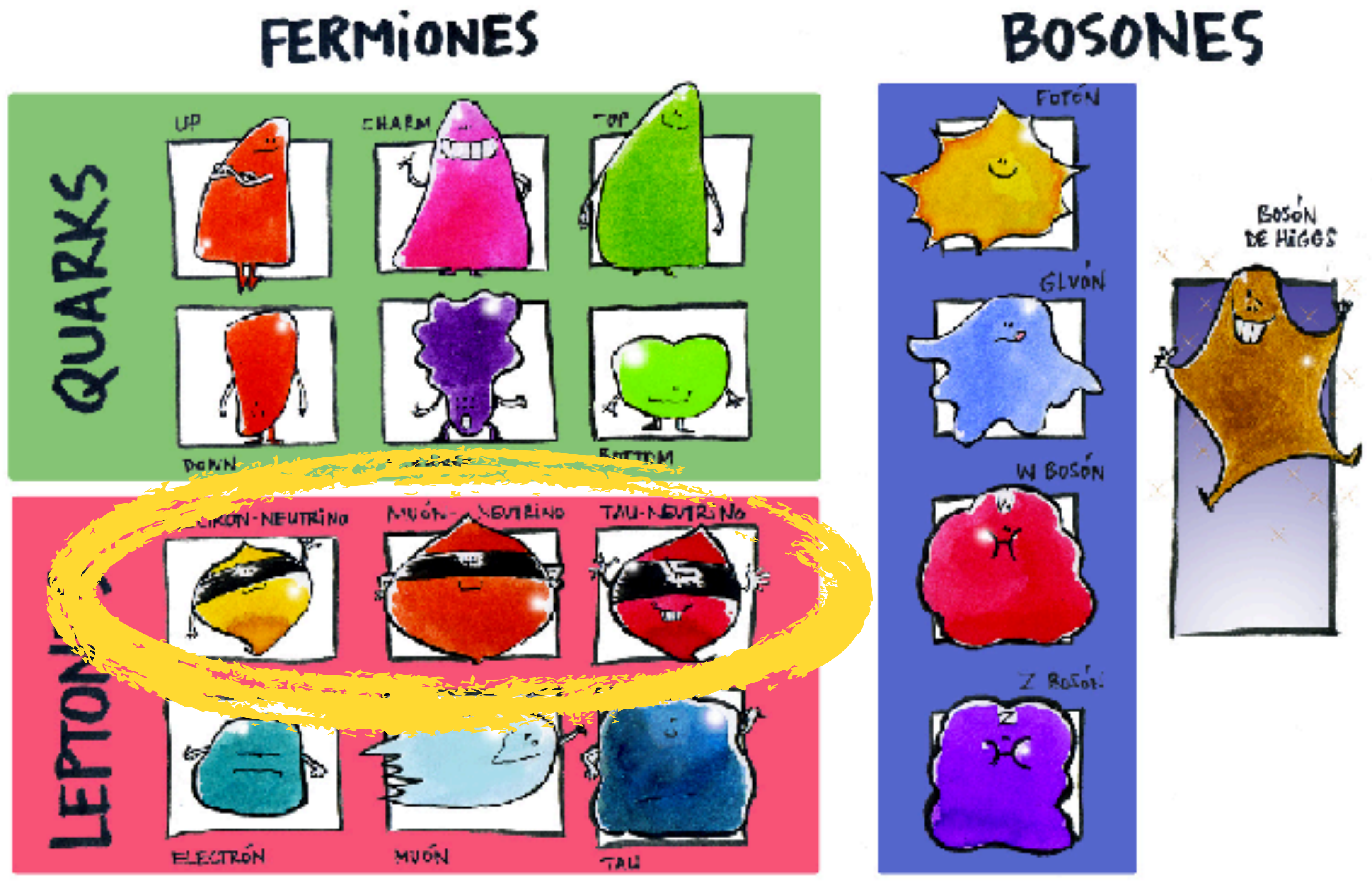
# Coherent Neutrino-Nucleus scattering at the ESS

F. Monrabal on behalf of the nuESS Coll.

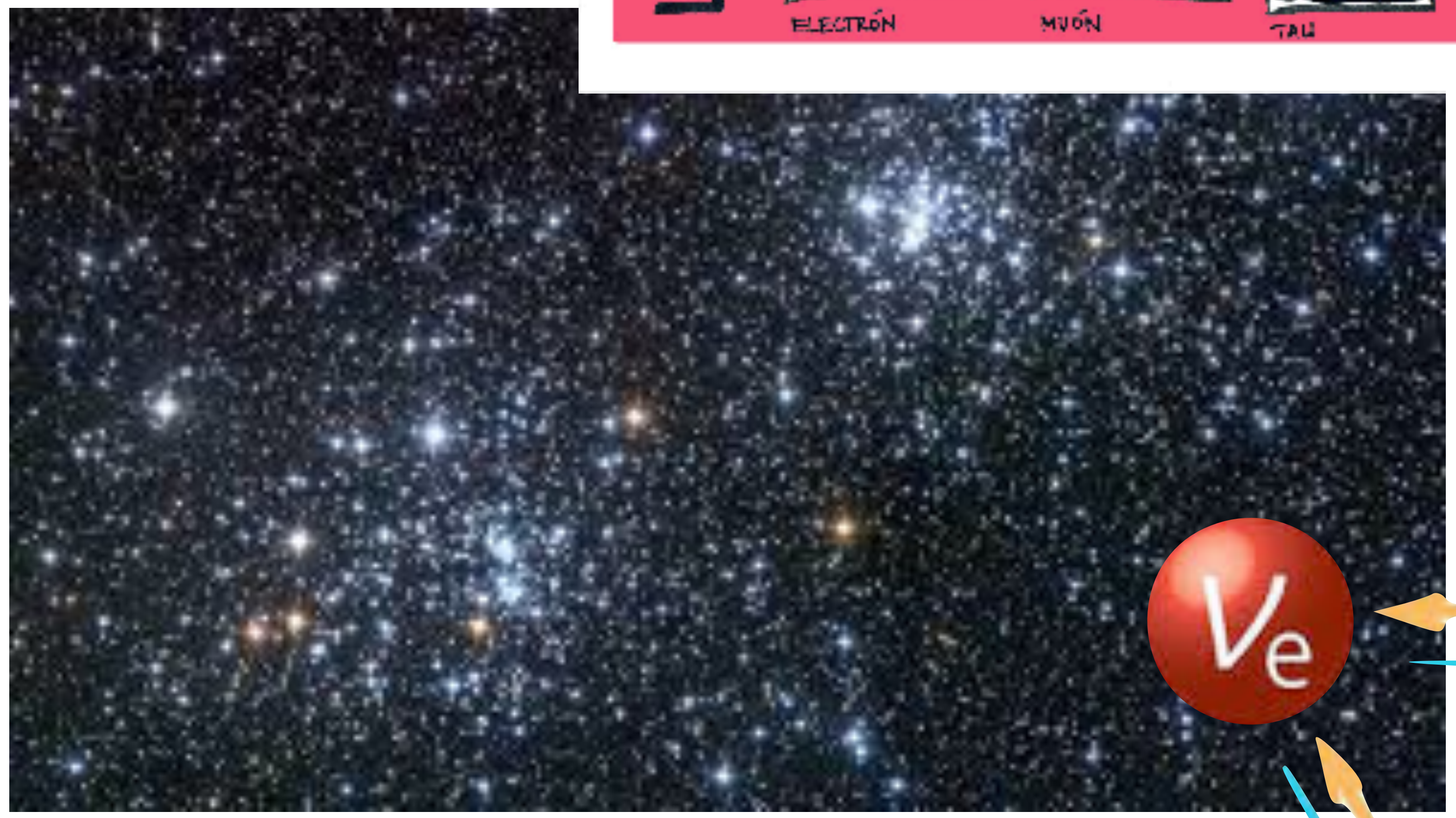
**ESS User's meeting, Lund 5-7 October 2022**

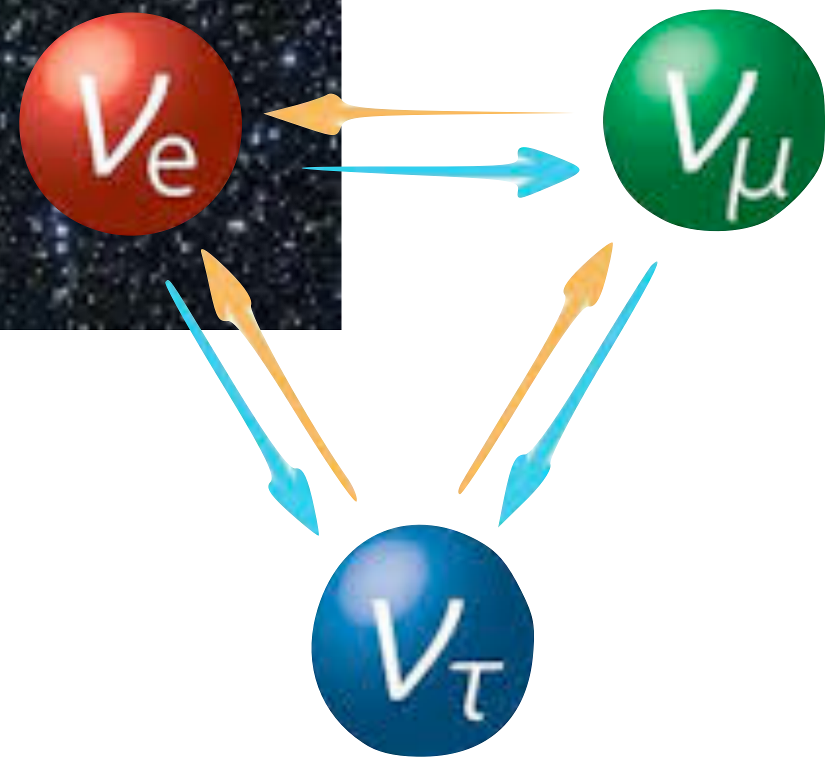
DIPC ikerbasque Basque Foundation for Science EUSKO JAURLARITZA GOBIERNO VASCO HEZKUNTZA SAILA DEPARTAMENTO DE EDUCACIÓN erc European Research Council

# Neutrinos: what we know




@raquelberryfinn






Interact only weakly

- No color, no electric charge

Three light ($<m_Z/2$) neutrino states

- νe, νμ, ντ flavors

Neutrino number density in Universe only outnumbered by photons

- $n(\nu+\bar{\nu}) \approx 100$ cm$^{-3}$ per flavor

From neutrino oscillations:

- Neutrinos are massive (lightest known fermions)
- Large flavor mixing

# Neutrinos…

Most elusive particles ever detected

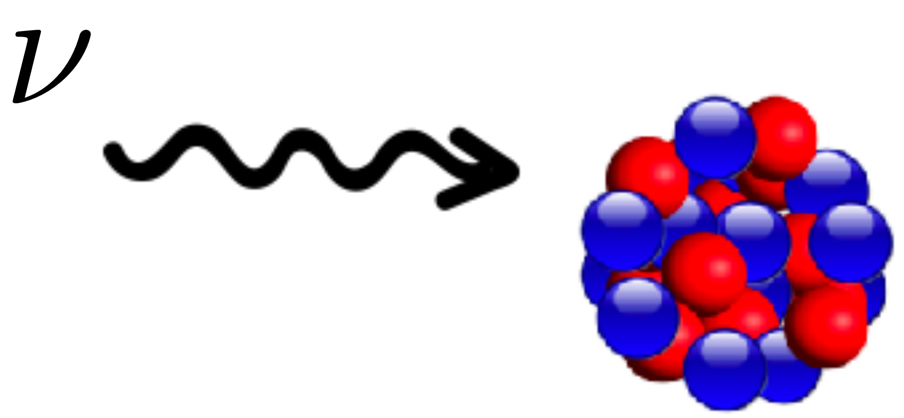
Nobel Prize in Physics in 1988, 1995, 2002, 2015,…

First demonstration of Physics beyond the Standard Model

Detecting neutrinos requires very large detectors with tons of active material. Right?

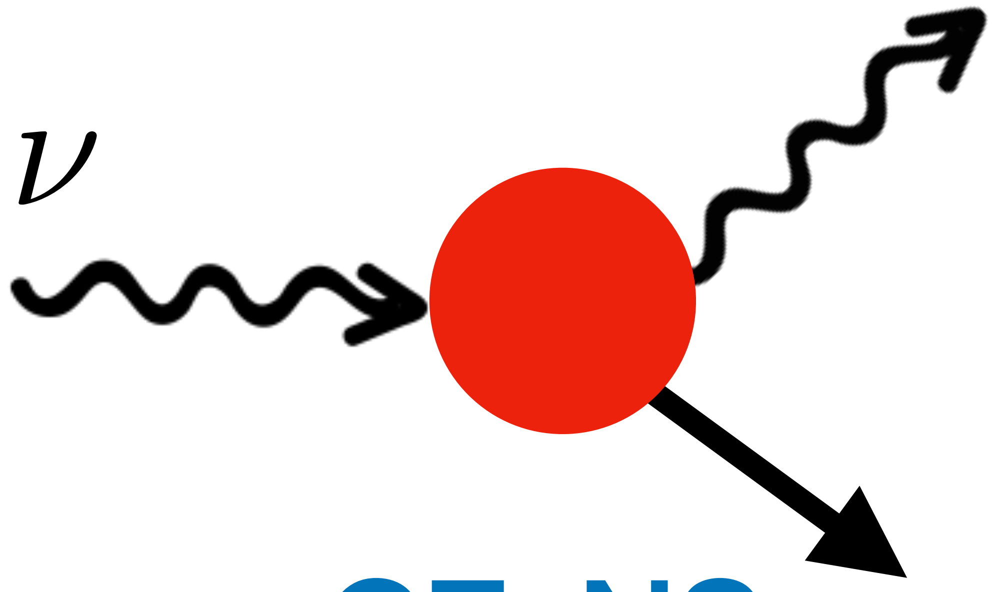
# COHERENT NEUTRINO NUCLEUS SCATTERING

# Coherent Elastic Neutrino-nucleus scattering




Long wavelength, “sees” all nucleons simultaneously

$$\sigma \sim N^2$$



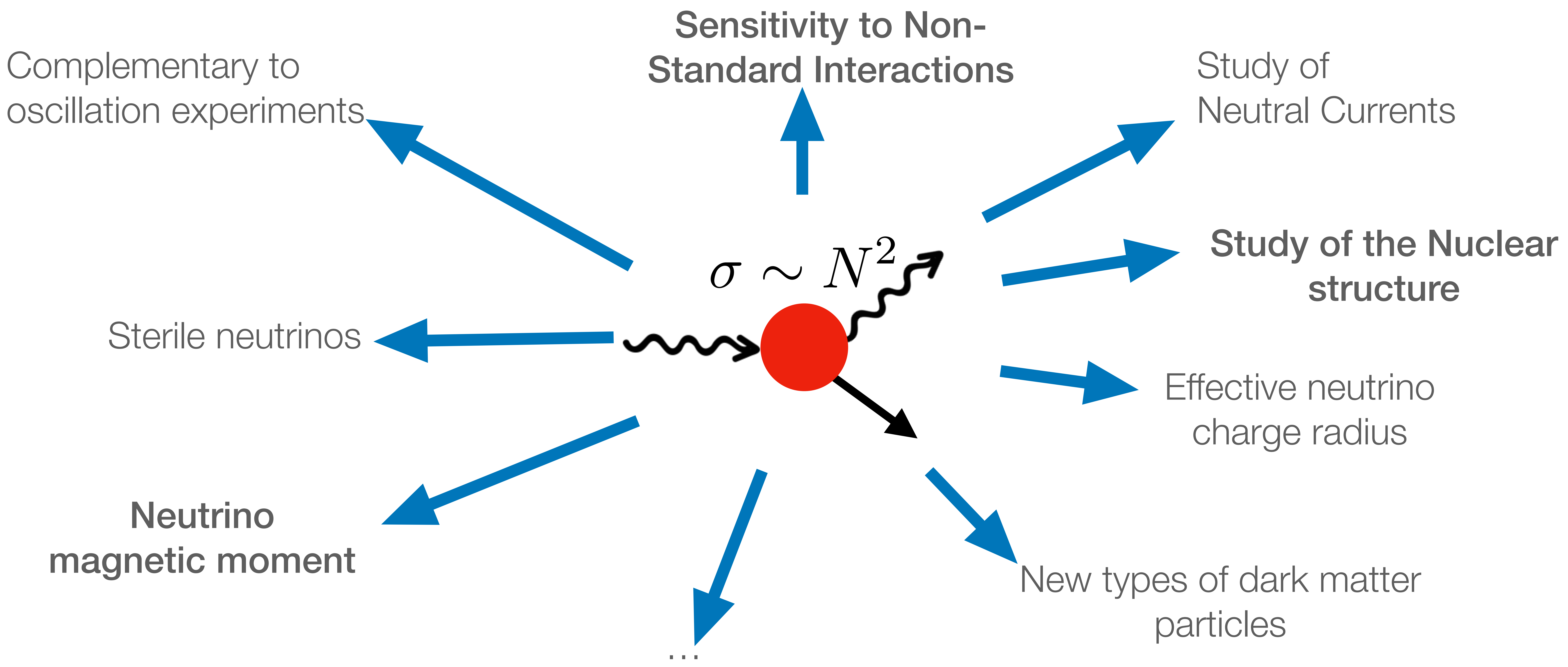

CEvNS

Cross section increases as $N^2$. Four orders of magnitude increase for large nucleus!


First observation published in 2017

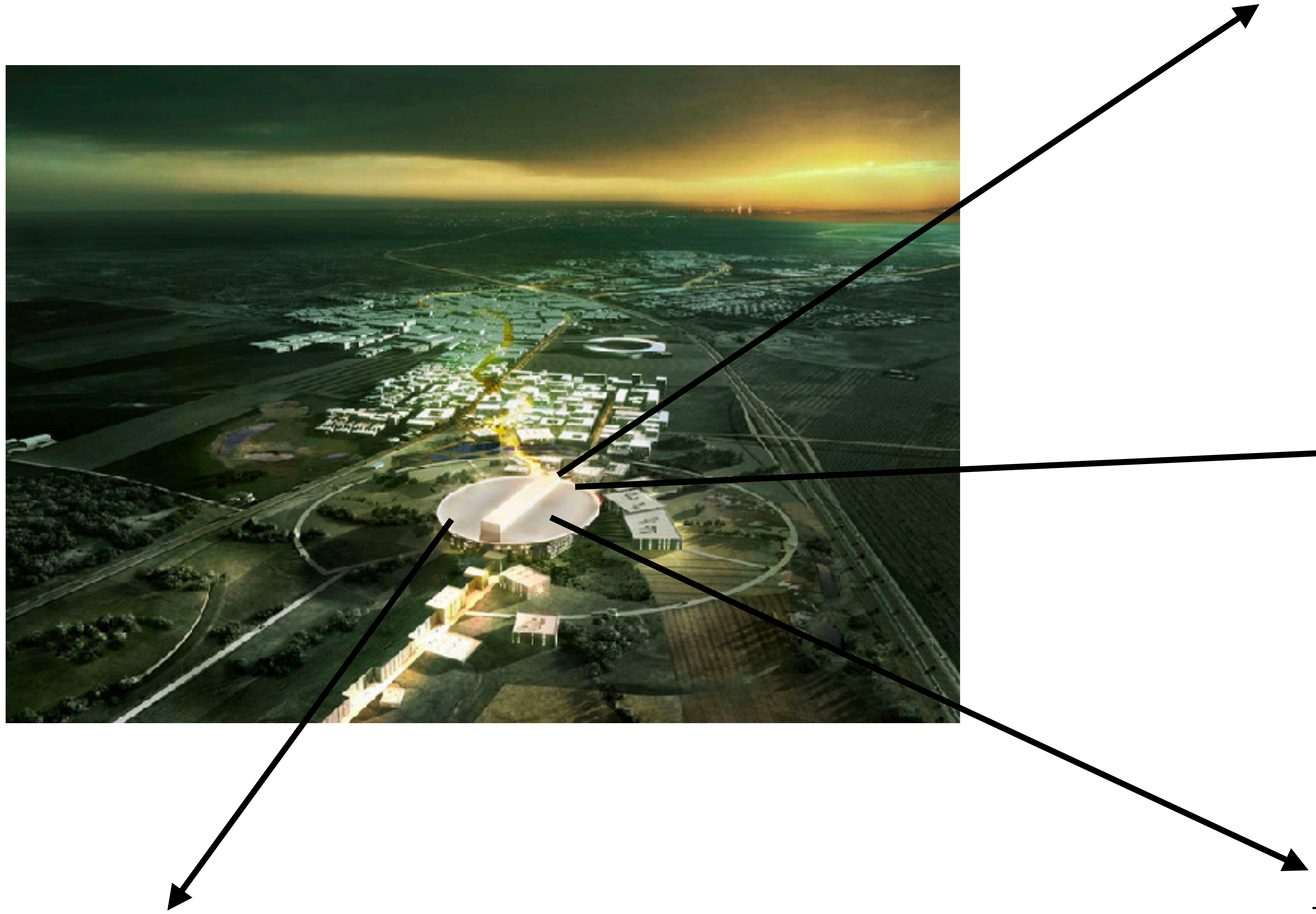
# Coherent Elastic Neutrino-nucleus scattering

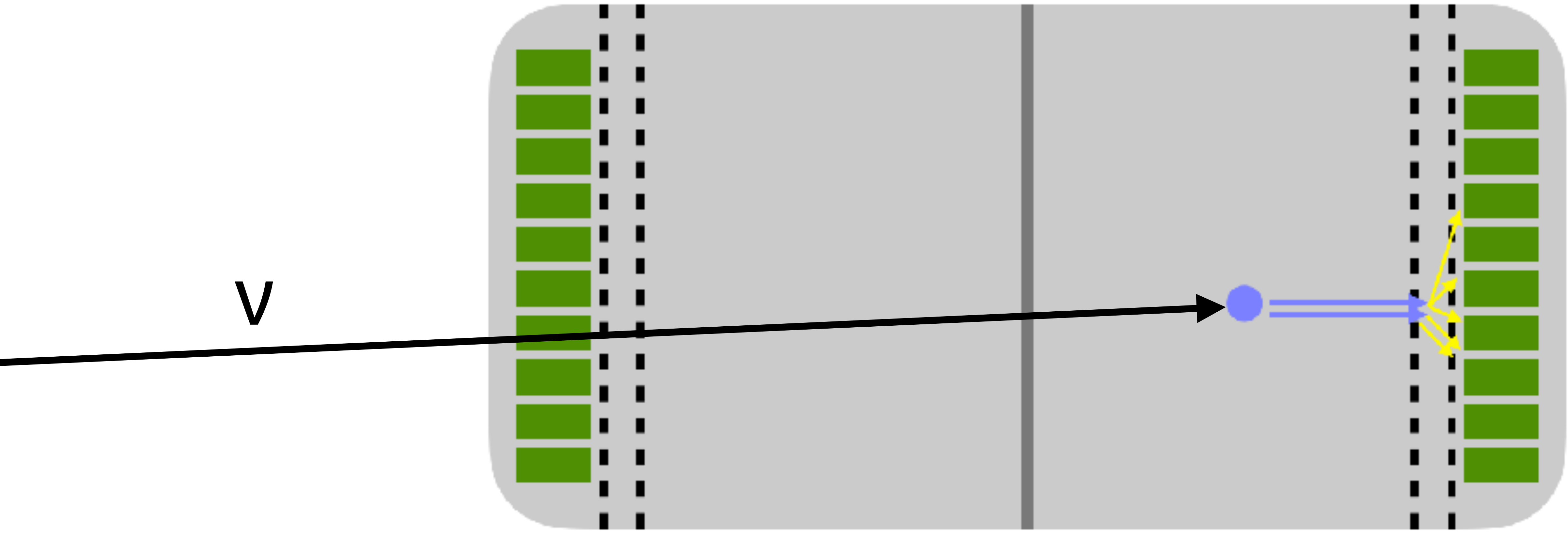
## Very rich physics



# Detecting CEvNS

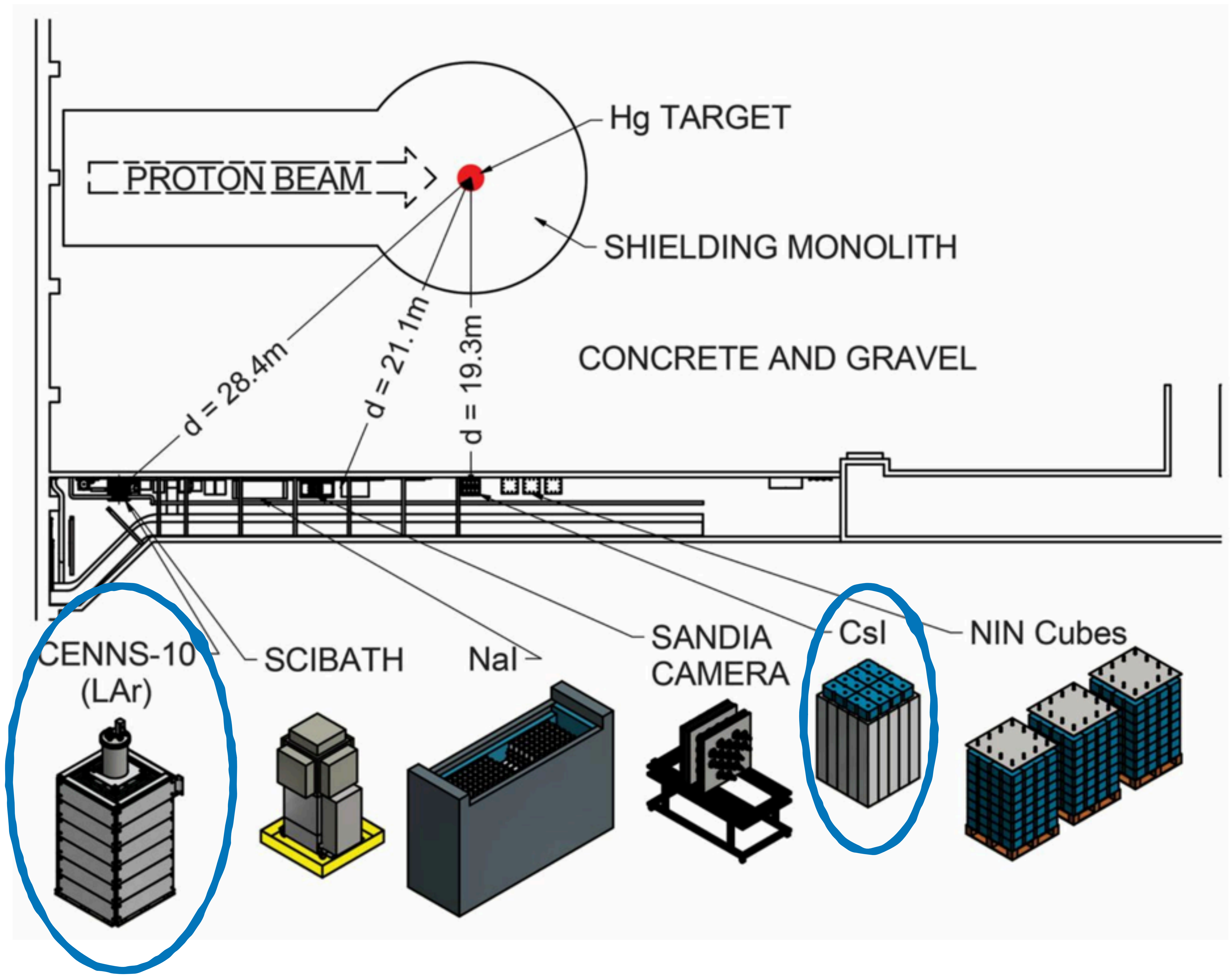
CEvNS sources, must be sufficiently intense in yield, and low enough in neutrino energy so the coherence condition can be satisfied.



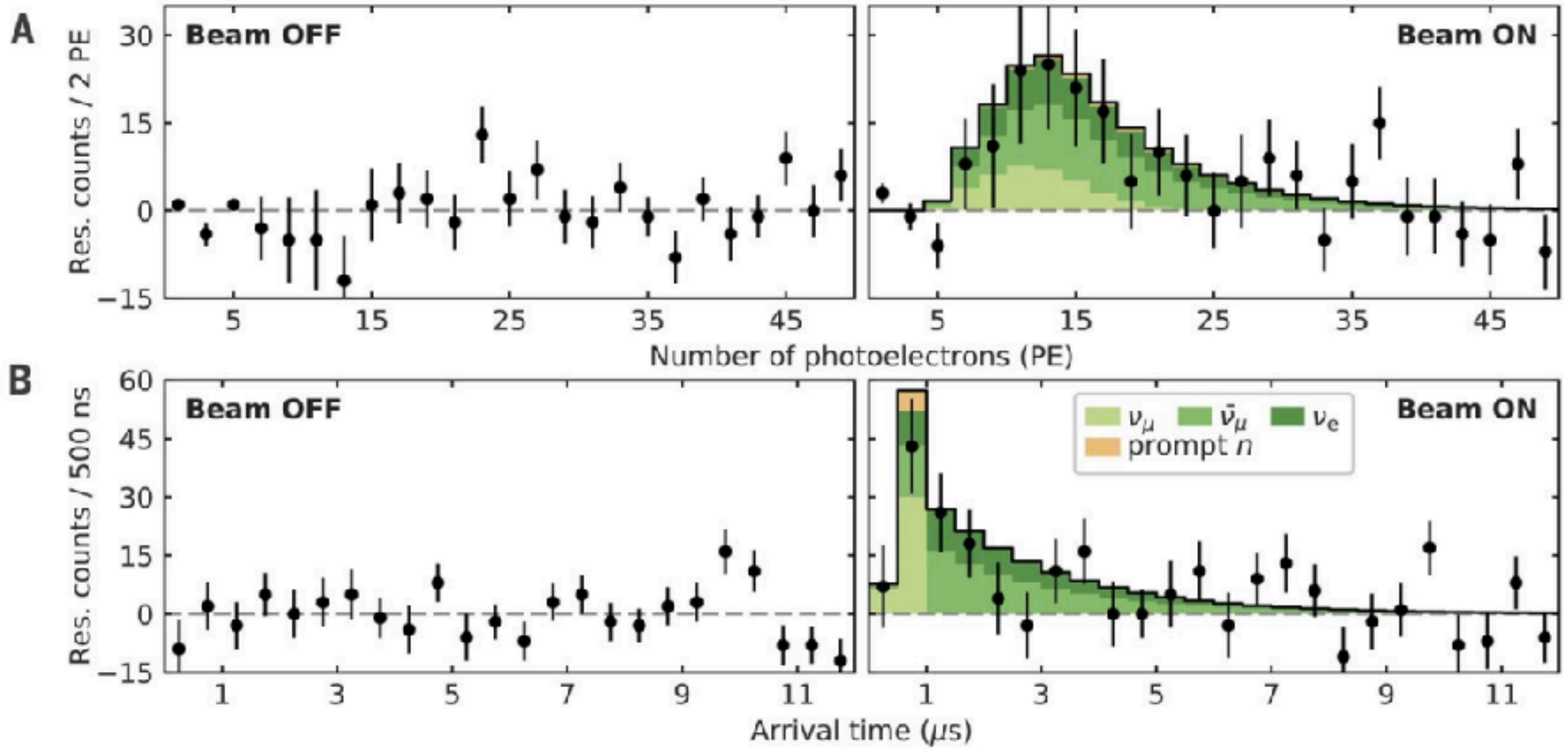



~10 kg size detectors.

# Detecting CEvNS: First observation



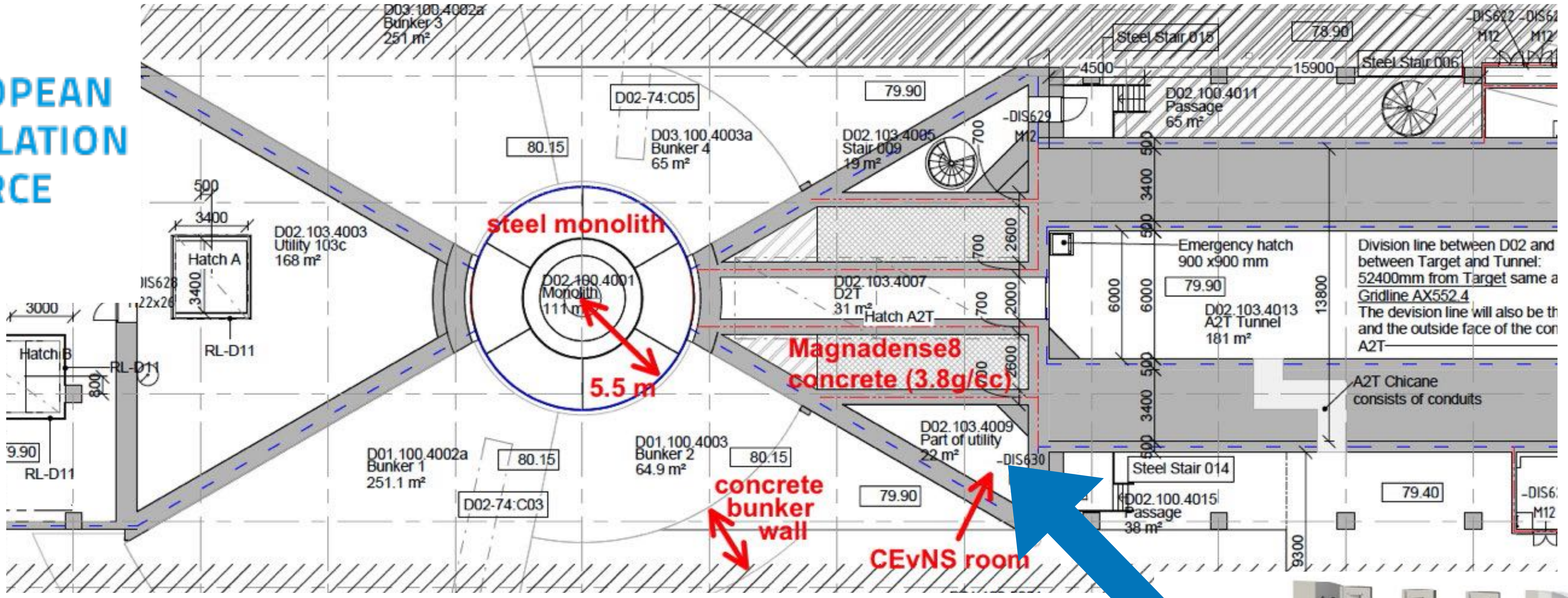

Science 357, 1123–1126 (2017)

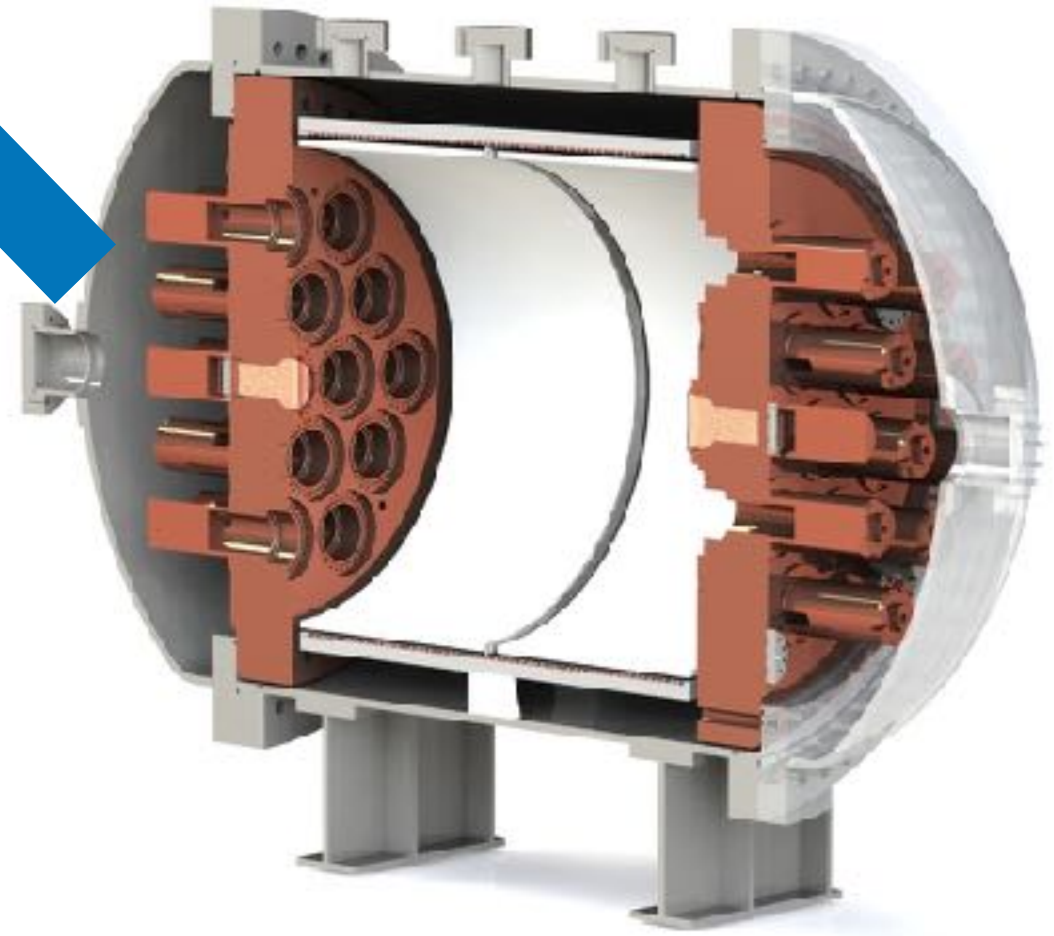



Detection of the coherent scattering less than 5 years ago demonstrates a new mechanism to observe neutrinos.

# Detecting CEvNS: Future observations

EUROPEAN SPALLATION SOURCE



**ESS** will produce the largest low energy neutrino flux of the next generation facilities.

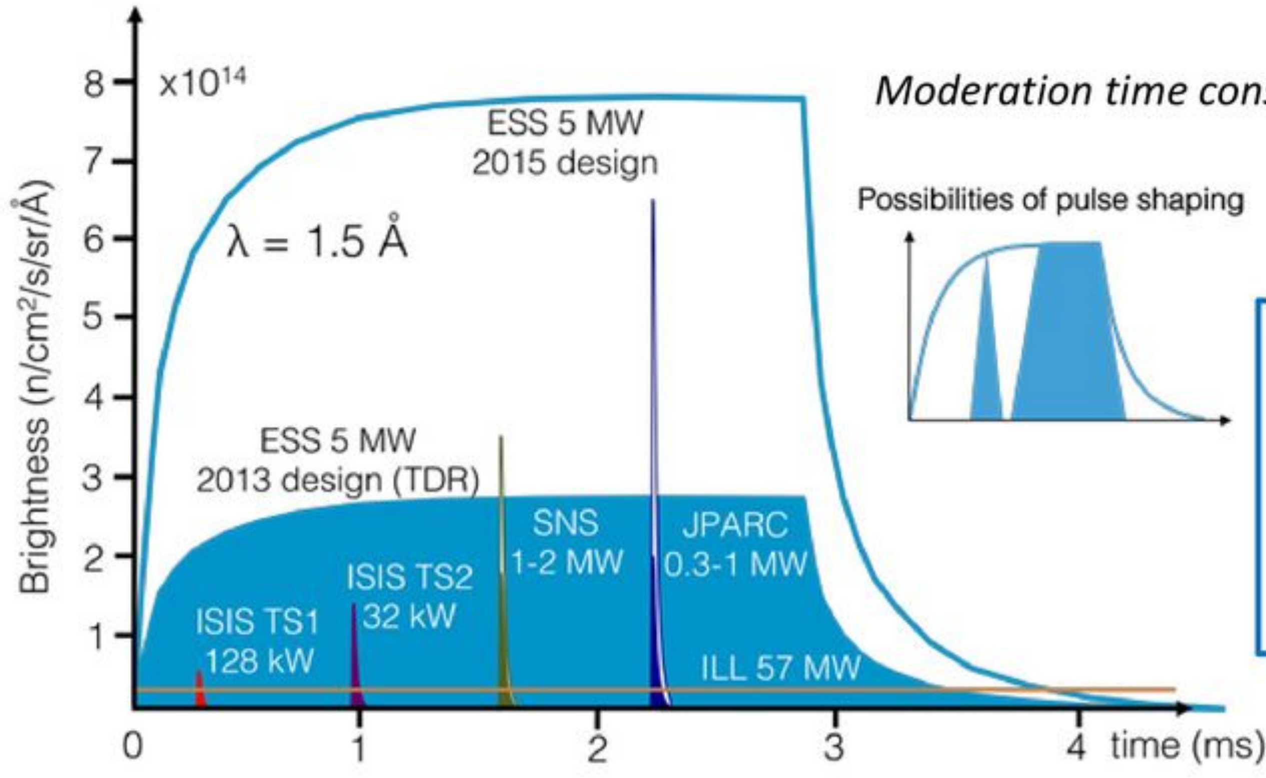
# A new opportunity for CEvNS

## 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.
- A great opportunity for Europe to lead this physics program!

### 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 |

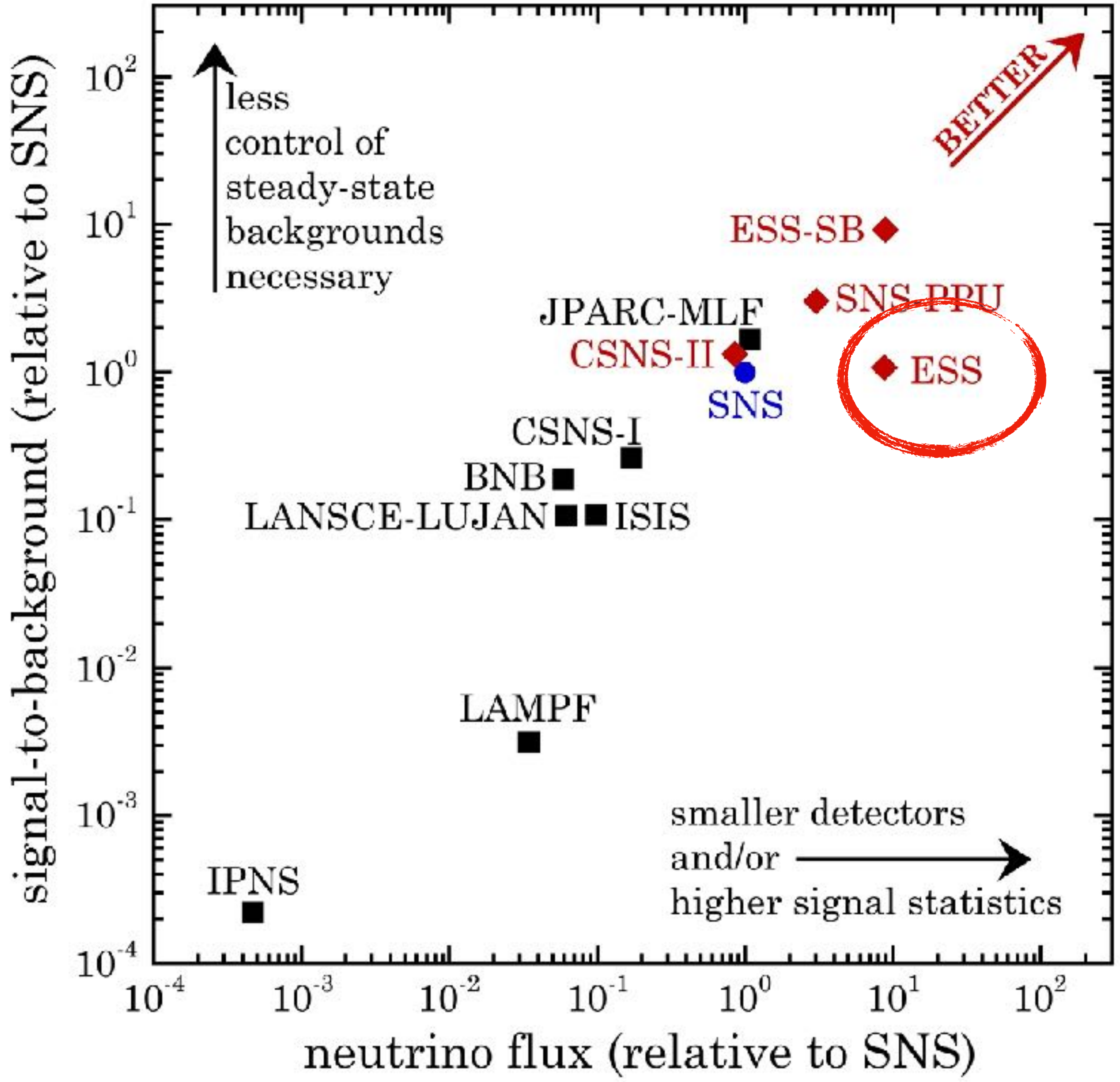



Time-averaged brightness:
**ESS ~ ILL**
Peak brightness:
**ESS ~ 30 × ILL**

2

# A new opportunity for CEvNS

## Comparison with current and future facilities

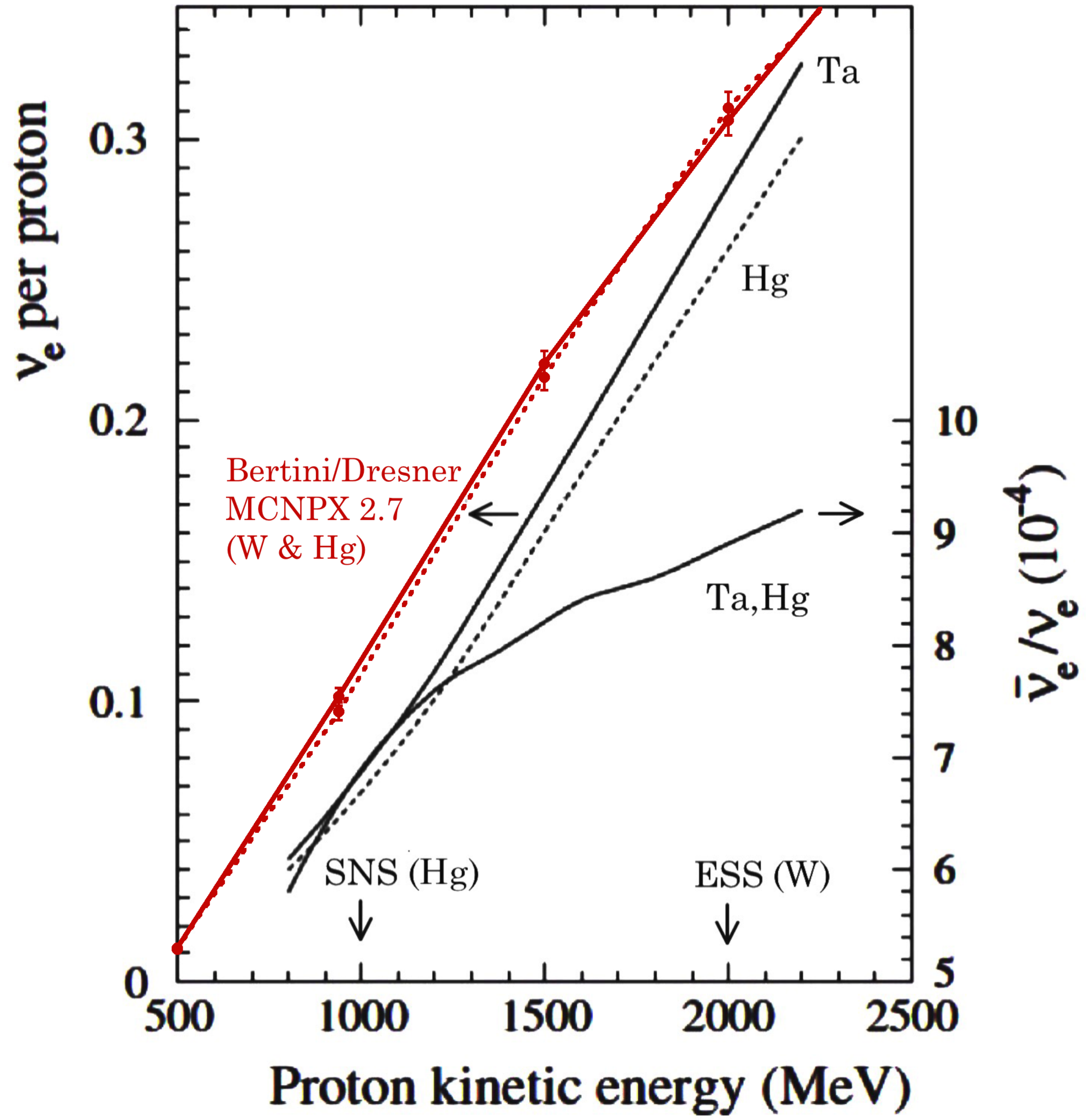


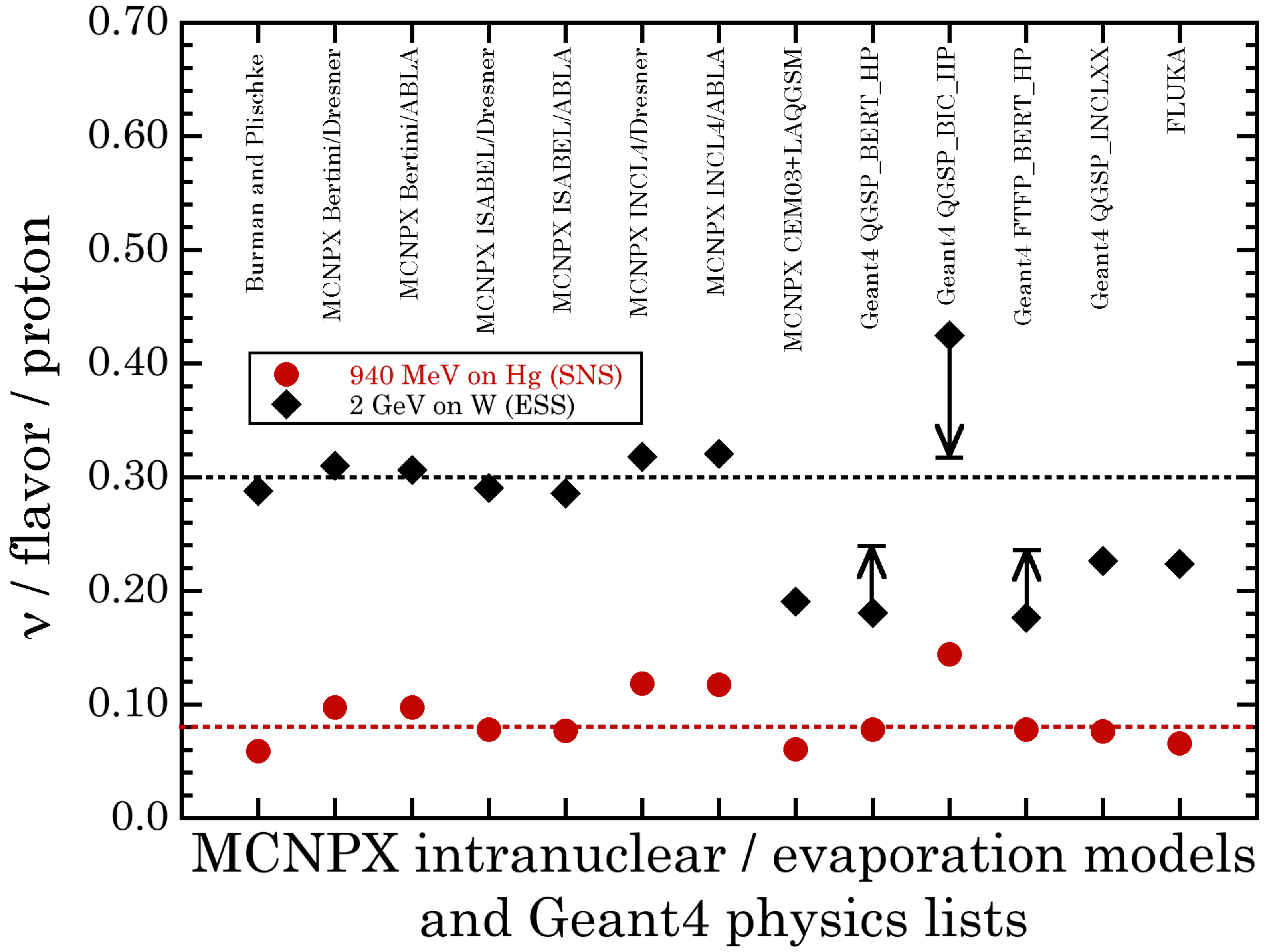

- ESS will produce the largest low energy neutrino flux of the next generation facilities.
- This is a unique opportunity that allows the use of small detectors.
- Diversity of technologies not statistically limited guarantees the phenomenological exploitation of the measurements.

# A new opportunity for CEvNS

## ESS vs SNS

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

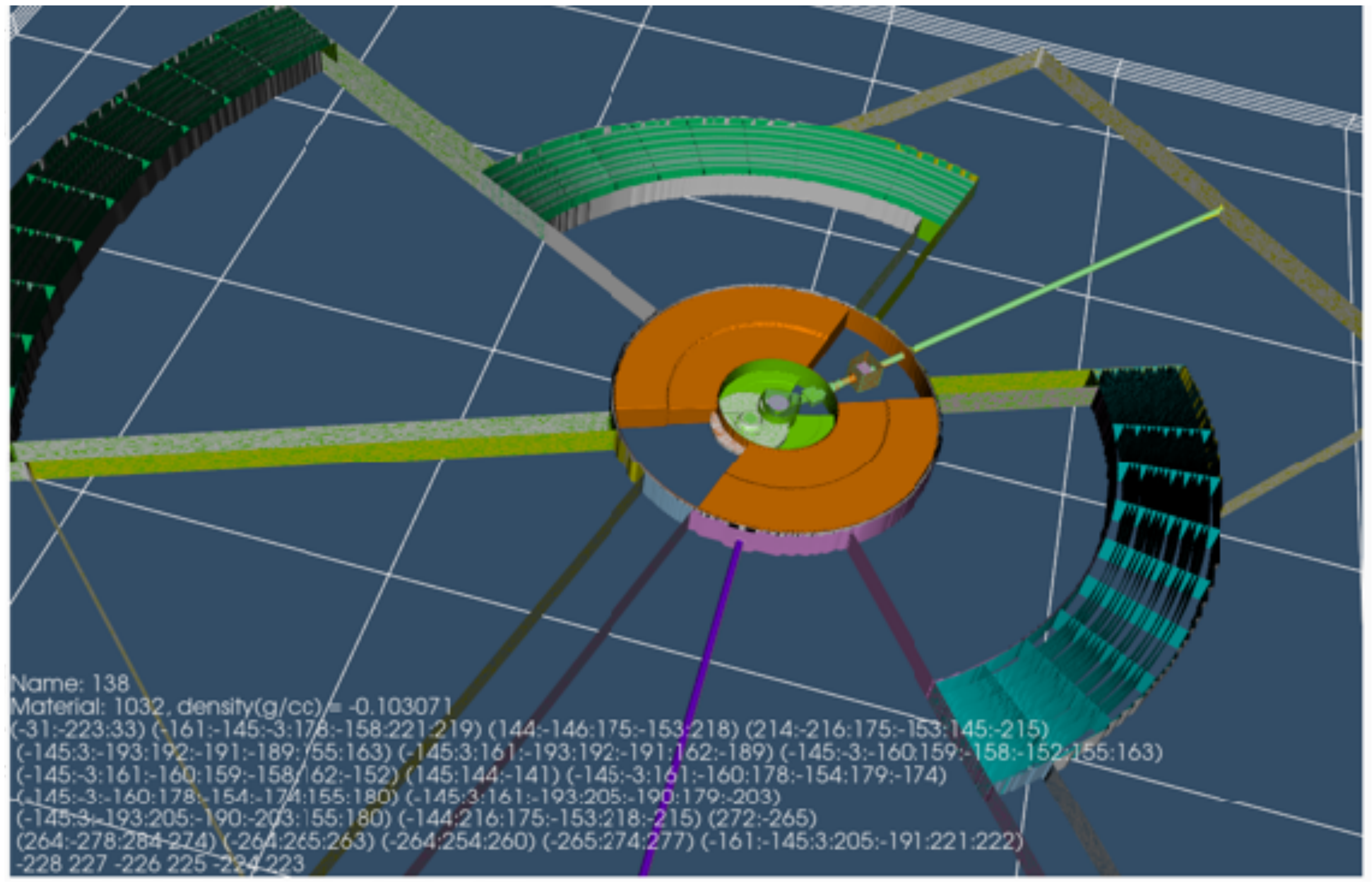


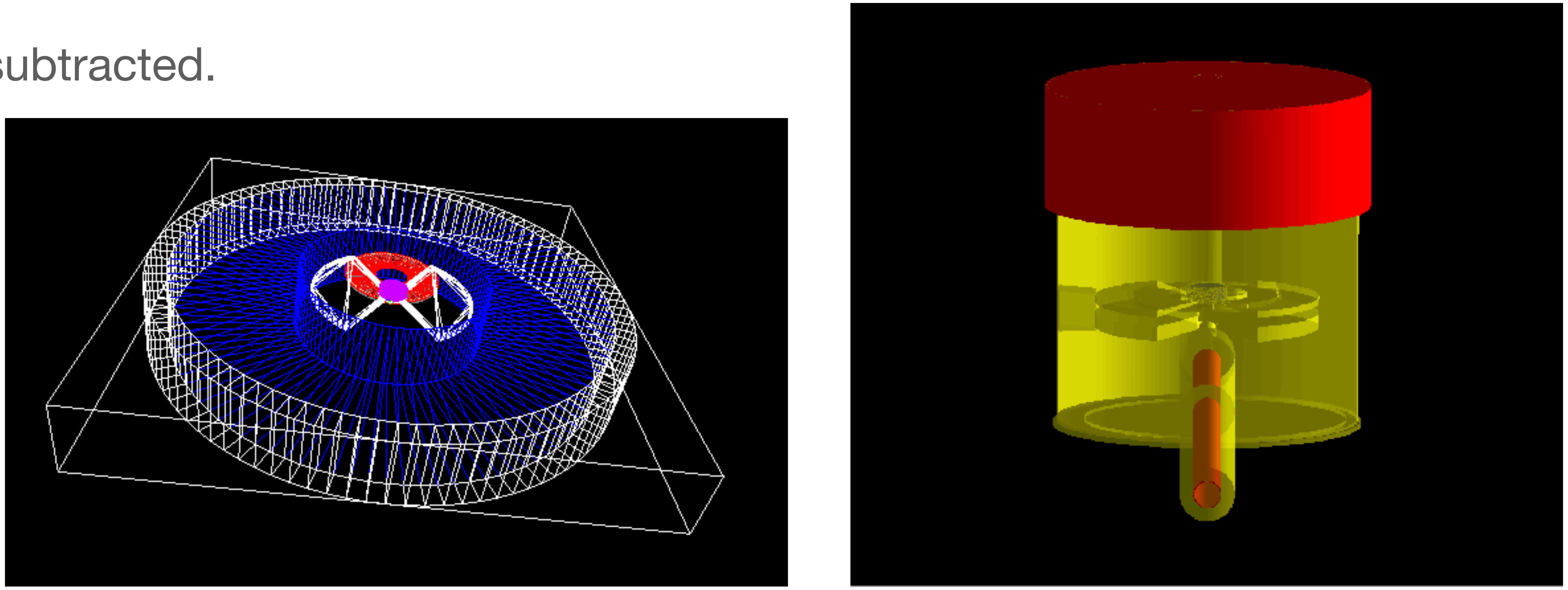
# A new opportunity for CEvNS

## Background at the ESS

- We need to find locations where the prompt neutrons from the ESS tungsten target do not compete with CEvNS signals.
- Working together with Ben Gurion University and U. Chicago, with support from ESS personel
- Two promising locations have already been identified.
- Steady-state background can be subtracted.




Radiation transportation code using MCNPX



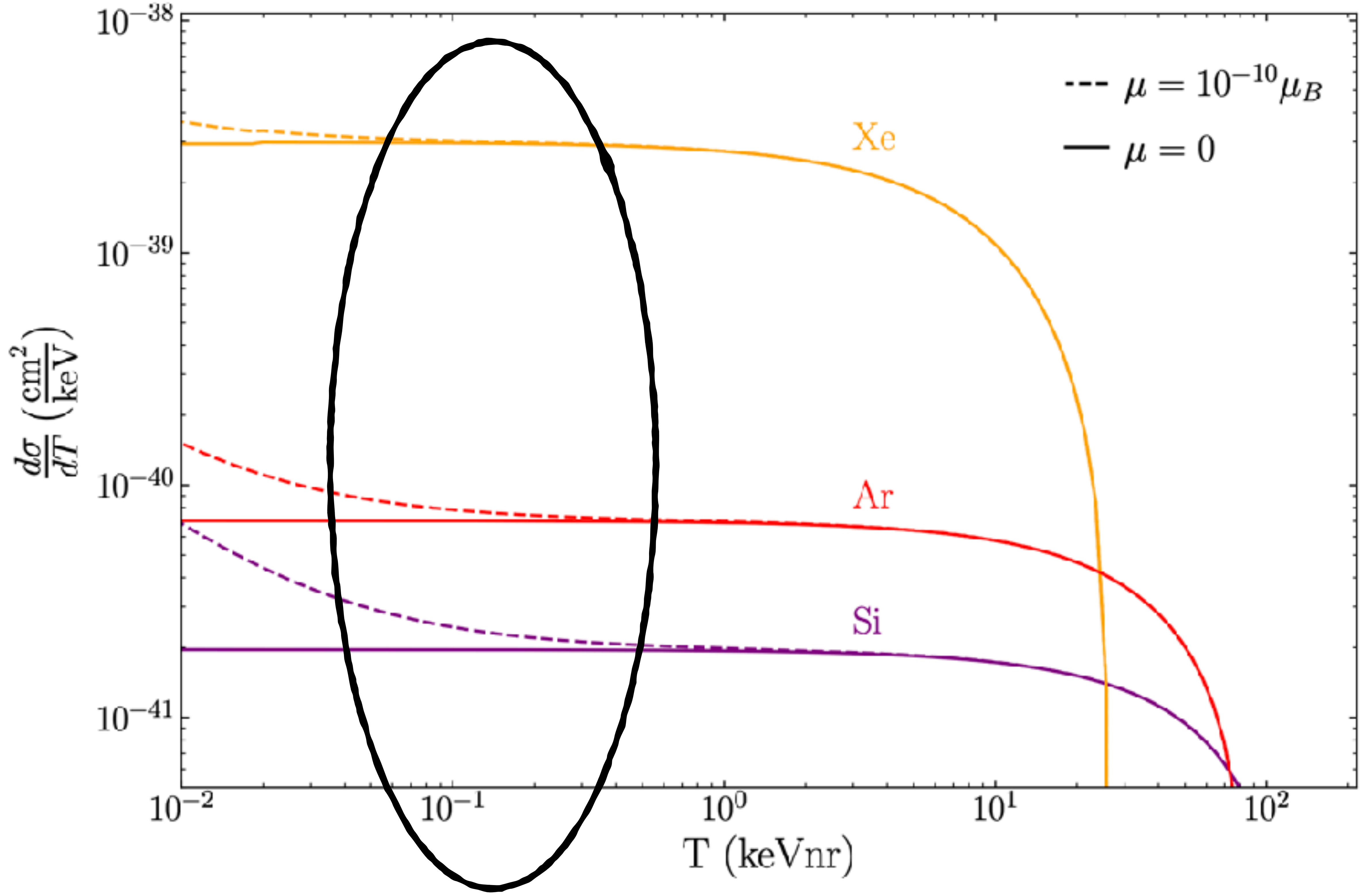
Compare results with Geant4 simulation toolkit

# Detecting CEvNS

## Detectors

Neutrino magnetic moment, new physics!

Ultra low energy threshold is crucial



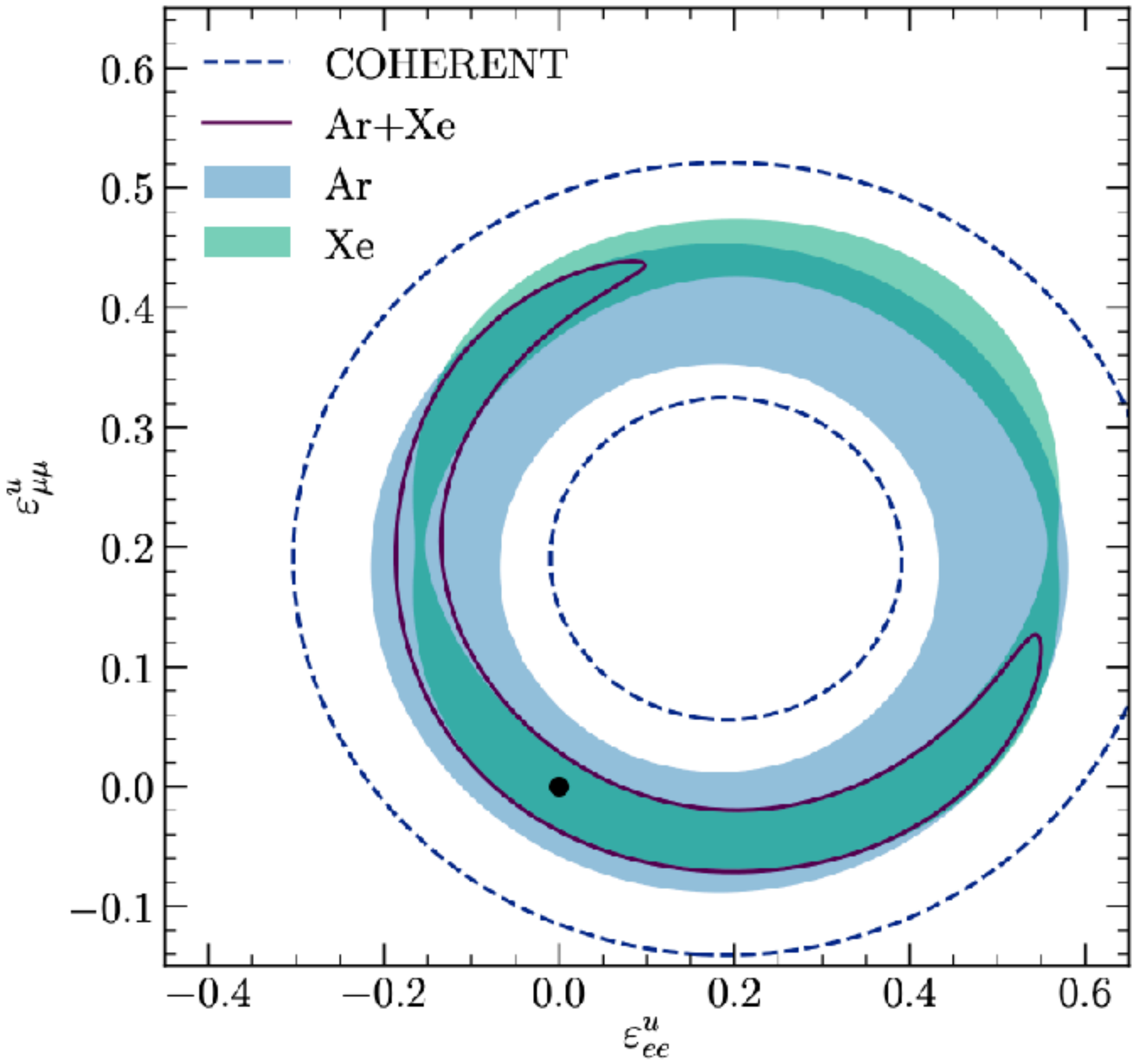

Interesting physics concentrates at low energies

# Detecting CEvNS

## Detectors

Non-Standard neutrino-quarks interactions

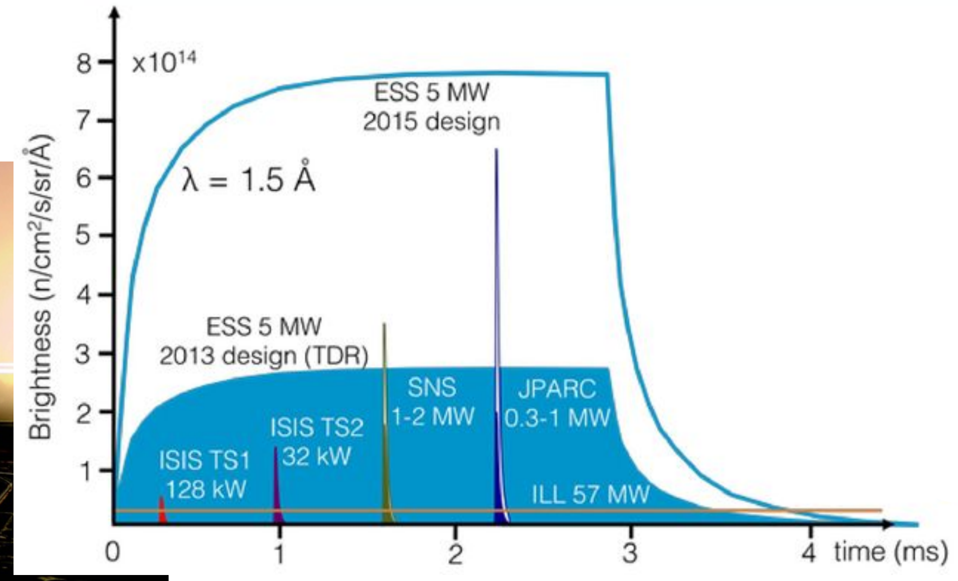
Operation with different nuclei helps breaking degeneracies



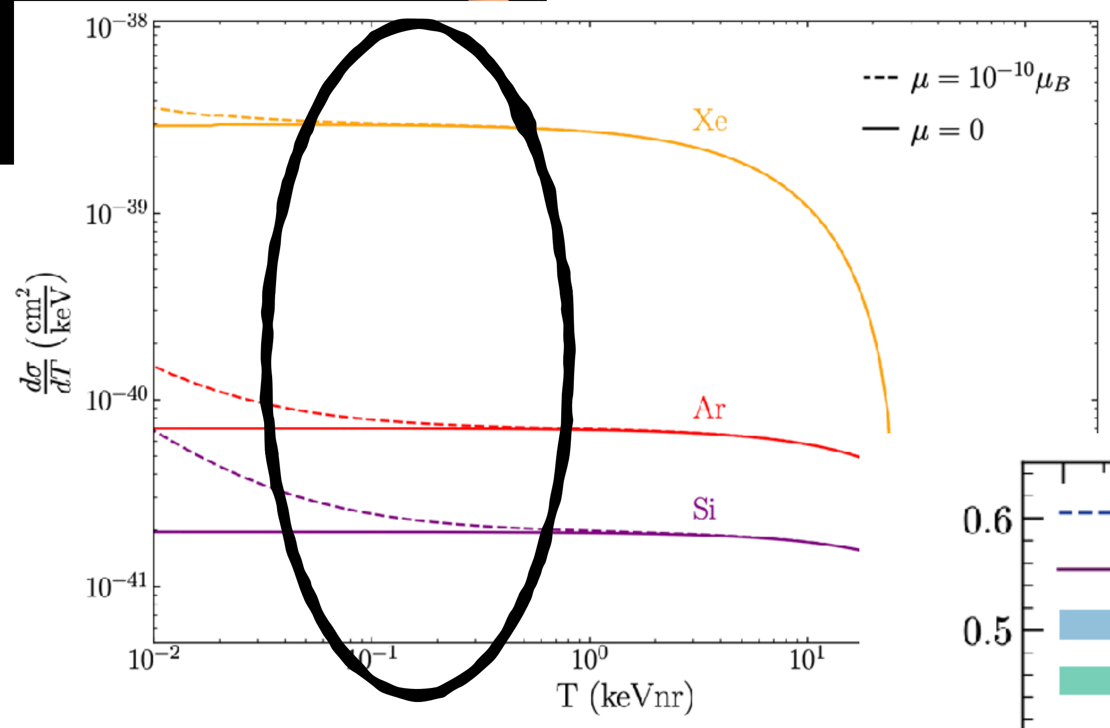

A full experimental program must allow for operation with different targets.

# Detecting CEvNS

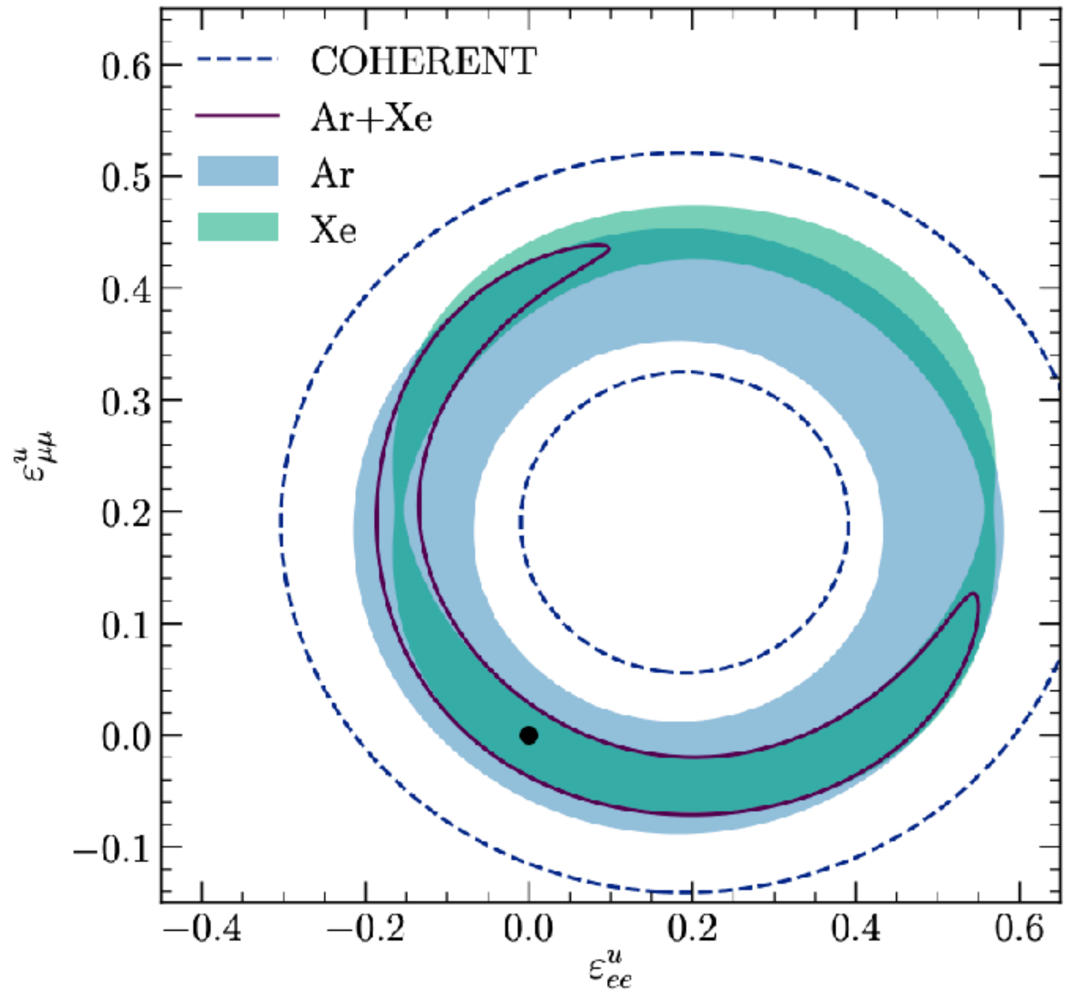
## Specs.


- Large flux of MeV neutrinos




- Detectors with low energy threshold




- Operation with different nuclei

# Detectors at the ESS

- Combination of technologies to minimise possible systematic effects.
- Use of different nuclei to allow for exploring larger fraction of the phase space.
- Look for similar nuclei with different technologies.

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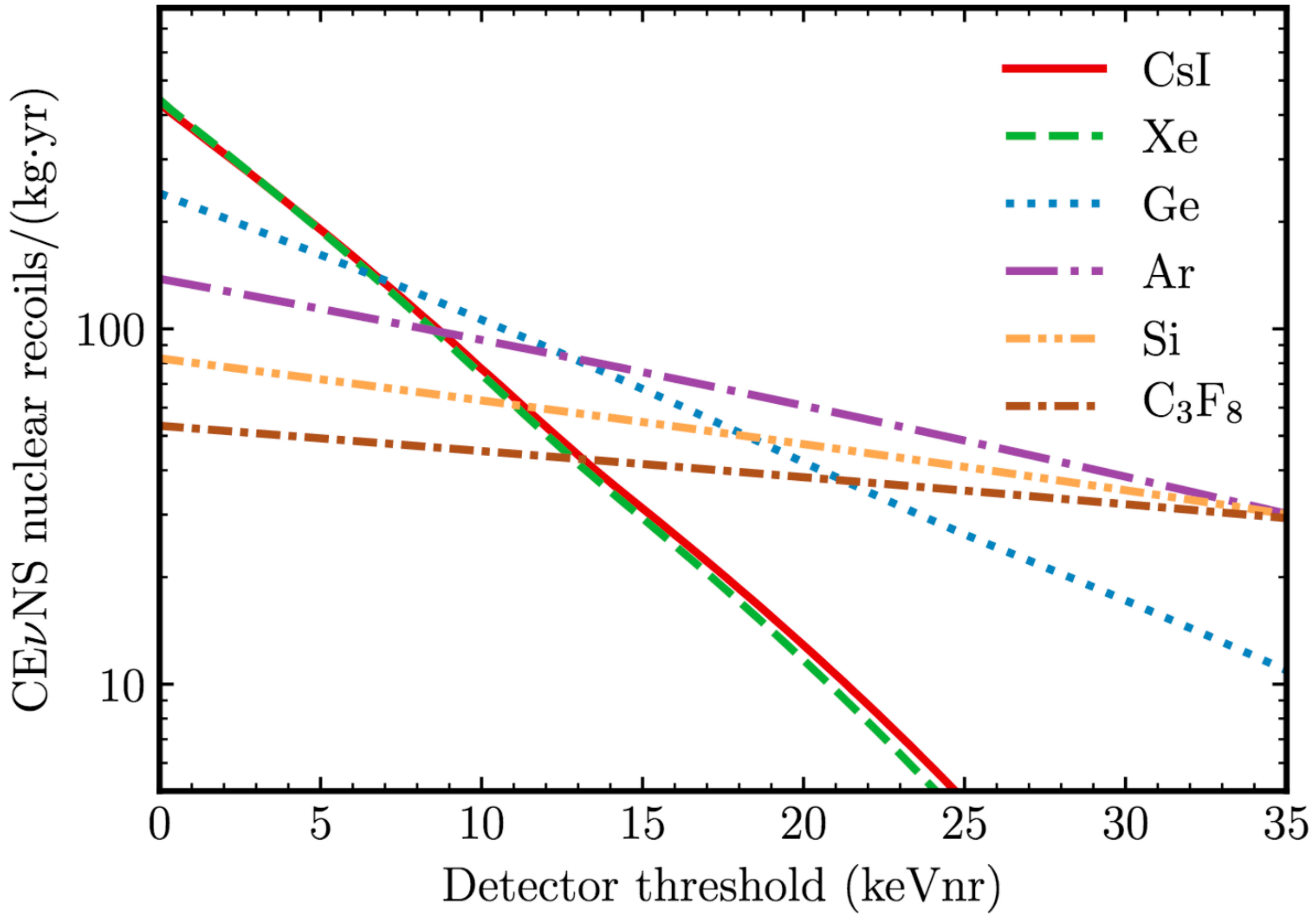
**Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source**

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 |



# Detectors at the ESS: nuESS collaboration

- International collaboration making an effort to build a next-generation coherent neutrino detectors.

Gaseous detectors:
GanESS

F.Monrabal,
J.J Gomez-Cadenas

Cryo CsI & PPT
Germaniums

J. Collar,
A. Simón

Neutron propagation simulations

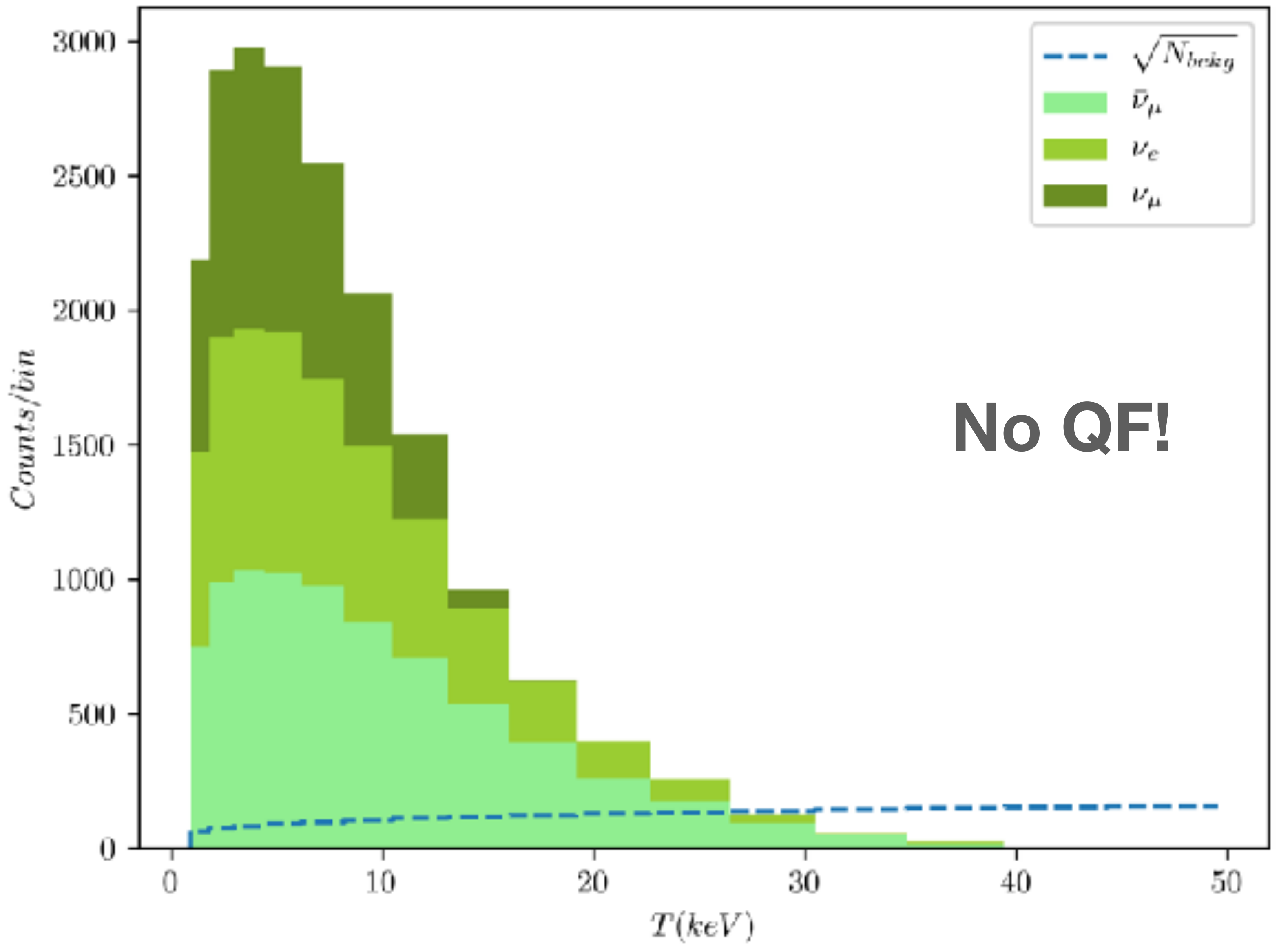
E. Gilad,
C. Castagna (BGU)

J. Renner
(U. Santiago)

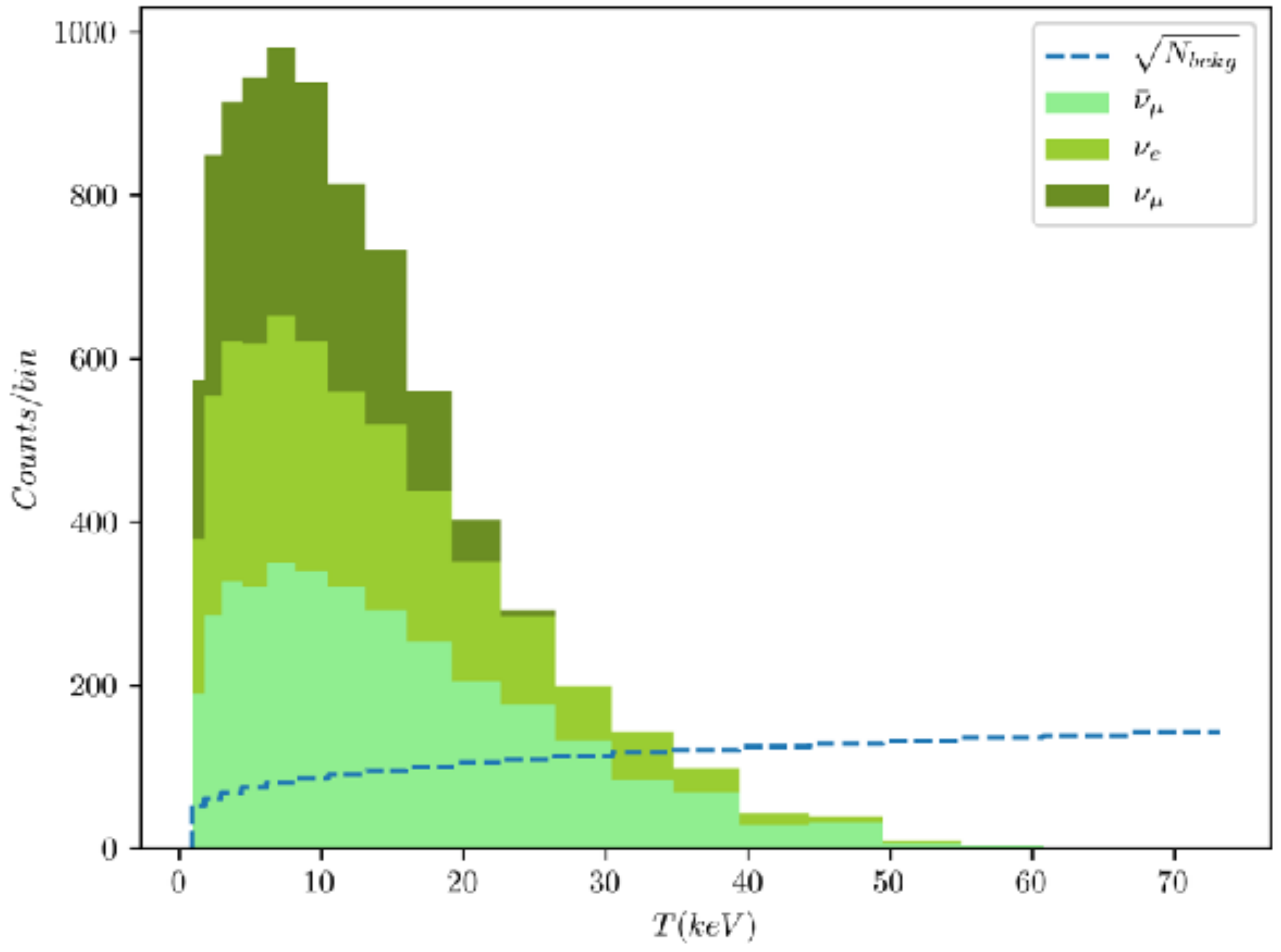
# Gaseous detectors?

The main problem with gaseous detectors is their relatively low density when compared with solid scintillators (CsI) or liquid detectors.

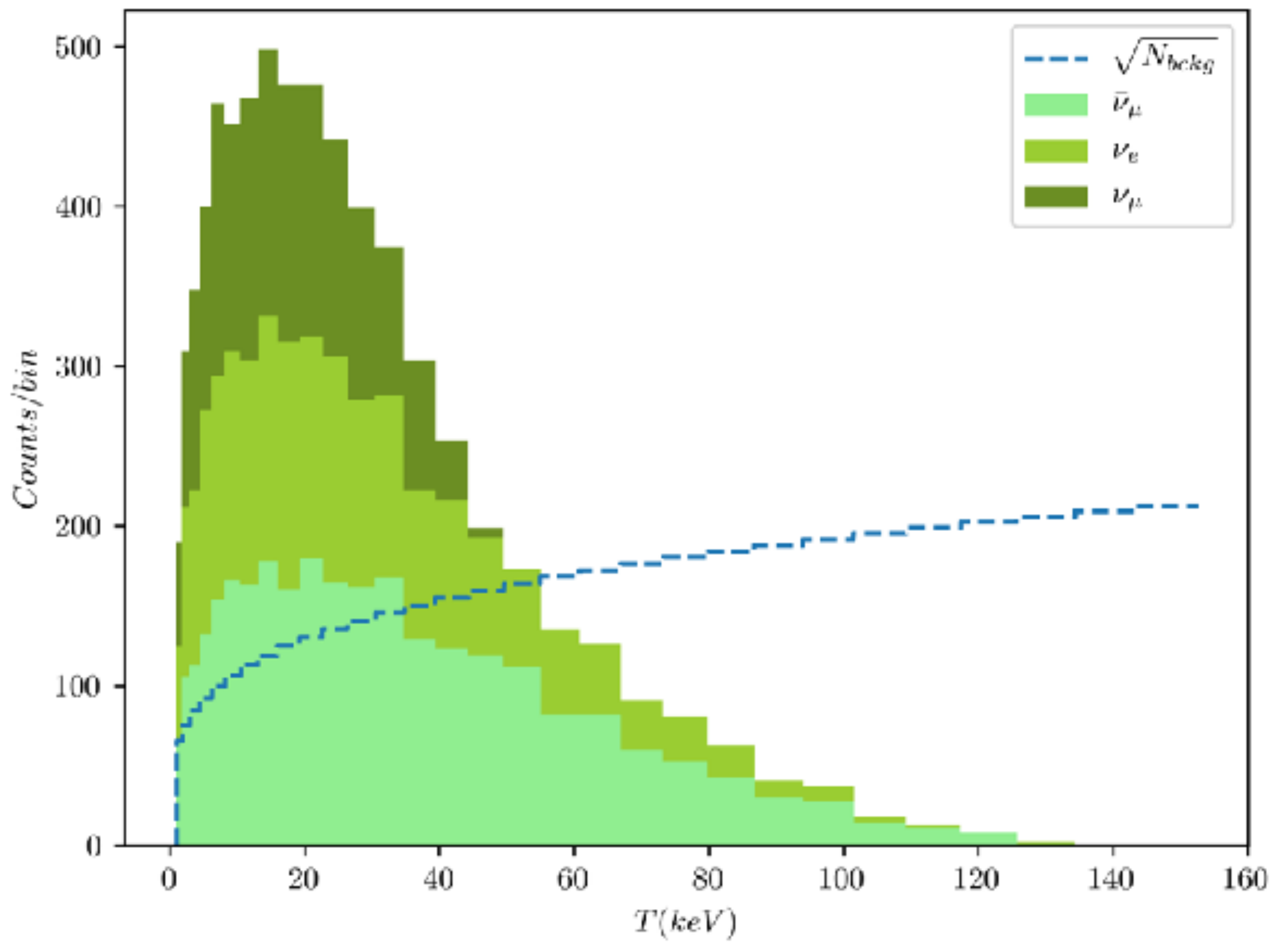
Thanks to the large neutrino flux produced by the ESS, detectors with ~20 kg won't be limited by statistics




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




Same detector filled with Krypton

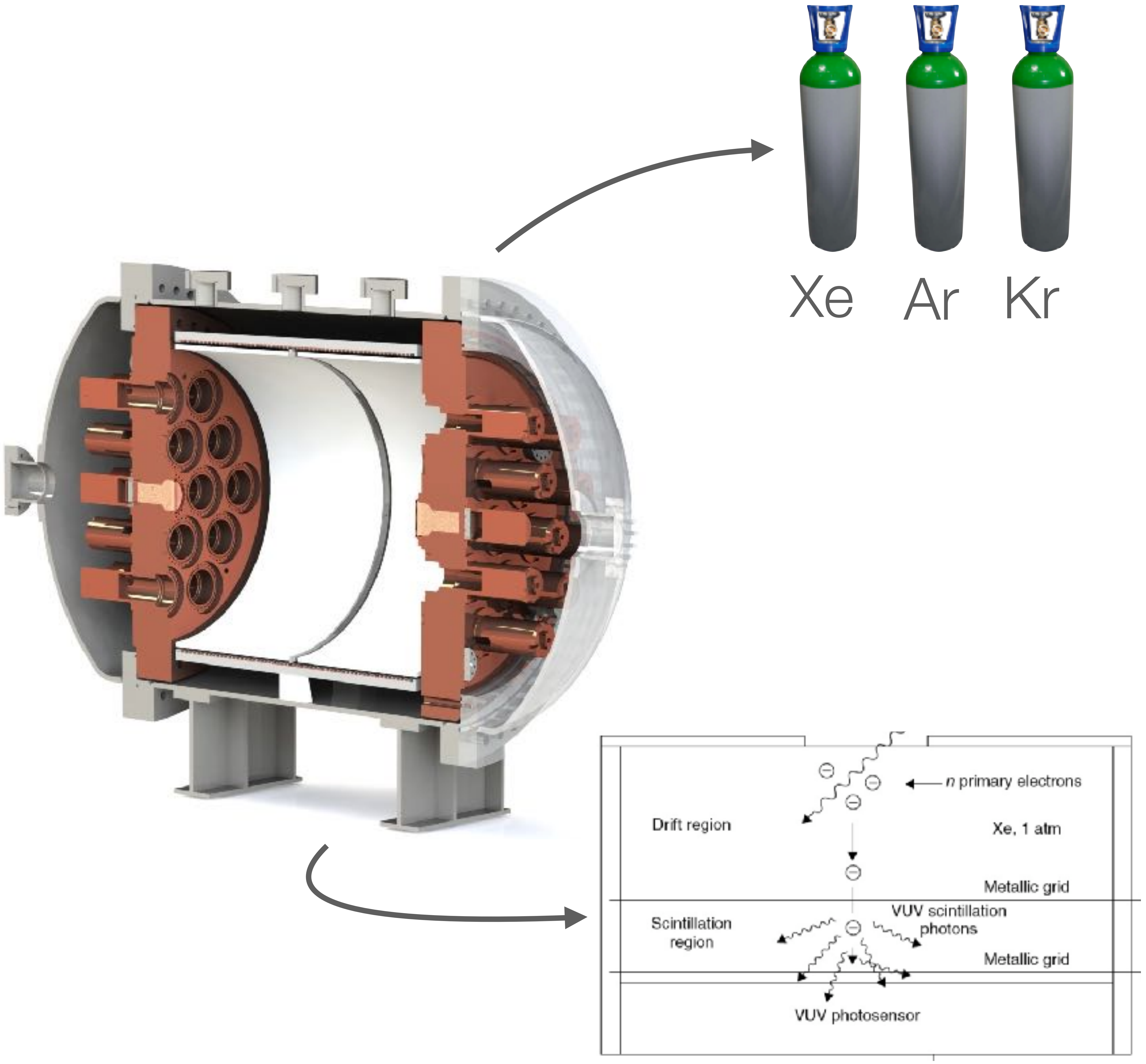



Same detector filled with Argon

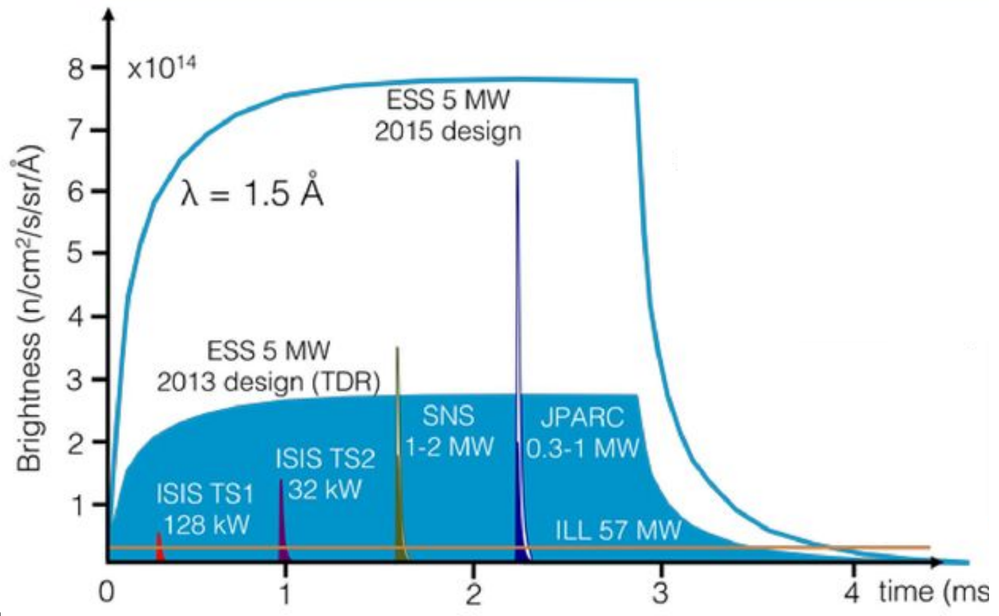
# Gaseous detectors?

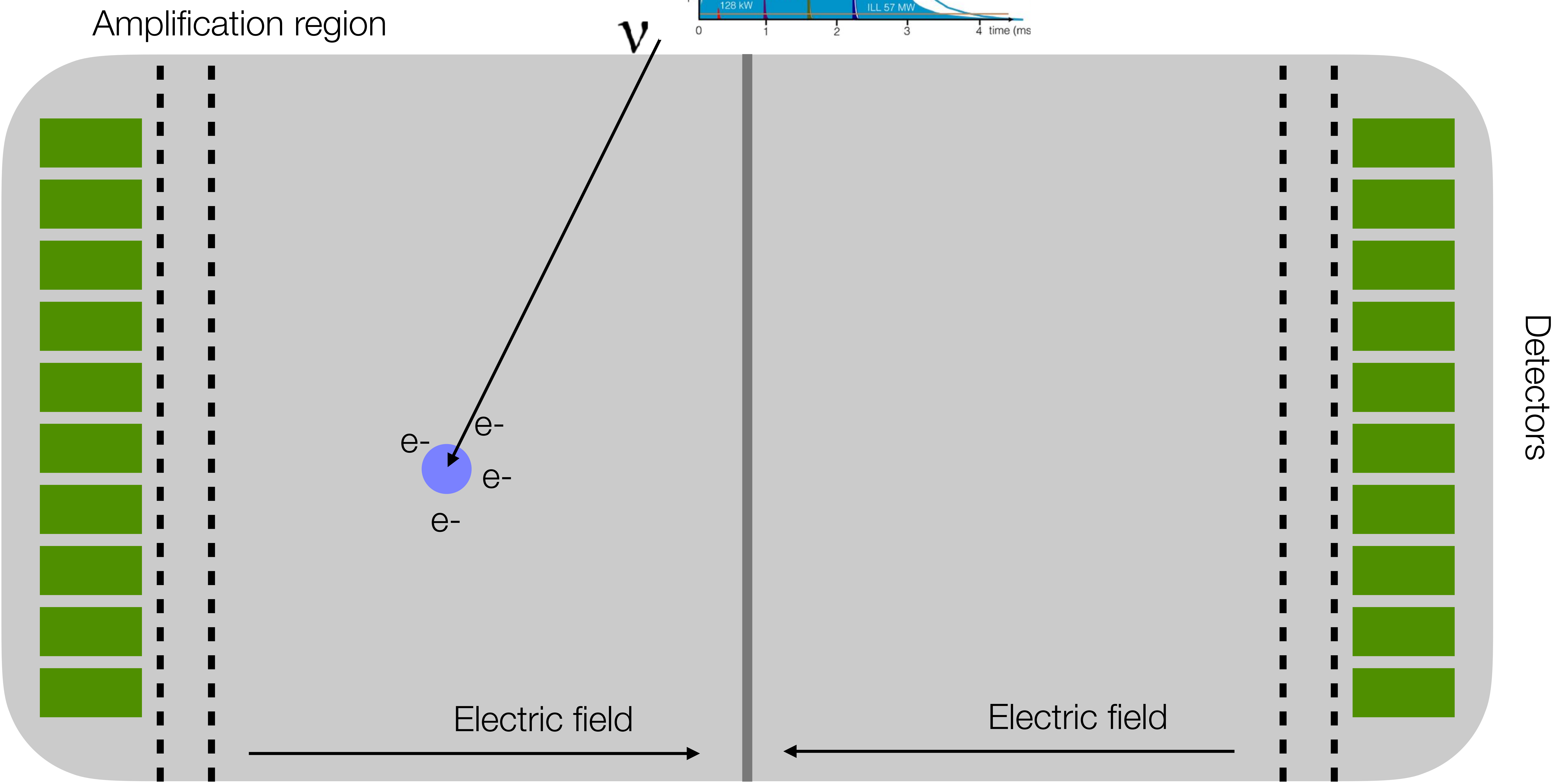
High pressure gaseous detector have other advantages:

- Simpler, no need of a cryogenic system.
- Larger EL amplification: Signals as low as 1-2 ionized electrons can be detected. This reduces the expected energy threshold to less than 1 keVee.
- Allow to operate with different nuclei in the same set-up with minimal increase of the costs.
- High pressure xenon technology developed by the NEXT collaboration for bb0v searches.
    - Most of the solutions already developed for low-background experiments.
    - Some R&D will be needed for very low energies, and possible higher pressures.

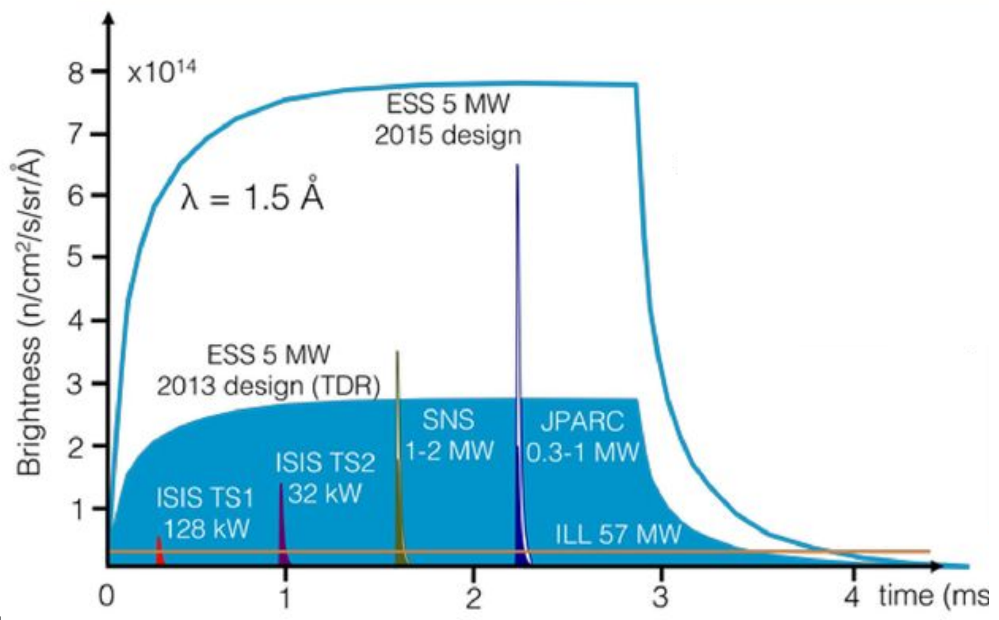


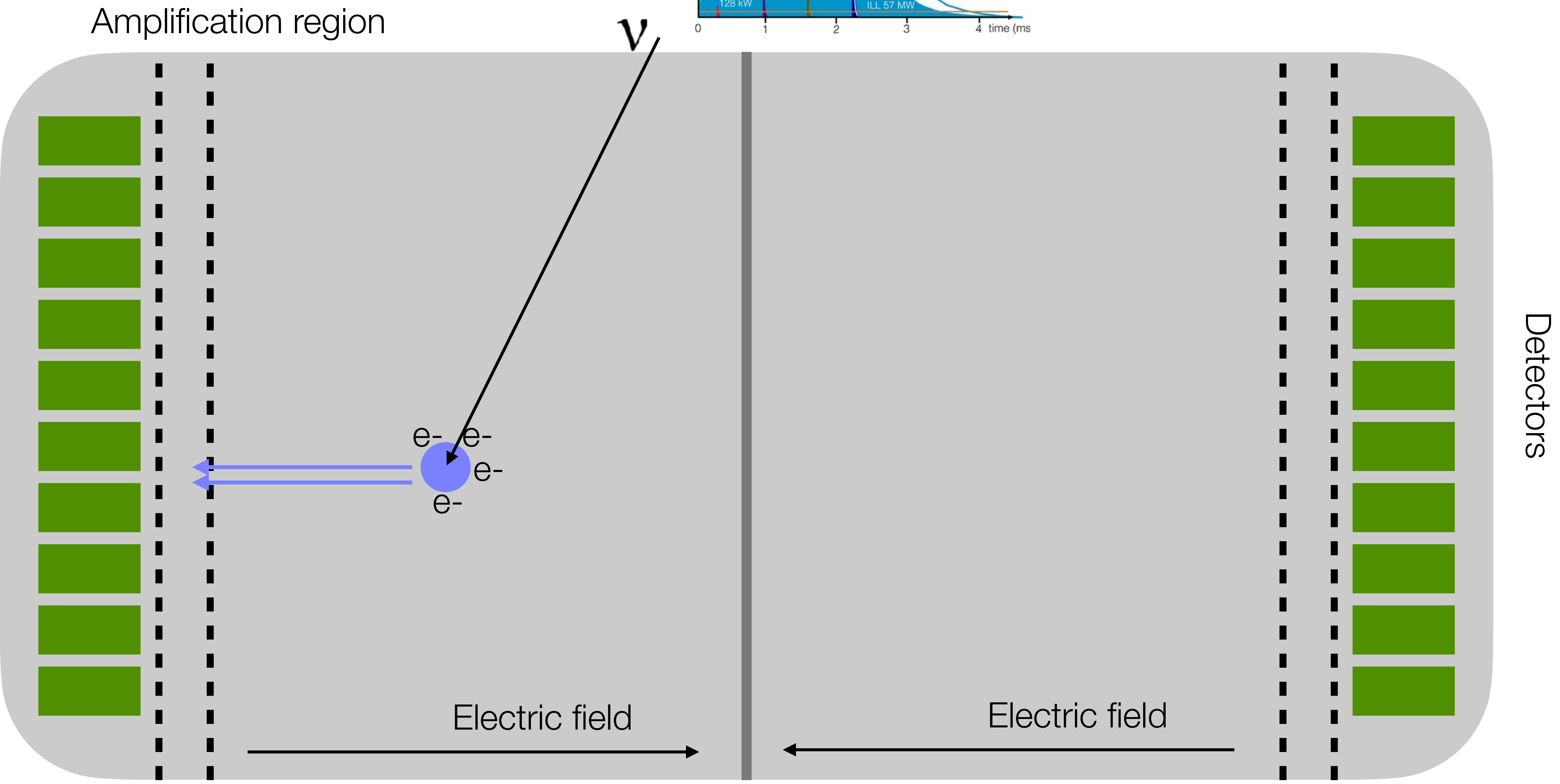
# GanESS concept



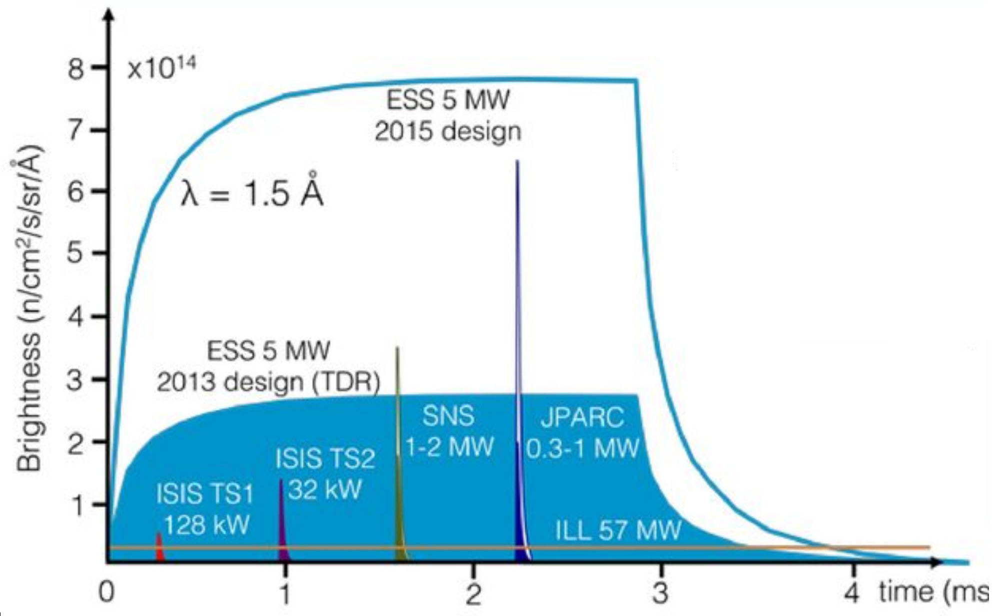



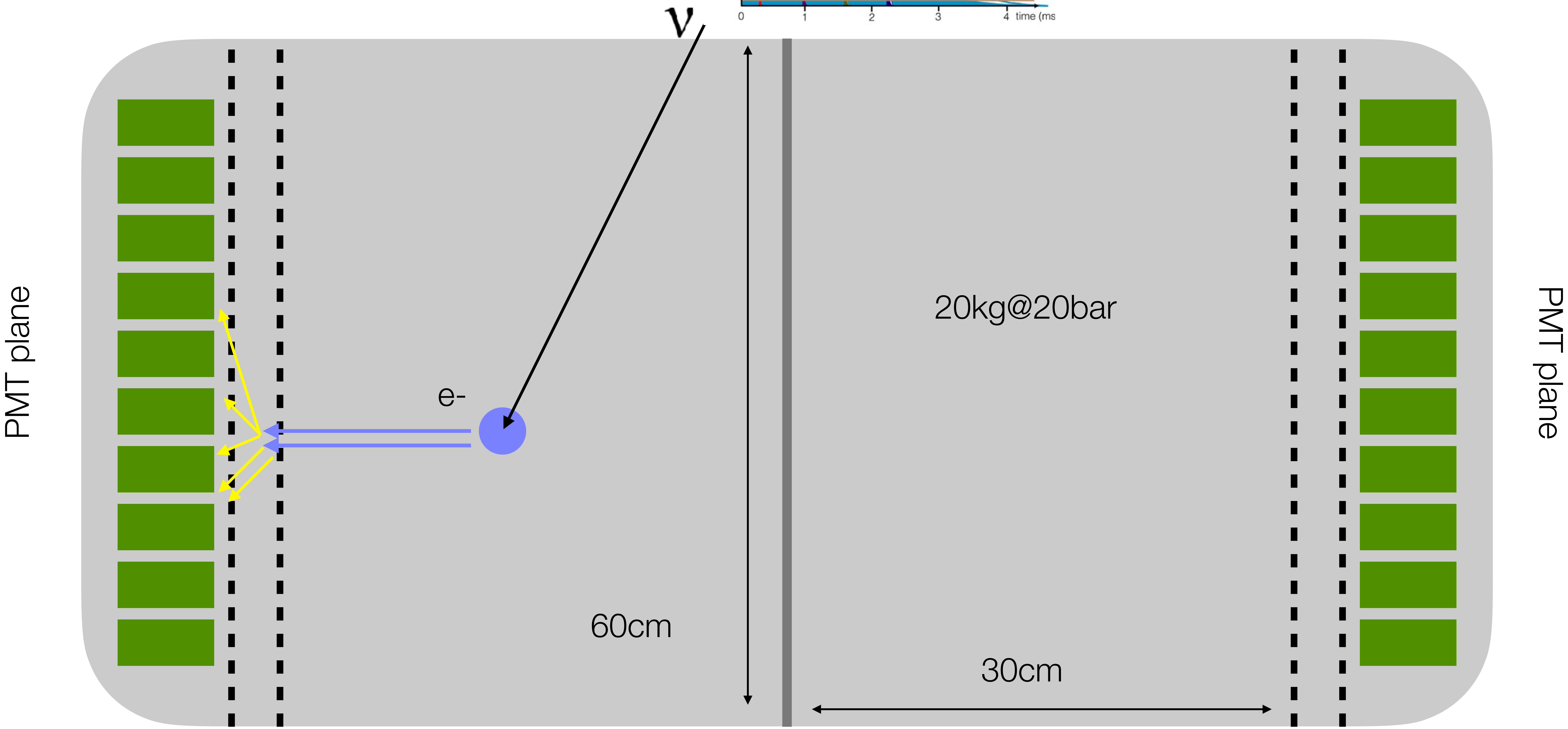
# GanESS concept



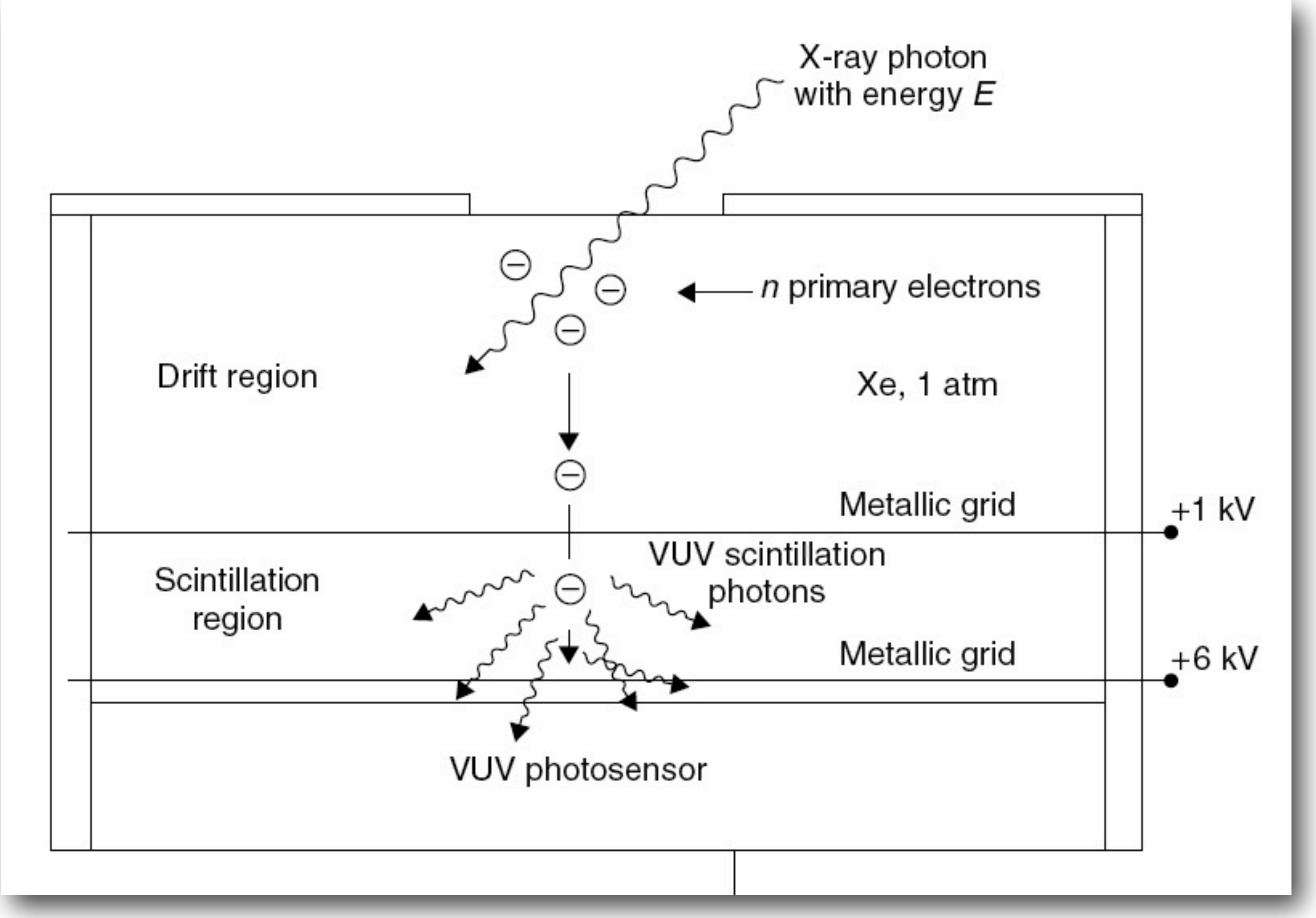



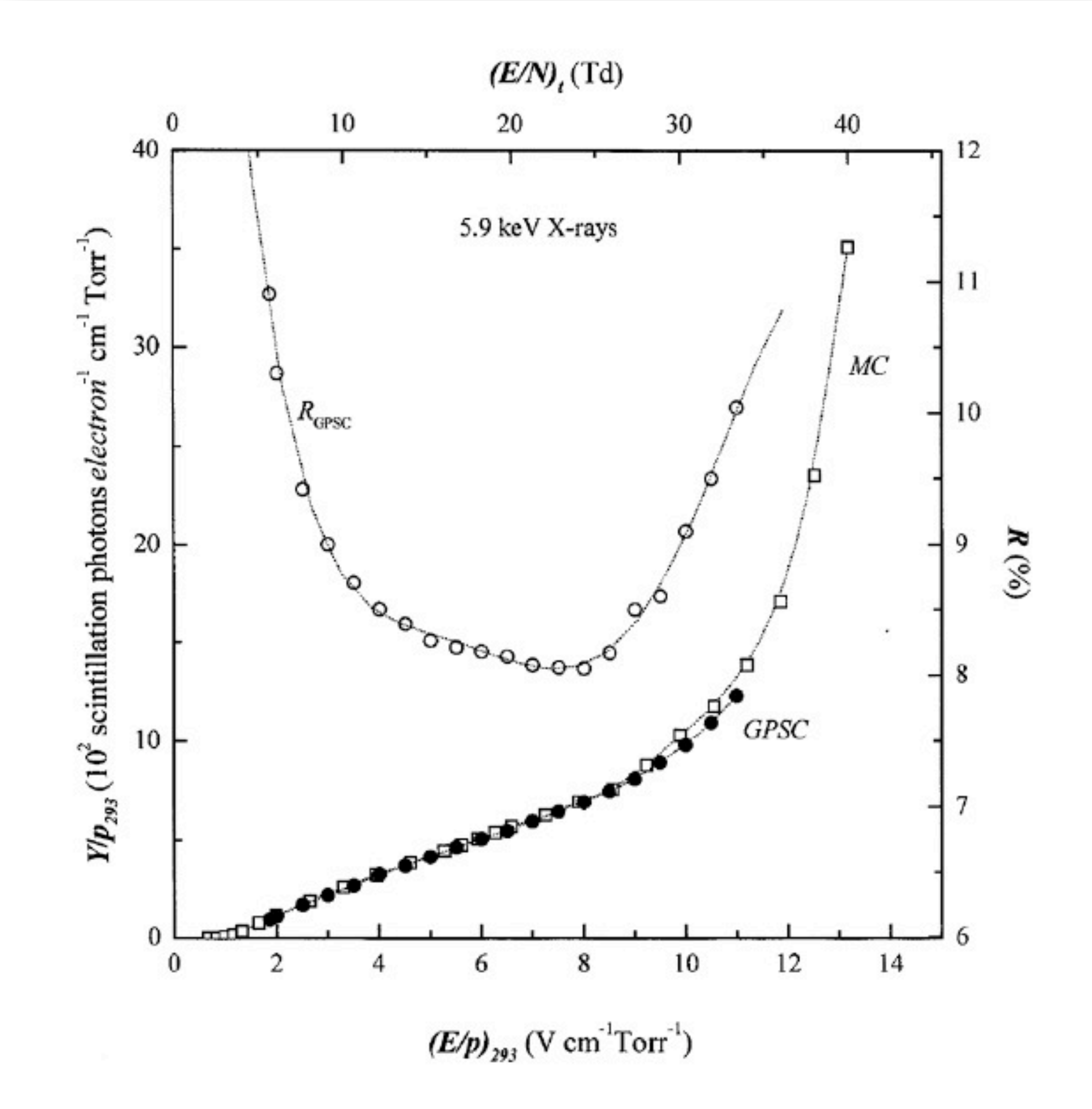
# GanESS concept



# Amplification preserving resolution: Electroluminescence

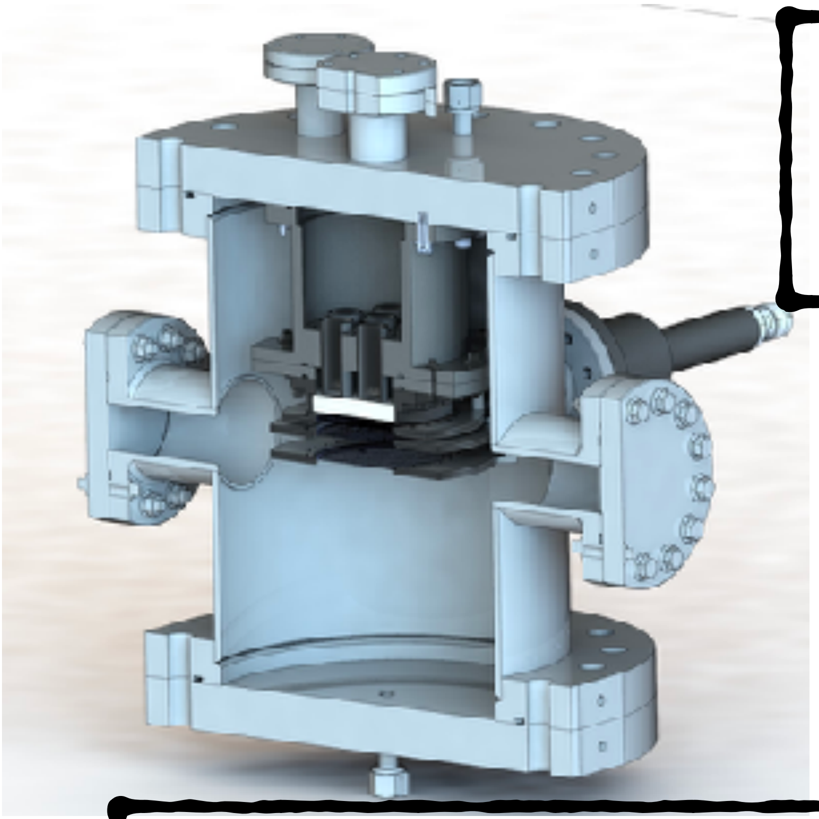



- Emission of scintillation light after atom excitation by a charge accelerated by a moderately large (no charge gain) electric field.
- Linear process, huge gain (1500 ph./e-) at $3 < E/p < 6$ kV/cm/bar.
- Large gain at high pressure allows for very low threshold.
- More stable at high pressure, no need of quenchers.

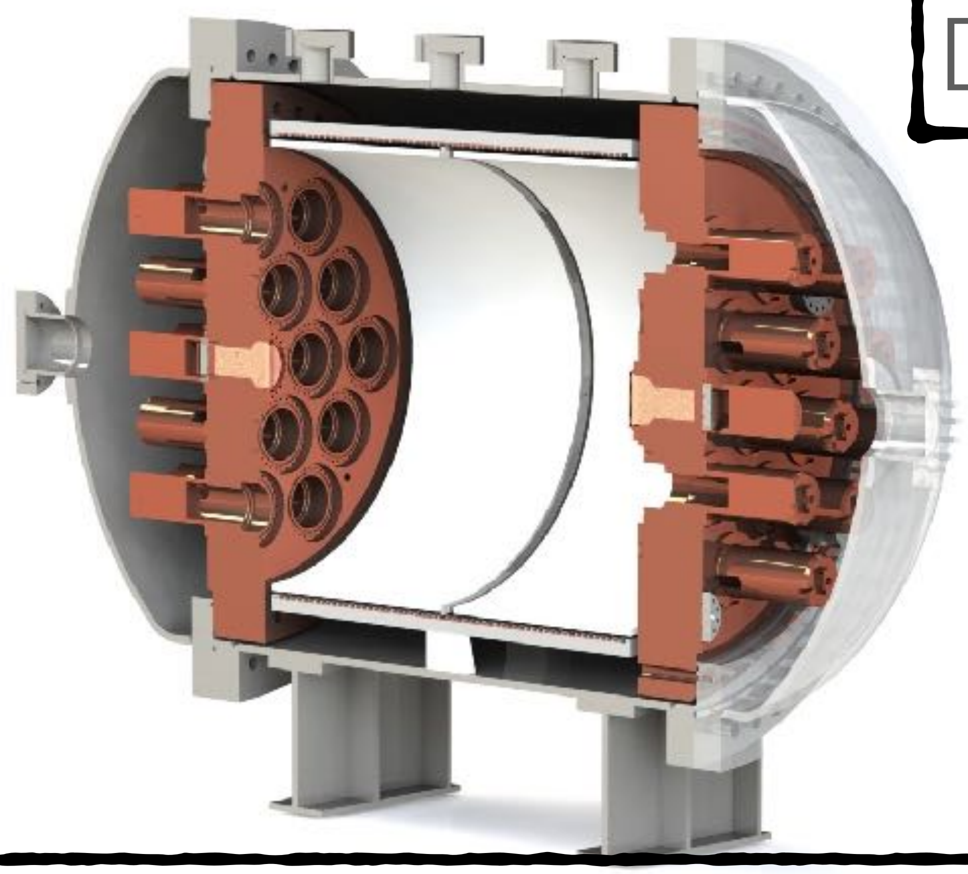
# GaNESS project

## Initial steps



Gaseous Prototype (GaP)

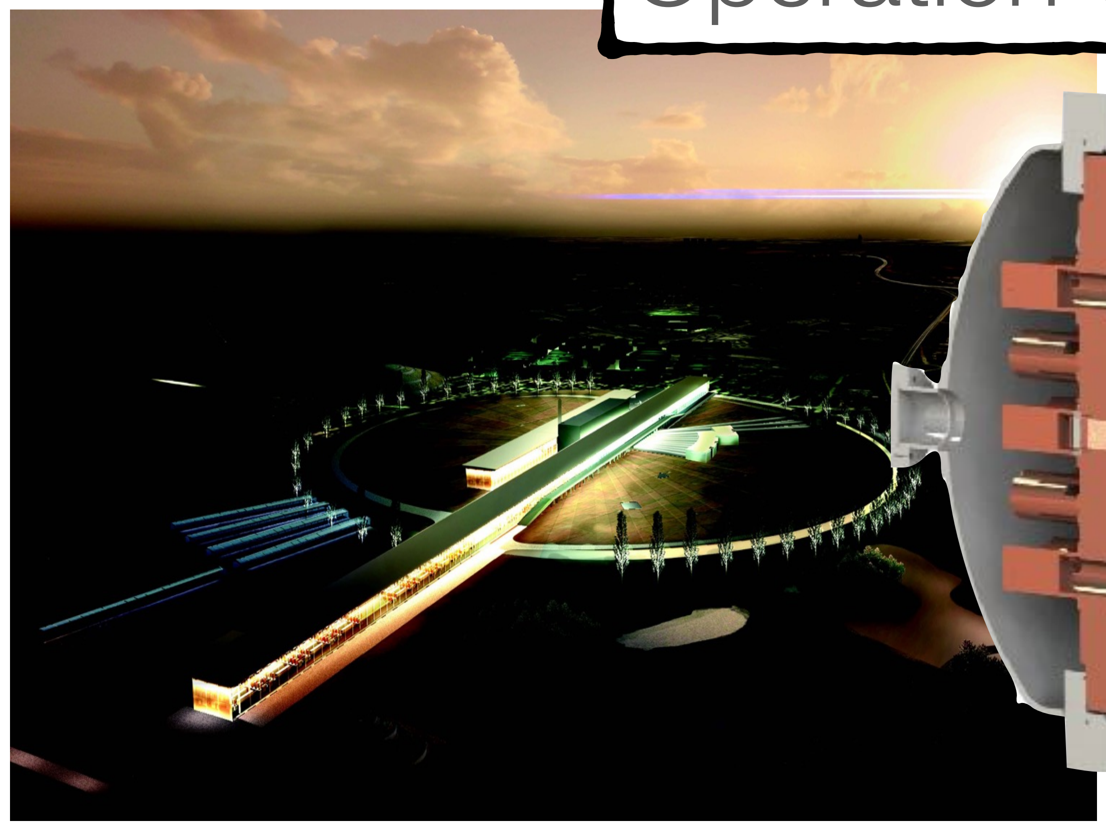
R&D,
Study of
nuclear recoils

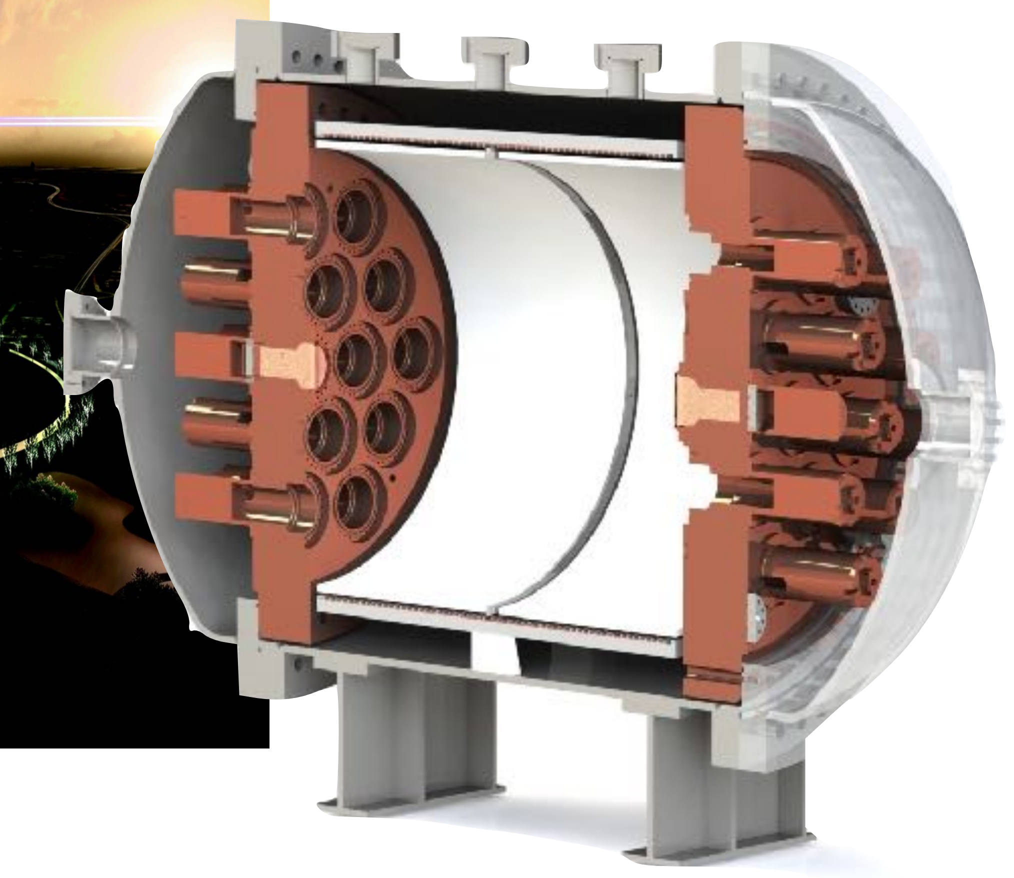


Detector construction, GanESS@DIPC

High pressure technology developed by the PI within the NEXT experiment

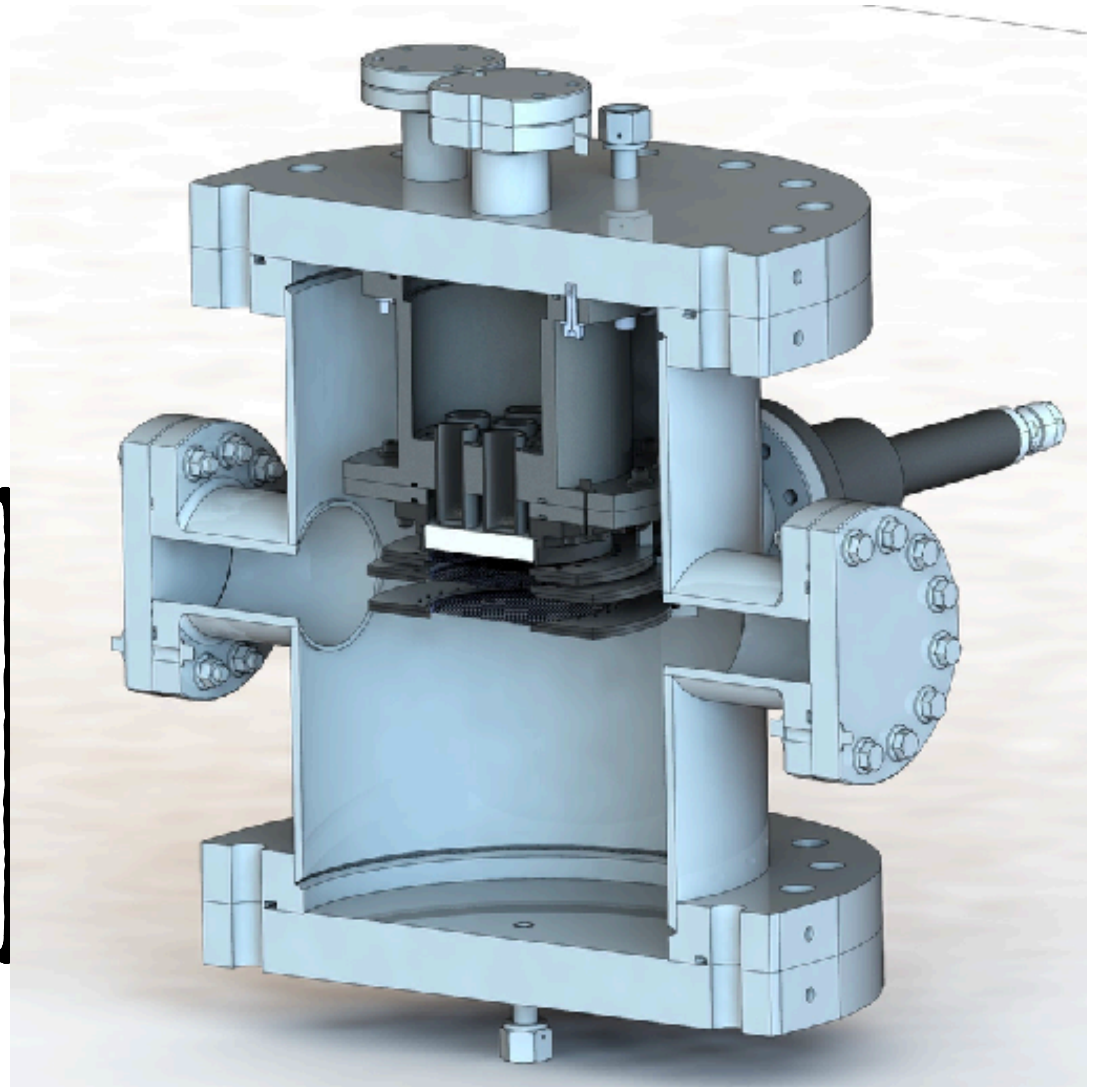
Operation GanESS@ ESS



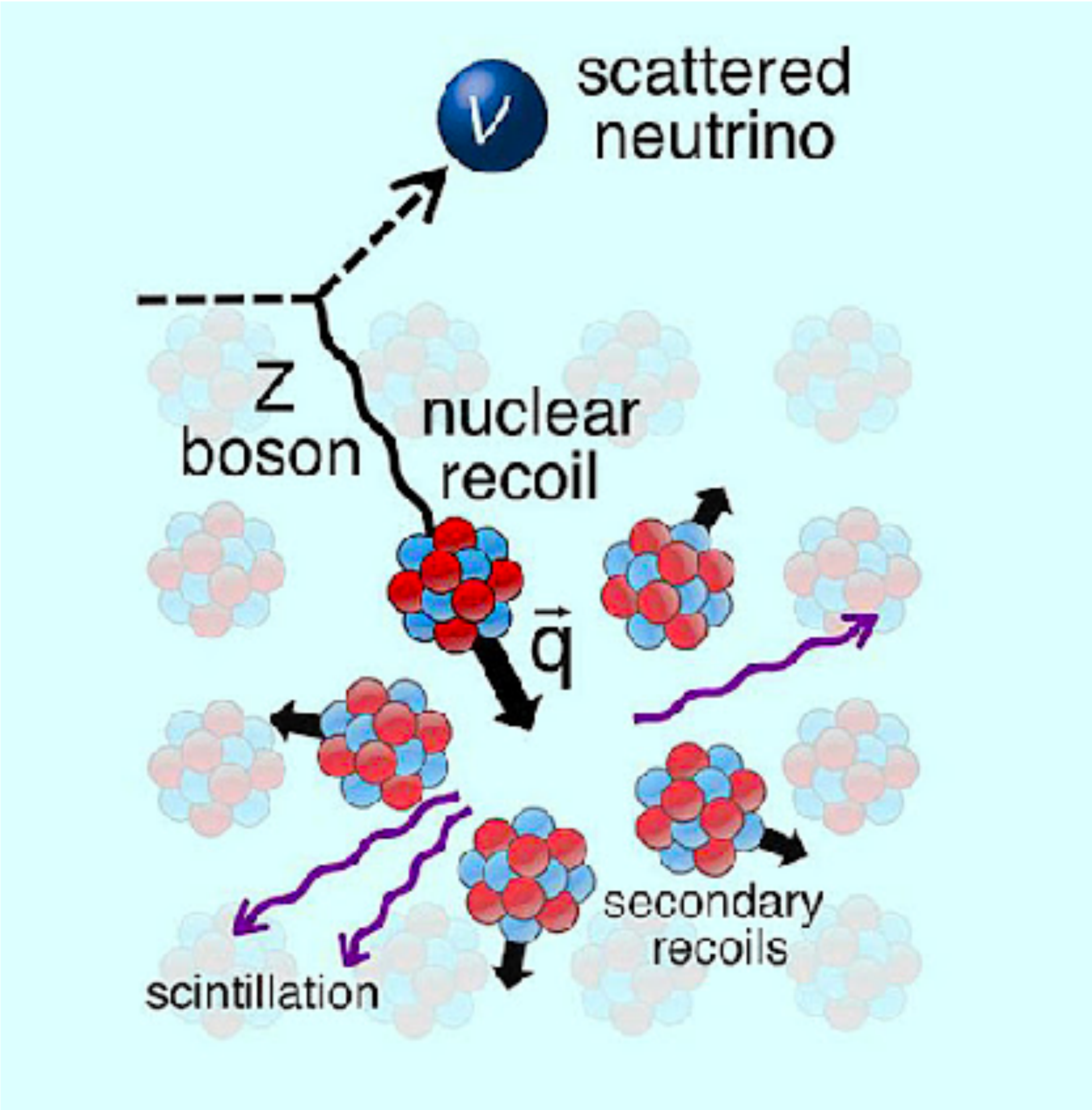


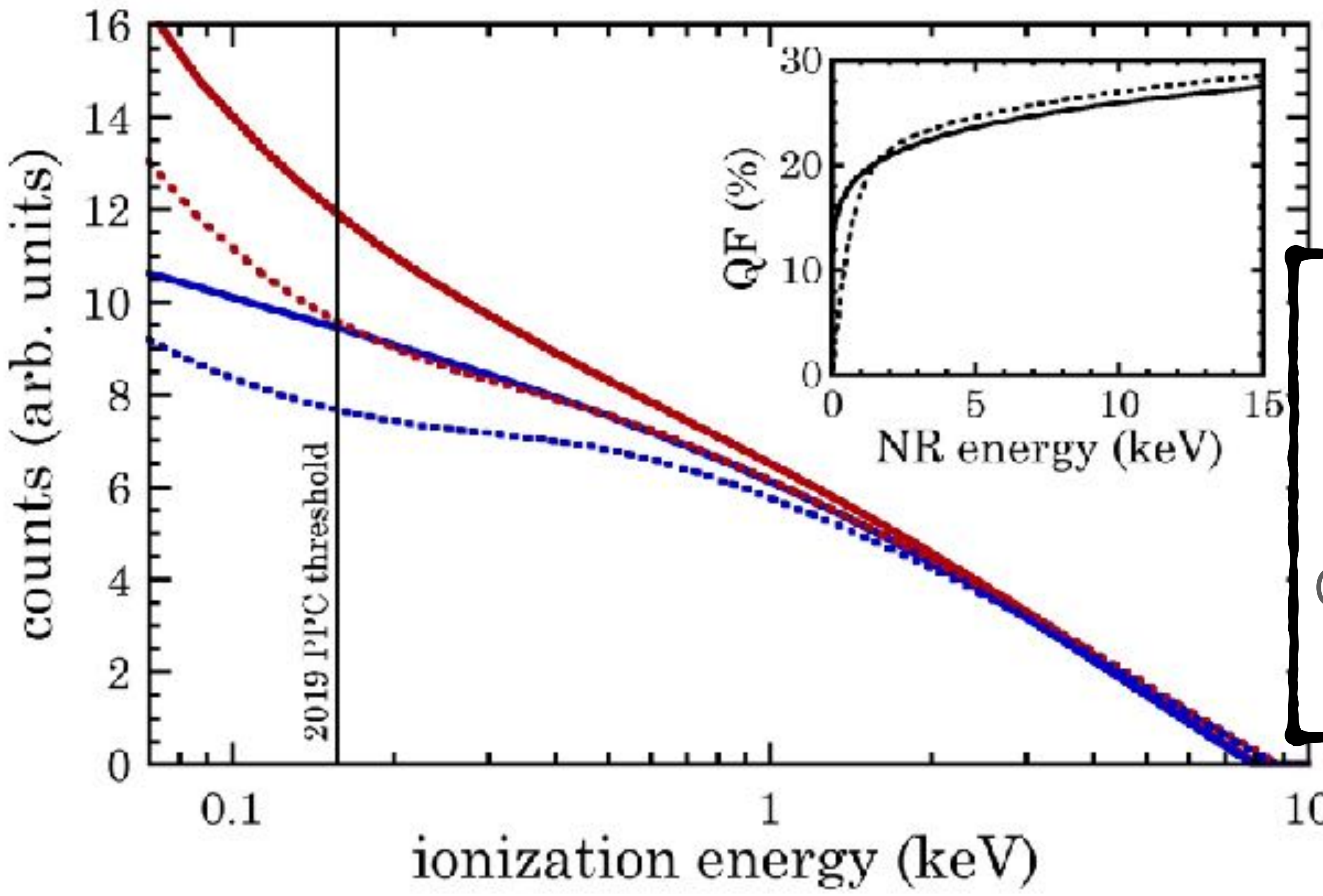
# GaNESS project: GaP

## The Gaseous Prototype (GaP) system



- Test for high pressure (up to 50 bar) and operation with different gases.
- Characterisation of the **response to nuclear recoil** at low energies.



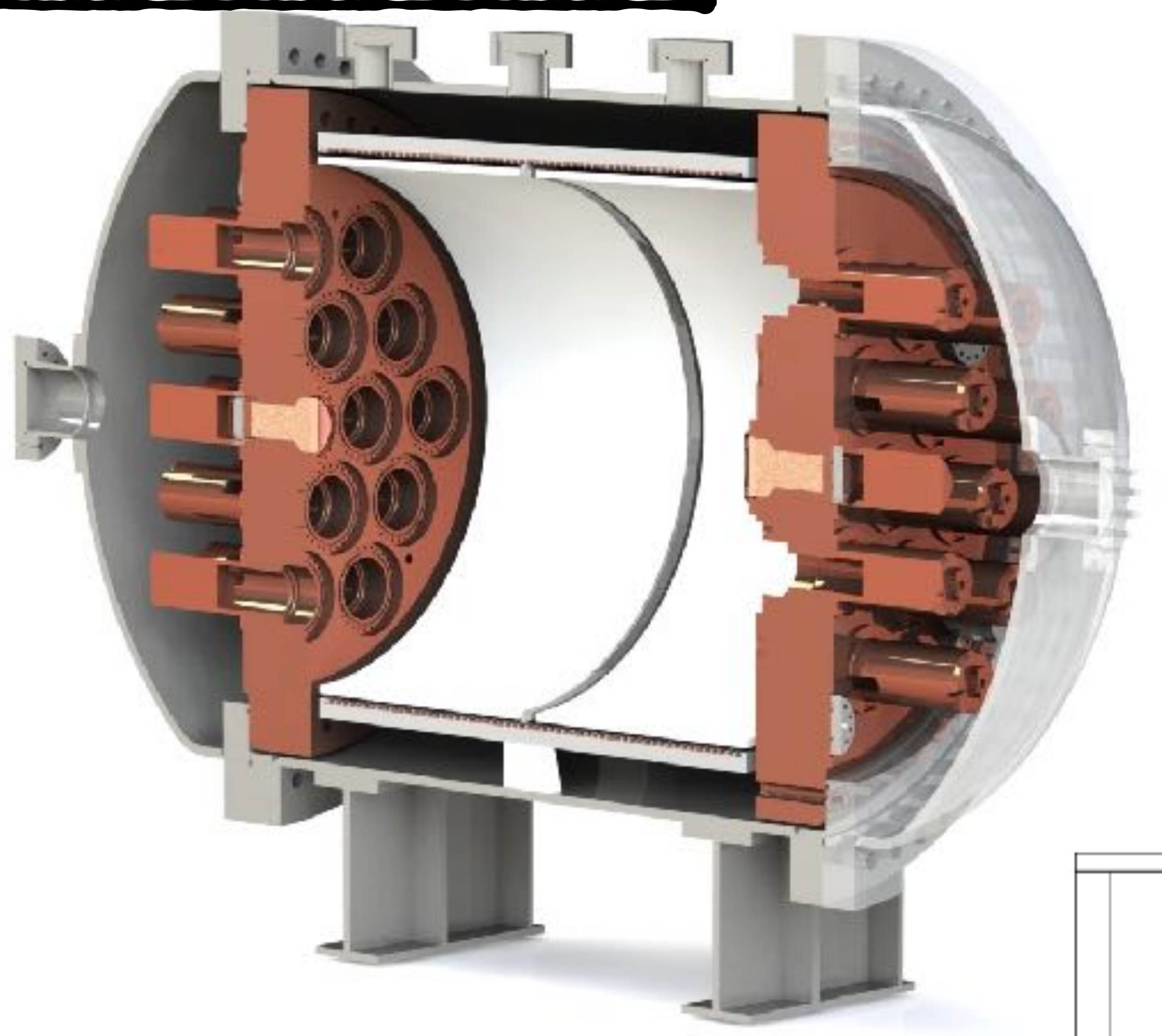



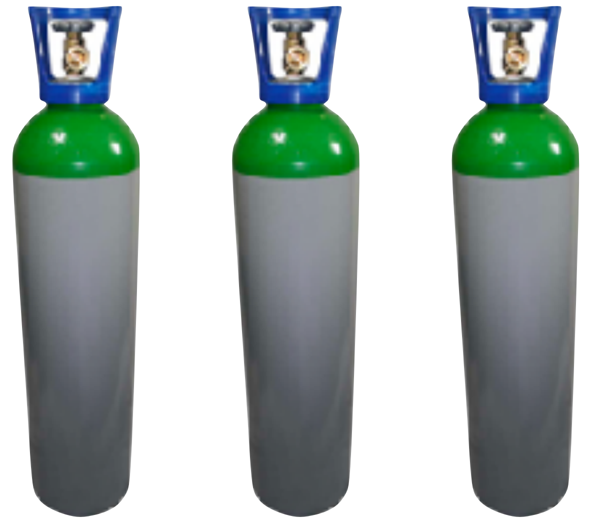

Expected number of events for different values of the neutrino magnetic moment (blue-red) and different models of the quenching factor (solid-dashed)

# GaNESS project

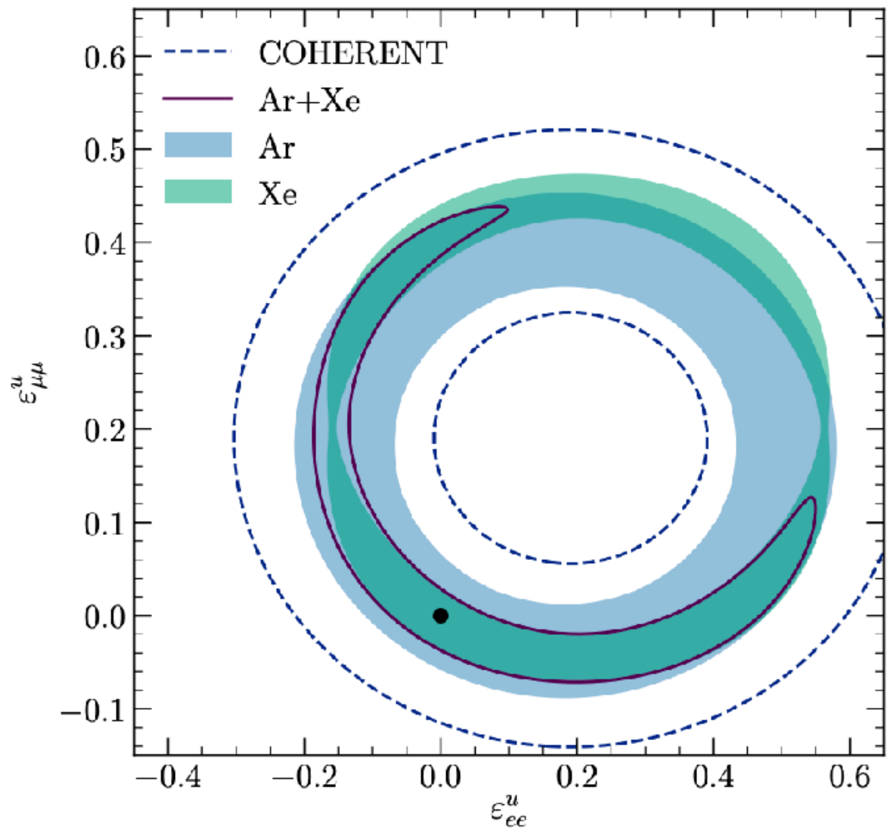
## Gaseous TPC

Detector construction

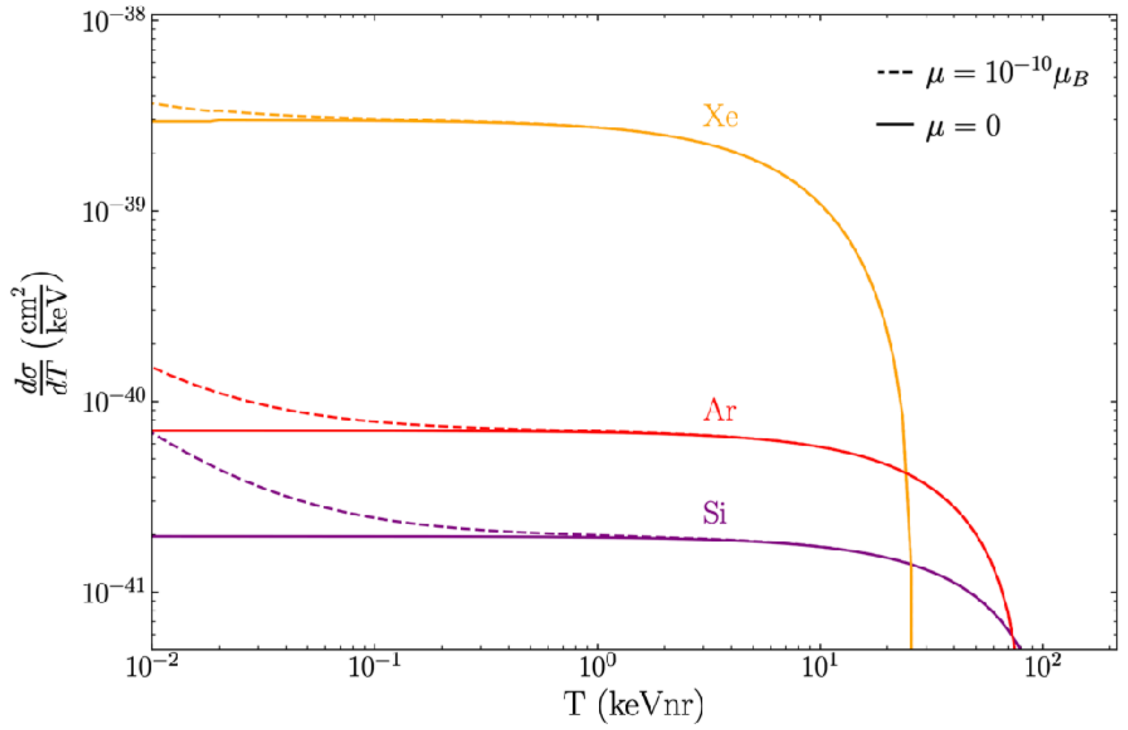


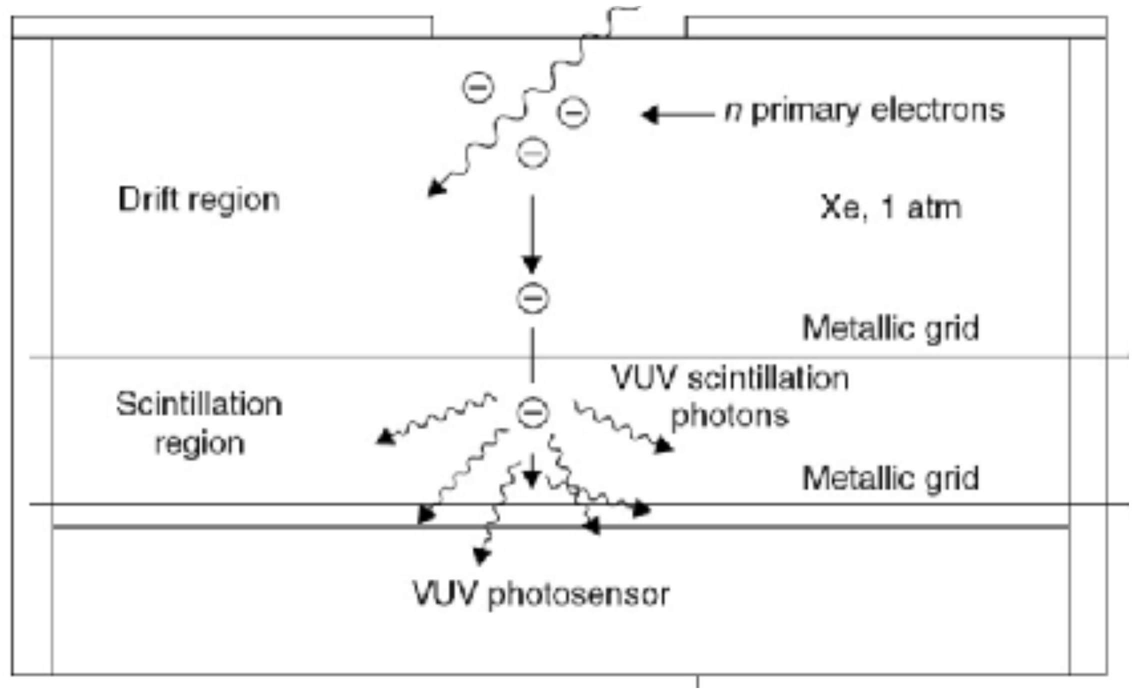


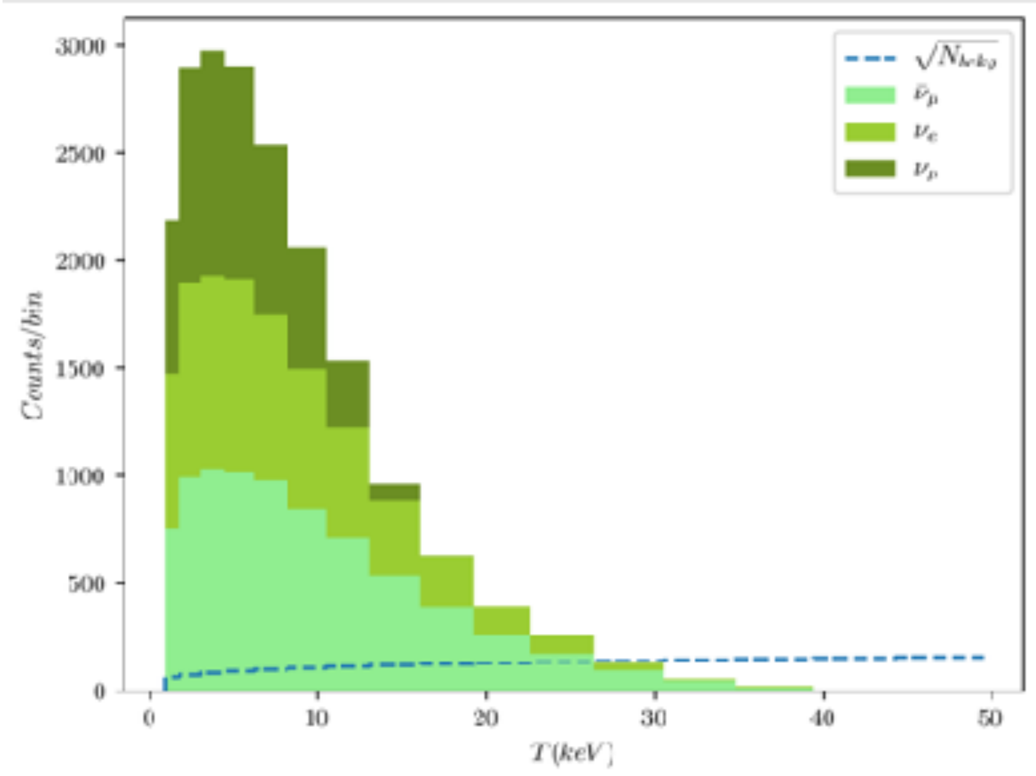
Xe Ar Kr




Physics exploitation

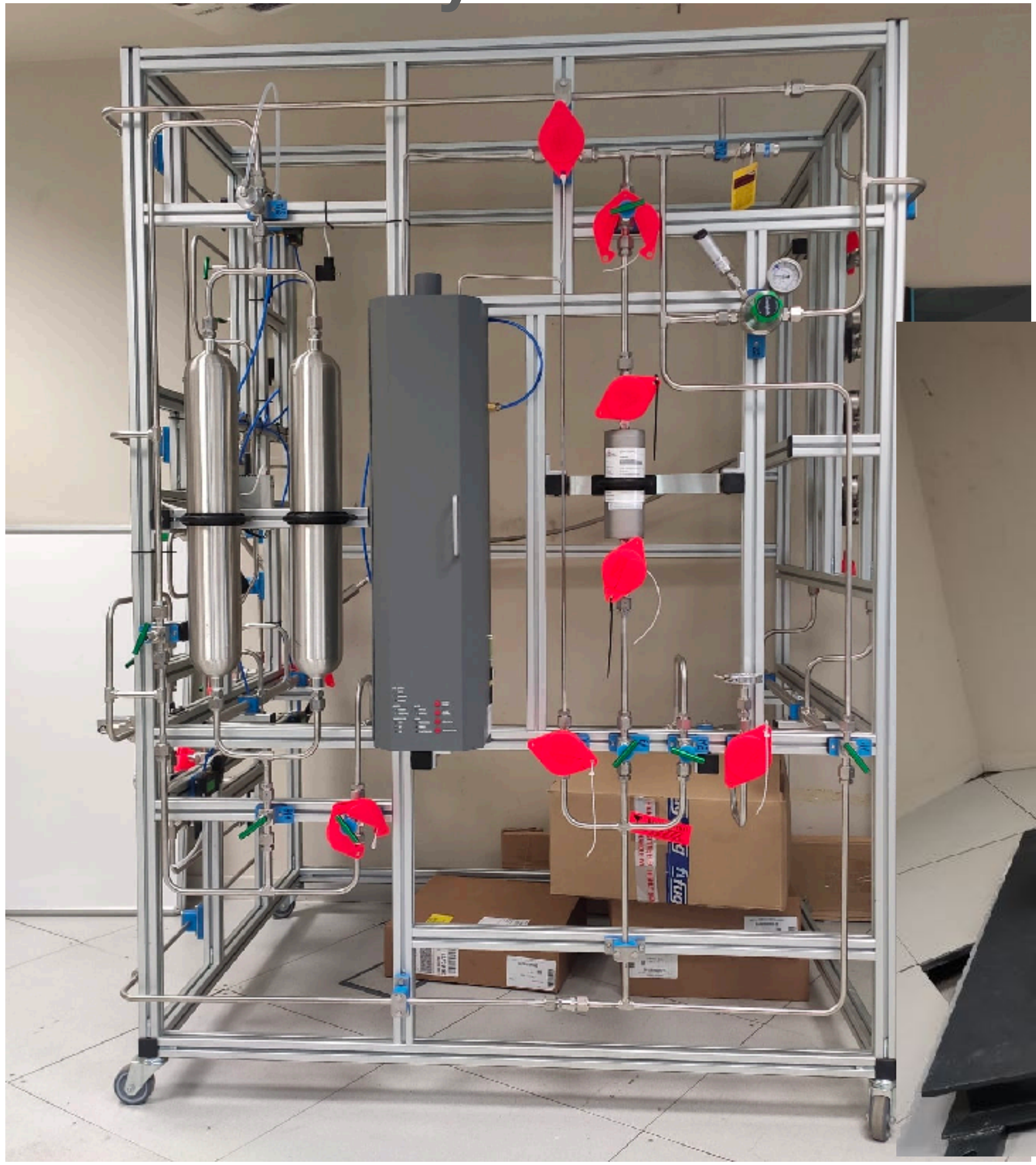


# GanESS Status

## Laboratory



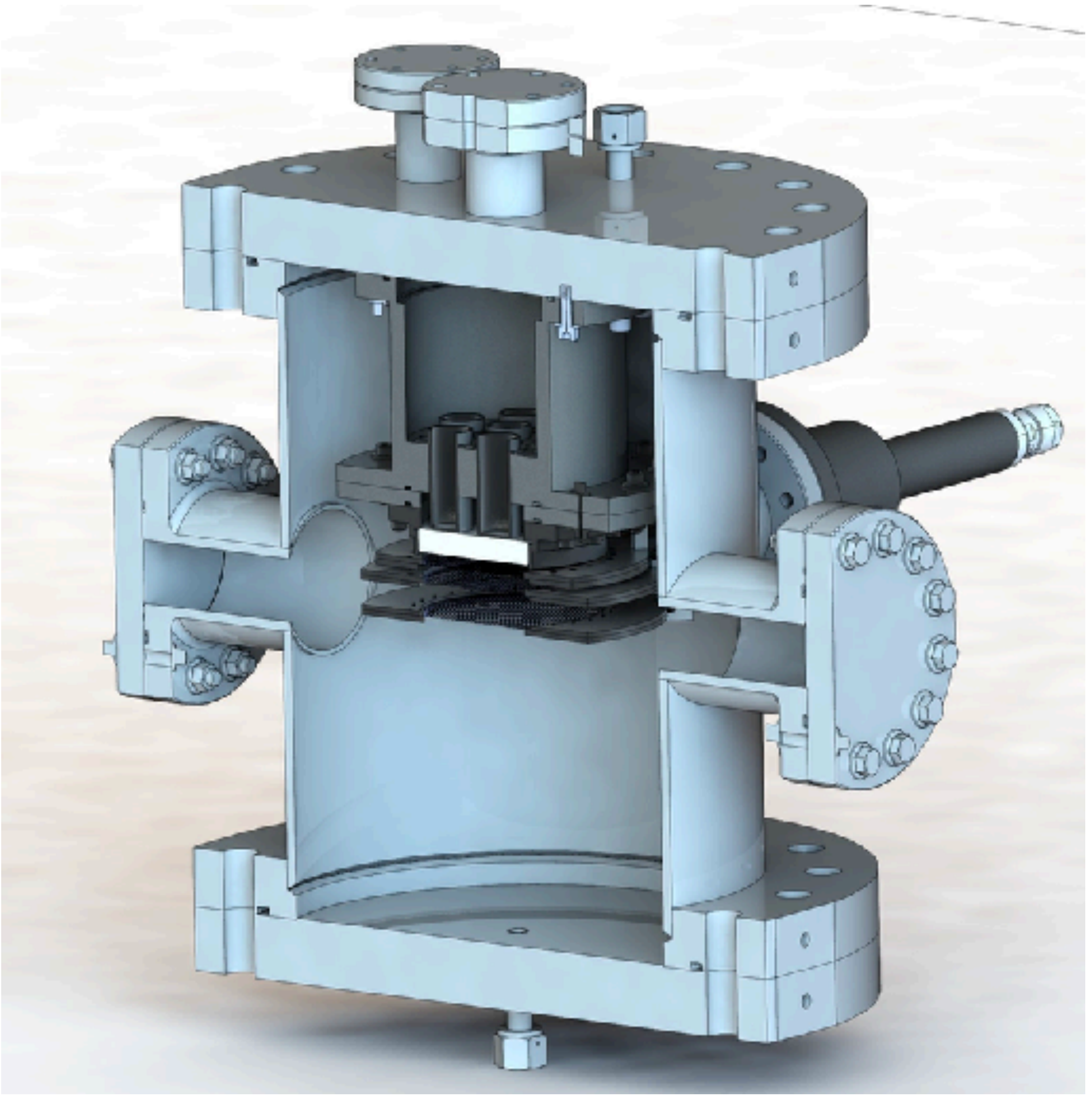
Gas circuit already at the DIPC

Two stages 10 to 50 bar compressor.
Already designed for the large detector.

Power supplies and HV modules ready

# 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)

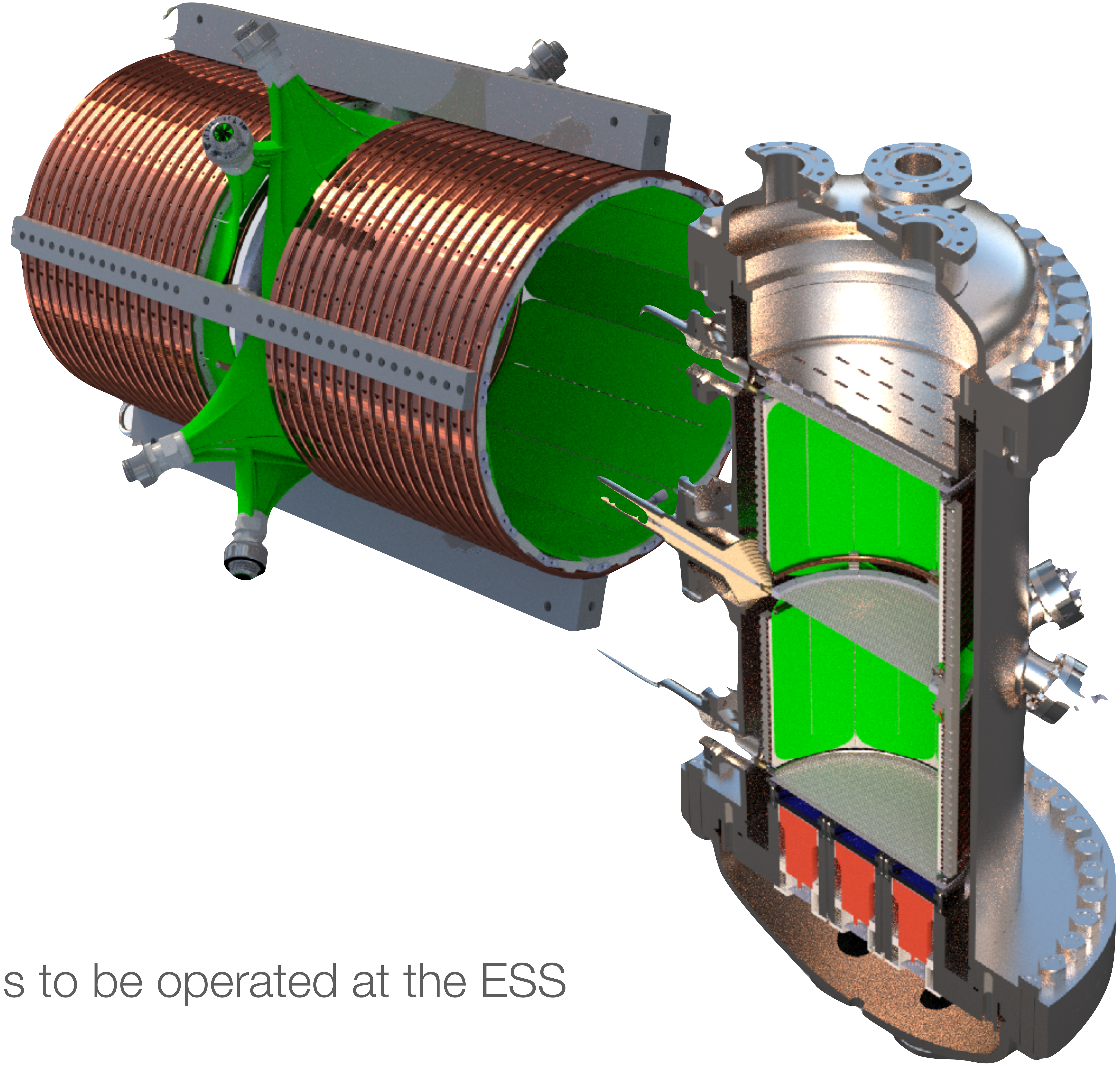
# GanESS Status

## Design of large detector

Symmetric medium size detector being designed:

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

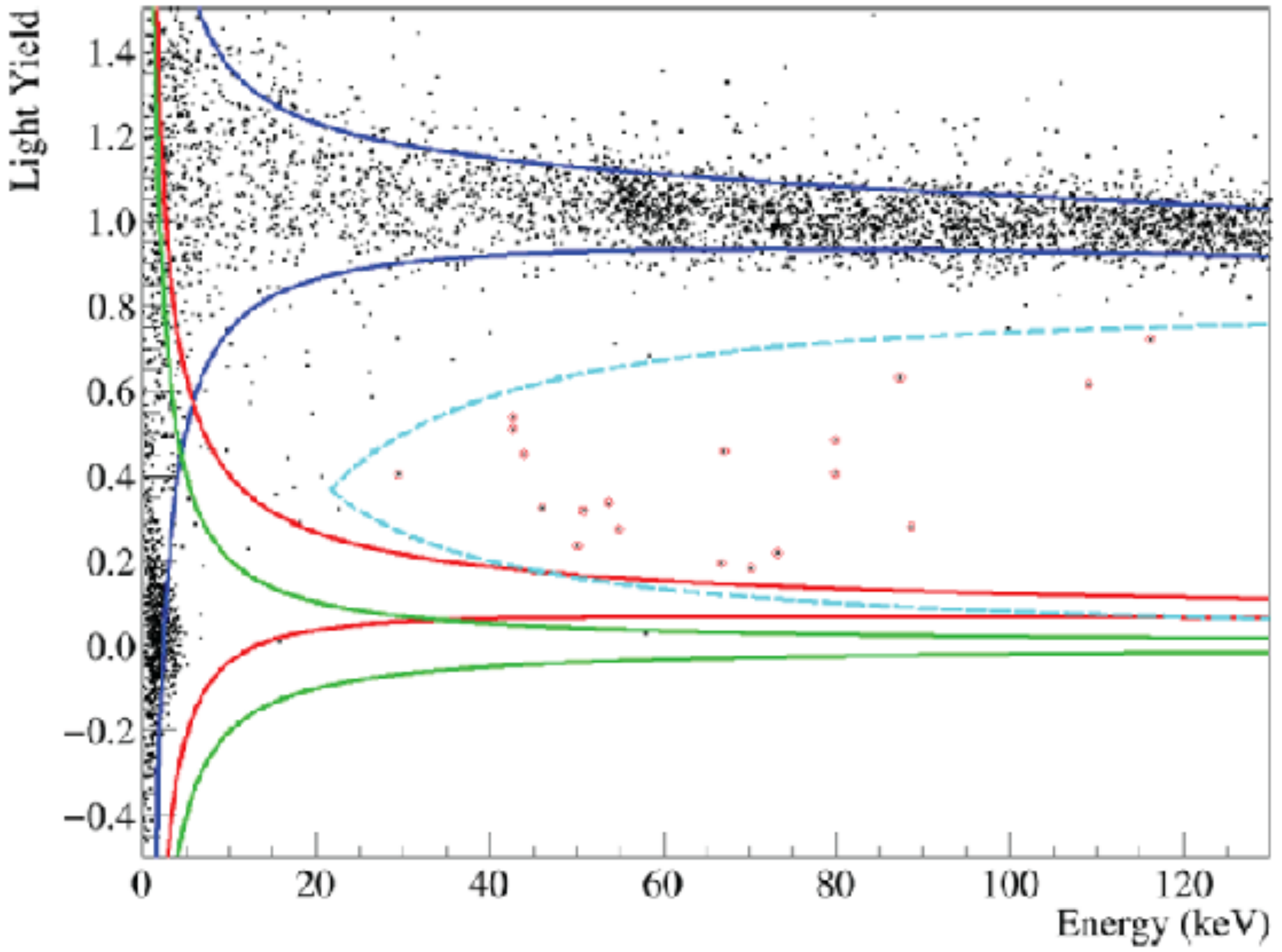
- Possibility to observe S1
- More uniform detector response



Test final solutions to be operated at the ESS

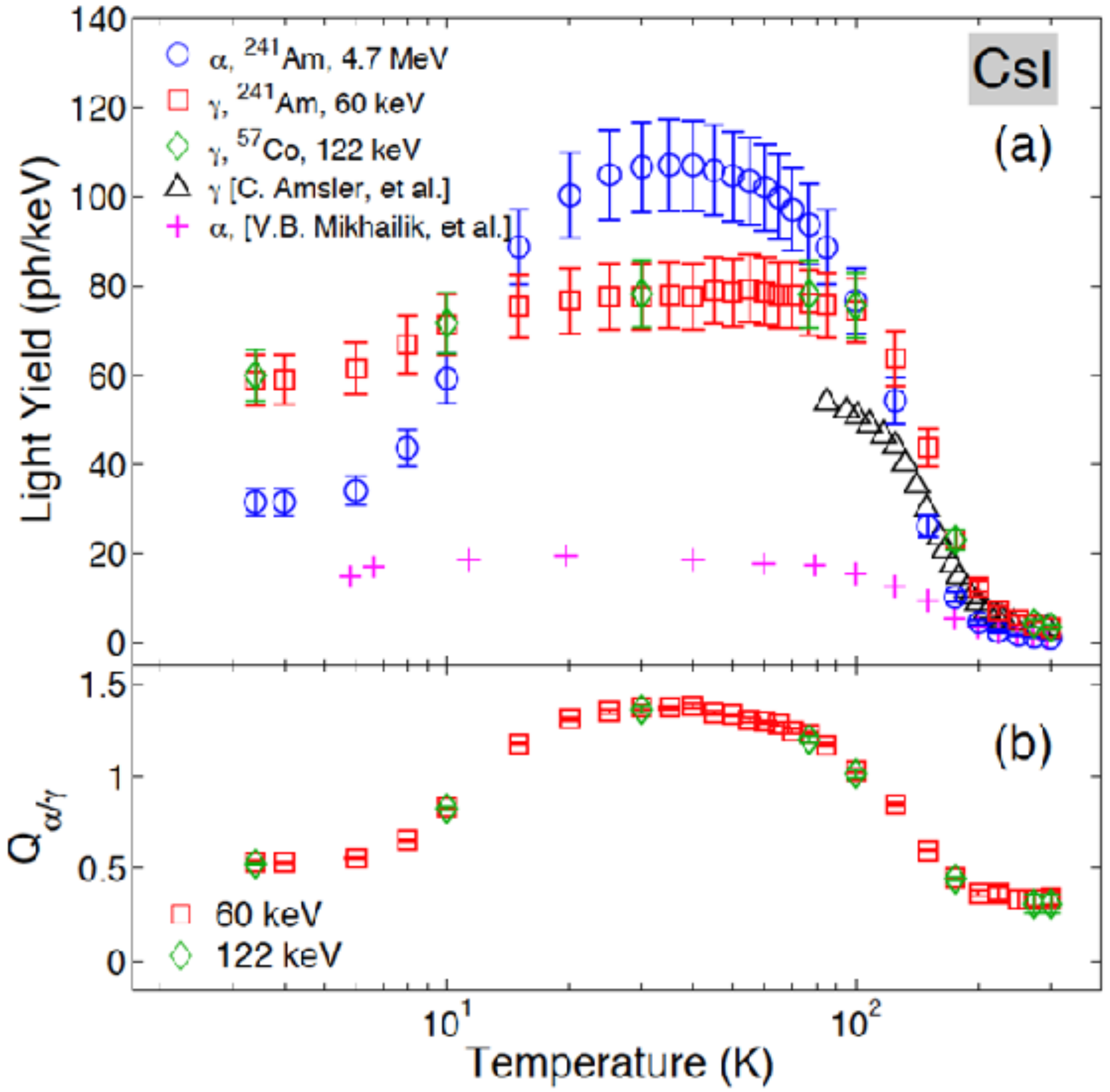
# Cryo CsI

- Signal STATISTICS needed to explore new physics




arXiv:1602.08884

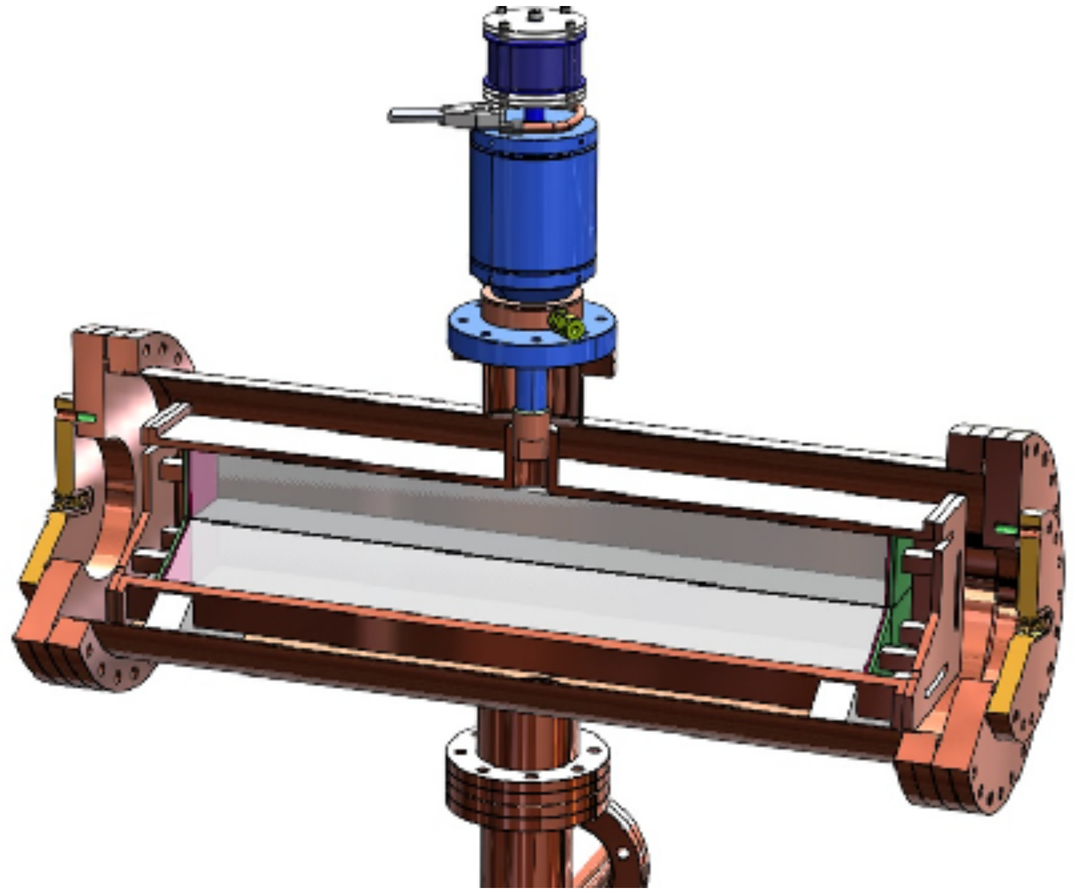
Electron-nuclear recoil separation capabilities

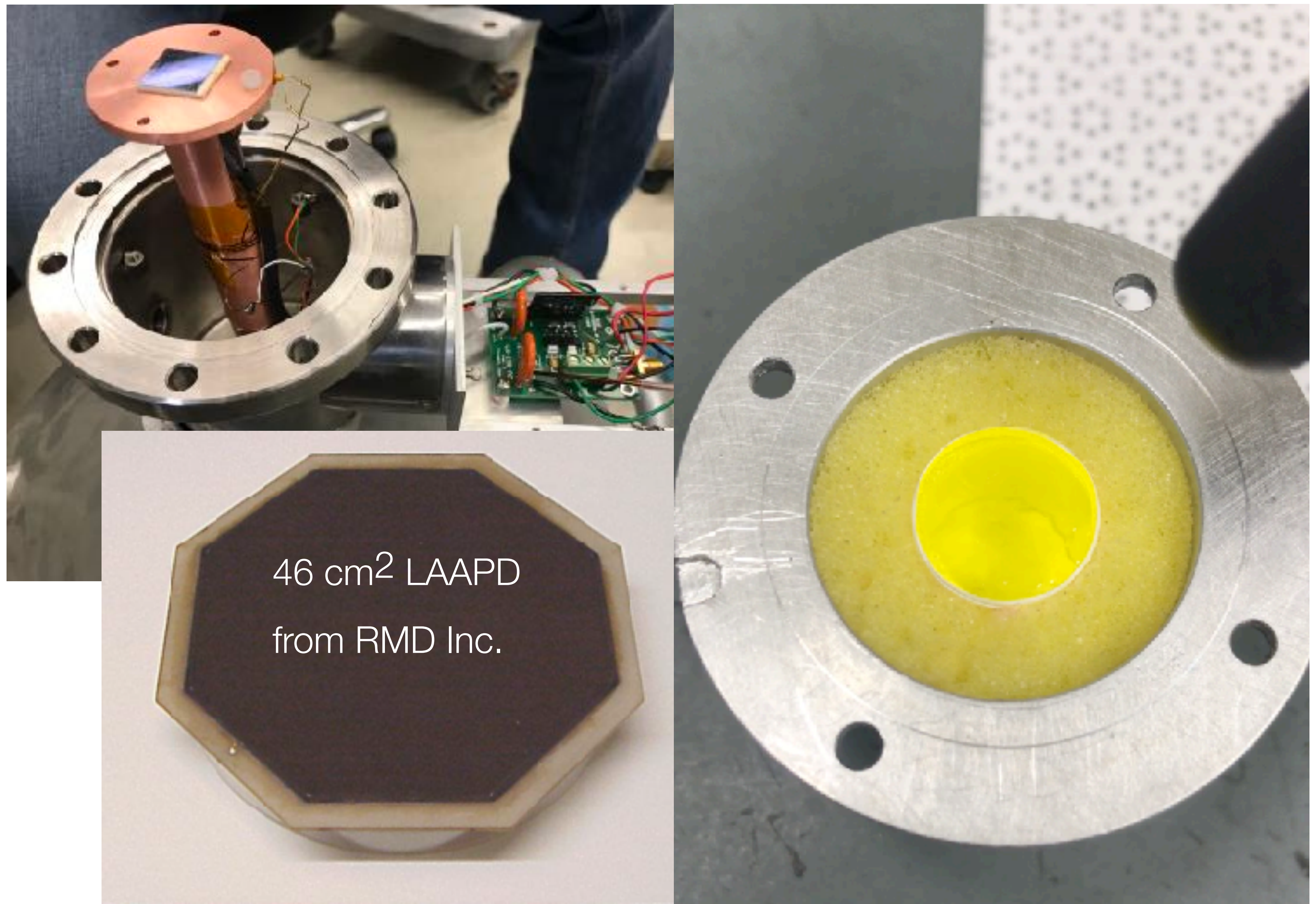


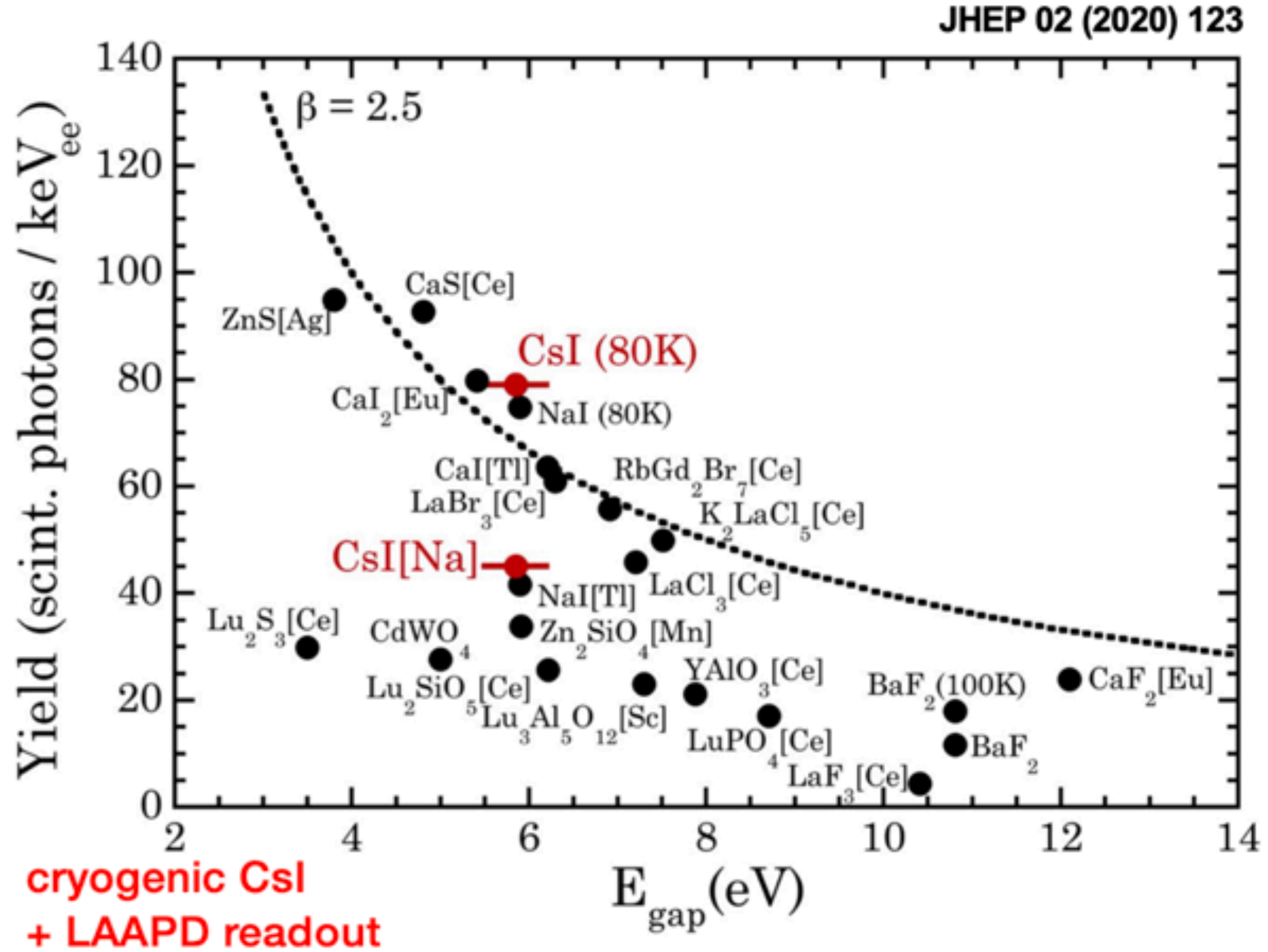

Ultra-low threshold thanks to the inner structure and the high light yield.

# Cryo CsI

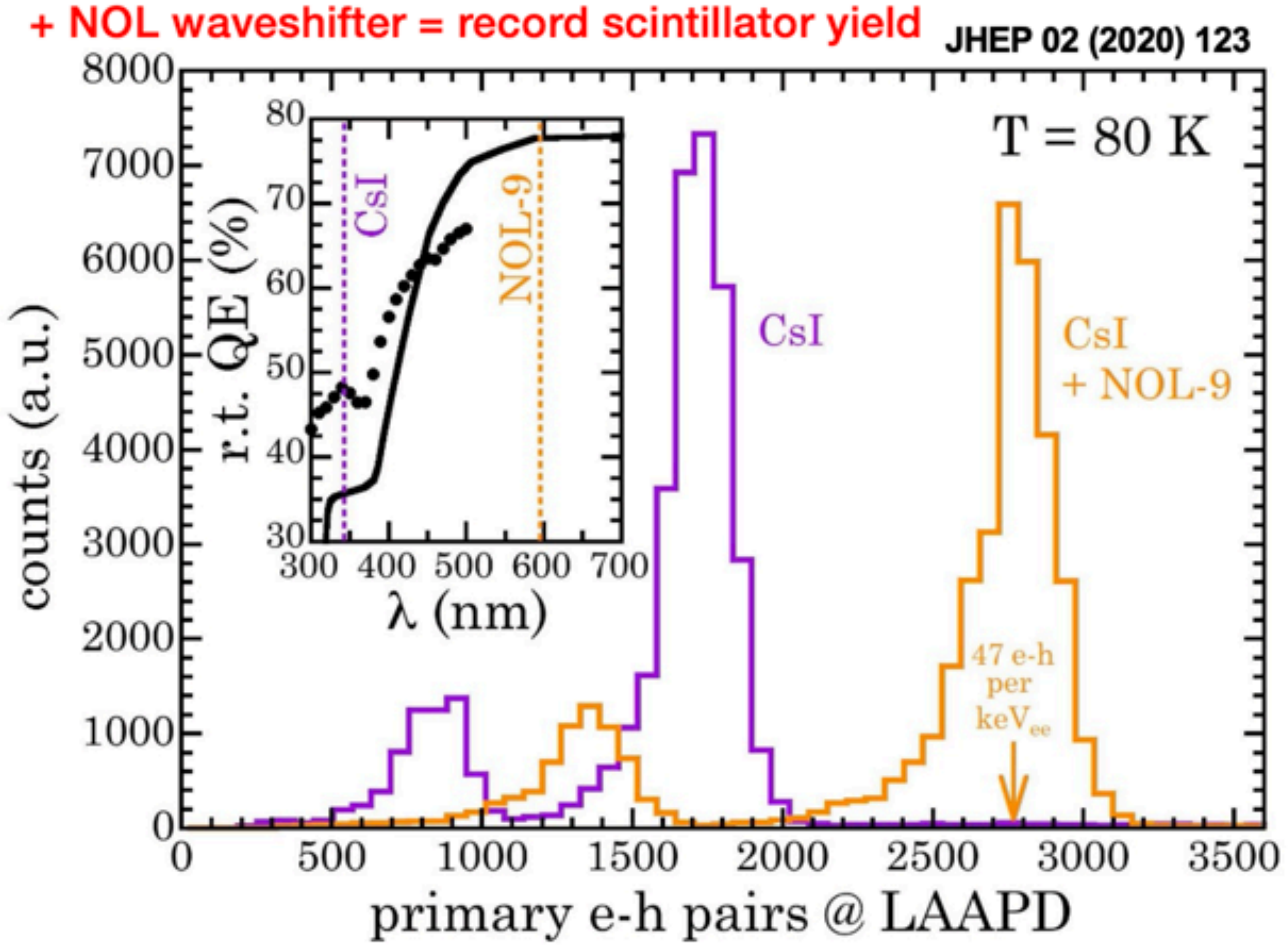
- Development of 32 kg CsI scintillator crystals operated at cryogenic temperatures.
- Light output enlarged thanks to the development of organic wavelength shifters.
- Production of large area APD to improve signal.





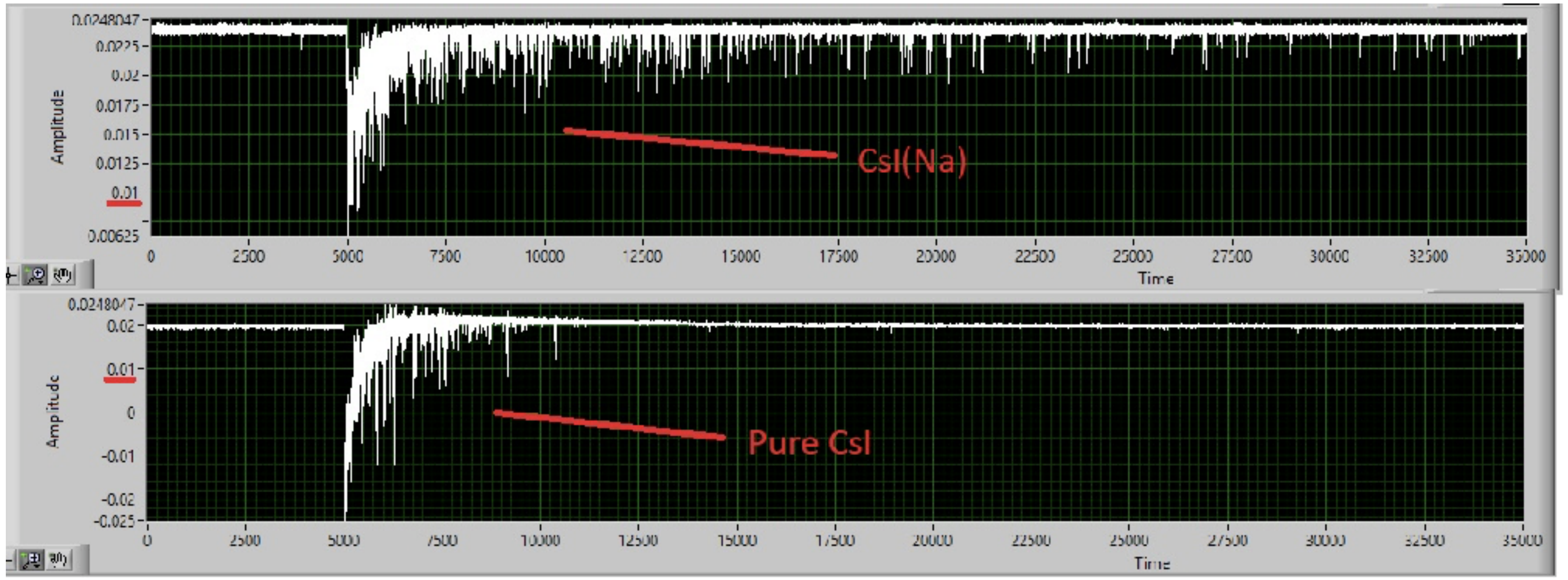



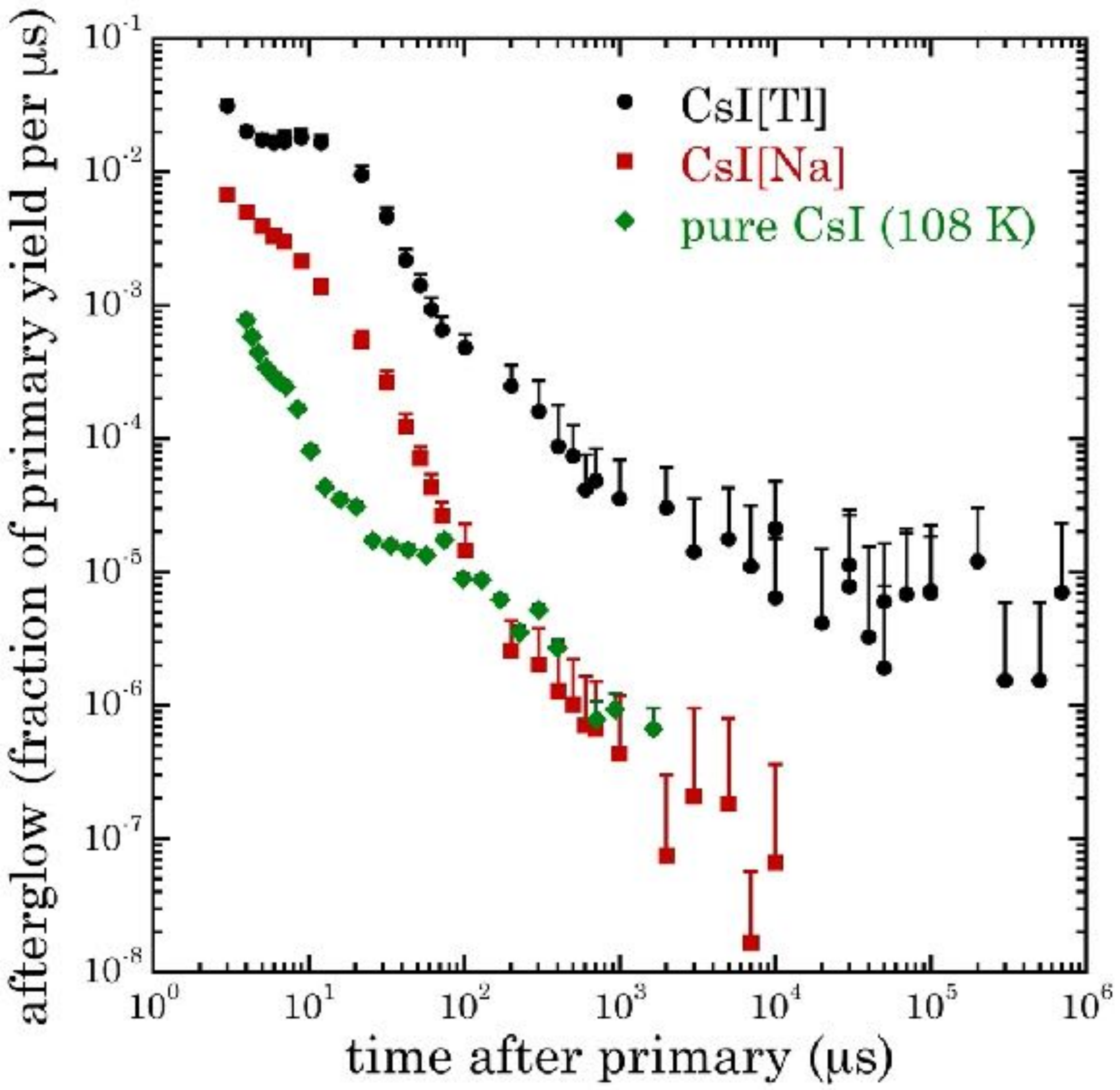

**cryogenic CsI**
**+ LAAPD readout**
**+ NOL waveshifter = record scintillator yield**



# Cryo CsI

- Transition from CsI(Na) to CsI



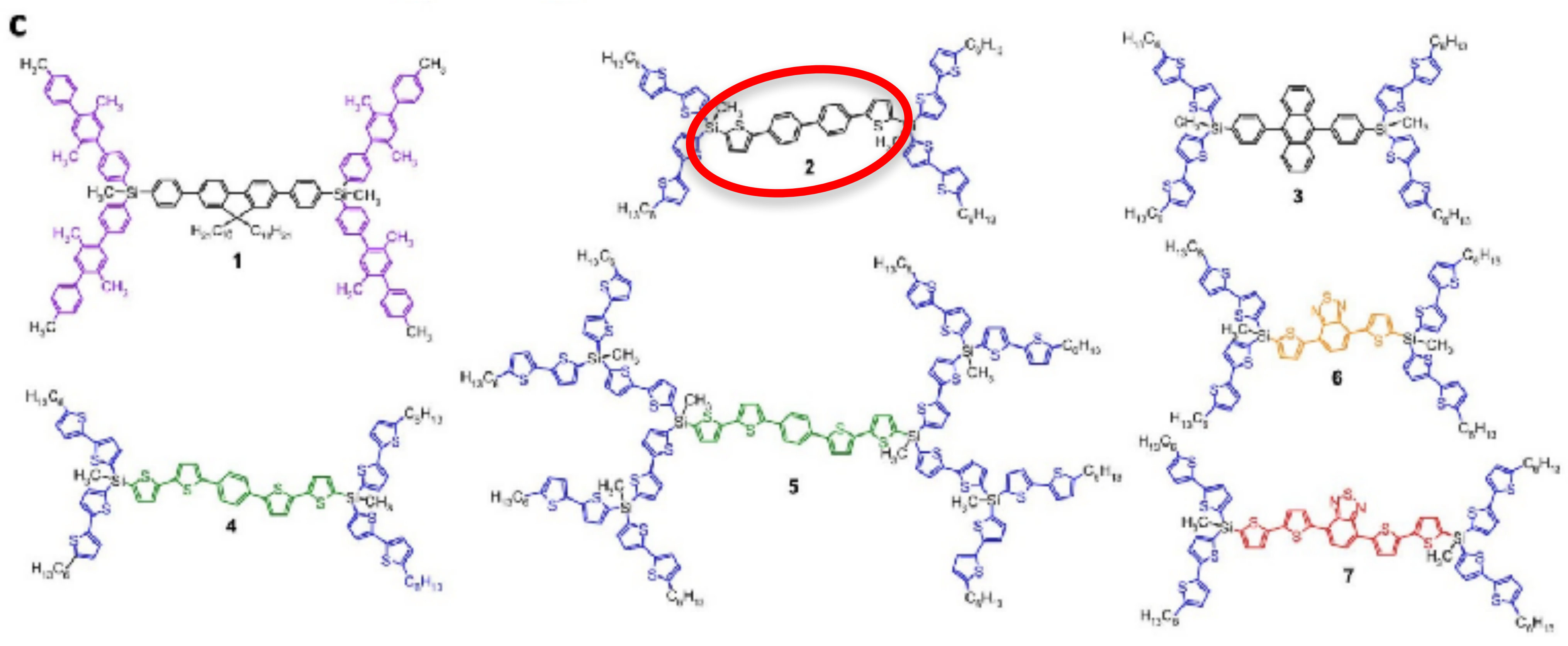

CsI[Tl] excessive afterglow

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

Reduction of the after glow improves Energy threshold.

# Cryo CsI

- Development of organic wavelength shifters



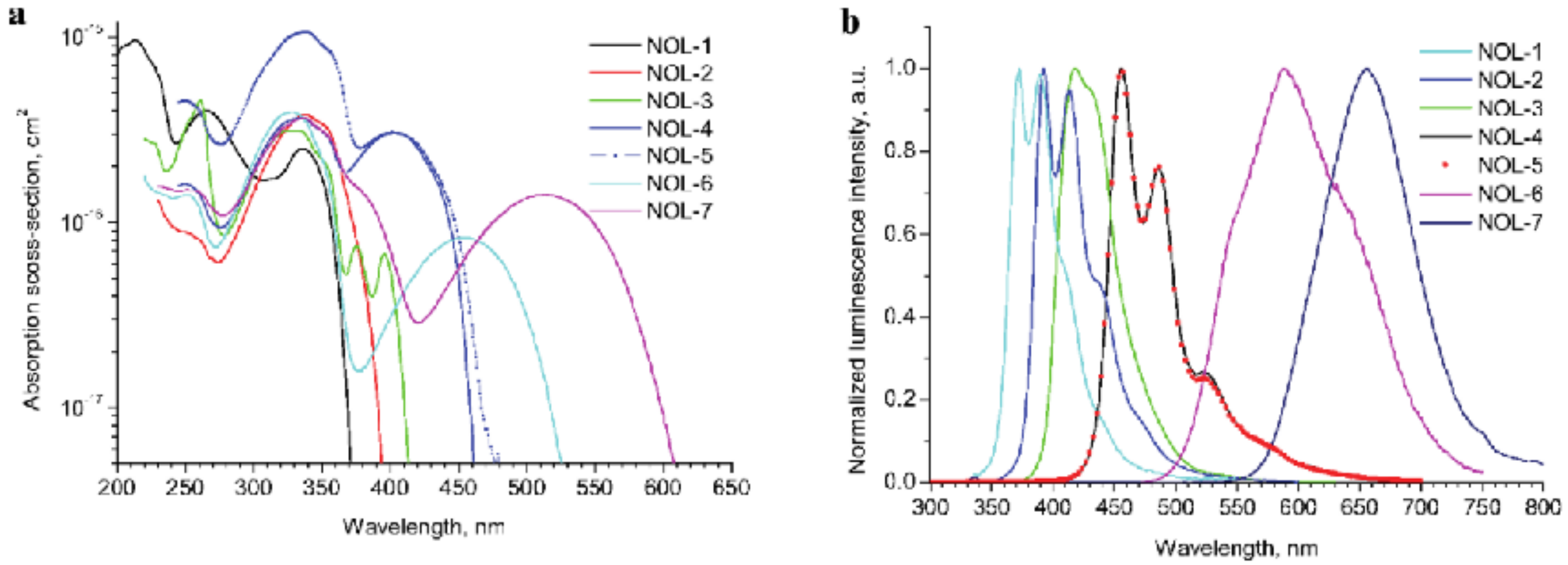



**Figure 2 | Optical properties of NOLs in dilute THF solutions.** (a), Spectral distributions of absorption cross-sections ($C = 10^{-5}$ M). (b), Luminescence spectra ($C = 10^{-6}$ M).

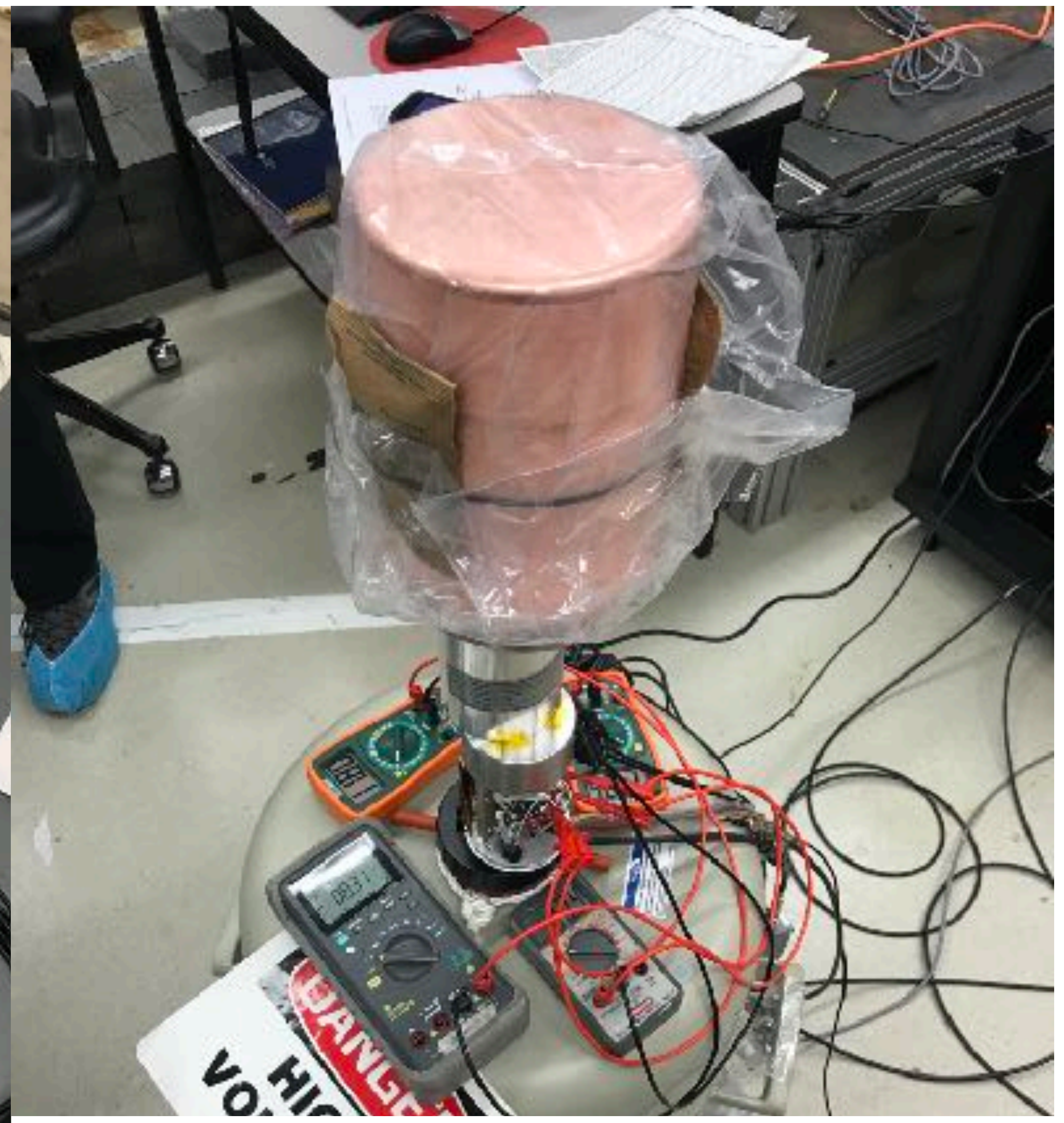
Wide spread of tailored absorption-emission spectra (~50 compounds)

PLQY between 50-99%

Almost a factor two improvement with respect current techniques.

# PPC Germanium

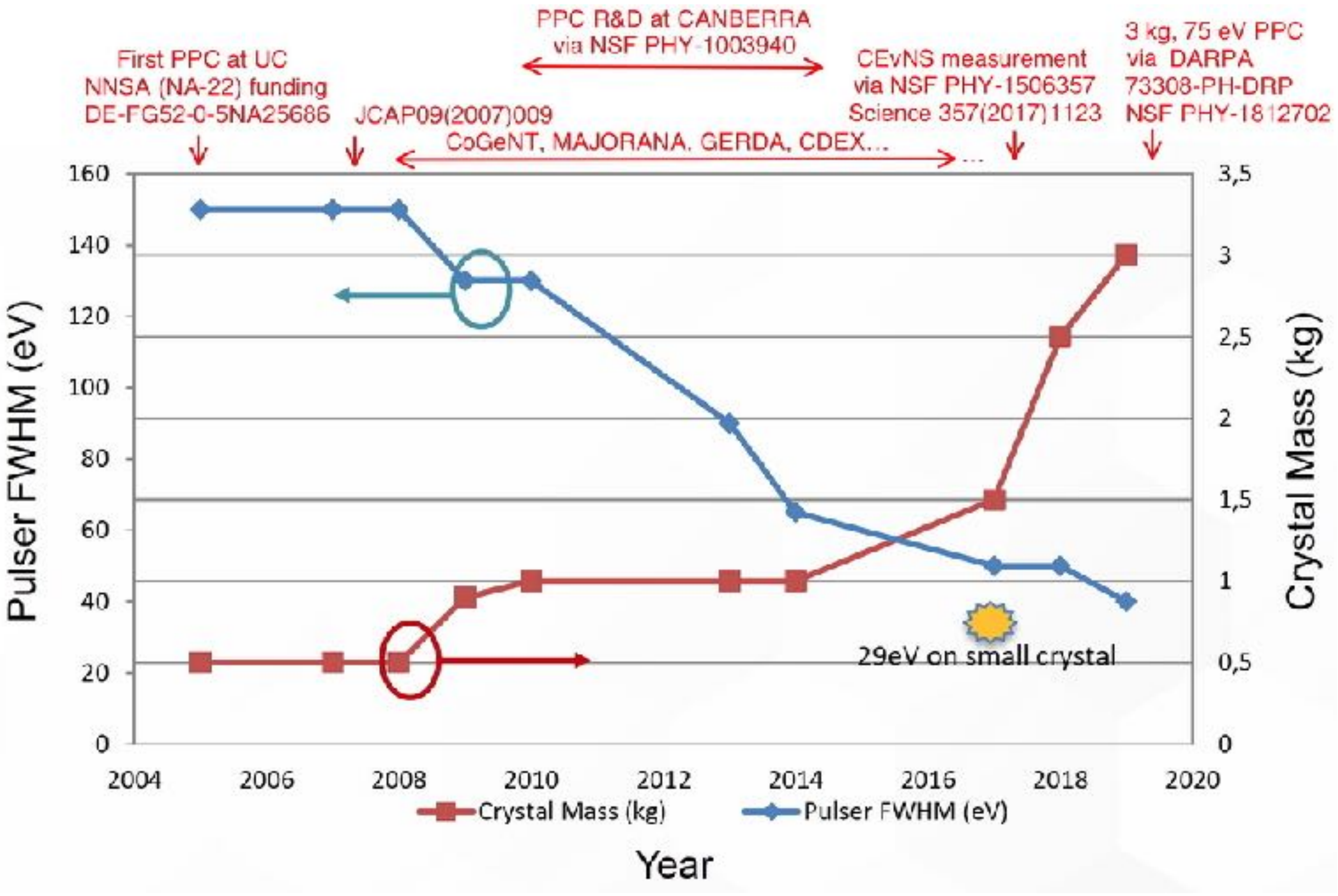
- Large evolution of the technology in the last years.
- Extremely low threshold (~150eV) with excellent energy resolution

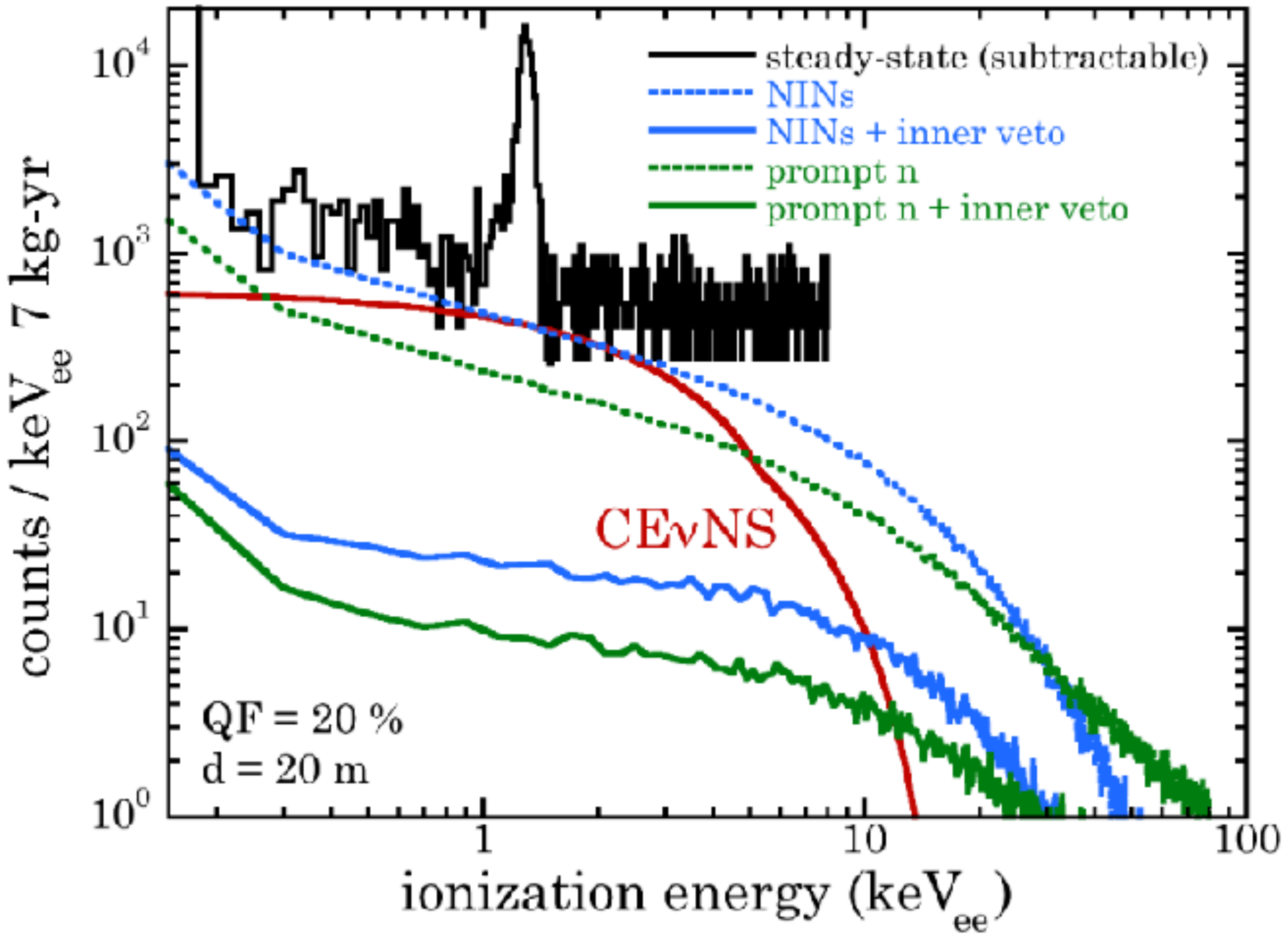


Largest, lowest threshold PPC

(3 kg, 200 eV)

European
Research
Council

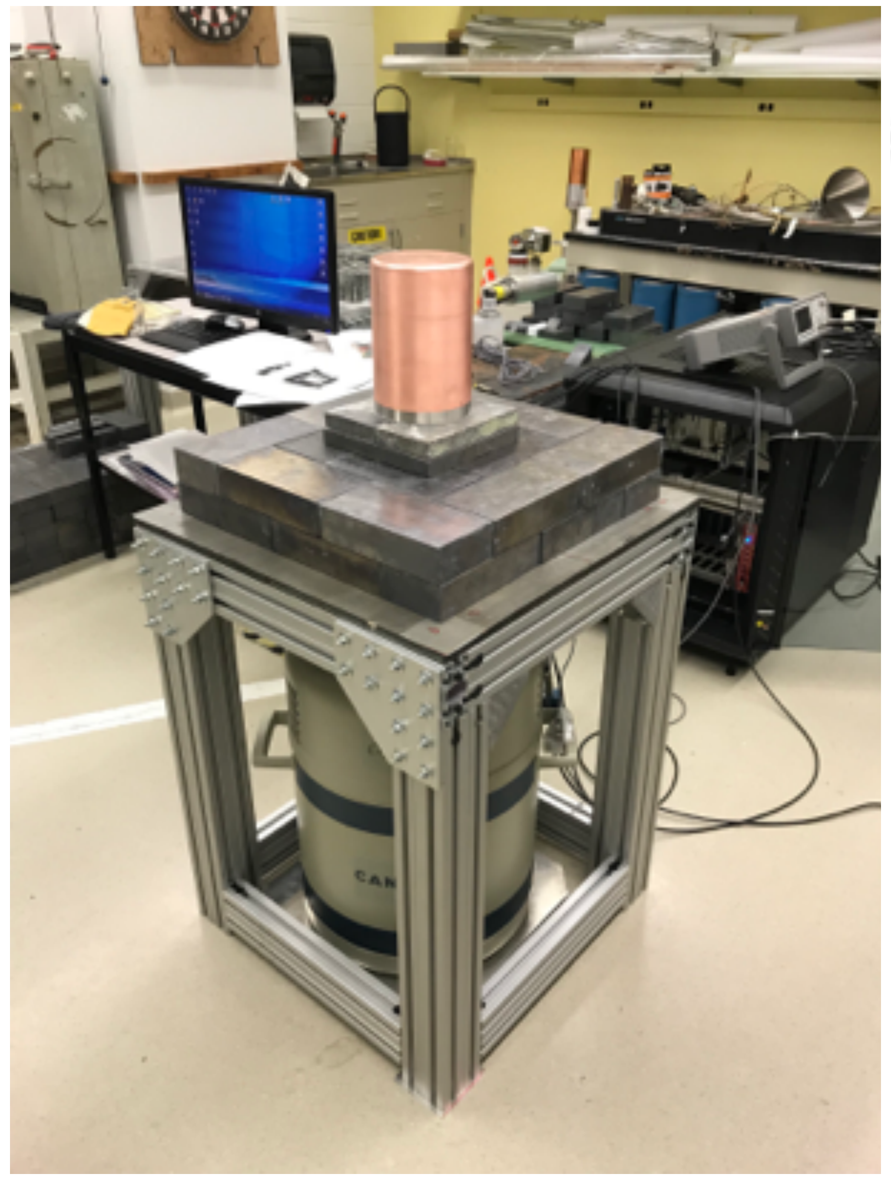


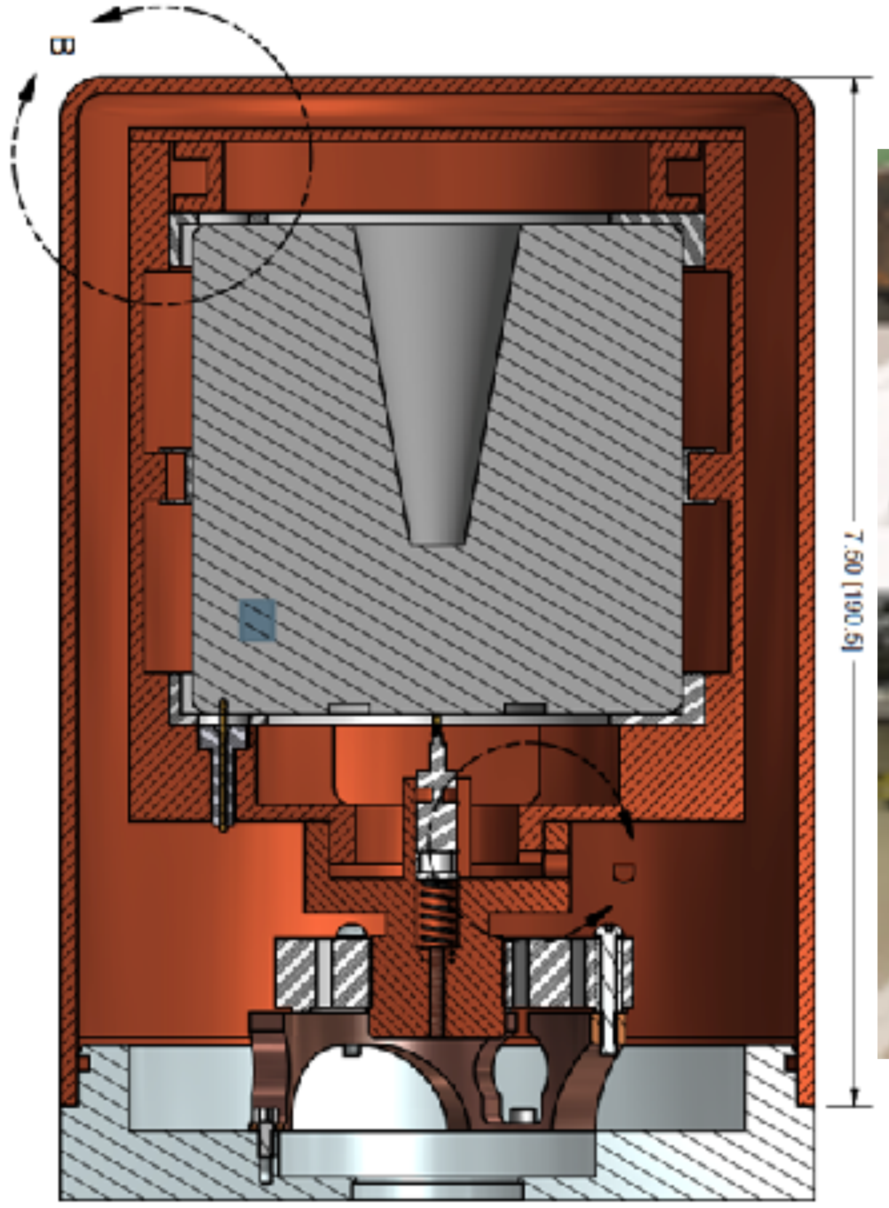



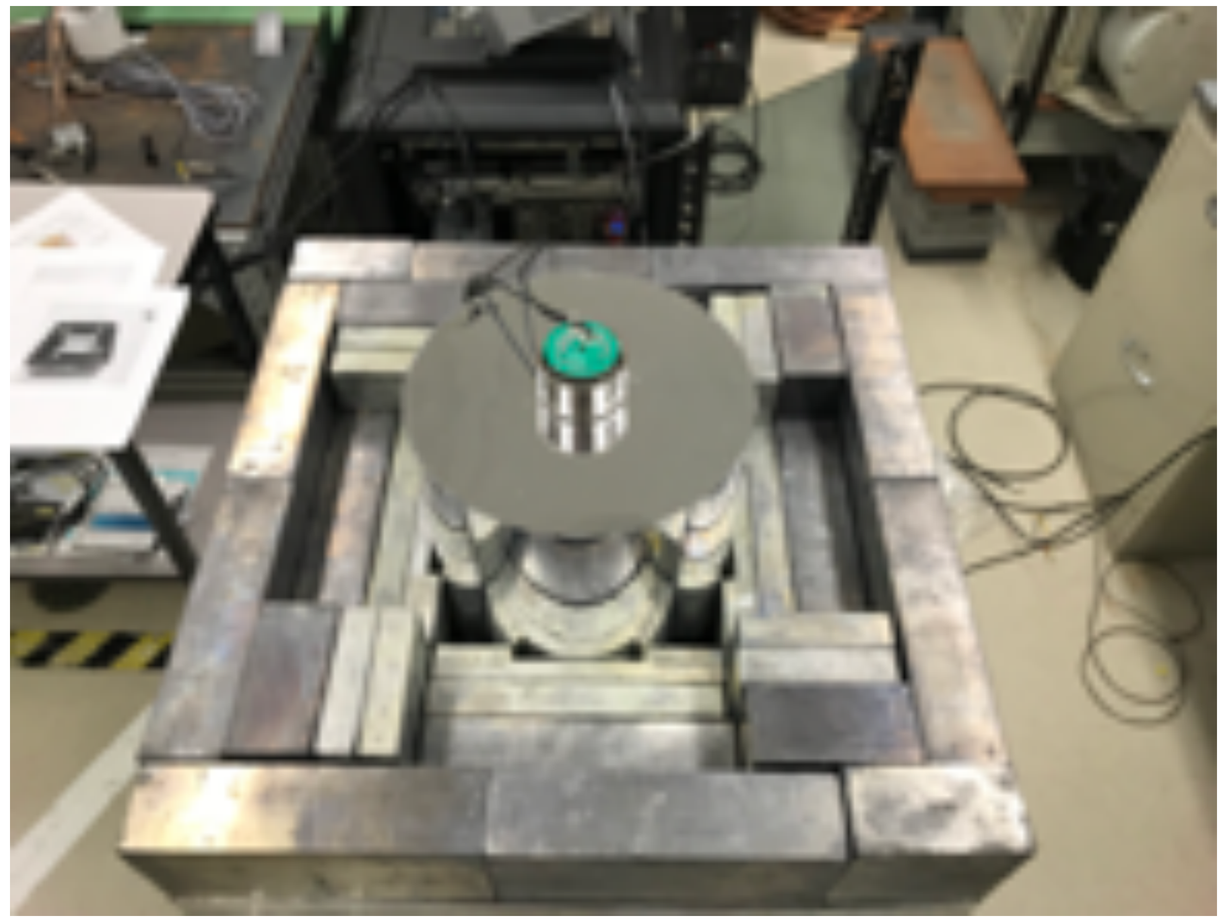
# PPC Germanium

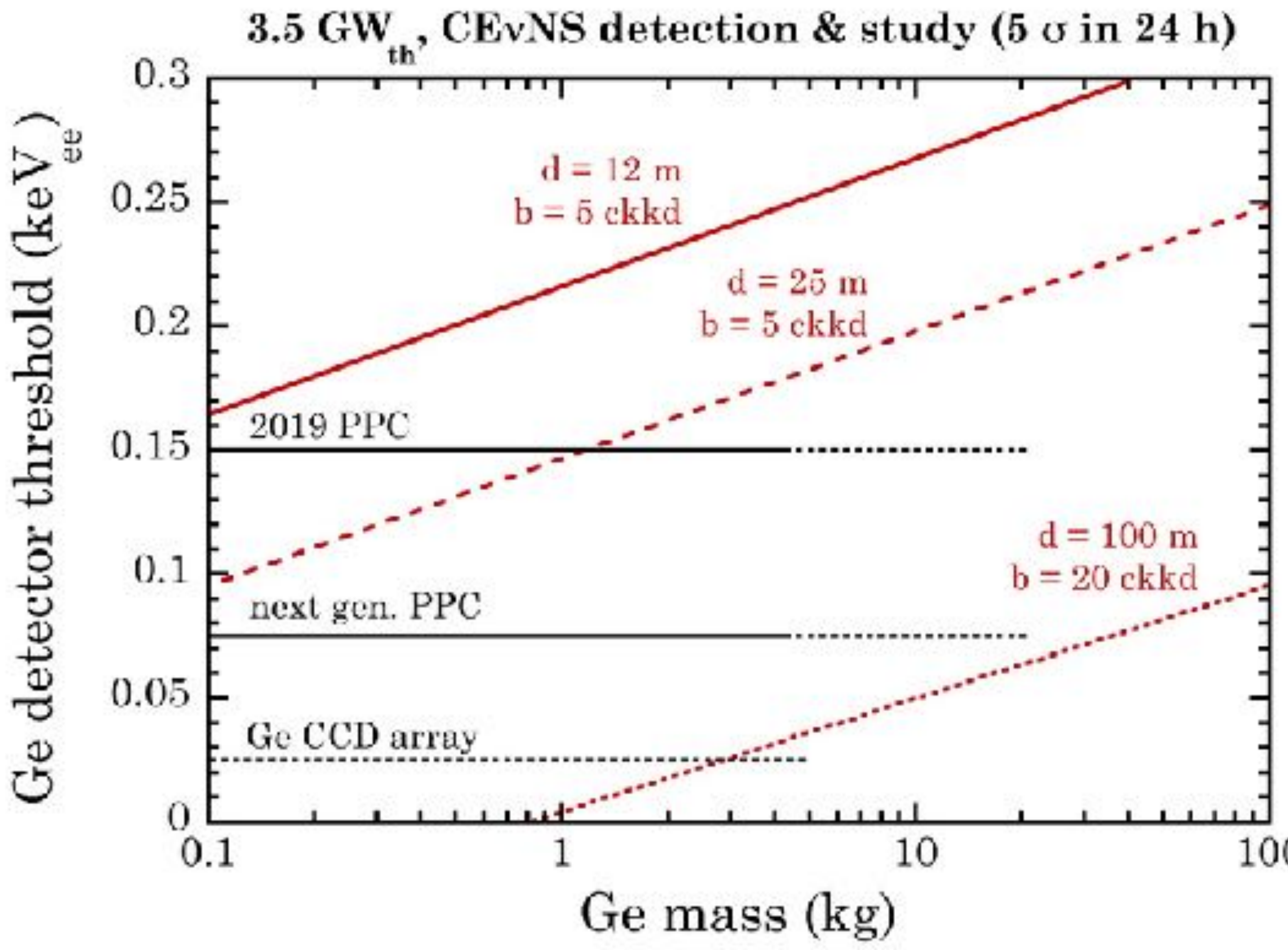
Combination ideal for precision CE$\nu$NS studies:

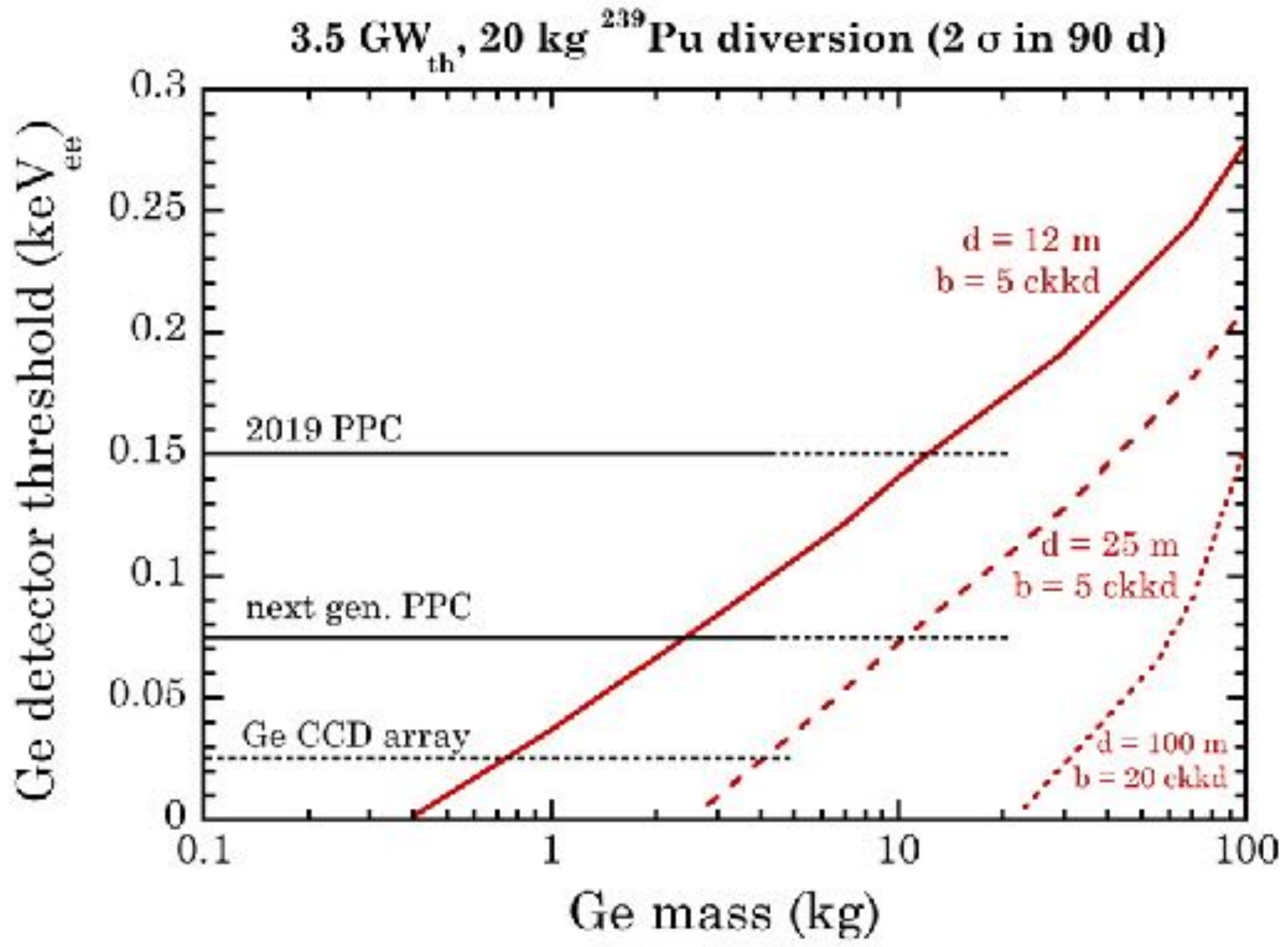
- Mass
- Radiopurity
- Energy Resolution
- Low Threshold



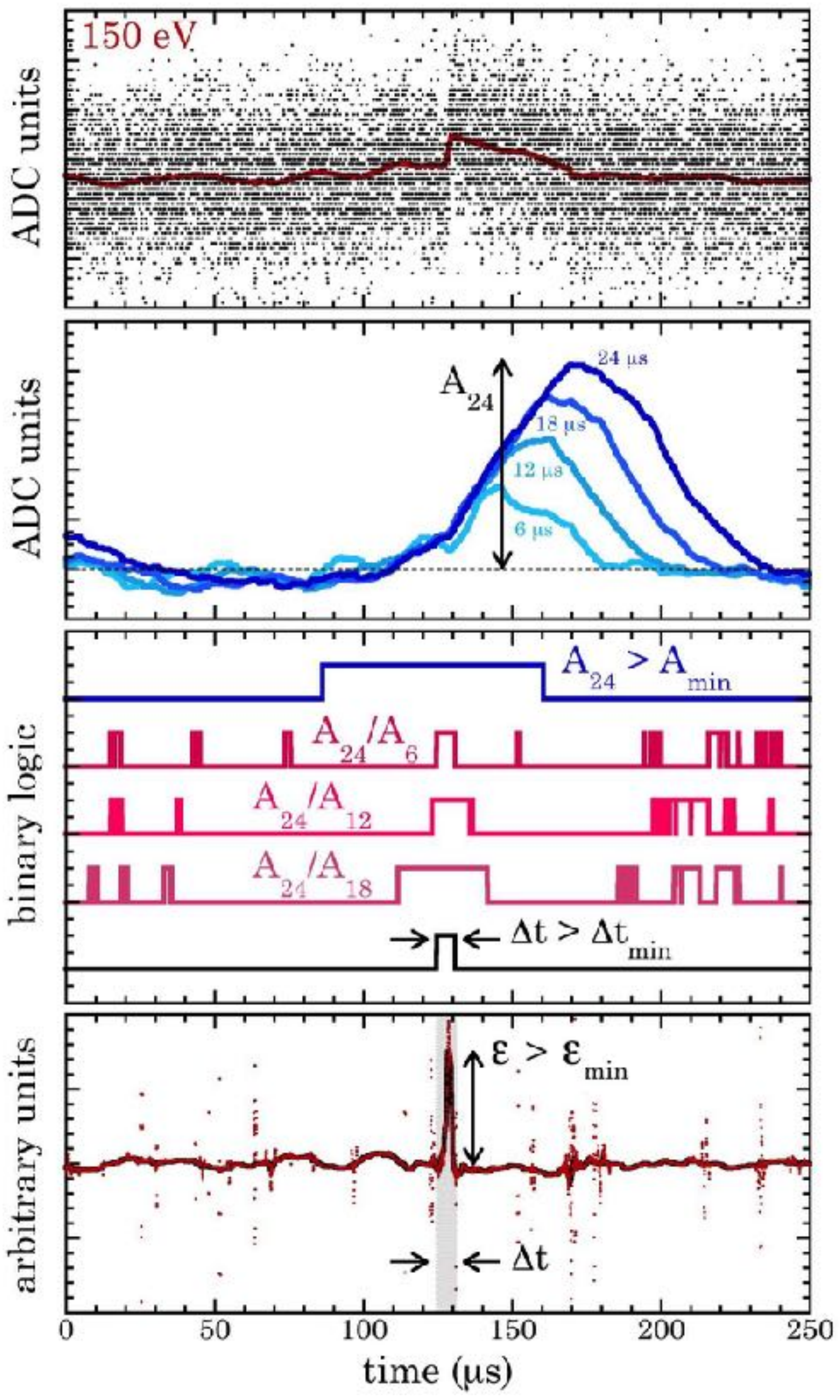




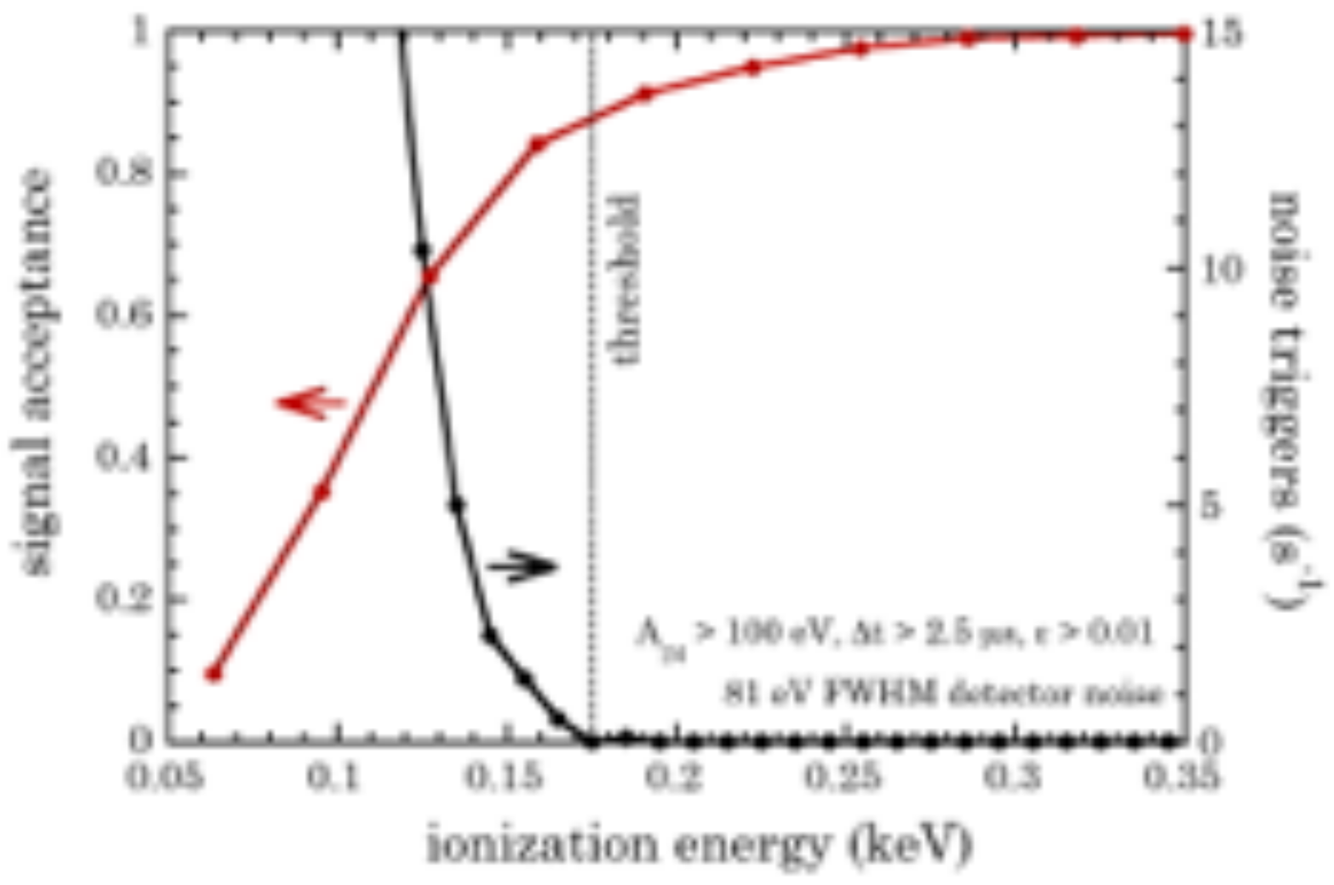


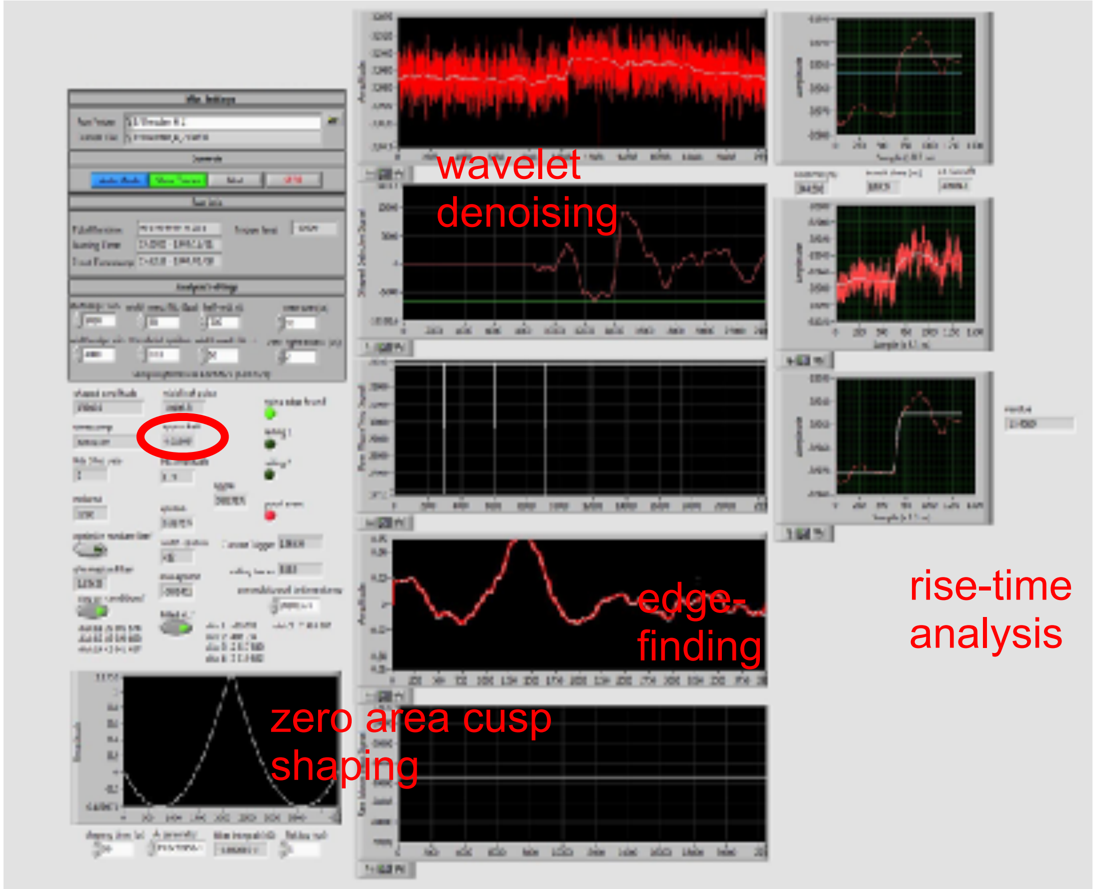
# Lowering the E threshold in PPC Germanium

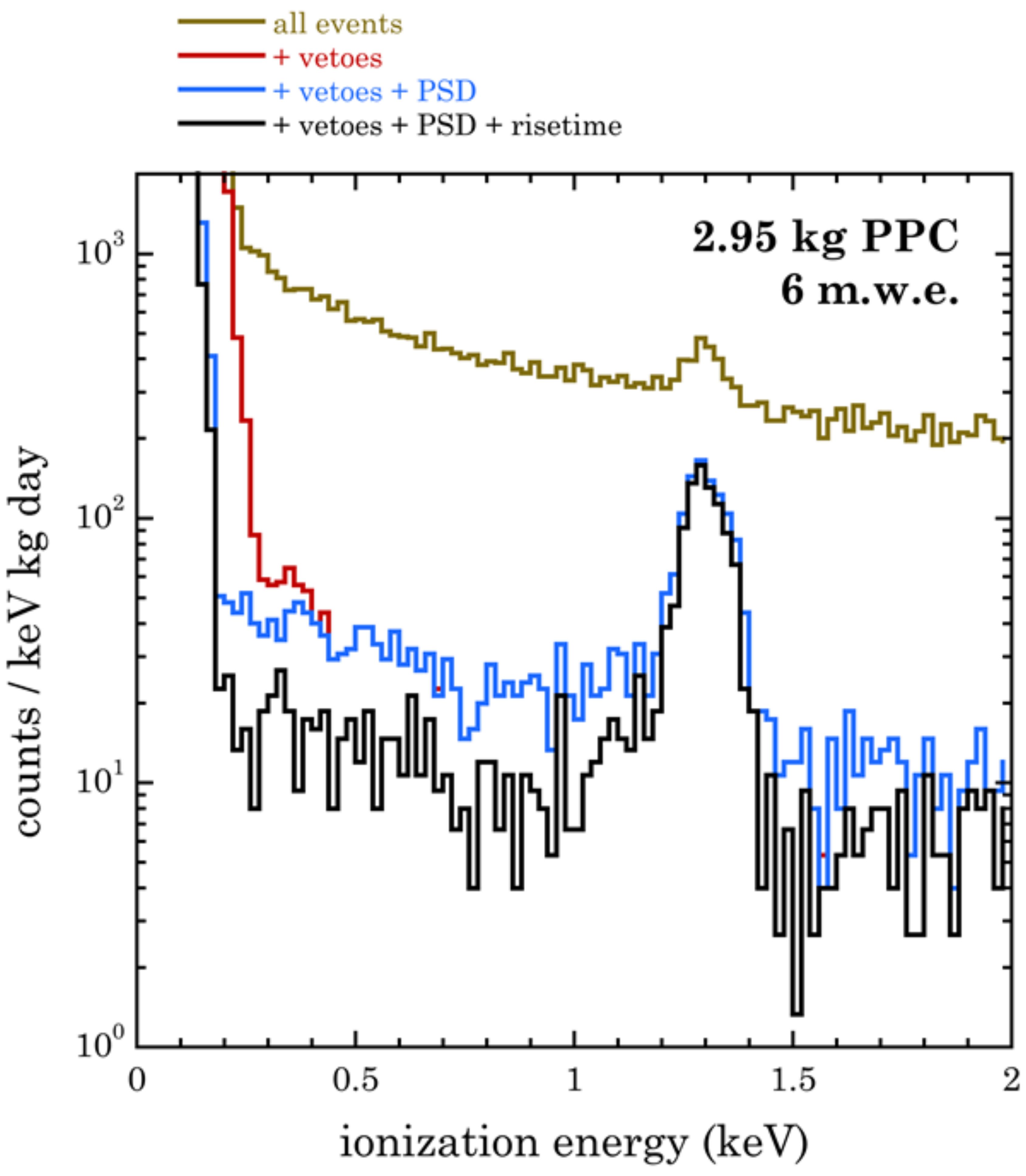



FPGA shaping condition fulfillment




PSD (in action)

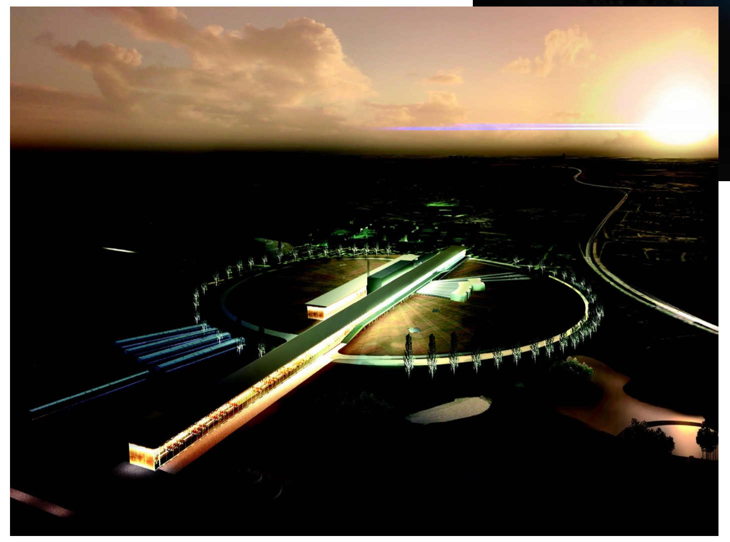


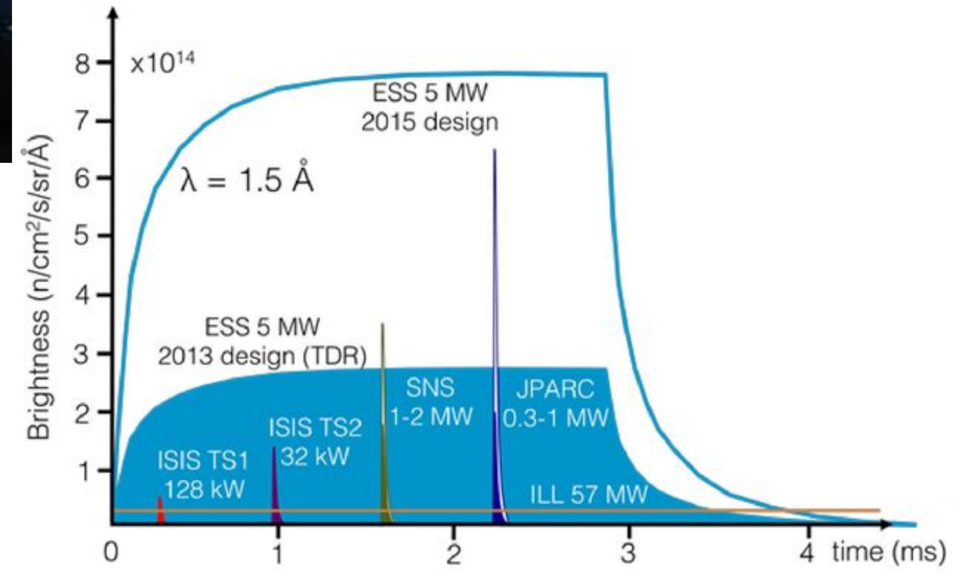



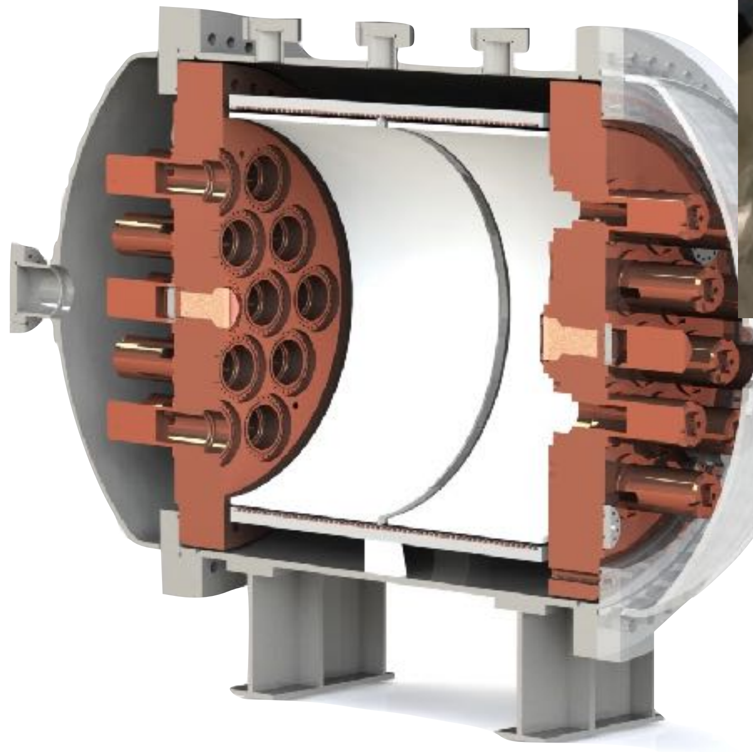

Analysis threshold of 180 eV

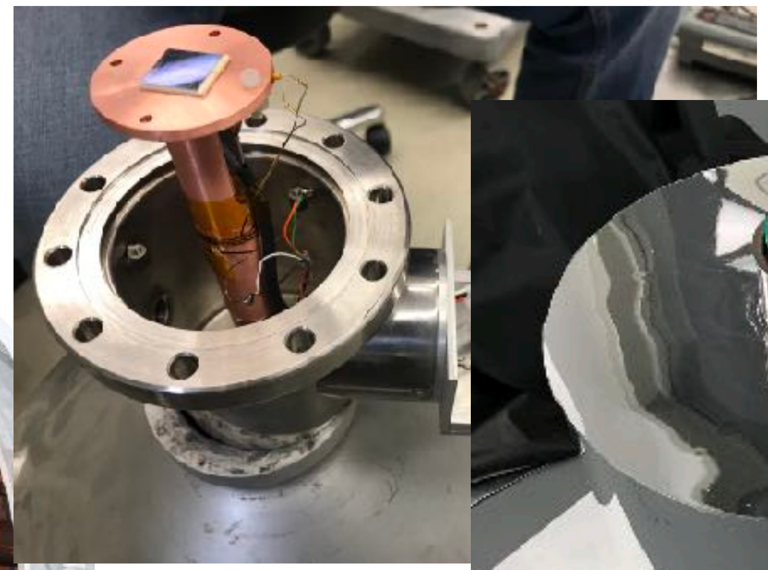
# Coherent neutrino interactions: Summary

- CEvNS detection opens a **new avenues in the search of physics beyond the Standard Model**.
- **ESS** will become the largest low-energy neutrino source. Perfect facility to study this process.
- We aim to produce a series of detectors to observe the process at the ESS with a variety of nuclei.
- Opportunity to **lead a world-class neutrino program** in the coming years with a **large discovery potential**.



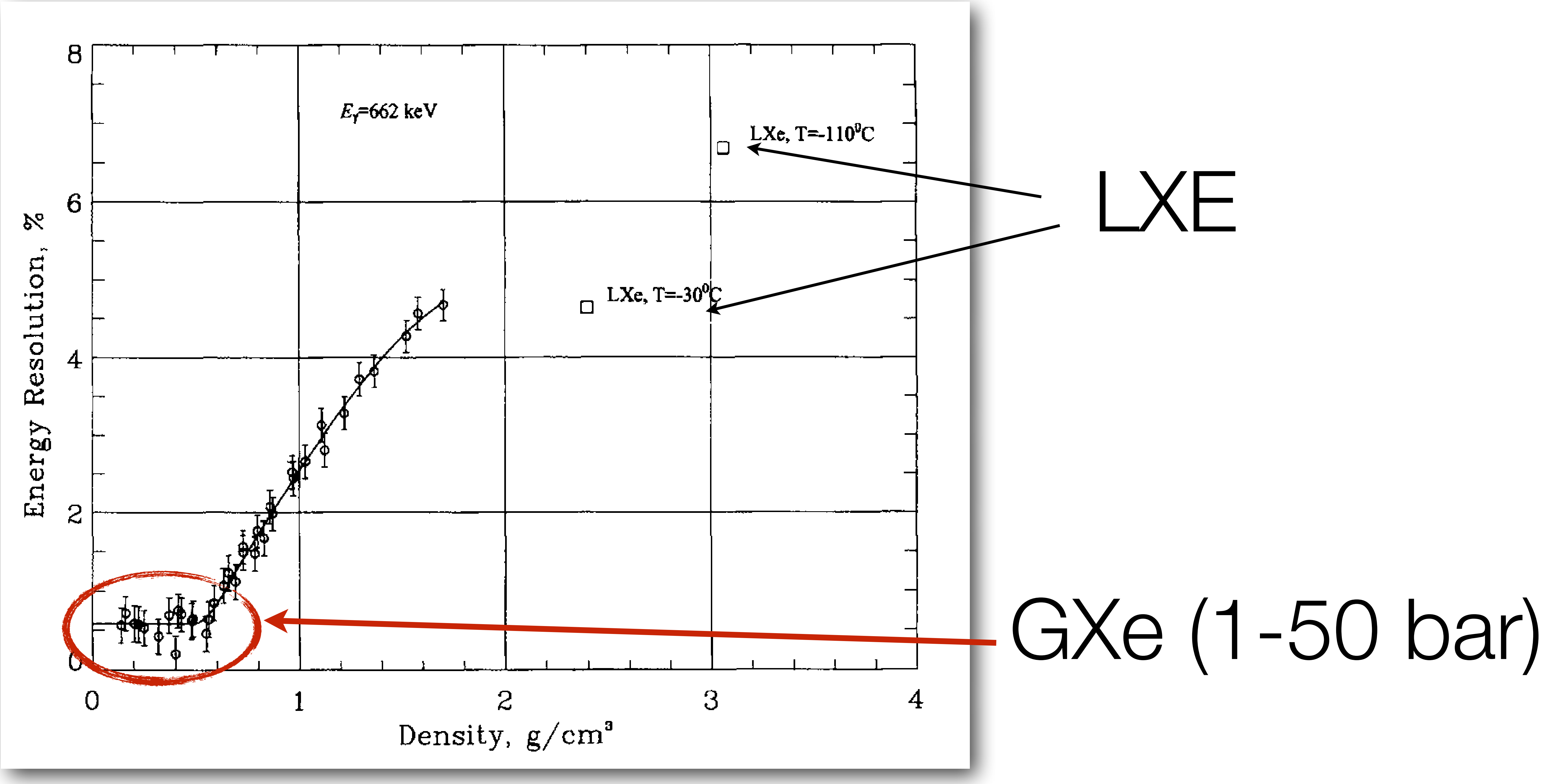





# Back-up

# Energy resolution in HPXe

Bolotnikov and Ramsey,
NIM A 396 (1997)



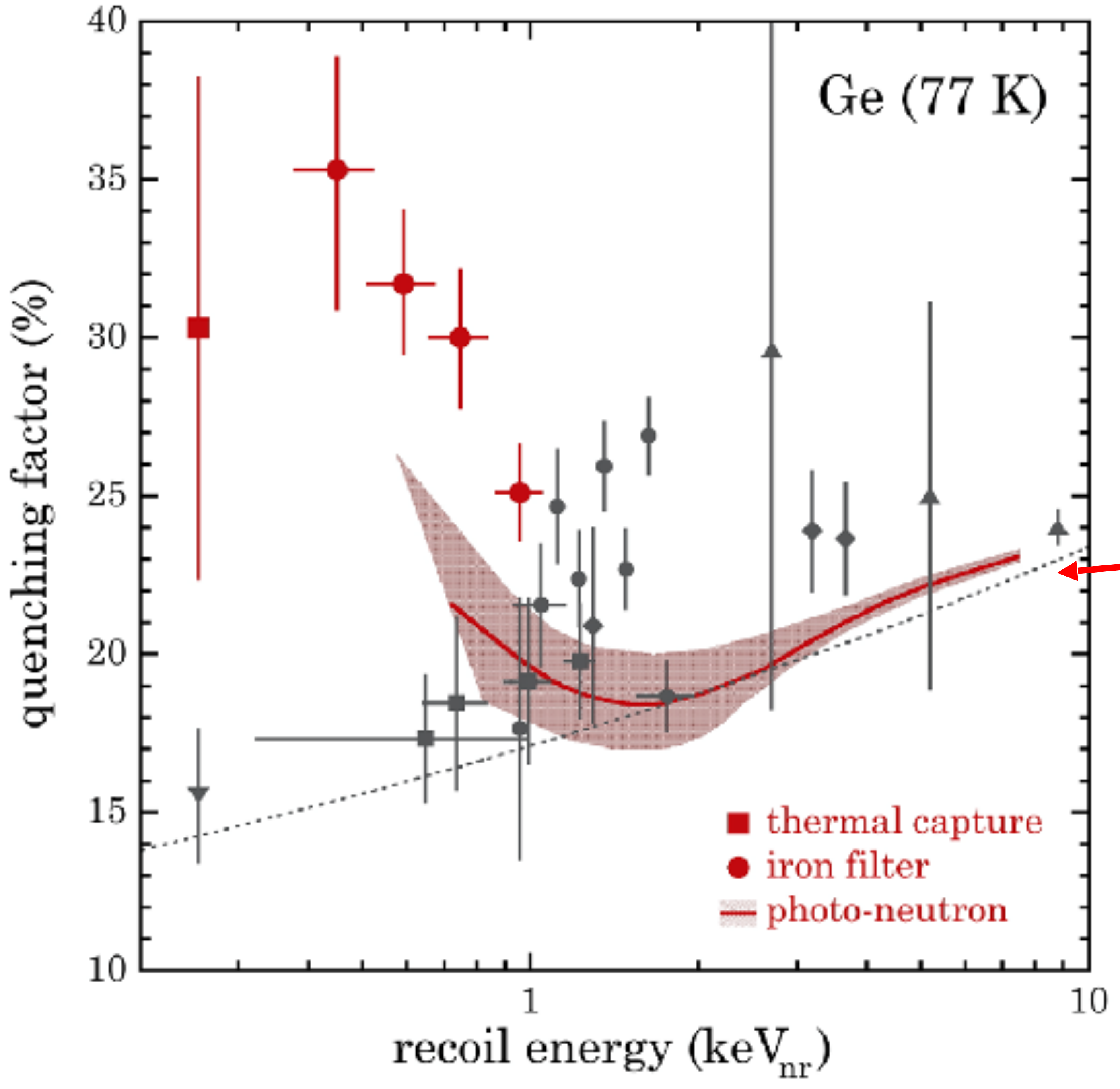

- Very good energy resolution up to ~50 bar.
- Best experimental result: 0.6%@662keV.
- It will allow for a better spectrum reconstruction, thus better sensitivity to deviations from SM.

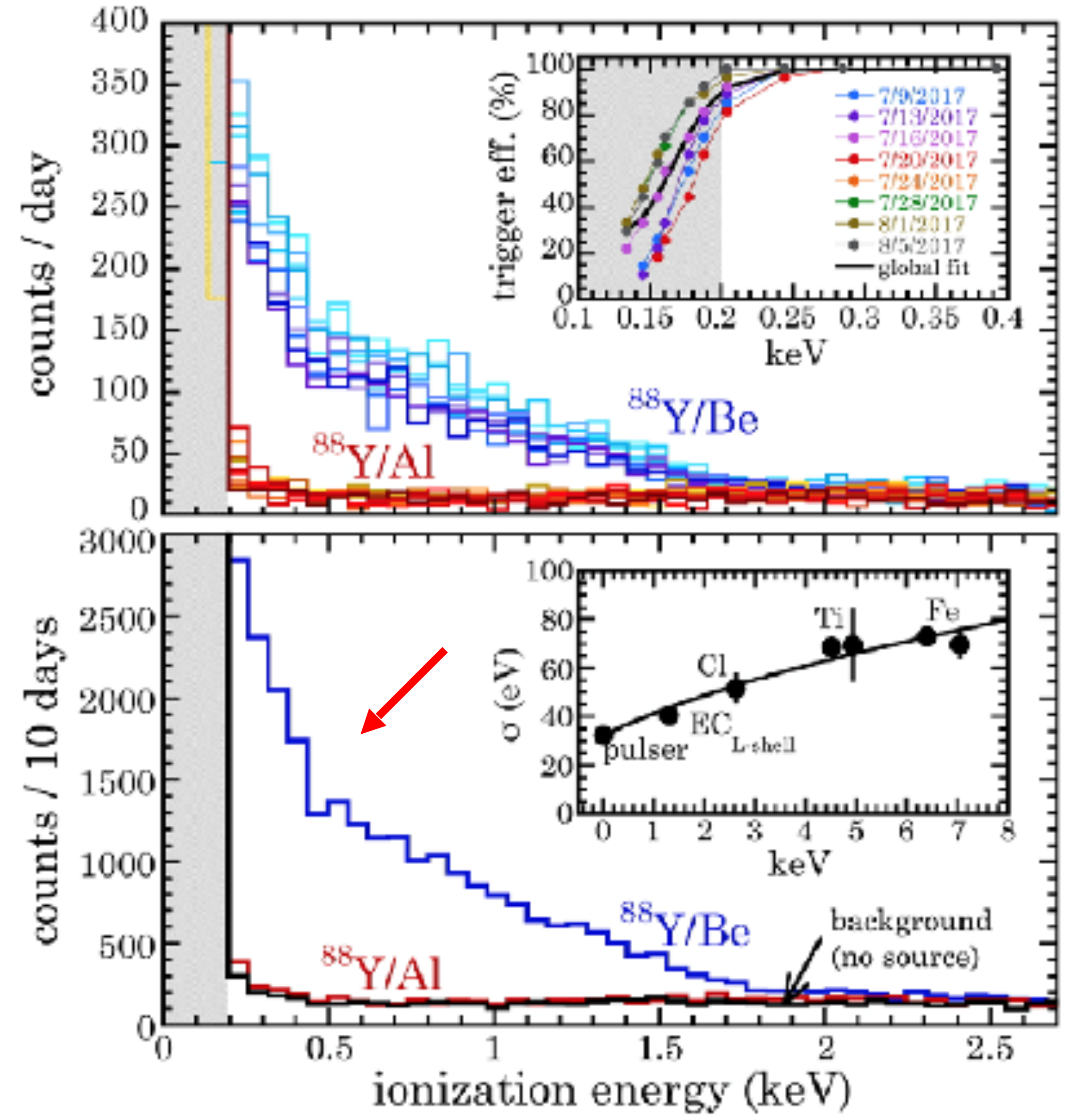
# Understanding Ge NR response

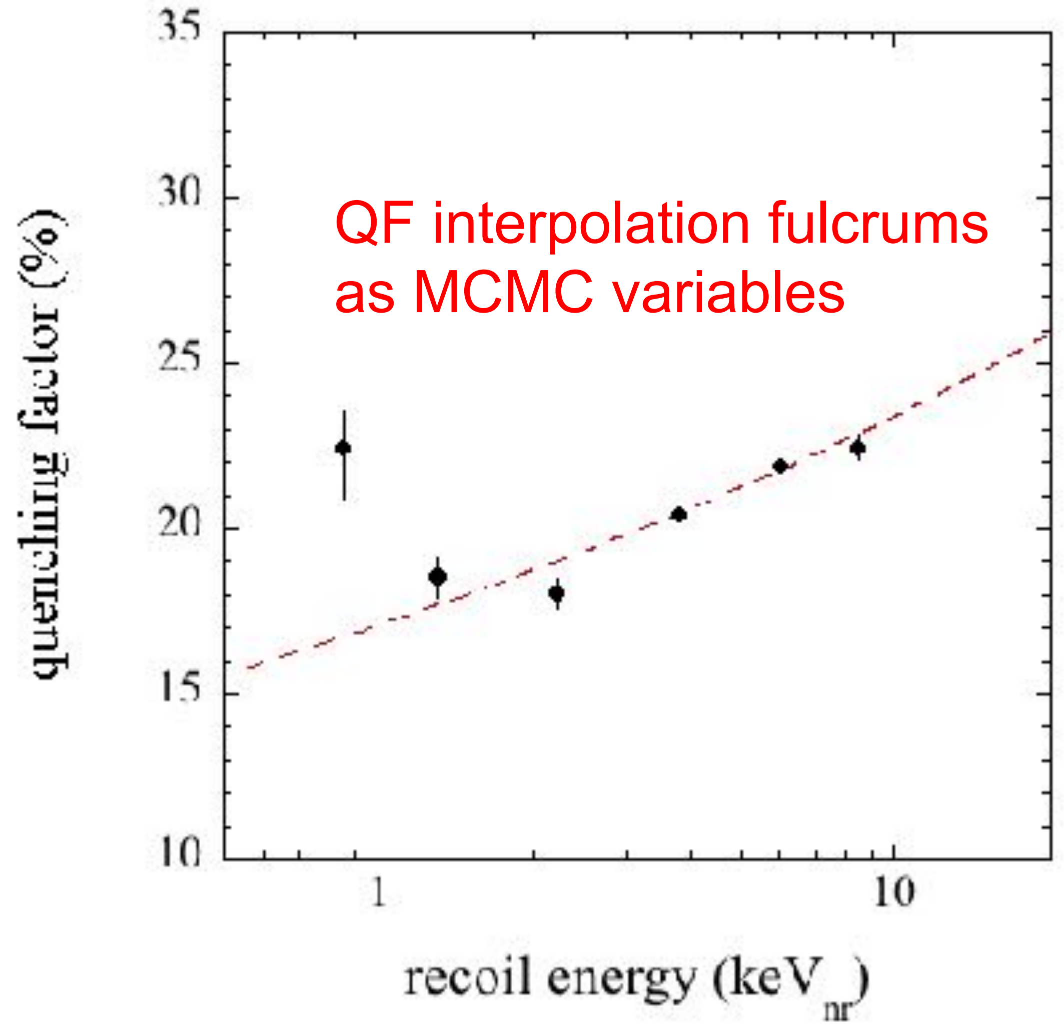
PHYSICAL REVIEW D **103**, 122003 (2021)

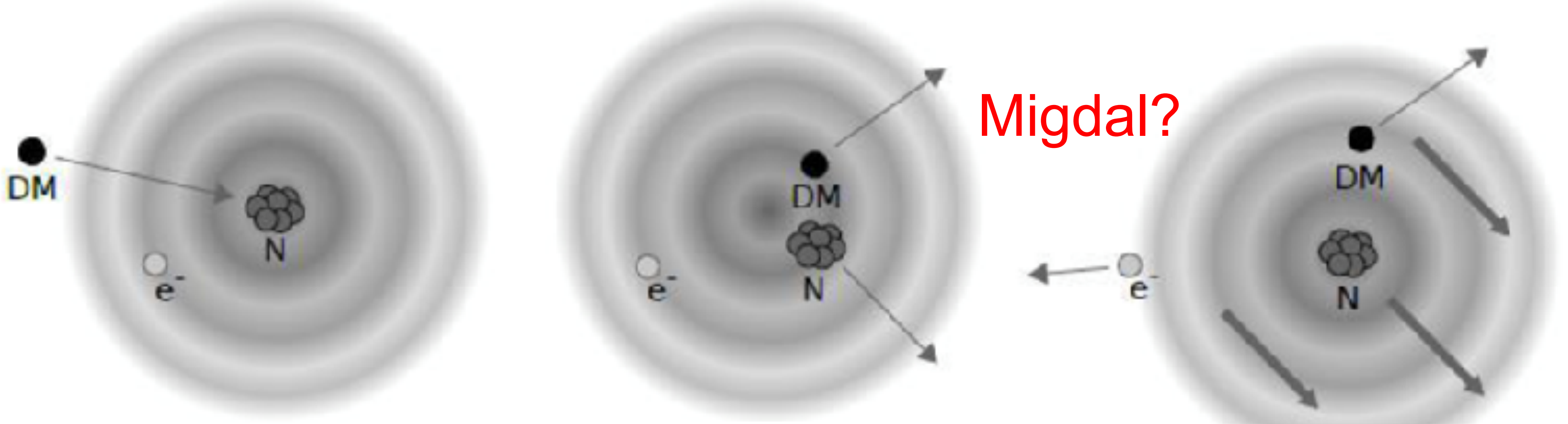
**Germanium response to sub-keV nuclear recoils: A multipronged experimental characterization**

J. I. Collar, A. R. L. Kavner, and C. M. Lewis




PHYSICAL REVIEW A **97**, 023402 (2018)

PRL **108**, 243201 (2012)

# OSURR measurement

**Calibration of nuclear recoils at the 100 eV scale using neutron capture**

L. Thulliez,[a] D. Lhuillier,[a,*] F. Cappella,[b] N. Casali,[b] R. Cerulli,[c,d] A. Chalil,[a] A. Chebboubi,[e] E. Dumonteil,[a] A. Erhart,[f] A. Giuliani,[g] F. Gunsing,[a] E. Jericha,[h] M. Kaznacheeva,[f] A. Kinast,[f] A. Langenkämper,[f] T. Lasserre,[a,f] A. Letourneau,[a] O. Litaize,[e] P. de Marcillac,[g] S. Marnieros,[g] T. Materna,[a] B. Mauri,[a] E. Mazzucato,[a] C. Nones,[a] T. Ortmann,[f] L. Pattavina,[d,i] D.V. Poda,[g] R. Rogly,[a] N. Schermer,[f] O. Serot,[e] G. Soum,[a] L. Stodolsky,[j] R. Strauss,[f] M. Vignati,[b,k] M. Vivier,[a] V. Wagner[f] and A. Wex[f]

2021 JINST 16 P07032

0.4 $keV_{nr}$ -> if Lindhard, it won't be visible

A binary test for the form of the QF below 1 keV