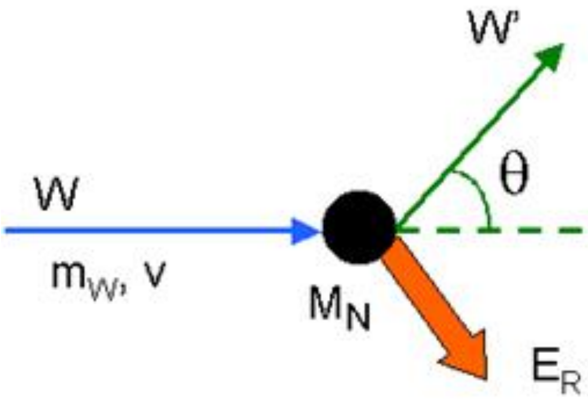
CEνNS at the European Spallation Source

J.I. Collar + J.J. Gomez-Cadenas + F. Monrabal

Uppsala, Feb. 27, 2020

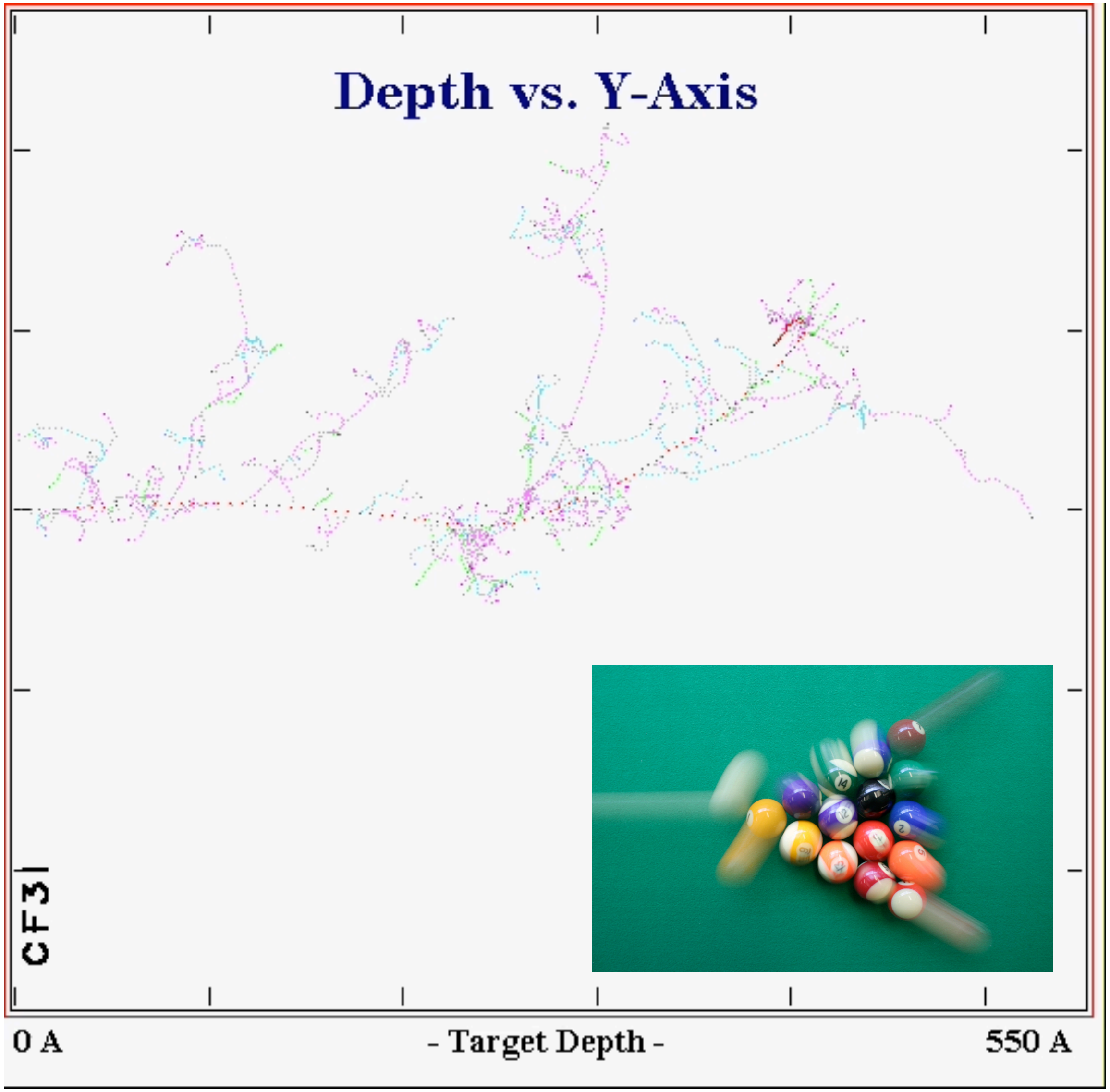
Nuclear recoils: things that go bump in the dark

Old shoe
(elastic scattering of fast neutrons)
but interest renewed
by WIMP and neutrino detection.



Microscopic behavior
(e.g. dense energy concentration)
can be exploited for NR identification.

Quenching of signal at low-energy



Most active area of particle detector R&D in last ~30 yrs?

CEvNS: the advent of "miniature" neutrino detectors

Dinosaur heretic looks for redemption *p. 1088*

Increase inclusion to increase STEM diversity *p. 1101*

Fluorescent or magnetic cotton fibers *p. 1118*

Science

$15
15 SEPTEMBER 2017
sciencemag.org

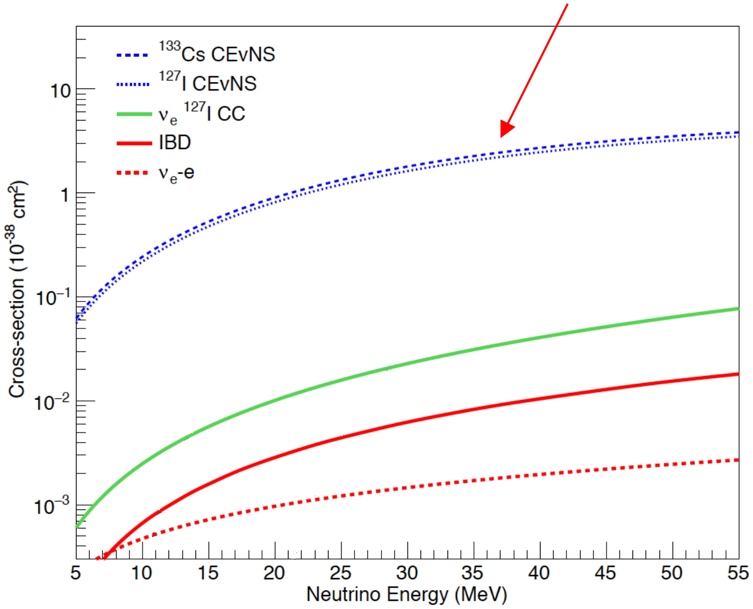
AAAS

SPOTTING A GHOST

A compact detector spies neutrinos scattering from nuclei
pp. 1098 & 1123

CEvNS has largest ν x-section

The catch: low-E NRs are the only detectable signature



A 10c introduction to coherent ν-N scattering (CEνNS)

- <u>Uncontroversial</u> Standard Model process

D.Z. Freedman
Phys. Rev. D 9 (1974) 1389

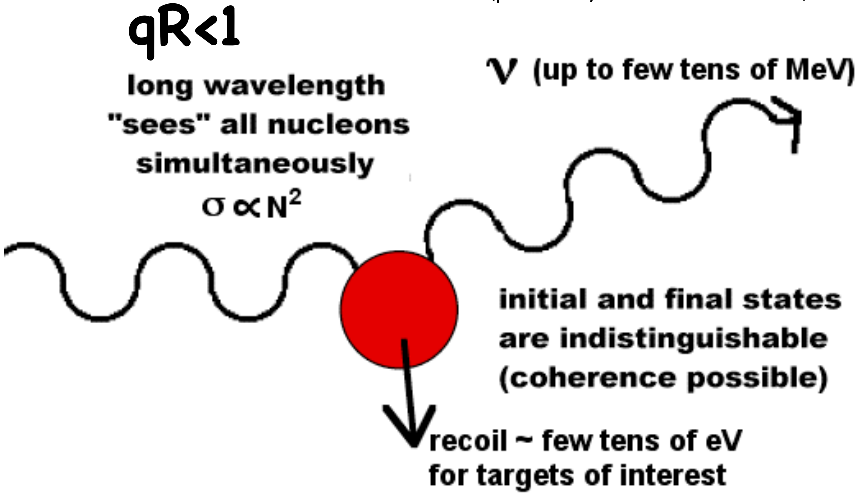
- Large enhancement to cross-section for E_ν < few tens of MeV ($\sigma \propto N^2$, possible only for neutral current)
- 43 yrs until successful detection… combination of source & detector technology was missing:

Detector mass must be at least ~1 kg (reactor experiment) + *<u>recoil</u>* energy threshold << 1keV

(recoils lose just 10-20% of E to ionization or scintillation)

- Cryogenic bolometers and many other methods proposed over the last four decades.

Cabrera, Krauss & Wilczek
Phys. Rev. Lett. 55, 25–28 (1985)
(prehistory of CDMS detectors)



Fundamental physics (partial list):

- Largest σ_ν in SN dynamics: should be measured to validate models (J.R. Wilson, PRL 32 (74) 849)
- A large detector can measure total E and T of SN ν_μ, ν_τ ⇒ determination of ν oscillation pattern and mass of ν star (J.F.Beacom, W.M.Far & P.Vogel, PRD 66(02)033011)
- Coherent σ same for all known ν… oscillations observed in a coherent detector ⇒ evidence for $\nu_{sterile}$ (A.Drukier & L.Stodolsky, PRD 30 (84) 2295)
- Sensitive probe of weak nuclear charge ⇒ test of radiative corrections due to new physics above weak scale (L.M.Krauss, PLB 269, 407)
- More sensitive to NSI and new neutral bosons than ν factories. Also effective ν charge radius (J. Barranco et al., hep-ph/0508299, hep-ph-0512029)
- σ critically depends on μ_ν: observation of SM prediction would increase sensitivity to μ_ν by > an order of magnitude (A.C.Dodd *et al*, PLB 266 (91) 434)
- Sensitive probe of neutron dens. distribution

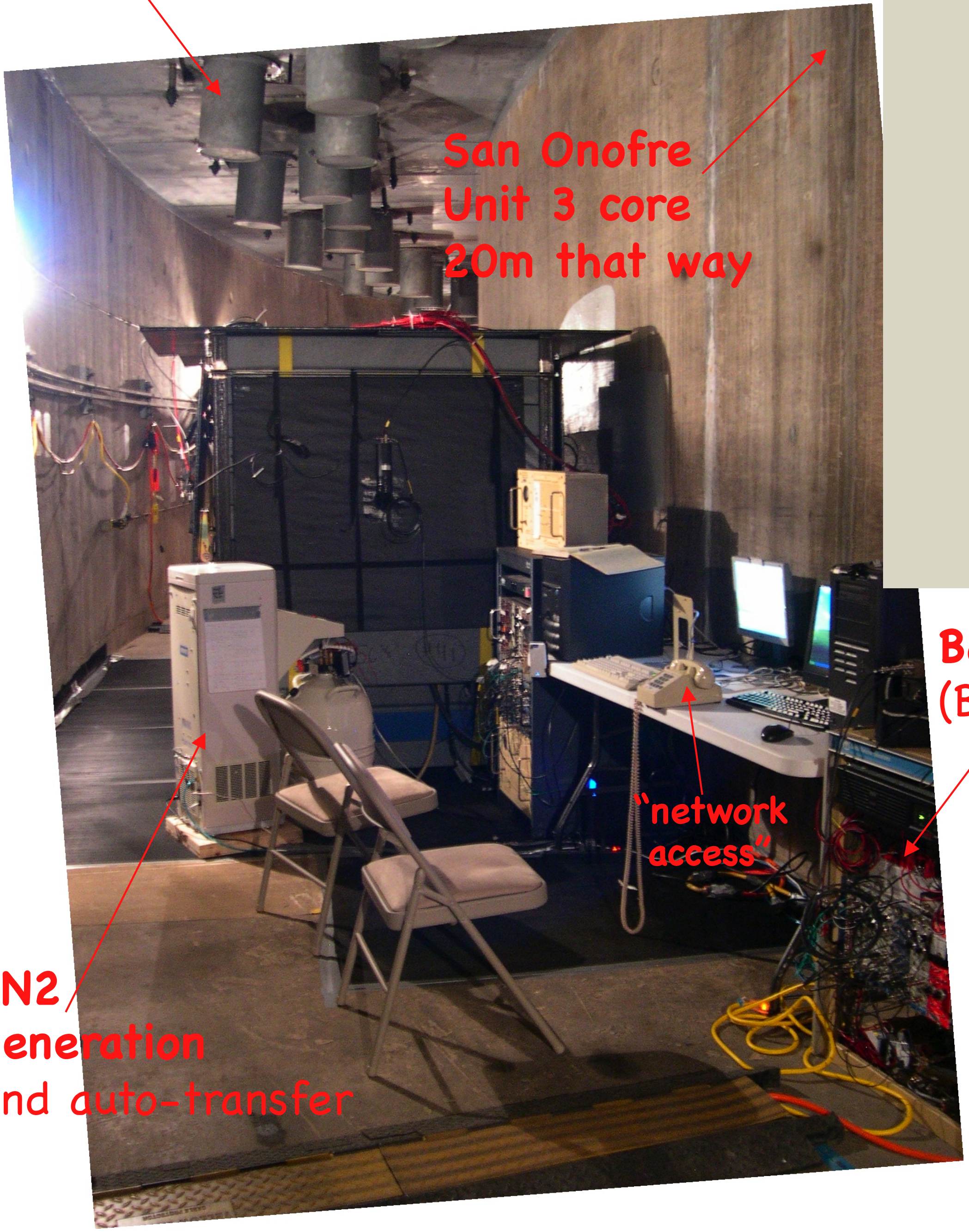
Smallish detectors… <u>"ν technology"?</u>

- Monitoring of nuclear reactors against illicit operation or fuel diversion: present proposals using conventional 1-ton detectors reach only > ~3 GWt reactor power
- Geological prospection, planetary tomography… the list gets much wilder.

WIMP hunters need a hobby

“Tendons”

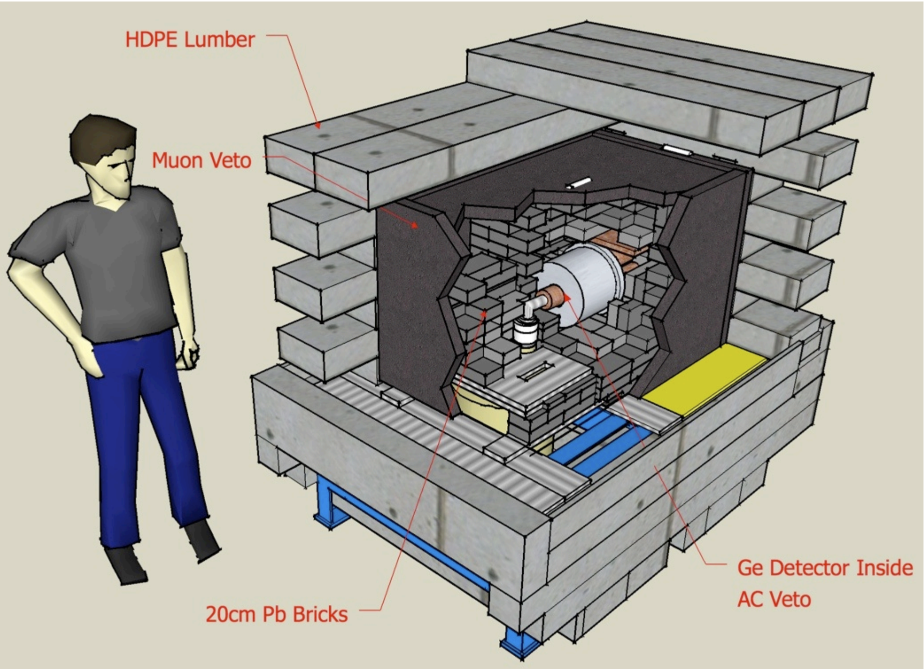
↑
30 mwe



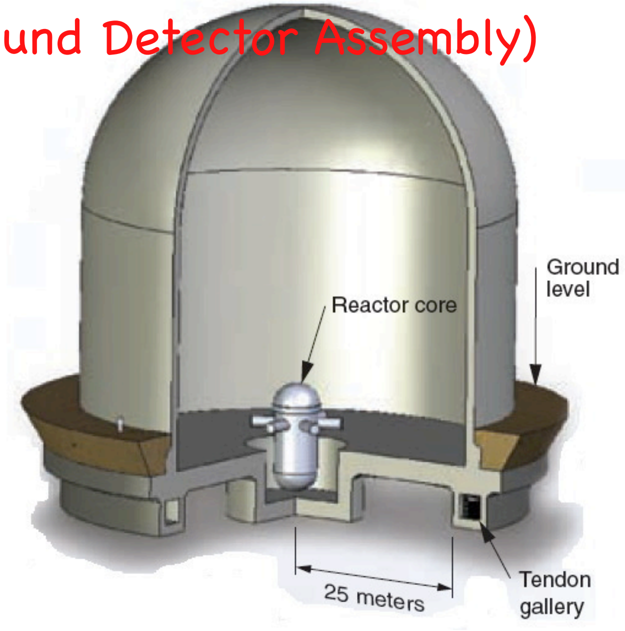
San Onofre
Unit 3 core
20m that way

“network
access”

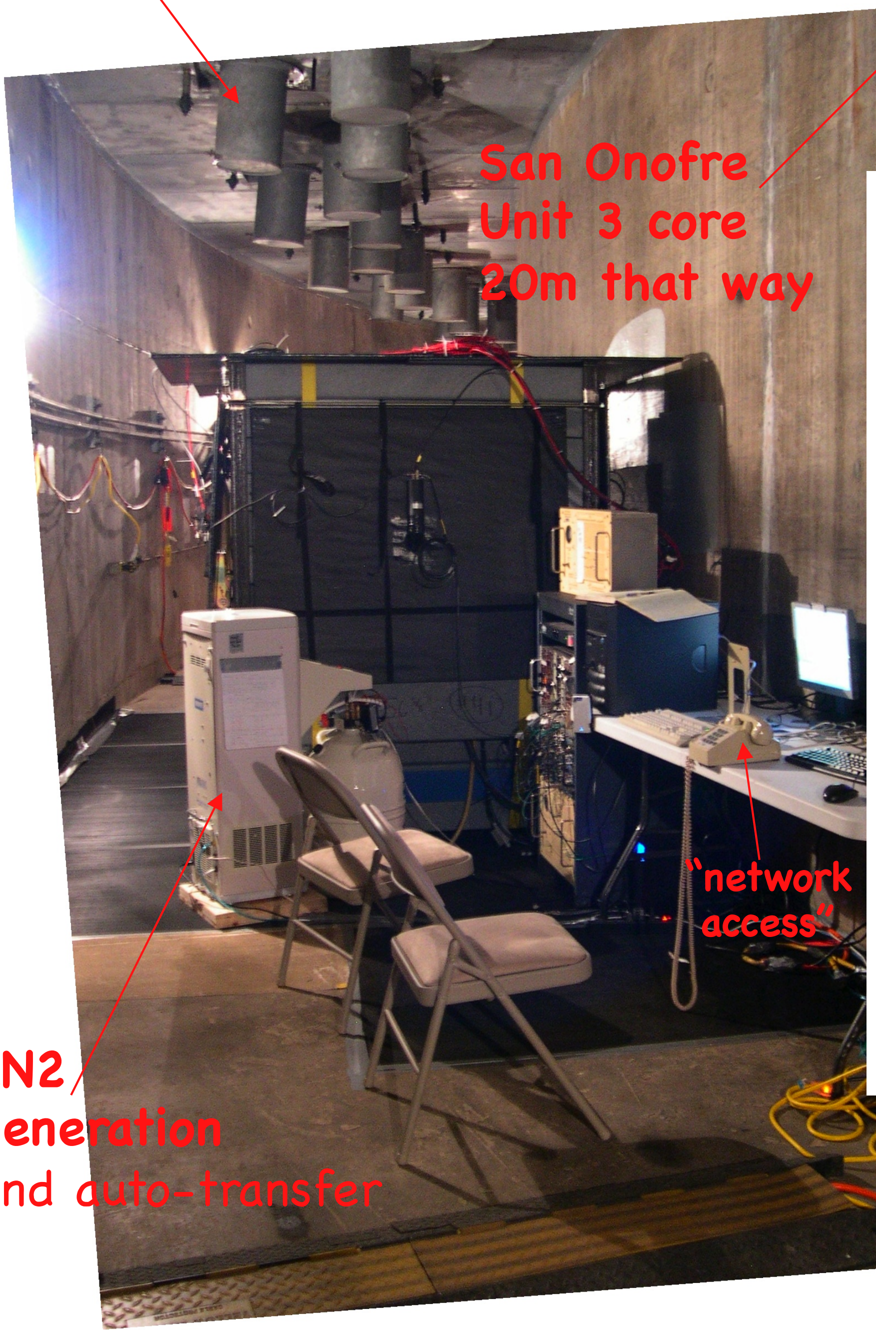
LN2
generation
and auto-transfer



BaDAss
(Background Detector Assembly)



So close, and yet so far



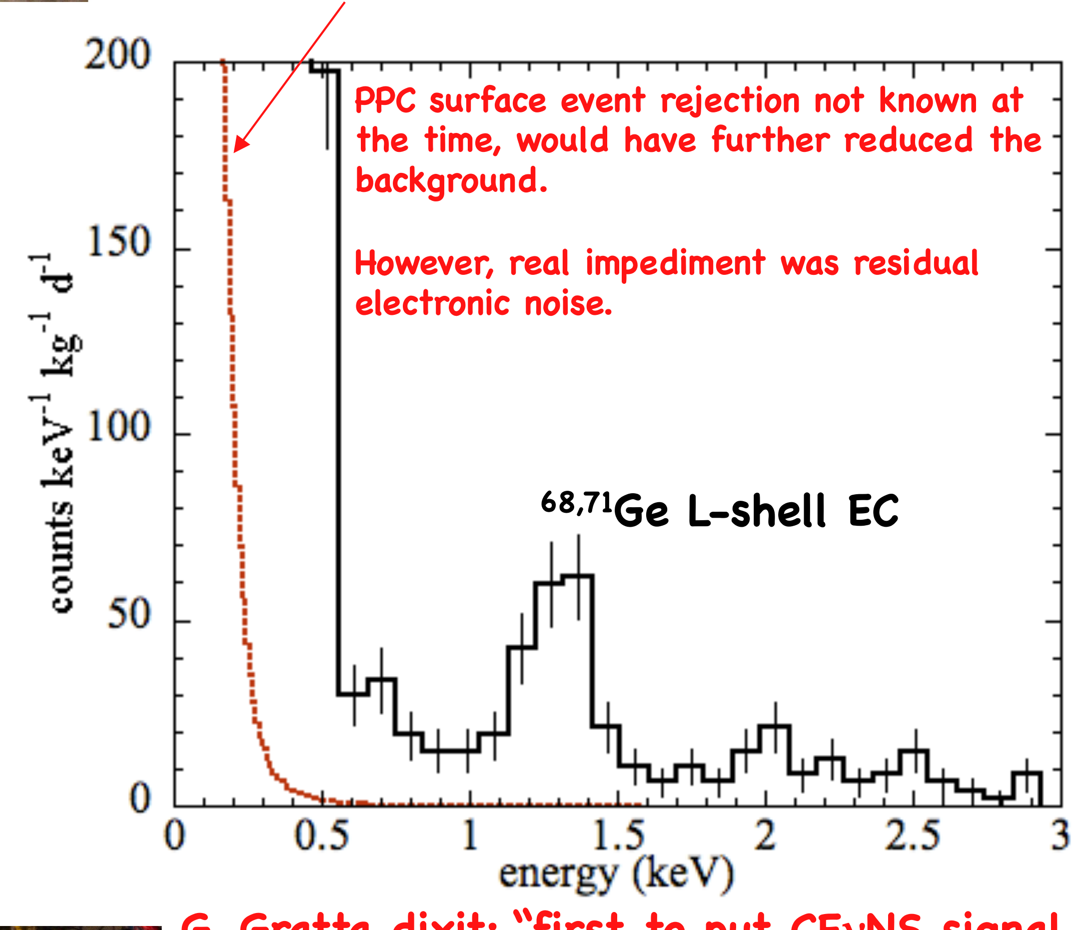
"Tendons"

↑ 30 mwe

San Onofre Unit 3 core 20m that way

"network access"

LN2 generation and auto-transfer



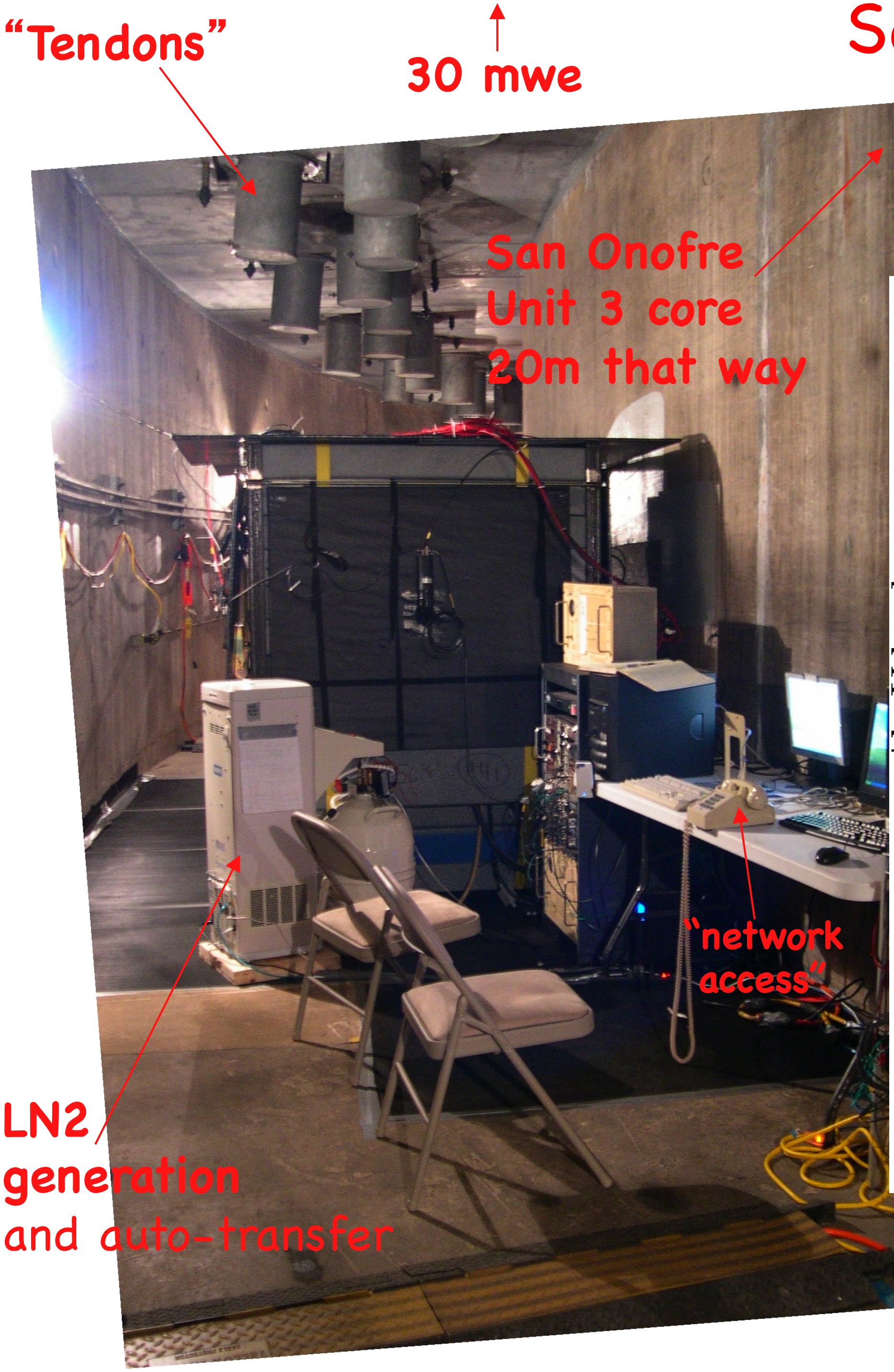
Expected CEvNS signal (resolution folded in)

PPC surface event rejection not known at the time, would have further reduced the background.

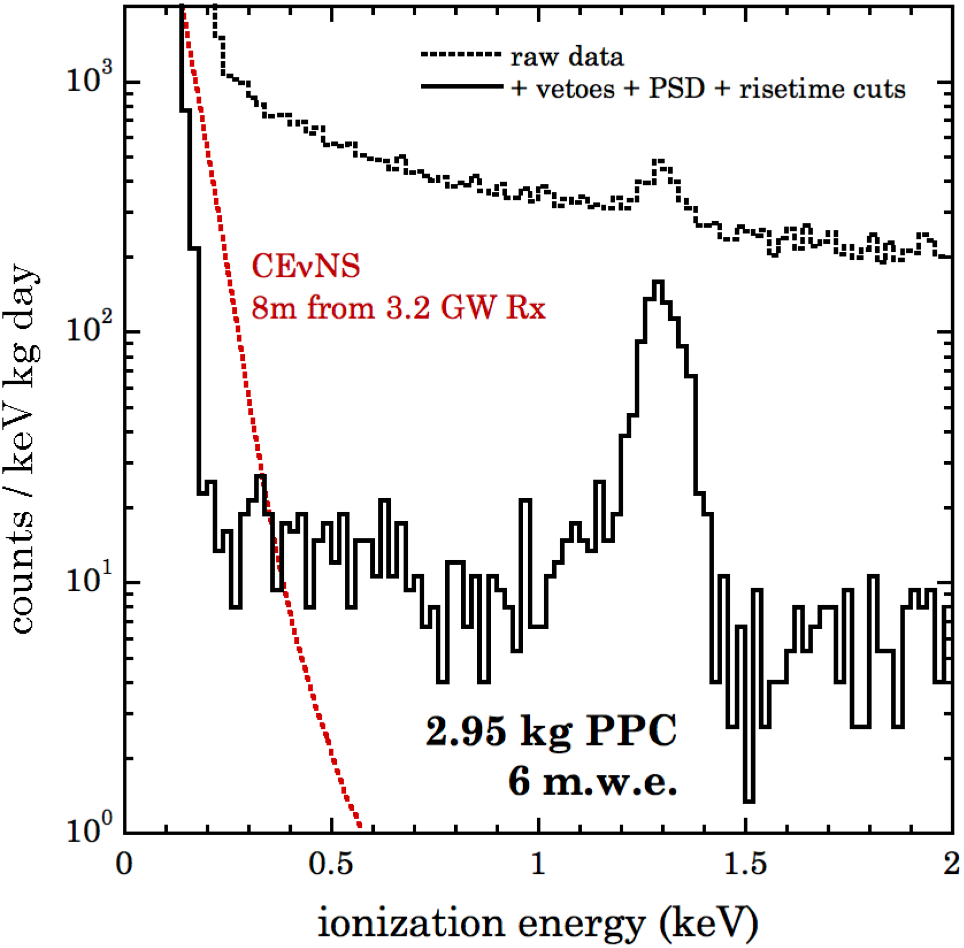
However, real impediment was residual electronic noise.

G. Gratta dixit: "first to put CEvNS signal and backgrounds on a linear-linear plot…"

So close, and yet so far



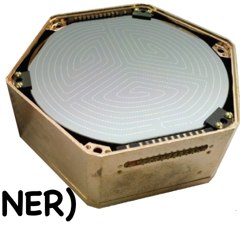
Latest PPCs may be up to snuff!

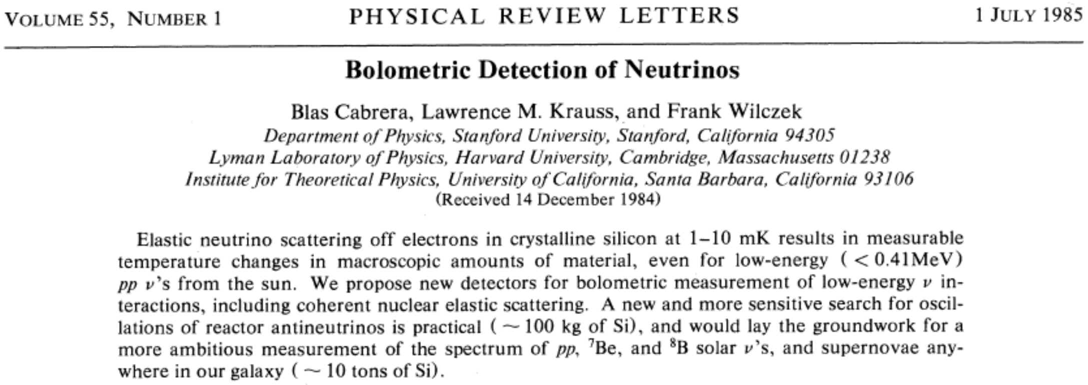


Other reactor enthusiasts:

RICOCHET

Coherent Neutrino Scattering with Cryogenic Crystal Detectors **(also MINER)**





VOLUME 55, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JULY 1985

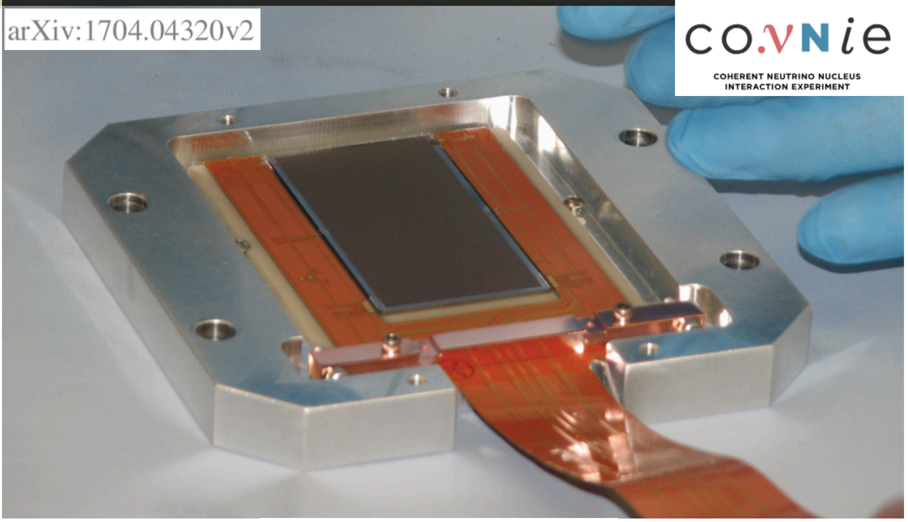
Bolometric Detection of Neutrinos

Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek

Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)

Elastic neutrino scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy (< 0.41 MeV) pp ν's from the sun. We propose new detectors for bolometric measurement of low-energy ν interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical (~ 100 kg of Si), and would lay the groundwork for a more ambitious measurement of the spectrum of pp, ^{7}Be, and ^{8}B solar ν's, and supernovae anywhere in our galaxy (~ 10 tons of Si).

CONNIE 2014-2015 sensor:

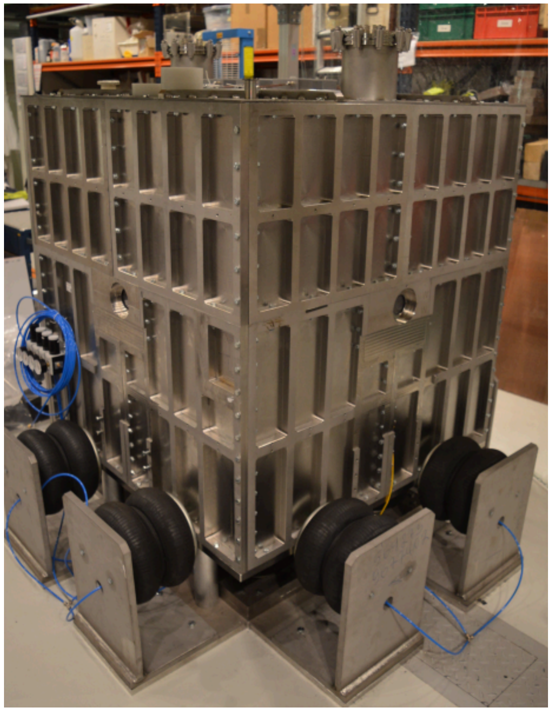


arXiv:1704.04320v2

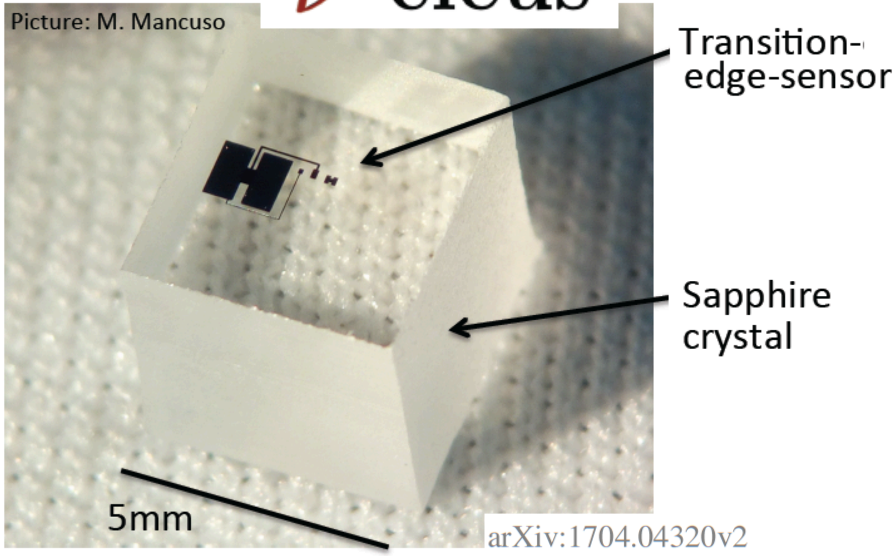
CO.νNie

COHERENT NEUTRINO NUCLEUS INTERACTION EXPERIMENT

CoνUS



ν-cleus

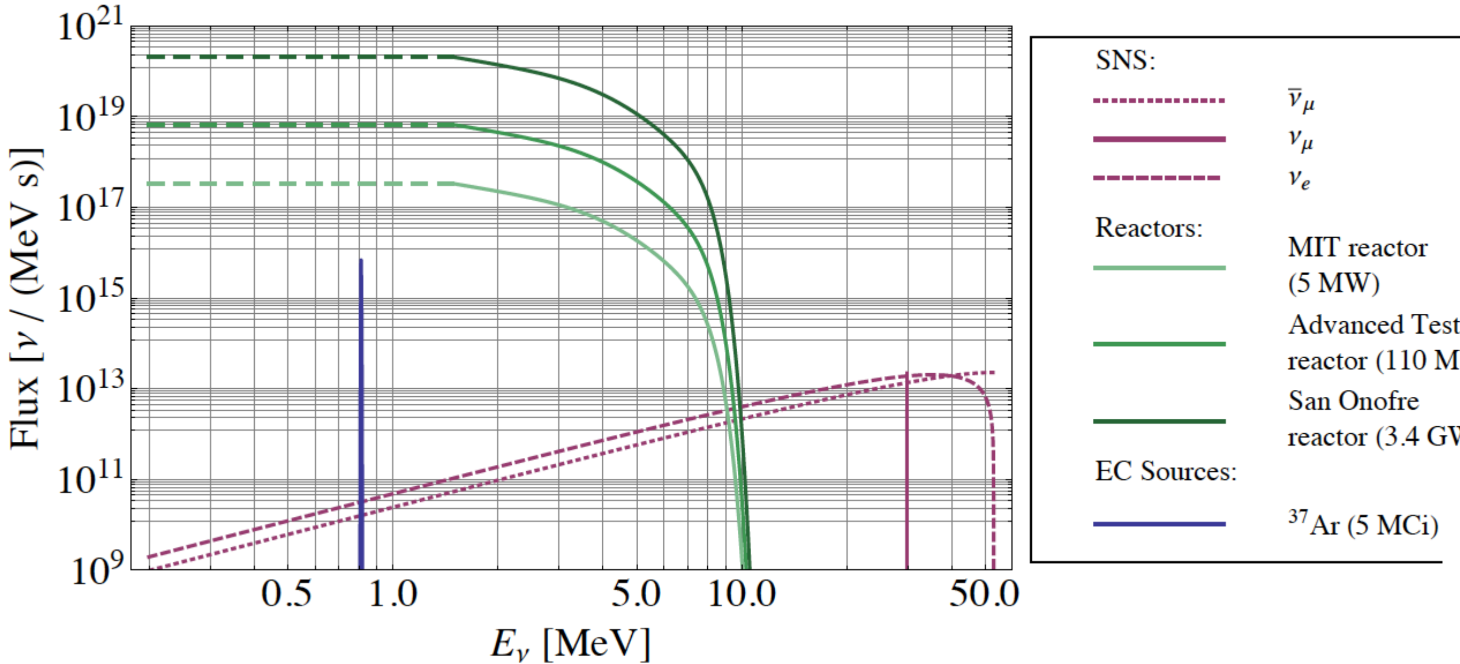


Picture: M. Mancuso

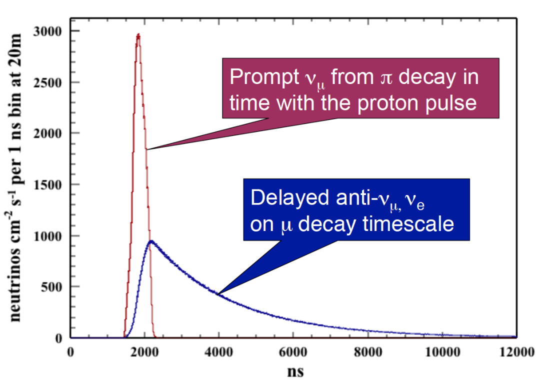
arXiv:1704.04320v2

Technological applications: reactor monitoring is around the corner
(compact microbolometer arrays and CCDs are almost there)

Fortunately, reactors are not the only game in town:



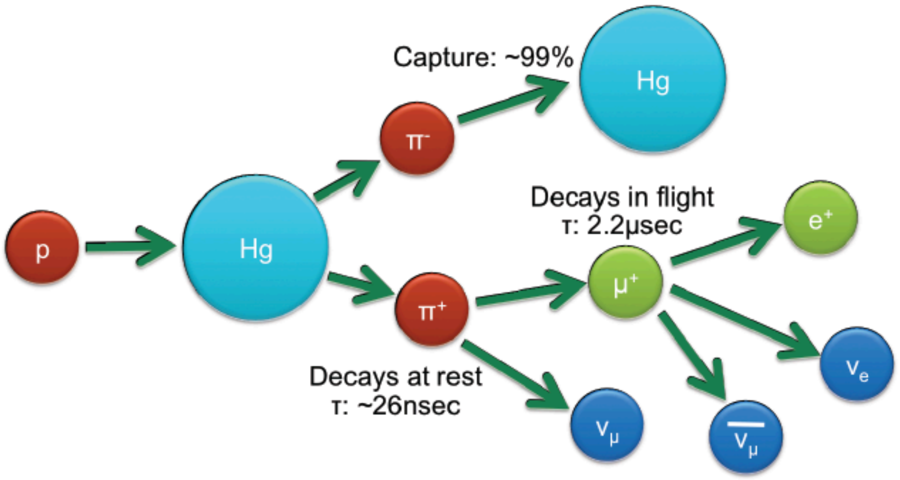
60 Hz *pulsed* source



Prompt ν_μ from π decay in time with the proton pulse

Delayed anti-ν_μ, ν_e on μ decay timescale

SNS @ ORNL: 200x more
n's than ν's,
but we'll take it
(~10^{22} n/day...)

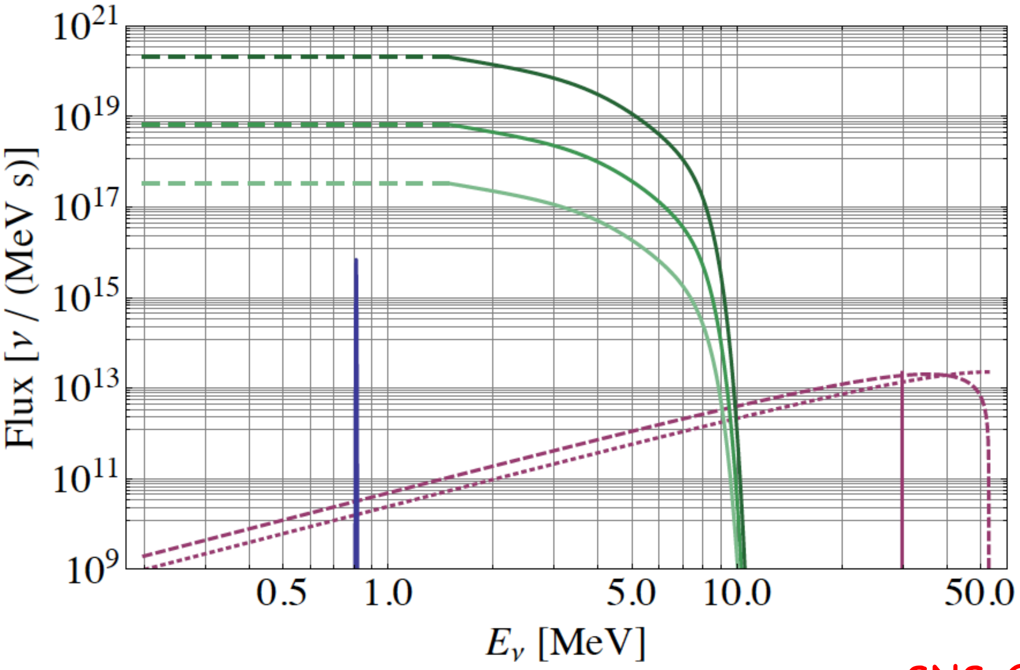


Capture: ~99%

Decays in flight
τ: 2.2μsec

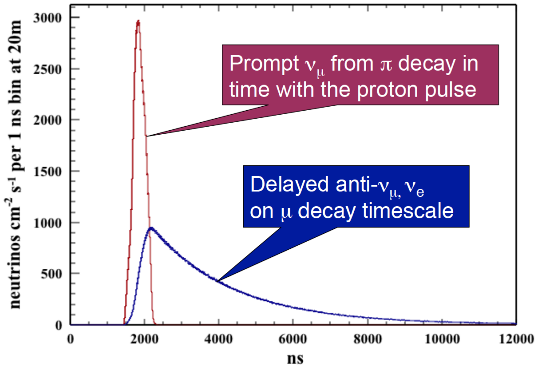
Decays at rest
τ: ~26nsec

Fortunately, reactors are not the only game in town:



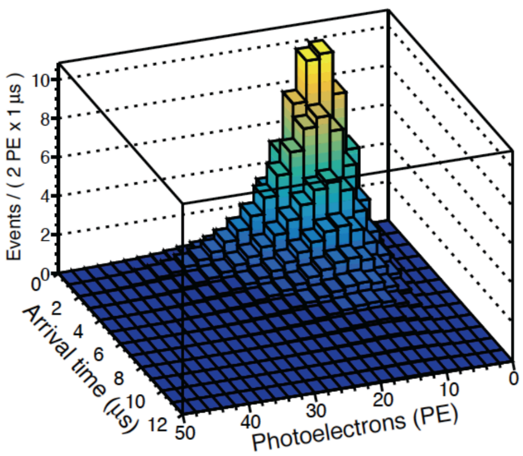
Means environmental background reduction by X 1,600

60 Hz *pulsed* source



SNS @ ORNL: 200x more n's than ν's, but we'll take it ($\sim 10^{22}$ n/day…)

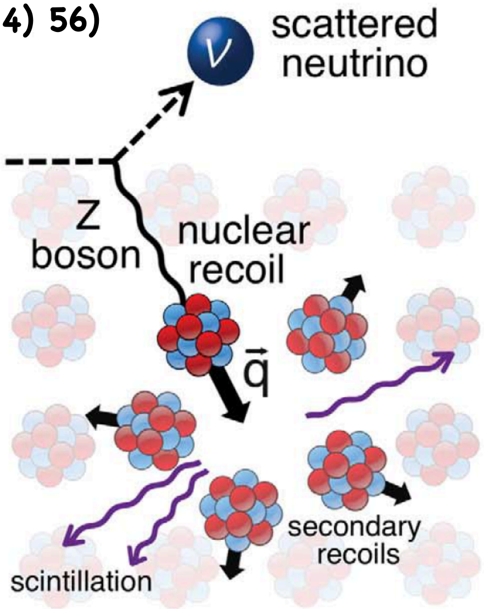
Summed CEνNS PDF

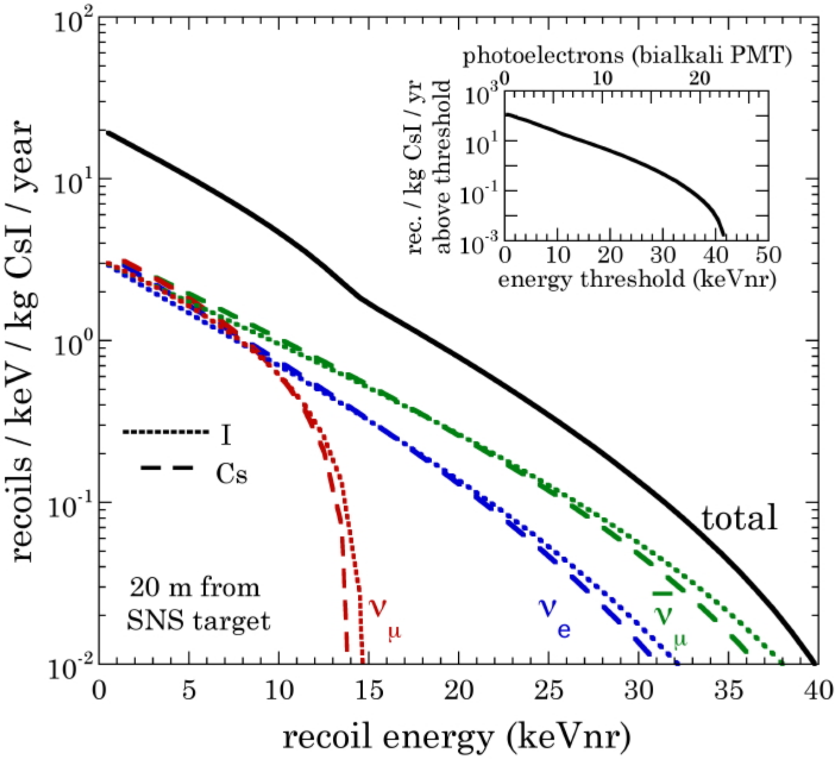


Expected CEνNS signal is characteristic in <u>both</u> energy and time

Why CsI[Na]? (NIM A773 (2014) 56)

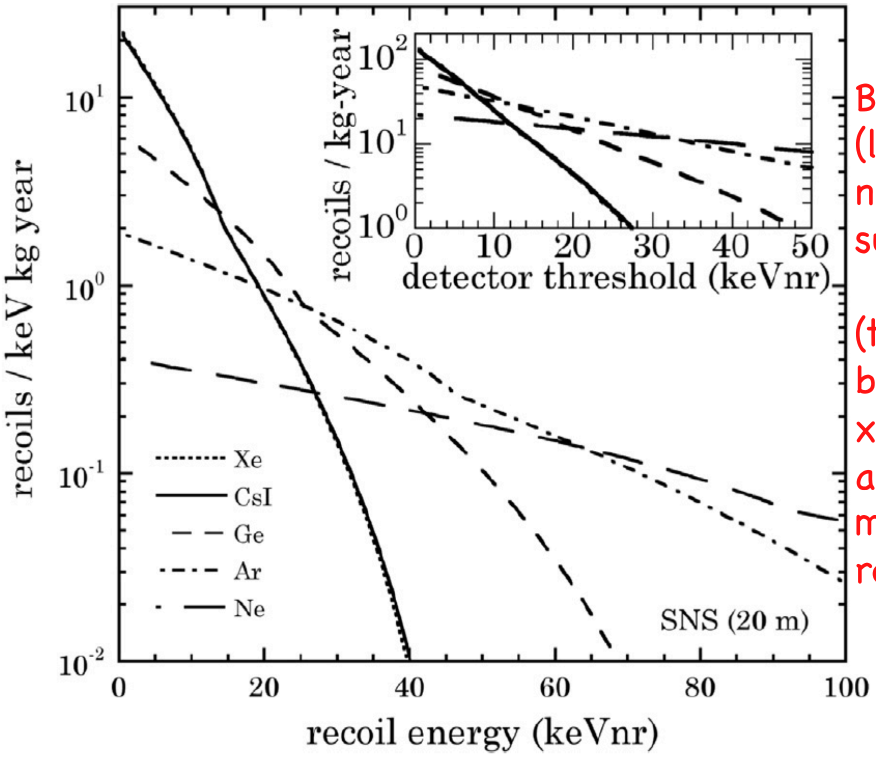
- Large N^2 => large x-section.
- Cs and I surround Xe in Periodic Table: they behave much like a single recoiling species, greatly simplifying understanding the NR response.
- Quenching factor in energy ROI sufficient for ~5 keVnr threshold (we measured this upfront).
- Some statistical NR/ER discrimination may be possible at low-E (with large statistics).
- Sufficiently low in intrinsic backgrounds (U, Th ,K-40, Rb-87, Cs-134,137) Measurements in complete SNS shield and 6 m.w.e. indicated we were ready)
- Practical advantages: High light yield (64 ph/keVee), optimal match to bialkali PMTs, rugged, room temperature, inexpensive ($1/g), modest afterglow (CsI[Tl] not a viable option for surface experiment).
- Expect few hundred ν recoils/year in 14 kg detector at SNS (before cuts).





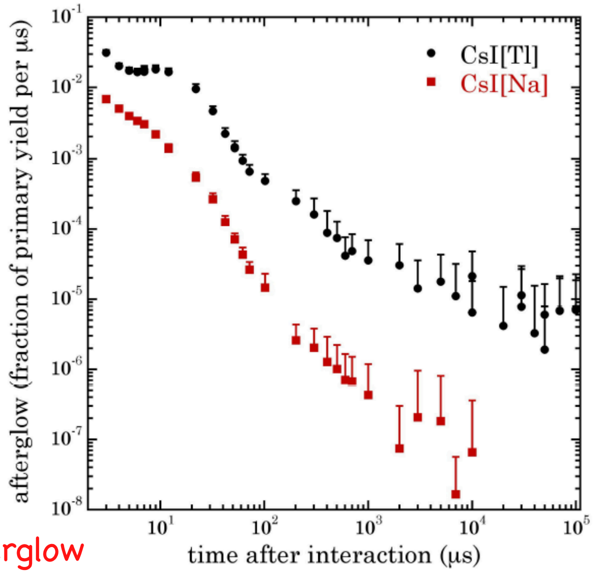
Why CsI[Na]? (NIM A773 (2014) 56)

- Large N^2 => large x-section.
- Cs and I surround Xe in Periodic Table: they behave much like a single recoiling species, greatly simplifying understanding the NR response.
- Quenching factor in energy ROI sufficient for ~5 keVnr threshold (we measured this upfront).
- Some statistical NR/ER discrimination may be possible at low-E (with large statistics).
- Sufficiently low in intrinsic backgrounds (U, Th ,K-40, Rb-87, Cs-134,137) Measurements in complete SNS shield and 6 m.w.e. indicated we were ready)
- Practical advantages: High light yield (64 ph/keVee), optimal match to bialkali PMTs, rugged, room temperature, inexpensive ($1/g), modest afterglow (CsI[Tl] not a viable option for surface experiment).
- Expect few hundred ν recoils/year in 14 kg detector at SNS (before cuts).



Brute force (large N^2) not sufficient!

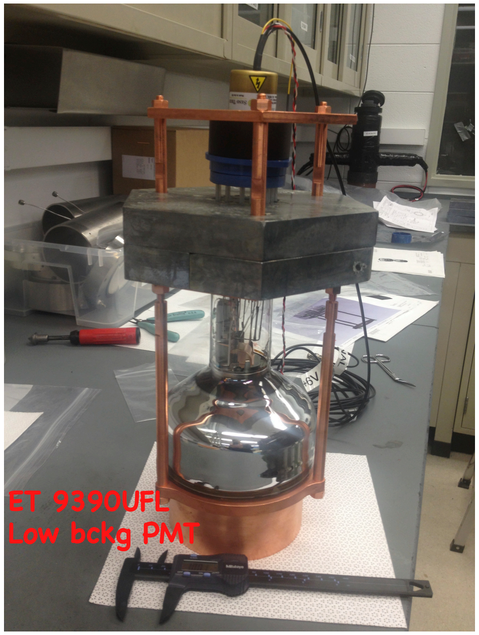
(tradeoff between x-section and maximum recoil E)



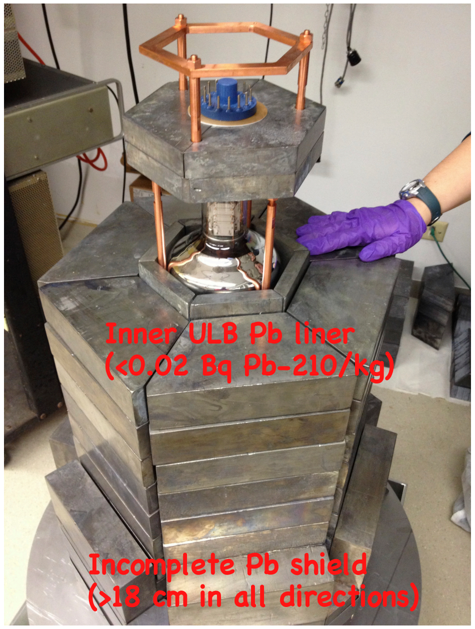
CsI[Tl] not an option due to excessive afterglow

Preliminaries: bckg & characterization studies w/ 2 kg prototype

2 kg test crystal.
Screened salts,
electroformed Cu can
(PNNL), ULB window and
reflector.

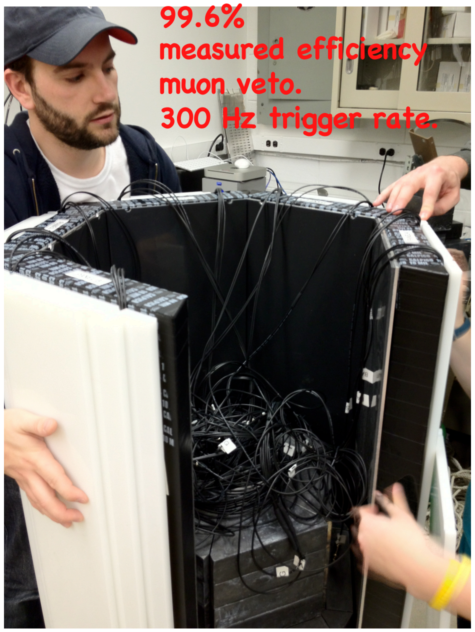


ET 9390UFL
Low bckg PMT



Inner ULB Pb liner
(<0.02 Bq Pb-210/kg)

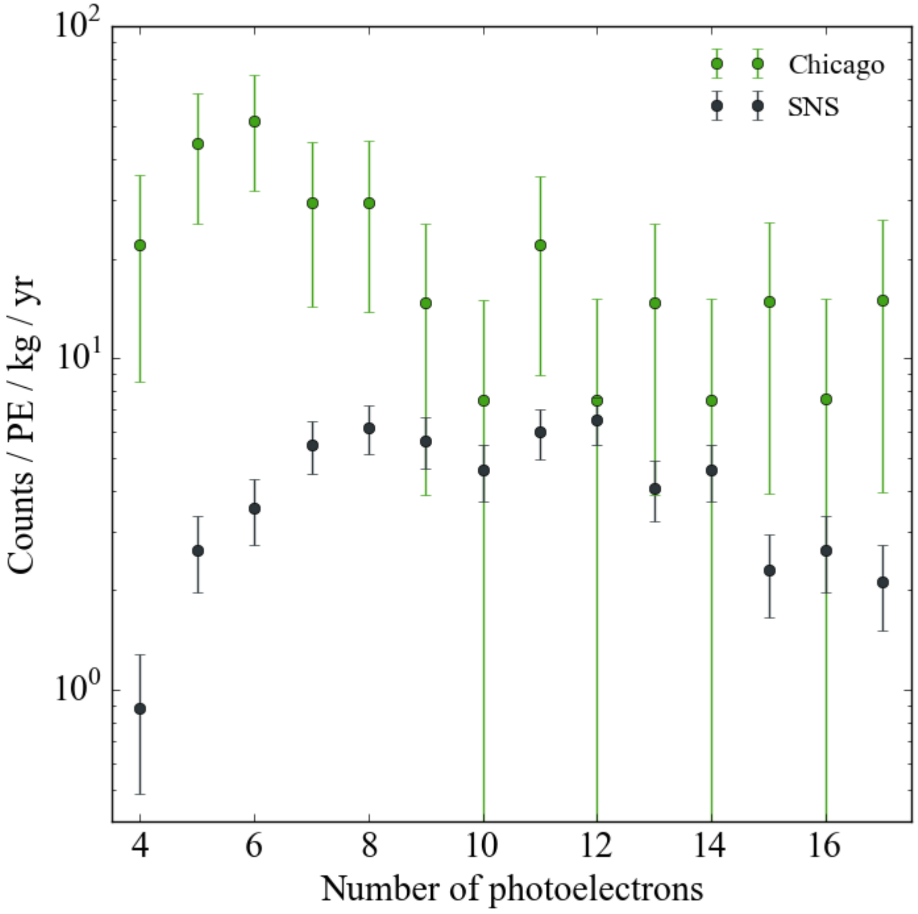
Incomplete Pb shield
(>18 cm in all directions)



99.6%
measured efficiency
muon veto.
300 Hz trigger rate.

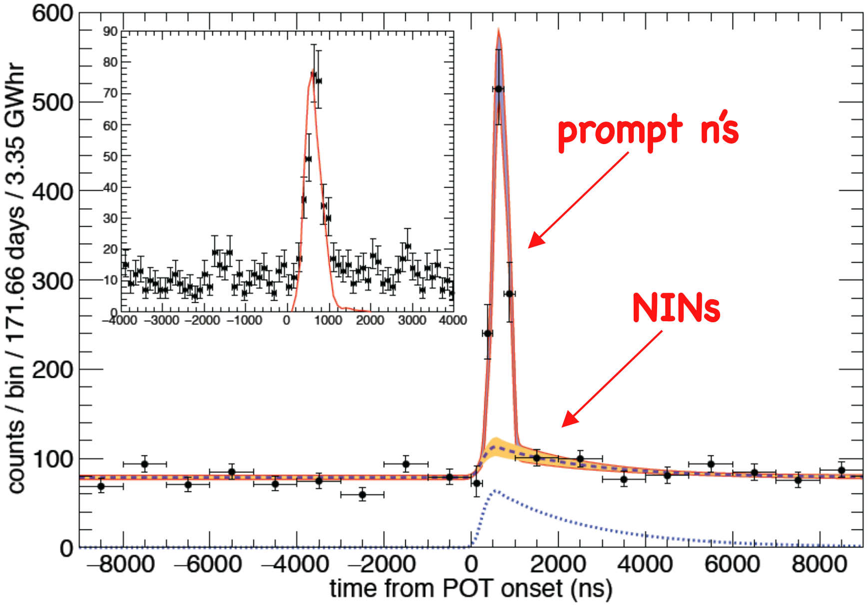
Pulsed SNS signal leads to very low bckg.

We improved on prototype background level!

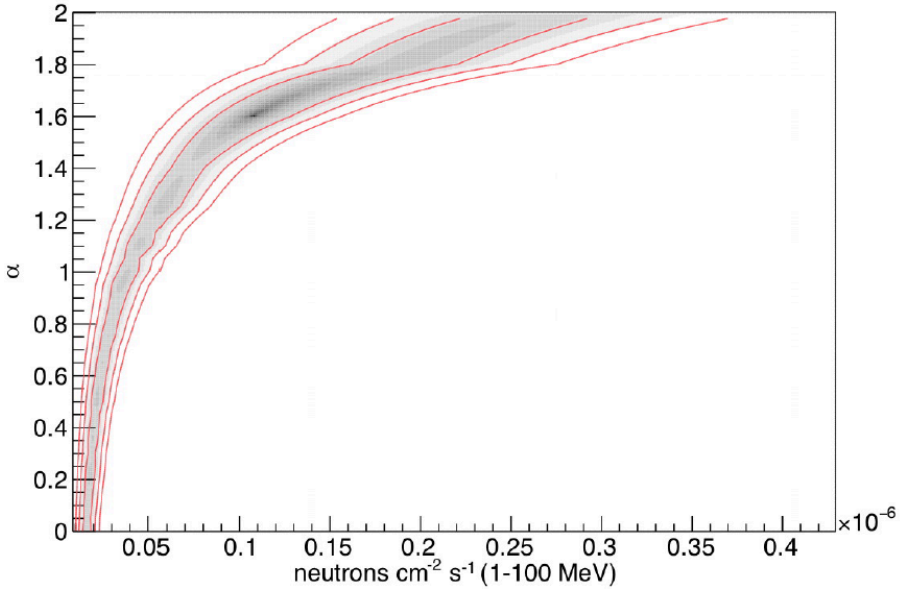


Preliminaries: *in situ* neutron bckg measurements

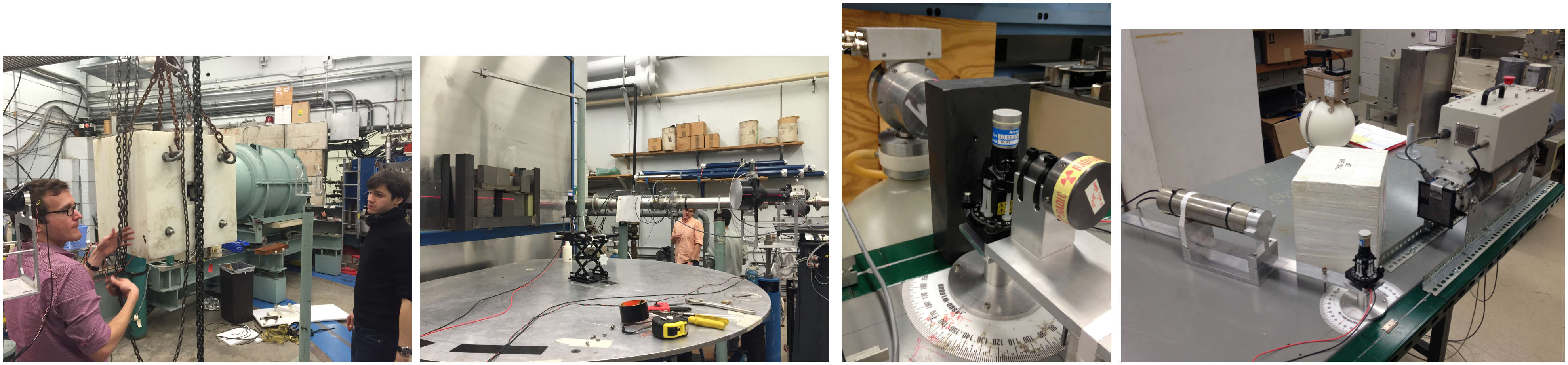
The “neutrino alley” @ SNS



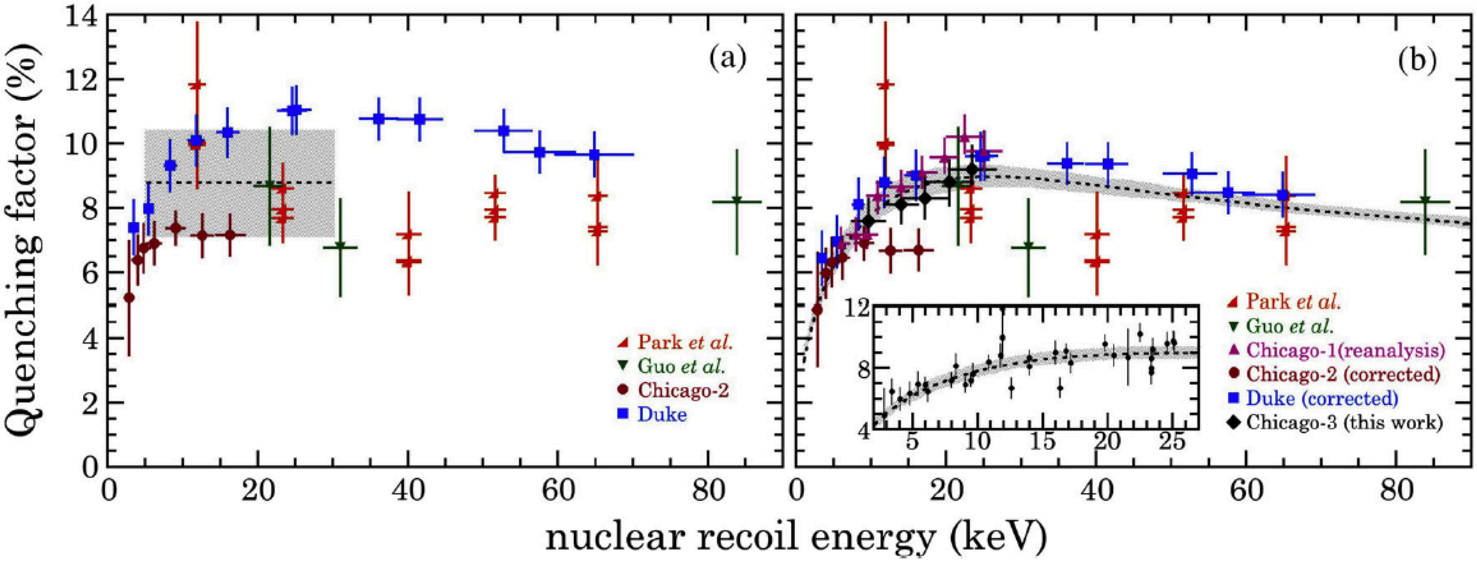
Measured NIN and prompt n bckg rates were x50 and x20 smaller than CEνNS signal rate.



Preliminaries: Quenching factor (QF) measurements



PHYSICAL REVIEW D **100**, 033003 (2019)



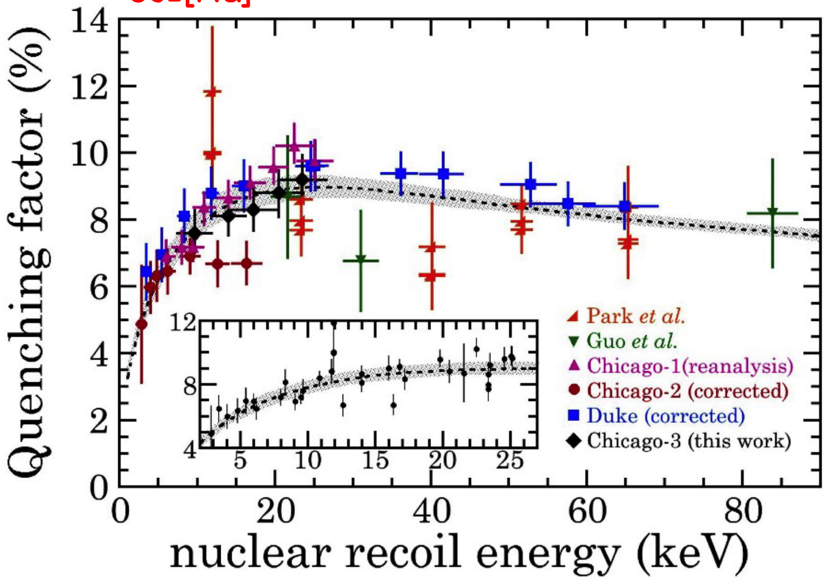
QF is the main systematic affecting CEvNS sensitivity to new physics.

Progress is possible...

Toto, we're not in Kansas anymore:

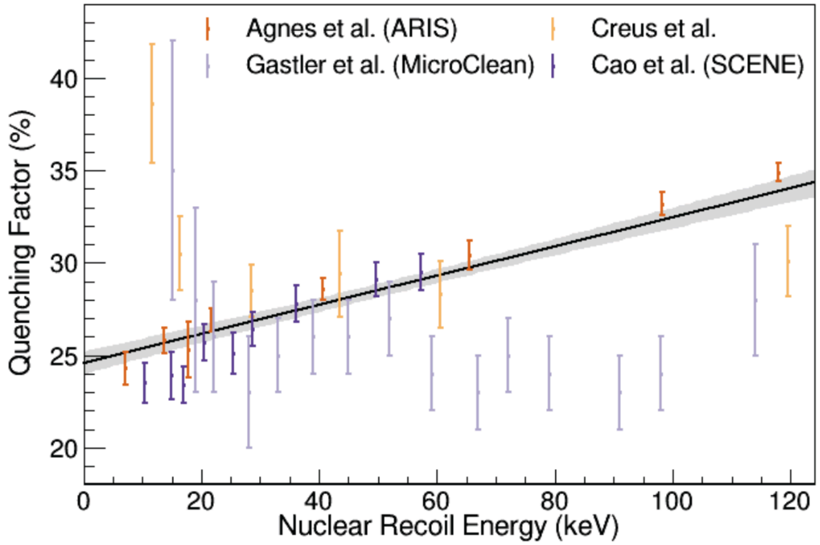
for CEνNS studies, the QF is the crux

CsI[Na]



5% uncertainty in 5-25 keV ROI
Physics-based model (Birks + kinematic threshold)

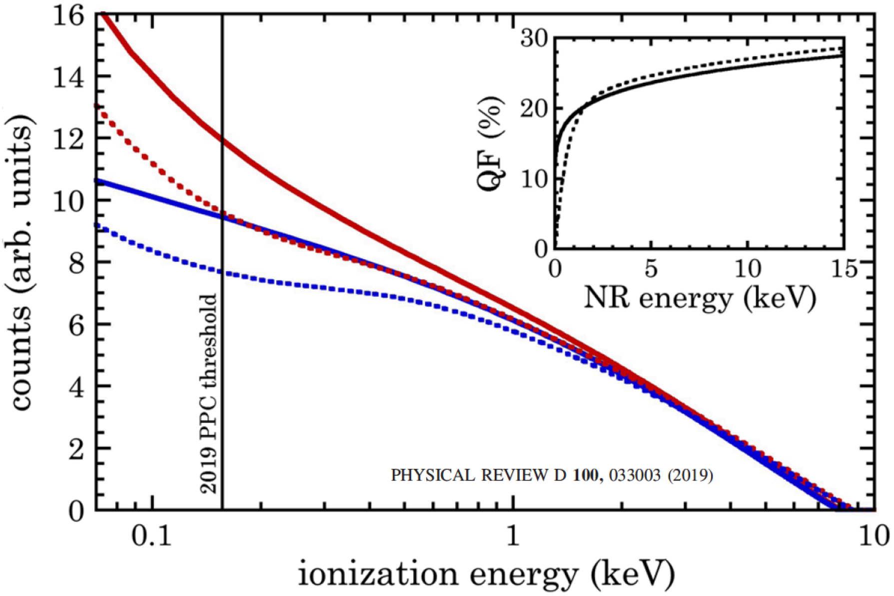
LAr (COHERENT collab.)



2% uncertainty in >20 KeV ROI claimed (?!)
Linear fit (because "it isn't completely unreasonable")

We are not looking for WIMPs:
we have predictable signals.

Time to start taking this subject seriously… it can make the difference between discoveries and embarrassment.



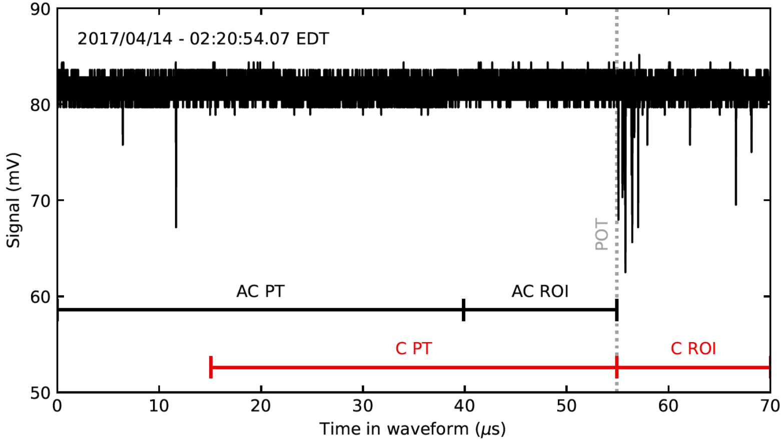
PHYSICAL REVIEW D 100, 033003 (2019)

HPGe

First observation of CEνNS

(6.7σ, 15 mo of data, ~3.5 yr total)

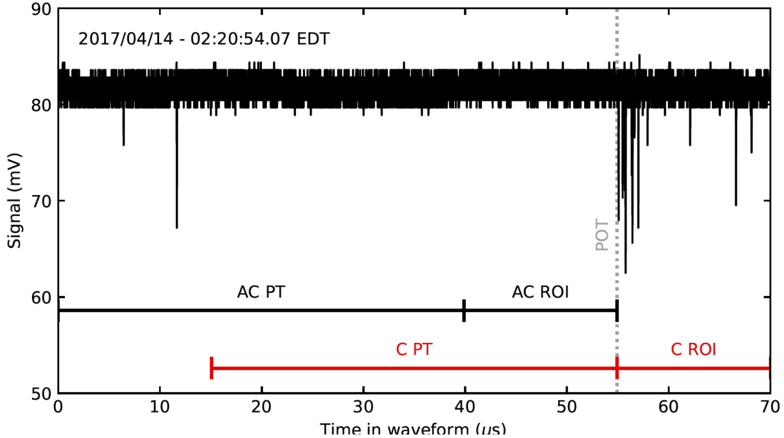
Signal and bckg regions
(blind optimization of cuts)

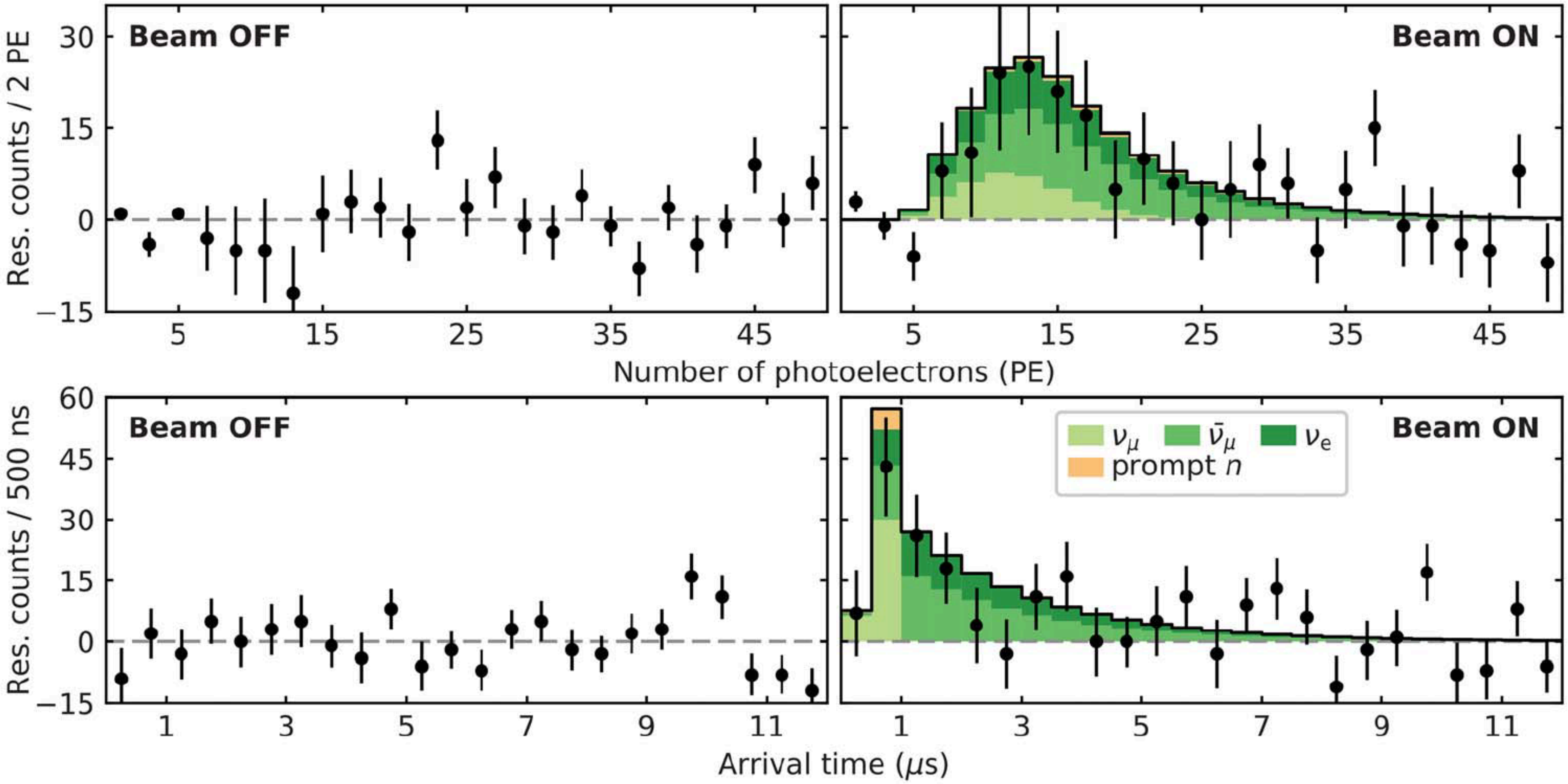


First observation of CEνNS

(6.7σ, 15 mo of data, ~3.5 yr total)

Signal and bckg regions
(blind optimization of cuts)





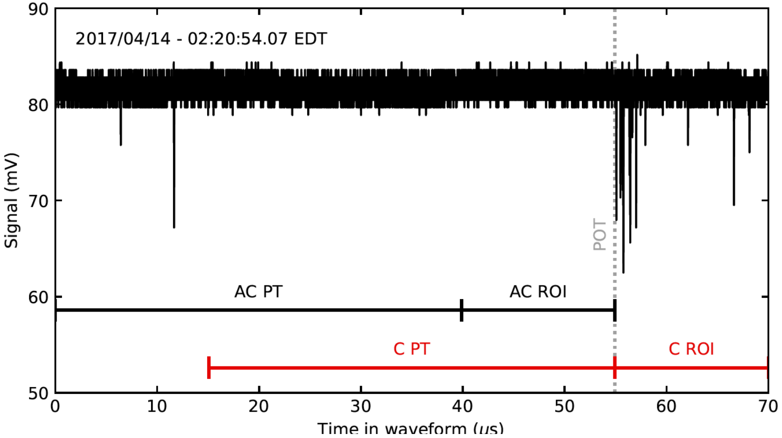
Histograms
are
SM prediction
(not a fit)

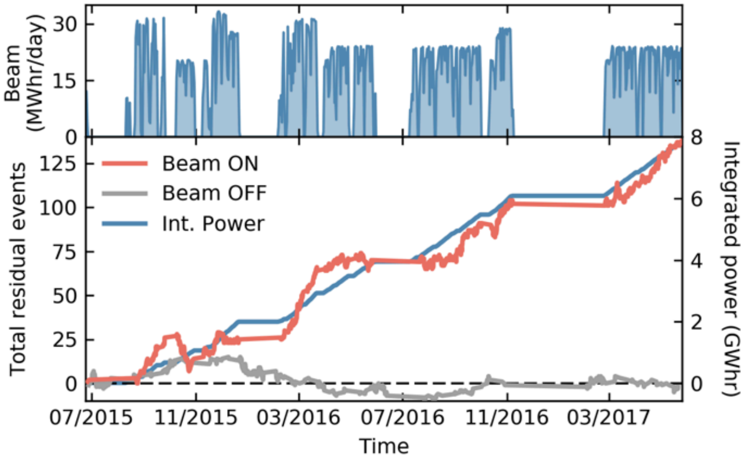
Negligible
beam-related
backgrounds

First observation of CEνNS

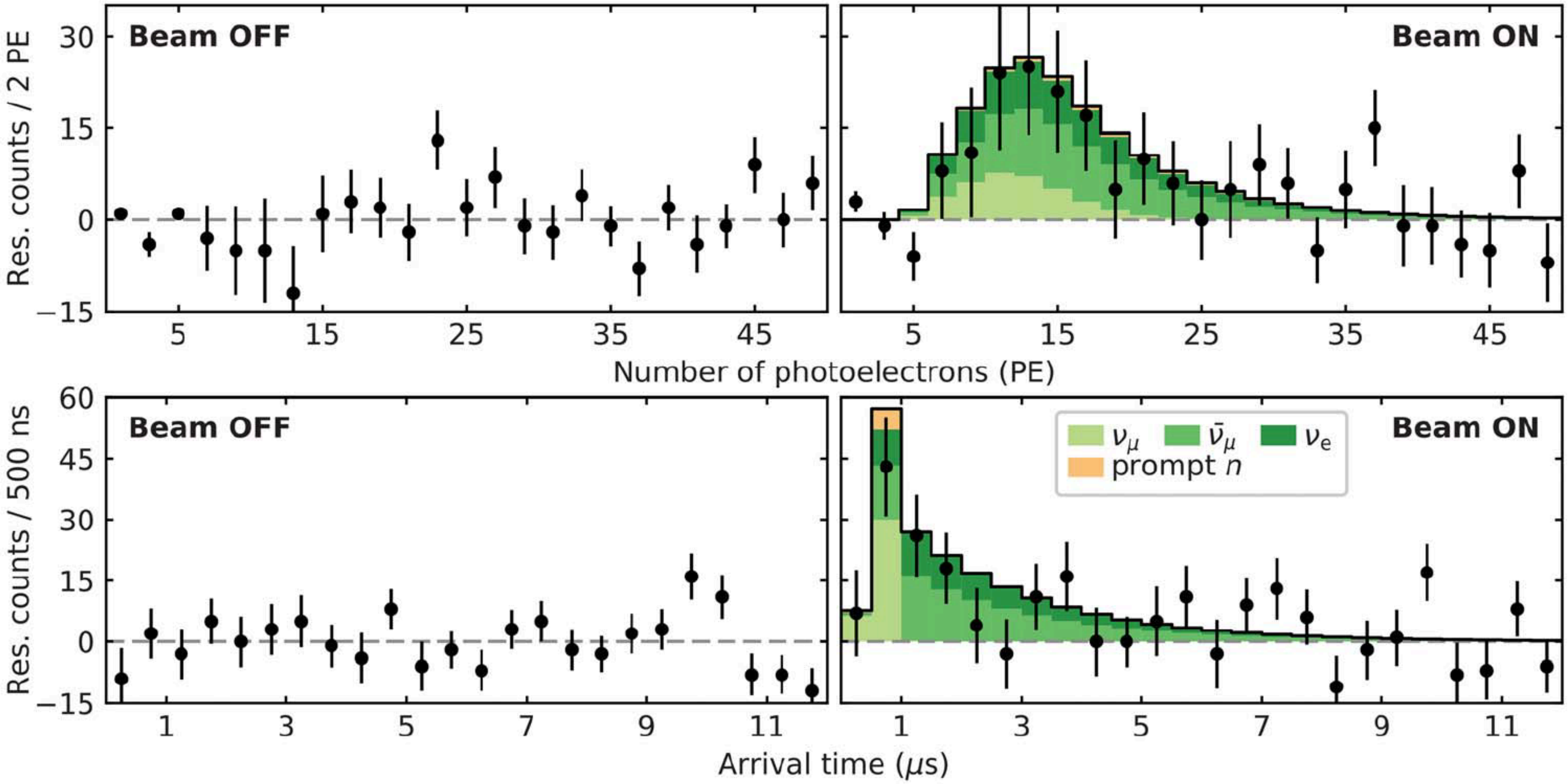
(6.7σ, 15 mo of data, ~3.5 yr total)

Signal and bckg regions
(blind optimization of cuts)





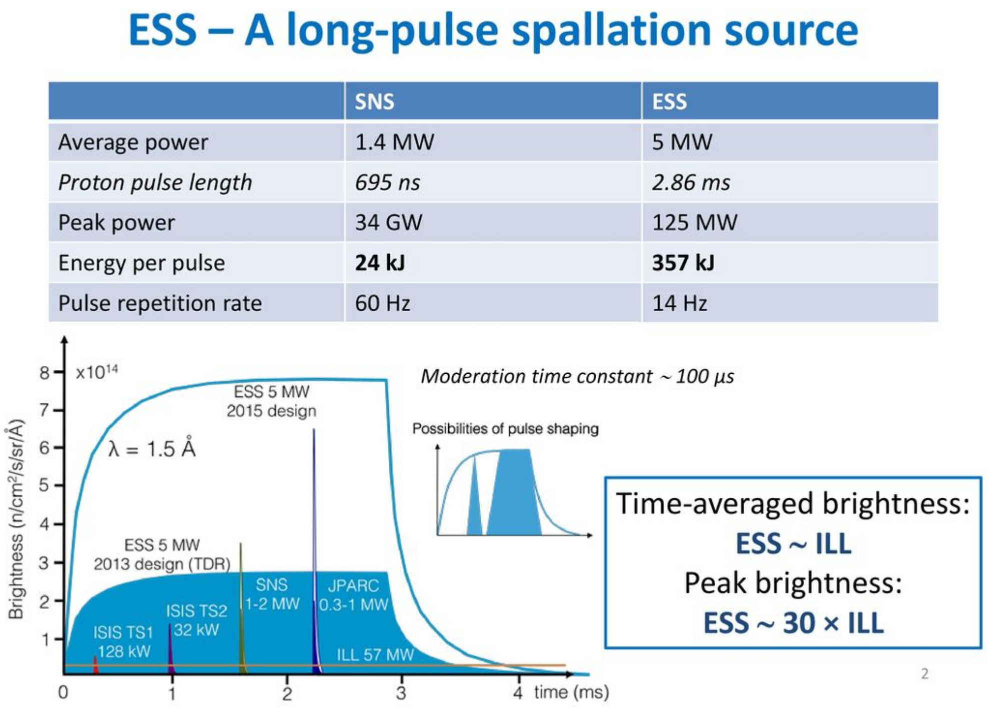
Strong correlation to instantaneous beam power



Histograms are SM prediction (not a fit)

Negligible beam-related backgrounds

A new and *definitive* opportunity for CEνNS: the ESS



ESS – A long-pulse spallation source

	SNS	ESS
Average power	1.4 MW	5 MW
Proton pulse length	*695 ns*	*2.86 ms*
Peak power	34 GW	125 MW
Energy per pulse	**24 kJ**	**357 kJ**
Pulse repetition rate	60 Hz	14 Hz

Time-averaged brightness:
ESS ~ ILL
Peak brightness:
ESS ~ 30 × ILL

X10 the DAR ν production of the SNS (= signal STATISTICS = sensitivity to new physics)

x2.5 SNS current & x2 SNS energy (=~x4 SNS ν/p)

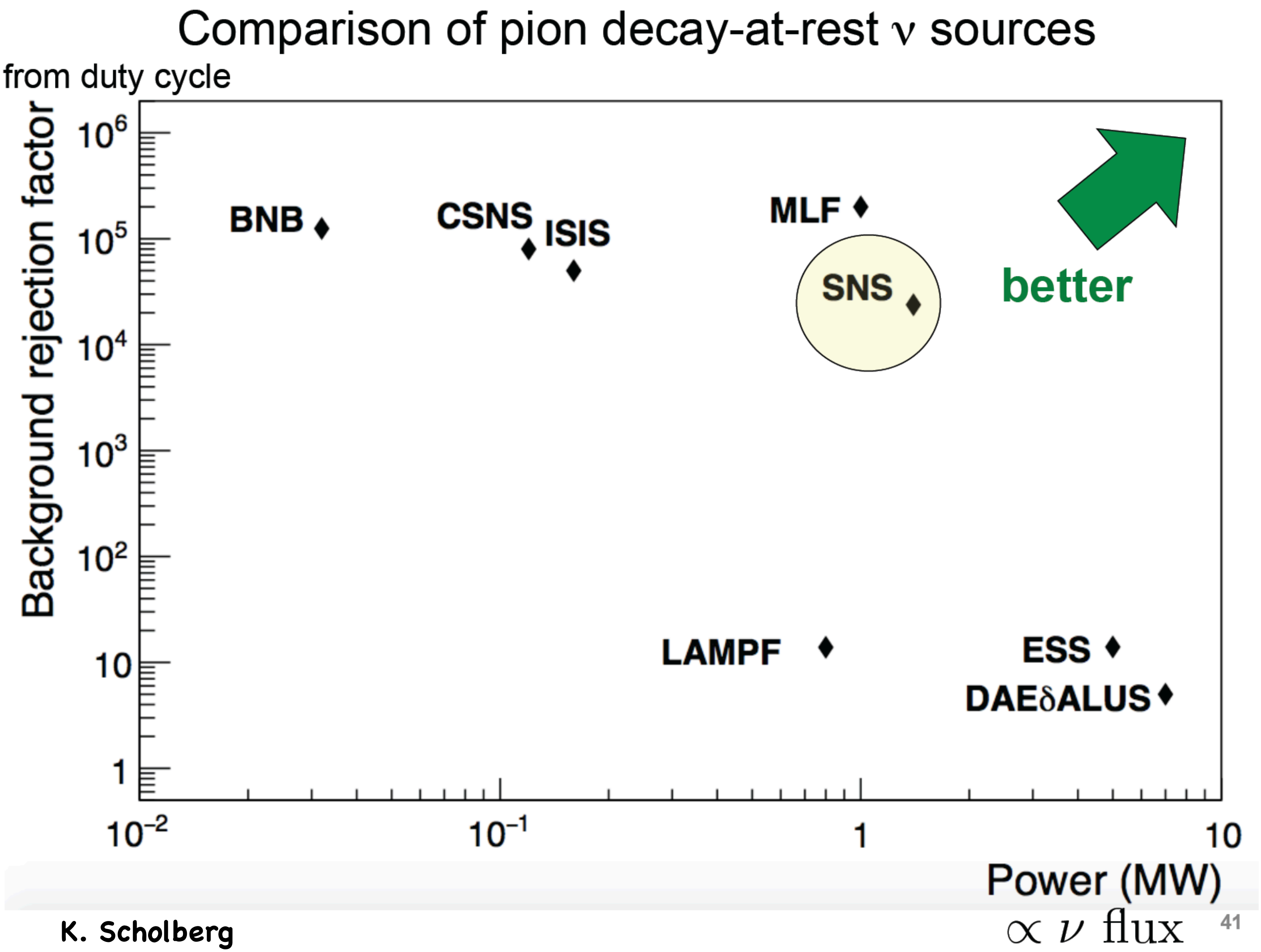
Slightly <u>better</u> signal-to-bckg than SNS, after including beam timing (steady-state bckgs are subtractable)

SNS signal rate is excruciatingly slow (e.g.,~300 CsI[Na] events in over 4 yr). ESS provides X10 the throughput.

Statistical uncertainties become negligible, while keeping detectors small and low-cost -> best possible sensitivity to CEνNS at spallation sources is within reach, limited by irreducible systematics (Φ_ν, QF) only.

First POT expected for 2021 (the time to start thinking CEνNS @ ESS is NOW)

Trompe l'oeil: find the three fallacies in this picture

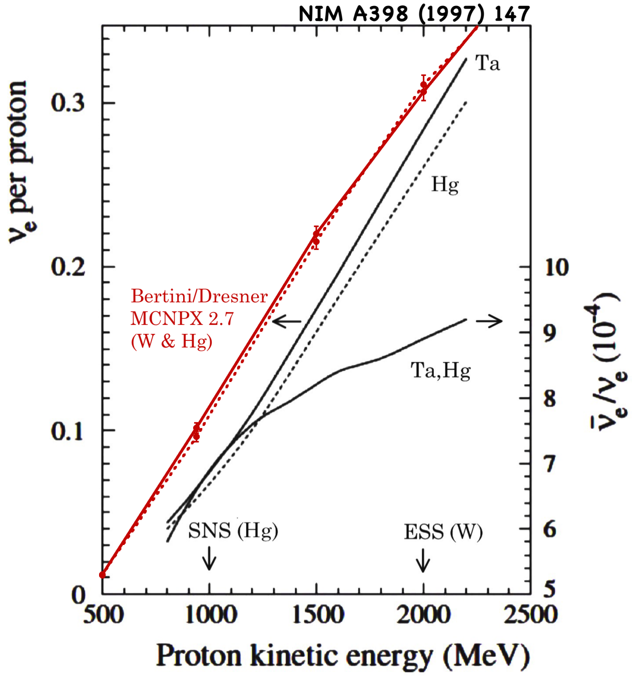


K. Scholberg

Trompe l'oeil: find the three fallacies in this picture

1) Neutrino flux depends
on proton current
and on proton energy.
ν/p grows dramatically with E_p
$\Rightarrow$ ν production @ ESS is x9.2 @ SNS

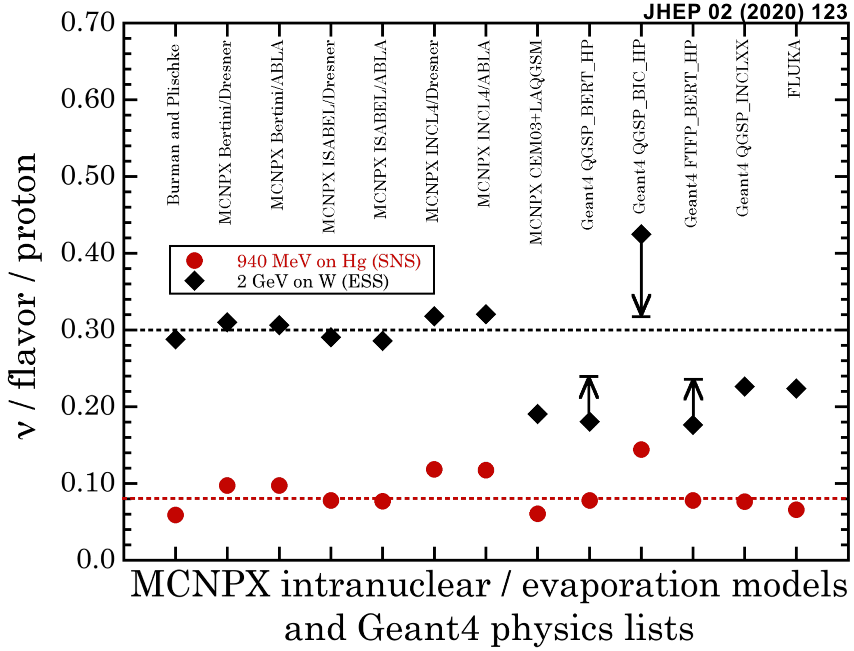
NIM A398 (1997) 147



2) Steady-state backgrounds
are subtractable
$\Rightarrow$ signal-to-background f.o.m. depends
on square root of duty cycle
(slightly better signal/bckg at ESS)

3) Differences in ESS and SNS
duty cycles for ν detection
are simply wrong, by a large factor.
(J-PARC MLF is also better than SNS).

JHEP 02 (2020) 123



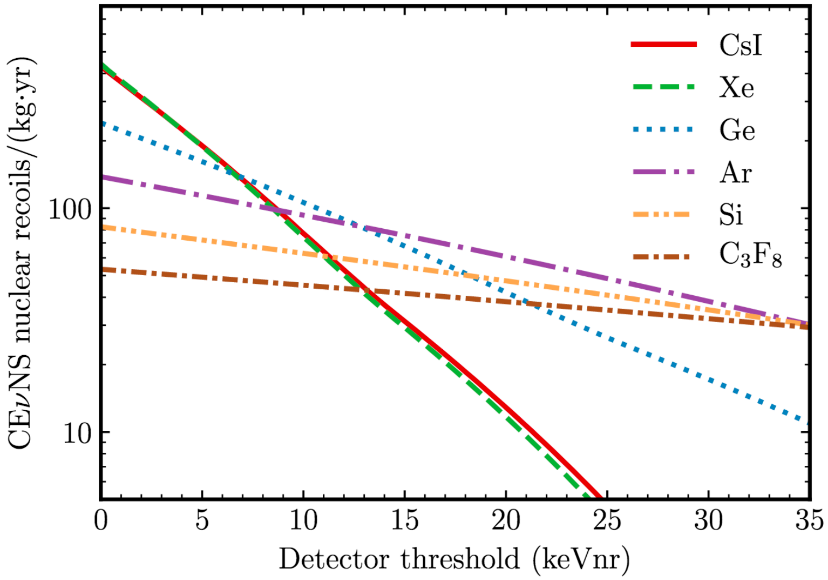
The best CEνNS source deserves the best CEνNS detectors

JHEP 02 (2020) 123

Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

D. Baxter,[1] J.I. Collar,[1,*] P. Coloma,[2,†] C.E. Dahl,[3,4] I. Esteban,[5,‡] P. Ferrario,[6,7,§]
J.J. Gomez-Cadenas,[6,7,¶] M. C. Gonzalez–Garcia,[5,8,9,**] A.R.L. Kavner,[1] C.M. Lewis,[1]
F. Monrabal,[6,7,††] J. Muñoz Vidal,[6] P. Privitera,[1] K. Ramanathan,[1] and J. Renner[10]

Detector Technology	Target nucleus	Mass (kg)	Steady-state background	E_{th} (keV_{ee})	QF (%)	E_{th} (keV_{nr})	ΔE/E (%) at E_{th}	E_{max} (keV_{nr})	CEνNS NR/yr @20m, $>E_{th}$
Cryogenic scintillator	CsI	22.5	10 ckkd	0.1	~10 [71]	1	30	46.1	8,405
Charge-coupled device	Si	1	1 ckkd	0.007 (2e⁻)	4-30 [97]	0.16	60	212.9	80
High-pressure gaseous TPC	Xe	20	10 ckkd	0.18	20 [104]	0.9	40	45.6	7,770
p-type point contact HPGe	Ge	7	15 ckkd	0.12	20 [118]	0.6	15	78.9	1,610
Scintillating bubble chamber	Ar	10	0.1 c/kg-day	-	-	0.1	~40	150.0	1,380
Standard bubble chamber	C_3F_8	10	0.1 c/kg-day	-	-	2	40	329.6	515



ALL these technologies are sensitive to 1 keVnr nuclear recoils (no easy feat!)

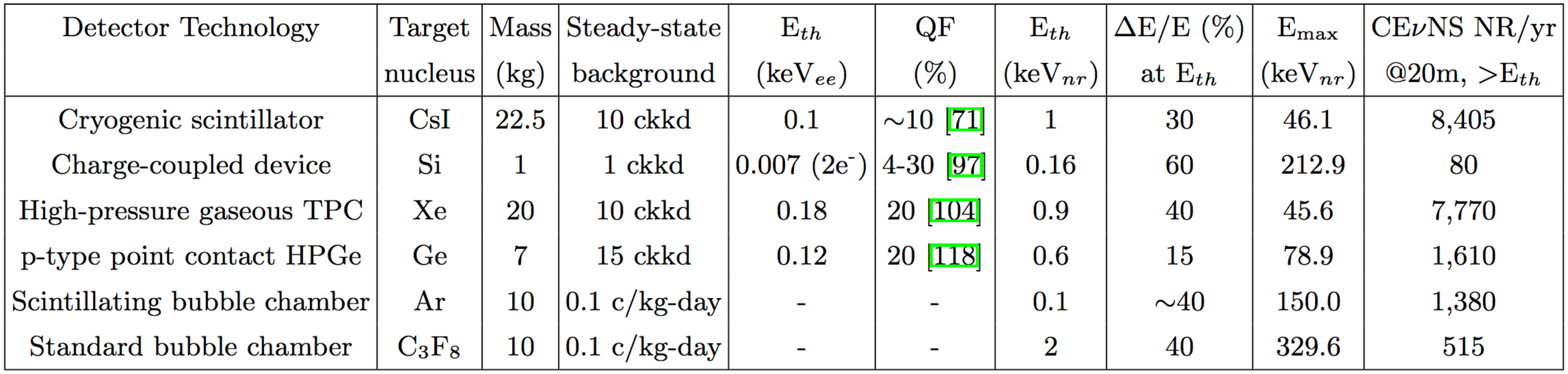
Reason: a lot of interesting physics concentrates at low-E (e.g. ν magnetic moment). Also, maximum statistics.

The best CEνNS source deserves the best CEνNS detectors

JHEP 02 (2020) 123

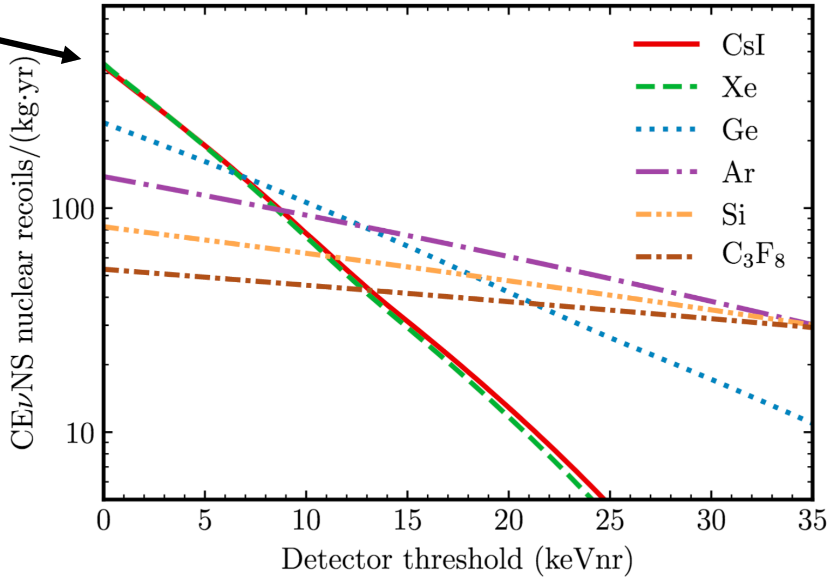
Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

D. Baxter,[1] J.I. Collar,[1,*] P. Coloma,[2,†] C.E. Dahl,[3,4] I. Esteban,[5,‡] P. Ferrario,[6,7,§]
J.J. Gomez-Cadenas,[6,7,¶] M. C. Gonzalez–Garcia,[5,8,9,**] A.R.L. Kavner,[1] C.M. Lewis,[1]
F. Monrabal,[6,7,††] J. Muñoz Vidal,[6] P. Privitera,[1] K. Ramanathan,[1] and J. Renner[10]



Detector Technology	Target nucleus	Mass (kg)	Steady-state background	E_{th} (keV_{ee})	QF (%)	E_{th} (keV_{nr})	ΔE/E (%) at E_{th}	E_{max} (keV_{nr})	CEνNS NR/yr @20m, $>E_{th}$
Cryogenic scintillator	CsI	22.5	10 ckkd	0.1	~10 [71]	1	30	46.1	8,405
Charge-coupled device	Si	1	1 ckkd	0.007 ($2e^-$)	4-30 [97]	0.16	60	212.9	80
High-pressure gaseous TPC	Xe	20	10 ckkd	0.18	20 [104]	0.9	40	45.6	7,770
p-type point contact HPGe	Ge	7	15 ckkd	0.12	20 [118]	0.6	15	78.9	1,610
Scintillating bubble chamber	Ar	10	0.1 c/kg-day	-	-	0.1	~40	150.0	1,380
Standard bubble chamber	C_3F_8	10	0.1 c/kg-day	-	-	2	40	329.6	515

Interesting CsI/Xe overlap (same response, different systematics)

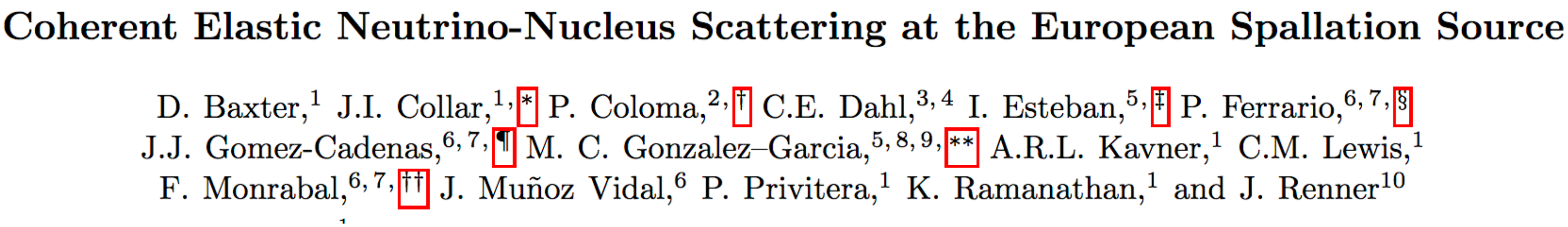


ALL these technologies are sensitive to 1 keVnr nuclear recoils (no easy feat!)

Reason: a lot of interesting physics concentrates at low-E (e.g. ν magnetic moment). Also, maximum statistics.

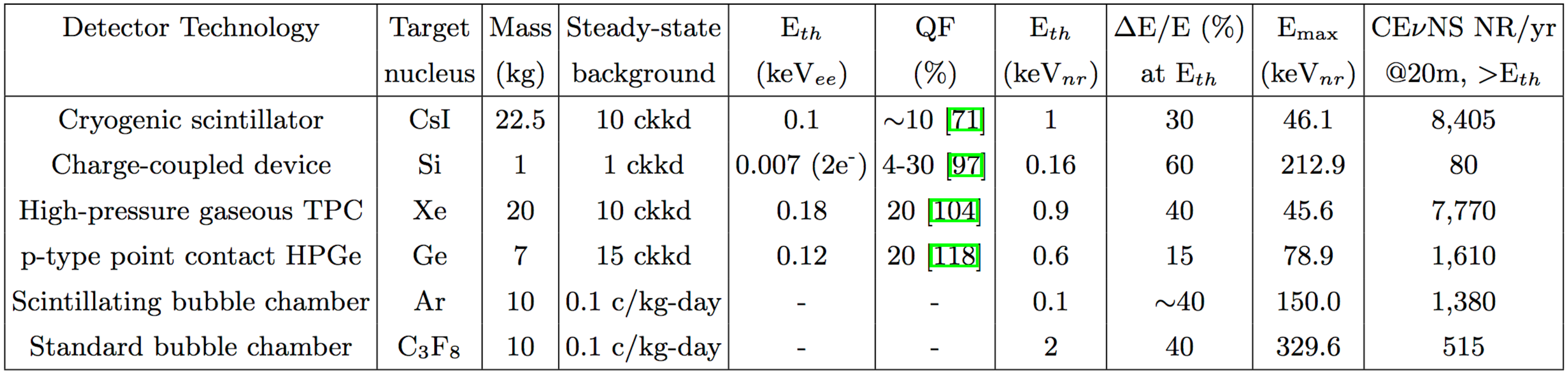
The best CEνNS source deserves the best CEνNS detectors

JHEP 02 (2020) 123

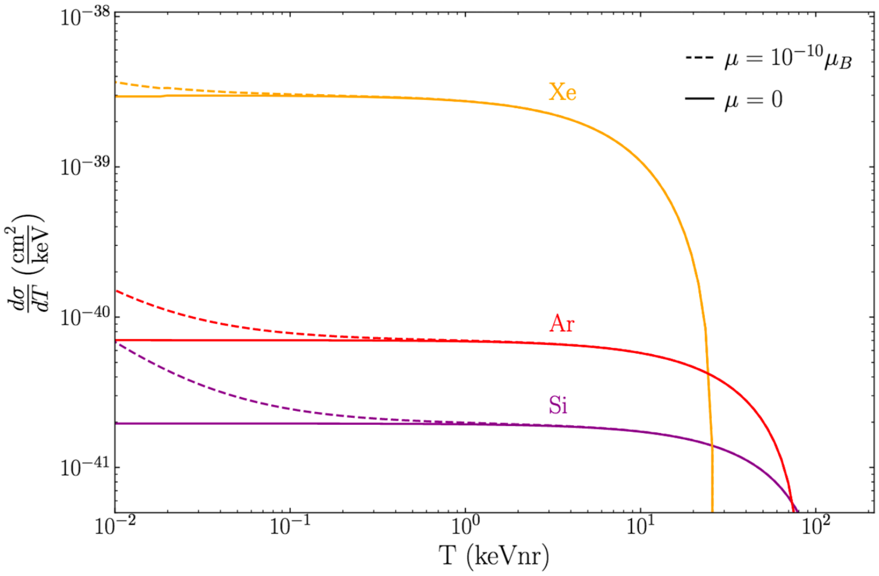


Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

D. Baxter,[1] J.I. Collar,[1,*] P. Coloma,[2,†] C.E. Dahl,[3,4] I. Esteban,[5,‡] P. Ferrario,[6,7,§]
J.J. Gomez-Cadenas,[6,7,¶] M. C. Gonzalez–Garcia,[5,8,9,**] A.R.L. Kavner,[1] C.M. Lewis,[1]
F. Monrabal,[6,7,††] J. Muñoz Vidal,[6] P. Privitera,[1] K. Ramanathan,[1] and J. Renner[10]



Detector Technology	Target nucleus	Mass (kg)	Steady-state background	E_{th} (keV$_{ee}$)	QF (%)	E_{th} (keV$_{nr}$)	ΔE/E (%) at E_{th}	E_{max} (keV$_{nr}$)	CEνNS NR/yr @20m, >E_{th}
Cryogenic scintillator	CsI	22.5	10 ckkd	0.1	∼10 [71]	1	30	46.1	8,405
Charge-coupled device	Si	1	1 ckkd	0.007 (2e$^-$)	4-30 [97]	0.16	60	212.9	80
High-pressure gaseous TPC	Xe	20	10 ckkd	0.18	20 [104]	0.9	40	45.6	7,770
p-type point contact HPGe	Ge	7	15 ckkd	0.12	20 [118]	0.6	15	78.9	1,610
Scintillating bubble chamber	Ar	10	0.1 c/kg-day	-	-	0.1	∼40	150.0	1,380
Standard bubble chamber	C_3F_8	10	0.1 c/kg-day	-	-	2	40	329.6	515

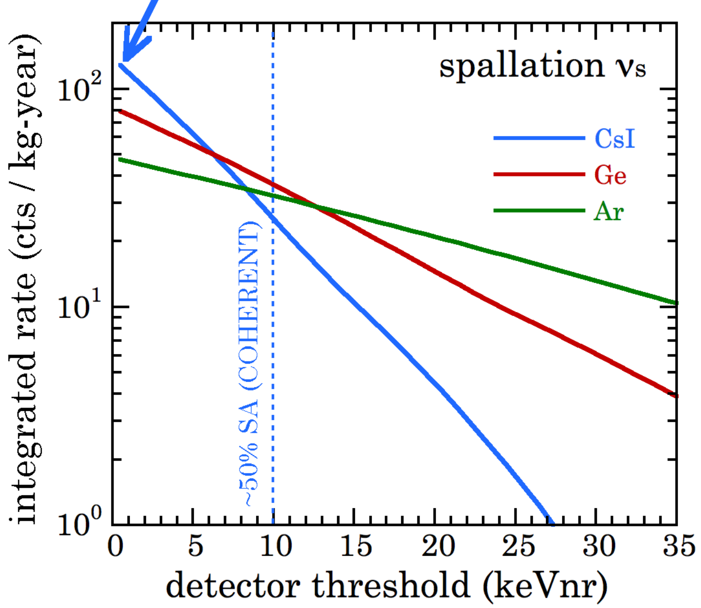


ALL these technologies are sensitive to 1 keVnr nuclear recoils (no easy feat!)

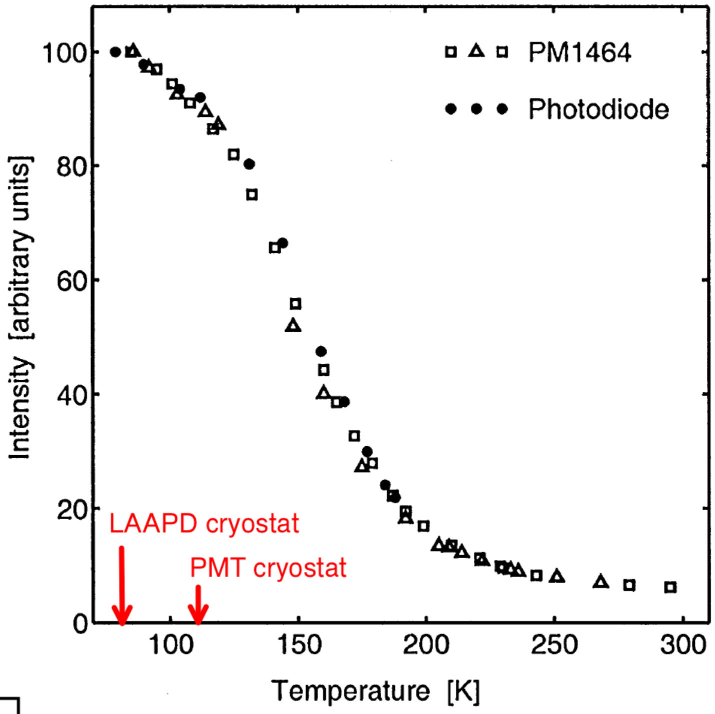
Reason: a lot of interesting physics concentrates at low-E (e.g. ν magnetic moment). Also, maximum statistics.

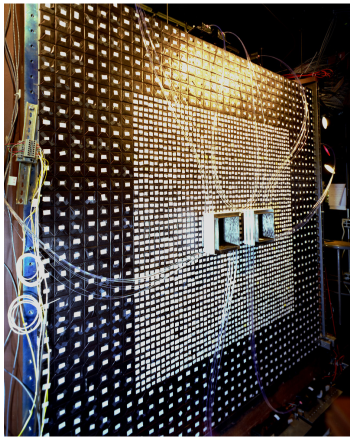
Beyond CsI[Na]: cryogenic (80K) pure CsI

x10 increase in rate/kg possible

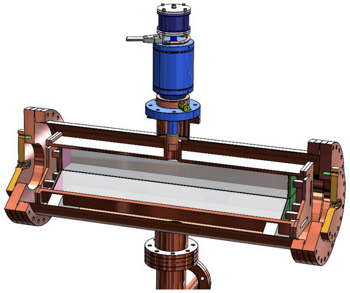


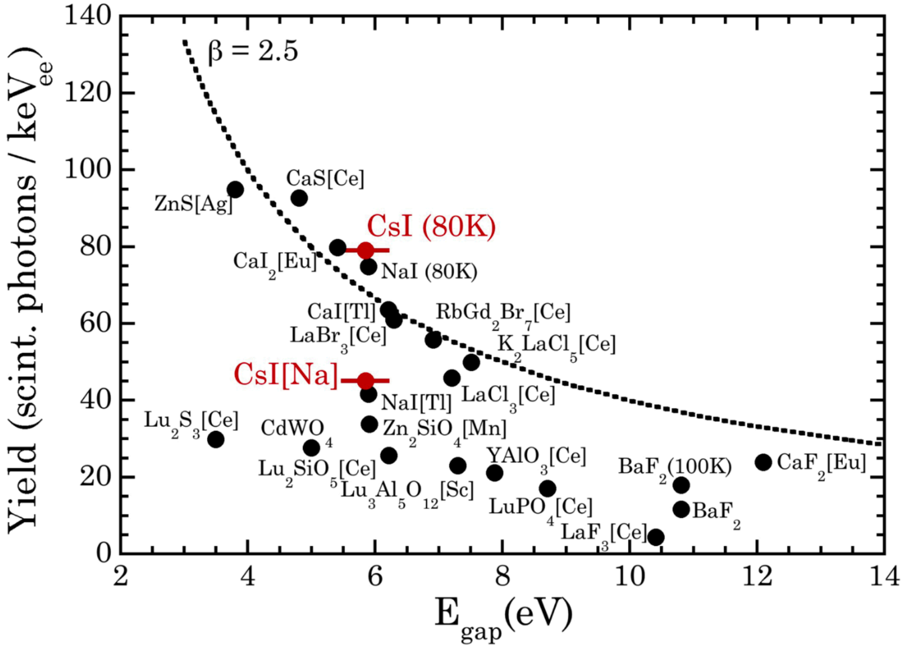
C. Amsler et al. / Nuclear Instruments and Methods in Physics Research A 480 (2002) 494–500





1.7 T of CsI crystals in storage at UC (start with 22 kg...)



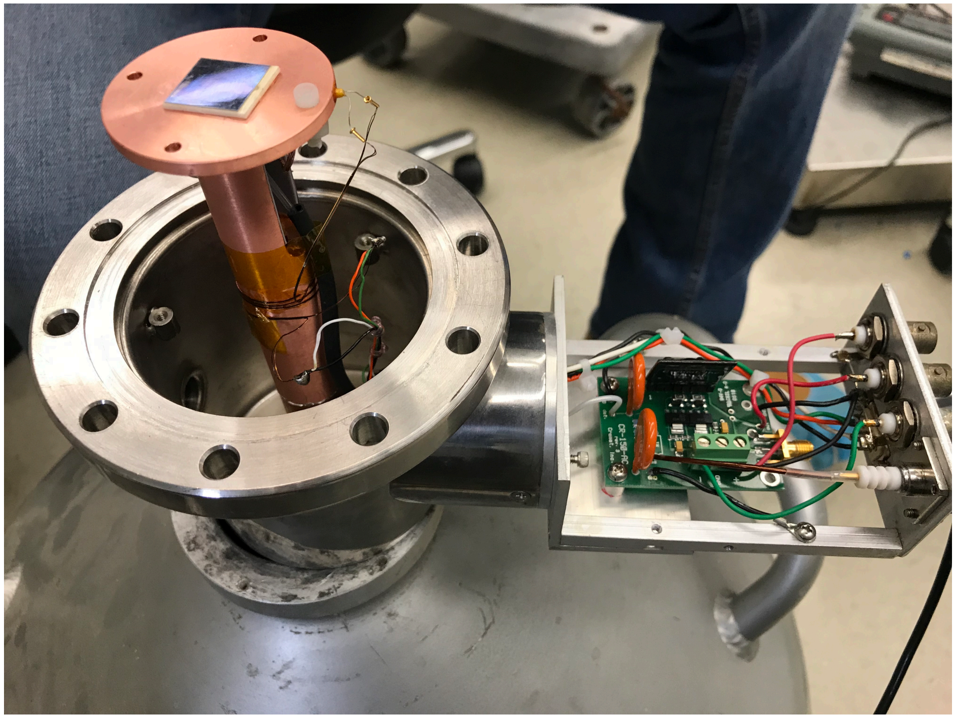


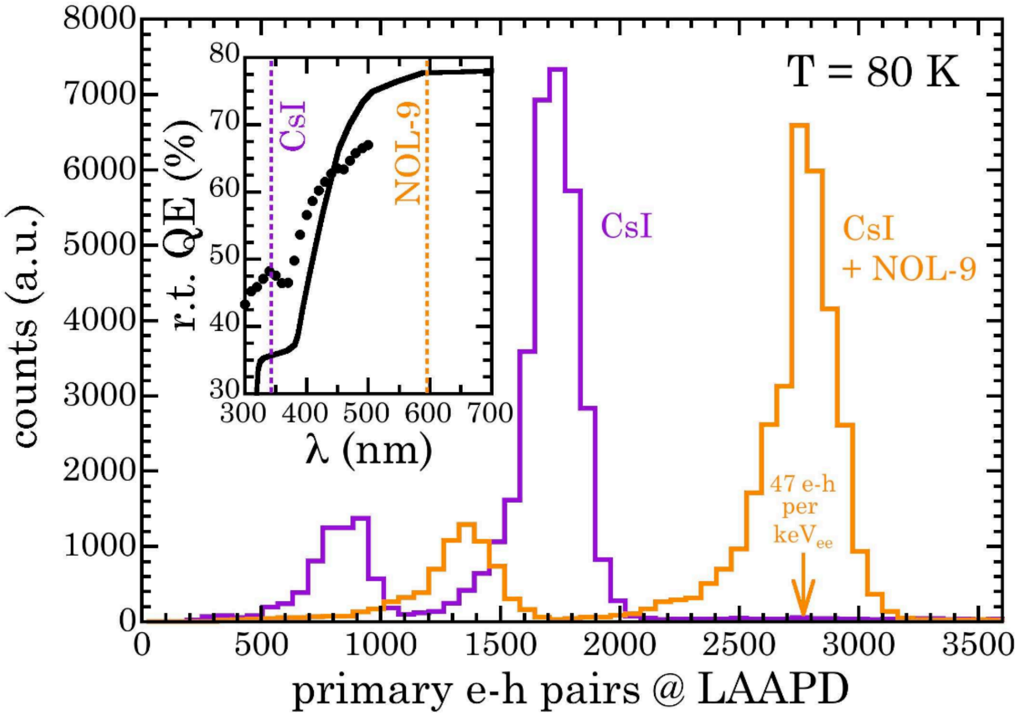
Signal STATISTICS needed for new ν physics via CEνNS:

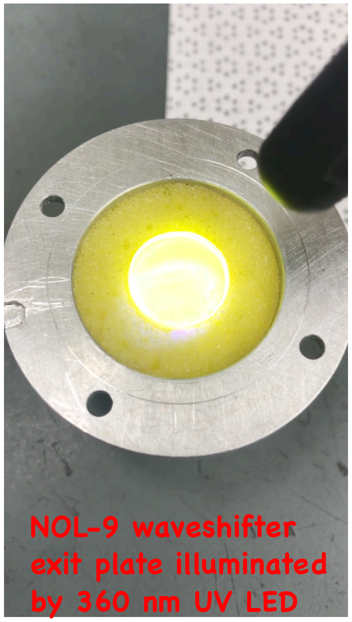
The cryogenic CsI perfect trifecta:

- >80 photons/keV
- Ultralow-noise of cryogenic LAAPDs (few e-h)
- ~80% QE via use of NOL-9 waveshifter to yellow

Beyond CsI[Na]: cryogenic (80K) pure CsI







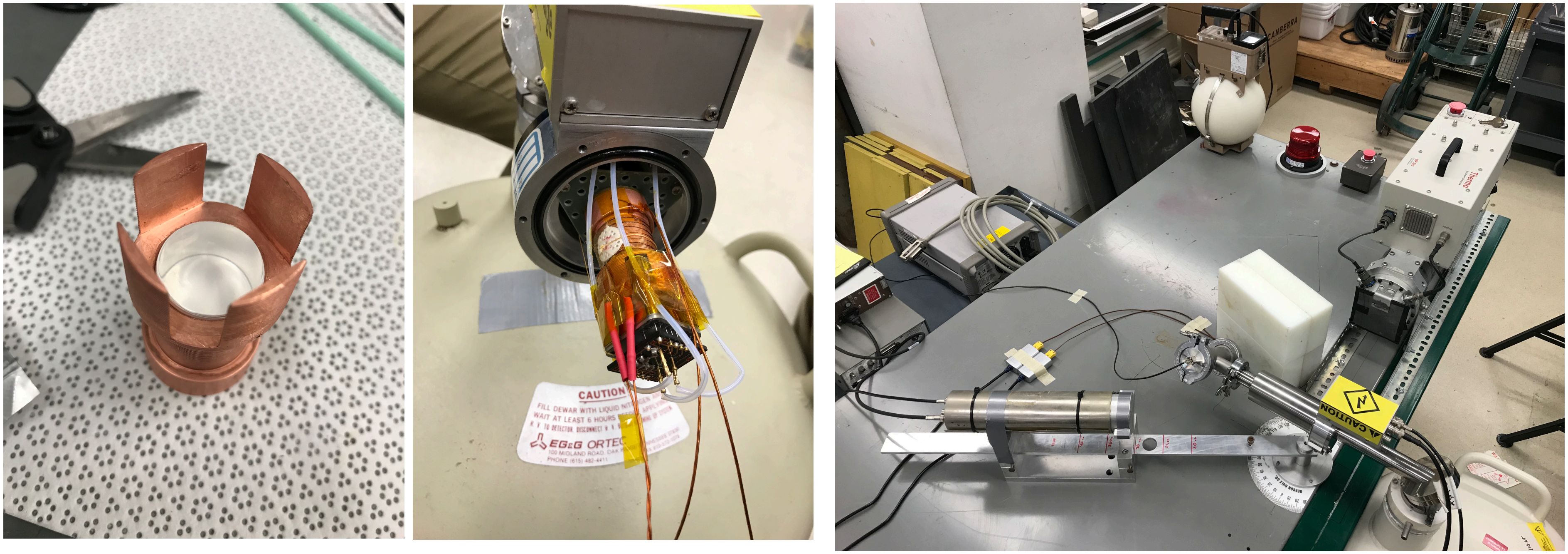
NOL-9 waveshifter exit plate illuminated by 360 nm UV LED

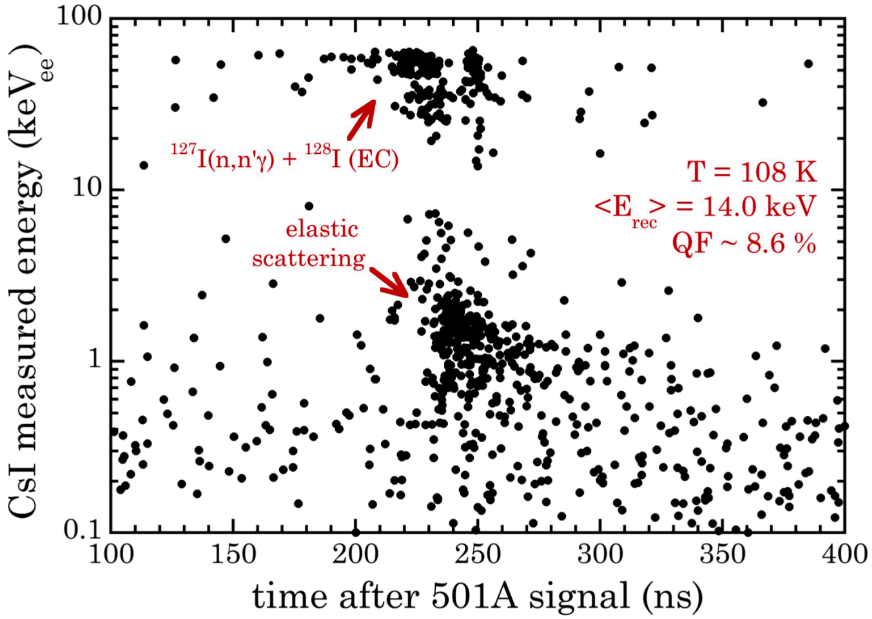
Signal STATISTICS needed for new ν physics via CEνNS:

The cryogenic CsI perfect trifecta:

- >80 photons/keV
- Ultralow-noise of cryogenic LAAPDs (few e-h)
- ~80% QE via use of NOL-9 waveshifter to yellow

Beyond CsI[Na]: cryogenic (80K) pure CsI





Signal STATISTICS needed for new ν physics via CEνNS:

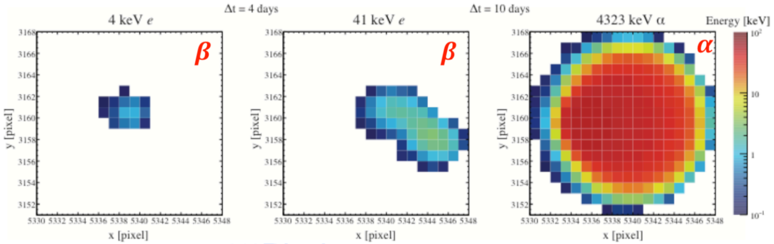
The cryogenic CsI perfect trifecta:

- >80 photons/keV
- Ultralow-noise of cryogenic LAAPDs (few e-h)
- ~80% QE via use of NOL-9 waveshifter to yellow

Dark Matter in CCDs

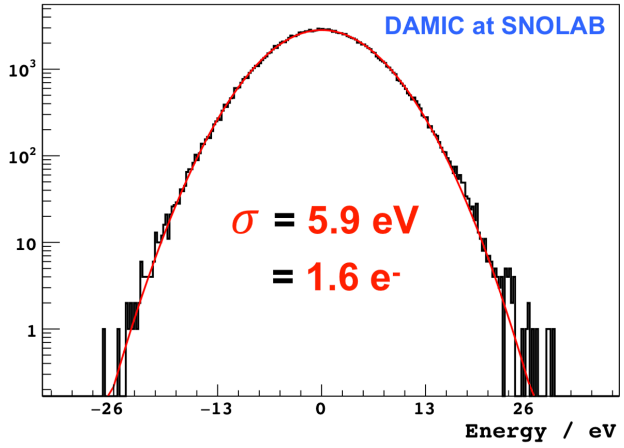
- Exquisite spatial resolution: unique background characterization and rejection

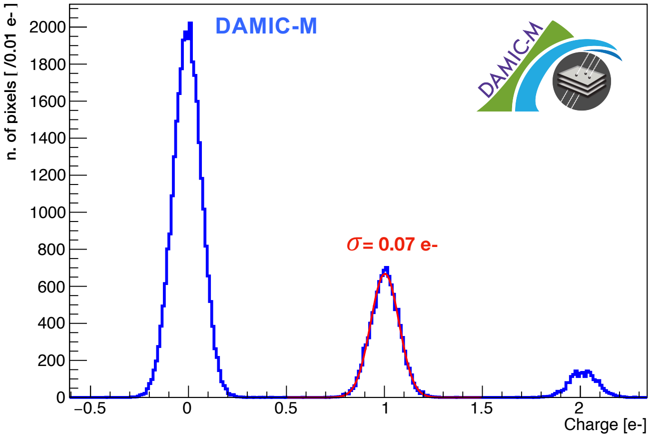
Unparalleled rejection of intrinsic backgrounds!



^{210}Pb decay sequence

- Extremely low dark current (2×10^{-22} A cm^{-2}, < 0.001 e/pixel/day)
- Resolution of 2 e- achieved at SNOLAB, and 0.07 e- achieved in DAMIC-M CCDs



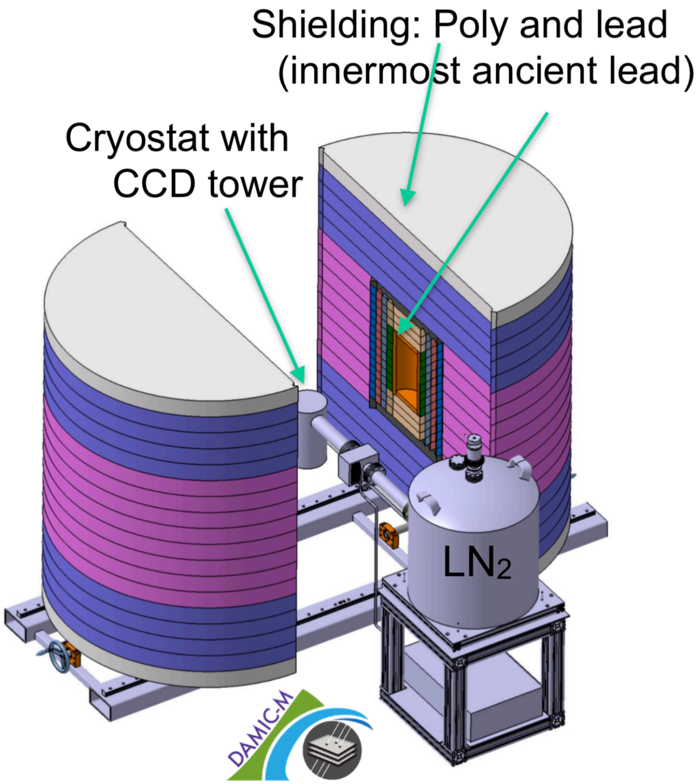


DAMIC-M DAMIC at **Laboratoire Souterrain de Modane**

- 50 CCDs (kg-size target mass)
- Most massive CCDs ever built (>10 g each)
- **Single electron resolution** with “skipper” readout (demonstrated by Fermilab SENSEI group)
- A fraction of dru background

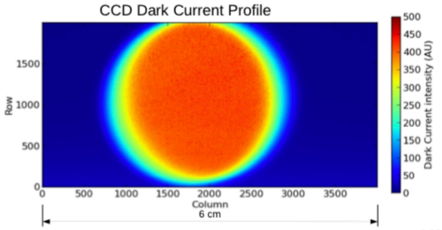
- “Classical” design (Ge detectors and DAMIC at SNOLAB)

- R&D and design up to 2021
- Construction 2022
- Installation in 2023



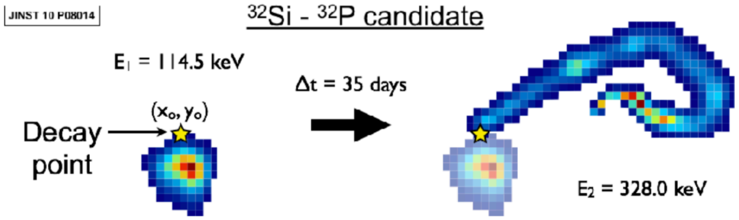
DAMIC-M Backgrounds

- Most relevant backgrounds identified by DAMIC at SNOLAB
- Cosmogenic tritium: minimize exposure to cosmic rays with shielding during transport/fabrication; CCD packaging and test underground at LSM. Also, R&D ongoing to evaluate tritium removal by wafers/CCDs baking.



Activation of a DAMIC CCD at the LANSCE neutron beam. Tritium clearly detected; rate measurement being finalized.

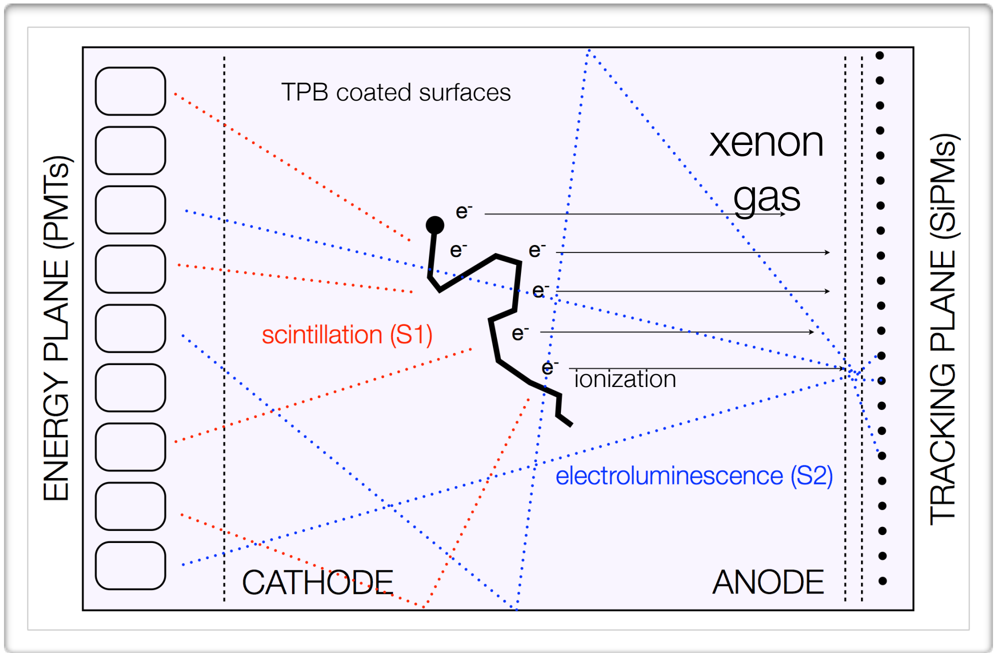
- Cosmogenic ^{32}Si: spatial correlations



- Surface ^{210}Pb: minimize exposure to radon (radon-free clean room at LSM for CCD packaging/test; installation in radon-free tent)
- Radiogenic background: material selection and electro formed copper

Challenging goal: 0.1 dru

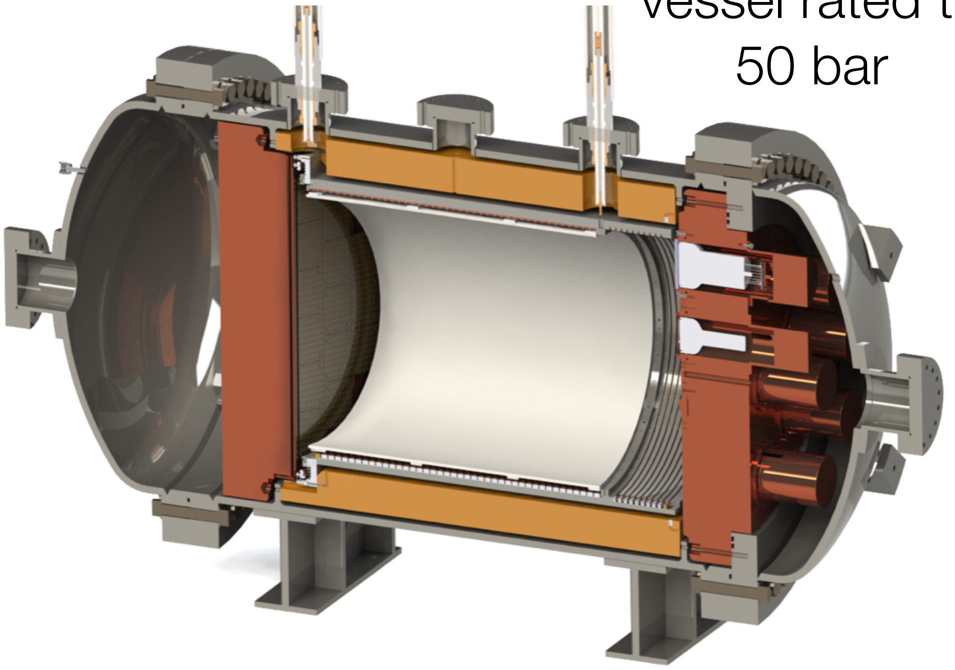
High pressure gas xenon detectors



EL mode is essential to get lineal gain, therefore avoiding avalanche fluctuations and fully exploiting the excellent Fano factor in gas

- It is a High Pressure Xenon (HPXe) TPC operating in EL mode.
- It is filled with 100 kg of Xenon enriched at 90% in Xe-136 (in stock) at a pressure of 15 bar.
- The event energy is integrated by a plane of radiopure PMTs located behind a transparent cathode (energy plane), which also provide t0.
- The event topology is reconstructed by a plane of radiopure silicon pixels (MPPCs) (tracking plane).

NEXT-NEW



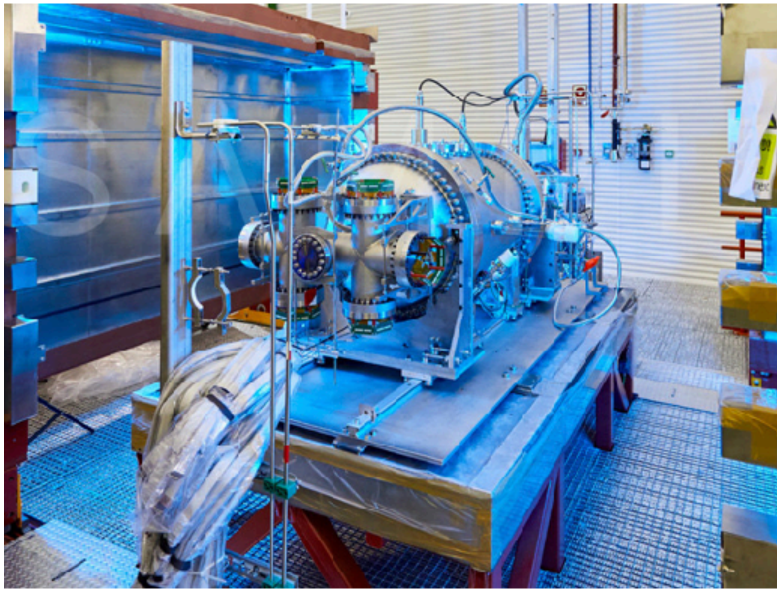
Tracking plane with SiPMs

Pressure vessel rated to 50 bar

Copper shield:
6cm in the main body,
12 cm in the end caps

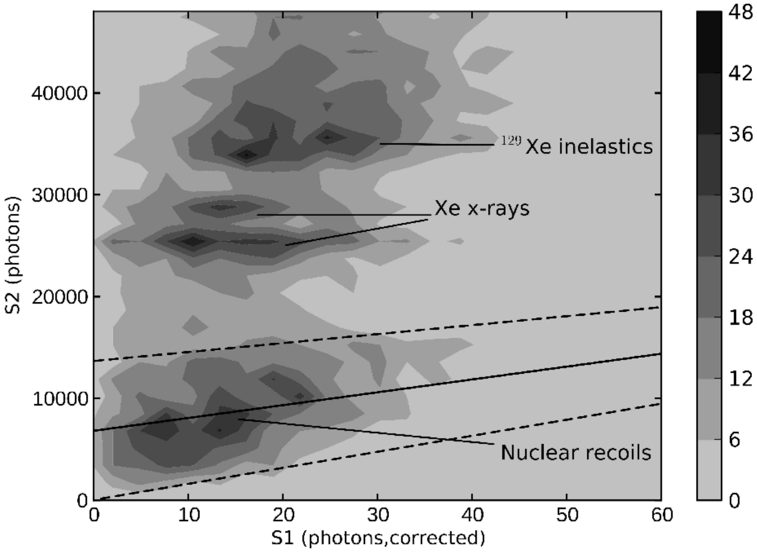
Energy plane with PMTs

Taking data at the LSC

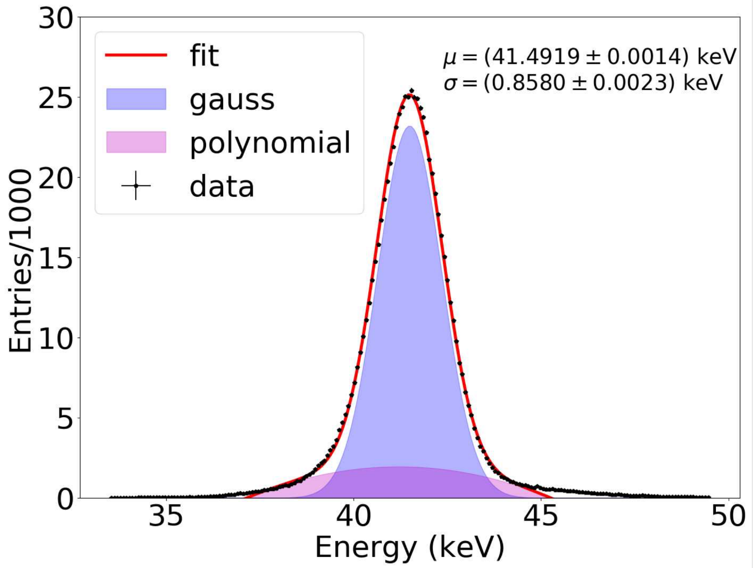


Detector can be optimised for operation at the ESS

Nuclear recoils and energy resolution in gas xenon



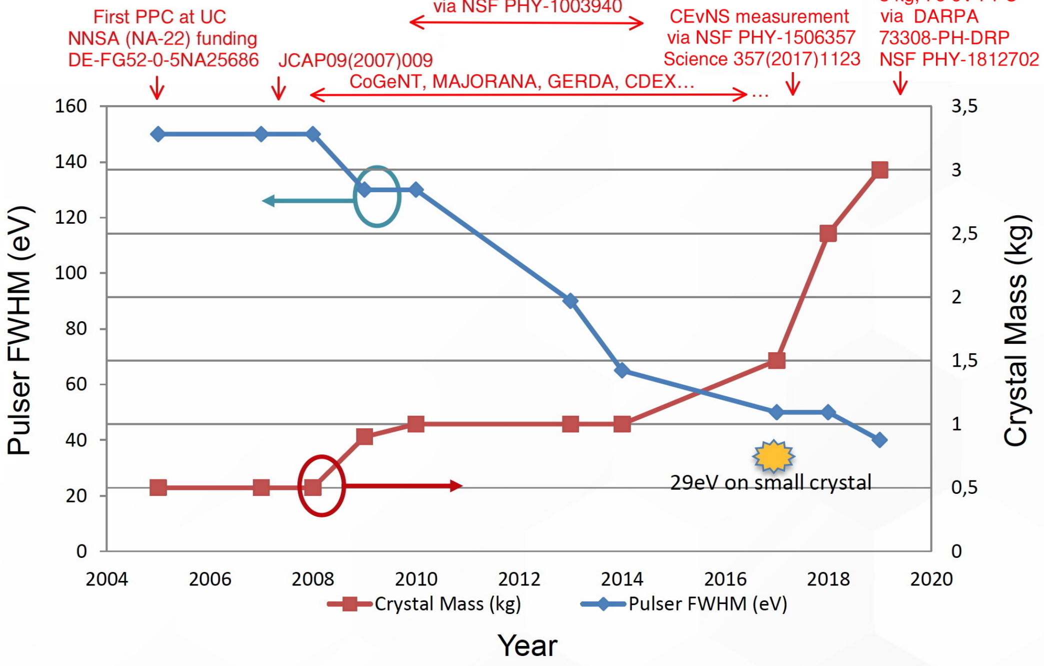
Nuclear recoil identification in gaseous xenon



Energy reconstruction in NEW of 41.5 keV events. Energy resolution is 4.85% FWHM

P-type Point Contact (PPC) germanium detectors

arXiv:nucl-ex/0701012


First PPC at UC
NNSA (NA-22) funding
DE-FG52-0-5NA25686

JCAP09(2007)009

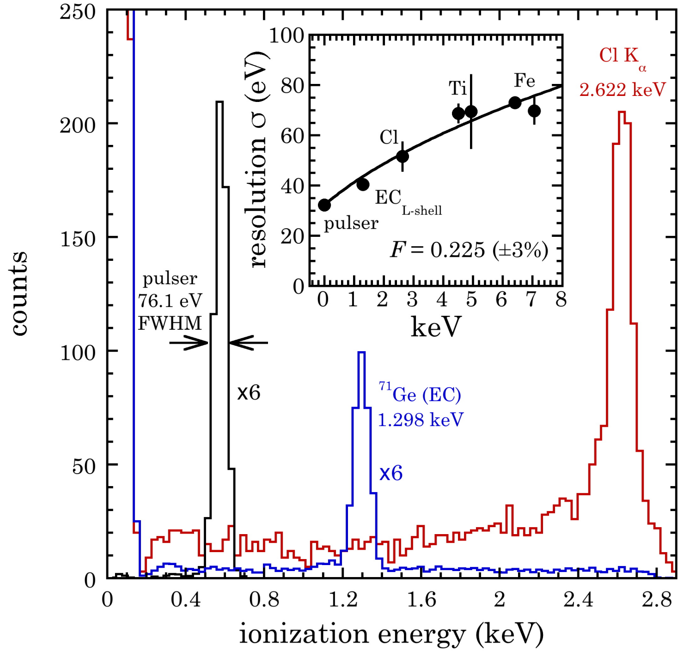
PPC R&D at CANBERRA
via NSF PHY-1003940

CoGeNT, MAJORANA, GERDA, CDEX…

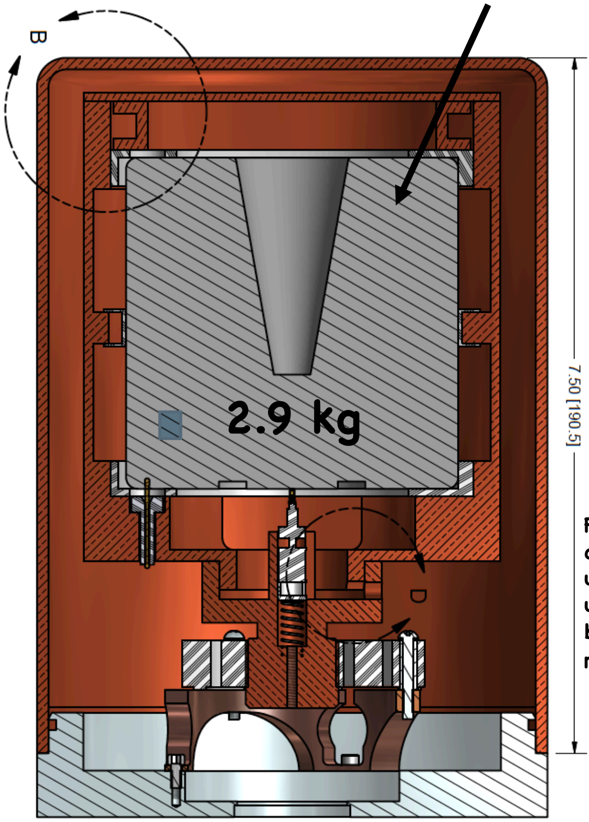
CEvNS measurement
via NSF PHY-1506357
Science 357(2017)1123

3 kg, 75 eV PPC
via DARPA
73308-PH-DRP
NSF PHY-1812702

29eV on small crystal

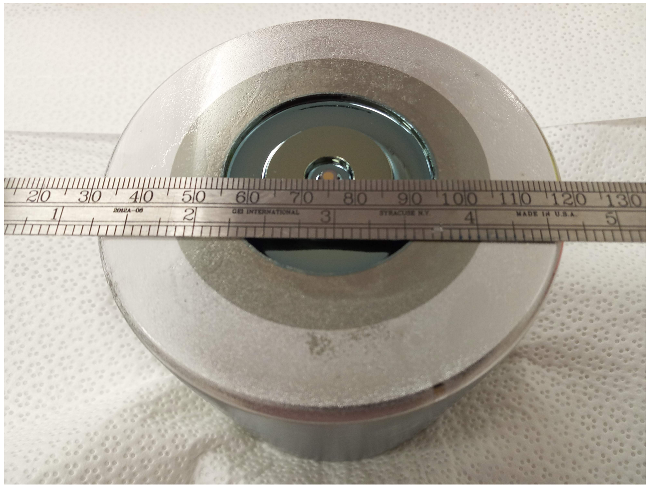


Inverted coax PPC
NIM A 665 (2011) 25

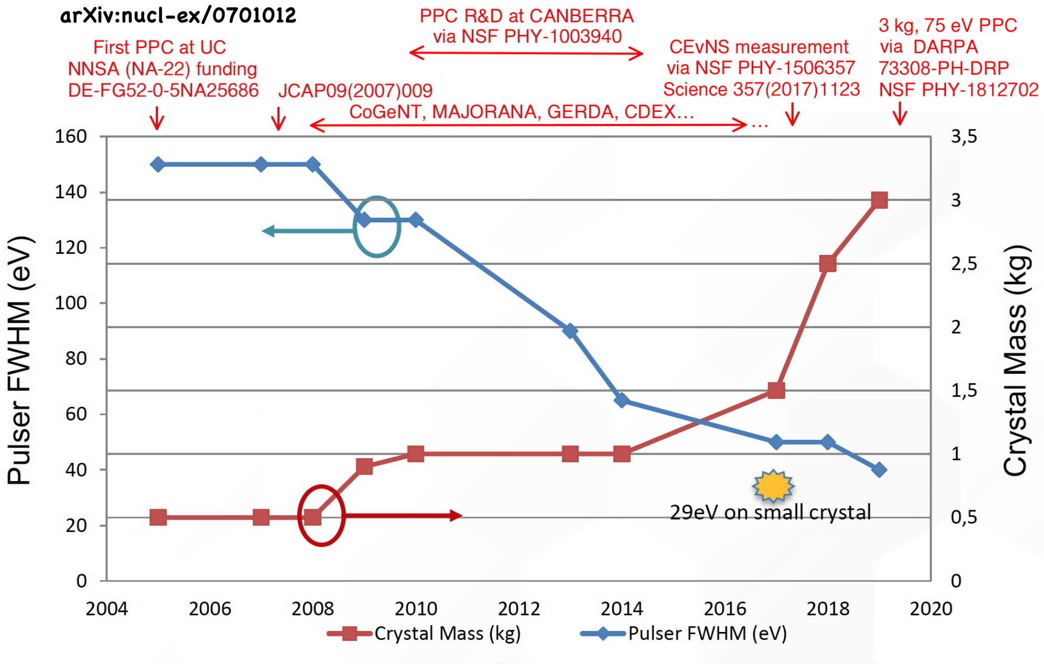


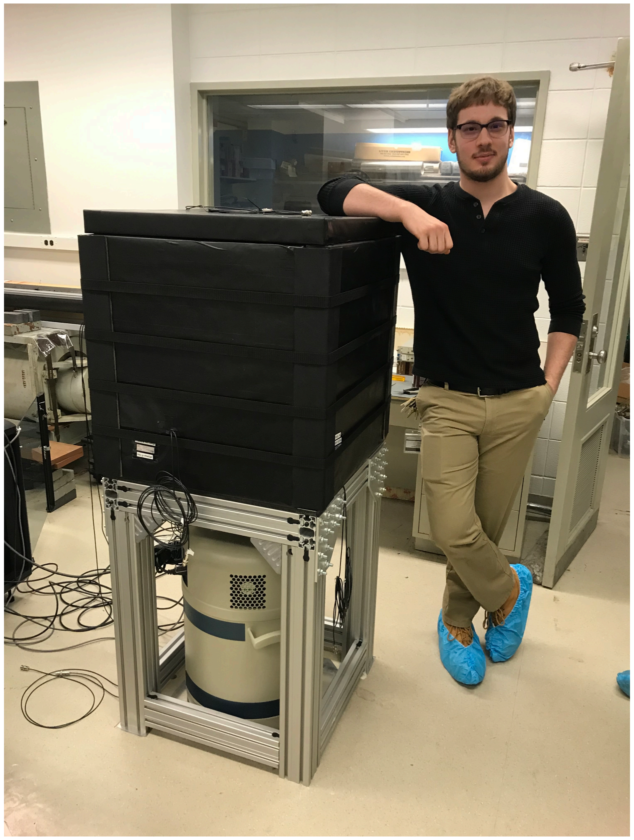
Finalized design uses ultra-low background materials.

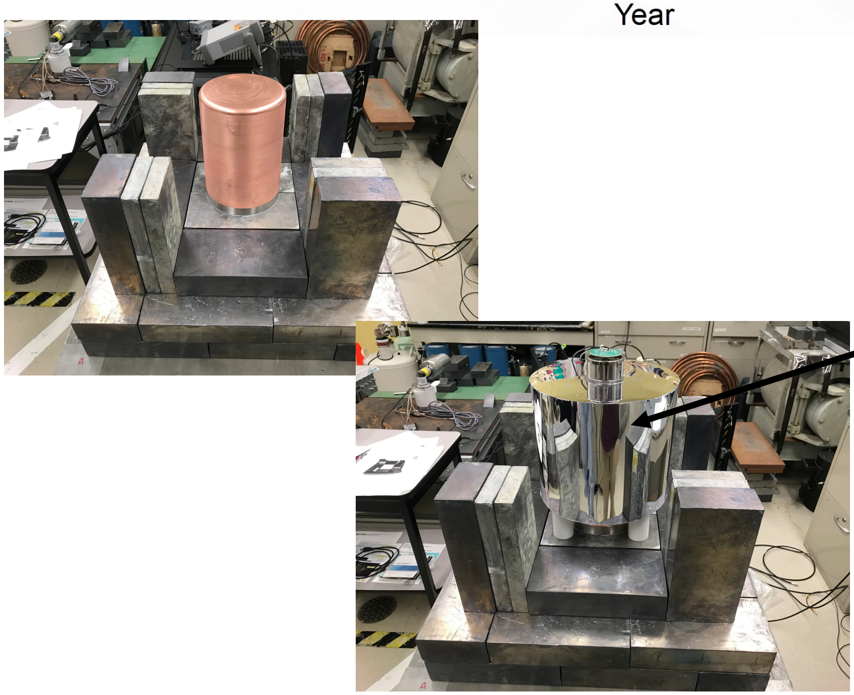
Ge PPC:
unique combination of mass, radiopurity, threshold and resolution provide ideal tool for precision CEvNS studies, and practical applications (reactor monitoring)



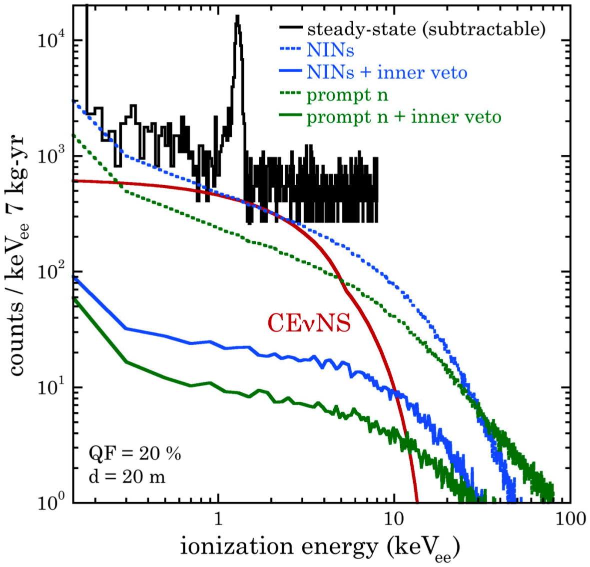
P-type Point Contact (PPC) germanium detectors





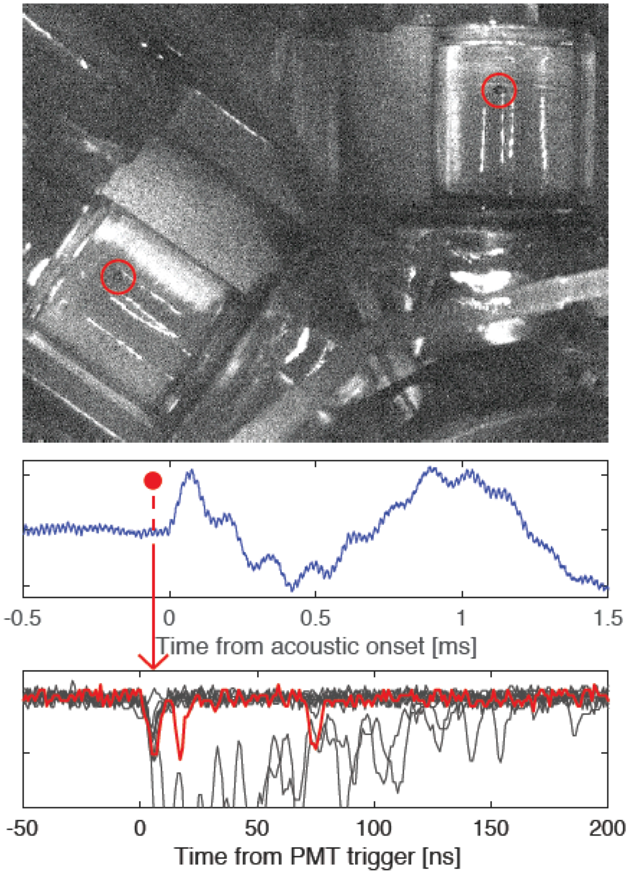


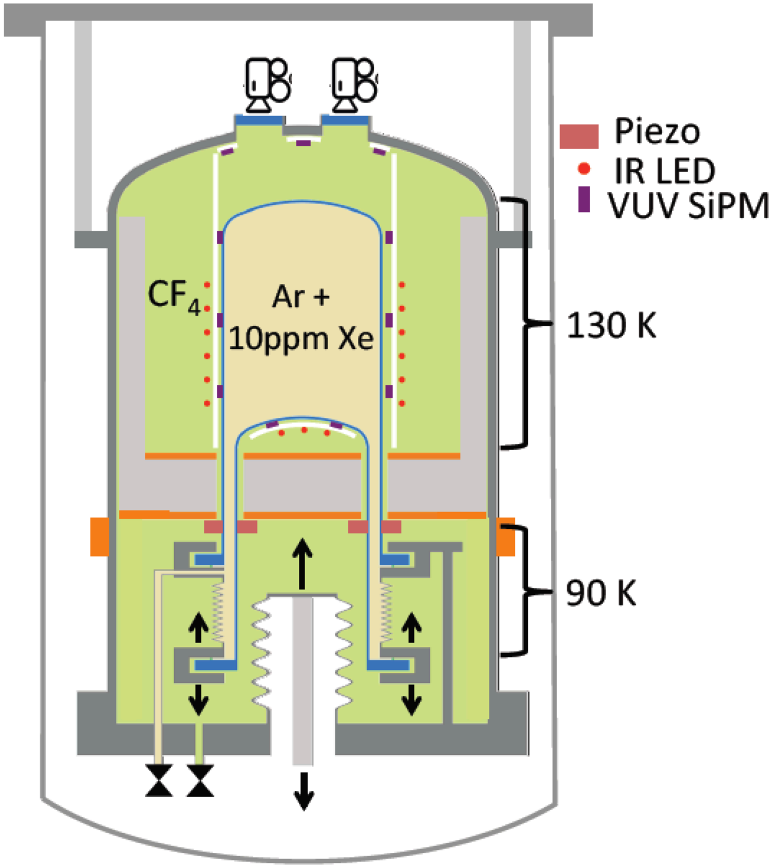
Inner plastic scintillator veto is highly effective against beam-related neutron backgrounds

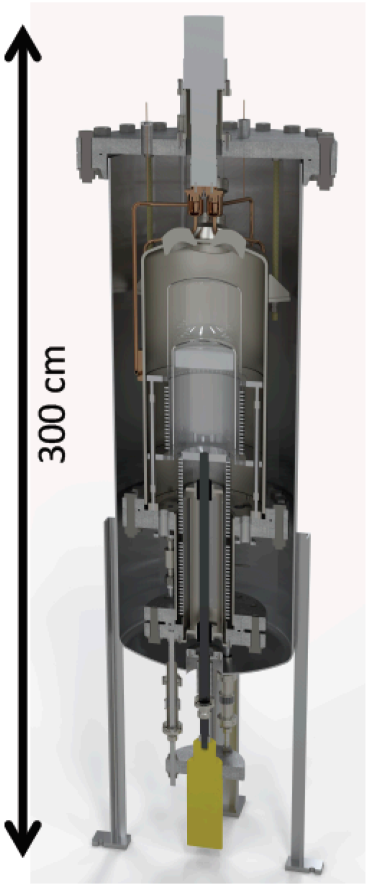


Moderately superheated scintillating bubble chambers

Phys. Rev. Lett. **118**, 231301 (2017)





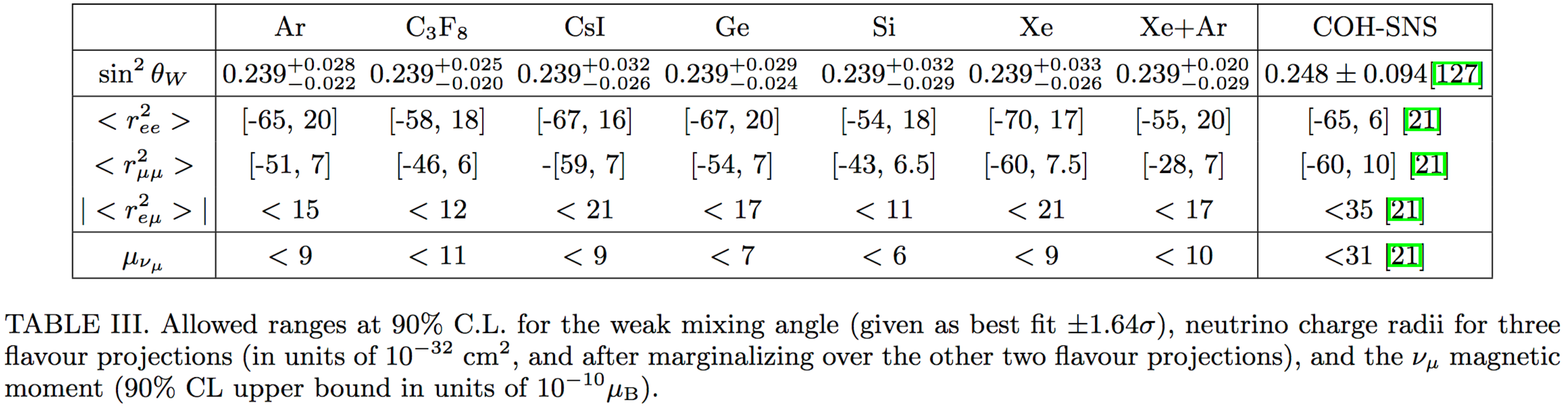


Lowest threshold, highest background discrimination of any NR detector.
10 kg device for CEvNS under construction at FNAL/Northwestern.

Sensitivity to ν properties will be hard to improve beyond ESS

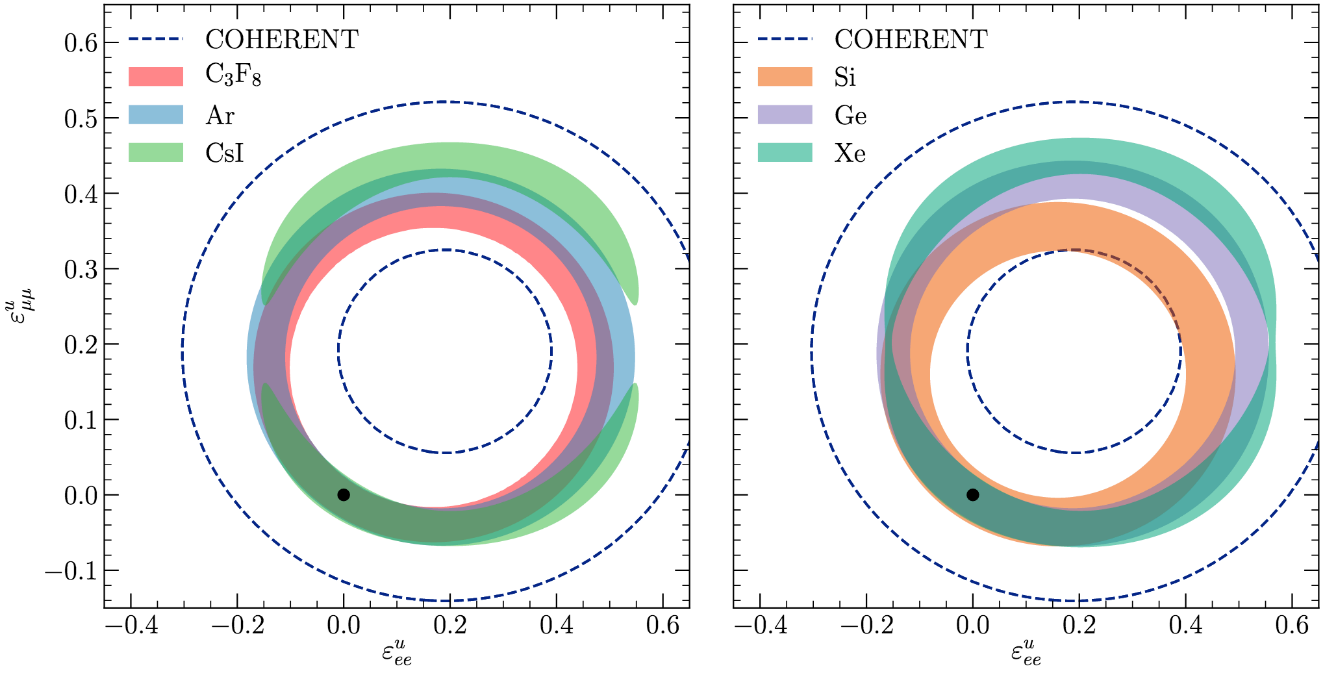
(limited by systematics only, statistical uncertainty is negligible at ESS)

JHEP 02 (2020) 123



	Ar	C_3F_8	CsI	Ge	Si	Xe	Xe+Ar	COH-SNS
$\sin^2\theta_W$	$0.239^{+0.028}_{-0.022}$	$0.239^{+0.025}_{-0.020}$	$0.239^{+0.032}_{-0.026}$	$0.239^{+0.029}_{-0.024}$	$0.239^{+0.032}_{-0.029}$	$0.239^{+0.033}_{-0.026}$	$0.239^{+0.020}_{-0.029}$	0.248 ± 0.094[127]
$< r^2_{ee} >$	[-65, 20]	[-58, 18]	[-67, 16]	[-67, 20]	[-54, 18]	[-70, 17]	[-55, 20]	[-65, 6] [21]
$< r^2_{\mu\mu} >$	[-51, 7]	[-46, 6]	-[59, 7]	[-54, 7]	[-43, 6.5]	[-60, 7.5]	[-28, 7]	[-60, 10] [21]
$\lvert < r^2_{e\mu} > \rvert$	< 15	< 12	< 21	< 17	< 11	< 21	< 17	<35 [21]
μ_{ν_μ}	< 9	< 11	< 9	< 7	< 6	< 9	< 10	<31 [21]

TABLE III. Allowed ranges at 90% C.L. for the weak mixing angle (given as best fit $\pm 1.64\sigma$), neutrino charge radii for three flavour projections (in units of 10^{-32} cm^2, and after marginalizing over the other two flavour projections), and the ν_μ magnetic moment (90% CL upper bound in units of $10^{-10}\mu_B$).

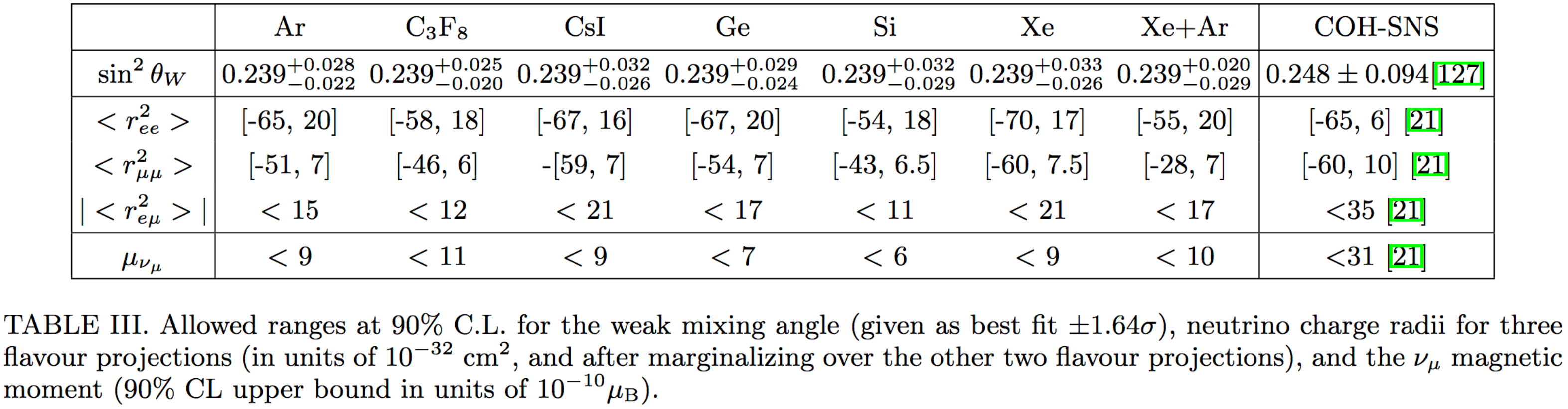


NSI, magnetic moment,
ν charge radius,
weak mixing angle,
sterile ν, DM candidates…
The list is long…

Sensitivity to ν properties will be hard to improve beyond ESS

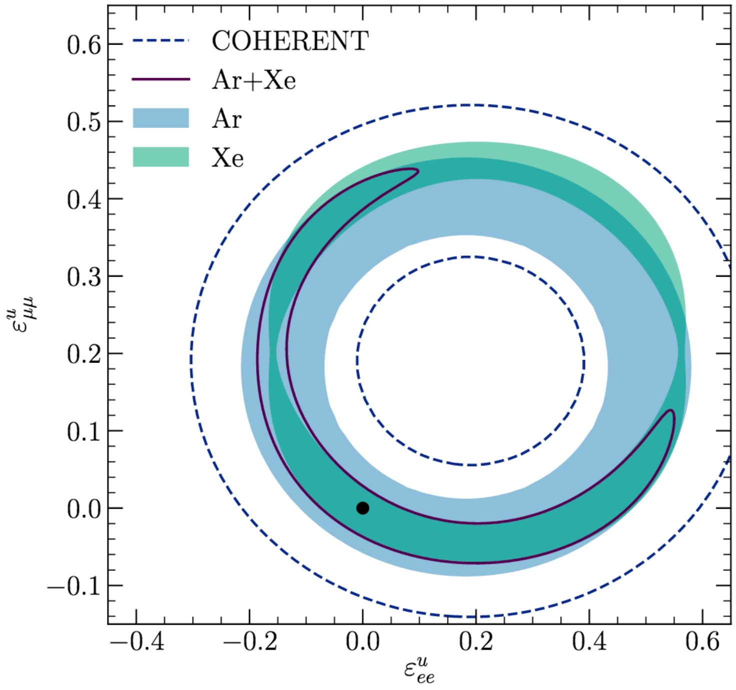
(limited by systematics only, statistical uncertainty is negligible at ESS)

JHEP 02 (2020) 123



	Ar	C_3F_8	CsI	Ge	Si	Xe	Xe+Ar	COH-SNS
$\sin^2\theta_W$	$0.239^{+0.028}_{-0.022}$	$0.239^{+0.025}_{-0.020}$	$0.239^{+0.032}_{-0.026}$	$0.239^{+0.029}_{-0.024}$	$0.239^{+0.032}_{-0.029}$	$0.239^{+0.033}_{-0.026}$	$0.239^{+0.020}_{-0.029}$	0.248 ± 0.094[127]
$< r^2_{ee} >$	[-65, 20]	[-58, 18]	[-67, 16]	[-67, 20]	[-54, 18]	[-70, 17]	[-55, 20]	[-65, 6] [21]
$< r^2_{\mu\mu} >$	[-51, 7]	[-46, 6]	-[59, 7]	[-54, 7]	[-43, 6.5]	[-60, 7.5]	[-28, 7]	[-60, 10] [21]
$\lvert < r^2_{e\mu} > \rvert$	< 15	< 12	< 21	< 17	< 11	< 21	< 17	<35 [21]
μ_{ν_μ}	< 9	< 11	< 9	< 7	< 6	< 9	< 10	<31 [21]

TABLE III. Allowed ranges at 90% C.L. for the weak mixing angle (given as best fit $\pm 1.64\sigma$), neutrino charge radii for three flavour projections (in units of 10^{-32} cm^2, and after marginalizing over the other two flavour projections), and the ν_μ magnetic moment (90% CL upper bound in units of $10^{-10}\mu_B$).



Multiple (small) detectors allow for improved sensitivity
(and redundancy in testing anomalies)

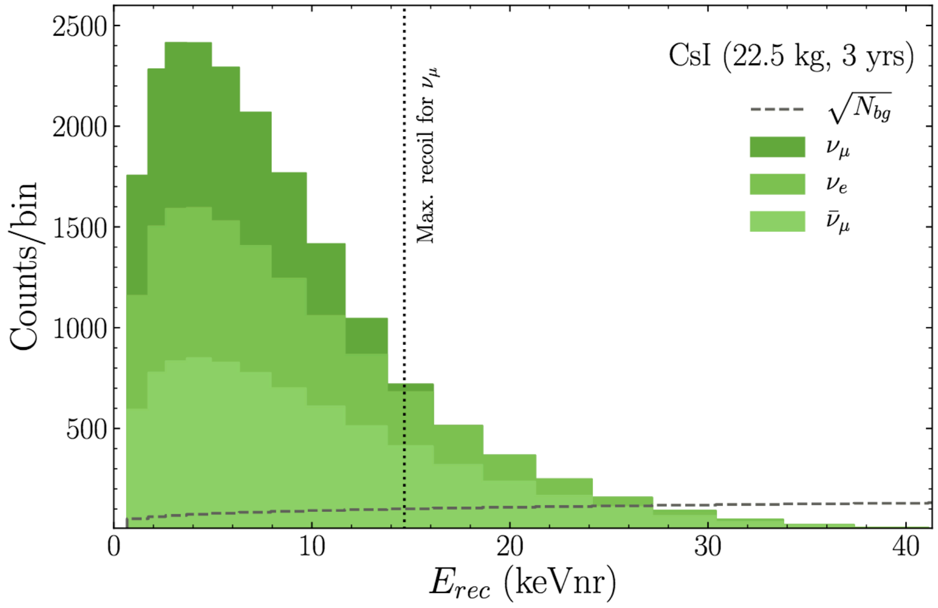
Sensitivity to ν properties will be hard to improve beyond ESS

(limited by systematics only, statistical uncertainty is negligible at ESS)

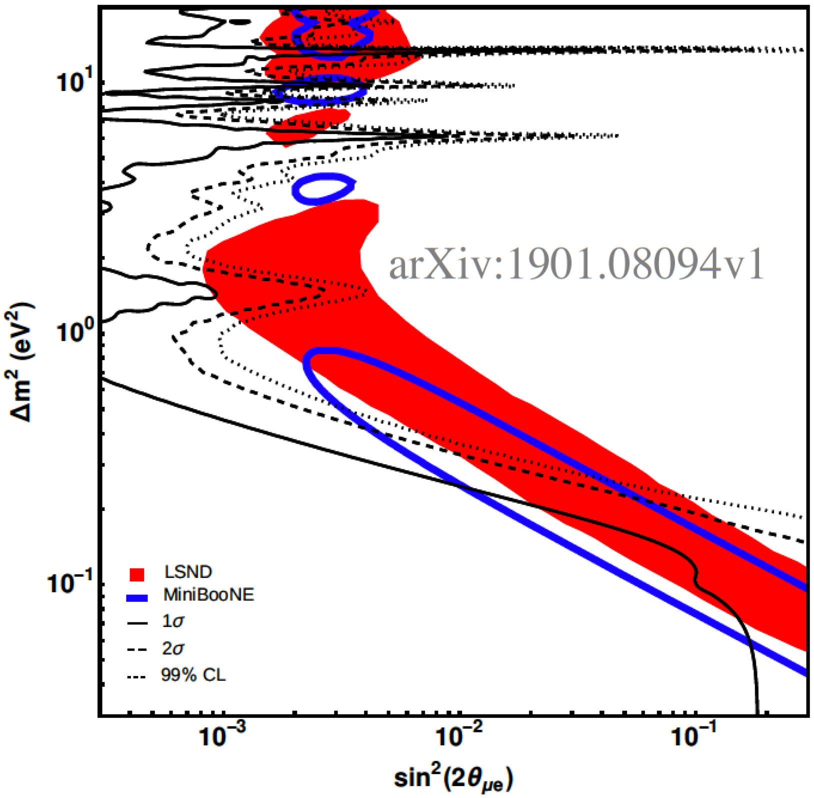
Sobering comparison:
8,000 CEνNS events/yr from 22 kg cryo-CsI @ ESS
vs. 3,000 from 750 kg LAr @ SNS

arXiv:1911.00762v2

arXiv:1911.06422v1



Also, ~1 keV CsI vs ~20 keV LAr threshold
(new physics from CEνNS concentrates at low energy)

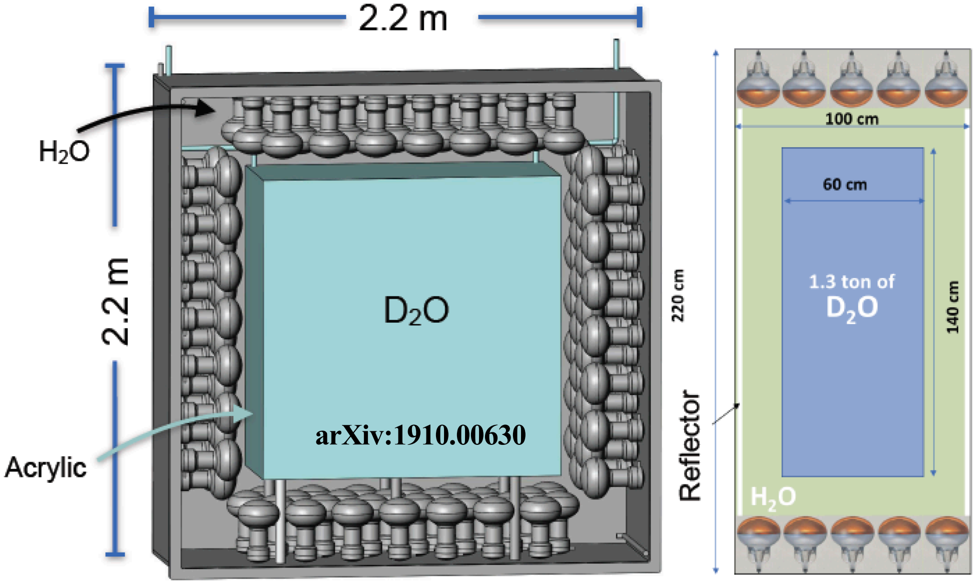


Searches for sterile ν's via CEνNS:
"direct detection" of the undetectable...

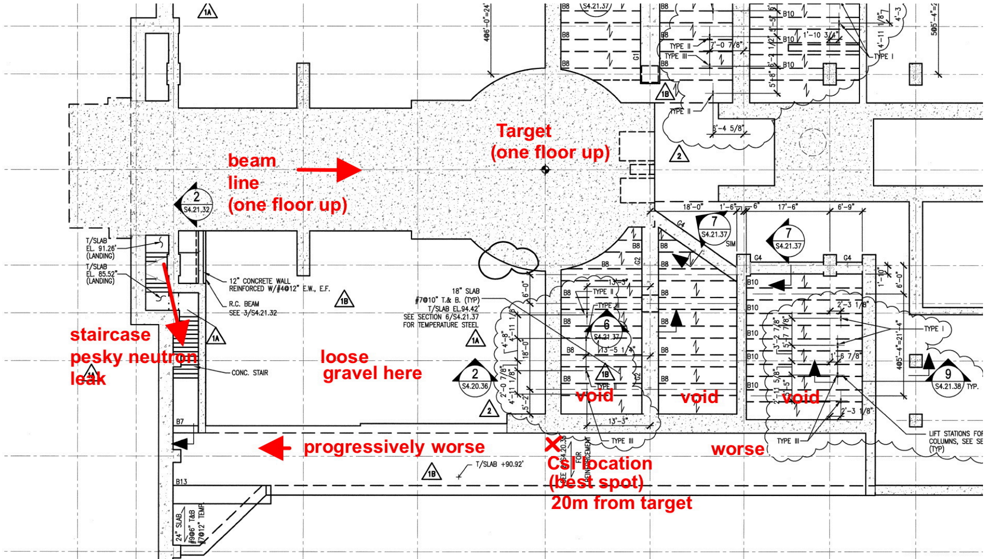
Much work to do before ESS POT!

- CEνNS detector construction/modifications
- Quenching Factor studies
- neutron bckg measurements/simulations (siting @ ESS)
- neutrino flux characterization
- applications (phenomenology)

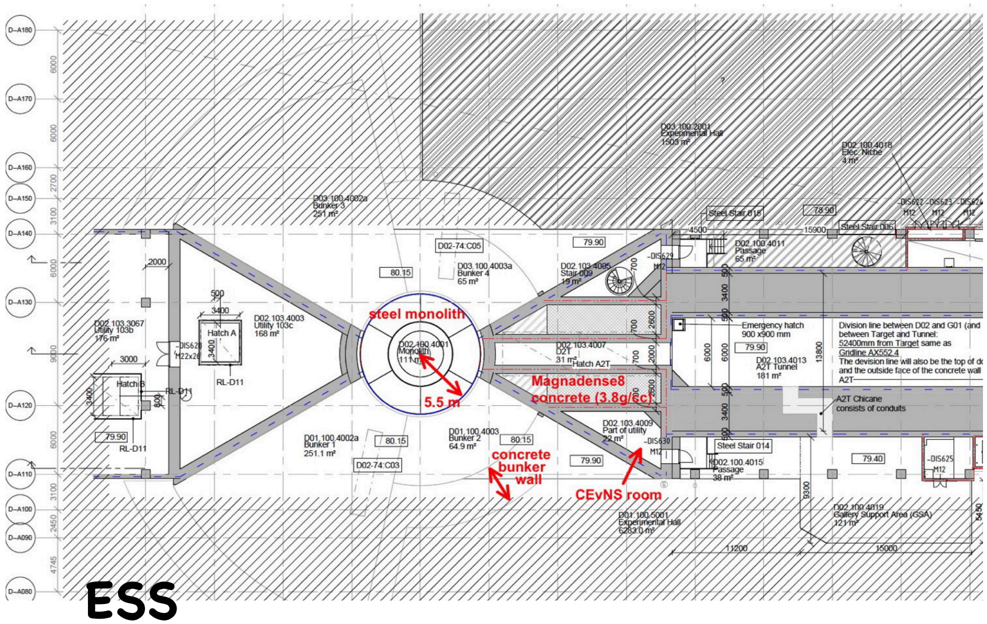
$\nu_e + d \rightarrow p + p + e^-$ 5.5×10



Darryl Dowling, ORNL



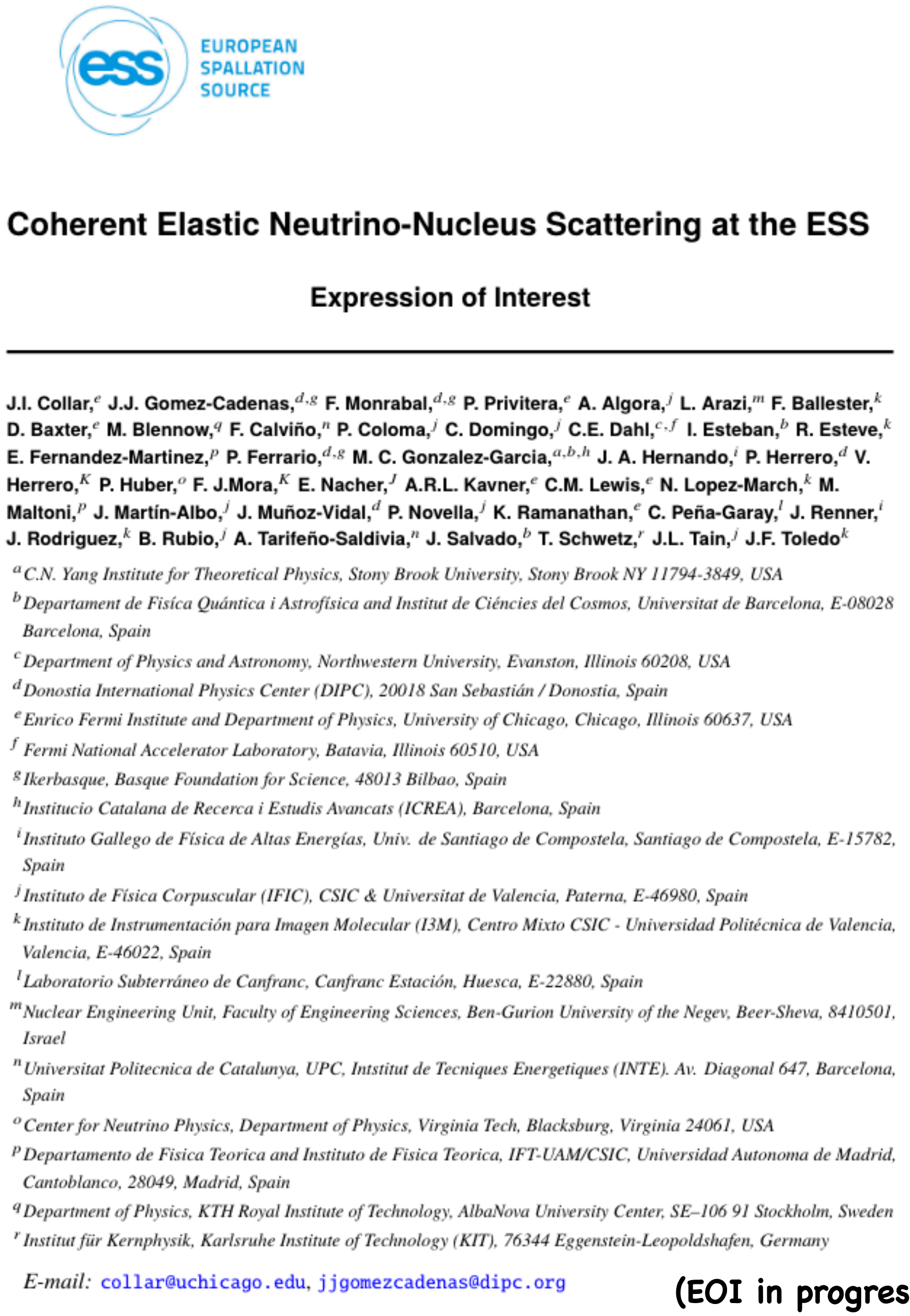
SNS



ESS

Much work to do before ESS POT!

- CEνNS detector construction/modifications
- Quenching Factor studies
- neutron bckg measurements/simulations
  (siting @ ESS)
- neutrino flux characterization
- applications (phenomenology)



EUROPEAN
SPALLATION
SOURCE

Coherent Elastic Neutrino-Nucleus Scattering at the ESS

Expression of Interest

J.I. Collar,[e] J.J. Gomez-Cadenas,[d,g] F. Monrabal,[d,g] P. Privitera,[e] A. Algora,[j] L. Arazi,[m] F. Ballester,[k] D. Baxter,[e] M. Blennow,[q] F. Calviño,[n] P. Coloma,[j] C. Domingo,[j] C.E. Dahl,[c,f] I. Esteban,[b] R. Esteve,[k] E. Fernandez-Martinez,[p] P. Ferrario,[d,g] M. C. Gonzalez-Garcia,[a,b,h] J. A. Hernando,[i] P. Herrero,[d] V. Herrero,[K] P. Huber,[o] F. J.Mora,[K] E. Nacher,[J] A.R.L. Kavner,[e] C.M. Lewis,[e] N. Lopez-March,[k] M. Maltoni,[p] J. Martín-Albo,[j] J. Muñoz-Vidal,[d] P. Novella,[j] K. Ramanathan,[e] C. Peña-Garay,[l] J. Renner,[i] J. Rodriguez,[k] B. Rubio,[j] A. Tarifeño-Saldivia,[n] J. Salvado,[b] T. Schwetz,[r] J.L. Tain,[j] J.F. Toledo[k]

[a] *C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook NY 11794-3849, USA*
[b] *Departament de Fisíca Quántica i Astrofísica and Institut de Ciéncies del Cosmos, Universitat de Barcelona, E-08028 Barcelona, Spain*
[c] *Department of Physics and Astronomy, Northwestern University, Evanston, Illinois 60208, USA*
[d] *Donostia International Physics Center (DIPC), 20018 San Sebastián / Donostia, Spain*
[e] *Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*
[f] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[g] *Ikerbasque, Basque Foundation for Science, 48013 Bilbao, Spain*
[h] *Institucio Catalana de Recerca i Estudis Avancats (ICREA), Barcelona, Spain*
[i] *Instituto Gallego de Física de Altas Energías, Univ. de Santiago de Compostela, Santiago de Compostela, E-15782, Spain*
[j] *Instituto de Física Corpuscular (IFIC), CSIC & Universitat de Valencia, Paterna, E-46980, Spain*
[k] *Instituto de Instrumentación para Imagen Molecular (I3M), Centro Mixto CSIC - Universidad Politécnica de Valencia, Valencia, E-46022, Spain*
[l] *Laboratorio Subterráneo de Canfranc, Canfranc Estación, Huesca, E-22880, Spain*
[m] *Nuclear Engineering Unit, Faculty of Engineering Sciences, Ben-Gurion University of the Negev, Beer-Sheva, 8410501, Israel*
[n] *Universitat Politecnica de Catalunya, UPC, Intstitut de Tecniques Energetiques (INTE). Av. Diagonal 647, Barcelona, Spain*
[o] *Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*
[p] *Departamento de Fisica Teorica and Instituto de Fisica Teorica, IFT-UAM/CSIC, Universidad Autonoma de Madrid, Cantoblanco, 28049, Madrid, Spain*
[q] *Department of Physics, KTH Royal Institute of Technology, AlbaNova University Center, SE–106 91 Stockholm, Sweden*
[r] *Institut für Kernphysik, Karlsruhe Institute of Technology (KIT), 76344 Eggenstein-Leopoldshafen, Germany*

E-mail: collar@uchicago.edu, jjgomezcadenas@dipc.org

(EOI in progress)