Neutrino Sources

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June 10, 2021

quarks

+2/3  up	+2/3  charm	+2/3  top
-1/3  down	-1/3  strange	-1/3  bottom

leptons

0  electron neutrino	0  muon neutrino	0  tau neutrino
-1  electron	-1  muon	-1  tau

What can we make with those?

Combinations of 2 quarks: $u\ \bar{d}$ $q = +\frac{2}{3}e + \frac{1}{3}e = +e$

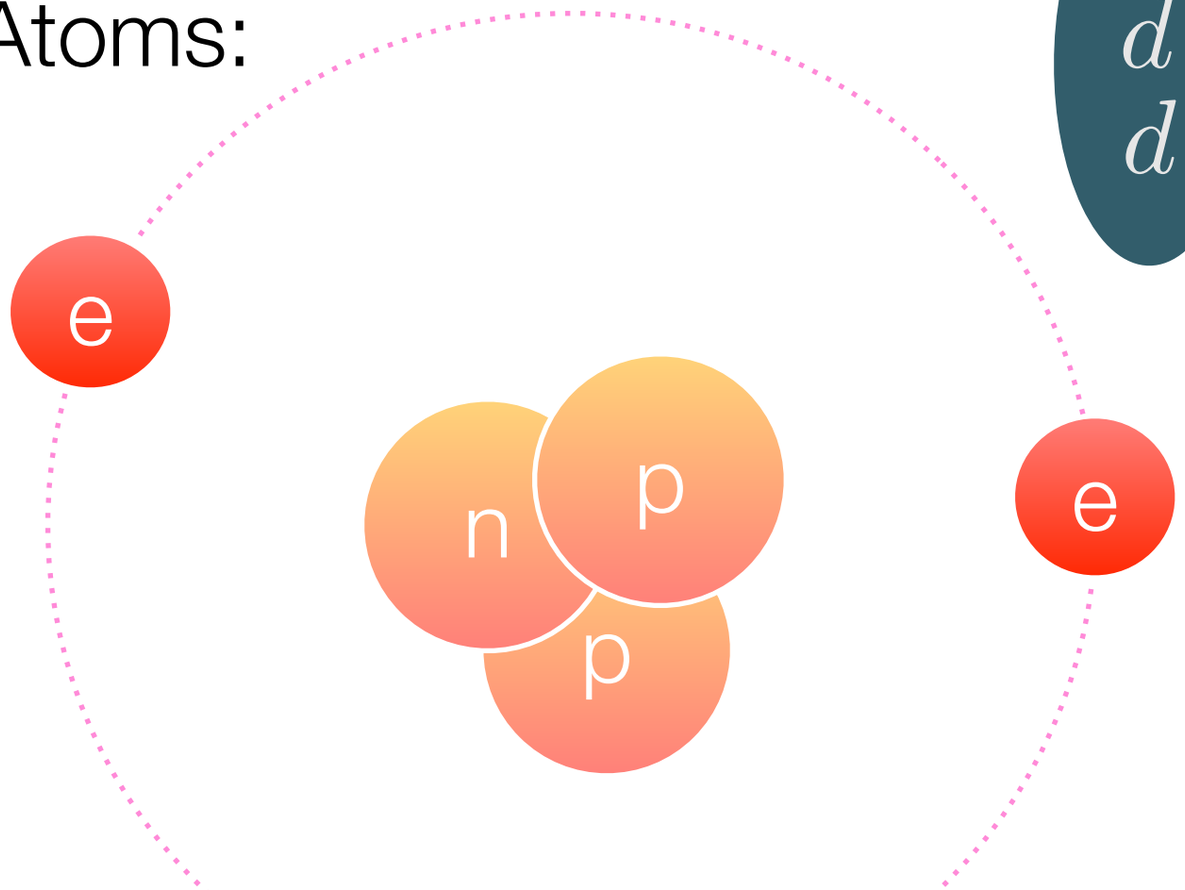
pion, “π+”

Combinations of 3 quarks: $u\ u\ d$ $q = +\frac{2}{3}e + \frac{2}{3}e + (-\frac{1}{3})e = +e$

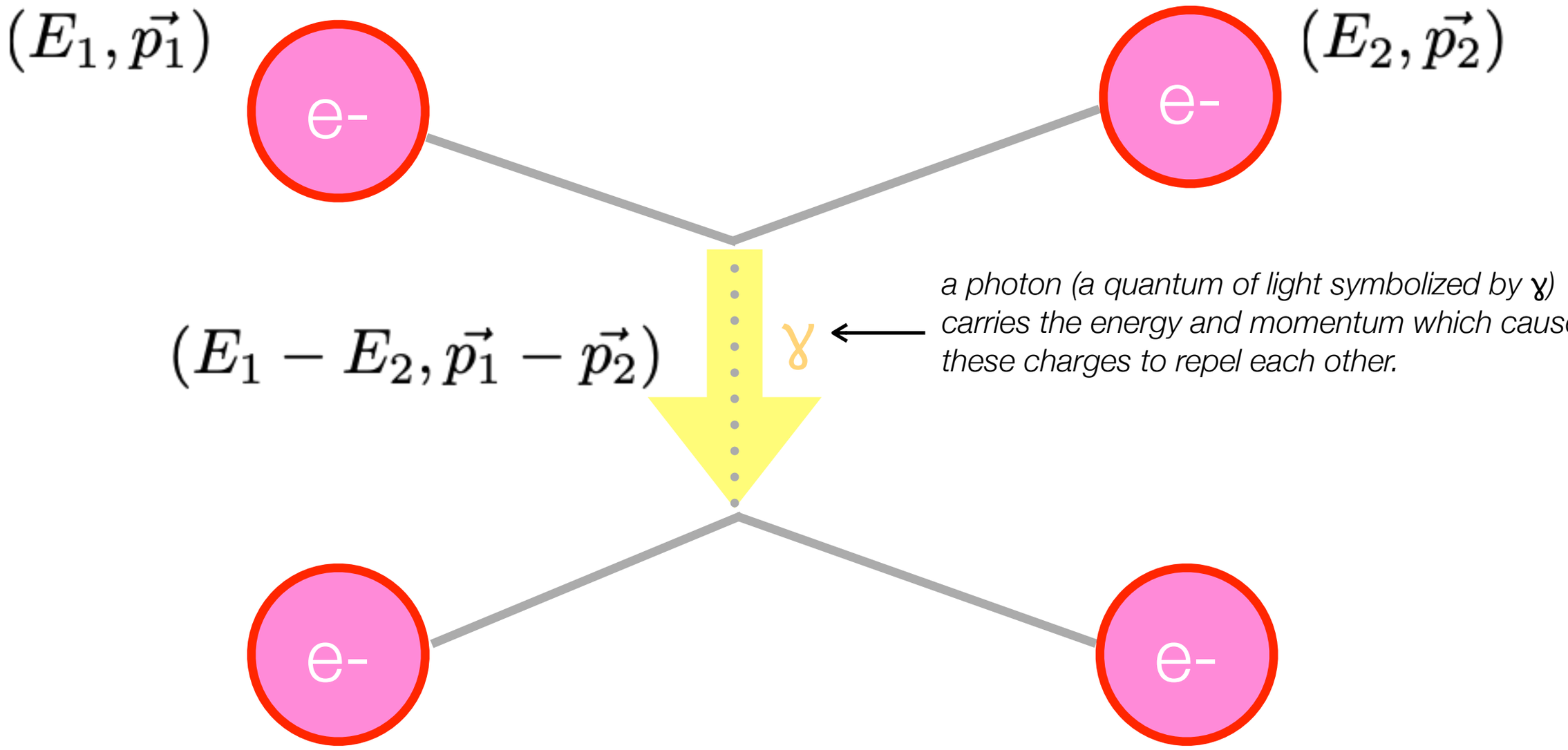
proton

Atoms: $u\ d\ d$ $q = +\frac{2}{3}e + (-\frac{1}{3}e) + (-\frac{1}{3})e = 0$

neutron

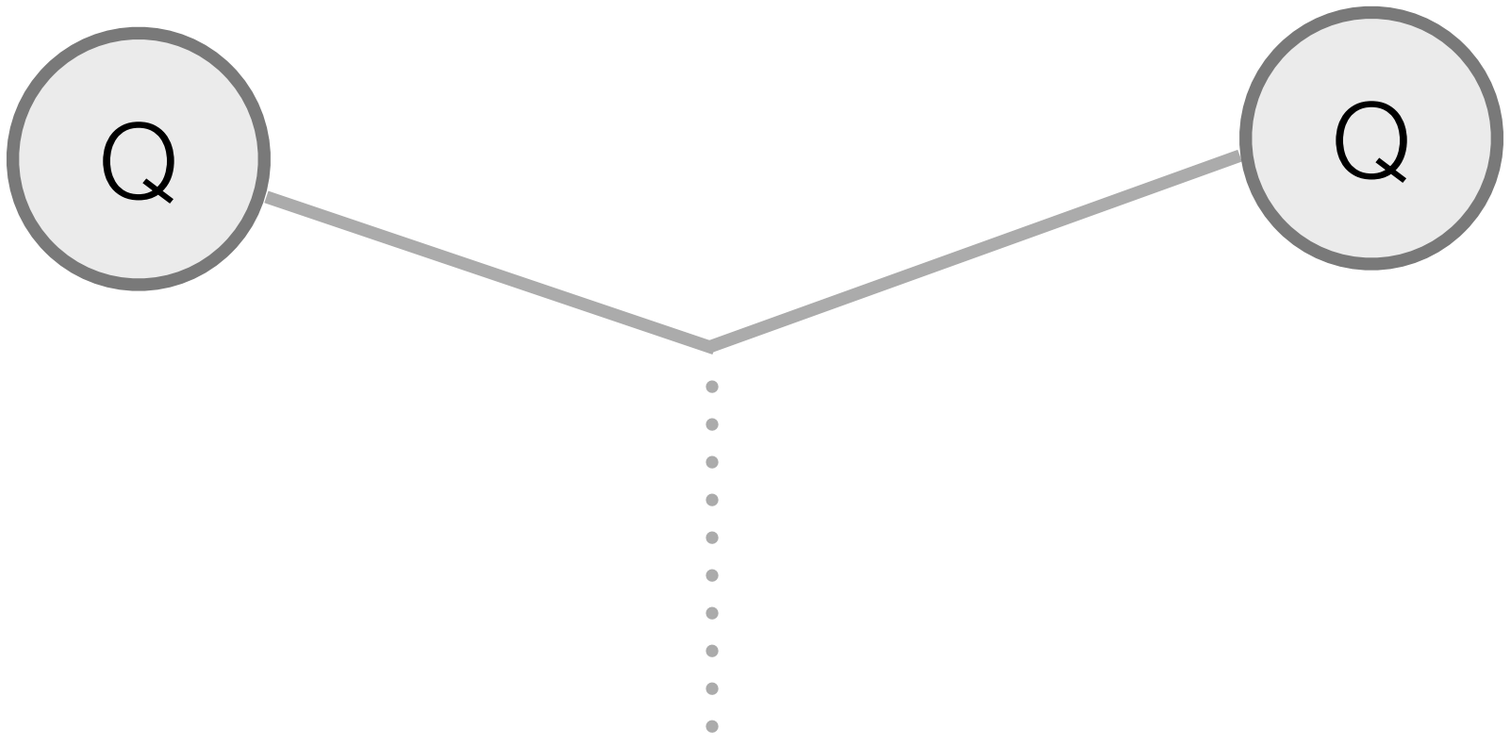


Forces are exchanges of particles



a photon (a quantum of light symbolized by γ) carries the energy and momentum which cause these charges to repel each other.

Basic unit



How many diagrams can we make with the basic unit?

quarks

+2/3  up	+2/3  charm	+2/3  top
-1/3  down	-1/3  strange	-1/3  bottom

leptons

0  electron neutrino	0  muon neutrino	0  tau neutrino
-1  electron	-1  muon	-1  tau

"Weak isospin"

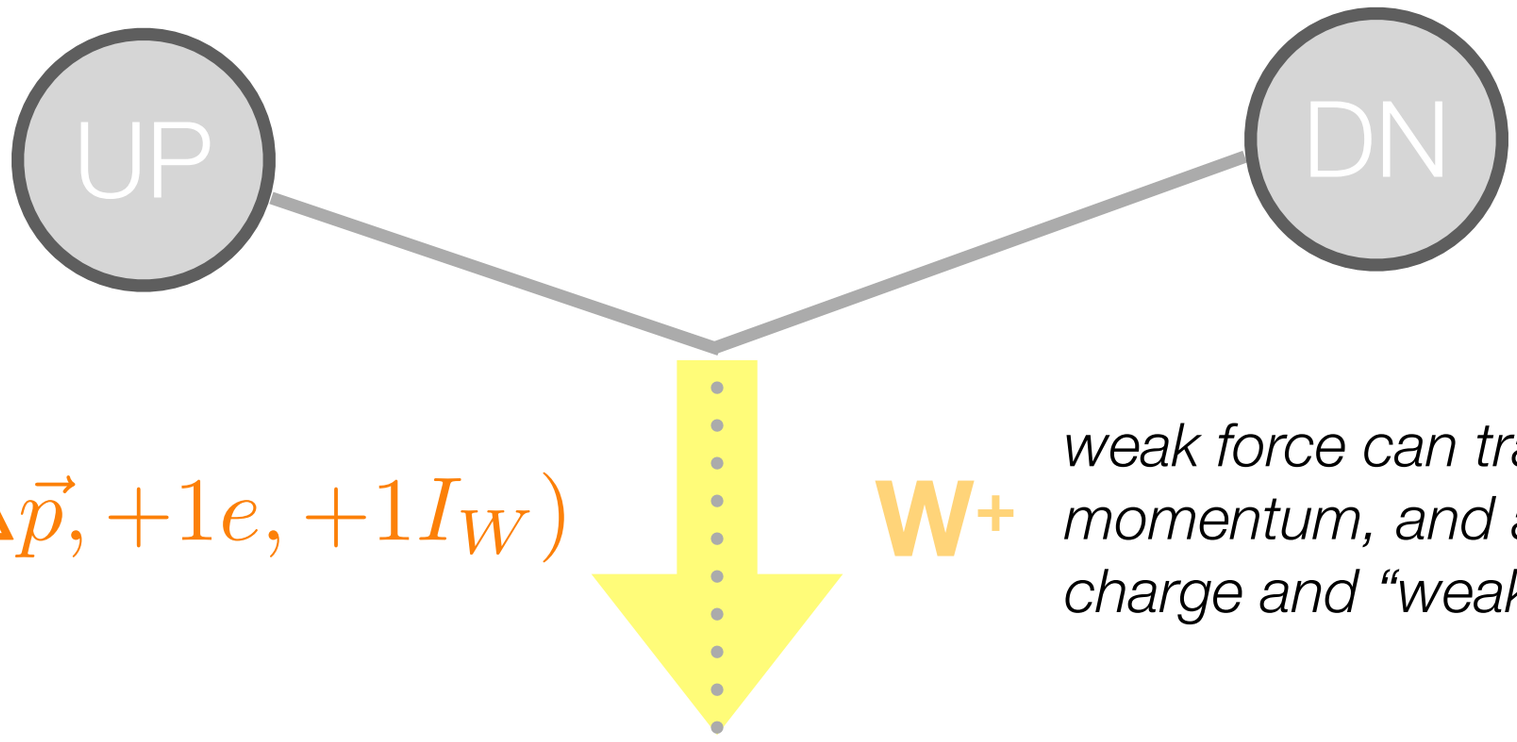
+1/2 ↑

-1/2 ↓

+1/2 ↑

-1/2 ↓

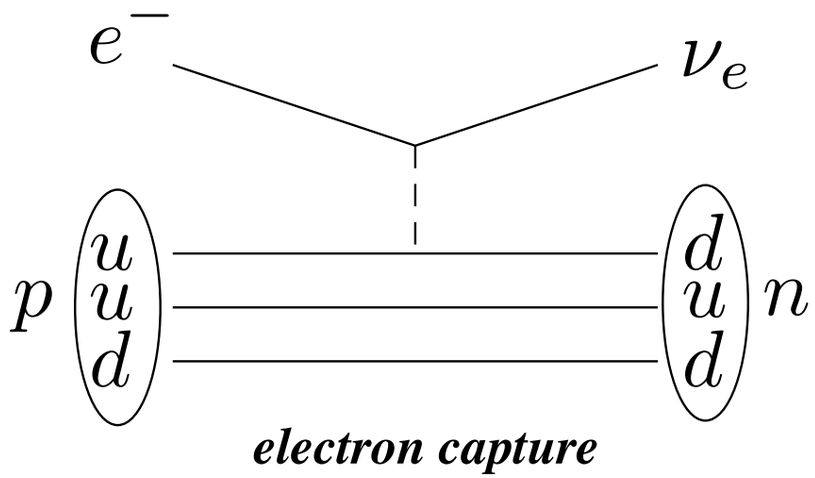
Basic unit for the weak force



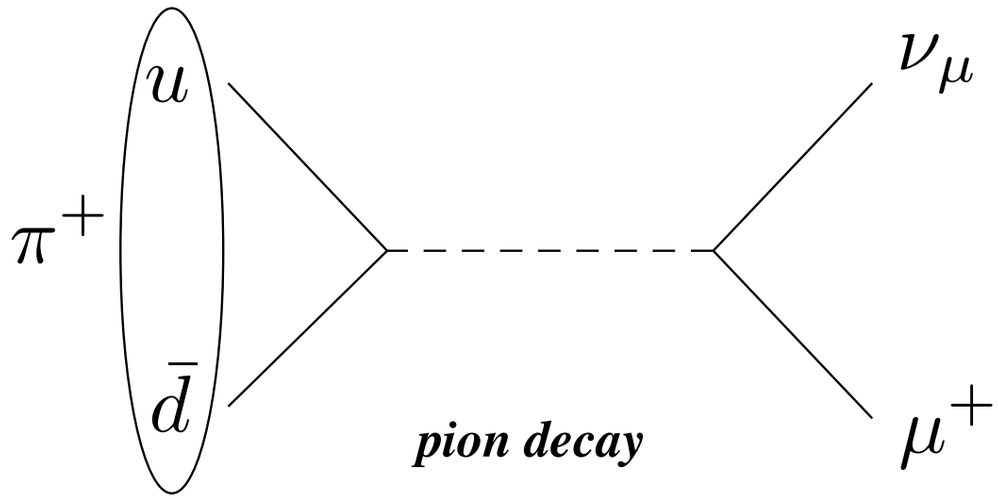
weak force can transfer energy, momentum, and also electric charge and "weak isospin"

There is also a neutral carrier of the weak force, the Z^0 boson, which transfers energy, momentum, but no charge or Iw. Generally, the Z boson does not play a big role in neutrino production; supernova explosions are one exception.

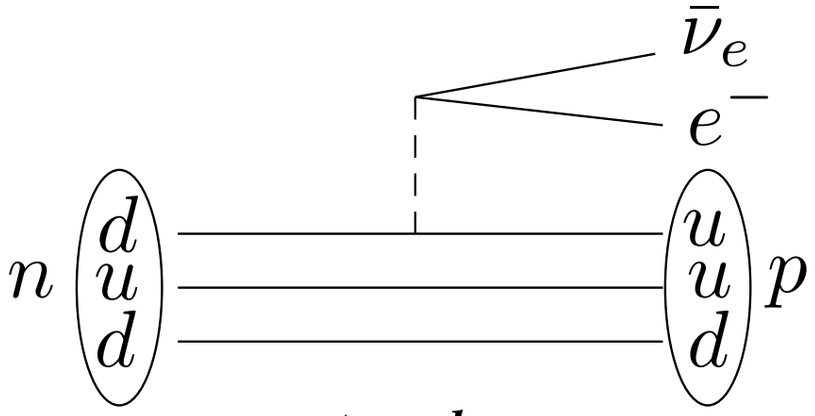
What sorts of diagrams are possible now?



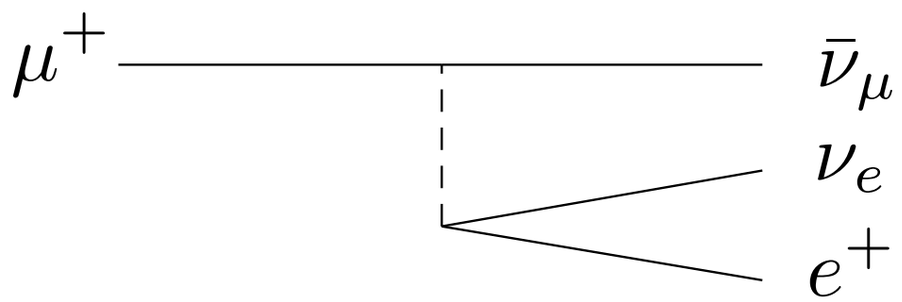
electron capture



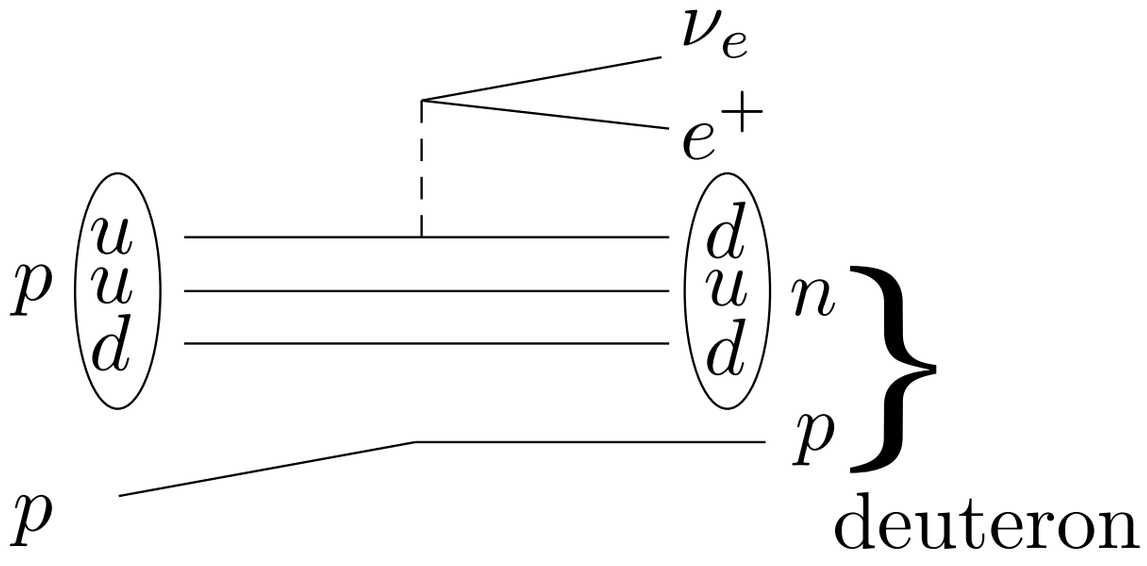
pion decay



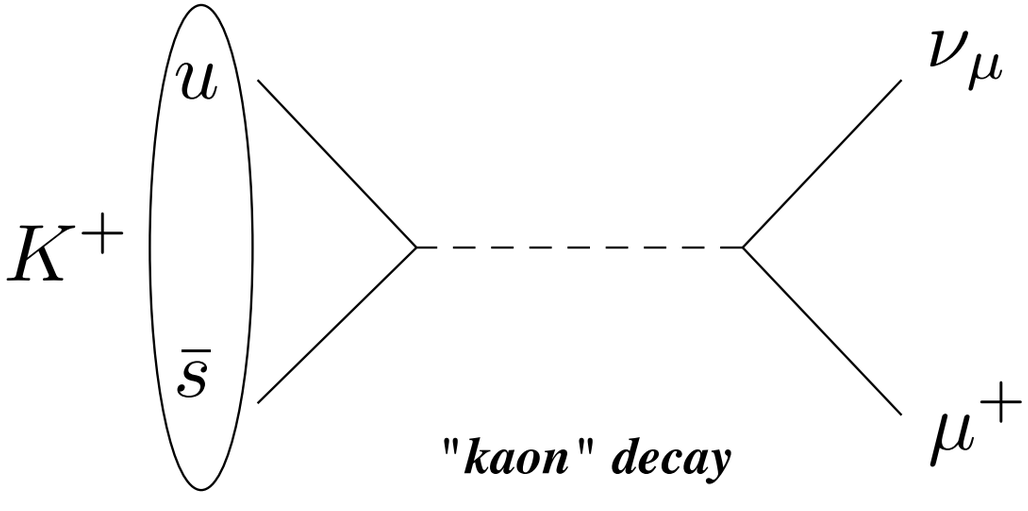
neutron decay



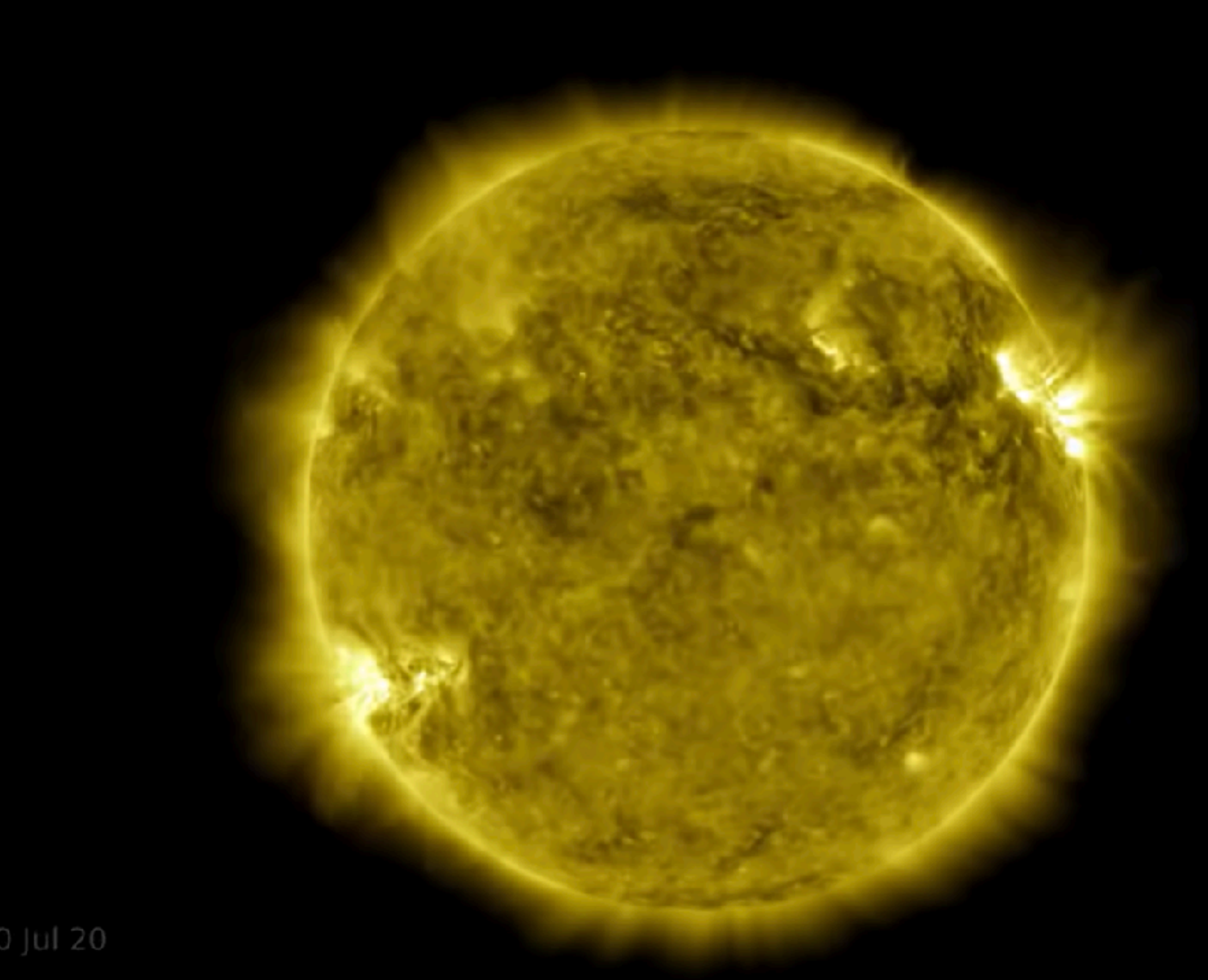
muon decay



nuclear fusion

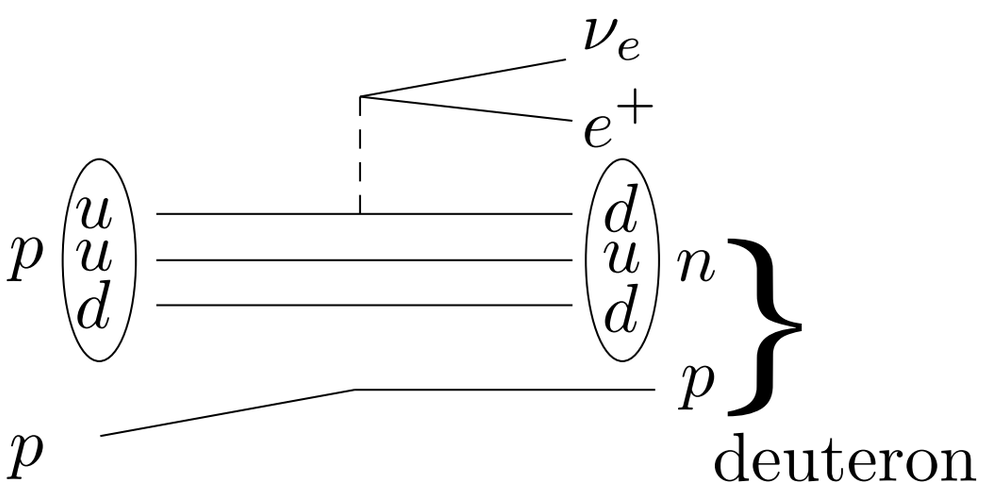


"kaon" decay

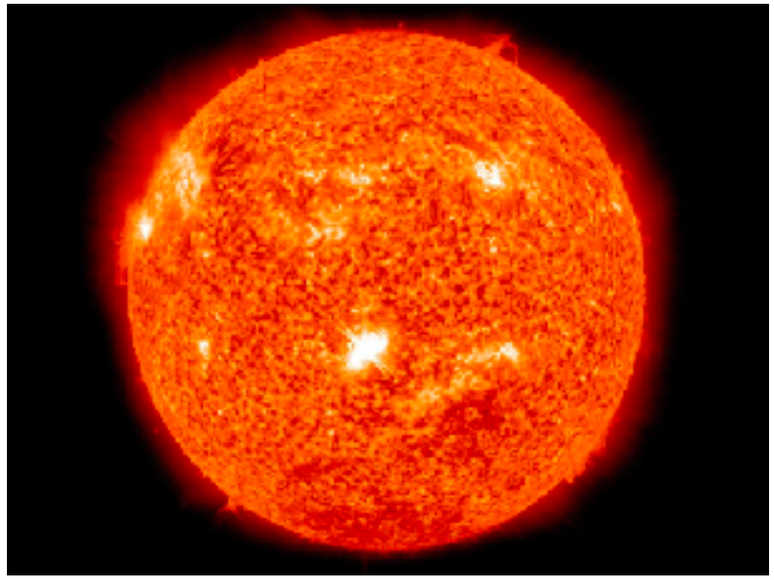


NASA’s Solar Dynamics Observatory

https://youtu.be/l3QQQu7QLoM



nuclear fusion



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

pep

0,23 %

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

10^{-5} %

84,92 %

$^2H + p^+ \rightarrow {}^3He + \gamma$

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

0,1 %

99,9 %

^7Be

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

$^7Be + p^+ \rightarrow {}^8B + \gamma$

^8B

$^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

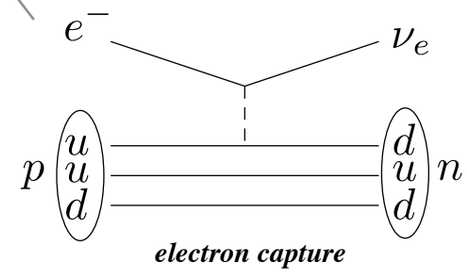
$^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

$^8Be^* \rightarrow {}^4He + {}^4He$

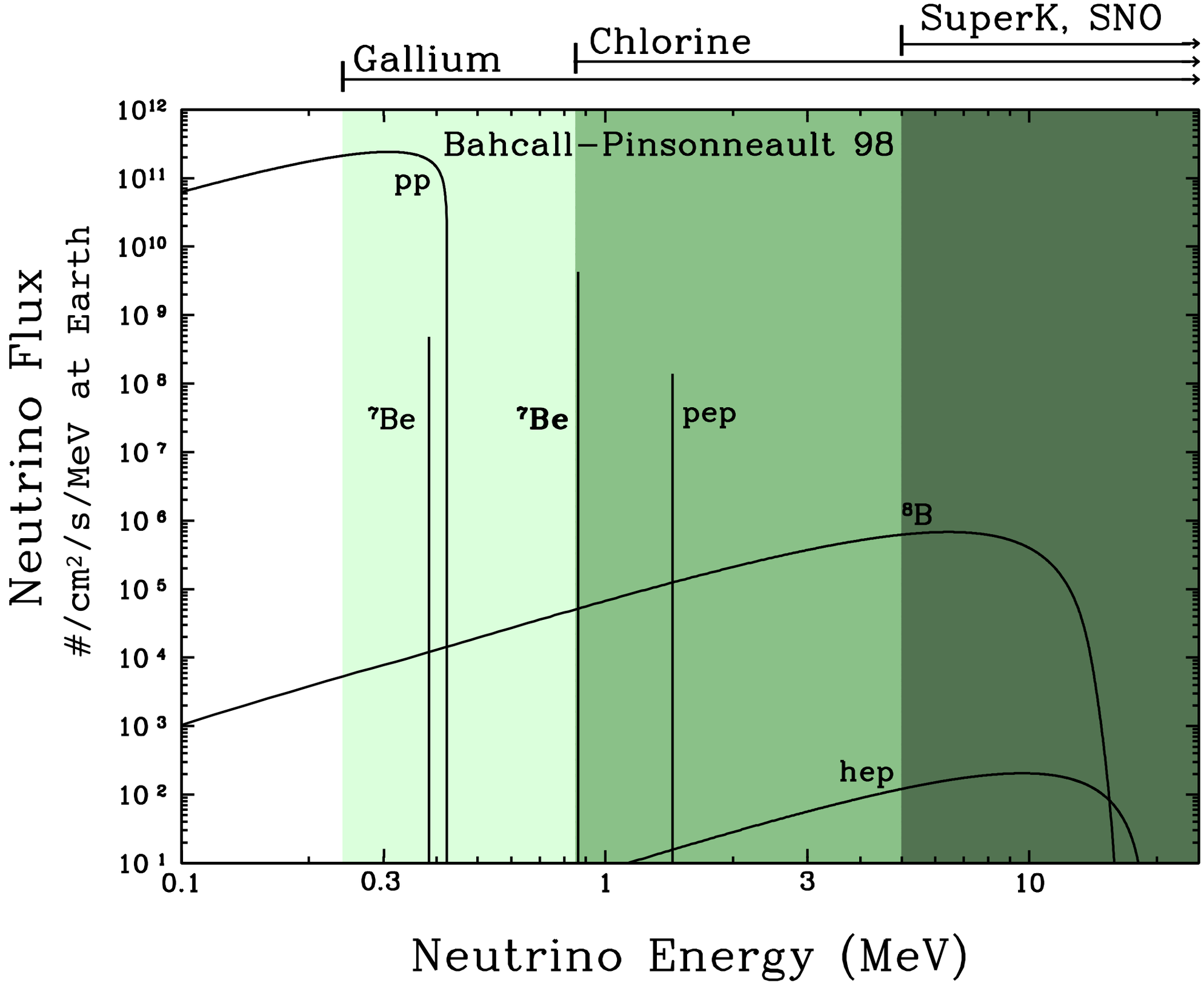
ppIII



electron capture

https://en.wikiversity.org/wiki/Stars/Sun/Standard_models/Quiz

http://www.sns.ias.edu/~jnb/SNviewgraphs/SNspectrum/energyspectra.html

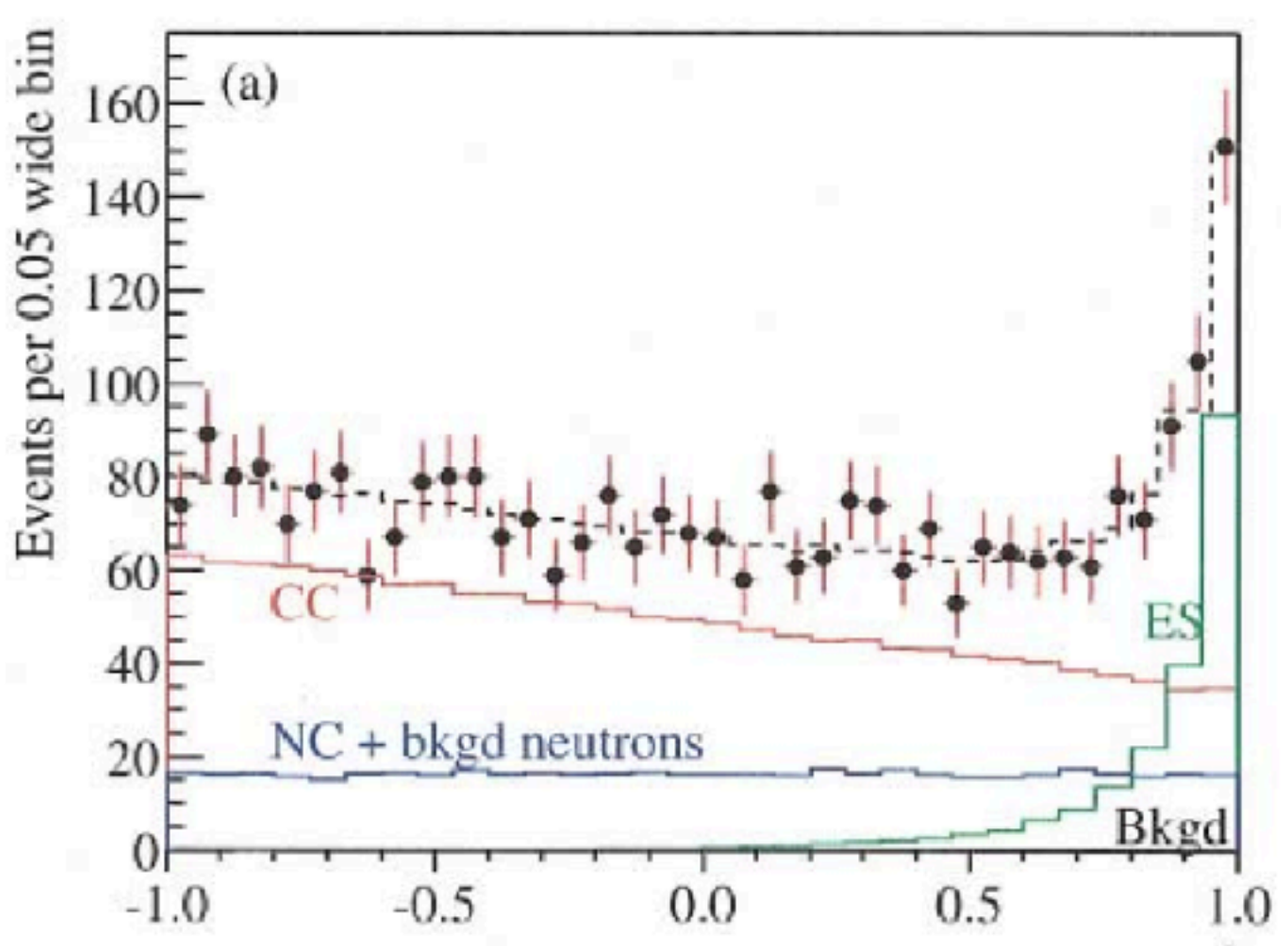


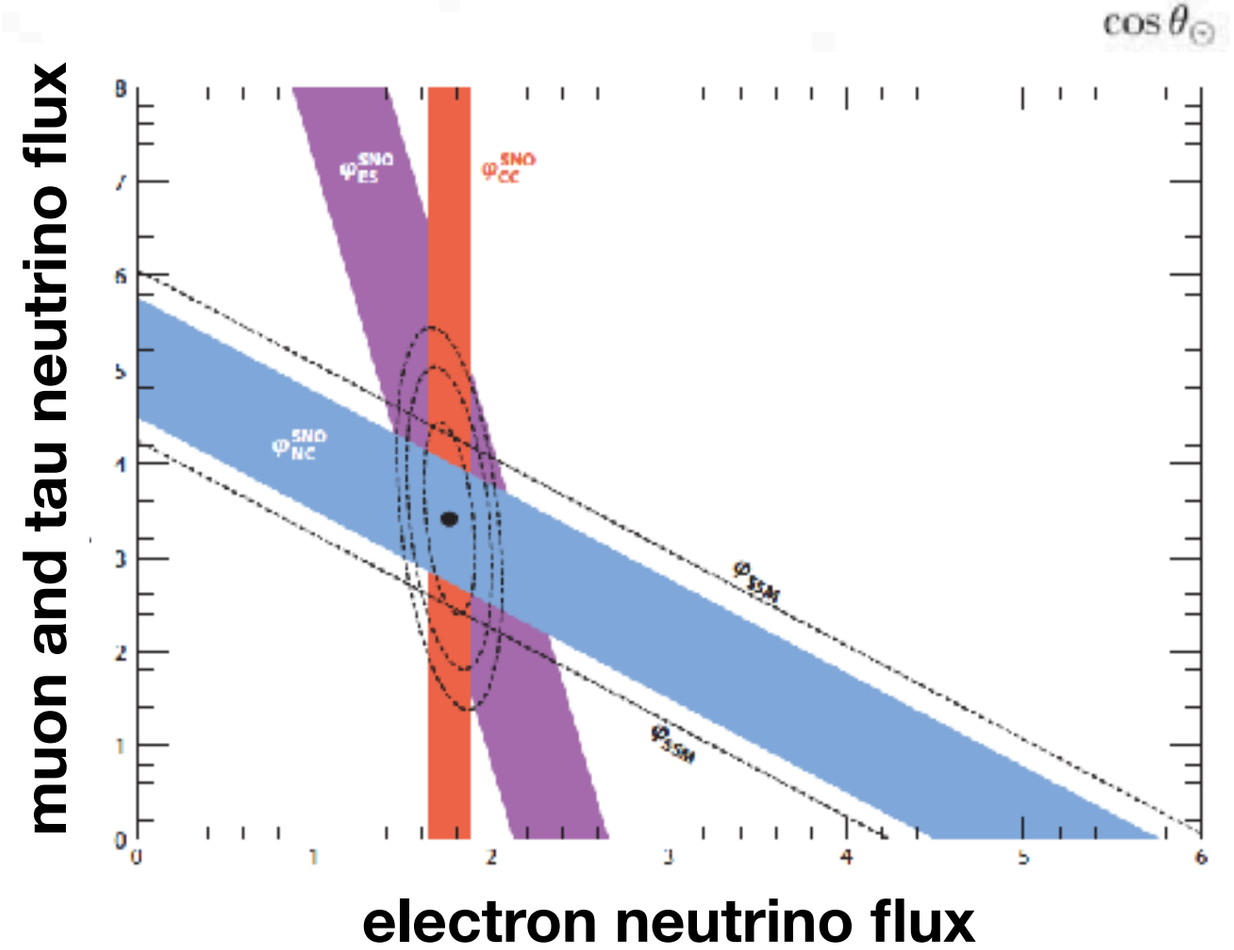
NB: As you can see from the top there are experiments which can see these neutrinos. However, to se the scale: To most people working in experimental HEP, ~1 MeV is considered "low energy". We typically work with 1000x more energy than this.

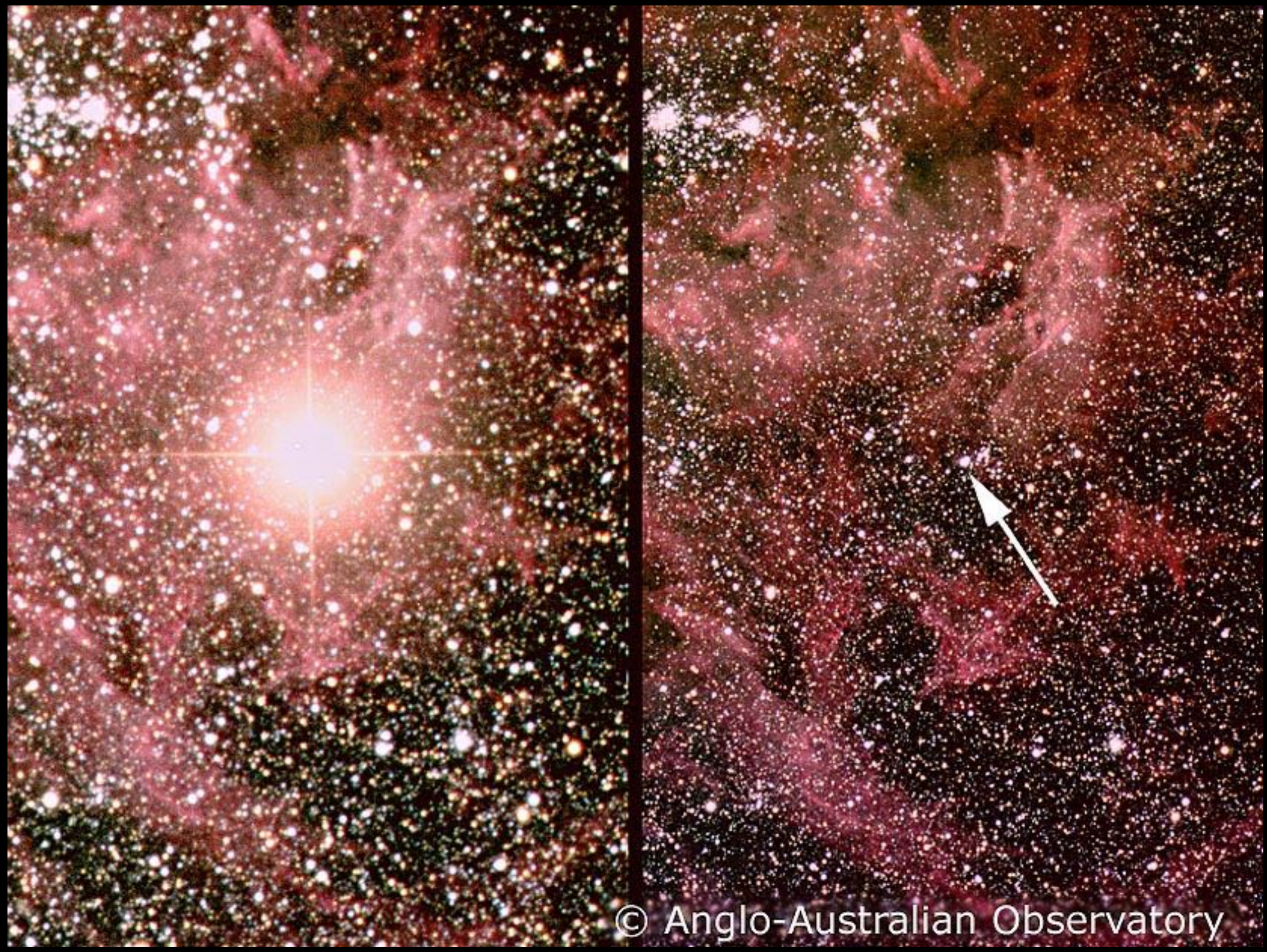
Sudbury Neutrino Observatory (SNO)

Phys. Rev. Lett. **89**, 011301 – Published 13 June 2002

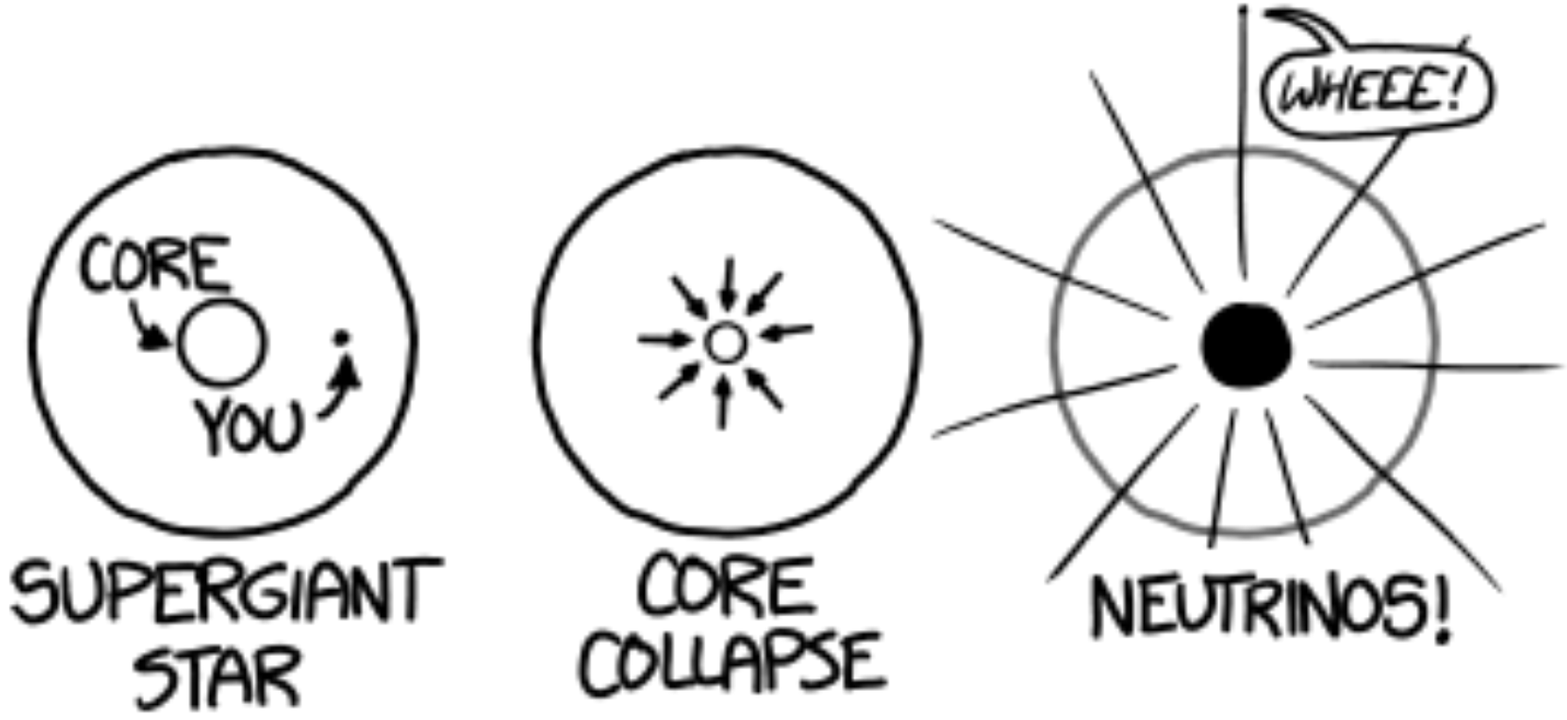
Neutrino flux contains muon and tau neutrinos

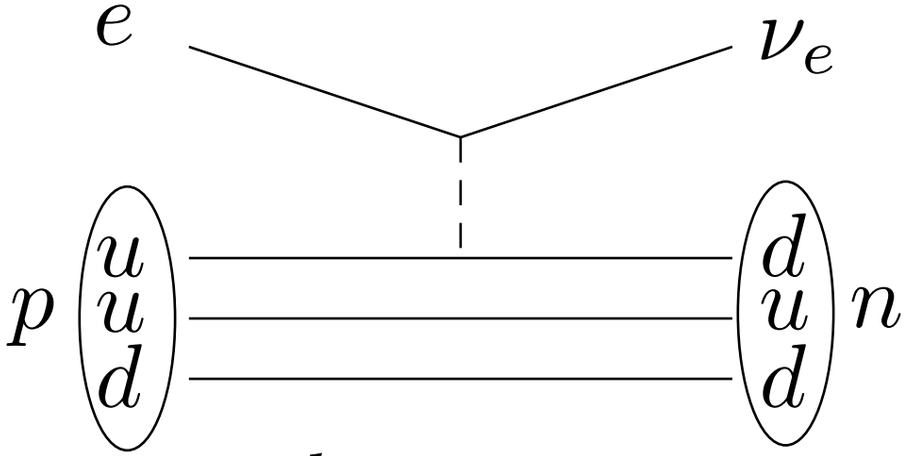




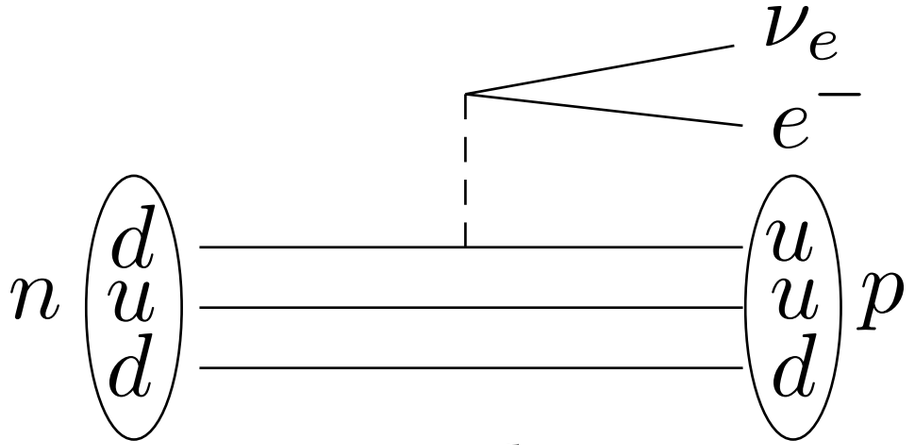

© Anglo-Australian Observatory

https://what-if.xkcd.com/73/

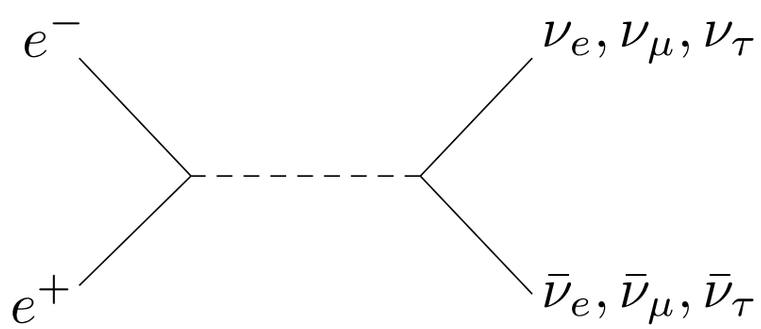




electron capture



neutron decay



neutrino pair production

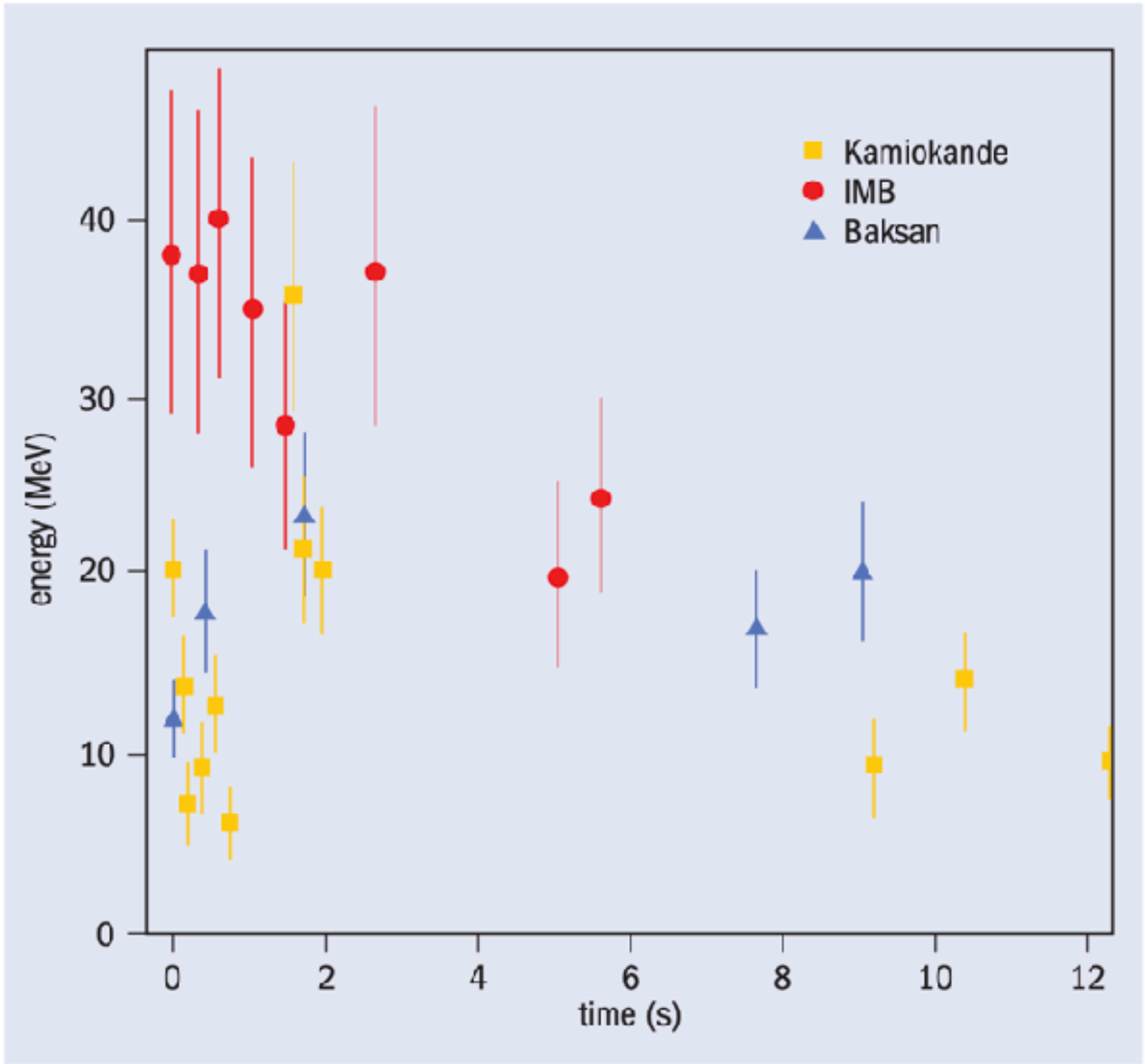
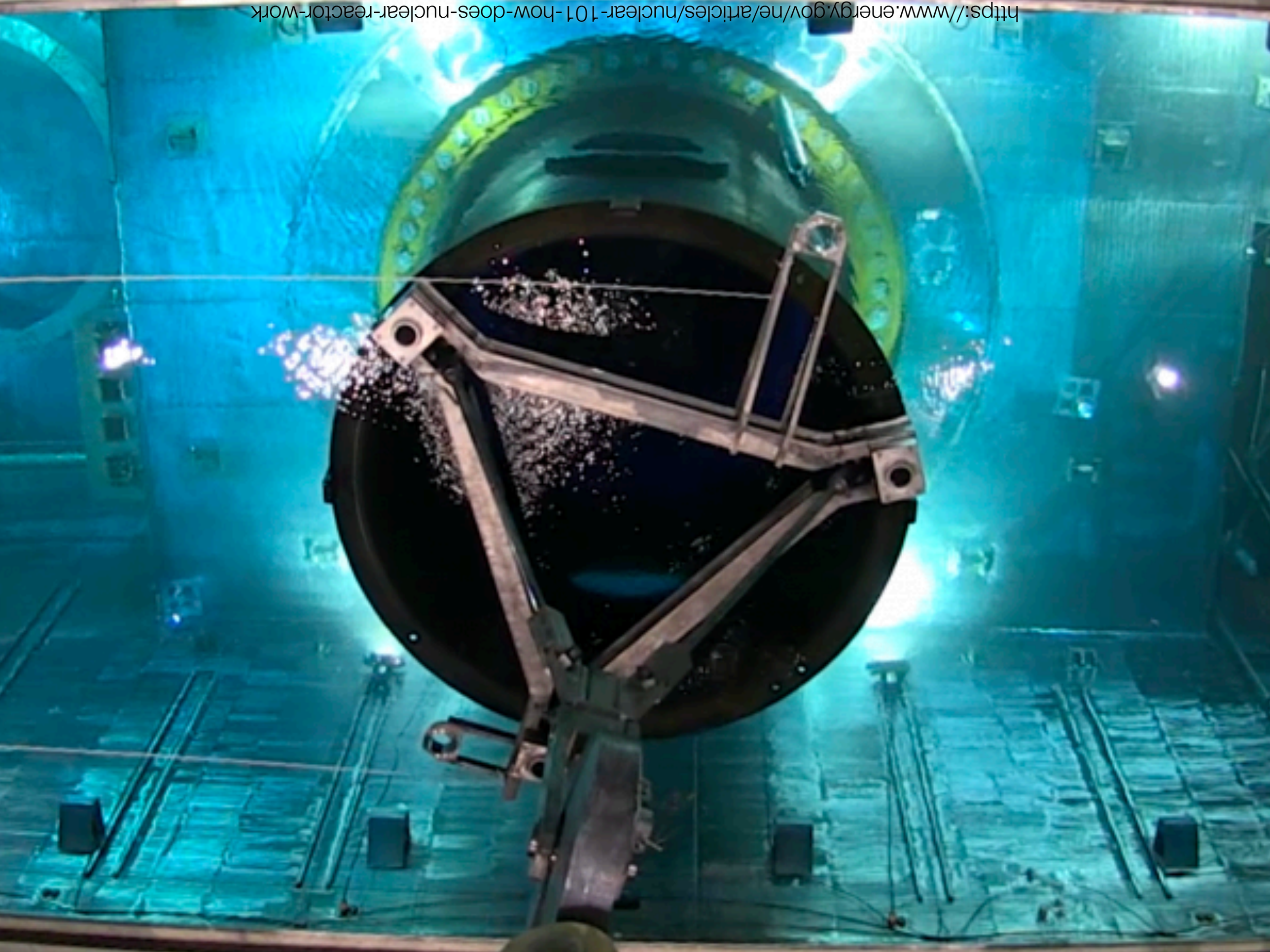
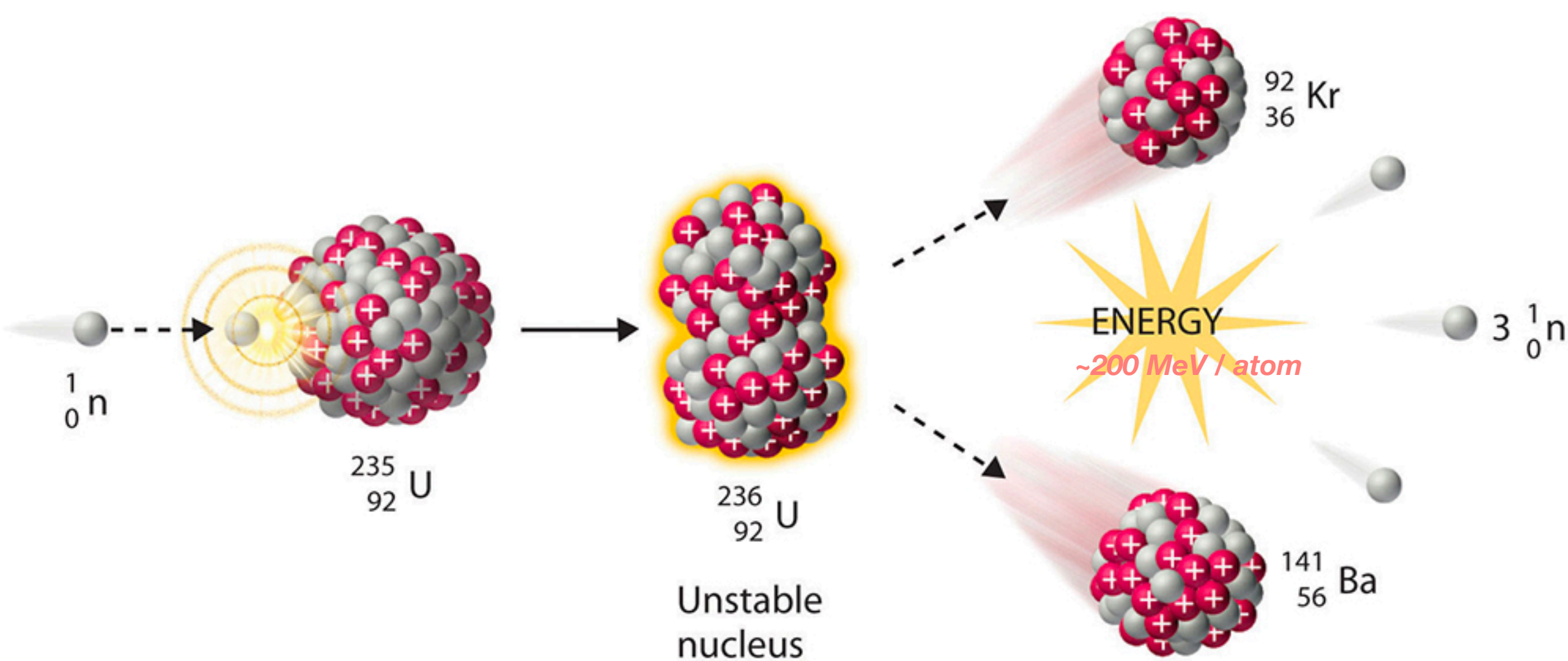


Fig. 3. SN1987A neutrino events observed by Kamiokande, IMB and Baksan showed that the neutrino burst lasted about 13 s.

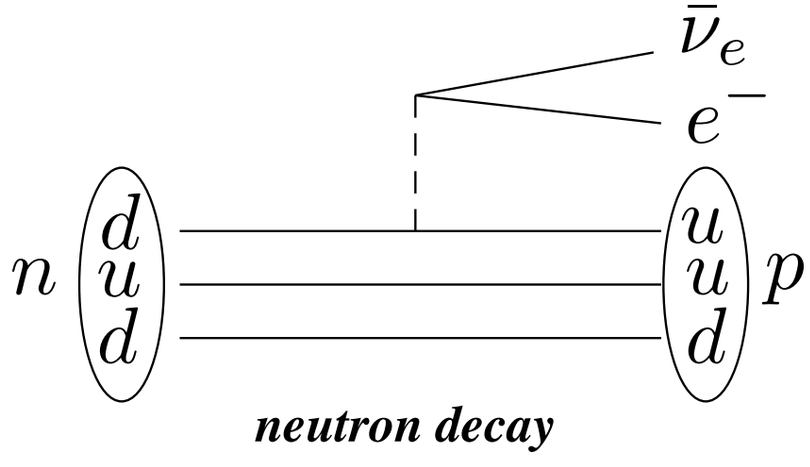
https://www.energy.gov/ne/articles/nuclear-101-how-does-nuclear-reactor-work



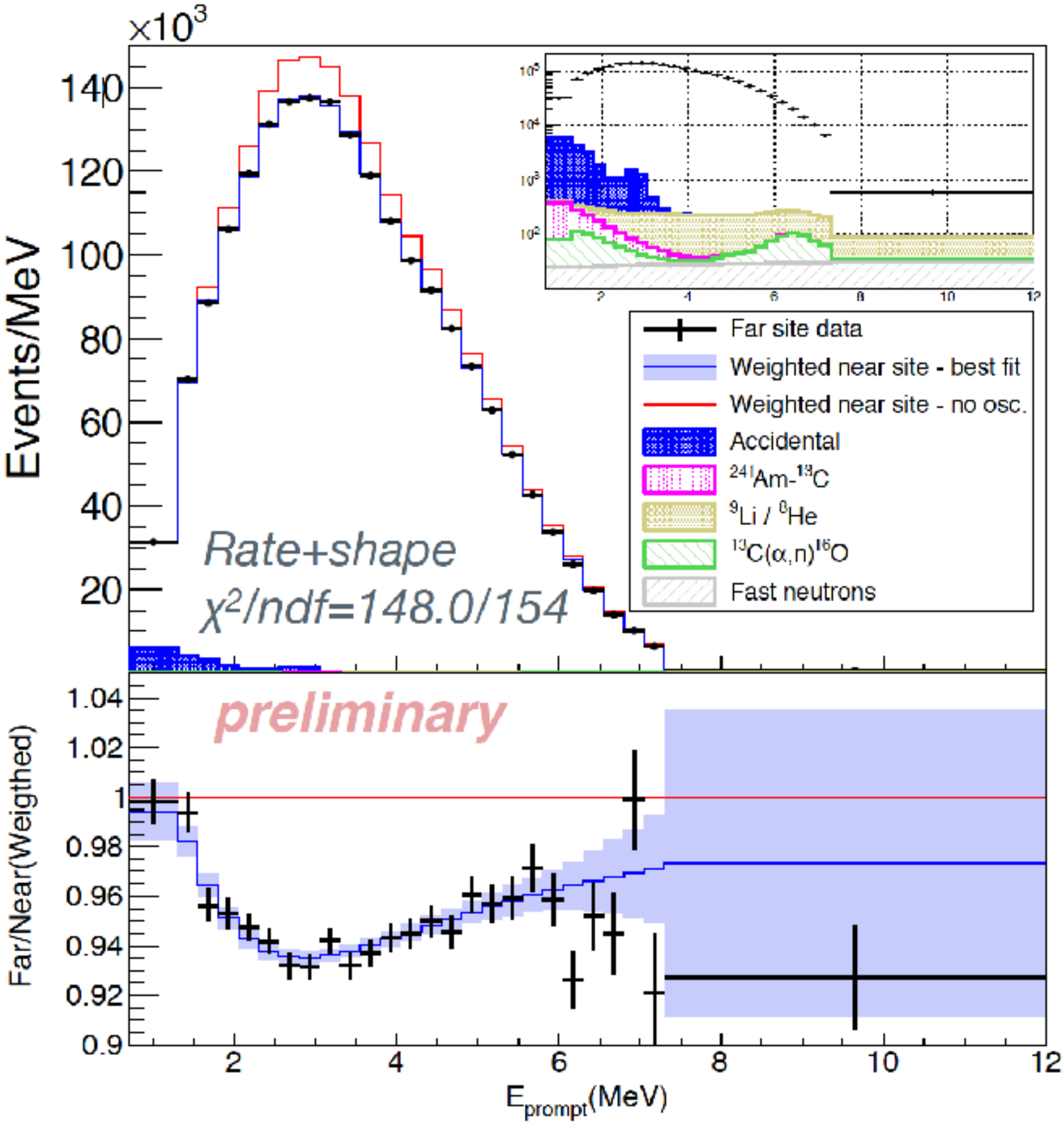


https://www.accessscience.com/content/nuclear-fission/458400

Some of many fission products which can undergo beta decay

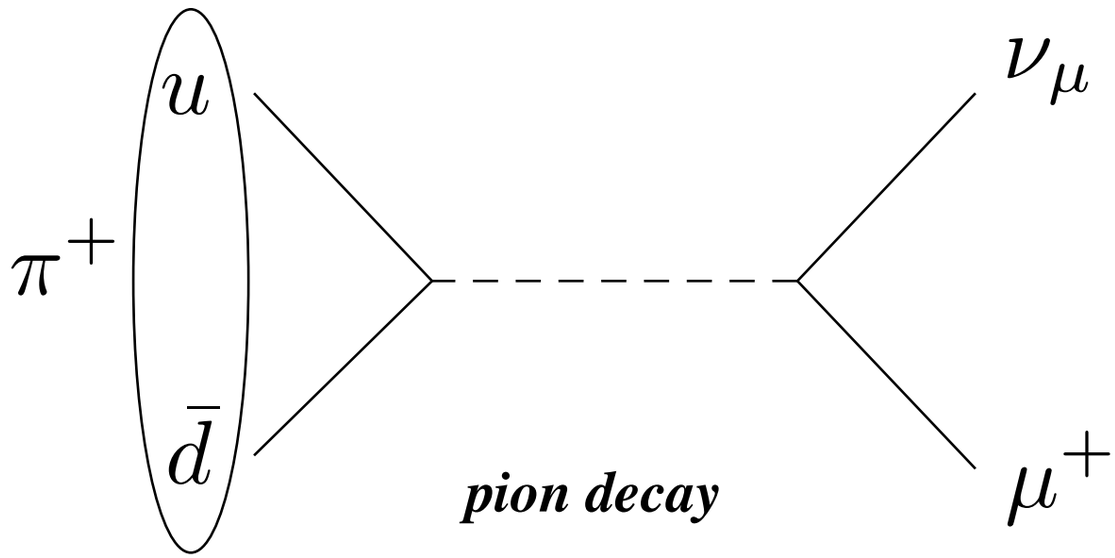


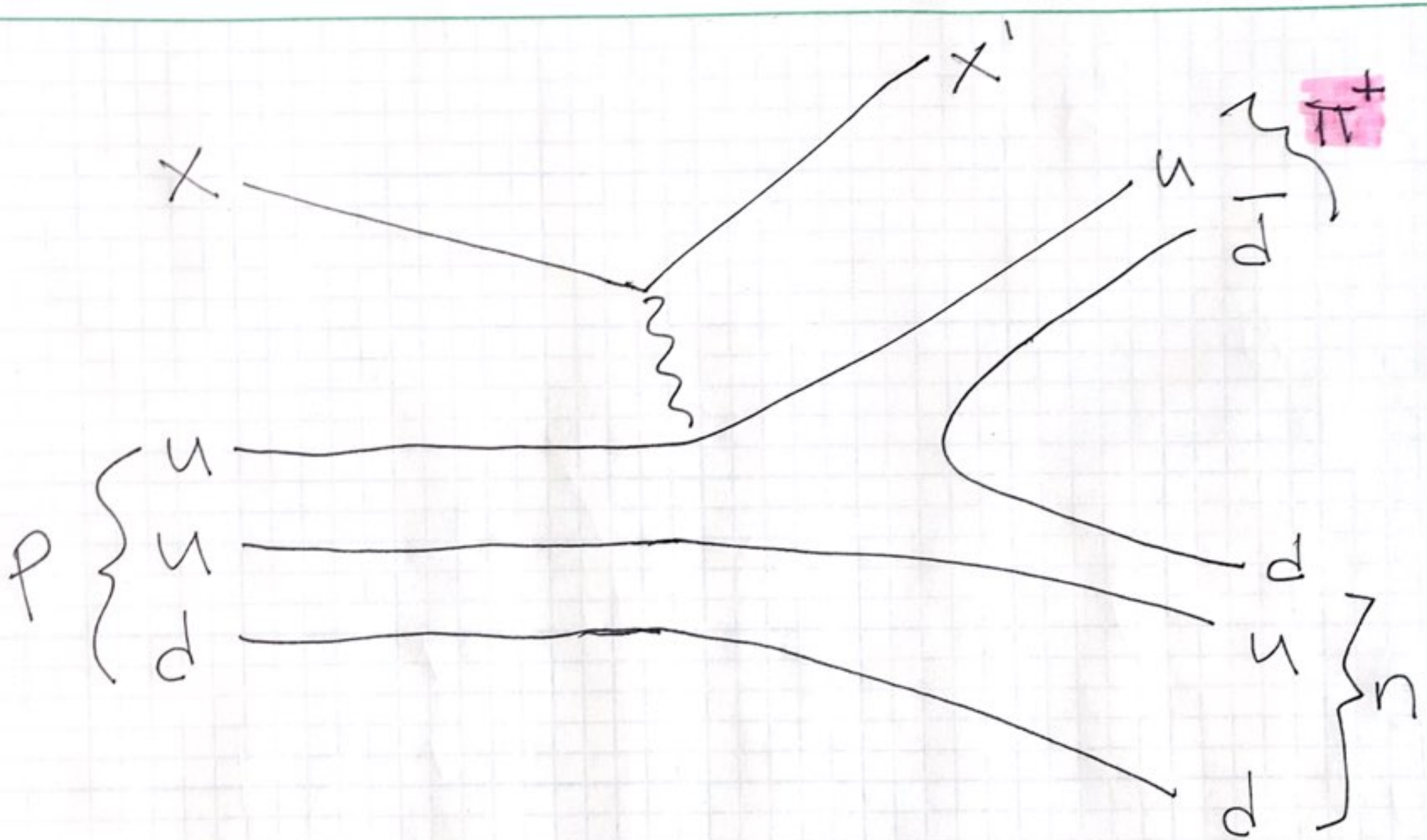
neutron decay

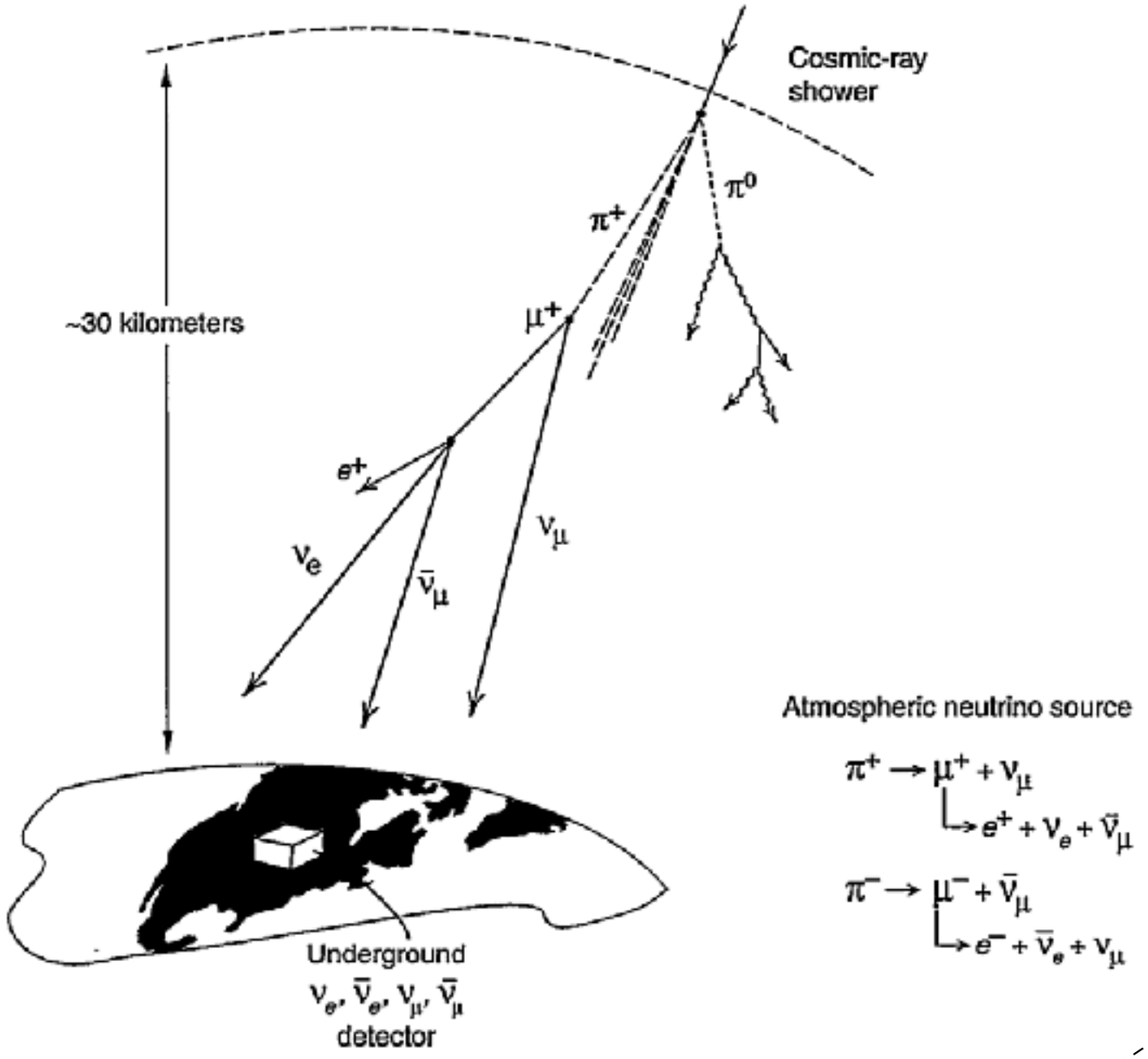


Reactor spectrum measured by Daya Bay experiment

Sources of muon neutrinos

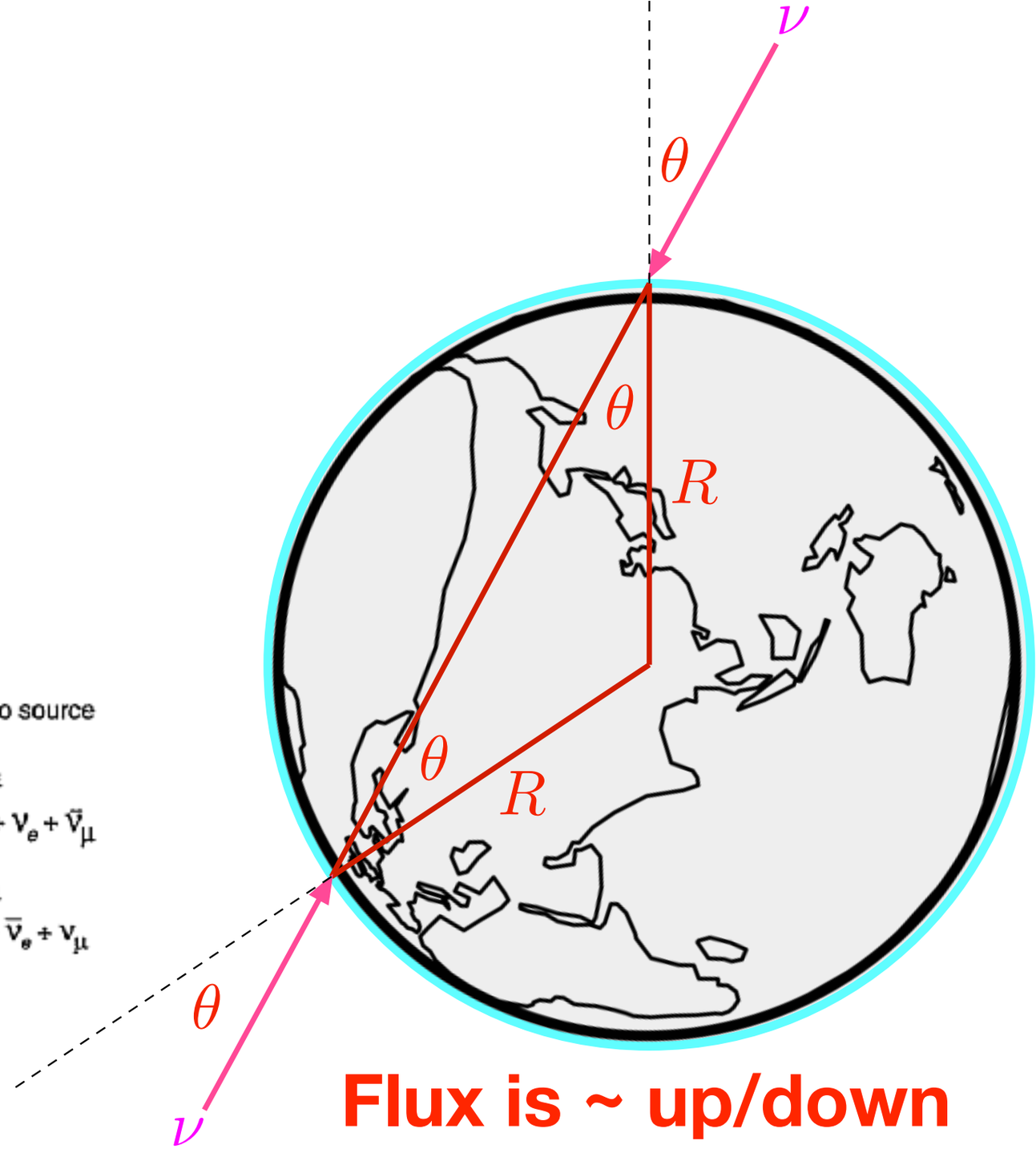



x
x'
u
d
π+
p
u
u
d
d
u
n
d



Atmospheric neutrino source

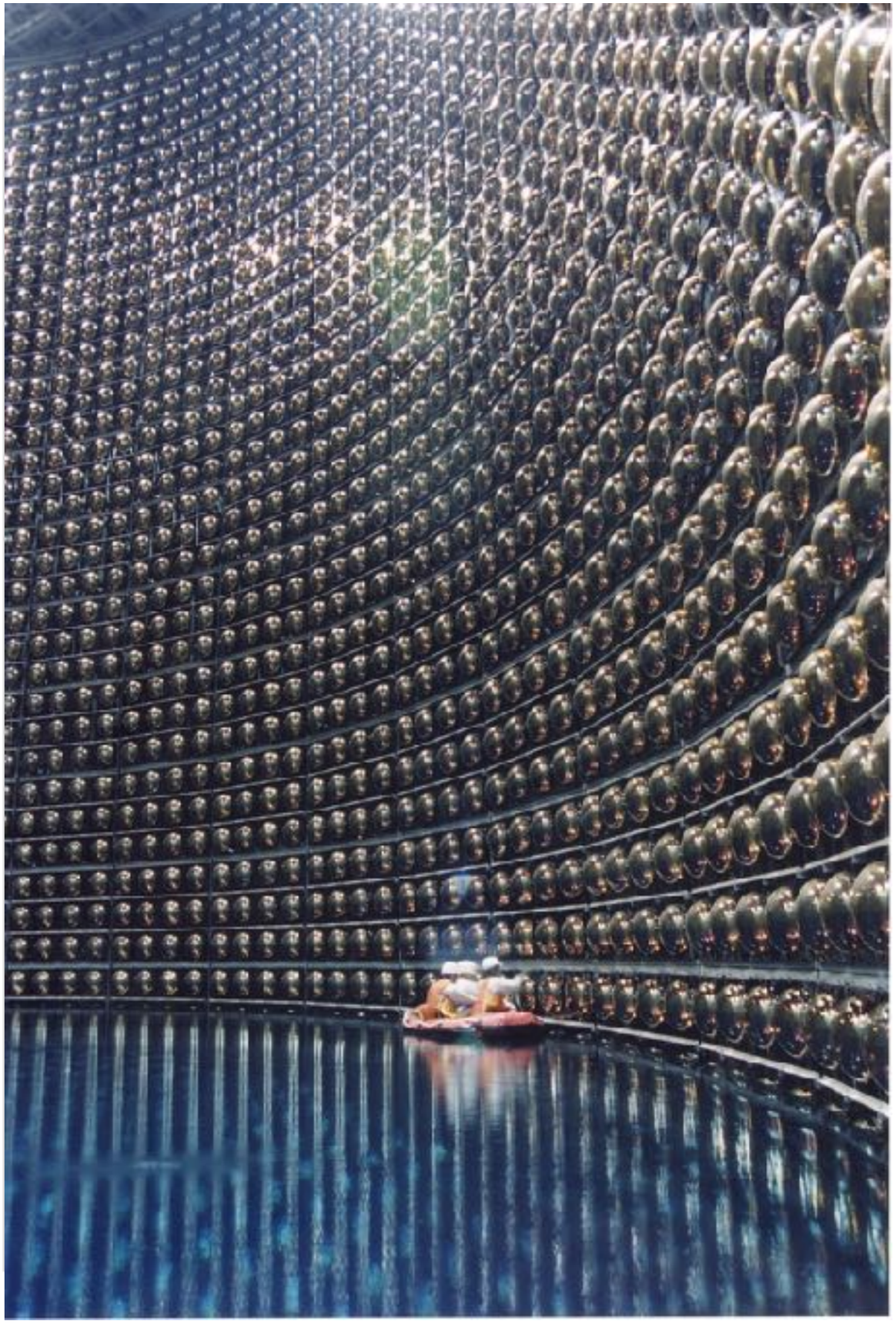
$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\quad\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu$$
$$\quad\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



$$\nu_\mu : \nu_e \simeq 2 : 1$$

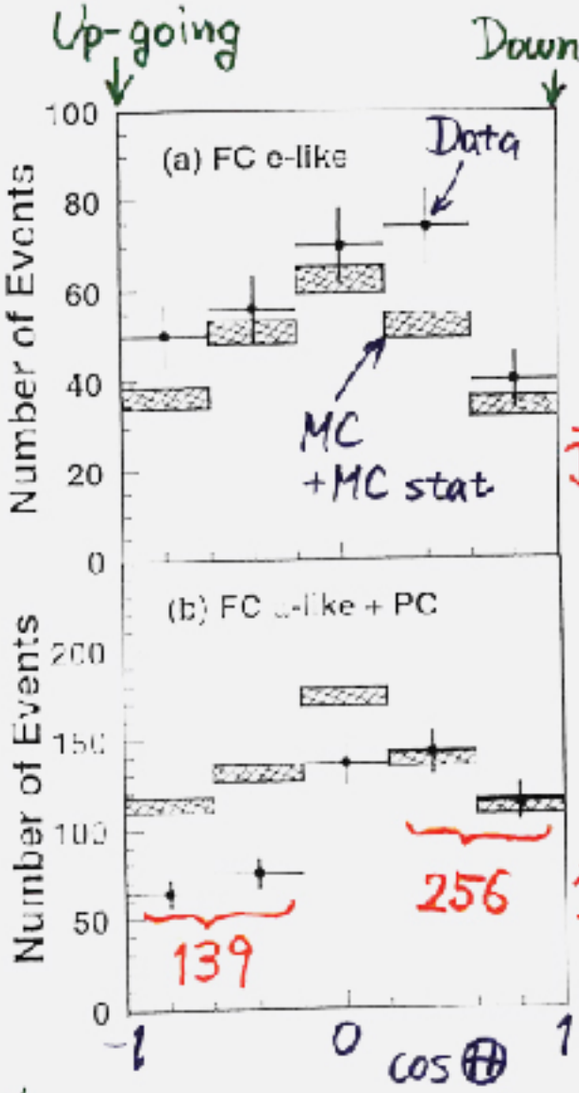
Flux is ~ up/down symmetric

Atmospheric neutrinos



Super-Kamiokande

Zenith angle dependence (Multi-GeV)



e: χ^2(shape) = 2.8/4 dof

$\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

μ: χ^2(shape) = 30/4 dof

$\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$ (6.2σ !!)

※ Up/Down syst. error for μ-like

Prediction (flux calculation ····· ≲1%, 1km rock above SK ···· 1.5%) 1.8%

Data (Energy calib. for ↑↓ ···· 0.7%, Non ν Background ····· < 2%) 2.1%

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

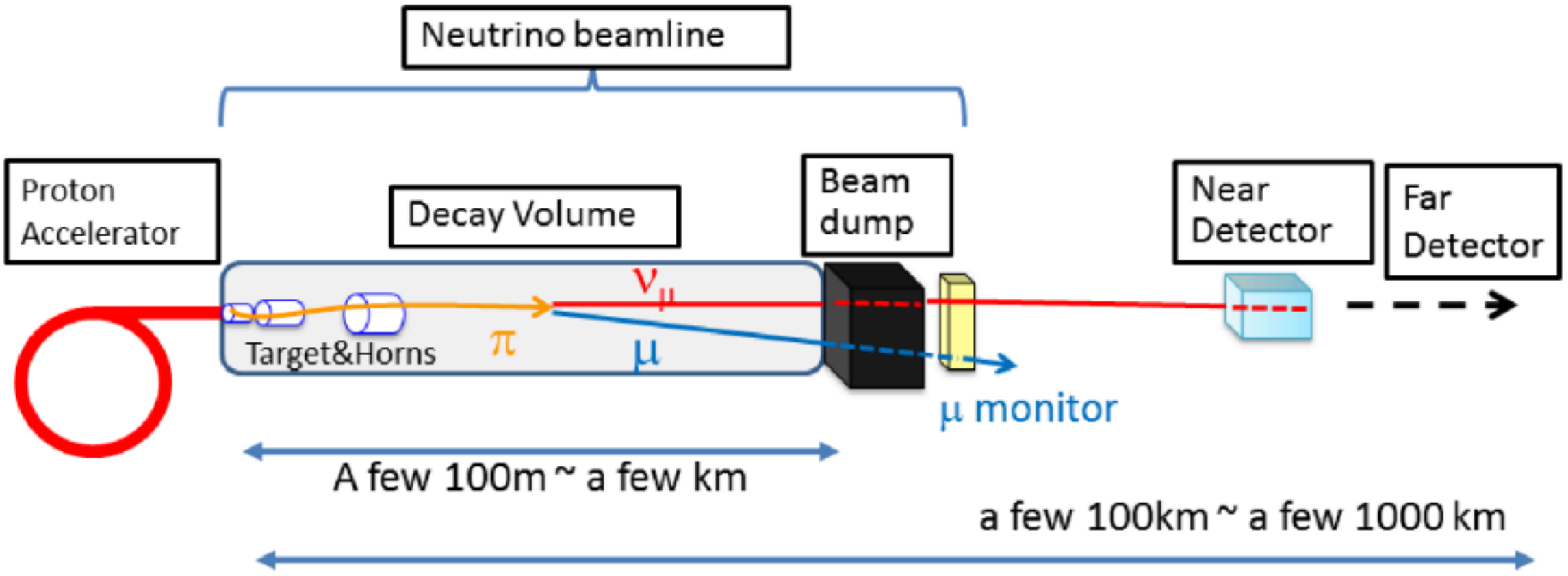
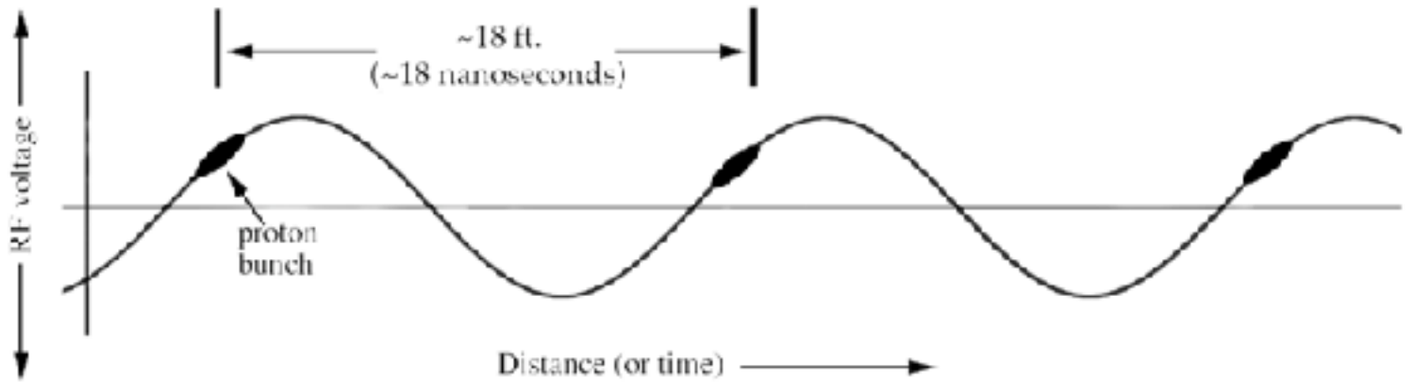


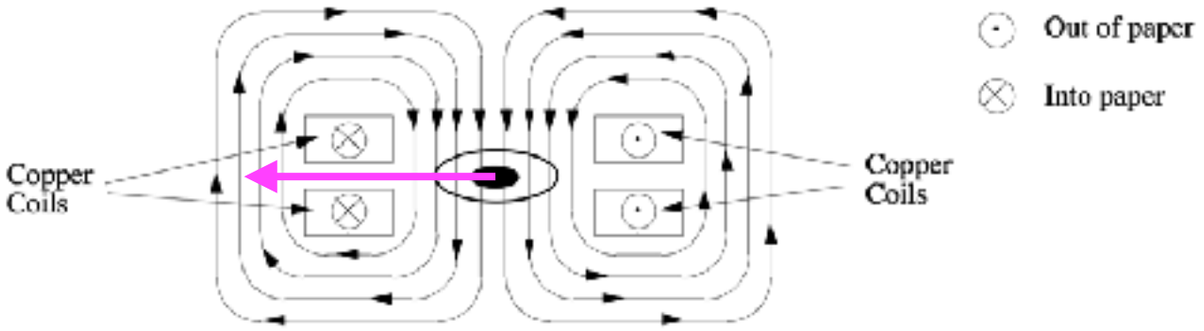
FIGURE 1. Components of the accelerator neutrino experiment

Fermi National Accelerator Laboratory

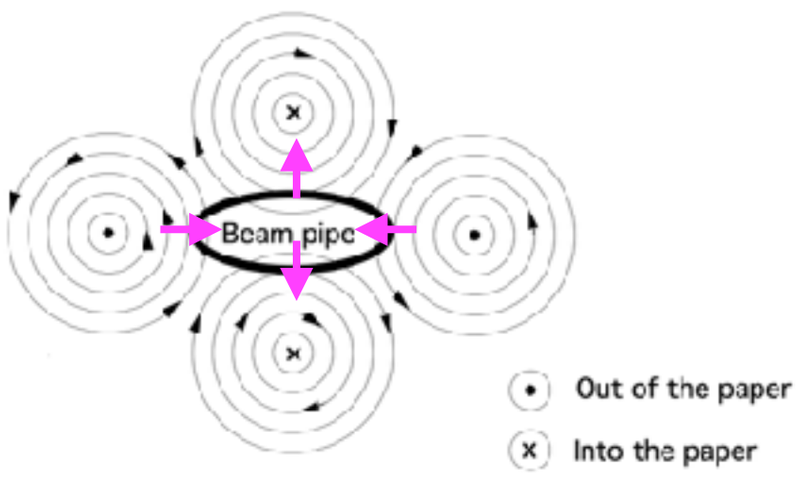
Accelerator terminology



Beam is accelerated by applying a pulsed electric field; 56 MHz “Radio Frequency”, RF. The beam naturally falls into the minima of these “buckets”



To make the beam travel in a circle it is deflected by dipole magnets.



To keep the beam inside the pipe, it is squeezed in the vertical and horizontal directions by quadrupole magnets

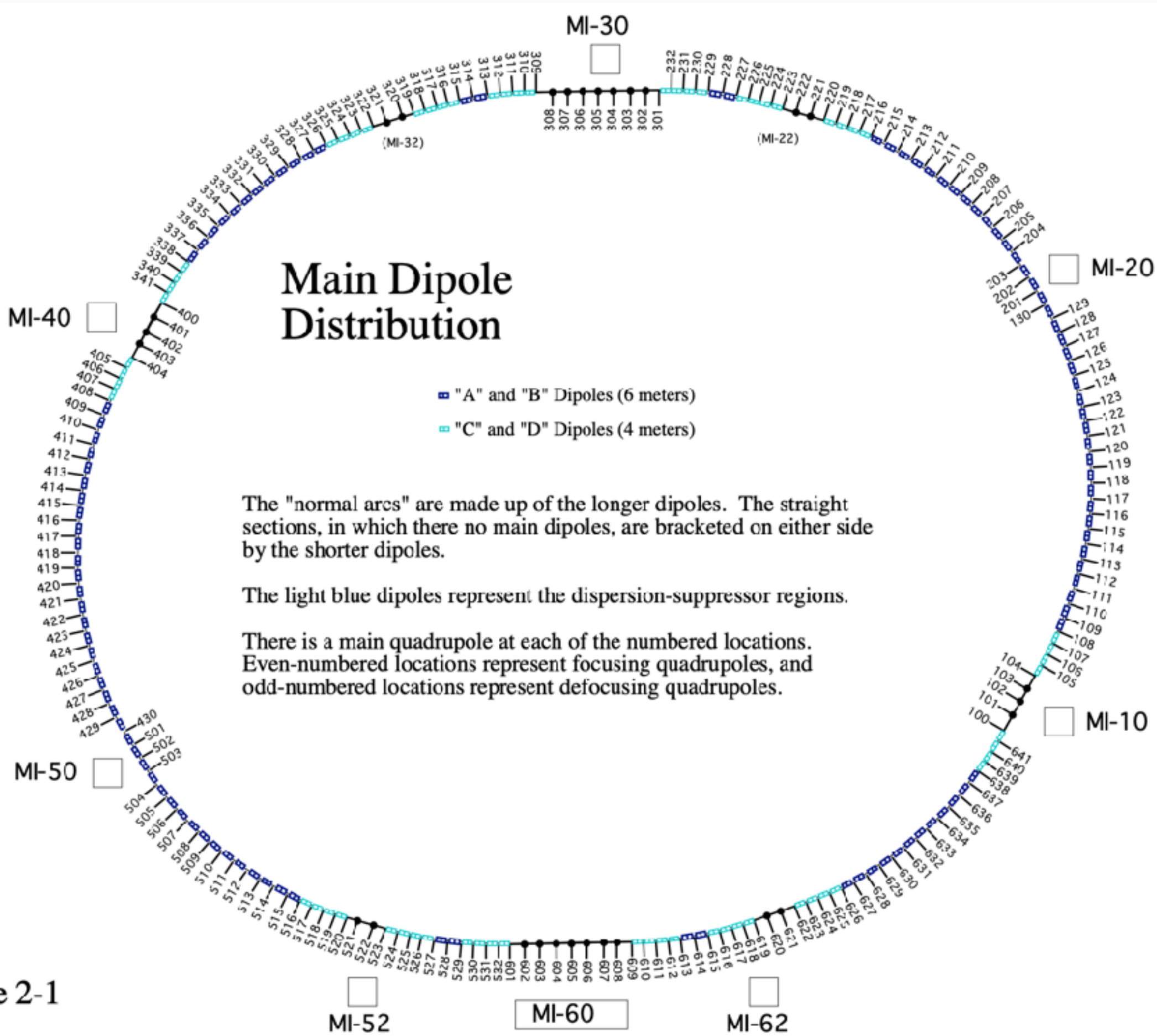
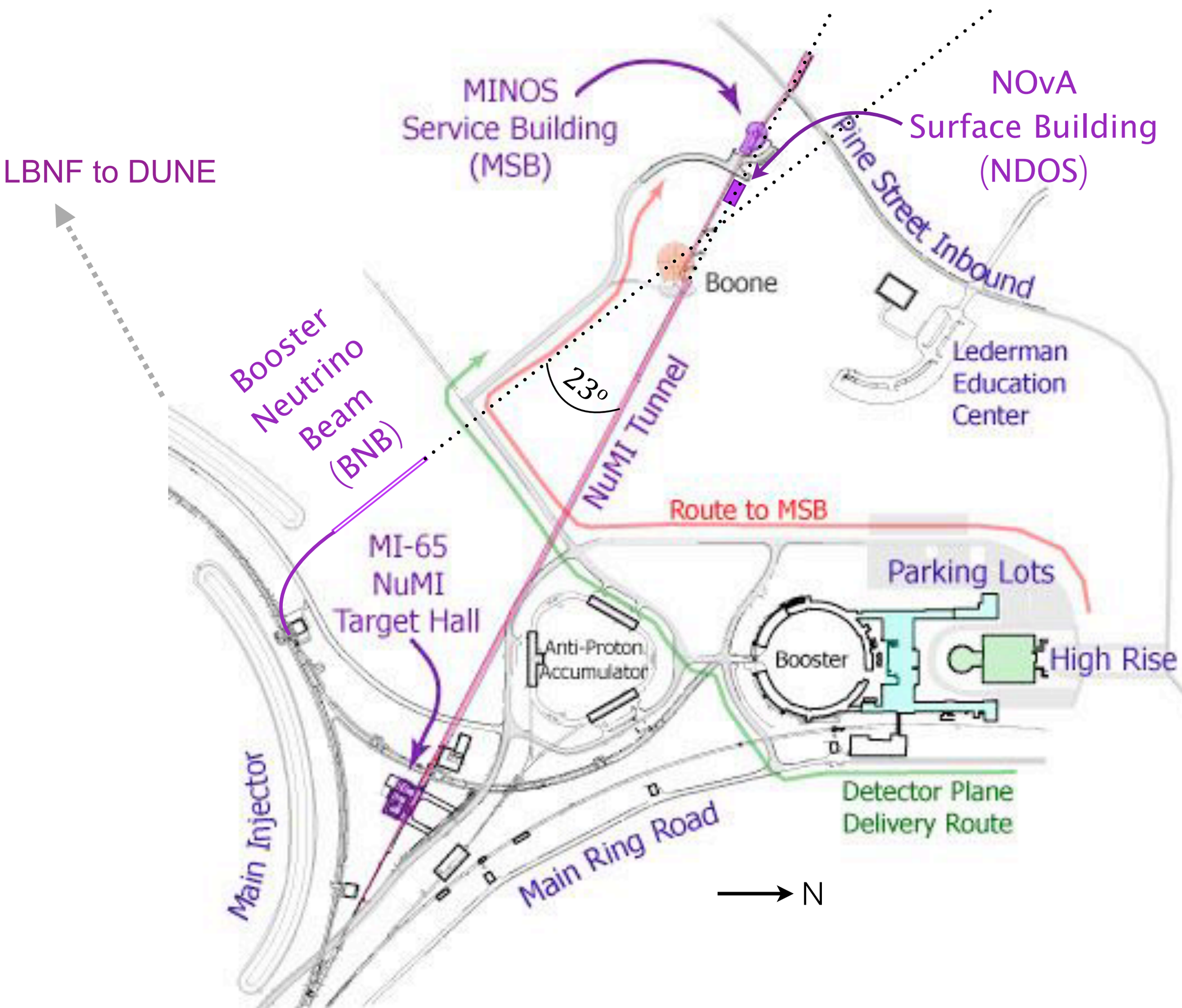
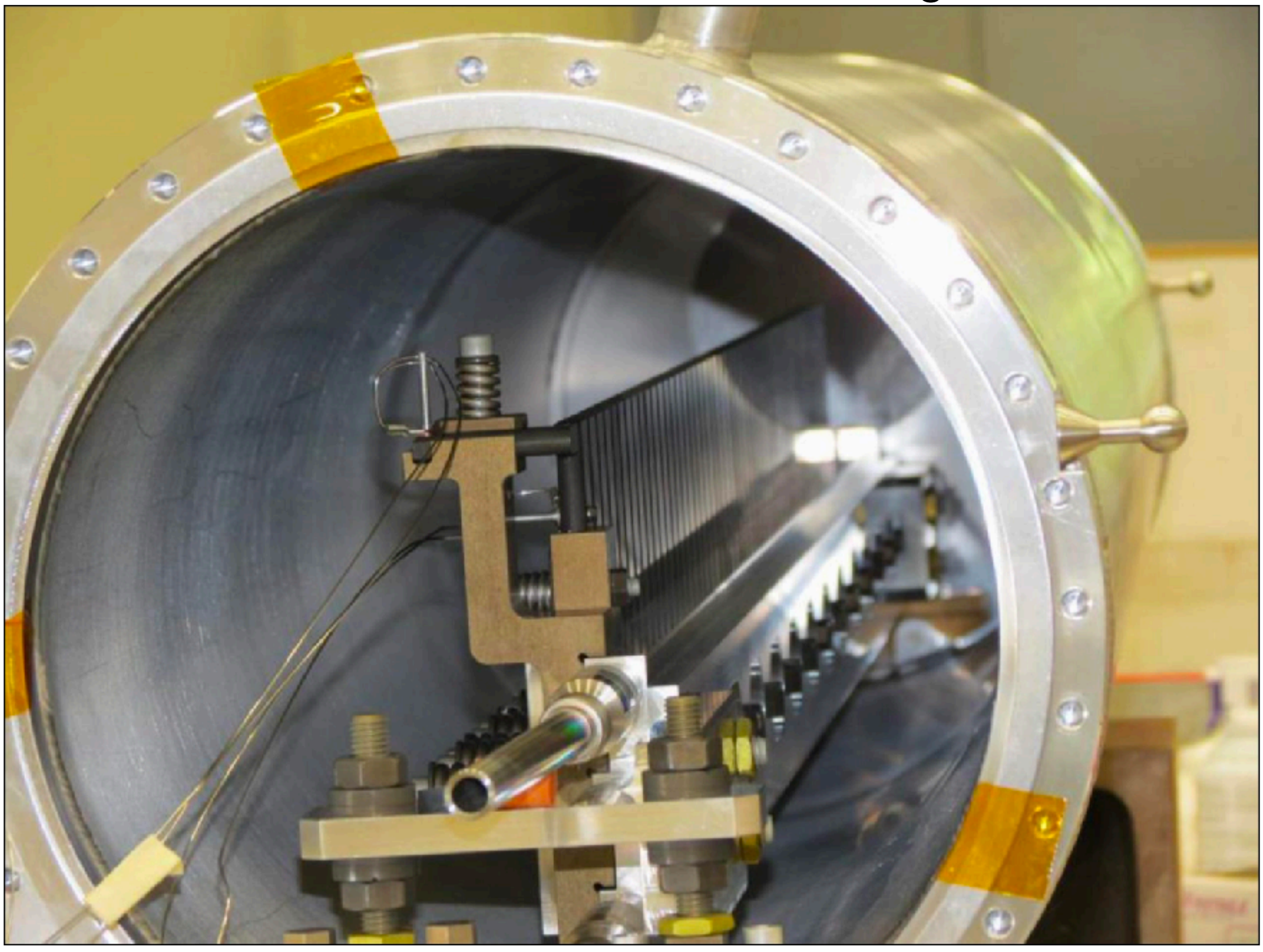
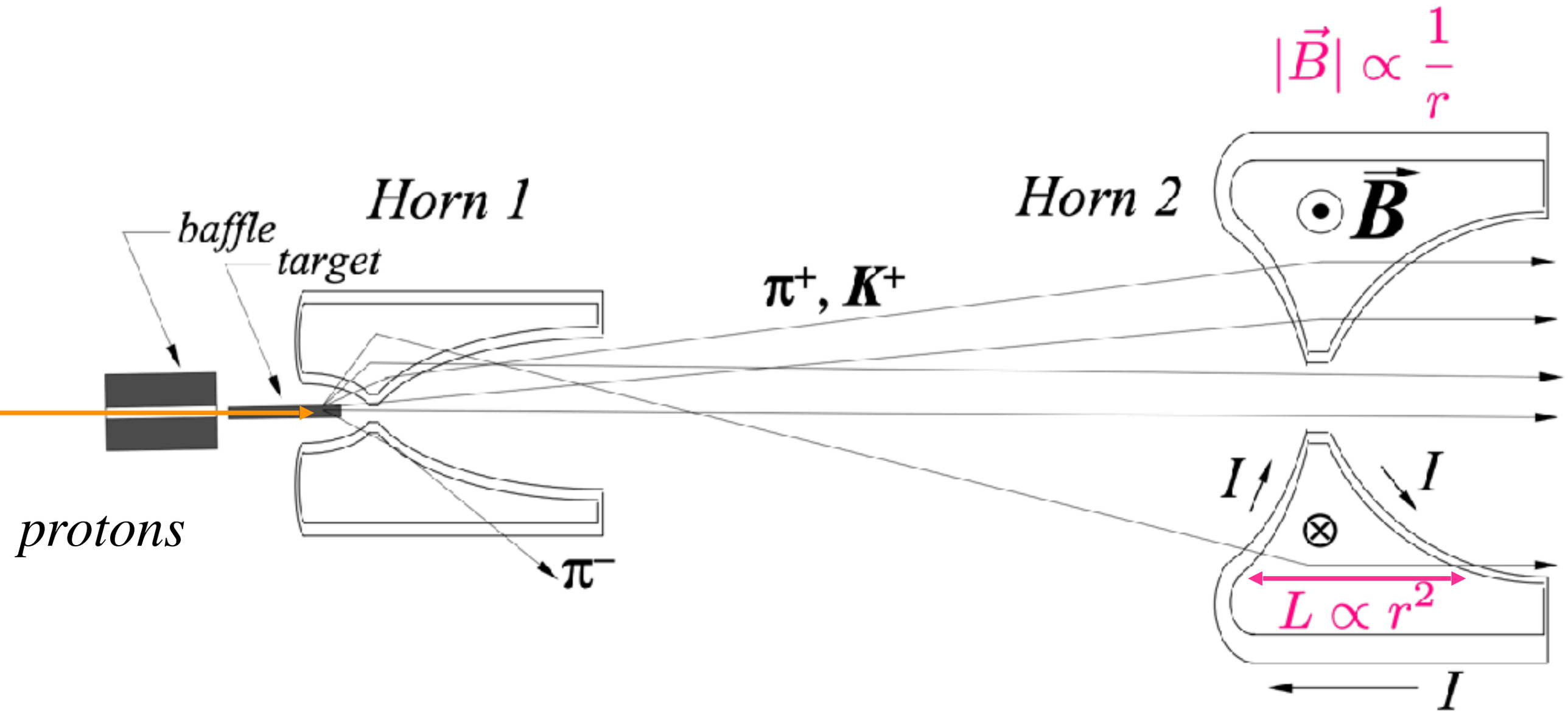

MI-30
MI-20
MI-40
MI-10
MI-50
MI-52
MI-60
MI-62
(MI-32)
(MI-22)
Main Dipole Distribution
"A" and "B" Dipoles (6 meters)
"C" and "D" Dipoles (4 meters)
The "normal arcs" are made up of the longer dipoles. The straight sections, in which there no main dipoles, are bracketed on either side by the shorter dipoles.
The light blue dipoles represent the dispersion-suppressor regions.
There is a main quadrupole at each of the numbered locations. Even-numbered locations represent focusing quadrupoles, and odd-numbered locations represent defocusing quadrupoles.

Figure 2-1


LBNF to DUNE
MINOS
Service Building
(MSB)
NOvA
Surface Building
(NDOS)
Pine Street Inbound
Boone
Booster
Neutrino
Beam
(BNB)
23°
NuMI Tunnel
Lederman
Education
Center
Route to MSB
MI-65
NuMI
Target Hall
Parking Lots
Anti-Proton
Accumulator
Booster
High Rise
Main Injector
Main Ring Road
Detector Plane
Delivery Route
N

NuMI Neutrino Production Target

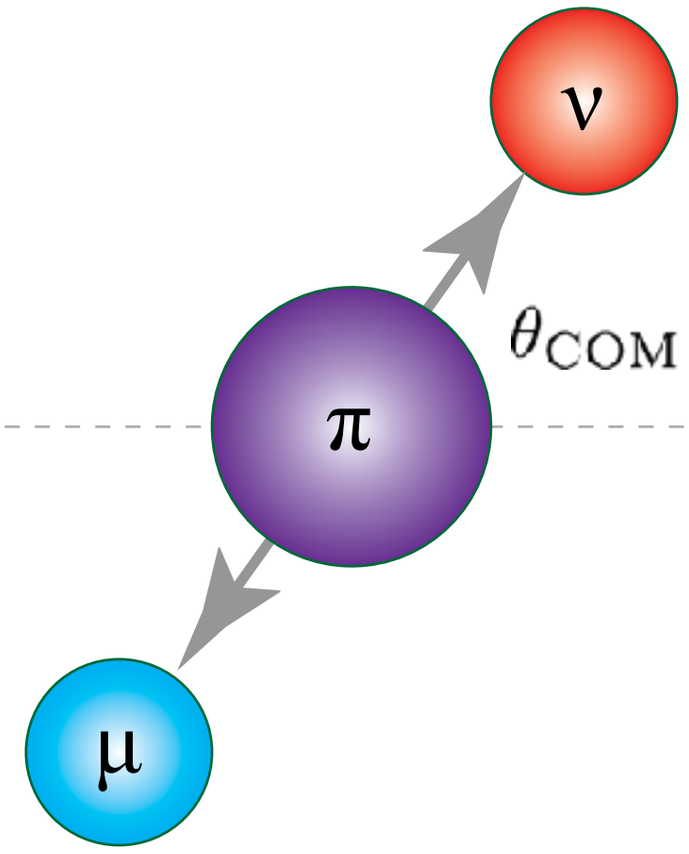




$$p_{\text{kick}} \propto B \cdot L \propto r$$

Center of mass frame

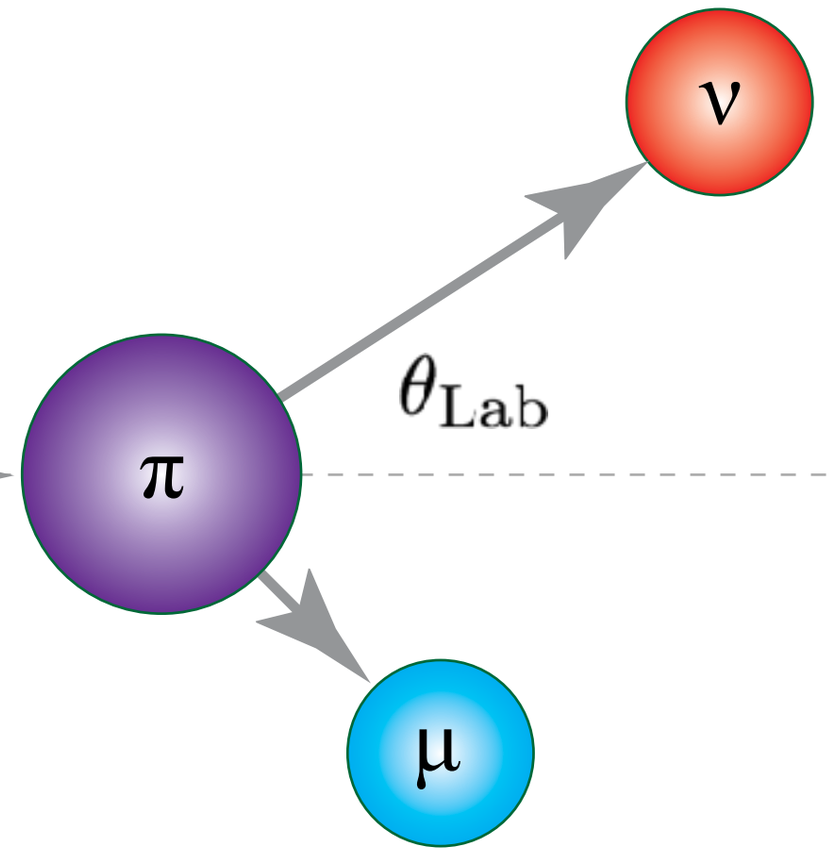
$$p_{\mathrm{COM}} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$$



Boosted frame

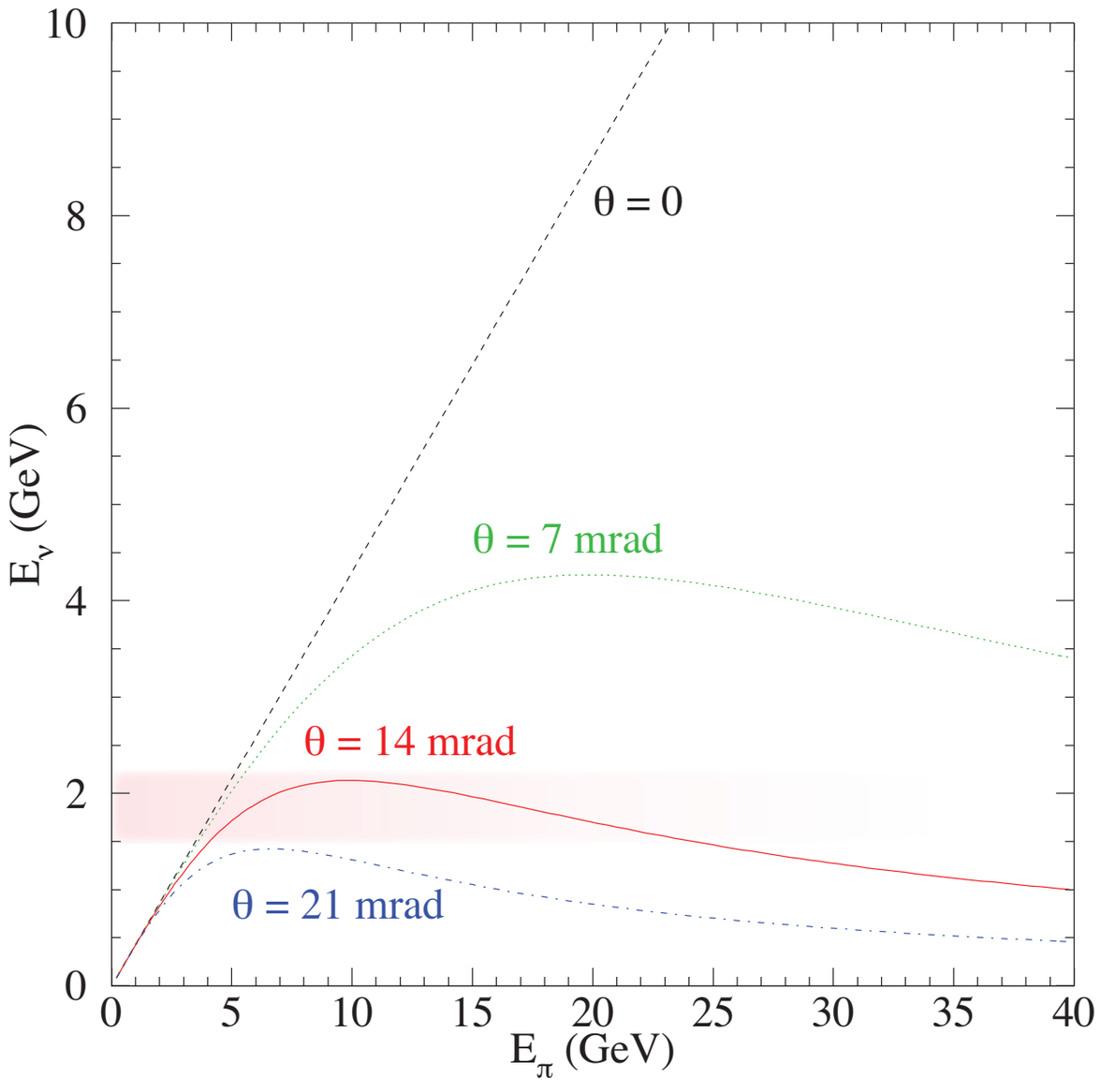
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta_{\mathrm{Lab}}^2}$$

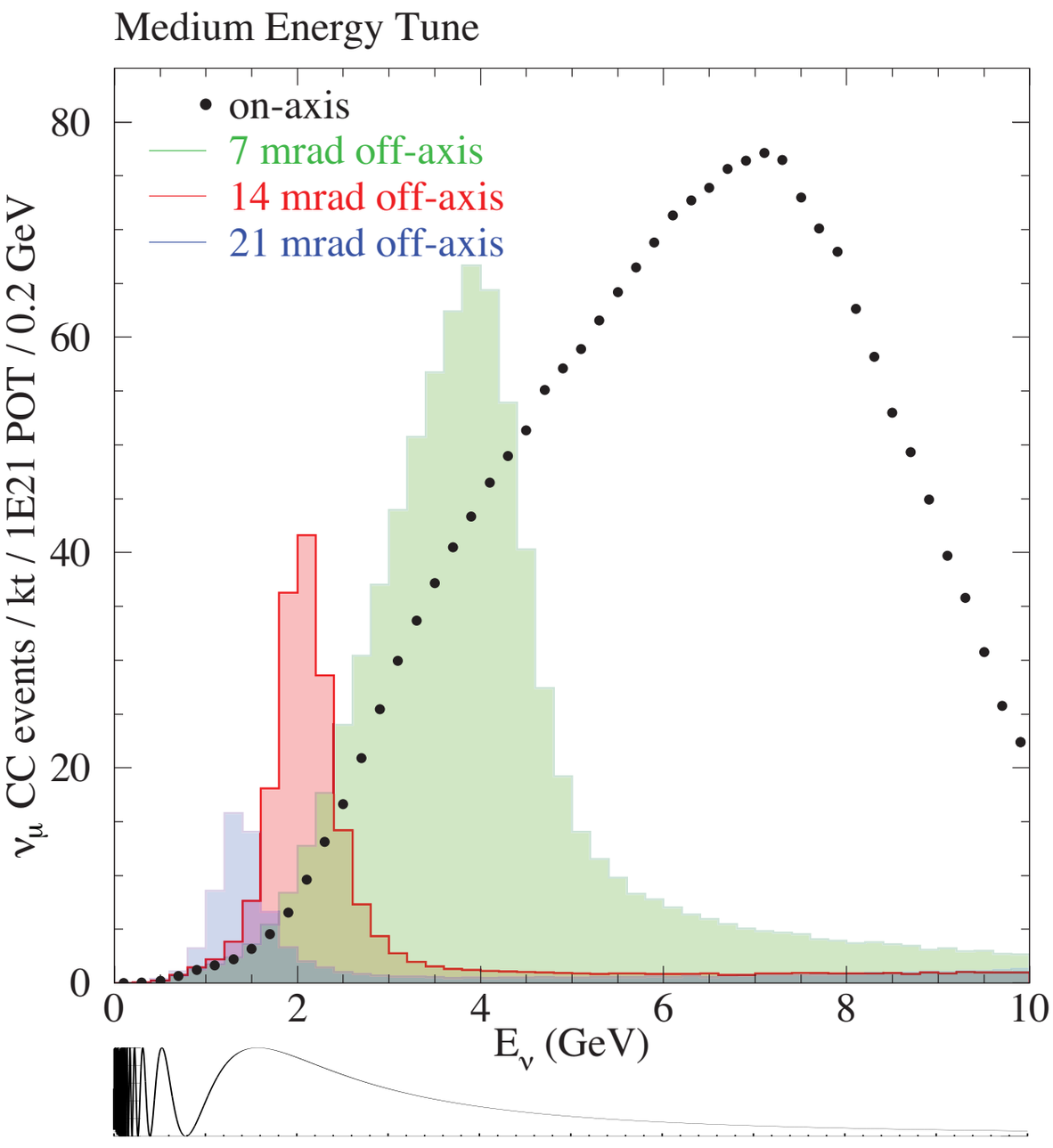
$$\gamma = \frac{E_\pi}{m_\pi}$$



Selecting neutrino energy | Angle is energy

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta^2_{\mathrm{Lab}}}$$





Selecting neutrino energy

Angle is energy (NuMI example)

Neutrino fluxes to be sent to DUNE

Eur.Phys.J.C 80 (2020) 10, 978

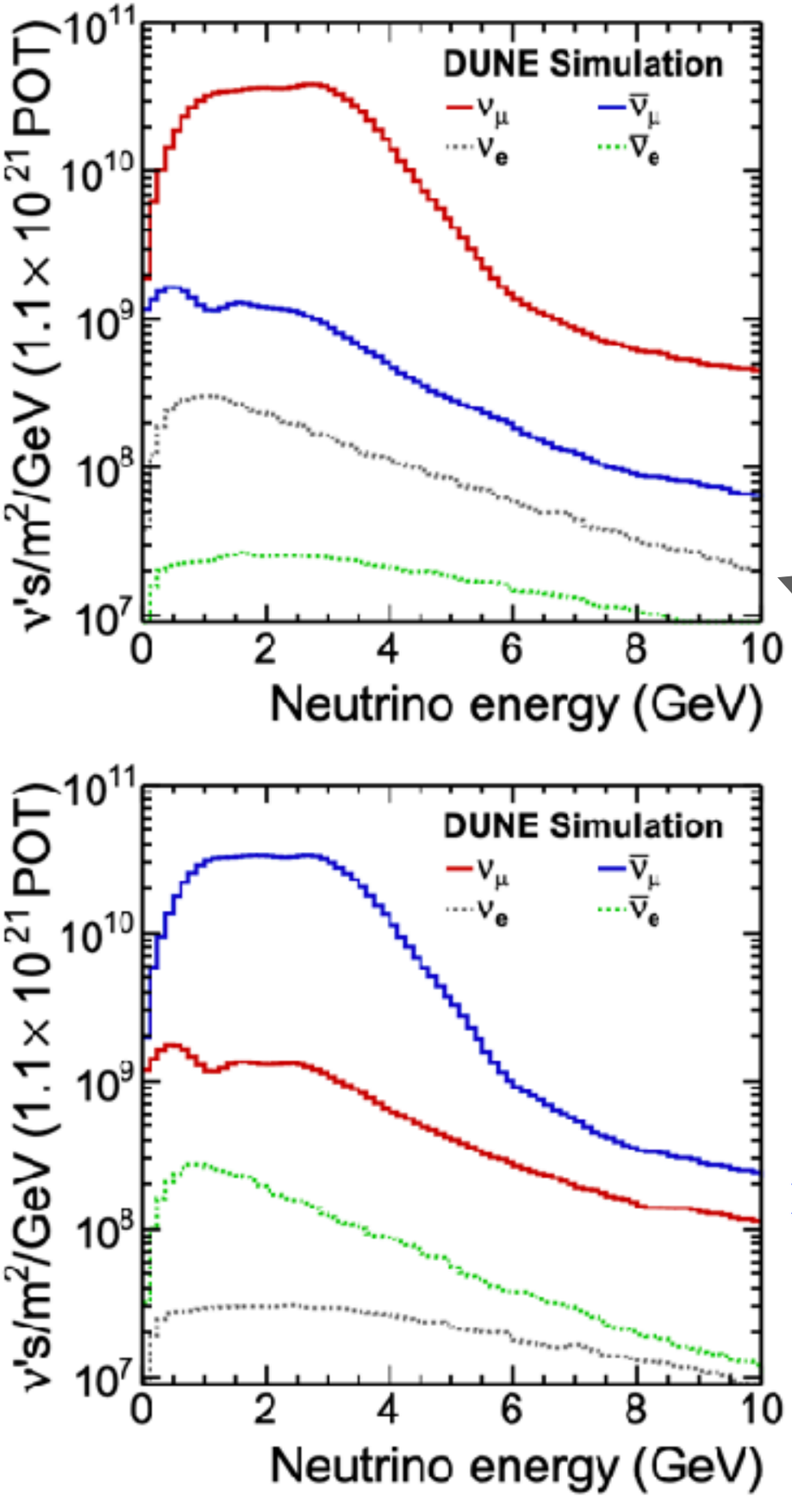


Fig. 2 Neutrino fluxes at the FD for neutrino-enhanced, FHC, beam running (top) and antineutrino, RHC, beam running (bottom).

Can't defocus "wrong-sign" component completely

muon lifetime ~100x longer than pion lifetime. There will always be ~1% electron contamination in a pion beam.

Conservation of charge means that it will always be easier to make neutrinos than antineutrinos when using proton beams

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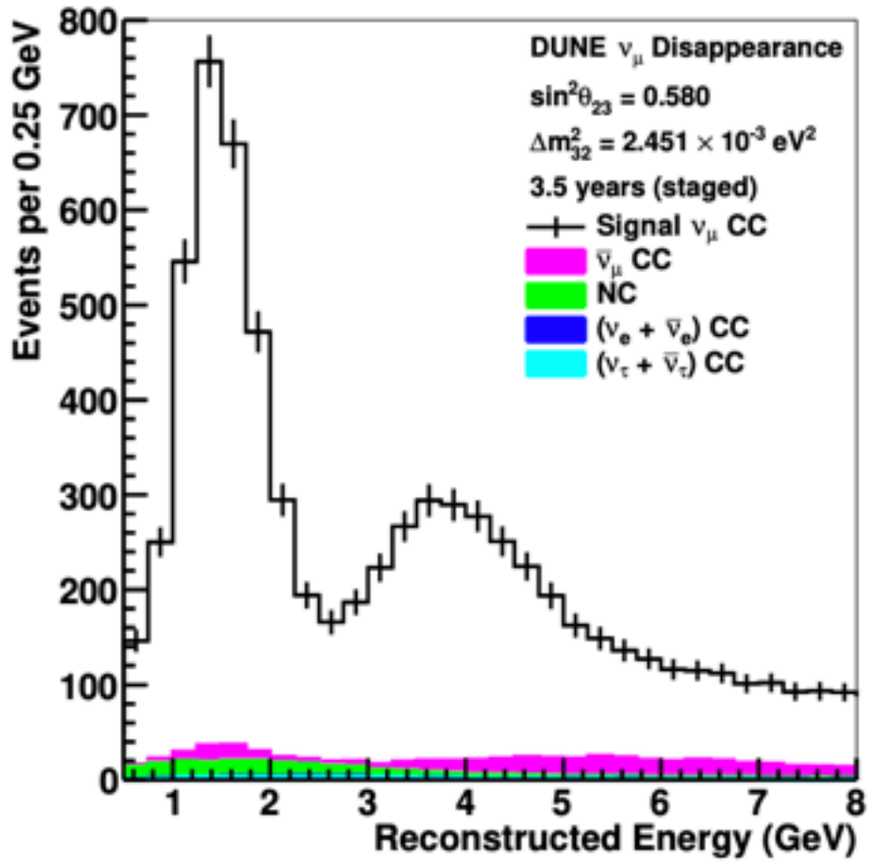
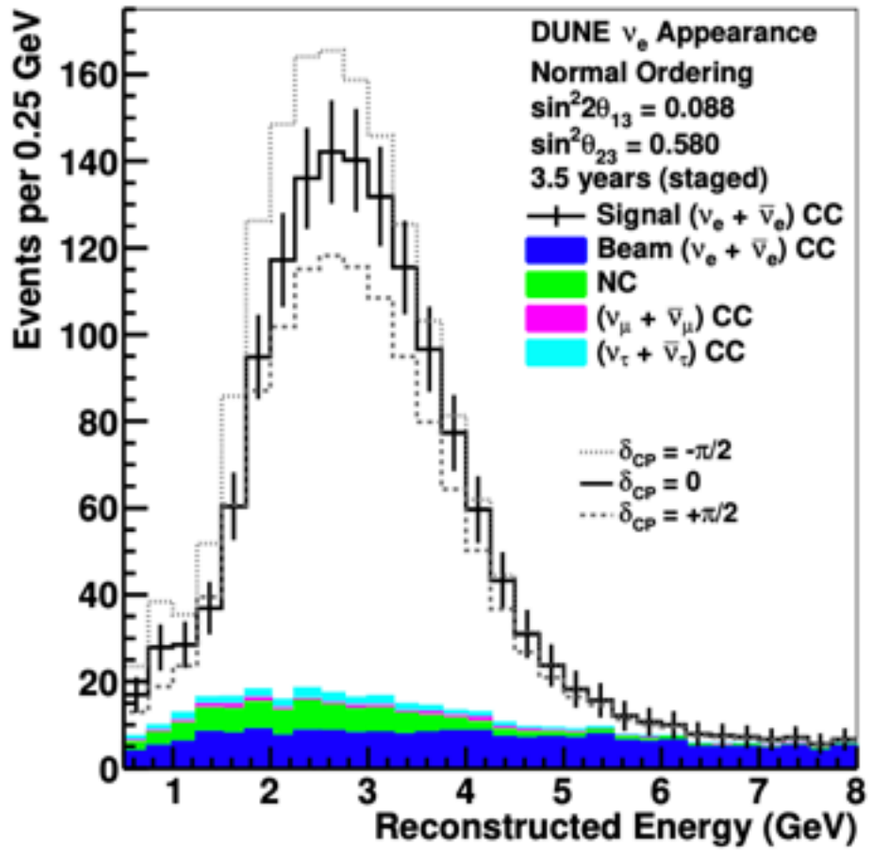
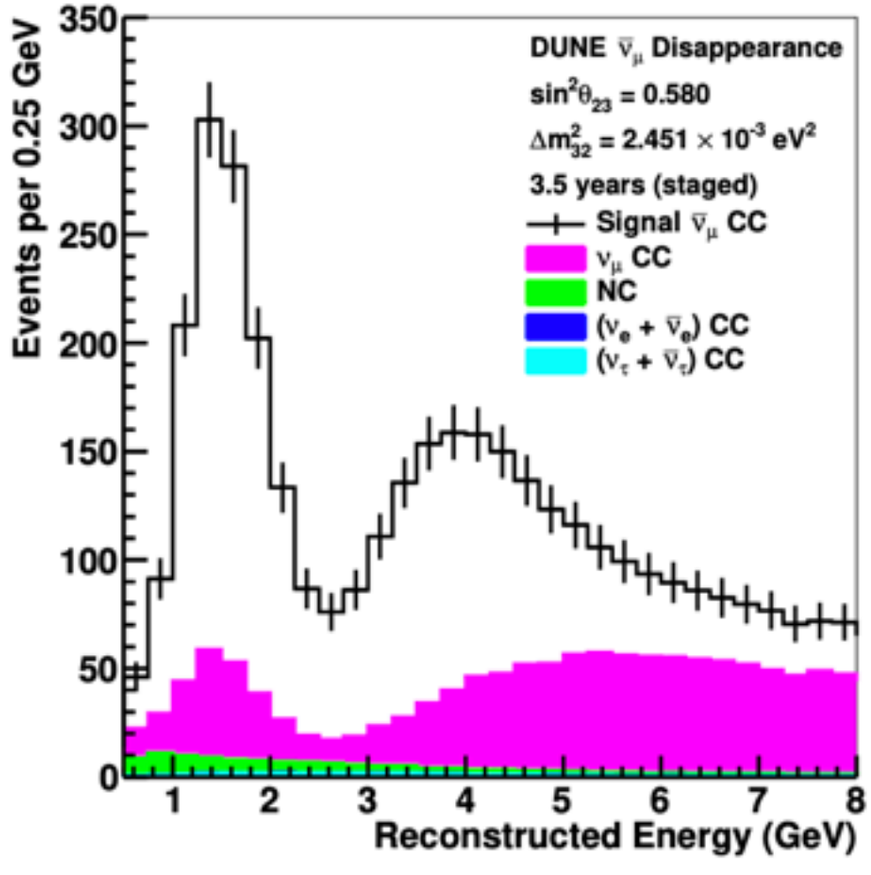
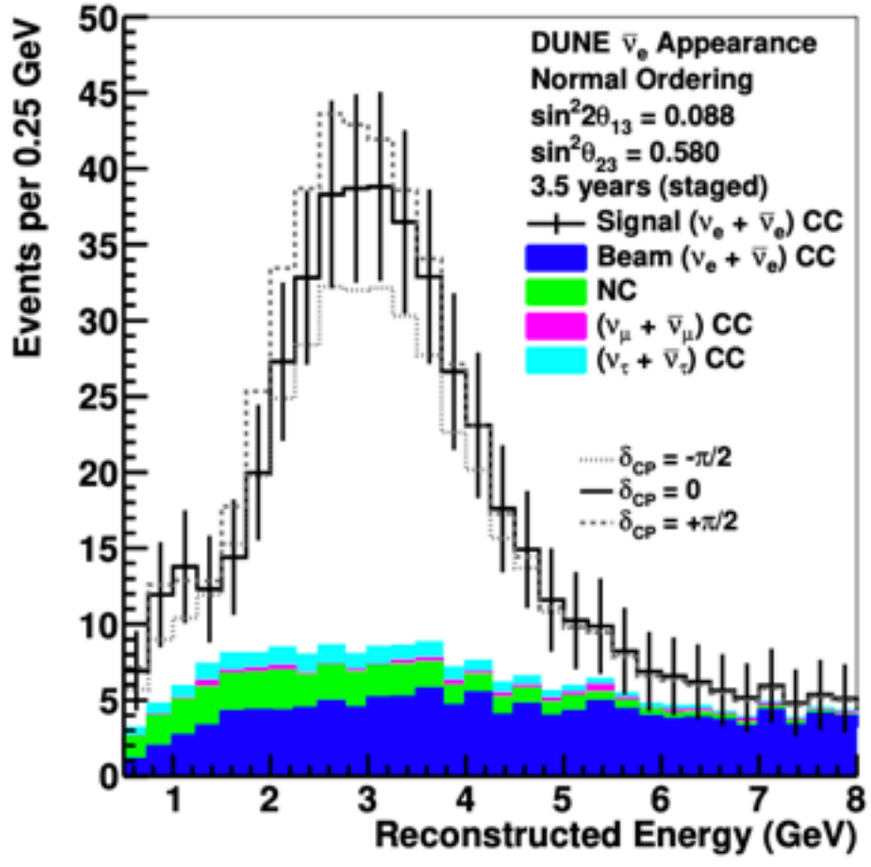
Oscillated neutrino spectra at DUNE

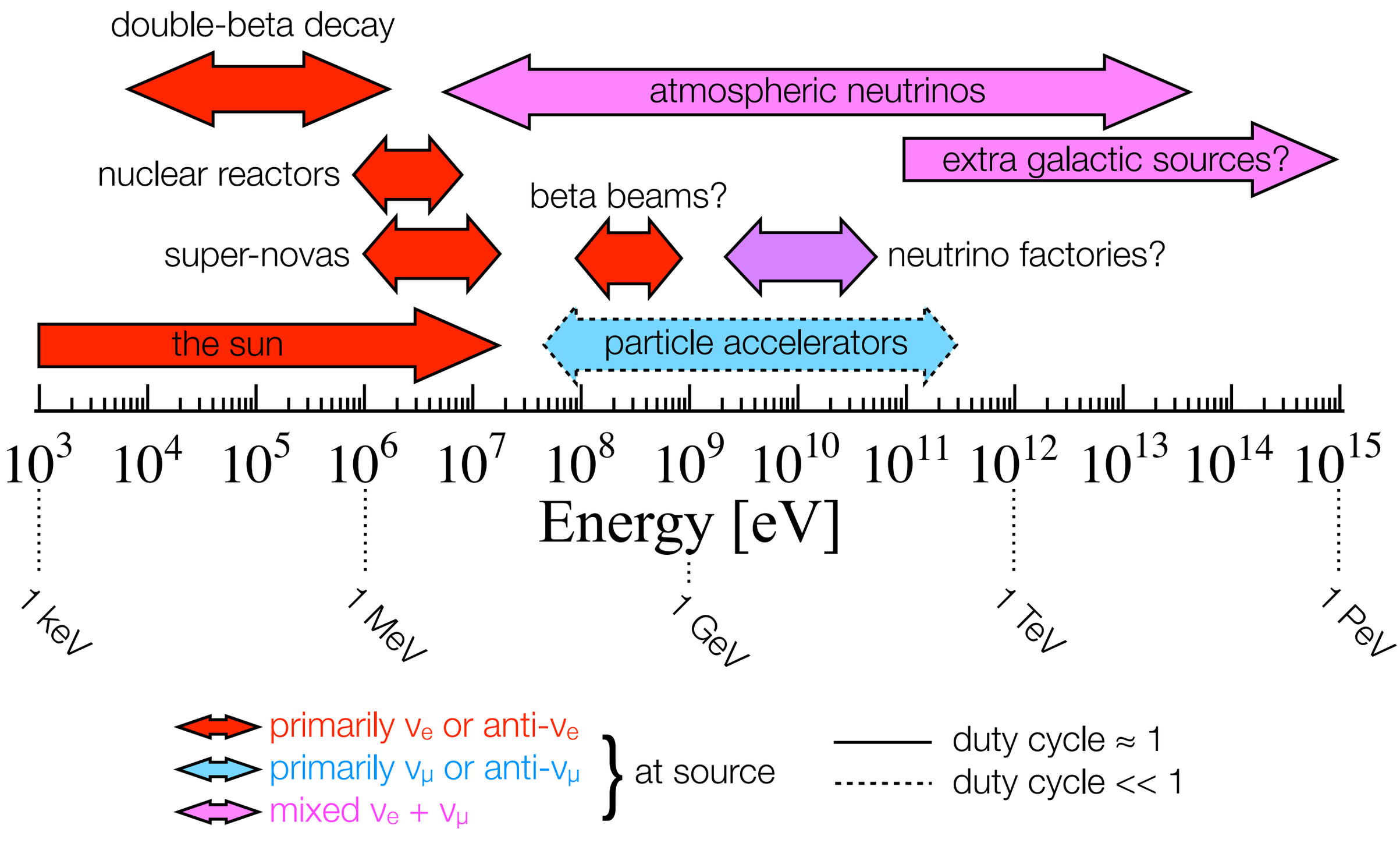








Sources for neutrino detectors



	ν_e	ν_μ	ν_τ	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	E_ν	Physics Topics
Sun	✓						0.1 - 10 MeV	Neutrino oscillations (“12” sector), solar physics
Supernova	✓	✓	✓	✓	✓	✓	1 - 30 MeV	Astrophysics, neutrino speed / mass, oscillations
Reactor				✓			1 - 8 MeV	Neutrino oscillations (“13” and “12” sector), neutrino cross-section, sterile neutrino searches
Atmospheric neutrinos	✓	✓		✓	✓		0.1 - 100 GeV	Neutrino oscillations (“23” sector), sterile neutrino search
Accelerators (positive focus)	✓	✓		✓	✓		0.1 - 10 GeV	Neutrino oscillations (“23” and “13” sector), CPV search, sterile neutrino search, neutrino cross-sections
Accelerators (negative focus)	✓	✓		✓	✓		0.1 - 10 GeV	Neutrino oscillations (“23” and “13” sector), CPV search, sterile neutrino search, neutrino cross-sections