Neutrino Sources

International Neutrino Summer School 2026

Laura Fields, University of Notre Dame

Source of this craziness: Google Gemini

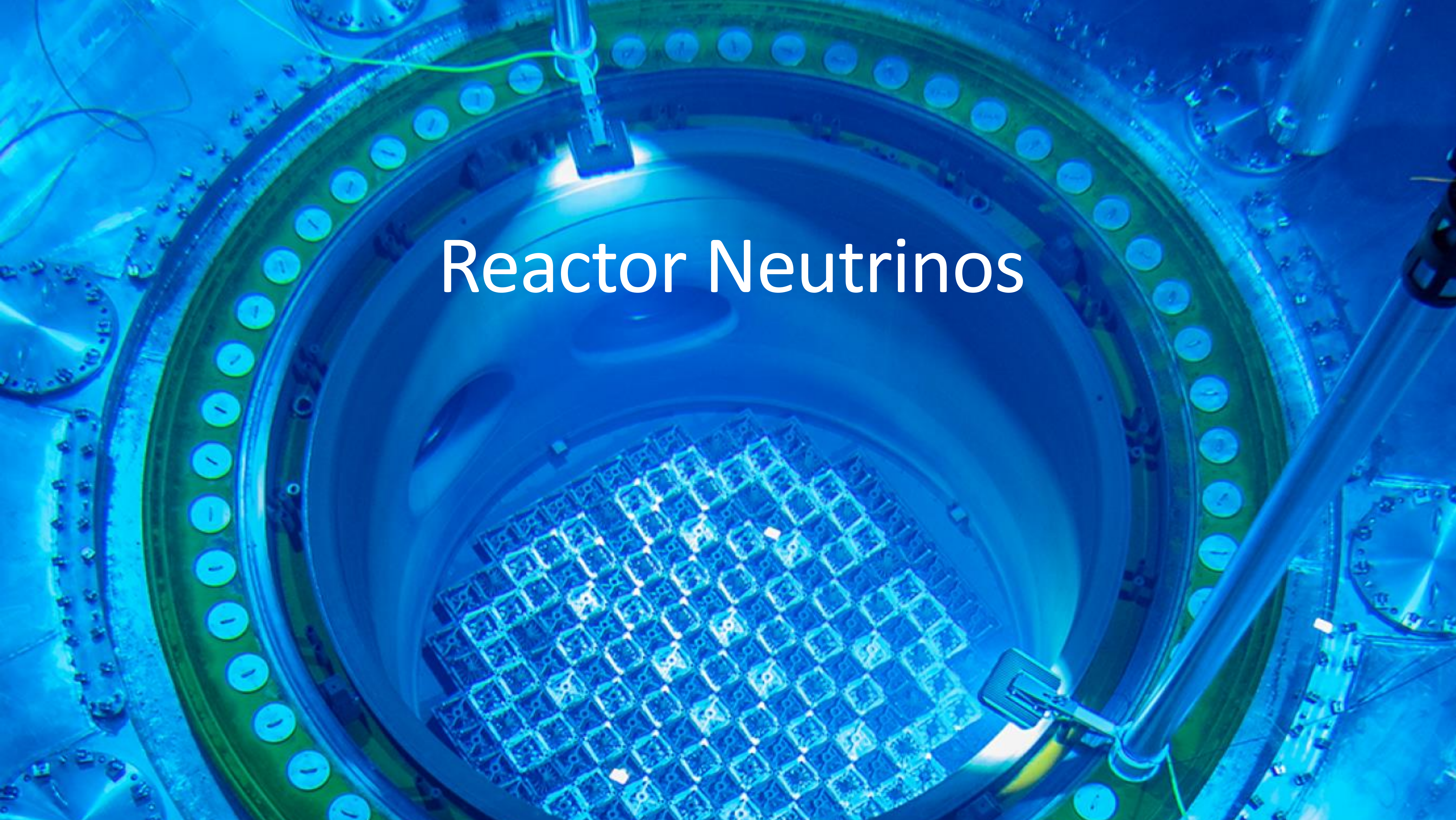
Order of Operations

- Some preliminaries
  - Weak Interactions
  - Neutrino flux predictions
- Natural Sources
  - Solar
  - Astrophysical
  - Big Bang
  - Atmospheric
  - Terrestrial
- Artificial Sources
  - Reactors
  - Pion decay in flight
  - Pion decay at rest
  - Radioactive Isotope Sources
  - LHC Neutrinos
  - Potential Future Sources

Yesterday

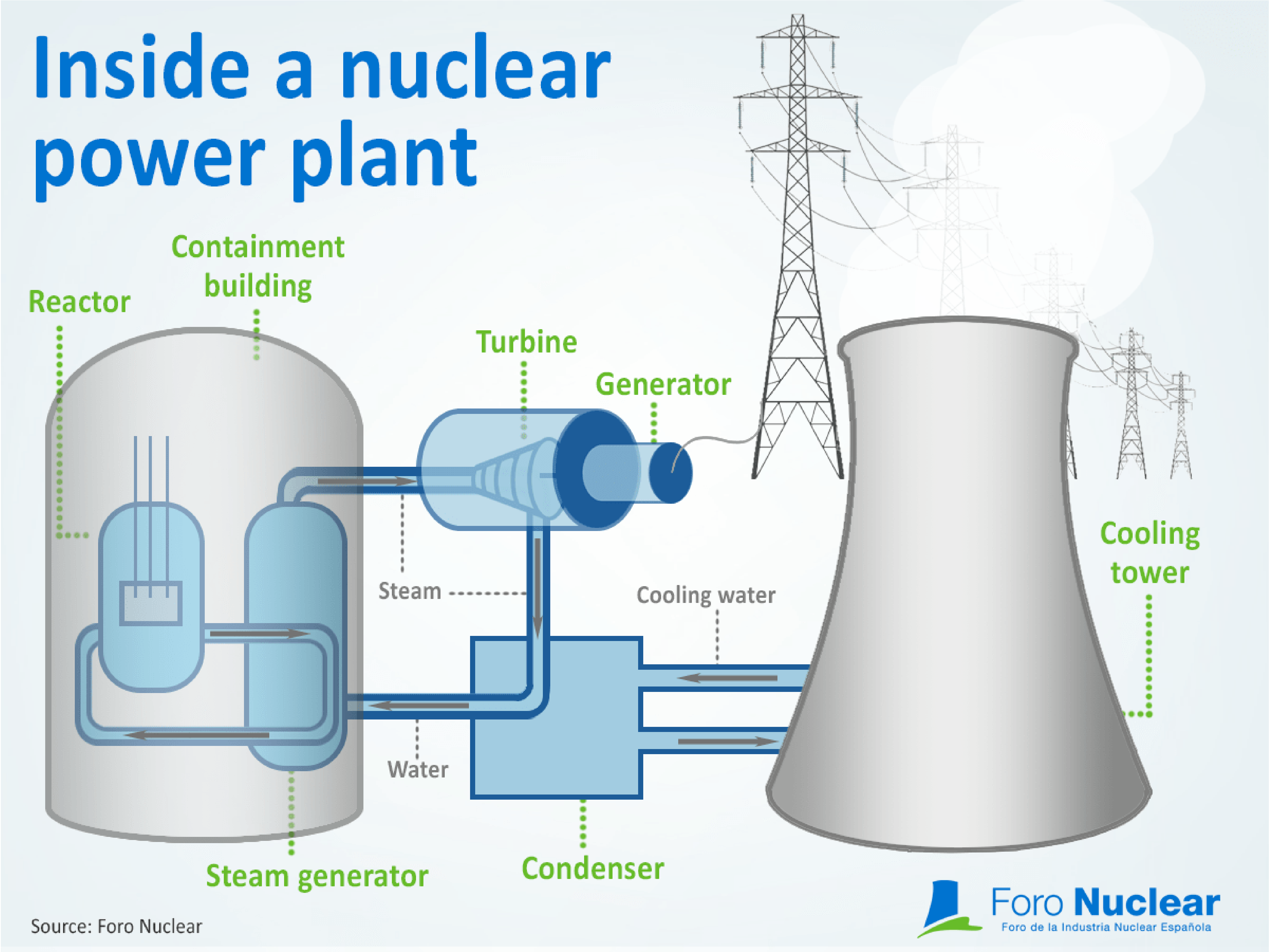
Today

Reactor Neutrinos

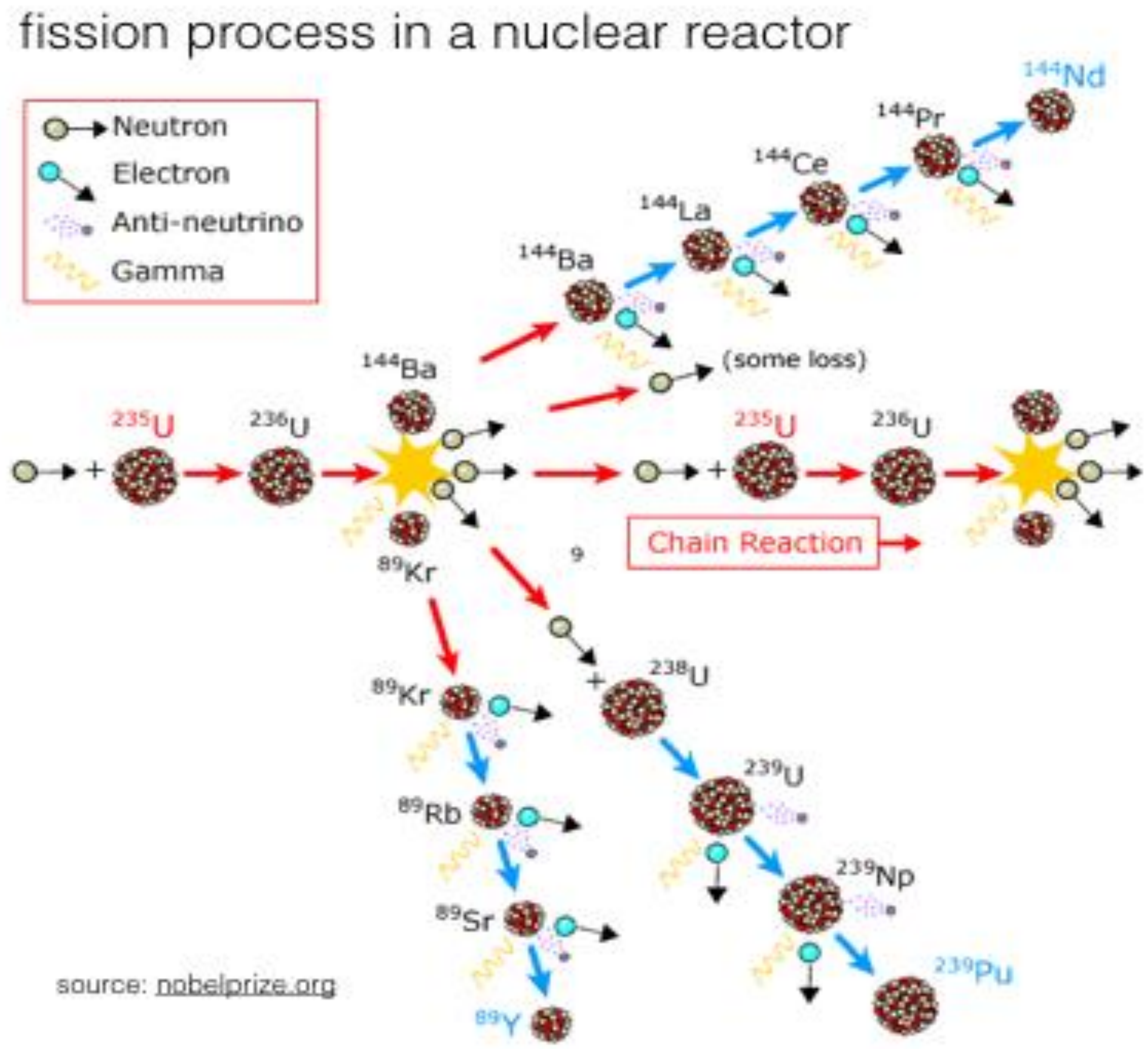


Nuclear Reactor Basics

- Nuclear reactions in the reactor core create thermal energy that turns water into steam
- A turbine and generator convert the thermal energy in the steam to electricity
- The steam is cooled and the process repeats

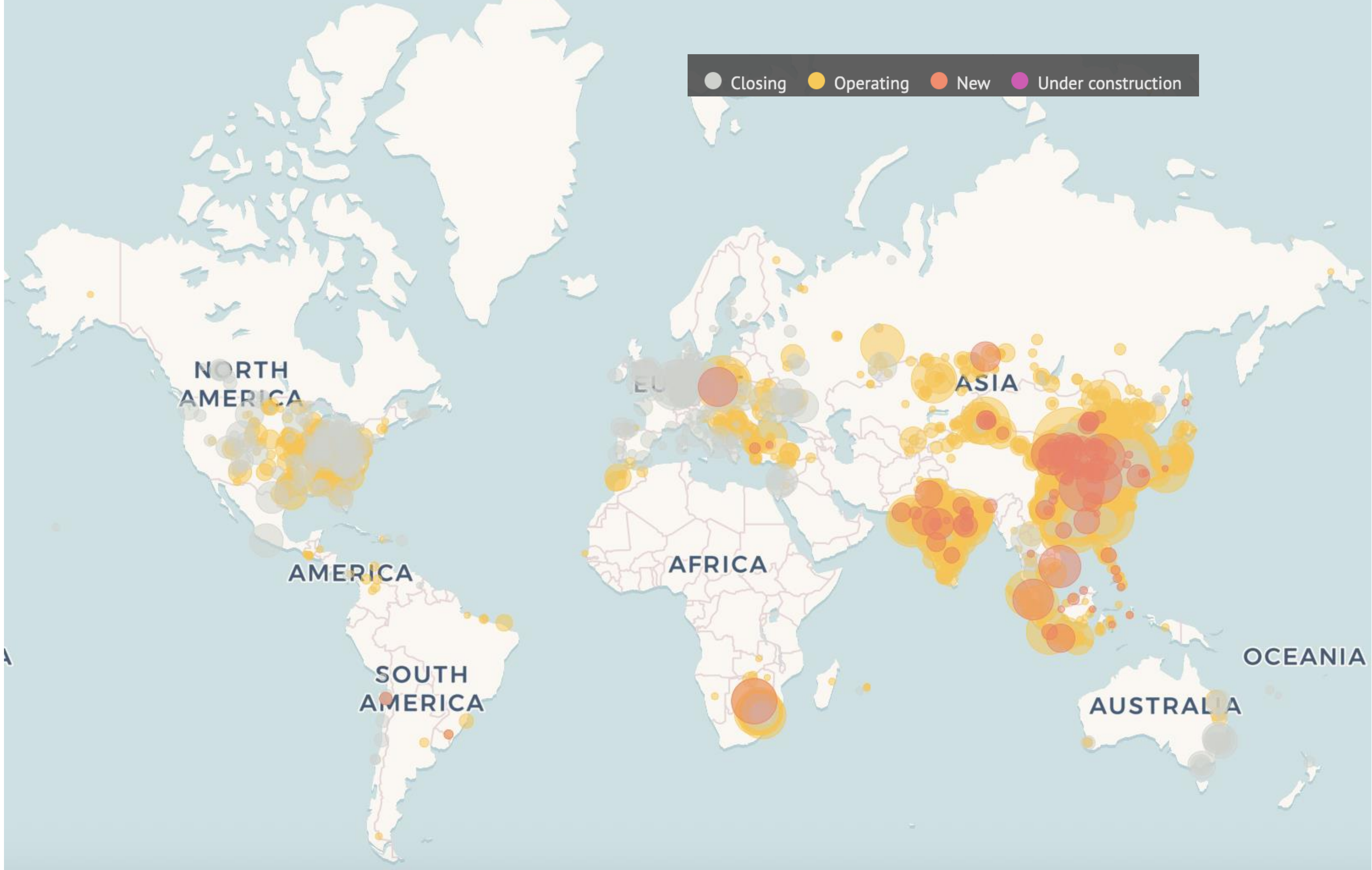


Nuclear Reactor Basics

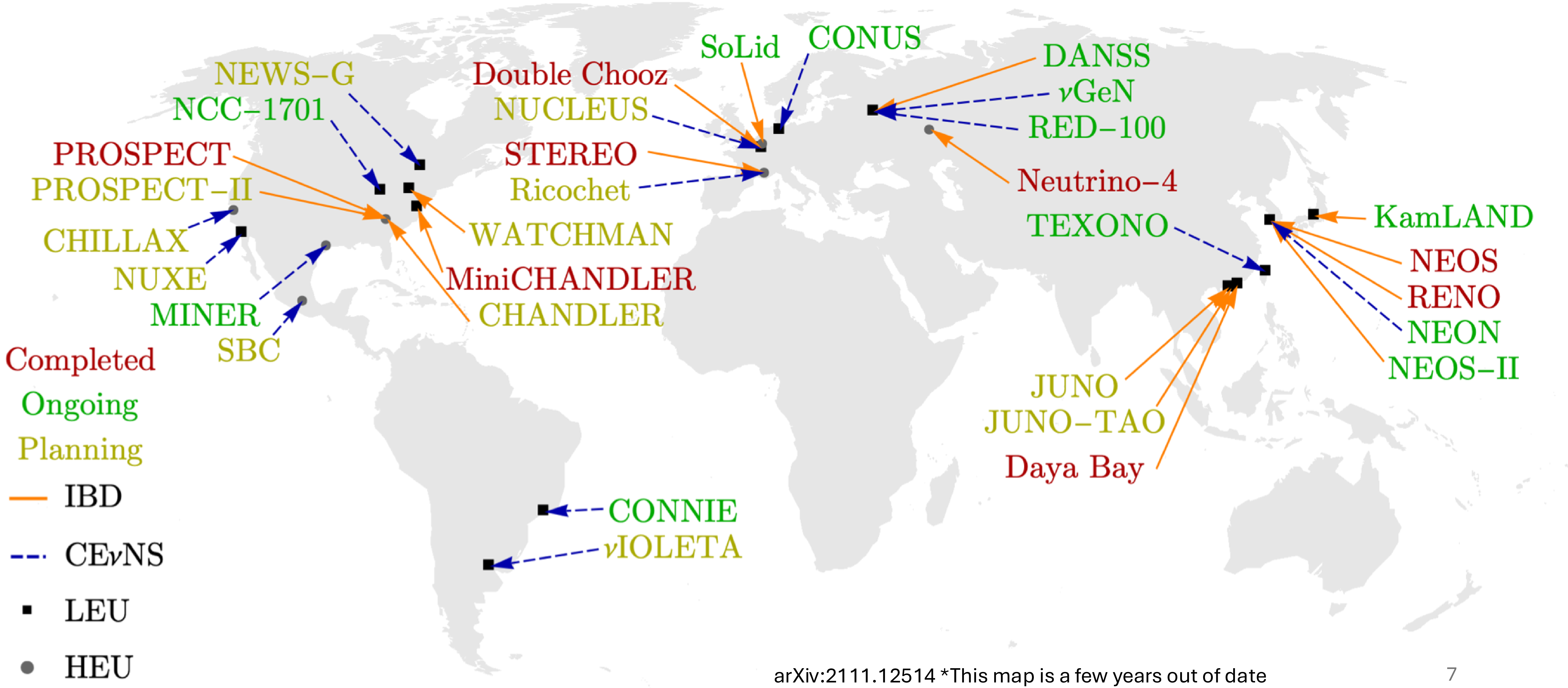


Reactors Around The World

https://www.carbonbrief.org/mapped-worlds-coal-power-plants/ Map for 2019

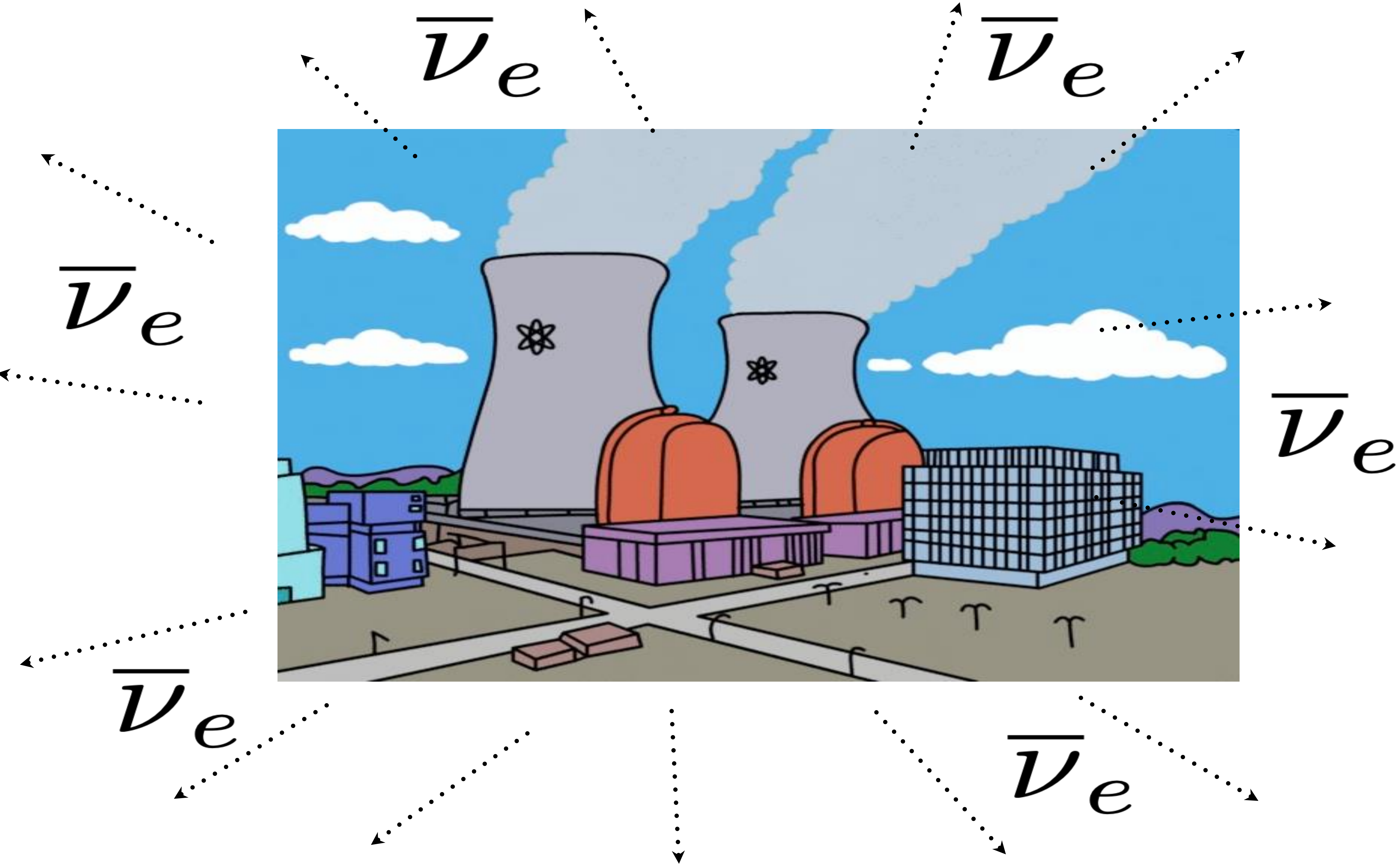


Reactor Neutrinos Around The World



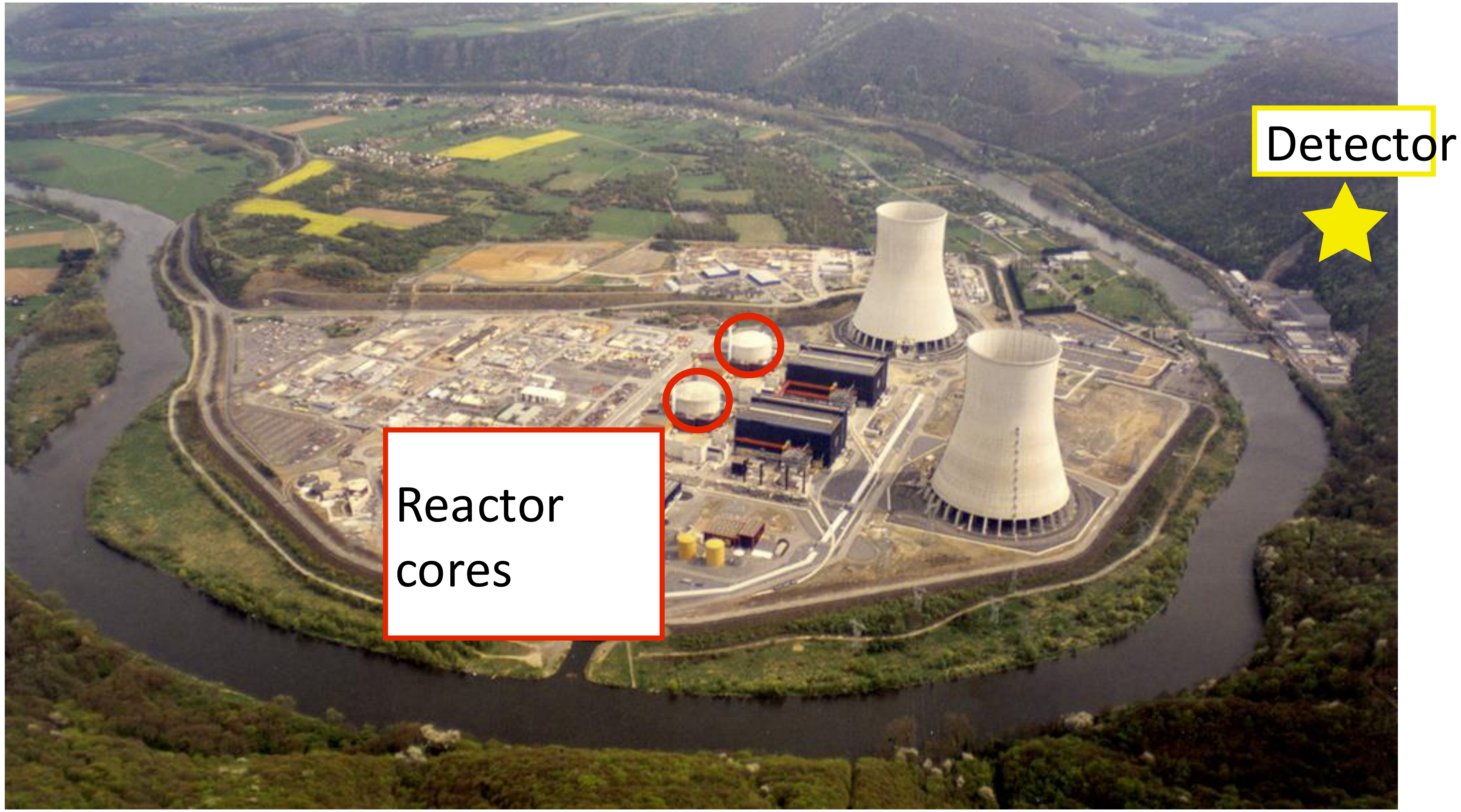
arXiv:2111.12514 *This map is a few years out of date

Reactor Neutrinos



- A typical 4 GW thermal reactor produces about 10^{21} neutrinos per seconds
- This drawing (from the Simpsons!) is very similar to the setup at the Chooz power plant in Northern France (site of the Chooz and Double Chooz experiments)

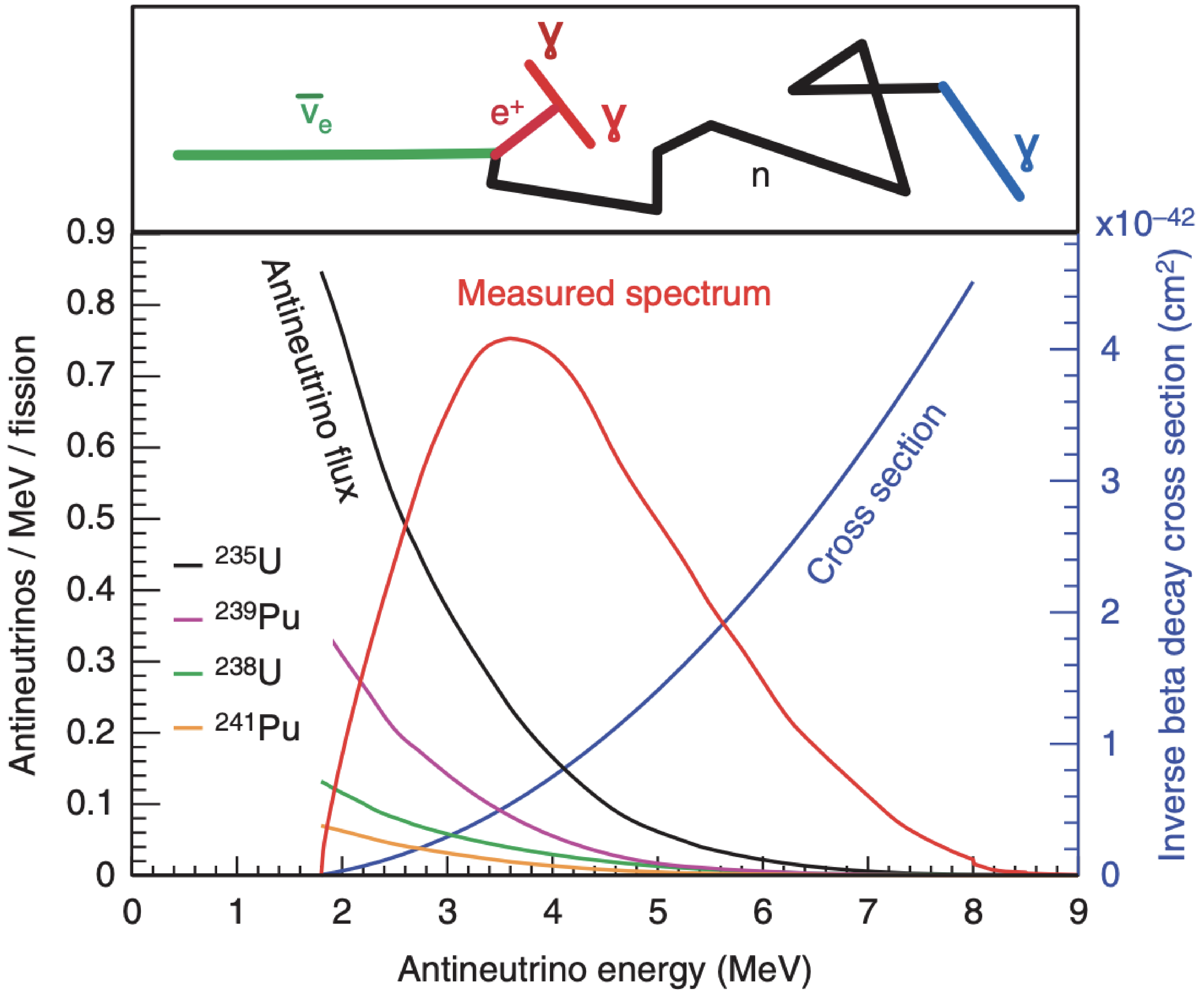
Example: Double CHOOZ



Detected via Inverse Beta Decay (IBD): $\overline{\nu}_e p \rightarrow e^+ n$

Flux and cross section

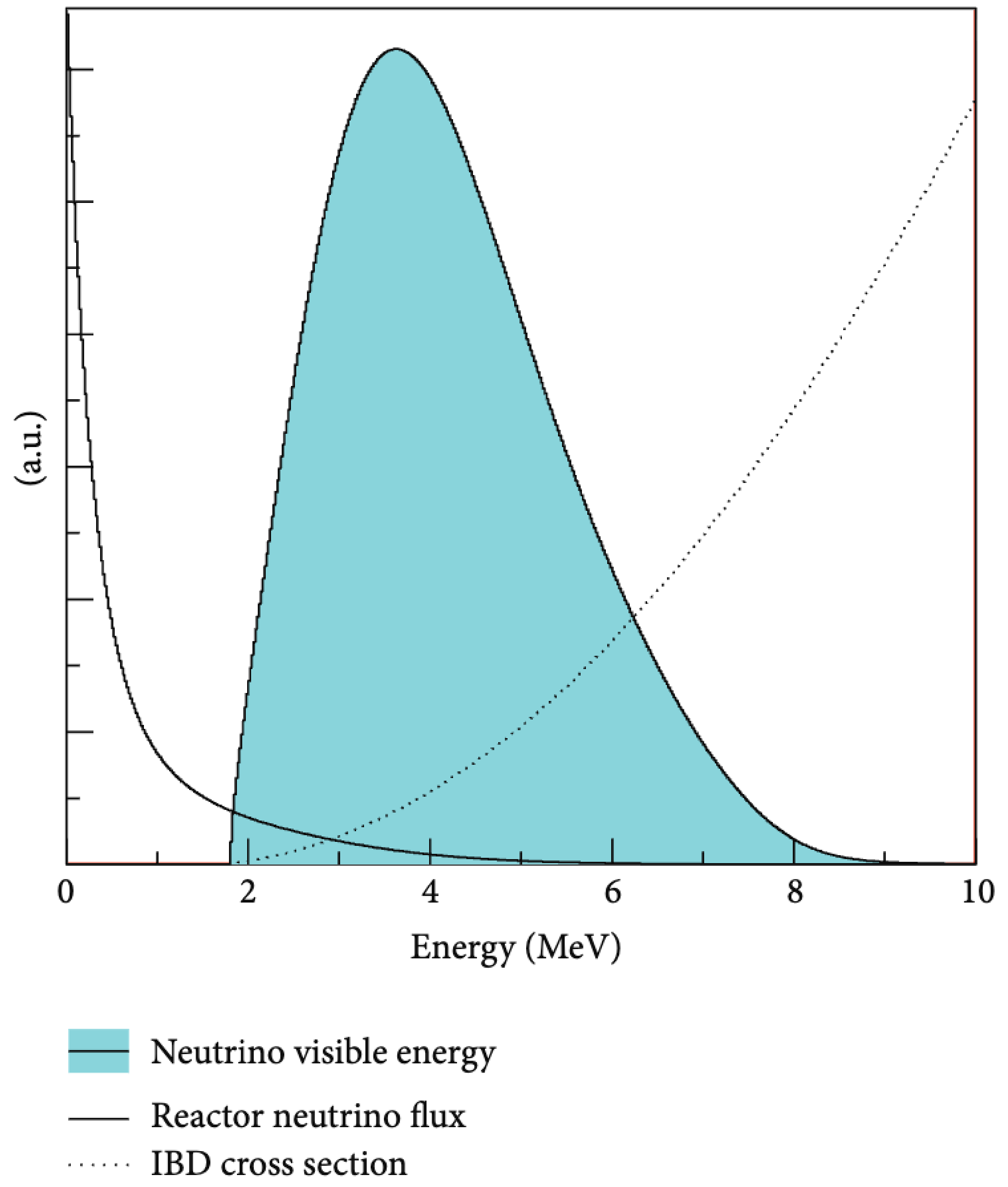
[Nature Communications](#) **volume 6**, Article number: 6935 (2015)



- Reactor fluxes are purely electron antineutrinos (before oscillation), falling sharply from 1.8 GeV
- Typically measured via Inverse Beta Decay, which has a threshold of 1.8 MeV
- IBD cross section rises sharply, resulting in an event rate energy range of ~2-8 GeV, peaked around 4 GeV

Flux and cross section

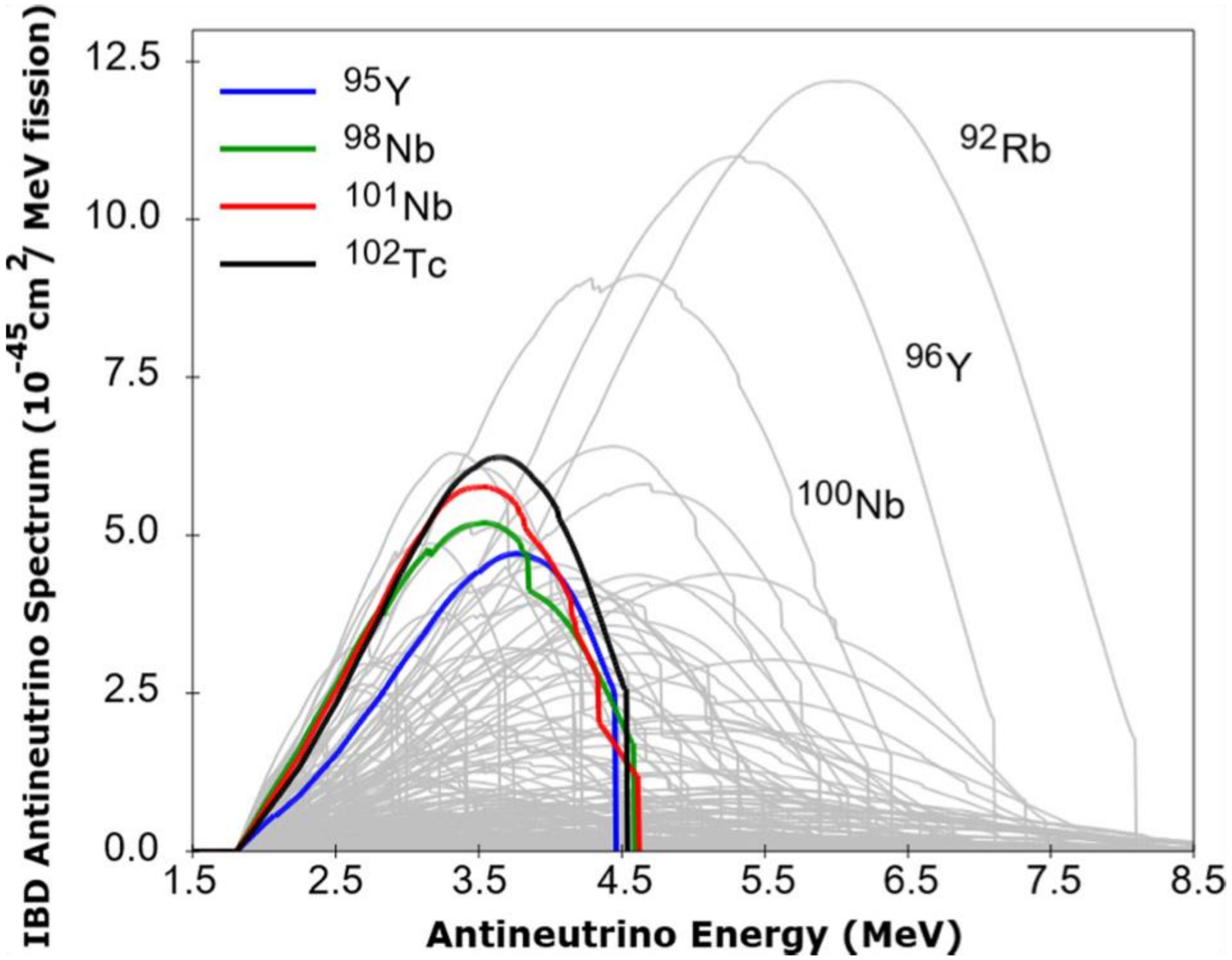
Advances in High Energy Physics 2015, Issue 1



- Reactor fluxes below 1.8 GeV largely unexplored, but are predicted to rise sharply

Flux components

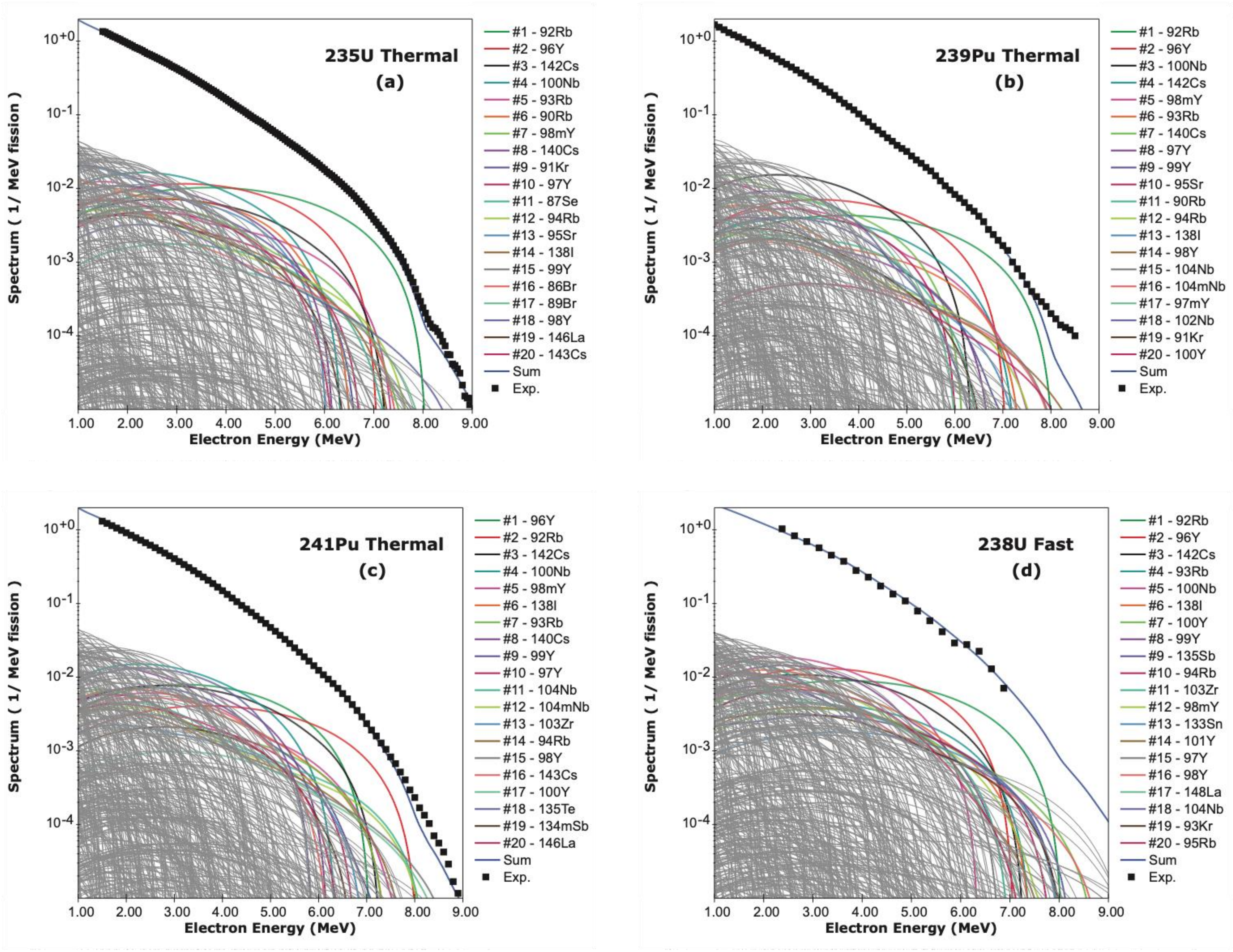
Expected Daya Bay (LEU) antineutrino spectra



PHYSICAL REVIEW C 98, 014323 (2018)

~1000 different beta-decaying isotopes contribute to the reactor electron antineutrino flux!

Flux components



PHYSICAL REVIEW C **91**, 011301(R) (2015)

Four different isotopes undergo fission in a nuclear reactor

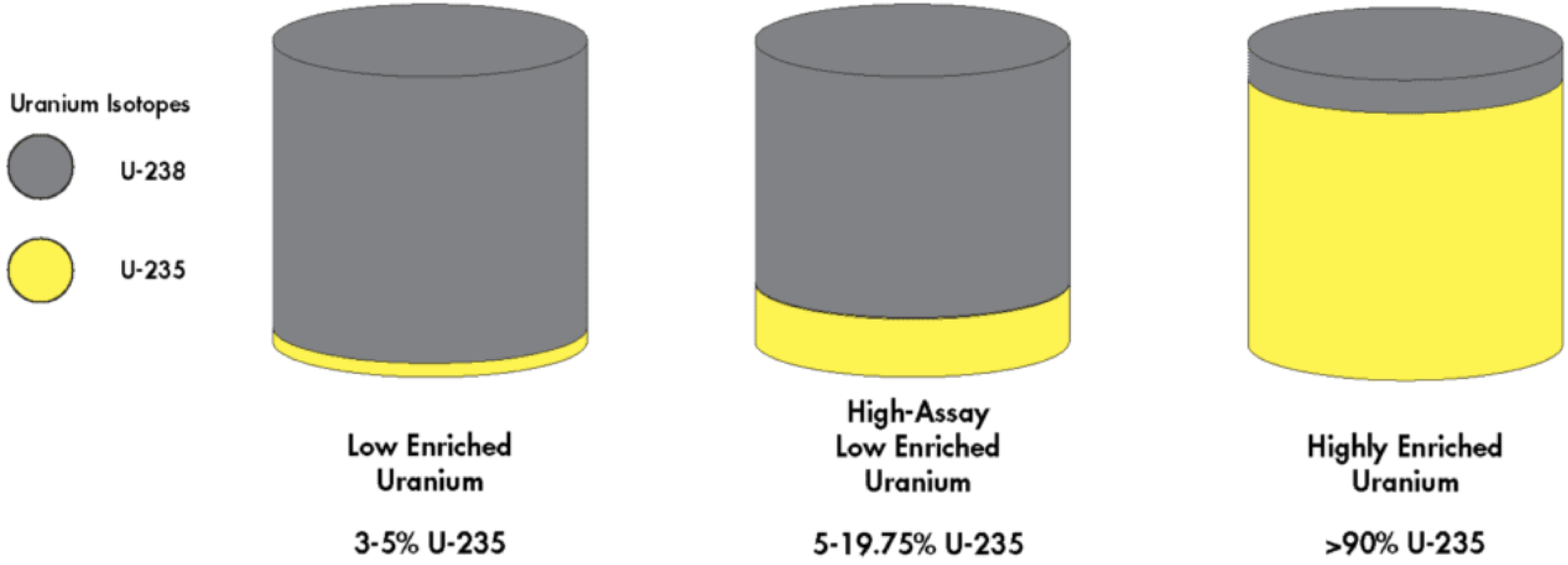
238U and 235U are present in original fuel

238U can undergo neutron capture followed by beta decay to produce 239Pu, and more neutron capture to become 241Pu

238U requires ”Fast” (high energy neutrons) in order to undergo fission

HEU and LEU

Next gen commercial reactors
Not currently used for
neutrino physics, but maybe
someday?



Current commercial reactors
These are used by most
reactor neutrino experiments

"Research reactors" that need
weapons-grade fuel and are
therefore subject to strict
security protocols. Used by a
few experiments (PROSPECT,
STEREO, SoLid, Neutrino-4)

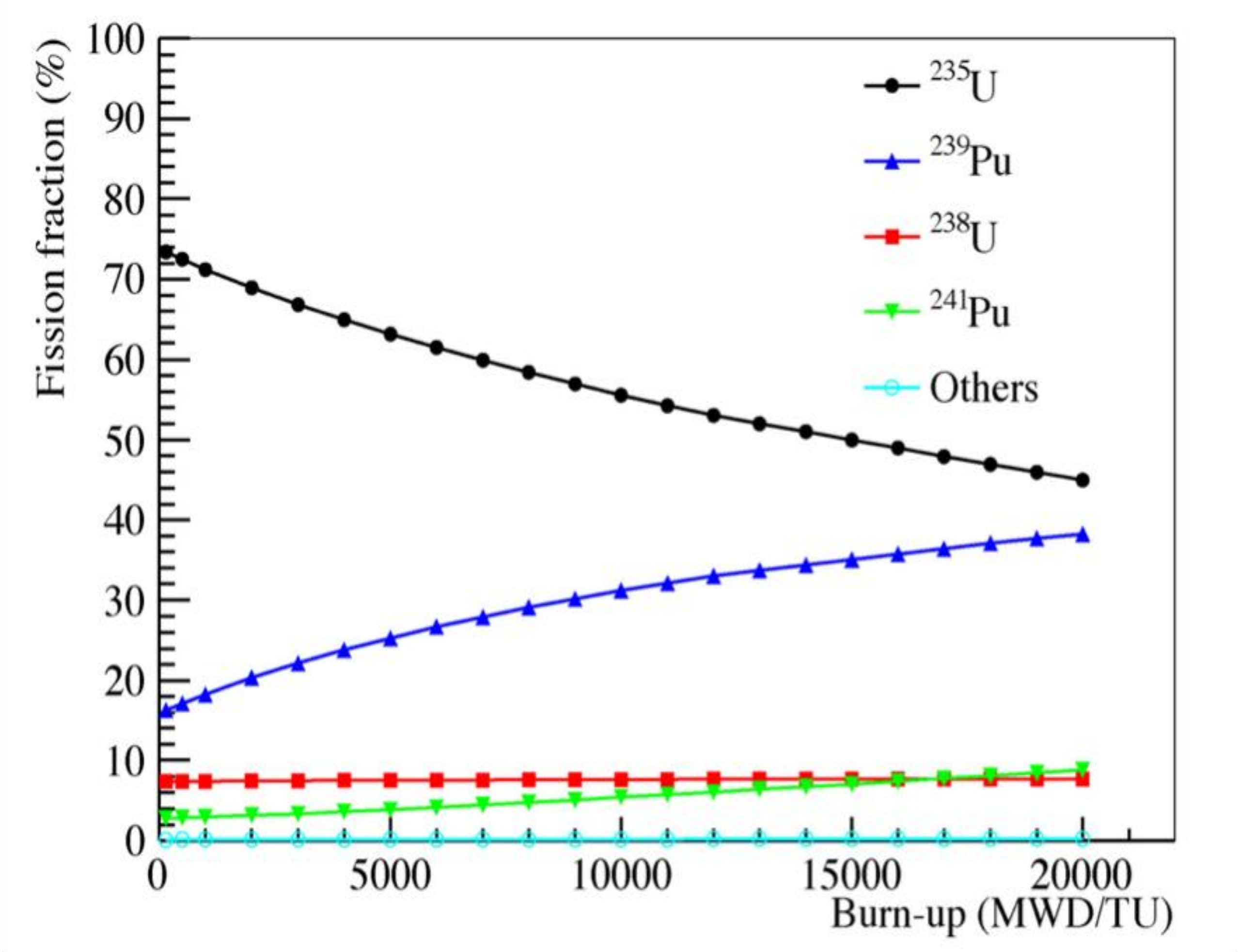
HEU and LEU

Natural Uranium:

235: 0.7% abundant
238: 99.3% abundant

Fuel Isotope	Time-Averaged Fission Fraction	
	Conventional Fuel	HEU fuel
^{235}U	0.59	>0.99
^{238}U	0.07	<0.01
^{239}Pu	0.29	<0.01
^{241}Pu	0.05	<0.01

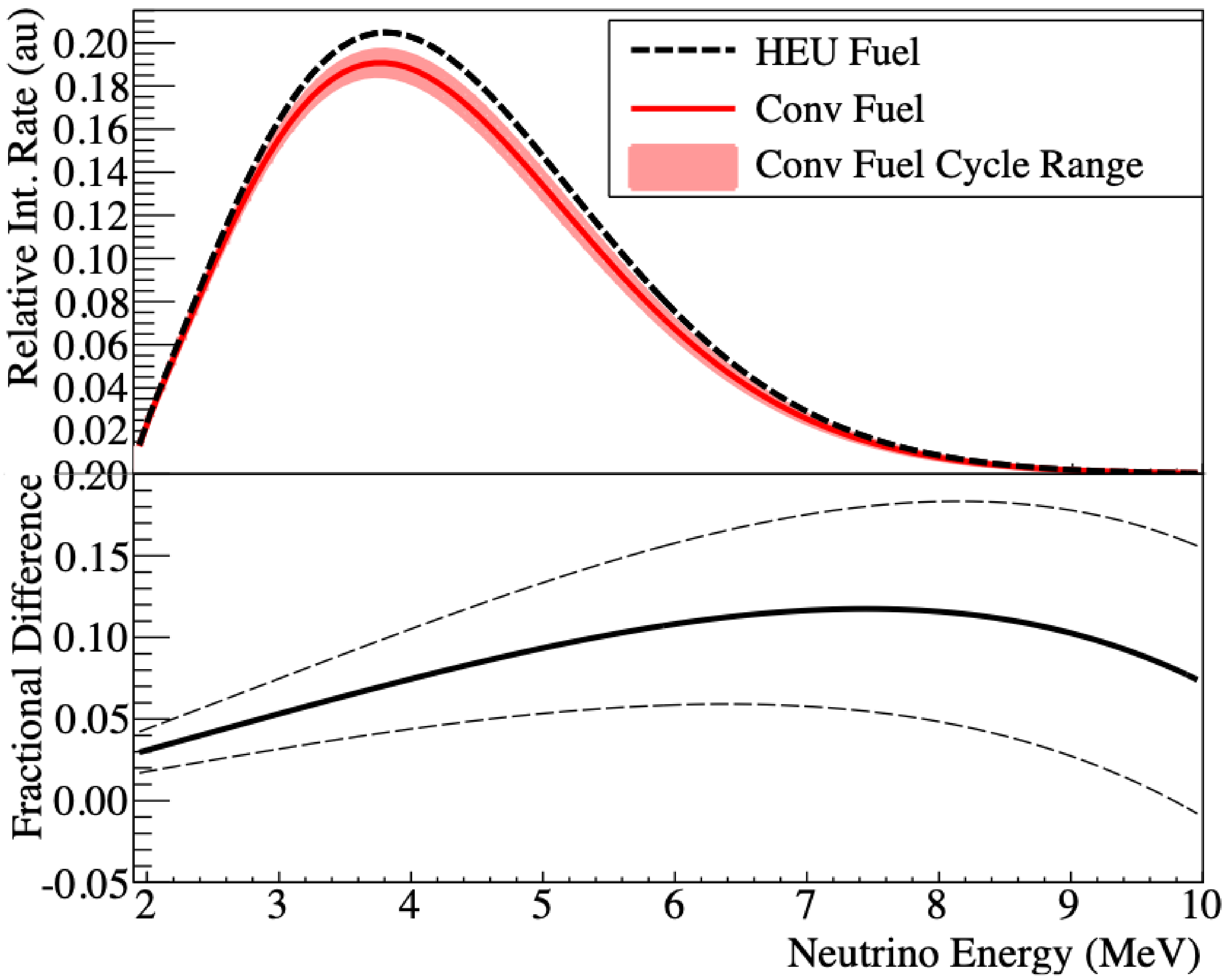
PRD 87 073008 (2013)

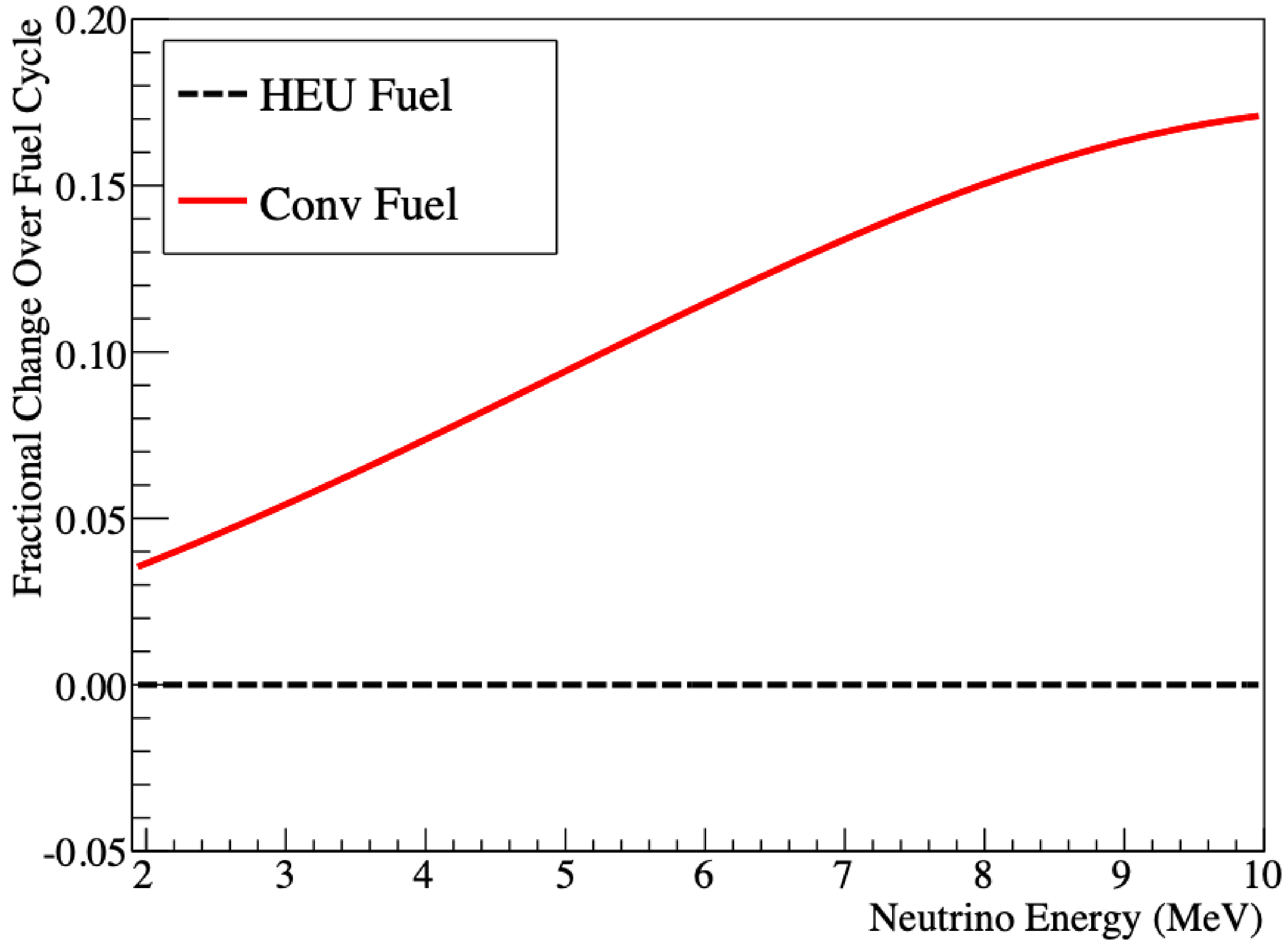


l [17]

The fission fraction evolution for a typical running cycle of one Daya Bay reactor

LEU (e.g. Daya Bay) reactor flux evolves in time

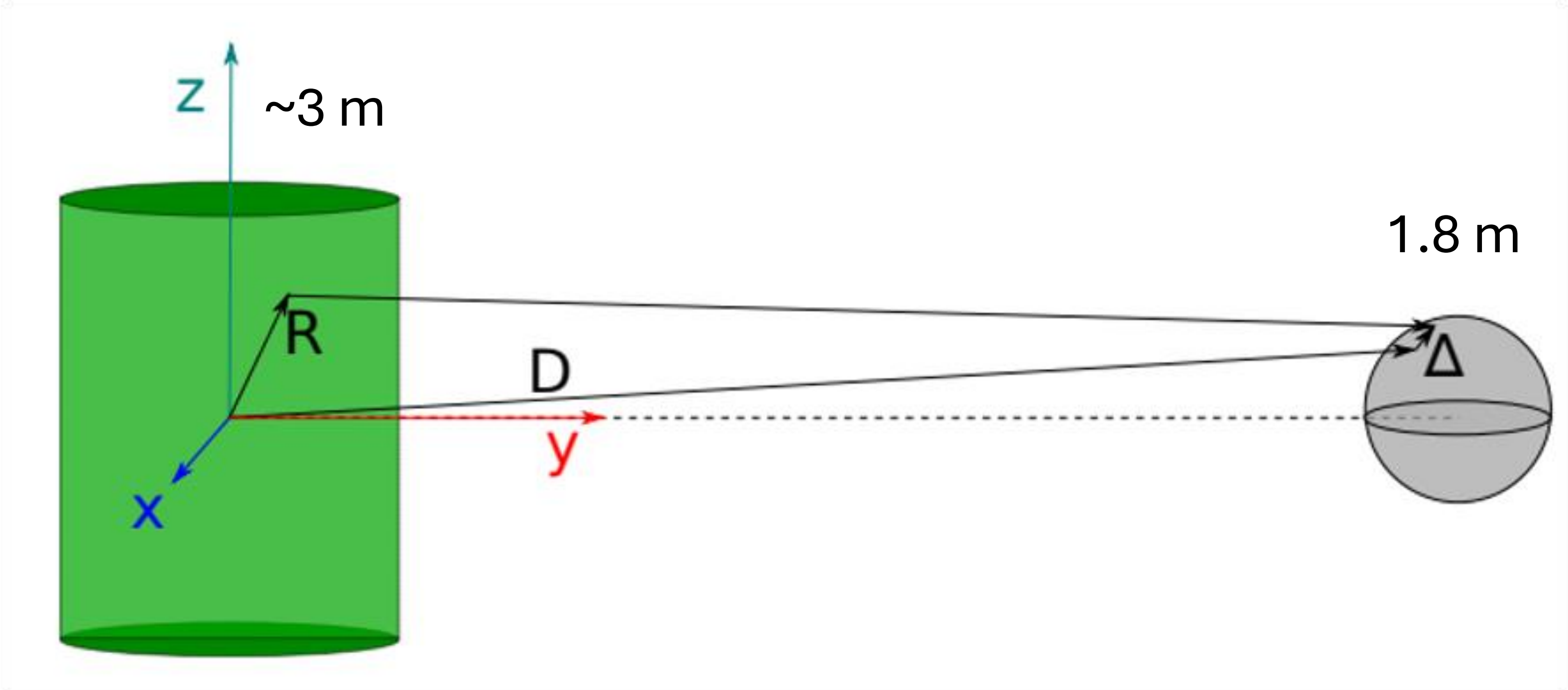




LEU reactor sources have a dynamic electron antineutrino flux.
HEU reactor sources are static.

Commercial vs Research Reactors

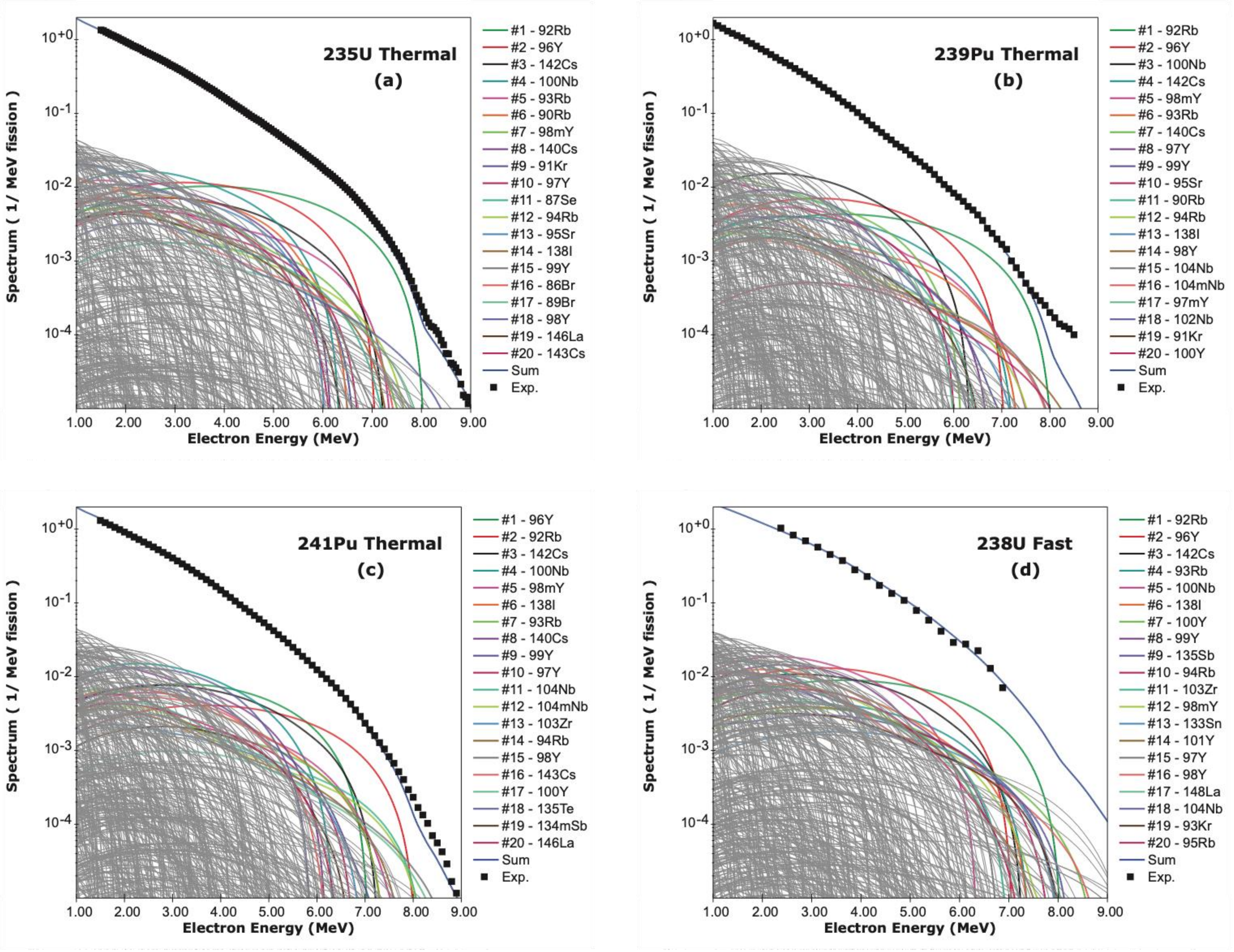
- Other than HEU and LEU, there are significant differences between commercial and research reactors.
  - Power: GW-scale (commercial) vs. MW-scale (research)
  - Ability to get close to the core
  - Ability to turn off and on
  - Extent of the core or cores (relevant for L/E-dependent osc. measurement)



Significant L/E smearing due to large extent of commercial core.

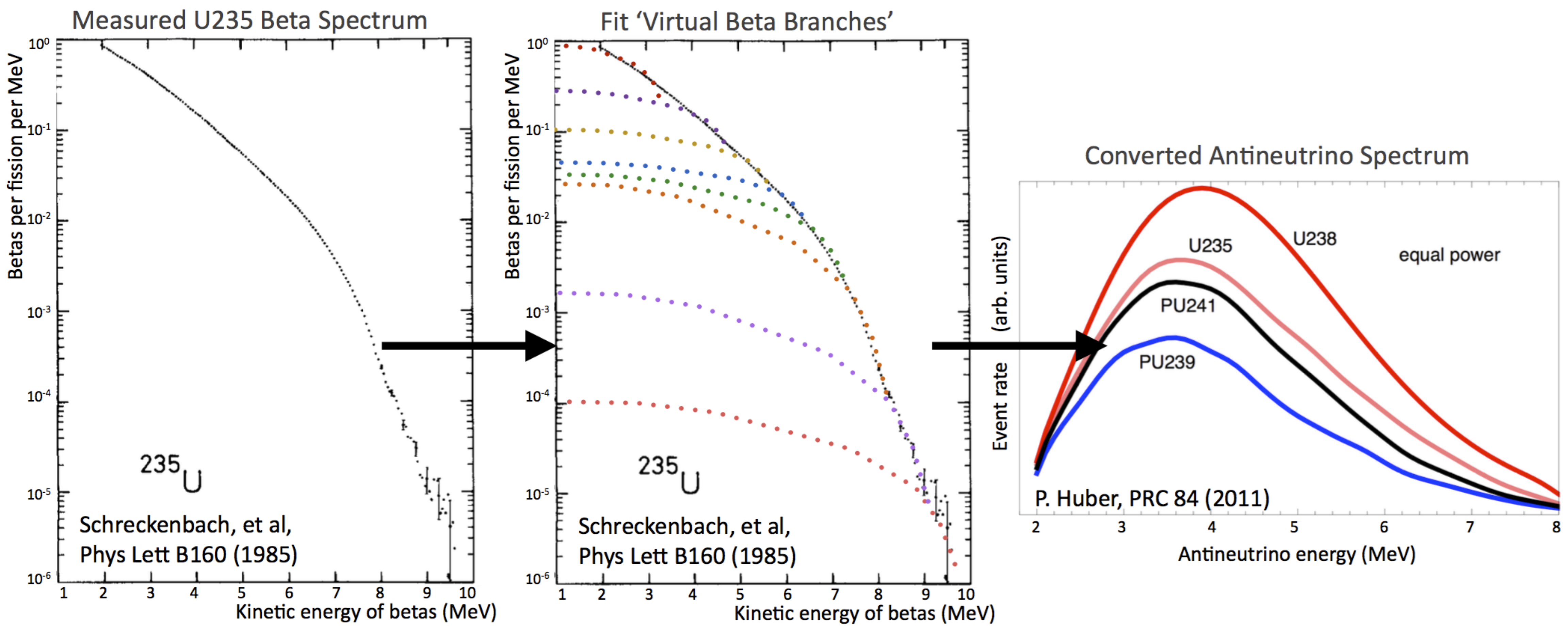
Reactor Flux Predictions – Summation method

- Spectrum computed from the “bottom up”, relying on cumulative fission yields and beta decays for each fission product (summing 1000s of isotopes and beta branches).
- But, tabulated information is sometimes inaccurate or missing. Correlations (e.g. between independent and cumulative fission yields) not taken into account. Uncertainties are often ignored.



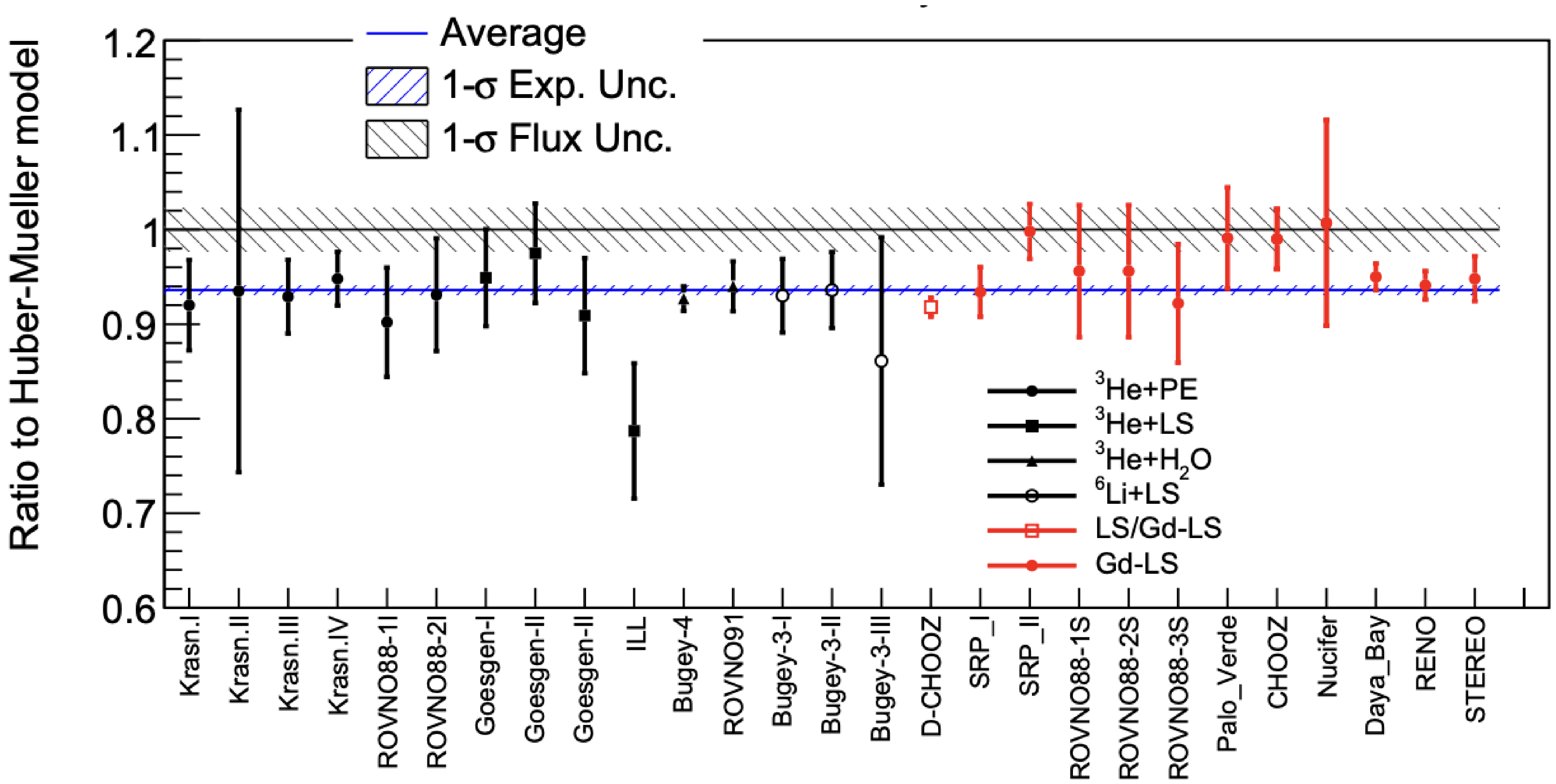
PHYSICAL REVIEW C **91**, 011301(R) (2015)

Reactor Flux Predictions – Conversion Method



- Relies on measurements of electron spectra from ^{235}U, ^{239}Pu, and ^{241}Pu (e.g. from ILL and KI research reactors).
- Conversion of electron spectra to antineutrino spectra is possible, but requires some nuclear physics input
- Also, measurements do not include ^{238}U (fission from fast-n only), which accounts for <10% of LEU flux.

Reactor flux landscape



Progress in Particle and Nuclear Physics 136 (2024) 104106

Experiments have observed event rates ~6% lower than conversion method flux prediction.

This was what's known as the reactor antineutrino anomaly.

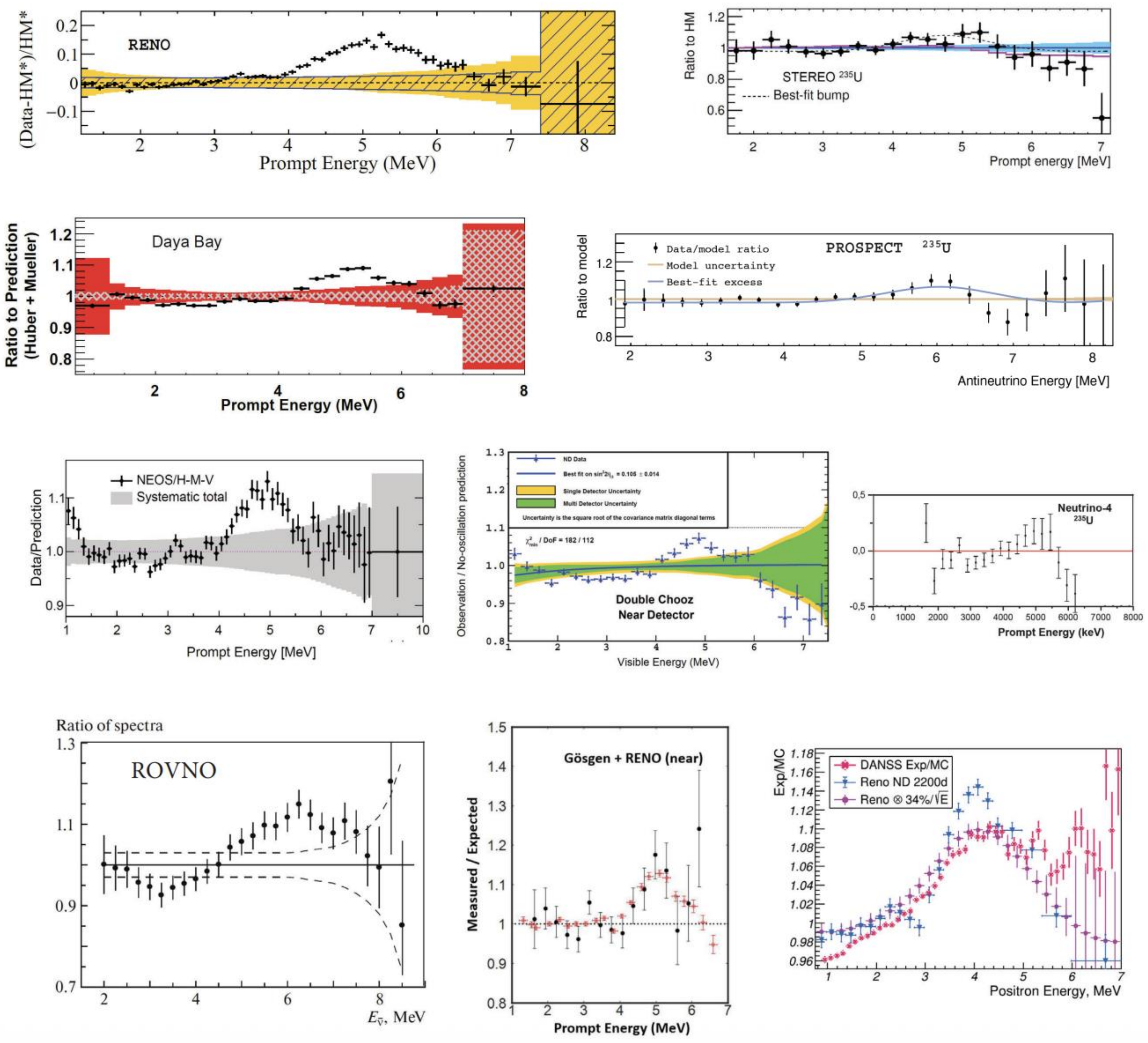
Although potentially consistent with a sterile neutrino, it is generally thought to be due to an underestimation of flux uncertainties.

Reactor flux landscape

In addition to the normalization discrepancy known as the RAA,

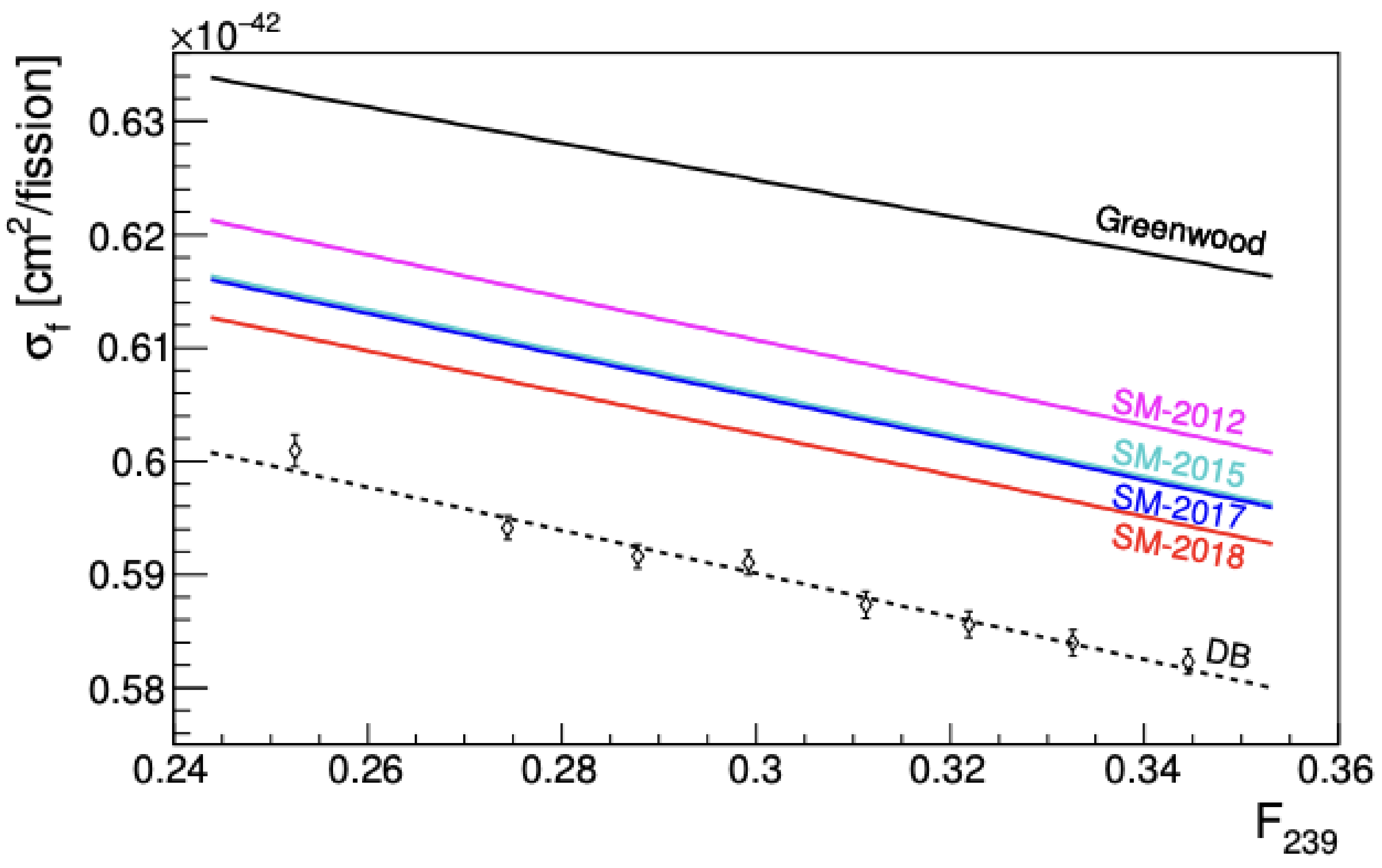
Many experiment event rates vs energy show a bump at 5 GeV that is not predicted by models (and not consistent with a sterile neutrino)

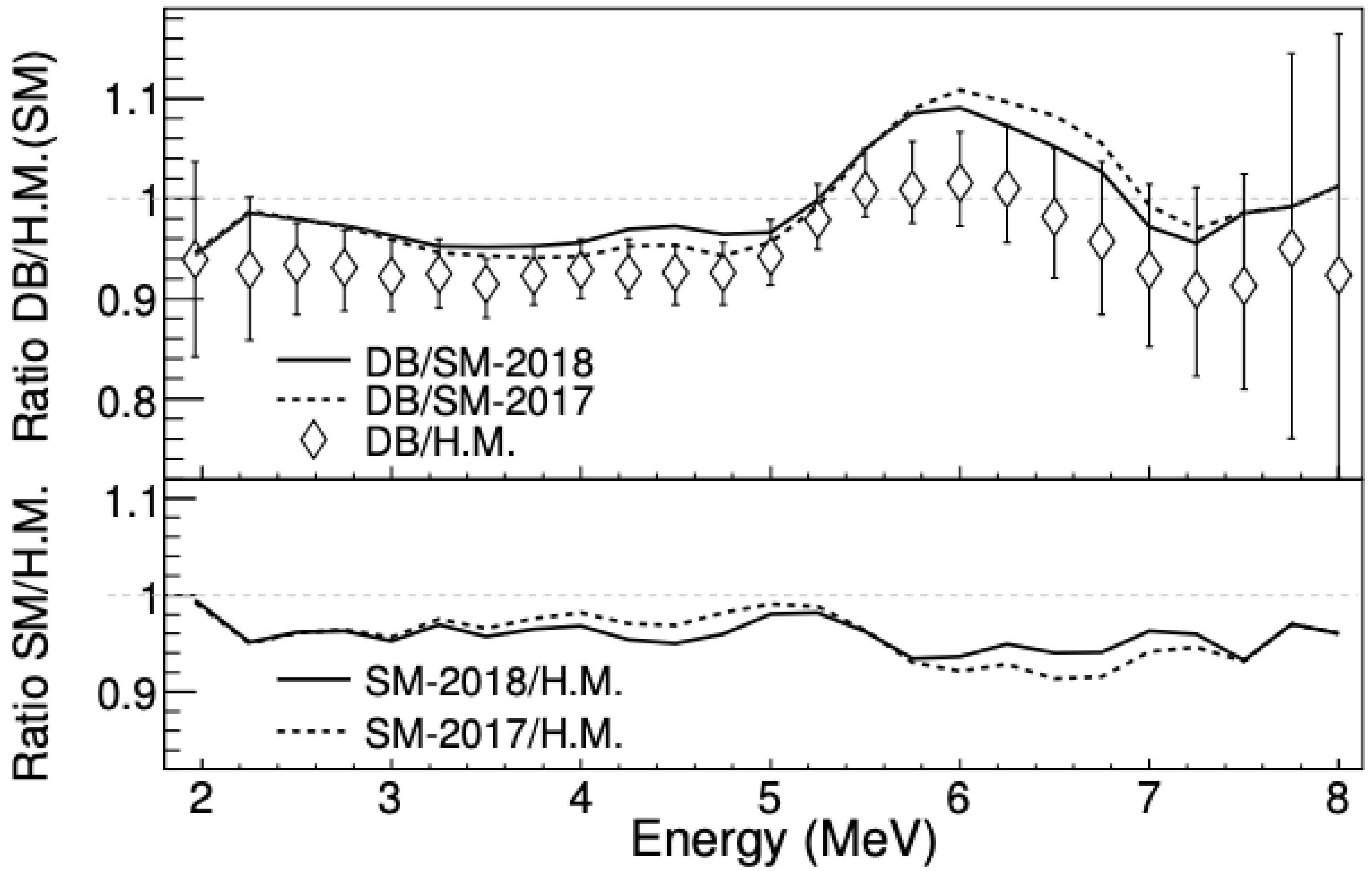
Progress in Particle and Nuclear Physics 136 (2024) 104106



Reactor flux landscape

Phys. Rev. Lett. 123 (2) (2019) 022502





Recent summation model predictions differ from experiment by < 2%

But spectral discrepancy remains.

Reactor Neutrinos: What to Look Forward To

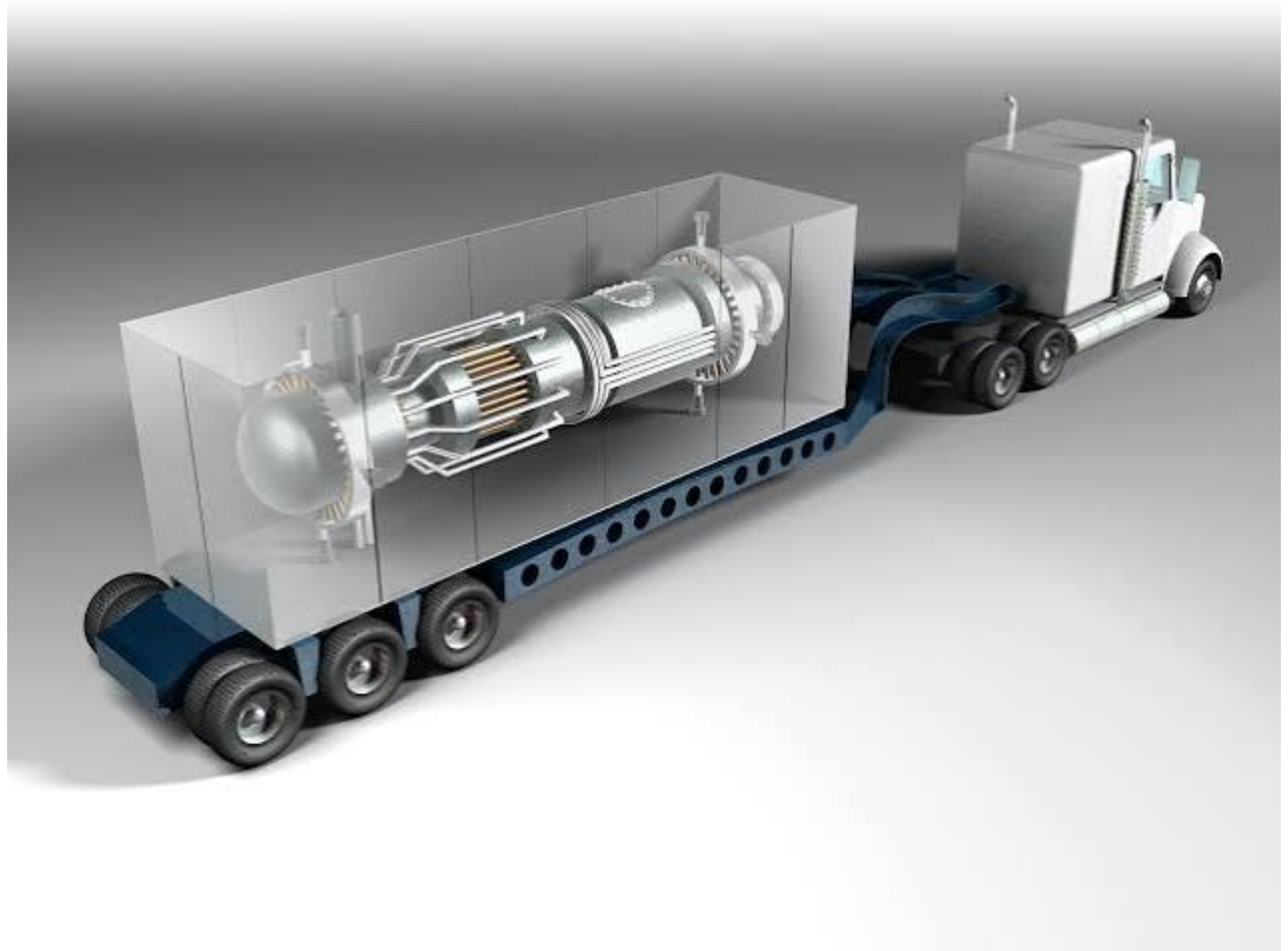
- Continued improvement in reactor flux modeling (especially with new beta spectra measurements); Will they shed light on the 5-7 MeV bump and normalization?

- Many awesome results from JUNO and JUNO-TAO

- Reactor measurements of CEvNS (following first measurement by CONUS+)

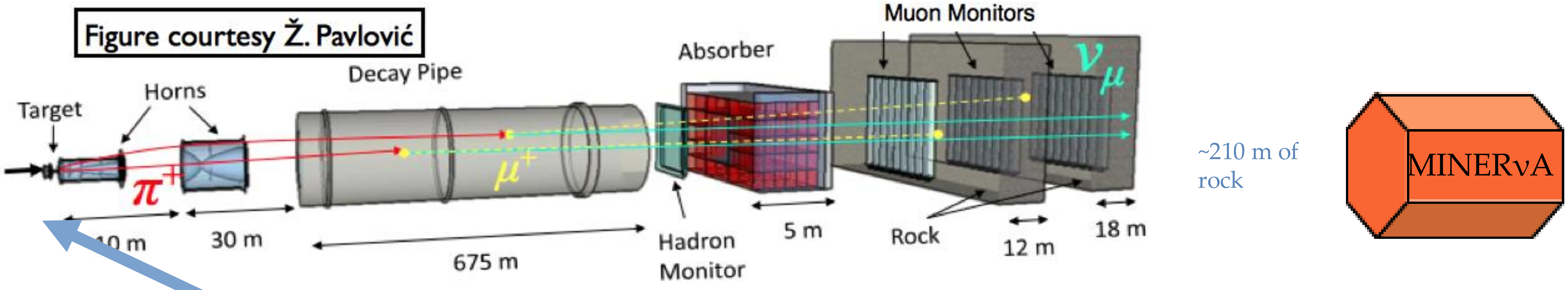
- Microreactor neutrinos?

- Maybe: Build a reactor underground and couple it to an ultra-large detector.



Decay-In-Flight Accelerator Neutrinos

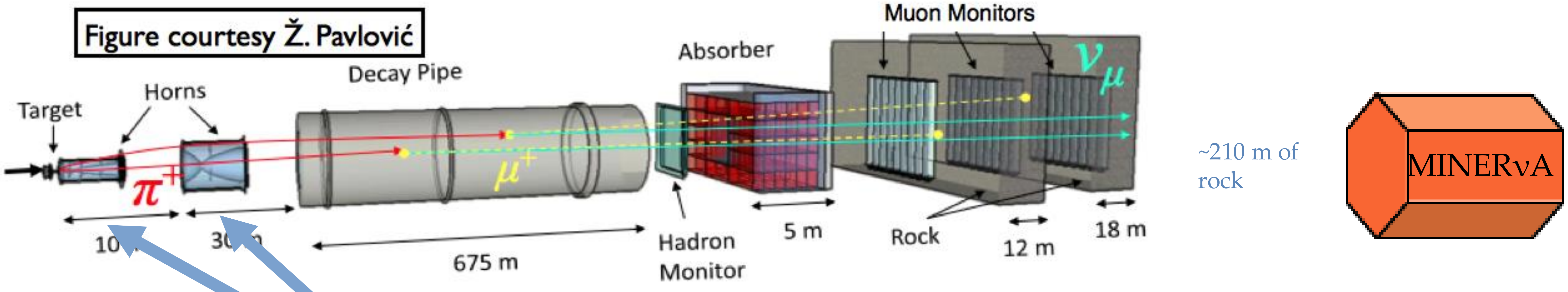
Accelerator Neutrinos: Decay in Flight



The NuMI neutrino beam starts with a 120 GeV proton beam from Fermilab's main injector

Protons impinge on a graphite target, creating charged pions and kaons (among other things)

Accelerator Neutrinos: Decay in Flight

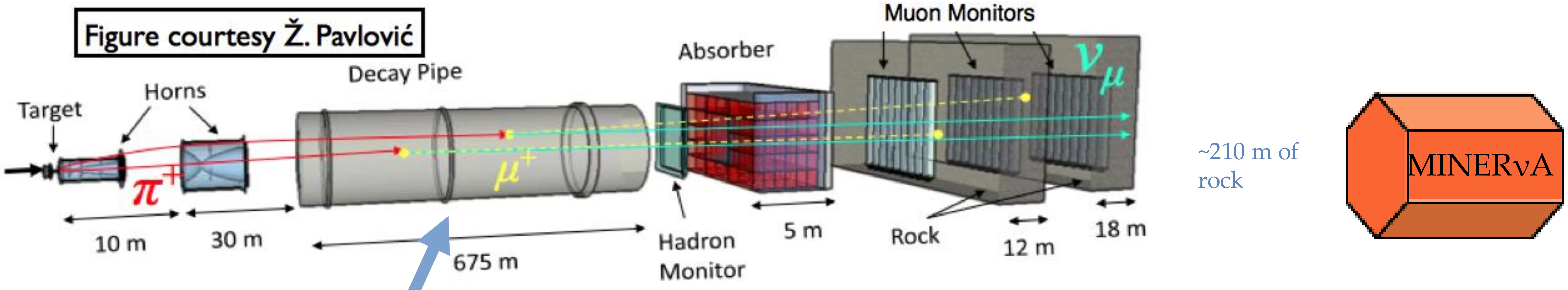


The pions and kaons are focused by a pair of focusing horns.

Horns are basically large electromagnets

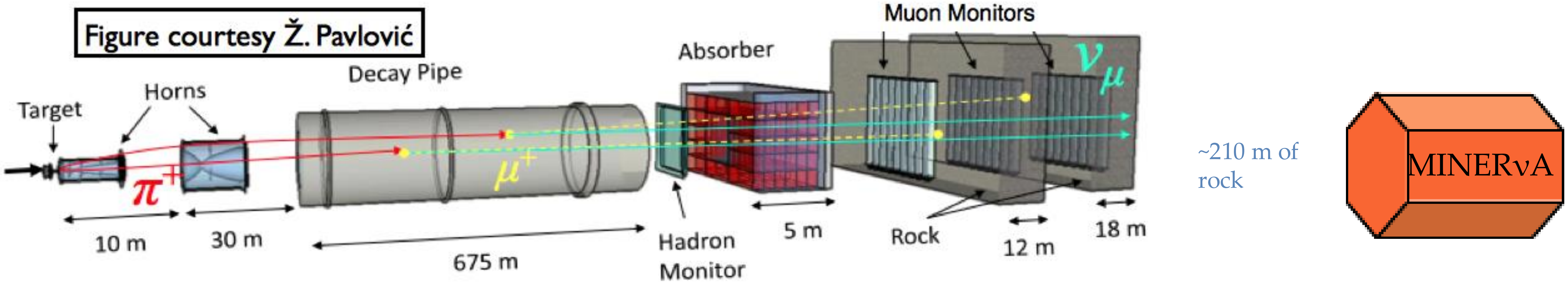
We can configure them to create neutrino beams or antineutrino beams

Accelerator Neutrinos: Decay in Flight



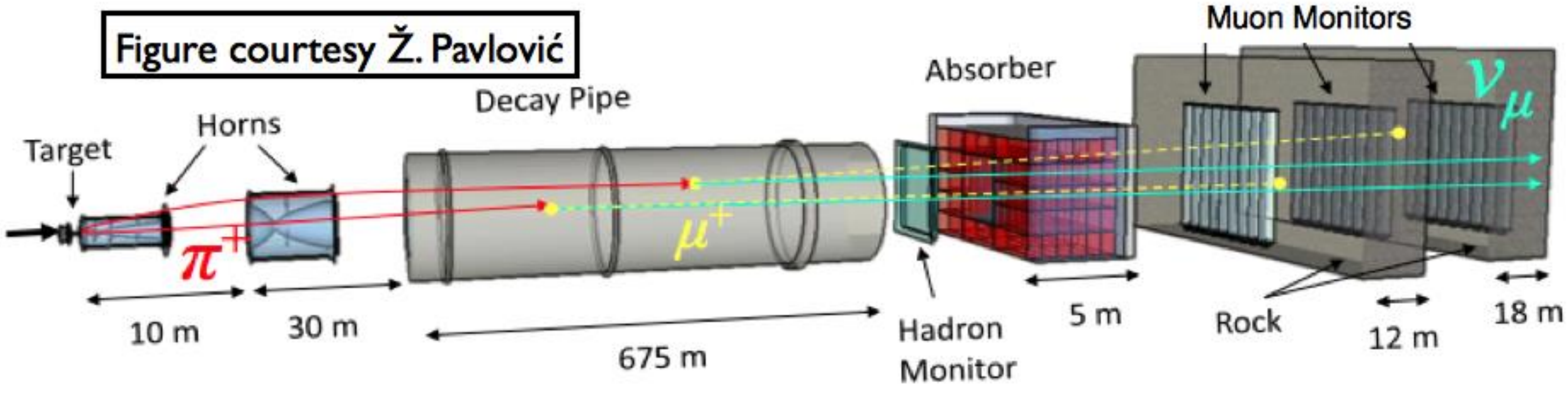
The pions and kaons decay in a 675 m long pipe, producing muons and neutrinos

Accelerator Neutrinos: Decay in Flight

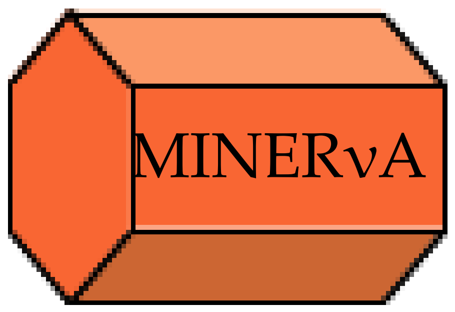


Everything but neutrinos is stopped in using an absorber+rock

Accelerator Neutrinos: Decay in Flight

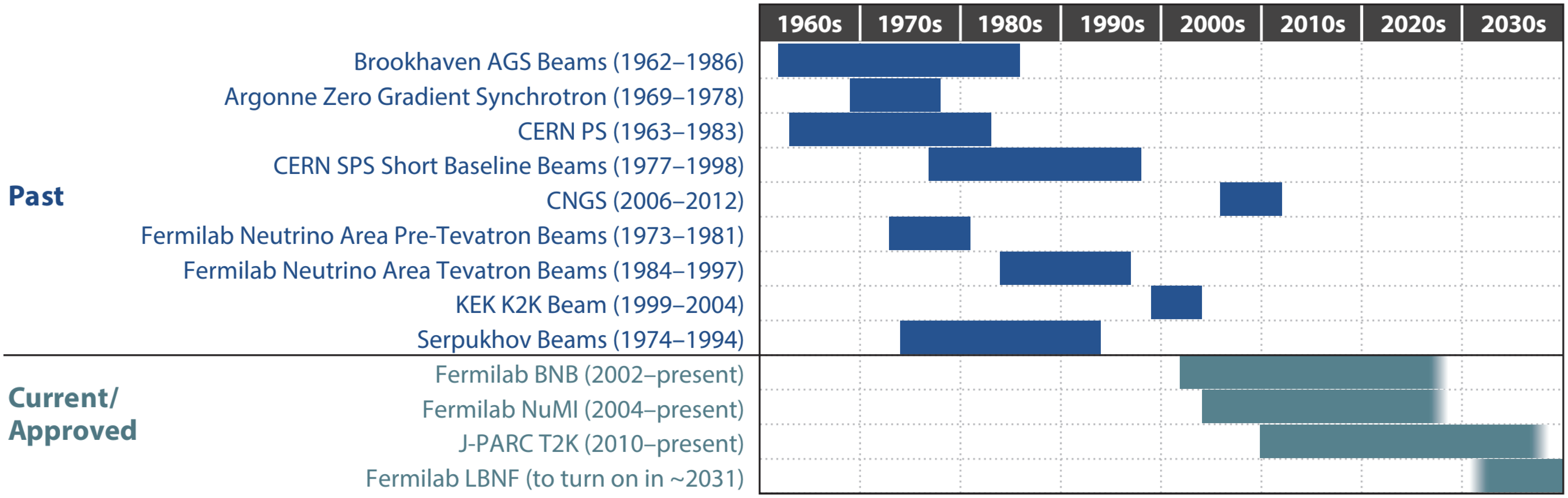


~210 m of rock



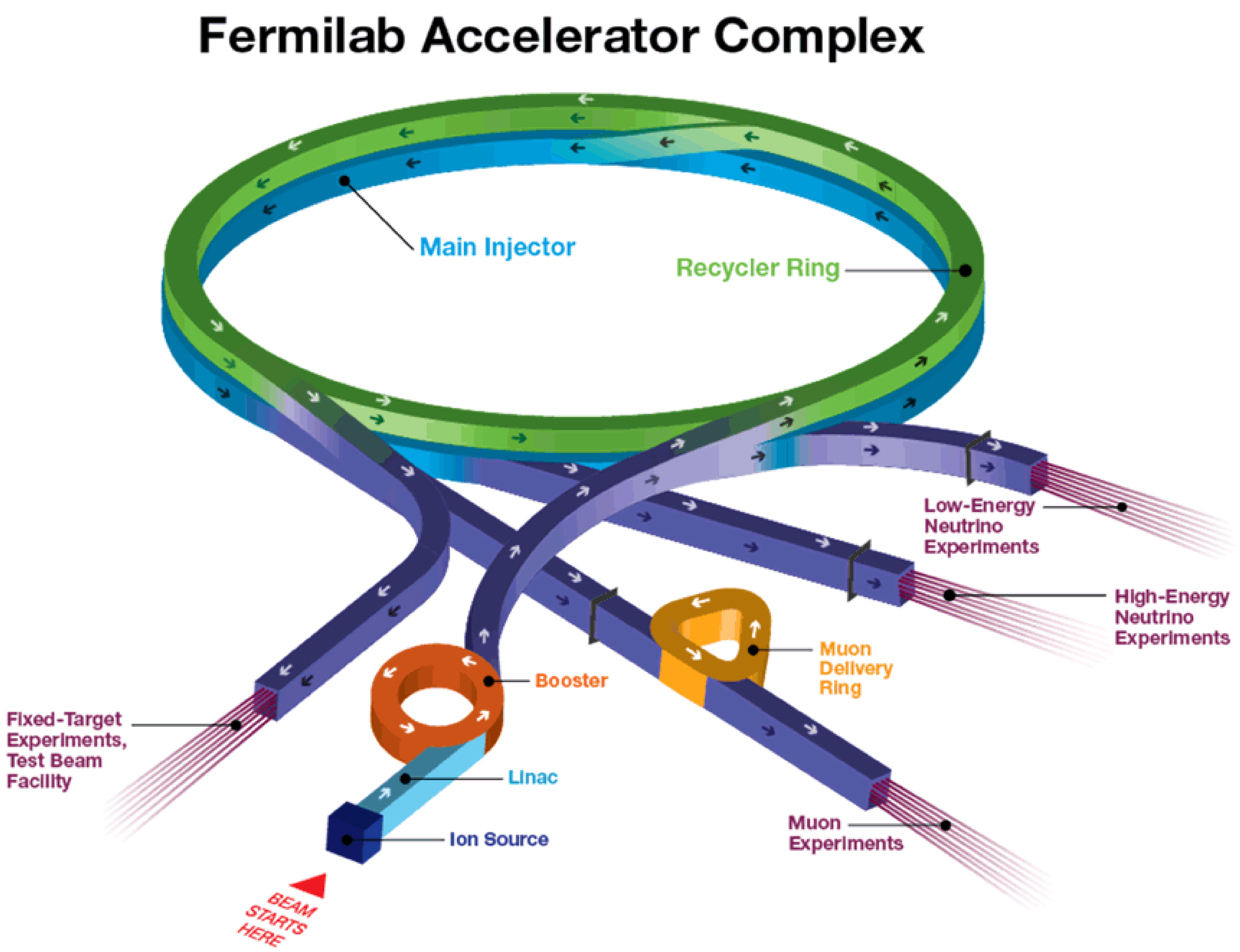
Only neutrinos arrive at the detector

Accelerator Neutrinos Past and Present

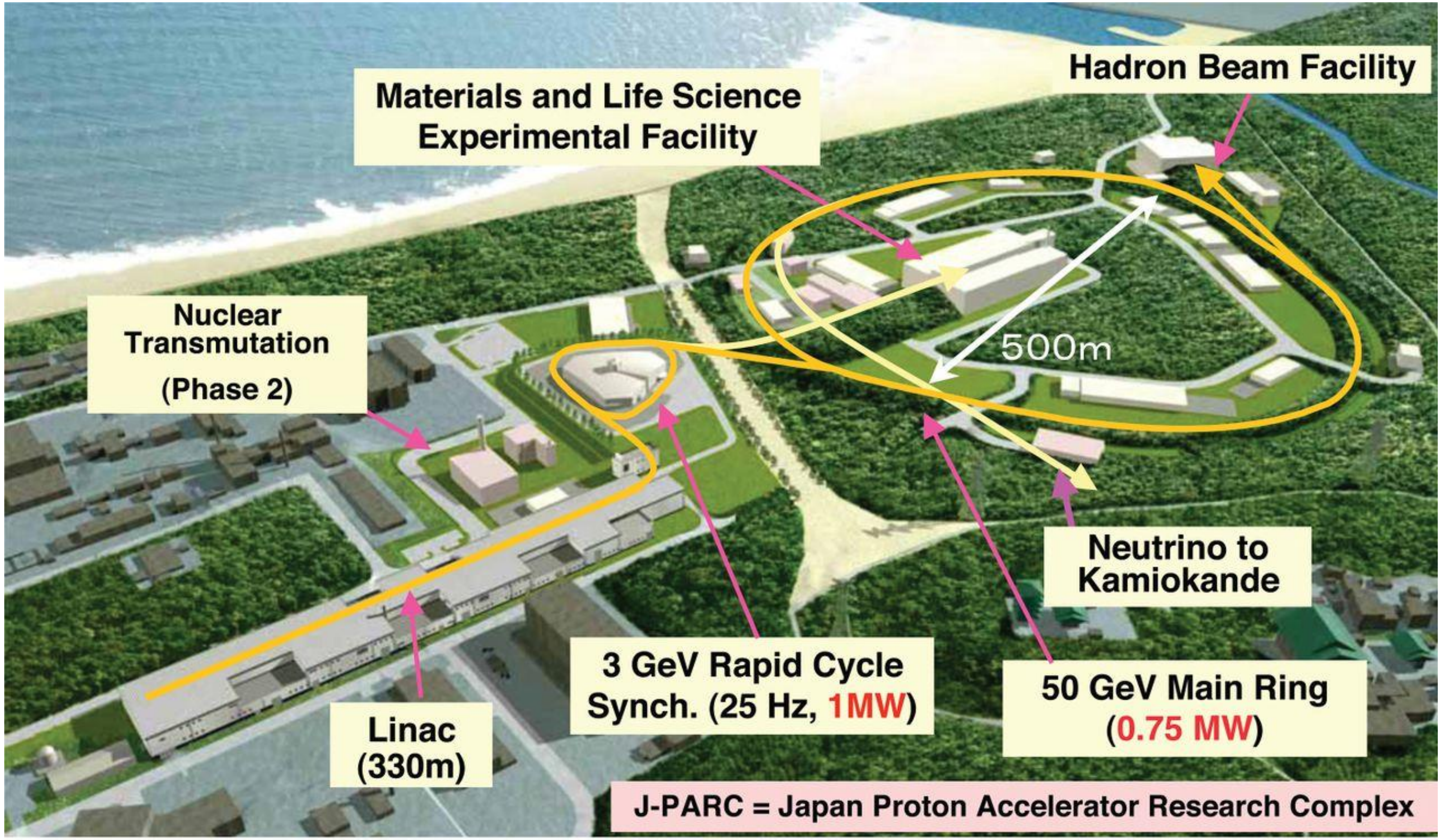


Protons

- beam is pulsed (10^{-5} duty factor is typical), including with ~ns substructure
- Beam shapes are ~2d gaussians with radius of order 10 mm
- Fermilab produces neutrino beams with 8 GeV and 120 GeV protons

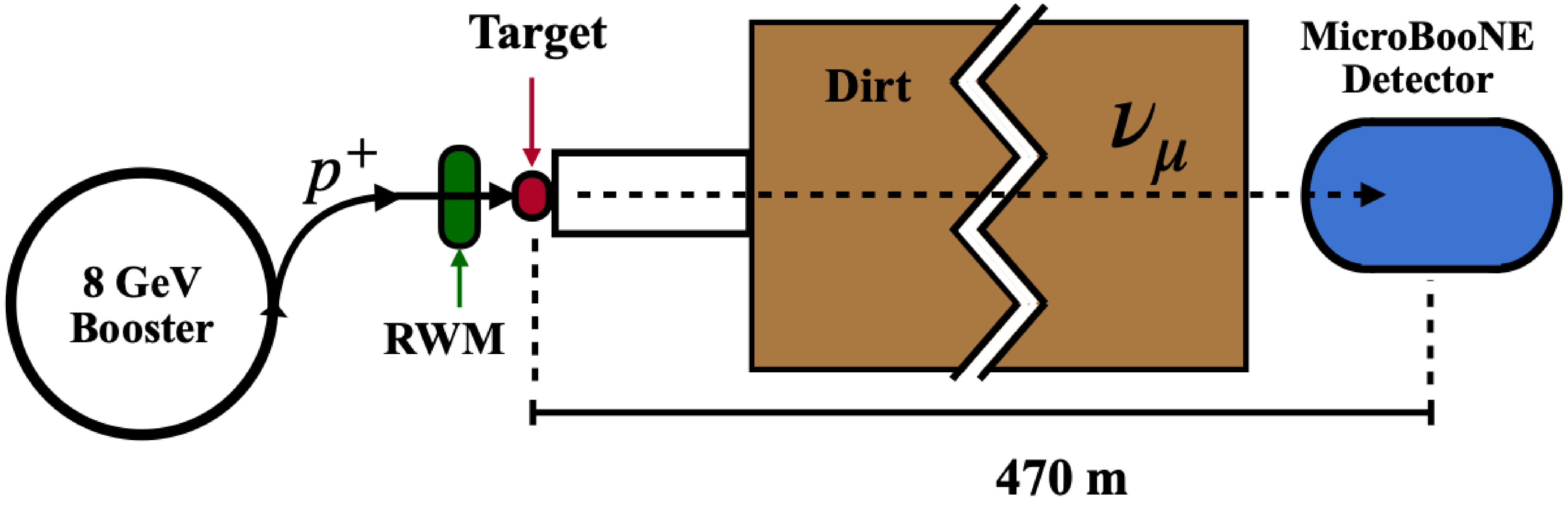


Protons



- JPARC produces a neutrino beams with 30 GeV protons
- Also decay at rest neutrinos – see next section

Beam timing example: Fermilab BNB



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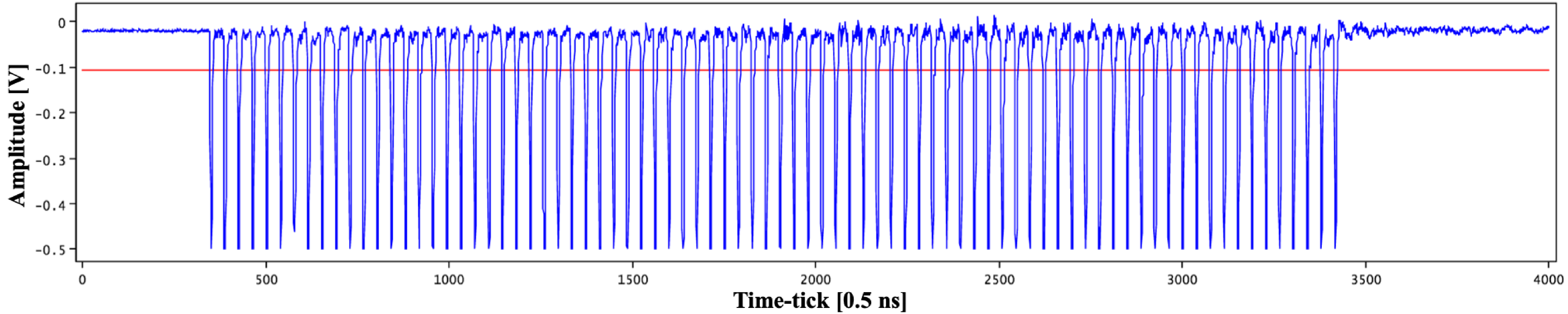


Each pulse consists of 81 bunches (1.3-1.5 ns each).

Average pulse rate of ~15 Hz

Beam Power

- Power calculation example for LBNF:
  - 120 GeV Protons
  - Spills arrive every 1.2 s
  - Each spill contains 7.5e13 protons
- 120 GeV/proton * 7.5e13 protons/spill * 1.6 x 10^-10 J / GeV / 1.2 s / spill =1,200,000 J/s =1.2 MW
- Note this is power delivered during standard operation

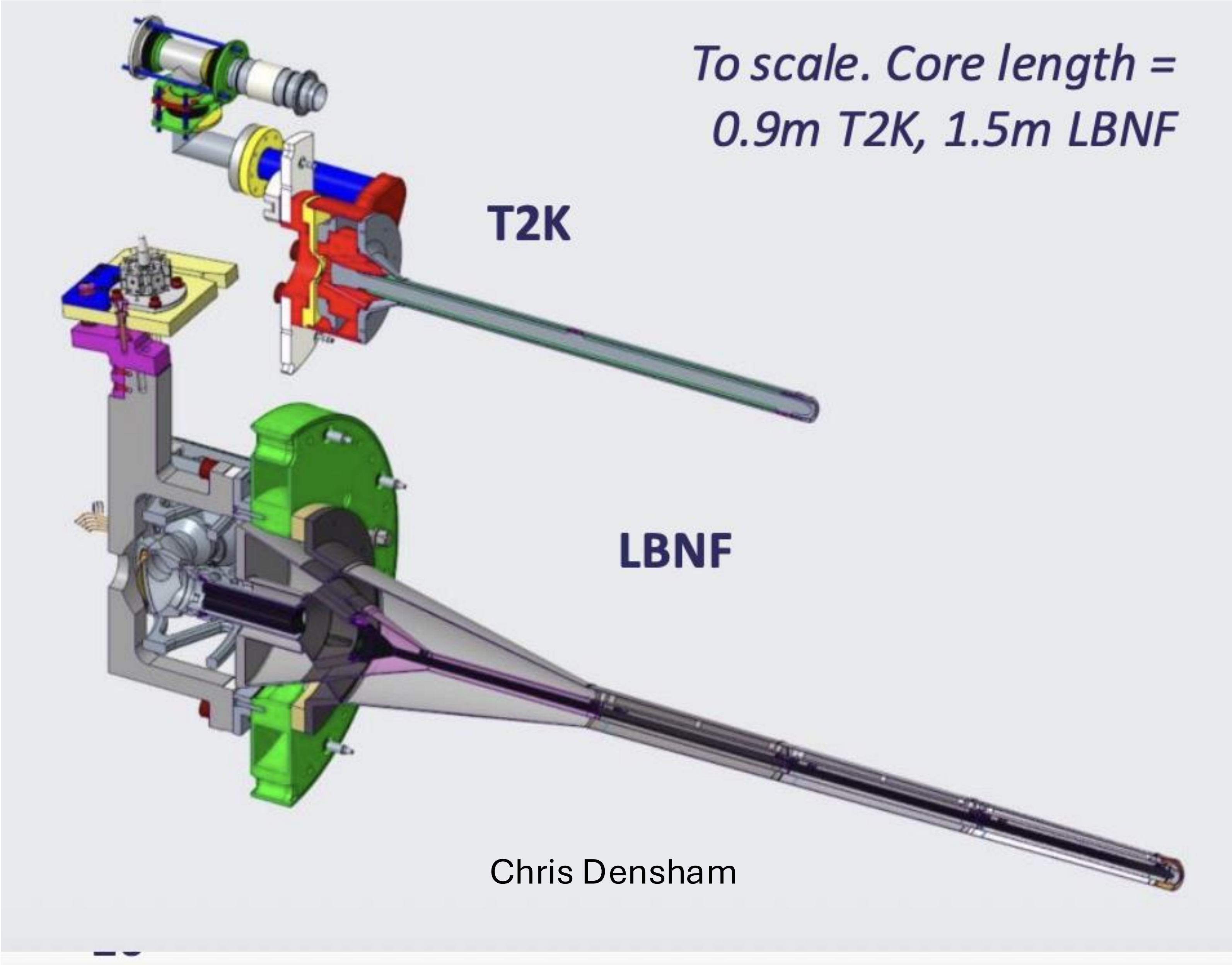
NuMI beam power: up to 1000 kW

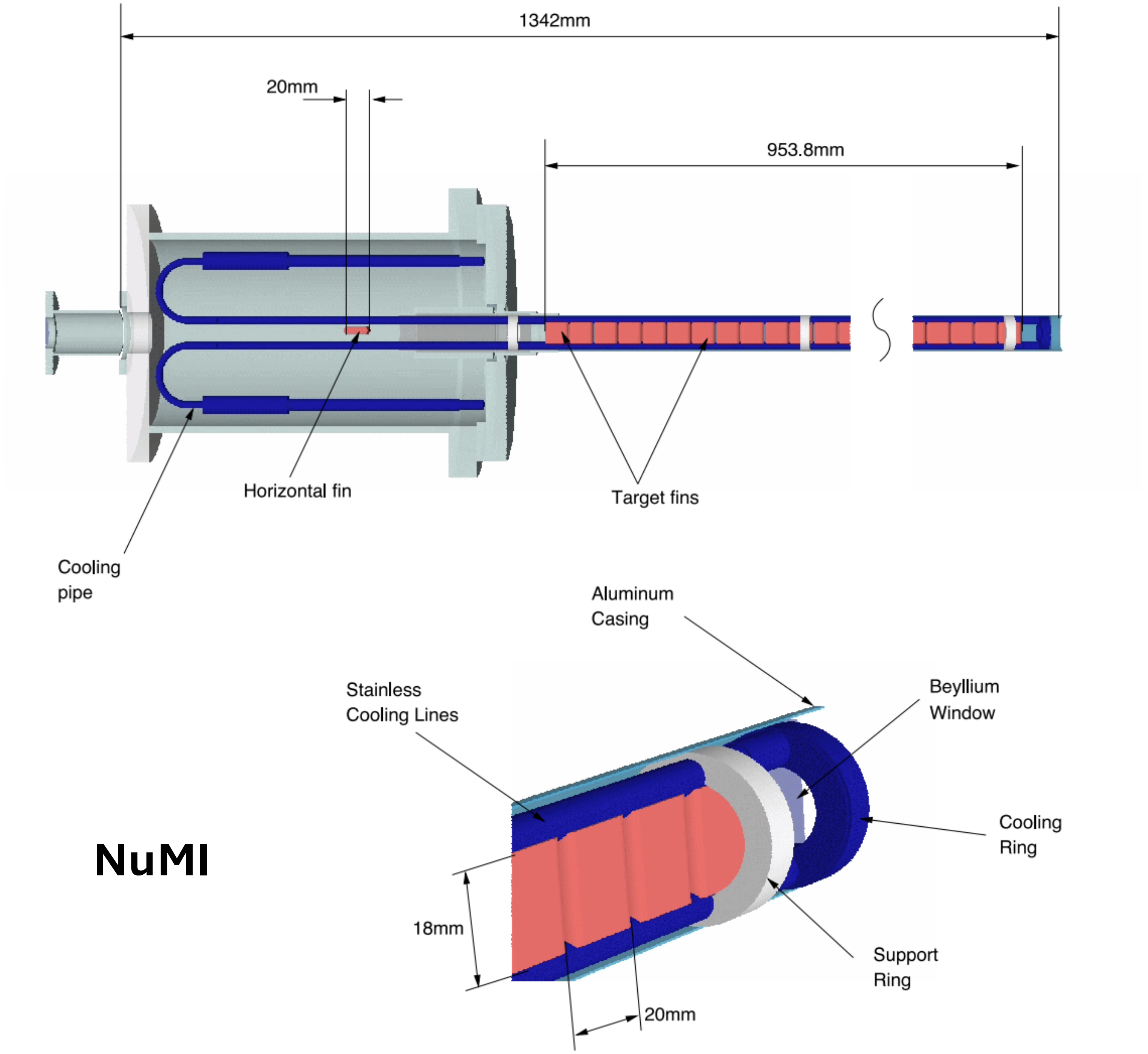
T2K beam power: up to 760 kW, going to 1.3 for HyperK

Future LBNF: 1200 kW (upgrade to 2400 kW)

Target

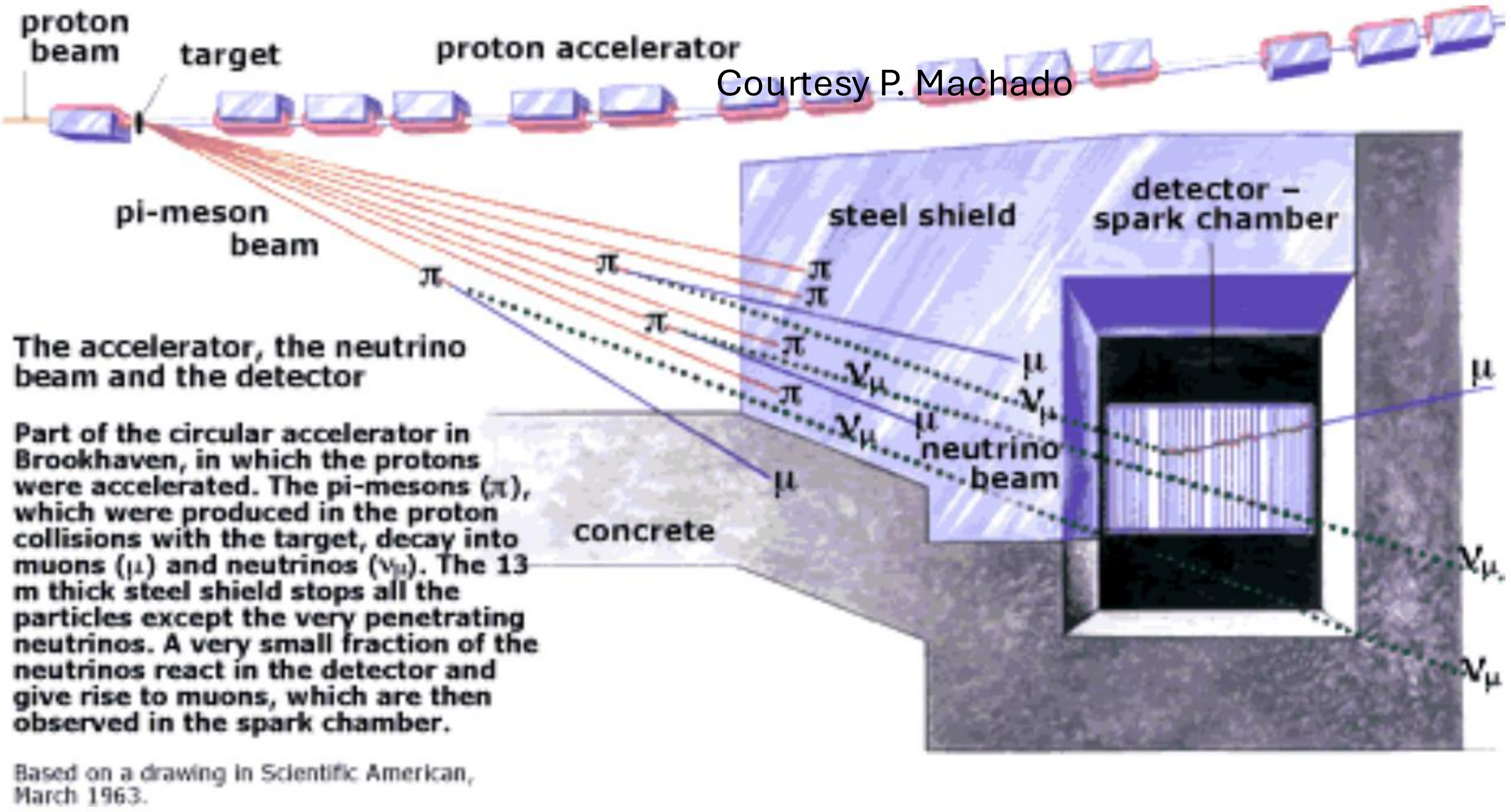
Keys: make sure it doesn't break, produce as many pions as possible, make sure the pions that do get produced don't get absorbed in the target material.





The First Neutrino Beam

BROOKHAVEN NATIONAL LABORATORY



Courtesy P. Machado

There was no focusing of hadrons produced in the target — the detector simply saw neutrinos that happened to point towards it.

Invention of Neutrino Horns

The concept of a horn-focused neutrino beam was **proposed by Simon van de Meer**

- Revolutionizing neutrino physics was **far from the only interesting thing** that van de Meer did
- He won the **Nobel prize for inventing Stochastic cooling** of particle beams, which allowed for intense p/pbar collisions, and led to the discovery of the W and Z bosons
- He is **one of two accelerator physicists** to get the Nobel prize, the other being Earnest Lawrence, who invented cyclotrons.

Why are they called horns?

According to Sasha Kopp in arXiv:physics/0609129, it might be because neutrino beam horns look kind of like a Swiss Alpenhorn

But apparently Panofsky also called it a “Horn of plenty”.

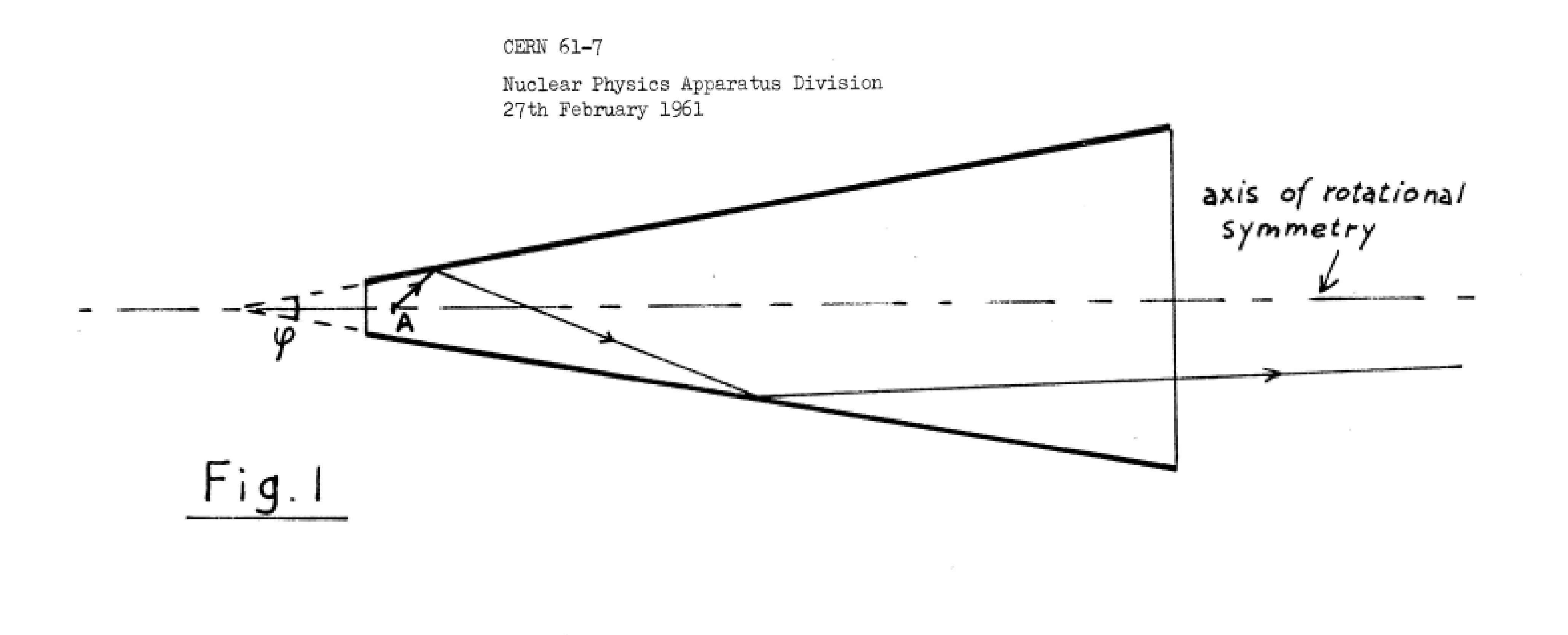
Why are they called horns?

BNB Horn Inner Conductor (Bartozek Engineering)

But apparently Panofsky also called it a "Horn of plenty".

Analogy with Optics

van de Meer compared his electromagnetic horn concept to a conical reflecting surface



CERN 61-7

Nuclear Physics Apparatus Division
27th February 1961

At each point of reflection, light becomes more parallel (by an amount equal to the opening angle of the horn) until it becomes straight enough to leave the horn

Analogy with Optics

A magnetic horn works similarly to conical reflecting surface, but for charged particles:

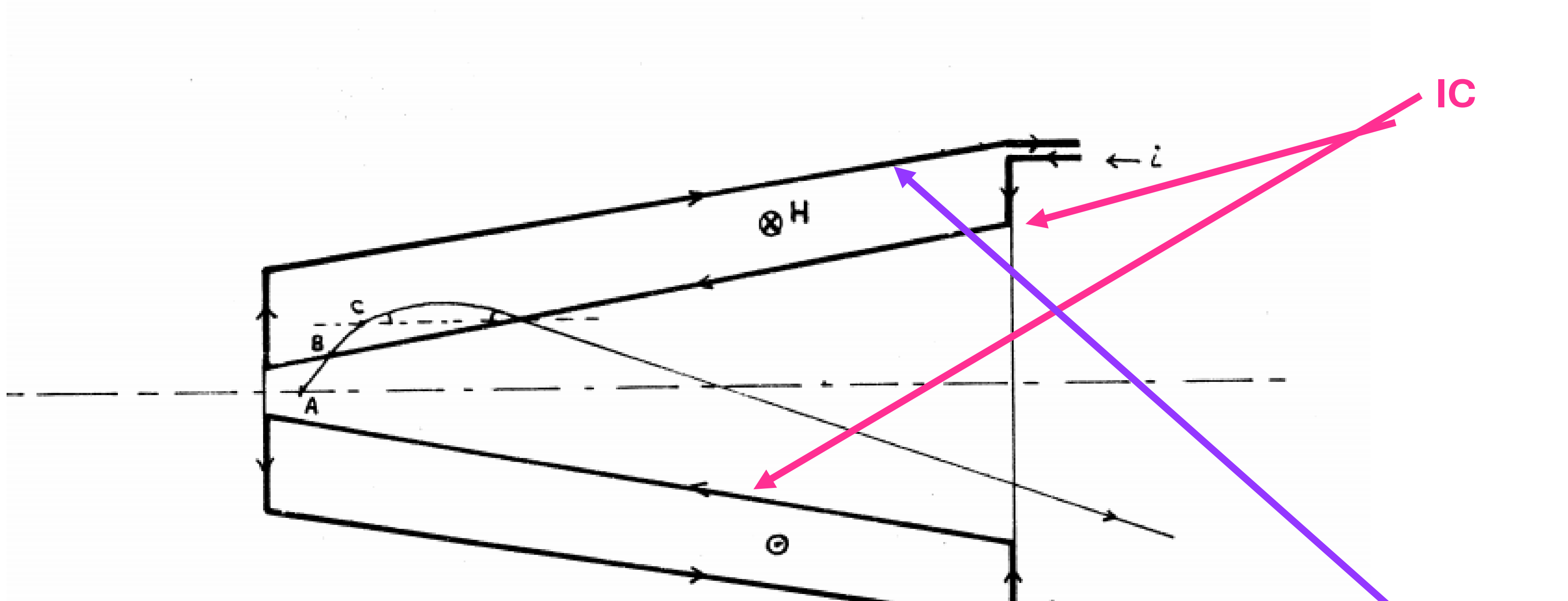
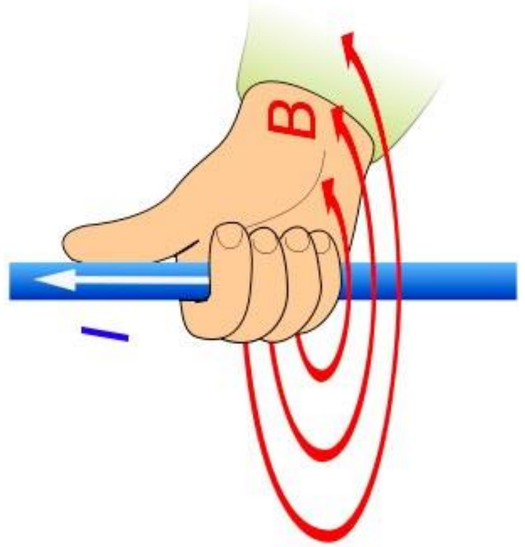


Fig. 2

- Current flows on the inner (IC) and outer (OC) conductors in opposite directions

$$\oint \mathbf{B} \cdot d\mathbf{l} = \mu_0 I_{\text{enc}}$$



A magnetic field is created between the conductors, as described by Ampere

Analogy with Optics

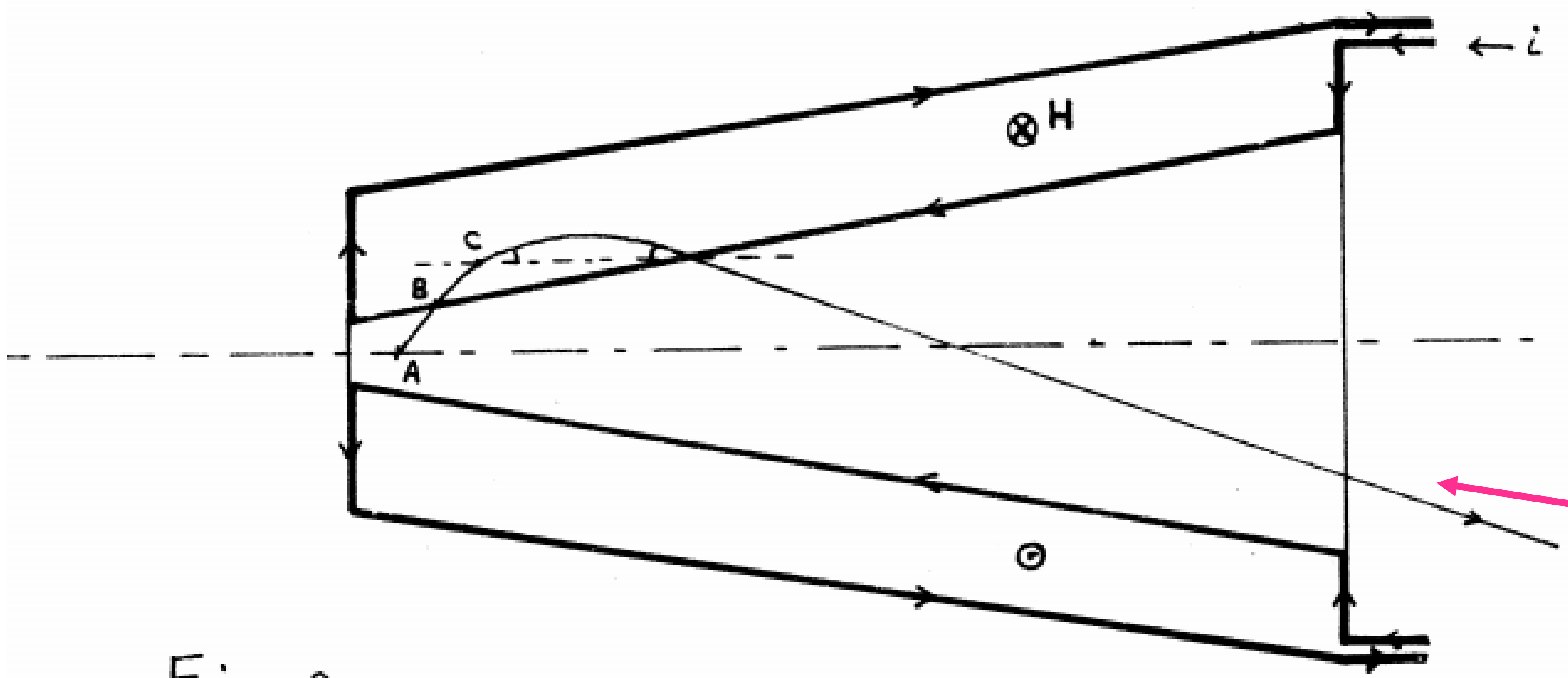


Fig.2

Neutrino horns typically carry VERY high currents (hundreds of kiloAmperes), creating magnetic fields of up to 3 Tesla at the smallest radii

Area between the IC surfaces and outside of the OC are nominally field free

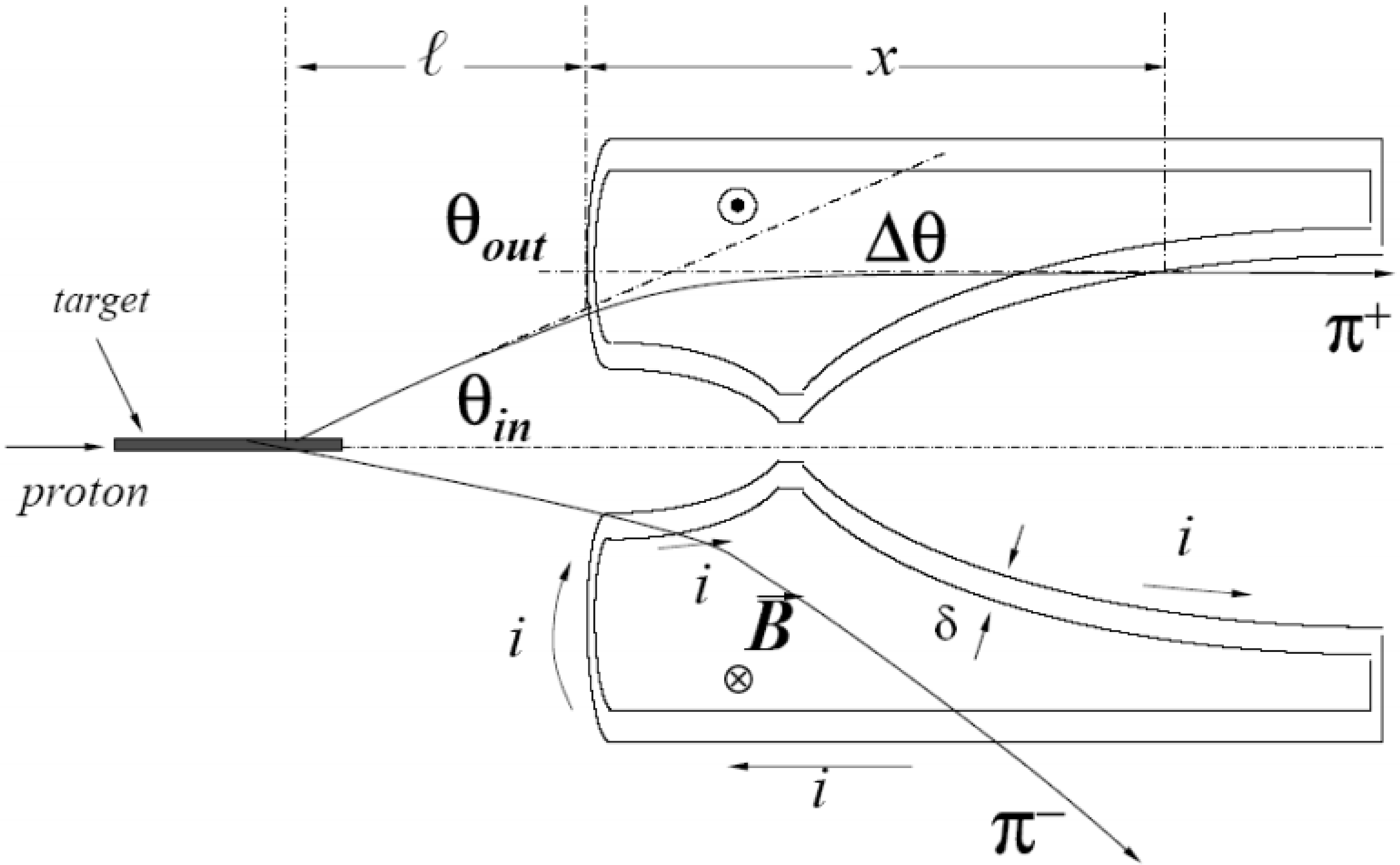
In practice, defects in the horn mean there are small fields here.

Horn Focusing

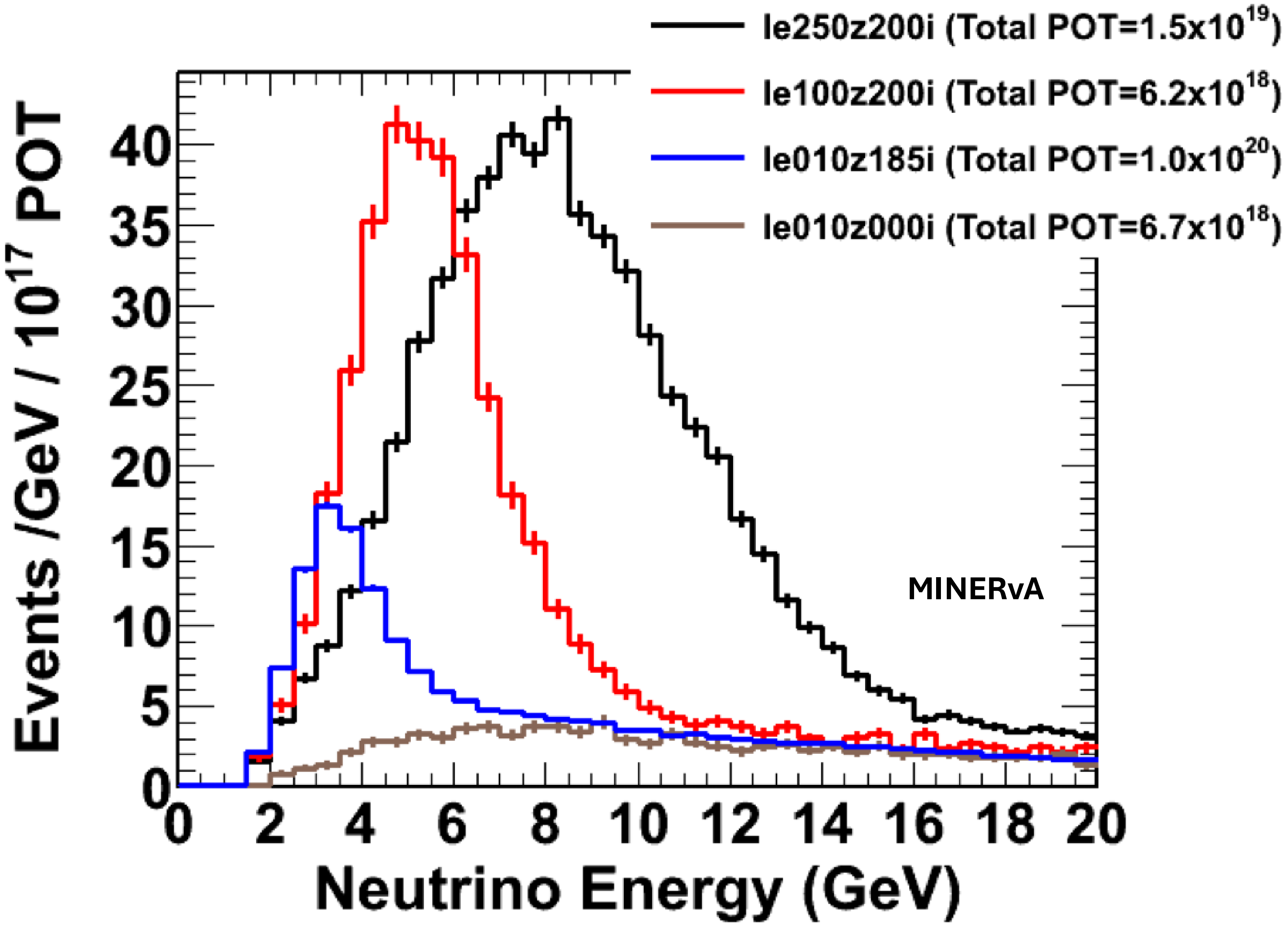
Depending on orientation of current, either positively or negatively charged particles will be focused -> this is how we create neutrino beams and antineutrino beams.

In a neutrino beam, particles with many different energies and angles will be ejected from the target

Selecting horn position and inner conductor shape can select pions (and therefore neutrinos) with desired energy



Horns are Very Effective



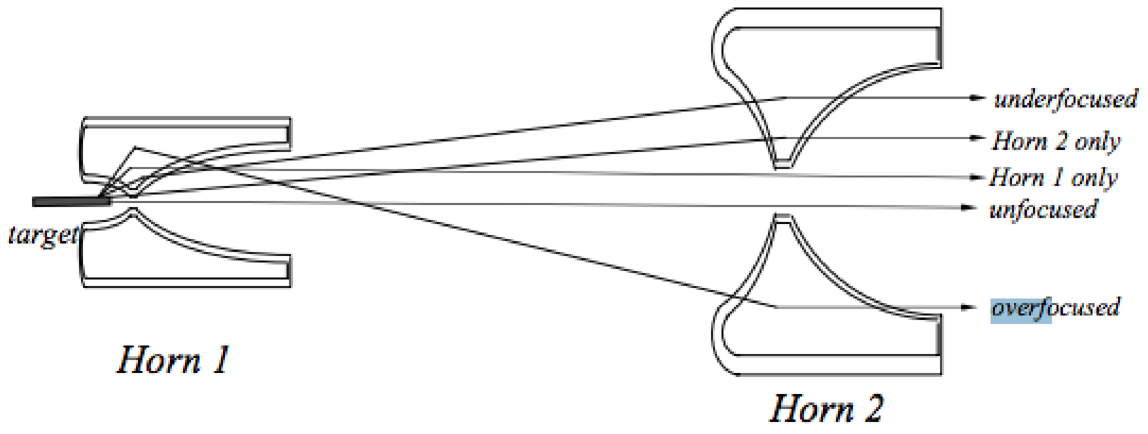
Target and horns in various positions

Horn off (no focusing)

Multi Horn Systems

- A natural evolution of the neutrino horns is a multi-horn system, e.g. the NuMI beam:

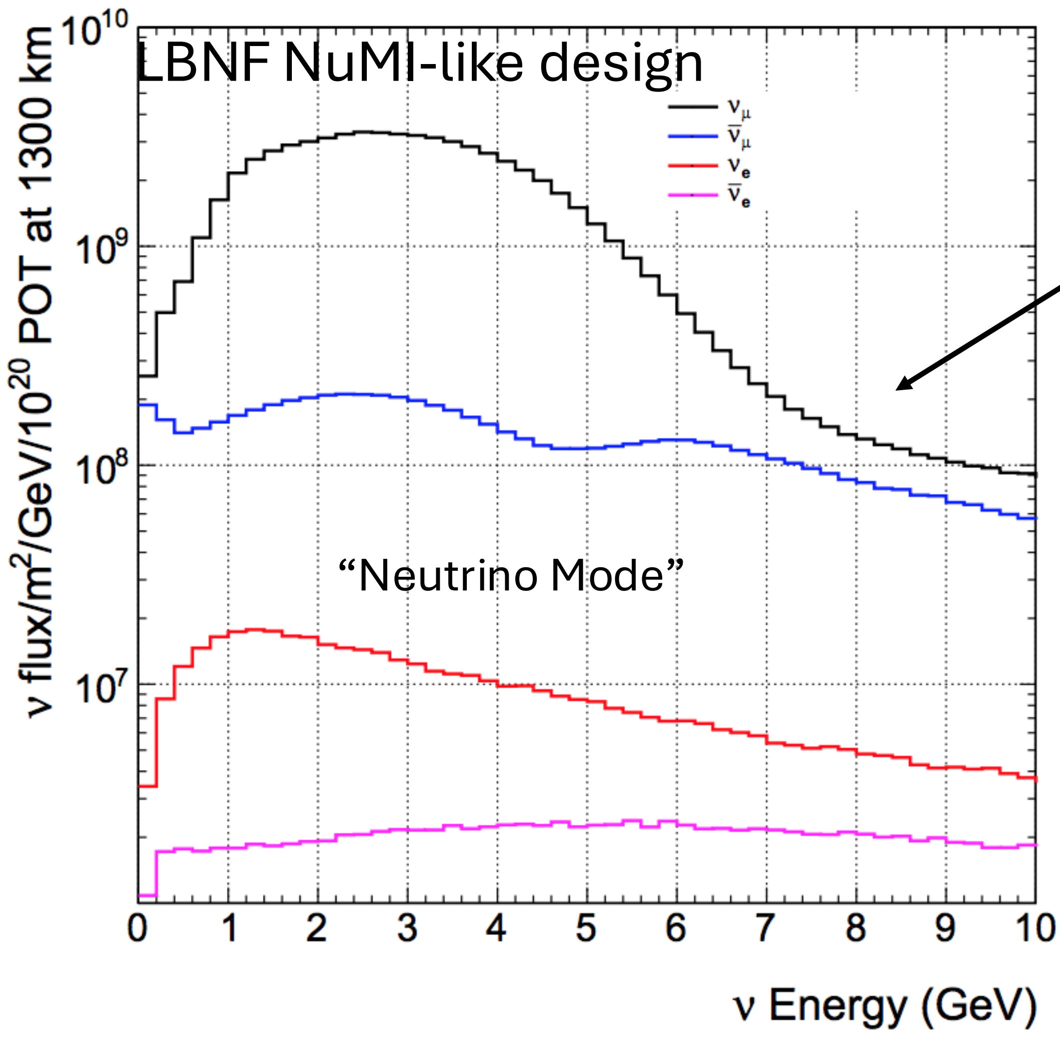
Z. Pavlovic



- Increase neutrino flux by focusing hadrons not focused by first horn
- Later horns generally have larger aperture, so that they do not disturb particles focused by the first horn
- T2K and DUNE beam designs now include three horns

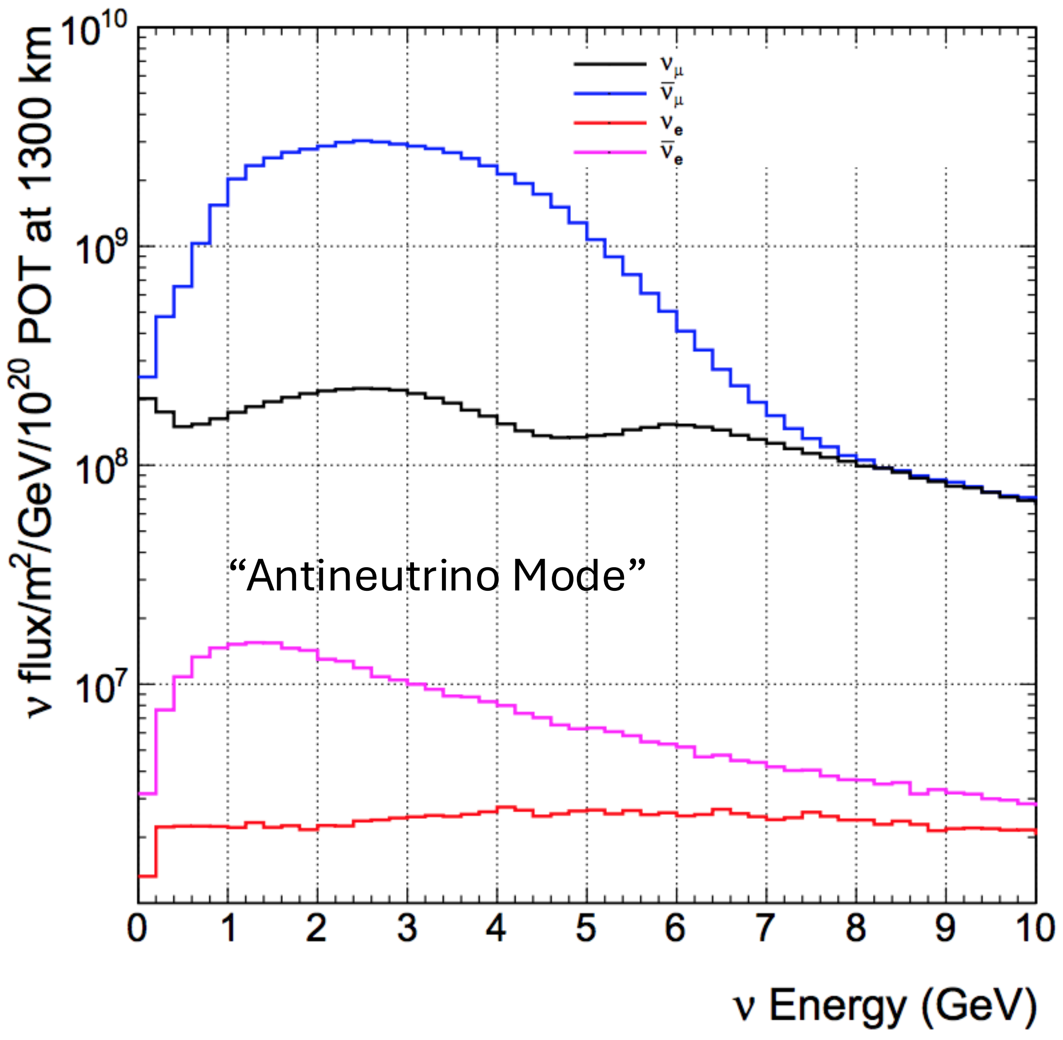
“Wrong Sign” Deflection

In any target, both positively and negatively charged pions will be created; the positively charged ones will go on to make neutrinos and the negative ones will make antineutrinos. This helps us create neutrino and antineutrino-enhanced beams



Current oriented to focus positively charged particles

Often called “Forward Horn Current”



“Wrong Sign” Deflection

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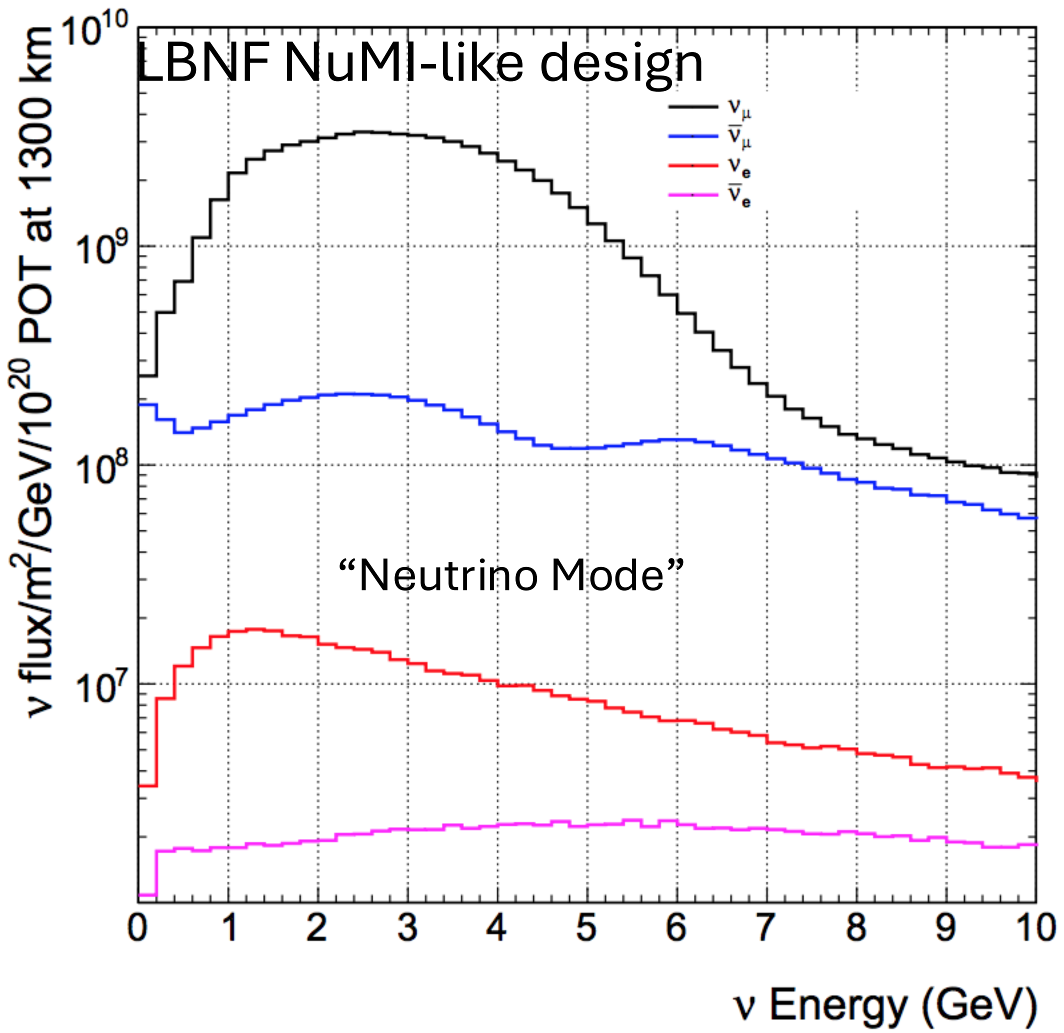
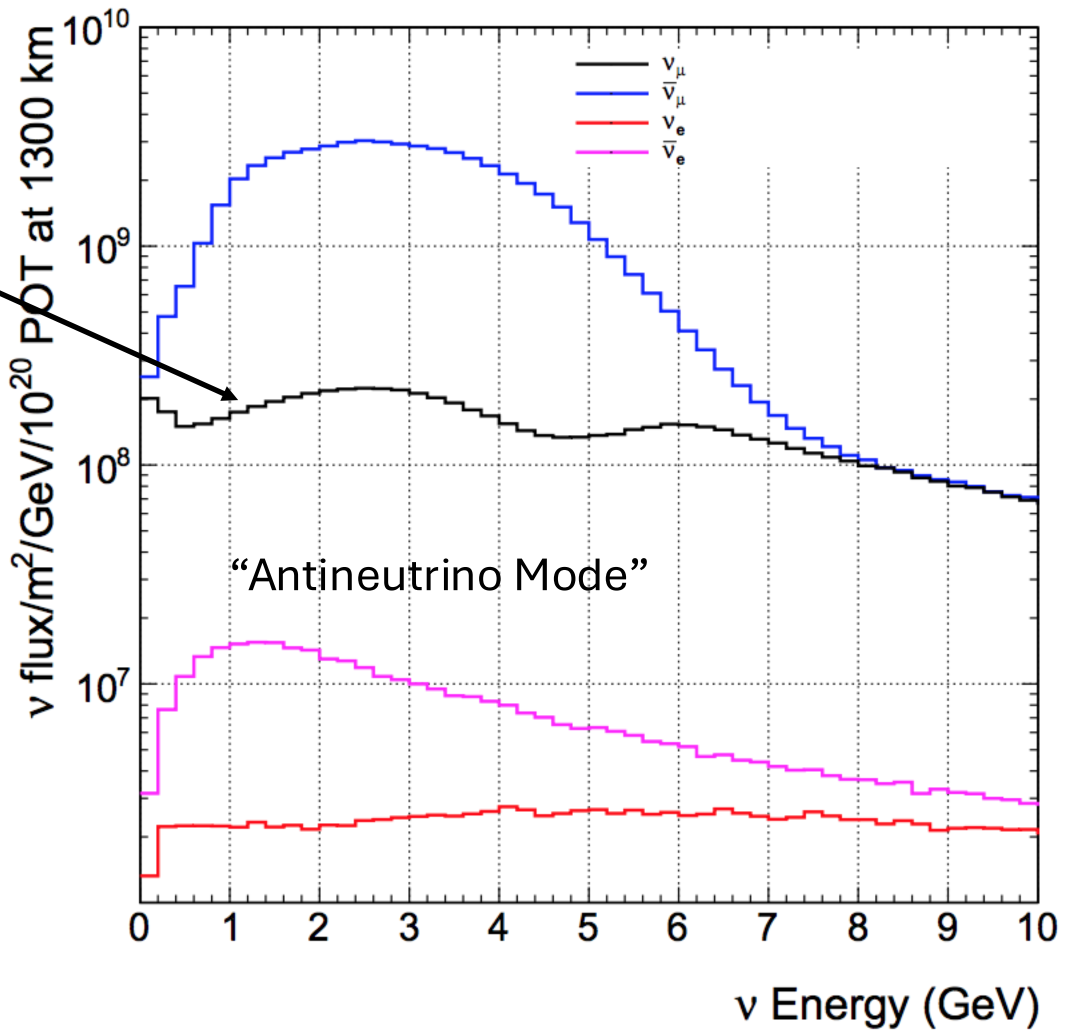


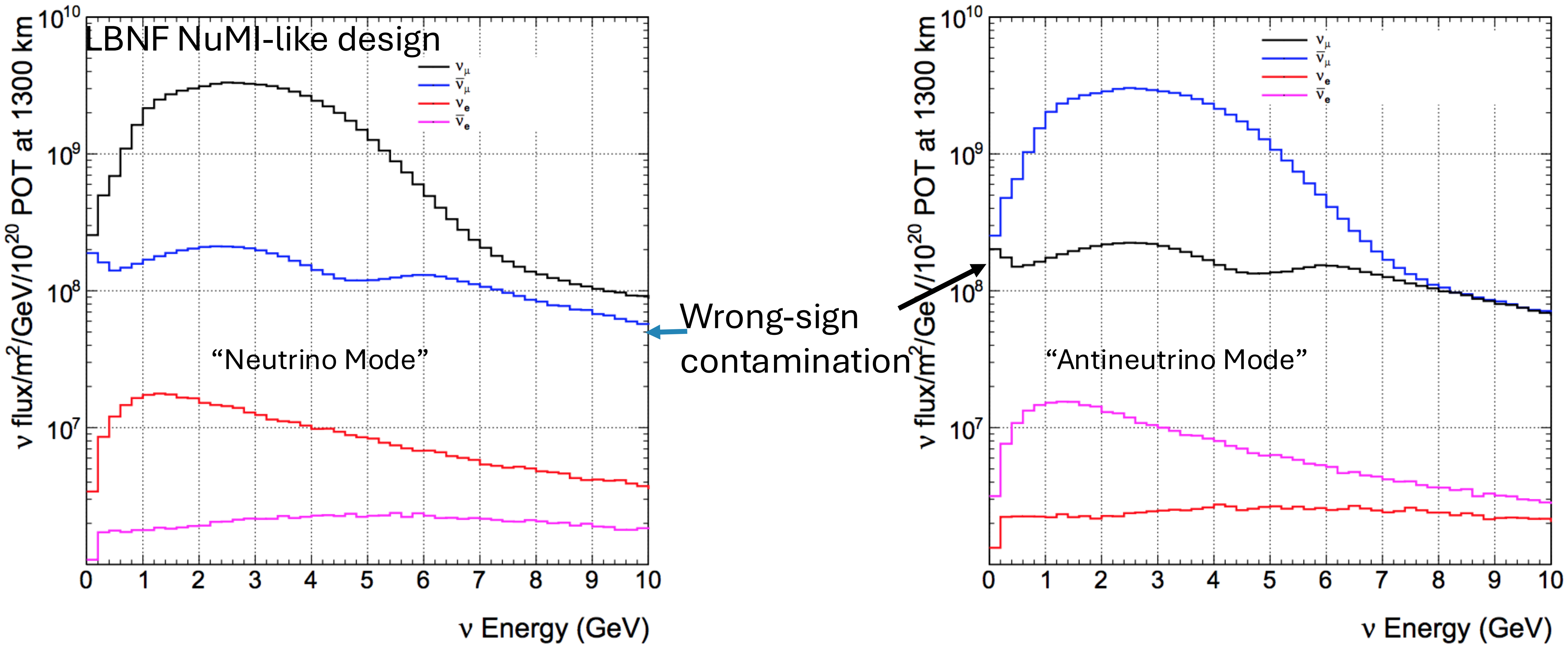
Current oriented to focus negatively charged particles

Often called “Reverse Horn Current”

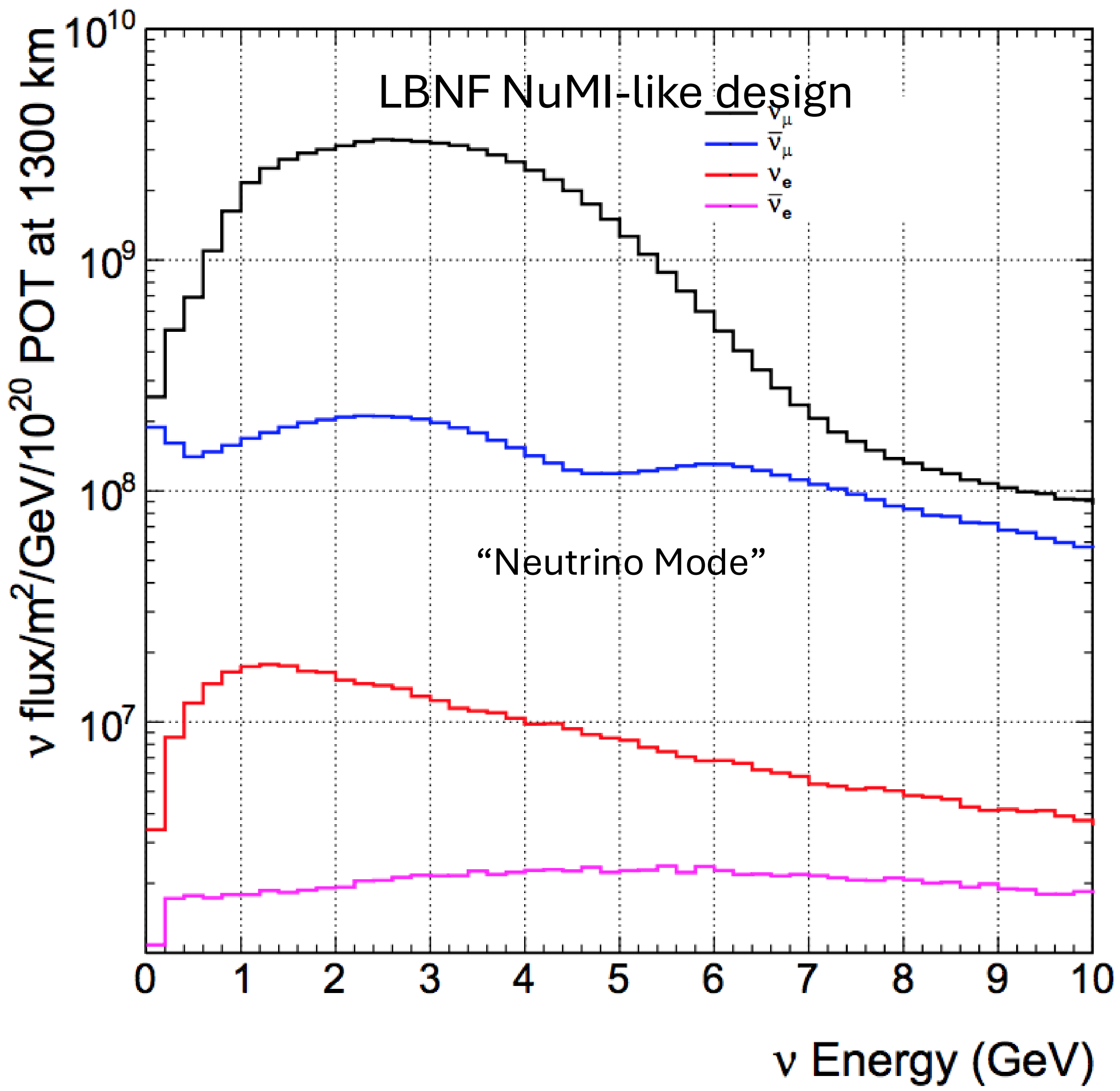


“Wrong Sign” Deflection

In any target, both positively and negatively charged pions will be created; the positively charged ones will go on to make neutrinos and the negative ones will make antineutrinos. This helps us create neutrino and antineutrino-enhanced beams



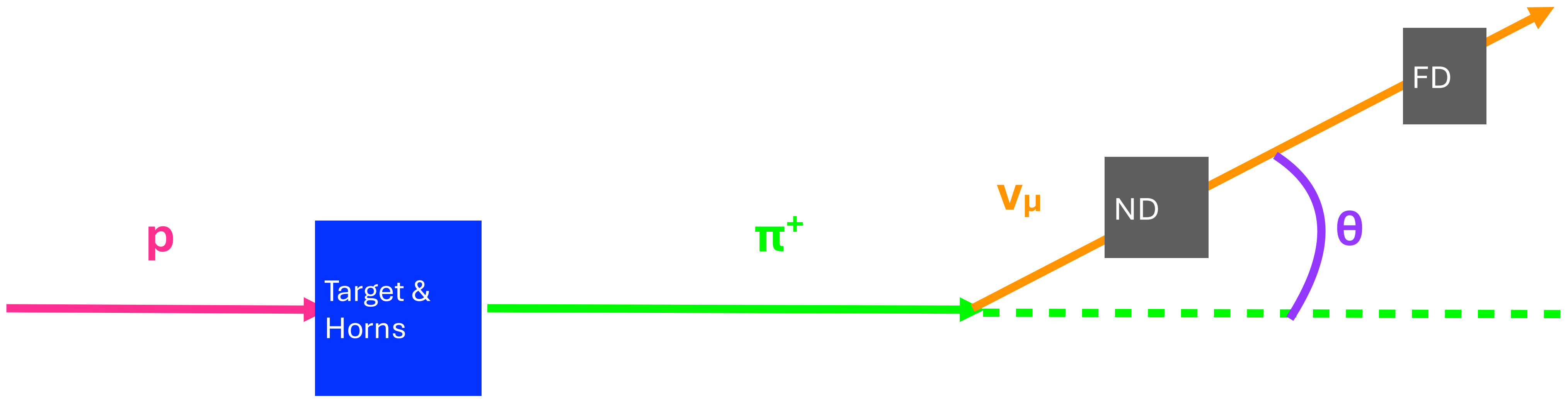
Other Backgrounds



- A small fraction (~1/100th of the flux) will be electron neutrinos from kaon and muon decays
  - Electron neutrinos will have a focusing peak, although slightly different in shape than the muon neutrino peak
- And there will be a long "high energy tail" of muon neutrinos
  - The high energy tail comes from hadrons that go straight through the neck of the horn, without being focused

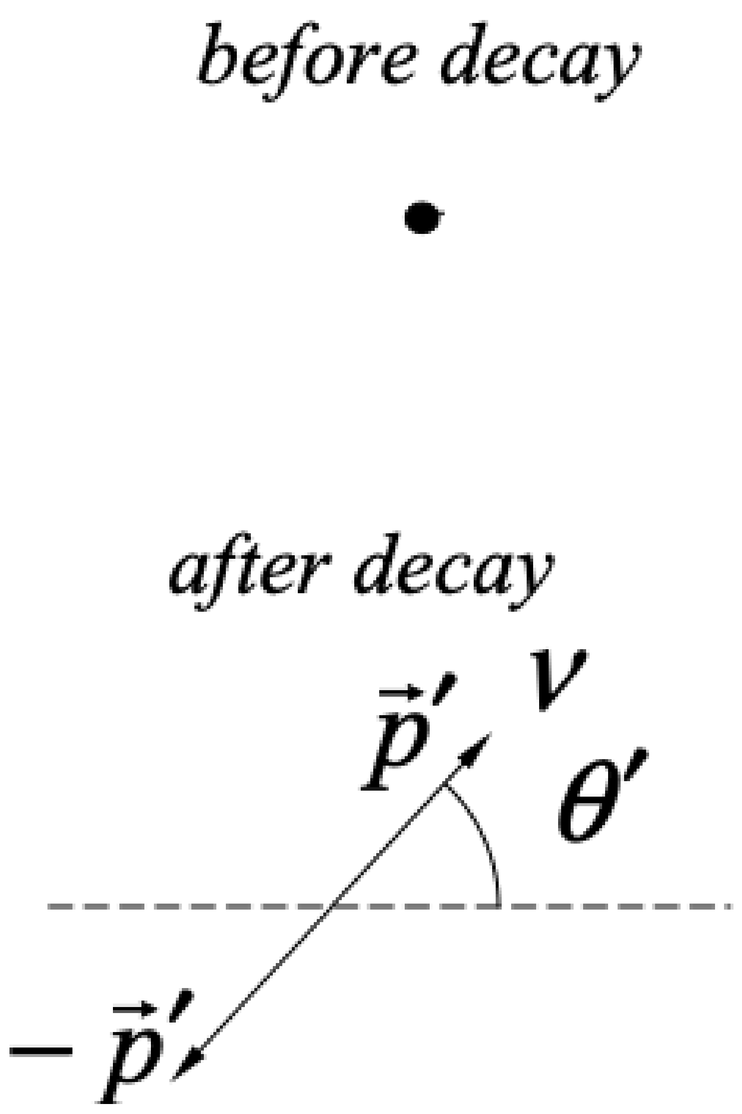
Off-Axis Beams

- Both NOvA (on NuMI) and T2k are “off-axis detectors”:

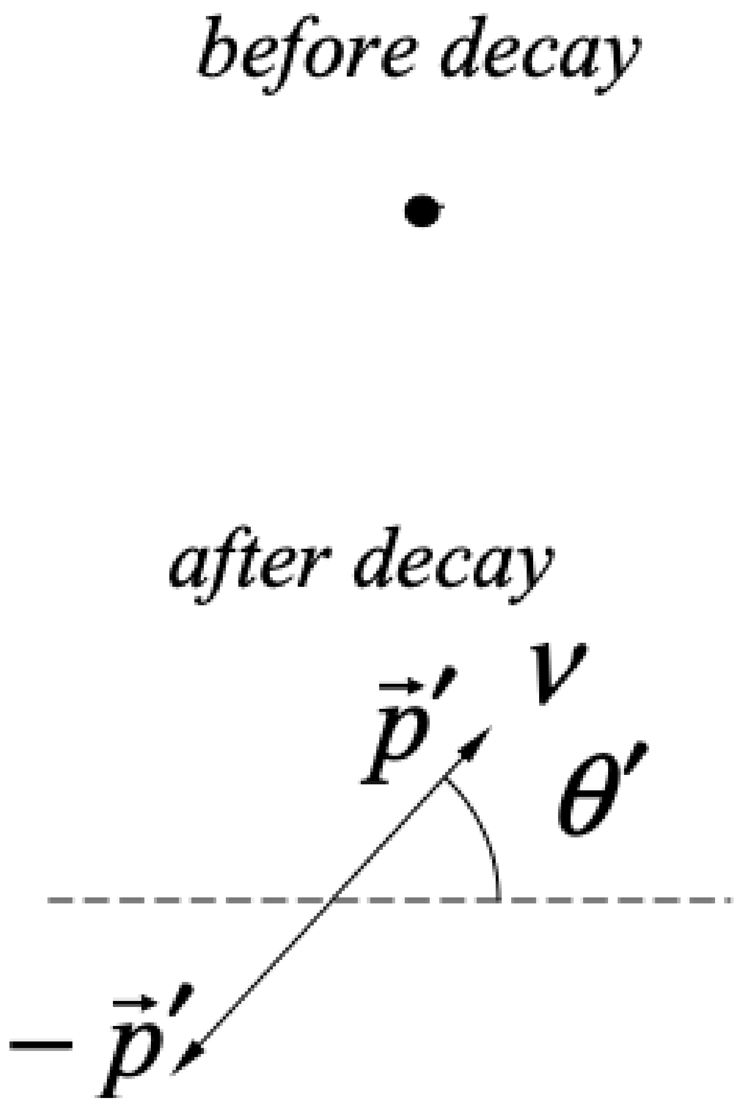


- To understand why, let’s talk a little about pion decay….

Pion Decay: Center of Mass Frame



Pion Decay: Center of Mass Frame



Energy/Momentum Conservation

$$E_\pi = m_\pi = E_\mu + E_\nu$$

$$\vec{p}_\pi = 0 = \vec{p}_\mu + \vec{p}_\nu$$

$$E_\mu = \sqrt{p_\mu^2 + m_\mu^2}$$

$$E_\nu = \sqrt{p_\nu^2 + m_\nu^2} \approx p_\nu$$

Relativistic Energy/Momentum Relation

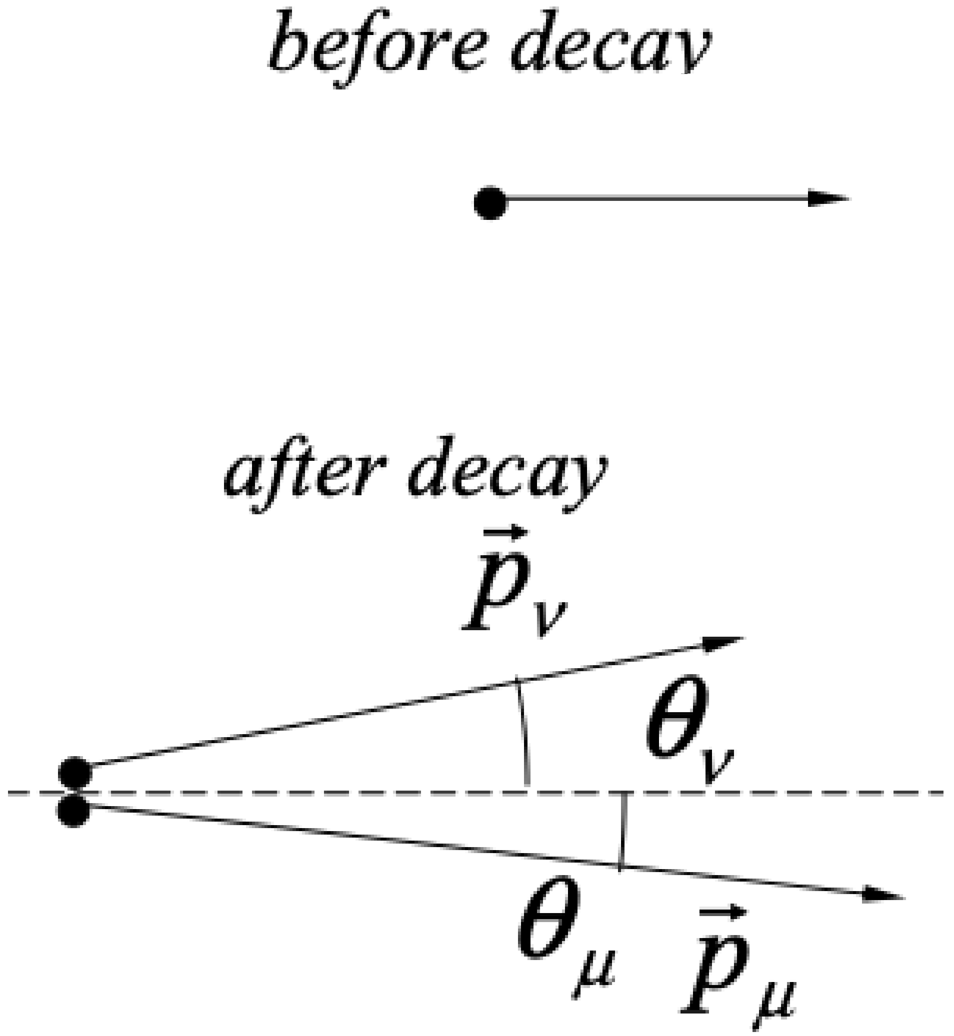
$$E_\nu = \frac{m_\pi}{2}\left(1 - \frac{m_\mu^2}{m_\pi^2}\right)$$

$$\approx 29.8\ MeV$$

$$\frac{dN}{d\Omega} \sim \frac{1}{4\pi}$$

(Isotropic)

Pion Decay: Laboratory Frame

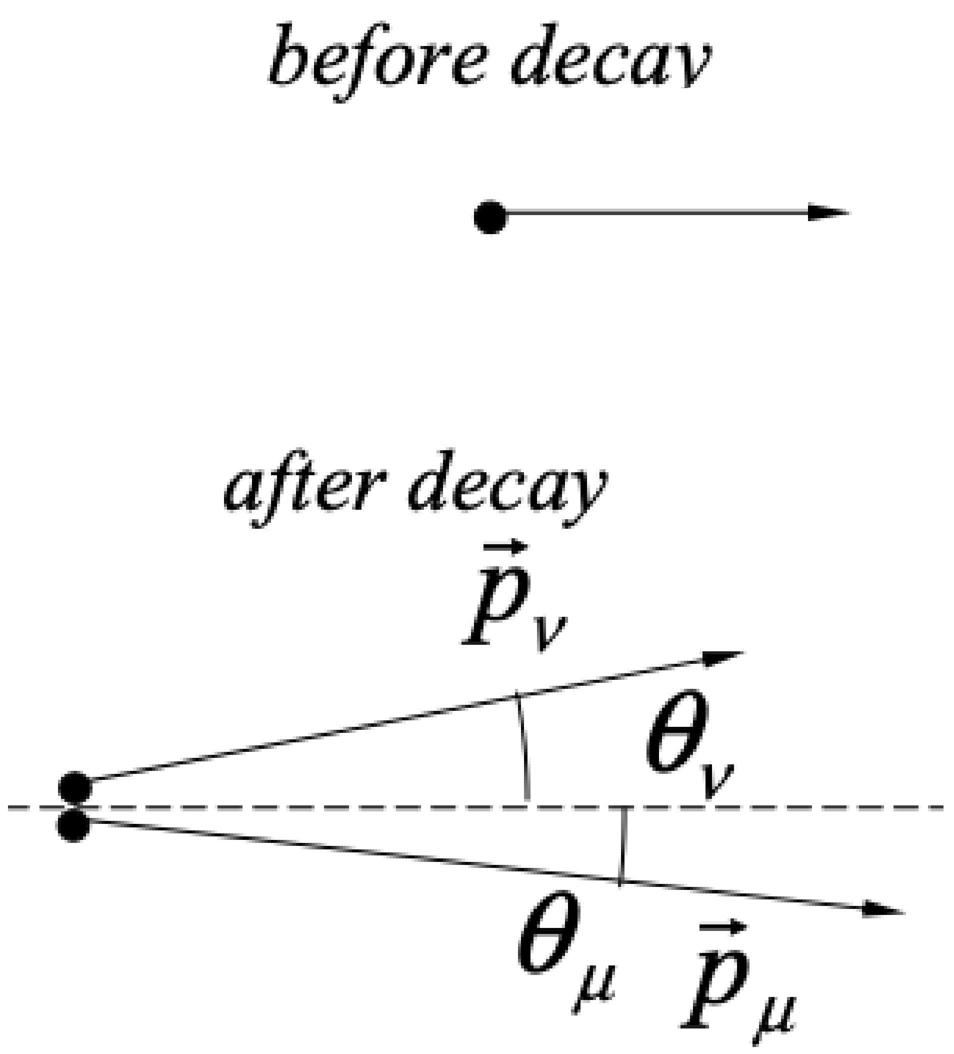


In the laboratory frame, the pion has some momentum. Boosting the momentum and angle to the laboratory frame, we have:

$$\cos\theta = \frac{\beta + \cos\theta^*}{1 + \beta\cos\theta^*}$$

Where $\beta = \frac{p_\pi}{E_\pi}$ .As β approaches 1, the isotropic neutrinos in the center of mass frame are forced into a smaller and smaller forward cone

Pion Decay: Laboratory Frame

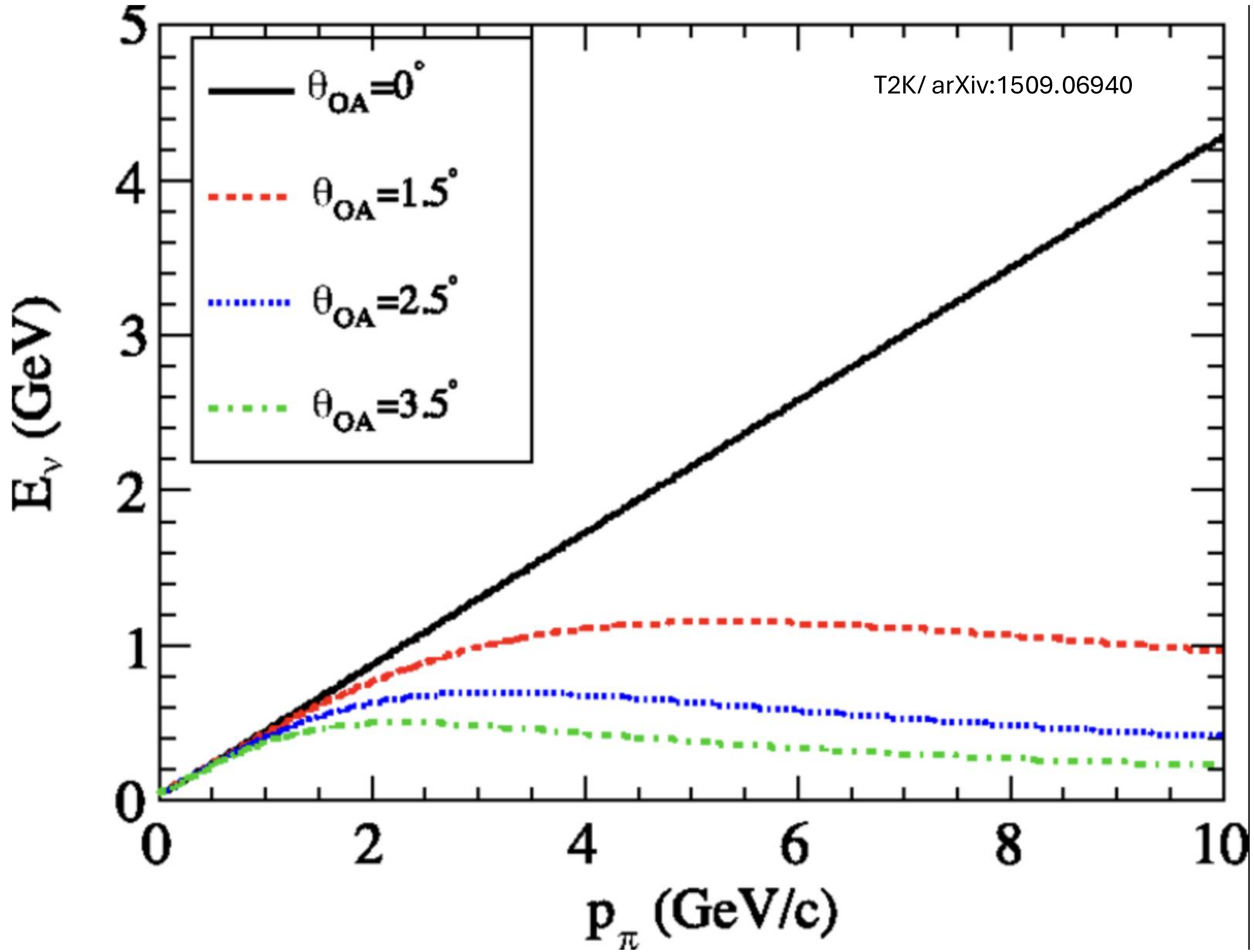


The energy of the neutrino also shifts in the lab frame

$$E_\nu = E_\pi \frac{1 - m_\mu^2/m_\pi^2}{1 + \gamma^2\theta^2} \approx \frac{0.43 E_\pi}{1 + \gamma^2\theta^2}$$

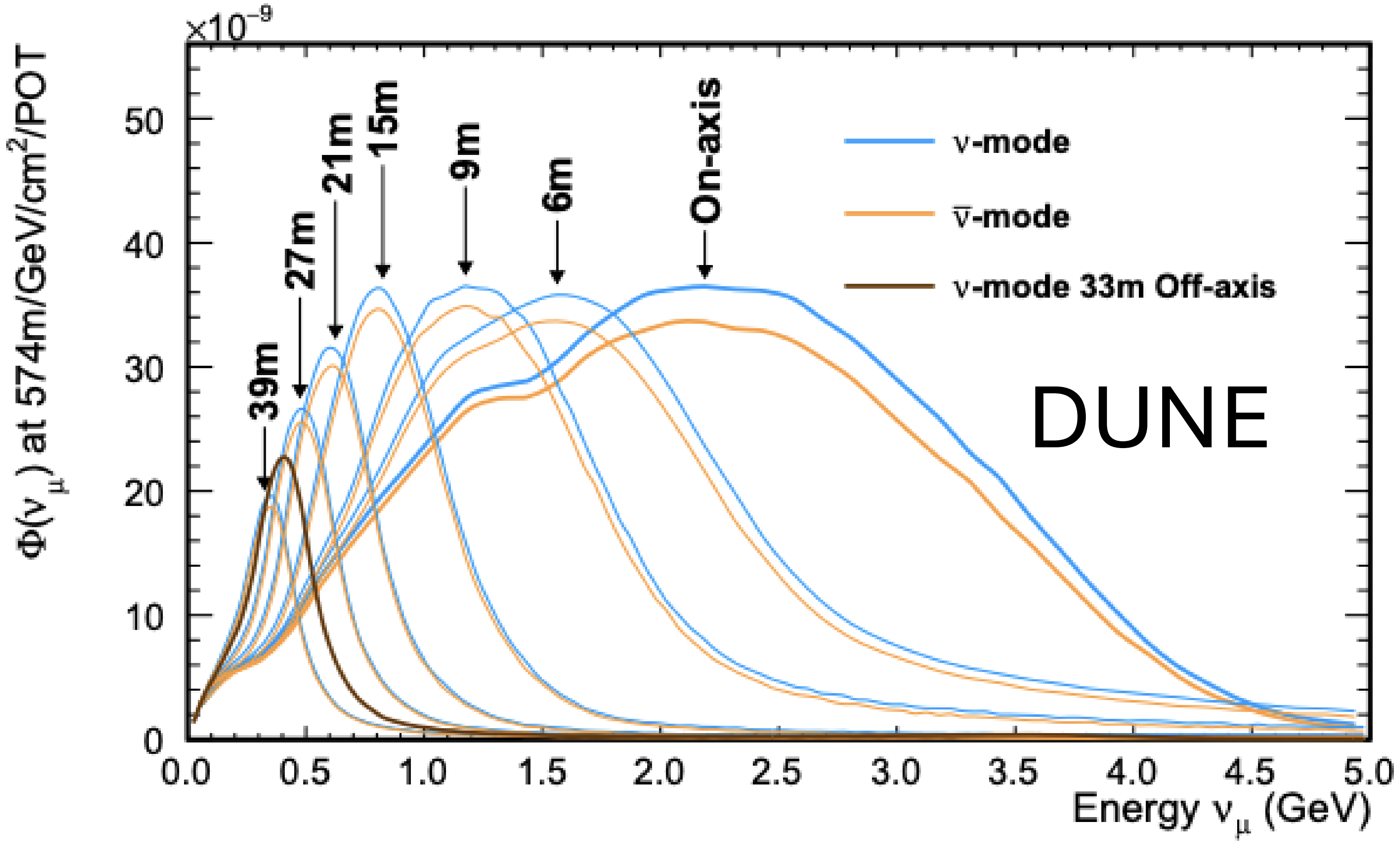
On-axis ($\theta = 0$), $E_\nu = 0.43\ E_\pi$

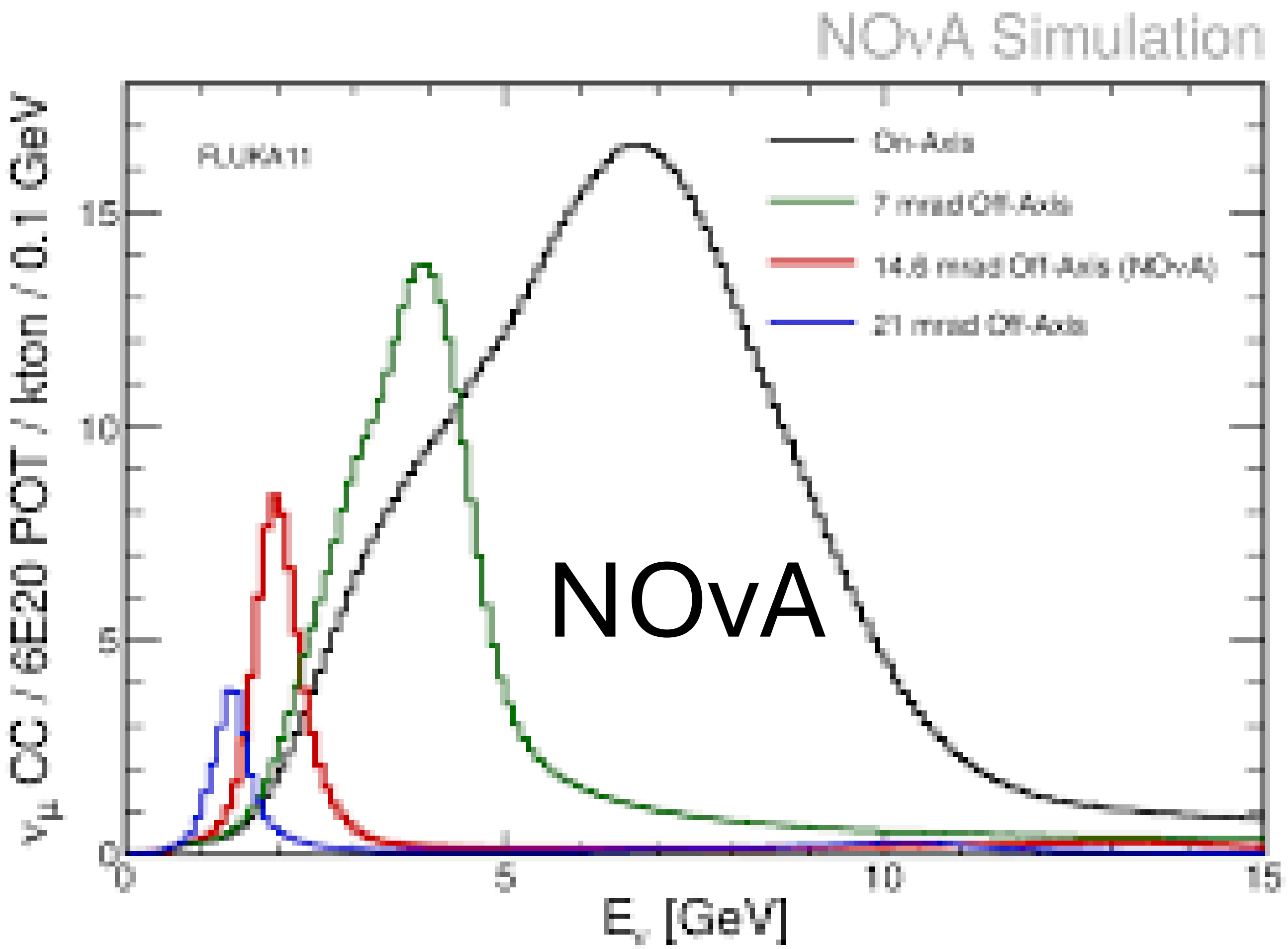
Off-Axis Effect

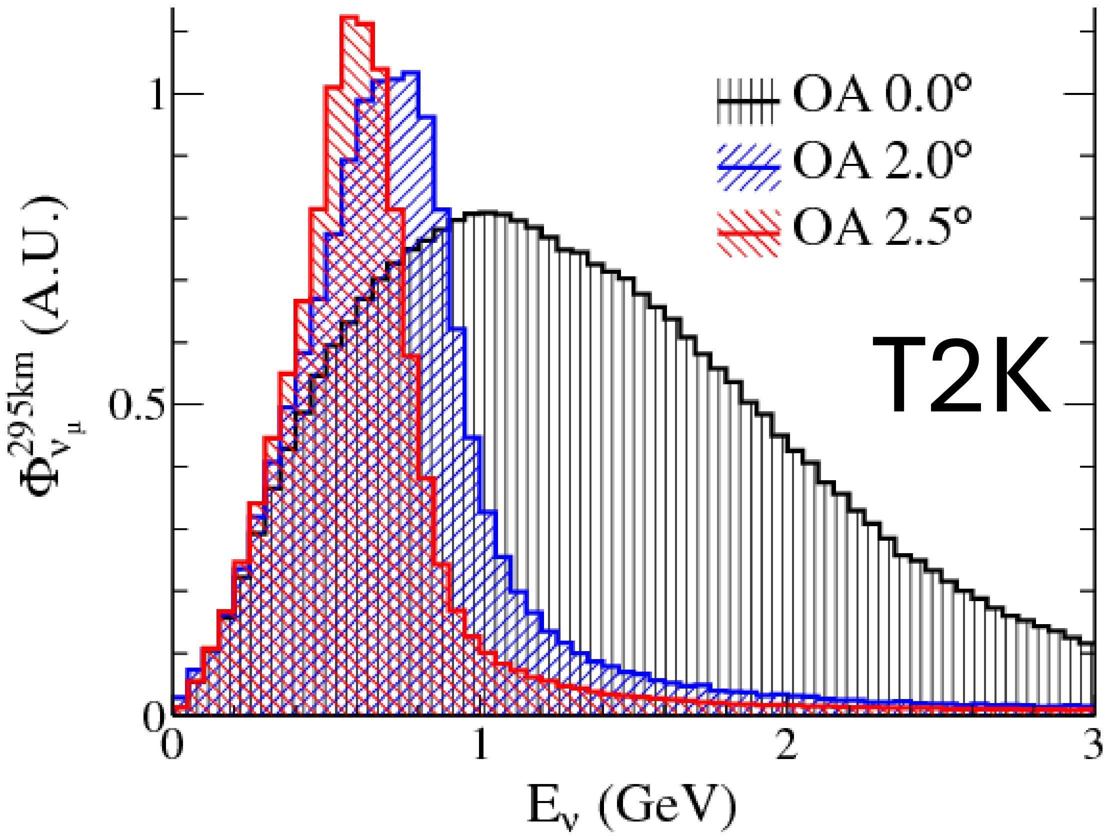


- At off axis angles, all pion energies tend to create a similar neutrino energy
- This creates a lower energy, more strongly peaked beam

Pion Decay At Experiments

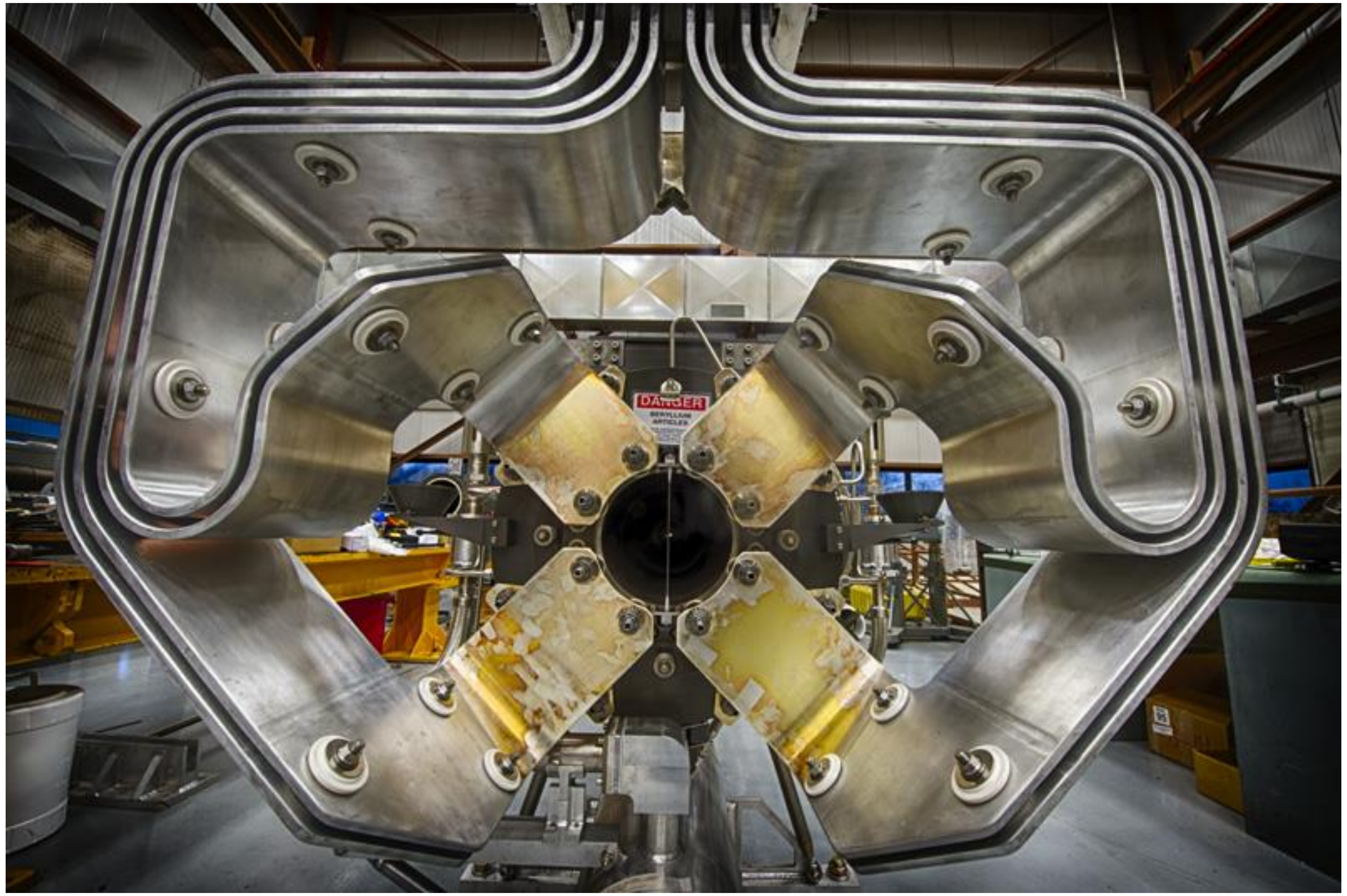






Horn Practicalities

Like, these are a bit more elaborate than your cellphone charging cable, no?



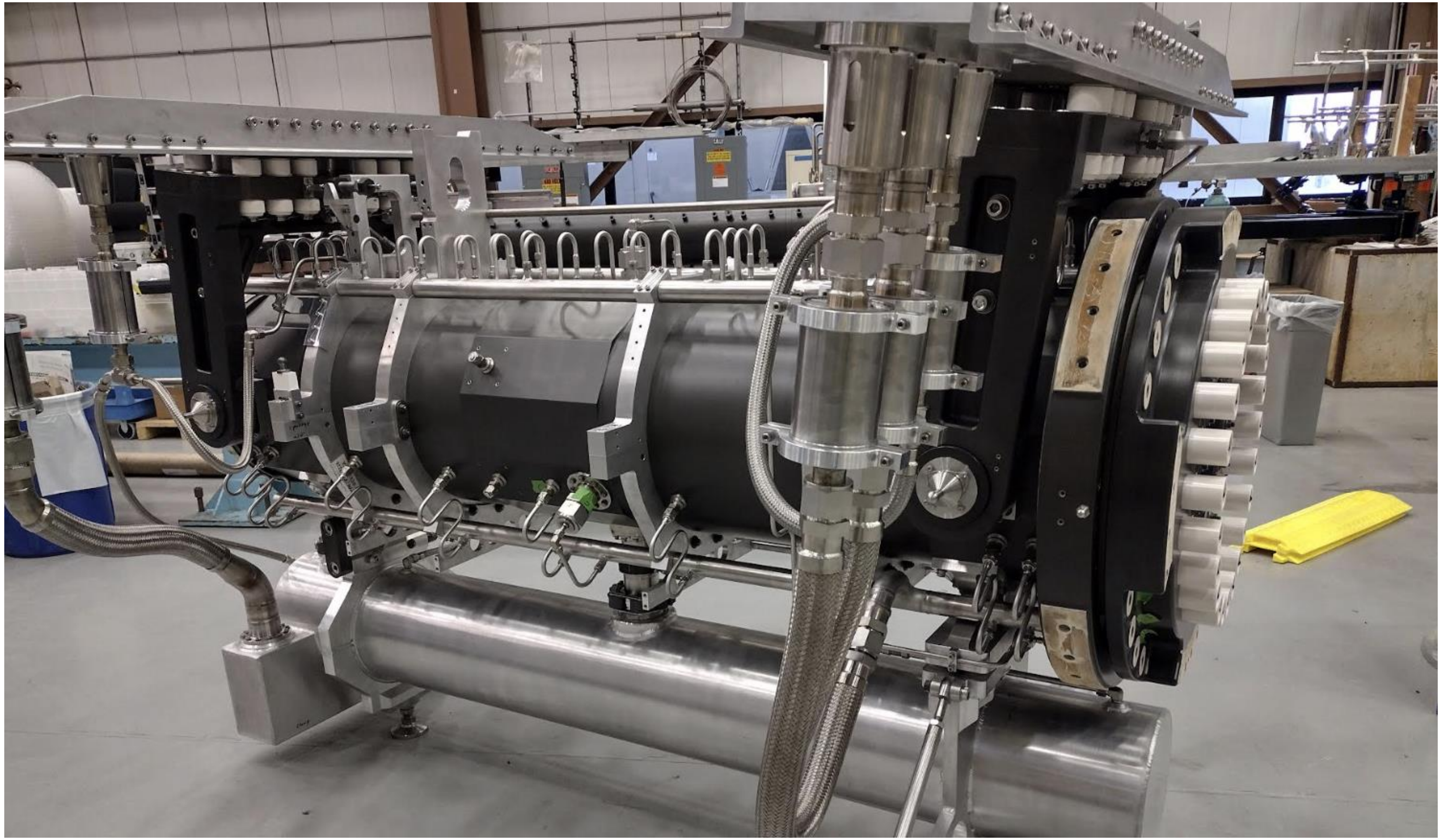
End view of NuMI Horn,
showing
strip lines that bring in
185 kA of current

Horn + Target Practicalities

- Some of the things that have to be **considered if you are a beam design engineer**:
  - Material eats pions, so the physicists will want the horn to have **as little material possible**
  - But beams have to **withstand crazy conditions**
    - **Heat load** comes from both resistive heating when the horn is pulsed and interactions of beam particles in the conductors
    - **Mechanical stresses** that come with hundred amp pulses; these increase with shorter pulses
  - You’re going to need **a lot of cooling**
    - **Inner conductors** sprayed with water during operation
    - **Strip lines** (power cords from previous slide) air or water cooled
  - Everything needs to **survive millions of pulses** per year
    - And you’re going to need to prove that to a lot of people using **detailed simulations**
  - The horn is going to be **extremely radioactive** when it fails, so you need a plan to repair it remotely and eventually remove it and store it safely for a long time

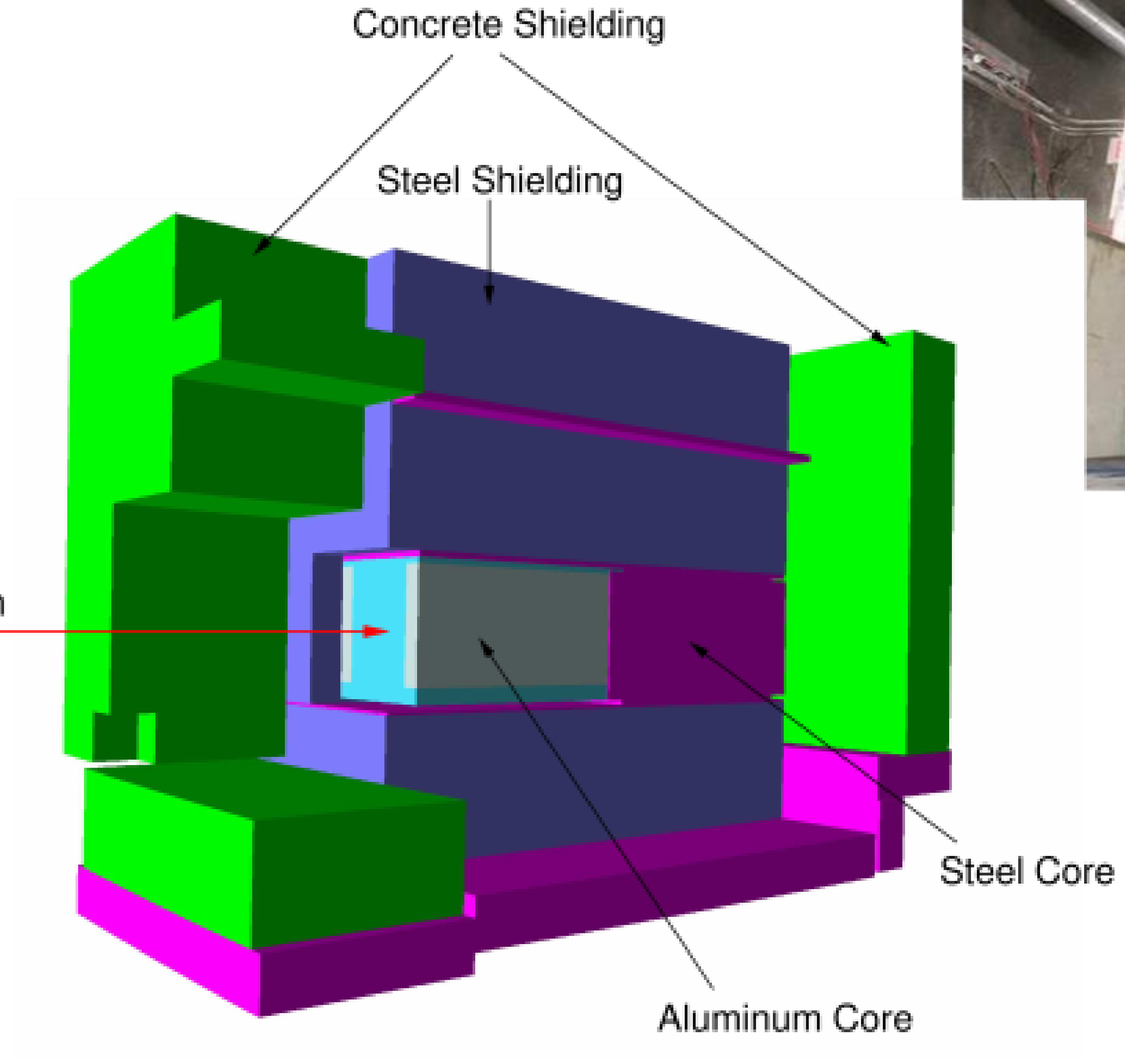
Horn Practicalities

LBNF Prototype Horn



Decay Pipe and Absorber

NuMI example (decay pipe length = 675 m)

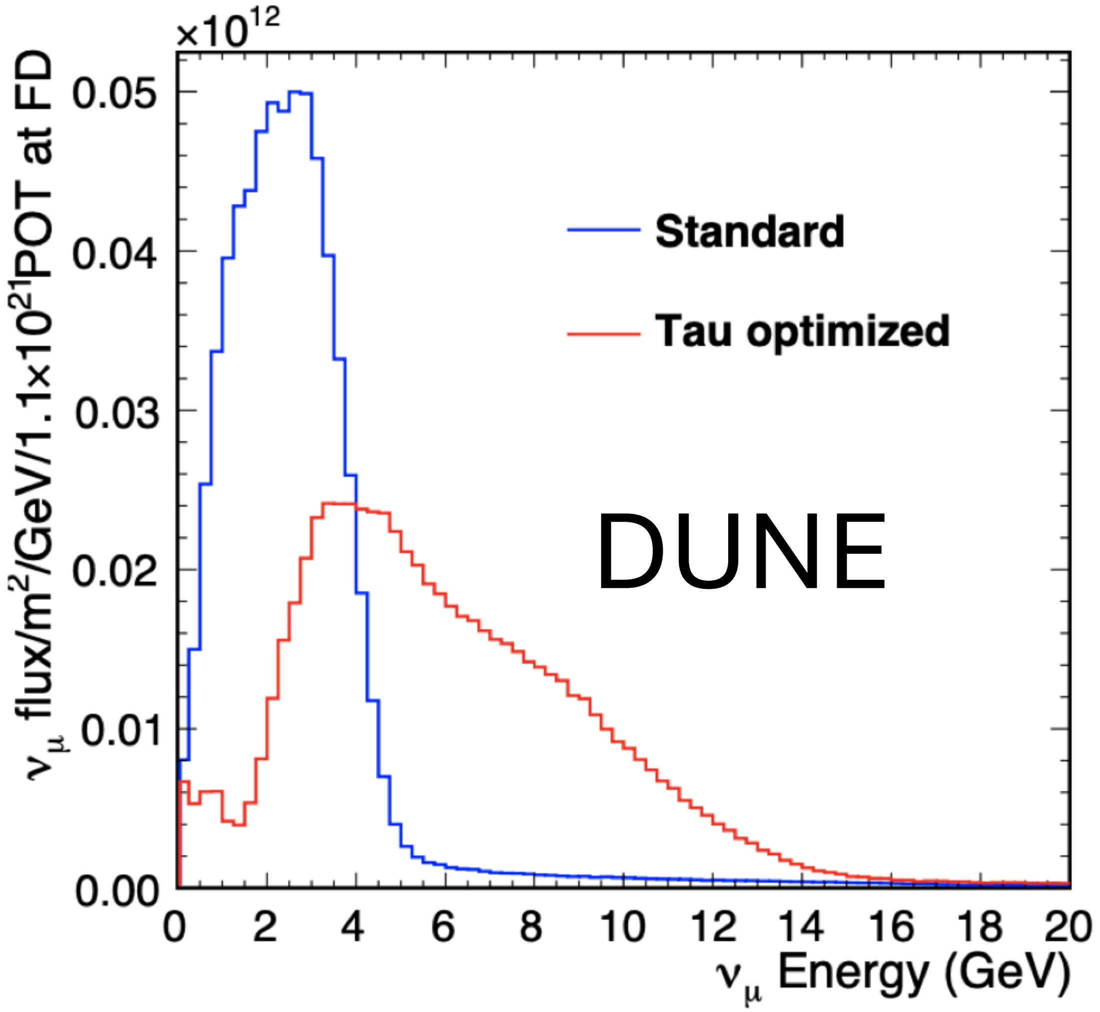


1507.06690

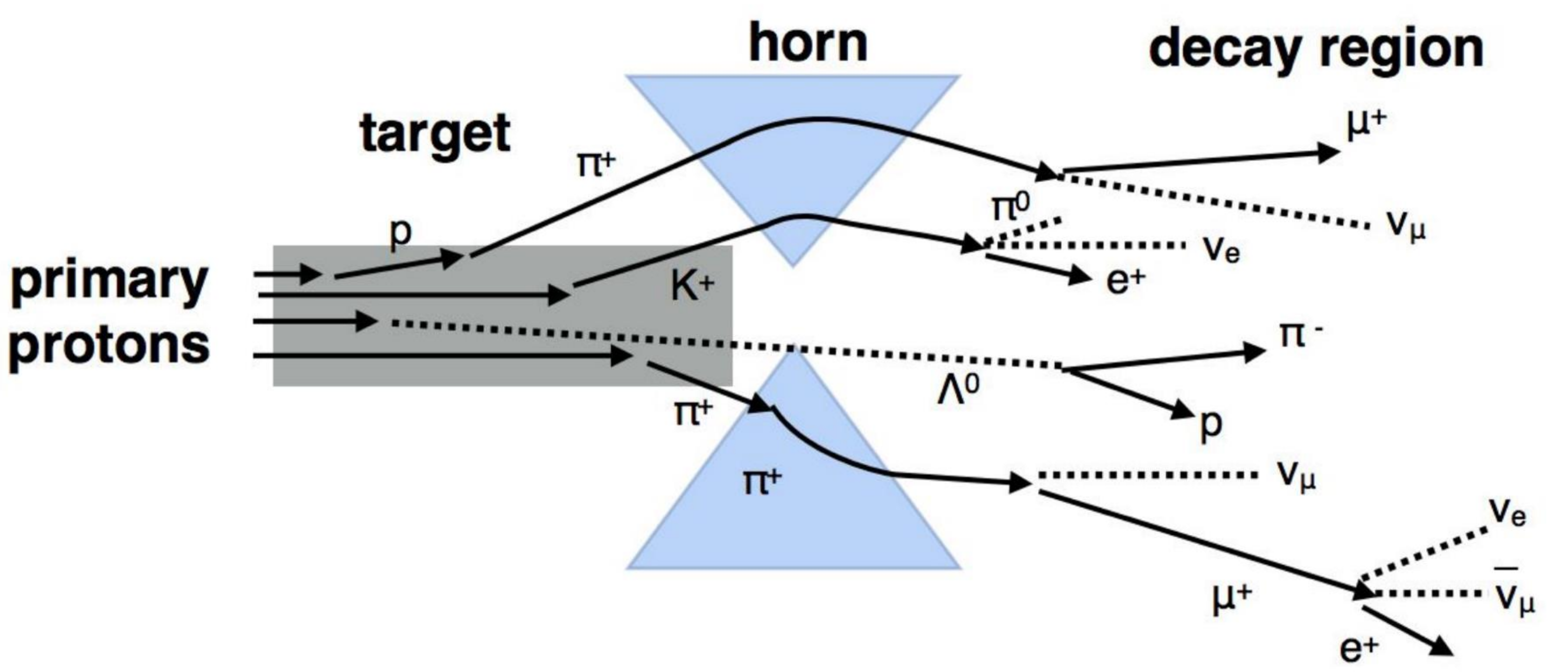
Modifiying the Beam Characteristics

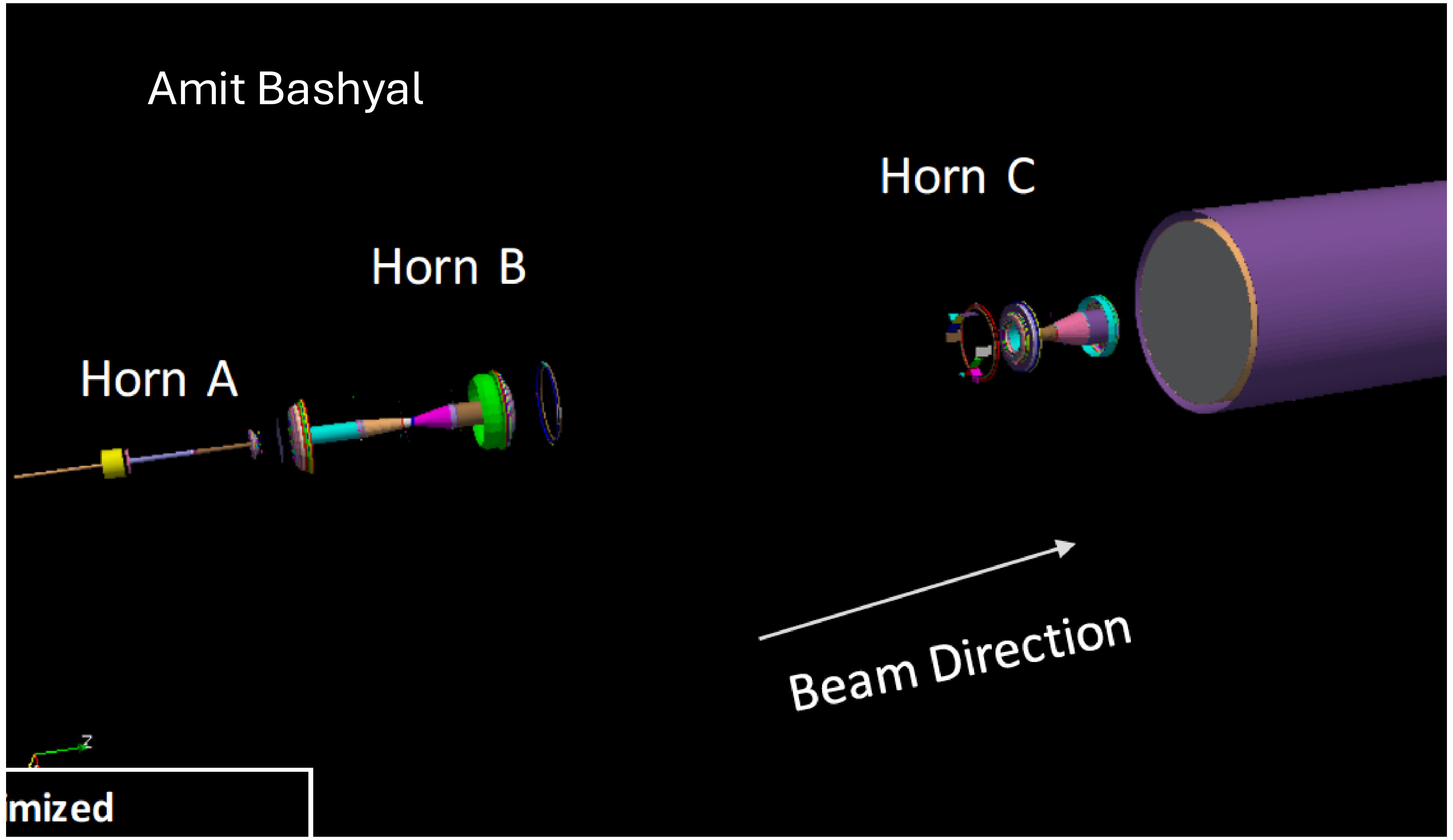
Of course, you can flip direction of current in the horns to create an antineutrino beam.

But, also: The target can be retracted upstream in order to produce a higher energy neutrino beam.
Other possible knobs: horn position, horn current, proton energy.
Decay pipe modifications have also been envisioned (BNB).



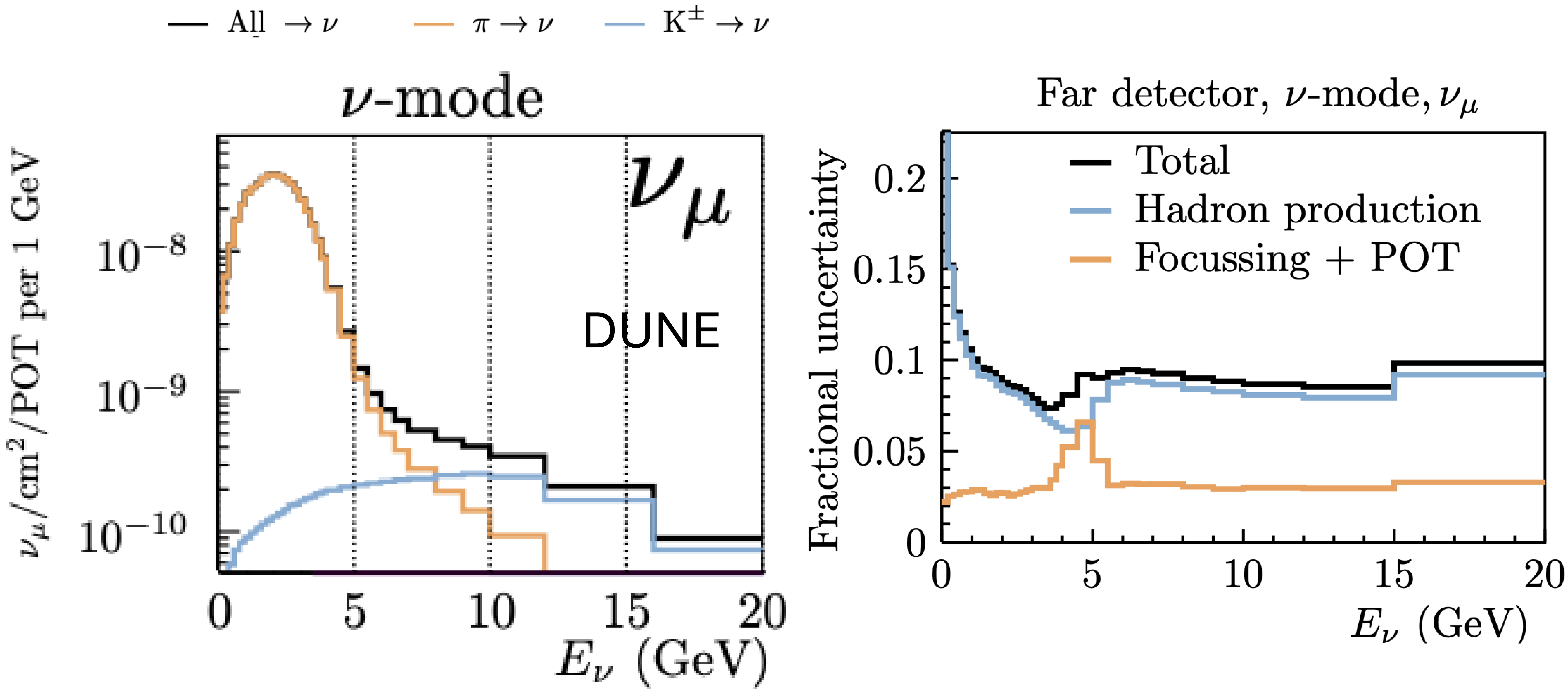
DIF Beam Uncertainties





- Typically use **Geant4 or FLUKA to simulate** primary interactions of 120 GeV protons on the targets, reinteractions in the target and other beam materials, and decay to neutrinos

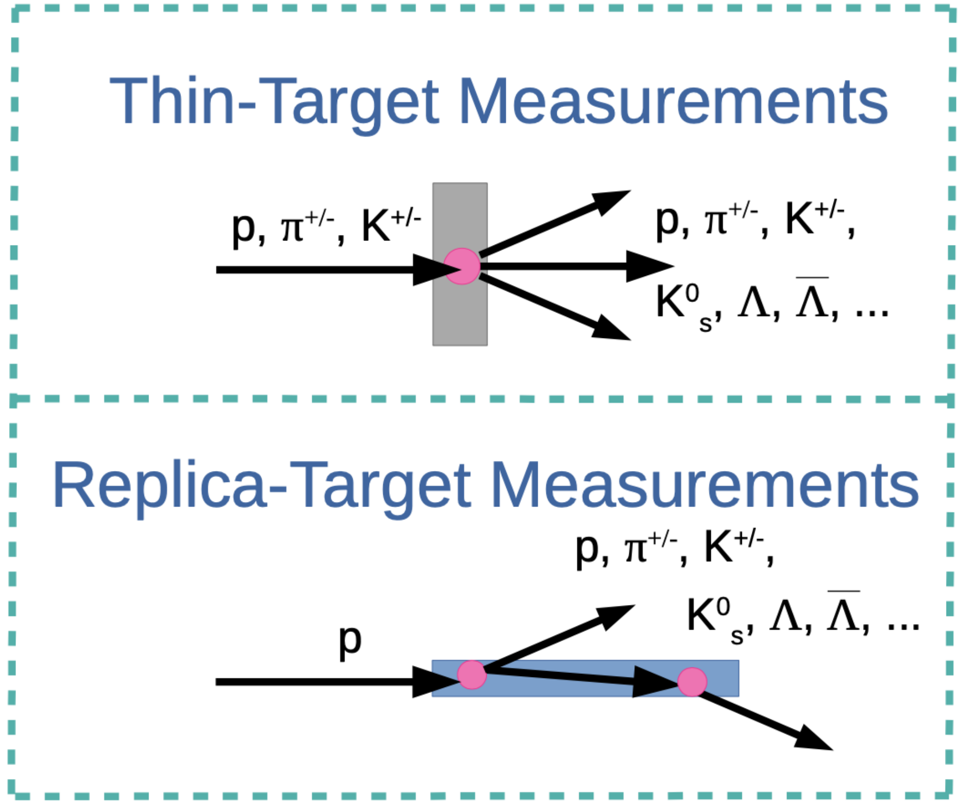
DIF Beam Uncertainties

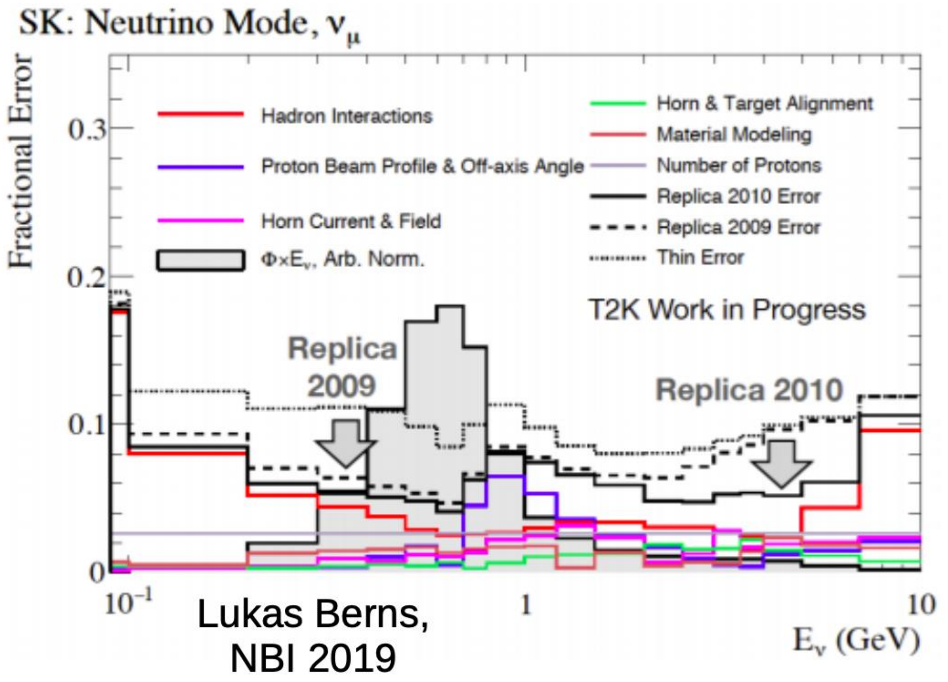


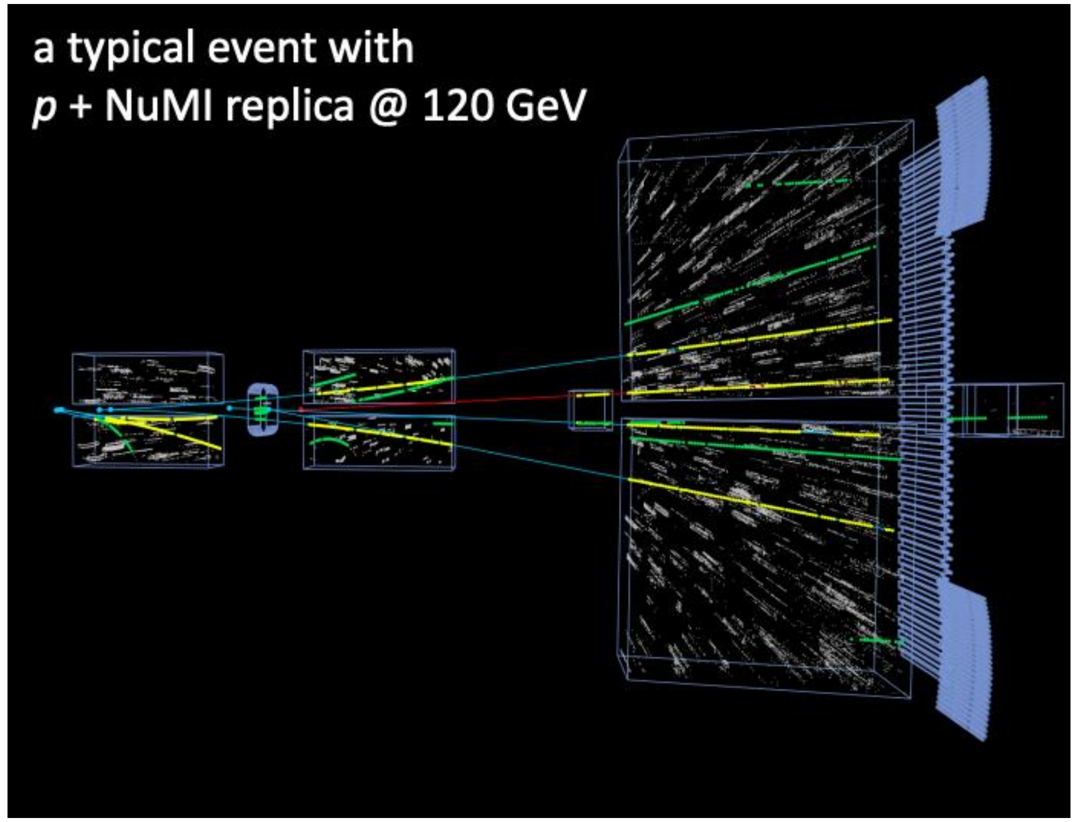
DIF Beam Uncertainties

- Detailed beam-based alignment procedures and monitoring during run are necessary to assure that alignment parameters stay within tolerances assumed for flux uncertainties

DIF Beam Uncertainties





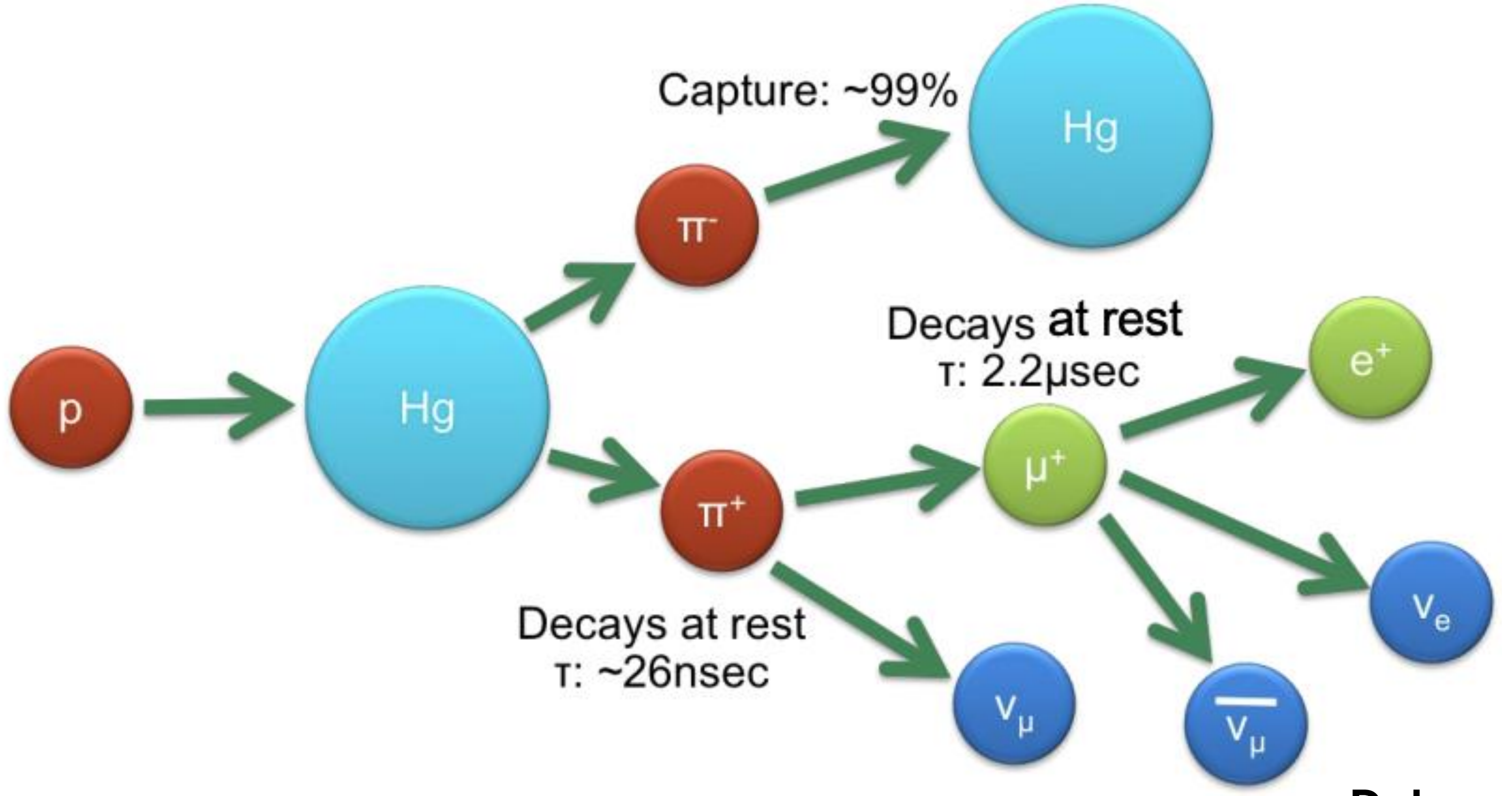


- A broad program of hadron production measurements is underway by NA61/SHINE at CERN and EMPHATIC at Fermilab
- Replica target measurements by NA61 roughly halved T2K flux uncertainties due to hadron production

Decay At Rest Accelerator Neutrinos

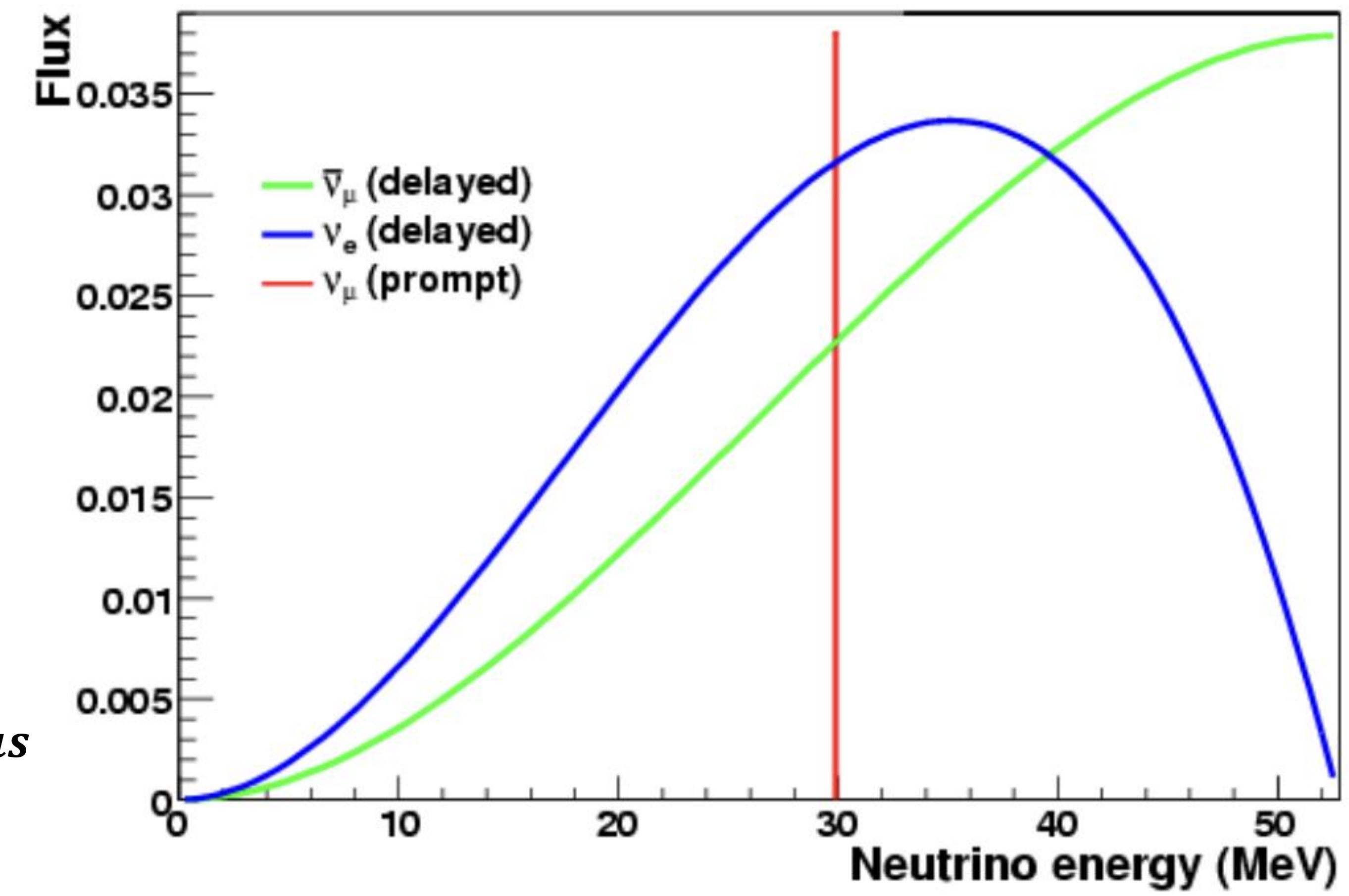
Pion and muon decay-at-rest neutrinos

Kate Scholberg



"Prompt"

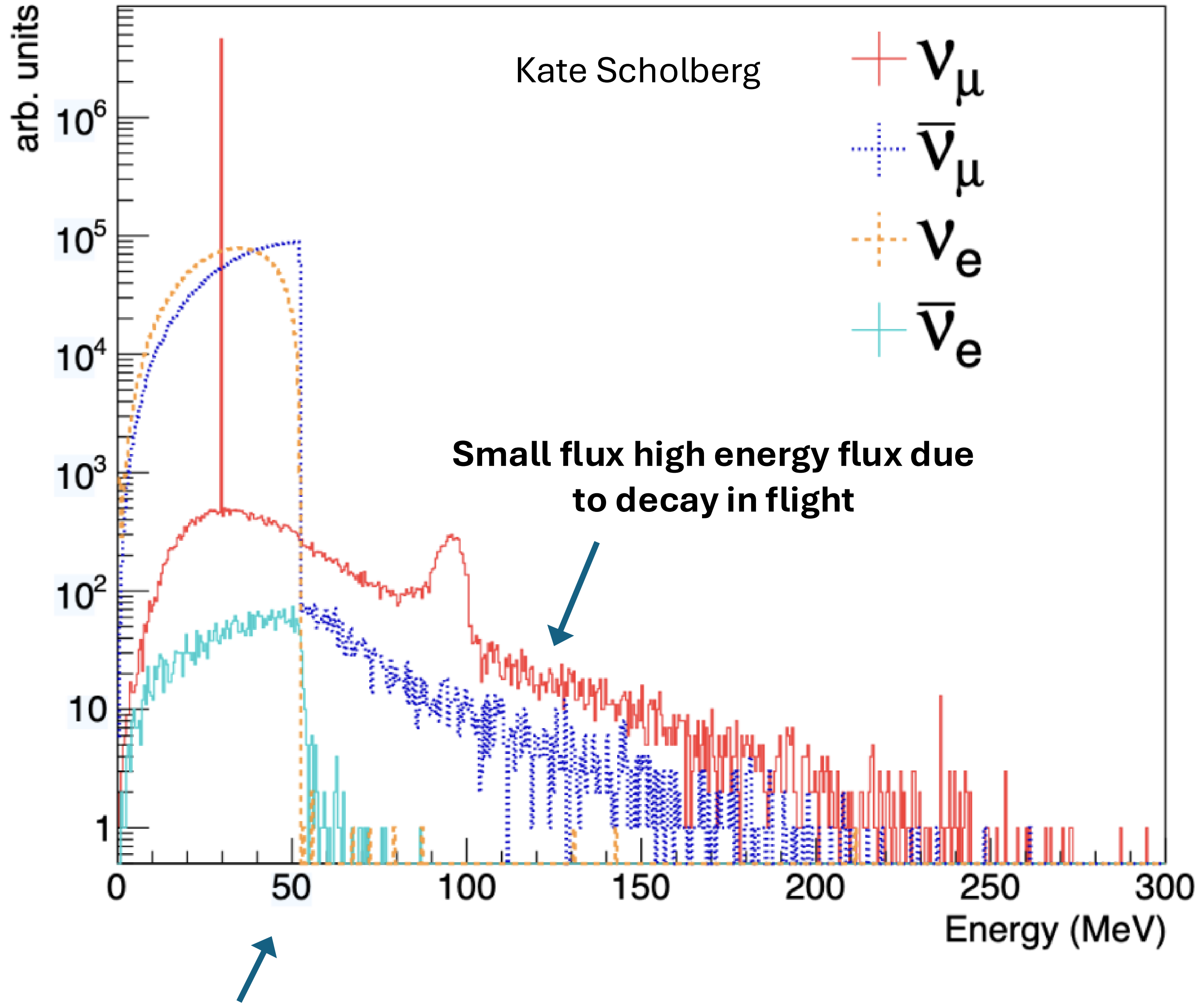
Delayed by 2.2 μs muon lifetime

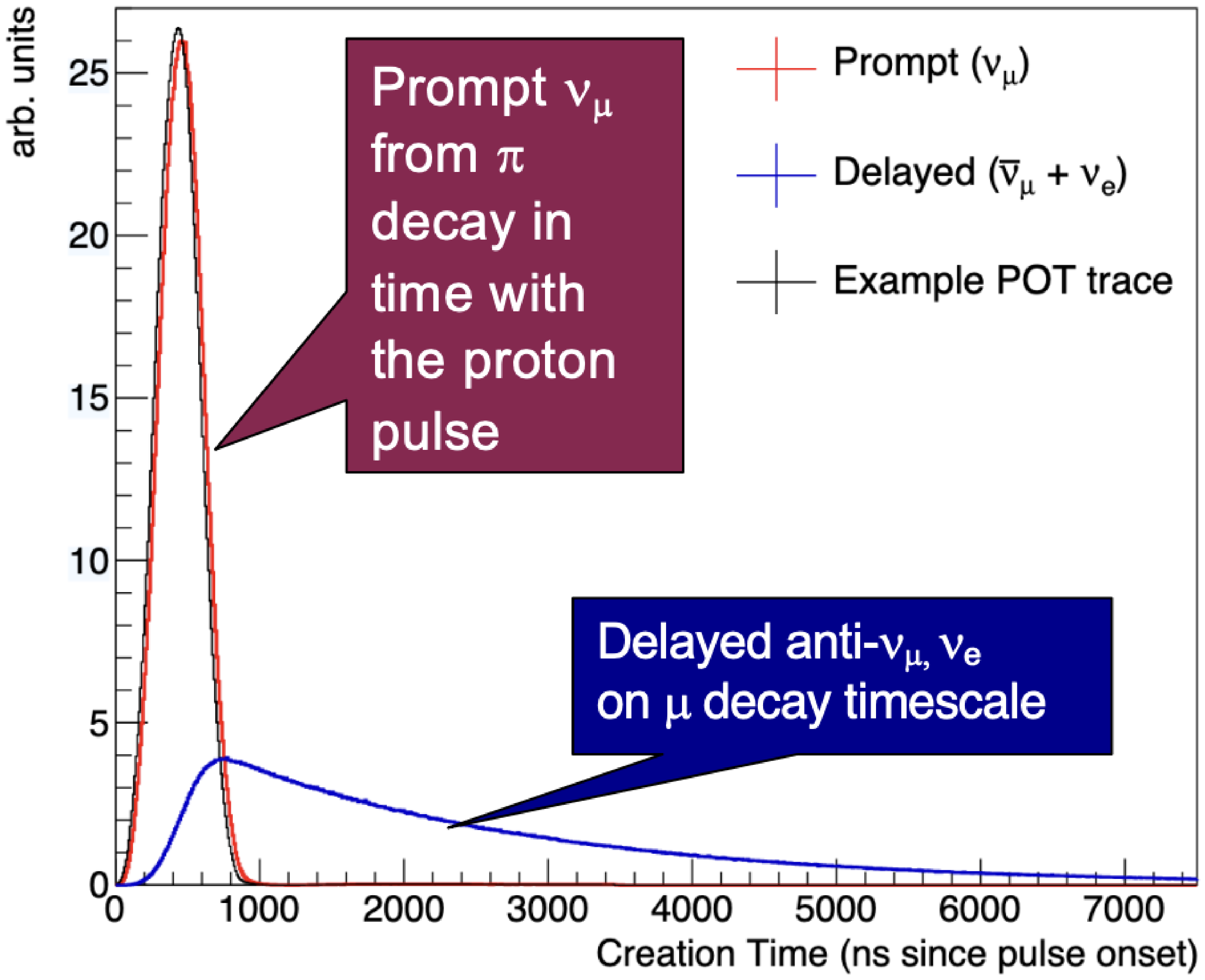


– Three neutrino flavors with well understood time, flavor, and energy content
– Often available for free at neutron spallation sources

Pion and muon decay-at-rest neutrinos

– More detailed flux simulation for the SNS at Oak Ridge

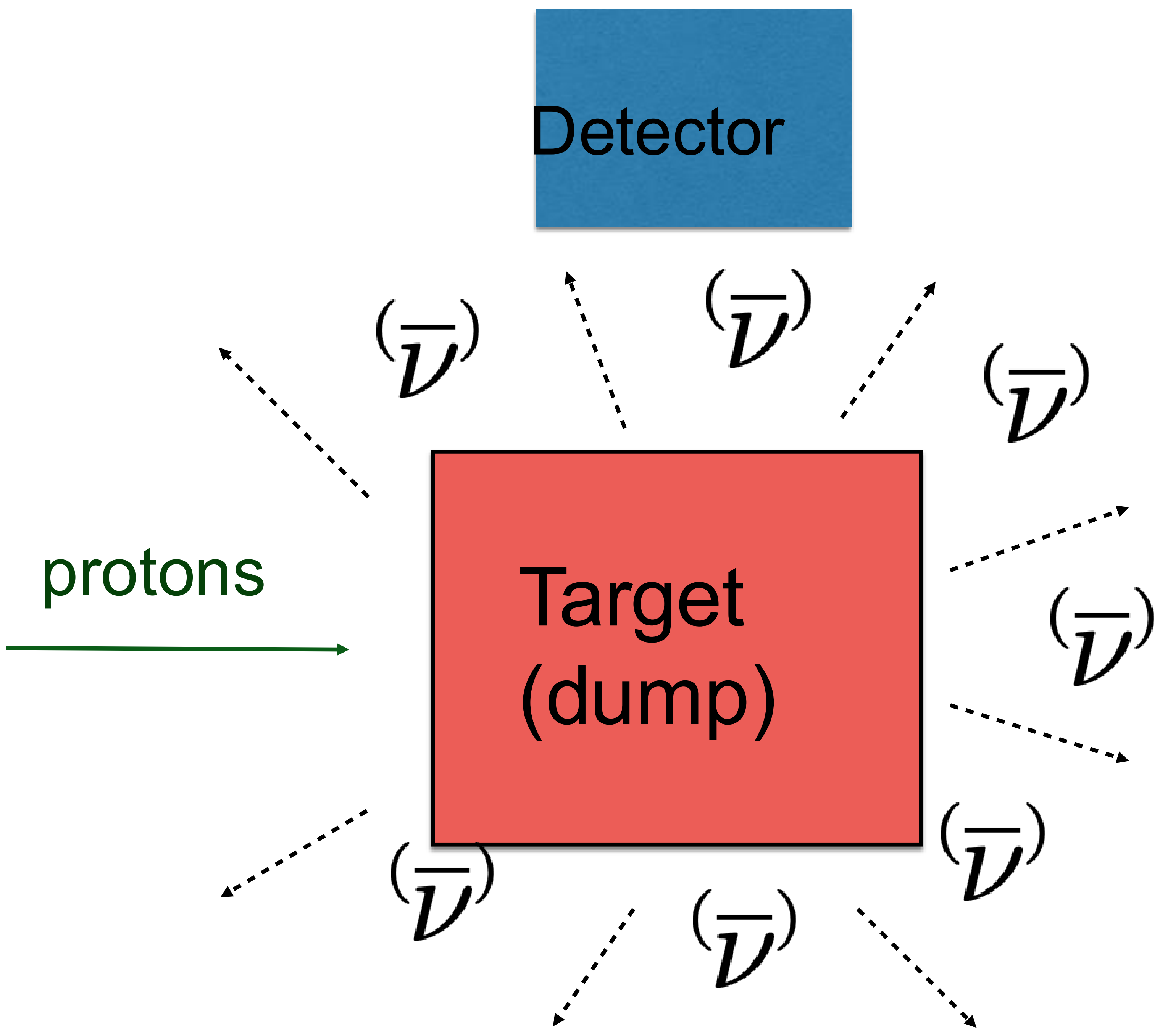




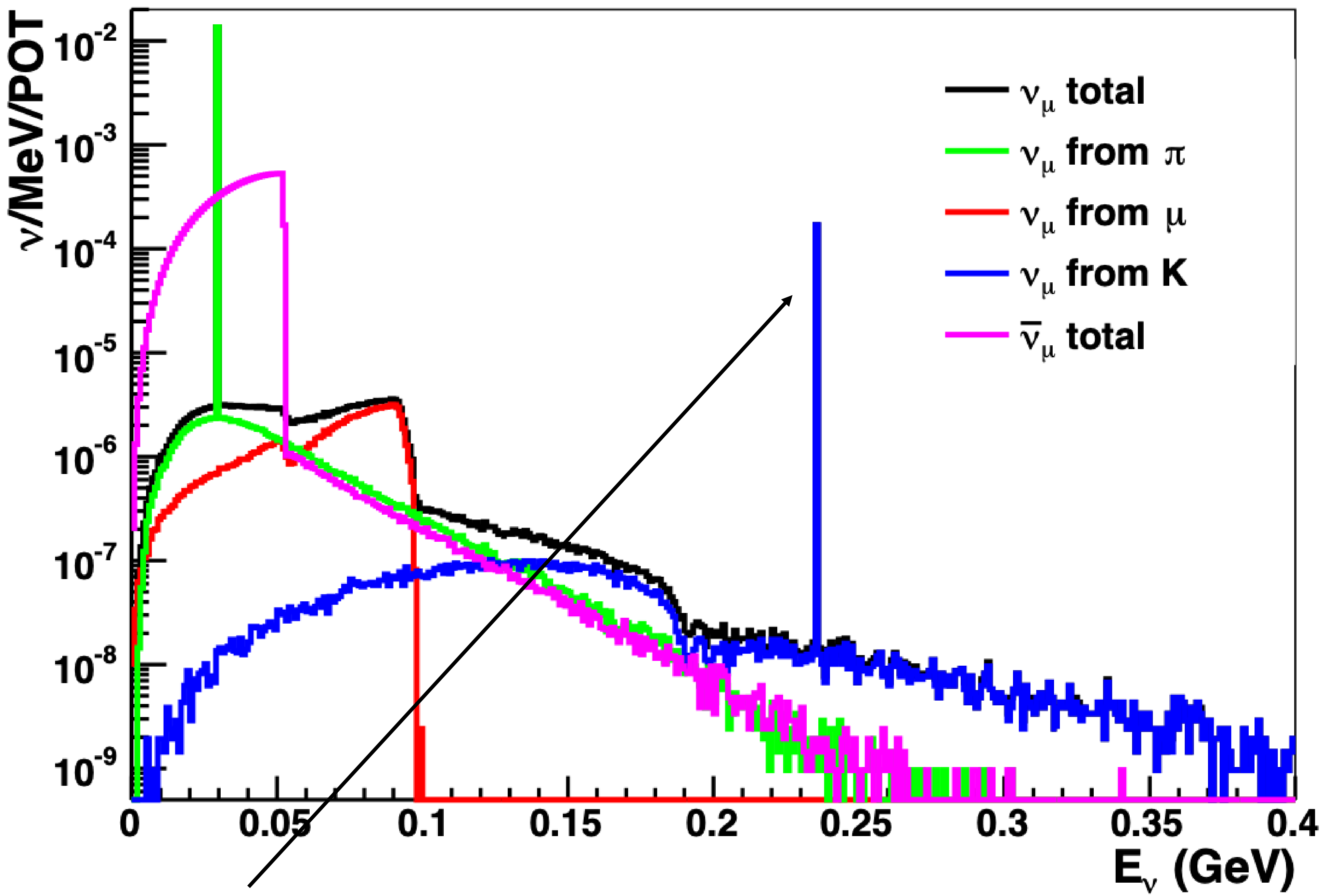
Small flux from π^- that aren't absorbed by a nucleus

Kaon decay-at-rest neutrinos

(Above 2-3 GeV primary proton energy)



example: ν_μ flux at J-PARC spallation neutron facility

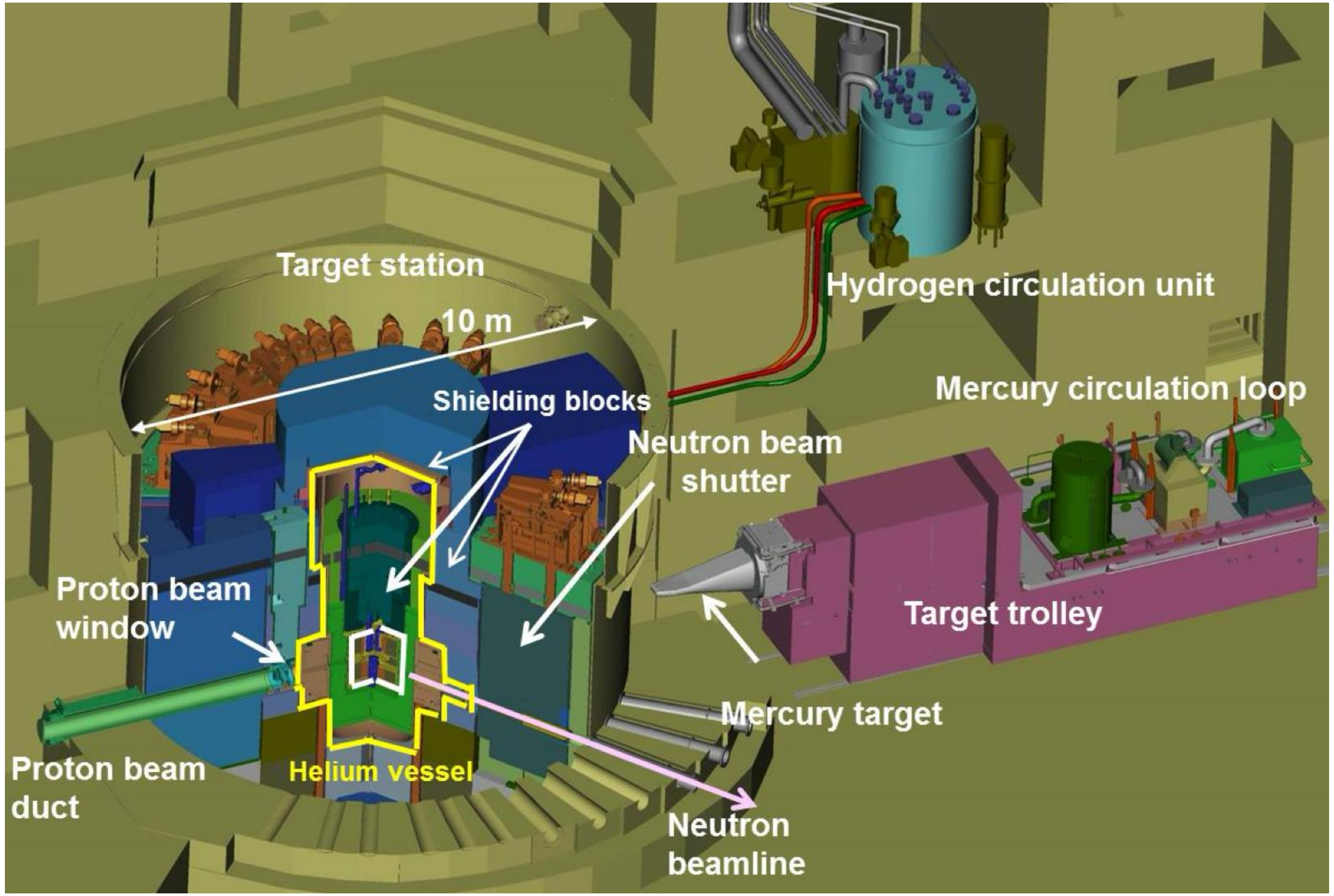


E=236 MeV if kaon decays at rest

$$K^+ \rightarrow \mu^+ \nu_\mu$$

(branching ratio=64%)

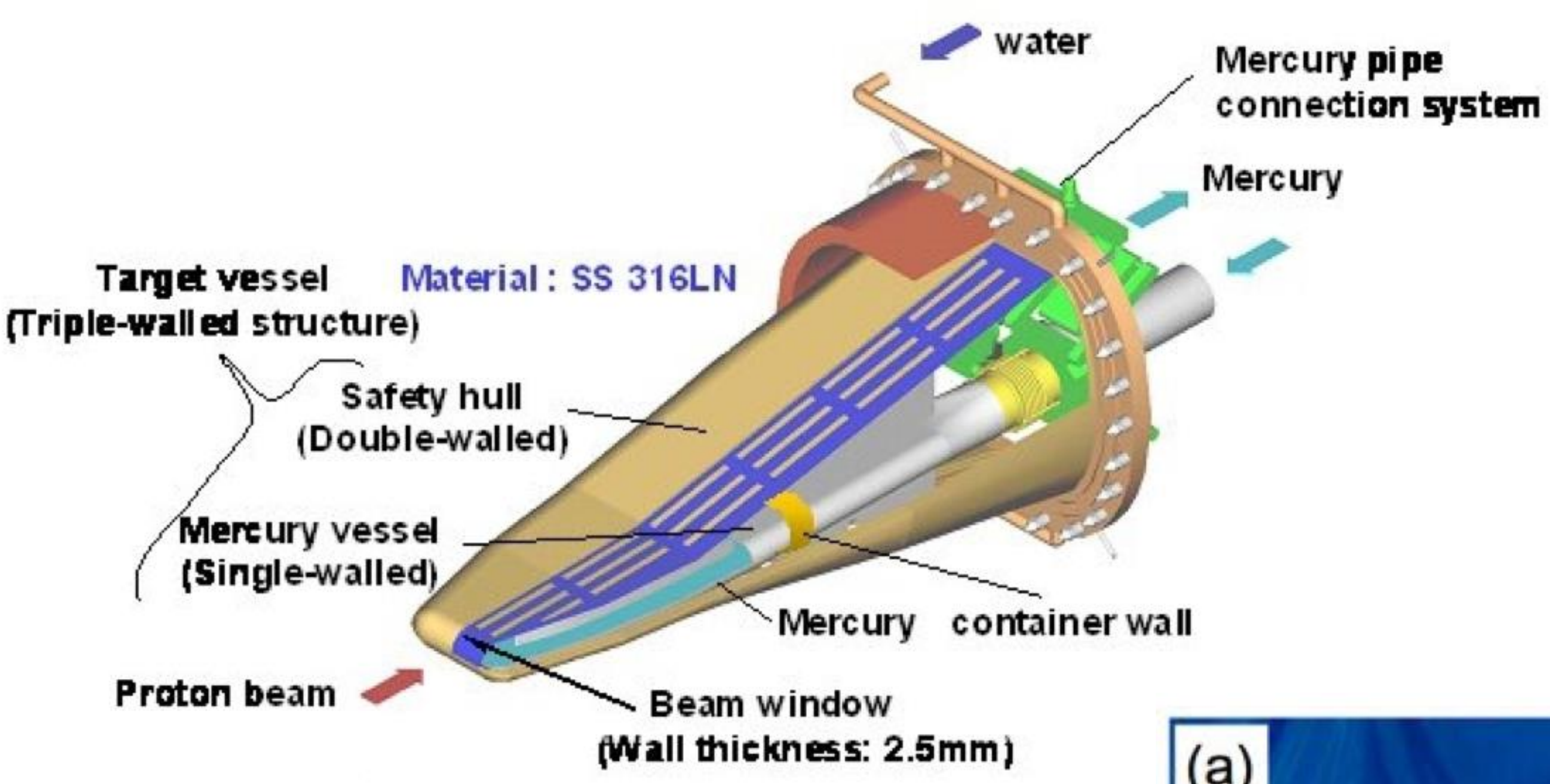
Example: J-PARC Spallation Neutron Source



3 GeV protons on a mercury target @ 830 kW

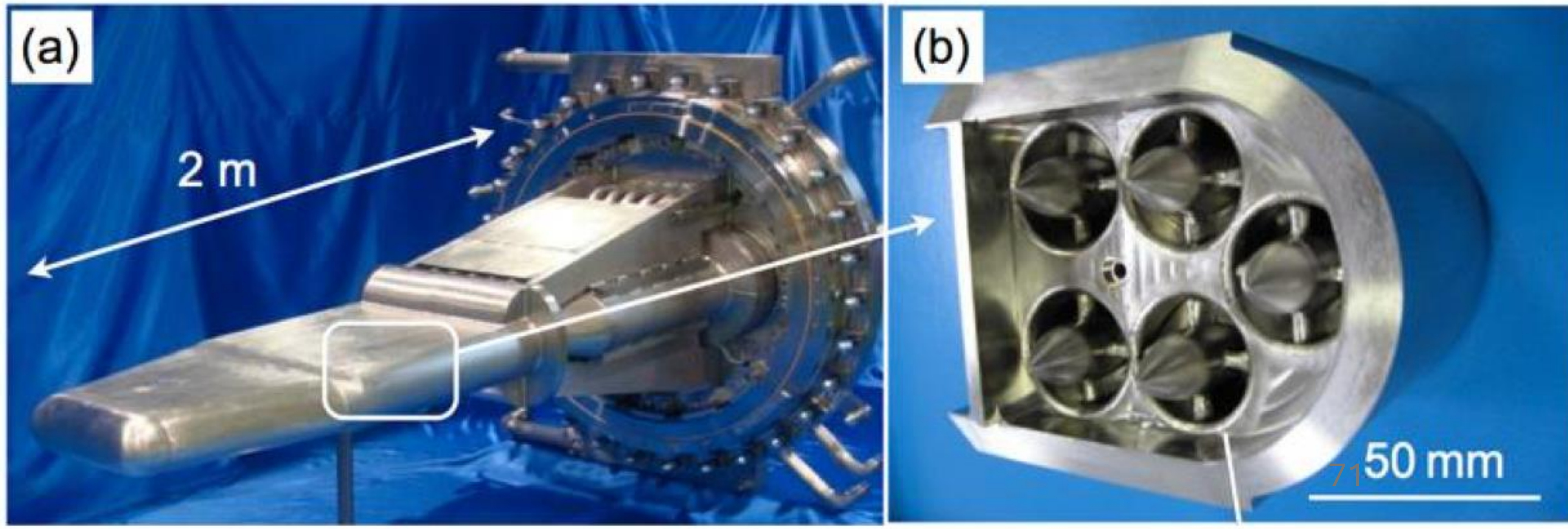
Example: J-PARC production target

Mercury is circulated at 154 kg/s!

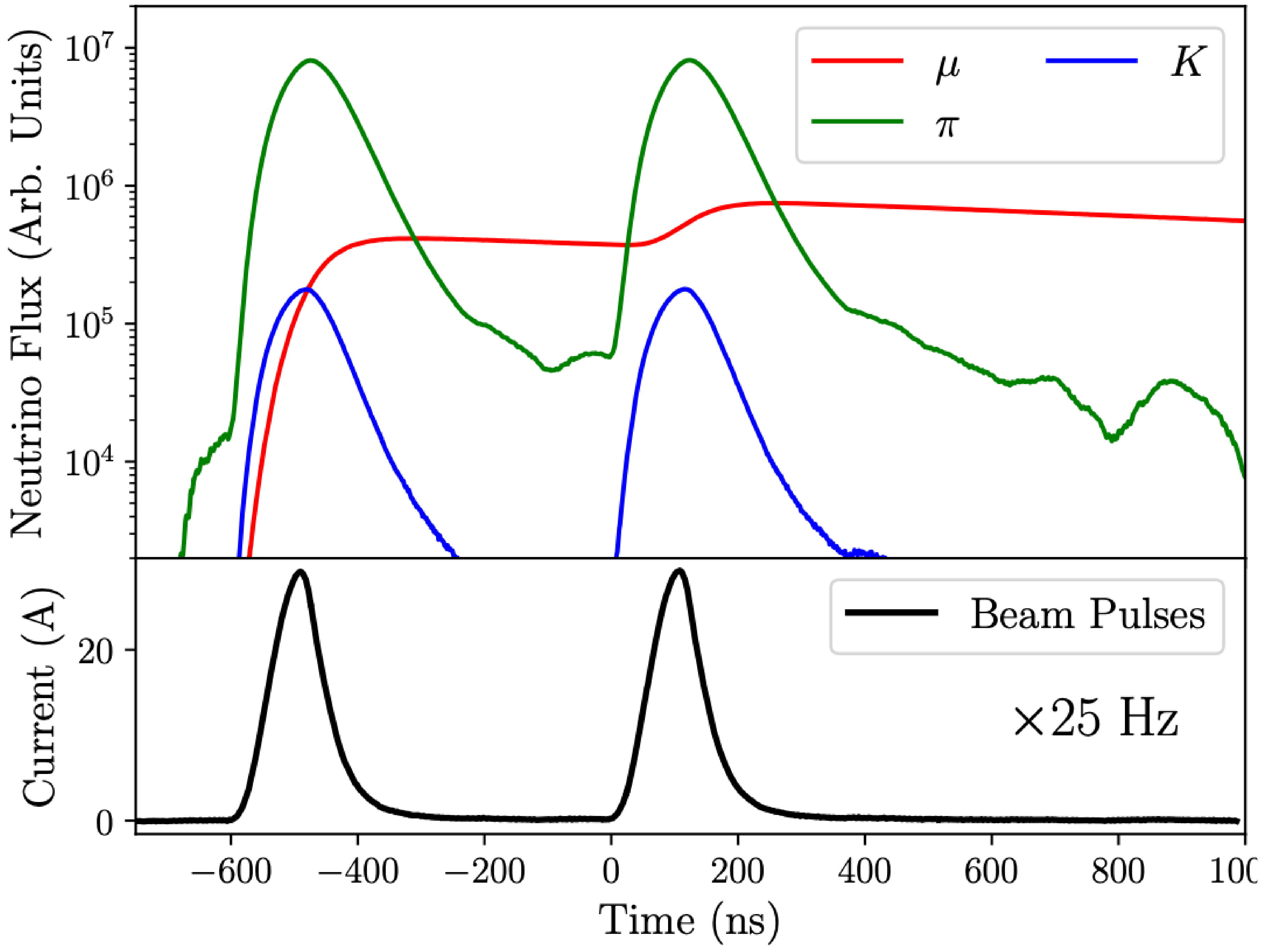


Neutron/neutrino production target is a double-walled SS vessel with circulating mercury.

Heavy target material and shielding ensure an almost entirely DAR source.



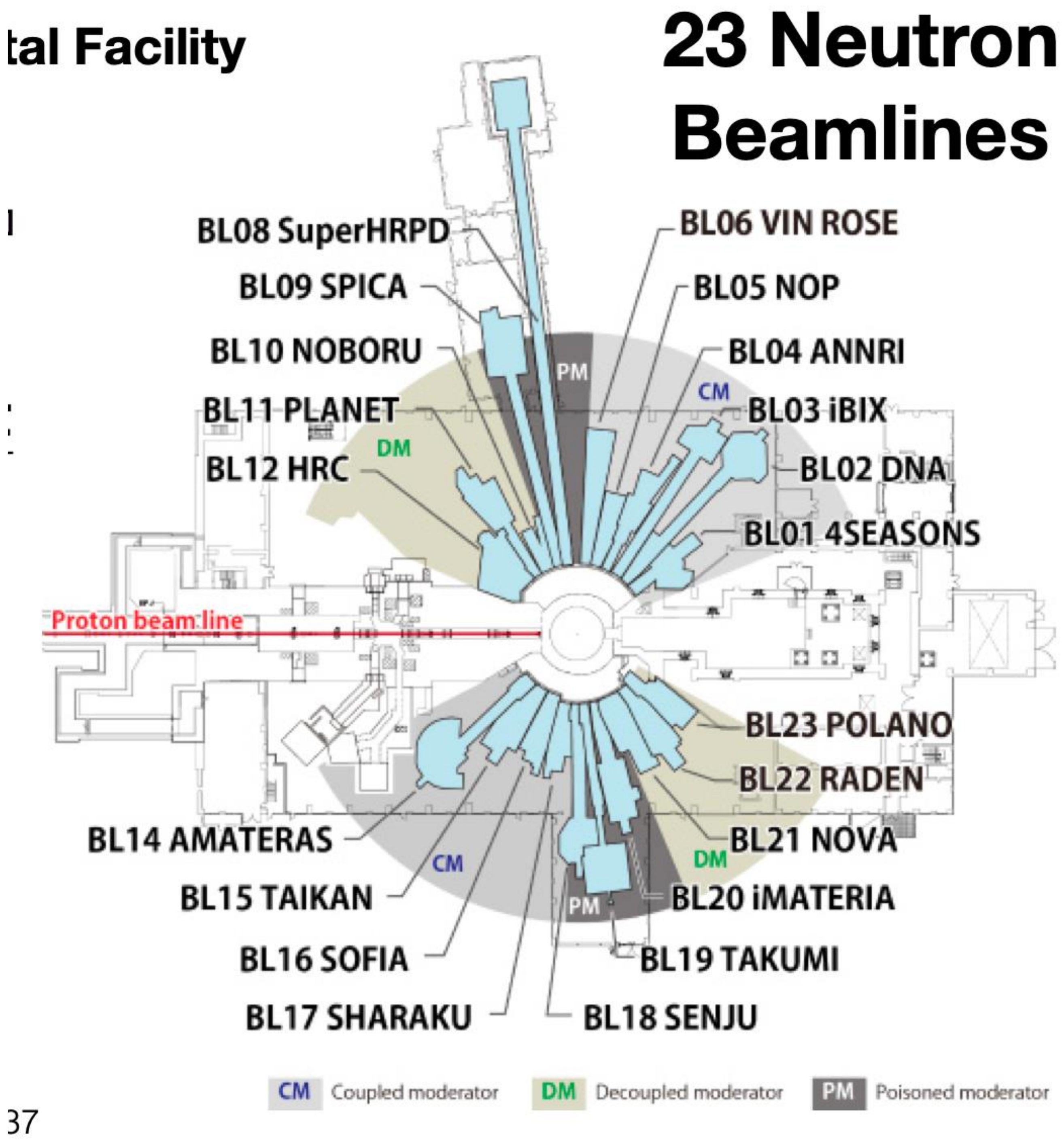
J-PARC spallation source beam timing



The J-PARC beam is delivered in two close pulses at 25 Hz, producing “prompt” (pion and kaon) and “delayed” (muon) neutrinos.

The beam is only on for ~5E-6 of the time!
That is good for mitigating steady-state background.

Issues with Spallation Neutron Source Facilities



Most intense sources of accelerator-based neutrinos
But not really made to host neutrino experiments

J-PARC Spallation Neutron Source is inside the “Materials and Life Science” (MLF) Building.

JSNS^2 (at the J-PARC MLF) needs to remove their full detector and 50 tons of liquid scintillator (separately) every year so that the target maintenance area can be accessed.

COHERENT (SNS) is inside “Neutrino alley”, a service corridor.

COHERENT

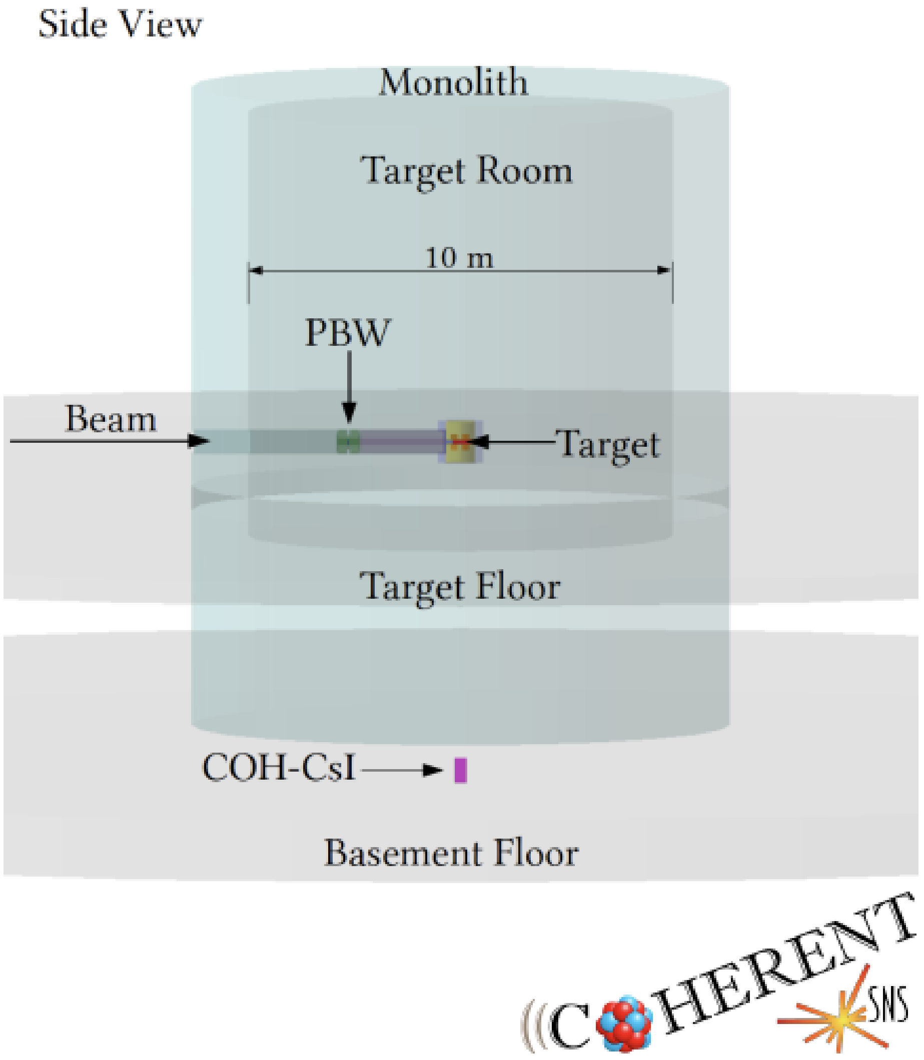

NEUTRINO ALLEY


Dinosaur heretic looks for redemption p. 1088
Increase inclusion to increase STEM diversity p. 1101
Fluorescent or magnetic cotton fibers p. 1118
Science
$15
15 SEPTEMBER 2017
sciencemag.org
AAAS
SPOTTING A
GHOST
A compact detector spies neutrinos scattering from nuclei
pp. 1098 & 1123

Decay at Rest Fluxes

- Flux uncertainties at DAR sources dominated by hadron production uncertainties
- Small contributions from other sources
  - Backgrounds from beta decay of activated target
  - Hadron production outside of target
- COHERENT estimates their flux uncertainty to be ~10%
- Data taking with a D20 Cherenkov detector is underway now -> will use $\nu_e + d \rightarrow p + p + e^-$ (known to 2-3%) as a standard candle to measure flux

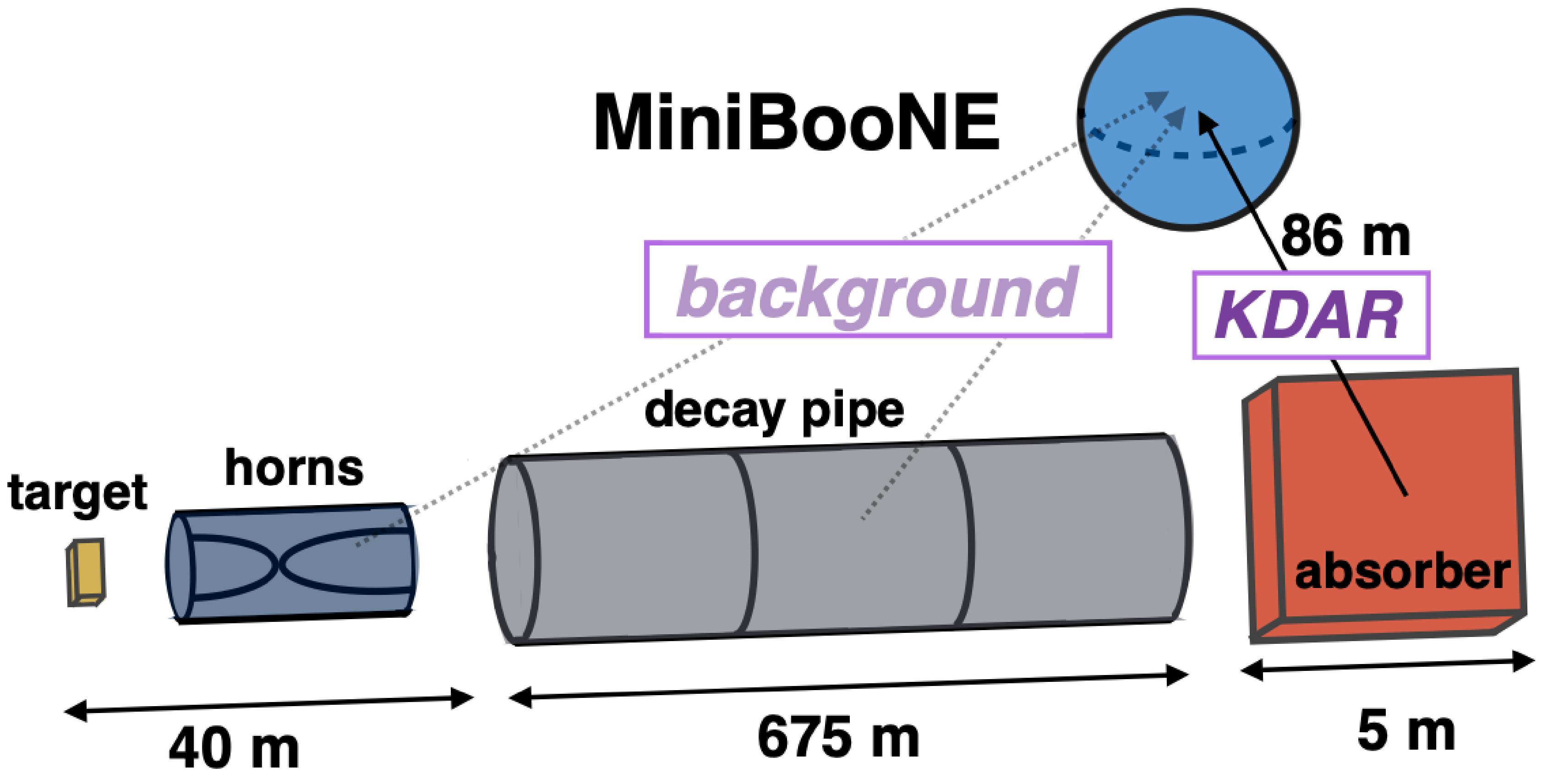
Details in *Phys. Rev. D* **106** 032003 (2022)

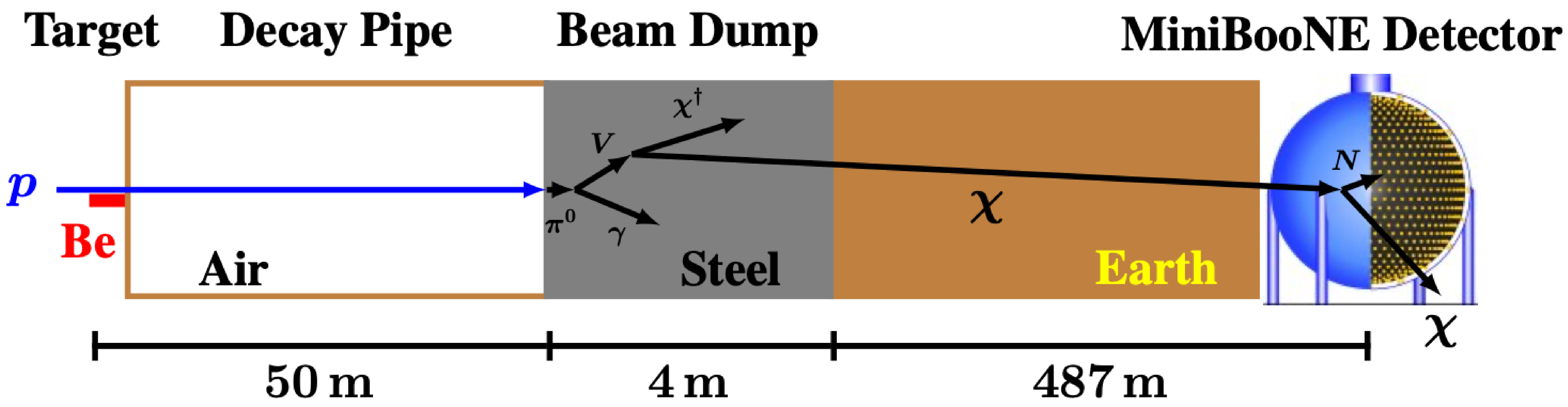


Modeled by Eric Day, CMU

Sneaky decay-ay-rest sources

The beam dump/absorber at an accelerator decay-in-flight source can provide a decay-at-rest source.





What to look forward to with DAR Sources

- Lots from COHERENT:
  - Precisions measurements of CEvNS -> BSM searches
  - CEvNS across many nuclear targets, with many detector technologies
  - Other cross section measurements for Supernova neutrino modeling
- Sterile neutrino search at JSNS2
- Further future:
  - Beam-off-target (DAR) running at DIF beams
  - A dedicated DAR source (e.g. at Fermilab) (w/ no facilities issues, optimized target).

Radioactive Isotope Sources

Electron capture source (e.g. BEST)

- Electron neutrino source, historically used to calibrate solar neutrino detectors.
- Produced by irradiating ^{50}Cr with a reactor (neutron capture).
- Measure radioactive Germanium produced in neutrino interaction with Gallium target:
- Other sources are also possible (^{65}Zn, ^{37}Ar, ^{144}Ce, ...)

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

$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e$$

	^{51}Cr			
E_ν [keV]	747	752	427	432
B.R.	0.8163	0.0849	0.0895	0.0093
$\sigma[10^{-46}\ \mathrm{cm}^2]$	60.8	61.5	26.7	27.1

PHYSICAL REVIEW D **78**, 073009 (2008)

$$\tau_{1/2} = 27.7 \text{ days}$$

2207.10928

96.5% enriched ^{50}Cr disks (^{50}Cr is 4.3% natural abundance)

A nice idea! Well known spectra and can bring source to underground detector!

Electron capture source

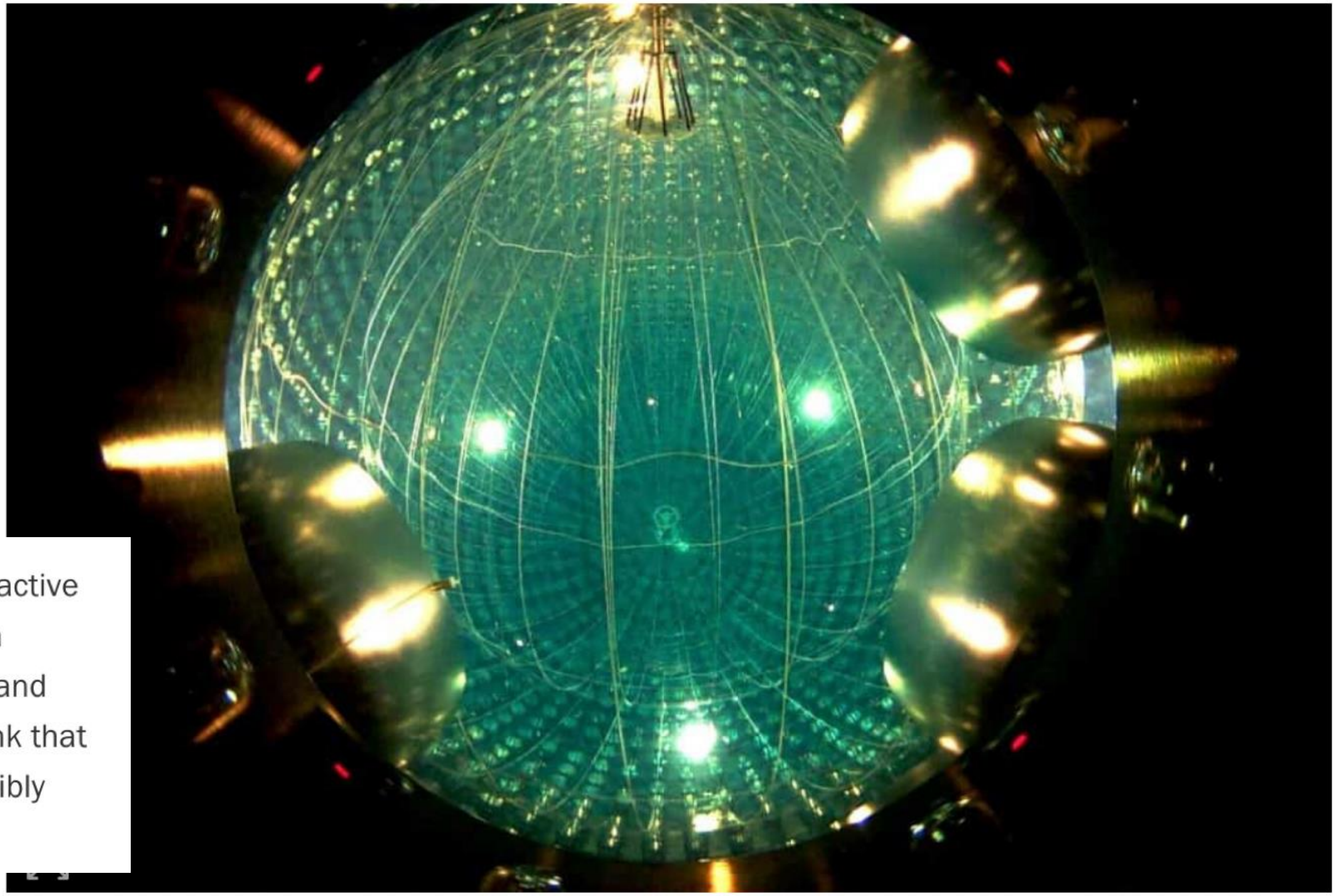
physicsworld

Magazine | Latest

NUCLEAR PHYSICS | NEWS

Experts point to Russia as source of radioactive ruthenium leak

29 Jul 2019



Nuclear sleuthing: Researchers claim that a leak of radioactive ruthenium in 2017 could have happened when a nuclear plant in Russia exploded whilst creating a neutrino source for the Borexino experiment at the Gran Sasso National Laboratory in central Italy. (Courtesy: Borexino collaboration/LNGS/INFN)

The botched production of a powerful neutrino source is the most likely cause of a radioactive cloud that enveloped much of Europe in the autumn of 2017. That is the conclusion of a group of radiation experts from across the continent who have used isotope monitoring and chemical analysis to try and understand where the leak came from. The researchers think that the isotope involved – ruthenium-106 – was probably released during an accident, possibly an explosion, involving spent fuel at the Mayak reprocessing plant in southern Russia.

But, note: sources with high enough intensity are hard to make, and very dangerous

Electron capture source

But despite the dangers, BEST was able to confirm measurements by SAGE and GALLEX that found rates ~20% lower than models with low uncertainty

This is the Gallium Anomaly, which remains unexplained.

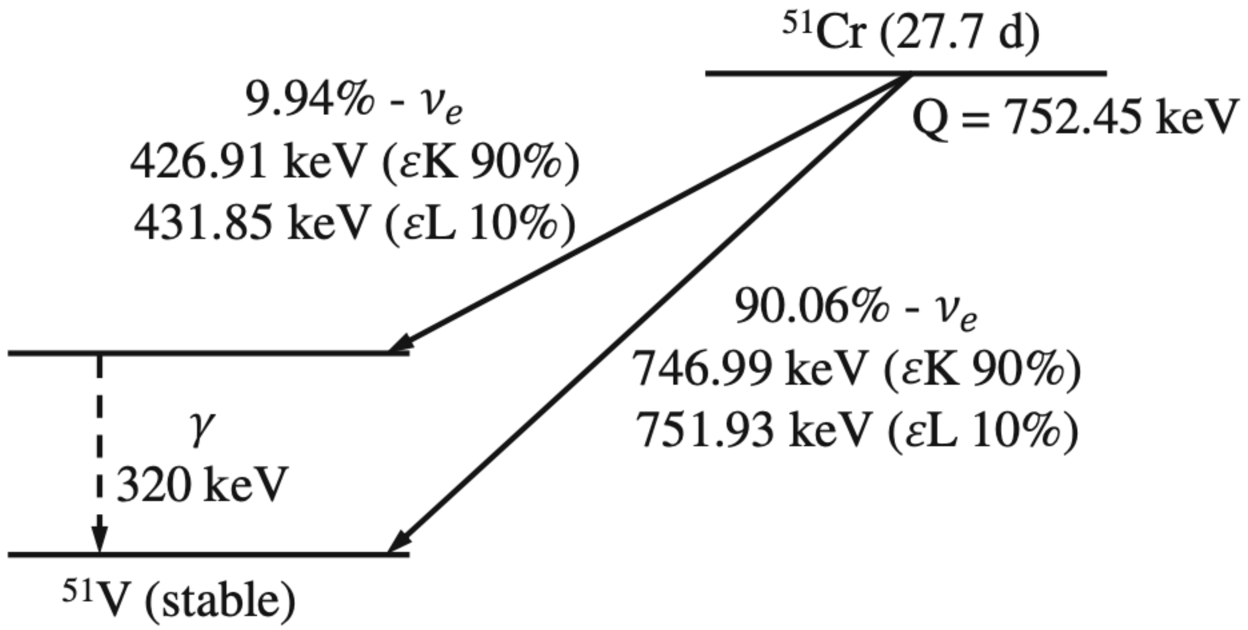
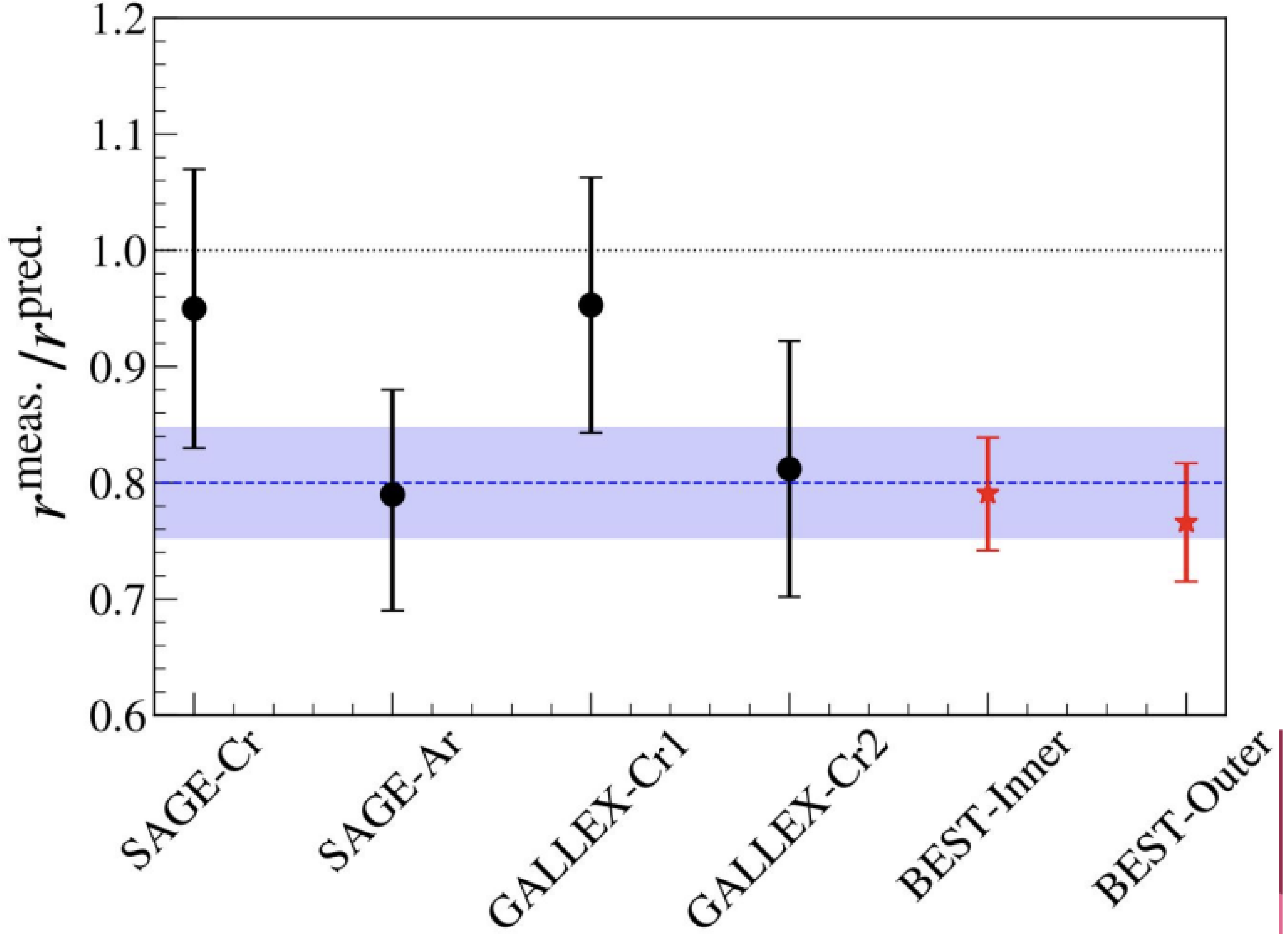


Fig. 1 ^{51}Cr decay scheme [25]

Phys. Rev. C **105**, 065502



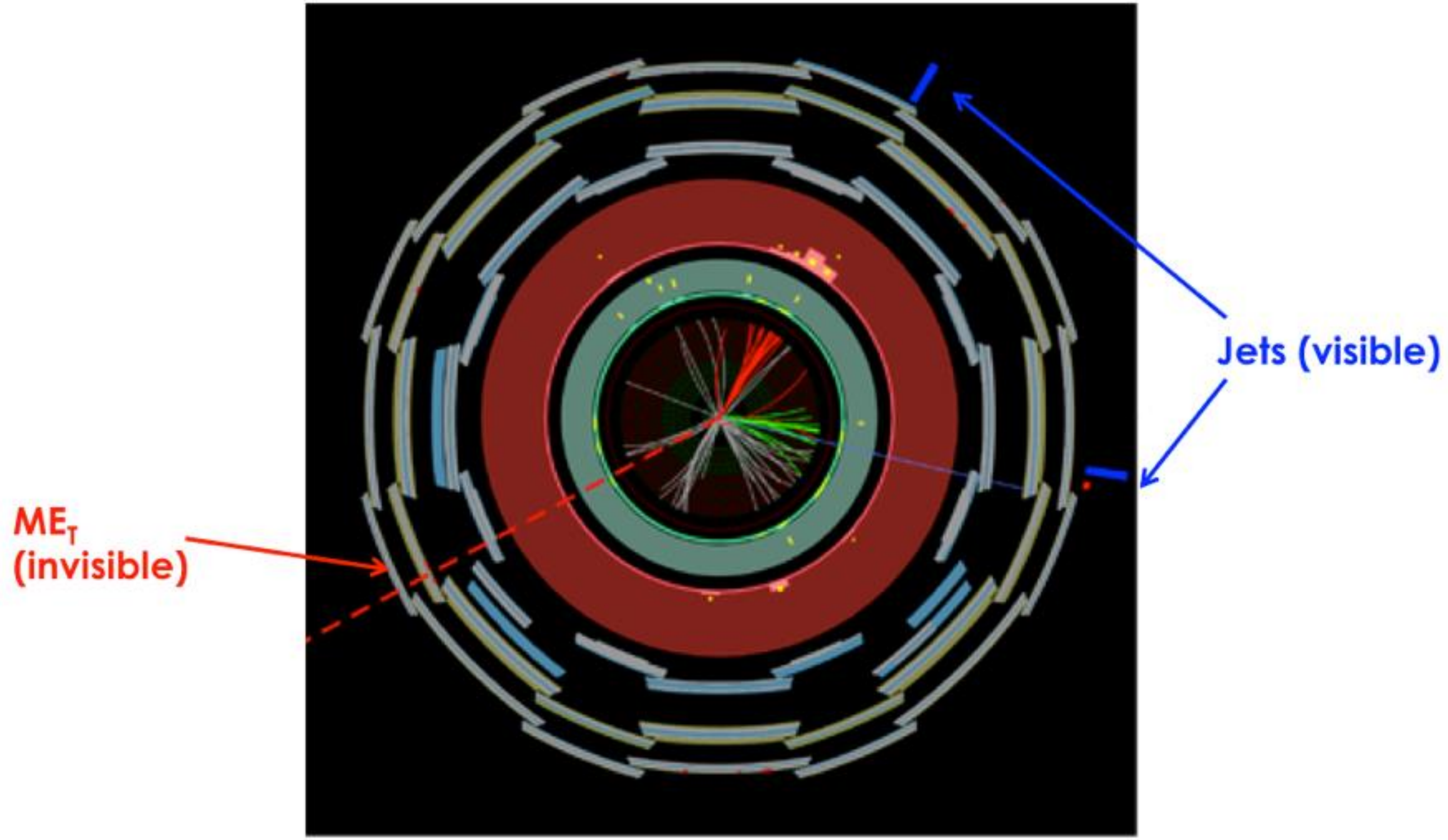
What to look forward to

- Given the difficulties with making these sources, it’s not clear what the future will bring, but maybe:
  - Safe production of an electron capture source and measurement with a big underground detector.
  - Application of the BEST technique (^{51}Cr) with other isotopes.
  - Detection with other channels (e.g. electron scattering)
  - IsoDAR/DAEdALUS (See future possibilities)


LHC Neutrinos

Neutrinos at colliders

https://atlas.cern/updates/blog/what-happens-when-energy-goes-missing



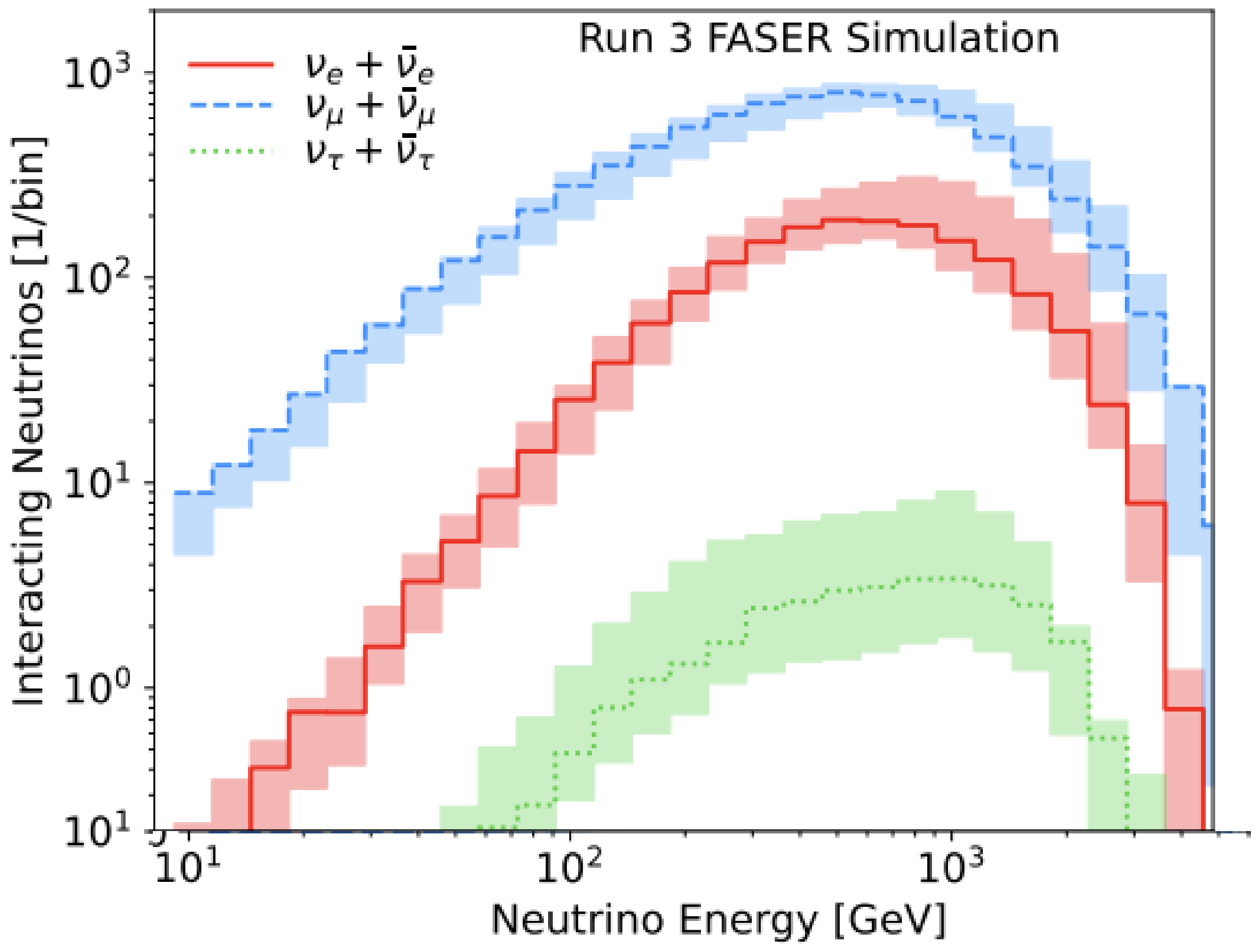
Neutrinos have long been produced at Colliders

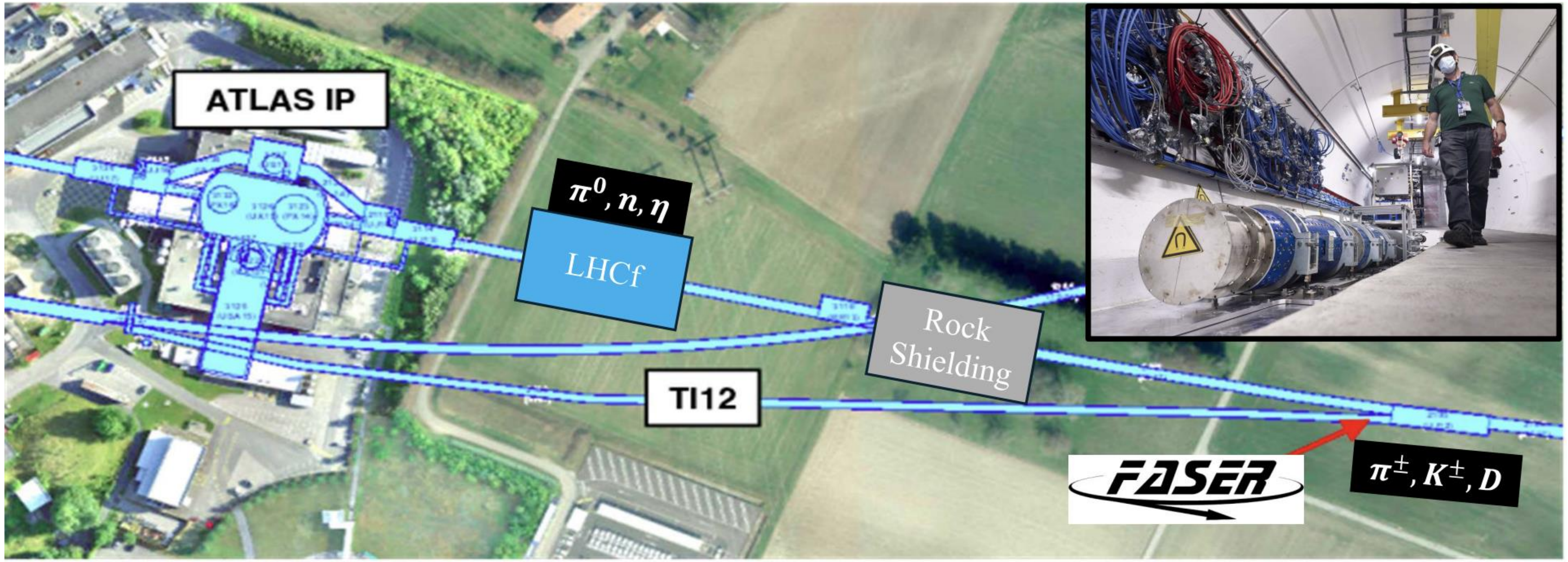
But they have generally been considered "missing energy"

Neutrinos at colliders

That is changing with the FASER experiment near the ATLAS interaction point

Sees very forward neutrinos from pp collisions, primarily due to pi/k/charm decay





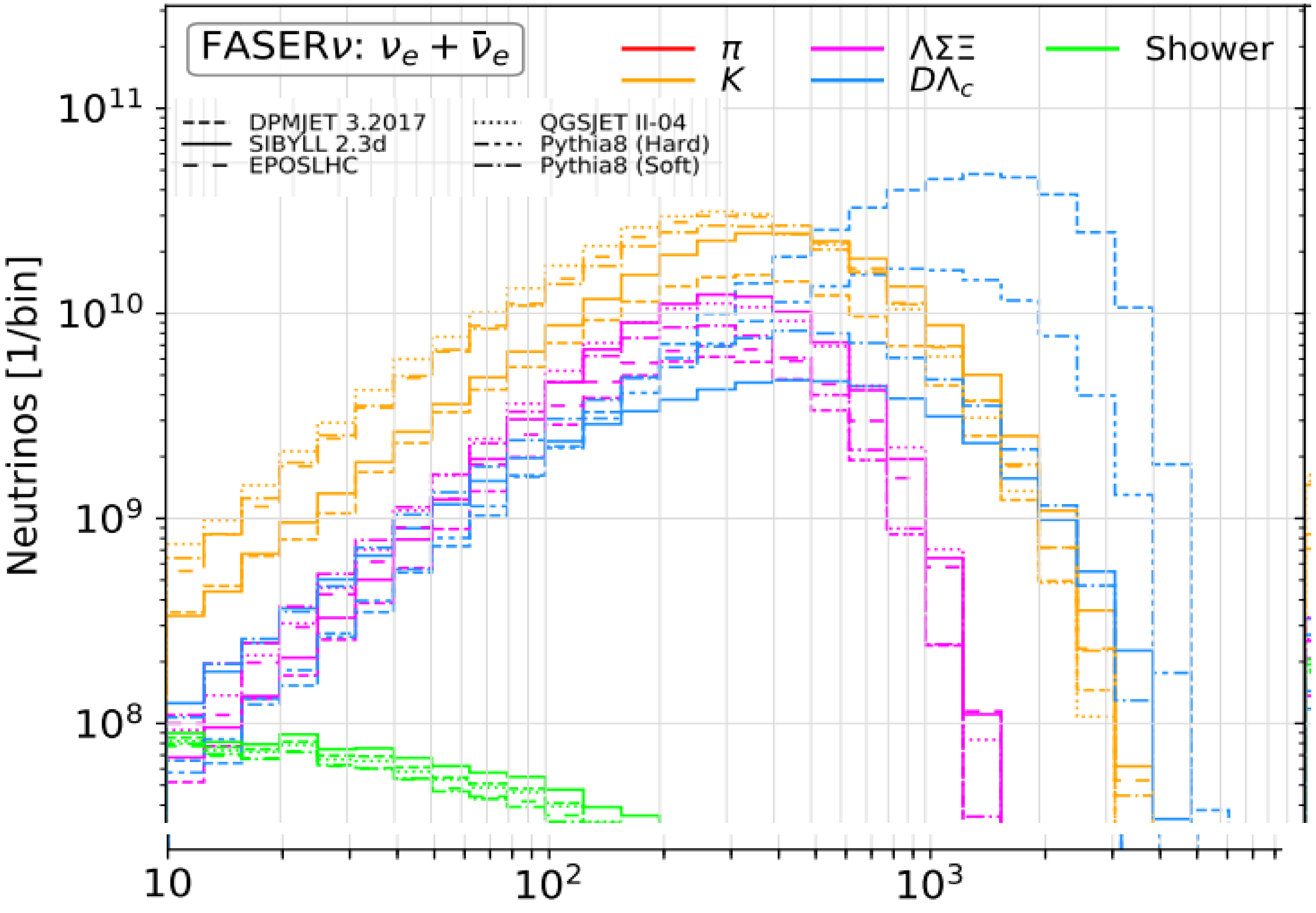
Max Feig, NuFlux 2026

Neutrinos at colliders

Hadron production largely unconstrained in this region

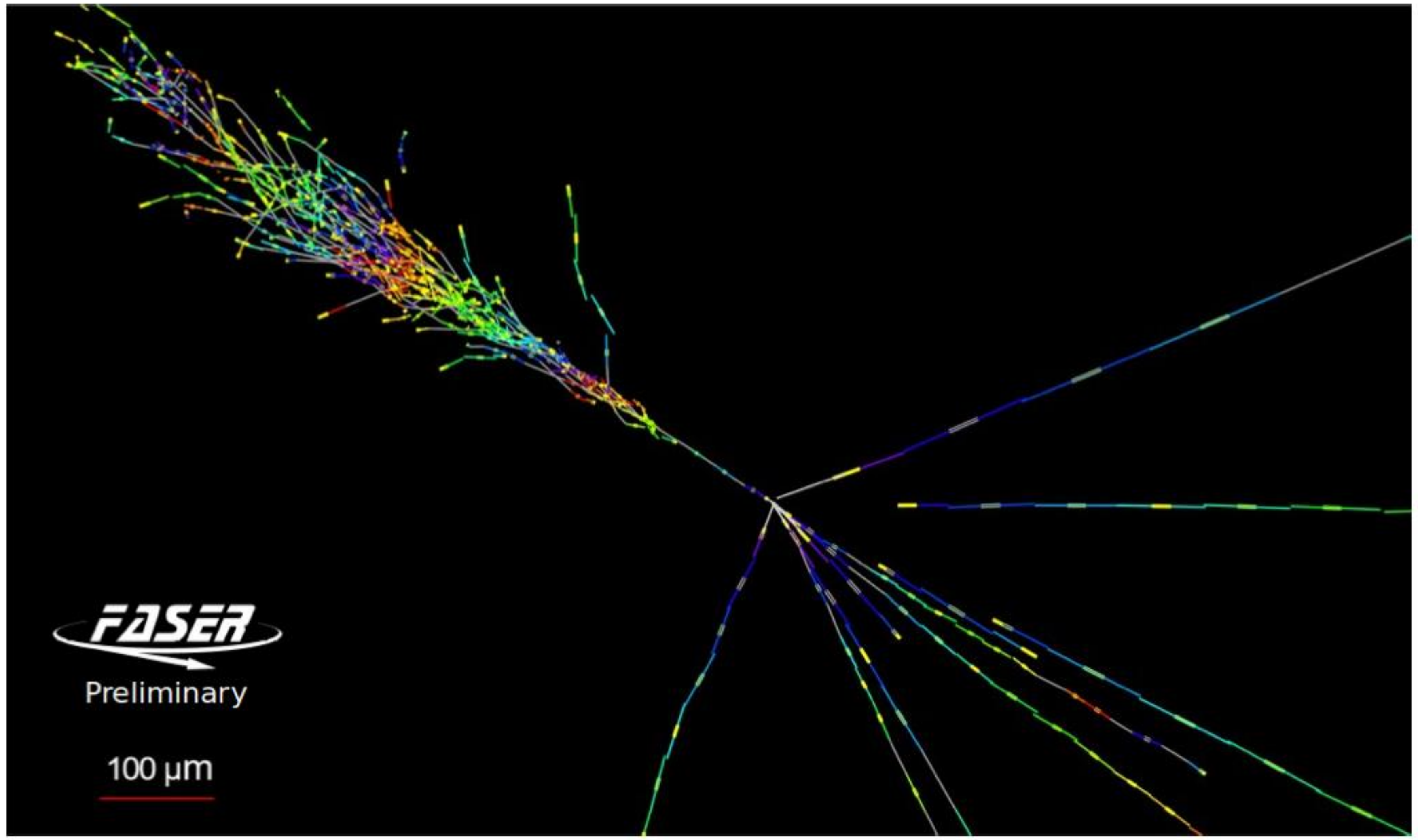
- Light hadrons ~ $\mathcal{O}(10)\%$
- Charm hadrons $\mathcal{O}(100)\%$

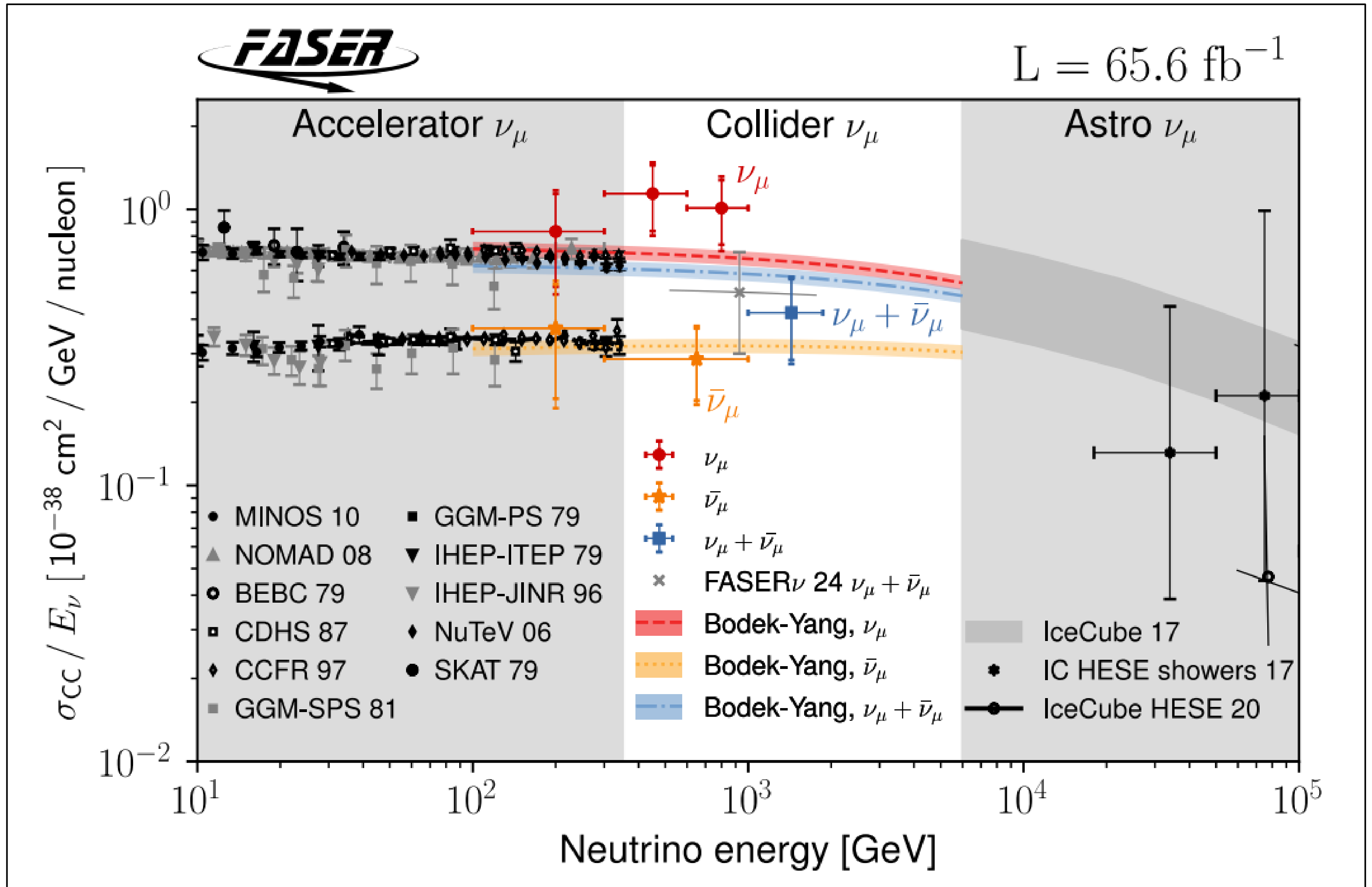
Neutrino measurements at FASER are constraining this flux for the first time



Neutrinos at colliders

FASER recently announced first observation of collider neutrinos!
Among other potential physics, fills in the gap between accelerator and astrophysical cross section measurements





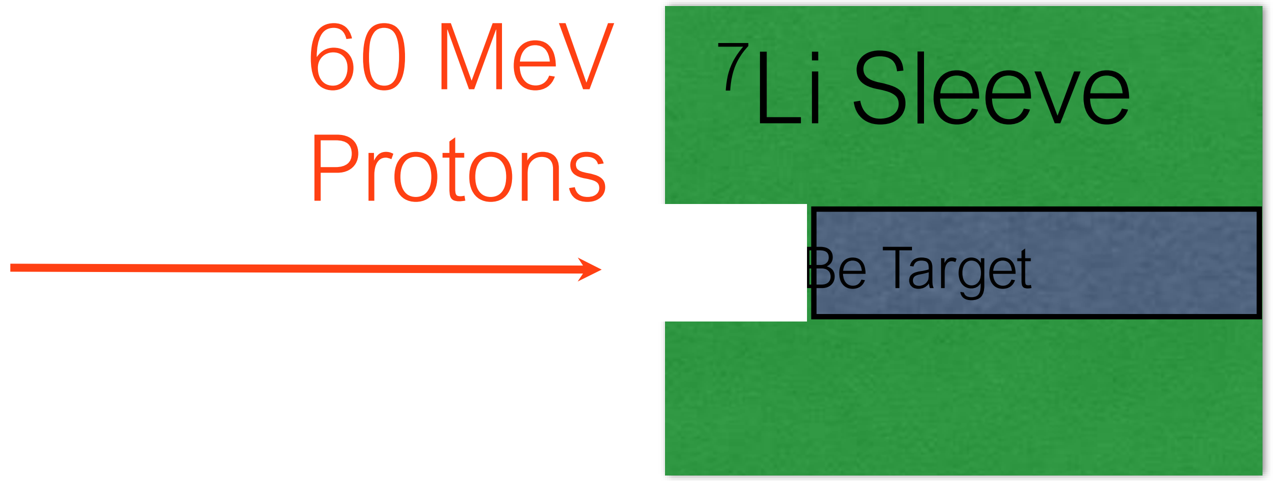
FASER '24

What to Look Forward to w/ Collider Neutrinos

- FASER and another experiment (SND@LHC) will complete LHC Run 3 – expect ~10,000 neutrino interactions, including a handful of tau neutrinos
- Potential "Future Physics Facility" for Hi-Lumi LHC
    - Space designed specifically for upgraded versions of FASER and SND, and also potentially other experiments (e.g. Liquid Argon)

Future Possibilities

The IsoDAR concept

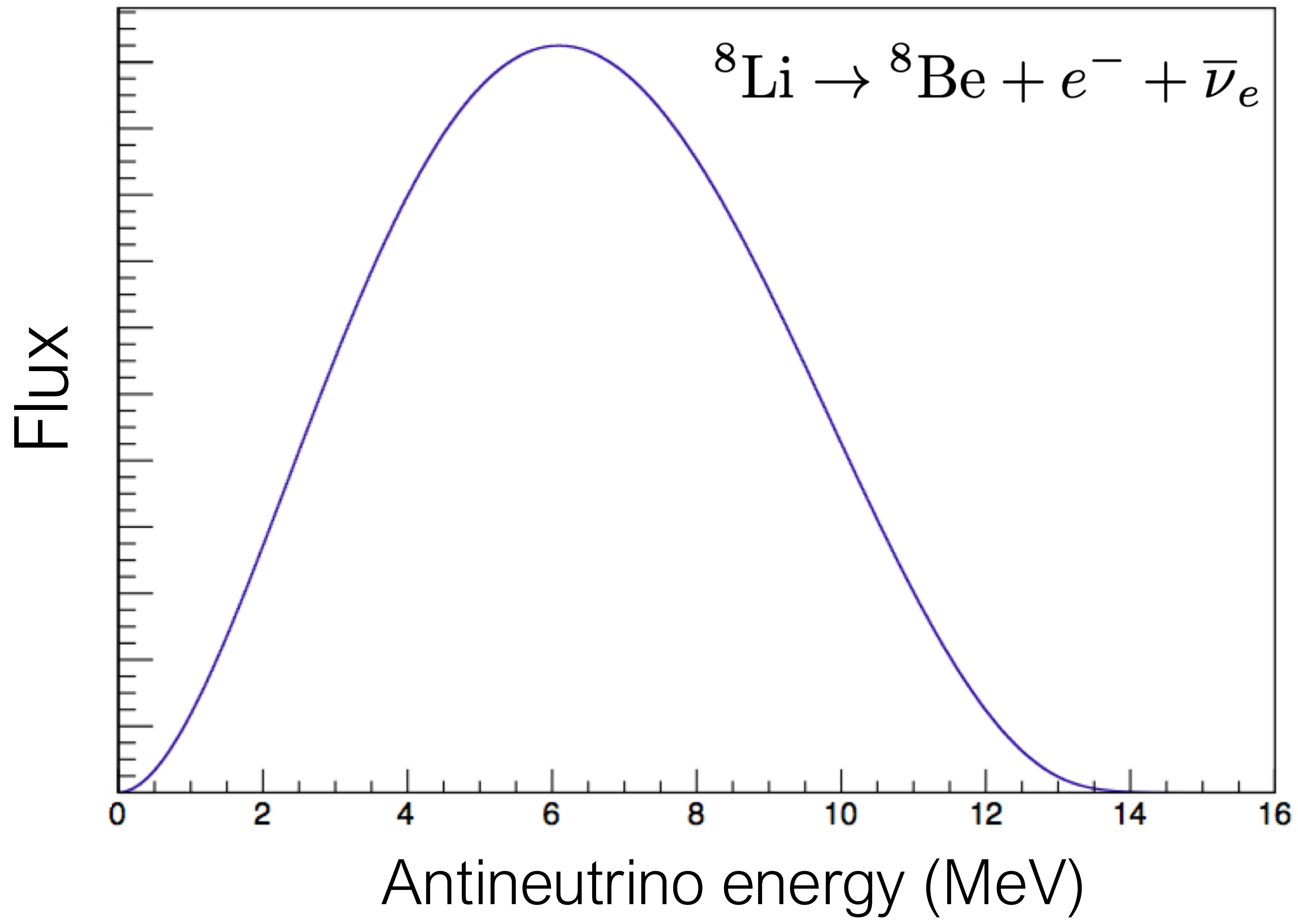


$$p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$$

$$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$$
$$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$$

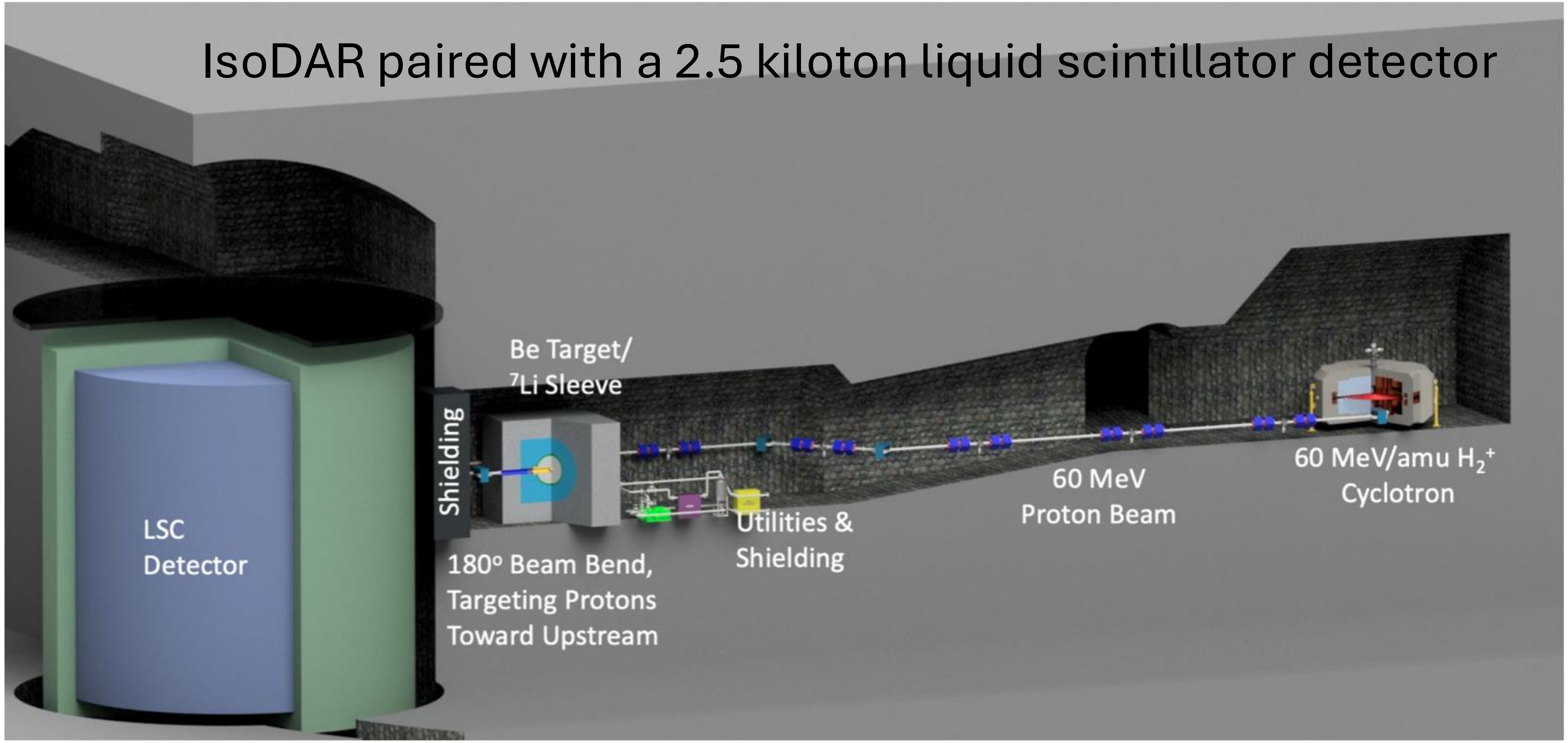
$t_{1/2}$=0.84 s

$$^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

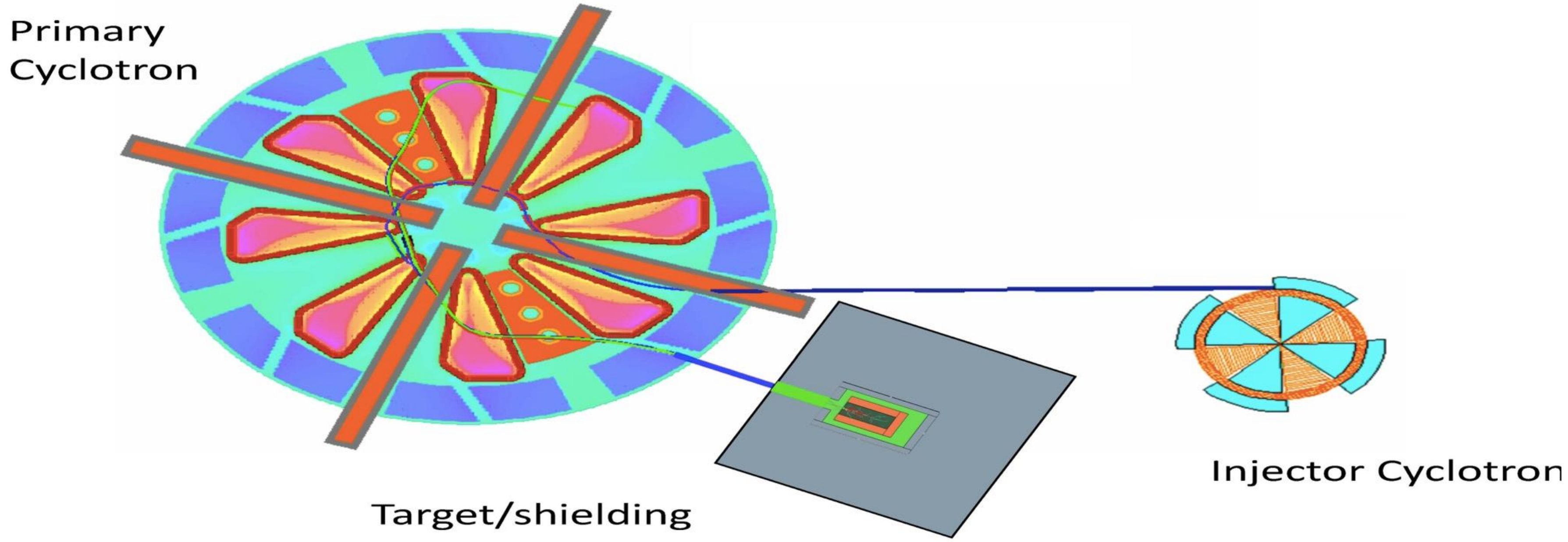


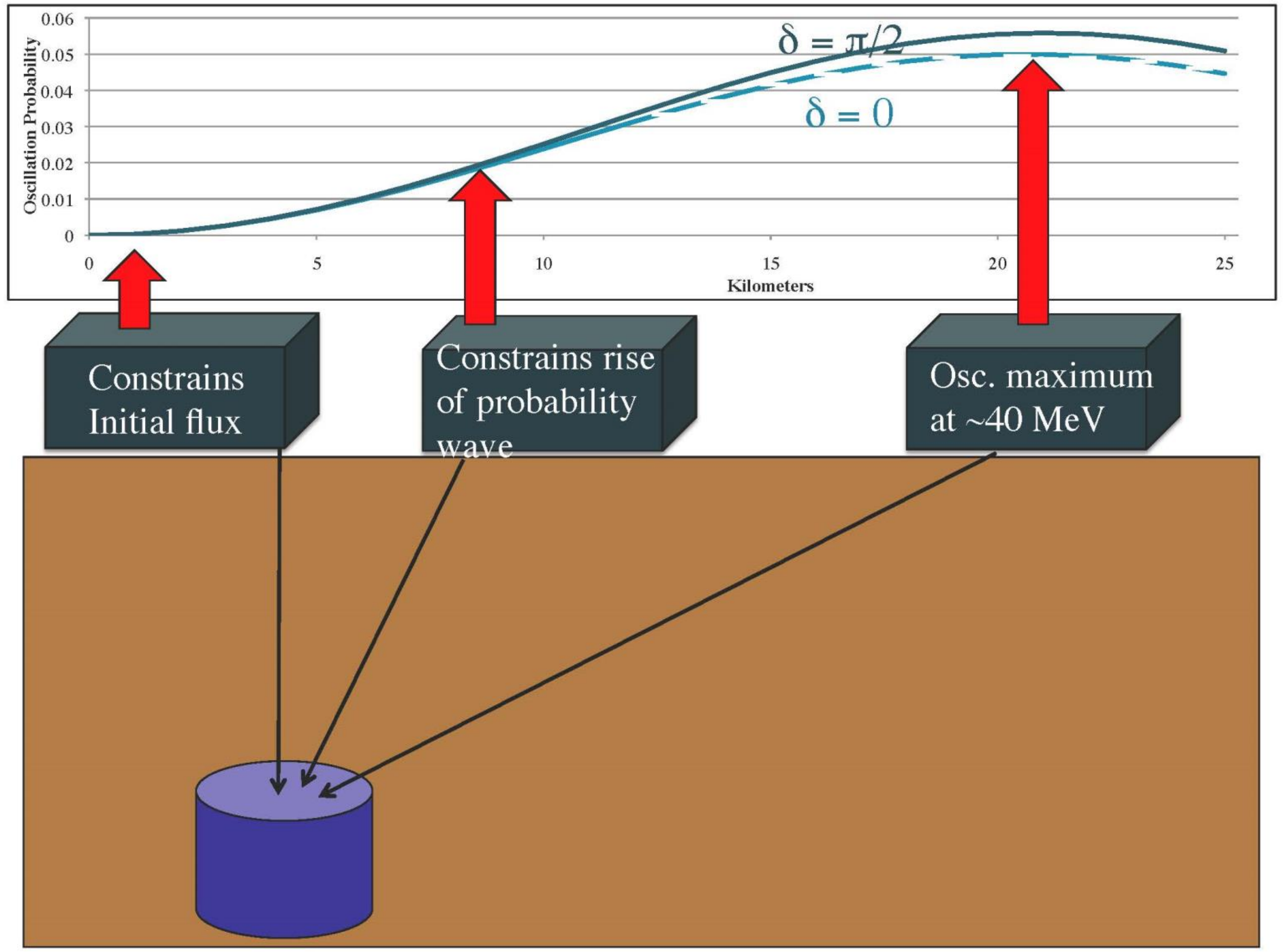
Well understood energy spectrum

IsoDAR@Yemilab in Korea



DAEdALUS





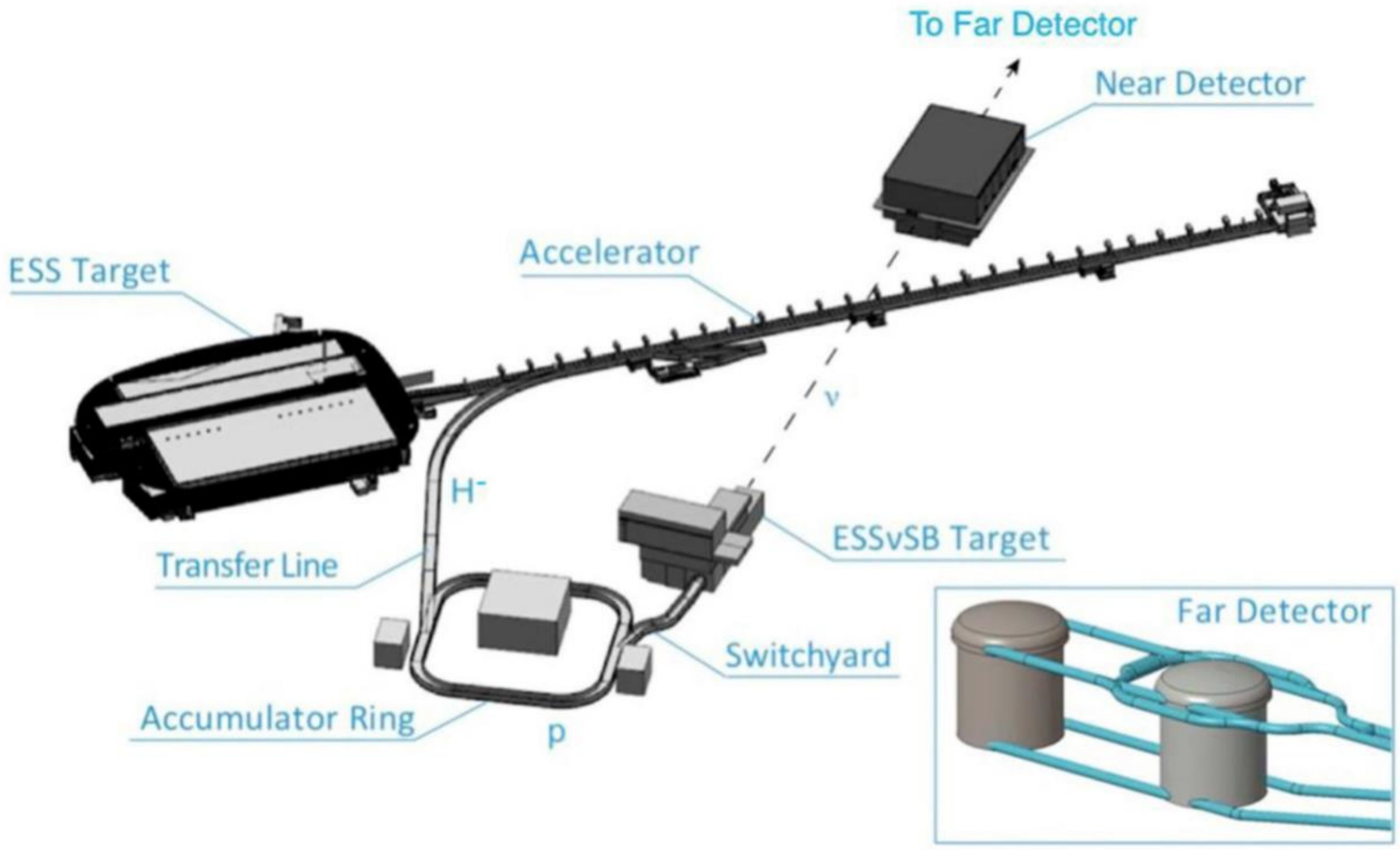
DAEdALUS expands the IsoDAR cyclotron decay-at rest concept with multiple accelerated modules, each coupled to a single large detector

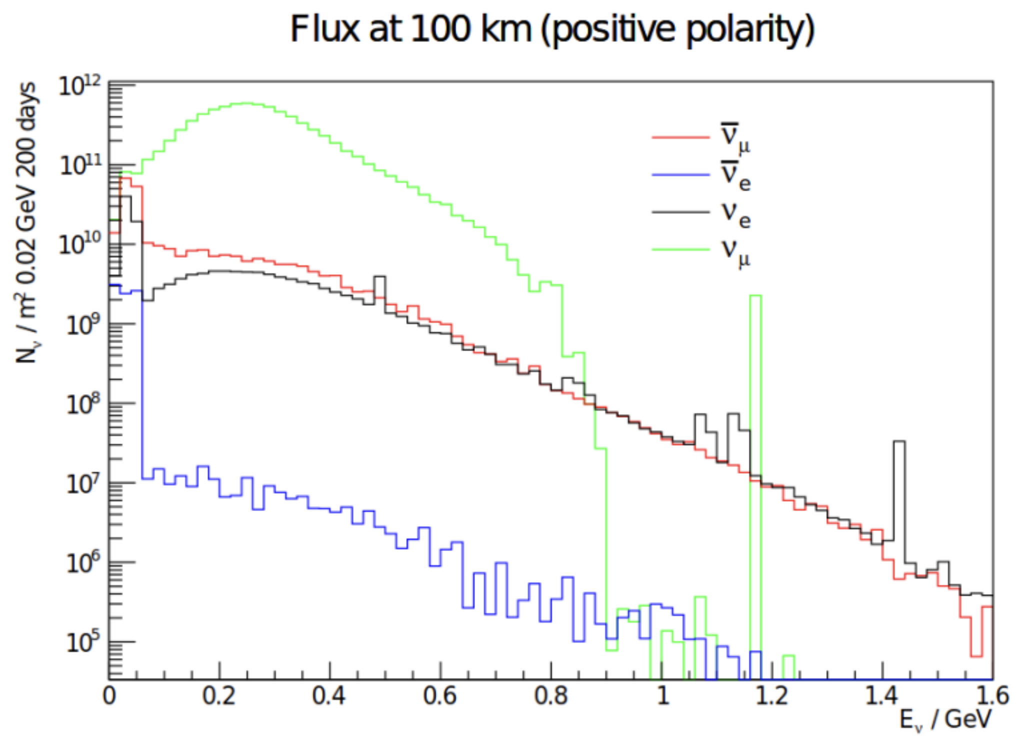
ESSnu Superbeam

Proposes to upgrade the European Spallation Source (in Lund Sweden) Linac to 10 MW, and use half of that for a horn-focused pion DIF beam to study neutrino oscillations

Also proposes large water Cherenkov detector 250 km away (also in Sweden)

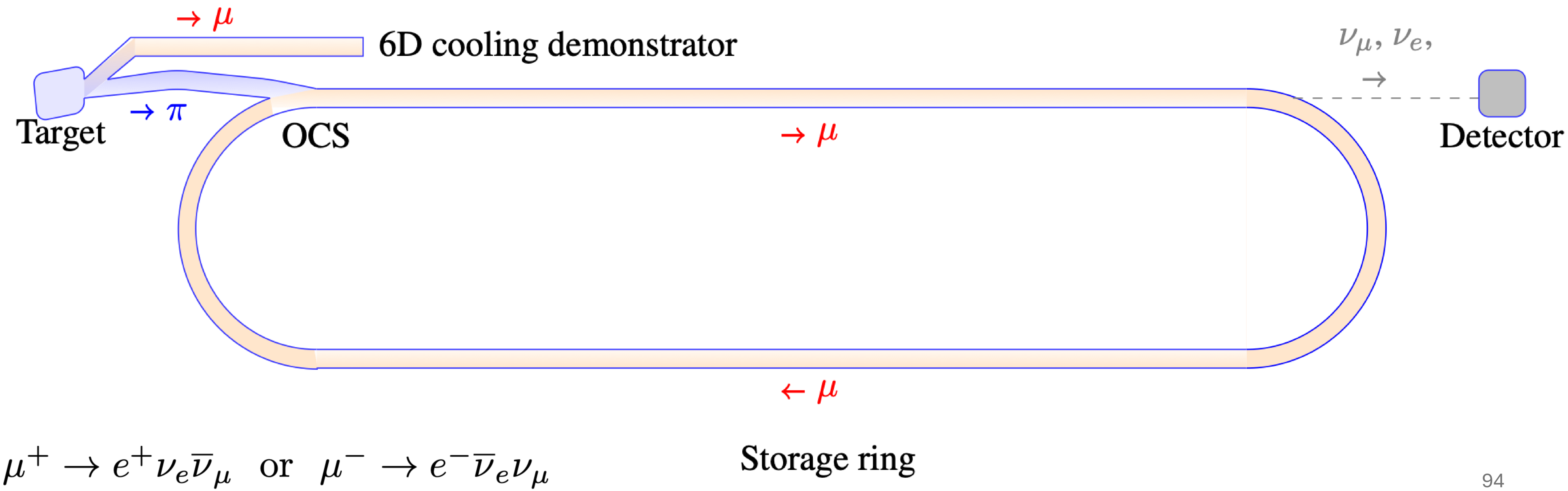
2.5 GeV proton beam spread across 4 separate target/horn combos





Neutrinos from stored muons

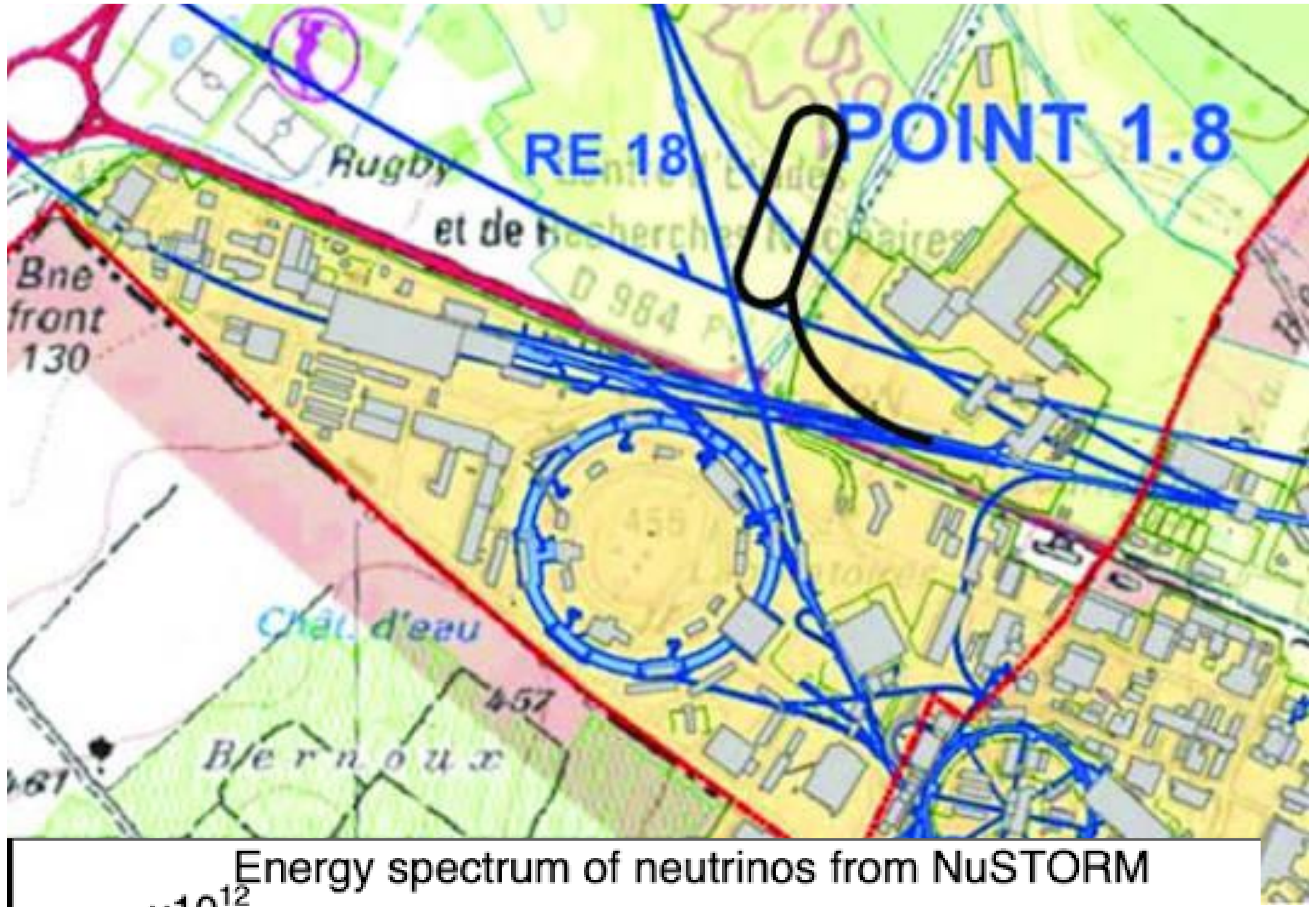
- Relies on muons from a storage ring to produce a pure beam of muon and electron flavor neutrinos and antineutrinos.
- Challenge is wrangling the muons in your accelerator.

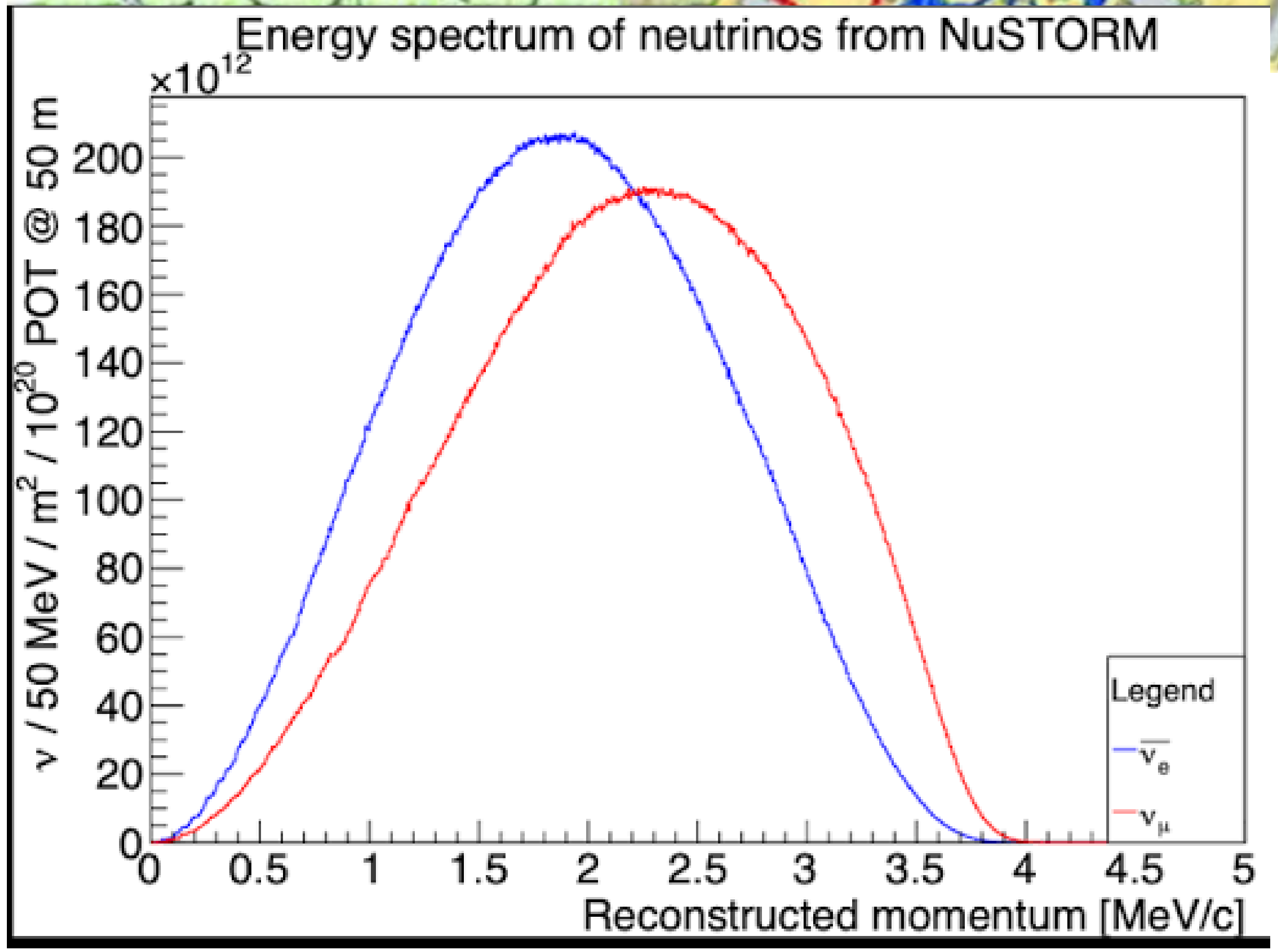


$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu \quad \text{or} \quad \mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$$

NuStorm at CERN

- NuStorm is a proposed muon storage facility at CERN
  - Has established feasibility
  - Currently in R&D phase
- If approved, would be a well understood source of neutrinos and a key step towards a muon collider

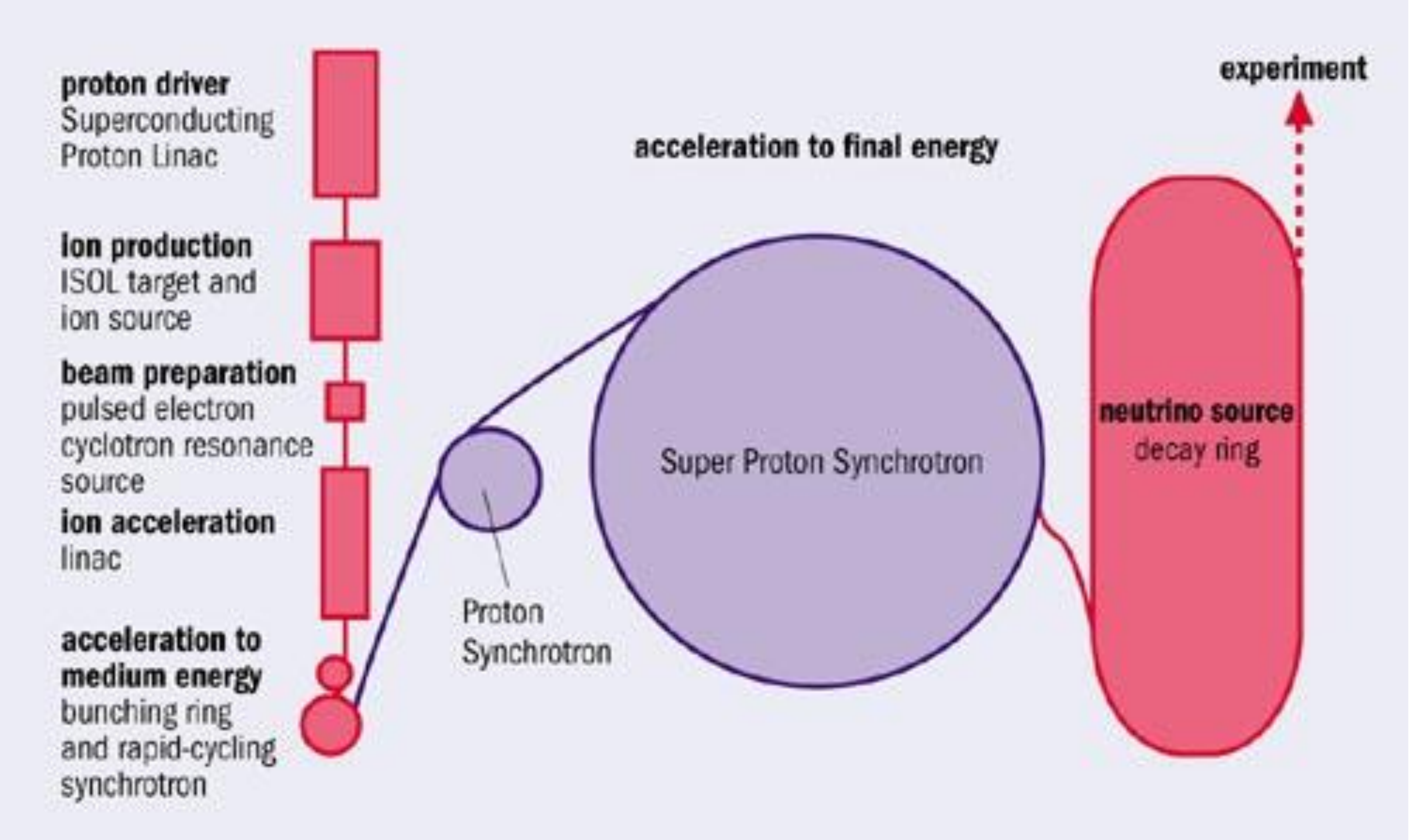




Muon Collider

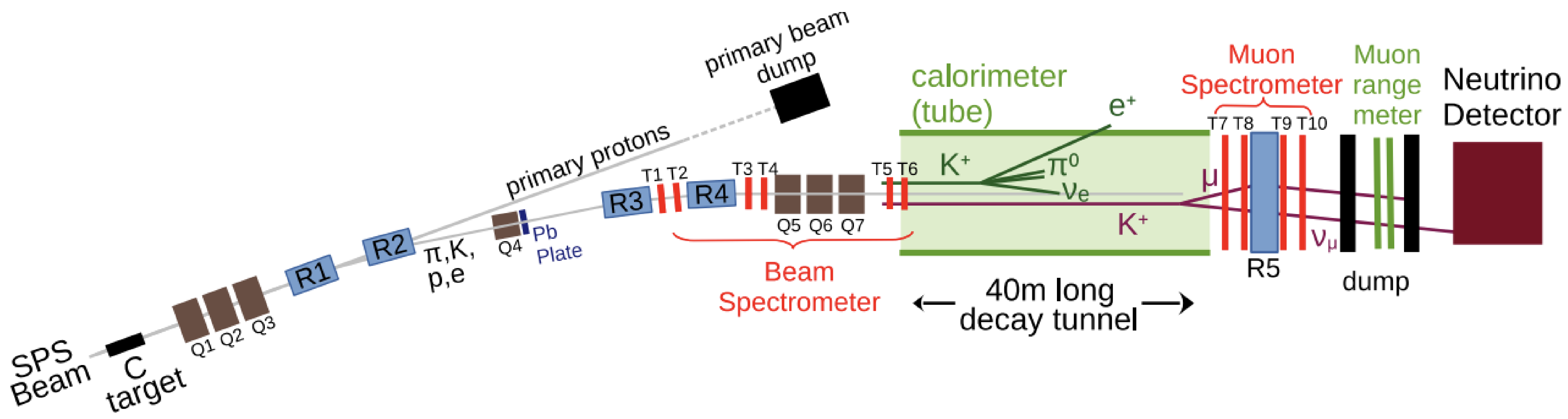
- Recent P5 report supported Muon Collider R&D in the US
- If realized, a muon collider would be the world's most intense and well characterized neutrino source, through muon decay
- Would provide ~10^4 neutrino interactions per second in a kTon scale detector, at very high energy -> tests of SM, search for BSM
- It produces so many neutrinos that they become a human health hazard, mitigated by minimizing straight sections of muon path

Beta Beam



- Proposed at CERN in 2002 as a pure source with well understood spectrum for studying neutrino oscillations
- Accelerate radioactive ions (He-6 or Ne-18) to high momentum, they decay in a decay ring, producing a neutrino beam

NuScope



- Recently proposed: NuScope would be a novel short-baseline DIF beam at CERN
  - Beam would would be instrumented such that hadrons and muons would be measured event by event, so that the neutrino energy can be calculated
  - Aimed at measuring neutrino cross sections (which could become a standard candle for flux prediction) and sterile searches

The End


Where do my neutrinos come from?
The common particle physicist's view: