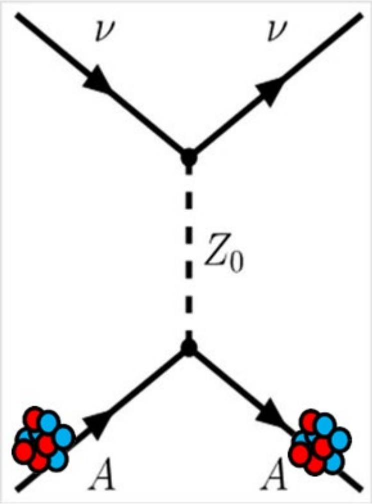
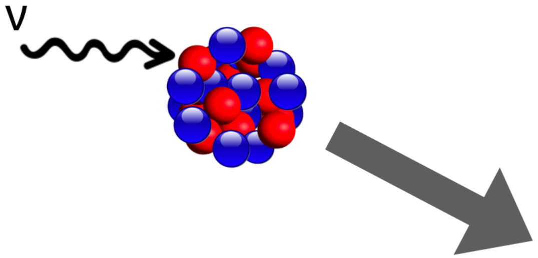
Coherent Elastic Neutrino-Nucleus Scattering at the ESS



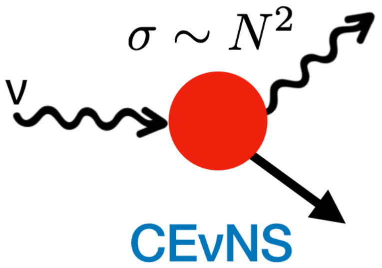
ELSE LYTKEN, JOAKIM CEDERKÄLL, LUND UNIVERSITY

SPECIAL THANKS TO JUAN COLLAR & FRANCESC MONRABAL

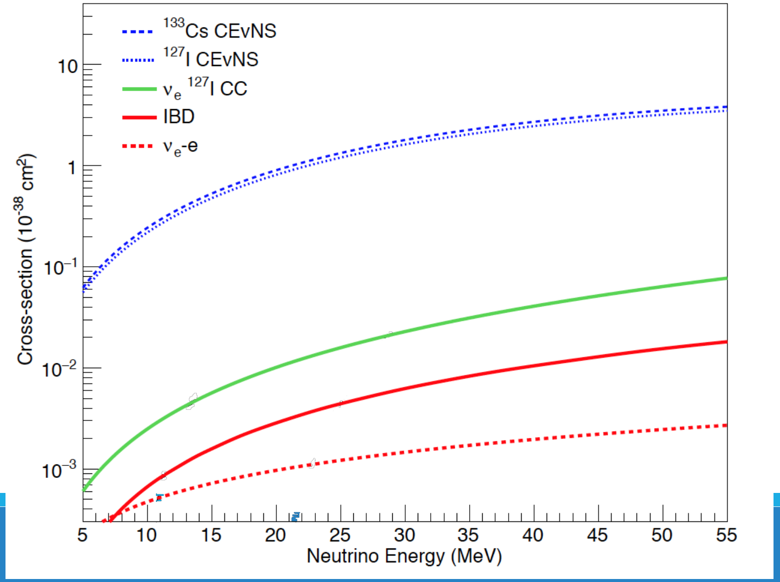
What is Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)?



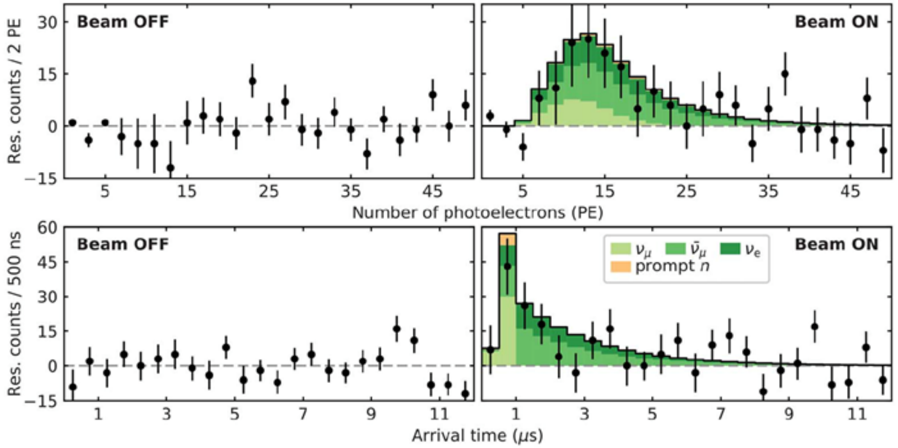
Long wavelength, "sees" all nucleons simultaneously



Cross section increases as N^2.
(largest of all -> small detectors)
CATCH: sub-keV to few keV recoils are only observable.



Process first observed at SNS in 2017



Max recoil energy is $\approx 2E_\nu^2/M$

Why is CEνNS important?

Can give input to several research questions, such as:

- ✓ Study of the neutral current and sensitivity to the weak mixing angle and non-standard neutrino interactions
- ✓ Study of the nuclear structure – minimally disruptive of the nucleus
- ✓ New types of particles such as sterile neutrinos
- ✓ Lepton universality tests
- ✓ Input to dark matter searches and even sensitivity to new dark matter particles
- ✓ Effective neutrino charge radius
- ✓ Neutrino magnetic moment
- ✓ Better understanding of supernovas (where neutrinos carry the energy out first, and CEνNS is the dominant mode)

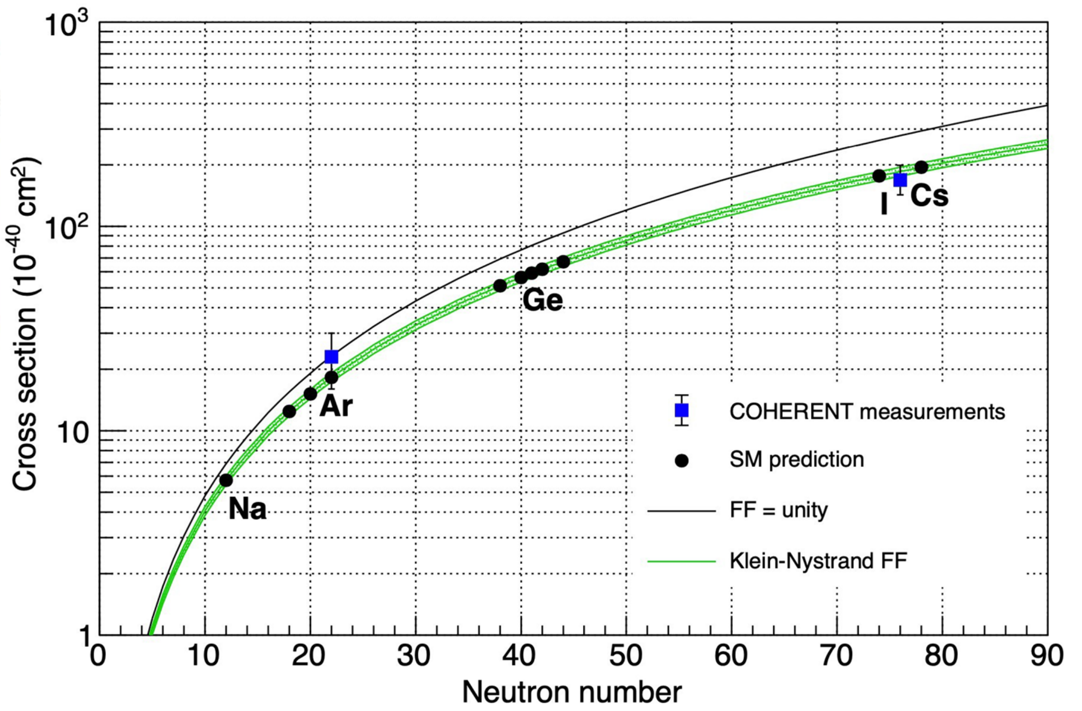
complementary to measurements at the big neutrino experiments!

The rate is a clean Standard Model prediction:

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

small nuclear uncertainties

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



$F(Q)^2$ is the nuclear form factor
Supresses σ for large Q

For instance of sterile neutrinos, a magnitic moment of the neutrinos, or new light mediator particles!

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

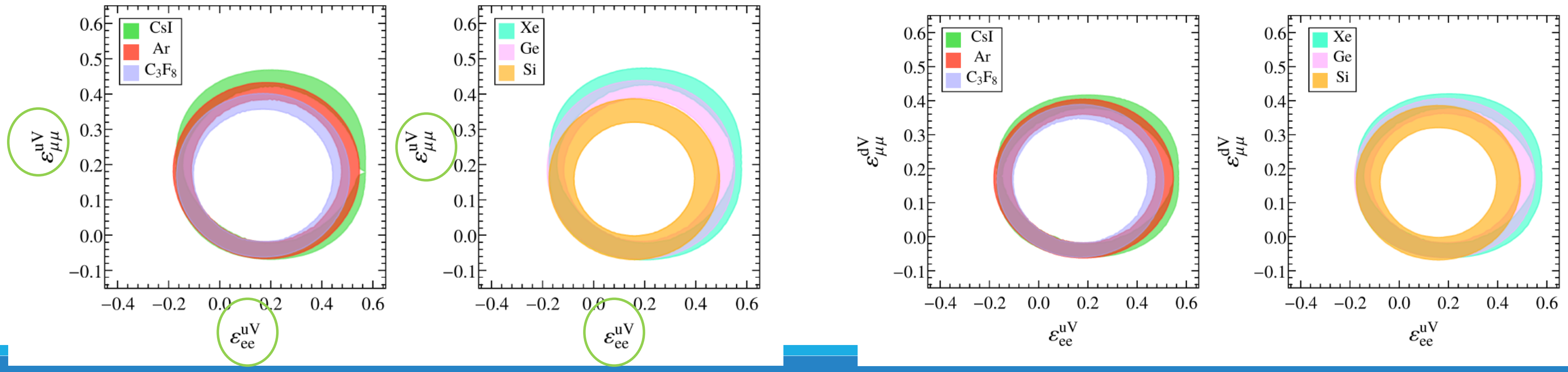
Non-standard neutrino-quarks interactions

Allowing for neutrino interactions not currently included in the Standard Model:

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

$$G_V = \left[\left(g_V^p + 2\sum \epsilon_{\alpha\beta}^{uV} + \sum \epsilon_{\alpha\beta}^{dV}\right) Z + \left(g_V^n + \sum \epsilon_{\alpha\beta}^{uV} + 2\sum \epsilon_{\alpha\beta}^{dV}\right) N\right] F_{\rm nuclear}^V\left(Q^2\right)$$

$$G_A = \left[\left(g_A^p + 2\sum \epsilon_{\alpha\beta}^{uA} + \sum \epsilon_{\alpha\beta}^{dA}\right)(Z_\uparrow - Z_\downarrow) + \left(g_A^n + \sum \epsilon_{\alpha\beta}^{uA} + 2\sum \epsilon_{\alpha\beta}^{dA}\right)(N_\uparrow - N_\downarrow)\right] F_{\rm nuclear}^A\left(Q^2\right)$$

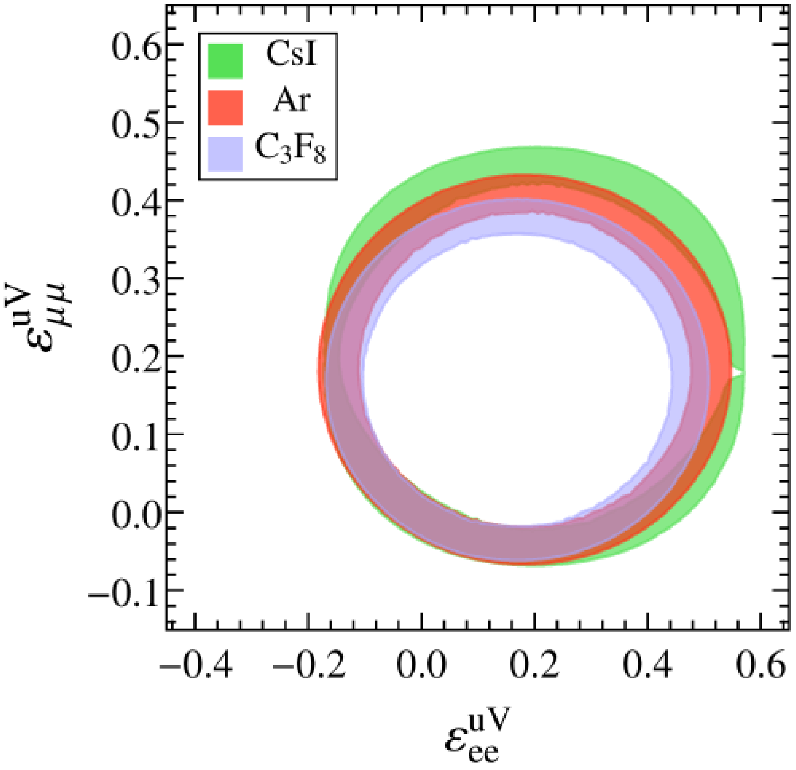


Etc.

Plots from arXiv:2208.11771

Non-standard neutrino-quarks interactions

Expected 90% C. L. sensitivity after 3 years @ESS



Operation with different nuclei helps breaking degeneracies

A full experimental program must allow for operation with different targets.
Currently plan for at least two different targets

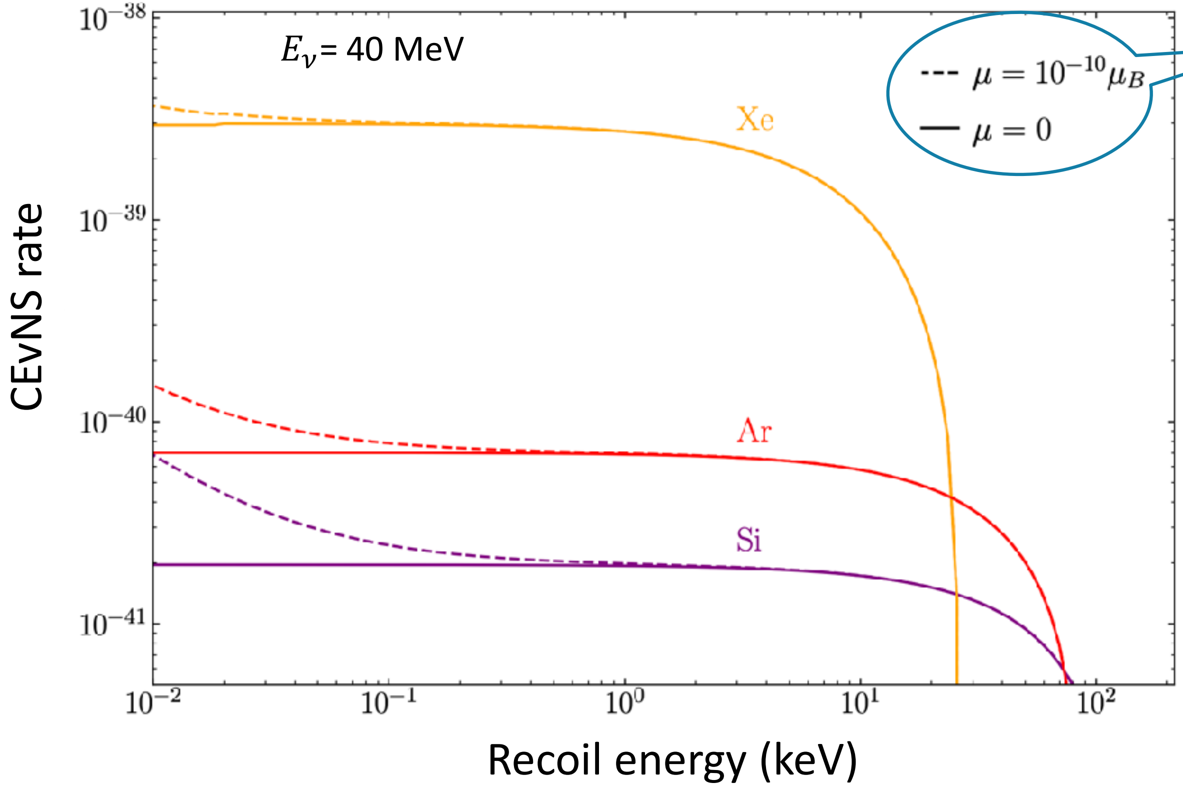
Plots from arXiv:2208.11771

Neutrino magnetic moment

In Beyond Standard Models with a magnetic moment for the neutrino, the effective weak mixing angle changes dependent on the effective charge radius for the neutrino.

Interesting physics concentrates at low energies

Ultra low energy threshold is crucial



ν magnetic moment

μ_B is Bohrs magneton

ESS upper bounds $\mu(\nu_\mu)$ at 90% CL

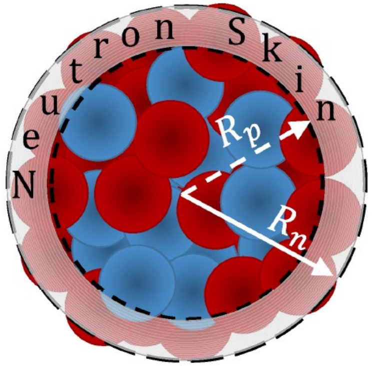
Ar	CsI	Ge	Si	Xe
< 9	< 9	< 7	< 6	< 9

$* 10^{-10} \mu_B$

(arXiv 1911.00762)

Plot from JHEP 02 (2020) 123

Weak charge radius/neutron skin thickness



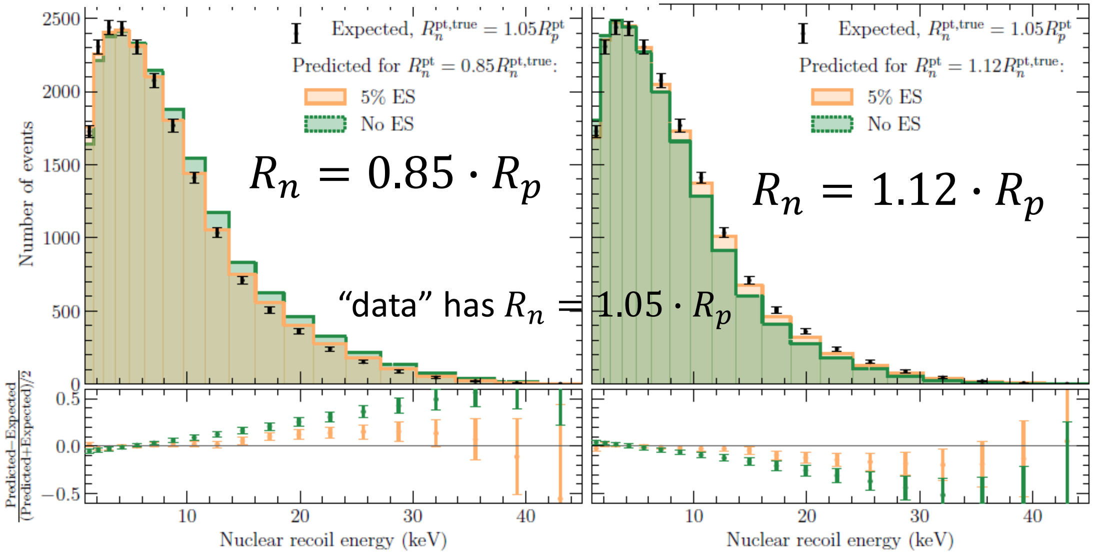
CEvNS: measure the weak form factors and the weak charge distribution, and most direct measurment of difference in the nucleon radii $\Delta R_{np} = R_n - R_p$, the neutron skin.

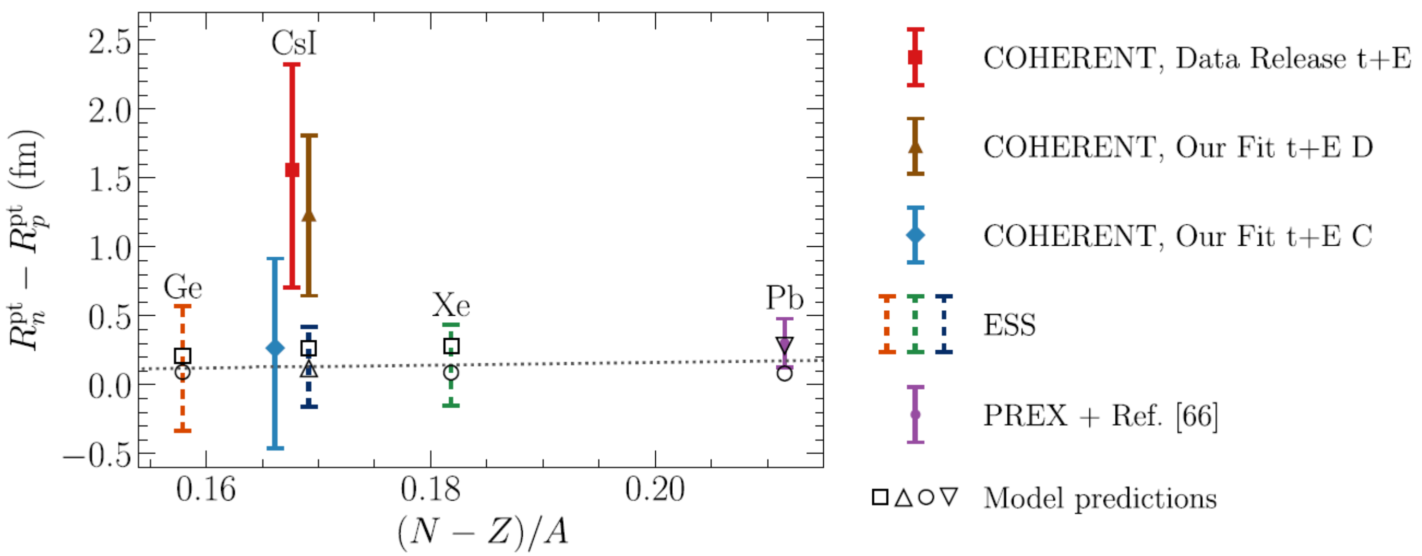
Important for nuclear structure and pressure, including astrophysics neutron stars.

R_p from electron-nucleon scattering for neutrons needs the neutral current weak interactions. Compare E_{recoil} spectrum to simulations to extract radii:

JHEP08(2020) 030 and references

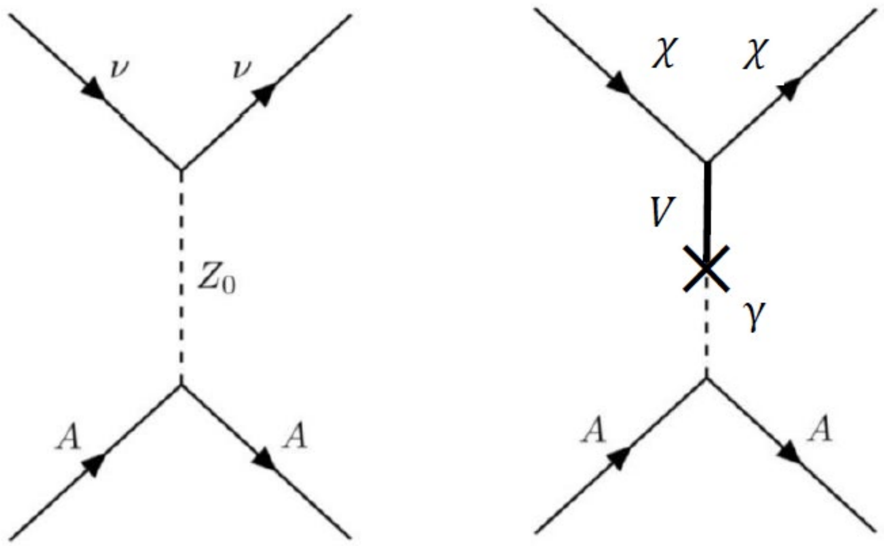
ESS expectations, CsI 3 years





Implications for Dark Matter searches

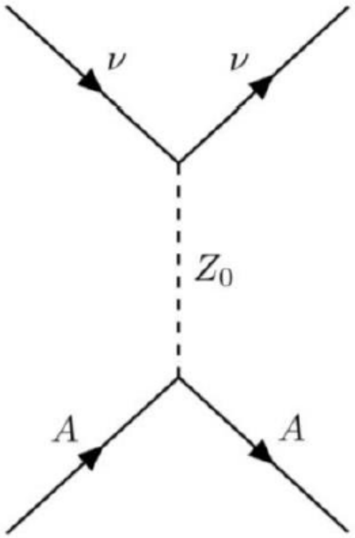
Coherent ν-A scattering   Coherent DM-A scattering



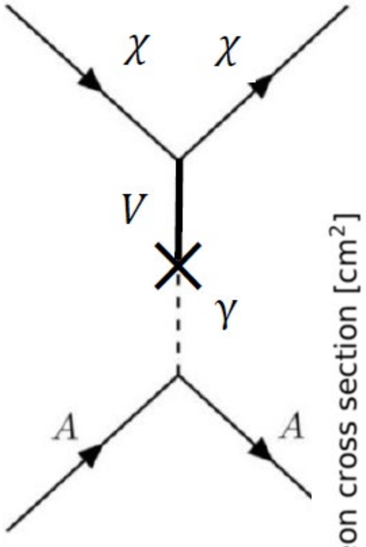
If the detector is sensitive to the low recoil from neutrino interactions it should also be sensitive to certain types of dark matter

Implications for Dark Matter searches

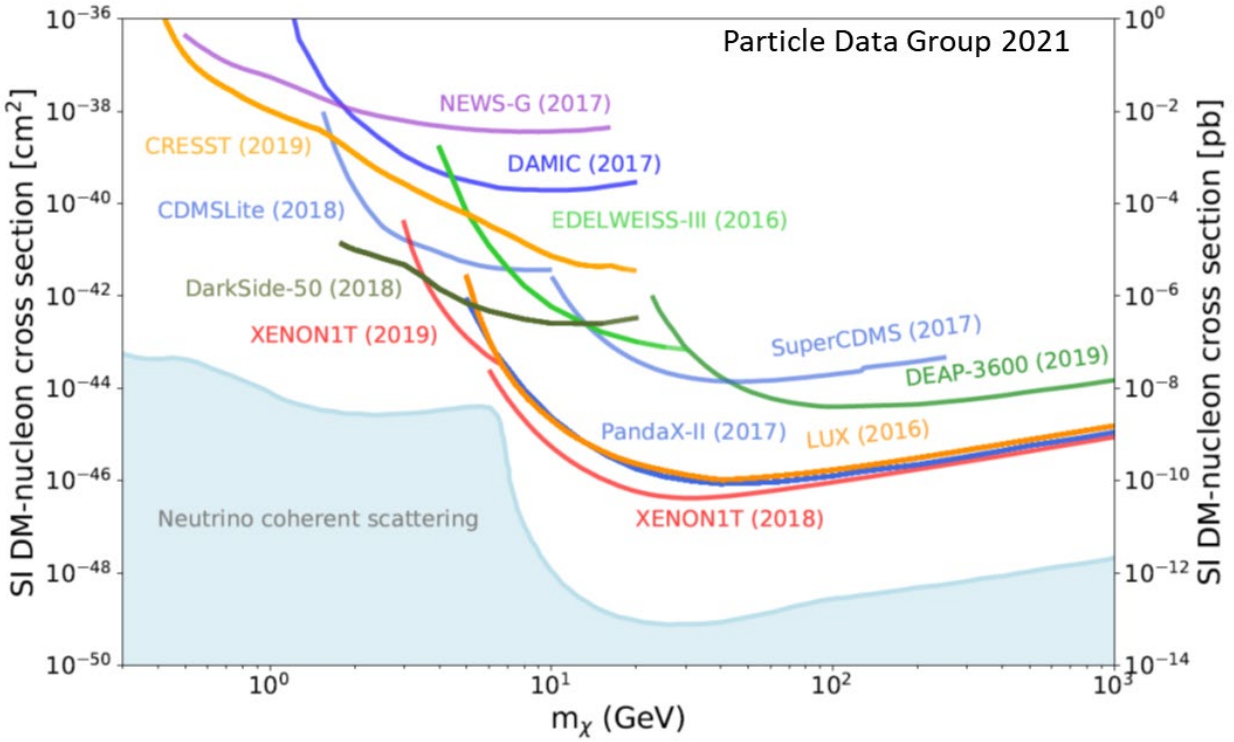
Coherent ν-A scattering



Coherent DM-A scattering



Understanding coherent neutrino scattering is therefore also an important component in dedicated dark matter experimental searches



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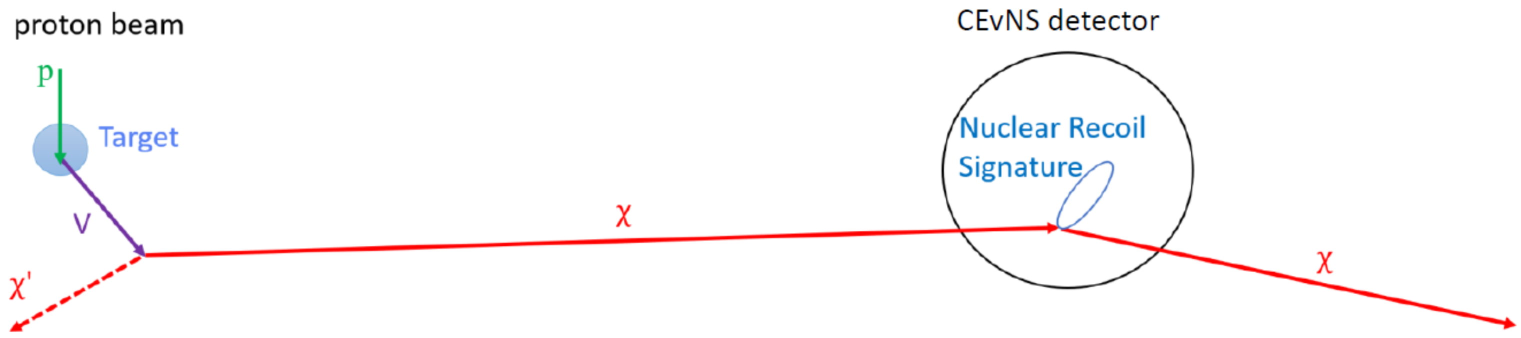
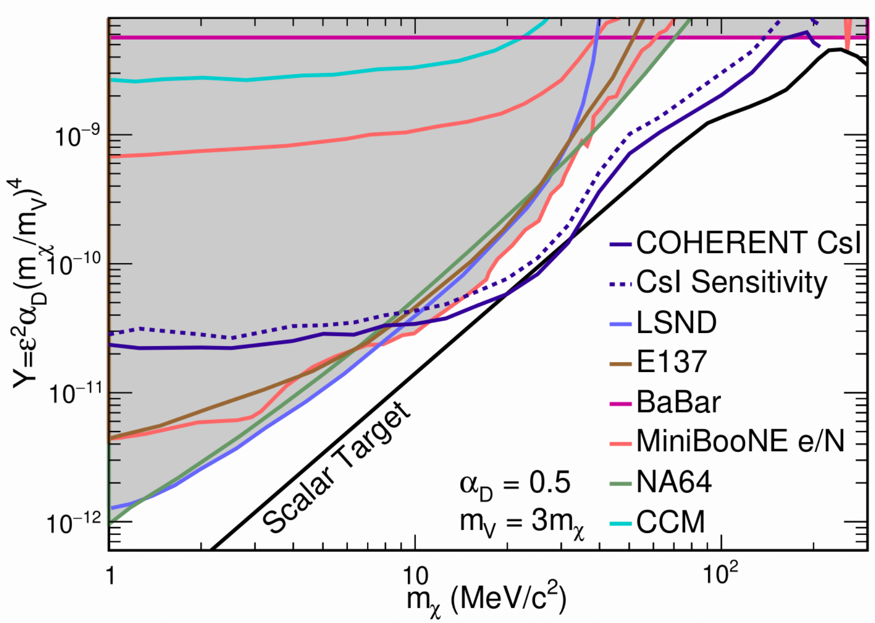
arXiv: 2110.1145
arXiv:2205.12414

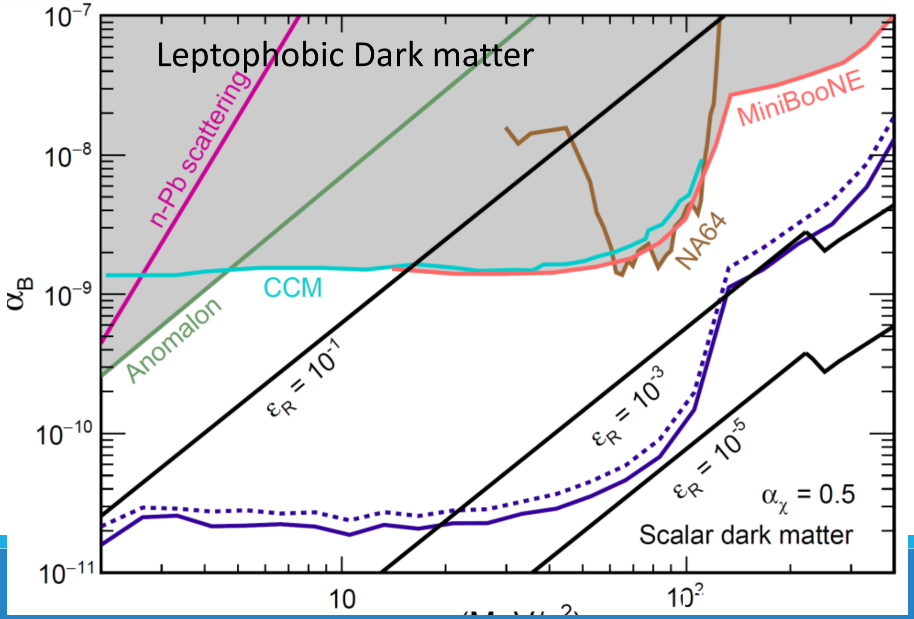
Dark Matter searches





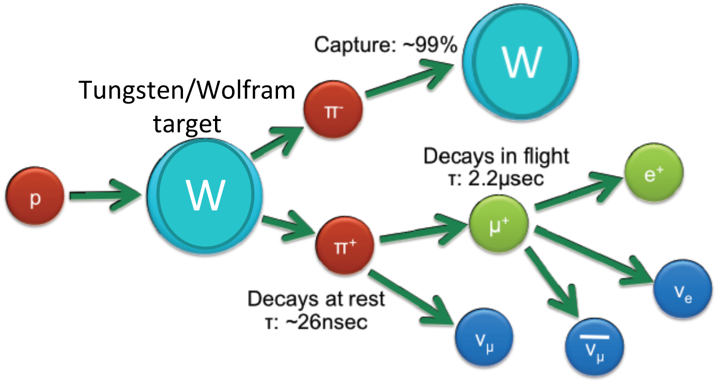
Search for accelerator-produced low mass dark matter, via portal particles (V) produced in the target.

- Would show up as small excess in event counts
- Large dependence on dark matter and/or portal parameters. Recoil E can be larger than for standard neutrino -scattering
- Sensitivity to dark matter without or with small coupling to leptons



Why at the ESS?

Ample source of neutrinos, low enough energy to get coherent scattering

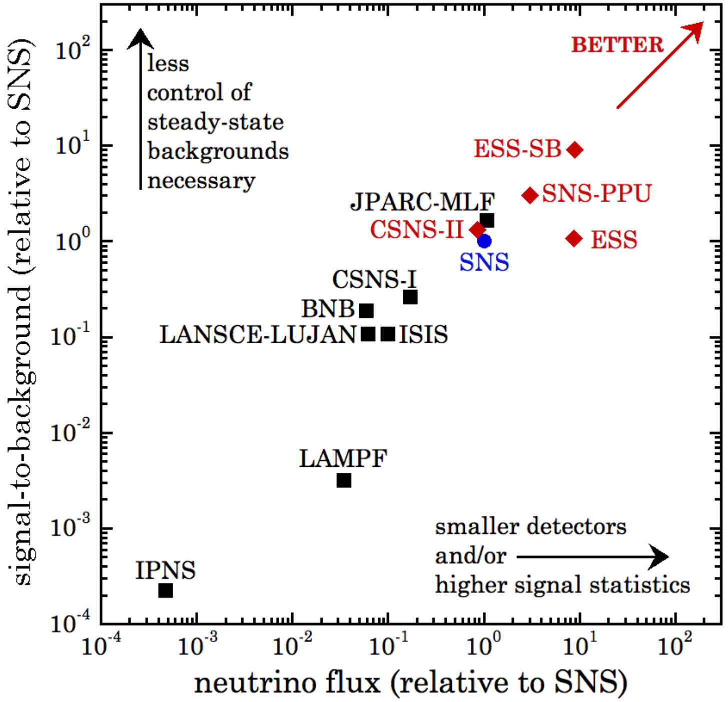


ESS provides:

✓ Largest low E ν flux at next generation facilities

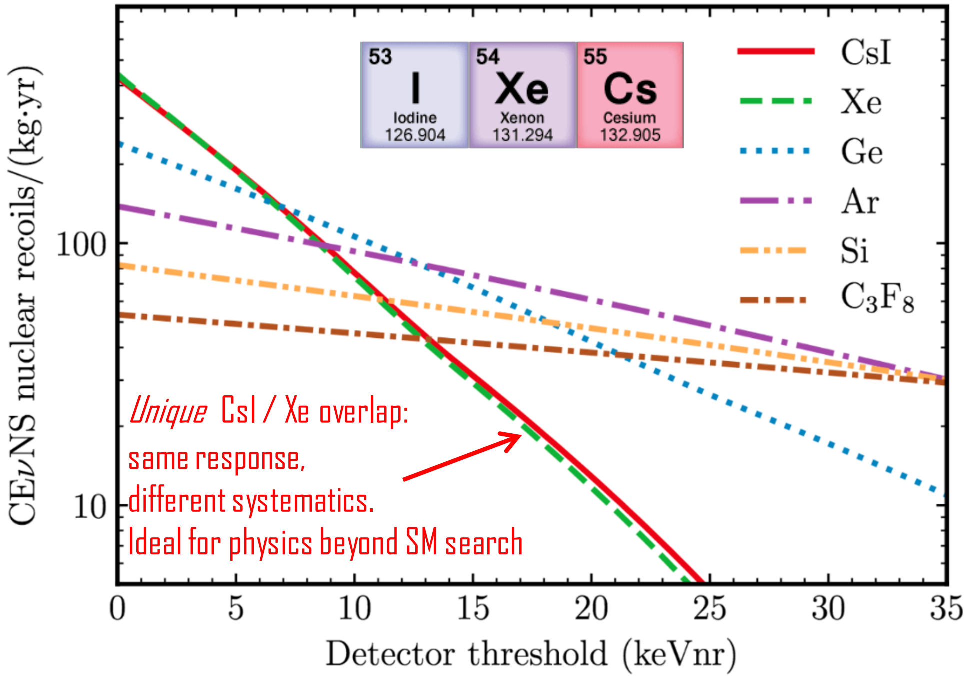
This allows for relatively small detectors ($\mathcal{O}$(20 kg))

✓ Pulsed beam to control backgrounds

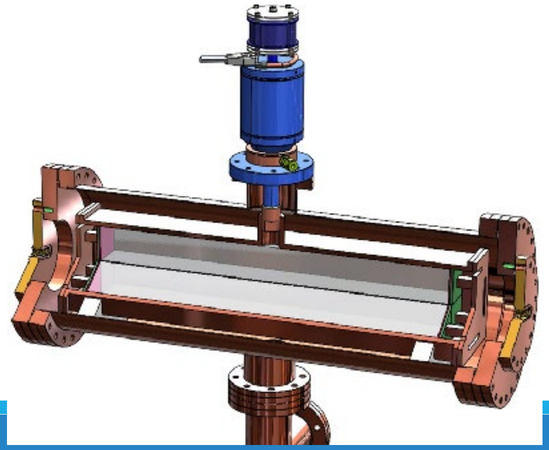


Detectors for the νESS

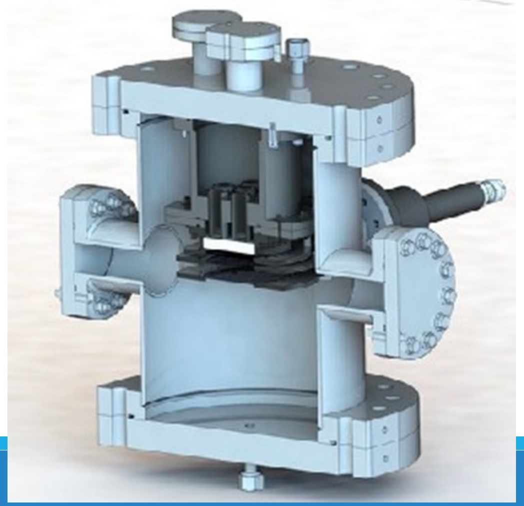
- Combination of technologies to minimise possible systematic effects.
- Use of different nuclei to allow for exploring larger fraction of the phase space, and similar nuclei with different technologies
- Right now two main technologies are being tested and developed, using CsI and Xe.

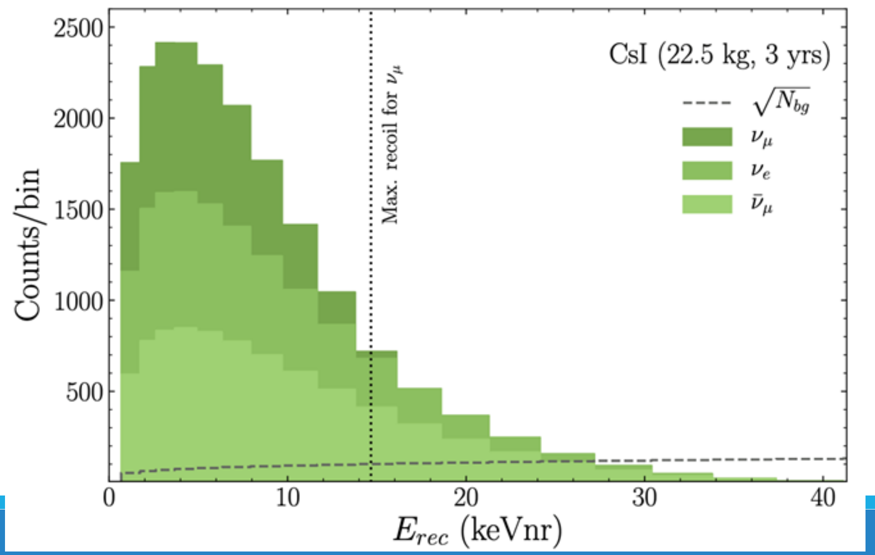


CsI scintillating crystals

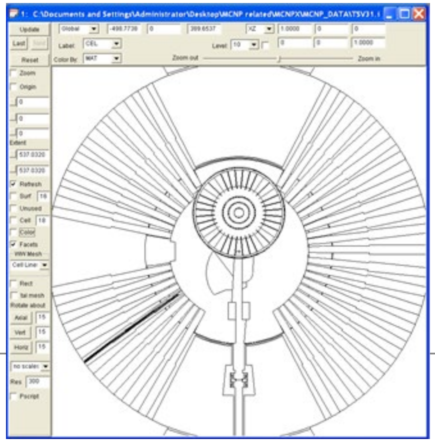


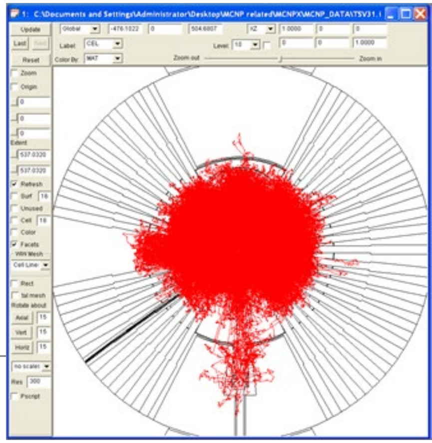
Gaseous detector prototype



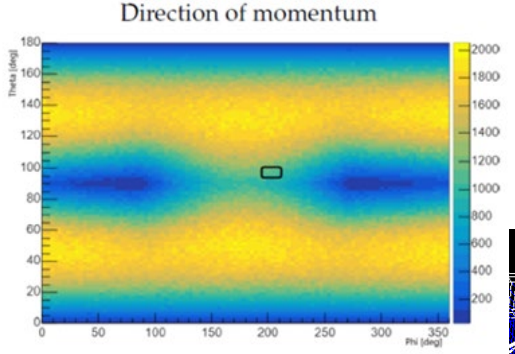


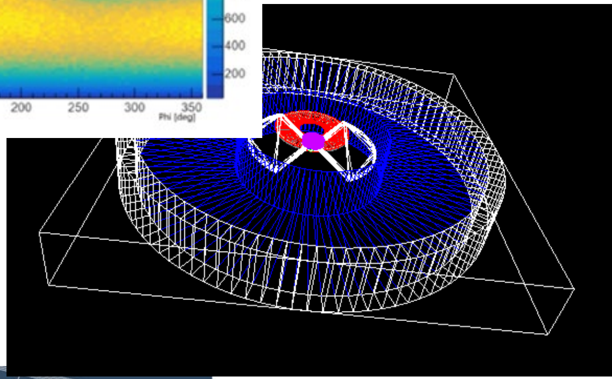
Backgrounds and simulation

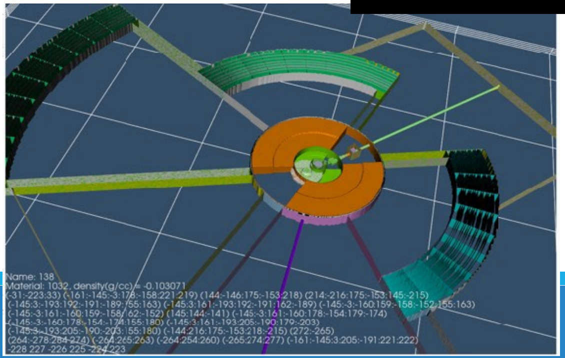




- Prompt neutrons from the ESS target are the main background!
- We need to find detector locations where the neutrons do not compete with CEvNS signals.
- Need shielding of detectors
- We need to measure the neutron background on-site once the ESS is running but for now have only simulations – we are using and comparing results from different simulation tools, MCNPX, PHITS, GEANT
- Steady-state background can be subtracted.

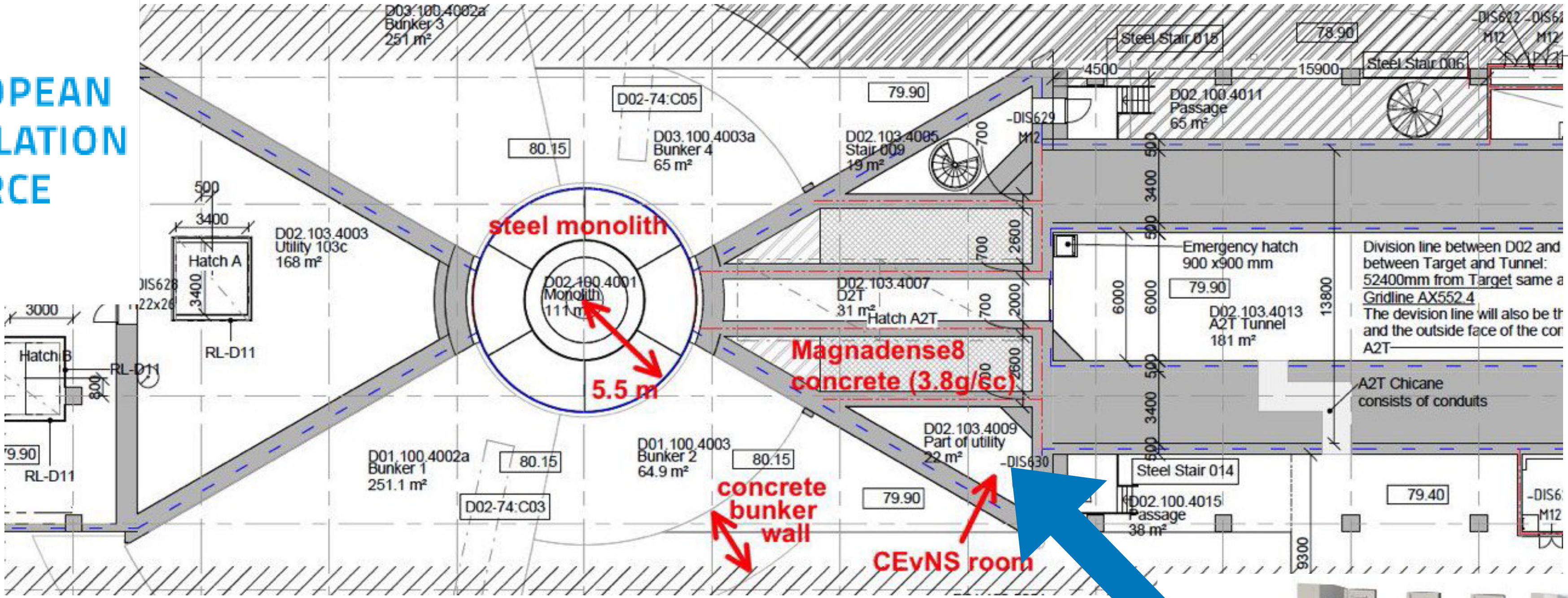


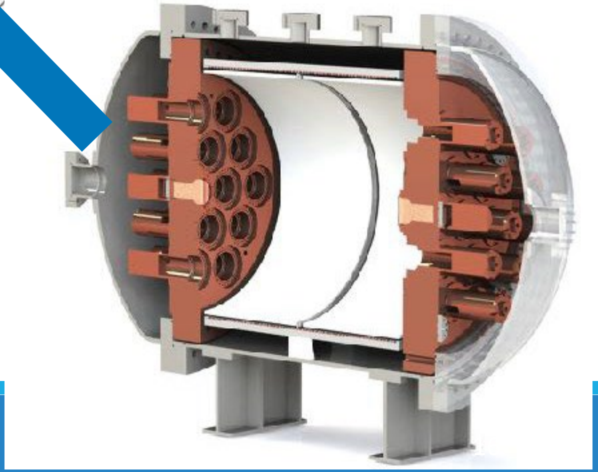




νESS: possible location

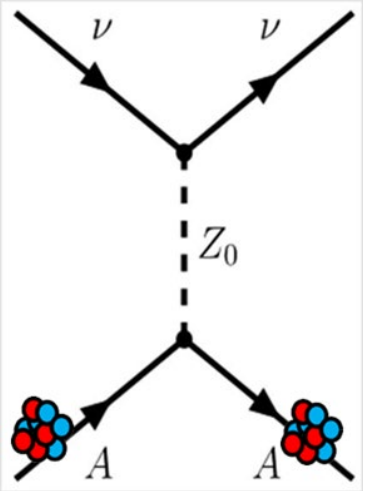
EUROPEAN SPALLATION SOURCE





No need for a beam line ....

Summary & outlook

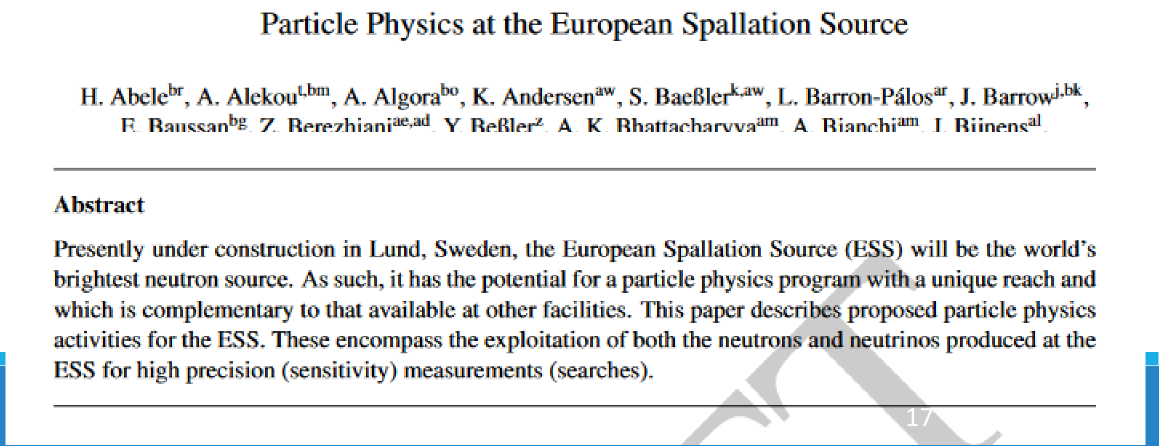


The ESS gives us an opportunity to build up a world-leading neutrino programme with precise measurements and large discovery potential

Coherent Elastic Neutrino-Nucleus scattering makes it possible to achieve this with small-scale detectors

We are working with other ESS fundamental physics on a fundamental physics@ESS paper

Currently collaborating νESS institutes: University of Chicago, University of Santiago, Ben Gurion University, Lund University
Support from ESS personel.



Particle Physics at the European Spallation Source

H. Abele[br], A. Alekou[t,bm], A. Algora[bo], K. Andersen[aw], S. Baeßler[k,aw], L. Barron-Pálos[ar], J. Barrow[j,bk], F. Baussan[bg], Z. Berezhiani[ae,ad], Y. Beßler[z], A. K. Bhattacharyya[am], A. Bianchi[am], J. Bijnens[al]

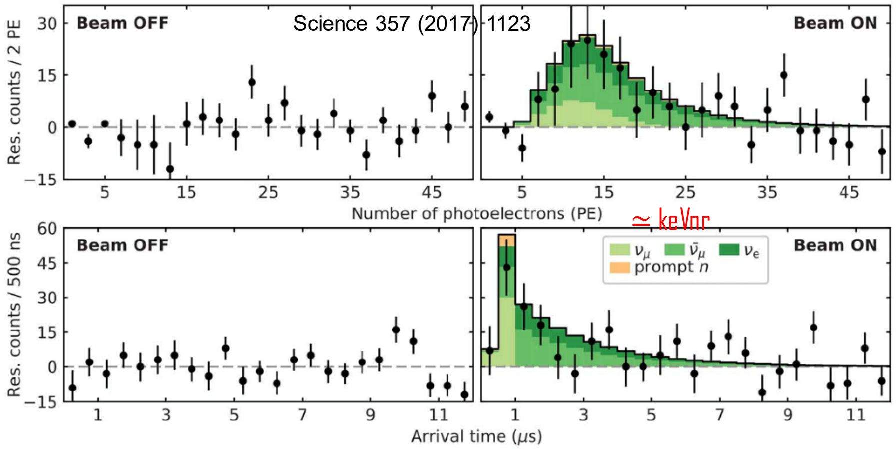
Abstract

Presently under construction in Lund, Sweden, the European Spallation Source (ESS) will be the world's brightest neutron source. As such, it has the potential for a particle physics program with a unique reach and which is complementary to that available at other facilities. This paper describes proposed particle physics activities for the ESS. These encompass the exploitation of both the neutrons and neutrinos produced at the ESS for high precision (sensitivity) measurements (searches).

Backup

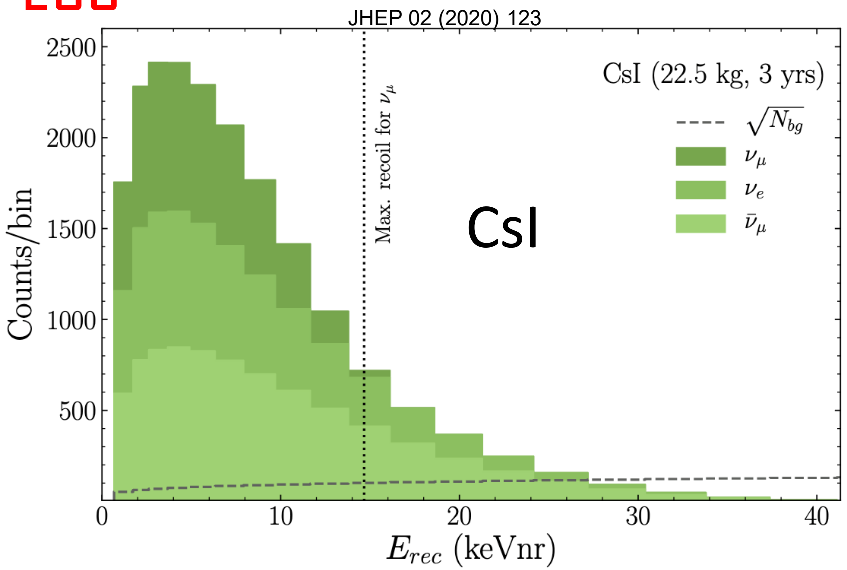
Expected recoil energies

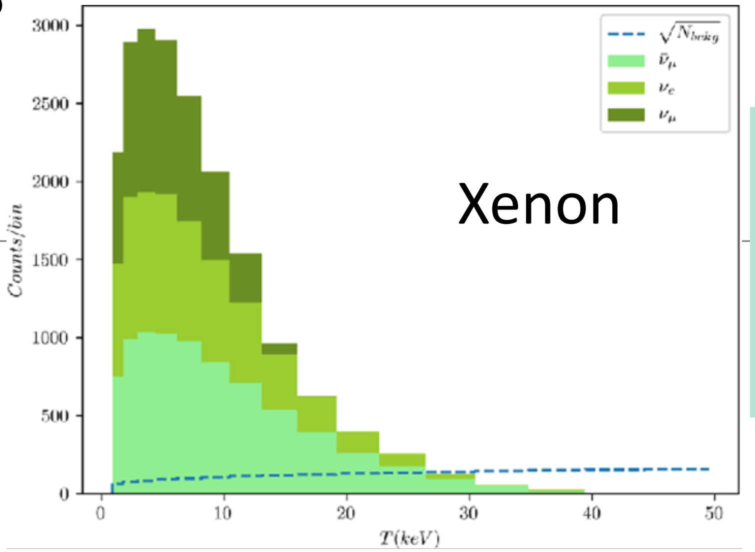
SNS



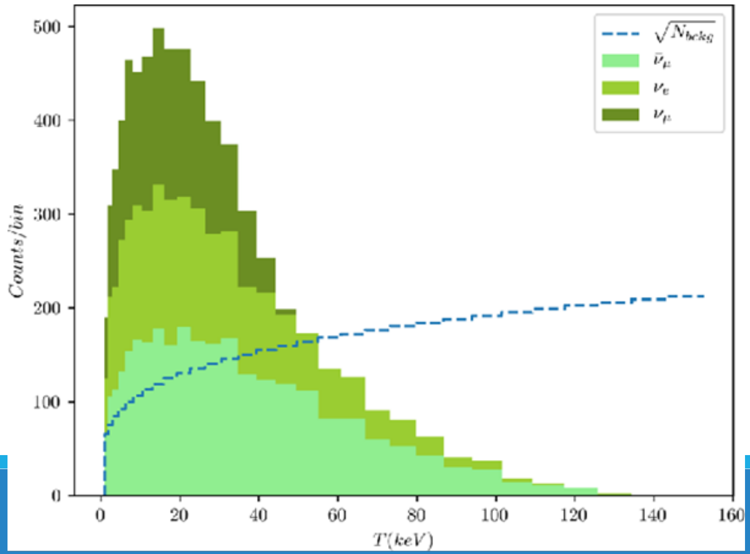
~×10 ν flux
~×10 low-E signal acceptance

ESS





Events after 3 years running a 20 kg Xe detector at 20 m from ESS target

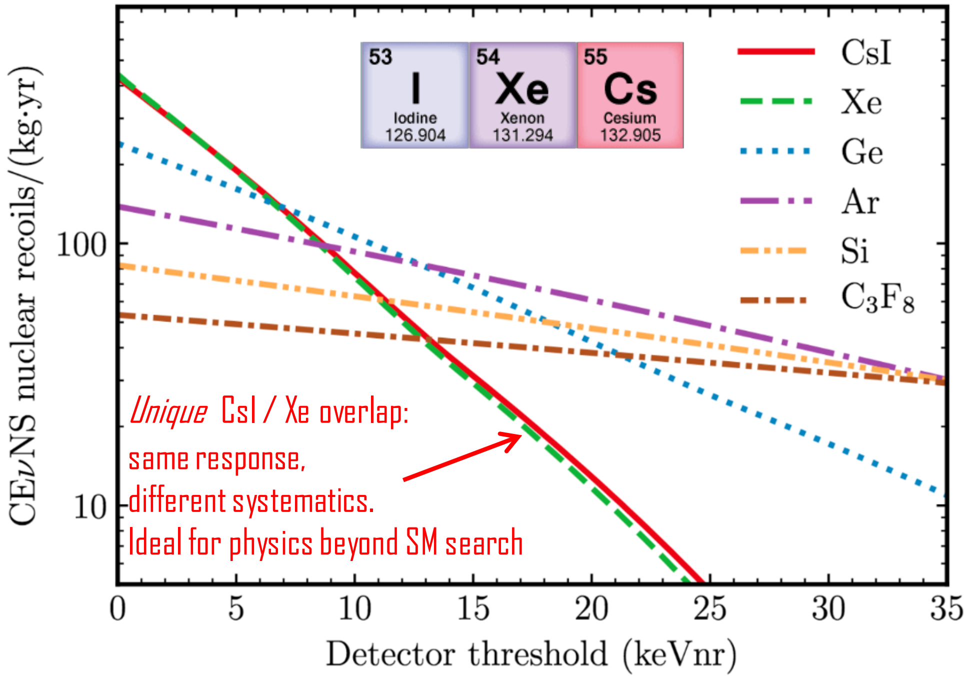


Argon

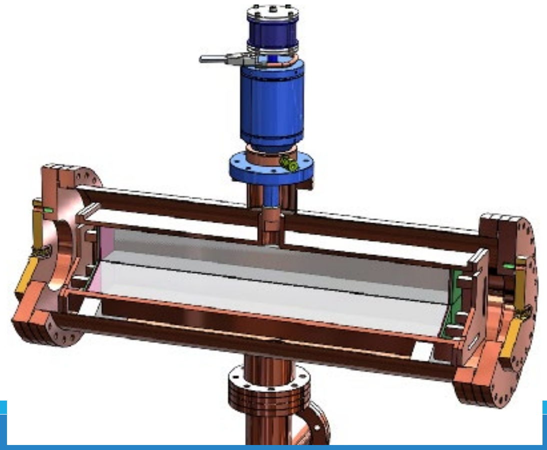
Gaseous detectors have smaller densities but not statistically limited at the ESS due to high ν flux

Detectors for the νESS

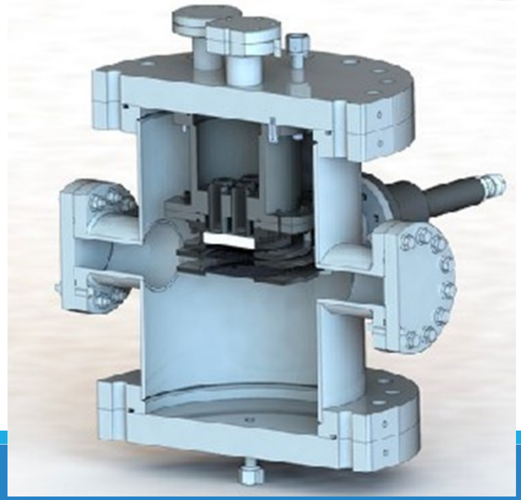
- Combination of technologies to minimise possible systematic effects.
- Use of different nuclei to allow for exploring larger fraction of the phase space, and similar nuclei with different technologies
- Right now two main technologies are being tested and developed, using CsI and Xe.

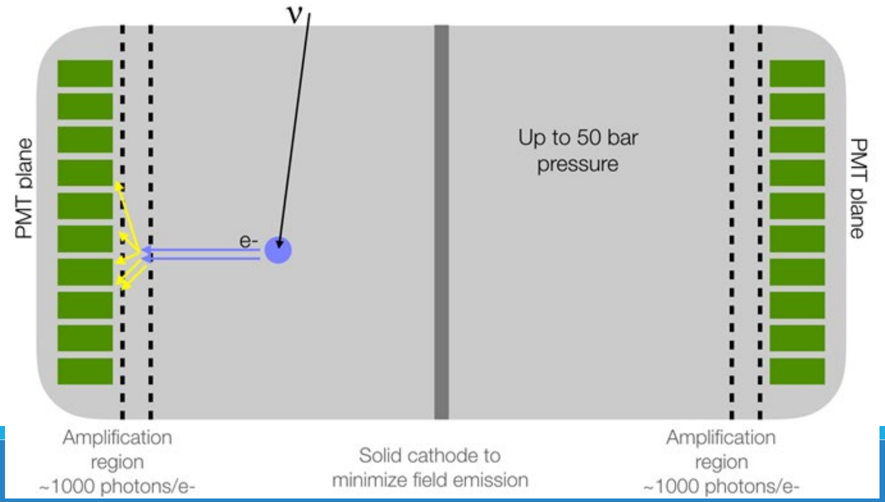


CsI scintillating crystals



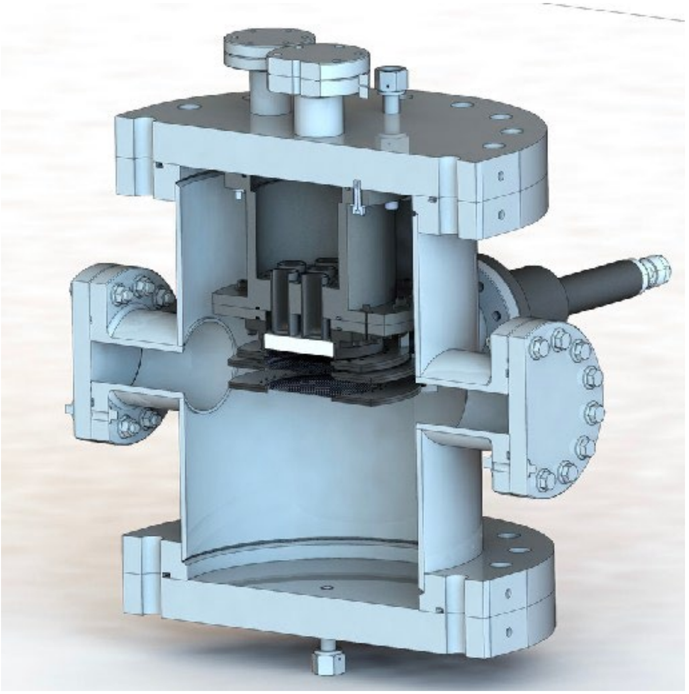
Gaseous detector prototype





GanESS Status

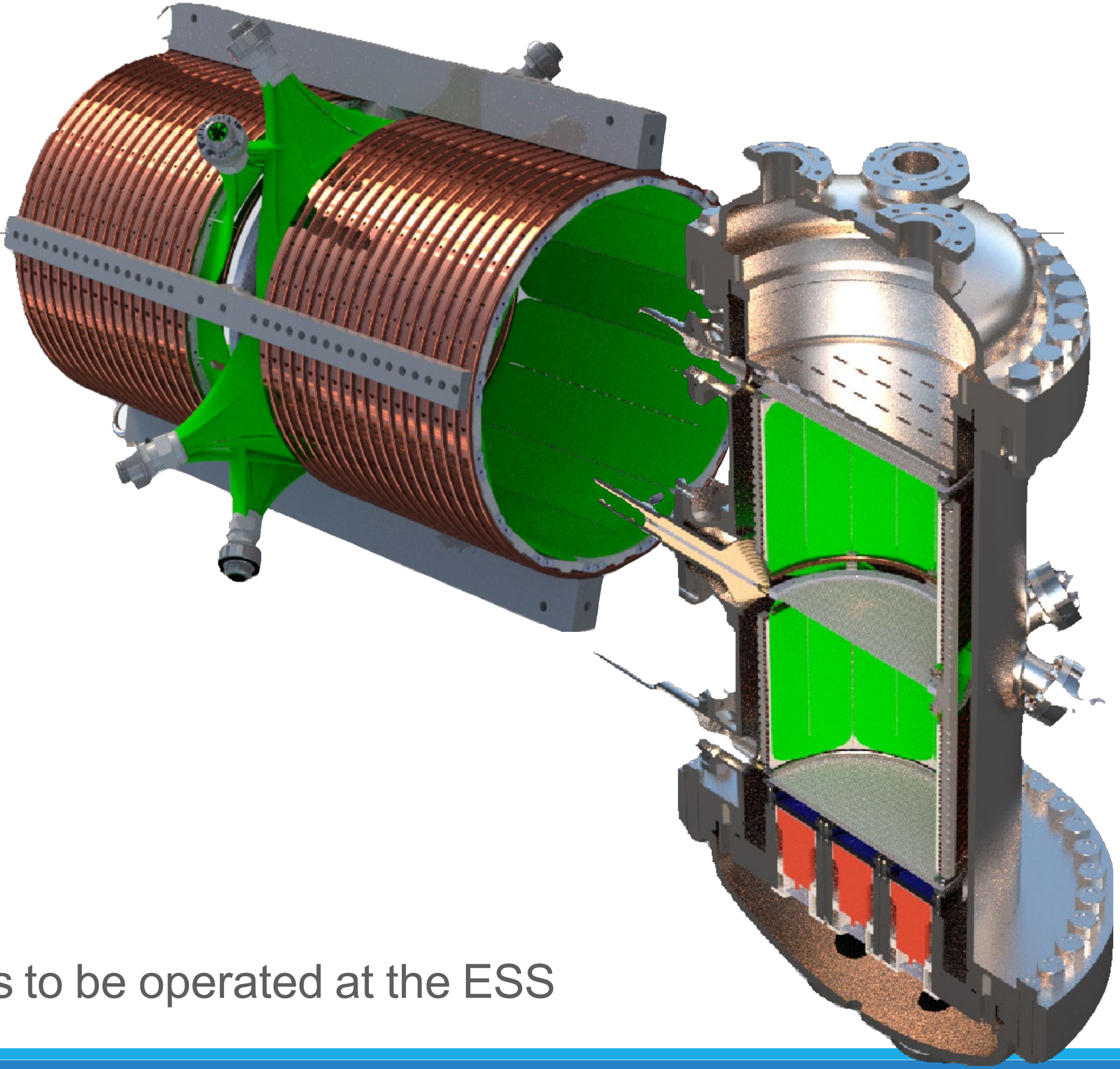
The Gaseous Prototype (GaP) system



- GaP vessel almost ready to operate.
- Expected initial operation before end of the year
- GaP system designed to measure Quenching Factor (QF)

GanESS Status

Design of large detector



Symmetric medium size detector being designed:

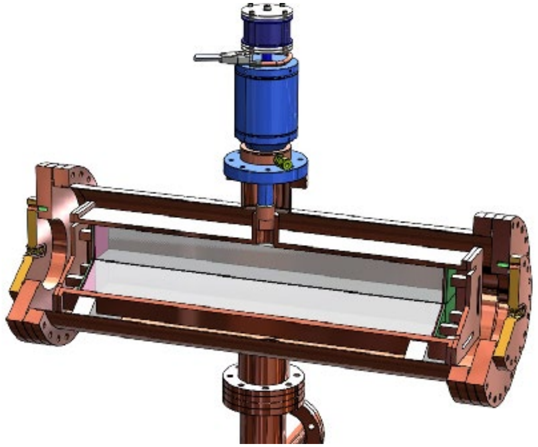
Explore the possibility to introduce optical fibres to optimise light collection:

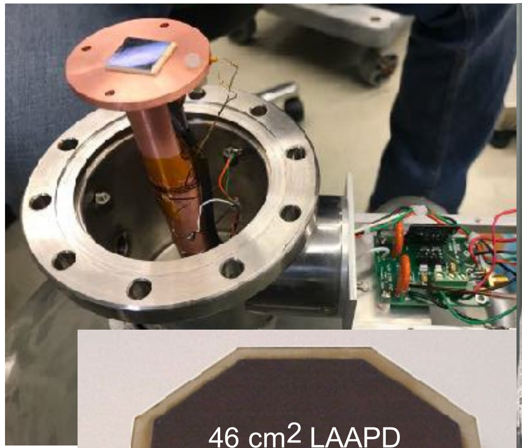
- Possibility to observe S1
- More uniform detector response

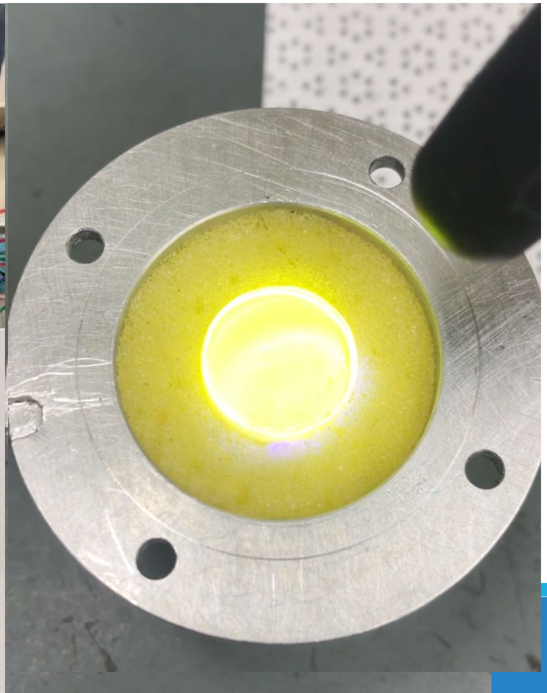
Test final solutions to be operated at the ESS

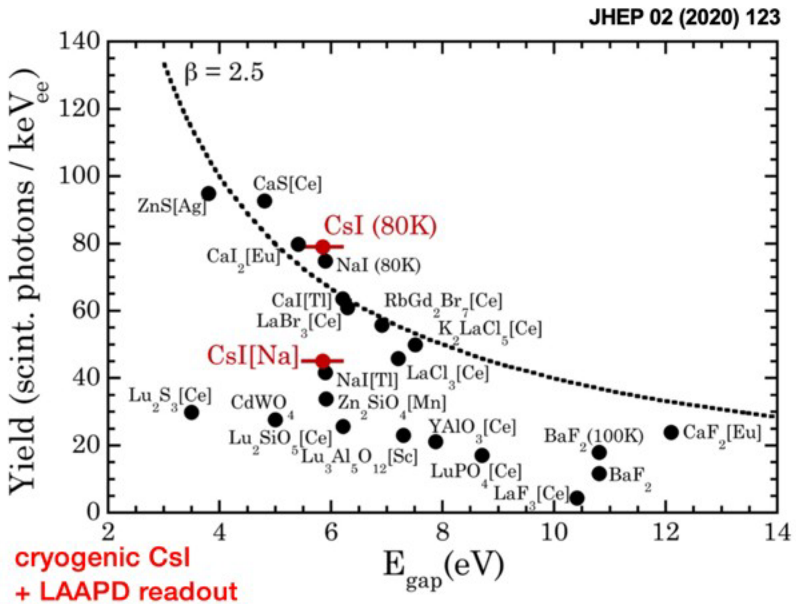
Cryo CsI

- Development of 32 kg CsI scintillator crystals operated at cryogenic temperatures.
- Light output enlarged thanks to the development of organic wavelength shifters.
- Production of large area APD to improve signal.

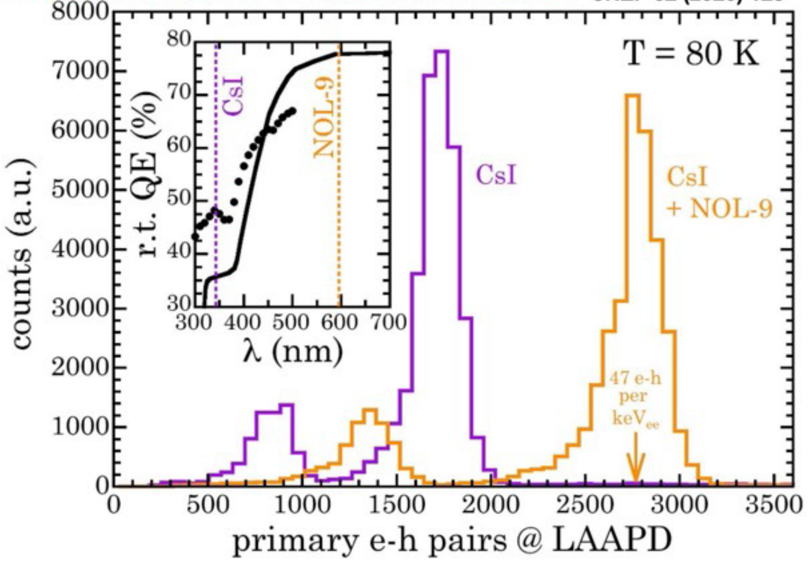






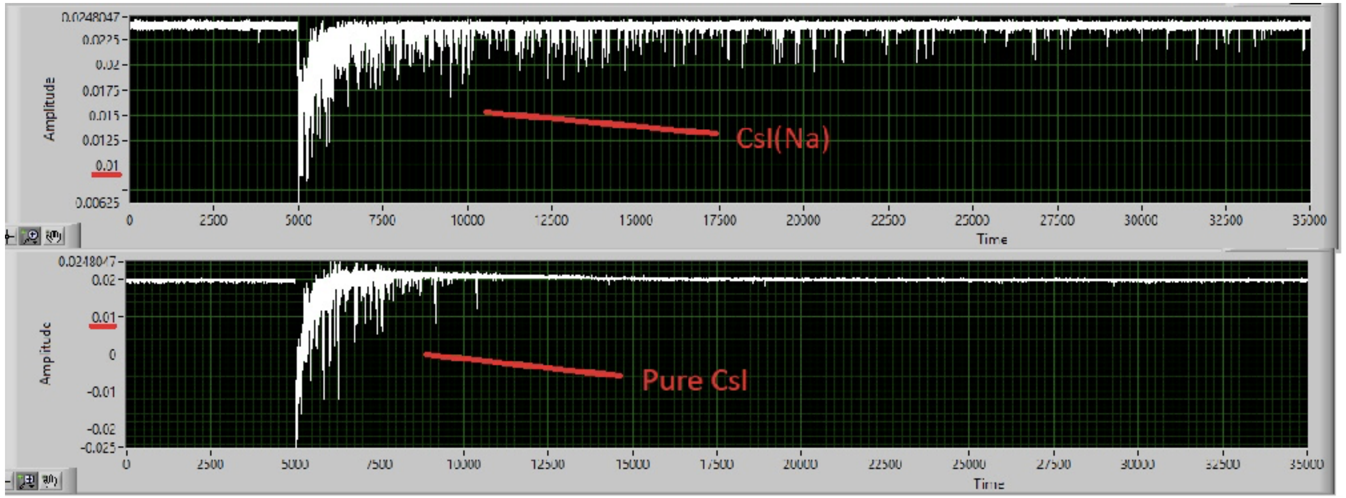


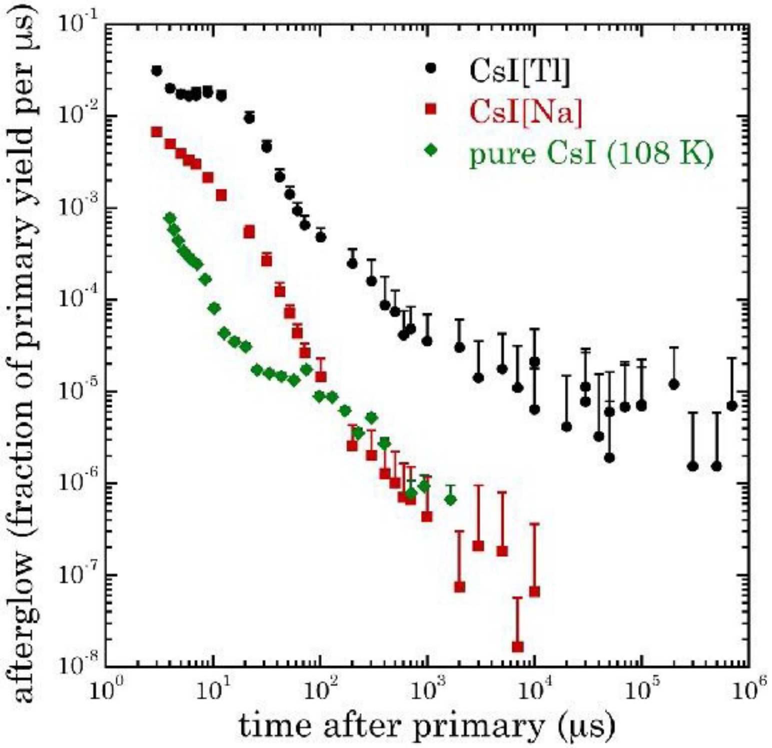
cryogenic CsI
+ LAAPD readout
+ NOL waveshifter = record scintillator yield



Cryo CsI

- Transition from CsI(Na) to CsI





CsI[Tl] excessive afterglow

CsI[Na] workable, but with significant signal acceptance loss

Reduction of the after glow improves Energy threshold.