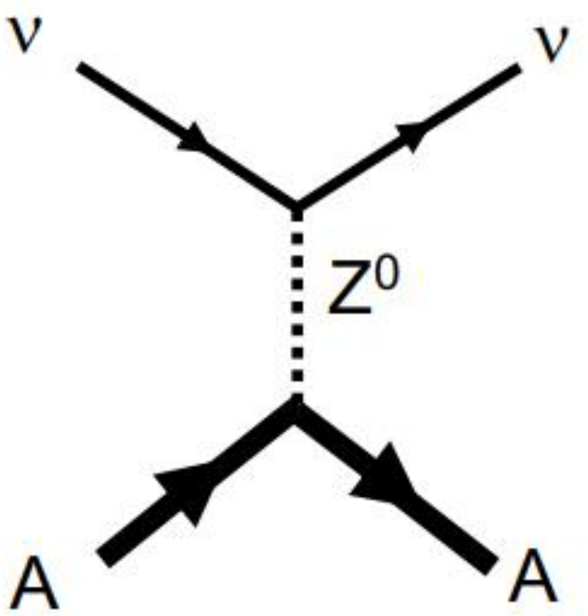
CryoCsI - a future COHERENT detector

Keyu/Coco Ding

CNP research day 2024

Coherent Elastic neutrino-nucleus scattering

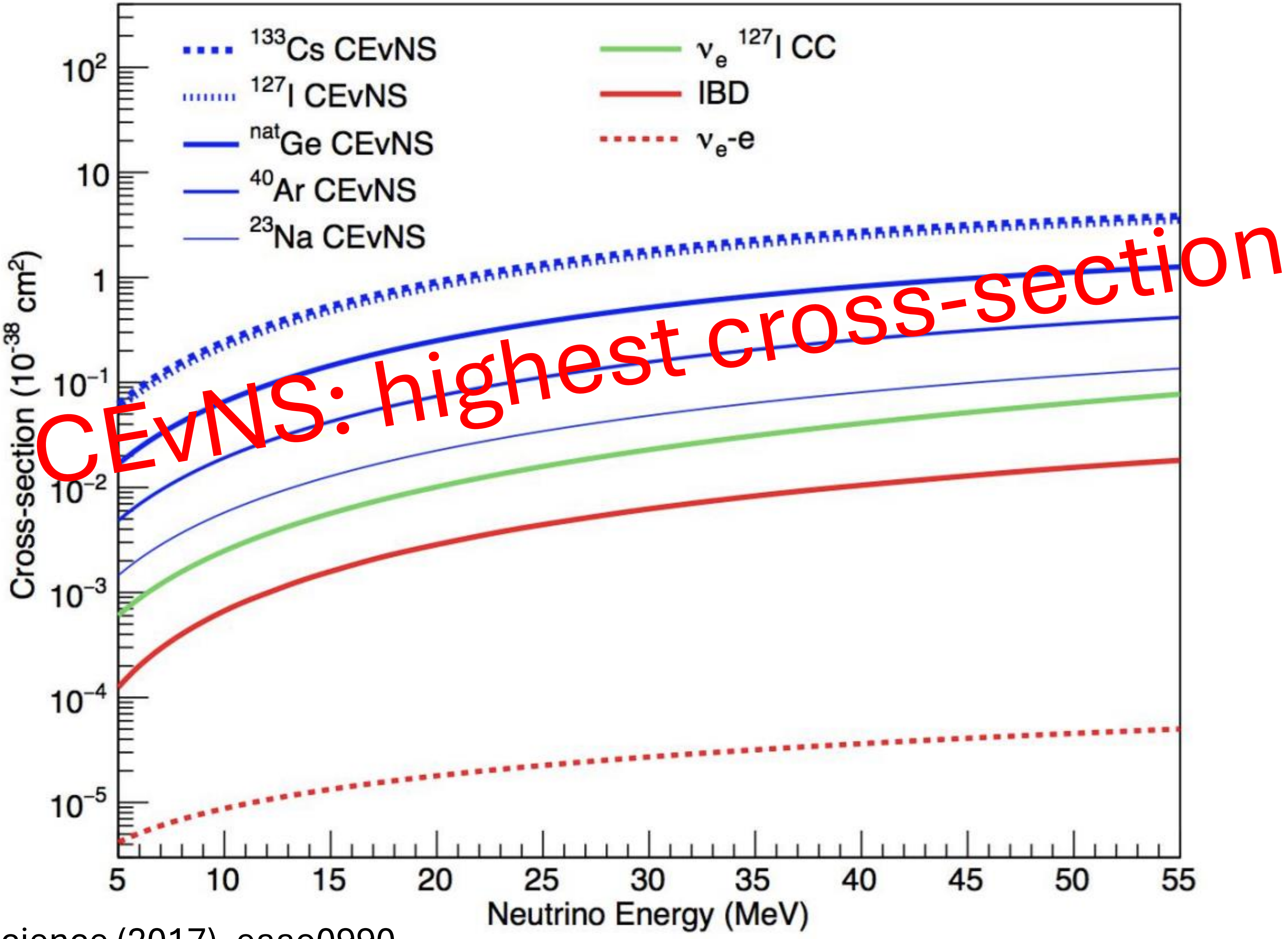
$$\nu + A \rightarrow \nu + A$$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV

Experimental signature: **tiny energy** deposited by nuclear recoils in the target material

Neutrino interactions



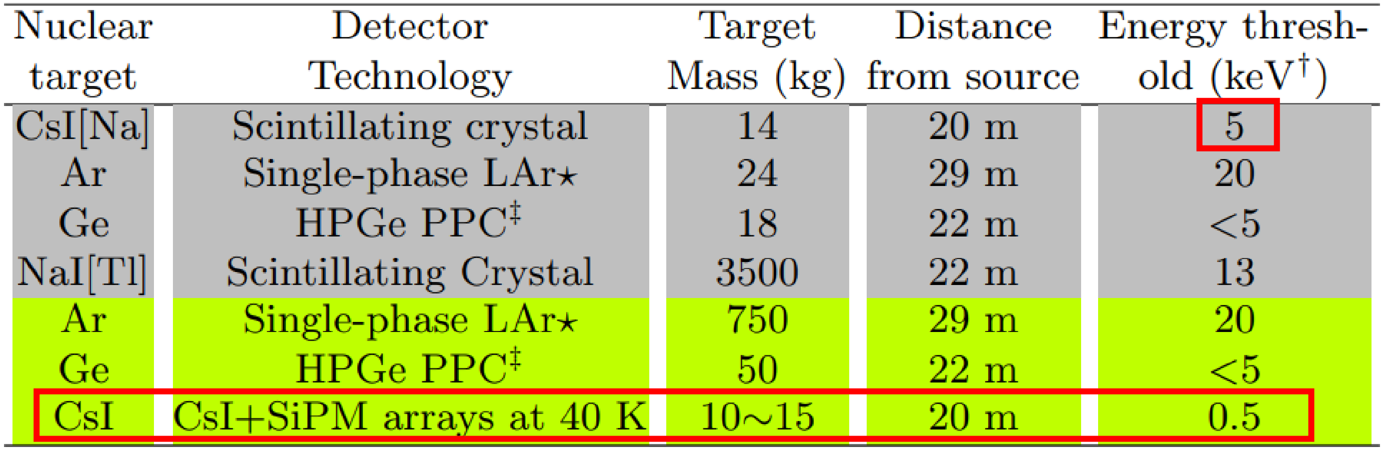
CEvNS: highest cross-section

Science (2017), eaao0990

COHERENT Snowmass whitepaper

CEvNS detectors

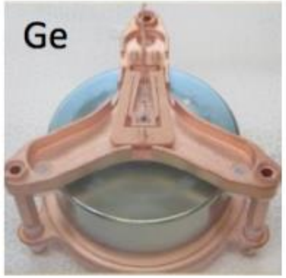
TABLE I. Parameters of subsystems for CEvNS detection.

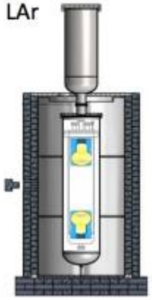


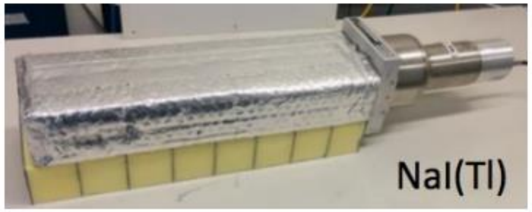
Nuclear target	Detector Technology	Target Mass (kg)	Distance from source	Energy threshold (keV†)
CsI[Na]	Scintillating crystal	14	20 m	5
Ar	Single-phase LAr*	24	29 m	20
Ge	HPGe PPC‡	18	22 m	<5
NaI[Tl]	Scintillating Crystal	3500	22 m	13
Ar	Single-phase LAr*	750	29 m	20
Ge	HPGe PPC‡	50	22 m	<5
CsI	CsI+SiPM arrays at 40 K	10∼15	20 m	0.5

Finished Planned, *liquid argon, ‡*p*-type point-contact, †nuclear recoil energy, approximate threshold

Multiple detectors for N^2 dependence of the cross section







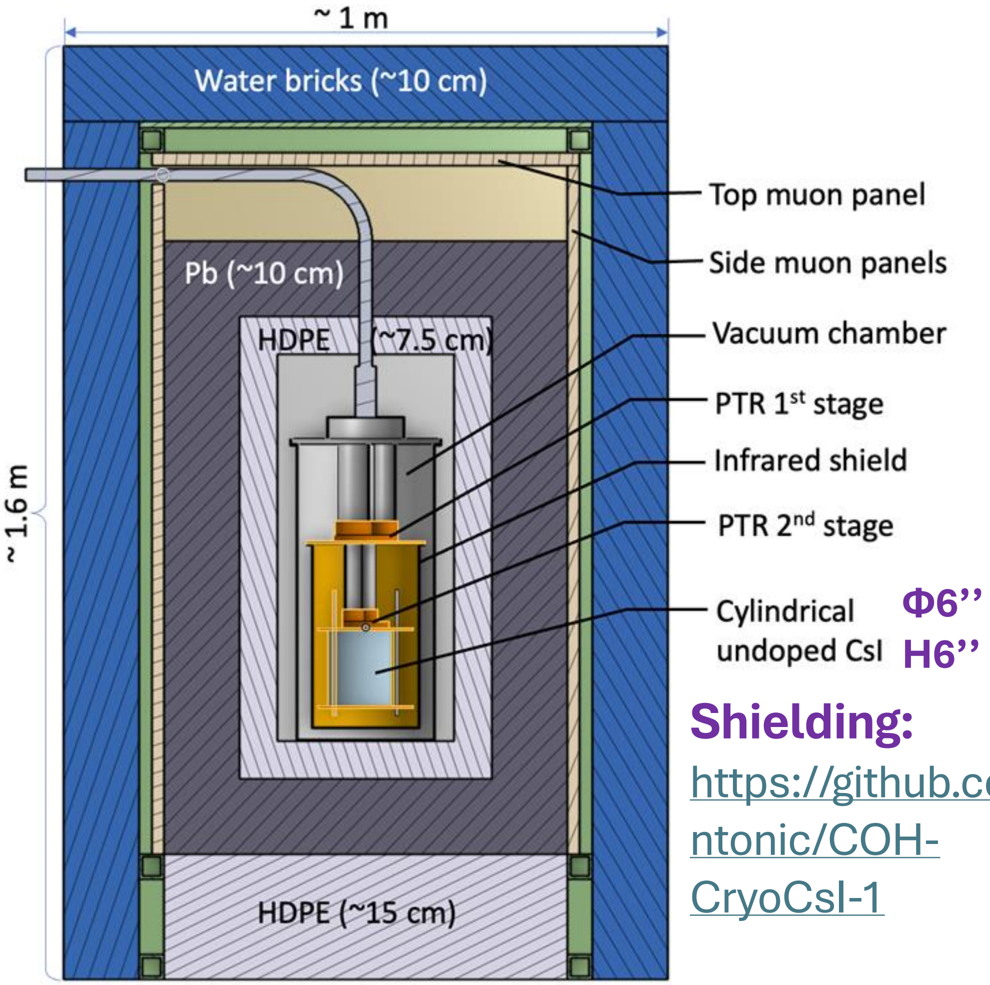
All by COHERENT!!!

First CEvNS measurement on CsI: *Science (2017), eaao0990*

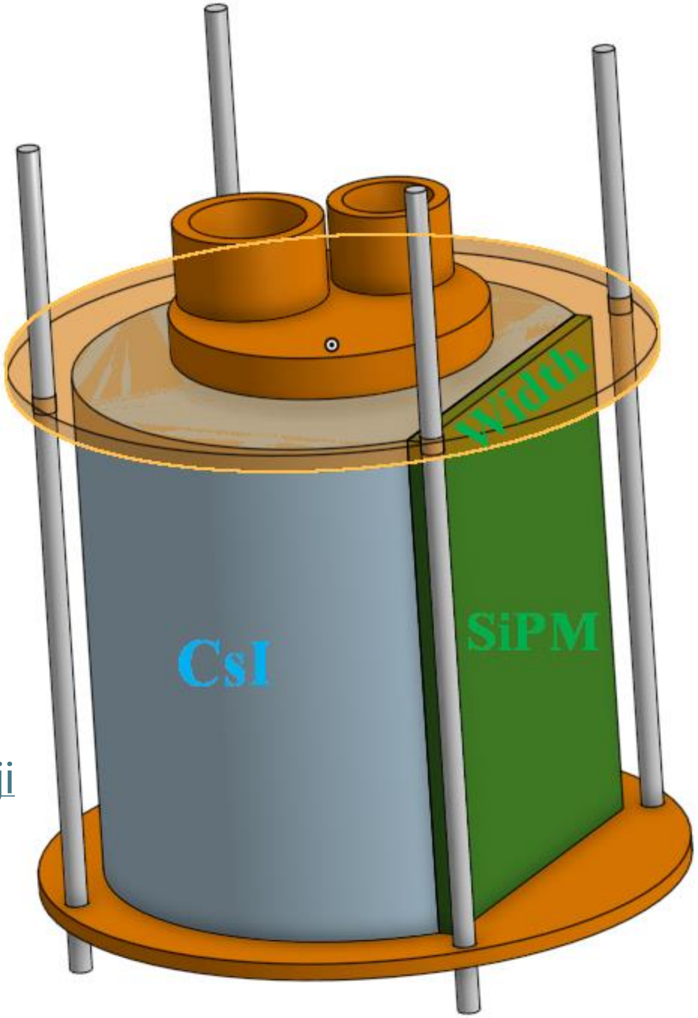
First CEvNS measurement on Ar: *PRL 126 012002 (2021)*

First CEvNS measurement on Ge: arxiv:2406.13806

CryoCsI design



Shielding: https://github.com/jintonic/COH-CryoCsI-1



CryoCsI scale:

- **COH-CryoCsI-1: 10kg, 3 years exposure**
- **COH-CryoCsI-2: 700kg, 5 years exposure**

Accessing new physics with an undoped, cryogenic CsI CEvNS detector for COHERENT at the SNS

Phys. Rev. D 109, 092005

Configuration:

- Beam power: 2.0 MW (2025)
- Mass: 10 kg, 19.7 m away from the beam
- Light yield: 50 PE/keVee
- Coincident trigger (2PE) on two SiPMs
- Quenching factor: 15% with 10% uncertainty
- Threshold: 500 eVnr
- Rate of beam-correlated neutron: ≈ 21 neutron events per year
- < 1 selected dark count per year
- Steady-state background: same rate as the original CsI detector, below 1.5 keVee (constant)

List of physics:

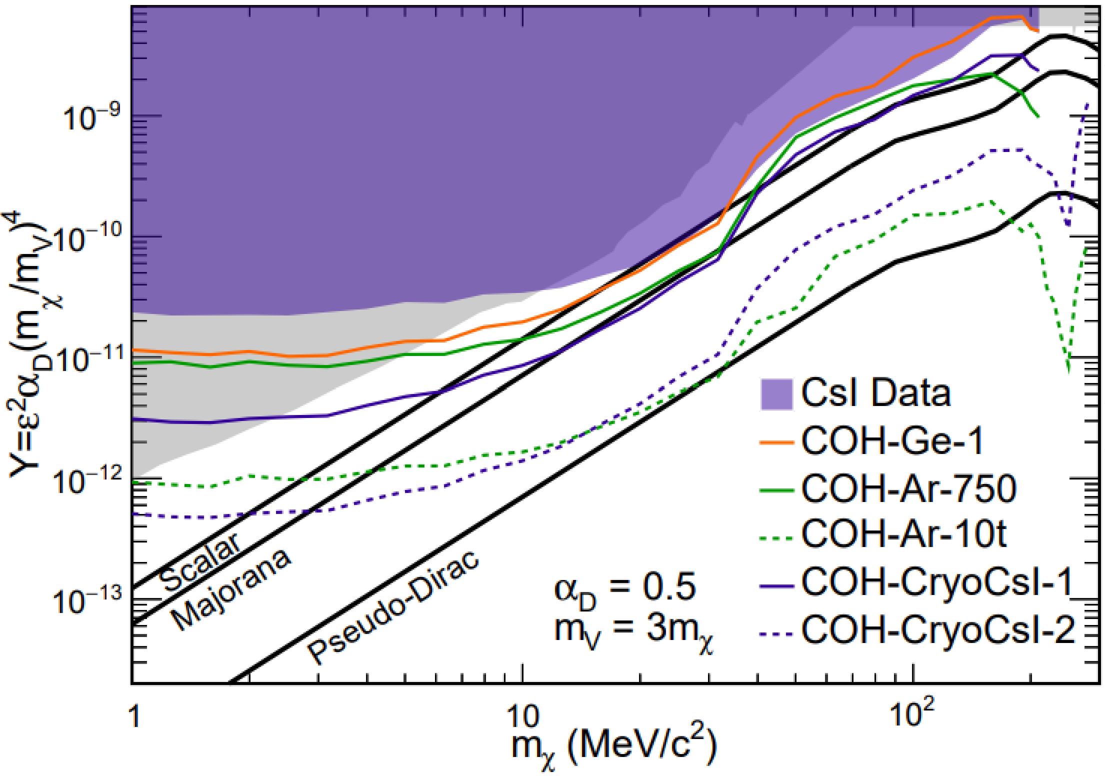
- CEvNS
- Hidden-sector dark-matter
- Neutrino-quark non-standard interactions (NSI)

- Light mediator (also NSI)
- Neutron radius
- Sterile neutrino
- Supernova neutrino
- Weak mixing angle
- Neutrino magnetic moment

Great courtesy of Dan Pershey

Sensitivities on hidden-sector DM

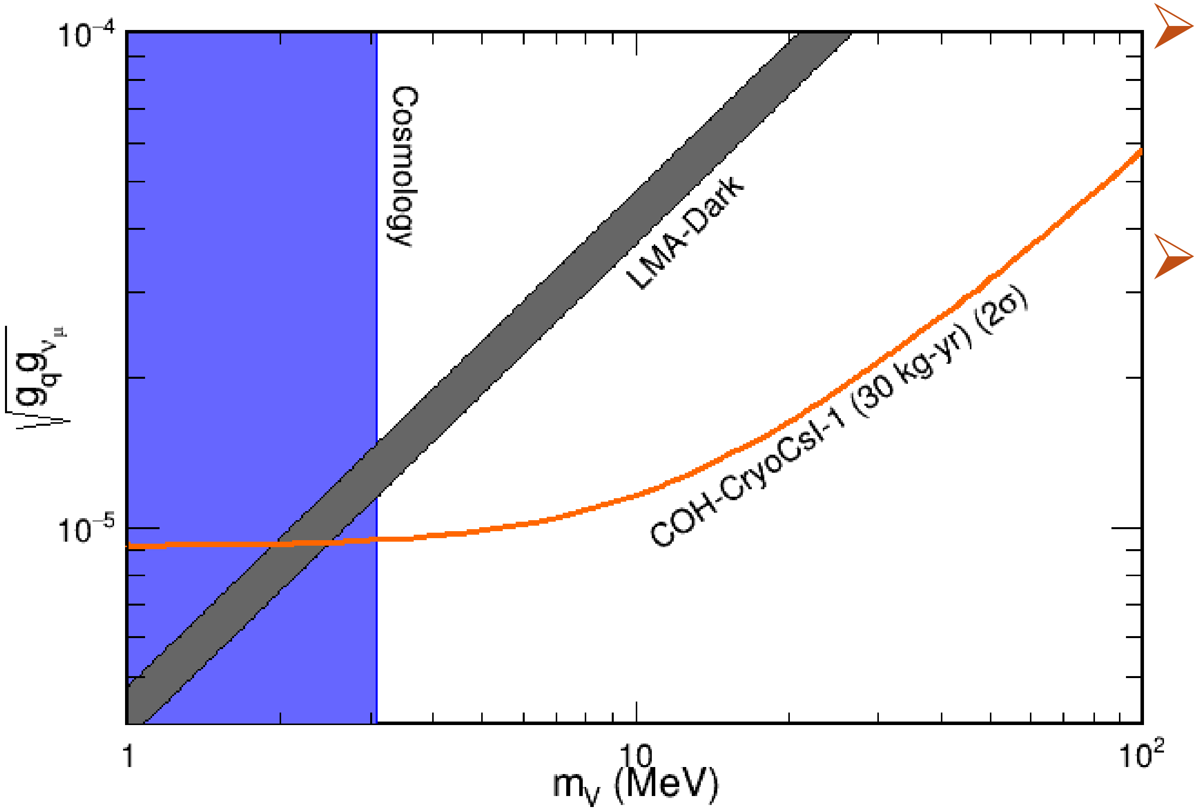
$$\pi^0 \rightarrow \gamma + V \rightarrow \gamma + \chi^\dagger + \chi$$



- **Dimensionless quantity (relates to the cosmological relic density of DM) as a function of hidden DM mass**
- **Three models: DM interactions with visible matter in the hot early Universe, explain the DM abundance today**

- **Observable: excess on CEvNS energy spectrum**
- **COH-Cryo-CsI-1 detector will explore some regions in the Scalar and Majorana models**
- **COH-Cryo-CsI-2 detector will explore most regions in the Scalar and Majorana models and some in the Pseudo-Dirac model**

Sensitivity on NSI



- ν_μ-coupled NSIs as a function of mediator mass
- LMA-Dark solution that would lead to wrong interpretations of the neutrino mass ordering, CP-violating phase, and mixing angles due to nontrivial NSI couplings

- Observable: enhancement or reduction on CEvNS energy spectrum
- COH-CryoCsI-1 will disfavor couplings above the orange curve
- Results before DUNE, T2HK, and JUNO!

Back up

CEvNS cross section in SM

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

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

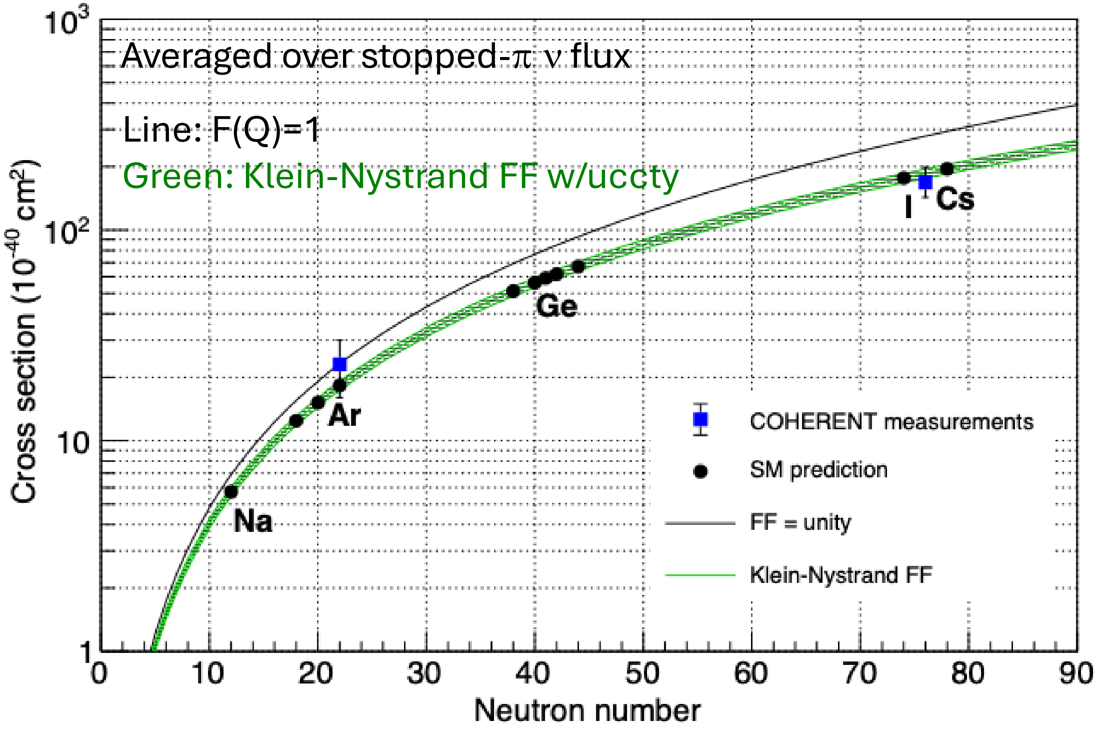
Form factor: F=1 ➔ full coherence

weak nuclear charge

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

$$\Rightarrow \boxed{\frac{d\sigma}{dT} \propto N^2}$$

Different target matters

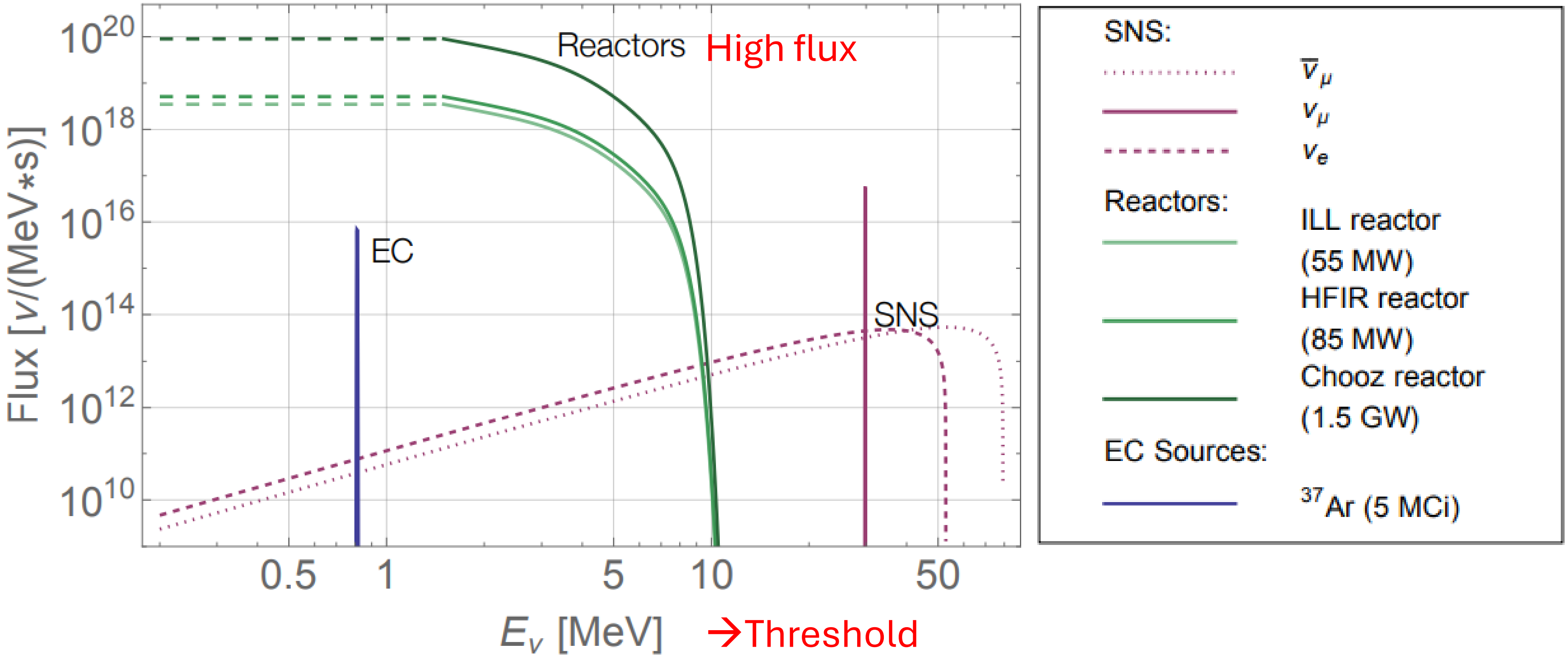


Averaged over stopped-π ν flux

Line: F(Q)=1

Green: Klein-Nystrand FF w/uccty

Neutrino sources for CEvNS detection

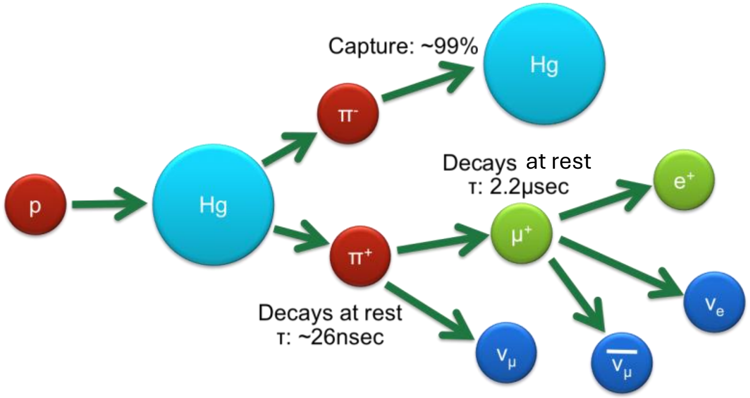


High flux

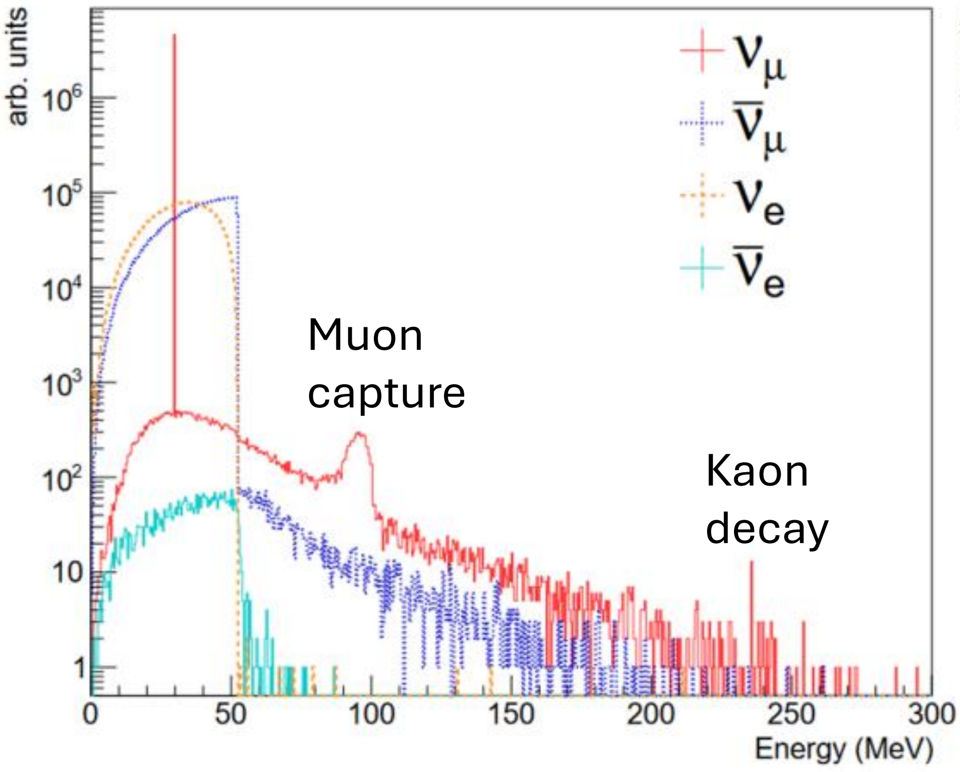
→Threshold

- **SNS:**
  - **Less stringent threshold, high background suppression**
- **Reactor:**
  - **higher flux, background issue**

Stopped-Pion (pDAR) Neutrinos

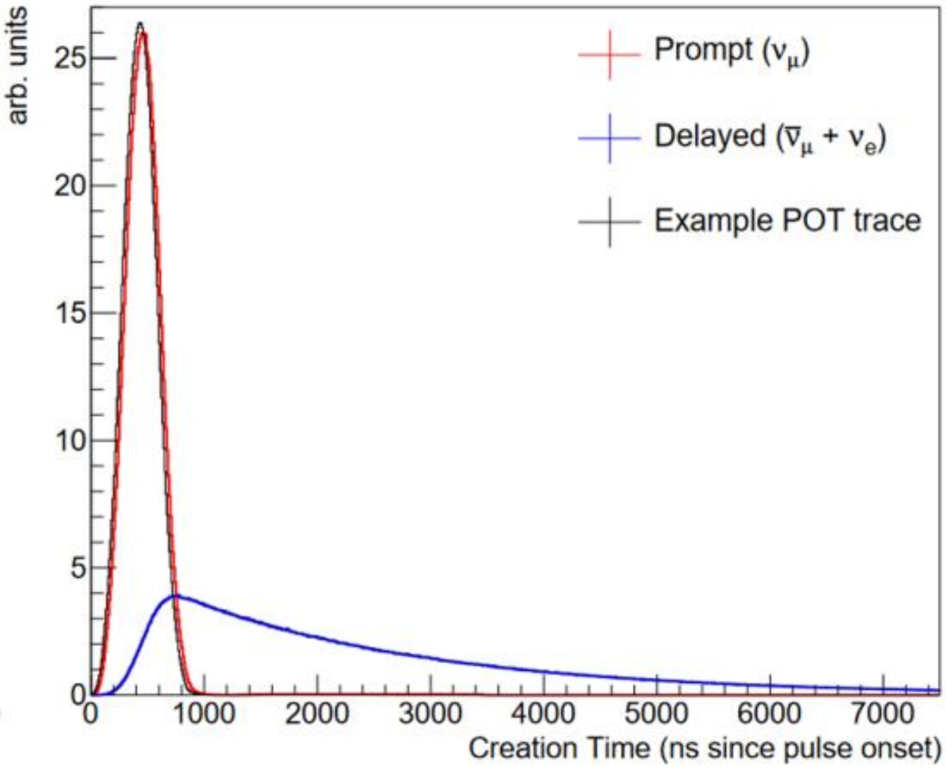


Distributions of neutrino energy (left) and creation time (right) produced at the SNS predicted by our Geant4 simulation

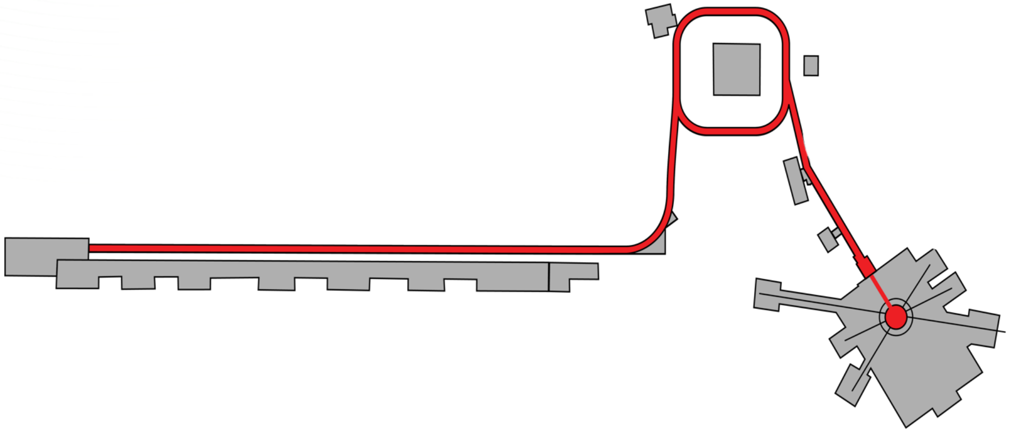


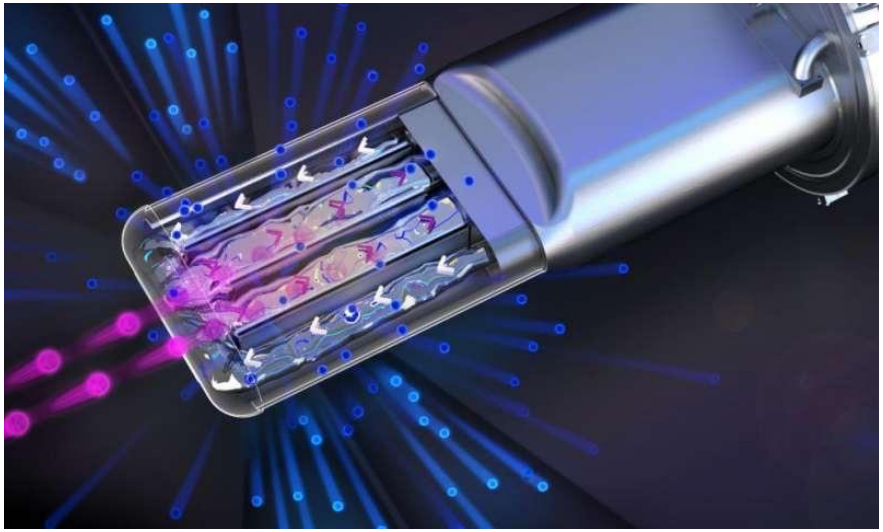
Muon capture

Kaon decay



Stopped-Pion (pDAR) Neutrinos

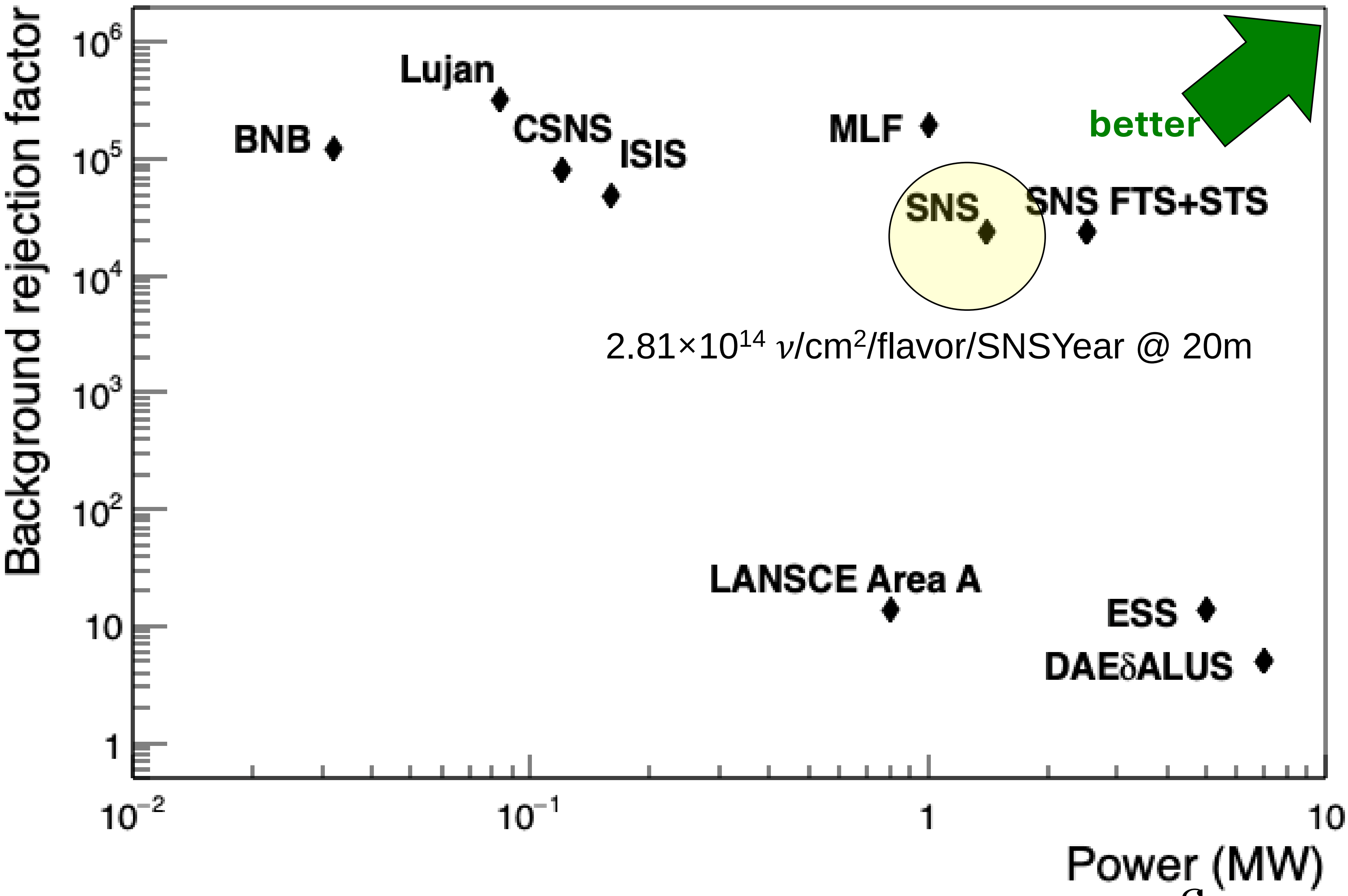




“Jet-flow” Target

- **Superconducting H^- LINAC: 1 GeV @ 1.4MW @ 60 Hz**
- **Storage Ring: 1200 pulses, 1us Period, 350ns FWHM; pulsed structure helps suppress background where reactor neutrinos don’t have this benefit**
- **Operation ~5000 hours per year**

Comparison of pDAR ν sources



2.81×10^{14} ν/cm^2/flavor/SNSYear @ 20m

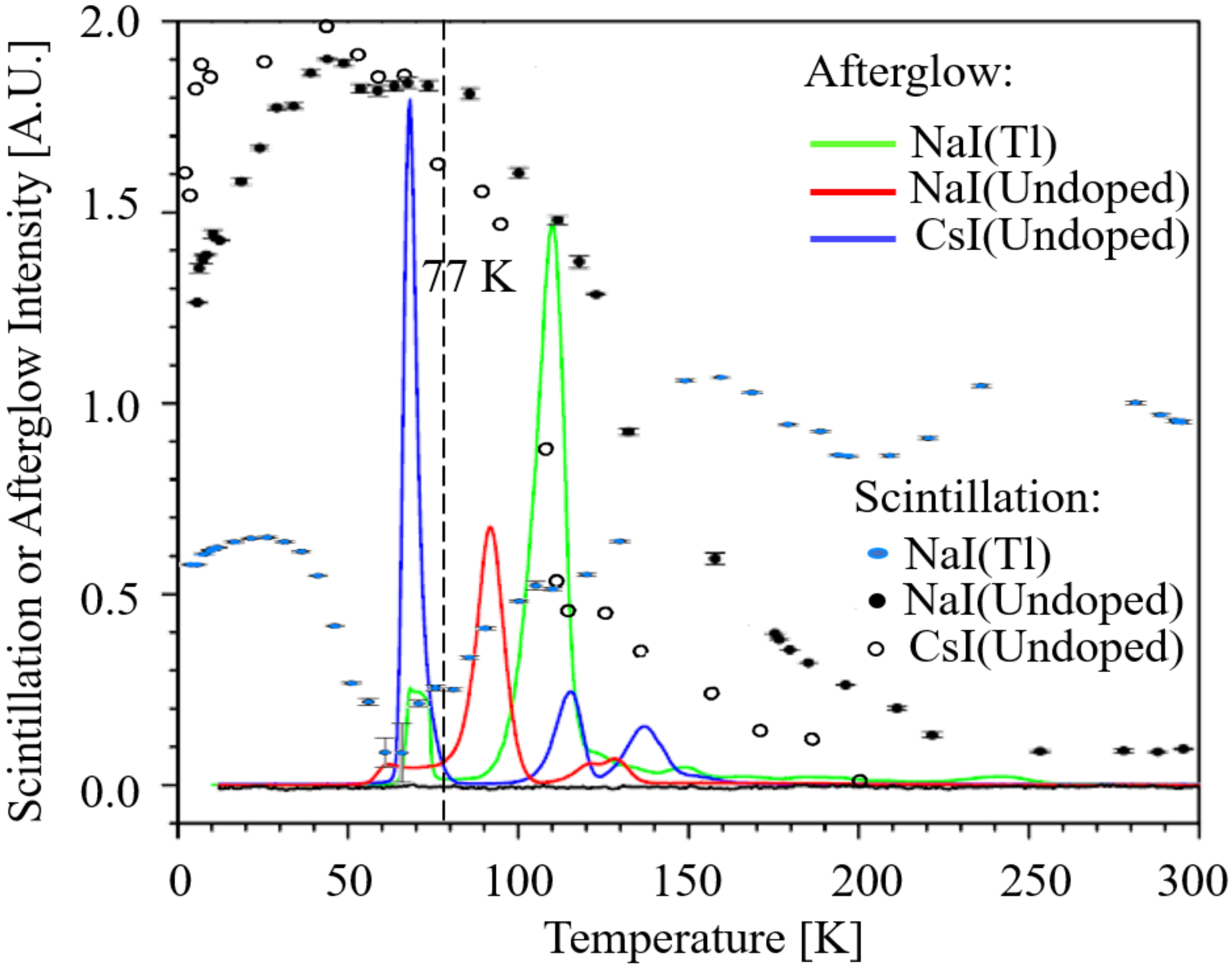
$\propto \nu$ flux

Cryogenic Undoped Scintillating Crystal

Astroparticle Physics 49 (2013) 44–51

Three ingredients:

CryoCsI = undoped CsI + SiPM arrays @ cryogenic temperature



Undoped CsI @ 40 K

- ➢ **Maximum light yield**
- ➢ **Minimum afterglow**

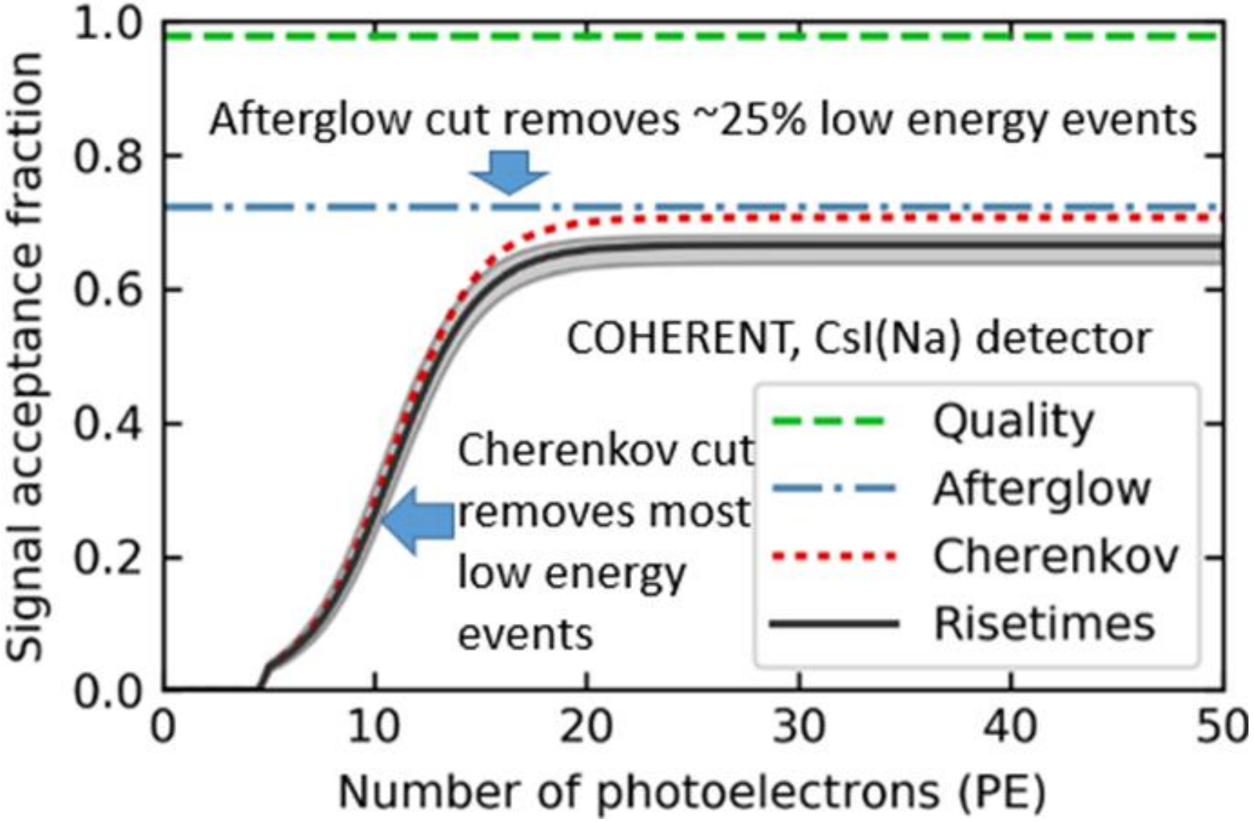
(a fraction of scintillation light that remains present for a certain time after the radiation excitation stops)

Cryogenic Undoped Scintillating Crystal

Science. eaao0990 (2017)

Three ingredients:

CryoCsI = undoped CsI + SiPM arrays @ cryogenic temperature



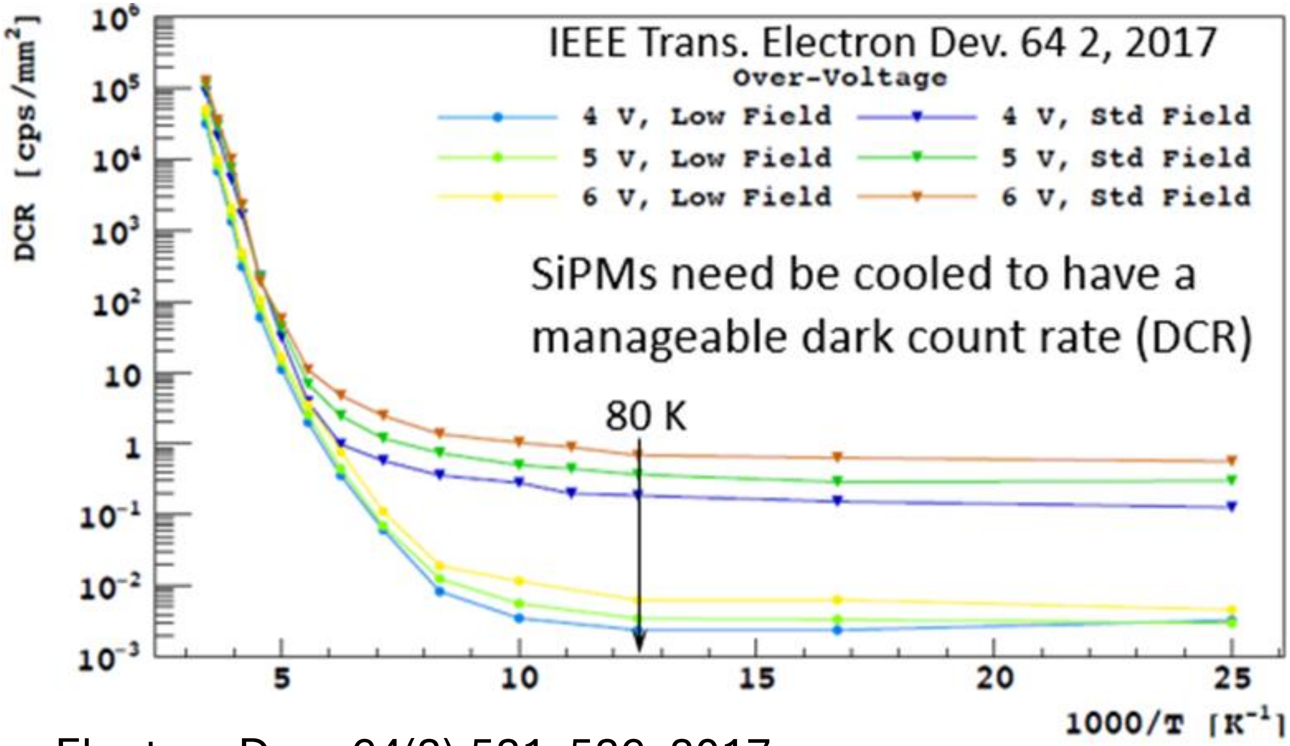
SiPM arrays

- ➢ **No quartz window, no worries of Cherenkov cut**

Cryogenic Undoped Scintillating Crystal

Three ingredients:

CryoCsI = undoped CsI + SiPM arrays @ cryogenic temperature



IEEE Trans. Electron Dev. 64 2, 2017

SiPMs need be cooled to have a manageable dark count rate (DCR)

80 K

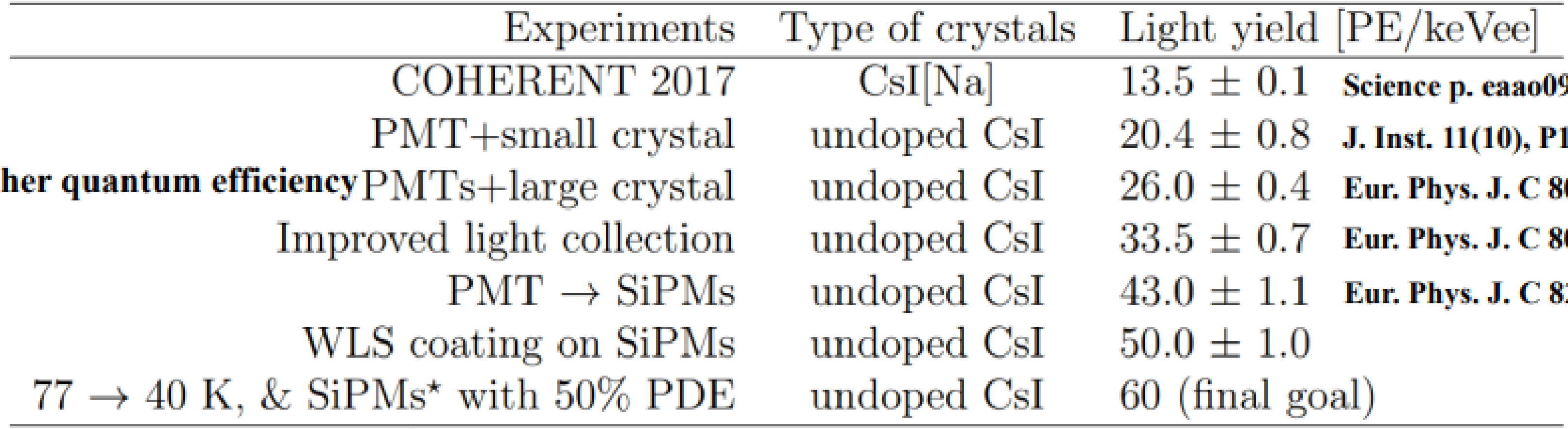
Electron Dev., 64(2):521–526, 2017

SiPM arrays at cryogenic T

- ➢ **Low dark count rate**

Development of CryoCsI

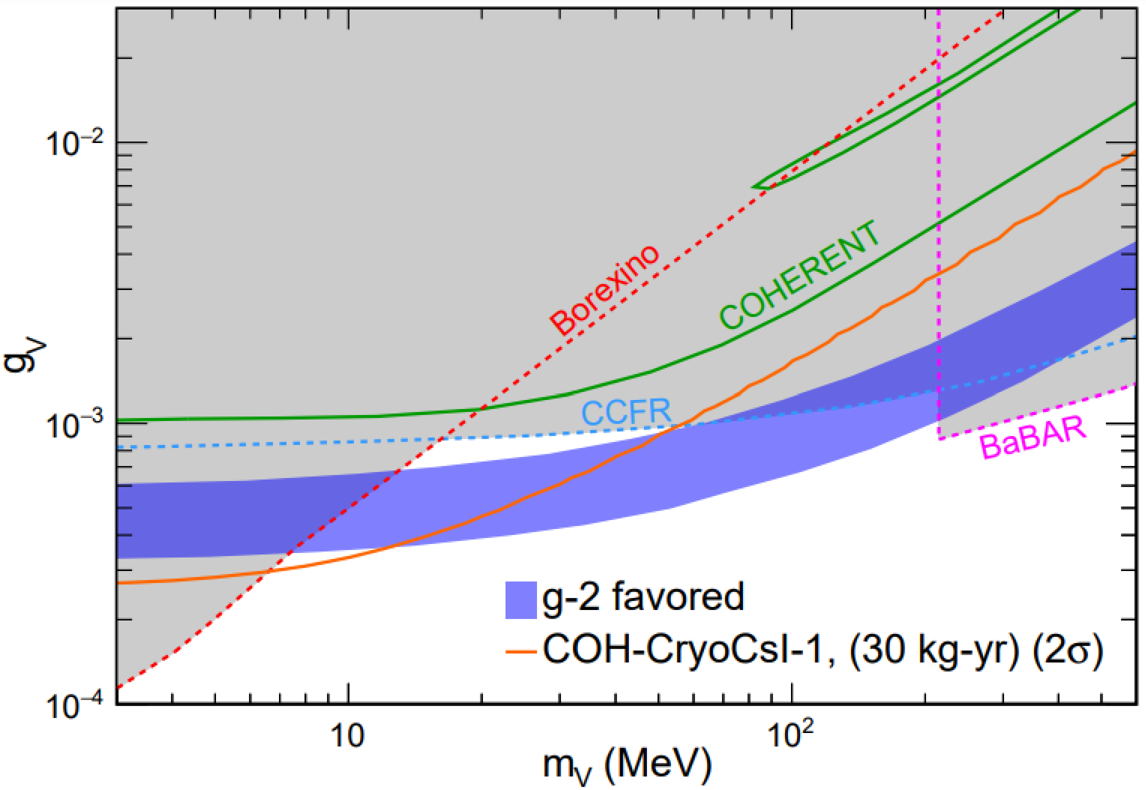
Summary of light yield improvement



	Experiments	Type of crystals	Light yield [PE/keVee]	
	COHERENT 2017	CsI[Na]	13.5 ± 0.1	**Science p. eaao0990 (2017)**
	PMT+small crystal	undoped CsI	20.4 ± 0.8	**J. Inst. 11(10), P10003 (2016)**
higher quantum efficiency	PMTs+large crystal	undoped CsI	26.0 ± 0.4	**Eur. Phys. J. C 80, 547 (2020)**
	Improved light collection	undoped CsI	33.5 ± 0.7	**Eur. Phys. J. C 80(12), 1146 (2020)**
	PMT → SiPMs	undoped CsI	43.0 ± 1.1	**Eur. Phys. J. C 82, 344 (2022)**
	WLS coating on SiPMs	undoped CsI	50.0 ± 1.0	
	77 → 40 K, & SiPMs* with 50% PDE	undoped CsI	60 (final goal)	

- **The responses to electron recoils of undoped CsI measured with PMTs**
- **The response to electron recoil of undoped CsI measured with SiPMs**
- **The responses of nuclear recoils of undoped CsI**
- **Designing a 10-kg prototype**

Sensitivity on BSM light mediators

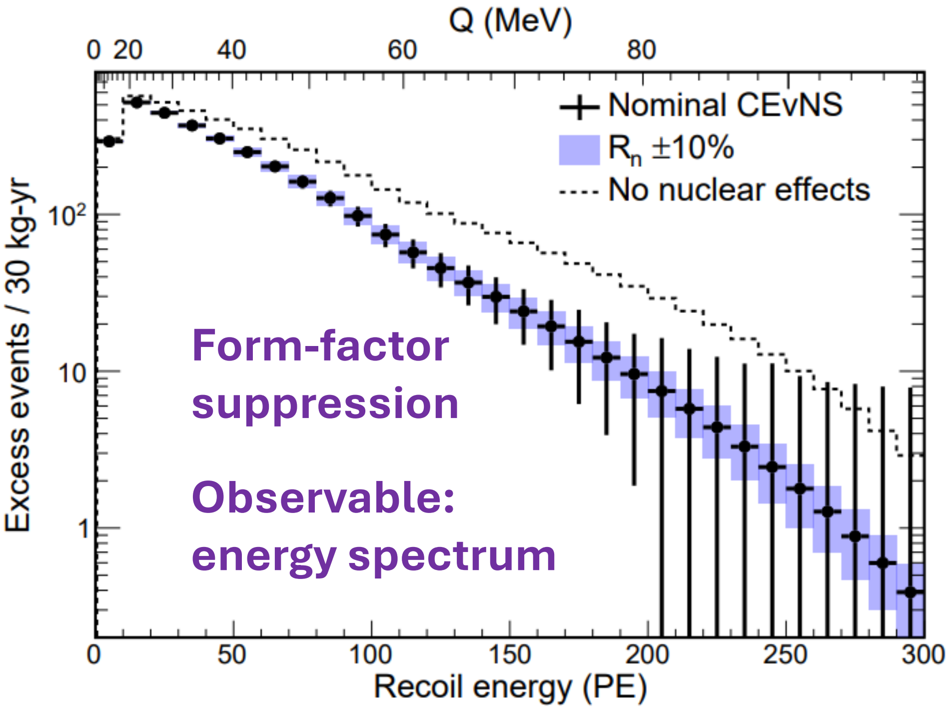


- $L_\mu - L_\tau$ **vector boson resulting in a U(1) dark-photon (V), which can explain dark matter and the neutrino masses**
- **g_V is the charge of the new force**

- **Observable: event rate**
- **COH-Cryo-CsI-I detector will test about half of the remaining parameter space which might explain the g − 2 anomaly**
- **COH-Cryo-CsI-II detector will almost completely exclude or confirm** $L_\mu - L_\tau$!

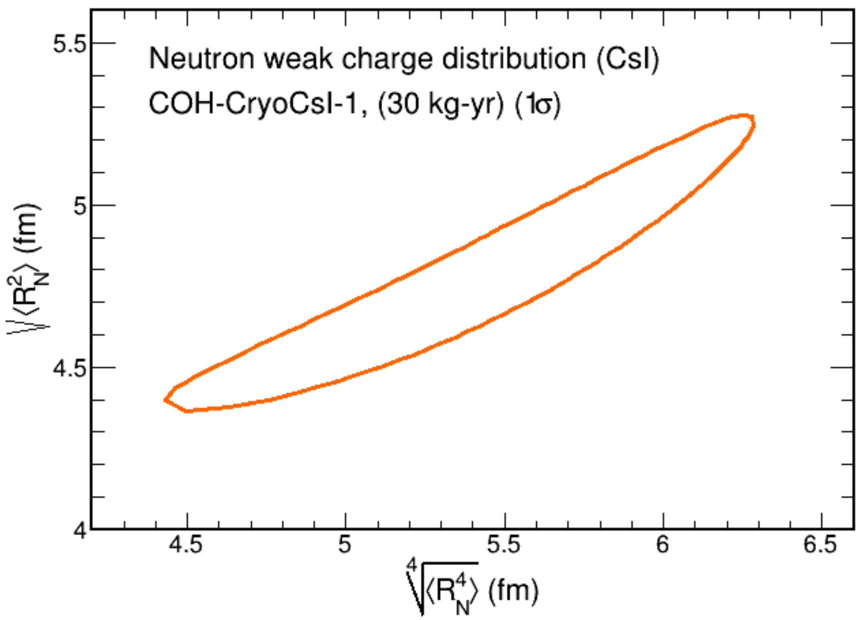
Mattia Atzori Corona's talk on Magnificent CEvNS 2023

Sensitivities on neutron radius



Form-factor suppression

Observable: energy spectrum



- **Left: CEvNS energy spectrum with/without nuclear effects**
- **Right: Neutron radius versus a term that relates to a quadratic in the expansion of the form factor**

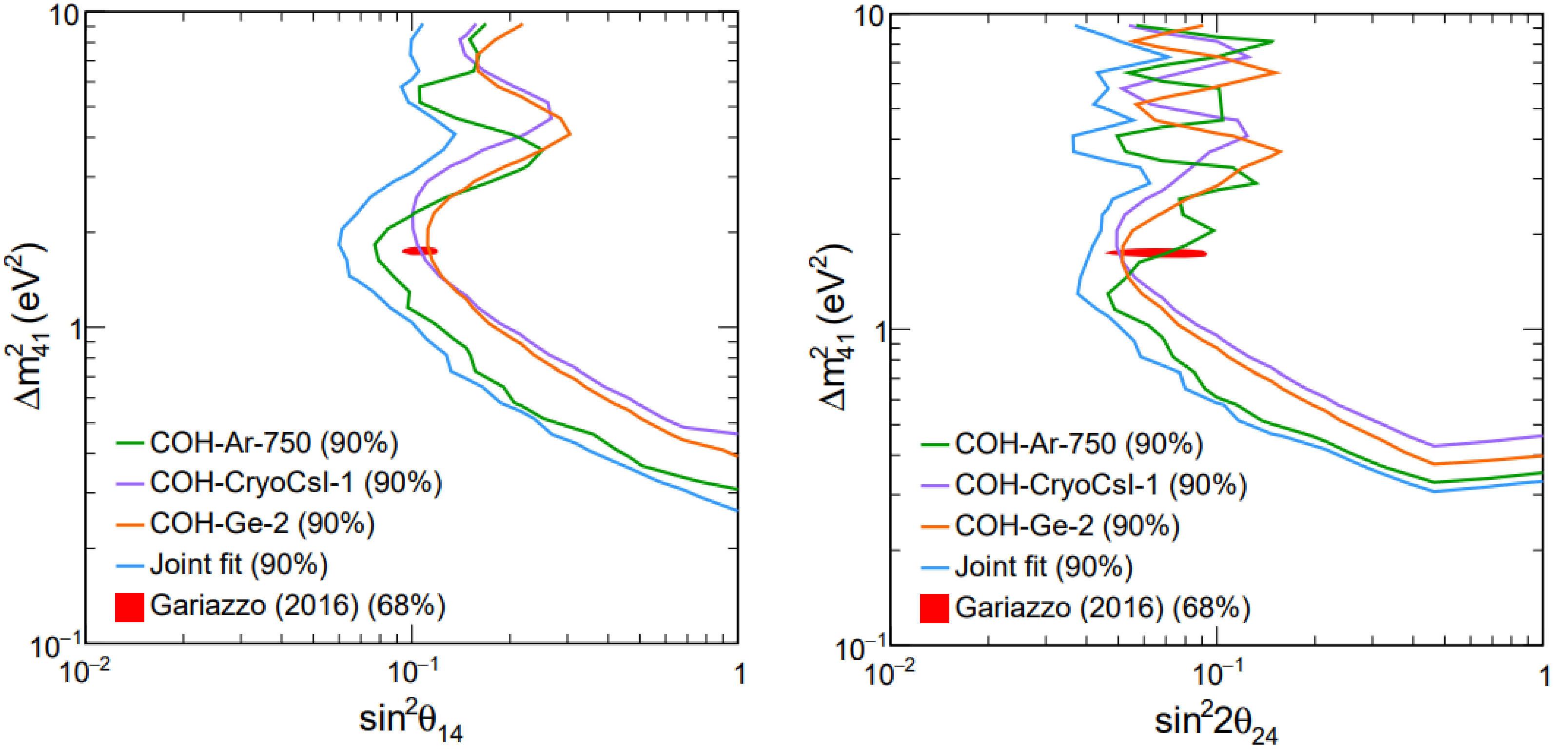
- **COH-Cryo-CsI-I: 2.9% precision on Rn**
- **COH-Cryo-CsI-2 : 0.5% precision on Rn**

Matteo Cadeddu’s talk on Magnificent CEvNS 2023

Sensitivities on sterile neutrinos

$$1 - P(\nu_e \to \nu_s) = 1 - \sin^2 2\theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

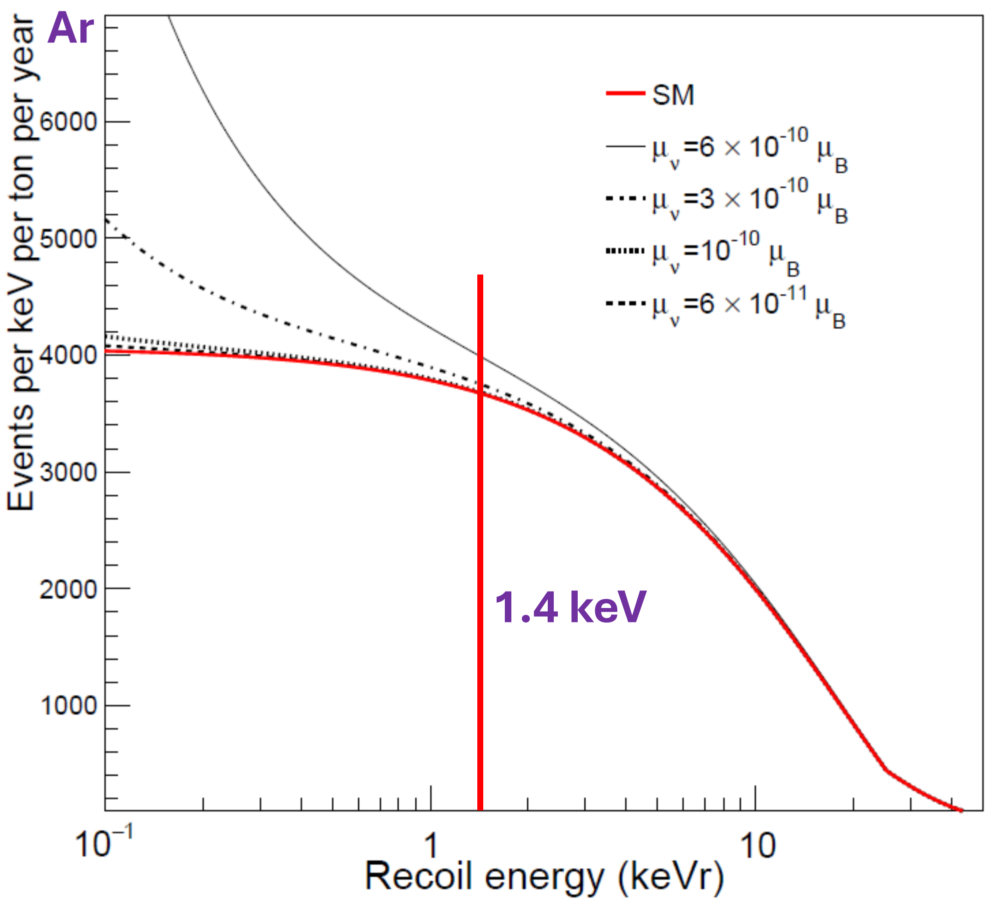
$$1 - P(\nu_\mu \to \nu_s) = 1 - \cos^4 \theta_{14} \sin^2 2\theta_{24} \cos^2 \theta_{34} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$



- **Observable: energy spectrum, evidence: low energy excess**
- **The mass differences versus the mixing angles**
- **Right top, excluded region**
- **Shadowed region, possible existence of sterile neutrinos**

Observable on magnetic moment

e.g. arXiv:1505.03202, 1711.09773, 2207.05036



- **Non-zero neutrino magnetic moment modifies CEvNS event rate at low energies**
- **Current limit: LZ and XENONnT**
- **All assuming the same amount of signal detected, nu_eff means three flavors contribution, nu_e means only nu_e contributes**

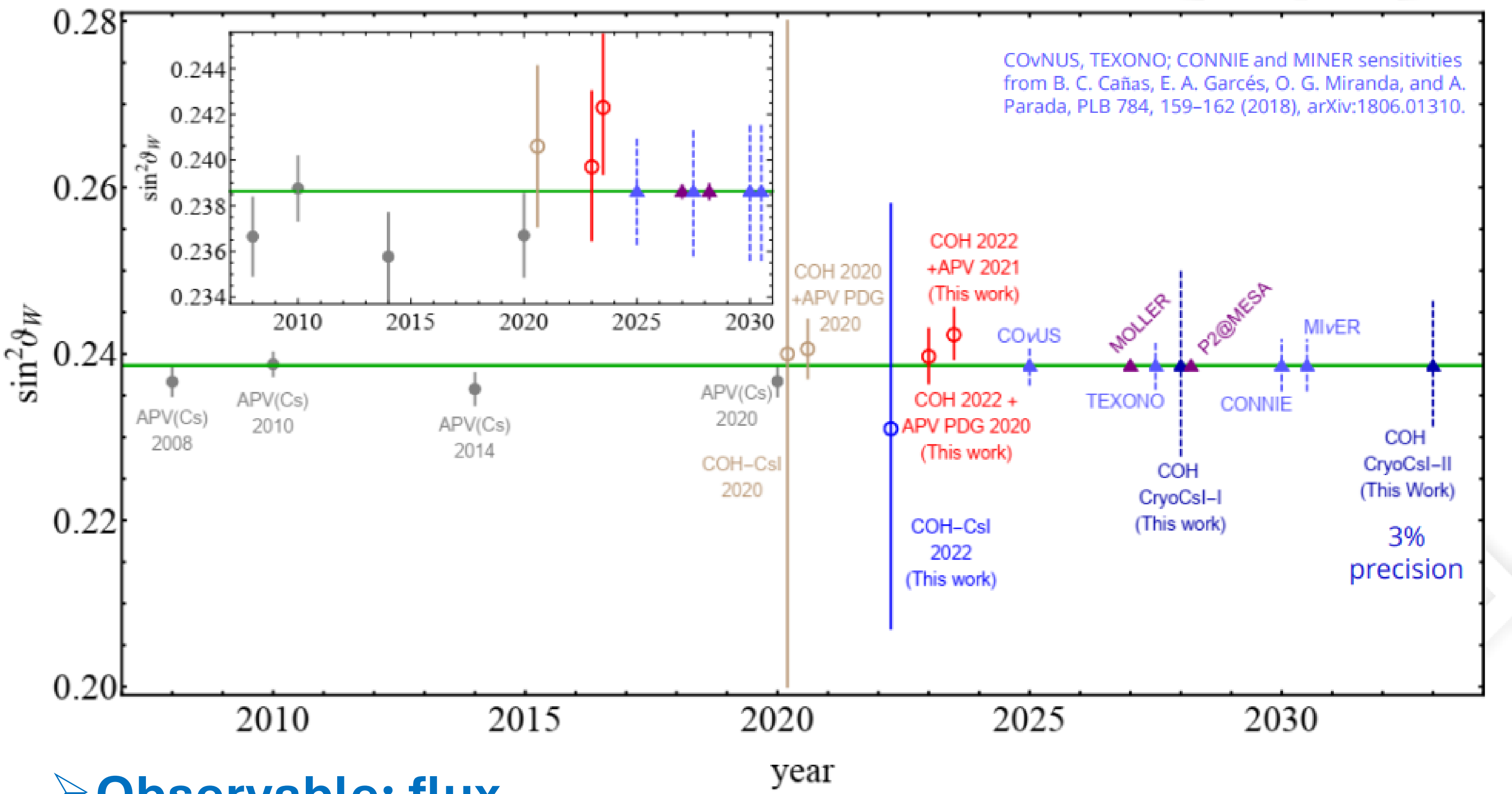
$$\mu_\nu = \frac{3 e_0 G_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3.2 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B ,$$

	$\lvert\mu_\nu\rvert [\times 10^{-11} \mu_B]$	$q_\nu\ [\times 10^{-13} e_0]$	
		FEA	EPA
ν_{eff}	< 1.1	[-3.0, 4.7]	[-1.5, 1.5]
ν_e	< 1.5	[-3.6, 6.5]	[-2.1, 2.0]
ν_μ	< 2.3	[-8.9, 8.8]	[-3.1, 3.1]
ν_τ	< 2.1	[-8.1, 8.1]	[-2.8, 2.8]

Matteo Cadeddu’s talk on Magnificent CEvNS 2023

COHERENT Snowmass whitepaper

Sensitivities on weak mixing angle



COνNUS, TEXONO; CONNIE and MINER sensitivities from B. C. Cañas, E. A. Garcés, O. G. Miranda, and A. Parada, PLB 784, 159–162 (2018), arXiv:1806.01310.

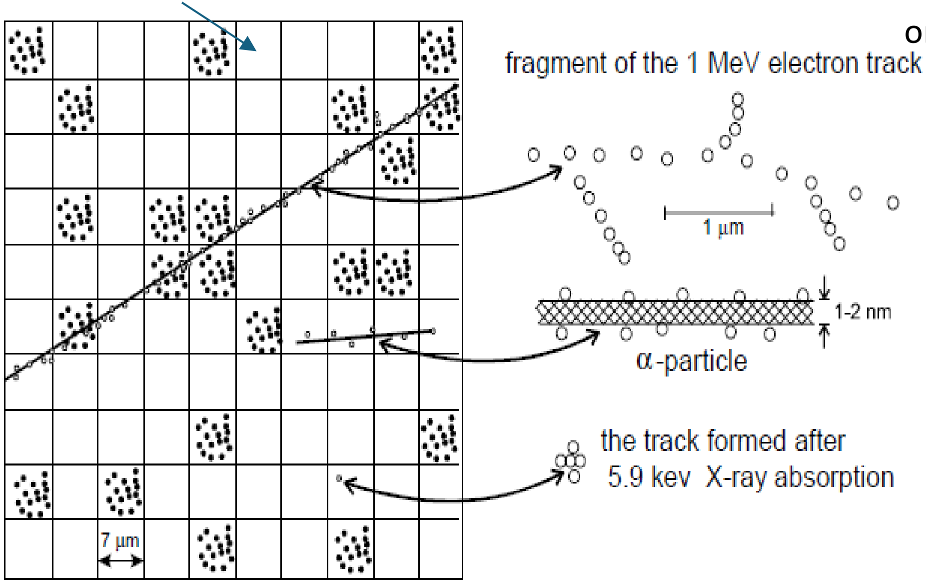
- **Observable: flux**
- **COH-Ge-2 is more sensitive**
- **Joint fit of COH-Ar-750, COH-CryoCsI-1, and COH-Ge-2 give 2.1% precision**

BRIT. J. APPL. PBYS., 1966, VOL. 17

Track length & quenching

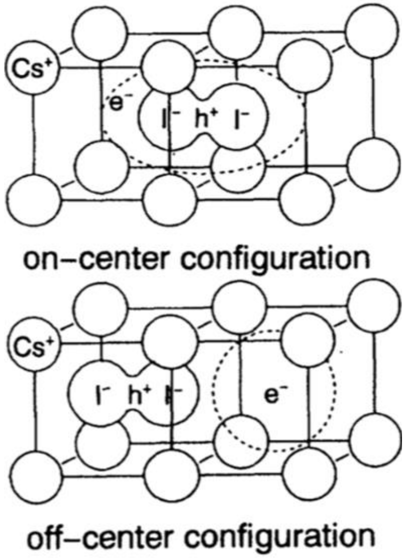
For doped crystals:
rely on dopants

Dopants (scintillation centers)



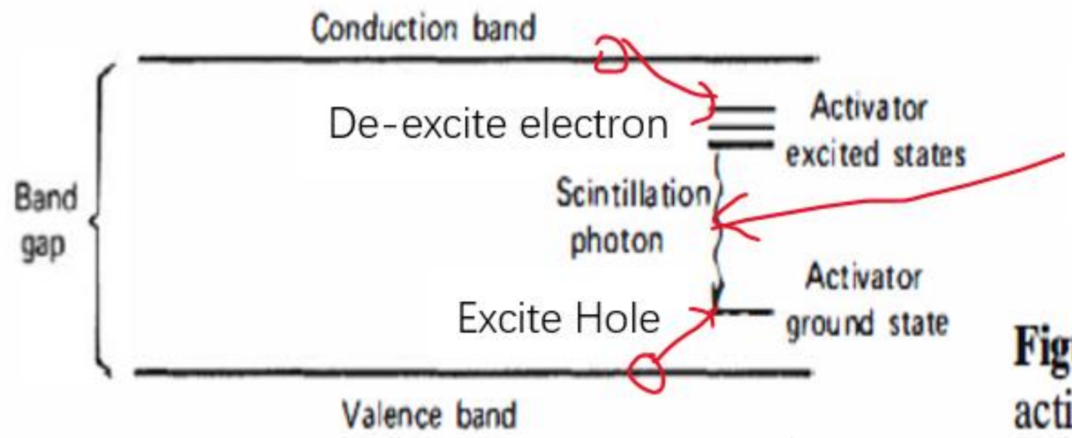
For undoped crystals:

Scintillation centers are self-trapped holes, which are everywhere in the crystal. The light yield should not depend on the track length as strong as that in doped crystals.



Right temperature, if it’s too hot, lattice vibrating tends to shake off ions; if it’s too cold, ions freeze and stay, holes don’t have enough energy to pull them together

Scintillation mechanism



Photon energy is smaller than the band gap energy so it escapes.

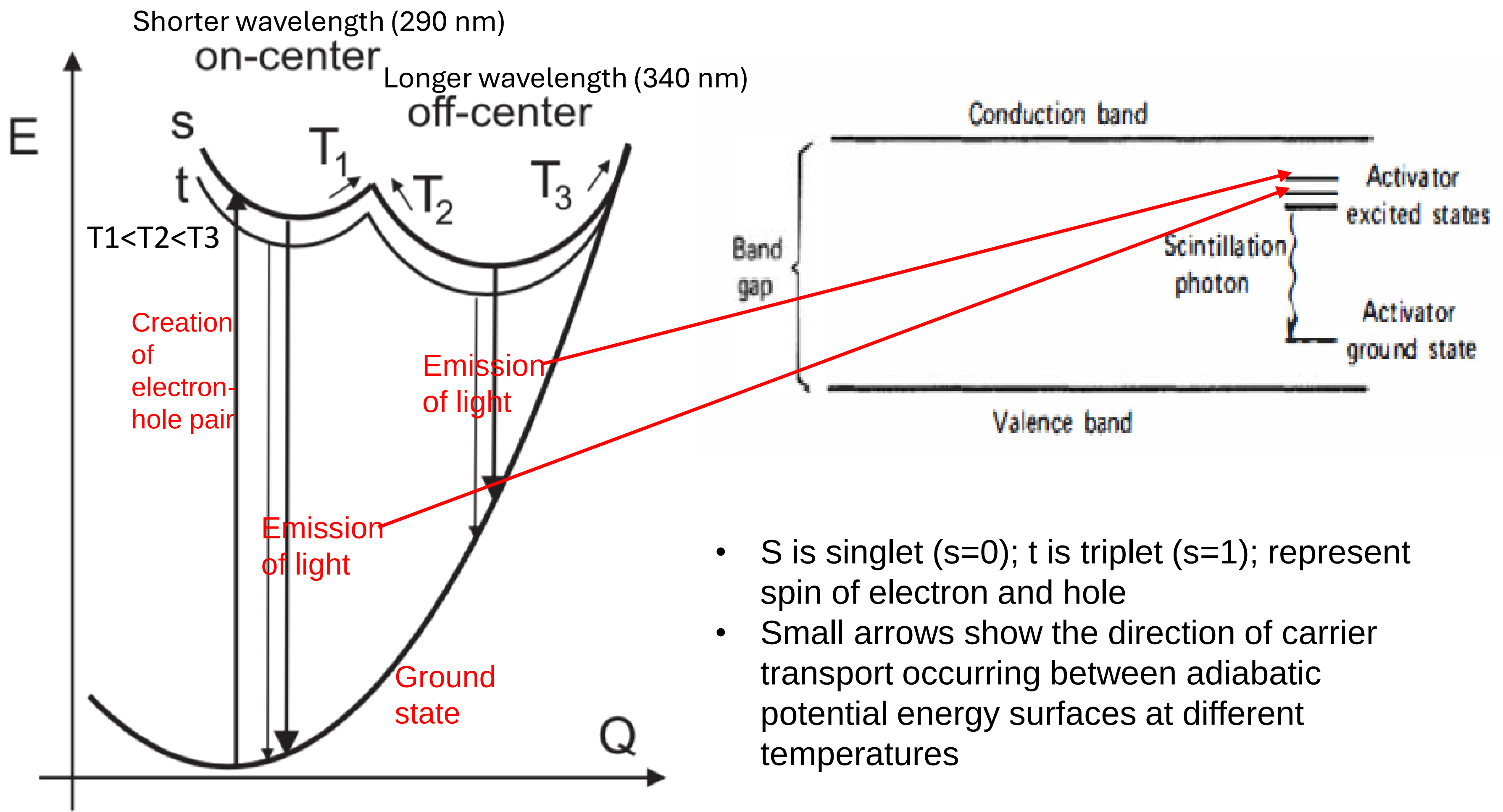
Figure 8.6 Energy band structure of an activated crystalline scintillator.

(No free moving electrons)

Only escaped scintillation photons can be seen.

Recoils (electrons or nuclei) ionize atoms. Electrons ionized out of atoms move around and lose energy gradually. A portion of free electrons and holes may have some chance to drop into the luminescence center. The recombination of electrons and holes creates scintillation light.

H. Nishimura, M. Sakata, T. Tsujimoto, and M. Nakayama. Origin of the 4.1-eV luminescence in pure CsI scintillator. Phys. Rev. B, 51(4):2167, 1995.



V. B. Mikhailik, *et al*. physica status solidi (b), 252(4):804, 2015

- S is singlet (s=0); t is triplet (s=1); represent spin of electron and hole
- Small arrows show the direction of carrier transport occurring between adiabatic potential energy surfaces at different temperatures