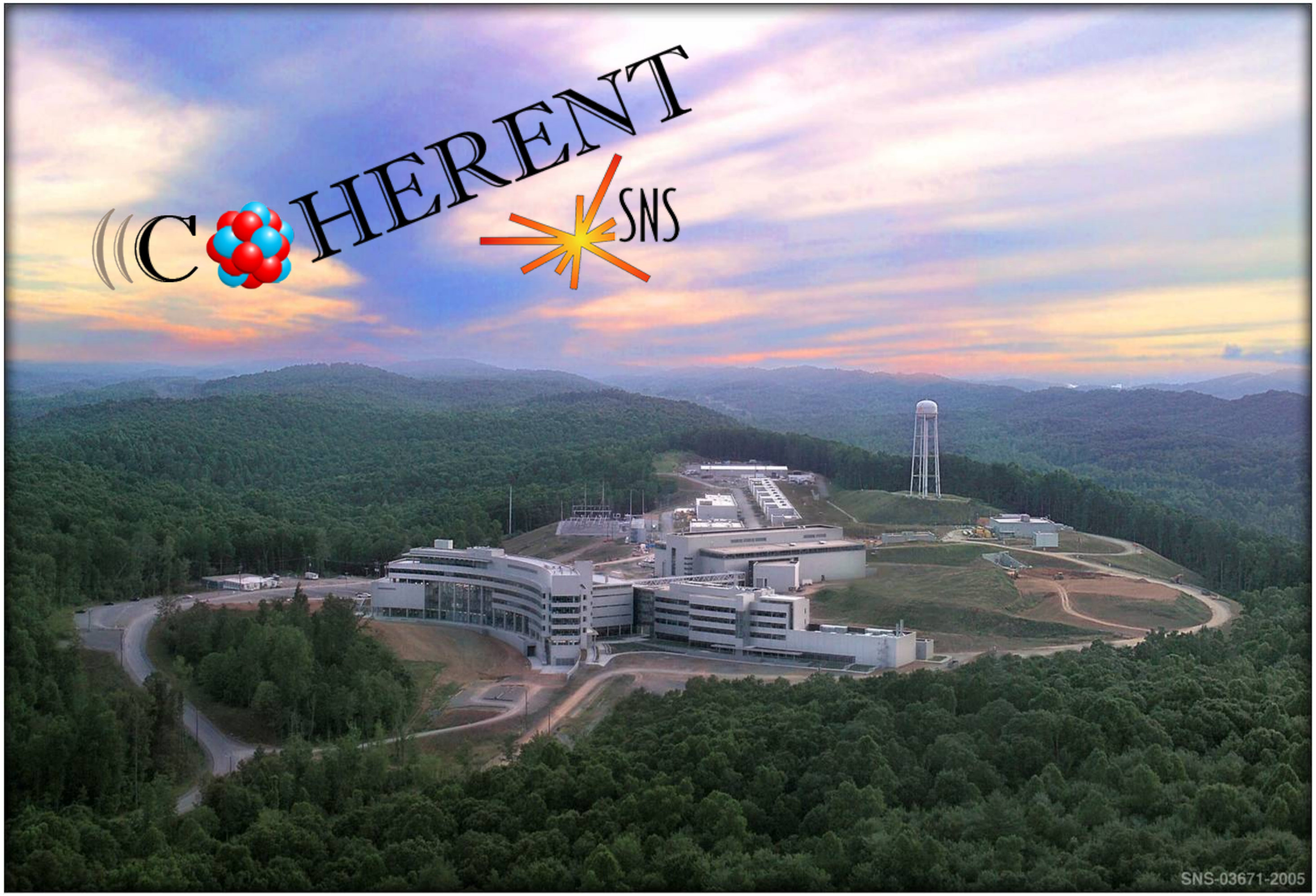
Observation of

Coherent Elastic Neutrino-Nucleus Scattering



Kate Scholberg, Duke University
COFI Seminar
September 12, 2017

OUTLINE

- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light** with CsI[Tl]
- Status and prospects for COHERENT

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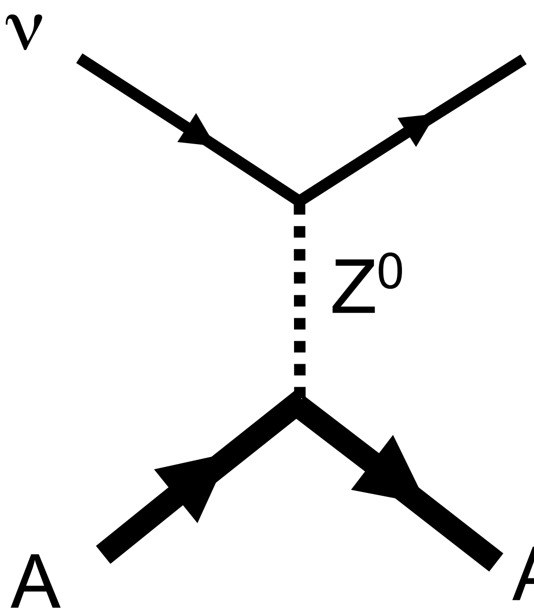
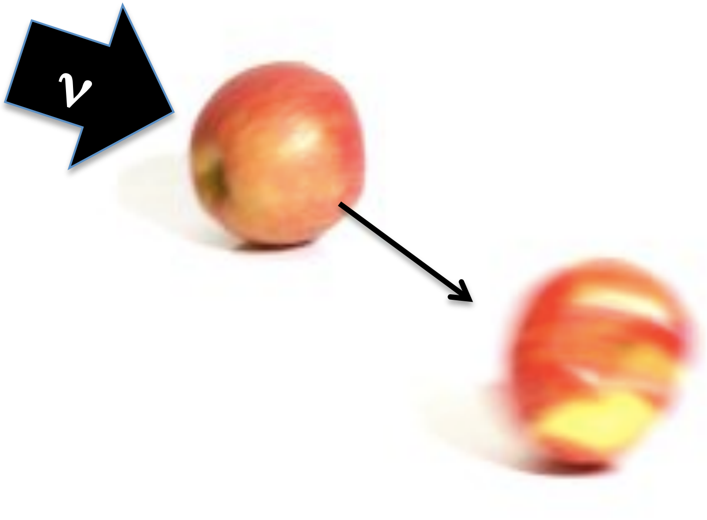
Coherent elastic neutrino-nucleus scattering (CEvNS)

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



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



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

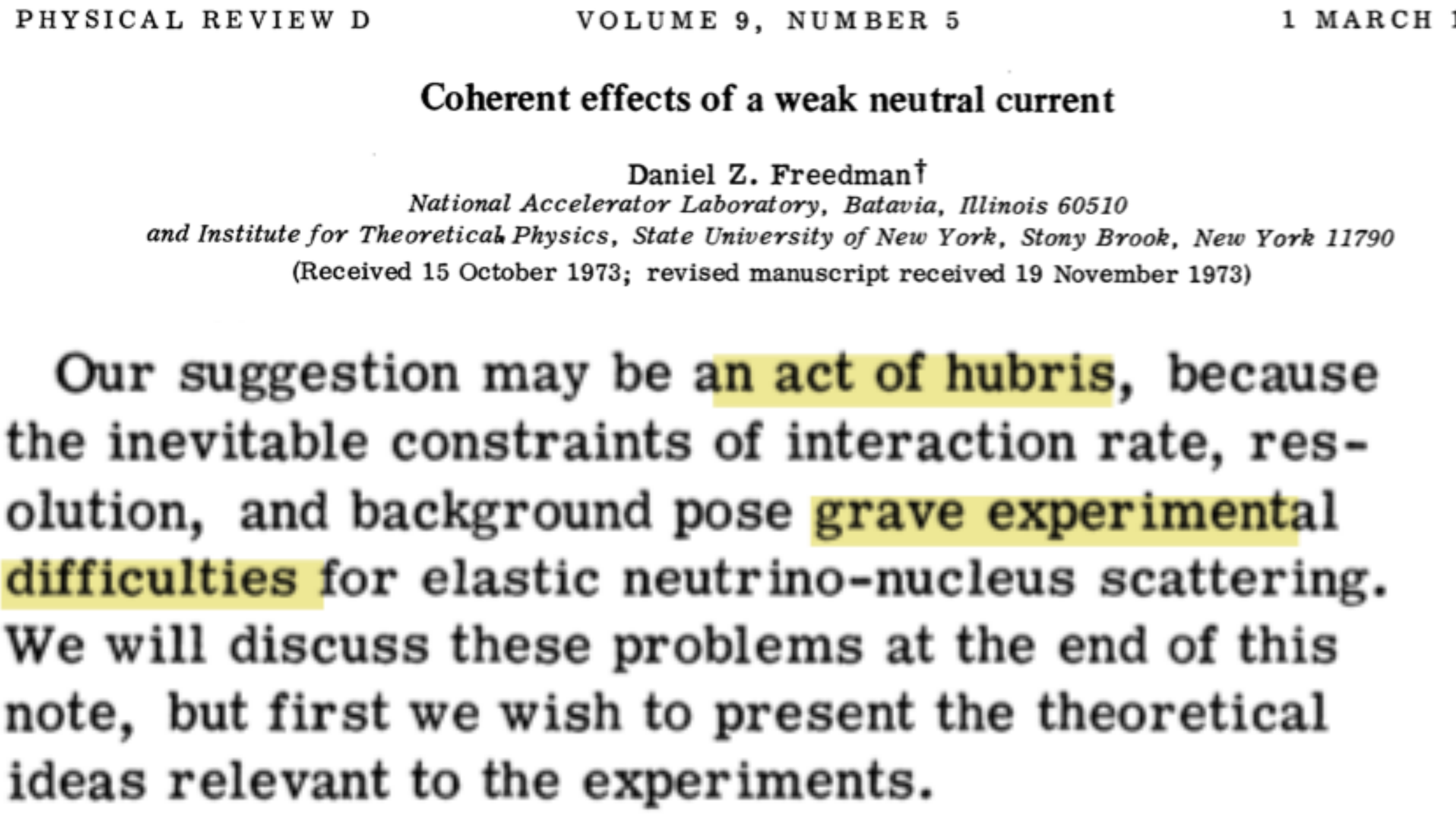
$$\frac{d\sigma}{d\Omega} \sim A^2 |f(\mathbf{k}', \mathbf{k})|^\mathbf{2}$$

Momentum transfer $\mathbf{Q} = \mathbf{k}' - \mathbf{k}$

For $QR << 1$,

[total xscn] ~ A^2 * [single constituent xscn ($|f|^2$)]

First proposed 43 years ago!



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

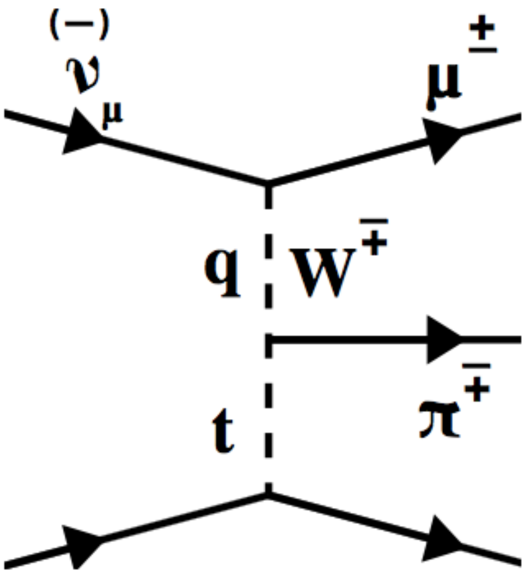
Coherent effects of a weak neutral current

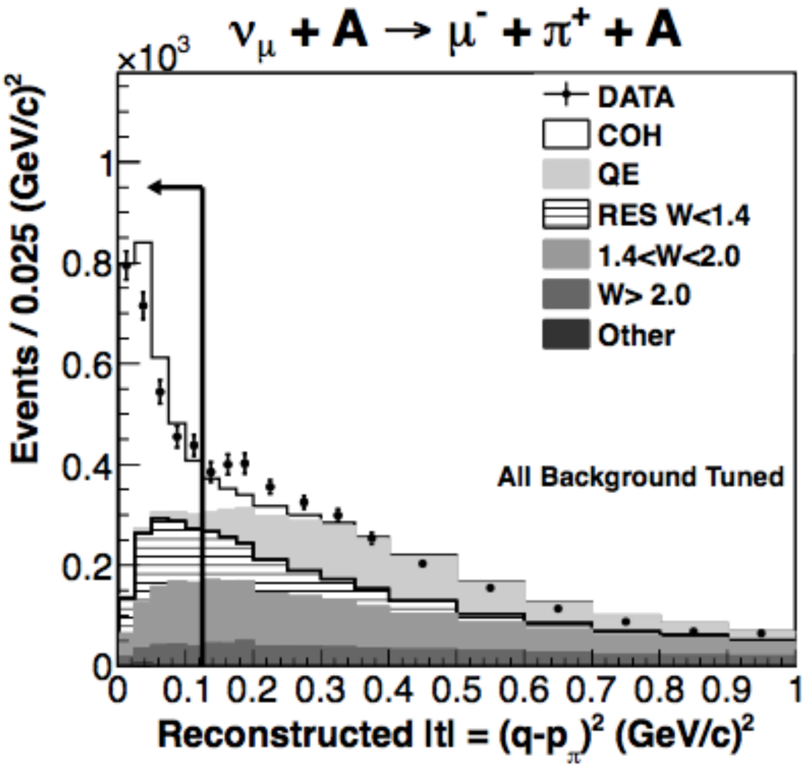
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

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

This is ***not*** coherent pion production, a strong interaction process ***(inelastic)***





A. Higuera et. al, MINERvA collaboration,
PRL 2014 113 (26) 2477

not
THAT!

`\begin{aside}`

Literature has CNS, CNNS, CENNS, ...

- I prefer including "E" for "elastic"... otherwise it gets frequently confused with coherent pion production at ~GeV neutrino energies
- I'm told "NN" means "nucleon-nucleon" to nuclear types
- CEνNS is a possibility but those internal Greek letters are annoying

➔**CEvNS**, pronounced "sevens"...

spread the meme!

`\end{aside}`

The cross section is cleanly predicted in the Standard Model

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2} \right]$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
$Q = \sqrt{(2 M T)}$: momentum transfer

G_V, G_A: SM weak parameters

vector $G_V = g_V^p Z + g_V^n N,$ ← dominates

axial $G_A = g_A^p (Z_+ - Z_-) + g_A^n (N_+ + N_-)$ ← small for most nuclei, zero for spin-zero

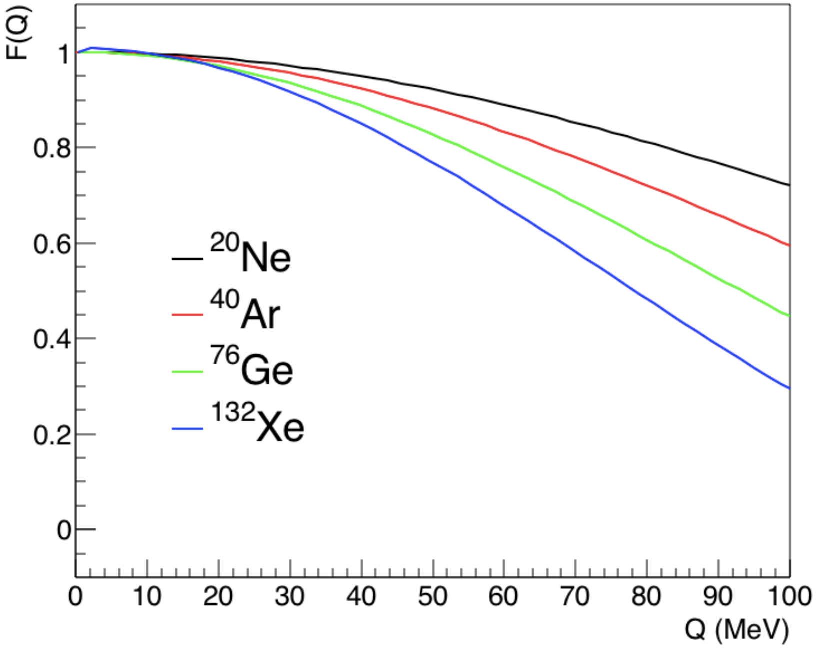
$$\begin{aligned} g_V^p &= 0.0298 \\ g_V^n &= -0.5117 \\ g_A^p &= 0.4955 \\ g_A^n &= -0.5121. \end{aligned}$$

The cross section is cleanly predicted in the Standard Model

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{\pi} F^2(Q) \left[(G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_\nu^2} \right]$$

E_ν: neutrino energy
T: nuclear recoil energy
M: nuclear mass
Q = √ (2 M T): momentum transfer

F(Q): nuclear form factor, <~5% uncertainty on event rate



form factor suppresses cross section at large Q

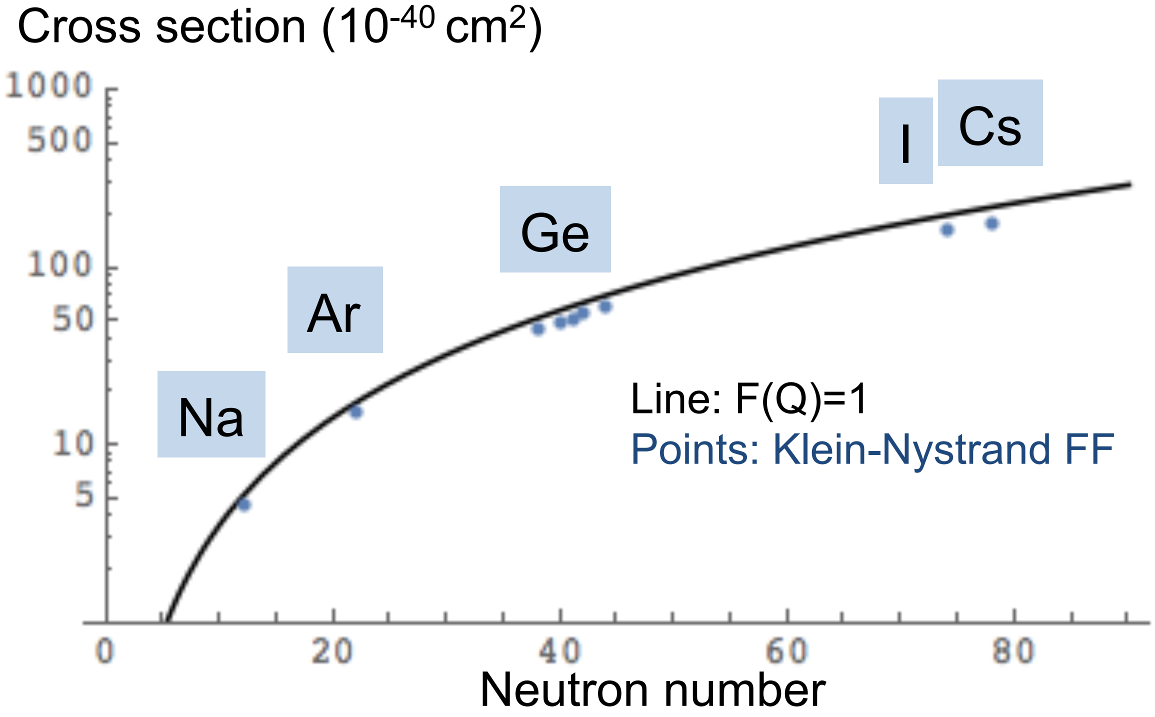
For T<<E$_\nu$, neglecting axial terms:

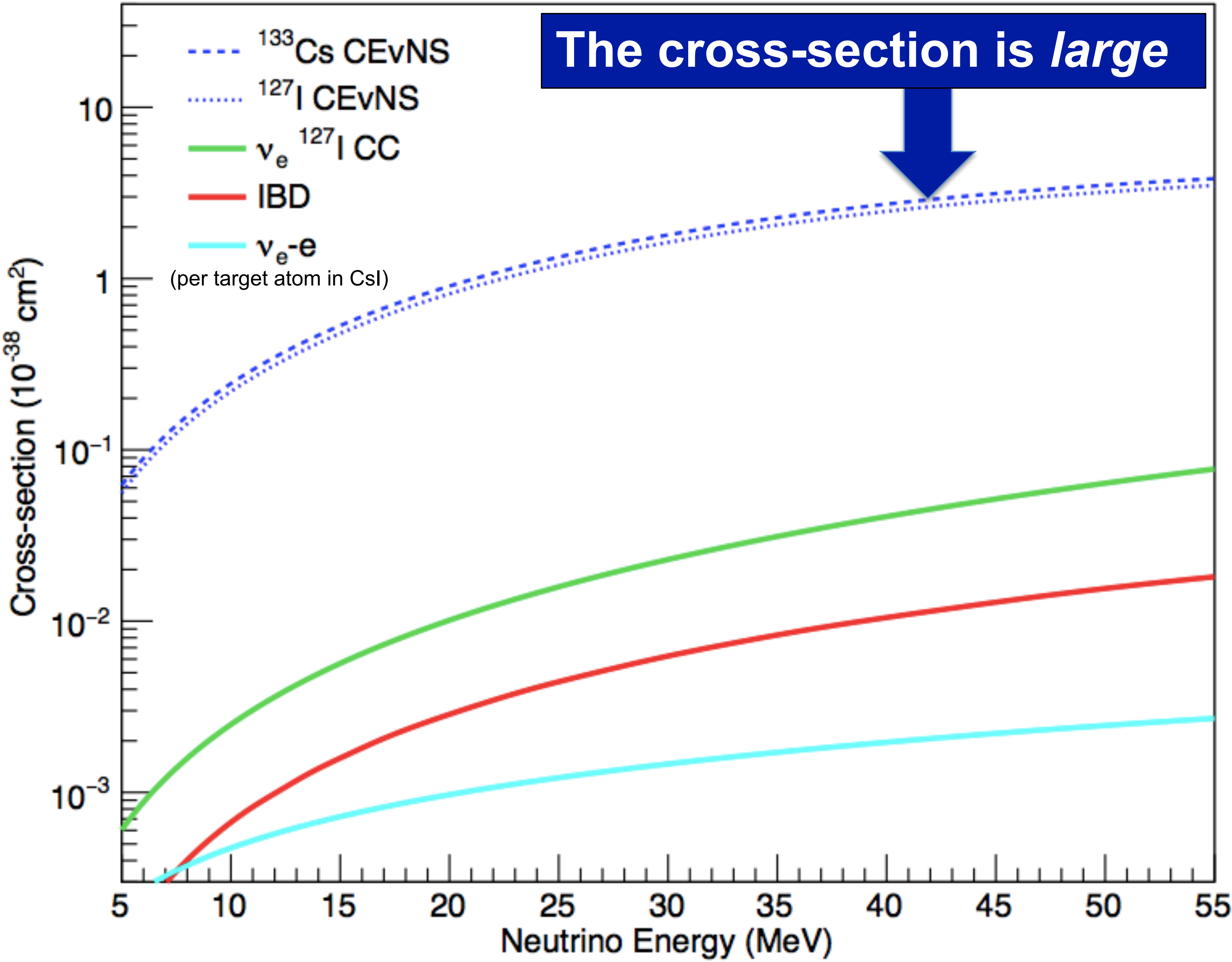
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$

$Q_W = N - (1 - 4\sin^2\theta_W)Z$: weak nuclear charge

$\sin^2\theta_W = 0.231$,
so protons unimportant

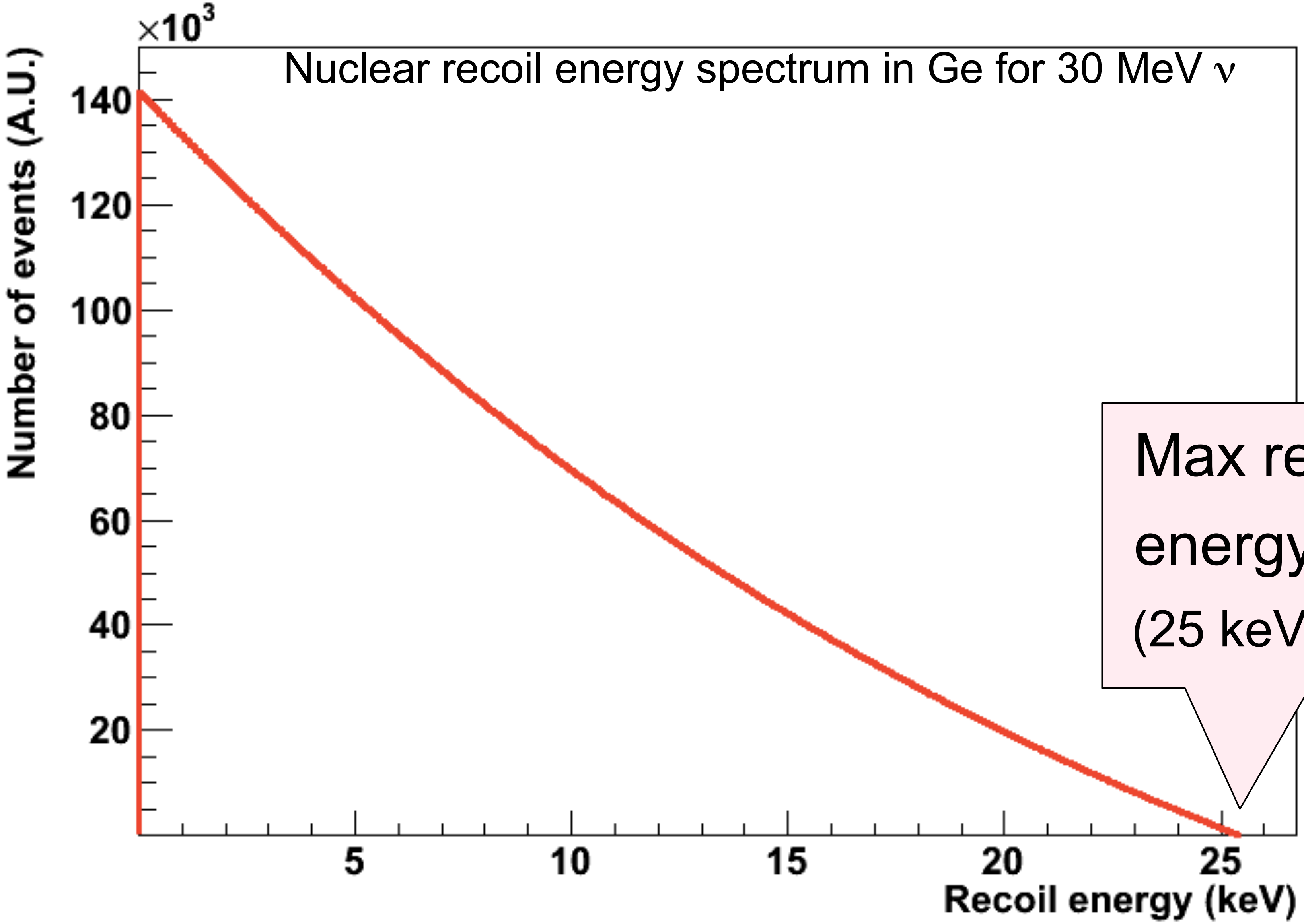
$$\Rightarrow \boxed{\frac{d\sigma}{dT} \propto N^2}$$





The cross-section is *large*

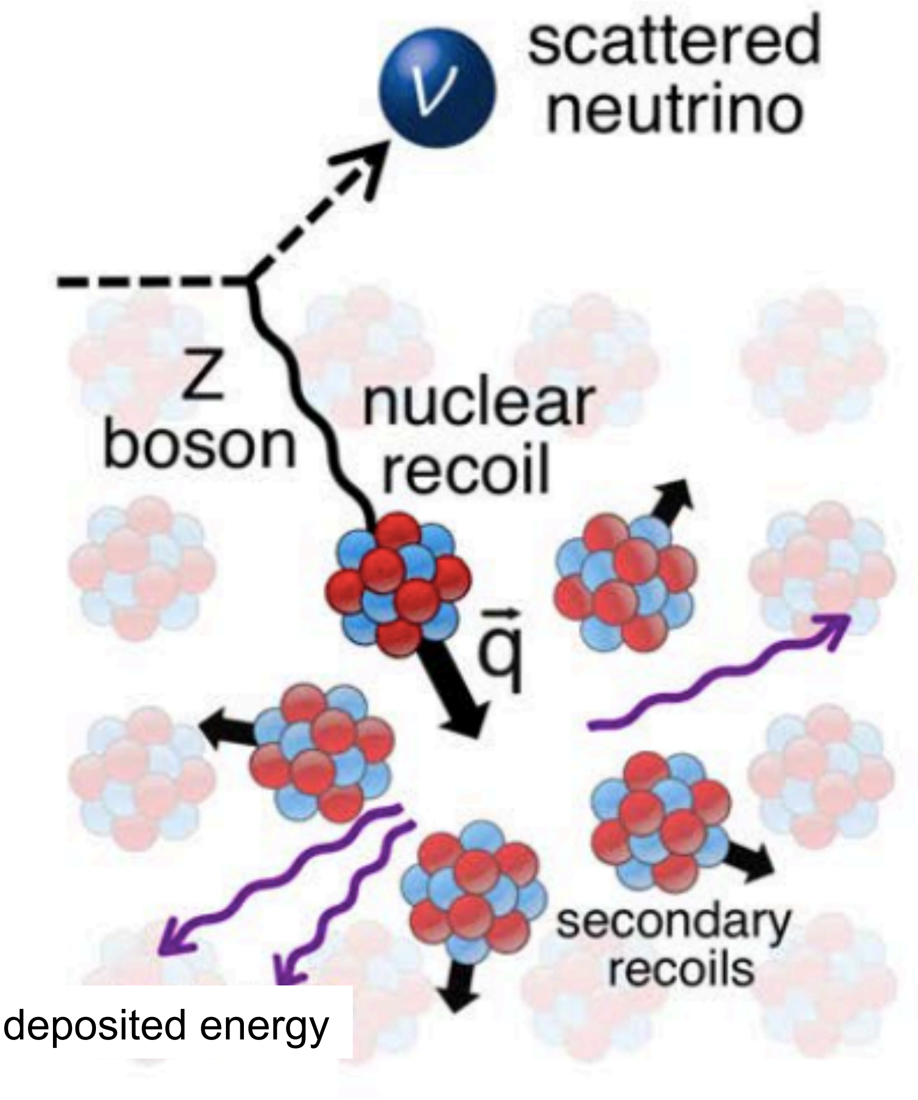
Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**



Max recoil energy is $2E_\nu^2/M$ (25 keV for Ge)

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

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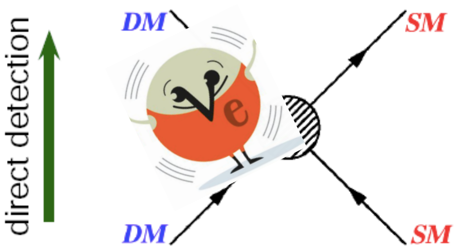
CEvNS: what's it good for?

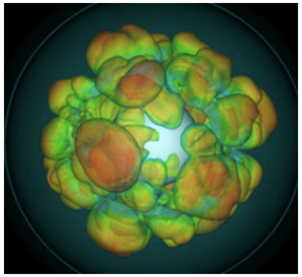
① So
② Many
③ Things

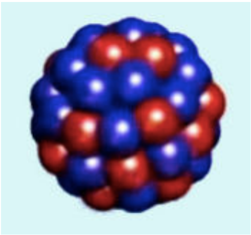
!

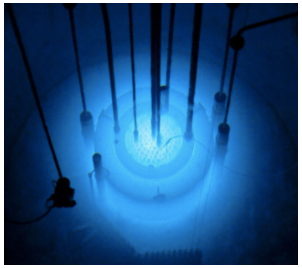
(not a complete list!)

- Dark matter direct-detection background
- Well-calculable cross-section in SM:
  - $\sin^2\theta_{Weff}$ at low Q
  - **Probe of BSM physics**
    - Non-standard interactions of neutrinos
    - New NC mediators
    - Neutrino magnetic moment
- New tool for sterile neutrino oscillations
- Astrophysical signals (solar & SN)
- Supernova processes
- Nuclear physics:
  - Neutron form factors
  - g_A quenching
- Possible applications (reactor monitoring)

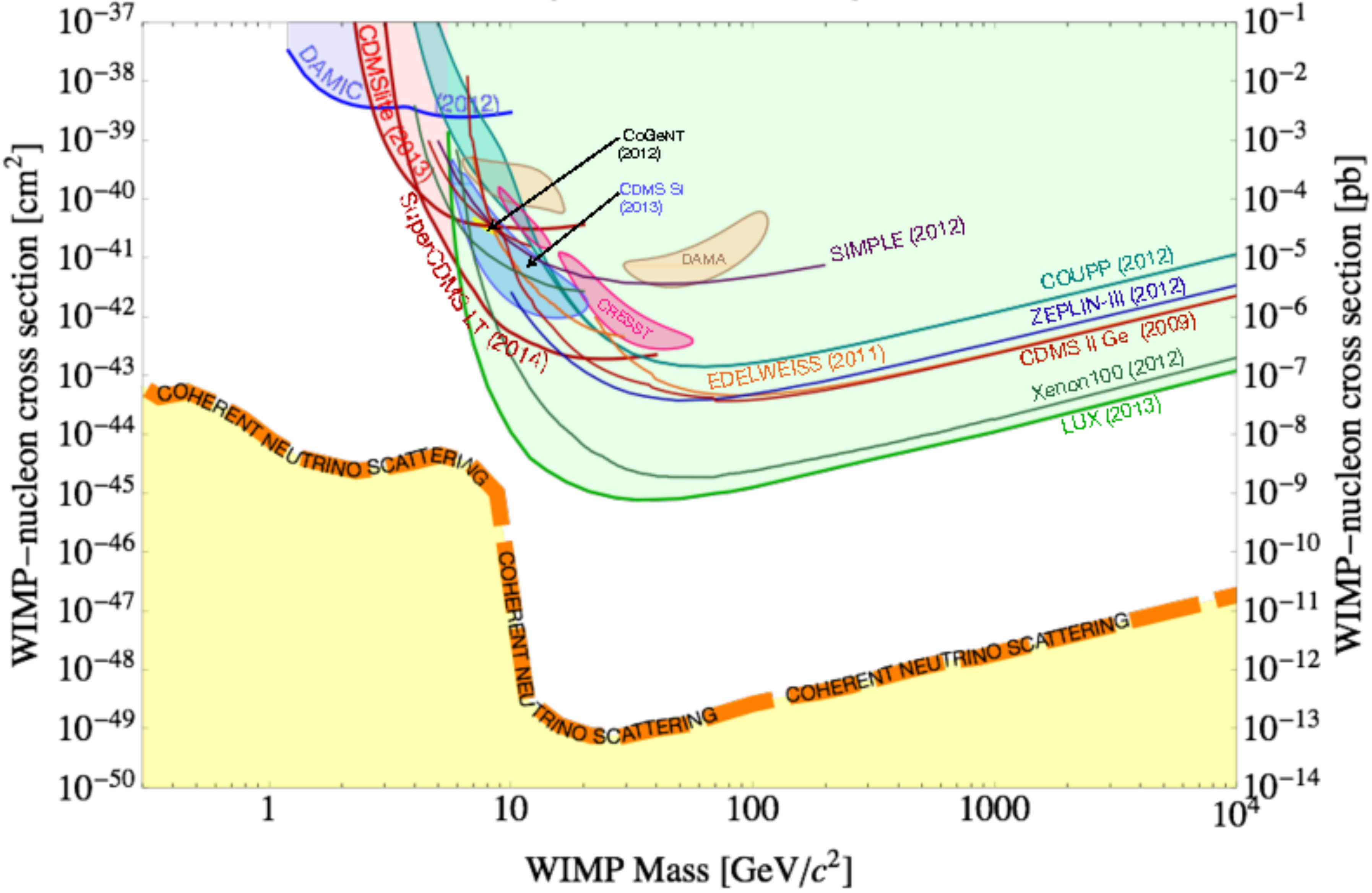








CEvNS from natural neutrinos creates ultimate background for direct DM search experiments

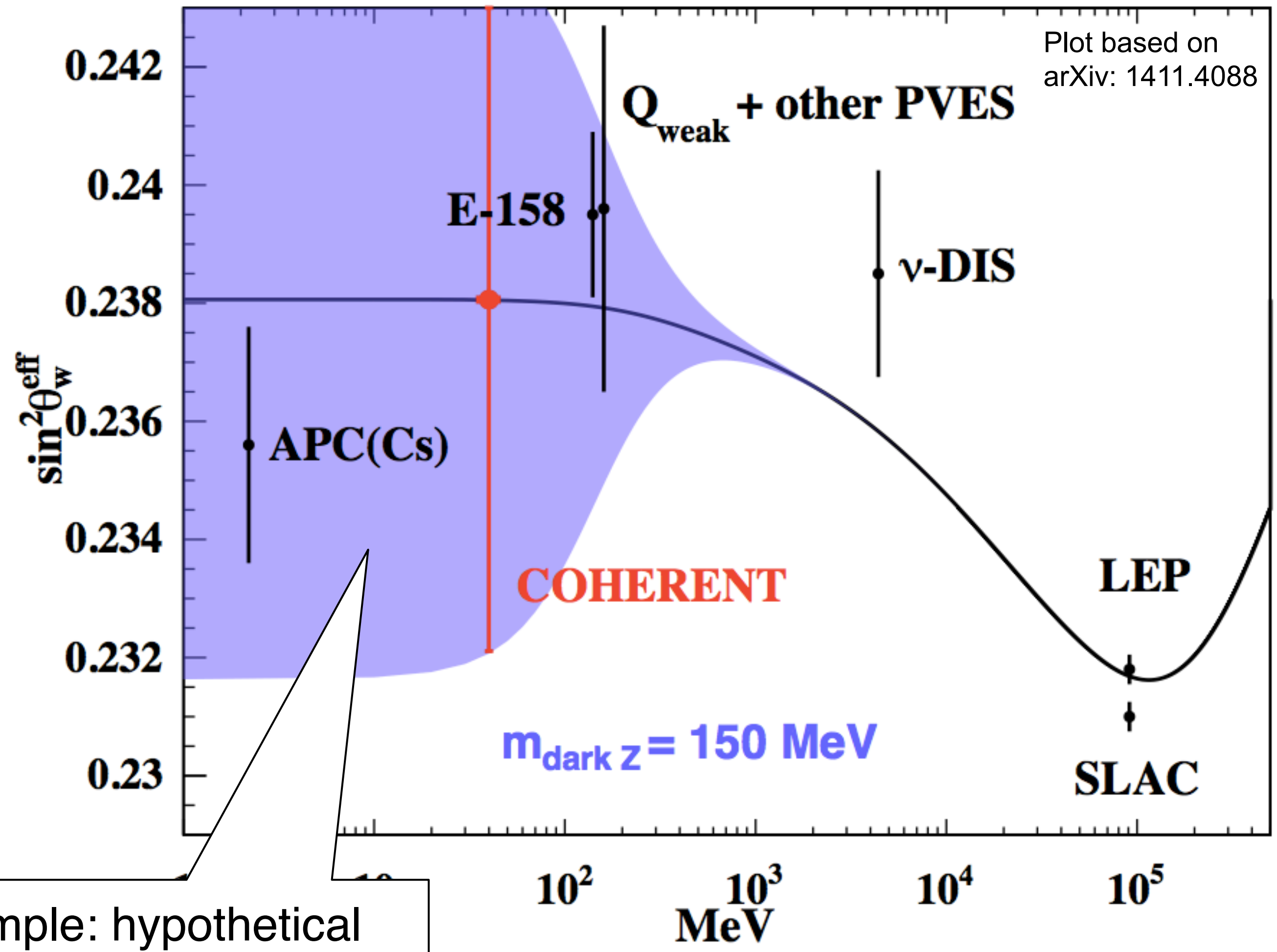


J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

Understand nature of background (& detector response, DM interaction)

Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ; **deviation probes new physics**

$$\sigma \sim \frac{G_f^2 E^2}{4\pi}\left(N - (1 - 4\sin^2\theta_W)Z\right)^2$$



Plot based on arXiv: 1411.4088

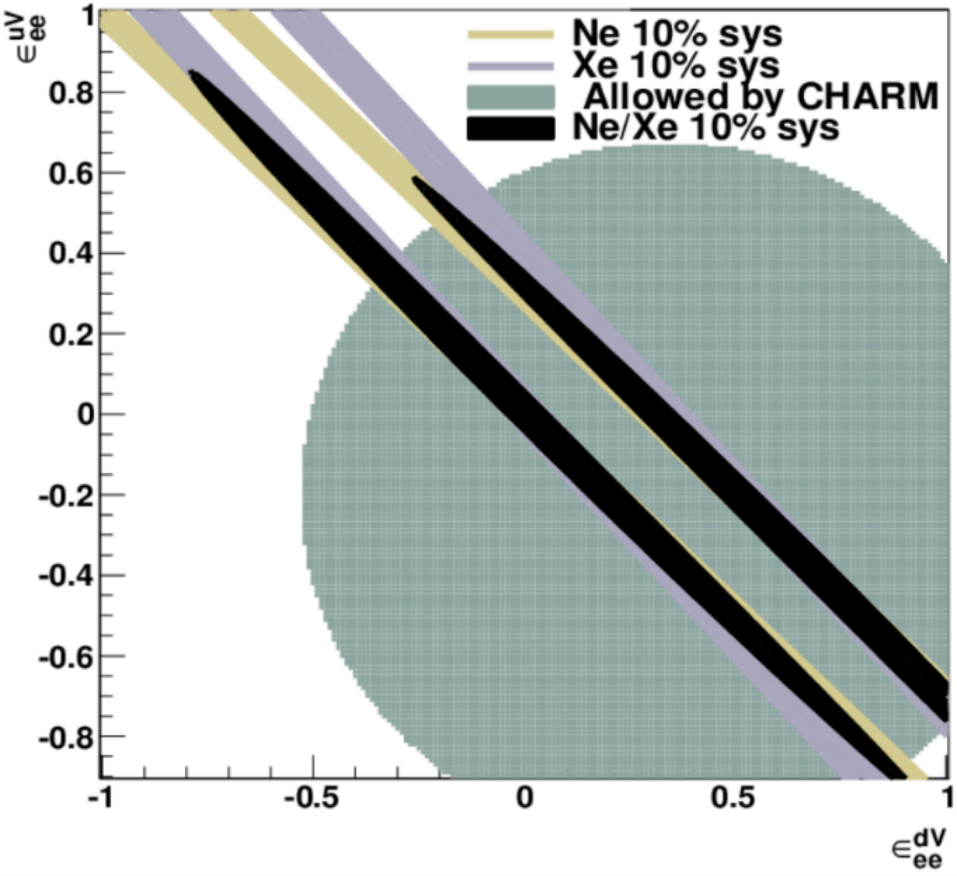
Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

CEvNS sensitivity is @ low Q;
need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$



J. Barranco et al., JHEP 0512 (2005), K. Scholberg, PRD73, 033005 (2006), 021

Can improve ~order of magnitude beyond CHARM limits with a first-generation experiment (for best sensitivity, want ***multiple targets***)

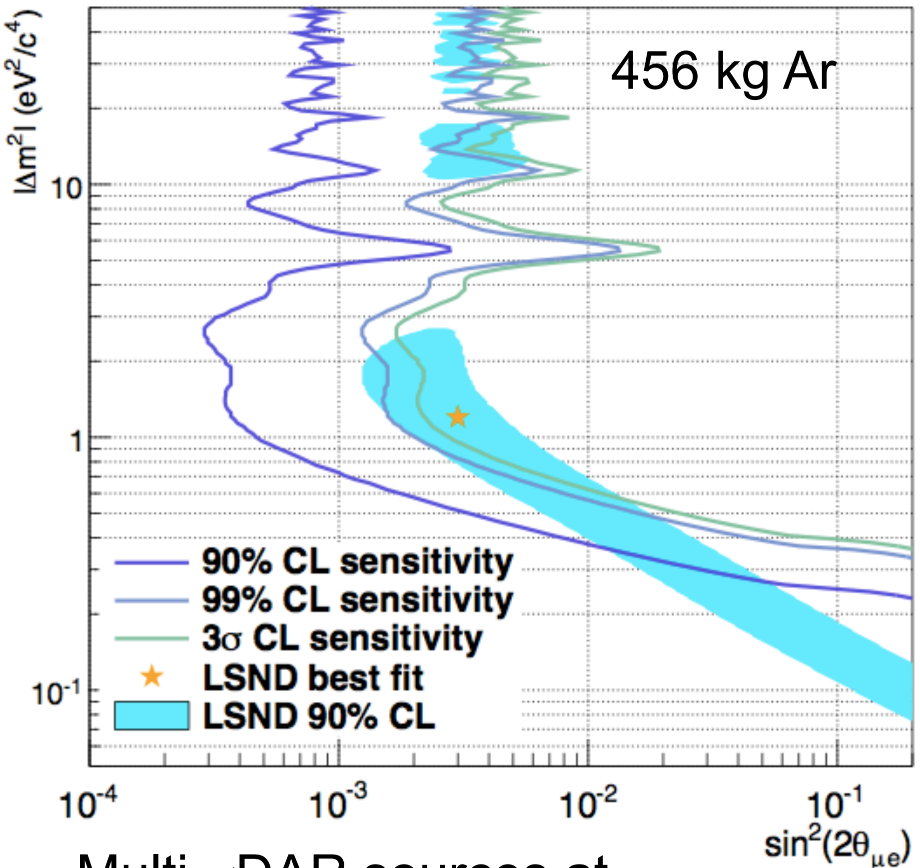
More studies: see https://sites.duke.edu/nueclipse/files/2017/04/Dent-James-NuEclipse-August-2017.pdf

Oscillations to sterile neutrinos w/CEvNS

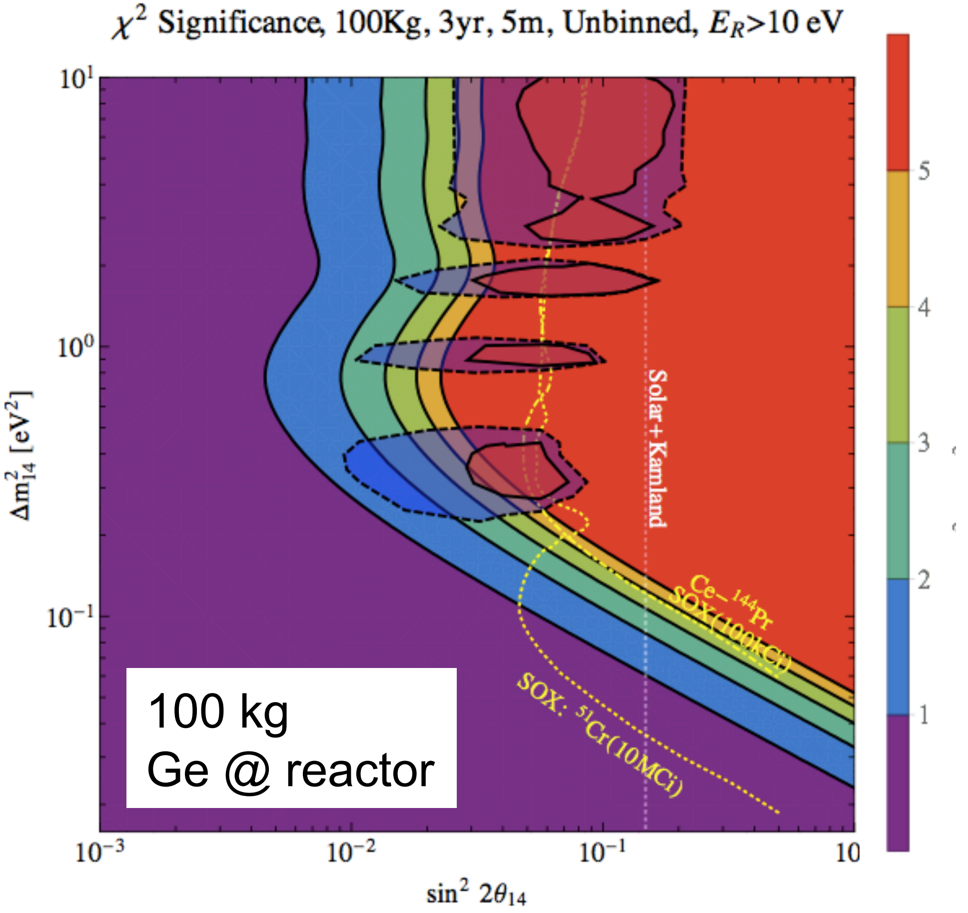
(NC is flavor-blind): a potential new tool;

look for deficit and spectral distortion vs L,E

Examples:



Multi-πDAR sources at different baselines (20 & 40 m)



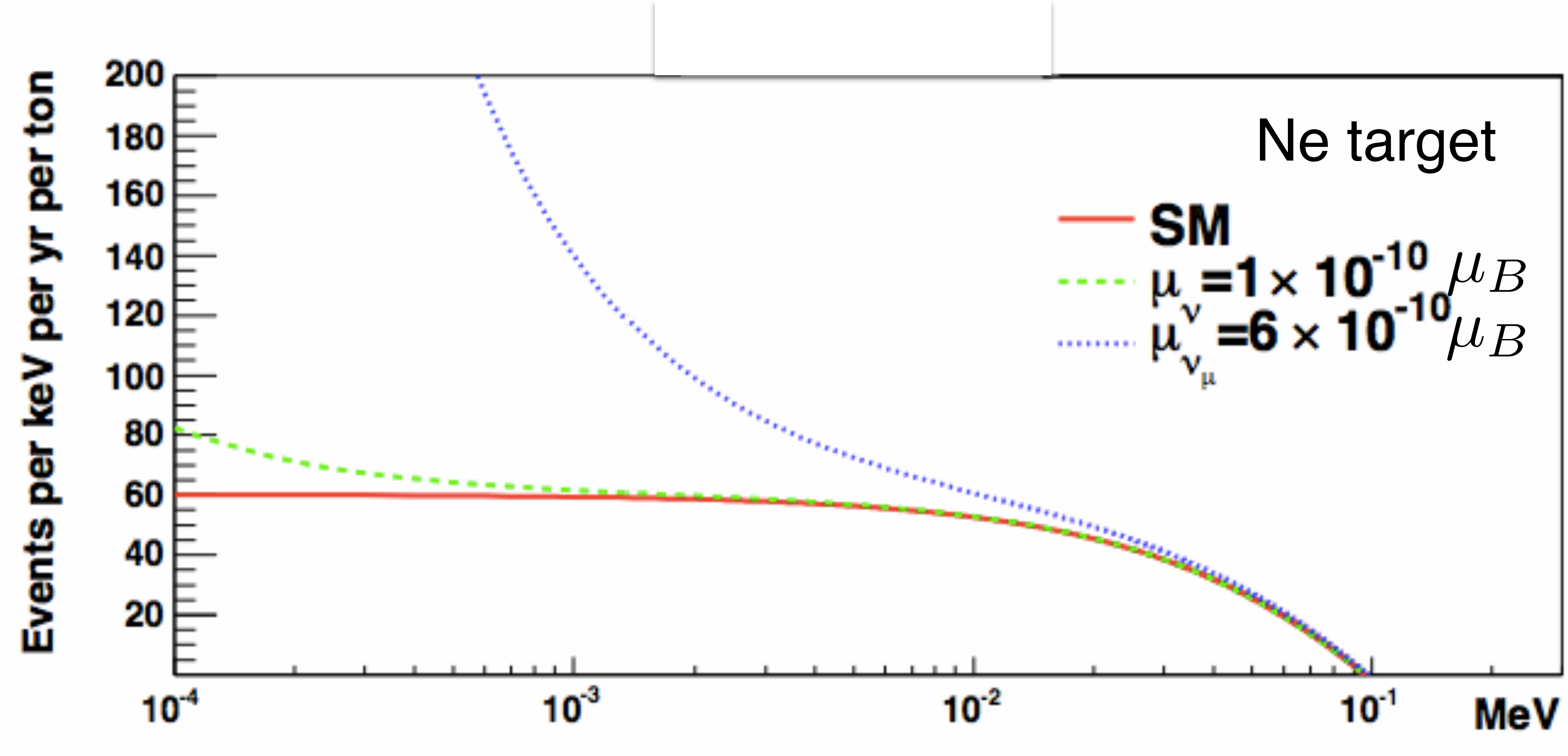
B. Dutta et al, arXiv:1511.02834

Anderson et al., PRD86 (2012) 013004, arXiv:1201.3805

Neutrino magnetic moment

Signature is **distortion at low recoil energy E**

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T}+\frac{T}{4E_\nu^2}\right)$$



➔requires low energy threshold

See also Kosmas et al., arXiv:1505.03202

Nuclear physics with CEvNS

If systematics can be reduced to ~ few % level,
we can start to explore nuclear form factors

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105

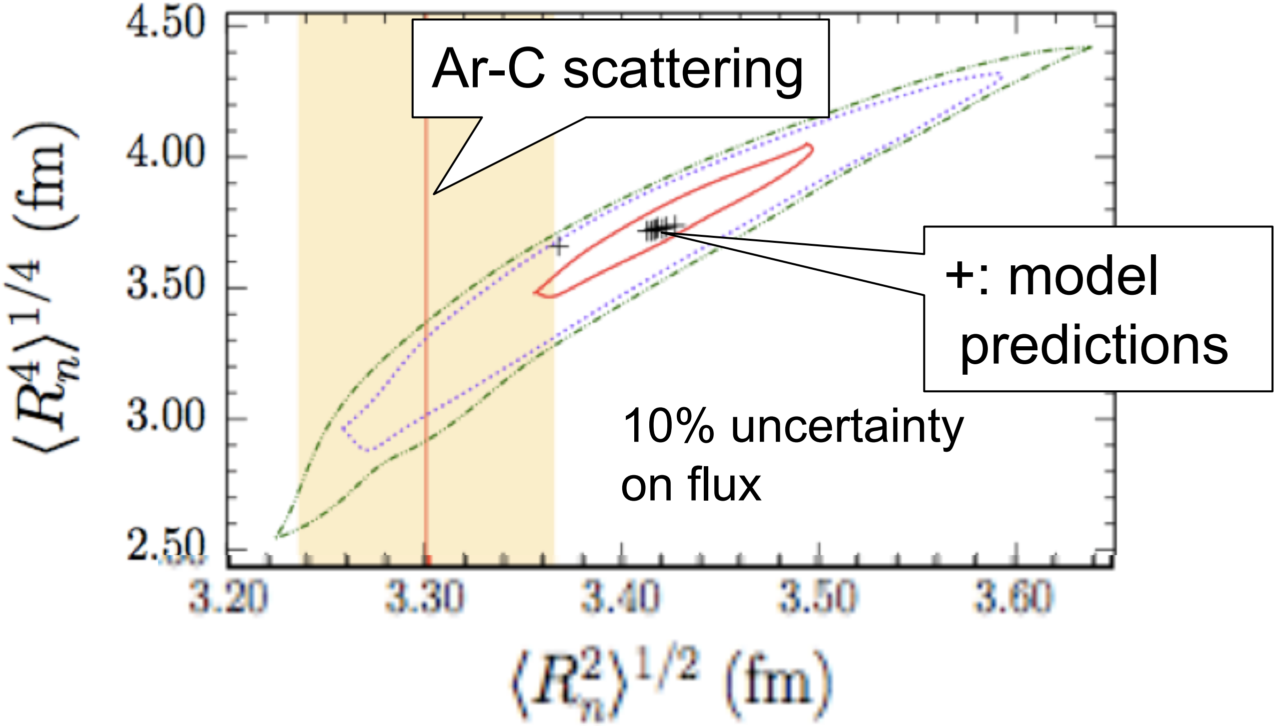
K. Patton et al., PRC86 (2012) 024612

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2-\frac{MT}{E_\nu^2}\right)$$

Form factor: encodes information about nuclear (primarily neutron) distributions

Fit recoil ***spectral shape*** to determine the $F^2(Q)$ moments
(requires very good energy resolution,good systematics control)

Example:
tonne-scale
experiment
at πDAR source



Ar-C scattering

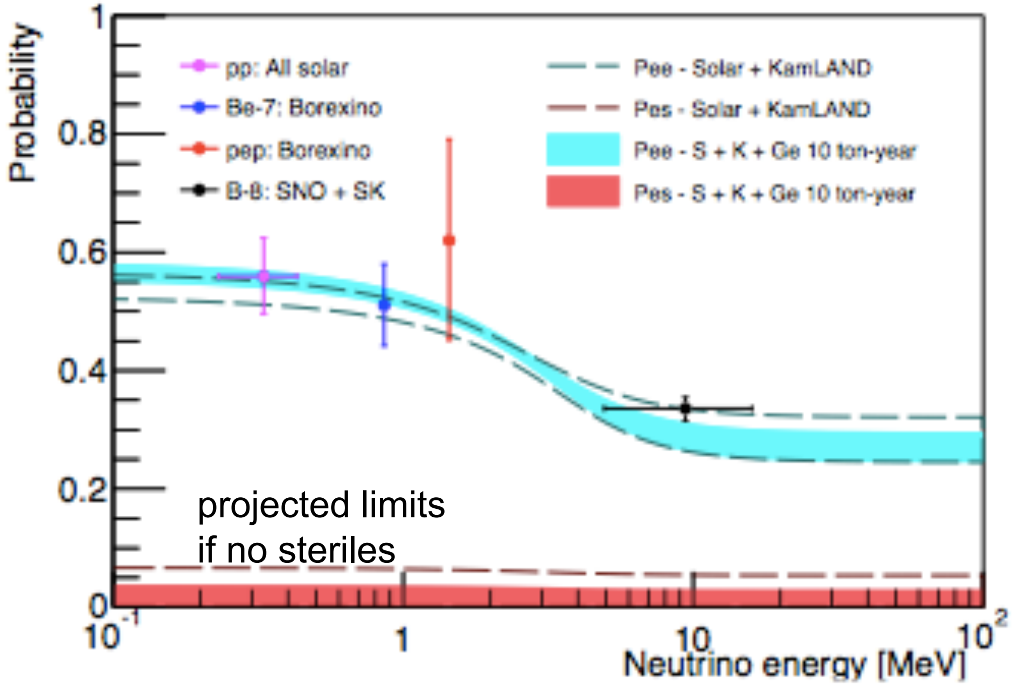
+: model predictions

10% uncertainty on flux

Also note: tonne-scale low-threshold underground can look at **astrophysical neutrinos**

Solar neutrinos

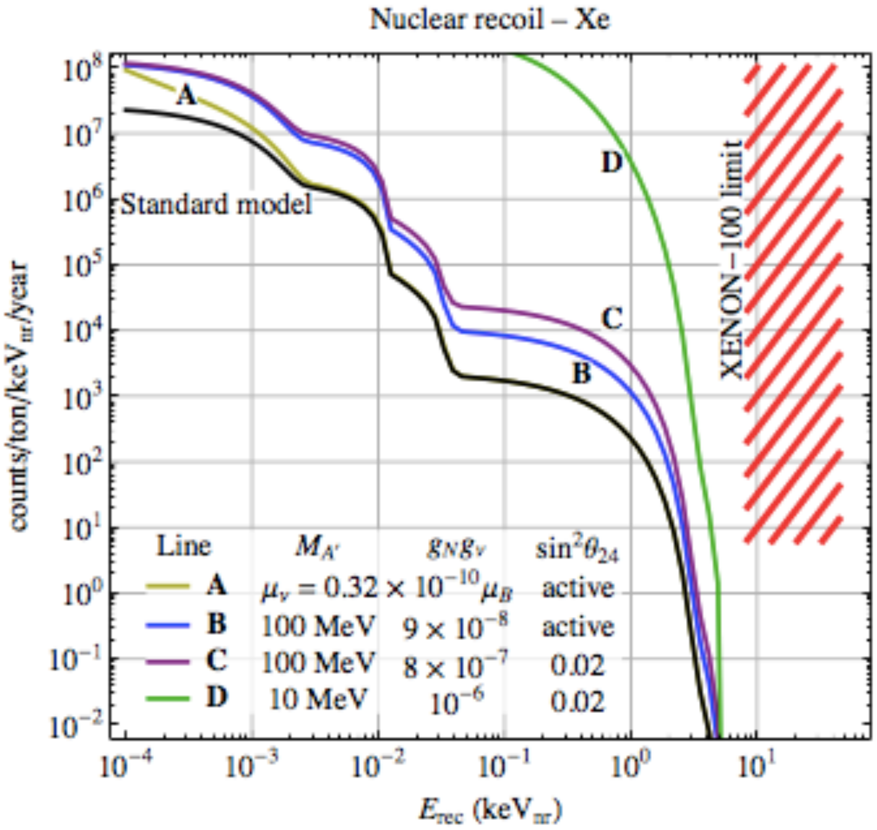
J. Billard et al.,
Phys.Rev. D91 (2015) no.9, 095023



projected limits
if no steriles

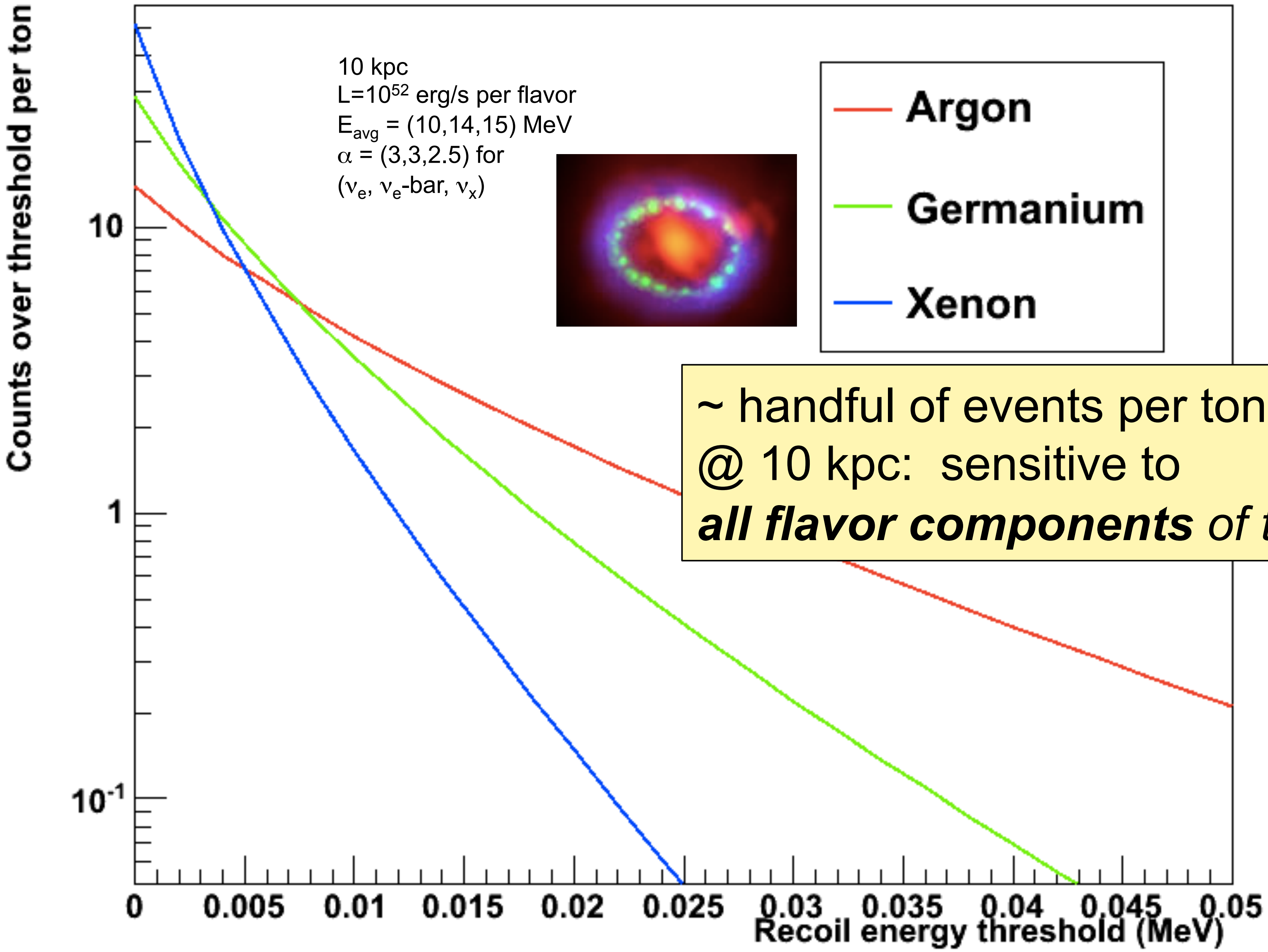
Rule out sterile oscillations
using CEvNS (NC),
10 ton-year of Ge

R. Harnik et al., JCAP 1207 (2012) 026



Effect of new physics on
CEvNS recoil spectrum

Supernova neutrinos in tonne-scale DM detectors



10 kpc
L=10^{52} erg/s per flavor
E_{avg} = (10,14,15) MeV
α = (3,3,2.5) for
(ν_e, ν_e-bar, ν_x)

~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components *of the flux*

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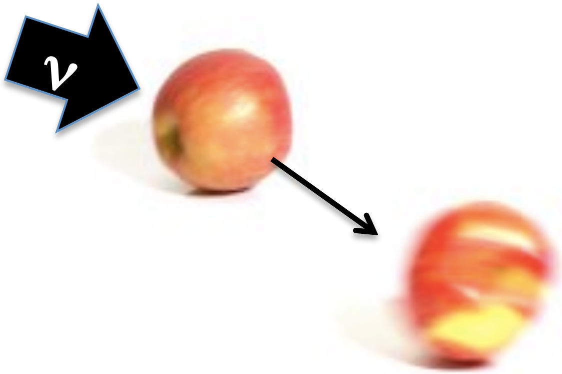
How to detect CEvNS?



You need a neutrino source
and a detector

What do you want for your ν source?

✓ High flux

✓ Well understood spectrum

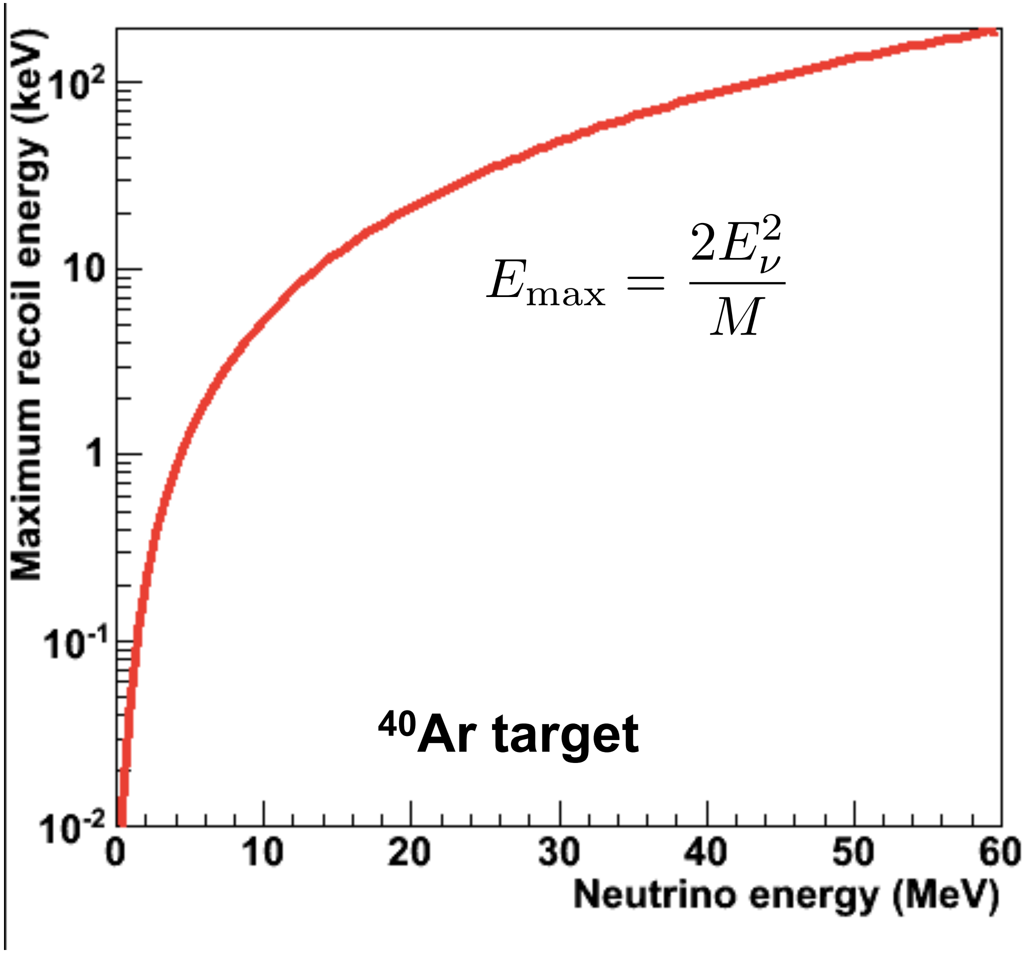
✓ Multiple flavors (physics sensitivity)

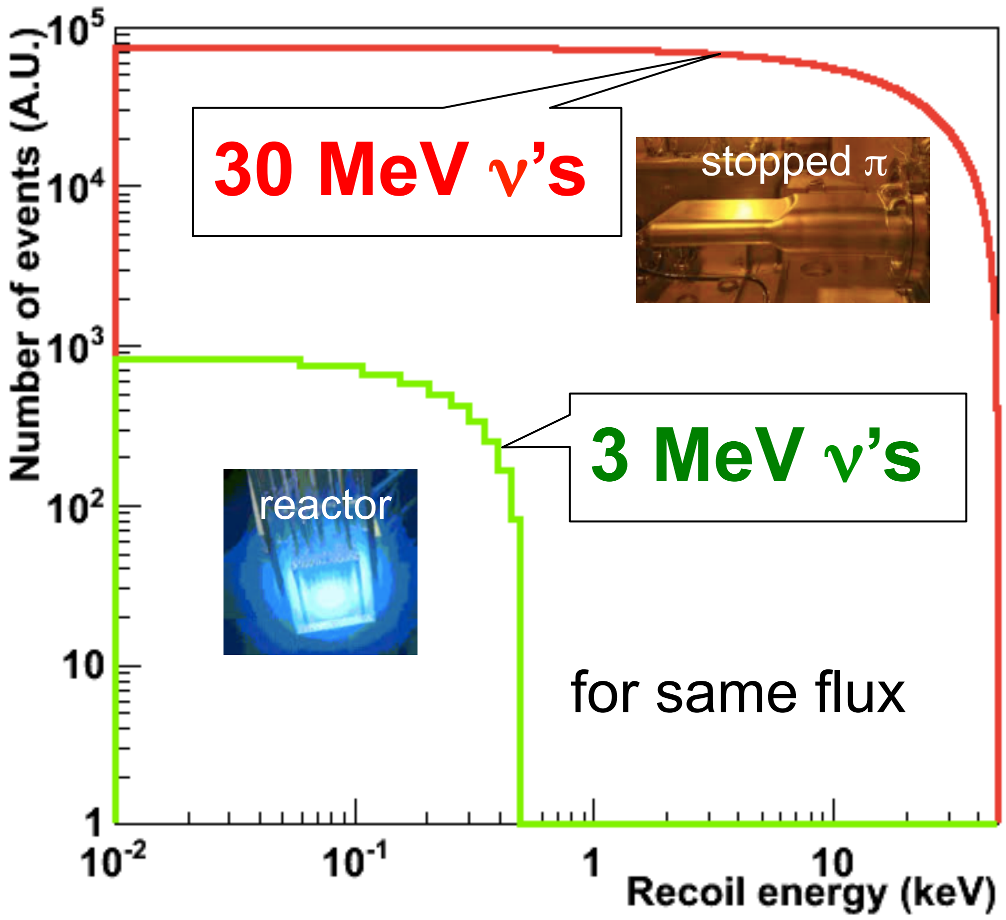
✓ Pulsed source if possible, for background rejection

✓ Ability to get close

✓ Practical things: access, control, ...

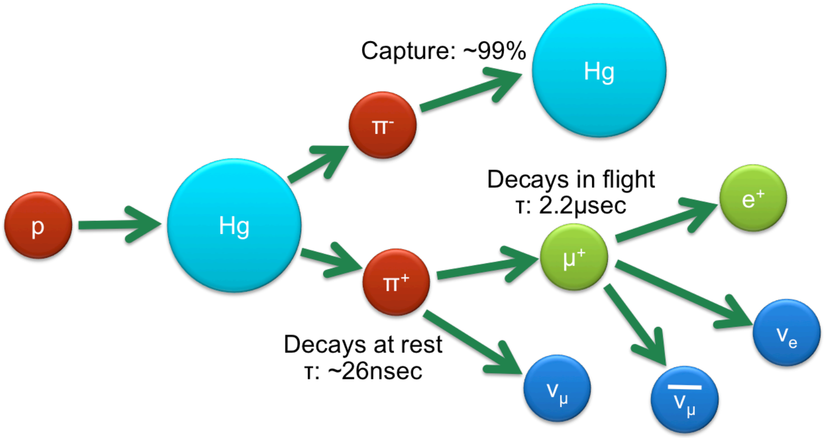
Both **cross-section and maximum recoil energy increase with neutrino energy**:

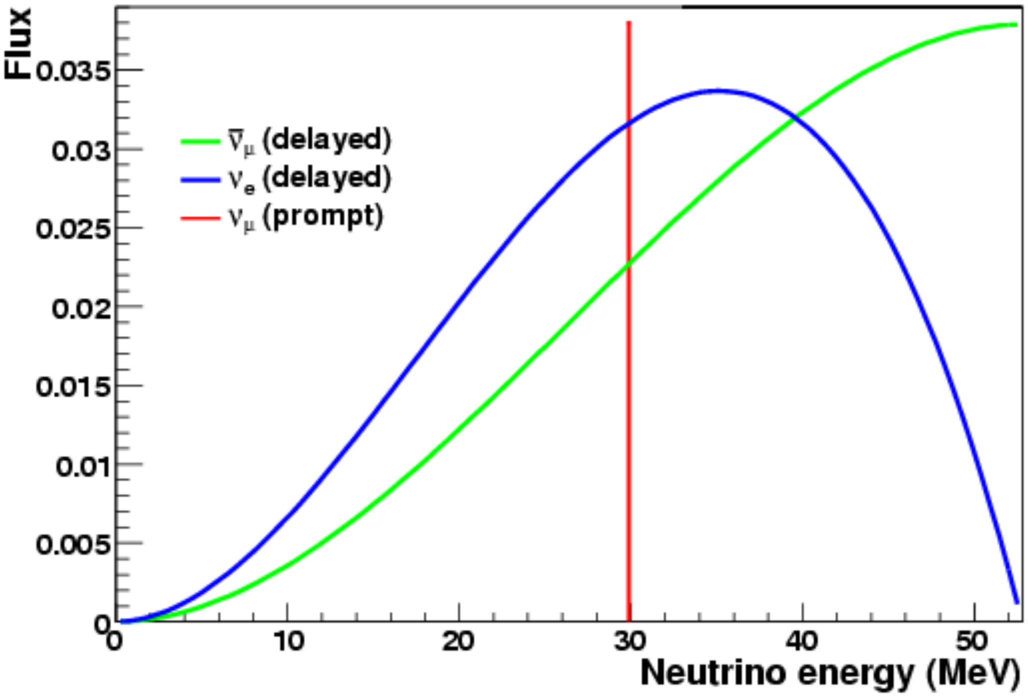




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





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

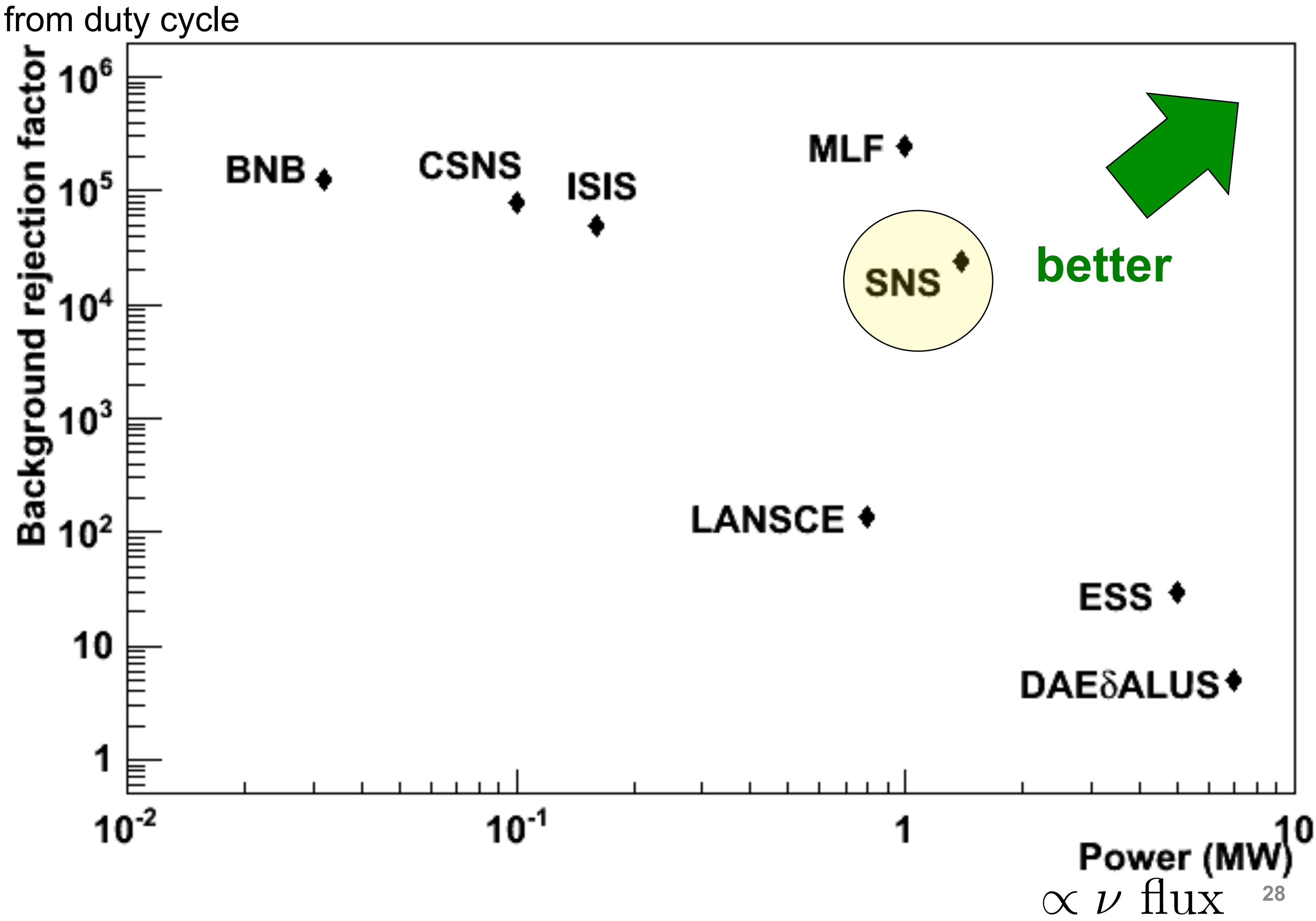
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

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

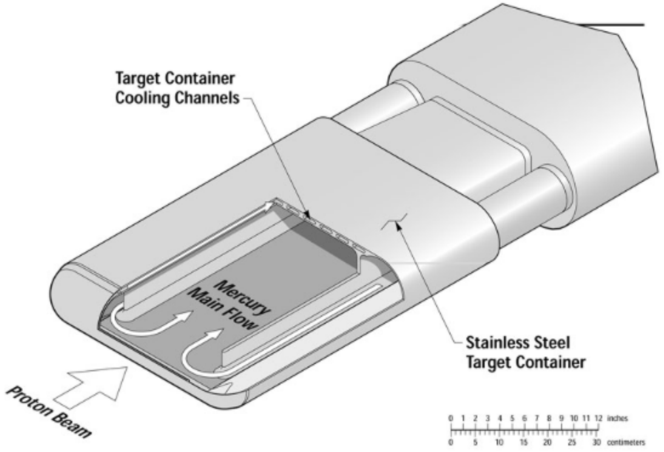
3-body decay: range of energies
between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Comparison of pion decay-at-rest ν sources



Spallation Neutron Source

Oak Ridge National Laboratory, TN



Proton beam energy: 0.9-1.3 GeV

Total power: 0.9-1.4 MW

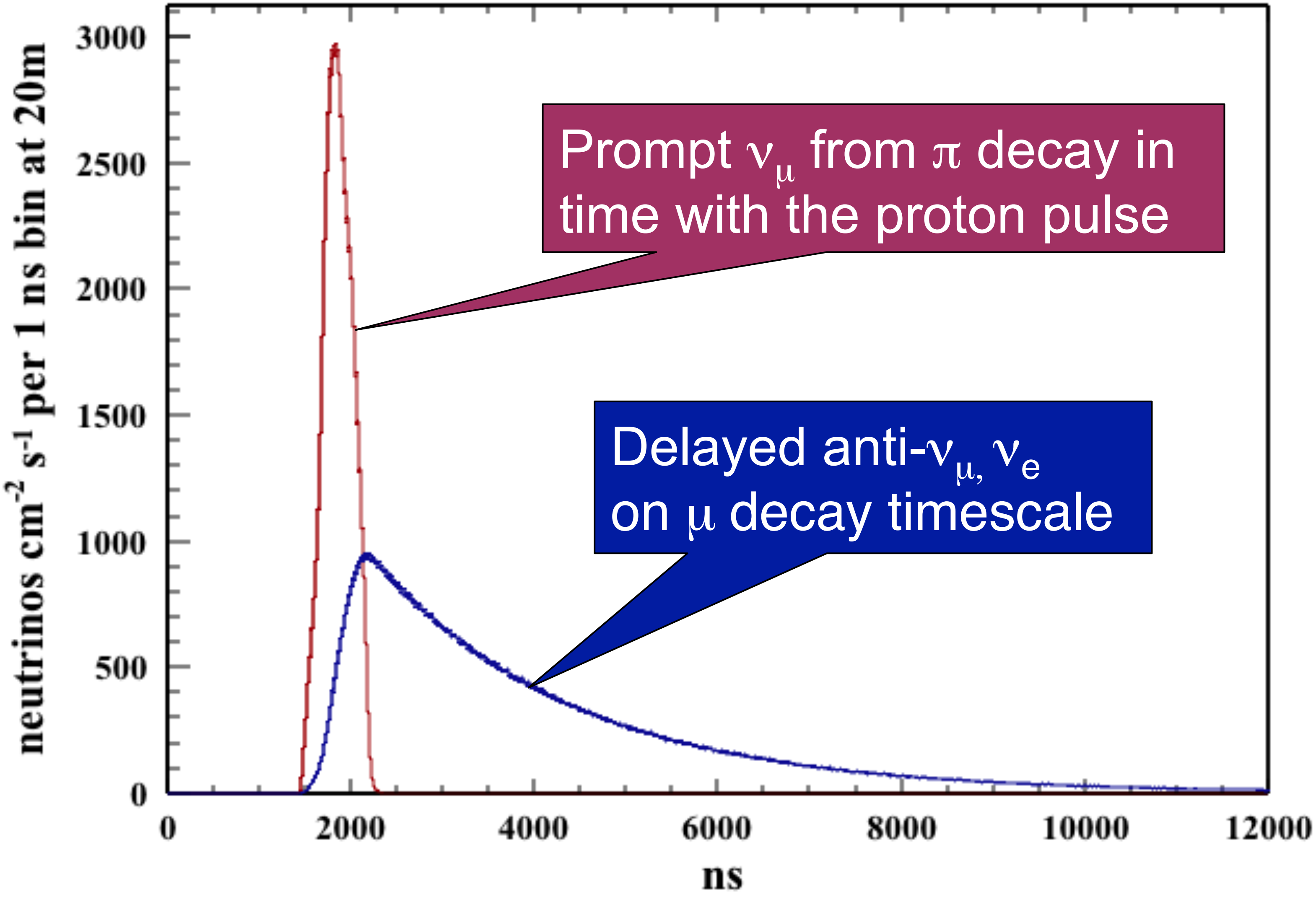
Pulse duration: 380 ns FWHM

Repetition rate: 60 Hz

Liquid mercury target

Time structure of the SNS source

60 Hz *pulsed* source



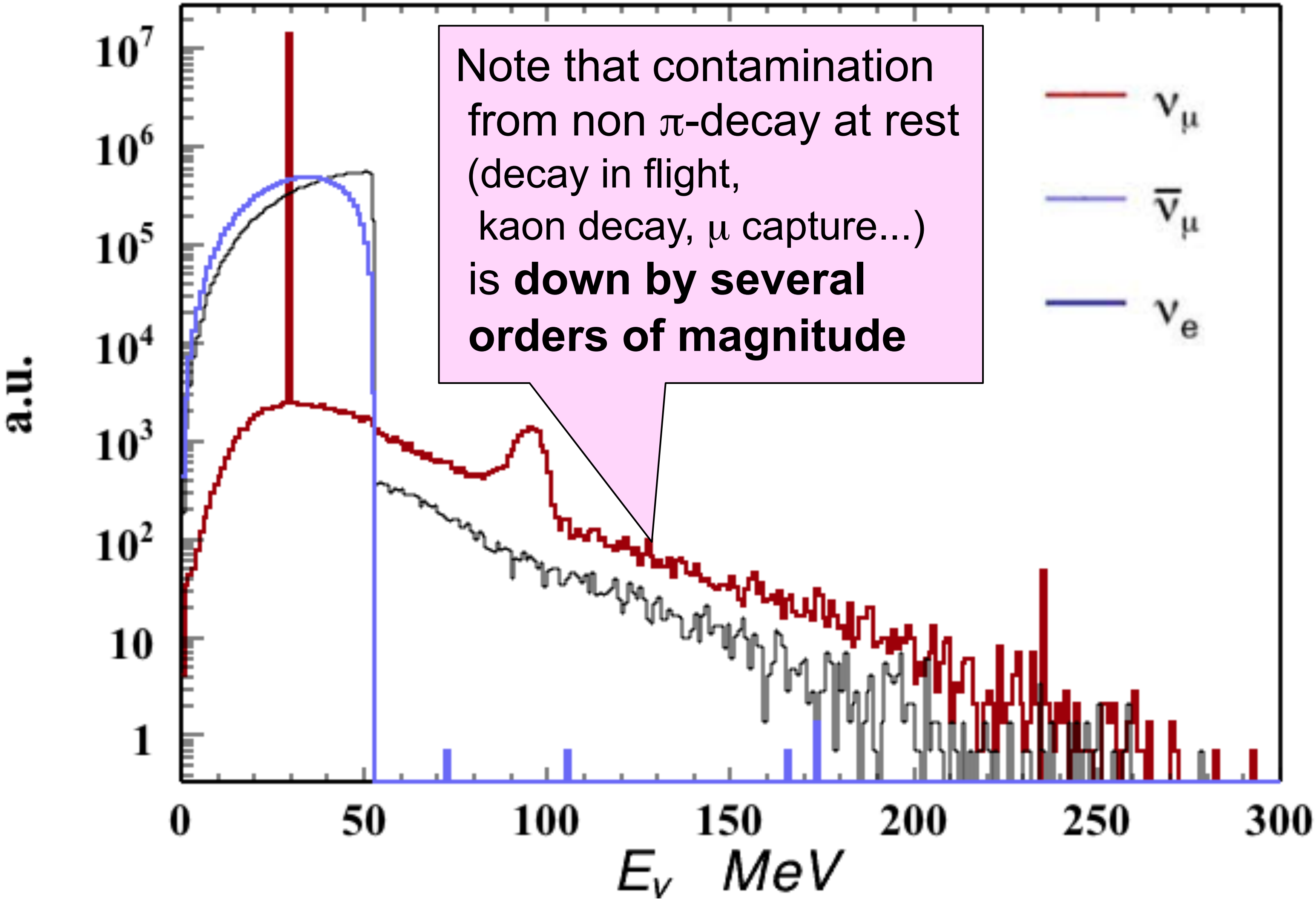
Prompt ν_μ from π decay in time with the proton pulse

Delayed anti-ν_μ, ν_e on μ decay timescale

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

The SNS has **large, extremely clean** DAR ν flux

0.08 neutrinos per flavor per proton on target

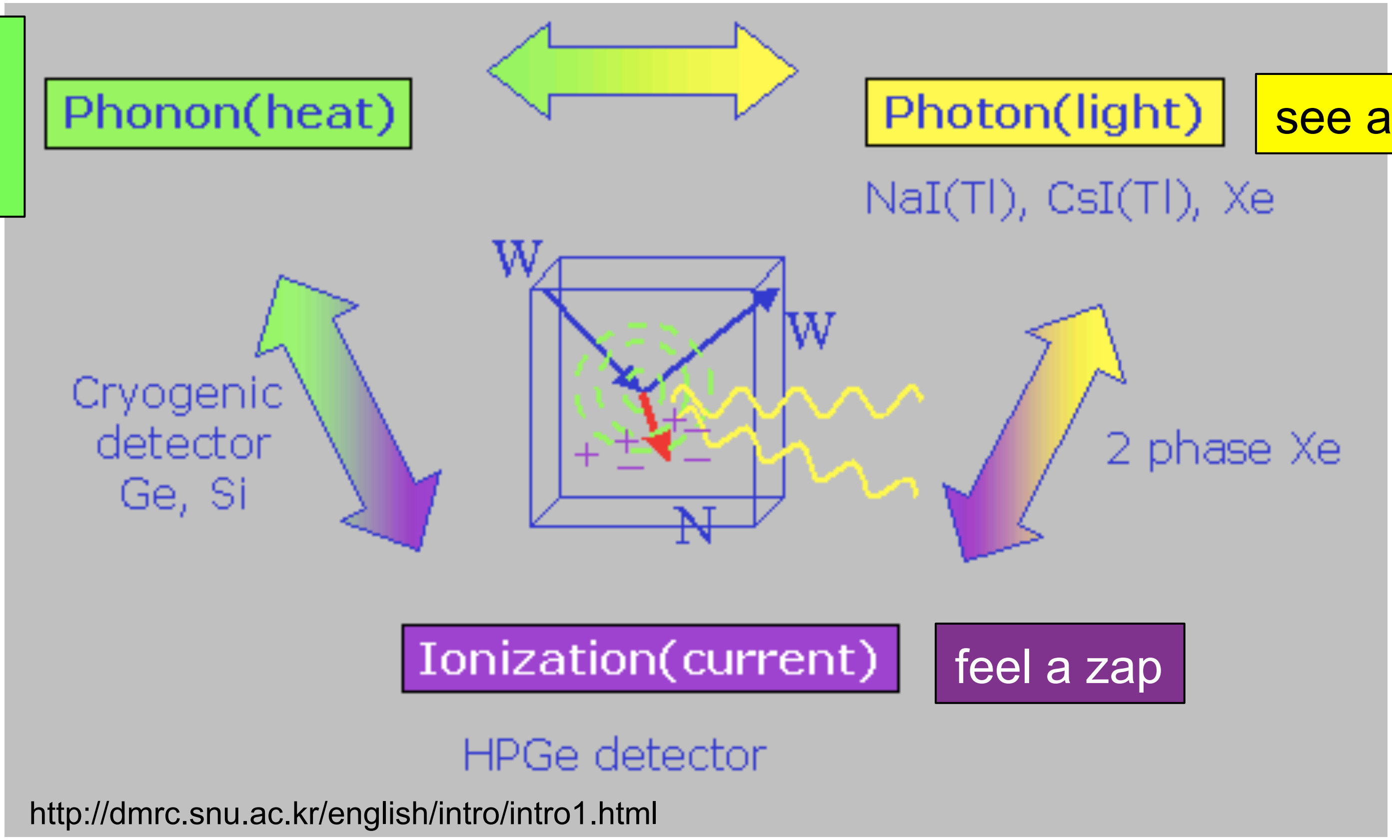


Note that contamination
from non π-decay at rest
(decay in flight,
kaon decay, μ capture...)
is **down by several orders of magnitude**

SNS flux (1.4 MW):
430 x 10^5 ν/cm²/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



feel a warm pulse

Phonon(heat)

Photon(light)

see a flash

NaI(Tl), CsI(Tl), Xe

Cryogenic detector Ge, Si

2 phase Xe

Ionization(current)

feel a zap

HPGe detector

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

- low background (although for beam, requirements less stringent than for WIMPs)
- low energy threshold
- energy resolution
- fast timing
- nuclear recoil discrimination
- well-known (and large if possible) **quenching factor** (fraction of observable energy, keVr = QF* keVee)

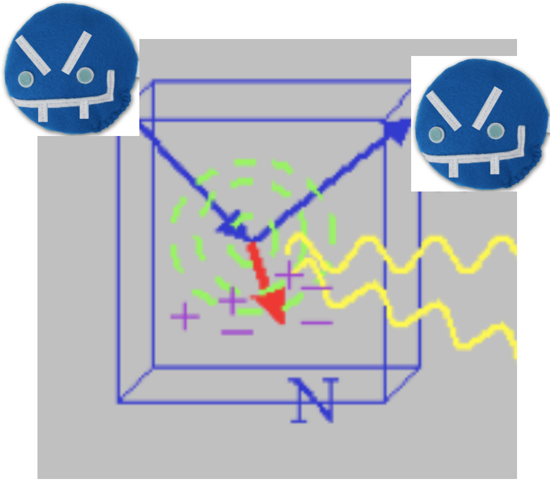
Backgrounds

Usual suspects:

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

Neutrons are especially not your friends*

(although they sometimes give you a hand with calibration)



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

*Thanks to Robert Cooper for the "mean neutron"

A “friendly fire” in-time background: **Neutrino Induced Neutrons (NINs)**

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Bi}^* + e^- \quad \mathrm{CC}$$

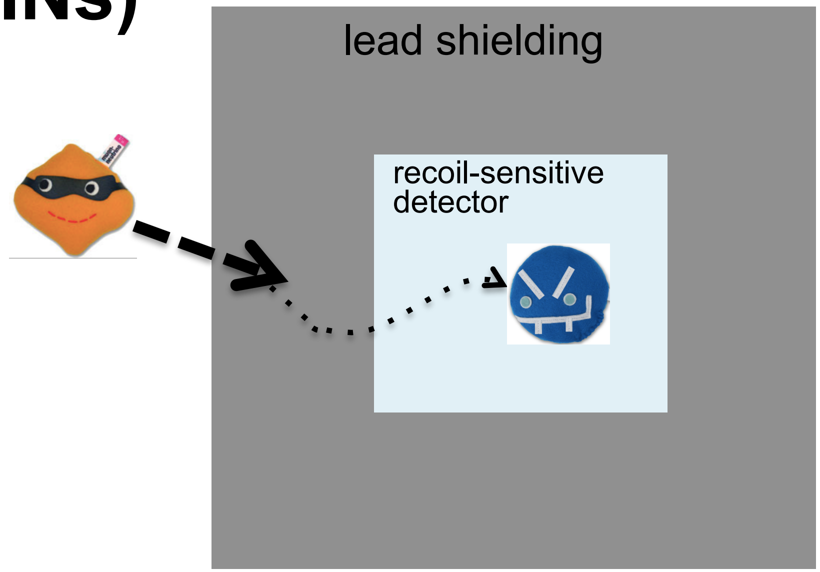
$$\searrow$$

1n, 2n emission

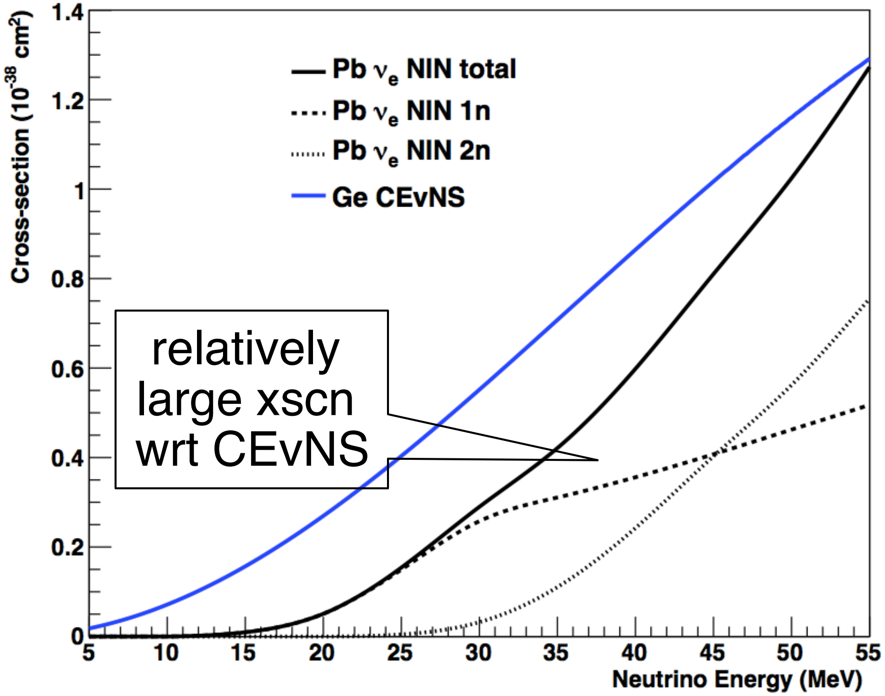
$$\nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb}^* + \nu_x \quad \mathrm{NC}$$

$$\searrow$$

1n, 2n, γ emission



- potentially non-negligible background from shielding
- requires careful shielding design
- large uncertainties (factor of few) in xscn calculation
- [Also: a signal in itself, e.g, HALO SN detector]



relatively large xscn wrt CEvNS

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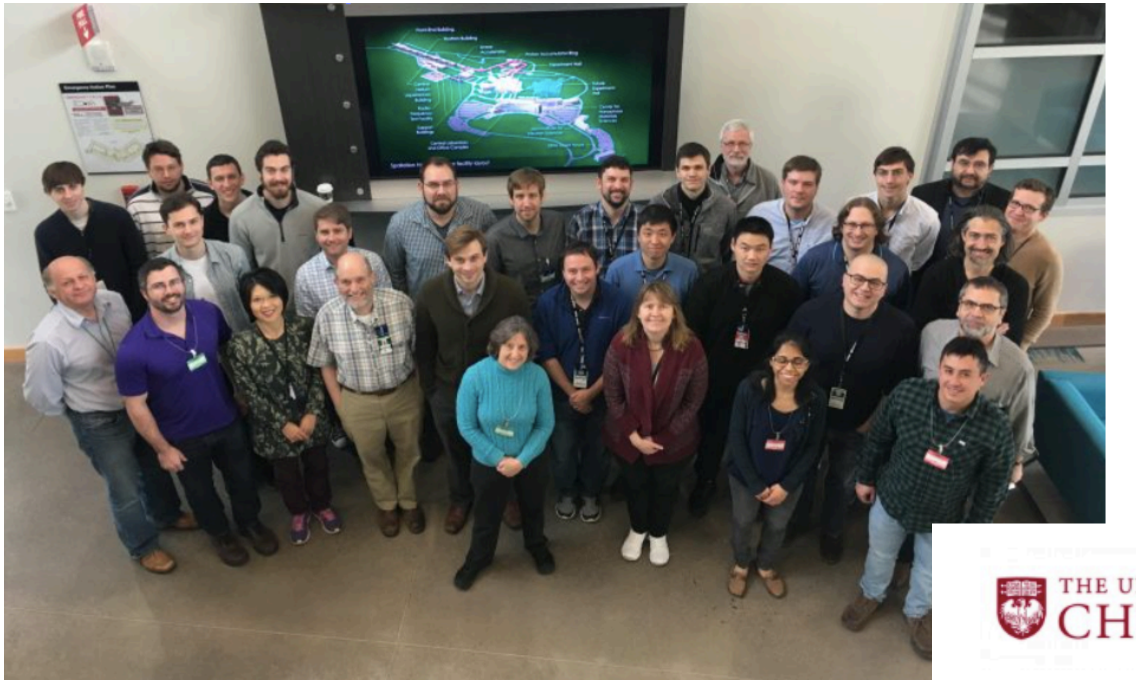
The COHERENT collaboration

http://sites.duke.edu/coherent



COHERENT

SNS
SPALLATION NEUTRON SOURCE

~80 members,
19 institutions
4 countries

arXiv:1509.08702

U.S. DEPARTMENT OF ENERGY
Office of Science

NSF

KICP

NNSA
National Nuclear Security Administration

CNEC

THE UNIVERSITY OF CHICAGO

Duke UNIVERSITY

UF UNIVERSITY of FLORIDA

KAIST

Laurentian University
Université Laurentienne

Los Alamos
NATIONAL LABORATORY
EST. 1943

BERKELEY LAB

MEPhI

NORTH CAROLINA CENTRAL UNIVERSITY

NC STATE UNIVERSITY

NM STATE UNIVERSITY

OAK RIDGE
National Laboratory

Carnegie Mellon University

Sandia National Laboratories

THE UNIVERSITY of TENNESSEE UT
KNOXVILLE

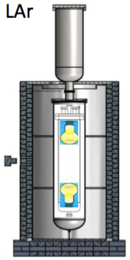
TUNL

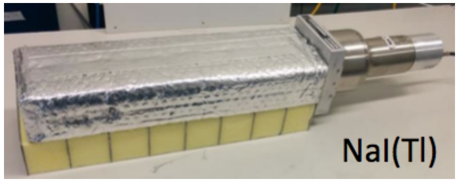
W
UNIVERSITY of WASHINGTON

COHERENT CEvNS Detectors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)
CsI[Na]	Scintillating Crystal	14.6	19.3	6.5
Ge	HPGe PPC	10	22	5
LAr	Single-phase	22	29	20
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13

Multiple detectors for N^2 dependence of the cross section

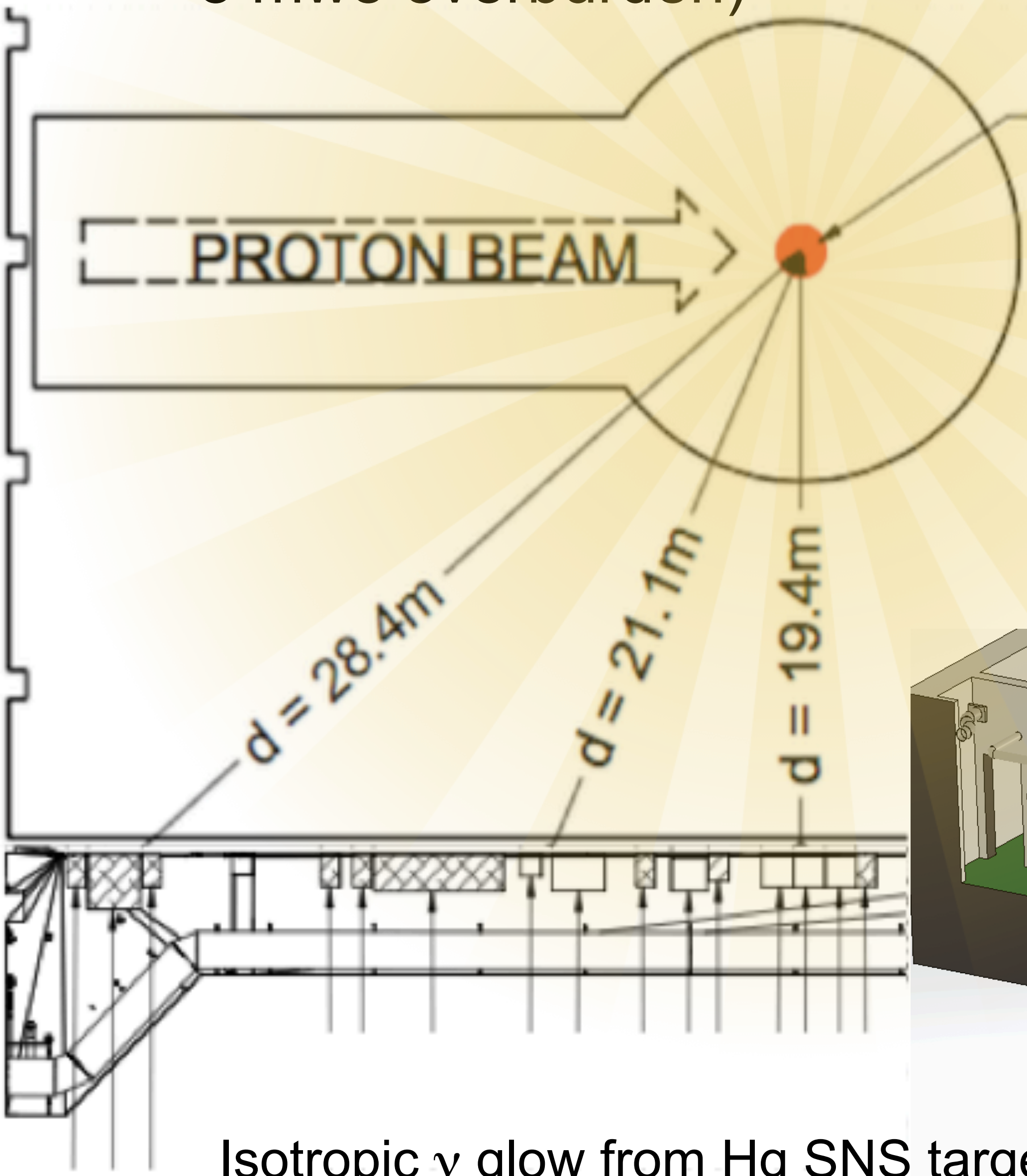


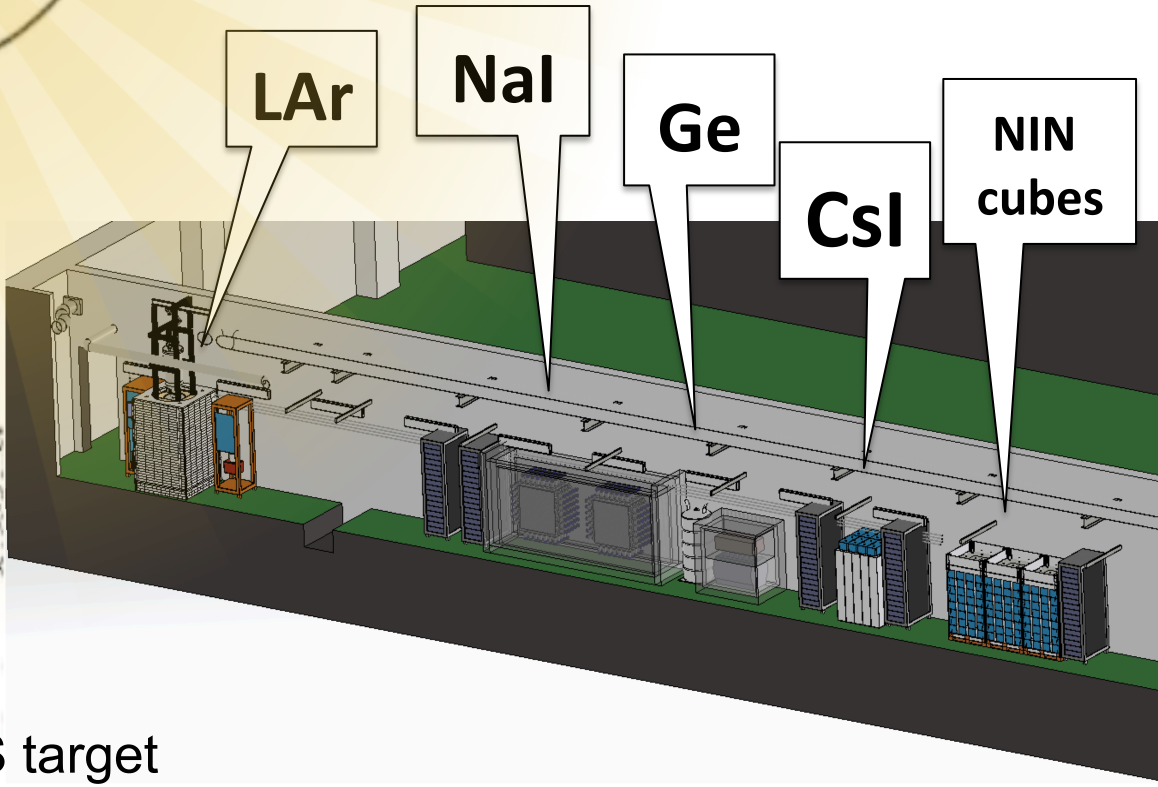


Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

View looking
down “Neutrino Alley”



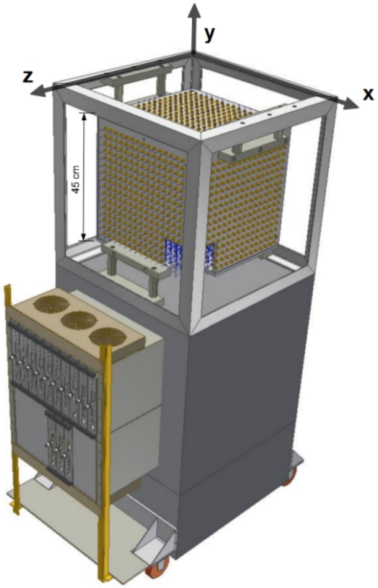


Isotropic ν glow from Hg SNS target

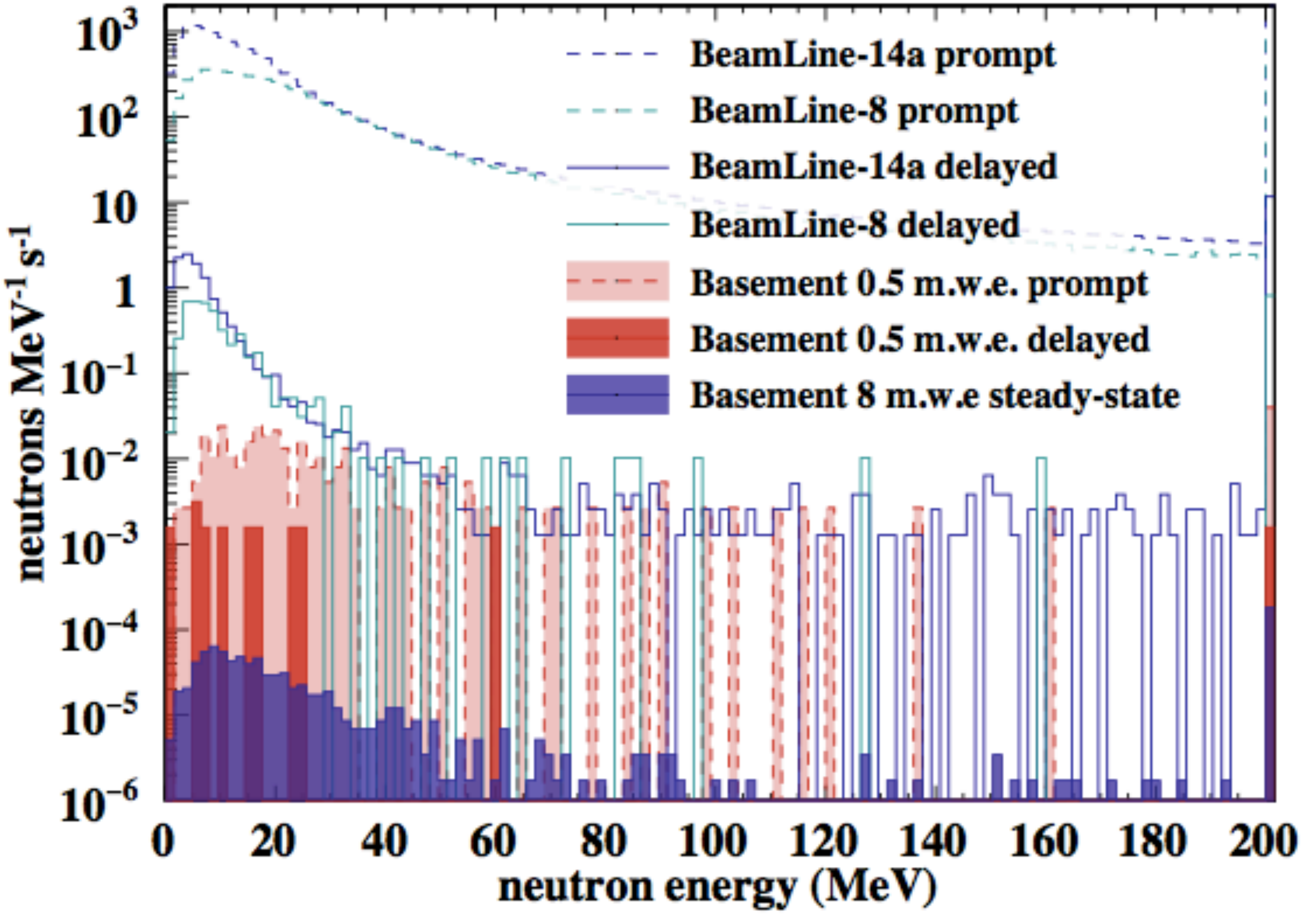
Neutron Backgrounds

Several background measurement campaigns have shown that Neutrino Alley in the basement is neutron-quiet

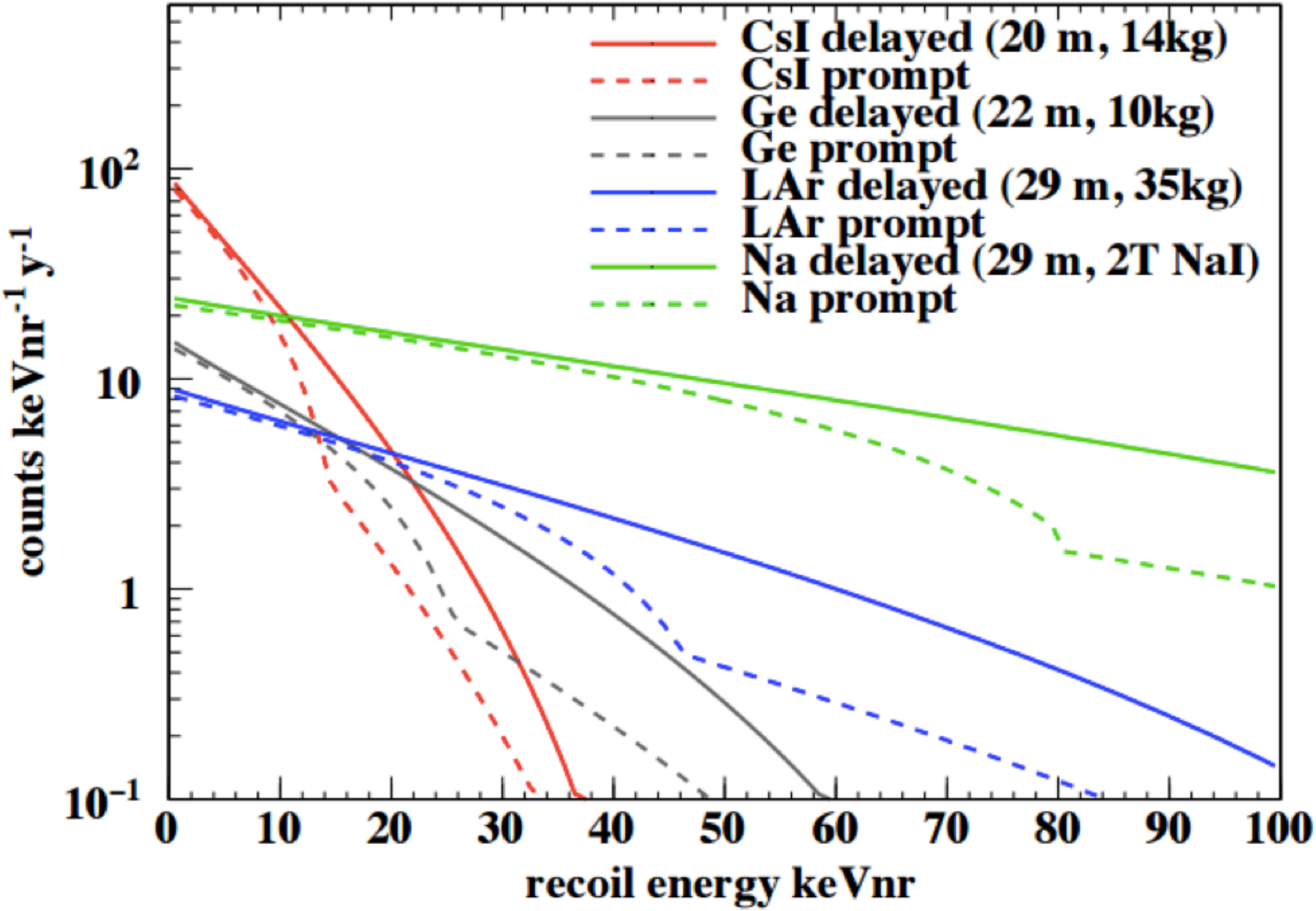
SciBath



Sandia scatter cam



Expected recoil energy distribution



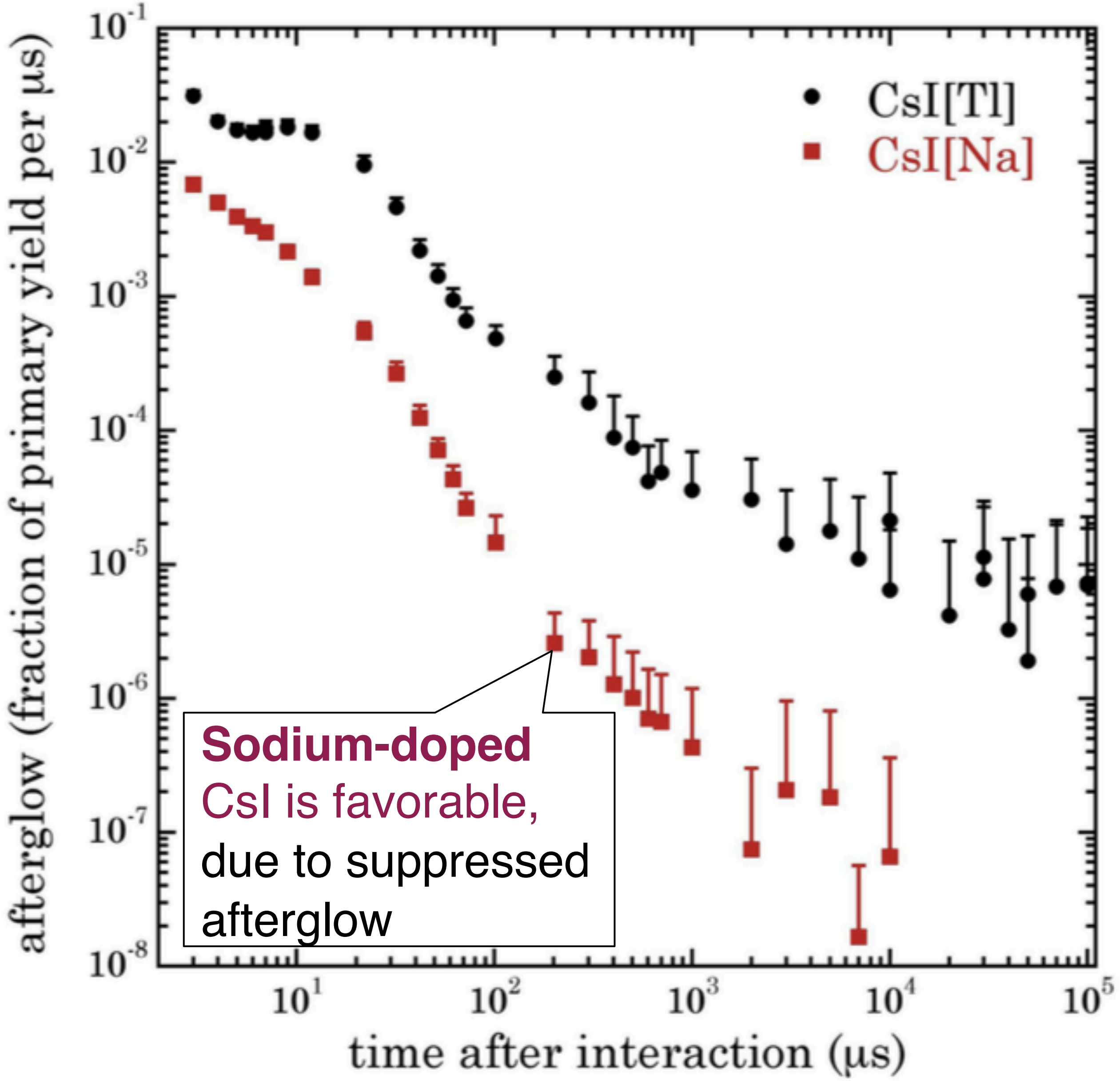
Prompt defined as first μs; note some contamination from ν_e and ν_μ-bar

OUTLINE

- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations
  (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light with CsI[Tl]**
- Status and prospects for COHERENT

The First COHERENT Result: CsI[Na]

Led by U. Chicago group



Sodium-doped CsI is favorable, due to suppressed afterglow

J.I. Collar et al., NIM A773 (2016) 56-67

Scintillating crystal

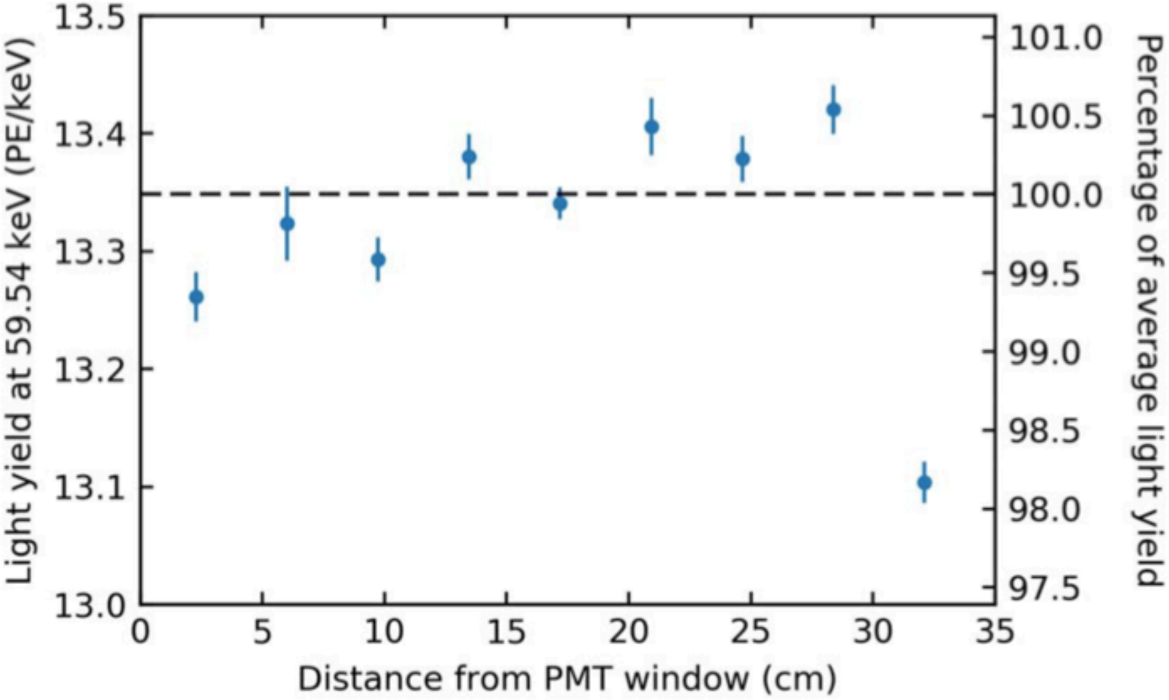
- high light yield
- low intrinsic bg
- rugged and stable
- room temperature
- inexpensive

2 kg test crystal @U. Chicago.

Amcrys-H, Ukraine

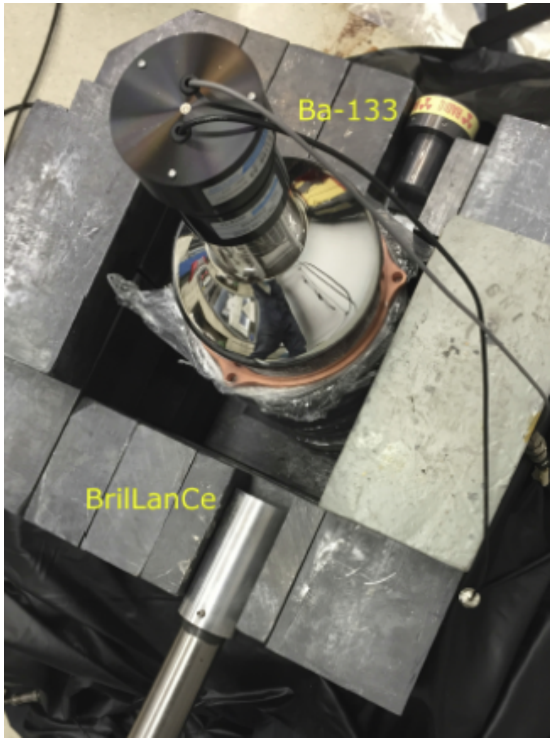
Calibration of 14.6-kg detector at U. Chicago (^{241}Am, ^{133}Ba)

^{241}Am



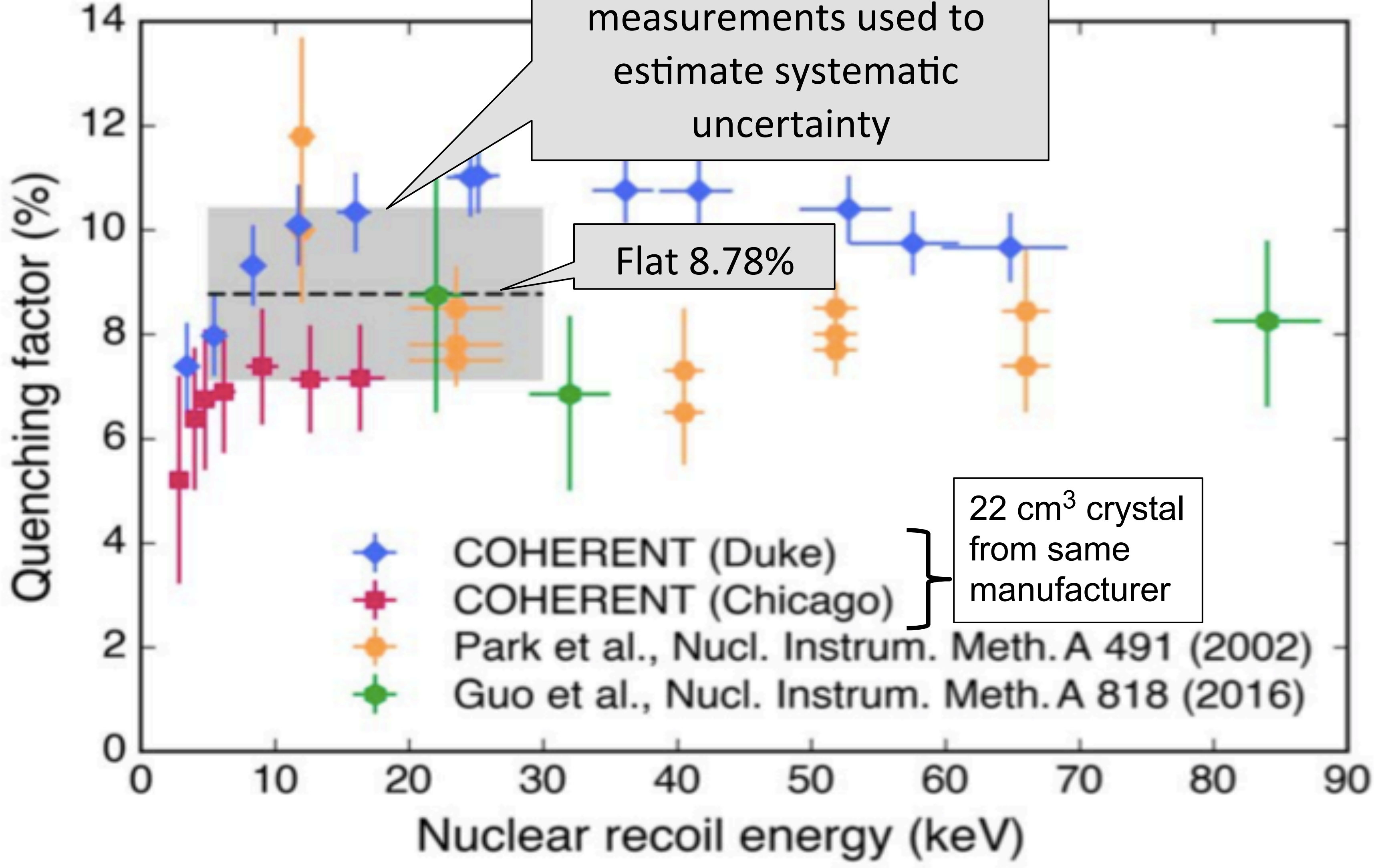
Light yield:
13.35 pe/keVee,
uniform within ~2%

^{133}Ba



Used to determine event selection efficiency

CsI quenching factor measurements at TUNL w/ neutrons



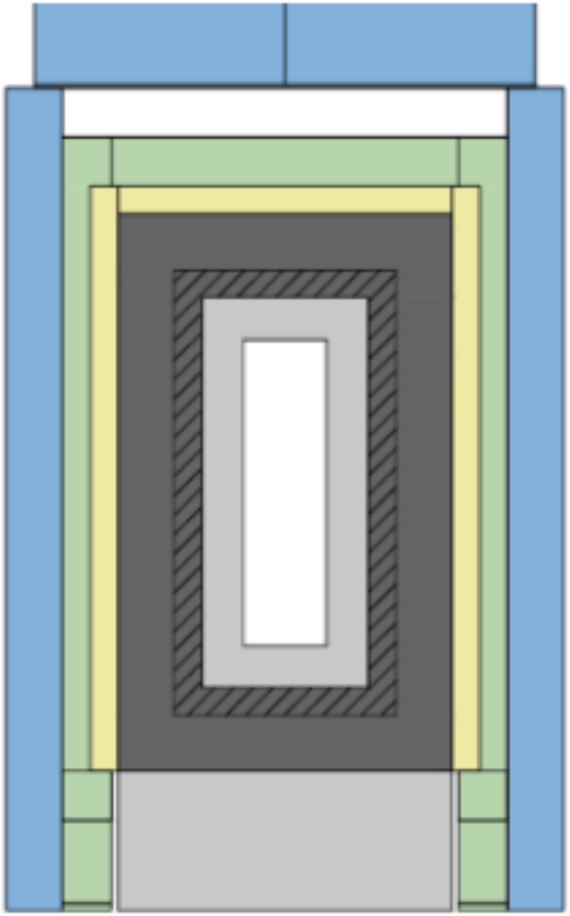
Discrepancy between two measurements used to estimate systematic uncertainty

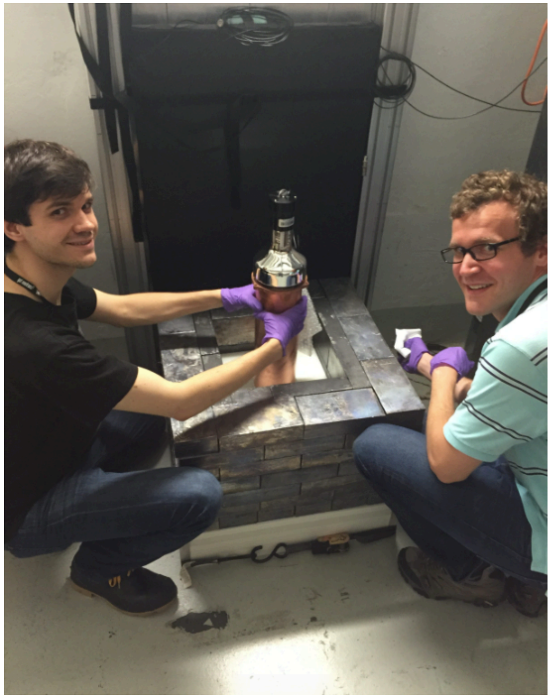
Flat 8.78%

22 cm^3 crystal from same manufacturer

$$\underbrace{13.348\ \text{pe/keVee}}_{\text{ee light yield}} * \underbrace{0.0878\ \text{keVee/keVr}}_{\text{QF}} = \mathbf{1.2\ pe/keVr}$$

The CsI Detector in Shielding in Neutrino Alley at the SNS





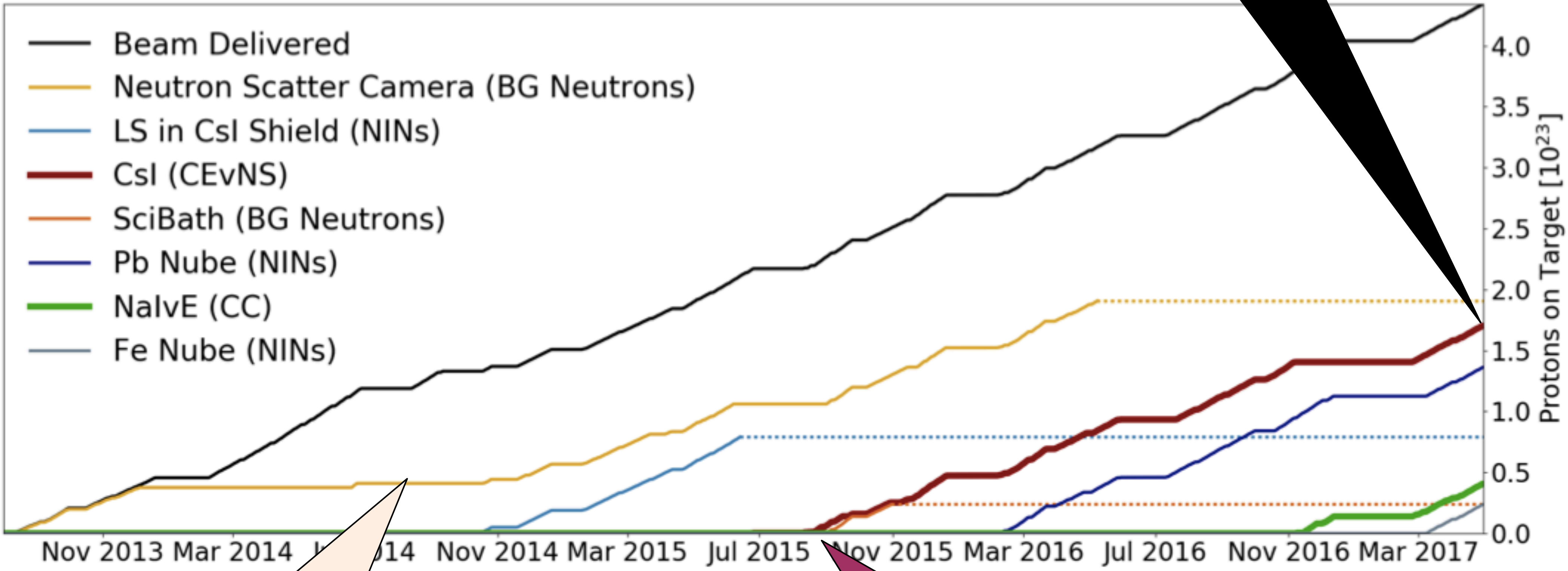
A hand-held detector!

Almost wrapped up...

Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3”	2”	4”	2”	4”
Colour	⬜	▨	⬛	🟨	🟦

COHERENT data taking

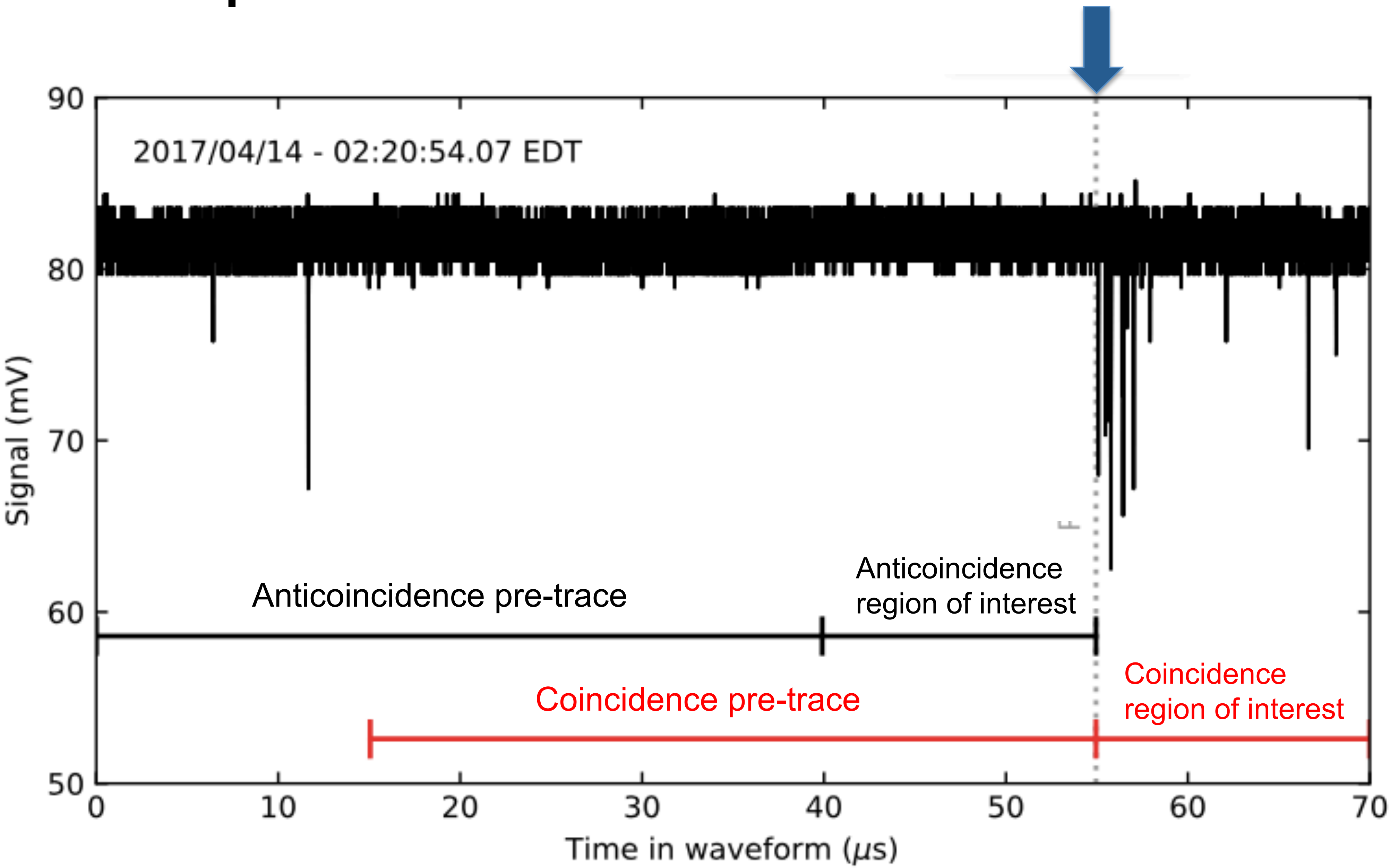
1.76 x10^{23} POT delivered to CsI (7.48 GWhr)



Neutron background data-taking for ~2 years before first CEvNS detectors

CsI data-taking starting summer 2015

Example CsI waveform



Protons on target

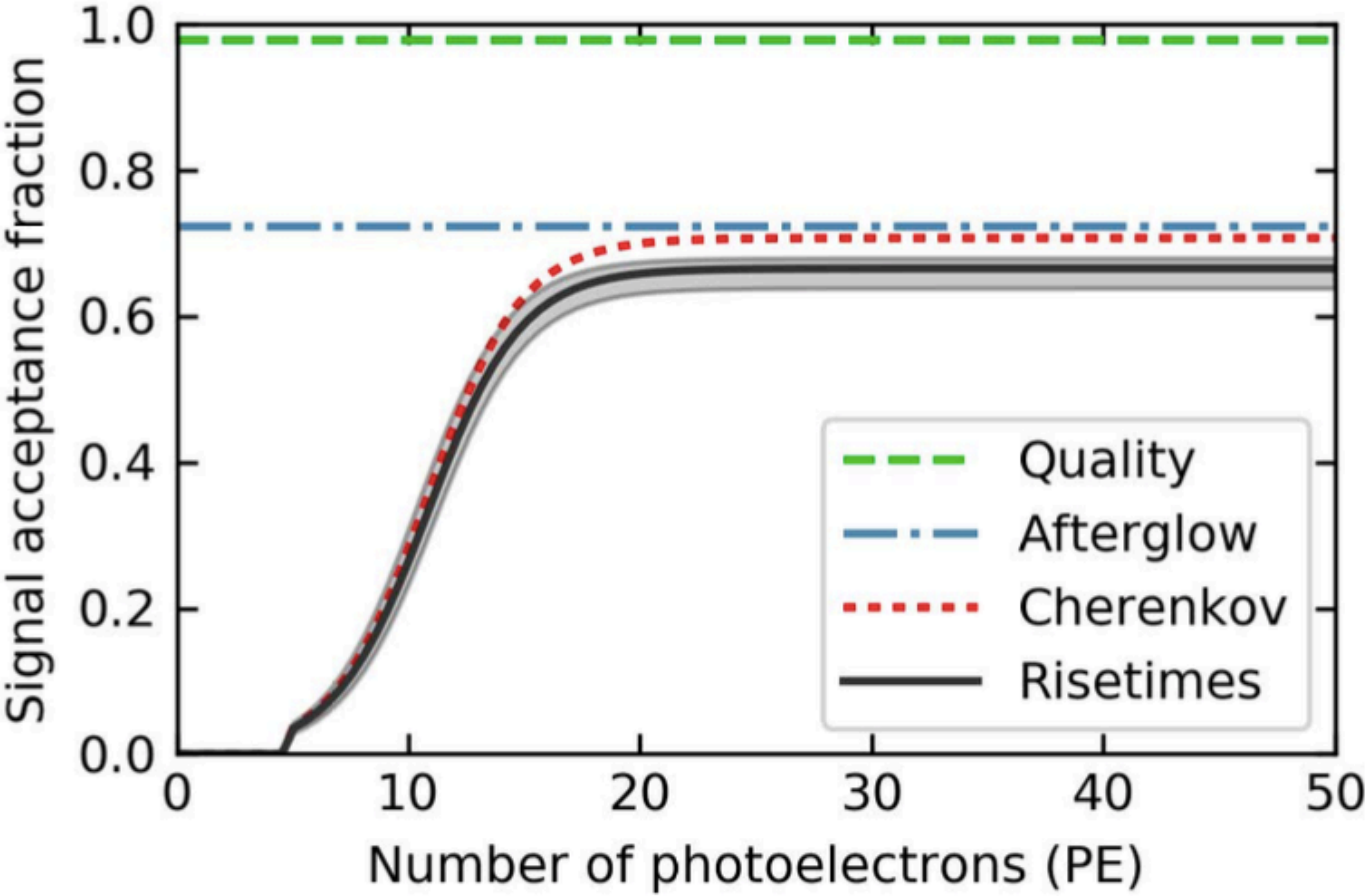
- (C ROI) – (AC ROI) = CEvNS + Beam-on bg
- Pretraces used for afterglow background removal

Event Selection Cuts

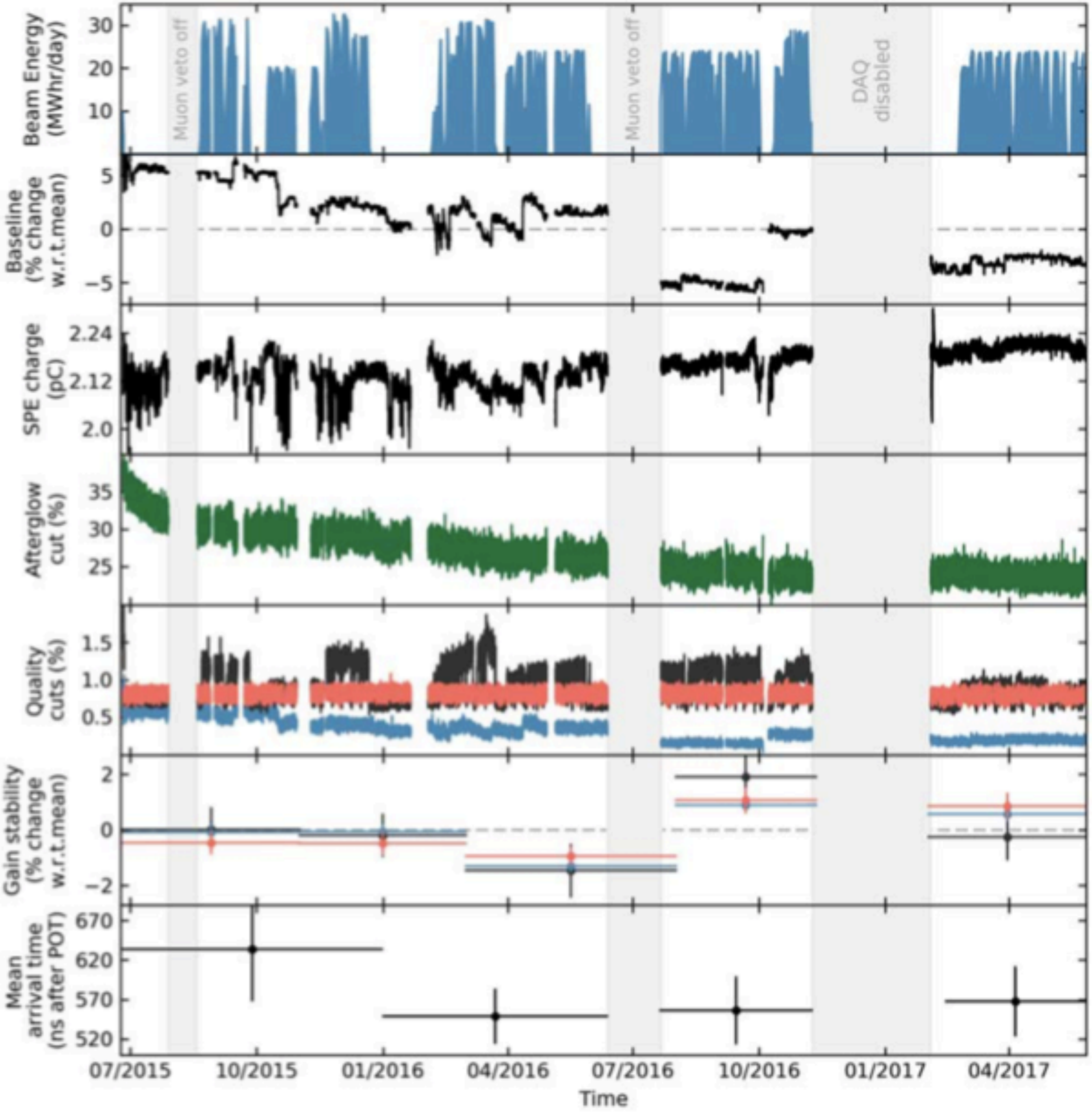
Quality	Remove coincidences in muon veto, deadtime from PMT saturation blocking, digitizer range overflow	Select recoil-like low-energy pulses, reject muons
Afterglow	Reject signals with >=4 peaks (~spe) in pretrace	Remove afterglow (phosphorescence) contamination
"Cherenkov"	Require minimum number of peaks in the scintillation signal	Remove accidental coincidences between Cherenkov emission in PMT window and dark counts/ afterglow
Risetime	Pulse-shape based	Remove misidentified scintillator onset, accidental groupings of dark counts, etc.

- **2 independent analyses** with slightly different cut optimization yield consistent results
- "Analysis I" presented here

Event selection cut efficiencies



Data quality and stability: **fluctuations small and understood**



Energy to SNS target

CsI channel baseline

PMT SPE mean charge, used for gain fluctuation correction

Afterglow event removal fraction

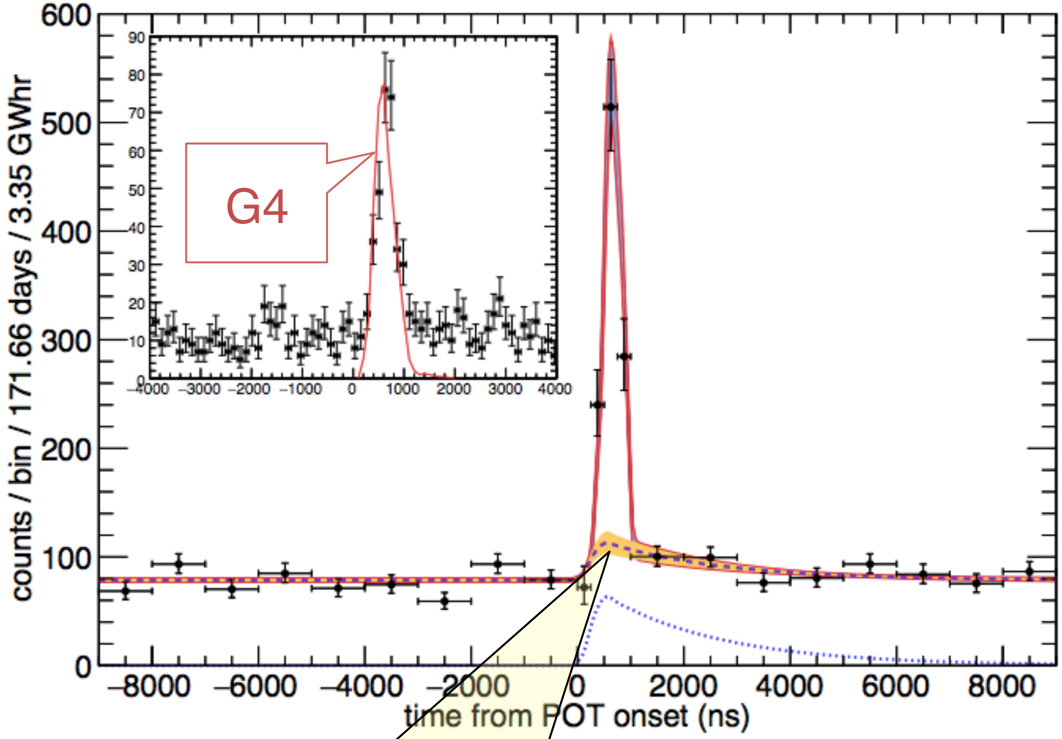
Muon veto cut
Linear gate cut
DAQ overflow cut

Gain from internal crystal backgrounds

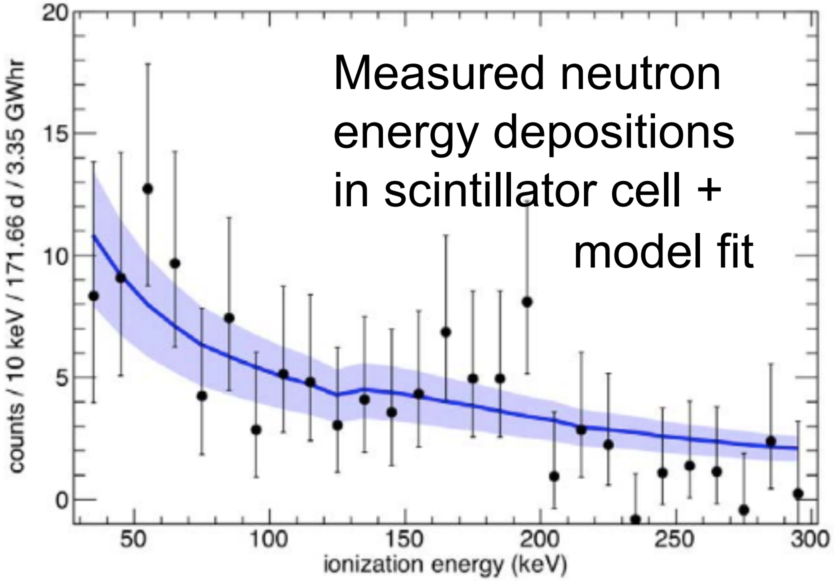
POT signal delay from muon panel neutron coincidences

Neutron backgrounds

- Evaluated using EJ-301 liquid scintillator cell deployed inside CsI shielding before CsI deployment
- Consistent with Geant4 simulation for SNS production & shielding



NINs: non-zero component at 2.9σ
(factor ~1.7 lower than prediction)



Measured neutron energy depositions in scintillator cell + model fit

(consistent w/other measurements)

Expect: 0.93 ± 0.23 beam n events/GWhr

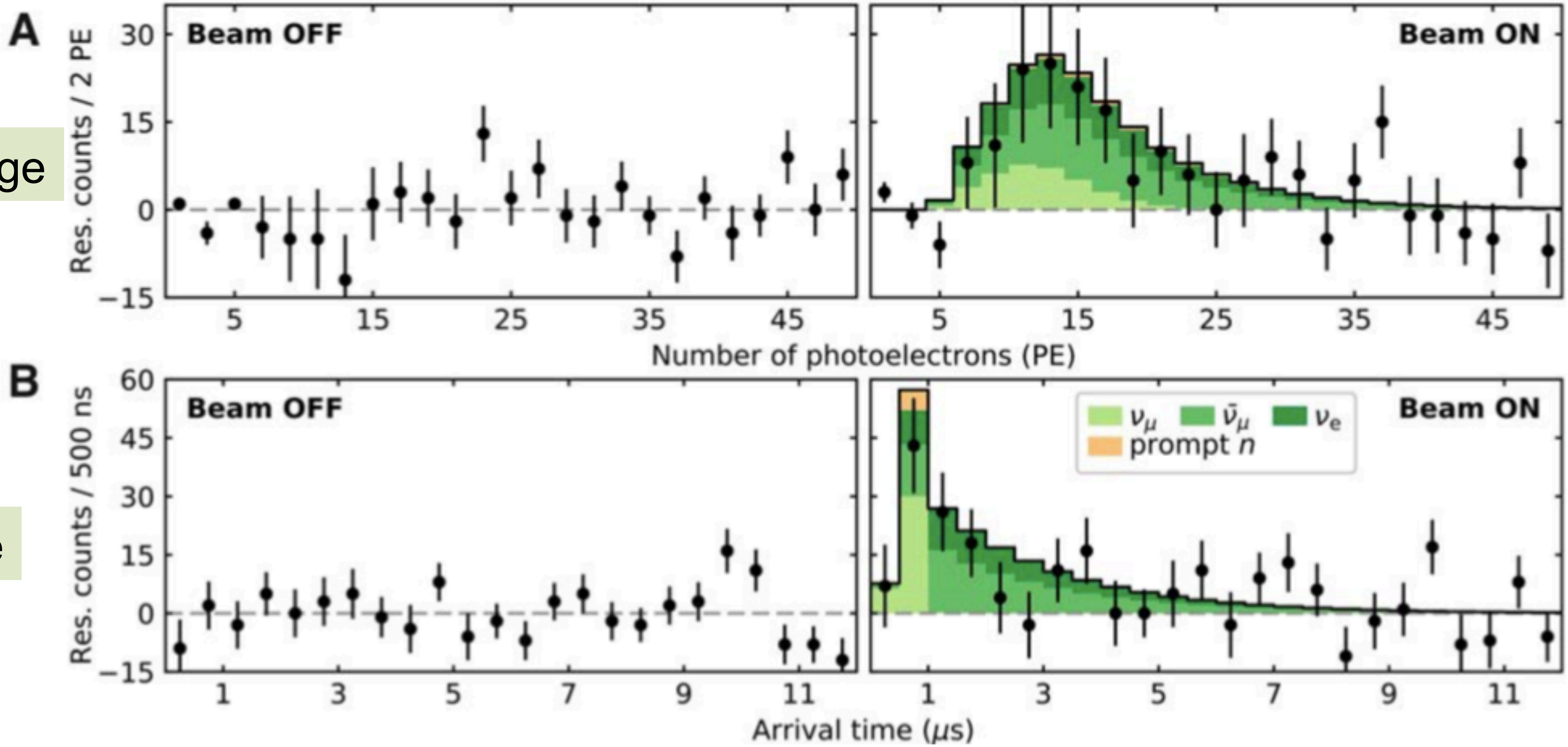
0.54 ± 0.18 NIN events/GWhr (neglected)

<~11 neutron events in CsI dataset

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...

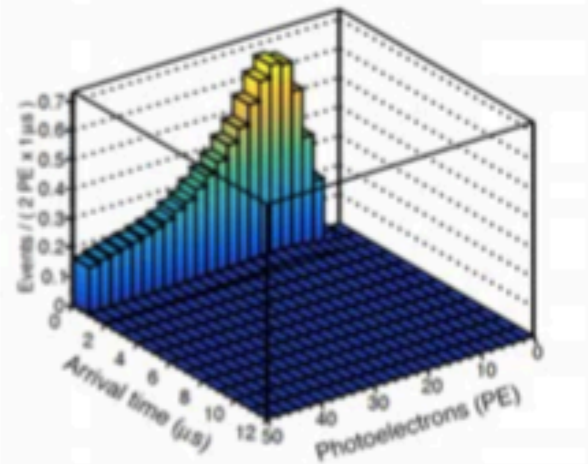
+ See all authors and affiliations

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

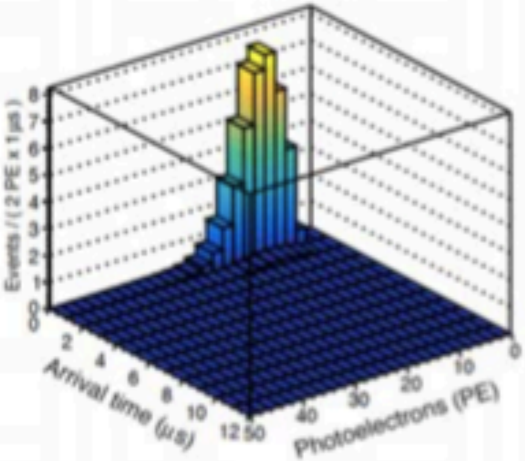
D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

Likelihood analysis: 2D in energy (PE) and time

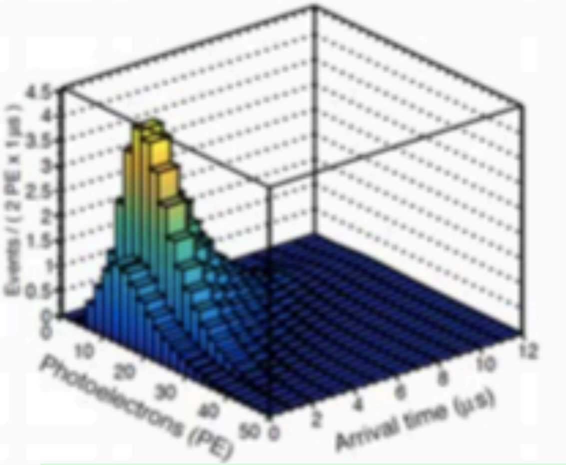
Prompt neutrons



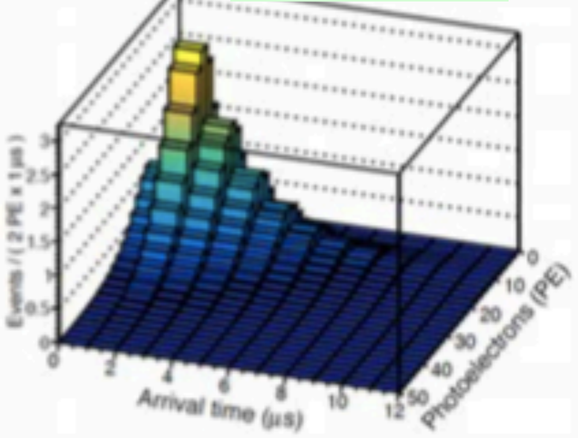
CEvNS ν_μ



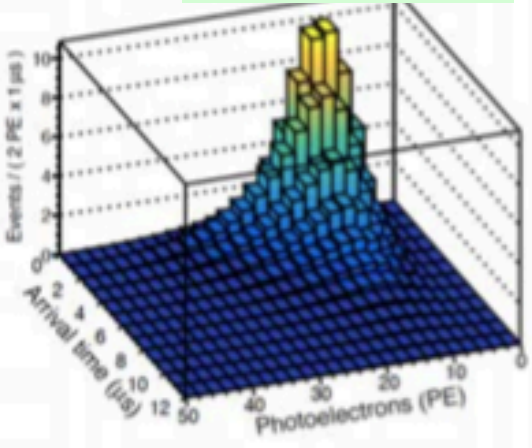
CEvNS ν_μ-bar



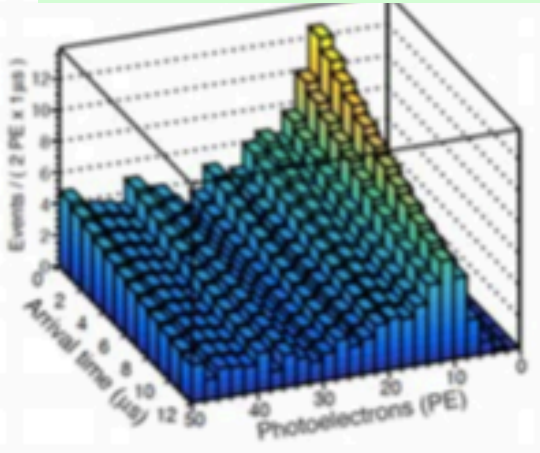
CEvNS ν_e



CEvNS total



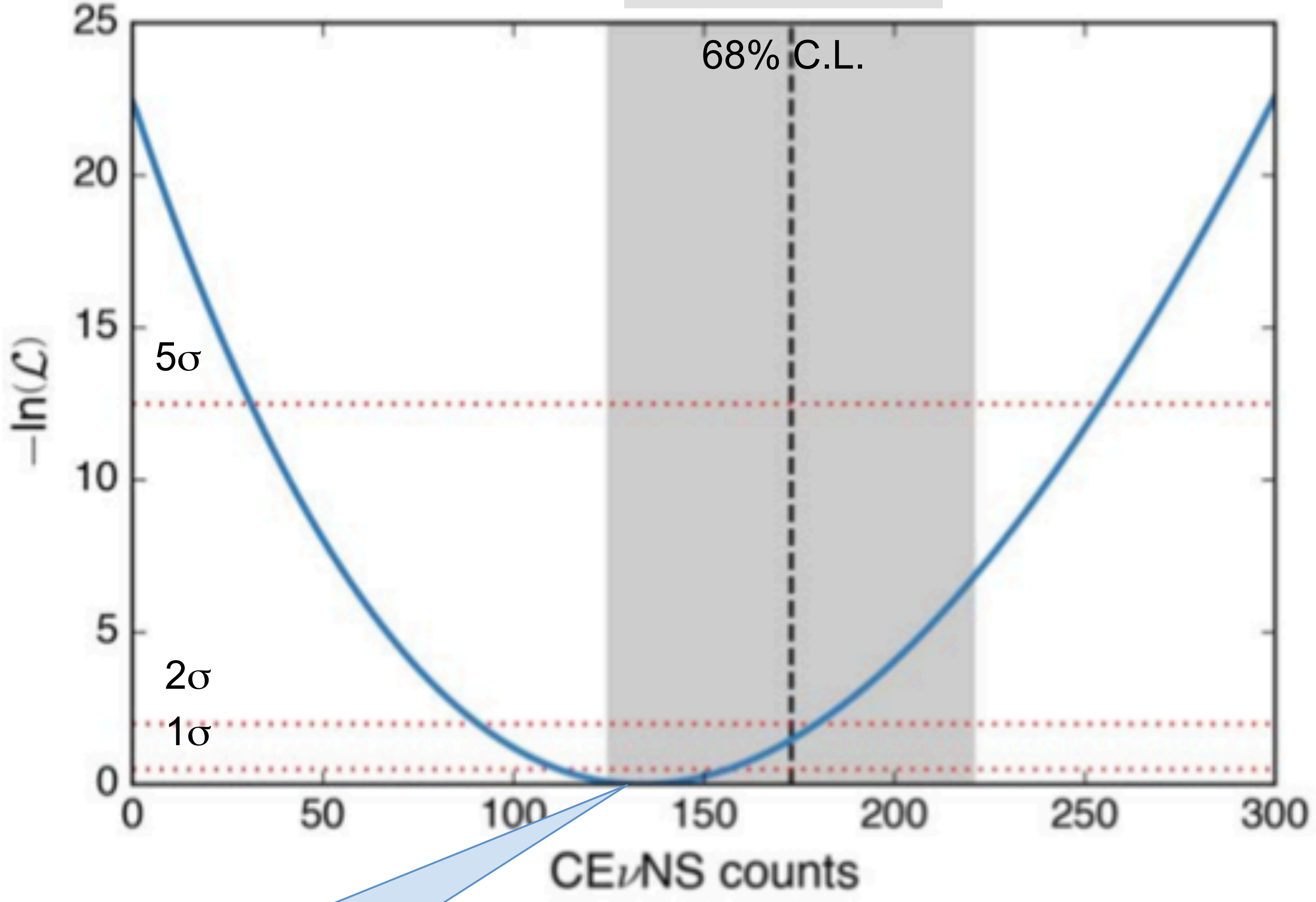
Steady-state background



$6 \leq PE \leq 30, 0 \leq t \leq 6000$ ns

Results of 2D energy, time fit

SM prediction, 173 events



Best fit: **134 ± 22** observed events

No CEvNS rejected at 6.7σ, consistent w/SM within 1σ

Signal, background, and uncertainty summary numbers

$6 \leq PE \leq 30$, $0 \leq t \leq 6000$ ns

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	7.0 ± 1.7
Beam-on bg: NINs (neglected)	4.0 ± 1.3
Signal counts, single-bin counting	136 ± 31
Signal counts, 2D likelihood fit	**134 ± 22**
Predicted SM signal counts	**173 ± 48**

Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

Dominant uncertainty

What constraints do these data make on new interactions?

A first example: simple counting to constrain **non-standard interactions (NSI)** of neutrinos with quarks

Davidson et al., JHEP 0303:011 (2004)
Barranco et al., JHEP 0512:021 (2005)

“Model-independent” parameterization

$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

ε’s parameterize new interactions

“Non-Universal”: ε_{ee}, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

Flavor-changing: $\varepsilon_{\alpha\beta}$, where $\alpha \neq \beta$

⇒ some are quite poorly constrained (~unity allowed)

Cross-section for CEvNS including NSI terms

For flavor α, *spin zero* nucleus, and E<<k,M:

$$\left(\frac{d\sigma}{dE}\right)_{\nu N} = \frac{G_F^2 M}{\pi} F^2(2MT)\left[1 - \frac{MT}{2E_\nu^2}\right] \times$$

$$\{[Z(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV}) + N(g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})]^2$$ non-universal

$$+ \sum_{\alpha\neq\beta} [Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})]^2\}$$ flavor-changing

$$\left.\begin{array}{l} g_V^p = (\frac{1}{2} - 2\sin^2\theta_W), \quad g_V^n = -\frac{1}{2} \end{array}\right\}$$ SM parameters

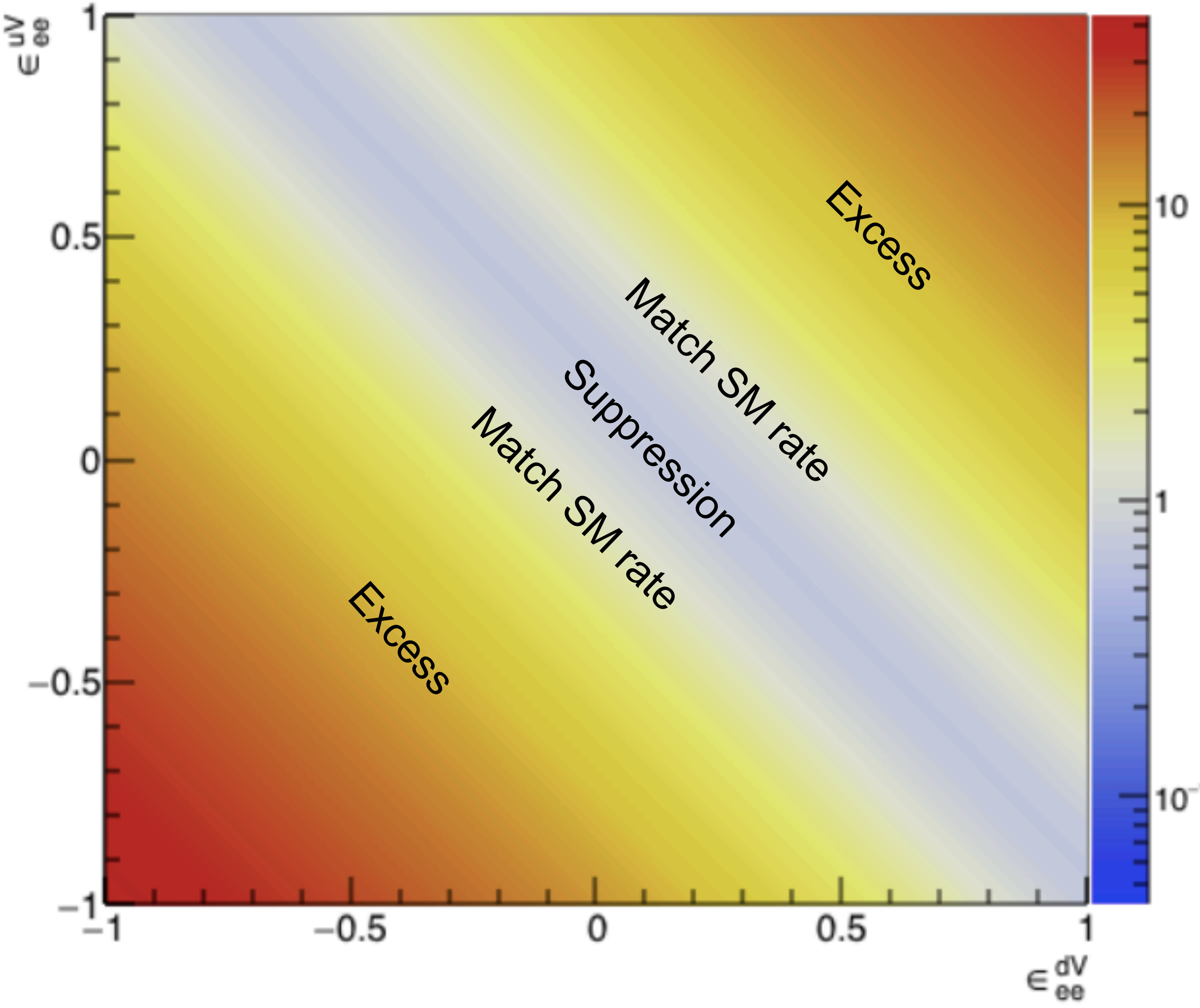
$$\varepsilon_{\alpha\beta}^{qV} = \varepsilon_{\alpha\beta}^{qL} + \varepsilon_{\alpha\beta}^{qR}$$

- NSI with these assumptions affect ***total cross-section***, ***not differential shape of recoil spectrum***
- size of effect depends on N, Z
  (different for different elements)
- ε's can be negative and parameters can cancel

Ratio of rate with NSI to SM rate (all flavors in stopped-pion beam)

ε_{ee}^{uV} vs ε_{ee}^{dV} parameters (assume others zero)

CsI

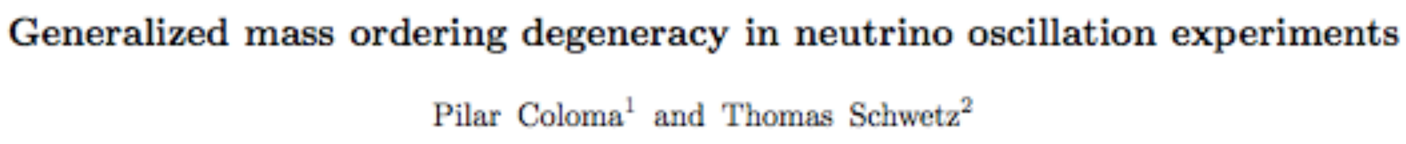


Note that for

$$Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) = \pm(Z g_V^p + N g_V^n),$$

the rate is the same as for the SM, so parameters will be allowed

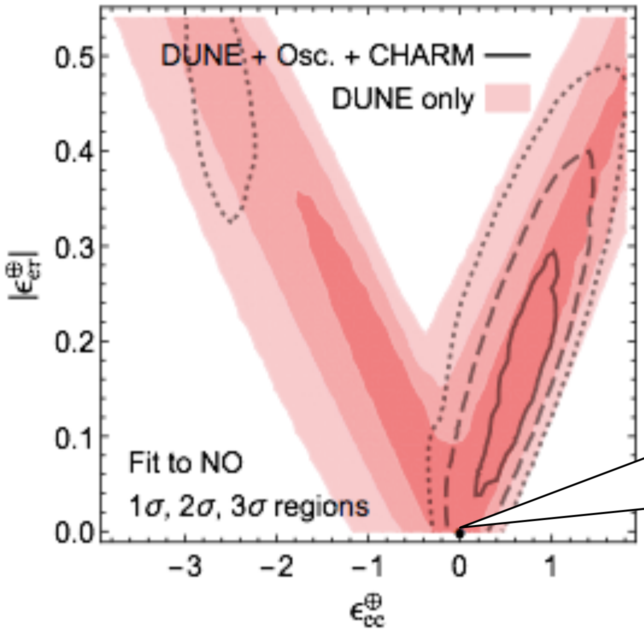
Get slightly different slope for different targets



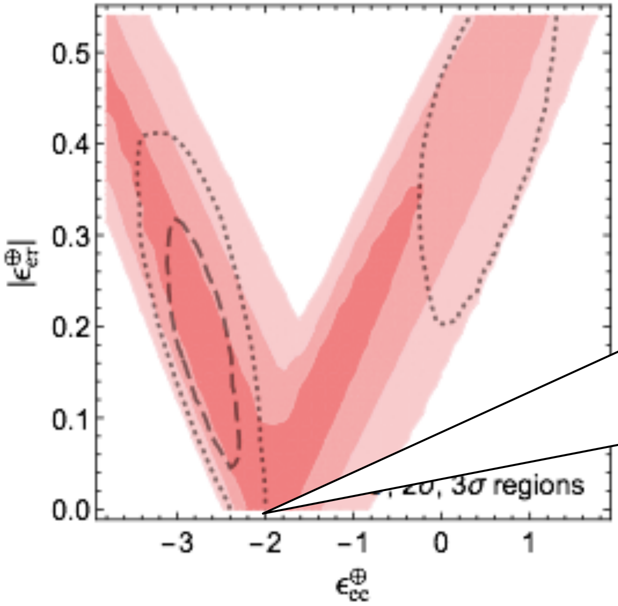
Generalized mass ordering degeneracy in neutrino oscillation experiments

Pilar Coloma[1] and Thomas Schwetz[2]

Phys.Rev. D94 (2016) no.5, 055005,
Erratum: Phys.Rev. D95 (2017) no.7, 079903
Also: P. Coloma et al., JHEP 1704 (2017) 116



Normal ordering w/no NSI...



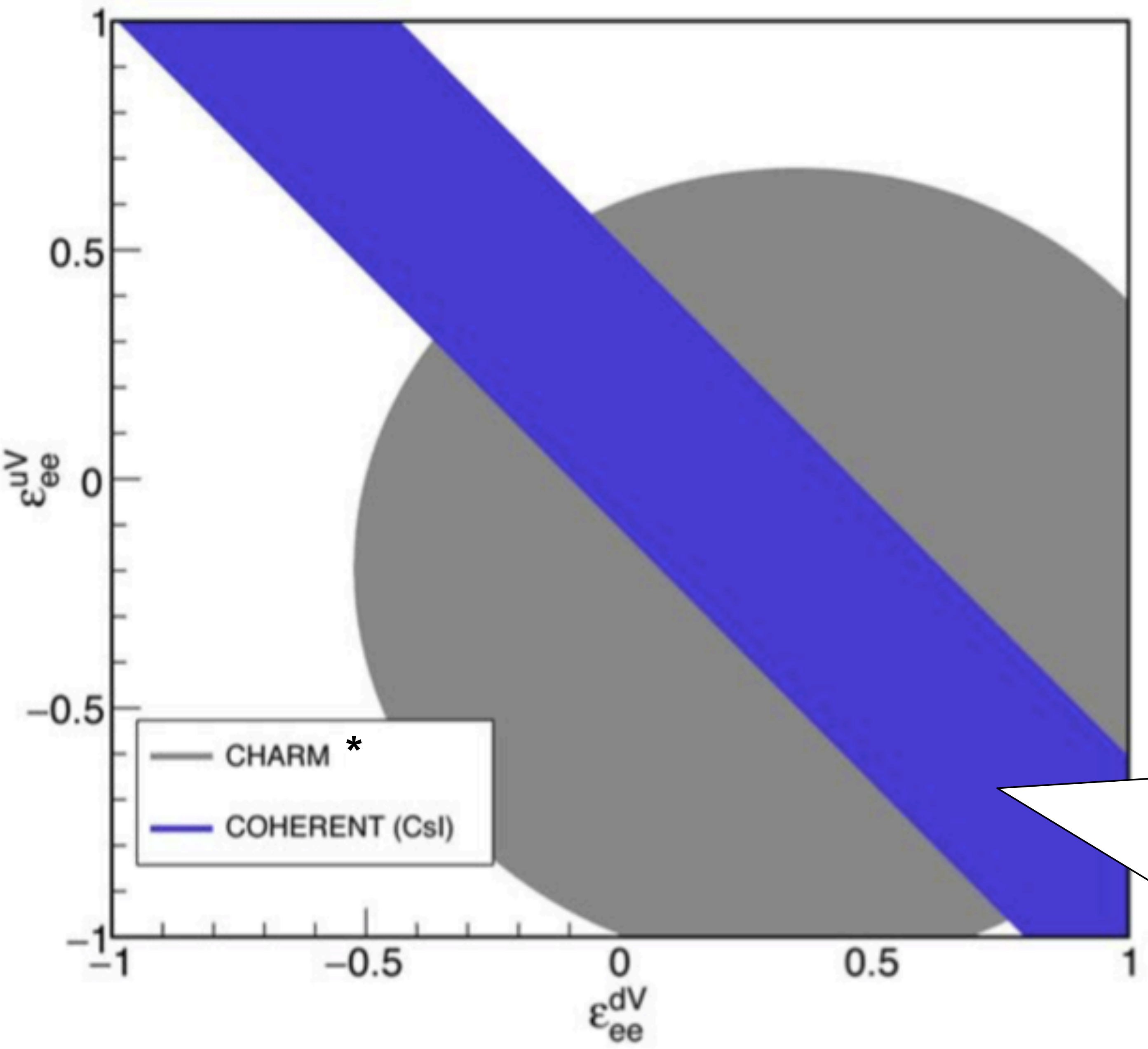
...looks just like inverted ordering w/NSI

If you allow for NSI to exist, you can't tell the neutrino mass ordering in long-baseline experiments

... NC scattering can constrain NSI...

➔DUNE may need this...

χ^2 fit results for current CsI data set: 90% allowed region



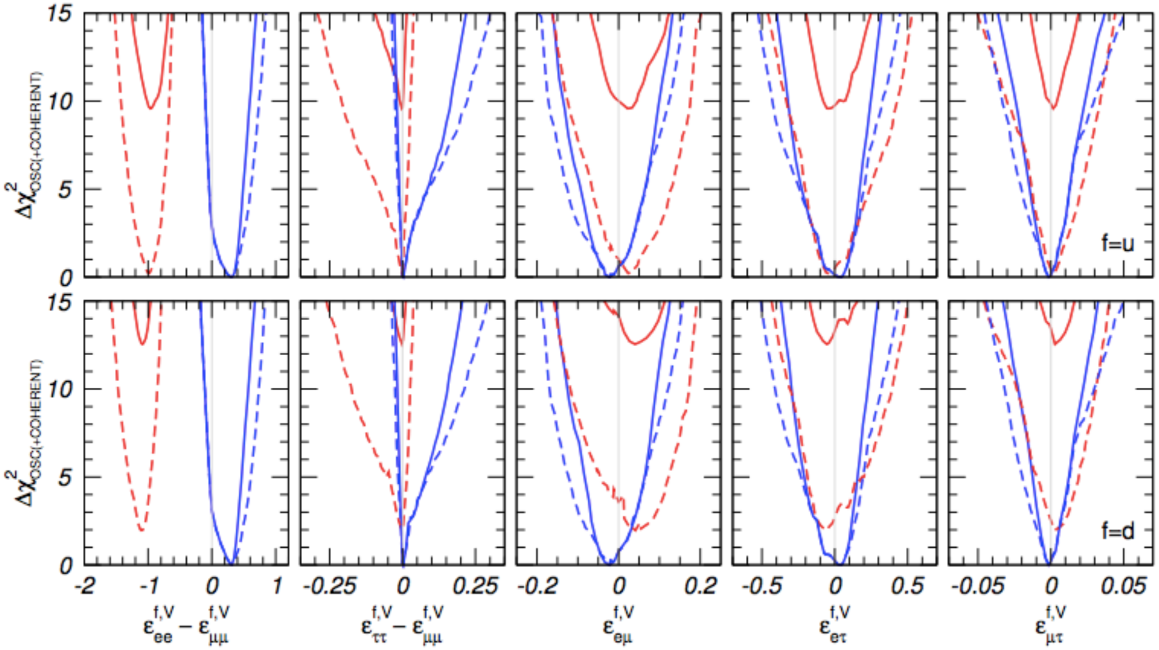
- Simple one-bin analysis
- Assume all other ε's zero

Separate bands not resolved due to current uncertainty (dominated by QF).. will improve, and different N targets will help

*CHARM constraints apply only to heavy mediators

A COHERENT enlightenment of the neutrino Dark Side

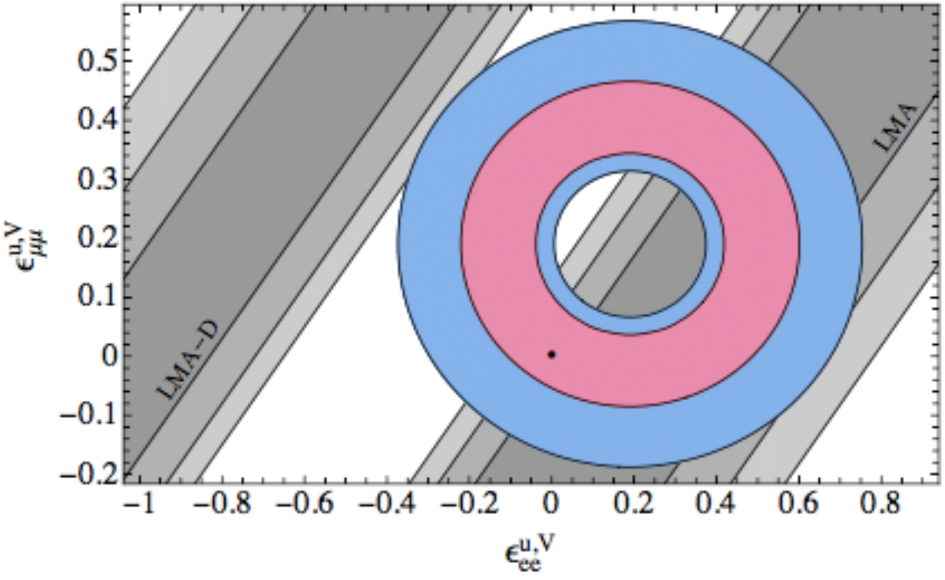
Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,,[2,3,4,†] Michele Maltoni,,[5,‡] and Thomas Schwetz[6,§]



Global fits to COHERENT + oscillation experiments

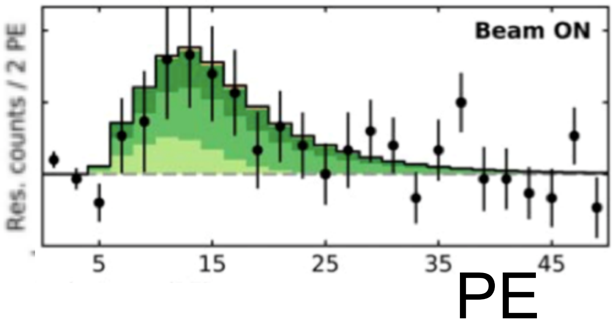
Solid: COHERENT
Dashed: COHERENT + osc
Blue: LMA ($\theta_{12} < \pi/4$)
Red: LMA-D ($\theta_{12} > \pi/4$)
("dark side", still allowed with NSI)

1σ, 2σ allowed regions projected in (ε_{ee}^{uV}, $\varepsilon_{\mu\mu}^{uV}$) plane



Already meaningful constraints!

This is the first measurement of low-energy NC neutrino-hadron interaction with event-by-event *spectral information*

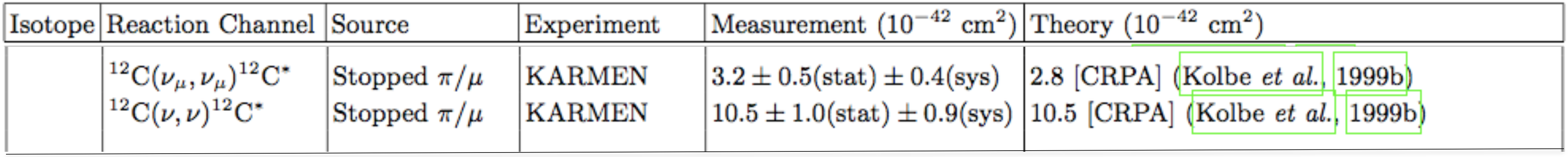


Low energy (<~100 MeV) NC measurements so far:

J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

^{12}C excitation

15-MeV gamma observed

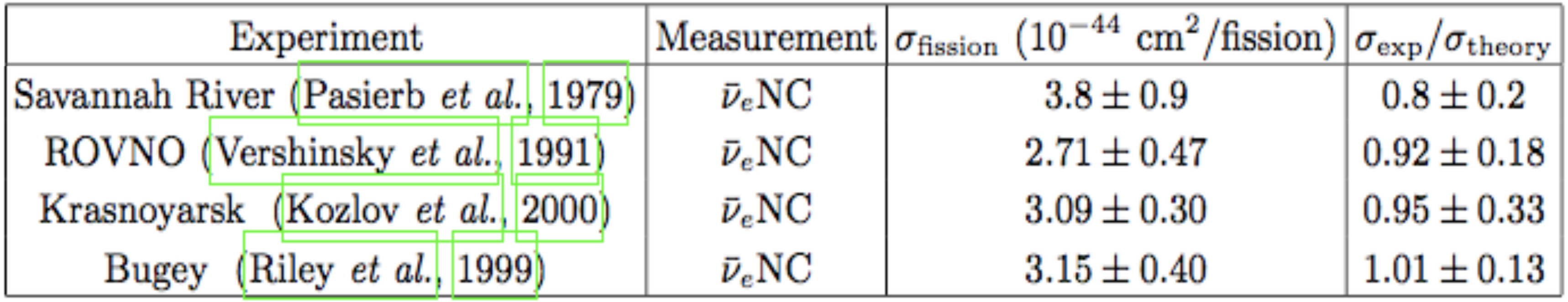


Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
	$^{12}C(\nu_\mu, \nu_\mu)^{12}C^*$	Stopped π/μ	KARMEN	$3.2 \pm 0.5(stat) \pm 0.4(sys)$	2.8 [CRPA] (Kolbe *et al.*, 1999b)
	$^{12}C(\nu, \nu)^{12}C^*$	Stopped π/μ	KARMEN	$10.5 \pm 1.0(stat) \pm 0.9(sys)$	10.5 [CRPA] (Kolbe *et al.*, 1999b)

Deuterium breakup

$d(\bar{\nu}_e, \bar{\nu}_e)pn$

neutron counting



Experiment	Measurement	σ_{fission} (10^{-44} cm^2/fission)	$\sigma_{\text{exp}}/\sigma_{\text{theory}}$
Savannah River (Pasierb *et al.*, 1979)	$\bar{\nu}_e$NC	3.8 ± 0.9	0.8 ± 0.2
ROVNO (Vershinsky *et al.*, 1991)	$\bar{\nu}_e$NC	2.71 ± 0.47	0.92 ± 0.18
Krasnoyarsk (Kozlov *et al.*, 2000)	$\bar{\nu}_e$NC	3.09 ± 0.30	0.95 ± 0.33
Bugey (Riley *et al.*, 1999)	$\bar{\nu}_e$NC	3.15 ± 0.40	1.01 ± 0.13

That's it... (not many CC measurements in this range either)

Another phenomenological analysis, making use of spectral fit:

COHERENT constraints on
nonstandard neutrino interactions

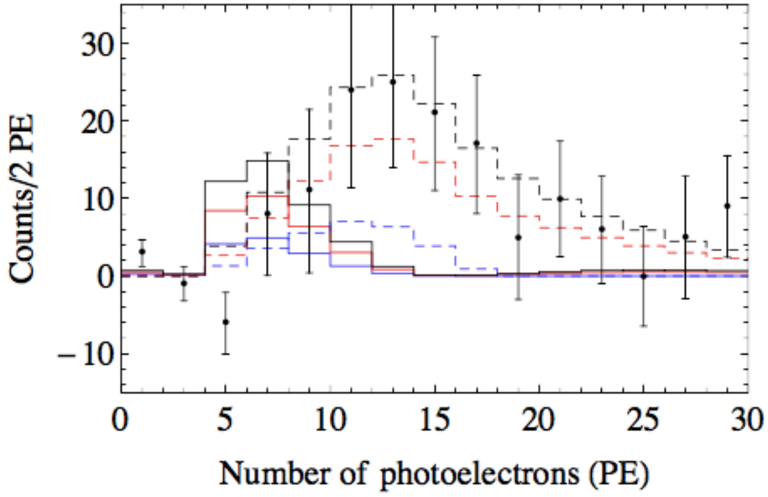
Jiajun Liao and Danny Marfatia
arXiv:1708.04255

SM weak charge

Effective weak charge in presence of light vector mediator Z’

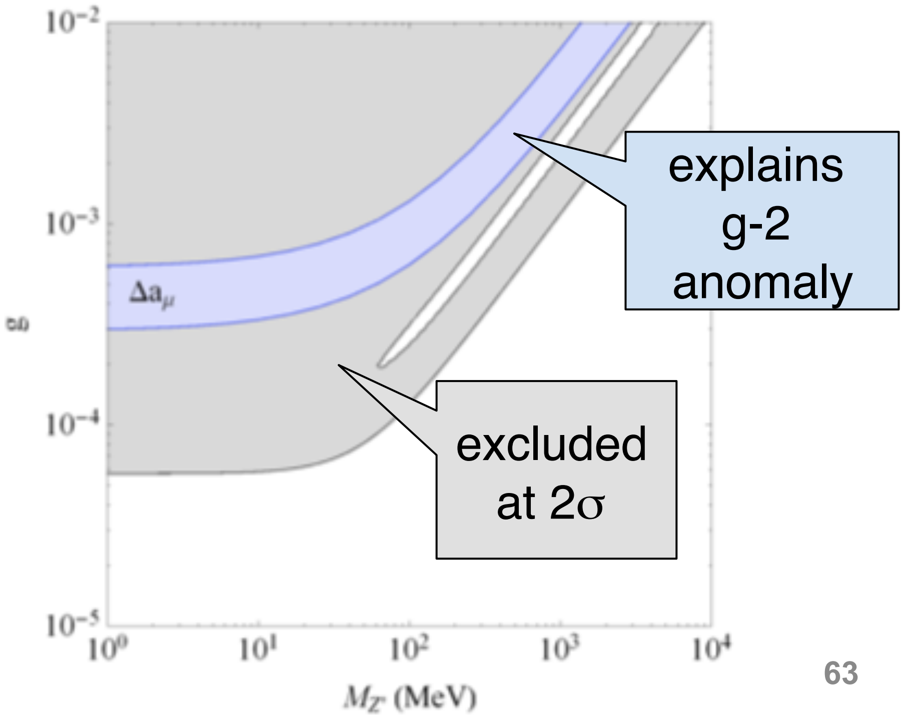
$$Q^2_{\alpha,\mathrm{SM}} = (Z g_p^V + N g_n^V)^2 \quad \Rightarrow \quad Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right)\right]^2$$

- Q^2-dependence ➔ *affects recoil spectrum*
- 2 parameters: g, $M_{Z'}$



Dashed: SM
Solid: NSI w/ $M_{z'}$= 10 MeV, g=10^{-4}

Blue: ν_μ
Red: $\nu_\mu + \nu_\mu$_bar
Black: $\nu_\mu + \nu_\mu$_bar + ν_e



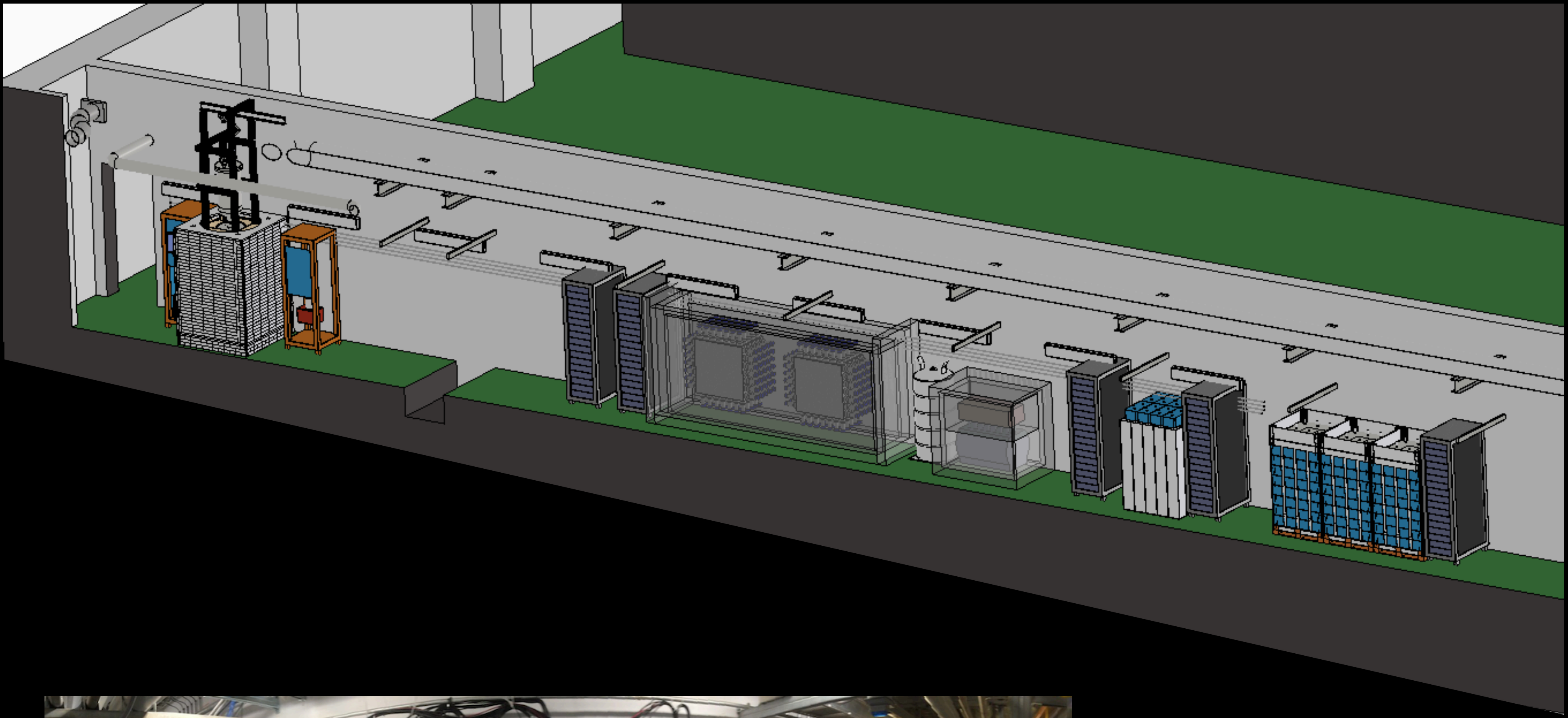
explains g-2 anomaly

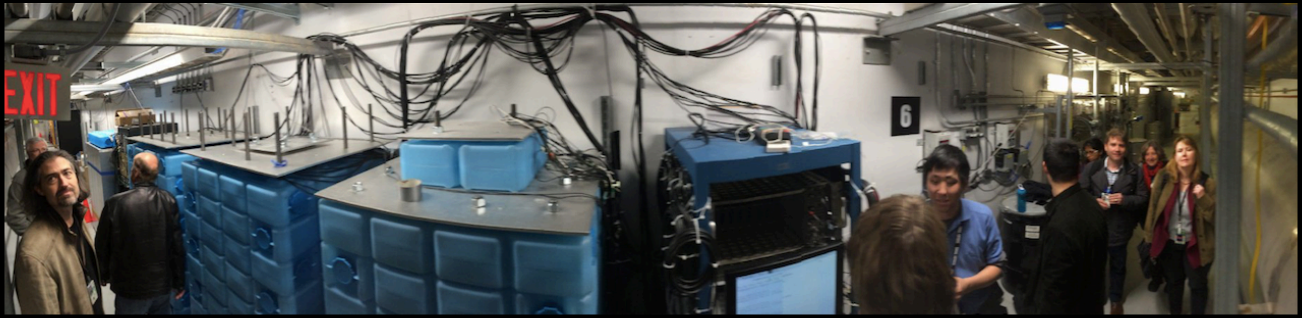
excluded at 2σ

OUTLINE

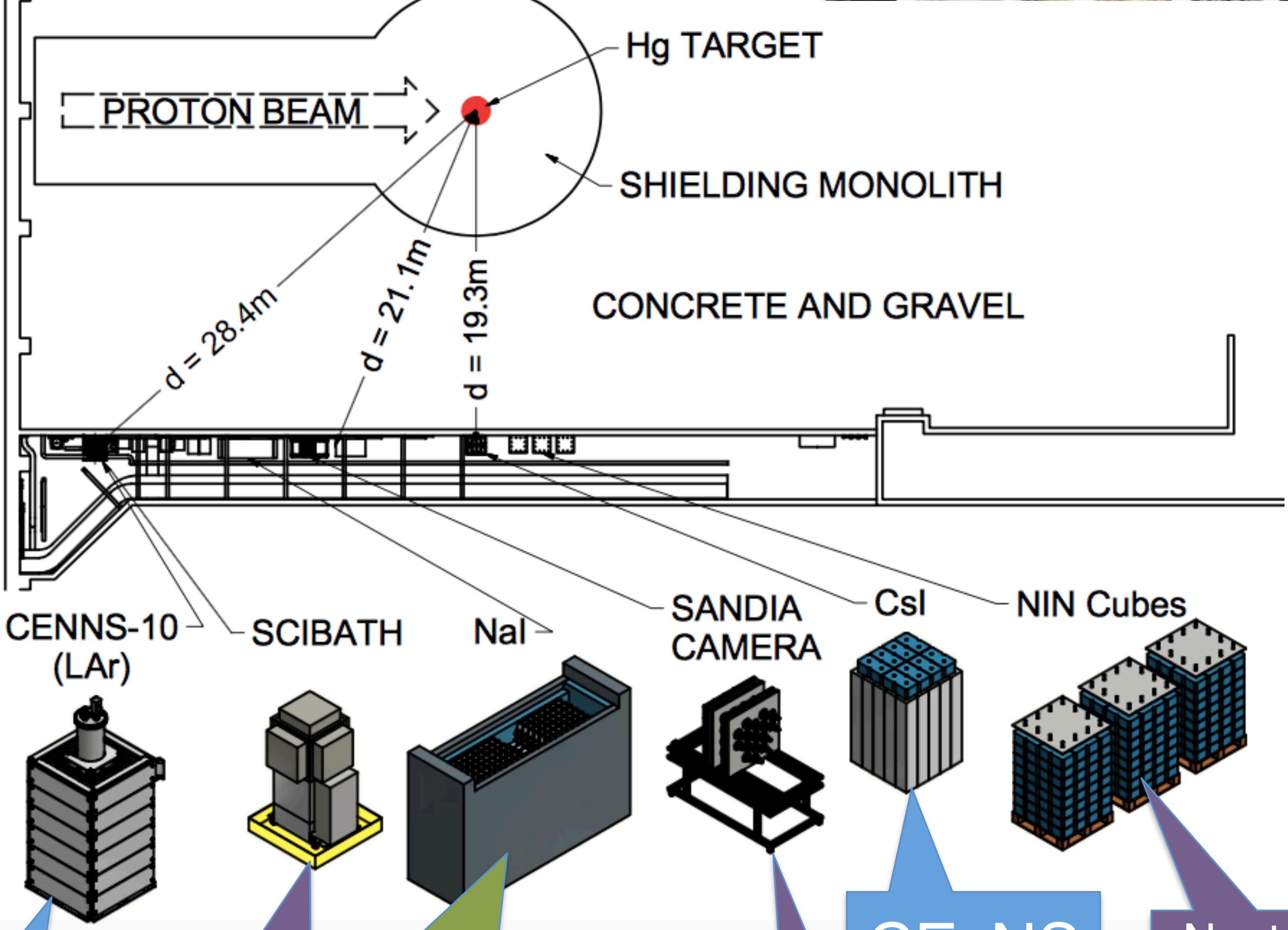
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations
  (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light** with CsI[Tl]
- **Status and prospects for COHERENT**

What’s Next for COHERENT?





Deployments so far in Neutrino Alley



CEvNS

Neutron backgrounds

ν_eCC on ^{127}I

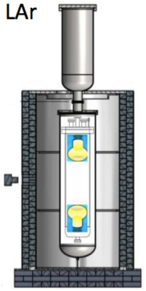
Neutron backgrounds

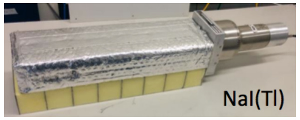
CEvNS

Neutrino-induced neutrons

COHERENT **CEvNS** Detector Status and Near Future

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date
CsI[Na]	Scintillating Crystal	14.6	20	6.5	9/2015
Ge	HPGe PPC	10	22	5	2017
LAr	Single-phase	22	29	20	12/2016, upgraded summer 2017
NaI[Tl]	Scintillating crystal	185*/ 2000	28	13	*high-threshold deployment summer 2016

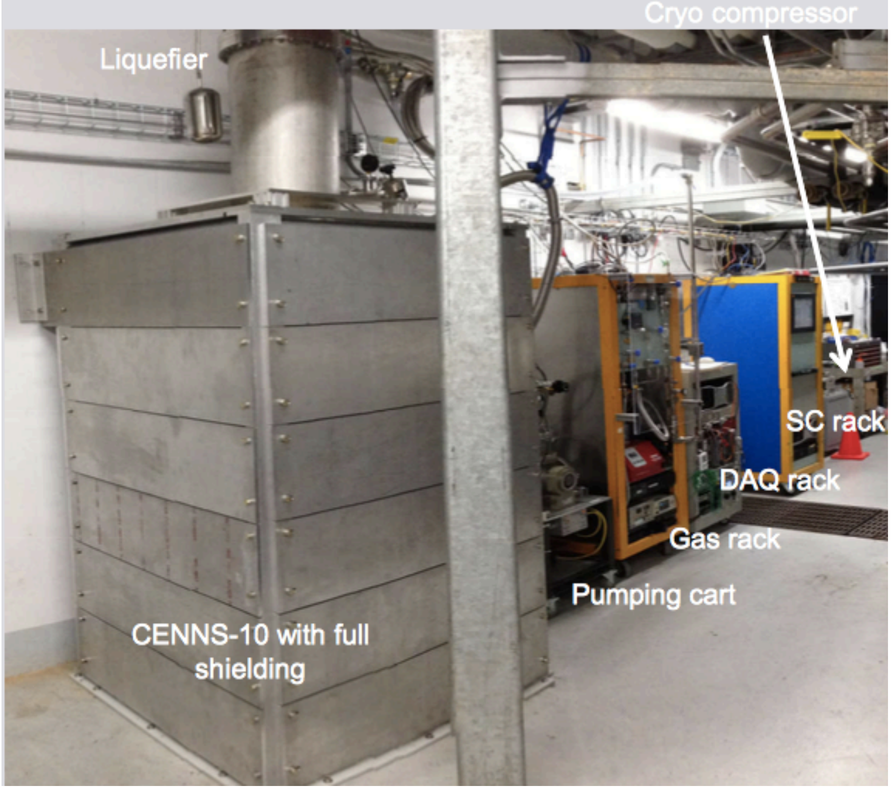




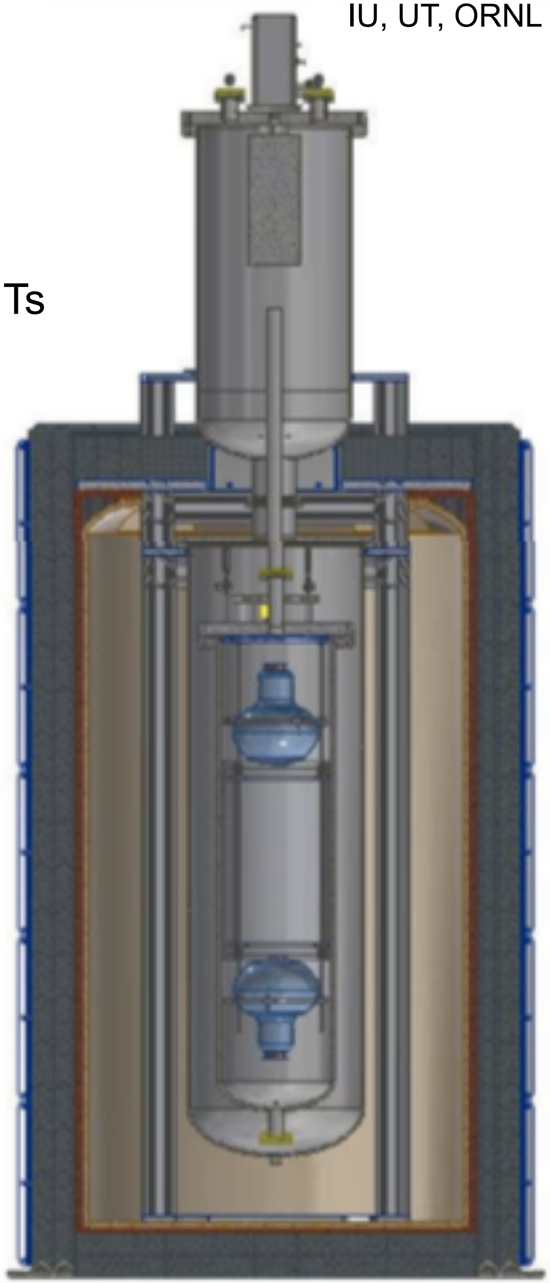
- CsI will continue running
- 185 kg of NaI installed in July 2016
  - taking data in high-threshold mode for CC on ^{127}I
  - PMT base modifications to enable low-threshold CEvNS running
- LAr single-phase detector installed in December 2016
  - upgraded w/TPB coating of PMT & Teflon, running since May 2017
- First Ge detectors to be installed late 2017

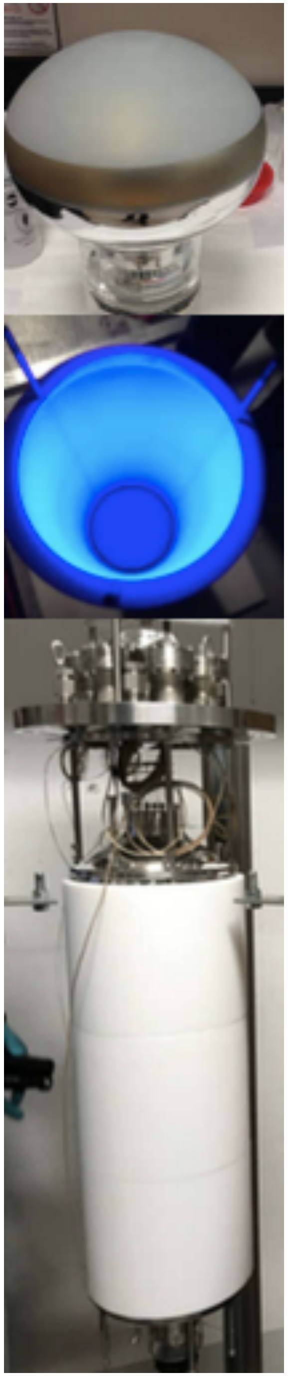
Single-Phase Liquid Argon

- ~22 kg fiducial mass
- 2 x Hamamatsu 5912-02-MOD 8” PMTs
    - 8” borosilicate glass windown
    - 14 dynodes
    - QE: 18%@ 400 nm
- Wavelength shifter: TB-coated teflon walls and PMTs
- Cryomech cryocooler − 90 Wt
    - PT90 single-state pulse-tube cold head



IU, UT, ORNL



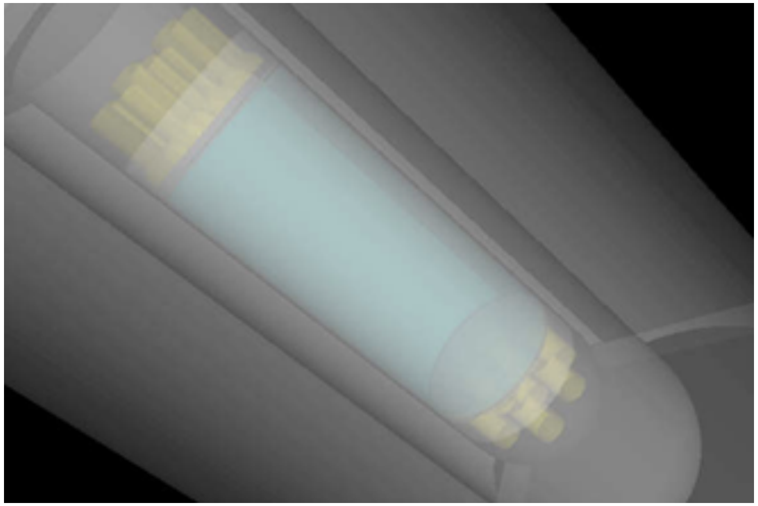


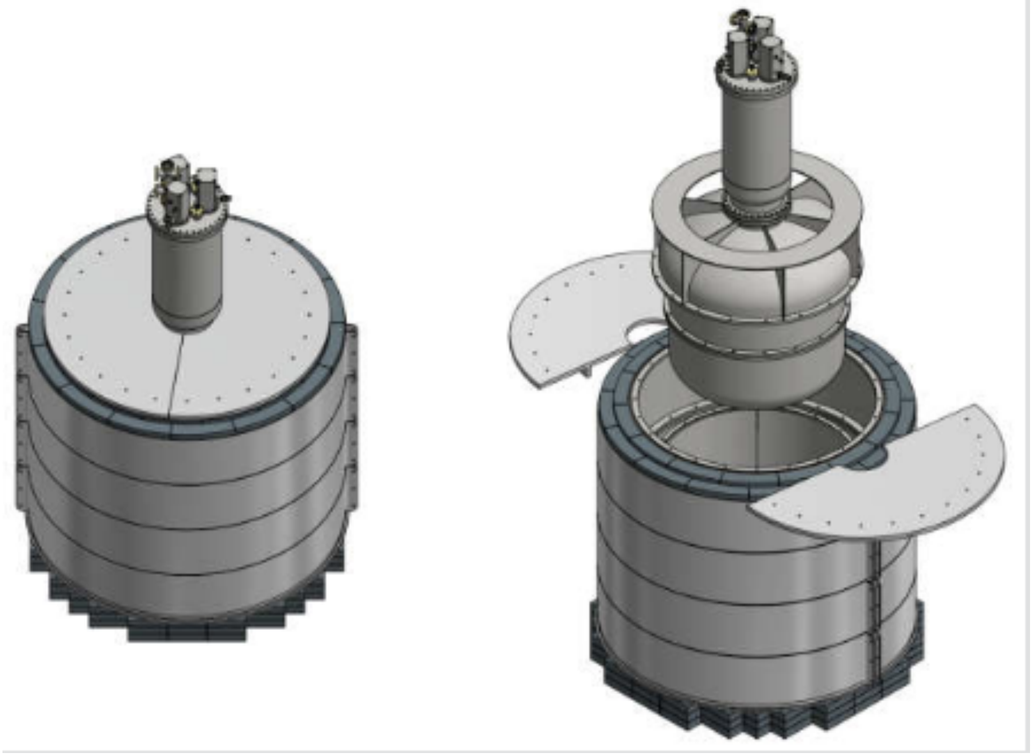
Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB

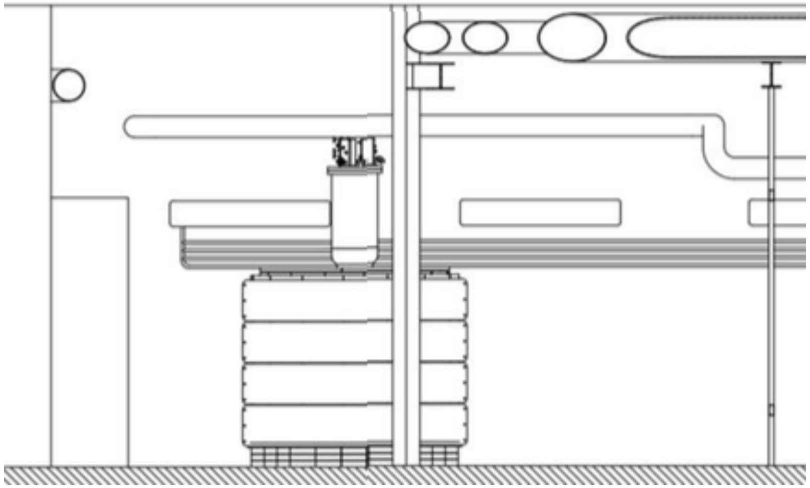
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

Future LAr concepts

- 1-tonne scale feasible in Neutrino Alley
- Considering depleted argon
  to reduce ^{39}Ar background
- Considering SiPMs

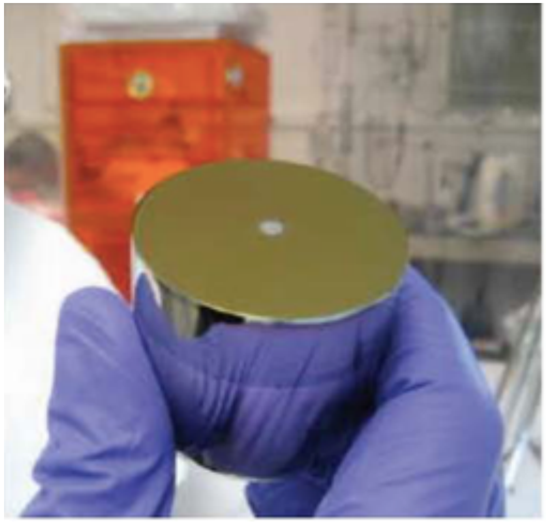




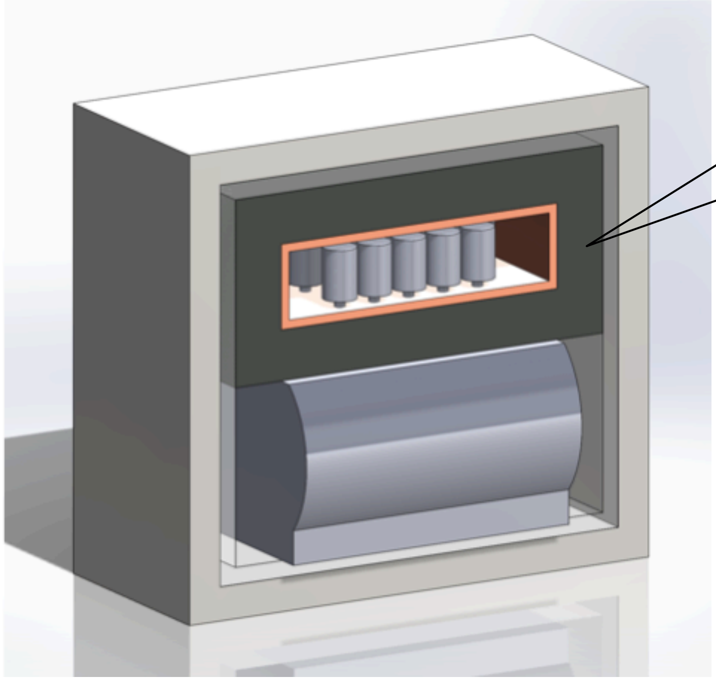


High-Purity Germanium Detectors

P-type Point Contact



- Excellent low-energy resolution
- Well-measured quenching factor
- Reasonable timing



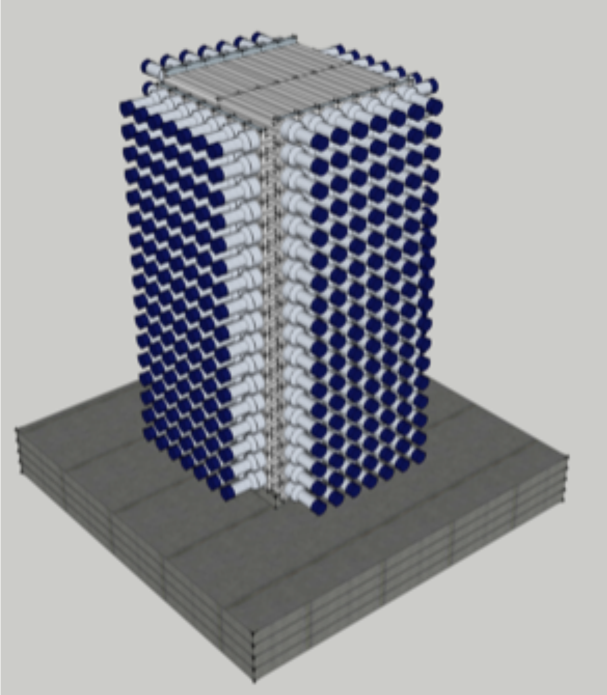
- Canberra cryostats in multi-port dewar
- Compact poly+Cu+Pb shield
- Muon veto
- Designed to enable additional detectors

- 10 kg of detectors available (MAJORANA unenriched prototypes)
- Under refurbishment/test at NCSU, Duke and LANL
- Dewar fabrication nearly complete
- Future: additional 2.5 kg detectors (UChicago, NCSU)

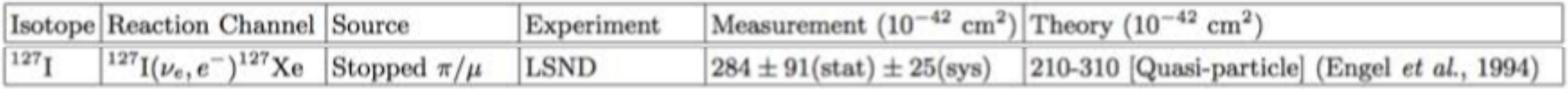
Sodium Iodide (NaI[Tl]) Detectors (NaIvE)

- up to 9 tons available, 2 tons in hand
- QF measured
- require PMT base refurbishment (dual gain) to enable low threshold for CEvNS on Na measurement
- development and instrumentation tests underway at UW, Duke

Multi-ton concept



In the meantime: **185 kg deployed at SNS** to go after ν_e**CC on** ^{127}**I**

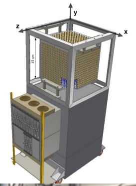


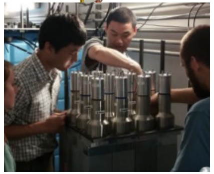
Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{127}I	^{127}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

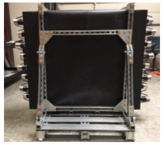
J.A. Formaggio and G. Zeller, RMP 84 (2012) 1307-1341

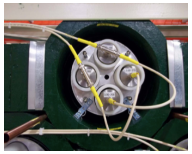
COHERENT Non-CEvNS Detectors ("In-COHERENT")

Sandia Neutron Scatter Camera	Multiplane liquid scintillator	Neutron background	Deployed 2014-2016
SciBath	WLS fiber + liquid scintillator	Neutron background	Deployed 2015
NaI[Tl]	Scintillating crystal	ν_eCC	High-threshold deployment summer 2016
Lead Nube	Pb + liquid scintillator	NINs in lead	Deployed 2016
Iron Nube	Fe + liquid scintillator	NINs in iron	Deployed 2017
MARS	Plastic scintillator and Gd sandwich	Neutron background	Under deployment
Mini-HALO	Pb + NCDs	NINs in lead	In design





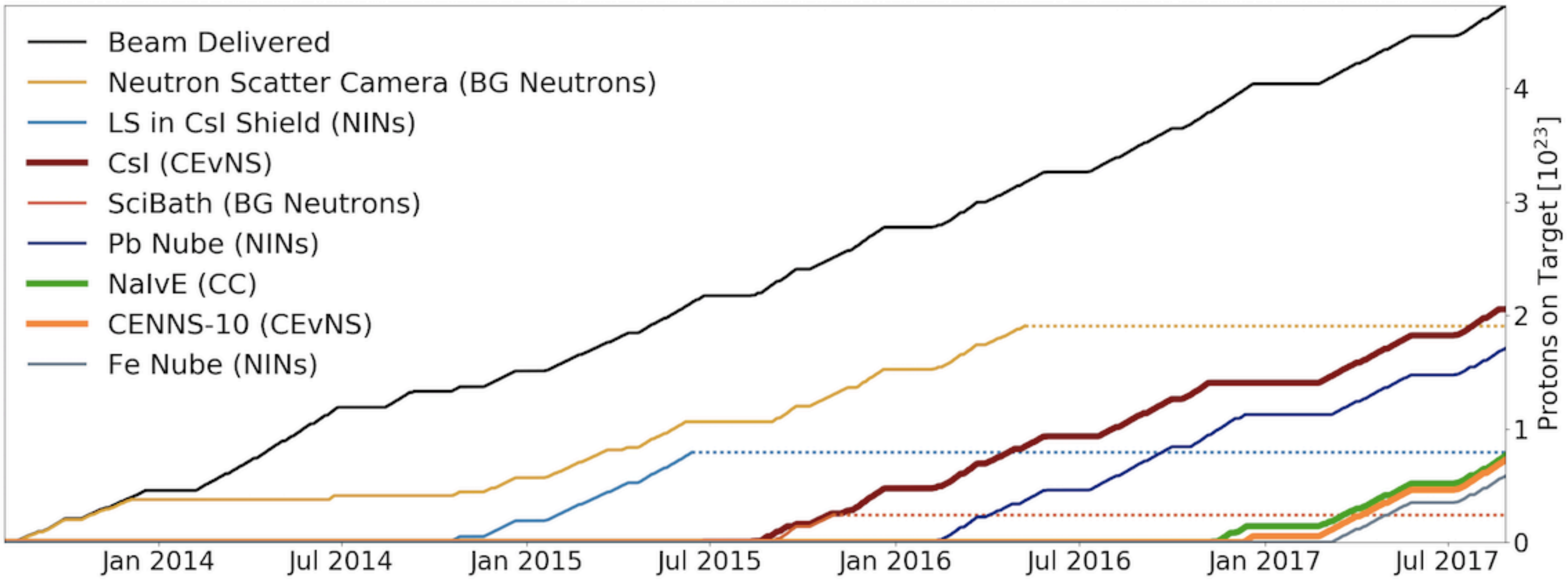


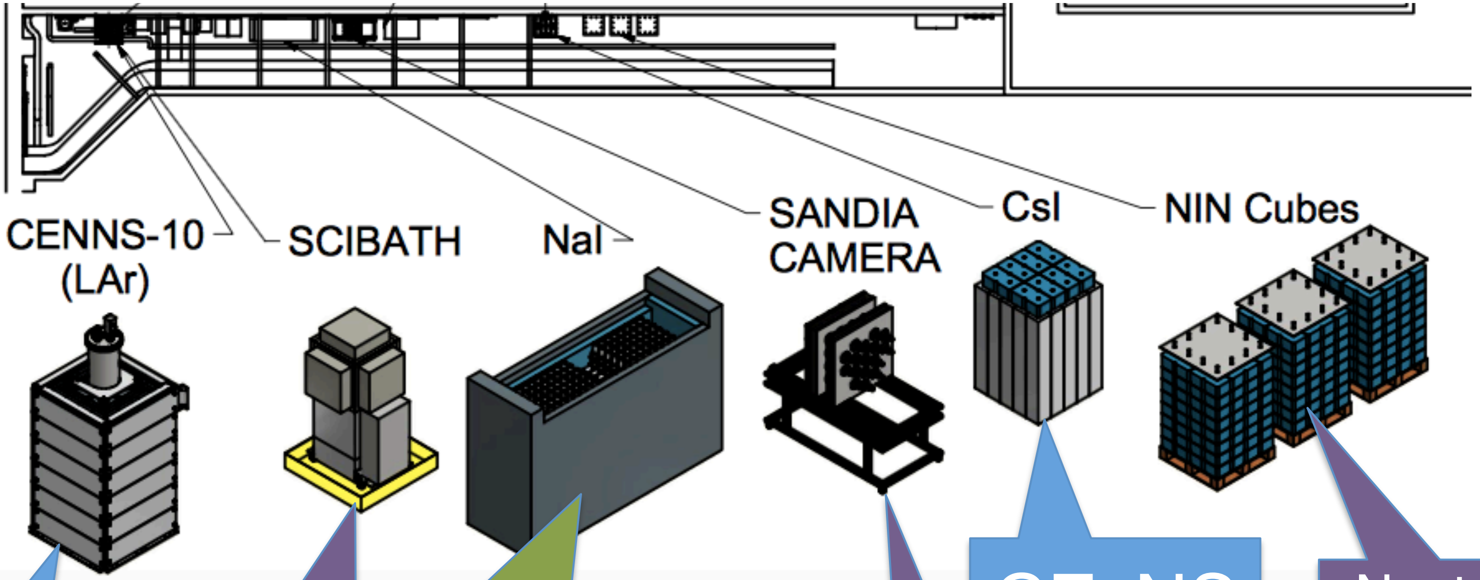


And many more ideas and activities for Neutrino Alley and beyond...

- Inelastic CC and NC in Ar, Pb, ...
- Other crystal or scint deployments in CsI shield
- Flux normalization using D_2O (well known xscn)
- Ancillary measurements: QF
- Directional detectors
- ...

Protons on target delivered so far





CEvNS

Neutron backgrounds

ν_eCC on ^{127}I

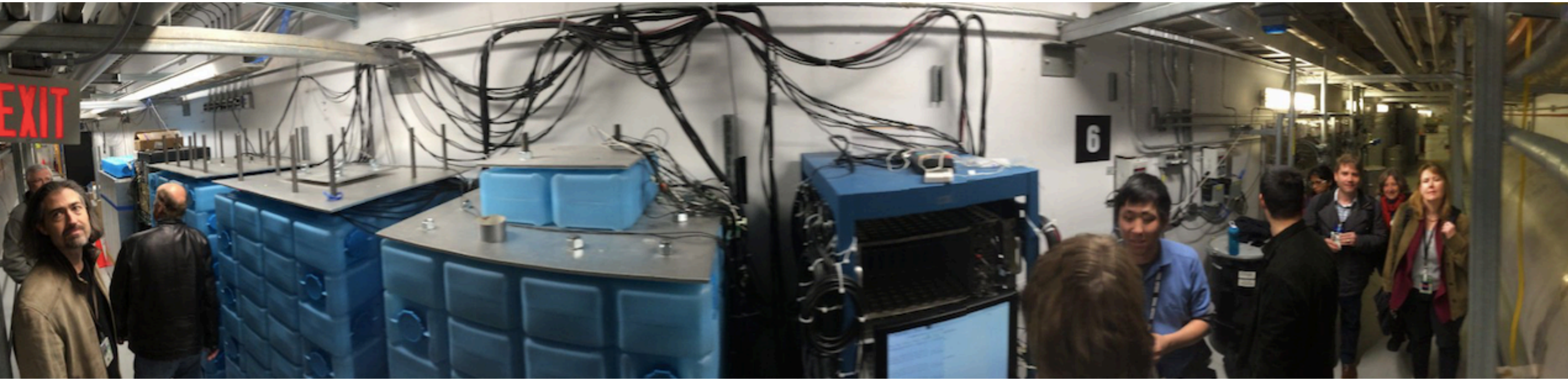
Neutron backgrounds

CEvNS

Neutrino-induced neutrons

Summary

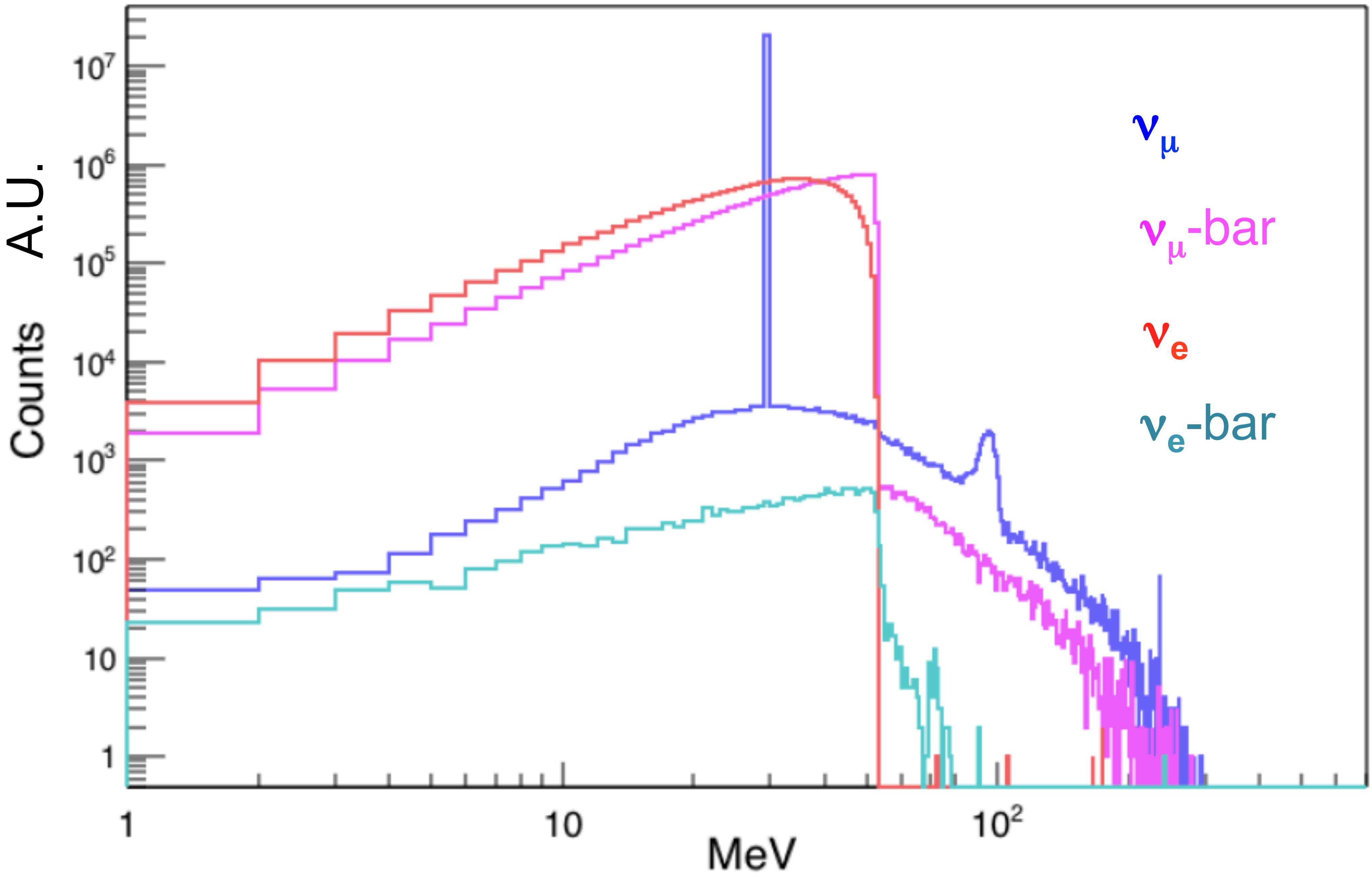
- **First measurement of CEvNS** in COHERENT CsI[Na] in Neutrino Alley at the SNS
- Multiple physics motivations
  - DM bg, SM test, astrophysics, nuclear physics, ...
- Low-hanging fruit: **meaningful bounds on ν NSI**



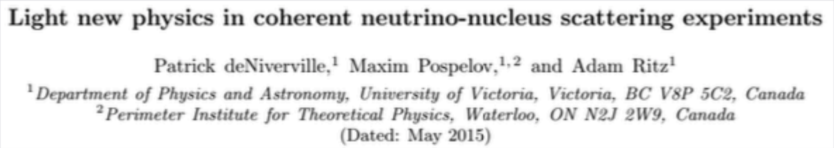
- **It's just the beginning....**
- Multiple targets, upgrades and new ideas in the works!
- Other CEvNS experiments will soon join the fun (CONNIE, CONUS, MINER, RED, Ricochet, Nu-cleus...)

Extras/backups

Spectrum including very small contribution of ν_e-bar



Light DM
direct detection
possibilities



Light new physics in coherent neutrino-nucleus scattering experiments

Patrick deNiverville,[1] Maxim Pospelov,[1,2] and Adam Ritz[1]

[1]*Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 5C2, Canada*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
(Dated: May 2015)

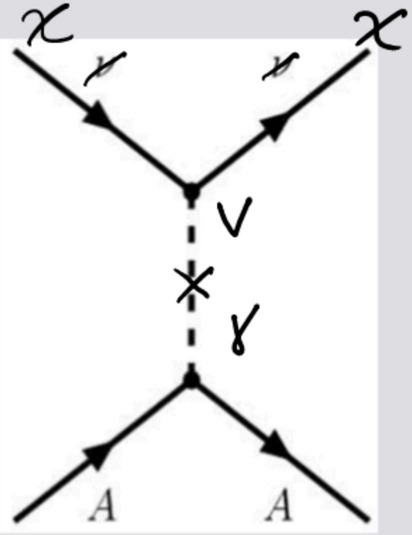
production:

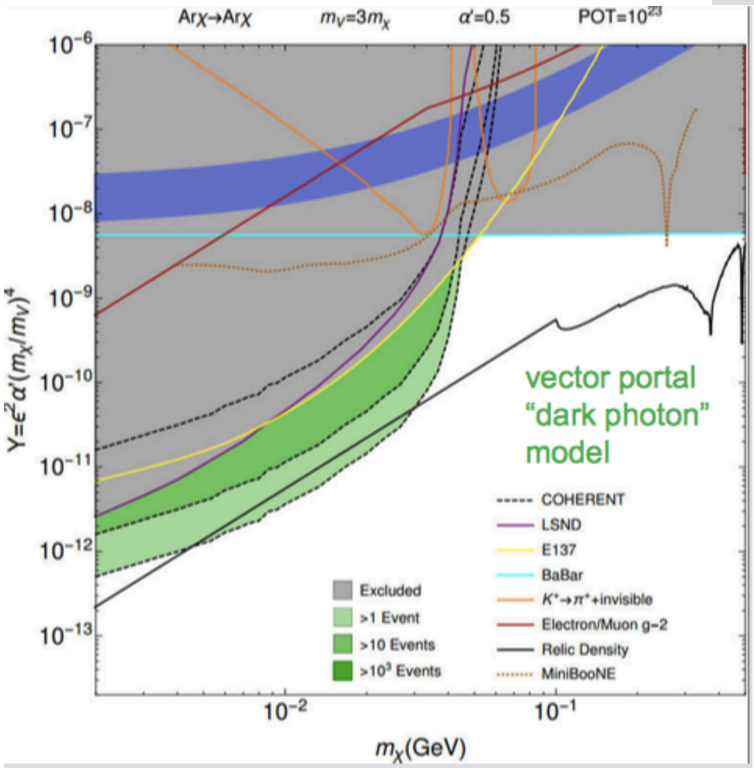
proton → target → $\pi^{0,\pm}$ →

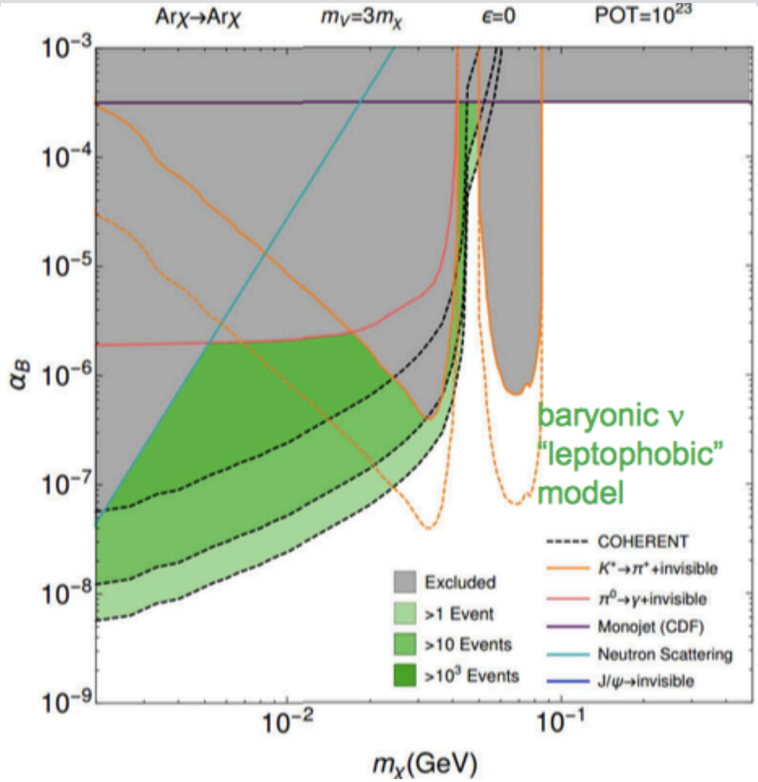
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

$$\pi^- + p \longrightarrow n + V^{(*)} \longrightarrow n + \chi^\dagger + \chi$$

detection:





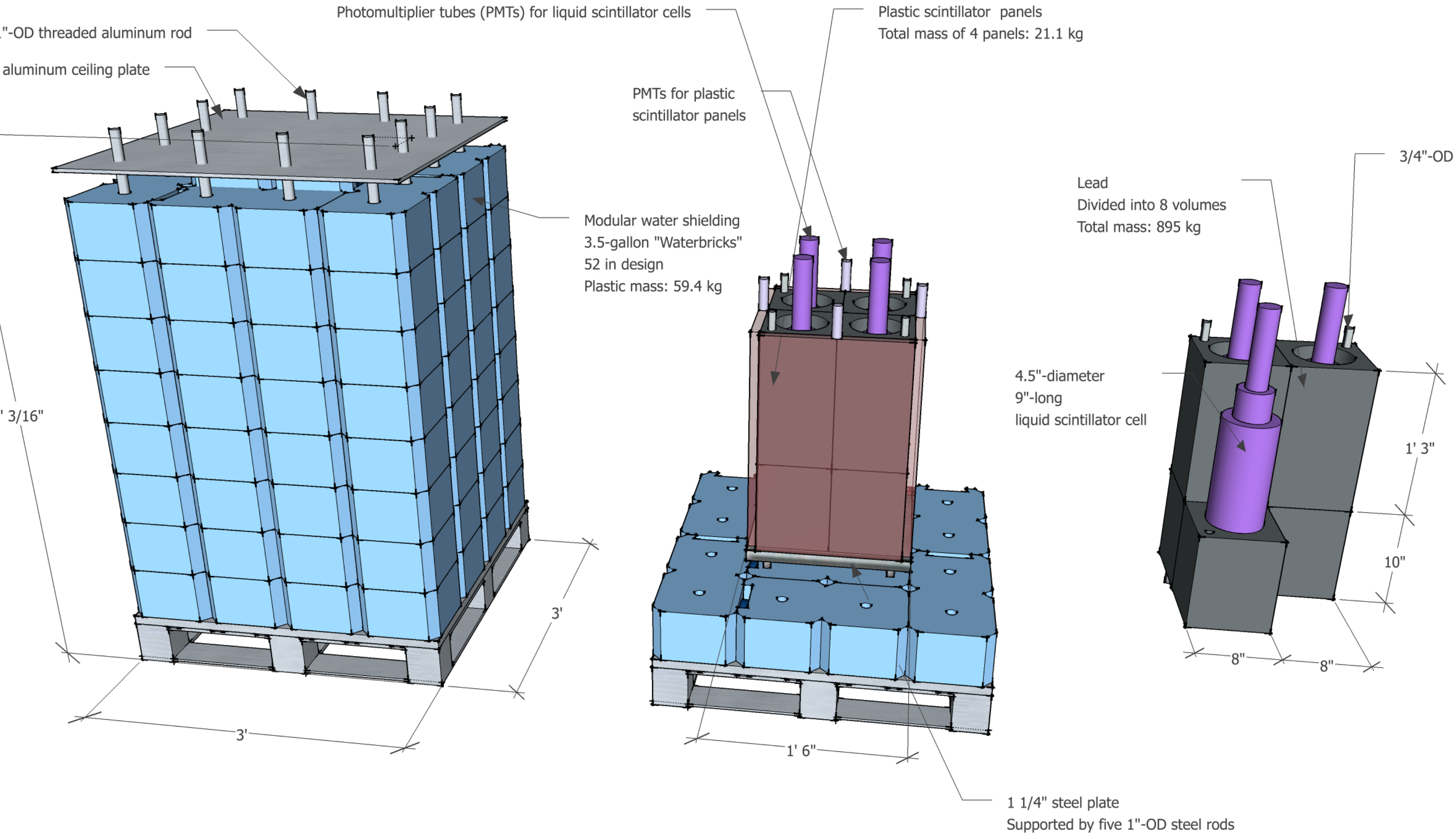


1 ton LAr
E_{rec}>20keVnr
10^{23} POT

R. Tayloe
Cosmic Visions 2017

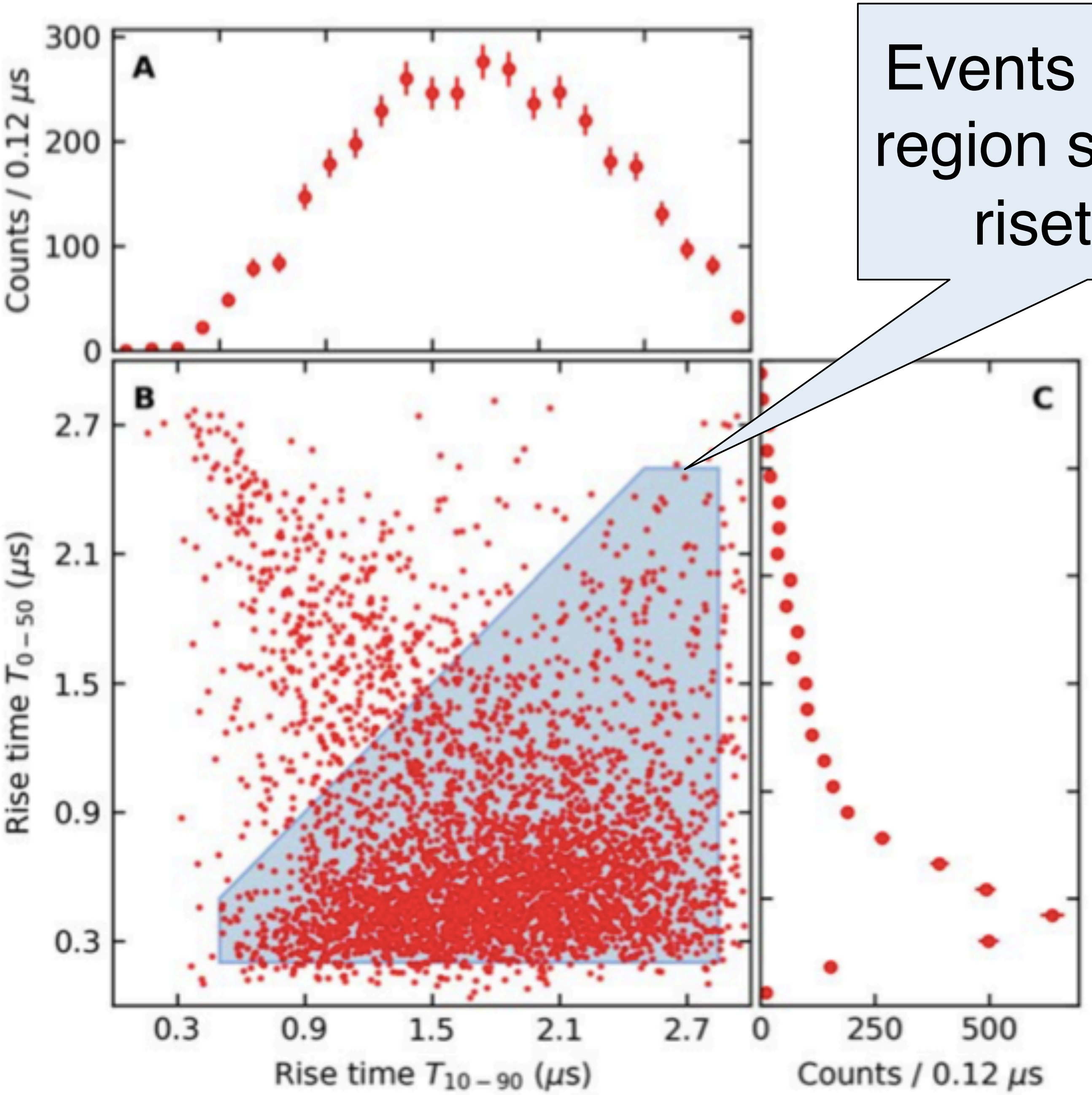
NIN measurement in SNS basement with Nubes

Liquid scintillator surrounded by Pb, Fe (swappable for other NIN targets) inside water shield

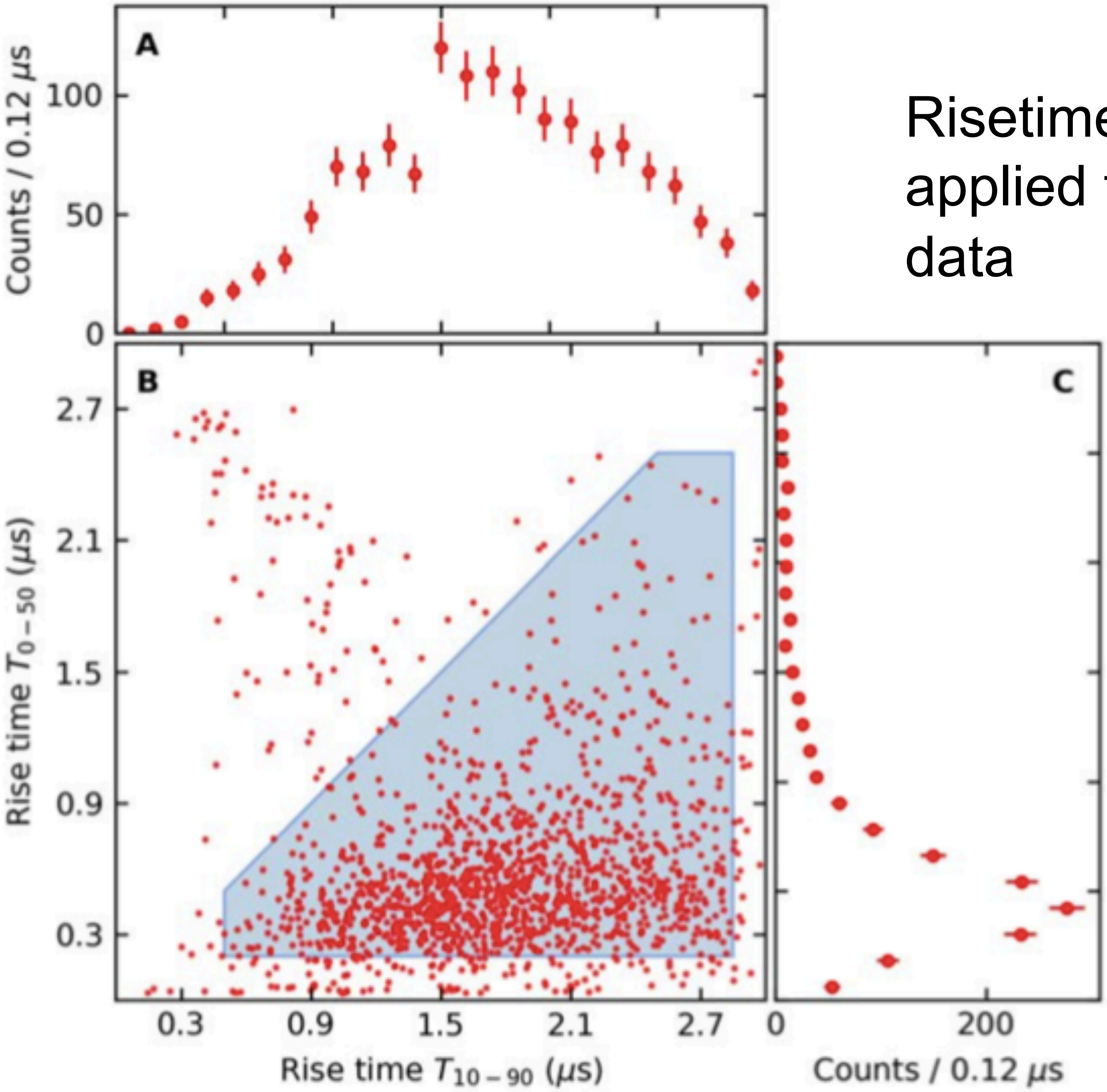


P. Barbeau

Evaluation of 14.6-kg detector risetime-cut efficiency w/ ^{133}Ba data



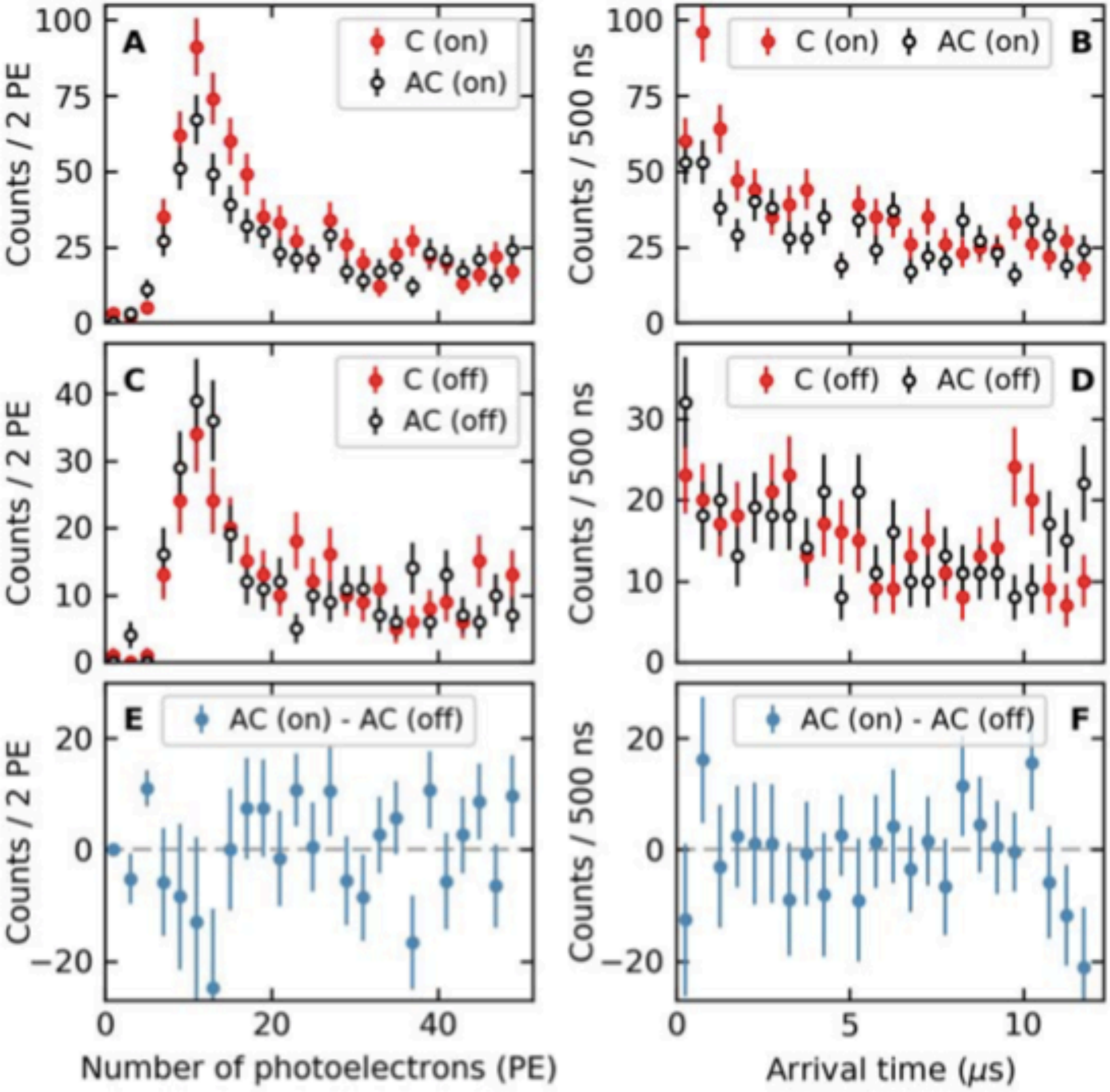
Events in shaded region selected by risetime cut



Risetime cut applied to SNS data

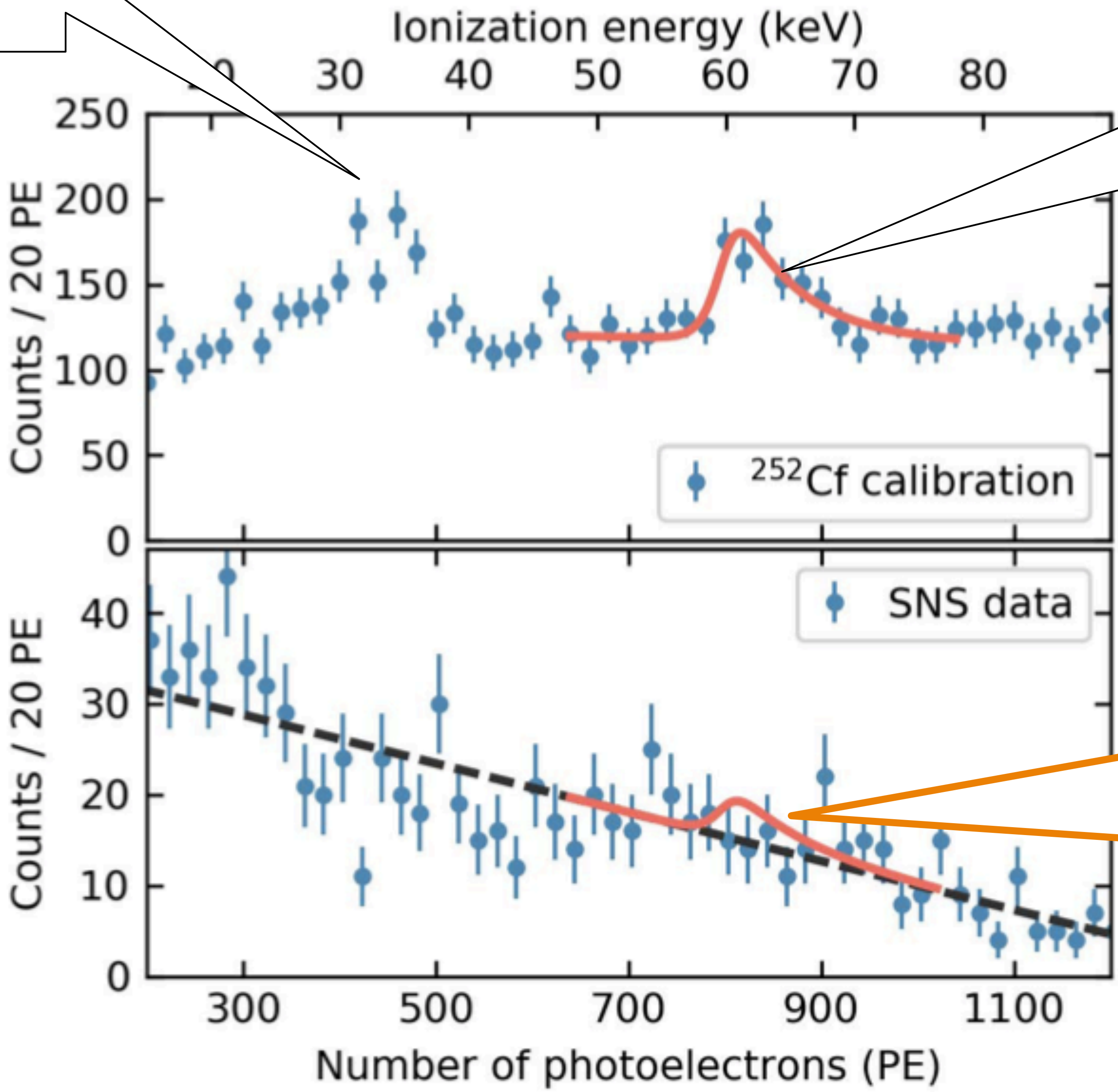
Charge

Time



A
C (on)
AC (on)
Counts / 2 PE
100
75
50
25
0
B
C (on)
AC (on)
Counts / 500 ns
C
C (off)
AC (off)
40
30
20
10
D
C (off)
AC (off)
E
AC (on) - AC (off)
−20
F
AC (on) - AC (off)
Number of photoelectrons (PE)
Arrival time (μs)
0
5
10
20
40

In-Situ bg limit on in-beam neutrons



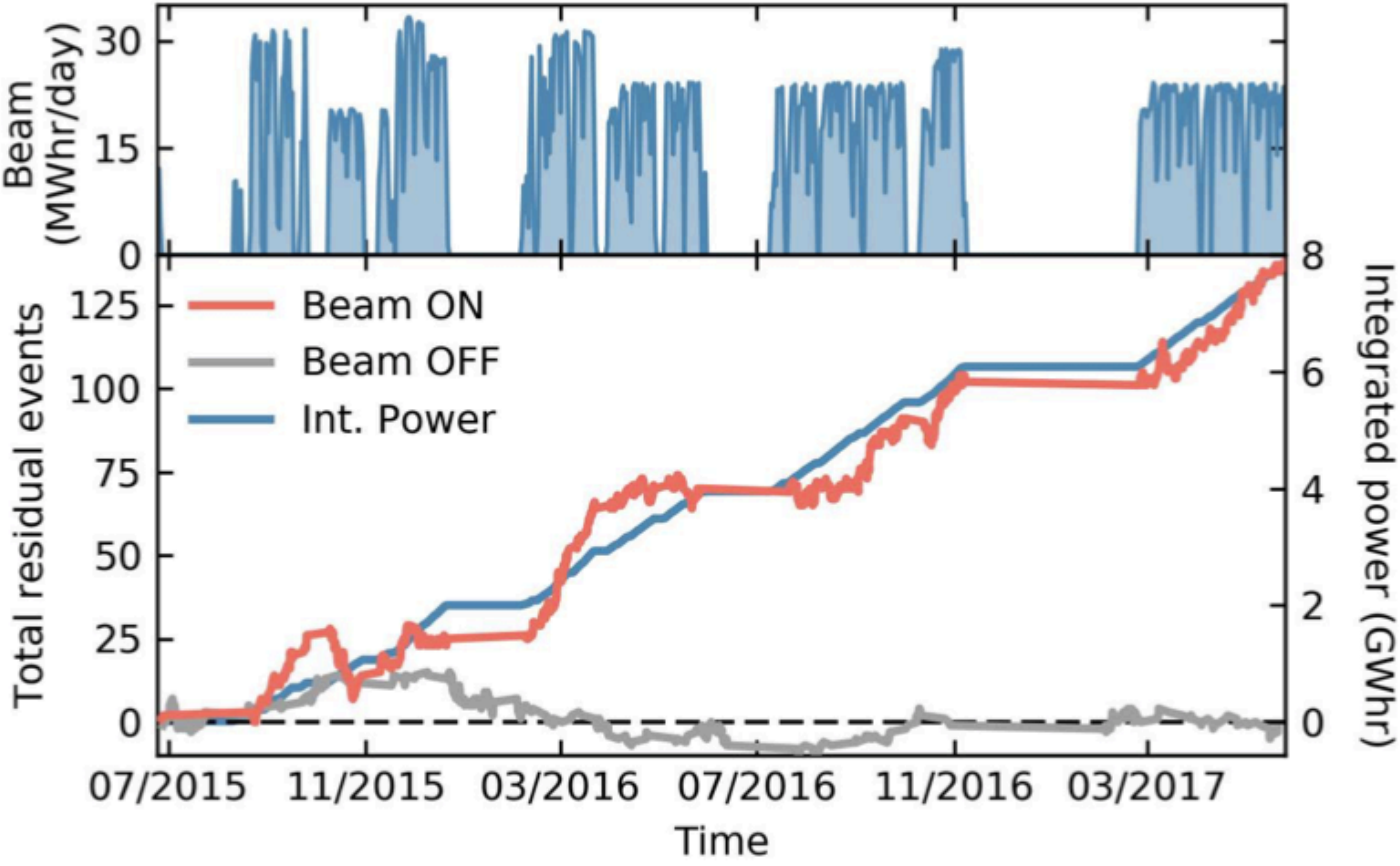
Electron capture decay of ^{128}I at 31.8 keV

Inelastic scattering peak (57.6 keV) recoil + γ's

Neutron source outside shielding

90% CL maximum allowed neutron counts for Beam-ON data

Total residual counts vs time
consistent w/ entirely beam-induced events



χ^2 with pull for our situation, including background

(simple one-bin analysis)

$$\chi^2 = \frac{\left(N_{\text{meas}} - N_{NSI}(\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV})[1+\alpha] - B_{\text{on}}[1+\beta]\right)^2}{\sigma_{\text{stat}}^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2 .$$

N_{meas} steady-state background-subtracted counts

$N_{\text{NSI}}(\varepsilon_{ee}^{uV}, \varepsilon_{ee}^{dV})$ expected signal with NSI

B_{ss} expected steady-state background

B_{on} expected beam-on background

$$\sigma_{\text{stat}} = \sqrt{N_{\text{meas}} + 2B_{\text{SS}} + B_{\text{on}}}$$

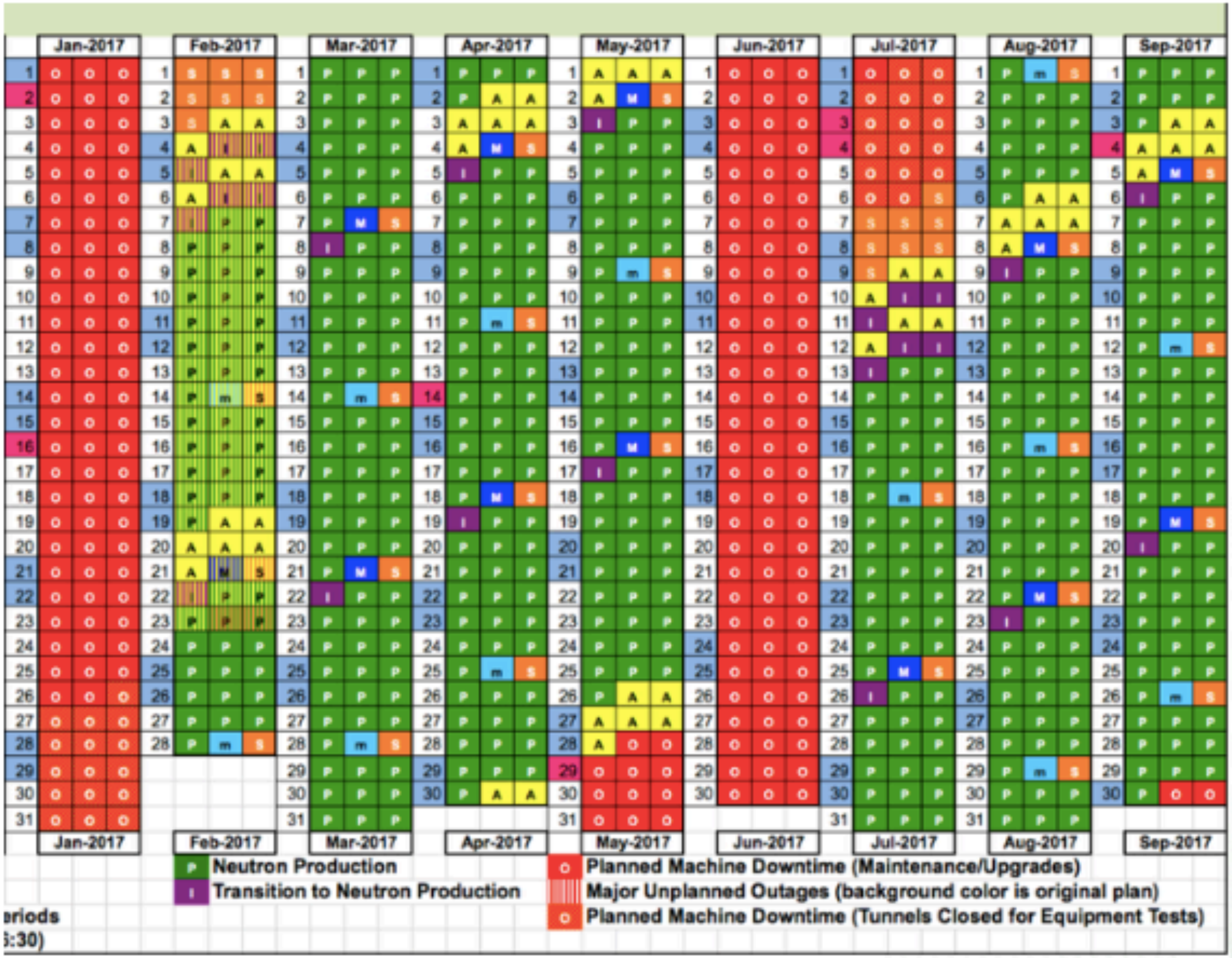
$\sigma_{\text{sys,SS}} = 0$ expected systematic on steady-state bg (assume zero because well measured)

α: for signal normalization systematic uncertainty

β: for beam-on background normalization uncertainty

SNS Beam Schedule

- 2100 hours @ 1 MW
- 1600 hours @ 1.2 MW



	Jan-2017			Feb-2017			Mar-2017			Apr-2017			May-2017			Jun-2017			Jul-2017			Aug-2017			Sep-2017		
1	O	O	O	S	S	S	P	P	P	P	P	P	A	A	A	O	O	O	O	O	O	P	m	S	P	P	P
2	O	O	O	S	S	S	P	P	P	P	A	A	A	M	S	O	O	O	O	O	O	P	P	P	P	P	P
3	O	O	O	S	A	A	P	P	P	A	A	A	I	P	P	O	O	O	O	O	O	P	P	P	P	A	A
4	O	O	O	A	I	I	P	P	P	A	M	S	P	P	P	O	O	O	O	O	O	P	P	P	A	A	A
5	O	O	O	I	A	A	P	P	P	I	P	P	P	P	P	O	O	O	O	O	O	P	P	P	A	M	S
6	O	O	O	A	I	I	P	P	P	P	P	P	P	P	P	O	O	O	O	O	S	P	A	A	I	P	P
7	O	O	O	I	P	P	P	M	S	P	P	P	P	P	P	O	O	O	S	S	S	A	A	A	P	P	P
8	O	O	O	P	P	P	I	P	P	P	P	P	P	P	P	O	O	O	S	S	S	A	M	S	P	P	P
9	O	O	O	P	P	P	P	P	P	P	P	P	P	m	S	O	O	O	S	A	A	I	P	P	P	P	P
10	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P	O	O	O	A	I	I	P	P	P	P	P	P
11	O	O	O	P	P	P	P	P	P	P	m	S	P	P	P	O	O	O	I	A	A	P	P	P	P	P	P
12	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P	O	O	O	A	I	I	P	P	P	P	m	S
13	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P	O	O	O	I	P	P	P	P	P	P	P	P
14	O	O	O	P	m	S	P	m	S	P	P	P	P	P	P	O	O	O	P	P	P	P	P	P	P	P	P
15	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P	O	O	O	P	P	P	P	P	P	P	P	P
16	O	O	O	P	P	P	P	P	P	P	P	P	P	M	S	O	O	O	P	P	P	P	m	S	P	P	P
17	O	O	O	P	P	P	P	P	P	P	P	P	I	P	P	O	O	O	P	P	P	P	P	P	P	P	P
18	O	O	O	P	P	P	P	P	P	P	M	S	P	P	P	O	O	O	P	m	S	P	P	P	P	P	P
19	O	O	O	P	A	A	P	P	P	I	P	P	P	P	P	O	O	O	P	P	P	P	P	P	P	M	S
20	O	O	O	A	A	A	P	P	P	P	P	P	P	P	P	O	O	O	P	P	P	P	P	P	I	P	P
21	O	O	O	A	M	S	P	M	S	P	P	P	P	P	P	O	O	O	P	P	P	P	P	P	P	P	P
22	O	O	O	I	P	P	I	P	P	P	P	P	P	P	P	O	O	O	P	P	P	P	M	S	P	P	P
23	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P	O	O	O	P	P	P	I	P	P	P	P	P
24	O	O	O	P	P	P	P	P	P	P	P	P	P	P	P	O	O	O	P	P	P	P	P	P	P	P	P
25	O	O	O	P	P	P	P	P	P	P	m	S	P	P	P	O	O	O	P	M	S	P	P	P	P	P	P
26	O	O	O	P	P	P	P	P	P	P	P	P	P	A	A	O	O	O	I	P	P	P	P	P	P	m	S
27	O	O	O	P	P	P	P	P	P	P	P	P	A	A	A	O	O	O	P	P	P	P	P	P	P	P	P
28	O	O	O	P	m	S	P	m	S	P	P	P	A	O	O	O	O	O	P	P	P	P	P	P	P	P	P
29	O	O	O				P	P	P	P	P	P	O	O	O	O	O	O	P	P	P	P	m	S	P	P	P
30	O	O	O				P	P	P	P	A	A	O	O	O	O	O	O	P	P	P	P	P	P	P	O	O
31	O	O	O				P	P	P				O	O	O				P	P	P	P	P	P			
	Jan-2017			Feb-2017			Mar-2017			Apr-2017			May-2017			Jun-2017			Jul-2017			Aug-2017			Sep-2017		

P Neutron Production

I Transition to Neutron Production

O Planned Machine Downtime (Maintenance/Upgrades)

▥ Major Unplanned Outages (background color is original plan)

O Planned Machine Downtime (Tunnels Closed for Equipment Tests)

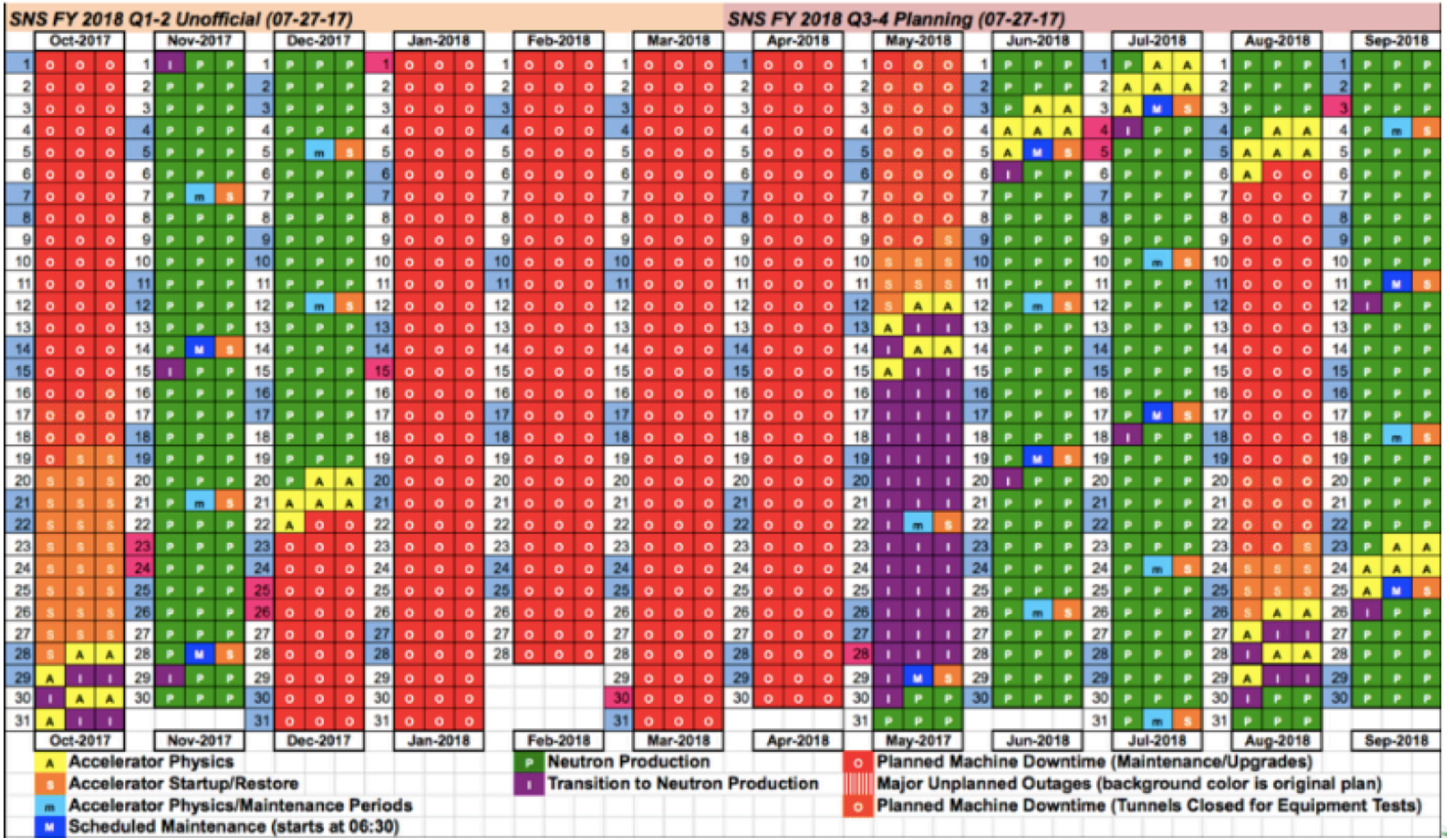
eriods

:30)

Production beam through September 30, 2017

SNS Beam Schedule

- 1100 hours @ 1.4 MW
- 5 month outage



SNS FY 2018 Q1-2 Unofficial (07-27-17)

	Oct-2017			Nov-2017			Dec-2017			Jan-2018			Feb-2018			Mar-2018		
1	O	O	O	I	P	P	P	P	P	O	O	O	O	O	O	O	O	O
2	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
3	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
4	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
5	O	O	O	P	P	P	P	m	S	O	O	O	O	O	O	O	O	O
6	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
7	O	O	O	P	m	S	P	P	P	O	O	O	O	O	O	O	O	O
8	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
9	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
10	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
11	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
12	O	O	O	P	P	P	P	m	S	O	O	O	O	O	O	O	O	O
13	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
14	O	O	O	P	M	S	P	P	P	O	O	O	O	O	O	O	O	O
15	O	O	O	I	P	P	P	P	P	O	O	O	O	O	O	O	O	O
16	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
17	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
18	O	O	O	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
19	O	S	S	P	P	P	P	P	P	O	O	O	O	O	O	O	O	O
20	S	S	S	P	P	P	P	A	A	O	O	O	O	O	O	O	O	O
21	S	S	S	P	m	S	A	A	A	O	O	O	O	O	O	O	O	O
22	S	S	S	P	P	P	A	O	O	O	O	O	O	O	O	O	O	O
23	S	S	S	P	P	P	O	O	O	O	O	O	O	O	O	O	O	O
24	S	S	S	P	P	P	O	O	O	O	O	O	O	O	O	O	O	O
25	S	S	S	P	P	P	O	O	O	O	O	O	O	O	O	O	O	O
26	S	S	S	P	P	P	O	O	O	O	O	O	O	O	O	O	O	O
27	S	S	S	P	P	P	O	O	O	O	O	O	O	O	O	O	O	O
28	S	A	A	P	M	S	O	O	O	O	O	O	O	O	O	O	O	O
29	A	I	I	I	P	P	O	O	O	O	O	O				O	O	O
30	I	A	A	P	P	P	O	O	O	O	O	O				O	O	O
31	A	I	I				O	O	O	O	O	O				O	O	O
	Oct-2017			Nov-2017			Dec-2017			Jan-2018			Feb-2018			Mar-2018		

SNS FY 2018 Q3-4 Planning (07-27-17)

	Apr-2018			May-2018			Jun-2018			Jul-2018			Aug-2018			Sep-2018		
1	O	O	O	O	O	O	P	P	P	P	A	A	P	P	P	P	P	P
2	O	O	O	O	O	O	P	P	P	A	A	A	P	P	P	P	P	P
3	O	O	O	O	O	O	P	A	A	A	M	S	P	P	P	P	P	P
4	O	O	O	O	O	O	A	A	A	I	P	P	P	A	A	P	m	S
5	O	O	O	O	O	O	A	M	S	P	P	P	A	A	A	P	P	P
6	O	O	O	O	O	O	I	P	P	P	P	P	A	O	O	P	P	P
7	O	O	O	O	O	O	P	P	P	P	P	P	O	O	O	P	P	P
8	O	O	O	O	O	O	P	P	P	P	P	P	O	O	O	P	P	P
9	O	O	O	O	O	S	P	P	P	P	P	P	O	O	O	P	P	P
10	O	O	O	S	S	S	P	P	P	P	m	S	O	O	O	P	P	P
11	O	O	O	S	S	S	P	P	P	P	P	P	O	O	O	P	M	S
12	O	O	O	S	A	A	P	m	S	P	P	P	O	O	O	I	P	P
13	O	O	O	A	I	I	P	P	P	P	P	P	O	O	O	P	P	P
14	O	O	O	I	A	A	P	P	P	P	P	P	O	O	O	P	P	P
15	O	O	O	A	I	I	P	P	P	P	P	P	O	O	O	P	P	P
16	O	O	O	I	I	I	P	P	P	P	P	P	O	O	O	P	P	P
17	O	O	O	I	I	I	P	P	P	P	M	S	O	O	O	P	P	P
18	O	O	O	I	I	I	P	P	P	I	P	P	O	O	O	P	m	S
19	O	O	O	I	I	I	P	M	S	P	P	P	O	O	O	P	P	P
20	O	O	O	I	I	I	I	P	P	P	P	P	O	O	O	P	P	P
21	O	O	O	I	I	I	P	P	P	P	P	P	O	O	O	P	P	P
22	O	O	O	I	m	S	P	P	P	P	P	P	O	O	O	P	P	P
23	O	O	O	I	I	I	P	P	P	P	P	P	O	O	S	P	A	A
24	O	O	O	I	I	I	P	P	P	P	m	S	S	S	S	A	A	A
25	O	O	O	I	I	I	P	P	P	P	P	P	S	S	S	A	M	S
26	O	O	O	I	I	I	P	m	S	P	P	P	S	A	A	I	P	P
27	O	O	O	I	I	I	P	P	P	P	P	P	A	I	I	P	P	P
28	O	O	O	I	I	I	P	P	P	P	P	P	I	A	A	P	P	P
29	O	O	O	I	M	S	P	P	P	P	P	P	A	I	I	P	P	P
30	O	O	O	I	P	P	P	P	P	P	P	P	I	P	P	P	P	P
31				P	P	P				P	m	S	P	P	P			
	Apr-2018			May-2017			Jun-2018			Jul-2018			Aug-2018			Sep-2018		

A Accelerator Physics
S Accelerator Startup/Restore
m Accelerator Physics/Maintenance Periods
M Scheduled Maintenance (starts at 06:30)
P Neutron Production
I Transition to Neutron Production
O Planned Machine Downtime (Maintenance/Upgrades)
▥ Major Unplanned Outages (background color is original plan)
O Planned Machine Downtime (Tunnels Closed for Equipment Tests)