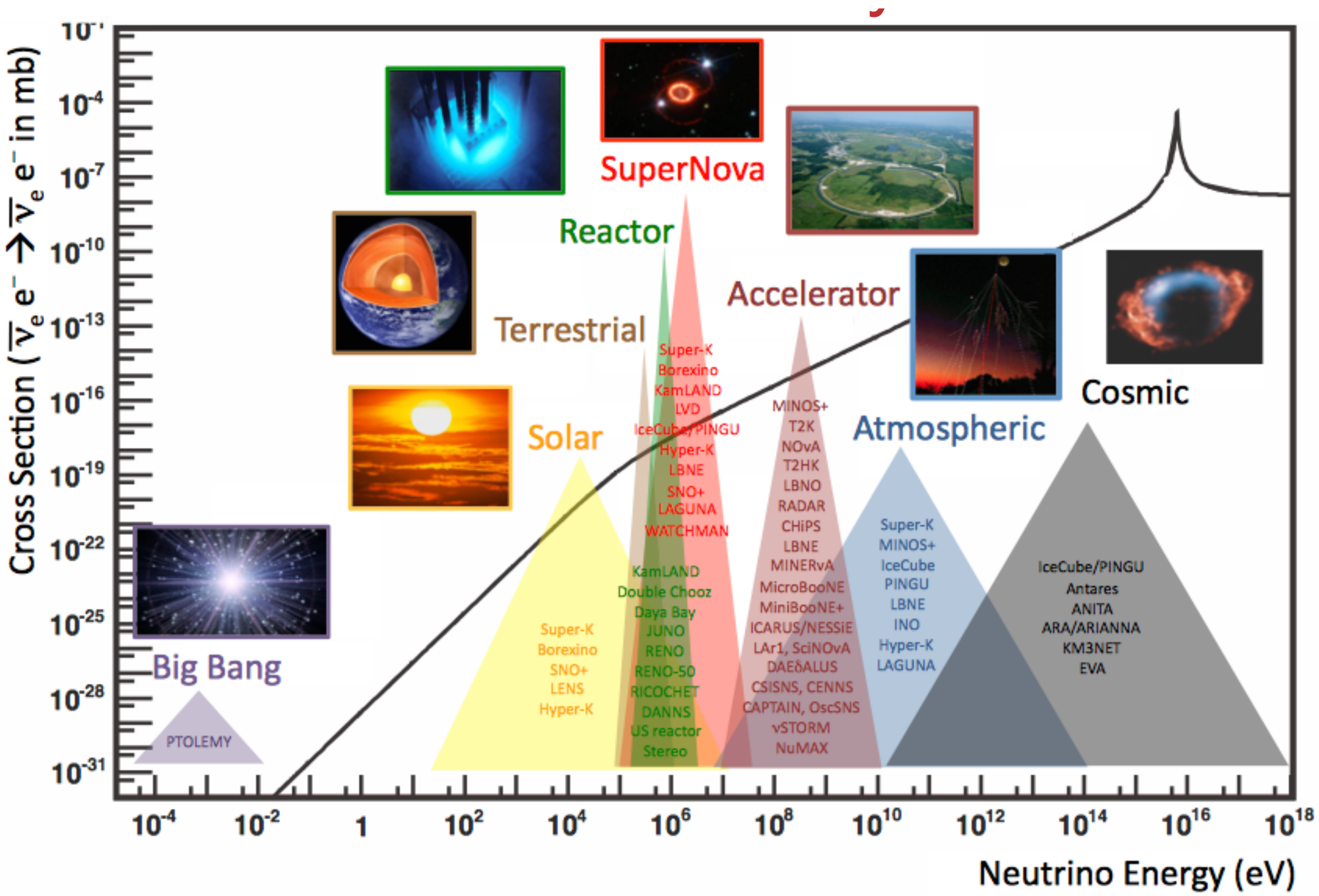
S.BORDONI

ACADEMIC TRAINING LECTURES: EXPERIMENTAL NEUTRINO PHYSICS

Part I

CERN, 15 March 2017

NEUTRINO SOURCES AND ENERGY RANGES



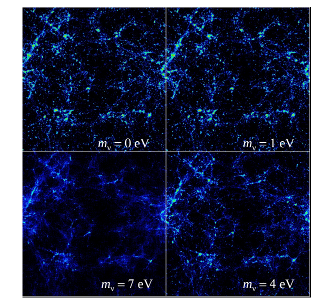
- Neutrinos are everywhere: ~20 orders of magnitude in energy
- Second most abundant particle in the universe

Predicted mass-less by the Standard Model, they are instead massive!

First evidence of physics beyond the Standard Model!

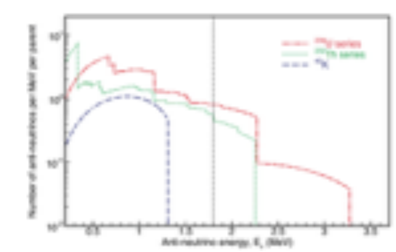
NEUTRINO SOURCES AND ENERGY RANGES

Neutrinos since they are neutral, and weakly interacting, they are **invaluable astronomical and terrestrial messengers**



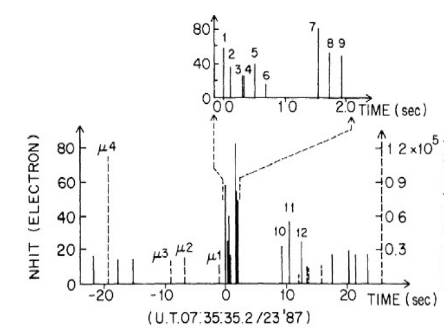
- if detected, **relic neutrinos** can bring information about the very first seconds after the **BigBang** $E_\nu = [10^{-4} - 10^{-2}$ eV]

Nature 03980 (2005)



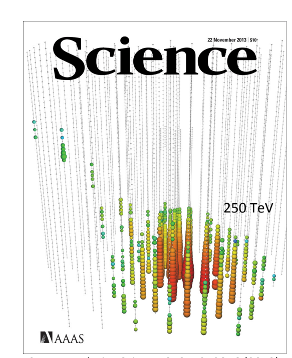
- **direct probe of Earth interior** down to 700m depth help to explain the origin of the heat produced inside the Earth E_ν = [~MeV]

- direct **information** about the **supernovae formation** process E_ν = [0.1 -100 MeV]



PhysRevLett.58.1490

- **cosmogenic neutrinos** produced by the extragalactic cosmic rays with CMB **can help to understand** the **nature and origin of cosmic rays** E_ν = [>100 GeV]



2-year analysis: Science **342**, 1242856 (2013)

NEUTRINO SOURCES AND ENERGY RANGES

- The sun is a pure source of ν_e with E_ν = [100eV - 100MeV]
  - Neutrinos from the nuclear fusion processes in the sun (Standard Solar Model)
  - direct and clean probe of the solar processes

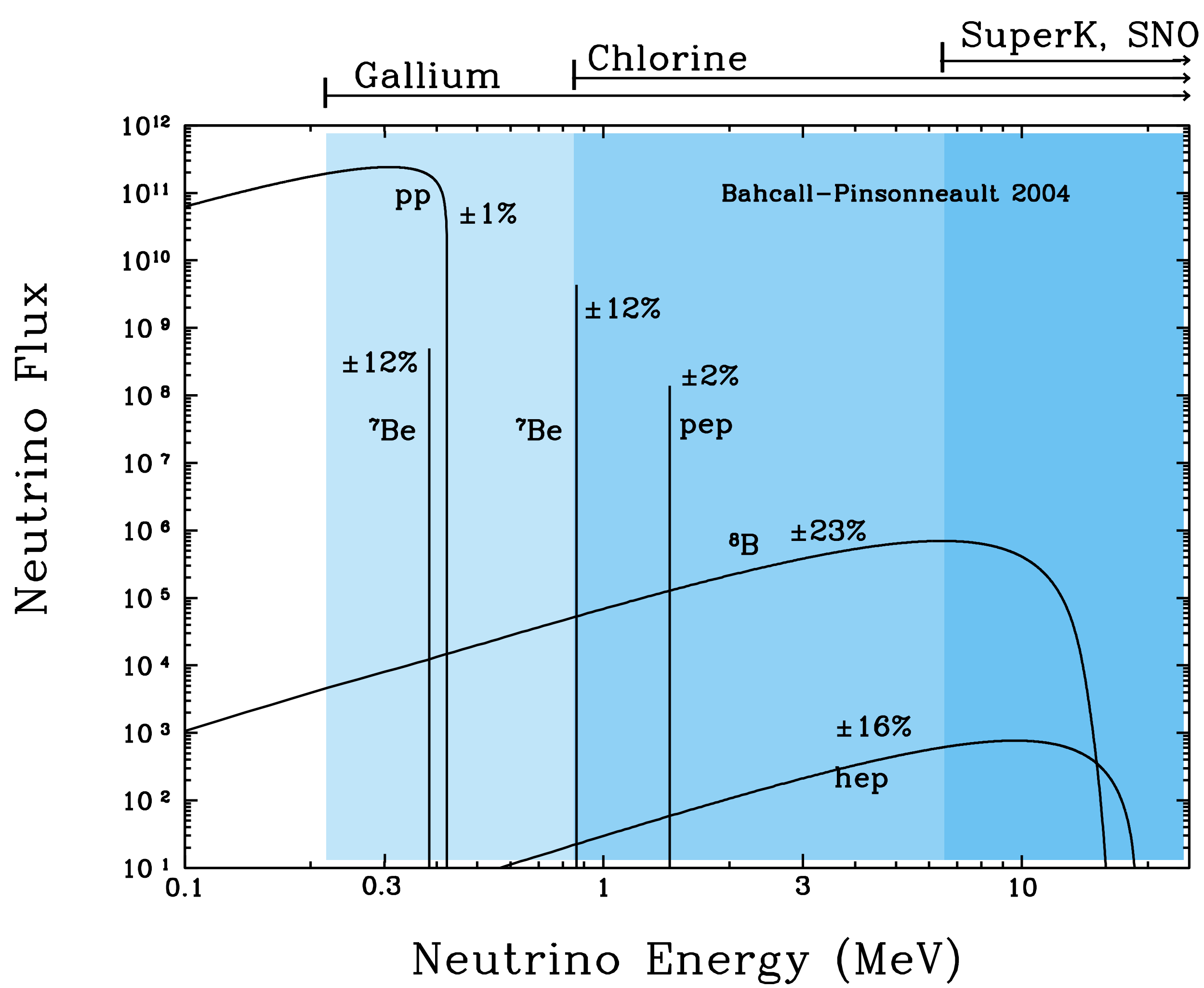
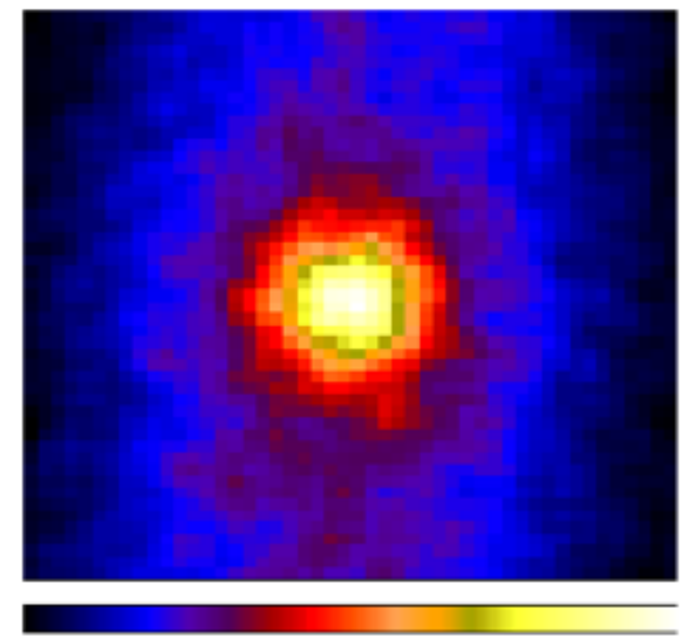
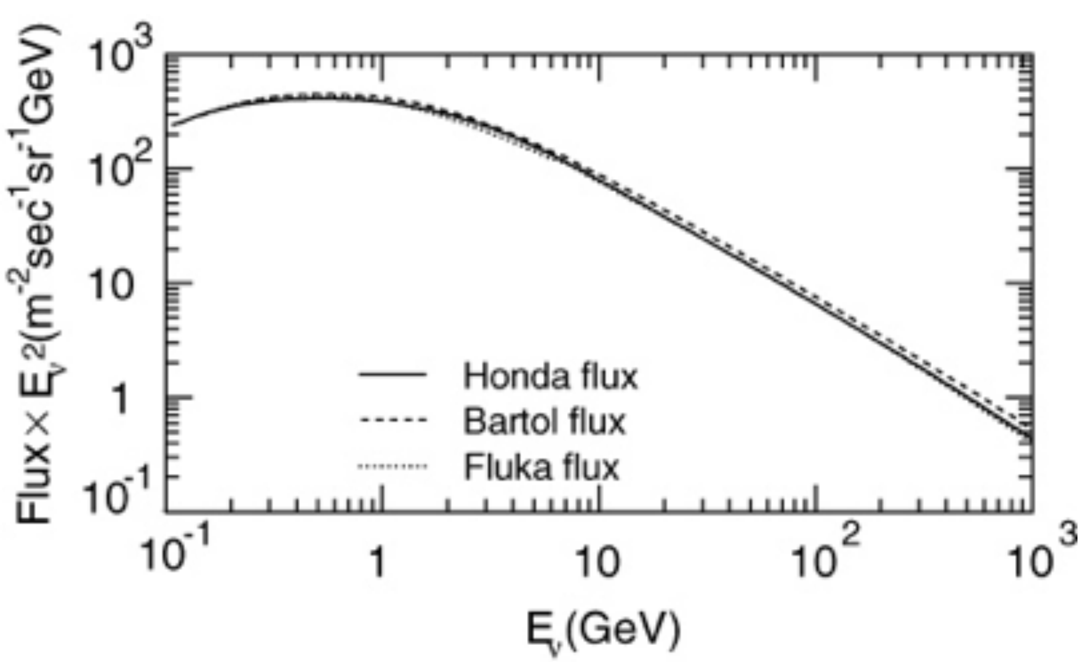


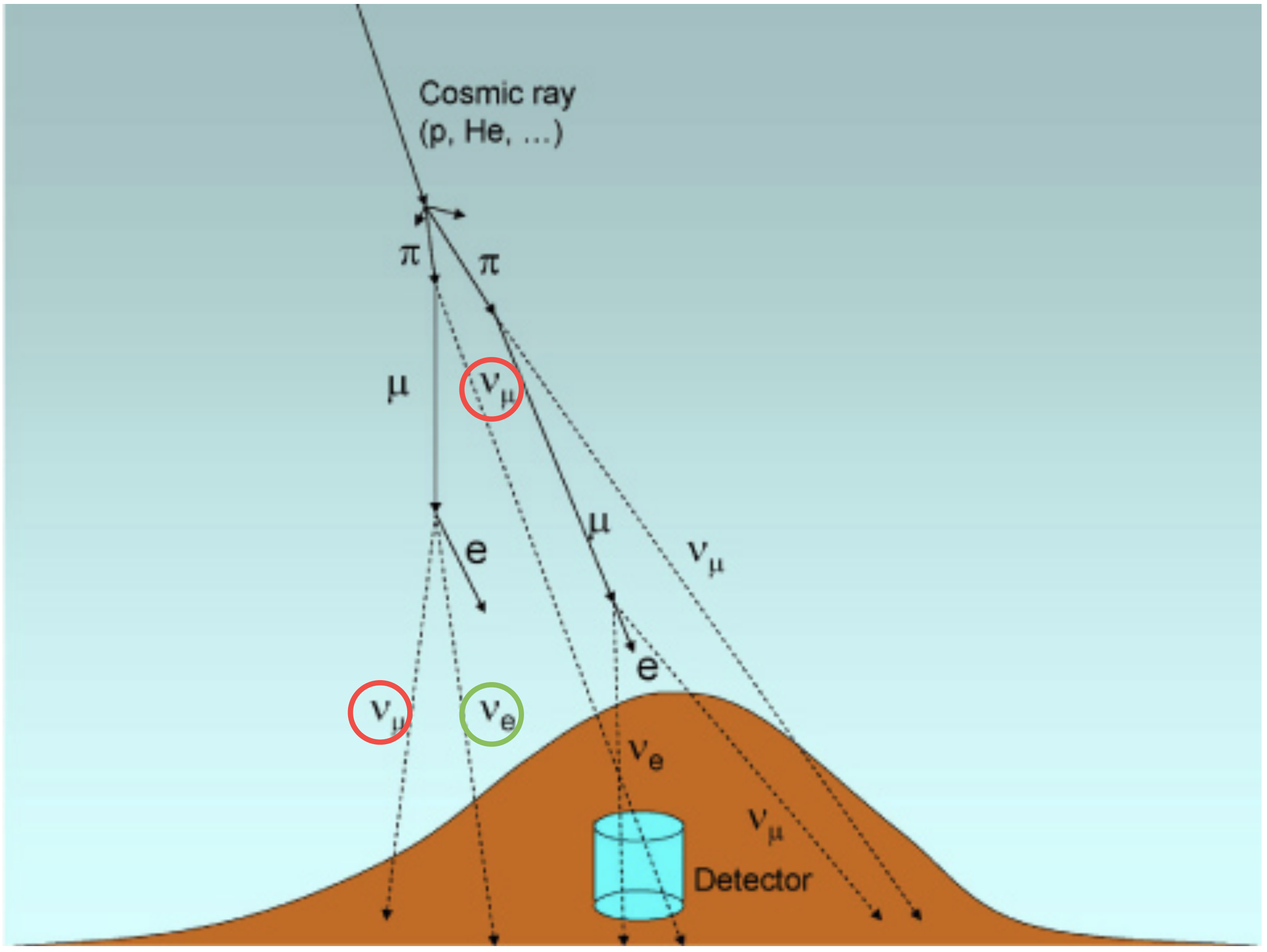
Image of the sun with neutrinos at Super-Kamiokande



NEUTRINO SOURCES AND ENERGY RANGES

- Atmospheric neutrinos come from the interaction of the cosmic rays with the Earth's atmosphere $E_\nu = [0.1 - 10^3 \text{ GeV}]$
  - subsequent decay of pions and muons
  - ratio of $\nu_\mu : \nu_e$ well known. *Expected* to be 2:1



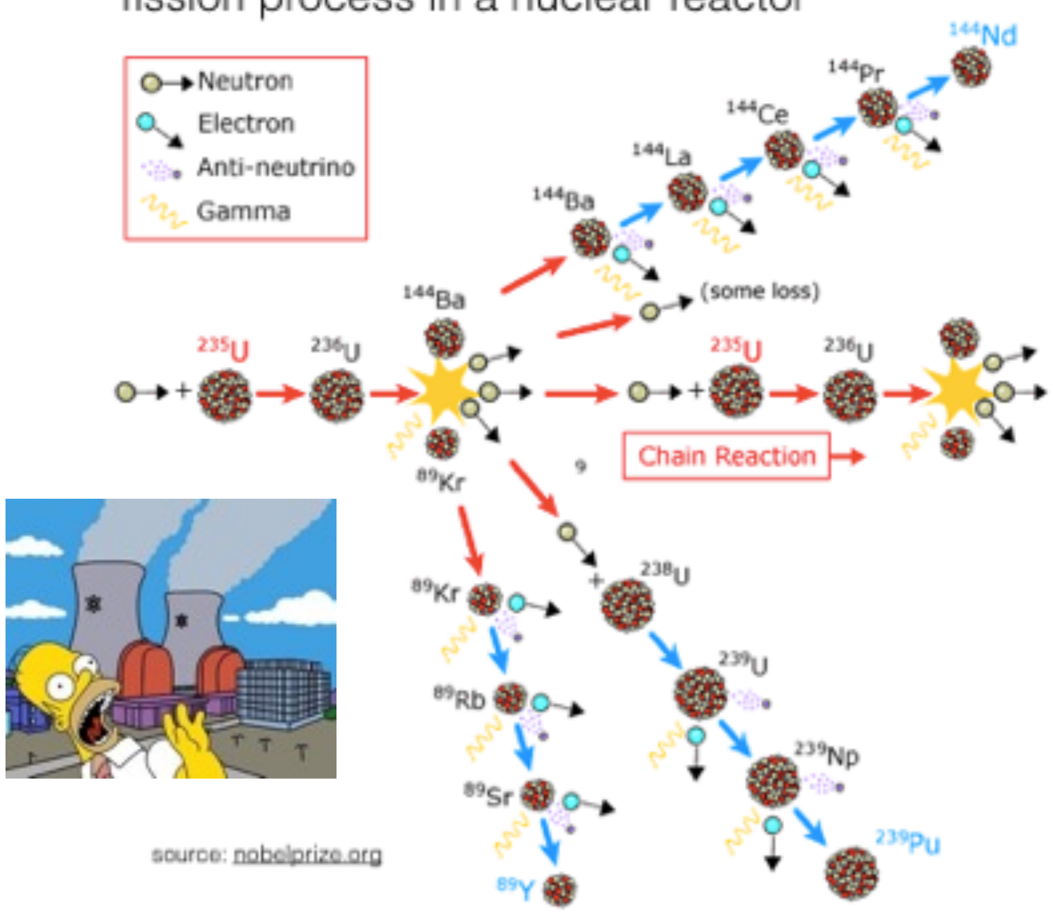


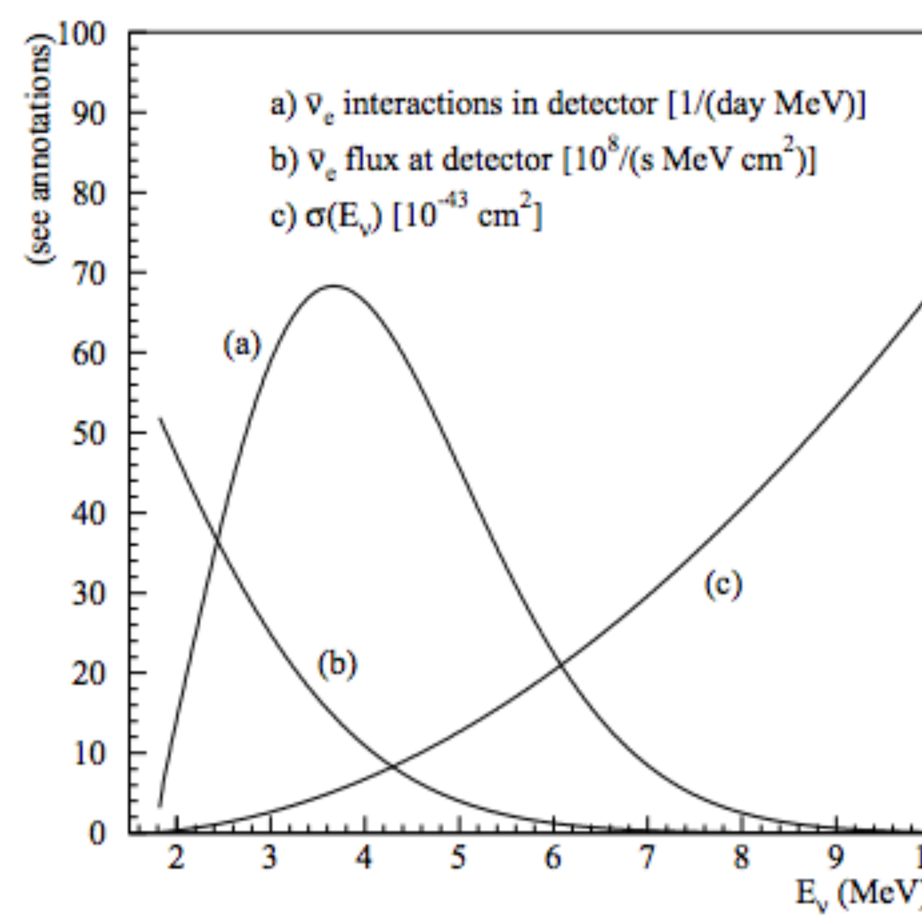
ARTIFICIAL SOURCES: REACTOR NEUTRINOS

Intense flux of anti-ν , produced “for free” by nuclear power plants. E_ν = [~MeV]

- used for the first observation of neutrinos (Reines & Cowen)
- anti-neutrinos from beta-decay of fission products. flux estimated by the fraction of isotopes that are fissioning at a given time and the reactor power
- average flux 10^{20} anti-ν_e / second

fission process in a nuclear reactor





Bemporad, Gratta, Vogle. RMP. 2002

ARTIFICIAL SOURCES: ACCELERATOR NEUTRINOS

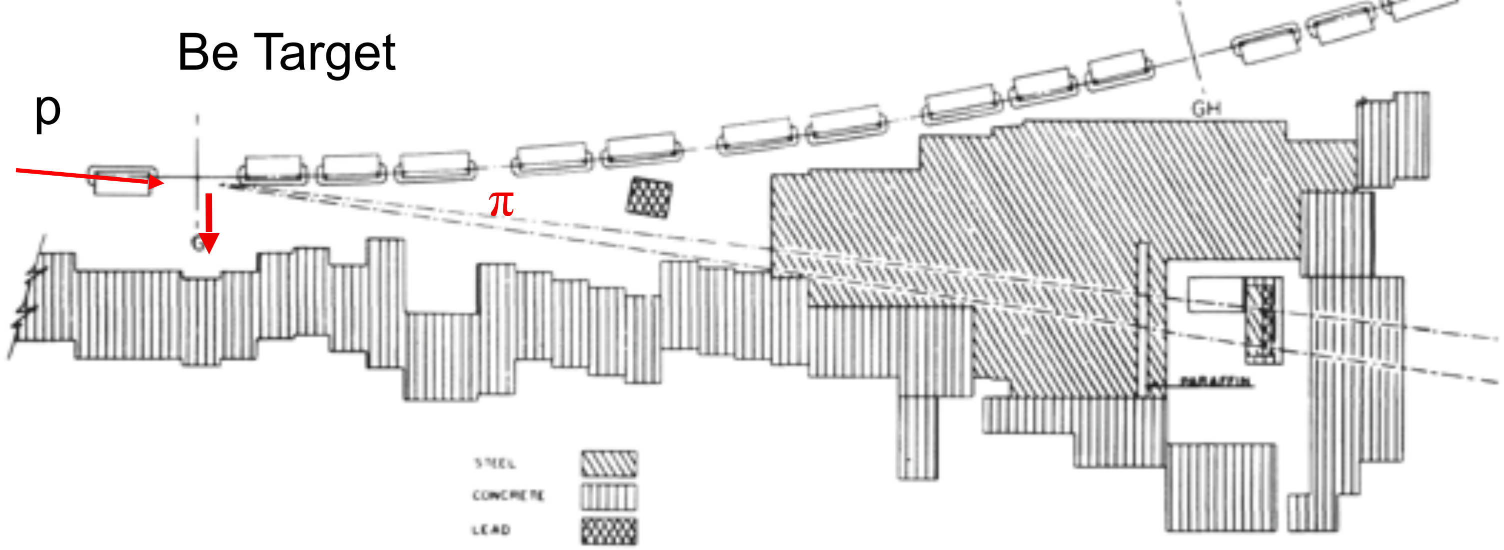
- Idea ~1960 from Pontecorvo and Schwartz. Basic principle still the same in modern experiment, better technique (focusing magnets)

1962 : first accelerator

1 ν / 1000Kg / day

$E_{\nu\mu} \sim$ 1GeV

Discovery of muon neutrino!



Phys.Rev.Lett. 9, 36 (1962)

Lederman, Schwartz, Steinberger

ARTIFICIAL SOURCES: ACCELERATOR NEUTRINOS

How to make a neutrino beam?

- Idea ~1960 from Pontecorvo and Schwartz. Basic principle still the same in modern experiment, better technique (focusing magnets)
- Neutrino beams from the decay of pions and kaons
- Possibility to produce both neutrino and anti-neutrino beams

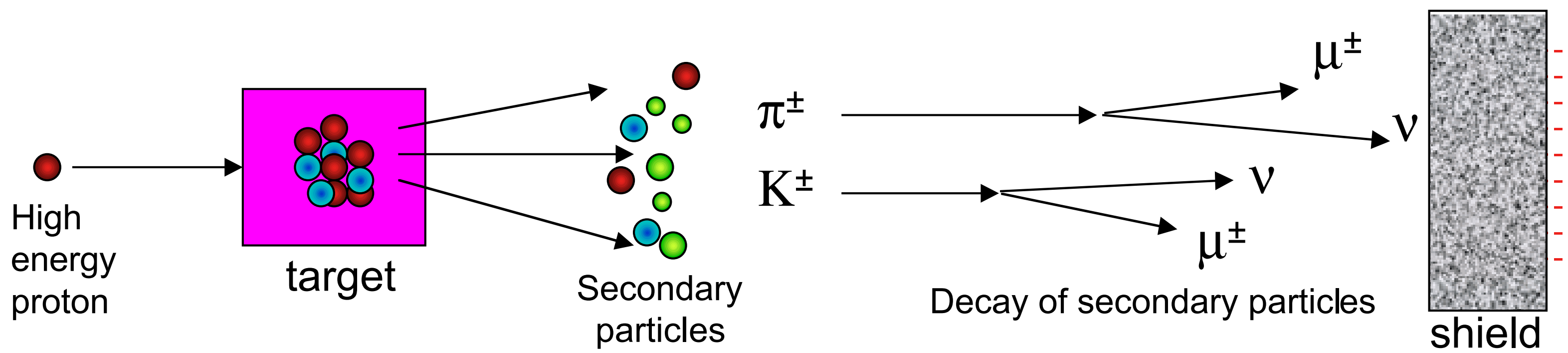
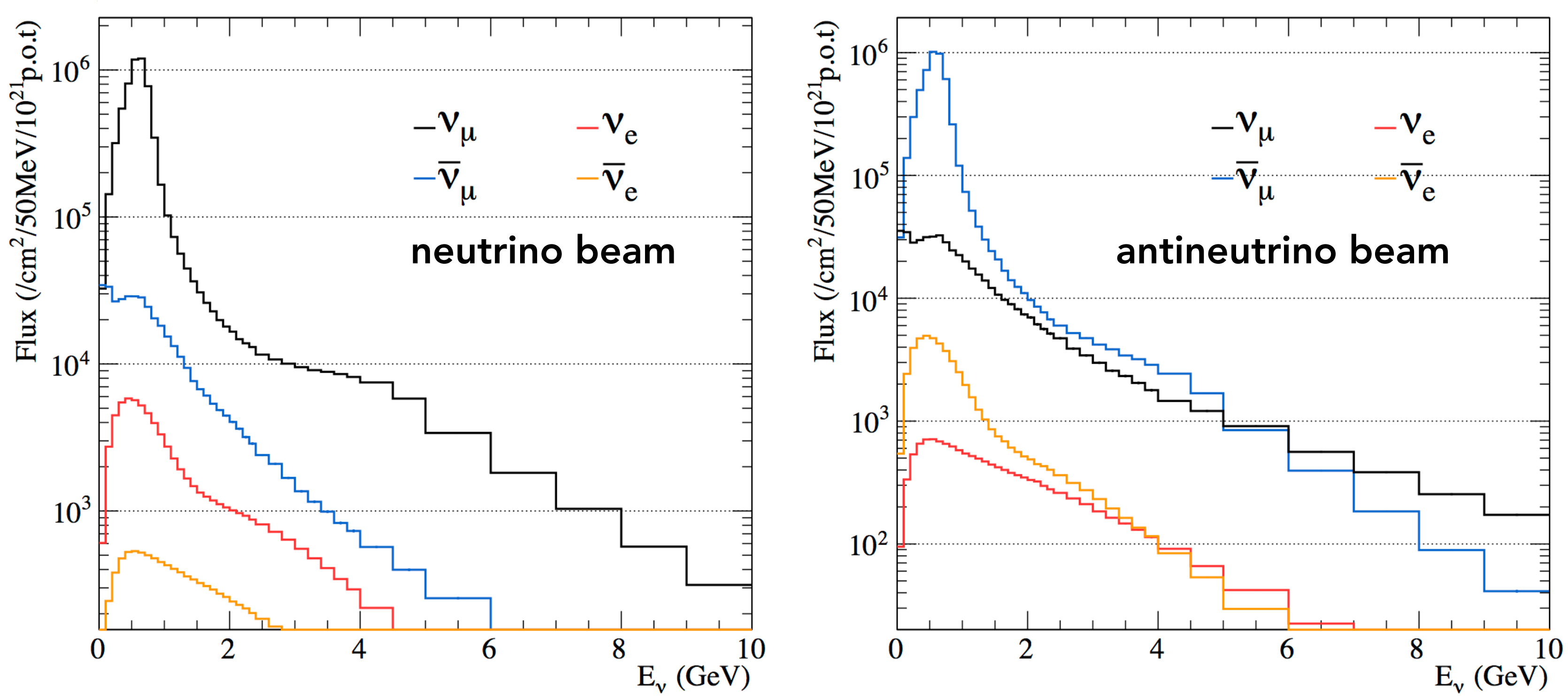


Image courtesy of A.Rubbia

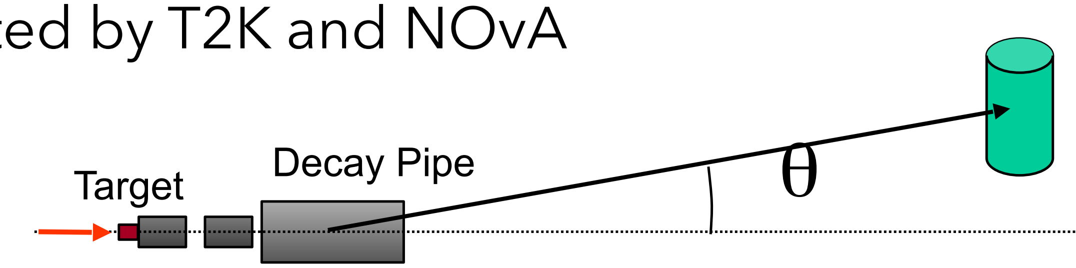


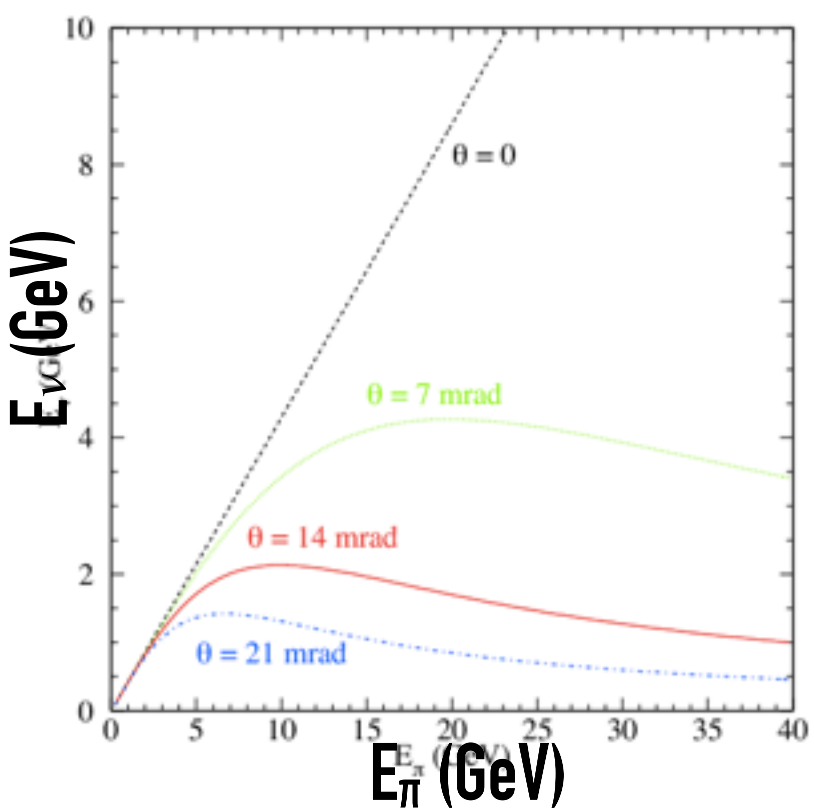
T2K flux at Super-Kamiokande

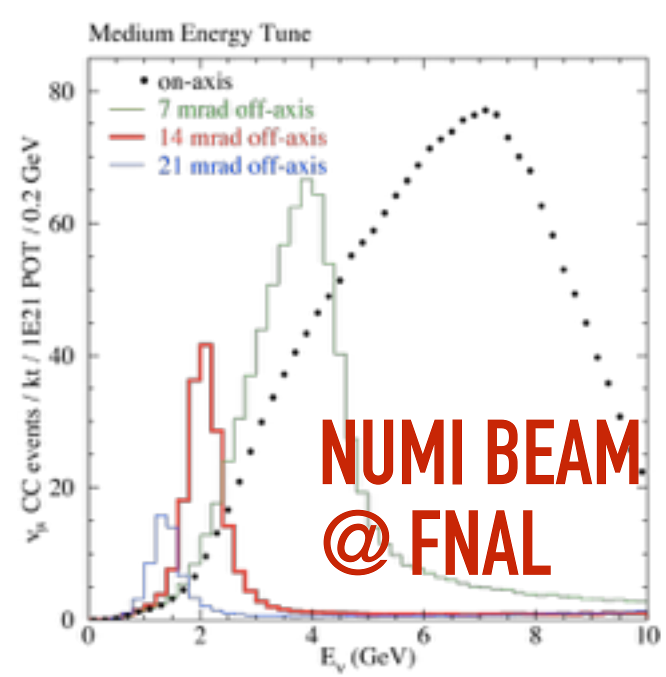
PRL 116, 181801 (2016)

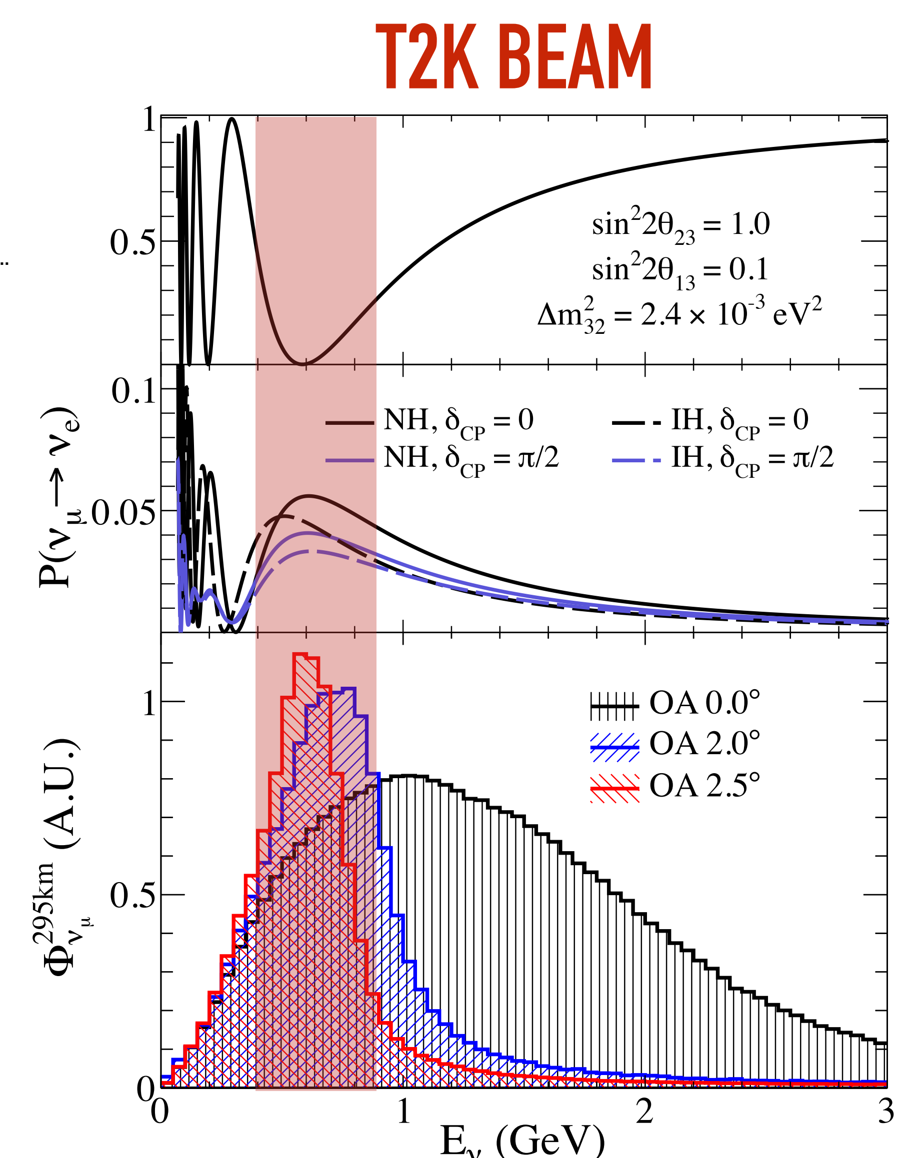
ARTIFICIAL SOURCES: ACCELERATOR NEUTRINOS

- The off-axis technique foresee detectors not aligned with the center of the neutrino flux but shifted of some degrees
  - Narrow-band and "low" energy beams: dependency from parent hadron energy removed
  - Technique adopted by T2K and NOvA









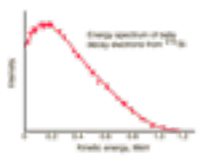
OVERVIEW OF THE LECTURES

- Lecture 1 :
  - brief overview of neutrino discoveries
  - neutrino state of the art: what we know and what we don't
  - neutrino interactions
  - neutrino main detections techniques

- Lecture 2 : neutrino oscillations
  - experimental measurements of the 3 neutrino mixing
  - status of sterile neutrinos searches

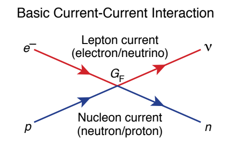
EARLY HISTORY OF NEUTRINOS

1914: Chadwick observe a continuum spectrum of the ß decay

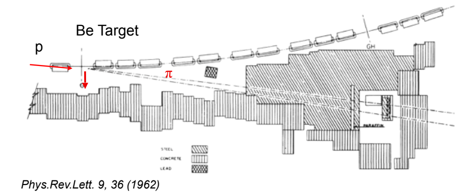


1930: Pauli postulate a new particle ("desperate remedy")

1934: Fermi named the neutrino and postulate the weak interaction



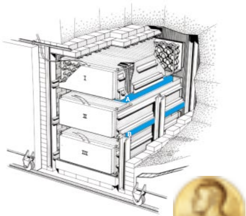
1962: Steinberg, Lederman, Schwartz detect the first muon neutrino 1988



1968: R.Davis detection of solar neutrinos and deficit observed 2002

1987: burst of neutrinos from SN 1987A beginning on neutrino astronomy

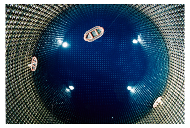
2014: hints of $\delta CP \neq 0$ by T2K, NOvA,...



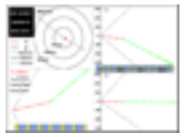
1956: Reines and Cowan experiment: first detection of neutrinos 1995

1957: Pontecorvo predicted neutrino oscillations

1958: Goldhaber et al. measure the lefthand helicity of neutrinos



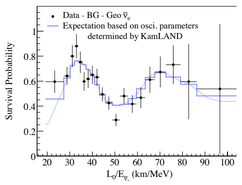
1998: SK reported an evidence of oscillation in atmospheric neutrinos 2015



2000: discovery of tau neutrino by the DONUT experiment

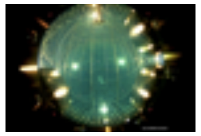
2001: SNO reported evidence of solar neutrino oscillations (observation of NC) 2015

2003: kamLAND detect disappearance of reactor anti-ν_e

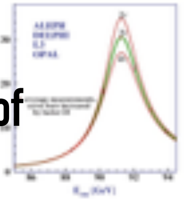


2012: DayaBay, Reno, Double Chooz measure θ_{13}

2007: BOREXINO detect ^{7}Be solar neutrinos



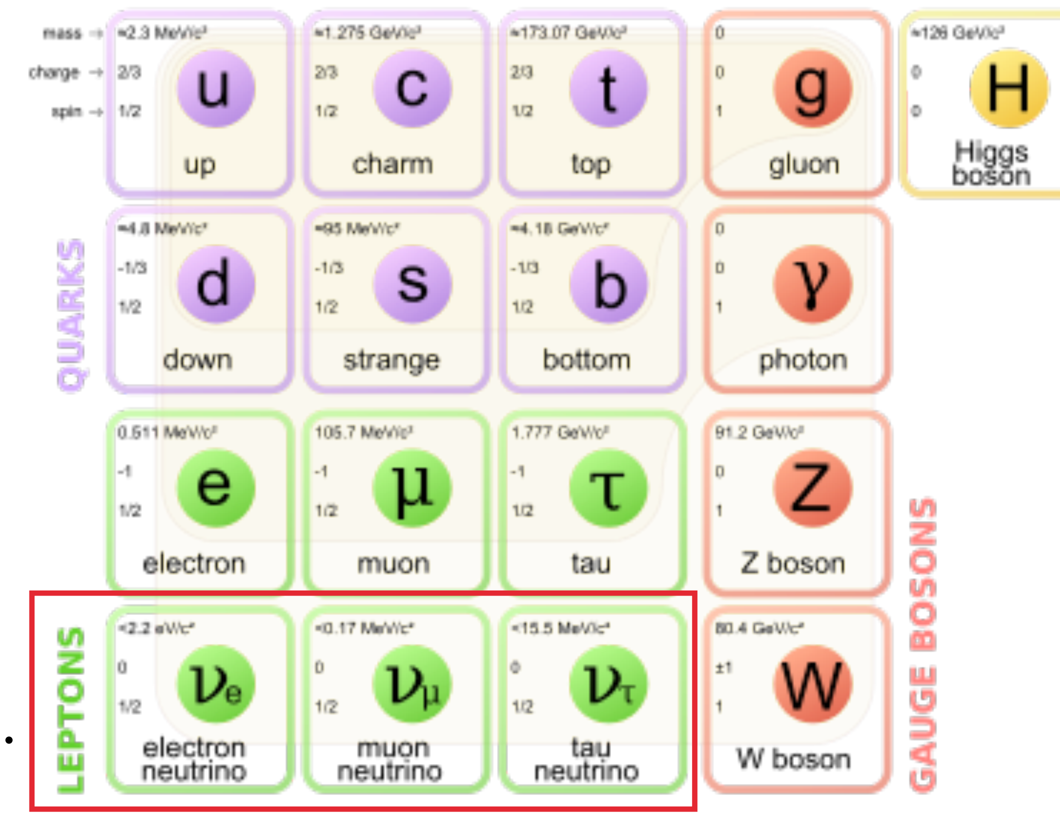
2006: LEP measure the invisible width of the Z boson



NEUTRINOS: THE KNOWNS AND THE UNKNOWNS

Neutrinos usually represented in the SM fundamental particle table. But in this representation many peculiarities are hidden

- <u>Leptons</u> but <u>neutral</u> : feel only weak (and gravitational) force
- Predicted massless but they do **oscillate**: many consequences (see following slide)
- As all other particle they should have an <u>anti-particle</u>: what if they were the <u>same particle?</u>
- 3 neutrinos observed in agreement with SM families but other <u>*"sterile"* neutrino</u> might exist..



NEUTRINOS: THE KNOWNS AND THE UNKNOWNS

- Neutrino oscillations can occur only if neutrinos have masses

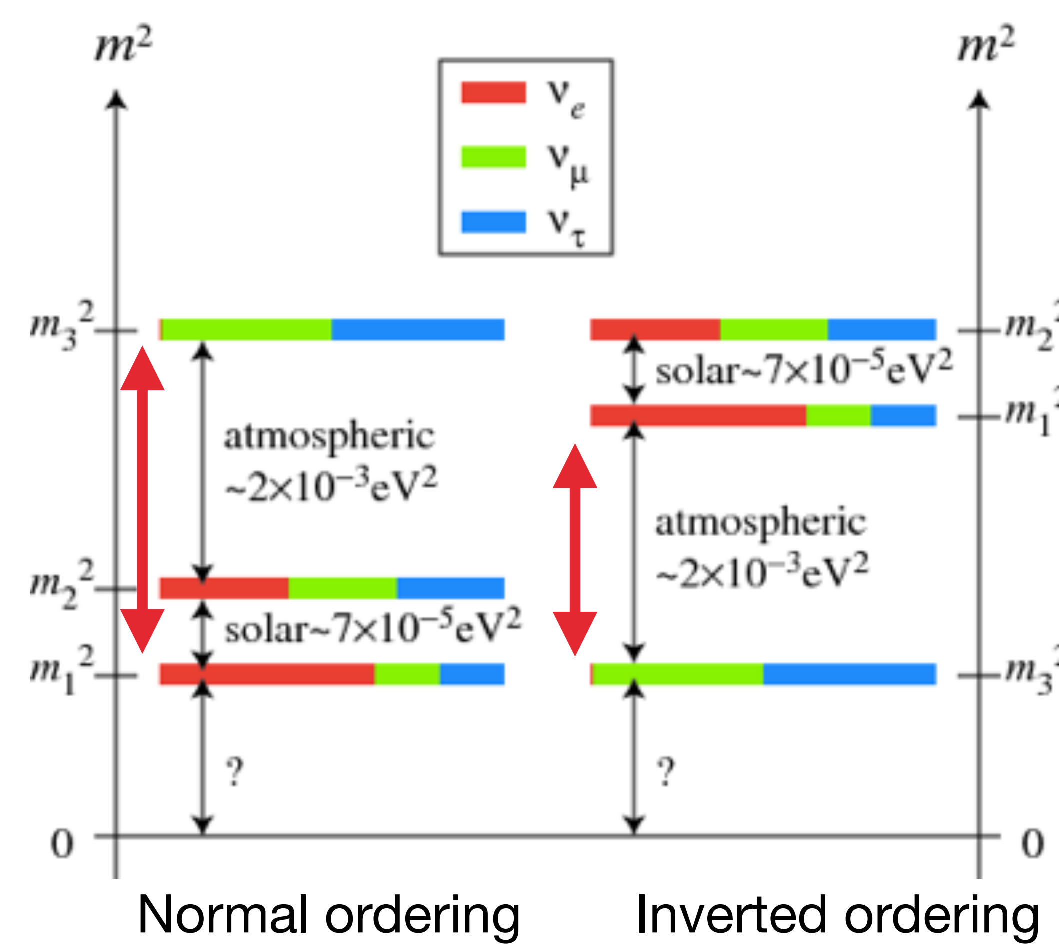
2 neutrino approximation:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta) \cdot \sin^2\left(\frac{1.267\,\Delta m^2[eV^2]\,\mathrm{L}_\nu[\mathrm{km}]}{\mathrm{E}[GeV]}\right)$$

first hint of BSM physics

- Oscillations give access to the **mass-squared differences: amplitude of the mass splitting, NOT the sign.**
  - 3 neutrinos: 2 independent mass-squared differences. Sign of Δm^2_{12} studied with solar neutrinos
  - two possibilities for Δm^2_{13}: which is the order ($\Delta m^2_{13}>0$ or $\Delta m^2_{31}<0$) ?

The Mass Hierarchy (MH) problem



NEUTRINOS: THE KNOWNS AND THE UNKNOWNS

- Considering the full 3-flavour neutrino mixing paradigm, neutrino oscillation can give access to CP violation in the lepton sector

$$\delta$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ \boxed{-s_{13}e^{i\delta}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $s_{ij} = \sin\theta_{ij}$; $c_{ij} = \cos\theta_{ij}$

- δ_{CP} term always related to θ_{13}. Need $\theta_{13} > 0$ to measure it

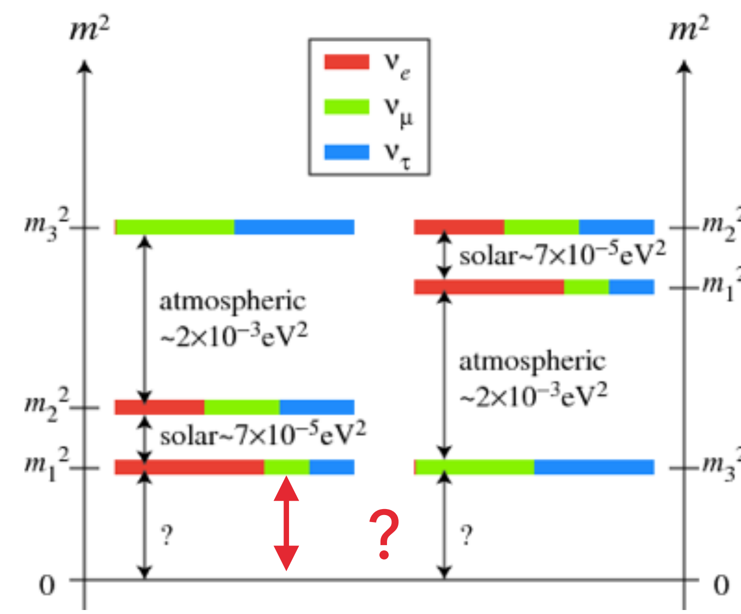
- Thanks to the relatively large size of θ_{13}, δ_{CP} can be studied looking for appearance signals using conventional beams

- Degenerate solution because of the MH

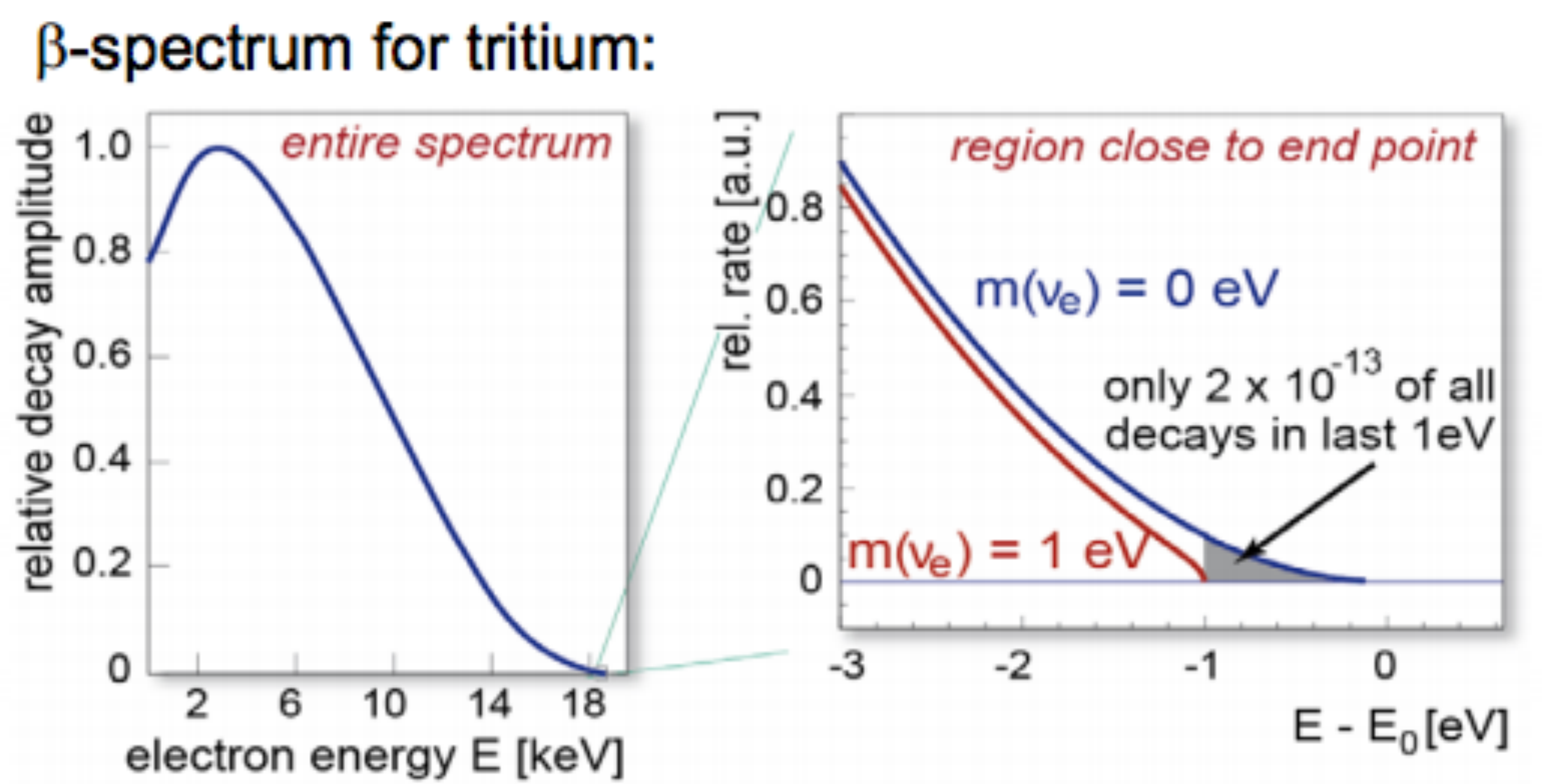
In tomorrow lecture, discussion about how to measure it

NEUTRINOS: THE KNOWNS AND THE UNKNOWNS

- The absolute scale of the neutrino mass is NOT known nor accessible with neutrino oscillation
- Direct measurement: simple kinematic of the ß decay: the non-zero neutrino mass change the end-point of the ß decay spectrum
  - Tritium ^{3}H is a good element: low end point and low half-time : maximise event rate



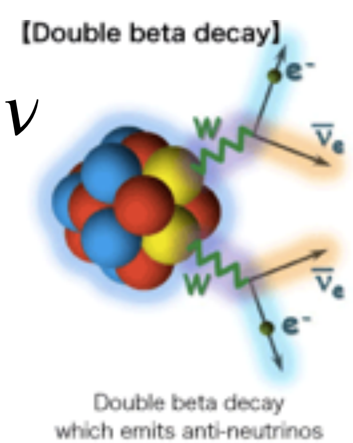
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \overline{\nu}_e$$

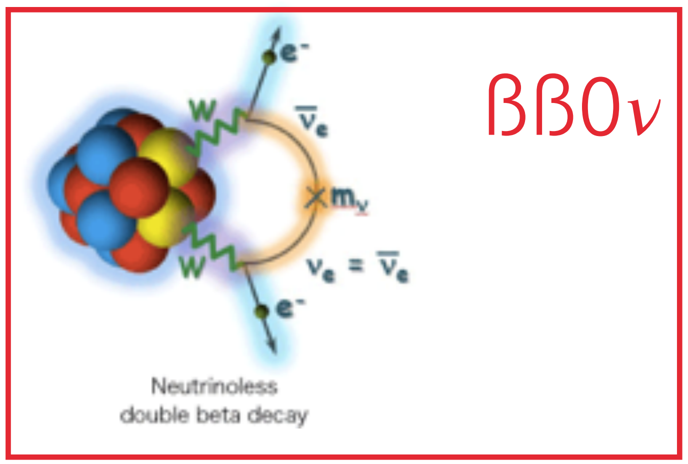


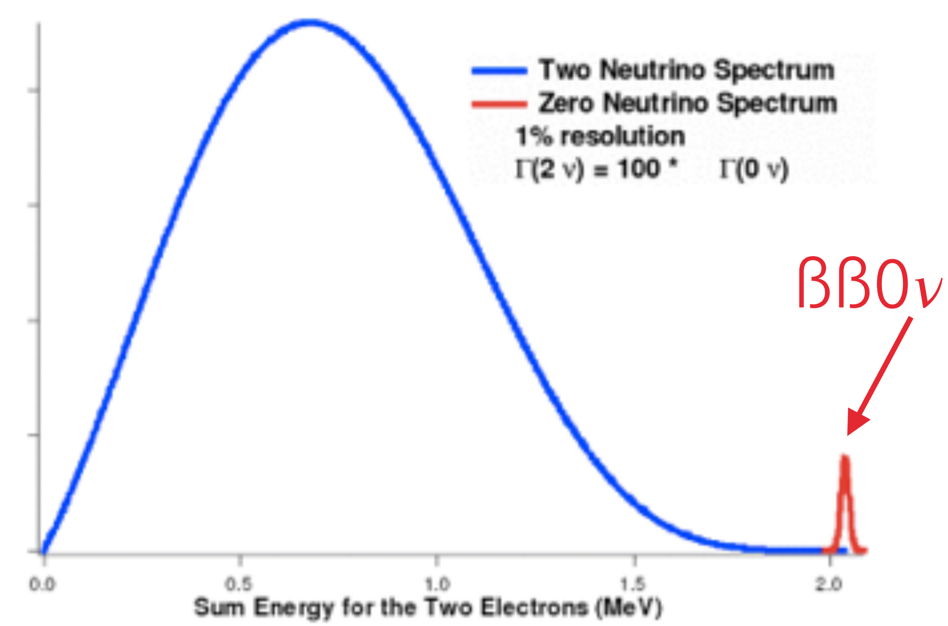
NEUTRINOS: THE KNOWNS AND THE UNKNOWNS

- Neutrinos are the only massive fermions to be neutral
- Neutrino is the only particle that could be it's own anti-particle (if Majorana)
- ßß0ν process that can reveal the **neutrino nature** (Dirac/Majorana)

ßß2ν







ßß0ν :

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$ *forbidden in SM*

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$

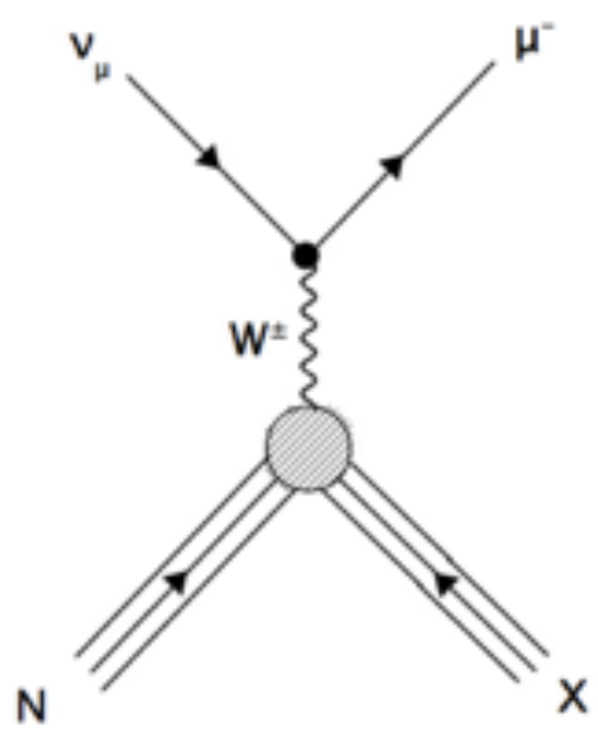
Many (challenging) experiments looking for ßß0ν process but not covered by these lectures

NEUTRINO INTERACTIONS AND MAIN DETECTION TECHNIQUES

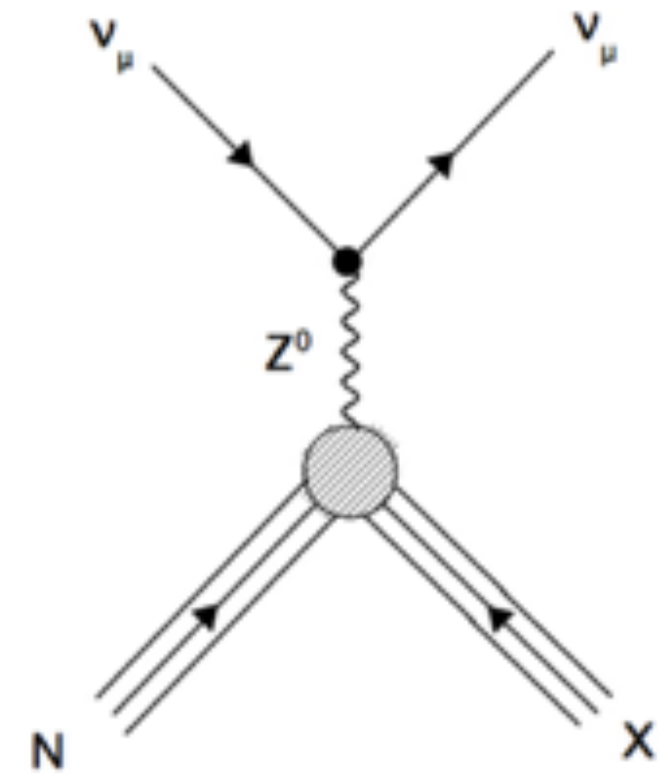
Neutrinos are not Missing ET ! :)

NEUTRINO INTERACTIONS

Charged Current



Neutral Current



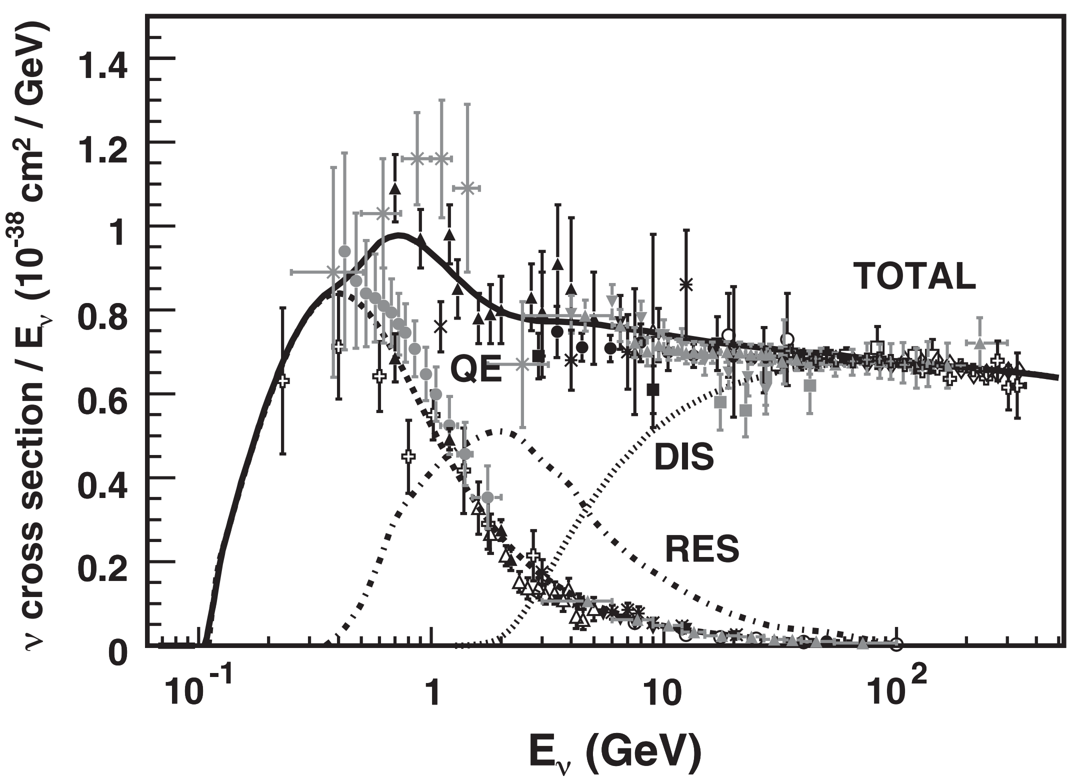
Out-coming lepton bring information about the determination of the neutrino flavour

But threshold of the interaction given by the lepton mass ($E_{\nu\mu}$ > 110 MeV, $E_{\nu\tau}$ >3.5 GeV)

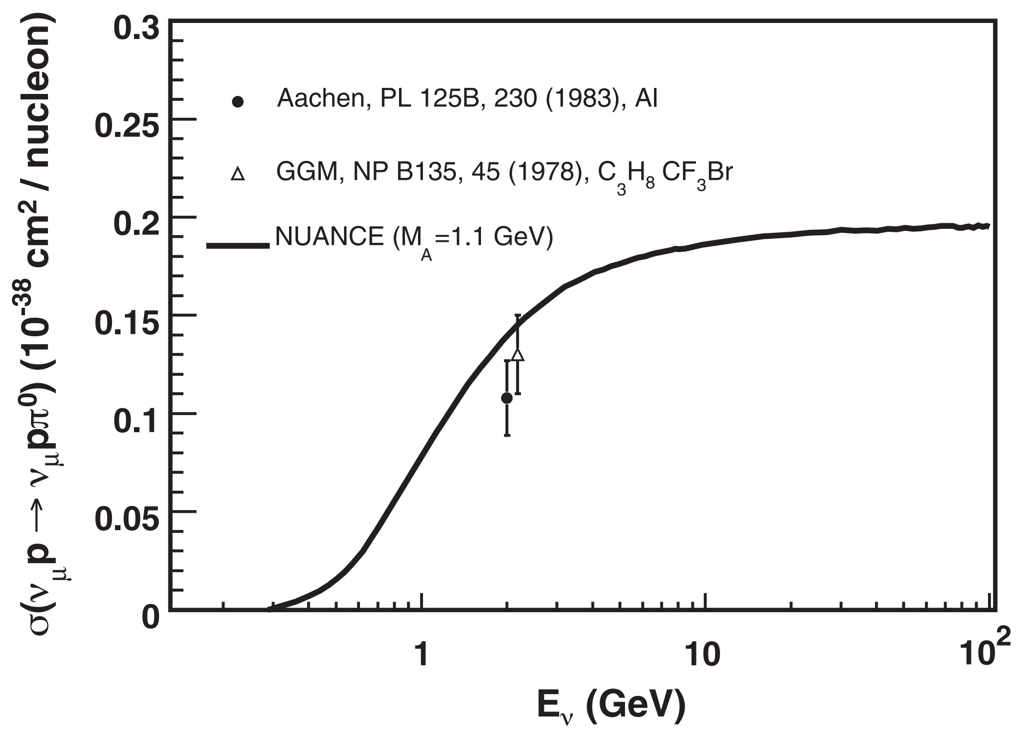
Blind wrt to oscillation: no information about the flavour of the interacting neutrino

NEUTRINO INTERACTION MODES FOR INTERMEDIATE ENERGY RANGE

Charged Current



Neutral Current



Rev. Mod. Phys. 84, 1307

Charge current	
CC-QuasiElastic	$\nu_\mu n \to \mu^- p$
CC-Resonance	$\nu_\mu N \to \mu^- \pi^{+,0} N$
CC-Deep Inelastic	$\nu_\mu N \to \mu^- X$

Neutral current	
NC-Elastic	$\nu_\mu(n,p) \to \nu_\mu(n,p)$
NC-Resonance	$\nu_\mu N \to \nu_\mu N \pi^{+,0}$
NC-Deep Inelastic	$\nu_\mu N \to \nu_\mu X$

O(10^{-38} cm²/ GeV) : particle interacting very weakly! need of (very) big detectors

DESIRABLE FEATURES FOR NEUTRINO DETECTION

- low energy threshold
  low-energy neutrinos (solar nu) or secondary particles (protons) can be detected and studied;
- good angular resolution
  particles direction accurately reconstructed (especially for astrophysical neutrinos)
- good particle identification
  e/μ discrimination essential for oscillation experiments, but π and proton ID also important
- good energy measurement
  reconstruction of the neutrino energy for oscillation measurements, astrophysics, $\beta\beta0\nu$ ..
- good time resolution
  time evolution of transient signals (supernova neutrinos, and other astrophysical sources);
- charge identification
  separation of leptons and anti-leptons (ν anti-ν CC interactions) important for oscillations

Not possible to have all of these features in one detector.

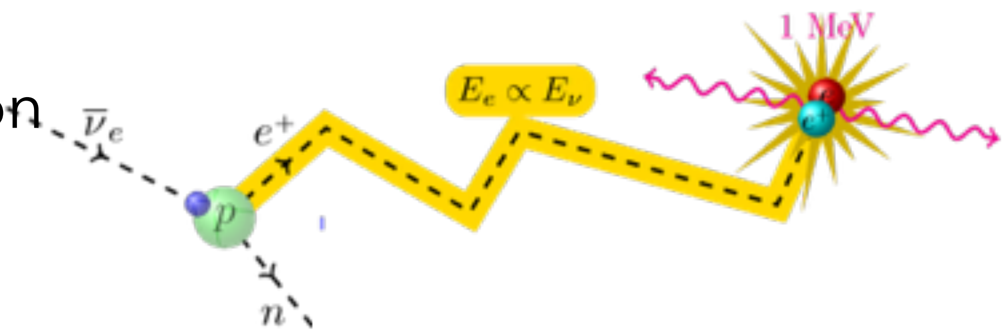
Needs to select the most appropriate technology for the aims of the experiment.

NEUTRINO DETECTION: LIQUID SCINTILLATORS

- Anti-neutrinos detected via Inverse ß- Decay (IBD)

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- search for 2 signal coincidence:
    - instantaneous annihilation of the positron (**prompt signal**)

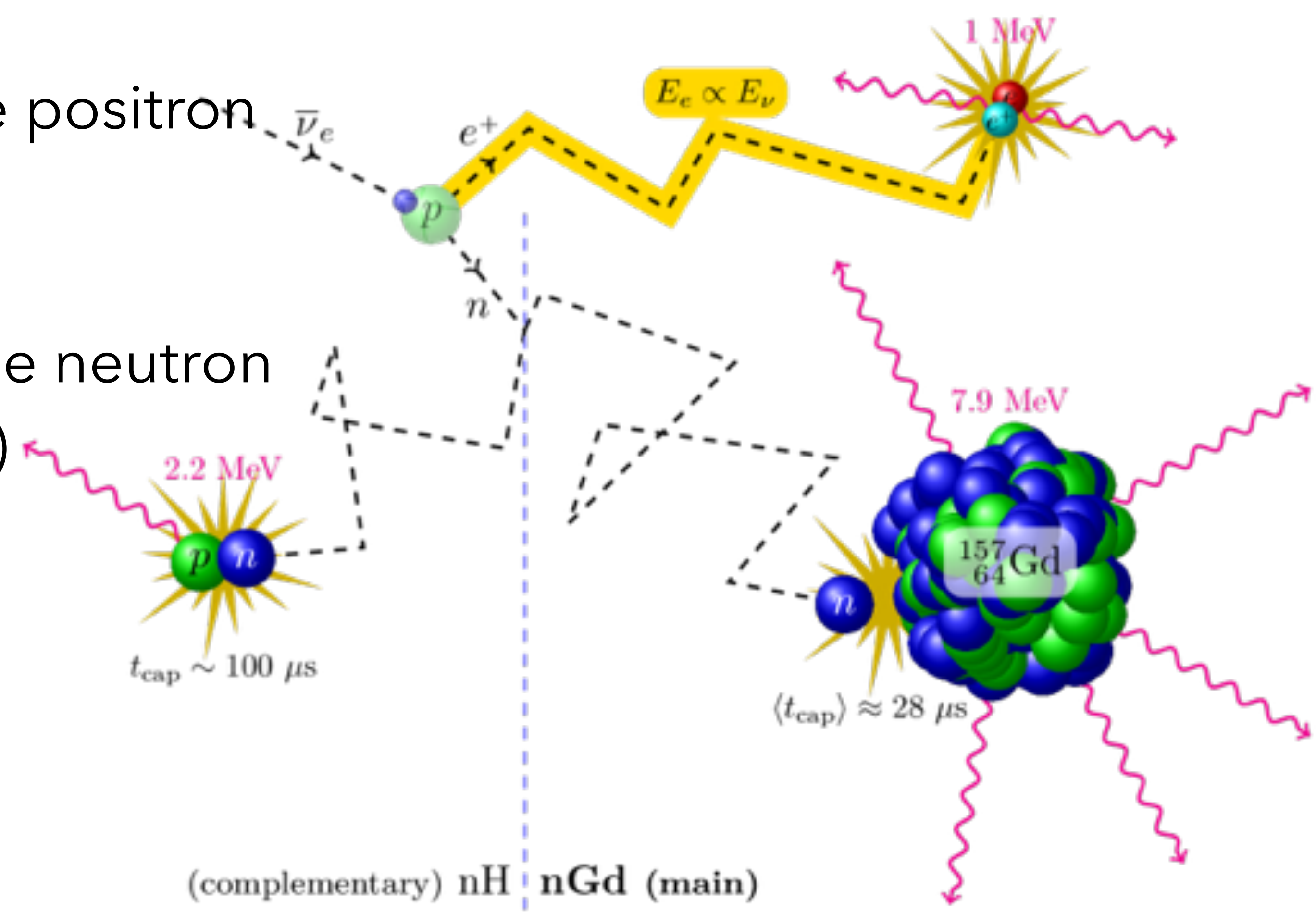


NEUTRINO DETECTION: LIQUID SCINTILLATORS

- Anti-neutrinos detected via inverse ß- decay (IBD)

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- search for 2 signal coincidence:
  - instantaneous annihilation of the positron (prompt signal)
  - thermalisation and capture of the neutron after some time (delayed signal)

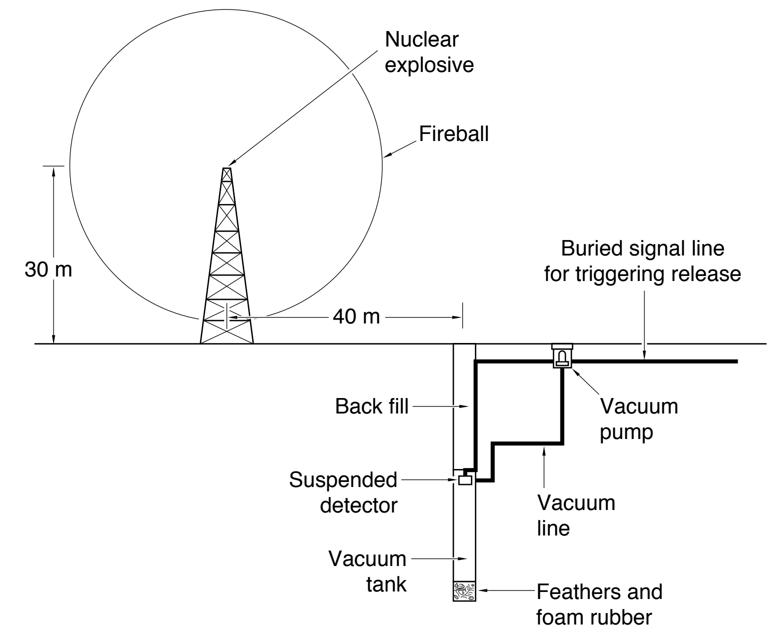


E_{Thr} for anti-neutrinos 1.8 MeV

LIQUID SCINTILLATORS ν DETECTORS: FEW EXAMPLES

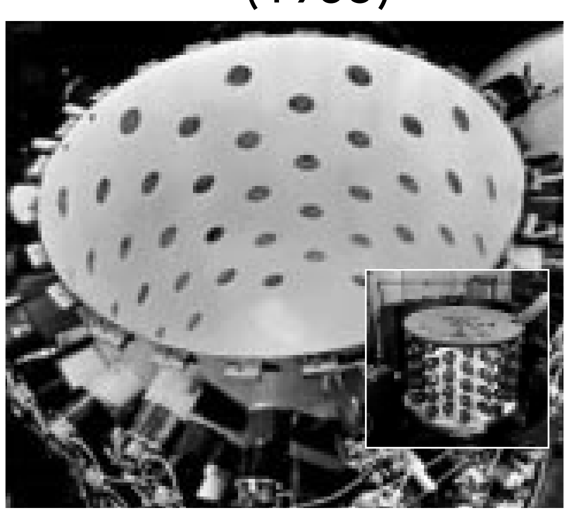
First neutrino detection!

- Reines and Cowan experiments - First idea to detect neutrinos : use IBD in liquid scintillator from a nuclear fission explosion!
- Finally using anti-neutrinos from reactor
- Evolution of the detector design to fight background:
  - "El Monstro" : first giant liquid scintillator detector (1m^3)
  - the Hanford experiment : Liquid scintillator doped with C_d for neutron capture (70 cm ⦰ x 75cm high)
  - The Savannah River experiment : H_20-C_d target + liquid scintillator



The Hanford neutrino detector

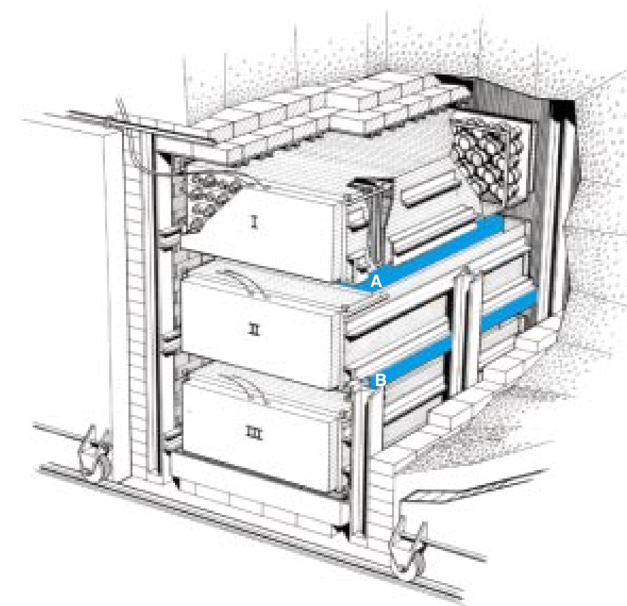
(1953)



"The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals. We felt we had the neutrino by the coattails, but our evidence would not stand up in court."

The Savannah River neutrino detector

(1956)



"We are happy to inform you that we have definitely detected neutrinos rom fission fragments by observing nverse beta decay of protons.

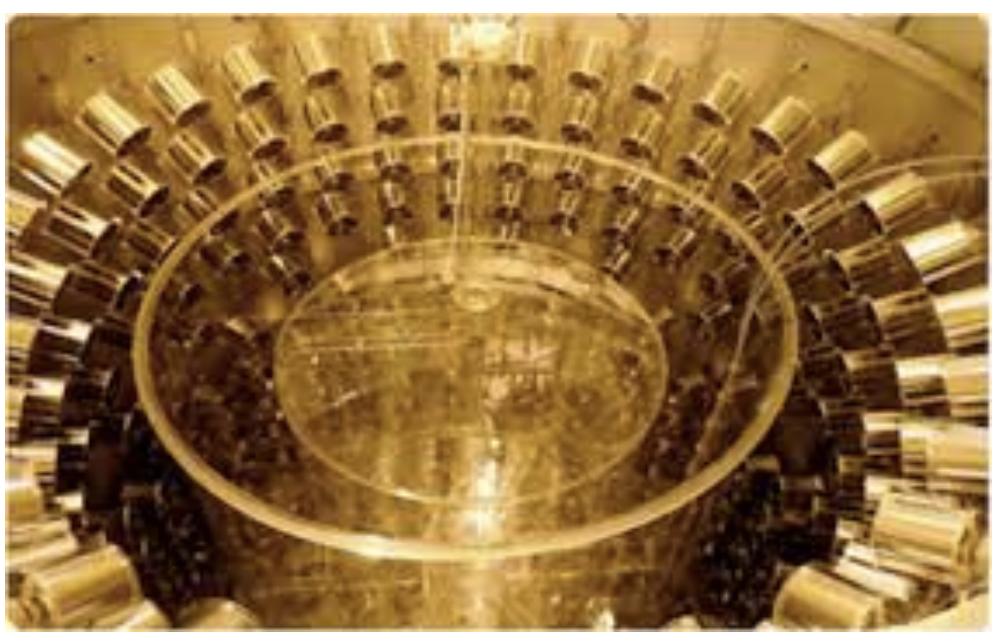
LIQUID SCINTILLATORS ν DETECTORS: FEW EXAMPLES

Measurement of θ_{13}

- Reactor experiments (Daya-Bay, RENO and Double Chooz) have similar design and strategy: detection of the IBD
- Liquid scintillator doped with Gd

image courtesy of Daya Bay

Double Chooz detector

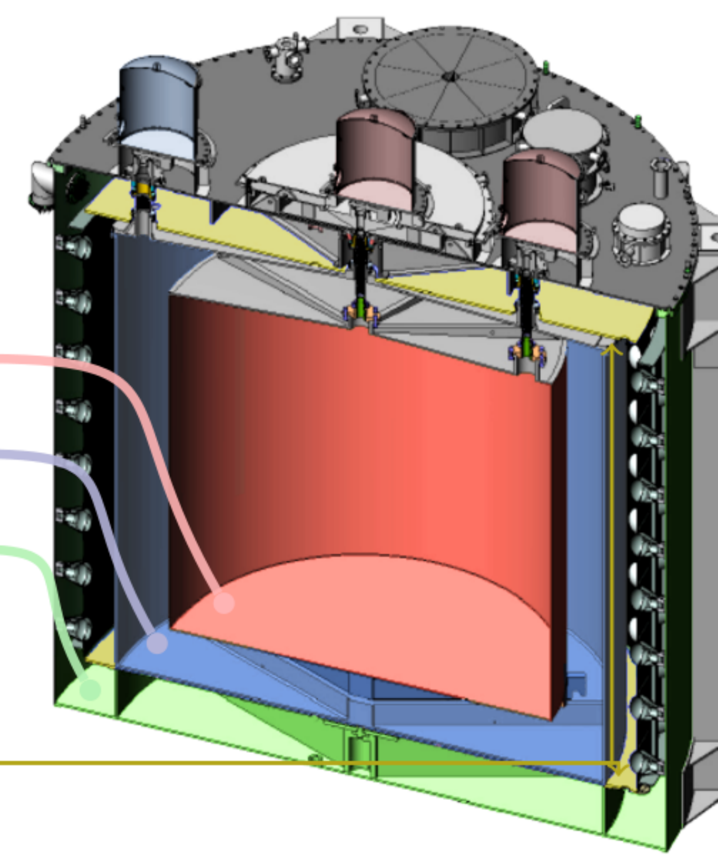


8 functionally identical detectors reduce systematic uncertainties

	3 zone cylindrical vessels		
	Liquid	Mass	Function
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

192 8 inch PMTs in each detector

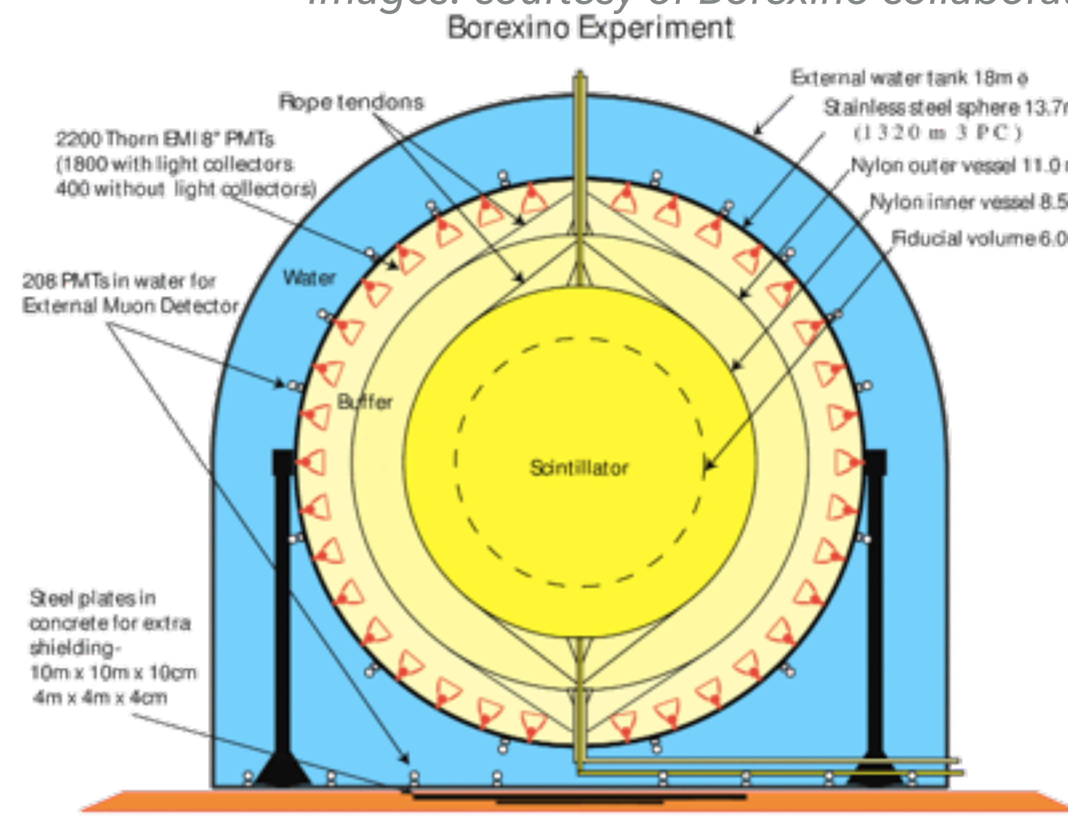
Top and bottom reflectors increase light yield and flatten detector response



LIQUID SCINTILLATORS ν DETECTORS: FEW EXAMPLES

Measurement of solar ν

Images: courtesy of Borexino collaboration



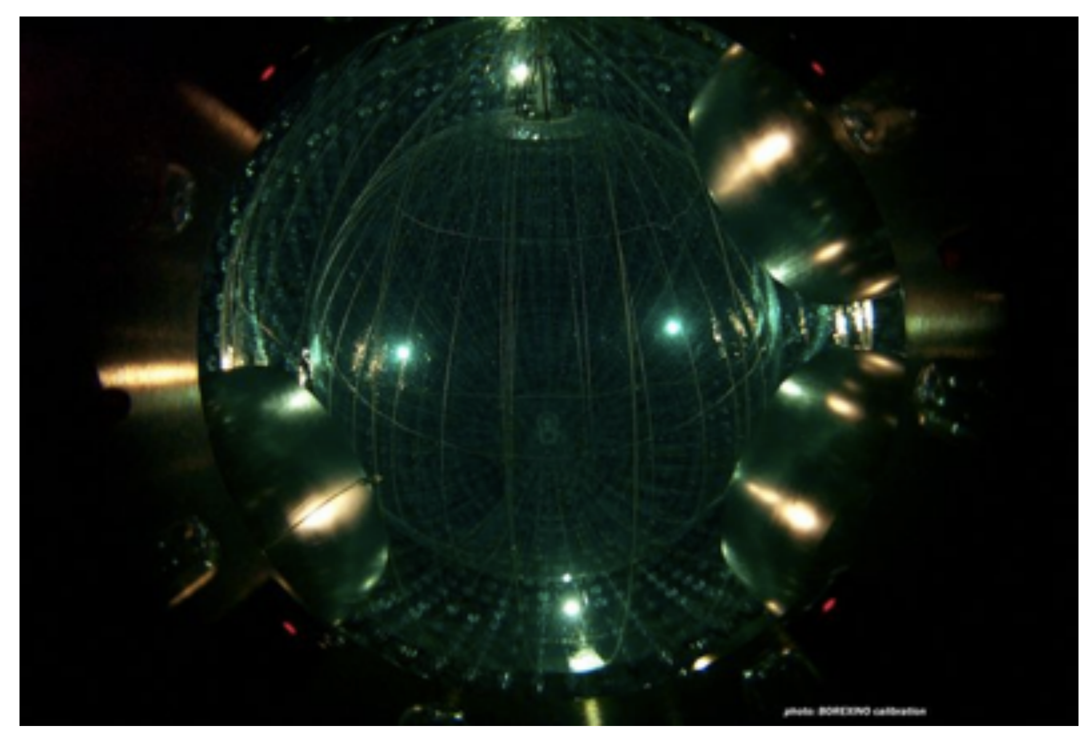
- Liquid scintillators are also sensitive to electron neutrinos going through elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Borexino (since 2007)

- Neutrino coming from the sun (^{7}Be, pep) but also geo-neutrinos and sterile neutrinos (SOX)

- Liquid scintillator in a stainless steel sphere



First measurements of solar ν

RADIOCHEMICAL SOURCES

- Very first approach to study solar neutrinos (Davis-Pontecorvo)
- Production of radioactive isotopes
- ^{37}Ar and ^{71}Ga are extracted chemically and counted by their decay products : no infos about neutrino energy or direction!

$$\nu_e + Ga^{71} \rightarrow Ge^{37} + e^-$$

E_{th} = 233 keV

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

E_{th} = 814 keV

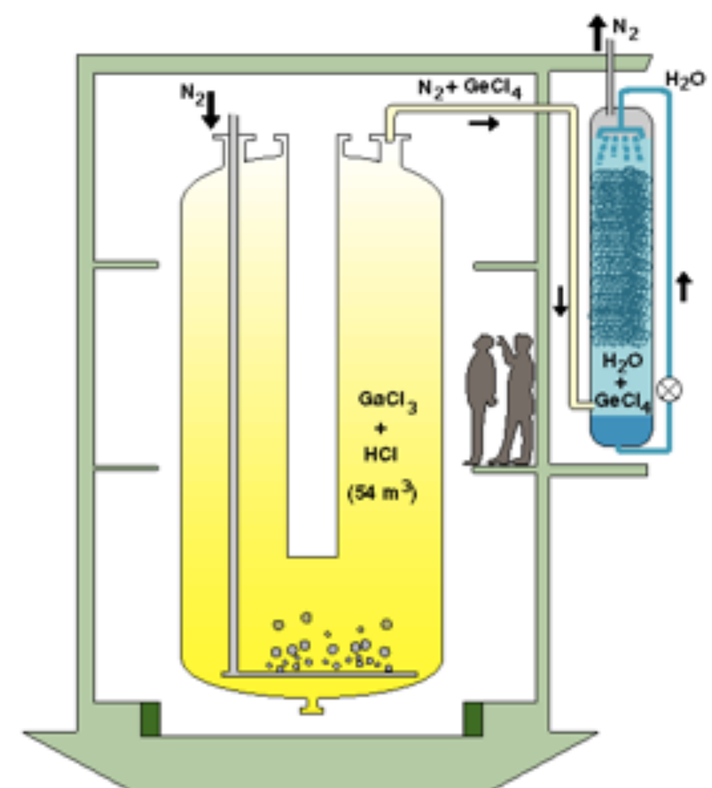
GALLEX (1991-1997)
LNGS Italy

615 tons of cleaning fluid C2Cl4
Expected 1.5 Ar atoms/day

image courtesy of BNL

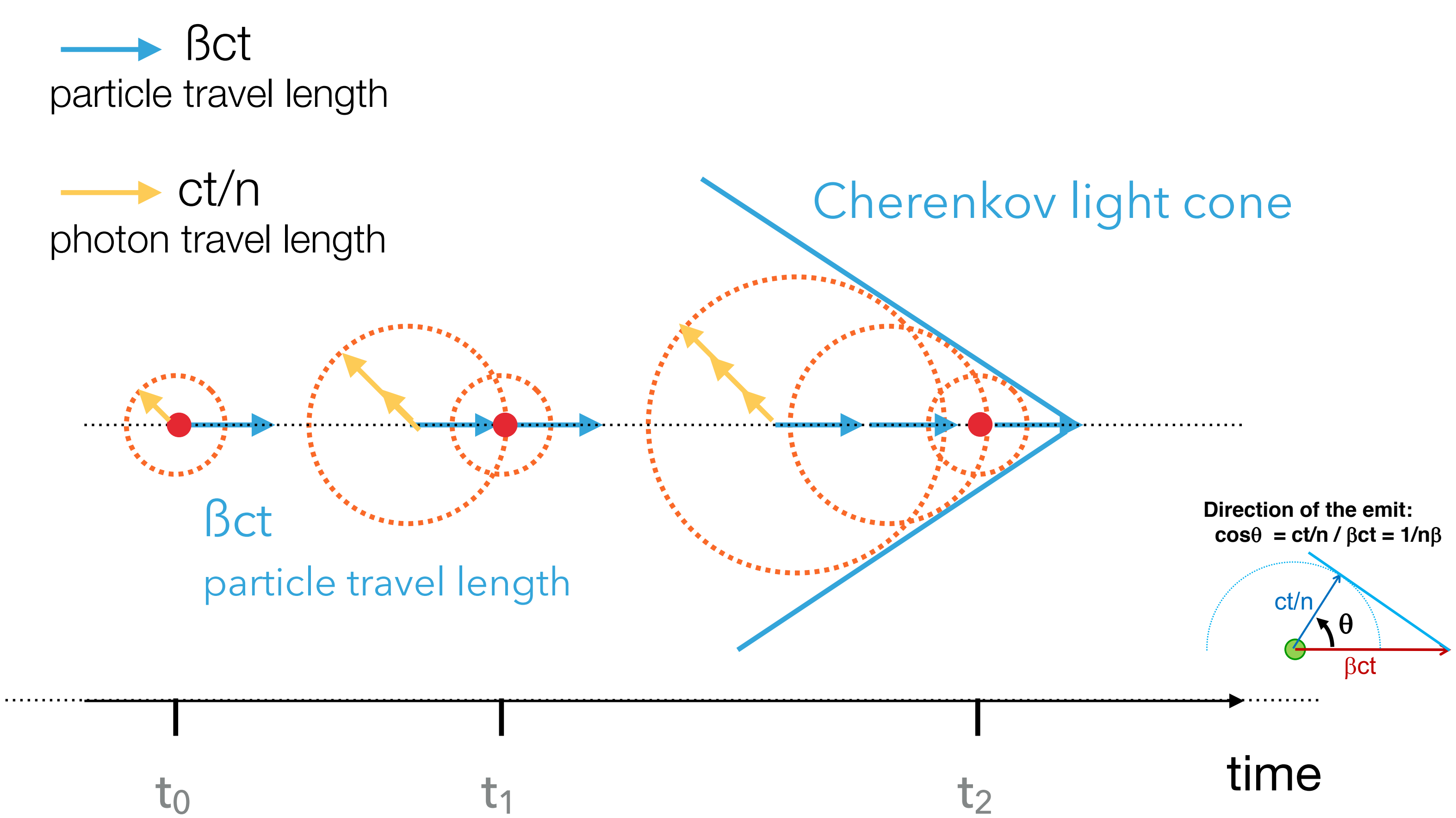
Davis experiment (1960's)
Homestake mine, South Dakota
(same as DUNE!)

615 tons of cleaning fluid C2Cl4
Expected 1.5 Ar atoms/day



NEUTRINO DETECTION: CHERENKOV RADIATION

- If the particle speed is higher than speed of light in that medium, Cherenkov radiation is emitted
  - Local perturbation (atom polarisation) of the EM field due to the particle passing through.
  - photons are emitted to restore the equilibrium when the particle is passed over : coherent emission of light



$$\beta > 1/n \simeq 0.75 \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \simeq 1.5$$

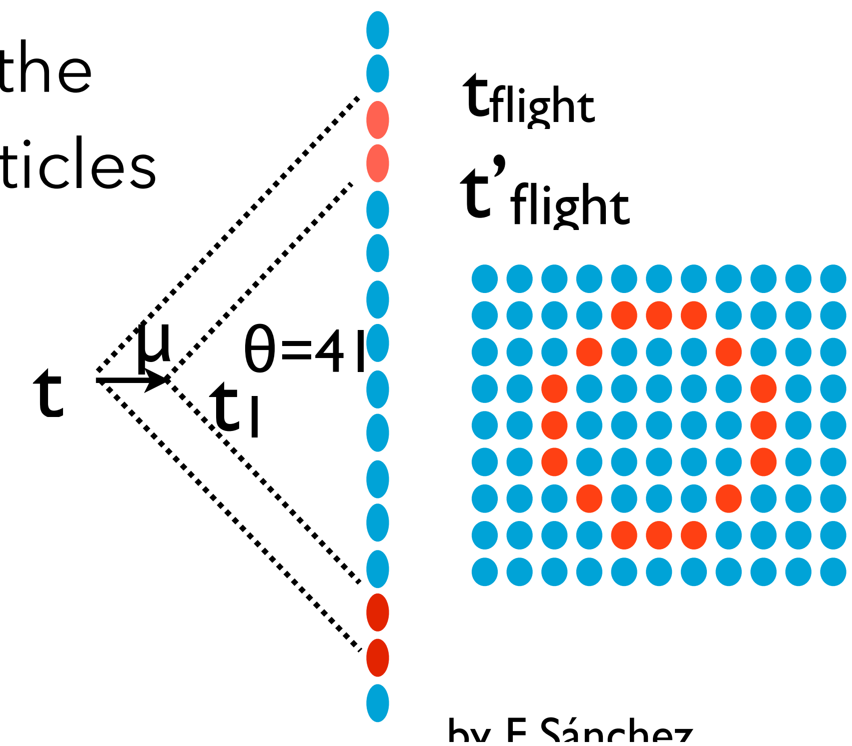
$$E_{Thr} = \gamma mc^2$$

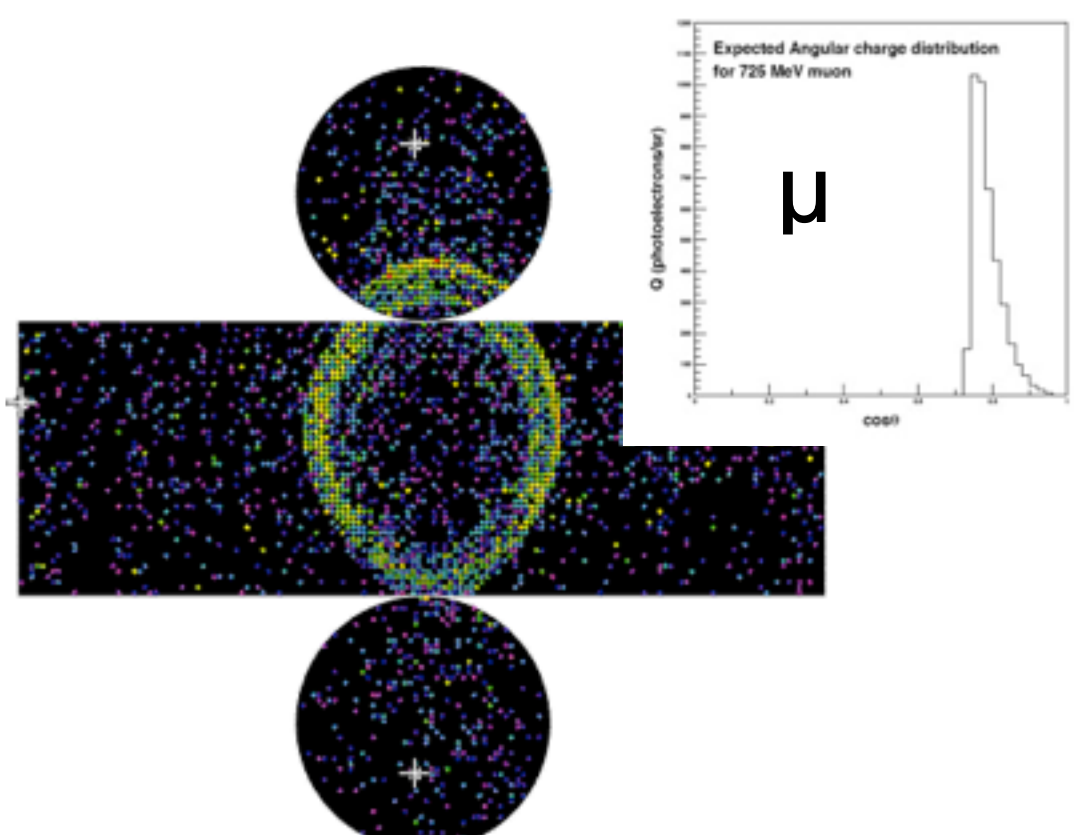
particle	E_{thr}
electrons	0.755 MeV
muons	160.3 MeV
pions	211.7 MeV
protons	1407 MeV

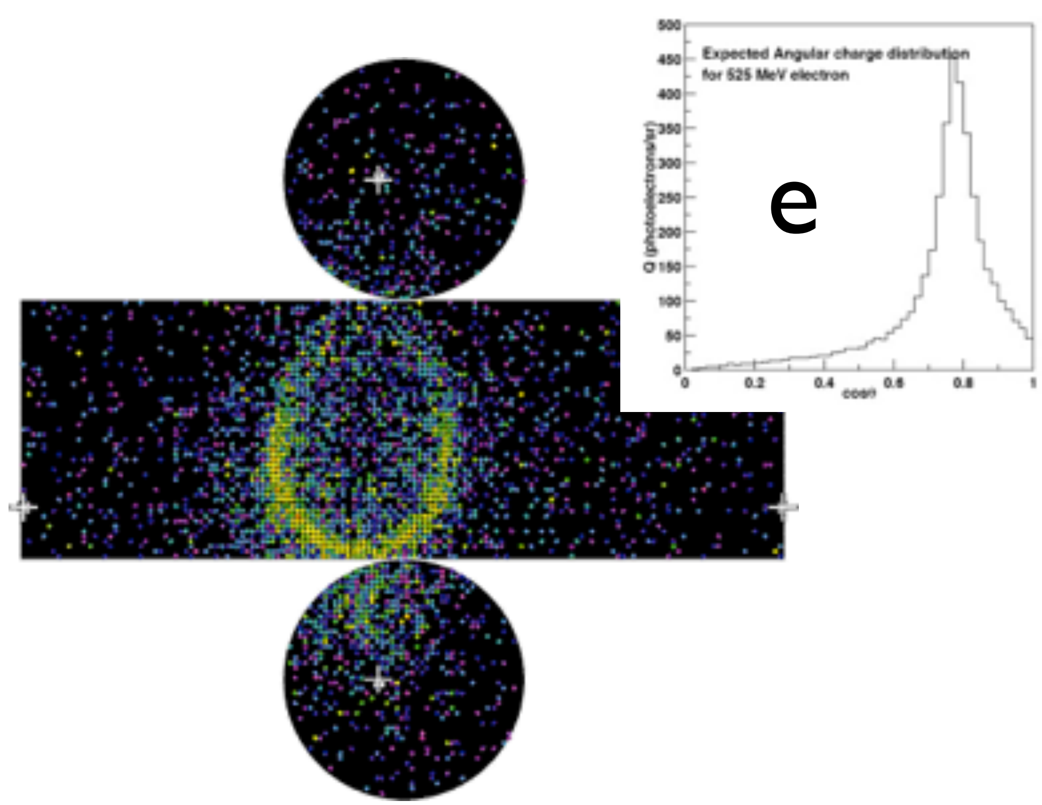
NEUTRINO DETECTION: PARTICLE IDENTIFICATION

- Angular distribution of the Cherenkov photons along the primary particle direction provide a key to identify particles

- Strong e/μ discrimination :
  muons: sharp and clear ring
  electrons: fuzzy ring due to multiple scattering and showering





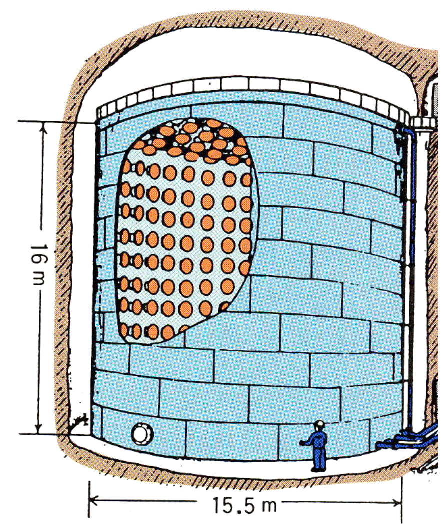


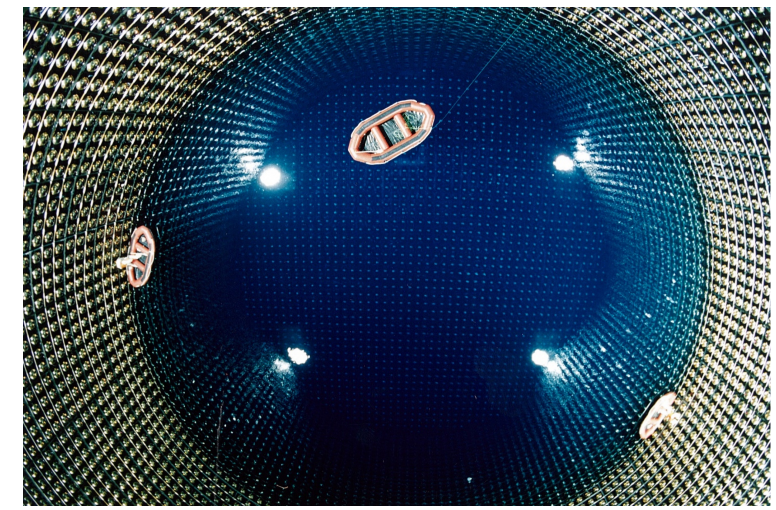
First measurements of ν oscillations, SN ν

SOME EXAMPLES OF CHERENKOV DETECTORS

Kamiokande (1983-1996)

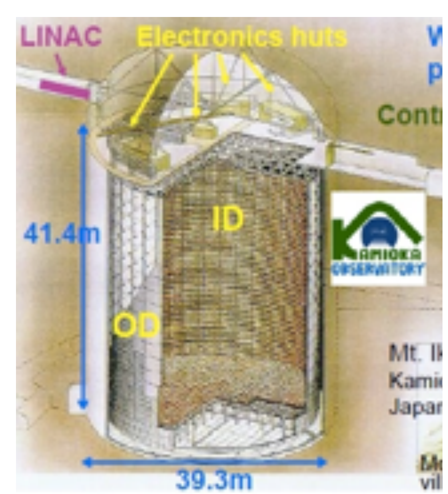
- Nucleon decay experiment
- 4.5ktons of ultra pure water
- 984 (ID) + 123 (OD) PMTs (20-25% coverage)
- **discovery of oscillations with atmospheric neutrinos**

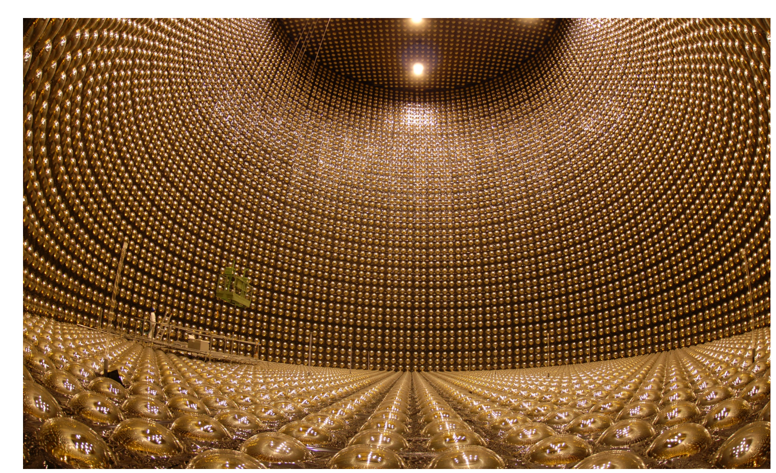




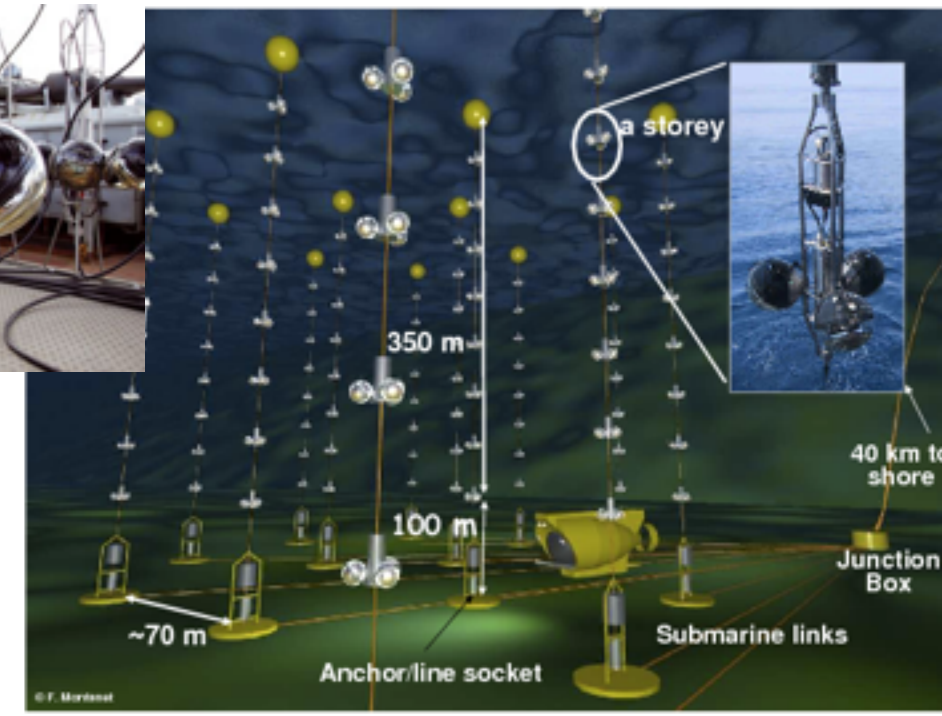
Super-Kamiokande (1996-today)

- atmospheric neutrinos experiment + FD for the T2K experiment
- 50ktons of ultra pure water
- 11k (ID) + 2k (OD) PMTs (40% coverage)





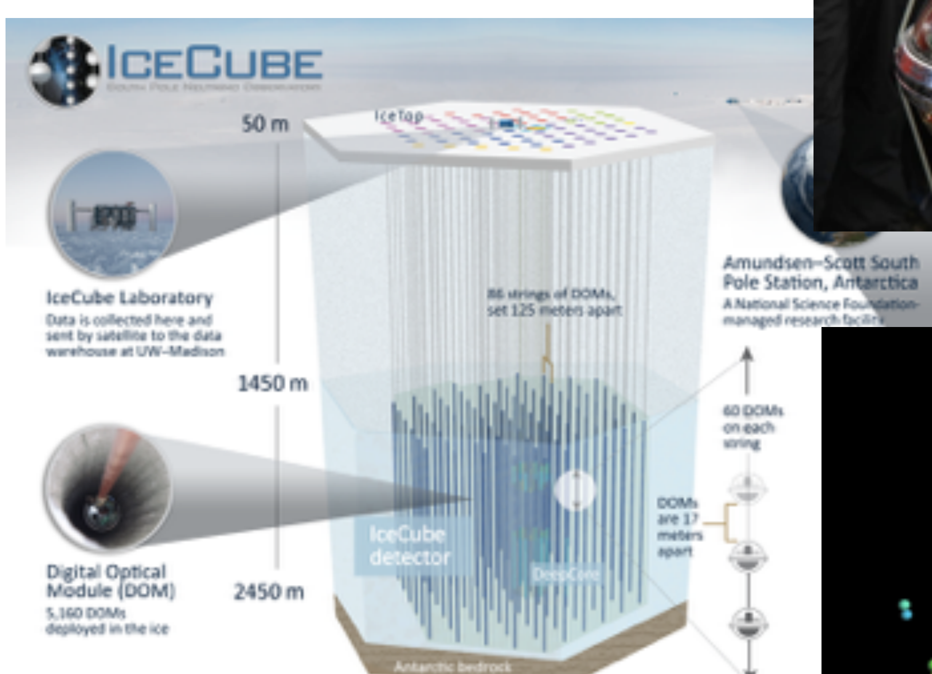
SOME EXAMPLES OF CHERENKOV DETECTORS

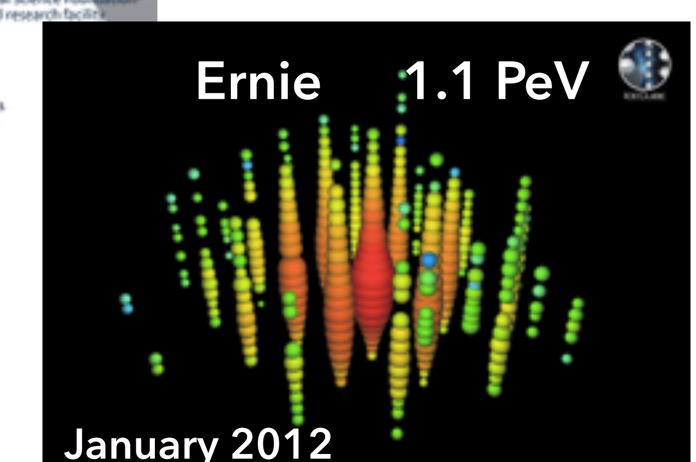


Antares (2008-2017)

- 12 separate vertical strings 350m long
- 75 optical modules each
- E_ν 10^{10} -10^{14} eV
- astro-particle physics (neutrino from cosmo)

First measurements of cosmic ν





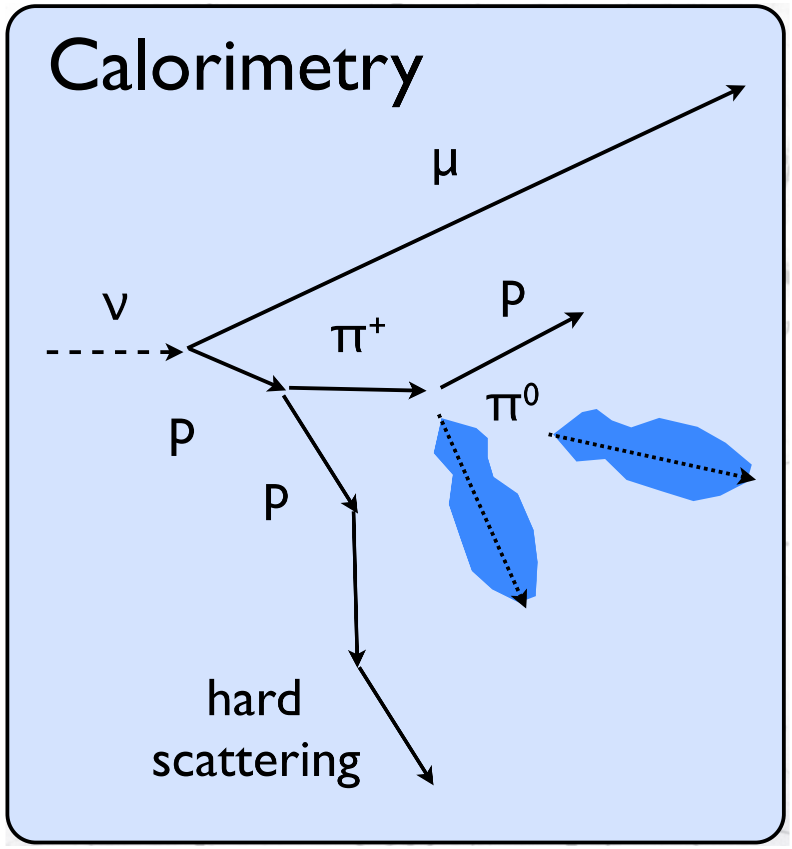
IceCube (2011 - today)

- cubic-kilometer particle detector made of Antarctic Ice
- 5,160 digital optical modules (DOMs) attached in vertical string frozen in 86 boreholes (in-ice detector)
- beginning of searches for cosmogenic neutrino interactions

TRACKING-CALORIMETRY

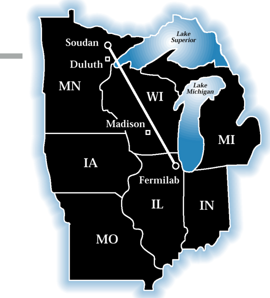
- Aim is to detect and identify all particles coming out from a neutrino interaction
- Two main types:
  - w/ alternating layers
  - monolithic (single volume)
- If magnetised:
  - Charge determination –> determination if neutrino or anti-neutrino event
  - Momentum from the curvature of the tracks

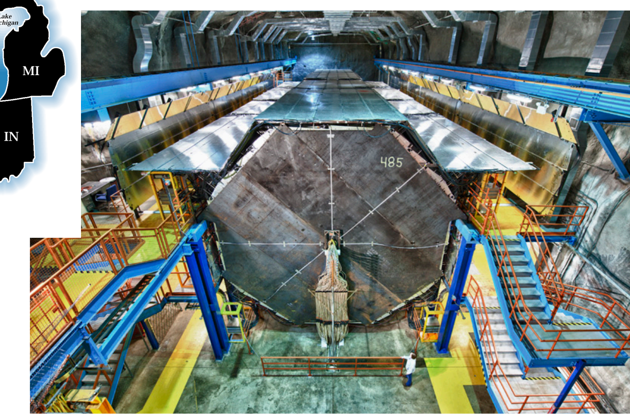
courtesy of F. Sanchez



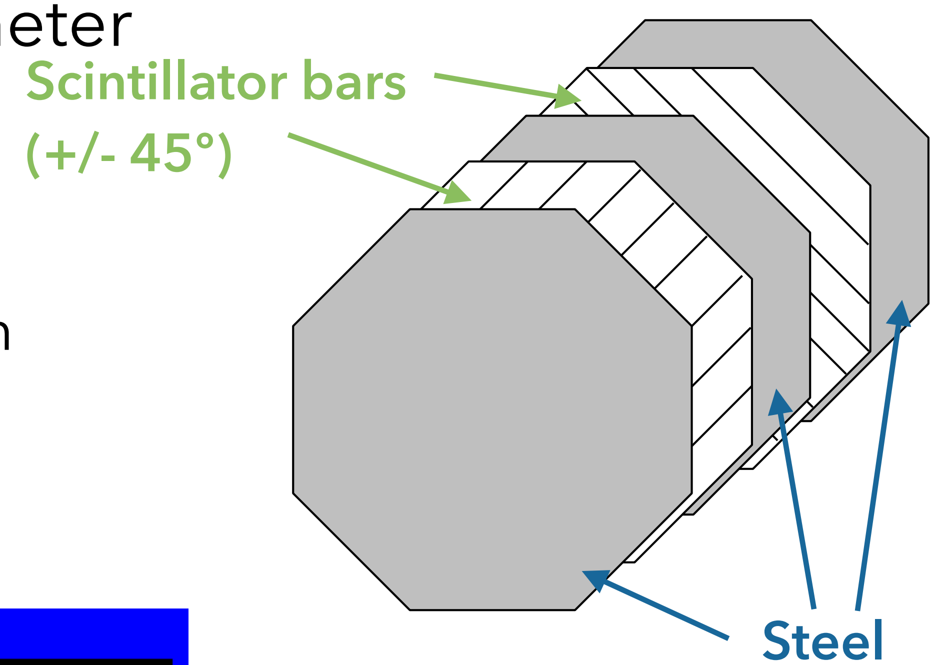
$E_\nu = E_{lepton} + E_{had}$

TRAKING–CALORIMETRY : MINOS/ MINOS+ (2003-2016)

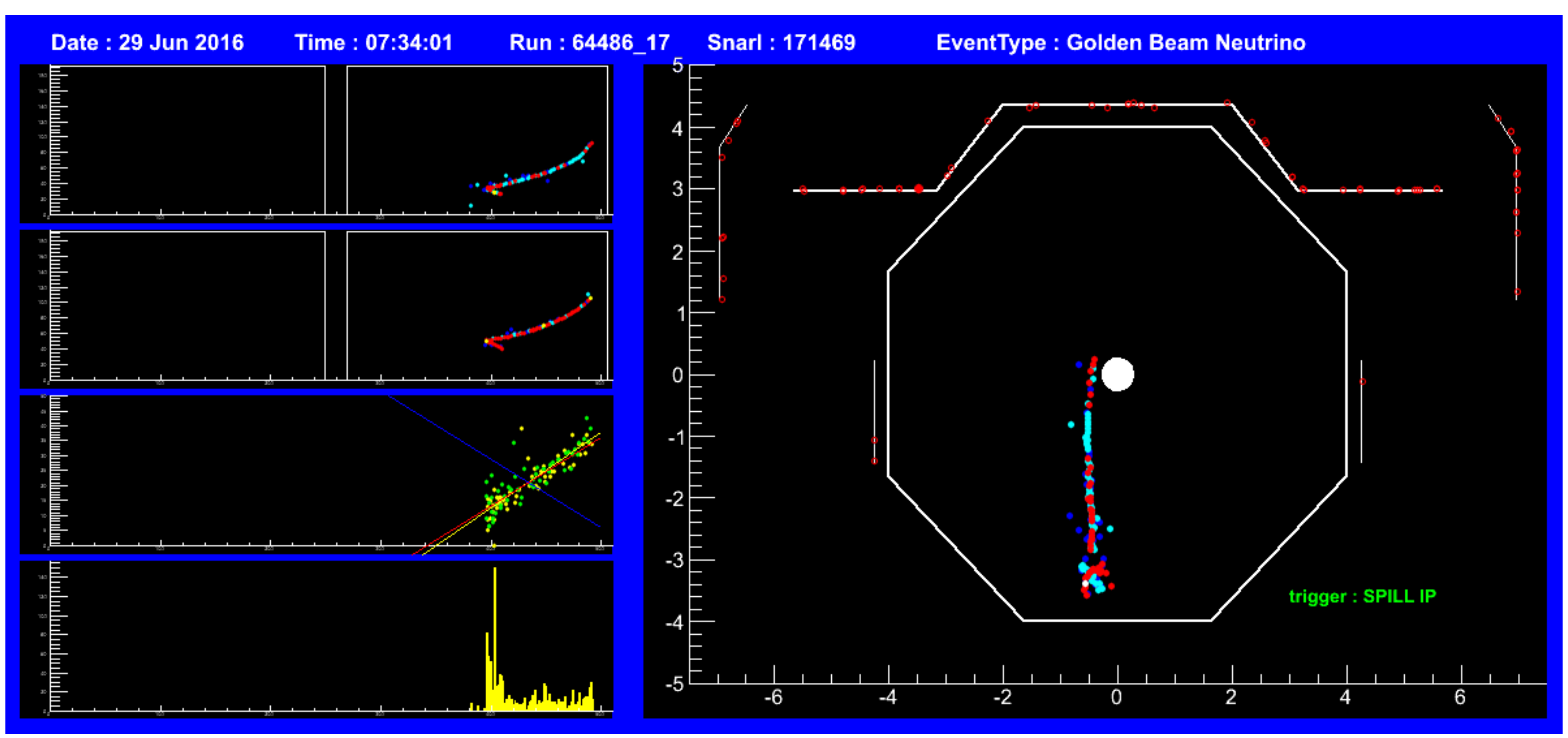


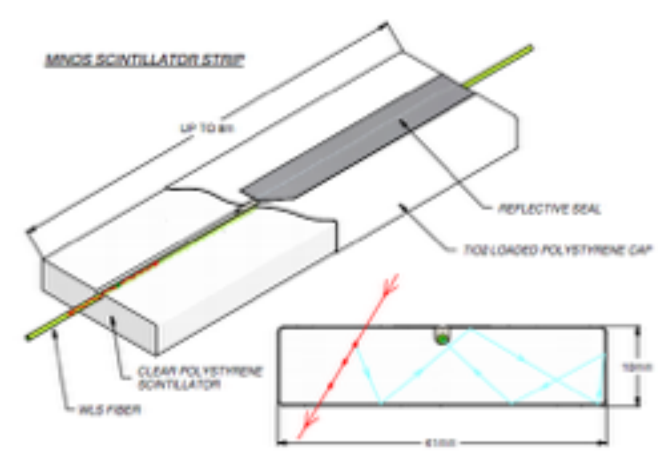


- LBL oscillation experiment in US (L ~735 km)
- Magnetised (1.3T) steel/scintillator sampling calorimeter w/ alternating planes:
  - 2.54cm steel absorber ~1.4 X_0
  - 1 cm thick plastic scintillator bars (4.1cm wide) arranged in orthogonal directions (alternating layers)



last neutrino event seen by MINOS

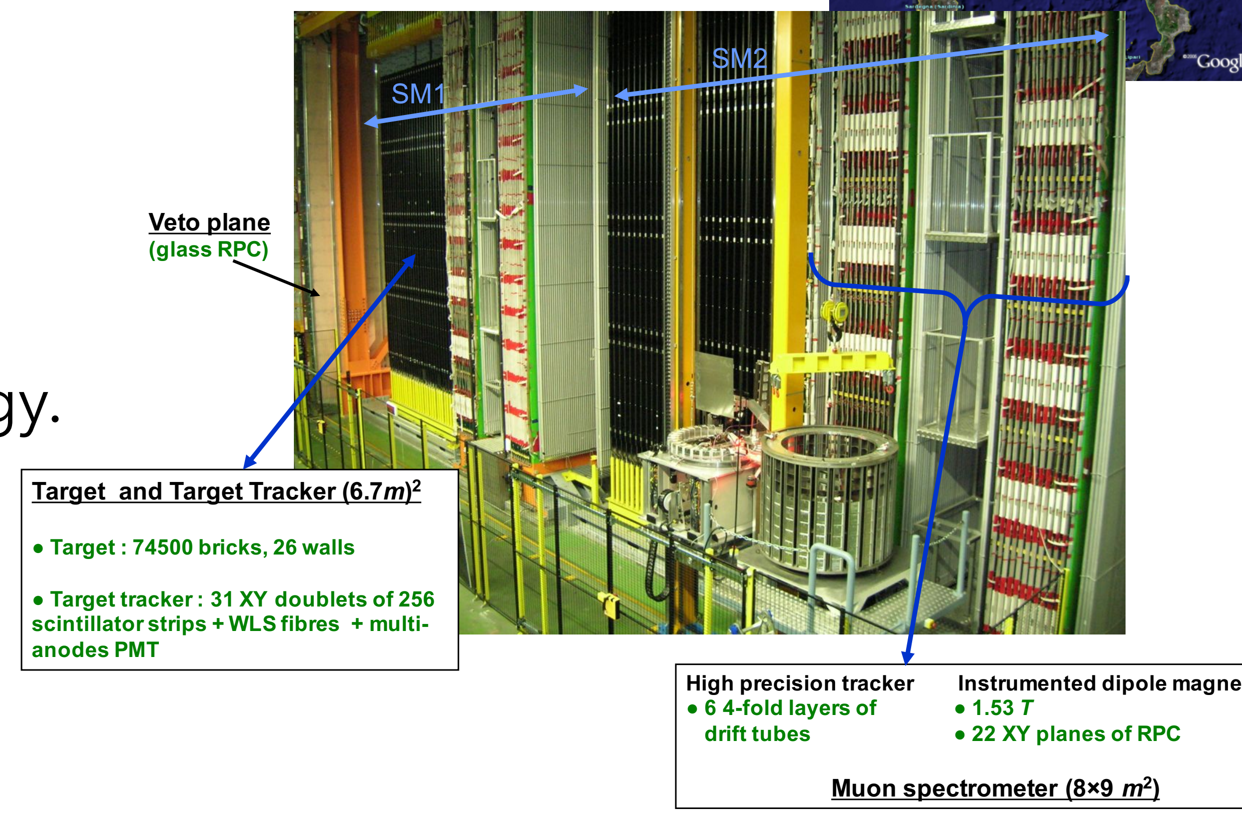




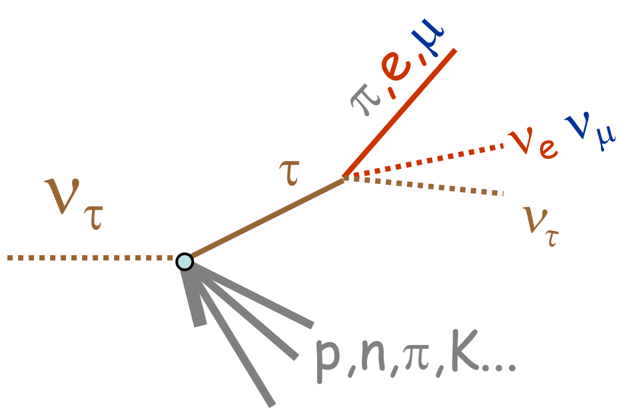
TRAKING–CALORIMETRY : OPERA

First detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations

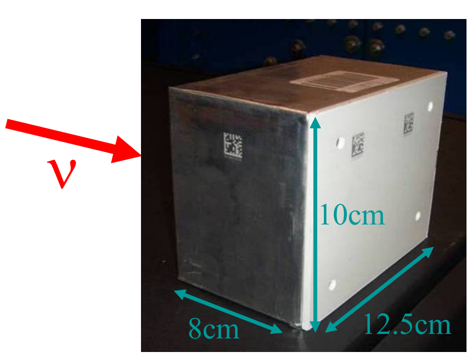
JINST 4(2009) p04018

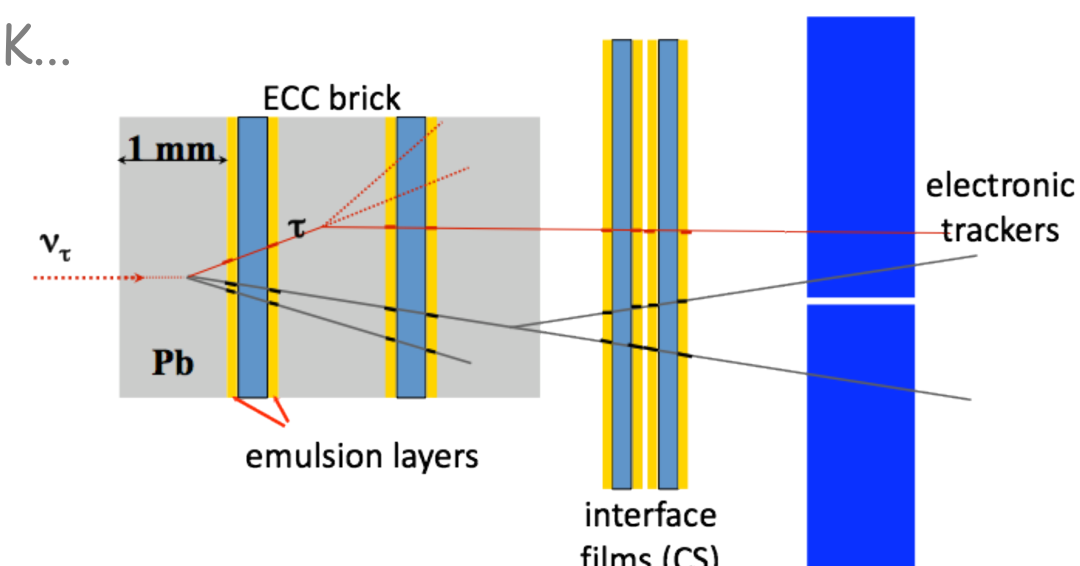


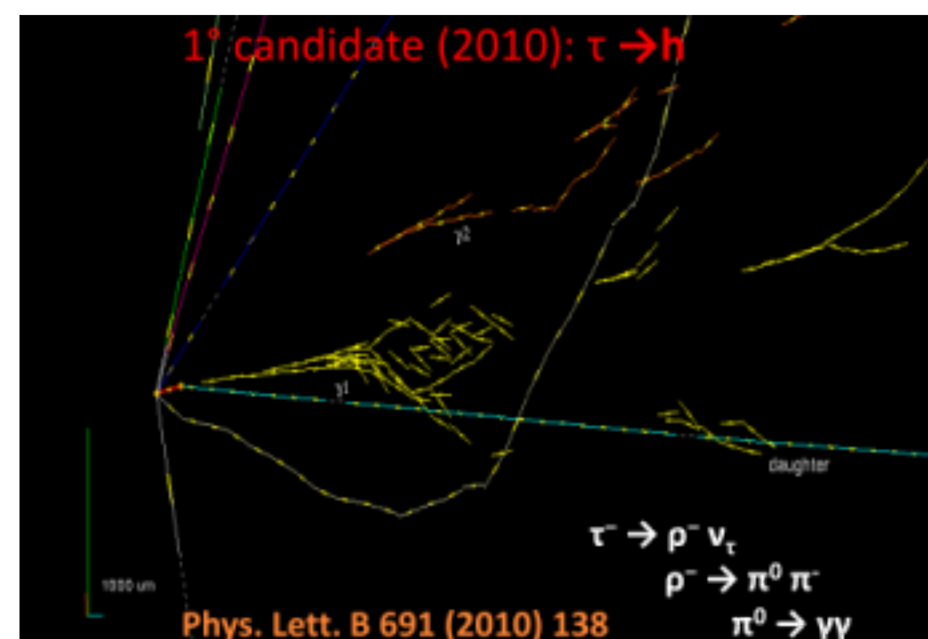
- Aim to detect $\nu_\mu \rightarrow \nu_\tau$ from CERN beam
- $<E_\nu>$ = 17 GeV
- Modular structure alternating lead sheets and emulsion films to detect the tau decay topology. (Target mass 1.25 ton detector)



the brick

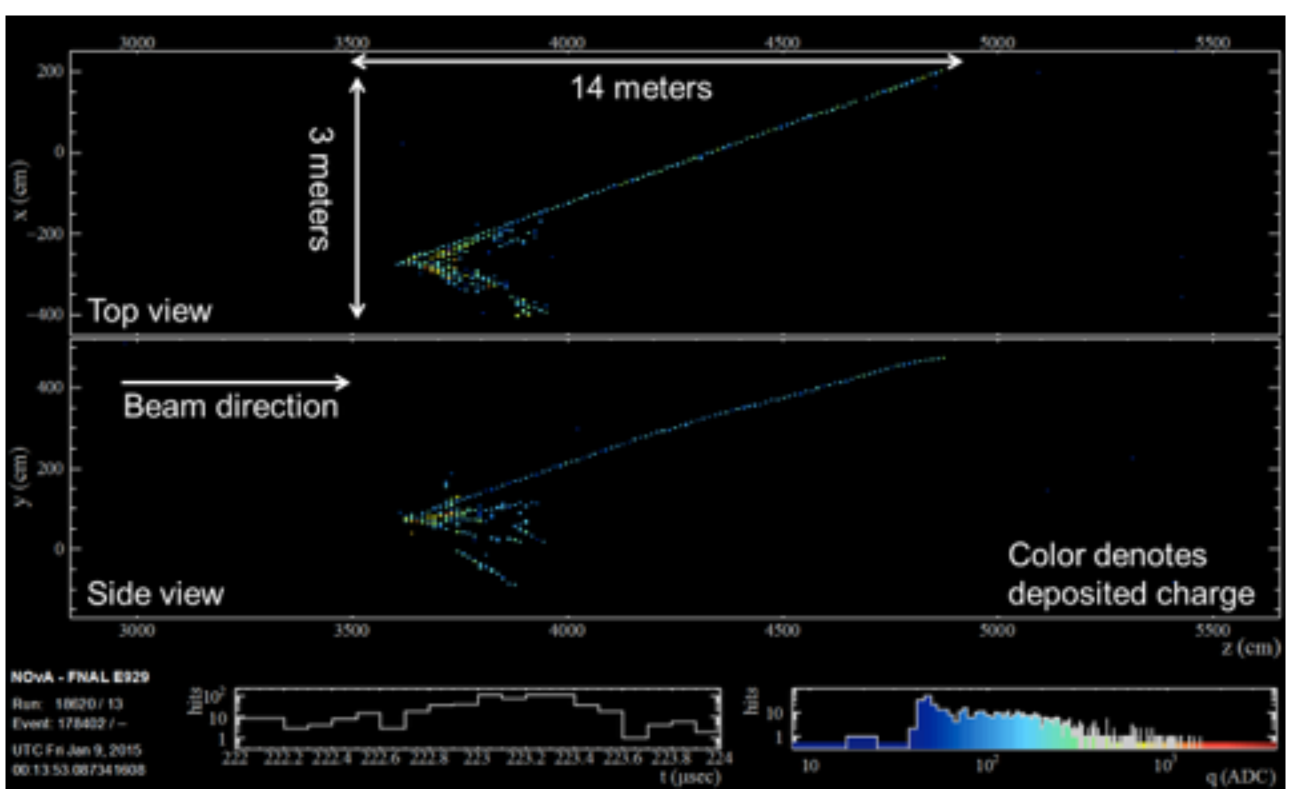


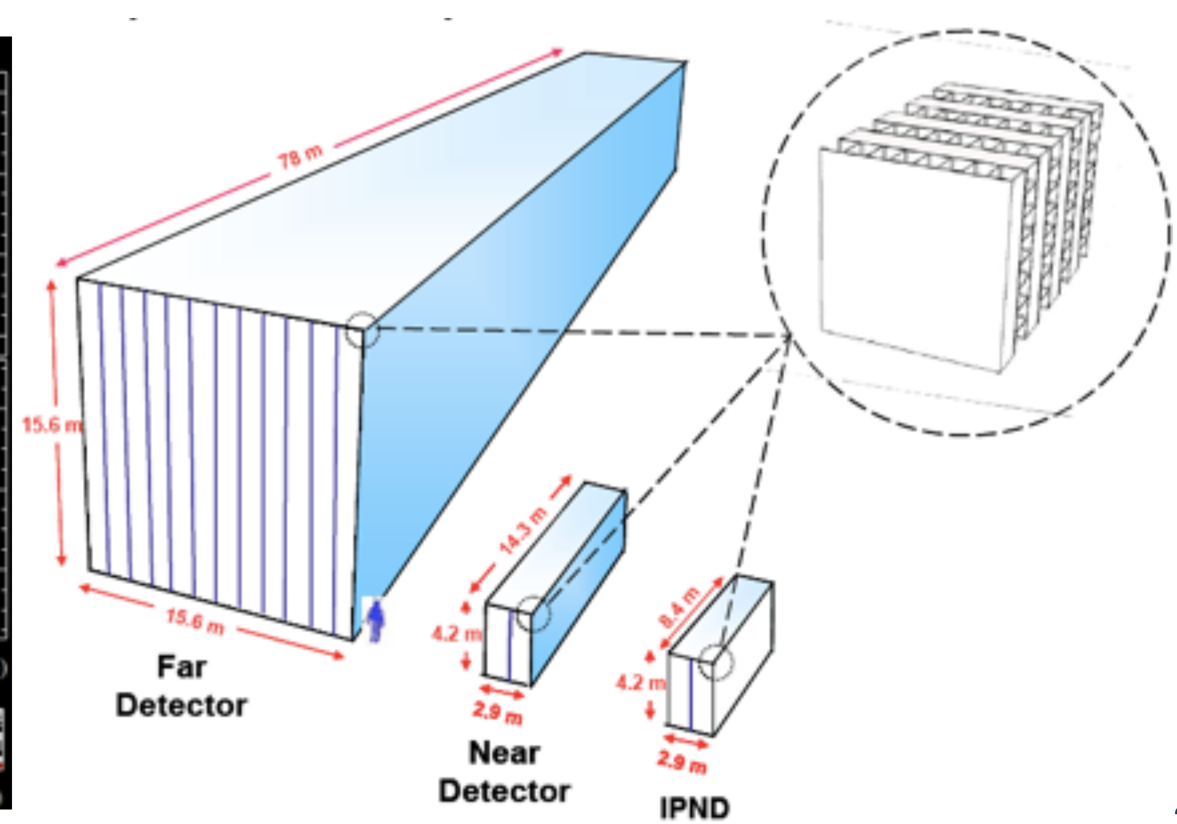




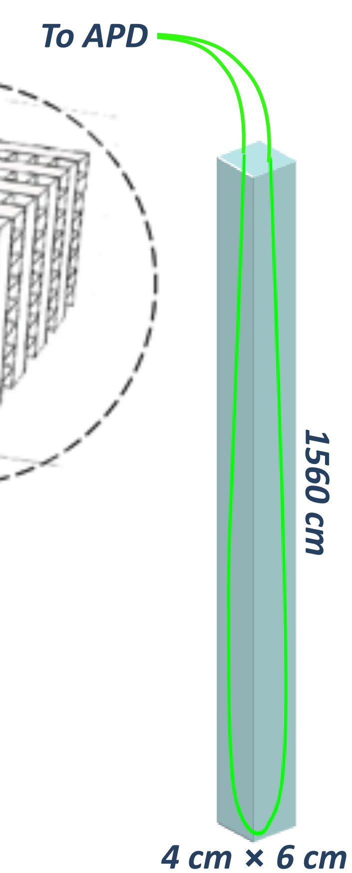
TRAKING-CALORIMETRY : NOvA (2014 - today)

- LBL oscillation experiment with E_ν ~2GeV
- 385,000 high refracting plastic PVC cells fill with liquid scintillators
- energy deposited by incoming particles collected by wavelength shifting fibres read by APDs



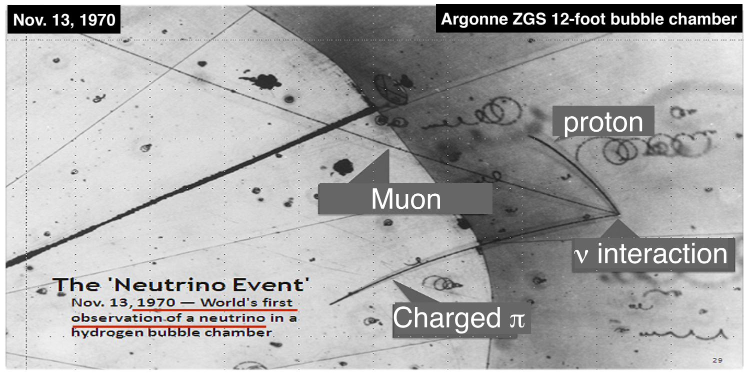


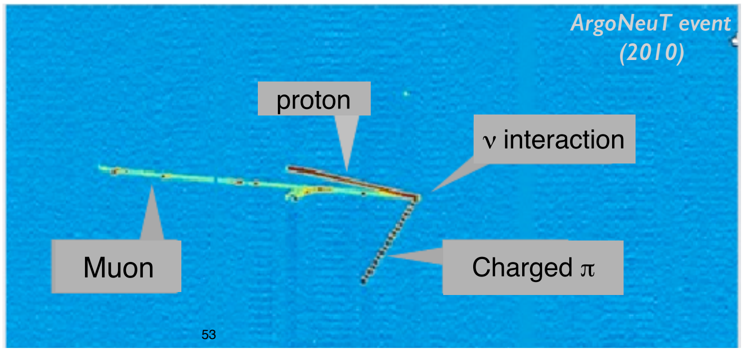
A NOνA cell

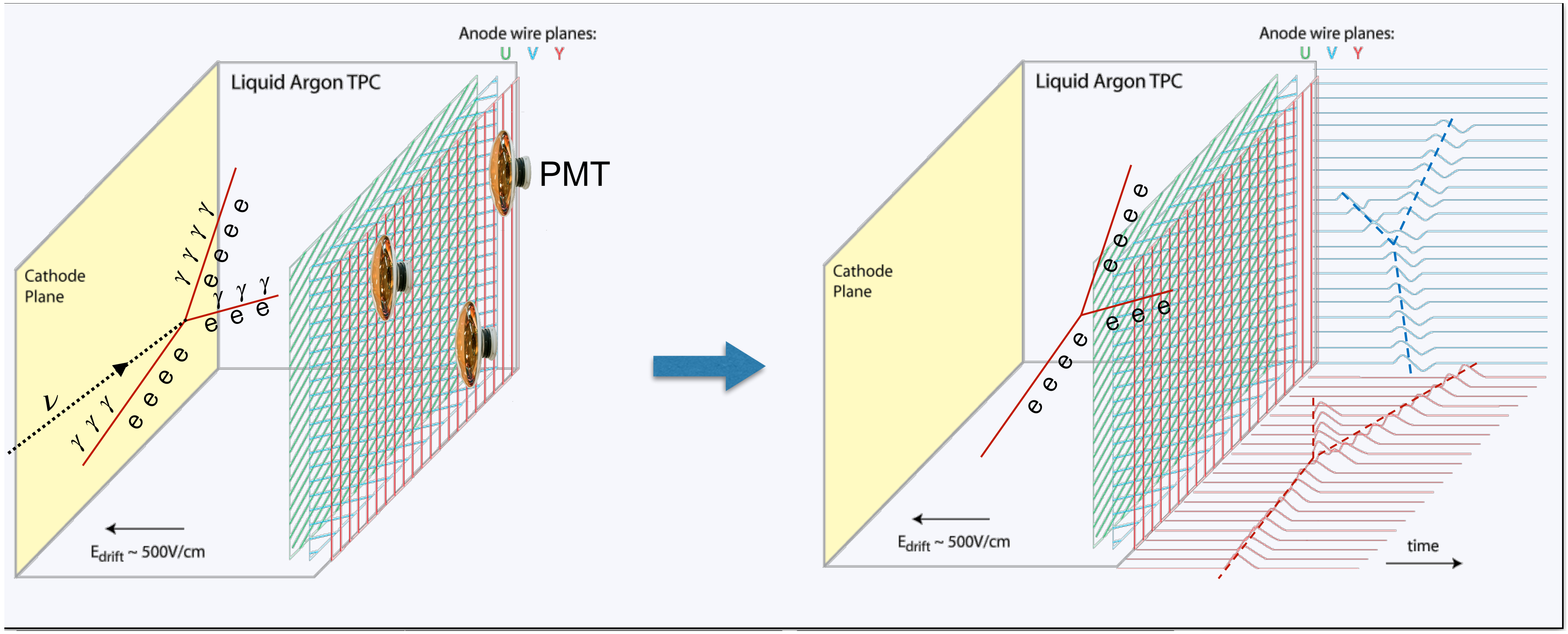


TRAKING–CALORIMETRY : LIQUID AR TPC

- Electronic "bubble chambers"
- Idea from the 70's (C.Rubbia) now largely adopted now for neutrino detectors, Dark matter searches..
- Detection :
  - scintillation light
  - ionisation
  - Cherenkov radiation (if relativistic particle and ß > 1/n)







WHY LAR ?

pros

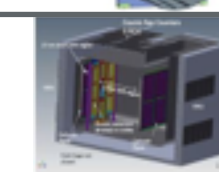
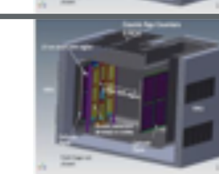
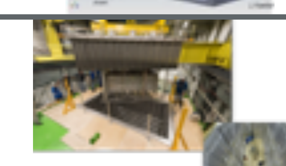
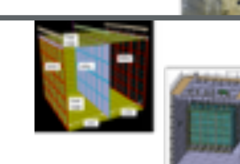
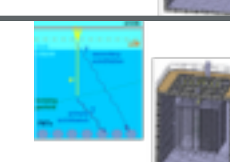
- easy to get (1% of earth atmosphere)
- ionise easily : low particle threshold
- fully active and self triggering (Ar scintillation light)
- good dielectric properties
- very fine tracking: 3D imaging
- calorimetry: total charge proportional to the deposited energy
- PID : dEdx along the track

cons

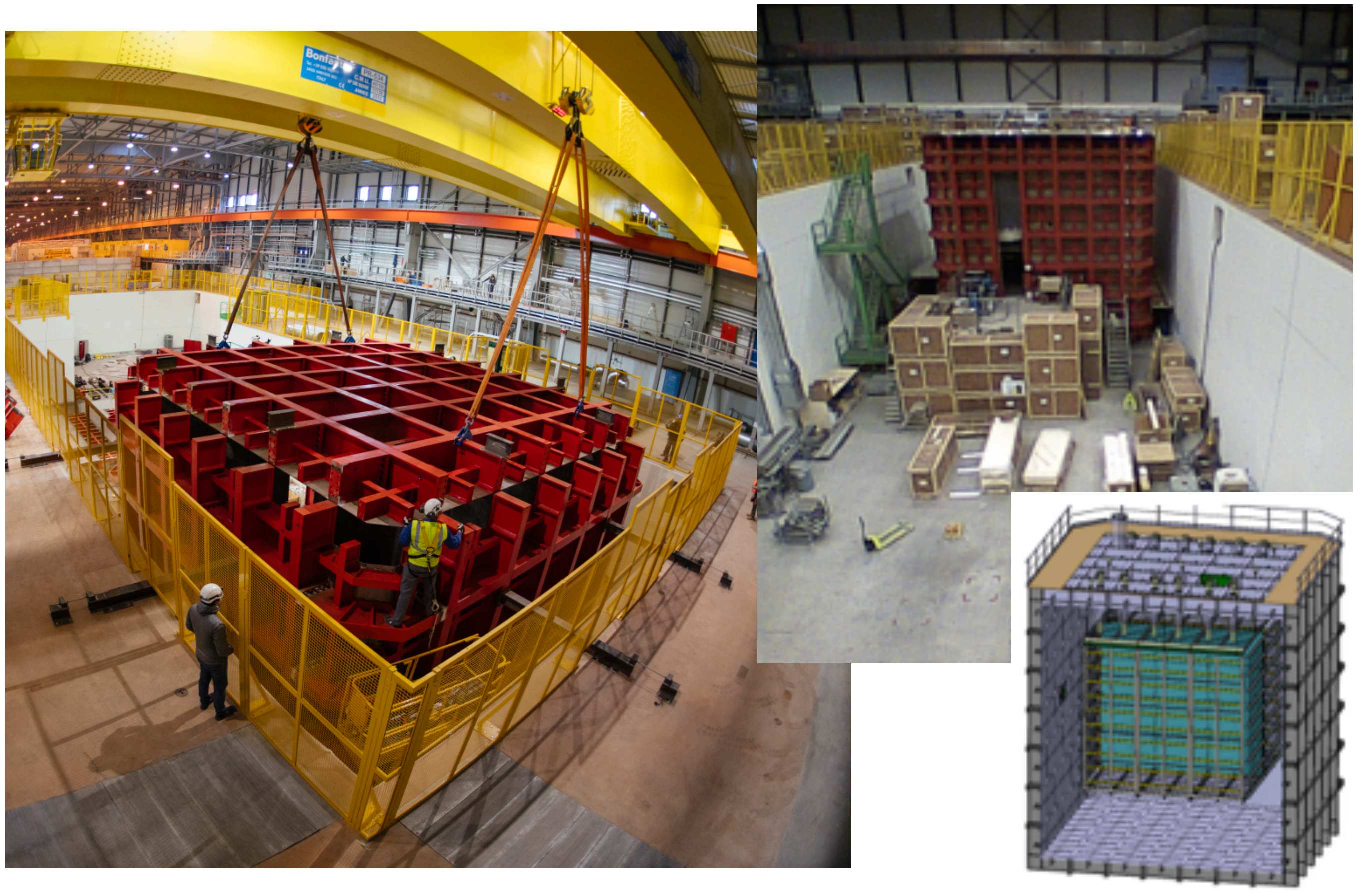
- LAr @ 87K : need cryogenics
- large mass = large volume = large drift ⇒ high purity (ppt) : filtering!
- very uniform E field over large areas
- scintillation light @128nm : wavelength shifter
- S/N not very high : cold electronics
- low v_d : not ideal for high event rates

NON EXHAUSTIVE COMPILATION OF LAR EXPERIMENTS

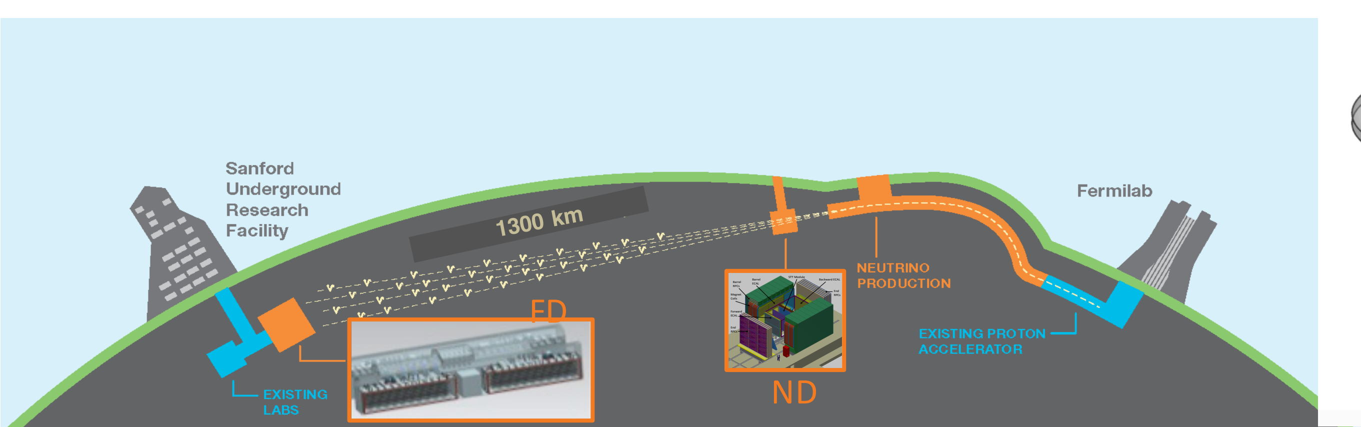
a.m. = active mass

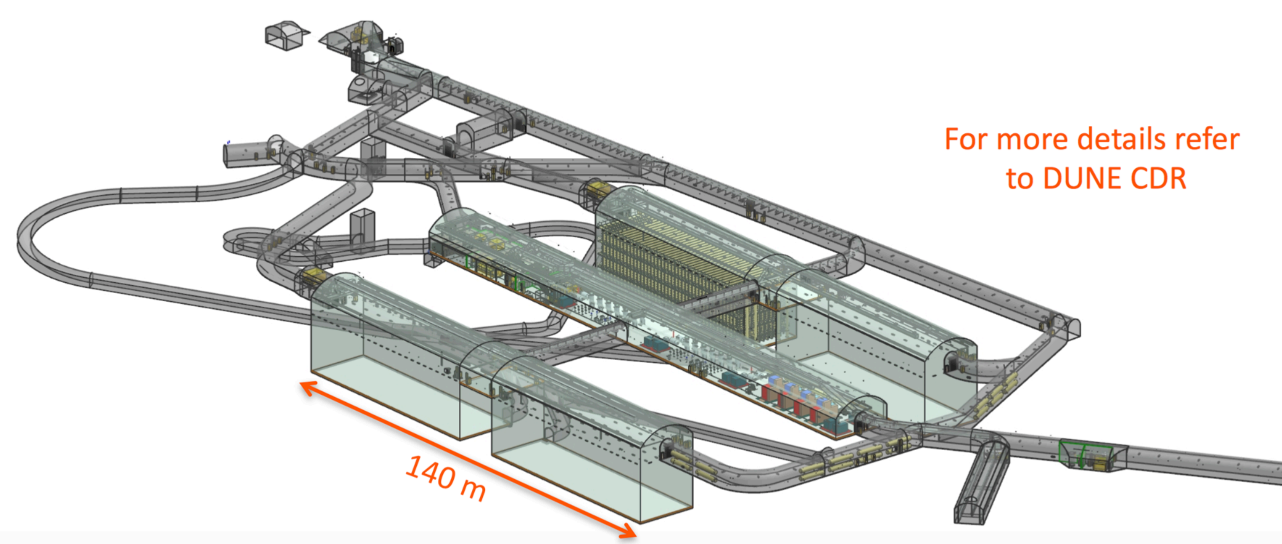
Detector	Operation	Mass (tons)	Max. drift d.	
ArgoNeuT / LArIAT	2008-2009 / 2015- oggi	0.77	47cm	
ICARUS	2010 - 2013	2x375 (476a.m.)	1.5m	
MicroBooNE	2015-today	170 (89a.m.)	2.5m	
35tons	2015-2016	35	2.2m	
SBND	>2018	112 am	4m	
WA105	2017	50	1m	
ProtoDUNE-SP	end 2018	770	3.6m	
ProtoDUNE-DP	end 2018	770	6m	
DUNE	>2026	4x 17ktons	6m (12m DP)	

LAR TPC PROTOTYPES AT CERN AND FUTURE EXPERIMENT



- protoDUNE : engineering prototype for DUNE modules 1:20 !





For more details refer to DUNE CDR

CONCLUSION – TAKE HOME MESSAGE

- Neutrino physics cover a very wide variety of topics : very hard task to be covered in few lectures
- Very large variety of detector techniques, addressing the different features and properties of neutrinos
- Many discoveries and breakthrough in the last 75years: very active domain with the aim to address some of the remaining open question in the next decade

Stay tuned!