CHANGING FLAVOR: THE UNIVERSE'S WEIRDEST PARTICLE

(NEUTRINO PHYSICS)

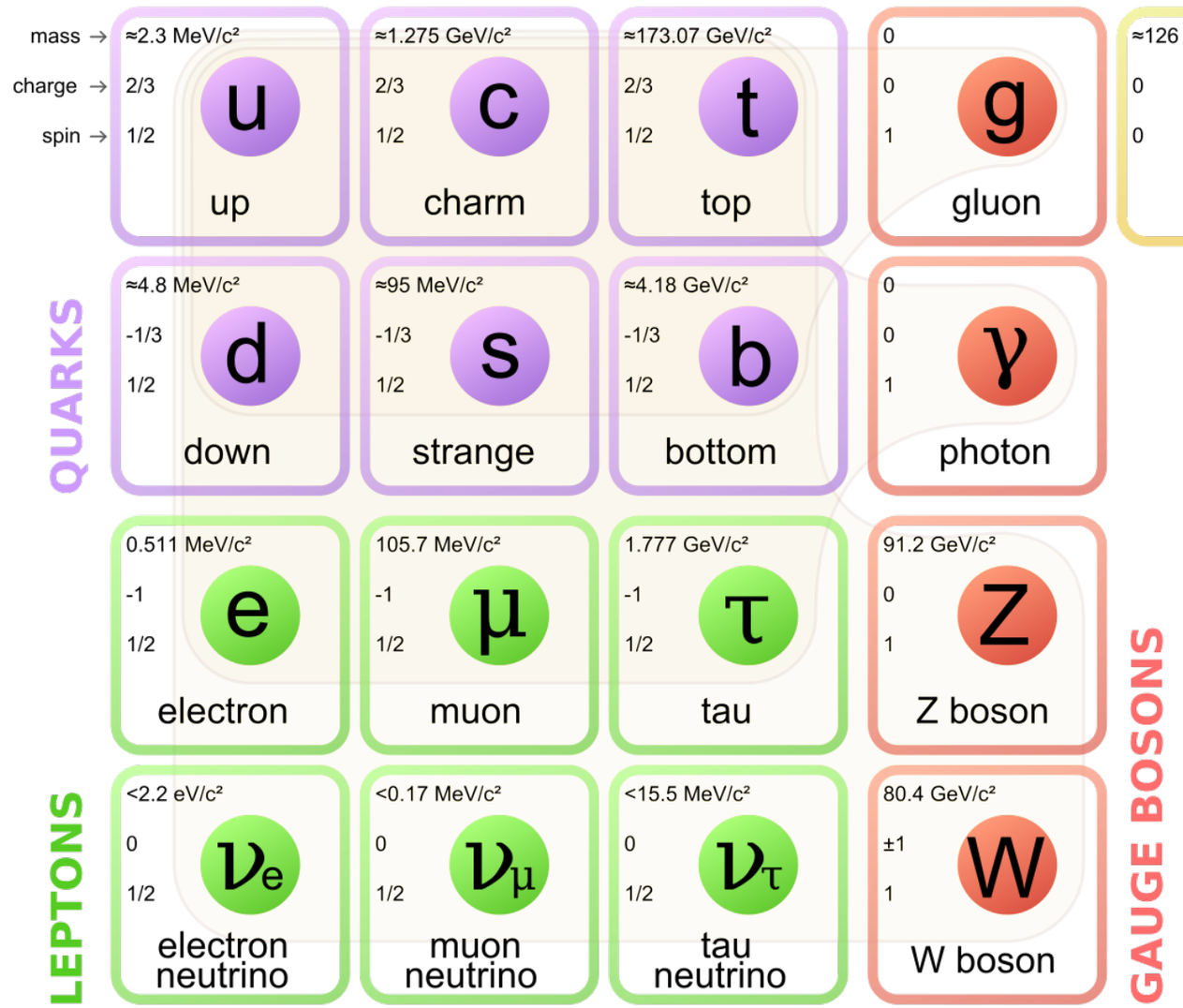
Kirsty Duffy, Fermilab

2020 Undergraduate Lecture Series

11th June 2020

Fermilab

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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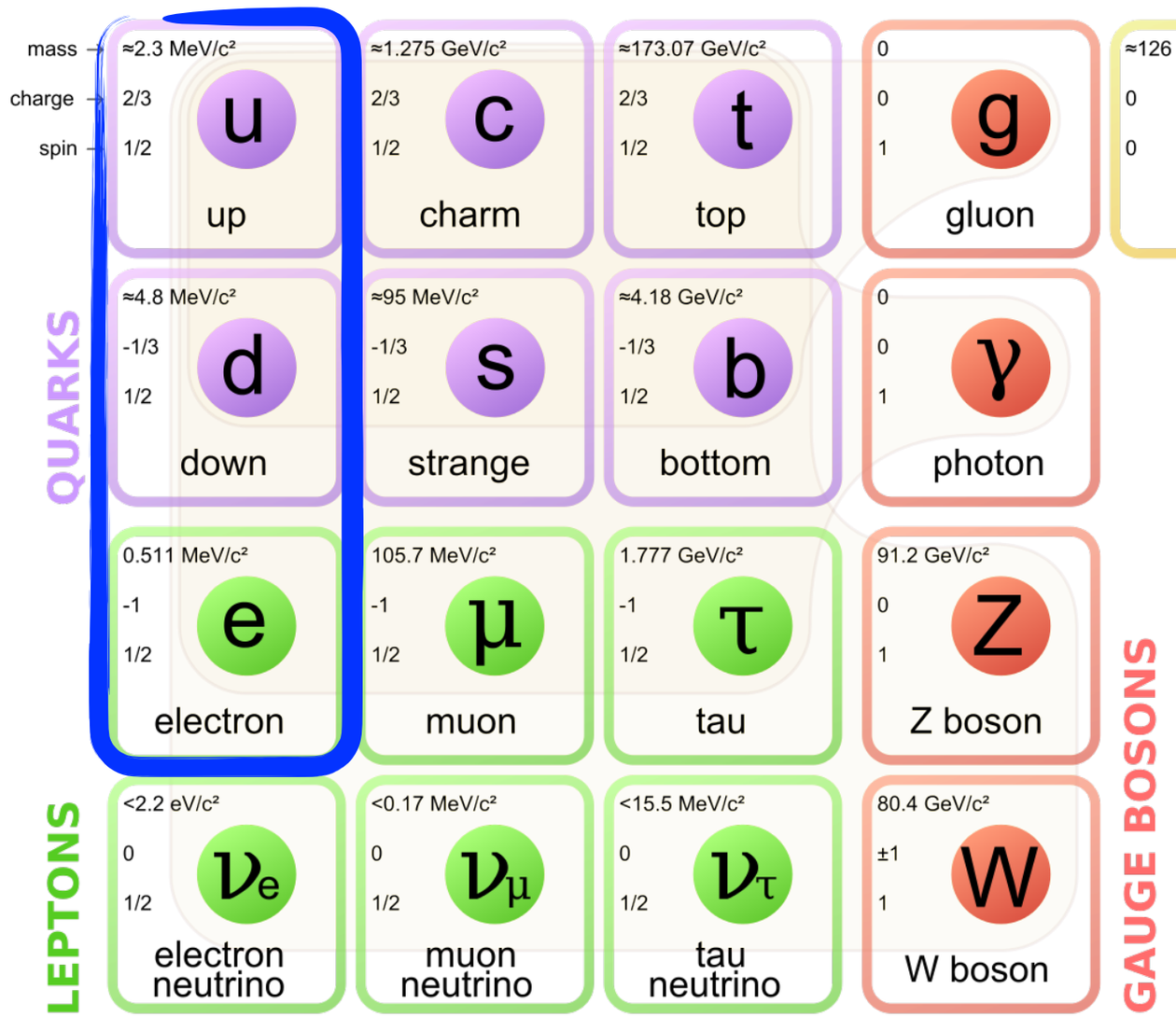

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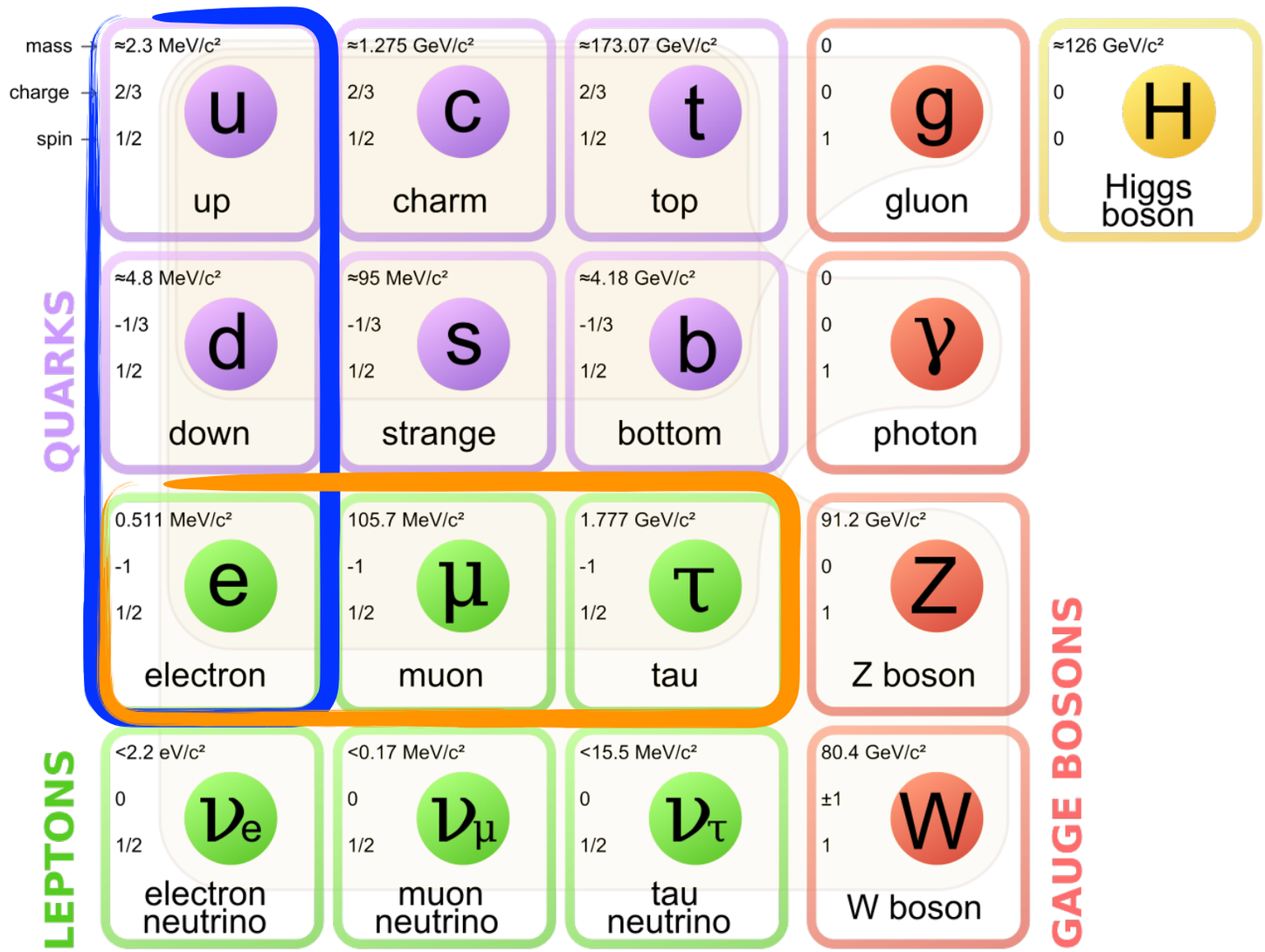

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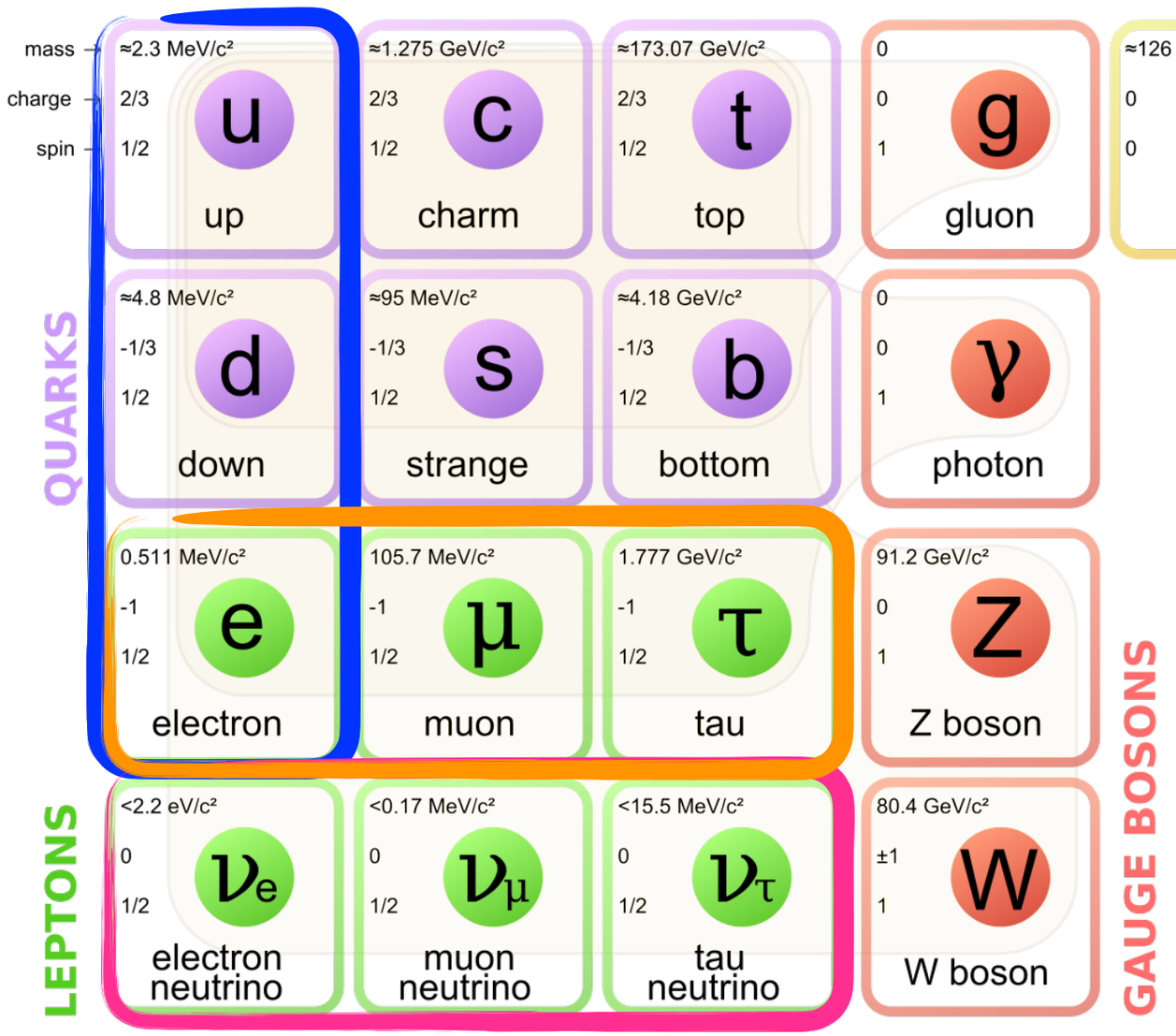

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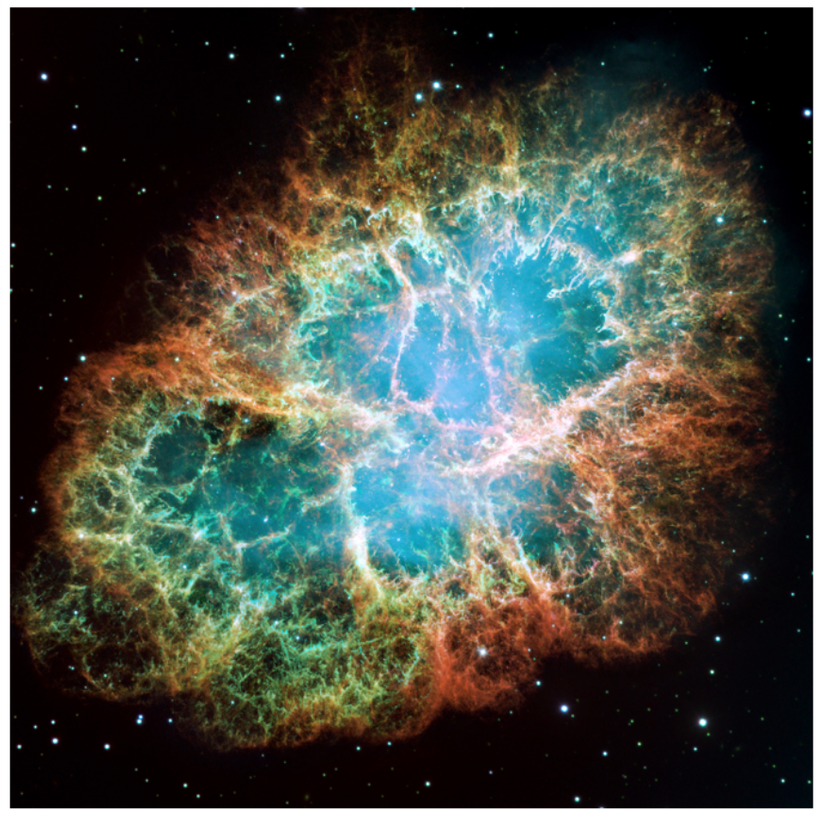

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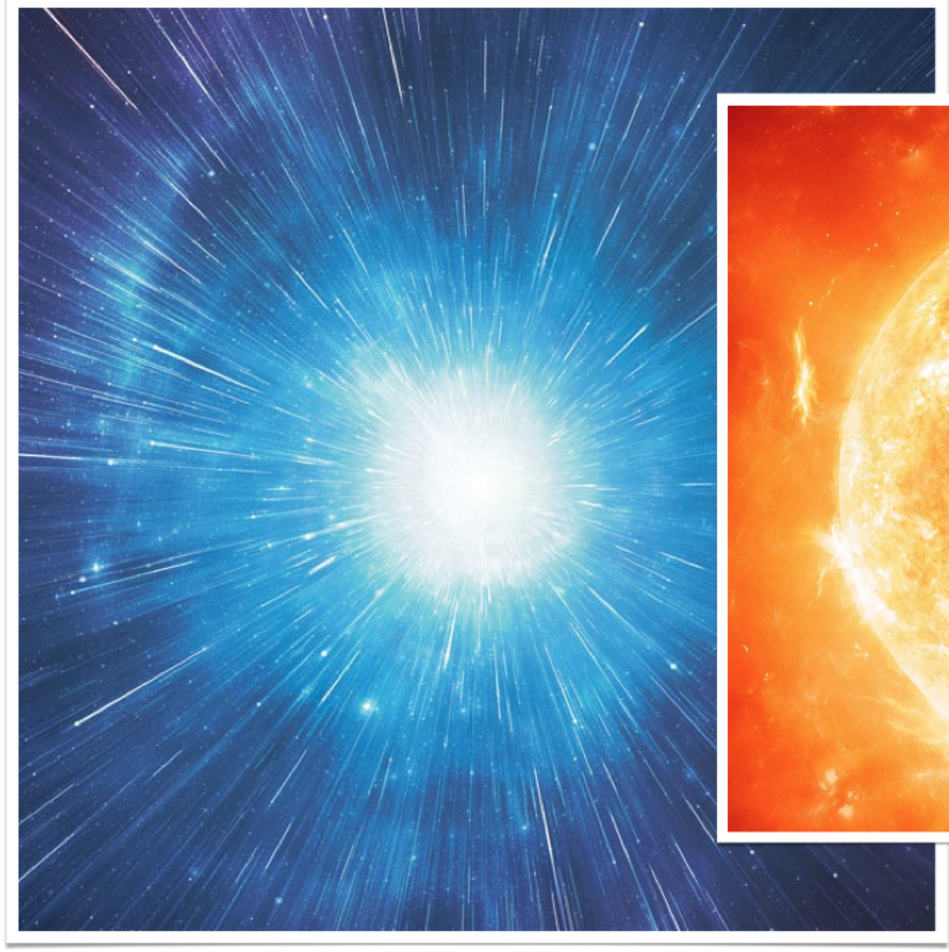

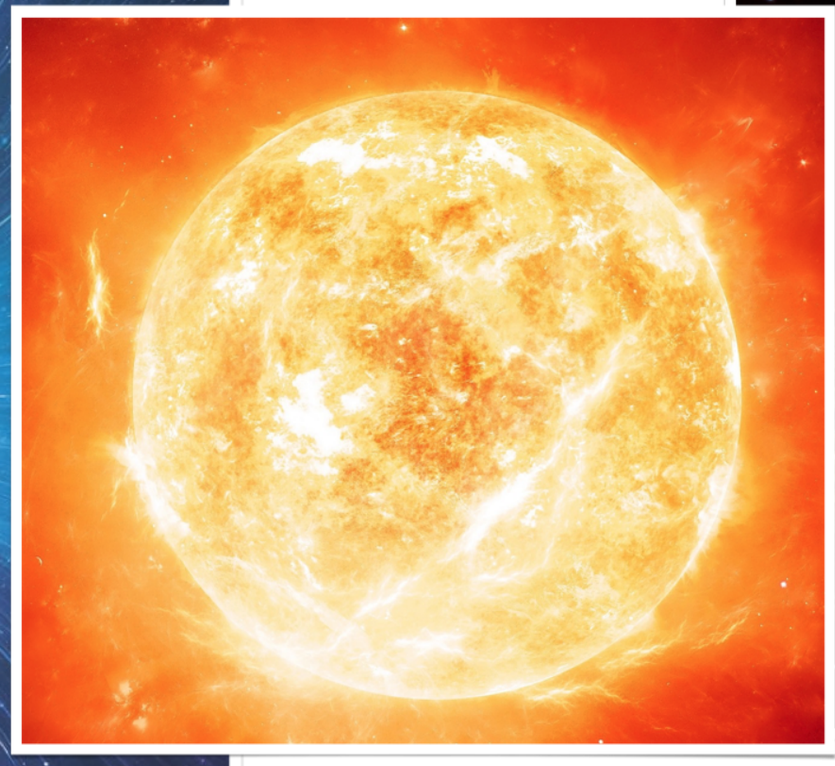

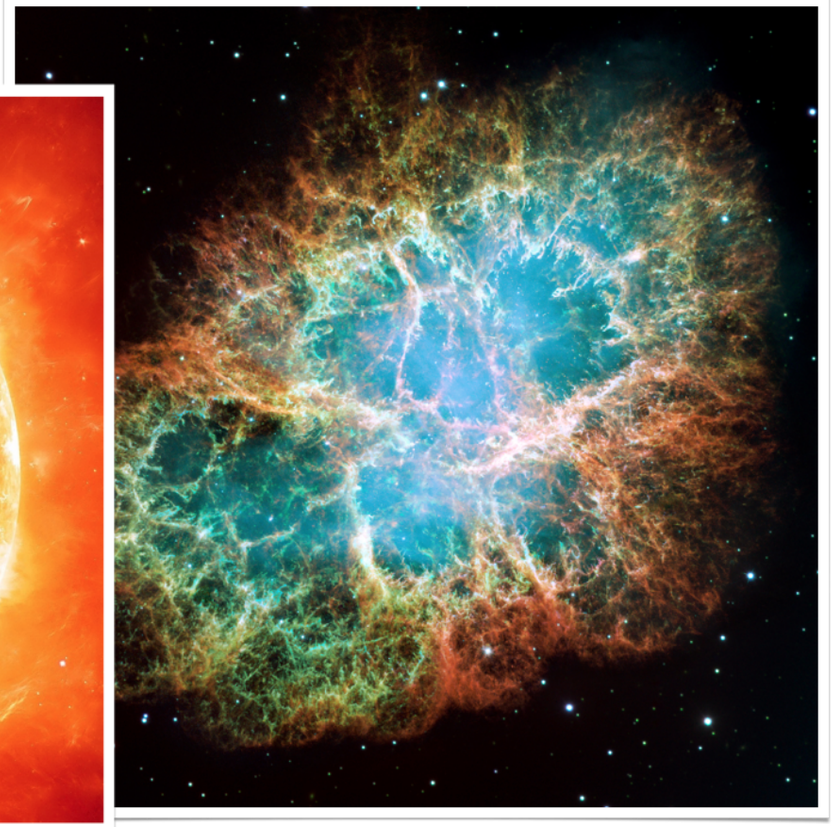

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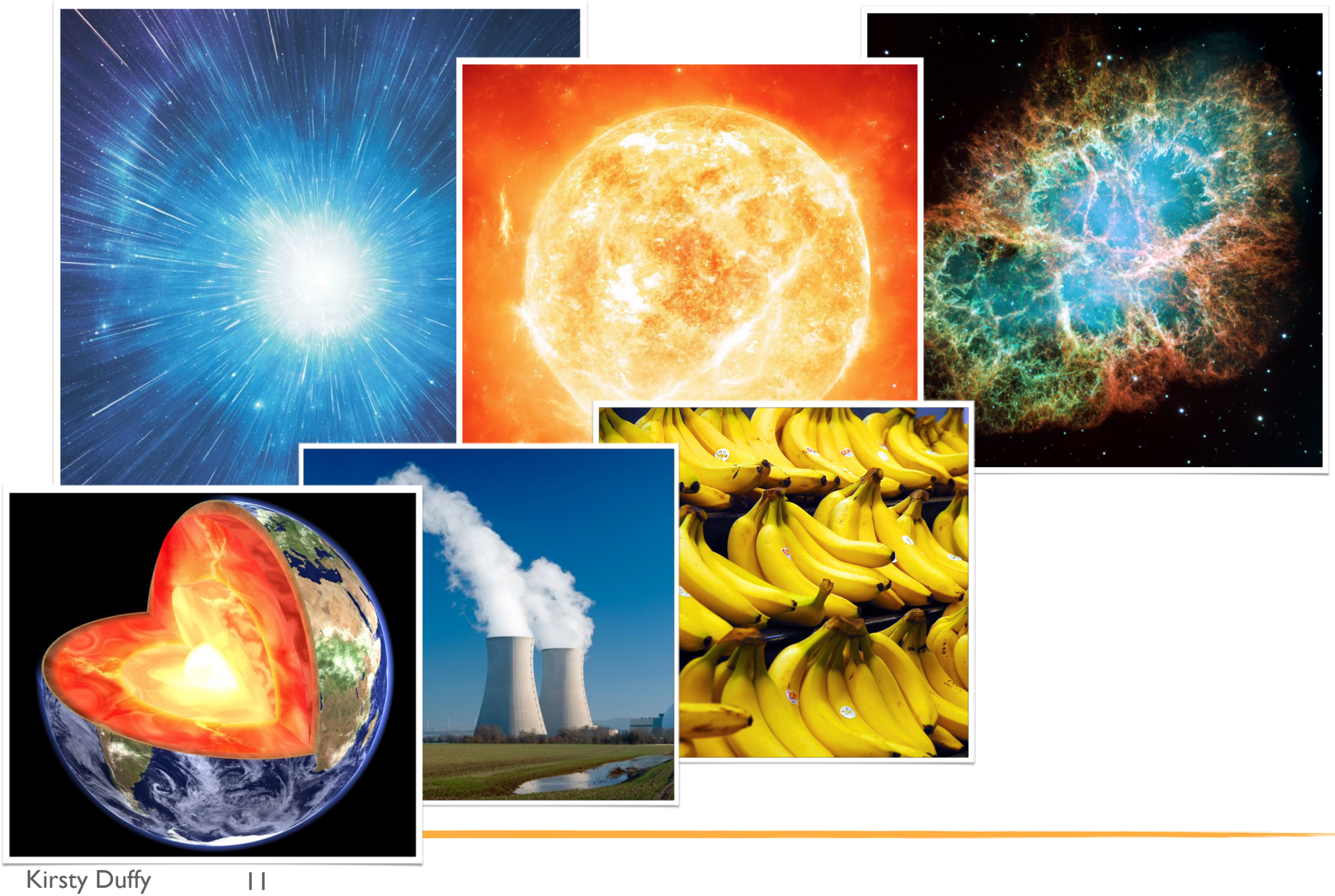

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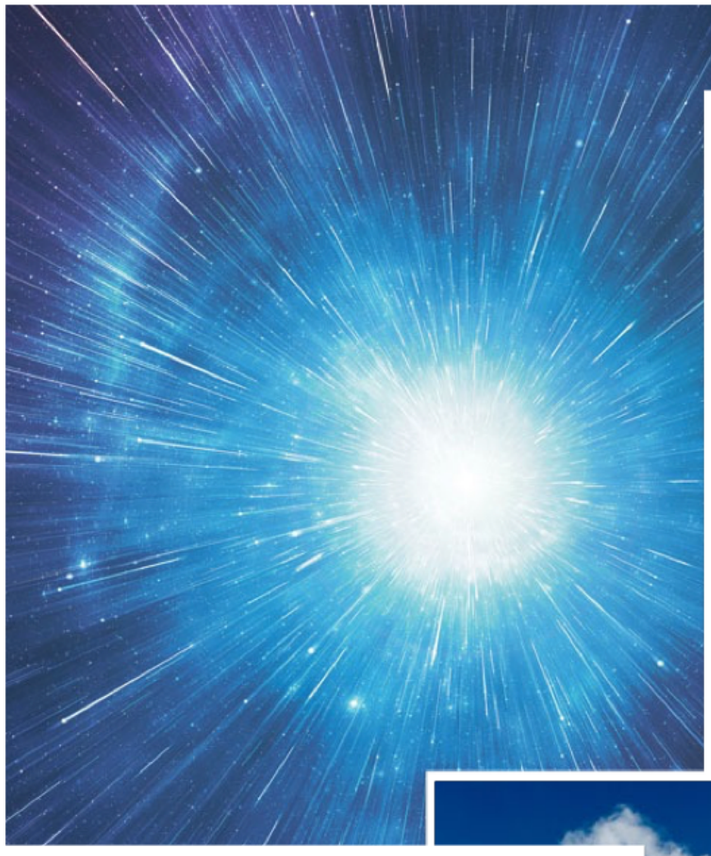
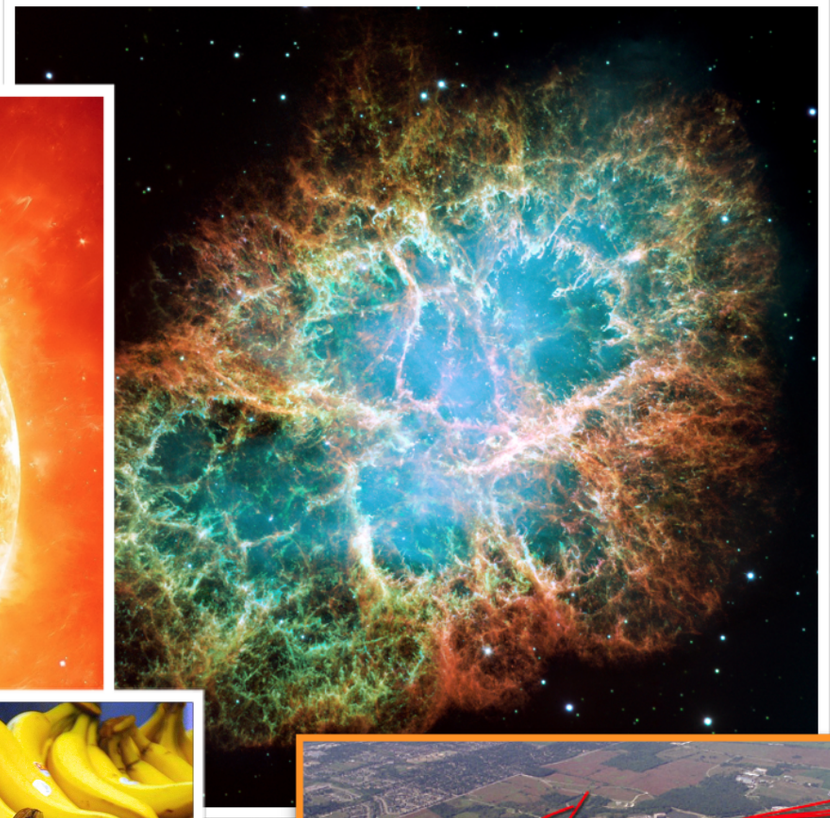
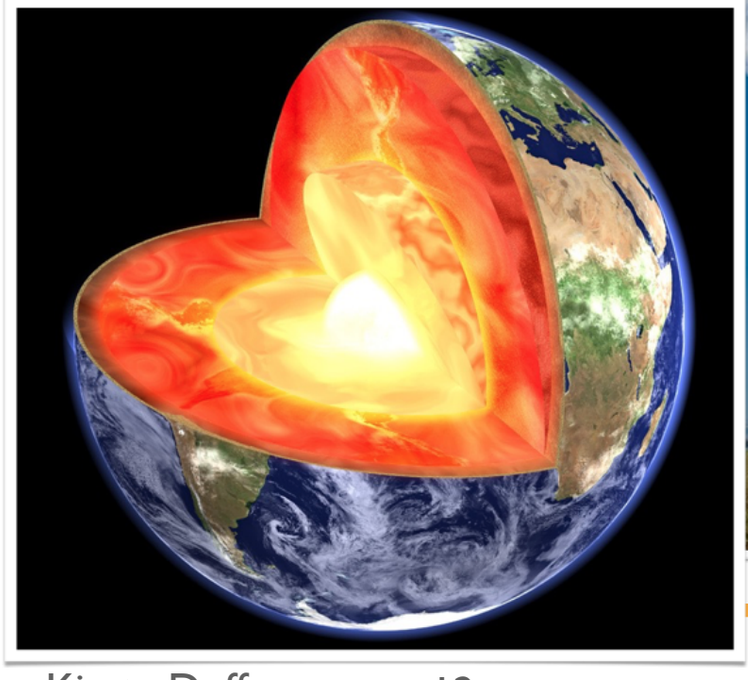
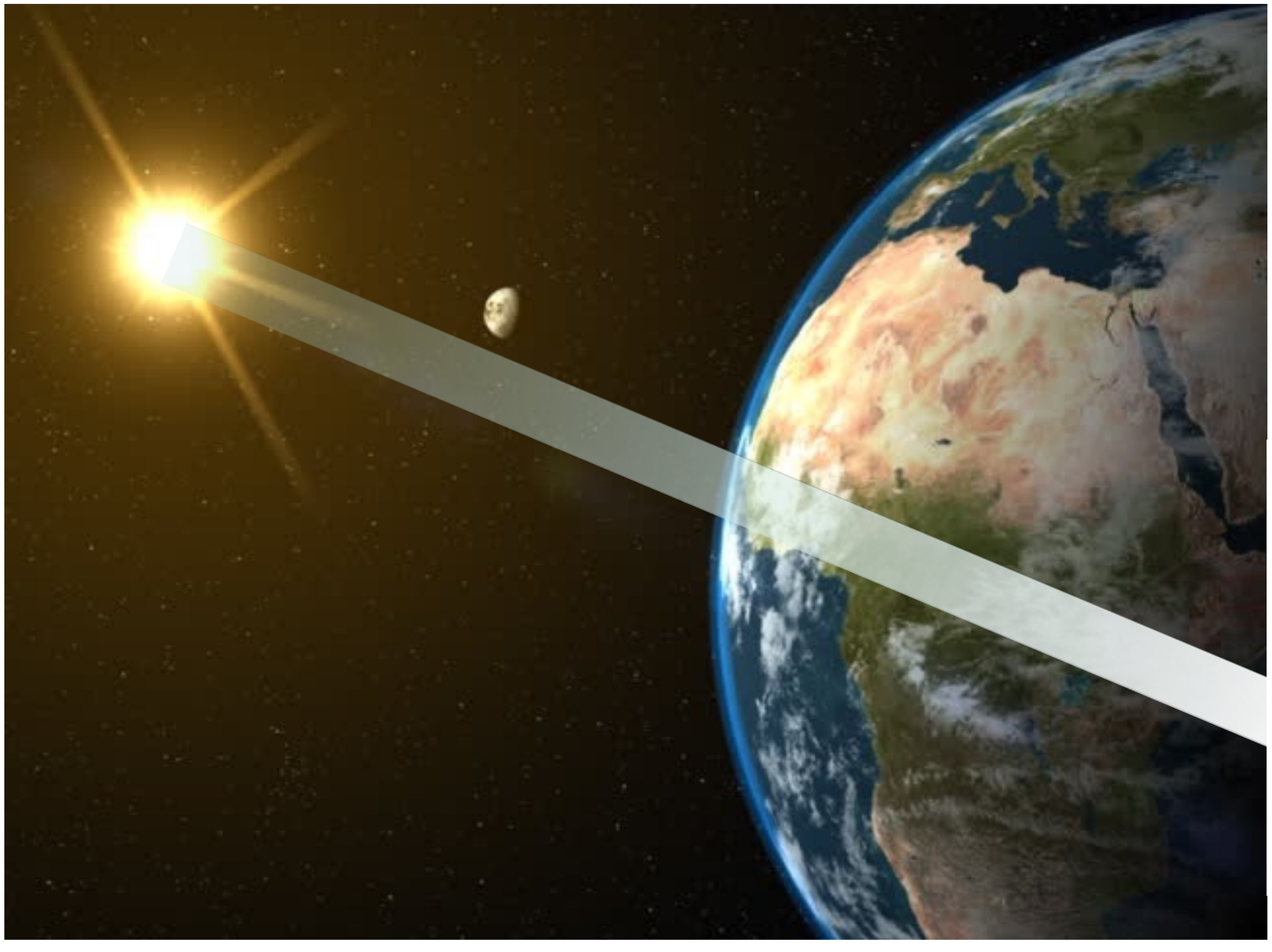




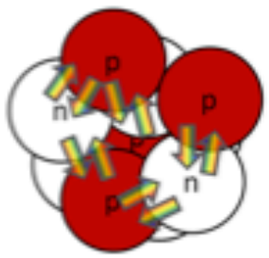
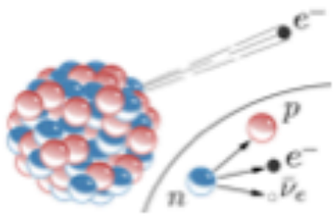


…BUT THEY ALMOST NEVER INTERACT



WHY IS THAT?

Do neutrinos interact via...

		Strength	Range	Force carrier
...strong force?		1	10^{-15} m (diameter of medium nucleus)	gluons g
...electro magnetism?		1/137	infinite	photon γ
...weak force?		10^{-6}	10^{-18} m (0.1% of proton diameter)	W&Z bosons
...gravity?		6×10^{-39}	infinite	?

A. Schukraft

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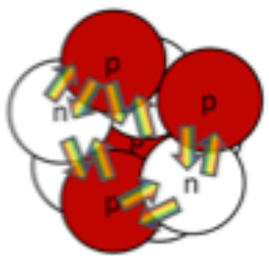
✗ ...strong force?		1	10^{-15} m (diameter of medium nucleus)	gluons g
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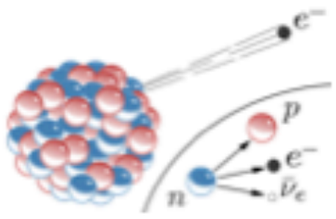
✔ ...weak force?		10^{-6}	10^{-18} m (0.1% of proton diameter)	W&Z bosons
✔ ...gravity?		6×10^{-39}	infinite	?

If they have mass - we'll get back to that…

A. Schukraft

SOME HISTORY

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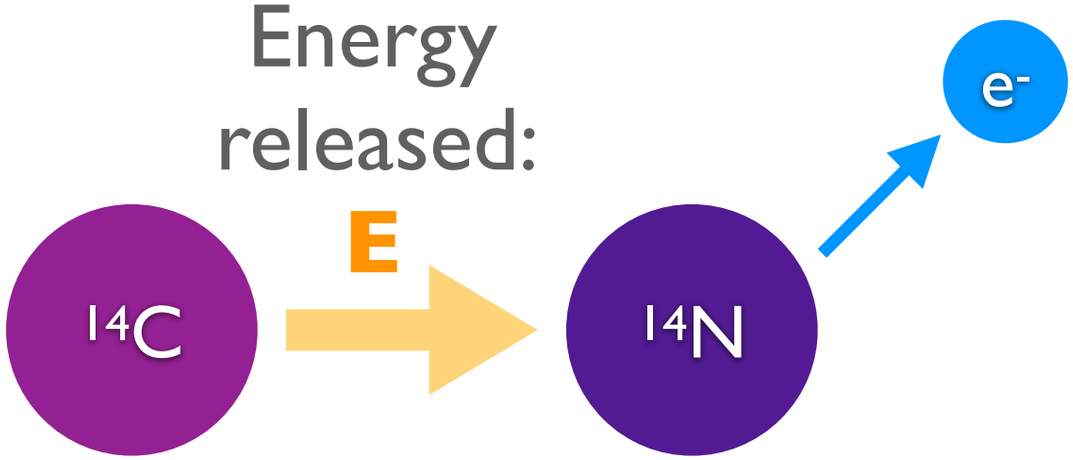
Energy released:



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

General 2-body problem:

$A \rightarrow B + C$

Conservation of momentum:

$p_A = p_B + p_C$

Conservation of energy:

$E_A = E_B + E_C$

$\rightarrow E_A^2 = m_Bc^2 + p_B^2 + m_Cc^2 + p_C^2$

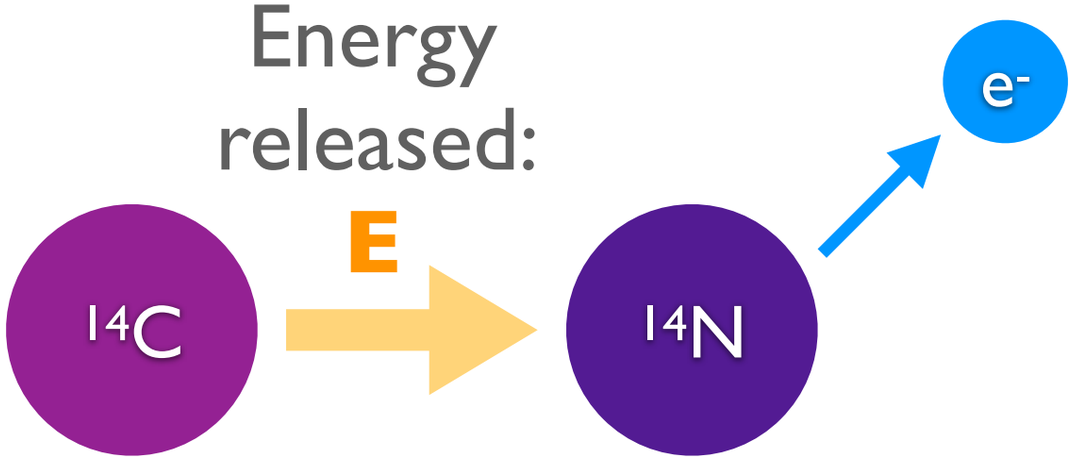
If p_B and p_C are our only unknowns → 2 equations with 2 unknowns, can solve exactly

Let's make it easier: assume $p_A = 0 \rightarrow p_B = -p_C$

$$p_C = 0.5 \times \sqrt{(E_A^2 - m_Bc^2 - m_Cc^2)}$$
$$p_B = -0.5 \times \sqrt{(E_A^2 - m_Bc^2 - m_Cc^2)}$$

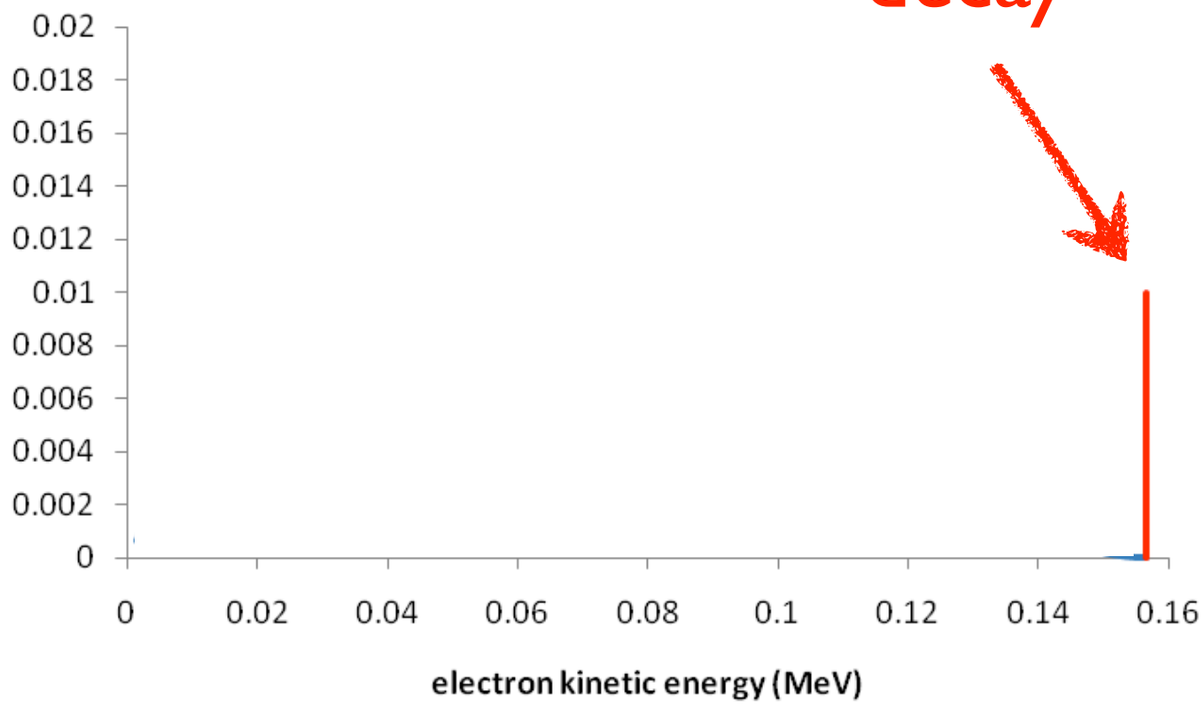
SOME HISTORY

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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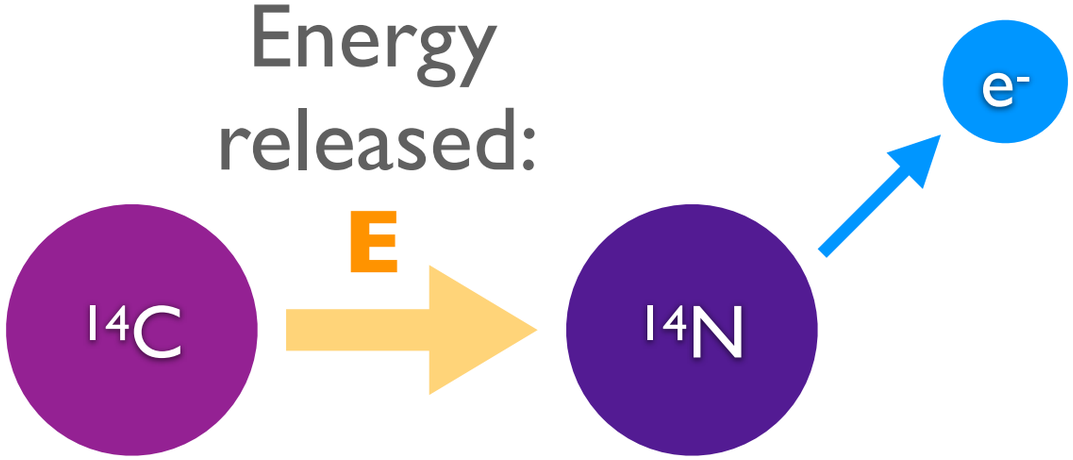
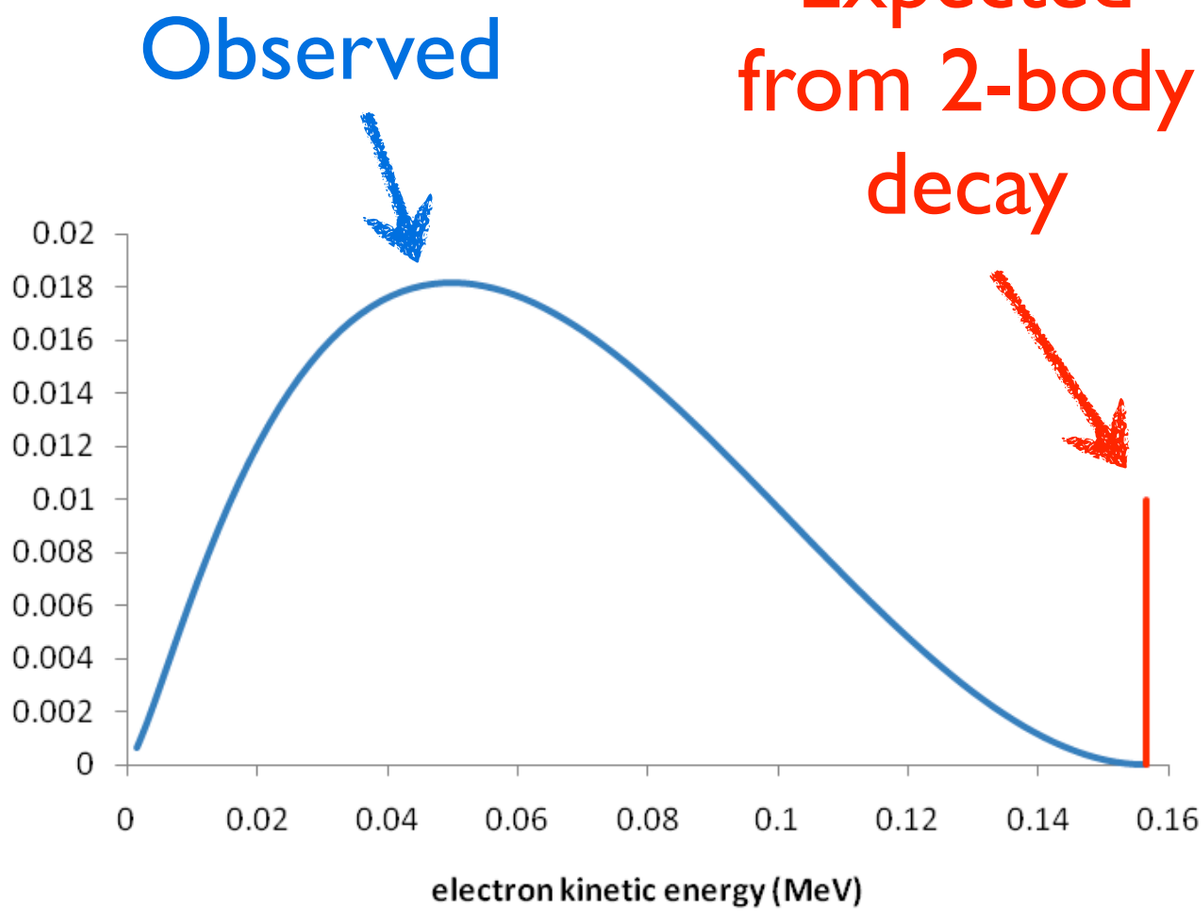




- **BIG PROBLEM**
- Energy not conserved?

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

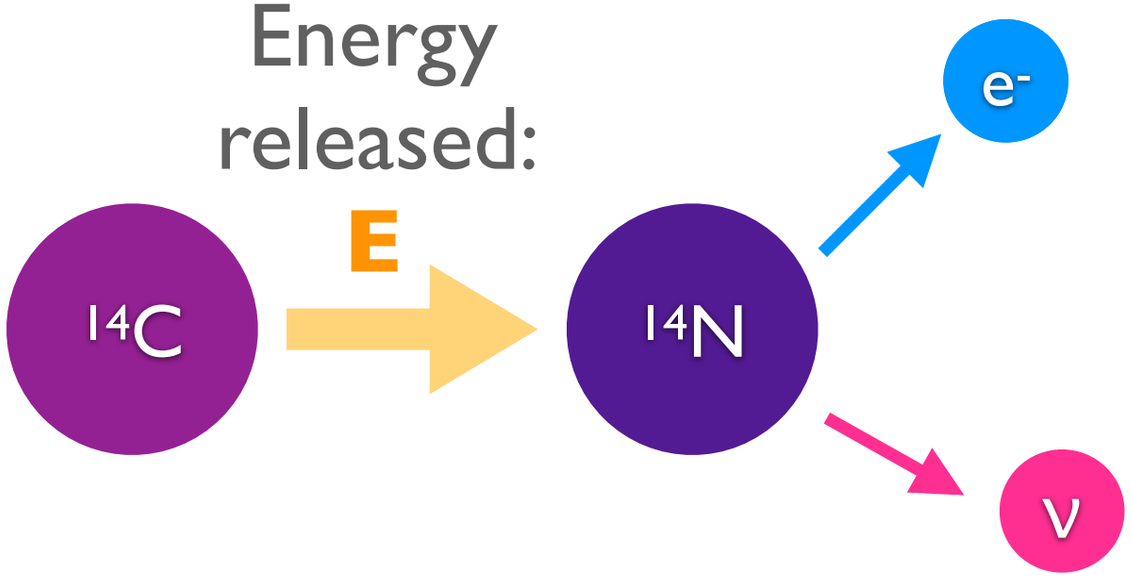
Physics Institute
of the ETH
Zürich

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
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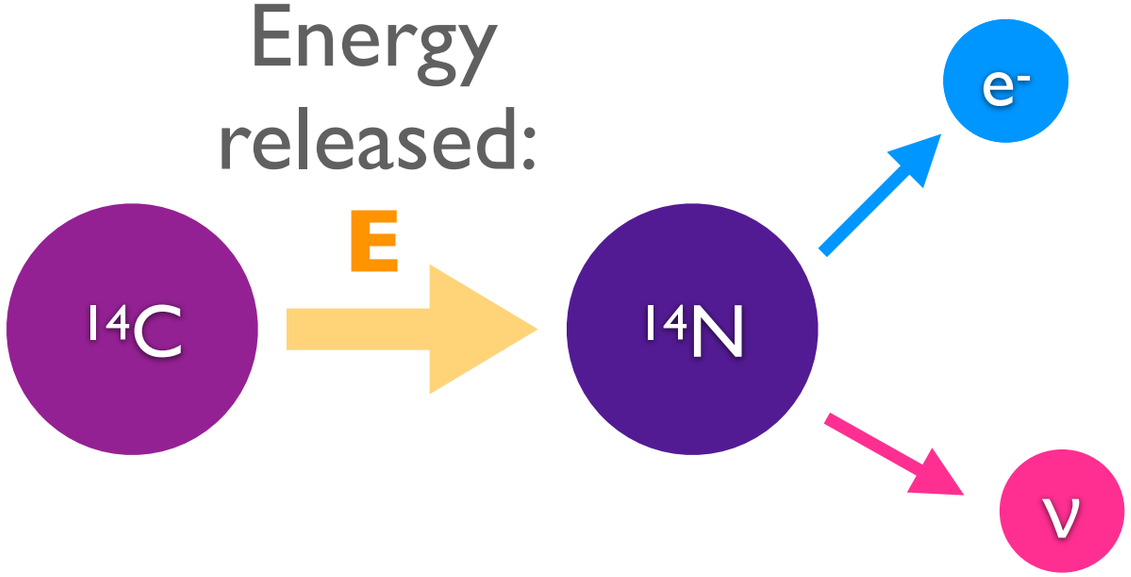

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  - Light
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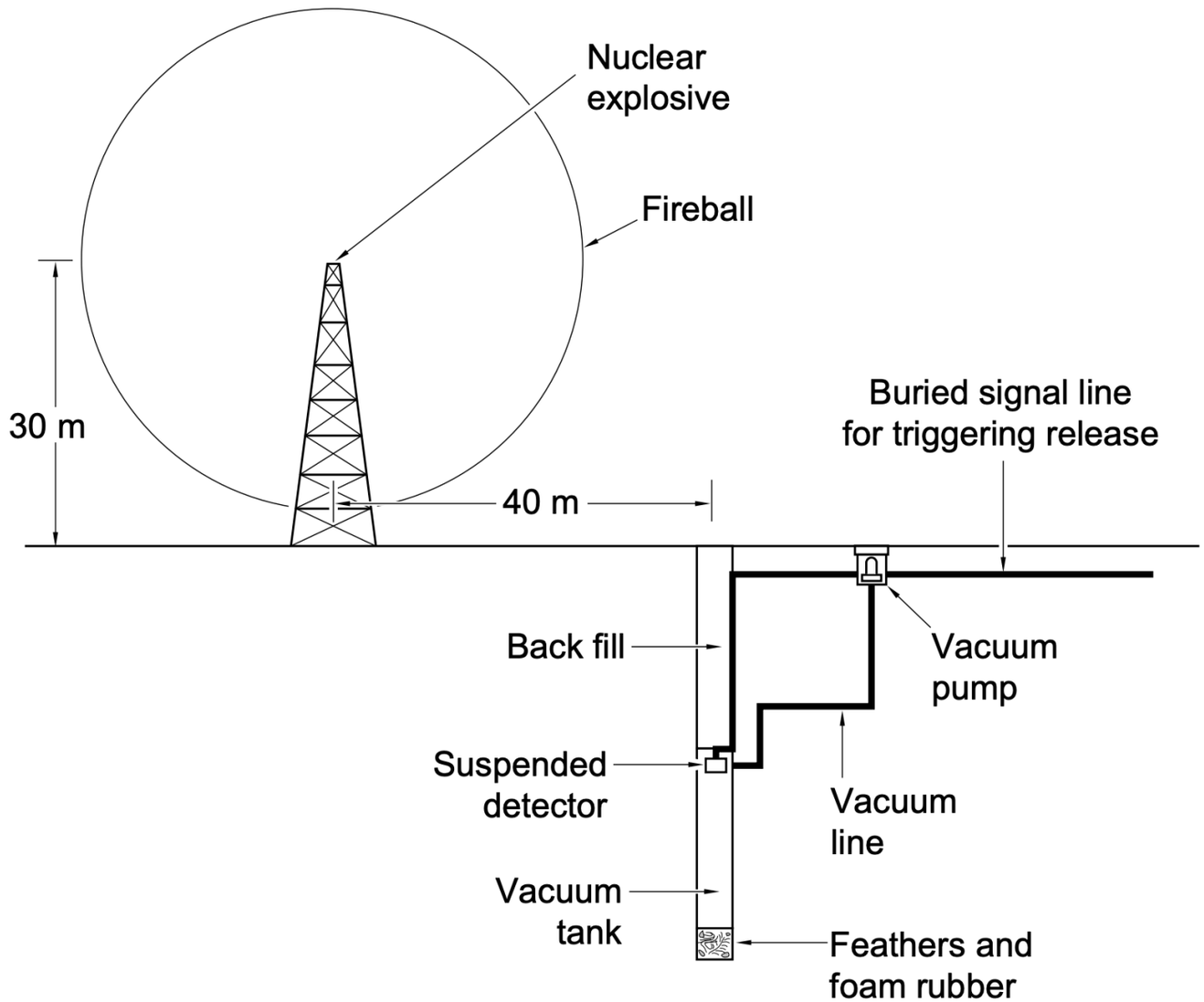
"I have done a terrible thing, I have postulated a particle that cannot be detected"

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

PROJECT POLTERGEIST

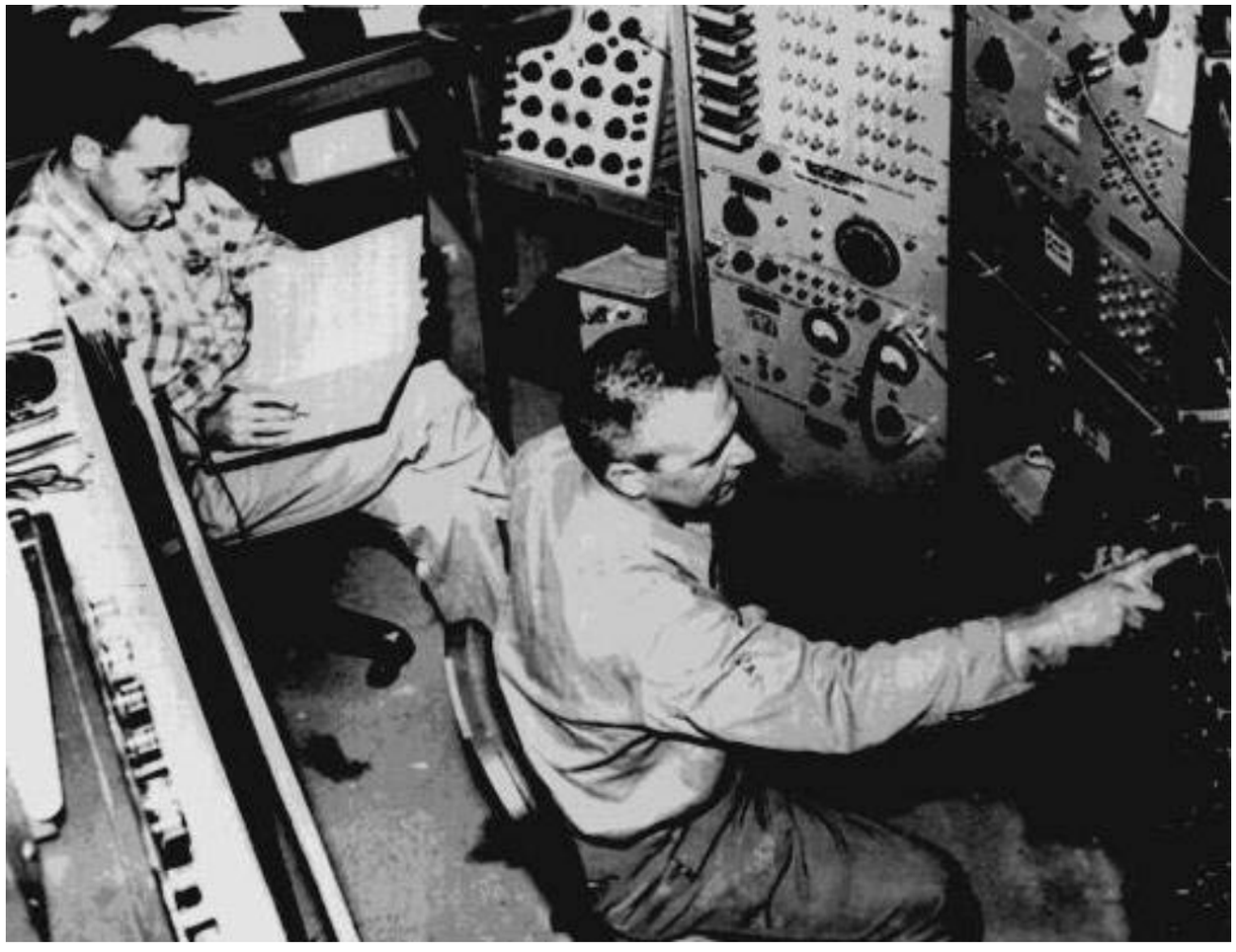
Simple plan:

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

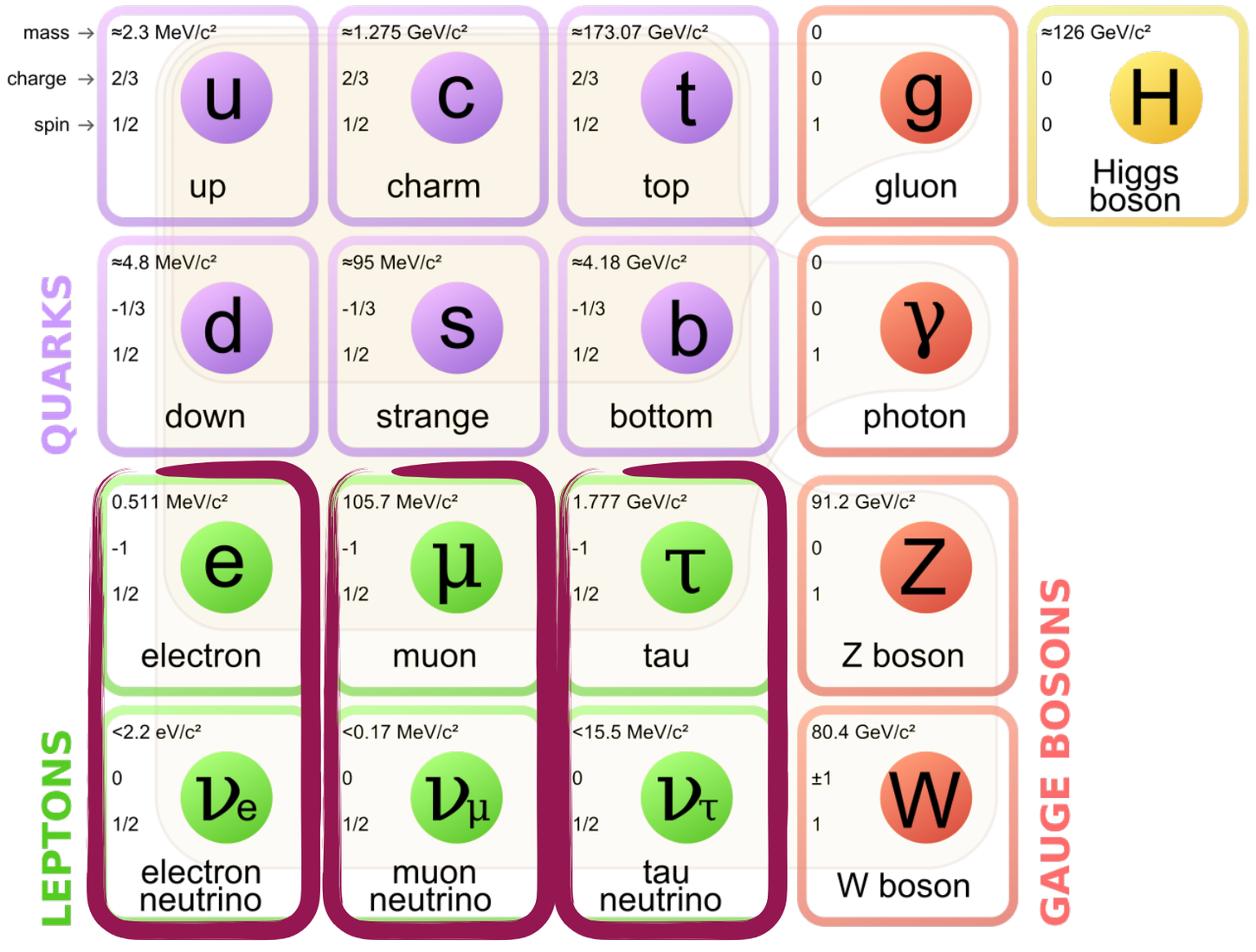
Fred Reines and Clyde Cowan eventually **detected the neutrino in 1956** in an experiment at the Savannah River nuclear power plant



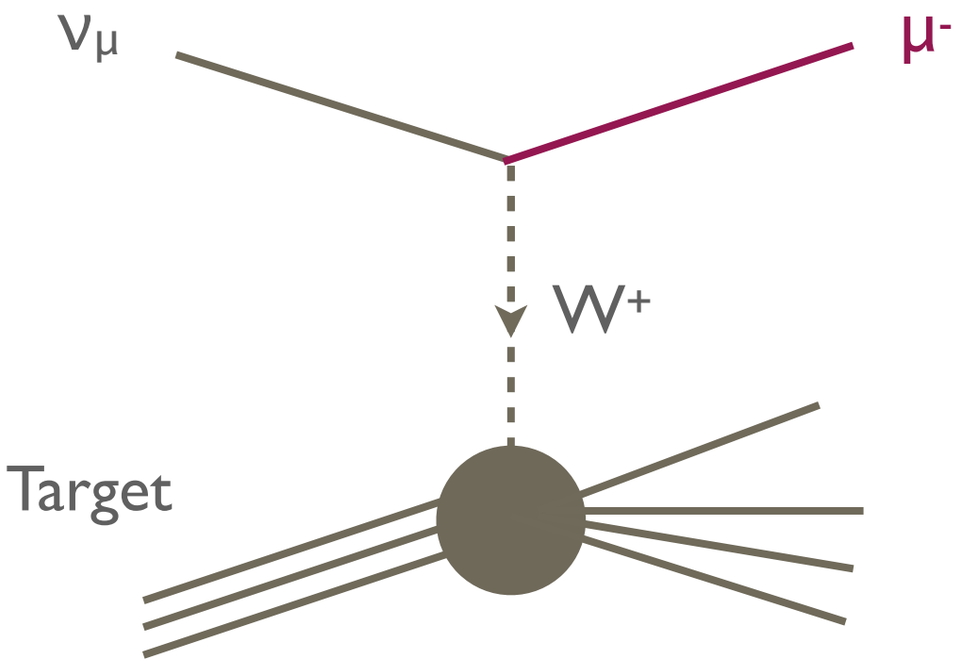
Telegram to Pauli, 14th June 1956:

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

THREE FLAVOURS OF NEUTRINO



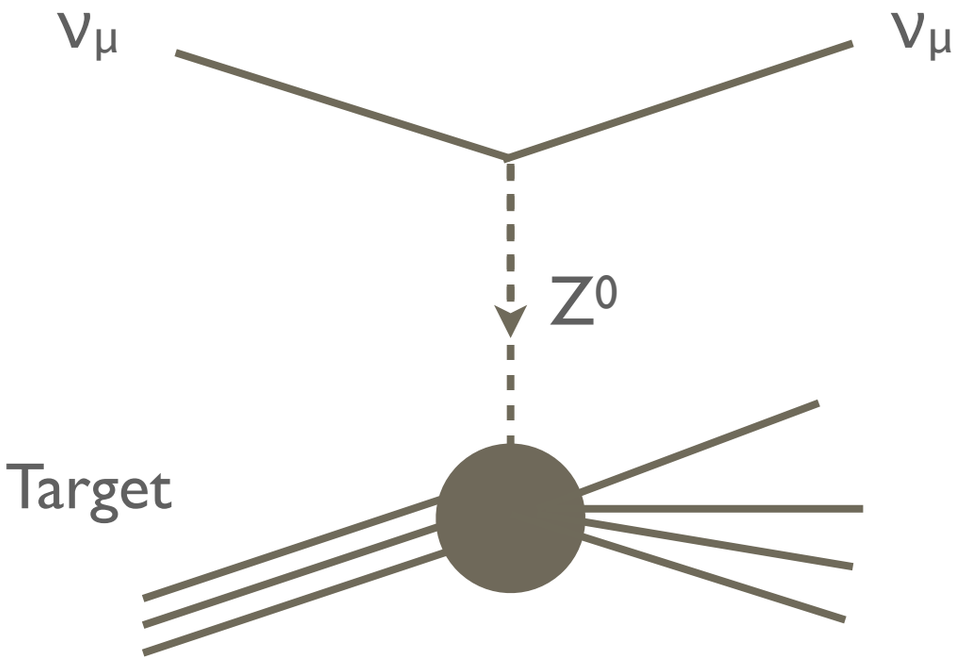
NEUTRINO INTERACTIONS



Charged-current

→ Exchange of W boson

→ **Lepton produced with same flavour as ν**



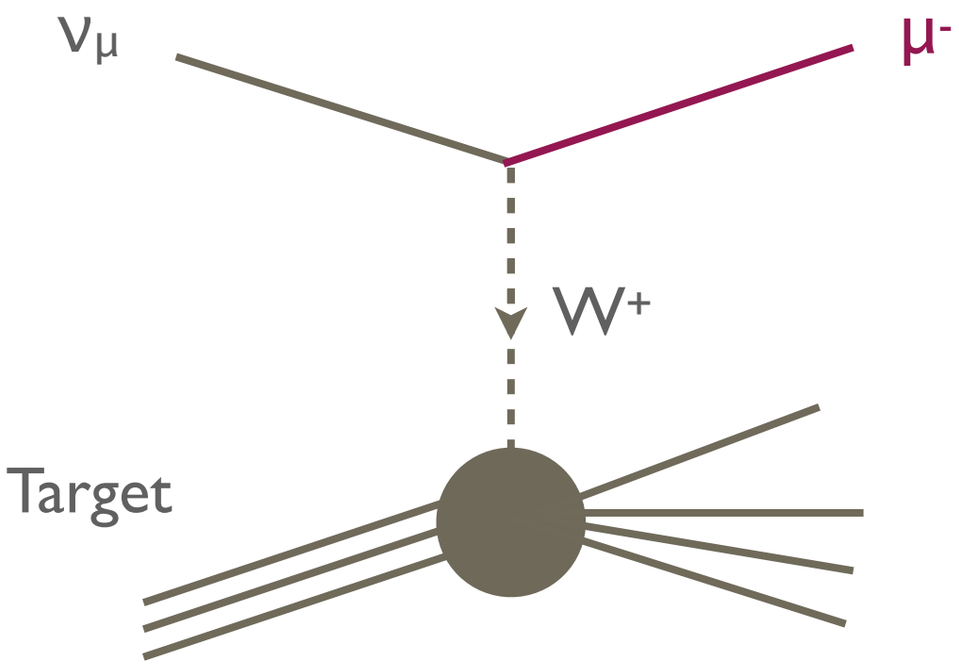
Neutral-current

→ Exchange of Z boson

→ Independent of ν flavour

→ **We will never know the flavour of the original ν!**

NEUTRINO INTERACTIONS



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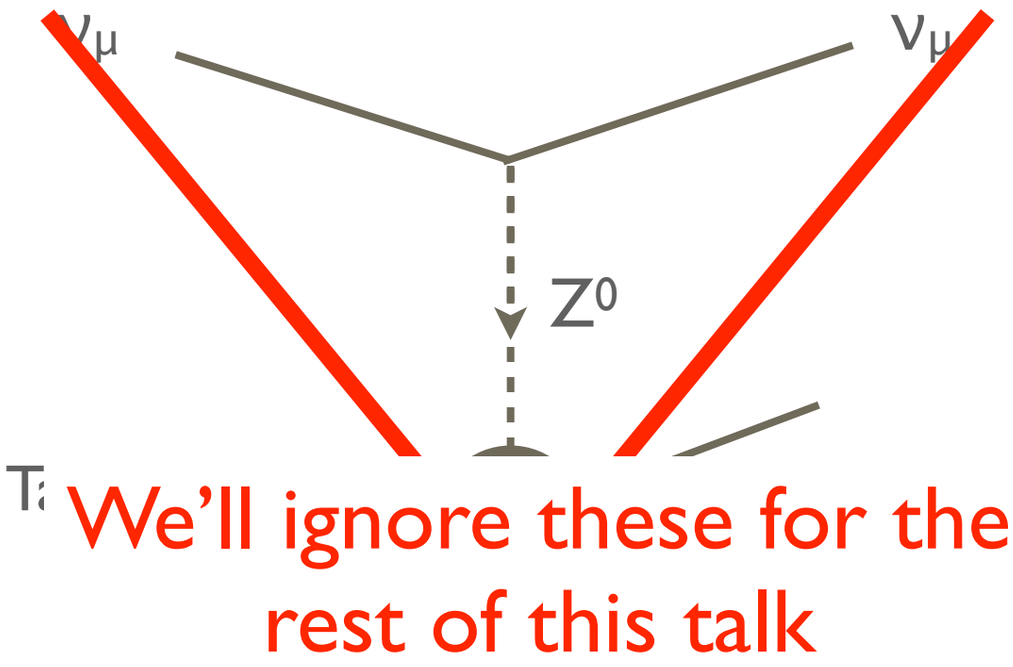

We'll ignore these for the rest of this talk

Neutral-current

→ Exchange of Z boson

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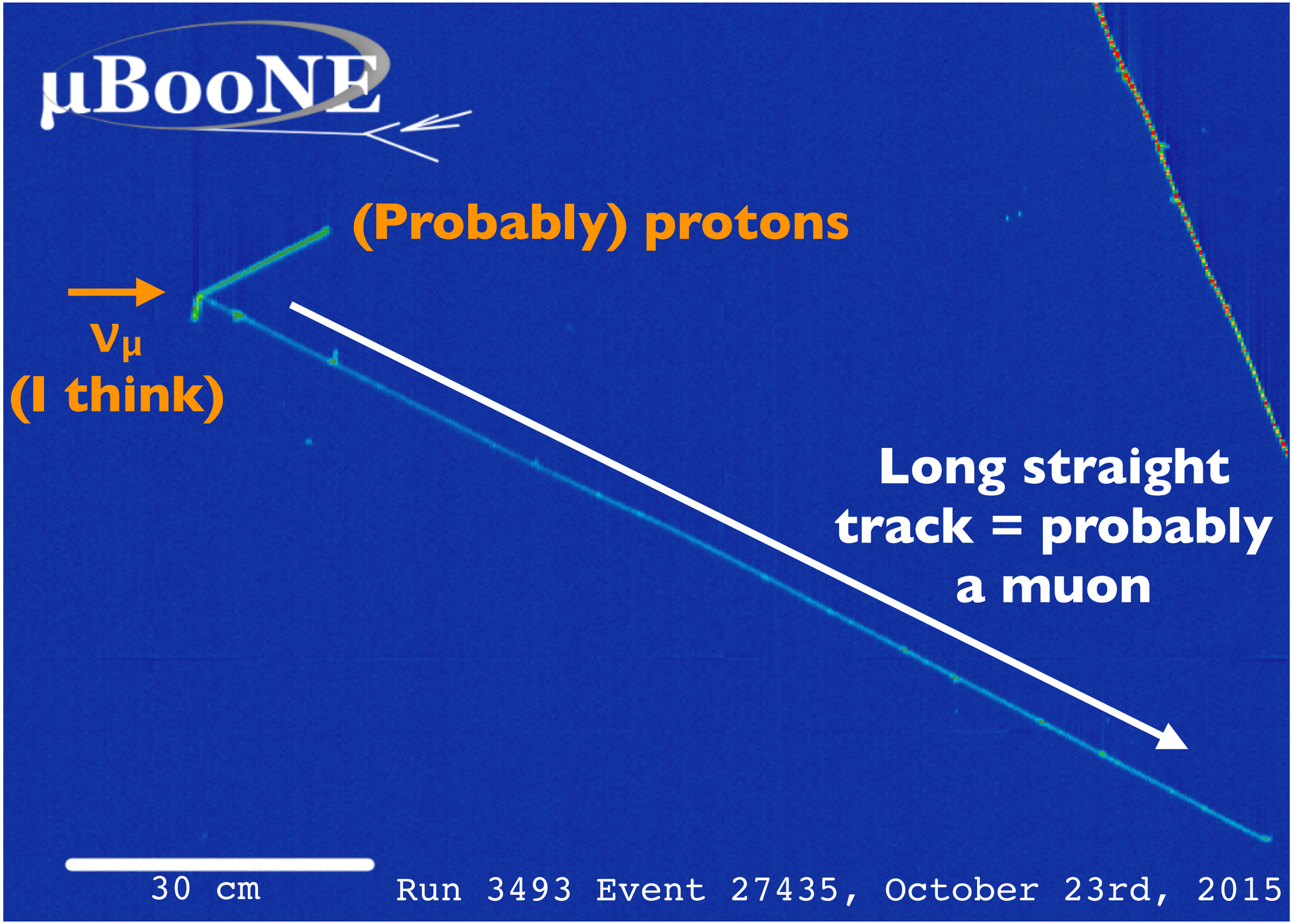
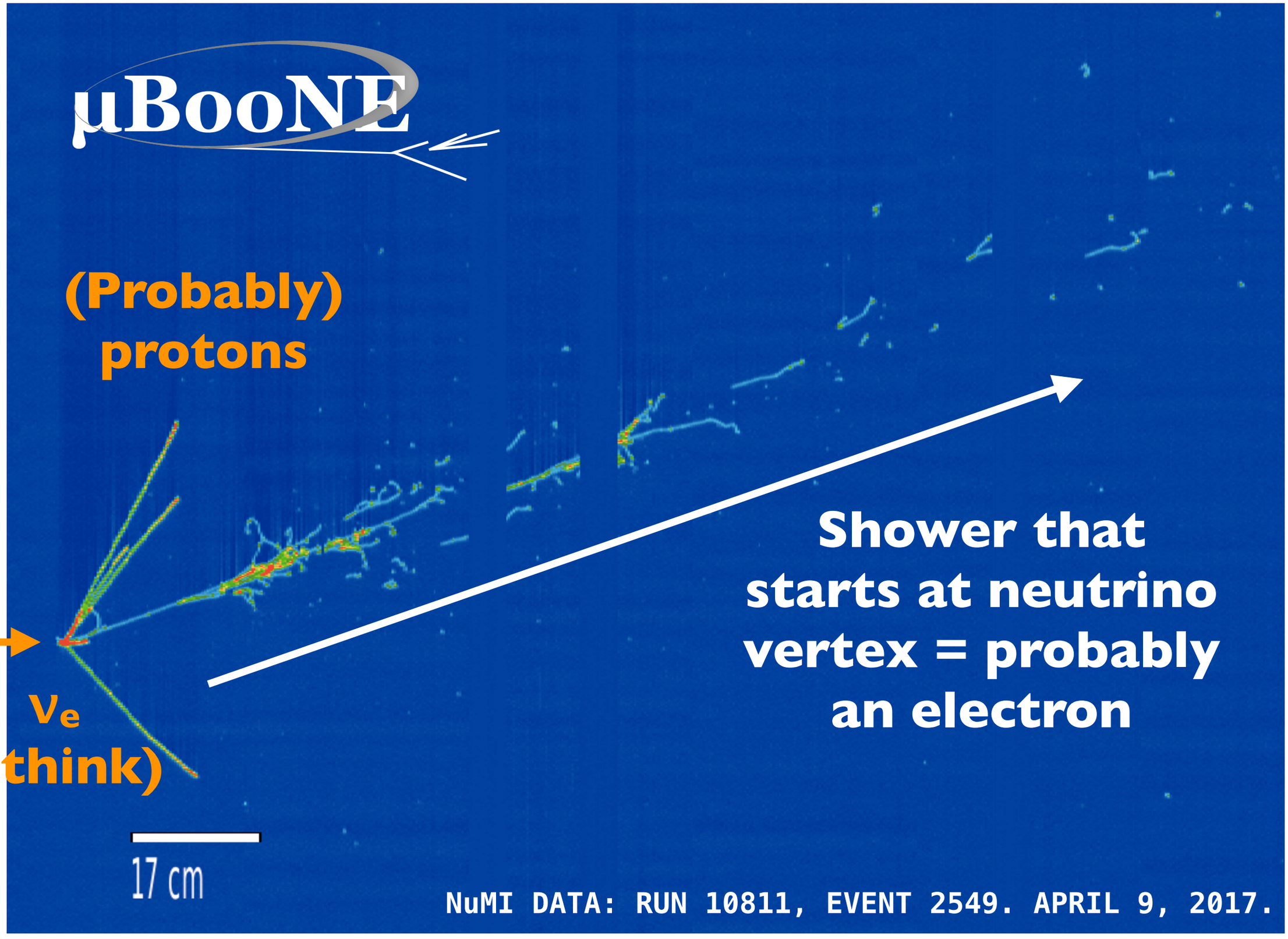
A DETOUR: HOW DO WE MEASURE NEUTRINOS?

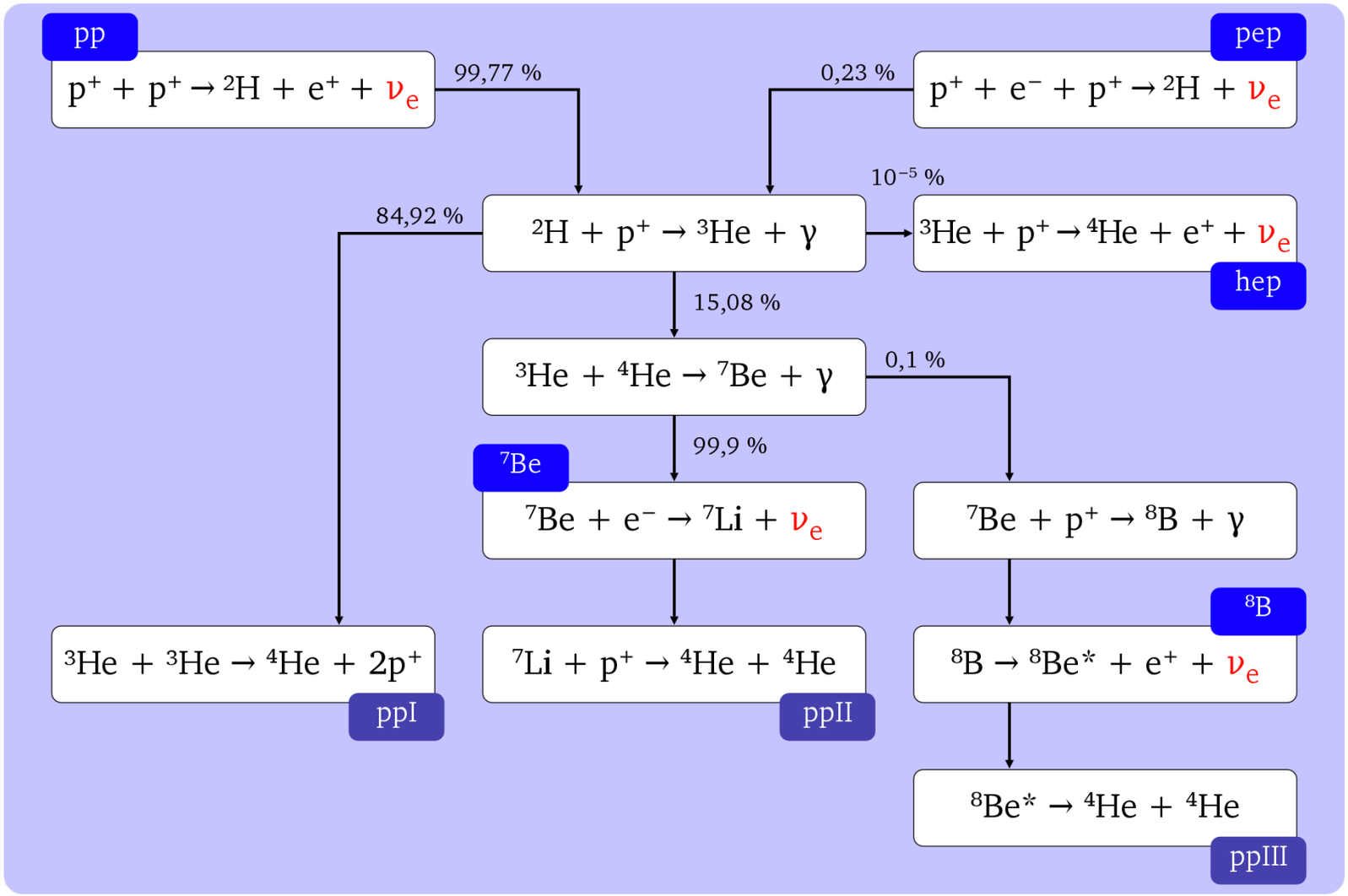
- **We can never "see" neutrinos**
- What we can (sometimes) see are the **particles that neutrinos produce** when they interact
- Then try to infer the presence of the neutrino and its flavor
  - In most cases: muon → muon neutrino, electron → electron neutrino


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.

BACK TO HISTORY…

SOLAR NEUTRINOS



The sun's energy comes from nuclear fusion via the pp and pep chains

→ multiple stages produce **low-energy electron neutrinos**

THE SOLAR NEUTRINO PROBLEM

- Ray Davis 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

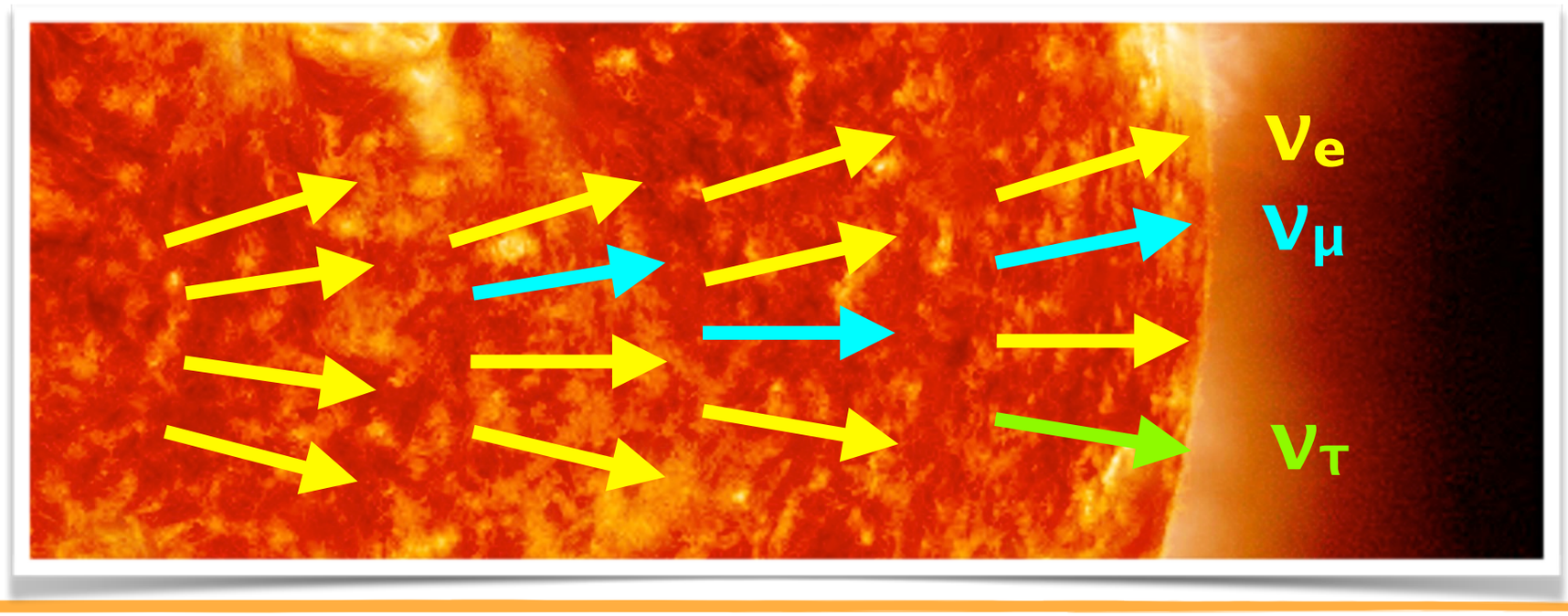
- Observed **2-3 times fewer neutrinos** than prediction
- Experimental errors?
  Results backed up by a number of different experiments (Kamiokande, GALLEX, SAGE, SNO)
- Bad solar models?
  Ruled out by SNO experiment

THE SOLAR NEUTRINO PROBLEM

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

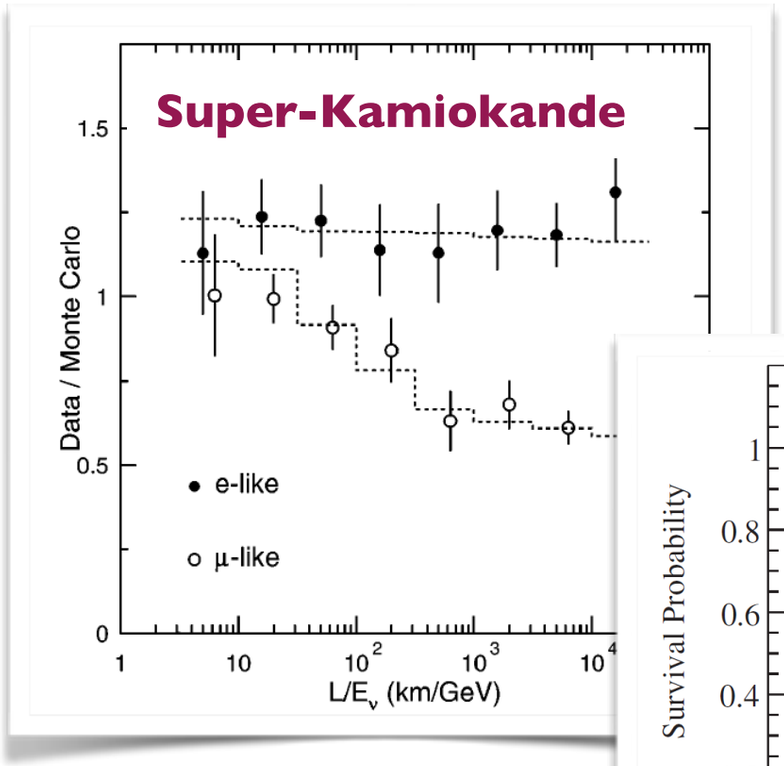
Davis only looked for ν_e, known to be produced in the sun

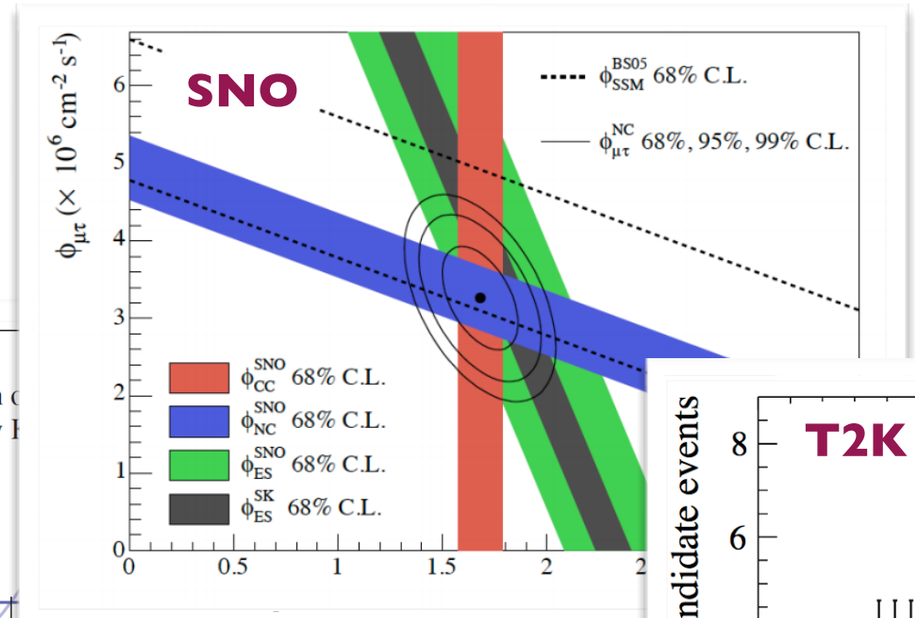
By the time they leave the sun, ½-⅔ have changed to ν_μ or ν_τ

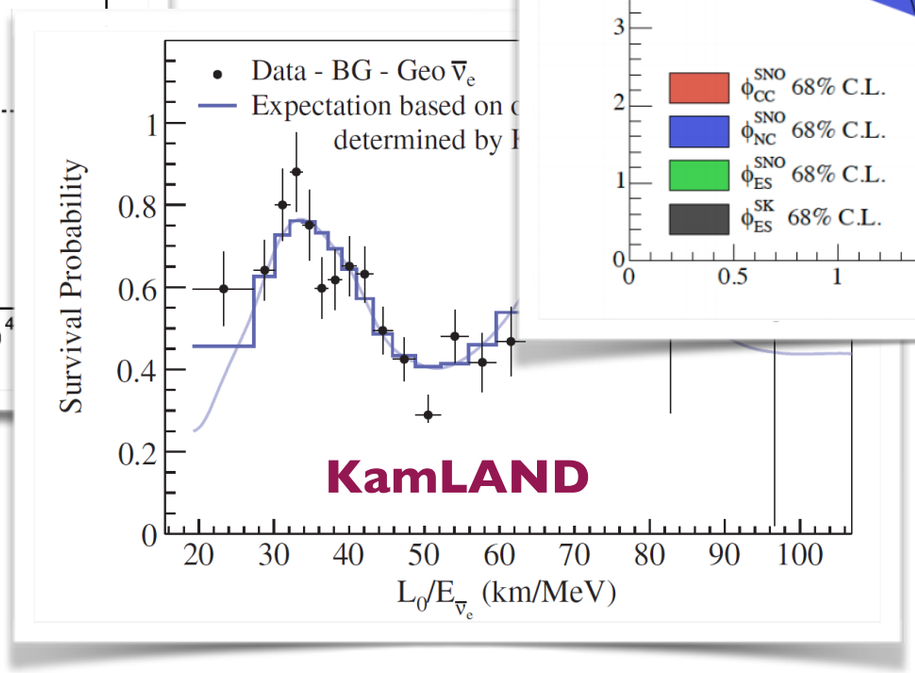


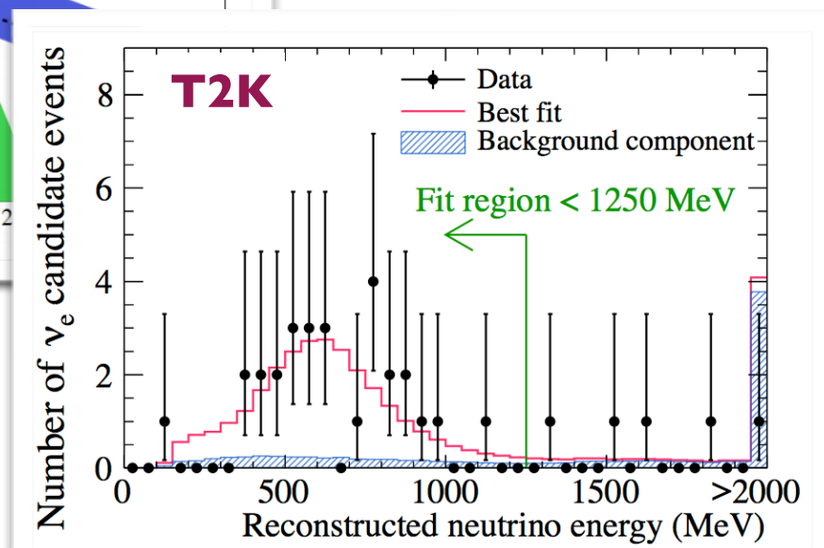
NEUTRINO FLAVOUR CHANGE

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









SO WHAT'S GOING ON?

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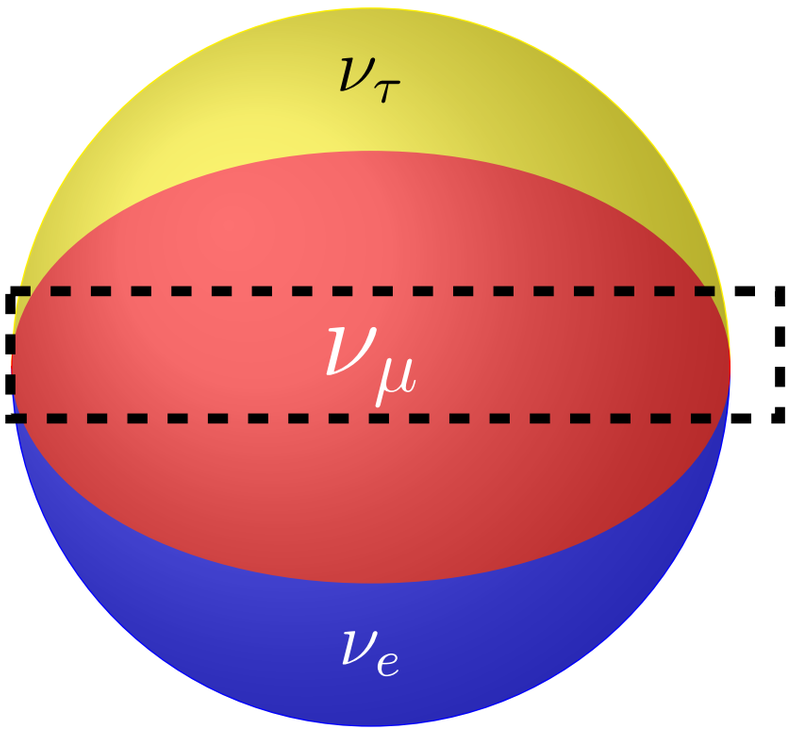
Artwork by Sandbox Studio, Chicago

- 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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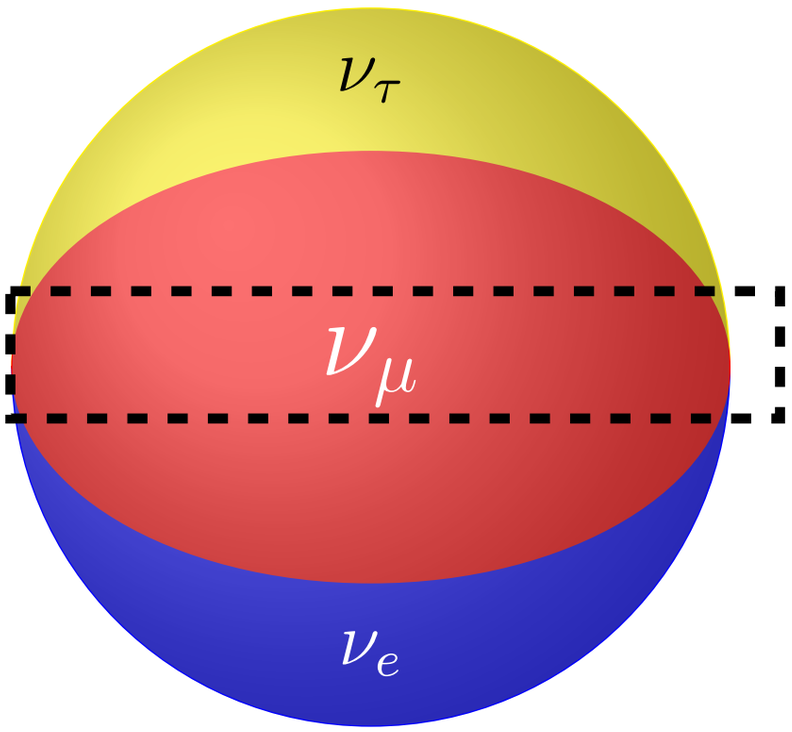

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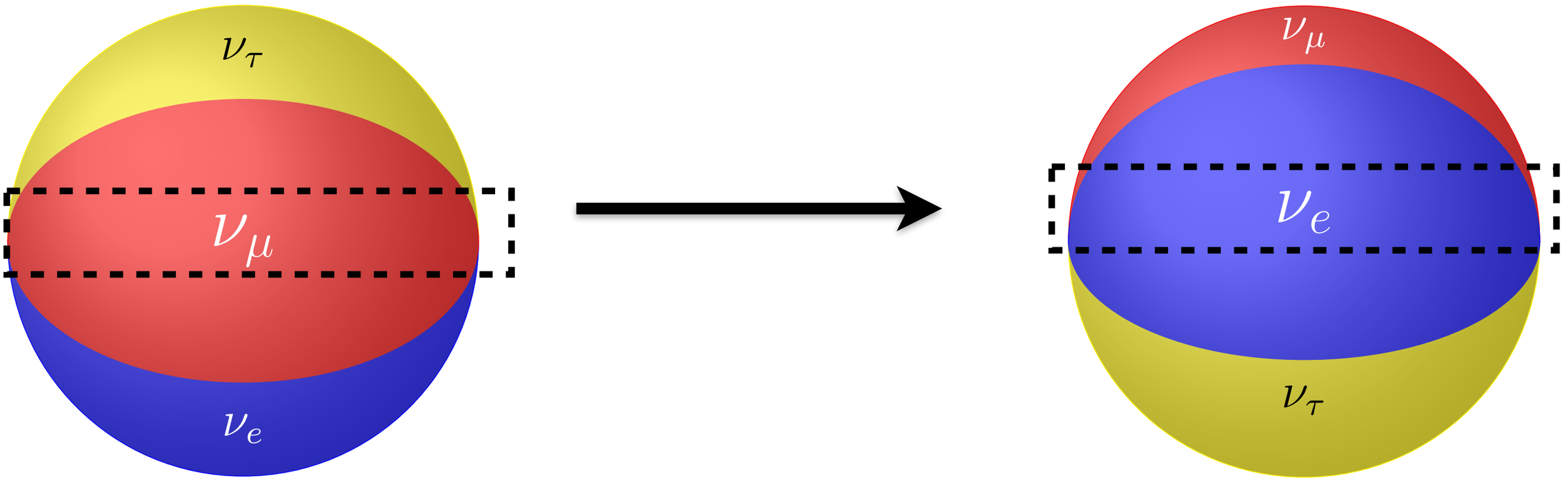
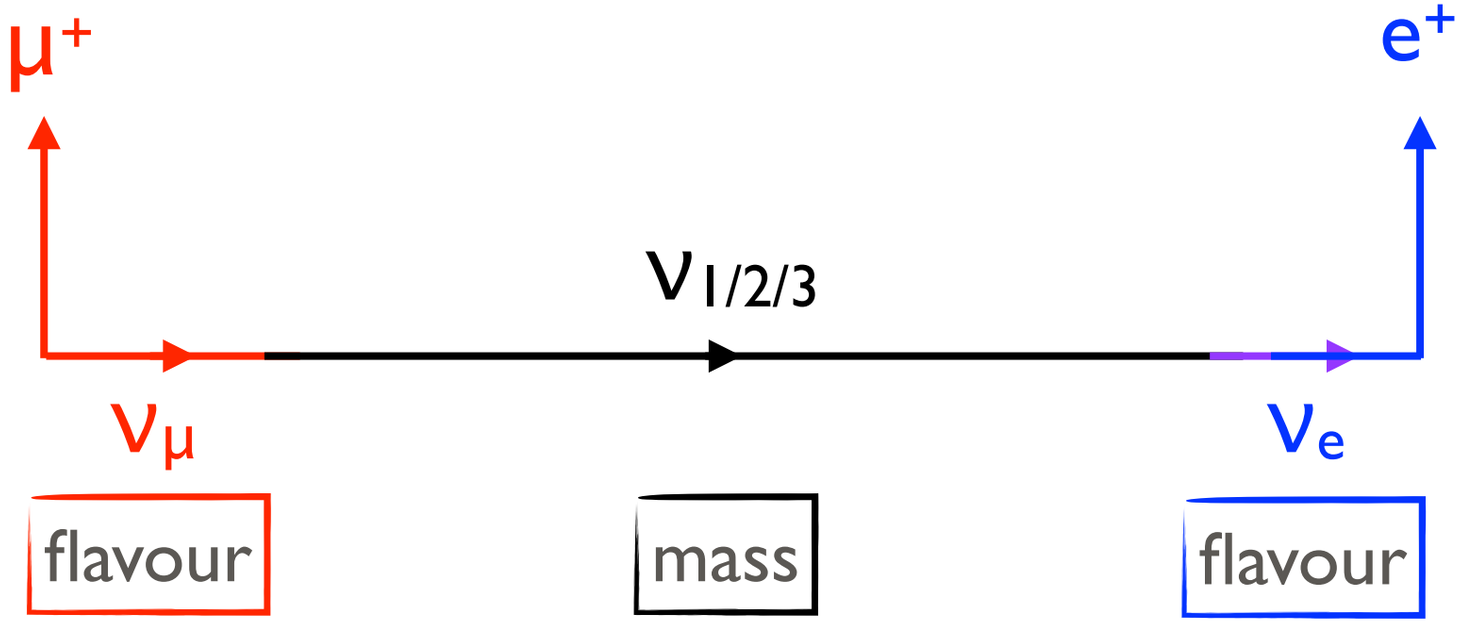
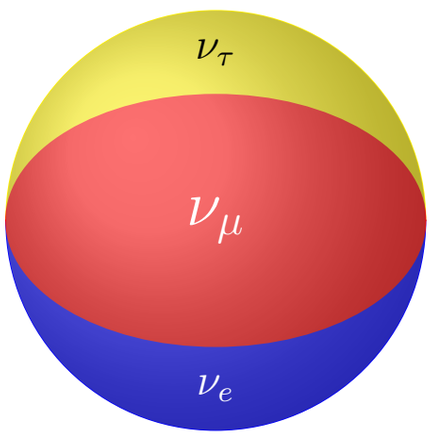


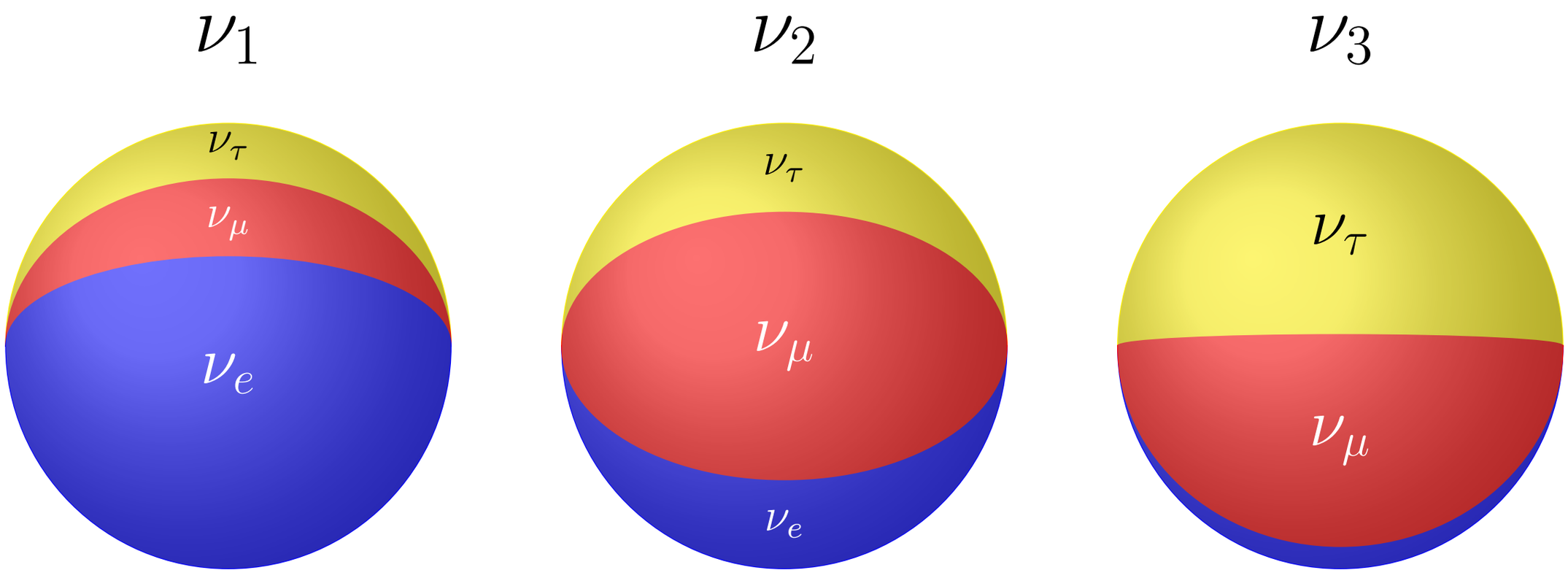
L. Pickering

NEUTRINO OSCILLATION





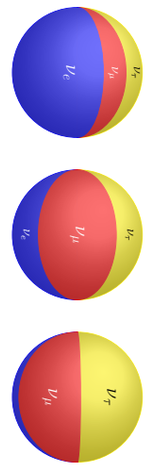
BUT THERE ISN'T ONLY ONE BEACH BALL



L. Pickering

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

NEUTRINO OSCILLATION

$c_{ij} = \cos\theta_{ij}$

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavour

mass

Four free parameters:

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

One phase δ_{CP}

Each mixing angle describes mixing between two mass states (3c2 = 3)

We'll come back to what this parameter does…

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**:

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

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

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

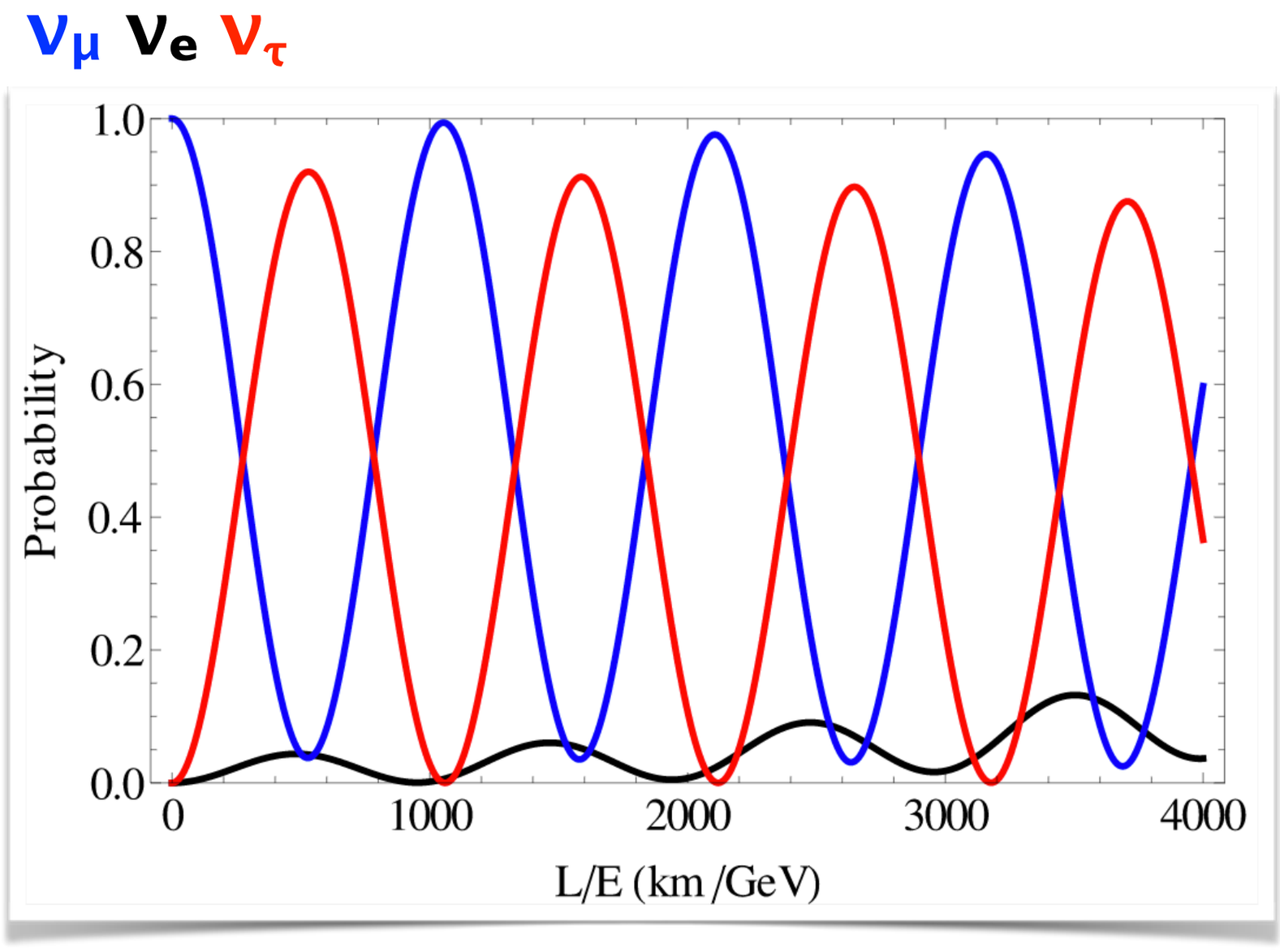
…and this term gives the **oscillation**

NEUTRINO OSCILLATION

$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

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

There are two **mass-squared splittings**: Δm^2_{32} and Δm^2_{21}



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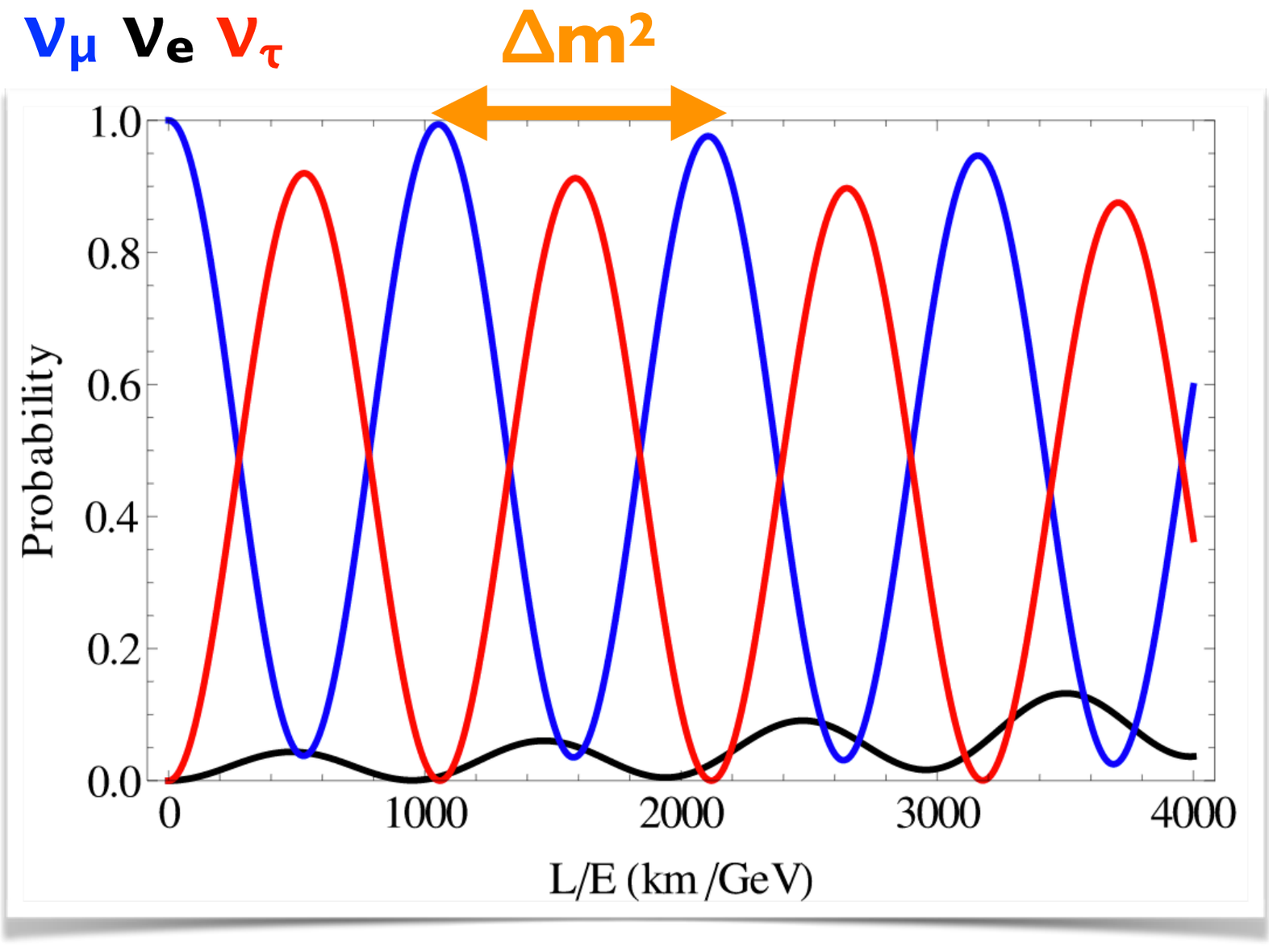

NEUTRINO OSCILLATION

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$$\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

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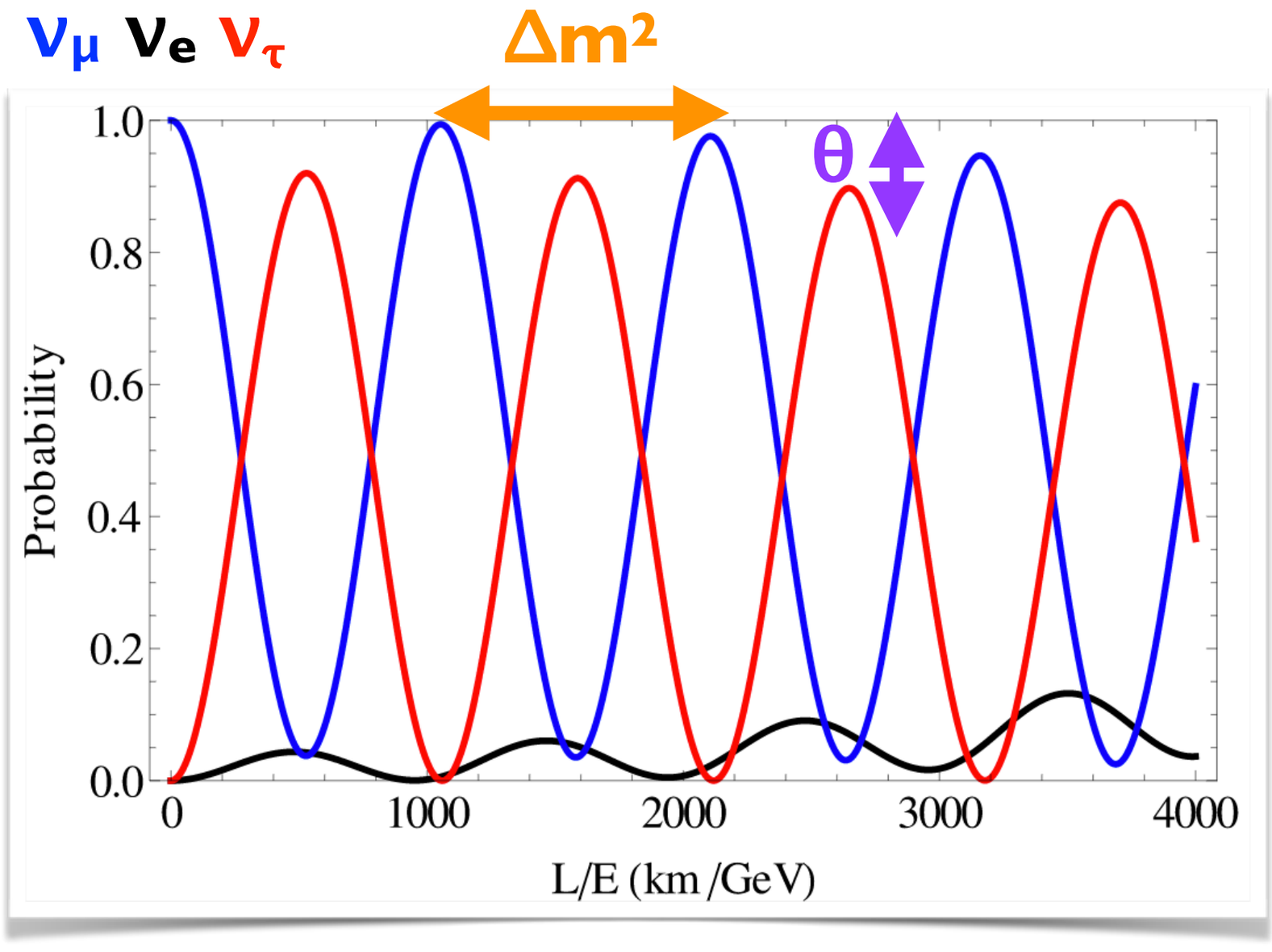


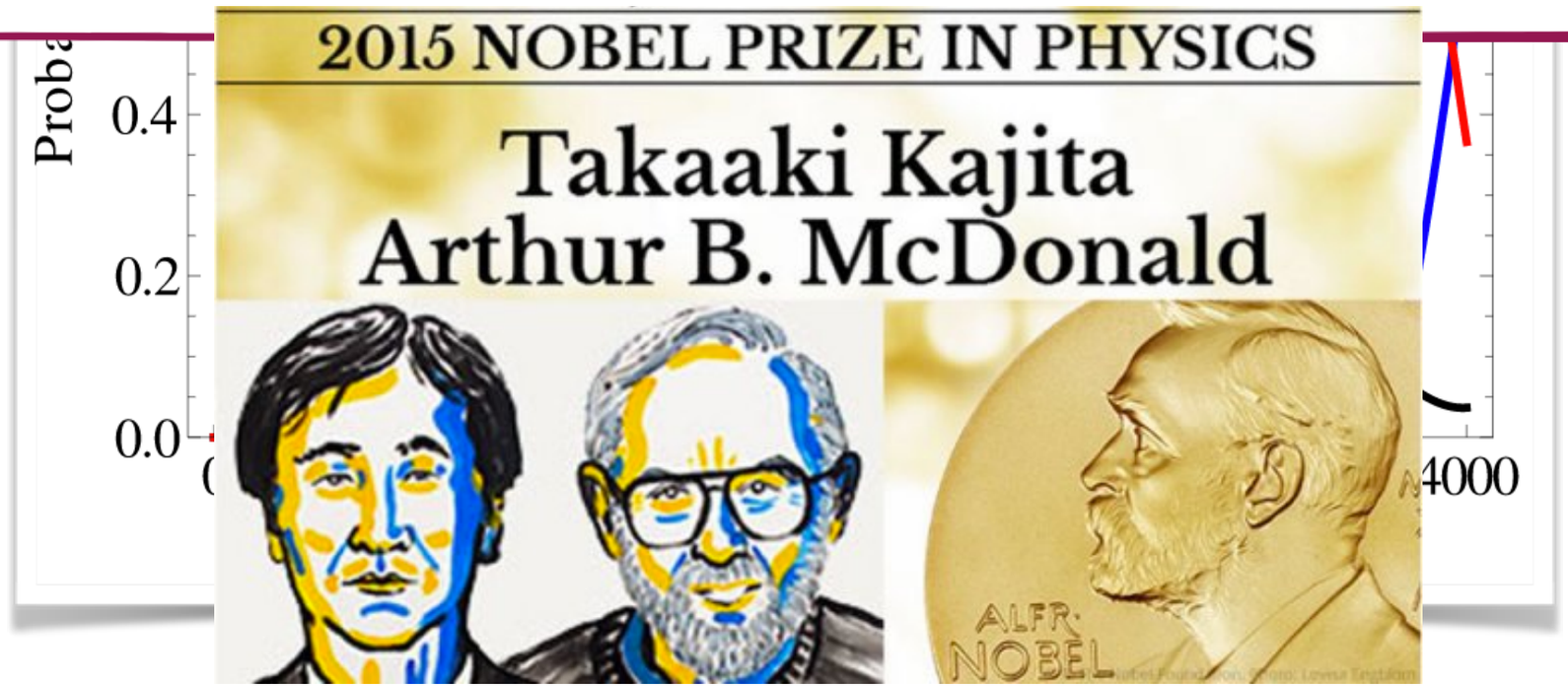
NEUTRINO OSCILLATION

$$\sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

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

Reason why neutrinos are exciting:

Neutrino oscillation → Neutrinos have mass → Physics beyond the Standard Model!



CURRENT MEASUREMENTS

Thanks to many experiments around the world, using different sources of neutrinos, we have measurements of almost all neutrino oscillation parameters:

θ_{12} ✔ solar ✔ reactor

θ_{23} ✔ atmos. ✔ accel.

θ_{13} ✔ solar ✔ reactor ✔ atmos. ✔ accel.

Δm^2_{21} ✔ solar ✔ reactor

$|\Delta m^2_{32}|$ ✔ atmos. ✔ accel.

δ_{CP} ? atmos. ? accel.

WHAT WE STILL DON'T KNOW

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

How many neutrinos are there?

How much do neutrinos weigh?

Which neutrino is heaviest? Which is

I wish I had time to talk about all of these questions! But today I'll focus on this one

Is neutrino oscillation different for neutrinos and antineutrinos?

mixing so large?

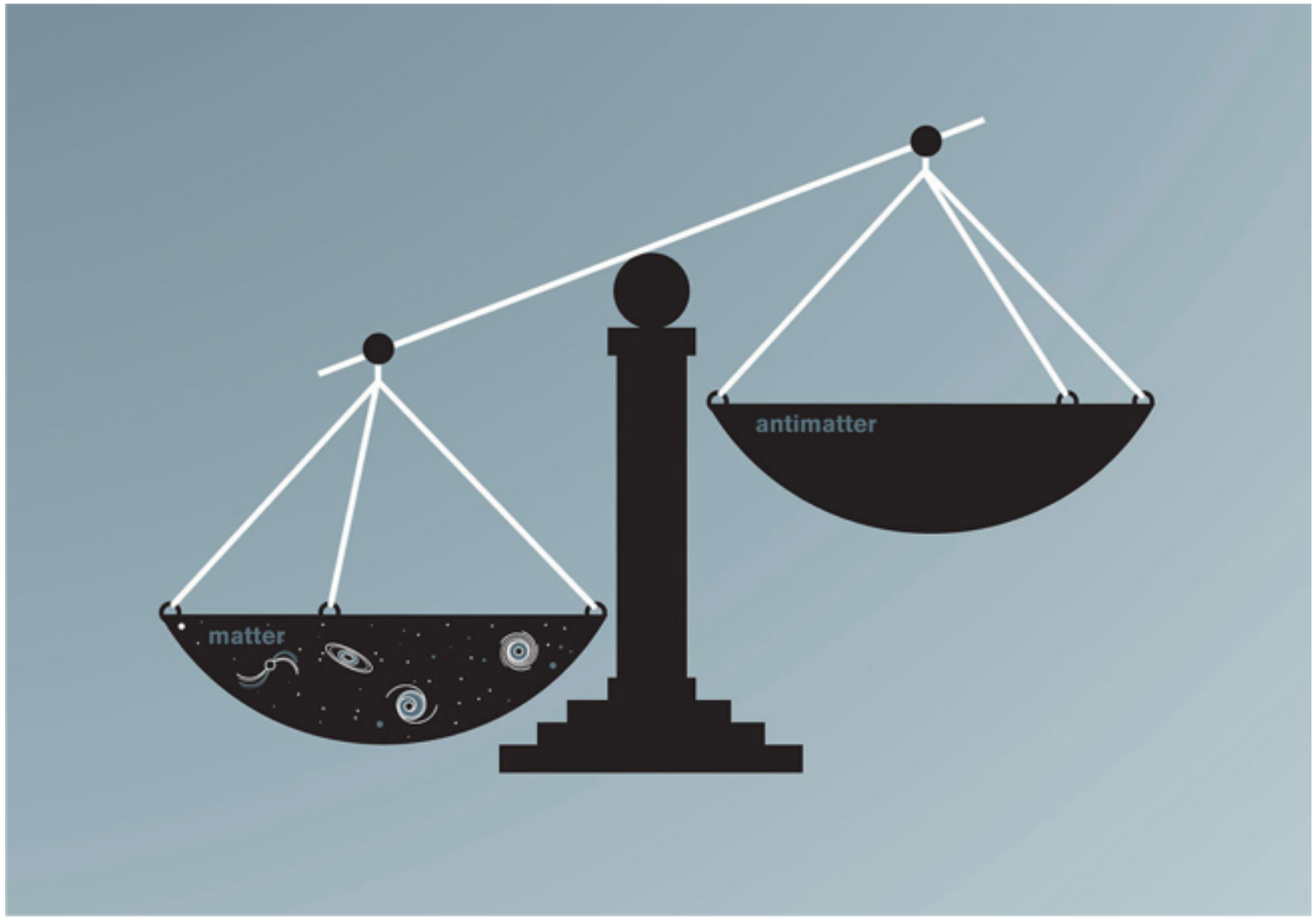
Why are neutrino masses so much smaller than all other particles?

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

Reason why neutrinos are exciting:

CP violation in neutrinos might explain the matter-antimatter asymmetry we see in the universe

→ neutrinos could explain why we exist!

oscillation different for neutrinos and antineutrinos?

Artwork by Sandbox Studio, Chicago

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**

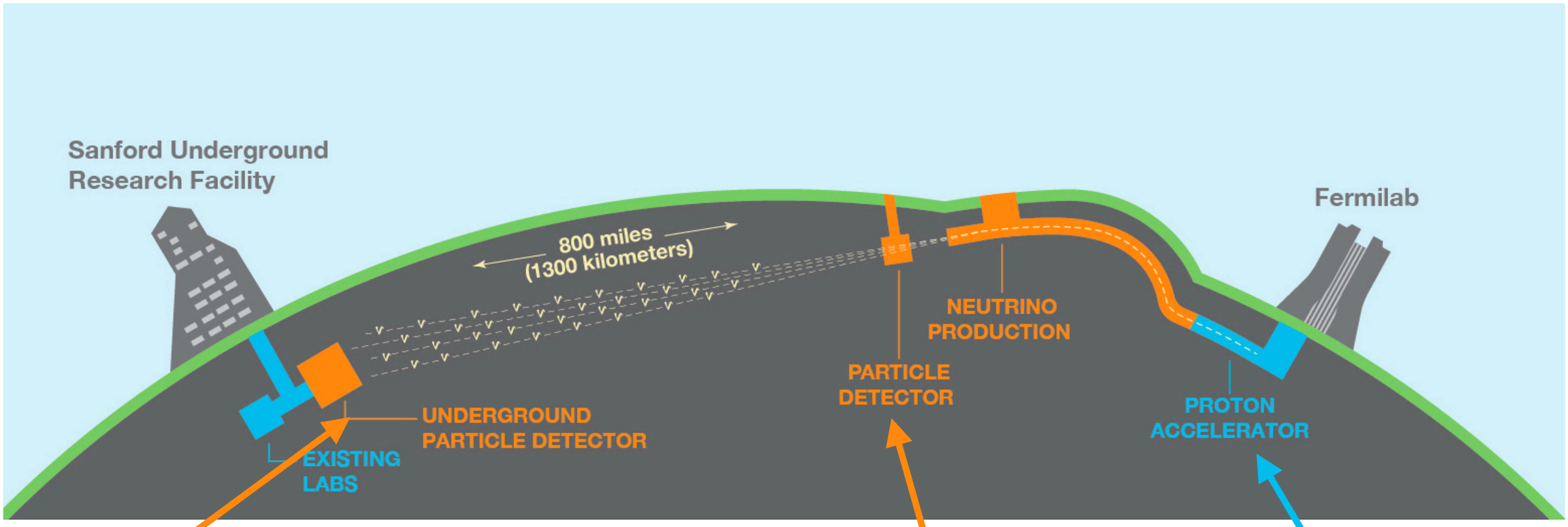
$$(+)-\Big[$$ **Something else**

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

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

ACCELERATOR NEUTRINOS

One way we are attempting to answer this question



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

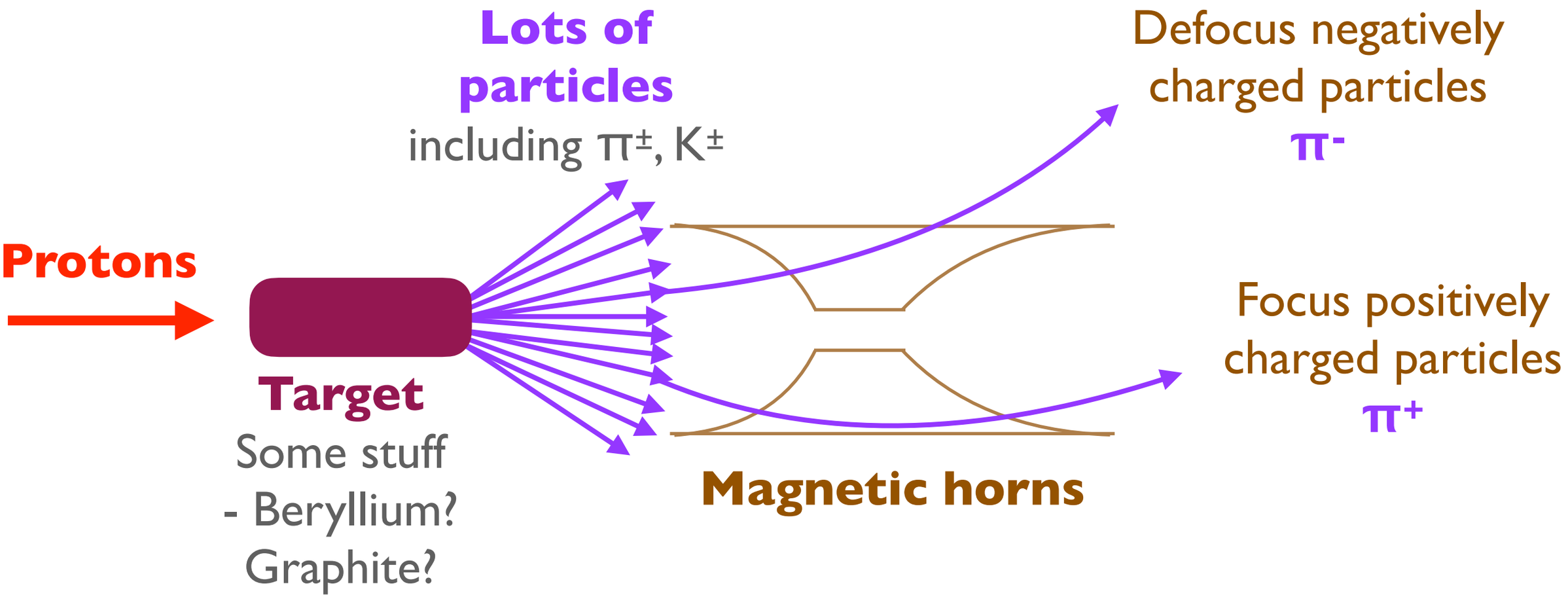
HOW TO MAKE A NEUTRINO BEAM

Lots of particles

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

Some stuff
- Beryllium?
Graphite?

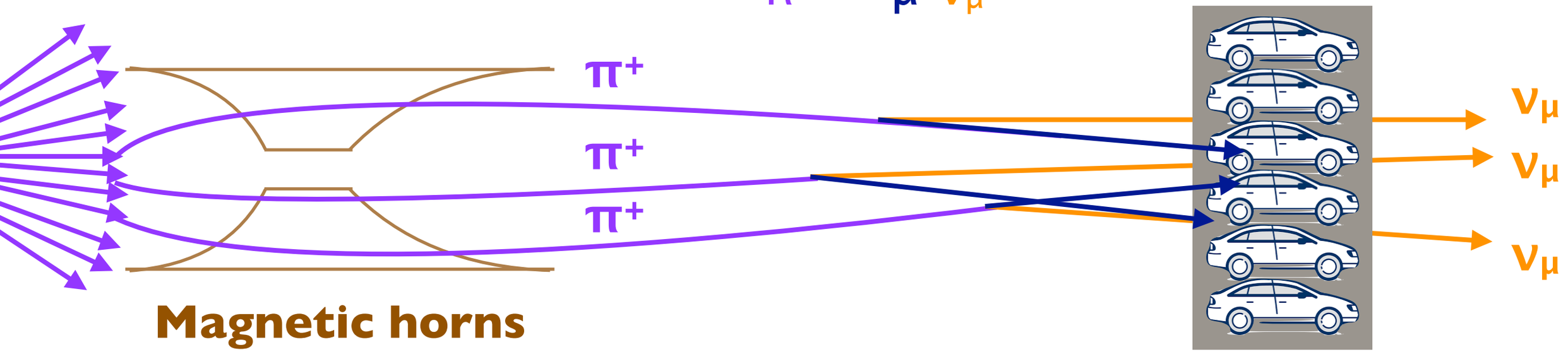
HOW TO MAKE A NEUTRINO BEAM



HOW TO MAKE A NEUTRINO BEAM

π^+ decay in flight

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



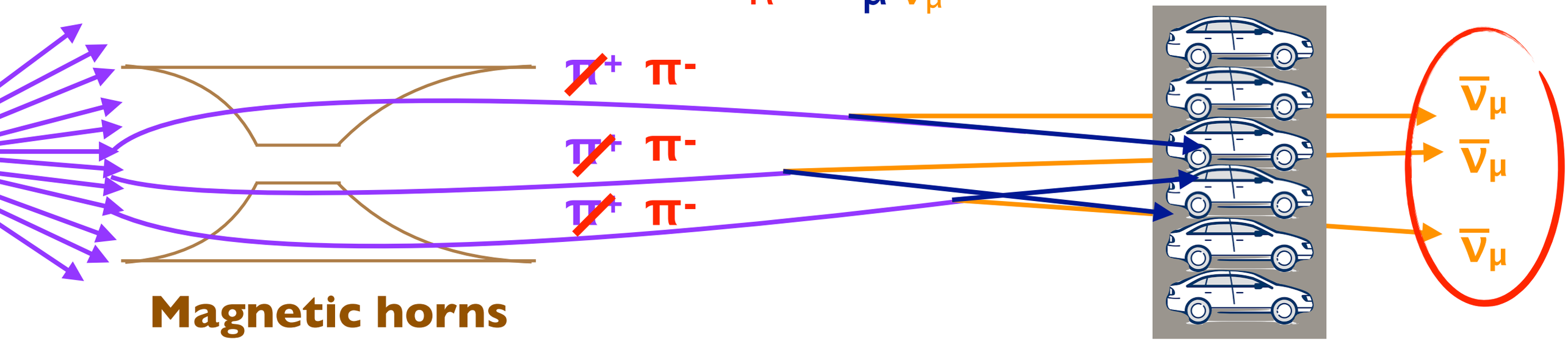
Magnetic horns

Steel absorber
stops all particles
except neutrinos

HOW TO MAKE A NEUTRINO BEAM

π^- decay in flight

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



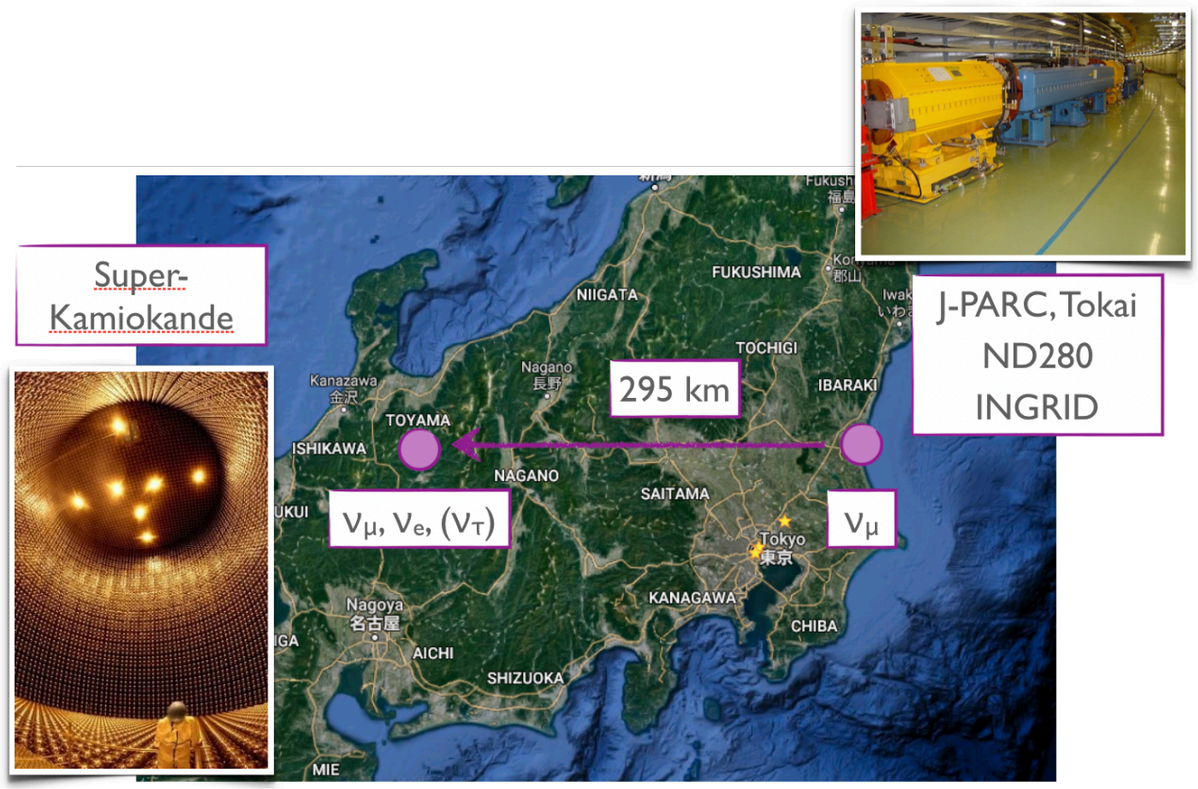
Magnetic horns

Steel absorber
stops all particles except neutrinos

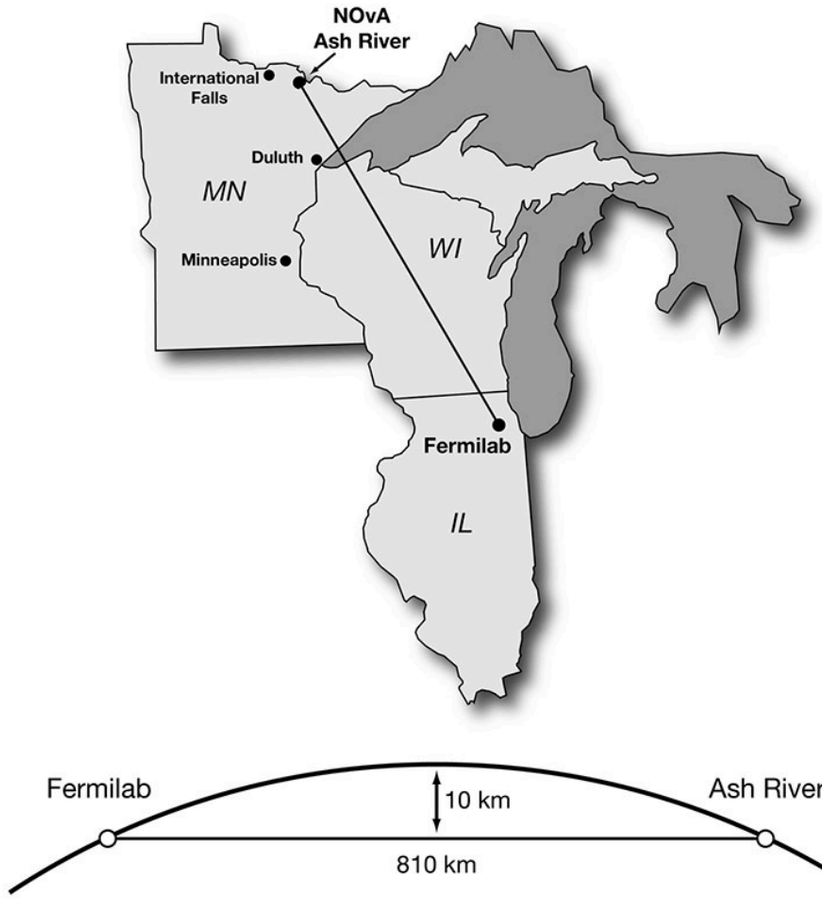
Can reverse the polarity of the horns to focus negatively charged particles instead
→ **produce a beam of antineutrinos instead of neutrinos**

THERE ARE ONLY TWO ACCELERATORS ON EARTH THAT MAKE NEUTRINOS

One in Japan...



...and one at Fermilab



T2K
(Tokai to Kamioka)

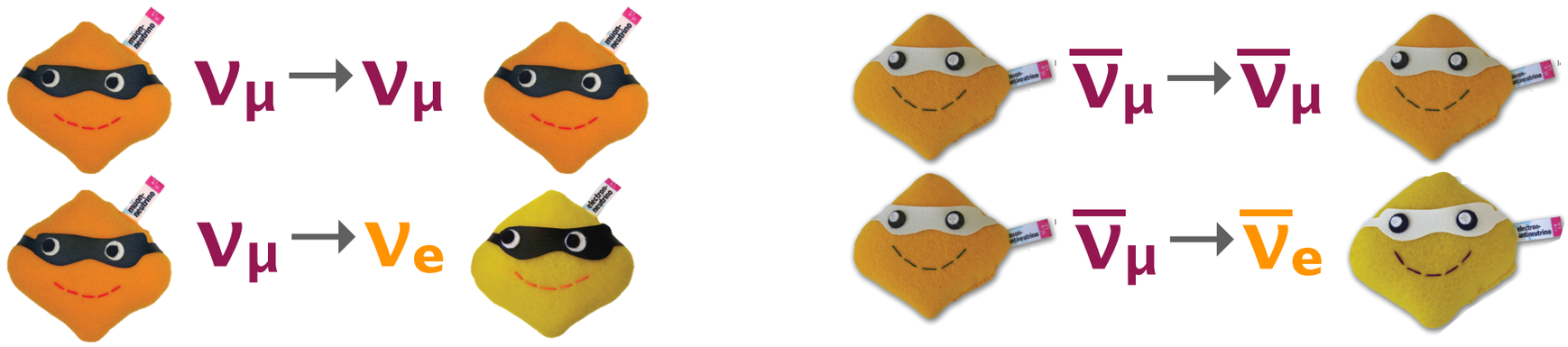
NOvA
(NuMI Off-axis ν_e Appearance)

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":



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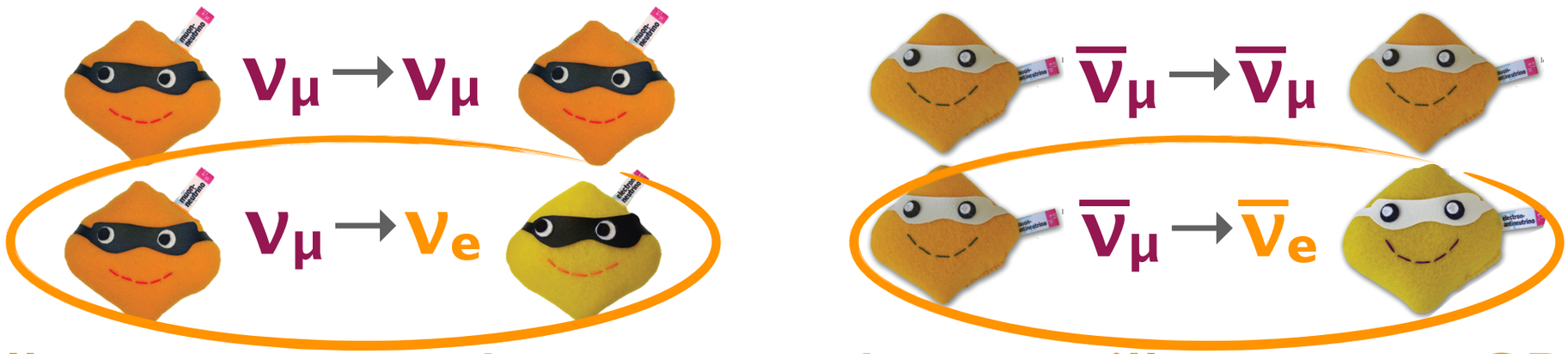


Essentially: comparing these two is how we'll measure CP violation

(it's a little more complicated than that but we only have an hour…)

What's next? DUNE

T2K and NOvA can start this measurement, but we need higher statistics to do it definitively → more neutrinos, larger detectors

Massive (40 kton) far detector

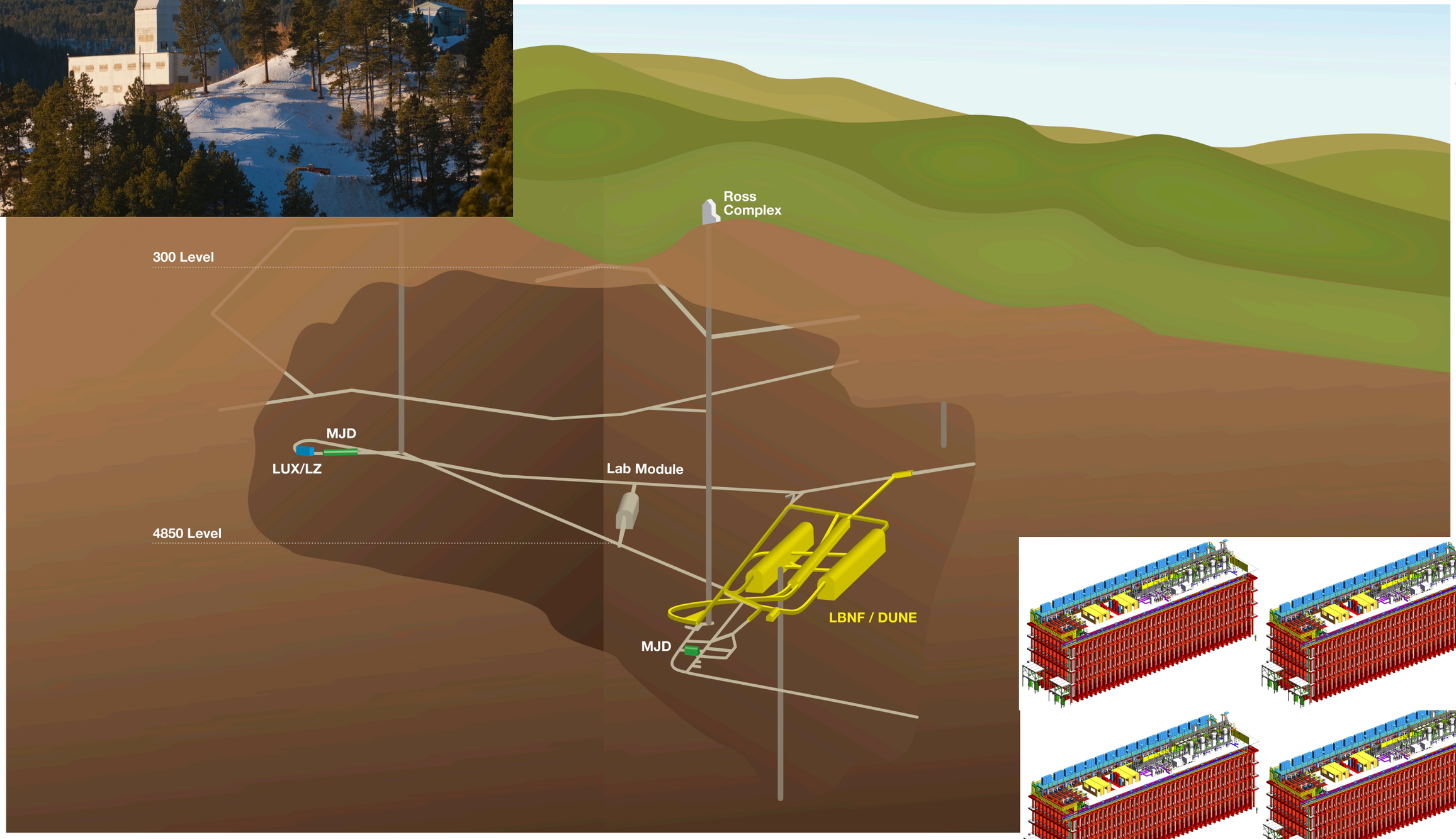
SURF

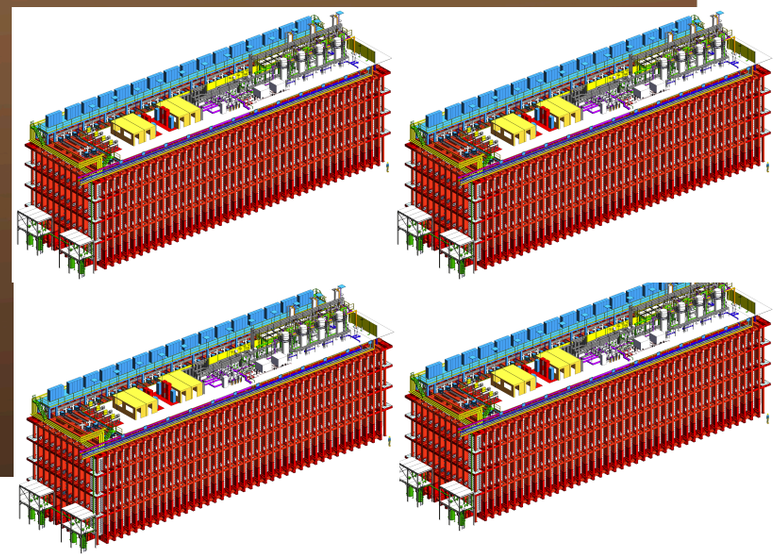
Sanford Underground Research Facility

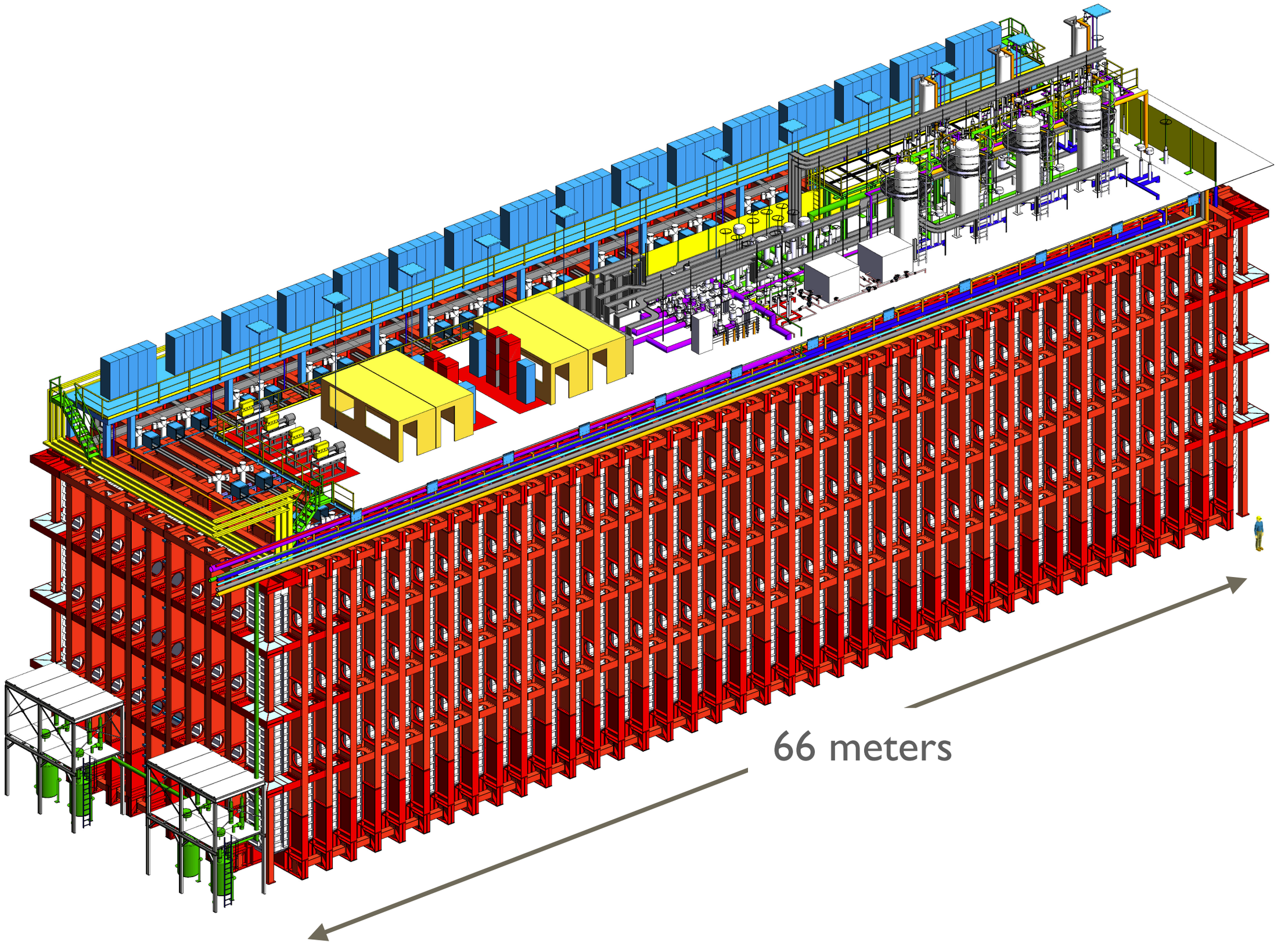
Precise near detector

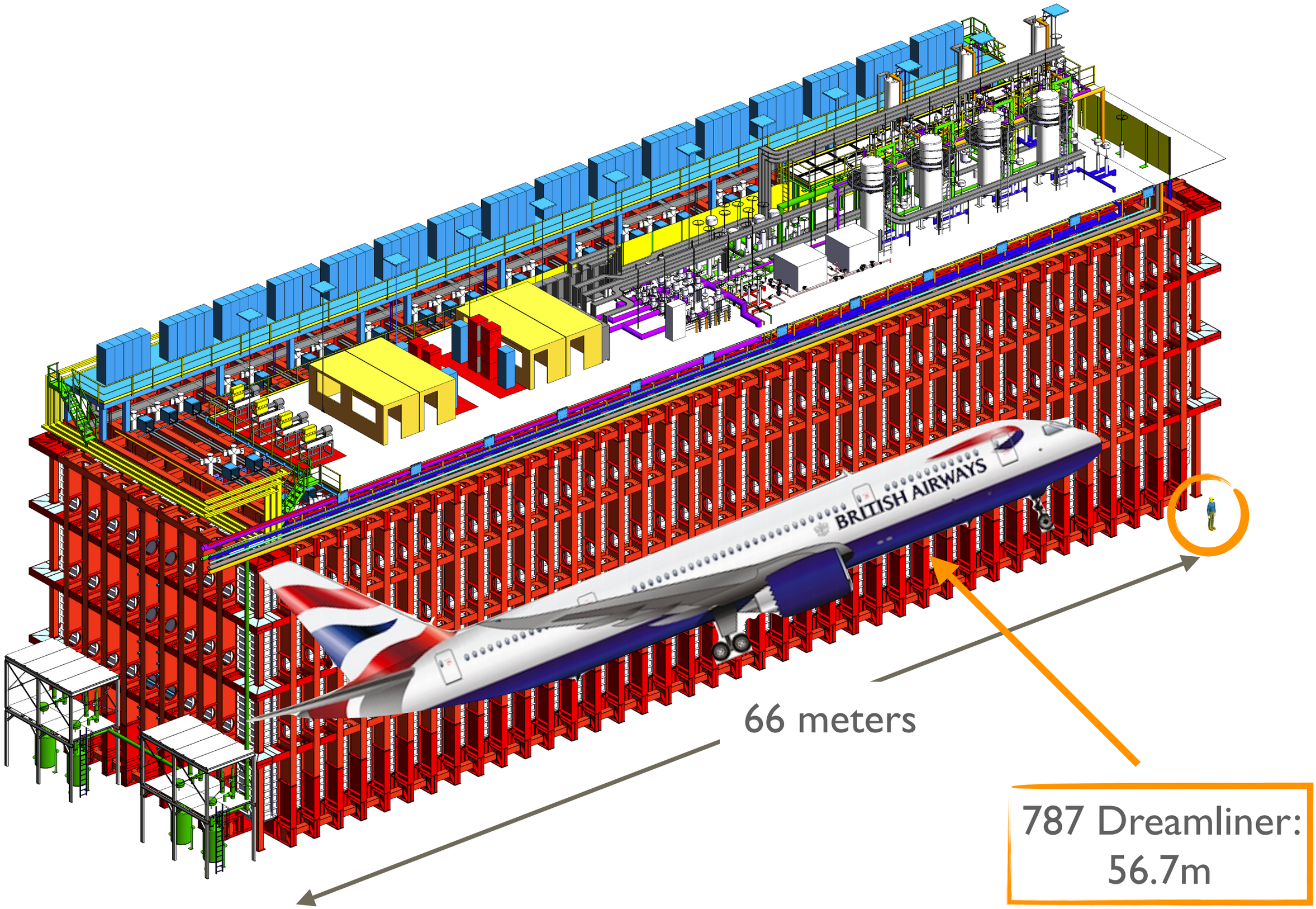
Fermilab

High-intensity neutrino beam


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



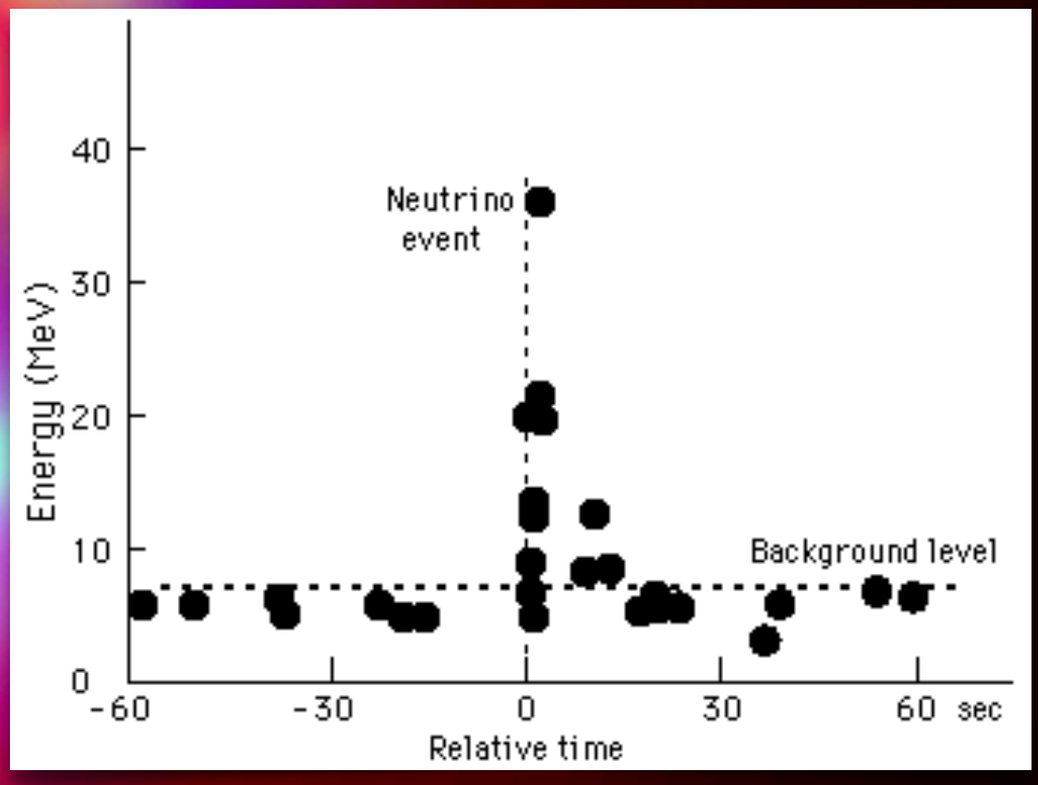

66 meters


BRITISH AIRWAYS
66 meters
787 Dreamliner:
56.7m

OTHER COOL NEUTRINOS WE CAN STUDY

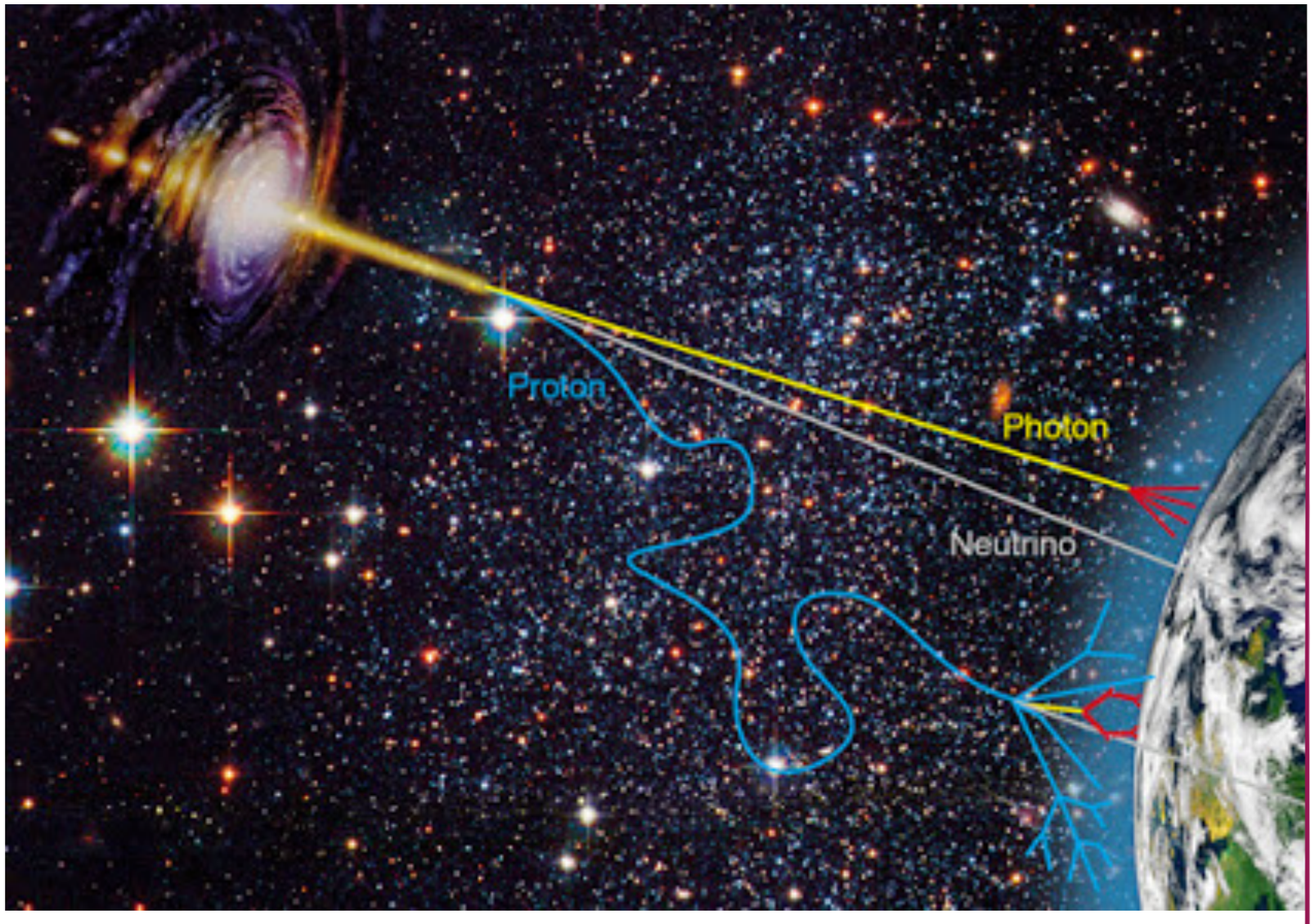
SUPERNOVA NEUTRINOS

Super-Kamiokande: 12
IMB: 8
Baksan: 5



Supernova 1987a

MULTI-MESSENGER ASTRONOMY



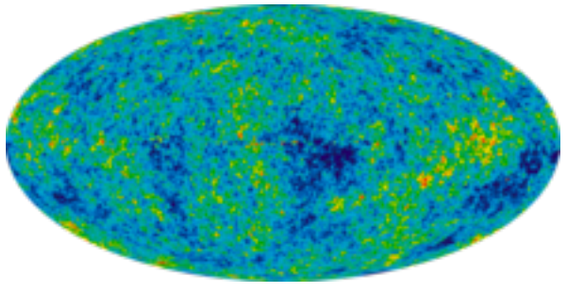
Examples of multi-messenger astronomy:

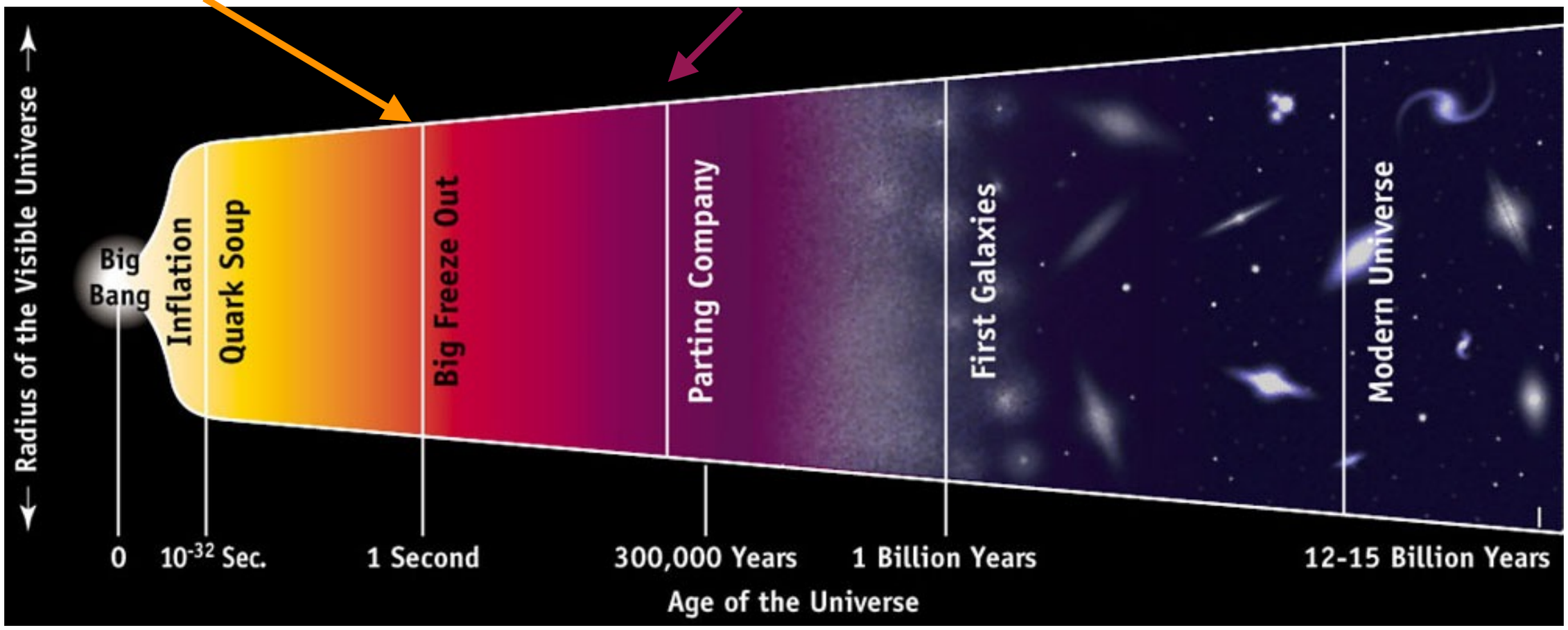
- Neutron star collision in August 2017: gravitational wave, gamma ray burst, optical signal
- September 2017: IceCube sees extremely-high energy neutrino event → gamma rays later seen from blazar with consistent position
- First time a neutrino detector used to locate an object in space!

COSMIC NEUTRINO BACKGROUND

Big-Bang Relic Neutrinos: 1 second old

Cosmic Microwave Background: ~300,000 years old

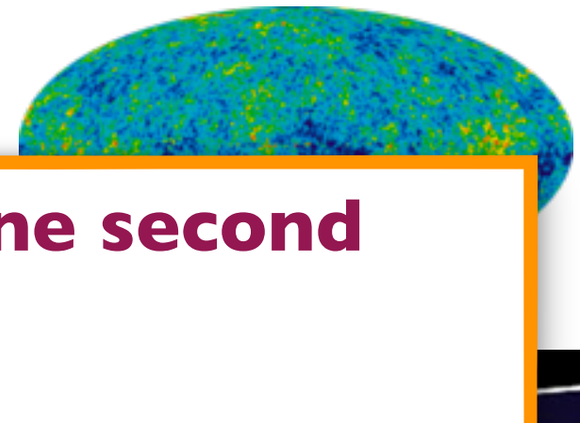




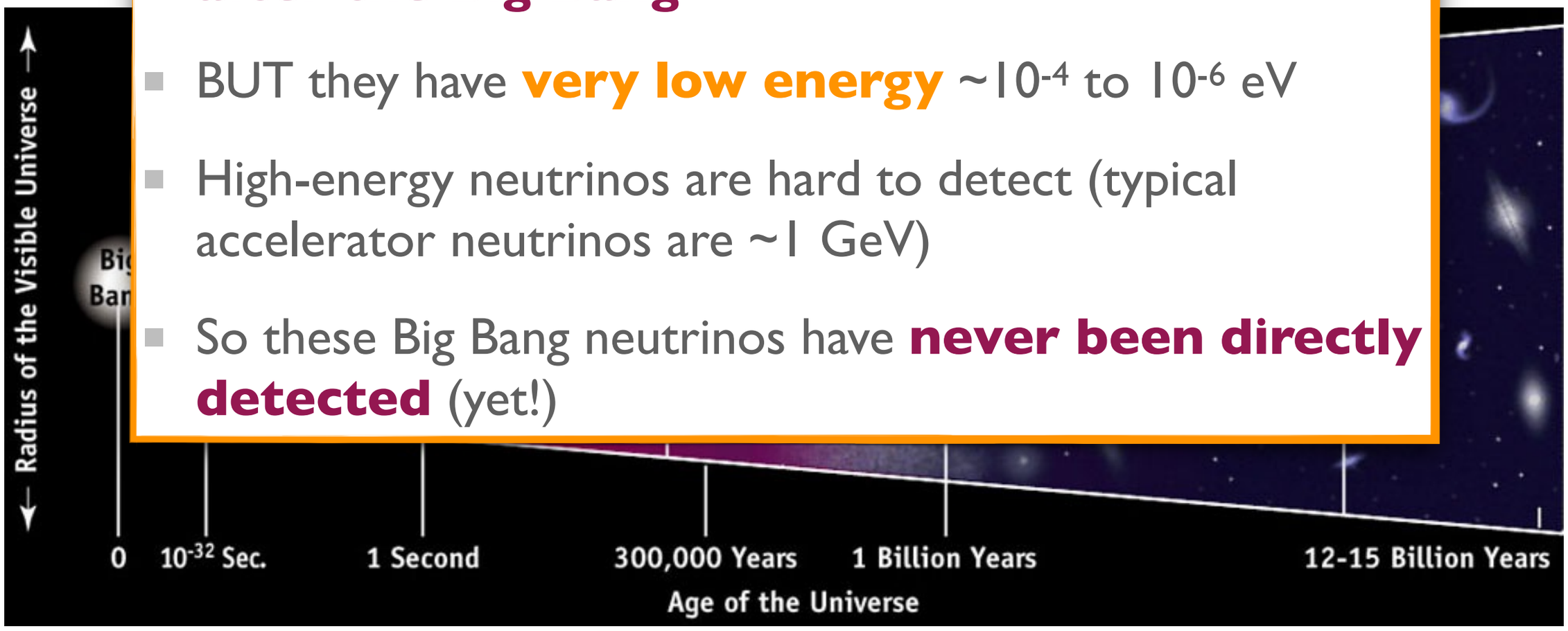
COSMIC NEUTRINO BACKGROUND

Big-Bang Relic Neutrinos: I secc

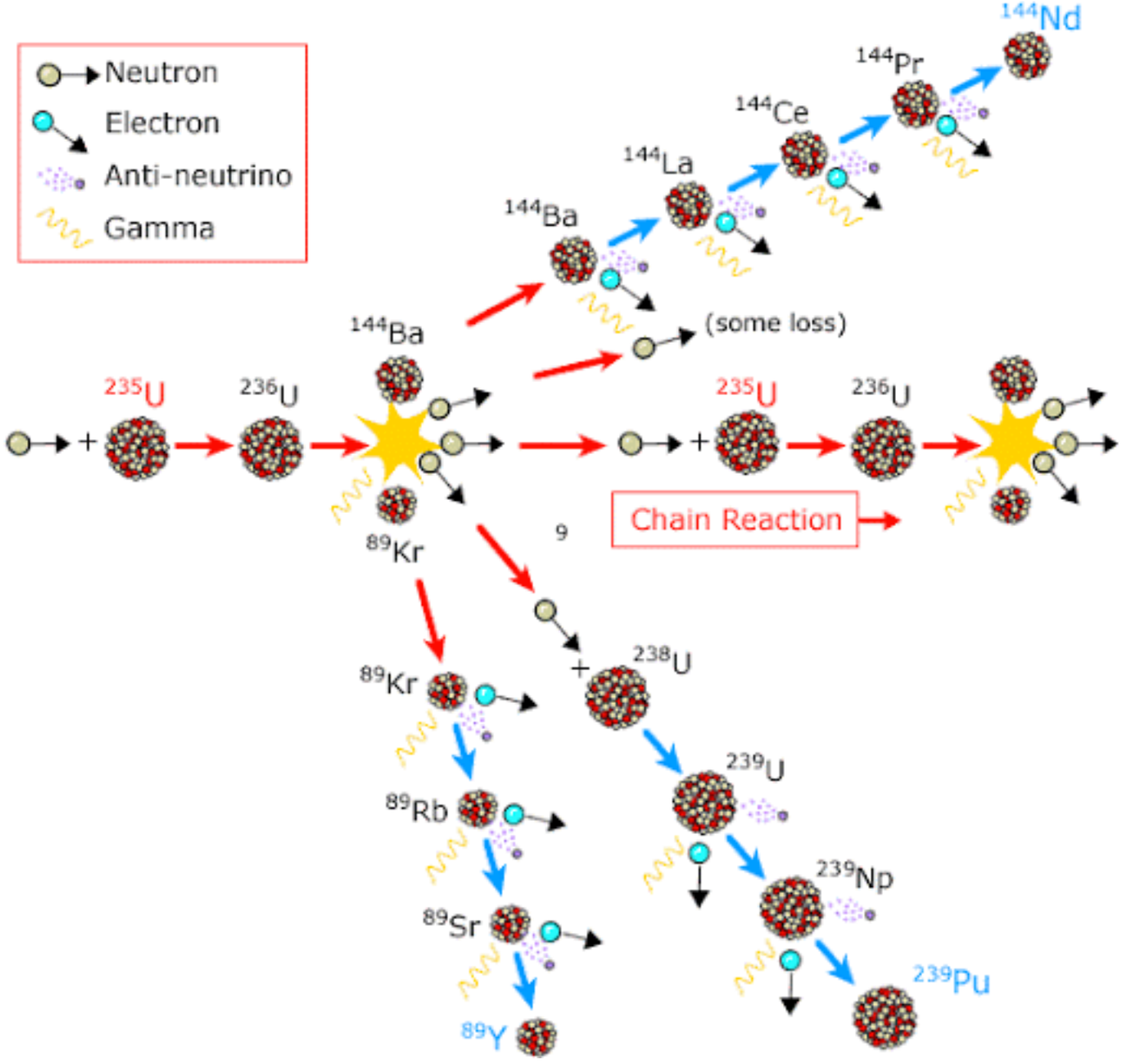
Cosmic Microwave Background:



- We are surrounded by neutrinos from **one second after the Big Bang**
- BUT they have **very low energy** ~10^{-4} to 10^{-6} eV
- High-energy neutrinos are hard to detect (typical accelerator neutrinos are ~1 GeV)
- So these Big Bang neutrinos have **never been directly detected** (yet!)



NEUTRINOS AND NUCLEAR NON-PROLIFERATION

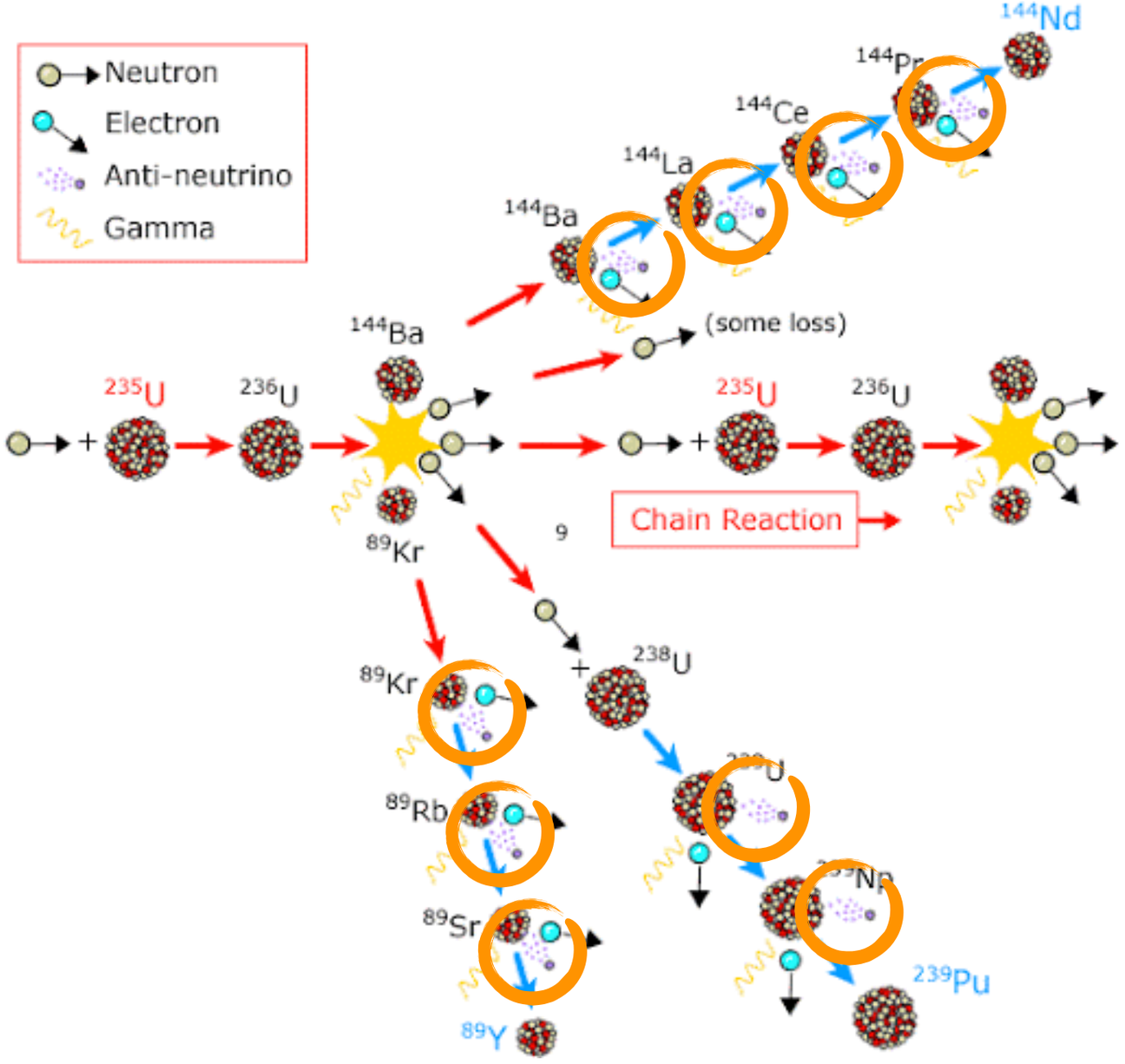


Nuclear reactors:

- 1) Produce a lot of electron antineutrinos
- 2) Produce Plutonium-239

Neutrinos can't be stopped so there is no way of shielding them. There are proposals to use neutrinos for nuclear nonproliferation

NEUTRINOS AND NUCLEAR NON-PROLIFERATION



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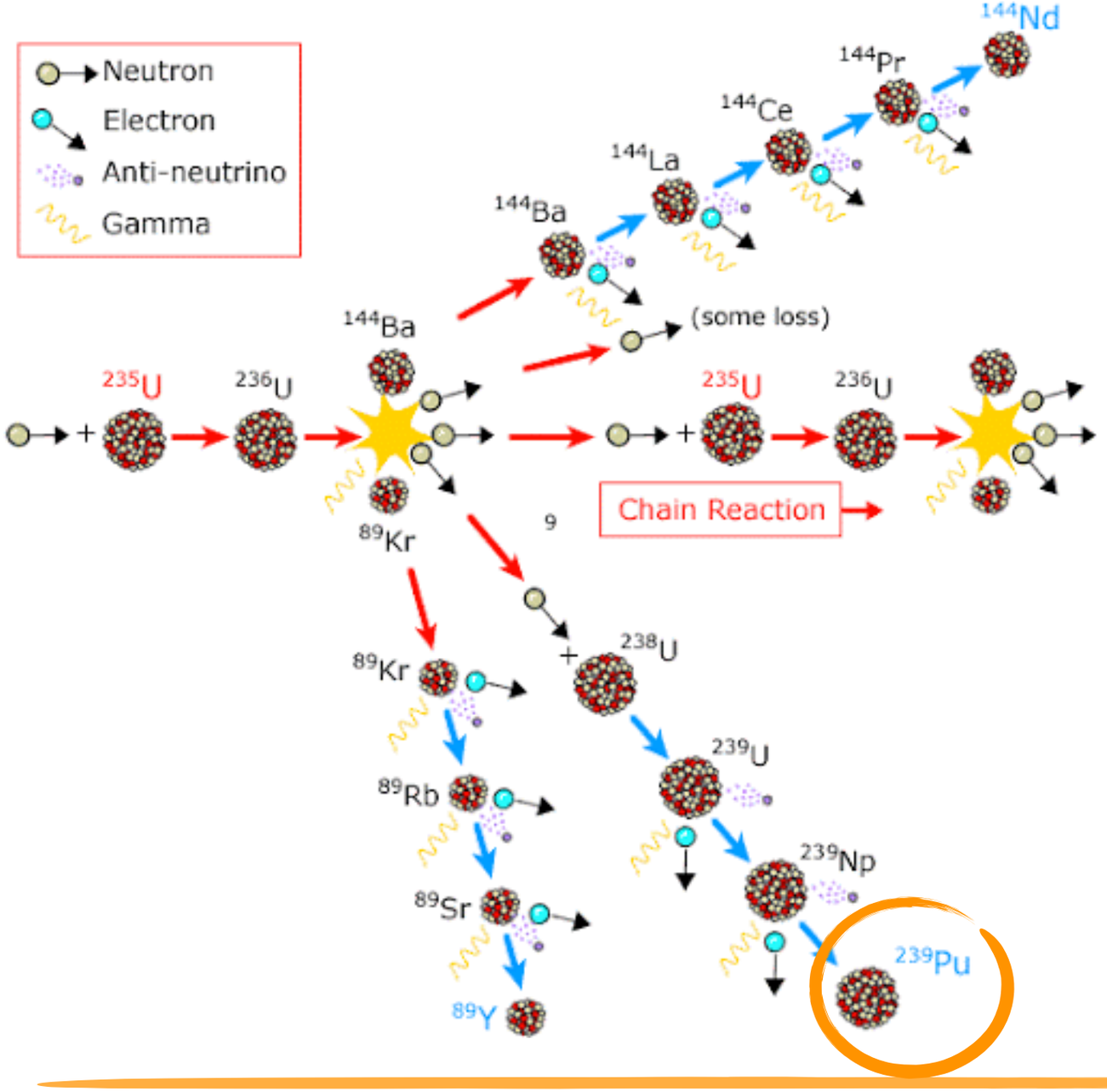

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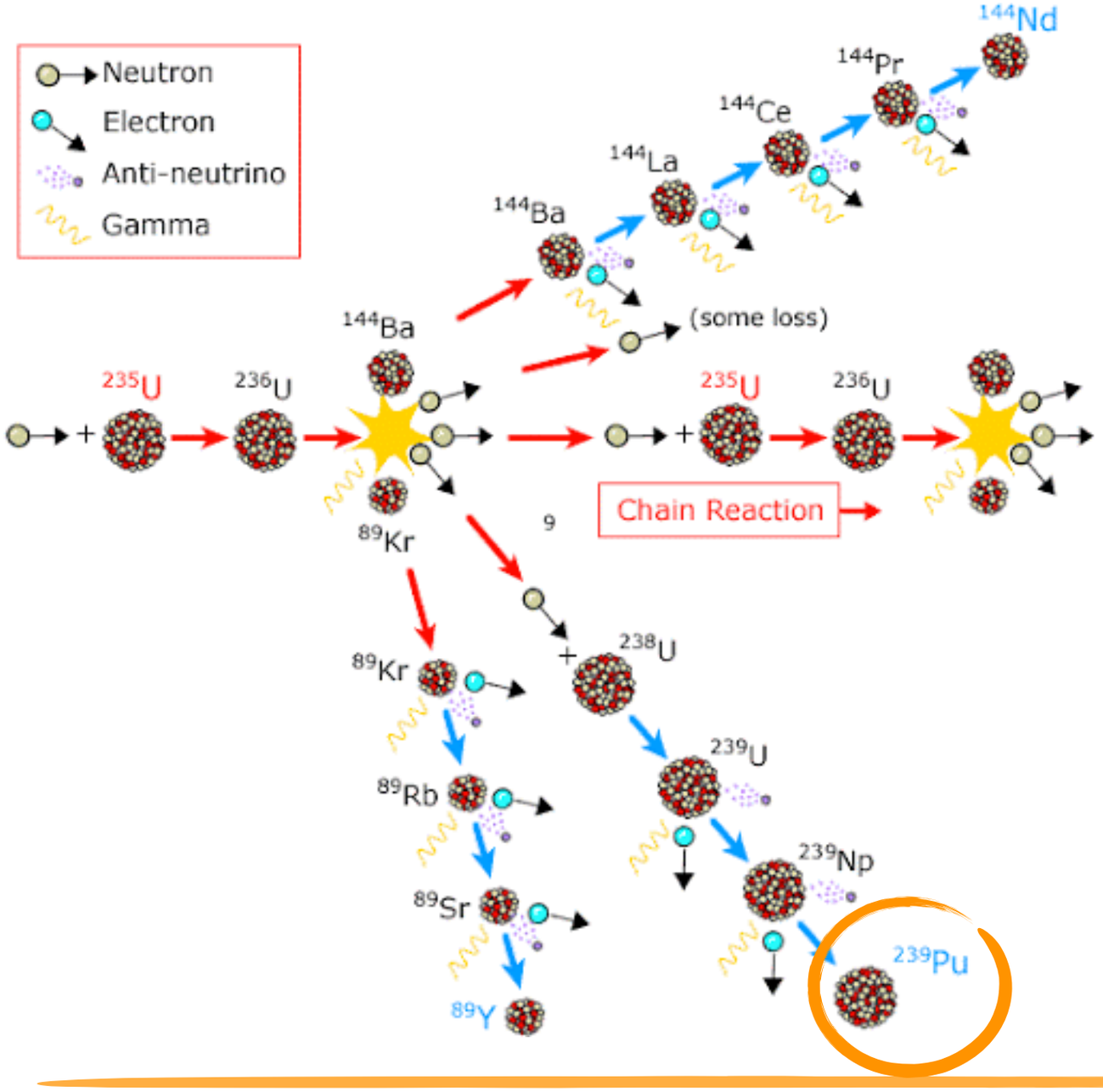
NEUTRINOS AND NUCLEAR NON-PROLIFERATION



These fall into two categories (note: both are proposed and under active research — not in action yet!)

1) Monitor **total number** of electron antineutrinos to see if there are **unknown reactors** operating in an area

2) Measure **neutrino energies** → neutrinos produced by ^{239}Pu decay are different energies to those produced by ^{235}U → work out if a reactor is **making plutonium** (or removing it for weapons)

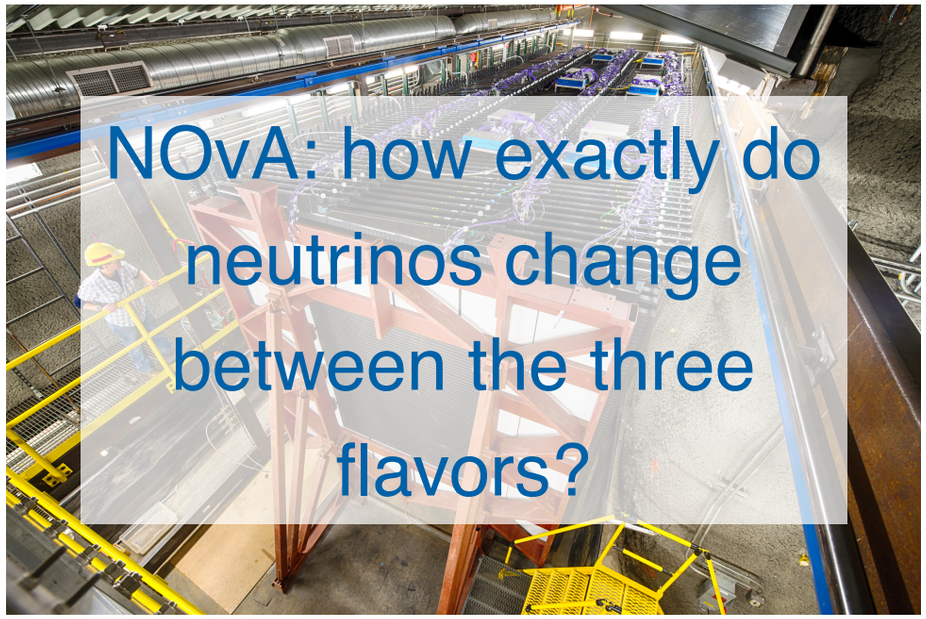
Phew! That was a lot. Let's recap:

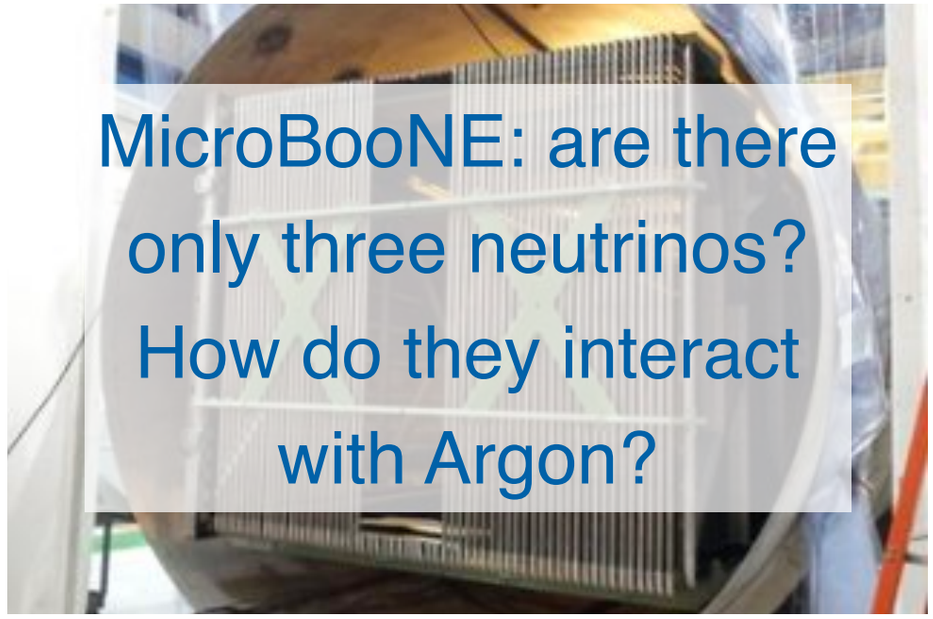
- Neutrinos are a type of fundamental particle, predicted by the Standard Model of Particle Physics
- But they're also the first evidence we have of physics beyond the Standard Model → neutrinos tell us that our understanding of (particle) physics is incomplete!
- The reason for that is that they oscillate — changing flavour as they travel over long distances
- There is a lot that we don't know about neutrinos, including whether they could explain why the universe exists, or teach us about how the universe was born. I've barely scratched the surface of what we do and don't know! If you're interested:
  - All things neutrino website: https://neutrinos.fnal.gov/
  - Summer school lectures INSS 2019: https://indico.fnal.gov/event/19346/

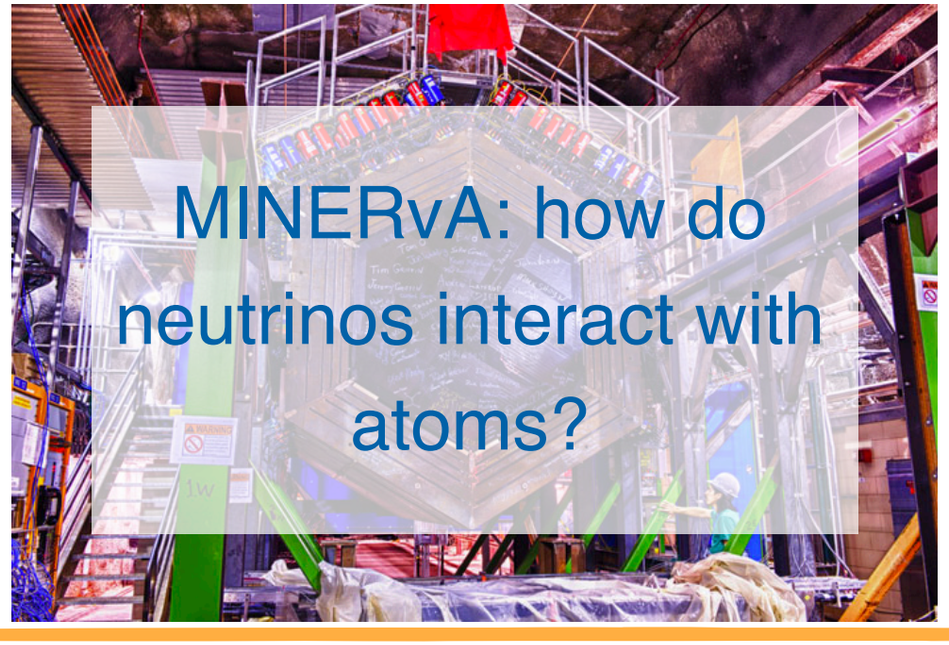
THANK YOU FOR LISTENING

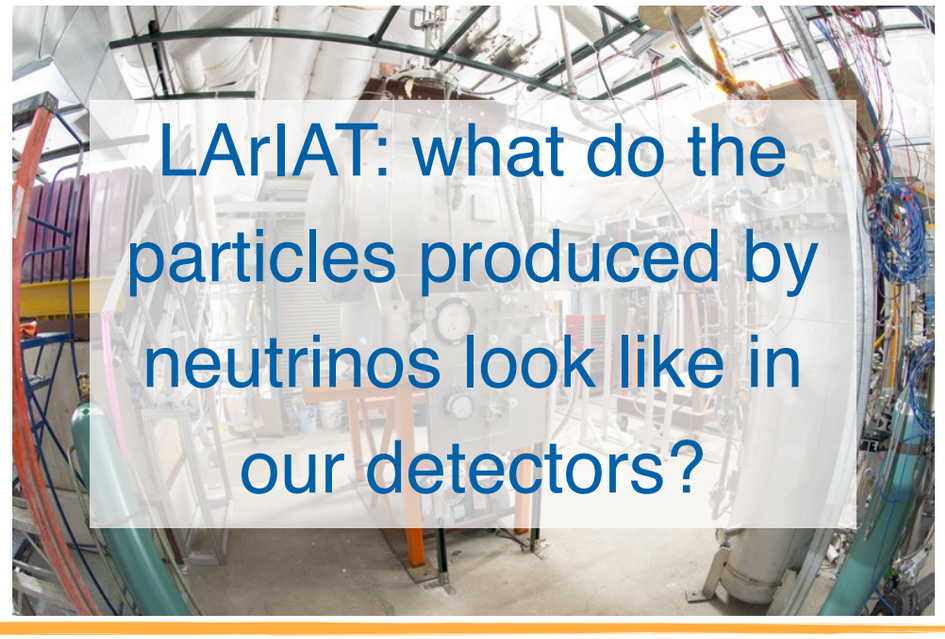
EXTRA SLIDES

NEUTRINO EXPERIMENTS AT FERMILAB (PRESENT)

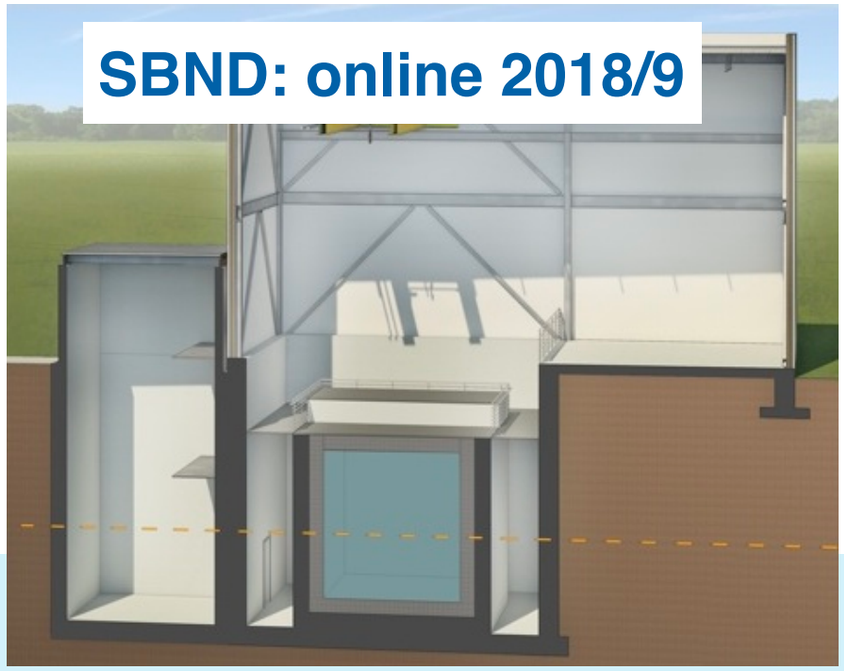


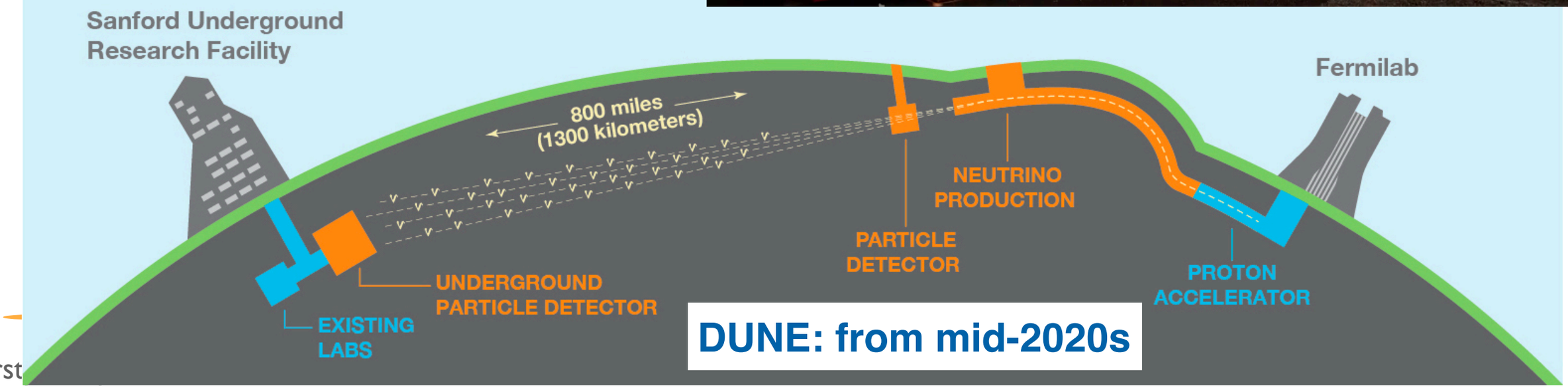






NEUTRINO EXPERIMENTS AT FERMILAB (FUTURE)





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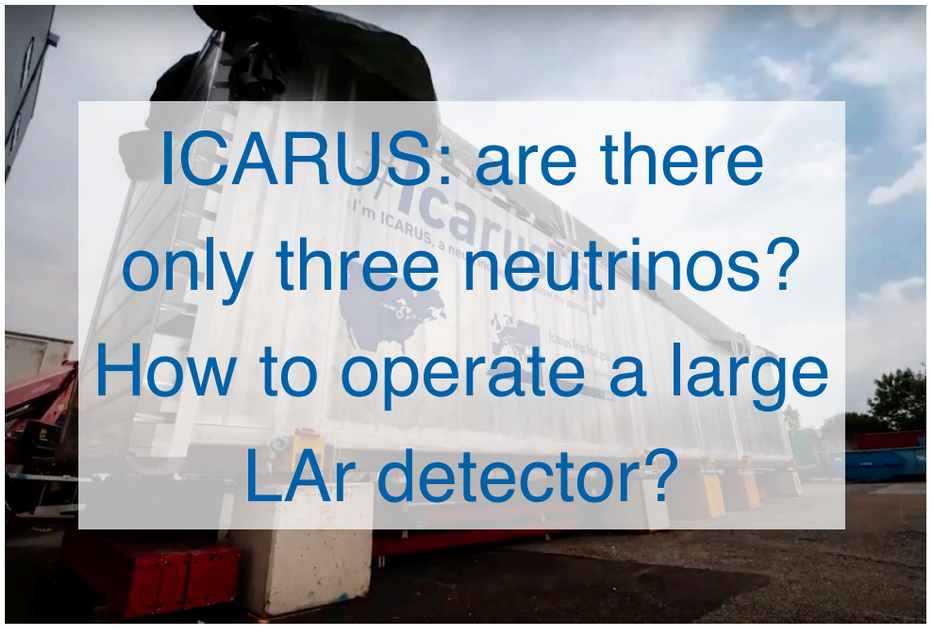
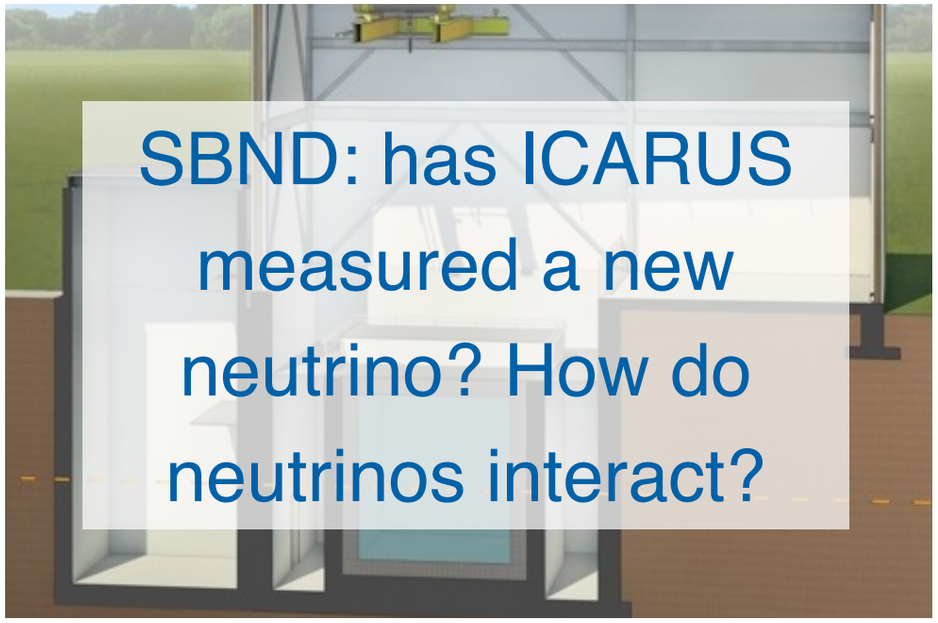
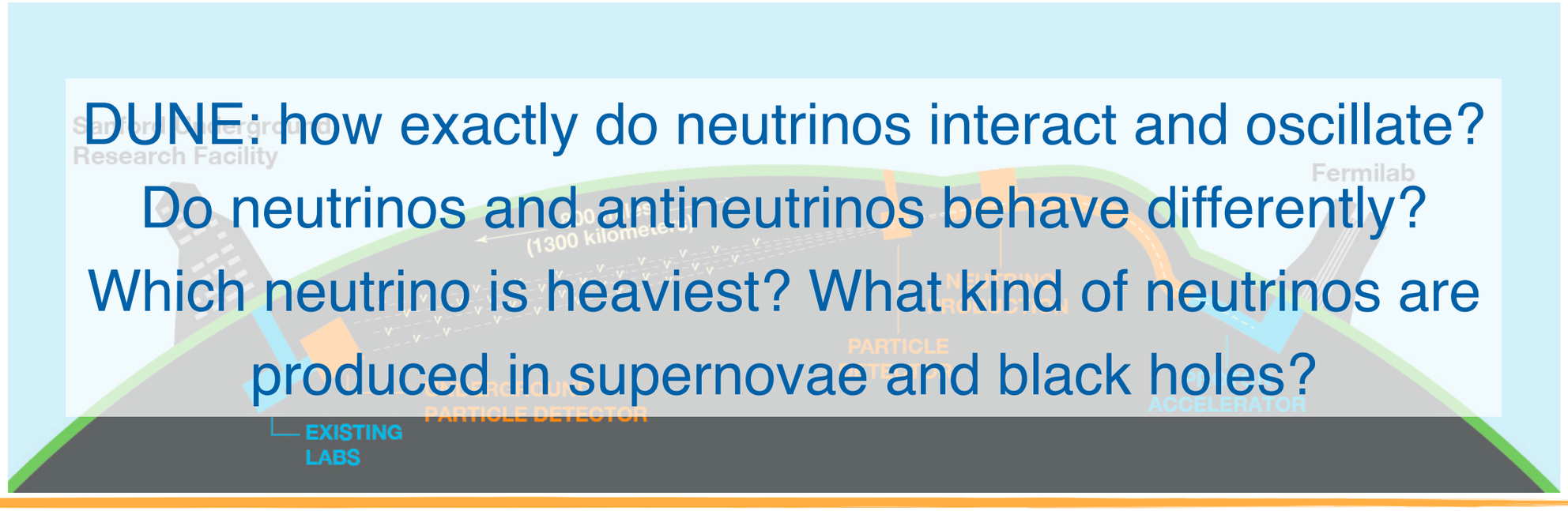




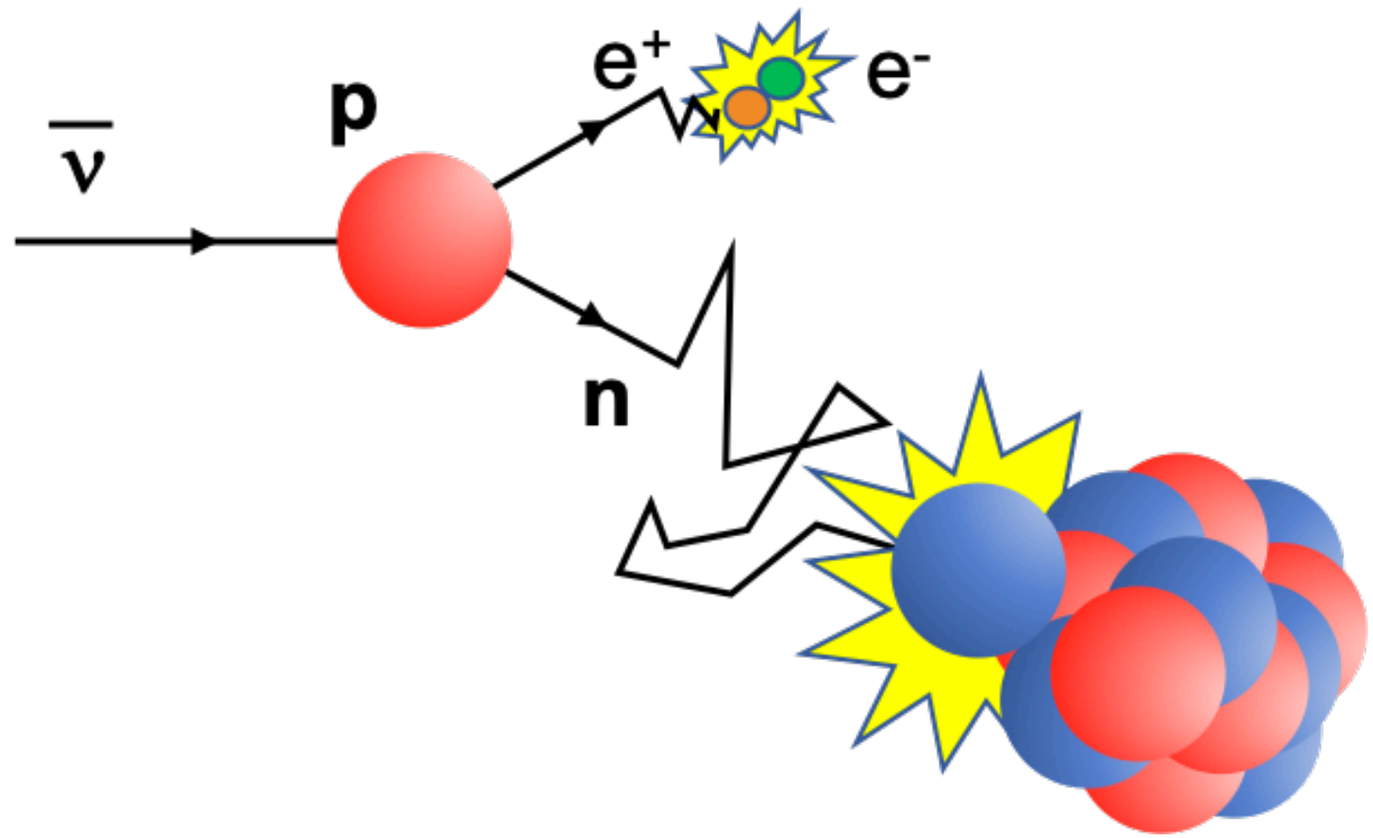


REACTOR NEUTRINOS

Neutrino oscillation parameters:

θ_{12} ✔ solar ✔ reactor
θ_{23}
θ_{13} ✔ solar ✔ react.
Δm^2_{21} ✔ solar ✔ reactor
$|\Delta m^2_{32}|$
δ_{CP}

- Fission in nuclear reactors produces a lot of low-energy electron antineutrinos
- Detectors look for the signs of inverse beta decay:



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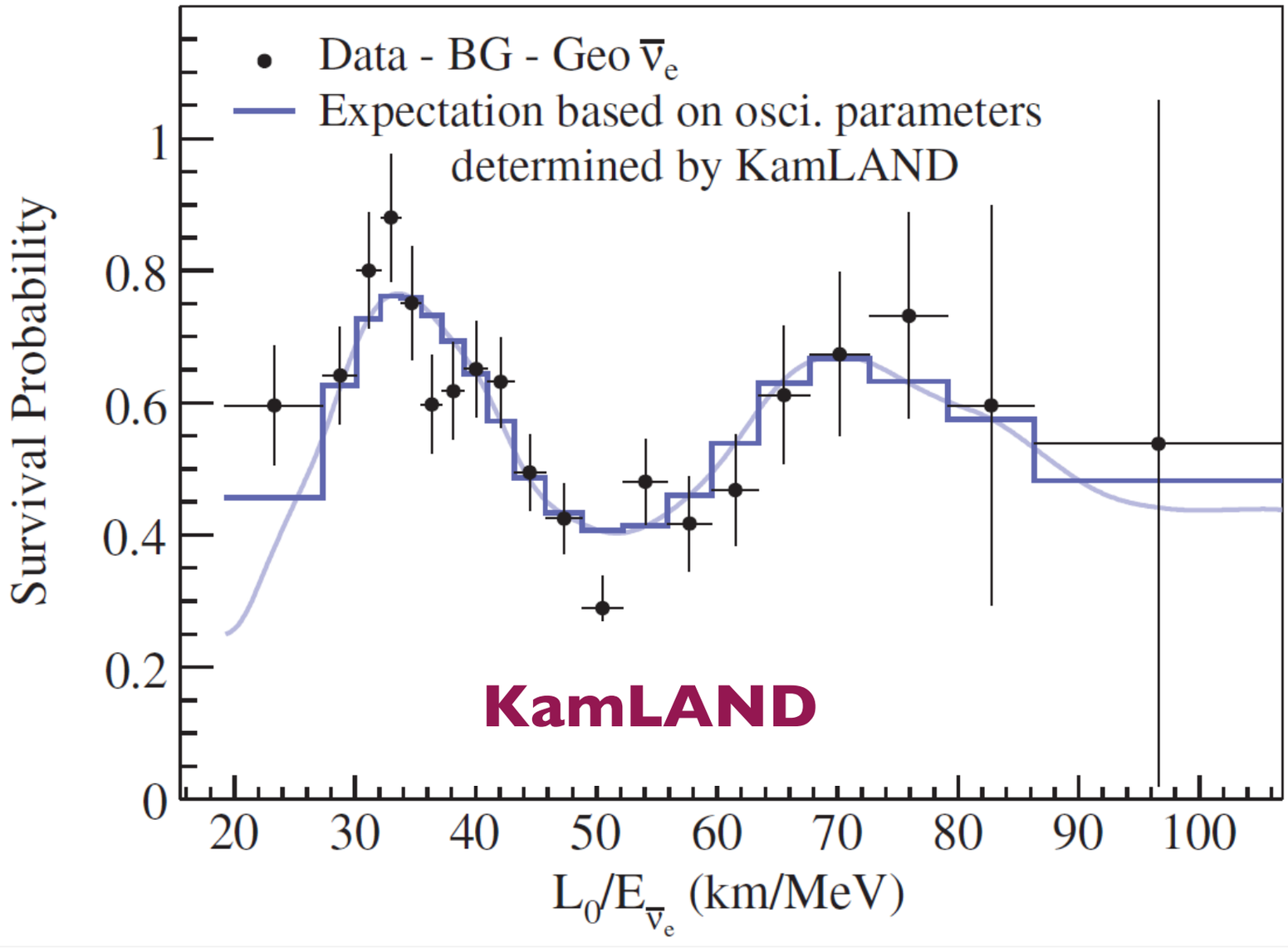
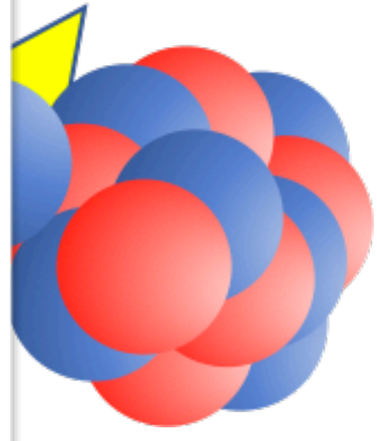
δ_{CP}

- Fissio… …y electron antine…
- Detec… signs … decay…

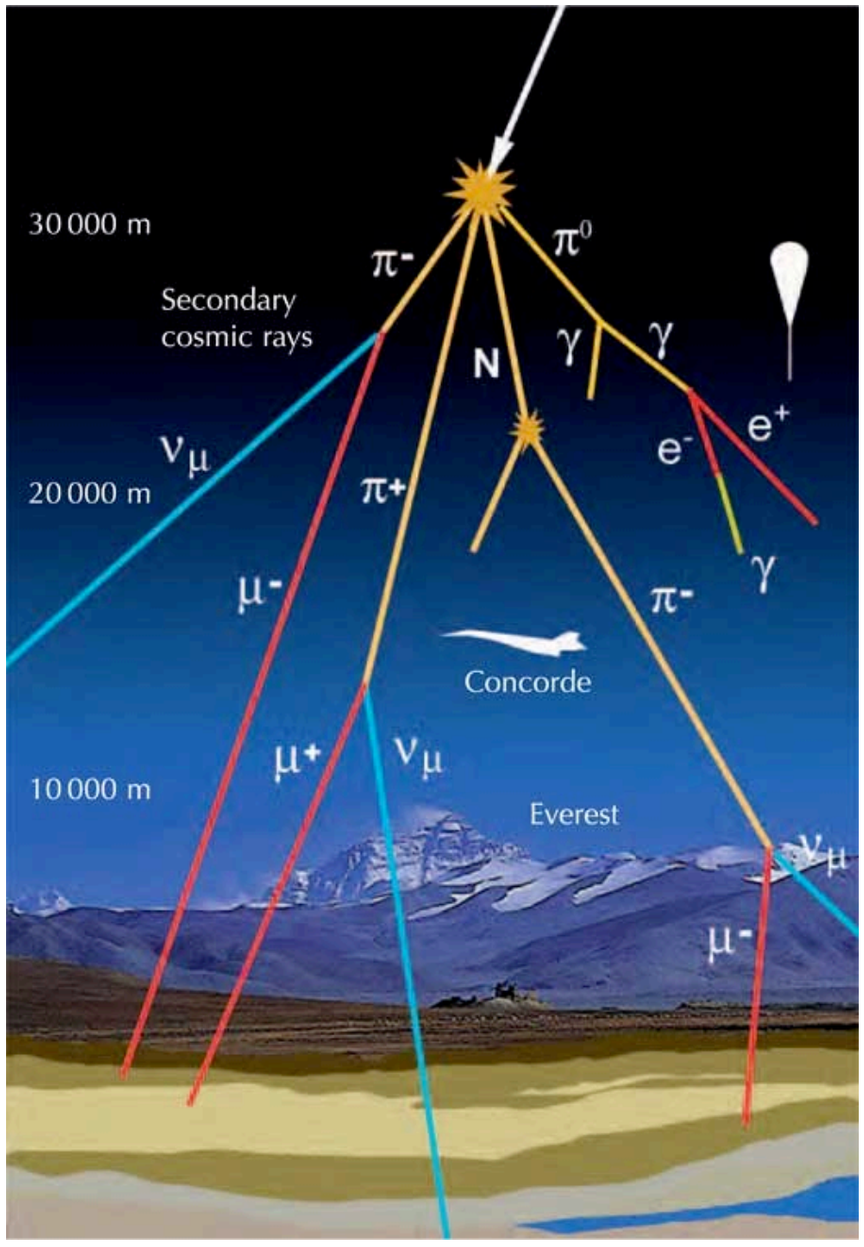




ATMOSPHERIC NEUTRINOS

Neutrino oscillation parameters:

θ_{12} ✔ solar ✔ reactor
θ_{23} ✔ atmos.
θ_{13} ✔ solar ✔ react. ✔ atm.
Δm^2_{21} ✔ solar ✔ reactor
$|\Delta m^2_{32}|$ ✔ atmos.
δ_{CP} ? atmos.



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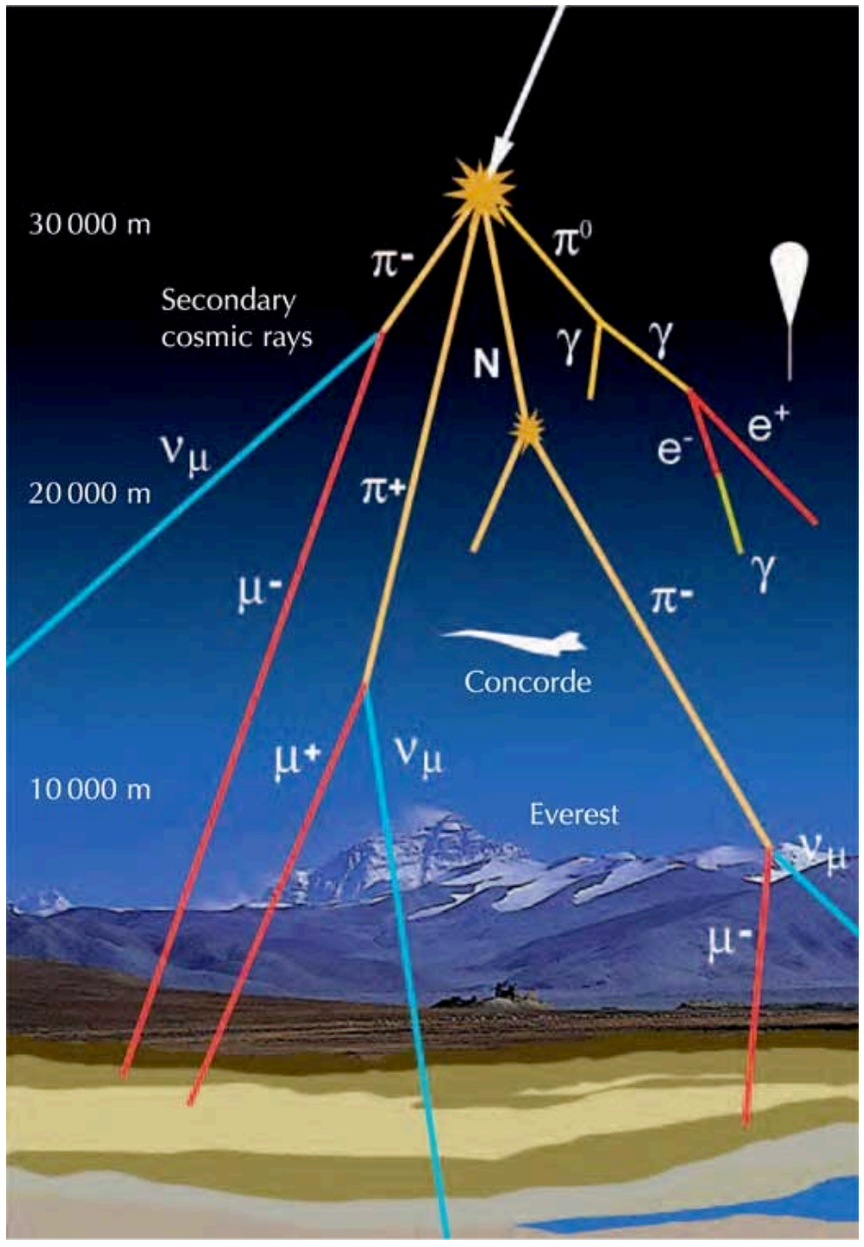

ATMOSPHERIC NEUTRINOS

Neutrino oscillation parameters:

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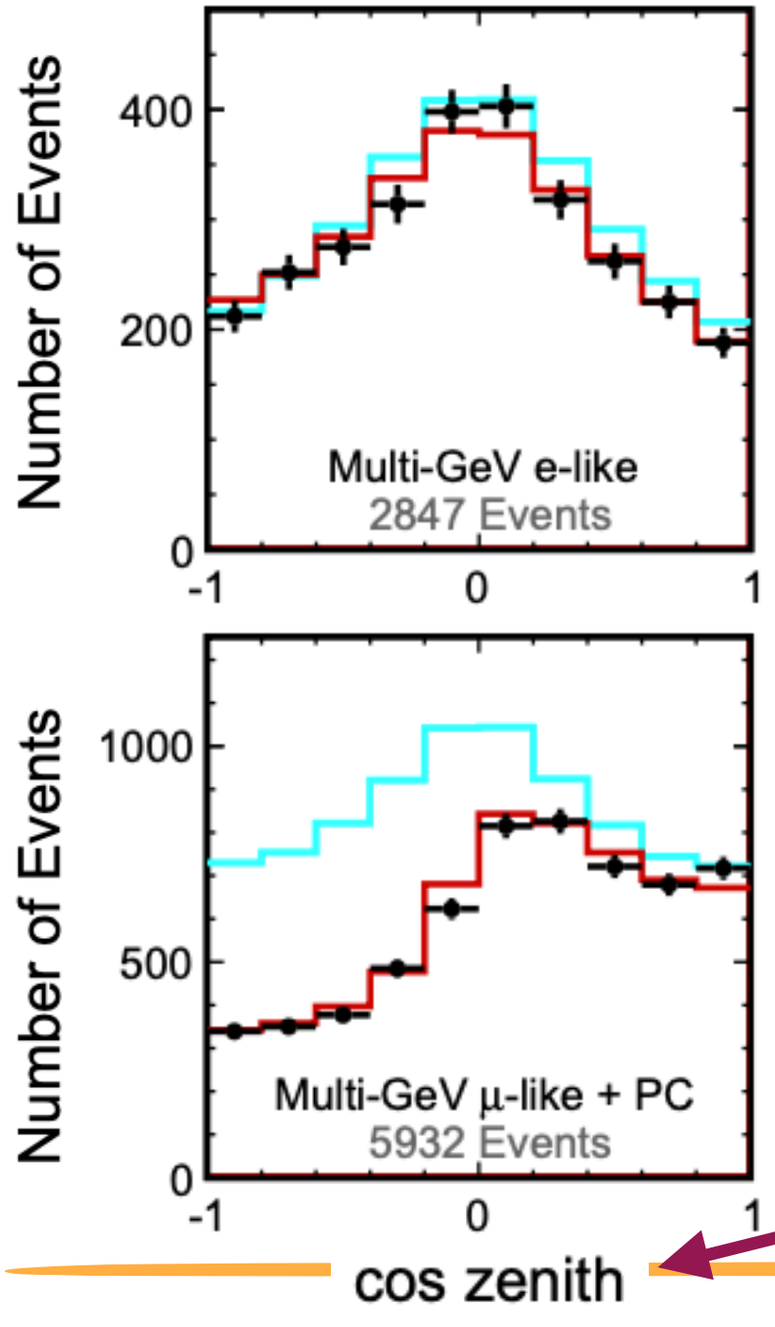
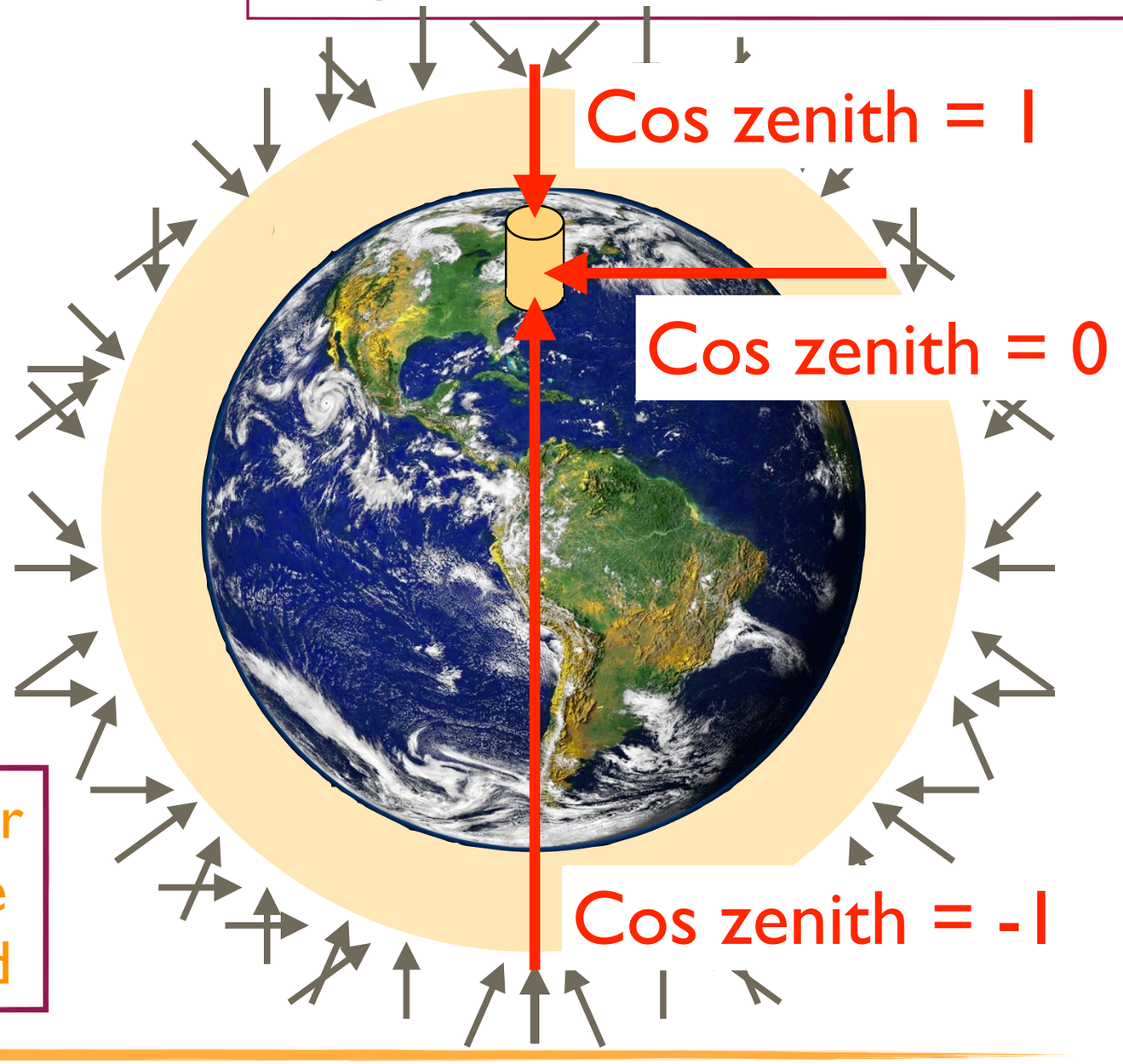


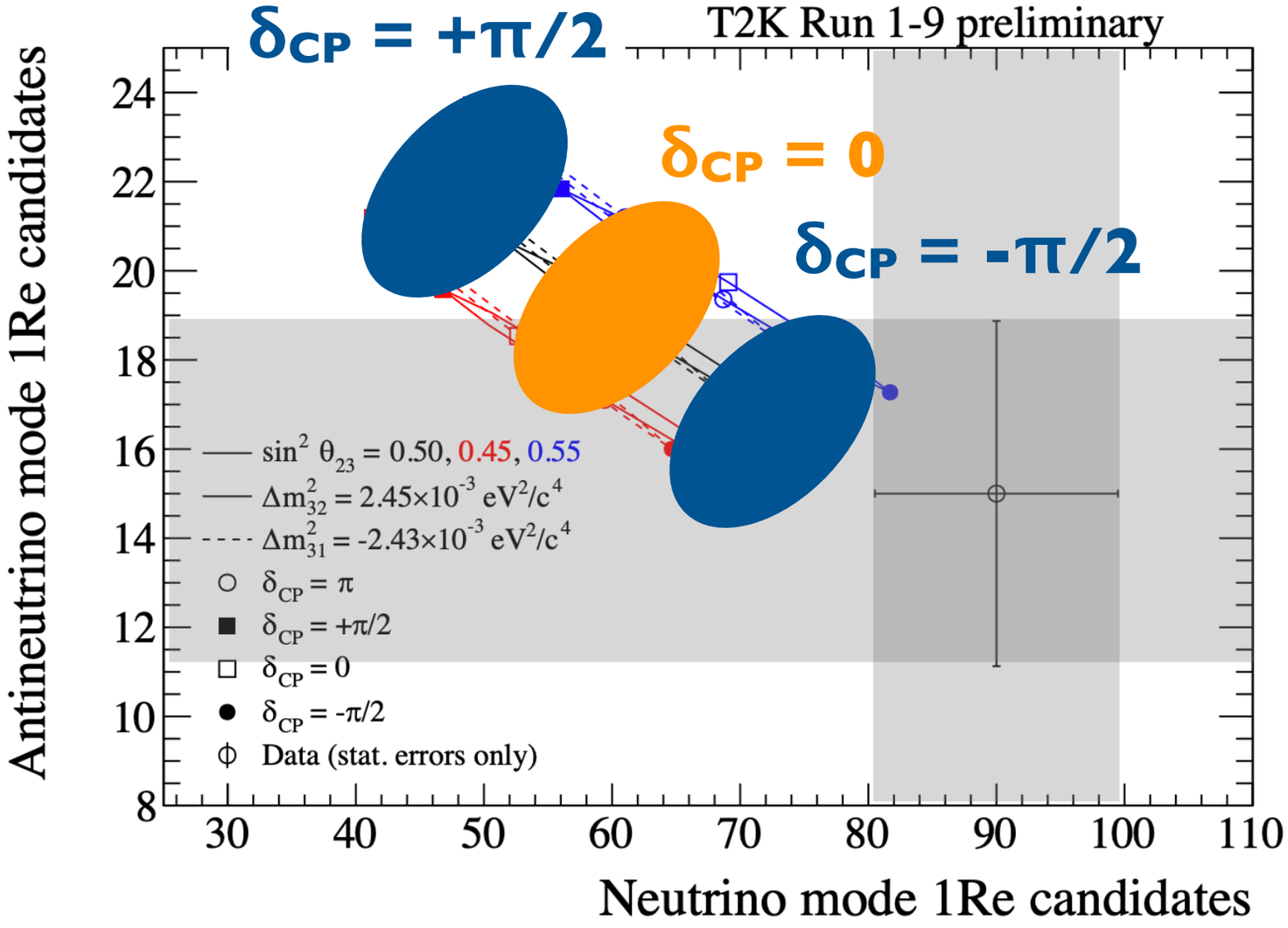


Proxy for distance travelled

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

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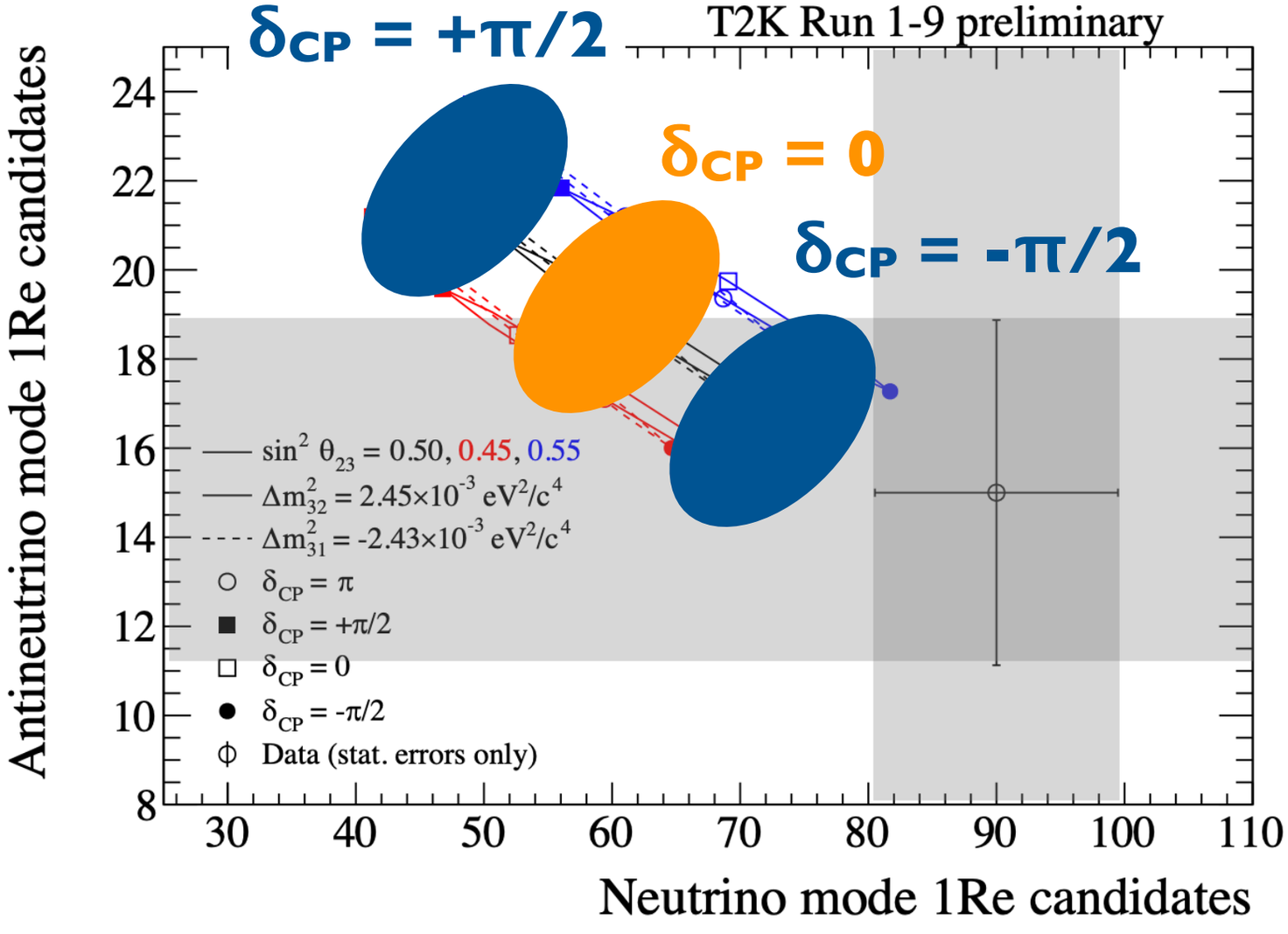
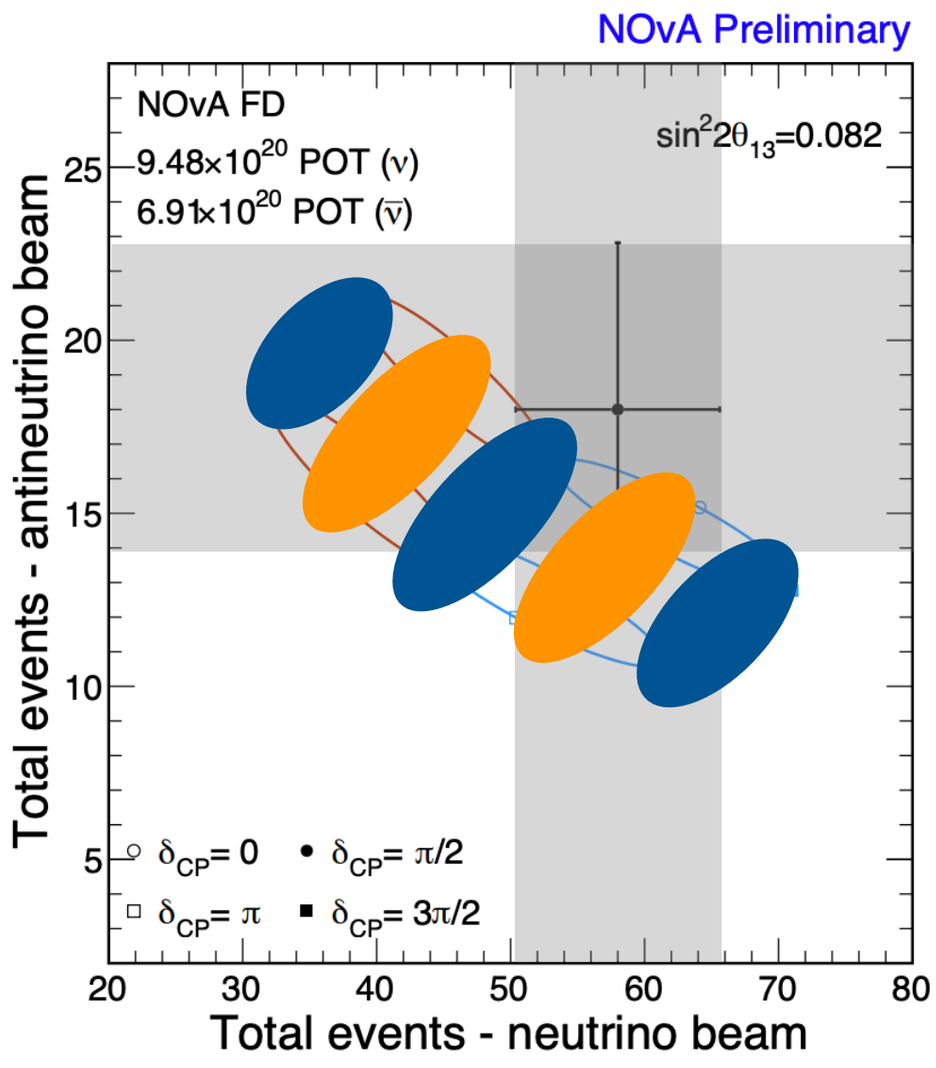




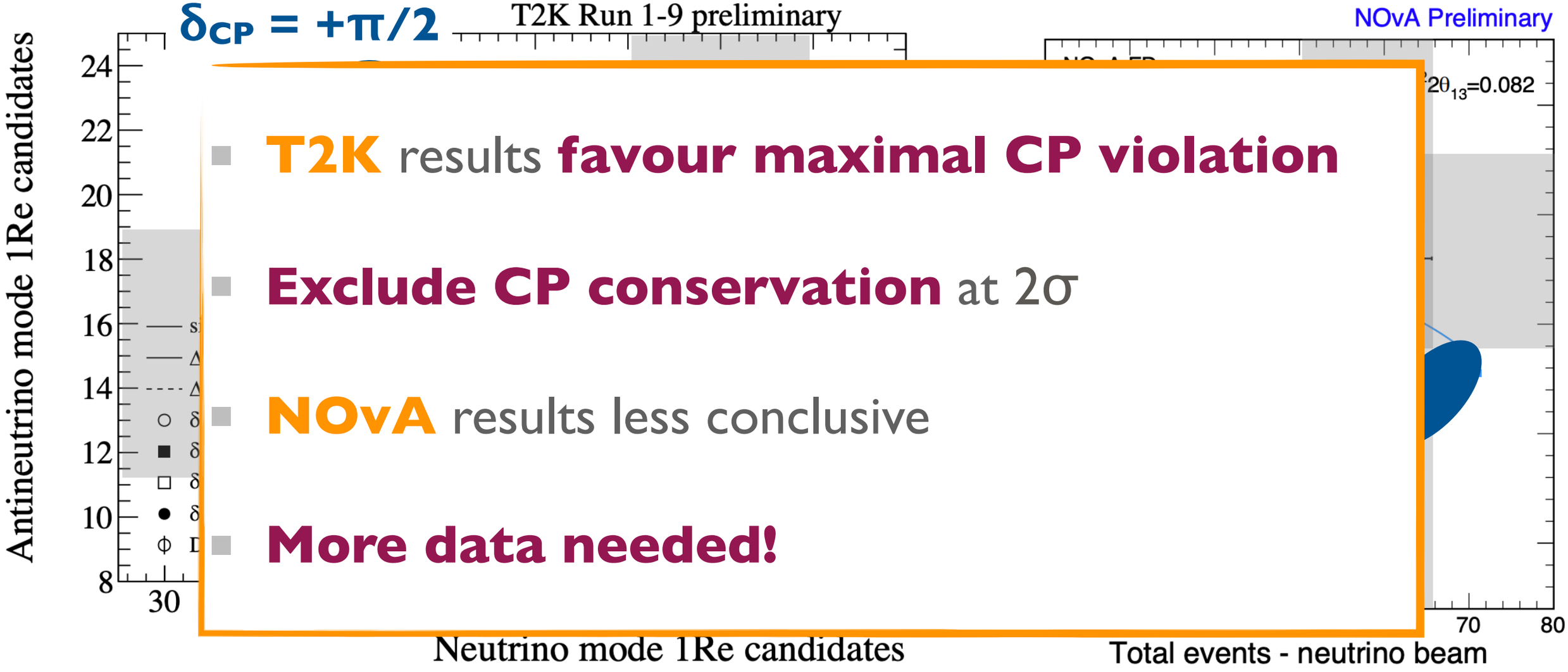
Figures from P. Dunne, FPCP 2019

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

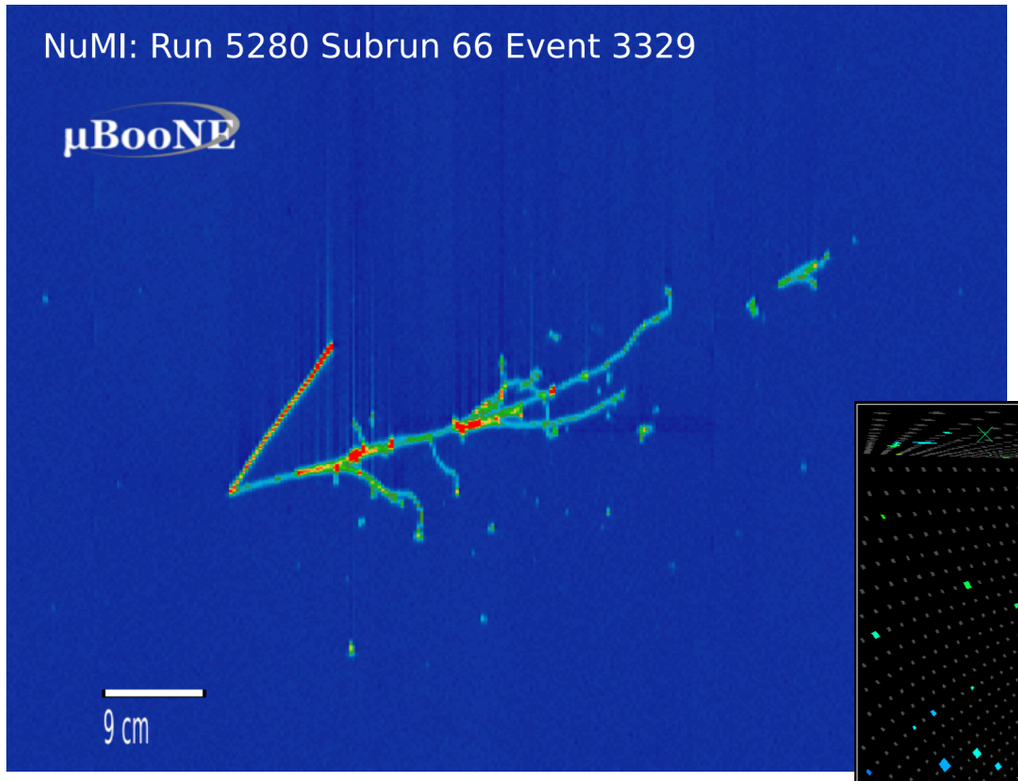
WHY LIQUID ARGON?

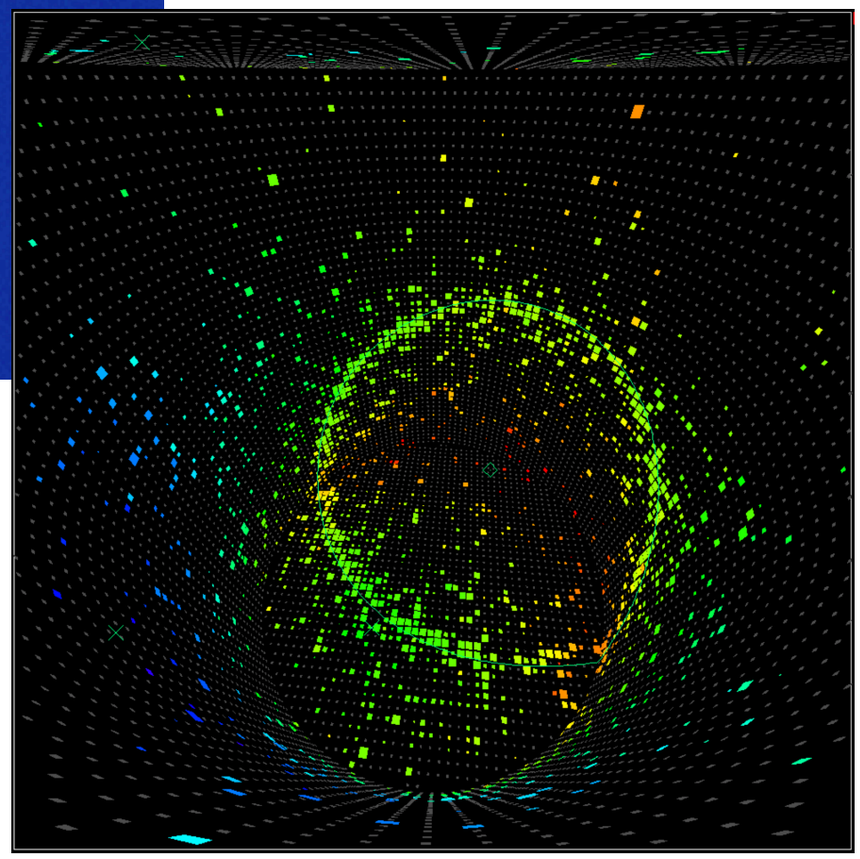
✔ Very high resolution images

✔ Very low thresholds

✔ Calorimetric information

✔ Electron/photon discrimination





WHAT CAN WE SAY ABOUT δ_{CP}?

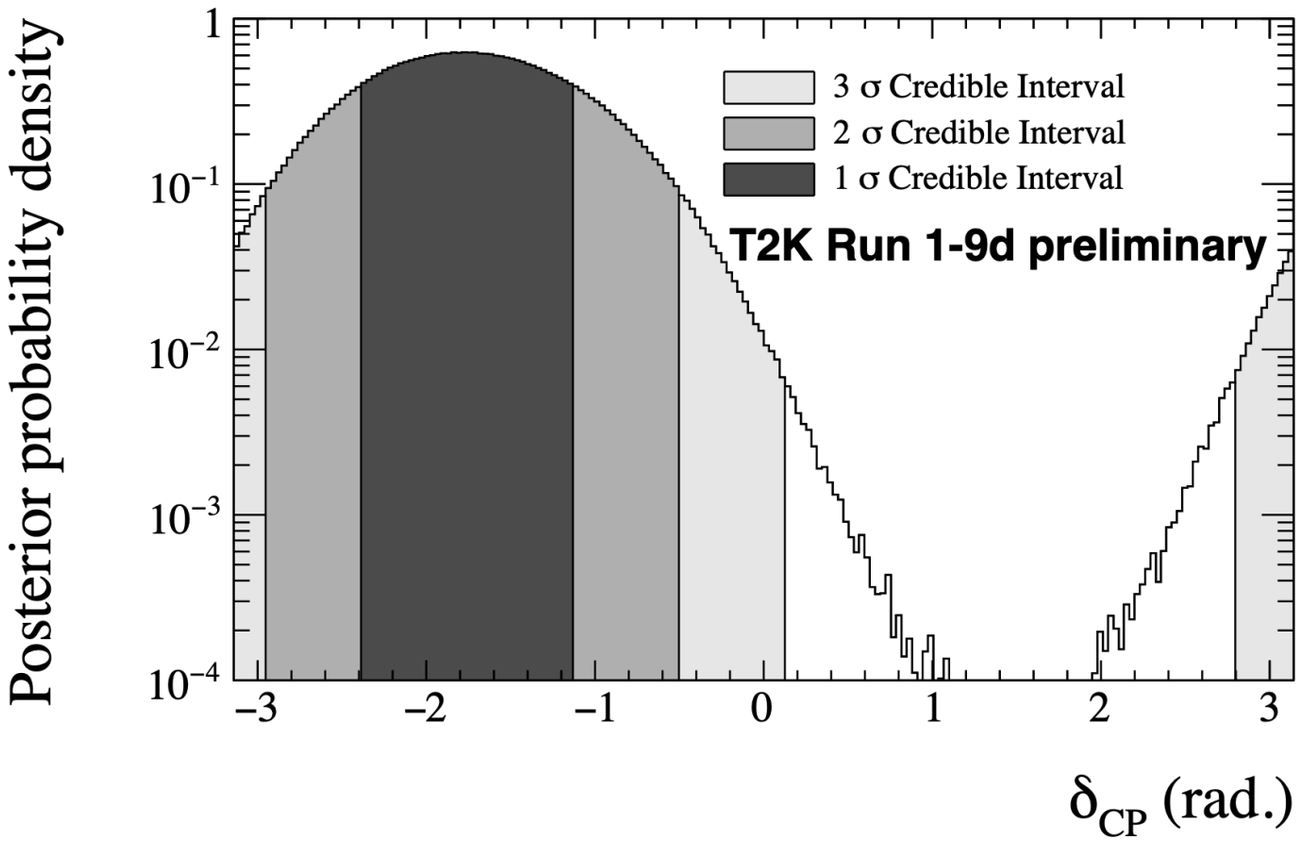
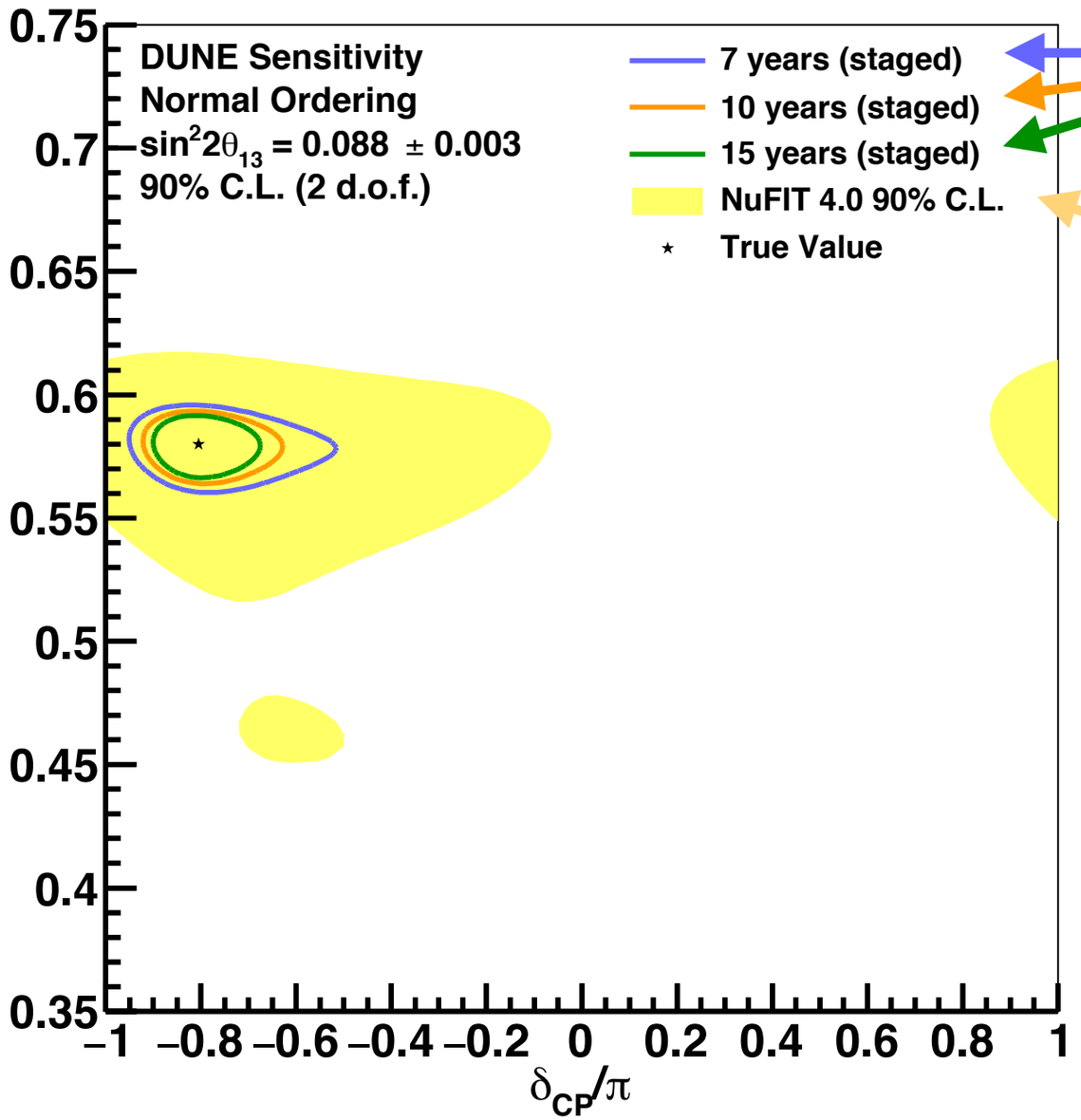


Figure from A. Kaboth, NuPhys 2018

- 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

PRECISE MEASUREMENTS OF NEUTRINO OSCILLATION

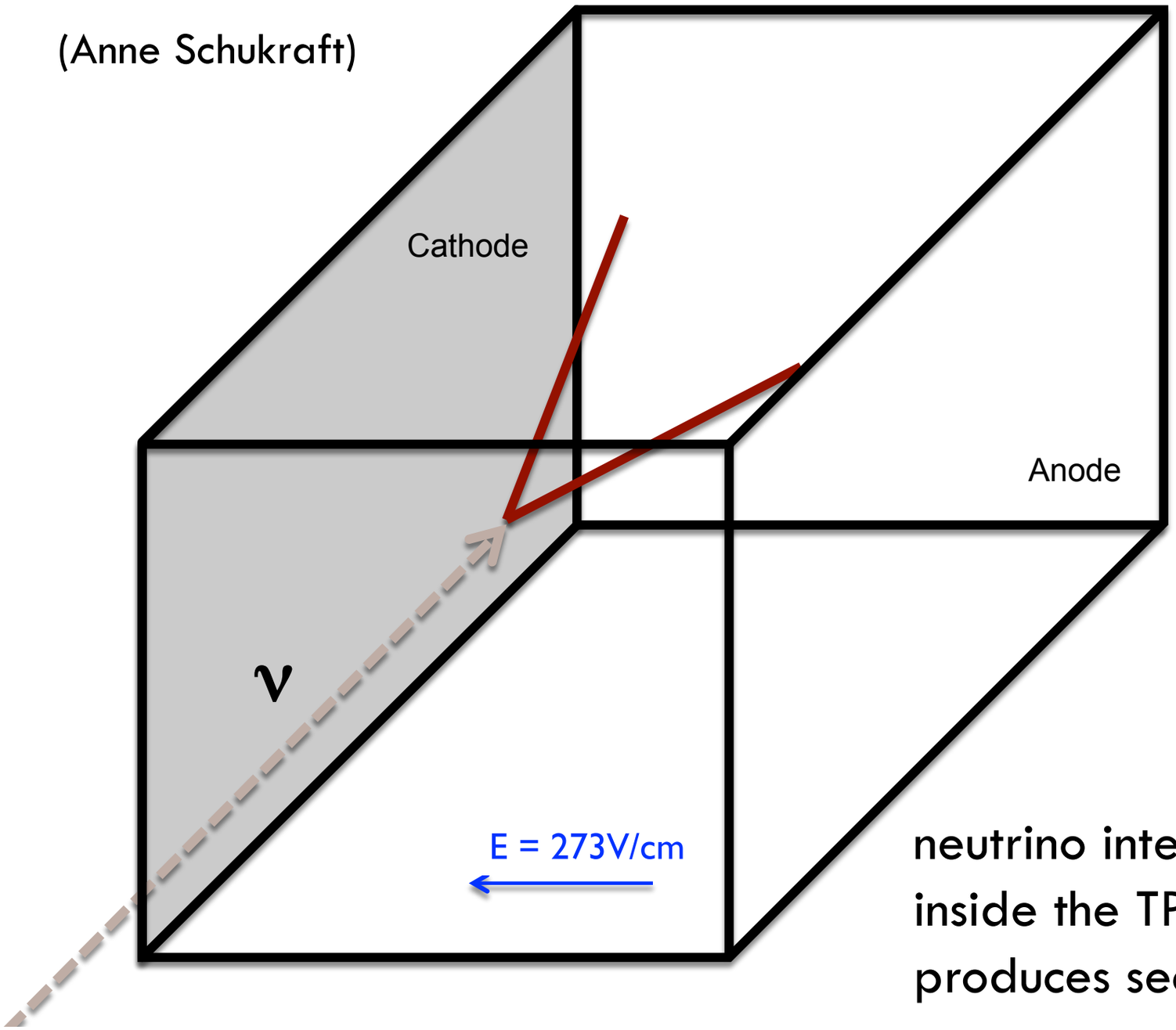


DUNE aim after
7, 10, 15 years

Current measurements

LIQUID ARGON TPC

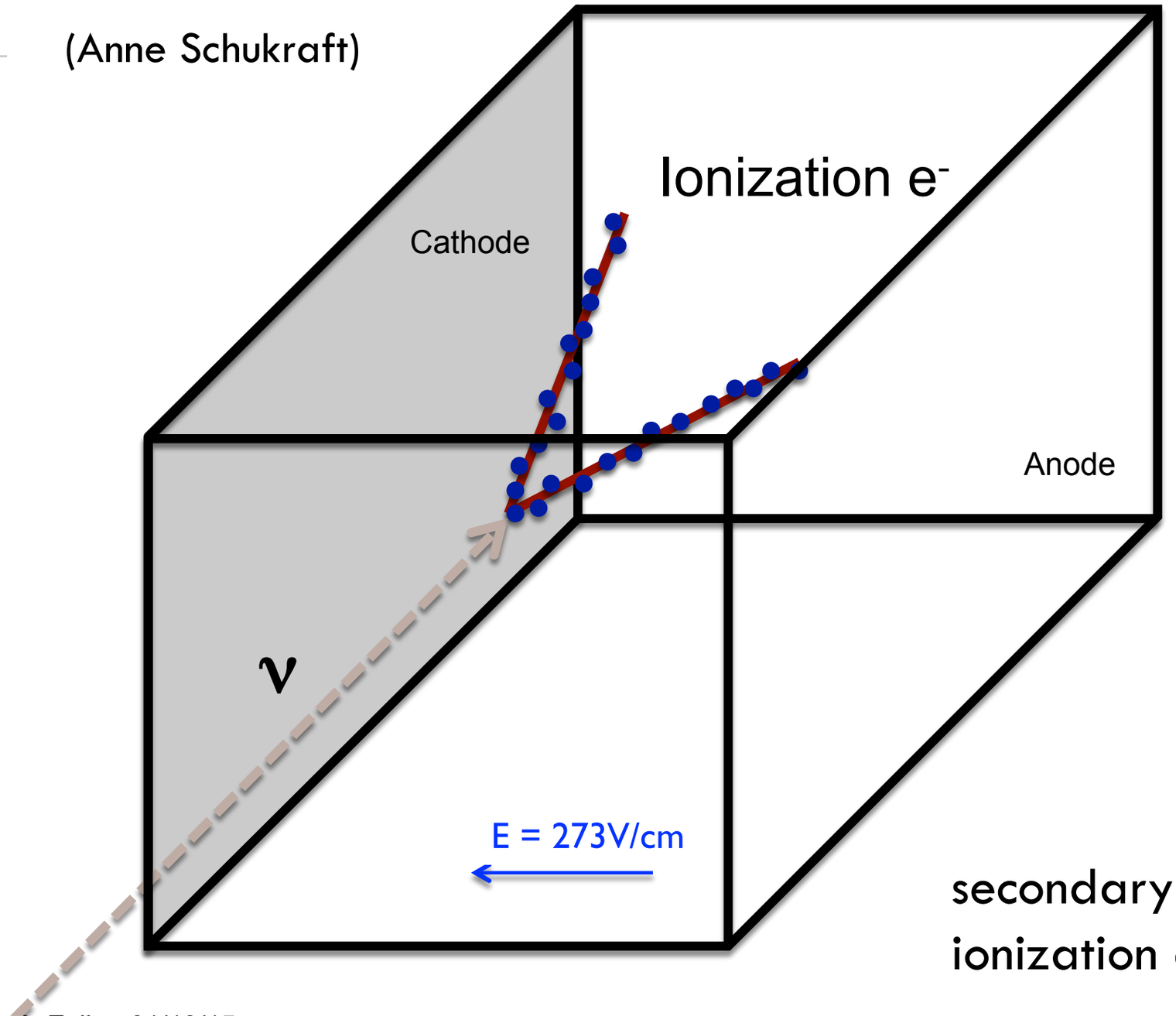
(Anne Schukraft)



neutrino interacts with the argon inside the TPC volume and produces secondary particles

LIQUID ARGON TPC

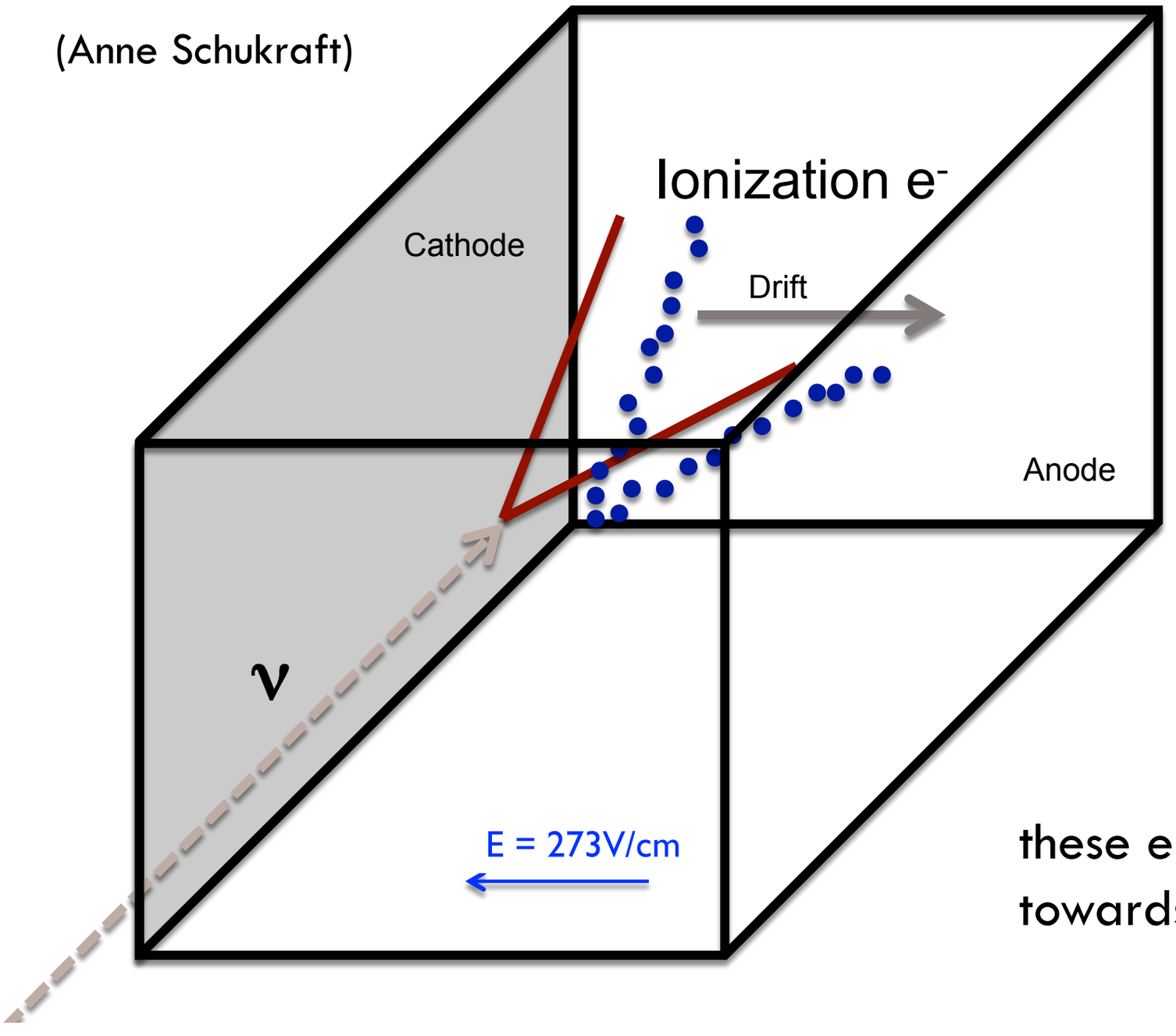
(Anne Schukraft)



secondary particles produce ionization electrons

LIQUID ARGON TPC

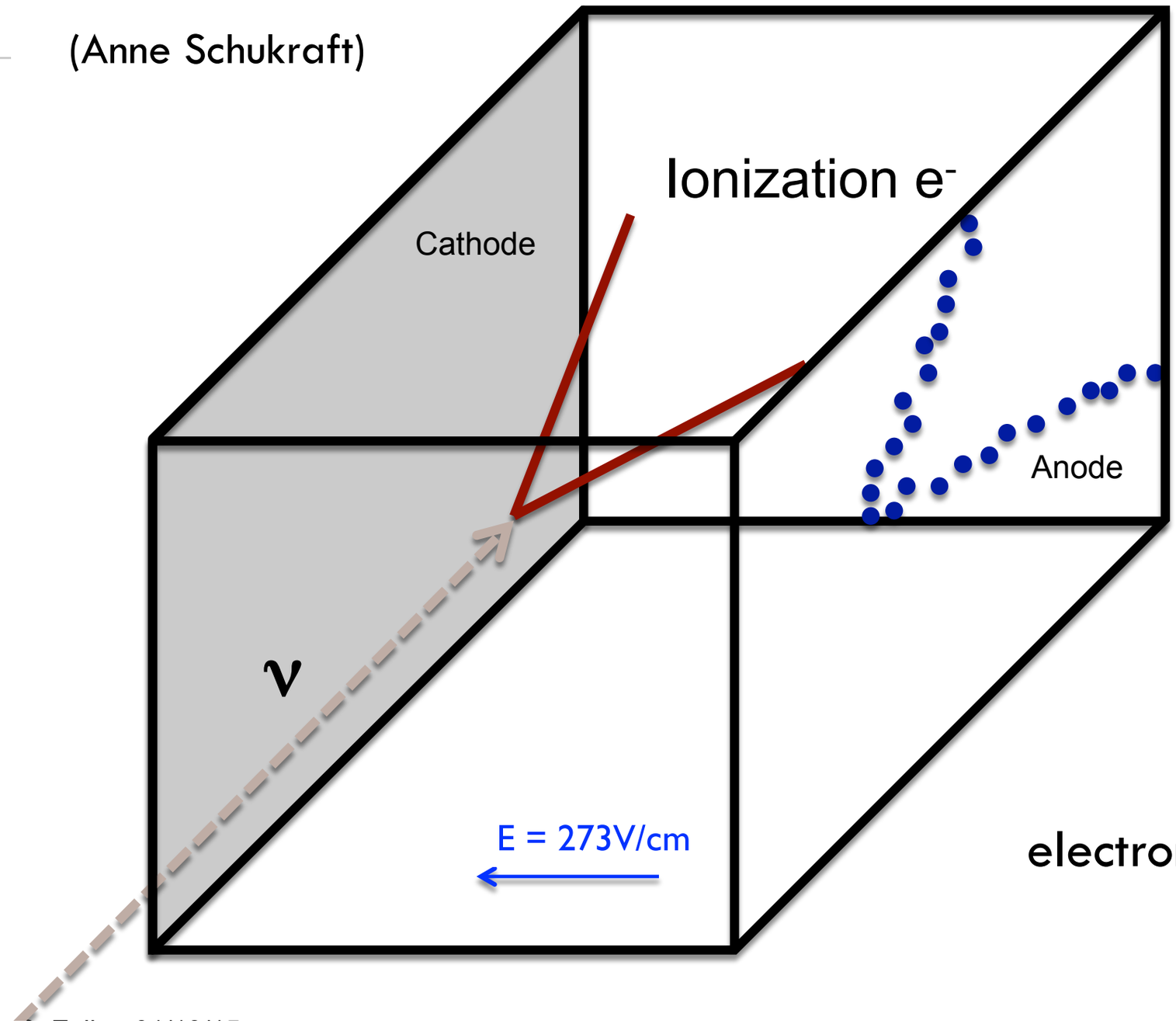
(Anne Schukraft)



these electrons drift towards the anode

LIQUID ARGON TPC

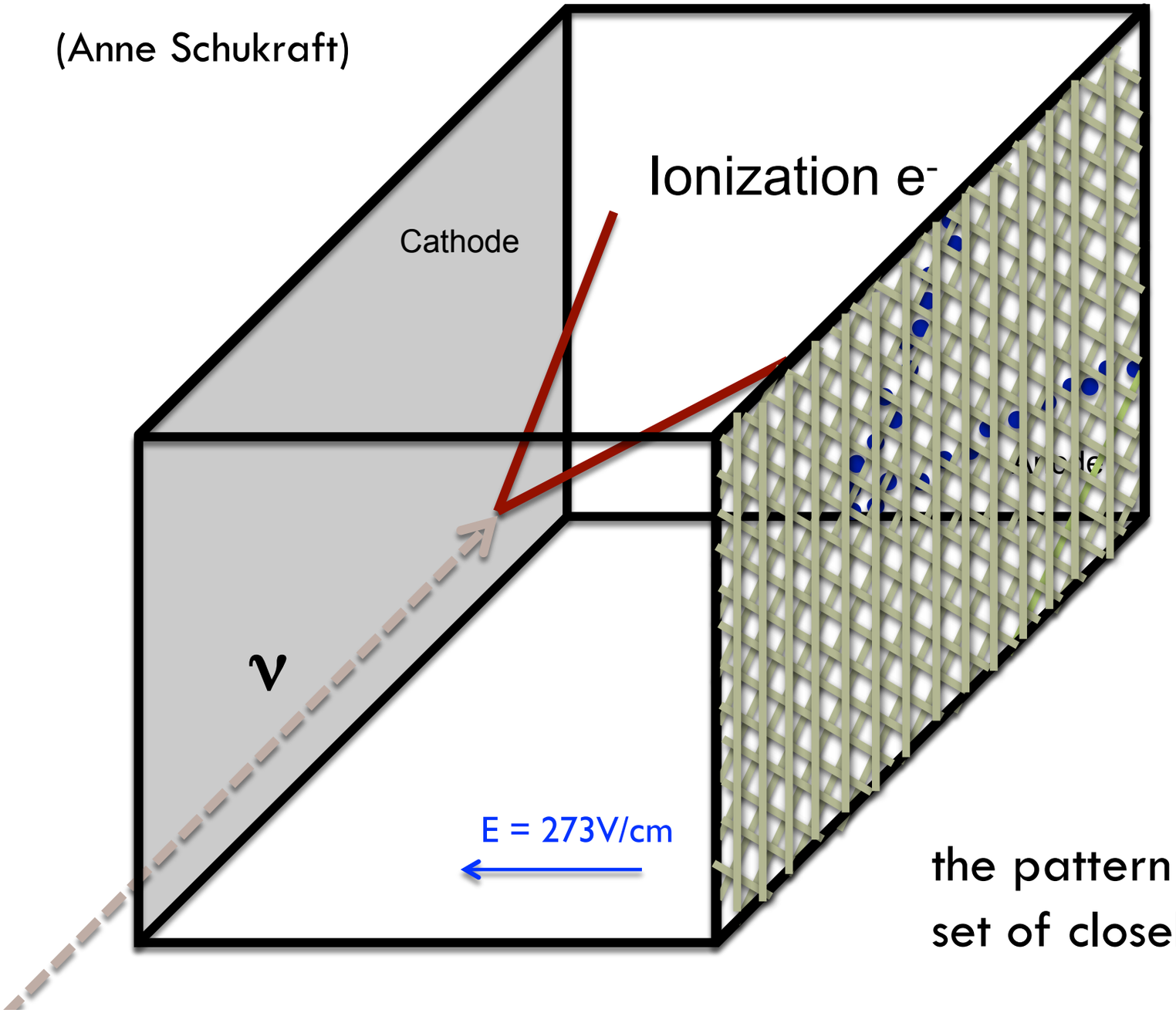
(Anne Schukraft)



electrons arrive at anode

LIQUID ARGON TPC

(Anne Schukraft)

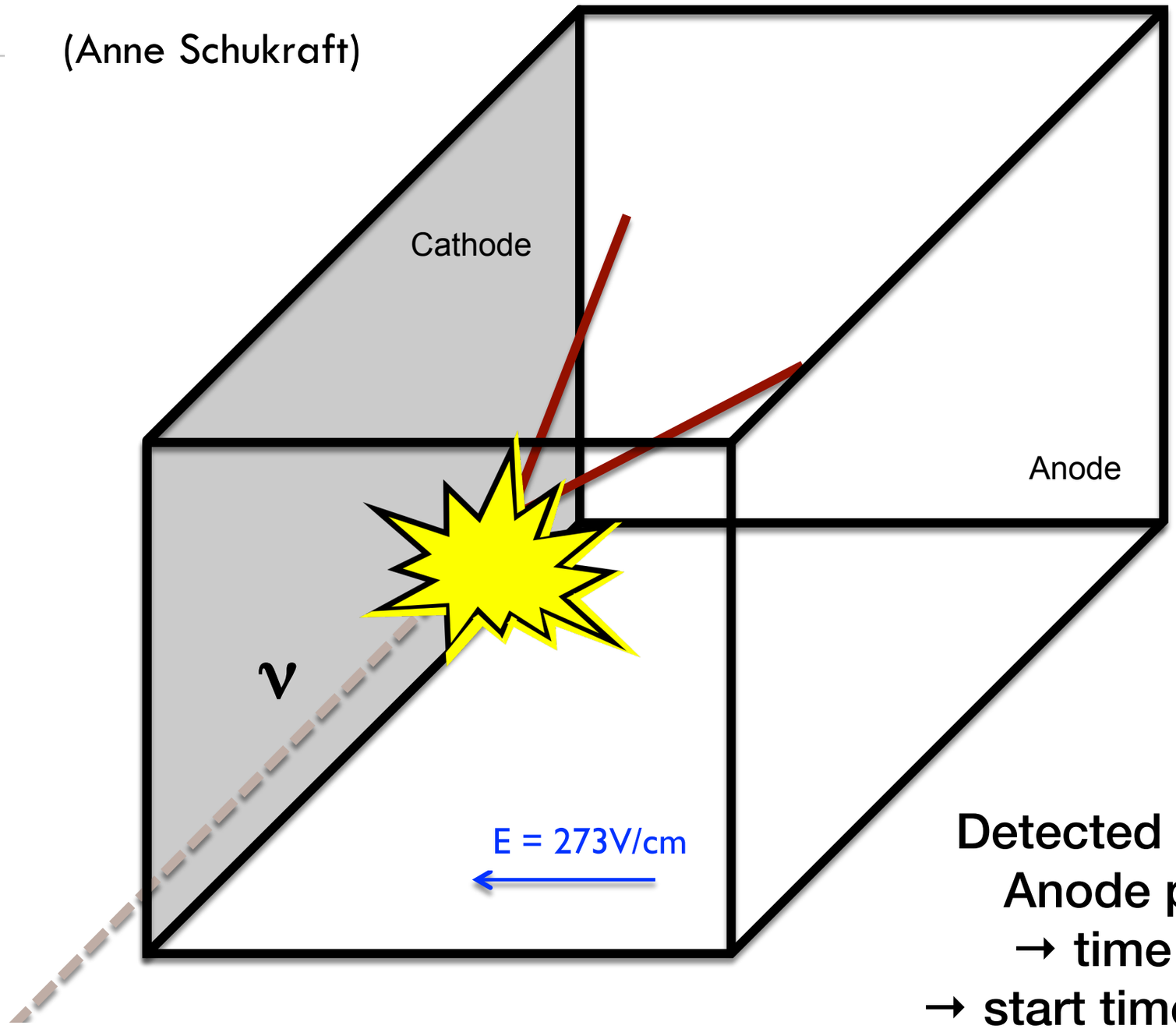


wire planes

the pattern is recorded on a set of closely spaced wires

LIQUID ARGON TPC

(Anne Schukraft)

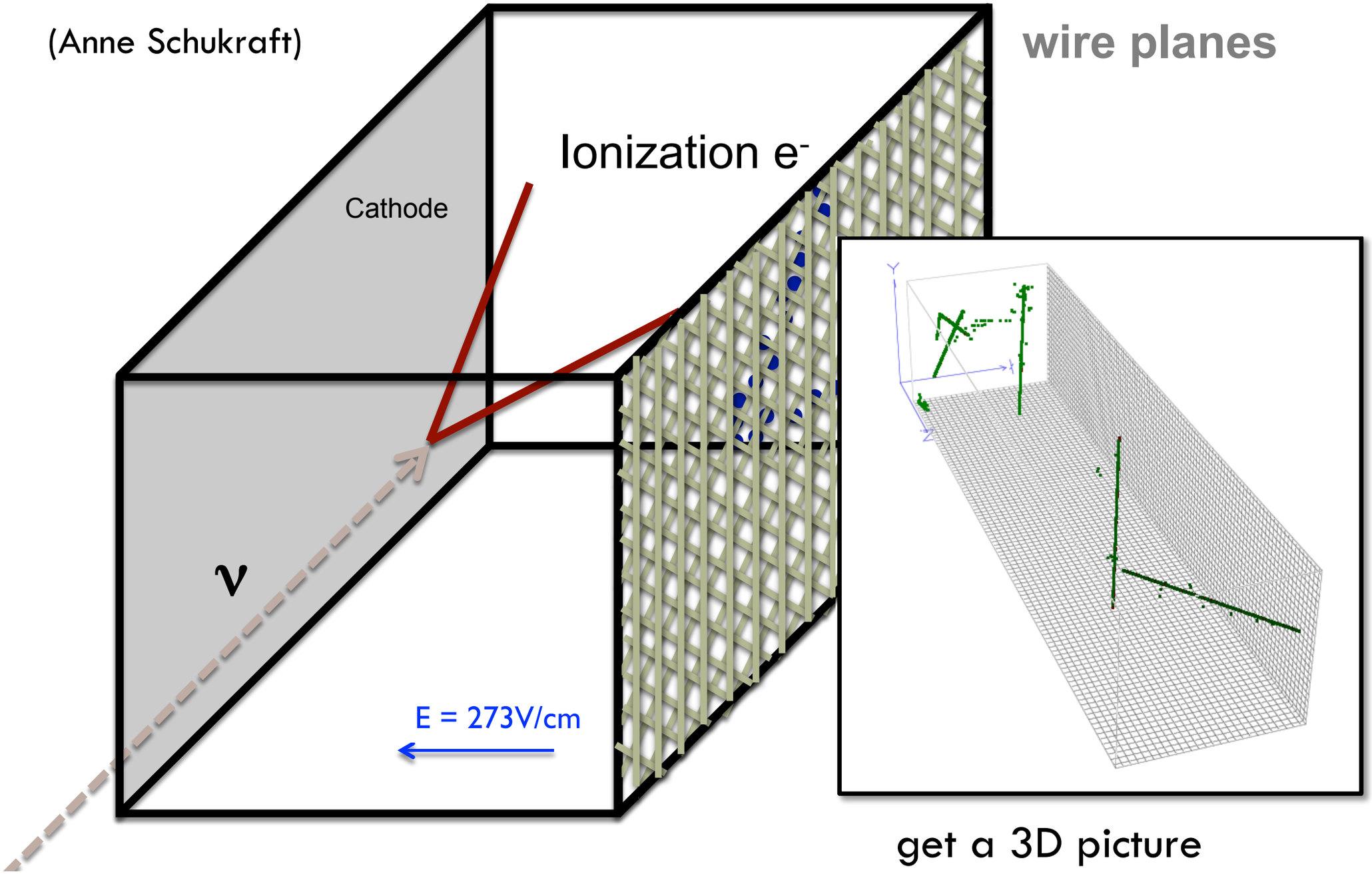


Flash of scintillation light at time of neutrino interaction

Detected by PMTs behind Anode plane to get t0
→ time of interaction
→ start time for electron drift

LIQUID ARGON TPC

(Anne Schukraft)



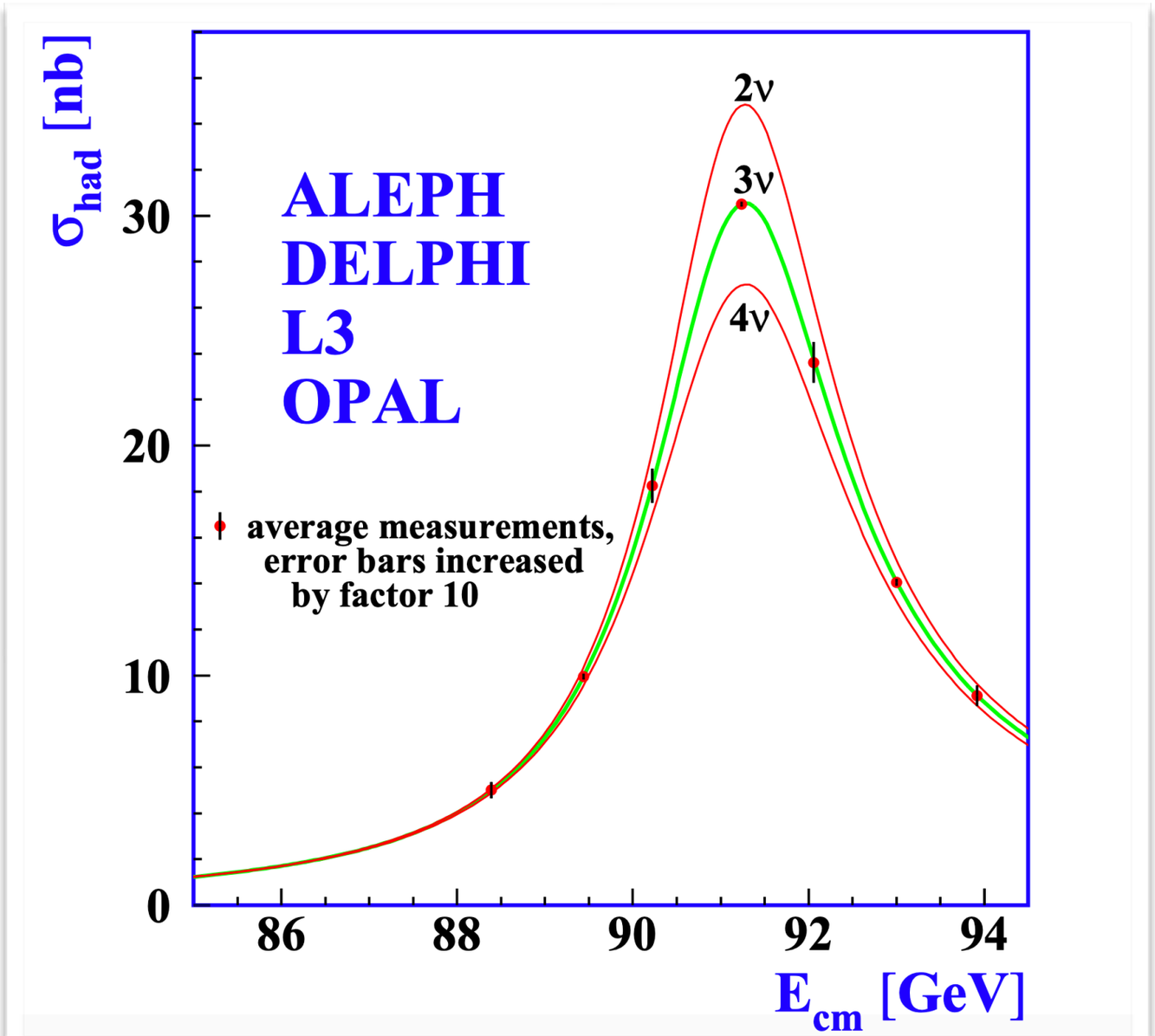
get a 3D picture

SUPERNOVA NEUTRINOS

Supernova 1987a: the only time we've seen supernova neutrinos

Detector (Threshold*/Size)	# of Events (*E*-range/Duration)
Mt. Blanc (7 MeV/90 T)†	5 (6–10 MeV/7 s)
Kamioka (8 MeV/2.14 kT)	2 (7–12 MeV/10 s)
IMB (30 MeV/5 kT)	none reported
Baksan (11 MeV/130 T)†	none reported
Kamioka (7 MeV/90 T)	11 (7–35 MeV/13 s)
IMB (30 MeV/5 kT)	8 (20–40 MeV/4 s)
Baksan (11 MeV/130 T)†	3 (12–17 MeV/10 s)
Mt. Blanc (7 MeV/90 T)†	2 (7–9 MeV/13 s)
Homestake ν_e (0.7 MeV/615 T)**	consistent with background
Optical	
lack of sighting	$m_v \gtrsim 8$ magnitude
photograph	$m_v = 6$ magnitude
discovery	$m_v = 4.8$ magnitude

NEUTRINOS: WHAT WE KNOW



- Three flavours that can be produced in decays of Z boson
- → three "active" flavours

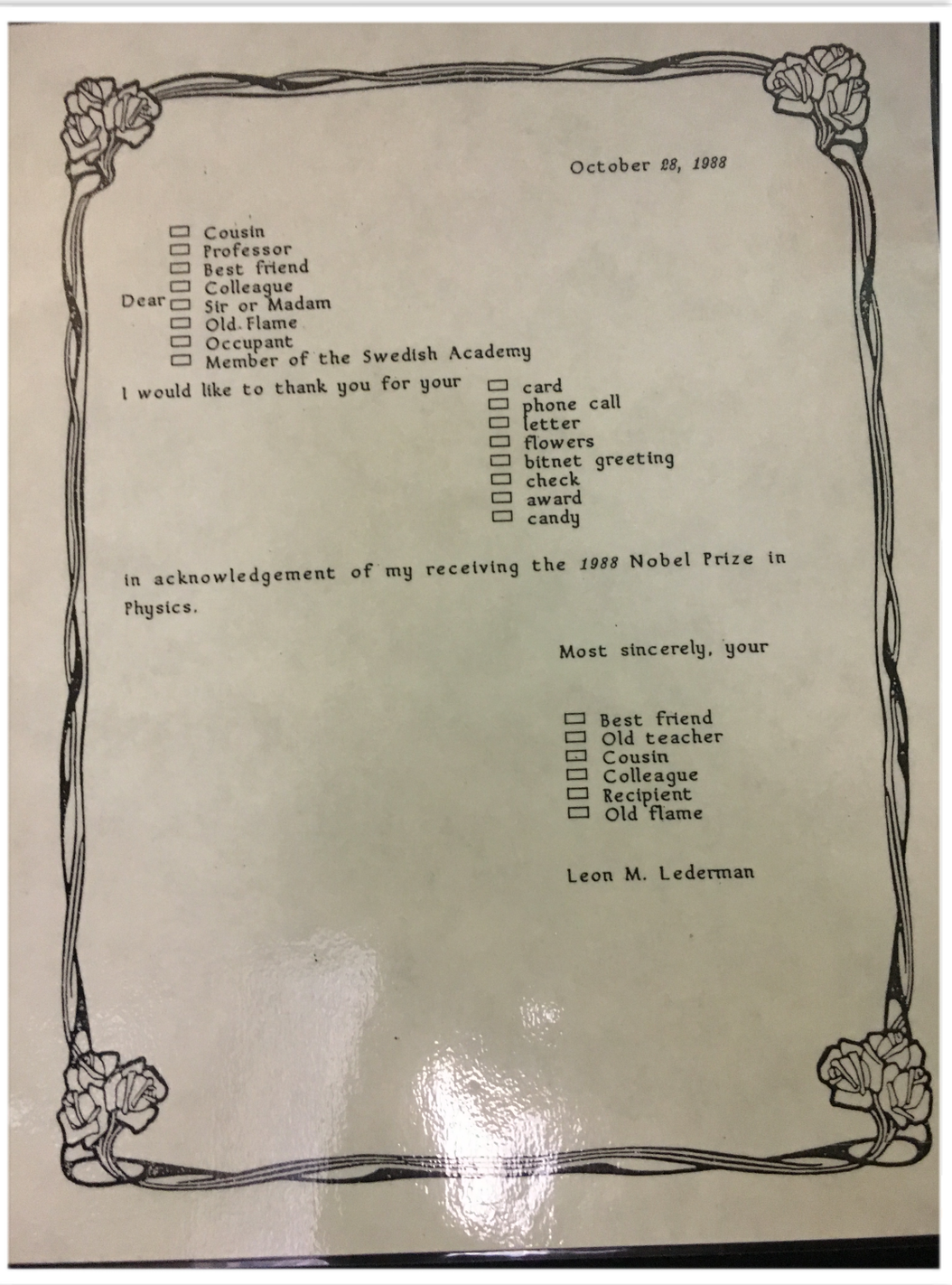
https://doi.org/10.1016/j.physrep.2005.12.006

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!

- Leon Lederman, Me
  and Jack Steinberge
  experiment at Broc
- Took a beam of neu
  it into a detector
- → found that almo
  (107/113) produce
  electrons
- **A new neutrino**
  muons?



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

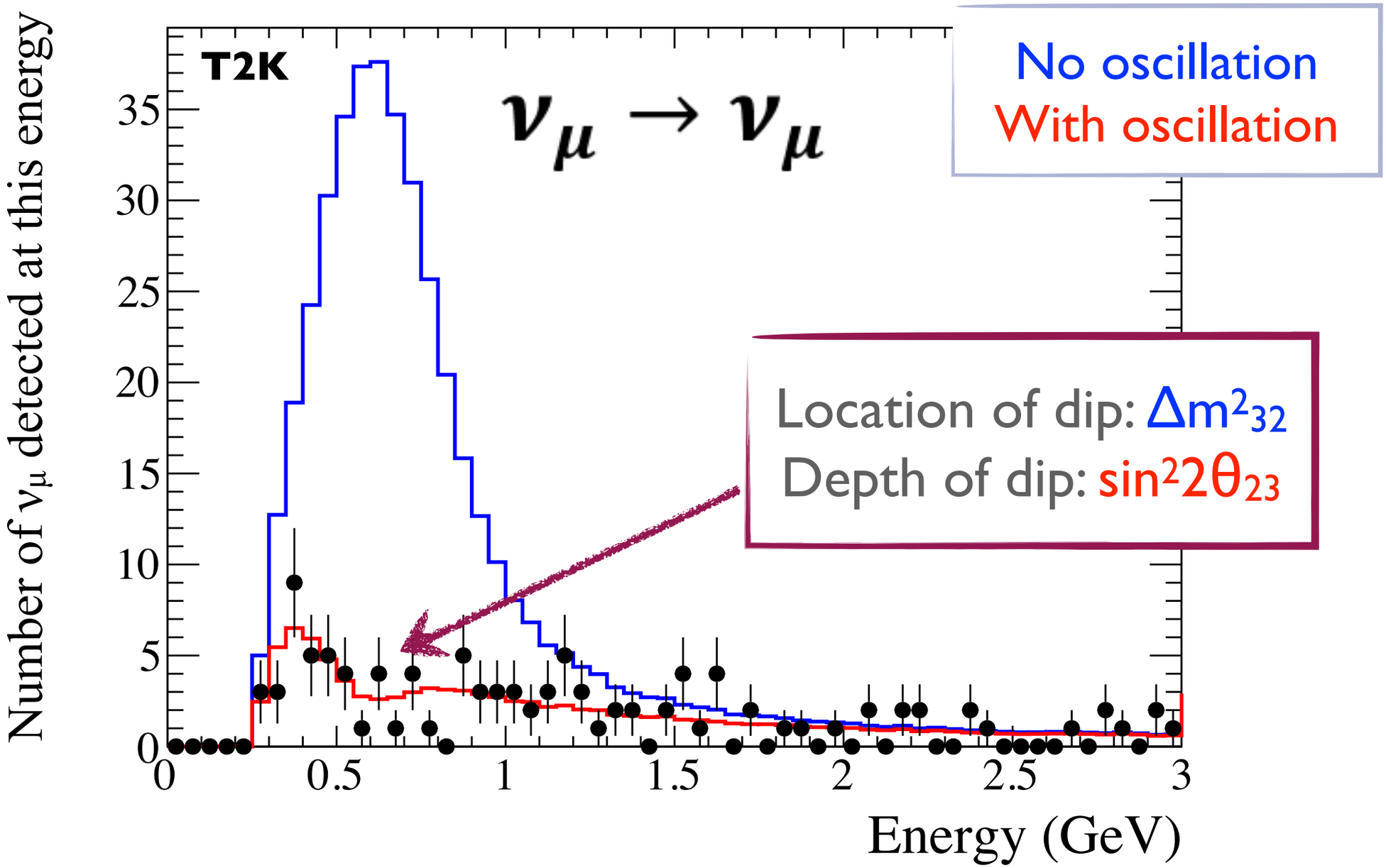
- ☐ Best friend
- ☐ Old teacher
- ☐ Cousin
- ☐ Colleague
- ☐ Recipient
- ☐ Old flame

Leon M. Lederman

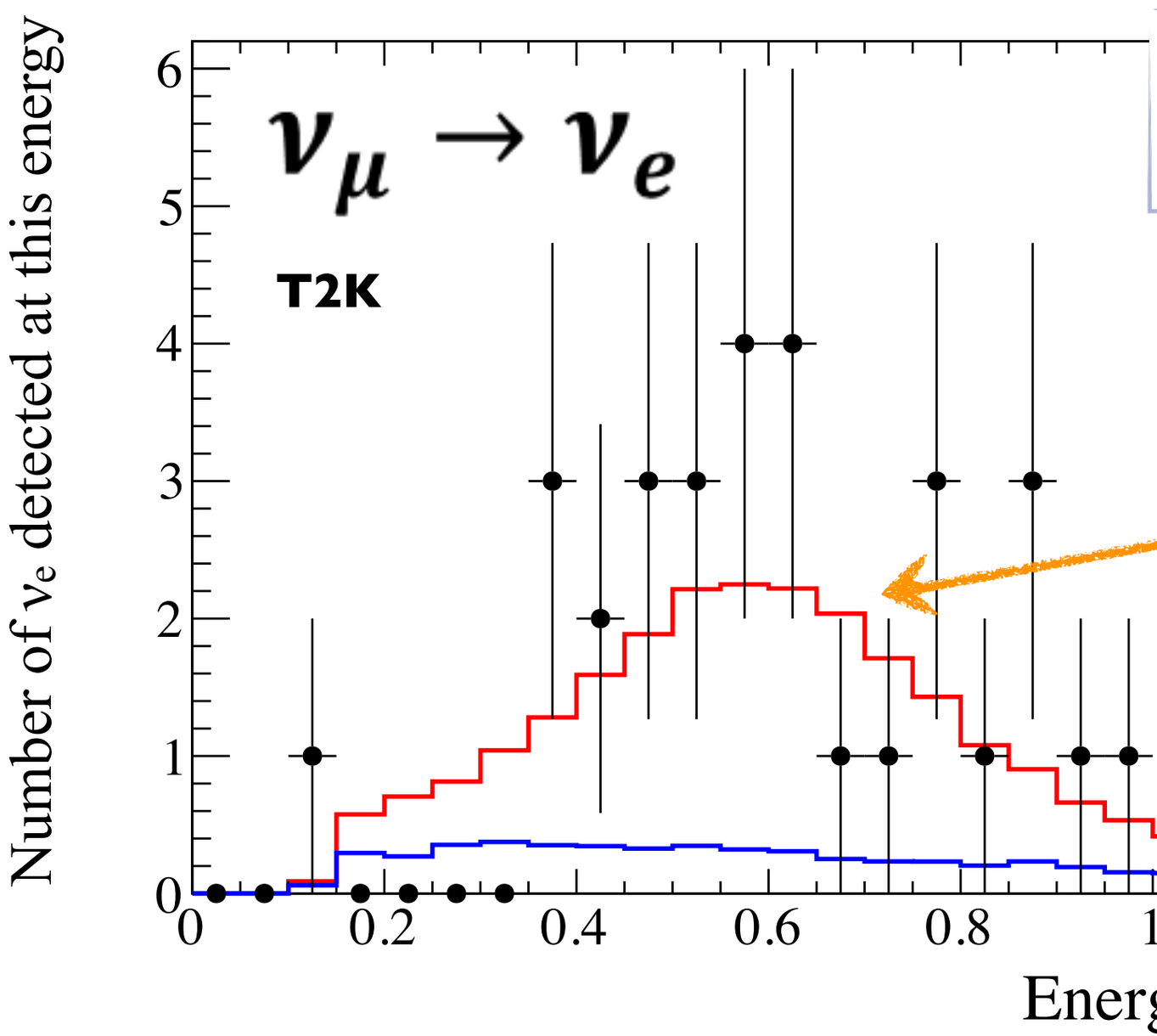
AND MORE NEUTRINOS!

- 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

NEUTRINO OSCILLATIONS: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu$



NEUTRINO OSCILLATIONS: $\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$



No oscillation
With oscillation

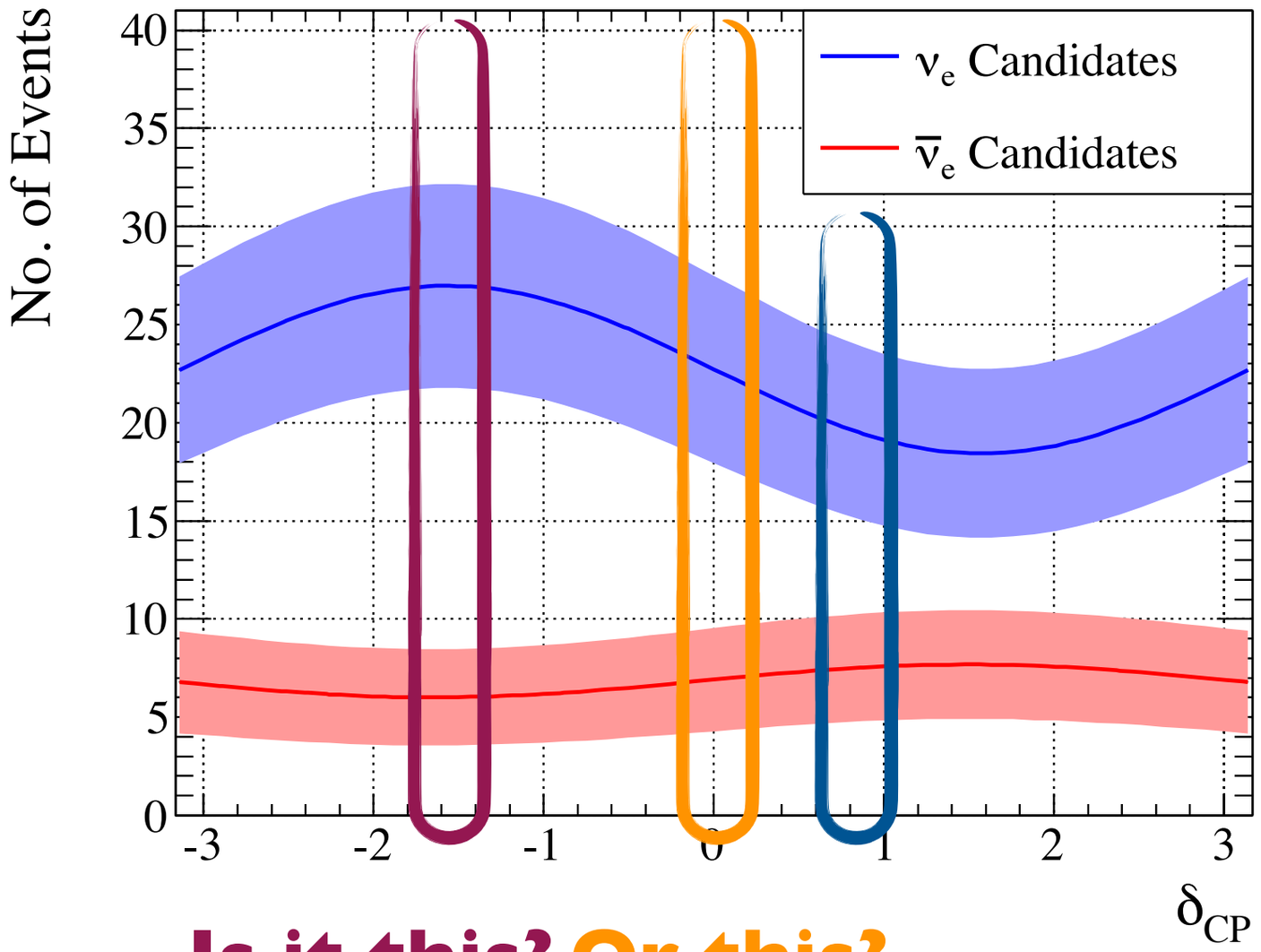
Height and shape of peak: $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}

DUNE WILL HAVE:

Neutrino oscillation parameters:

θ_{12} ✔ solar ✔ reactor
θ_{23} ✔ atmos. ✔ accel.
θ_{13} ✔ solar ✔ react. ✔ atm. ✔ acc.
Δm^2_{21} ✔ solar ✔ reactor
$|\Delta m^2_{32}|$ ✔ atmos. ✔ accel.
δ_{CP} ? atmos. ? accel.

- Huge detectors
- Very intense beam of neutrinos
- → higher statistics than we've ever had before
- Really nail down the **last two oscillation parameters**



Is it this? Or this?

Or this?