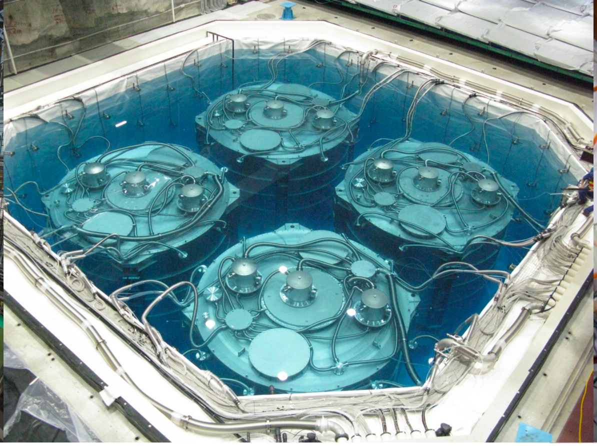

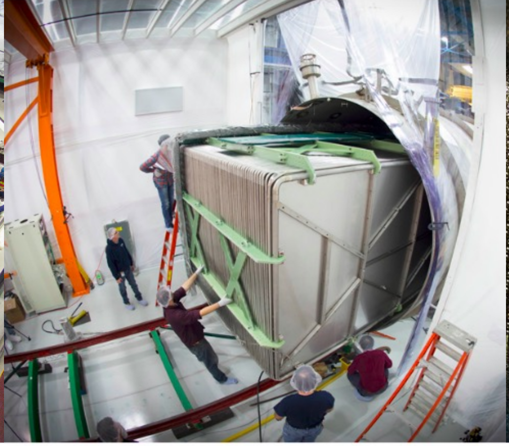

MANCHESTER 1824
The University of Manchester

Neutrino Detectors

Fermilab Neutrino University

June 16th 2022

Nicola McConkey

Aim + Outline

- **Aim:** To discuss how we measure neutrinos
  - How detectors help us to understand what's going on in ν interactions
  - Basic principles of how a particle detector works
  - Present some of the exciting technologies that we use
- What do we need from a neutrino detector?
- Gallery of neutrino detectors
- Neutrinoless double beta decay experiments
- Neutrino mass measurements

How do we measure neutrinos?

- Neutrinos are neutral particles with hardly any mass which barely interact at all

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m_ν<0.8eV (Katrin direct measurement, *Nature Phys.* 18 (2022) 2, 160-166)
m_ν <0.12eV (Cosmological constraint from Planck, *Astron. Astrophys.* **641**, A6 (2020).)

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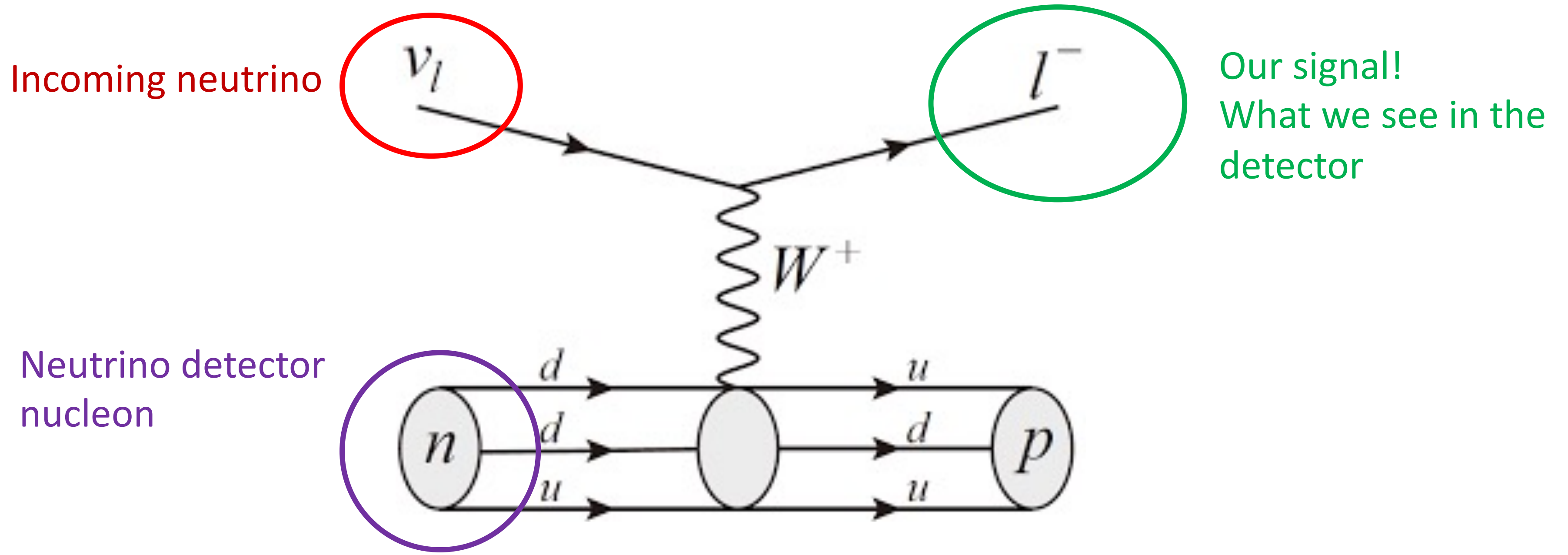
"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."

-Douglas Adams

Neutrino interactions in the detector

- We don't actually see the neutrinos themselves in a particle detector
- We (only) see what happens after they have interacted!



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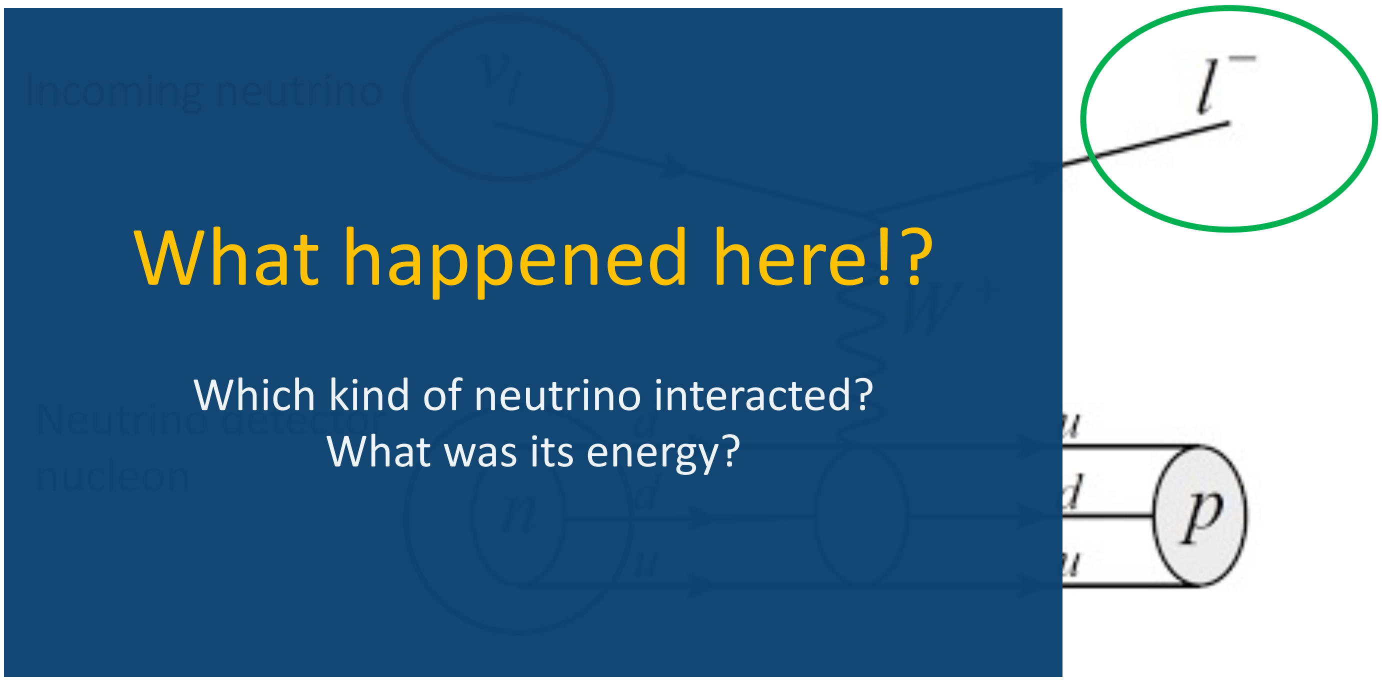
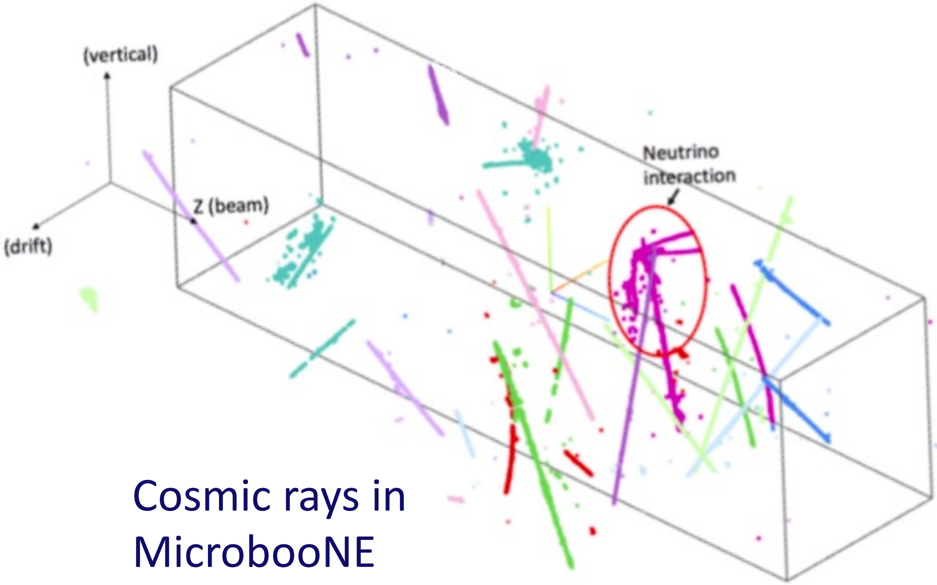


Our signal!
What we see in the detector

Charged-current Quasi-elastic interaction ???
Or was it background that looks like a neutrino event?

Wait, what's background?

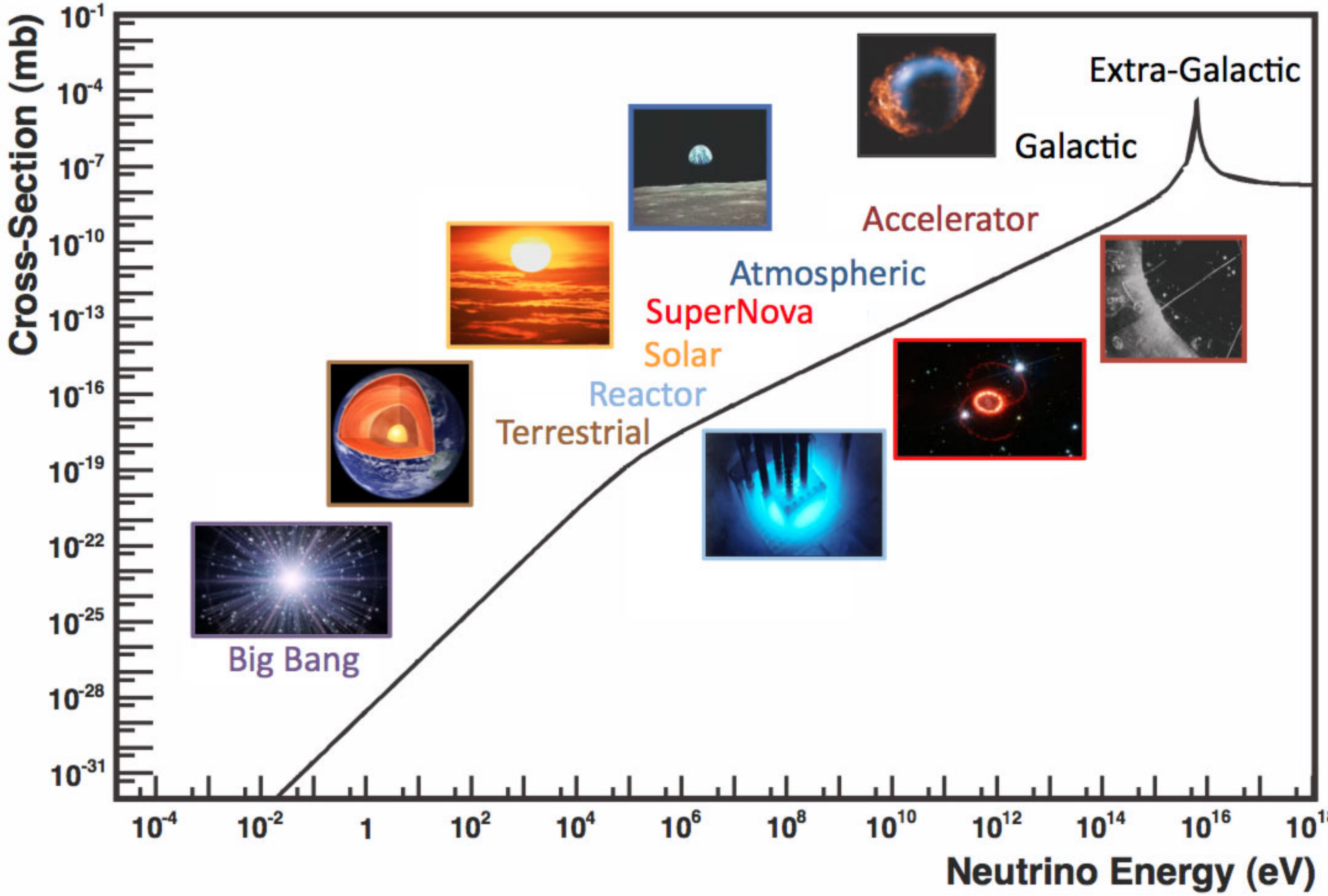
- Everything else that isn't the (neutrino) interaction that you're trying to measure is **background**
  - Our detectors are great at sensing particles – they see much more than the neutrinos that we want to measure!
- One big challenge for our neutrino detectors is to pick out ("tag") the neutrino event, and reject the background
- Some ways we can do that are
  - Fast timing
  - Position of event in the detector
  - External detectors
  - Eliminate the backgrounds
    - Underground detectors
    - Radiopure detectors



Cosmic rays in MicrobooNE

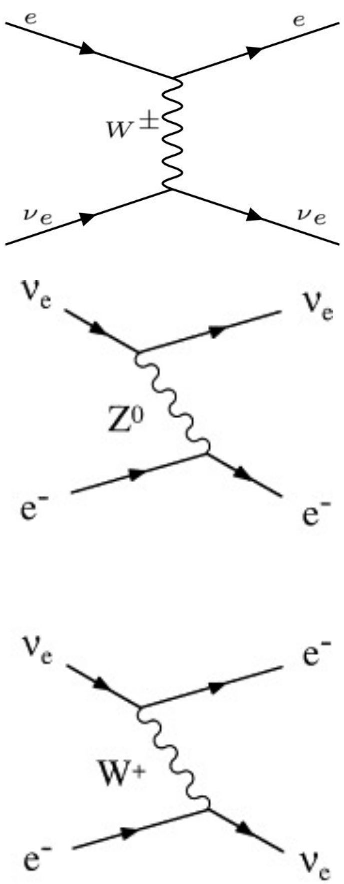
Measuring neutrinos is difficult

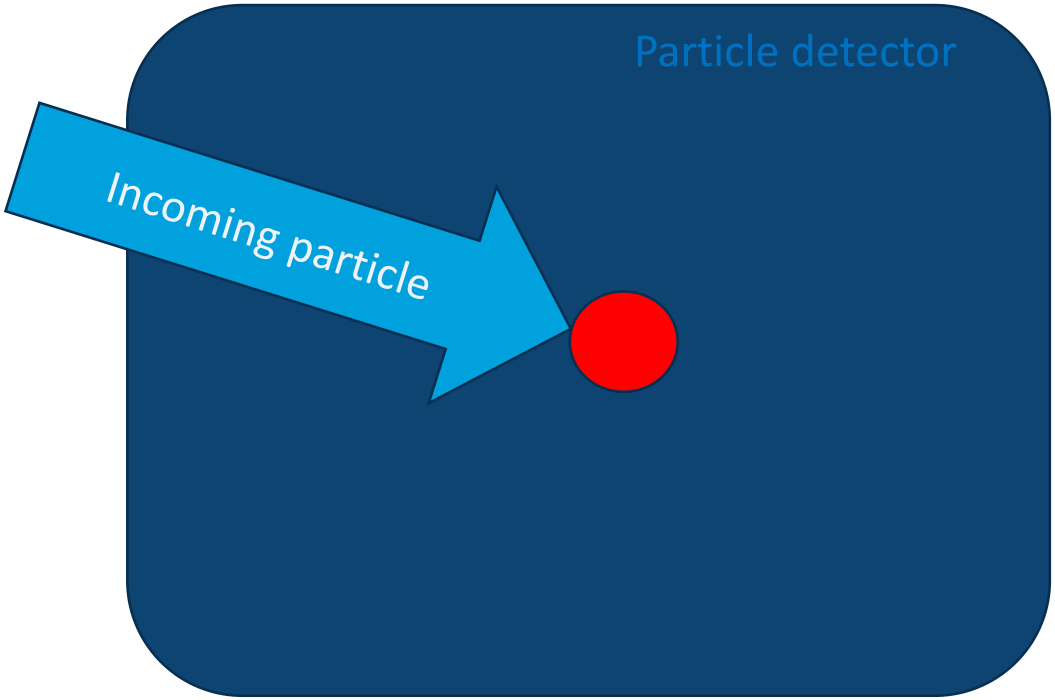
- ❑ …but we have measured a vast spectrum of them!



How does a particle detector work?

Particle interacts in the detector





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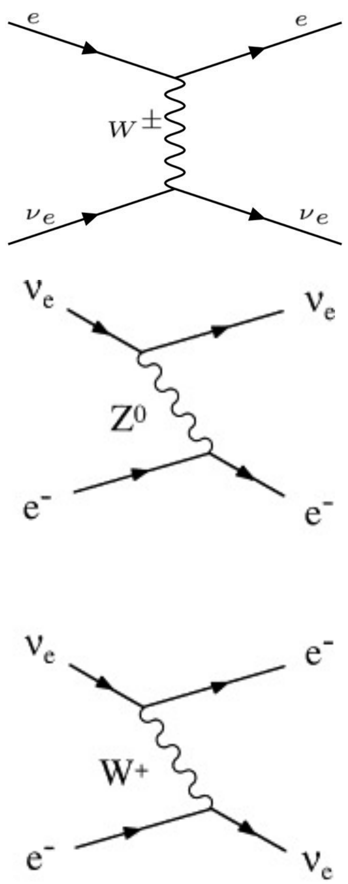

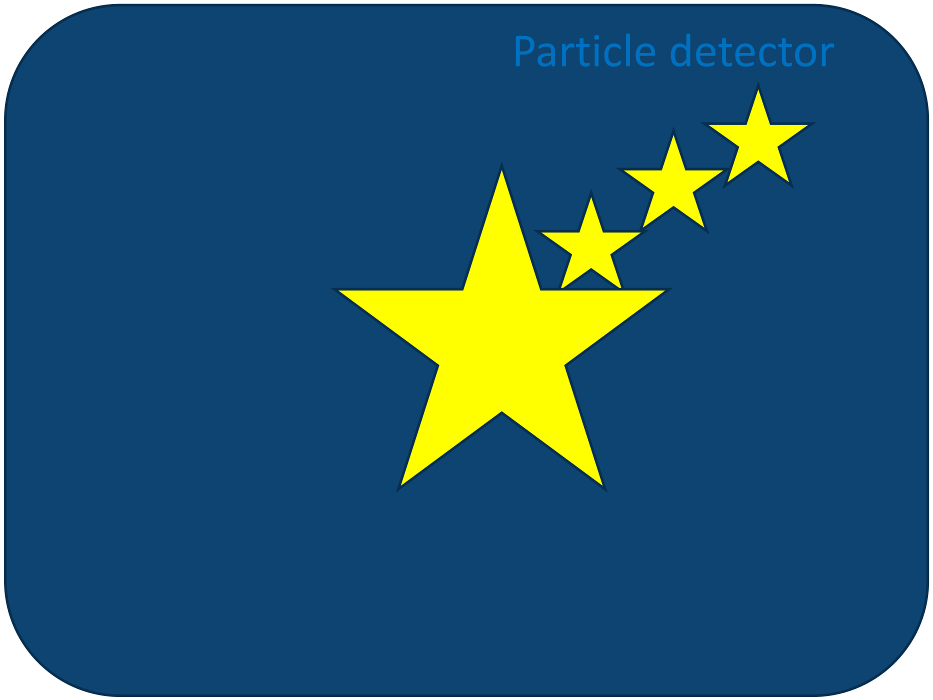

Energy deposited in the detector from the interaction

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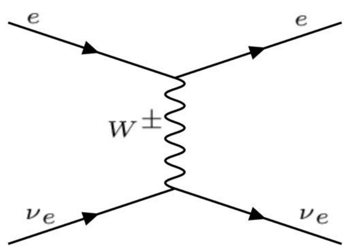
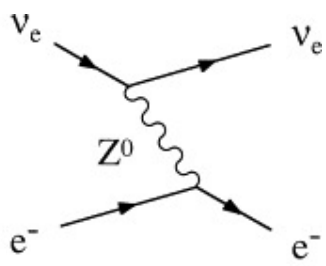
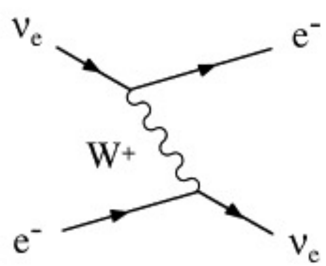
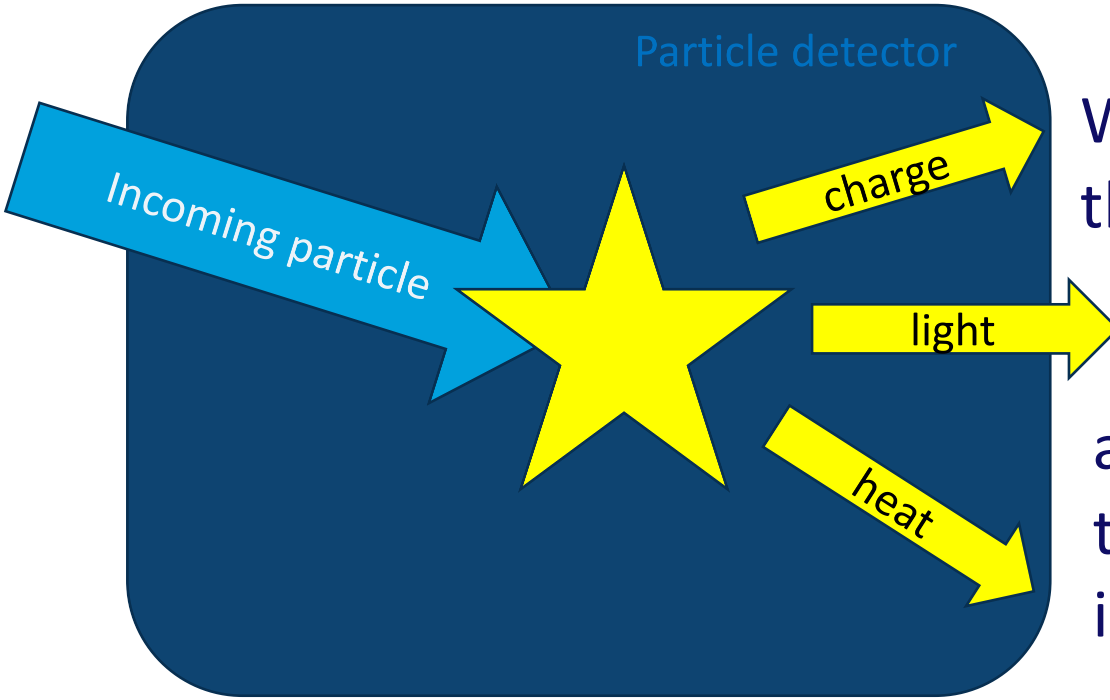
Particle interacts in the detector









We measure that energy

and identify the particle interaction

Energy deposited in the detector from the interaction

Particle detector checklist

- A particle detector needs to have:
  - Excellent energy resolution
  - Excellent timing resolution
  - Ideally position / tracking information

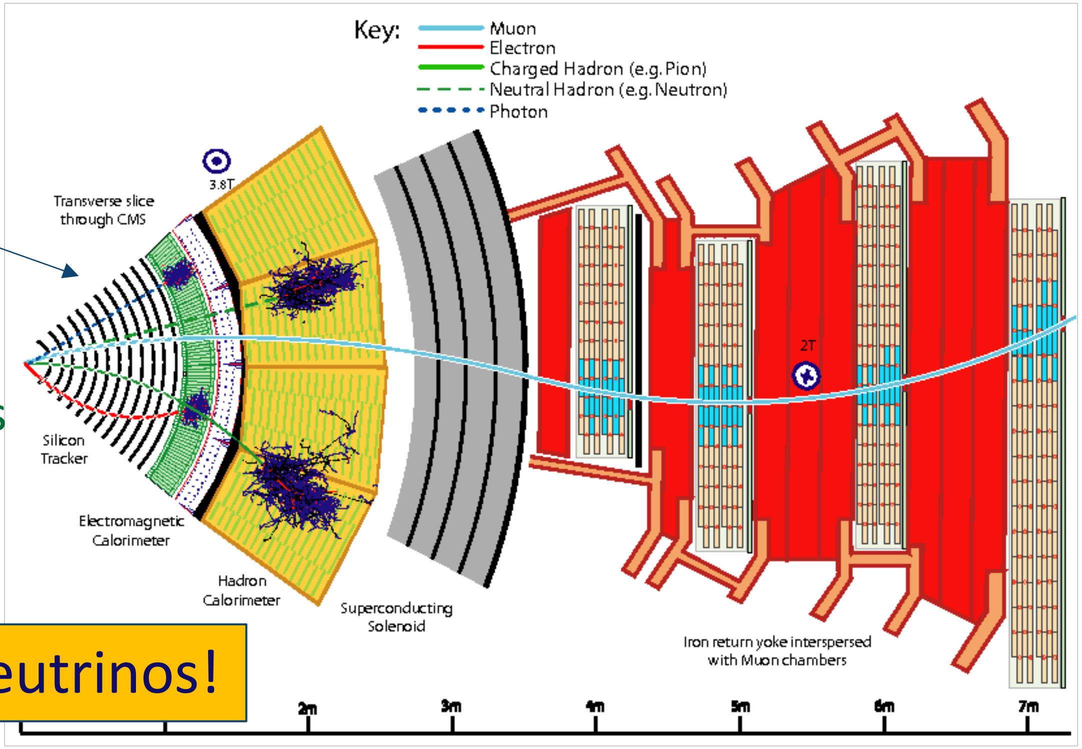
To reject backgrounds, and measure the *desired* particle interaction

Particle detector checklist

- A particle detector needs to have:
  - Excellent energy resolution
  - Excellent timing resolution
  - Ideally position / tracking information

To reject backgrounds, and measure the *desired* particle interaction

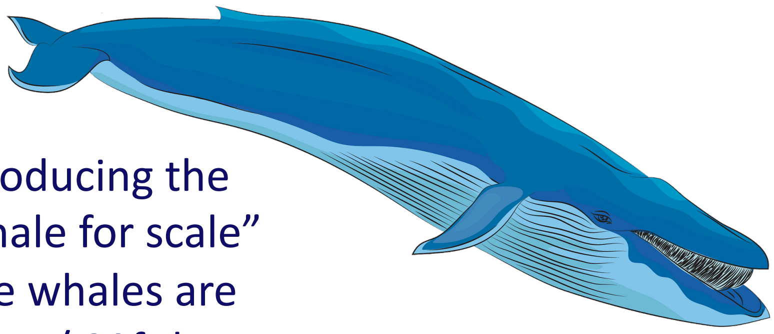
- CMS detector
  - In LHC at CERN
  - Detects interactions from colliding charged particles
    - Interaction point well defined



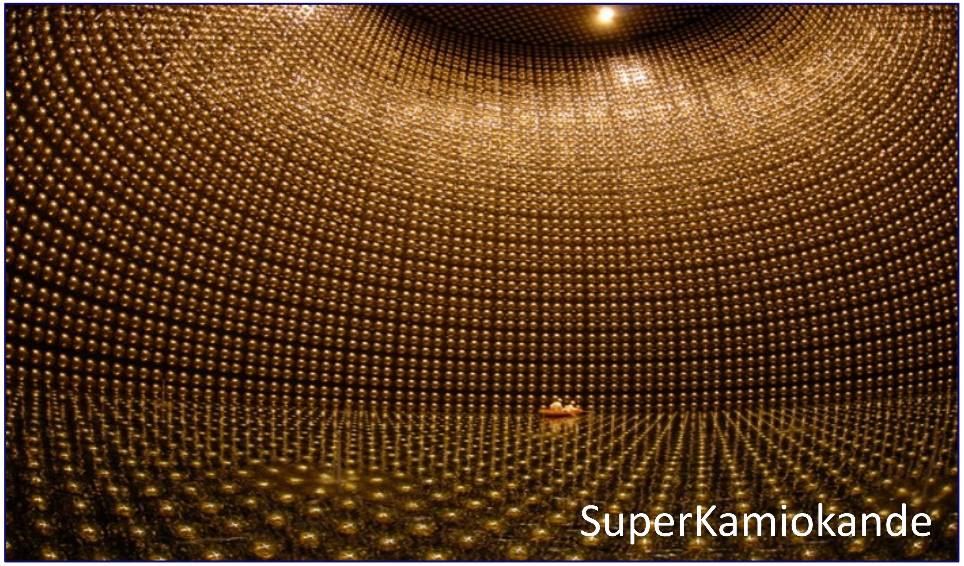
NOT good for measuring neutrinos!

Neutrino detector checklist

- A neutrino detector needs to have:
  - Excellent energy resolution everywhere in the detector
    - Neutrino interactions are likely to happen anywhere in the detector
    - Differentiate electrons from muons to tag the neutrino flavour
  - Excellent timing resolution
  - Ideally position / tracking / topological information
  - Large target mass
    - Large detector



Introducing the "whale for scale" Blue whales are ~25m / 80ft long



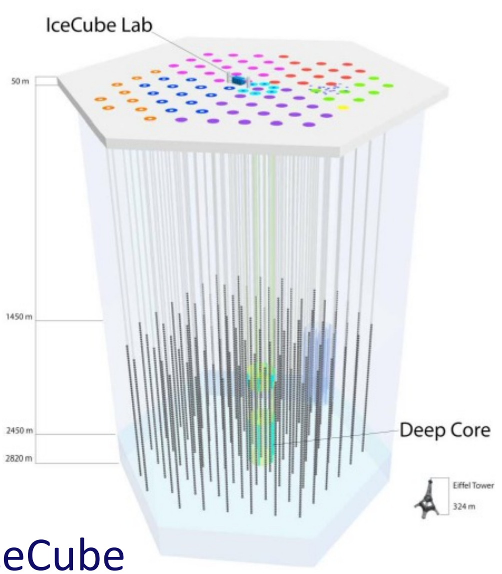
The giants of the particle detector world

- ❑ More target mass – more likely to stop a neutrino 😀
- ❑ More target mass – more expensive 🙁
  - Choose a material that is cheap and available in large quantities!

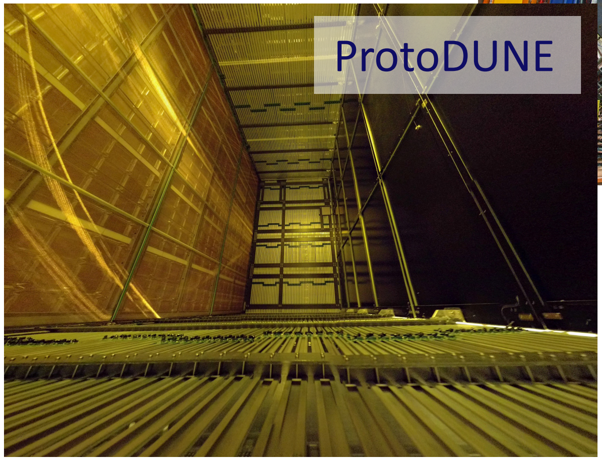
Water / ice

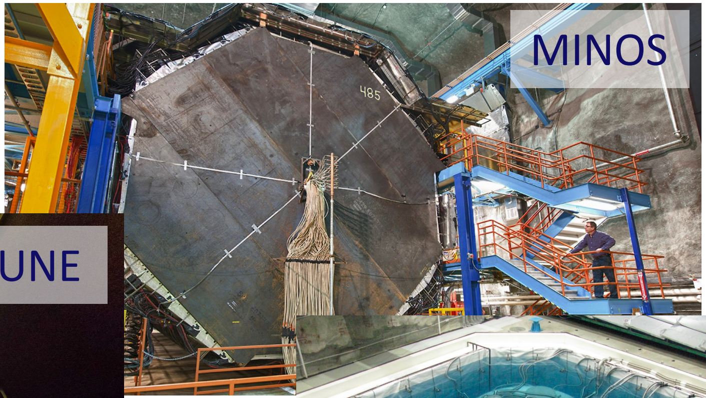
Argon

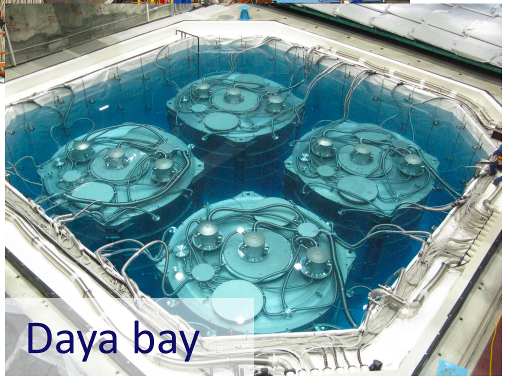
Liquid / solid Scintillator



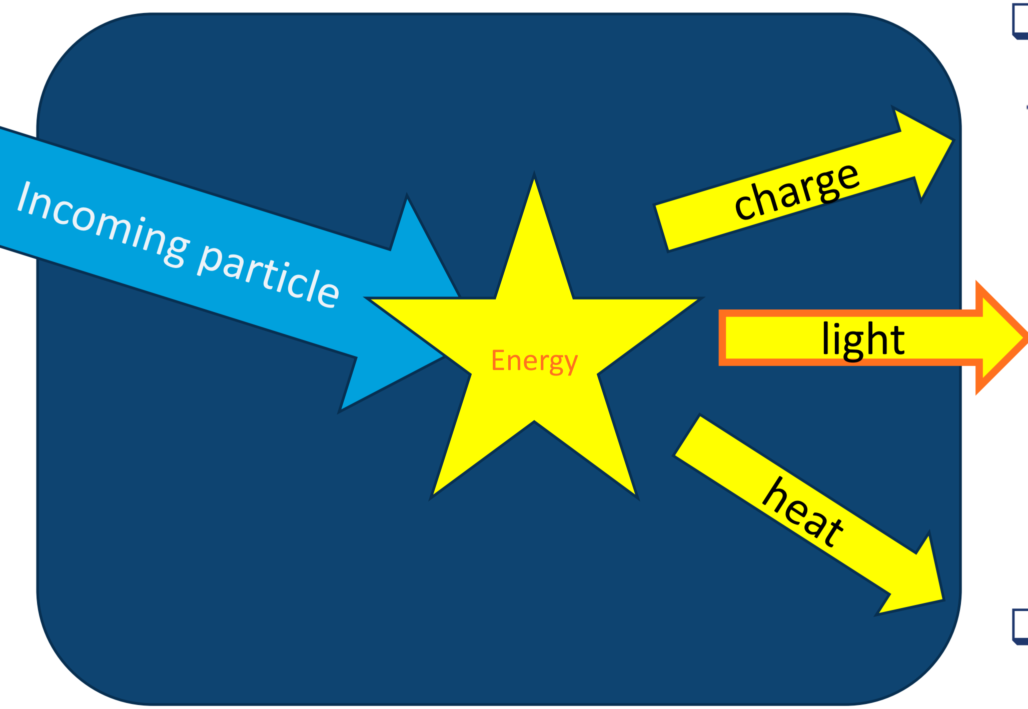
IceCube



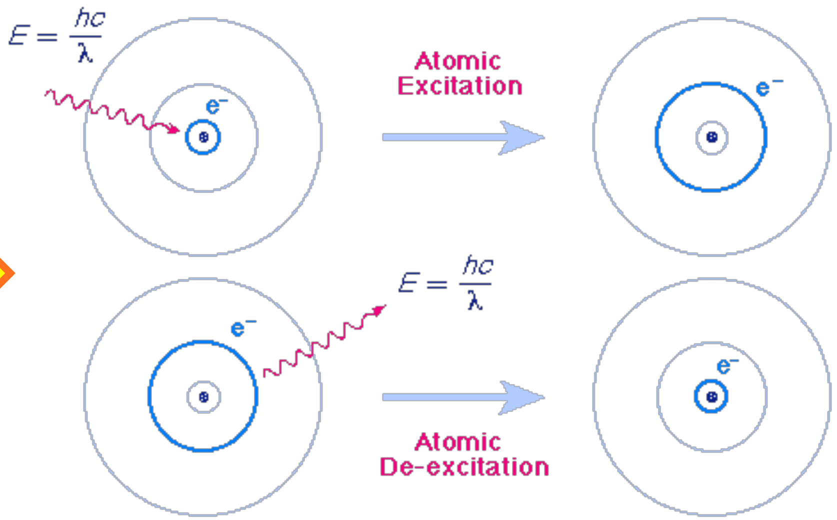




Scintillator detectors



- ❑ Scintillation

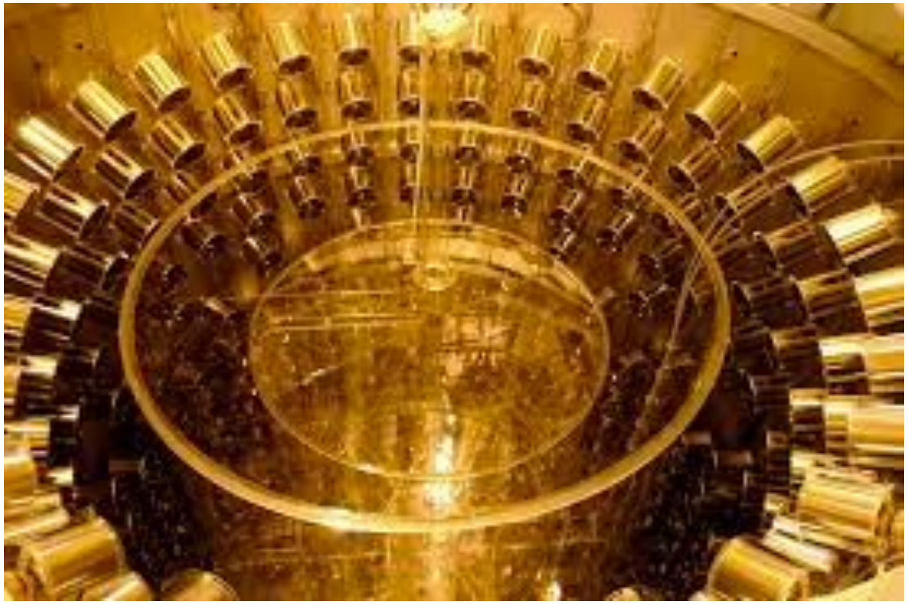


- ❑ These photons are the **detector signal**

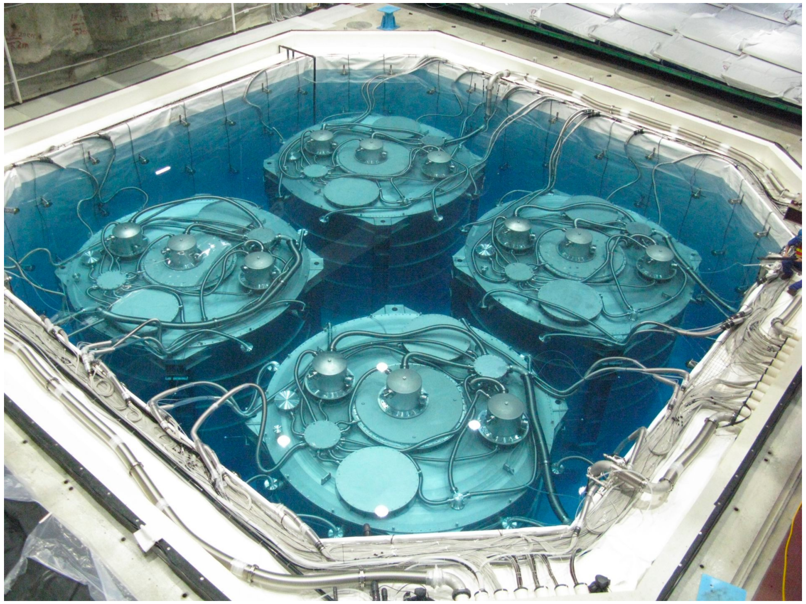
- ❑ Simplest scintillation detector is to simply collect all the light and count it
  - **Fast timing** with **pulse shape discrimination**, and **excellent energy resolution** allow for background rejection, and particle identification
  - A big box of liquid scintillator was the target for the first neutrino detector, made by Reines and Cowan 1956

Scintillator detectors

- ❑ Liquid scintillator has a low energy threshold ~MeV
  - Sensitive to solar neutrinos, reactor neutrinos…
- ❑ Tank of liquid surrounded by light sensors
  - Simple and cost effective to build



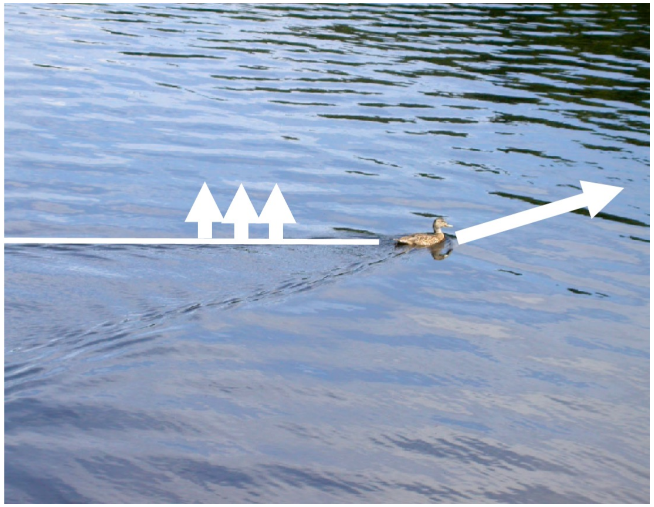
Double Chooz



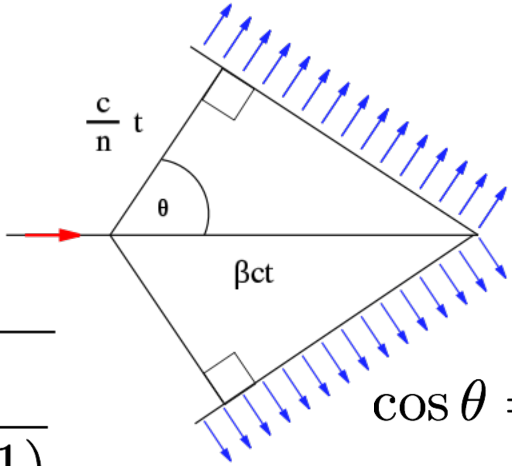
Daya Bay

Čerenkov detectors

- Cherenkov radiation is produced when a particle travels faster than the speed of light *in its medium*
  - Same principle as a sonic boom or wake



- Particle above threshold energy β= 1/n will emit light as it passes through the detector
  - It thereby loses energy and stops emitting light once it is below the threshold

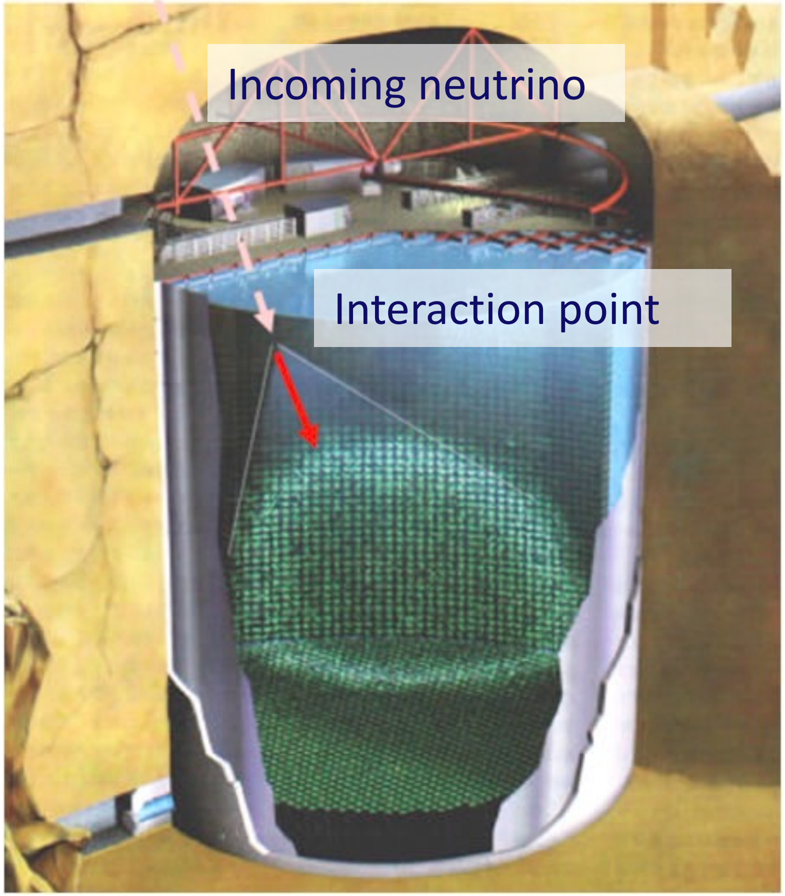


$$p \geq m\sqrt{\frac{1.}{(n^2-1)}}$$

$$\cos\theta = \frac{1}{n\beta}$$

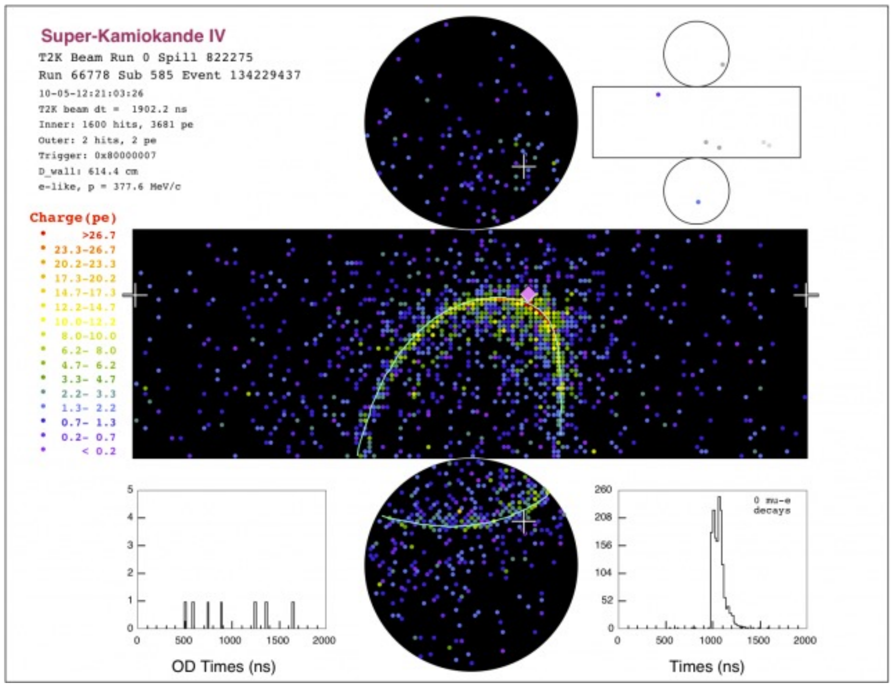
Čerenkov detectors

- Segmented optical readout can reconstruct the projected cone of light
- This signal is very powerful, and shows:
  - Direction of particle propagation
  - Where the particle was created (vertex position)
  - Particle energy
- The particle type identification can also be carried out
  - Electrons have short tracks: “fuzzy” rings because of multiple scattering
  - Muons have long tracks, and sharp rings

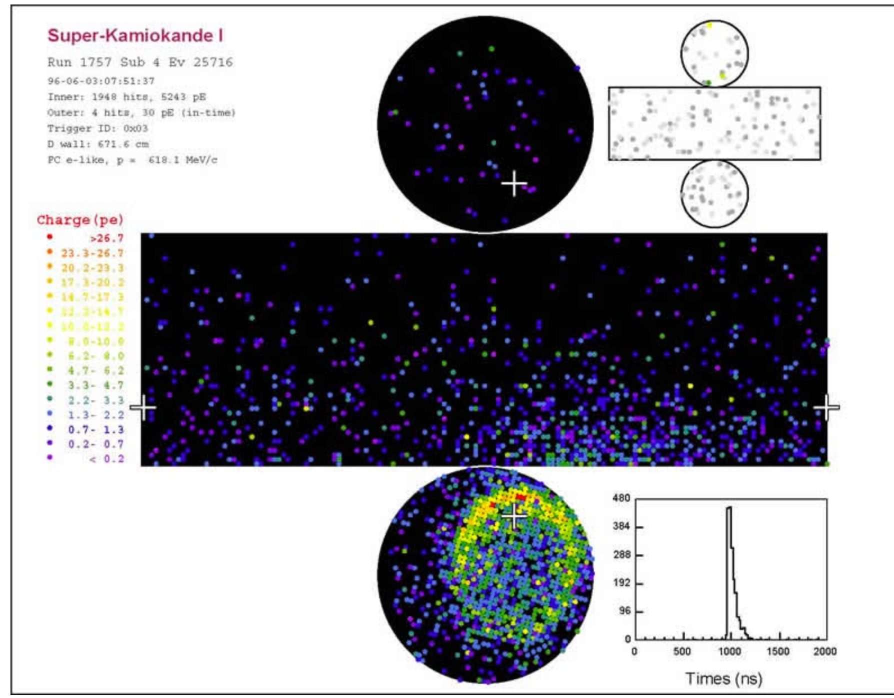


Super Kamiokande

Super Kamiokande Water Cerenkov events

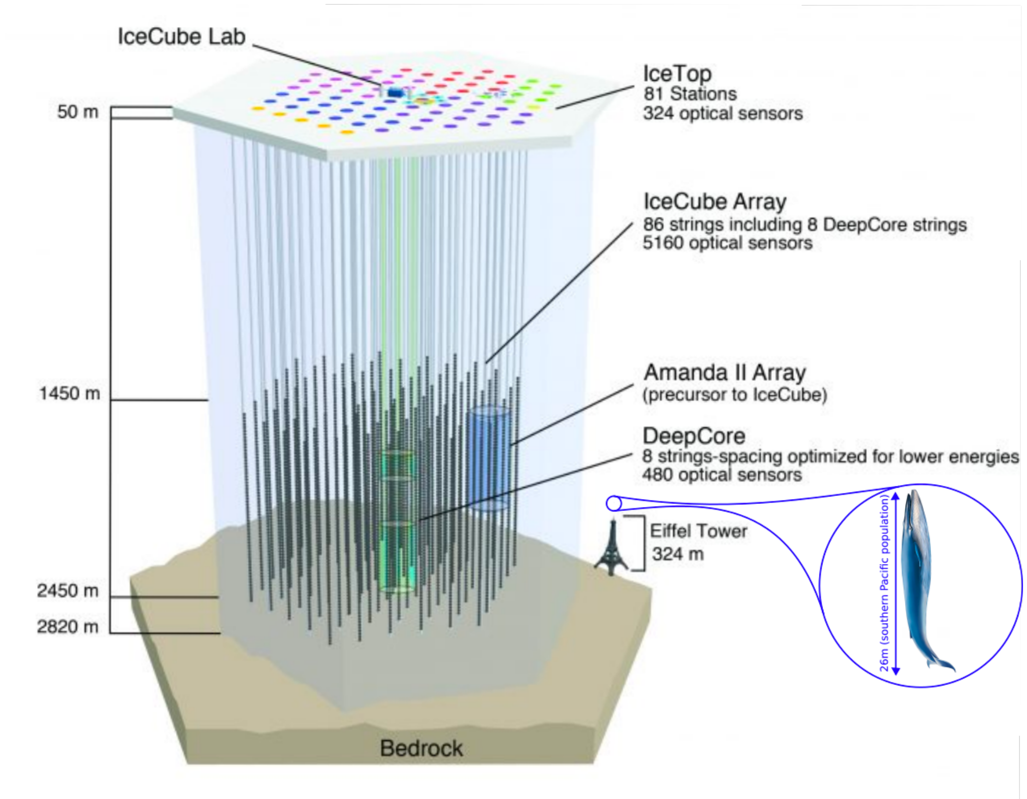


Muon event



Electron event

IceCube

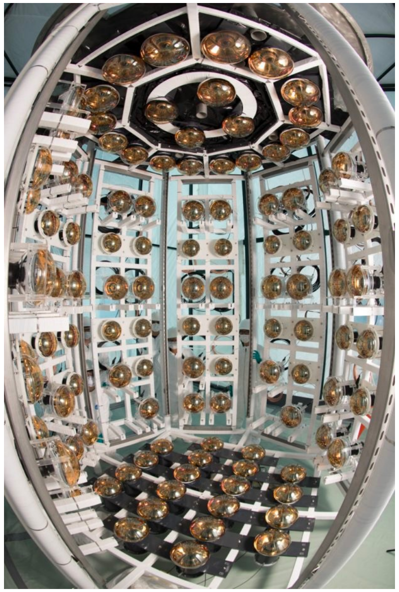


- ❑ IceCube uses Antarctic ice as the active medium for measuring neutrinos
- ❑ The largest particle detector on the planet!
  - $1km^3$ in size
- ❑ Light sensors are submerged in the ice to collect Cherenkov radiation from neutrinos
- ❑ Comparatively sparsely instrumented but has sensitivity to PeV neutrinos!

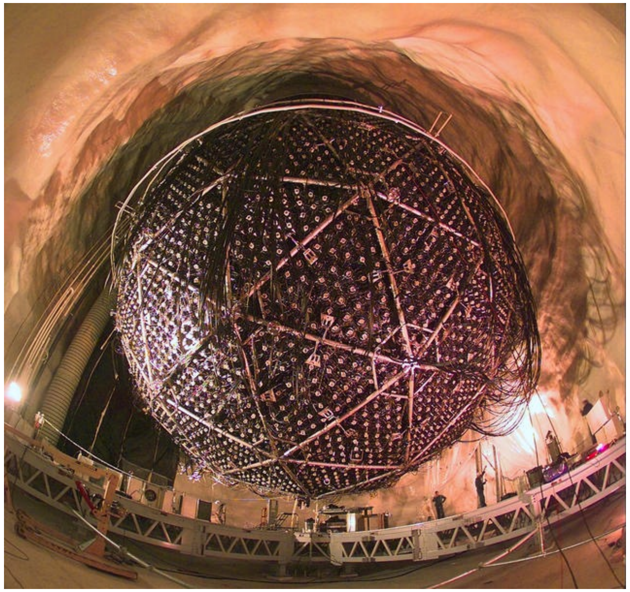
❑ IceCube will be covered in depth in a future lecture

Cerenkov detectors

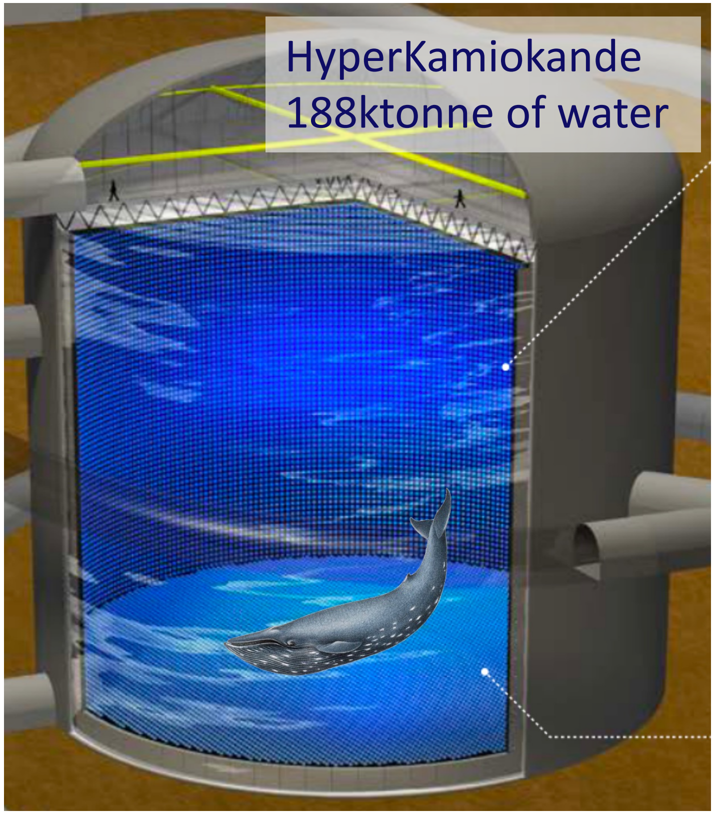
- Cherenkov detectors have already made a huge contribution to neutrino physics
  - SuperKamiokande and SNO are both Nobel prize winning detectors



ANNIE

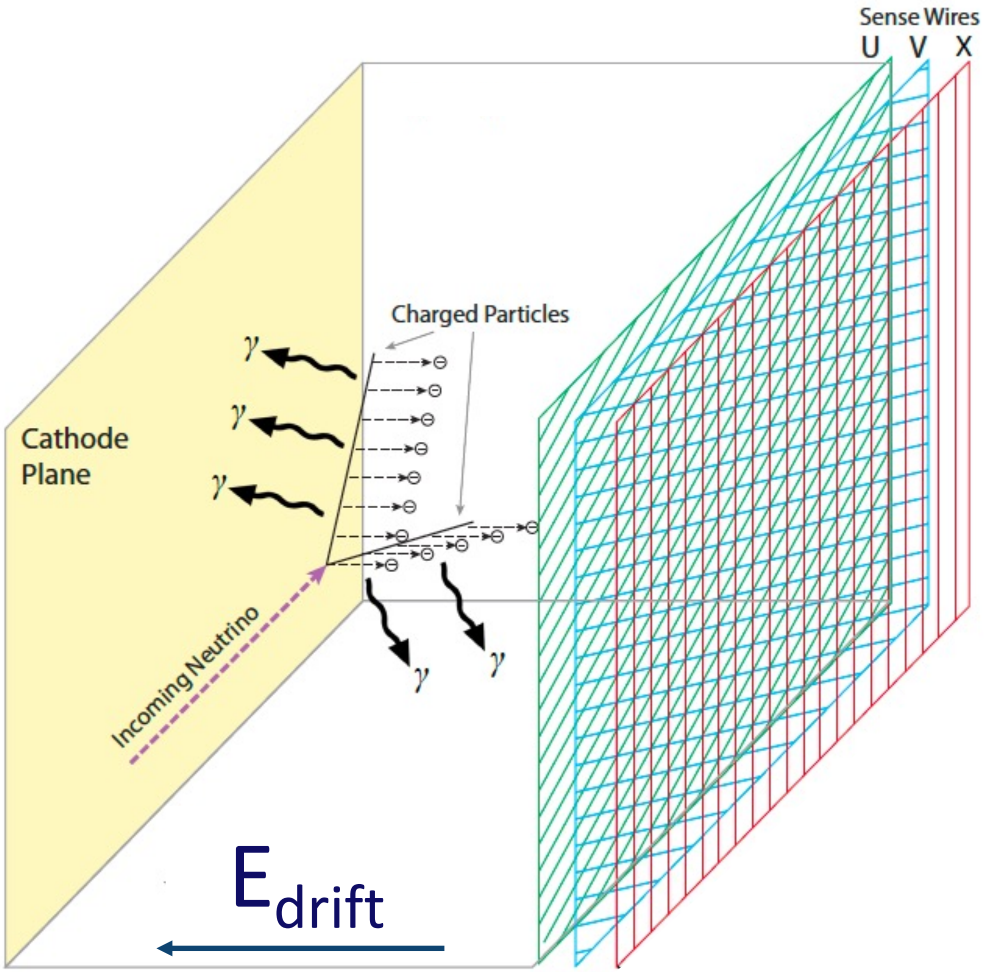


Sudbury Neutrino Observatory (SNO)



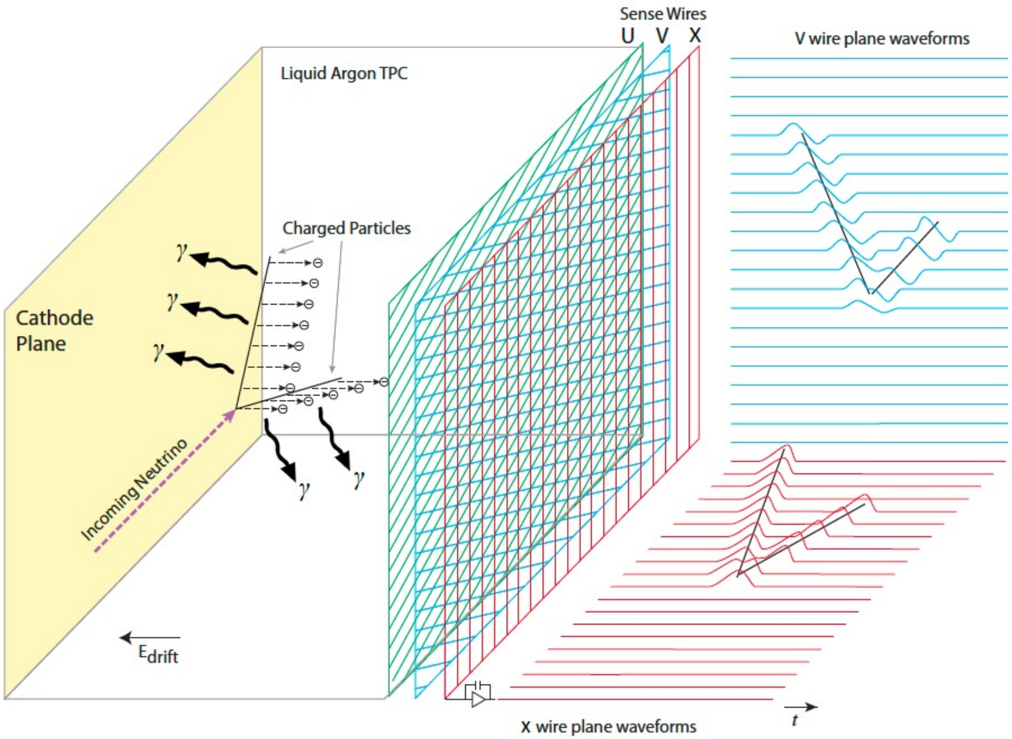
Time Projection Chambers (TPC)

- Detector volume
  - Filled with something with a good dielectric strength
    - Noble gases/liquids: Ar, Xe, He
- Apply **electric field**
- Particle interaction causes ionisation and scintillation
- Ionisation electrons drift towards the anode
- Use the anode to collect drifting ionisation electrons!
  - 2D position resolution from readout plane
  - 3rd dimension comes from readout over time

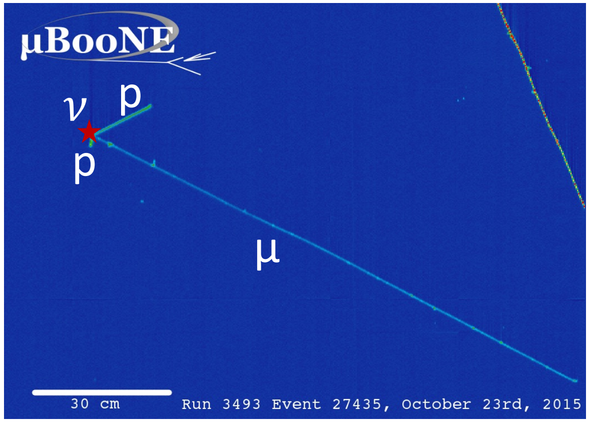


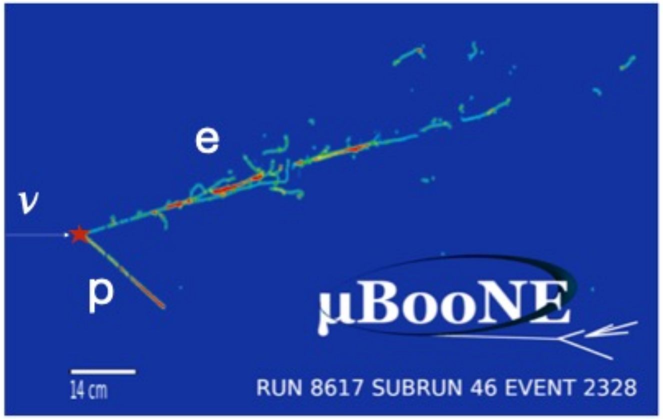
Time Projection Chambers (TPC)

- Drifting charge is slow
  - ~10us-10ms
- Timing resolution can come from light signal
  - Requires a detector medium which is ALSO a good scintillator
- Scintillation light gives a fast (~ns) signal



Excellent separation between muon and electron events, at a glance!





Introducing the LArTPC

- Liquid argon time projection chamber
- Neutrino detector wish list:
  - Excellent energy resolution throughout the detector
  - Position / tracking information
  - e/μ separation for neutrino flavour tagging
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  - Large target mass

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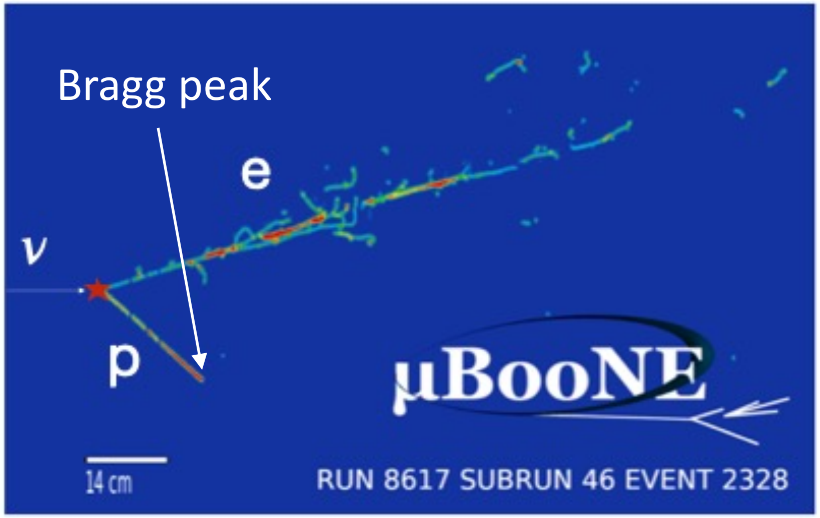

Amount of charge collected (dE/dx) is shown here as colour scale

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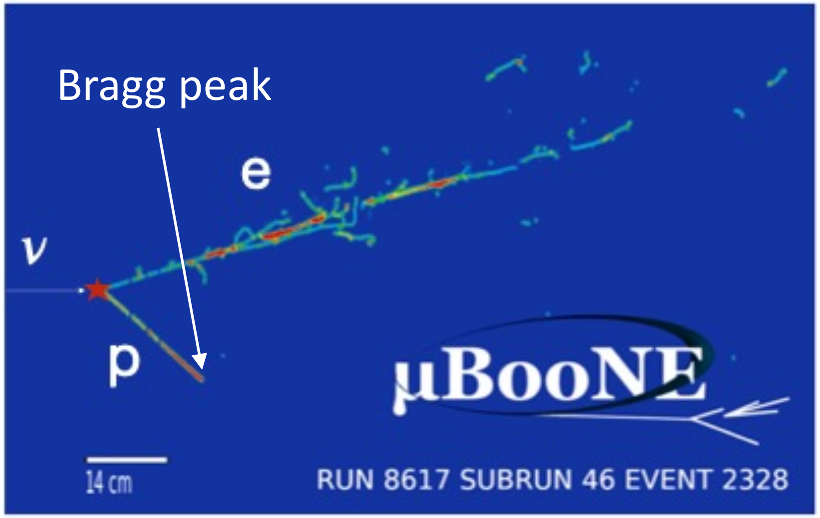

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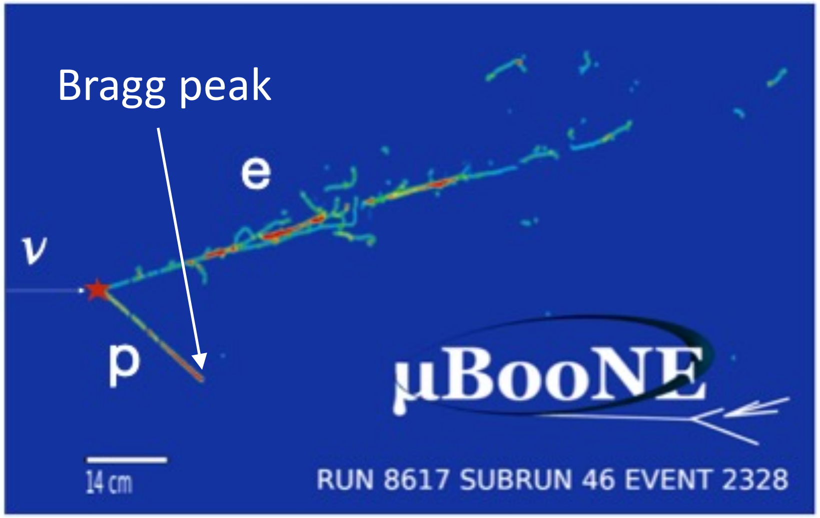

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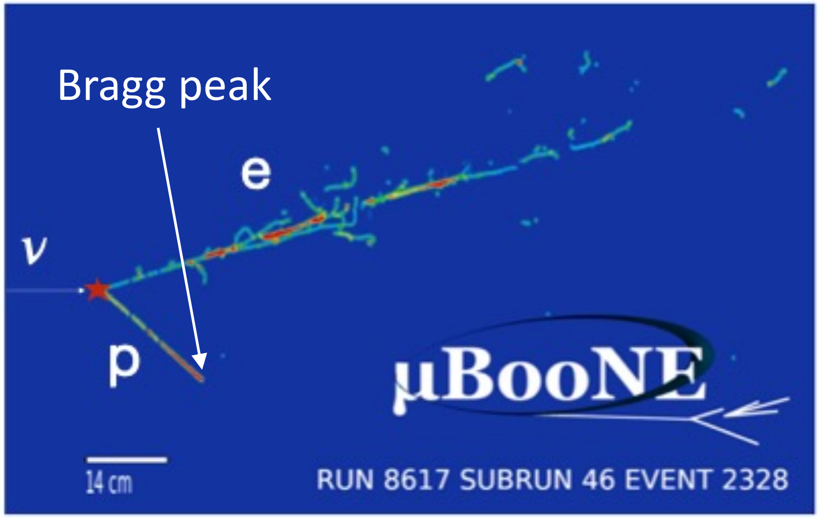

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Liquid argon is 1.4x density of water

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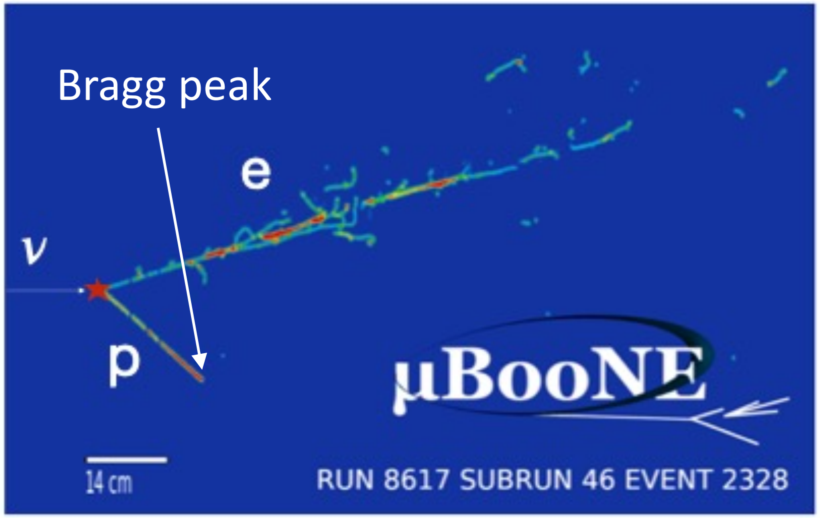
- ❑ Wait… what temperature is argon liquid at…?
- ❑ How do we get all that argon?



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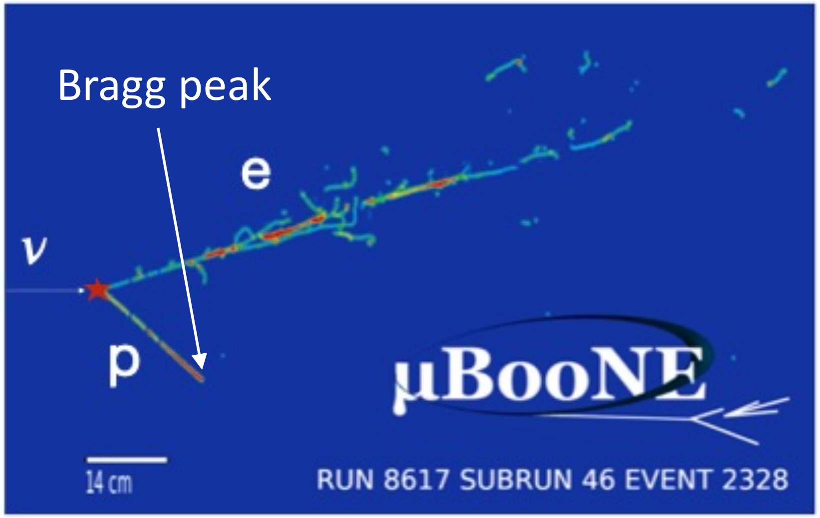


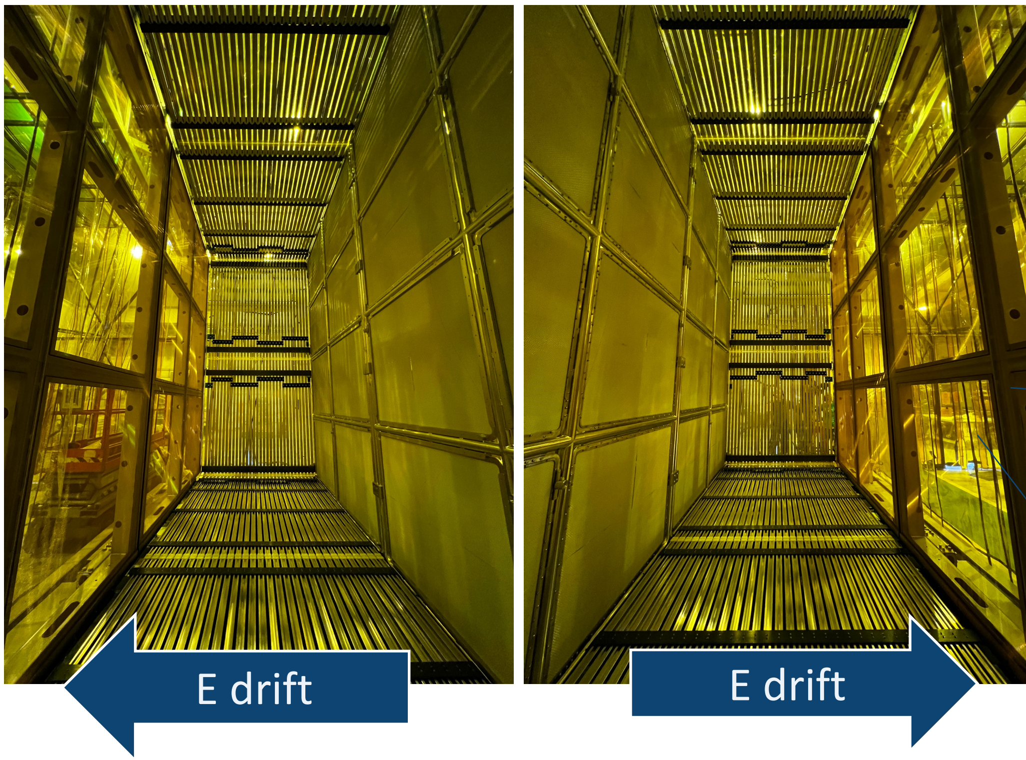
Argon is liquid between 83 and 87K (-302°F / 186°C)
~10K warmer than liquid nitrogen

This is an inconvenient temperature to have to maintain! (But certainly doable!)

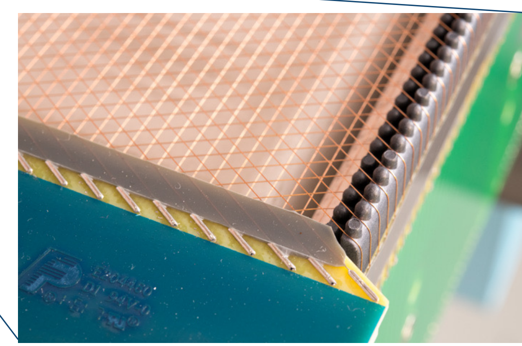
Argon is ~1% of air, and is the cheapest and most abundant noble gas

LAr TPC example: SBND

Short-Baseline Near Detector (SBND) – the latest, and greatest* LArTPC to be built!



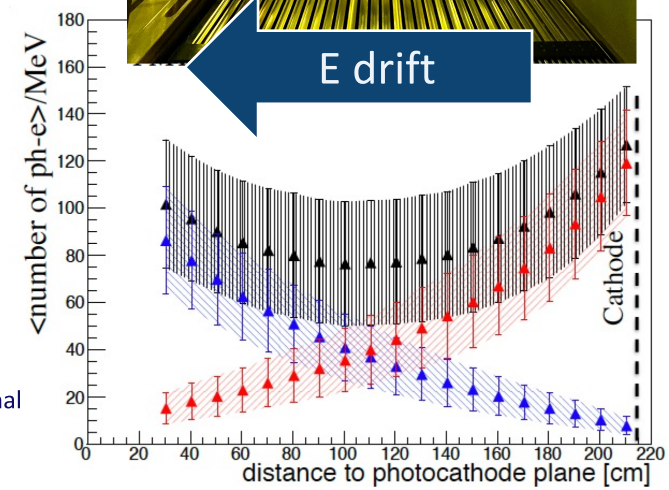
- ❑ Wire readout anode planes
  - Composed of many thousands of wires at a spacing of 3mm
- ❑ 2m drift distance to cathode
- ❑ 2 drift volumes



*in my extremely biased opinion

LAr TPC example: SBND

Light detectors go here: VUV + vis



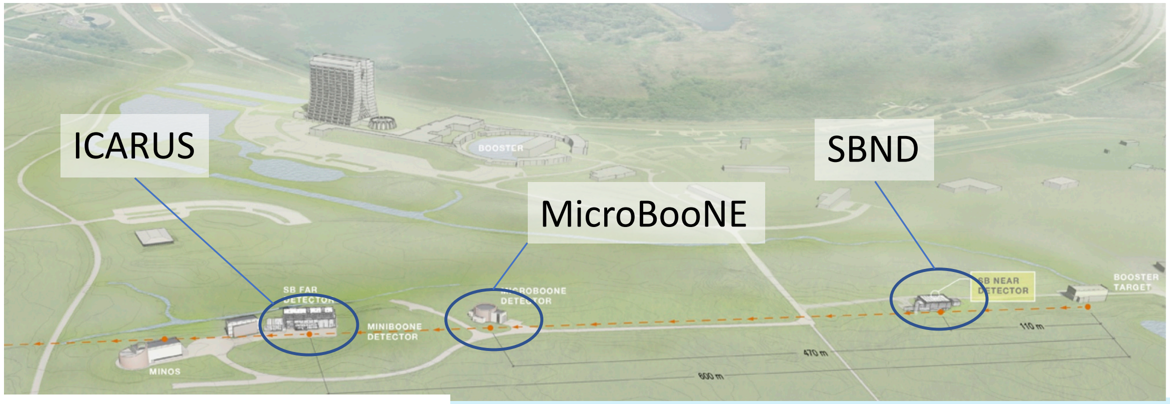
[D. Garcia-Gamez, Journal of Physics: Conf. Series 888 (2017) 012094]

- ❑ Argon scintillates at 128nm
  - Challenging for conventional readout technology
  - It won't pass through glass!
- ❑ Need to use wavelength shifter + light sensors

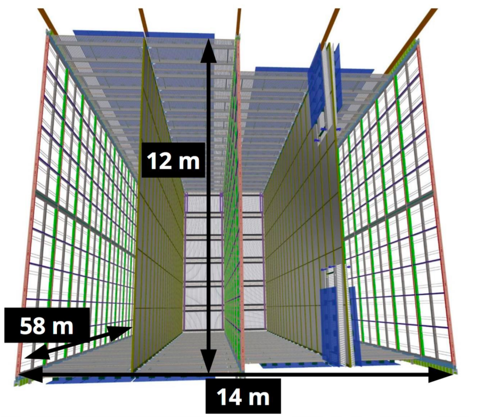
Wavelength shifting reflectors

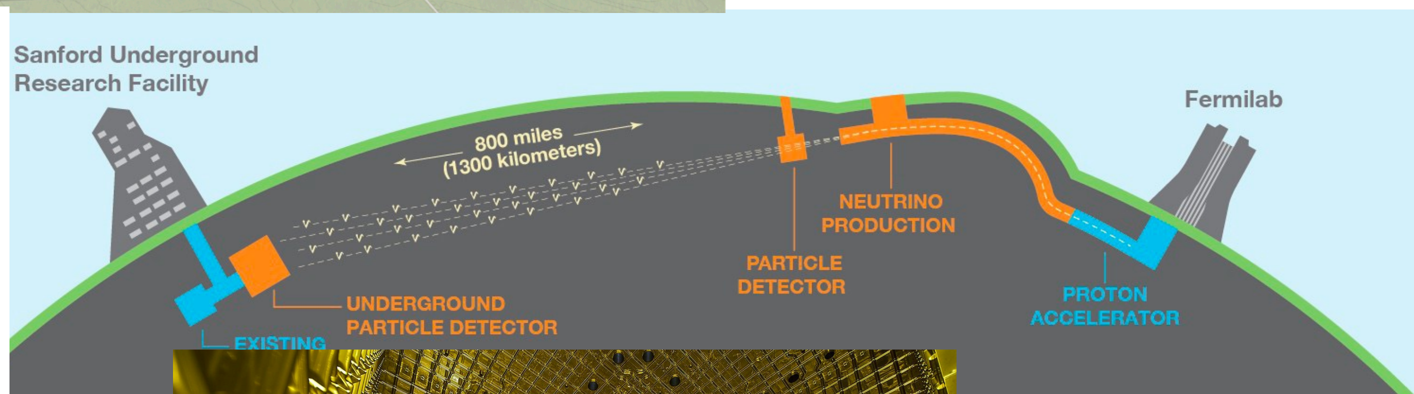
- ❑ SBND light detection system sensitive to VUV light and to visible light (reflected from the cathode)

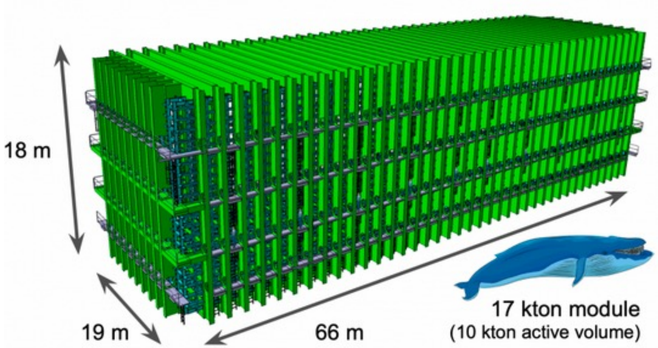
LAr TPCs and the future

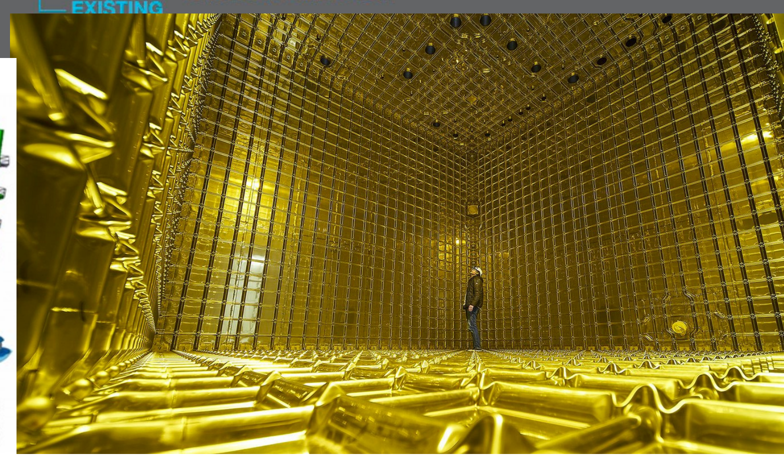


- LArTPCs are a very scalable technology
- Bigger detector, more neutrinos, better measurements







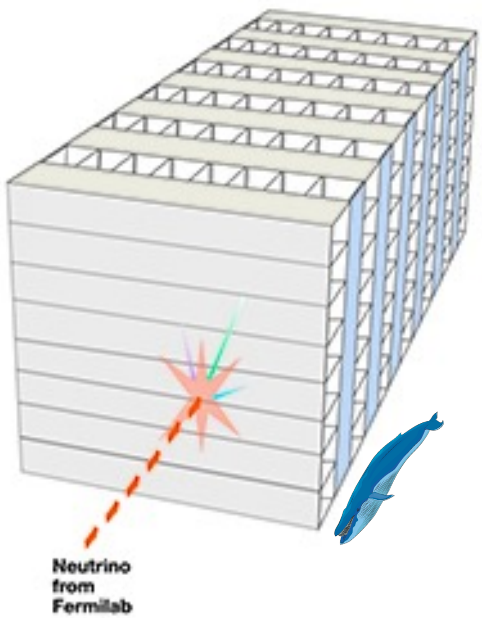


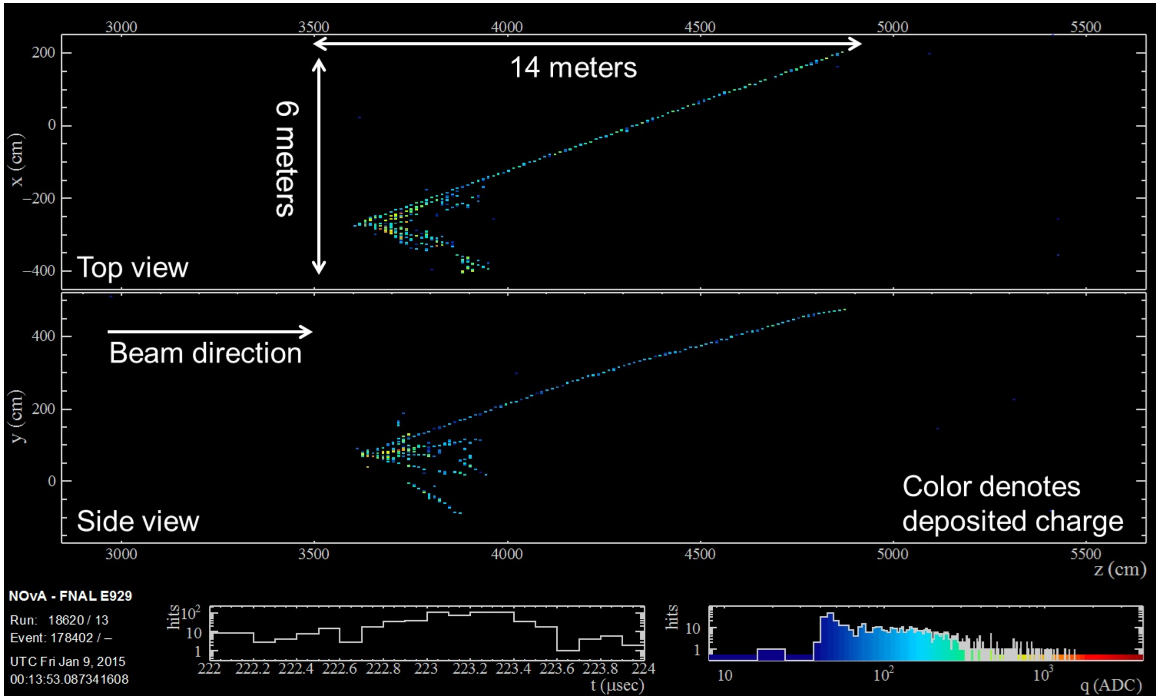
The DUNE far detector will have a 40kton active volume of LAr

It will see ~10 neutrino interactions per day

Scintillator detectors – the sequel!

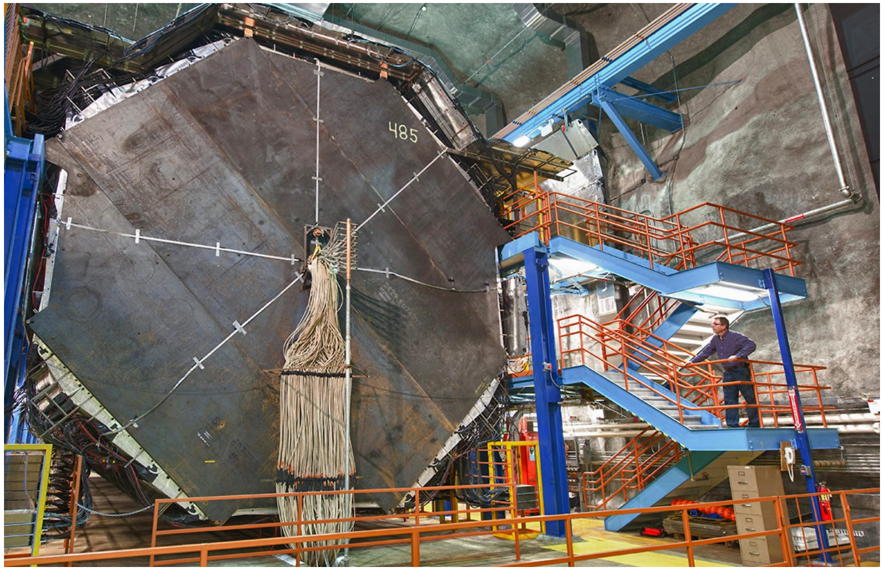
- Scintillator detectors are great! I want to use them for tracking!
  - Certainly possible, thinking outside of the box!
- Noνa: a liquid scintillator tracker
  - Optically isolated boxes of liquid scintillator

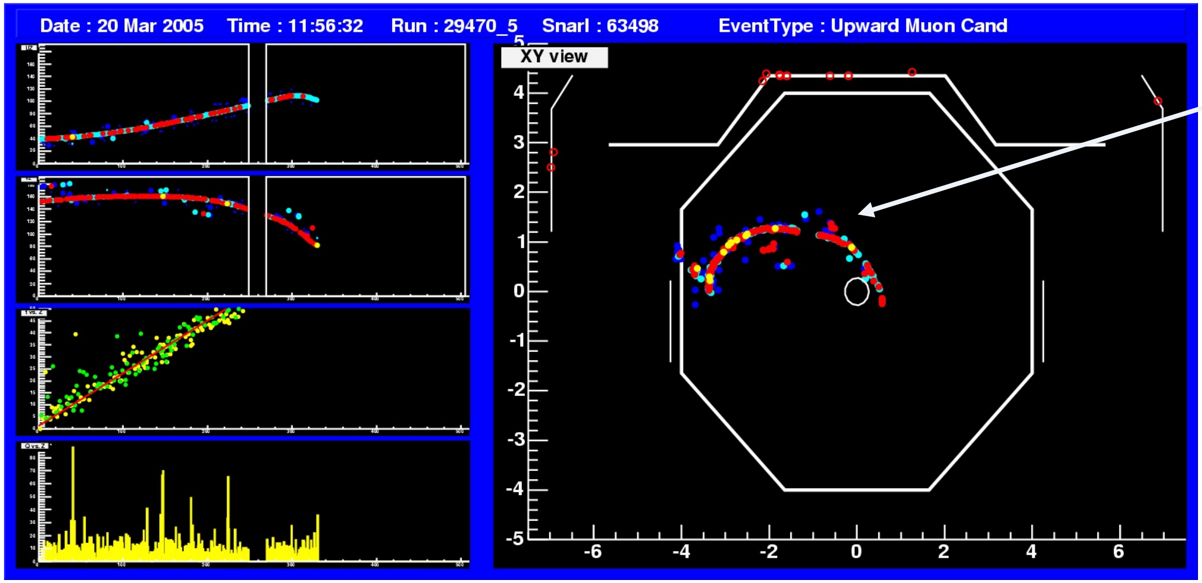




Scintillator detectors – the sequel!

- MINOS: a sampling calorimeter (2003-2012)
  - Combine planes of scintillation counters (solid strips) and layers of steel
- Steel adds target mass!
- Steel allows us to magnetise the detector!



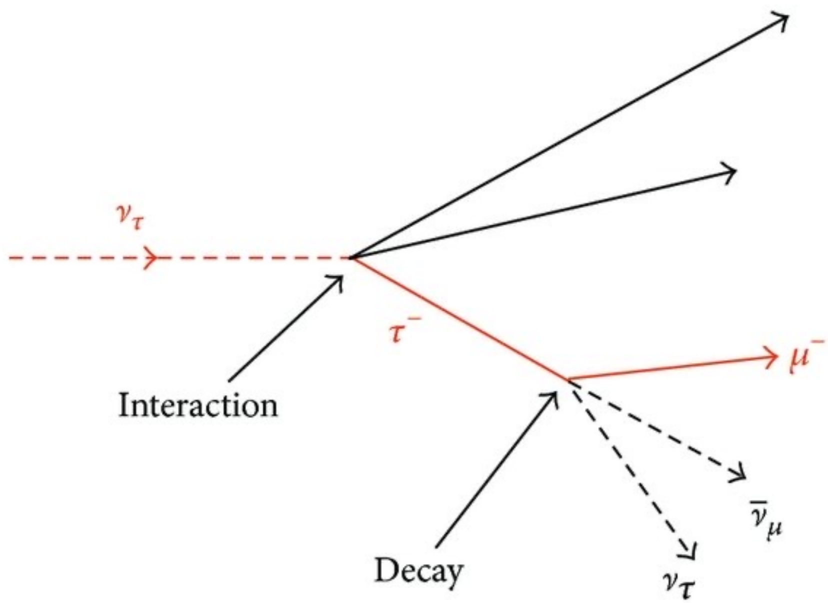


Magnetic field causes muon tracks to bend

Charge of muon allows us to tell if the incoming particle was a neutrino or antineutrino

A quick word on tau neutrinos

- Mostly we talk about measuring electron and muon neutrinos
- Tau neutrinos are **a big challenge** to tag
- Tau leptons have a lifetime of 2.9×10^{-13} s
  - That doesn't make a very big track in our detector
- Need specially designed detectors to see this level of precision

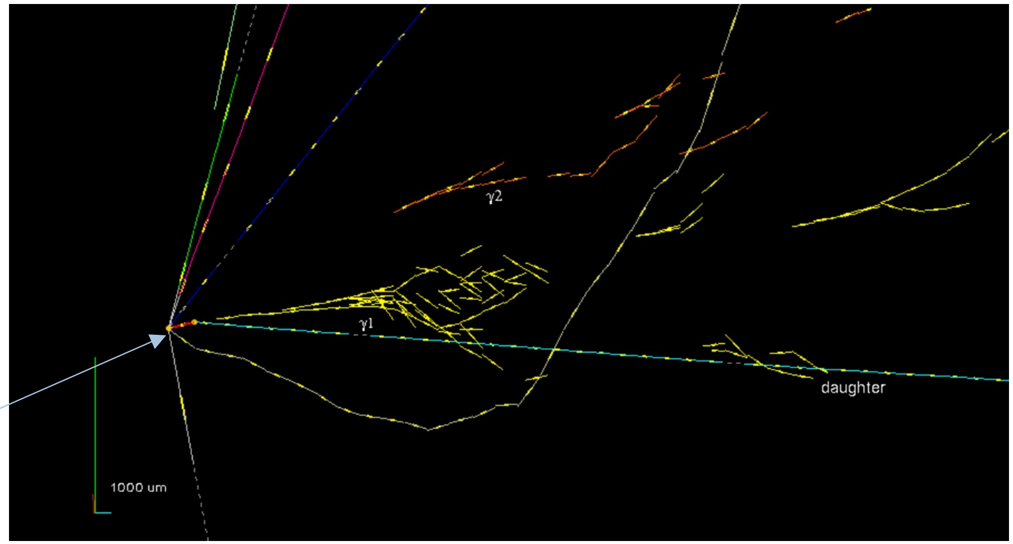


What is the type of detector material with the finest tracking granularity?

Emulsion detectors

- Essentially many layers of camera film
  - Exposure to a charged particle deposits energy and hence a track (over many sheets of film)

87μm τ track



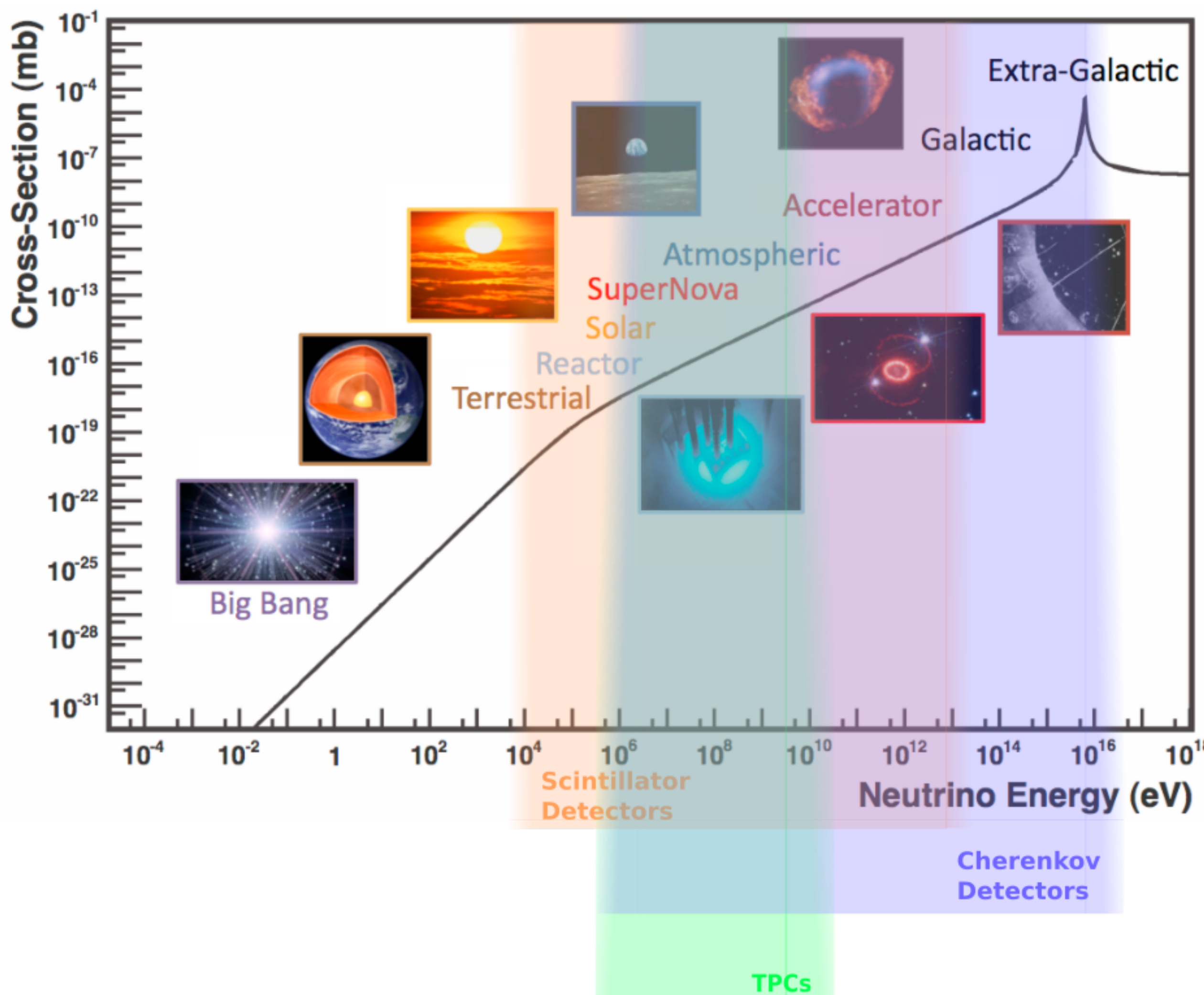
DONUT:
Phys.Lett.B 504 (2001) 218-224

OPERA:
Phys.Rev.Lett. 120 (2018) 21, 211801

- Challenges:
  - Completely analogue detector!
    - Have to develop each film offline
  - Not that dense of a material
    (OPERA used bricks of lead + emulsion to increase the target mass)

- Reward:
  - Direct observation of tau neutrinos!
  - We've seen 14 of them EVER

Overview of what we've seen so far



Other types of neutrino measurements

- Detectors to measure the **neutrino mass**
- Detectors to measure **neutrino-less double beta decay**

These topics will be covered in detail in future lectures

Other types of neutrino measurements

- Detectors to measure the neutrino mass
- Detectors to measure neutrino-less double beta decay

These topics will be covered in detail in future lectures

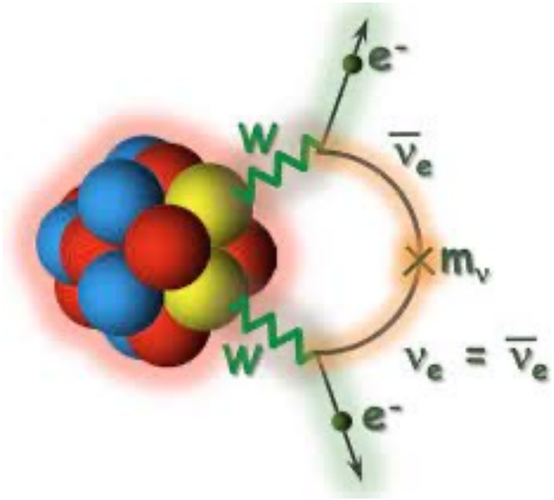
BUT

- These different measurements require different detector optimisations to succeed
- The detectors do follow the (neutrino) detector wishlist / checklist

- I will briefly touch on this topic

Neutrino-less double beta decay

- ❑ How does the detector need to be different?
- ❑ Observing a rare signal
  - Waiting for an isotope in the detector to decay
- ❑ Seriously Low Background
- ❑ We aim for **zero background** here
  - All the pieces of detector must be made out of “radiopure” material
  - No radioactive decays in the detector apart from the one we want to measure!



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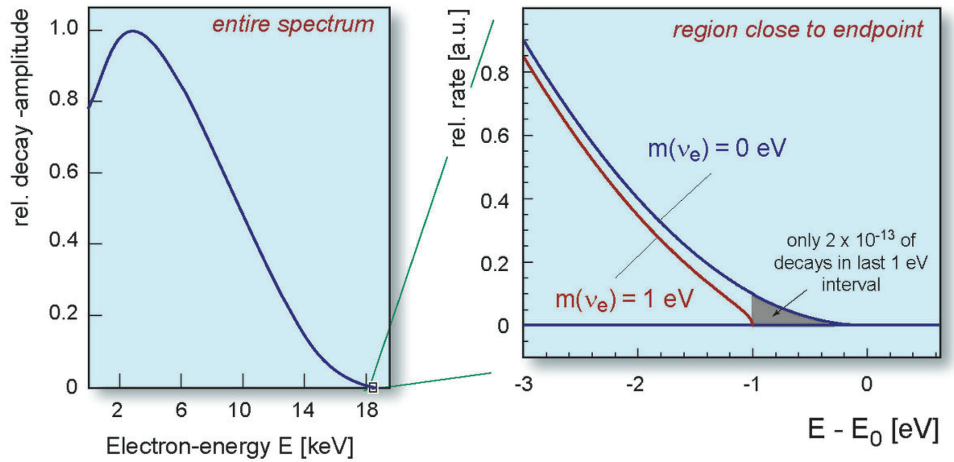
- CUORE – a scintillating bolometer detector
  - Measures the heat change in the detector due to the deposited particle decay energy
  - 6mK operating temperature

Neutrino mass measurement

- How does the detector need to be different
- Detector measures the endpoint of the beta decay spectrum
- Seriously good energy resolution
- The energy resolution of the detector is proportional to the sensitivity of the mass measurement



Summary and conclusions

- Neutrinos are challenging – but very possible – to measure!
  - Although we never "see" the neutrino, we can infer energy and flavour from the daughter particles we observe
- There are a wide array of different detectors which we can use to measure neutrinos!
  - Too many to discuss in one lecture!
- Particle detectors:
  - Wishlist of general detector parameters + specifics for neutrinos
  - Optimise your detector for what you want to measure!
- **Which one do you want to help build in the future?**

This could be you!