Neutrino Beams and Fluxes

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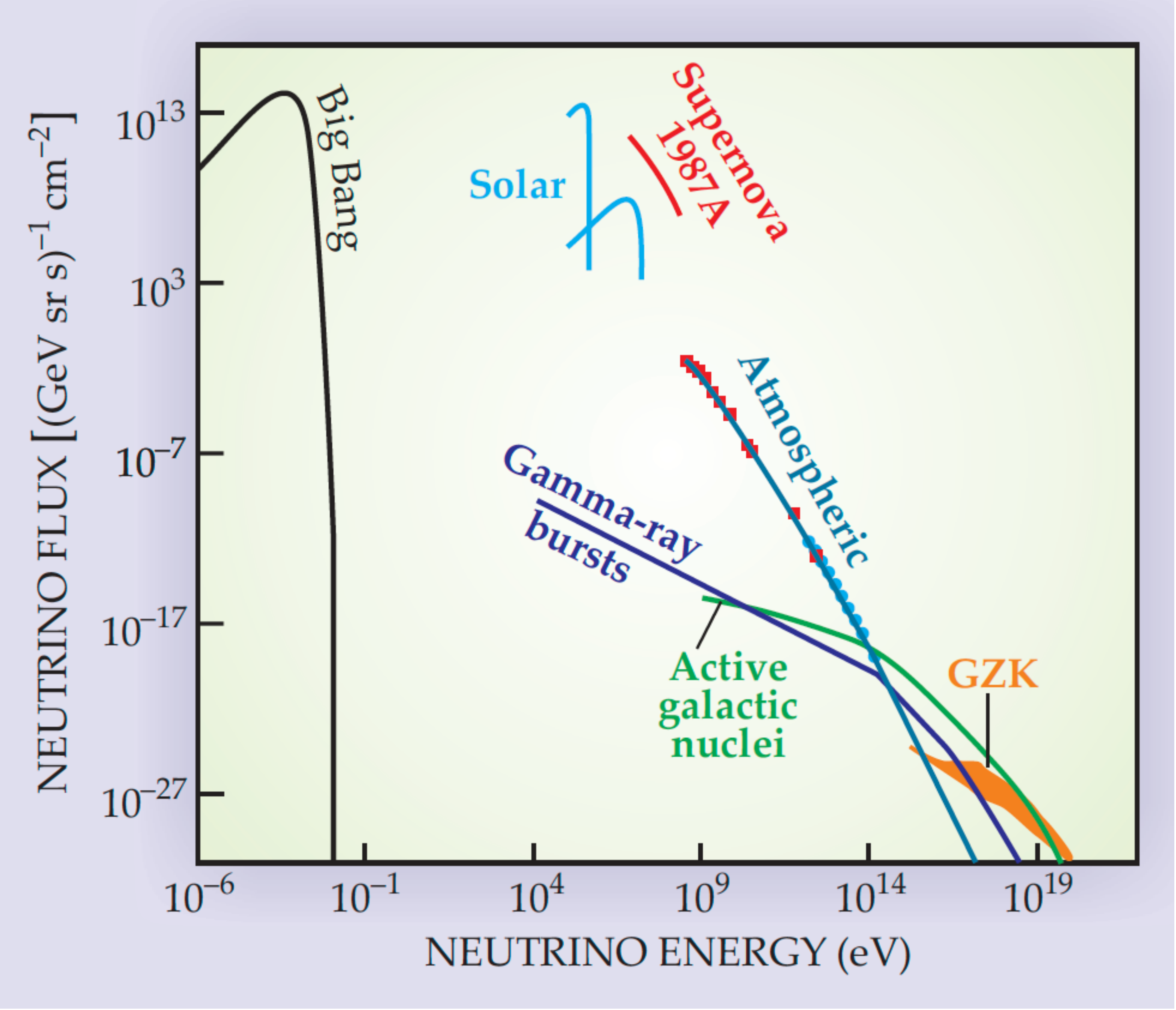
Hi! I’m Josh

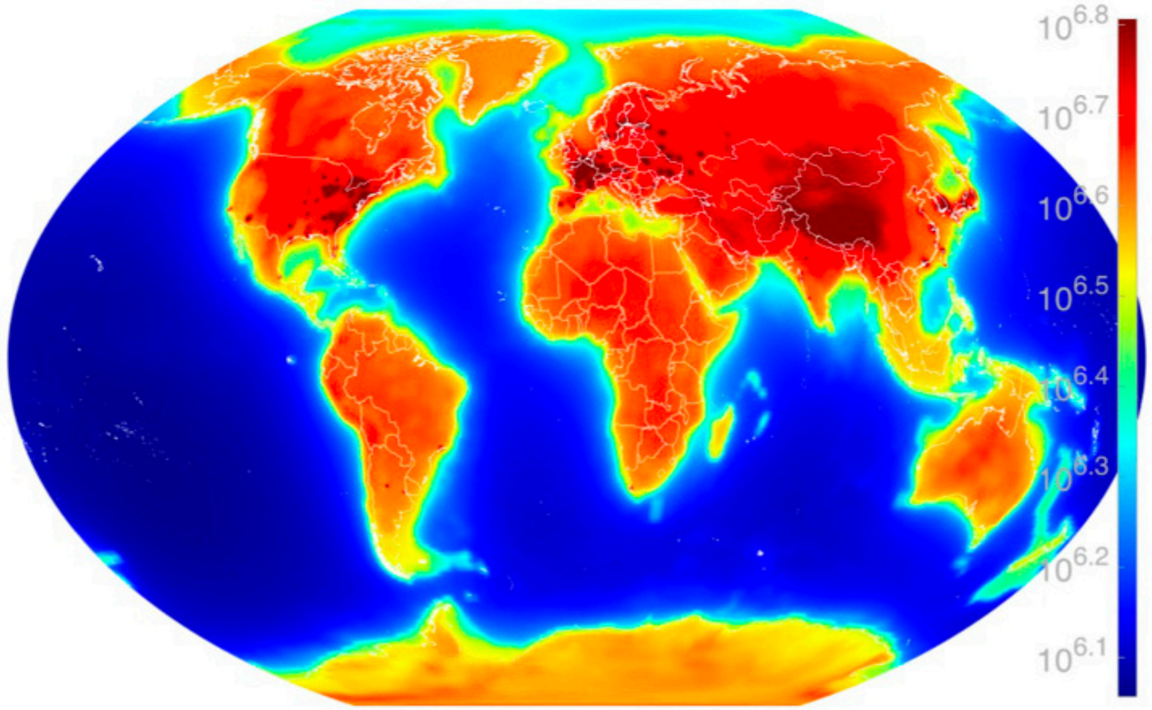
- Please email me if you want to discuss more: spitzj@umich.edu
- Also, feel free to catch me in person at a coffee break or lunch this week. I am friendly, I think.

This lecture does not cover: Astrophysical neutrinos

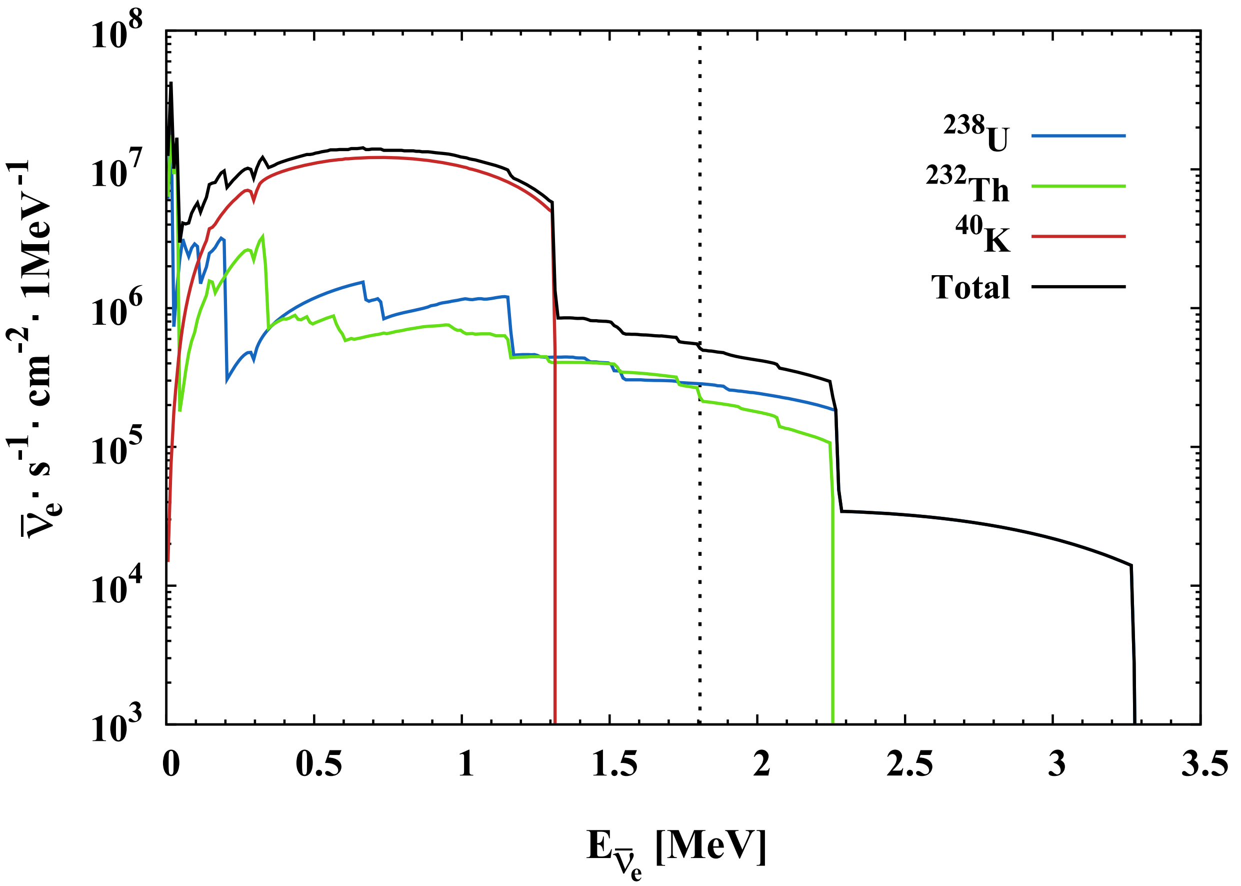


Physics Today

This lecture does not cover: geo-neutrinos



Geoneutrino (and reactor neutrino) flux



AGM2015: Antineutrino Global Map 2015

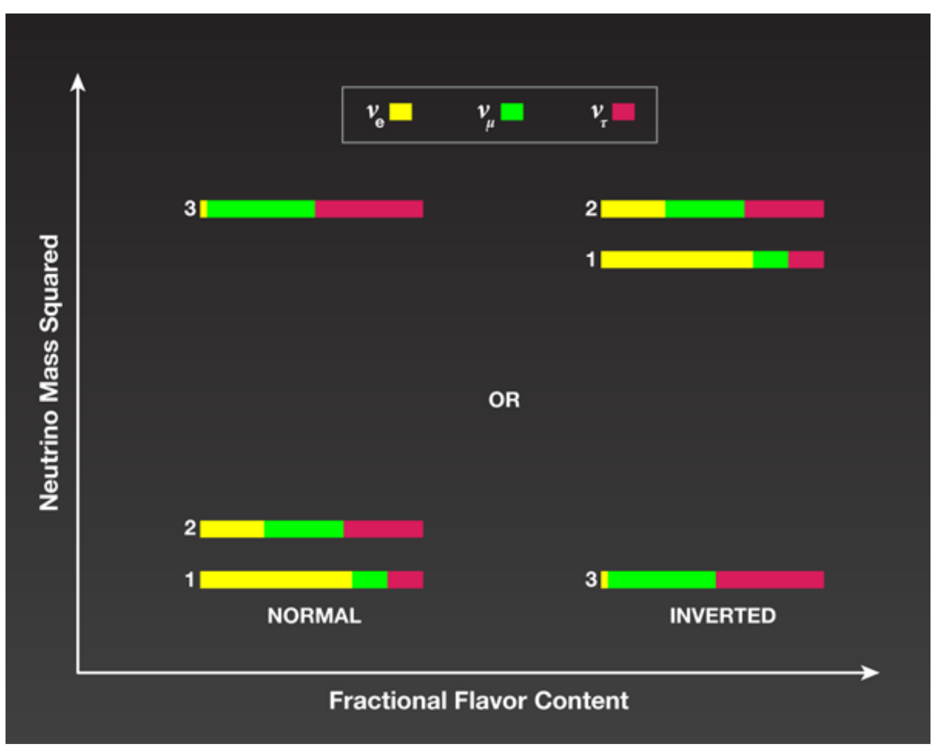
https://www.awa.tohoku.ac.jp/~sanshiro/research/geoneutrino/spectrum/

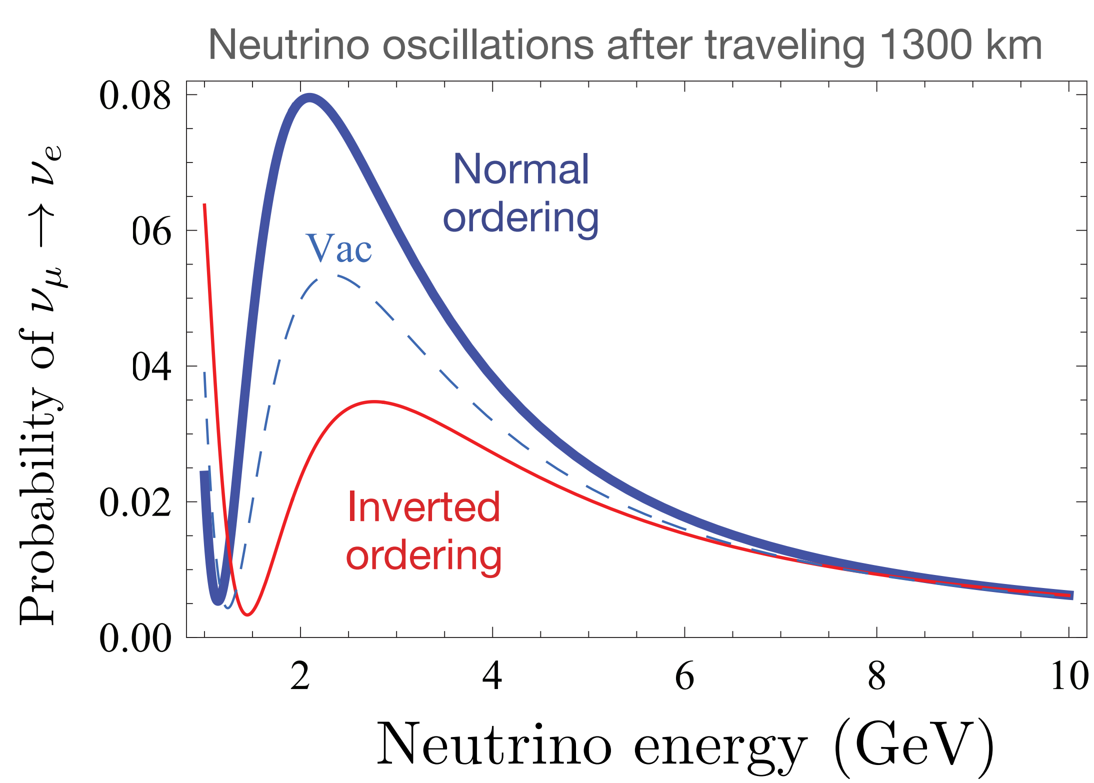
My focus here is on artificial neutrino sources

- Reactors
- Accelerator-based decay-in-flight
- Accelerator-based decay-at-rest
- Radioactive isotope (non-reactor) sources
- Others
    - Beta beam
    - Neutrino factory
    - Collider

The source is a means to an end

- What do you want to measure?
- DeltaCP, mass hierarchy, octant, other 3-nu mixing parameters, sterile neutrinos, neutrino-antineutrino mixing, other exotic mixing, non-standard interactions, neutrino decay, weak mixing angle, non-V-A contributions, neutrino magnetic moment, cross sections and nuclear physics (short-range correlations, strange spin, parton distribution, axial mass, …), Majorana or Dirac, tau neutrinos, absolute neutrino mass, lepton universality, Lorentz violation, supplemental measurements for astrophysics (e.g. supernova xsec), exotic particle searches (e.g. dark matter, axions), 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 (or, that is a favorable distance away for osc. measurements)

The source is useless without a detector

- Always need to think about the **combination** of source and detector(s).
- Are the source and detector(s) well suited to each other?
- Example of a bad match: nuclear reactor (amazingly intense source of electron antineutrinos) with LArTPC (amazing detector… but, no free protons):

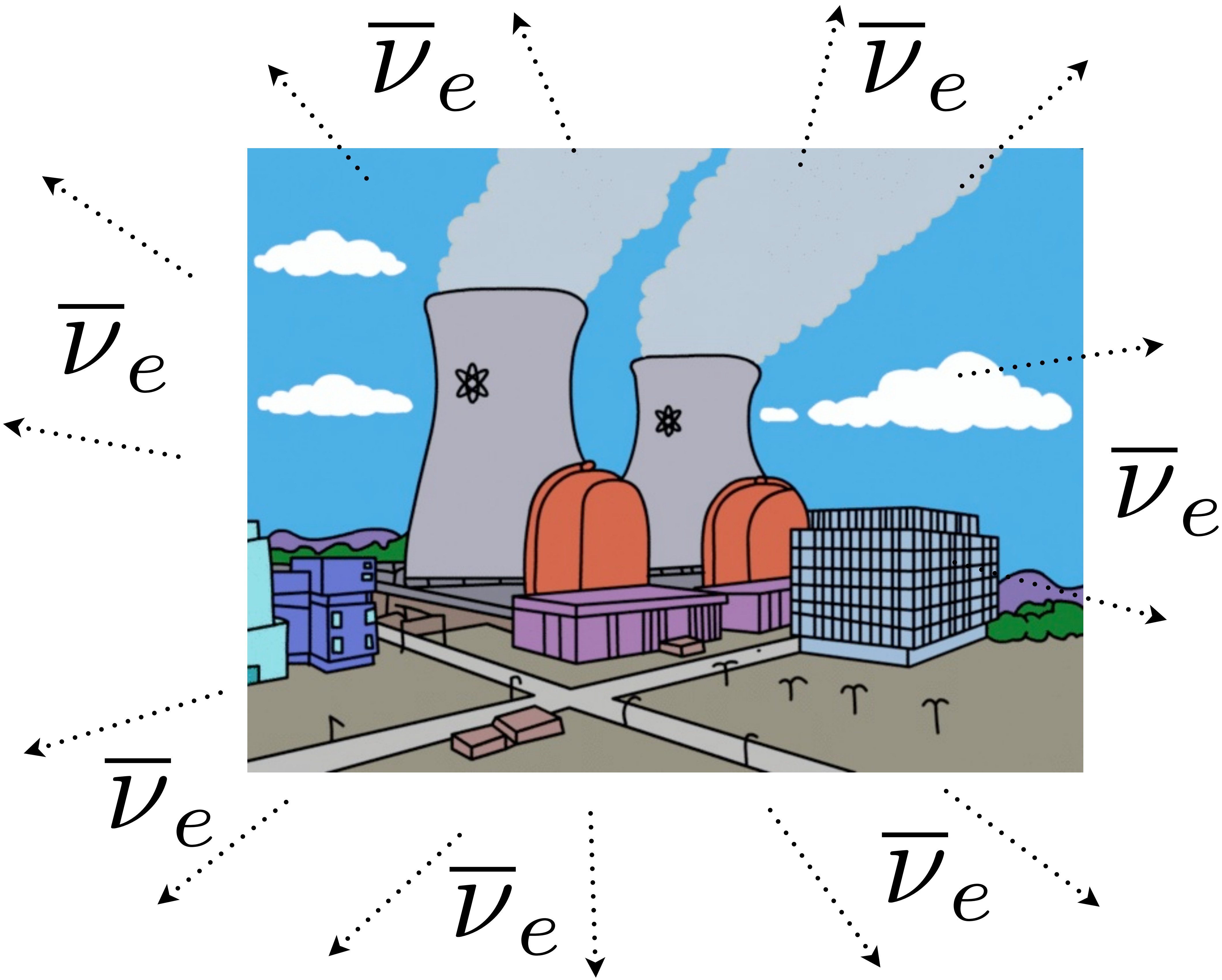
Dominant reactor antineutrino reaction mechanism:

$$\text{Inverse Beta Decay (IBD): } \overline{\nu}_e p \to e^+ n$$

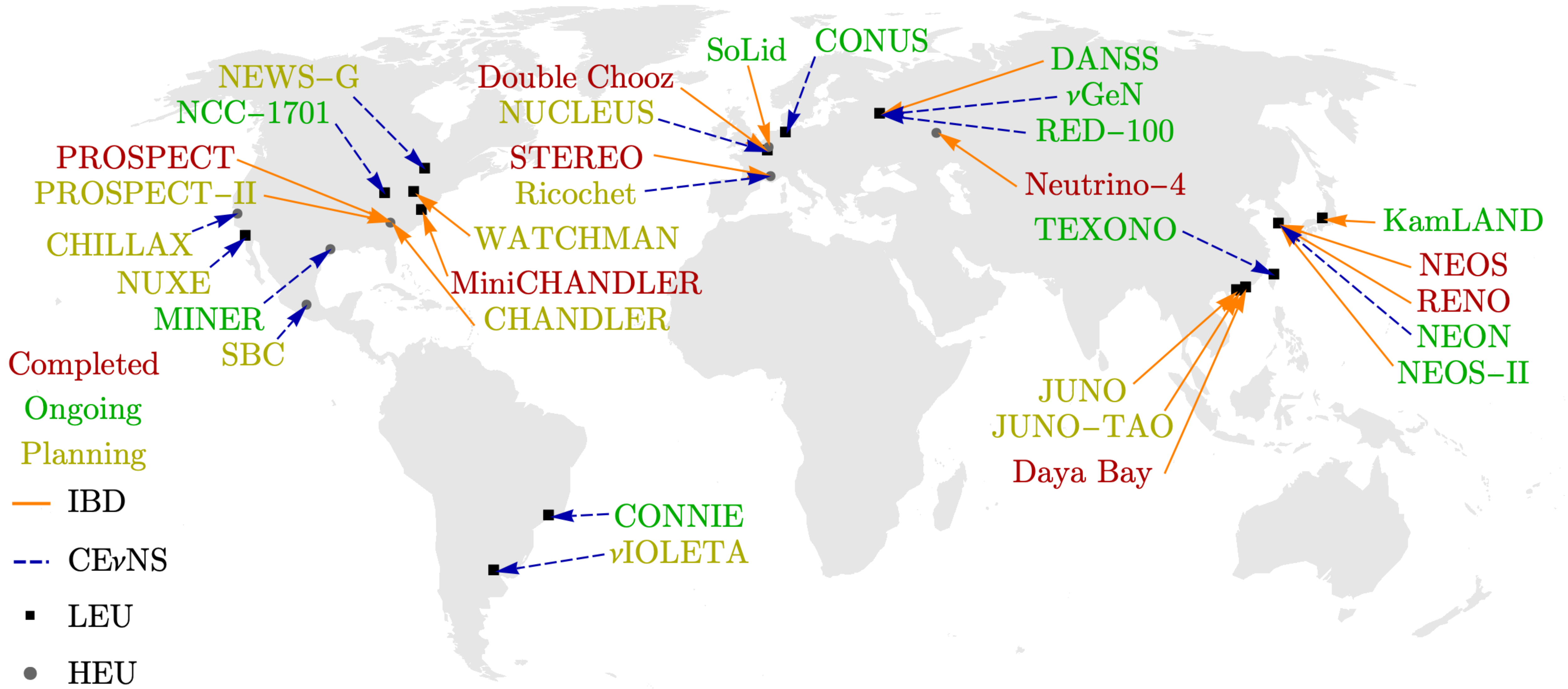
LArTPCs are blind to this!

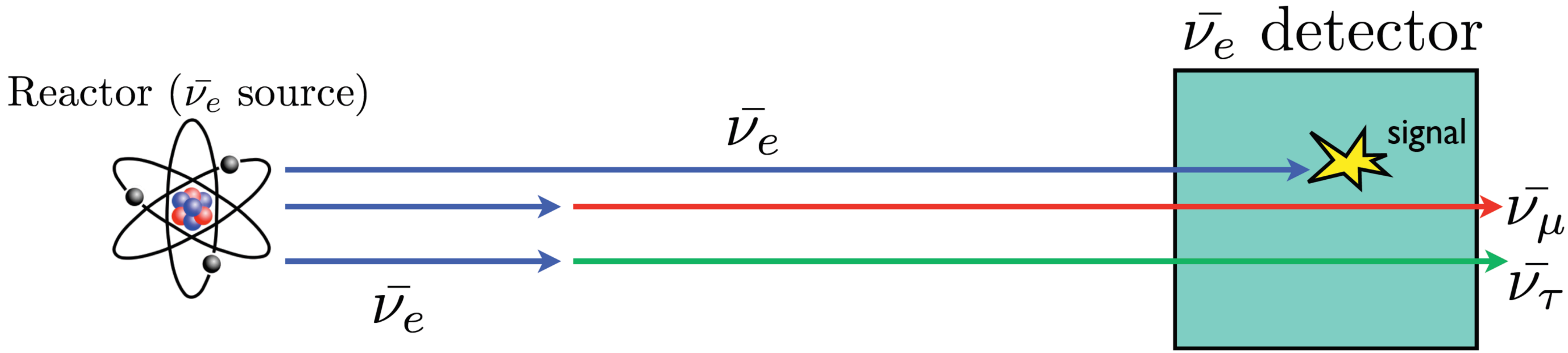
Reactor neutrinos

Nuclear reactors produce neutrinos

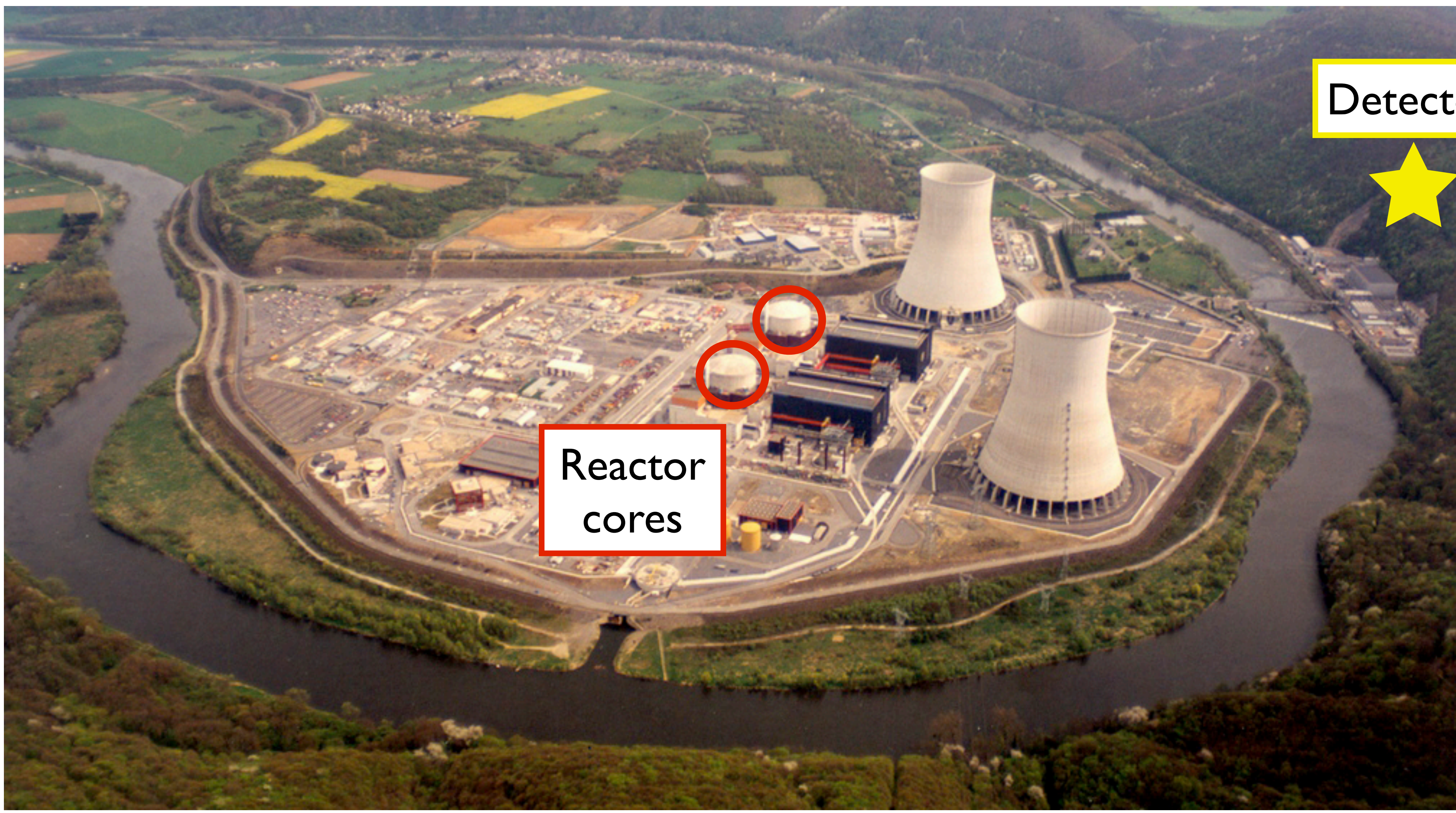


Reactor experiments around the world



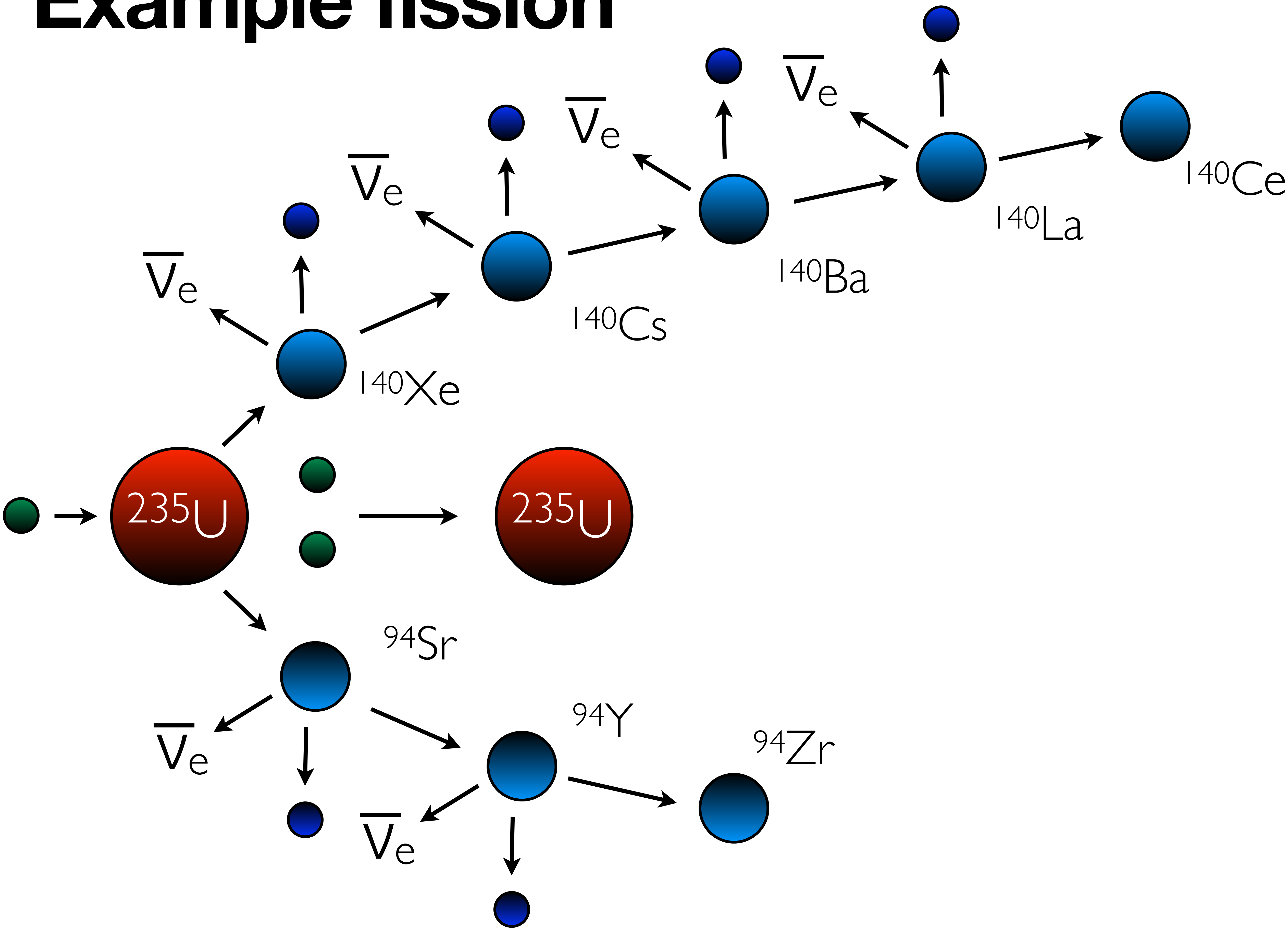


In a *disappearance experiment*, we look for a deficit of antineutrinos

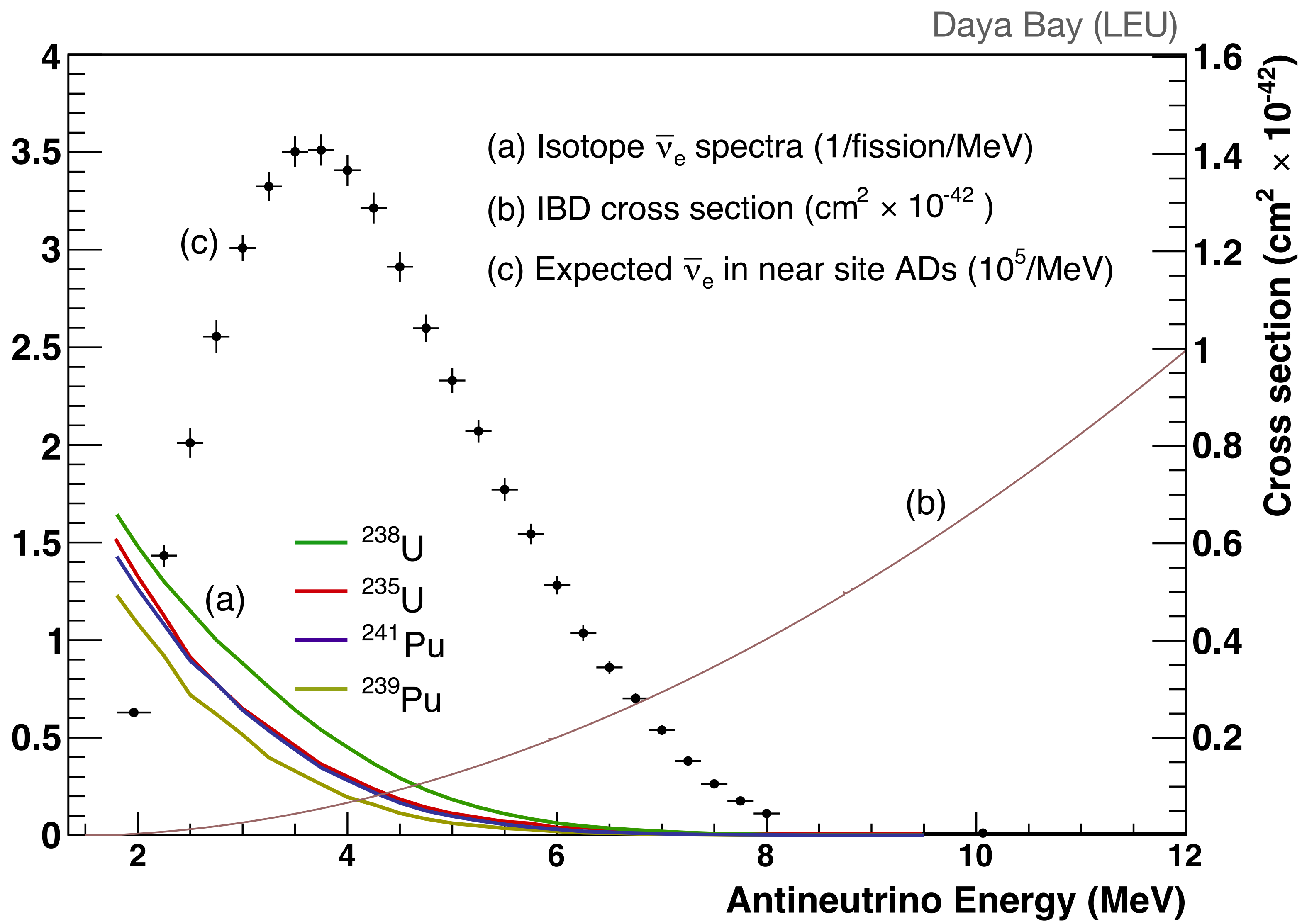


Detected via Inverse Beta Decay (IBD): $\overline{\nu}_e p \rightarrow e^+ n$

Example fission



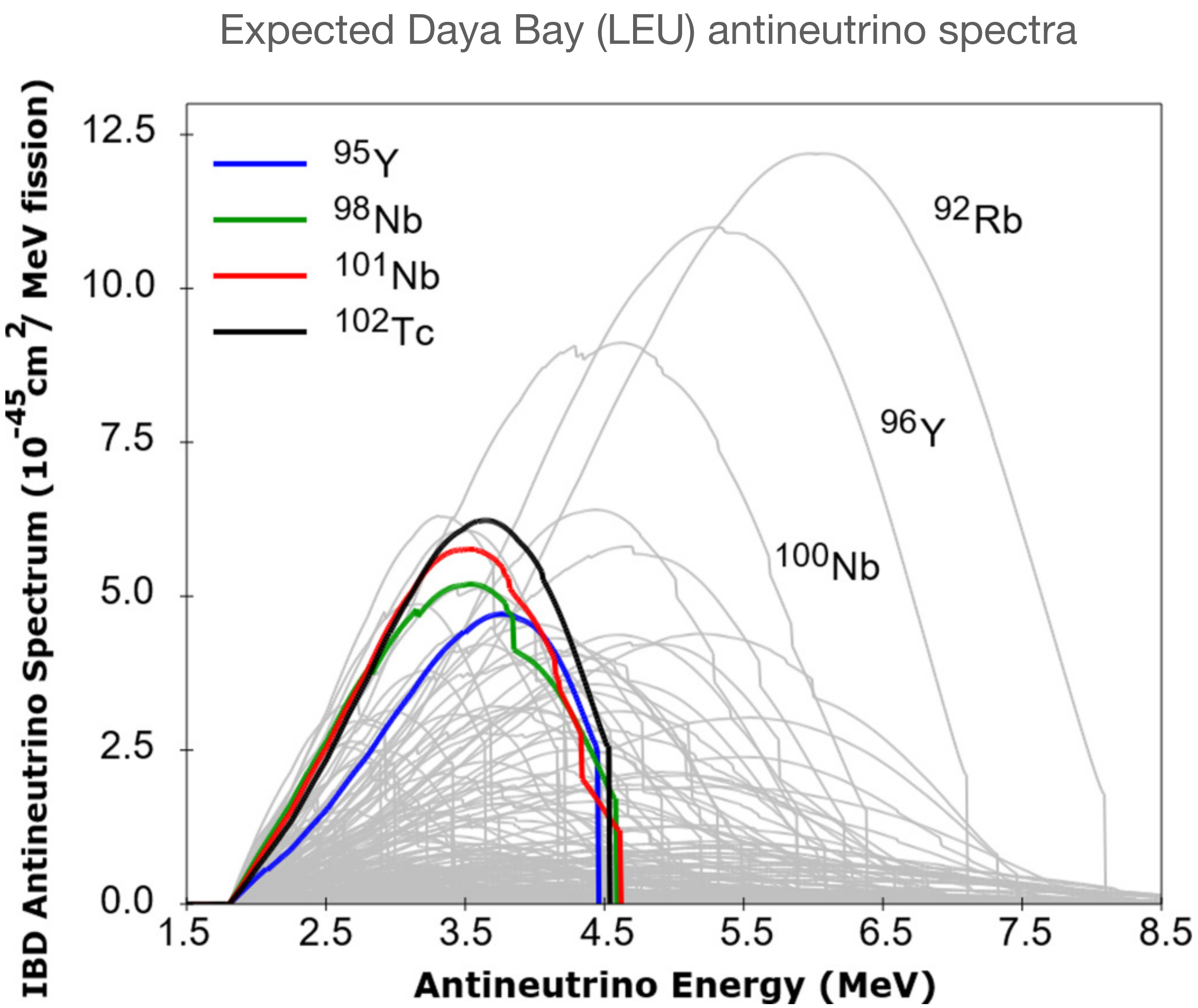
Flux and cross section



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

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

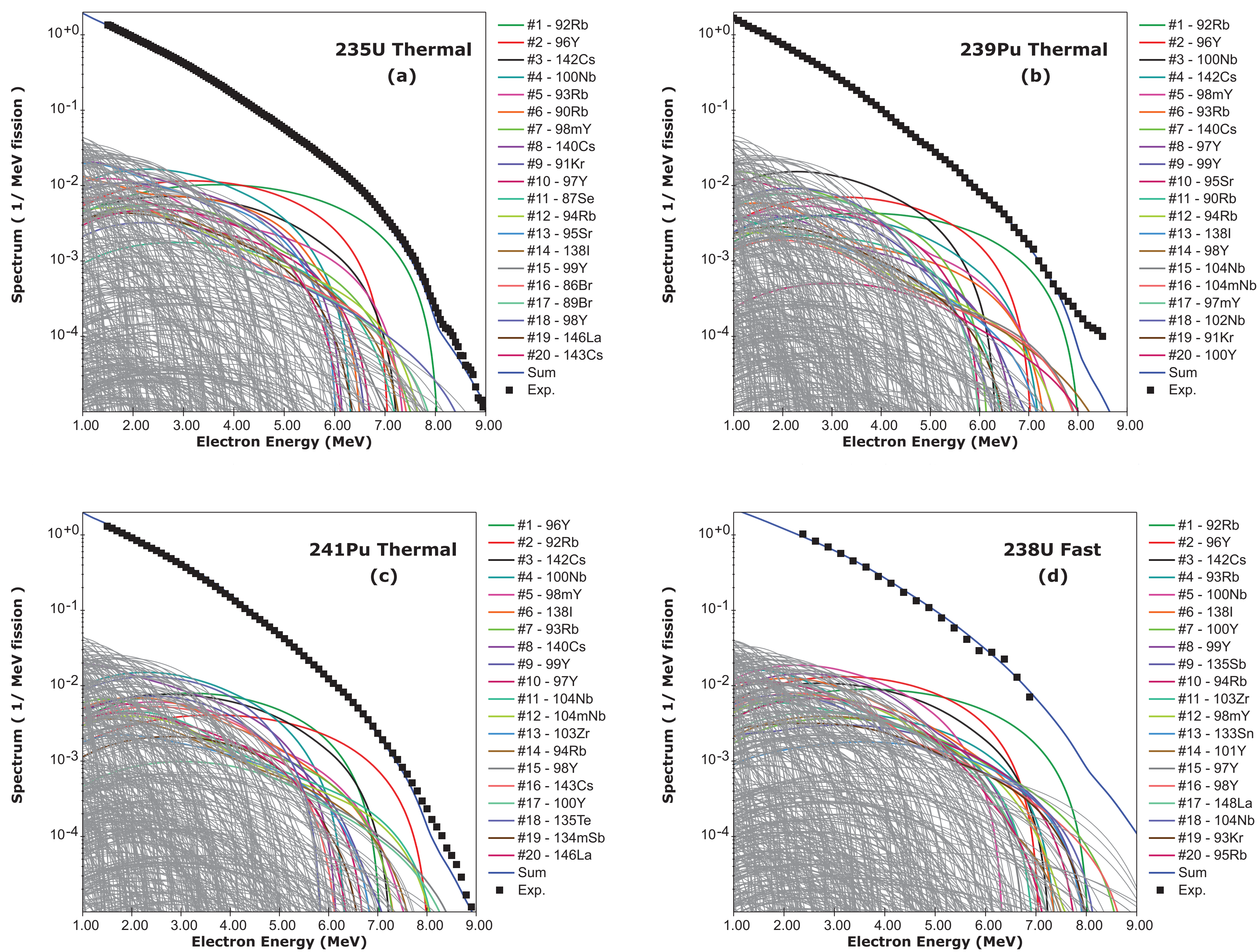
Flux components



~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)

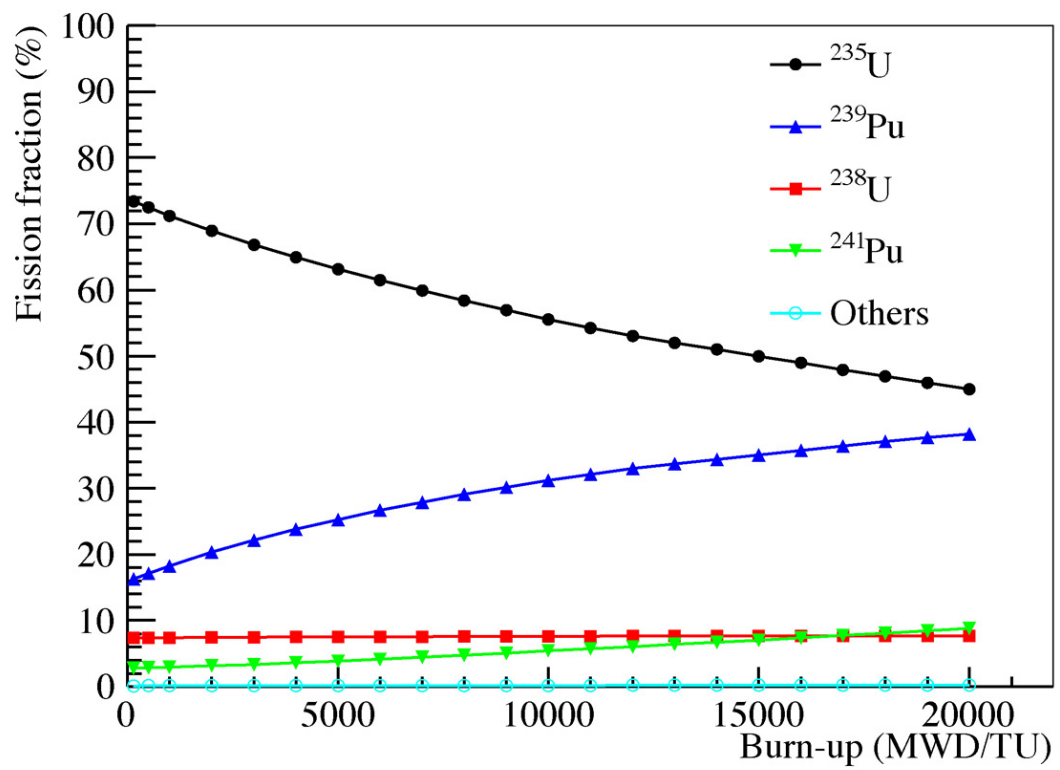
HEU and LEU

Natural Uranium:

235: 0.7% abundant
238: 99.3% abundant

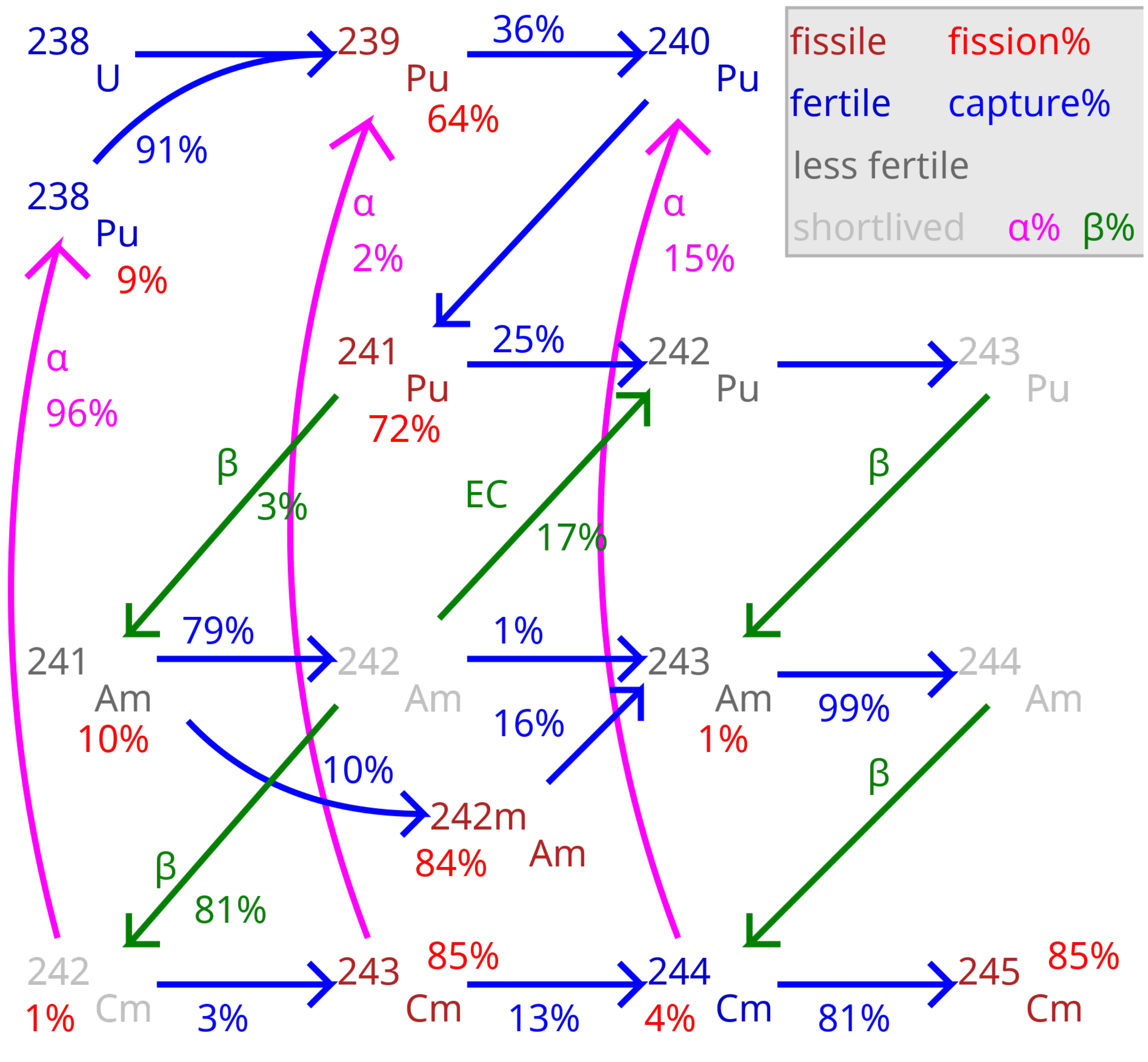
Fuel Isotope	Time-Averaged Fission Fraction	
	Conventional Fuel	HEU fuel
^{235}U	0.59	>0.99
^{238}U	0.07	<0.01
^{239}Pu	0.29	<0.01
^{241}Pu	0.05	<0.01

PRD 87 073008 (2013)



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

PRL 118 251801 (2017)


238
U
91%
239
Pu
64%
36%
240
Pu
fissile
fission%
fertile
capture%
less fertile
shortlived
α%
β%
238
Pu
9%
α
2%
α
15%
α
96%
241
Pu
72%
25%
242
Pu
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Am
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1%
99%
244
Am
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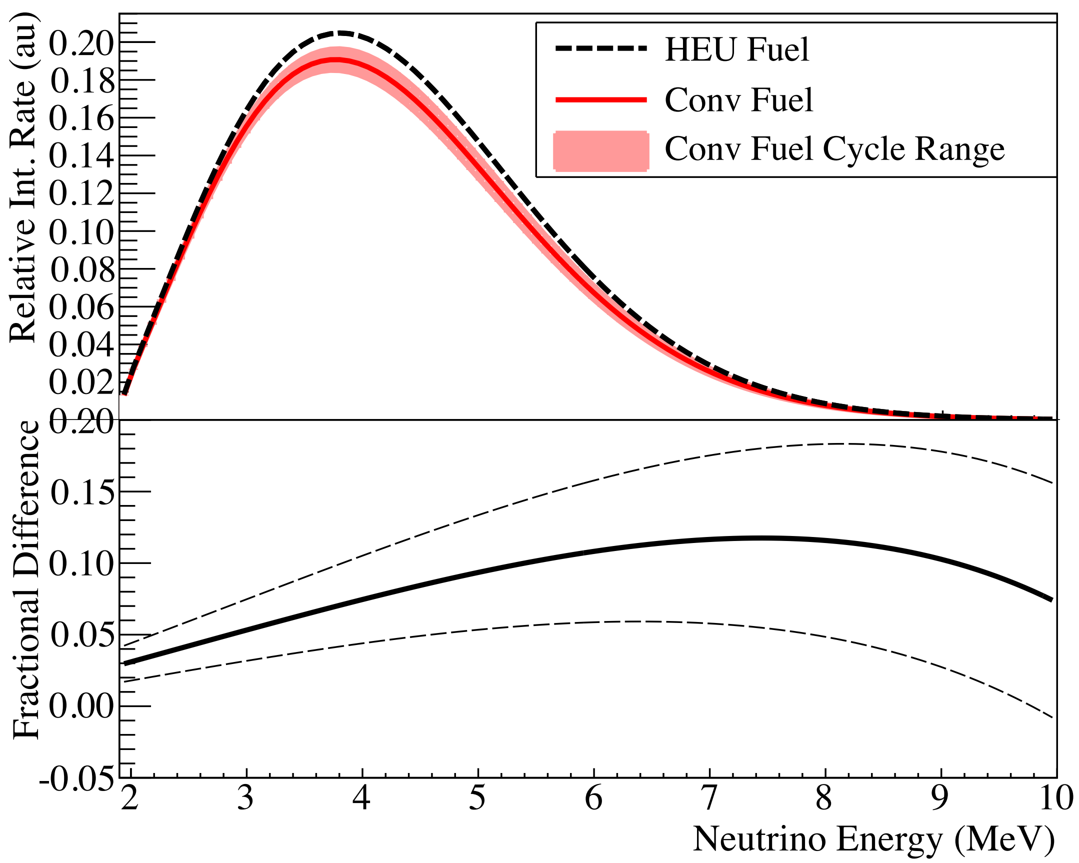
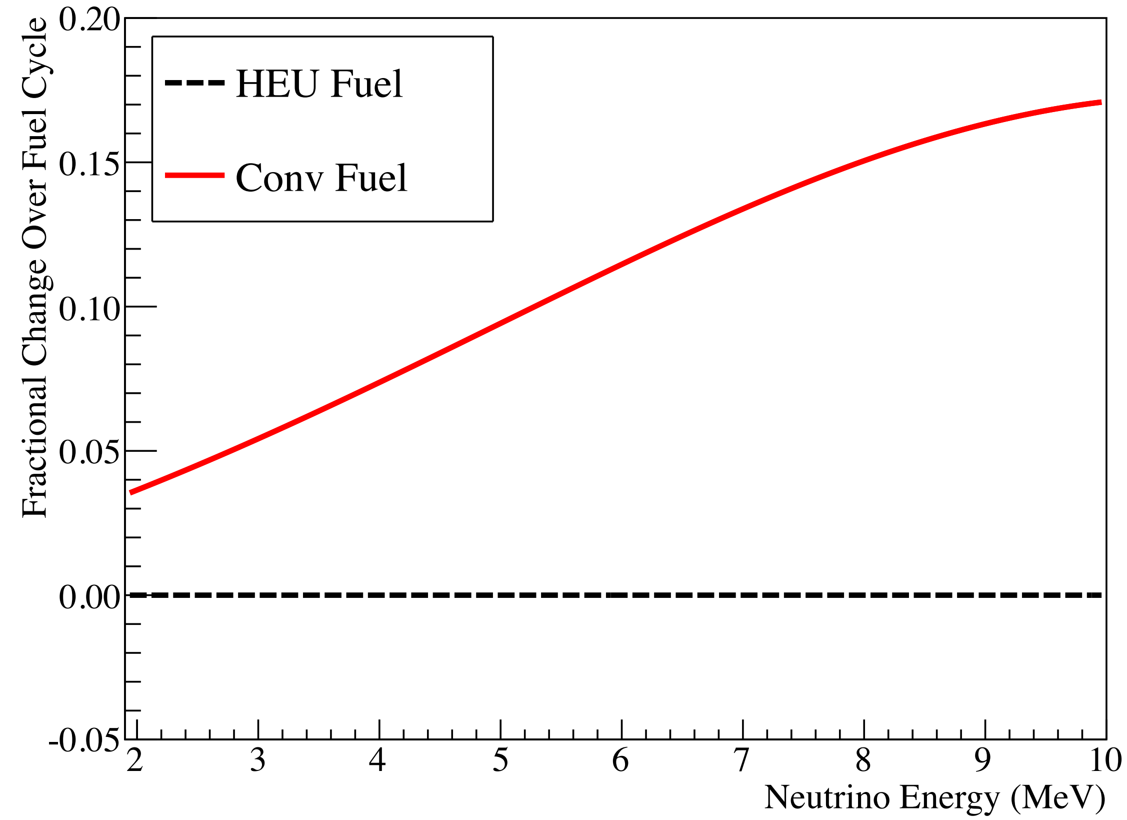
10%
242m
Am
84%
β
β
81%
242
Cm
1%
3%
243
Cm
85%
13%
244
Cm
4%
81%
245
Cm
85%

Wikipedia

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





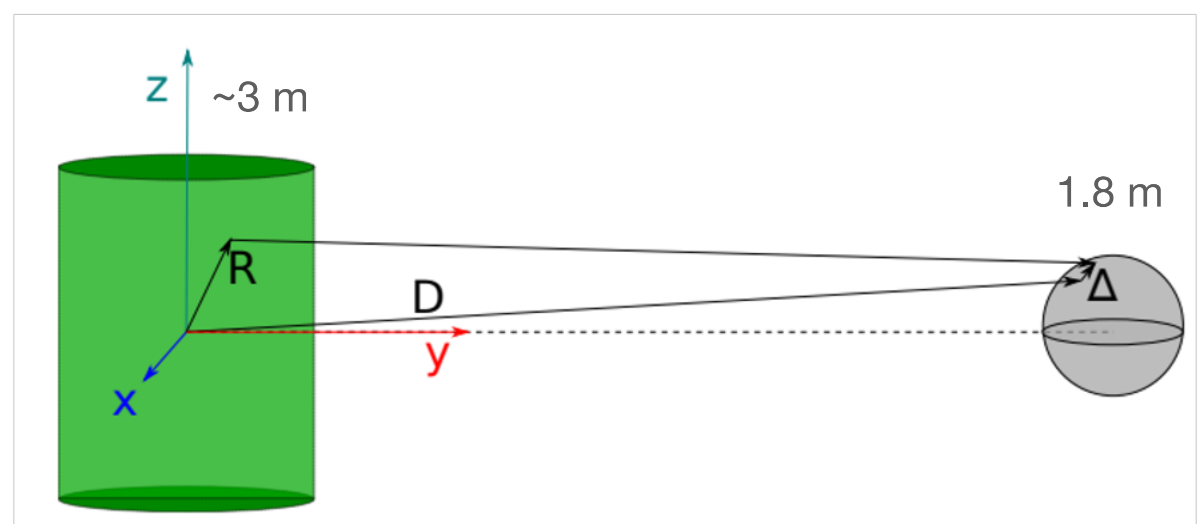
LEU reactor sources have a dynamic electron antineutrino flux.
HEU reactor sources are static.

PRD 87 073008 (2013)

Commercial vs. research reactor

- 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)

Note: significant L/E smearing due to large extent of commercial core.



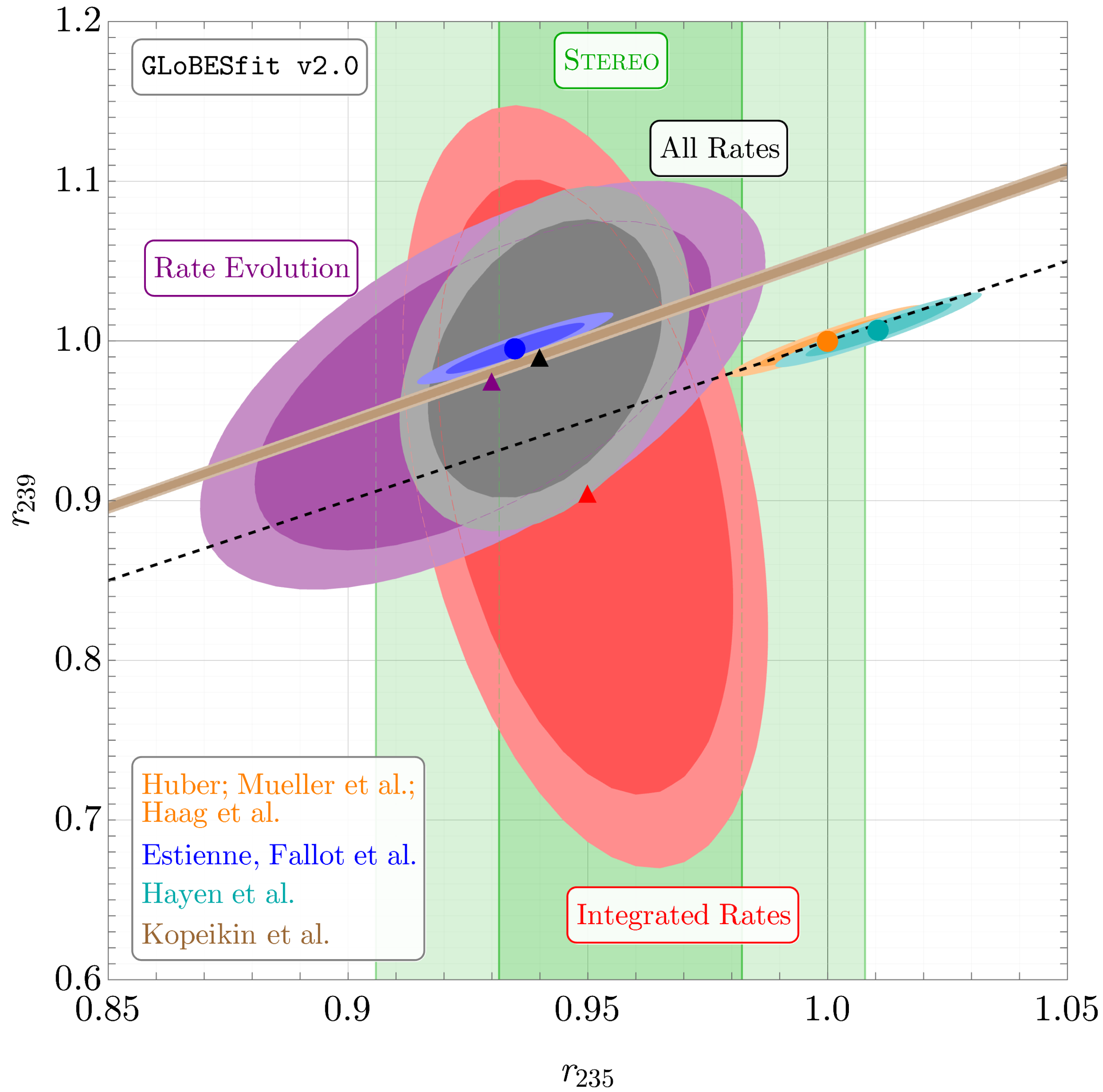
A JUNO reactor and JUNO-TAO near detector geometry

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

2005.01756



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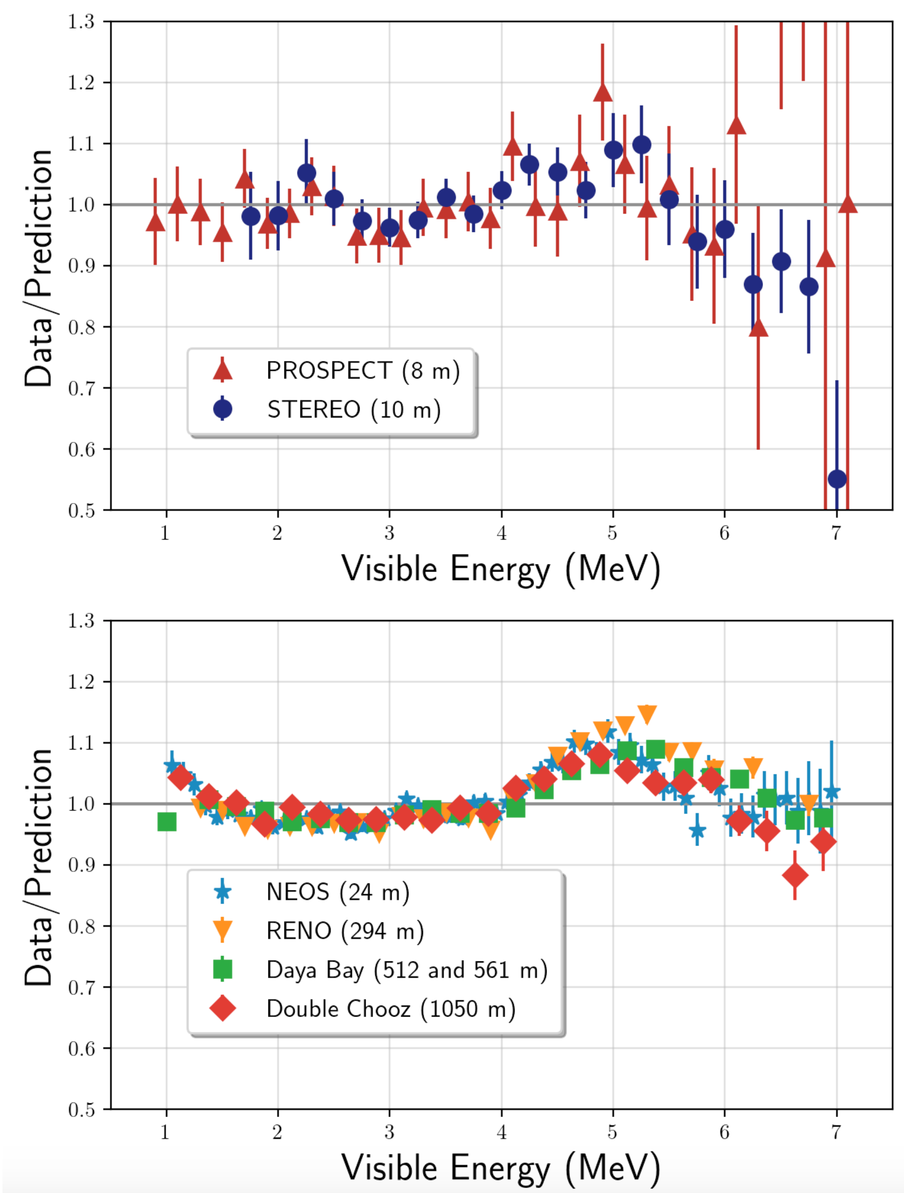


HEU

LEU

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

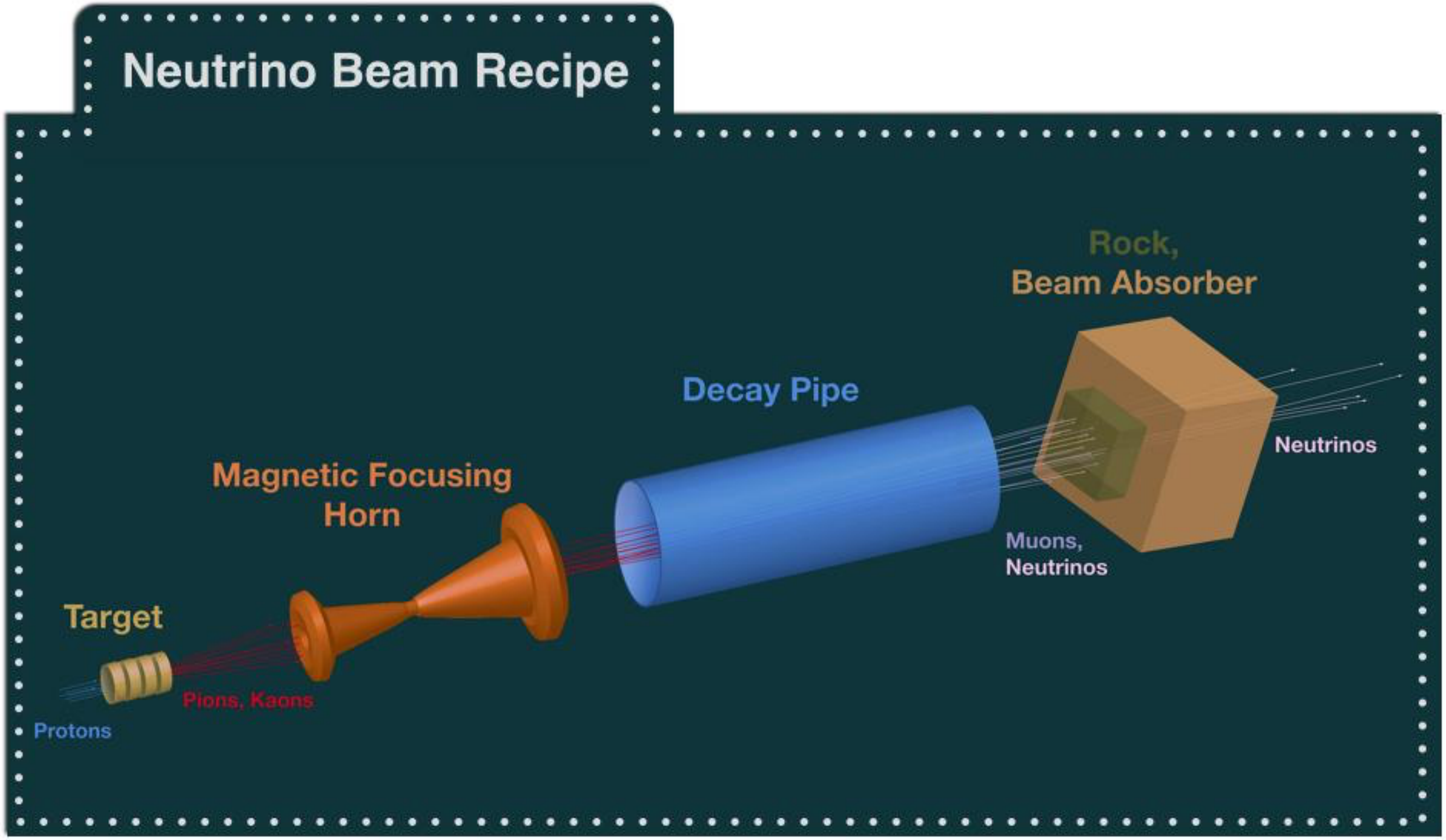
Reactor homework

- 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! There is wonderful electroweak physics here. 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.

Accelerator decay-in-flight neutrinos

(short- and long-baseline)

Creating a neutrino beam



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

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

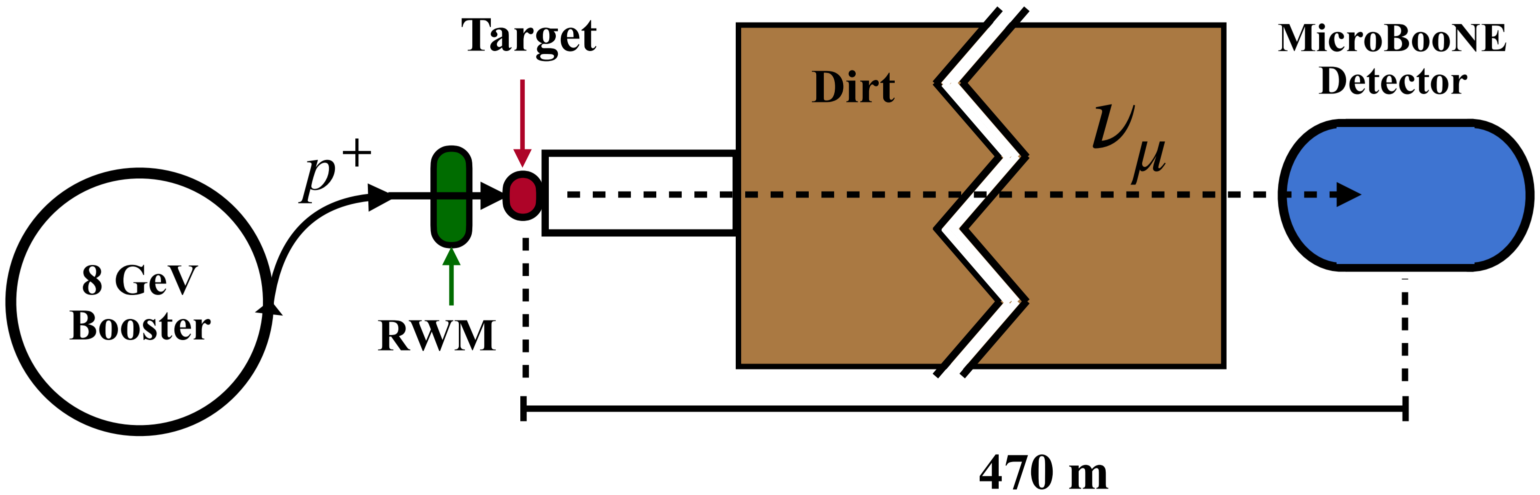
Protons

Main things to know:

-beam is pulsed (10^{-5} duty factor is typical), including with ~ns substructure

-proton beam has an extent on the target

Beam timing example: BNB



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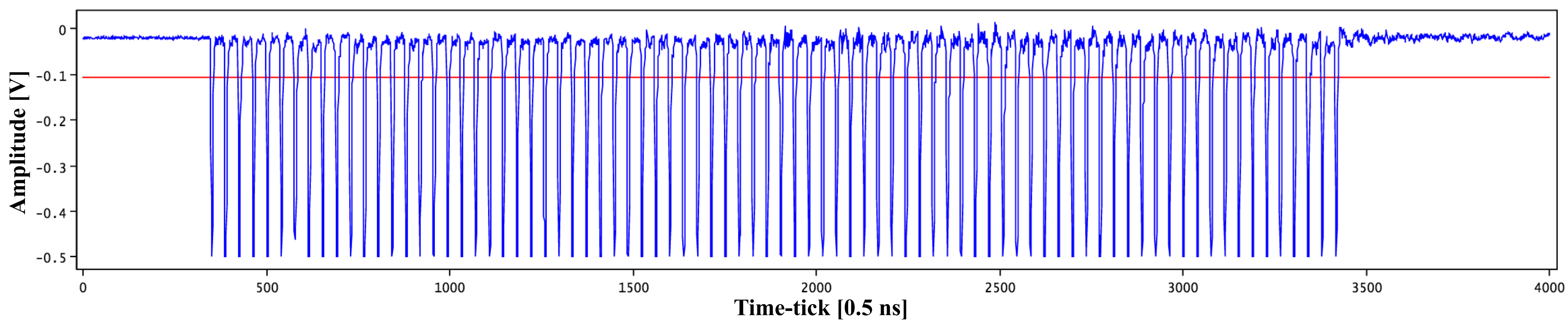
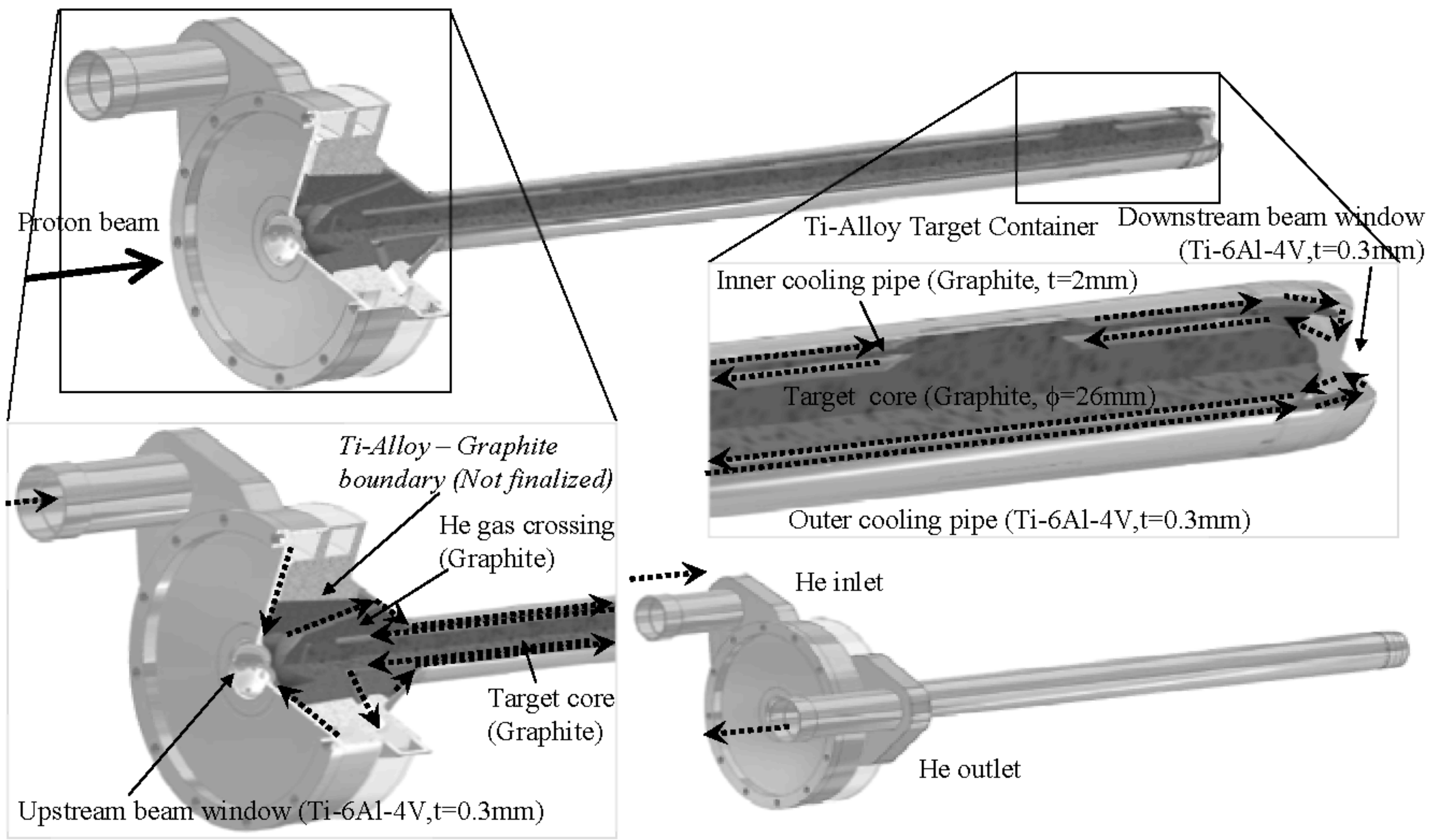


BNB RWM signal for 1 pulse (15 Hz)

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

Target

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

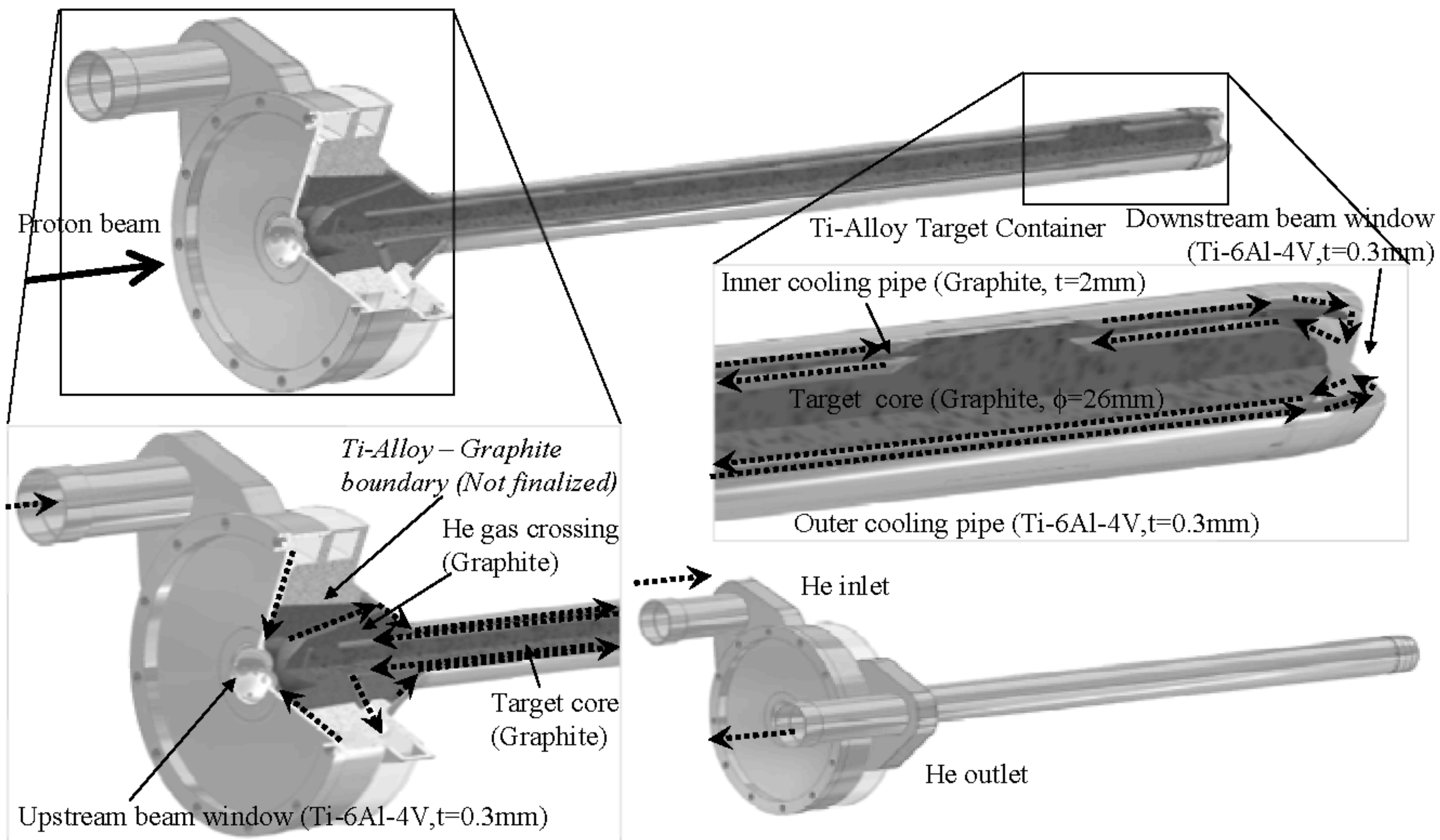


T2K target design

Typical NuMI beam power: 800 kW
Typical T2K beam power: 500-600 kW
Future LBNF (upgrade): 1200 kW (2400 kW)

Target

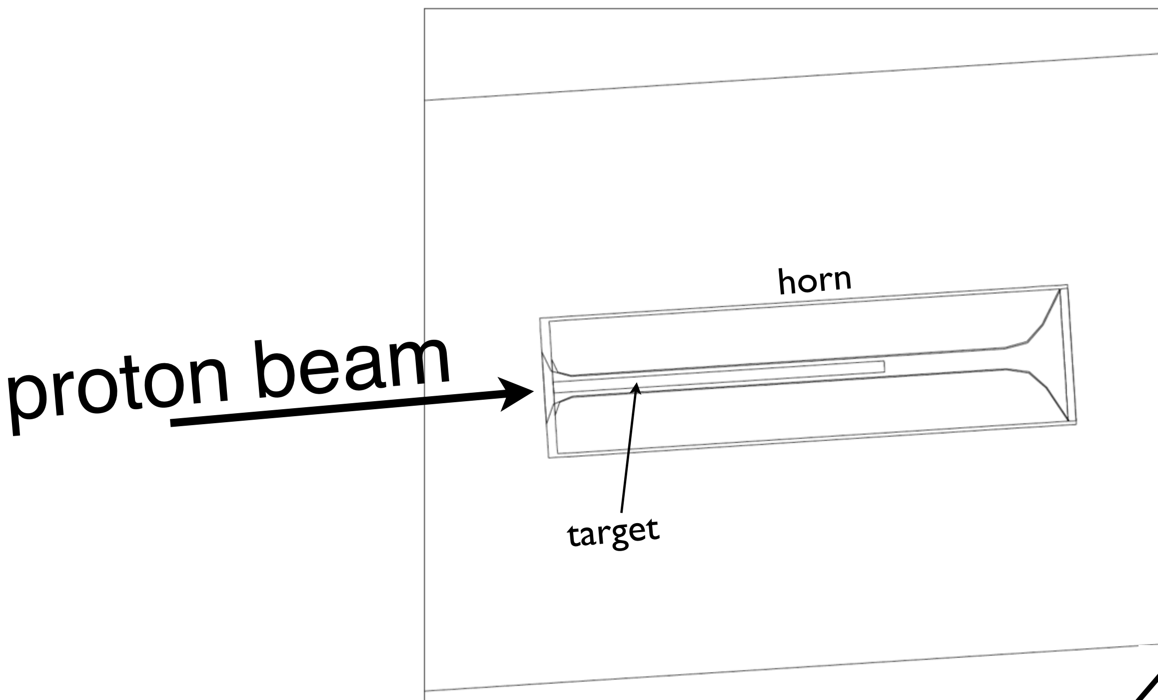
Target design is pretty similar throughout the world.
There are various cooling techniques, though.



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.

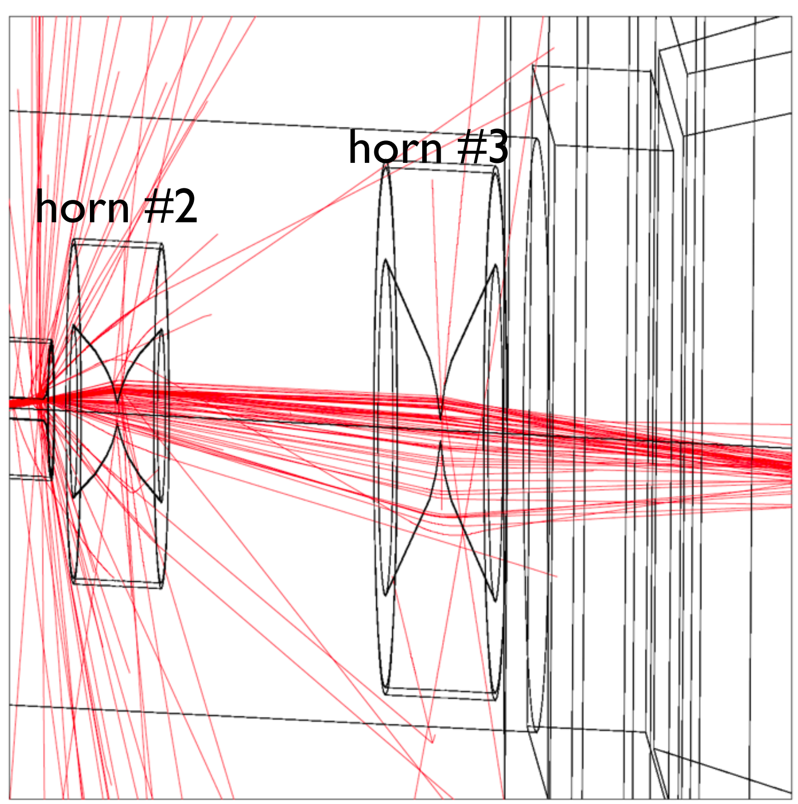
Creating a neutrino beam

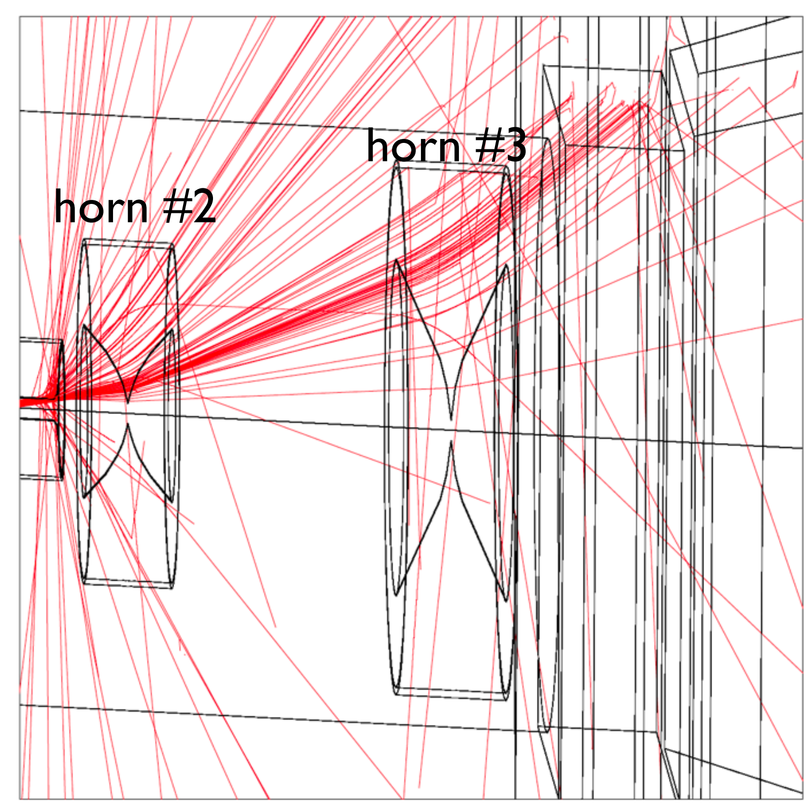


pion

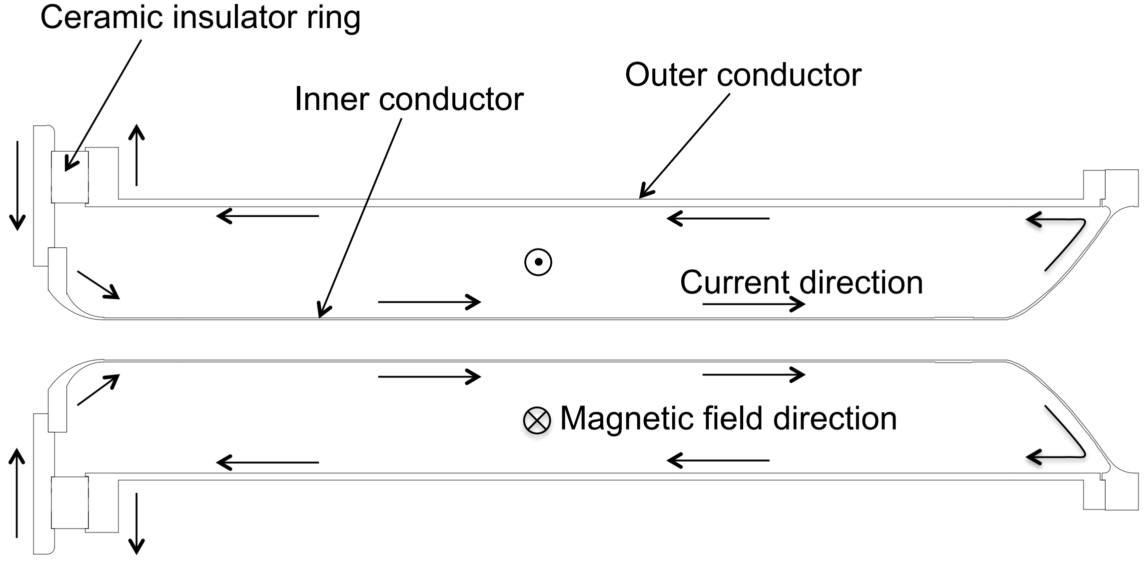
$$\pi^+ \to \mu^+ \nu_\mu$$

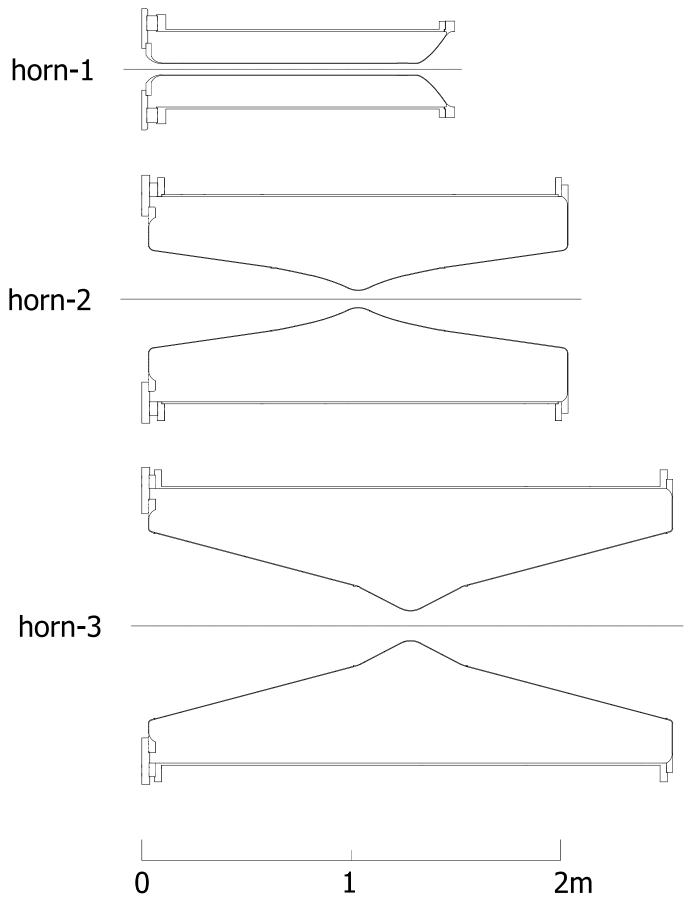
$$\pi^- \to \mu^- \overline{\nu}_\mu$$





The horns (big electromagnets)

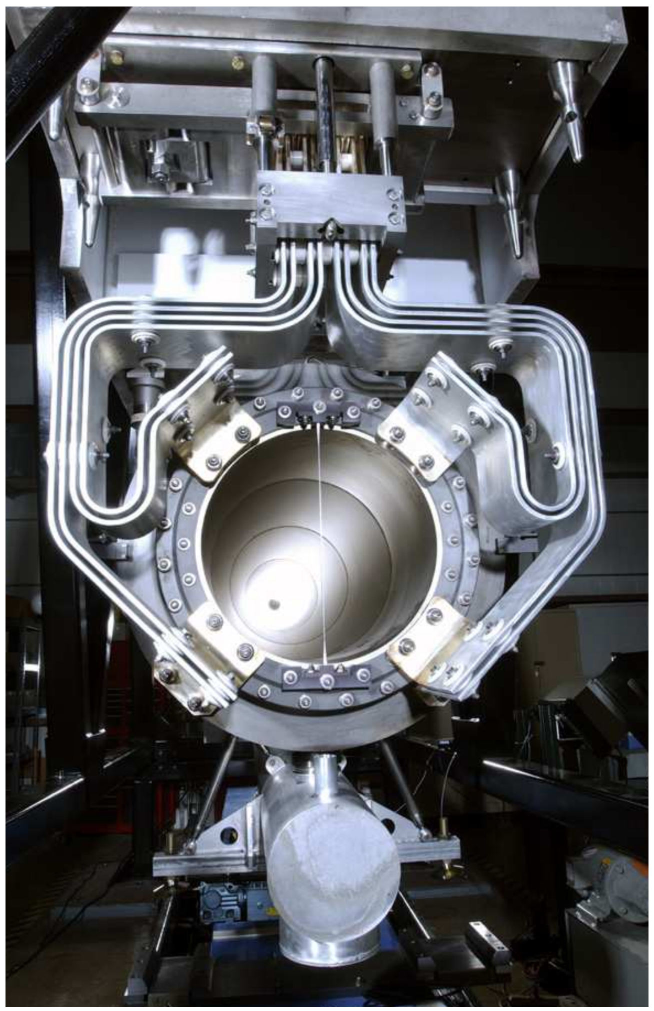




T2K horns

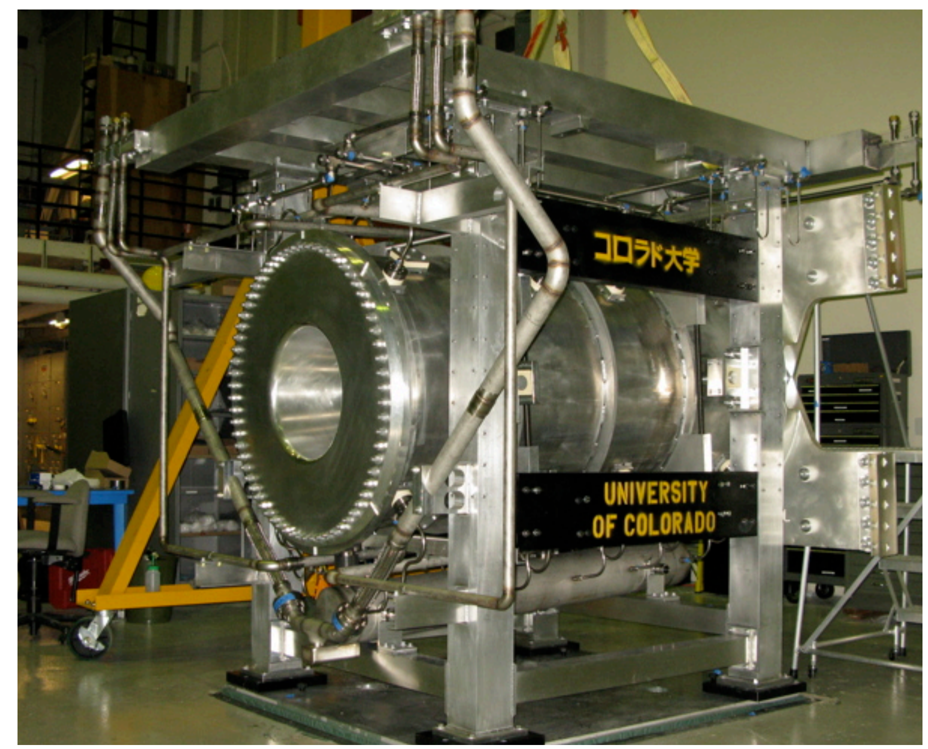
The horns (big electromagnets)

1507.06690



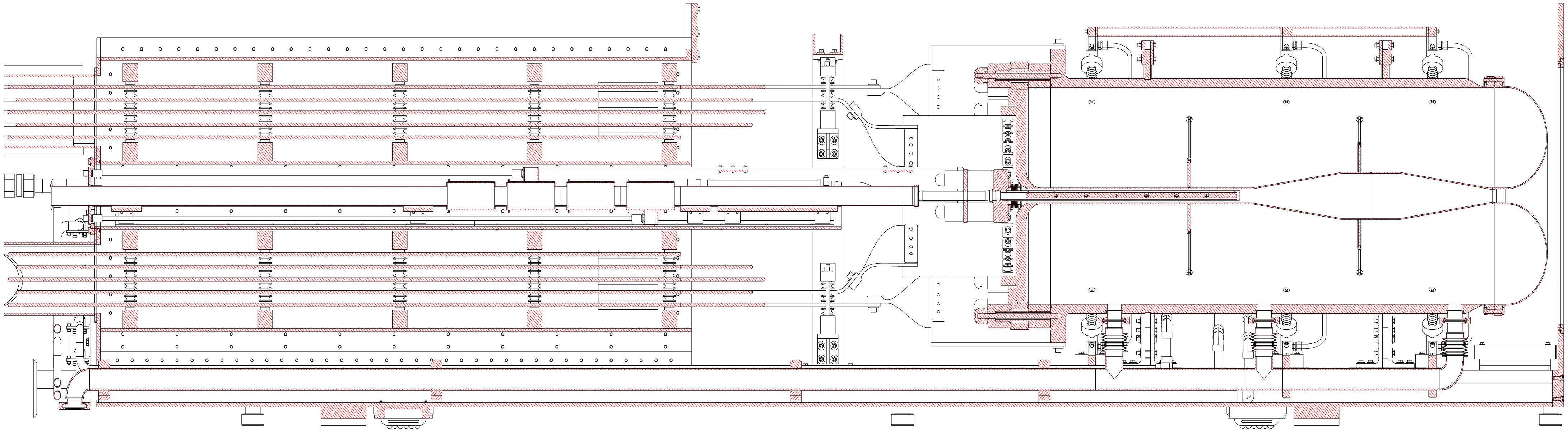
NuMI horn 2

1502.01737



T2K horn 2

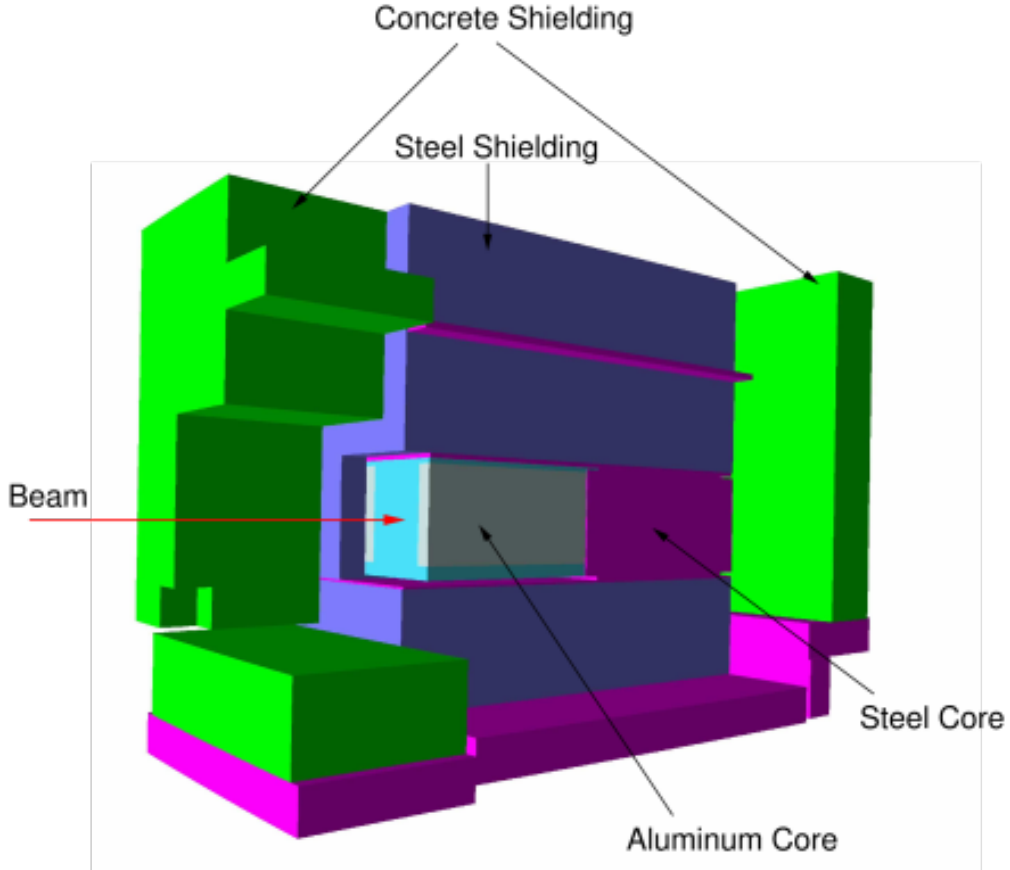
BNB horn

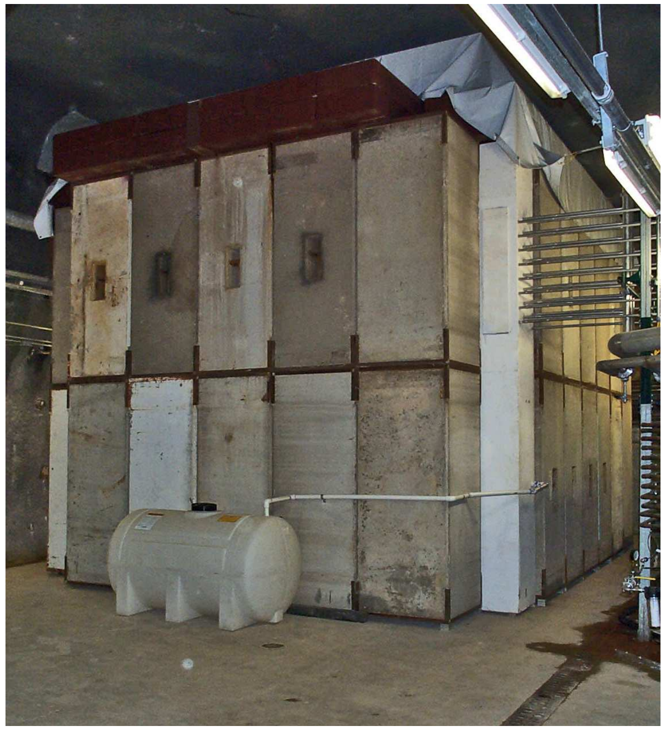


Decay pipe and absorber

NuMI example (decay pipe length = 675 m)

1507.06690

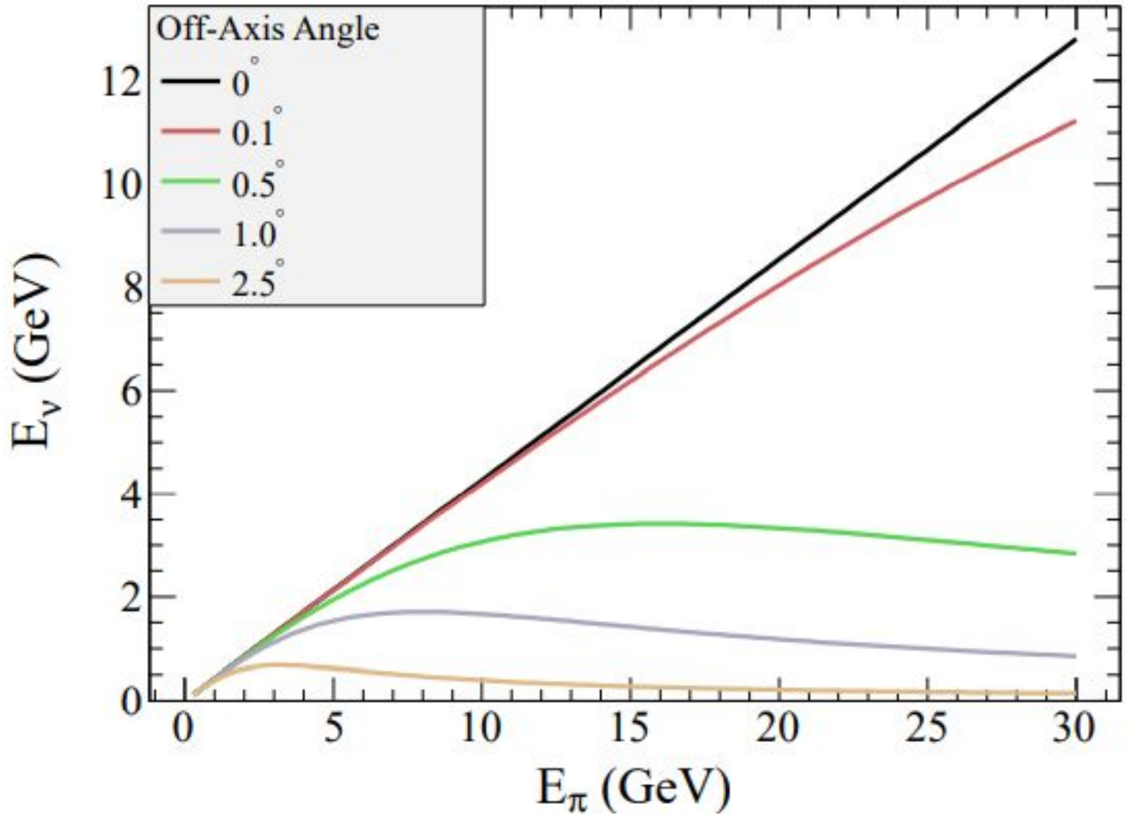


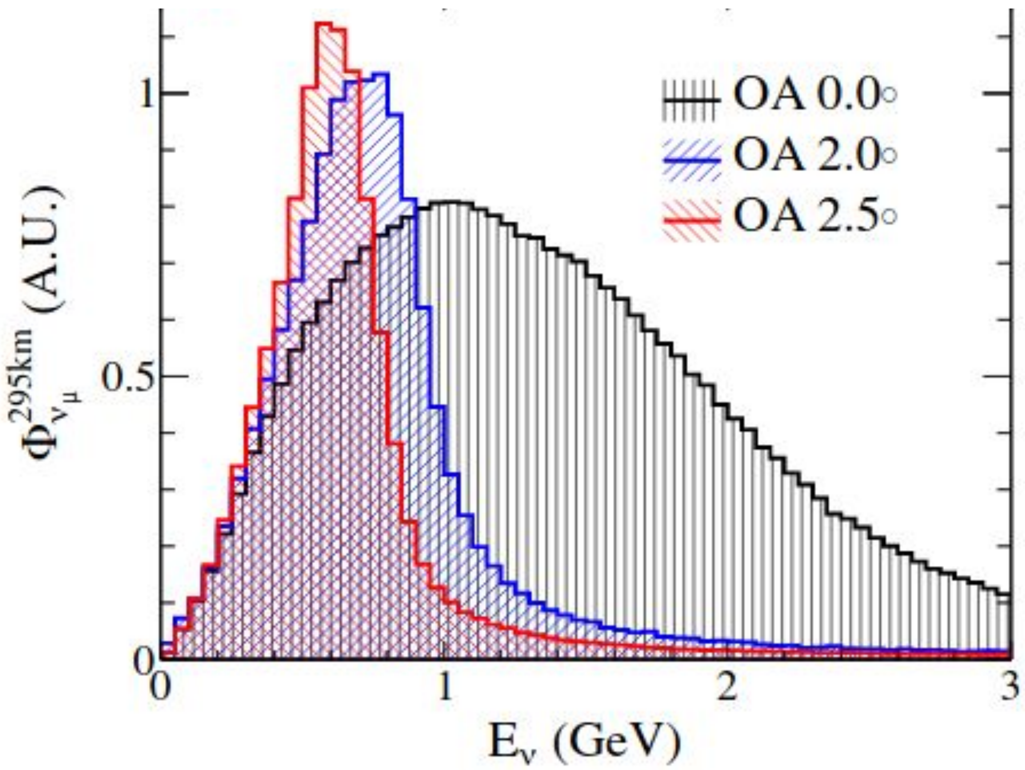


Off-axis technique

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

T2K example





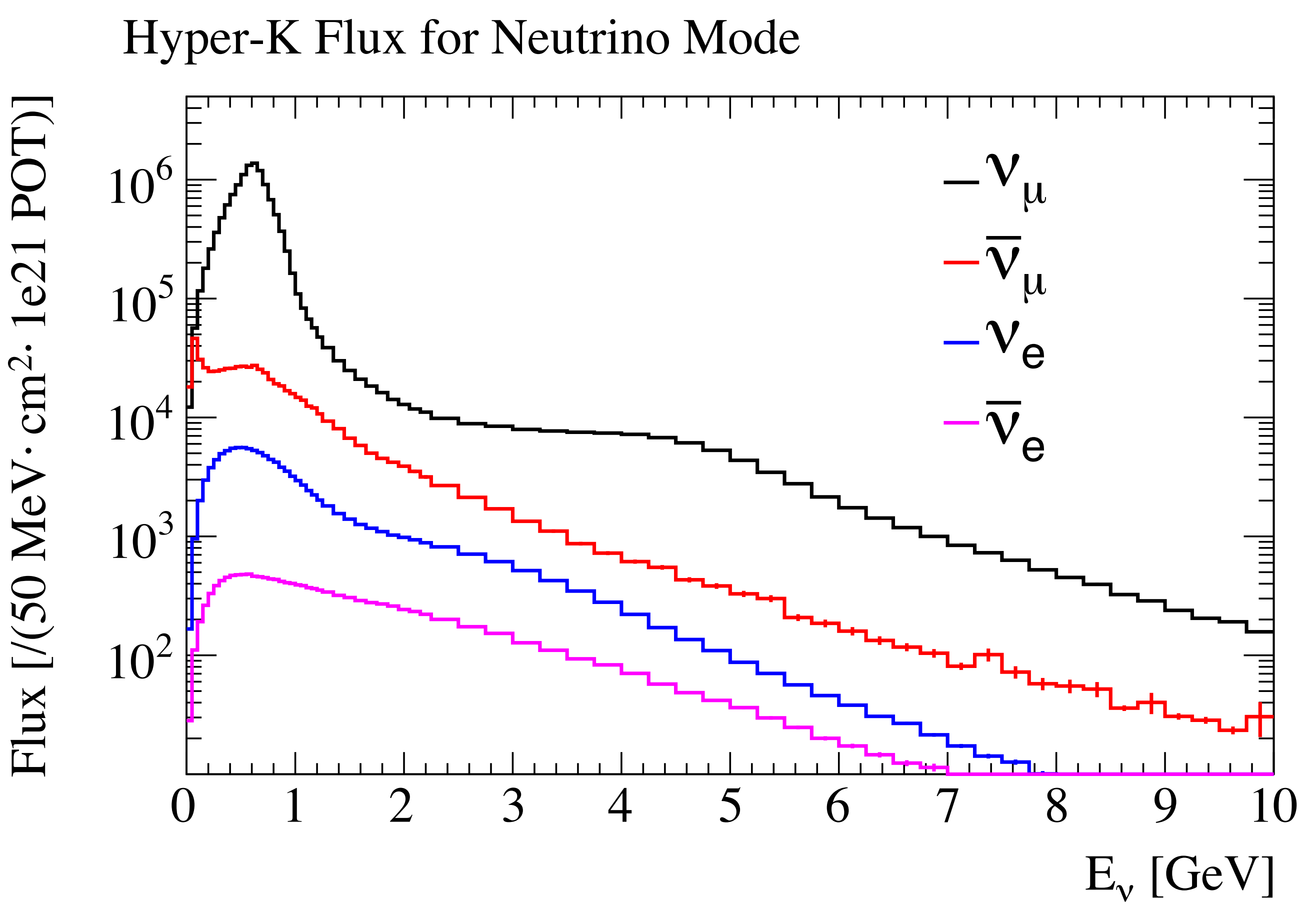
Examples of long-baseline off-axis experiments: T2K, NOvA

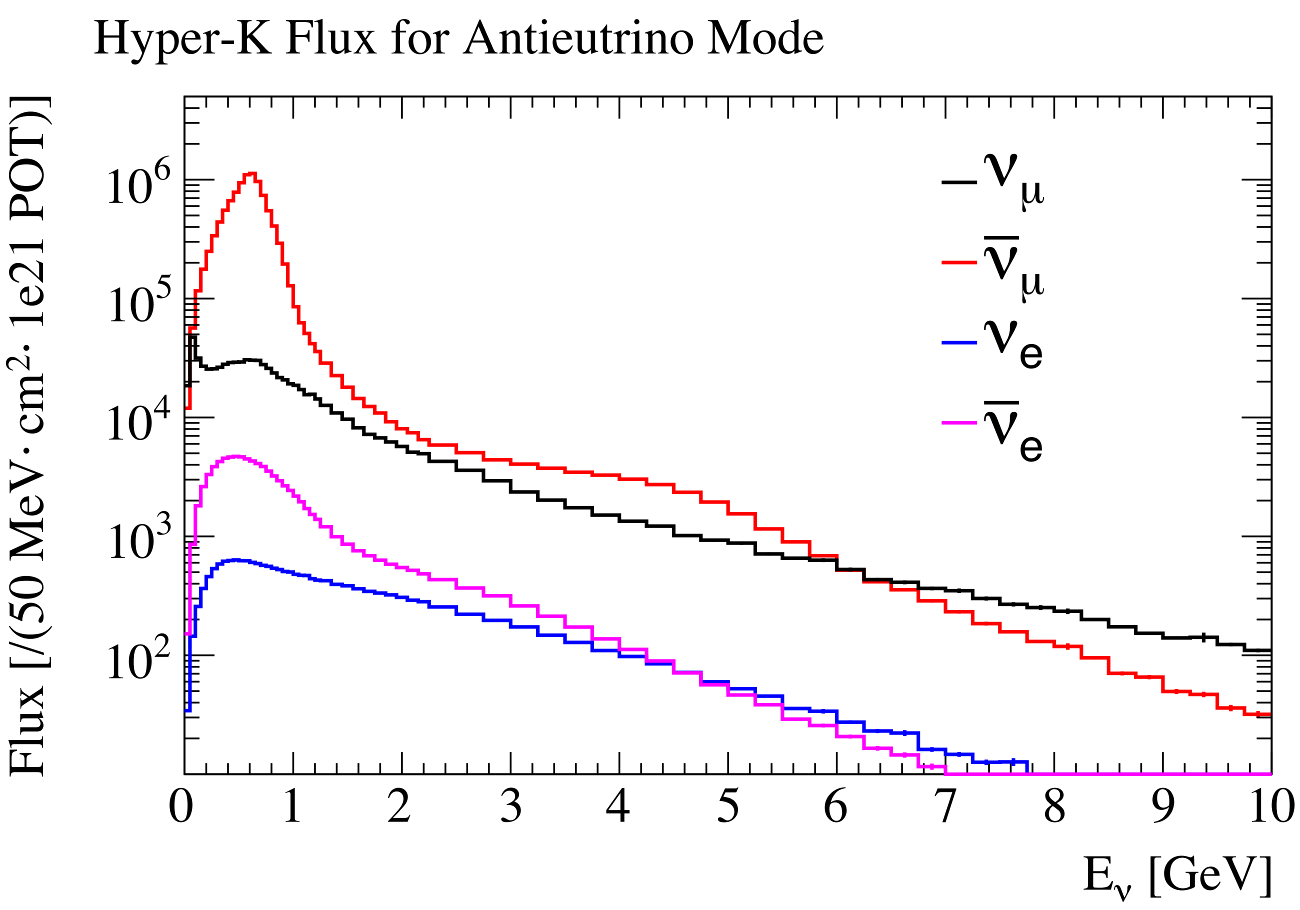
Examples of long-baseline on-axis experiments: MINOS, LBNF

Modifying the beam characteristics

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

Nice for studying CP violation (and neutrinos vs. antineutrinos, in general).
But, less pi- produced and antineutrino interaction cross section is lower.





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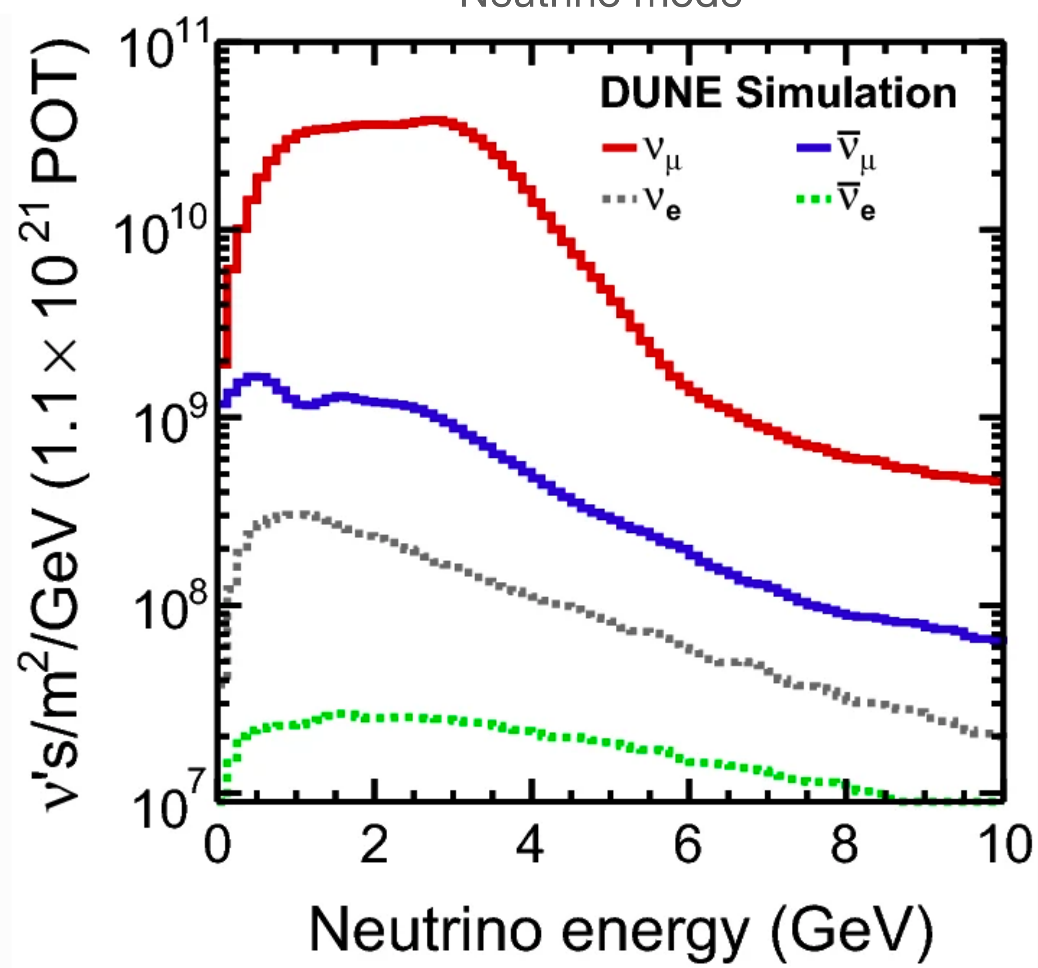
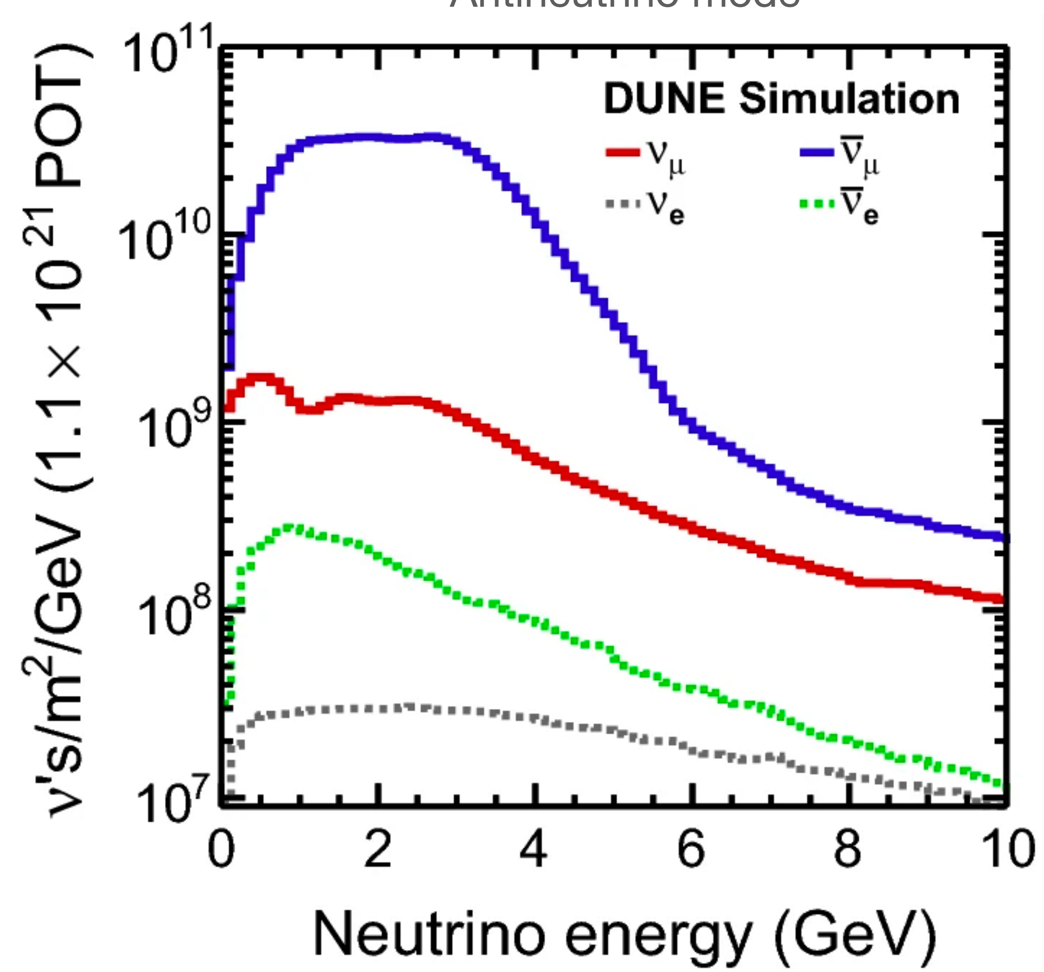
Neutrino mode



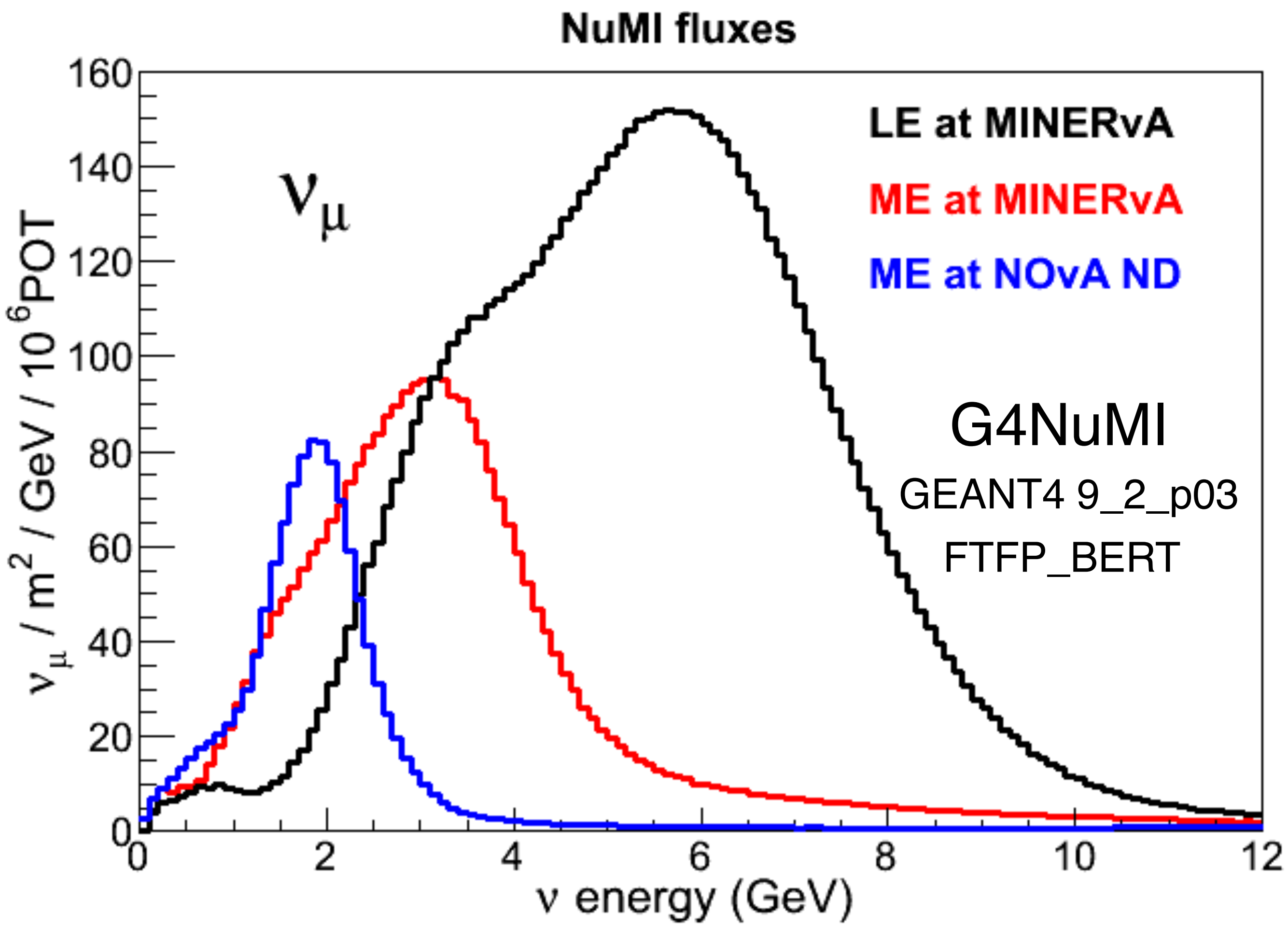
Antineutrino mode



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, proton energy.
Decay pipe modifications have also been envisioned (BNB).



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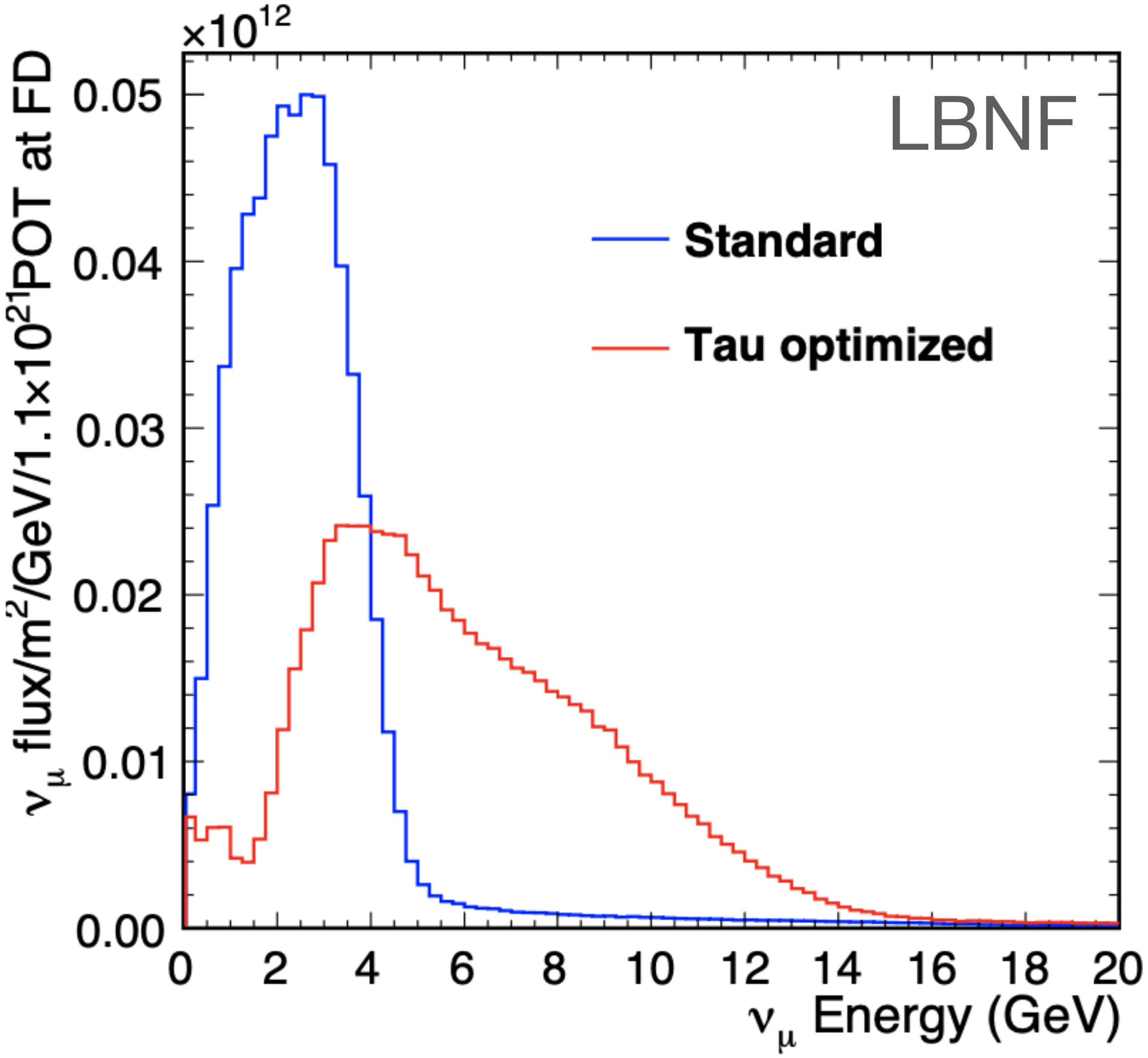
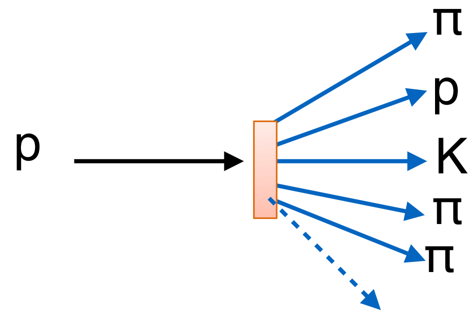


Predicting the flux

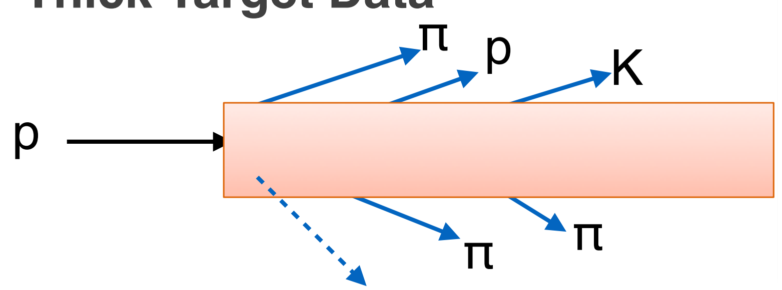
- Predicting the DIF neutrino flux can be very challenging!
    - How many pions/kaons are produced?
    - What are the kinematics (positions and momenta) of the pions/kaons as they exit the target?
    - How do the pions/kaons bend in the combination of horns?
    - What about the post-target materials 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

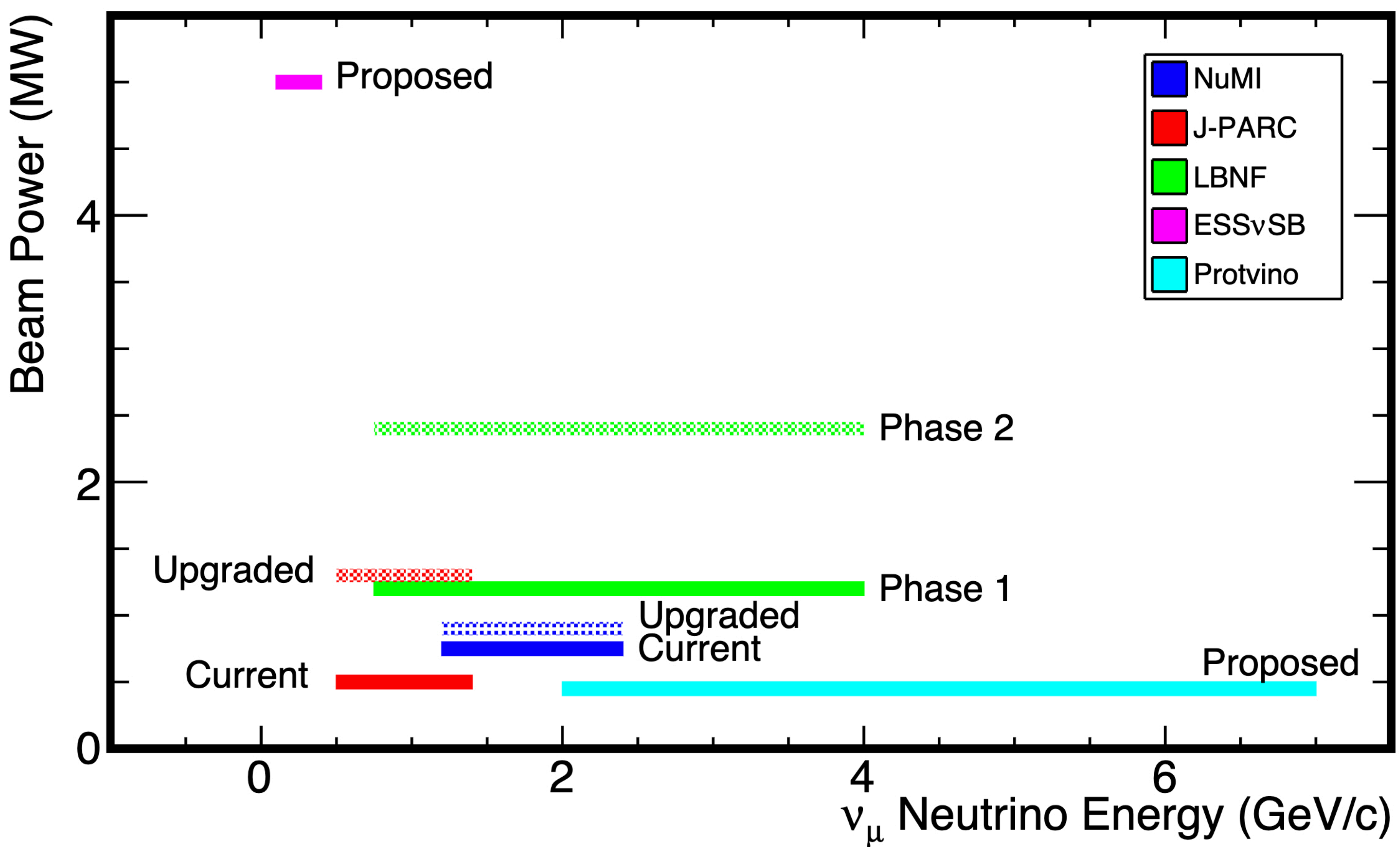


Thick Target Data



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

Current and future long-baseline beams



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

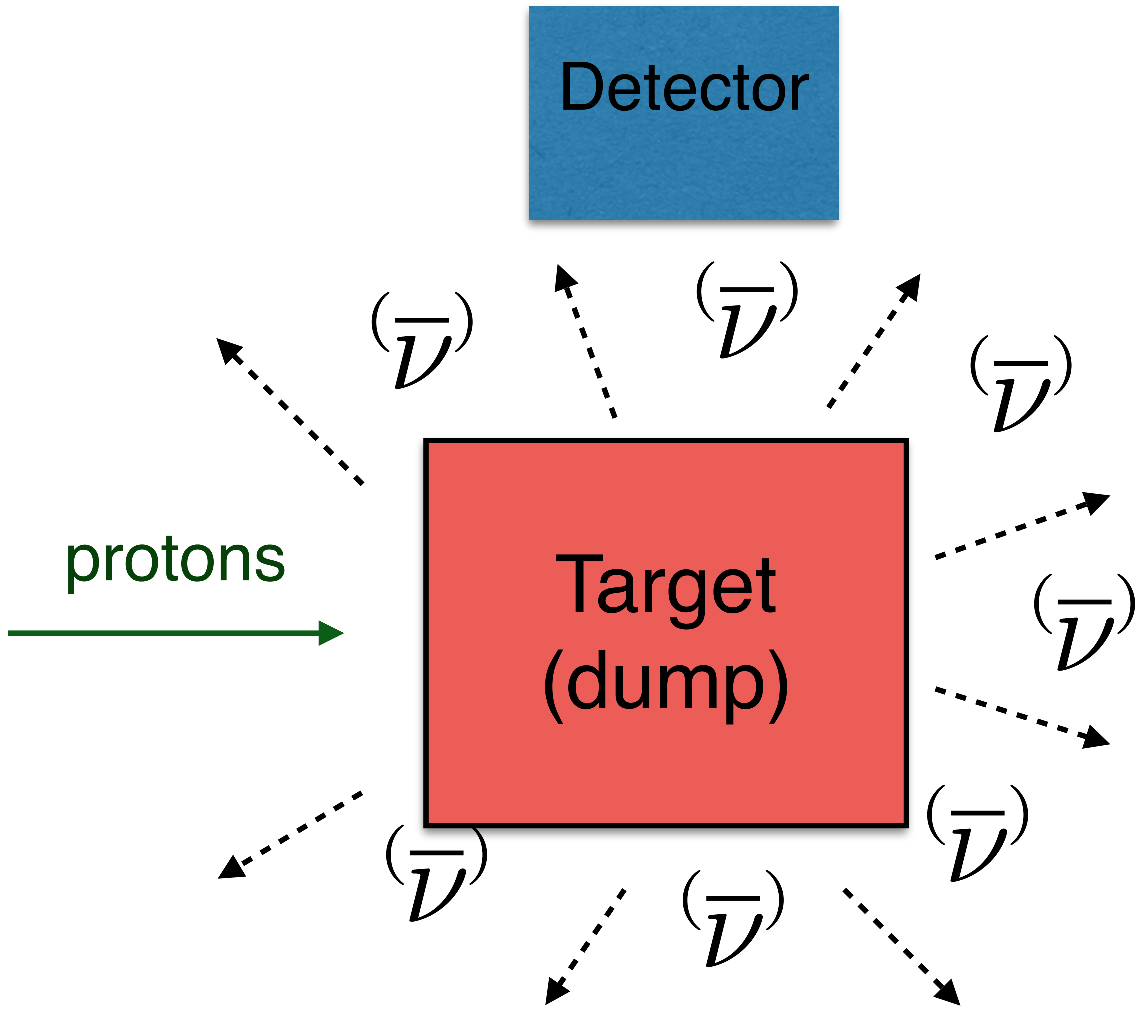
- Flavor content can be less pure.
- Energy spectra less well understood.
- Beam-based backgrounds can be significant (may need fancy detector).

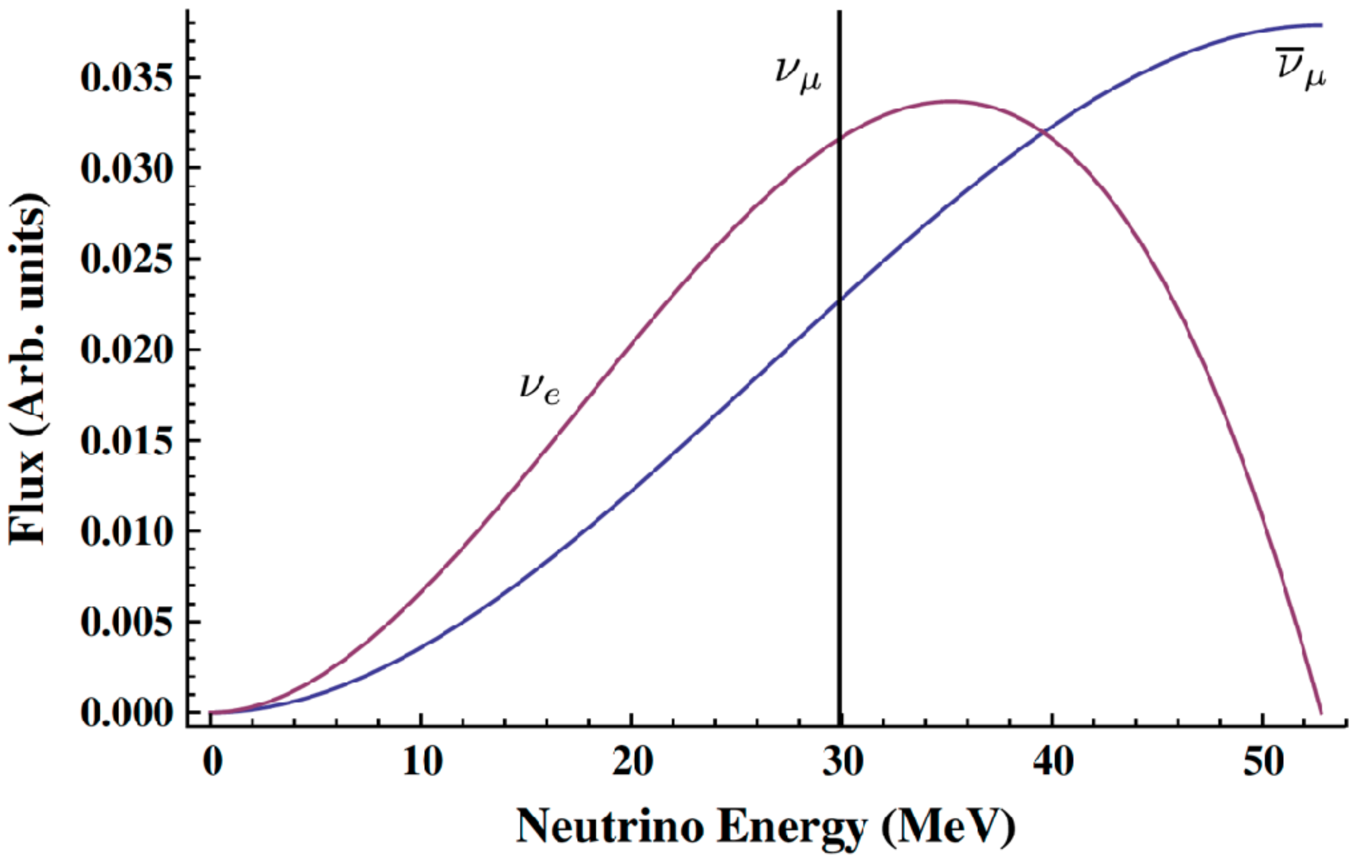
Accelerator decay-in-flight homework

- 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!
  - Targets and horns break. Pay attention to this.
- 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. And, almost all accelerator decay-in-flight experiments are stats. limited!
  - Make sure your beamline properties are well-matched to your physics (e.g oscillation maxima/minima) and detector abilities.
- Keep thinking of new ways to understand and take advantage of these beams. There are more good ideas still out there!
- Extra credit: Don't forget to look for dark matter and other exotic stuff.

Accelerator decay-at-rest neutrinos

Pion and muon decay-at-rest neutrinos

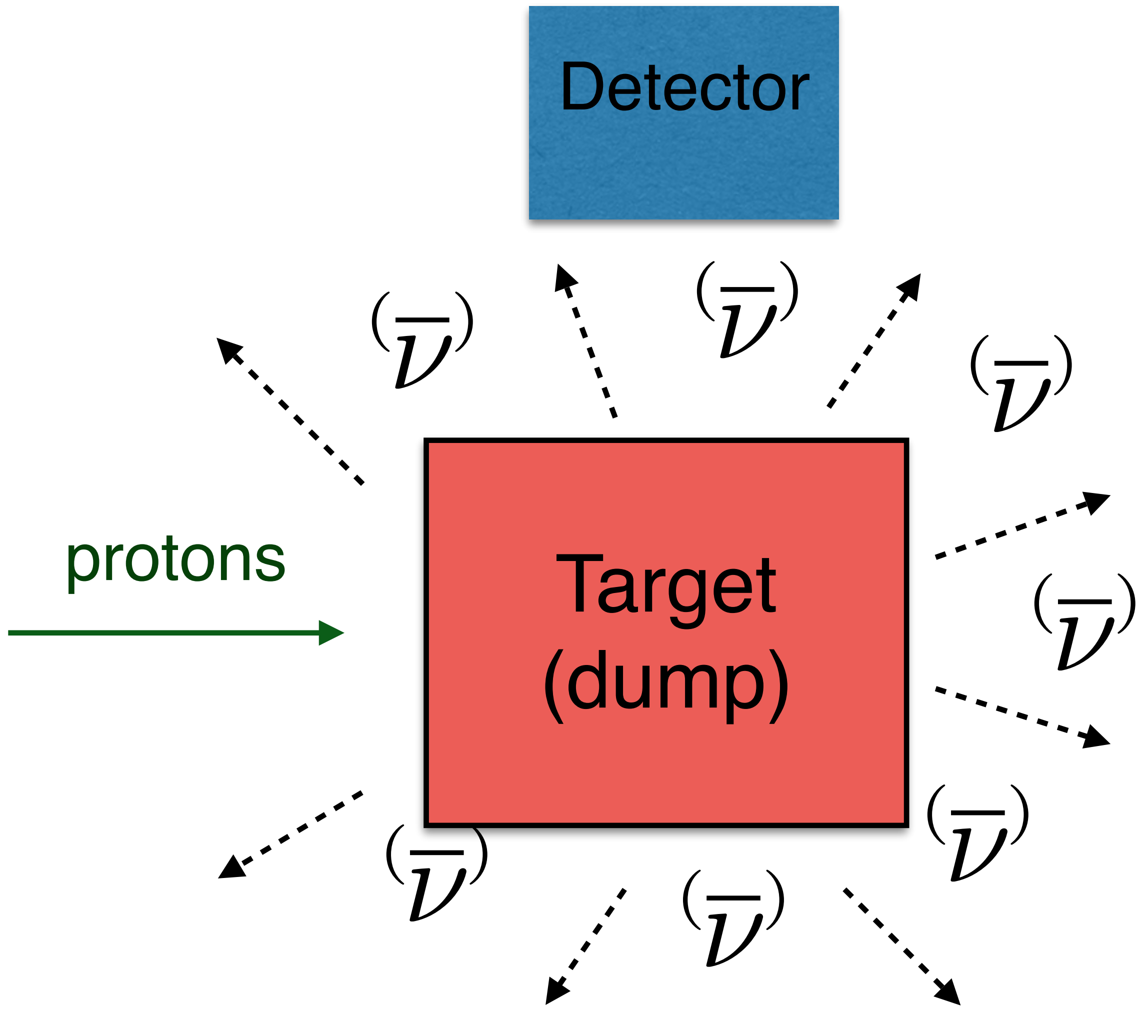




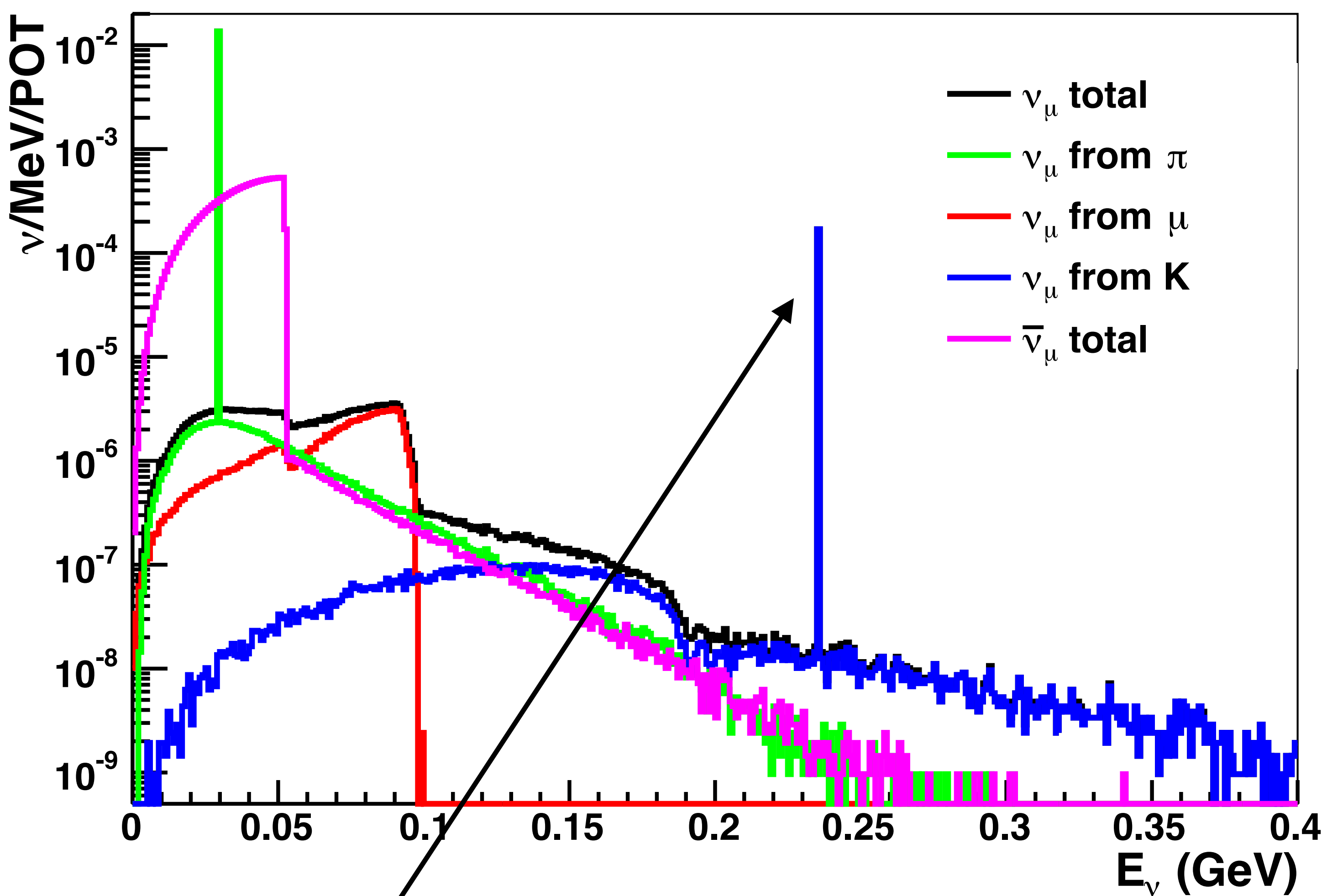
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$

Kaon decay-at-rest neutrinos

(Above 2-3 GeV primary proton energy)



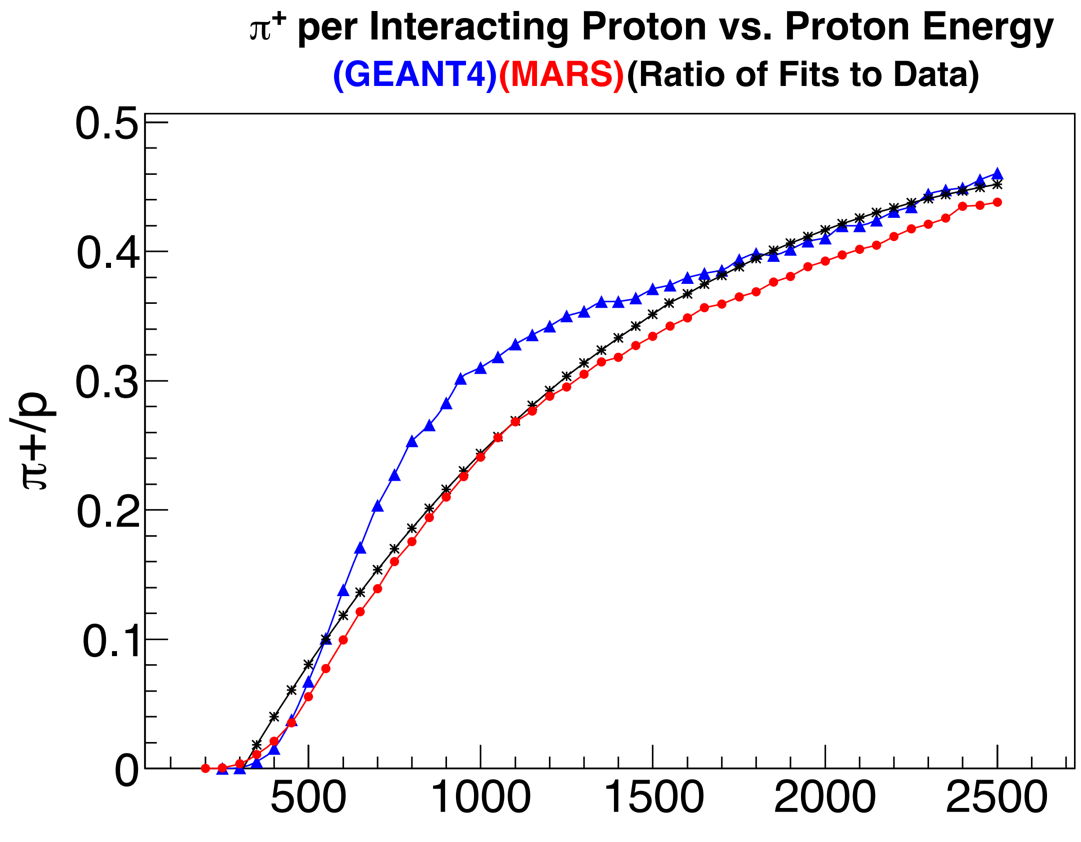
example: ν_μ flux at J-PARC spallation neutron facility (SNS shape is very similar, except no K)



E=236 MeV if kaon decays at rest

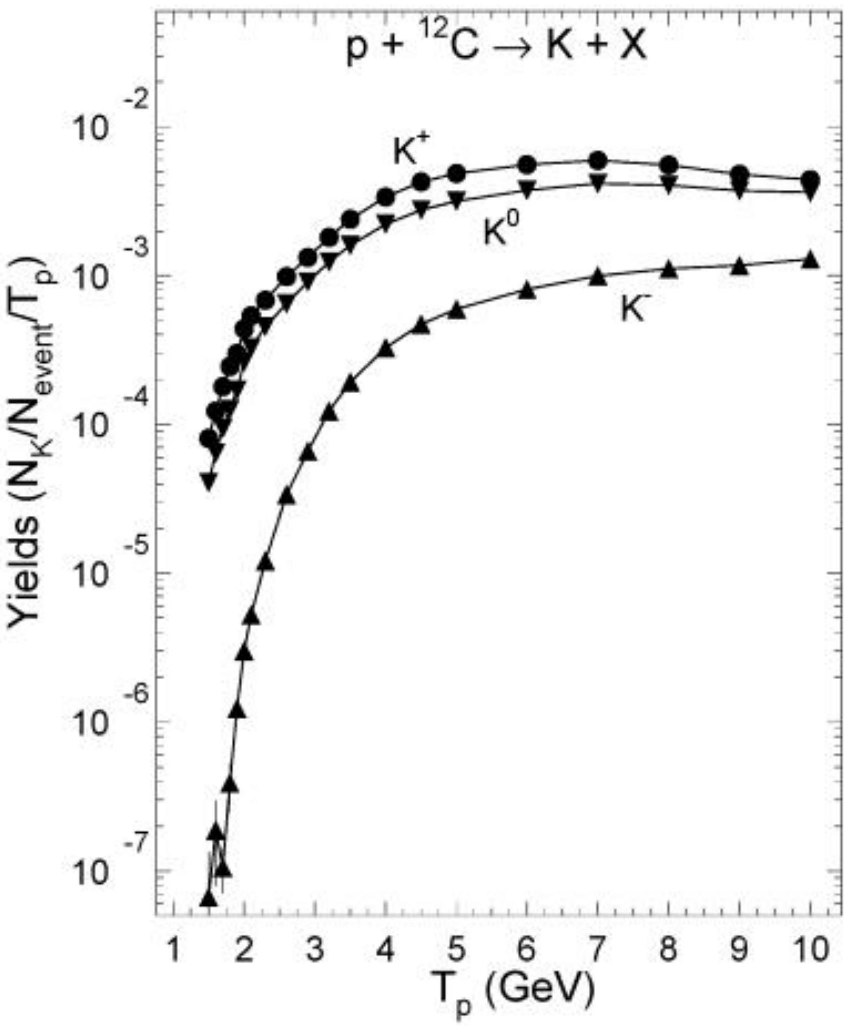
$K^+ \to \mu^+ \nu_\mu$ (branching ratio=64%)

Pion and kaon production



1205.5528

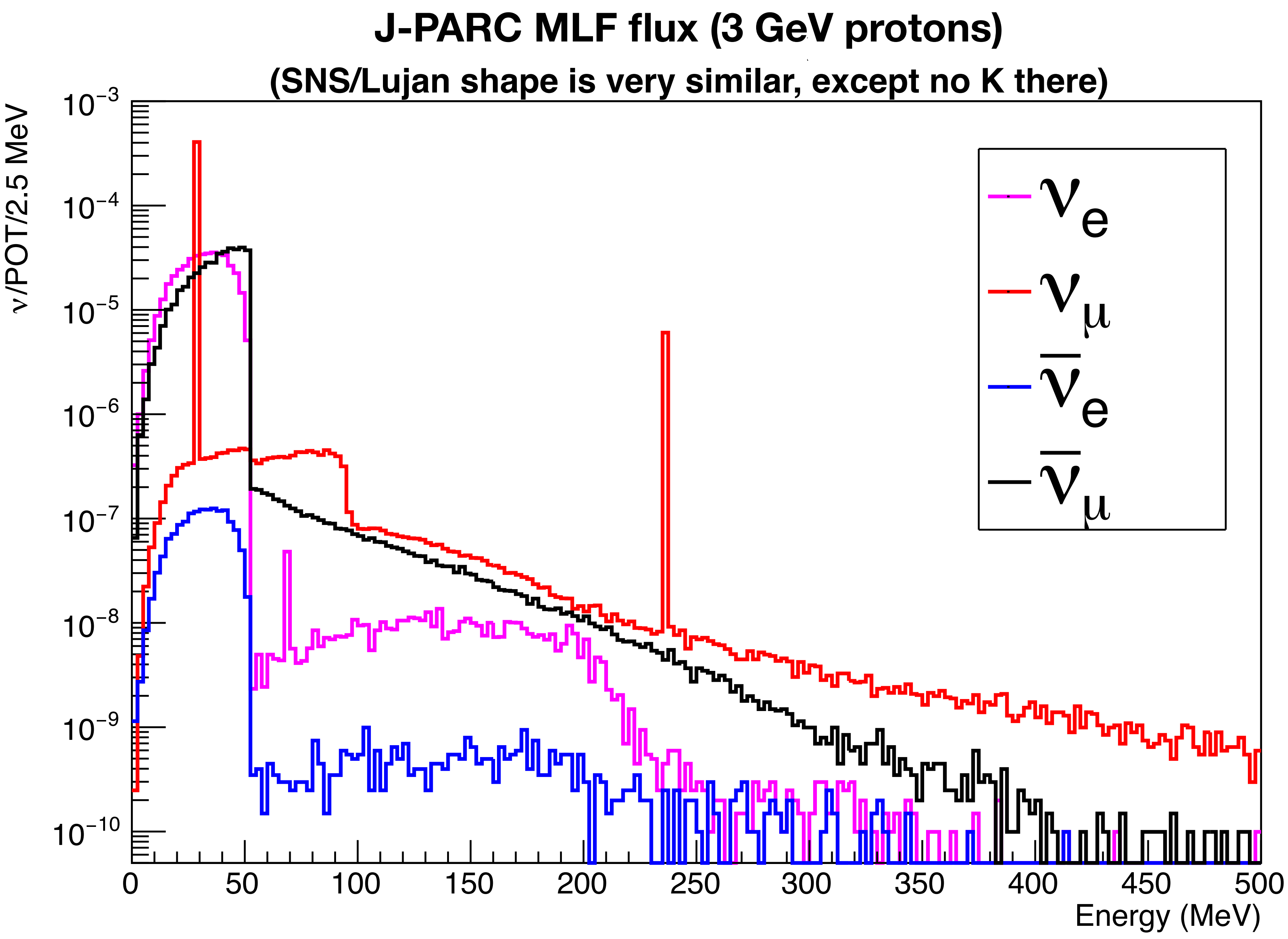
Fermilab-Conf-09-647-APC



Pion production sweet spot is ~1 GeV

Kaon production sweet spot is ~5-7 GeV

Detailed flux

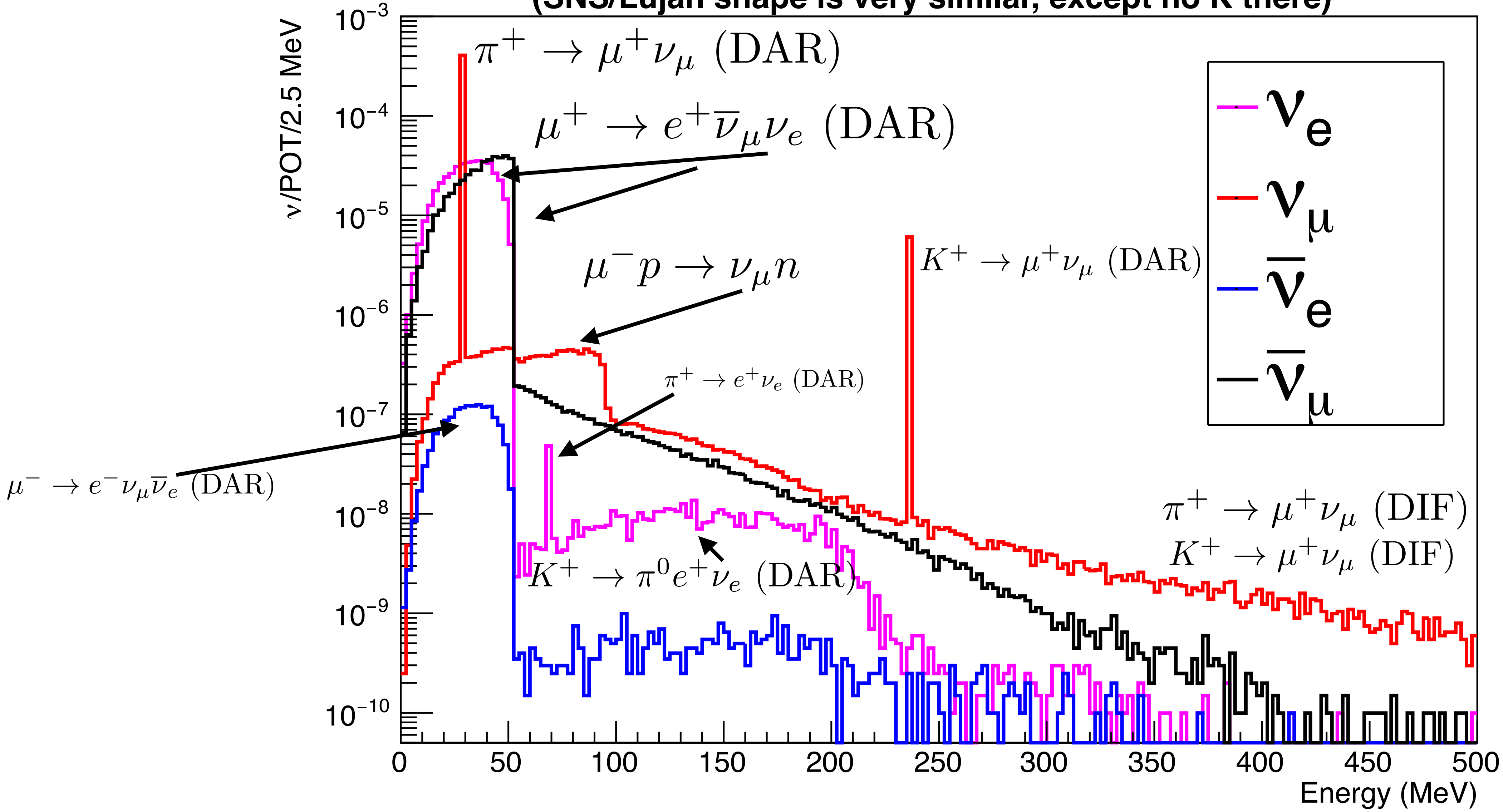


Neutrinos tend to be isotropic, but remember: these sources are ultra-powerful. SNS is 1.4 MW, J-PARC MLF is 800 kW (BNB is 32 kW).

Detailed flux

J-PARC MLF flux (3 GeV protons)

(SNS/Lujan shape is very similar, except no K there)



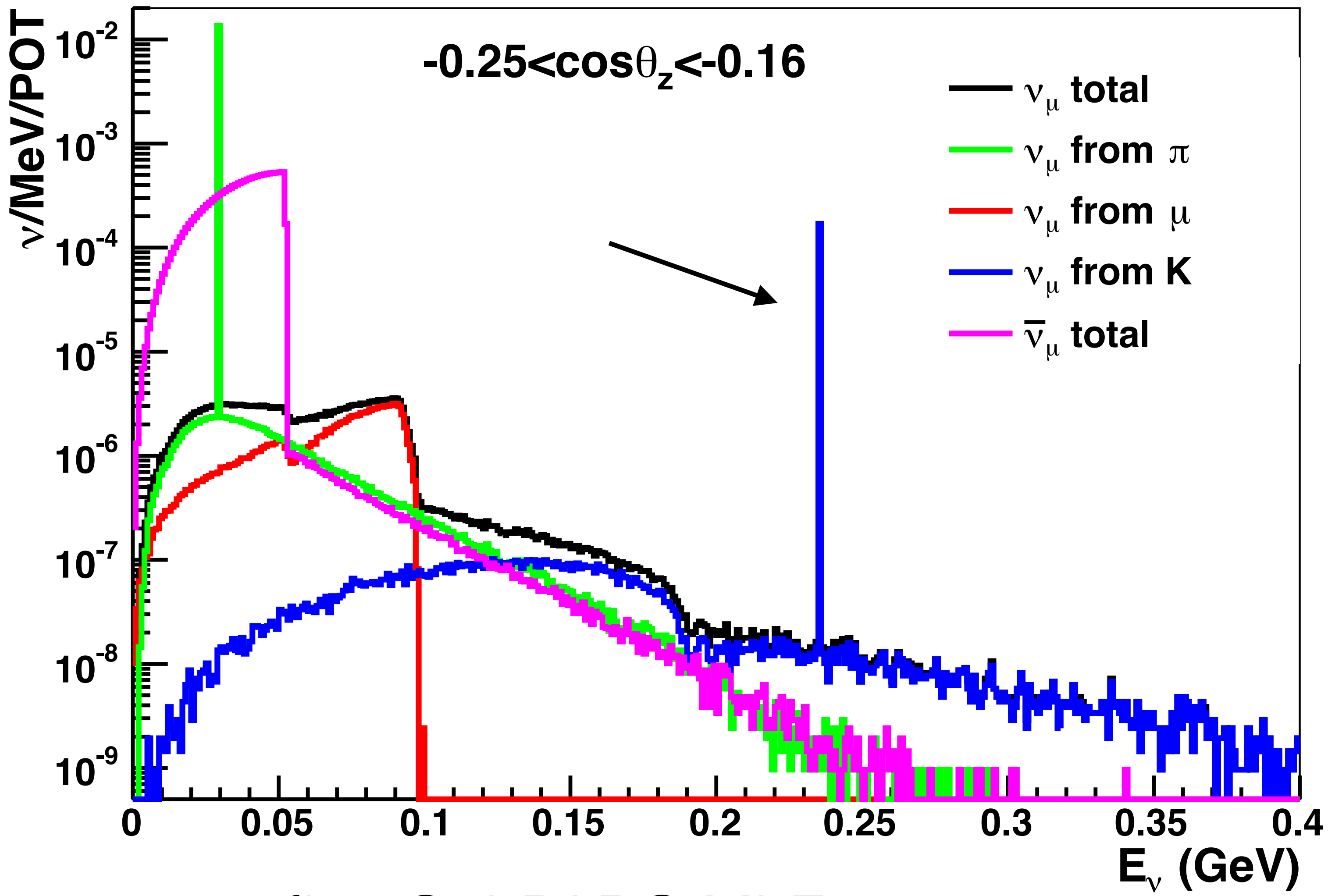
Neutrinos tend to be isotropic, but remember: these sources are ultra-powerful. SNS is 1.4 MW, J-PARC MLF is 800 kW (BNB is 32 kW).

What makes for a good decay-at-rest source?

- As usual, you want lots of POT with the protons at a favorable energy for doing the physics you're interested in.
- But, there are some other considerations.
    - Again, these sources were typically designed for non-neutrino physics.
    - Low-A materials near the target can increase the decay-in-flight flux, which is usually not favorable.
        - For example, if you are looking for short-baseline oscillations via numubar->nuebar, you don't want your pi- and mu- to decay-in-flight to produce a nuebar.
        - What you really want is just ultra-dense stuff completely surrounding the target.
    - Beware facilities issues!

Neutrino source lesson: If you choose your source wisely, you don't need a high-res detector

Example: KPIPE
A very pure flux of KDAR neutrinos!

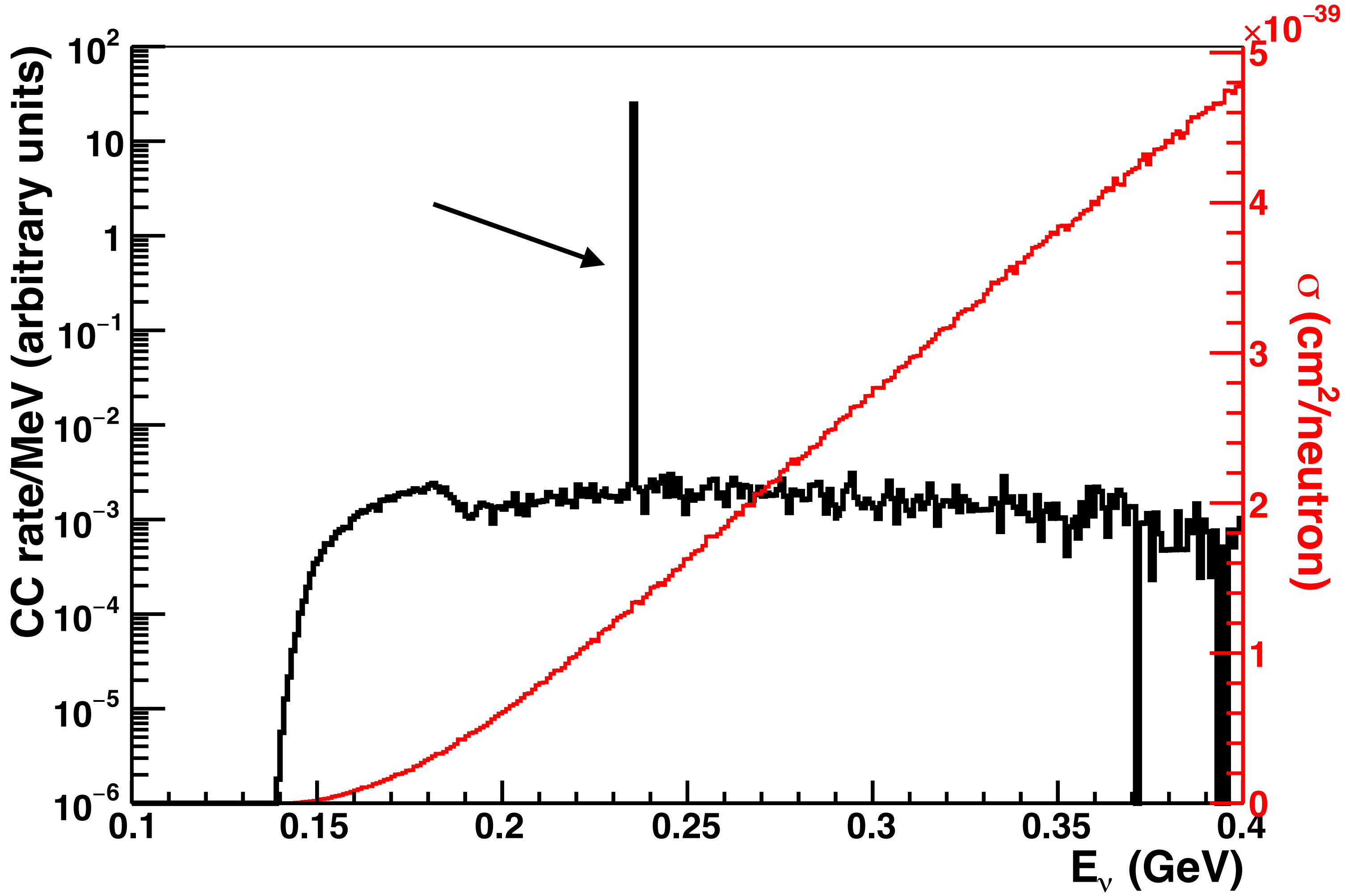


[1506.05811](https://arxiv.org/abs/1506.05811)

example flux @ J-PARC MLF

Neutrino source lesson: If you choose your source wisely, you don't need a high-res detector

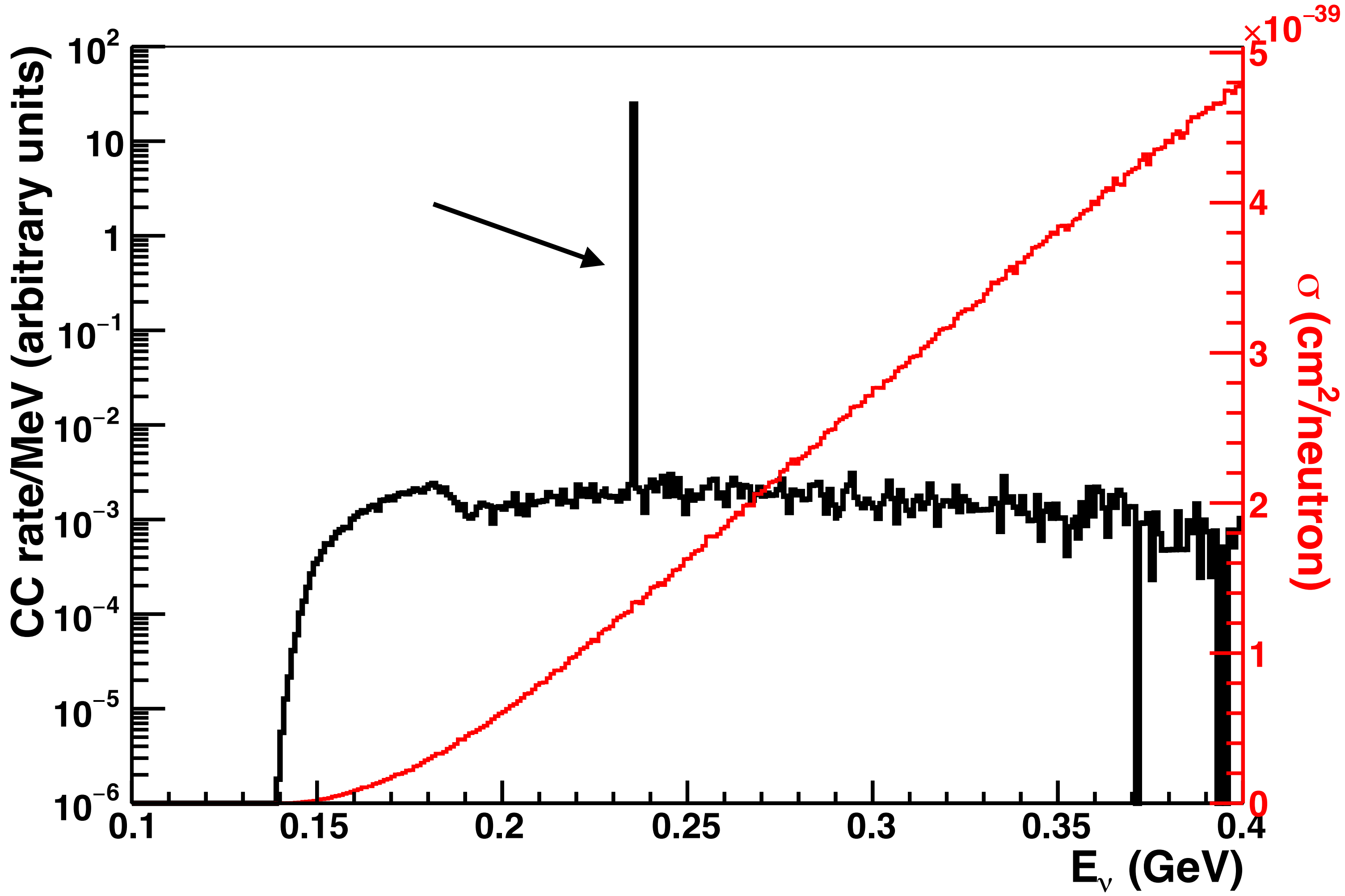
If you detect a muon-neutrino event, you can be 98.5% sure that it was a 236 MeV muon neutrino!



[1506.05811](https://arxiv.org/abs/1506.05811)

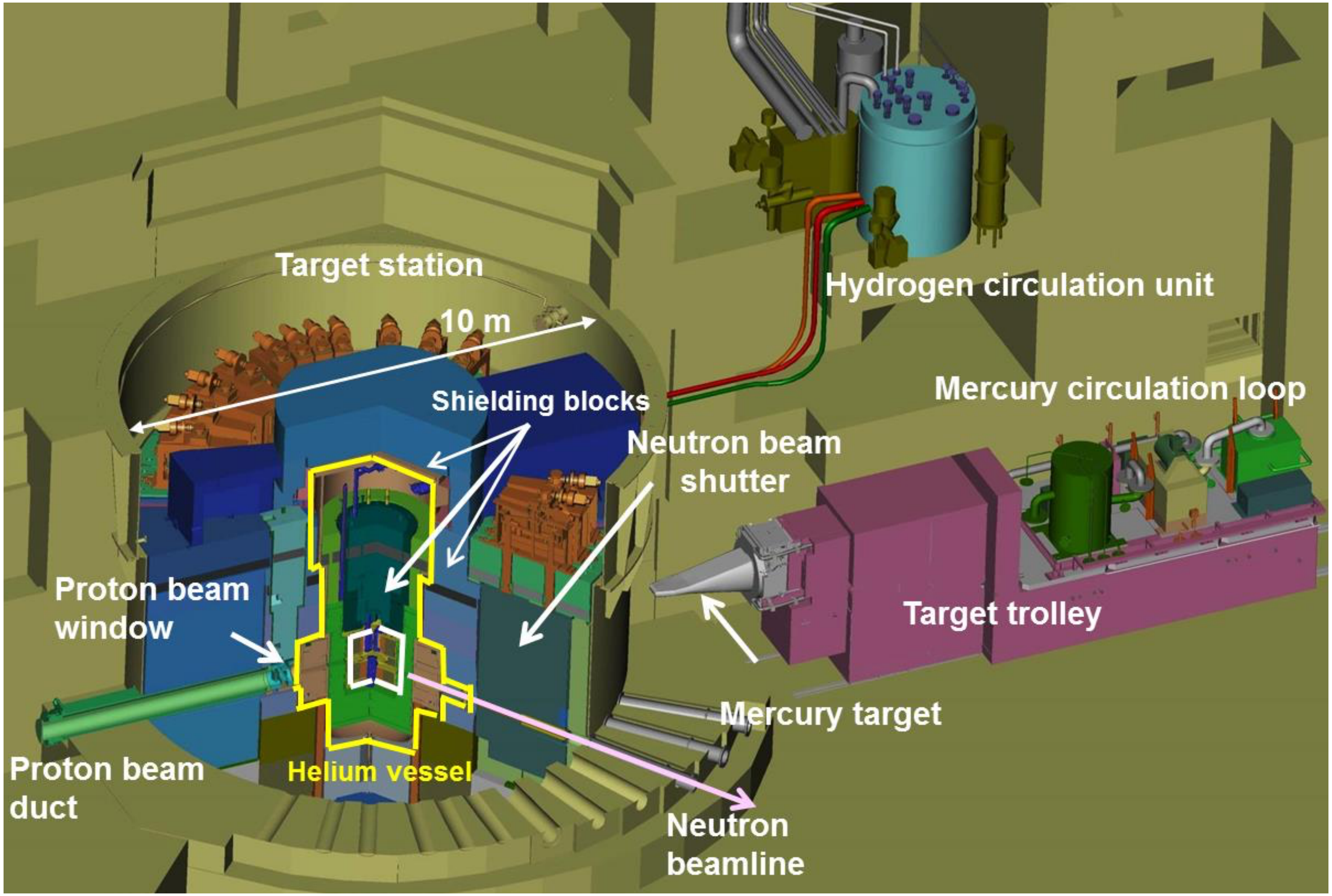
Neutrino source lesson: If you choose your source wisely, you don't need a high-res detector

Since you know the energy of the neutrino, you don't need to worry about energy resolution. KPIPE calls for 0.4% photocoverage. Just look for a double coincidence of a muon flash followed by muon decay flash.



1506.05811

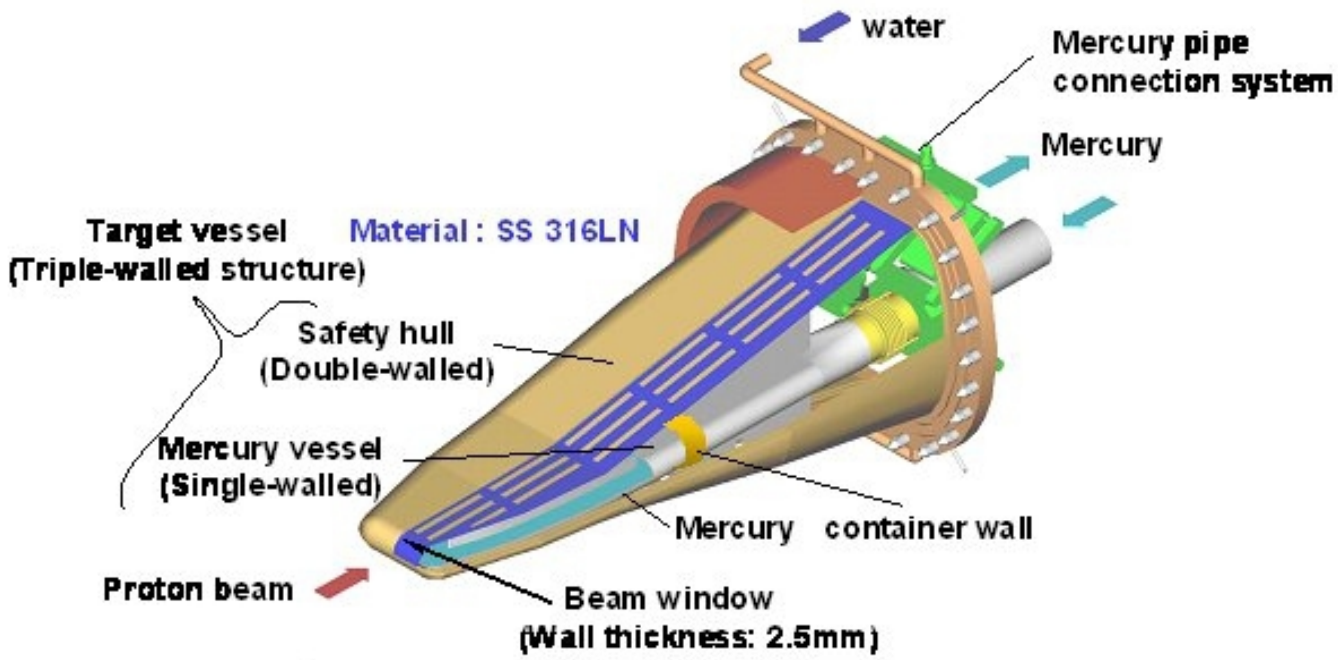
Example decay-at-rest source: J-PARC Spallation Neutron Source



3 GeV protons on a mercury target @ 830 kW

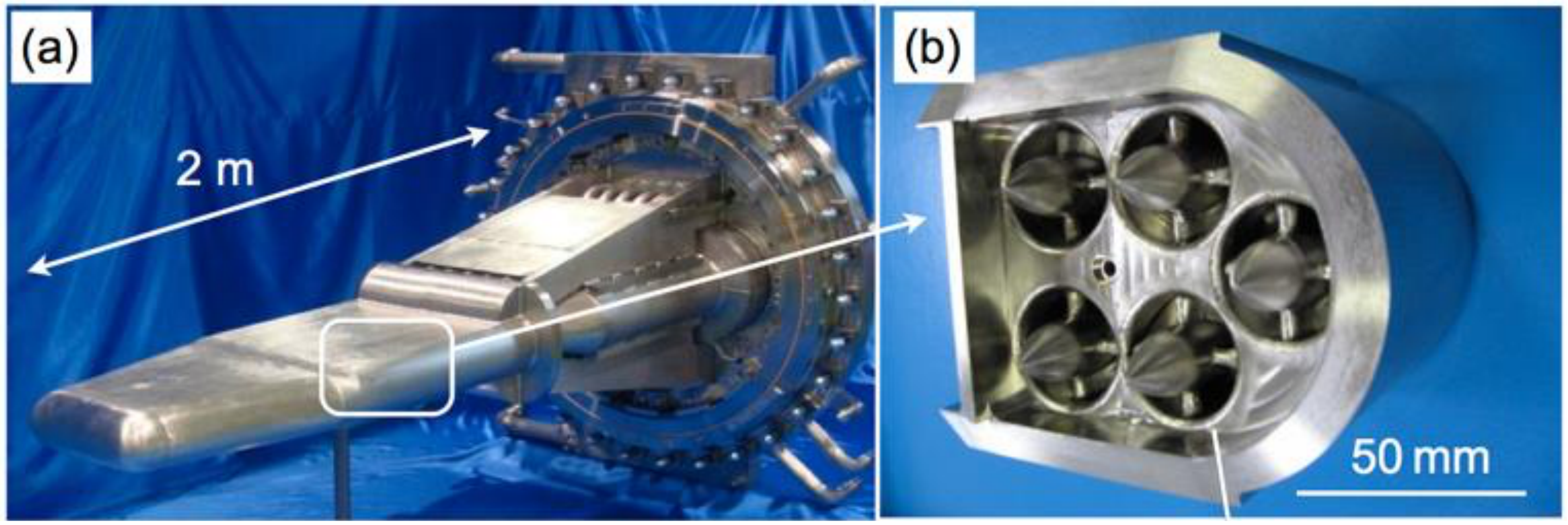
J-PARC production target

Mercury is circulated at 154 kg/s!

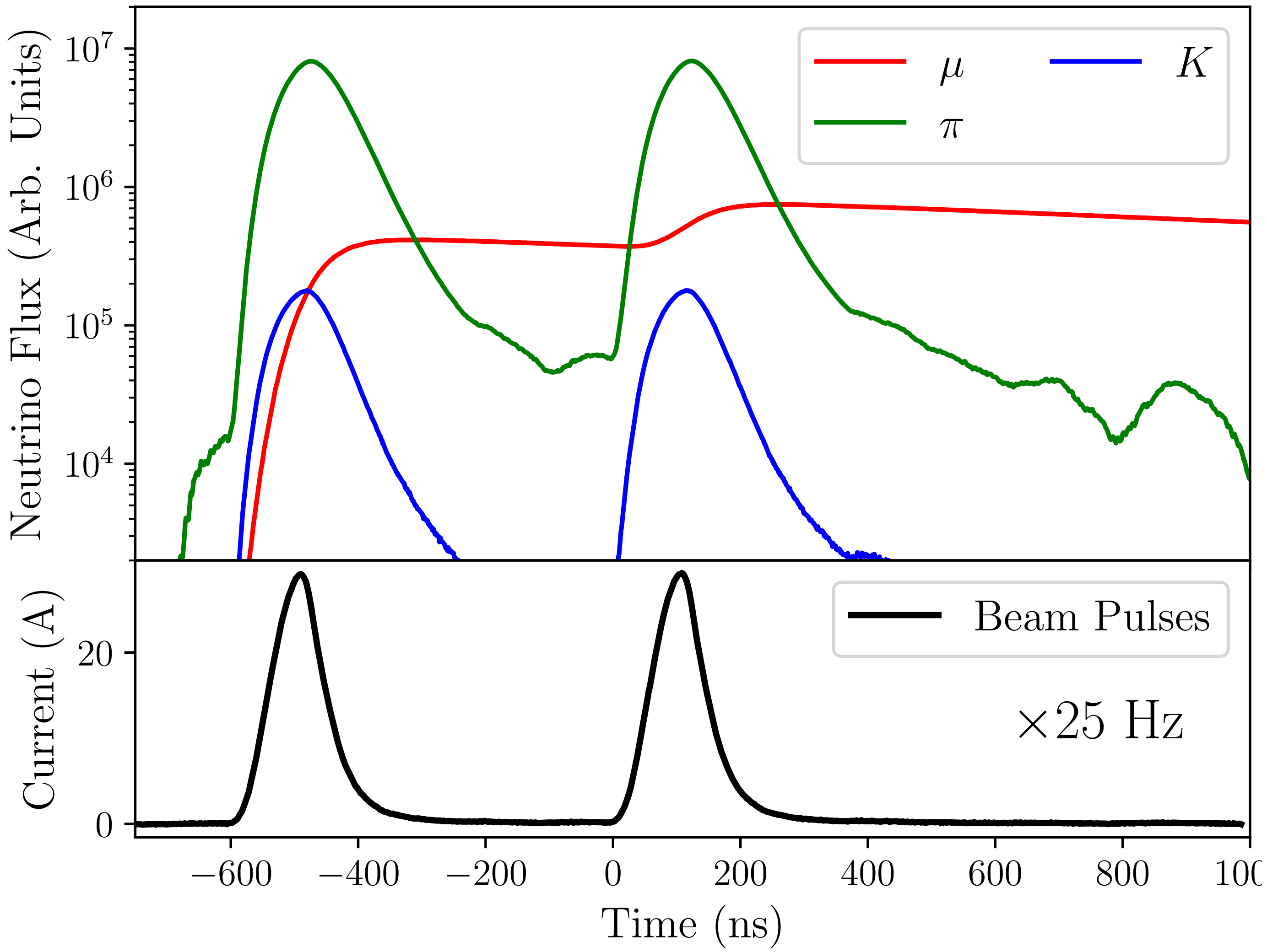


Neutron/neutrino production target is a double-walled SS vessel with circulating mercury.

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



J-PARC spallation source beam timing

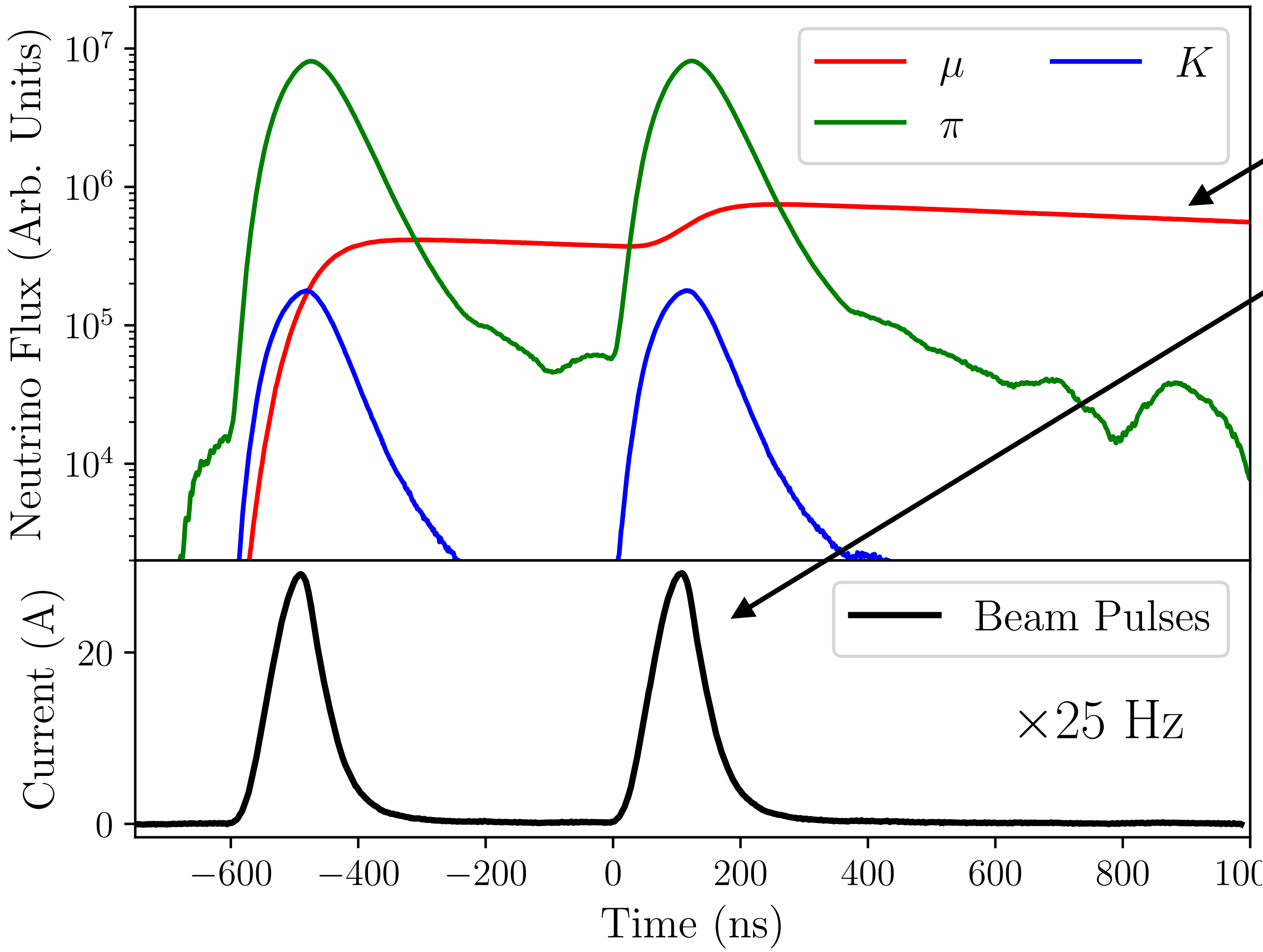


The J-PARC beam is delivered in two close pulses at 25 Hz, producing “prompt” (pion and kaon) and “delayed” (muon) neutrinos.

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 take full advantage of the narrow beam window because the muon has a longer lifetime than the beam pulse.

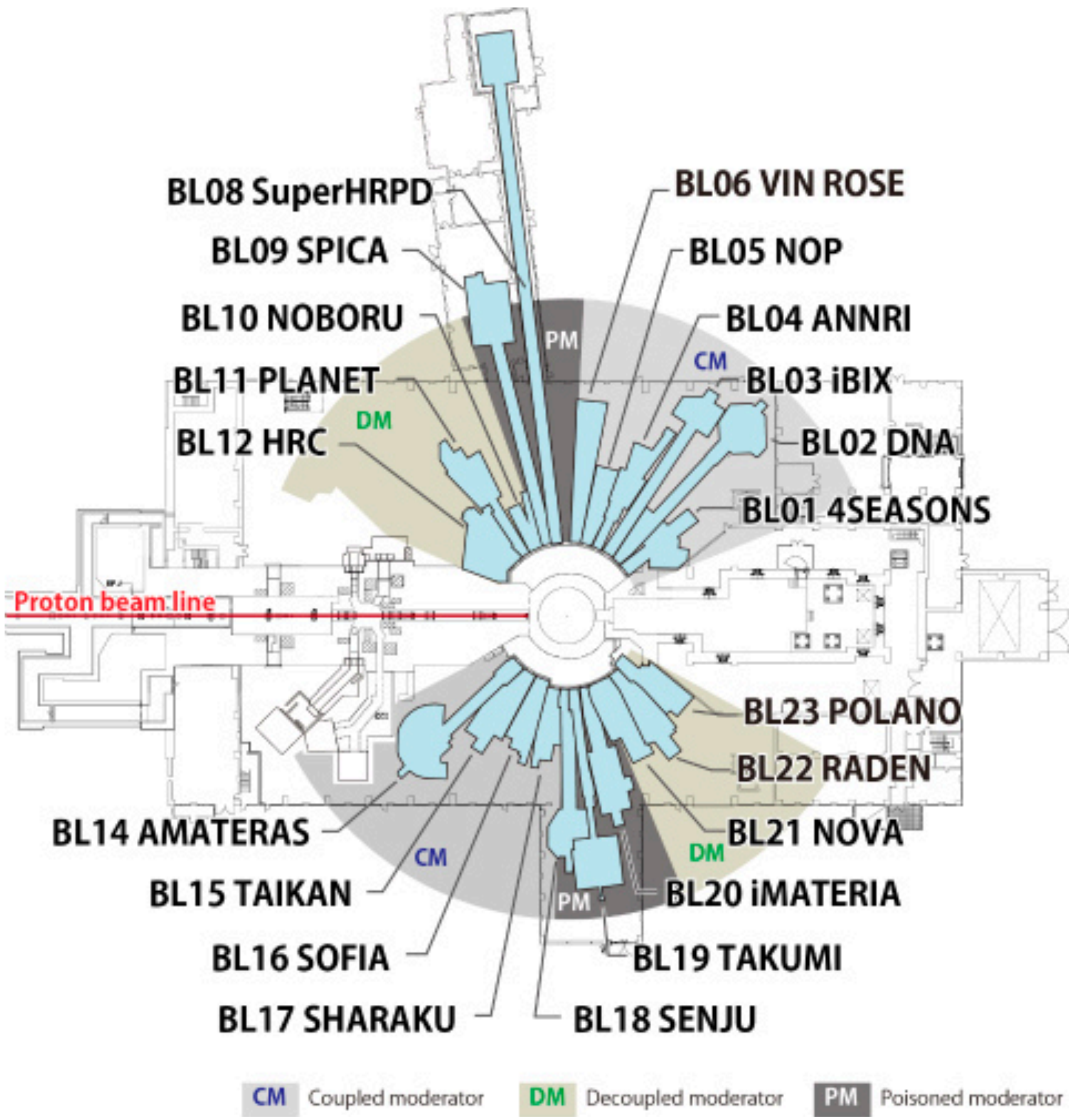


$$\mu^+ \rightarrow e^+ \overline{\nu}_\mu \nu_e \text{ (DAR)}$$

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

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.

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.

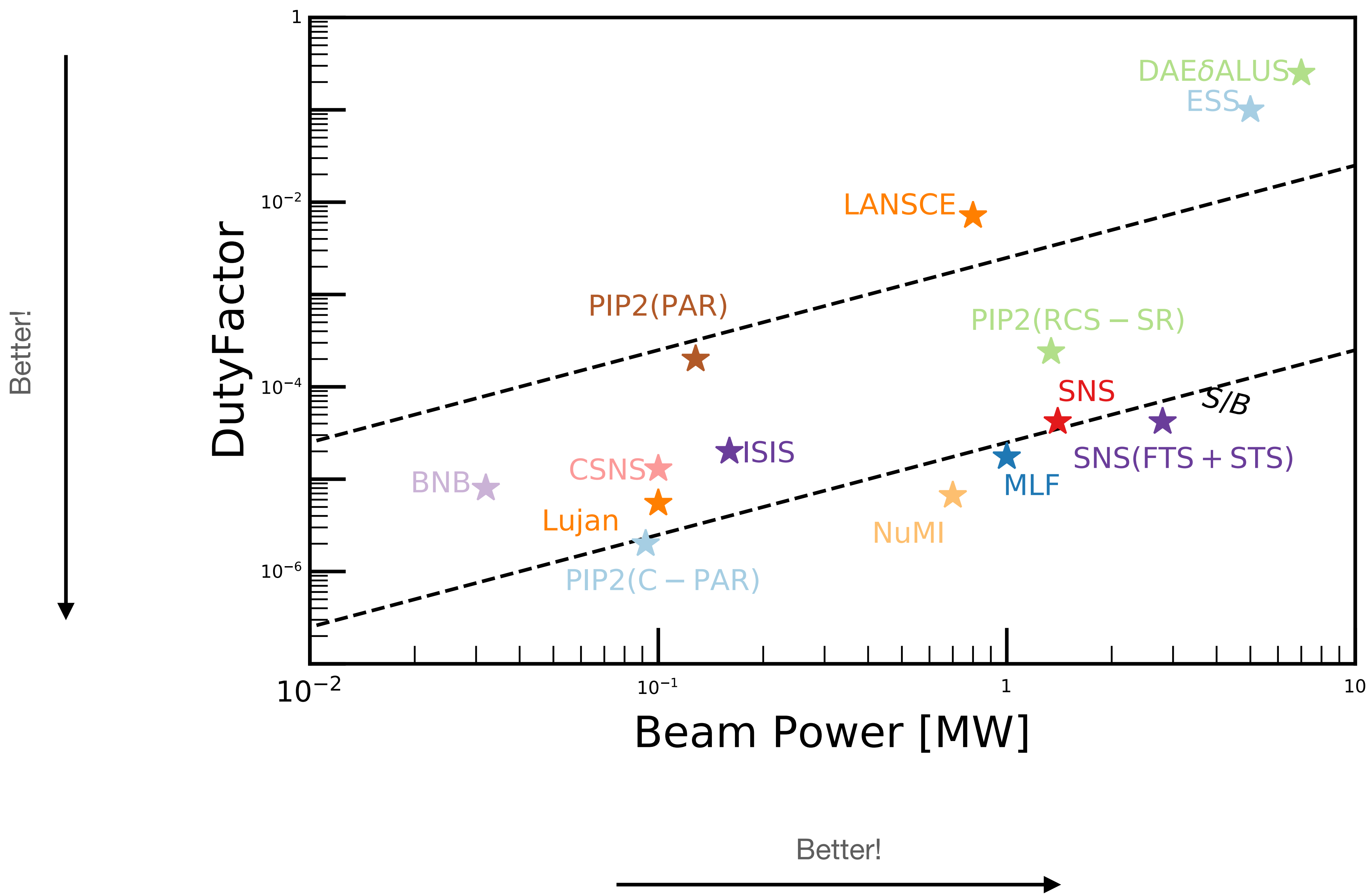
JSNS^2 is on the third floor of the MLF.

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

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

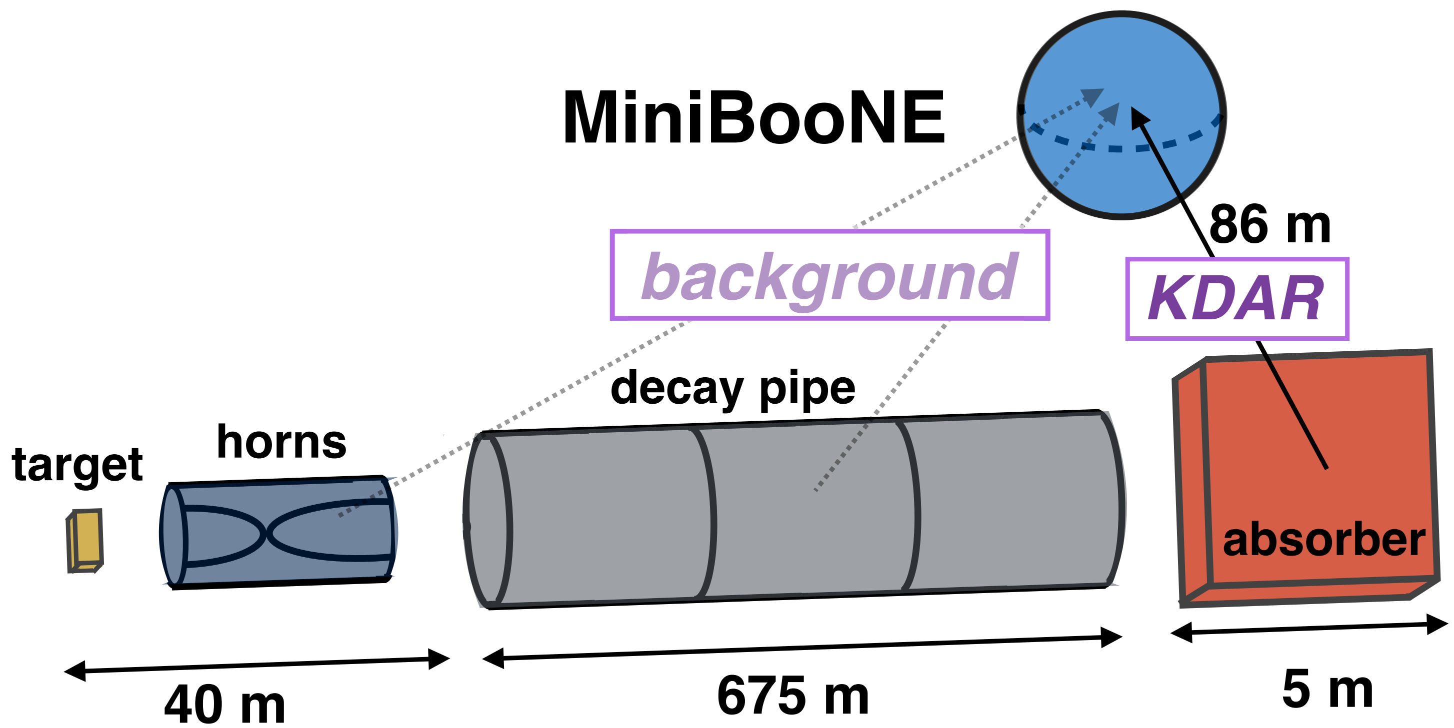
Beam characteristics

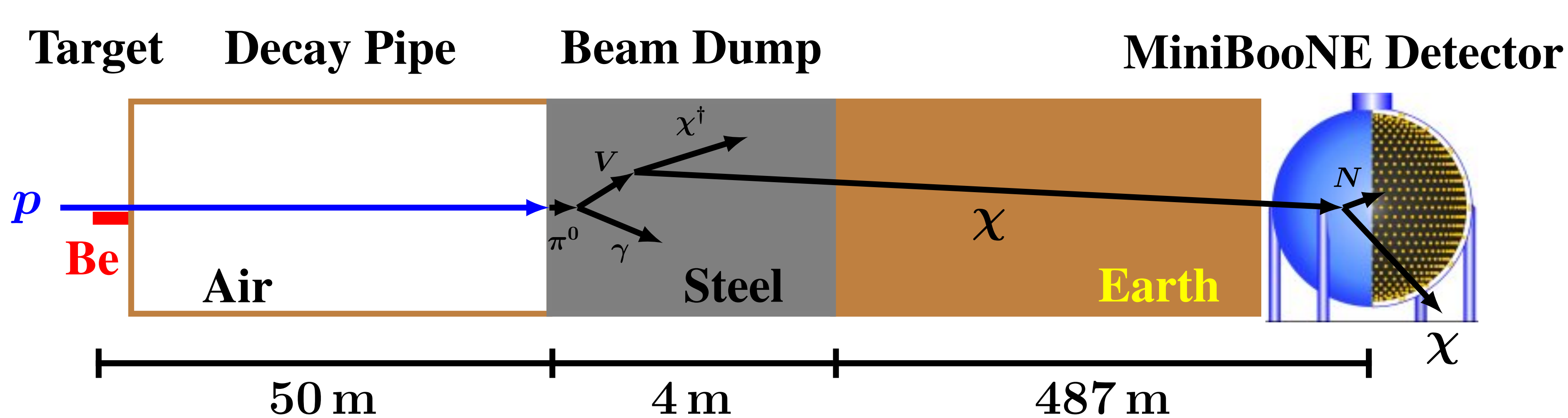
2103.00009, 2203.08079



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 (you guessed it!) Fermilab (w/ no facilities issues, optimized target).

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, …)

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

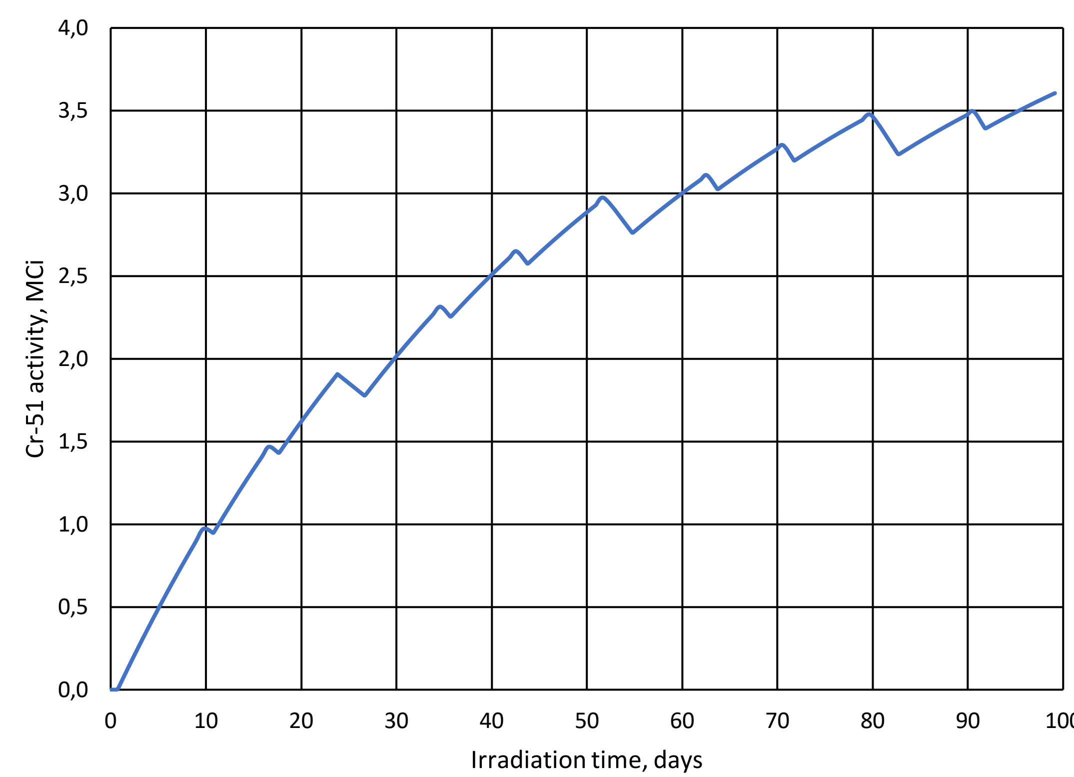
	^{51}Cr			
E_ν [keV]	747	752	427	432
B.R.	0.8163	0.0849	0.0895	0.0093
$\sigma[10^{-46}$ cm$^2]$	60.8	61.5	26.7	27.1

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

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

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

2207.10928



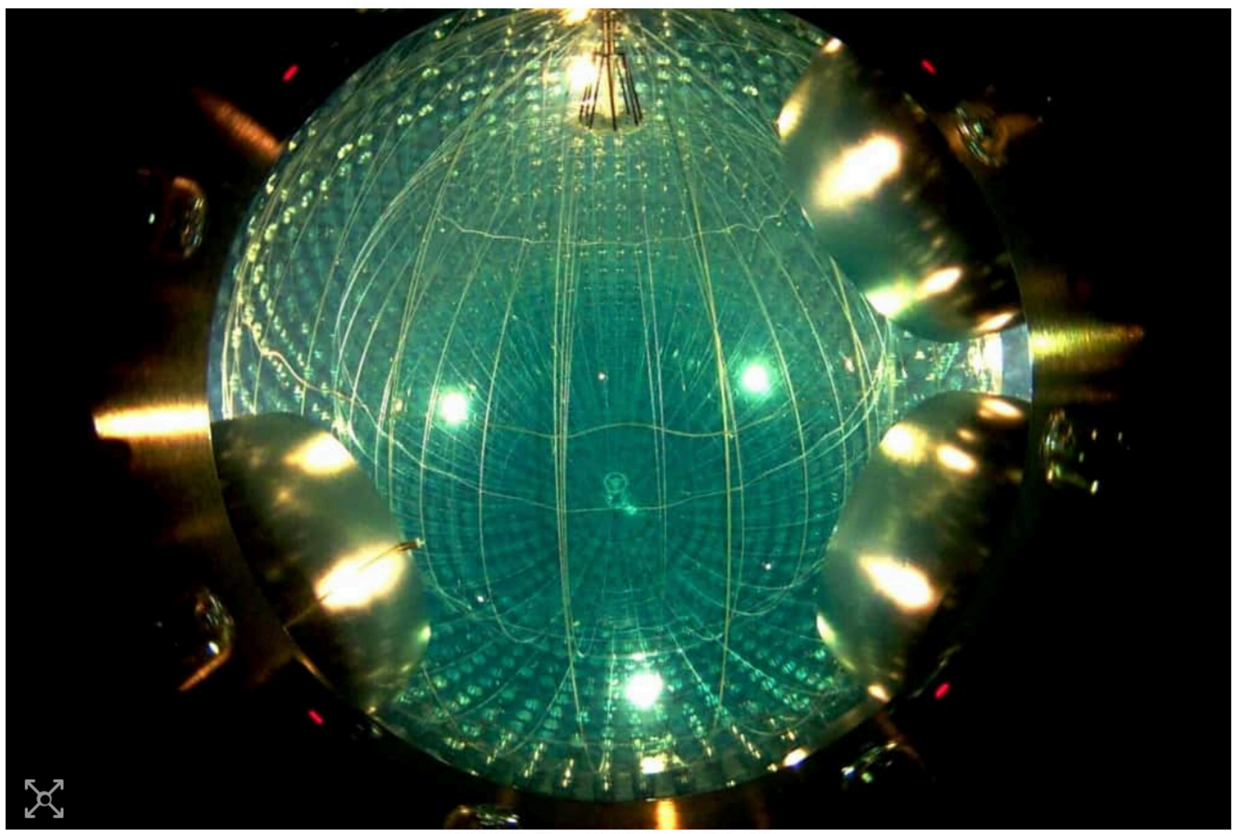
A nice idea! Well known spectra and can bring source to underground detector!

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

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)

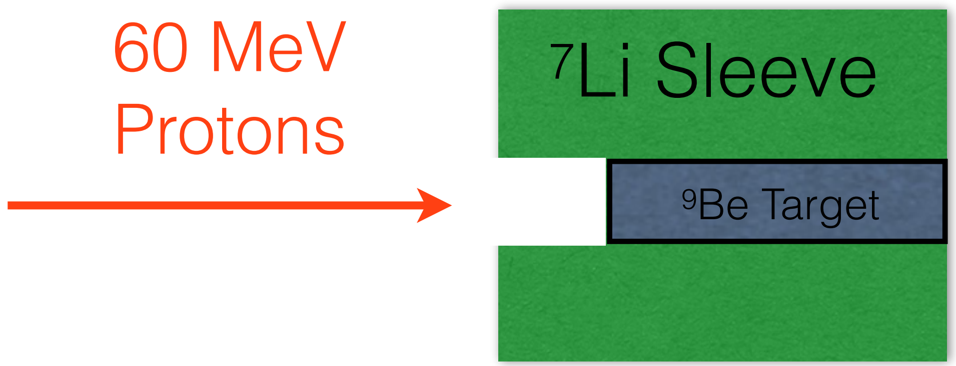
The botched production of a powerful neutrino source is the most likely cause of a radioactive cloud that enveloped much of Europe in the autumn of 2017. That is the conclusion of a group of radiation experts from across the continent who have used isotope monitoring and chemical analysis to try and 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.

IsoDAR

An “online” radioactive isotope source

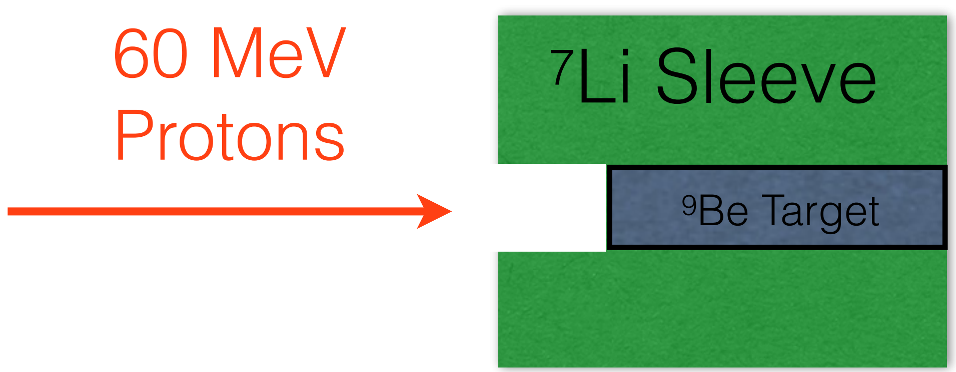
The IsoDAR concept

Produce energetic neutrinos with an extremely well understood energy spectrum



The IsoDAR concept

Produce energetic neutrinos with an extremely well understood energy spectrum

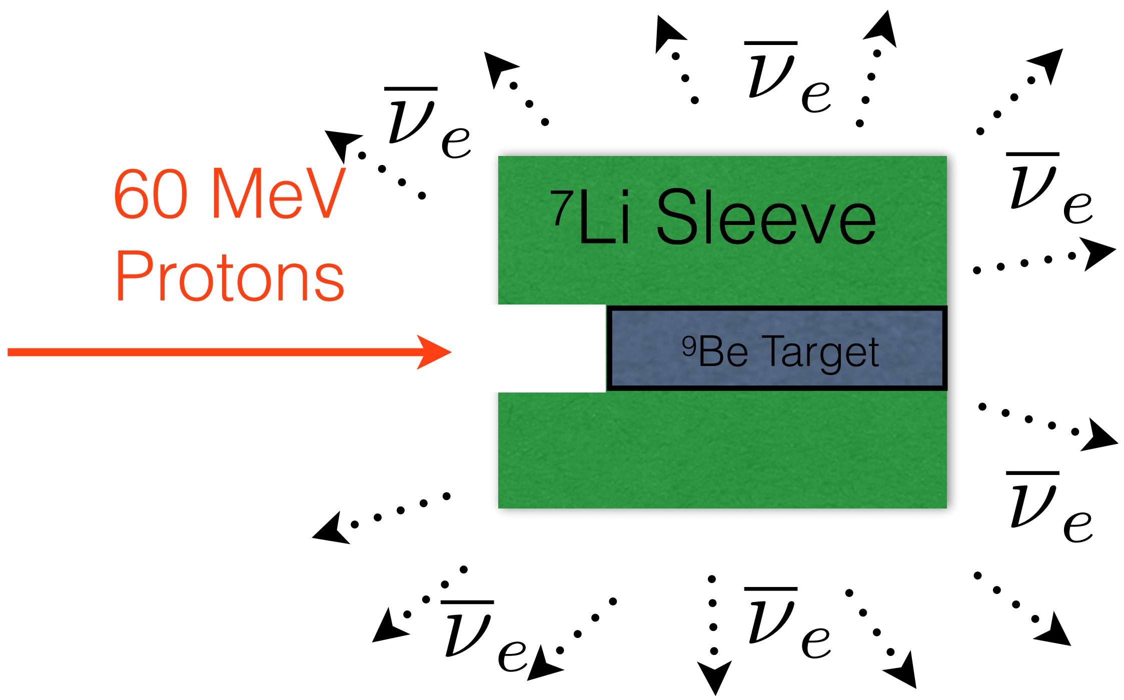


$$p + {}^{9}\text{Be} \rightarrow {}^{8}\text{Li} + 2p$$

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

The IsoDAR concept

Produce energetic neutrinos with an extremely well understood energy spectrum



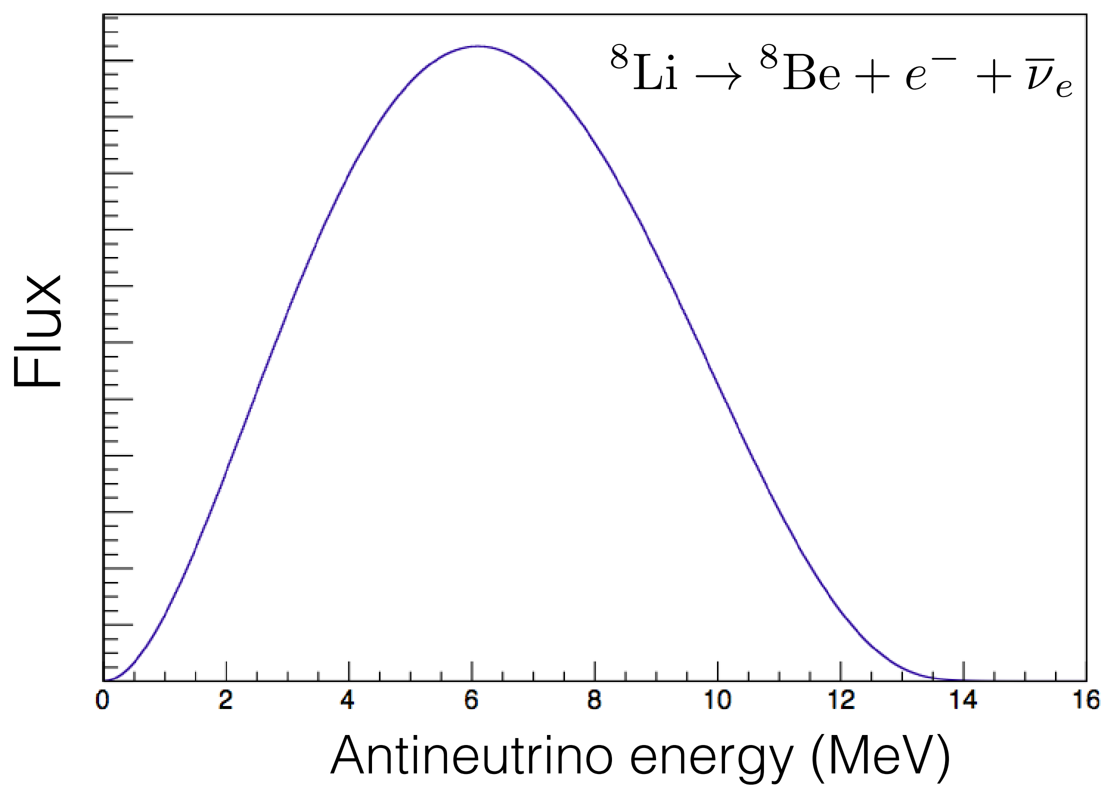
$$p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$$

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

$t_{1/2}$=0.84 s

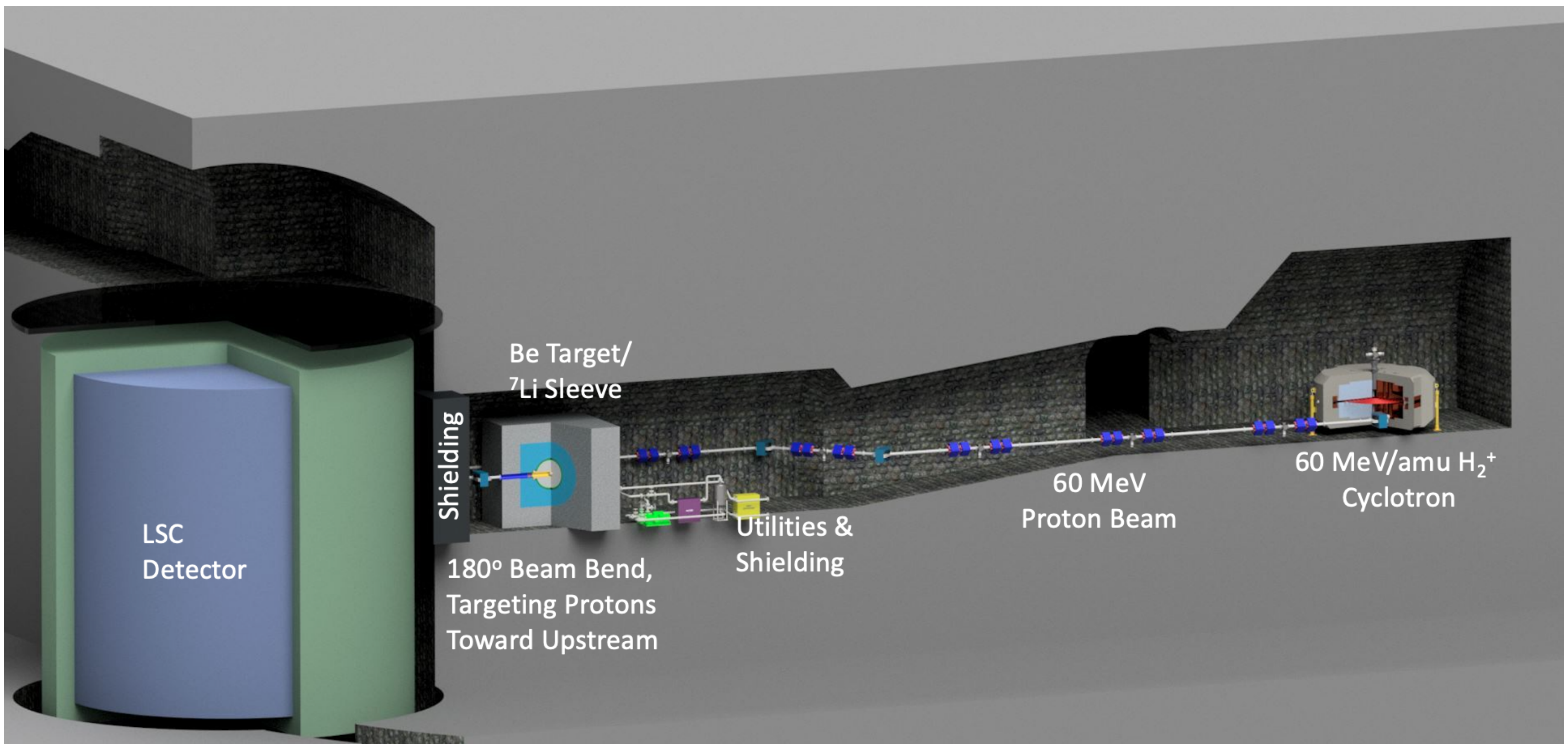
$$^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

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



IsoDAR@Yemilab in Korea

IsoDAR paired with a 2.5 kiloton liquid scintillator detector



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

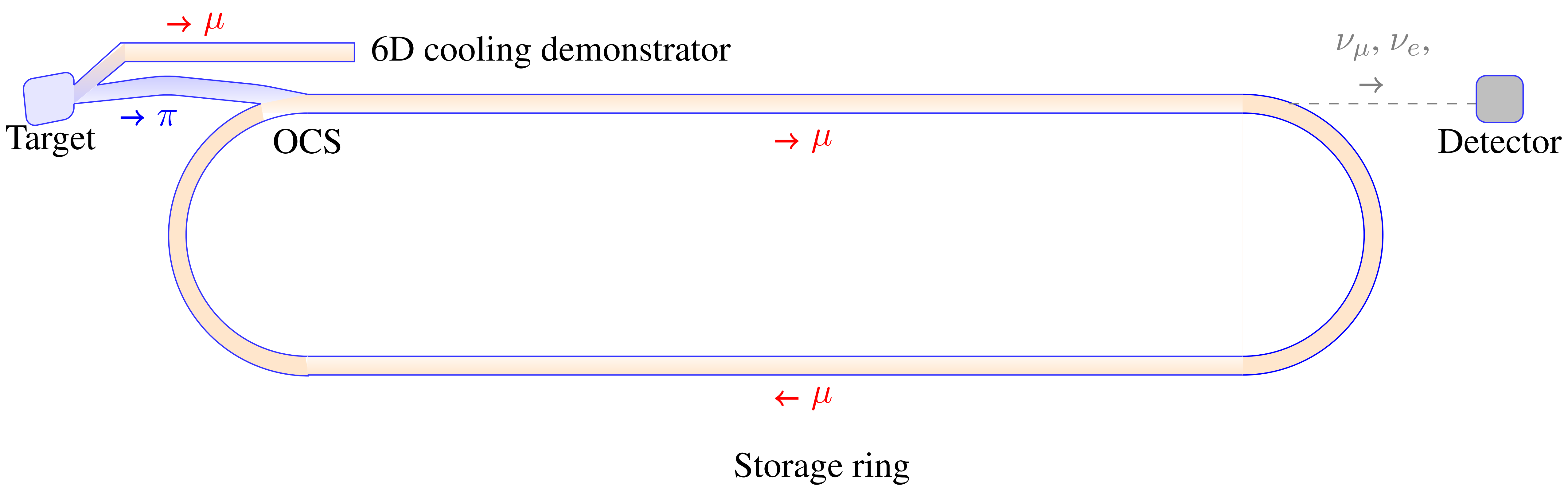
- Produce an electron capture source (safely!) and couple it to a big underground detector.
- Use the BEST technique (^{51}Cr) with other isotopes.
- Realize IsoDAR.
- Extra credit: Figure out how to create an *artificial* non-relativistic source of neutrinos. Couple it to (e.g) PTOLEMY.
  - ^{115}In (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
- Neutrinos from stored muons
  - 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).

Neutrinos from stored muons

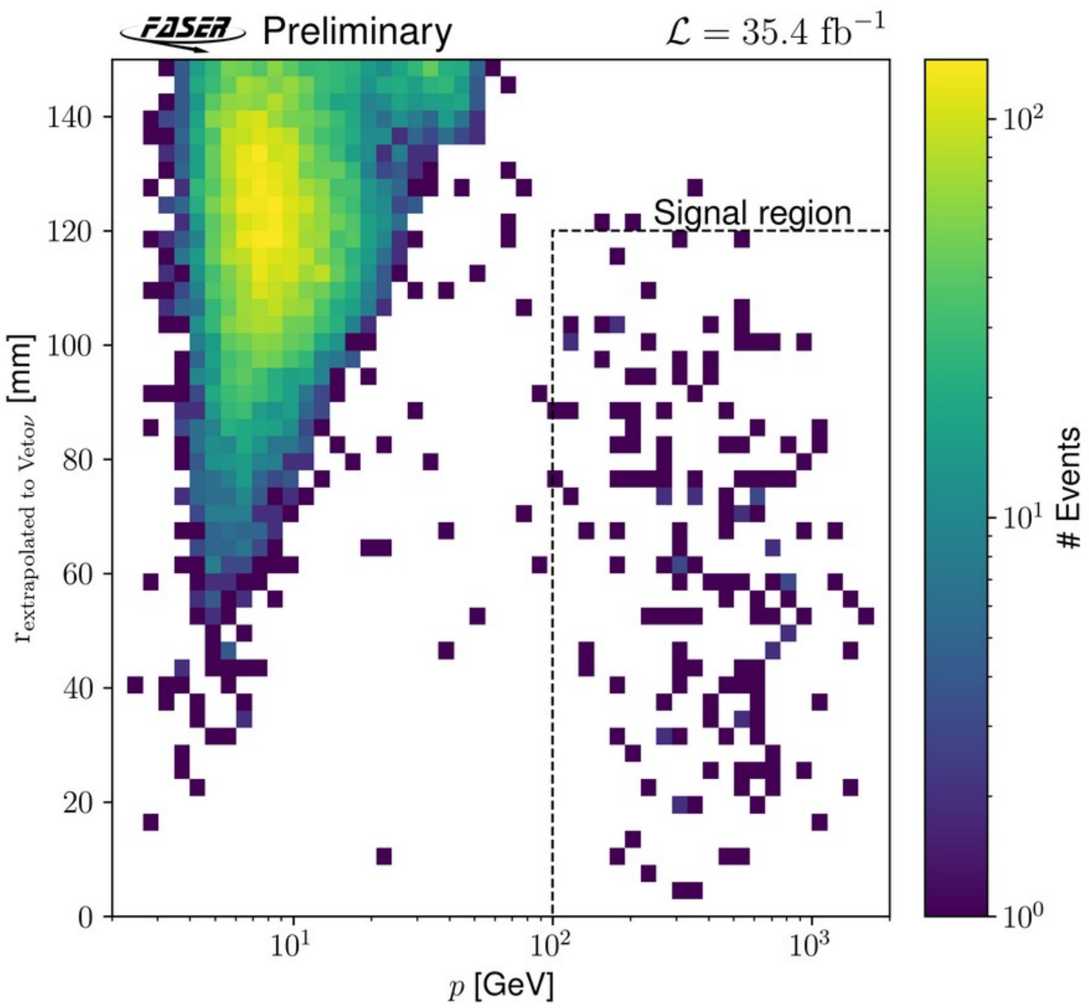
- Relies on muons from a storage ring to produce a pure beam of muon and electron flavor neutrinos and antineutrinos.
- Challenge is wrangling the muons in your accelerator.

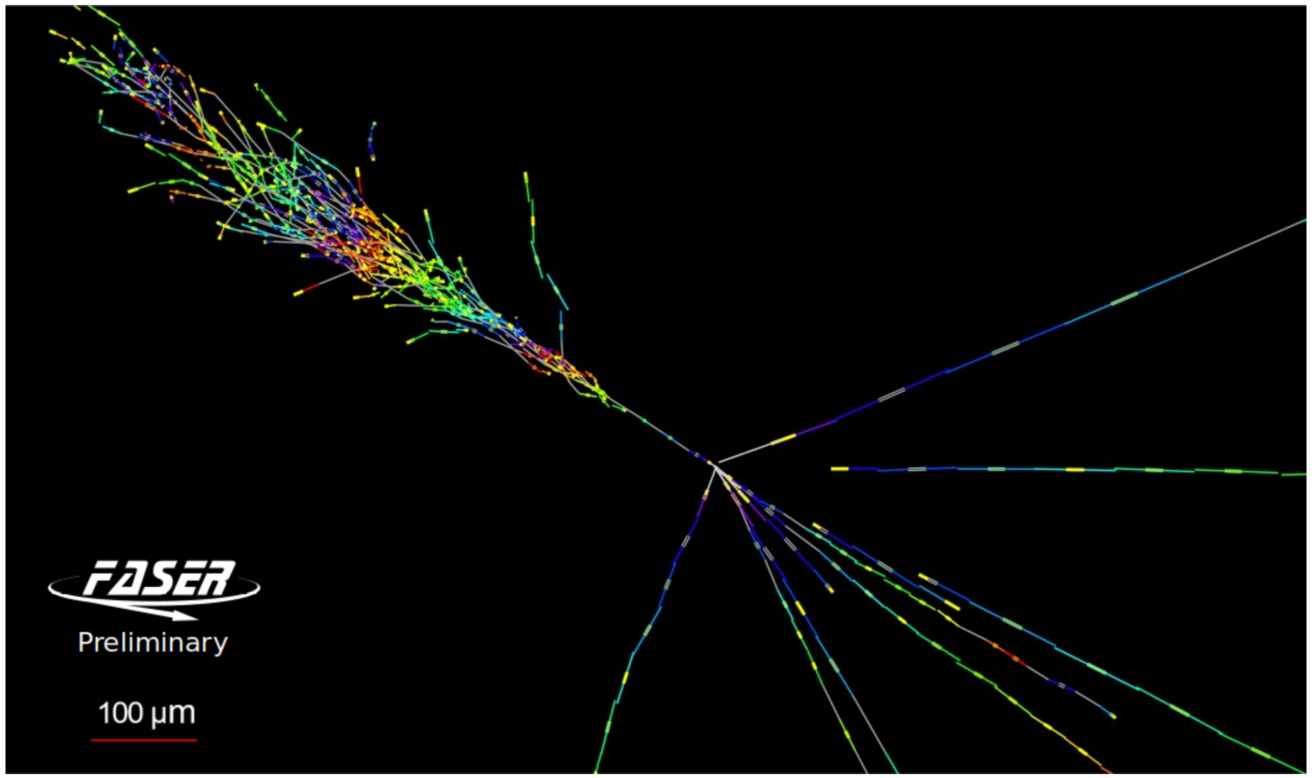


$$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu \quad \text{or} \quad \mu^- \to e^- \overline{\nu}_e \nu_\mu$$

Neutrinos at colliders

FASER recently announced first observation of collider neutrinos!
(provides new window into studying high-E neutrinos and new-territory in dark matter search)

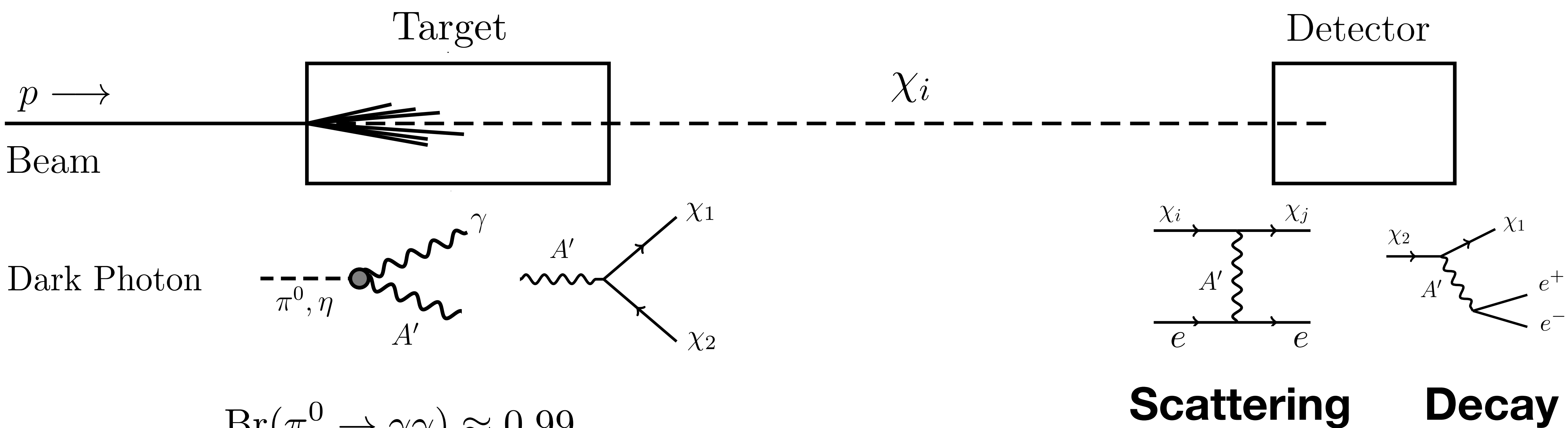




2303.14185

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)



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

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

My advice for you

- Do not think for one second that there are no more good neutrino source/detector/experiment/theory ideas out there and/or that the older+wiser physicists have thought of everything. This is very far from the truth. If you think otherwise, you are both wrong and in the wrong field.
- Get to know root, Geant4, and a neutrino generator very well.
    - Develop a work flow that allows you to ‘try something’ and see the result quickly.
- Don’t stare at your code too much. Think about the big picture and what you are really trying to do physics-wise and where your work fits. Come up with your own ideas.
- If at all possible, spend a lot of time at the lab where your experiment is. That is where the real magic happens.
- Go to seminars+colloquia, and chat with the ‘big, scary’ senior people. A lot of the time, their favorite part of the job is talking physics with energetic+bright young people.
- Develop your ideas with other people and share your code+expertise+knowledge (team-first mentality).
- Detector development is fun. But, don’t forget about the source!
    - Unfortunately IMHO, I estimate the R&D effort is 10:1 (detector:source).

End

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