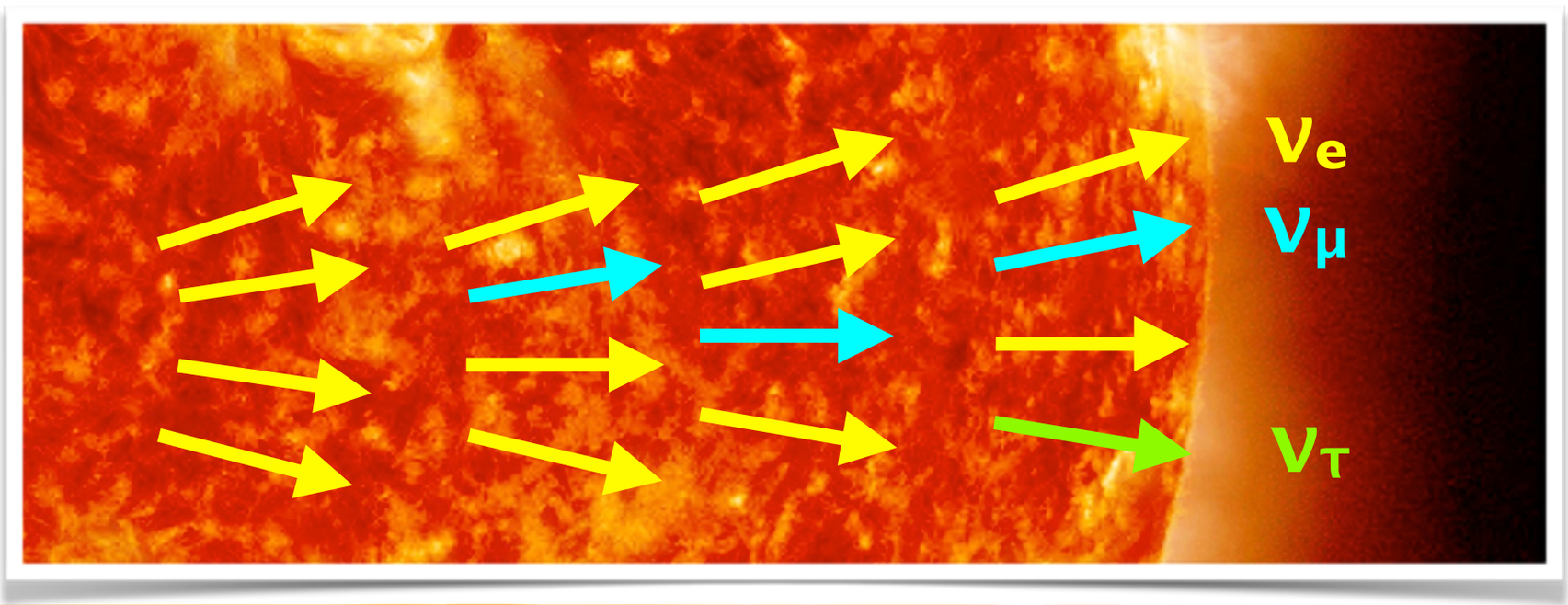
- Observed **2-3 times fewer neutrinos** than prediction
- Experimental errors?
  Results backed up by a number of different experiments (Kamiokande, GALLEX, SAGE, SNO)
- Bad solar models?
  Ruled out by SNO experiment

THE SOLAR NEUTRINO PROBLEM

An alternative explanation, unambiguously confirmed by SNO experiment: **neutrinos changing flavour**

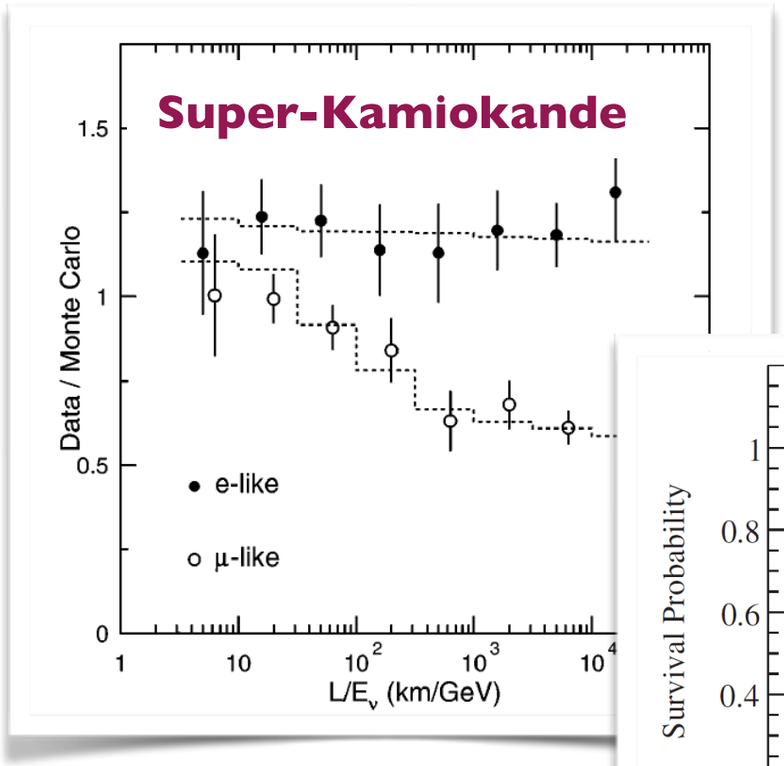
Davis only looked for ν_e, known to be produced in the sun

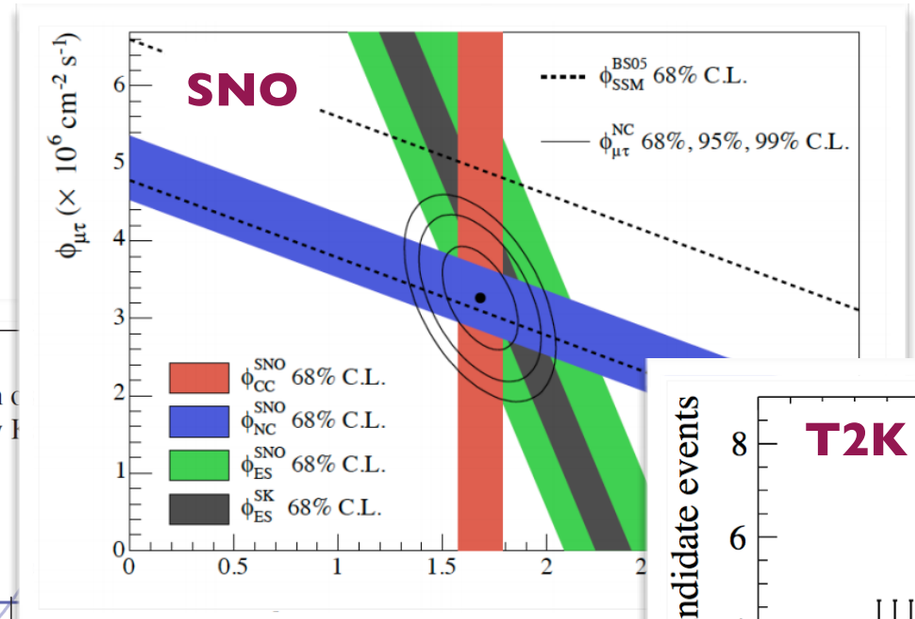
By the time they leave the sun, ½-⅔ have changed to ν_μ or ν_τ

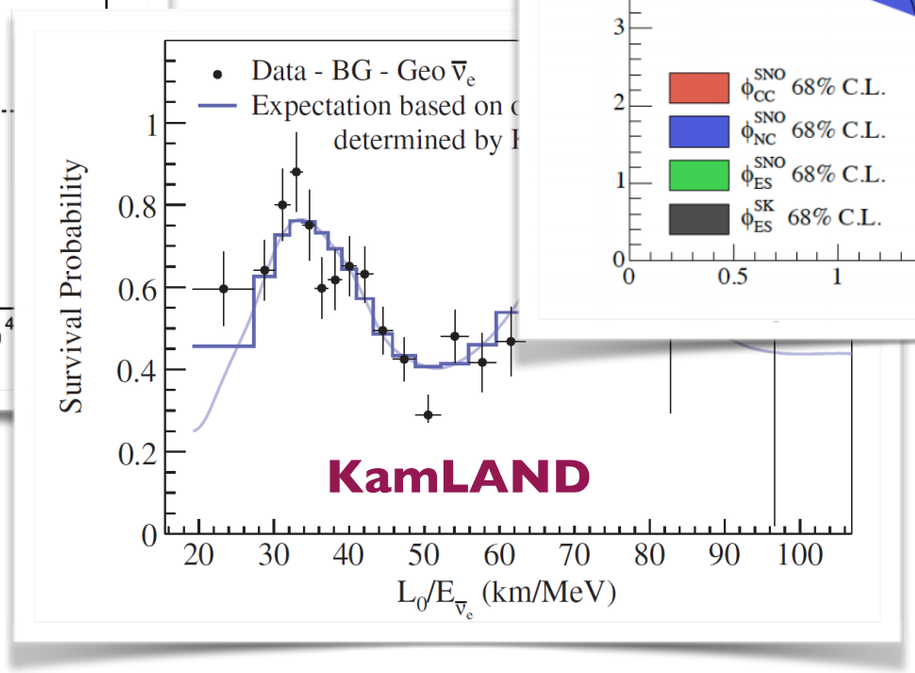


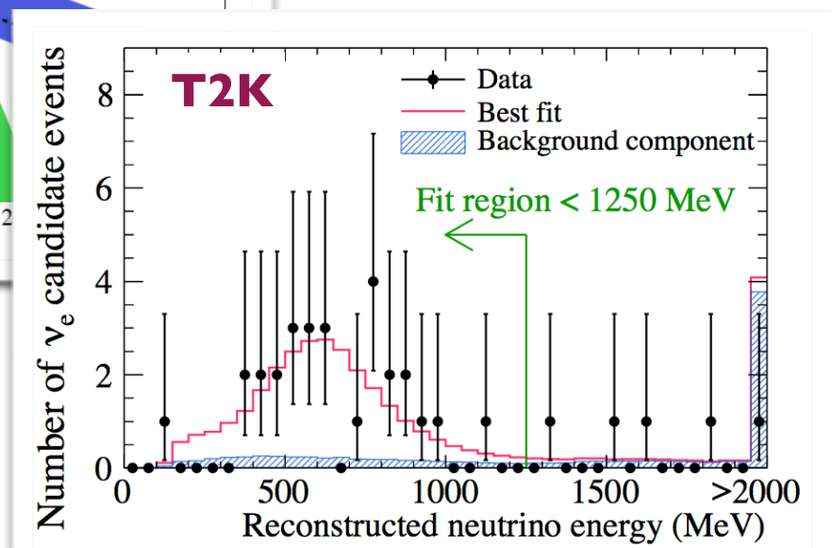
NEUTRINO FLAVOUR CHANGE

The evidence is now **overwhelming** that neutrino flavour change does happen









SO WHAT'S GOING ON?

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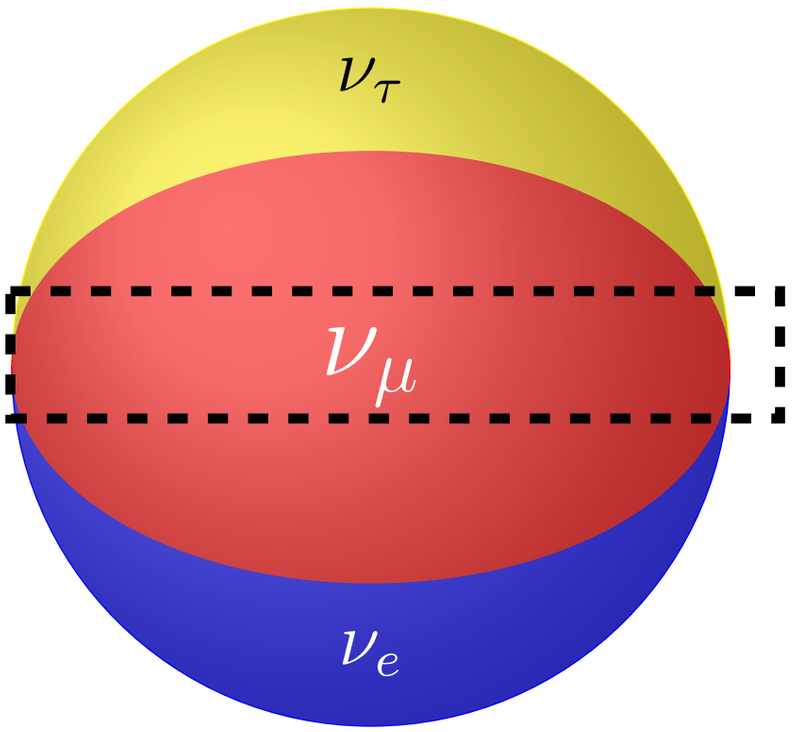
Artwork by Sandbox Studio, Chicago

- Flavour change can happen for **massive particles**
- The **states neutrinos exist in** (quantum mechanics jargon for "the neutrinos") are **different** depending on whether the neutrino is **interacting** or **freely travelling**

BEACH BALLS



L. Pickering

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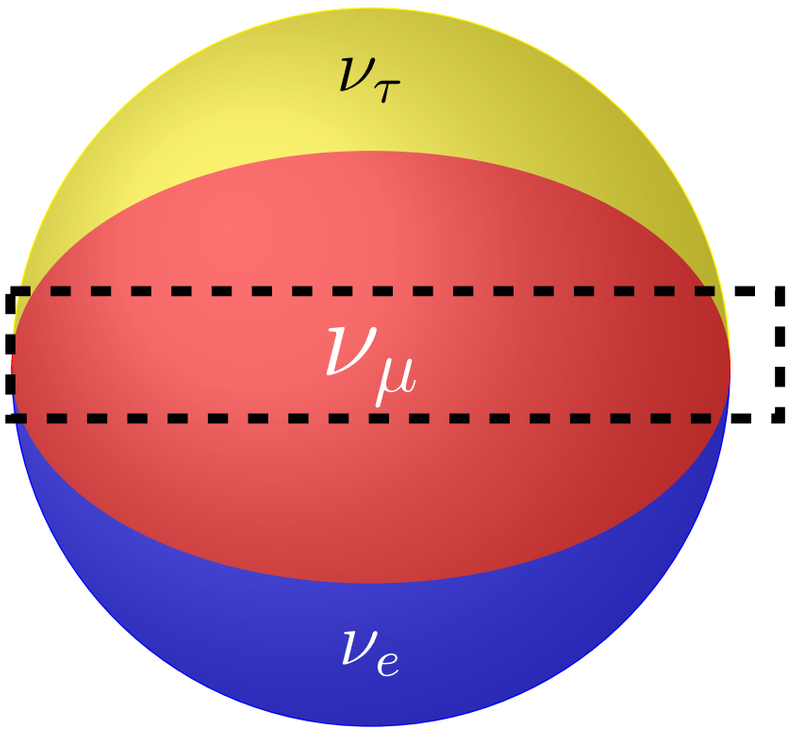

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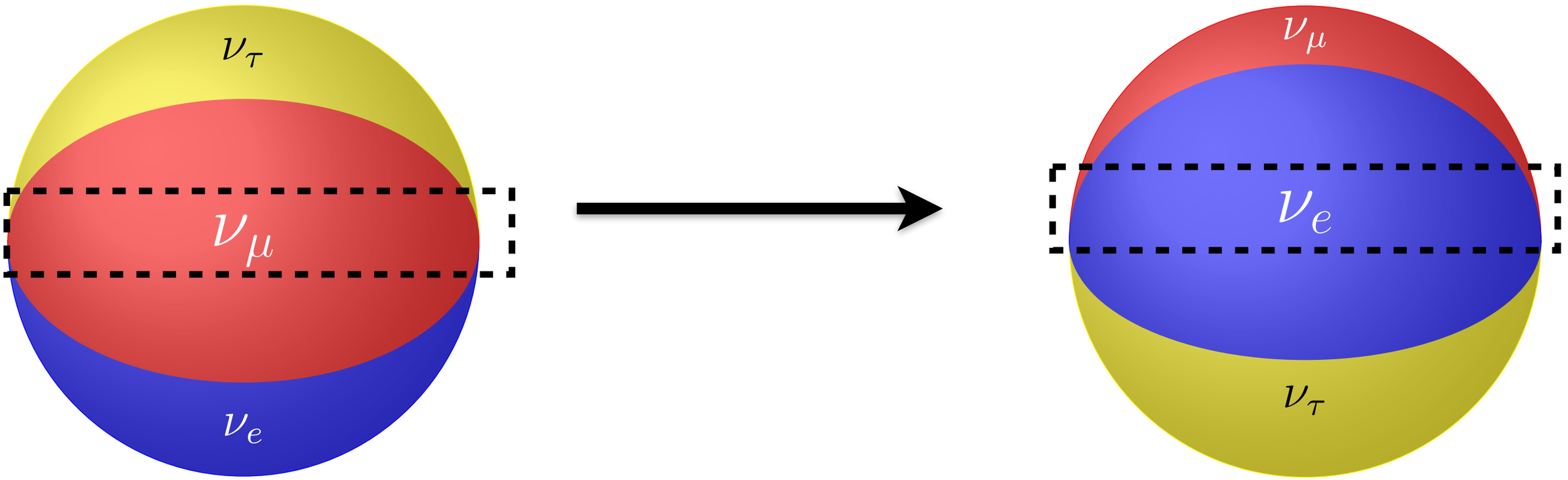

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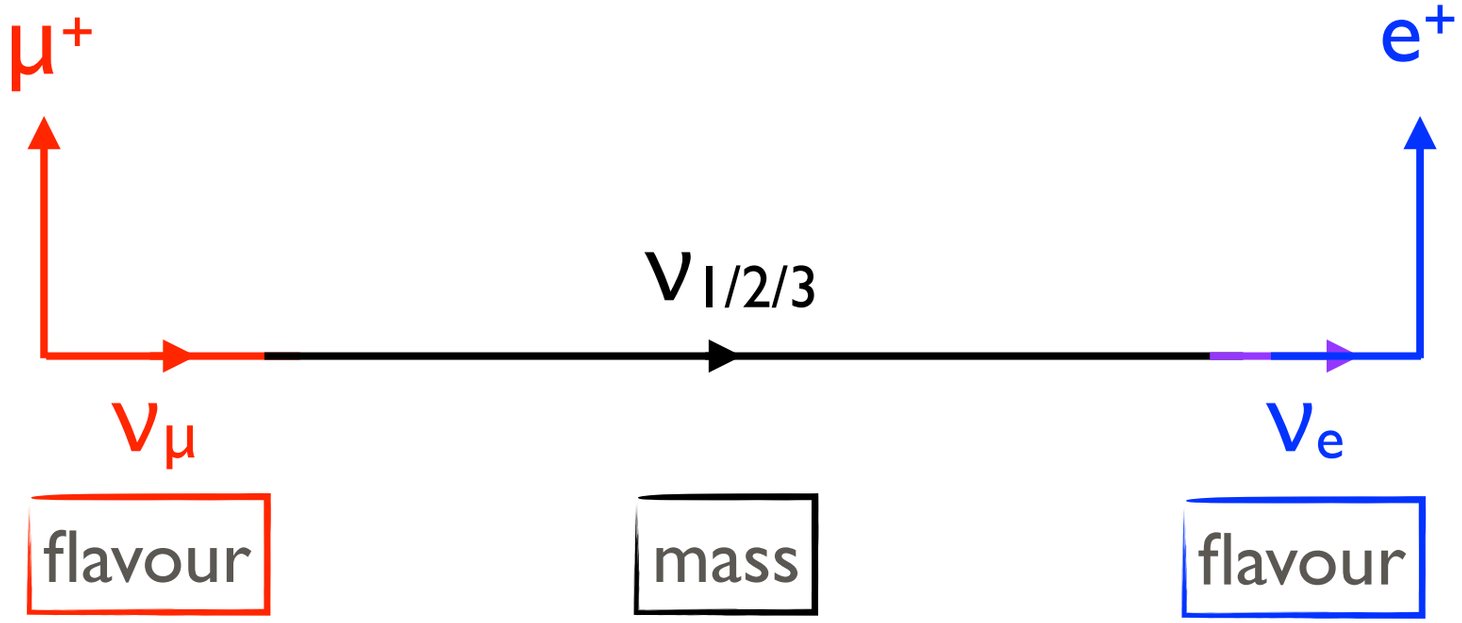
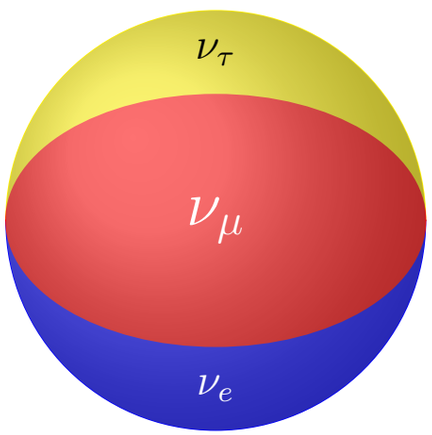
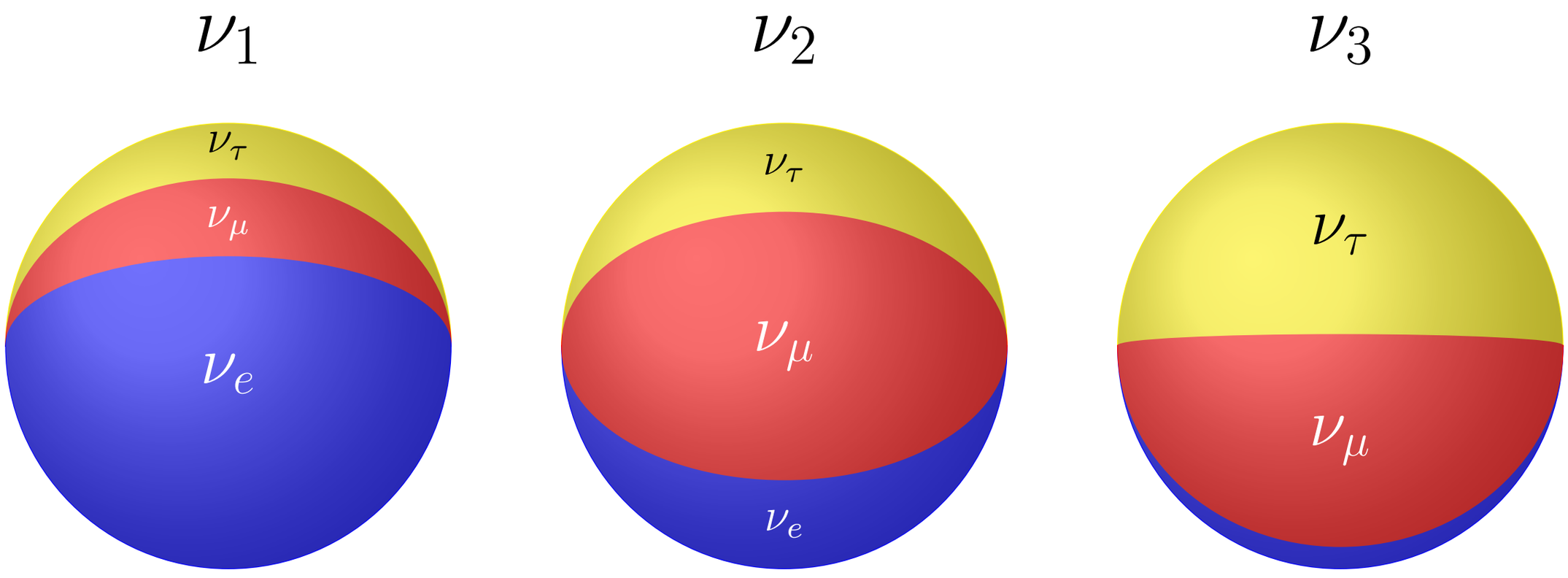
NEUTRINO OSCILLATION





BUT THERE ISN'T ONLY ONE BEACH BALL



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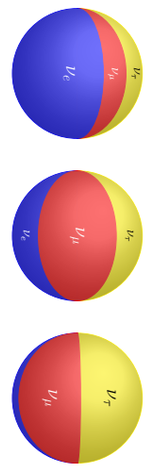
NEUTRINO OSCILLATION

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



flavour

mass

PMNS matrix

named after physicists Pontecorvo, Maki, Nakagawa, and Sakata

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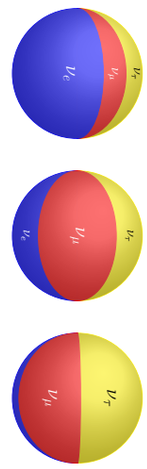

flavour

mass

PMNS matrix

named after physicists Pontecorvo, Maki, Nakagawa, and Sakata

Four free parameters:

Three mixing angles θ_{12}, θ_{23}, θ_{13}

One phase δ_{CP}

NEUTRINO OSCILLATION

- Imagine we have a **muon neutrino** (ν_μ) with **energy E**
- Let it travel some **distance L**, then calculate the **probability to still measure a muon neutrino**:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32}L}{4E} + (\text{solar, matter effect terms})$$

NEUTRINO OSCILLATION

- Imagine we have a **muon neutrino** (ν_μ) with **energy E**
- Let it travel some **distance L**, then calculate the **probability to still measure a muon neutrino**:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}] \sin^2 \frac{\Delta m^2_{32} L}{4E} + (\text{solar, matter effect terms})$$

Depends on **mixing angles** from the PMNS matrix

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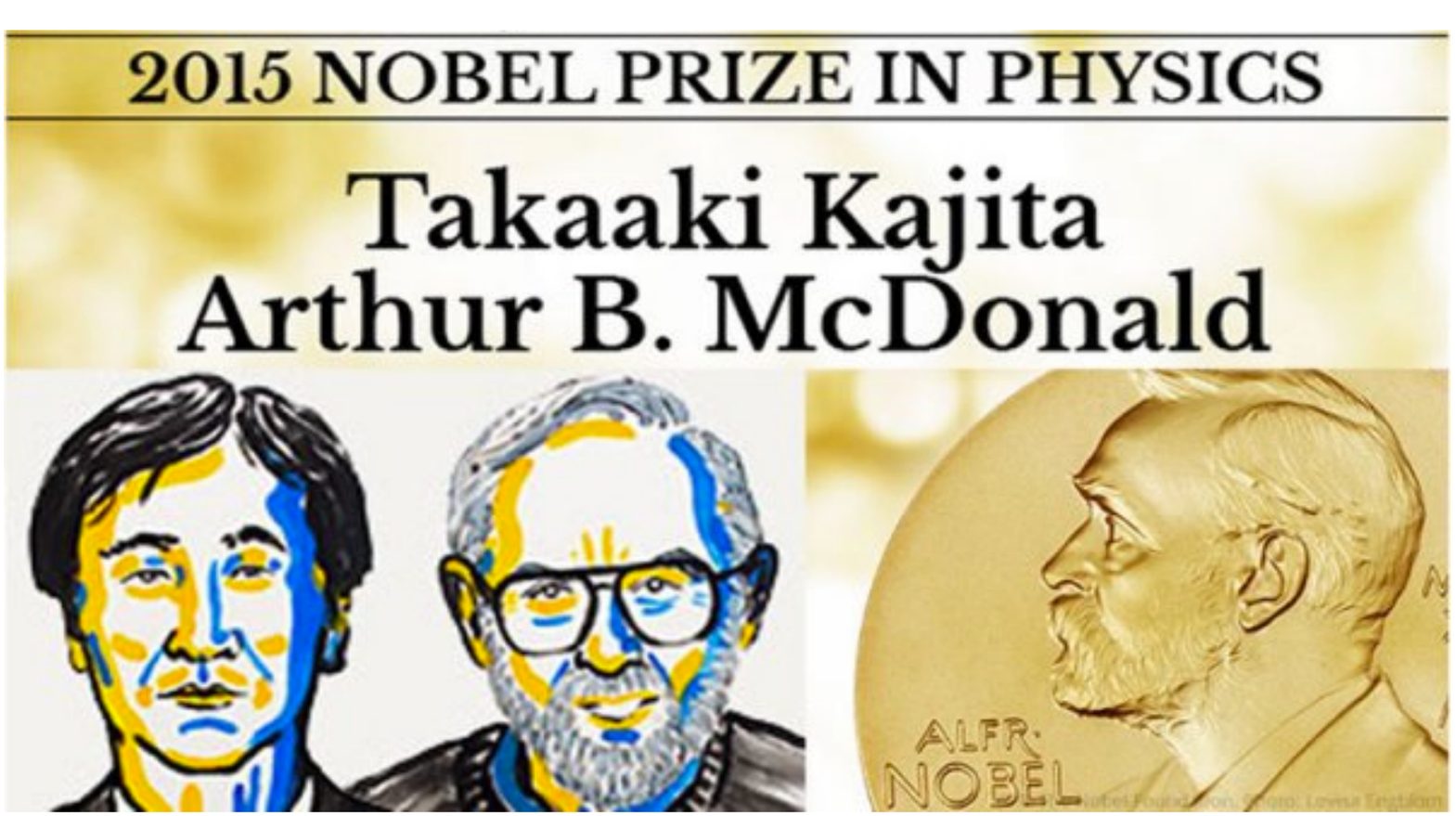
Depends on **mixing angles** from the PMNS matrix

…and **difference in squared masses**

NEUTRINO OSCILLATION

Neutrino oscillation ⇔ neutrinos have mass!

NOT in the Standard Model



ith **energy E**

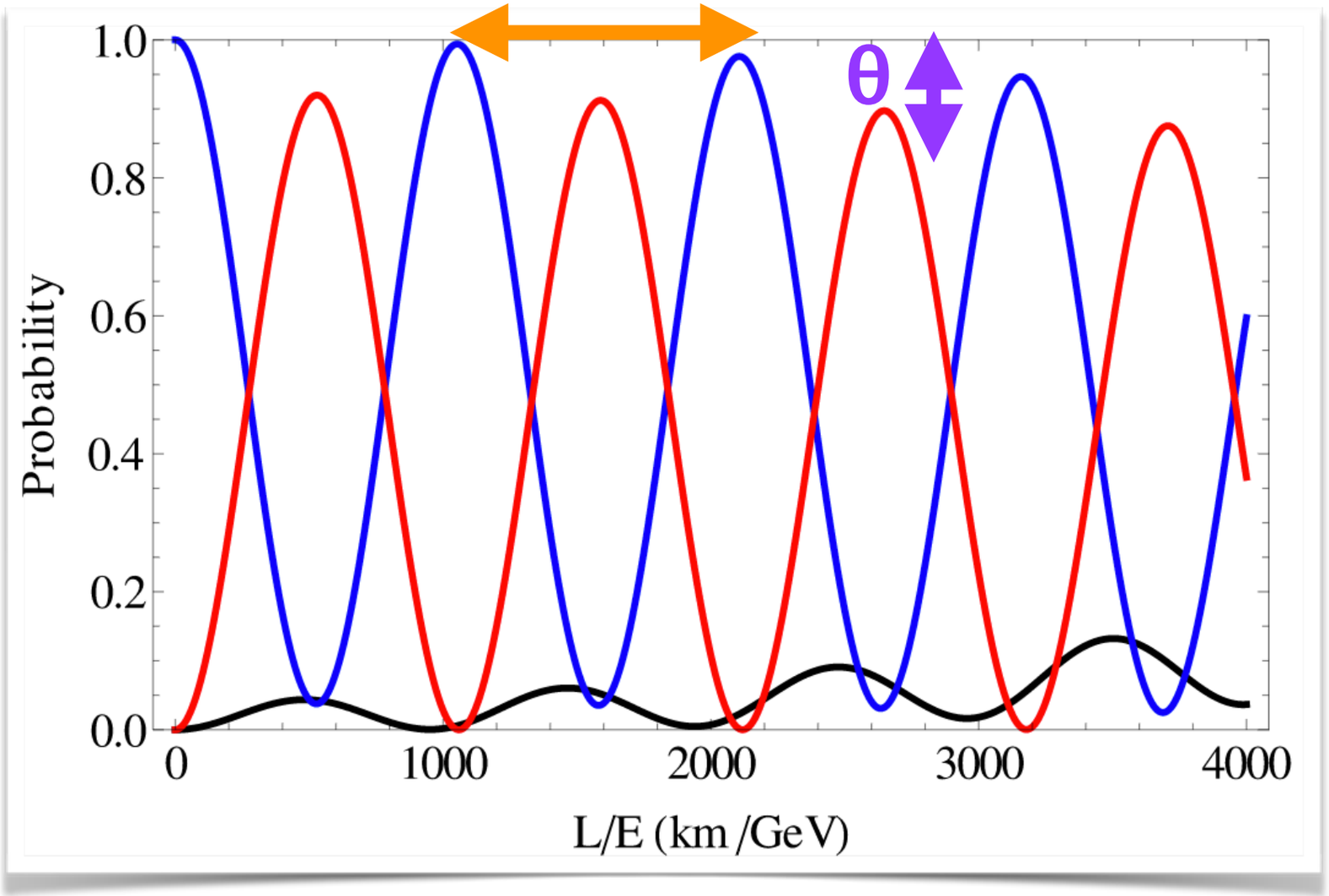
e the **probability**

Depends on **mixing angles** from the PMNS matrix

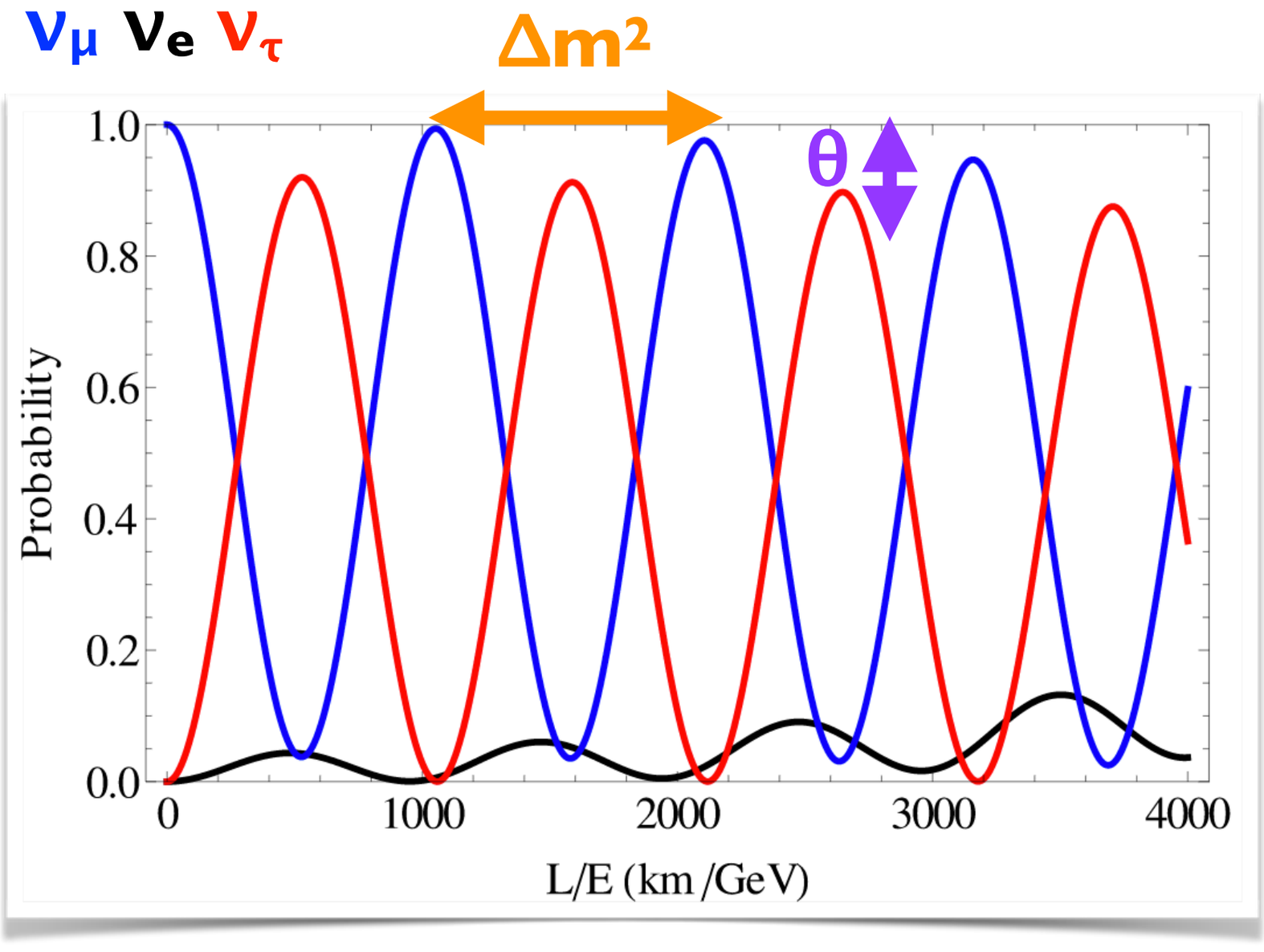
…and **difference in squared masses**

NEUTRINO OSCILLATION

ν_μ ν_e ν_τ



NEUTRINO OSCILLATION



Two **mass-squared splittings**

and three **mixing angles**

have now been measured

→ Entering into an era of **precision measurements**

OPEN QUESTIONS

How many neutrinos are there?

How much do neutrinos weigh?

Which neutrino is heaviest? Which is lightest?

Is neutrino oscillation different for neutrinos and antineutrinos?

Why is neutrino mixing so large?

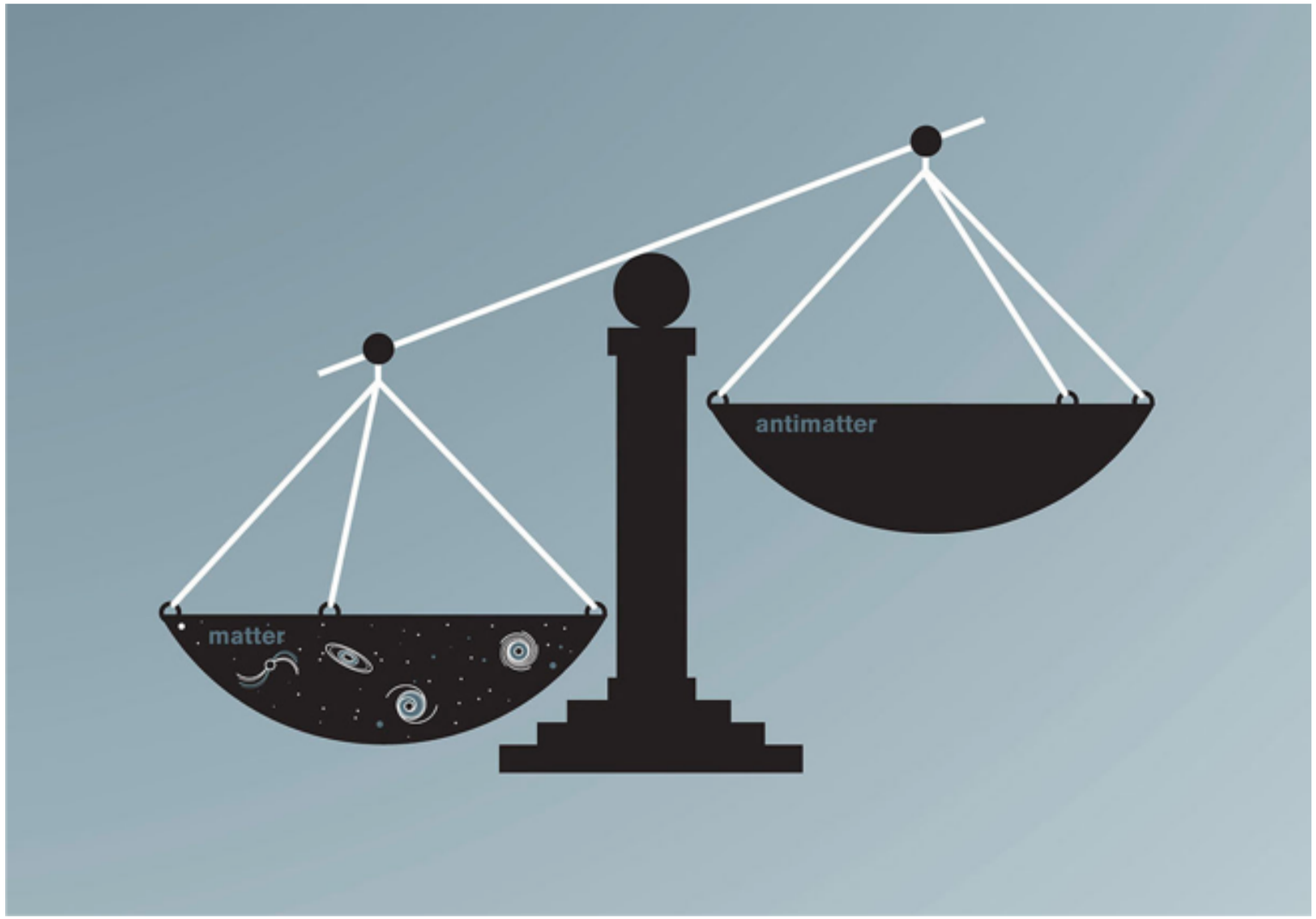
Why are neutrino masses so much smaller than all other particles?

Are neutrinos their own antiparticles?

OPEN QUESTIONS

Artwork by Sandbox Studio, Chicago

Is neutrino oscillation different for neutrinos and antineutrinos?



Processes that **violate CP symmetry** ↔ particles and antiparticles are different

OPEN QUESTIONS

Measure CP violation in neutrino/ antineutrino 'appearance'

Is neutrino oscillation different for neutrinos and antineutrinos?

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \mathbf{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\frac{\mathbf{\Delta m^2_{32}}L}{4E}$$
$$(+)-\Big[\sin 2\theta_{12}\mathbf{\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}}$$
$$\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\mathbf{\Delta m^2_{32}}L}{4E}\mathbf{\sin\delta_{CP}}\Big]$$
$$+\,(\text{CP-even, solar, matter effect terms})$$

OPEN QUESTIONS

Measure CP violation in neutrino/ antineutrino 'appearance'

Is neutrino oscillation different for neutrinos and antineutrinos?

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq$$ **Something**

$$(+)-\Big[$$ **Something else**

$$\mathbf{x}\ L \pm \sin\delta_{CP}\Big]$$

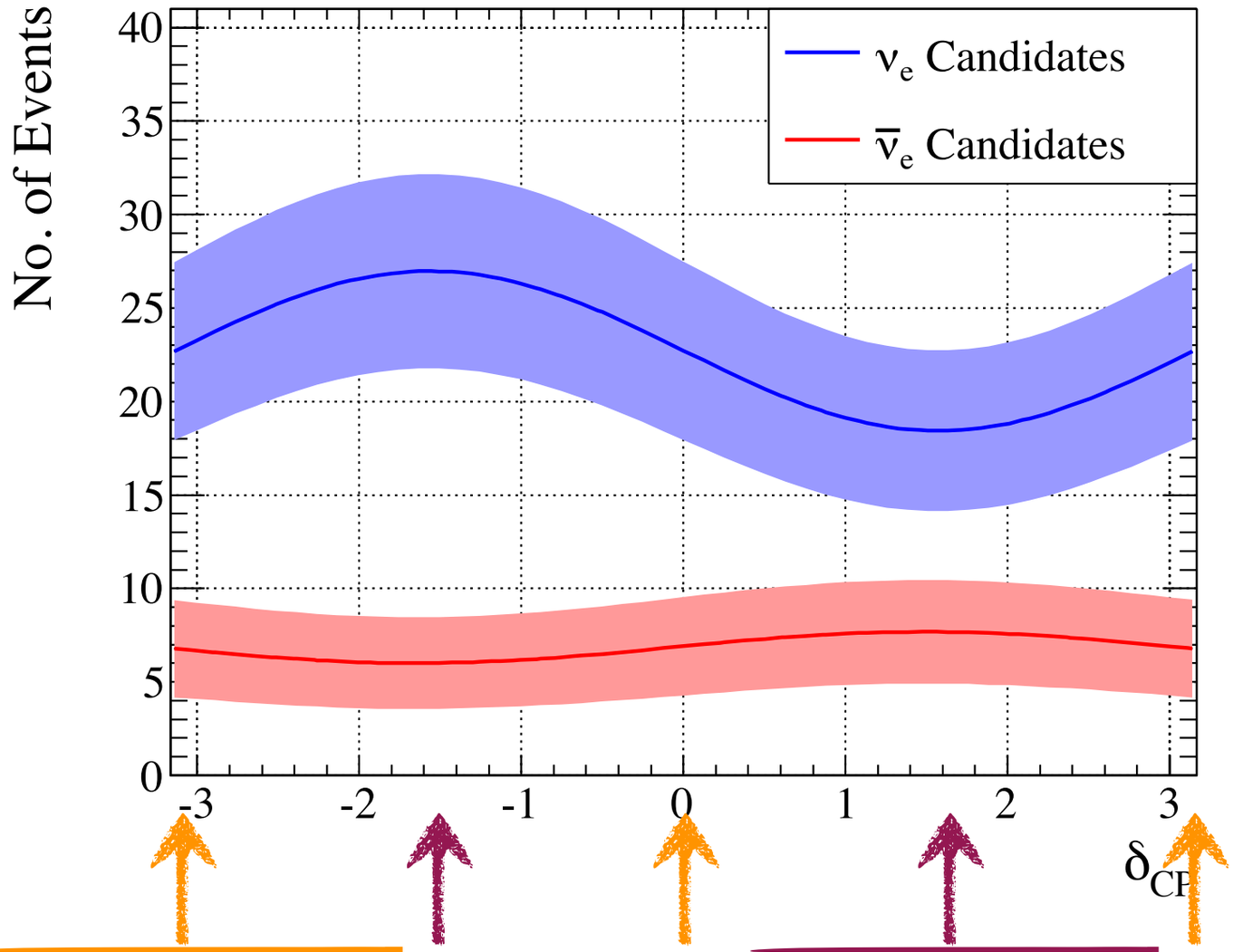
$$+ \text{(CP-even, solar, matter effect terms)}$$

OPEN QUESTIONS

$\bar{\nu}$ ν

$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e)$ ~ something **+/-** something else x **$\sin\delta_{CP}$**

Is neutrino oscillation different for neutrinos and antineutrinos?

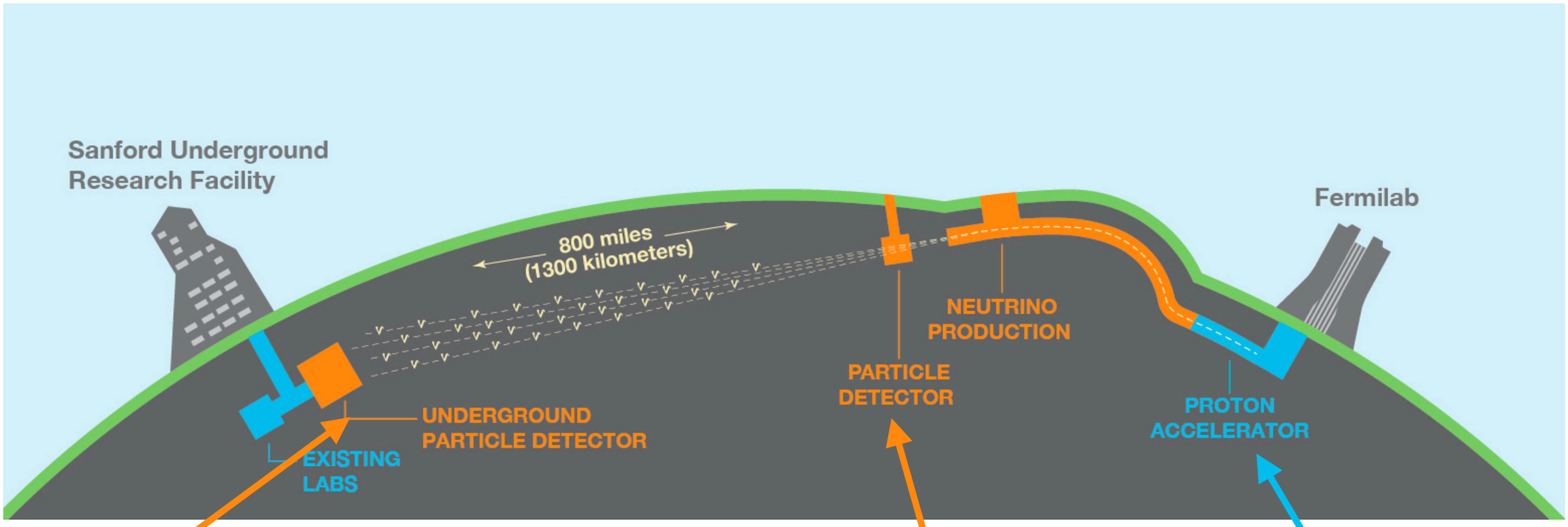


CP conservation

Maximal CP violation

CURRENT MEASUREMENTS

MEASURING NEUTRINO OSCILLATIONS ON EARTH



Measure at far detector: look for differences to near detector!

Travel a long distance …

Measure at near detector: confirm neutrino flavours, energies, interactions

Make neutrinos using particle accelerator

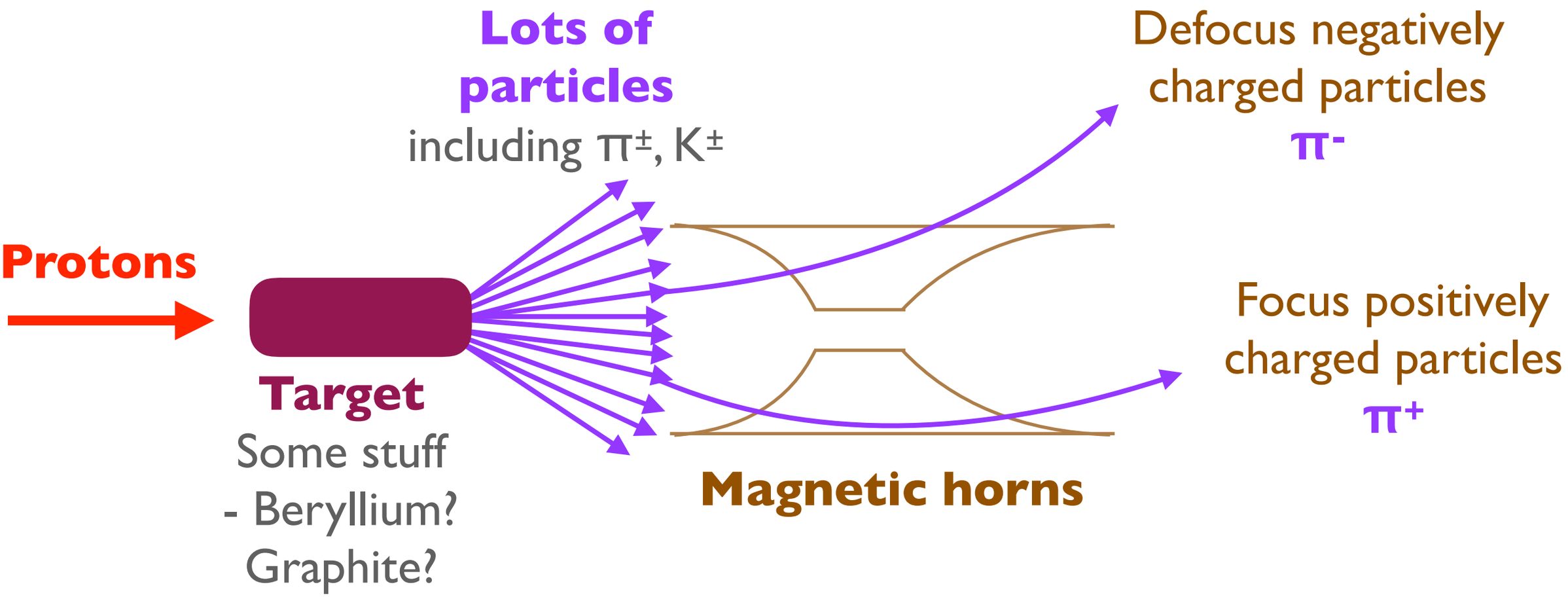
HOW TO MAKE A NEUTRINO BEAM

Lots of particles

including $\pi^{\pm}$, $K^{\pm}$

Some stuff
- Beryllium?
Graphite?

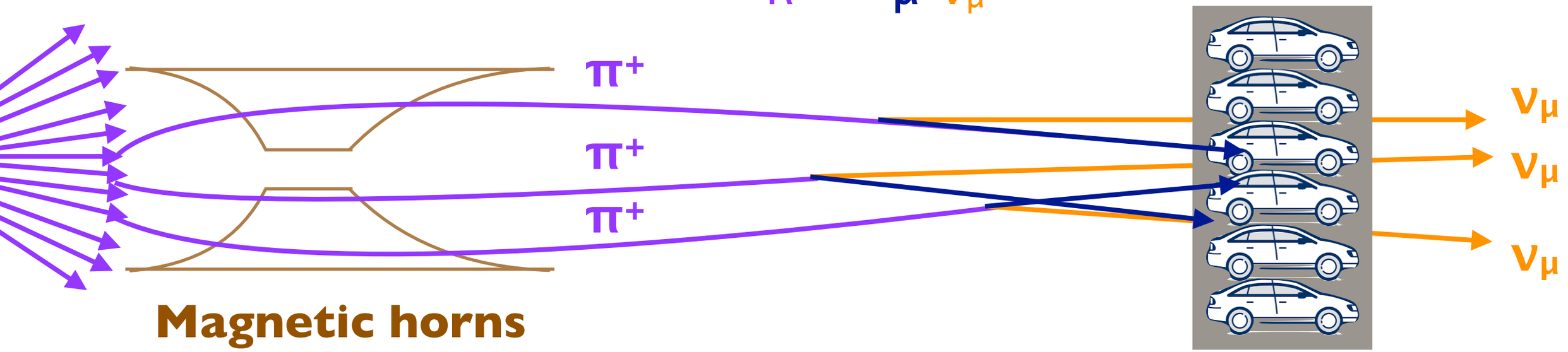
HOW TO MAKE A NEUTRINO BEAM



HOW TO MAKE A NEUTRINO BEAM

π^+ decay in flight

$\pi^+ \rightarrow \mu^+ \nu_\mu$



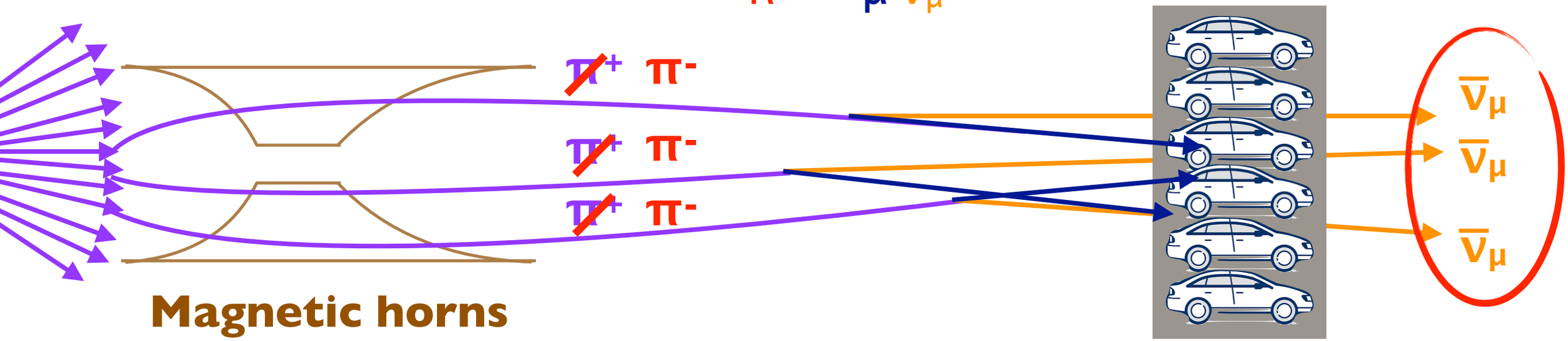
Magnetic horns

Steel absorber
stops all particles
except neutrinos

HOW TO MAKE A NEUTRINO BEAM

π^- decay in flight

$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$



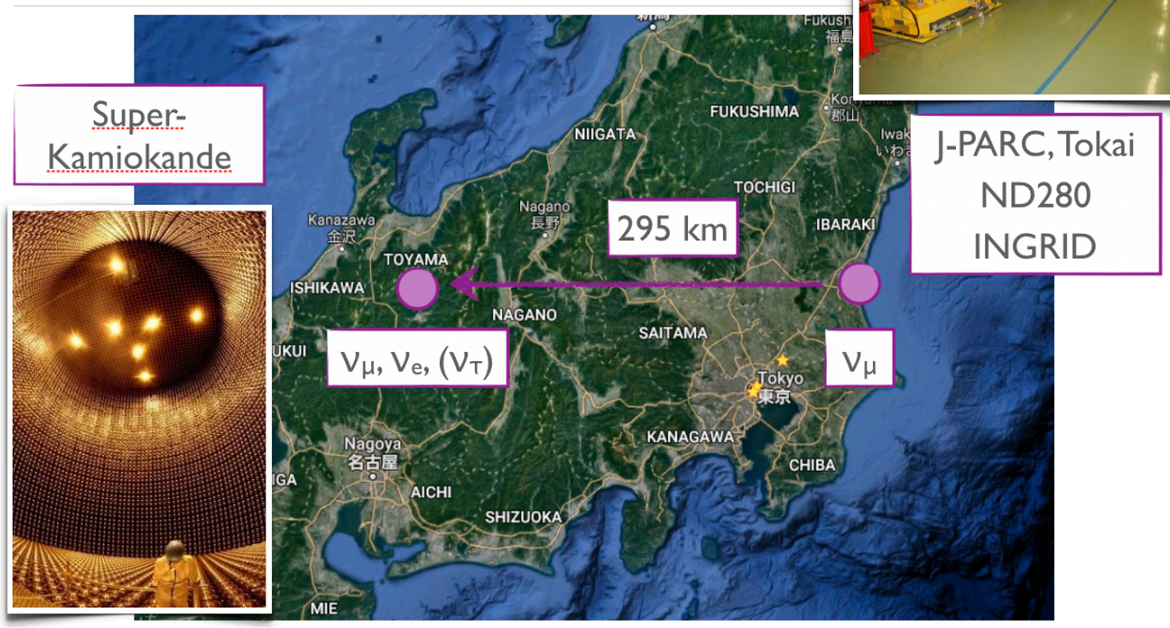
Magnetic horns

Steel absorber
stops all particles except neutrinos

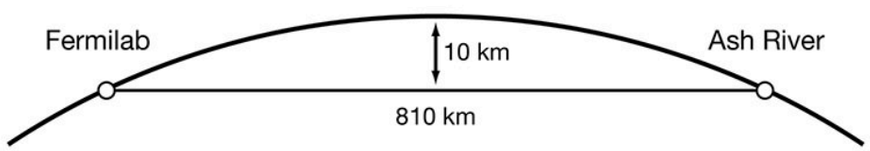
Can reverse the polarity of the horns to focus negatively charged particles instead
→ **produce a beam of antineutrinos instead of neutrinos**

LONG-BASELINE NEUTRINO OSCILLATION EXPERIMENTS

T2K
(Tokai to Kamioka)



NOvA
(NuMI Off-axis ν_e Appearance)

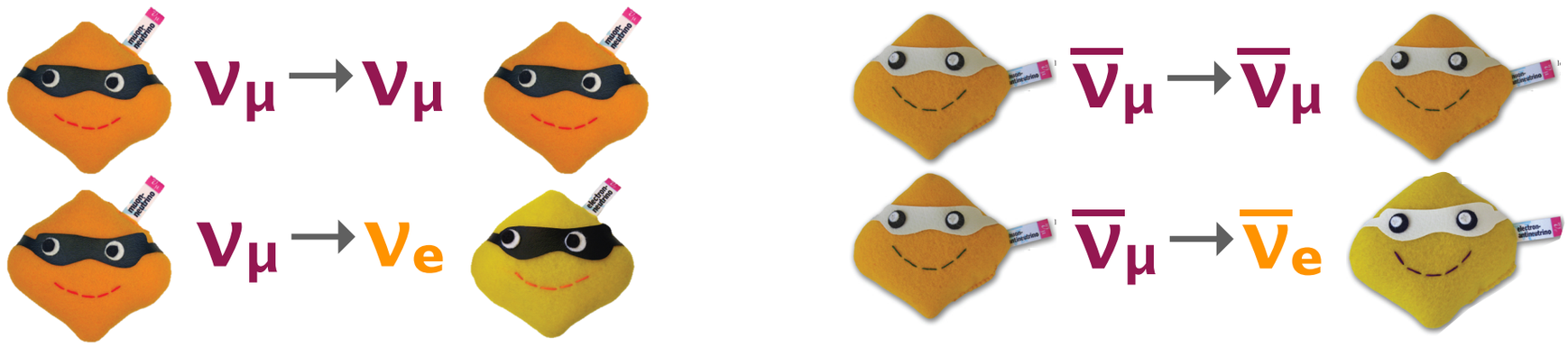


NEUTRINO OSCILLATION

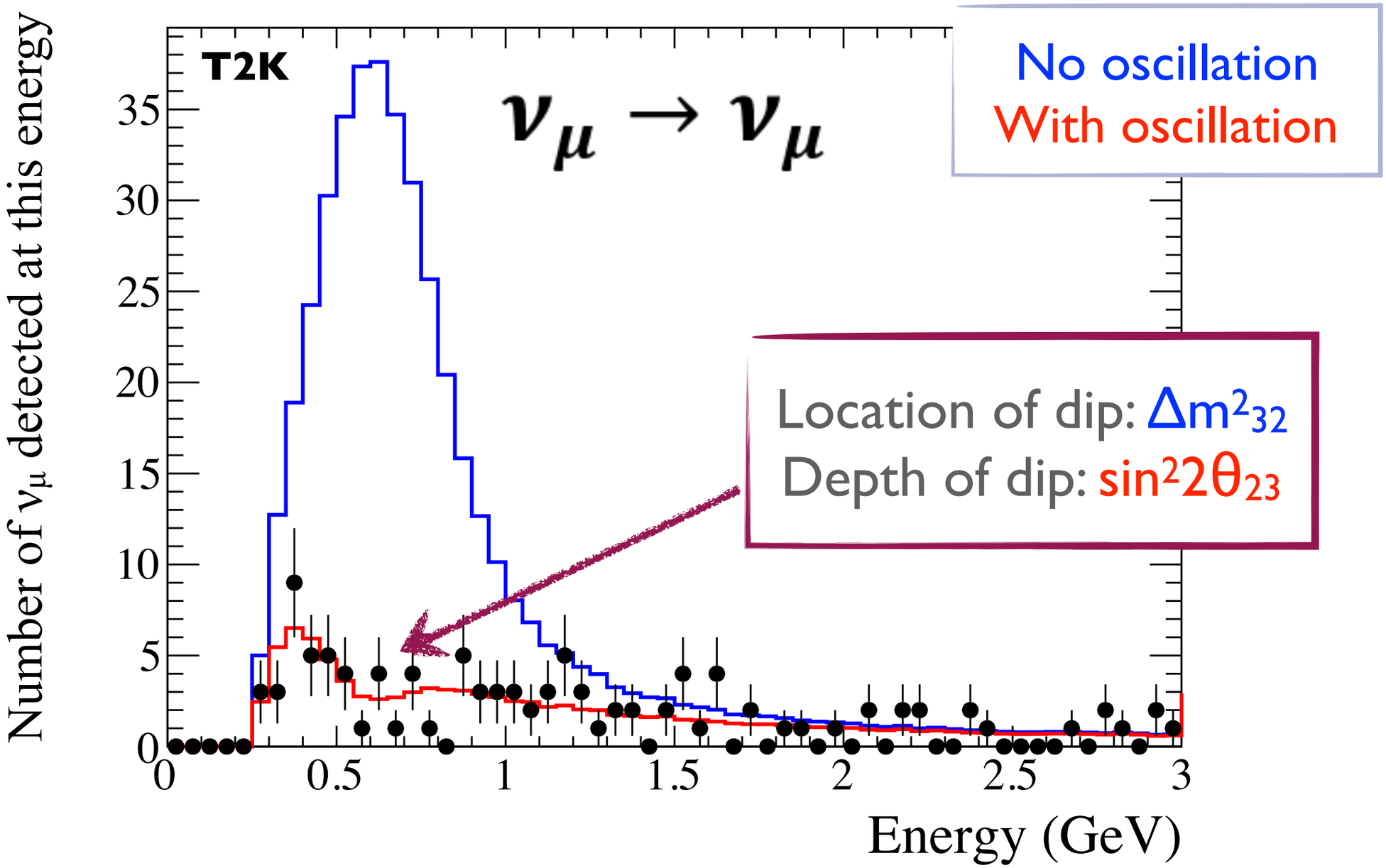
The neutrino beams we make are mostly ν_μ (or $\overline{\nu}_\mu$)

In our detectors we can measure ν_μ or ν_e (but usually not ν_τ)

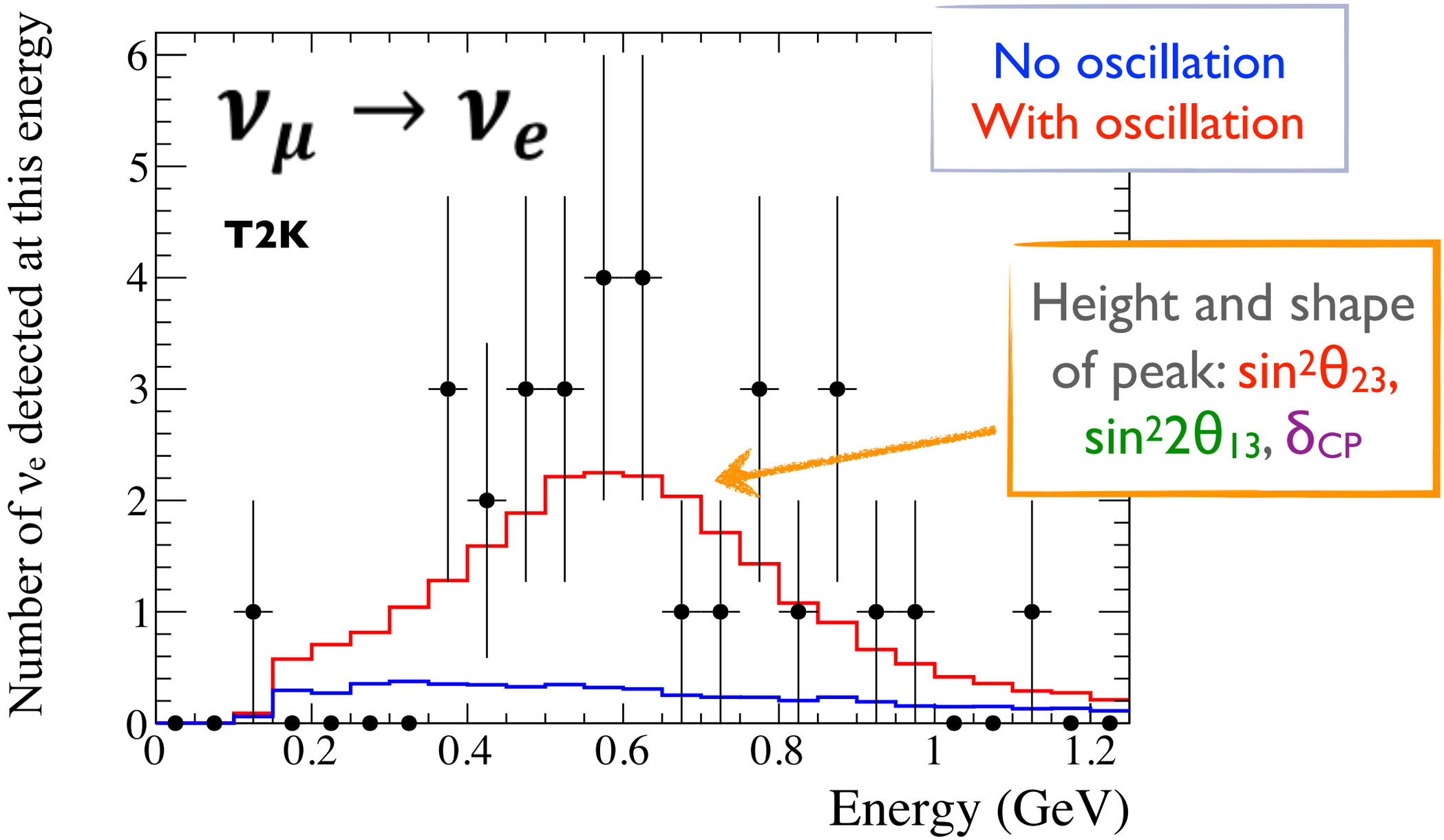
Measure neutrino oscillation in four "channels":



OSCILLATION ANALYSIS IN A NUTSHELL: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$



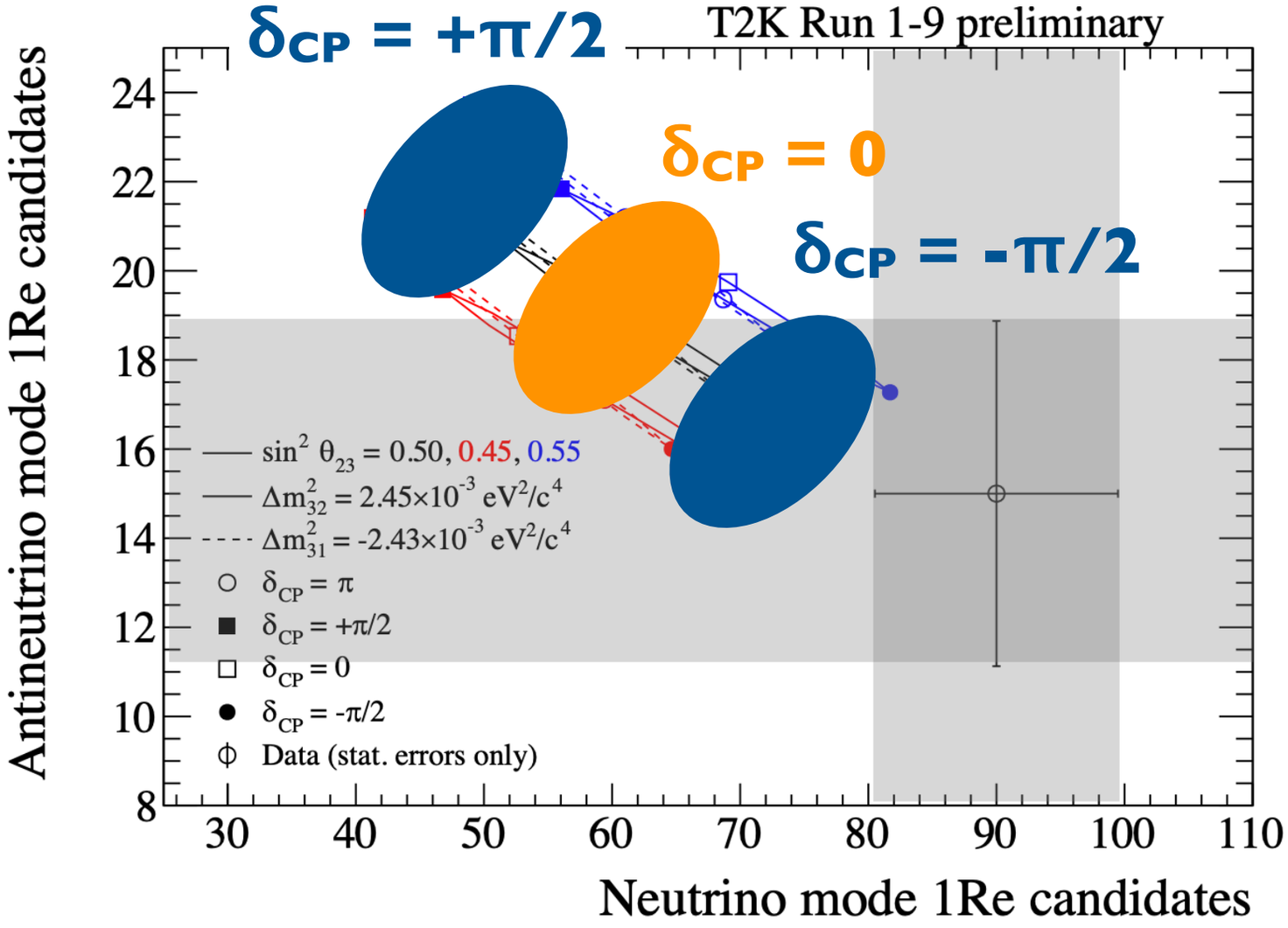
OSCILLATION ANALYSIS IN A NUTSHELL: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$



WHAT CAN WE SAY ABOUT δ_{CP}?

$\bar{\nu}$ ν

$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e)$ ~ something **+/-** something else x **$\sin\delta_{CP}$**



Figures from P. Dunne, FPCP 2019

WHAT CAN WE SAY ABOUT δ_{CP}?

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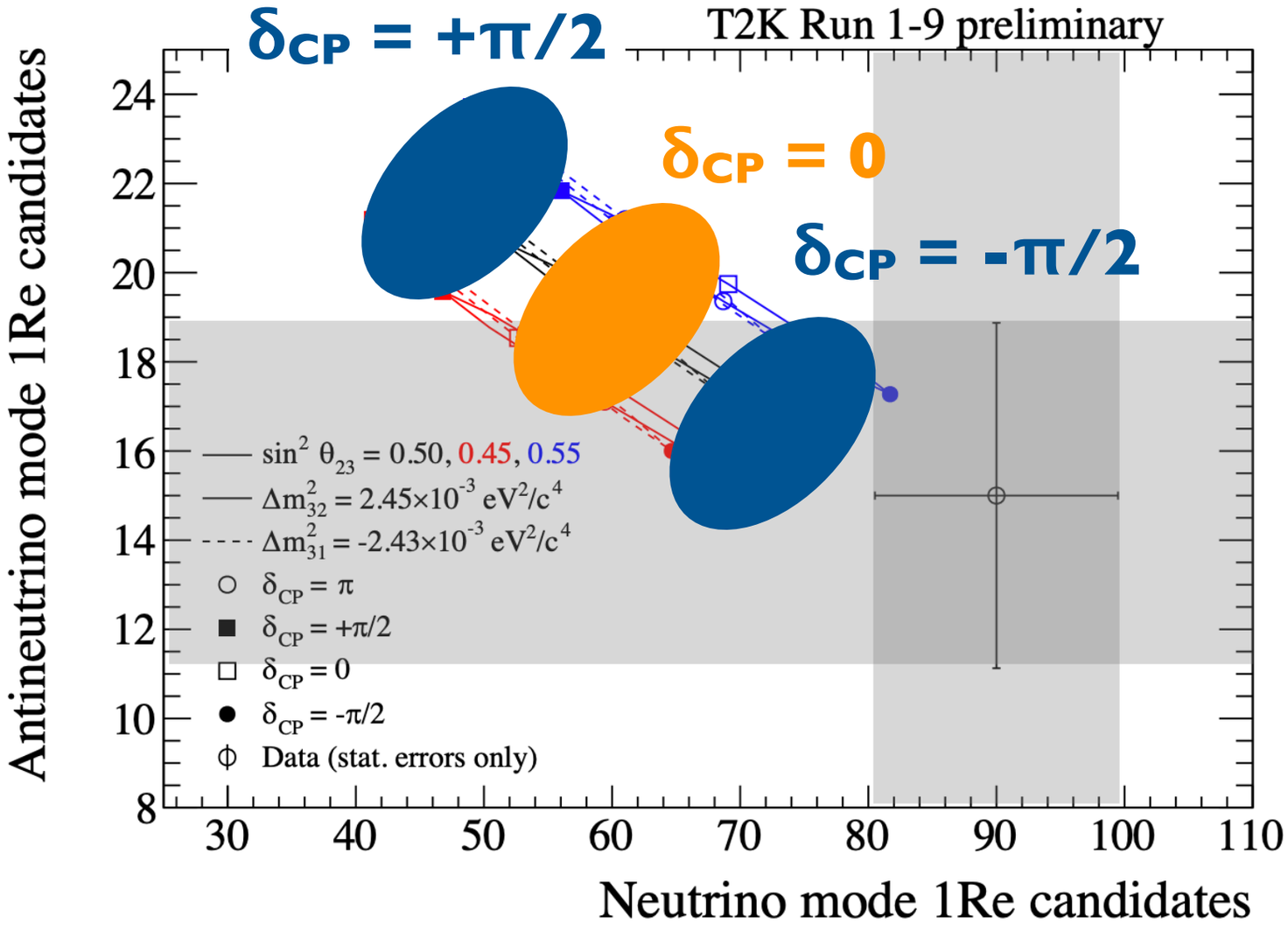
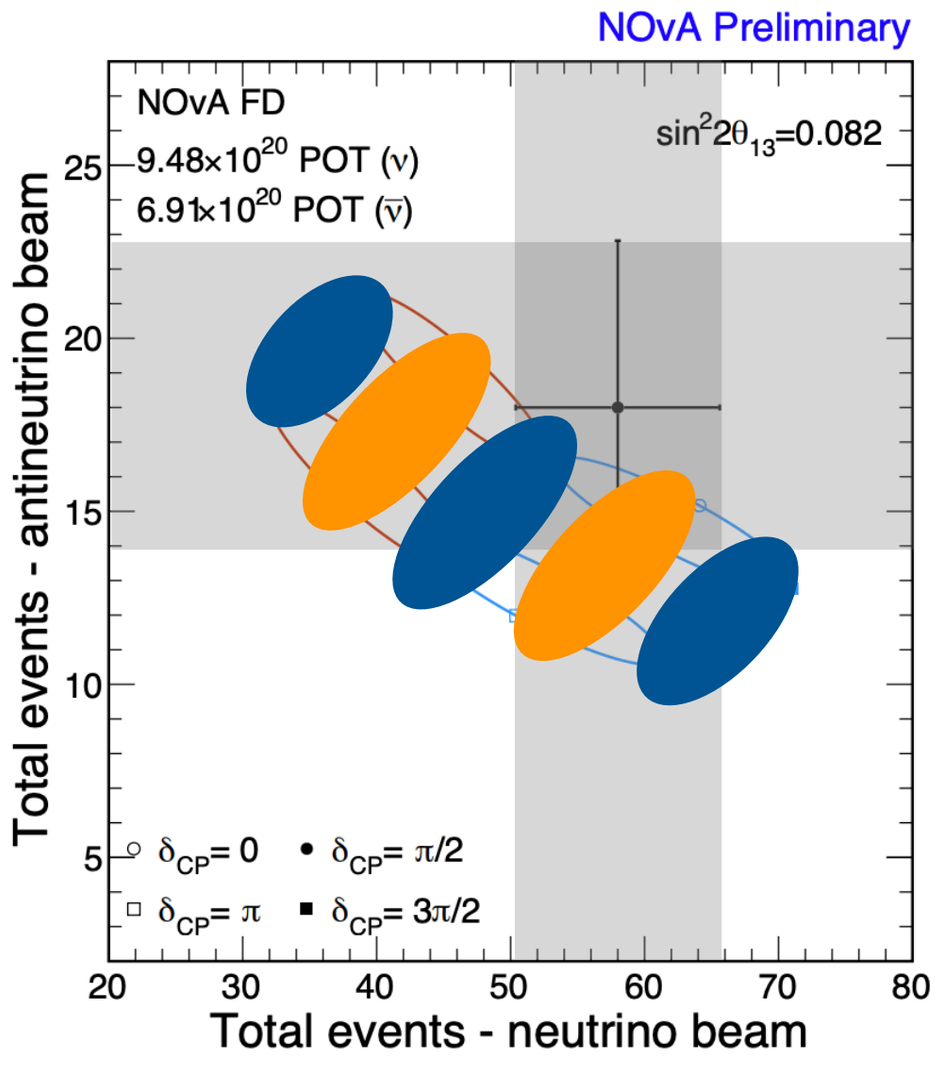




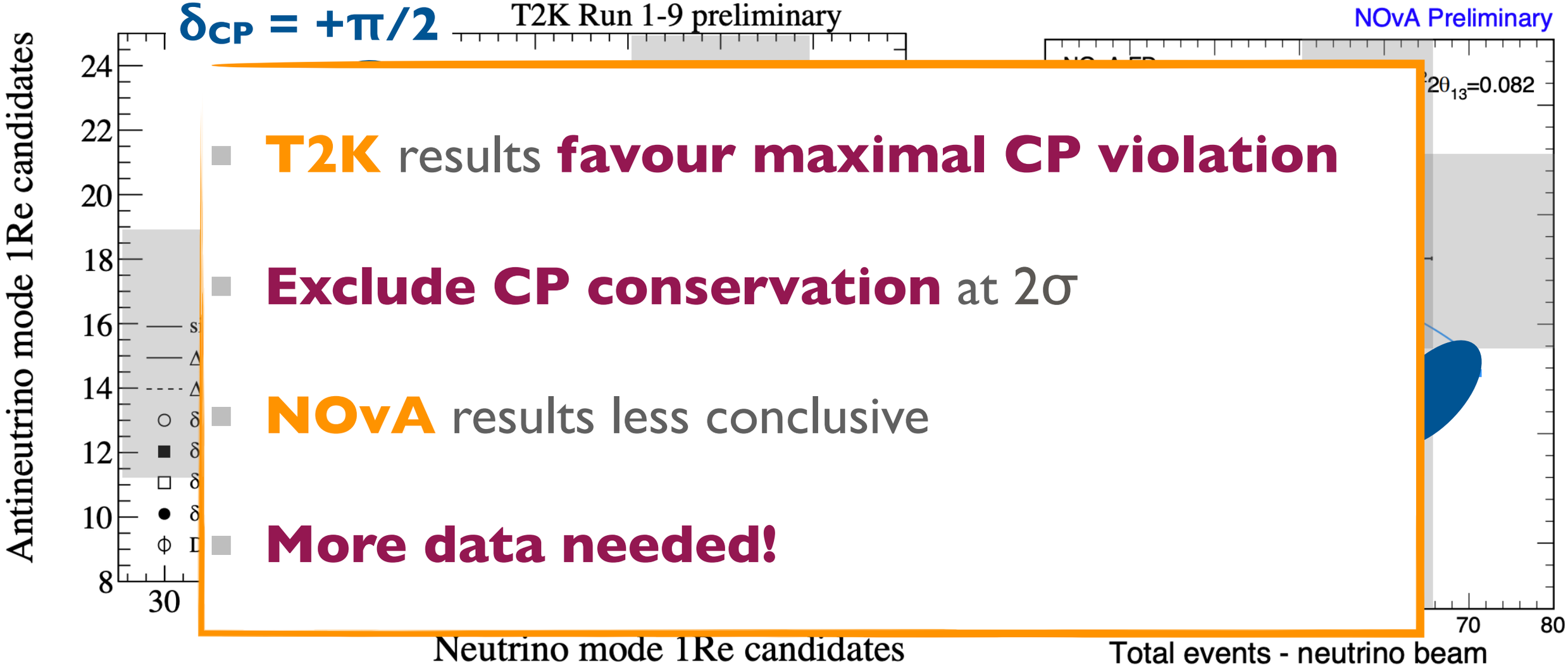
Figures from P. Dunne, FPCP 2019

WHAT CAN WE SAY ABOUT δ_{CP}?

$\bar{\nu}$ ν

$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e)$ ~ something **+/-** something else x **$\sin\delta_{CP}$**

$\delta_{CP} = +\pi/2$



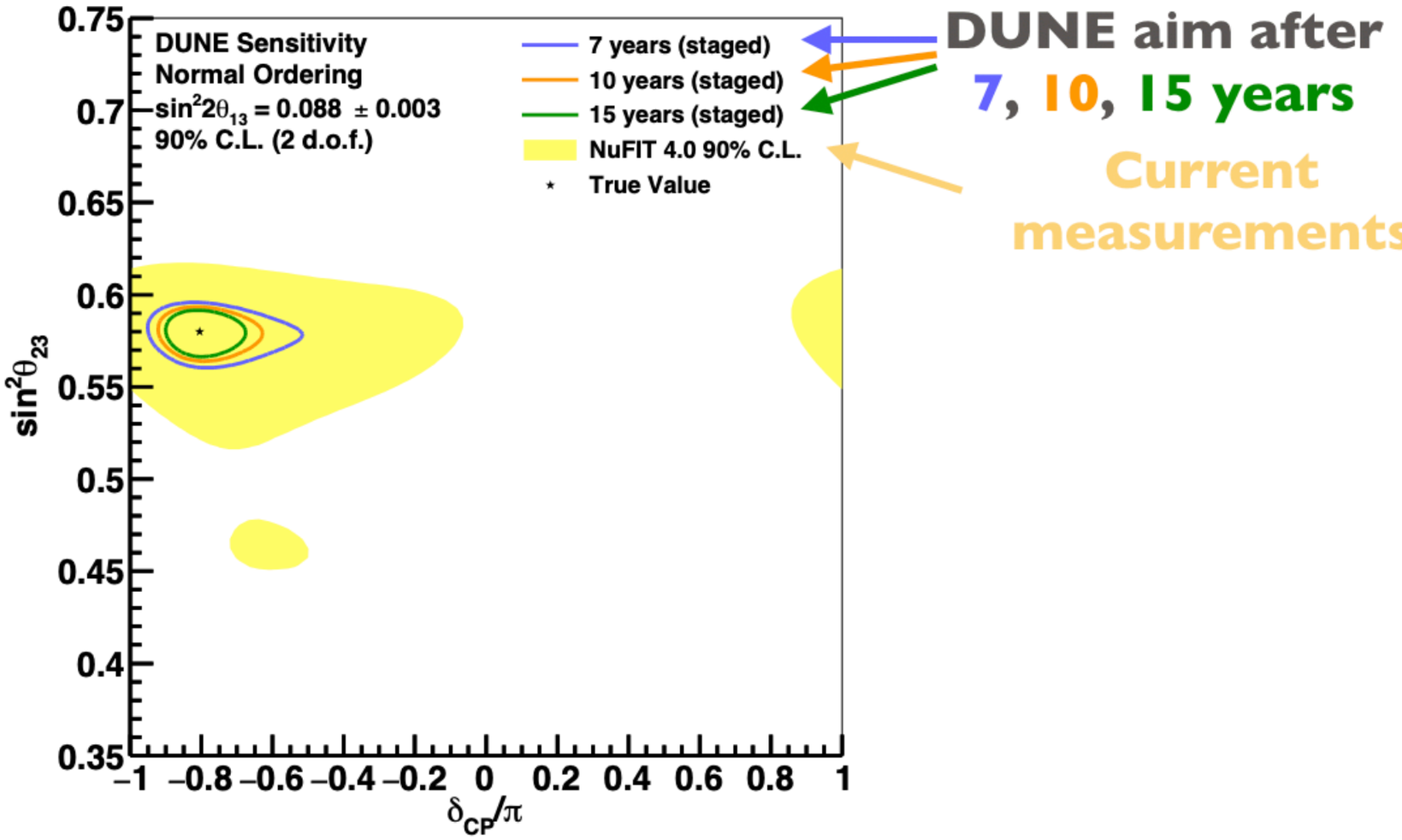
- **T2K** results **favour maximal CP violation**
- **Exclude CP conservation** at 2σ
- **NOvA** results less conclusive
- **More data needed!**

Figures from P. Dunne, FPCP 2019

WHAT'S NEXT?

LOOKING FORWARD

Next-generation experiments **DUNE** and **Hyper-Kamiokande** will measure neutrino oscillations with unprecedented precision



LOOKING FORWARD

Deep **U**nderground **N**eutrino **E**xperiment

→ 40kton **L**iquid **Ar**gon

→ build on current and future US LAr program:

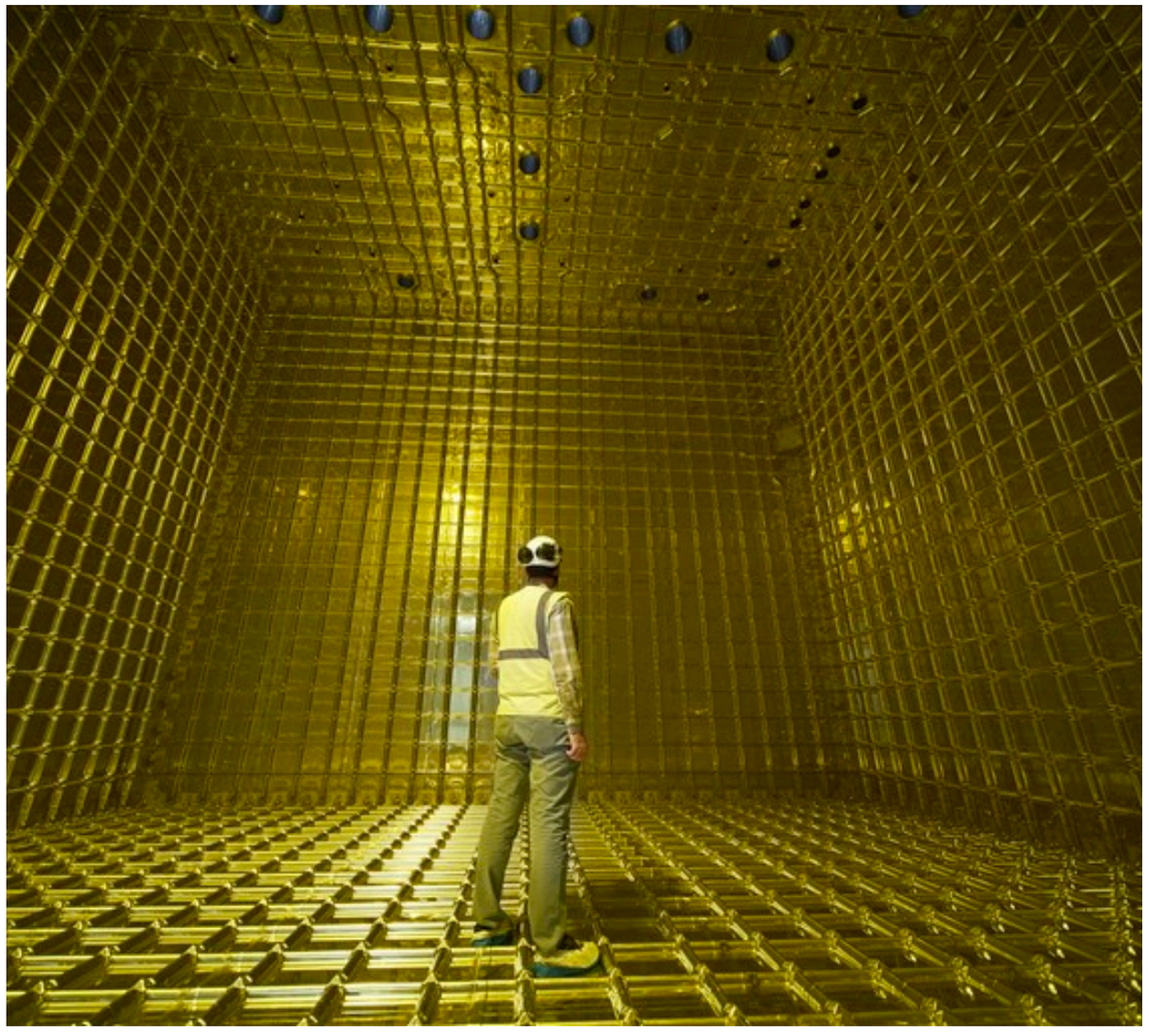
→ ArgoNeuT, LArIAT

→ **MicroBooNE**

→ ProtoDUNEs

→ SBND, ICARUS

All stems from pioneering work at Brookhaven in the 1970s!



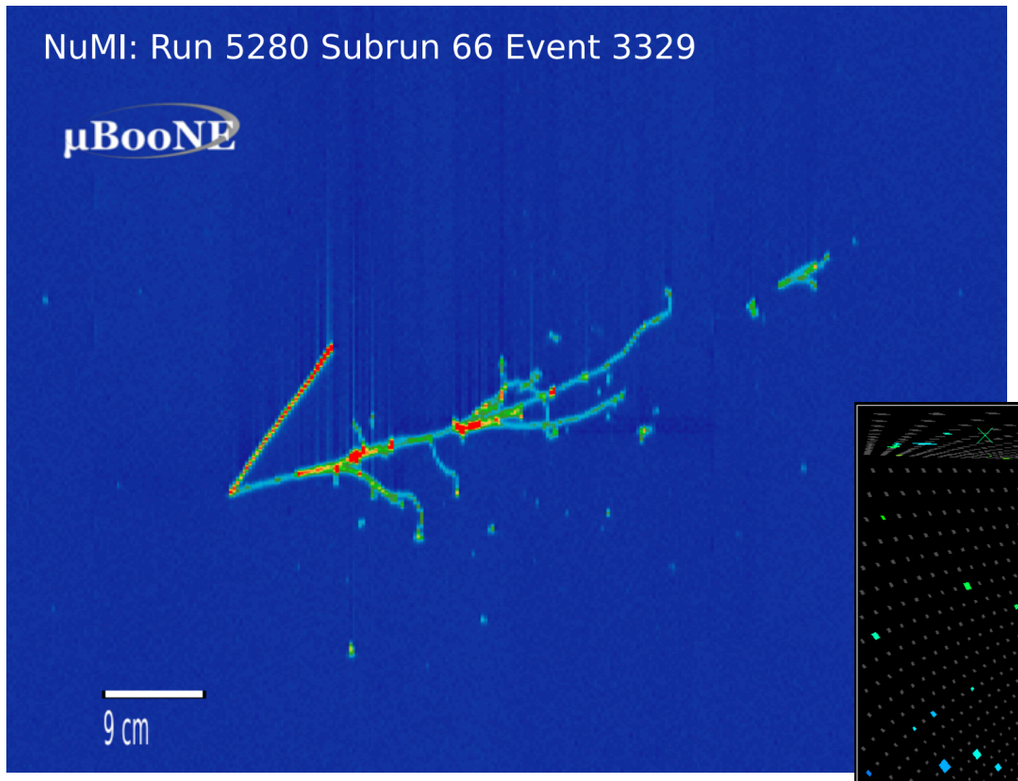
WHY LIQUID ARGON?

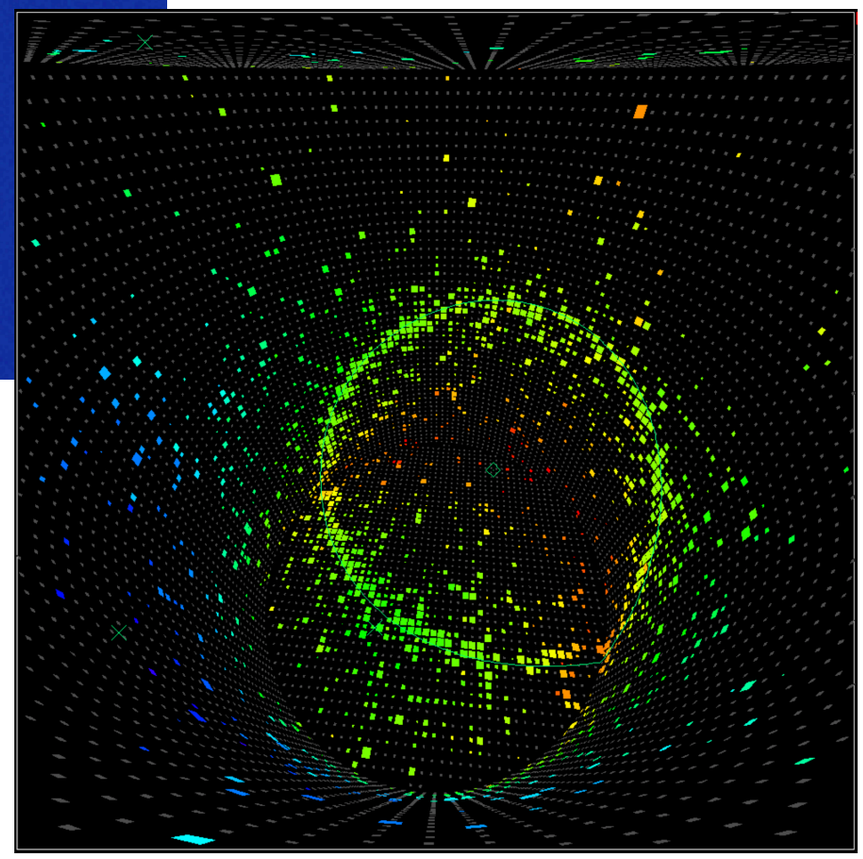
✔ Very high resolution images

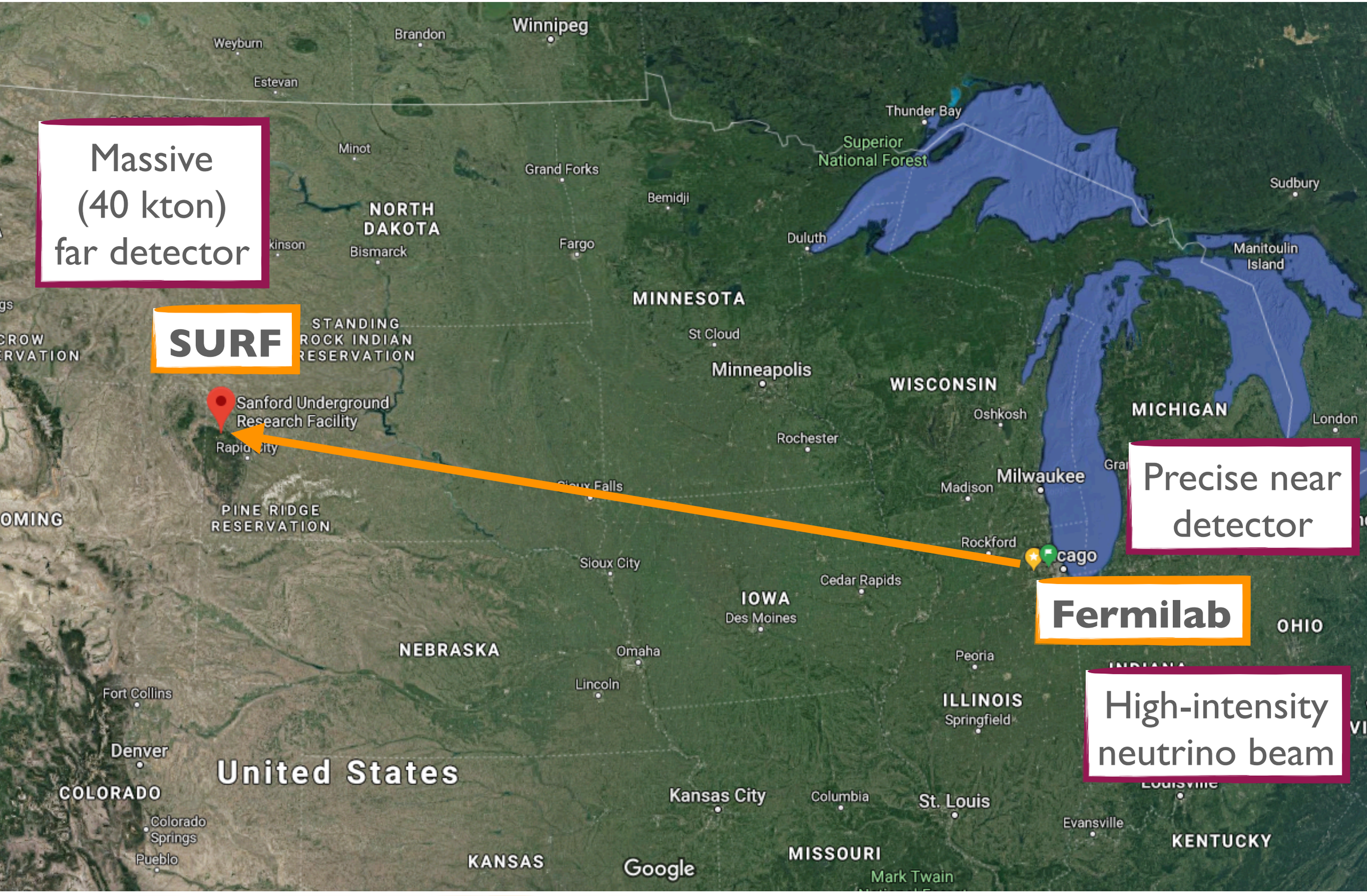
✔ Very low thresholds

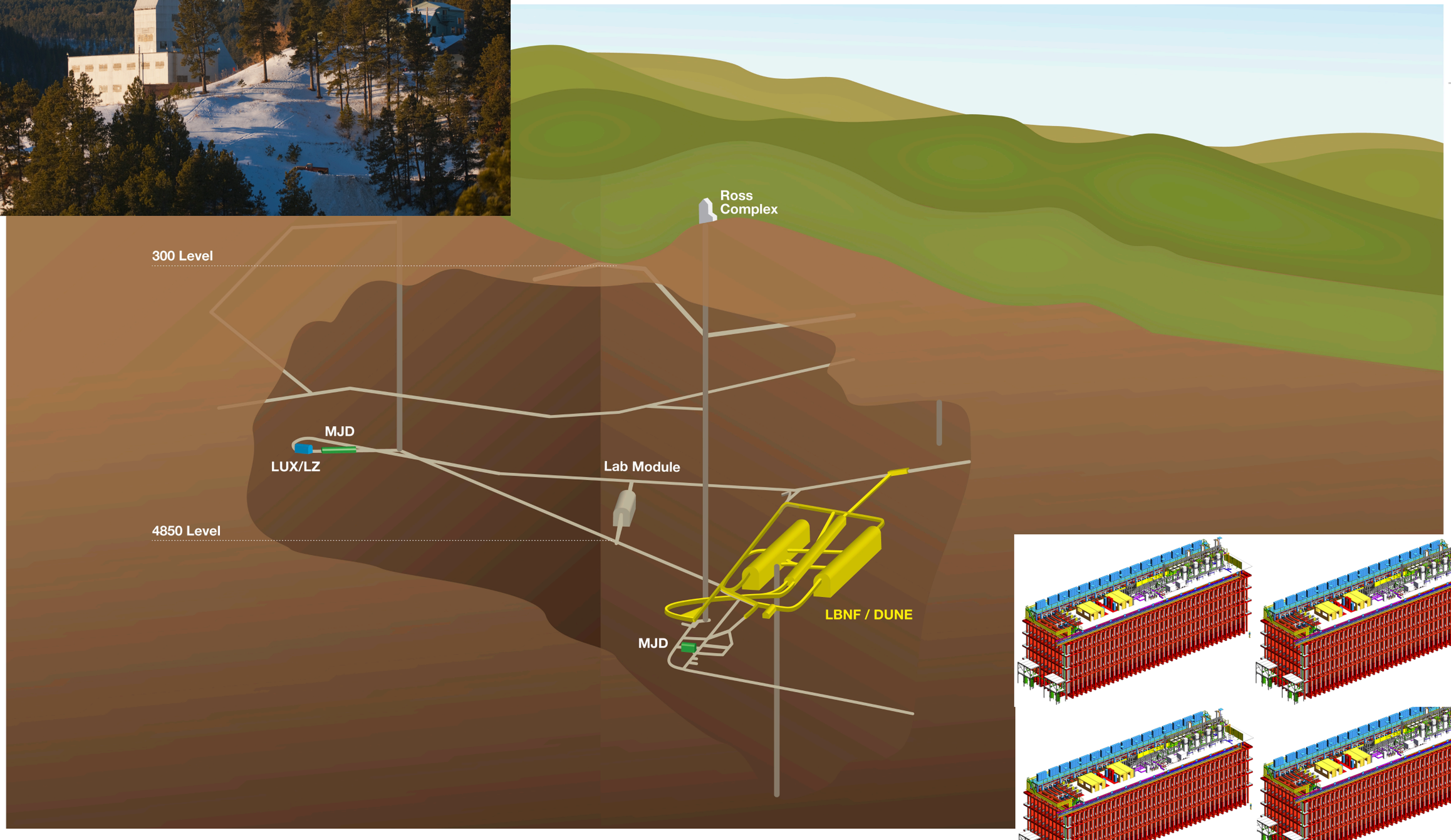
✔ Calorimetric information

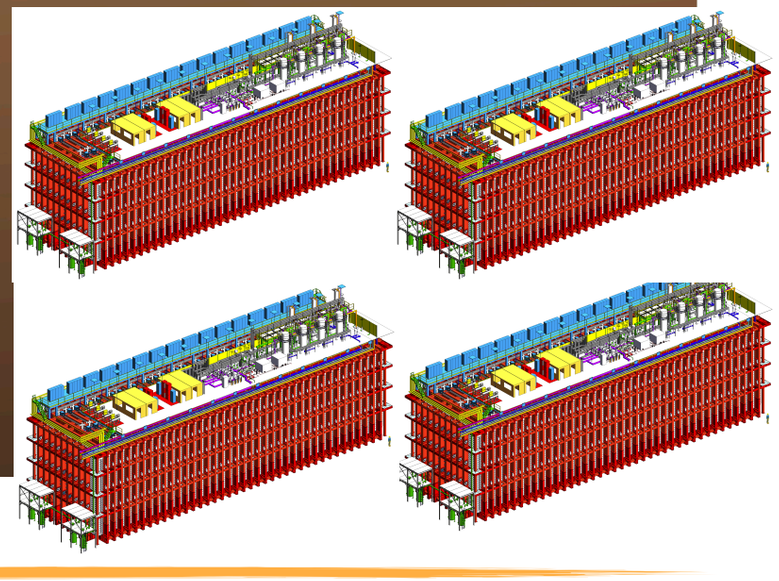
✔ Electron/photon discrimination

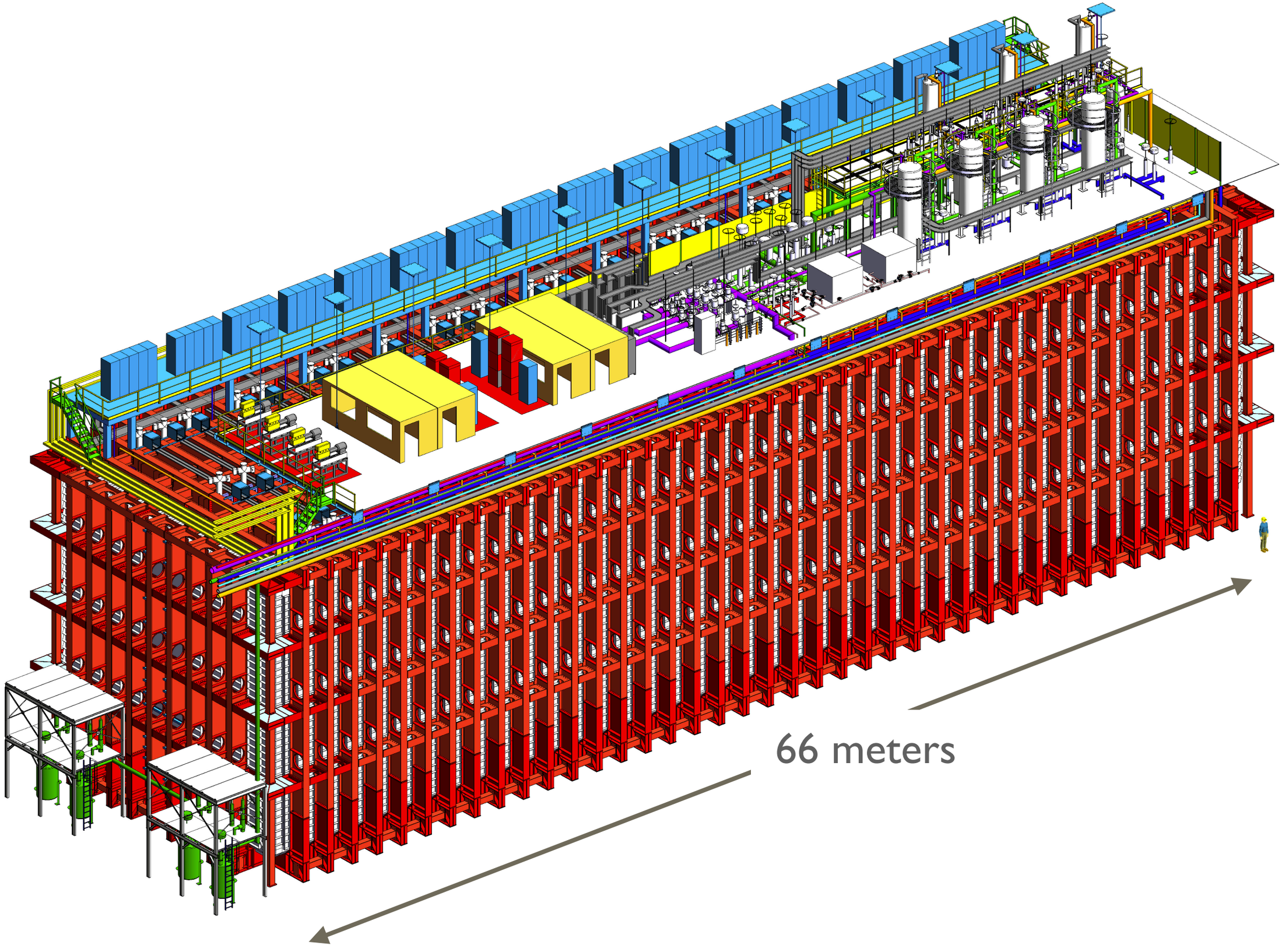


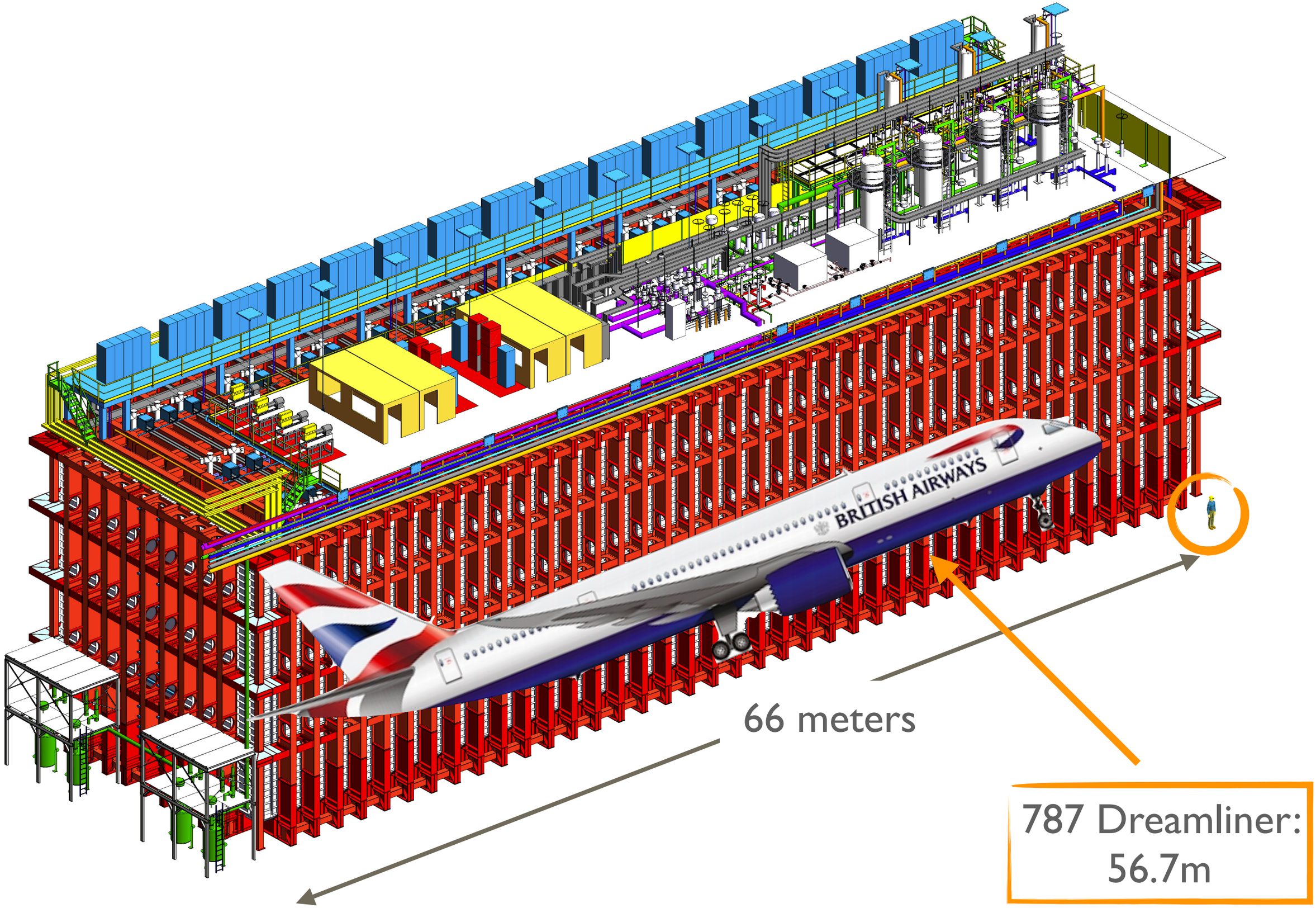



Massive (40 kton) far detector
SURF
Sanford Underground Research Facility
Precise near detector
Fermilab
High-intensity neutrino beam
Winnipeg
Brandon
Weyburn
Estevan
Minot
Grand Forks
Bemidji
Thunder Bay
Superior National Forest
Sudbury
Duluth
Manitoulin Island
NORTH DAKOTA
Bismarck
Fargo
MINNESOTA
St Cloud
Minneapolis
WISCONSIN
Oshkosh
MICHIGAN
London
Rochester
Milwaukee
Madison
Rockford
Chicago
Sioux Falls
PINE RIDGE RESERVATION
Sioux City
Cedar Rapids
IOWA
Des Moines
NEBRASKA
Omaha
Lincoln
Peoria
ILLINOIS
Springfield
OHIO
Fort Collins
Denver
COLORADO
United States
Kansas City
Columbia
St. Louis
Evansville
KENTUCKY
Colorado Springs
Pueblo
KANSAS
MISSOURI
Mark Twain
Google


Ross
Complex
300 Level
MJD
LUX/LZ
Lab Module
4850 Level
LBNF / DUNE
MJD




66 meters


BRITISH AIRWAYS
66 meters
787 Dreamliner:
56.7m

MicroBooNE: a 170 ton Liquid Argon Detector

Currently the only liquid argon detector in a neutrino beam

WHAT WE'VE LEARNT FROM MICROBOONE

Ionization electron signal processing in single phase LArTPCs. Part I. Algorithm Description and quantitative

Design and construction of the

R. Acciarri[g], C. Adams[aa], R. An[h], A. Aparicio[g], S. Apor
B. Baller[g] +Show full author list

Determination of muon momentum in the MicroBooNE LArTPC using an improved model of multiple Coulomb

Convolutional neural networks applied to neutrino events in a liquid argon time projection chamber

Measurement of cosmic-ray reconstruction efficiencies in the MicroBooNE LArTPC using a small external cosmic-ray counter

Michel electron reconstruction using cosmic-ray data from the MicroBooNE LArTPC

Eur. Phys. J. C (2019) 79:248
https://doi.org/10.1140/epjc/s10052-019-6742-3
THE EUROPEAN PHYSICAL JOURNAL C

Eur. Phys. J. C (2018) 78:82
https://doi.org/10.1140/epjc/s10052-017-5481-6
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector

Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC

R. Acciarri[g], C. Adams[bb], R. An[h], J. Anthony[c], J. Asaadi[y], M. Auger[a], L. Bagby[g], S. Balasubramanian[bb], B. Baller[g], C. Barnes[n] +Show full author list
Published 4 August 2017 • © 2017 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 12, August 2017

PHYSICAL REVIEW D **99,** 091102(R) (2019)

First measurement of ν_μ charged-current π^0 production on argon with the MicroBooNE detector

Rejecting cosmic background for exclusive neutrino interaction studies with Liquid Argon TPCs; a case study with the MicroBooNE

Design and construction of the MicroBooNE Cosmic Ray Tagger system

C. Adams[i], M. Alrashed[k], R. An[j], J. Anthony[c], J. Asaadi[aa], A. Ashkenazi[o], M. Auger[a]

PHYSICAL REVIEW LETTERS **123,** 131801 (2019)

First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at $E_\nu \sim 0.8$ GeV with the MicroBooNE Detector

FERMILAB-PUB-19-357-ND
Prepared for submission to JINST

Calibration of the charge and energy response of the MicroBooNE liquid argon time projection chamber using muons and protons

MicroBooNE Collaboration
C. Adams[j] M. Alrashed[l] R. An[k] J. Anthony[c] J. Asaadi[cc] A. Ashkenazi[p]

Prepared for submission to JINST

Reconstruction and Measurement of $O(100)$ MeV Energy Electromagnetic Activity from $\pi^0 \to \gamma\gamma$ Decays in the MicroBooNE LArTPC

MicroBooNE Collaboration
C. Adams[j] M. Alrashed[l] R. An[k] J. Anthony[c] J. Asaadi[cc] A. Ashkenazi[p]
S. Balasubramanian[hh] B. Baller[i] C. Barnes[q] G. Barr[r] V. Basque[o] M. Bass[b] F. Bay[dd]
S. Berkman[i] A. Bhanderi[o] A. Bhat[z] M. Bishai[b] A. Blake[m] T. Bolton[l] L. Camilleri[g] D. Caratelli[i]
I. Caro Terrazas[f] R. Carr[p] R. Castillo Fernandez[i] F. Cavanna[i] G. Cerati[i] Y. Chen[a] E. Church[u]
D. Cianci[g] E. O. Cohen[aa] J. M. Conrad[p] M. Convery[x] L. Cooper-Troendle[hh]
J. I. Crespo-Anadón[g] M. Del Tutto[i] D. Devitt[m] A. Diaz[p] L. Domine[x] K. Duffy[i] S. Dytman[y]
B. Eberly[h] A. Ereditato[a] L. Escudero Sanchez[c] J. Esquivel[c] J. J. Evans[o] R. S. Fitzpatrick[q]
B. T. Fleming[hh] N. Foppiani[i] D. Franco[hh] A. P. Furmanski[o] D. Garcia-Gamez[o] S. Gardiner[i]

Ionization electron signal processing in single phase LArTPCs. Part II. Data/simulation comparison and performance in MicroBooNE

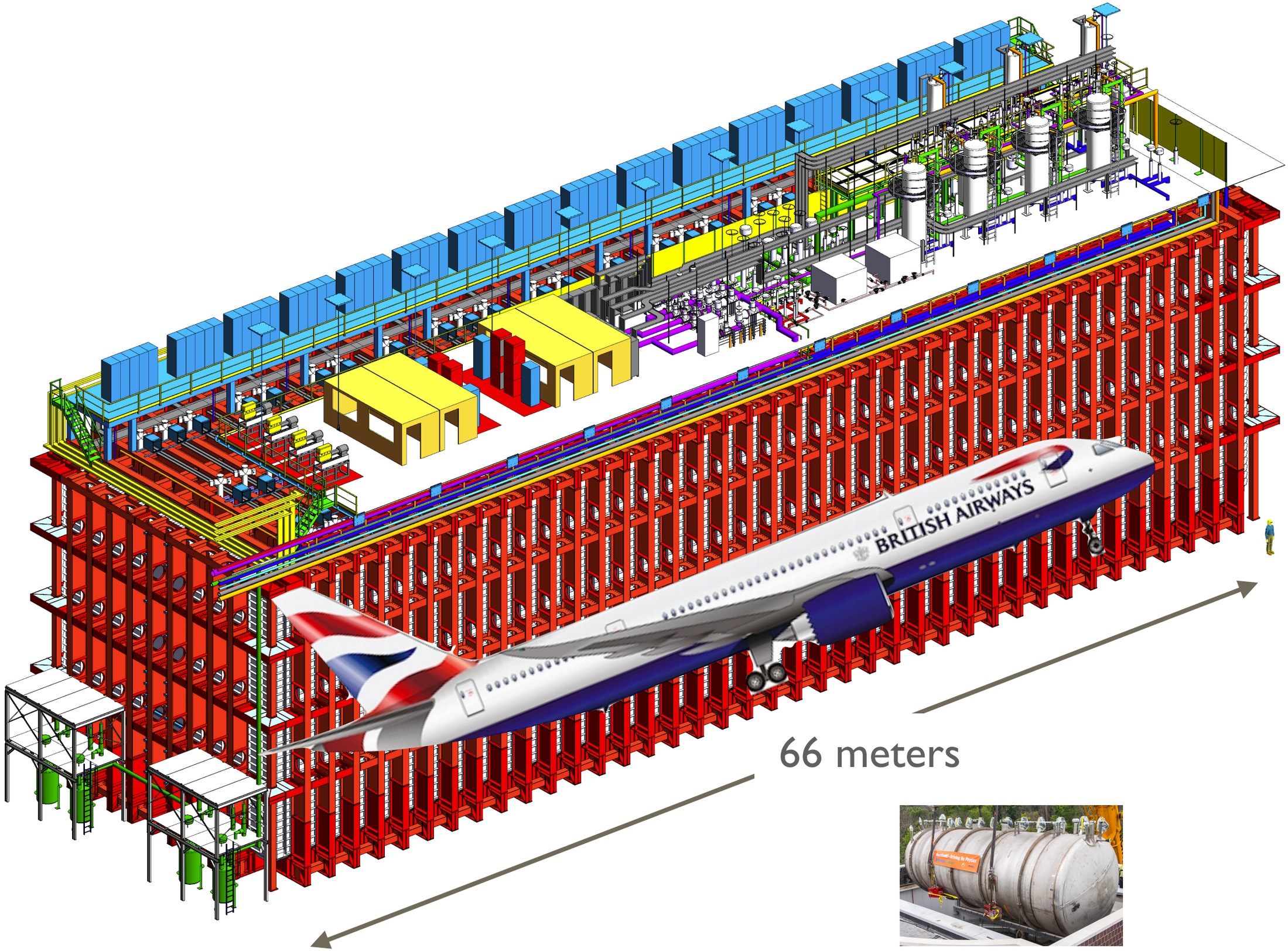
C. Adams[j], R. An[j], J. Anthony[c], J. Asaadi[aa], M. Auger[a], S. Balasubramanian[ee], B. Baller[h], C. Barnes[p], G. Barr[s], M. Bass[b] +Show full author list
Published 6 July 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 13, July 2018

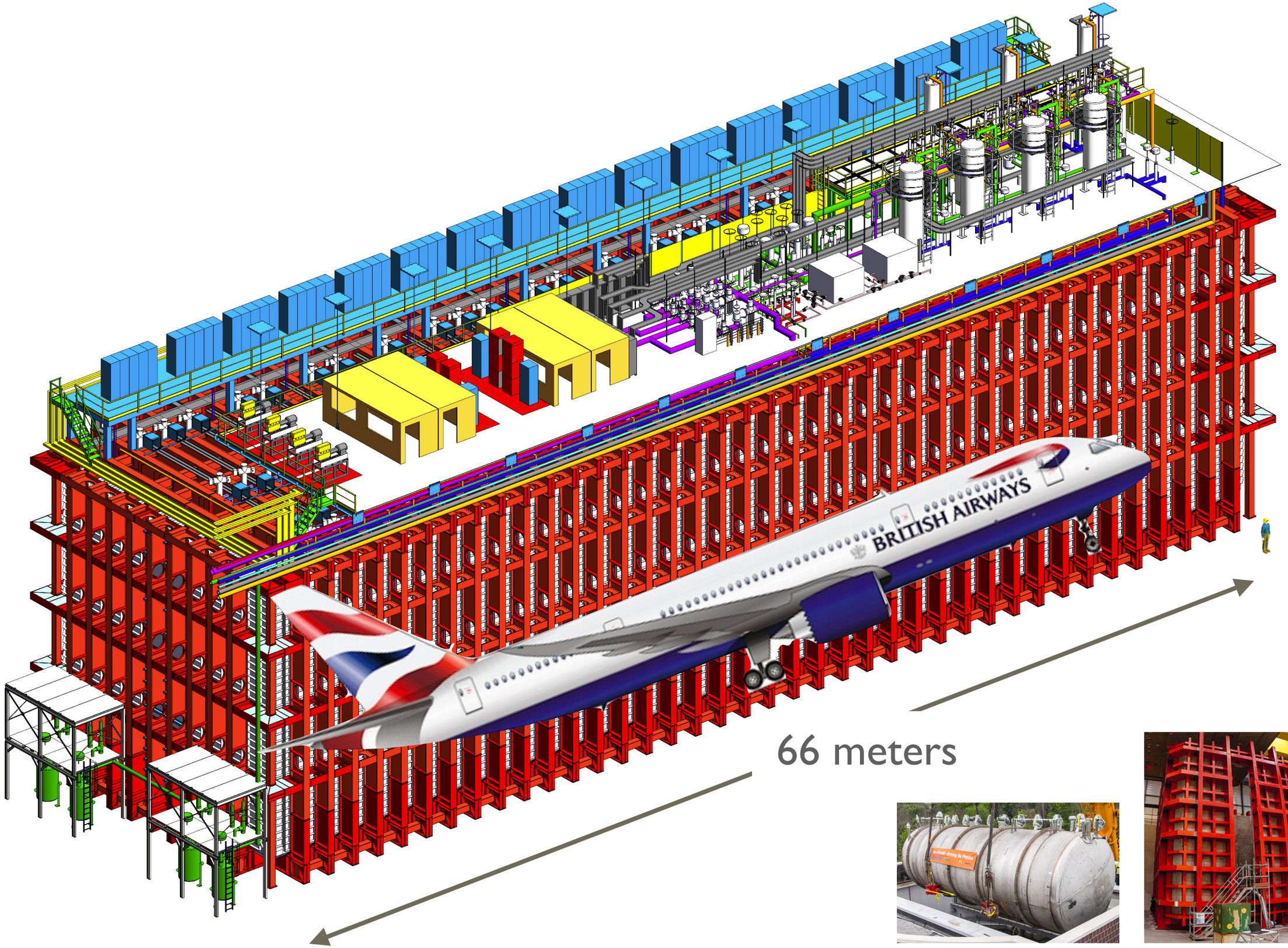
WHAT WE'VE LEARNT FROM MICROBOONE

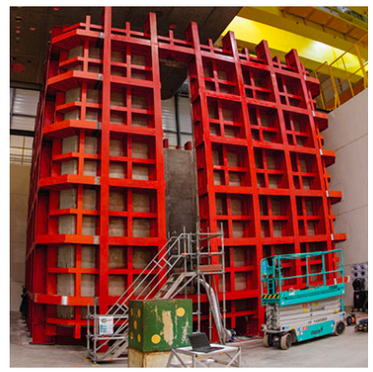
MicroBooNE has been **vital to improving our understanding of Liquid Argon detectors** and developing the tools to extract exciting physics results

- Cold electronics
- Signal processing and noise reduction in the data
- Automated reconstruction
- Neutrino interactions with argon

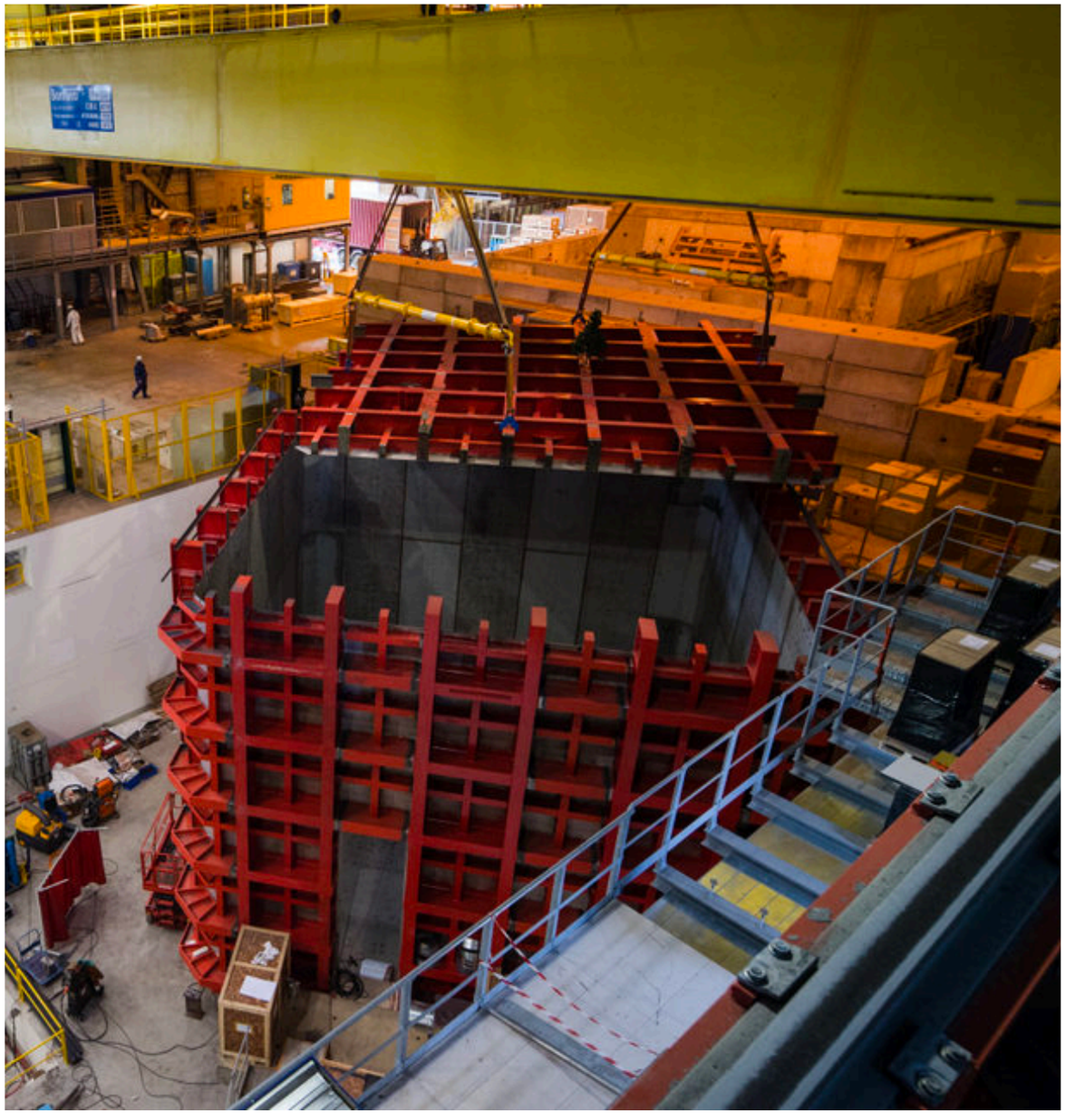
17 publications 36 public notes 16 PhD theses

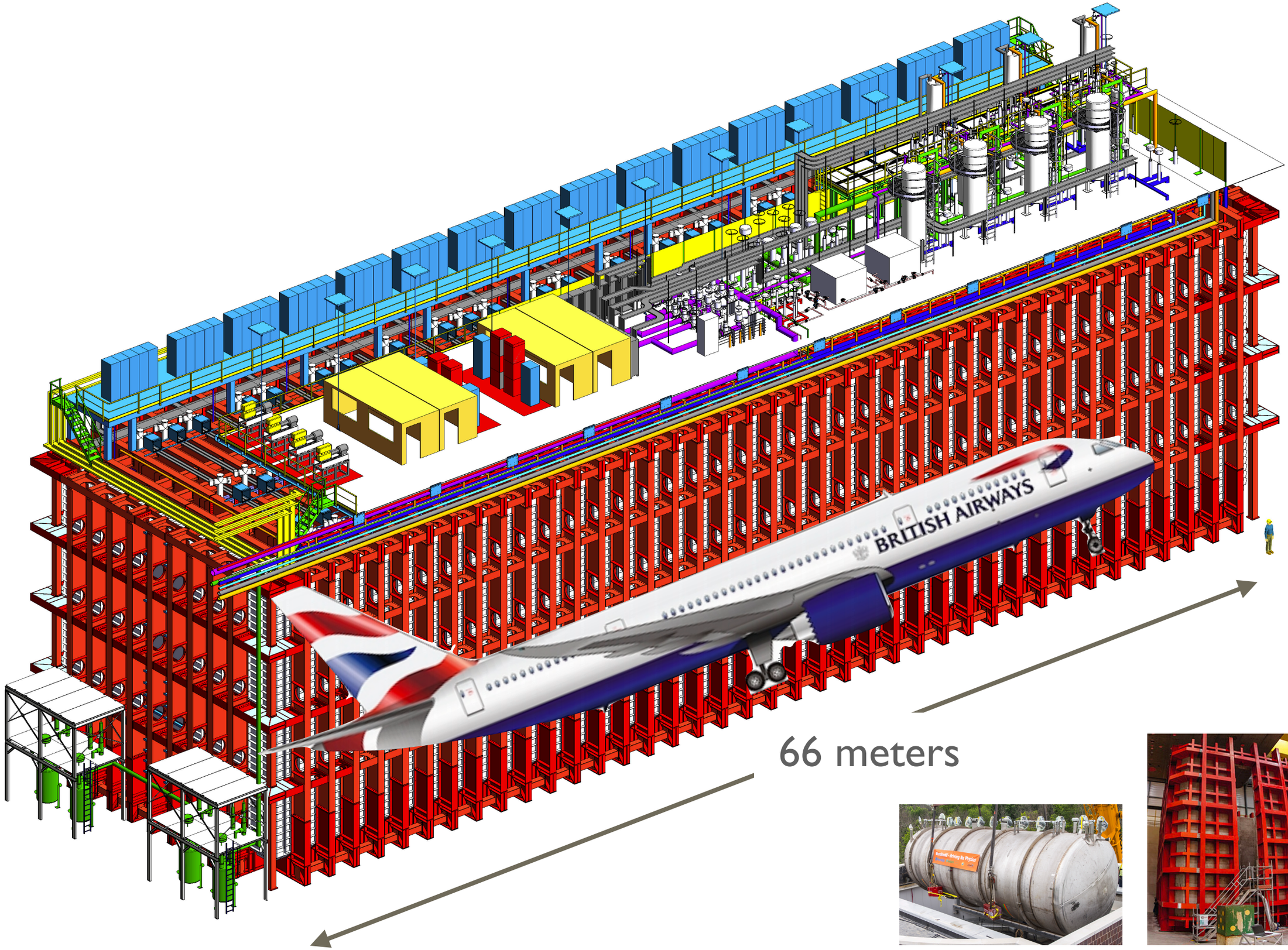

BRITISH AIRWAYS
66 meters

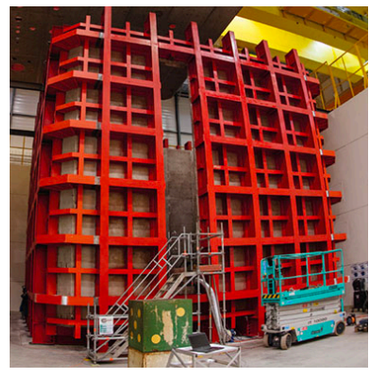

BRITISH AIRWAYS
66 meters

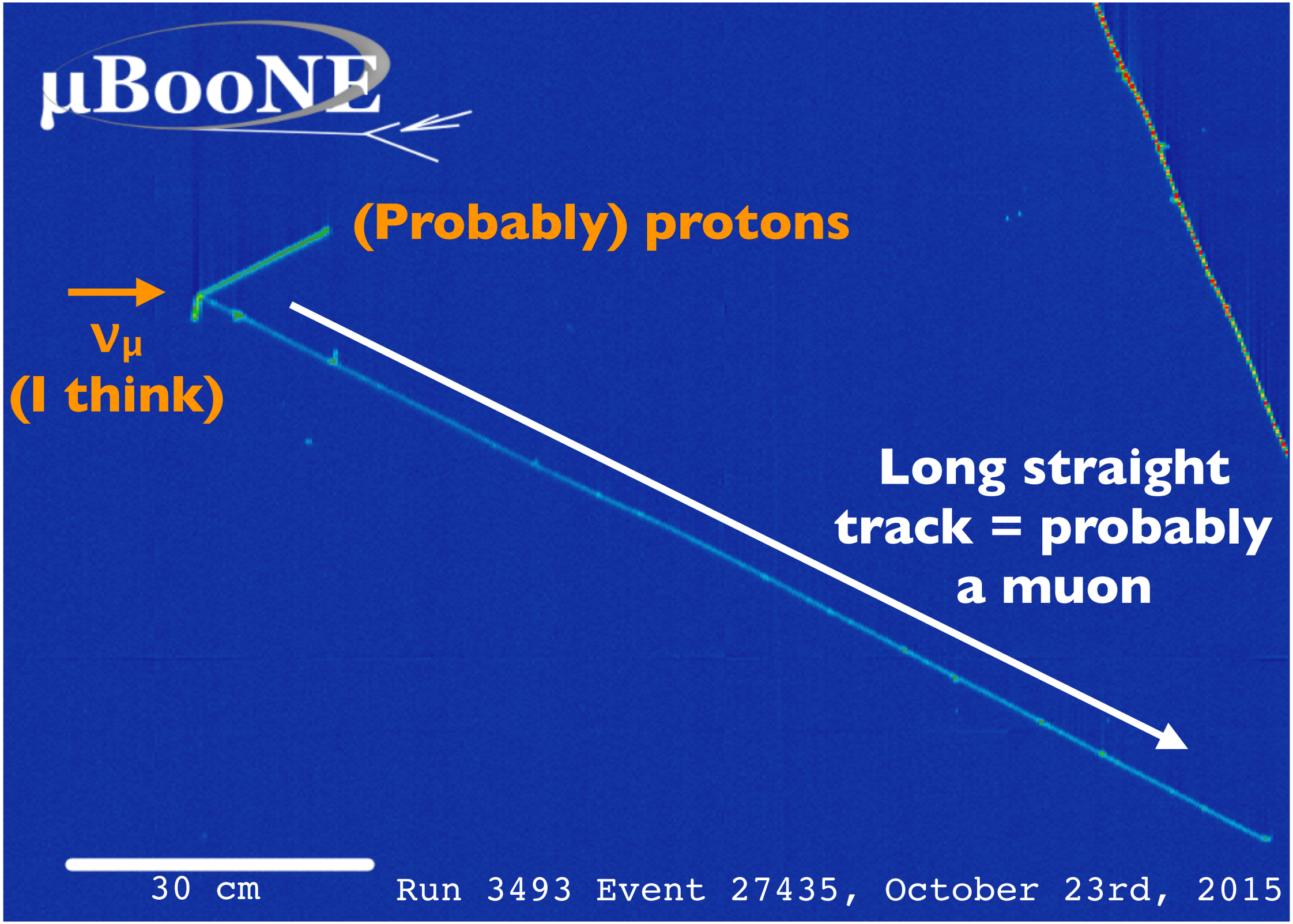


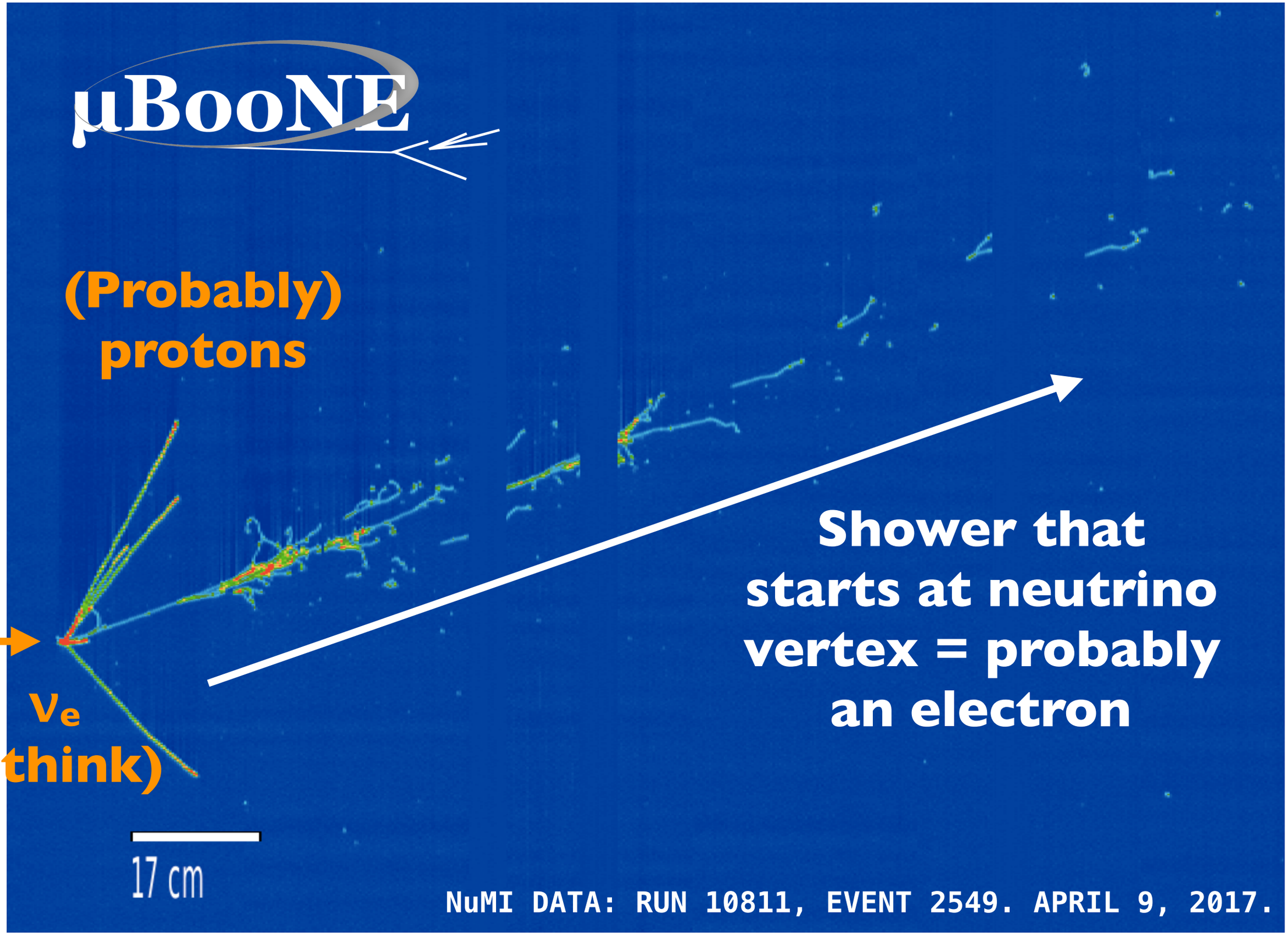
PROTODUNE(S)

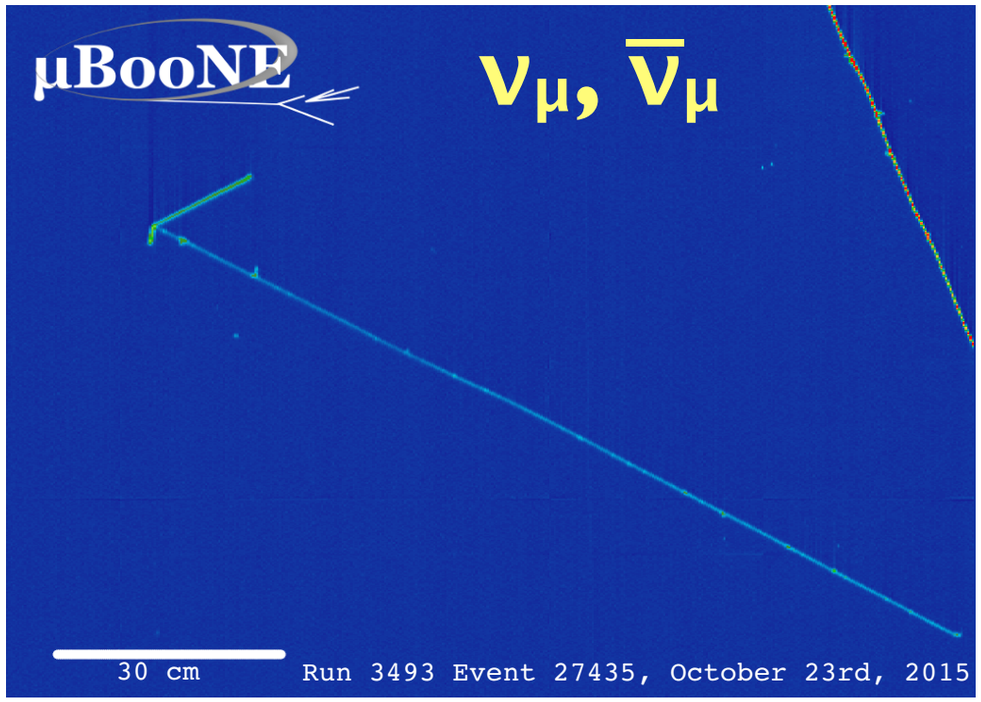


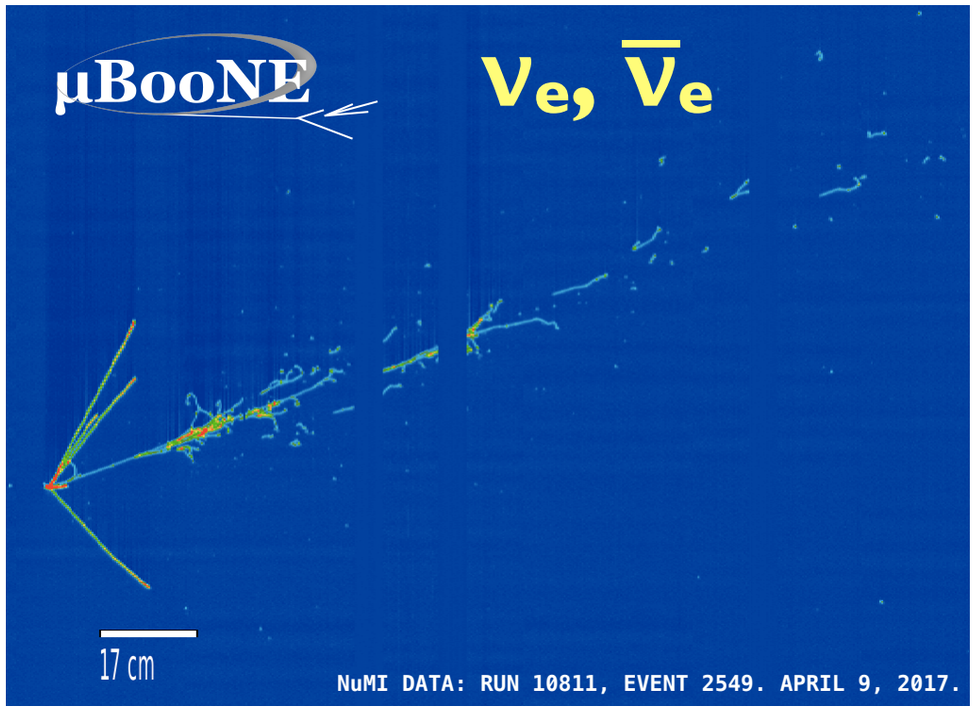

BRITISH AIRWAYS
66 meters

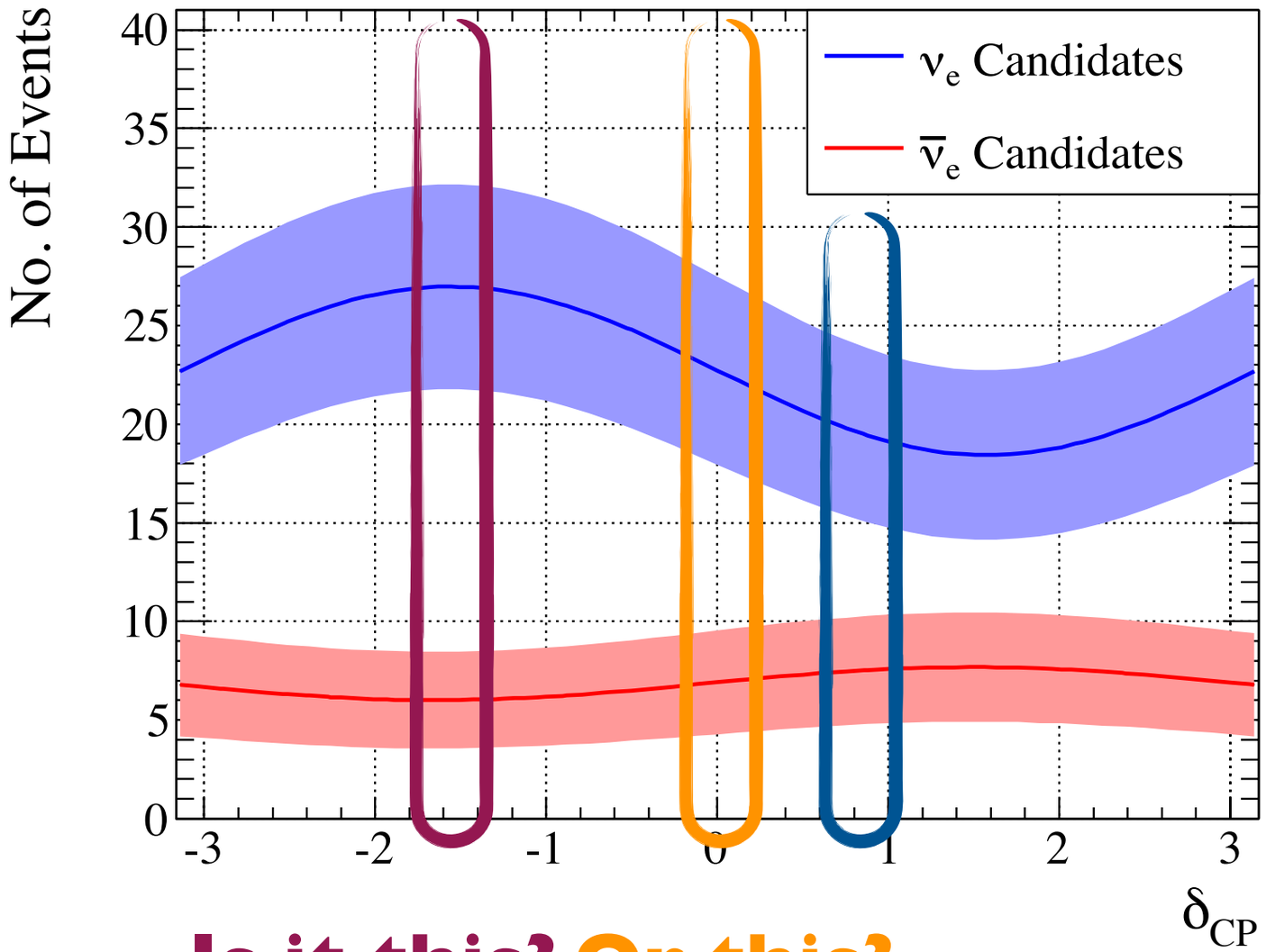



μBooNE
(Probably) protons
νμ
(I think)
Long straight track = probably a muon
30 cm
Run 3493 Event 27435, October 23rd, 2015


μBooNE
(Probably) protons
Shower that starts at neutrino vertex = probably an electron
ν_e (I think)
17 cm
NuMI DATA: RUN 10811, EVENT 2549. APRIL 9, 2017.





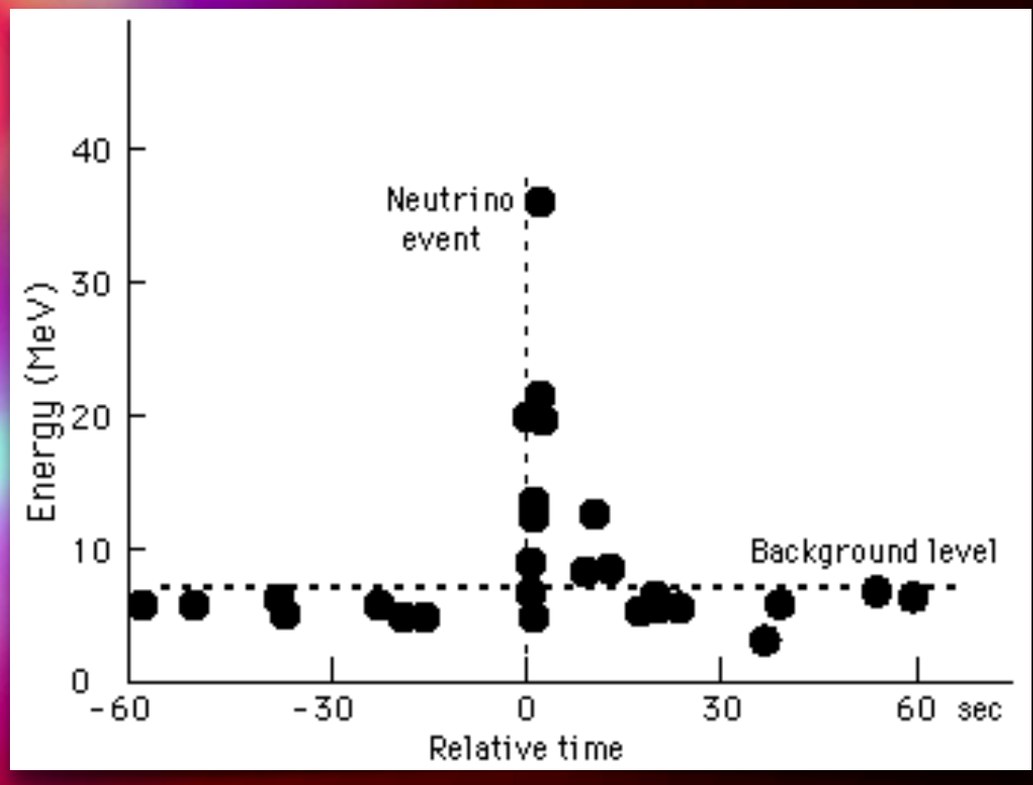


Is it this? Or this?

Or this?

SUPERNOVA NEUTRINOS

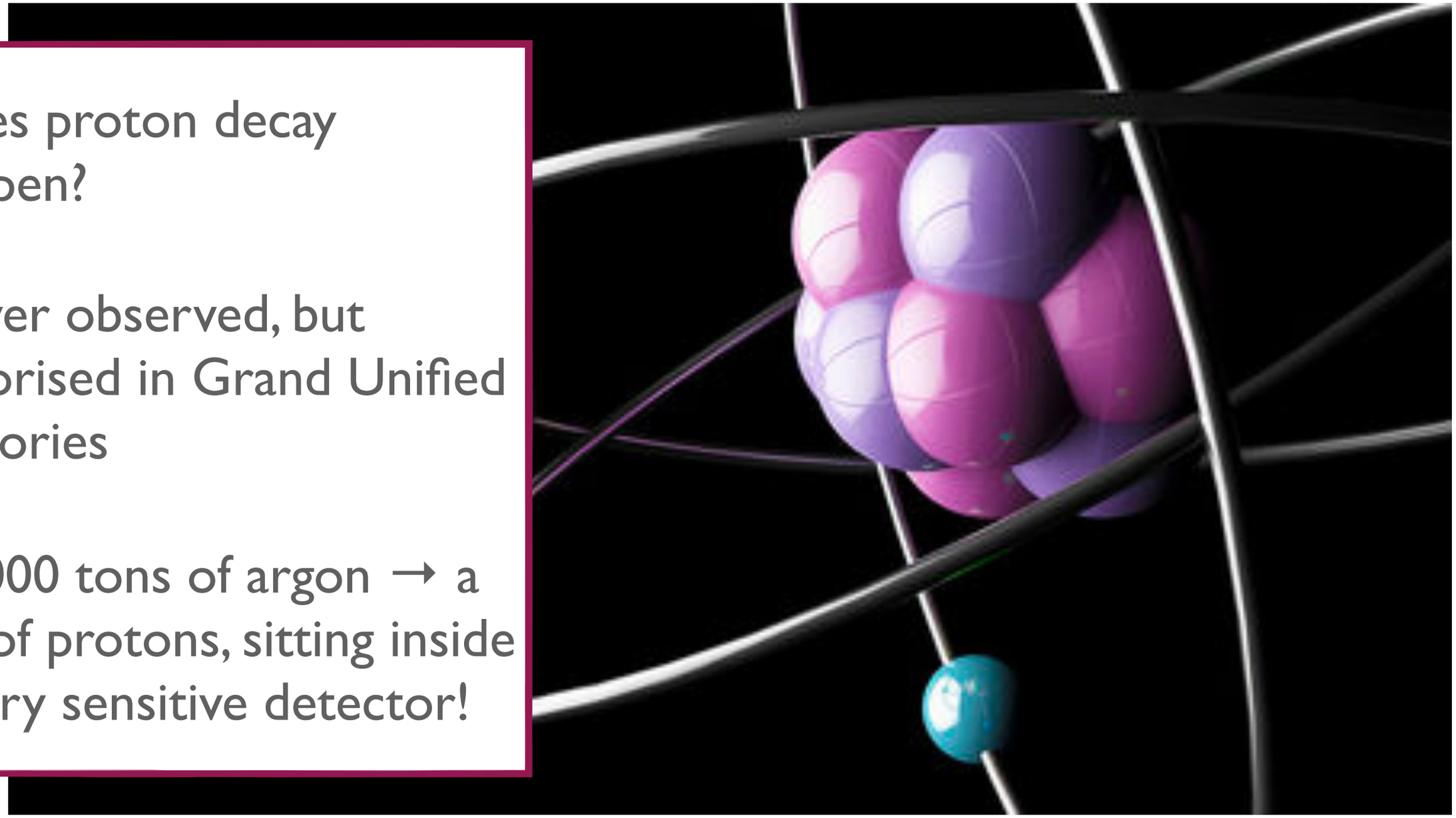
Super-Kamiokande: 12
IMB: 8
Baksan: 5



Supernova 1987a

PROTON DECAY

- Does proton decay happen?
- Never observed, but theorised in Grand Unified Theories
- 40,000 tons of argon → a lot of protons, sitting inside a very sensitive detector!



DUNE

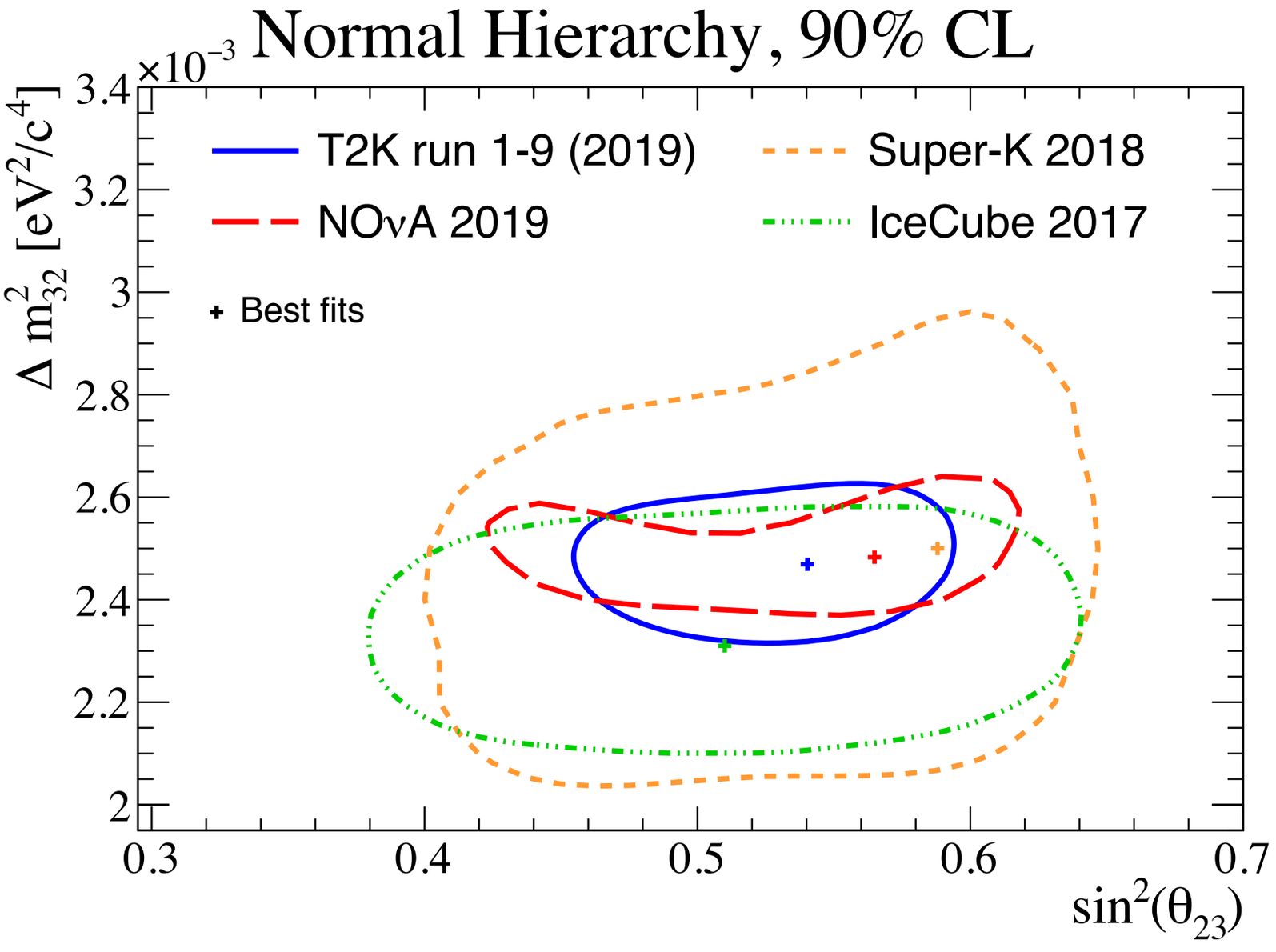
The detection of neutrino oscillation 18 years ago has opened the door to new discoveries beyond the Standard Model of Particle Physics.

Neutrinos could hold the answer to fundamental questions about the nature of the universe and neutrino oscillation experiments give us a new tool to study them.

We have already learned a lot from past and current experiments, and with DUNE on the horizon we look forward to new discoveries!

THANK YOU FOR LISTENING

MEASUREMENT OF $\sin^2\theta_{23}$ AND Δm^2_{32}



WHAT CAN WE SAY ABOUT δ_{CP}?

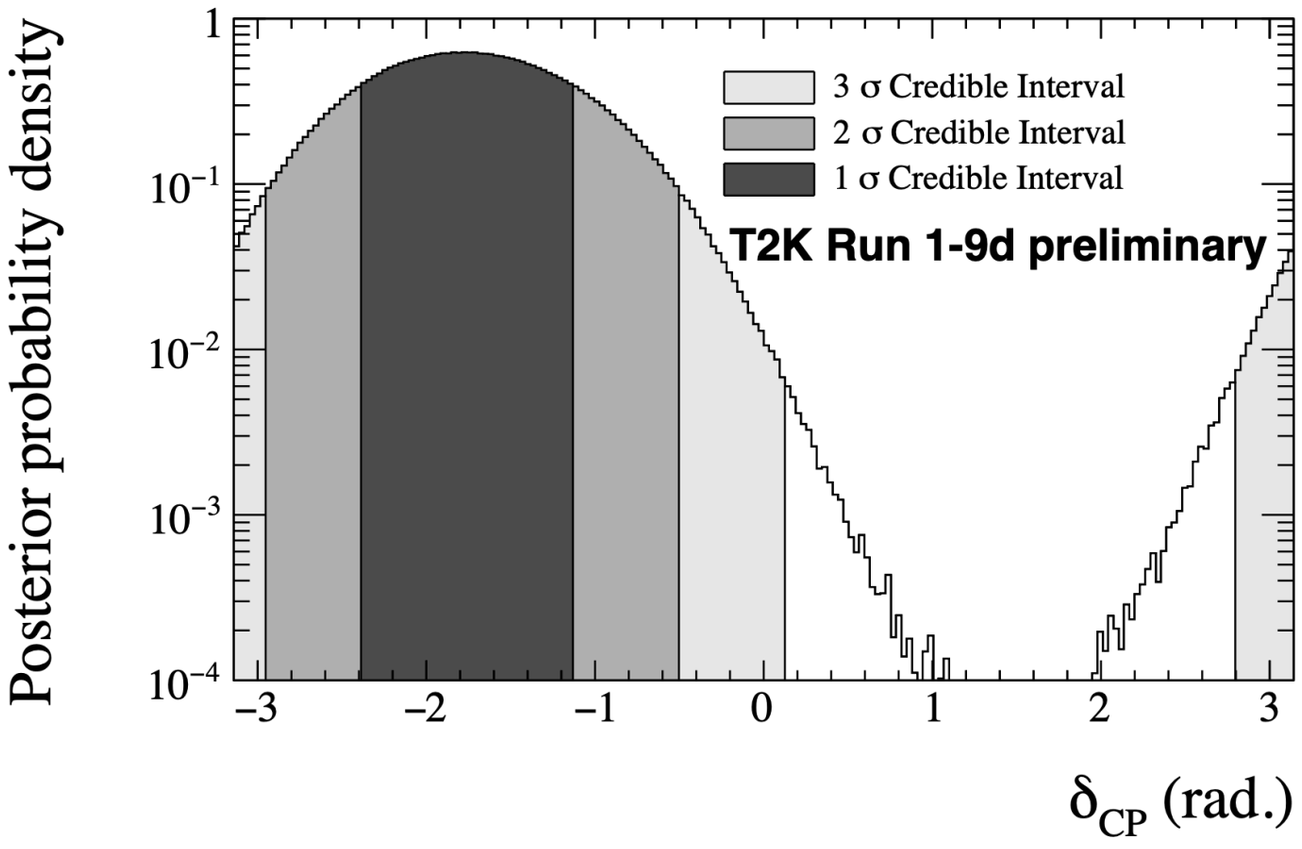


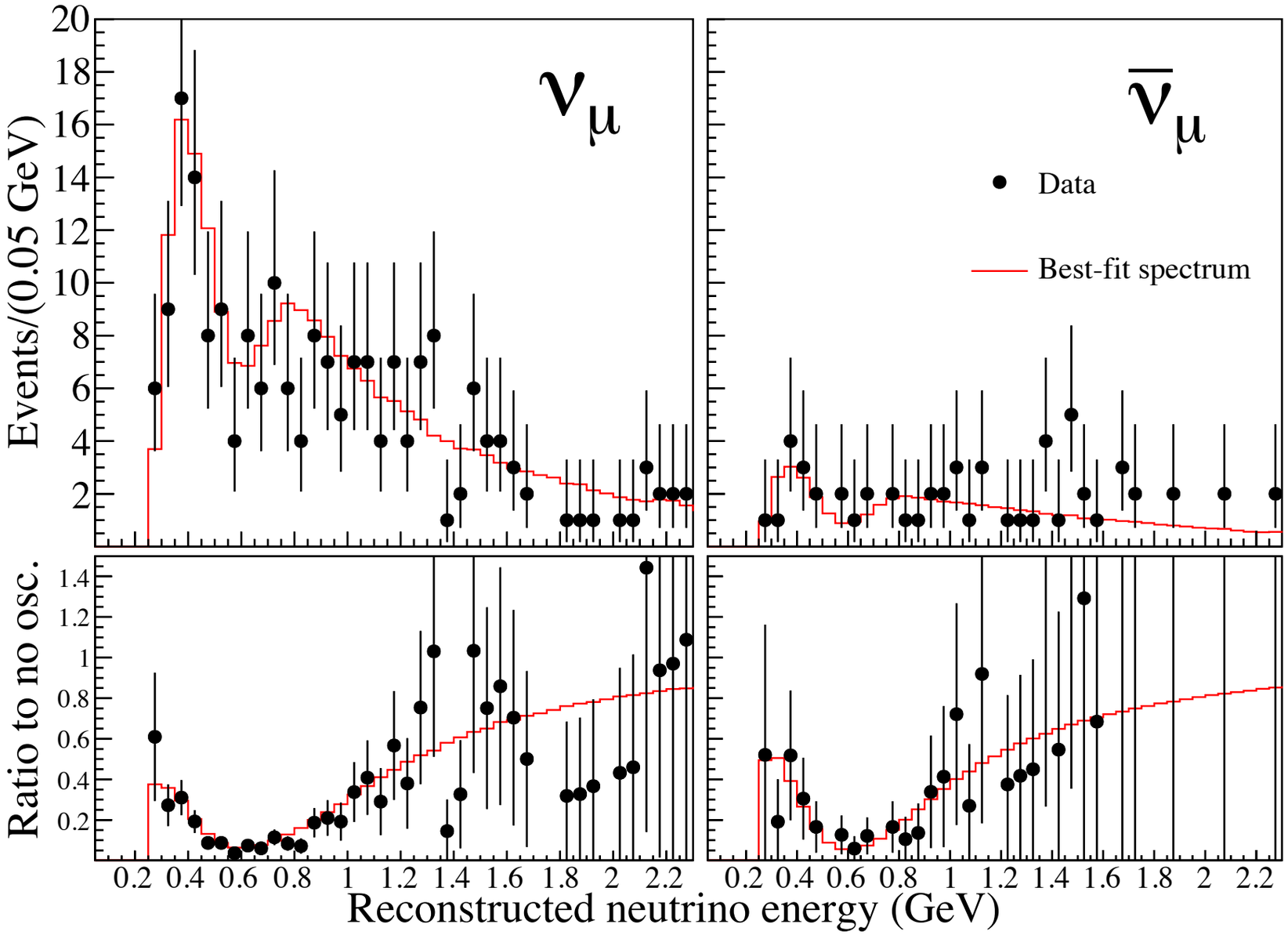
Figure from A. Kaboth, NuPhys 2018

- Best-fit value for δ_{CP} **consistent with maximal CP violation**: $\delta_{CP}=-\pi/2$, $\sin\delta_{CP}=-1$
- **Exclude CP conservation**: $\delta_{CP}=0,\pm\pi$ (ie. $\sin\delta_{CP} = 0$) at 2σ
- Result stronger than expected sensitivity

FIT FOR THE OSCILLATION PARAMETERS

Phys. Rev. Lett. 121, 171802 (2018)

ν_μ
240 events



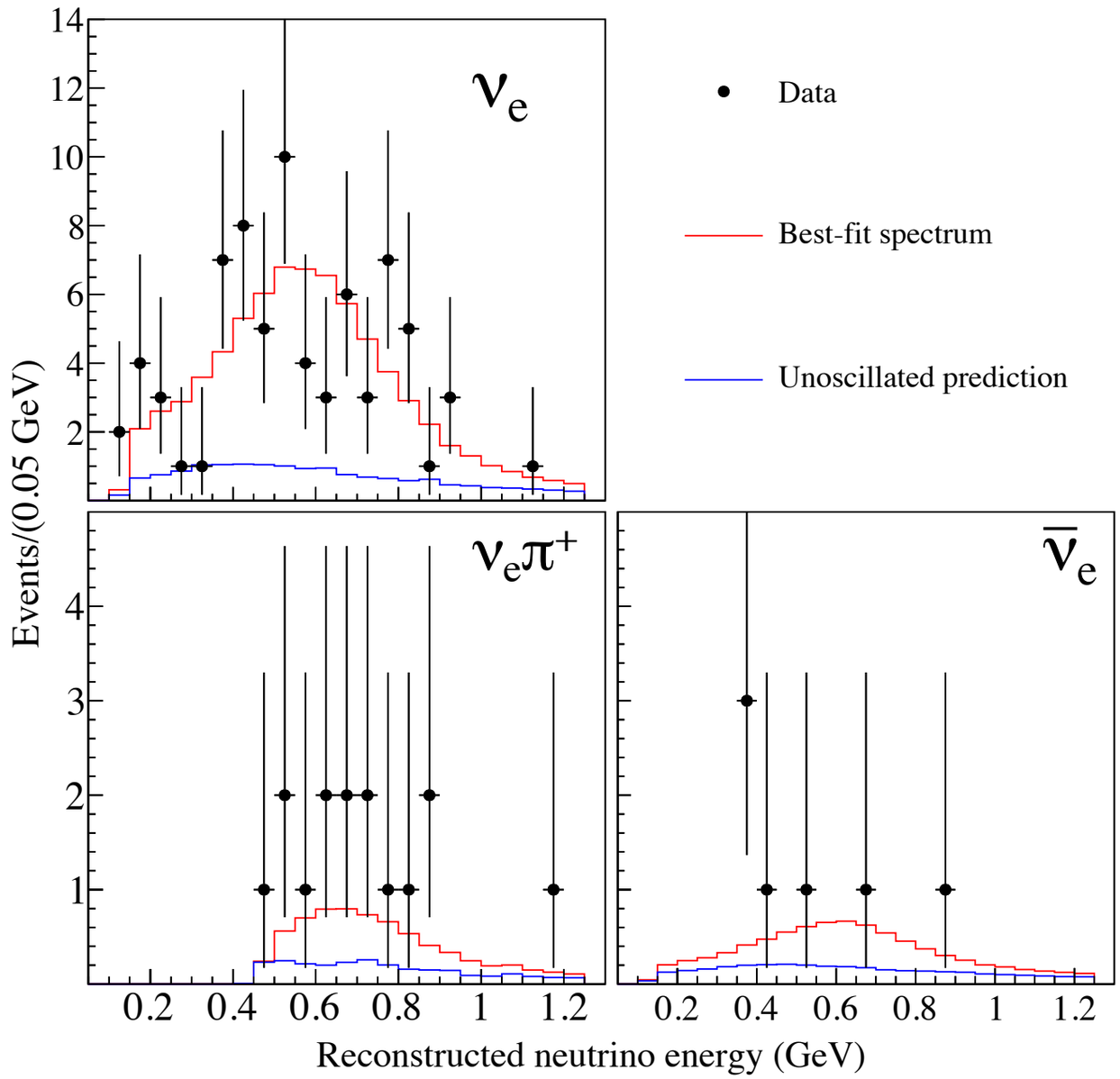
$\overline{\nu}_\mu$
68 events

FIT FOR THE OSCILLATION PARAMETERS

Phys. Rev. Lett. 121, 171802 (2018)

ν_e
74 events

$\nu_e\pi^+$
15 events



$\bar{\nu}_e$
7 events