CEvNS at the European Spallation Source and beyond

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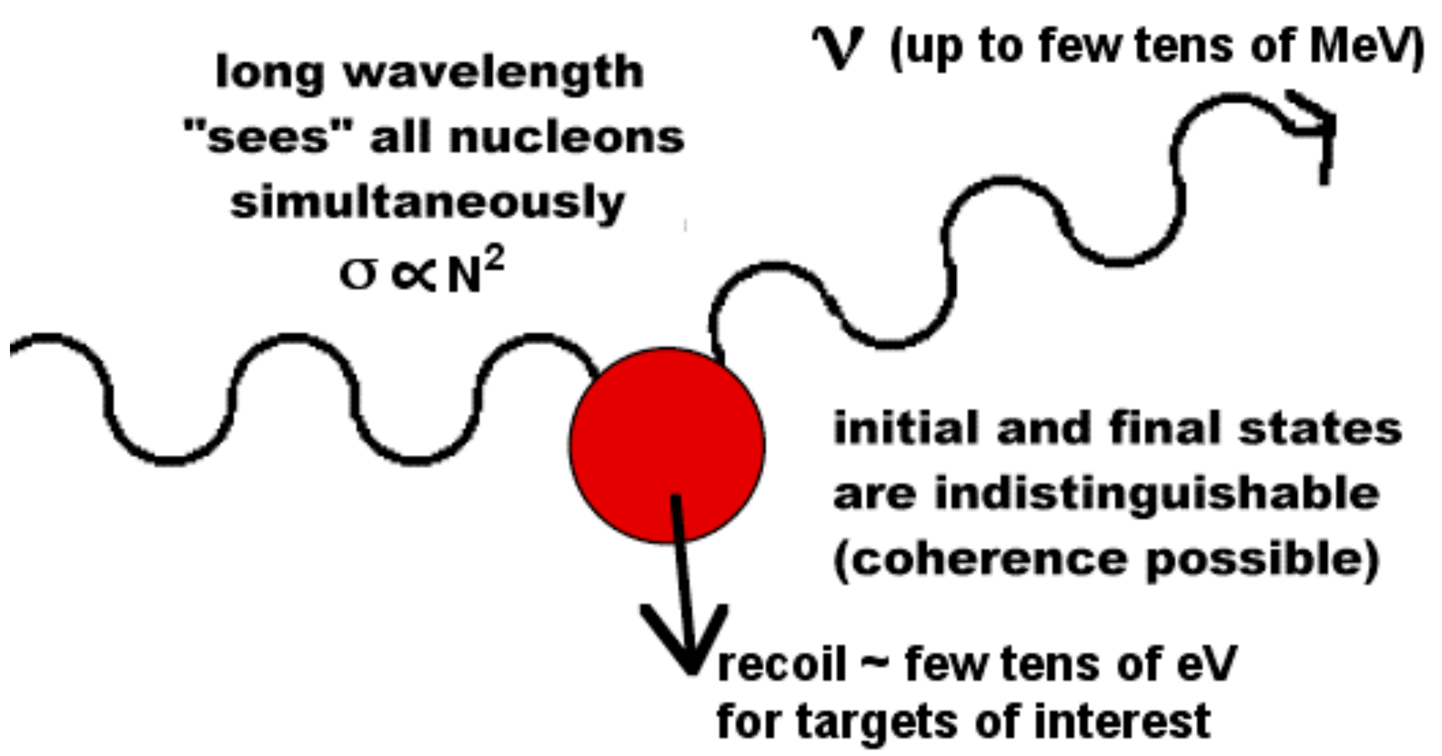
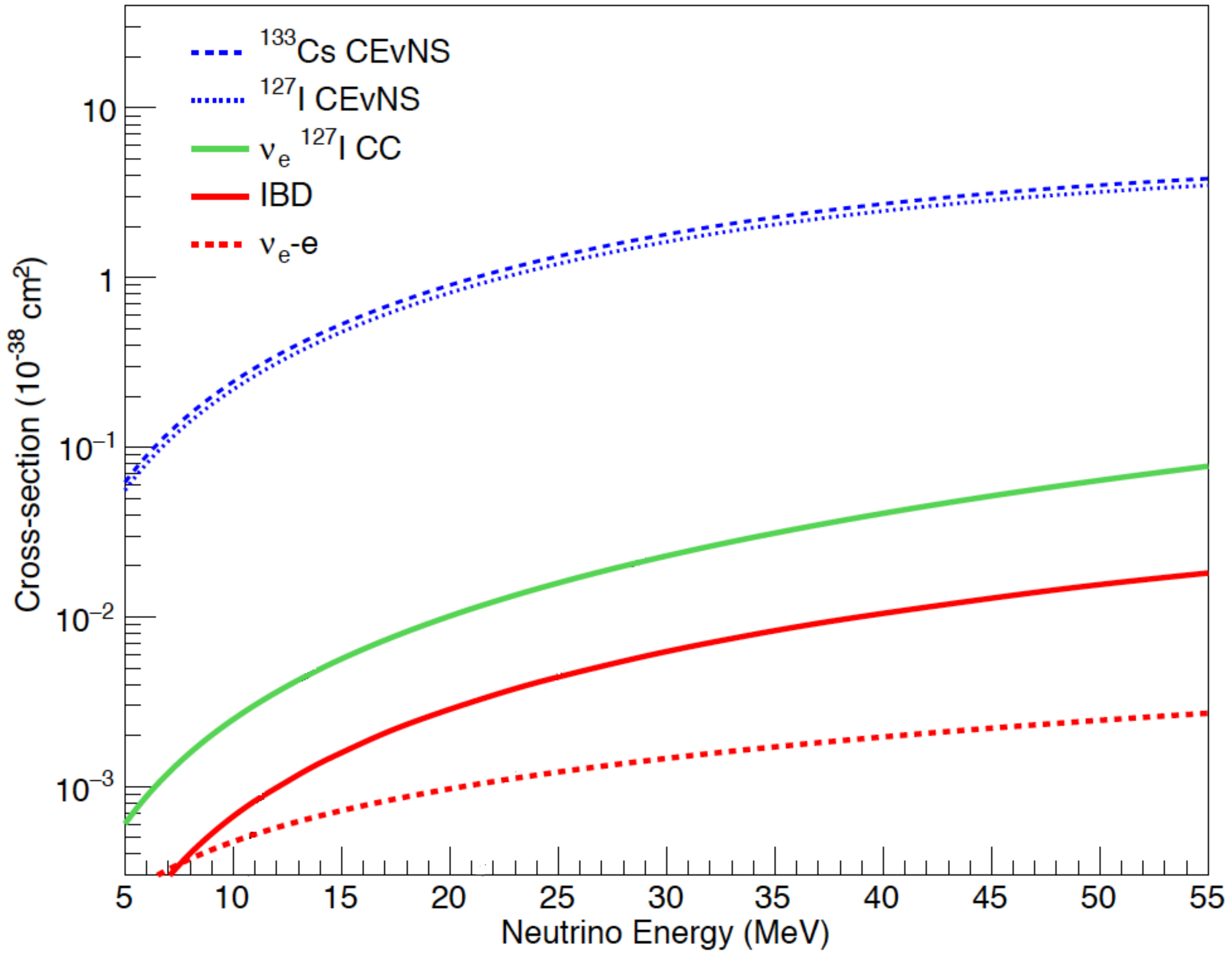
Coherent ν-N scattering

(CEνNS)

- Low-energy neutrinos can scatter off the atomic nucleus as a whole, via the weak neutral current.
- During this process the initial and final states of the nuclear target are indistinguishable, permitting a coherent contribution from all nucleons.
- The net result is a drastic enhancement to the cross-section, roughly proportional to the square of the number of neutrons present in the target nucleus.
- The single observable from CEνNS is a recoiling nucleus, which generates a signal in the few keV to sub-keV energy range.

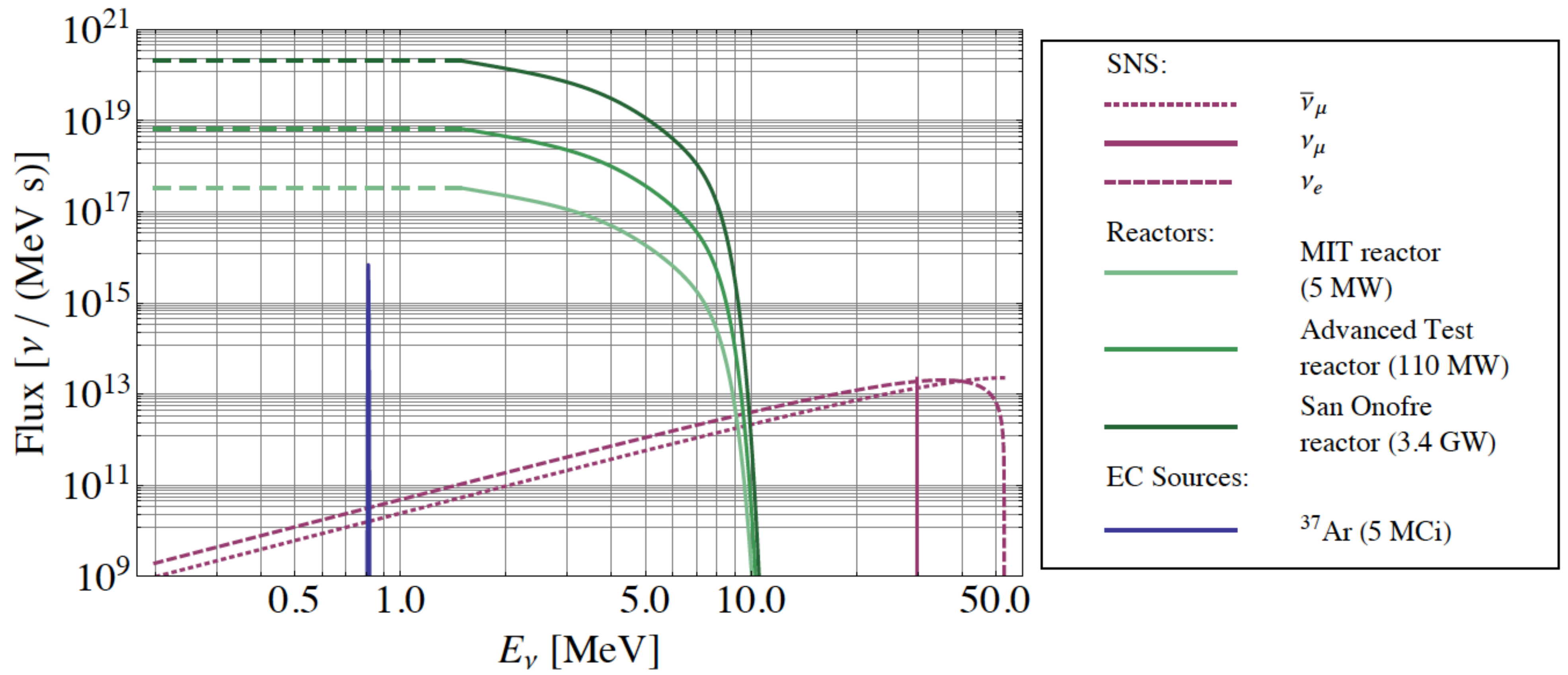




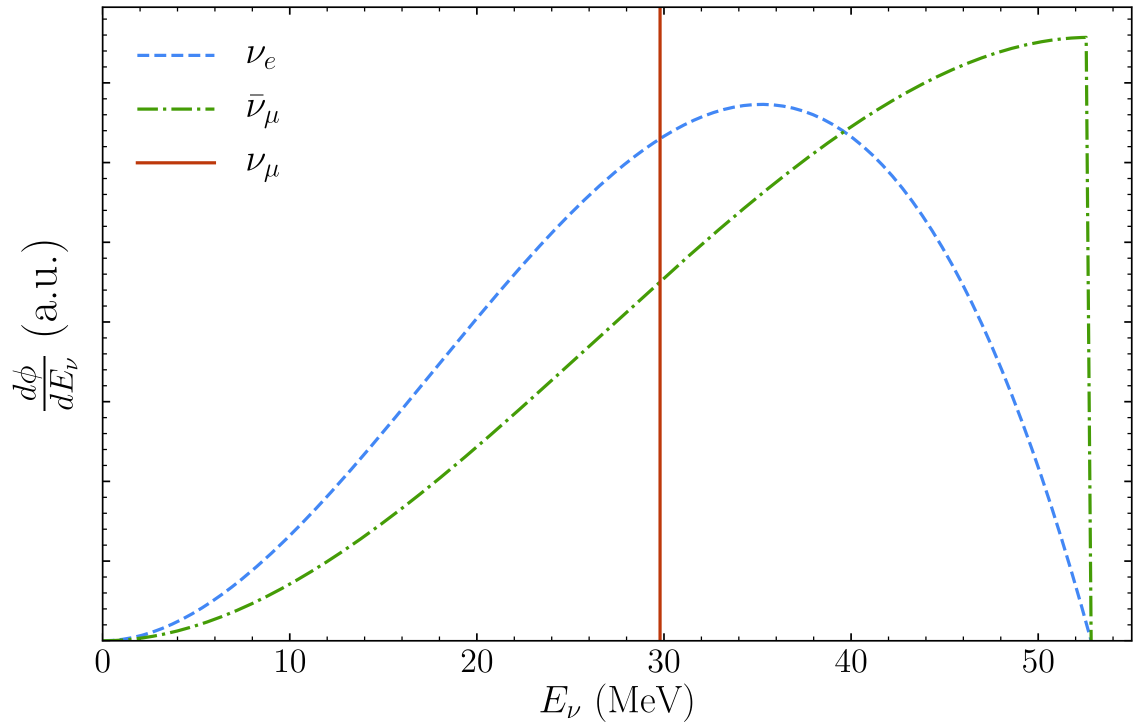
Coherent ν-N scattering

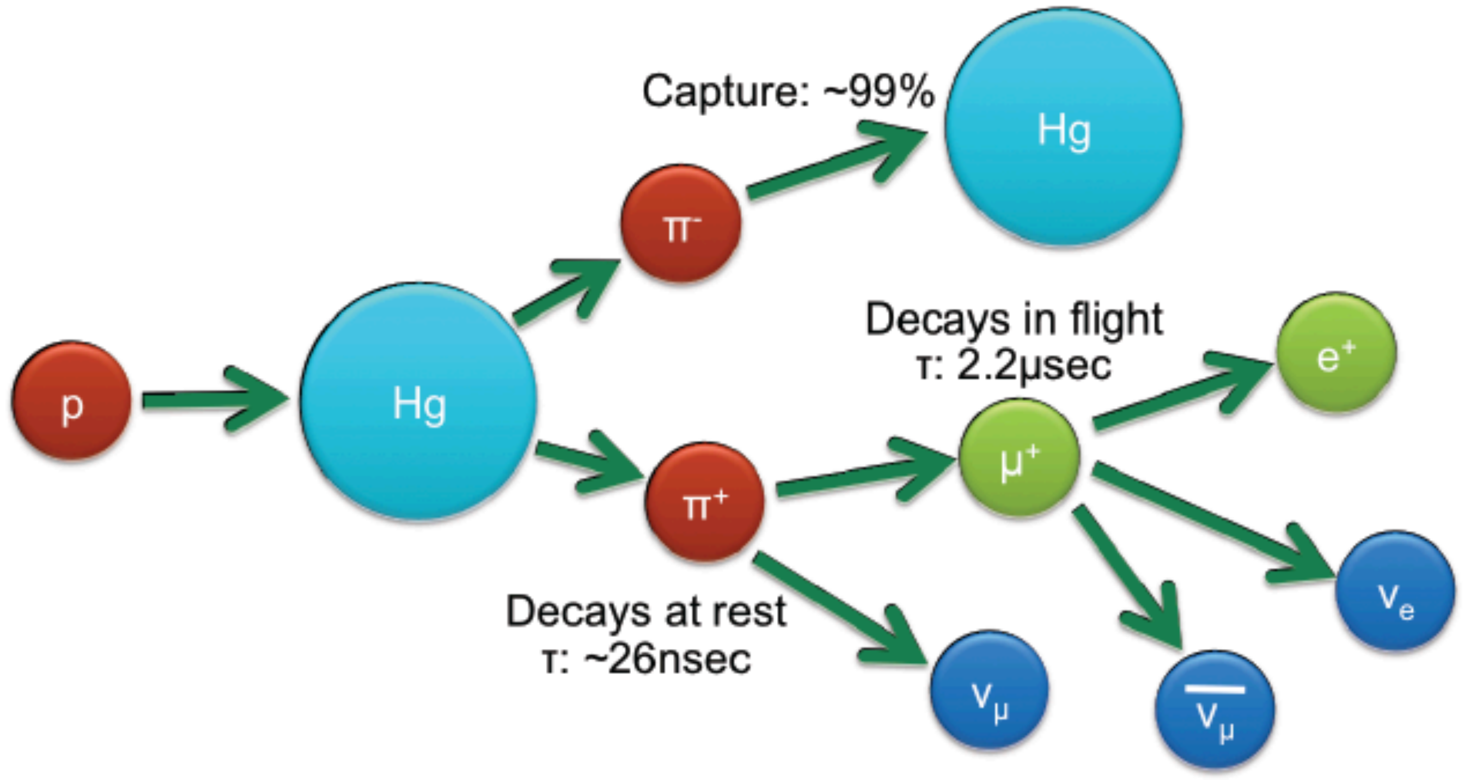
Sources

- CEνNS sources, must be sufficiently intense in yield, and low enough in neutrino energy so the coherence condition can be satisfied
- |Q|<1/R, where |Q| is the momentum transfer and R is the radius of the nucleus).
- Spallation sources produce nuclear recoils as energetic as allowed by the coherence condition, facilitating its detection.
- Pulsed beam timing reduced the impact of steady-state backgrounds



Enectali Figueroa-Feliciano / νMass 2013 / Milano





Coherent ν-N scattering

Detectors

- The single observable from CEvNS is a recoiling nucleus, which generates a signal in the few keV to sub-keV energy range.
- This requires detectors with ultra-low detection threshold. A common business with the Dark Matter Industry.
- Huge cross section (compare with all other neutrino interactions) allows “miniature detectors”

Coherent ν-N scattering

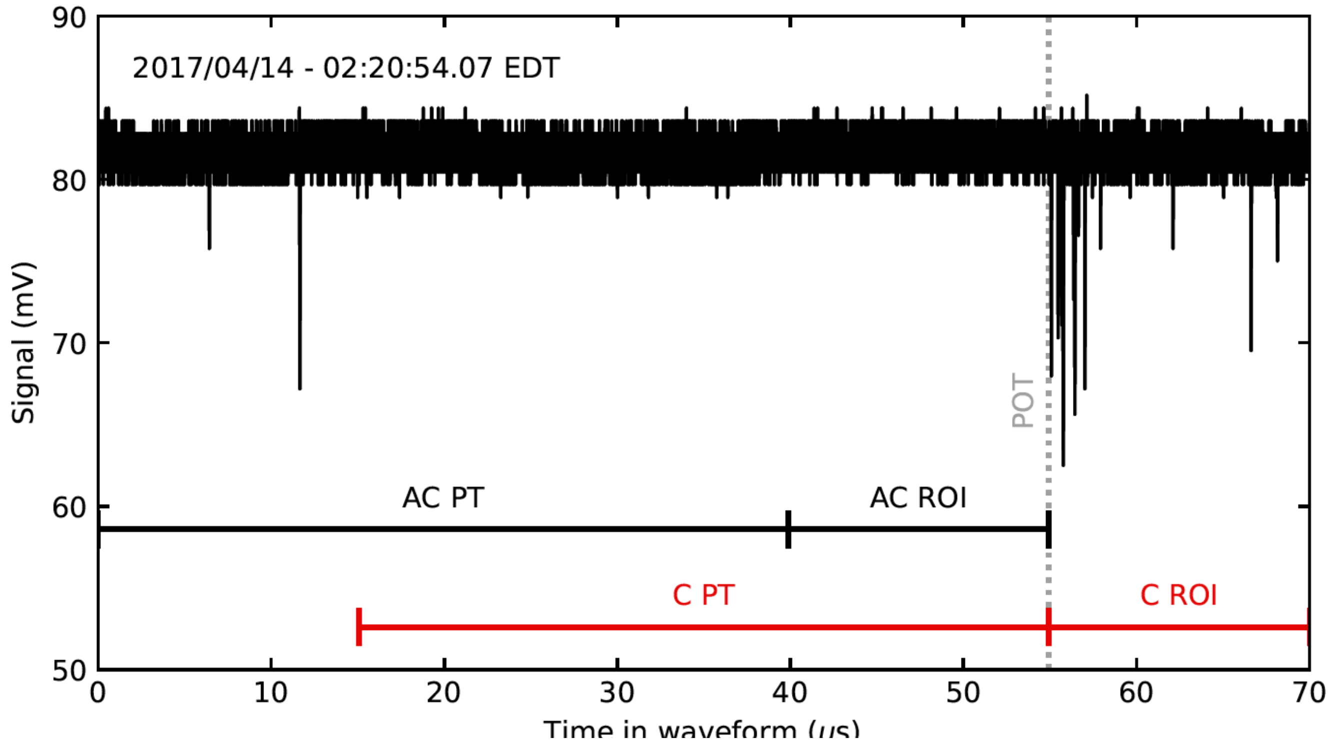
Detection

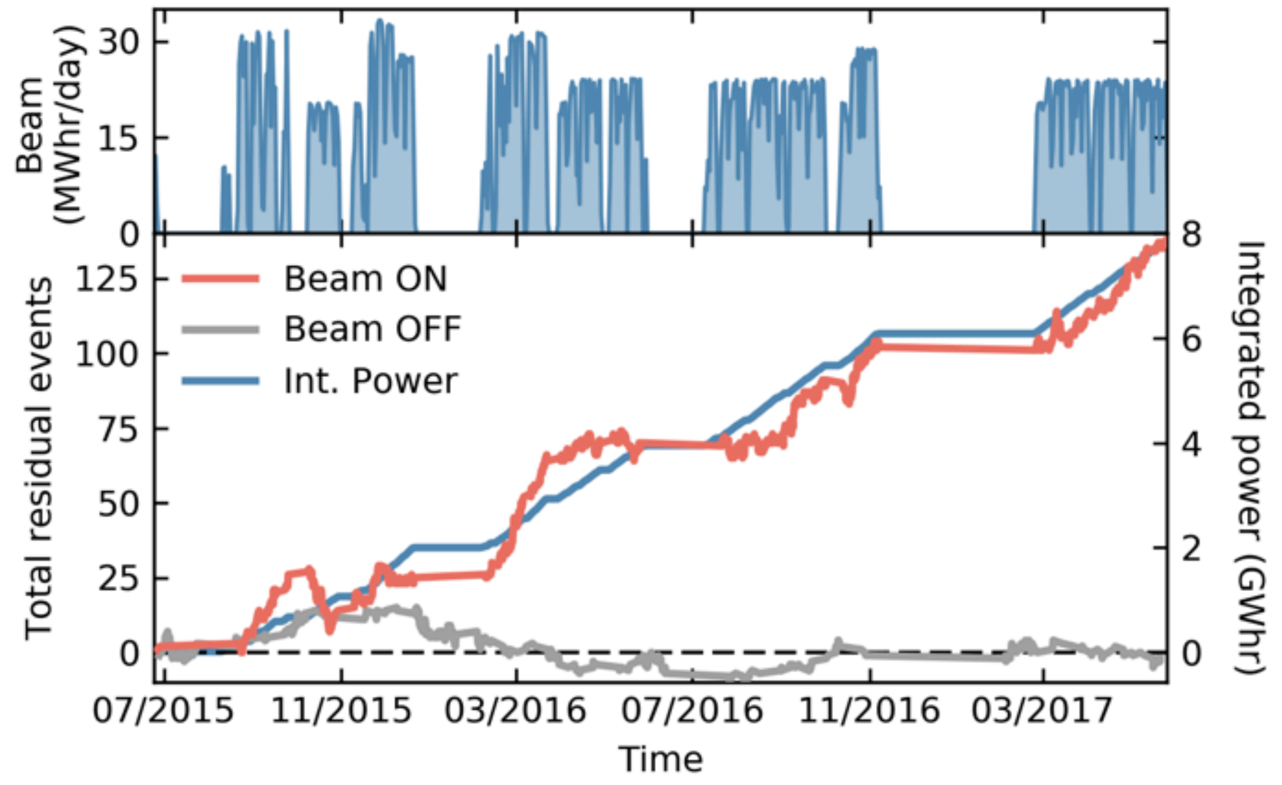
- CEvNS was experimentally demonstrated by the COHERENT experiment 43 years following its theoretical description, using the Spallation Neutron Source (SNS), at the Oak Ridge National Laboratory, USA.
- A low-background14.6 kg CsI[Na] scintillator was employed as the detecting medium.

First observation of CEνNS

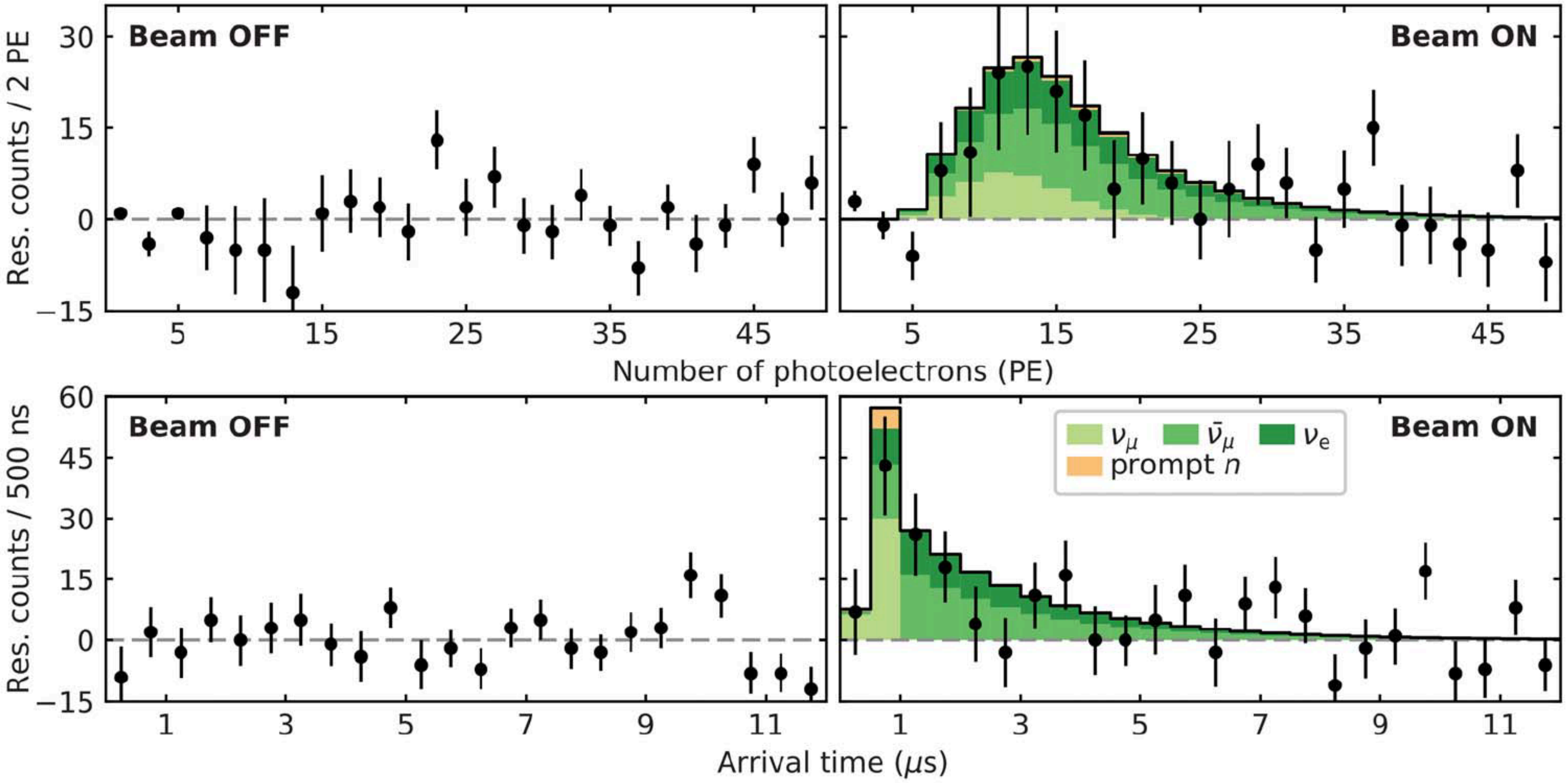
(6.7σ, 15 mo of data, ~3.5 yr total)

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

Coherent ν-N scattering: the physics case

- Non-standard neutrino interactions (NSI).
- Study of nuclear structure.
- Improving our understanding of neutrino electromagnetic properties
- Improving our understanding of the weak mixing angle
- Searches for sterile neutrinos
- Searches for new types of dark matter particles
- …

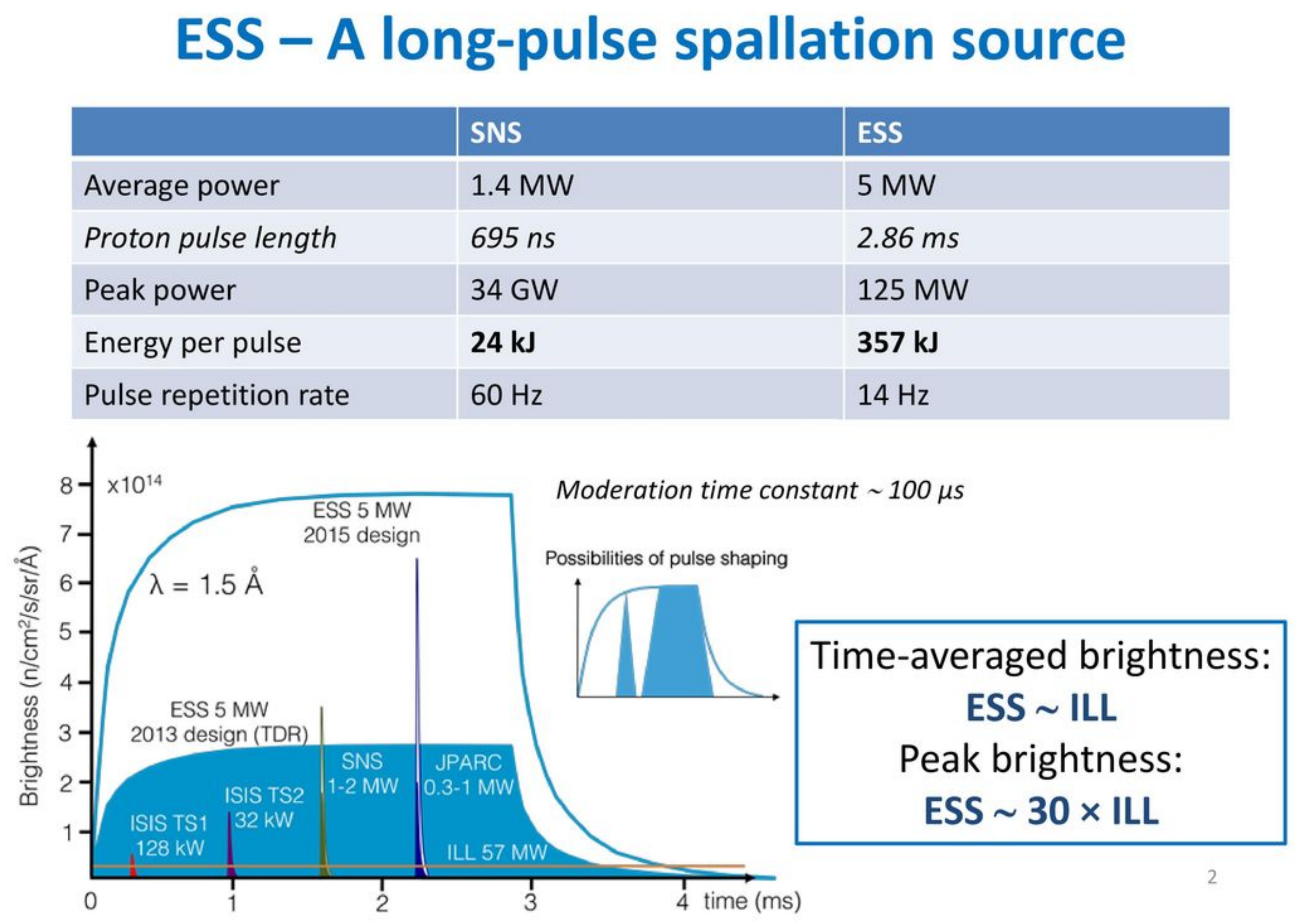
A new opportunity for CEvNS

The European Spallation Source (ESS)

- The ESS will combine the world's most powerful superconducting proton linac with an advanced hydrogen moderator, generating the most intense neutron beams for multi-disciplinary science.

- It will also provide an order of magnitude increase in neutrino flux with respect to the SNS.

- This will facilitate CEvNS measurements not limited in their sensitivity to new physics by poor signal statistics, while still employing non-intrusive, compact (few kg) neutrino detectors.



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

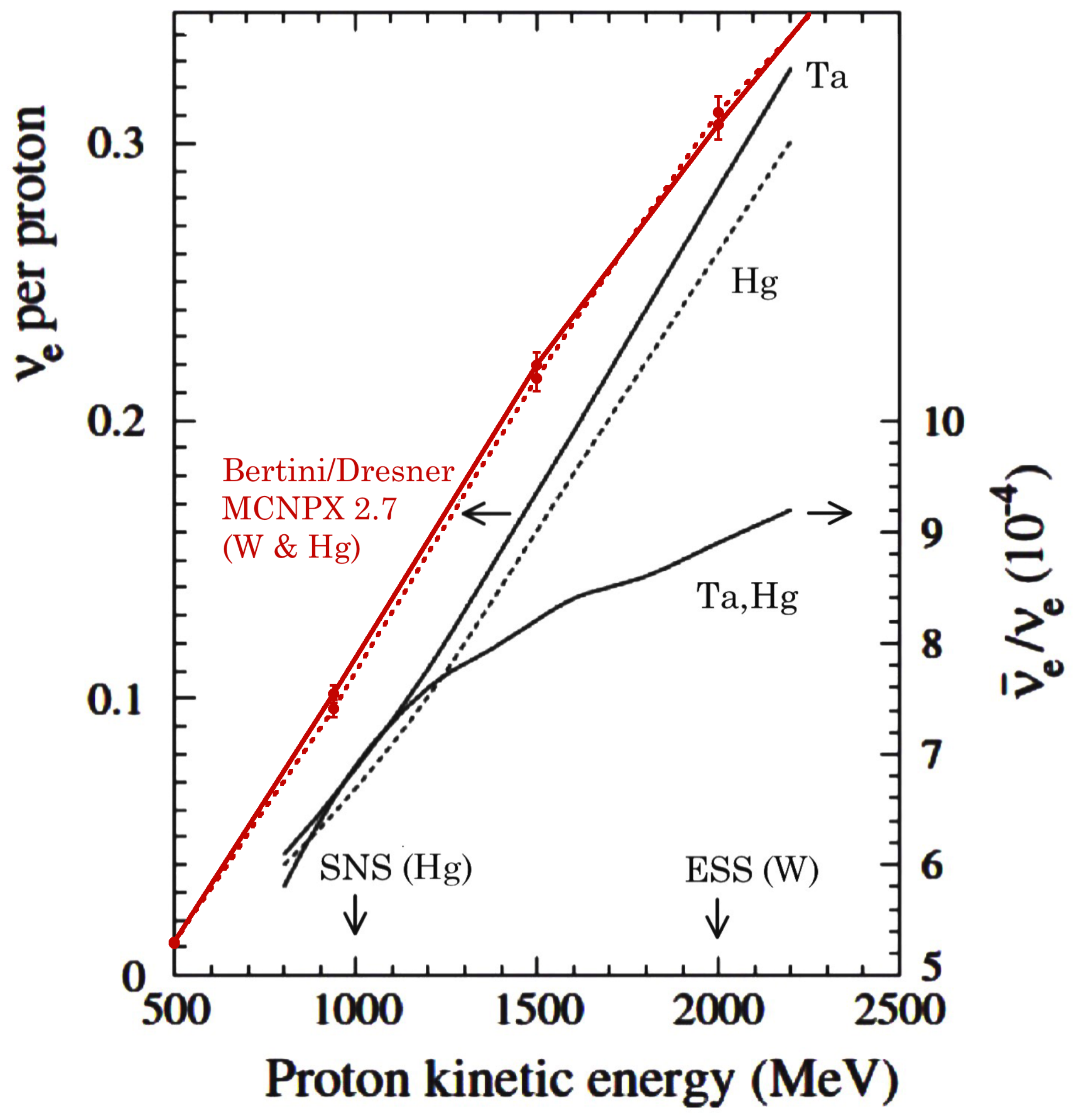
Moderation time constant ~ 100 μs

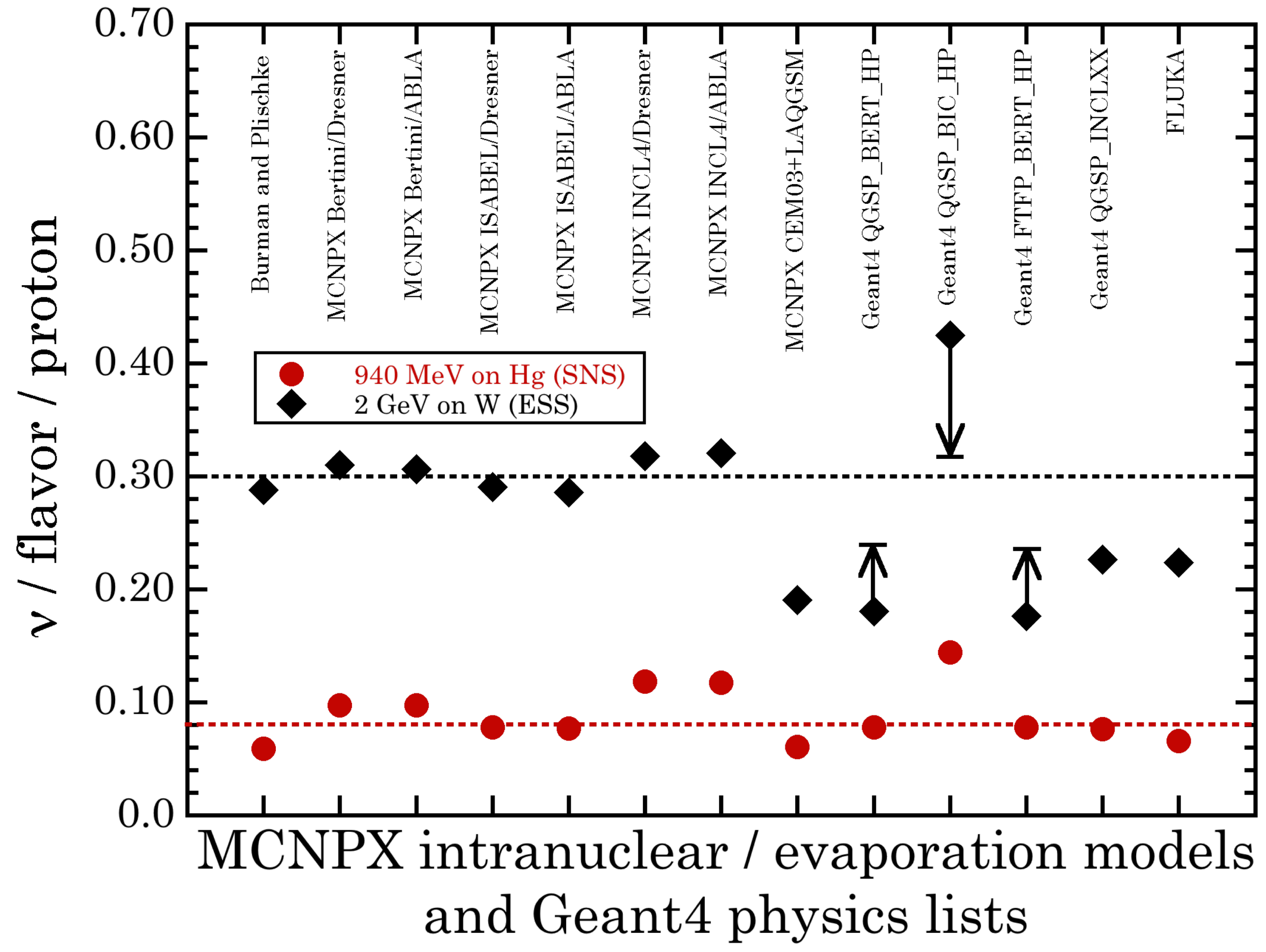
Time-averaged brightness:
ESS ~ ILL
Peak brightness:
ESS ~ 30 × ILL

A new opportunity for CEvNS

ESS vs SNS

- Neutrino flux depends on proton current and on proton energy. ν/p grows dramatically with Ep
- ν production @ ESS is x9.2 @ SNS
- Steady-state background can be subtracted.
- signal-to-background depends on square root of duty cycle (slightly better signal/bckg at ESS)

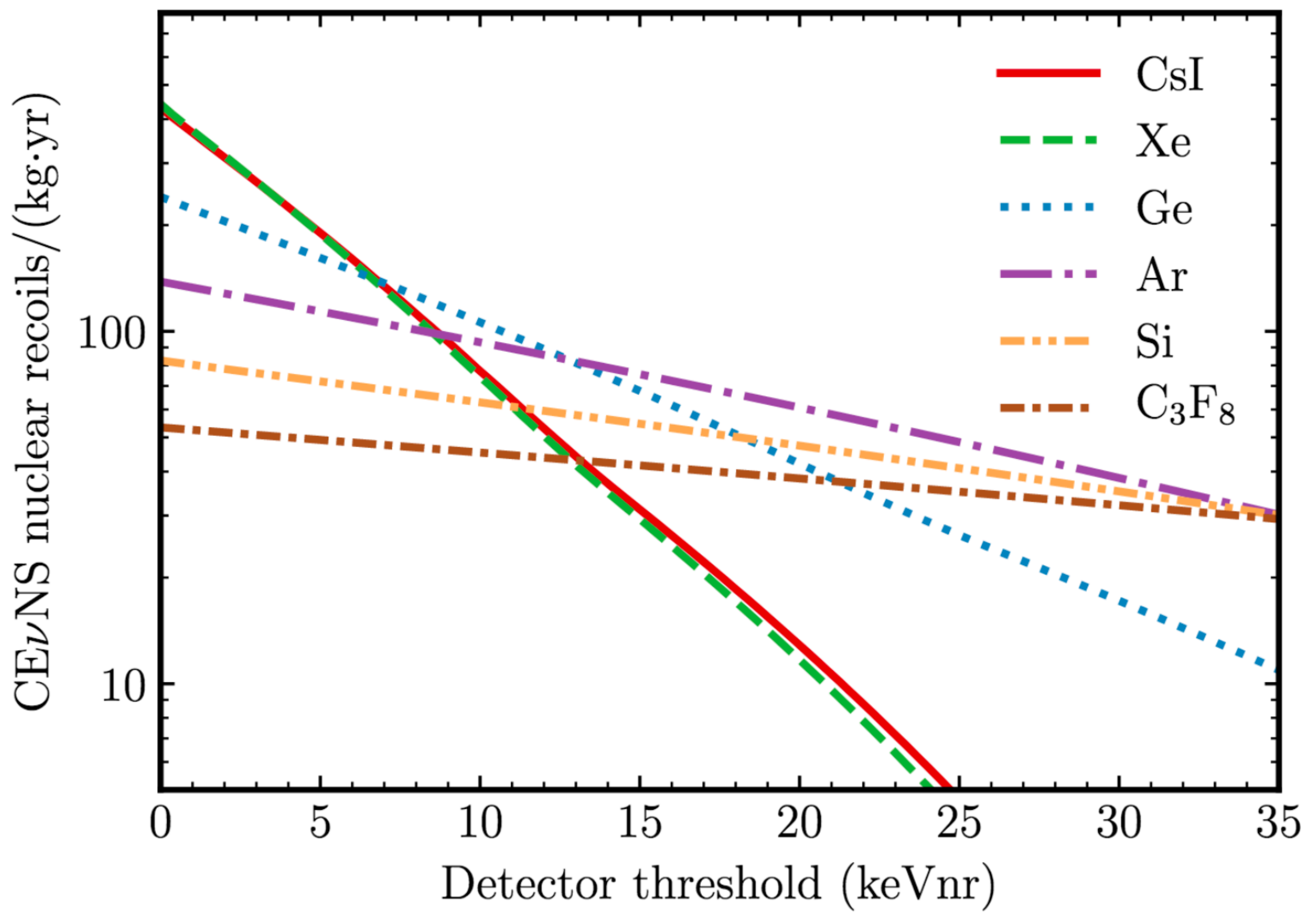




Detector technologies at ESS

A selection of examples

- Cryogenic (77 K) undoped CsI scintillator array
- Low-background CCD arrays with single-electron threshold
- High-pressure gaseous xenon (and other noble gases) chambers
- Low-threshold, multi-kg p-type point contact germanium detectors
- Moderately superheated liquids



- Technologies sensitive to 1 keVnr nuclear recoils
- Interesting physics concentrates at low-E (e.g. n magnetic moment). Also, maximum statistics.

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

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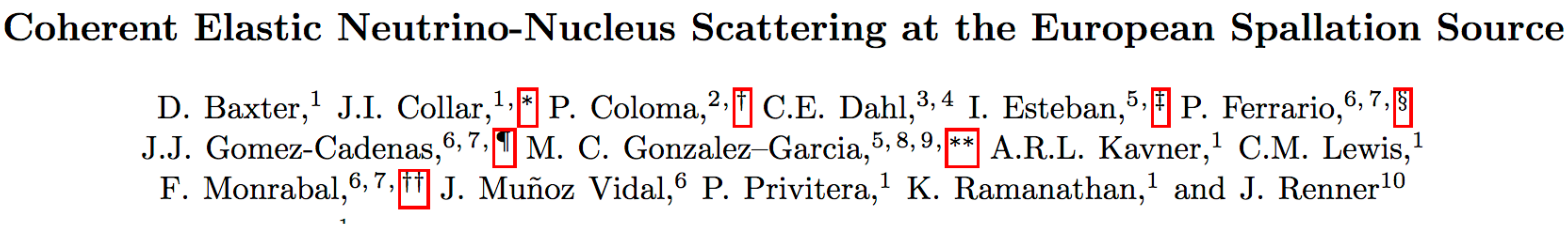

Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

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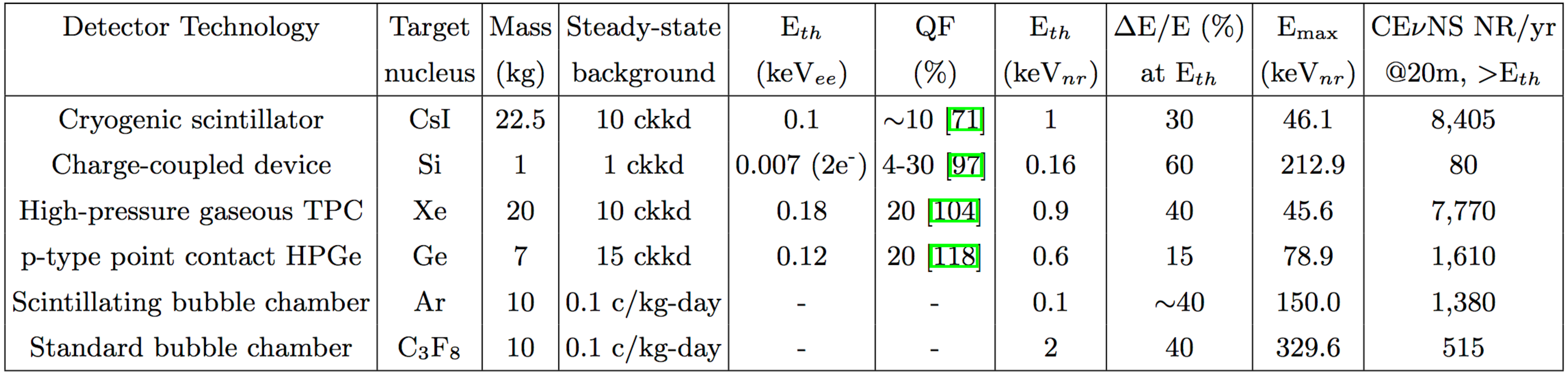
F. Monrabal,[6,7,††] J. Muñoz Vidal,[6] P. Privitera,[1] K. Ramanathan,[1] and J. Renner[10]

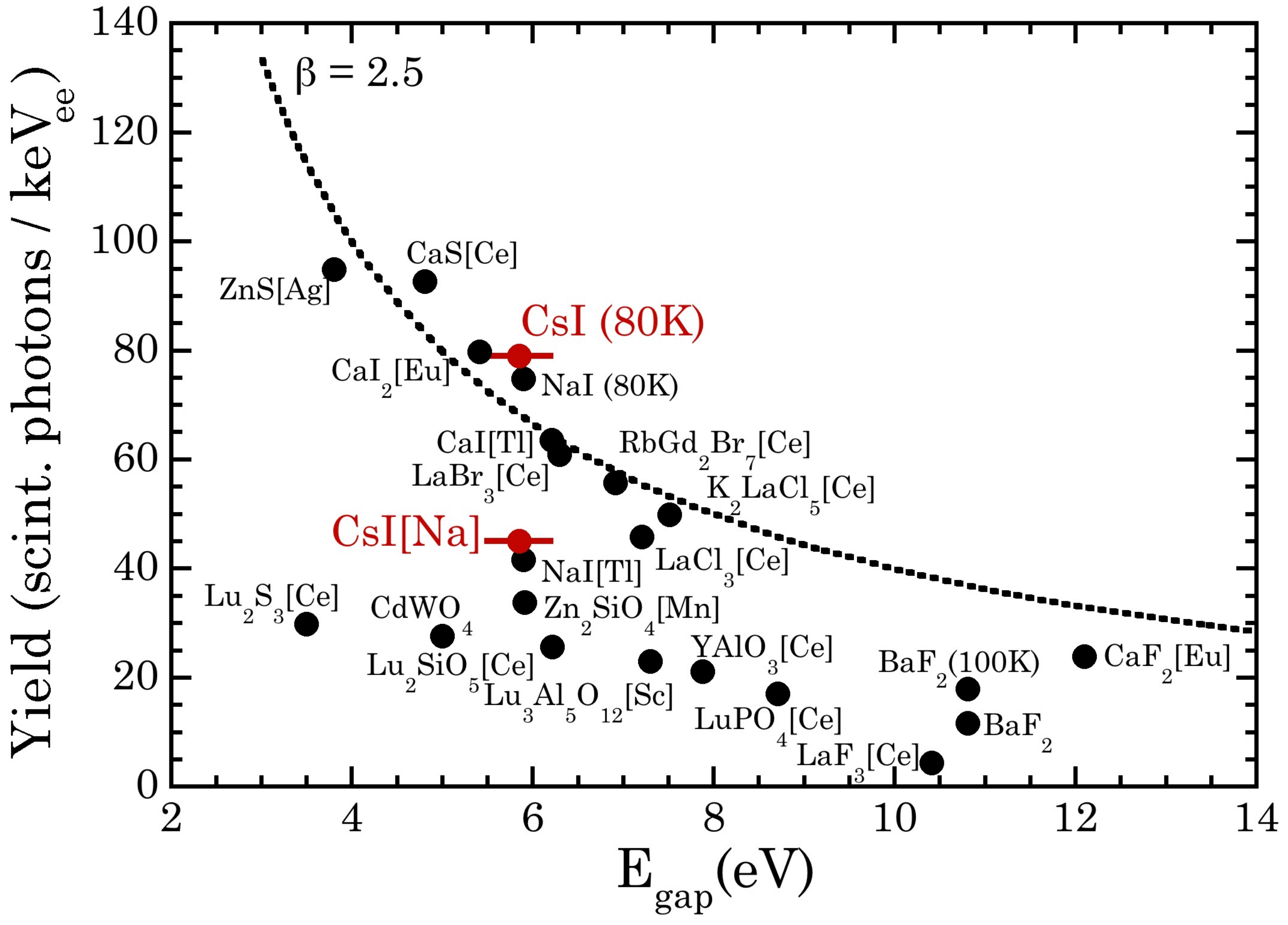


Detector Technology	Target nucleus	Mass (kg)	Steady-state background	E_{th} (keV_{ee})	QF (%)	E_{th} (keV_{nr})	$\Delta E/E$ (%) at E_{th}	E_{max} (keV_{nr})	CEνNS NR/yr @20m, $>E_{th}$
Cryogenic scintillator	CsI	22.5	10 ckkd	0.1	~10 [71]	1	30	46.1	8,405
Charge-coupled device	Si	1	1 ckkd	0.007 ($2e^-$)	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

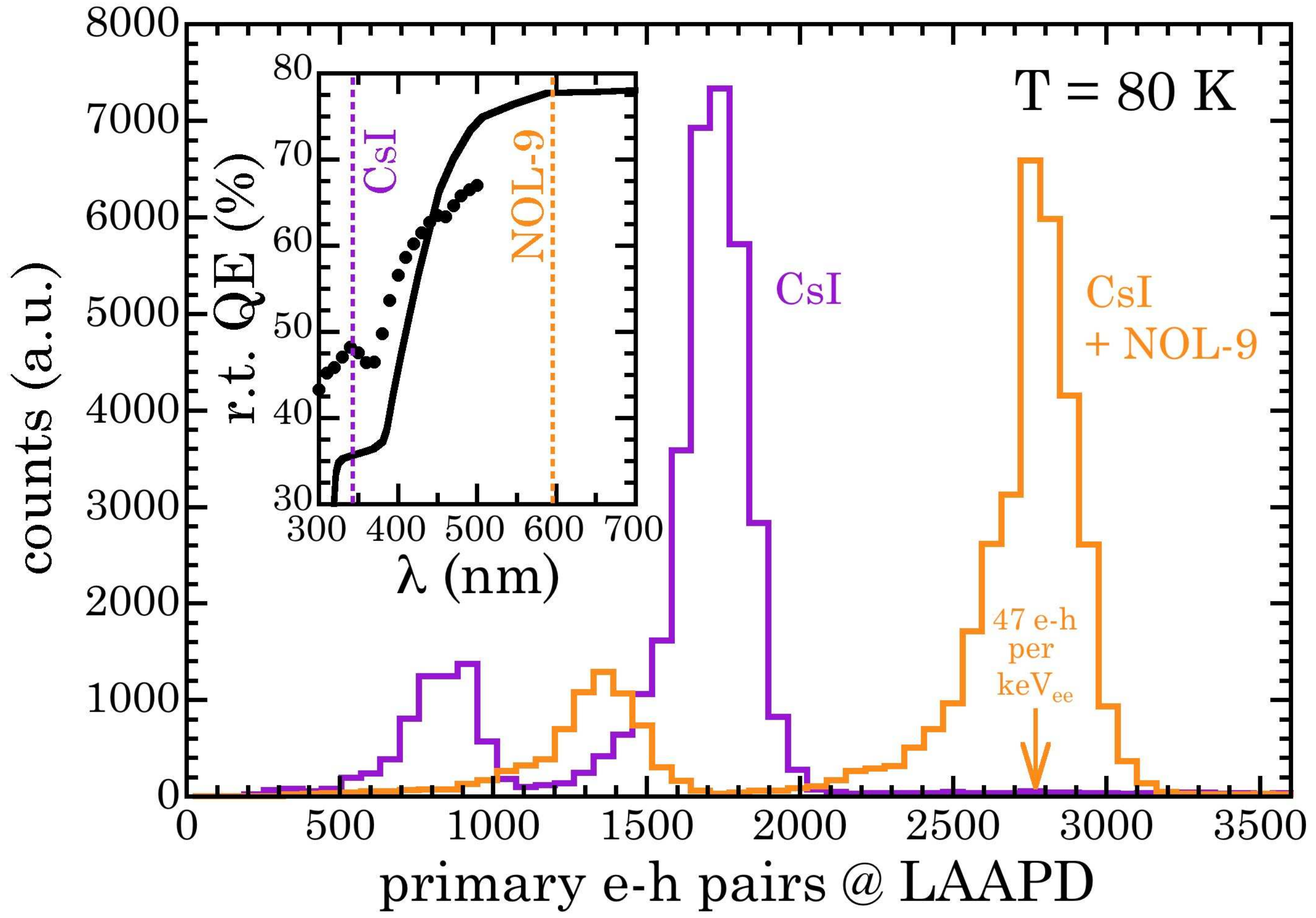
Cryogenic (77 K) undoped CsI scintillator array

- Pure CsI operated at liquid nitrogen temperature exhibits a light yield in the range 80-125 photons per keV

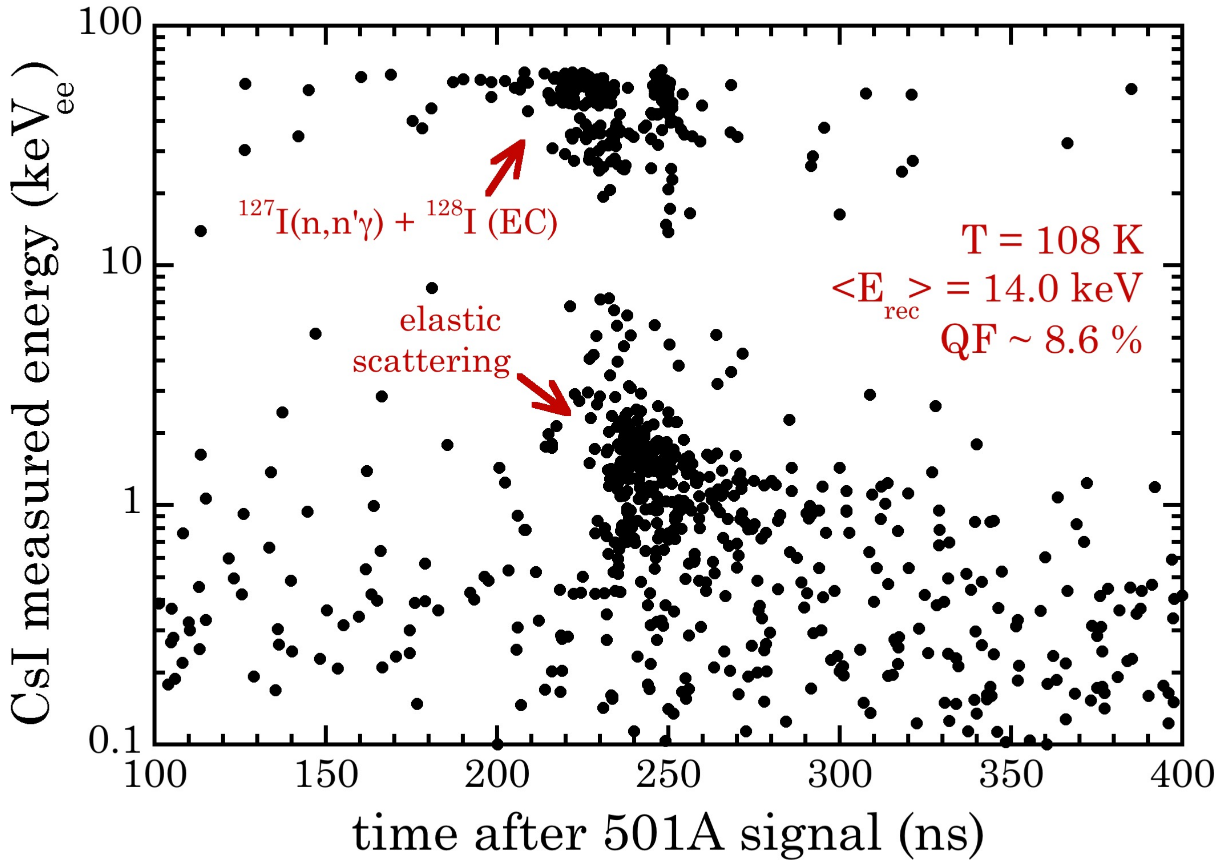
- Provided that a good quantum efficiency (QE) in the light sensor is achieved, this can facilitate the detection of low energy signals, with optimal resolution.



- **Light yield of scintillators and phosphors as a function of bandgap**



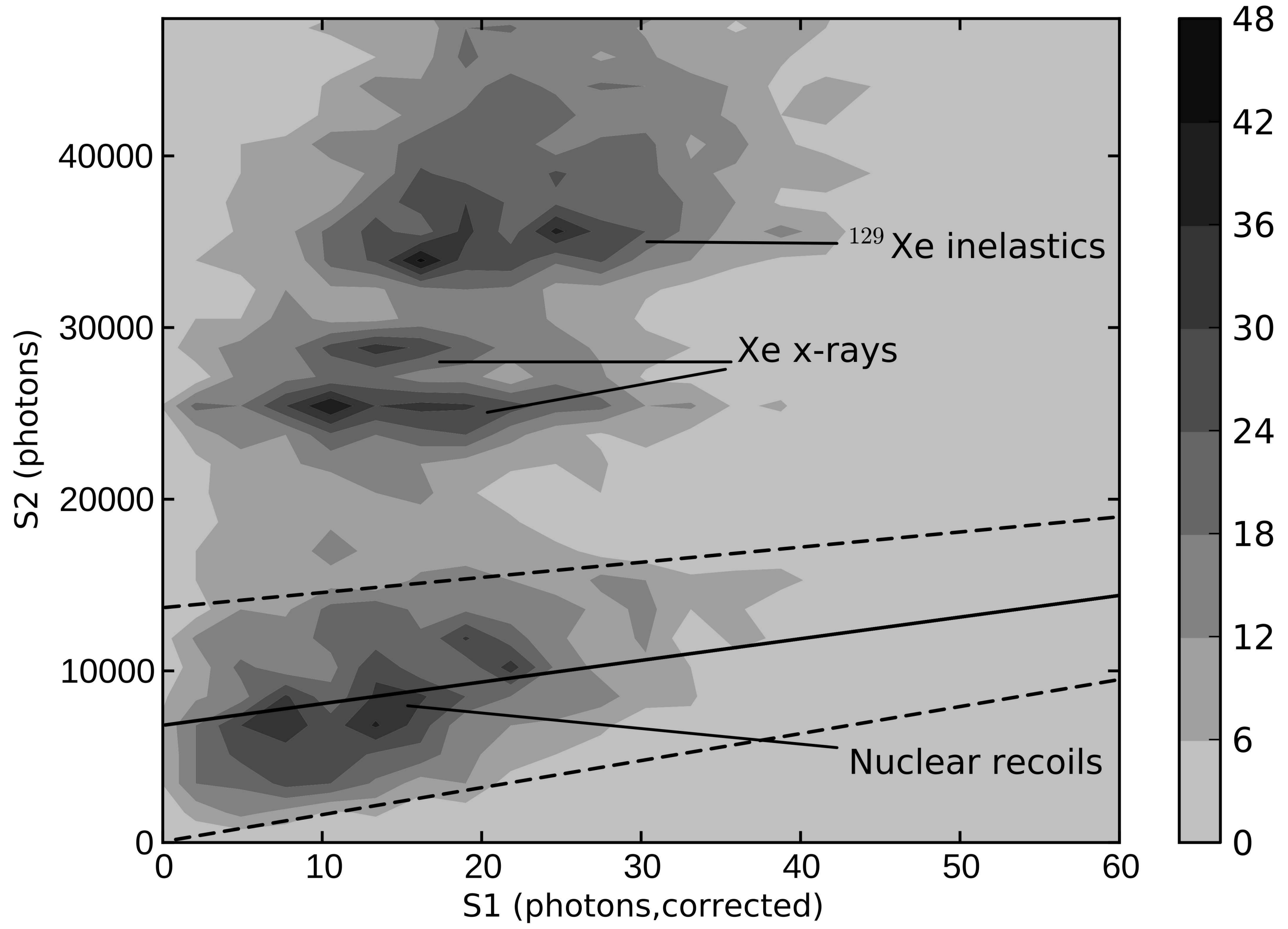
- **Response of a 3.2 cm3 cryogenic CsI crystal to 59.5 keV 241Am gammas, seen by a 1.3 × 1.3 cm2 LAAPD with and without a NOL-9**

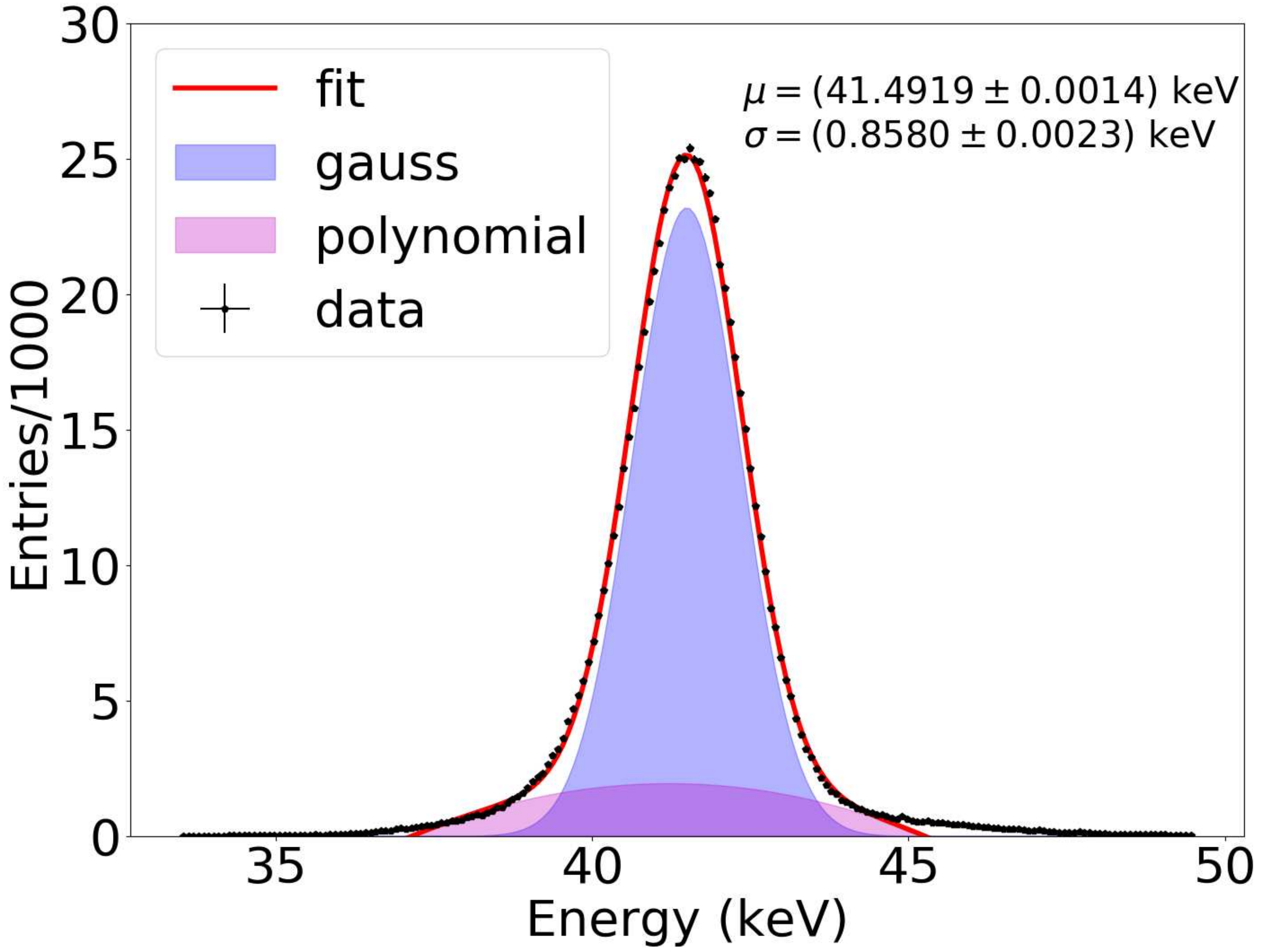


- **Measurement of nuclear quenching factor (QF) for cryogenic CsI. The figure displays the measured electron-equivalent energy (keVee) deposited by 14 keV Cs and I nuclear recoils induced by 2.2 MeV neutron scattering.**

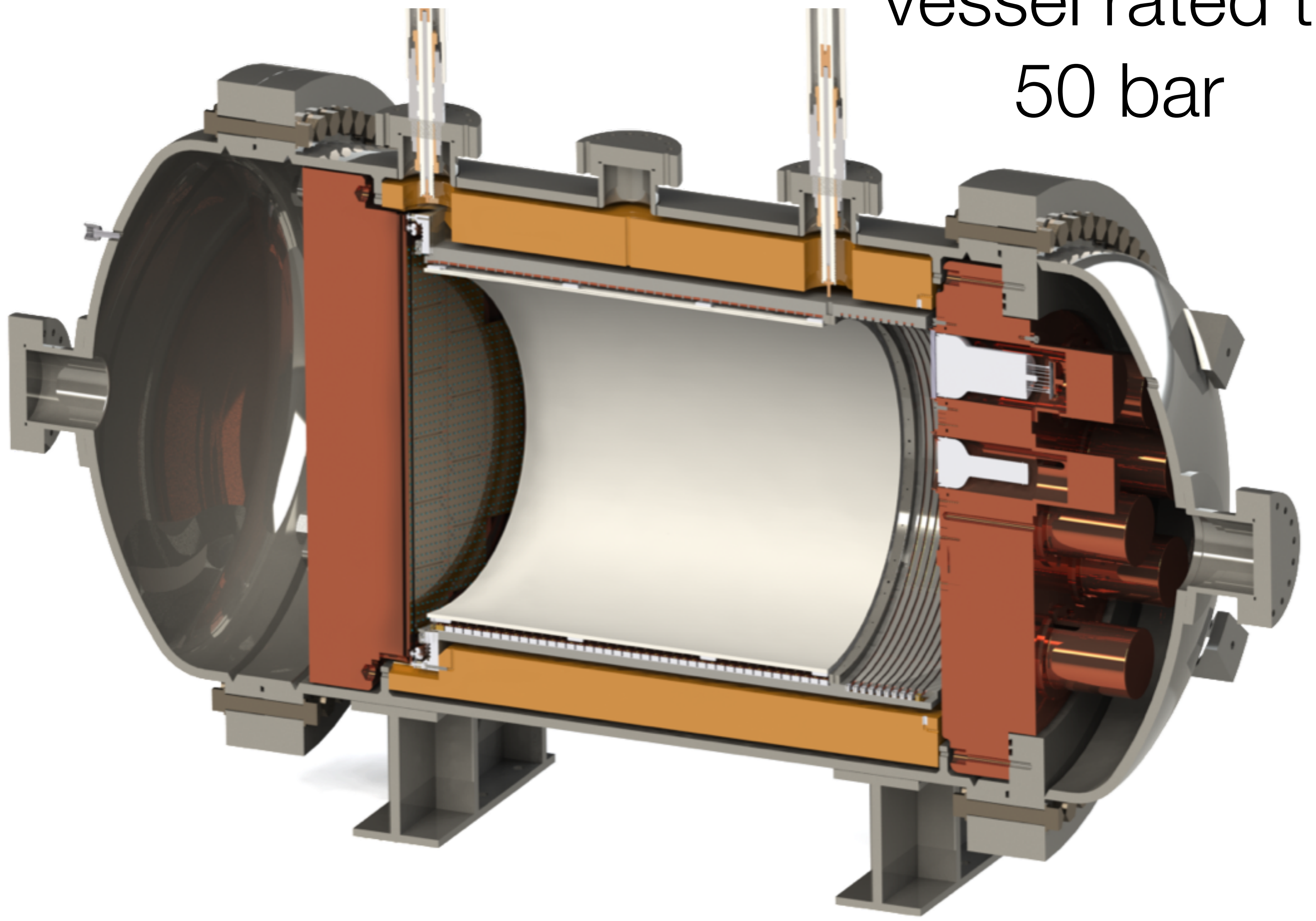
High pressure xenon (and other noble gases) chambers

- Using electroluminescence amplification, signals as low as 1-2 ionized electrons can be detected. This reduces the expected energy threshold to less than 0.2 keVee.
- Dedicated studies of the response of gaseous detectors to few-keV nuclear recoils will be necessary to reduce the present uncertainty on parameters such as the quenching factor.
- One interesting possibility for this detector design is the ability to use different noble gas targets within the same setup. This will allow to compare data taken with xenon, krypton, argon, neon, and even helium.





NEXT-NEW



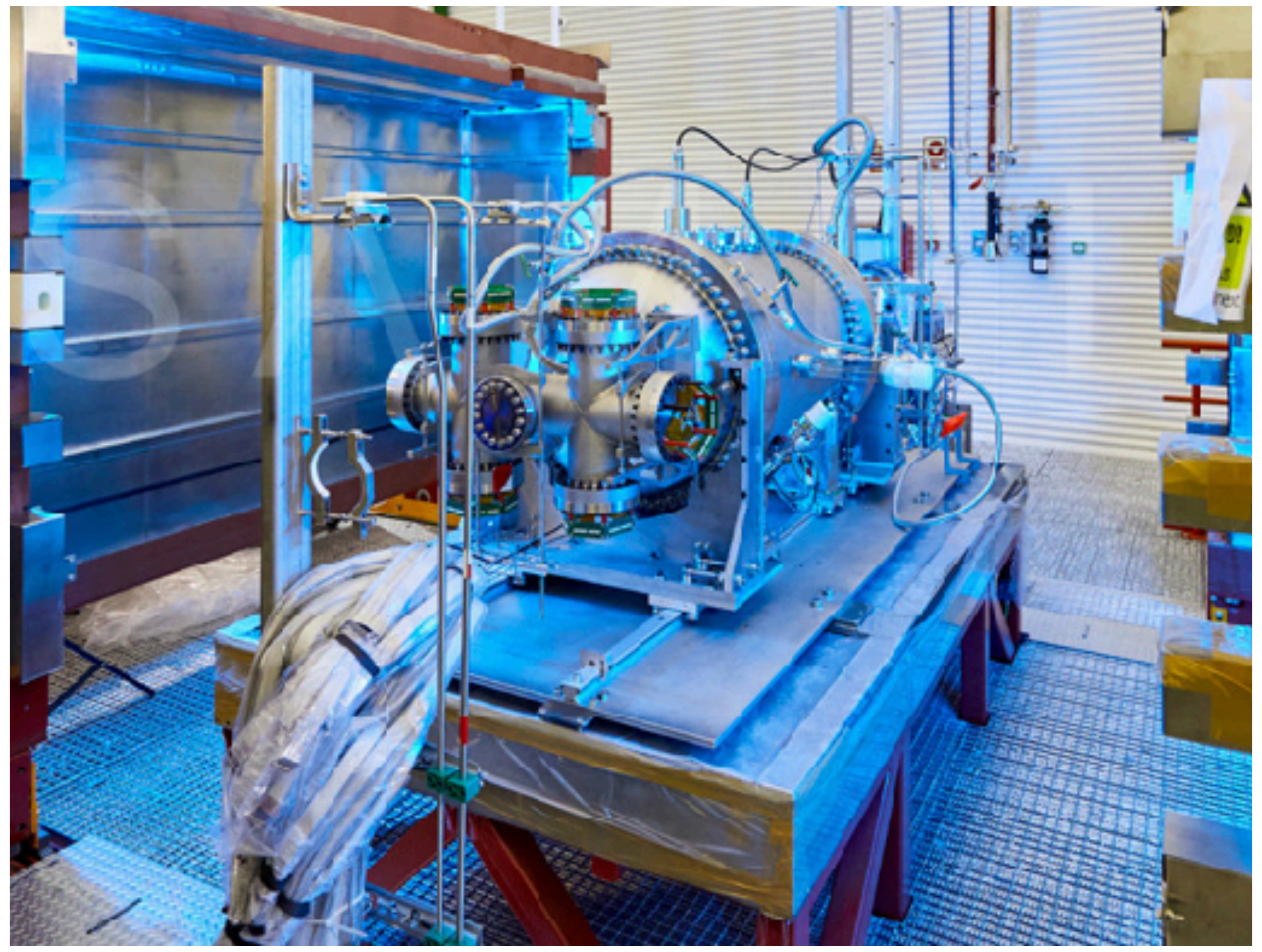
Tracking plane with SiPMs

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

Physics reach

(NON STANDARD INTERACTIONS NSI)

- Model-independent parametrization of the effects of NP at low energies through the addition of higher-dimensional operators to the SM Lagrangian
- Non-standard CC production and detection processes for neutrinos of flavor α
- Flavor-changing neutral-current (NC) in- teractions of neutrinos with other fermions (if α/= β), or to a modified NC interaction rate with respect to the SM expectation (if α = β).
- While CC NSI are severely constrained by the study of CC processes, such as meson and muon decays, constraining NC NSI is a much more challenging task.
- CEvNS experiments at spallation sources allow to constrain two of the three flavor-diagonal coefficients, since the neutrino flux contains both muon and electron neutrinos.

$$2\sqrt{2}G_F\epsilon_{\alpha\beta}^{ff',P}(\bar{\nu}_\alpha\gamma_\mu P_L\ell_\beta)(\bar{f}'\gamma^\mu Pf)$$

$$2\sqrt{2}G_F\epsilon_{\alpha\beta}^{f,P}(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{f}\gamma^\mu Pf)$$

Sensitivity to ν properties will be hard to improve beyond ESS

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

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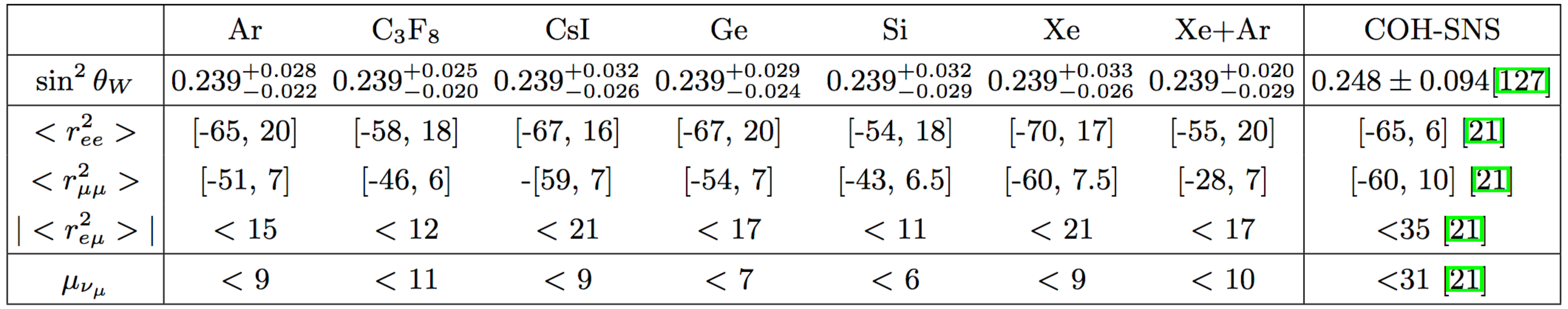
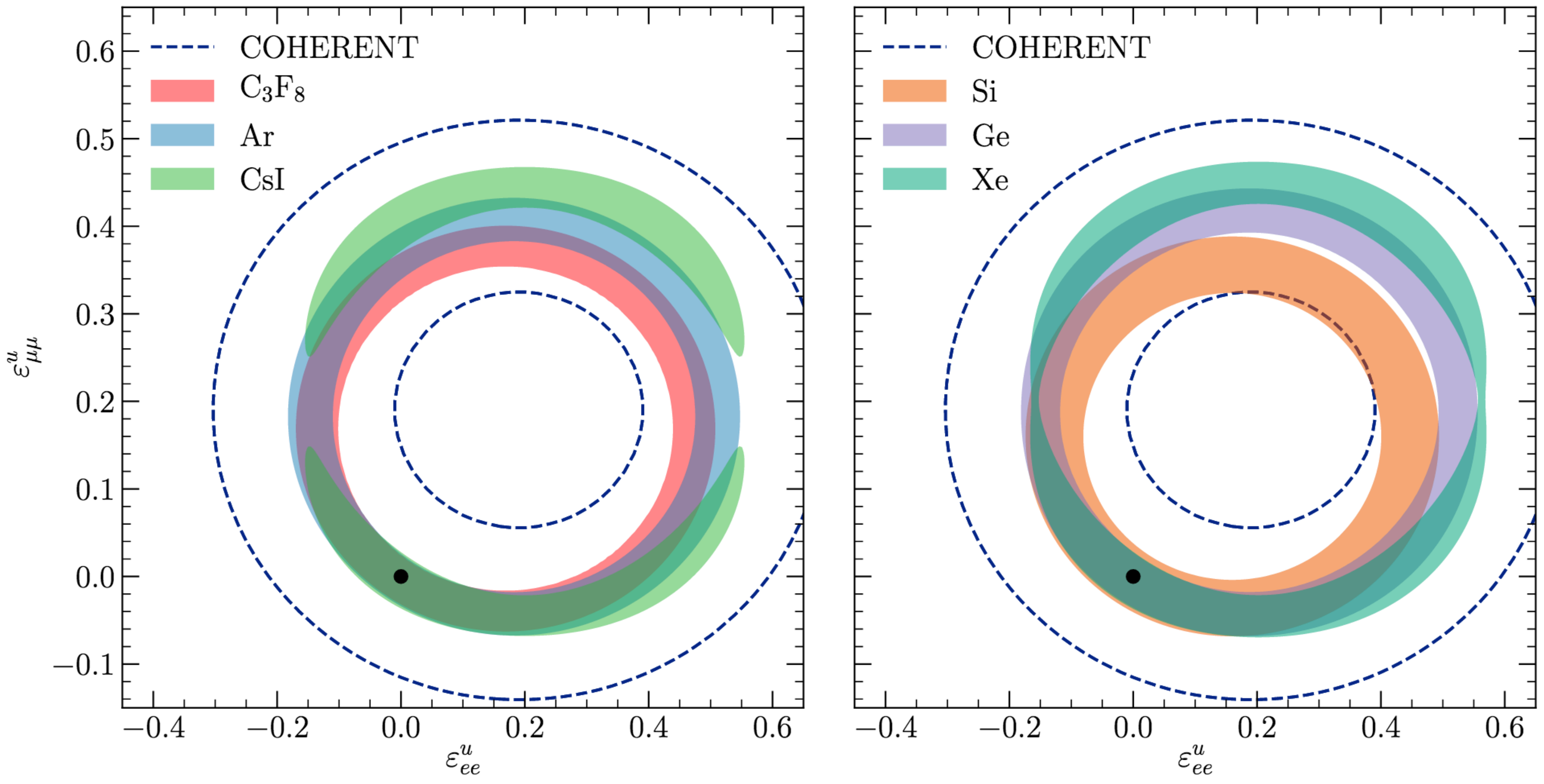


	Ar	C_3F_8	CsI	Ge	Si	Xe	Xe+Ar	COH-SNS
$\sin^2\theta_W$	$0.239^{+0.028}_{-0.022}$	$0.239^{+0.025}_{-0.020}$	$0.239^{+0.032}_{-0.026}$	$0.239^{+0.029}_{-0.024}$	$0.239^{+0.032}_{-0.029}$	$0.239^{+0.033}_{-0.026}$	$0.239^{+0.020}_{-0.029}$	0.248 ± 0.094[127]
$< r^2_{ee} >$	[-65, 20]	[-58, 18]	[-67, 16]	[-67, 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]
$\| < r^2_{e\mu} > \|$	< 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)

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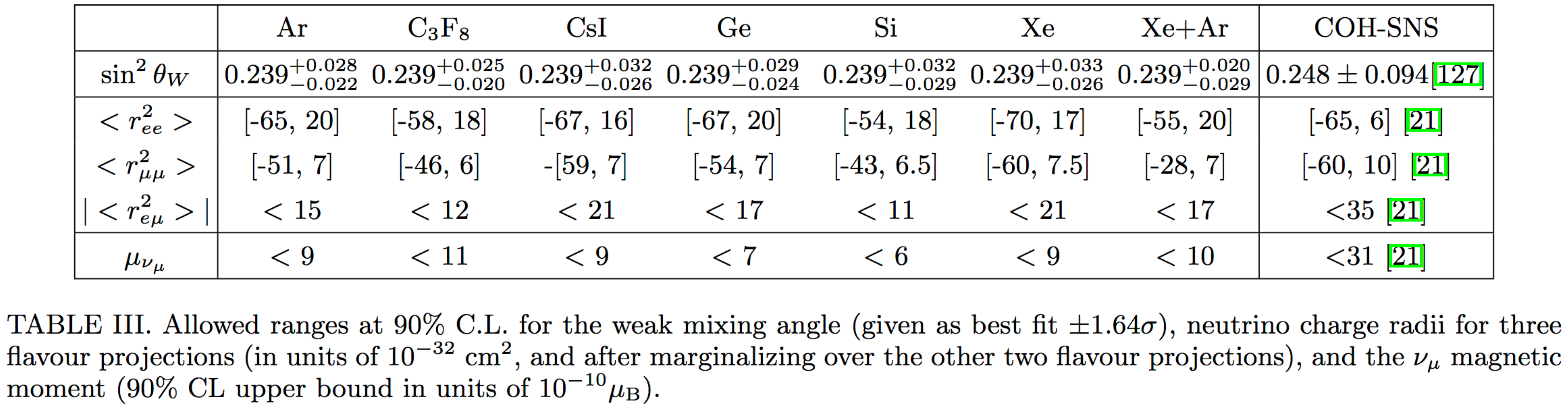

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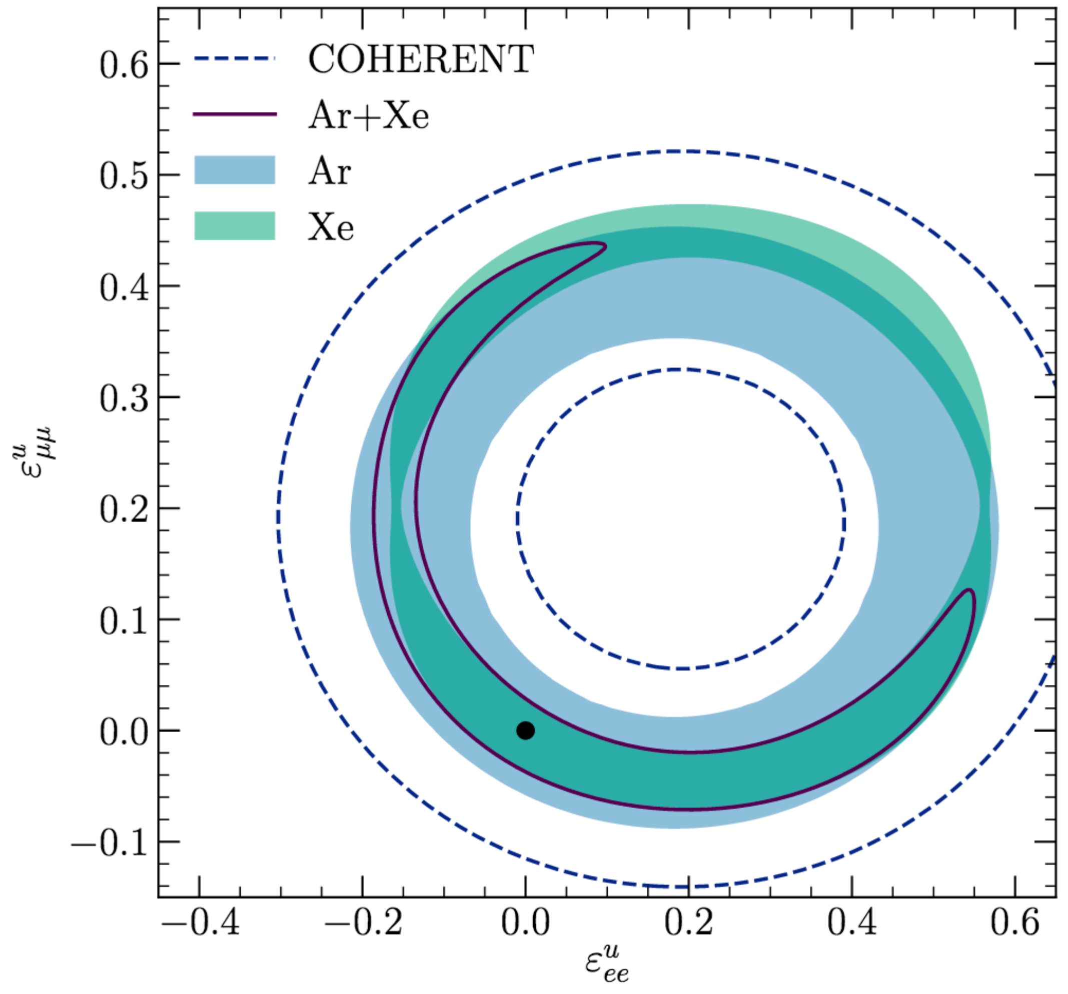
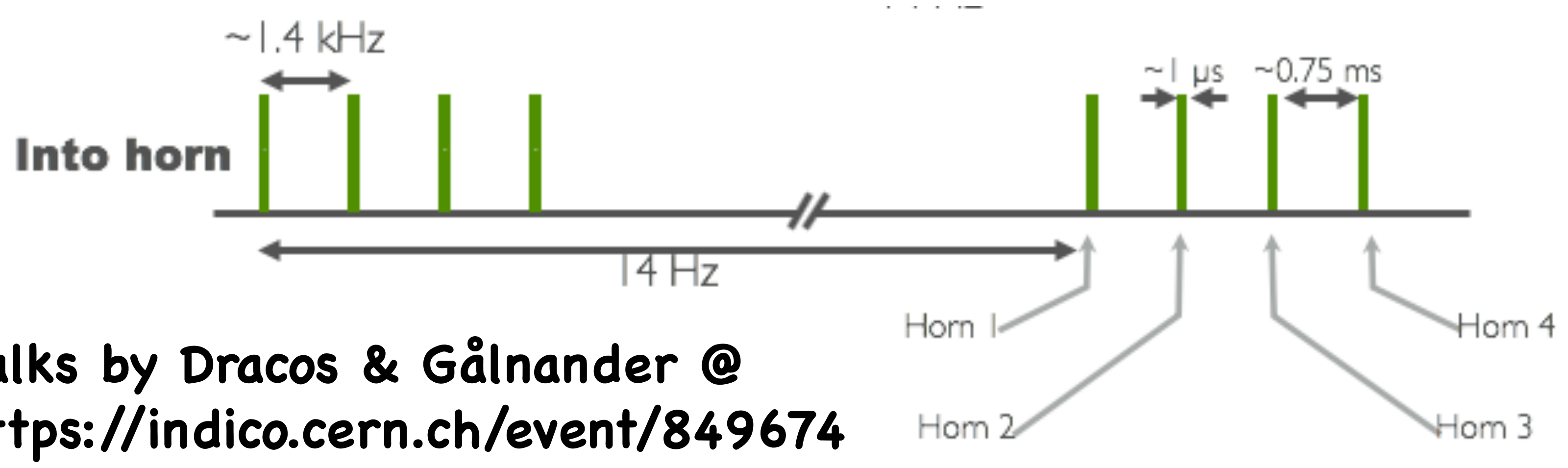


Multiple (small) detectors allow for improved sensitivity
(and redundancy in testing anomalies)

Taking it to the next level: ESSνSB

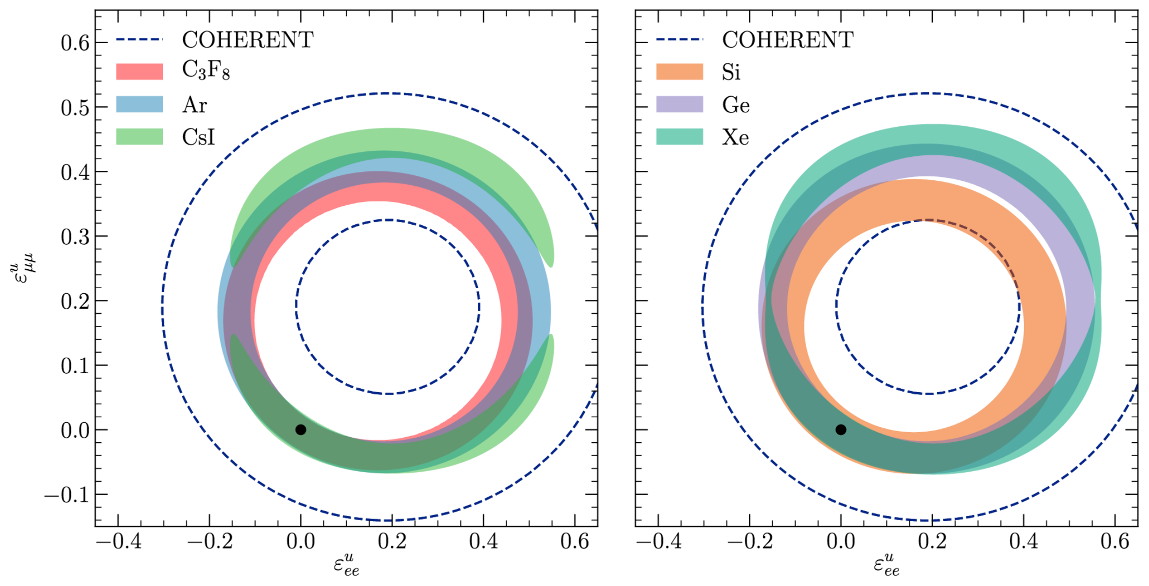
ESSνSB pulse compression brings:

- background drops with duty factor by x70
- timing information (prompt vs. delayed ν's)



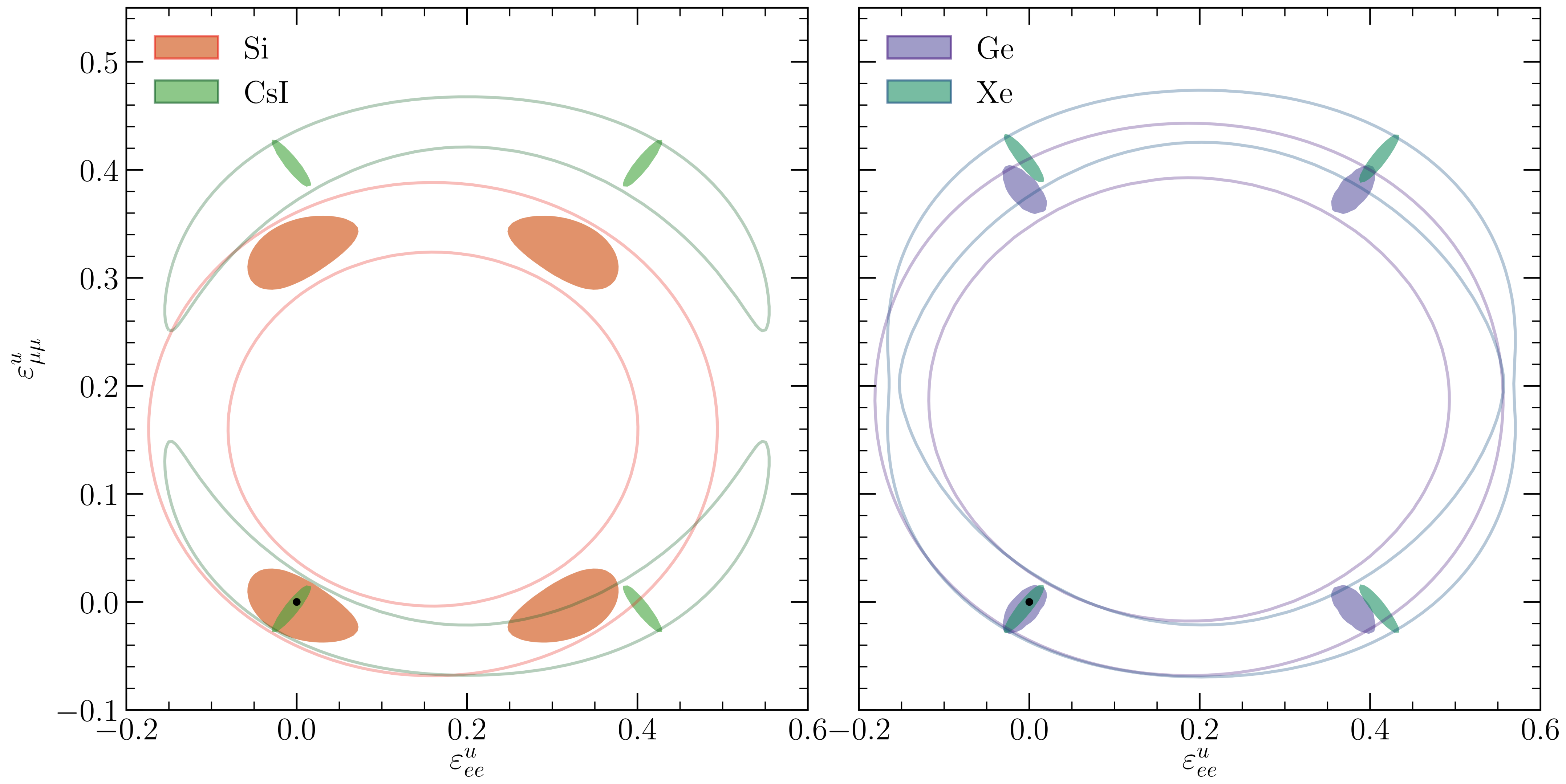
Talks by Dracos & Gålnander @ https://indico.cern.ch/event/849674

from this...



to this...

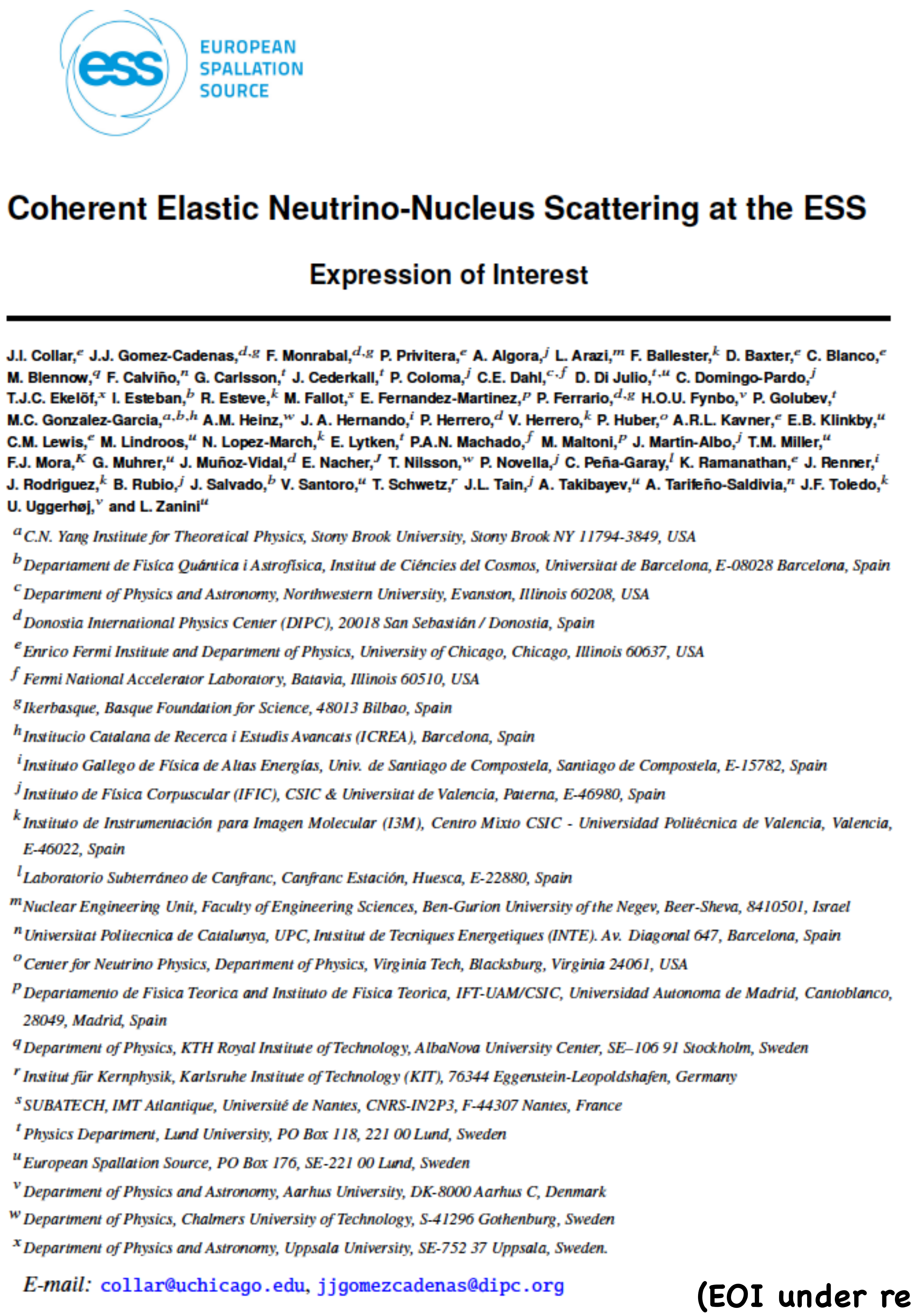
(improvement not limited to NSI, timing opens up other physics possibilities)



Preliminary study from I. Esteban, C. Gonzalez-Garcia, P. Coloma)

Much work to do before ESS POT!

- CEvNS 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

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(EOI under review)

ESS physics considered a high priority program in Basque Country

- Basque Country heavily involved in ESS
- ESS physics (neutron and neutrino physics) considered a high priority. “Neutrionics”:
- Substantial funding available for R&D and preparing physics program
- THANKS FOR YOUR ATTENTION