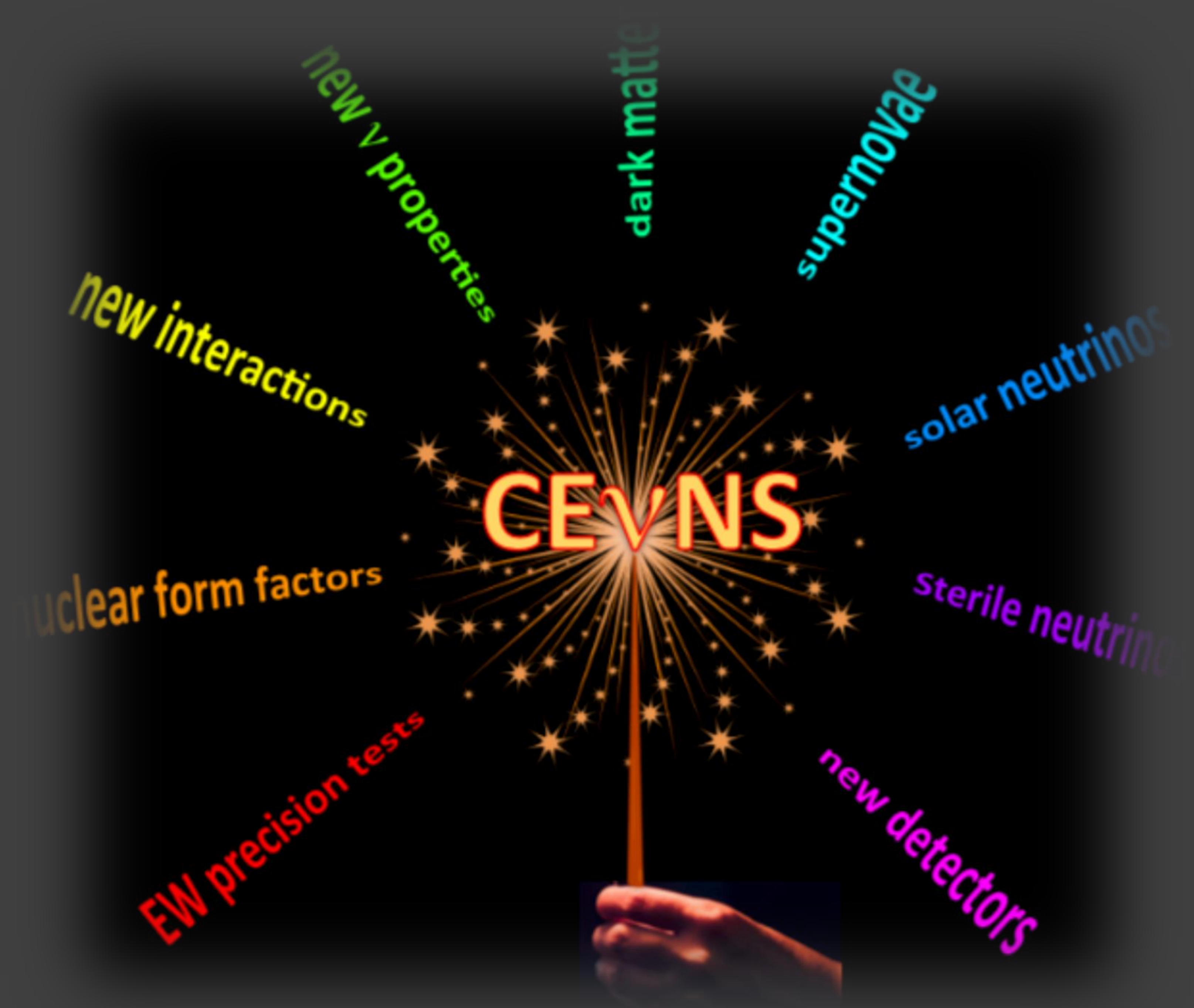


E. Lisi, Neutrino 2018

A big thank to the CEvNS community for their support in the preparation of this presentation

Coherent Elastic Neutrino-Nucleus Scattering

Jing Liu

University of South Dakota

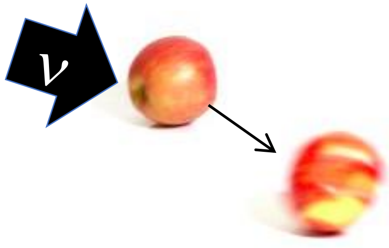
PIC2021, Aachen

What is CEvNS (It's not about apple!)

: nucleus

Neutrino Energy

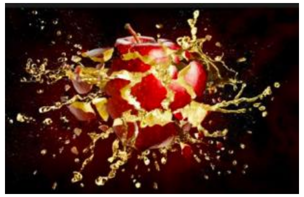
keV | MeV | GeV | TeV | PeV



Coherent elastic neutrino-nucleus scattering

Interactions with nuclei and electrons, minimally disruptive of the nucleus

Interactions with nucleons inside nuclei, often disruptive, hadron production



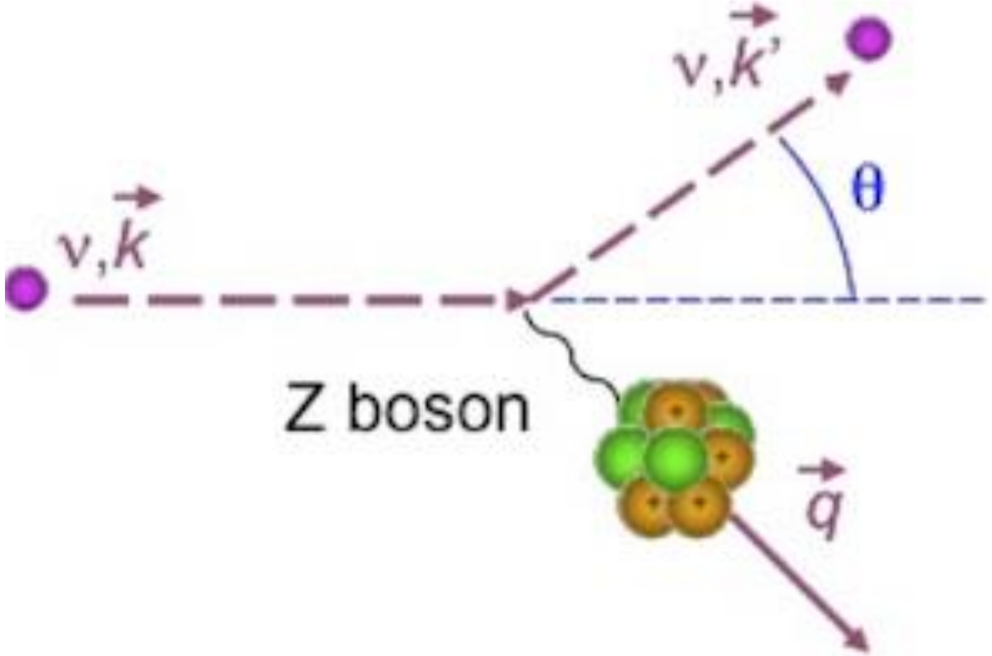
Deep Inelastic Scattering

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

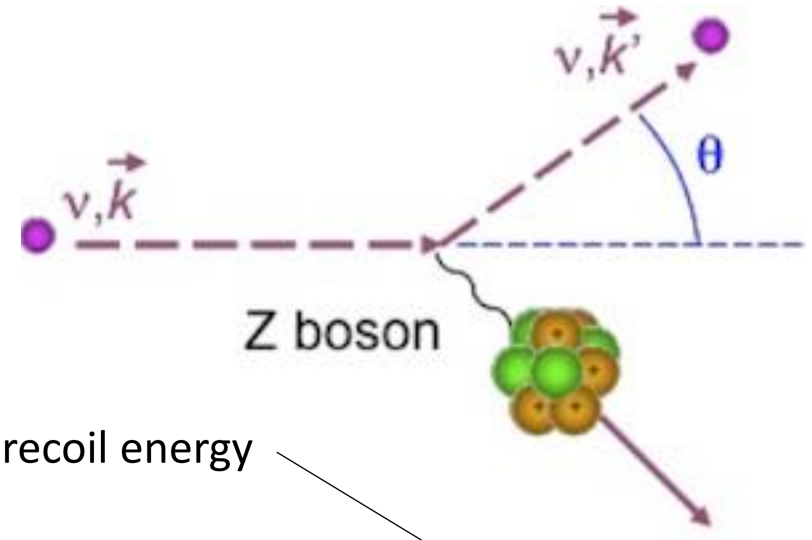
Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)



Differential cross section



Form factor

Nuclear mass

Momentum transfer, $\sqrt{2MT}$

Nuclear recoil energy

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

Incident neutrino energy

SM weak parameters: $G_V = g_V^p Z + g_V^n N$ & $G_A = g_A^p(Z_+ - Z_-) + g_A^n(N_+ - N_-)$

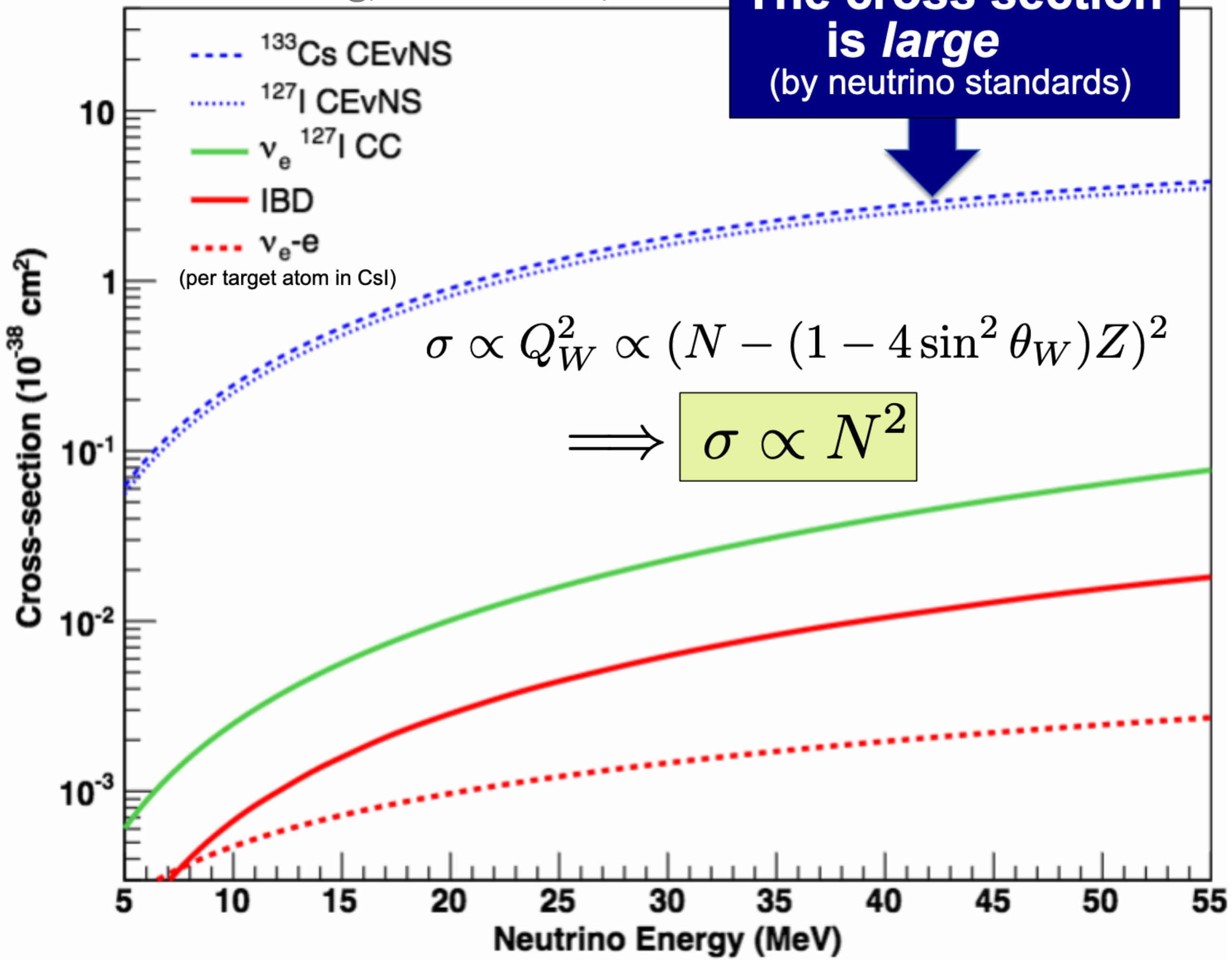
0.0298 -0.5117 0.4955 -0.5121 Spin up Spin down

dominates

arXiv:0508299

Good and bad

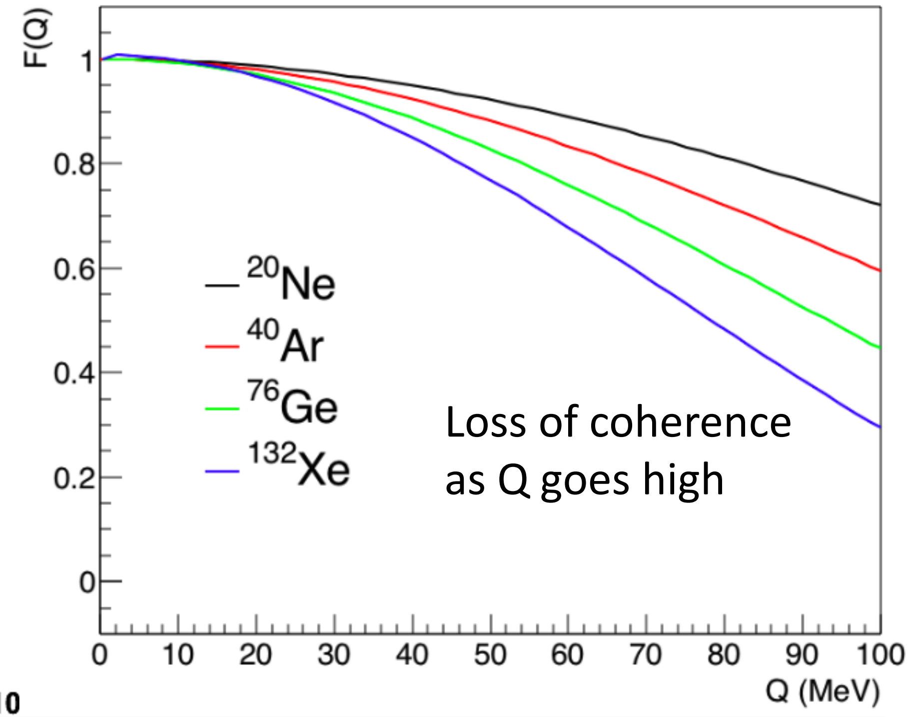
K. Scholberg, Lomonosov, 2021



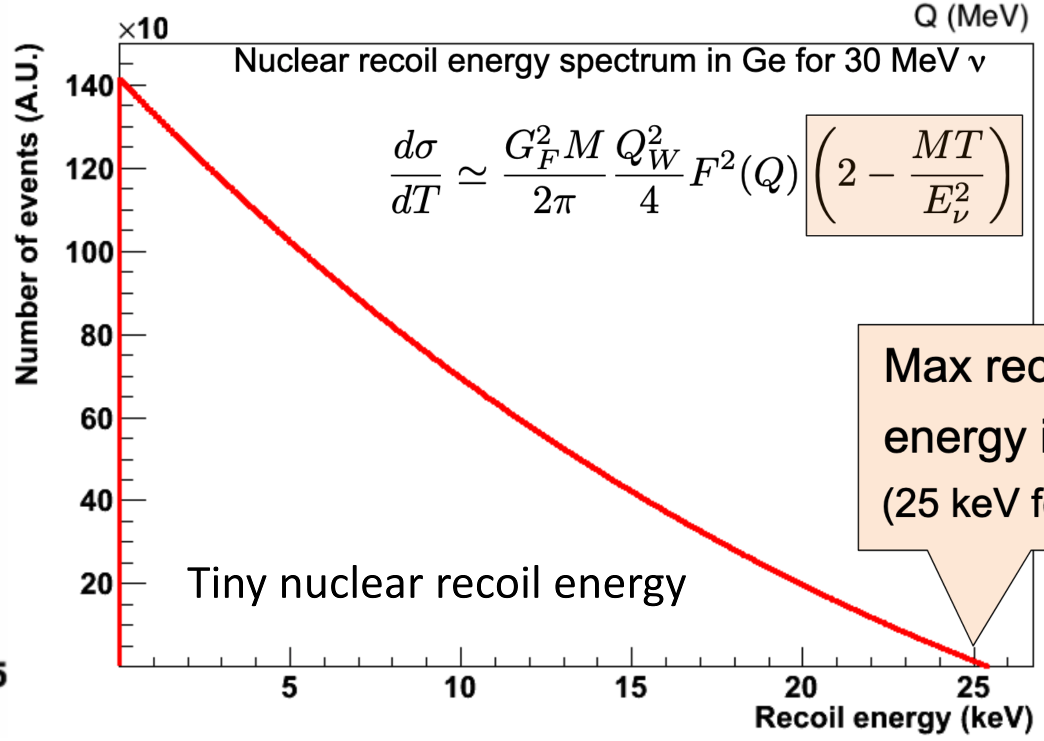
The cross section is *large*
(by neutrino standards)

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

$$\Longrightarrow \sigma \propto N^2$$



Loss of coherence as Q goes high

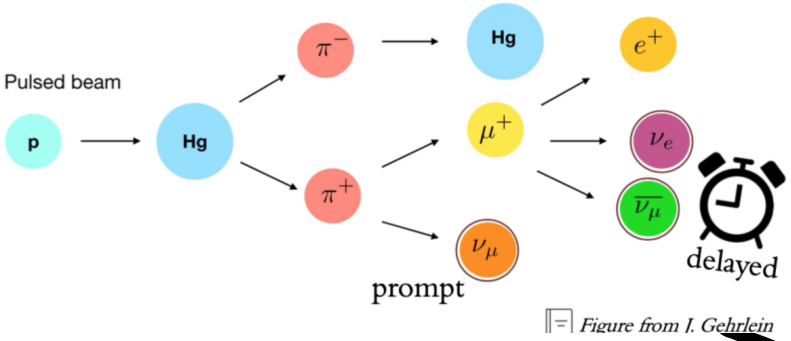


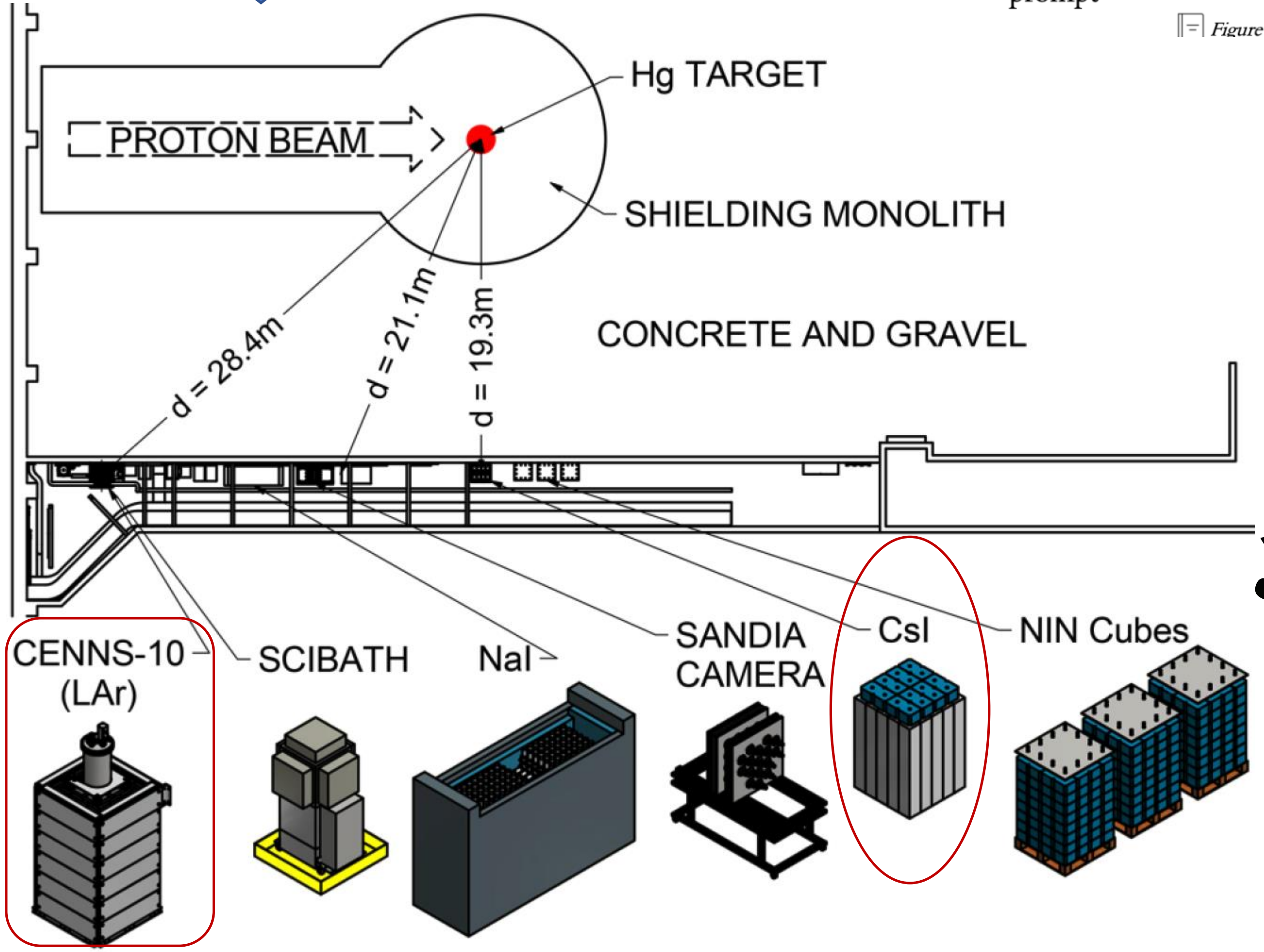
$$\frac{d\sigma}{dT} \simeq \frac{G_F^2 M}{2\pi}\frac{Q_W^2}{4}F^2(Q)\left(2 - \frac{MT}{E_\nu^2}\right)$$

Tiny nuclear recoil energy

Max recoil energy is ~$2E_\nu^2/M$ (25 keV for Ge)

SNS (Spallation Neutron Source)
ORNL (Oak Ridge National Lab)
COHERENT Collaboration



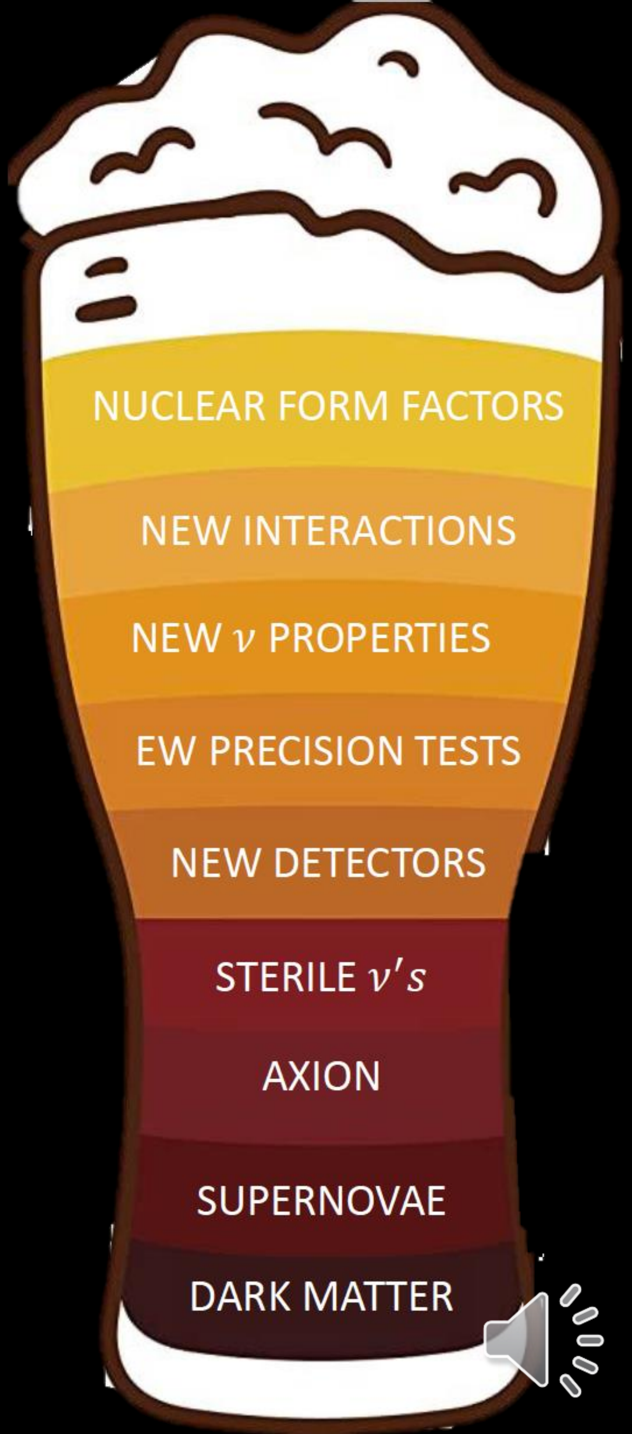


D. Akimov *et al.*, science.aao0990 (2017), Phys. Rev. Lett. 126, 012002 (2021)

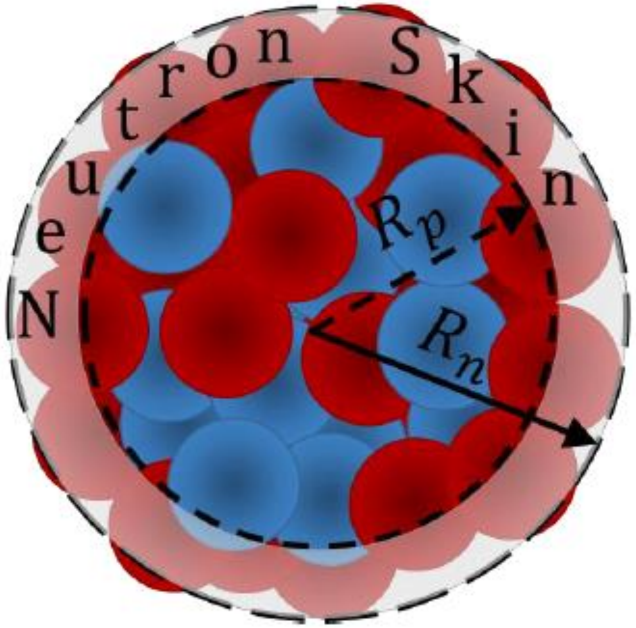
Why bother

- Particle physics
  - Precision test of SM
  - Beyond SM physics
- Nuclear physics
  - Nuclear form factor
  - Neutron distribution radius
- Astroparticle physics
  - Energy transport in supernovae
  - To detect SN neutrinos
- Applied physics
  - Reactor monitoring
  - Application for non-proliferation

- Cadeddu, M7s 2020
- Bonifazi, TAUP 2021
- Bernstein, Rev. Mod. Phys. 92 (2020) 011003



Neutron distribution



- Most information about nuclear sizes is from electron-nucleus scattering and are sensitive to proton distribution
- CEvNS can be used to probe neutron distribution:

$$\frac{d\sigma_{\nu-N}}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[N\, F_N(T, R_n) - (1 - 4\sin^2\theta_W)\, Z\, F_Z(T, R_p)\right]^2$$

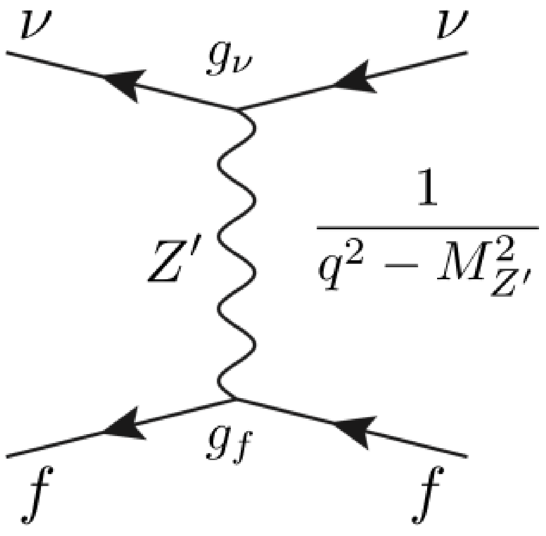
Two different form factors, one for the neutron distribution and one for the proton.

$(1 - 4\sin^2\theta_W) \sim 0.05$ moreover Z<N so the contribution of the proton form factor is negligible!!

Hence, **measurements of the process give information on the nuclear neutron form factor** which is more difficult to obtain in a model independent way.

[Phys. Rev. **D30**, 2295 (1984); JHEP **0512**, 021 (2005); Phys. Rev. **C86**, 024612 (2012), Phys. Rev. Lett. **120** (2018) 7, 072501; JHEP 1906:141 (2019) …]

Non-standard neutrino interaction (NSI)



$$\mathcal{L}_{\mathrm{NSI}}^{\mathrm{NC}} = -2\sqrt{2}G_{\mathrm{F}} \sum_{\alpha,\beta=e,\mu,\tau} (\overline{\nu_{\alpha L}}\gamma^{\rho}\nu_{\beta L}) \sum_{f=u,d} \varepsilon_{\alpha\beta}^{fV} (\bar{f}\gamma_{\rho}f)$$

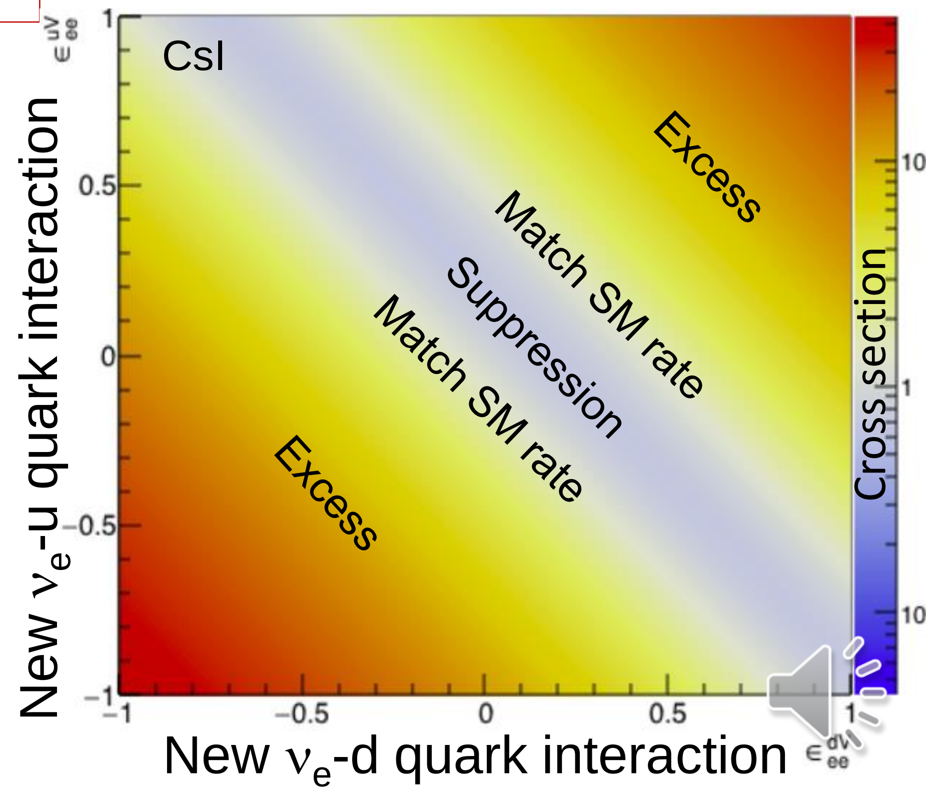
$$\epsilon_{\ell\ell}^{fV} = \frac{g_{Z'}^2 Q'_\ell Q'_f}{\sqrt{2}G_F\,(|\vec{q}|^2 + M_{Z'}^2)}$$

$$\frac{d\sigma_{\nu_\alpha\text{-}\mathcal{N}}}{dT}(E,T) = \frac{G_{\mathrm{F}}^2 M}{\pi}\left(1 - \frac{MT}{2E^2}\right) Q_\alpha^2,$$

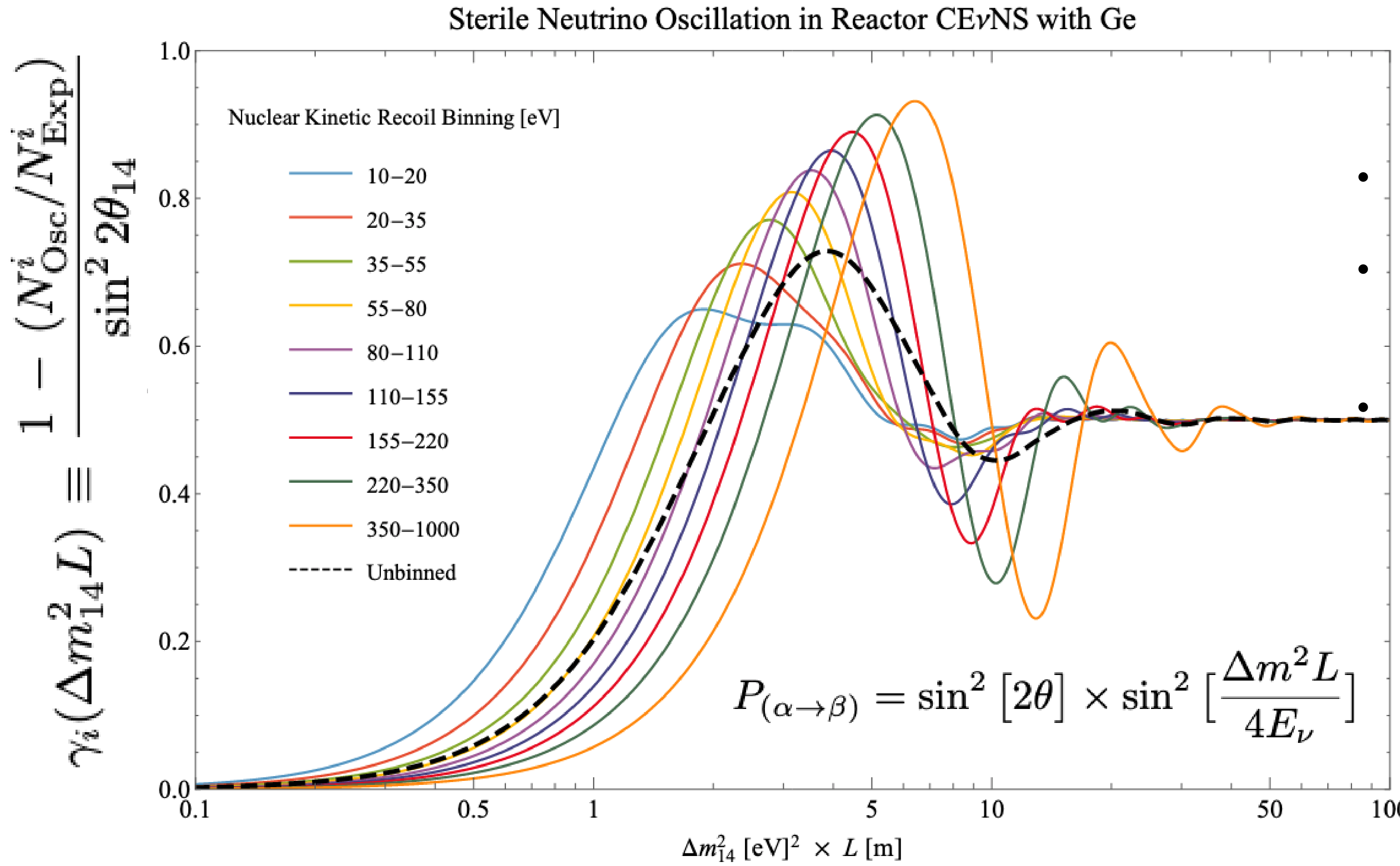
$$Q_\alpha^2 = [(g_V^p + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV})ZF_Z(|\vec{q}|^2) + (g_V^n + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})NF_N(|\vec{q}|^2)]^2 + \sum_{\beta\neq\alpha} |(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV})ZF_Z(|\vec{q}|^2) + (\varepsilon_{\alpha\beta}^{uV} + 2\varepsilon_{\alpha\beta}^{dV})NF_N(|\vec{q}|^2)|^2,$$

Scaling of the SM cross section

K. Scholberg, Lomonosov, 2021



Sterile neutrino

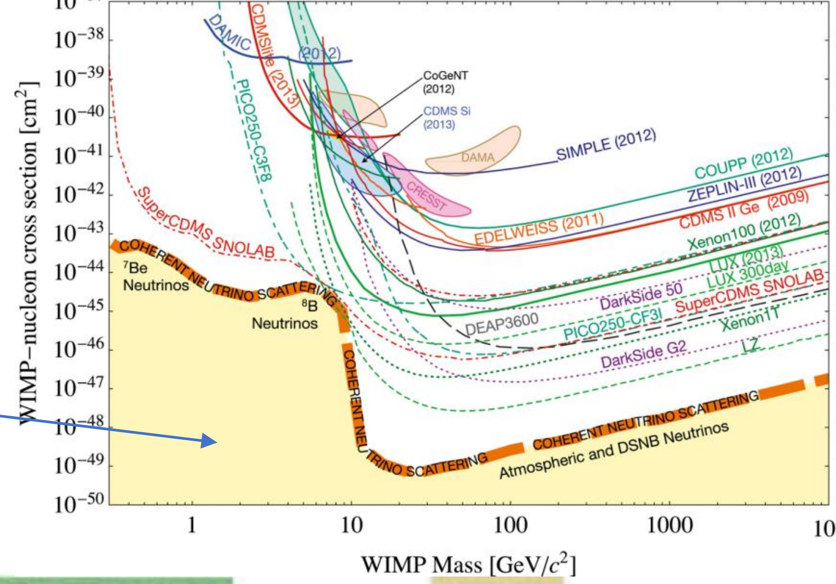


- CEvNS happens for all flavors
- And is insensitive to oscillations between known flavors
- A changing deficit of CEvNS at different distances from neutrino source indicates oscillations to/from a sterile neutrino

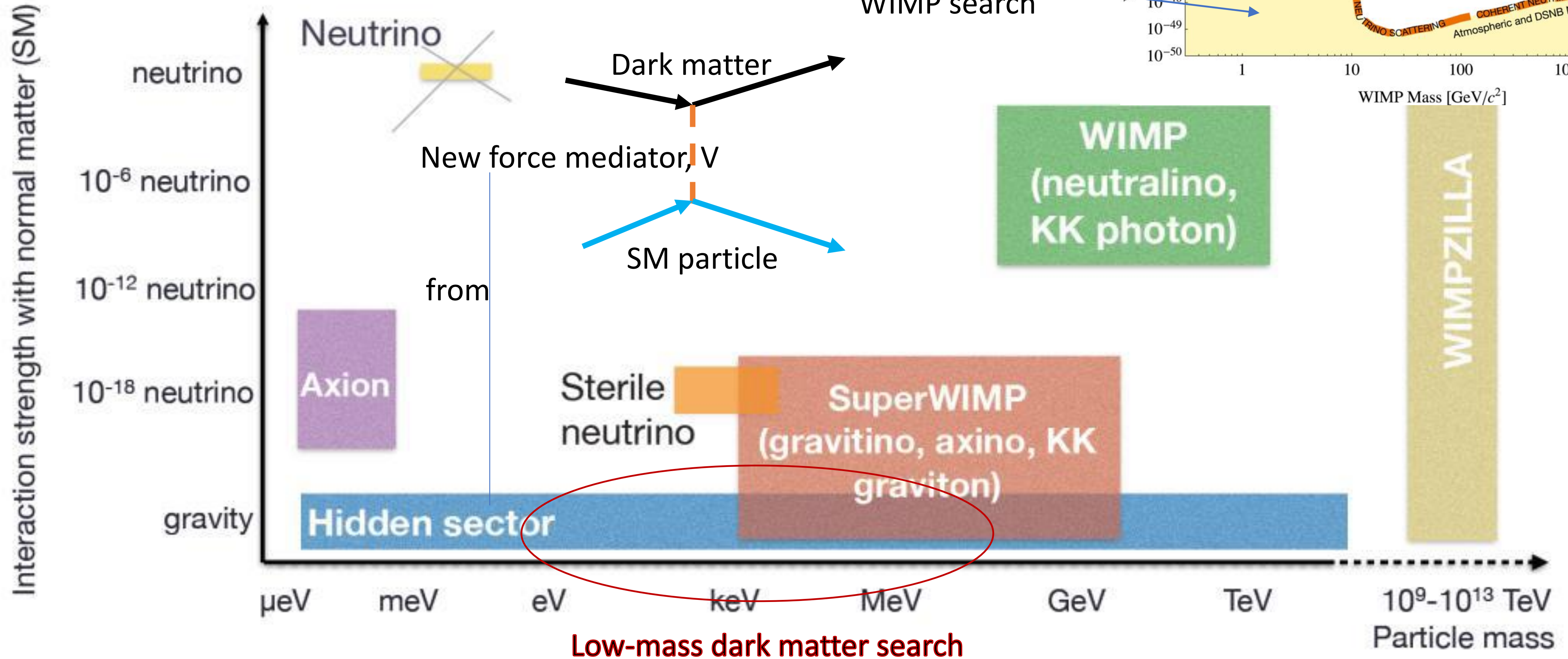
arXiv:1511.02834

Relation to

Dark matter search

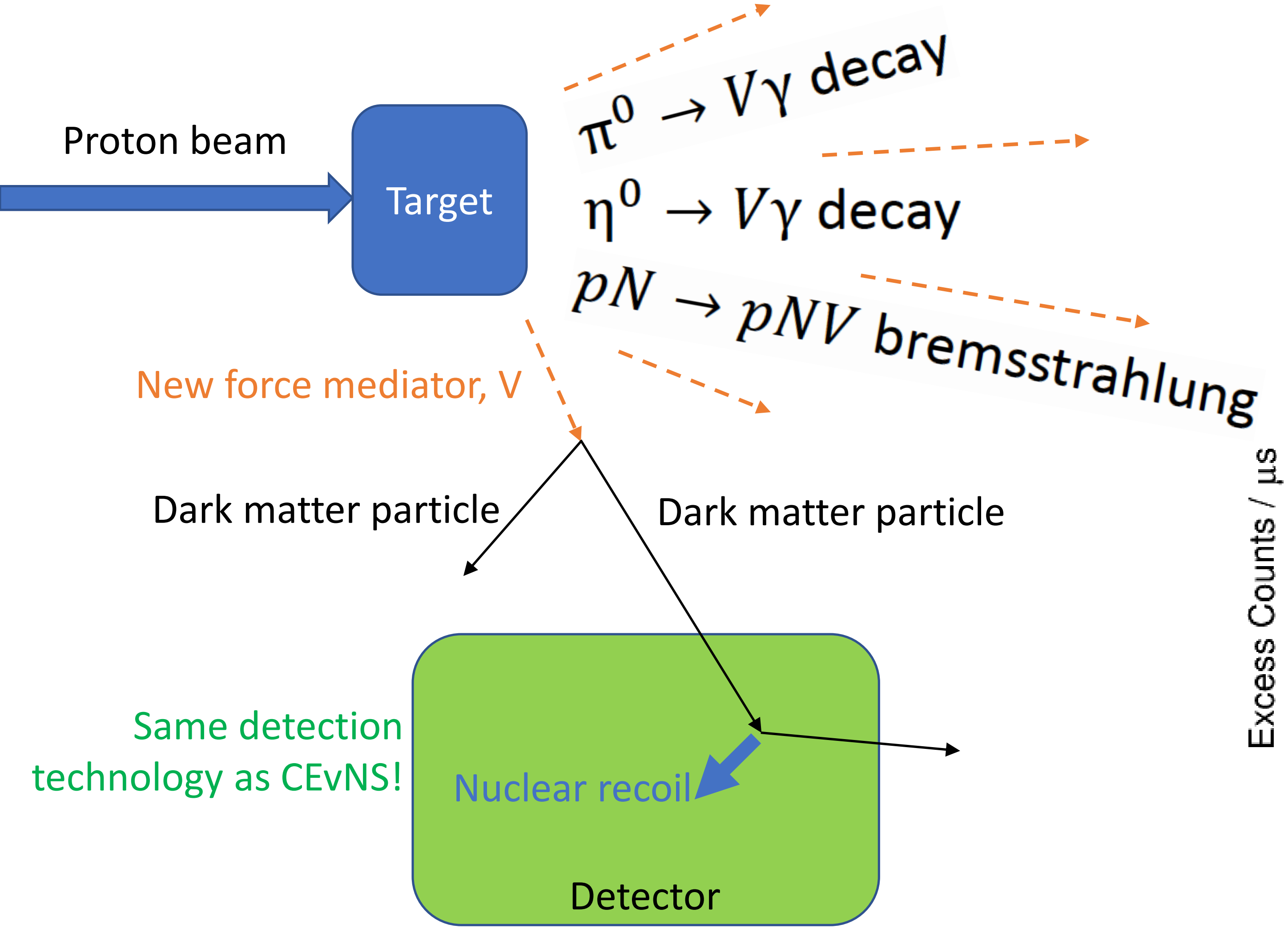


Background for WIMP search



Low-mass dark matter search

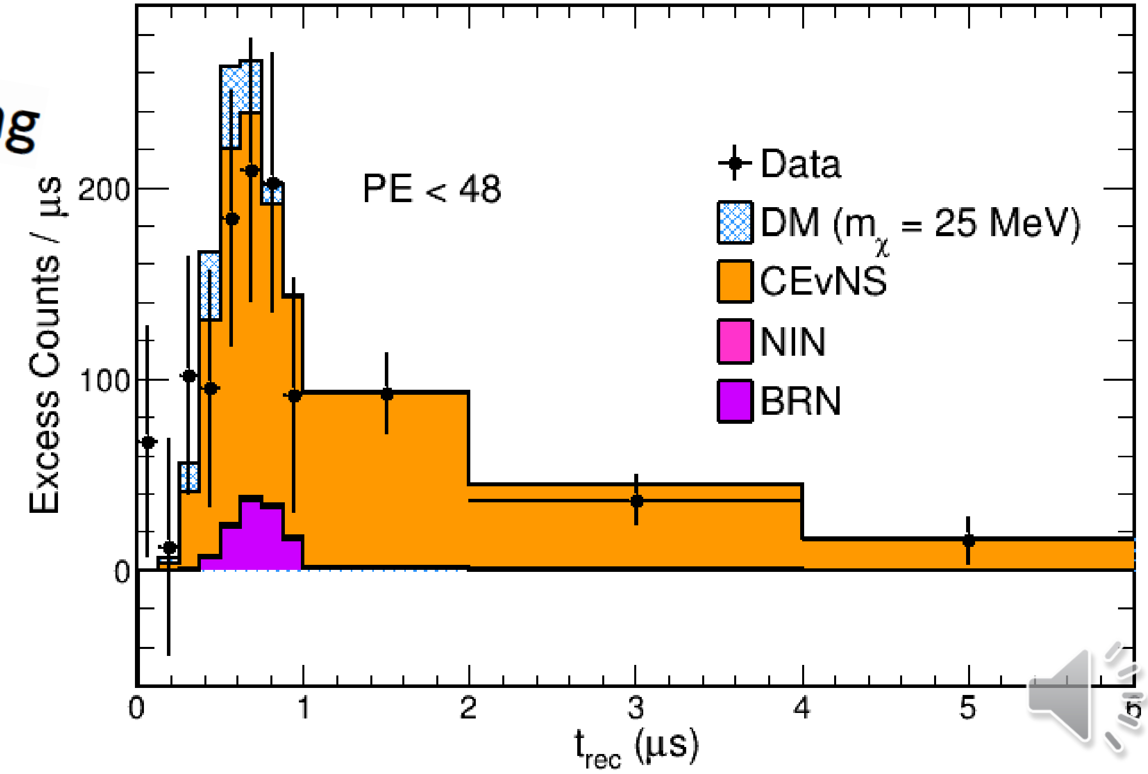
Accelerator-based dark matter search



D. Pershey, ORNL seminar, 2021

https://indico.phy.ornl.gov/event/126/

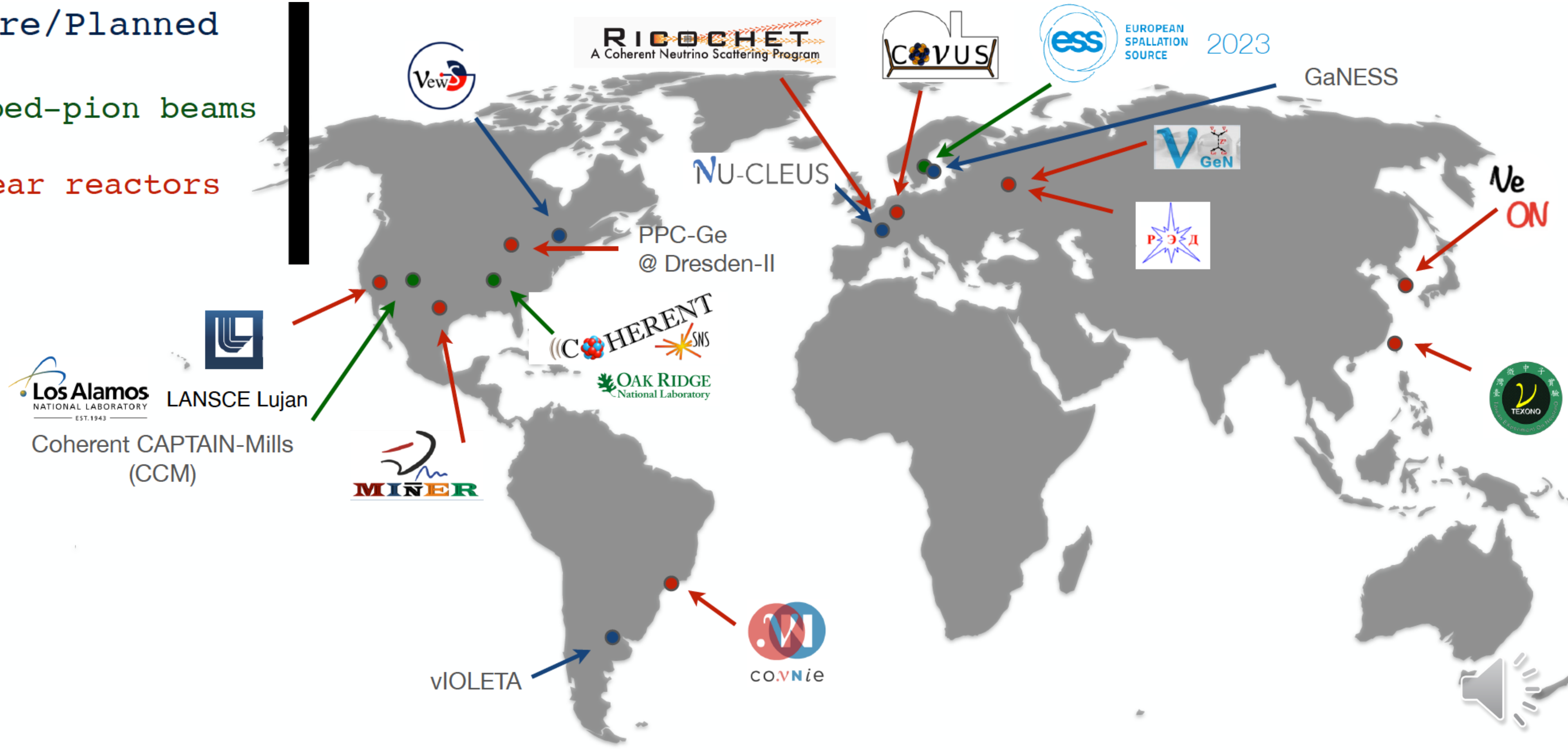
CEvNS: dominant background!



A global effort

Bonifazi, TAUP 2021

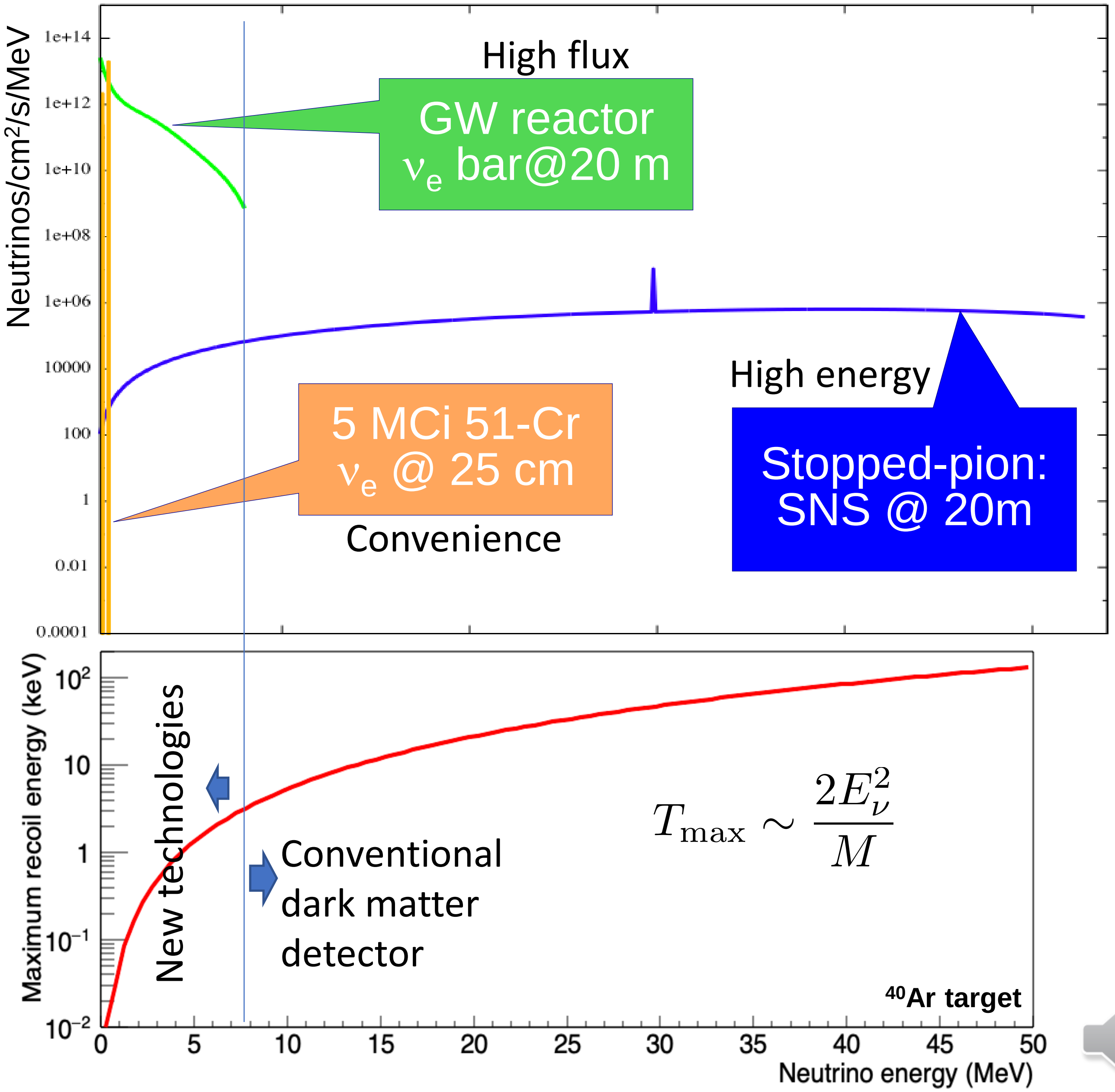
- Future/Planned
- Stopped-pion beams
- Nuclear reactors

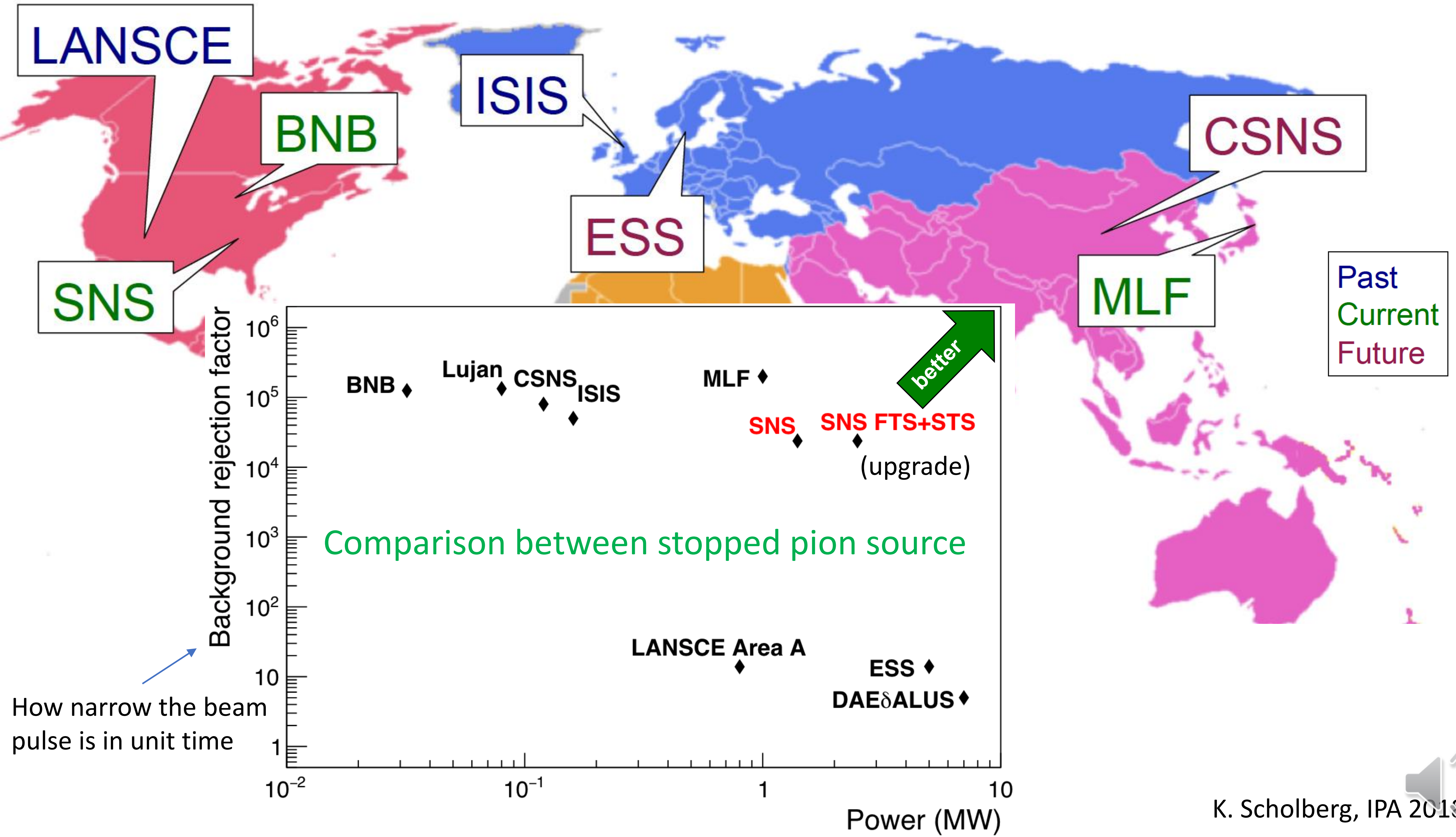


Neutrino sources

- The higher the E_ν, the easier to detect (But not too high to lose coherence)
- The higher the flux, the more events (but need to watch background)

K. Scholberg, Lomonosov, 2021





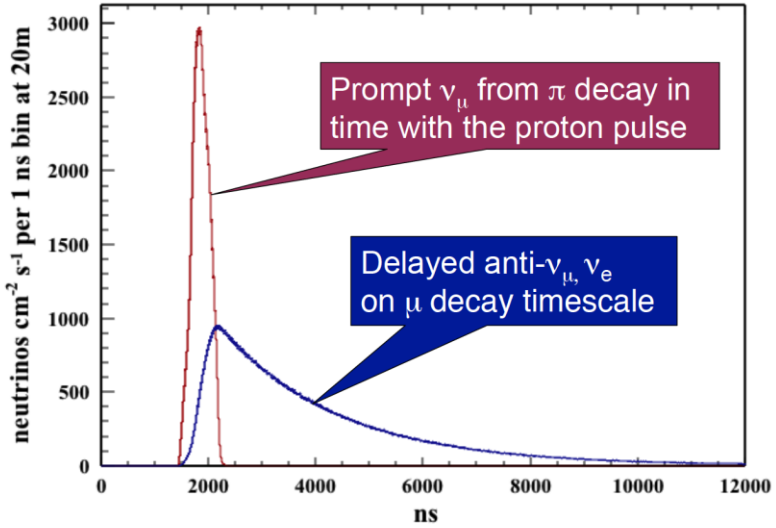
How narrow the beam pulse is in unit time

K. Scholberg, IPA 2018

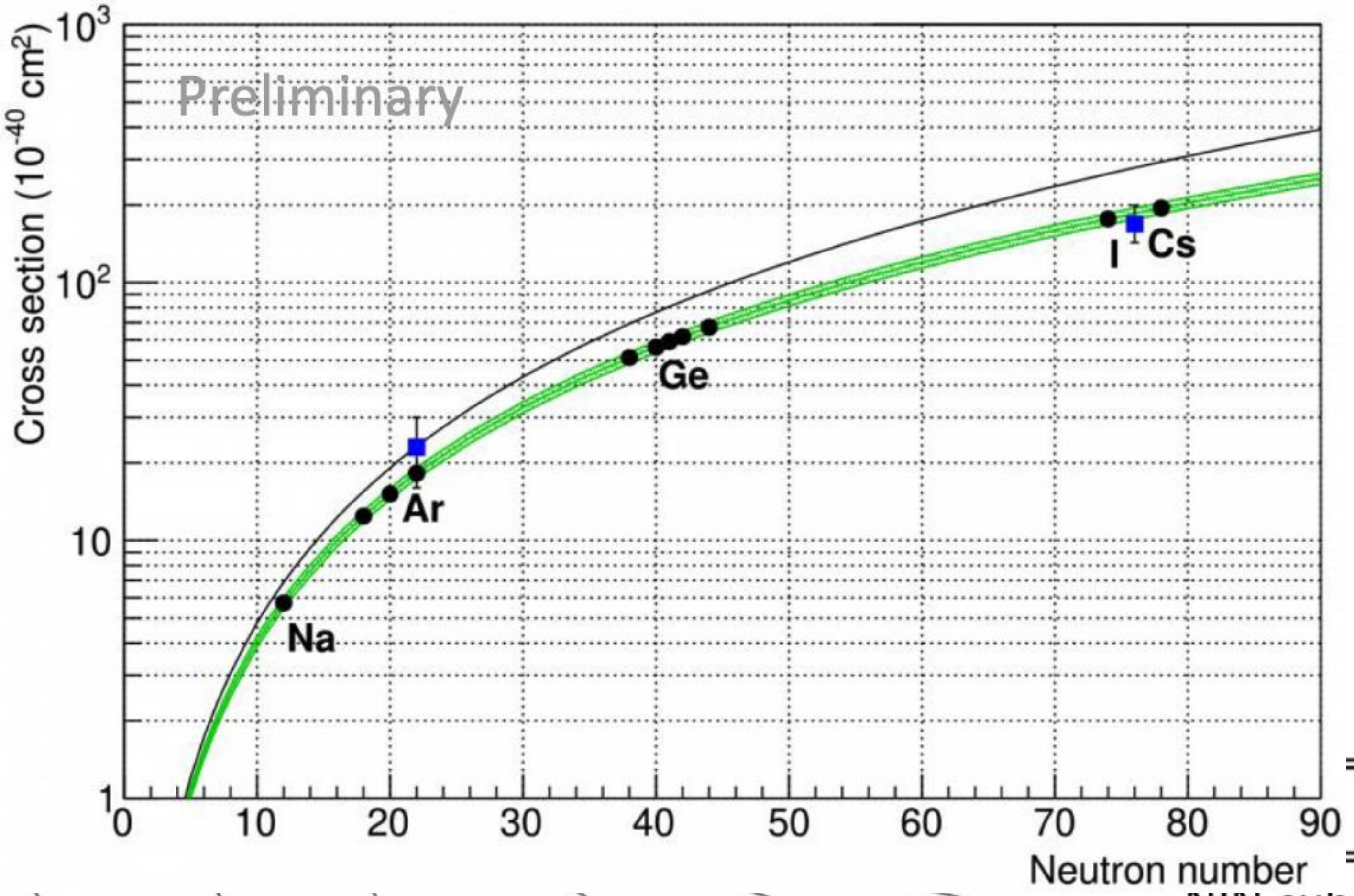
1 GeV protons, 600 ns pulse

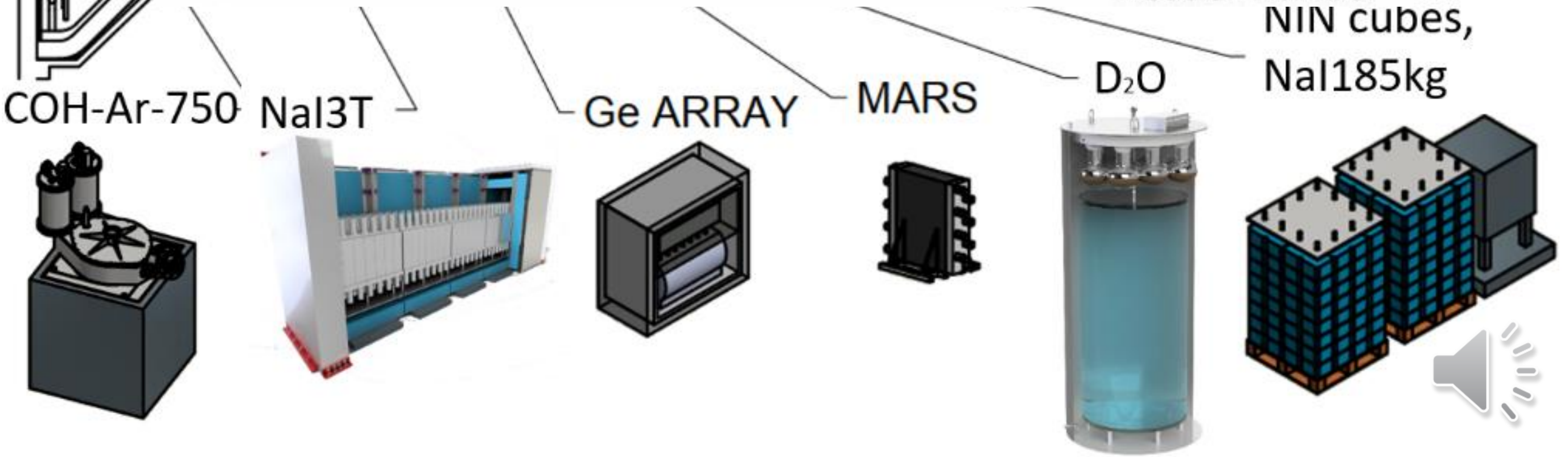
Time structure of the SNS source

60 Hz *pulsed* source ~1.3 MW

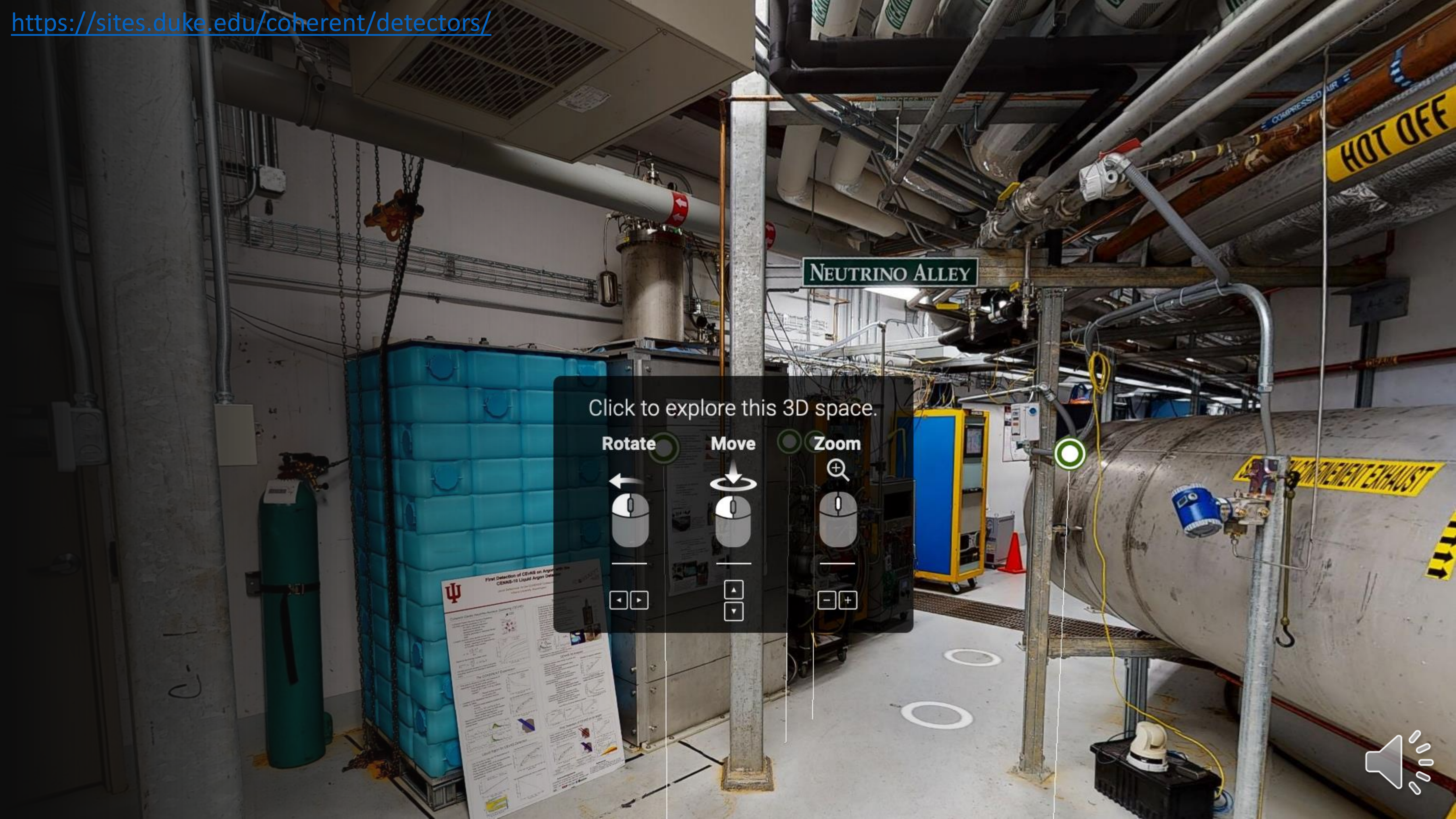


Background rejection factor ~few x 10^{-4}

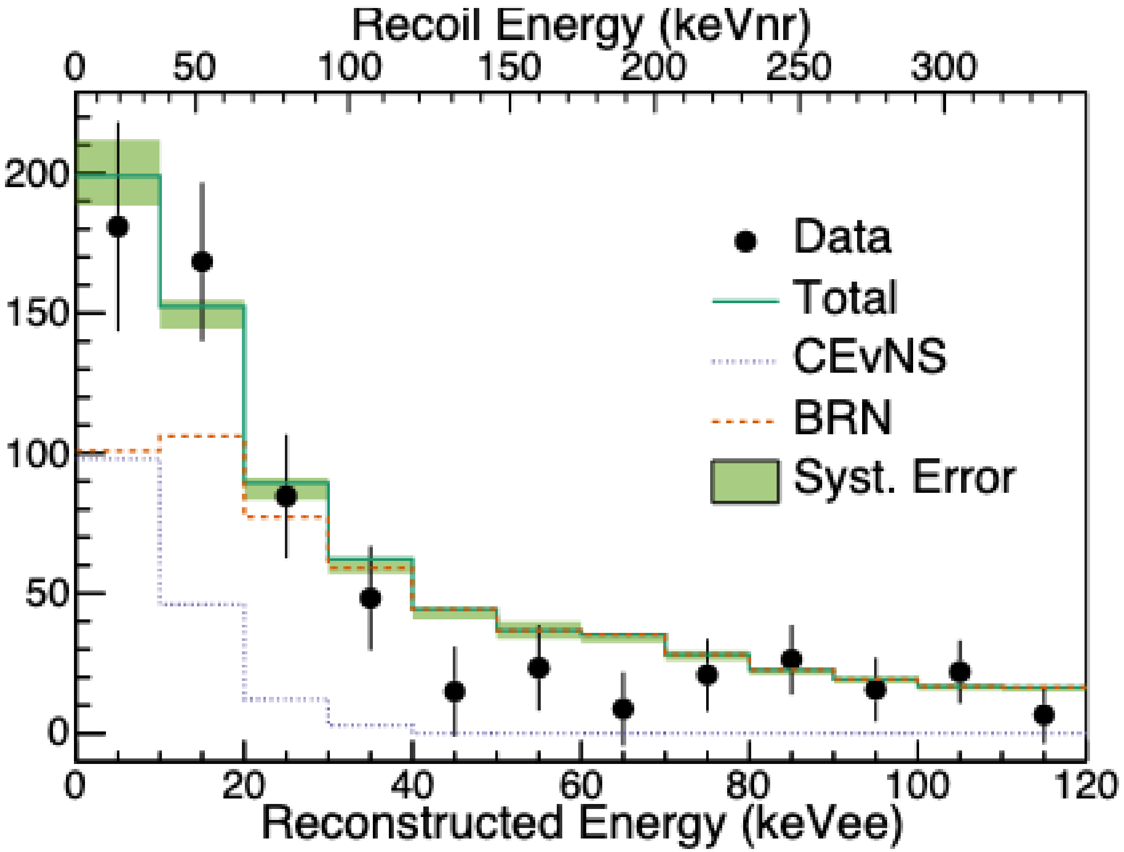


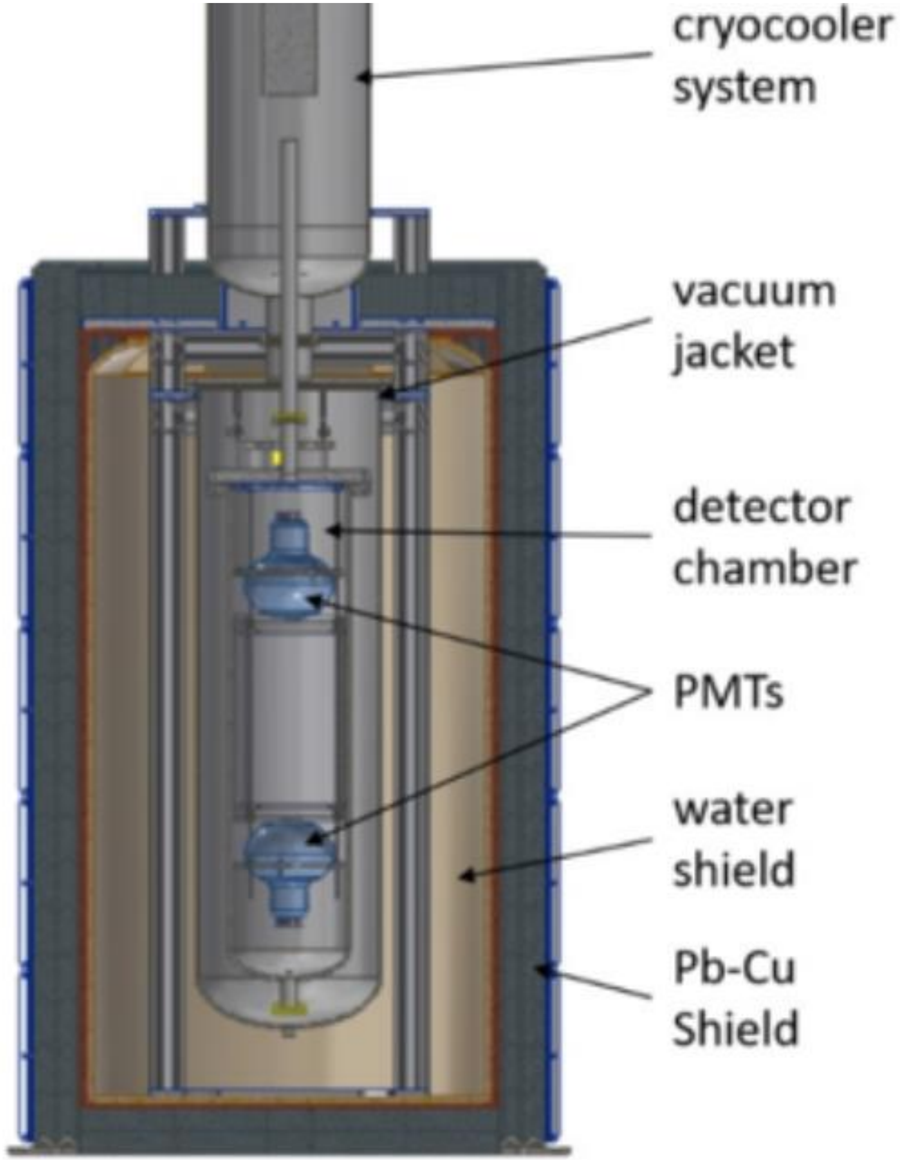


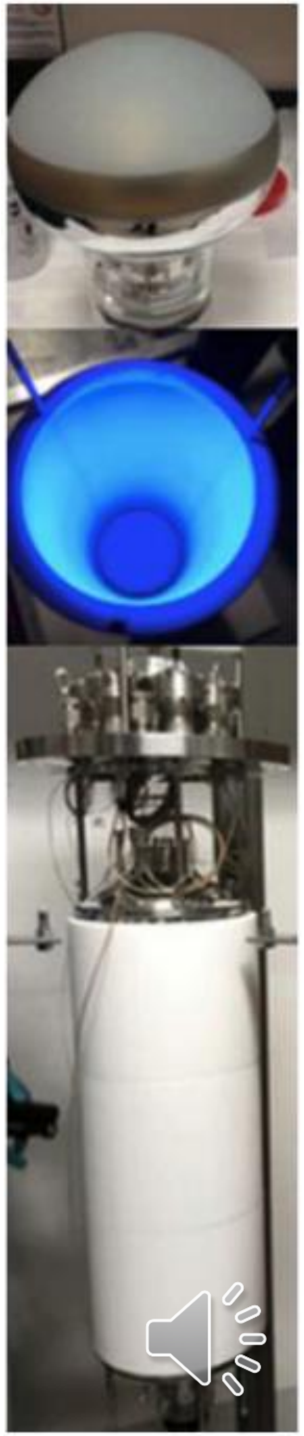
https://sites.duke.edu/coherent/detectors/



COH-Ar-10 single phase LAr scintillator

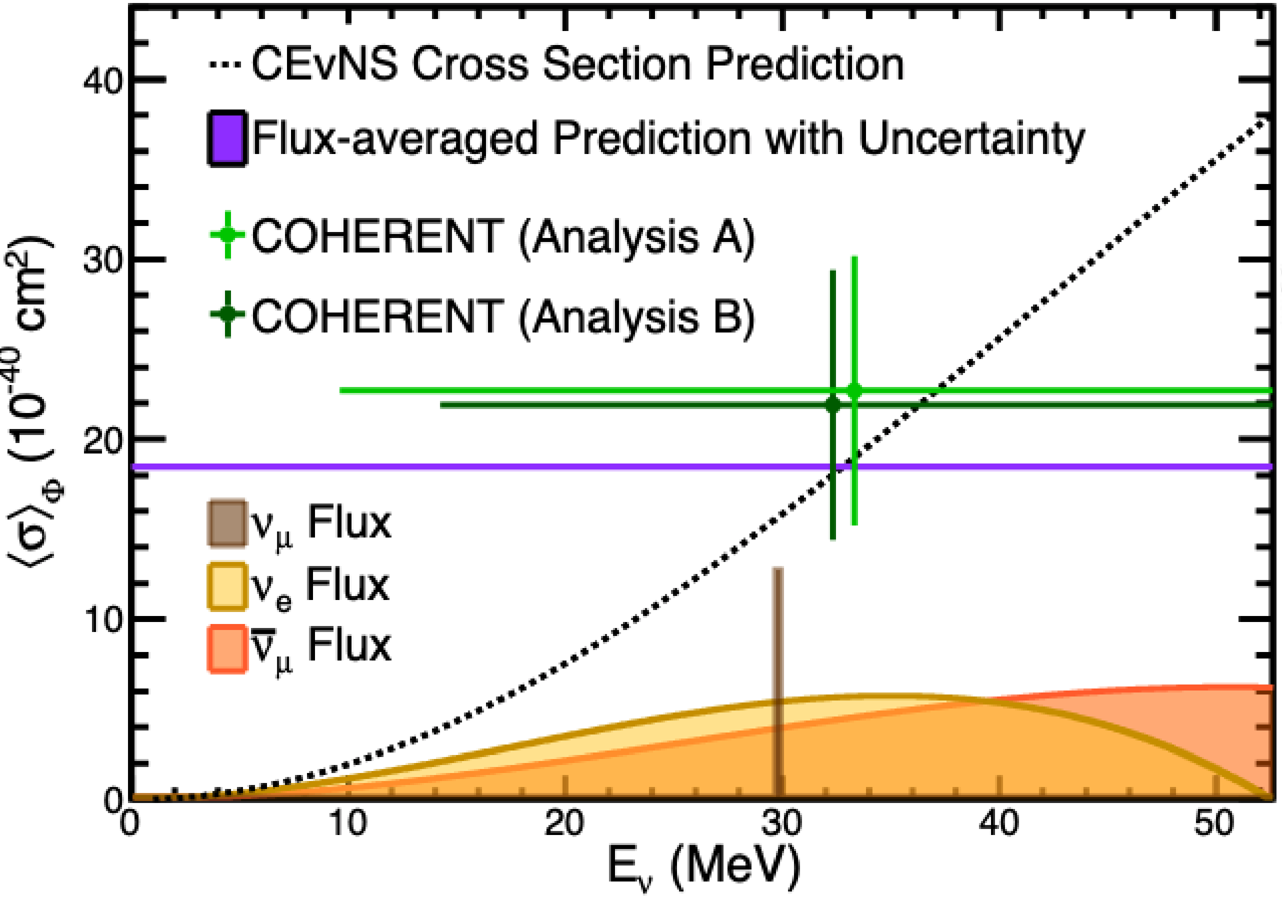


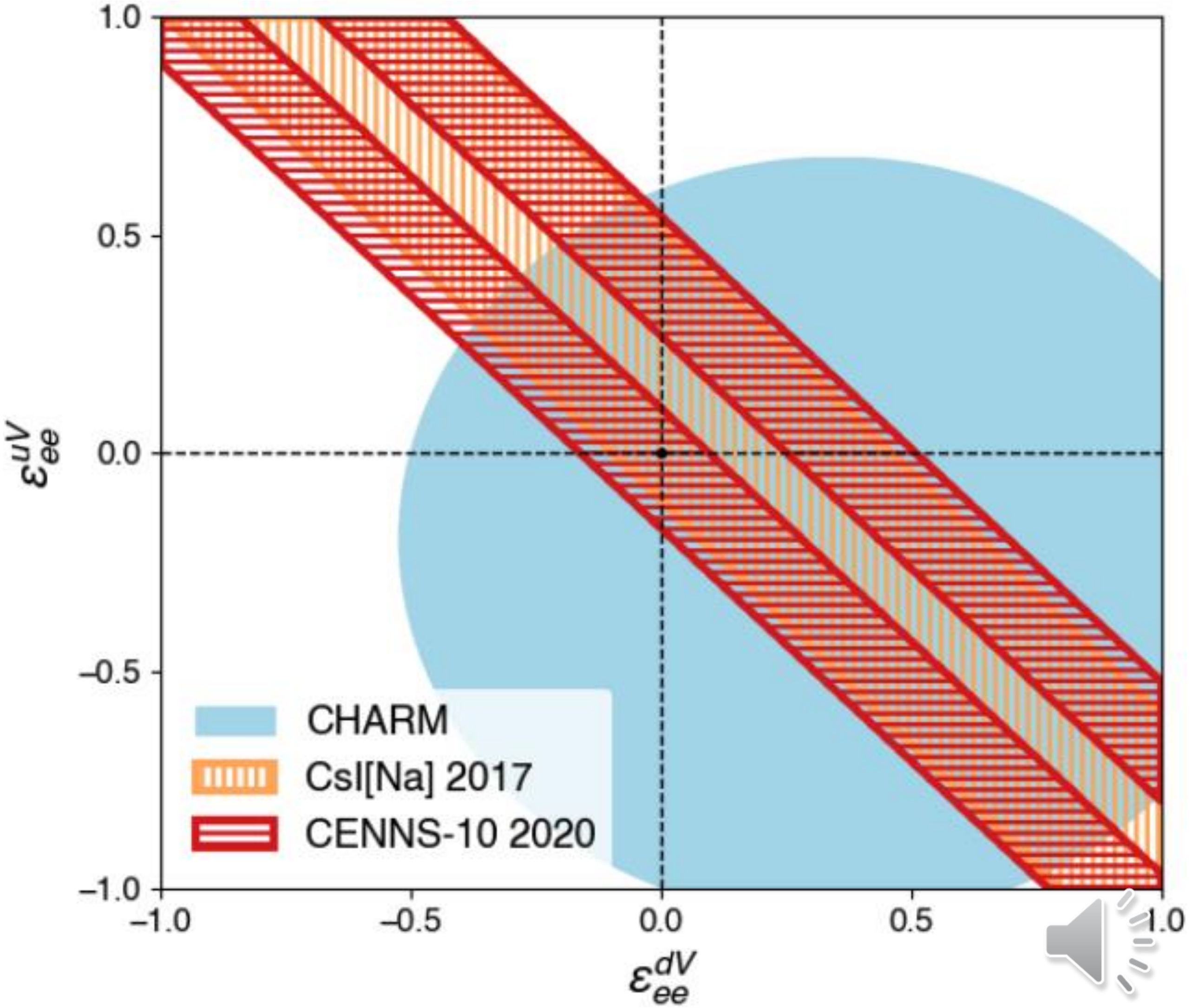




Phys. Rev. Lett. 126, 012002 (2021)

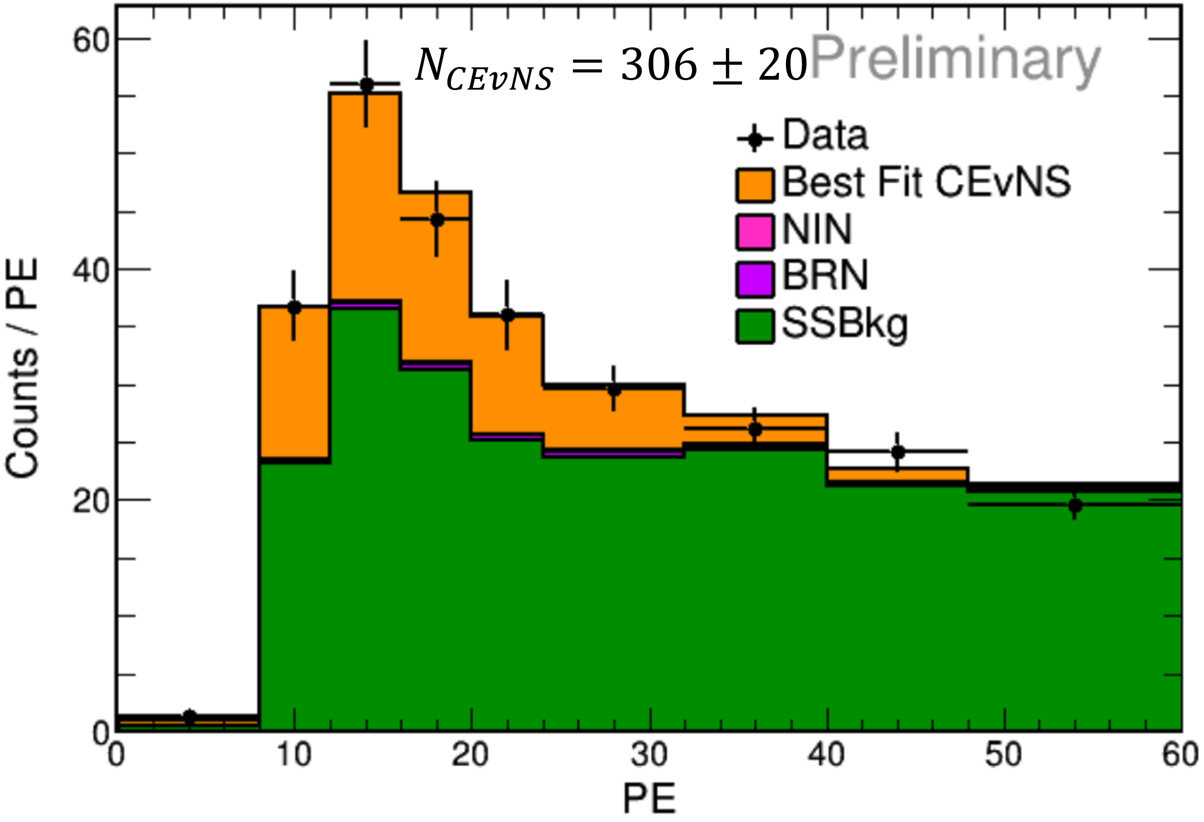
COH-Ar-10 single phase LAr scintillator

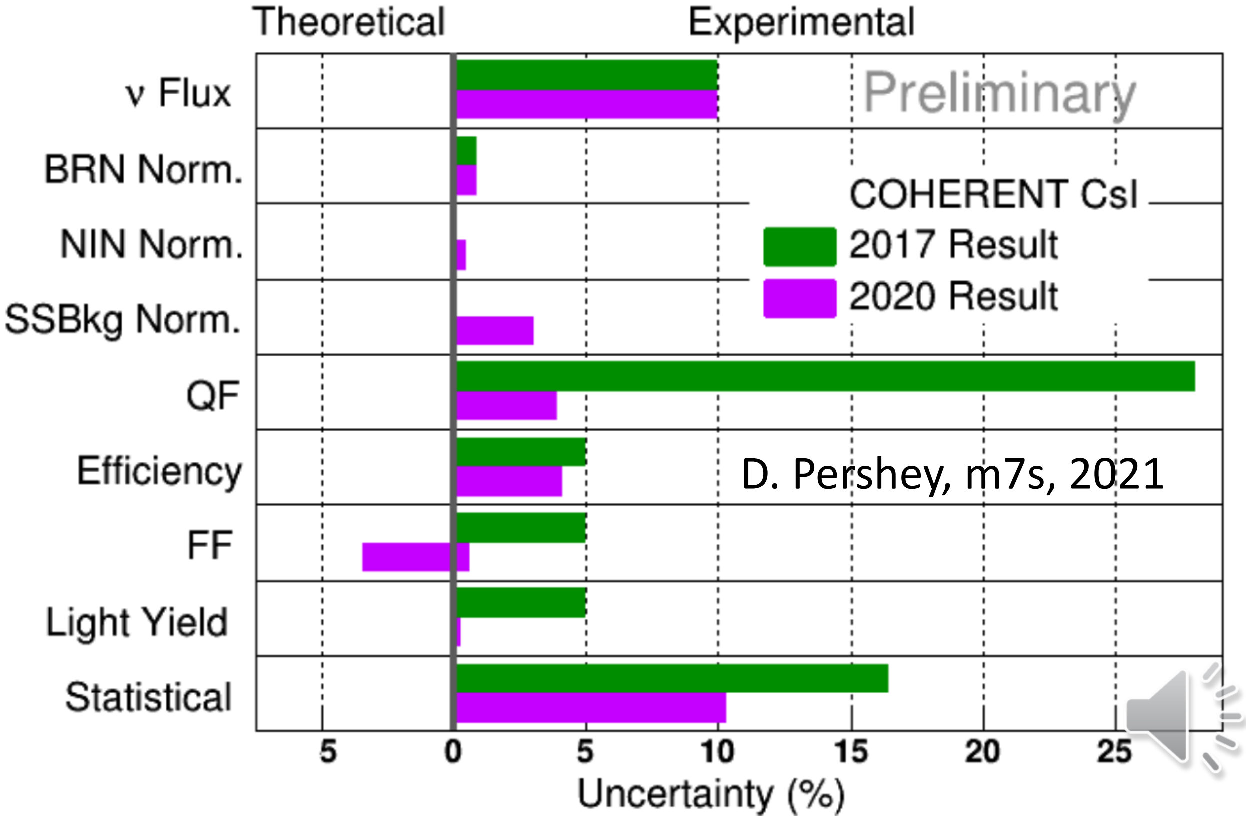




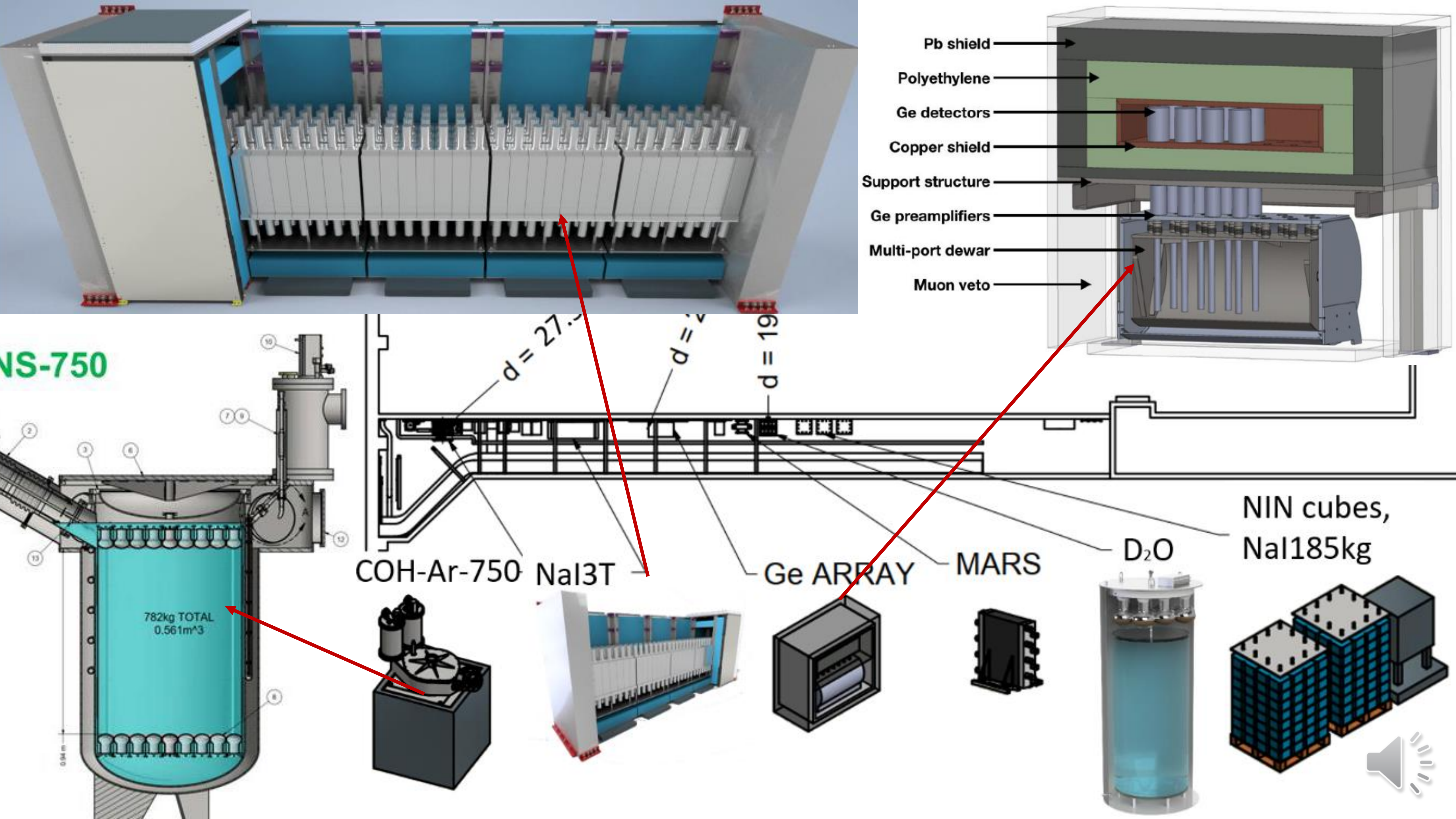
CsI(Na)

No-CEvNS rejection	11.6 σ
SM CEvNS prediction	$333 \pm 11(\mathrm{th}) \pm 42(\mathrm{ex})$
Fit CEvNS events	306 ± 20
Fit χ^2/dof	82.4/98
CEvNS cross section	$169^{+30}_{-26} \times 10^{-40}$ cm^2
SM cross section	$189 \pm 6 \times 10^{-40}$ cm^2





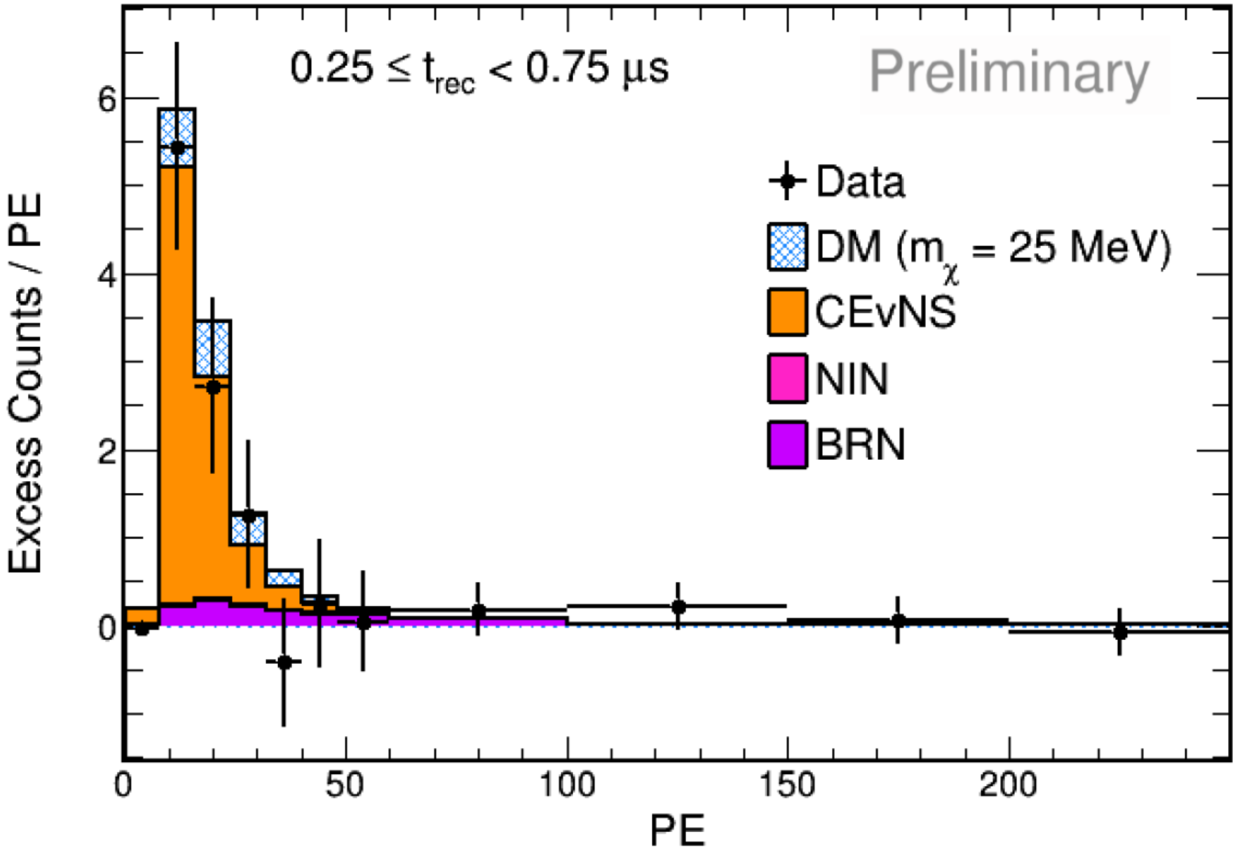
D. Pershey, m7s, 2021

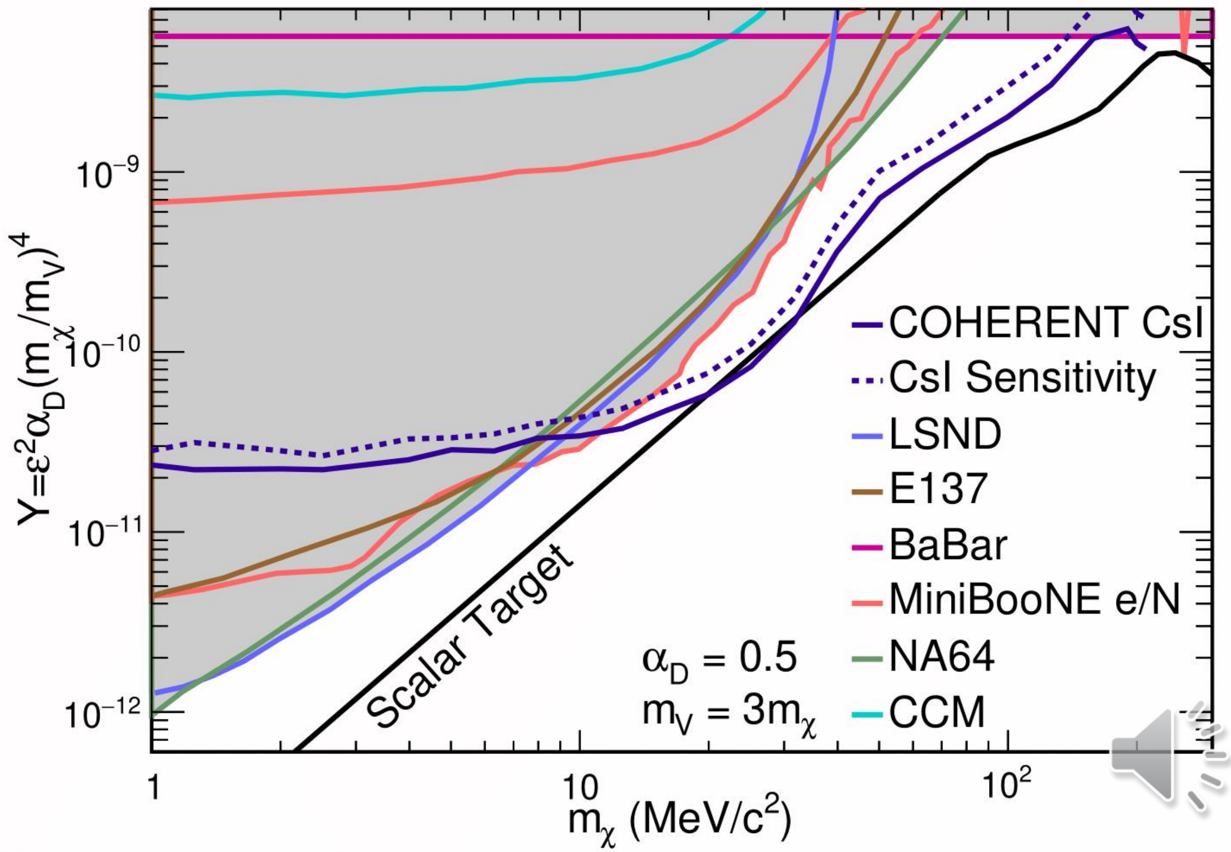

Pb shield
Polyethylene
Ge detectors
Copper shield
Support structure
Ge preamplifiers
Multi-port dewar
Muon veto
NS-750
782kg TOTAL
0.561m^3
d = 19
COH-Ar-750
NaI3T
Ge ARRAY
MARS
D₂O
NIN cubes,
NaI185kg

Accelerator-based dark matter search

D. Pershey, ORNL seminar, 2021

https://indico.phy.ornl.gov/event/126/

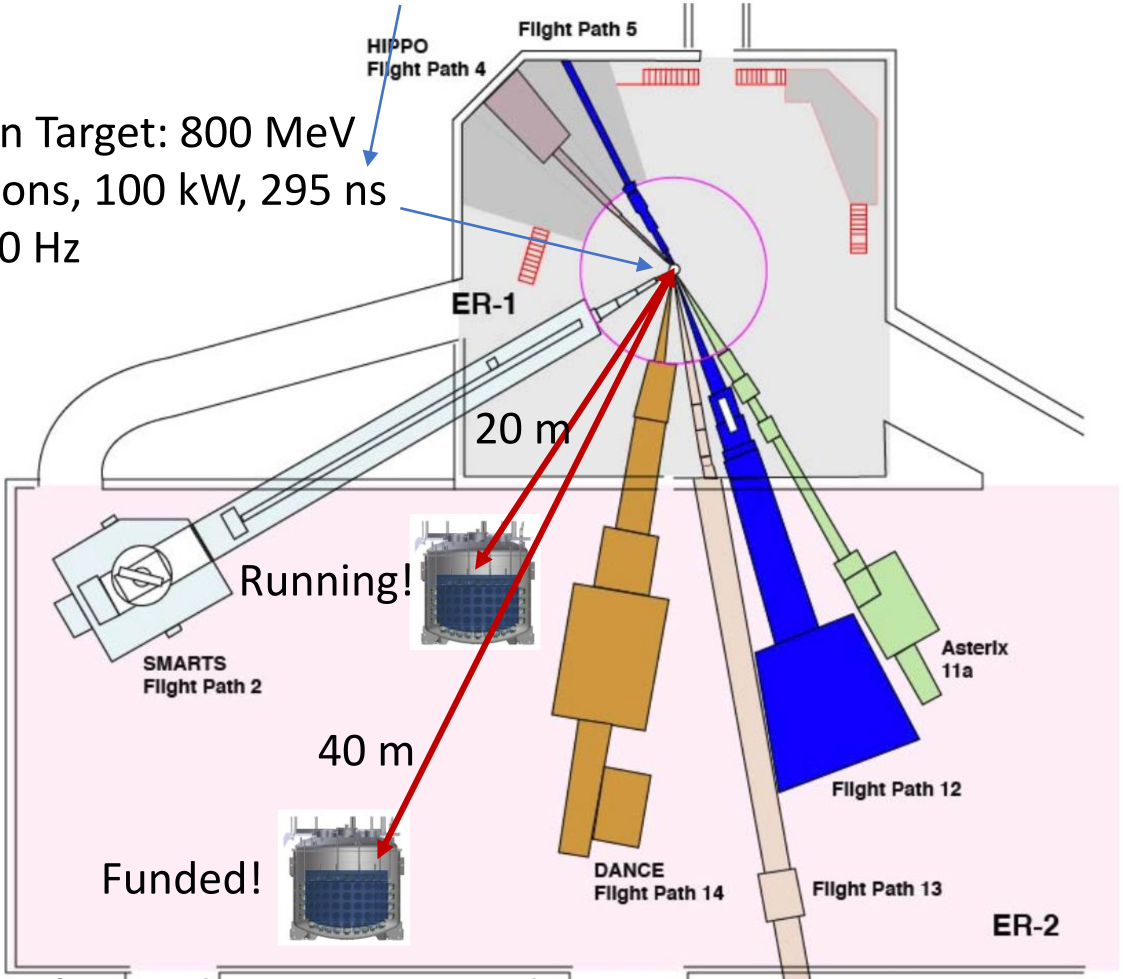




Coherent CAPTAIN-Mills (CCM) @ LANSCE

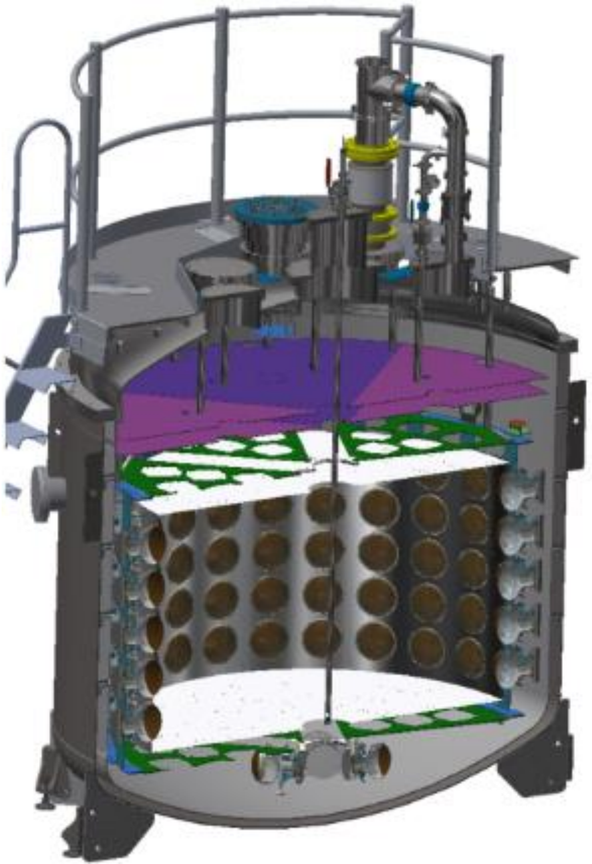
Excellent ambient background rejection power due to narrow beam pulses

Lujan Target: 800 MeV protons, 100 kW, 295 ns @ 20 Hz



Great for sterile neutrino search

- Muon neutrino flux: 4.74×10^5 nu/cm^2/s @ 20 m
- Light yield: ~0.015 Photoelectrons/keVee

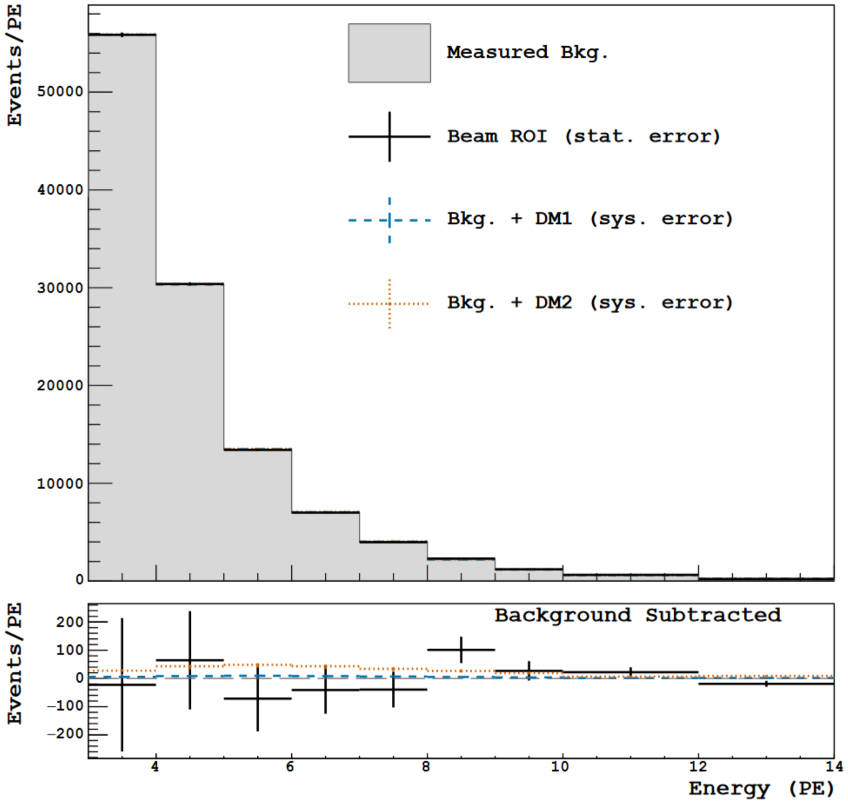


Large!

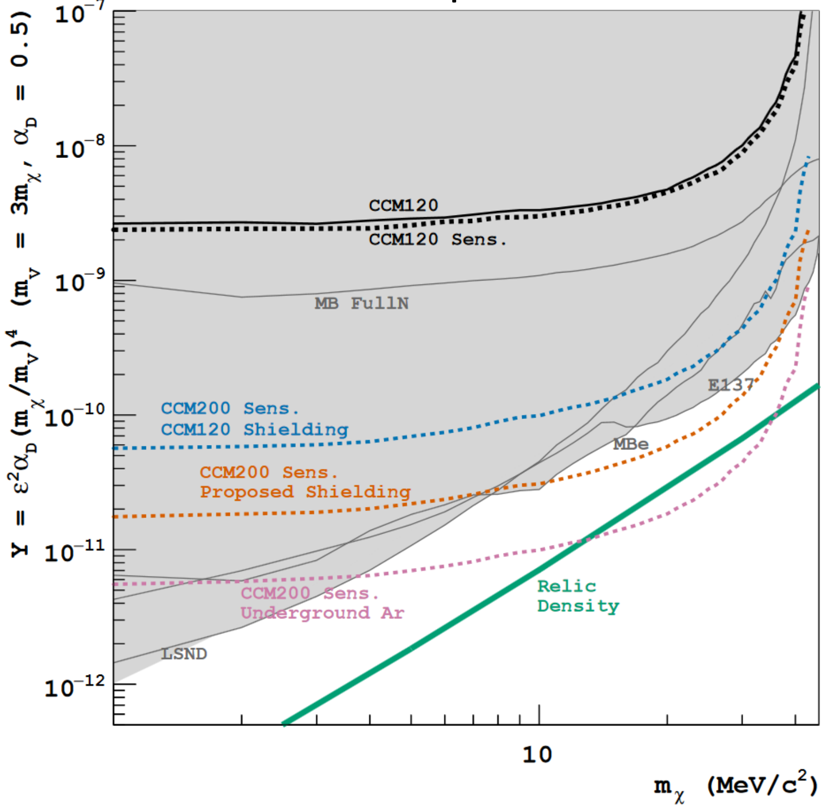
CCM: 10 ton Liquid Argon (LAr) detector instrumented with 200 8” PMT’s, veto region, shielding, fast electronics.

Dark matter search of CCM

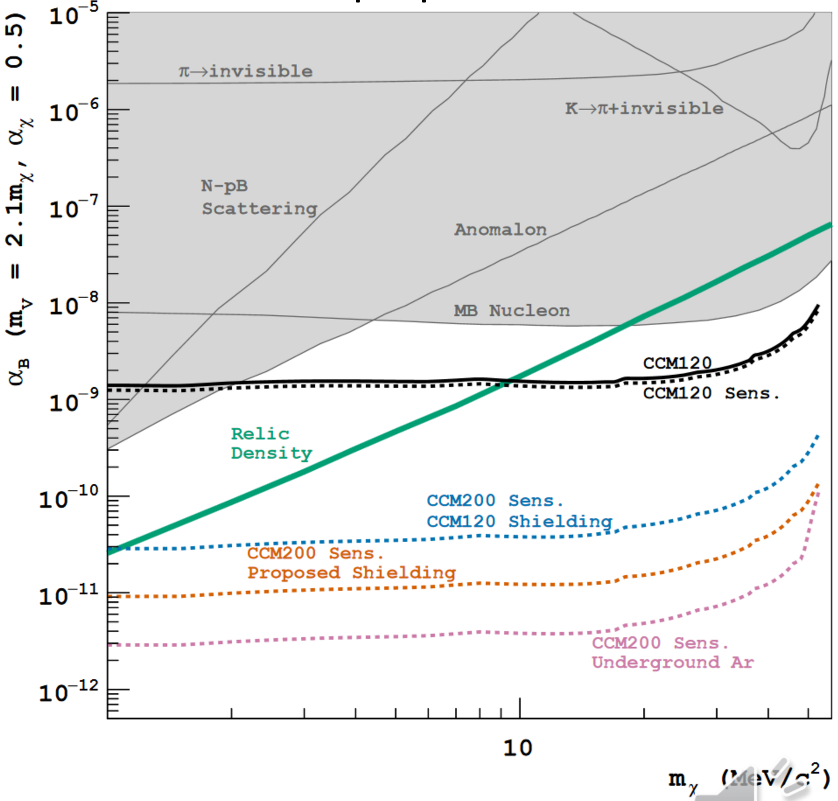
arXiv:2105.14020



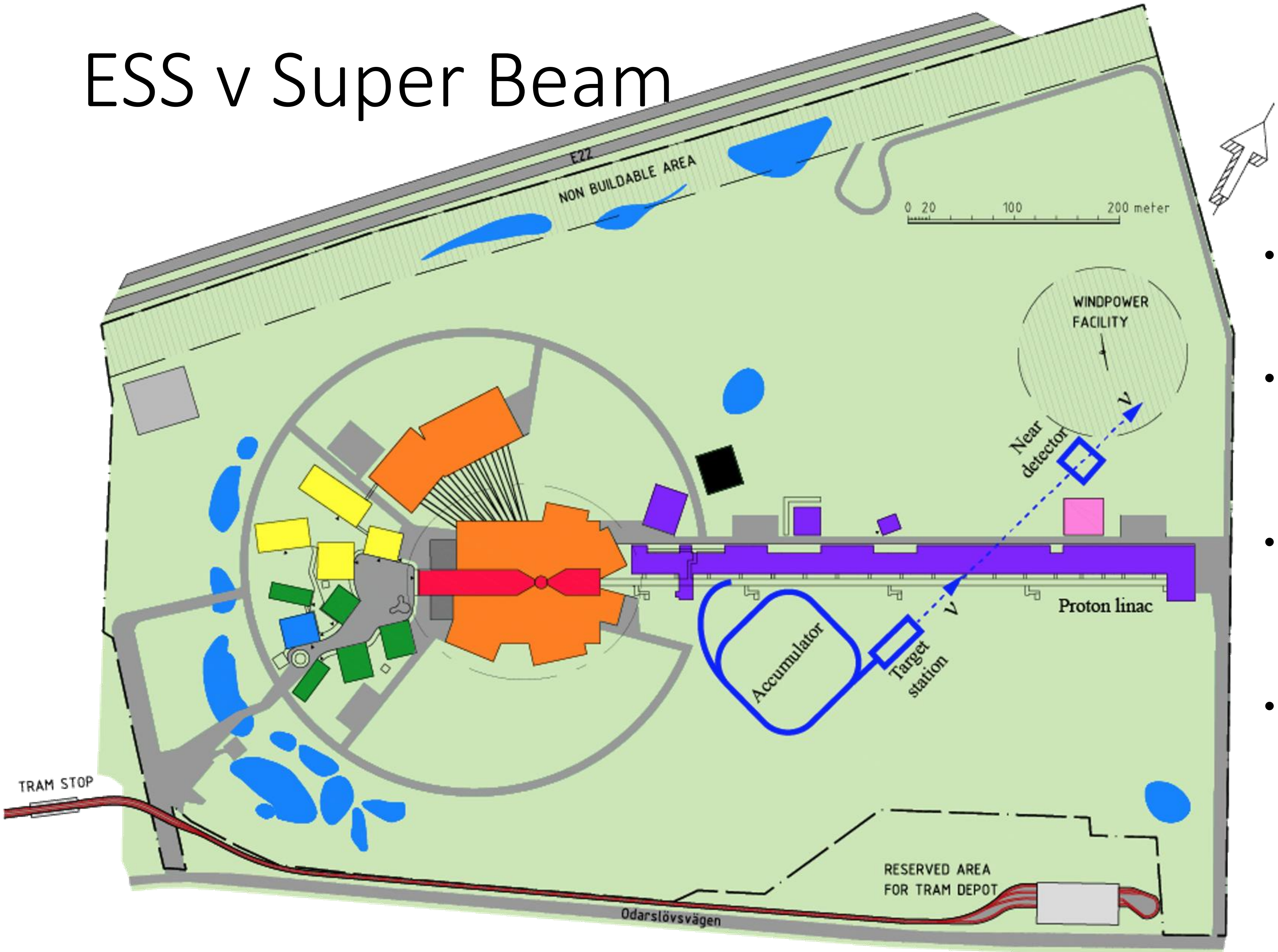
Vector portal



leptophobic



ESS v Super Beam



Compared to the SNS:

- More powerful beam
- Less narrower pulses

- Aim: add a neutrino facility on top of the ESS neutron one
- Add accumulator to compress to 1.3 µs the 2.86 ms proton pulses
- Underground near and far detectors for neutrino oscillations
- Can provide a muon beam for muon collider

Dracos, NuFact, 2021

JHEP 02 (2020) 123

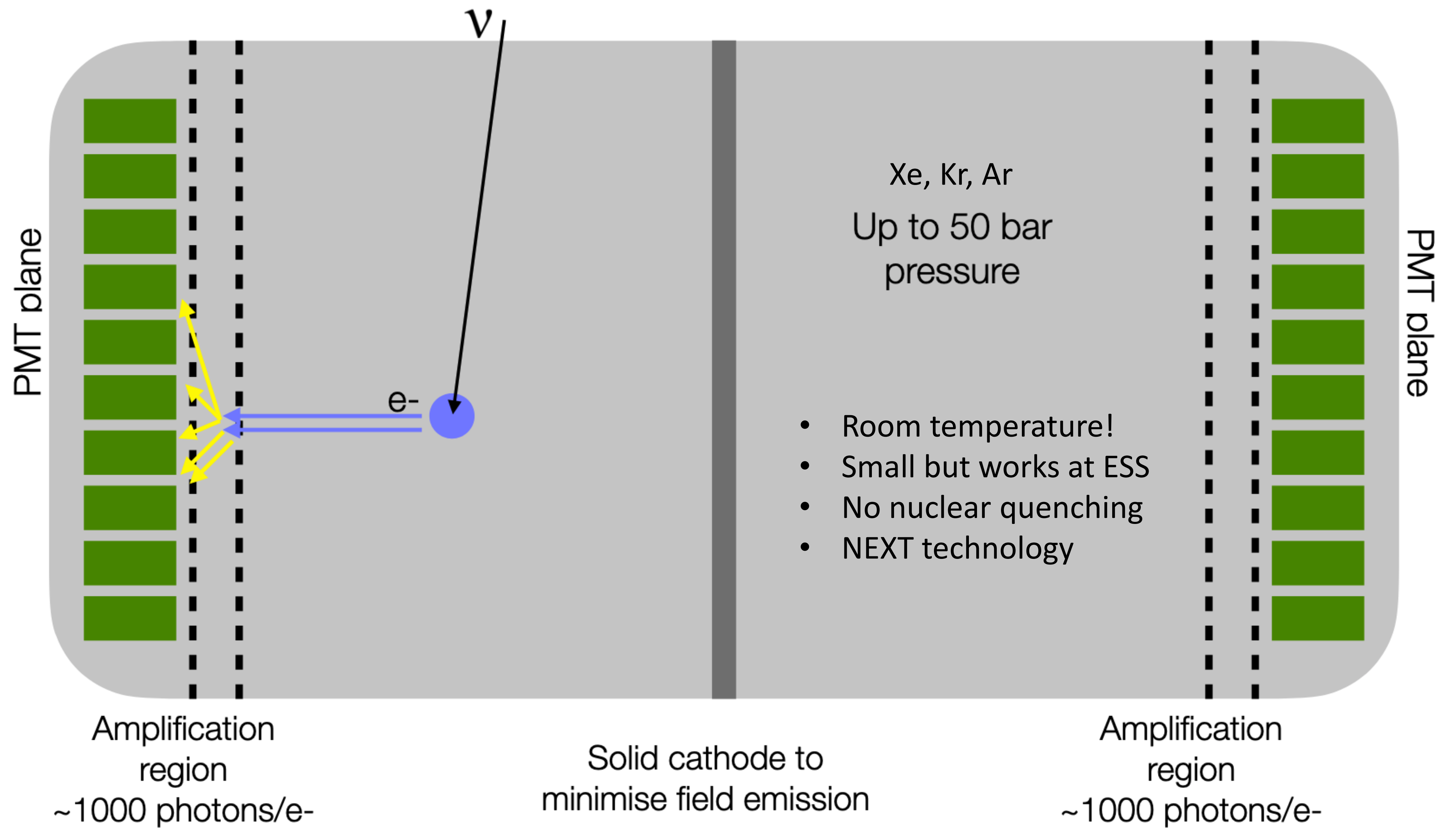
Coherent Elastic Neutrino-Nucleus Scattering at the European Spallation Source

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})	$\Delta E/E$ (%) 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

F. Monrabal, TAUP 2021

Gaseous detector for Neutrino physics at the ESS (GaNESS)



Low E_ν → low E_{recoil}
→ low threshold!
→ low threshold!
→ low threshold!

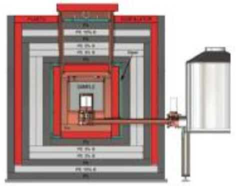
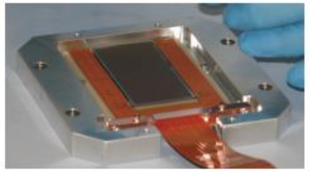
Close to continuously running core
→ Shielding!
→ Shielding!
→ Shielding!

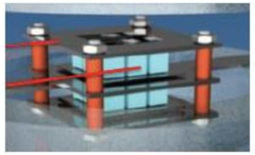
A lot more than stopped pion experiments!

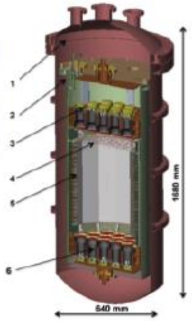
- Ionization detector
  - HPGe
  - Si CCDs
  - Liquid noble gas
- Bolometers
- Scintillators
- Bubble chamber
- …

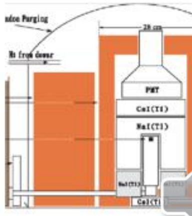
Reactor CEvNS Efforts Worldwide

Experiment	Technology	Location
CONNIE	Si CCDs	Brazil
CONUS	HPGe	Germany
MINER	Ge/Si cryogenic	USA
νEON	NaI(Tl)	Korean
Nu-Cleus	Cryogenic $CaWO_4$, Al_2O_3 calorimeter array	Europe
νGEN	Ge PPC	Russia
RED-100	LXe dual phase	Russia
Ricochet	Ge, Zn bolometers	France
TEXONO	p-PCGe	Taiwan







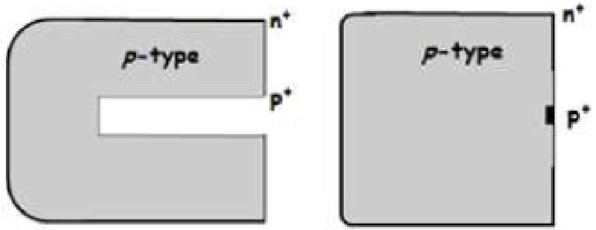
K. Scholberg, IPA, 2018

Comparison of the reactor sites

A. Lubashevskiy, TAUP 2021

Experiment	Location	Neutrino flux $\nu/(cm^2\ s)$	Overburden [m w. e.]
νGeN	KNPP, Russia	$>5\times10^{13}$	~50
CONUS	Brokdorf, Germany	2.4×10^{13}	10-45
TEXONO	Kuo-Sheng NPP, Taiwan	6.4×10^{12}	~30
RED-100	KNPP, Russia	1.7×10^{13}	>50?
CONNIE	Angra 2, Brazil	6.8×10^{12}	0
RICOCHET	ILL, France	2×10^{12}	~15
MINER	Texas A&M, USA	2×10^{12}	~5
NUCLEUS	Chooz, France	2×10^{12}	~3
Mark-I?	Dresden-II, USA	8.1×10^{13}	6?
NEON	Yeonggwang, Korea	7.1×10^{12}	~20

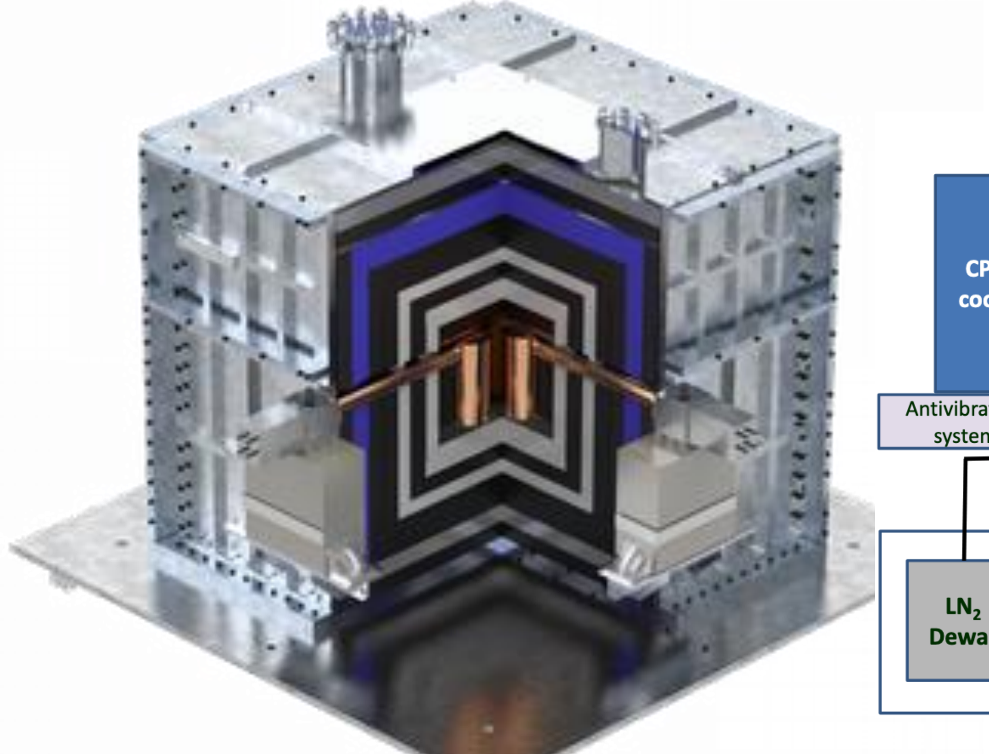
Point-contact Ge detector



- large mass
- tiny capacitance

CONUS

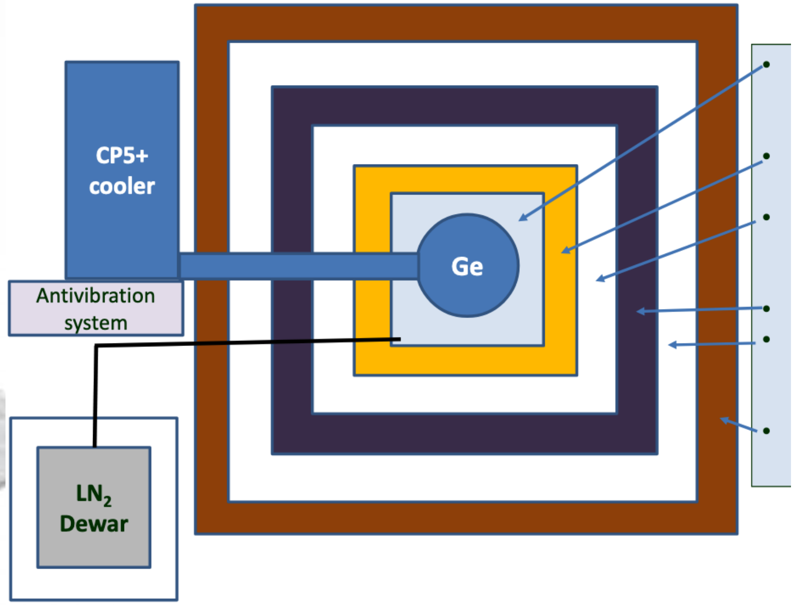
- Mass: 4 x ~1 kg
- Threshold: 300 eVee



Eur. Phys. J. C (2021) 81 :267

νGeN

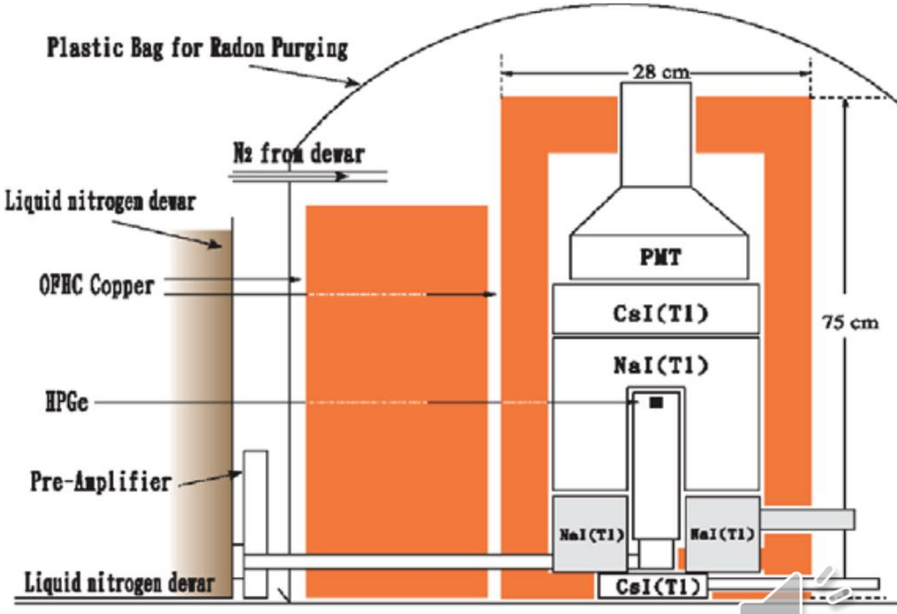
- Mass: 4 x ~1 kg
- Threshold: 250 eVee



A. Lubashevskiy, TAUP 2021

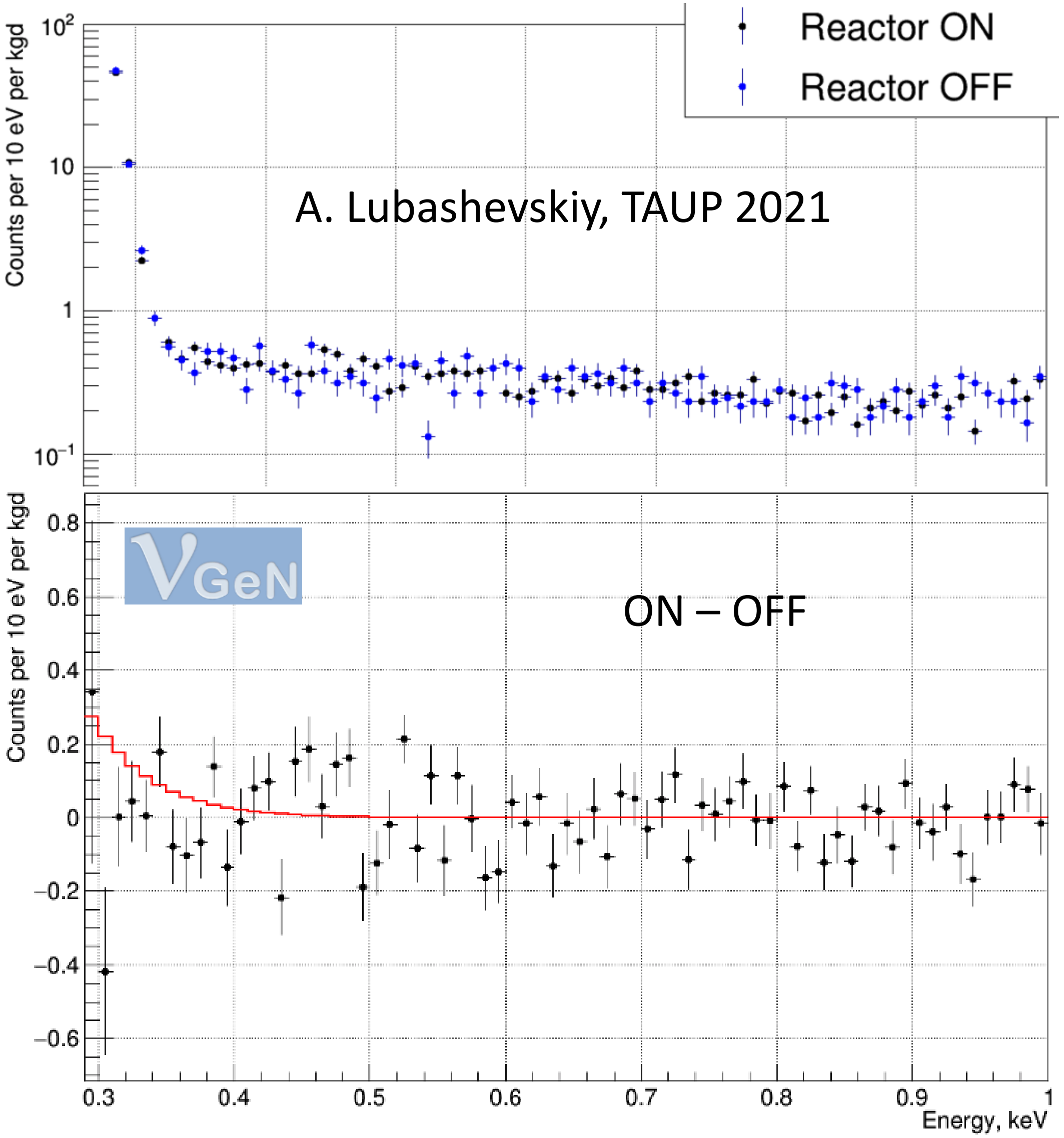
TEXONO

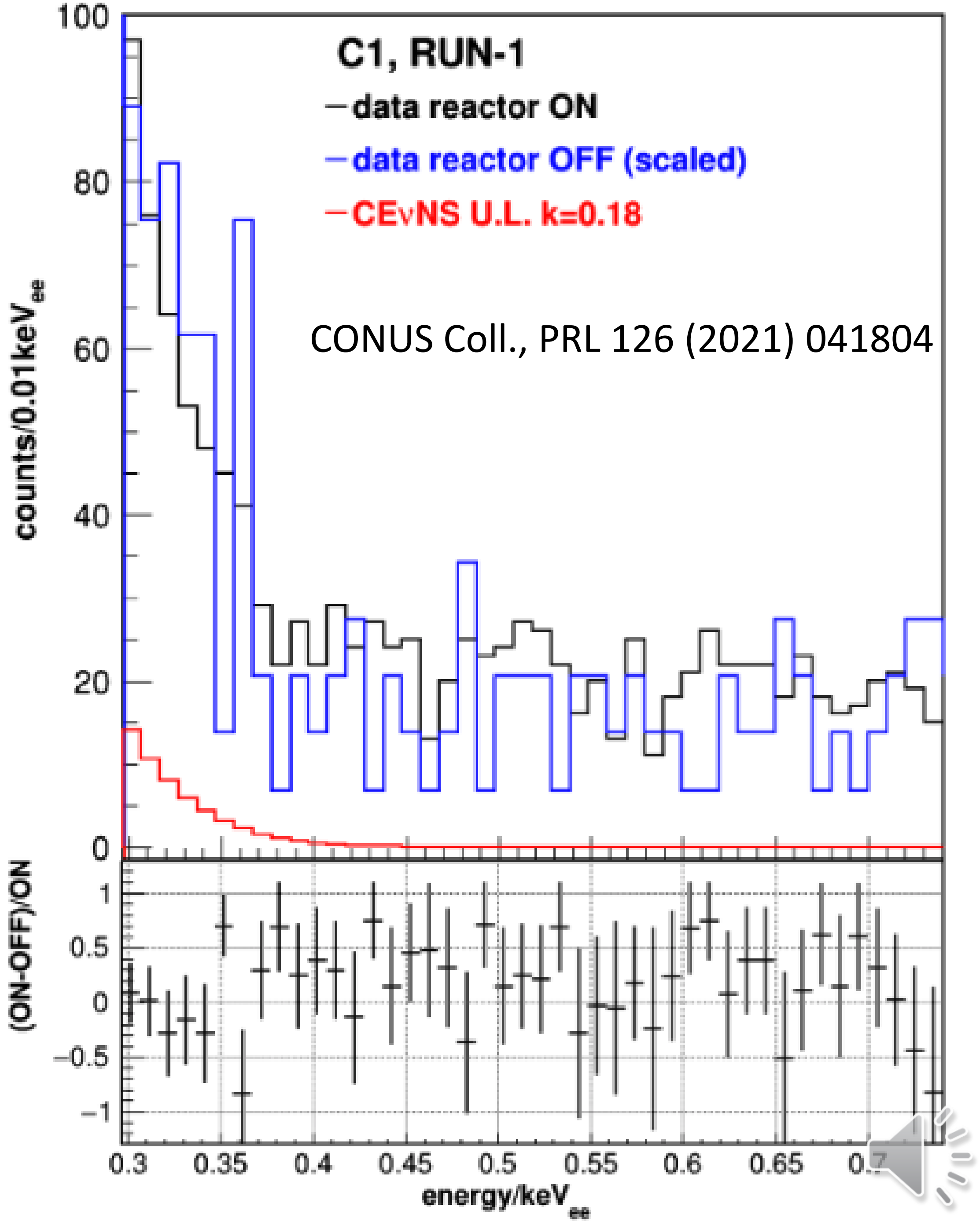
- Mass: 1.43 kg
- Threshold: 200 eVee



H. I. Wong, m7s, 2021

Ge achievement

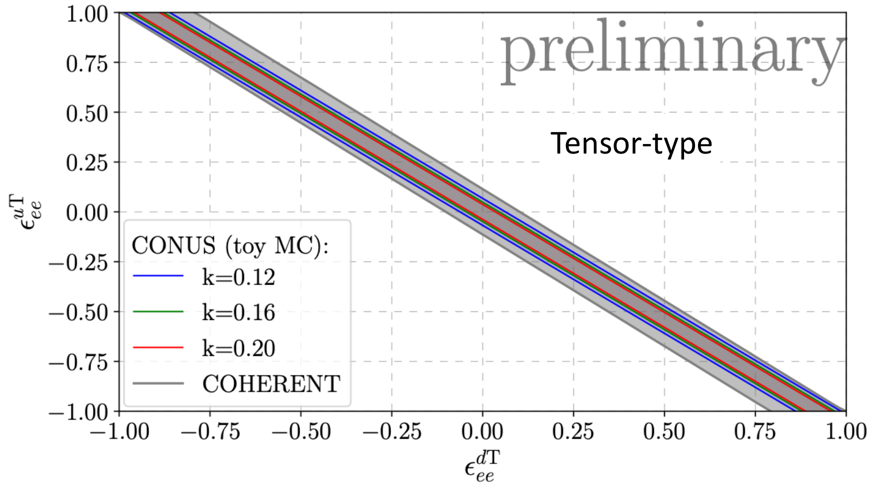


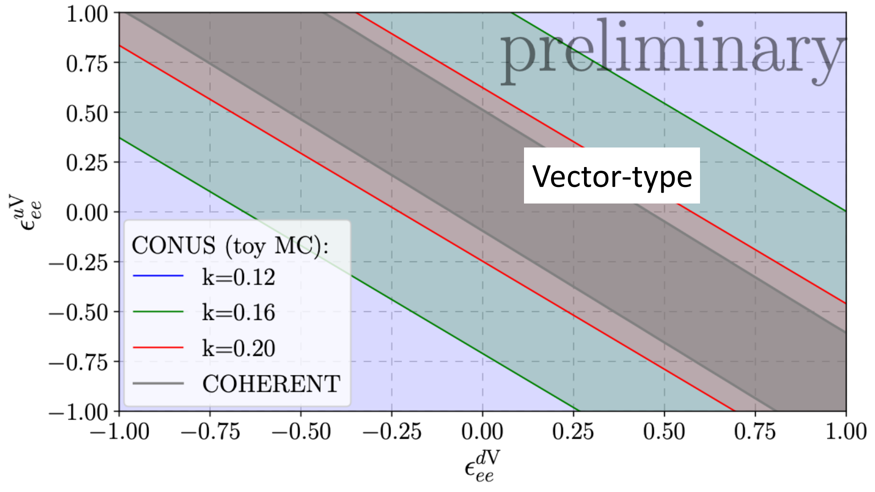


Sensitivities of CONUS

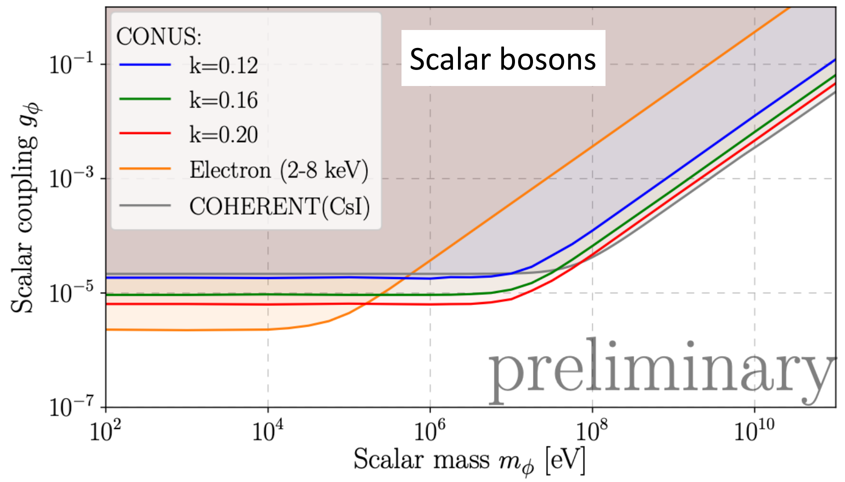
Publication in preparation!

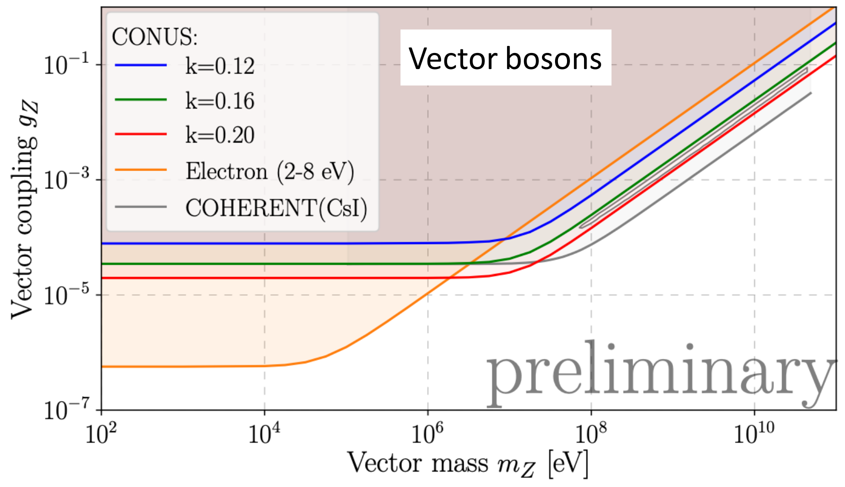
Non-standard interaction (NSI) operators





Dark matter search

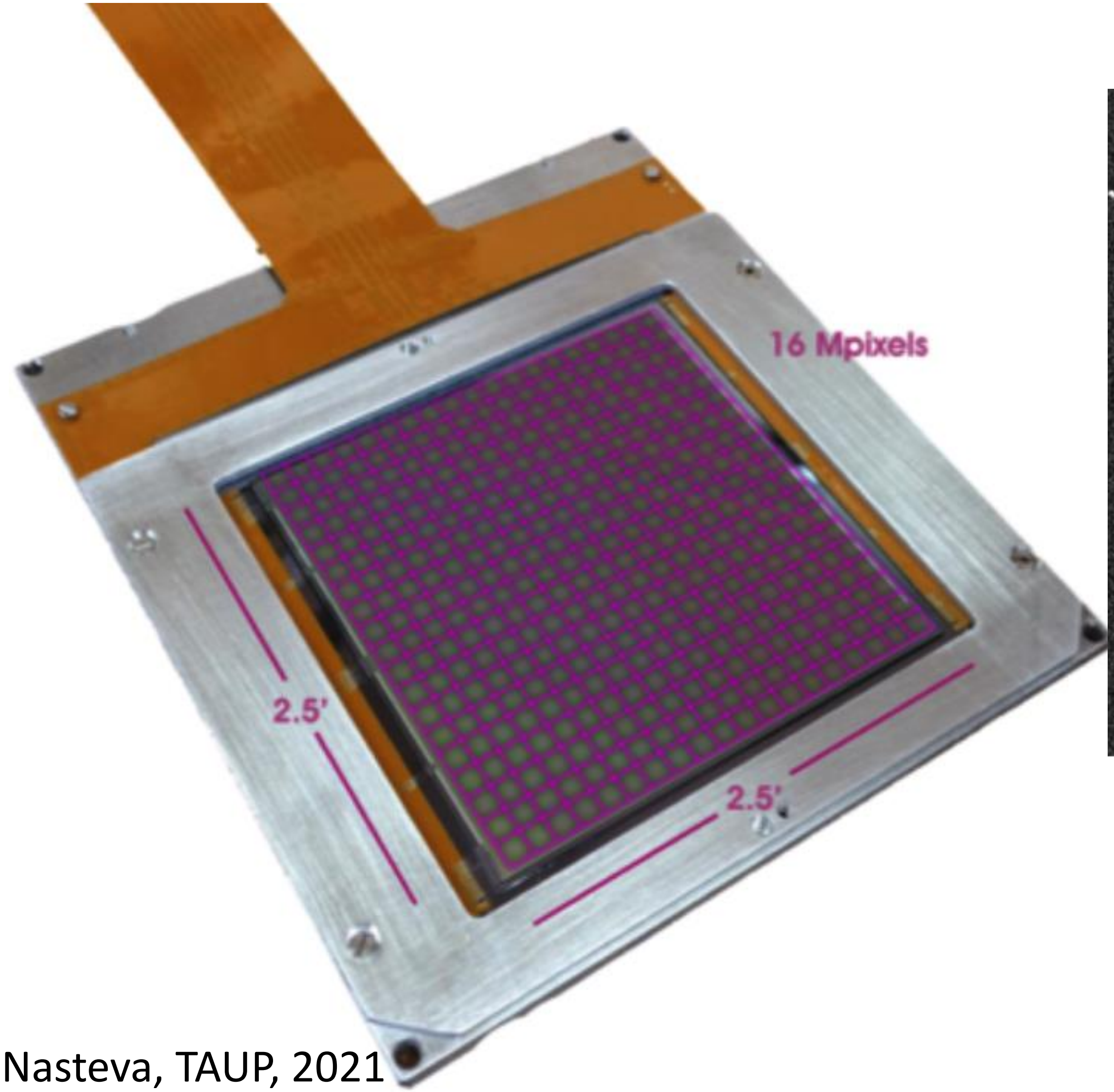


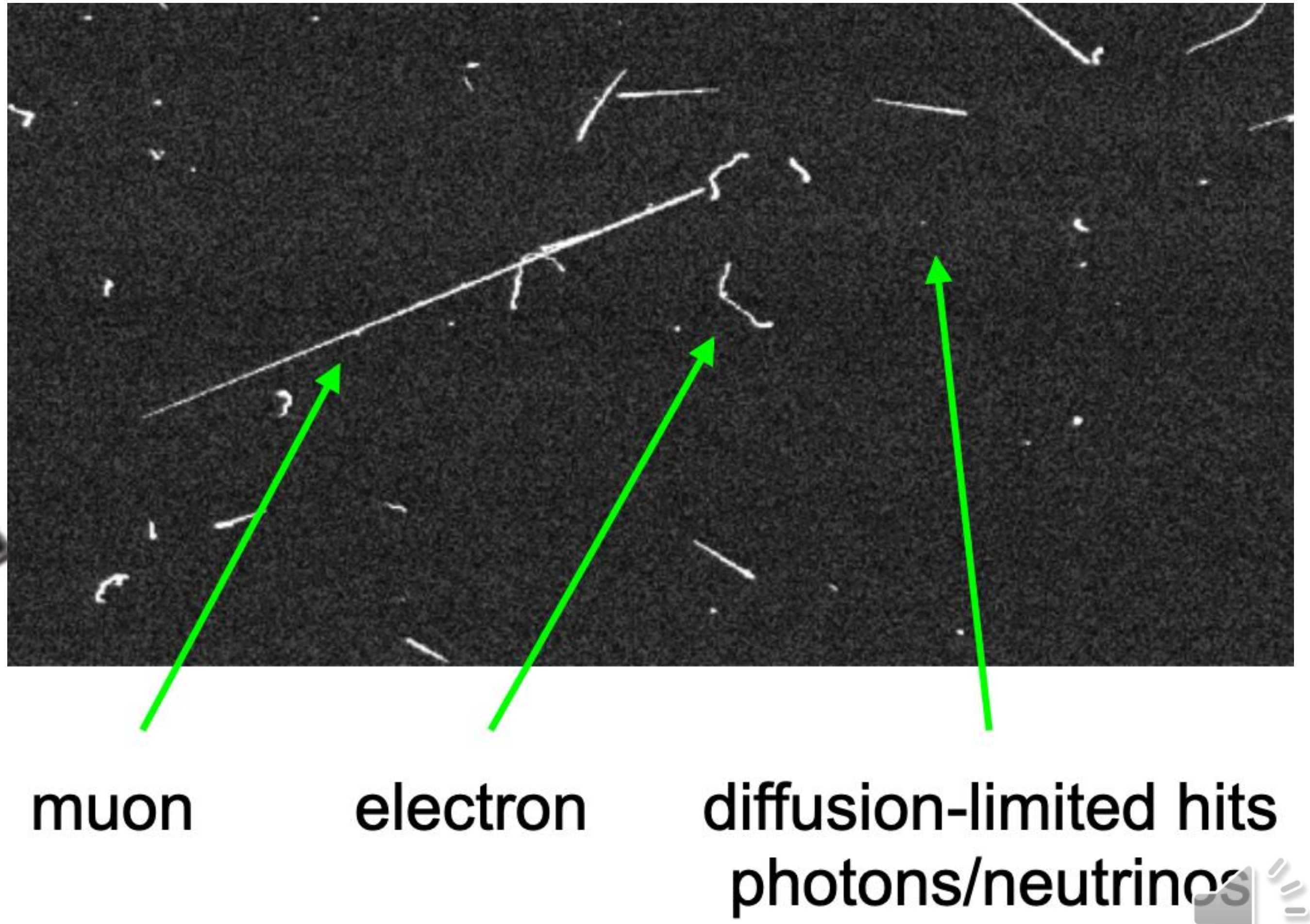


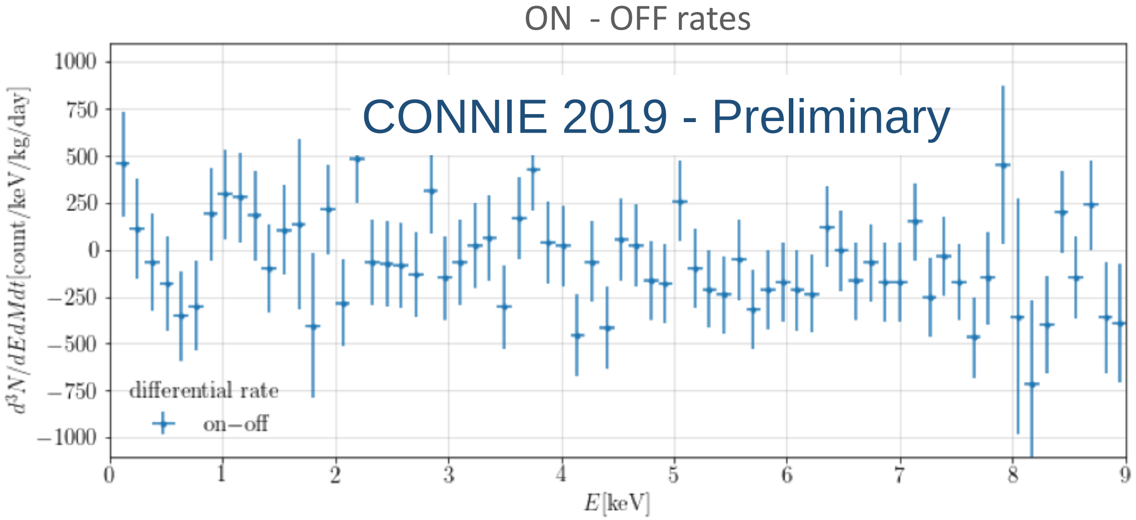
Charge-coupled device (CCD), Si

Pixelized Si wafer:

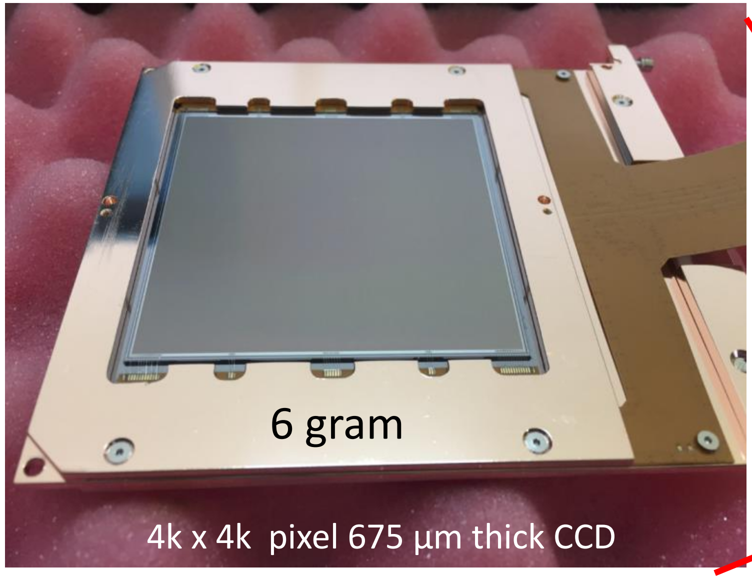
- Lower threshold than Ge
- Particle identification
- Less massive than Ge

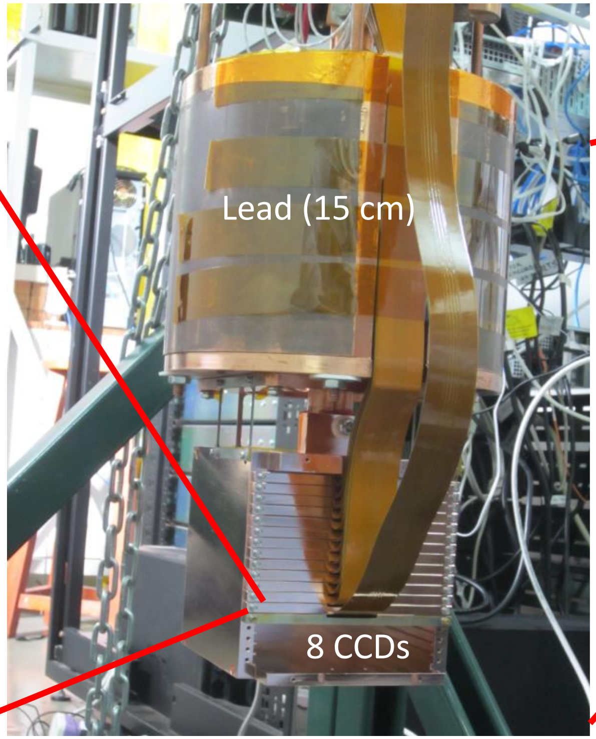


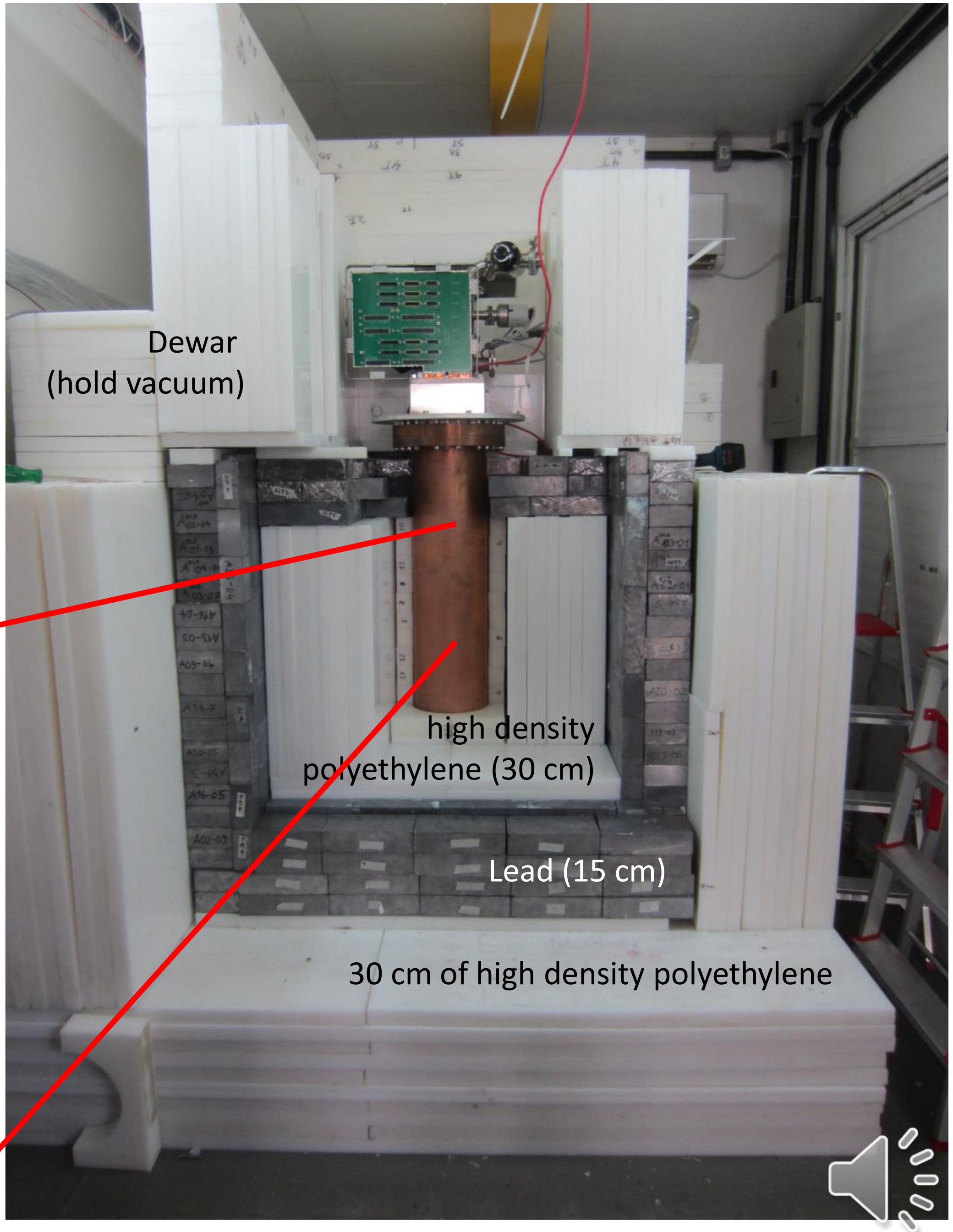




Irina, TAUP, 2021







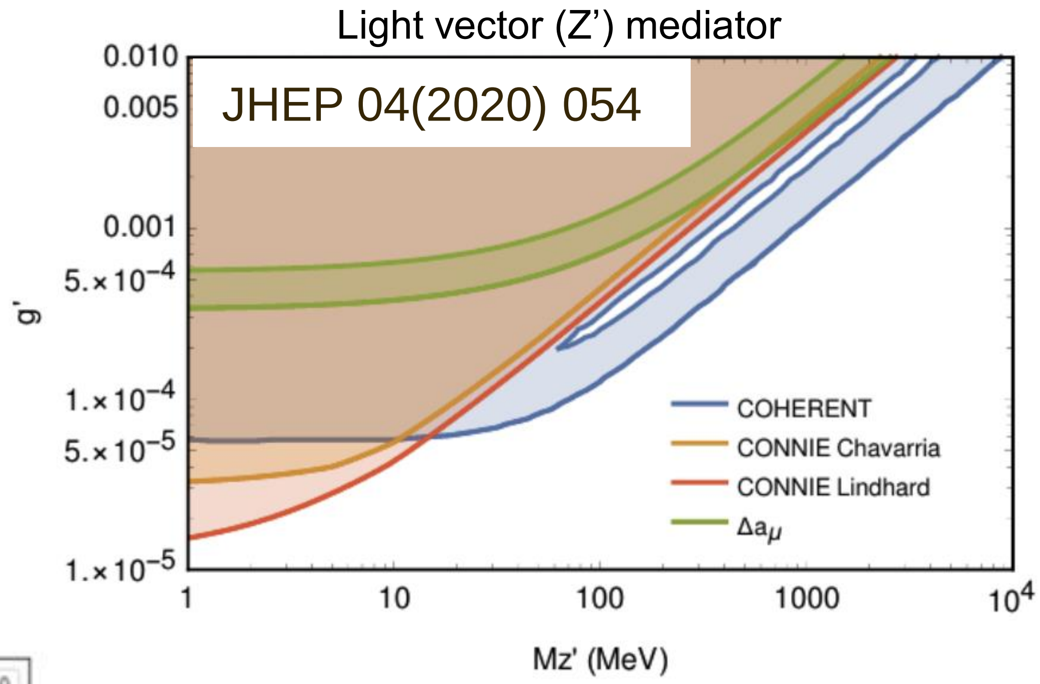
Developed by Lawrence Berkeley National Laboratory MicroSystems La

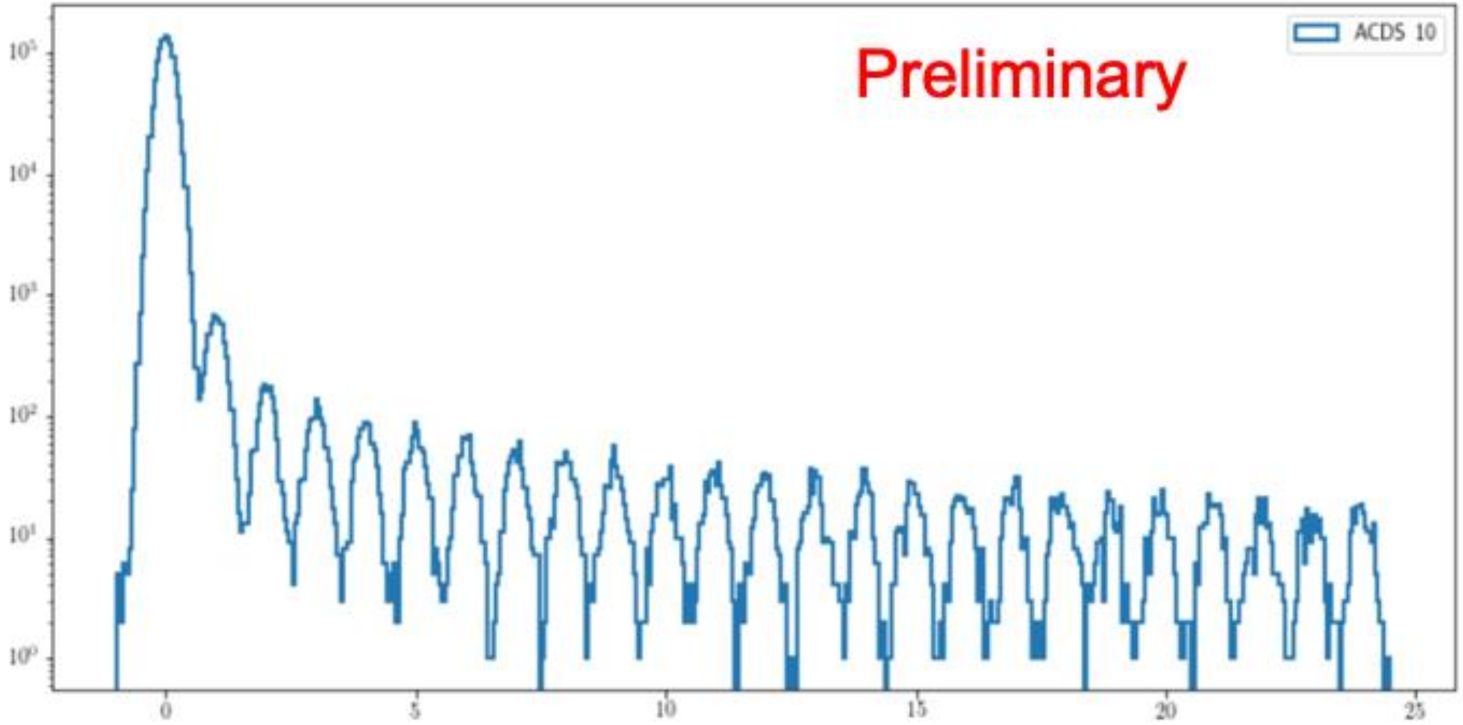
CCD achievement

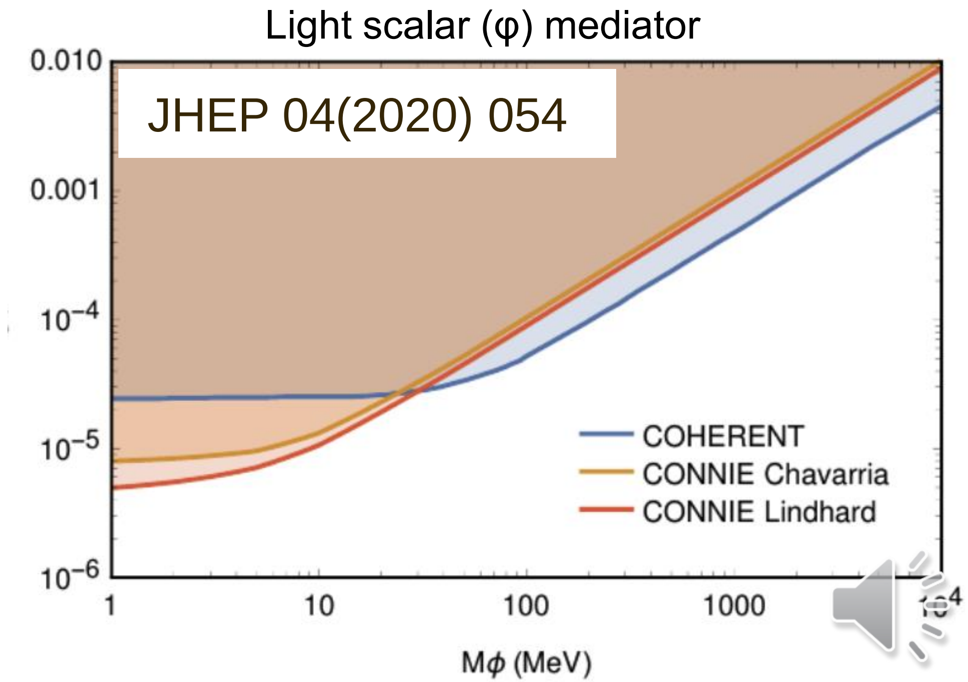
Skipper CCD:
repeatedly sample the same pixel to average out noise

- Single electron sensitivity!
- slow

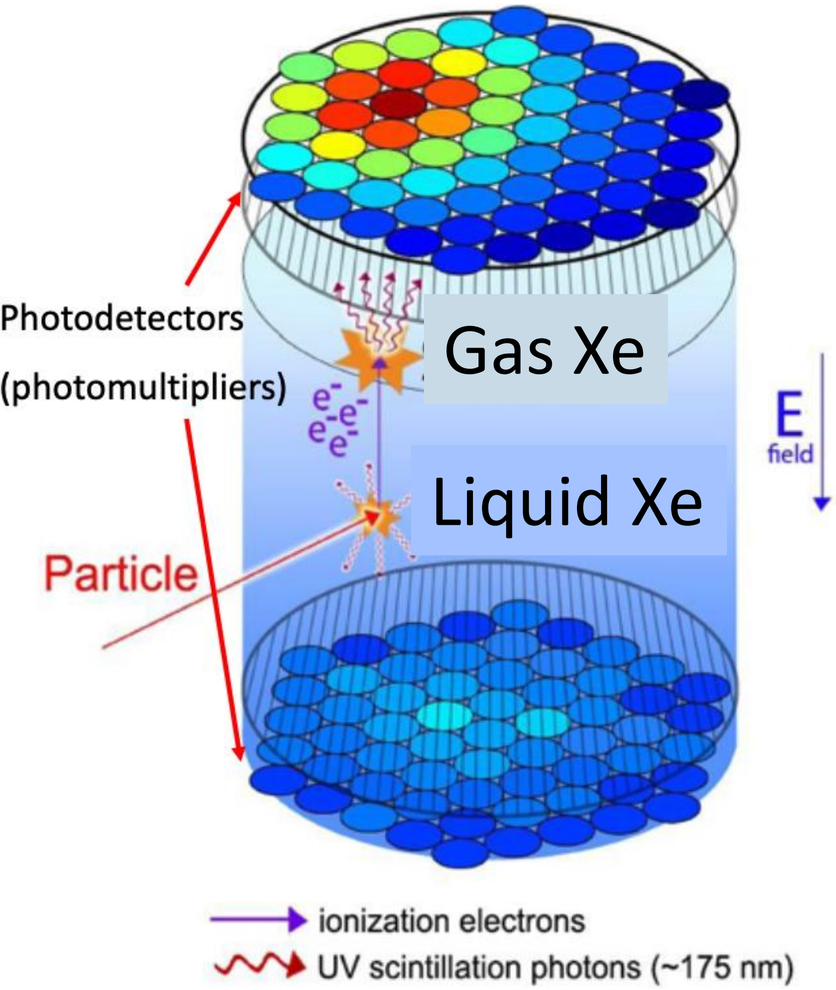
J. Tiffenberg et al,
PRL 119 (2017)



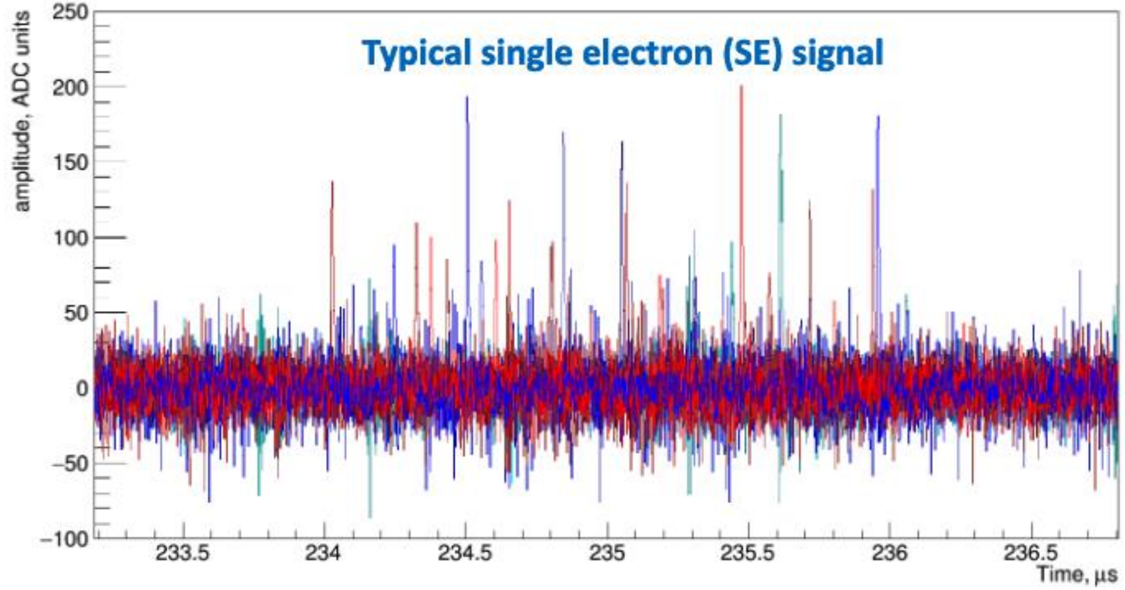




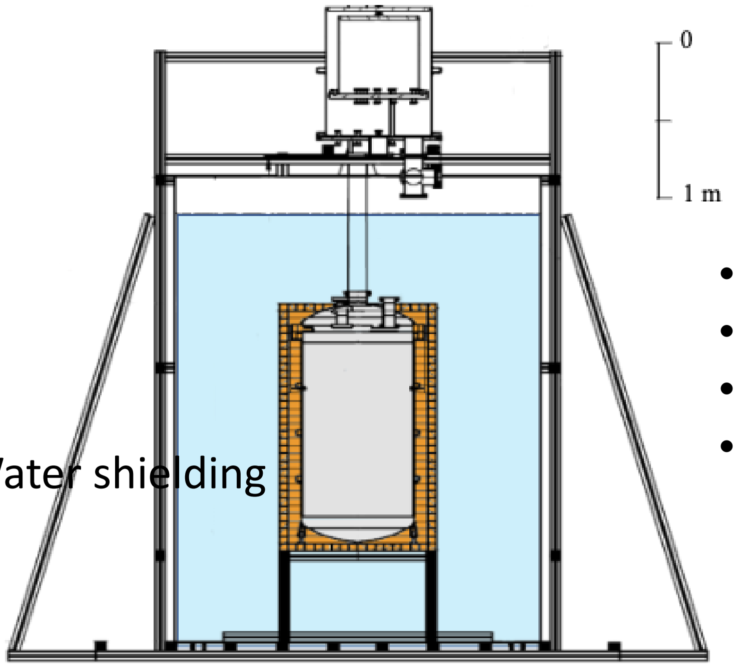
R E D
RUSSIAN EMISSION DETECTOR



CH Faham, Brown



Different colors → different PMTs



- Water shielding

D. Rudik, m7s, 2020

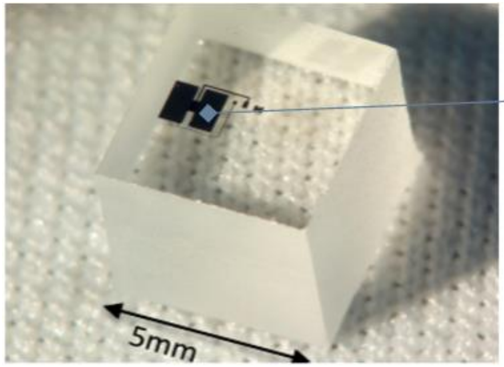
- 200 kg LXe, 100 in fiducial volume
- High E field to extract single electron
- ~ 30 photoelectrons in gas Xe / electron
- Background: trapped electrons

Bolometers (heat detectors at mK)

V. Wagner, TAUP, 2021

Target crystals:
Two 3x3 arrays with a total mass of
6g ($CaWO_4$) + 4g (Al_2O_3)

- Threshold: ~20 eV
- Instrumented holding structure



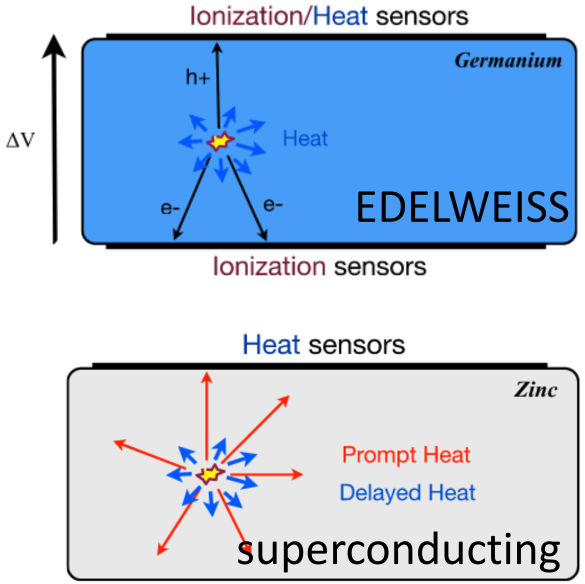
TES

Phys. Rev. D **96**, 022009 (2017)

T. Salagnac, m7s, 2020

RICOCHET
A Coherent Neutrino Scattering Program

- Threshold: 55 eV
- 30 g crystals
- Particle identification



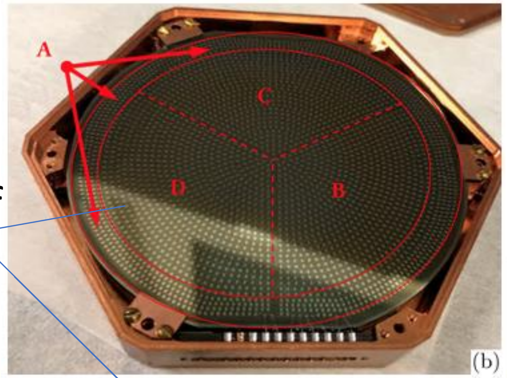
EDELWEISS R&D

superconducting

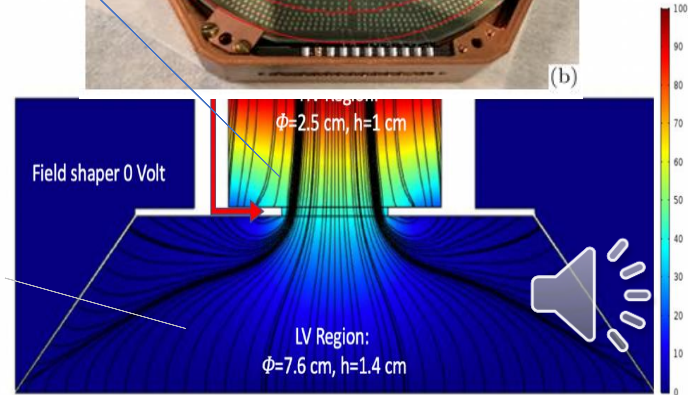
R. Mahapatra, m7s, 2020

MINER

- Threshold: ~100 eV
- 1~4 kg Hybrid Ge & HV Si
- Low threshold and/or PID
- Moving reactor core!

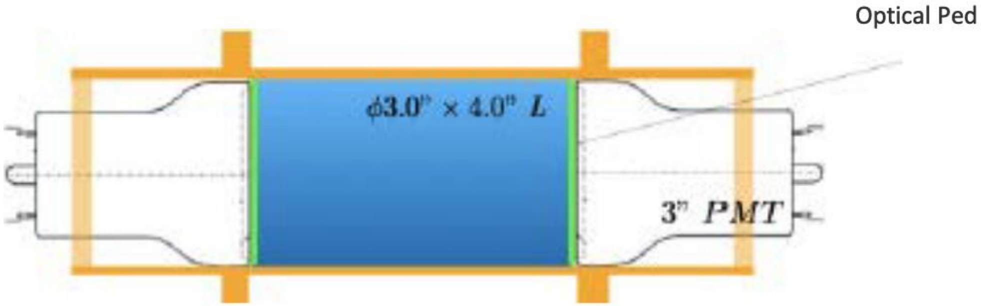


Luke phonon amplification of charge signals

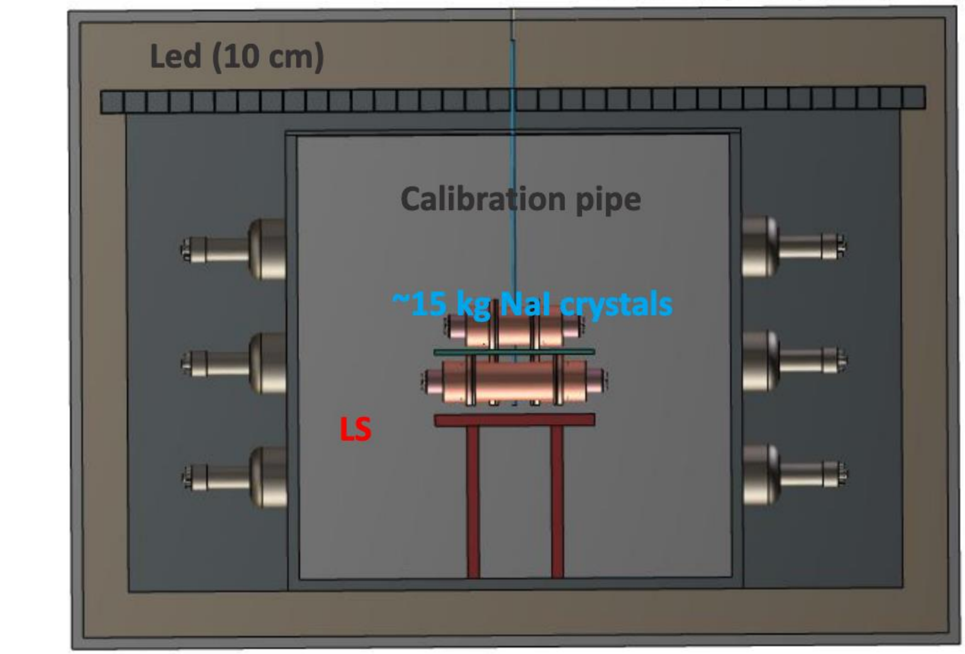


Particle identification

- COSINE + NEOS
- 15 kg NaI(Tl)
- light yield: 20~24 photoelectrons (PE)/keV → threshold: ~0.22 keV visible energy (5 PE)
- Liquid scintillator active shielding
- Physics run from Nov. 2020
  - ~ 4 months Reactor on data
  - ~ 1 week (190 hours) Reactor off data



NEON Encapsulation



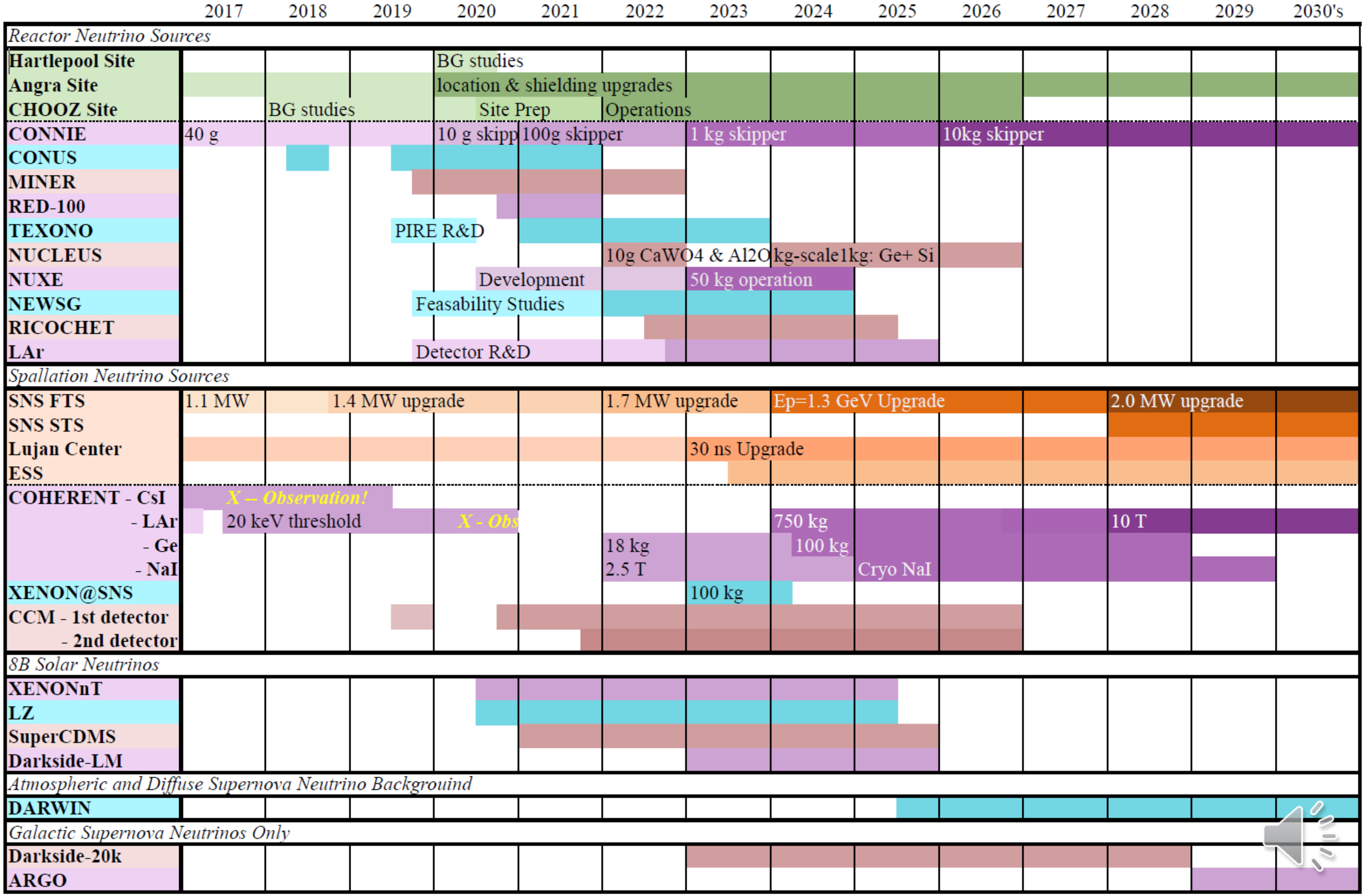
CEvNS timeline

May not be up to date & inclusive!

Demonstration of community effort

Big picture of the future of CEvNS

Thanks to Phil Barbeau



Mini
Magnificent CEvNS
2021

- Cyberspace
- Morning, US time on Oct. 6 & 7
- Contact organizing committee if you are interested in giving talks:
  - Phil Barbeau
  - Matt Green
  - Diane Markoff
  - Grayson Rich
  - Kate Scholberg
  - Raimund Strauss
  - Louis Strigari
  - Victoria Wagner

http://magnificentcevns.org/

Backups

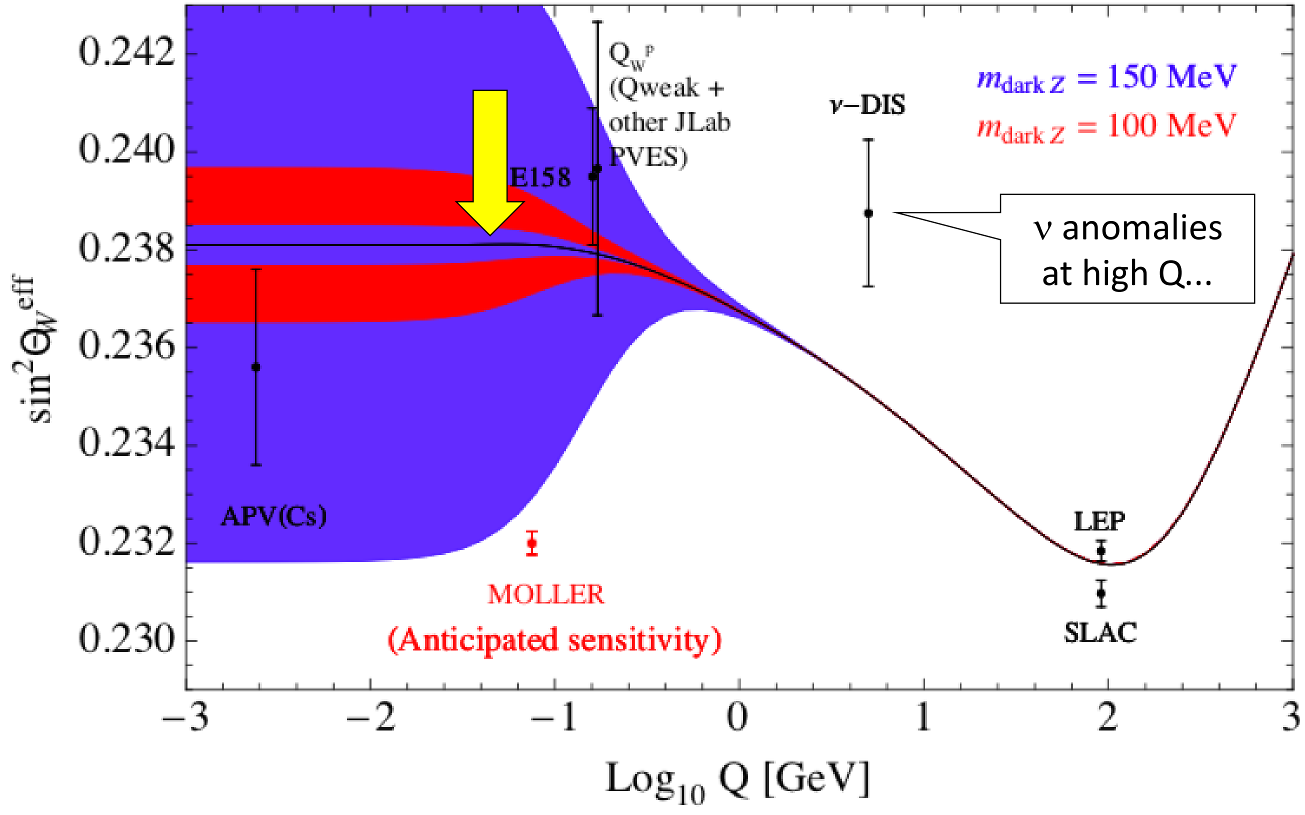
$$g_V^p = \rho_{\nu N}^{NC}\left(\frac{1}{2} - 2\hat{\kappa}_{\nu N}\hat{s}_Z^2\right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR},$$

$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}.$$

Here $\hat{s}_Z^2 = \sin^2\theta_W = 0.23120$, $\rho_{\nu N}^{NC} = 1.0086$, $\hat{\kappa}_{\nu N} = 0.9978$, $\lambda^{uL} = -0.0031$, $\lambda^{dL} = -0.0025$ and $\lambda^{dR} = 2\lambda^{uR} = 7.5 \times 10^{-5}$ are the radiative corrections given by the PDG

A new method for measuring the weak mixing angle at Q~0.04 GeV

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



MOLLER collaboration, arXiv:1411.4088

Other new physics results in a
distortion of the recoil spectrum (Q dependence)

BSM Light Mediators

SM weak charge

$$Q^2_{\alpha,\mathrm{SM}} = (Zg_p^V + Ng_n^V)^2$$

Effective weak charge in presence of light vector mediator Z'

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

specific to neutrinos and quarks

e.g. arXiv:1708.04255

Neutrino (Anomalous) Magnetic Moment

e.g. arXiv:1505.03202, 1711.09773

$$\left(\frac{d\sigma}{dT}\right)_m = \frac{\pi\alpha^2\mu_\nu^2 Z^2}{m_e^2}\left(\frac{1-T/E_\nu}{T} + \frac{T}{4E_\nu^2}\right)$$

Specific ~1/T upturn at low recoil energy

Sterile Neutrino Oscillations

$$P^{\mathrm{SBL}}_{\nu_\alpha\to\nu_\alpha}(E_\nu) = 1 - \sin^2 2\theta_{\alpha\alpha}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

"True" disappearance with baseline-dependent Q distortion

e.g. arXiv: 1511.02834, 1711.09773, 1901.08094

[redacted]

And squeezing down the possibilities for new physics...