Neutrino Oscillations

- Massive neutrinos are mixed: $$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}\,|\nu_i\rangle$$
- Mass eigenstates evolve as:

$$|\nu_i(\tau)\rangle = e^{-im_i\tau}\,|\nu_i(0)\rangle.$$

REST FRAME

$$|\nu_i(t)\rangle = e^{-i(E_i t - p_i L)}\,|\nu_i(0)\rangle$$

LAB FRAME

- Exploiting the fact that neutrinos are almost massless:

$$L \simeq t; \qquad E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2E} \quad \Rightarrow \quad |\nu_\alpha(L)\rangle \simeq \sum_{i=1}^{n} U^*_{\alpha i}\,\exp\left(-i\frac{m_i^2}{2E}L\right)|\nu_i(0)\rangle$$

- The amplitude for observing a state α at distance L with initial state β is given by:

$$\langle\nu_\beta|\nu_\alpha(L)\rangle = \sum_{i=1}^{n} U^*_{\alpha i}\,\exp\left(-i\frac{m_i^2}{2E}L\right)\sum_{j=1}^{n} U_{\beta j}\,\langle\nu_j|\nu_i\rangle$$

- Which yields **the probability:**

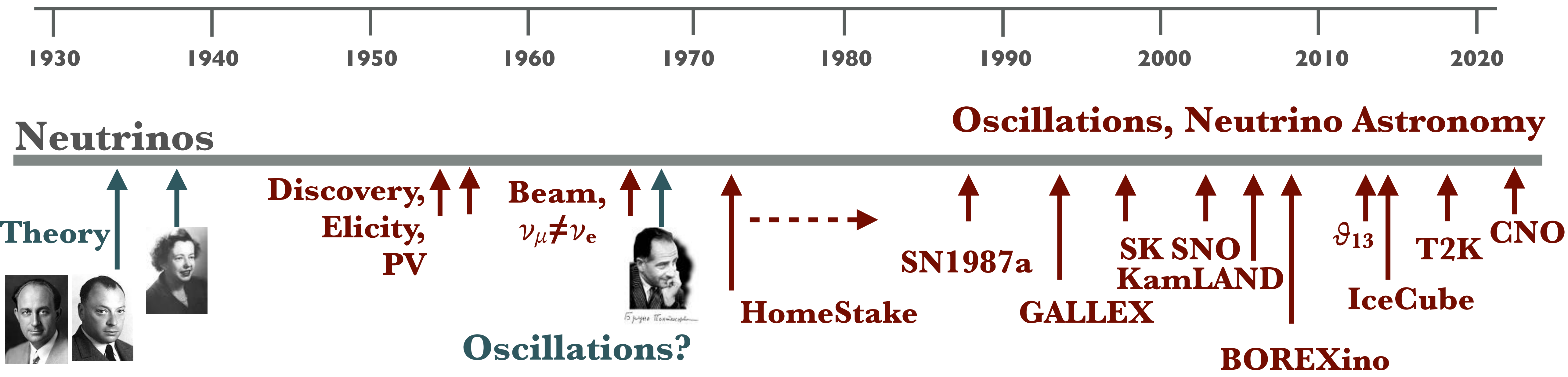
$$\xi_i^{\alpha\beta} = U^*_{\alpha i}\,U_{\beta i}; \qquad \epsilon_i = \frac{m_i^2}{2E}.$$

$$P_{\alpha\beta}(L) = |\langle\nu_\beta|\nu_\alpha(L)\rangle|^2 = \delta_{\alpha\beta} - 4\sum_{i=1}^{n}\sum_{j=i+1}^{n} \mathrm{Re}\left(\xi_i^{\alpha\beta}\,\xi_j^{*\alpha\beta}\right)\sin^2\frac{1}{2}(\epsilon_j - \epsilon_i)L$$
$$-2\sum_{i=1}^{n}\sum_{j=i+1}^{n} \mathrm{Im}\left(\xi_i^{\alpha\beta}\,\xi_j^{*\alpha\beta}\right)\sin(\epsilon_j - \epsilon_i)$$

- **DISCLAIMER:** This calculation, reported almost everywhere, is **WRONG. Plane waves have exactly defined momentum,** and in that case there can be no oscillation!
  - However, the correct calculation with **wave packets** yields the same result, up to the distance at which wave packets cease to overlap. **The formula is RIGHT, until coherence is lost.**

For a correct calculation with wave packets see e.g. Giunti-Kim

Experimental neutrino physics: state of the art

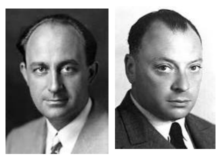


Experimental neutrino physics: state of the art

1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

Neutrinos — **Oscillations, Neutrino Astronomy**

Theory



Discovery, Elicity, PV

Beam, $\nu_\mu \neq \nu_e$

Oscillations?

HomeStake

SN1987a

GALLEX

SK SNO

KamLAND

BOREXino

ϑ_{13}

IceCube

T2K

$|\Delta m^2| = 2.47 \pm 0.04 \; 10^{-3}\ eV^2$

$\theta_{23} = 47.5 \pm 3.2°$

$\delta_D = ?\ (-\pi/2\ ?)$

$\theta_{13} = 8.56 \pm 0.15°$

$\delta m^2 = 7.40 \pm 0.21 \; 10^{-5}\ eV^2$

$\theta_{12} = 33.6 \pm 0.77°$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_D} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta_D} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

Atmospheric
Accelerators LBL
L ~ 700 km

Reactors L ~ 1 km
LBL L ~ 200 km

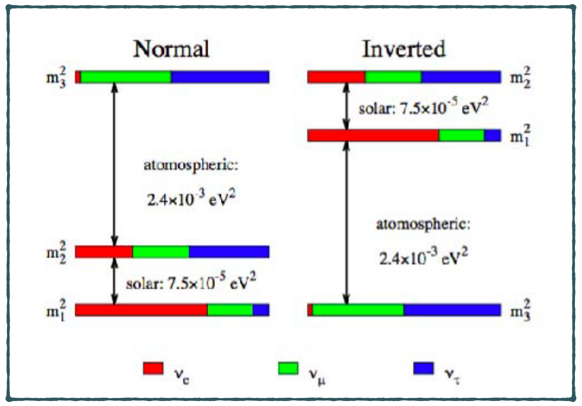
Solar
Reactors
L ~ 200 km

$0\nu\beta\beta$

Next generation (JUNO, T2HK, DUNE) has sufficient precision for global fits to almost all parameters

Combined T2K, Nova, etc analysis may yield an early "detection" of CP violation phase δ_D

$\nu \neq \bar{\nu}$?



Dirac vs Majorana ($\nu \neq \nu$?) — **$0\nu\beta\beta$**

U_{PMNS} unitary?

$\delta_{CP} \neq 0$?

$\Delta m^2 > 0$?

ϑ_{23} maximal? Octant ?

→ **OSCILLATIONS**

Absolute Mass scale — **Spectrometers, μBolometers, EUCLID**

CNO from the Sun — **BOREXino. DONE ! 2020**

Astrophysics — **IceCUBE, KM3Net**

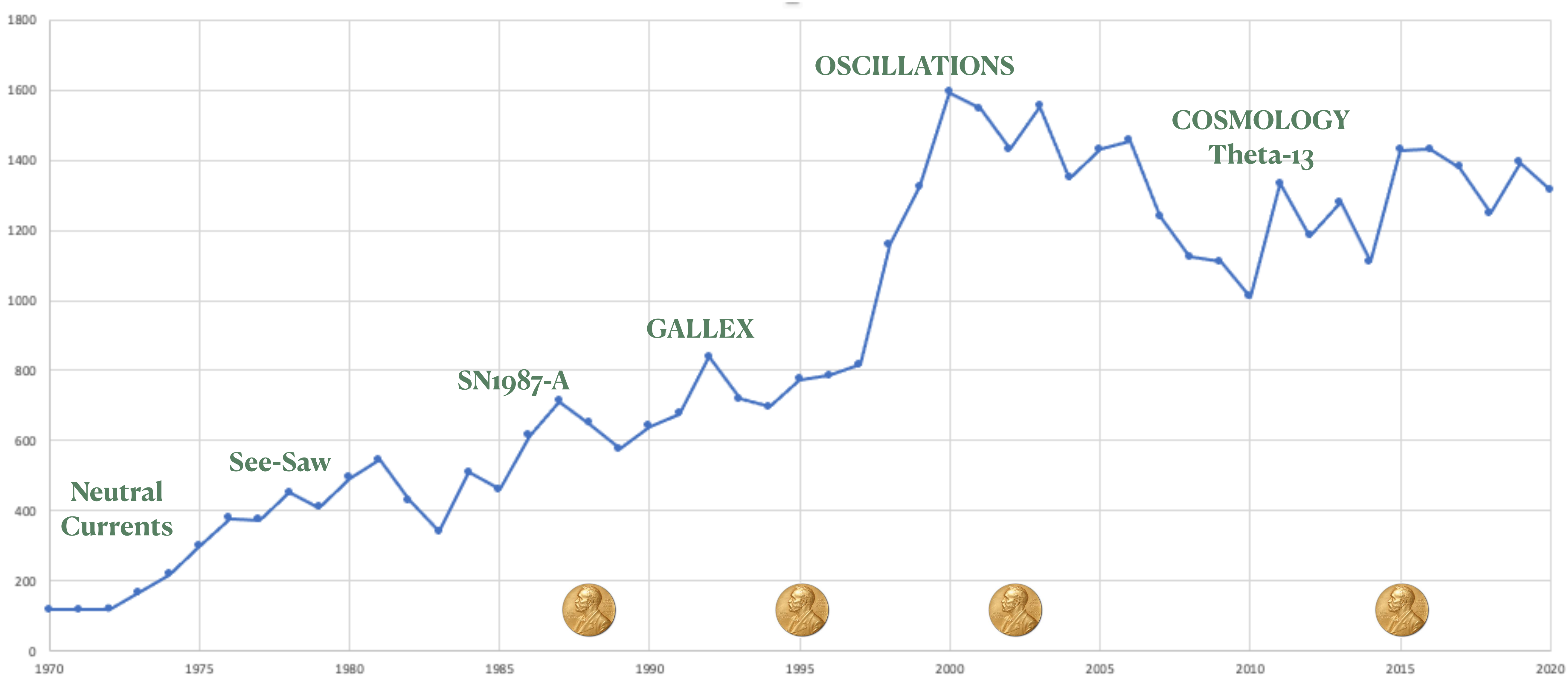
Multi-messenger (GW, photons) — **VIRGO-LIGO + Astronomy**

CνB — **R&D for PTolemy, Euclid, CMB fits**

SN (pulse and relics) — **Borexino, LVD, JUNO, SK, HK, DUNE**

An active and growing field

PAPERS WITH 'neutrino' IN TITLE
1970 - 2020 [inspire.hep]



Artificial and natural neutrino sources

- **Artificial**
  - Nuclear Reactors
  - Accelerators
  - Radioactive sources (in some special cases)

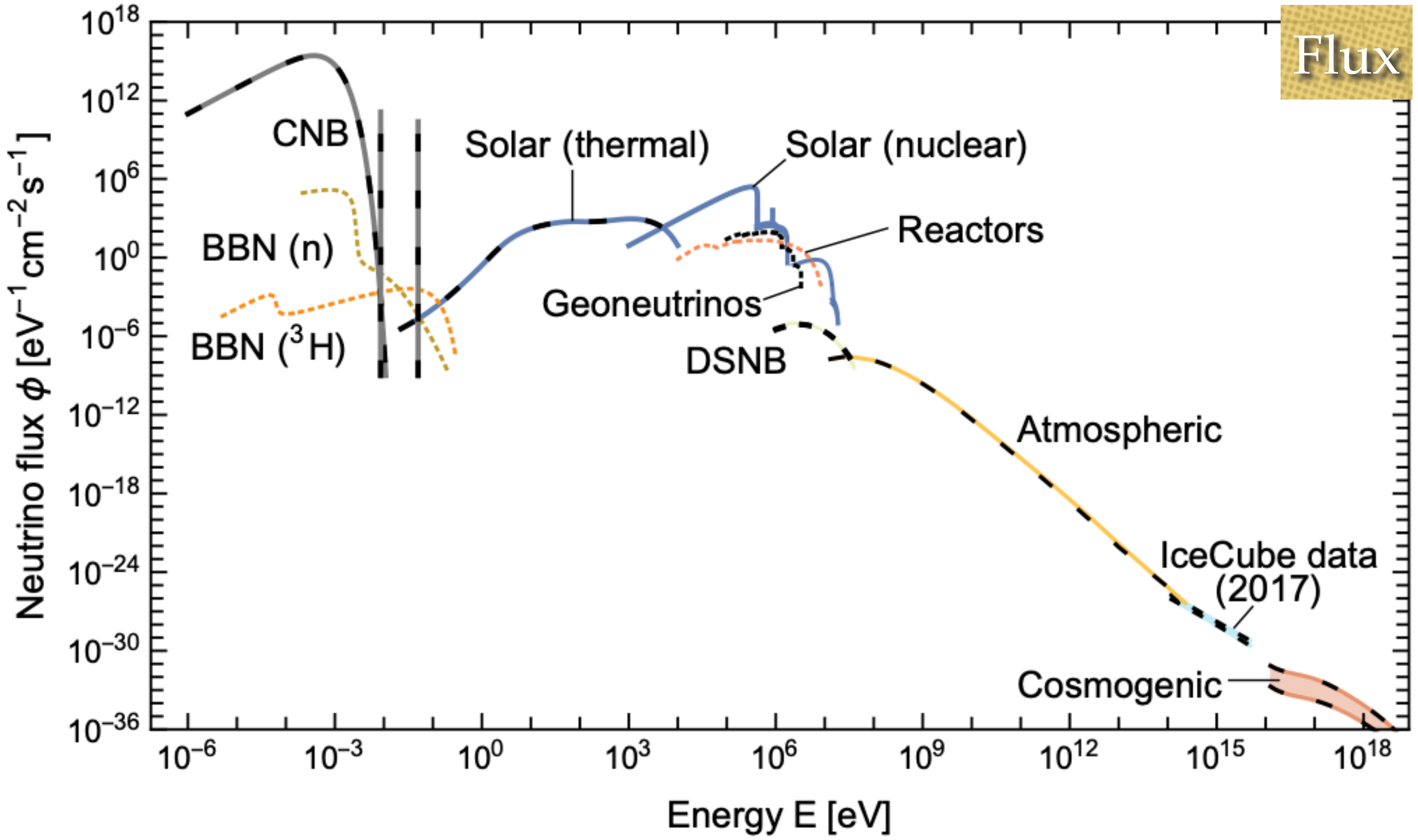
- **Natural**
  - Sun
  - Atmospheric
    - secondary from cosmic rays interaction in atmosphere
  - Cosmic
    - coming from outside Earth
  - Geo-neutrinos
    - from Earth bulk and crust radioactivity
  - Diffuse SN (statistical sum of many past SN events)
  - SN
    - only once so far, **SN1987a**
  - Relic (from big bang)

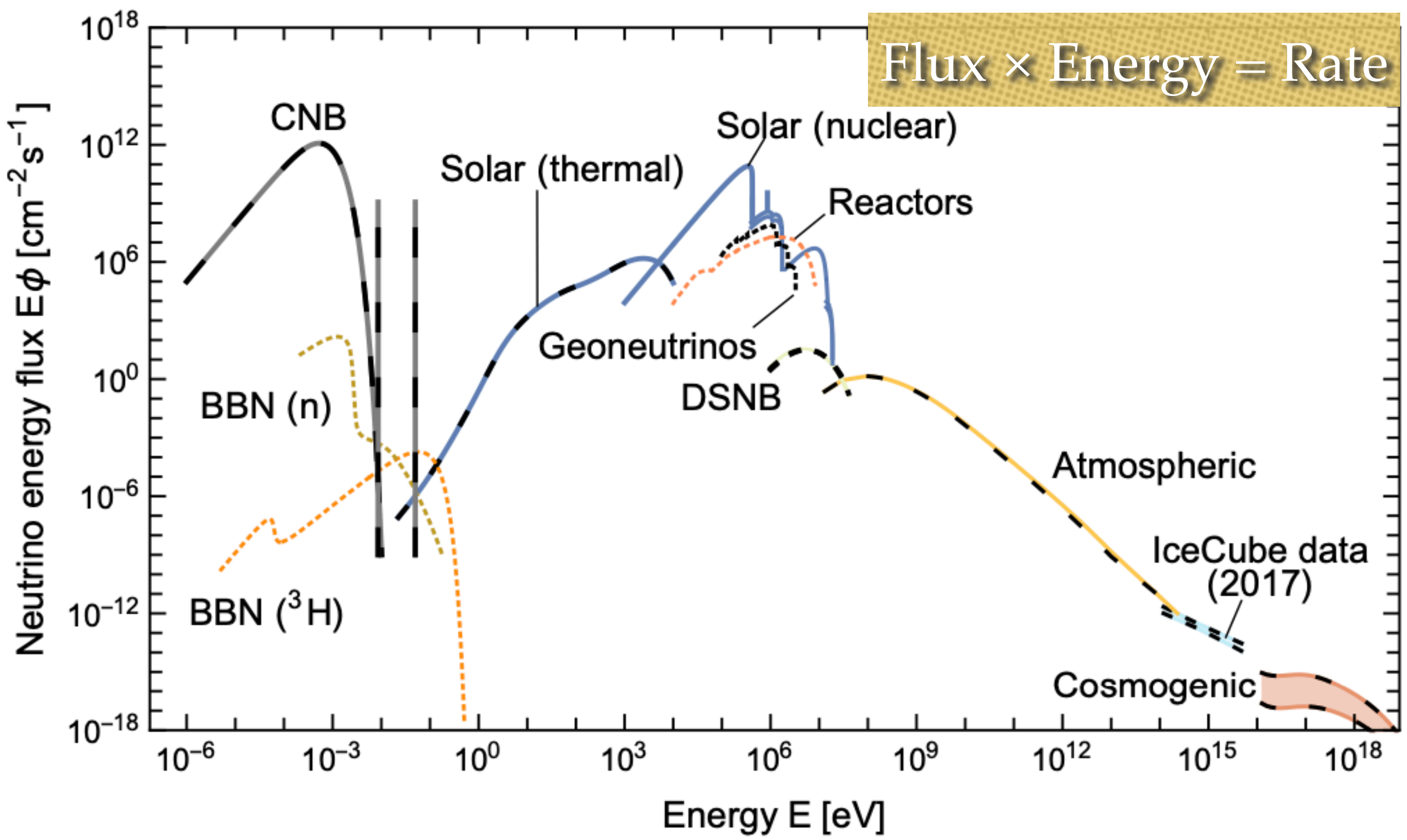
Natural neutrino sources

Neutrinos ———

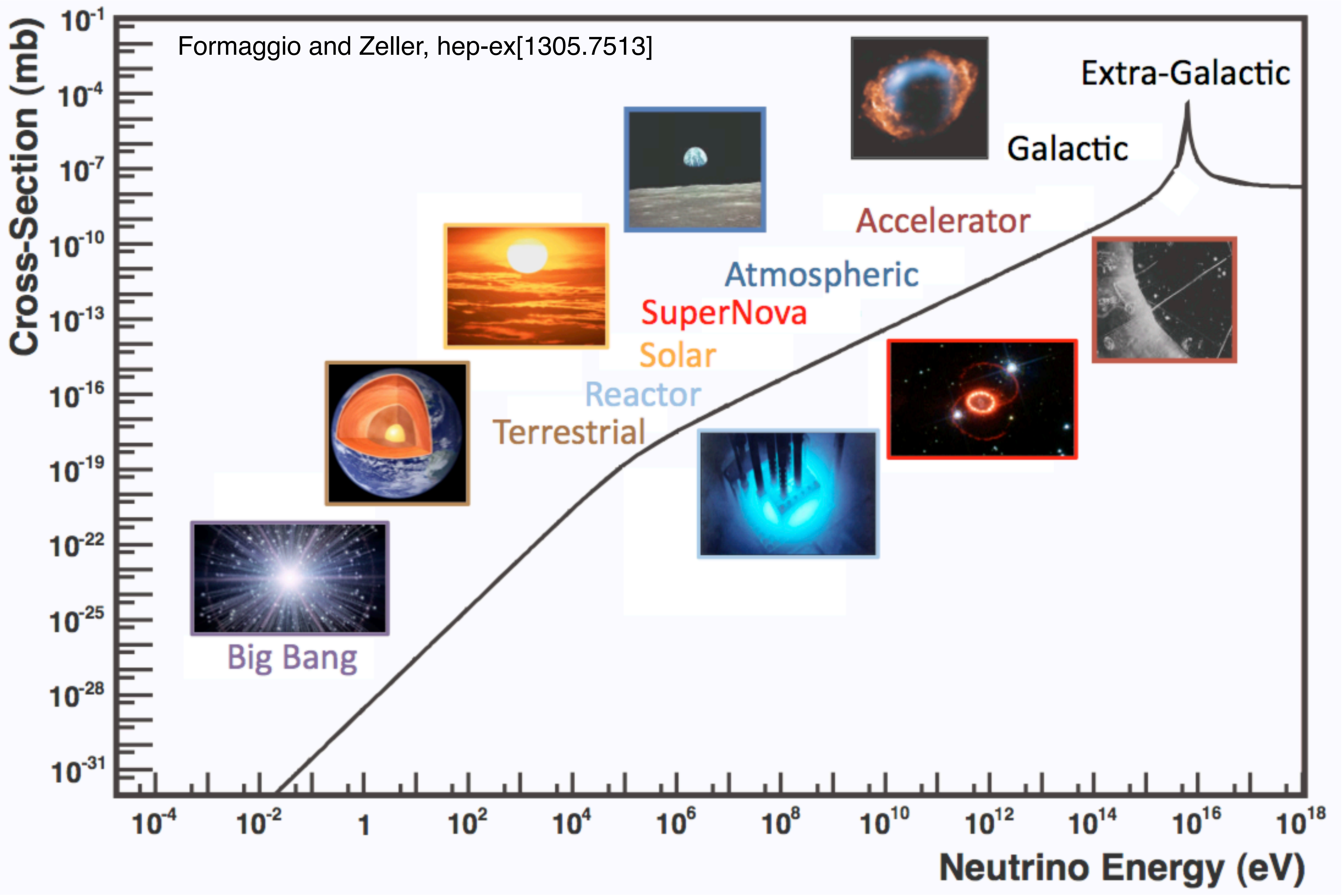
Anti-Neutrinos - - - - - -

From: arXiv: 1910.11878v3
(Vitagliano, Tamborra, Raffelt)





Neutrino energy ranges



Detecting neutrinos: key parameters and processes

$$N_{obs} = N_{targ}\ T \int_{E_{thr}}^{\infty} \Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu$$

NOTE: this formula is good for MC simulations. Real neutrino energy is usually unknown, so data analysis must be done using **reconstructed energy.** **A complex issue,** not covered.

- **N_{obs} :** number of detected events above
- **E_{thr}:** lower detection threshold (strongly dependent on technology)
- **N_{targ}:** number of targets (electrons, protons, nuclei)
  - Typical value $N_{targ} \sim 6\ 10^{26}\ kg^{-1}$ (e^- or p)
- **T:** exposure time ($2.7\ 10^7$ s / y typical up-time)
- ϕ: neutrino flux
  - **Sun:** ~ **10^6 - 10^{10} $cm^{-2}\ s^{-1}$** at Earth; **Reactors:** ~ **10^{12} $cm^{-2}\ s^{-1}$** @ 20 m; **Accelerators:** ~ **1 $cm^{-2}\ s^{-1}$** @ 1000 km
- **σ:** cross section (total for the specific FS)
- **ε:** efficiency/acceptance; usually large, but not always

- TWO SIGNIFICANT EXAMPLES:
  - **SOLAR (Borexino, elastic scattering on electrons)**

$$N_{obs} = [3.\ 10^{31} e^-] \times [86400\ s\ ] \times [6\ 10^9\ cm^{-2}s^{-1}] \left[\frac{0.7\ 10^{-45}\ cm^2}{(MeV)}\right] \simeq\ 50\ ev/day$$

100 t — **1 day** — **flux** — **cross section**

  - **ACCELERATOR (DUNE, inelastic scattering on Liquid Argon)**

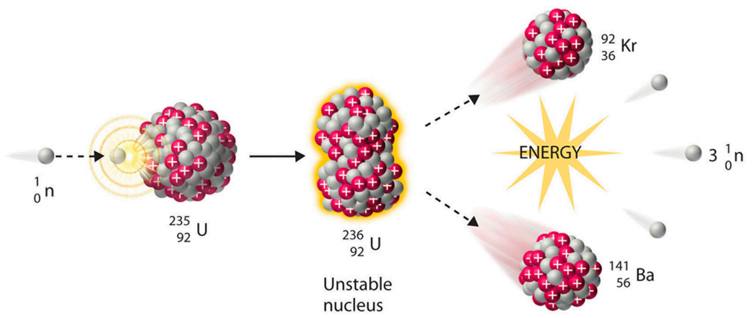
kTon required

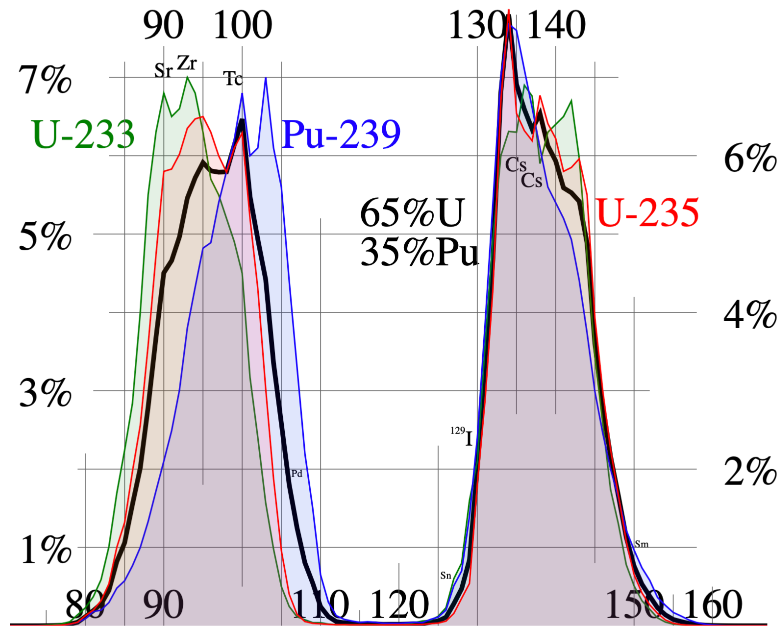
$$N_{obs} = [\frac{M}{1.67\ 10^{-27}\ kg}] \cdot [2.\ 10^7\ s\ ] \cdot [1\ cm^{-2}s^{-1}] \cdot \epsilon \cdot \left[\frac{0.7\ 10^{-38}\ E_\nu\ cm^2}{GeV}\right] \simeq 40\ 10^{-6} \frac{E_\nu}{GeV} \epsilon \frac{M}{kg}$$

Number of nucleons — **Effective year** — **Strong beam @ 1000 km** — **cross section**

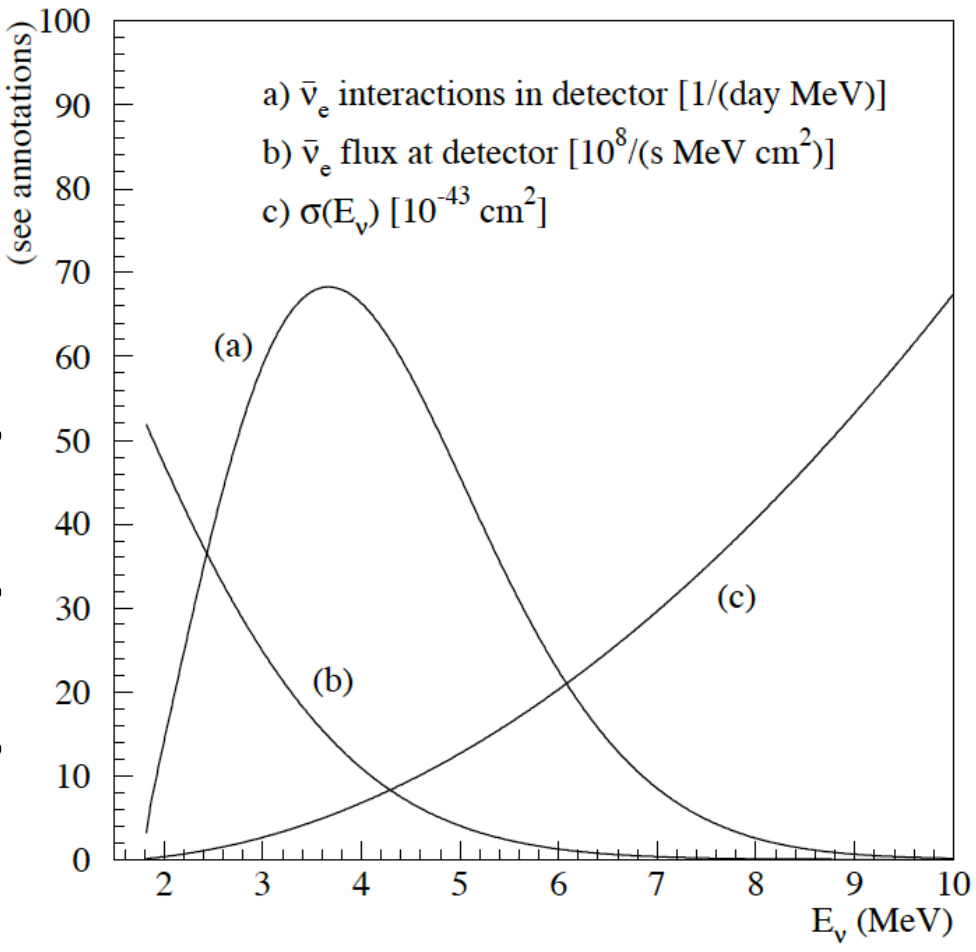
Nuclear reactors

- A reactor is a powerful source of **anti-neutrinos**
  - Each U fission yields 200 MeV on average, and 6 ν_e
    - Flux: ~ **2. 10^{20} s^{-1} GW^{-1},** isotropic, $<E_\nu> \simeq 0.5$ MeV
    - About ~ **4. 10^{12} s^{-1} cm^{-2}** for 1 GW at **20 m from the core**
- **The details of the anti-neutrino spectrum are hard to compute, and still subject of research**
  - Dominating process: ^{235}U **fission** and sub-sequent β decays **(6 on average)**





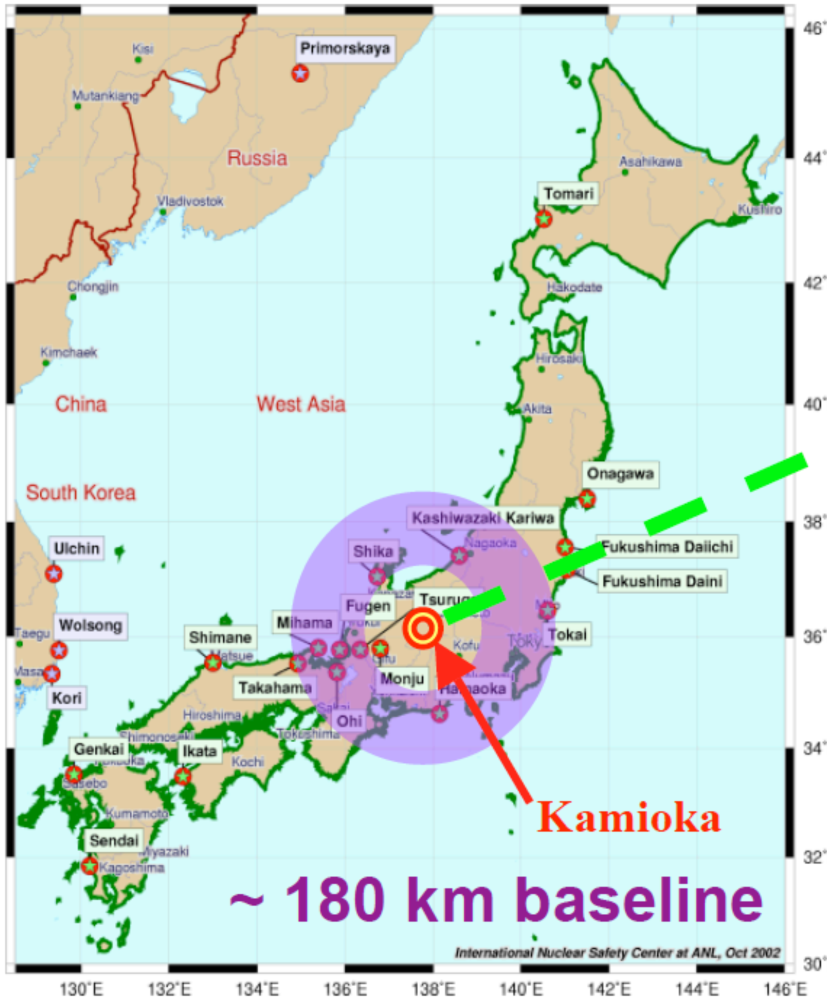
Fission products mass number A

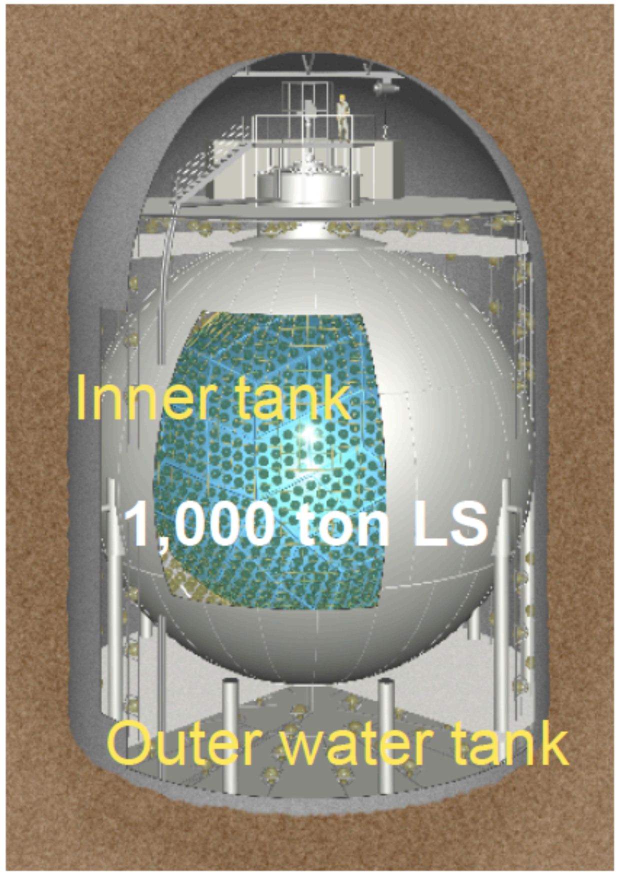


  - The flux depends on **reactor type** and also on **time** because **fuel composition evolves**

Example: KamLAND experiment

- **Kam**ioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector





34% photo-coverage with
1325 17” and 554 20” PMTs

2 flavor neutrino oscillation

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]l[m]}{E[\mathrm{MeV}]}\right)$$

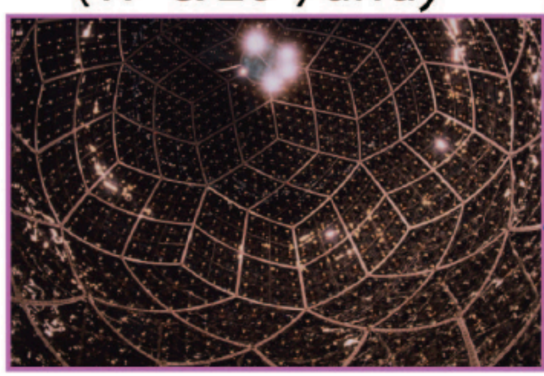
most sensitive region

$$\Delta m^2 = (1/1.27)\cdot(E[\mathrm{MeV}]/L[m])\cdot(\pi/2)$$
$$\sim 3\times 10^{-5}\mathrm{eV}^2$$

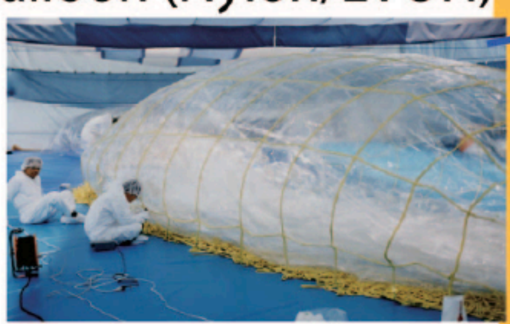
KamLAND detector

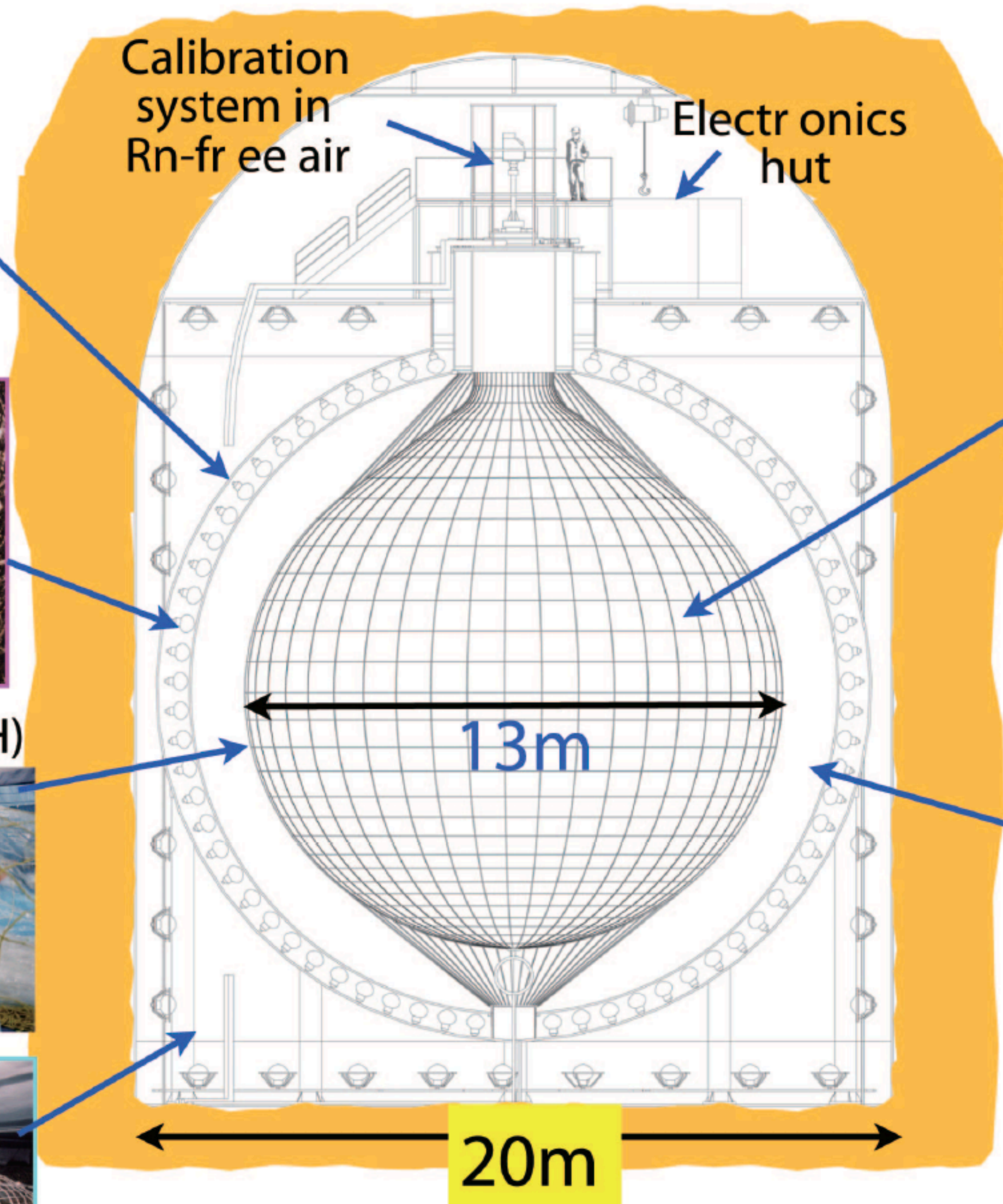
Stainless steel tank

1879 PMT
(17″& 20″) array



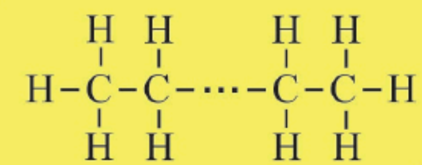
Balloon (Nylon/EVOH)



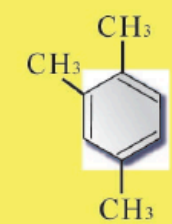


Outer detector : 3.2kton water shield and 225 20″PMT s to detect cosmic μ's)

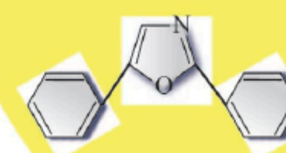
Liquid Scintillator ~1kton



Normal dodecane ($C_{12}H_{26}$) (80%)



Pseudocumene (20%)



PPO (1.36 ±0.03g/l)

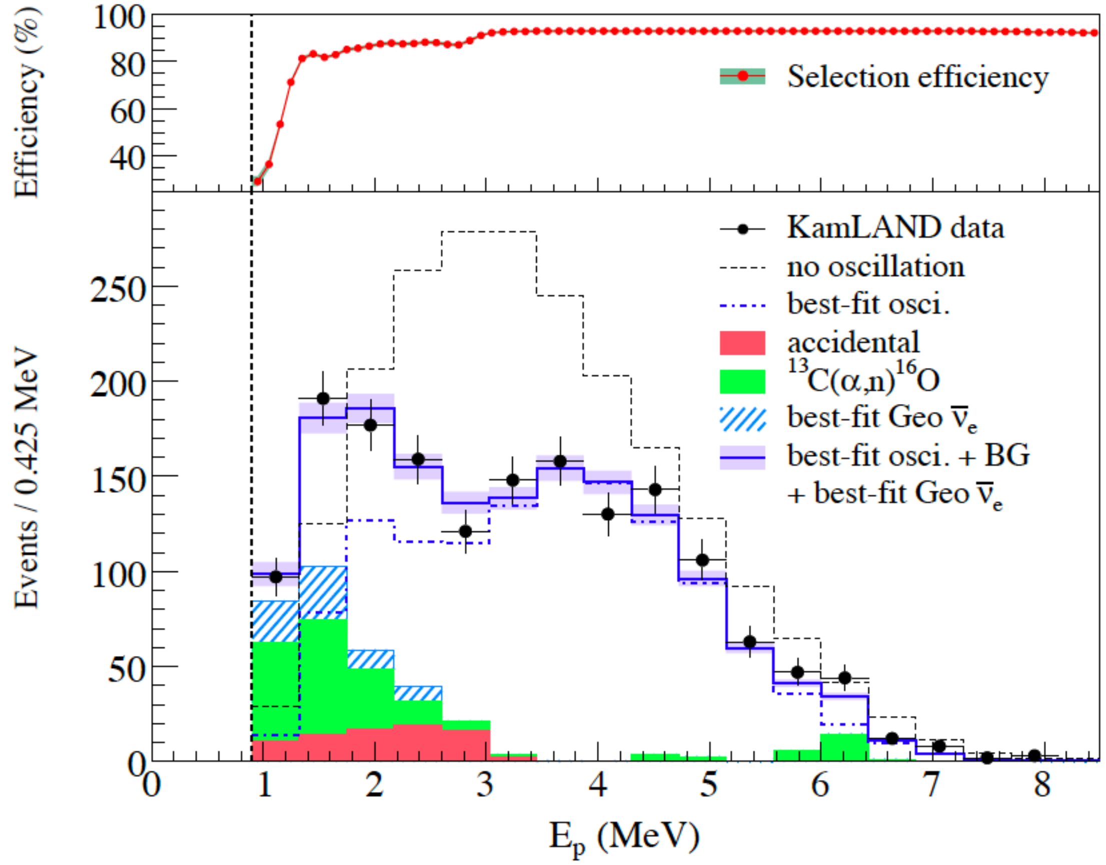
Buf fer Oil (dodecane)

Vertex r esolution ~12cm/ $\sqrt{E_{[MeV]}}$

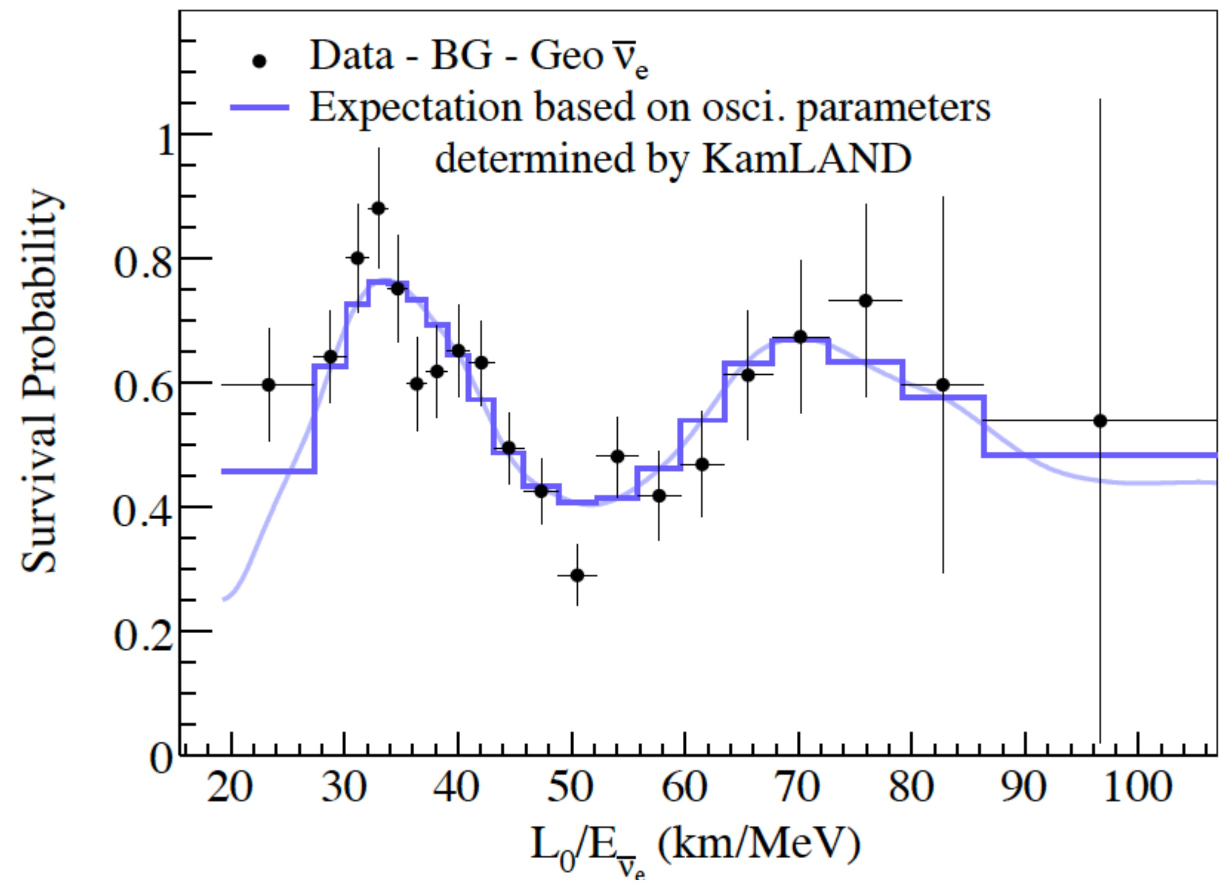
Ener gy resolution 6.5%/ $\sqrt{E_{[MeV]}}$

A neat oscillation experiment

Prompt Event Spectrum

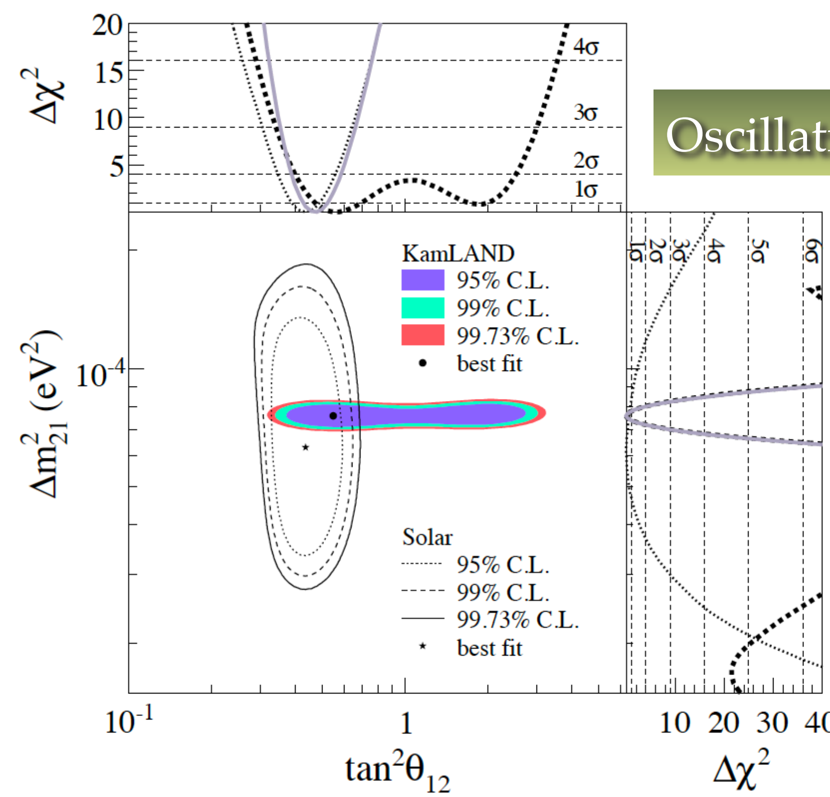


Survival probability



$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]l[m]}{E[\mathrm{MeV}]}\right)$$

Oscillation parameters



How to make a neutrino beam

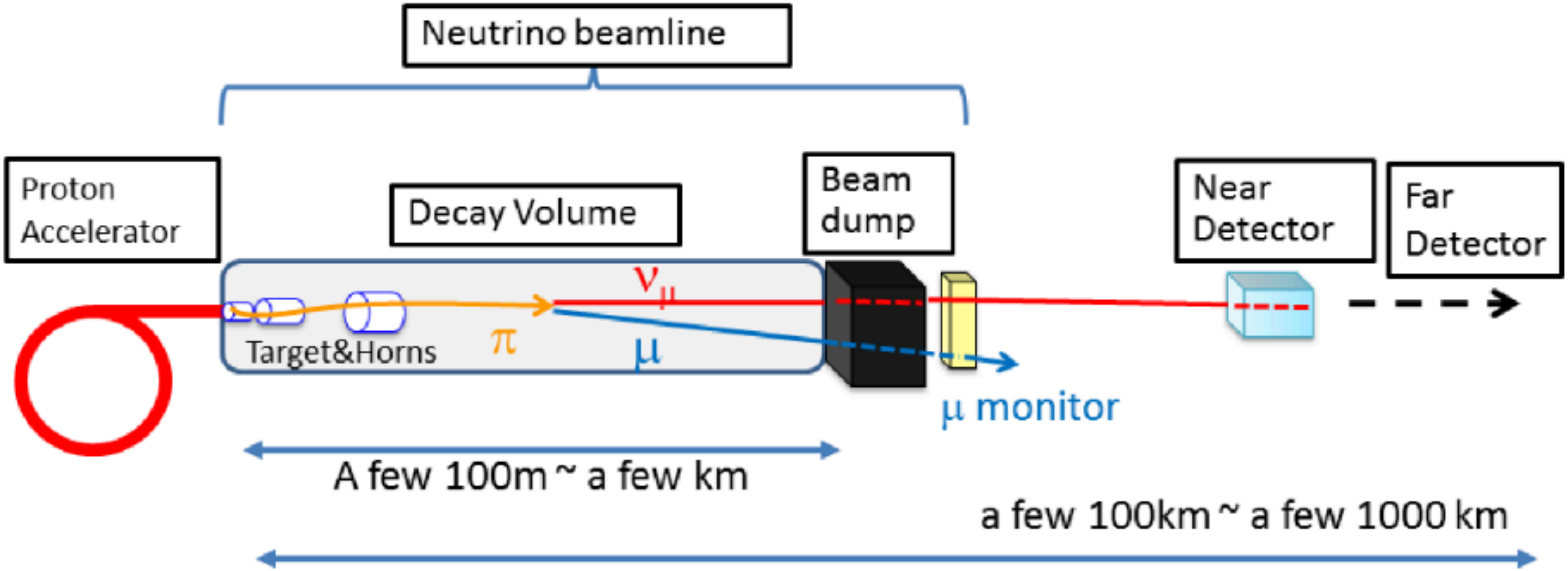
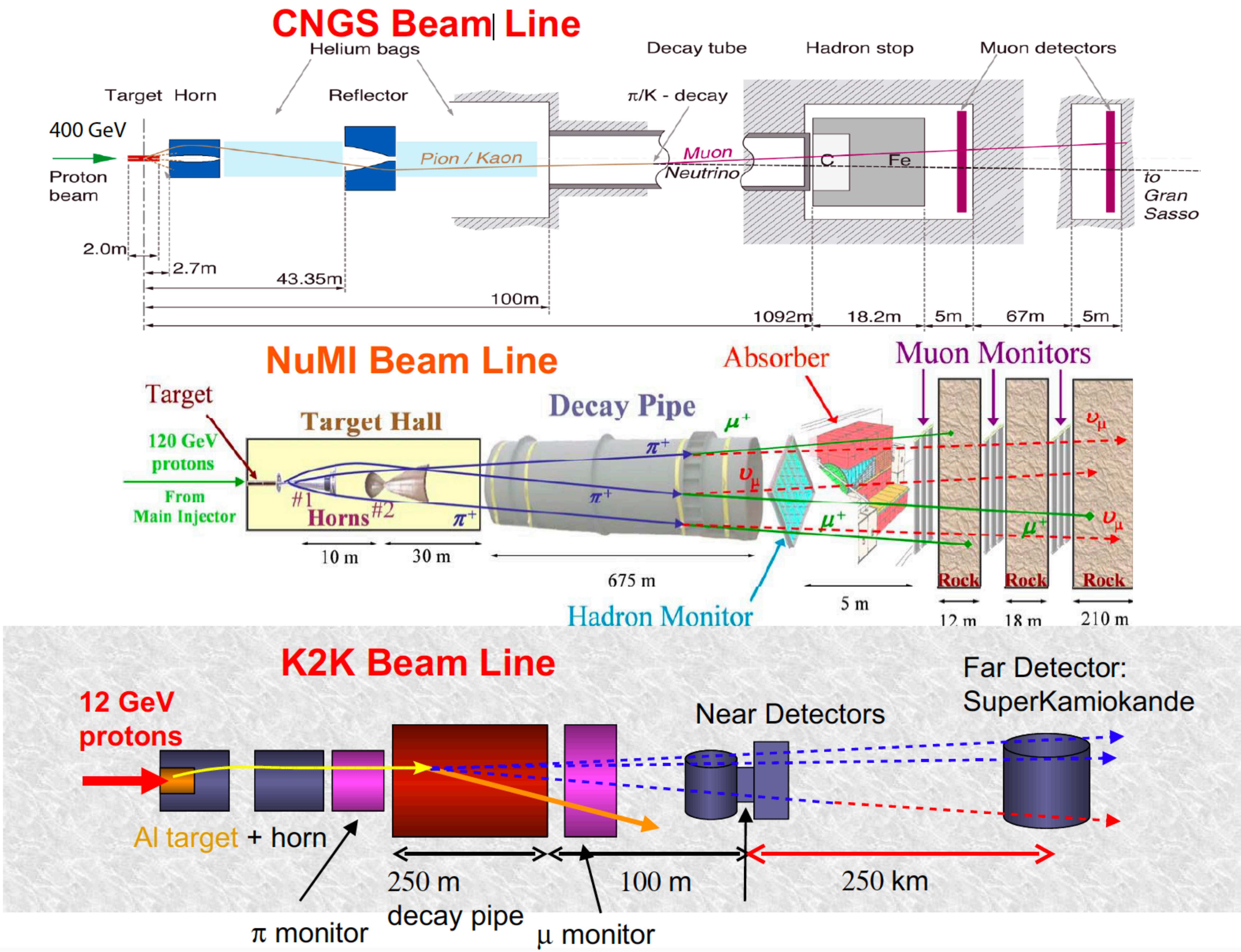


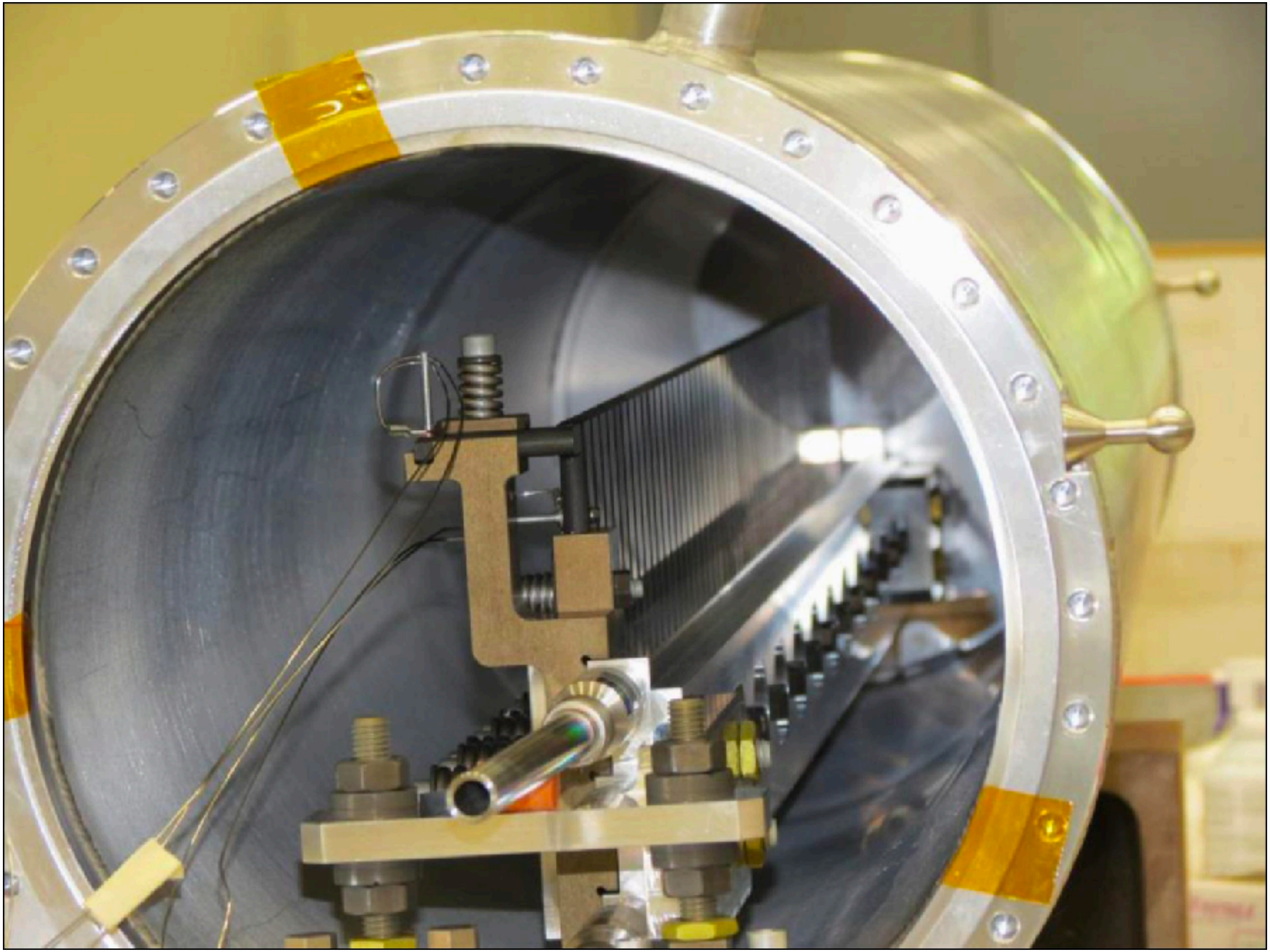
FIGURE 1. Components of the accelerator neutrino experiment

XXVI International Conference on Neutrino Physics and Astrophysics
AIP Conf. Proc. 1666, 130001-1–130001-6; doi: 10.1063/1.4915579

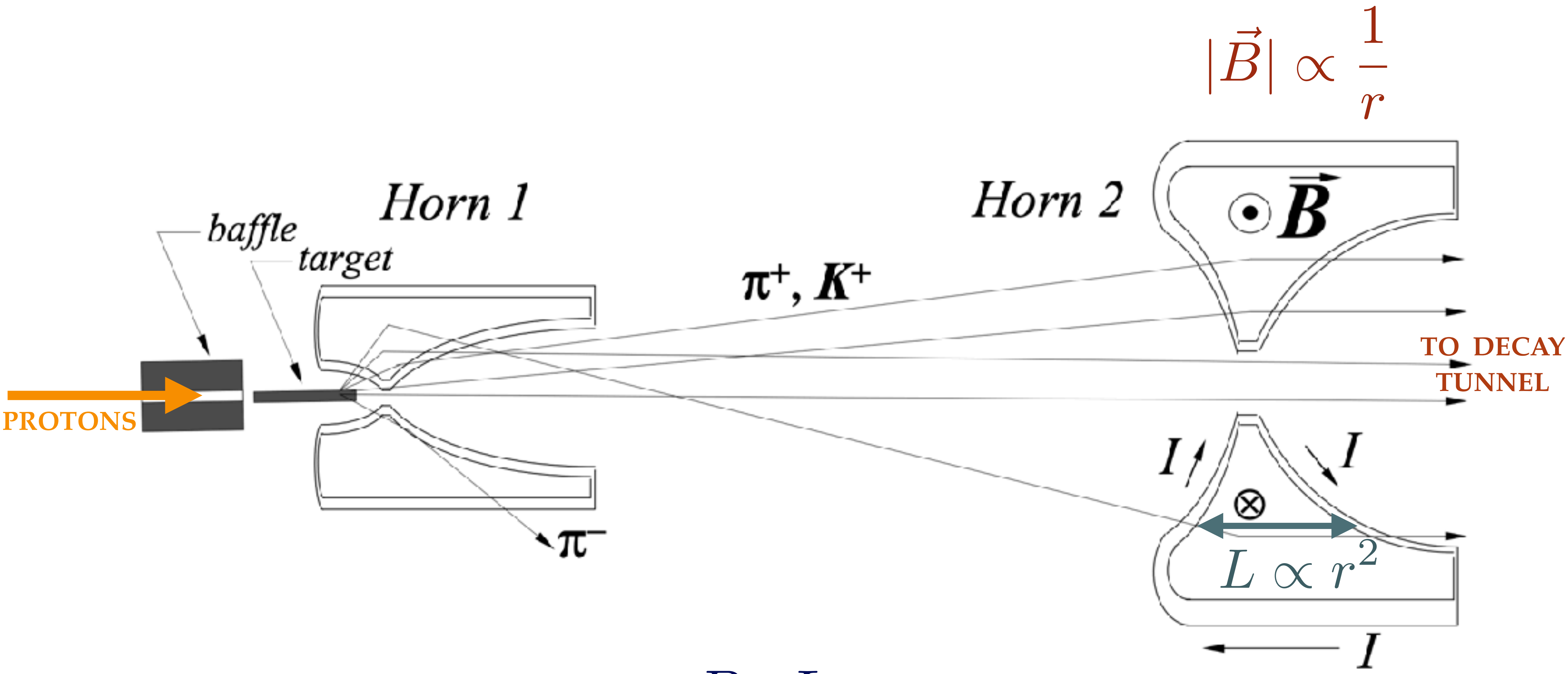
Neutrino beams: examples



NuMi target



Focussing

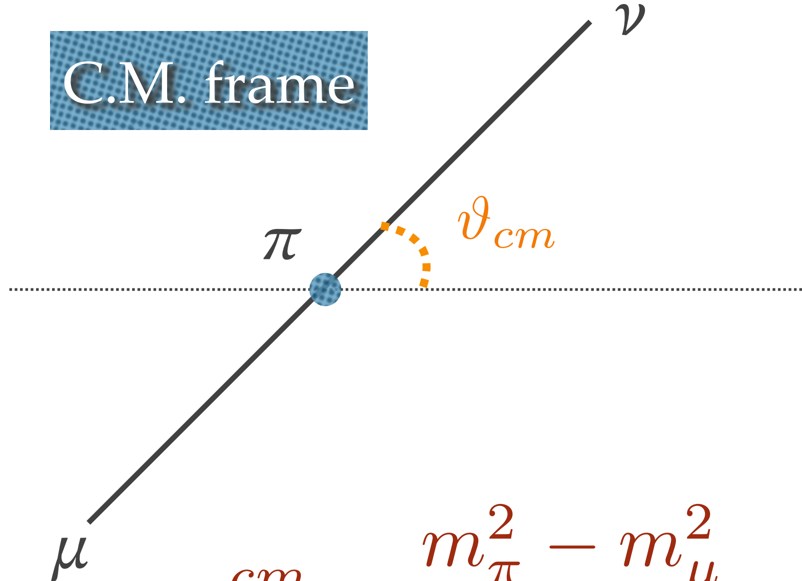


$$p_{kick} \propto B \cdot L \propto r$$

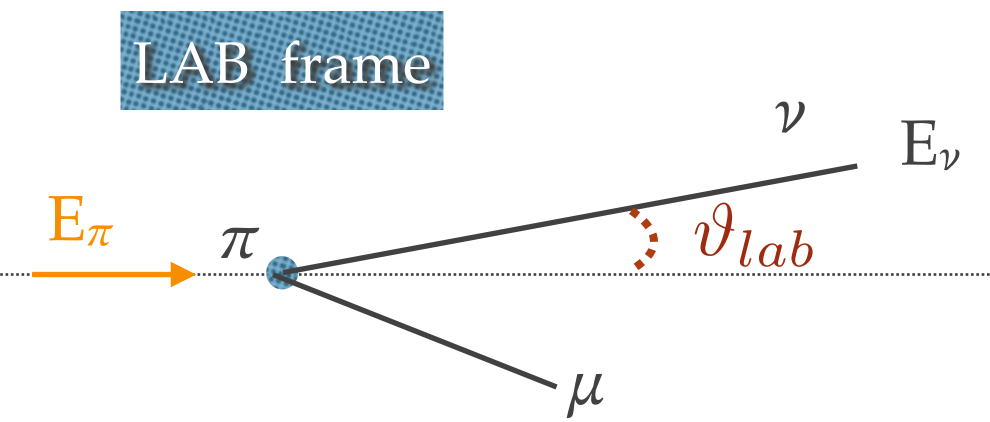
- "Forward" current: select π^+, and get mainly ν_μ
- "Reversed" current: select π^-, and get mainly $\bar{\nu}_\mu$

Horns

ON-axis vs OFF-axis: selecting neutrino energy



$$\gamma = \frac{E_\pi}{m_\pi}$$

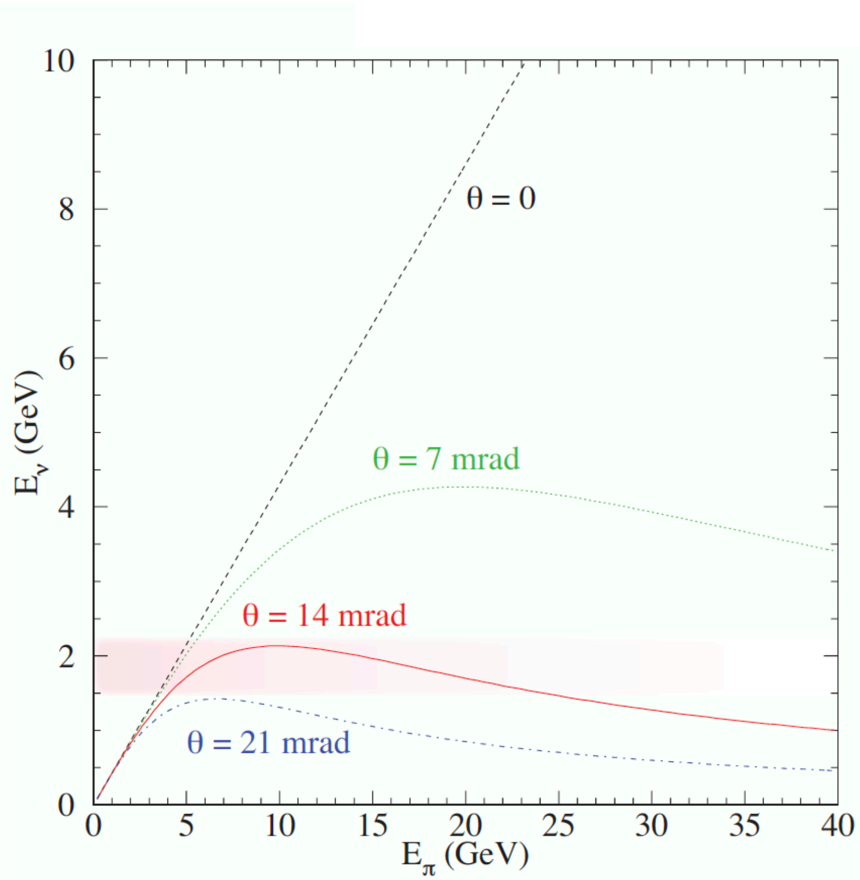


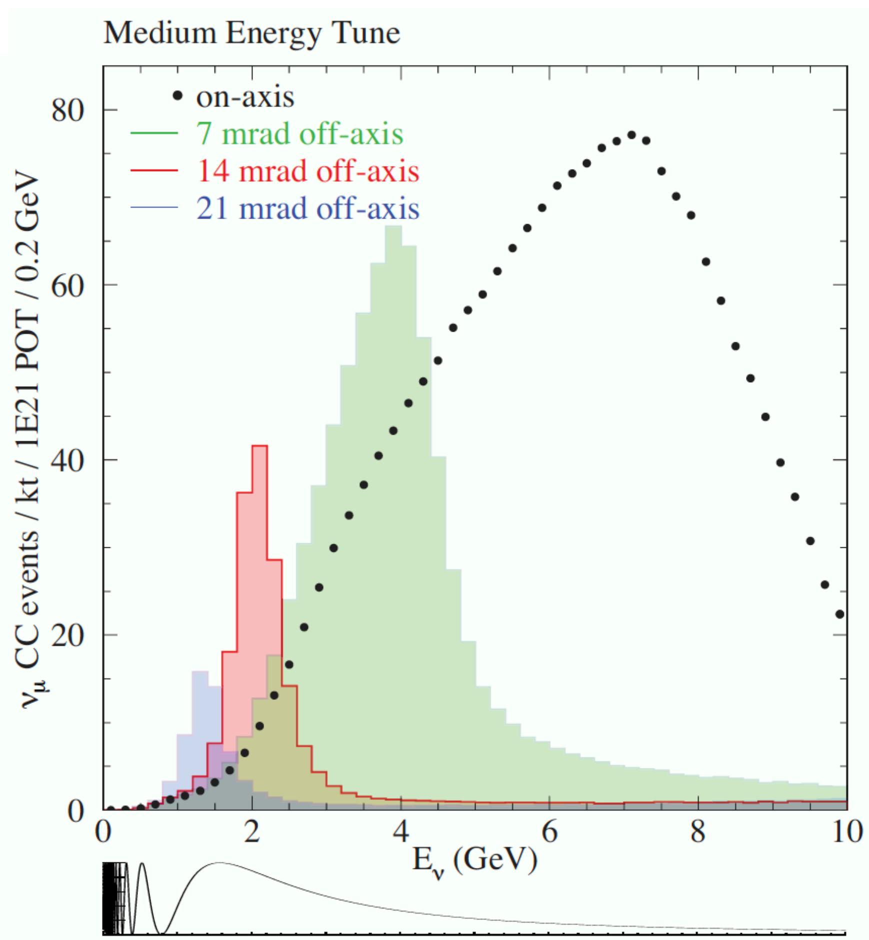
$$p_\nu^{cm} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$$

$$p_\nu^{lab} = E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \vartheta_{lab}^2}$$

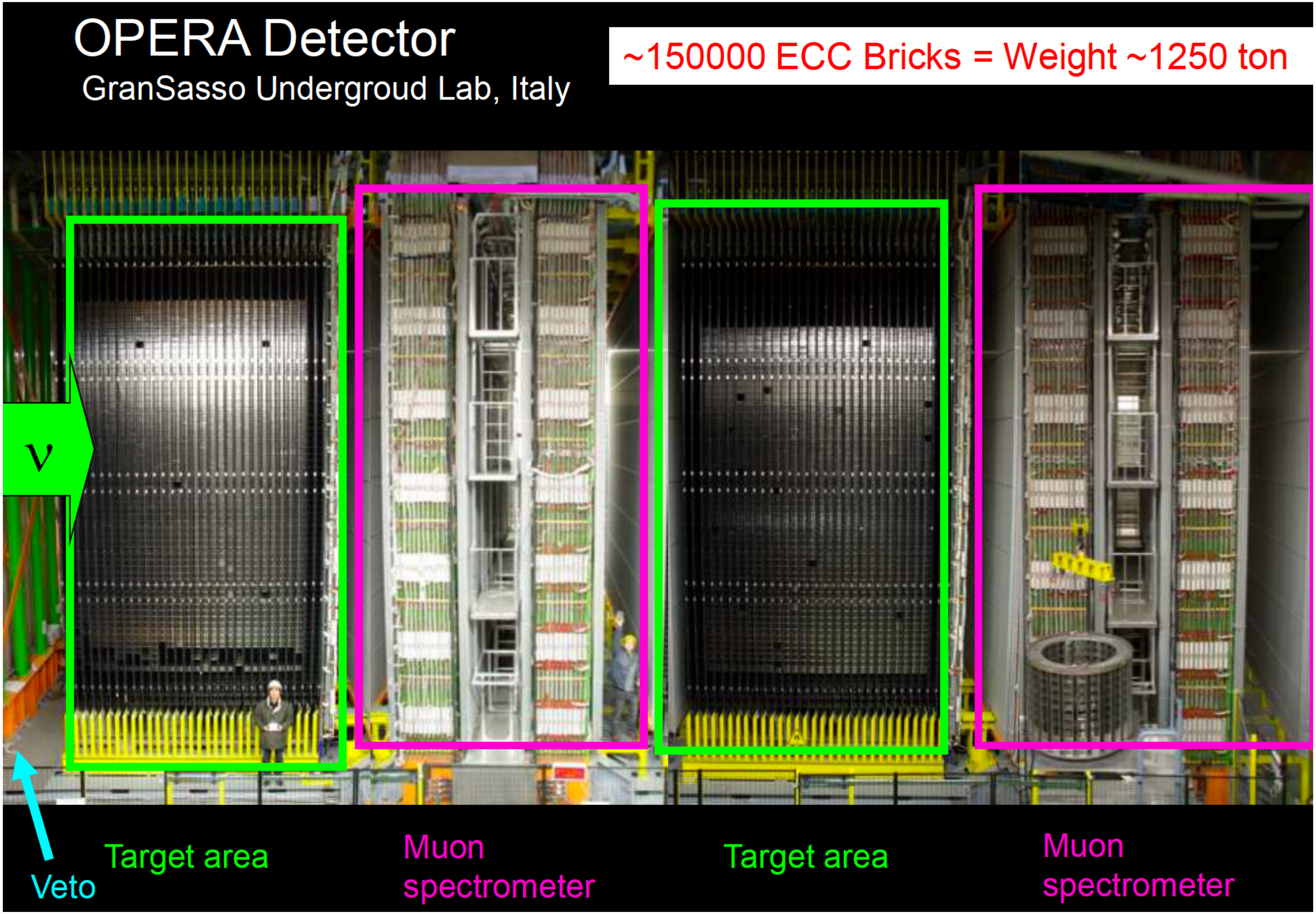
- **OFF-axis** there is a **strong correlation** between neutrino **energy and angle**

NuMi example

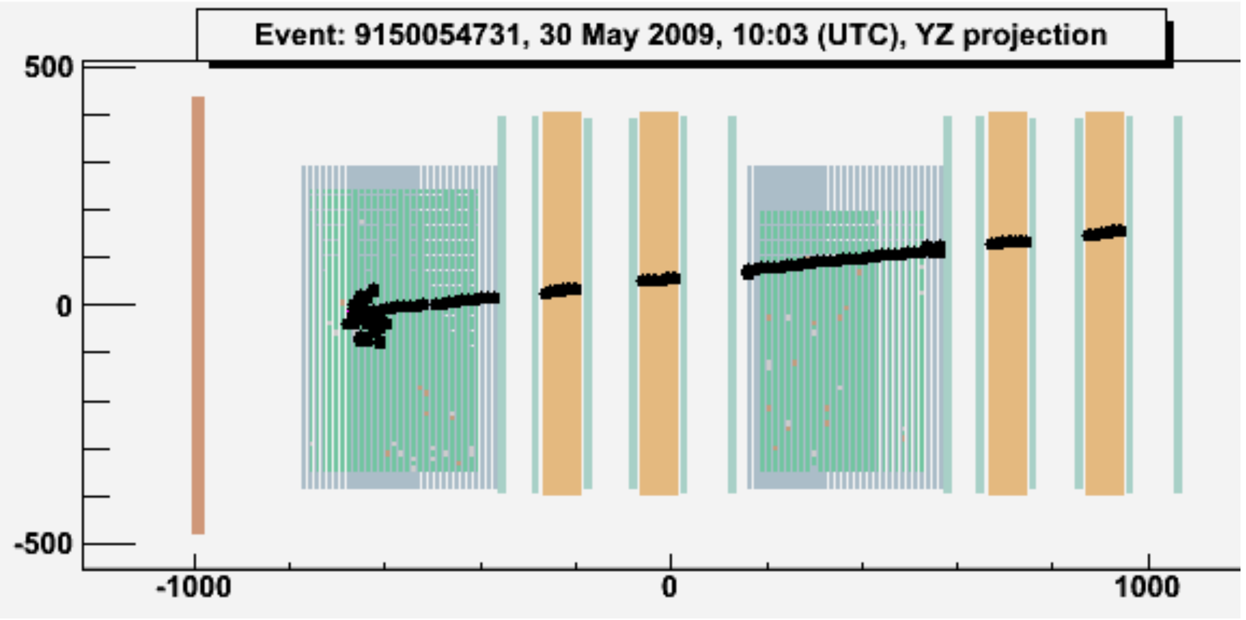


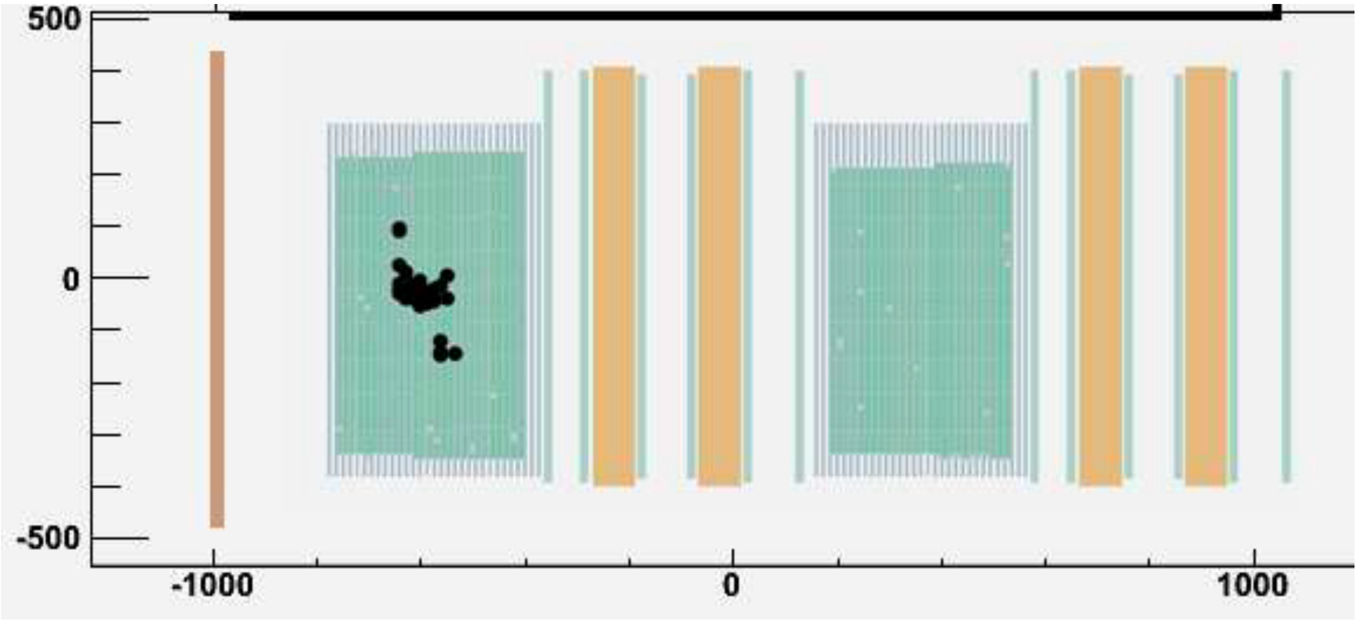


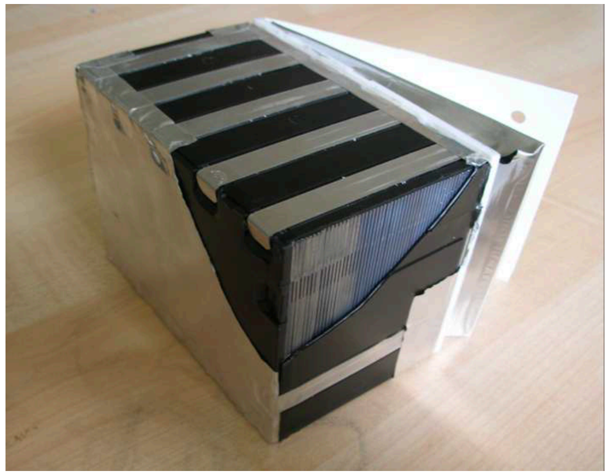
Example: Opera experiment @ LNGS



Example: Opera experiment at LNGS





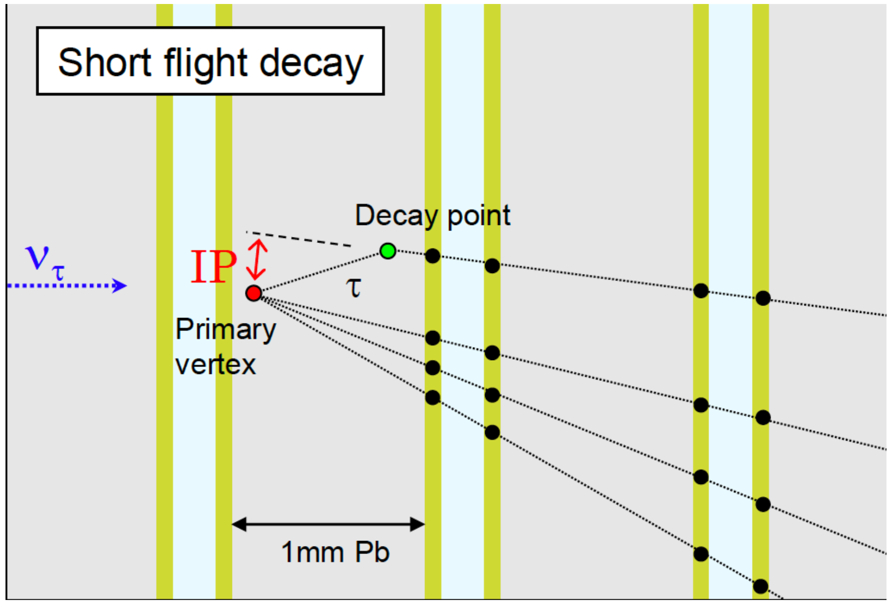


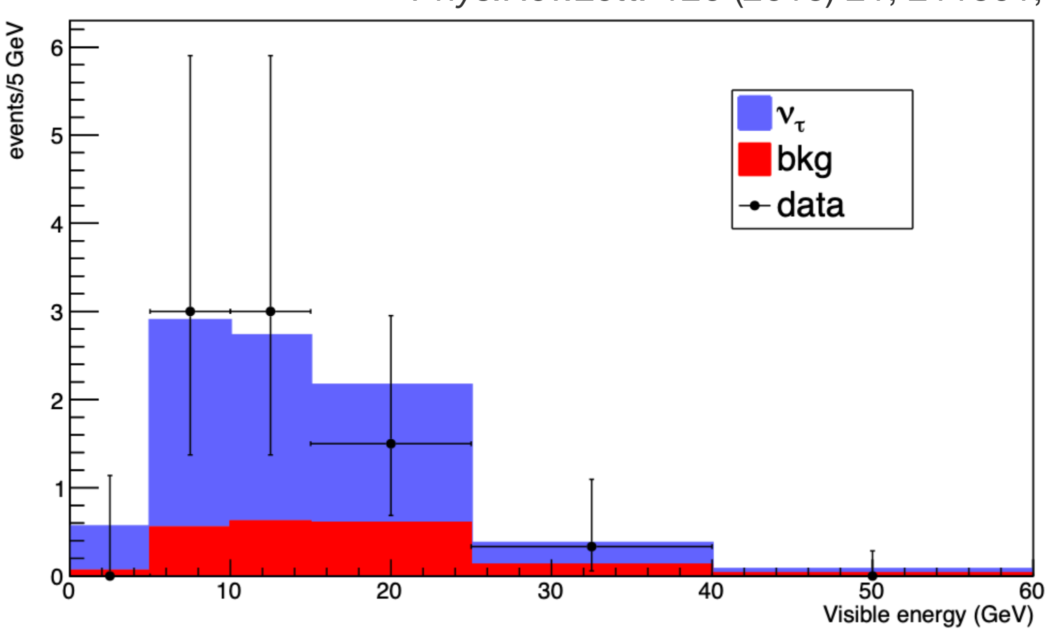
BRICK ID	72693	29570	23543	92217	130577	77152	27972	26670	136759	4838
Channel	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 3h$	$\tau \to 3h$
z_{dec} (μm)	435	1446	151	406	630	430	652	303	-648	407
p^T_{miss} (GeV/c)	0.52	0.31	/	0.55	0.30	0.88	1.29	0.46	0.60	> 0.50
ϕ_{lH} (degrees)	173	168	/	166	151	152	140	143	82	47
p^T_{2ry} (GeV/c)	0.47	/	0.69	0.82	1.00	0.24	0.25	0.33	/	/
p_{2ry} (GeV/c)	12	8.4	2.8	6.0	11	2.7	2.6	2.2	6.7	> 6.3
θ_{kink} (mrad)	41	87	245	137	90	90	98	146	231	83
m (GeV/c^2)	/	0.80	/	1.2	> 0.94	/	/	/	1.2	> 0.94
γ at decay vtx	2	0	0	0	0	1	0	0	0	2
charge_{2ry}	/	/	-1	/	/	/	/	/	/	/
BDT Response	0.32	-0.05	0.37	0.12	0.35	0.18	-0.25	-0.10	-0.04	-0.03

TABLE IV. Kinematical variables and BDT response for all ν_τ candidates.

10 candidates

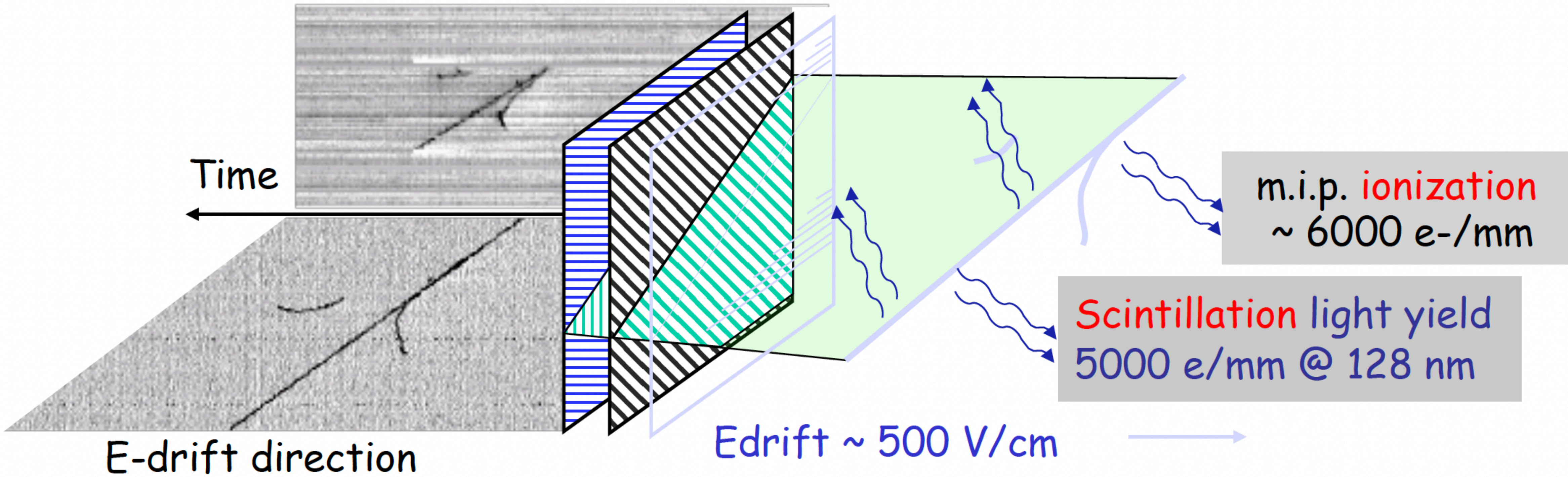
Phys.Rev.Lett. 120 (2018) 21, 211801,



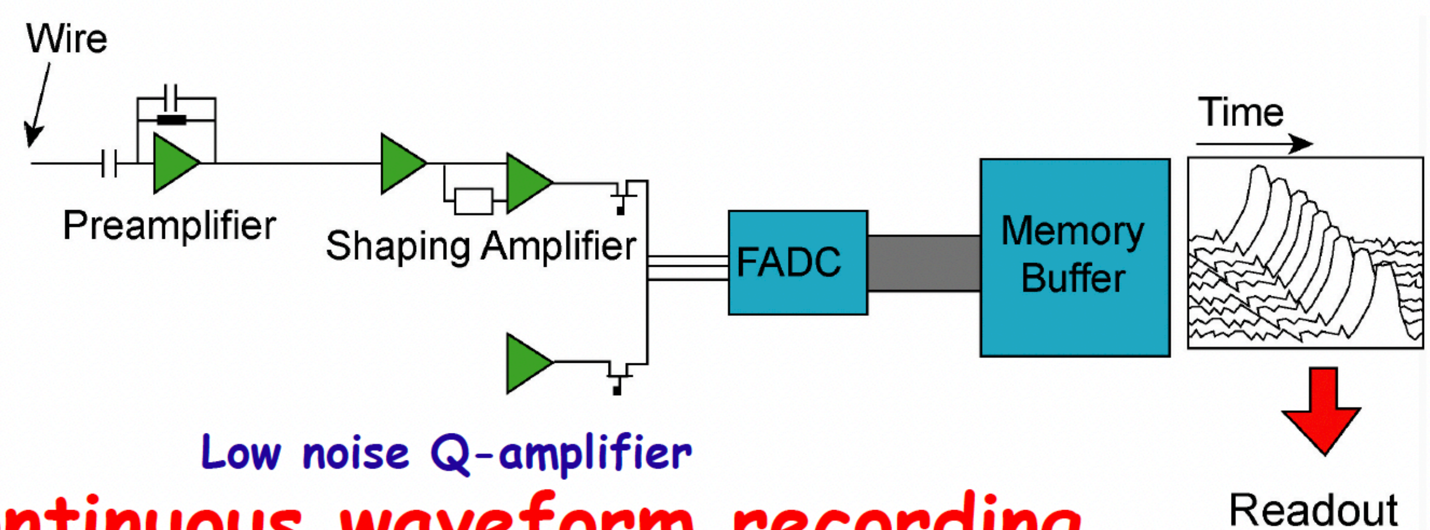


Example: Noble Liquid Detectors

A new, powerful detection technique initiated at CNGS



Drifting electrons are moving to transparent wire arrays oriented in different directions, where signals are recorded.



Continuous waveform recording

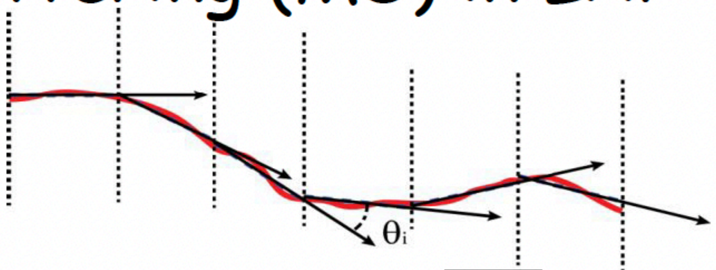
- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- Very good scintillator: T0

C. Rubbia, 2019

Measurement of muon momentum via multiple scattering

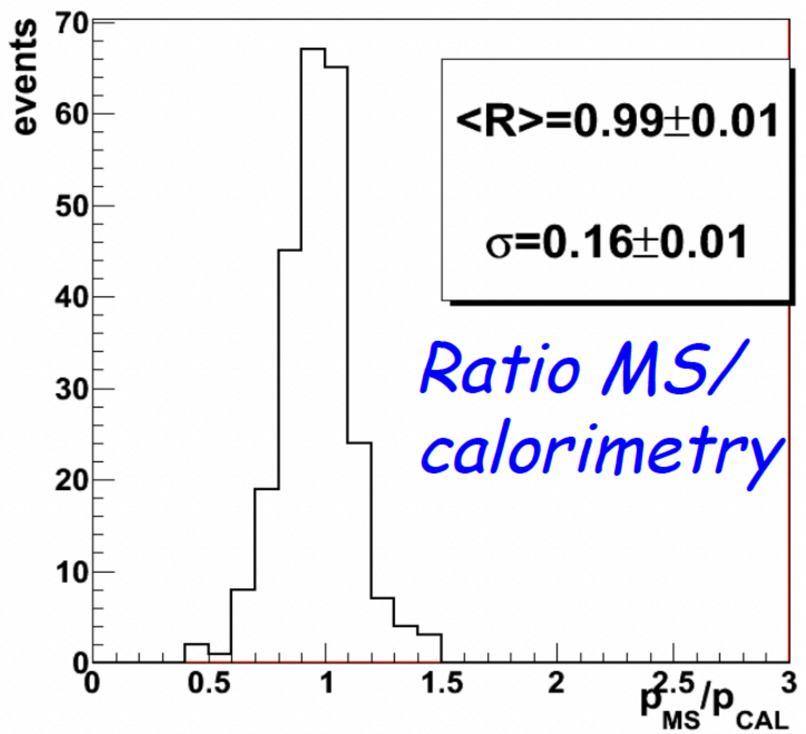
In absence of a magnetic field, the initial m momentum may be determinec through the reconstruction of multiple Coulomb Scattering (MS) in LAr

RMS of θ deflection of μ depends on p, spatial resolution σ and track segmentation

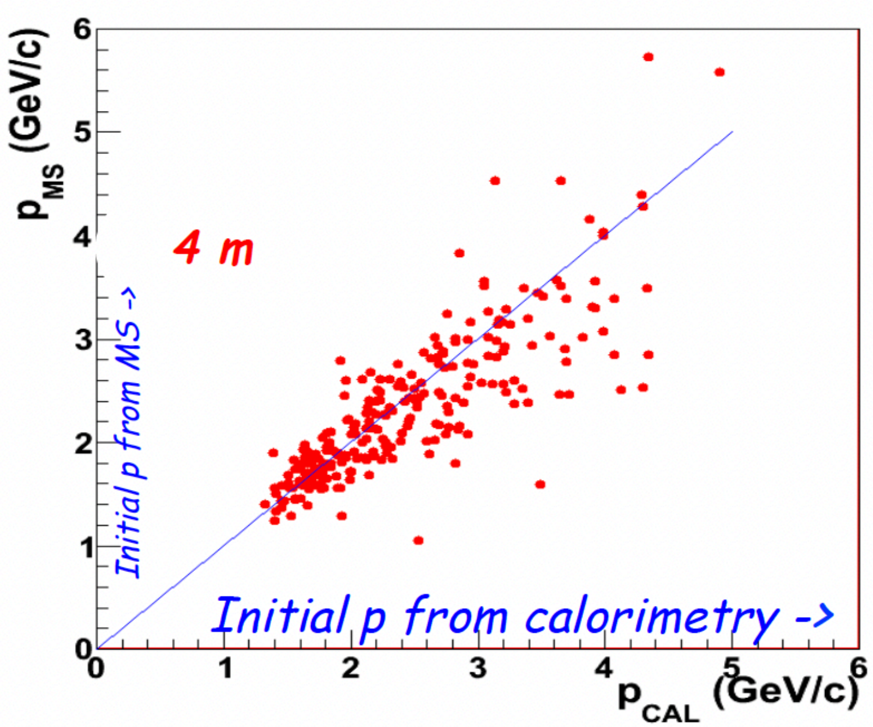


$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

Method tested on ~103 stopping μ' s from CNGS ν interactions in upstream rock, comparing PMS measured by MS with the corresponding calorimetric PCAL



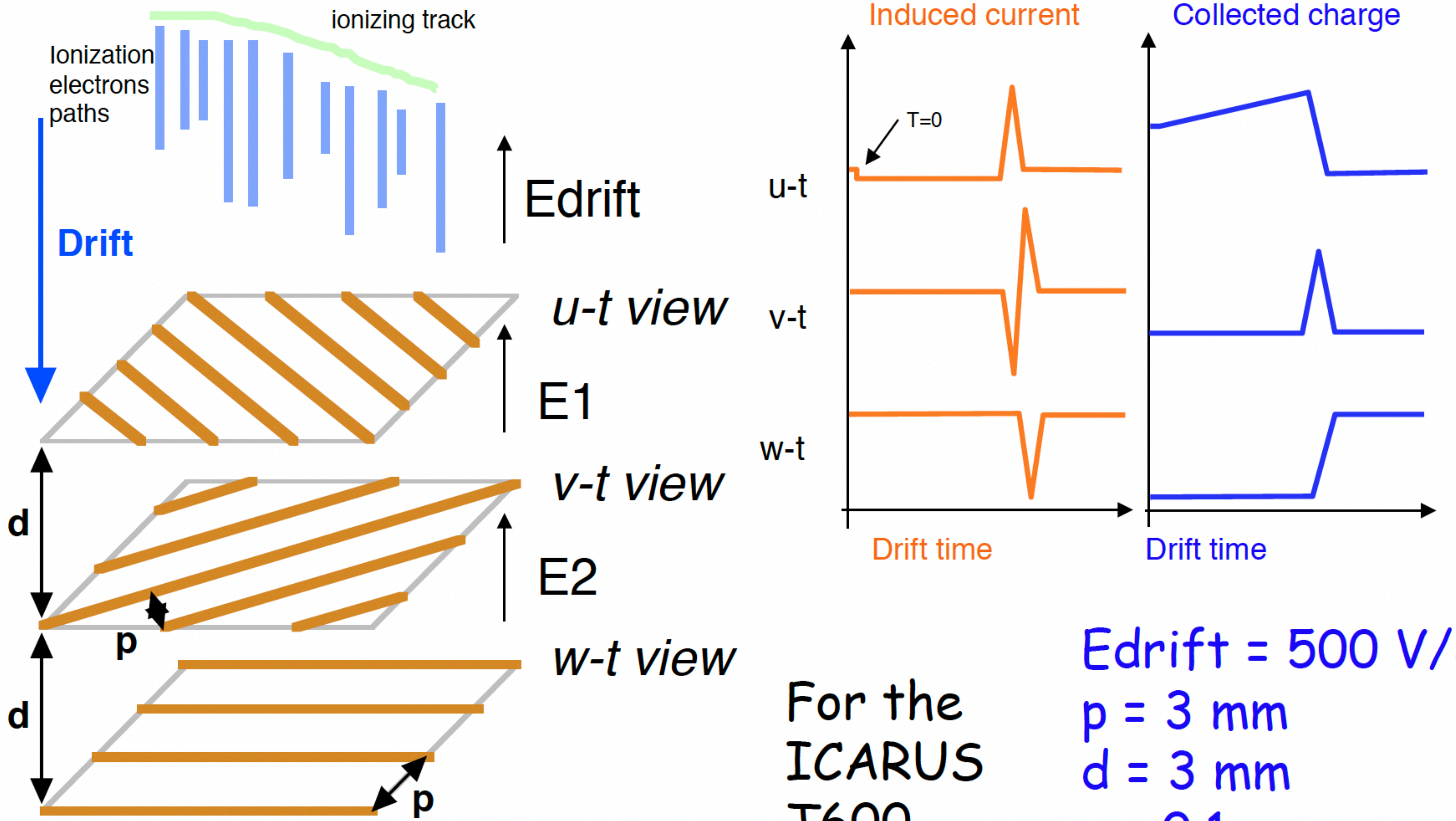
μ track length: > 5m
Used length: 4m



~16% resolution has been obtained in the 0.4-4 GeV /c momentum range of interest for the future short/long base-line experiments

C. Rubbia, 2019

Non destructive, multiple charge readout



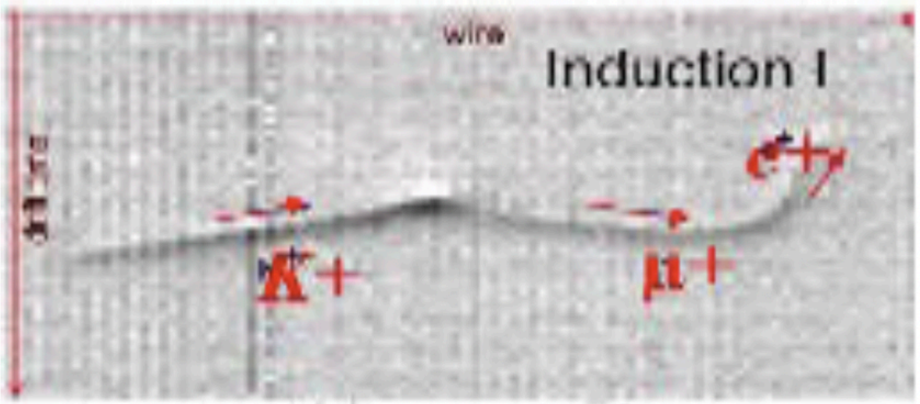
For the ICARUS T600

Edrift = 500 V/cm
p = 3 mm
d = 3 mm
r = 0.1mm

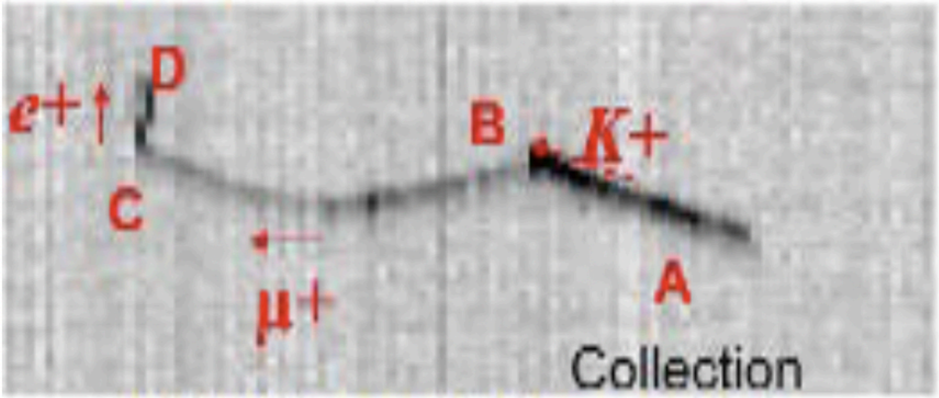
- At FNAL's shallow depth, the T600 will require two additions:
  - 3 m concrete overburden to mitigate the c. rays background,
  - Particles entering the detector must be removed with a Cosmic Rays Tagging (CRT) around the full LAr volume

C. Rubbia, 2019

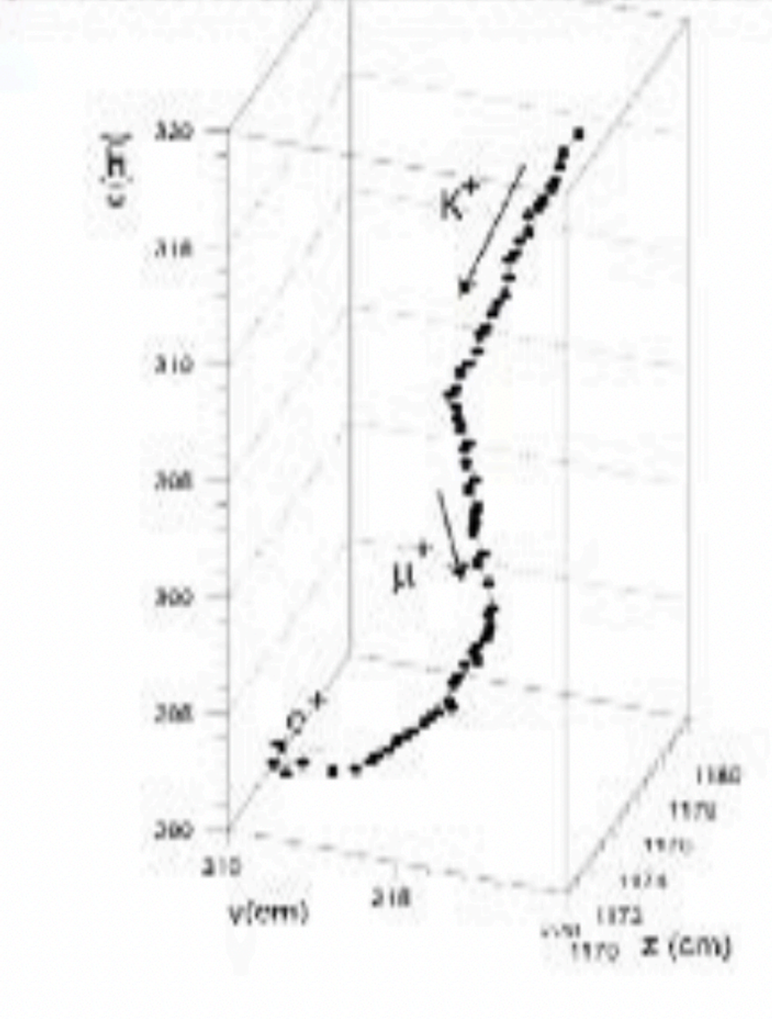
3 D particle Identification ($k^+ \to \mu^+ \to e^+$) at CNGS



ICARUS EVENT

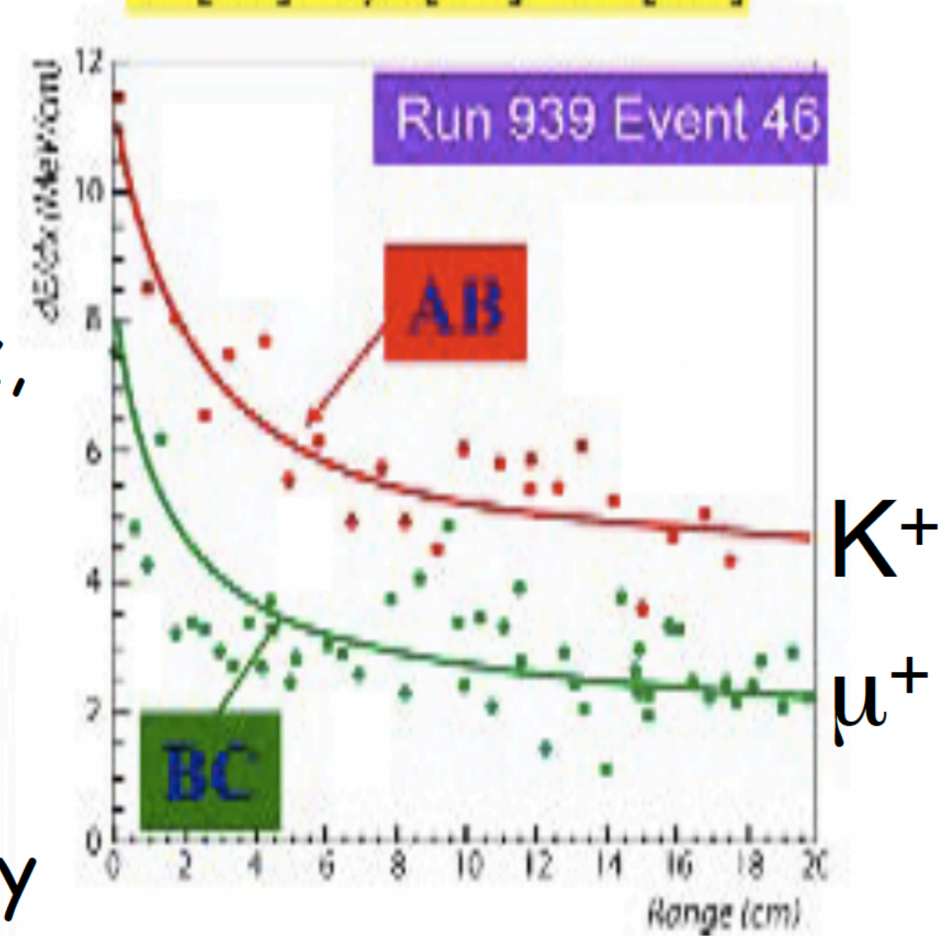


$$K^+[AB] \to \mu^+[BC] \to e^+[CD]$$



Efficient, low mis-identification, due to precise 3D reconstruction, dE/dx, range measurement

- stopping power
- recognition of secondary particle production after decay interaction



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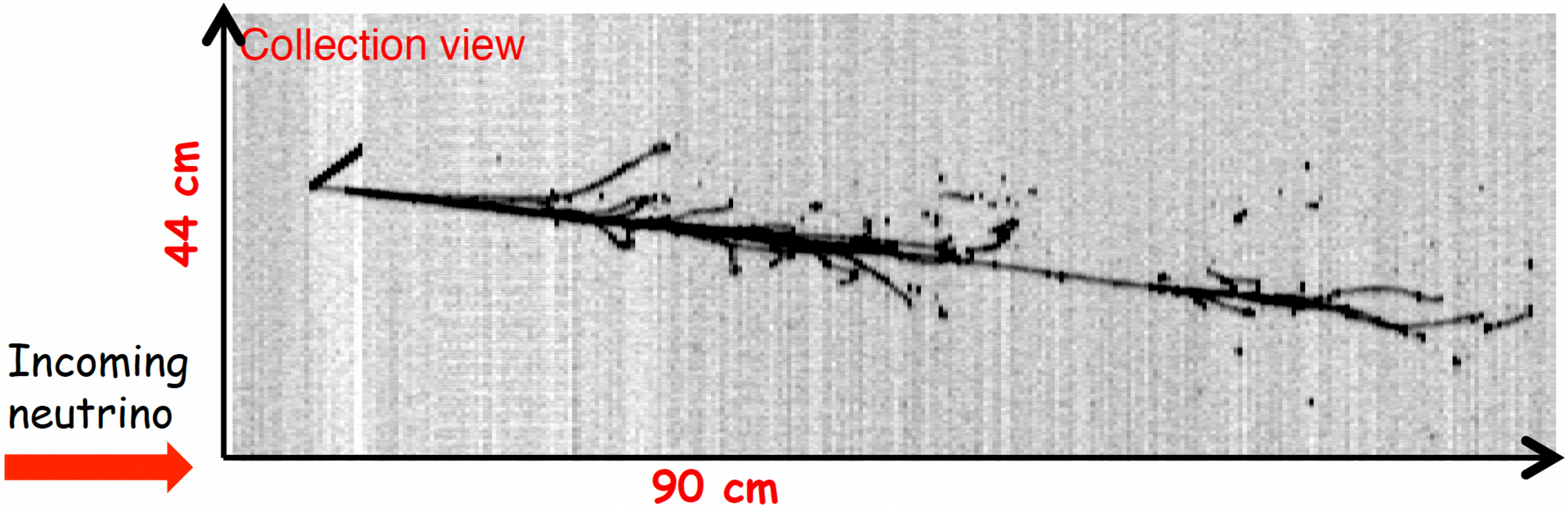
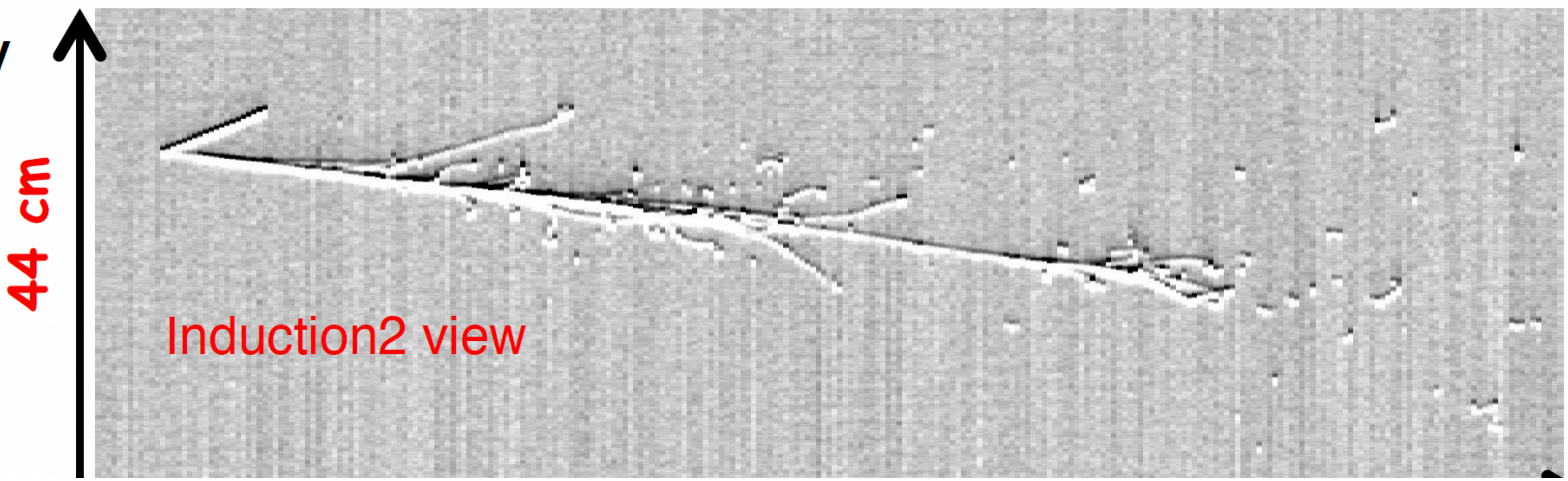
MC event Run 5 SubRun 44 Event 64

- A clear q.e. νe event: p + e.

Eν = 1.34 GeV Edep = 1.29 GeV



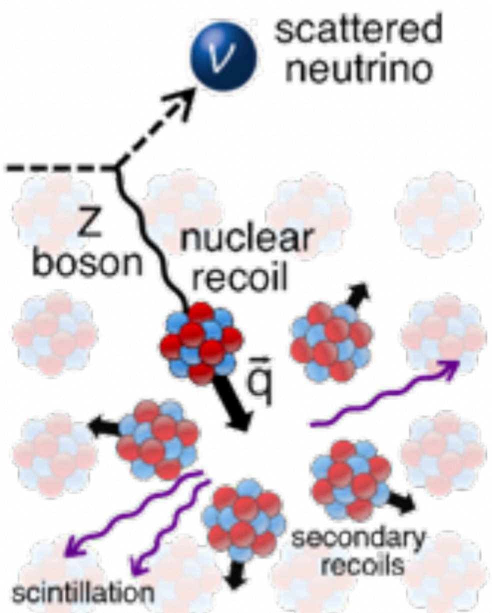
E_e = 1.21GeV
T_p = 93 MeV
R_p = 7cm
T_p/R_p = 13.2 MeV/cm

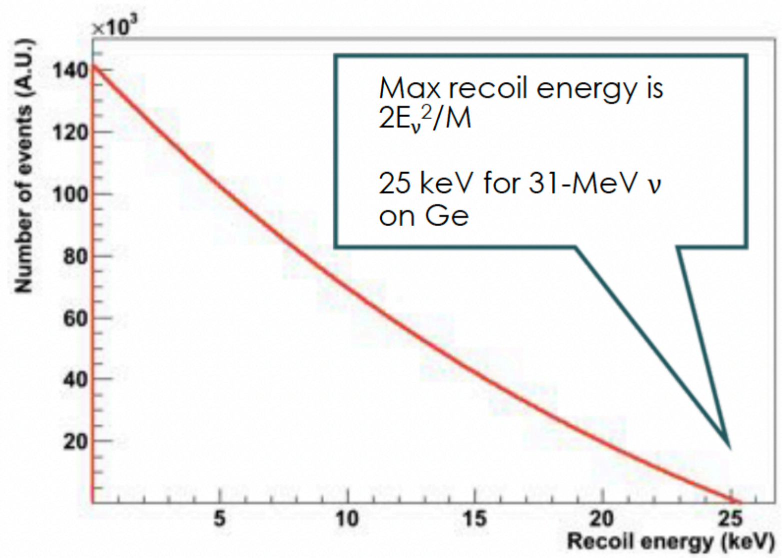


C. Rubbia, 2019

Coherent elastic neutrino-nucleus scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV





CEvNS cross section is well calculable in the Standard Model

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos\theta) \frac{(N - (1 - 4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

CEvNS cross section is large! $\propto N^2$

- Predicted in 1974 by D. Freedman
- Interesting test of the standard model
  - Sensitive to **non-standard interactions**
  - Largest cross section in **supernovae** dynamics
  - Background for future **dark matter** experiments
  - Sensitive to nuclear physics, **neutron skin** (neutron star radius)

- "act of hubris" - D. Freedman
  - Need a low threshold detector
  - Need an intense neutrino source

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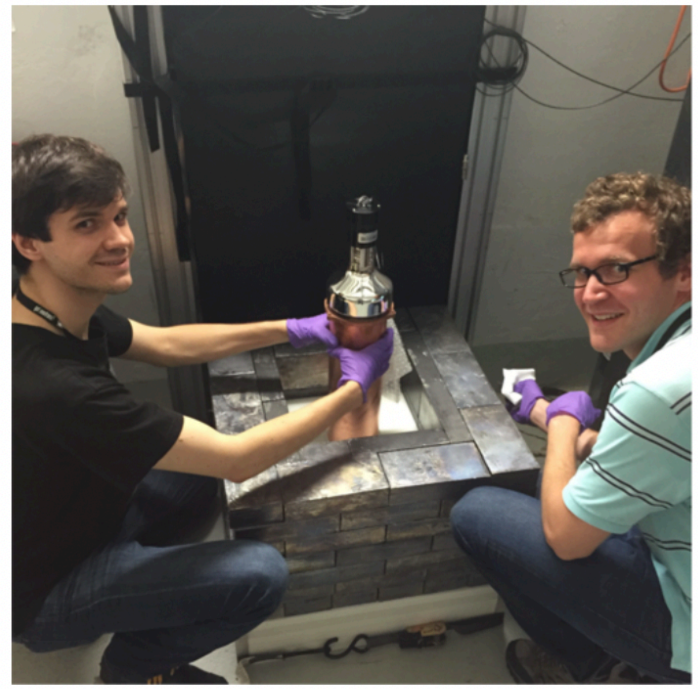
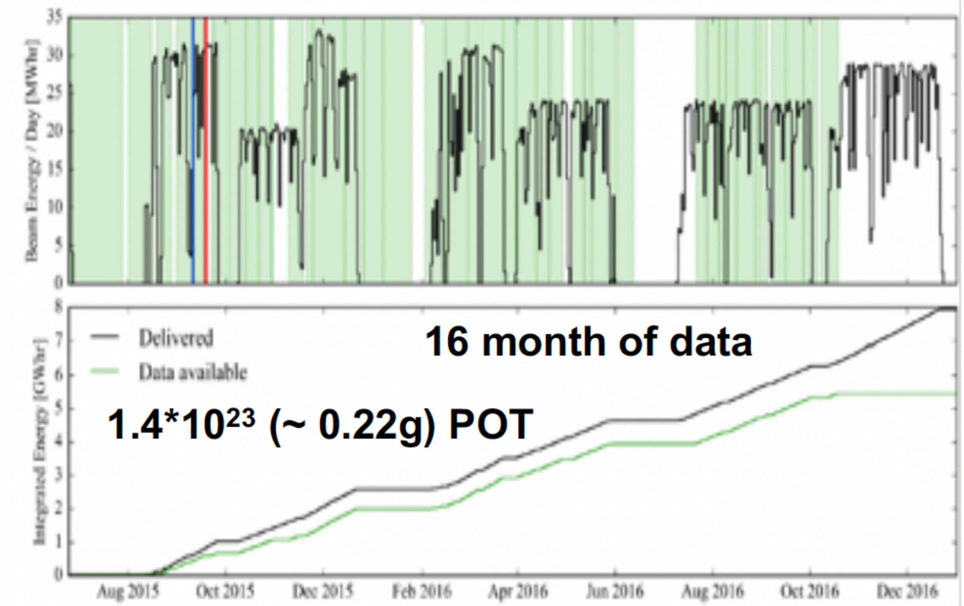
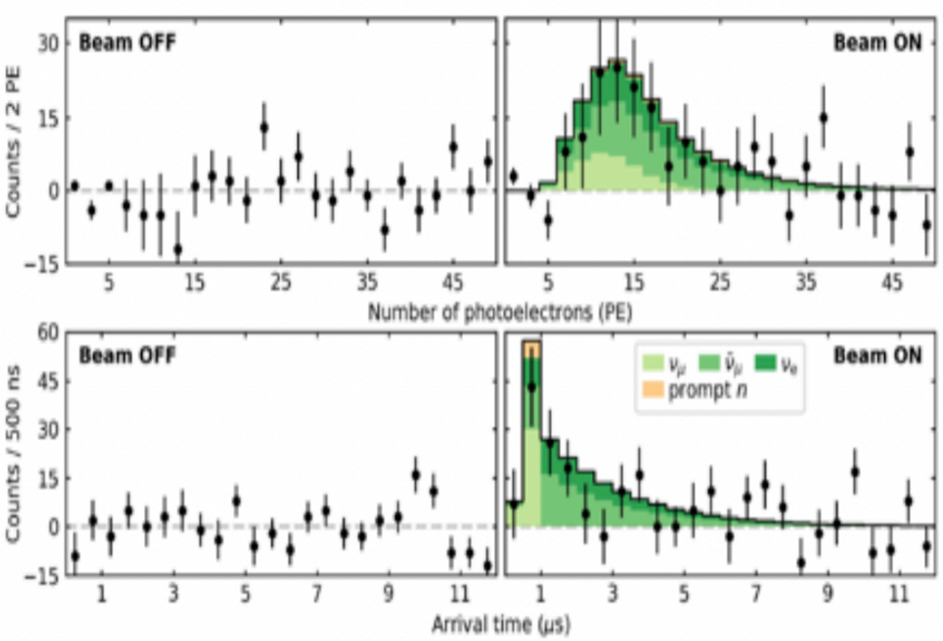
First Detection of CEvNS with CsI detector



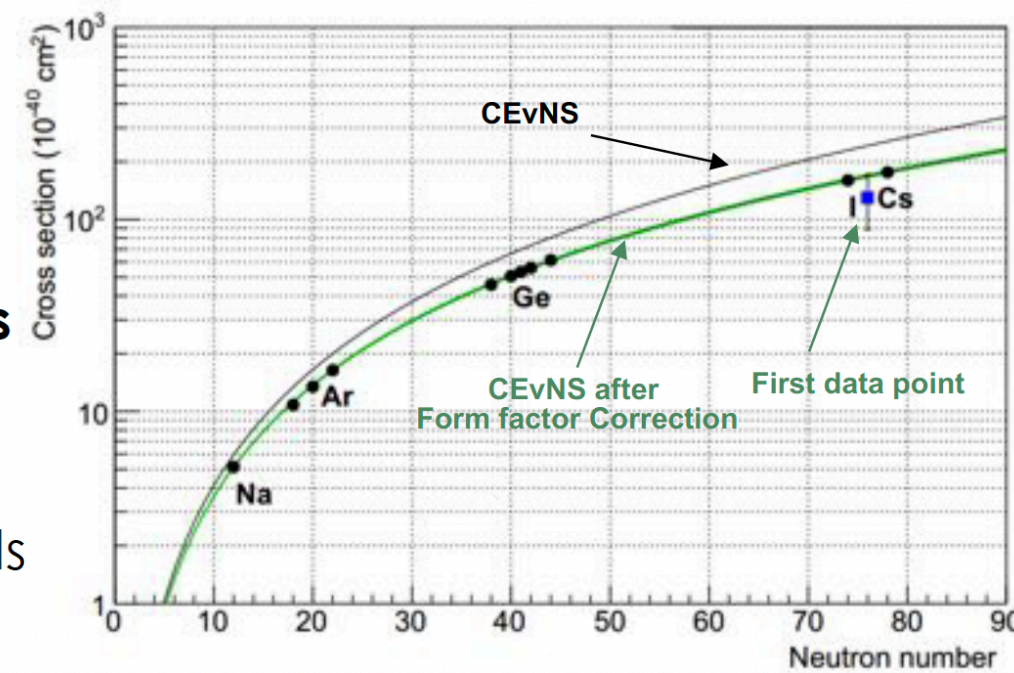




First working, hand held neutrino detector -14kg!!!

After 40 years, all the pieces have finally come together

- ✓ Intense Neutrino Source
- ✓ Sensitive Detectors
- ✓ Mitigation of Backgrounds



Neutrino 2020 Virtual Meeting

J. Newby

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