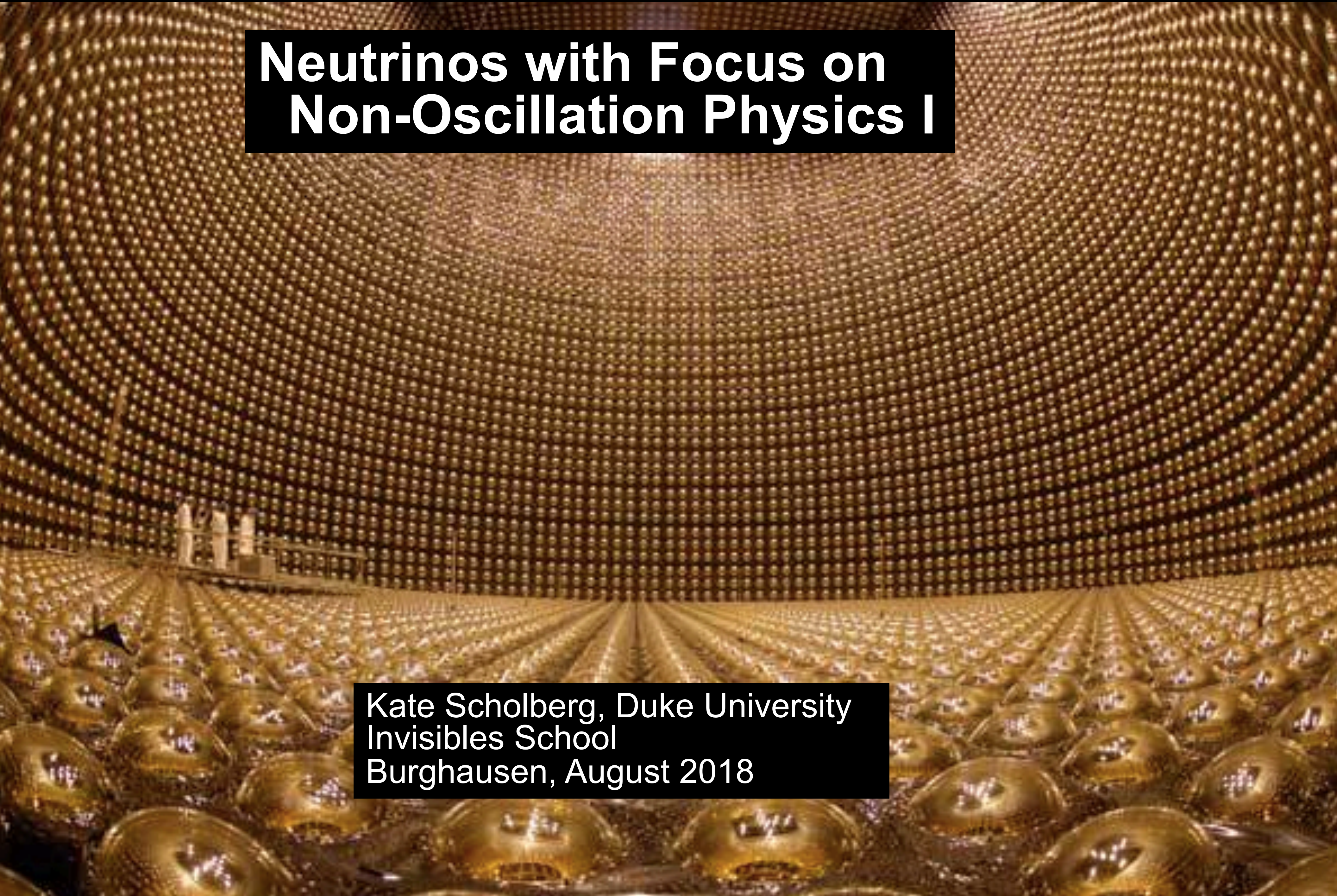
Neutrinos with Focus on Non-Oscillation Physics I



Kate Scholberg, Duke University
Invisibles School
Burghausen, August 2018

Lecture Overview

- Neutrino overview
  - Physics & astrophysics
  - A bit on neutrino oscillations
- Neutrino interactions with matter
  - Neutrino-nucleus cross sections at ~GeV energies
  - Neutrino-nucleus interactions at ~10-MeV energies

two examples

Lecture 1

- Neutrinos from core-collapse supernovae

Lecture 2

- Neutrino mass and the nature of the neutrino

Lecture 3

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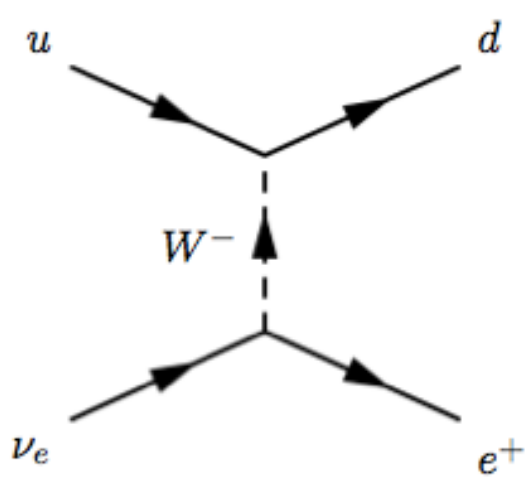
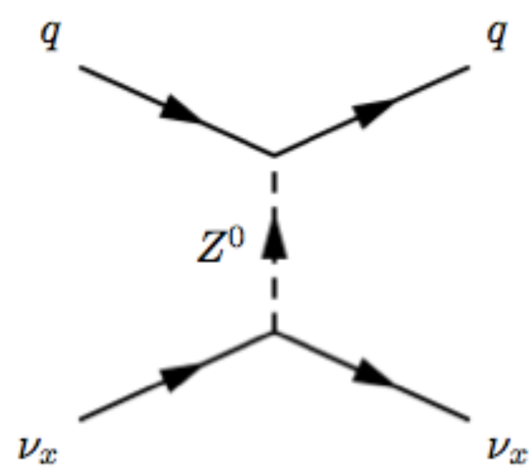
NEUTRINOS

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

neutral partners
to the charged leptons

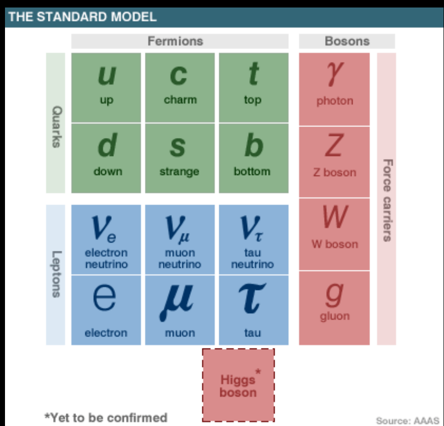
- Three flavors (families), neutrinos and antineutrinos
- Tiny masses (< 1 eV) and **oscillations** (flavor change)
- Interact *only* via *weak interaction* (& gravity)





Exchange of
W and Z bosons in
weak interactions

Why do neutrinos matter?



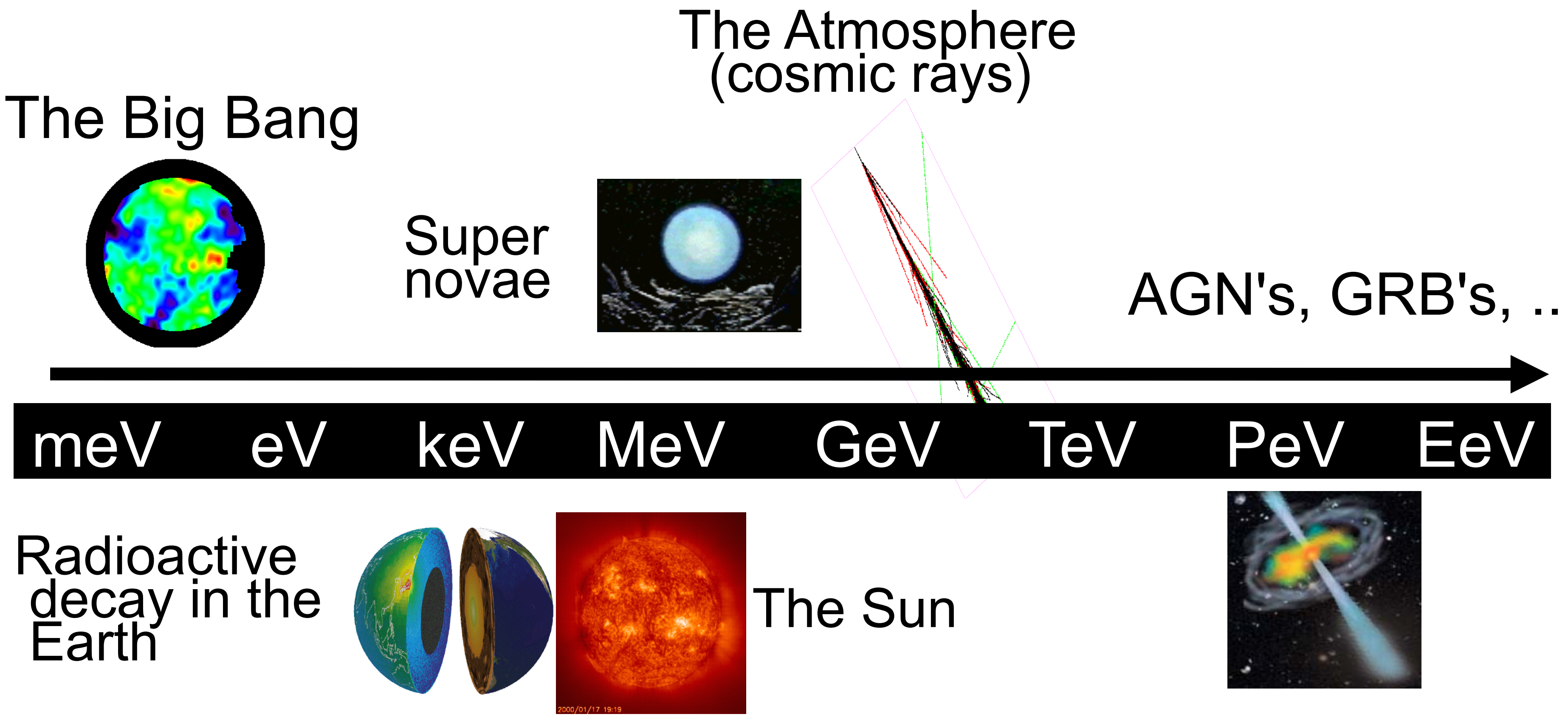
fundamental particles and interactions

astrophysical systems

cosmology

nuclear physics

Sources of ‘wild’ neutrinos

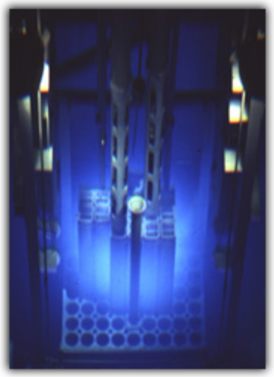


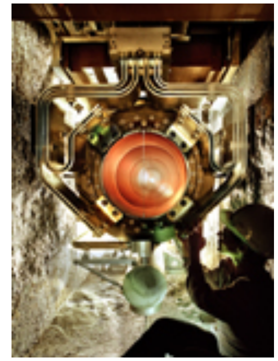
Sources of ‘tame’ neutrinos

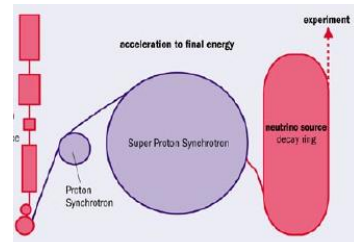
Proton accelerators

Beta beams

Nuclear reactors

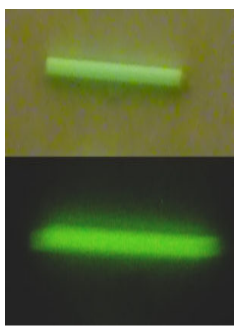


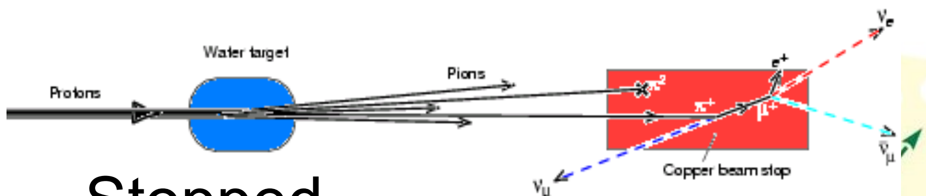




eV keV MeV GeV TeV

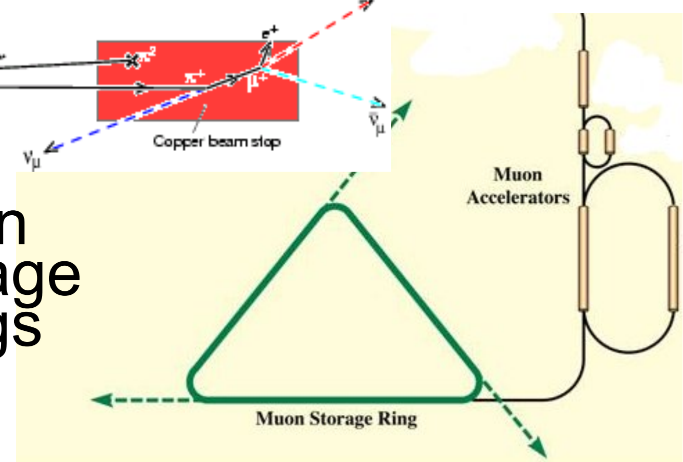
Artificial radioactive sources



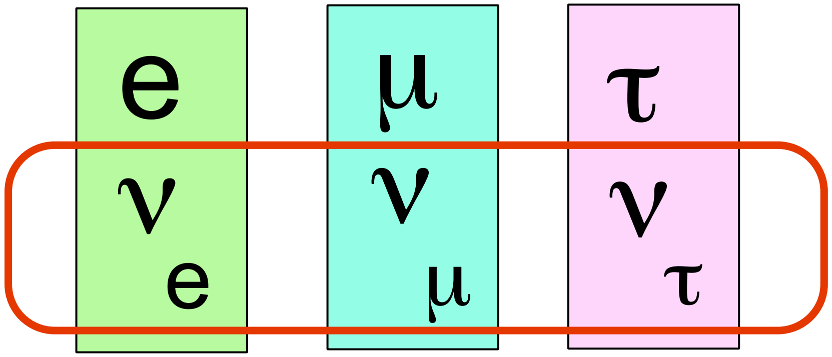


Stopped pion sources

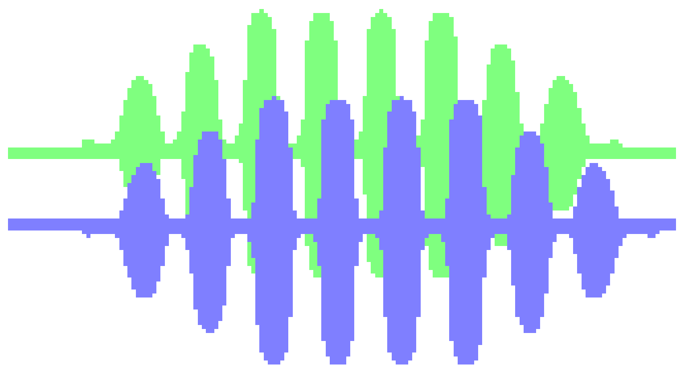
Muon storage rings



Neutrinos come in **three flavors** in the Standard Model



And in QM, the flavors **oscillate** as the neutrinos propagate



Massive neutrinos (as waves) propagate with different frequencies according to their masses;
the observed flavor change is **how we know neutrinos have mass**

Neutrino Mass and Oscillations

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in weak interactions

unitary mixing matrix

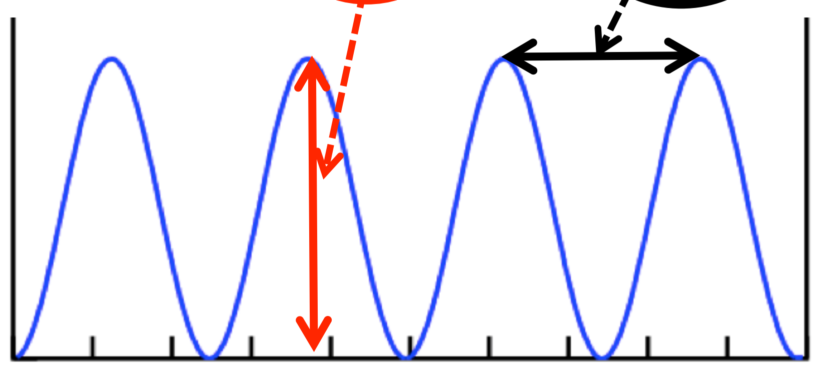
eigenstates of free Hamiltonian

If mixing matrix is not diagonal, get *flavor oscillations:*

energy- and baseline-dependent flavor change

2-flavor

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



The three-flavor paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

Parameterize mixing matrix U as

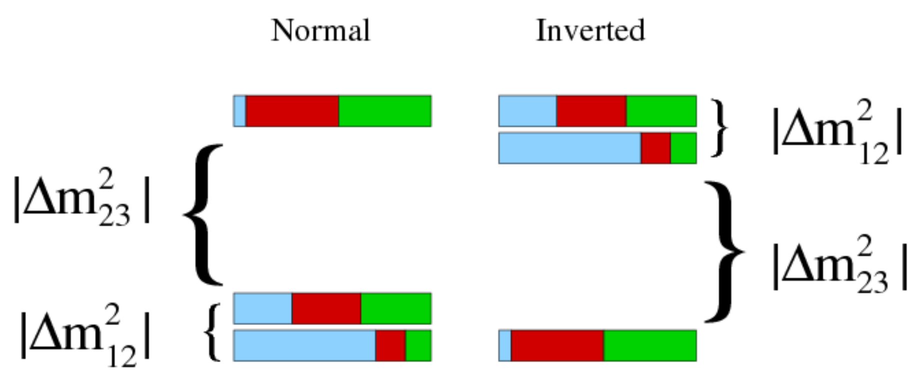
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2

signs of the mass differences matter



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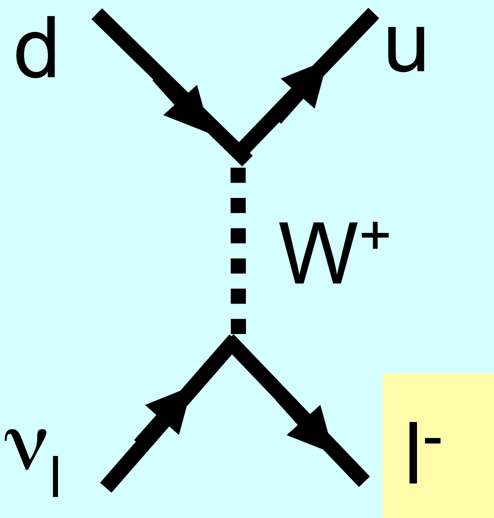
Neutrino interactions with matter

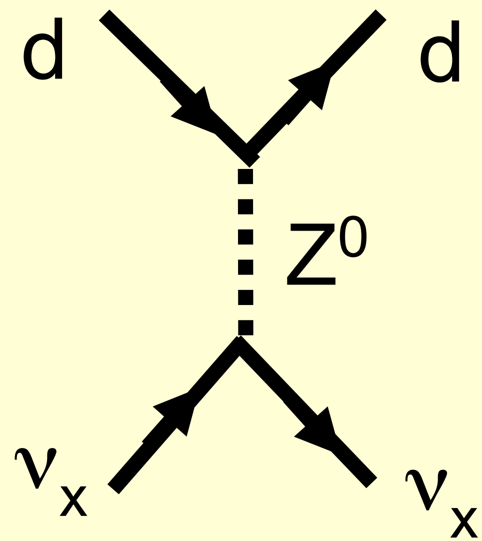
Charged Current (CC)



$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton with **flavor corresponding to neutrino flavor**
(must have enough energy to make lepton)

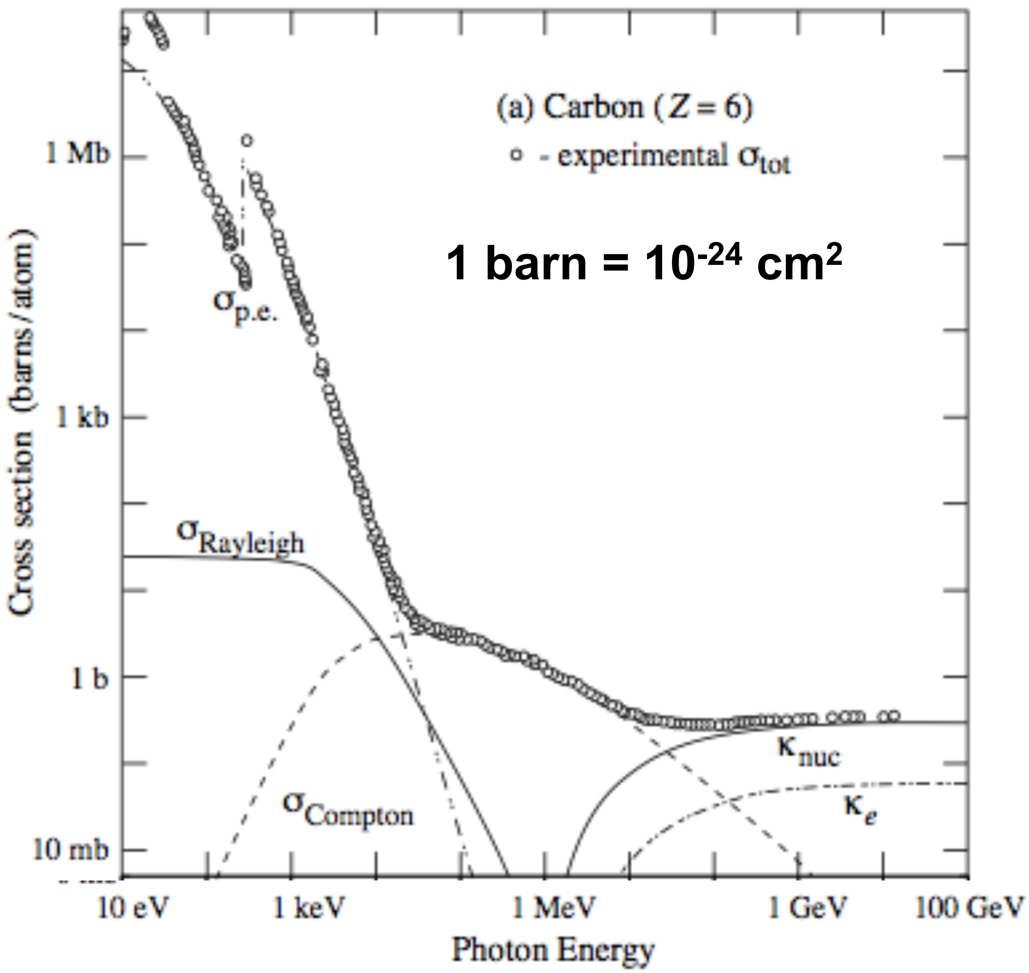
Neutral Current (NC)



Flavor-blind

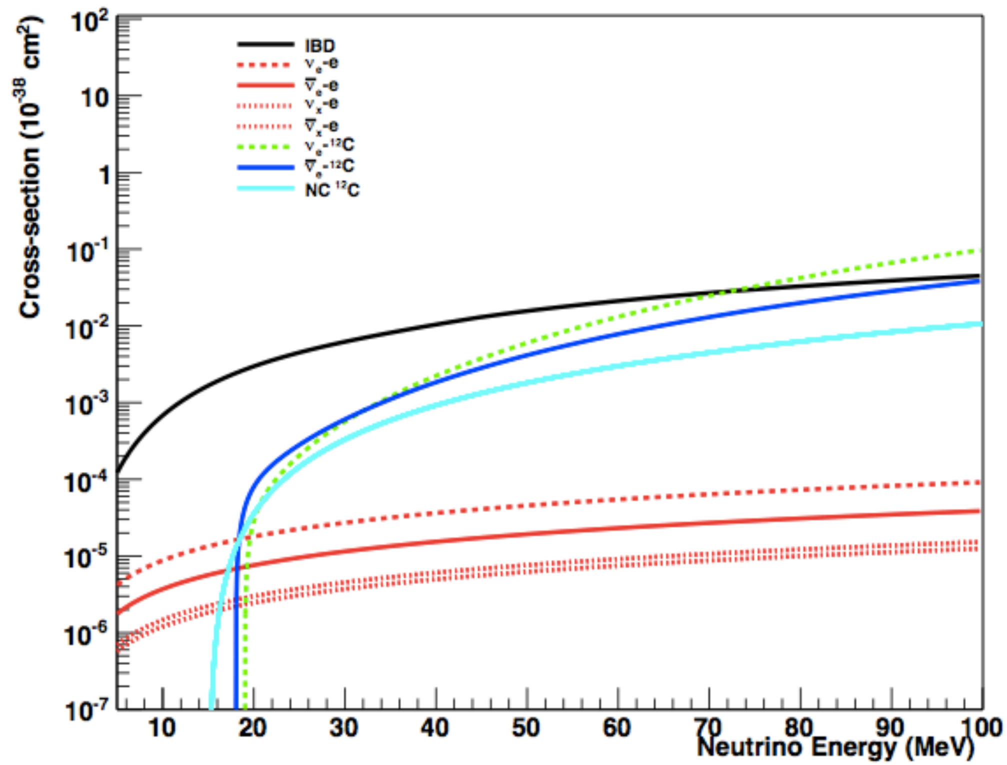
It’s called the weak interaction for a reason

Photon-matter cross-sections



$\sim 10^{-24}$ cm^2

Neutrino-matter cross-sections



$\sim 10^{-40}$ cm^2

~16-17 orders of magnitude smaller

In astrophysics, the weakness of the interaction is both a blessing and a curse...

- neutrinos bring information from deep inside objects, from regions where photons are trapped

- but they require heroic efforts to detect!

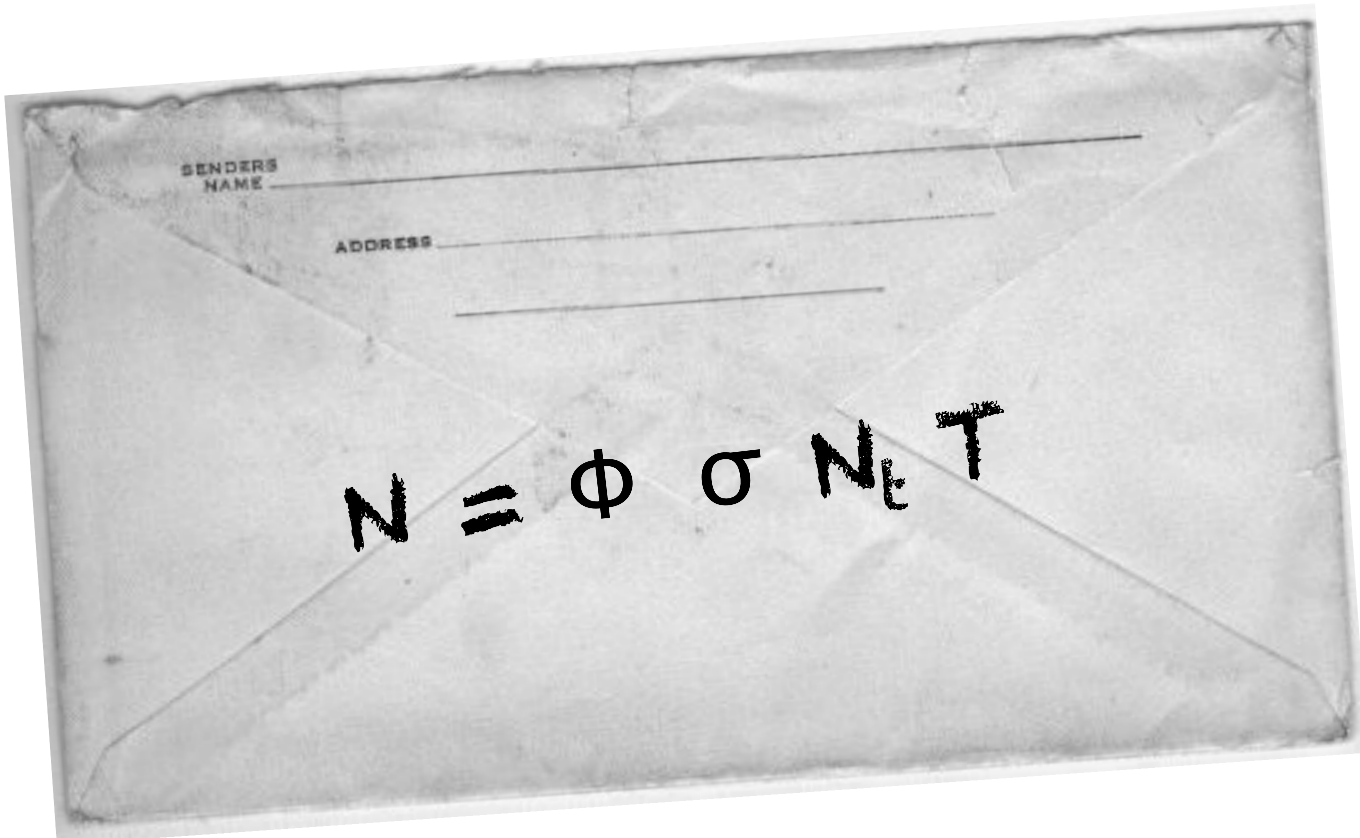
Interaction rates in a detector material

$$R = \overbrace{\Phi}^{\text{Flux}}\ \overbrace{\sigma}^{\text{Cross section}}\ \overbrace{N_t}^{\text{Number of targets}}$$

$$\propto \text{detector mass}, 1/D^2$$

(Note: fluxes, cross-sections are E_ν dependent)

In fact this may be the neutrino experimentalist's most useful back-of-the-envelope expression...



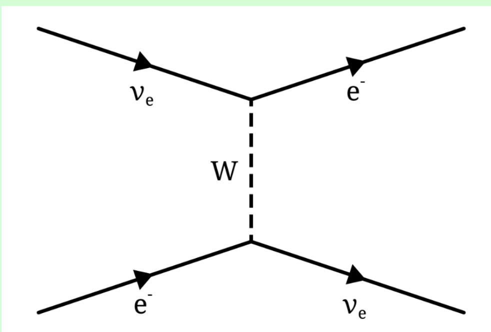
How many solar neutrinos will interact in your body during your lifetime?

$\sigma \sim 5 \times 10^{-44}$ cm^2 (electron scattering cross-section above a few MeV)
$\phi \sim 2 \times 10^6$ cm^{-2}s^{-1} (flux above a few MeV, mostly from ^{8}B neutrinos)

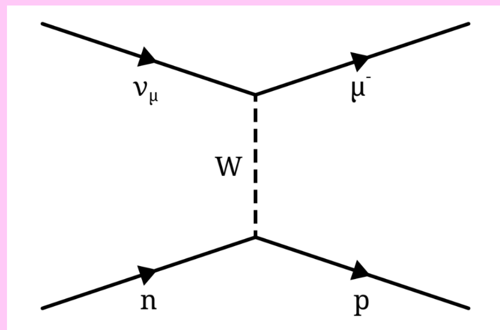
What you actually detect is the **secondary(ies)**... (and tertiaries...)

scattered particle, newly created particles, ejected nuclei, showers...

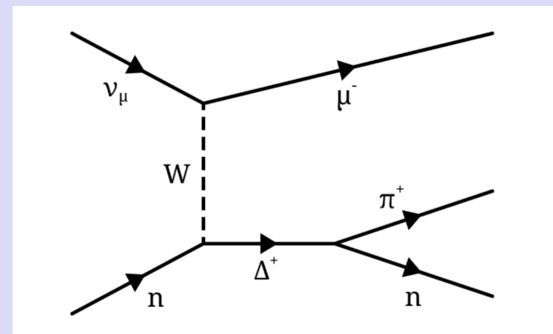
Common nomenclature for neutrino interactions



"Elastic"
same particles in as out

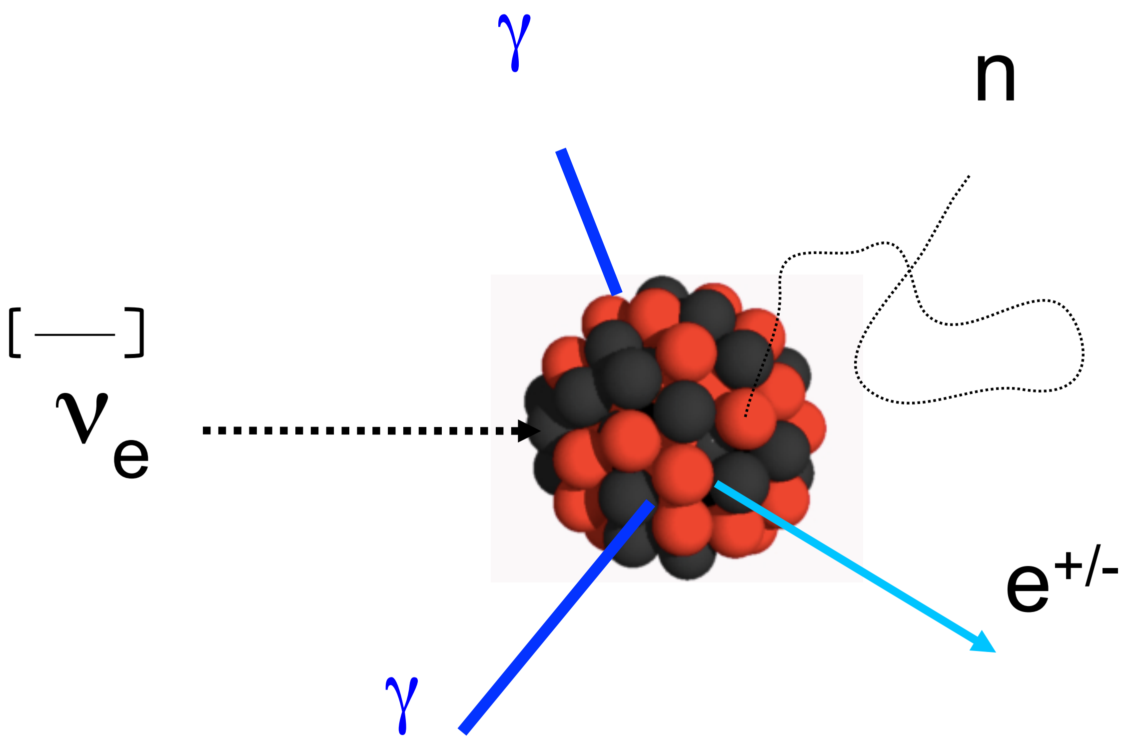


"Quasi-elastic"
different final-state particles but same number of particles



"Inelastic"
energy converted to new particles

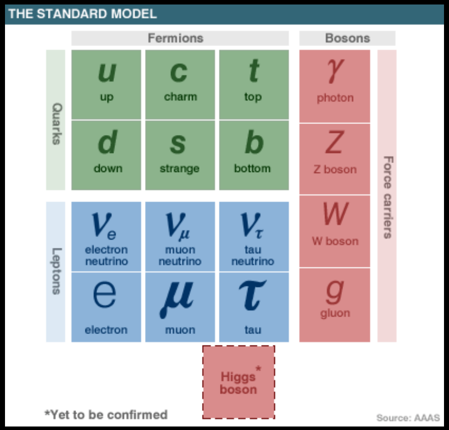
In many neutrino experiments,
neutrinos interact with **nuclei**



Observable final-state particles:

- lepton (for charged-current)
- de-excitation debris (γ's, ejected nucleons)
- if sufficient energy, newly-created particles
- recoil of the nucleus itself

Why do we need to measure neutrino-nucleus interactions?



fundamental particles and interactions

cosmology

We need to understand the nature of the neutrino

- interpretation of neutrino oscillation... how do the flavors change?
- are there new interactions? beyond the Standard Model physics?

Why do we need to measure neutrino-nucleus interactions?

We need to unfold the fluxes from astrophysical systems (Sun, supernovae, blazars, mergers...) from detection on Earth

astrophysical systems

Why do we need to measure neutrino-nucleus interactions?

We can learn about
the structure of nuclei,
reactor processes,...

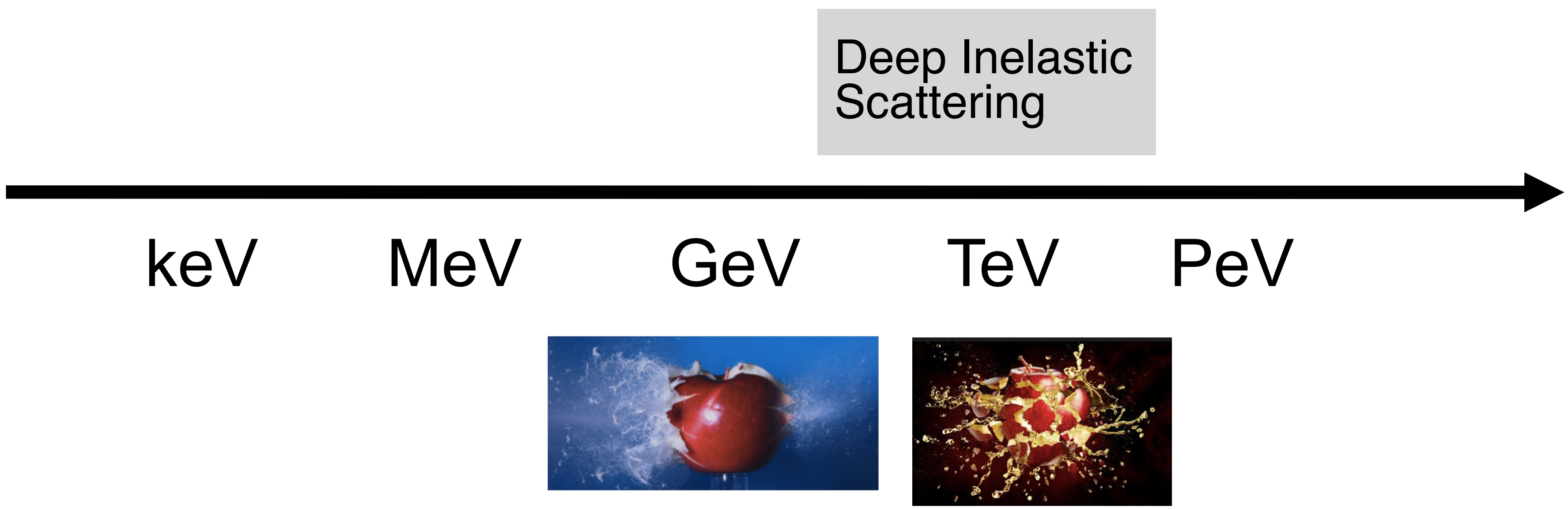
nuclear
physics

Neutrino Interactions with Nuclei in Different Energy Regimes

Deep Inelastic Scattering

keV MeV GeV TeV PeV

Neutrino Interactions with Nuclei in Different Energy Regimes



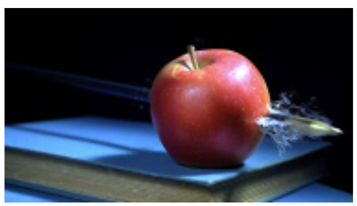
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Neutrino Interactions with Nuclei in Different Energy Regimes

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV



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Deep Inelastic Scattering

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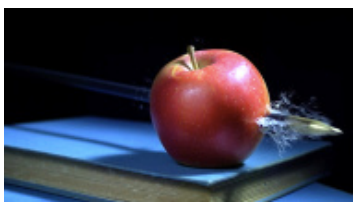

Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Example 1:
regime of
long-baseline oscillation
experiment

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two examples

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Long-baseline beam experiments for oscillation physics

Past — Current — Future

K2K
KEK to Kamioka
250 km, 5 kW

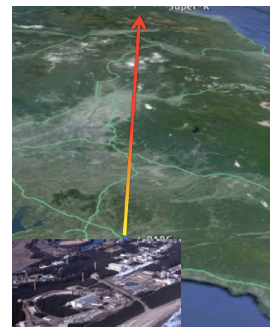
MINOS (+)
FNAL to Soudan
734 km, 400+ kW

CNGS
CERN to LNGS
730 km, 400 kW

NOνA
FNAL to Ash River
810 km, 400-700 kW

T2K (II)
J-PARC to Kamioka
295 km, 380-750 kW ➔>1 MW

LBNF/DUNE
FNAL to Homestake
1300 km, 1.2 MW (➔2.3 MW)



Hyper-K
J-PARC to Kamioka
295 km, 750 kW

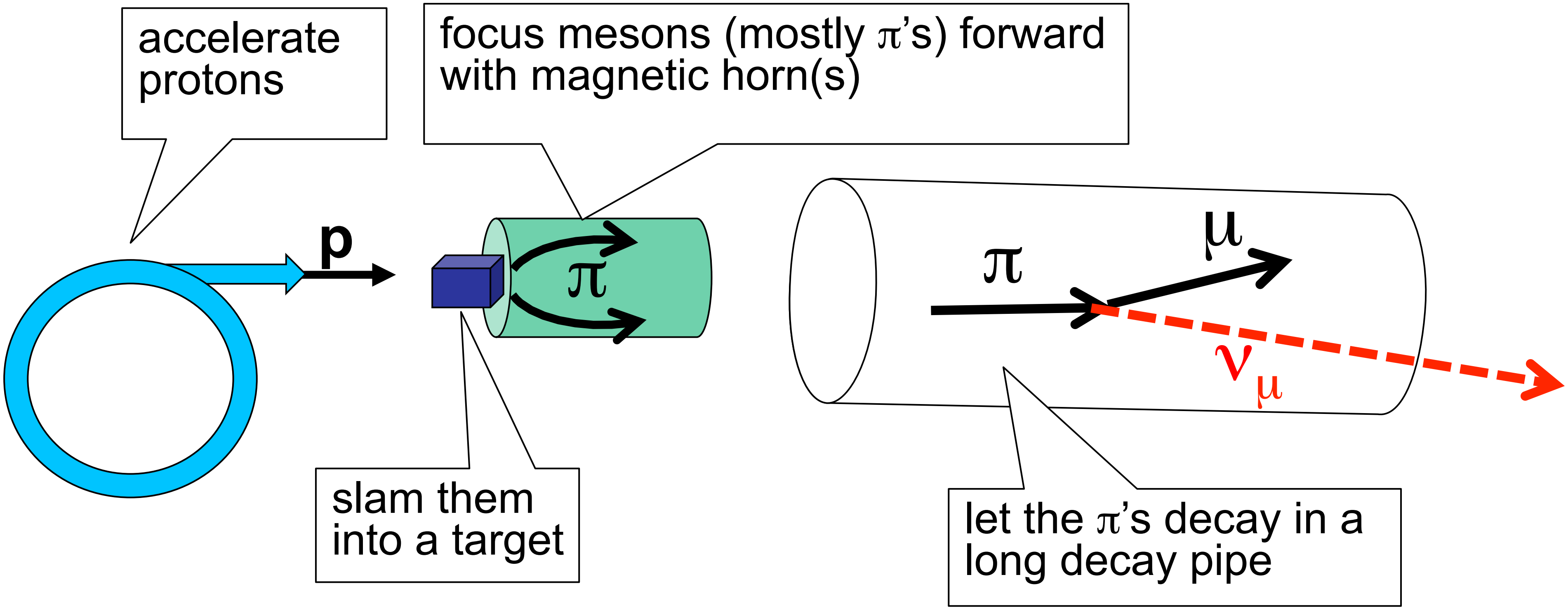
(➔1.3 MW)

And beyond...
ESSnuB,
neutrino factories...

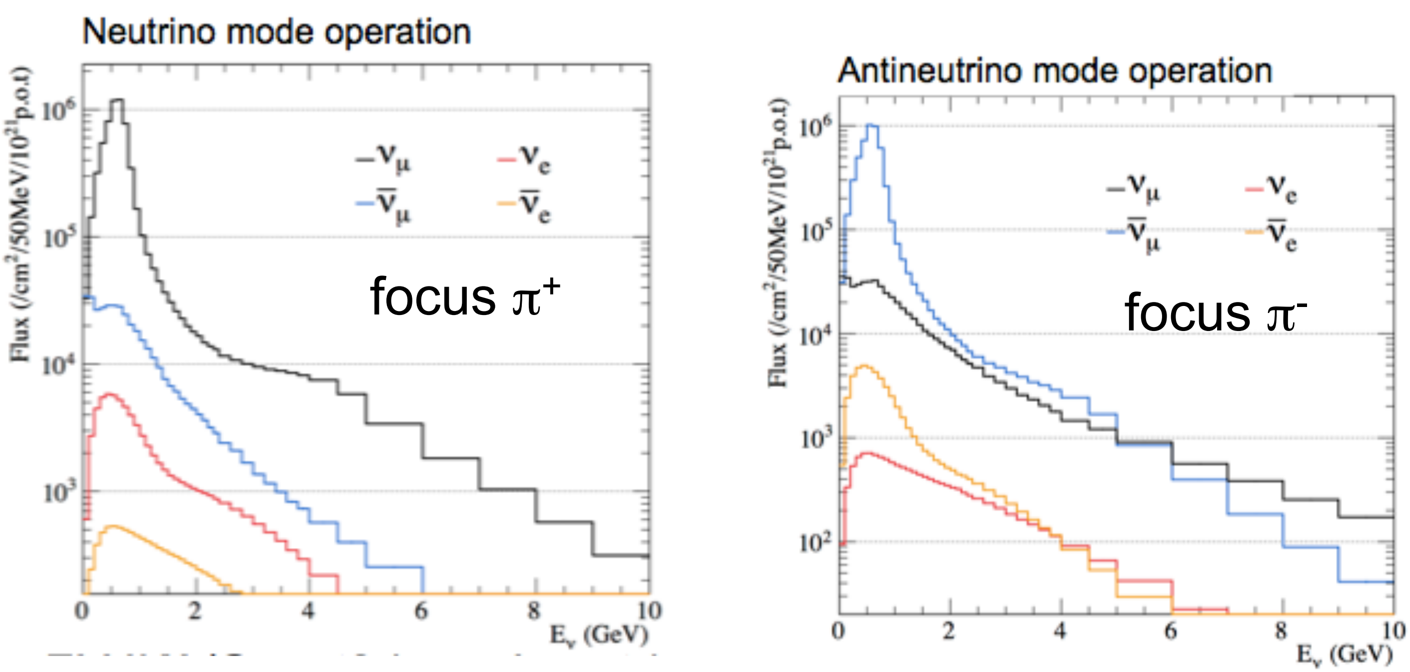




These make use of ~GeV neutrinos from π decay in flight

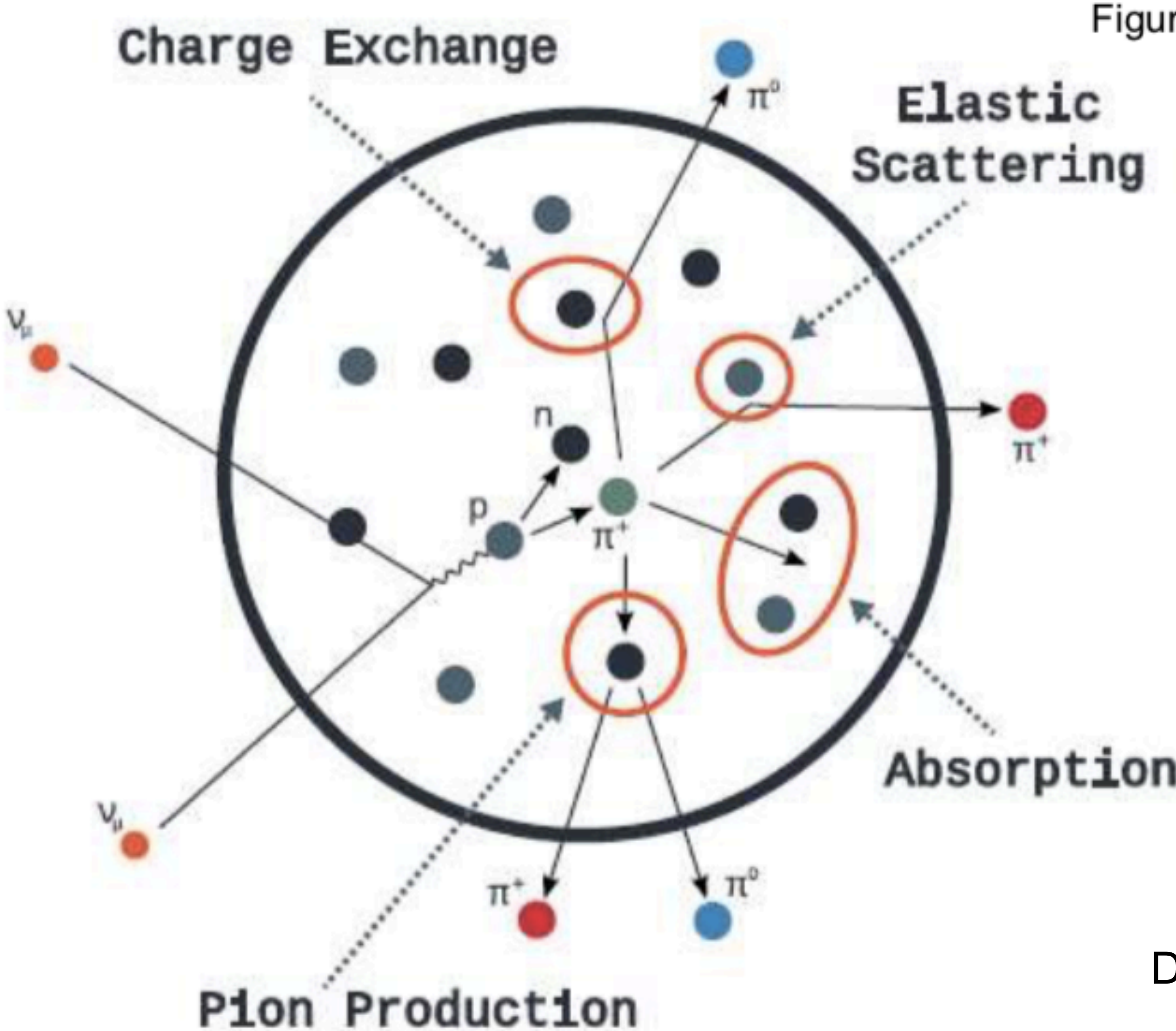


T2K beam



Neutrino-nucleus interactions in this regime have **complicated final states**

Figure by Tomasz Golan

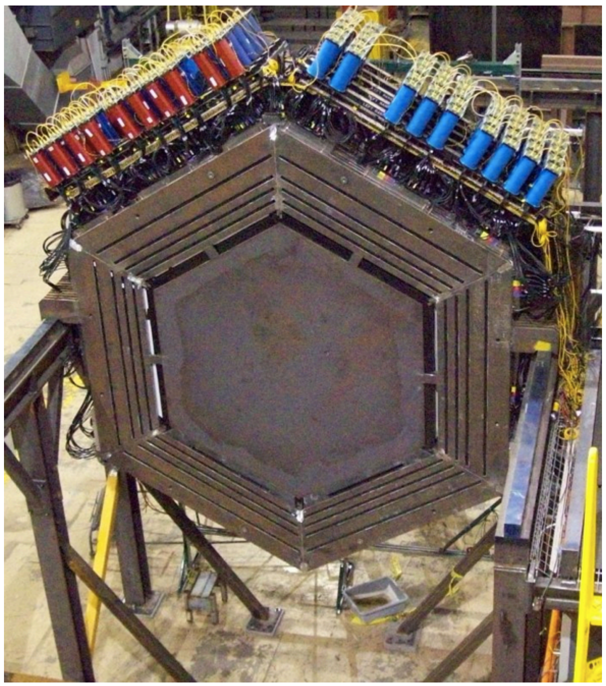


Need to "unfold" neutrino flavor, energy dependence for oscillation studies

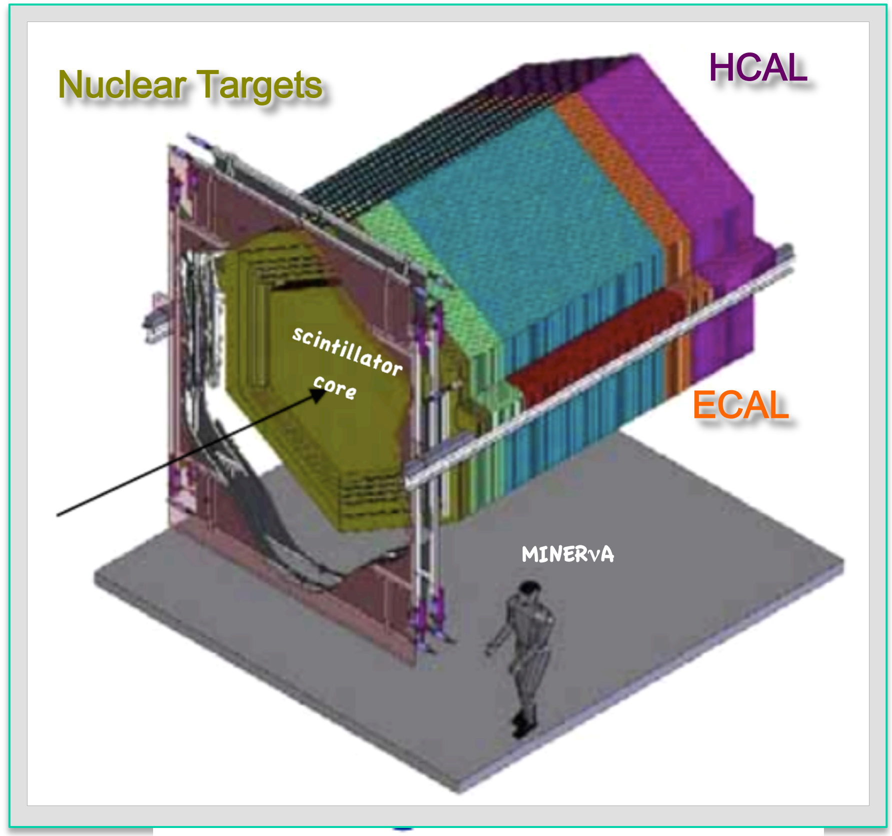
D. Ruterbories, Nu2018

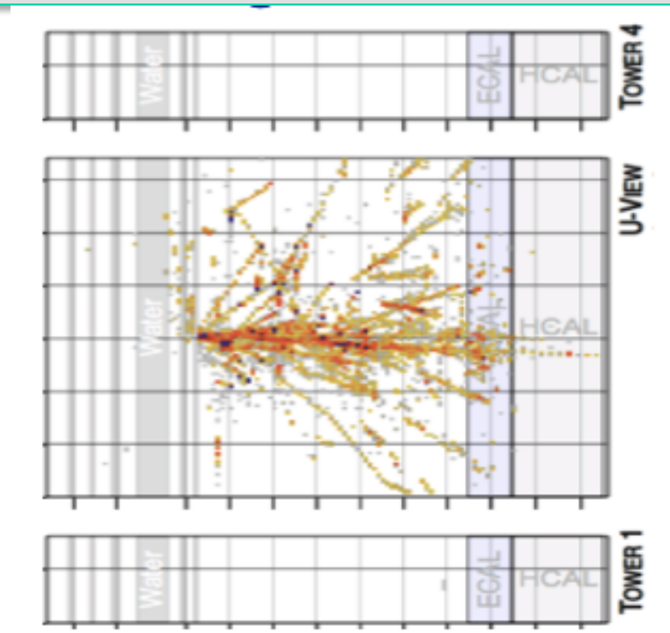
MINERνA

Detector at NuMI (Fermilab)
to measure cross-sections of
~GeV neutrinos on nuclear targets
(finely-segmented scintillator
+ em & hadronic calorimeters)



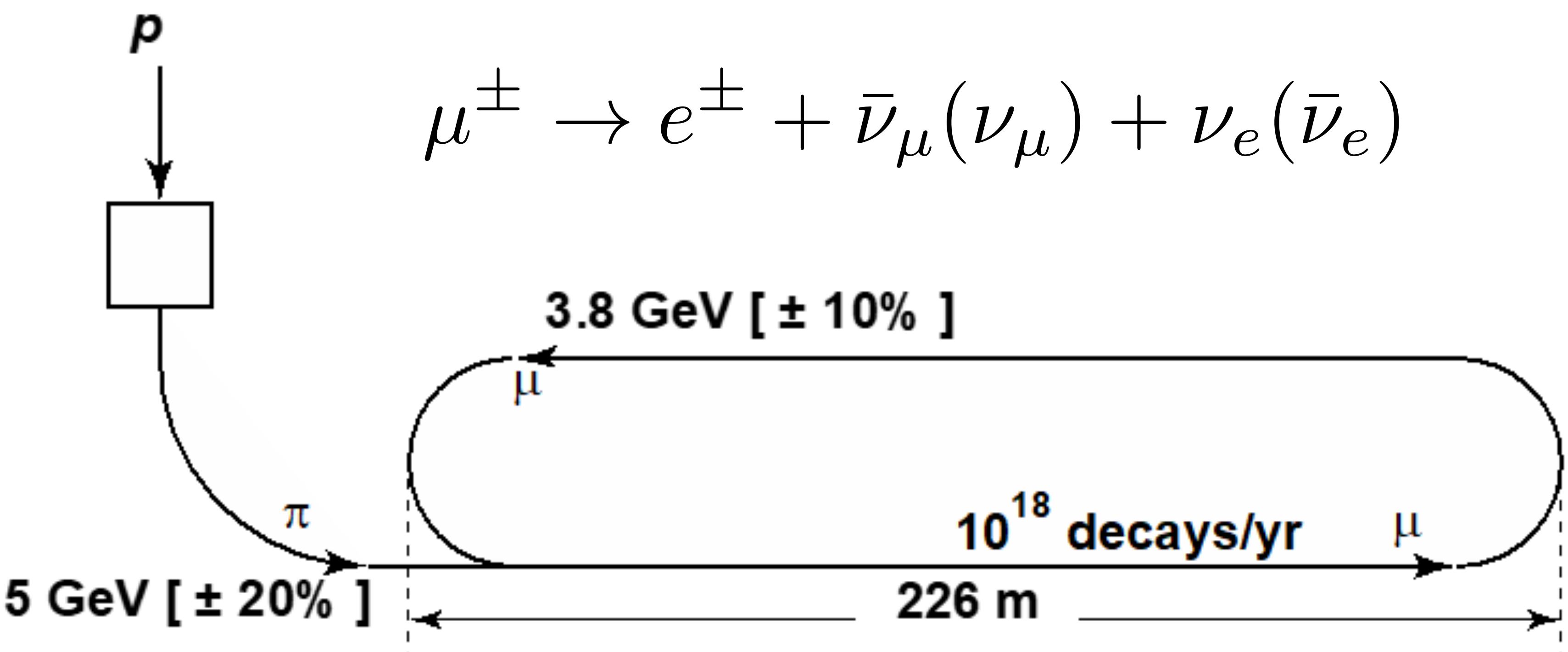
These studies are critical
for interpretation of
neutrino oscillation experiment





Muon (or radioactive isotope) storage rings
are conceptually attractive
for **well-understood neutrino flux**
from muon decay in flight, tunable energy
➔ good for **precision cross-section measurements**

$$\mu^\pm \to e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e)$$



e.g., NuSTORM

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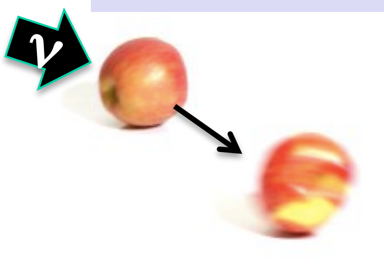
Example 2: the low-energy regime and the ***gentlest*** interaction with nuclei

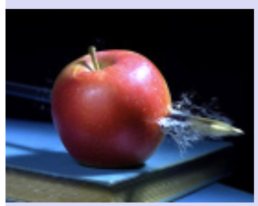
Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Deep Inelastic Scattering

keV MeV GeV TeV PeV



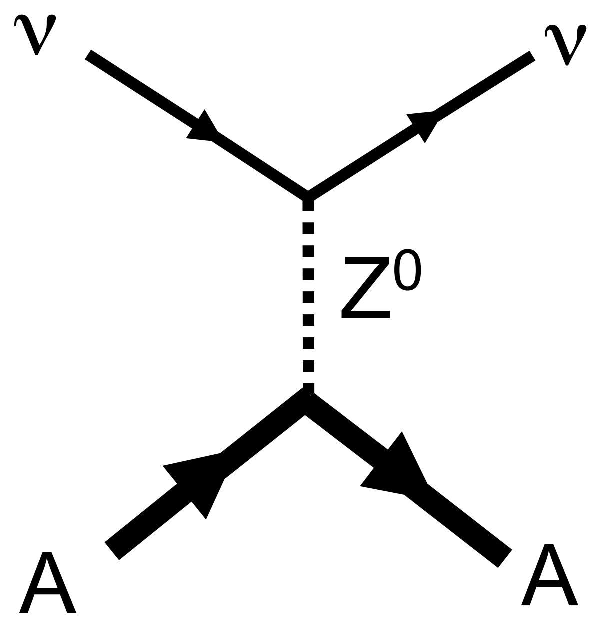


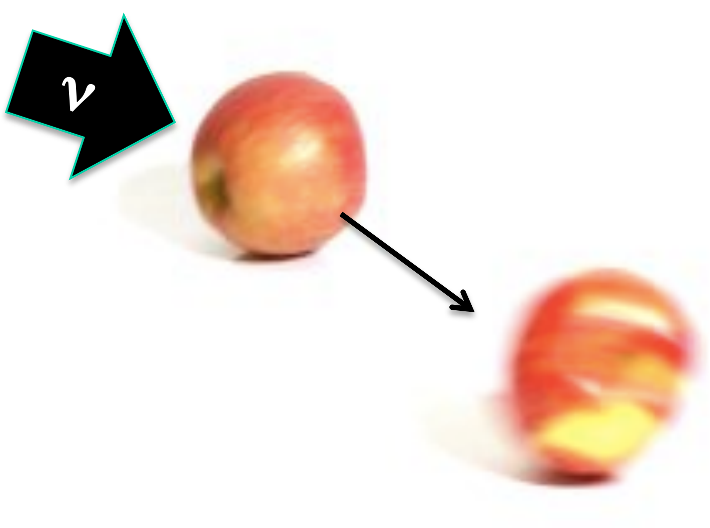
Interactions with nucleons inside nuclei, often disruptive, hadroproduction

Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV





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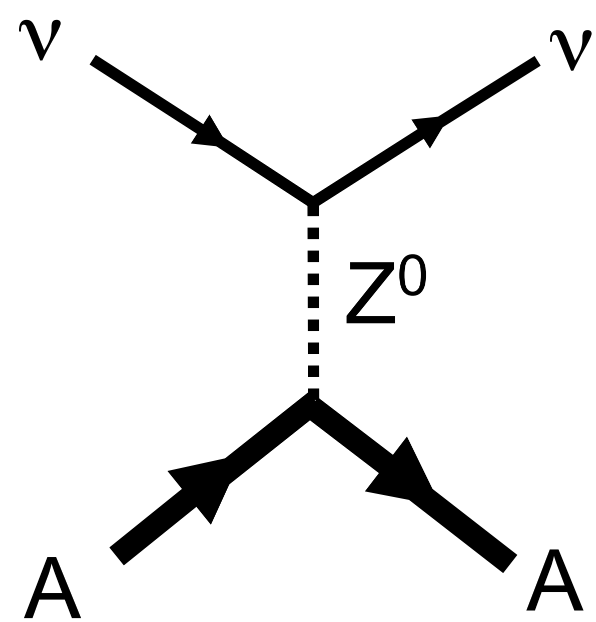
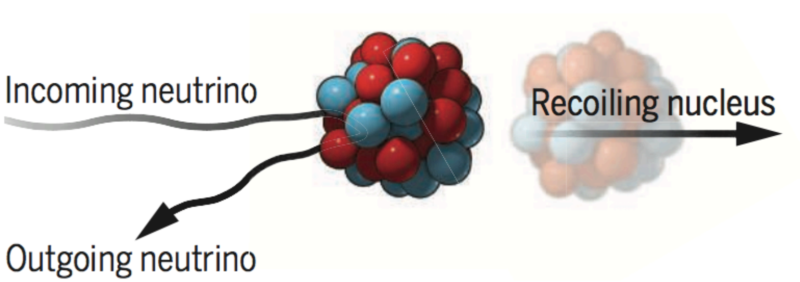




Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

A: no. of constituents

Image: J. Link *Science* Perspectives

First proposed 44 years ago!

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

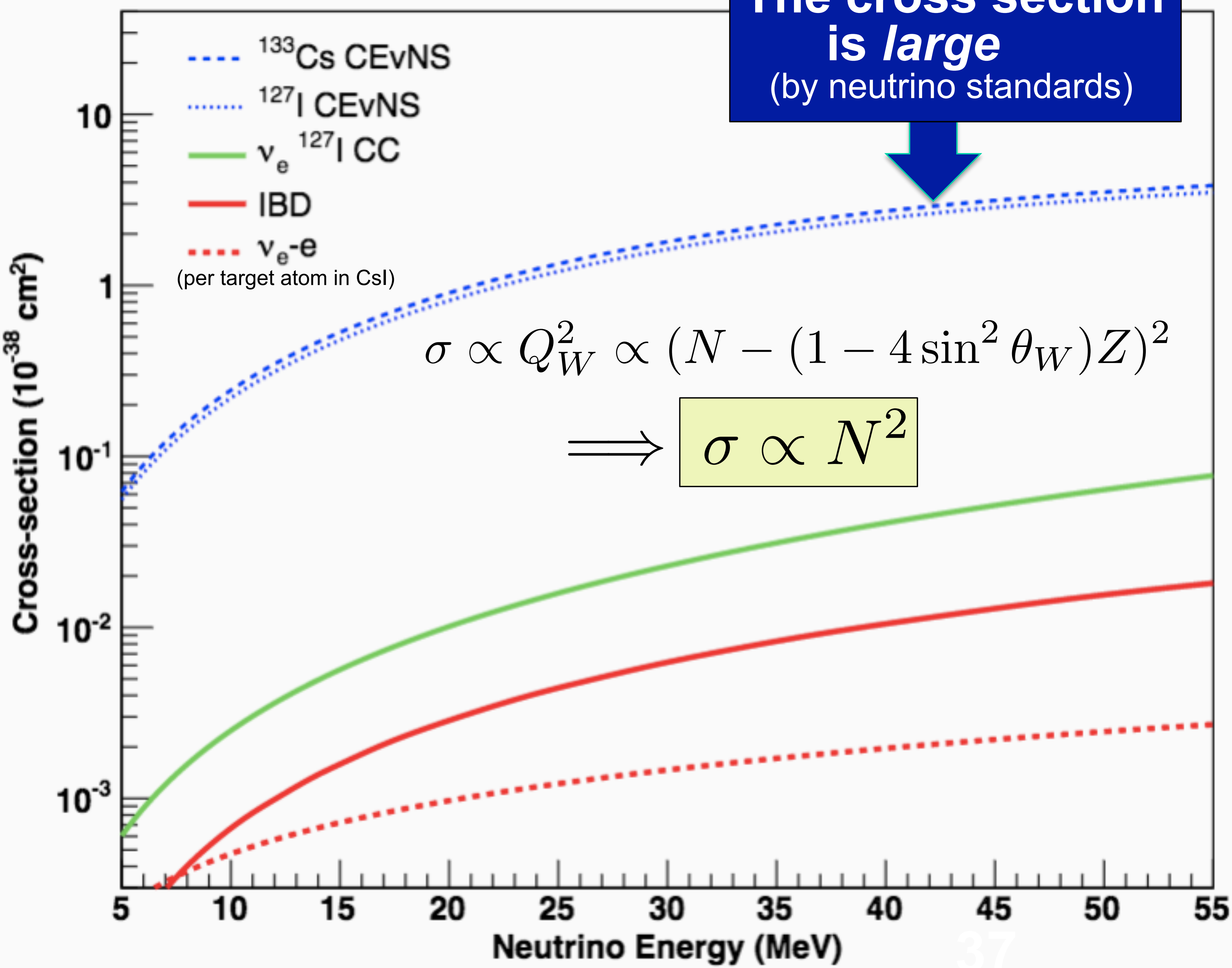
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

Also: D. Z. Freedman et al., "The Weak Neutral Current and Its Effect in Stellar Collapse", Ann. Rev. Nucl. Sci. 1977. 27:167-207

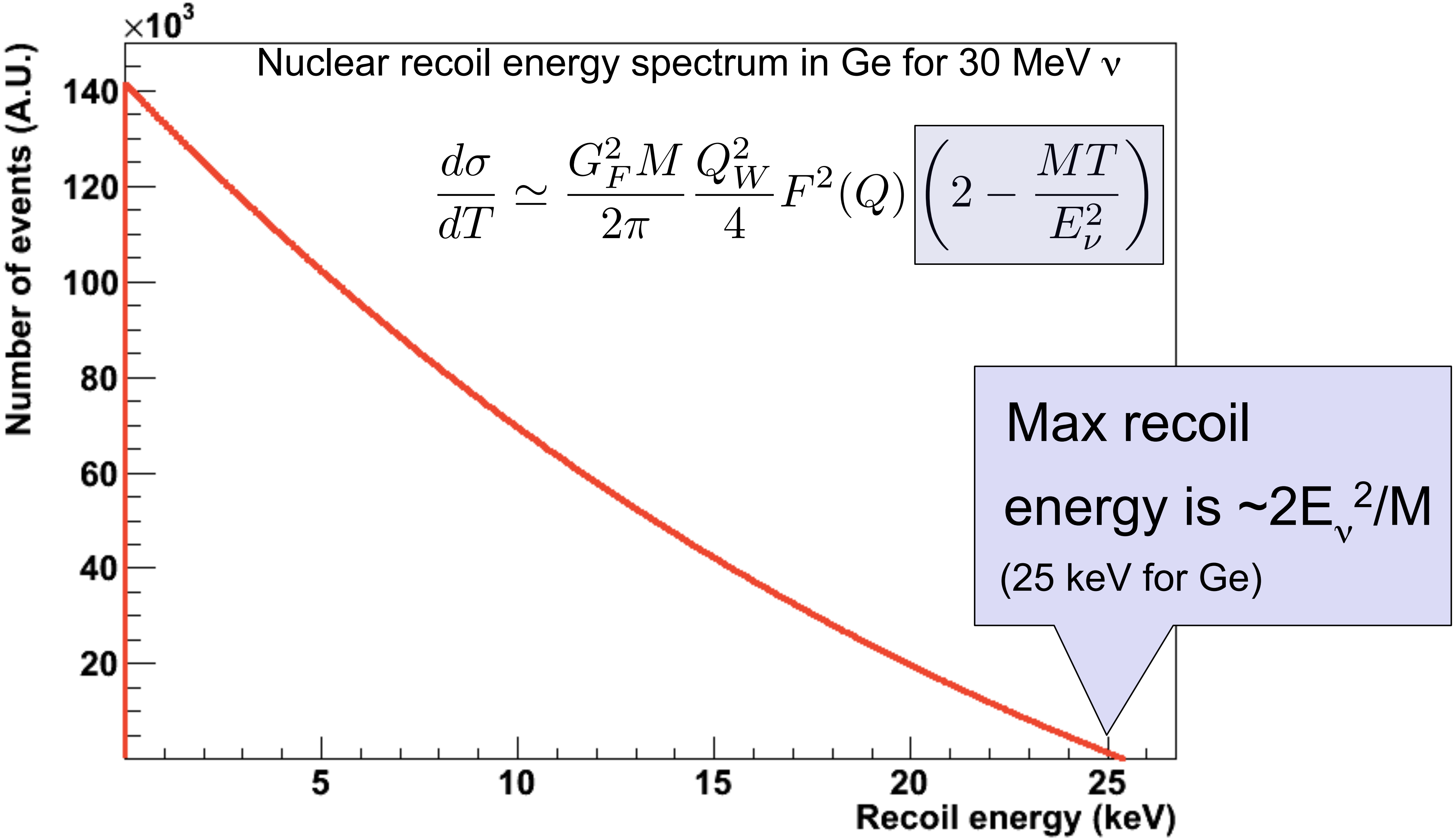
The cross section is *large*
(by neutrino standards)

$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$

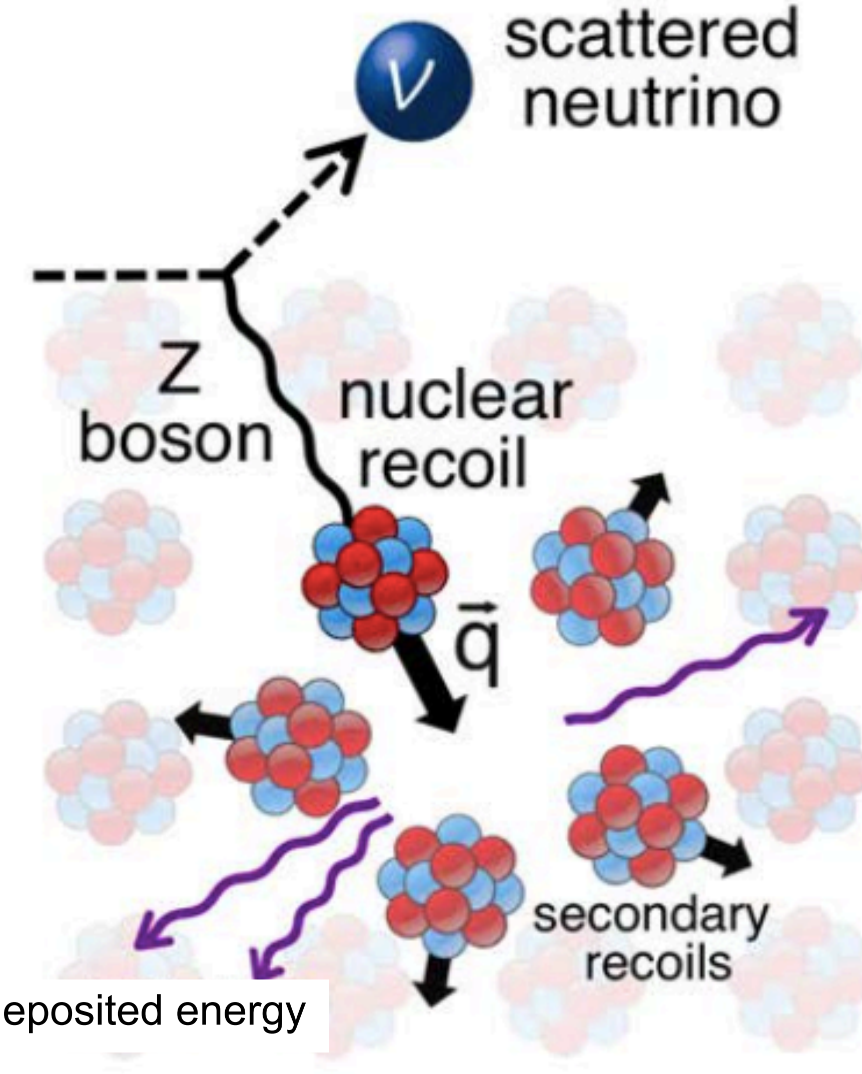


Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**



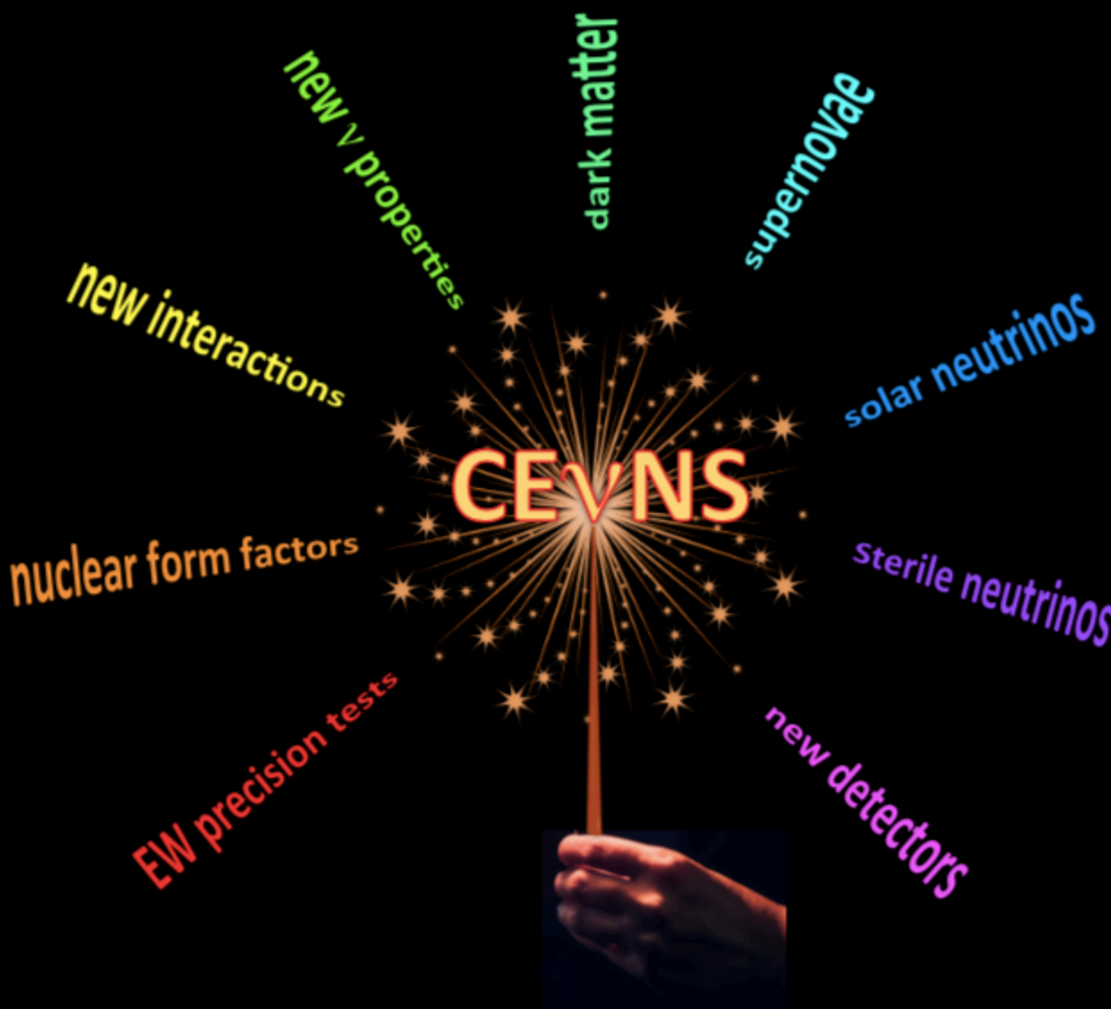
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material



➔ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10's of keV recoils

Why measure CEvNS?

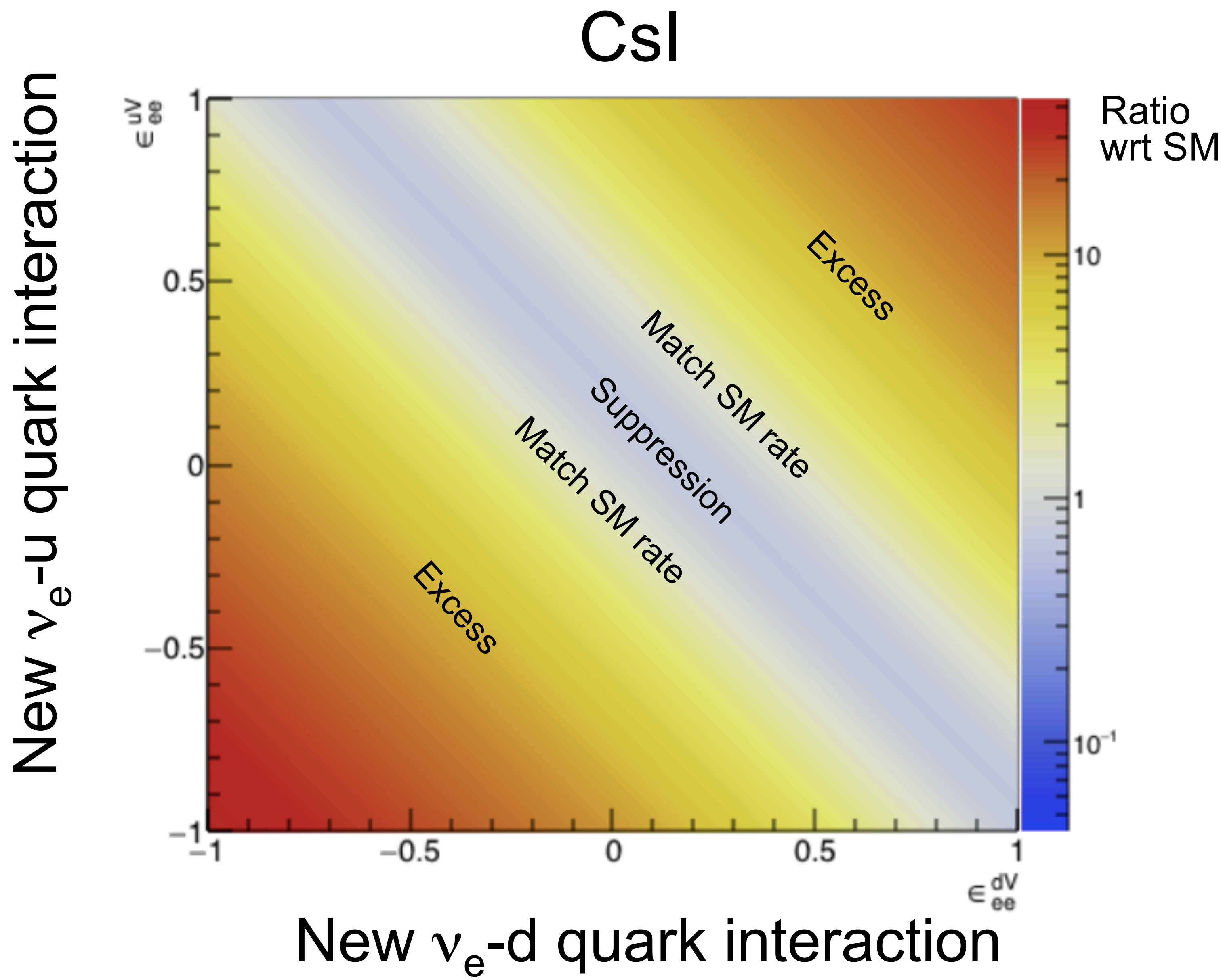


E. Lisi
Neutrino 2018

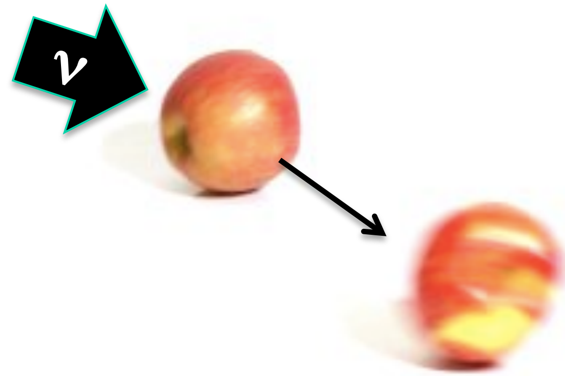
One example: hunting for **new interactions**
"Beyond-the-Standard-Model"

Signatures of **Beyond-the-Standard-Model Physics**

Look for a CEvNS **excess** or **deficit** wrt SM expectation



How to detect CEvNS?

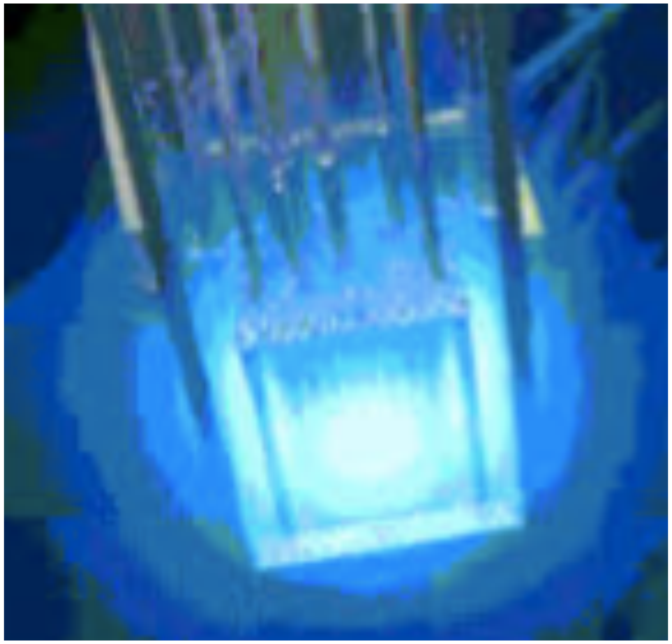


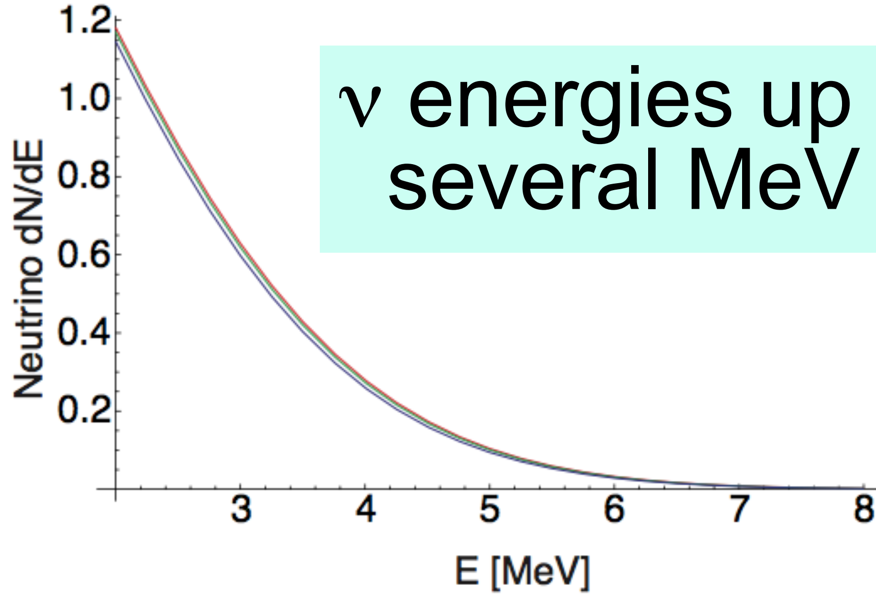
You need a neutrino source
and a detector

What do you want for your ν sourc

- ✓ High flux
- ✓ Well understood spectrum
- ✓ Multiple flavors (physics sensitivity)
- ✓ Pulsed source if possible, for background rejection
- ✓ Ability to get close
- ✓ Practical things: access, control, ...

Neutrinos from nuclear reactors

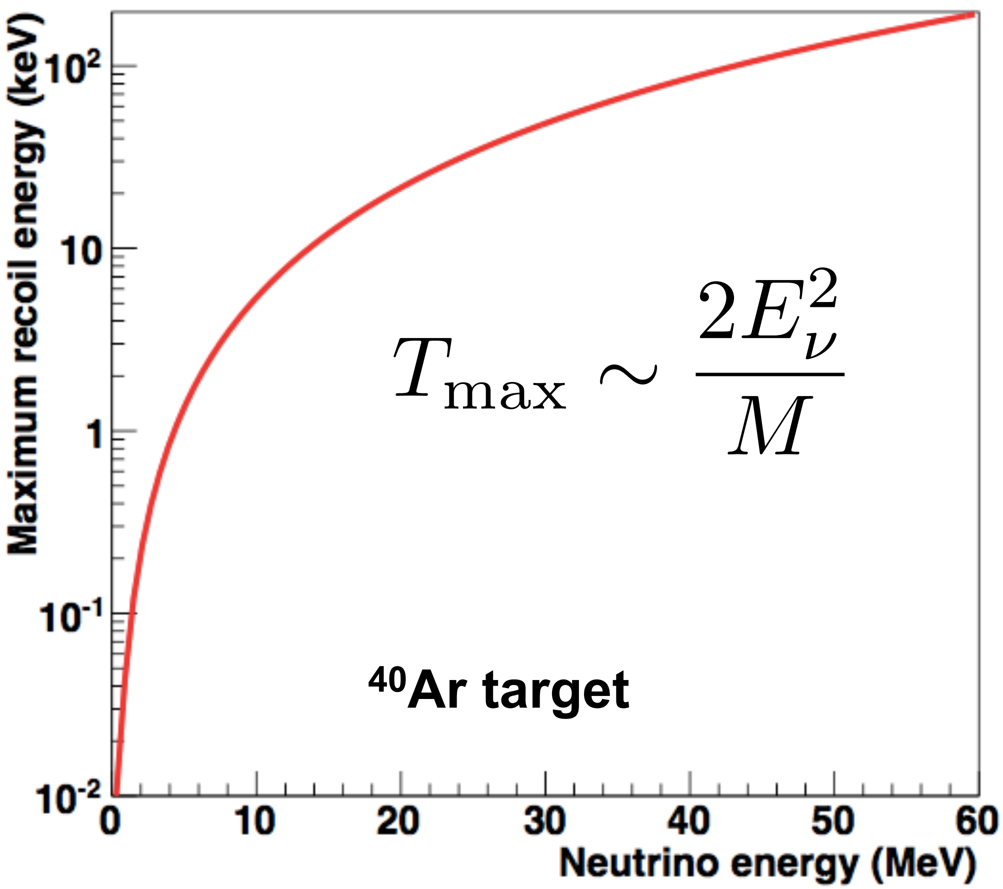


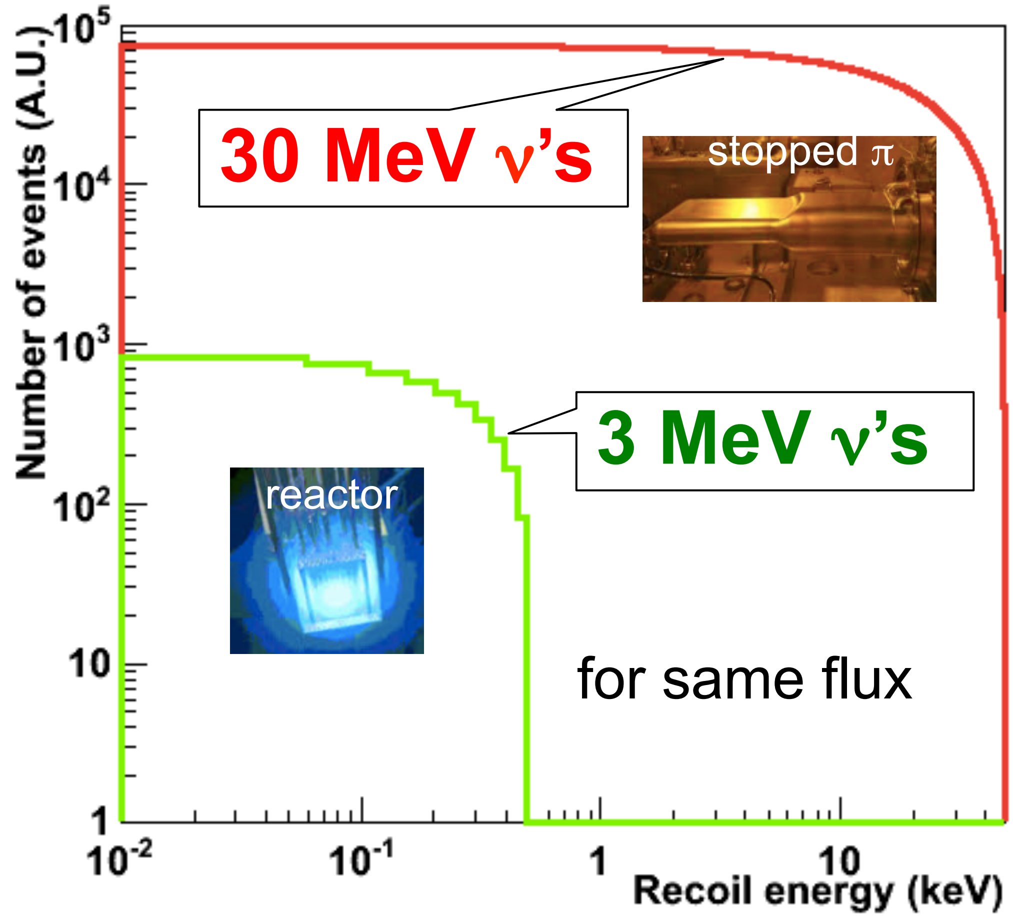


ν energies up to several MeV

- ν_e-bar produced in fission reactions (one flavor)
- **huge fluxes possible**: ~2×10^{20} s^{-1} per GW
- several CEvNS searches past, current and future at reactors, but **recoil energies<keV** and backgrounds make this very challenging

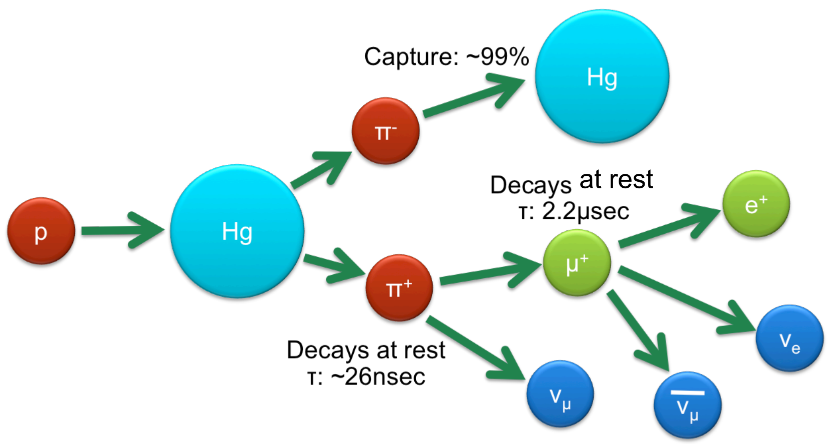
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

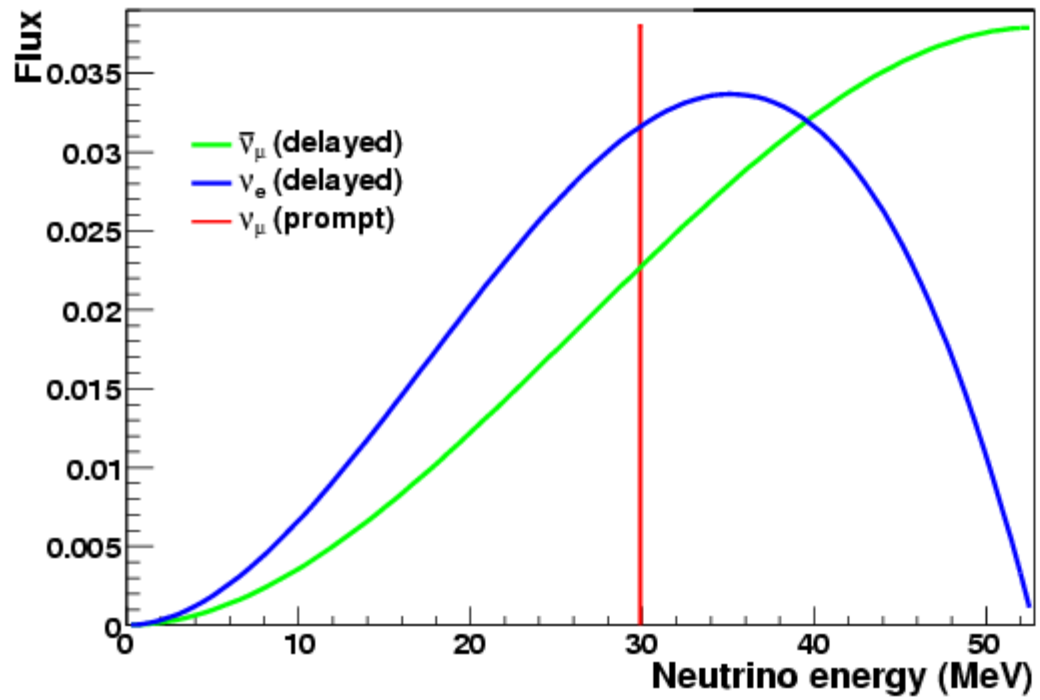




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

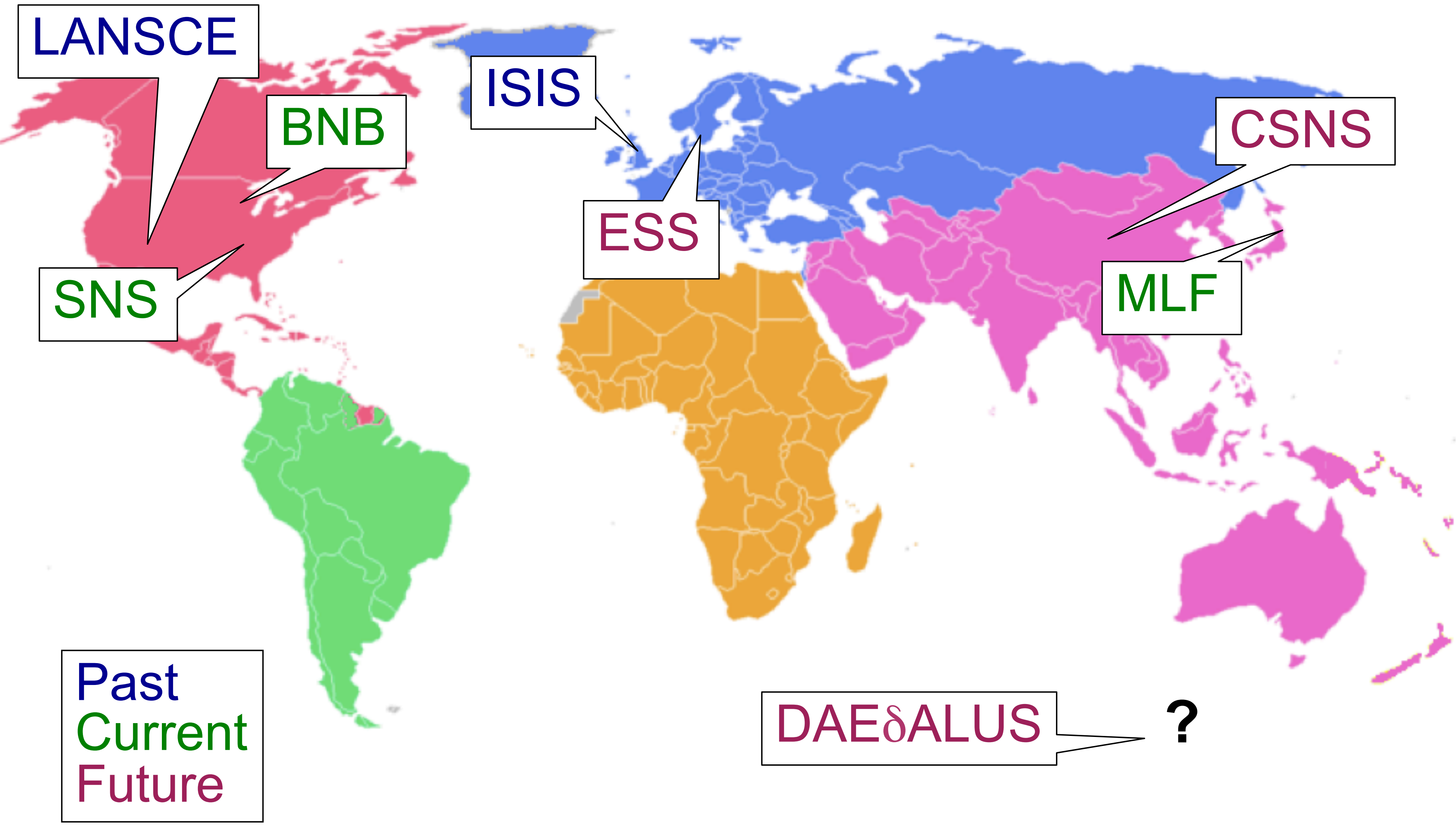
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

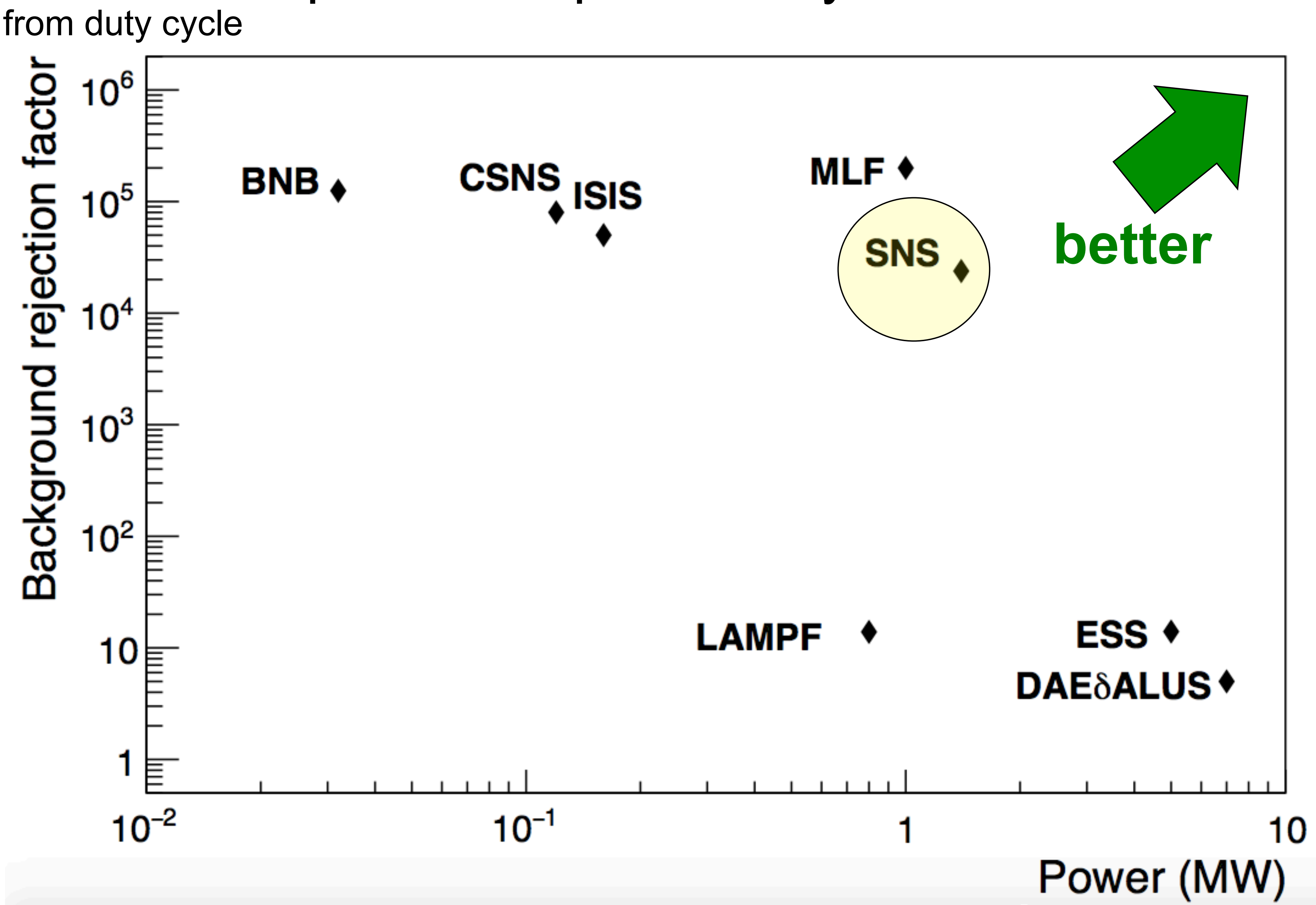
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

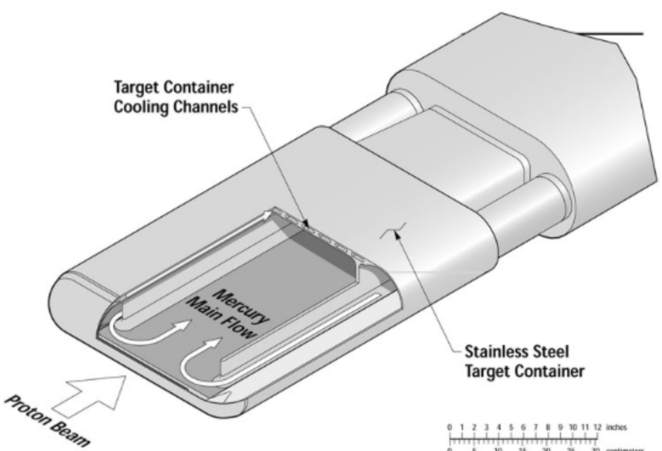
Stopped-Pion Neutrino Sources Worldwide



Comparison of pion decay-at-rest ν sources



$\propto \nu$ flux



Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

The neutrinos are free!

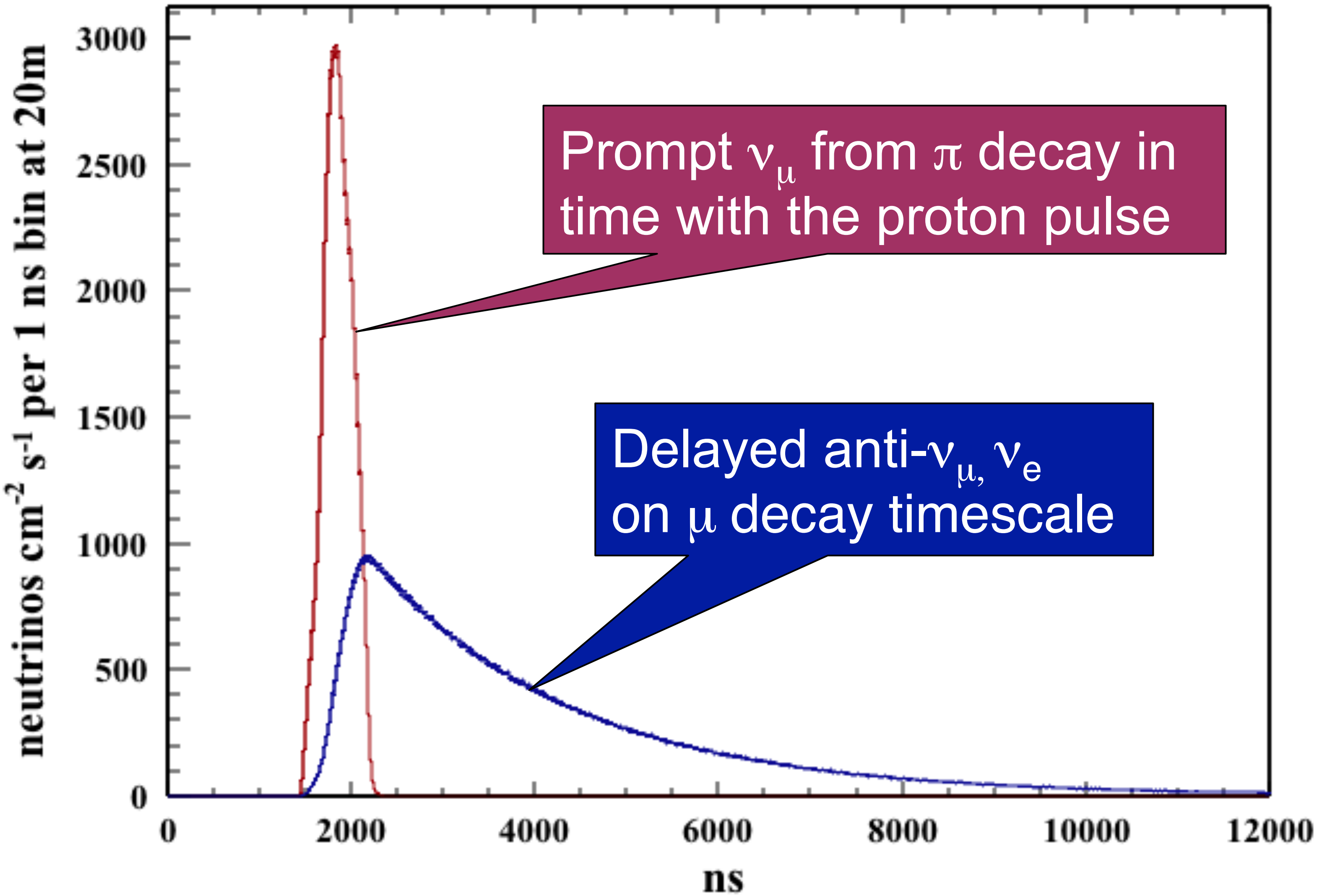
These are *not* crummy old cast-off neutrinos...

These are *not* crummy old cast-off neutrinos...

They are of the highest quality!

Time structure of the SNS source

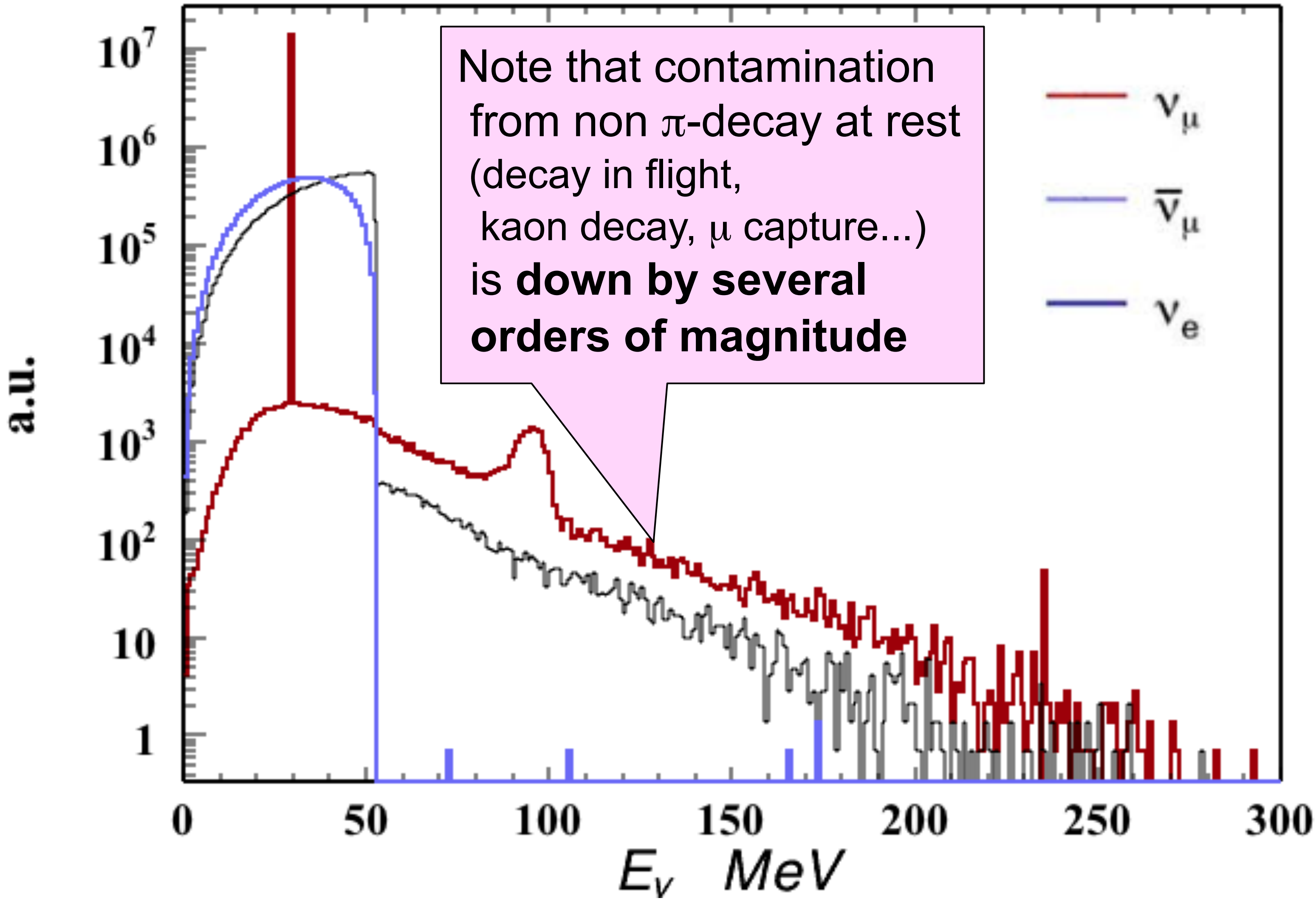
60 Hz *pulsed* source



Background rejection factor ~few x 10^{-4}

The SNS has **large, extremely clean** stopped-pion ν flux

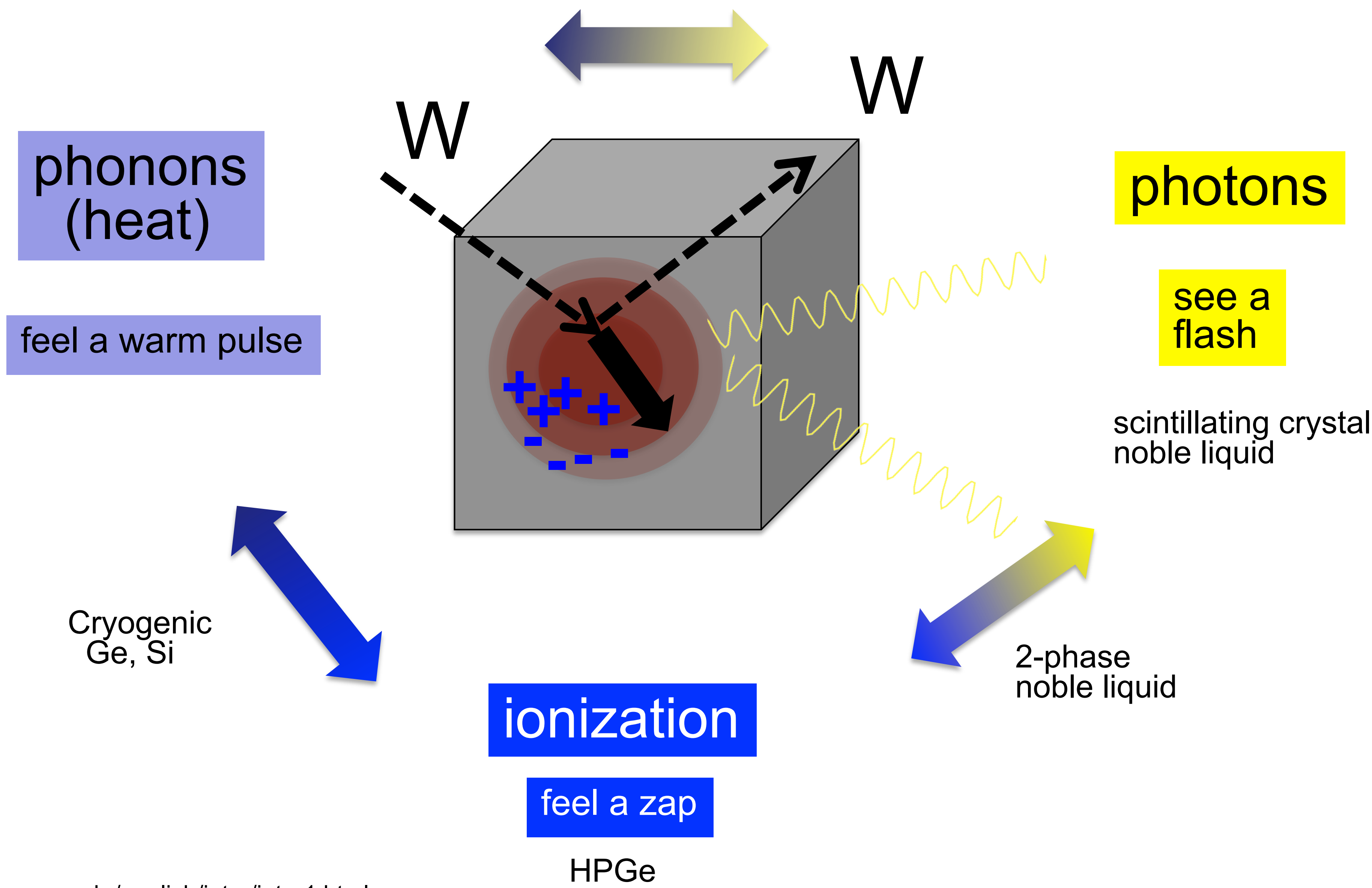
0.08 neutrinos per flavor per proton on target



SNS flux (1.4 MW):
430 x 10^5 ν/cm^2/s
@ 20 m

Now, ***detecting*** the tiny kick of the neutrino...

This is just like the tiny thump of a WIMP;
we benefit from the last few decades of low-energy nuclear recoil detectors



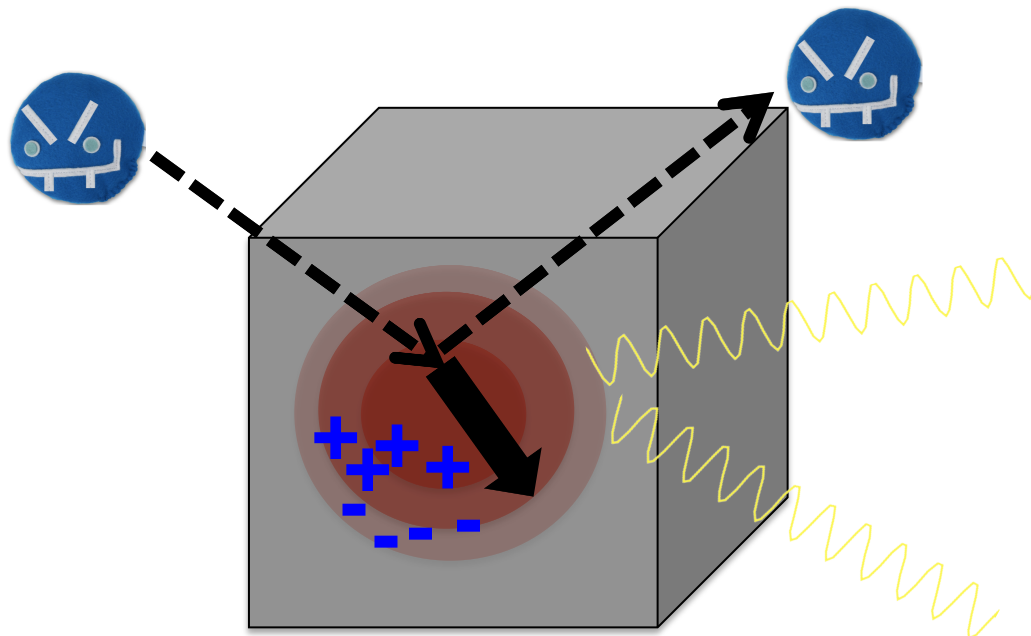
http://dmrc.snu.ac.kr/english/intro/intro1.html

Backgrounds

Usual suspects:

- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

Neutrons are especially not our friends*

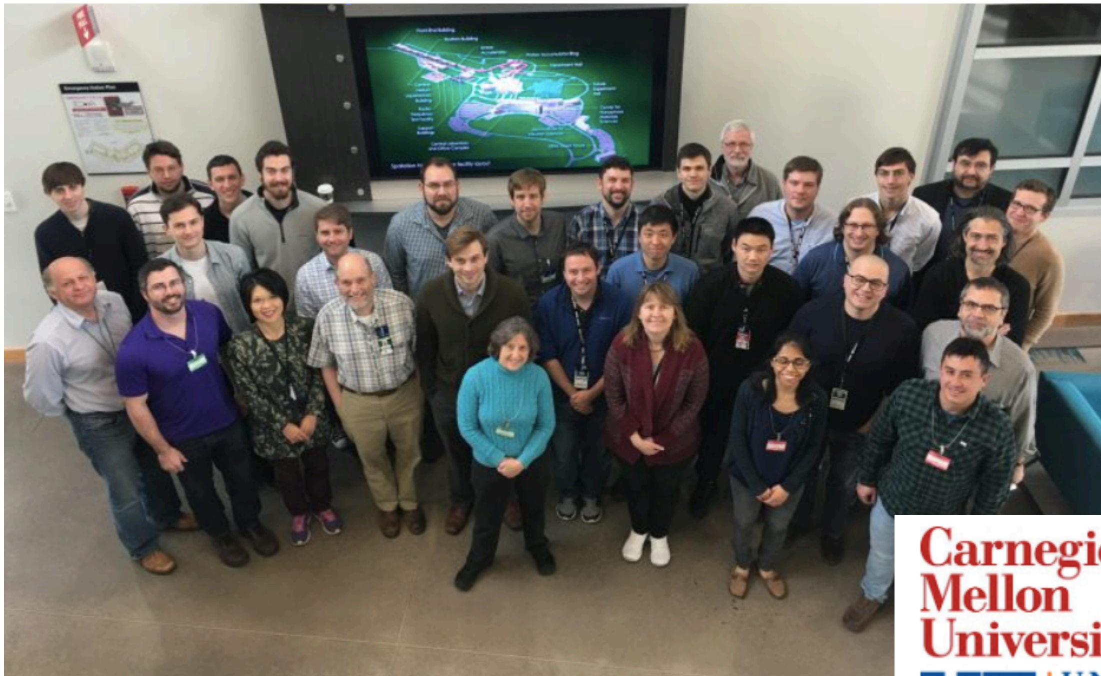


Steady-state backgrounds can be *measured* off-beam-pulse
... in-time backgrounds must be carefully characterized

*Thanks to Robert Cooper for the “mean neutron”

The COHERENT collaboration

http://sites.duke.edu/coherent



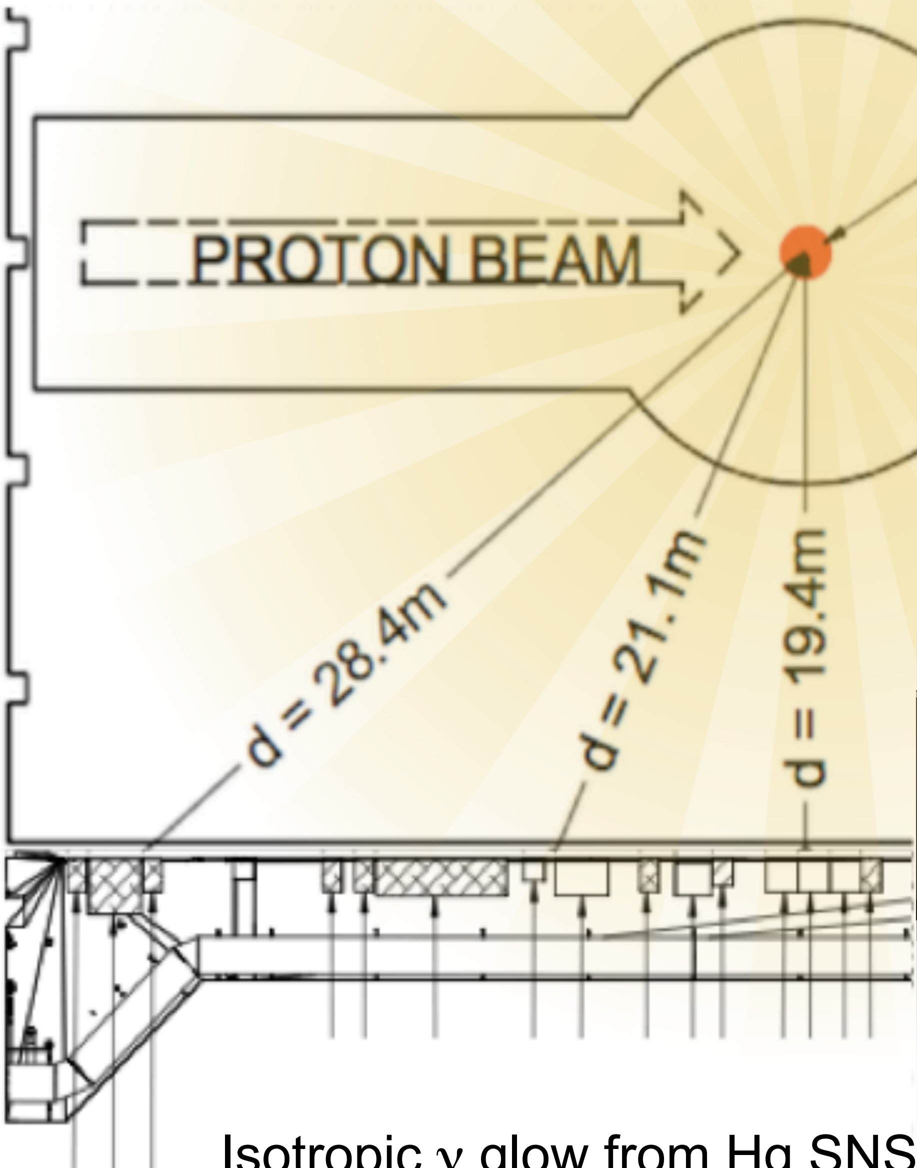
~80 members,
19 institutions
4 countries

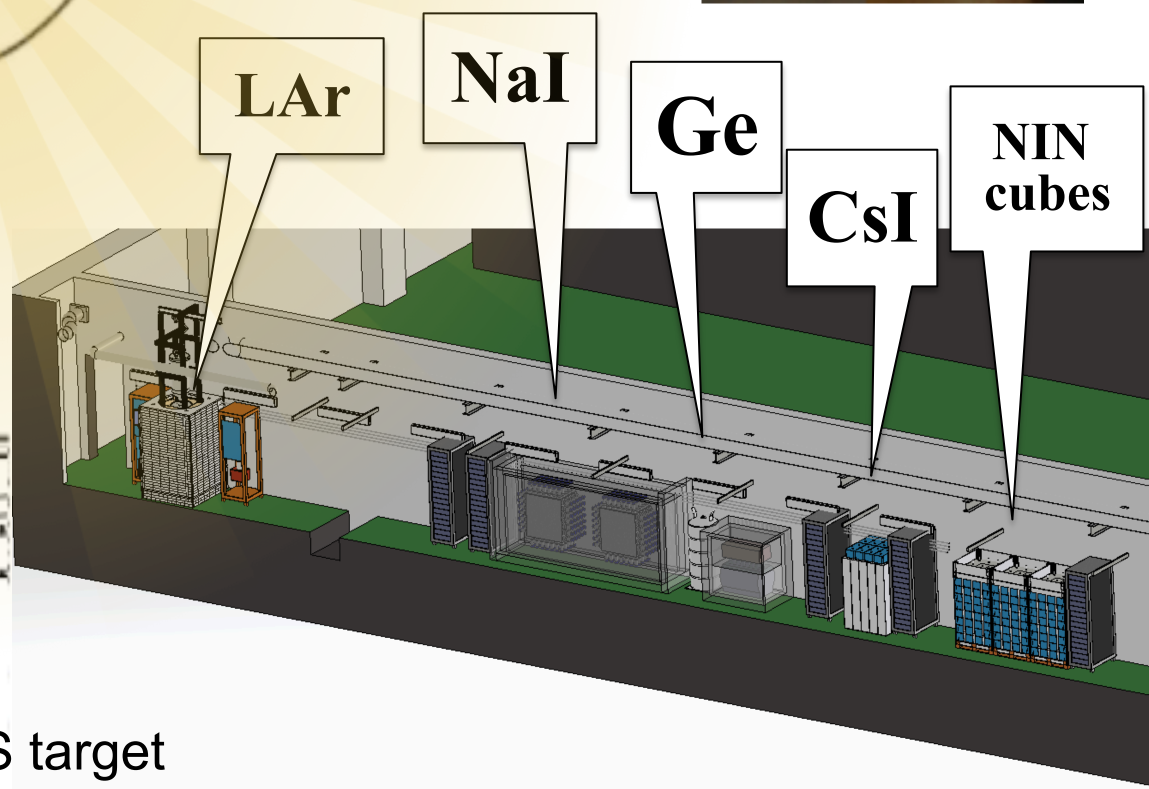
arXiv:1509.08702

Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

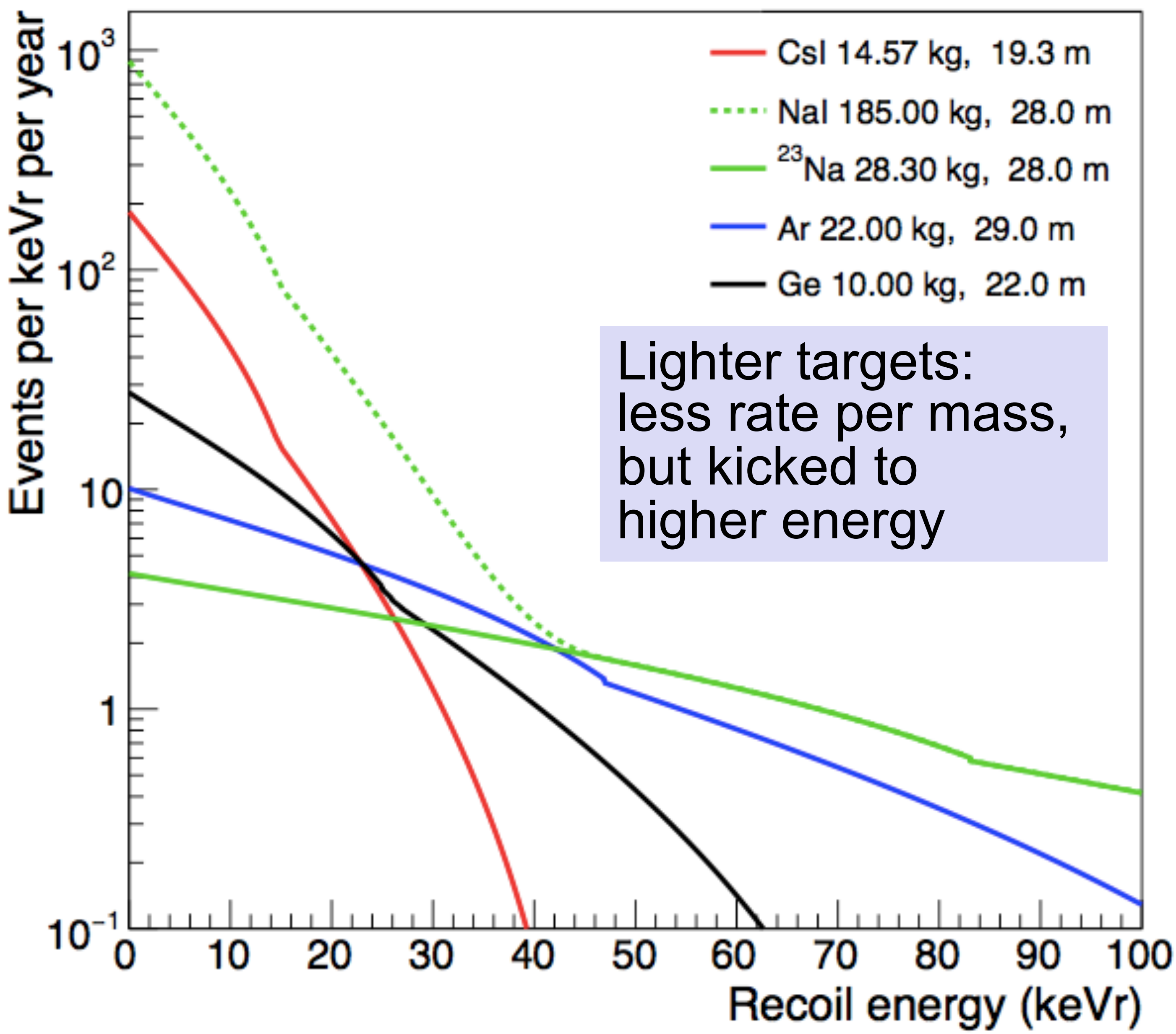
View looking
down “Neutrino Alley”



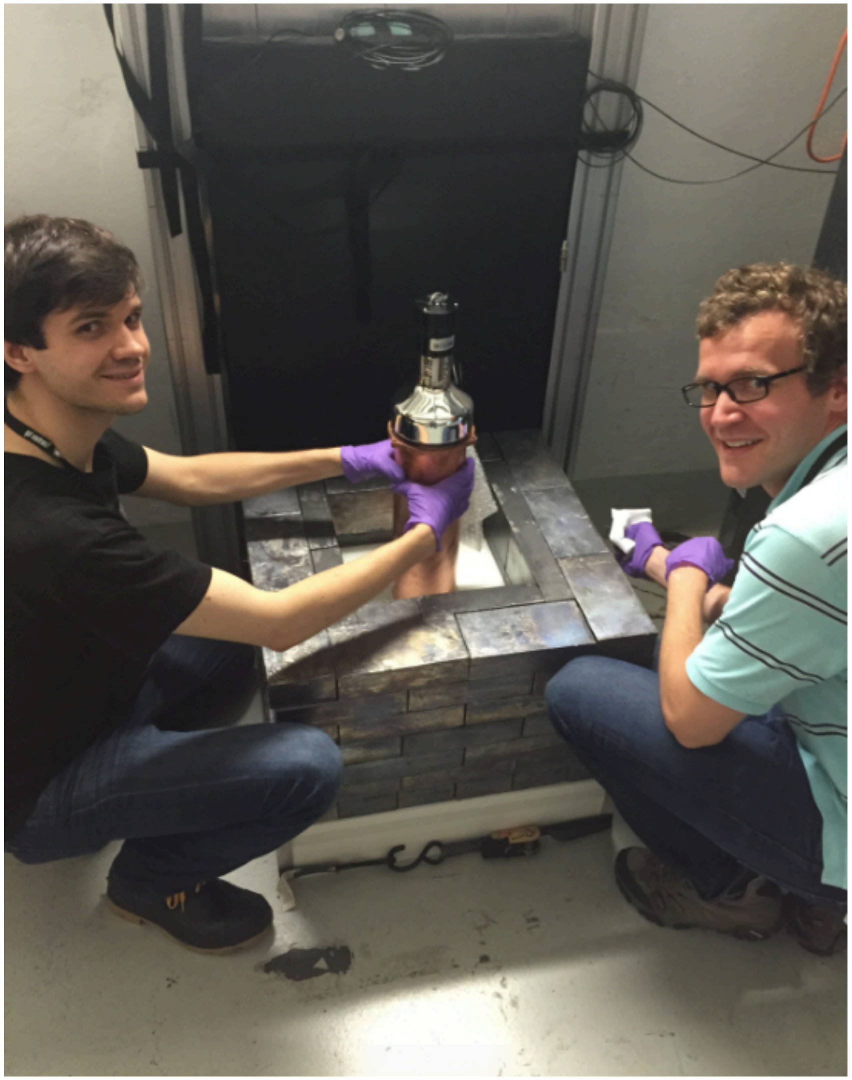


Isotropic ν glow from Hg SNS target

Expected recoil energy distribution



The CsI Detector in Shielding in Neutrino Alley at the SNS



A hand-held detector!

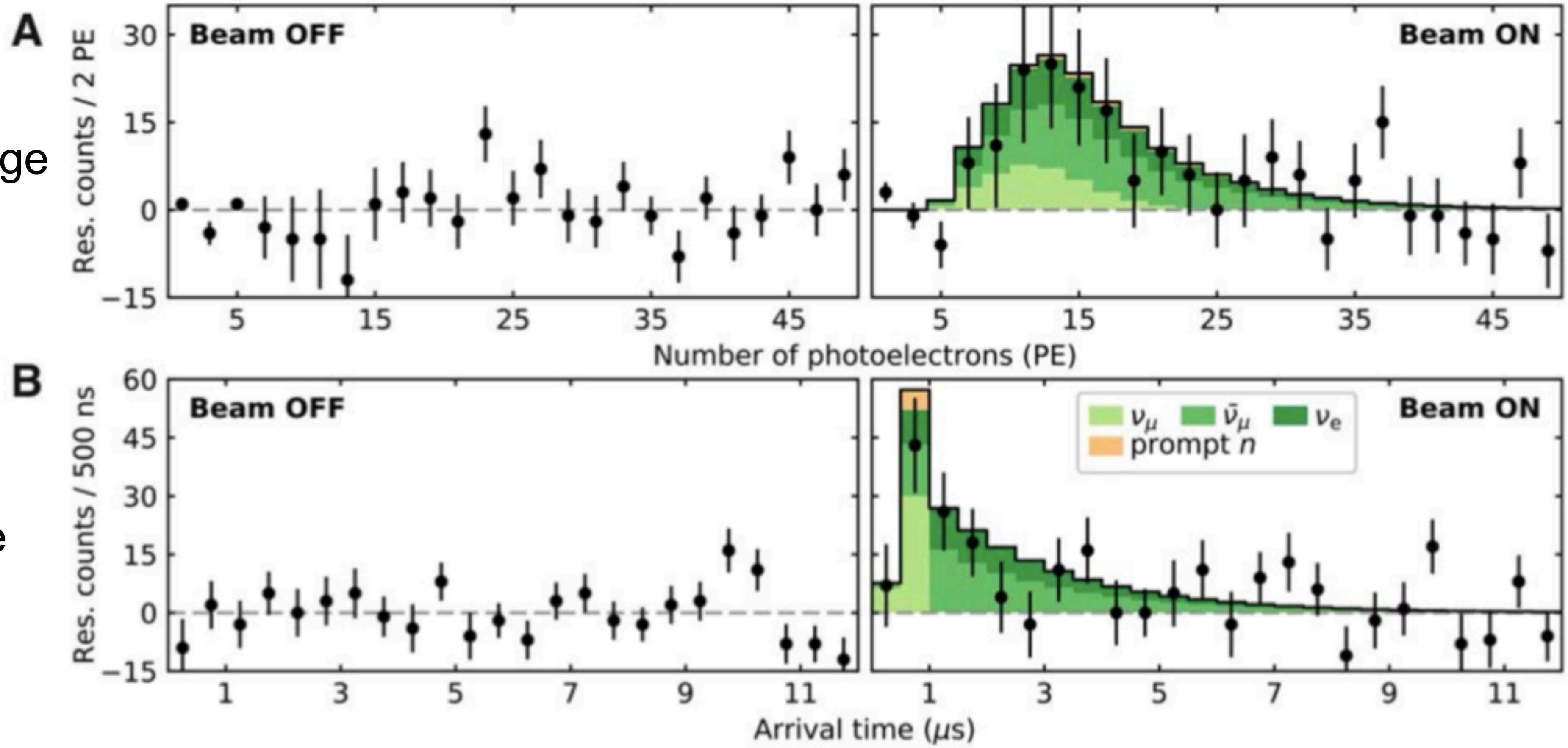
Almost wrapped up...

Detector designed and calibrated @ U. of Chicago

First light at the SNS with 14.6-kg CsI[Na] detector

Charge

Time



Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

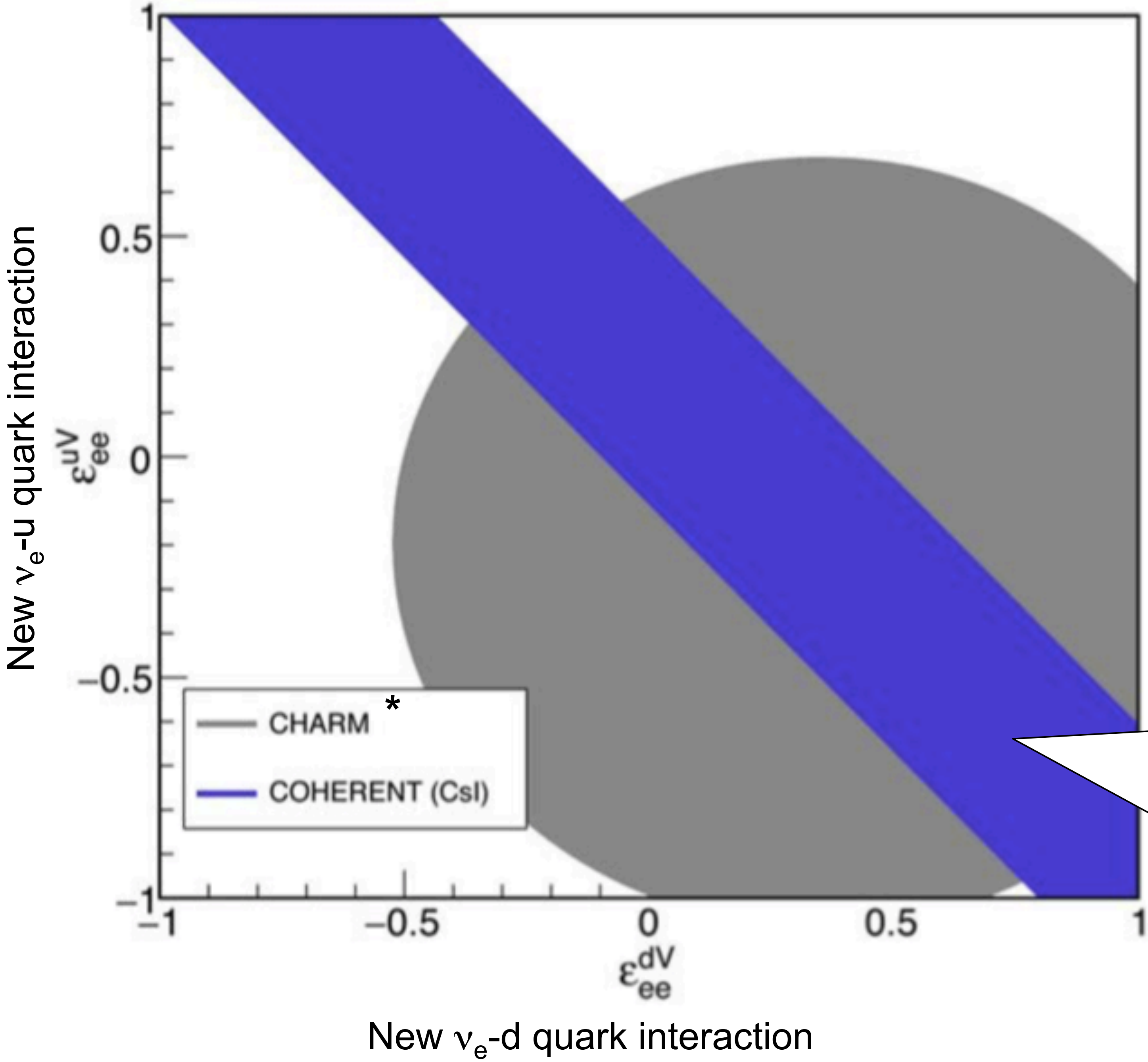
+ See all authors and affiliations

Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

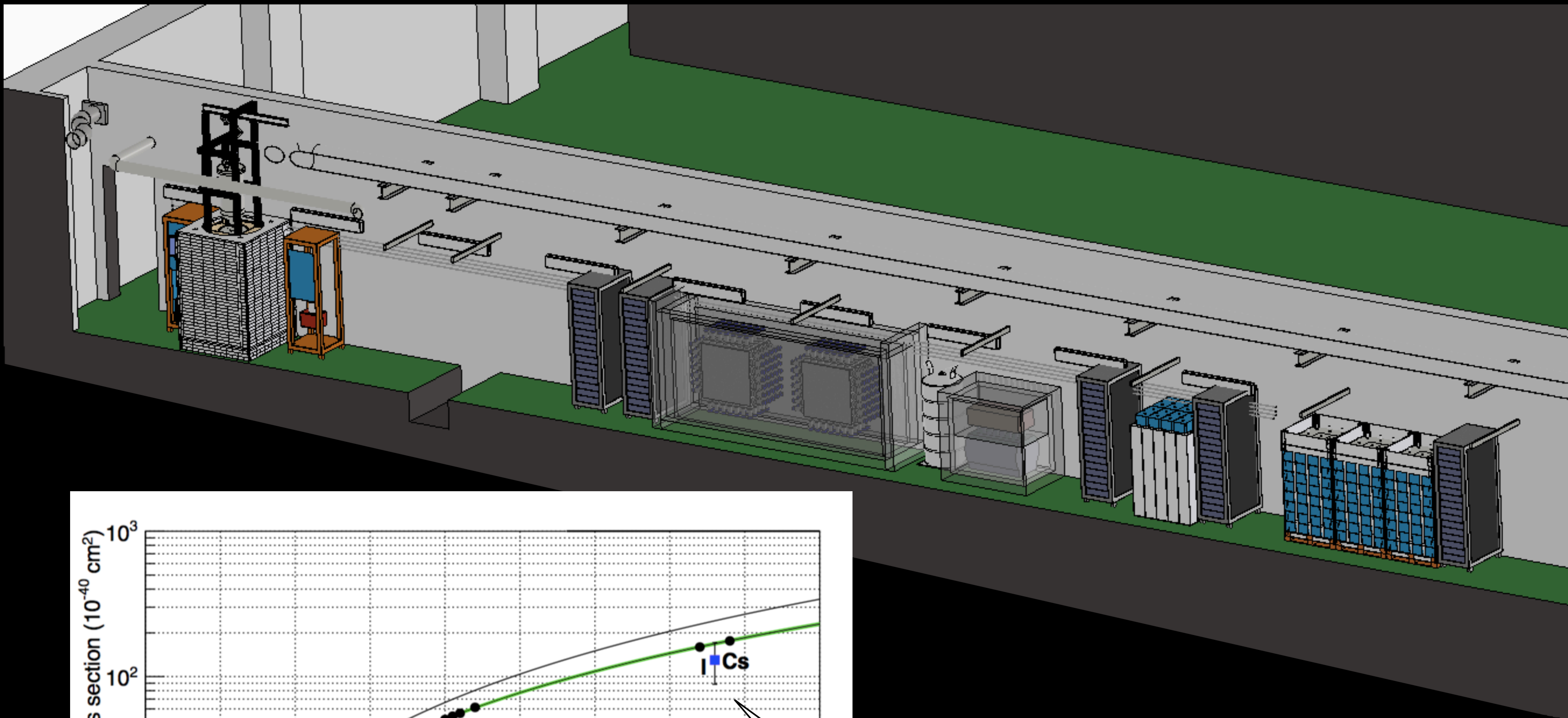
D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

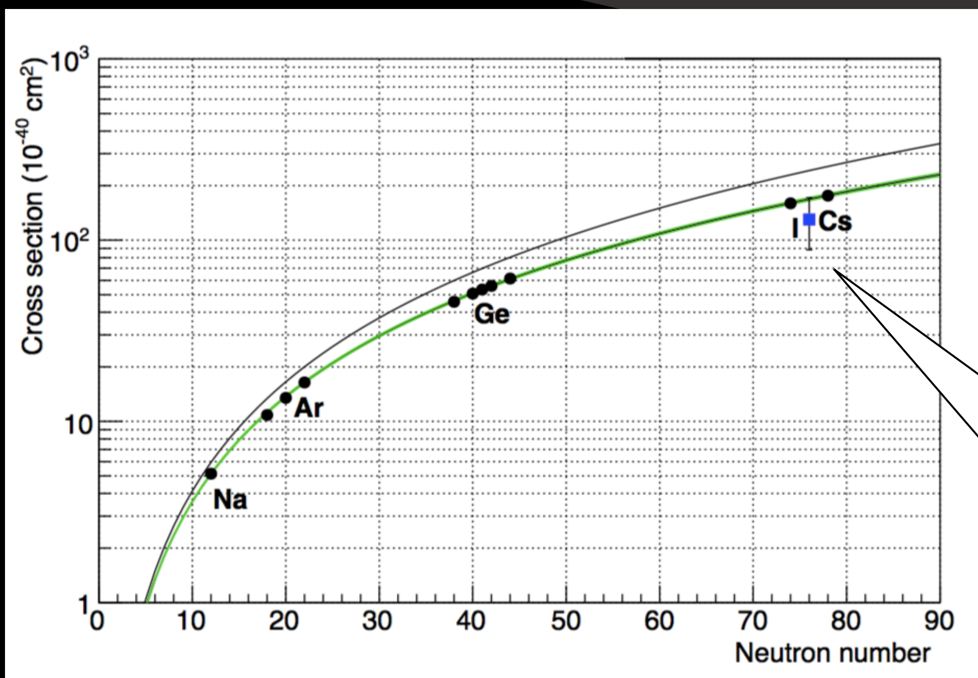
Neutrino non-standard interaction results for current CsI data set:



Parameters describing beyond-the-SM interactions outside this region disfavored at 90%

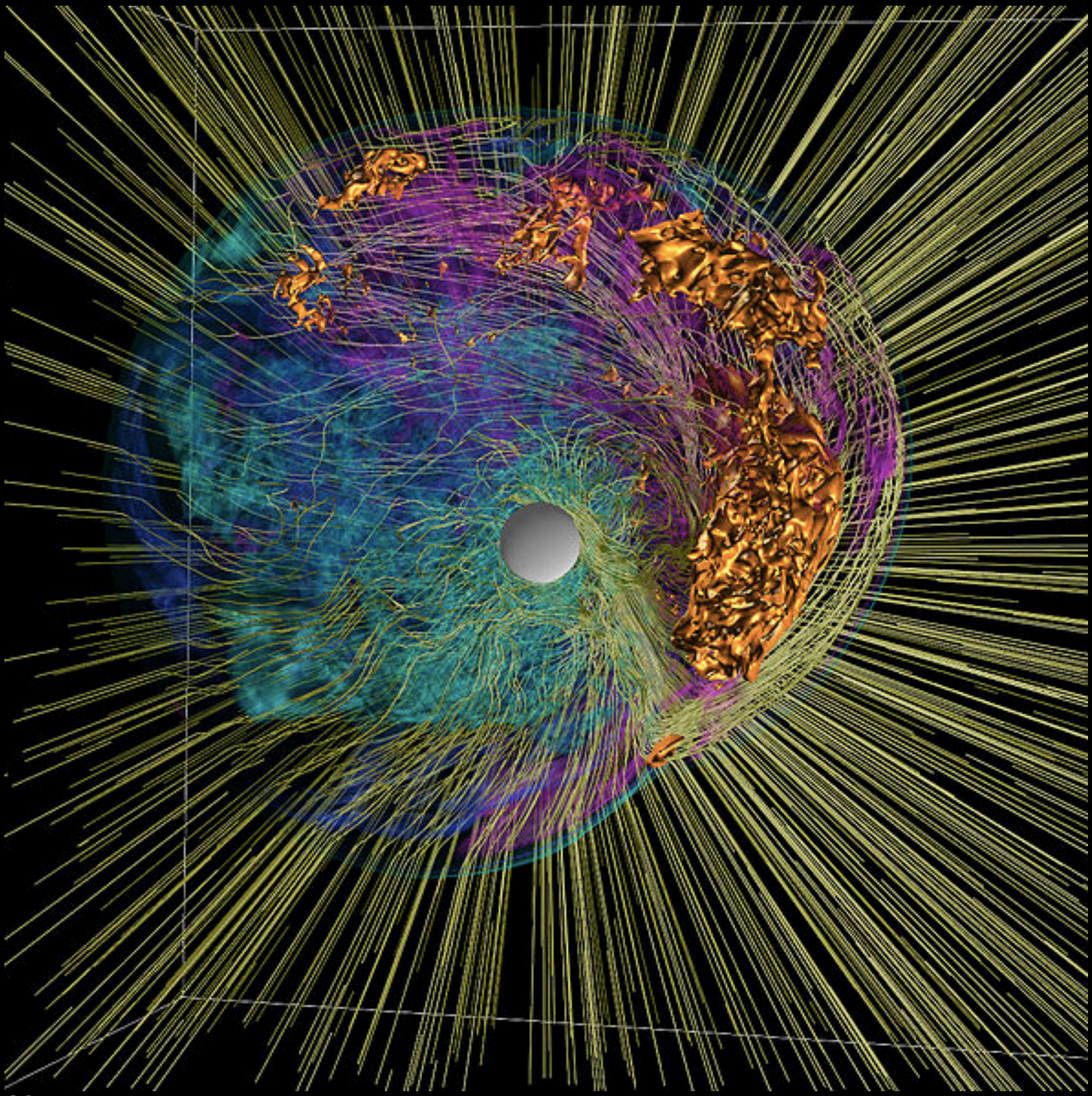
What's Next for COHERENT?





One measurement so far! Want to map out N^2 dependence

And there are many more potential opportunities for **neutrino physics with stopped-pion sources**



A. Mezzacappa

- interactions of supernova neutrinos
- neutrino oscillations
- nuclear structure
- low-energy detection technology
- ...

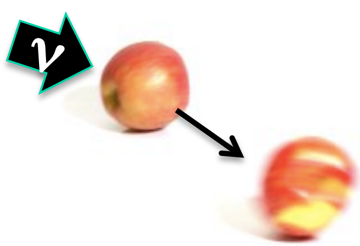
Take-Away Messages from this Lecture

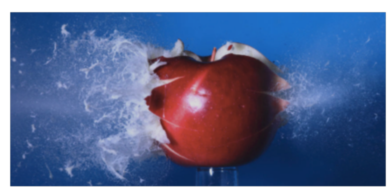
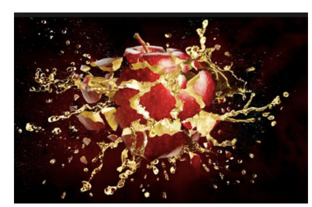
- **Neutrinos** matter for particle physics
  astrophysics
  cosmology
  nuclear physics

- Neutrinos interact with matter via charged- and neutral-current interactions ... weak interactions are rare but important!

. $$N = \phi\, \sigma\, N_t\, T$$ [use in your tutorial]

- Understanding of **neutrino interactions with nuclei** matters:
  - interpretation of neutrino experiments (oscillation, astrophysical)
  - search for beyond-the-SM physics
  - understanding of the nuclei themselves



Extras/backups