CEvNS and NINs: Observation of
Coherent Elastic Neutrino-Nucleus Scattering

Kate Scholberg, Duke University
FSU Colloquium,
March 1, 2018

OUTLINE

- Neutrinos and neutrino interactions
- 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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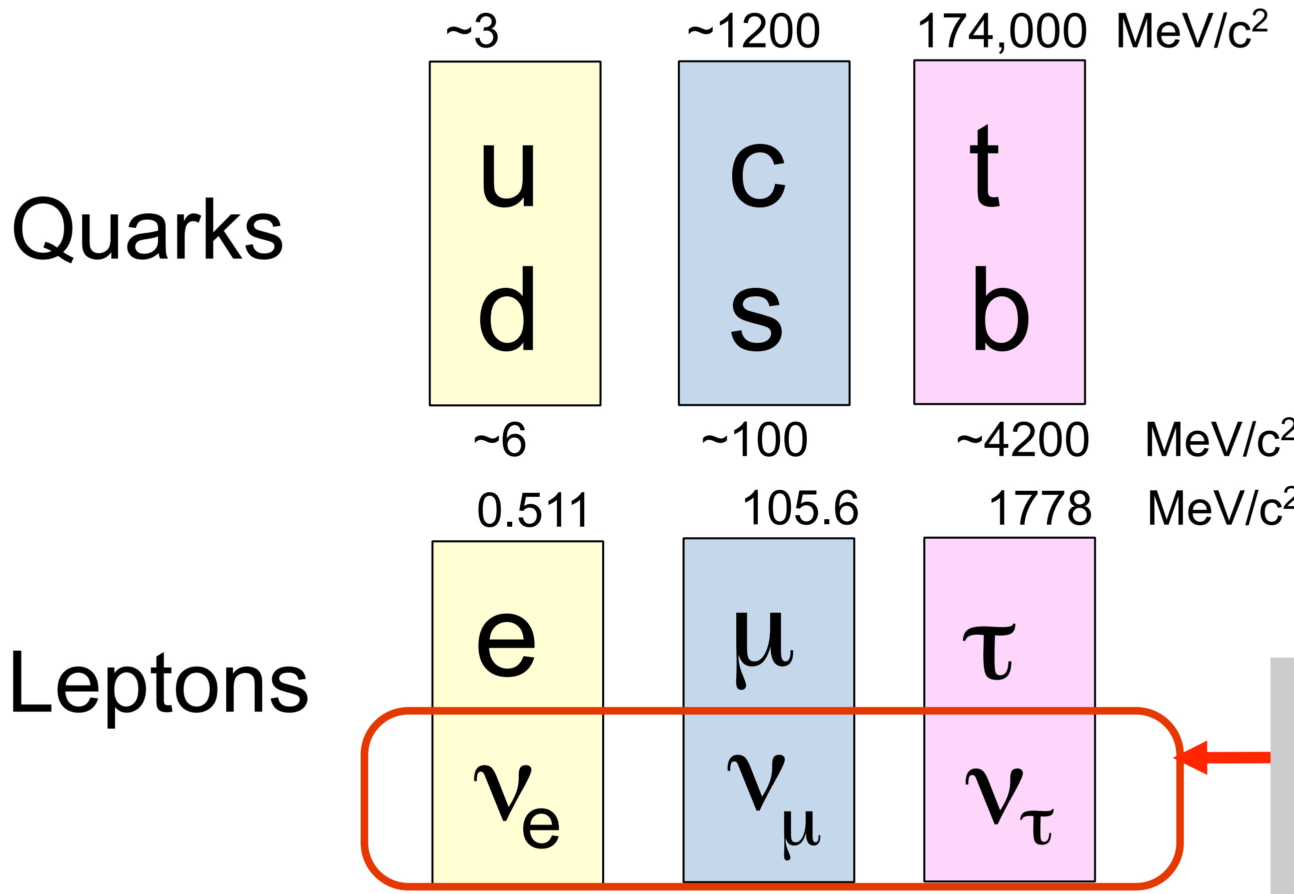
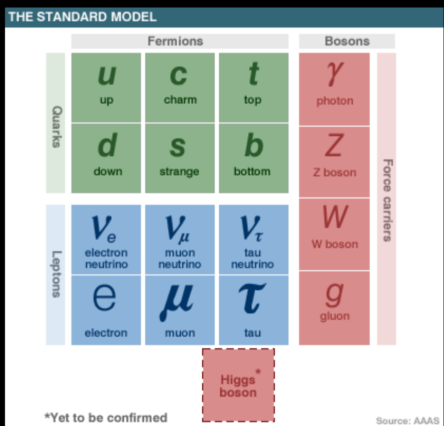
NEUTRINOS



In the Standard Model of particle physics, neutral partners to the charged leptons

- Spin 1/2
- Zero charge
- 3 flavors (families)
- Interact *only* via ***weak interaction*** (& gravity)
- Tiny mass (< 1 eV)

Why do neutrinos matter?



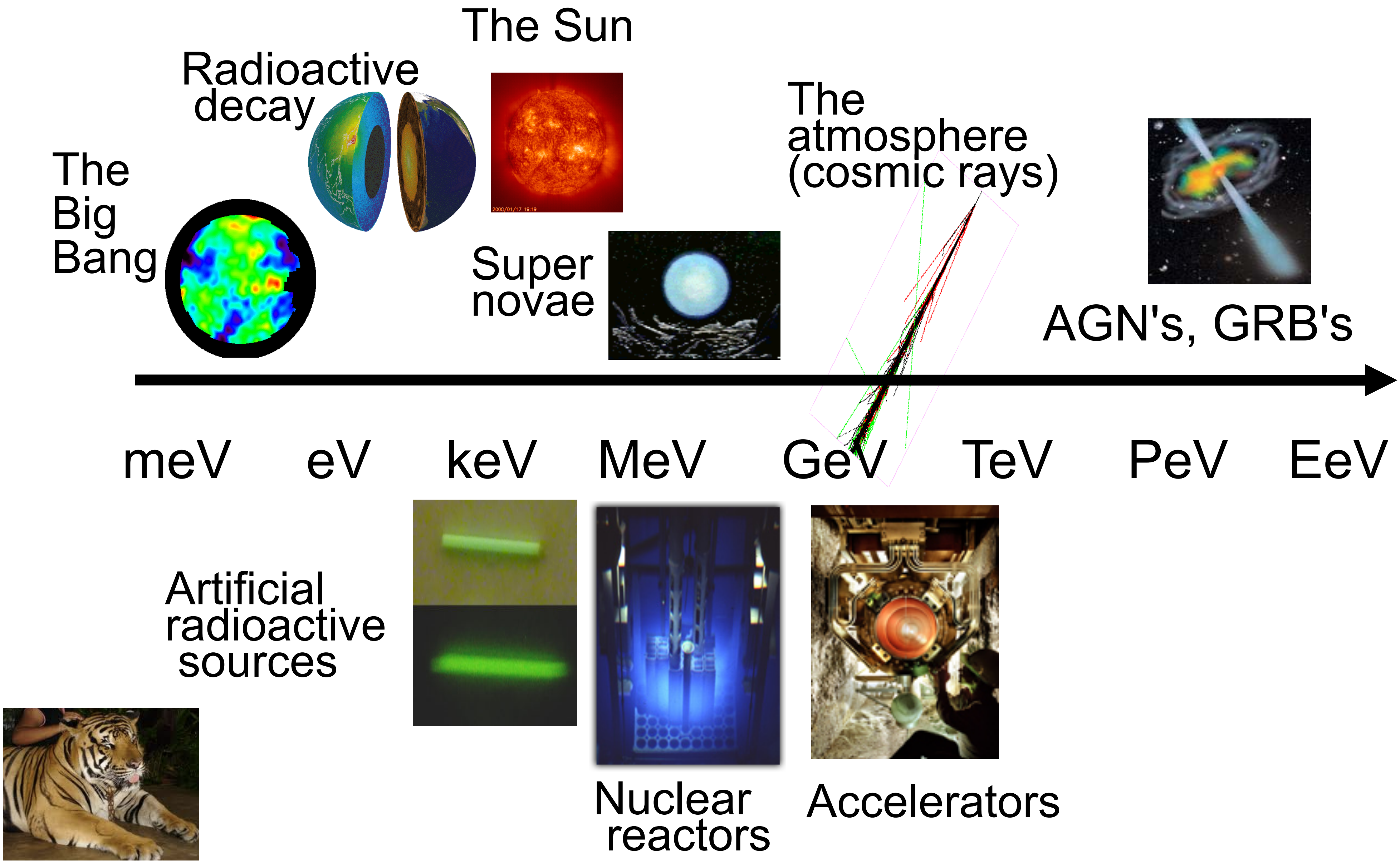
fundamental particles and interactions

astrophysical systems

cosmology

nuclear physics

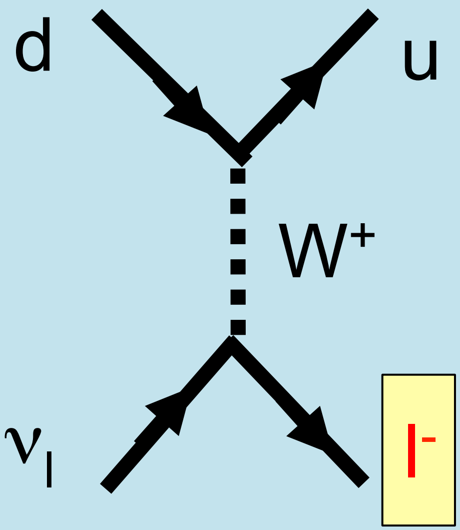
Wild and tame neutrinos



Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

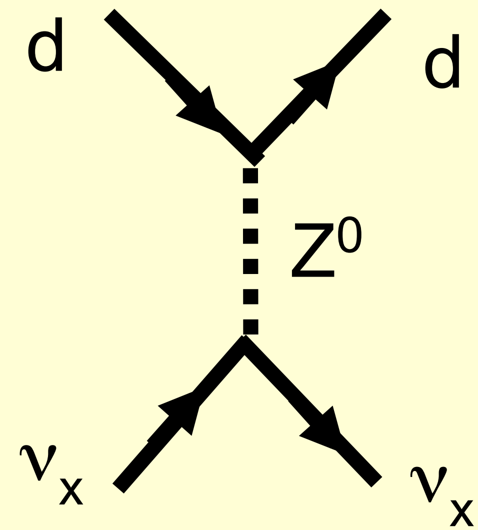


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy
to make lepton)

Neutral Current (NC)



Flavor-blind

Neutrino interactions with Nuclei

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

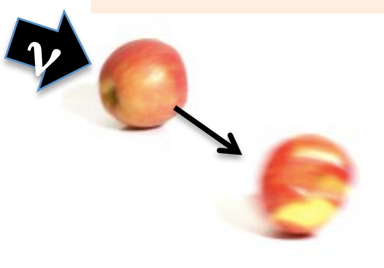
We are considering the low-energy regime and the ***gentlest*** interaction with nuclei

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

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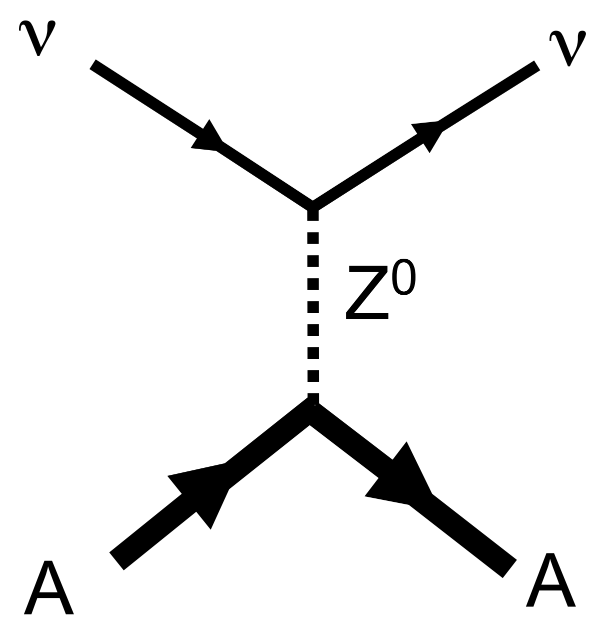
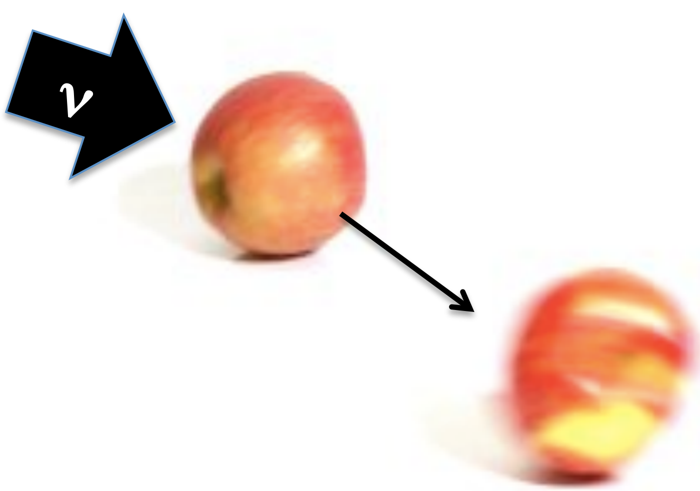
Coherent elastic neutrino-nucleus scattering (CEvNS)

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



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV



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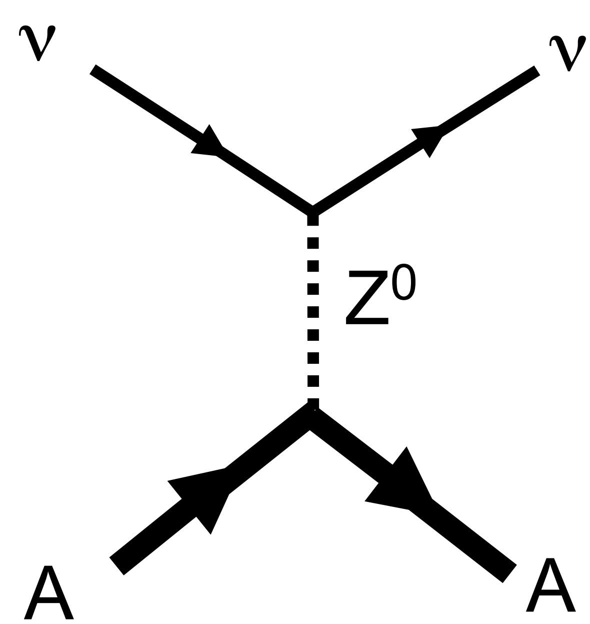
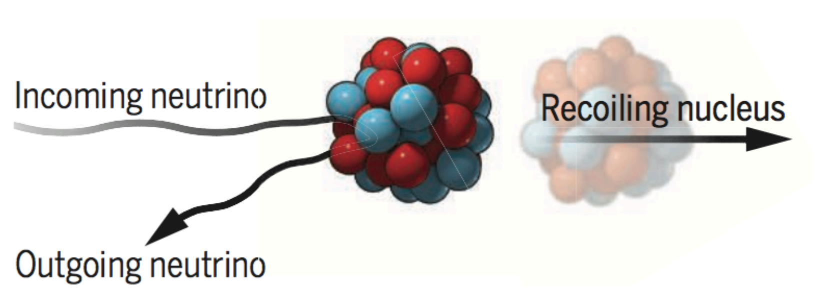


A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV



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

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

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

\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}

Standard Model prediction for differential cross section

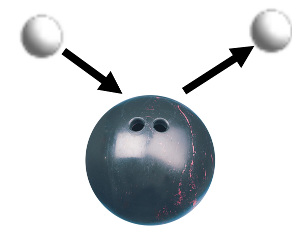
(probability of kicking a nucleus with recoil energy T)

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

Fermi constant (SM parameter)

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

kinematics:
ping-pong ball hits bowling ball



Form factor: F=1 ➔ full coherence

weak nuclear charge

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

Standard Model prediction for differential cross section

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weak nuclear charge

No. of neutrons

No. of protons

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

$\sin^2\theta_W = 0.231$, so protons unimportant $\Longrightarrow\ Q_W \propto N$

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

E_ν: neutrino energy
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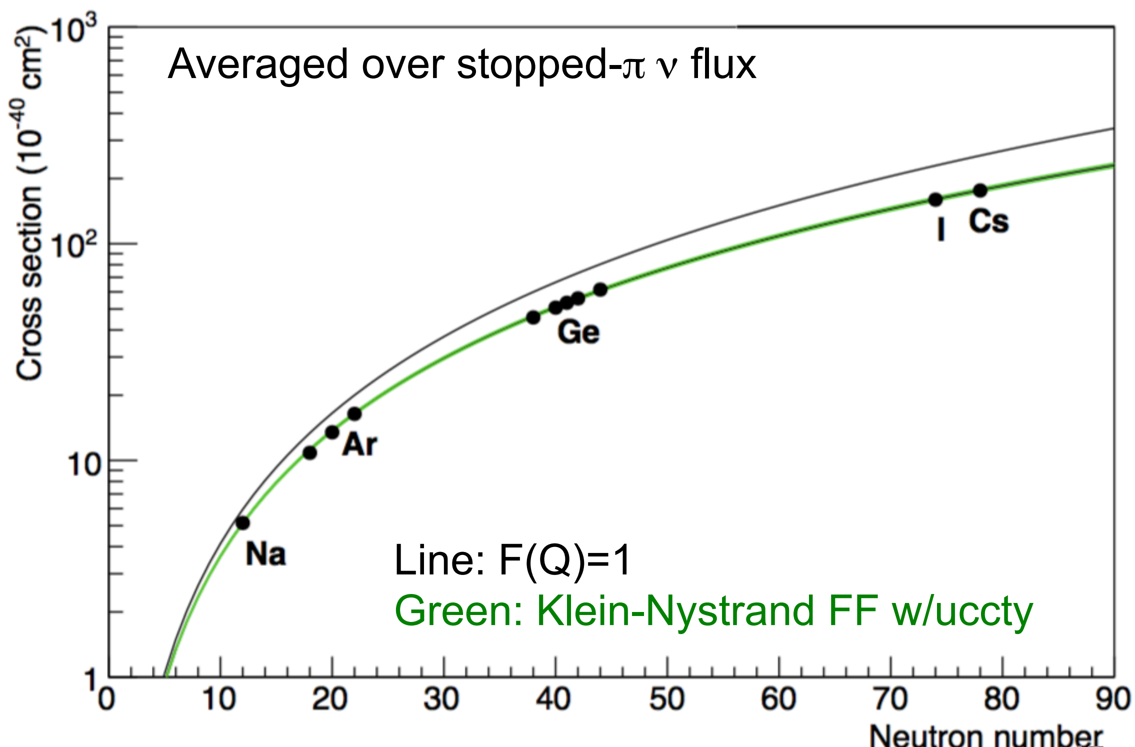
weak nuclear charge

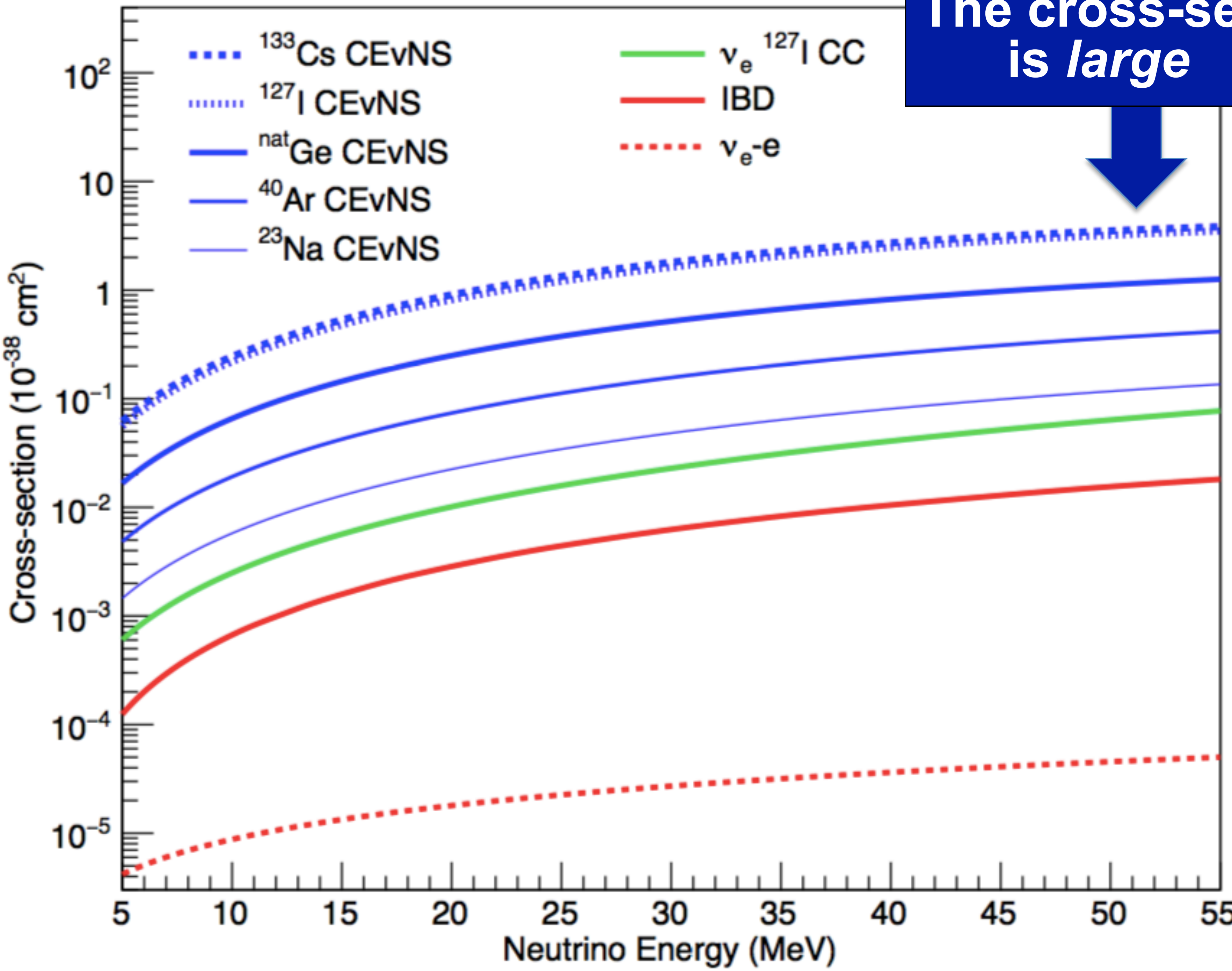
Form factor: F=1 ➔ full coherence

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

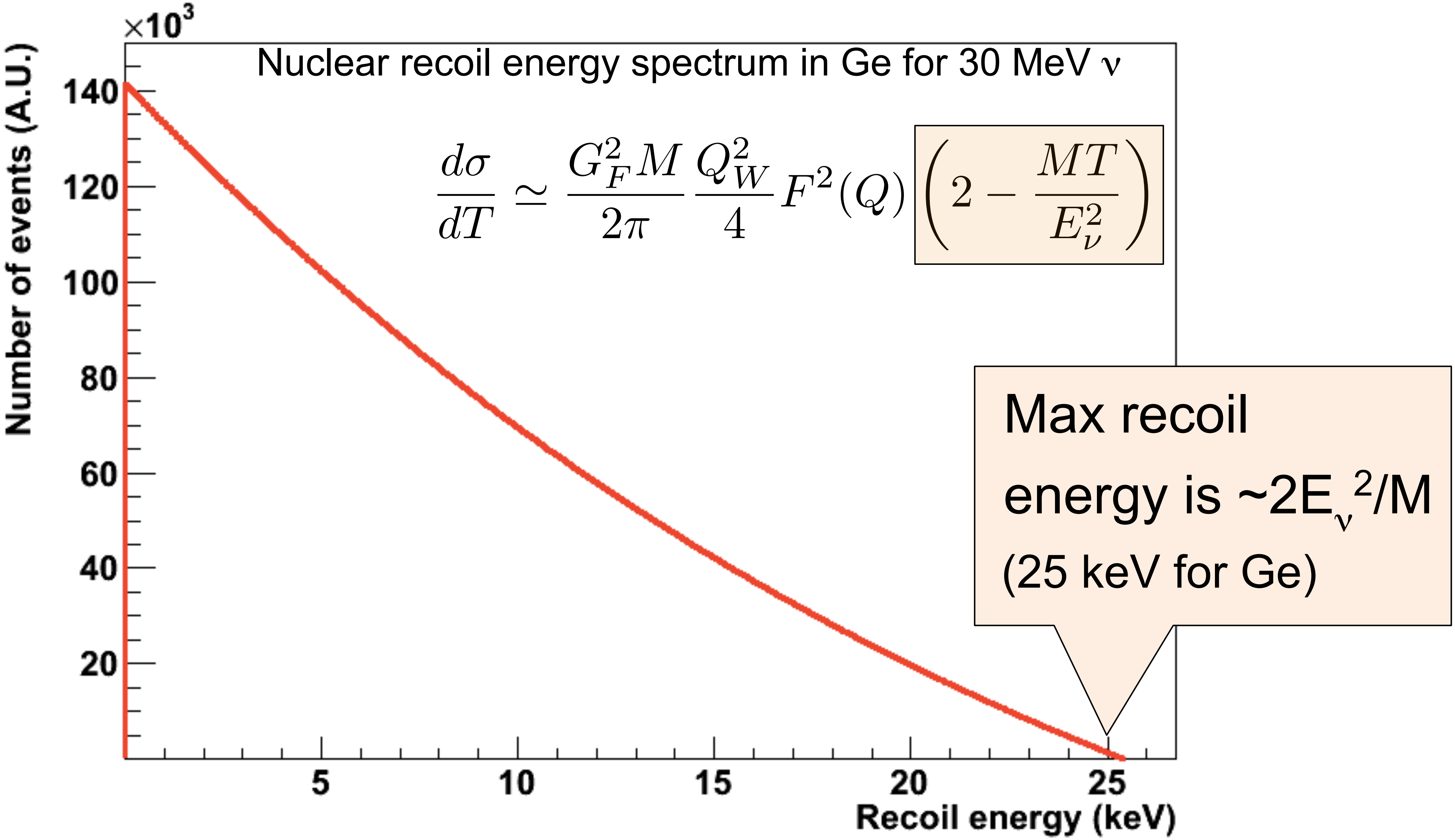
$$\Rightarrow \boxed{\frac{d\sigma}{dT} \propto N^2}$$



The cross-section is *large*

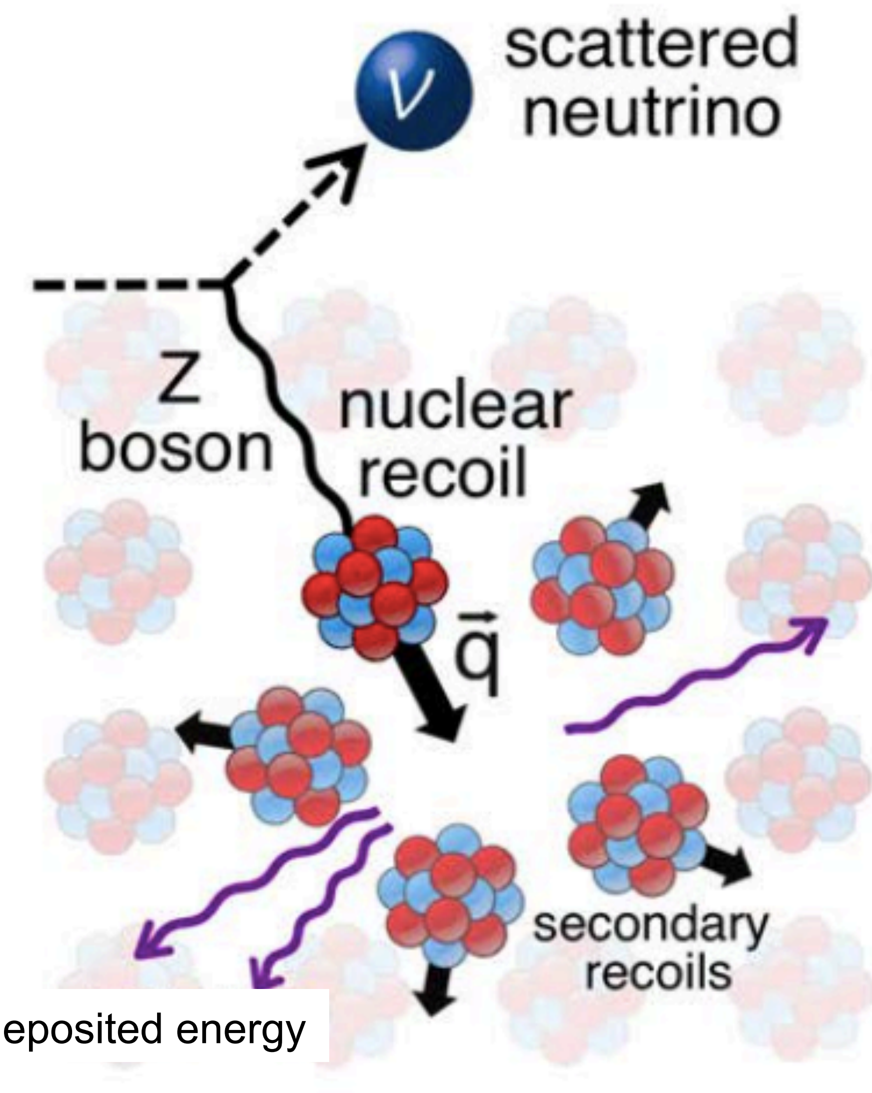


Large cross section (by neutrino standards) but hard to observe due to **tiny nuclear recoil energies:**



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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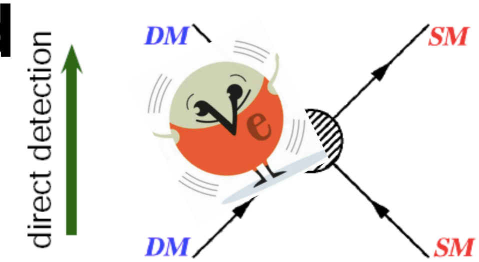
CEvNS: what's it good for?

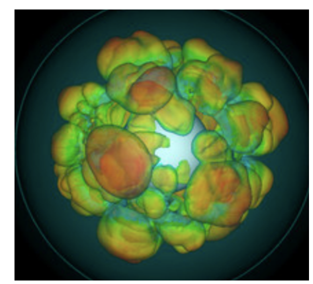
1 So
2 Many
3 Things
!

(not a complete list!)

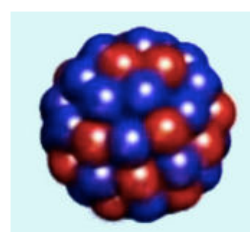


- **Dark matter direct-detection background**
- Well-calculable cross-section in SM:
    - $\sin^2\theta_{Weff}$ at low Q
    - **Probe of Beyond-the-SM physics**
        - Non-standard interactions of neutrinos
        - New NC mediators
        - Neutrino magnetic moment

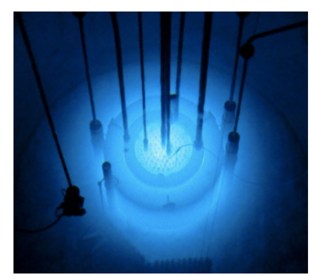
- New tool for sterile neutrino oscillations
- **Astrophysical signals (solar & SN)**



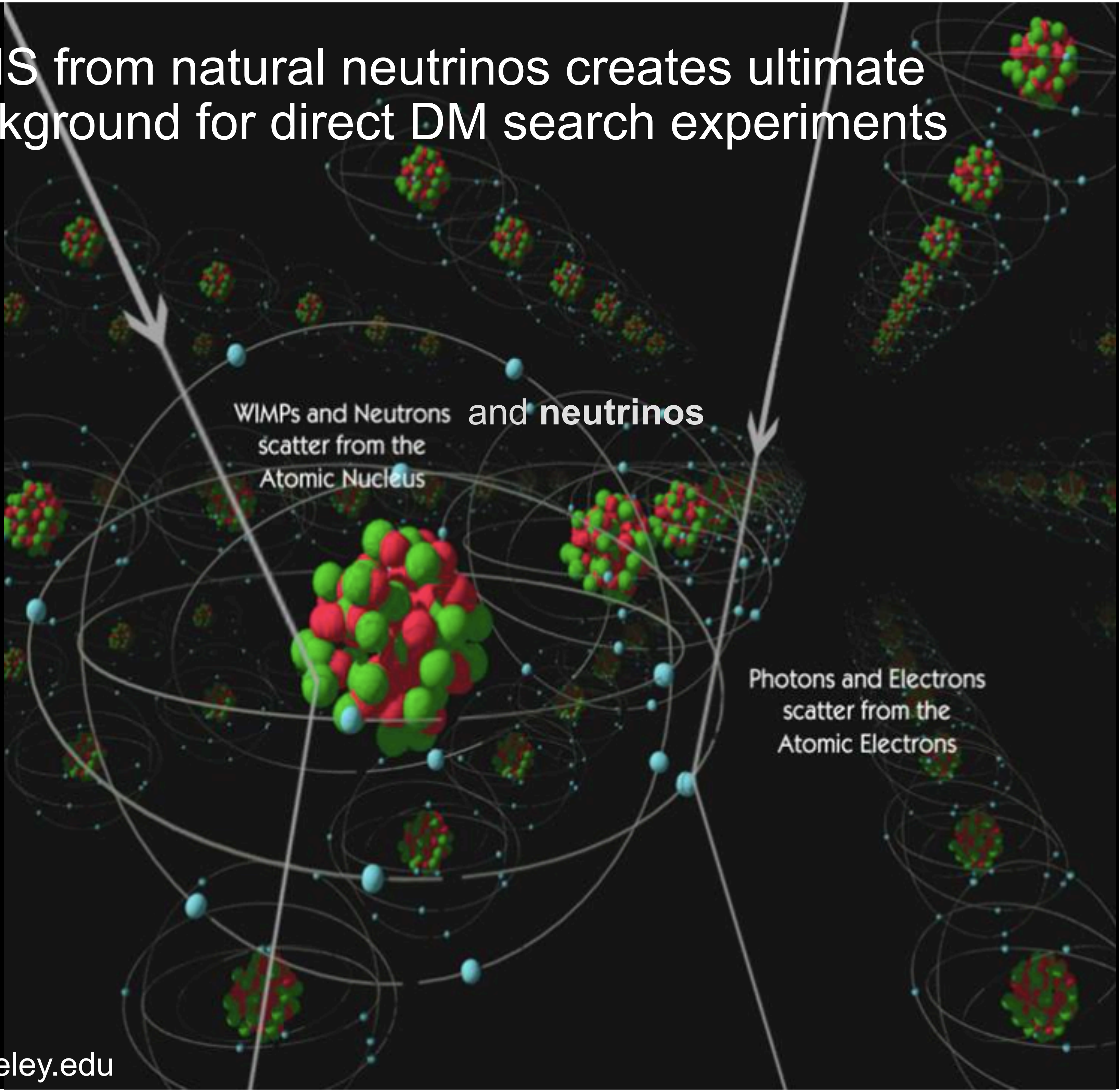
- Supernova processes
- Nuclear physics:
    - Neutron form factors
    - g_A quenching



- Possible applications (reactor monitoring)

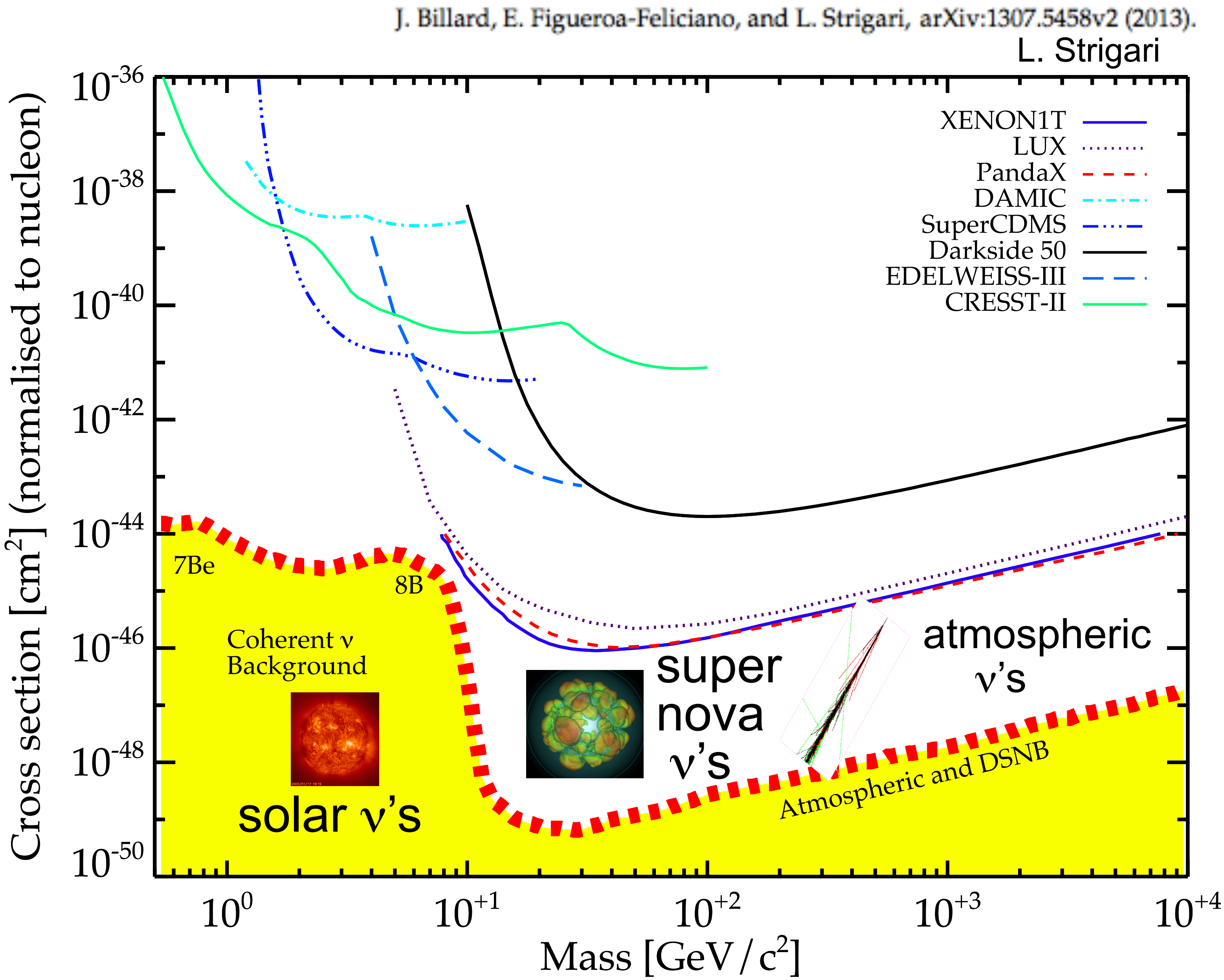


CEvNS from natural neutrinos creates ultimate background for direct DM search experiments



cdms.berkeley.edu

The so-called "neutrino floor" (**signal!**) for DM experiments

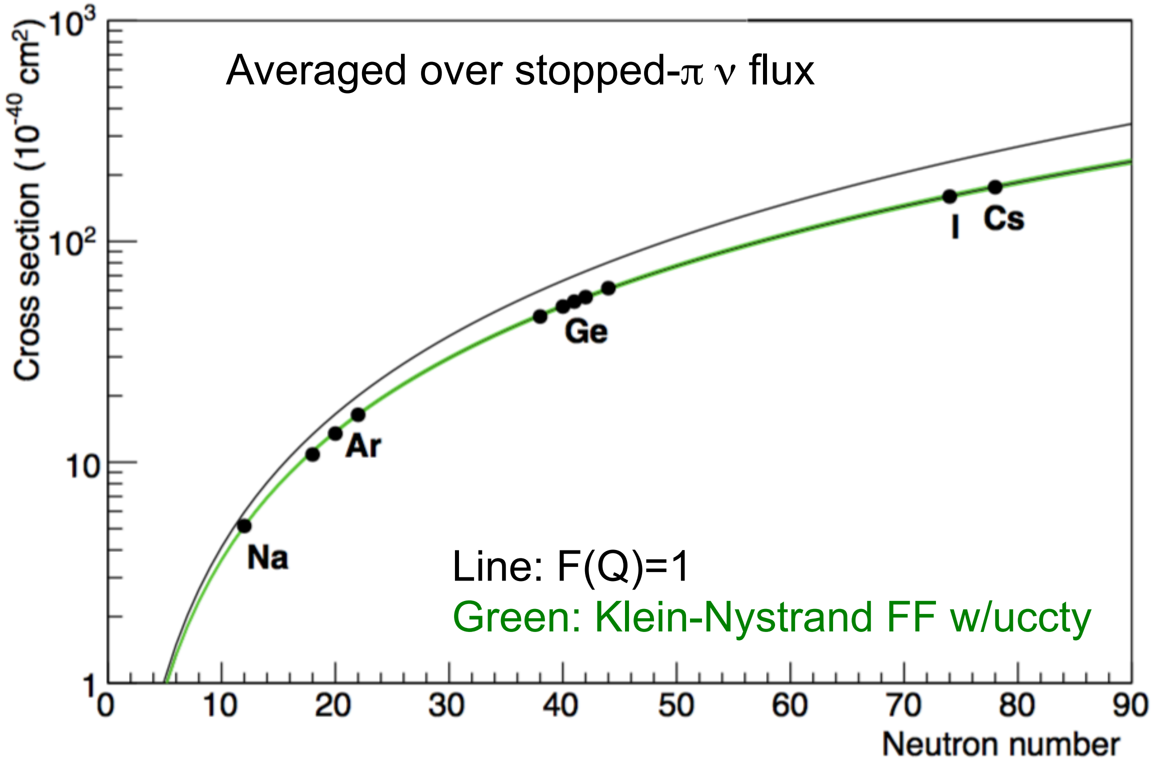


Measure CEvNS to understand nature of background/astro signal
(& detector response, DM interaction)

The CEvNS rate is a clean SM prediction

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

small nuclear uncertainties

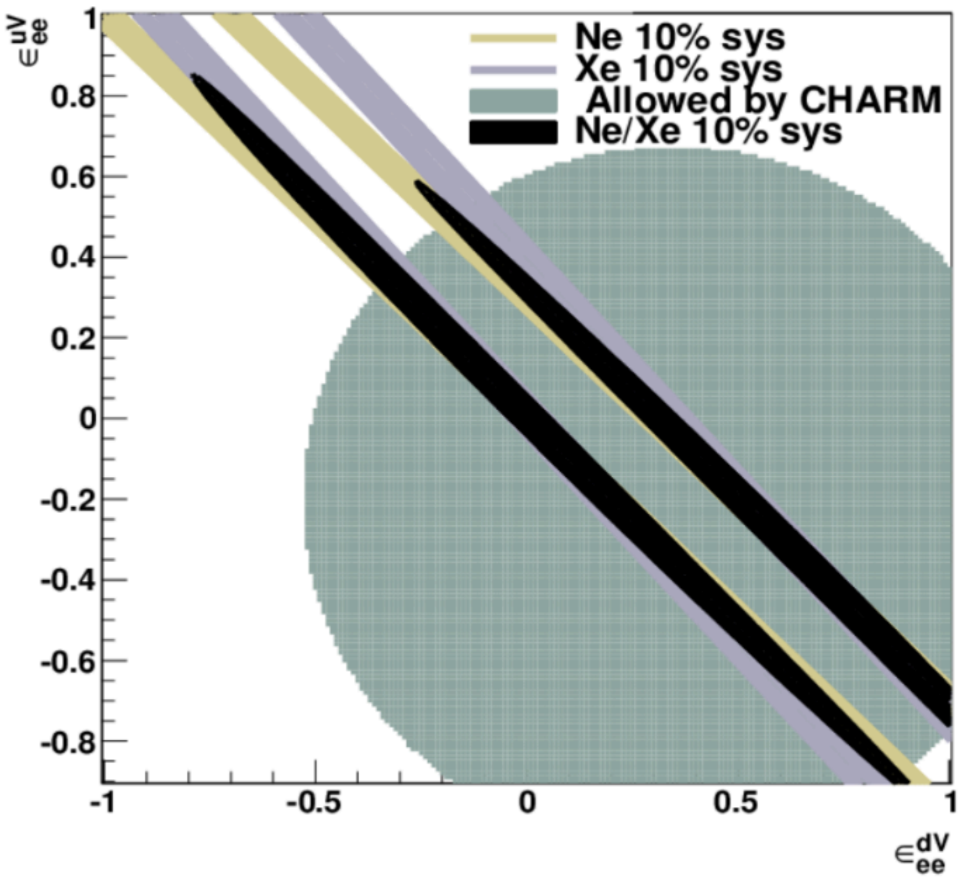


A deviation from α N^2 prediction can be a signature of beyond-the-SM physics

Non-Standard Interactions of Neutrinos:

new interaction **specific to ν's**

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



If these ε's are ~unity, there is a new interaction of ~Standard-model size... many not currently well constrained

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***)

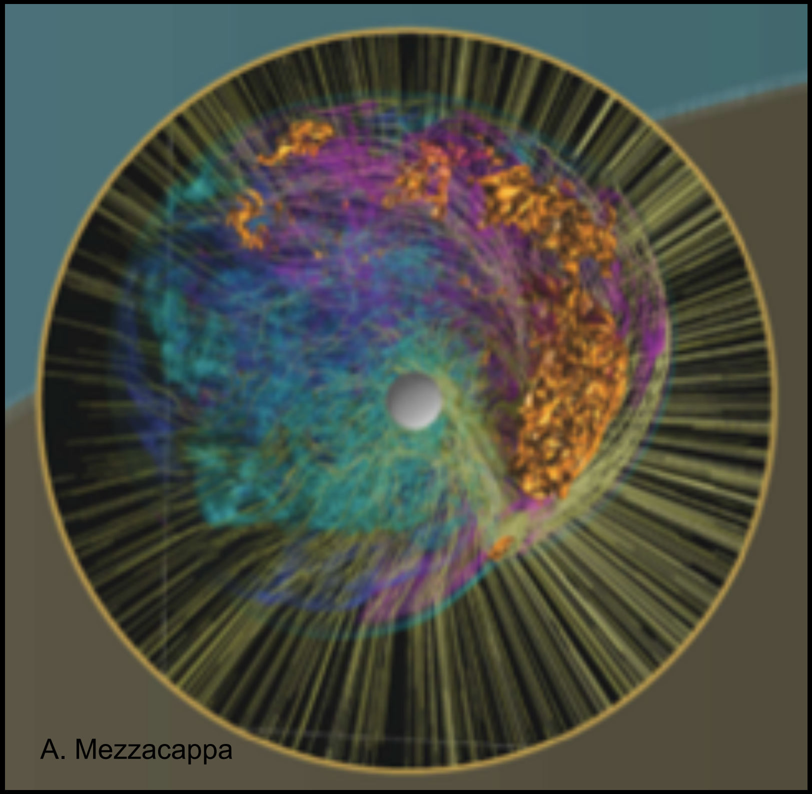
More studies: see https://sites.duke.edu/nueclipse/files/2017/04/Dent-James-NuEclipse-August-2017.pdf

Neutrinos from core-collapse supernovae

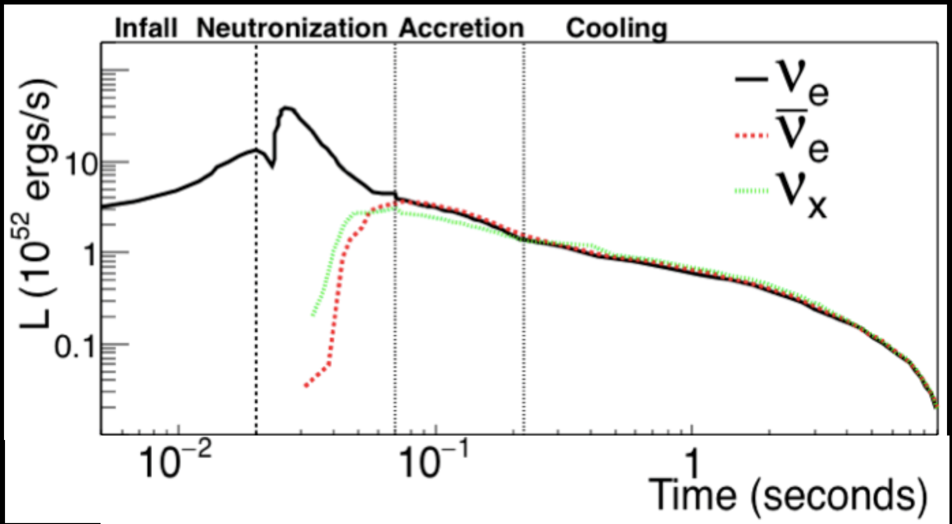
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

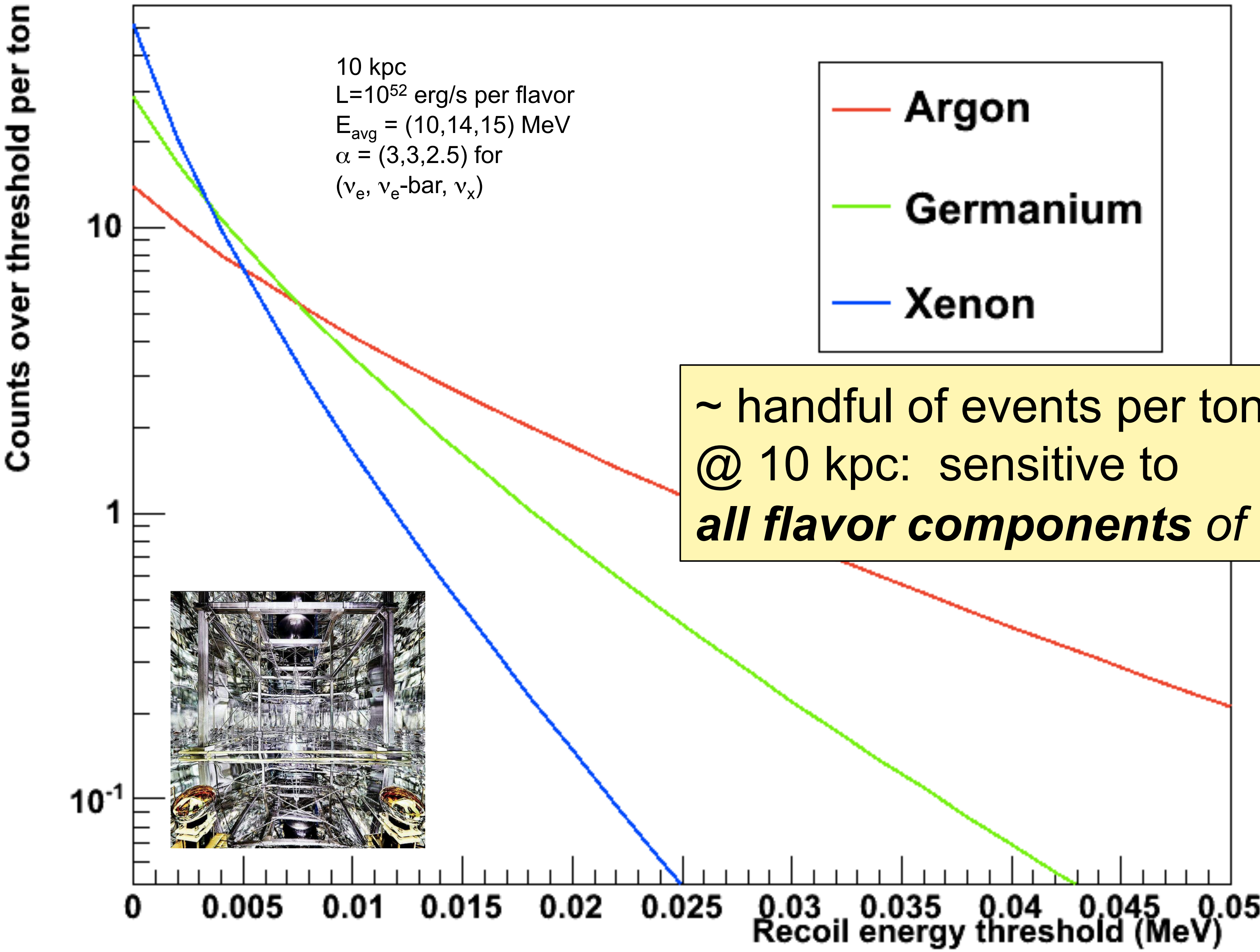
Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling



Timescale: *prompt* after core collapse, overall Δt~10's of seconds



Supernova neutrinos in tonne-scale DM detectors



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

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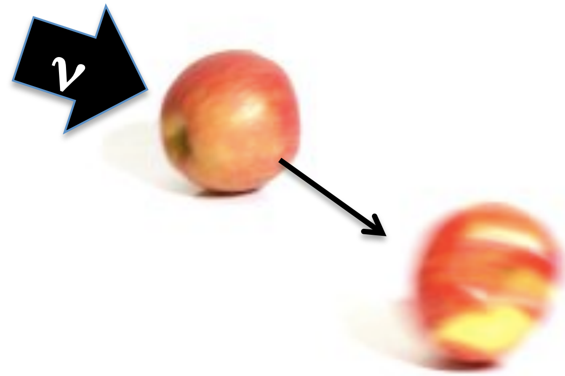
How to detect CEvNS?

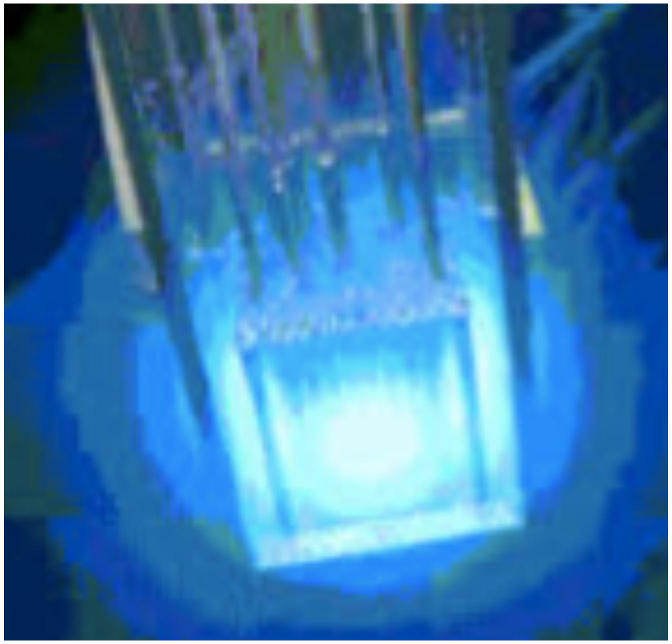


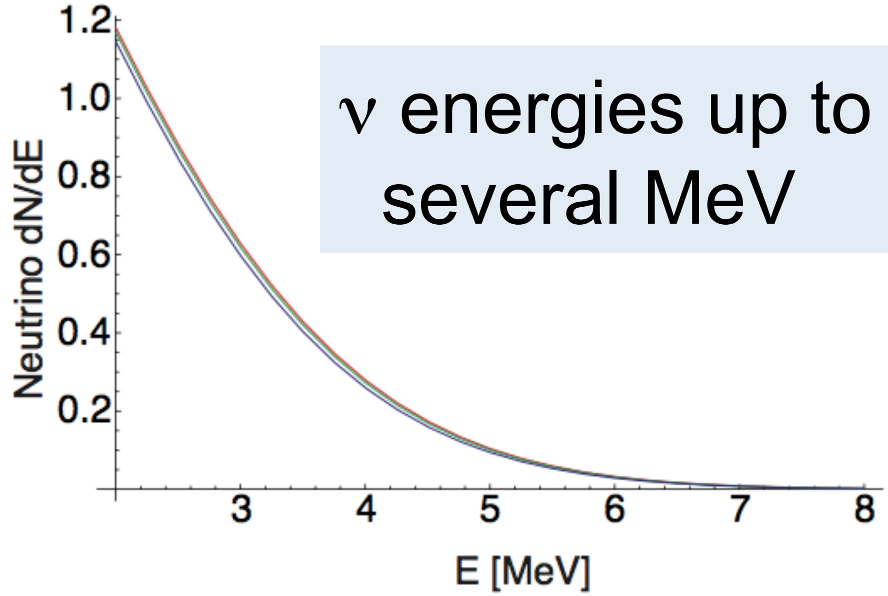
You need a neutrino source
and a detector

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, ...

Neutrinos from nuclear reactors

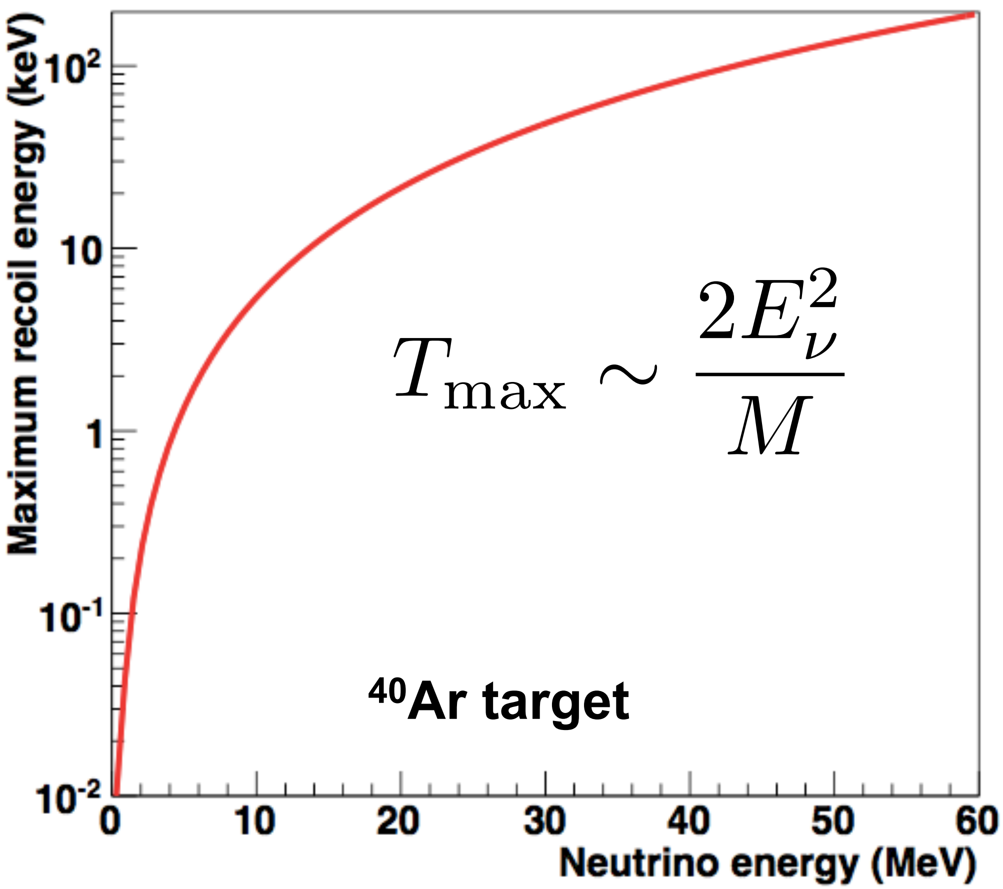


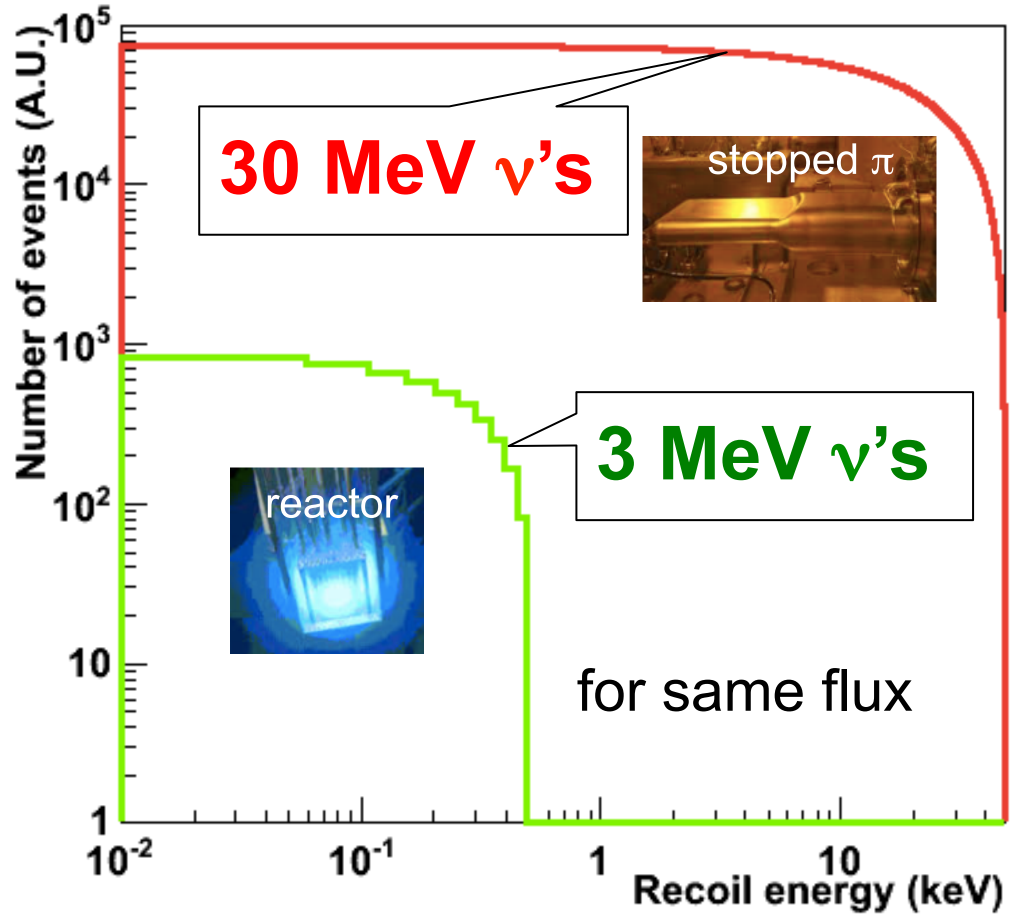


ν energies up to several MeV

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

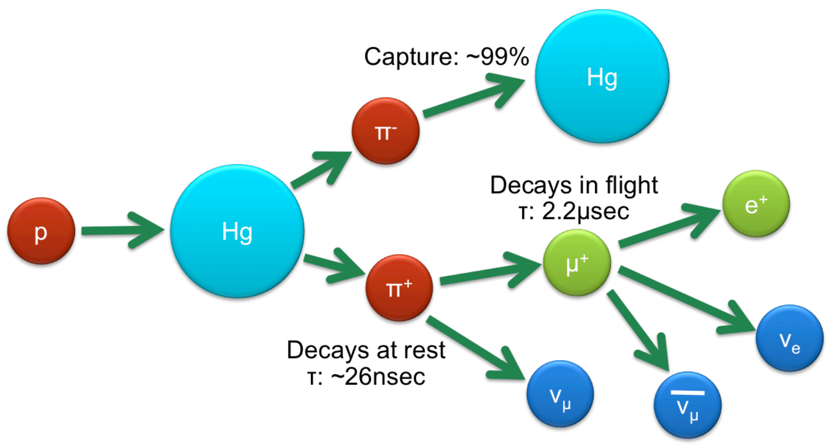
Both **cross-section** and **maximum recoil energy increase with neutrino energy**:

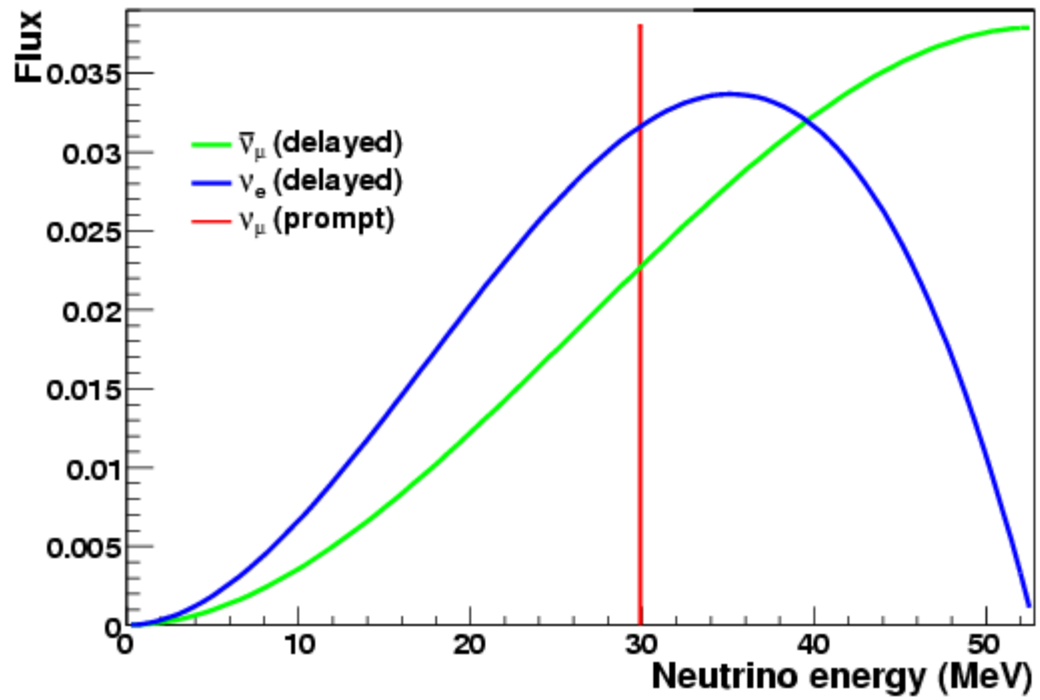




Want energy as large as possible while satisfying coherence condition: $Q \lesssim \frac{1}{R}$ (<~ 50 MeV for medium A)

Stopped-Pion (πDAR) Neutrinos





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

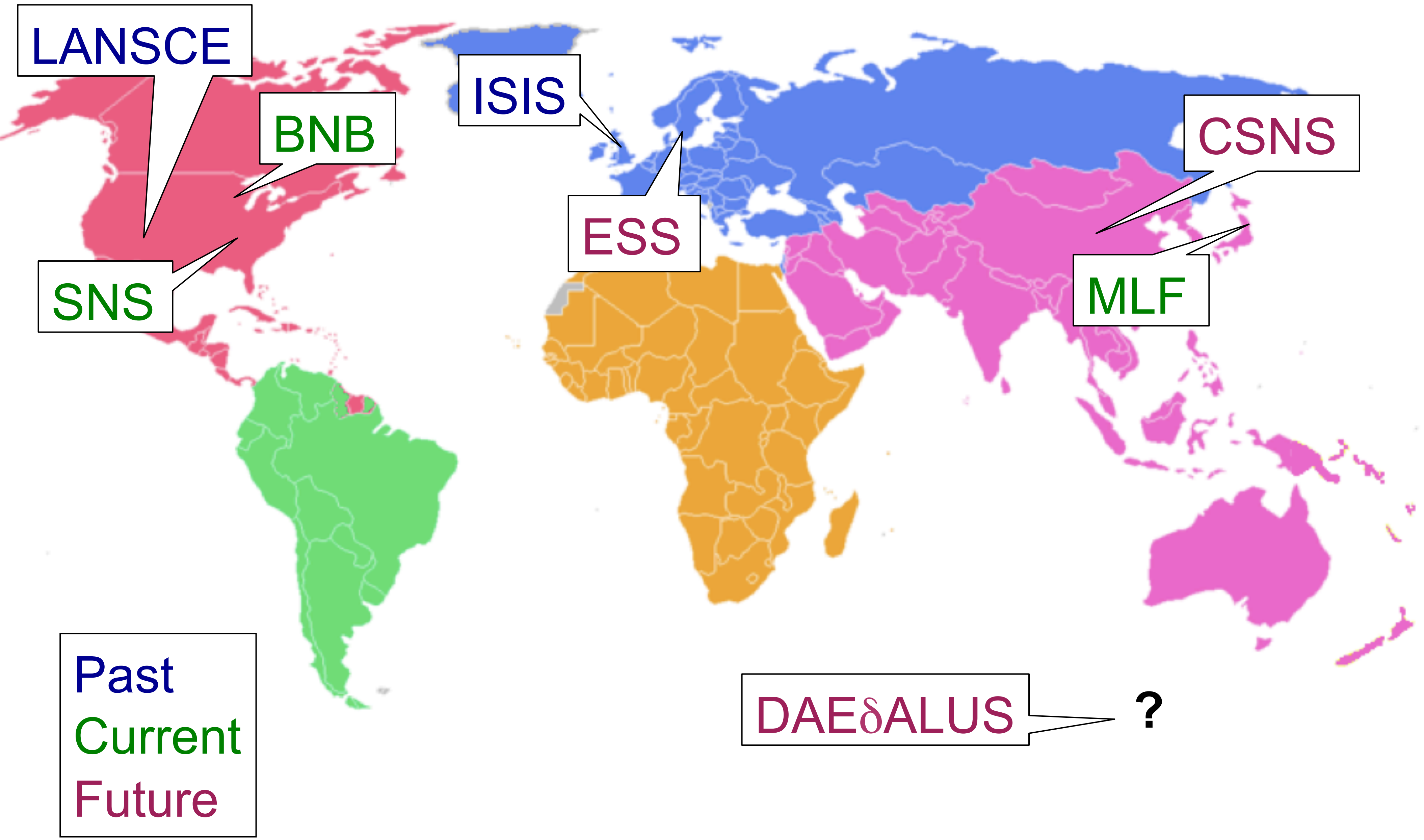
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

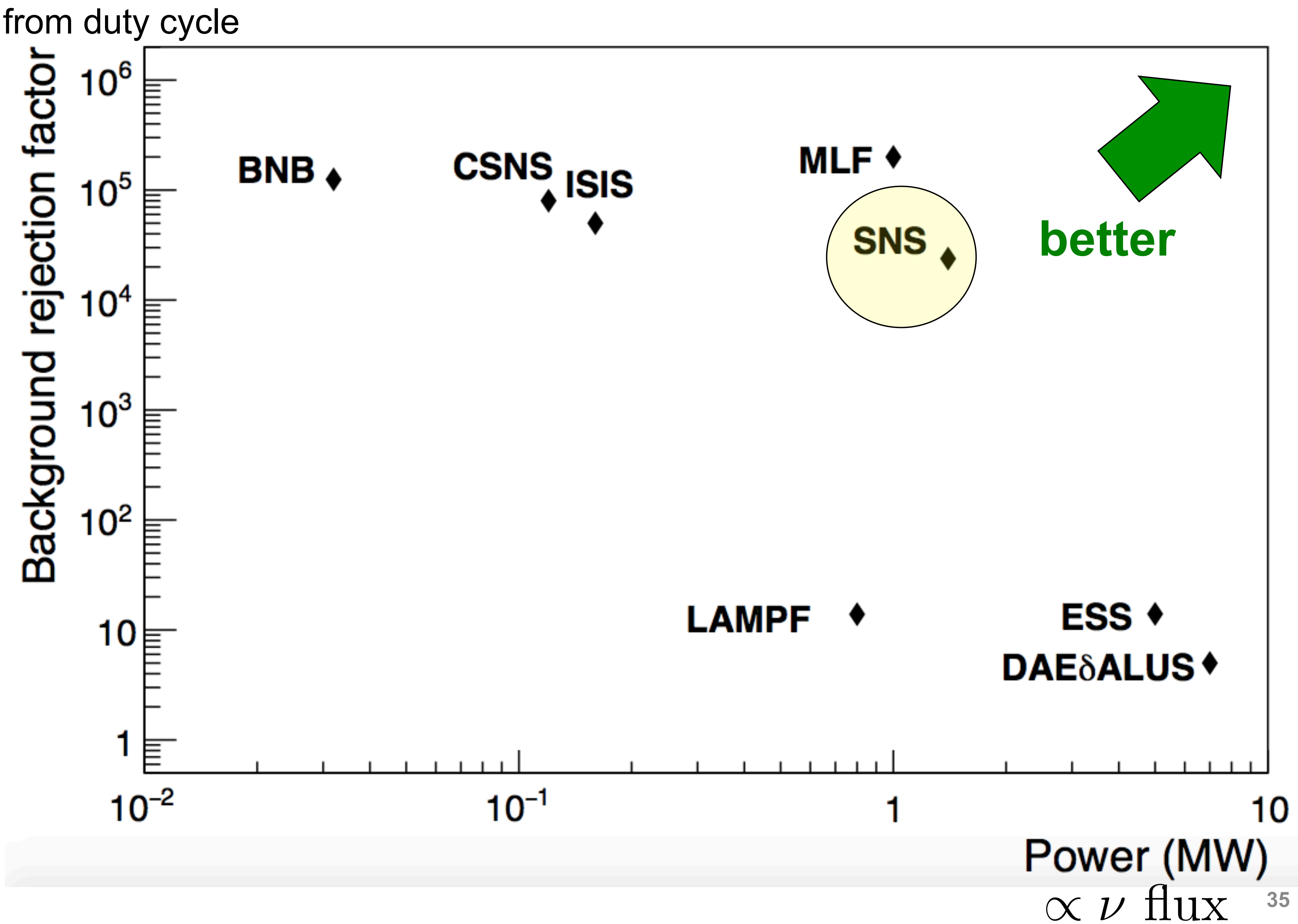
$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

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

Stopped-Pion Sources Worldwide

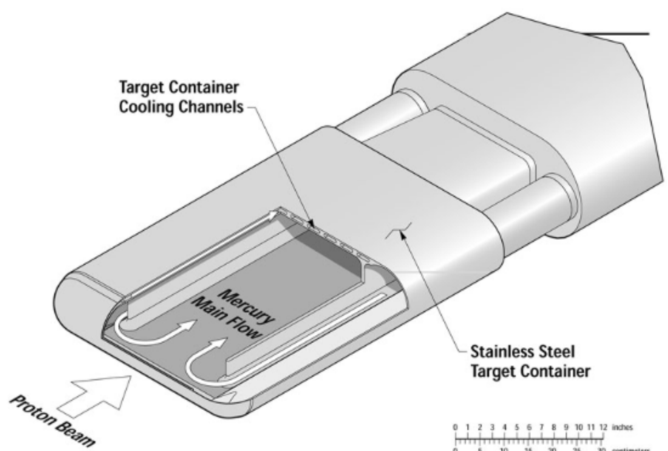


Comparison of pion decay-at-rest ν sources



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

The neutrinos are free!

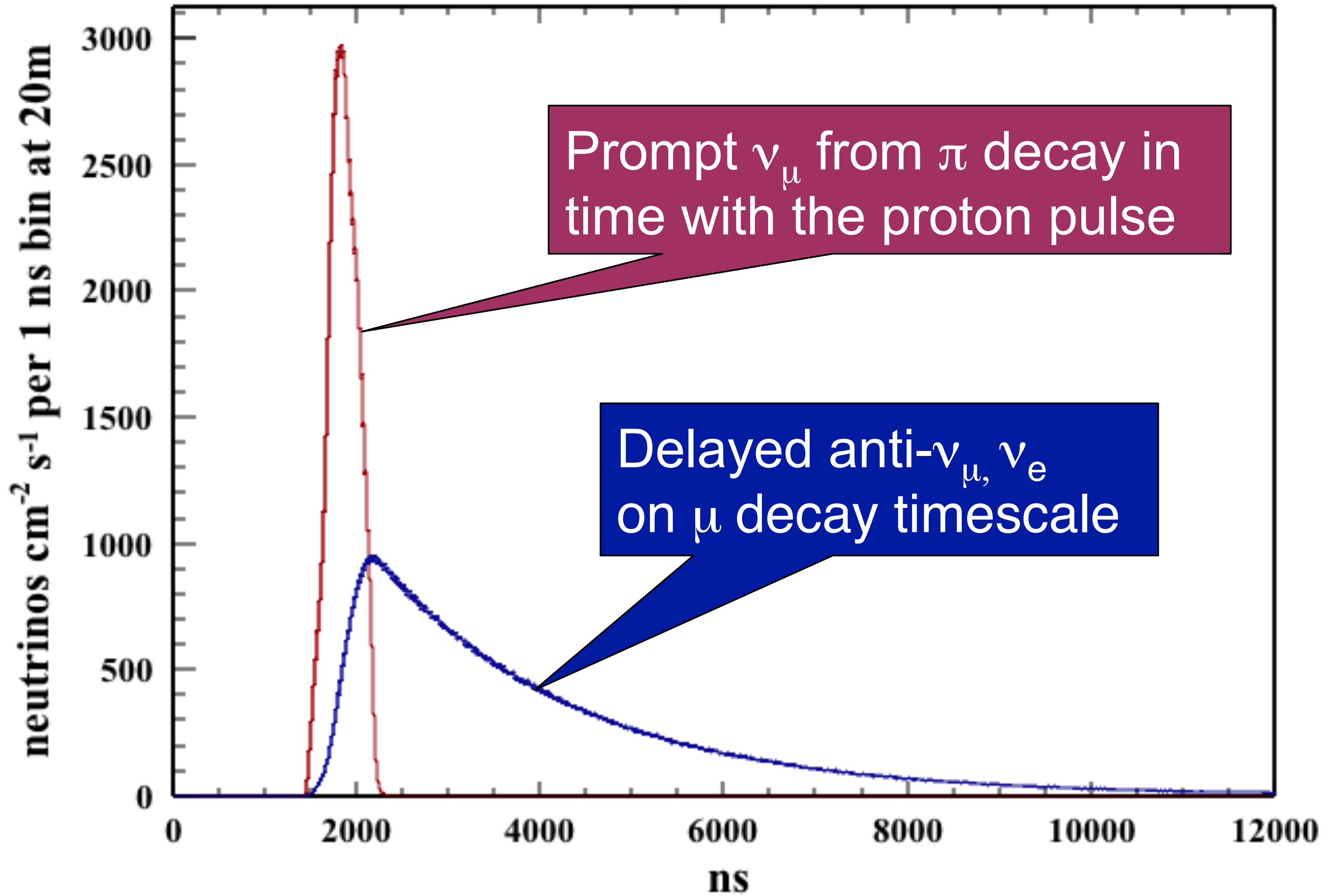
These are *not* crummy
old cast-off neutrinos...

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

They are of the highest quality!

Time structure of the SNS source

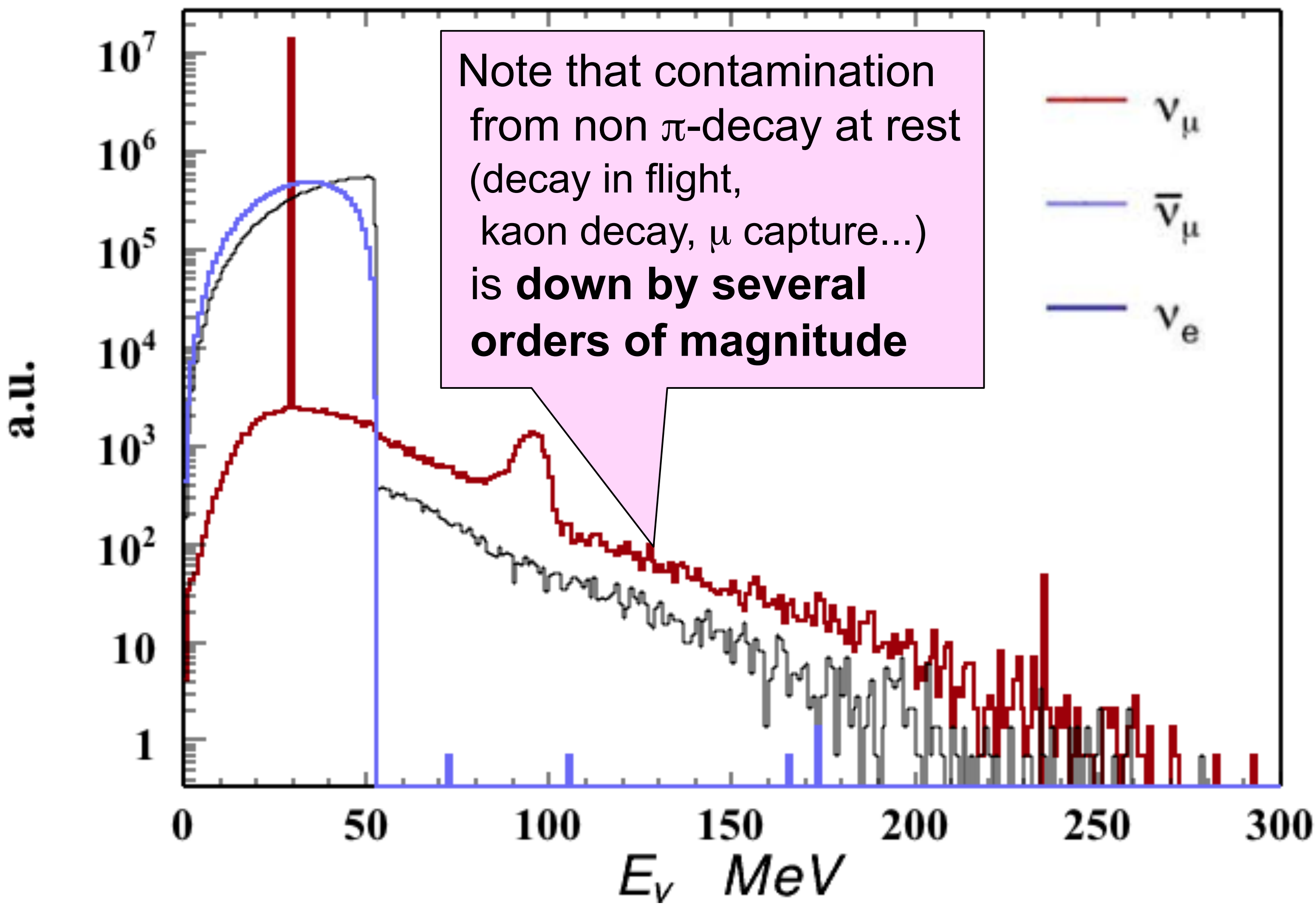
60 Hz *pulsed* source



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

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

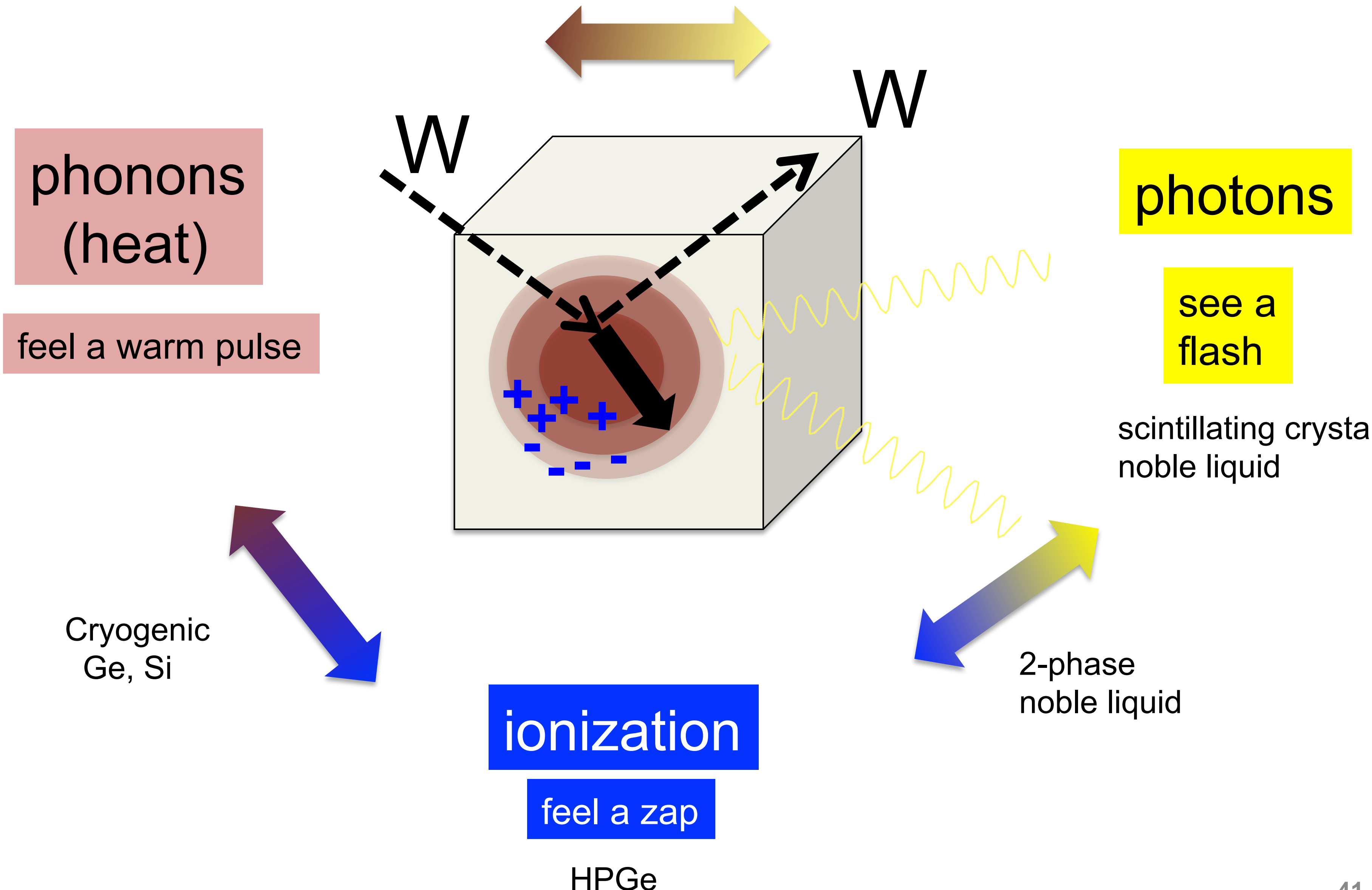
0.08 neutrinos per flavor per proton on target



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

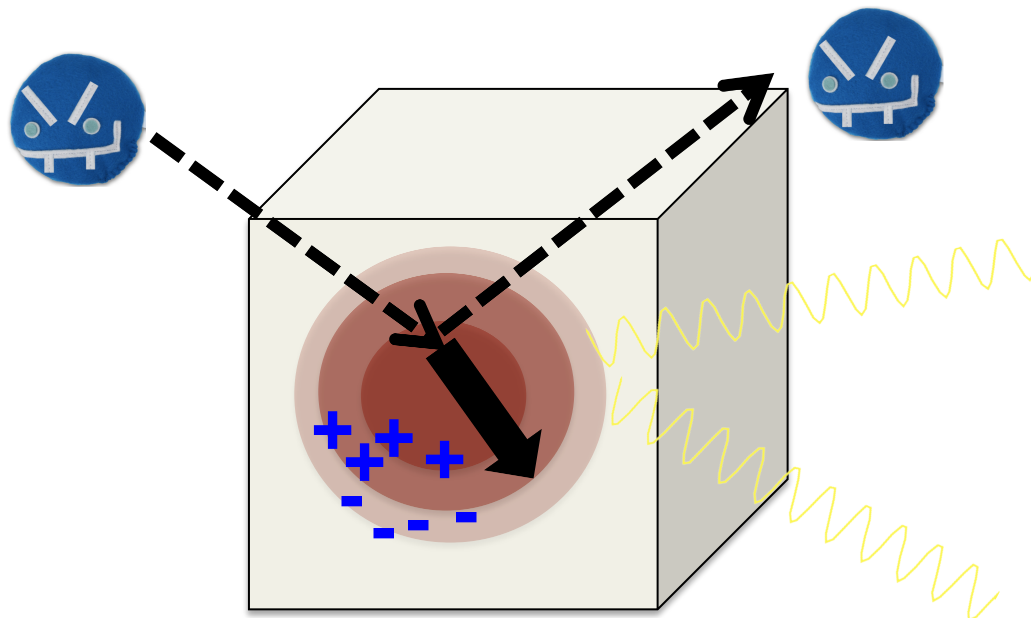


http://dmrc.snu.ac.kr/english/intro/intro1.html

Backgrounds

Usual suspects:
- cosmogenics
- ambient and intrinsic radioactivity
- detector-specific noise and dark rate

Neutrons are especially not your 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"

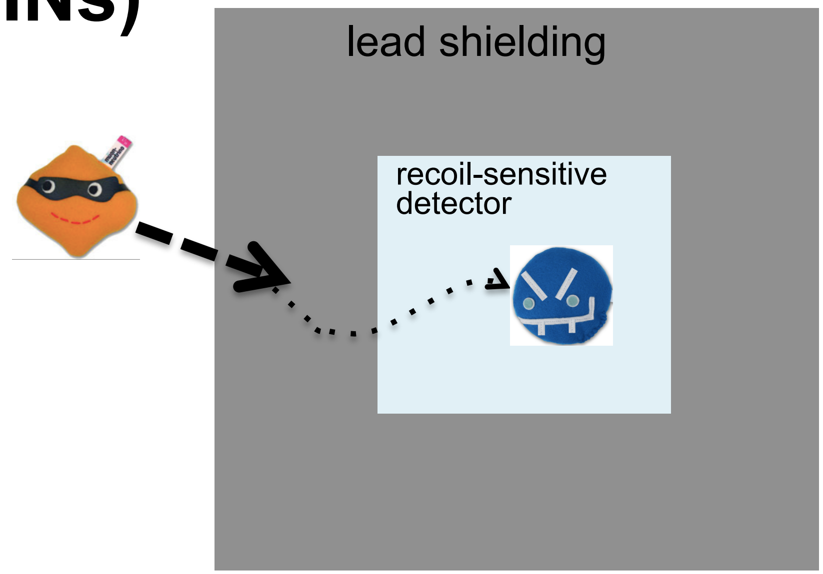
A "friendly fire" in-time background:
Neutrino Induced Neutrons (NINs)

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

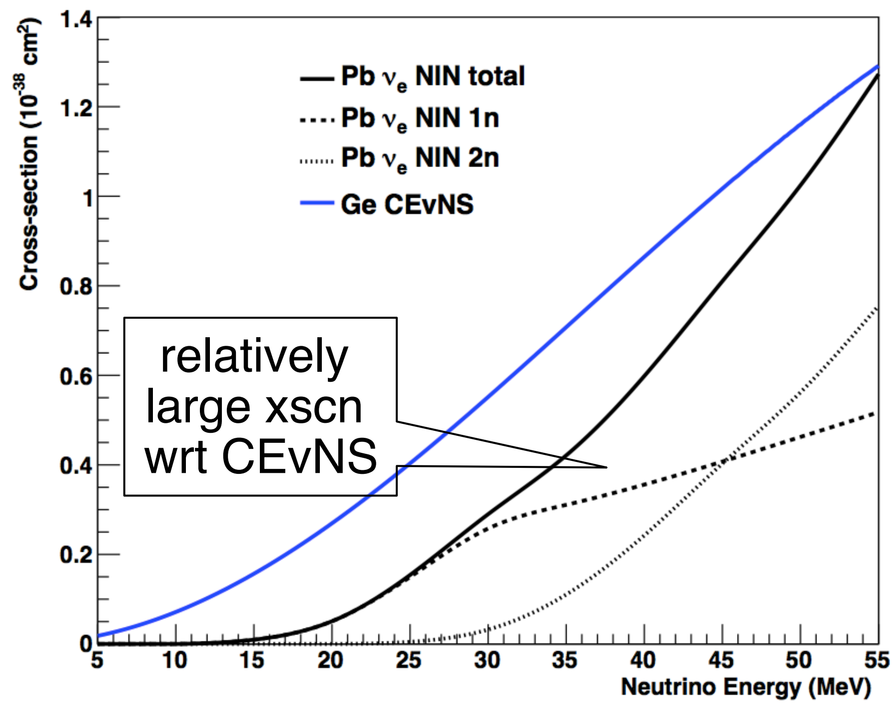
1n, 2n emission

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

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]



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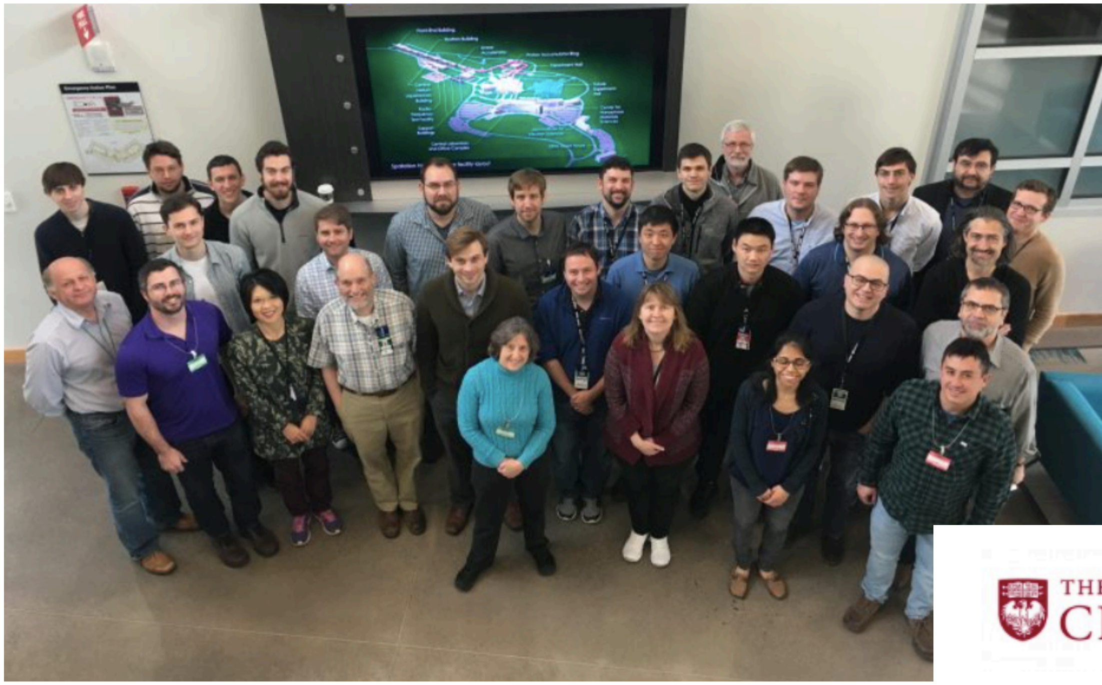
The COHERENT collaboration

http://sites.duke.edu/coherent



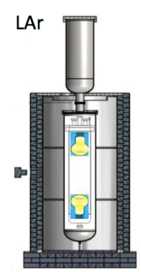
~80 members,
19 institutions
4 countries

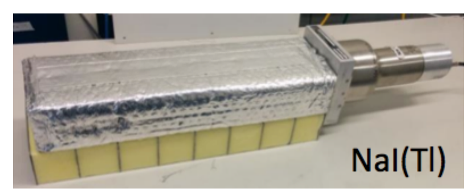
arXiv:1509.08702

COHERENT CEvNS Detectors

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

Multiple detectors for N^2 dependence of the cross section

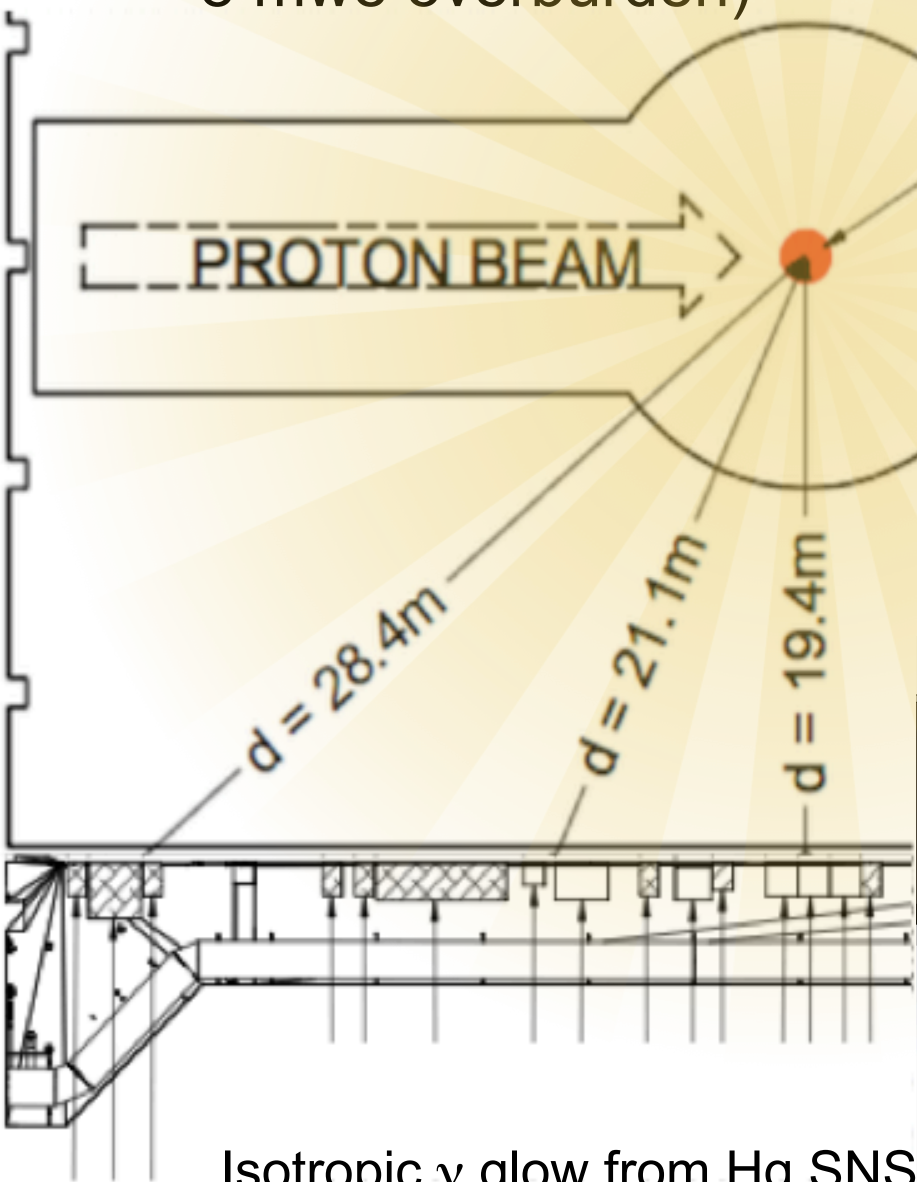


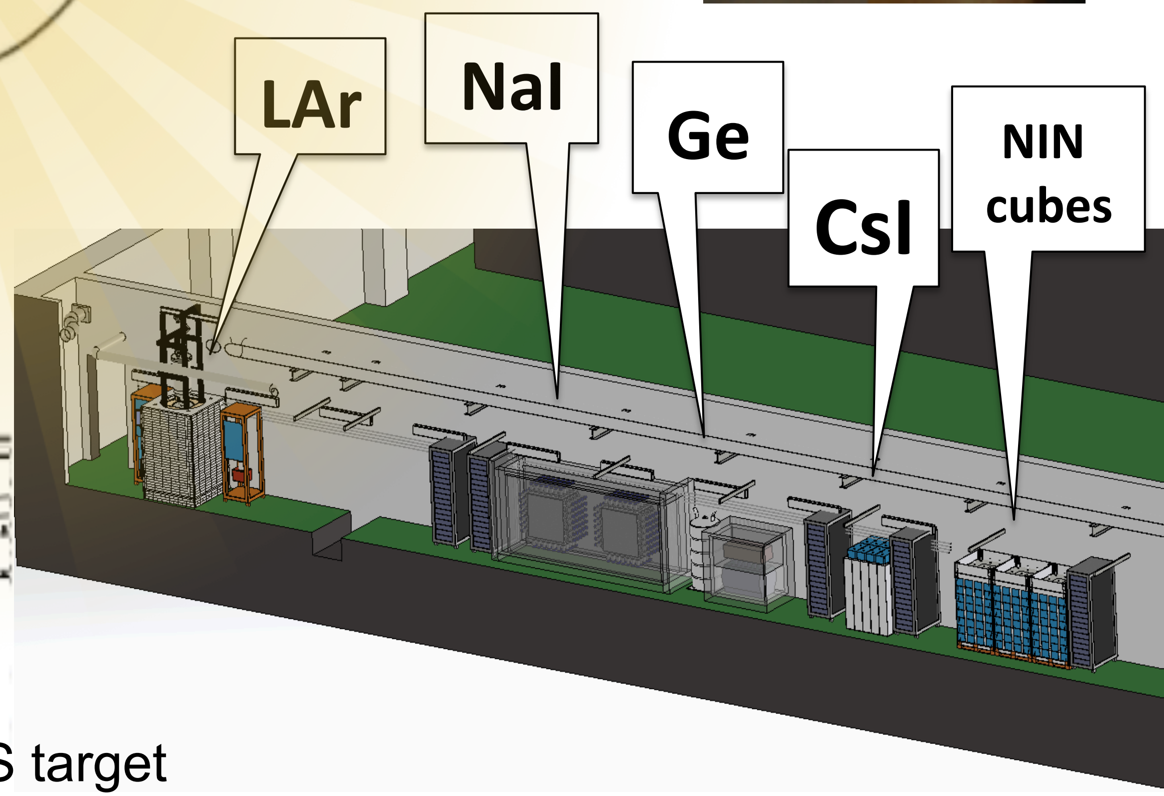


Siting for deployment in SNS basement

(measured neutron backgrounds low,
~ 8 mwe overburden)

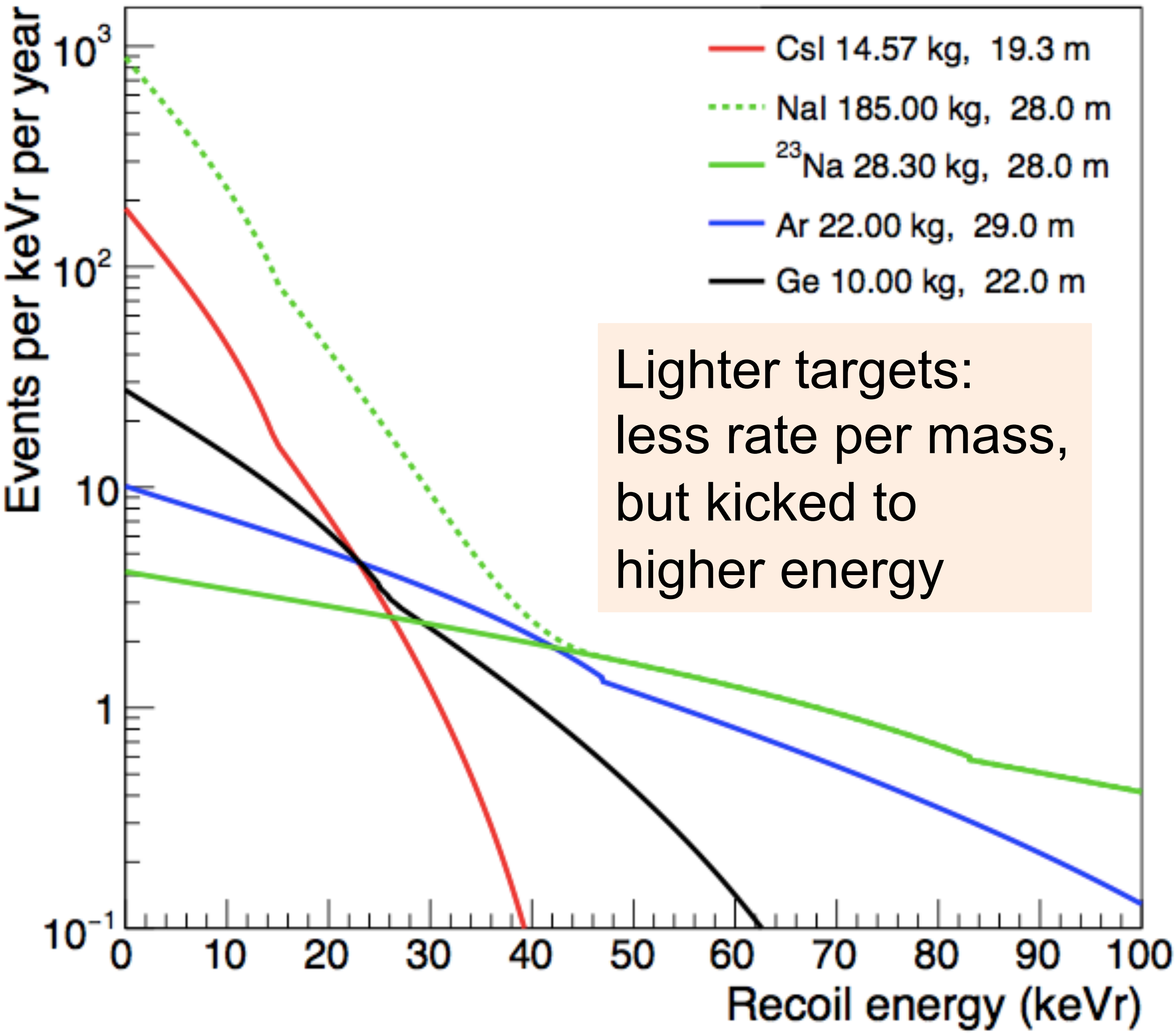
View looking down "Neutrino Alley"





Isotropic ν glow from Hg SNS target

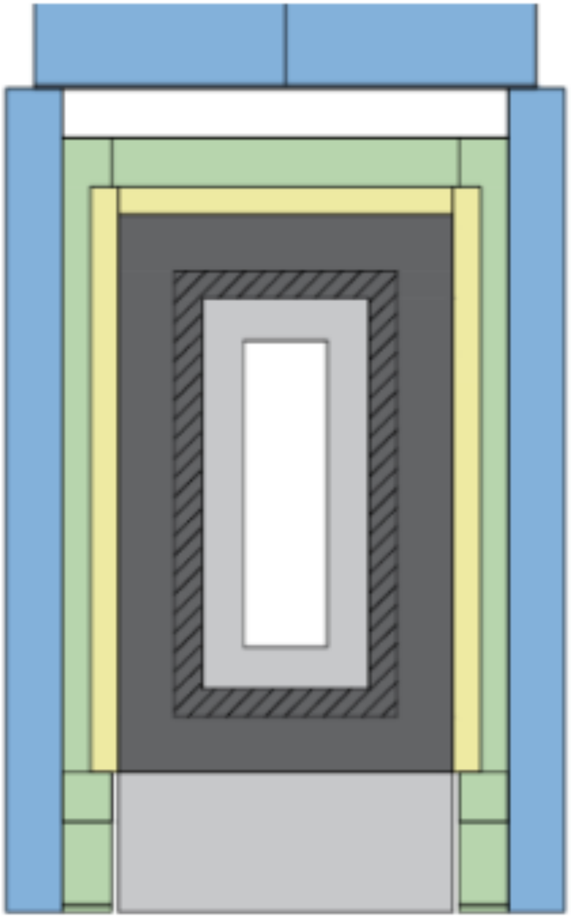
Expected recoil energy distribution

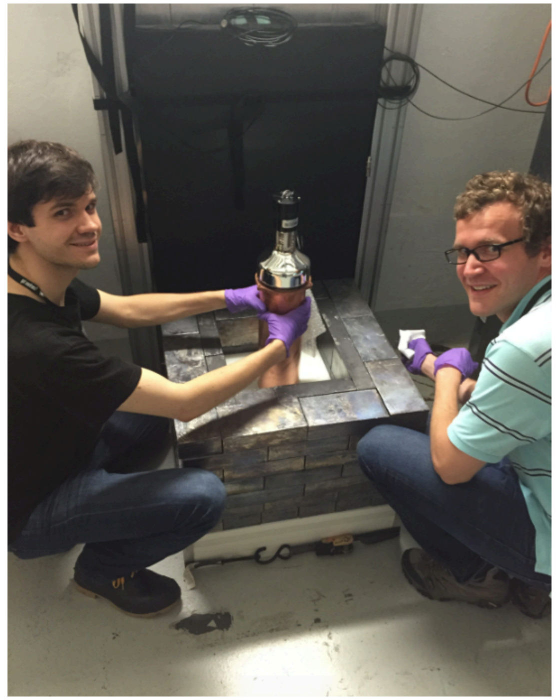


OUTLINE

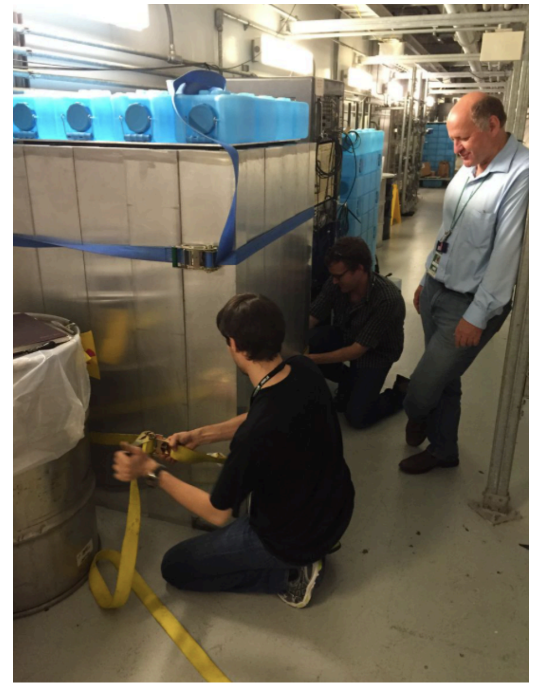
- Neutrinos and neutrino interactions
- Coherent elastic neutrino-nucleus scattering (CEvNS)
- Why measure it? Physics motivations (short and long term)
- How to measure CEvNS
- The COHERENT experiment at the SNS
- **First light with CsI[Tl]**
- Status and prospects for COHERENT

The CsI Detector in Shielding in Neutrino Alley at the SNS





A hand-held detector!



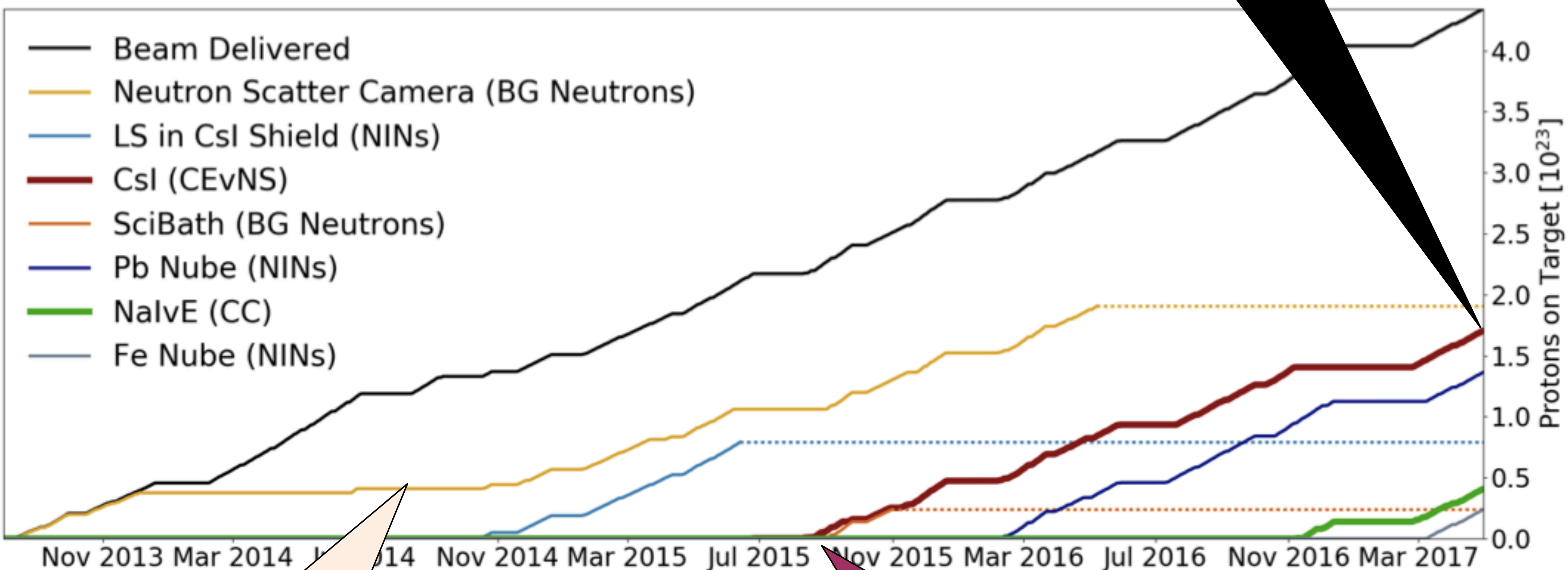
Almost wrapped up...

Layer	HDPE*	Low backg. lead	Lead	Muon veto	Water
Thickness	3"	2"	4"	2"	4"
Colour					

COHERENT data taking

protons on target (POT) $\propto \nu$ flux

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



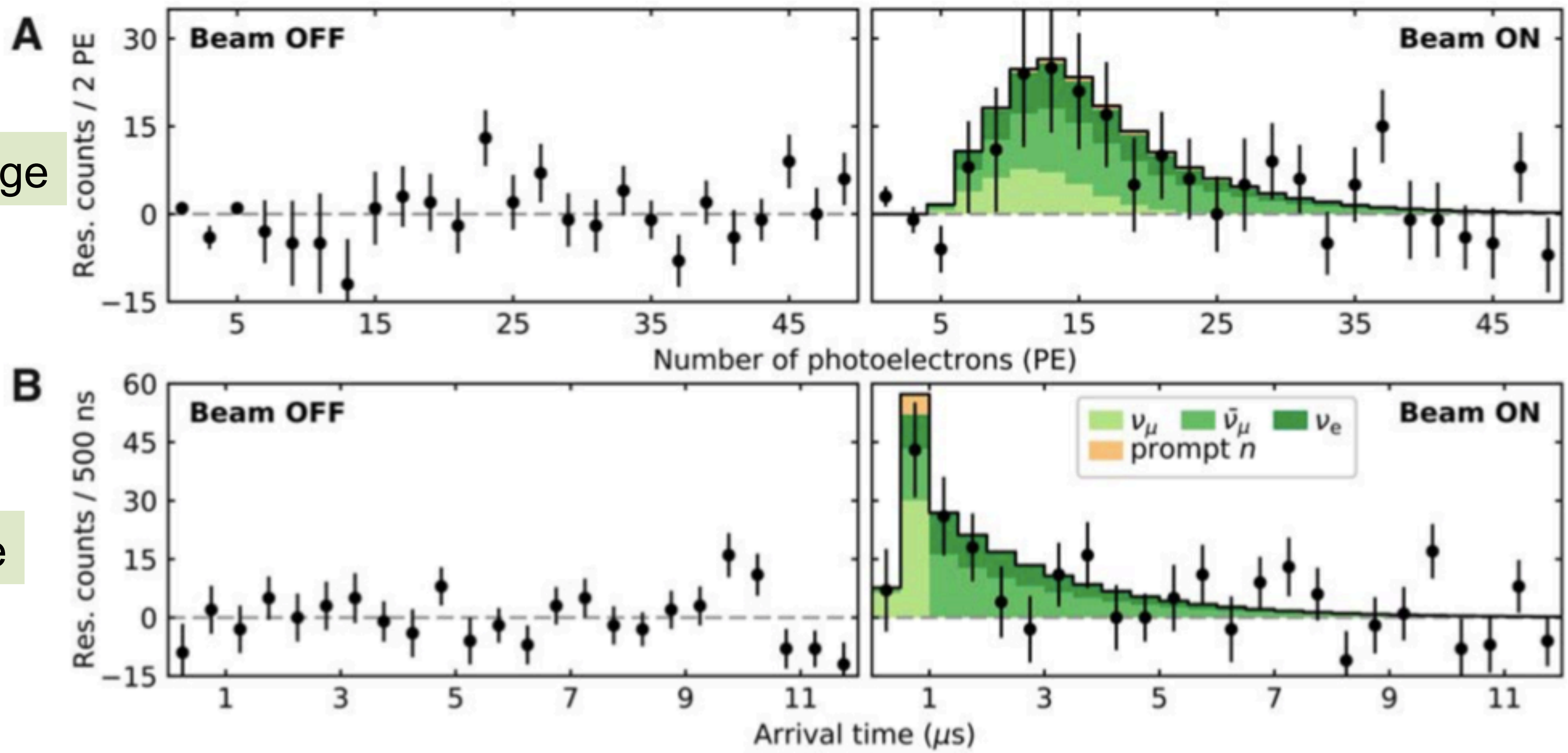
Neutron background data-taking for ~2 years before first CEvNS detectors

CsI data-taking starting summer 2015

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

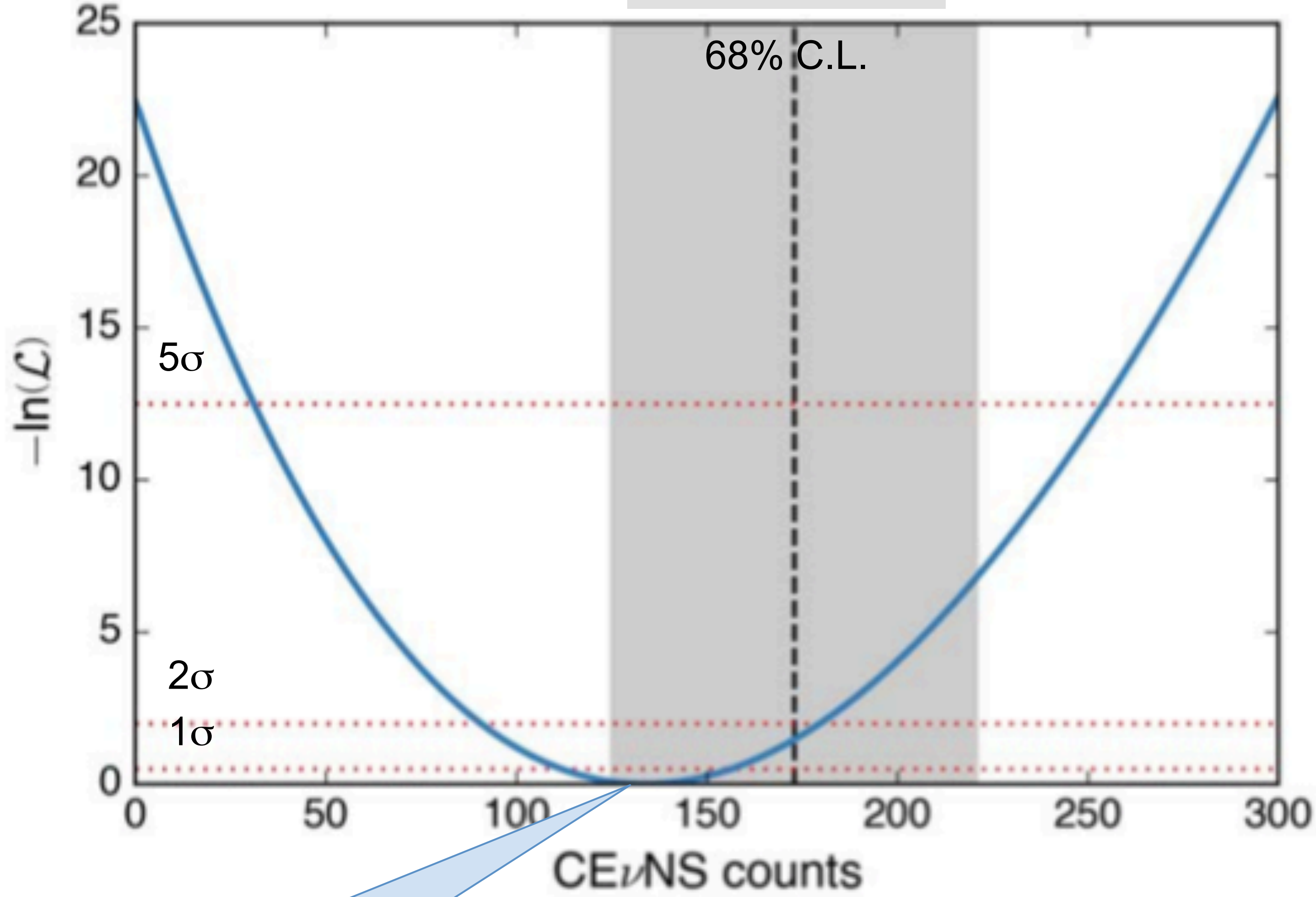
Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

Peer Reviewed
← see details

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

Results of 2D energy, time fit

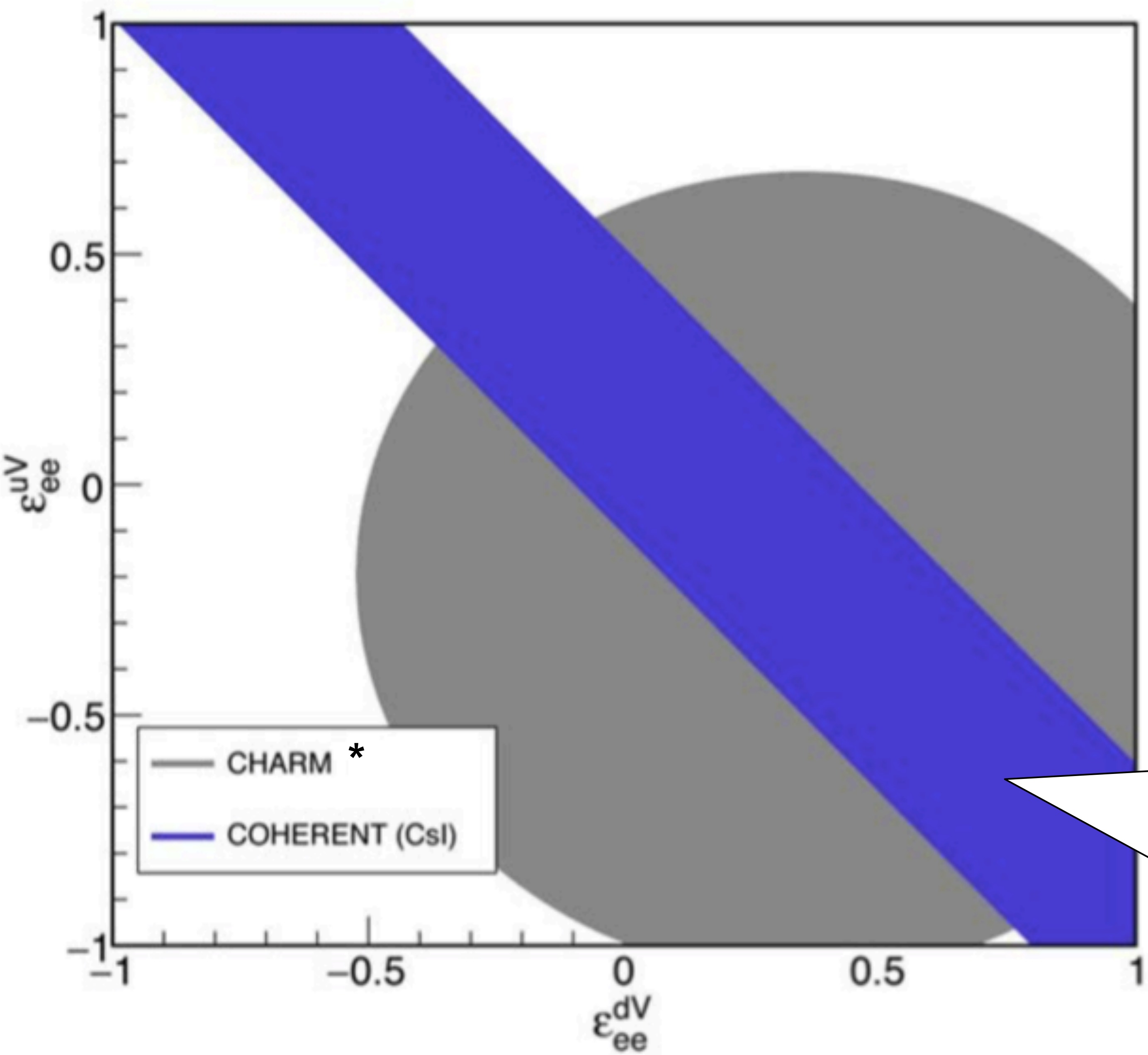
SM prediction, 173 events



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

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

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



- Assume all other ε's zero

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

*CHARM constraints apply only to heavy mediators

OUTLINE

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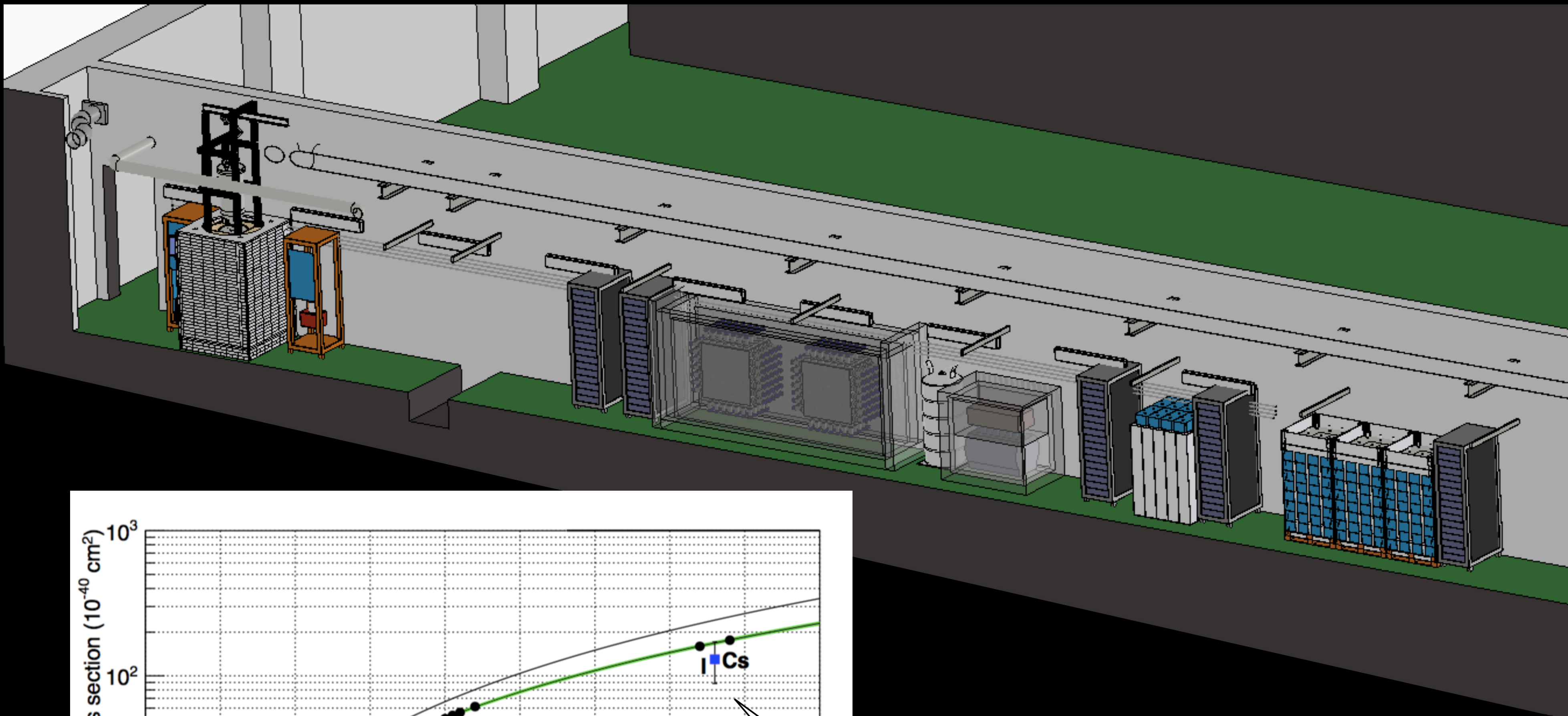
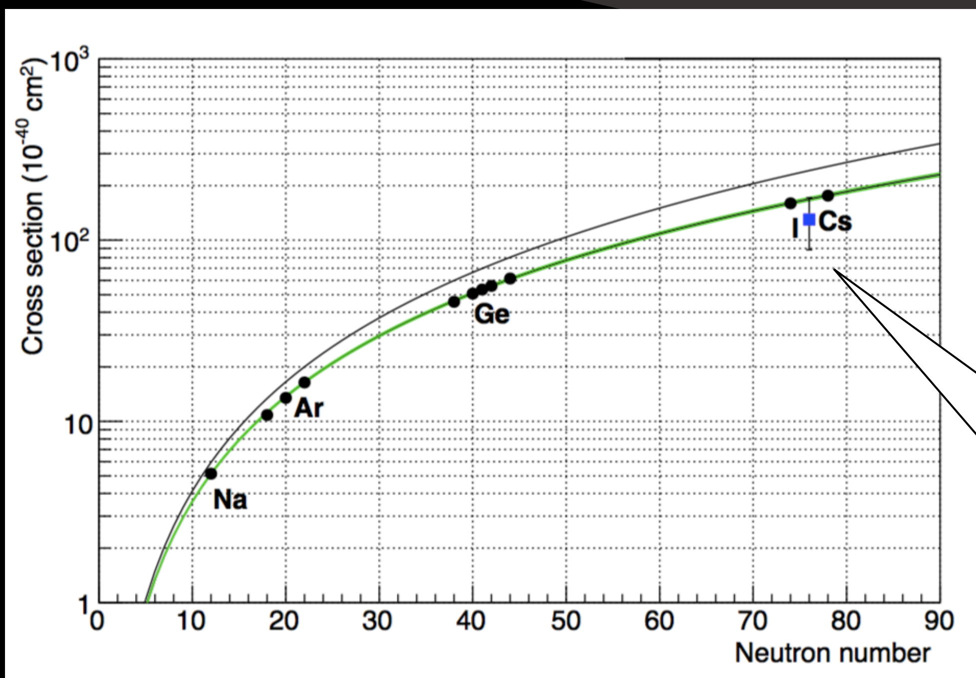
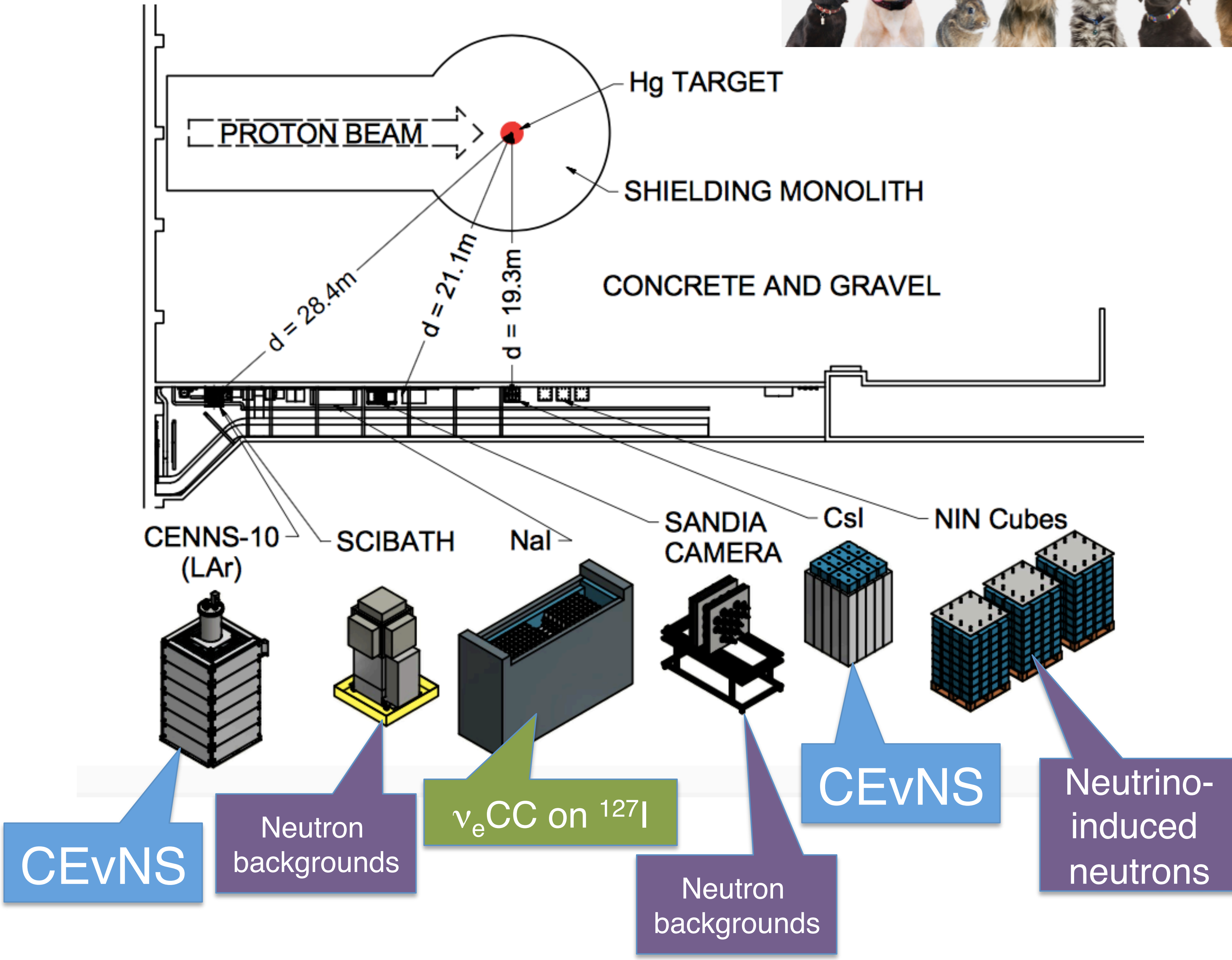
What's Next for COHERENT?





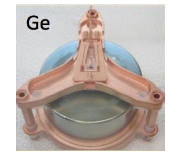
One measurement so far! Want to map out N^2 dependence

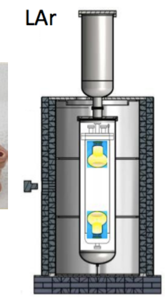
Deployments so far in Neutrino Alley

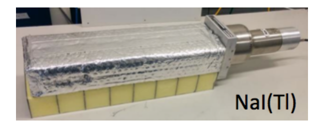


COHERENT **CEvNS** Detector Status and Near Future

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	2018
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 early 2018

COHERENT **CEvNS** Detector Status and Near Future

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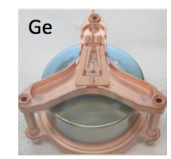
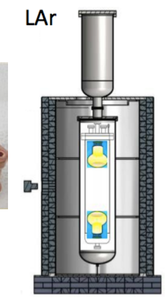
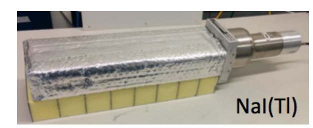
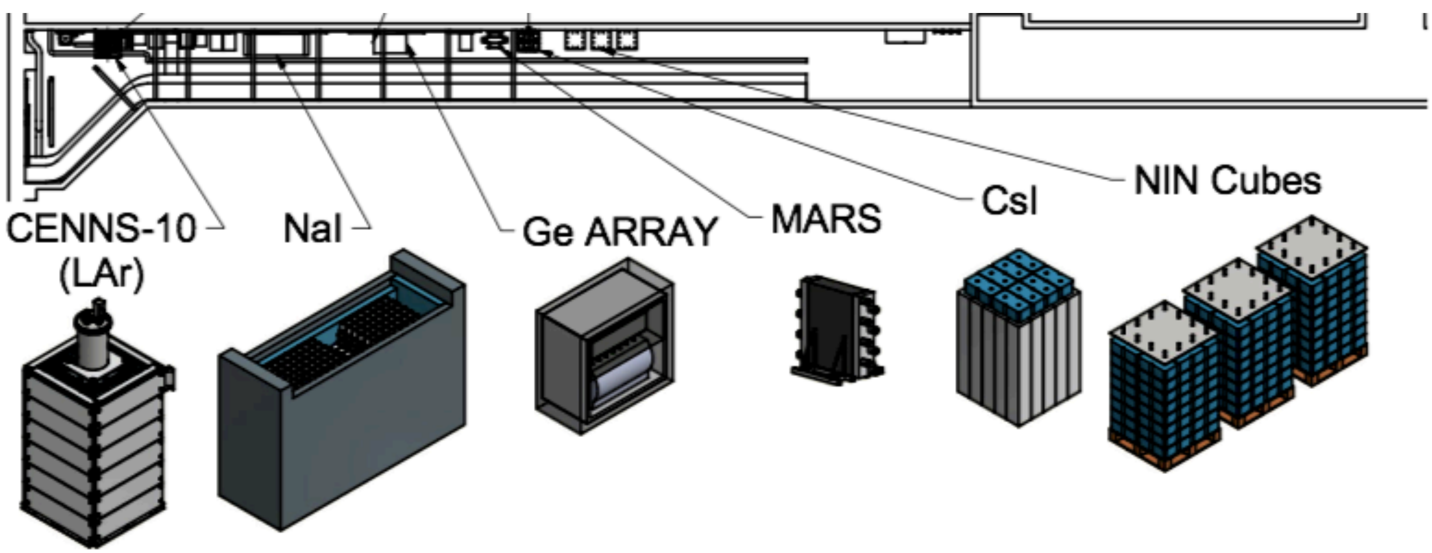


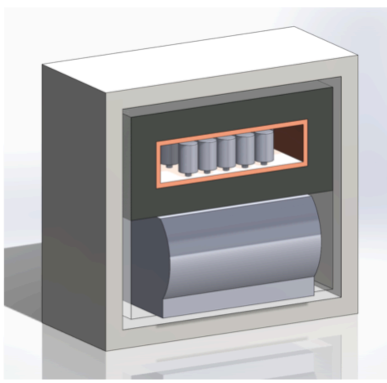


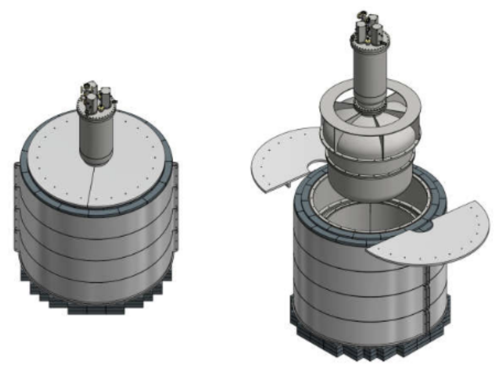


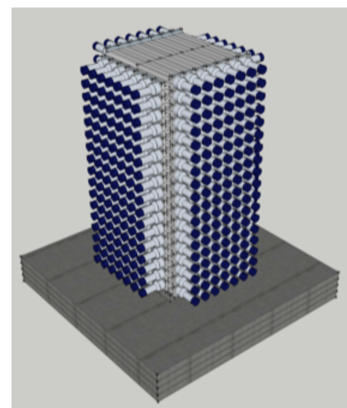


And beyond! upgrades and new ideas for Neutrino Alley

Nuclear Target	Technology
Ge	HPGe PPC
LAr	Single-phase
NaI[Tl]	Scintillating crystal







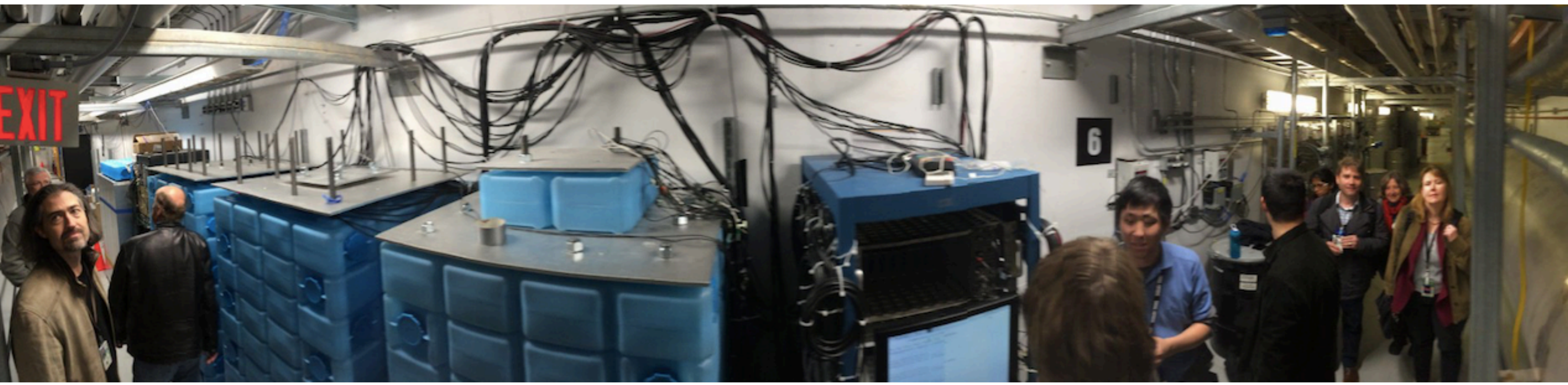
And more...

- 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: quenching factors
- Directional detectors
- ...

Summary

- **CEvNS:**
  - large cross section, but tiny recoils, α N^2
  - accessible w/low-energy threshold detectors, plus extra oomph of stopped-pion neutrino source
  - DM bg, SM test, astrophysics, nuclear physics, ...
- **First measurement** by COHERENT CsI[Na] at the SNS
- Low-hanging fruit:

  meaningful bounds on ν Non-Standard Interactions



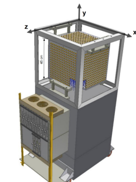
- **It's just the beginning....**
- Multiple targets, upgrades and new ideas in the works!
- Other CEvNS experiments will soon join the fun

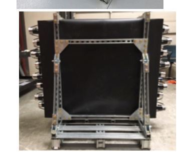
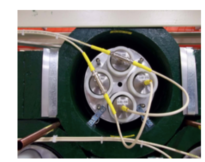
  (CONNIE, CONUS, MINER, RED, Ricochet, Nu-cleus...)

Extras/backups

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: quenching factors
- Directional detectors
- ...

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

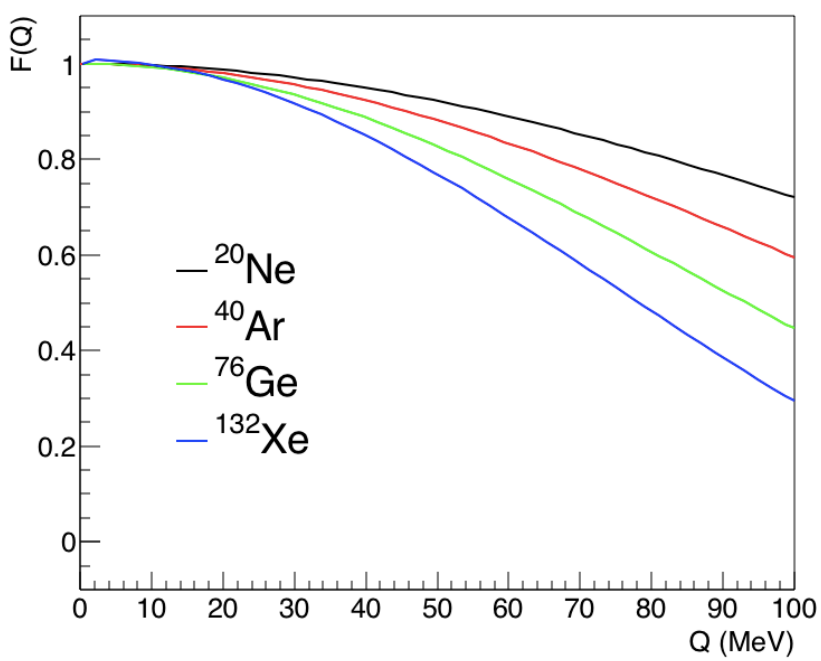
$$\boxed{\begin{aligned} g_V^p &= 0.0298 \\ g_V^n &= -0.5117 \\ g_A^p &= 0.4955 \\ g_A^n &= -0.5121. \end{aligned}}$$

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
$Q = \sqrt{(2 M T)}$: momentum transfer

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

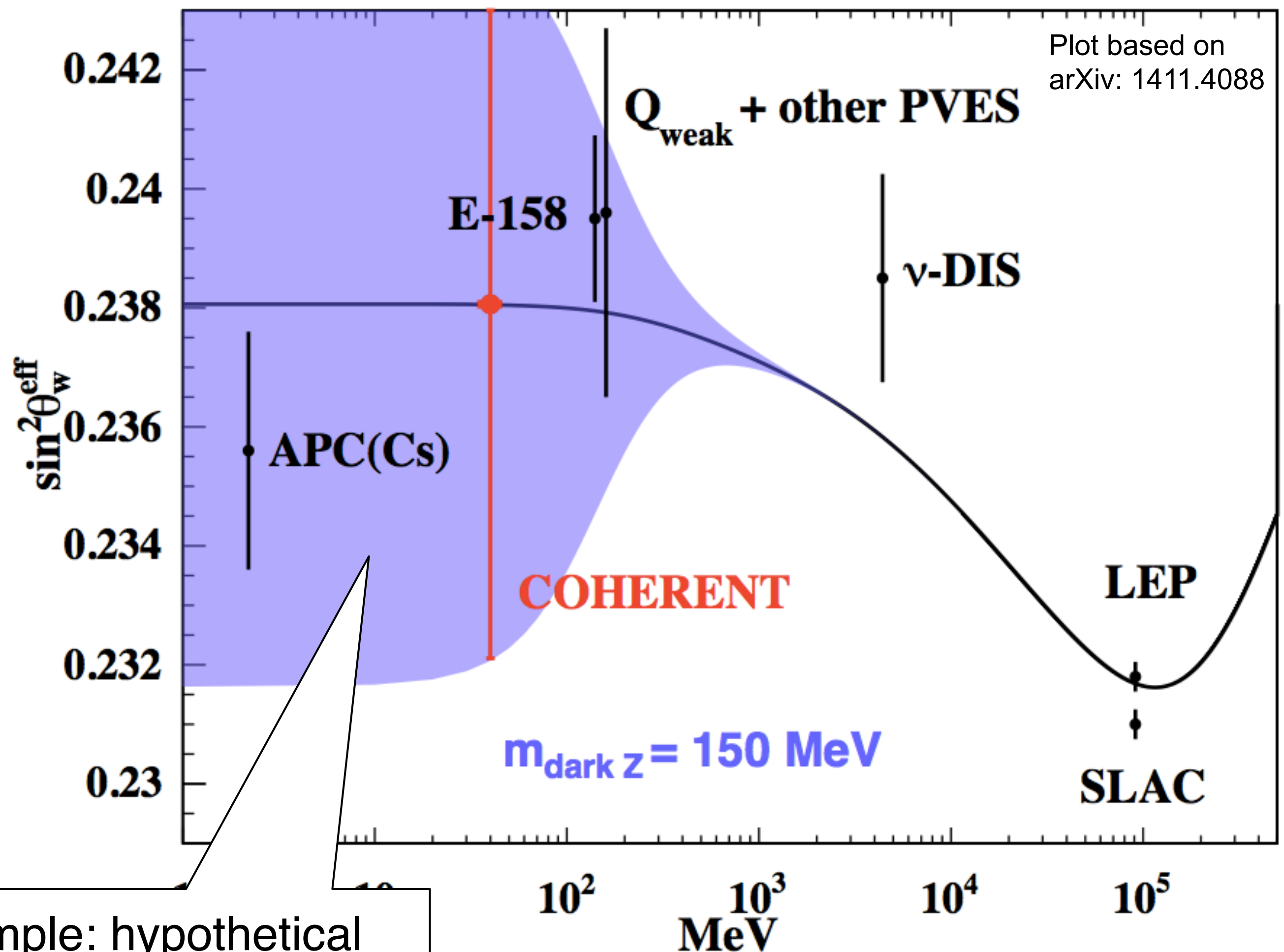


form factor suppresses cross section at large Q

Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ;

deviation probes new physics

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



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

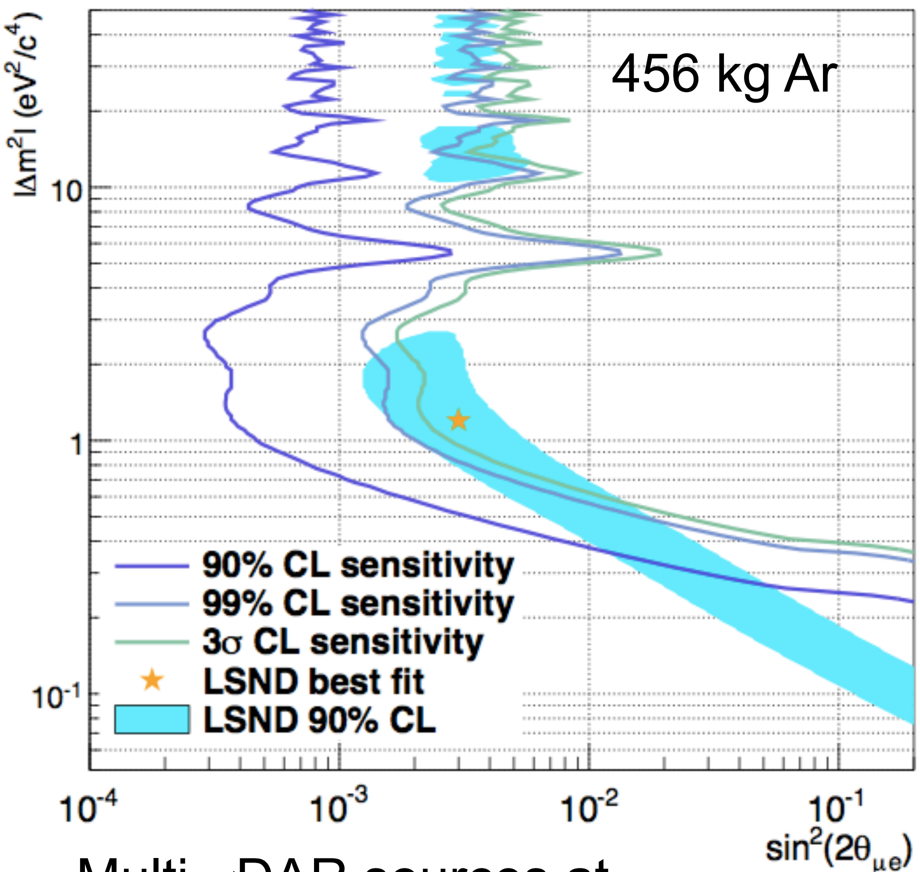
CEvNS sensitivity is @ low Q; need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

Oscillations to sterile neutrinos w/CEvNS

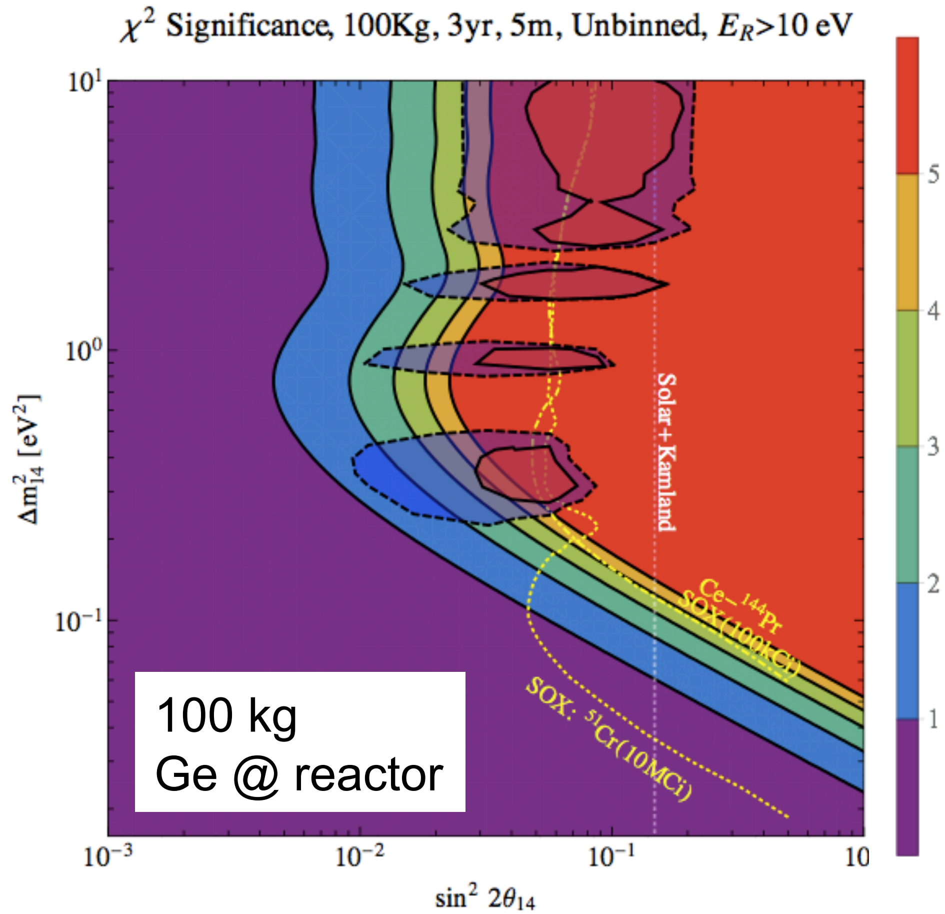
(NC is flavor-blind): a potential new tool;

look for deficit and spectral distortion vs L,E

Examples:



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



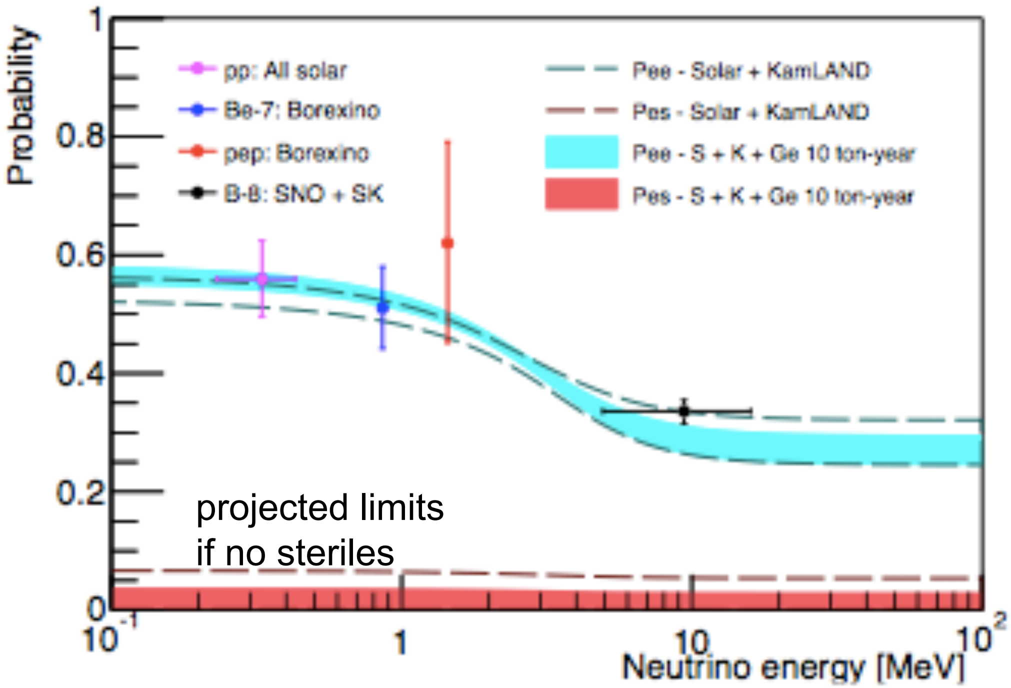
B. Dutta et al, arXiv:1511.02834

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

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

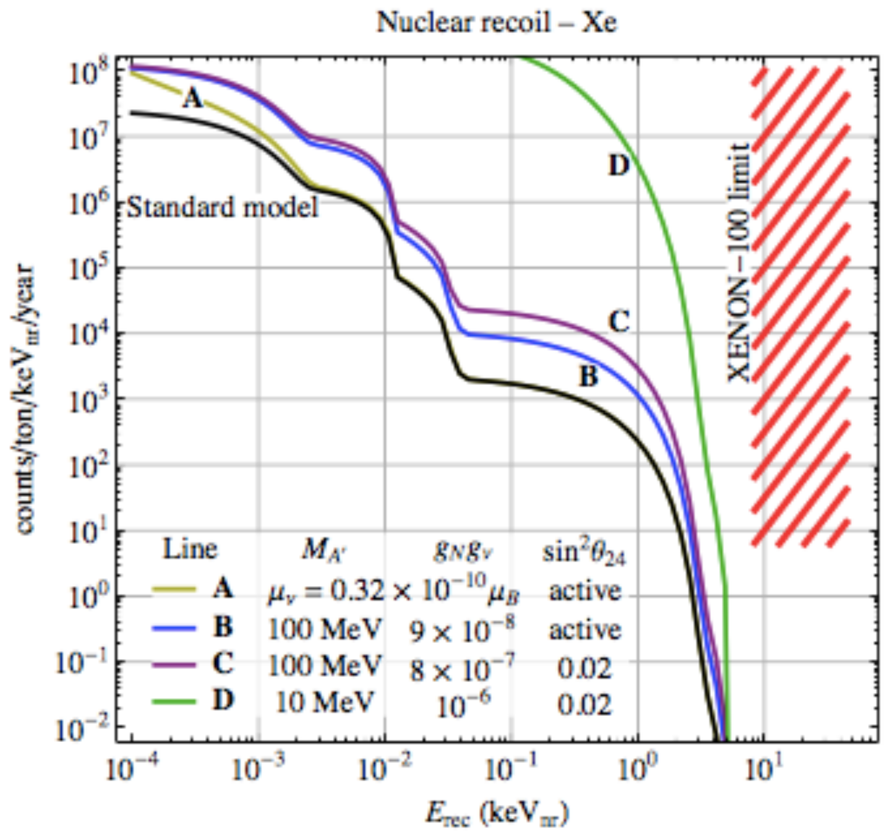
Solar neutrinos

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



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

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

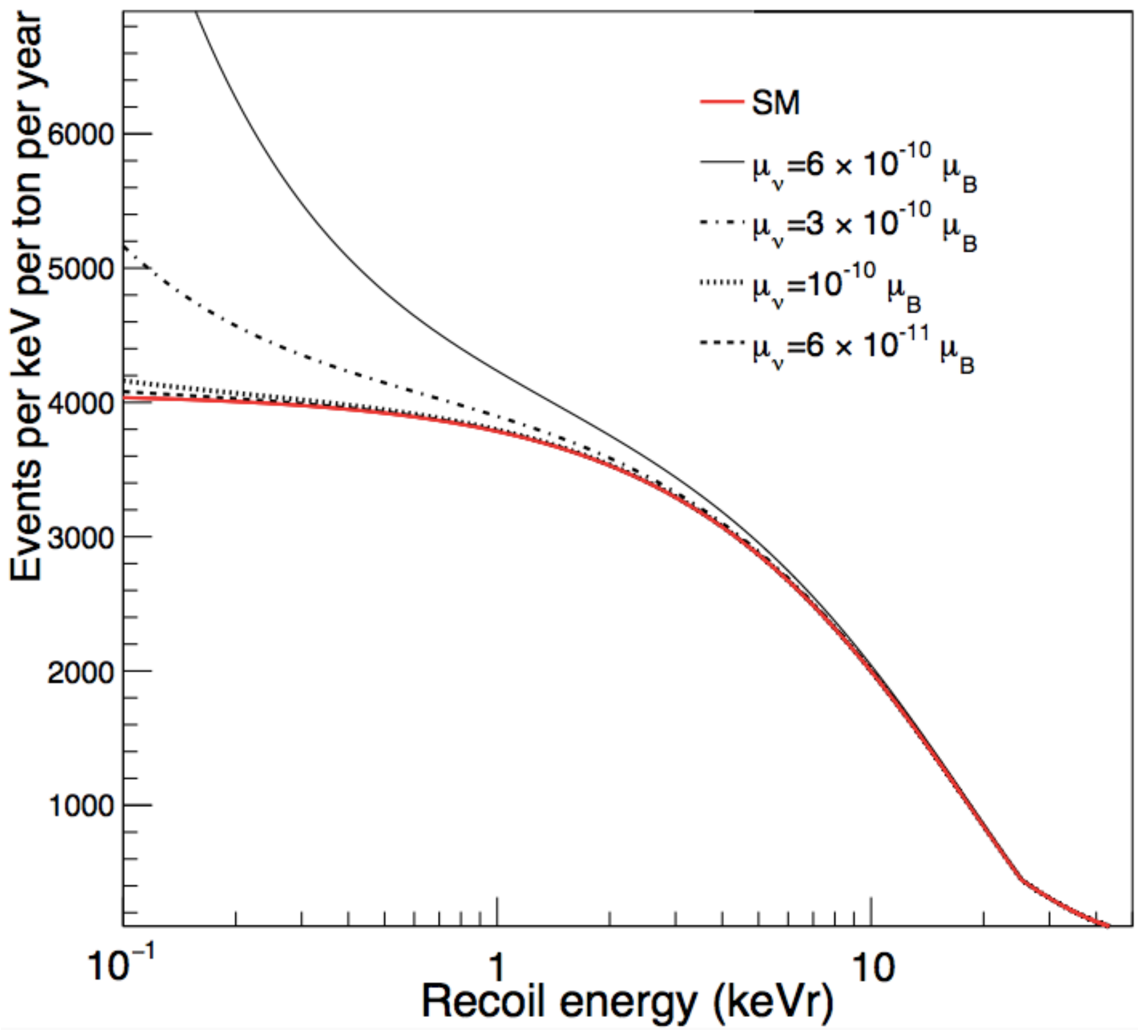


Effect of new physics on CEvNS recoil spectrum

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 very 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

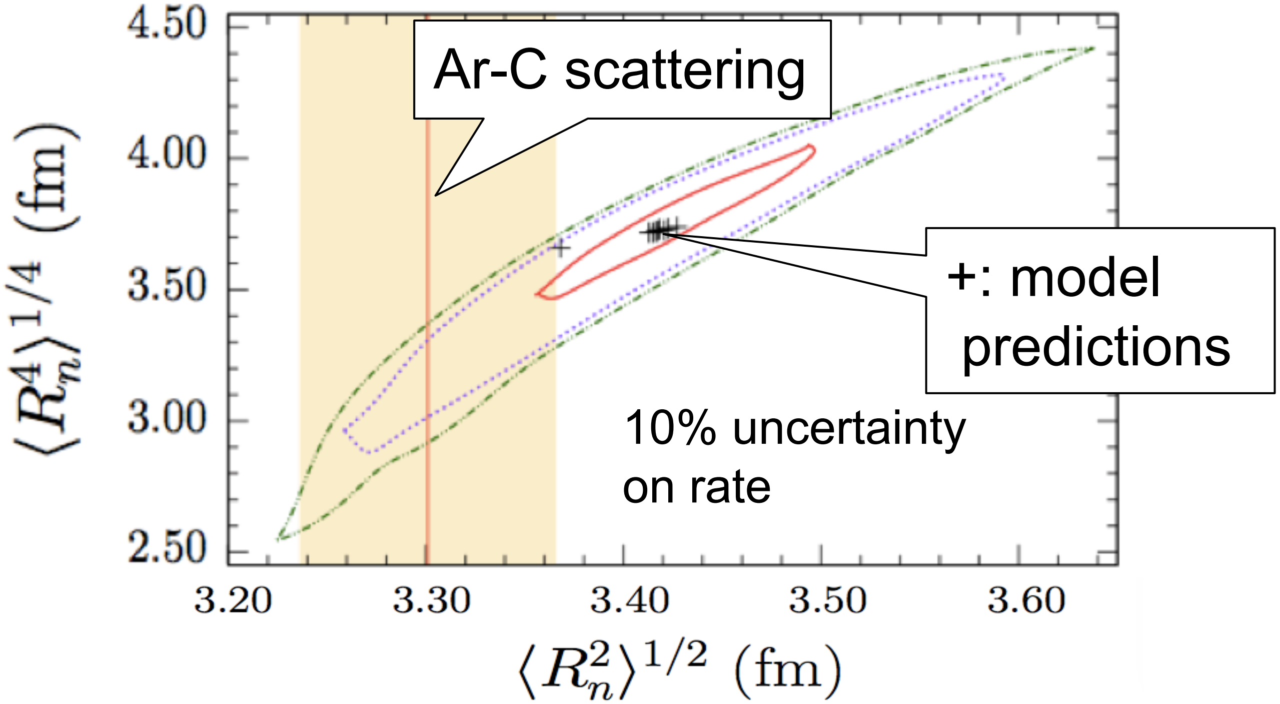
$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left(2 - \frac{MT}{E_\nu^2}\right)$$

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

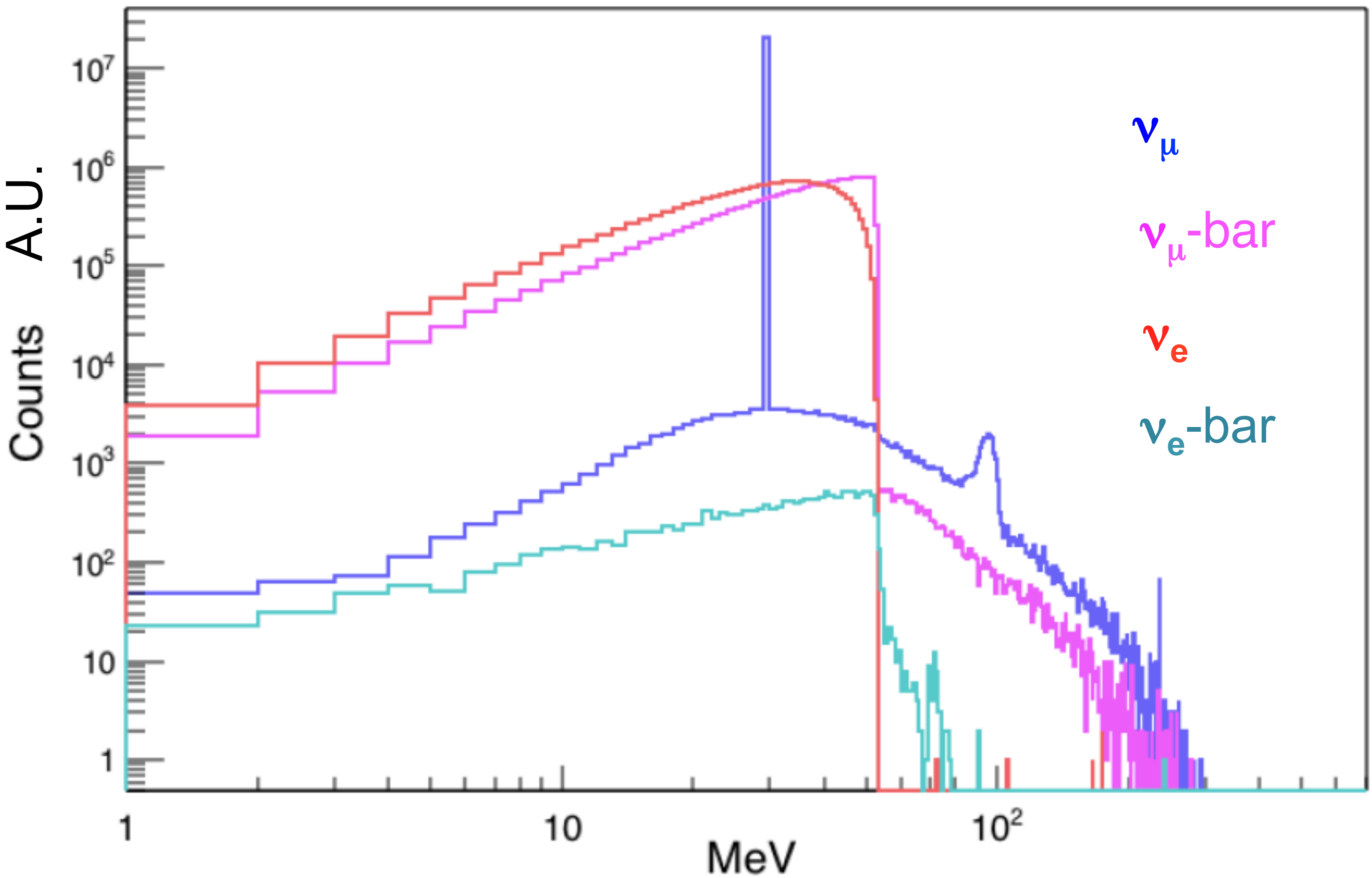
Fit recoil ***spectral shape*** to determine the $F^2(Q)$ moments

(requires very good energy resolution,good systematics control)

Example: tonne-scale experiment at πDAR source



Spectrum including very small contribution of ν_e-bar

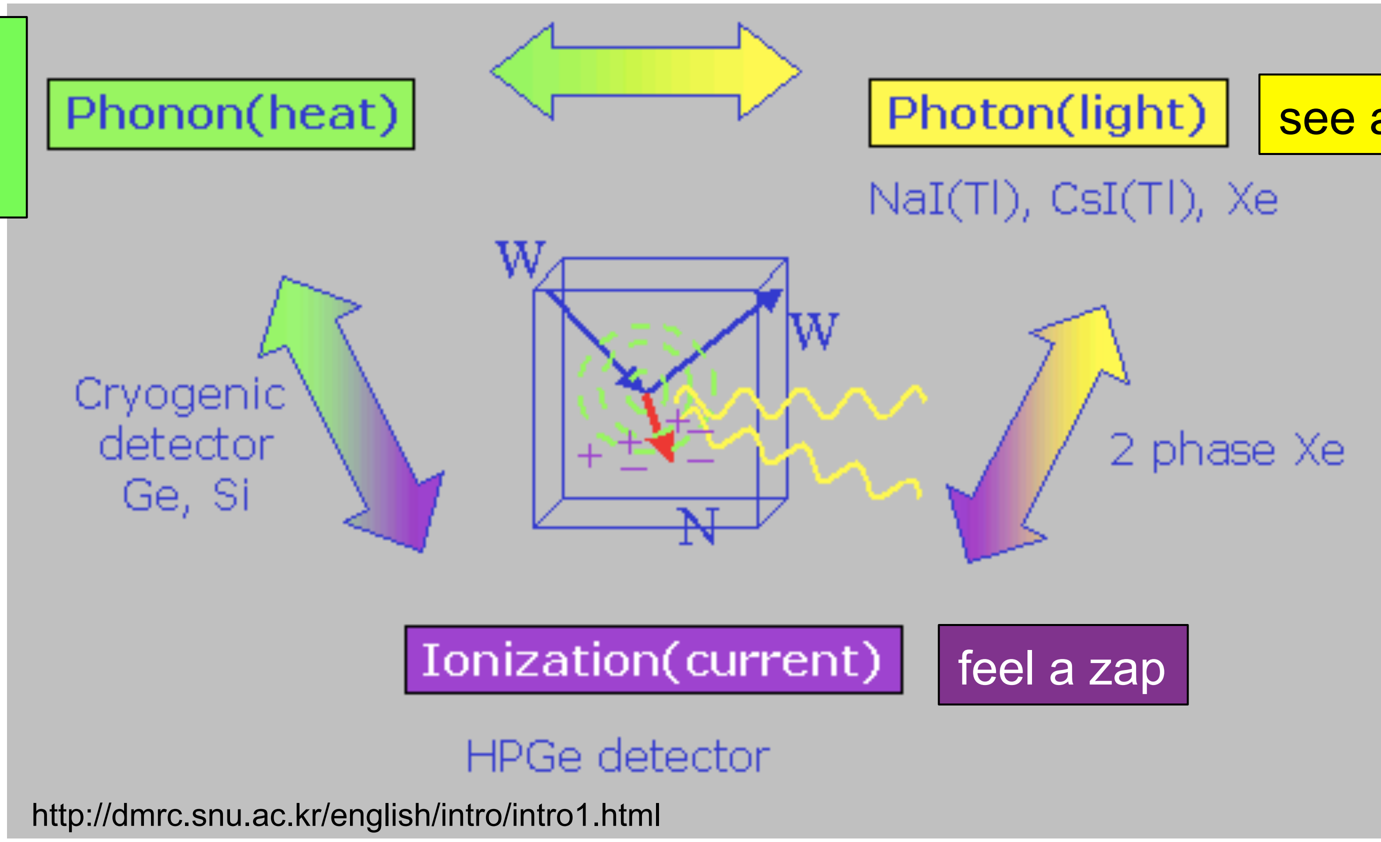


Now, ***detecting*** the tiny kick of the neutrino...

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

see a flash



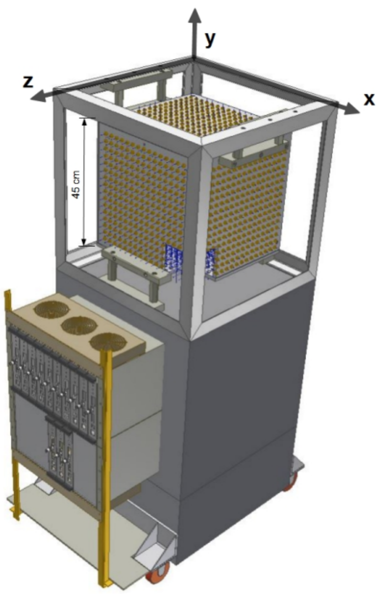
feel a zap

- 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)

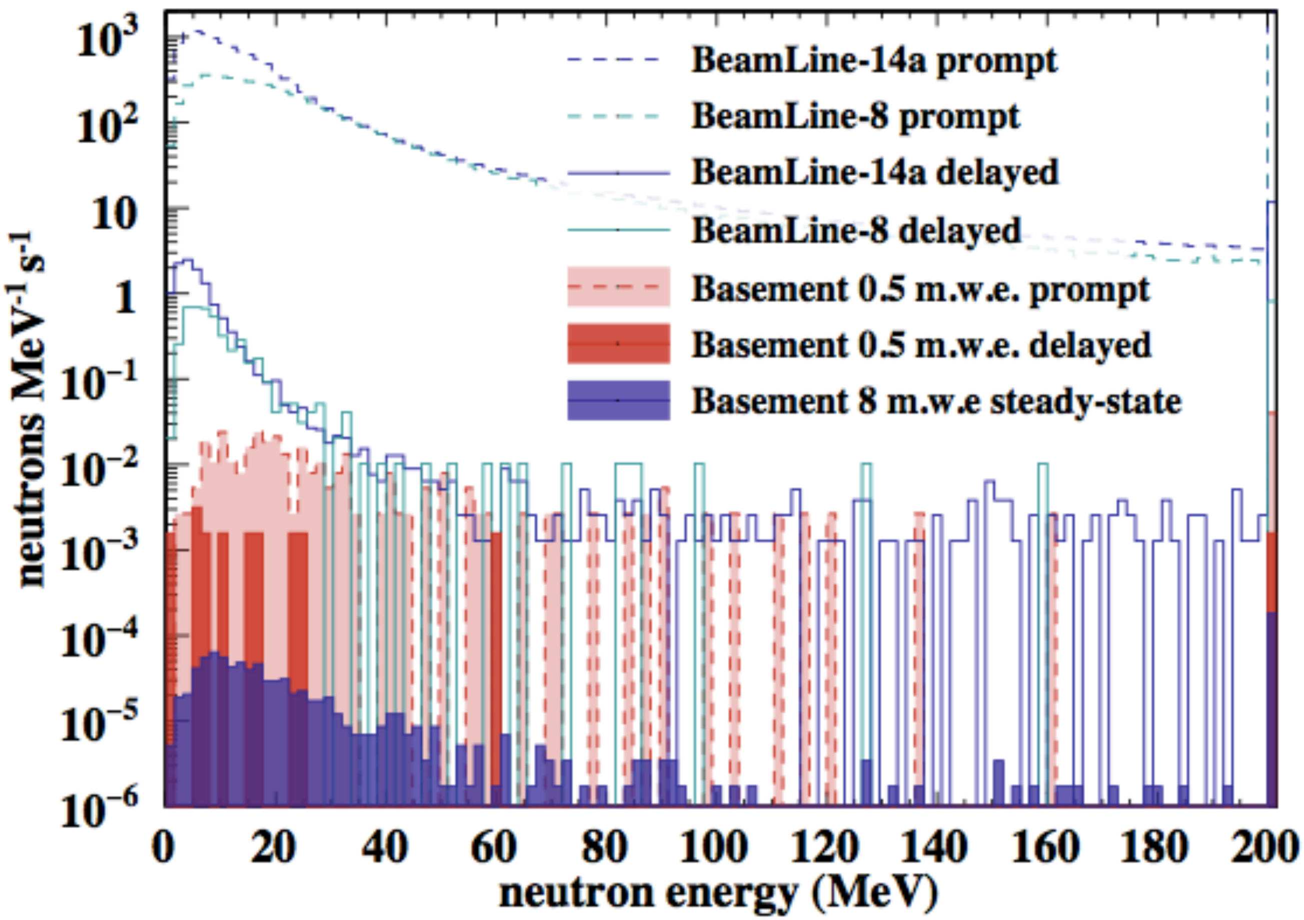
Neutron Backgrounds

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

SciBath

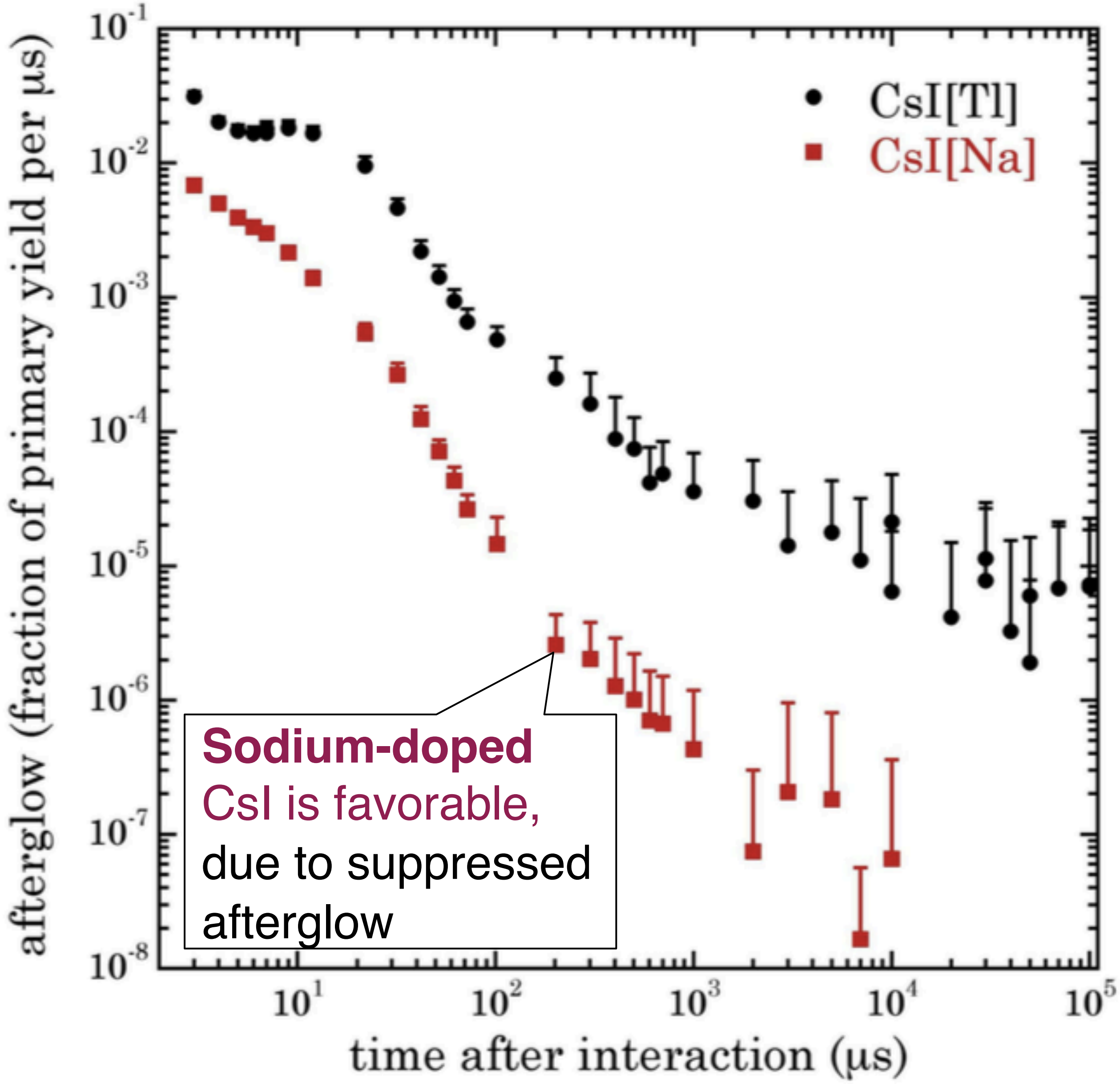


Sandia scatter cam



The First COHERENT Result: CsI[Na]

Led by U. Chicago group



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

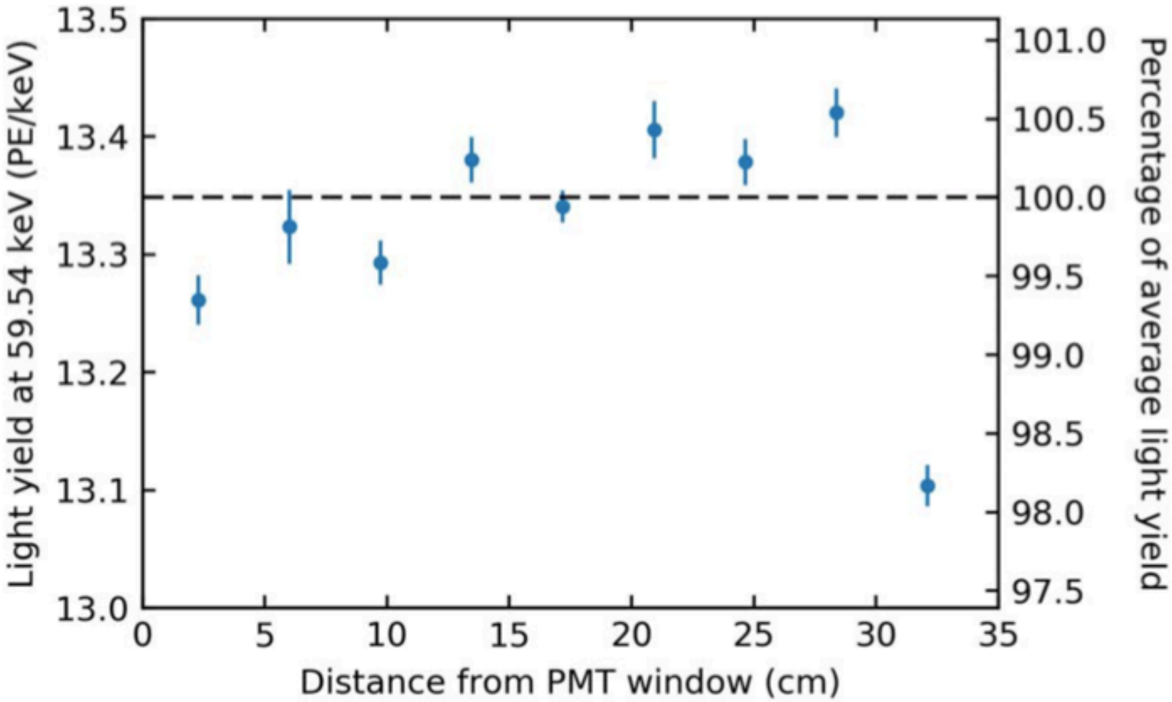
Scintillating crystal

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

2 kg test crystal @U. Chicago.
Amcrys-H, Ukraine

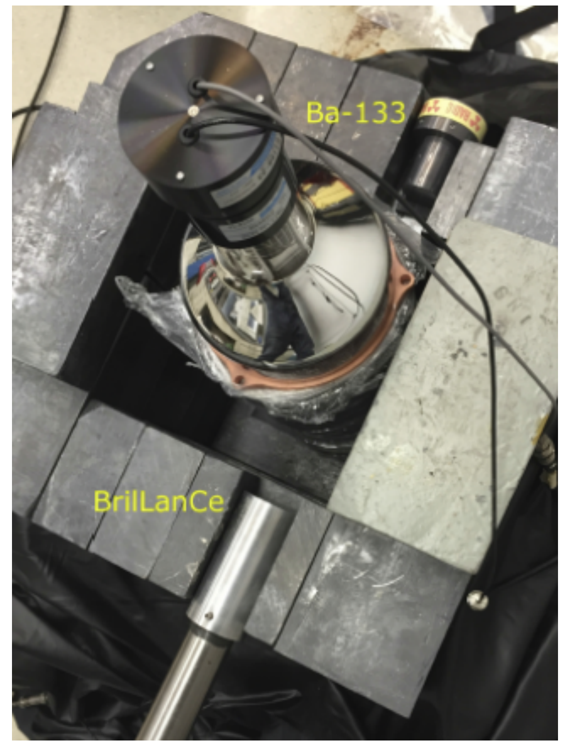
Calibration of 14.6-kg detector at U. Chicago (^{241}Am, ^{133}Ba)

^{241}Am



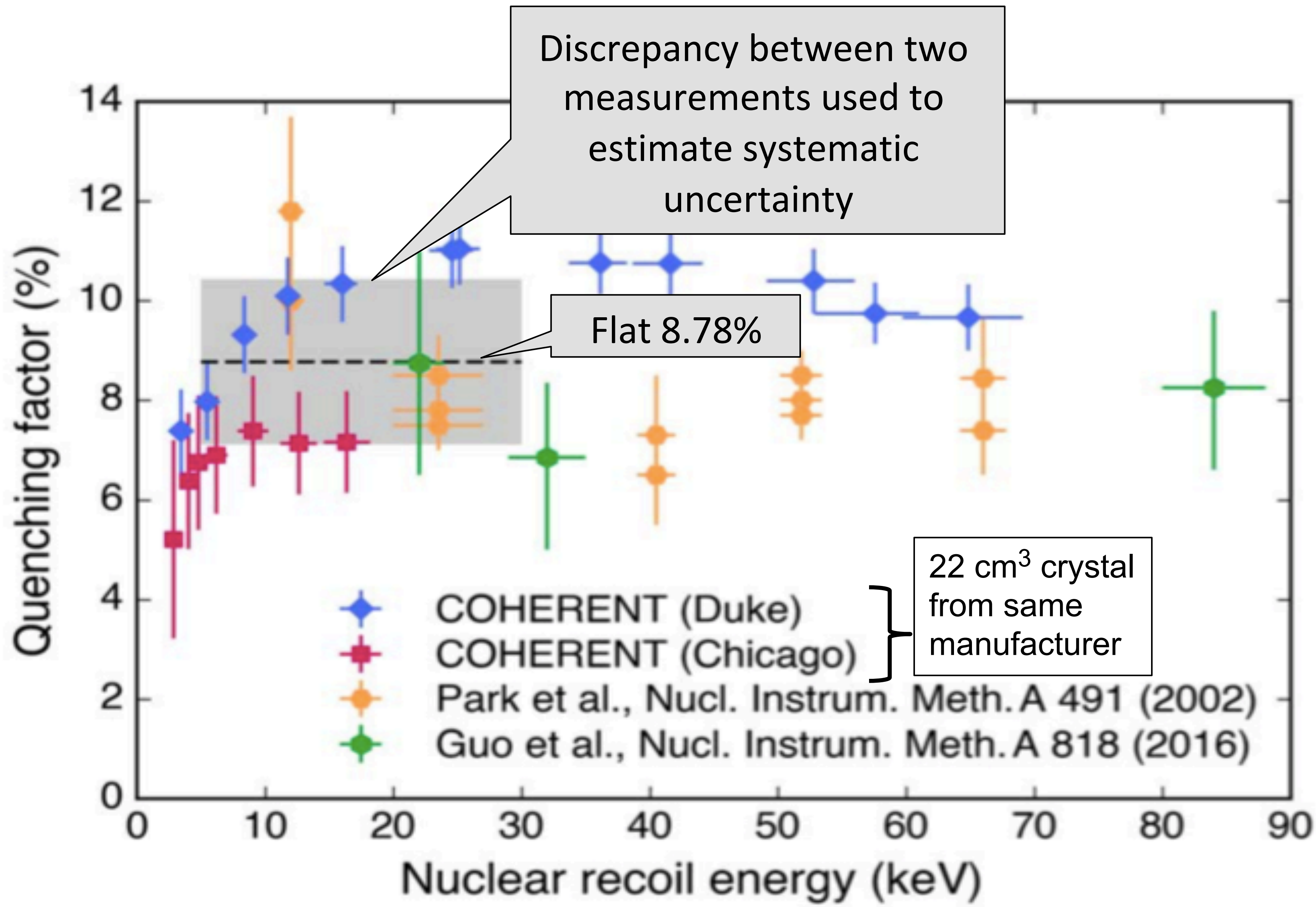
Light yield:
13.35 pe/keVee,
uniform within ~2%

^{133}Ba



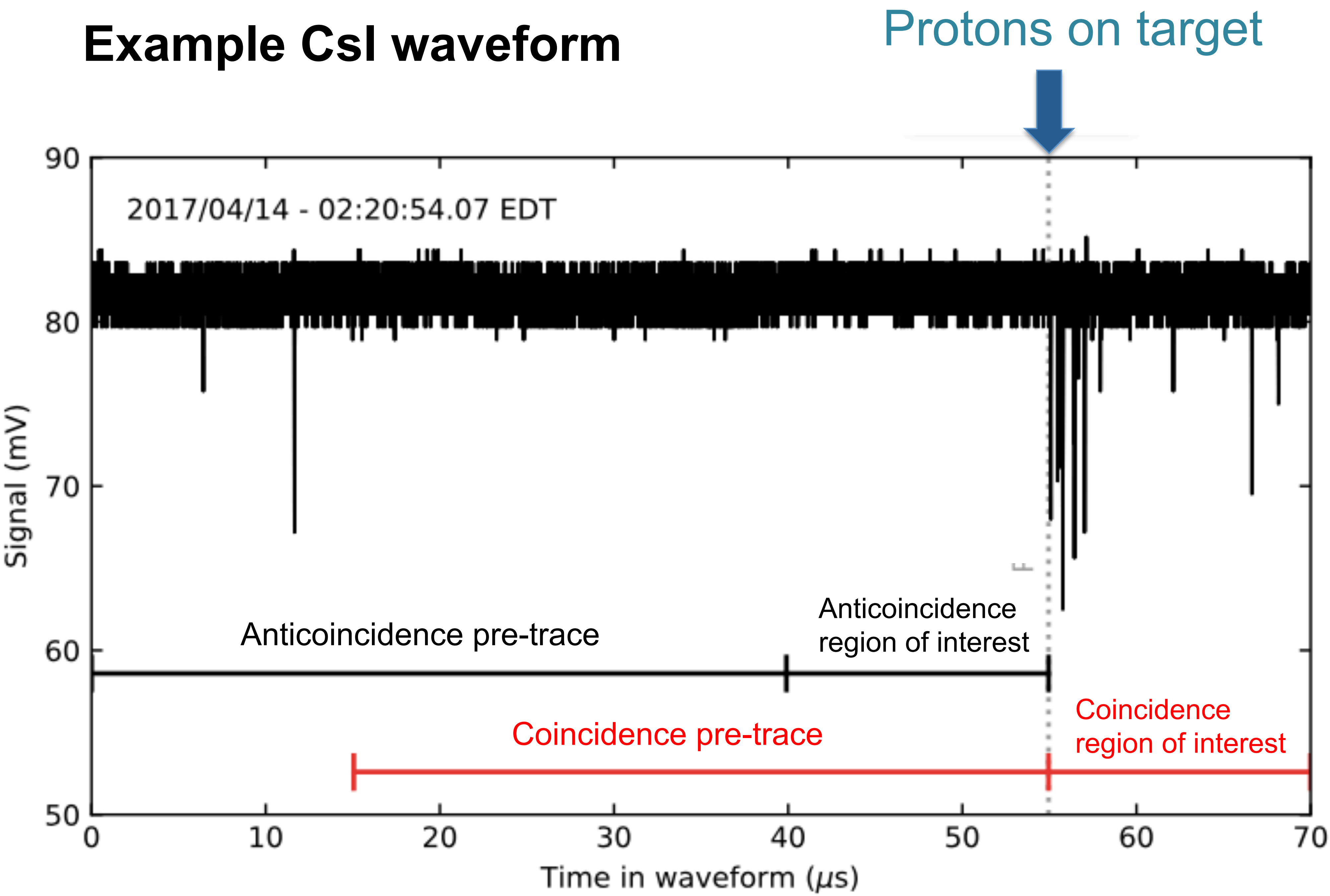
Used to determine
event selection efficiency

CsI quenching factor measurements at TUNL w/ neutrons



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

Example CsI waveform



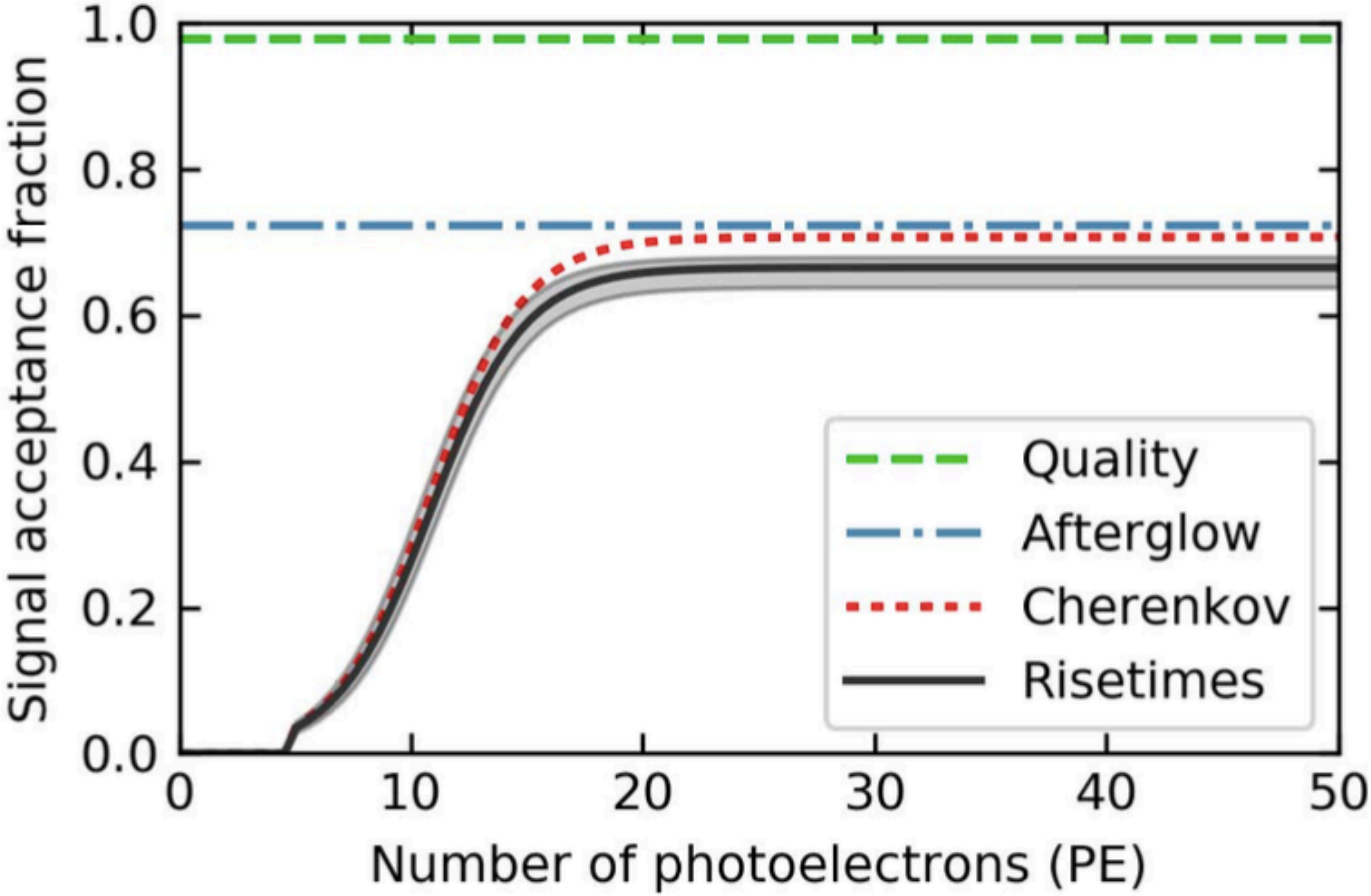
- (C ROI) – (AC ROI) = CEvNS + Beam-on bg
- Pretraces used for afterglow background removal

Event Selection Cuts

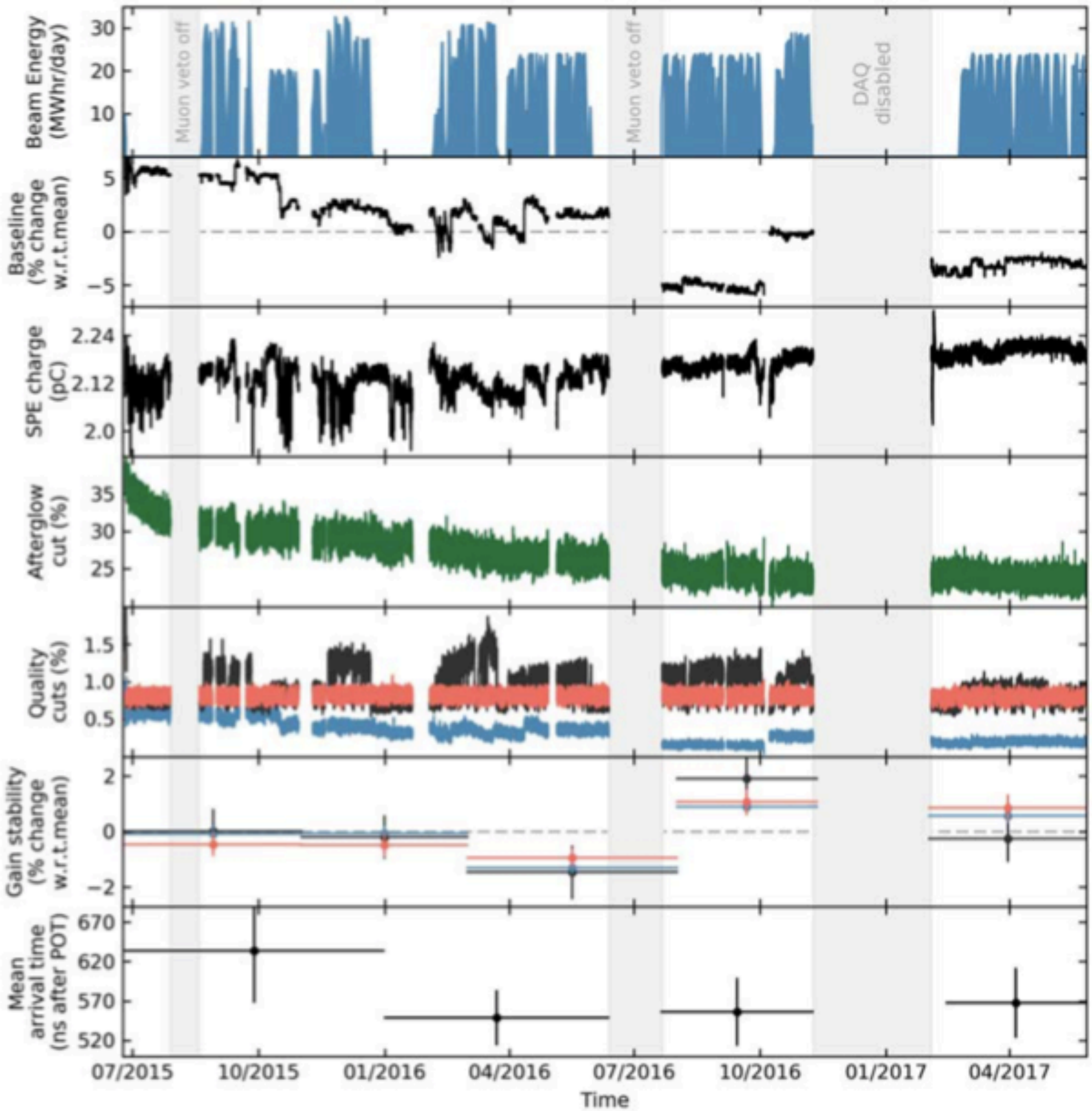
Quality	Remove coincidences in muon veto, deadtime from PMT saturation blocking, digitizer range overflow	Select recoil-like low-energy pulses, reject muons
Afterglow	Reject signals with >=4 peaks (~spe) in pretrace	Remove afterglow (phosphorescence) contamination
"Cherenkov"	Require minimum number of 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

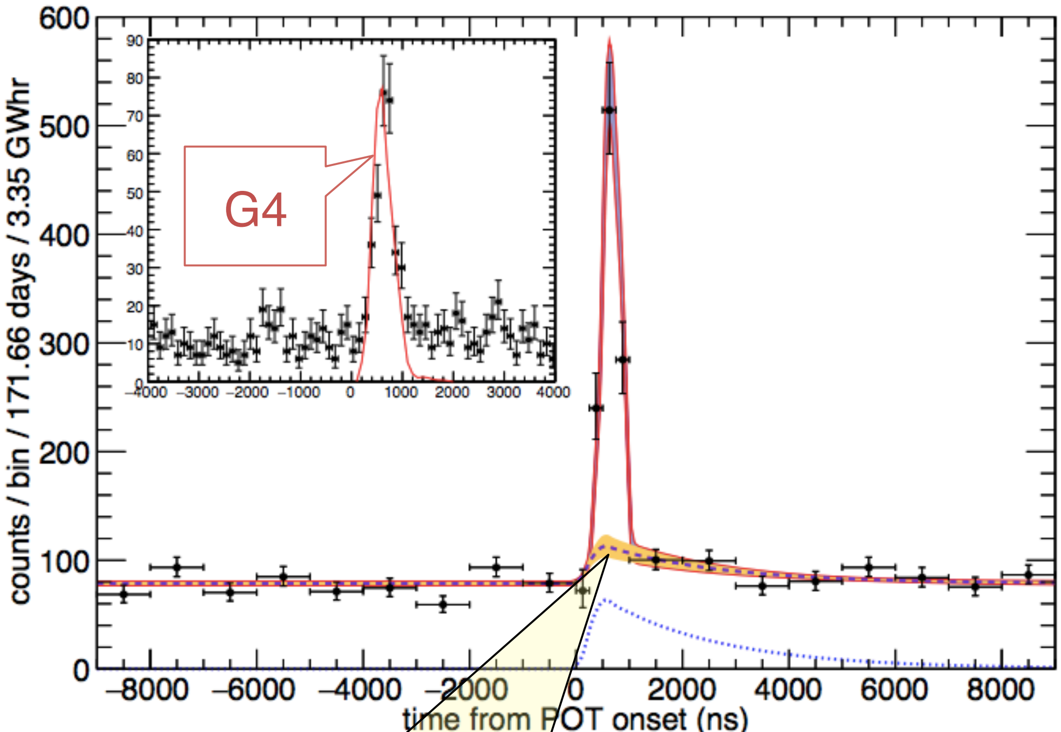
Muon veto cut
Linear gate cut
DAQ overflow cut

Gain from internal crystal backgrounds

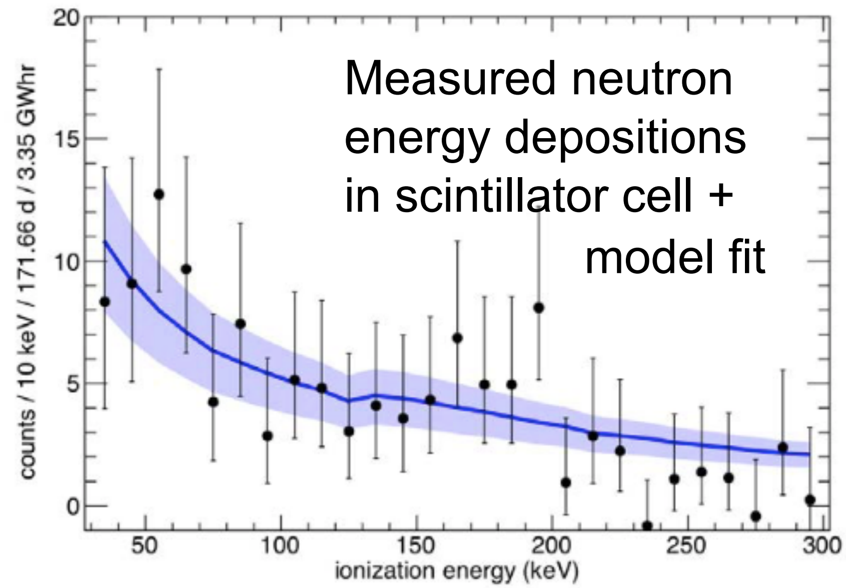
POT signal delay from muon panel neutron coincidences

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)



(consistent w/other measurements)

Expect: 0.92 ± 0.23 beam n events/GWhr
0.54 ± 0.18 NIN events/GWhr (neglected)

<~11 neutron events in CsI dataset

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

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

ε's parameterize new interactions

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

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

$\Rightarrow$ 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

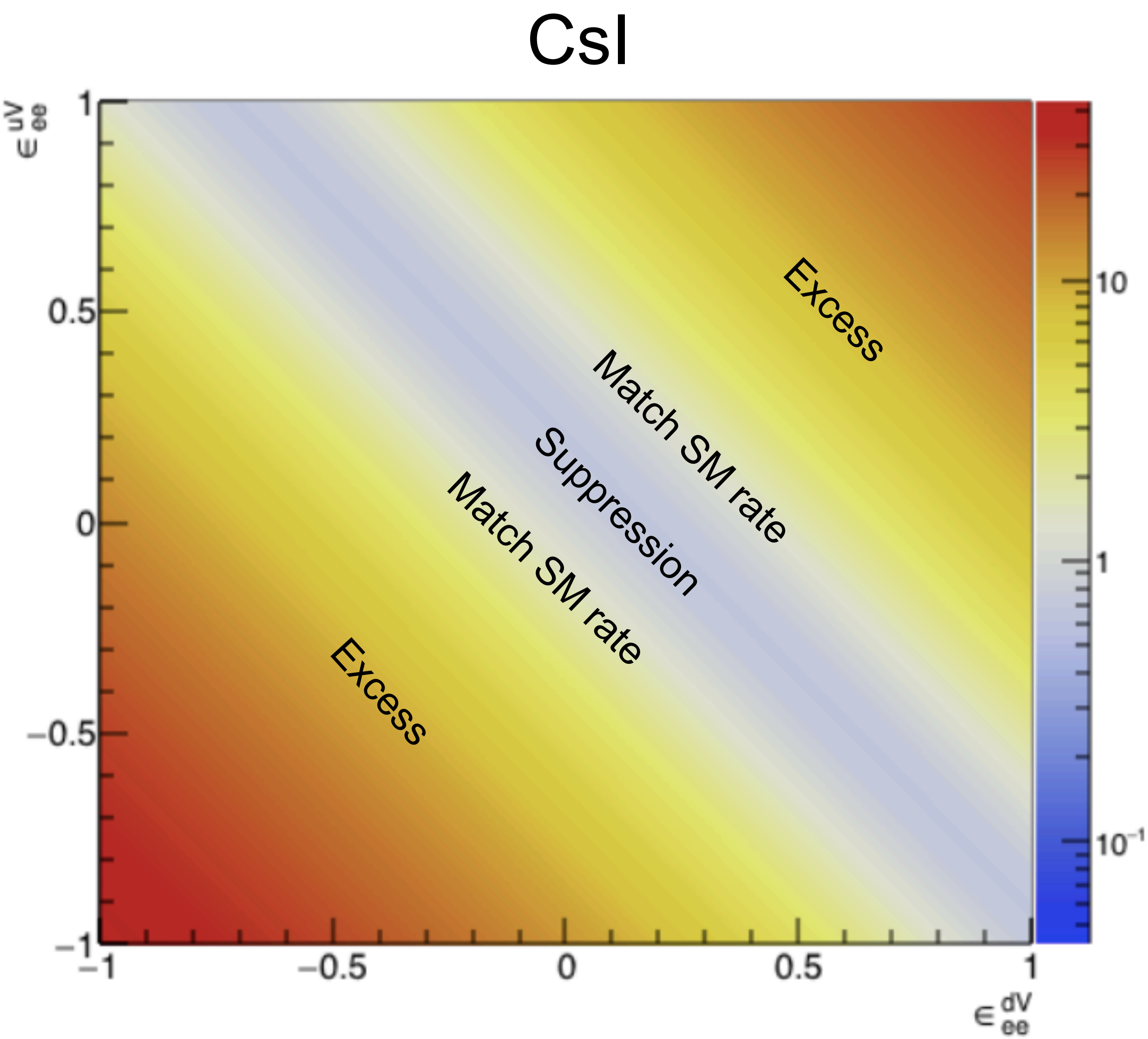
$$\left.\begin{array}{l} g_V^p = (\frac{1}{2} - 2\sin^2\theta_W), \quad g_V^n = -\frac{1}{2} \end{array}\right\}$$ SM parameters

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

- 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)



Note that for

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

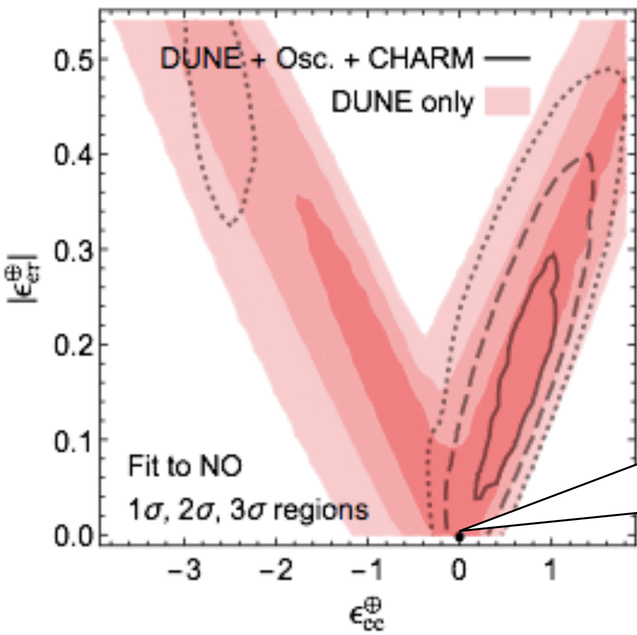
the rate is the same as for the SM, so parameters will be allowed

Get slightly different slope for different targets

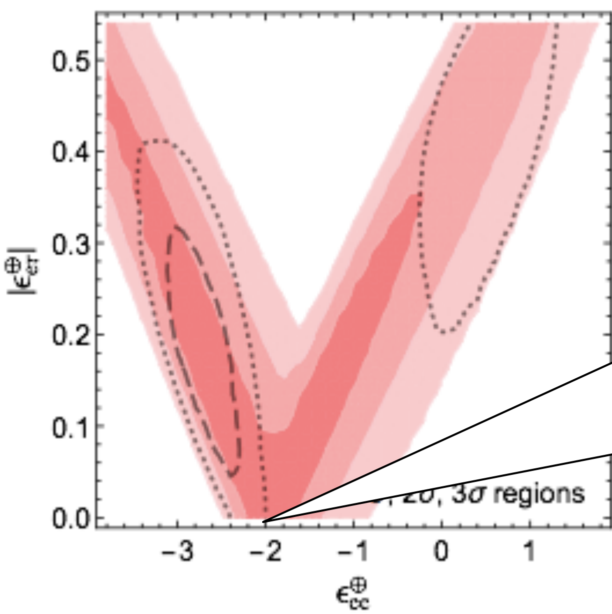
Generalized mass ordering degeneracy in neutrino oscillation experiments

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

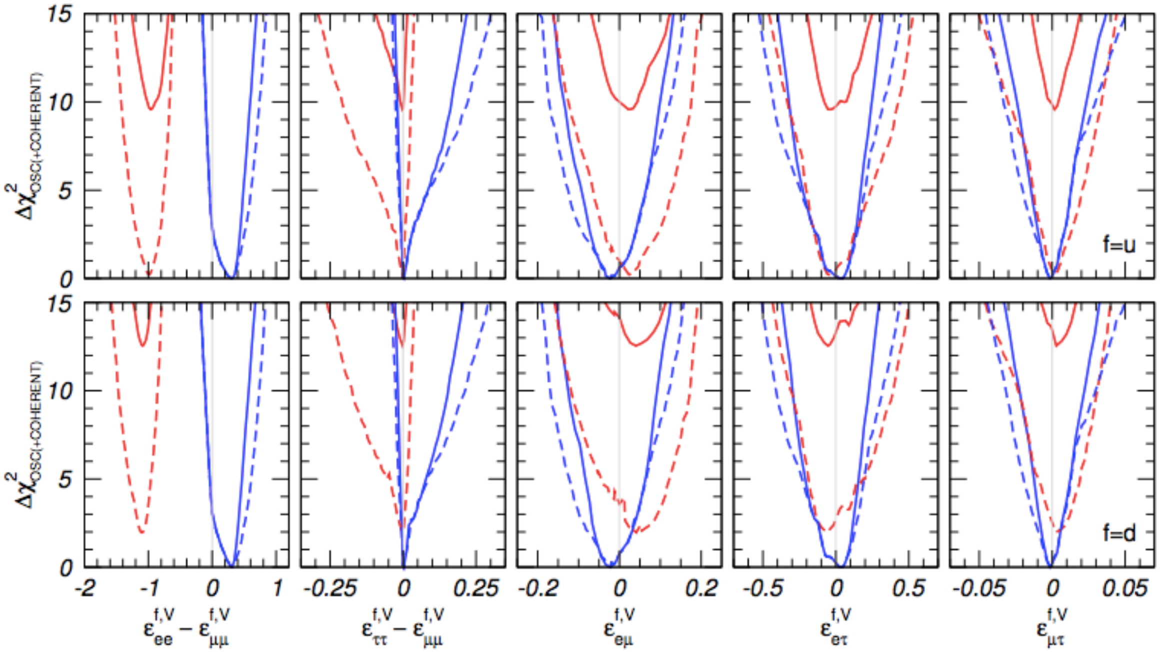
If you allow for NSI to exist, you can't tell the neutrino mass ordering in long-baseline experiments

... NC scattering can constrain NSI...

➔DUNE may need this...

A COHERENT enlightenment of the neutrino Dark Side

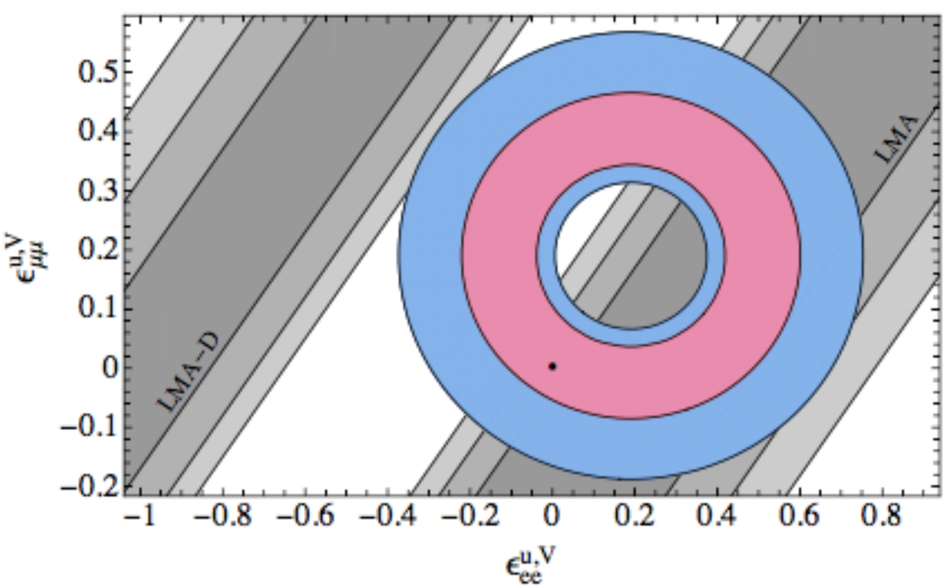
Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,,[2,3,4,†] Michele Maltoni,,[5,‡] and Thomas Schwetz[6,§]



Global fits to COHERENT + oscillation experiments

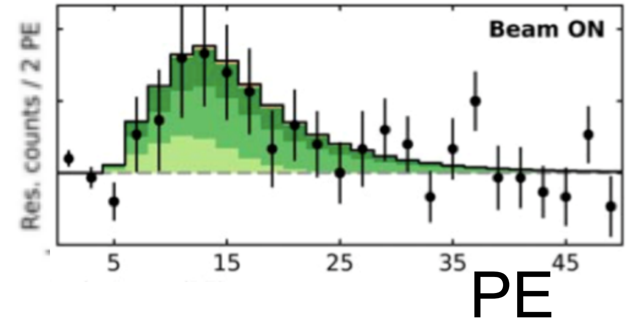
Solid: COHERENT
Dashed: COHERENT + osc
Blue: LMA ($\theta_{12} < \pi/4$)
Red: LMA-D ($\theta_{12} > \pi/4$)
("dark side", still allowed with NSI)

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

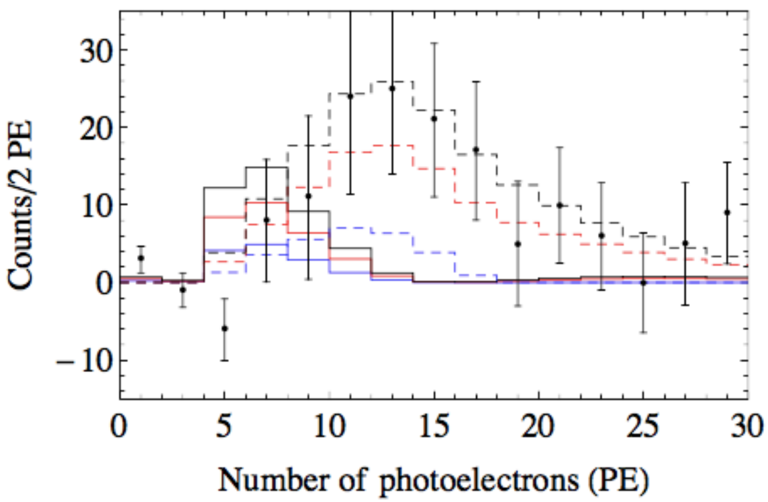
SM weak charge

$$Q^2_{\alpha,\mathrm{SM}} = (Z g_p^V + N g_n^V)^2$$

Effective weak charge in presence of light vector mediator Z'

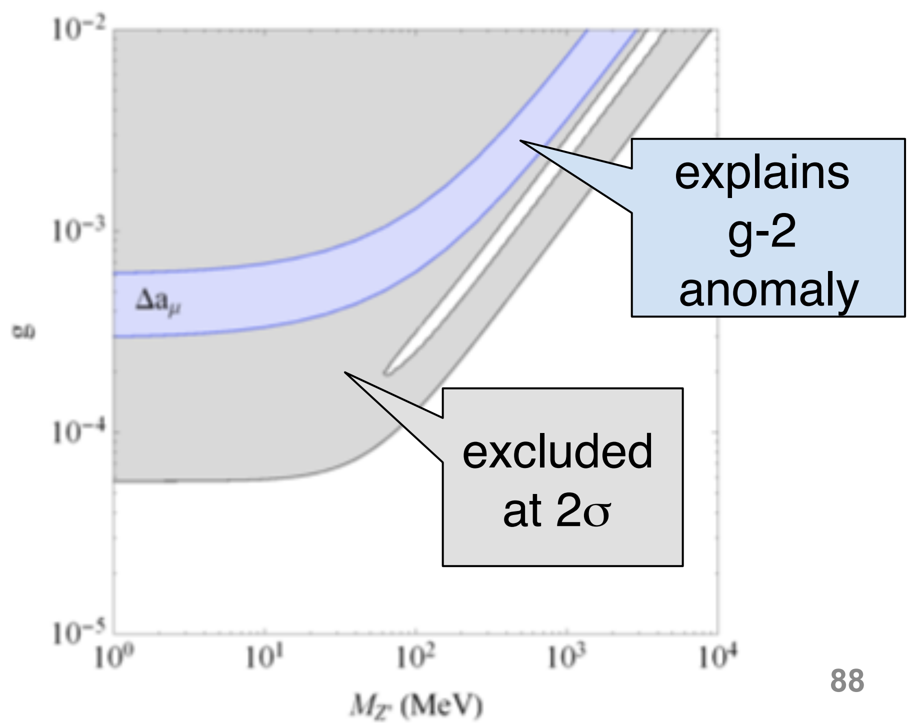
$$\Rightarrow \quad Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2+M^2_{Z'})}\right)\right]^2$$

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



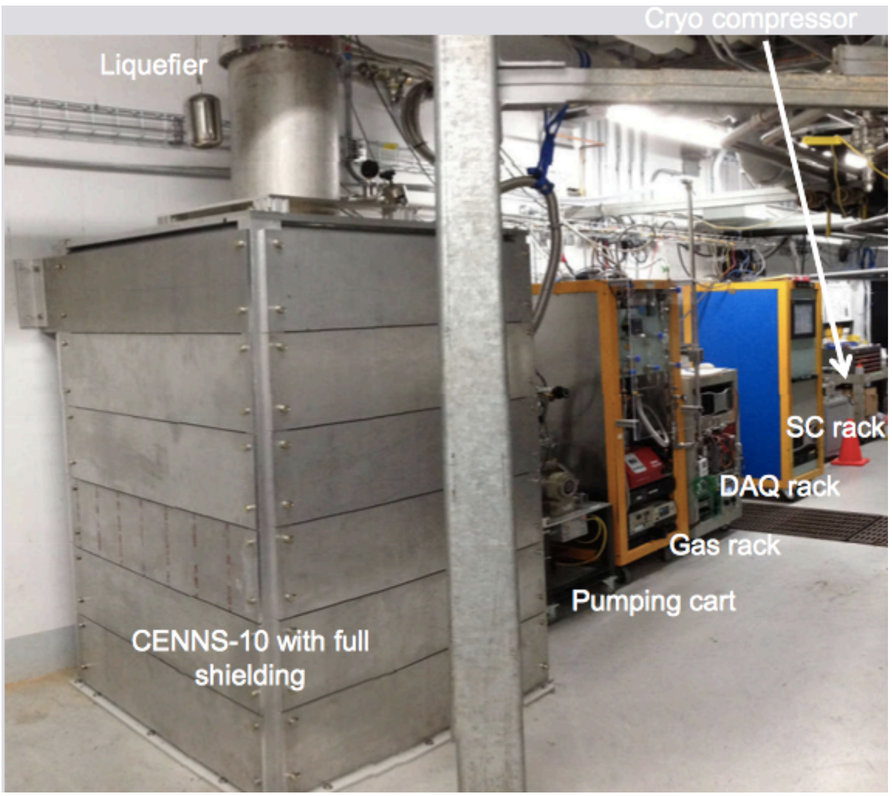
Dashed: SM
Solid: NSI w/ $M_{Z'}$= 10 MeV, g=10^{-4}

Blue: ν_μ
Red: ν_μ + ν_μ_bar
Black: ν_μ + ν_μ_bar + ν_e

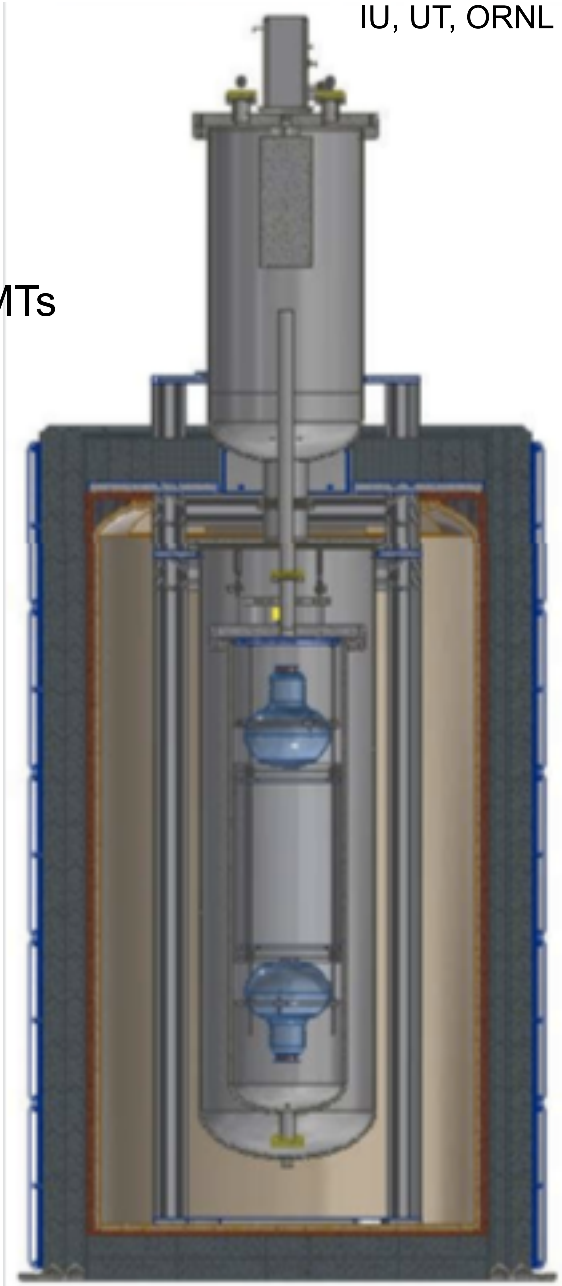


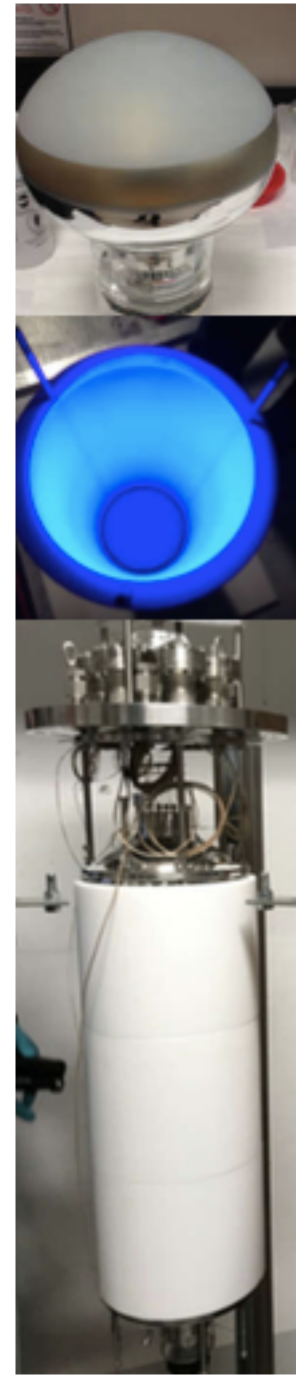
Single-Phase Liquid Argon

- ~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



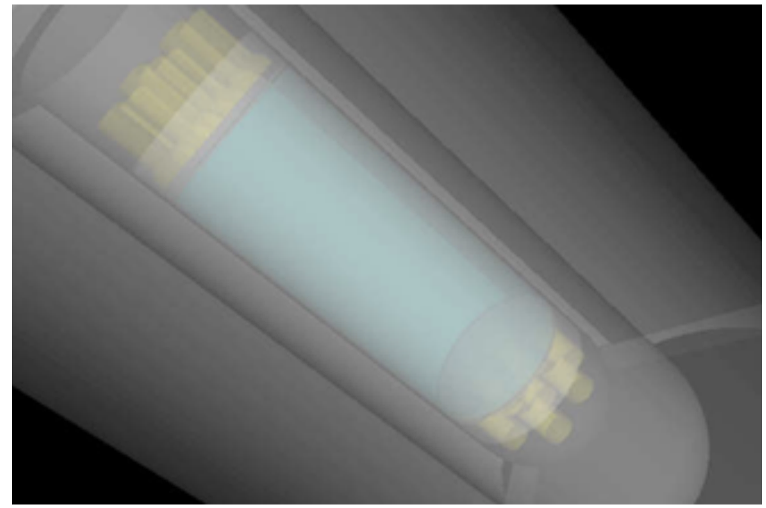


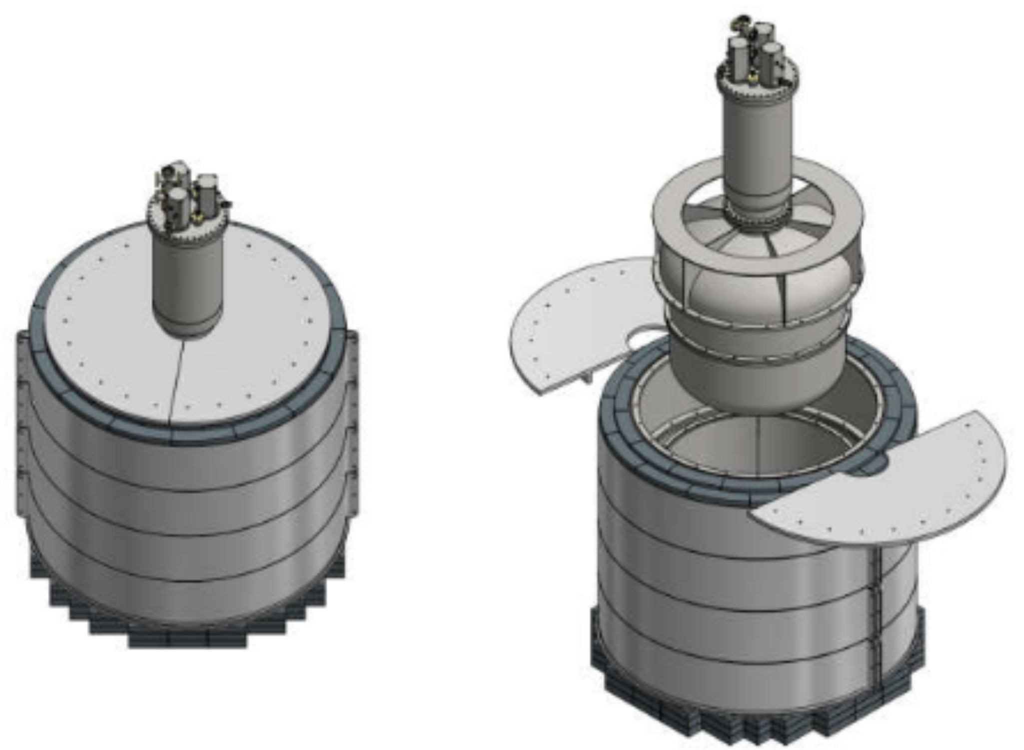
Detector from FNAL, previously built (J. Yoo et al.) for CENNS@BNB

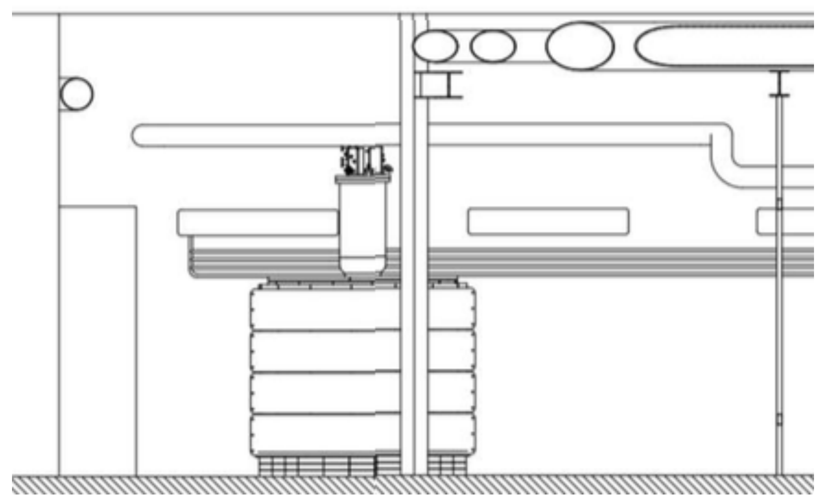
(S. Brice, Phys.Rev. D89 (2014) no.7, 072004)

Future LAr concepts

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

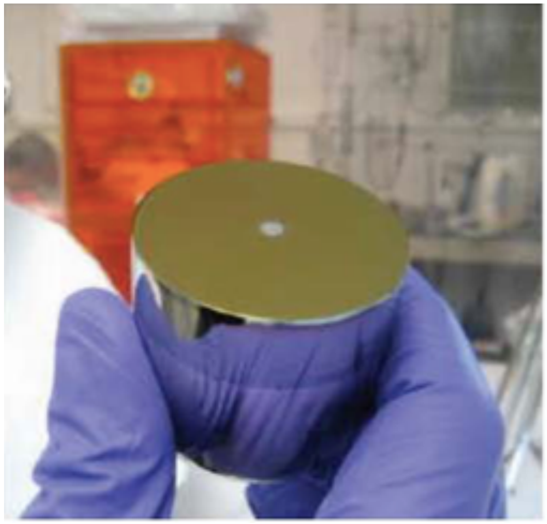






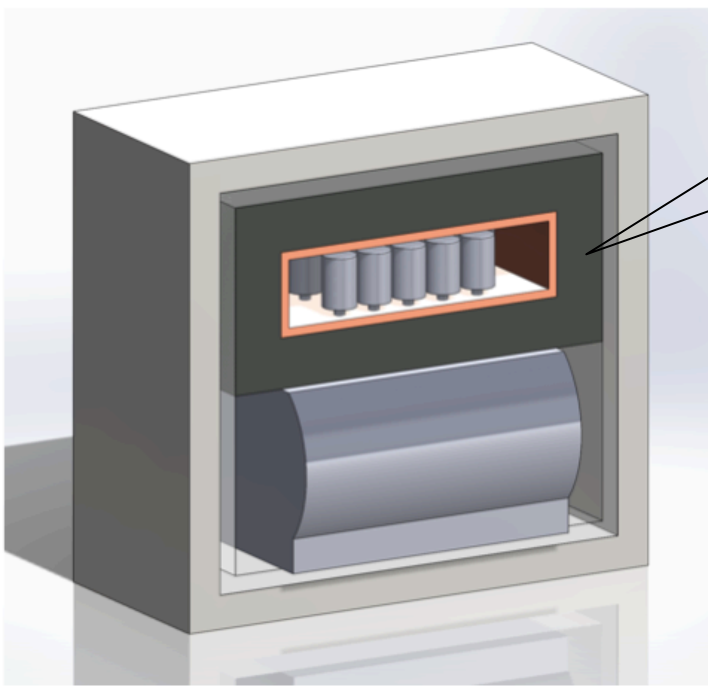
High-Purity Germanium Detectors

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

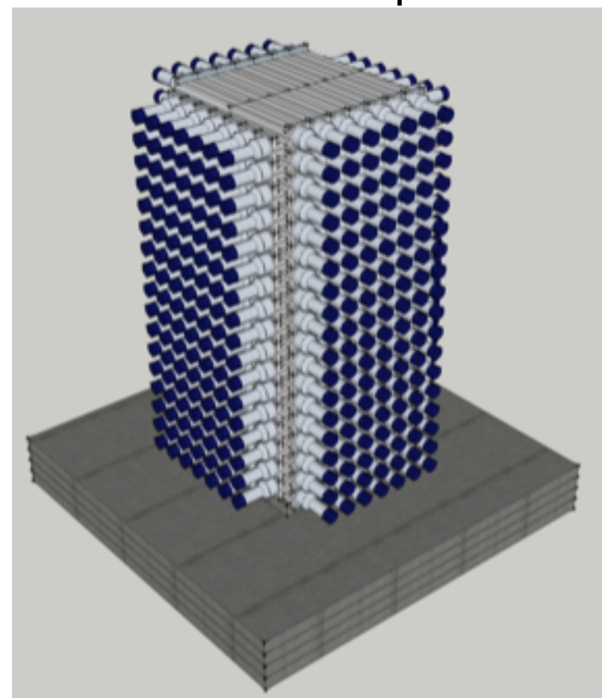


- 10 kg of detectors available (MAJORANA unenriched prototypes)
- Under refurbishment/test at NCSU, Duke and LANL
- Dewar fabrication nearly complete
- Future: additional 2.5 kg detectors (UChicago, NCSU)

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



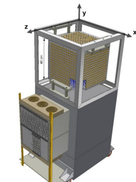
In the meantime: **185 kg deployed at SNS** to go after ν_e**CC on ^{127}I**

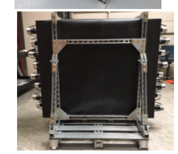
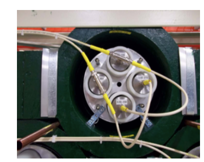
Isotope	Reaction Channel	Source	Experiment	Measurement (10^{-42} cm^2)	Theory (10^{-42} cm^2)
^{127}I	$^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$	Stopped π/μ	LSND	$284 \pm 91(\mathrm{stat}) \pm 25(\mathrm{sys})$	210-310 [Quasi-particle] (Engel *et al.*, 1994)

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

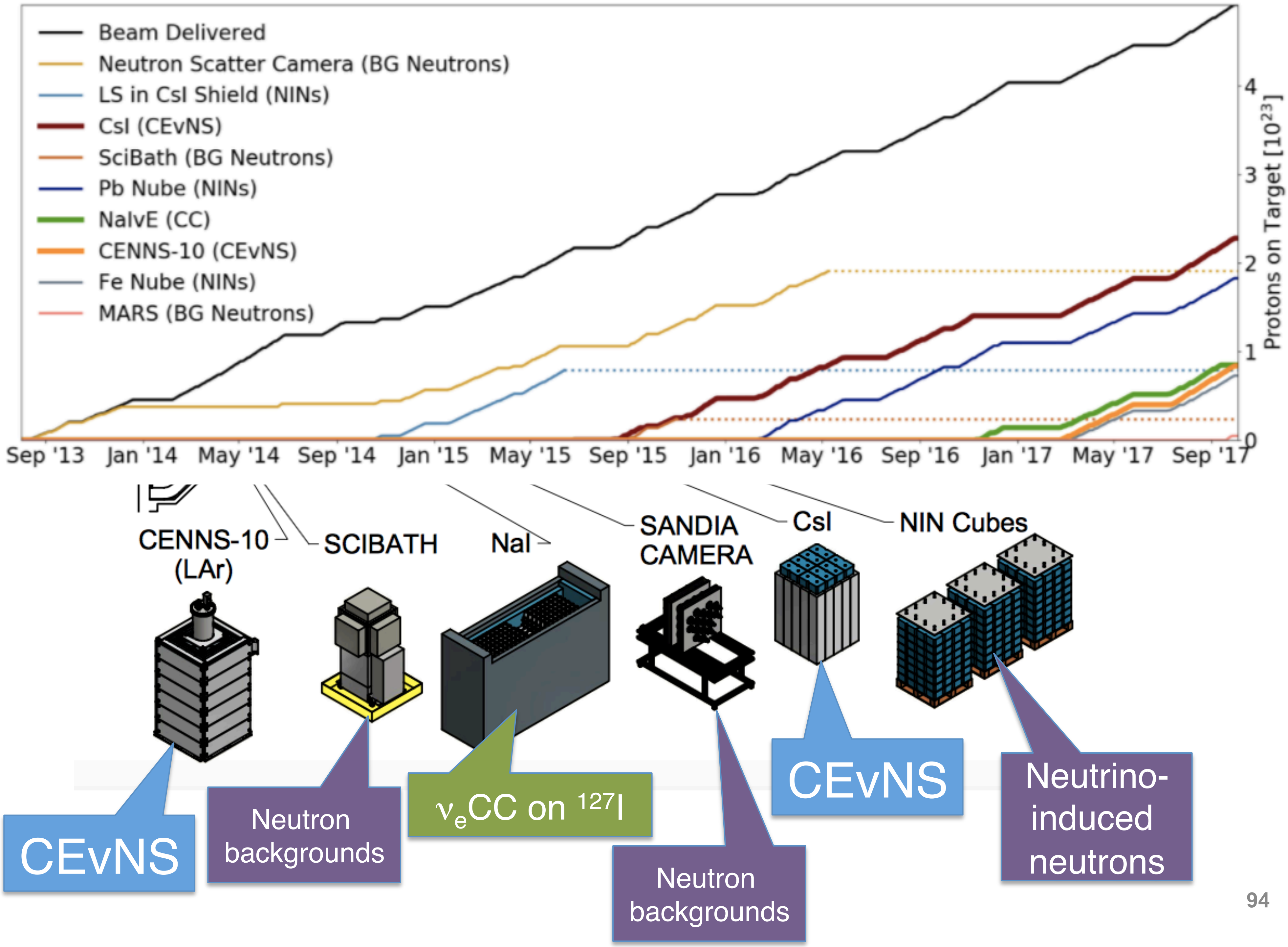



And many more ideas and activities for Neutrino Alley and beyond...

- 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: quenching factors
- Directional detectors
- ...

Protons on target delivered so far



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)

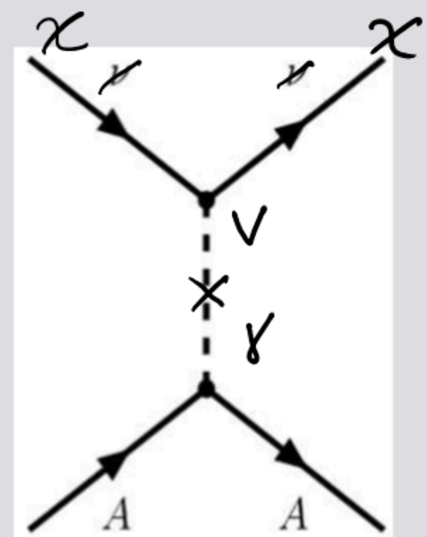
production:

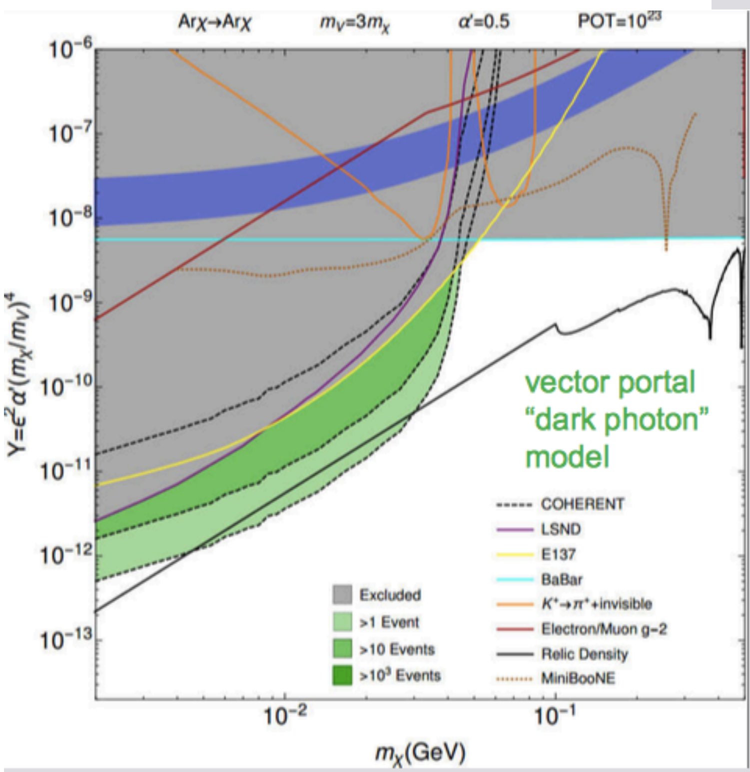
proton → target → $\pi^{0,\pm}$ →

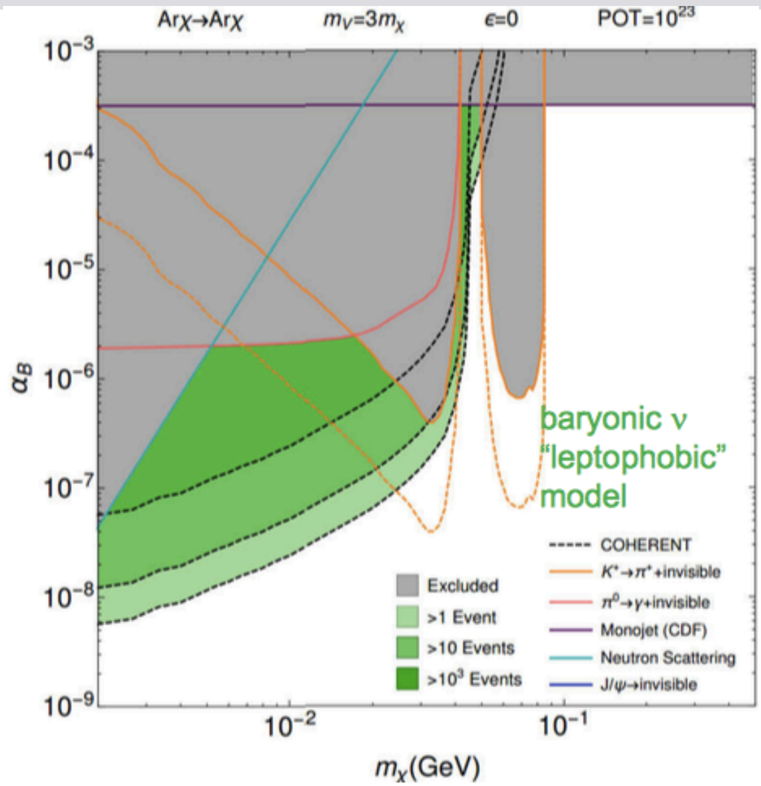
$$\pi^0 \longrightarrow \gamma + V^{(*)} \longrightarrow \gamma + \chi^\dagger + \chi$$

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

detection:





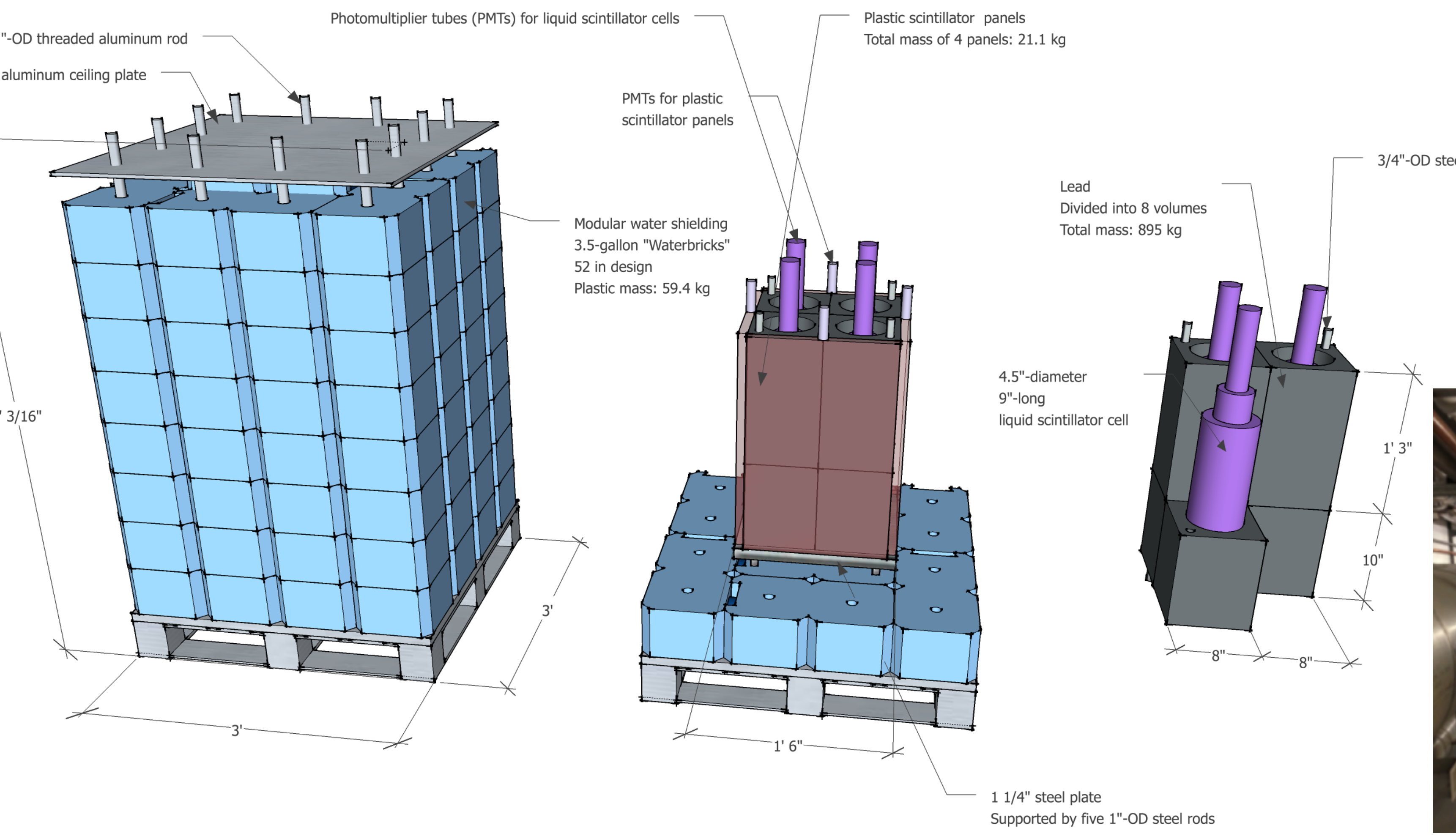


1 ton LAr
E_{rec}>20keVnr
10^{23} POT

R. Tayloe
Cosmic Visions 2017

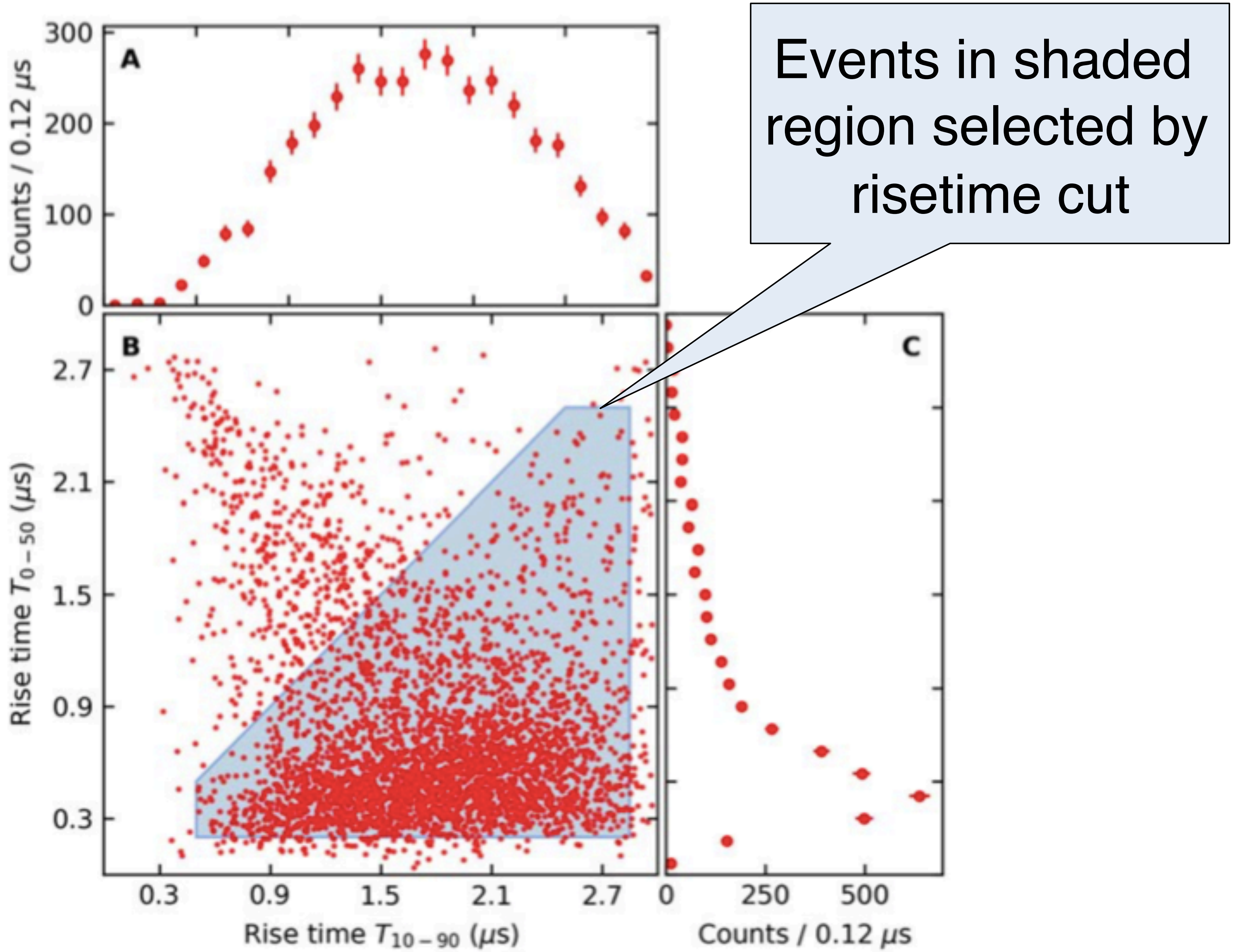
NIN measurement in SNS basement with Nubes

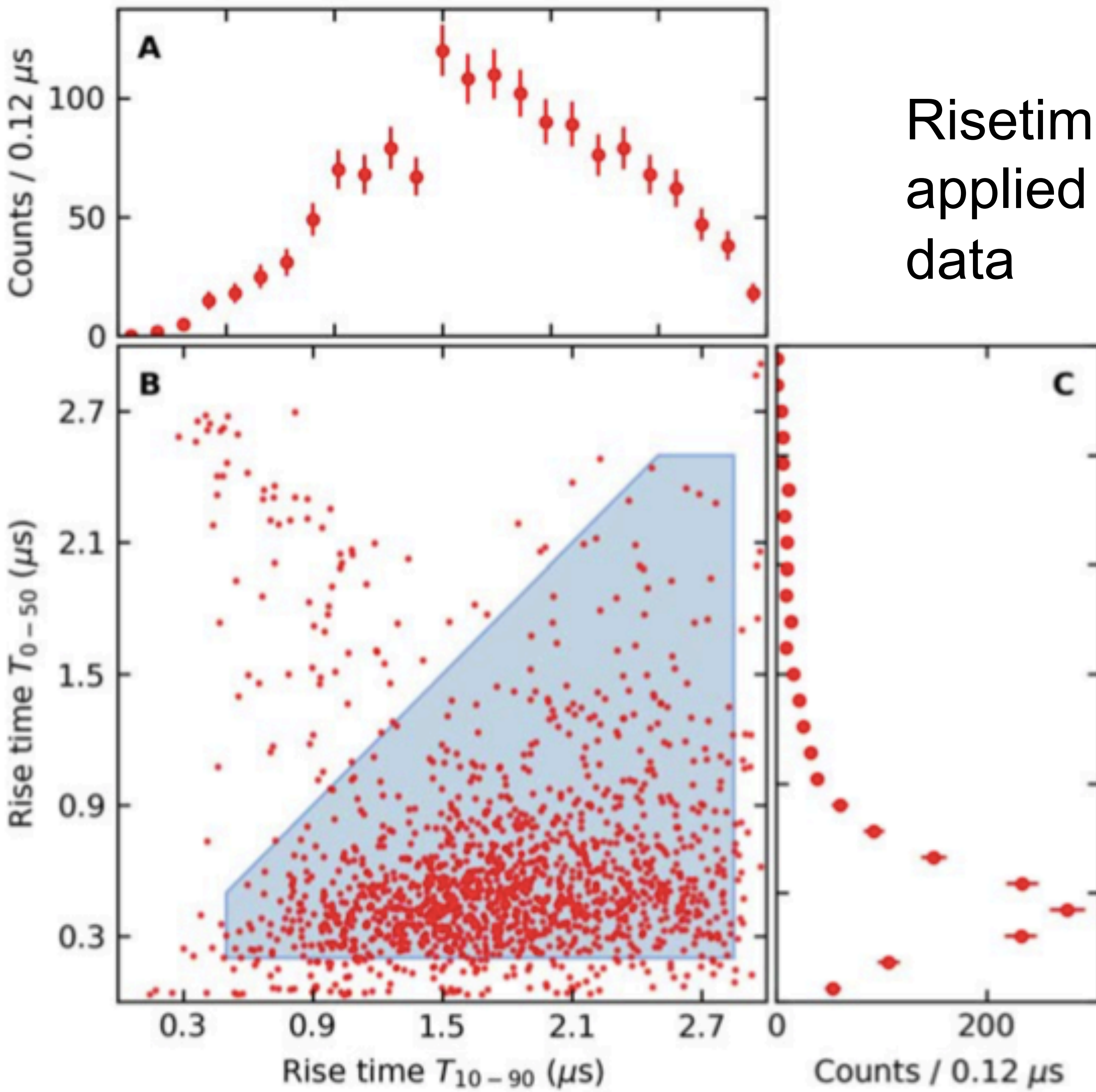
Liquid scintillator surrounded by Pb, Fe (swappable for other NIN targets) inside water shield



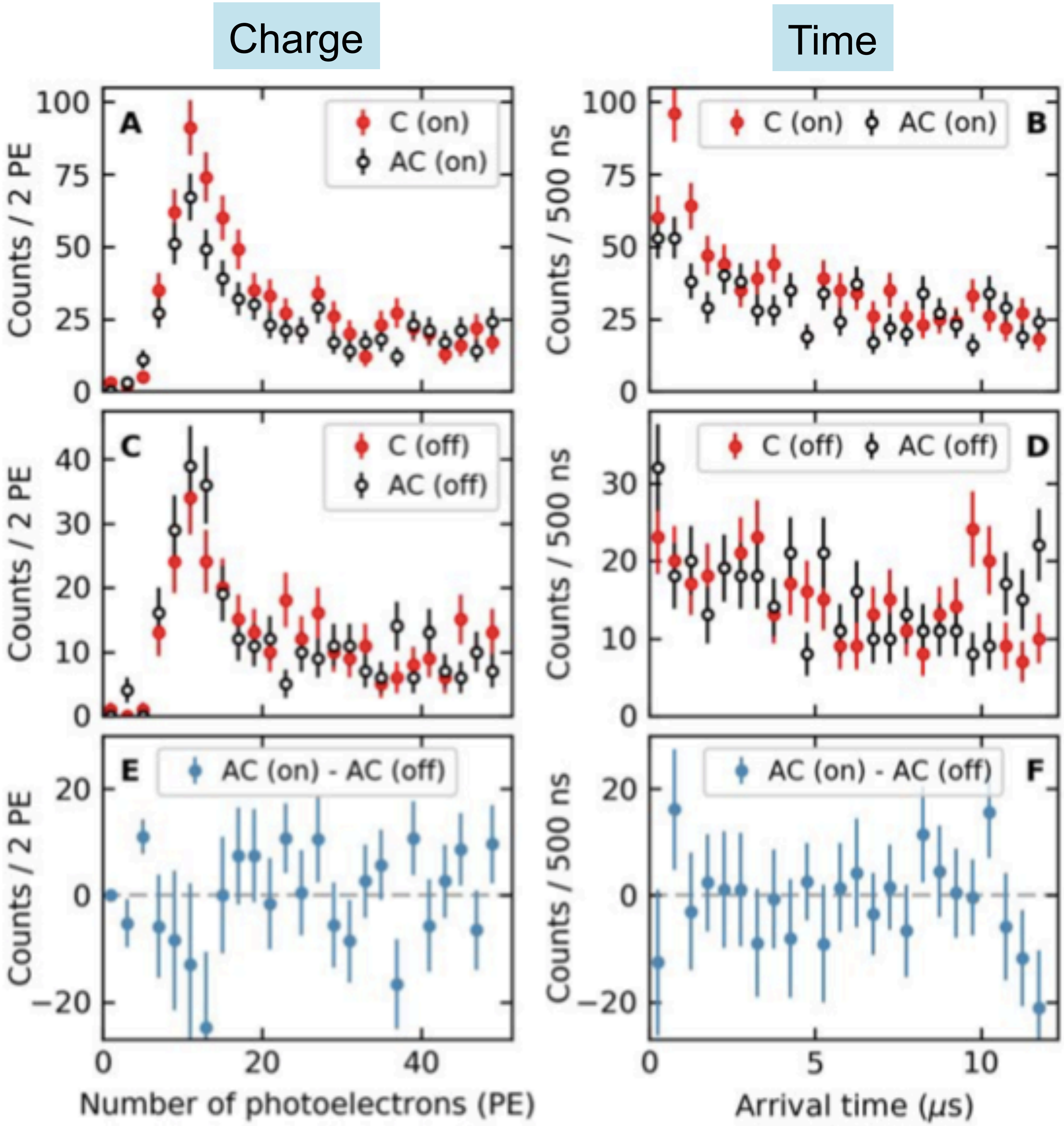
P. Barbeau

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



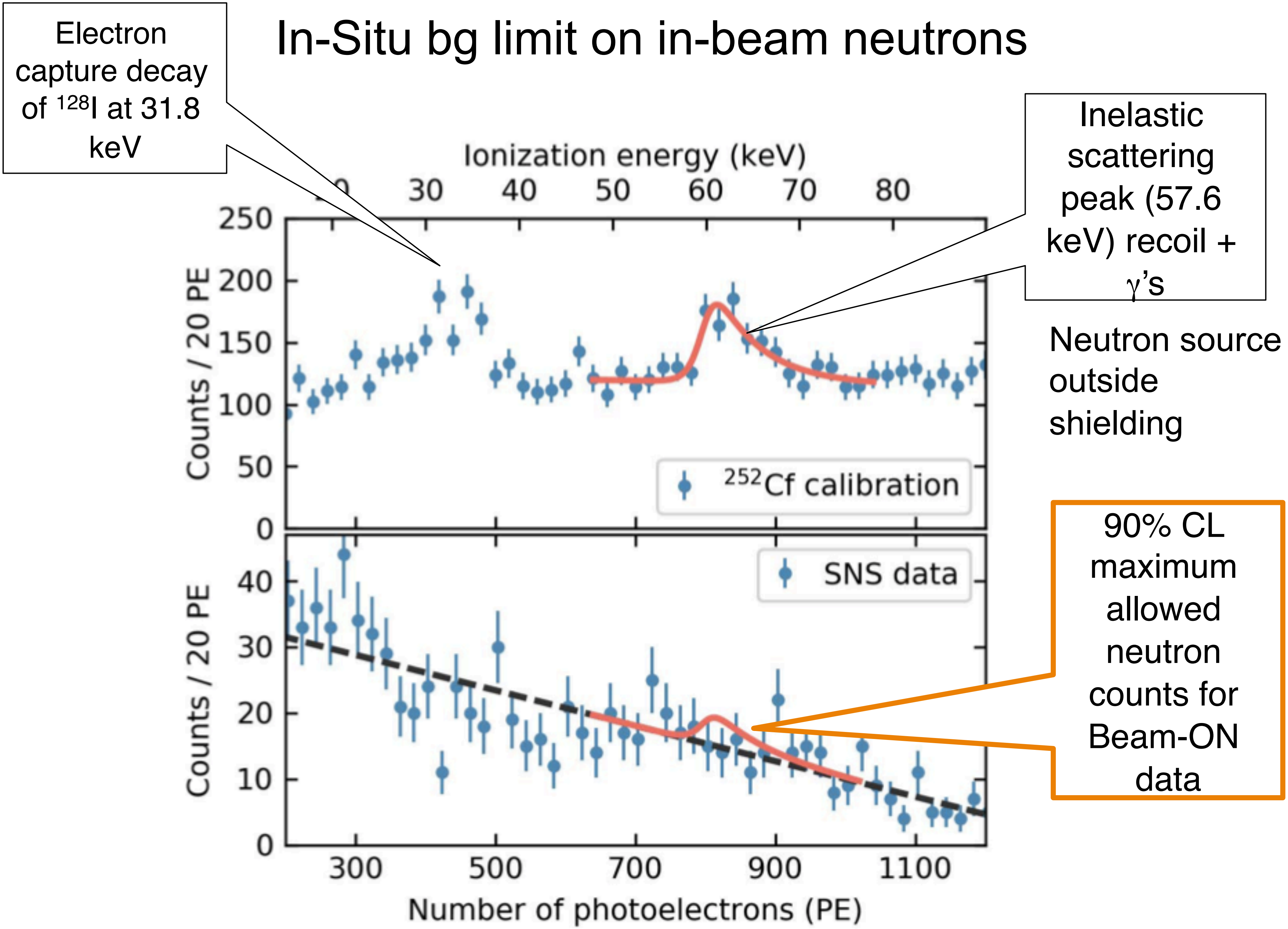


Risetime cut applied to SNS data

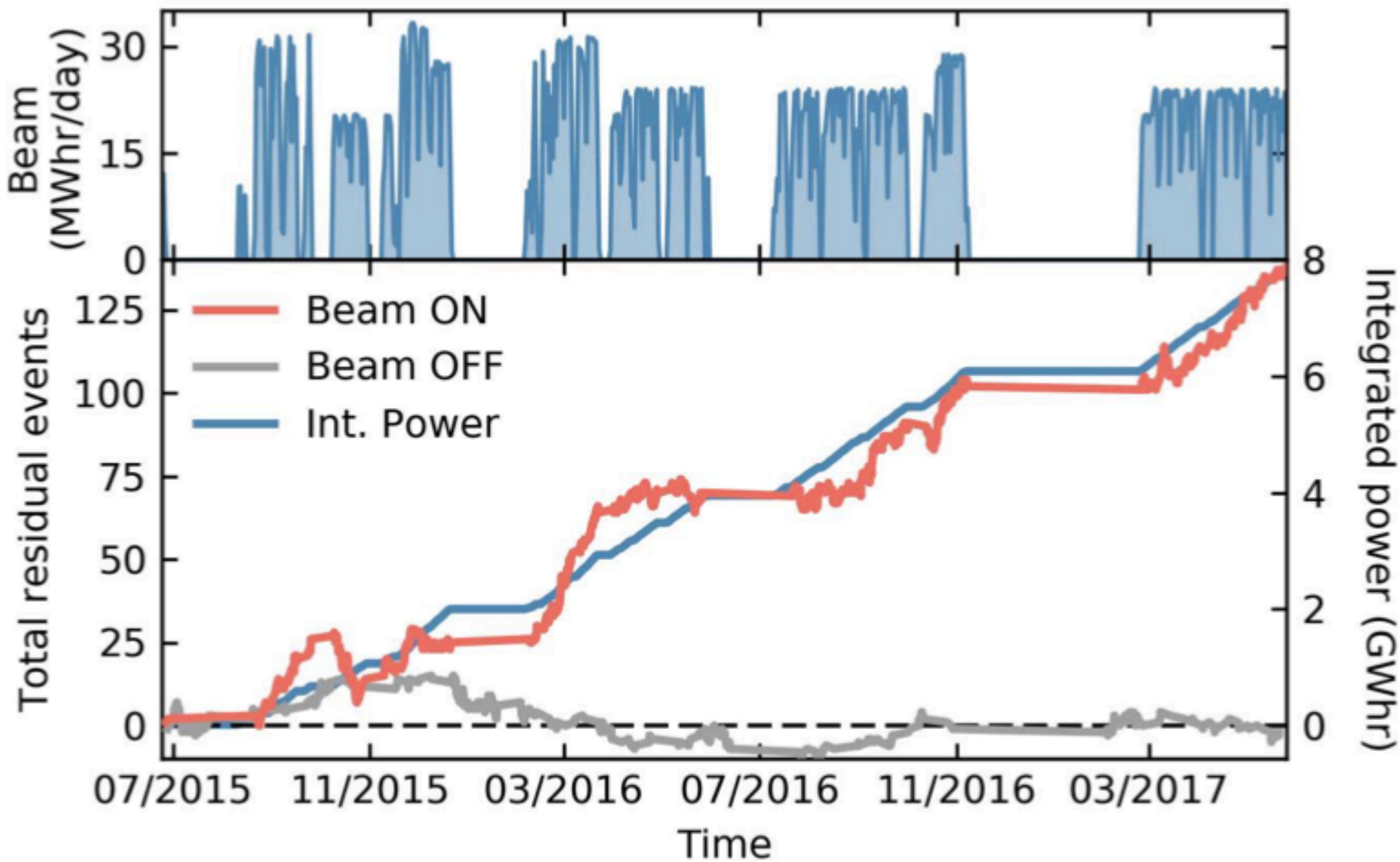


Charge
Time
A
C (on)
AC (on)
B
C
C (off)
AC (off)
D
E
AC (on) - AC (off)
F
Counts / 2 PE
Counts / 500 ns
Number of photoelectrons (PE)
Arrival time (μs)

In-Situ bg limit on in-beam neutrons



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



Signal, background, and uncertainty summary numbers

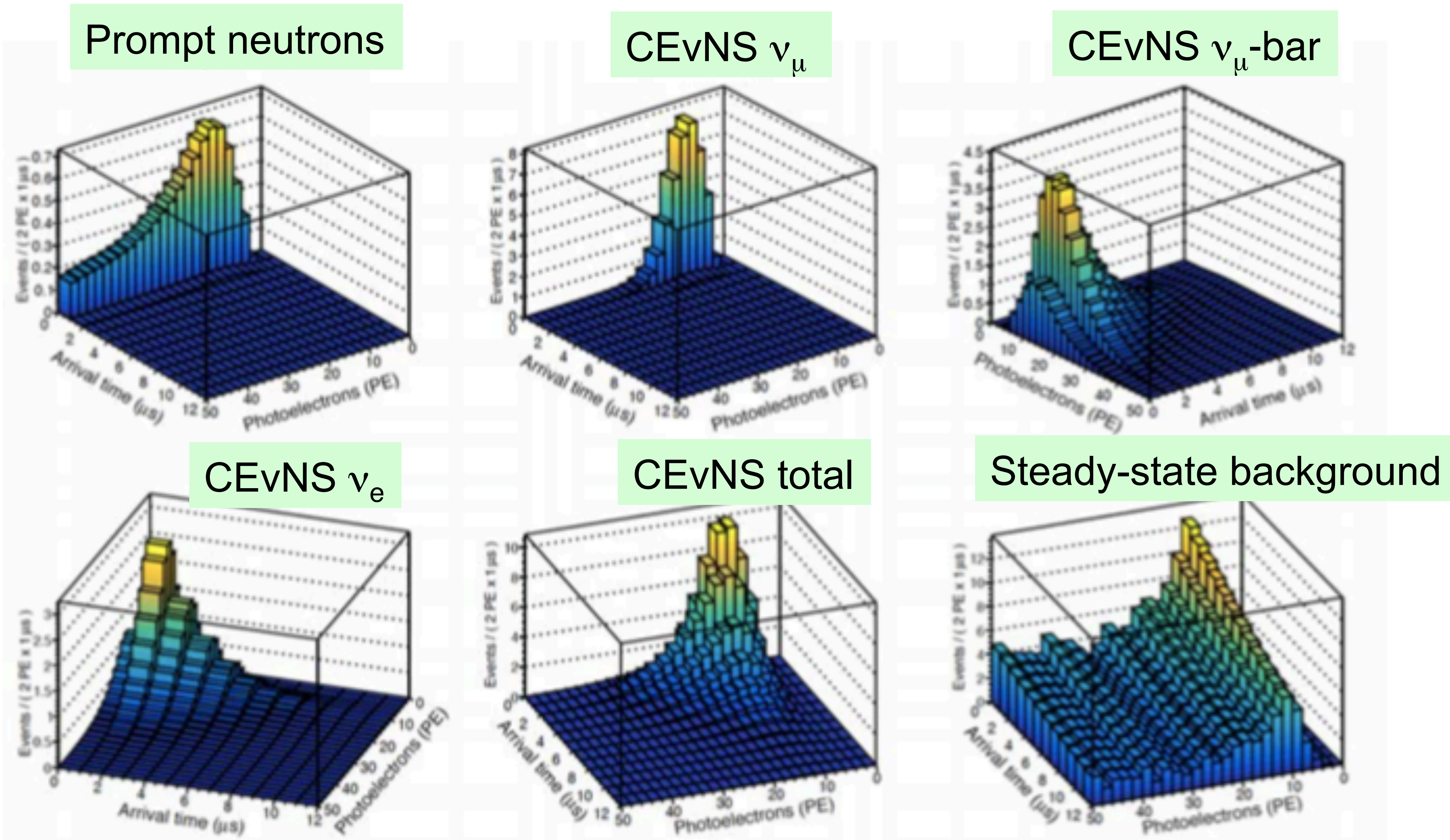
$6 \le PE \le 30$, $0 \le t \le 6000$ ns

Beam ON coincidence window	547 counts
Anticoincidence window	405 counts
Beam-on bg: prompt beam neutrons	6.9 ± 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

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



$6 \leq \text{PE} \leq 30,\ 0 \leq t \leq 6000$ ns

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

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

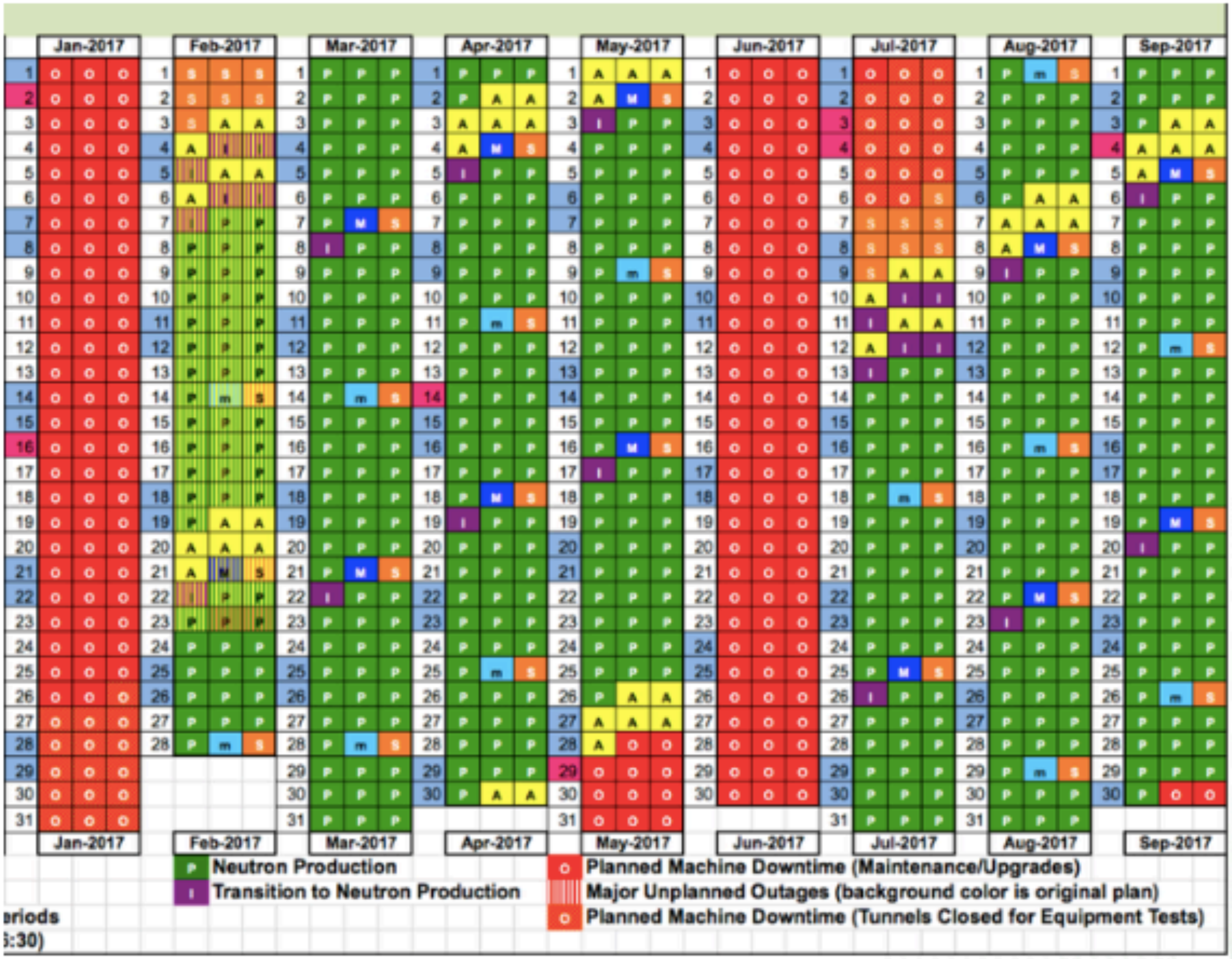
$\sigma_{\text{sys,SS}} = 0$ expected systematic on steady-state bg (assume zero because well measured)

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



Production beam through September 30, 2017

SNS Beam Schedule

- 1100 hours @ 1.4 MW
- 5 month outage