Artificial Neutrino Sources

Josh Spitz, University of Michigan

Neutrino University Lecture at Fermilab

7/28/2022

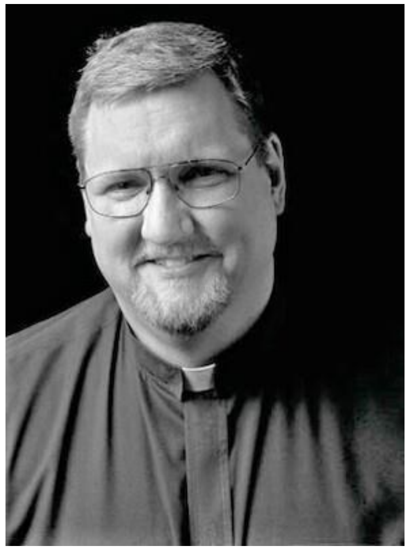
Neutrino University

It gets better!

Neutrino Presentations for Summer Students

Fermilab Summer 2010

Neutrino University (NeutU) is a series of informal, informative, and interactive presentations for summer students in the Fermilab Neutrino Program (Minerva, MiniBooNE, Minos, MicroBooNE and Nova). These presentations are intended to introduce students to some of the important ideas and experiments of neutrino physics, particularly those that are running or under construction at Fermilab.



Paul Nienaber (1955-2020),
first organizer of Neutrino University

LArTPCs and neutrino detection at FNAL

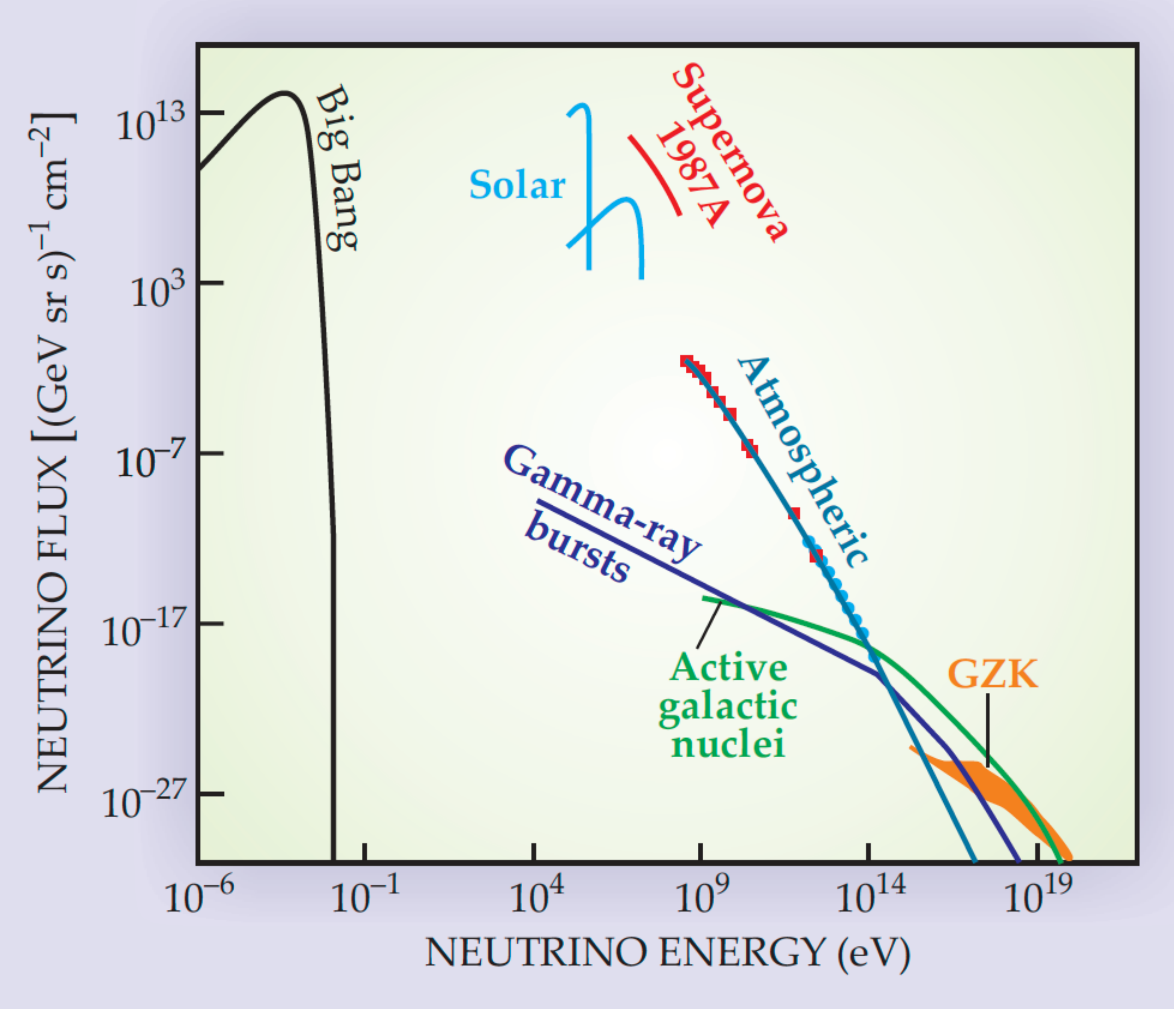
Joshua Spitz
Neutrino University
FNAL, 8/12/2010

Neutrino University

It gets better!

A NEWTrino?
A chameleon (w/ the ability to change "flavor")?
A lizard of some kind shaped like the Greek letter ν?

Nature's neutrinos

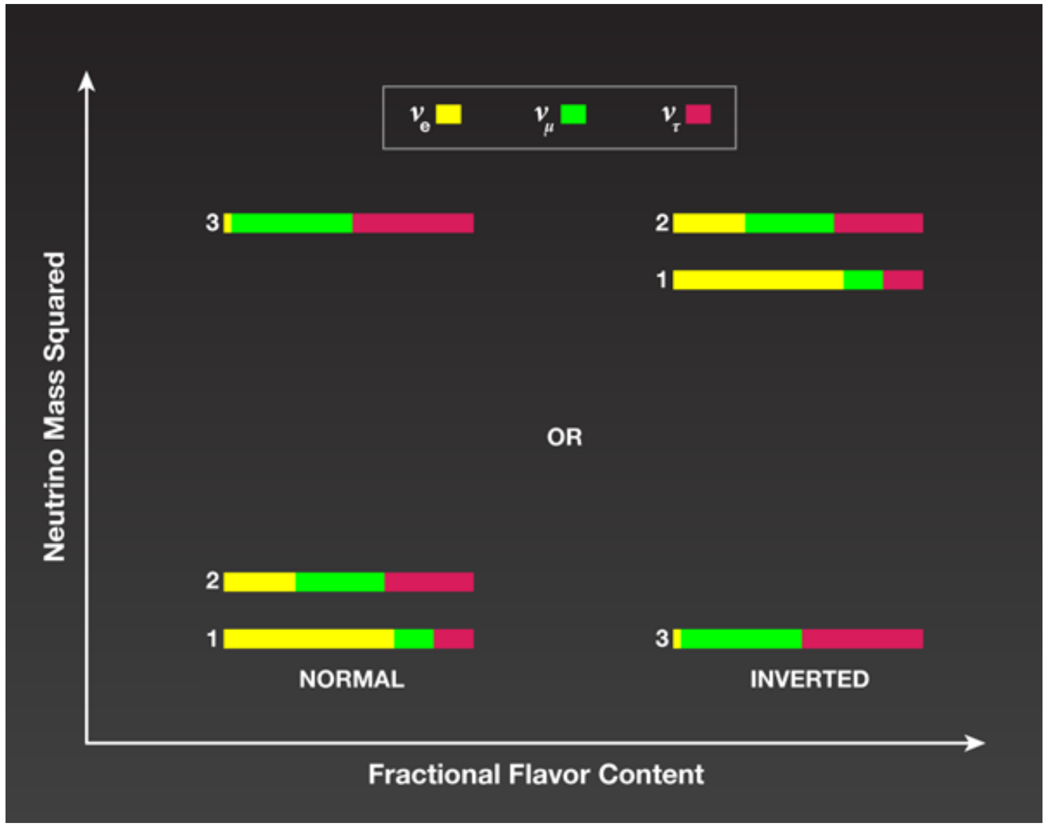


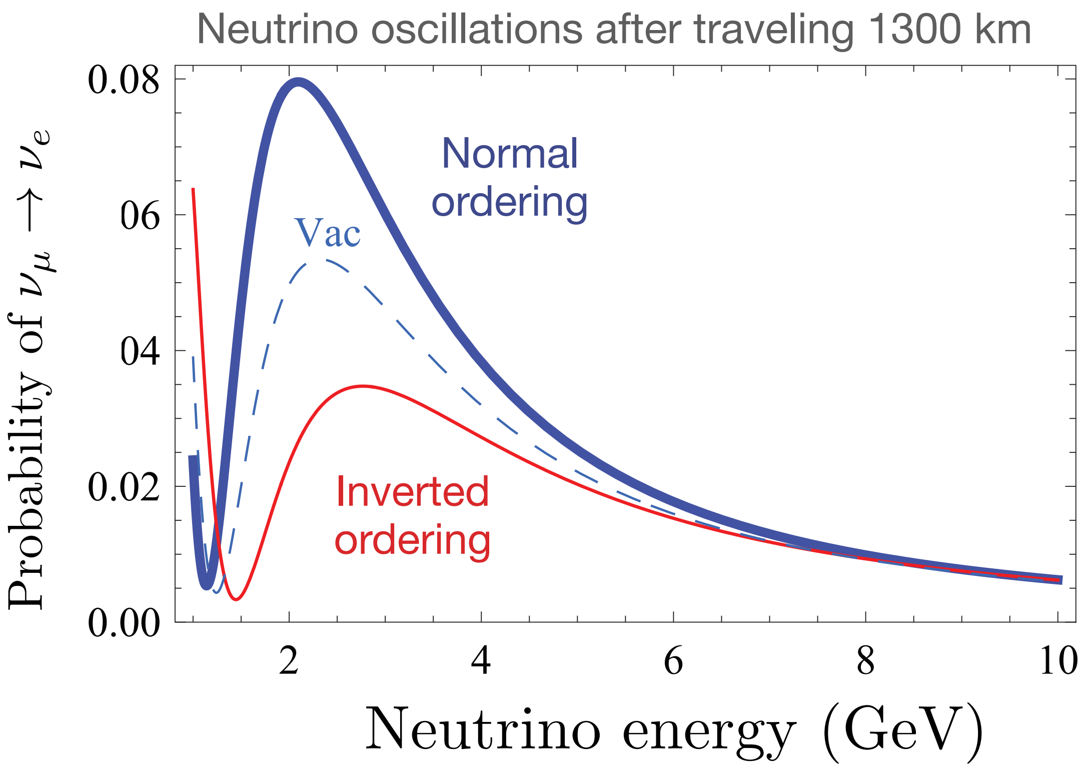
Physics Today

As far as artificial neutrino sources, the source is a means to an end

- First, what do you want to measure?

- DeltaCP, mass hierarchy, other 3-nu mixing parameters, sterile neutrinos, other exotic mixing, non-standard interactions, neutrino decay, weak mixing angle, cross sections and nuclear physics, Majorana or Dirac, tau neutrinos, absolute neutrino mass, lepton universality, Lorentz violation, supplemental measurements for astrophysics, something no one's thought of…



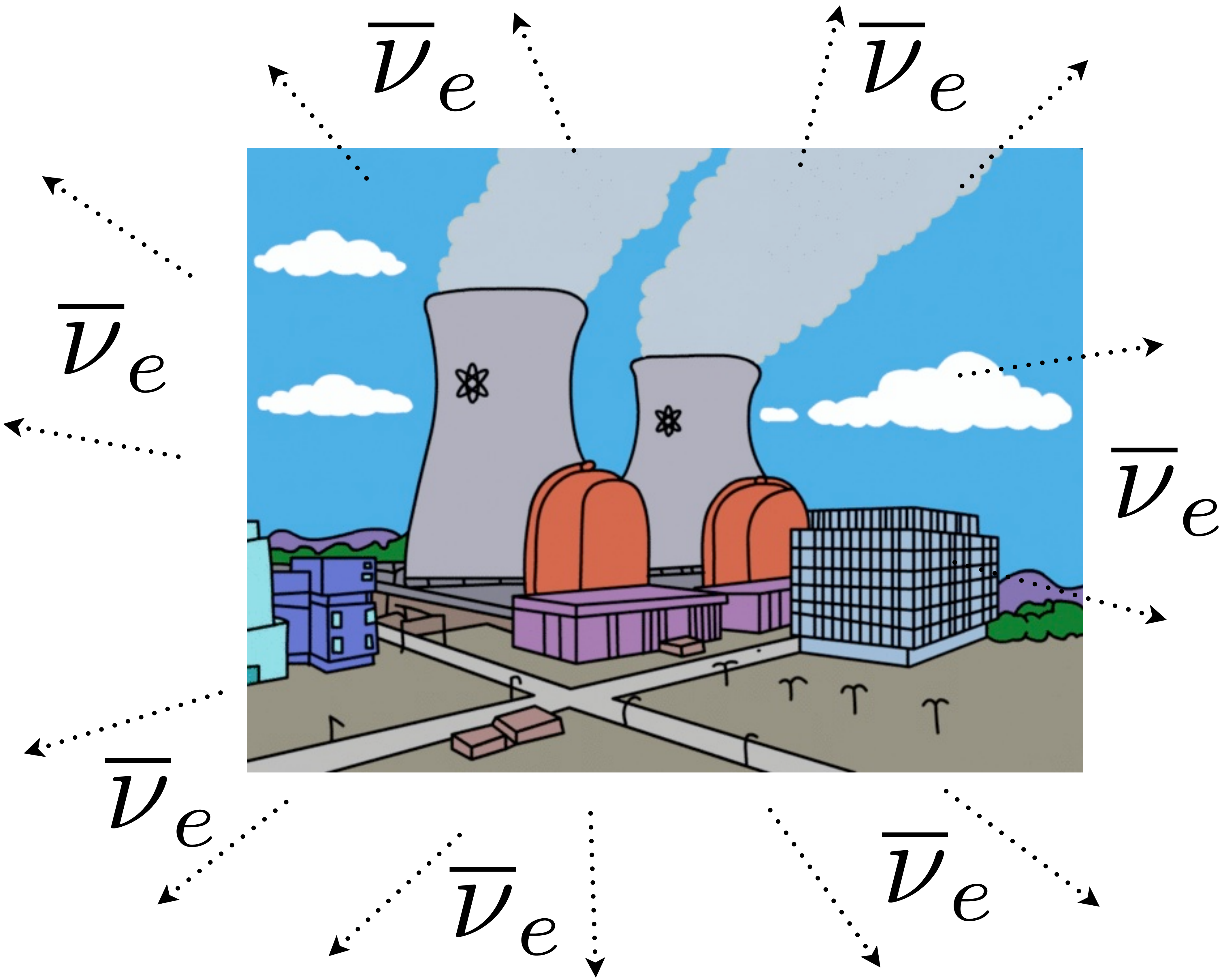


Whenever possible…

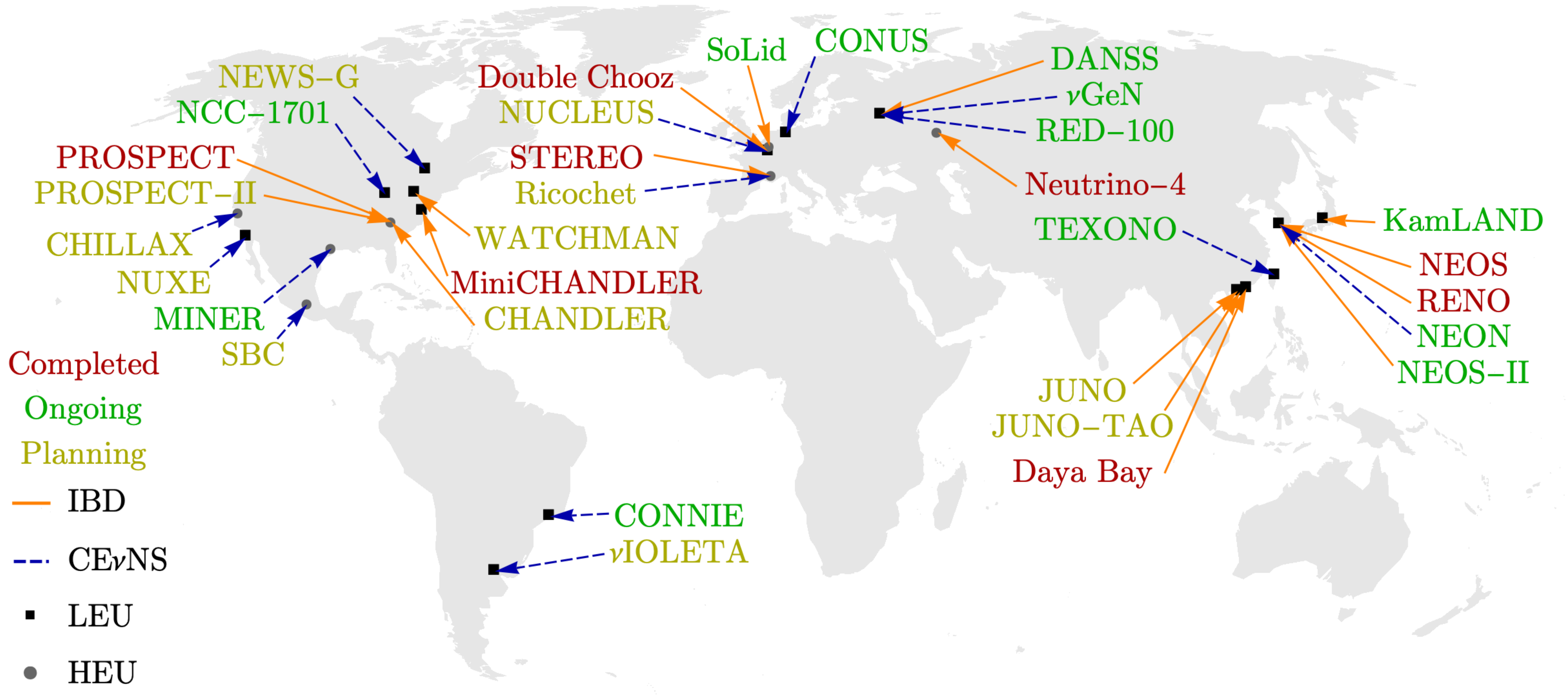
- Use a “free” source.
- Use a source that you understand.
- Use a pure source.
- Use an intense source.
- Use a source with a favorable energy for what you want to measure.
- Use a timed source of neutrinos.
- Use a source that has a favorable detection cross section.
- Use a source that has a favorable interaction signature.
- Use a compact source.
- Use a source that doesn’t evolve in time.
- Use a source that you can get close to.

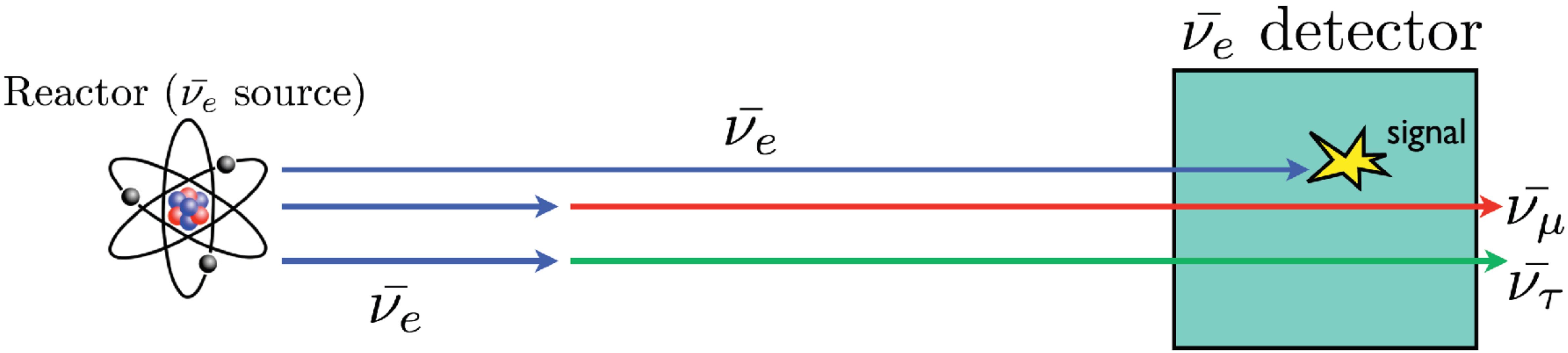
Reactor neutrinos

Nuclear reactors produce neutrinos

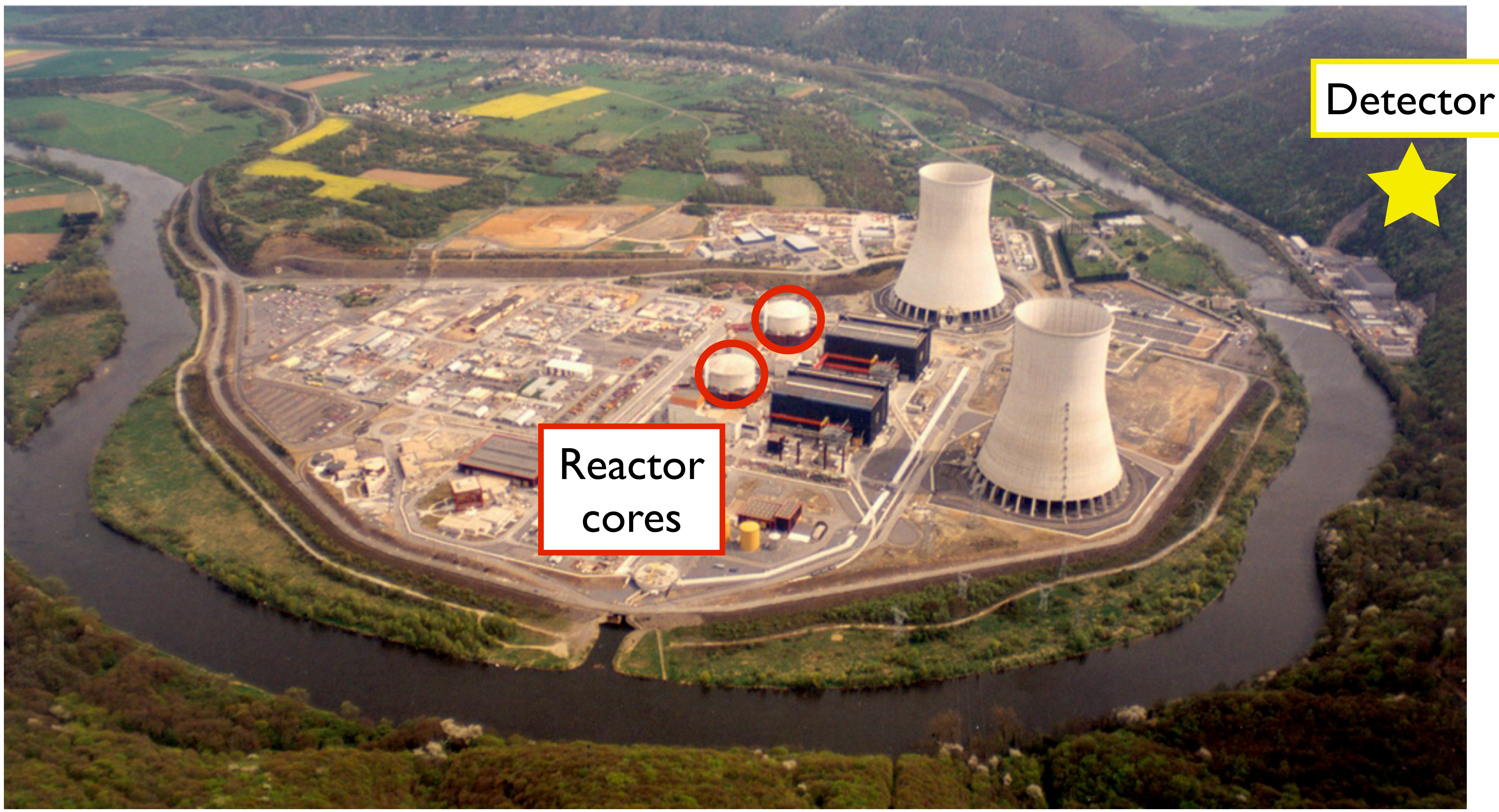


Reactor experiments around the world



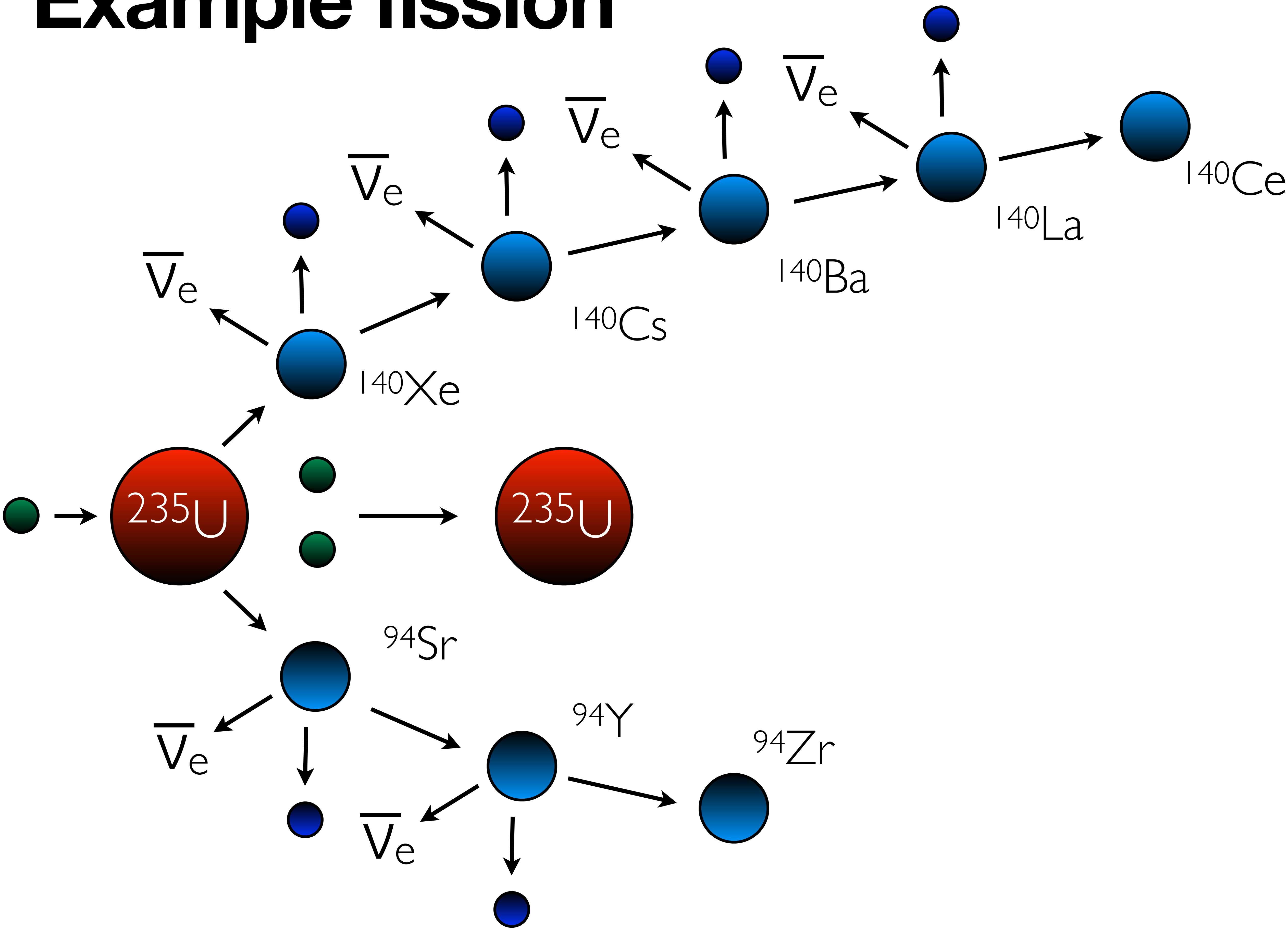


In a *disappearance experiment*, we look for a deficit of antineutrinos

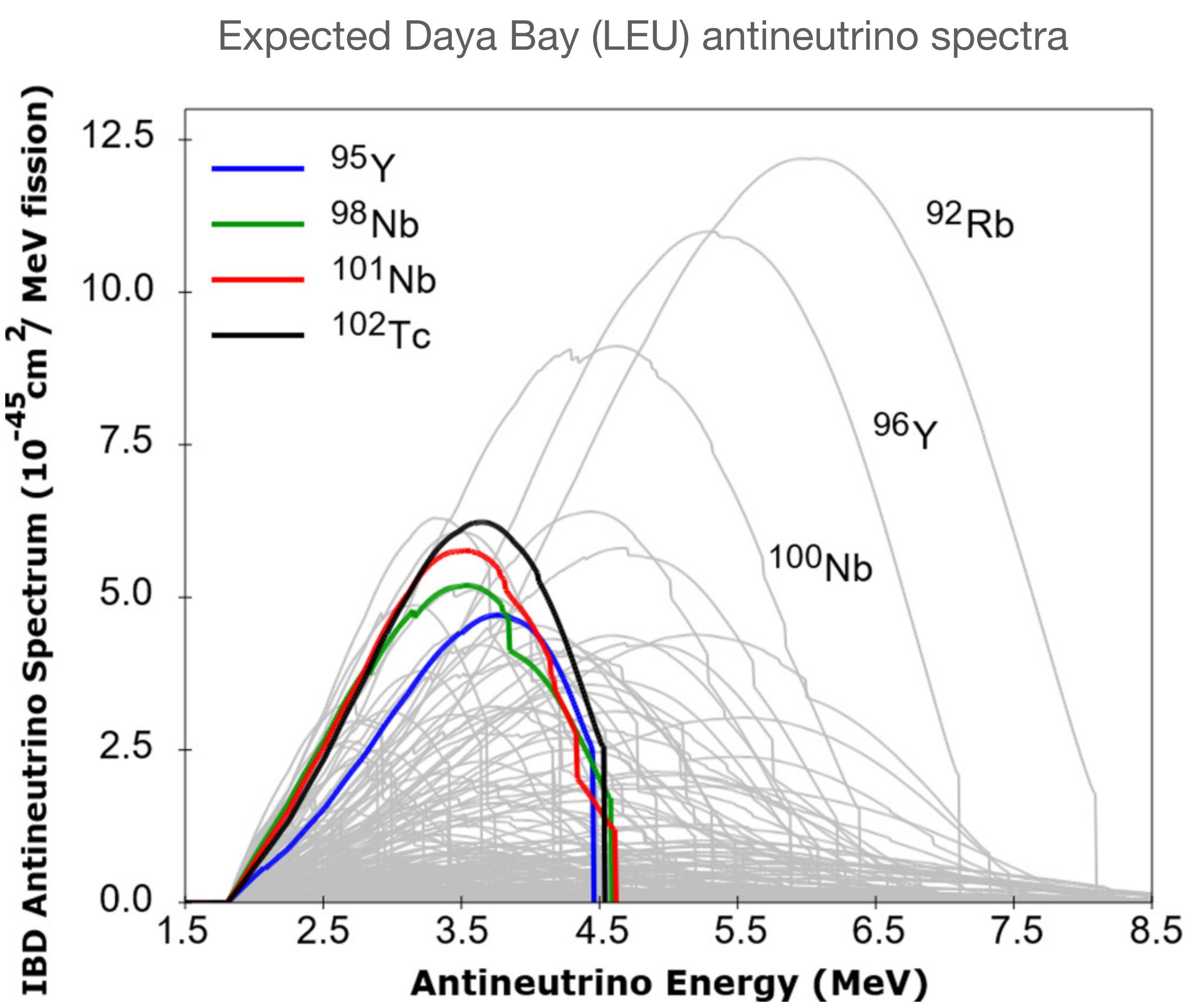


Detected via Inverse Beta Decay (IBD): $\overline{\nu}_e p \rightarrow e^+ n$

Example fission



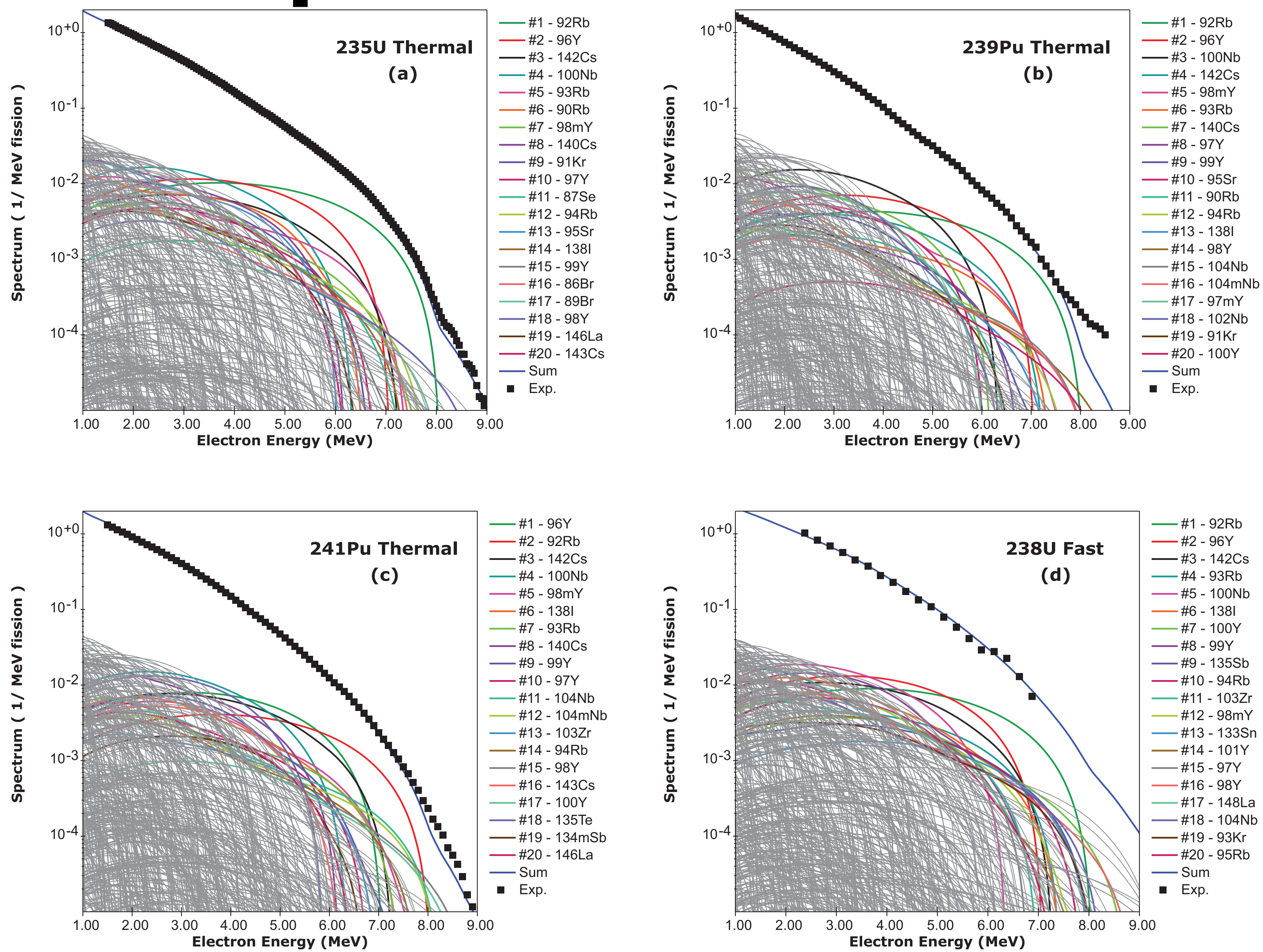
Flux components



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

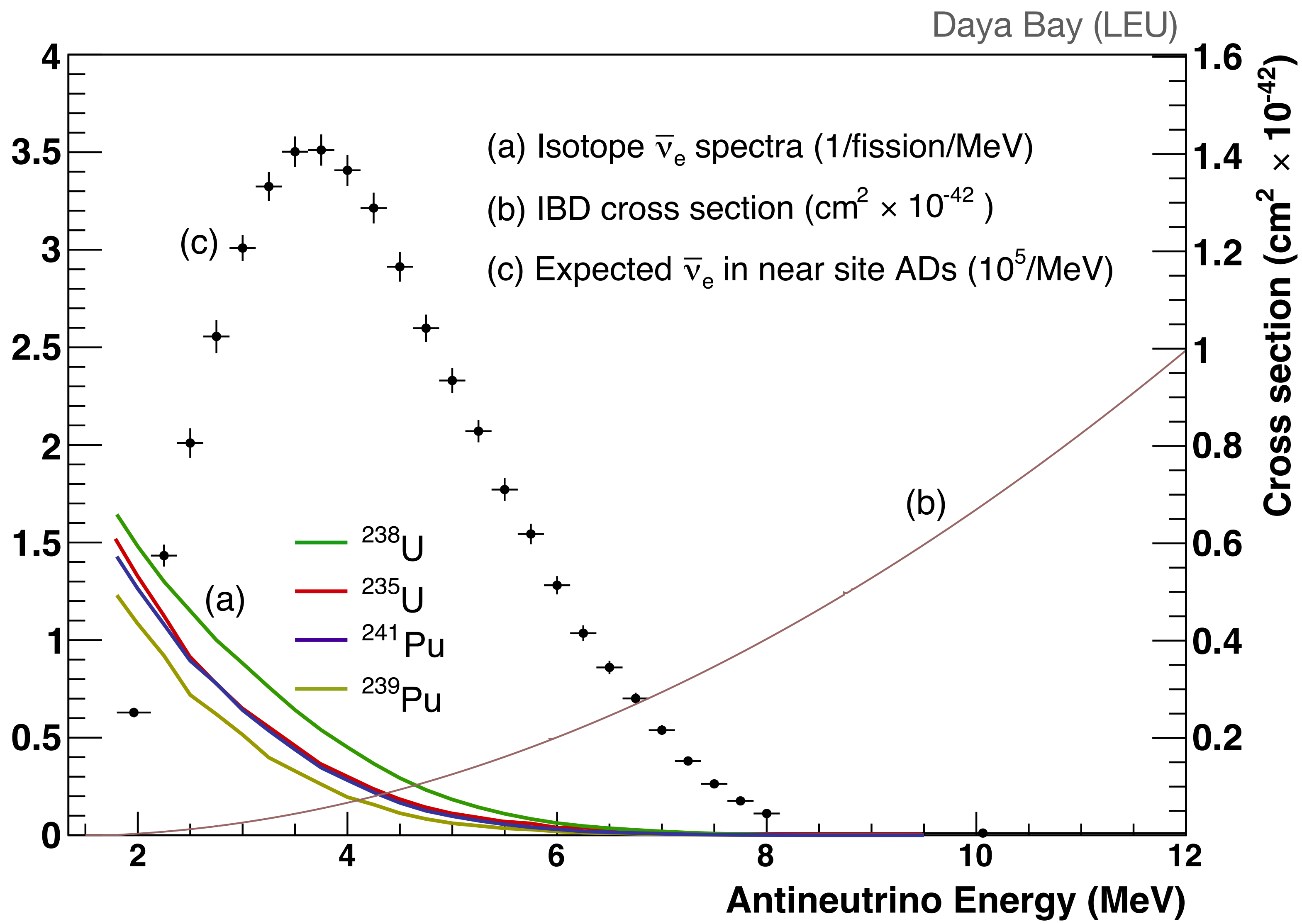
PHYSICAL REVIEW C **98**, 014323 (2018)

Flux components



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

Flux and cross section



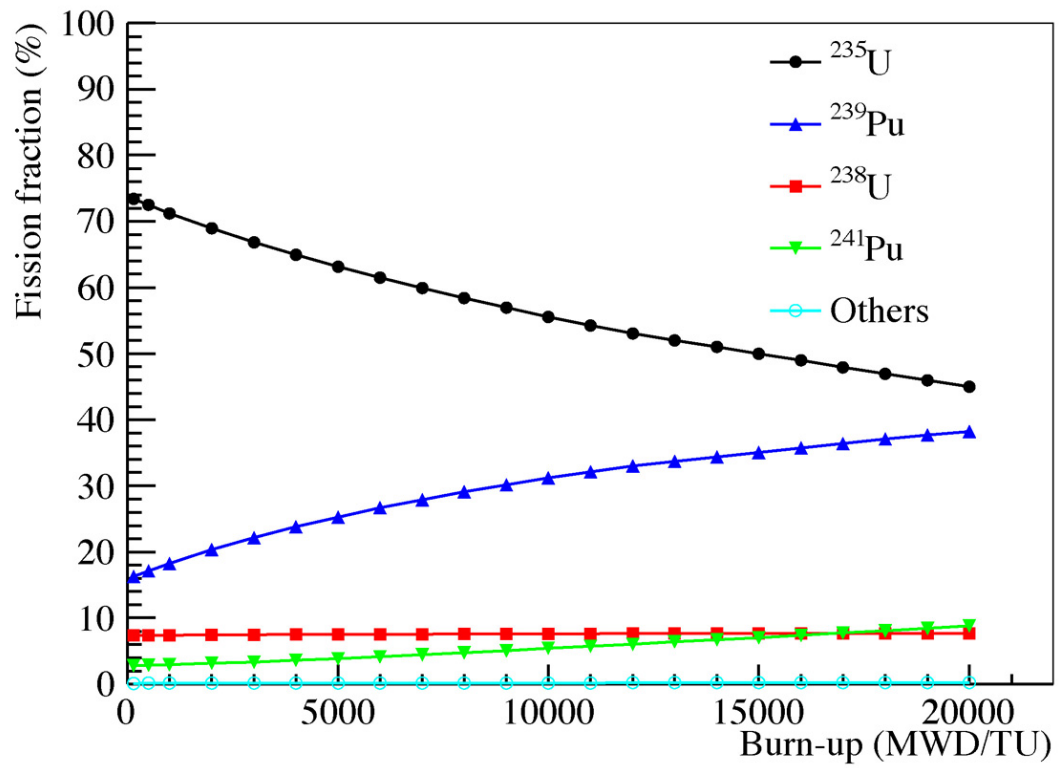
IBD ($\overline{\nu}_e p \to e^+ p$) is a common channel

Elastic ($\overline{\nu}_e e^- \to \overline{\nu}_e e^-$) and sevens ($\overline{\nu}_e A \to \overline{\nu}_e A$) are also possible

HEU and LEU

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

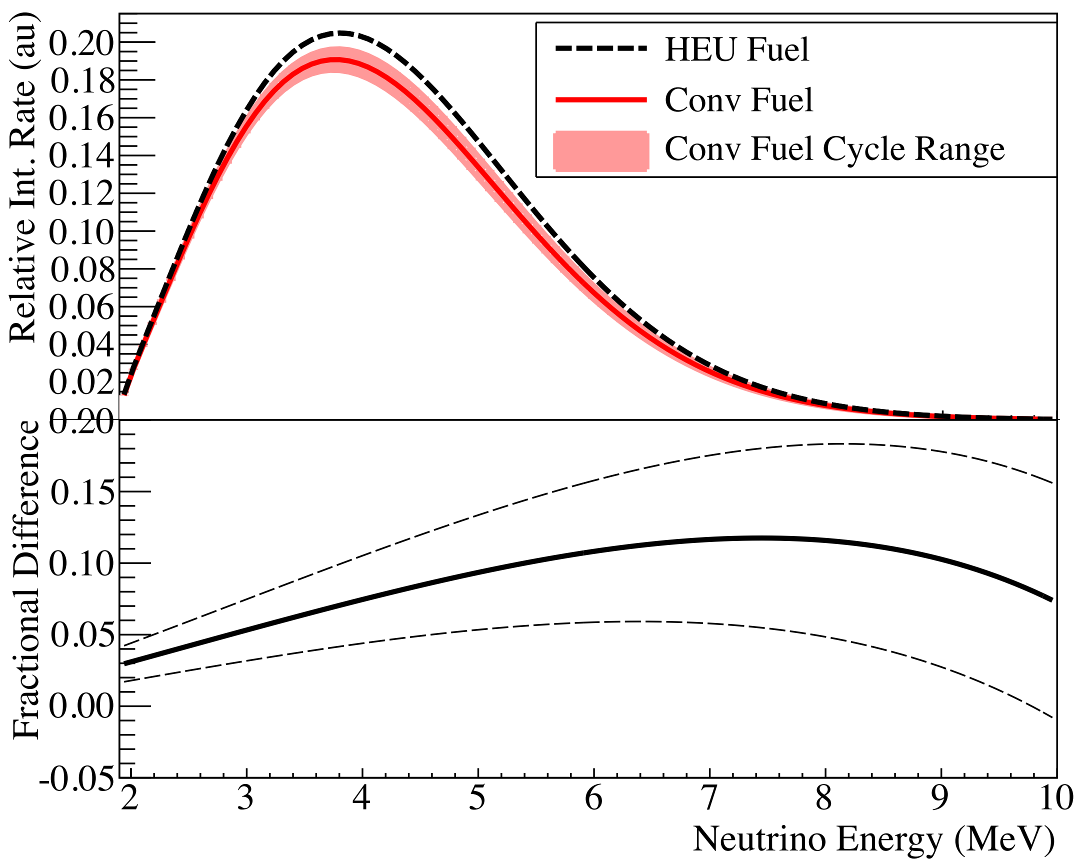
PRD 87 073008 (2013)

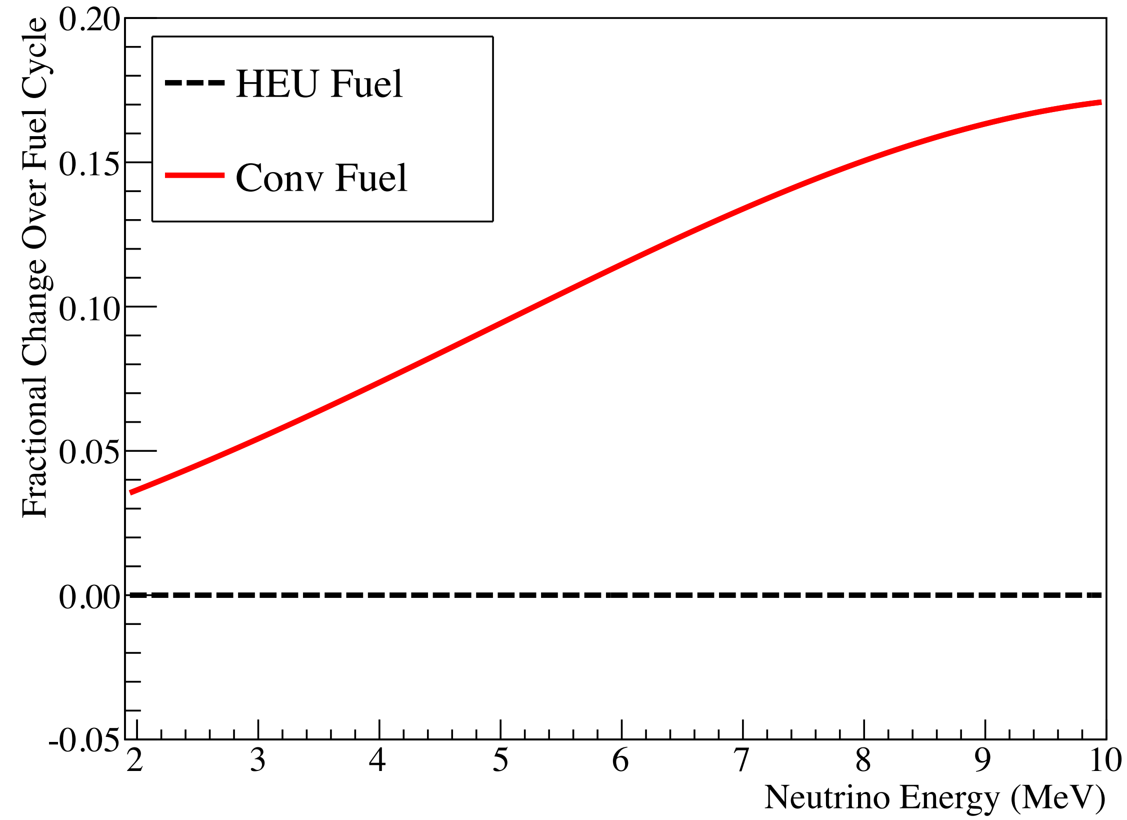


The fission fraction evolution for a typical running cycle of one Daya Bay reactor

PRL 118 251801 (2017)

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





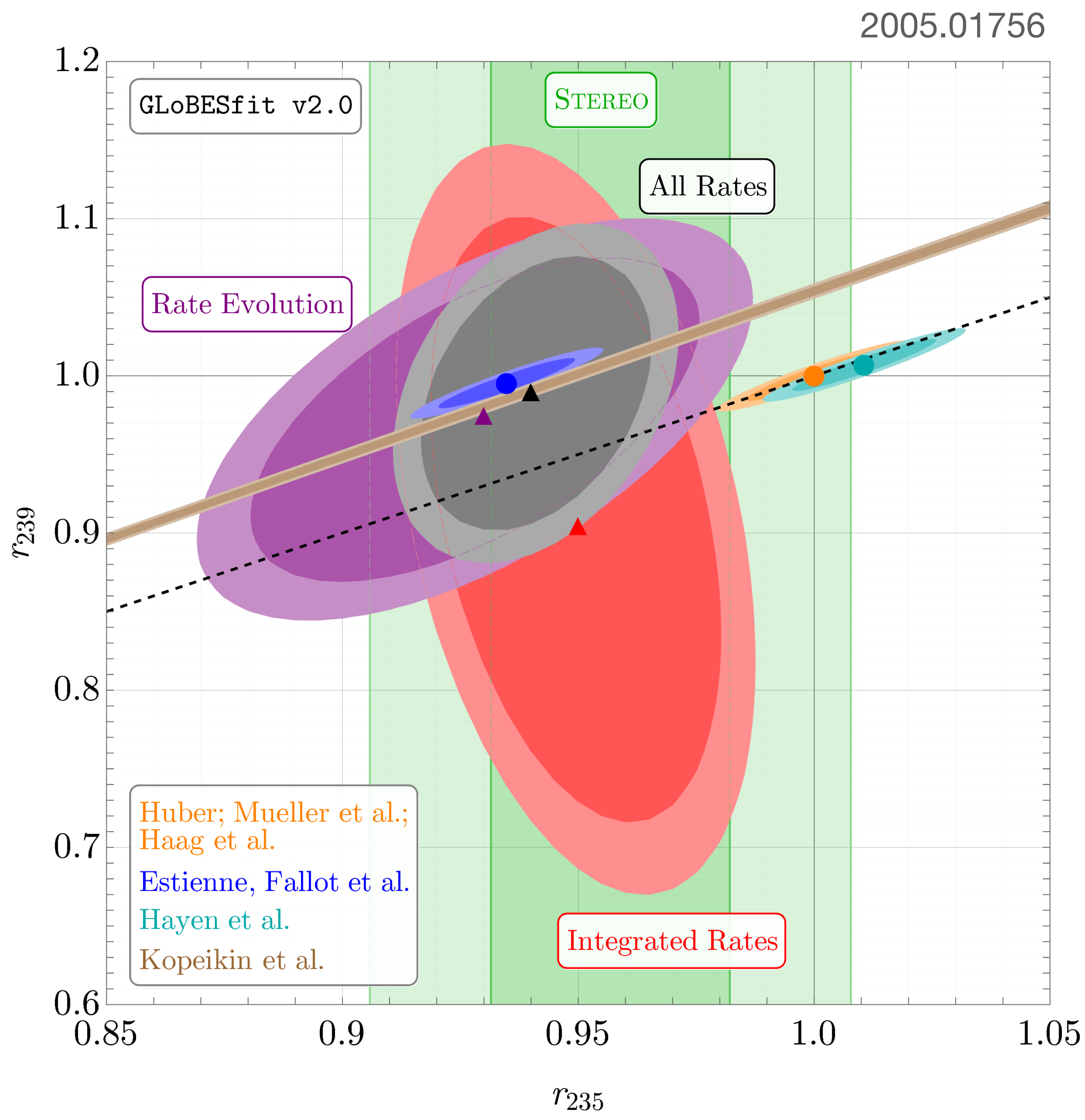
LEU reactor sources have a dynamic electron antineutrino flux.
HEU reactor sources are static.

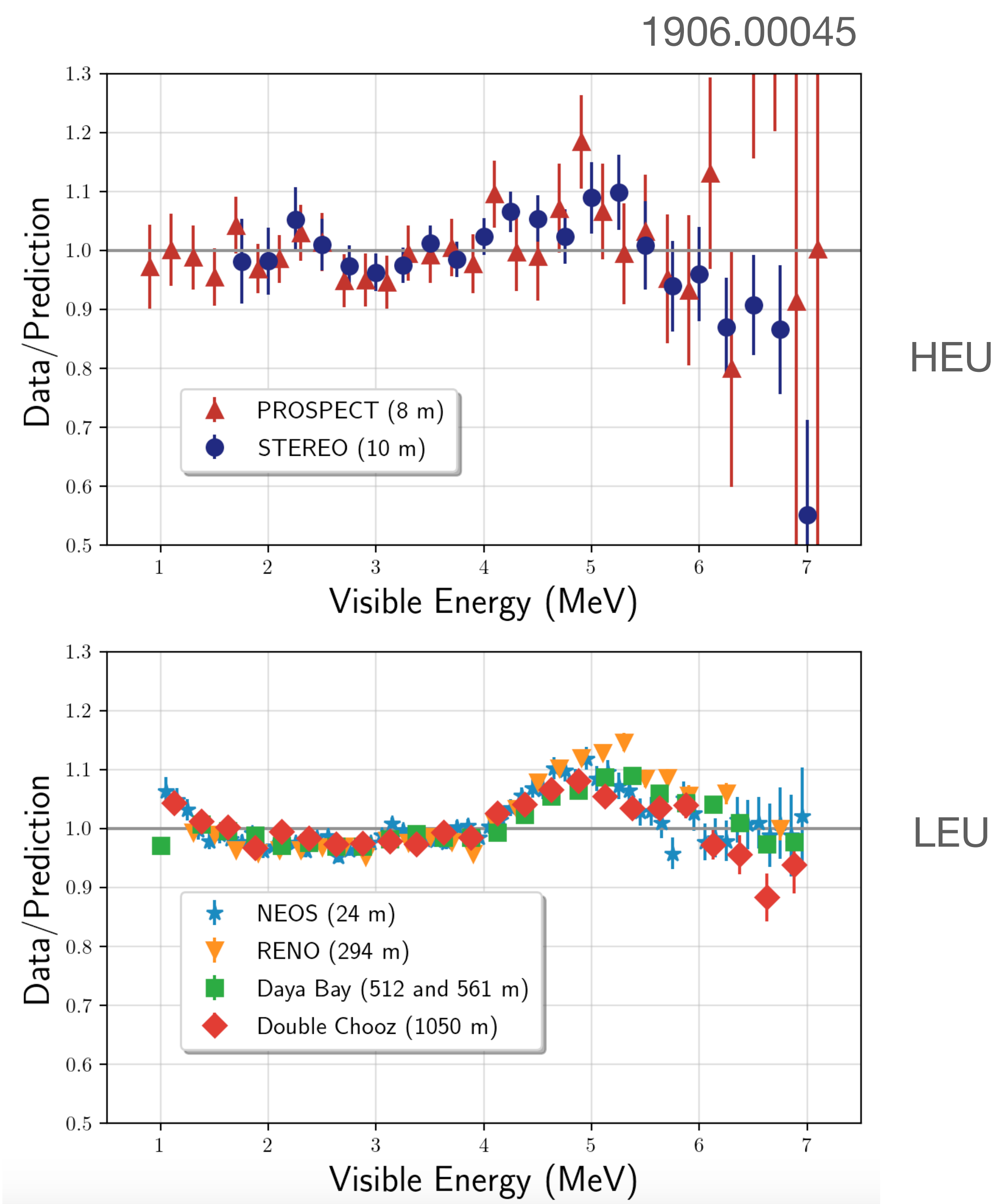
PRD 87 073008 (2013)

How to figure out the flux?

- 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.
- Conversion method
  - Relies on measurements of integral 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 (e.g. forbidden transitions and finite-size effects).
    - Also, measurements do not include ^{238}U (fission from fast-n only), which accounts for $<10\%$ of LEU flux.

Reactor flux landscape





Reactor neutrinos

Physics

- Short-baseline oscillations
- Exotic searches
- Sevens
- Electroweak physics
- Nuclear physics

Also: nuclear non-proliferation

Positives

- Very intense!
- IBD interaction channel
    - High xsec
    - Double coincidence
- Often “free”

Negatives

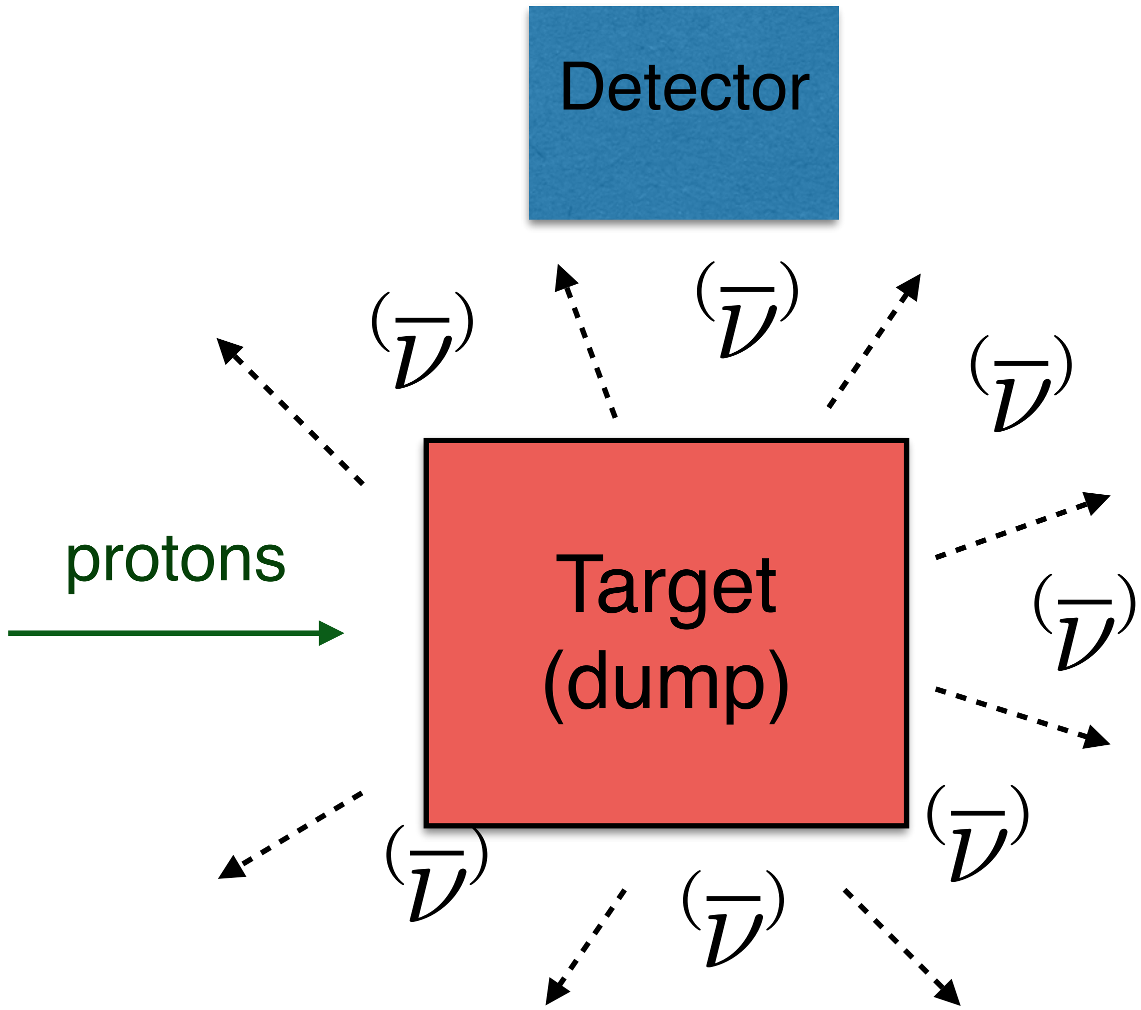
- On the surface
- “Source off” is rare (commercial only)
- Source is evolving (LEU only)
- Extended source (commercial only)
- Sometimes can’t get close

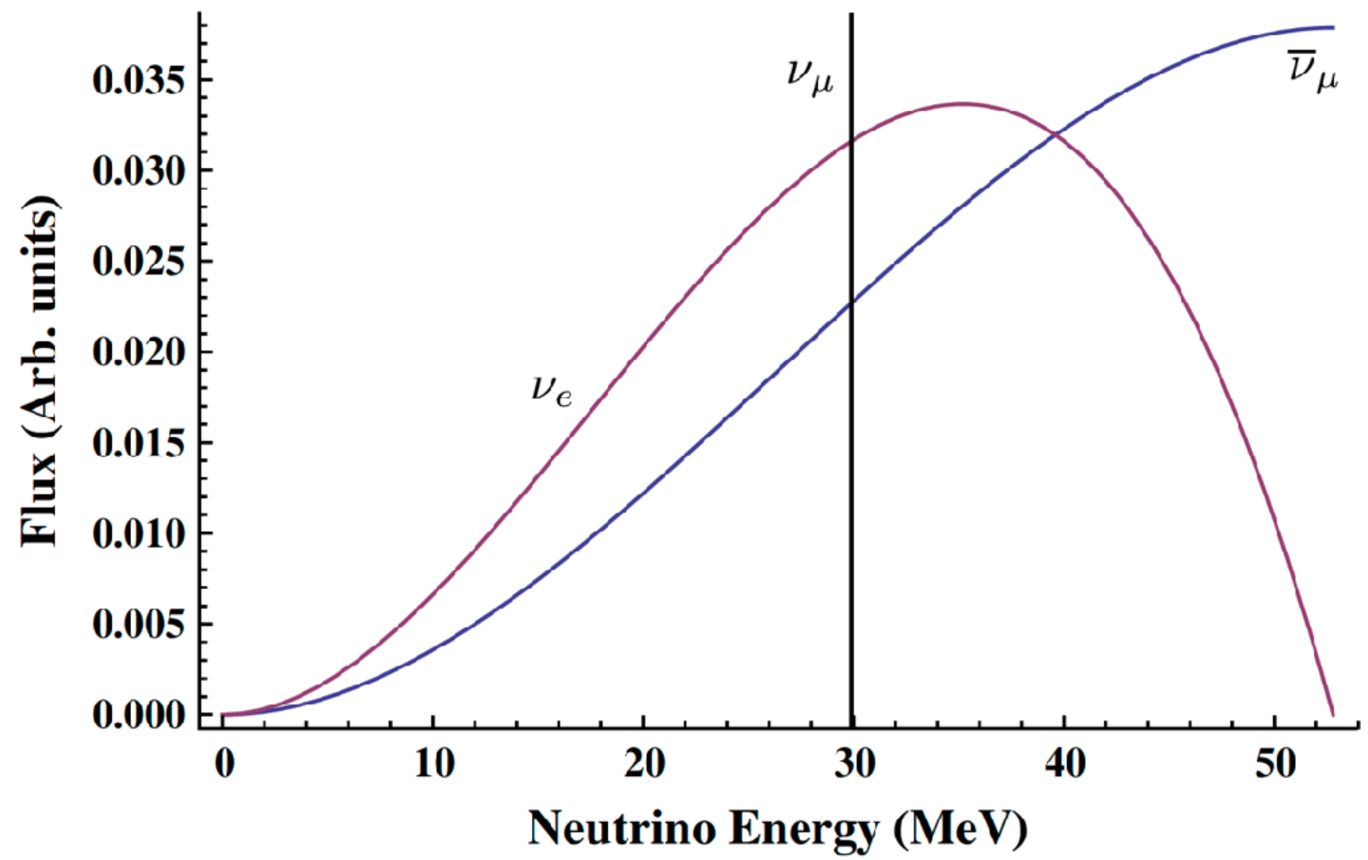
Reactor homework

- Keep pushing on reactor flux modeling (especially with new beta spectra measurements); figure out the 5-7 MeV bump, figure out the normalization.
- Build a detector that is worthy of your reactor! Reactor experiments are often (surprise!) *not* stats-limited.
- Use a reactor to measure Sevens.
- Keep measuring nuebar-elastic scattering! Where have these experiments gone? (Worldwide, we've only collected ~1000 nuebar-electron elastic scatters)
- Sit back and watch JUNO-TAO and JUNO make some amazing measurements.
- Extra credit: Build a reactor underground and couple it to an ultra-large free-proton-based detector.
- Extra credit: Predict the size of the electron antineutrino wavepacket as it is created in a reactor (which can affect oscillation probability).

Accelerator decay-at-rest neutrinos

Pion and muon decay-at-rest neutrinos

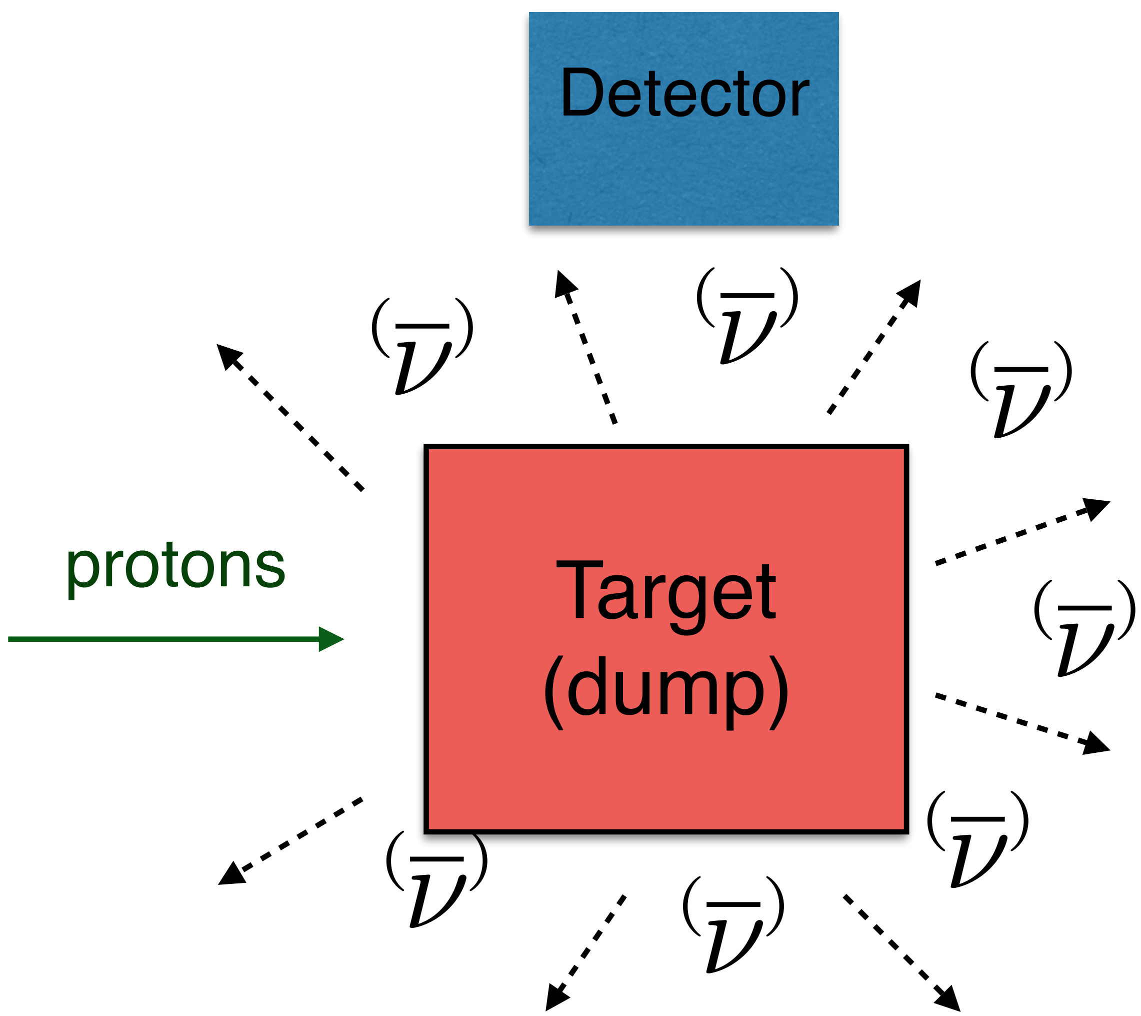


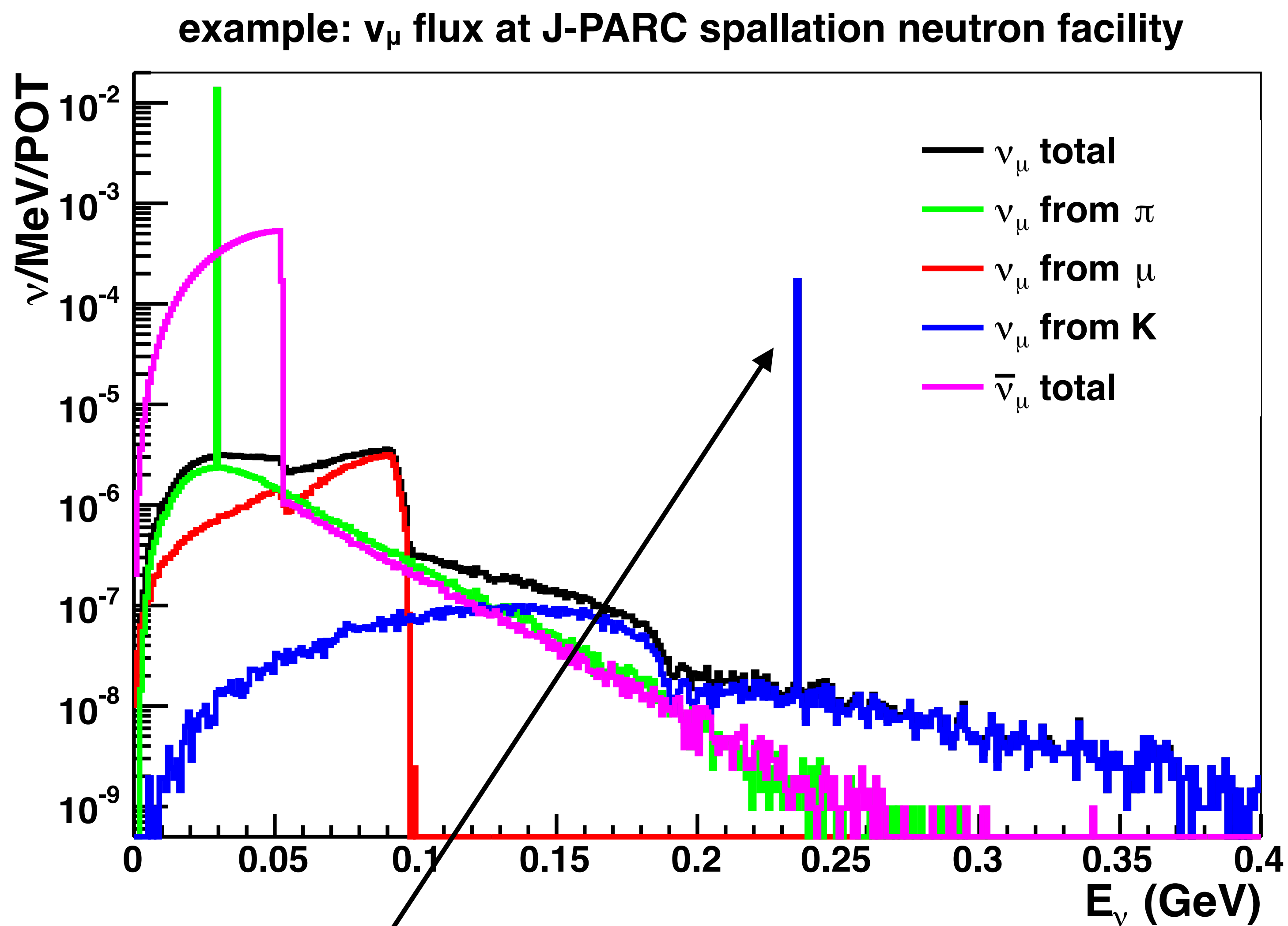


$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

Kaon decay-at-rest neutrinos

(Above 2-3 GeV primary proton energy)



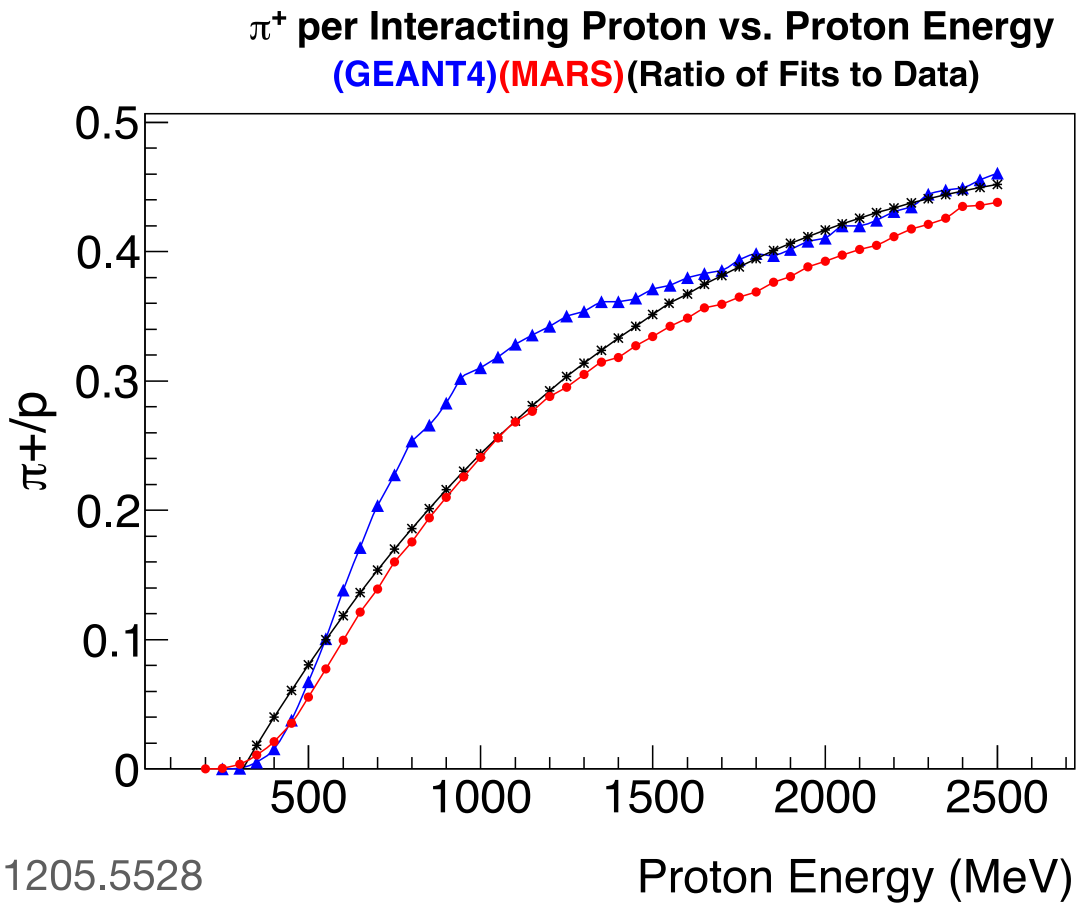


E=236 MeV if kaon decays at rest

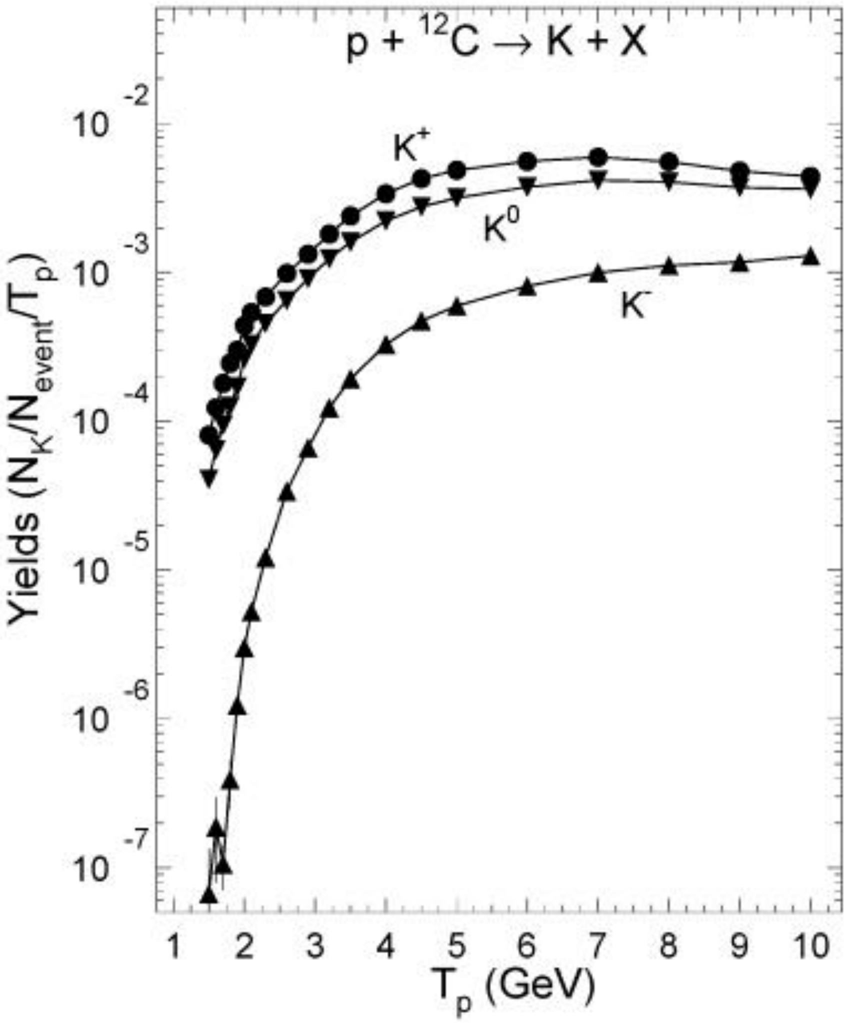
$$K^+ \rightarrow \mu^+ \nu_\mu$$ (branching ratio=64%)

Pion and kaon production

Fermilab-Conf-09-647-APC



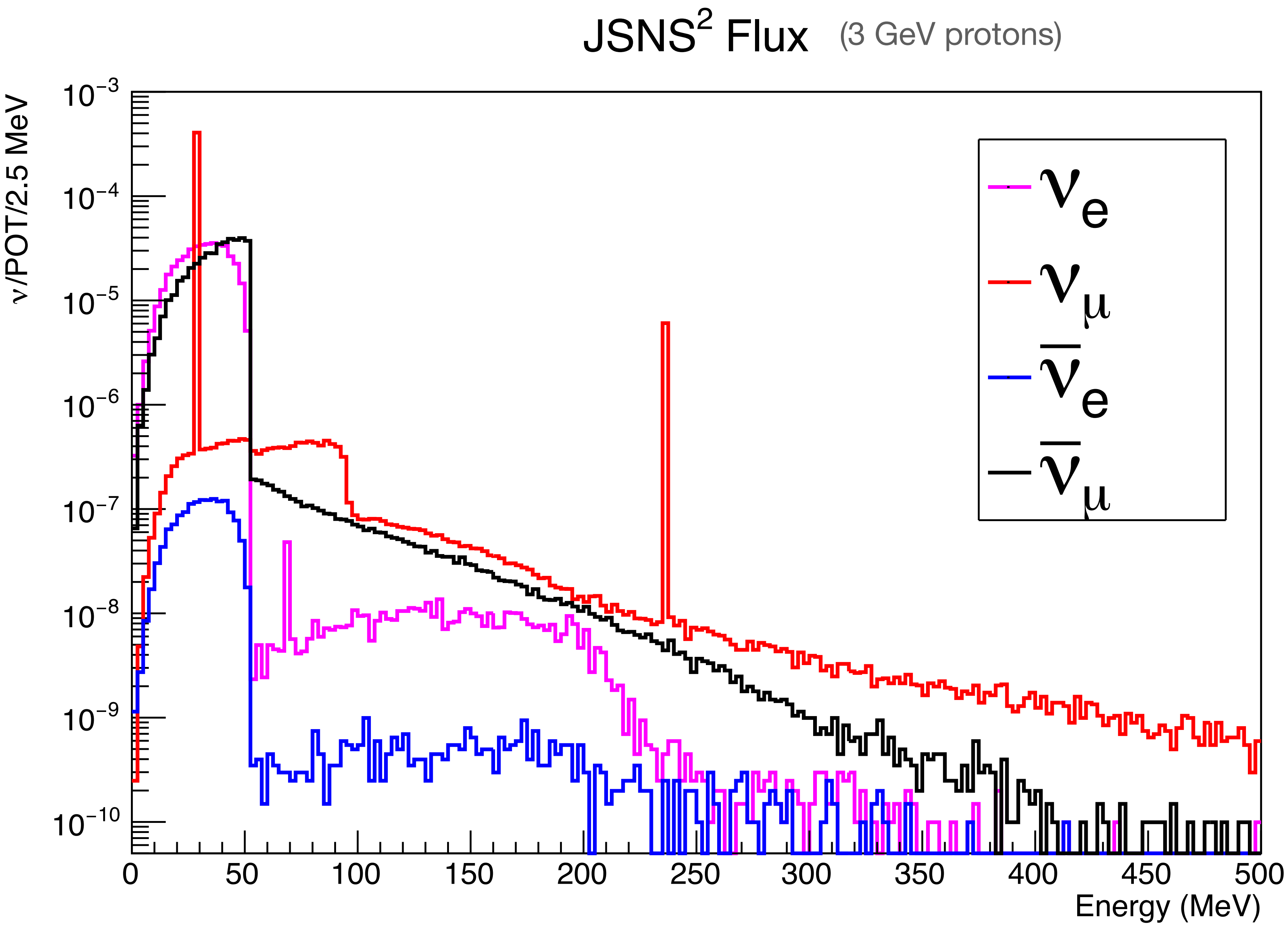
1205.5528



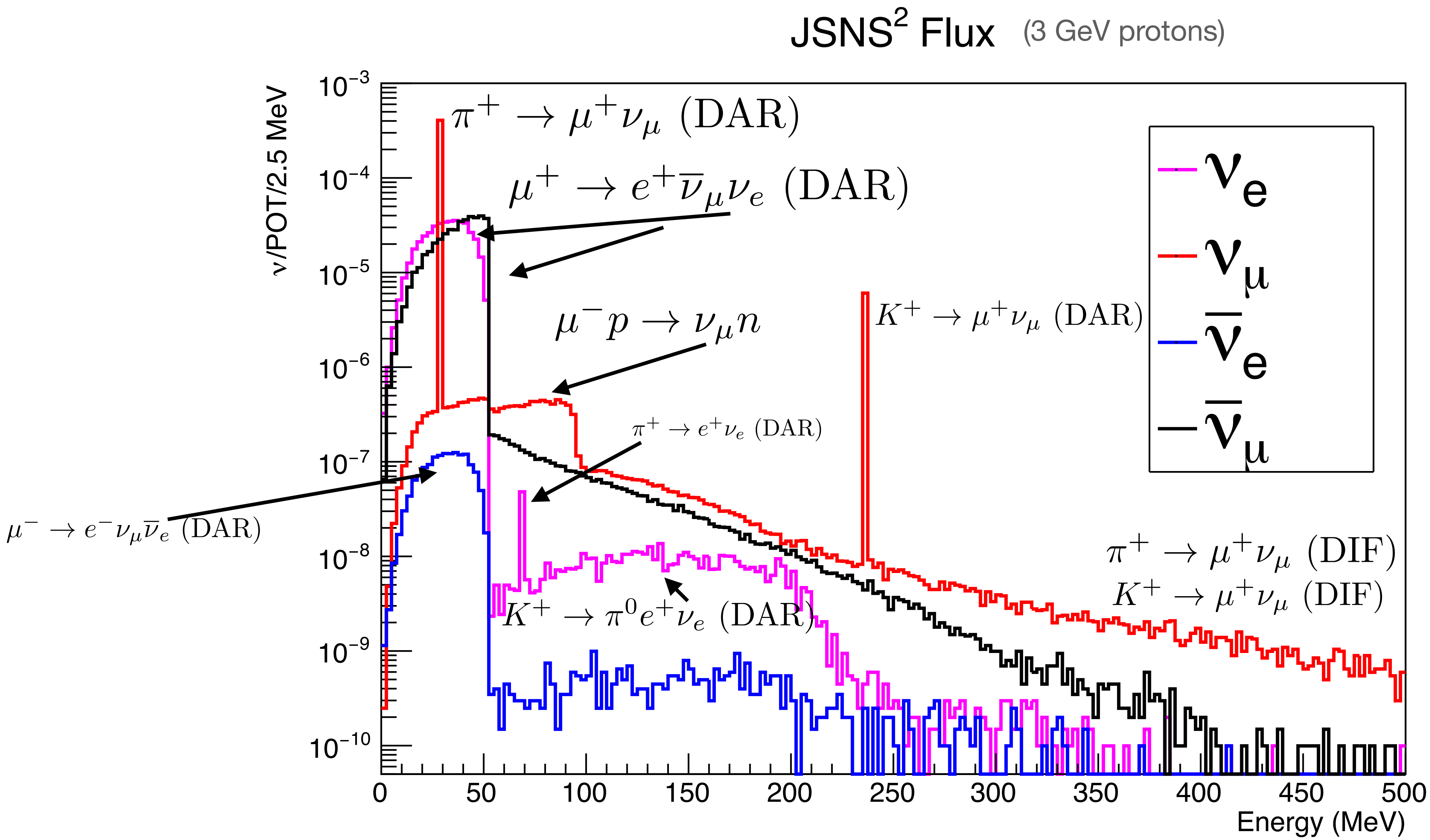
Pion production sweet spot is ~1 GeV

Kaon production sweet spot is ~5-7 GeV

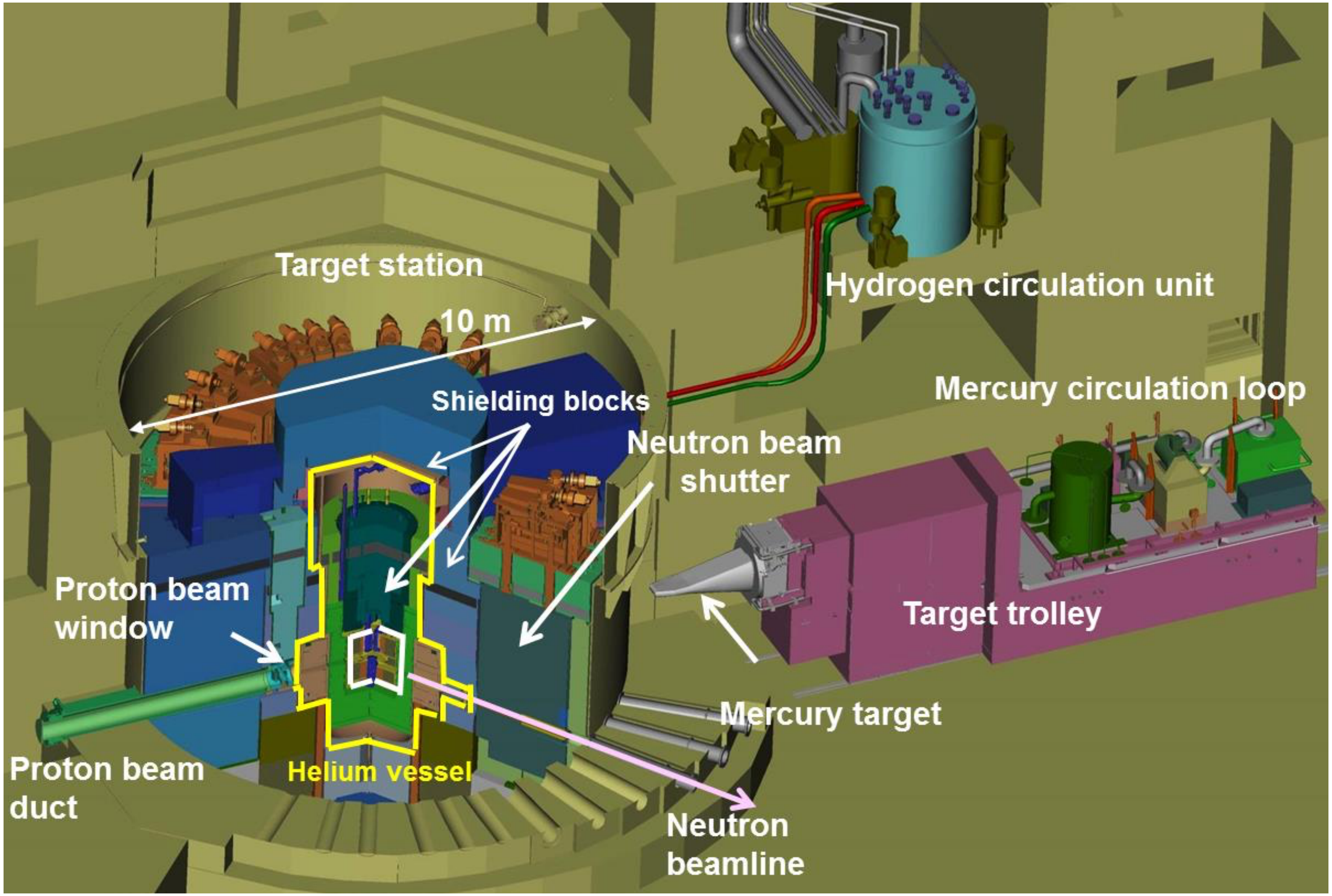
Detailed flux



Detailed flux



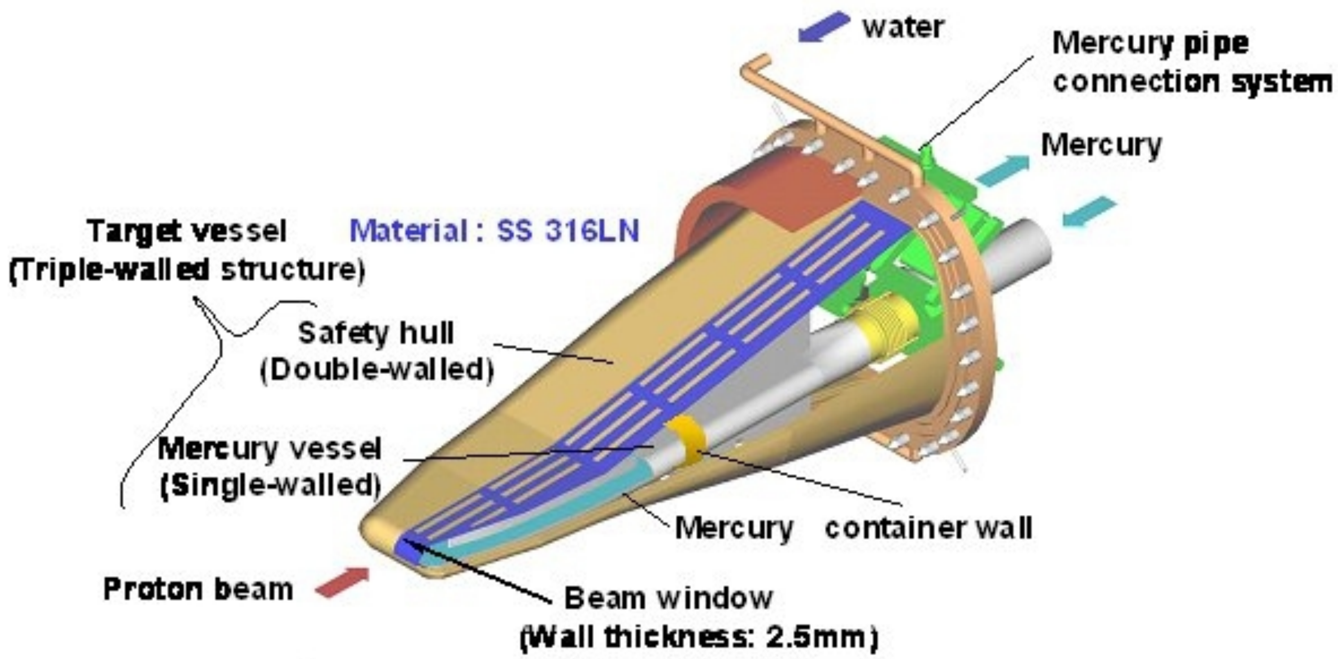
Example J-PARC Spallation Neutron Source



3 GeV protons on a mercury target @ 830 kW

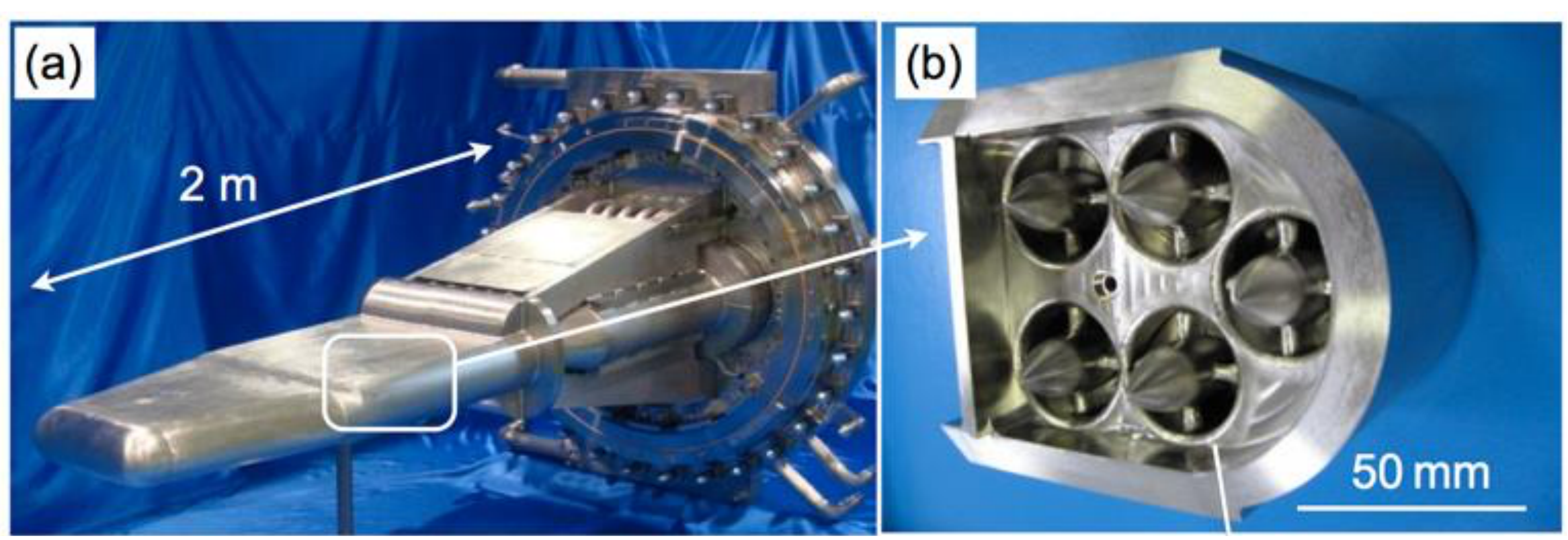
J-PARC production target

Mercury is circulated at 154 kg/s!

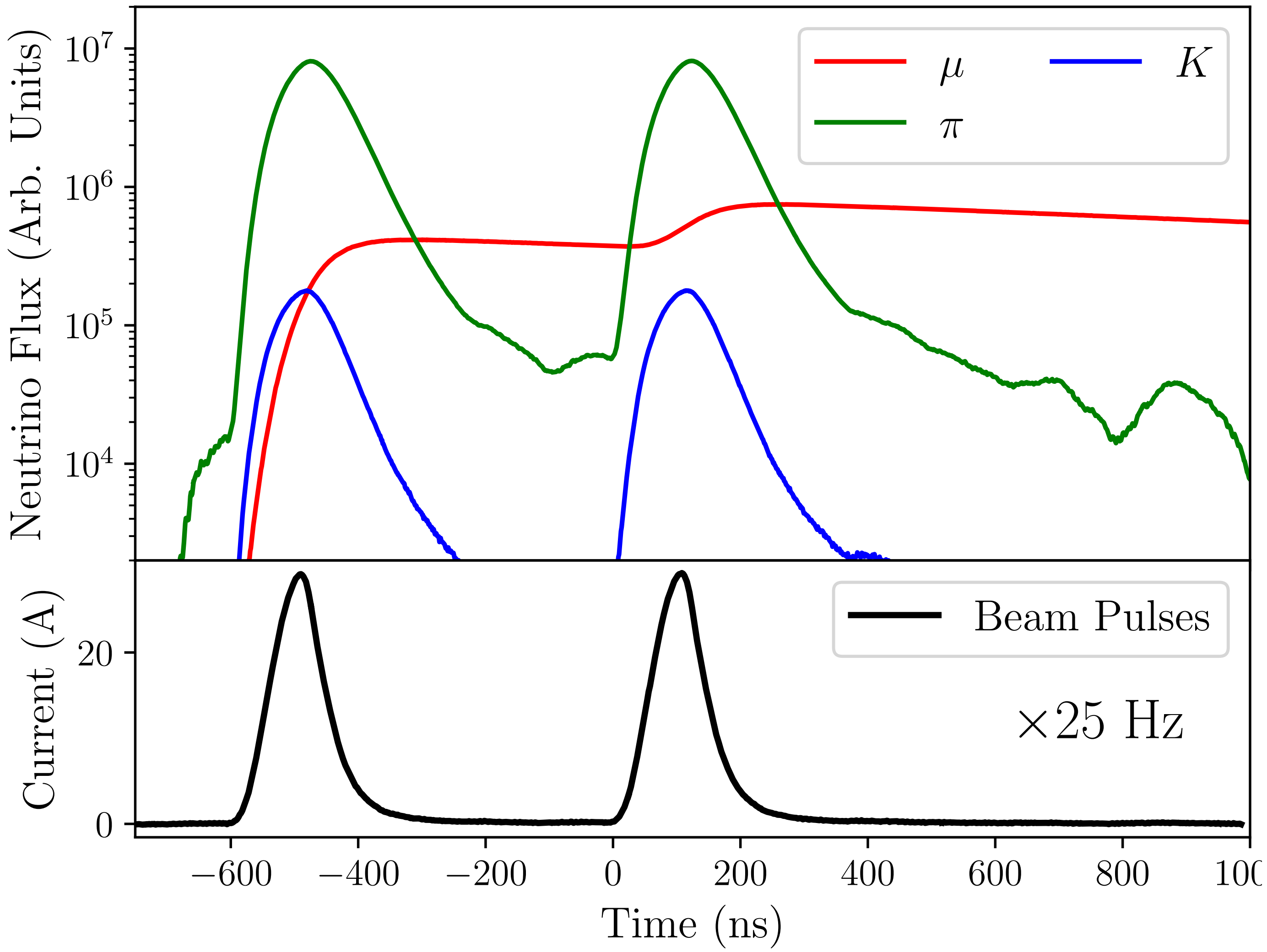


Neutron/neutrino production target is a double-walled SS vessel with circulating mercury.

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



J-PARC spallation source beam timing

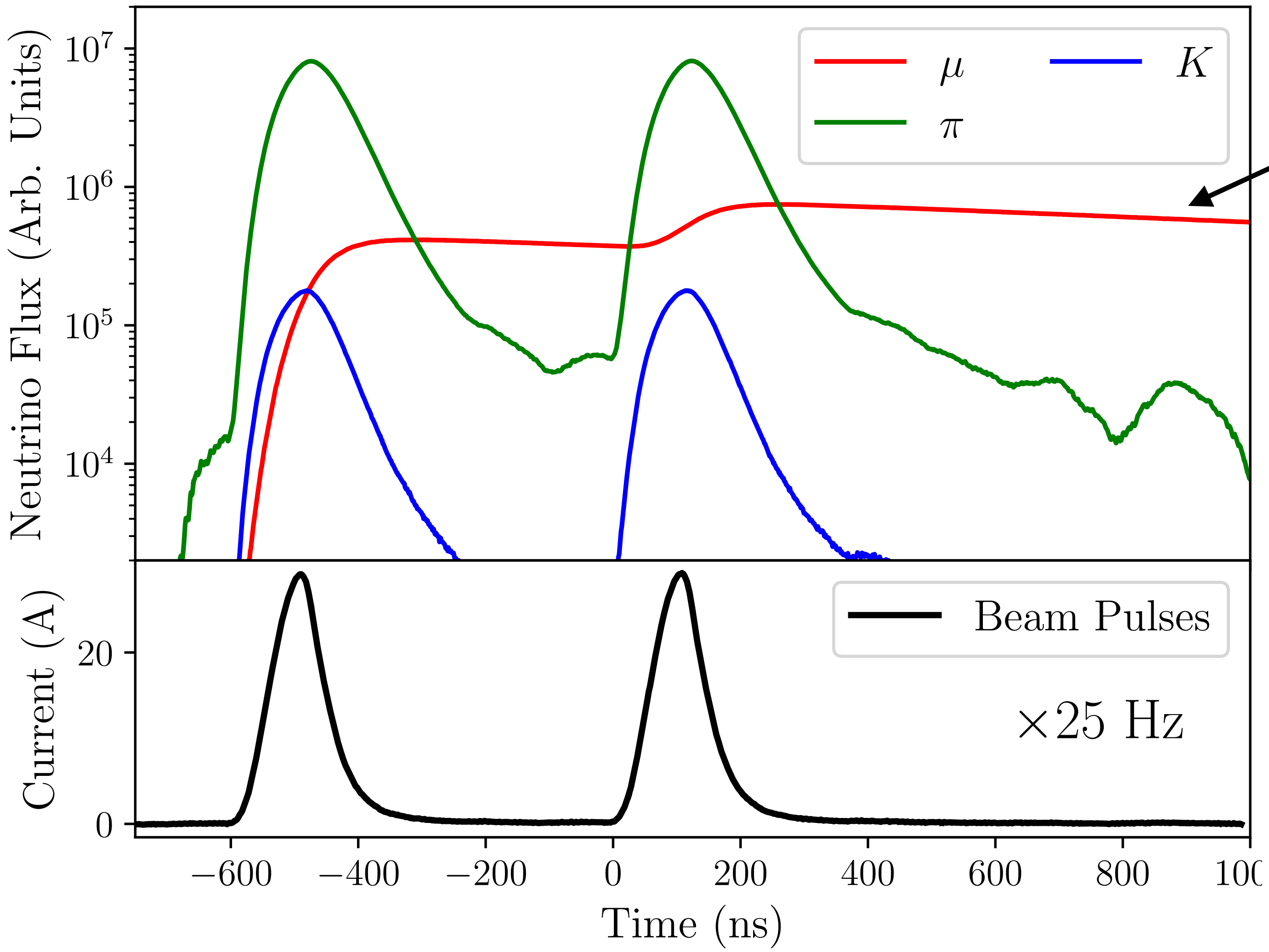


The J-PARC beam is delivered in two close pulses at 25 Hz, producing “prompt” (pion and kaon) and “delayed” (muon) neutrinos.

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

J-PARC spallation source beam timing

Note: if your physics relies on muon-indued neutrinos, you can't fully take advantage of the narrow beam window.

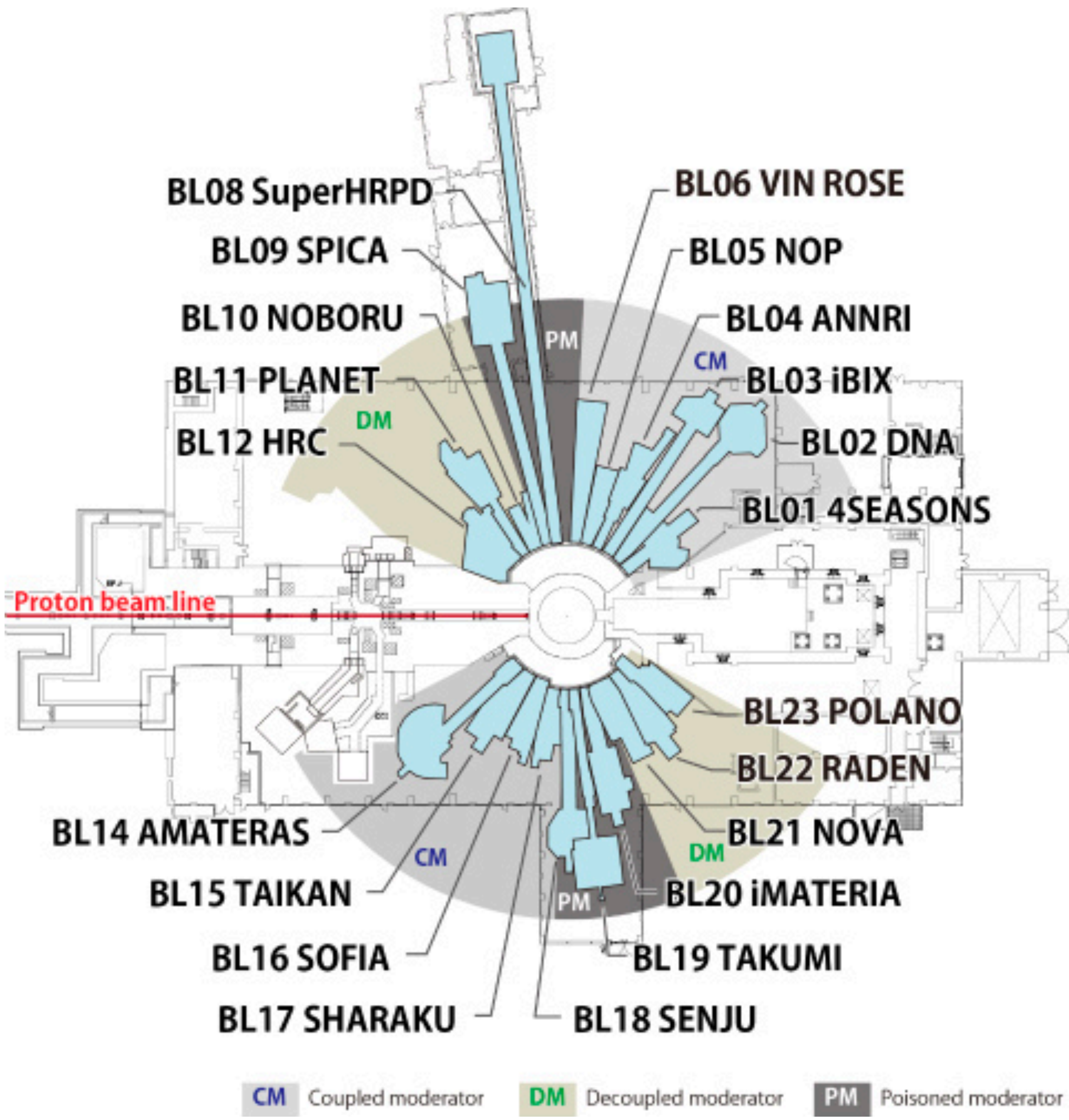


$$\mu^+ \to e^+ \overline{\nu}_\mu \nu_e \ \text{(DAR)}$$

$$\tau_\mu = 2.2\ \mu\text{s}$$

Spallation neutron source facilities issues

The world's most intense sources of accelerator-based neutrinos
were not really made to host neutrino experiments



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

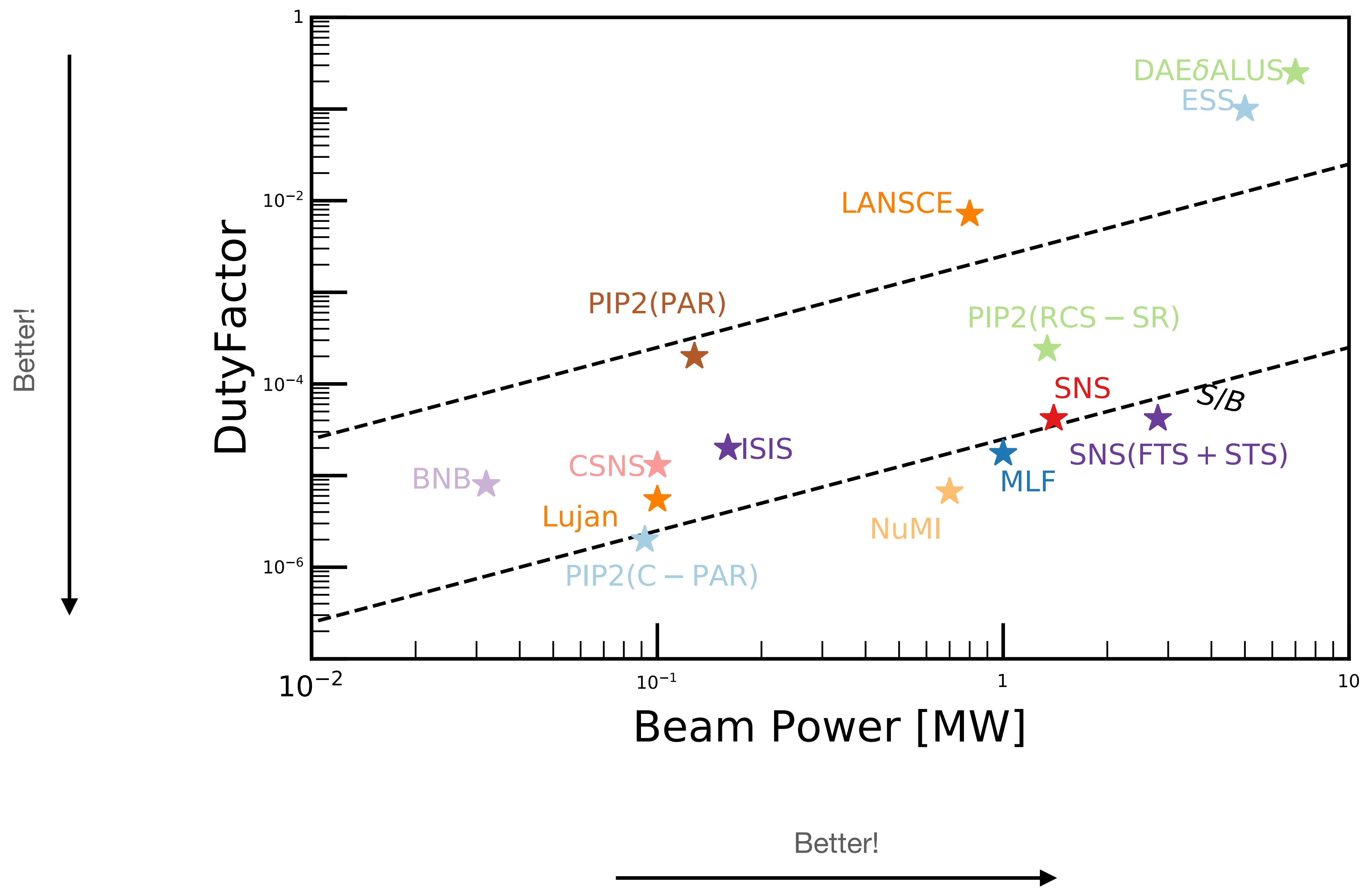
JSNS² (at the J-PARC MLF) needs to remove their full detector and 50 tons of liquid scintillator (separately) every year so that the target maintenance area can be accessed.

JSNS² is on the third floor of the MLF.

COHERENT is inside "Neutrino alley", a service corridor.

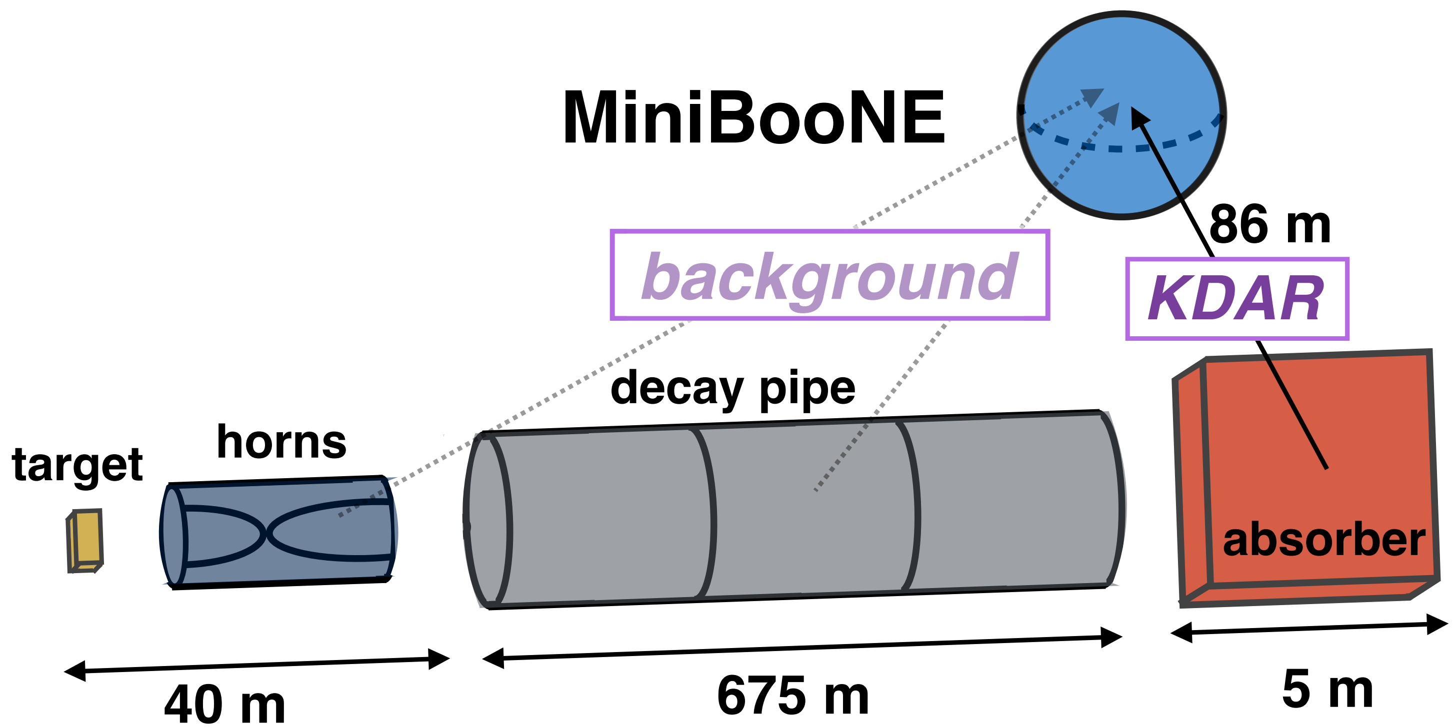
Beam characteristics

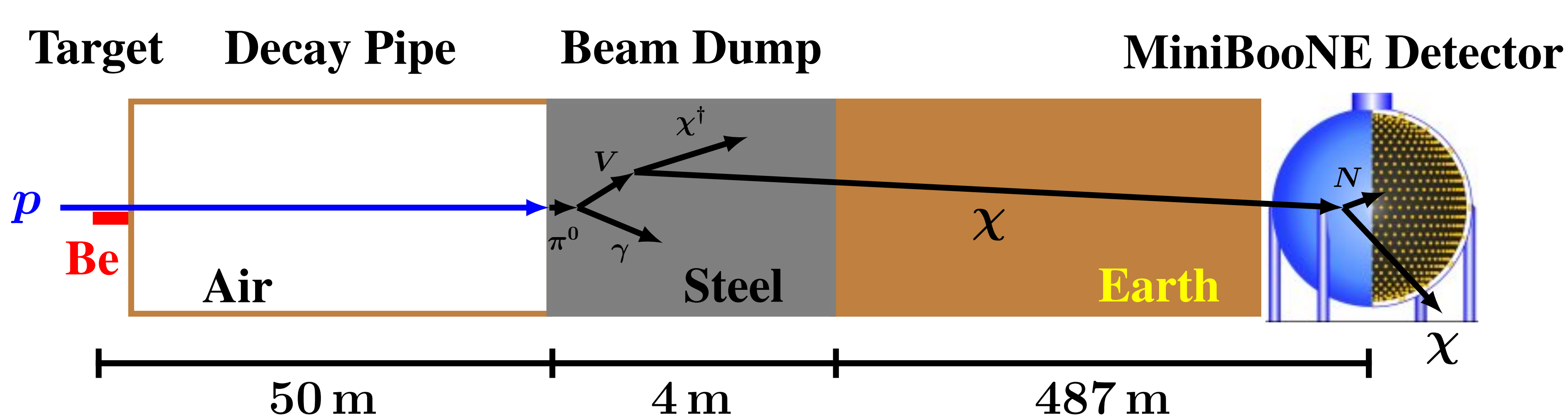
2103.00009, 2203.08079



Sneaky decay-ay-rest sources

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





Accelerator decay-at-rest neutrinos

Physics

- Short-baseline oscillations
- Sevens
- Exotic searches
- Neutrino xsec (for supernova and oscillations)
- Electroweak physics
- Nuclear physics

Positives

- Very intense!
- Beam duty factor (timing)
- Very pure
- Knowledge of flux is high

Negatives

- Isotropic source
- Facility issues are common
- Hard to get close to the source
- Sometimes need supplemental shielding

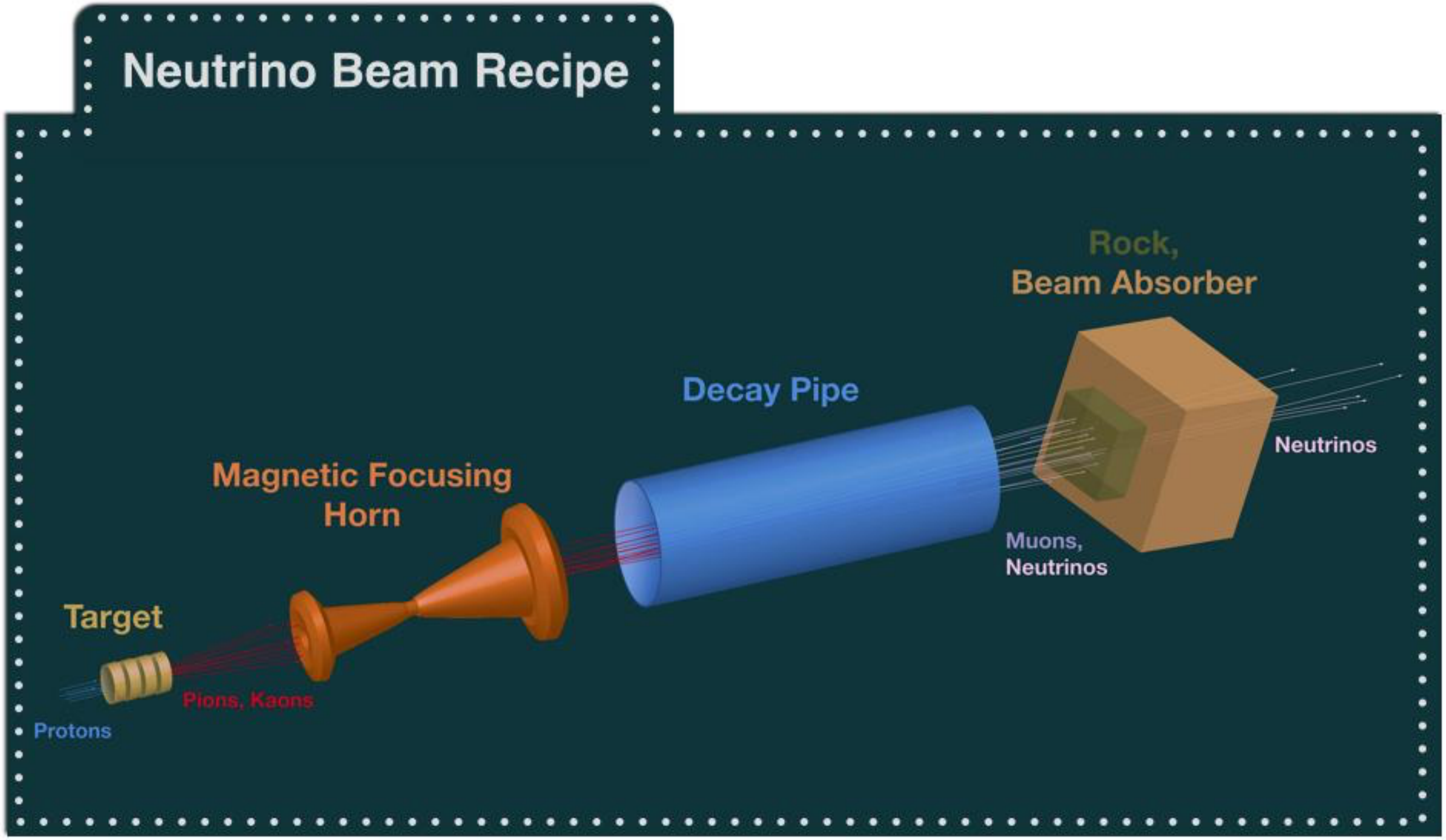
Accelerator decay-at-rest homework

- Take full advantage of the existing DAR sources!
  - Example: there exists no sevens experiment at the J-PARC MLF! The ORNL SNS second target station already exists. Hint: it's in Japan.
- Put more detectors at existing DAR sources!
- Explore more dedicated beam-off-target (DAR) running at DIF beams (ala MiniBooNE off-target running).
- Keep thinking about DAR physics at nominally-DIF sources.
  - Already, there have been many PRLs coming from this beam dump physics!
- Continue to look for exotic particle production at DAR sources.
- Extra credit: Build a dedicated DAR source at Fermilab (w/ no facilities issues, optimized target).

Accelerator decay-in-flight neutrinos

(short- and long-baseline)

Creating a neutrino beam

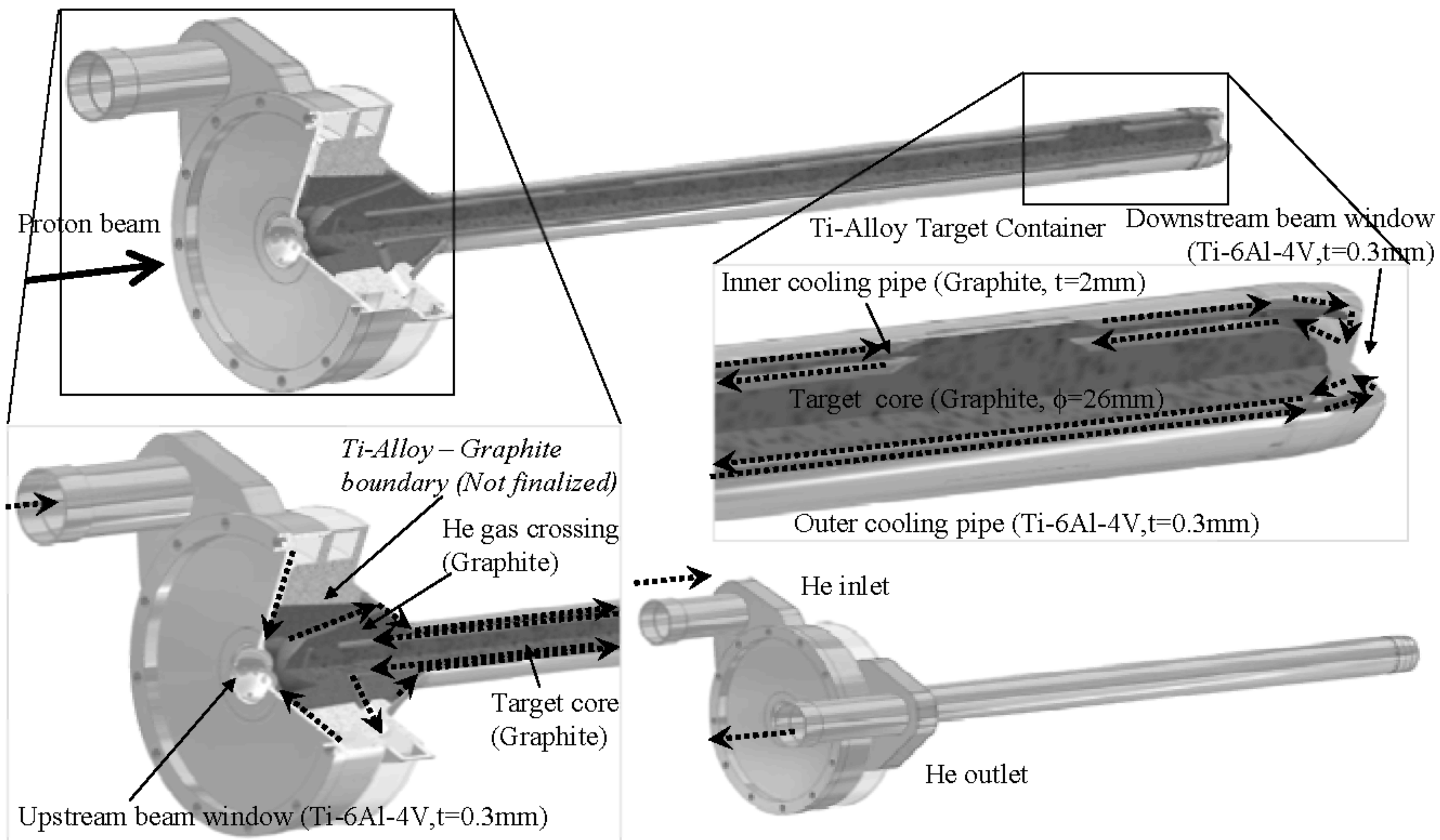


Neutrino beam $\pi^+ \to \mu^+ \nu_\mu$

Antineutrino beam $\pi^- \to \mu^- \overline{\nu}_\mu$

Target

Target design is pretty similar throughout the world.
There are various cooling techniques, though.

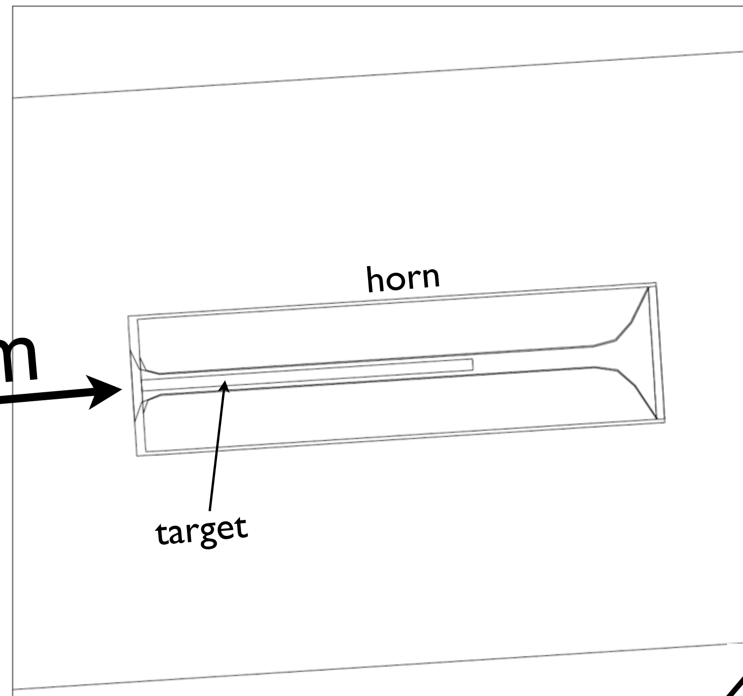


T2K target design

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.

Creating a neutrino beam

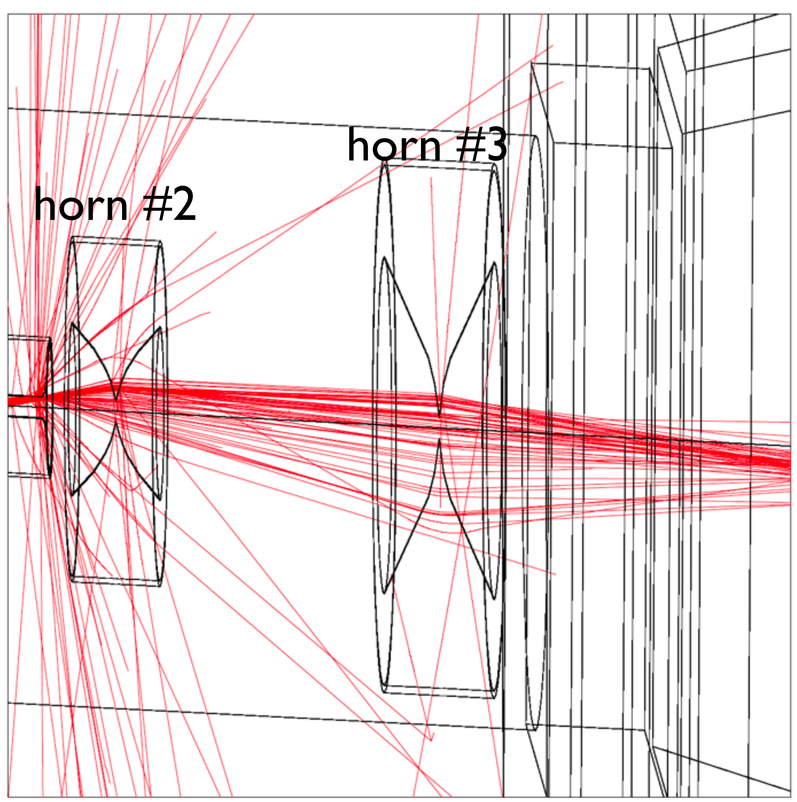
proton beam

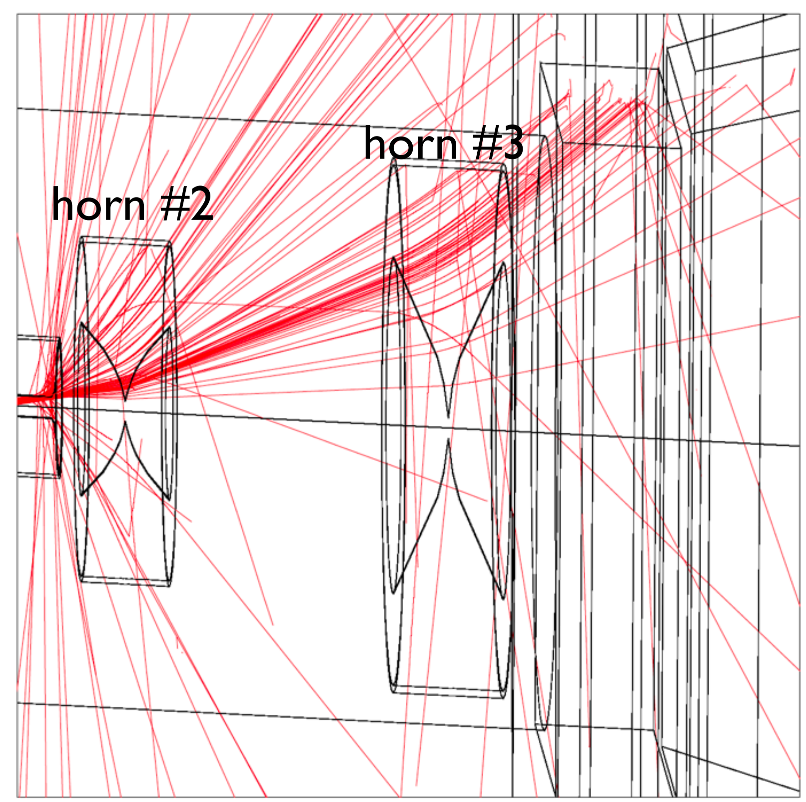


pion

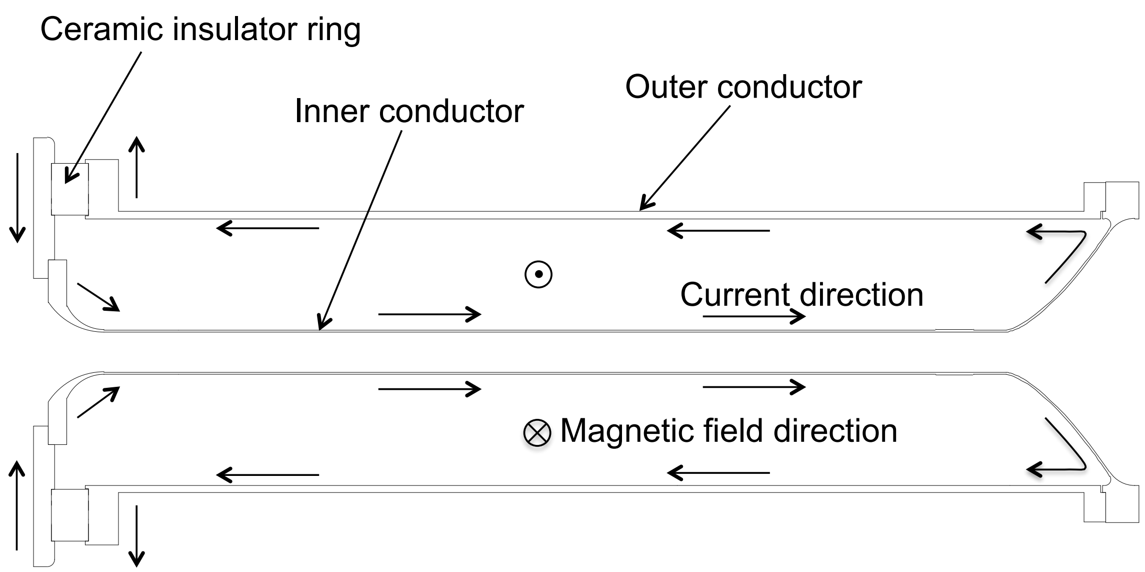
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

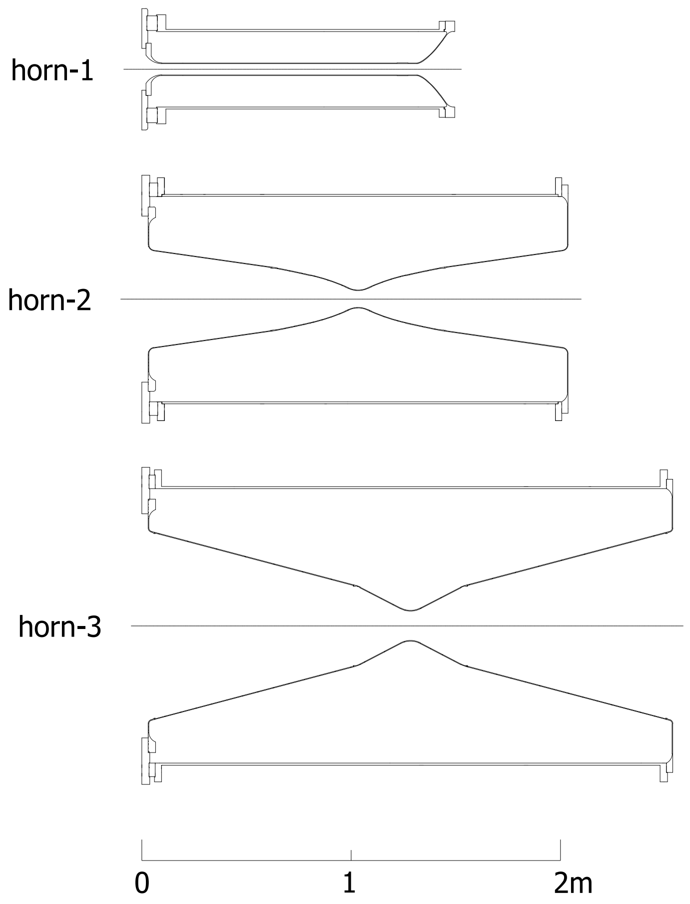
$$\pi^- \rightarrow \mu^- \overline{\nu}_\mu$$





The horns (big electromagnets)

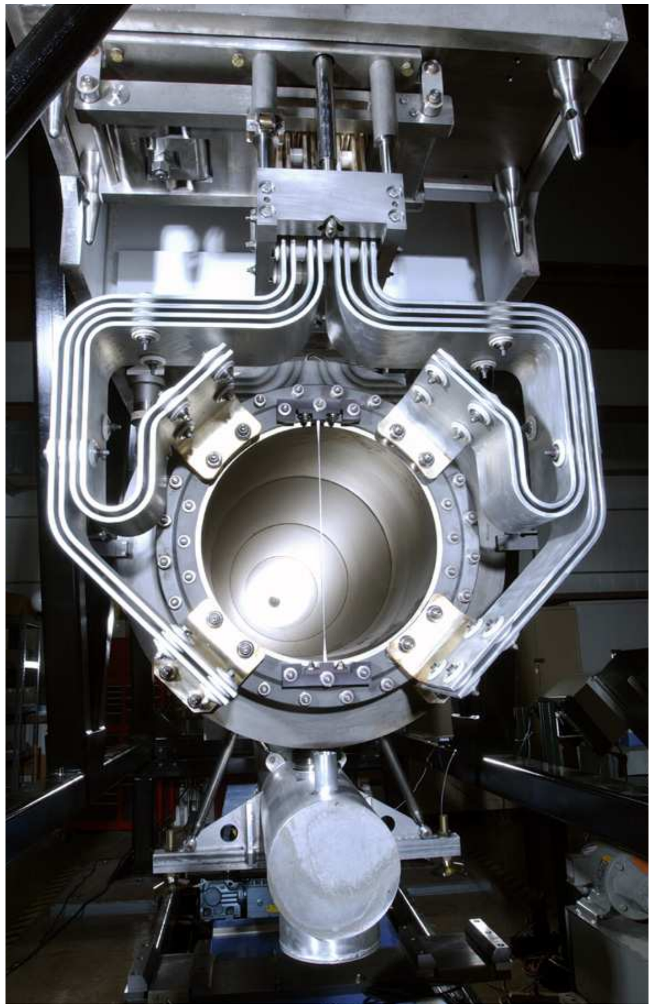




T2K horns

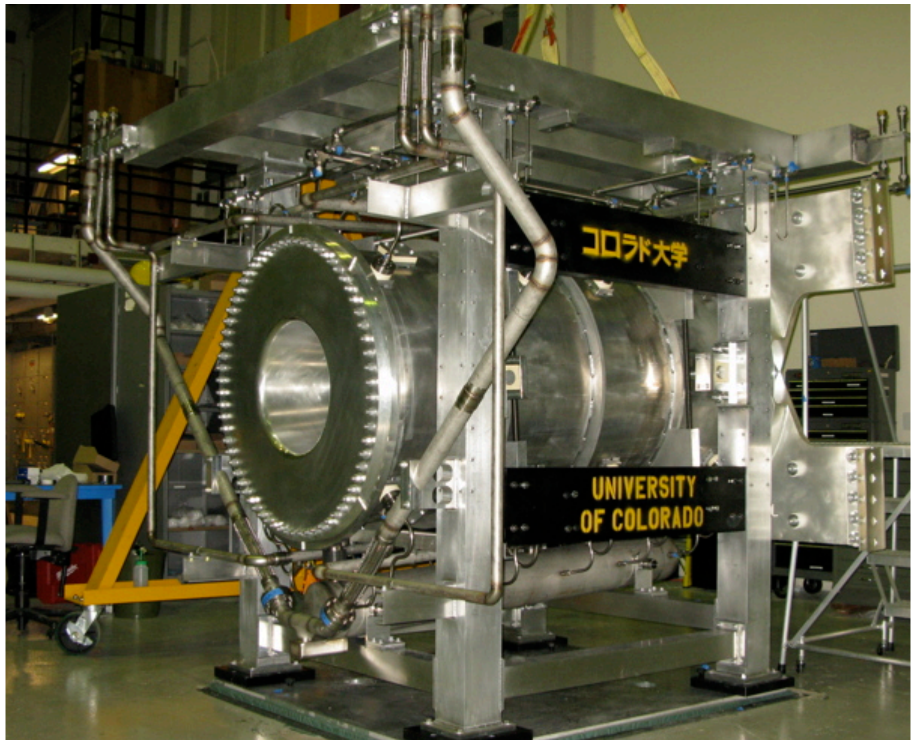
The horns (big electromagnets)

1507.06690



NuMI horn 2

1502.01737

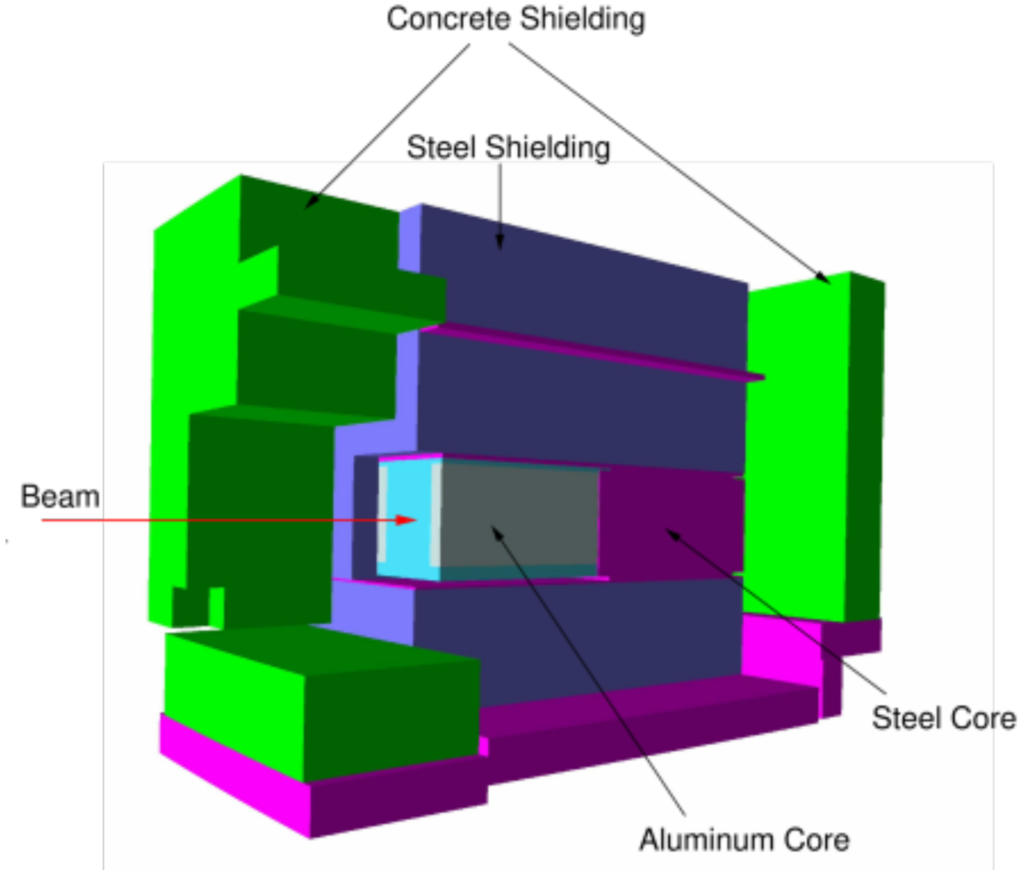


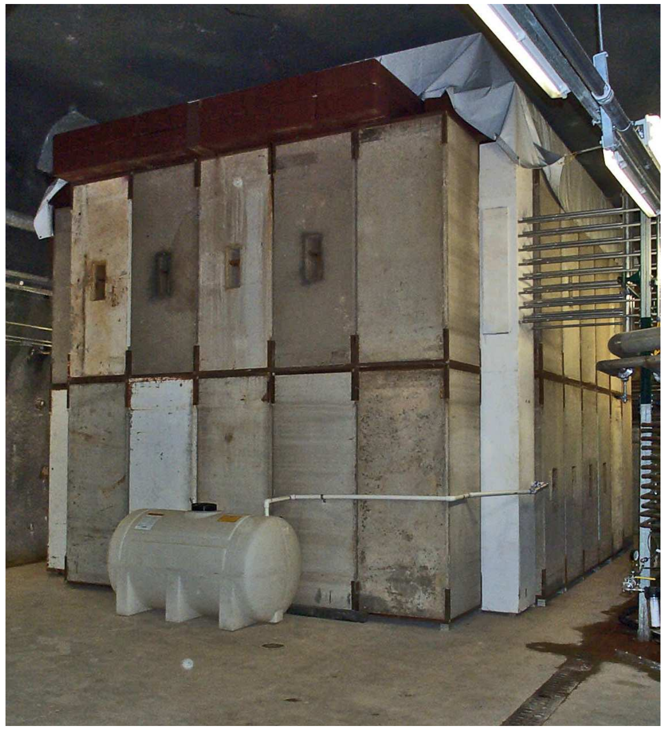
T2K horn 2

Decay pipe and absorber

NuMI example

1507.06690

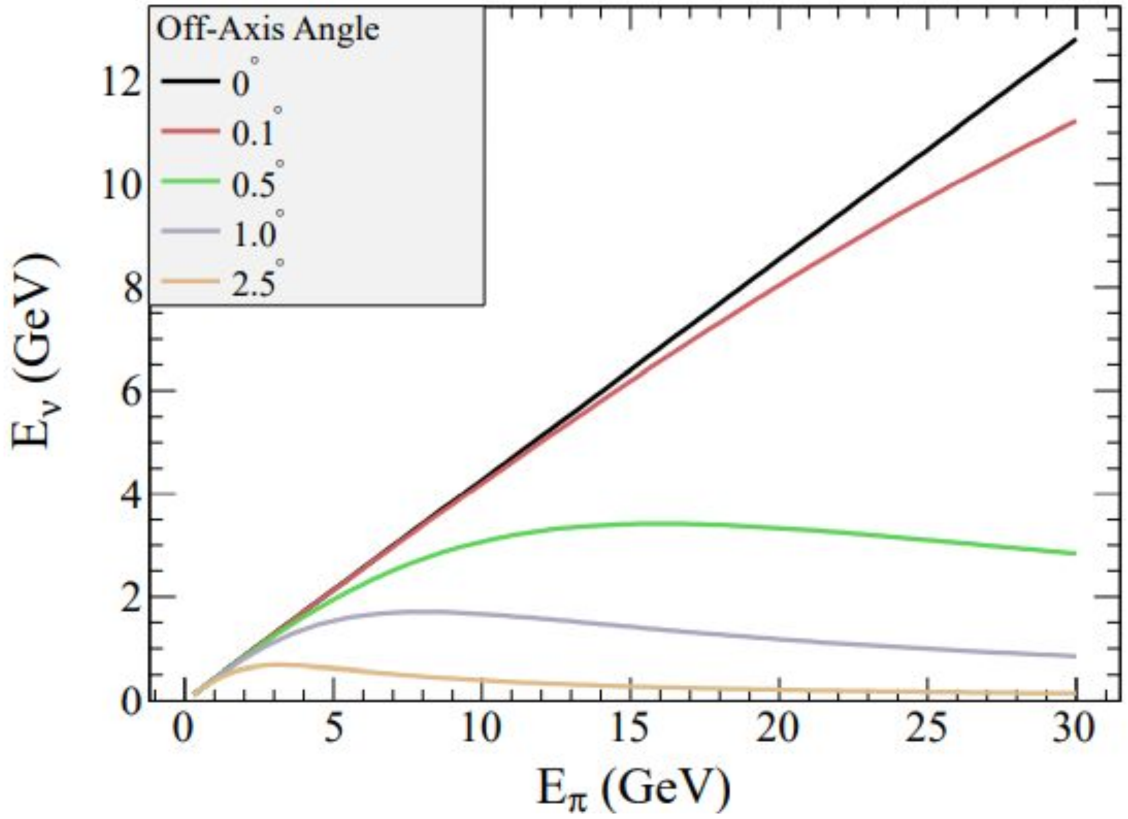


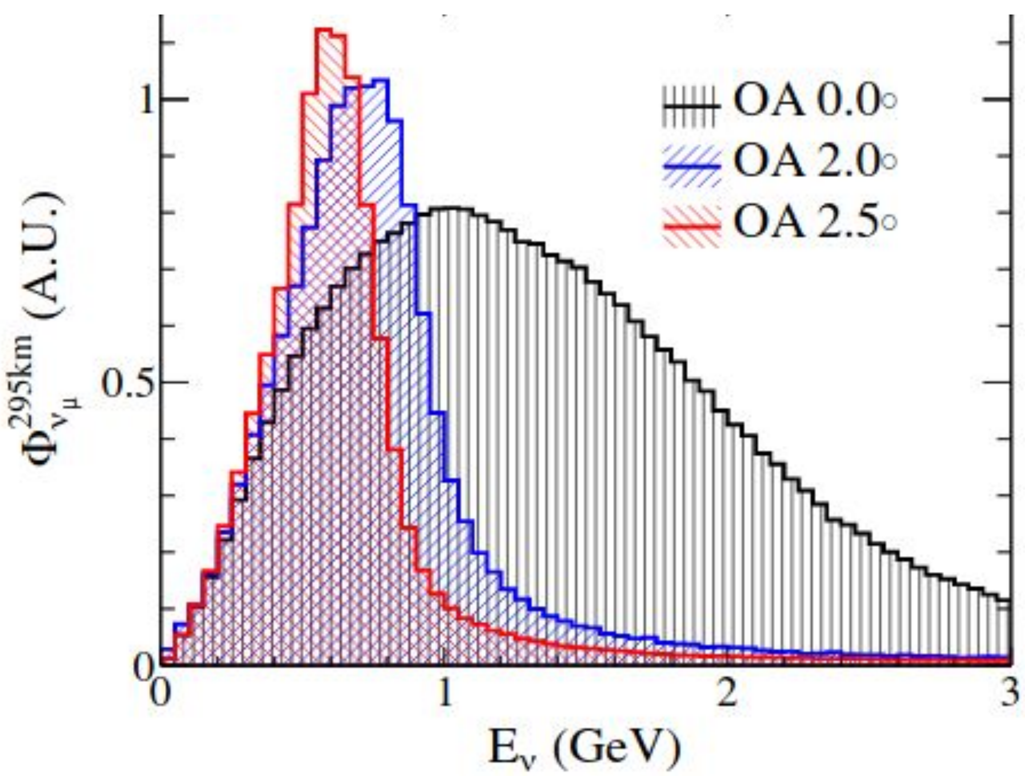


Off-axis technique

Placing your detector off-axis provides a more narrow-band beam.

T2K example





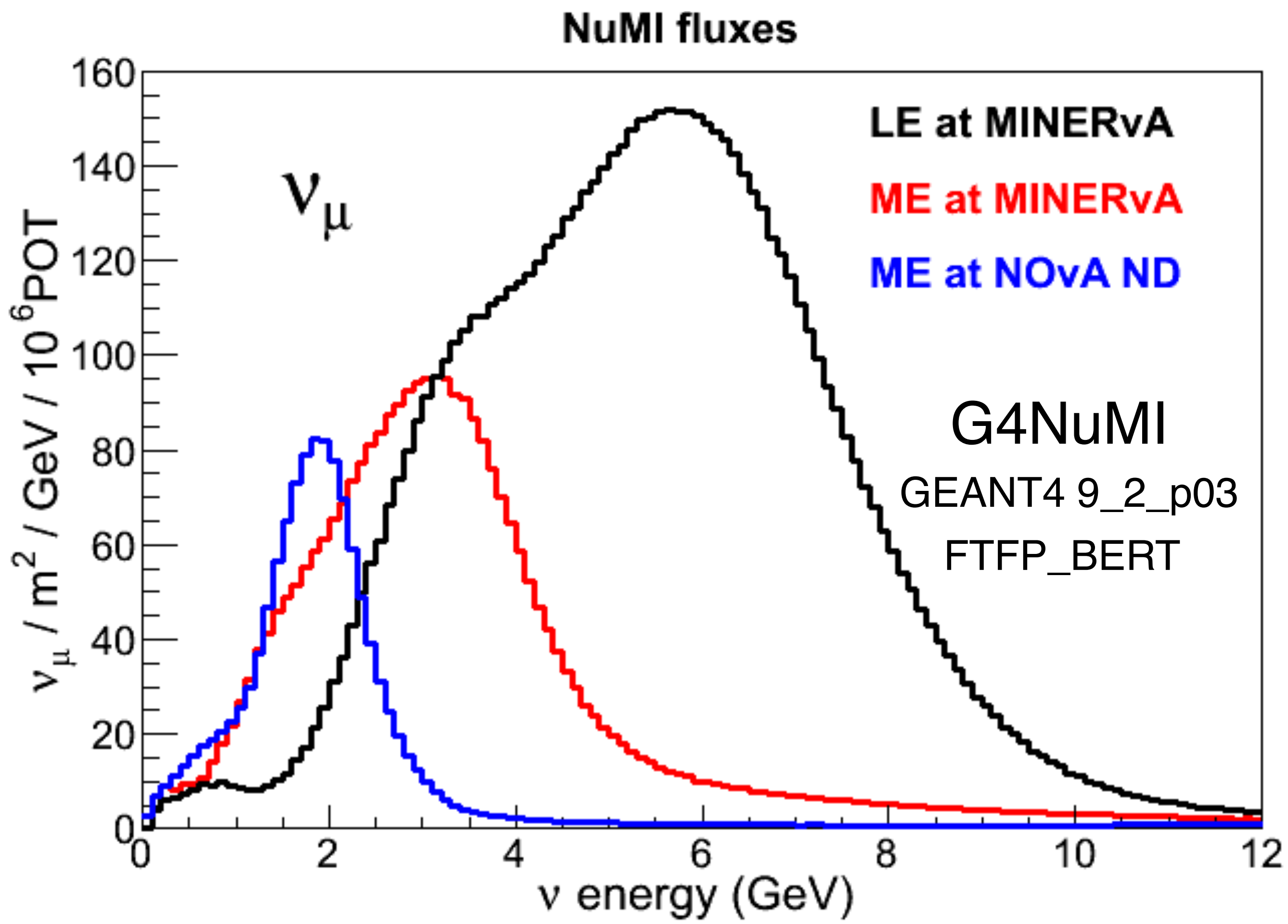
Examples of long-baseline off-axis experiments: T2K, NOvA

Examples of long-baseline on-axis experiments: MINOS, LBNF

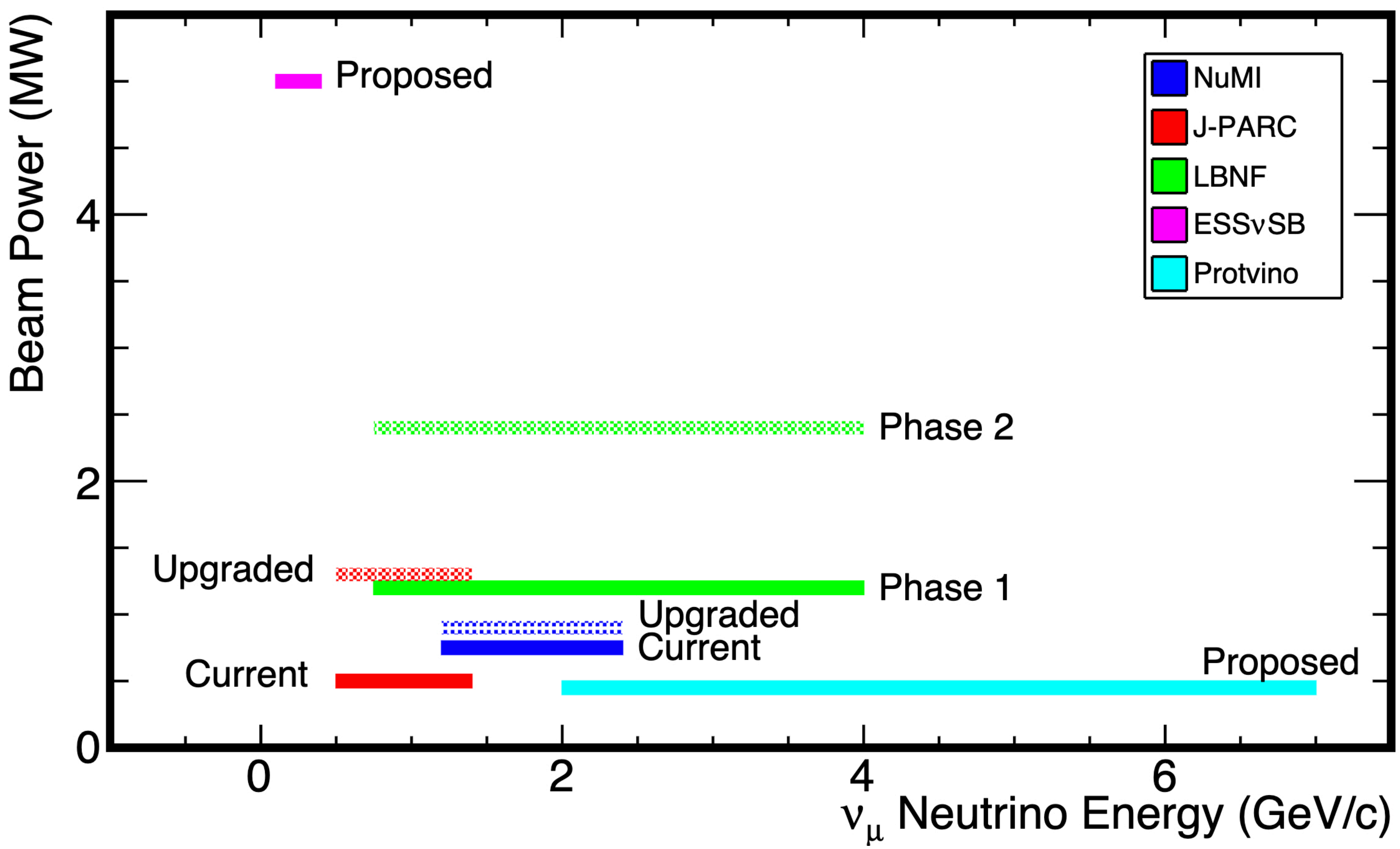
Modifying the beam characteristics

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.
Decay pipe modifications have also been envisioned (BNB).



Current and future long-baseline beams

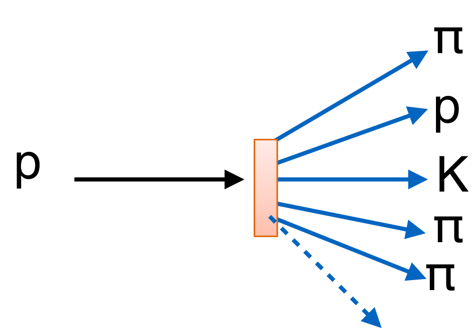


Predicting the flux

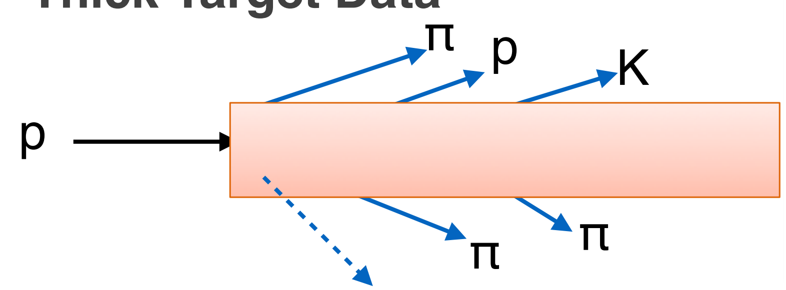
- Predicting the DIF neutrino flux can be very challenging!
  - How many pions/kaons are produced?
  - What are the kinematics (positions and momenta) of the pions/kaons as they exit the target?
  - How do the pions/kaons bend in the combination of horns?
  - What about the post-target materials that the pions/kaons interact with (target cooling, horn conductors, horn cooling, decay pipe cap, target station and decay pipe atmosphere, peripherals)?

There is an impressive worldwide program of dedicated hadron production experiments trying to understand the properties of pions/kaons as they exit the target

Thin Target Data



Thick Target Data



Example: NA61/SHINE experiment data is now used by T2K—>reduced flux uncertainty from 10% to 5% near peak.

Accelerator decay-in-flight neutrinos

Physics

- Short-baseline oscillations
- Long-baseline oscillations
- Exotic searches
- Tau neutrinos
- Neutrino xsec (for supernova and oscillations)
- Electroweak physics
- Nuclear physics

Positives

- Very intense!
- Beam duty factor (timing)
- Focused beam
- Can switch between neutrinos and antineutrinos.
- Can modify beam spectra for emphasizing particular physics (e.g. higher energy for tau neutrinos).

Negatives

- Flavor content is less pure.
- Energy spectra less well understood.
- Beam-based backgrounds can be significant (may need fancy detector).

Accelerator decay-in-flight homework

- Supplement fancy near detectors with hadron production measurements.
- Shoot more protons at the target, but make sure the target doesn't blow up.
  - Pay attention to the accelerator physics upstream of the target!
- Keep optimizing the beamlines (there are lots of knobs).
  - Remember: If your horn tweak results in a 10% increase in flux, that's the equivalent to adding 10% mass to the far detector.
  - Make sure your beamline properties are well-matched to your detector abilities (and oscillation maxima/minima).
- Keep thinking of new ways to understand and take advantage of these beams (recent example: NuPRISM concept). There are more good ideas out there!
- Extra credit: Don't forget to look for dark matter and other exotic stuff.

Radioactive isotope neutrinos

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: $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$
- Other sources are also possible (^{65}Zn, ^{37}Ar, ^{144}Ce, …)

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

	^{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

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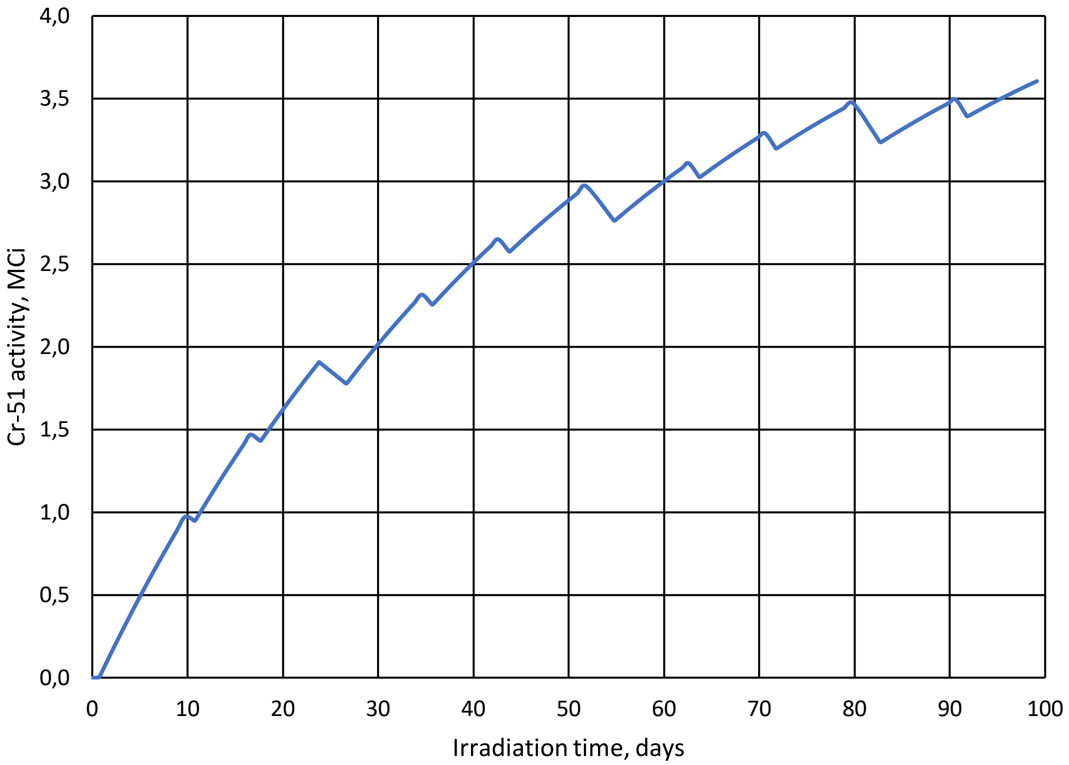
$$\tau_{1/2} = 27.7 \text{ days}$$

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



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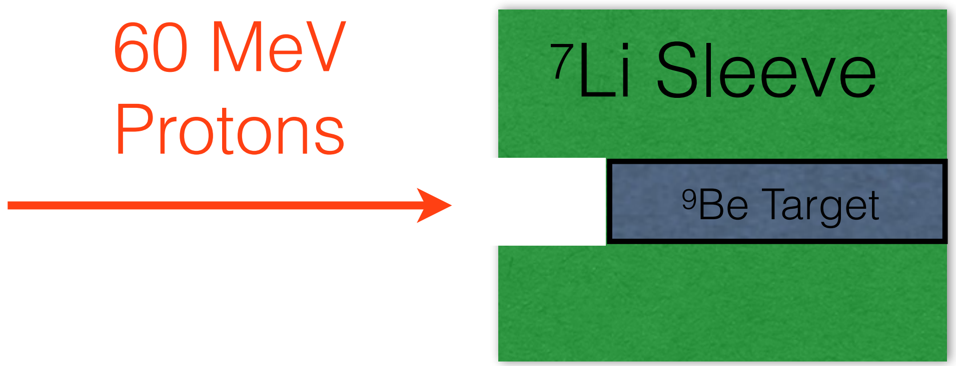
IsoDAR

An “online” radioactive isotope source

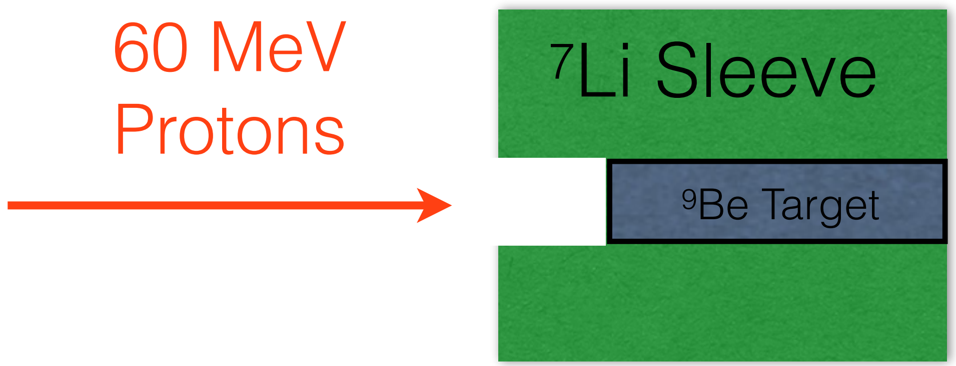
The IsoDAR concept

Produce energetic neutrinos with an extremely well understood energy spectrum



The IsoDAR concept

Produce energetic neutrinos with an extremely well understood energy spectrum

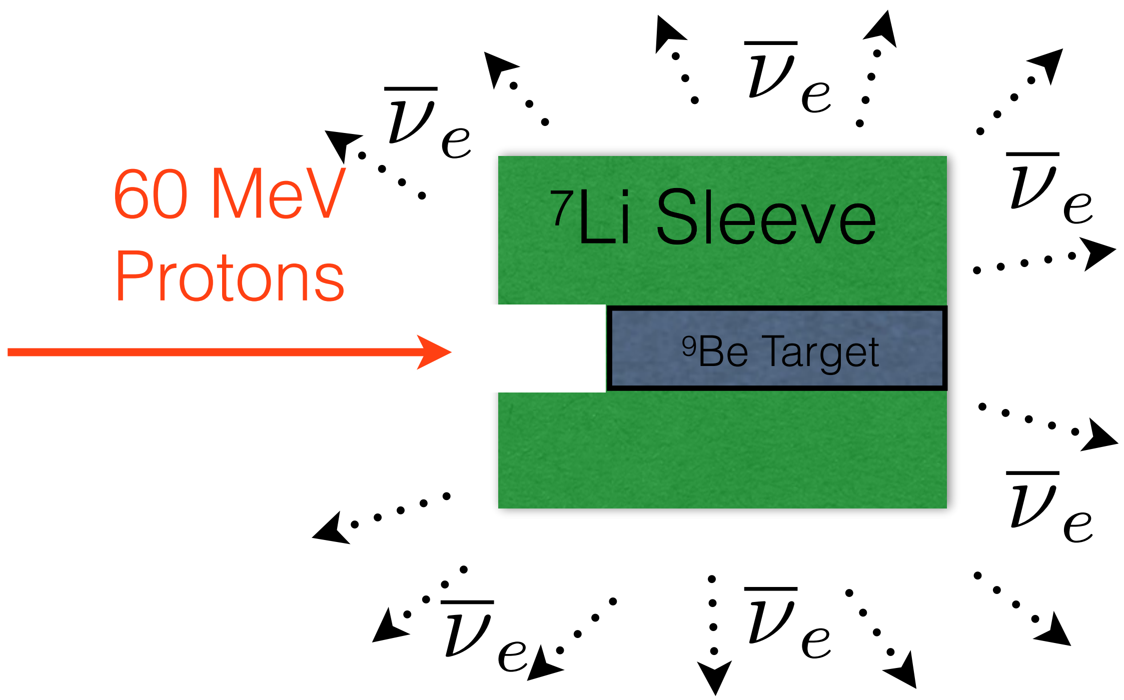


$$p + {}^9\text{Be} \rightarrow {}^8\text{Li} + 2p$$

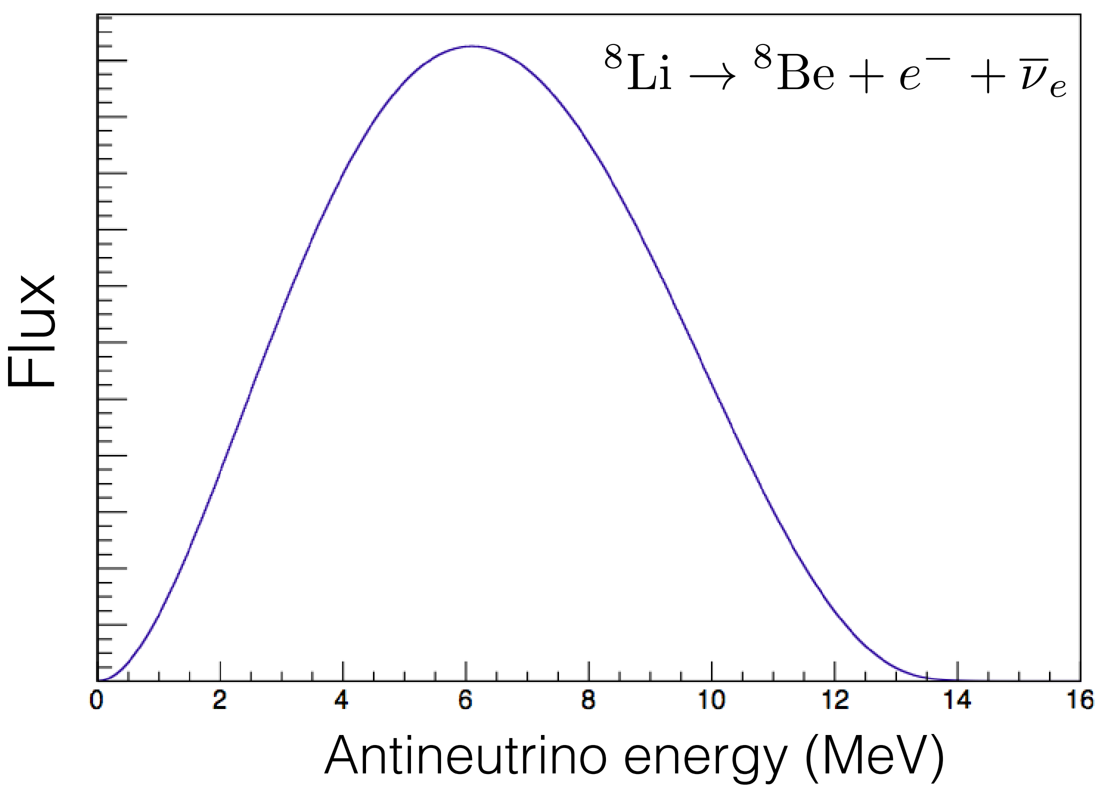
$$p + {}^9\text{Be} \rightarrow {}^9\text{B} + n$$
$$n + {}^7\text{Li} \rightarrow {}^8\text{Li} + \gamma$$

The IsoDAR concept

Produce energetic neutrinos with an extremely well understood energy spectrum



The IsoDAR flux is dominated by a single high-Q isotope (^{8}Li)



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

$$p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$$

$$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$$

$t_{1/2}$=0.84 s

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

Radioactive isotope neutrinos

Physics

- Short-baseline oscillations
- Exotic searches
- Electroweak physics
- Nuclear physics

Positives

- Flavor content is pure.
- Energy spectra very well understood.
- IBD interaction channel
    - High xsec
    - Double coincidence

Negatives

- Can be hard to make.
- Safety is an issue
- Electron-flavor (and disappearance) only
- Low-energy only
- Sensitive to radiogenic backgrounds
- Isotropic source

Radioactive isotope homework

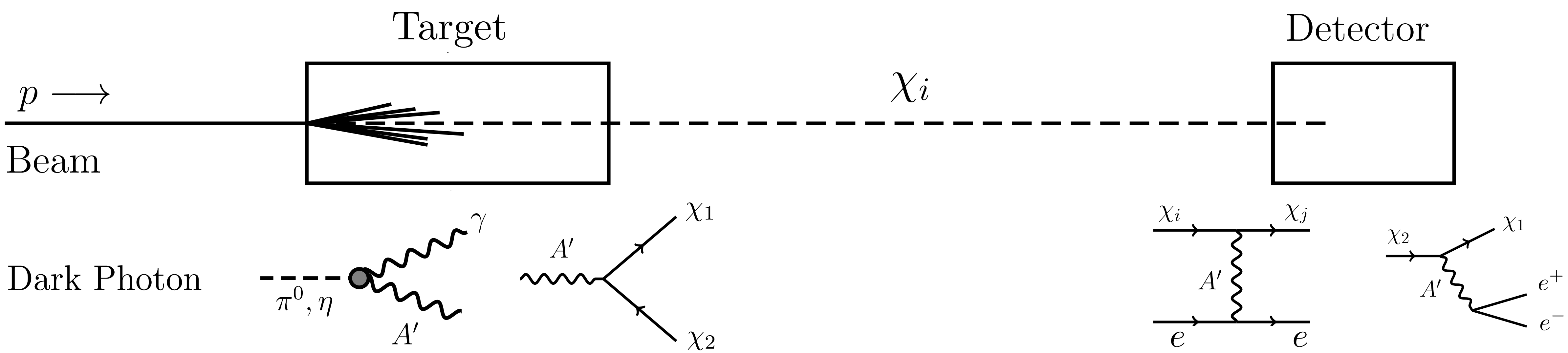
- Produce an electron capture source (safely) and couple it to a big underground detector.
- Use the BEST technique (^{51}Cr) with other isotopes.
- Realize IsoDAR.
- Extra credit: Figure out how to create an *artificial* non-relativistic source of neutrinos. Couple it to (e.g) PTOLEMY.
    - ^{115}In (beta-; Q-value~100 eV), ^{159}Dy (EC; Q_value~1 keV) are ultra-low-Q candidates (among many others), but you need to use a lot since the ultra-low-Q branching fractions are small!

Other artificial neutrino sources

- Beta beam
  - Accelerate beams of radioactive isotopes to produce a pure neutrino/antineutrino source.
    - ^{6}He (beta- decay) for antineutrinos, ^{18}Ne (beta+ decay) for neutrinos
- Neutrino factory
  - Relies on muons from a storage ring to produce a pure beam of muon and electron flavor neutrinos and antineutrinos.
- Neutrino detection at colliders (e.g. LHC—FASERν).

One final point: neutrino sources may also be sources of other, very exciting, stuff too!

High Luminosity Proton Beam (100's of MeV to 10's of GeV)



$$\mathrm{Br}(\pi^0 \to \gamma\gamma) \approx 0.99$$
$$\mathrm{Br}(\eta \to \gamma\gamma) \approx 0.39$$

Scattering **Decay**

Large boosts mean there are no kinematic constraints on the scattering like in traditional direct dark matter searches.

End