
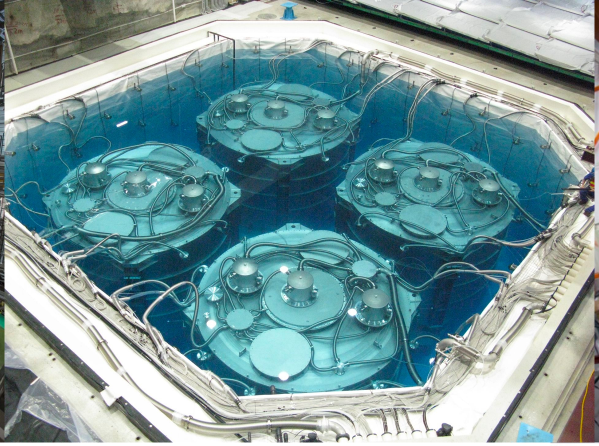
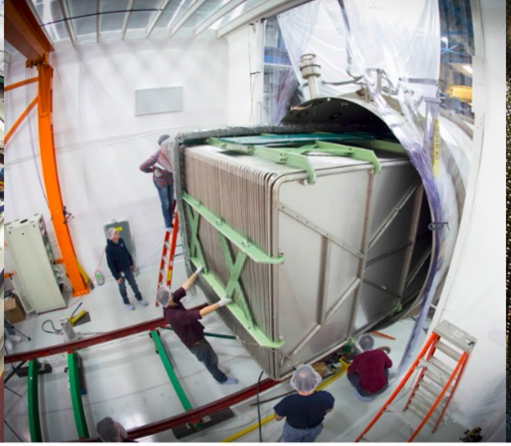


MANCHESTER 1824
The University of Manchester

# Liquid Argon Time Projection Chambers and other Neutrino Detectors

Latin America-UK LArSoft Workshop

September 6th 2022

Nicola McConkey

# Aim + Outline

- **Aim:** To discuss how we measure neutrinos
  - How detectors help us to understand what's going on in $\nu$ interactions
  - Basic principles of how a particle detector works
  - Present some details of the Liquid Argon Time Projection Chamber technologies that we use

- What do we need from a neutrino detector?

# How do we measure neutrinos?

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

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Neutrino mass is at least 600,000 x lighter than the electron ($m_e$=511keV)

**$m_\nu$<0.8eV** (Katrin direct measurement, *Nature Phys.* 18 (2022) 2, 160-166)
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Most neutrinos pass straight through the detector!

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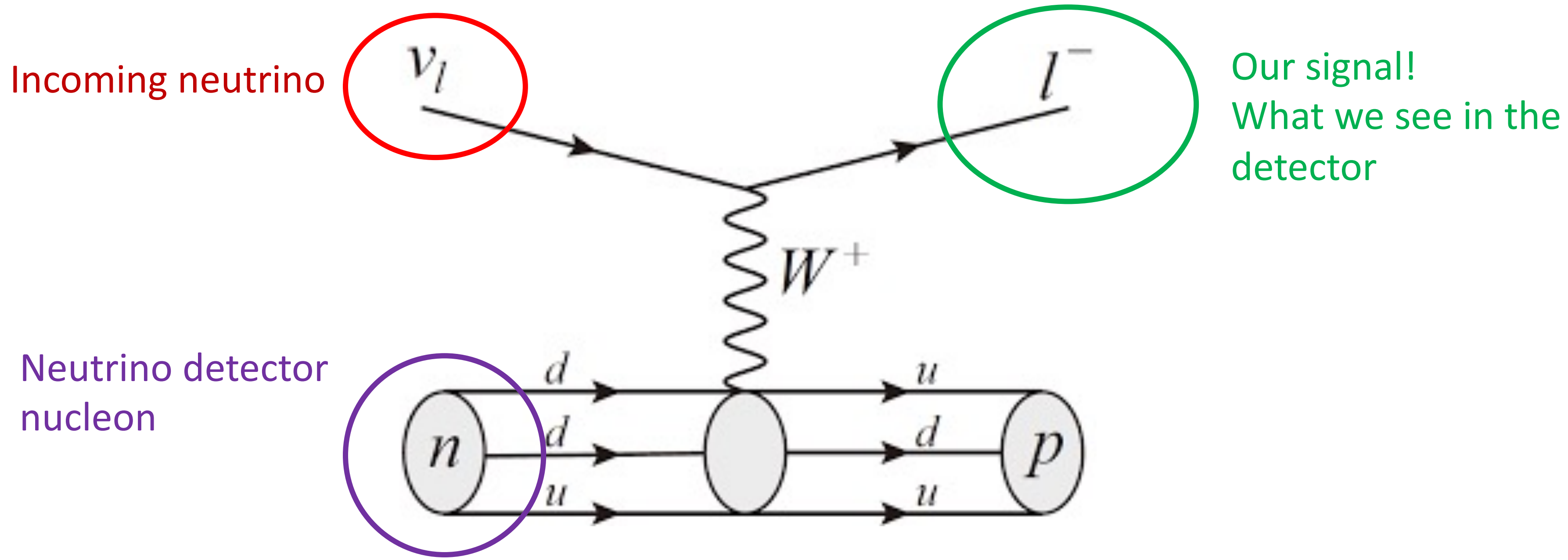
***"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich."***

**-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!




Charged-current Quasi-elastic interaction

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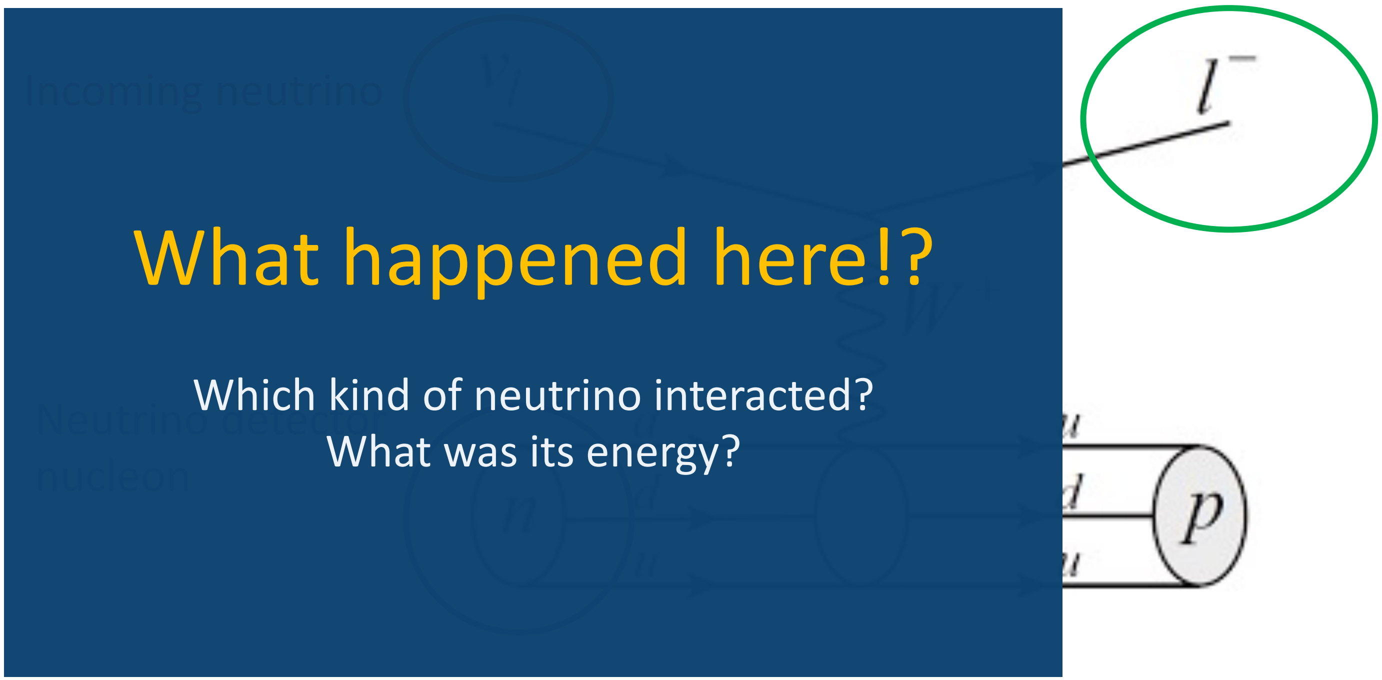
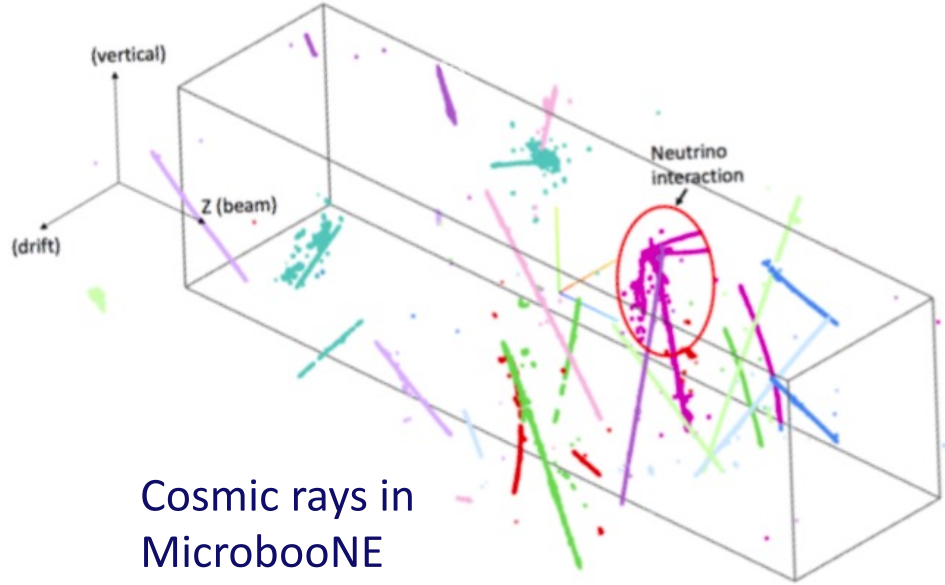



Our signal!
What we see in the detector

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

# Wait, what's background?

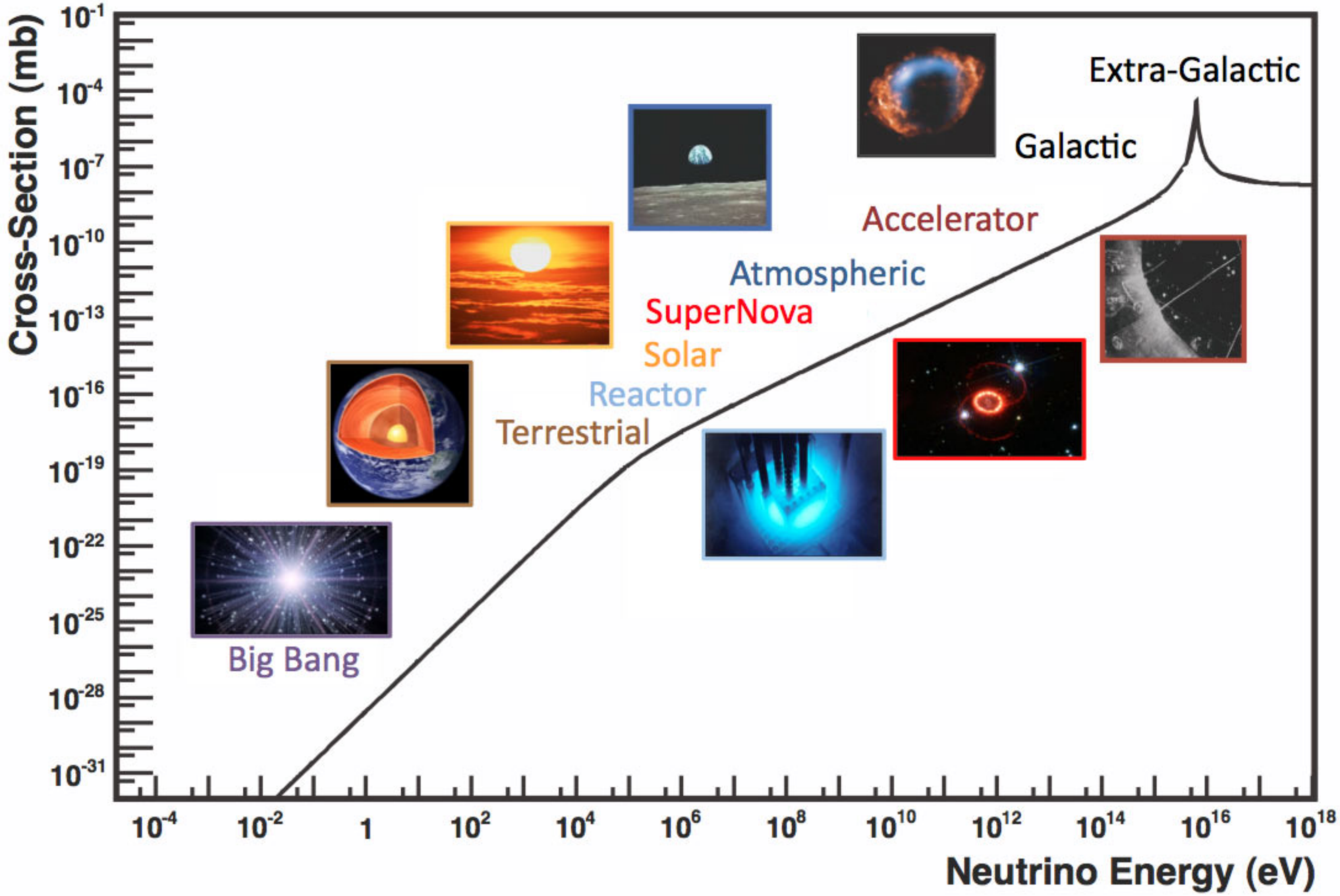
- Everything else that isn't the (neutrino) interaction that you're trying to measure is **background**
  - Our detectors are great at sensing particles – they see much more than the neutrinos that we want to measure!
- One big challenge for our neutrino detectors is to pick out ("tag") the neutrino 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

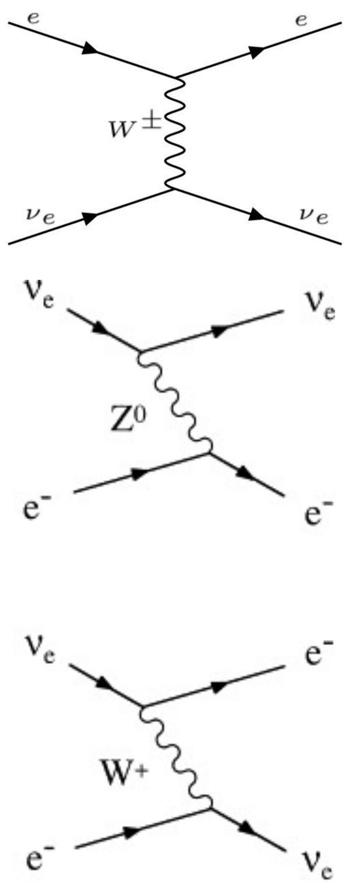
# Measuring neutrinos is difficult

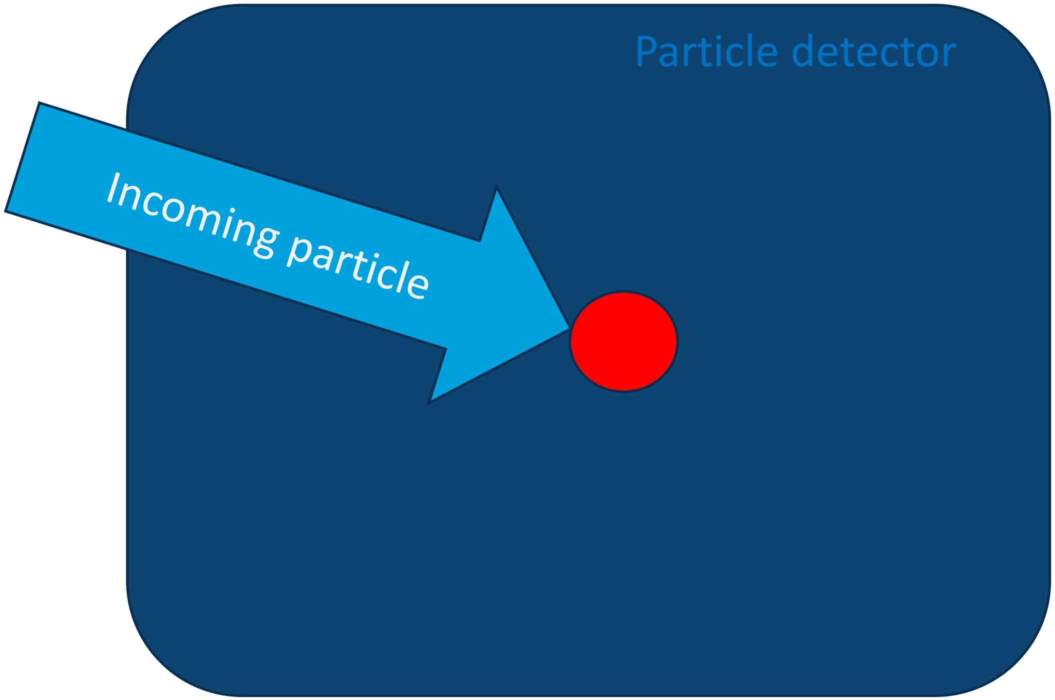
- ...but we have measured a vast spectrum of them!



# How does a particle detector work?

Particle interacts in the detector



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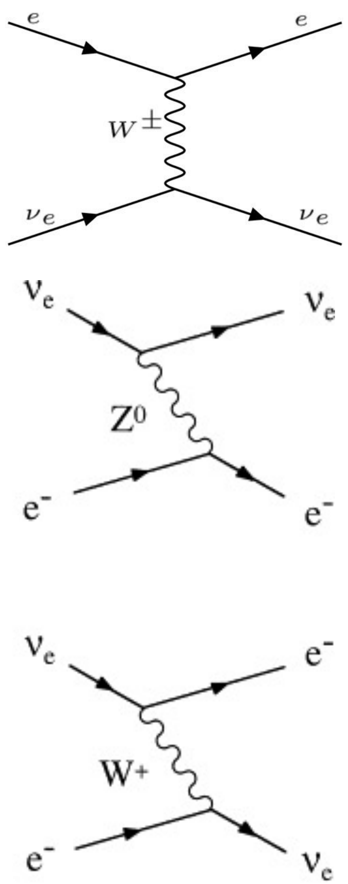


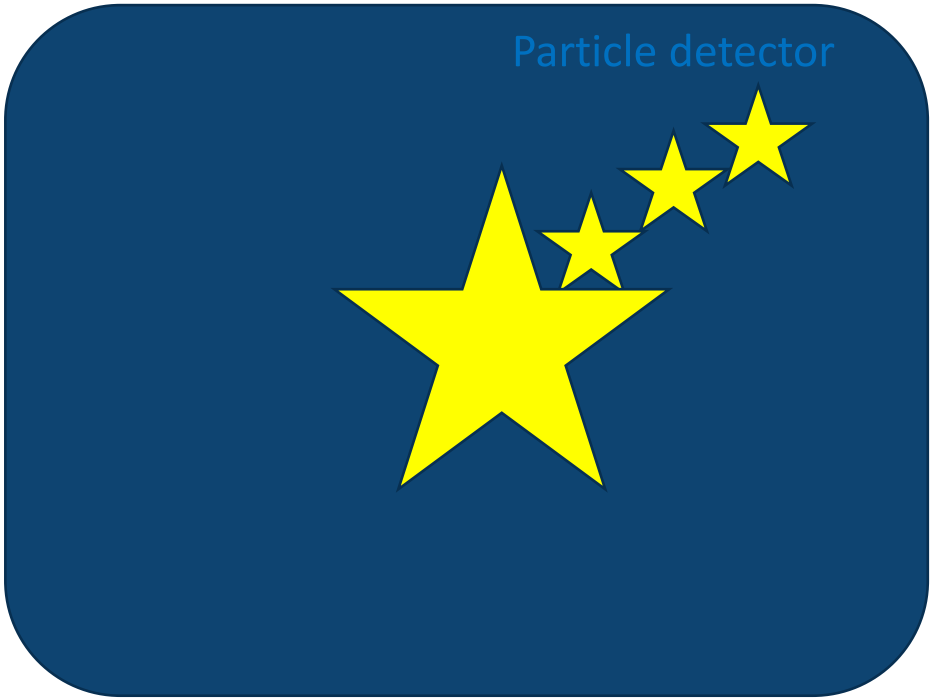


Energy deposited in the detector from the interaction

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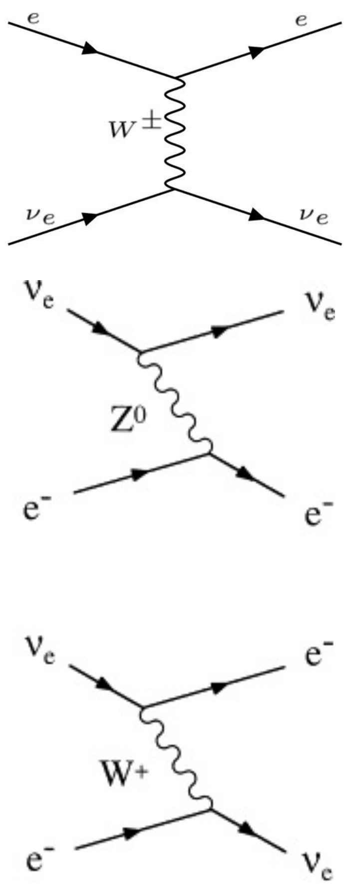
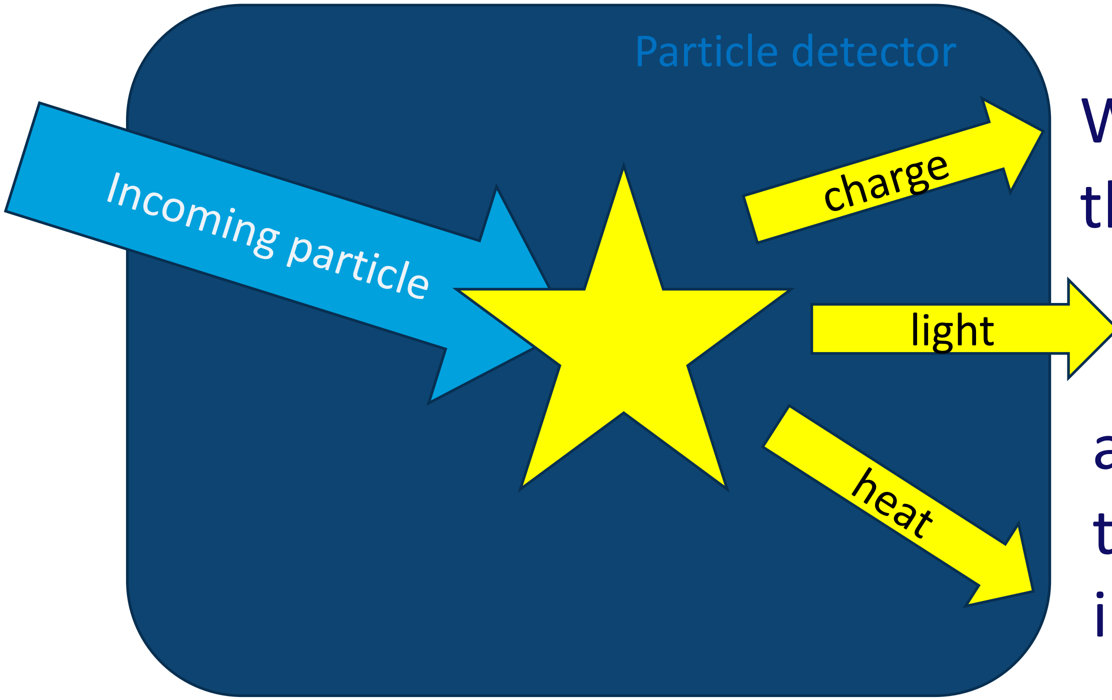
Particle interacts in the detector




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

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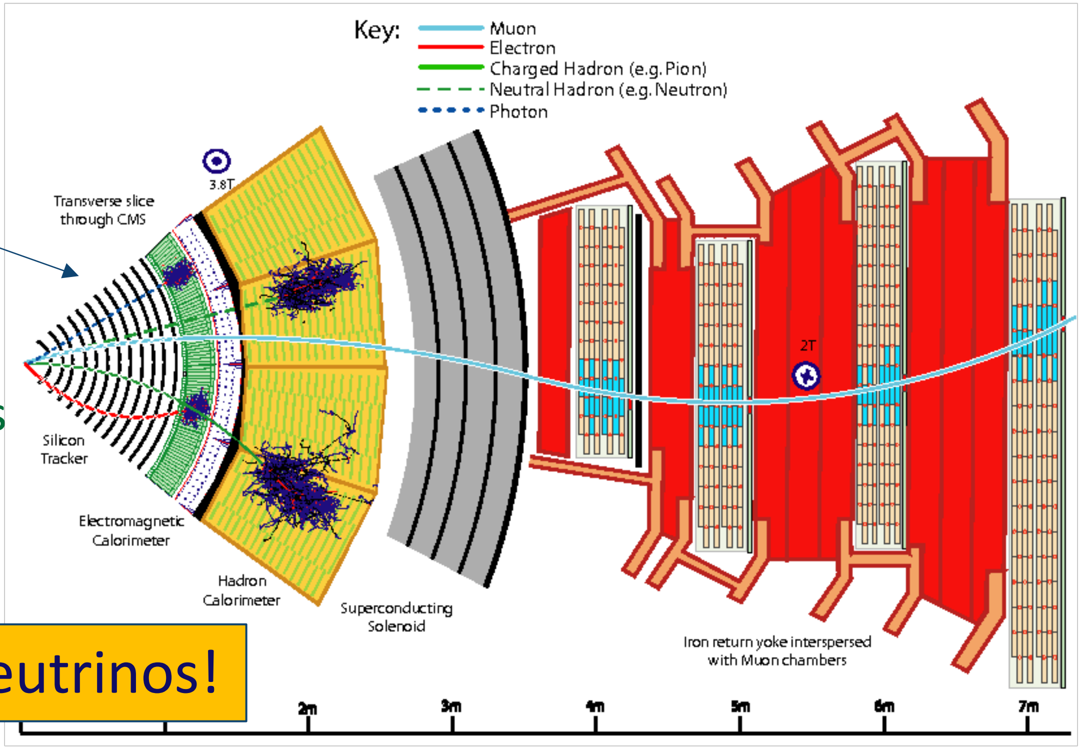
To reject backgrounds, and measure the *desired* particle interaction

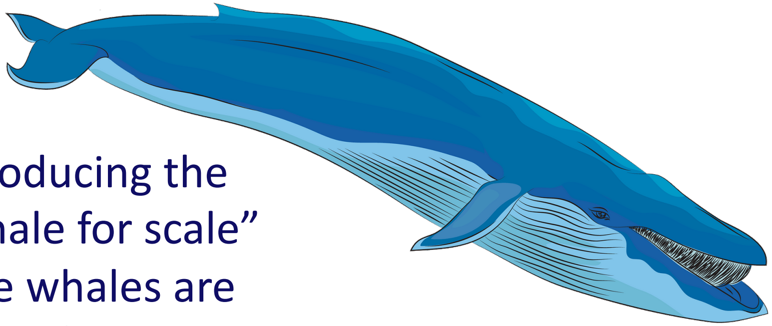
- CMS detector
  - In LHC at CERN
  - Detects interactions from colliding charged particles
    - Interaction point well defined



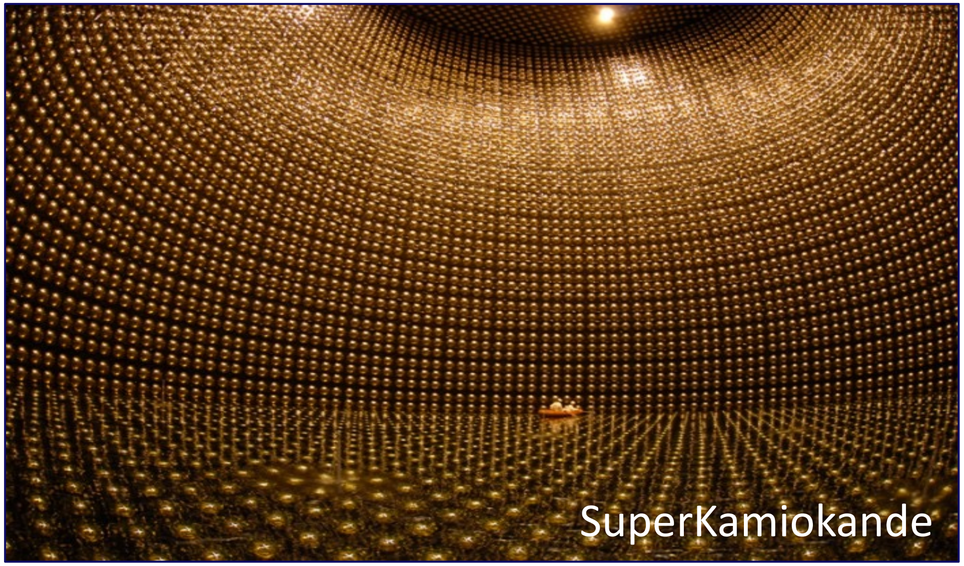

**NOT good for measuring neutrinos!**

# 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



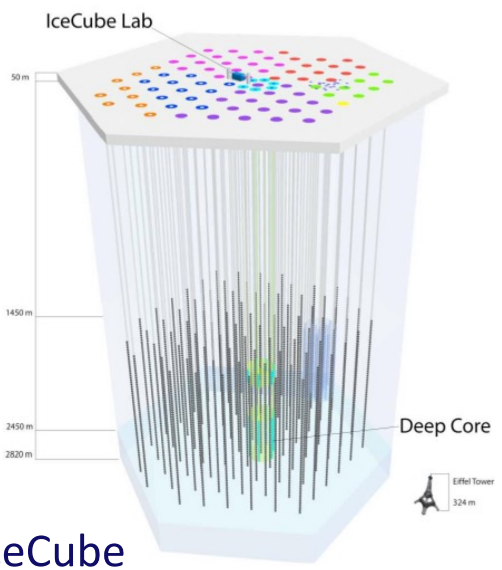
# The giants of the particle detector world

- ❑ 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!

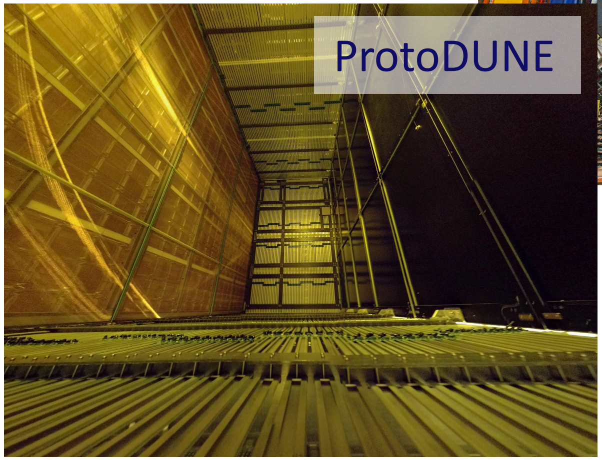
Water / ice

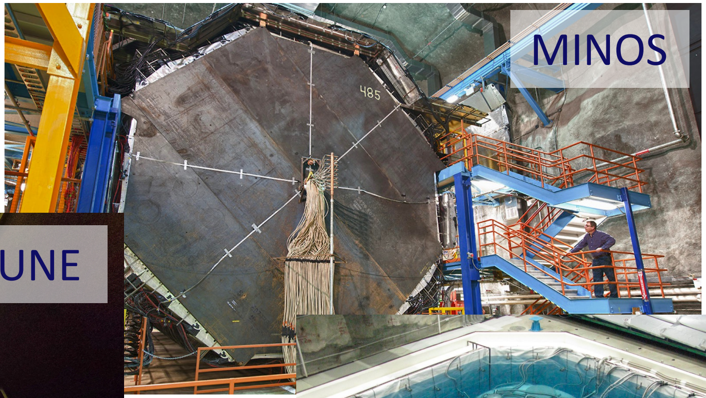
Argon

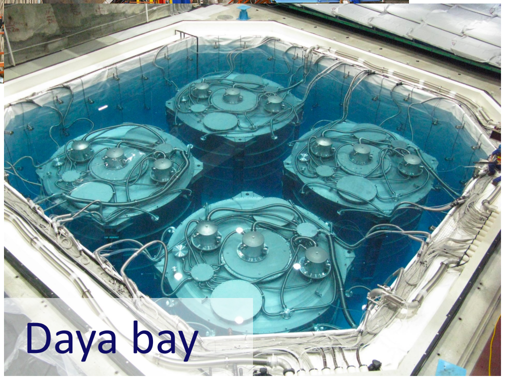
Liquid / solid Scintillator



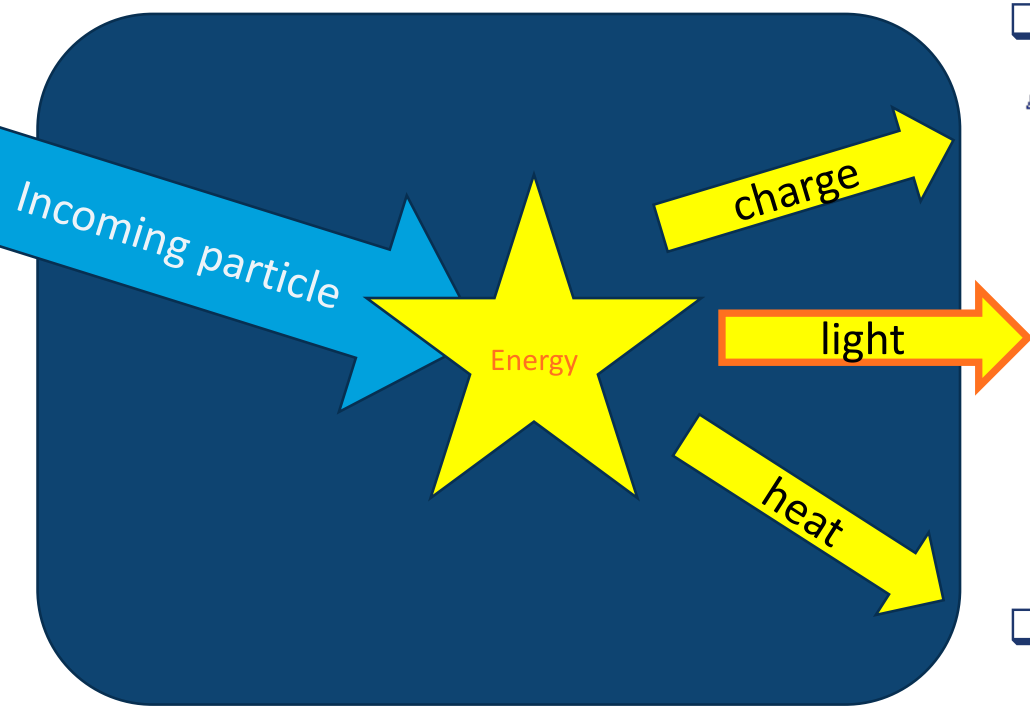

IceCube



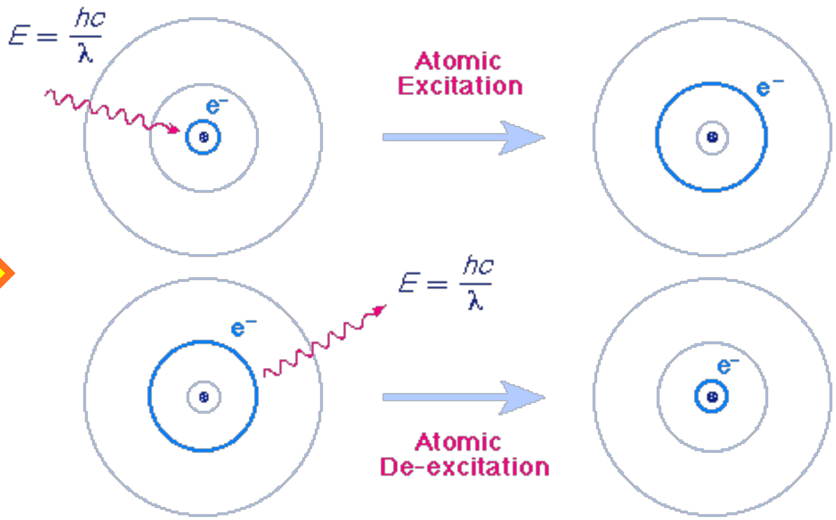



# Scintillator detectors



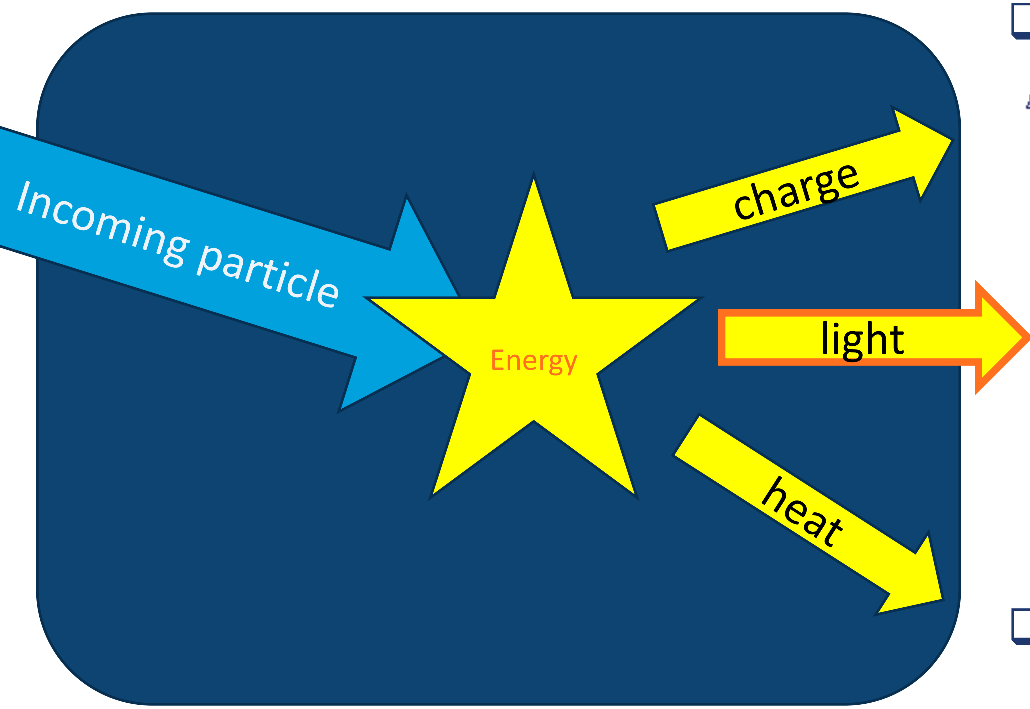

- Scintillation




- 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

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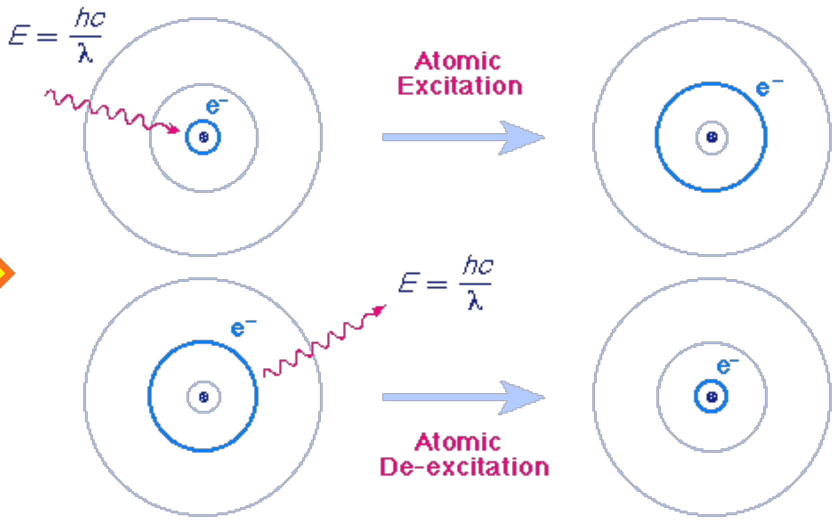


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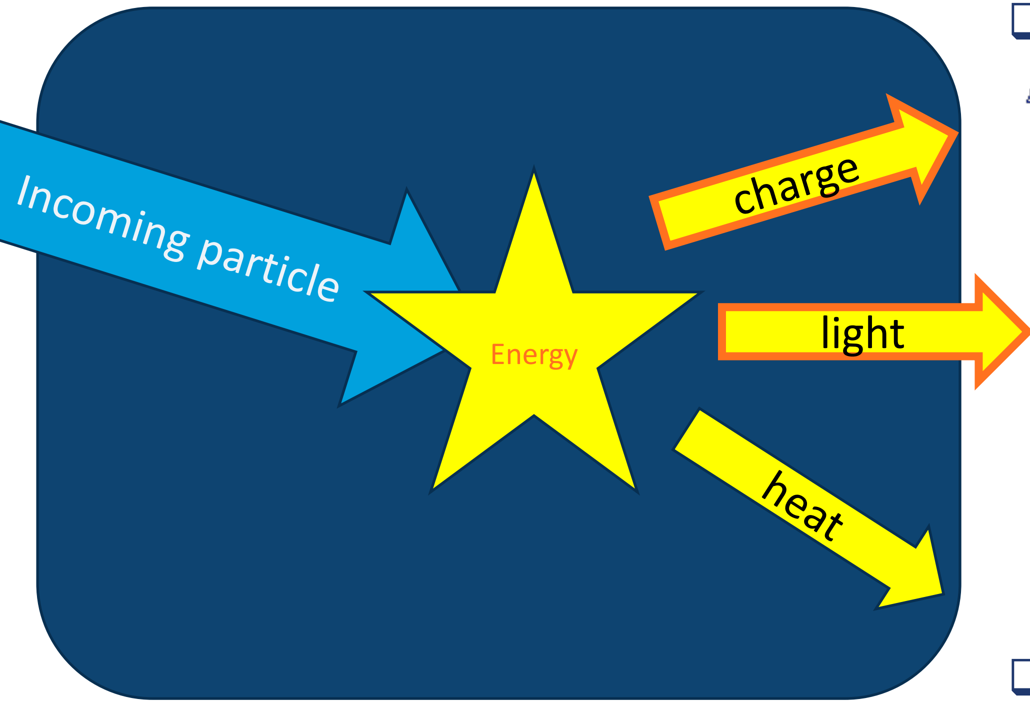
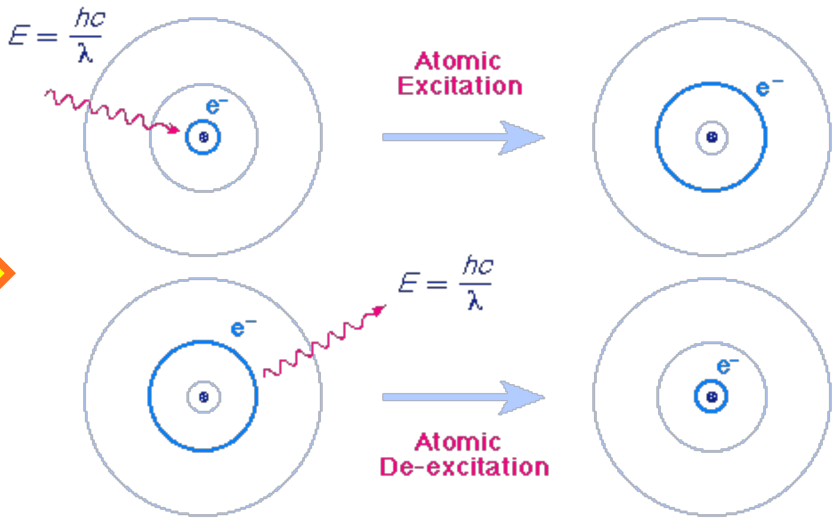
More details in the backup slides on:
- Scintillator detectors
- Cherenkov detectors

Neutrino detectors using solely light readout

# Charge and light collection




- Scintillation + Ionisation

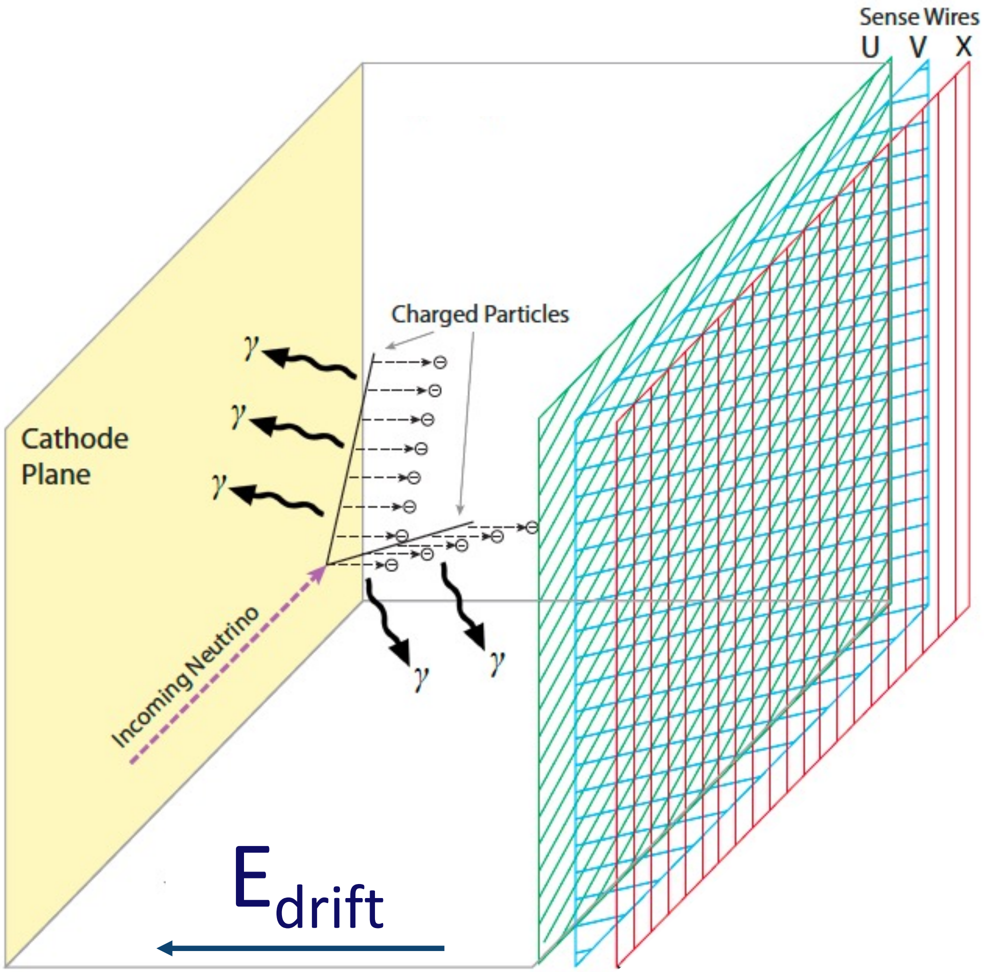



- These photons and ionisation electrons are the **detector signal**

- Detector collects both ionisation electrons **and** scintillation light

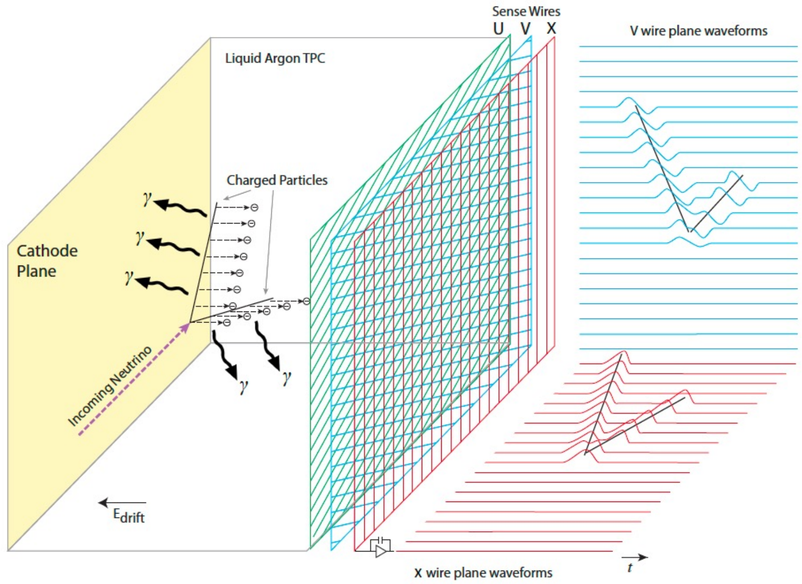
# Time Projection Chambers (TPC)

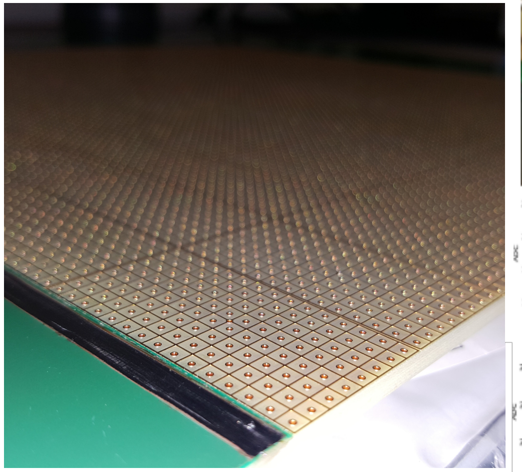
- ❑ Detector volume
  - Filled with something with a good dielectric strength
    - Noble gases/liquids: Ar, Xe, He
- ❑ Apply **electric field**
- ❑ Particle interaction causes **ionisation** and **scintillation**
- ❑ Ionisation electrons drift towards the anode
- ❑ Use the anode to collect drifting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

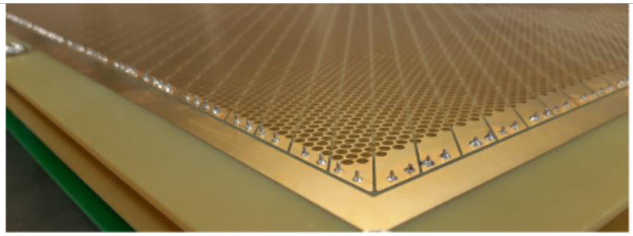


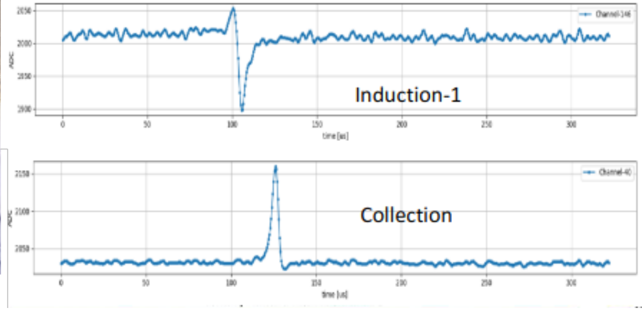
# Charge readout planes

- ❑ **Wire readout planes / strips**
  - Three planes of wires / strips to reduce ambiguity
    - Two induction planes (bipolar signal)
    - Collection plane (unipolar signal
  - Wire planes biased so electrons drift past induction planes to collection plane
- ❑ **Pixel pads**
  - No ambiguity due to pre-voxelised readout
  - Large number of readout channels



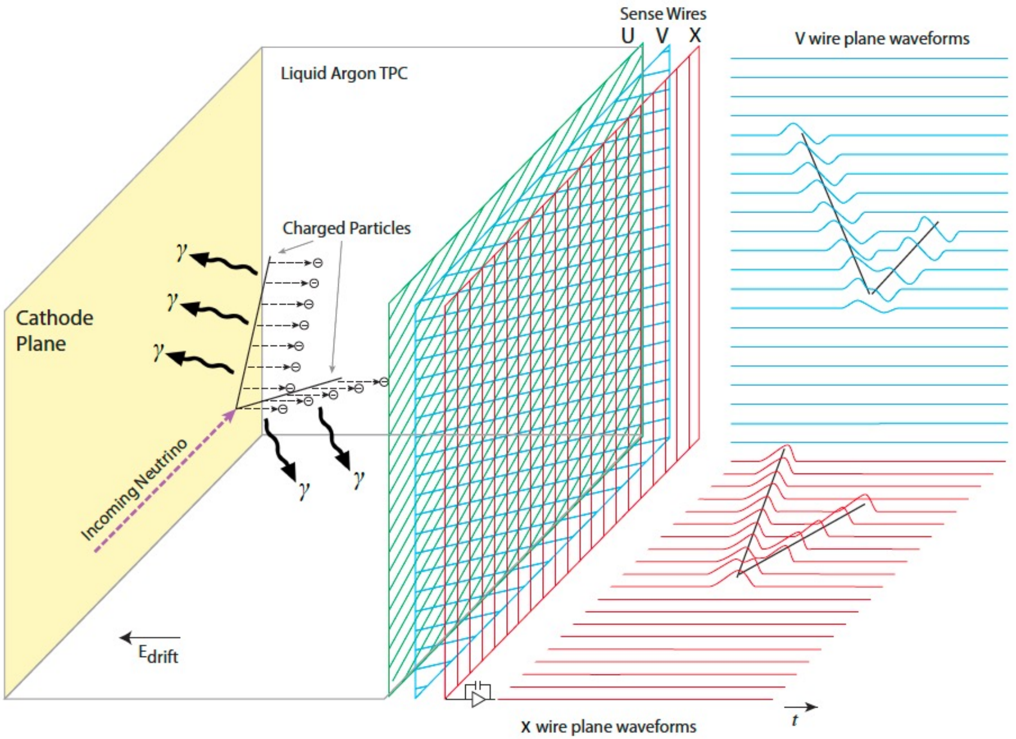





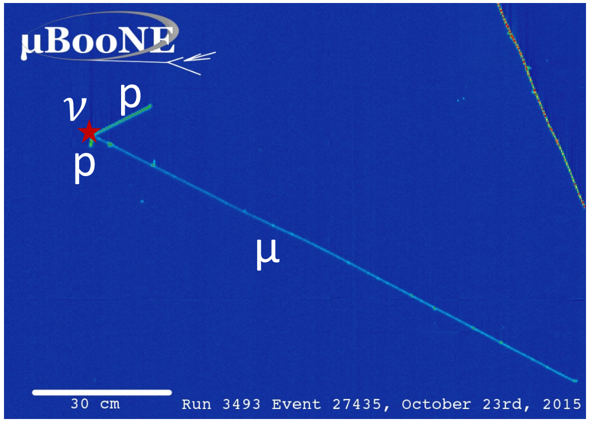


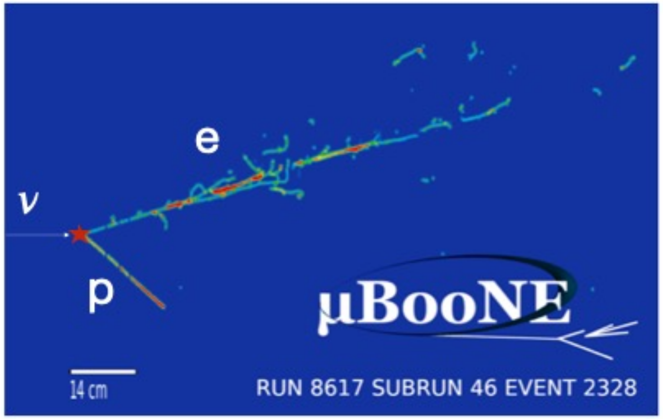
# Time Projection Chambers (TPC)

- 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
    - Excellent timing resolution
    - Large target mass

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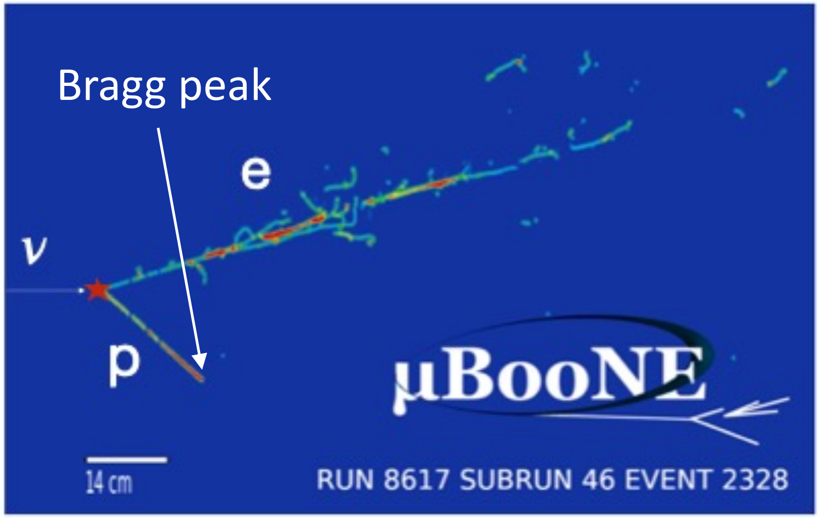


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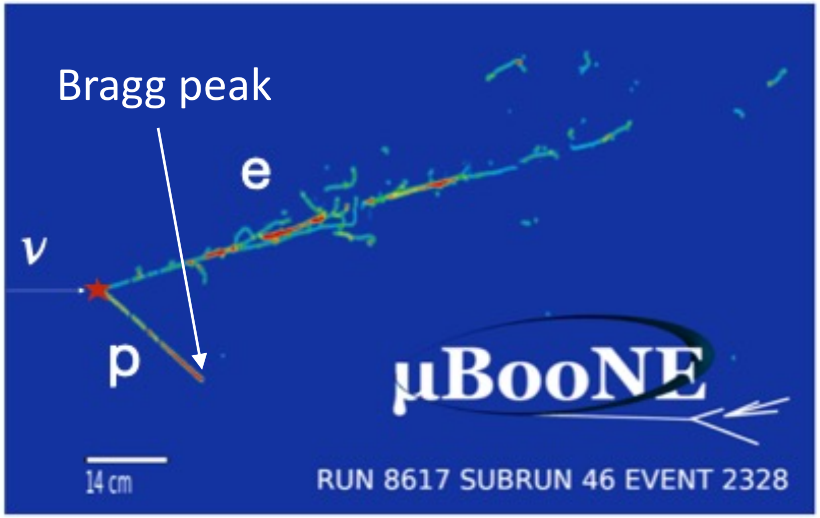


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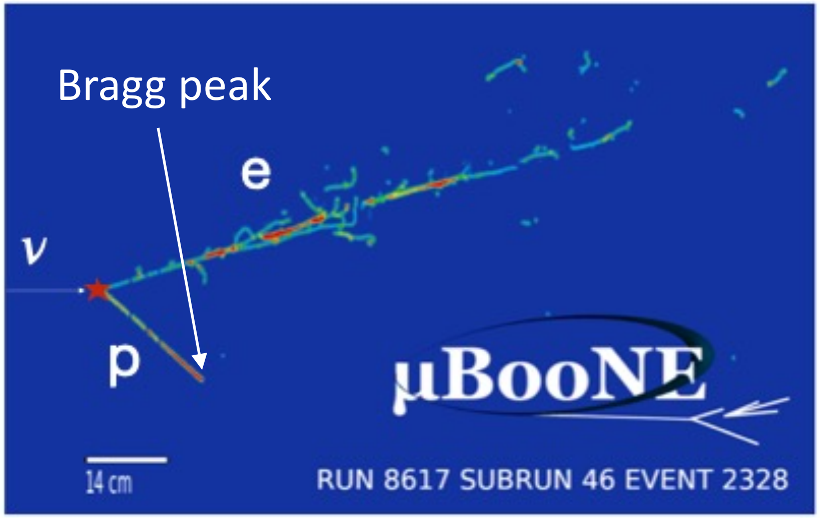


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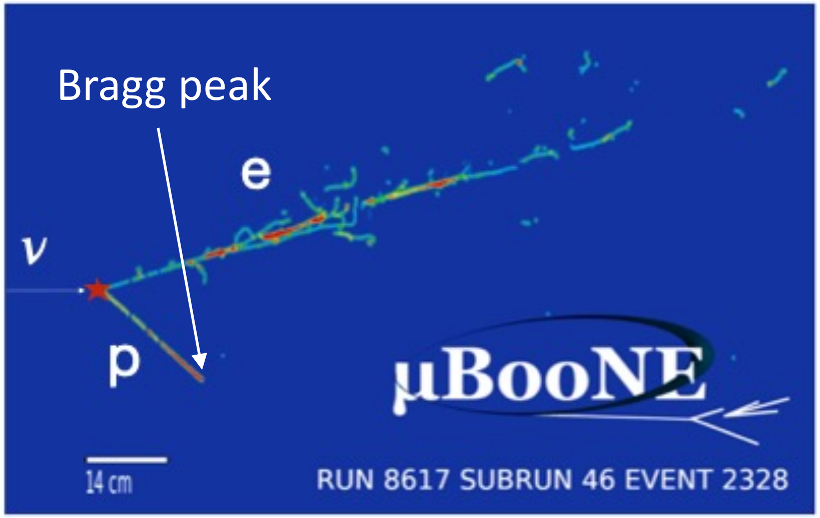


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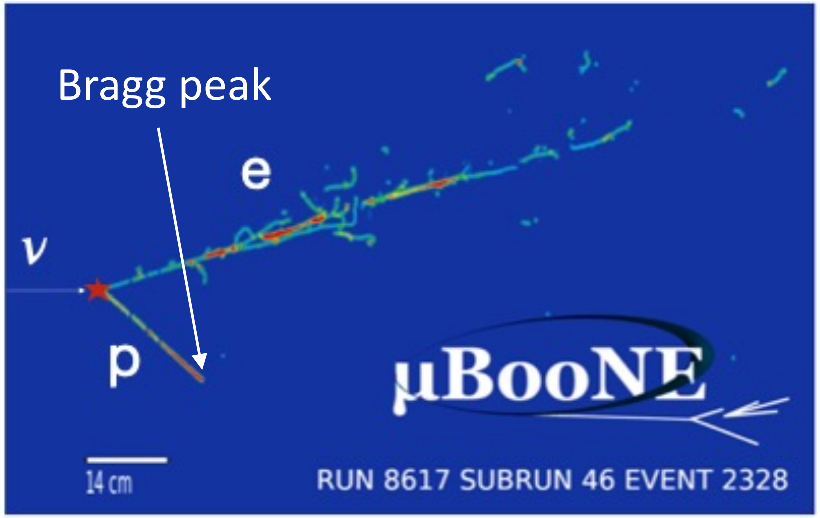
- Wait… what temperature is argon liquid at…?
- How do we get all that argon?

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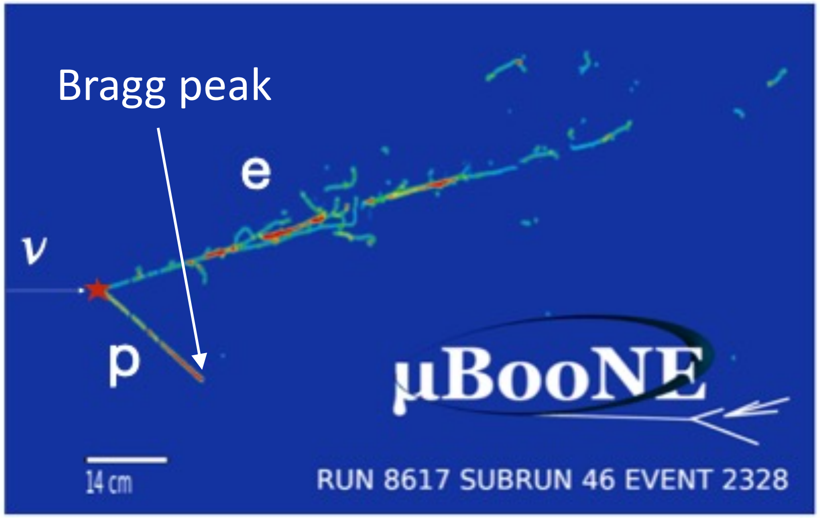


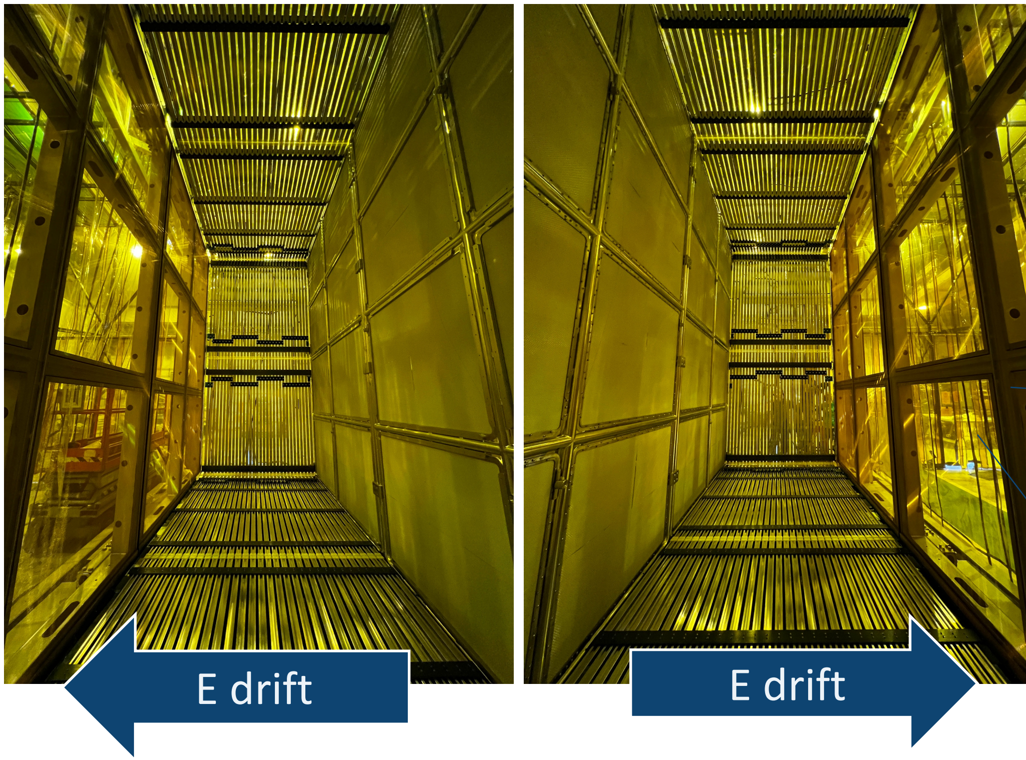

Argon is liquid between 83 and 87K (-302°F / 186°C)
~10K warmer than liquid nitrogen

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

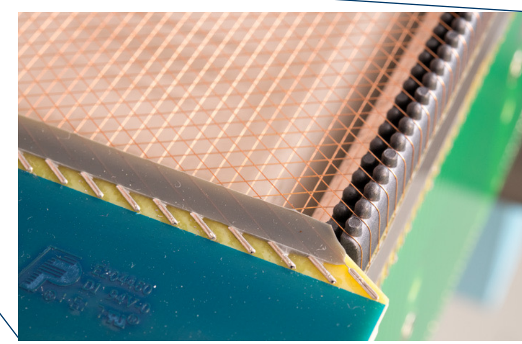
Argon is ~1% of air, and is the cheapest and most abundant noble gas

# 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

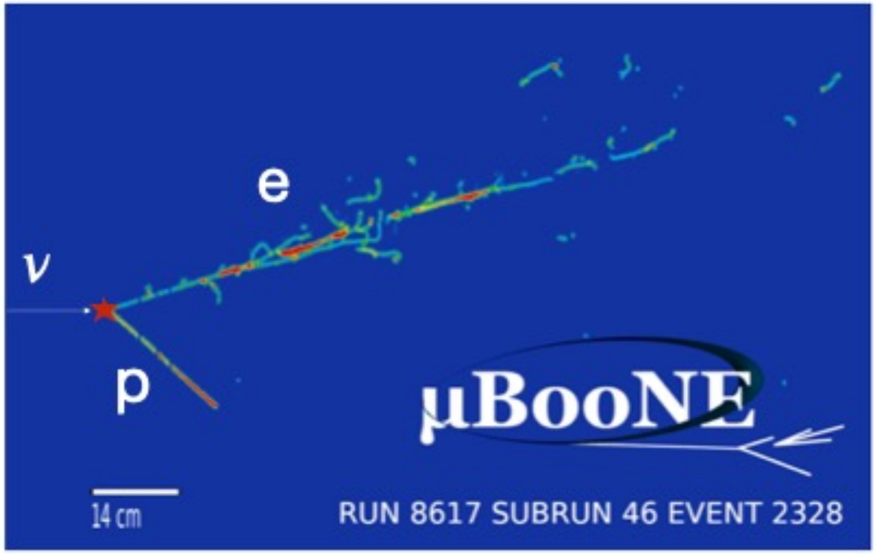


*in my extremely biased opinion

# Quick calculations to motivate automated reco

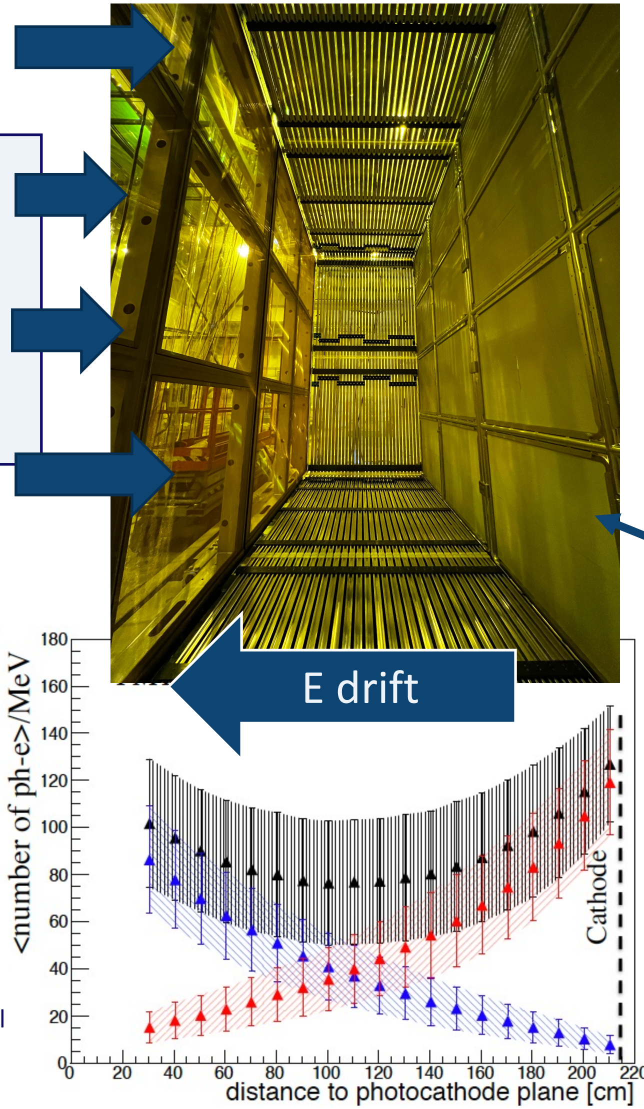
- SBND has 3 planes of wires at 3mm spacing over a 4mx4mx5m detector volume
  - 20,000 readout channels
- Each readout window is ~2ms long
- Neutrino spills from BNB at ~10Hz
- Vast quantities of data in which to search for neutrino interactions

- Automation necessary
  - Reconstruct particle interactions
  - Identify neutrino events
  - Reject background
  - Analyse neutrino data
- LArSoft framework covers this



# LAr TPC example: SBND

Light detectors go here: VUV + vis



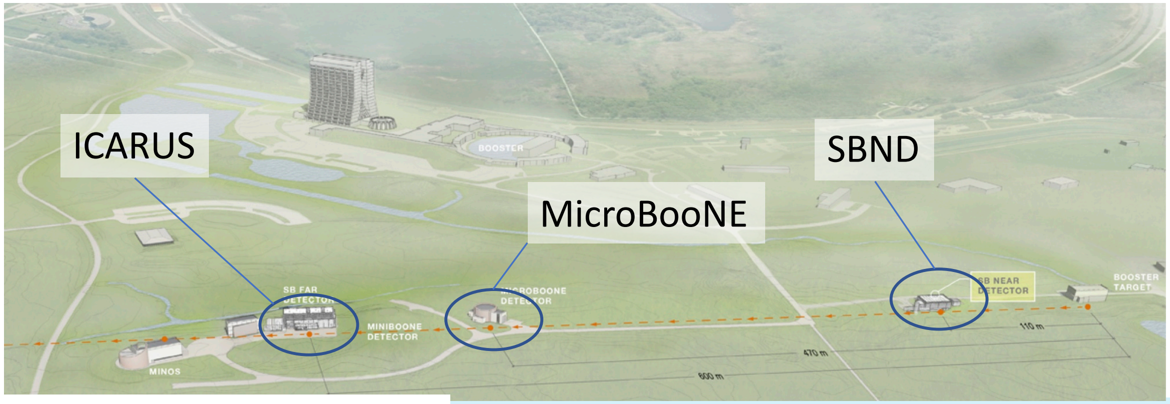

[D. Garcia-Gamez, Journal of Physics: Conf. Series 888 (2017) 012094]

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

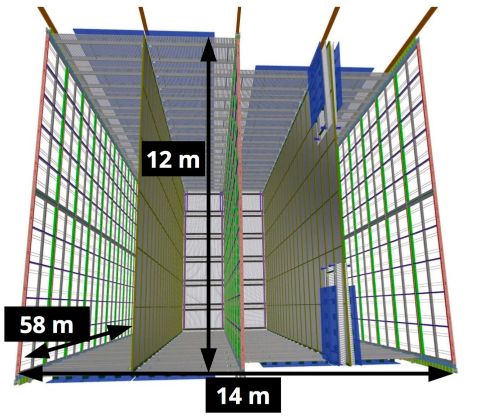
Wavelength shifting reflectors

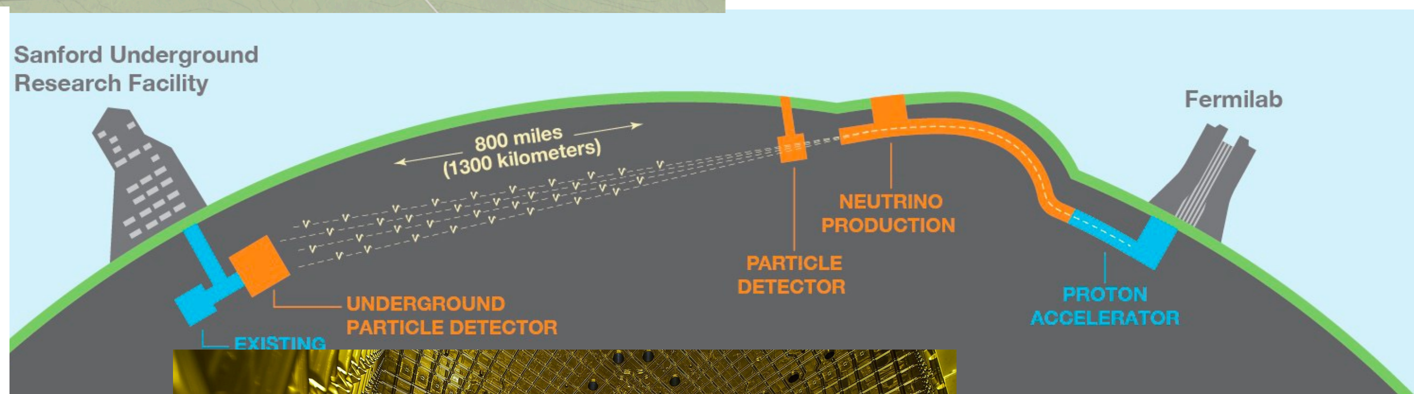
- ❑ SBND light detection system sensitive to VUV light and to visible light (reflected from the cathode)

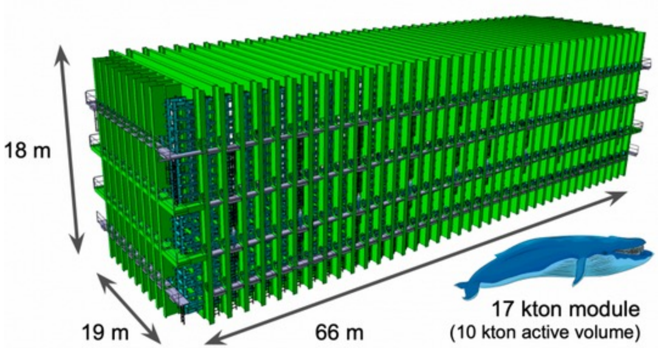
# LAr TPCs and the future

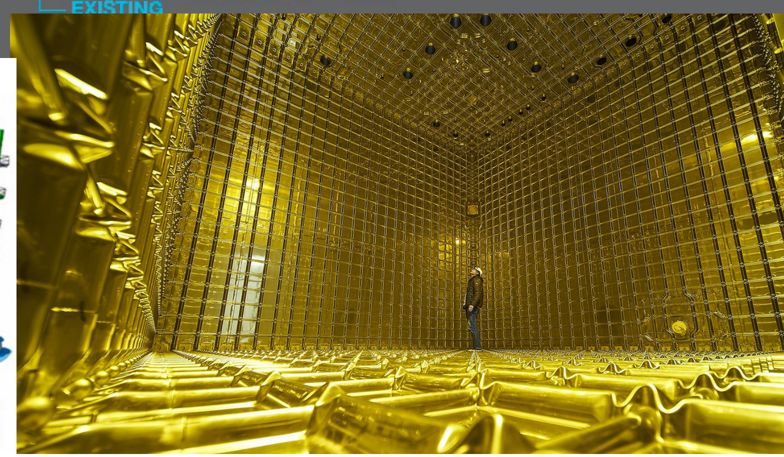



- LArTPCs are a very scalable technology
- Bigger detector, more neutrinos, better measurements



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

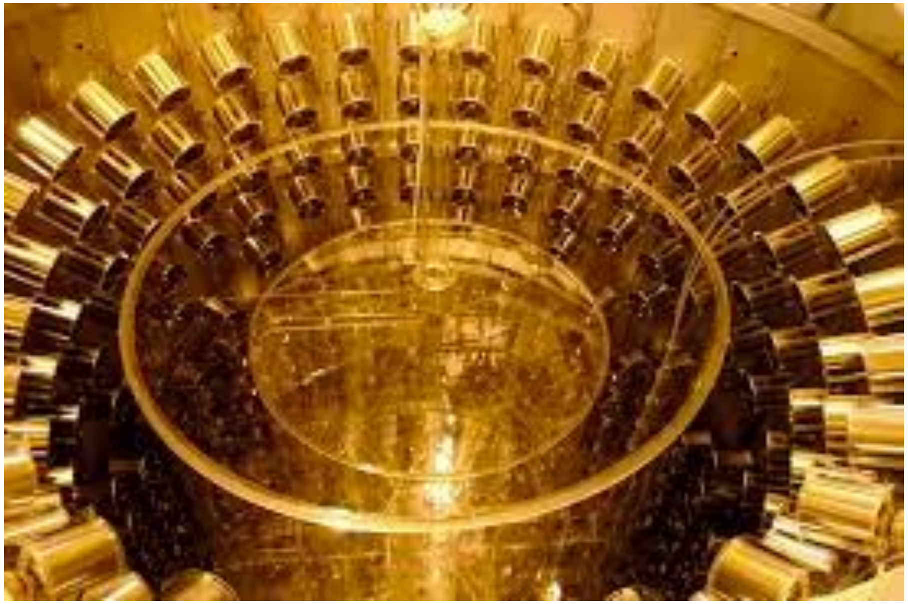
It will see ~10 neutrino interactions per day

# Summary and conclusions

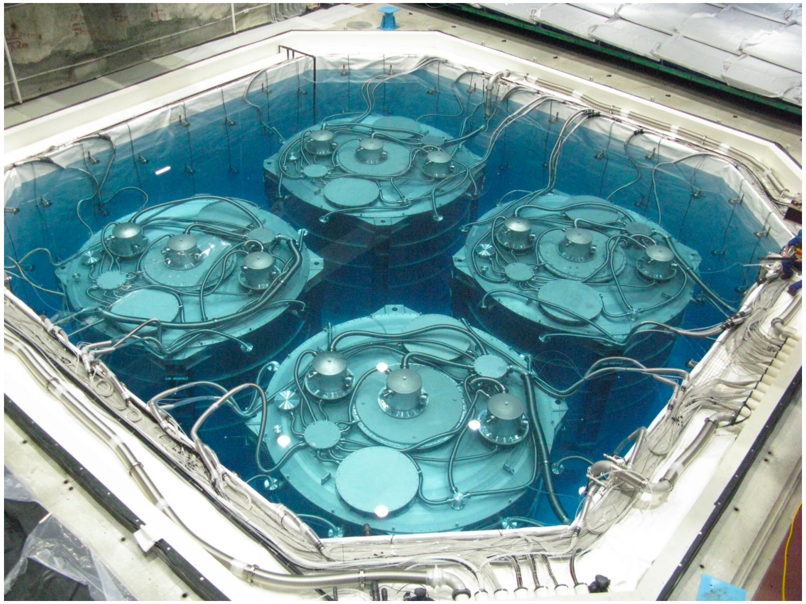
- ❑ Neutrinos are challenging – but very possible – to measure!
  - Although we never "see" the neutrino, we can infer energy and flavour from the daughter particles we observe
- ❑ Particle detectors:
  - Wishlist of general detector parameters + specifics for neutrinos
  - Optimise your detector for what you want to measure!
- ❑ Liquid Argon Time Projection Chambers (LArTPC)
  - Measure both scintillation and ionisation from particle interactions
  - Scintillation light at 128nm requires specially developed technology
  - Fine granularity charge picture across the whole detector
    - E.g. Wire plane or pixel readout
    - Motivates automated reconstruction and analysis

# 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



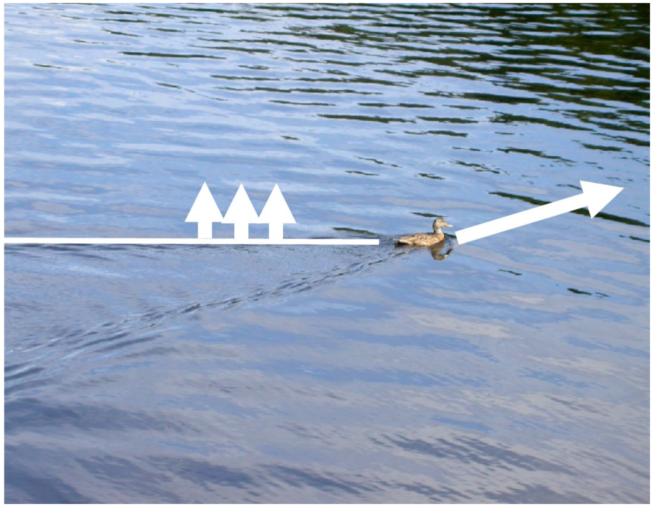
Double Chooz



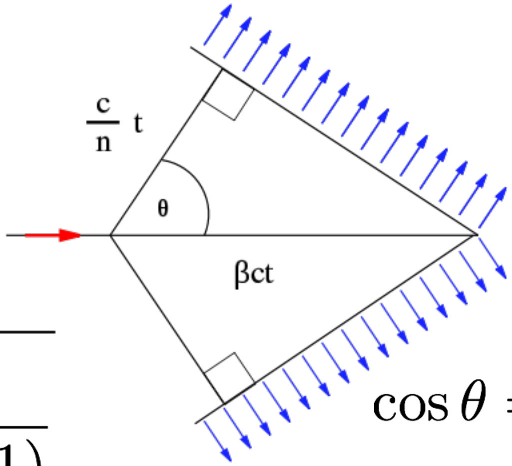
Daya Bay

# 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 $\beta = 1/n$ will emit light as it passes through the detector
  - It thereby loses energy and stops emitting light once it is below the threshold

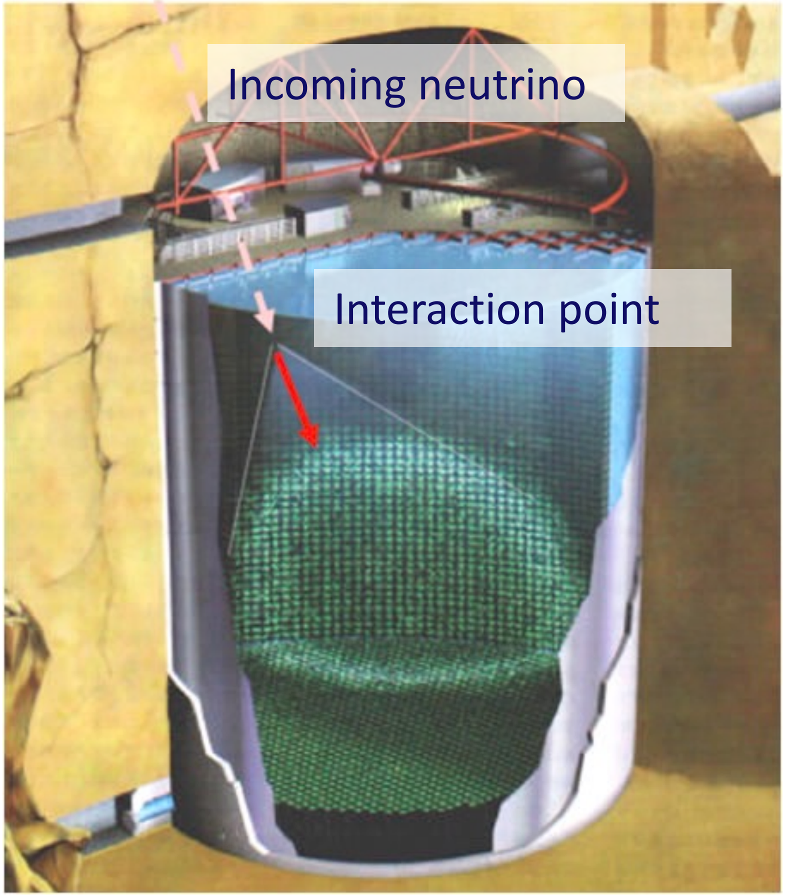



$$p \geq m\sqrt{\frac{1.}{(n^2-1)}}$$

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

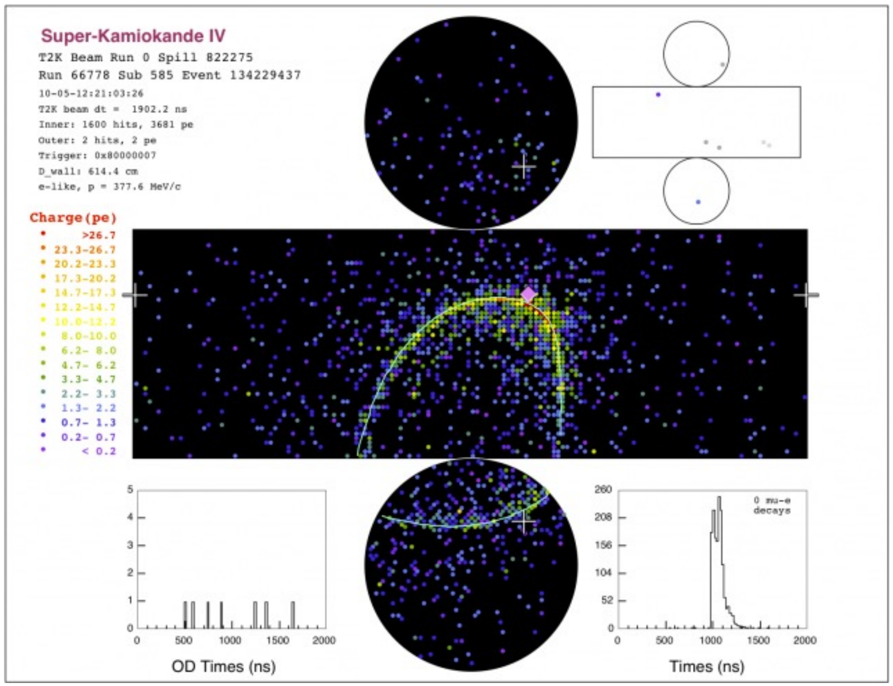
# Čerenkov detectors

- ❑ 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

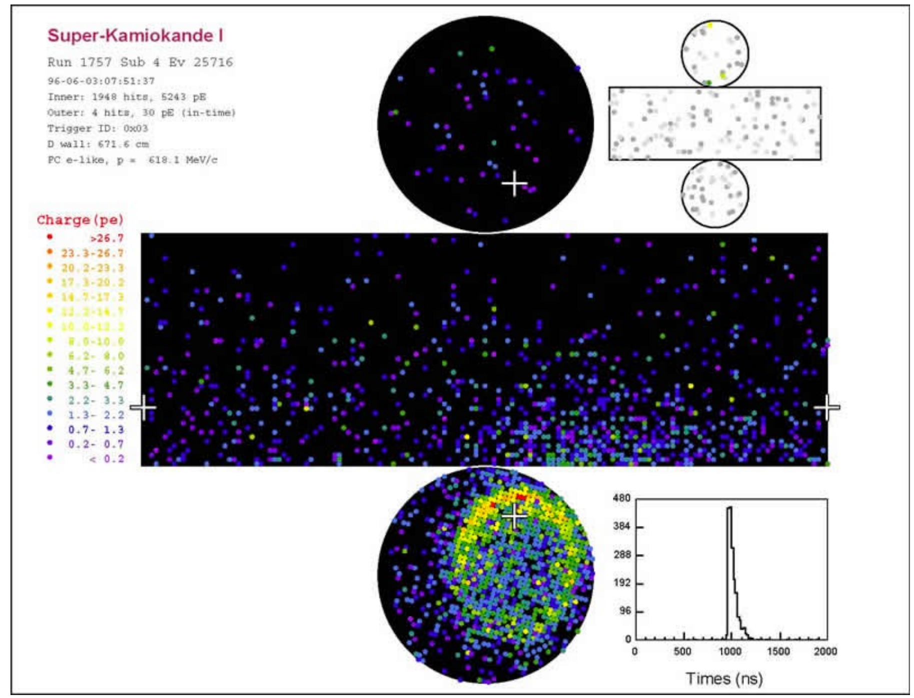



Super Kamiokande

# Super Kamiokande Water Cerenkov events

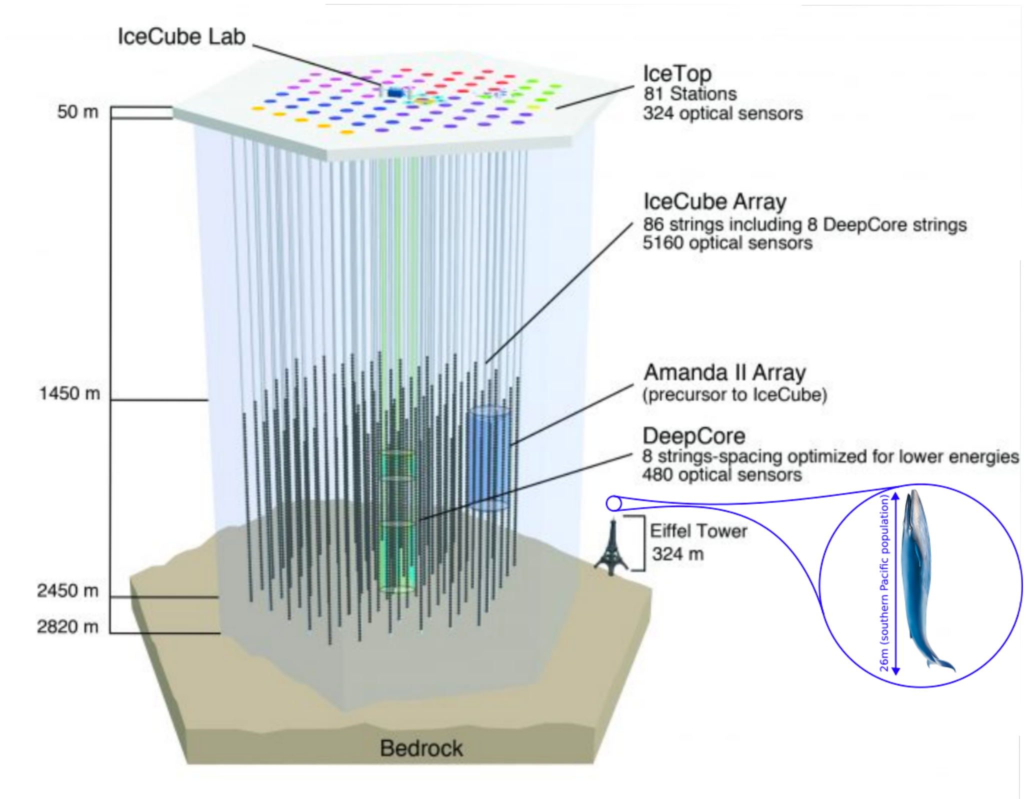



Muon event




Electron event

# IceCube

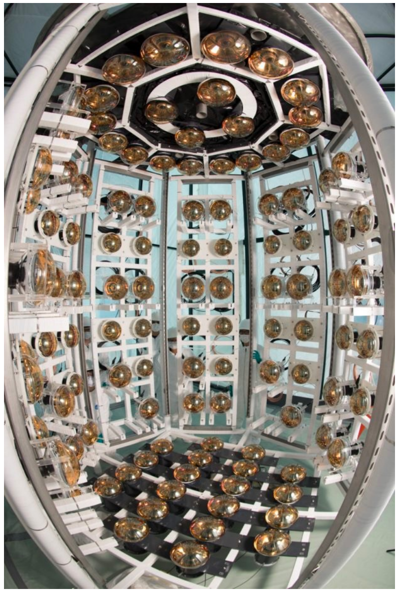



- ❑ IceCube uses Antarctic ice as the active medium for measuring neutrinos
- ❑ The largest particle detector on the planet!
  - $1km^3$ in size
- ❑ Light sensors are submerged in the ice to collect Cherenkov radiation from neutrinos
- ❑ Comparatively sparsely instrumented but has sensitivity to PeV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

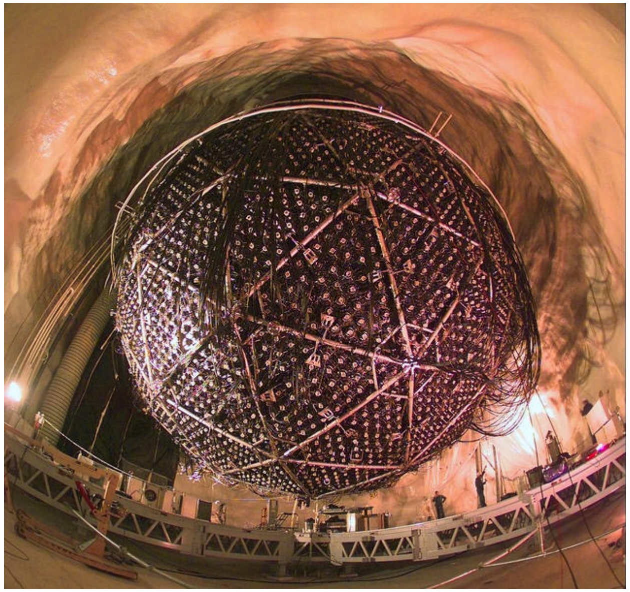
❑ IceCube will be covered in depth in a future lecture

# Cerenkov detectors

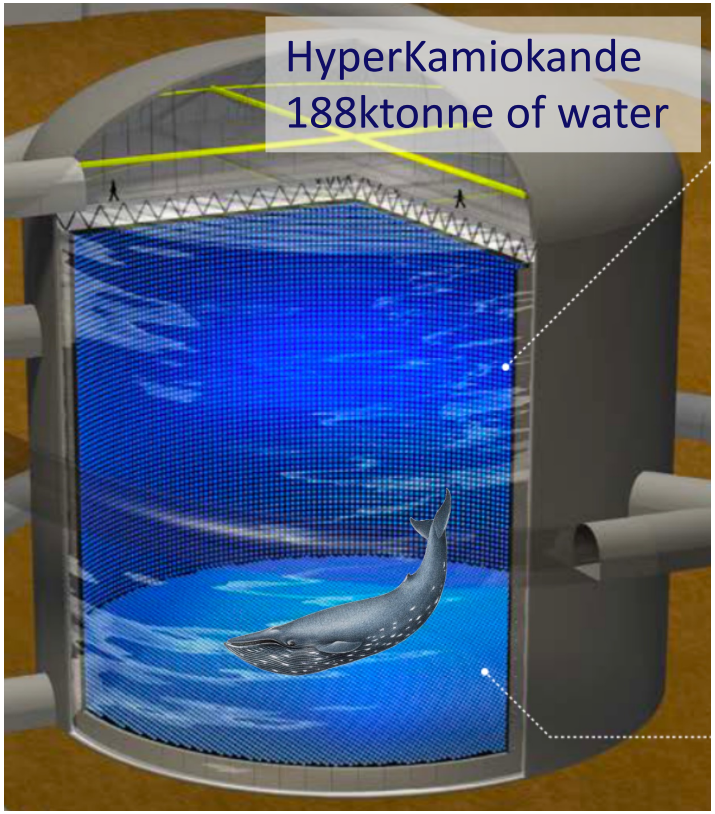
- Cherenkov detectors have already made a huge contribution to neutrino physics
  - SuperKamiokande and SNO are both Nobel prize winning detectors



ANNIE

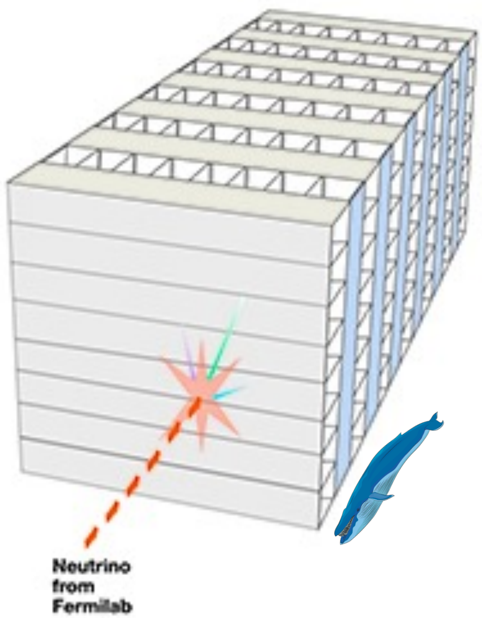


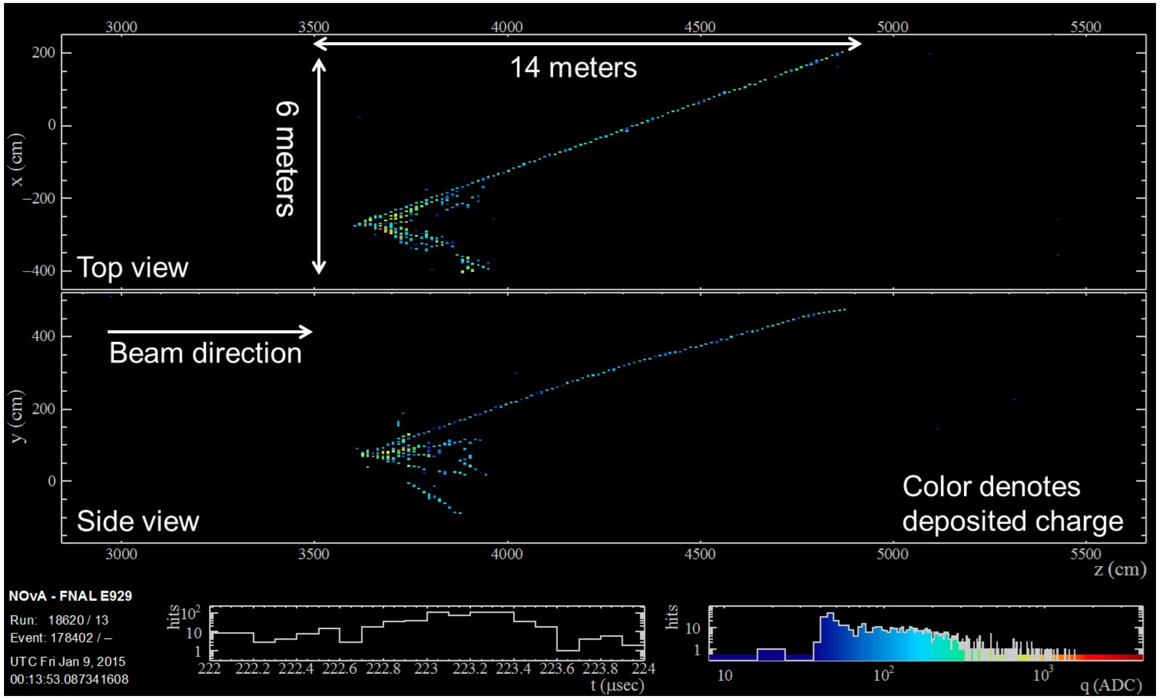
Sudbury Neutrino Observatory (SNO)



# Scintillator detectors – the sequel!

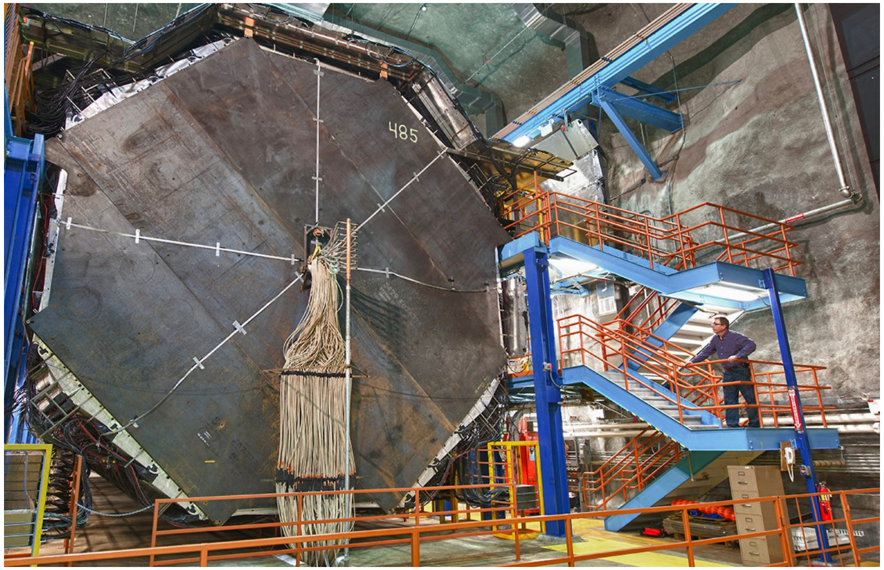
- Scintillator detectors are great! I want to use them for tracking!
  - Certainly possible, thinking outside of the box!
- Nova: a liquid scintillator tracker
  - Optically isolated boxes of liquid scintillator

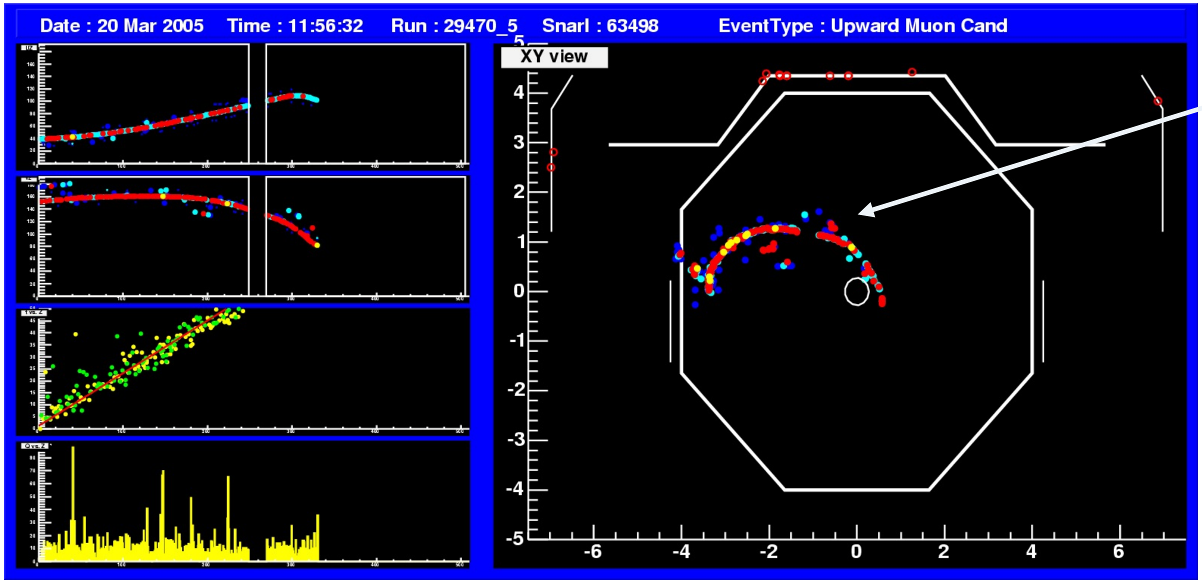


# Scintillator detectors – the sequel!

- 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!



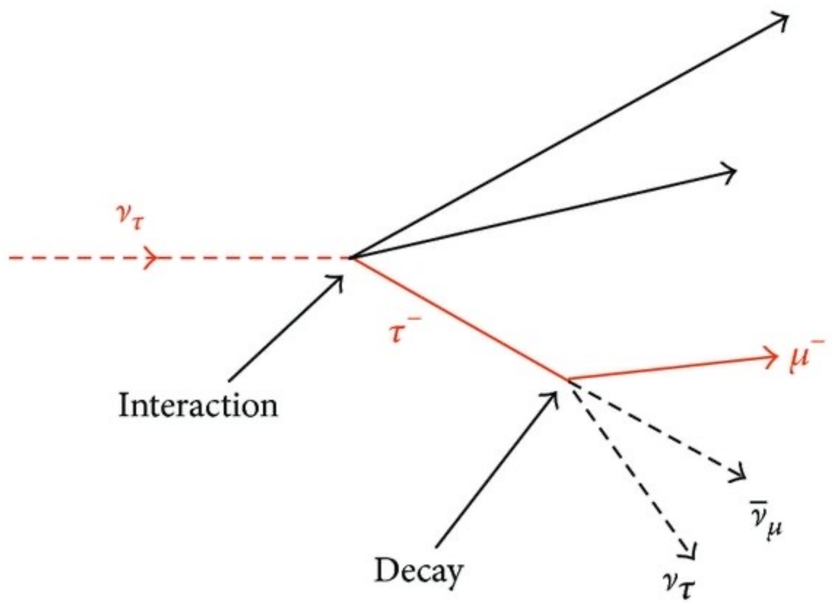




Magnetic field causes muon tracks to bend

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

# A quick word on tau neutrinos

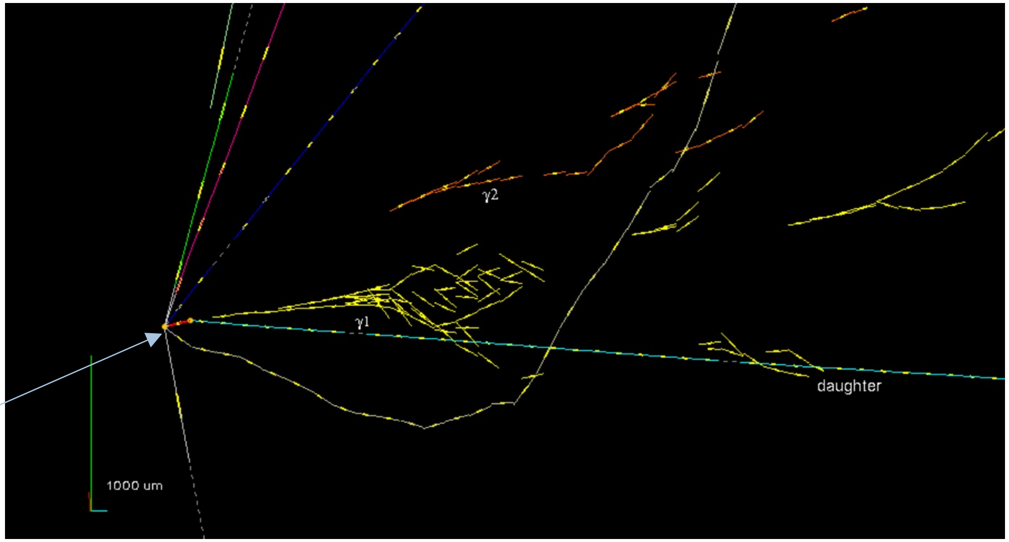
- ❑ Mostly we talk about measuring electron and muon neutrinos
- ❑ Tau neutrinos are **a big challenge** to tag
- ❑ Tau leptons have a lifetime of $2.9\times10^{-13}$ s
  - That doesn't make a very big track in our detector
- ❑ Need specially designed detectors to see this level of precision




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 (2 001) 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

# 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

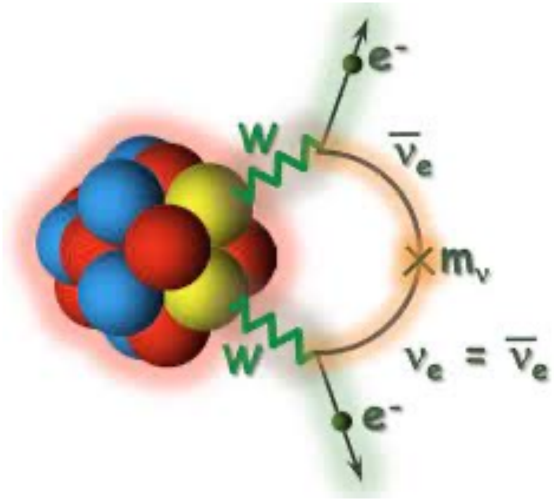
BUT

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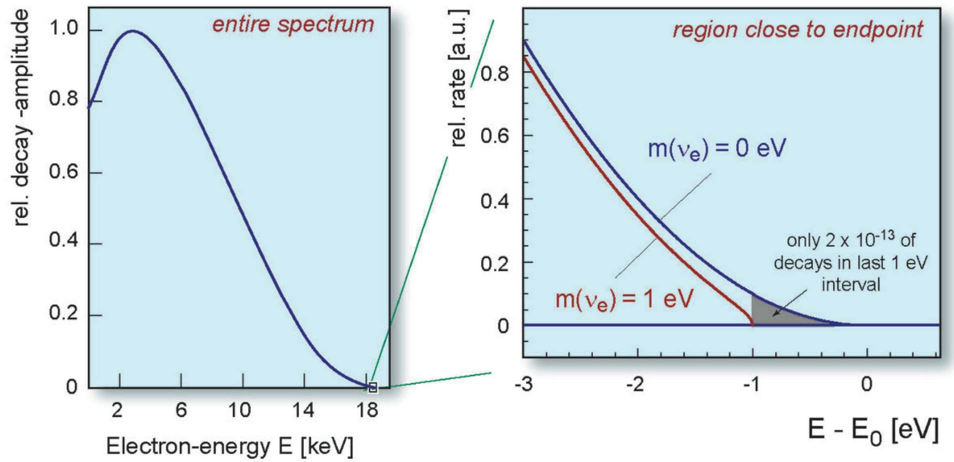
- ❑ CUORE – a scintillating bolometer detector
  - Measures the heat change in the detector due to the deposited particle decay energy
  - 6mK operating temperature

# 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




KATRIN experiment