Coherent Neutrino-Nucleus Elastic Scattering with Reactor and Solar Neutrinos

- Complementarities in νA_{el} among ν-sources
  - ☑ physics
  - ☑ Experimental Requirements
- Projects with Reactor and Solar ν's
  - ☑ Solar: LXe Experiments
  - ☑ Reactor: Variety of Techniques & Locations
- Prospects & Outlook

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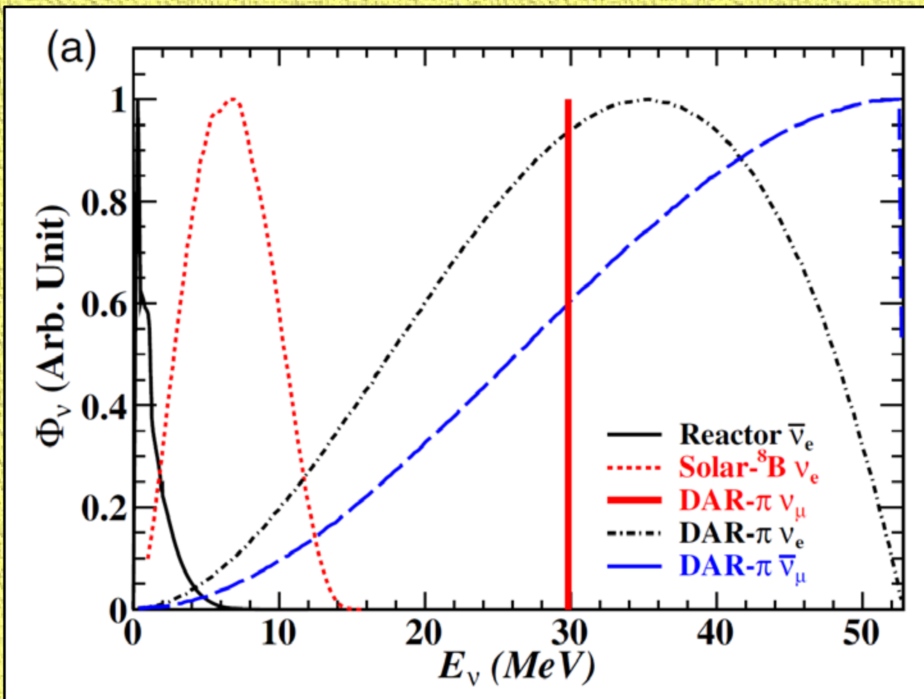
Sources: Input from Various Experiments and/or Slides/Papers in Public Domains

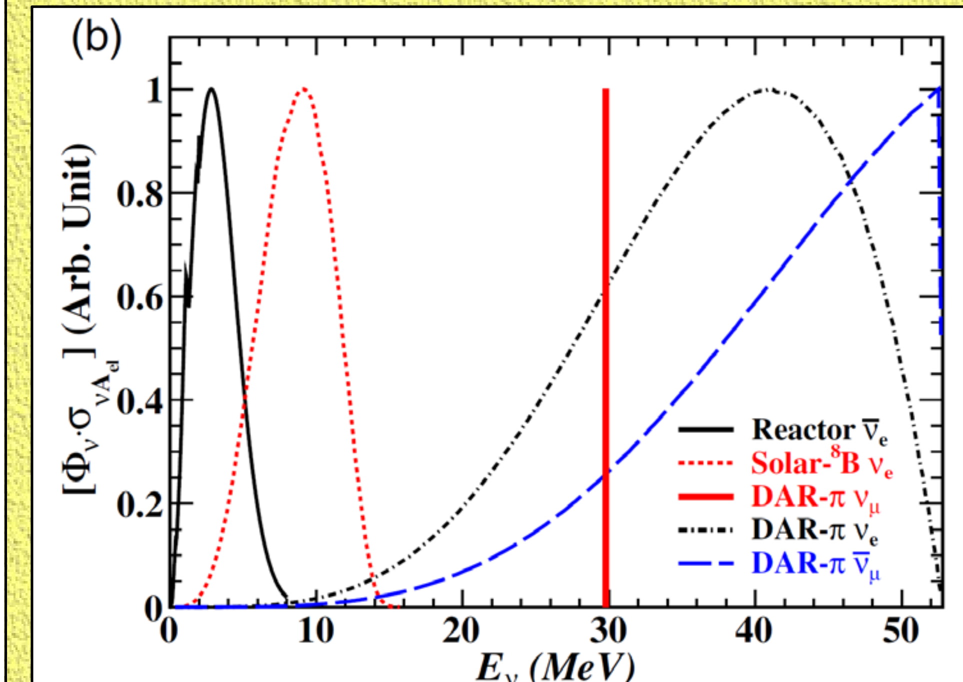
Observation of νA Elastic Scattering by COHERENT@π-DAR-ν *[Science-2017, 1st talk this Session]* set the stage for asking finer questions & with diverse techniques *[the shapes and shades of "fireworks"…]*

- Potentials on BSM/NSI *[next talk]*, nuclear physics form factors, astrophysics, applications …….
- Characterize Dependence on q^2, E_ν & Target (Z,N), manifested as
  - ☑ $FF(q^2) < 1$
  - ☑ Cross-sections "do not scale as $[N-Z(1-4\sin^2\theta_W)]^2$"
  - ☑ QM coherency transition – Quantify with "decoherence angle $\langle\phi\rangle$" *[PRD16]*

$$(\alpha \equiv \cos \langle\phi\rangle \in [0,1])$$

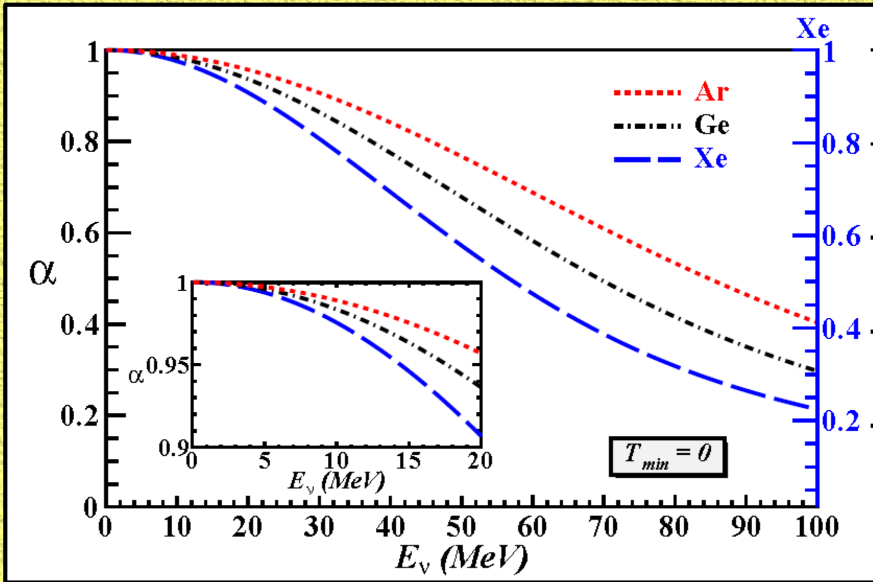
Different ν-Sources (E_ν) Probe Complementary Kinematical Regions

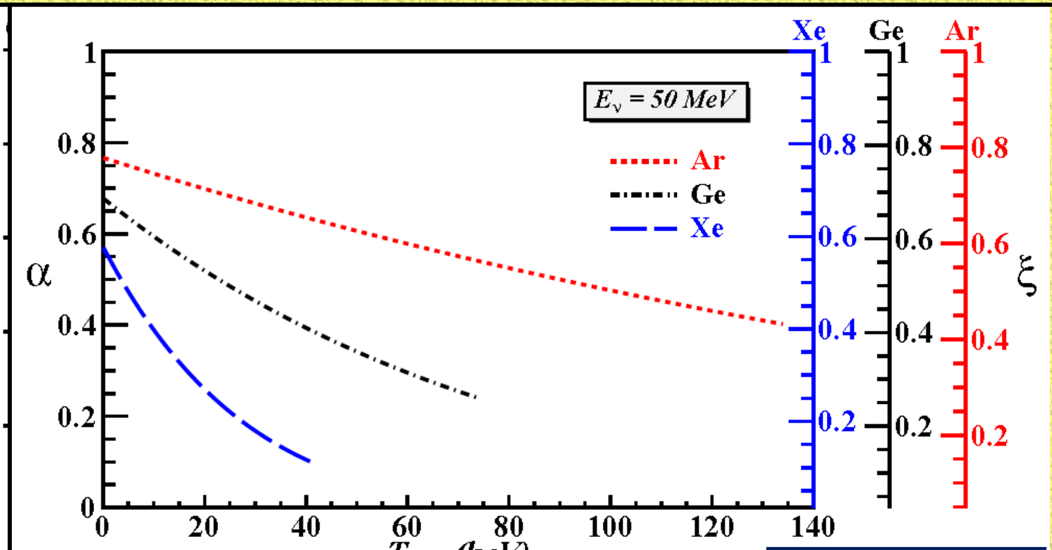




ν-Spectra

$\sigma(\nu A_{el})$ weighted ν-Spectra





ξ - Cross-section Ratio relative to Full Coherency

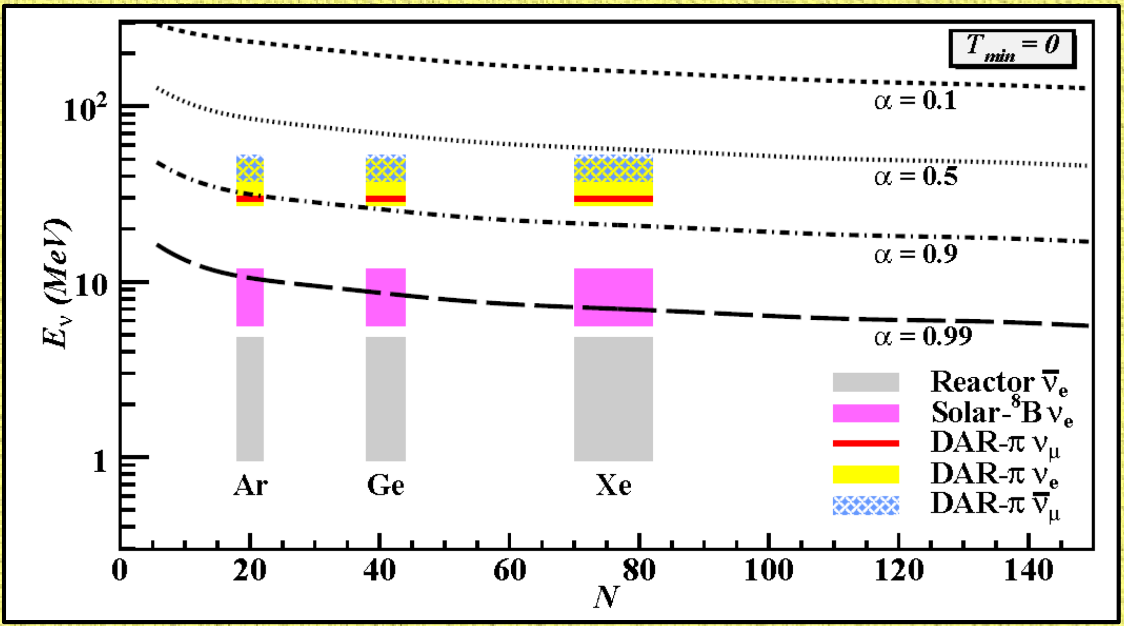
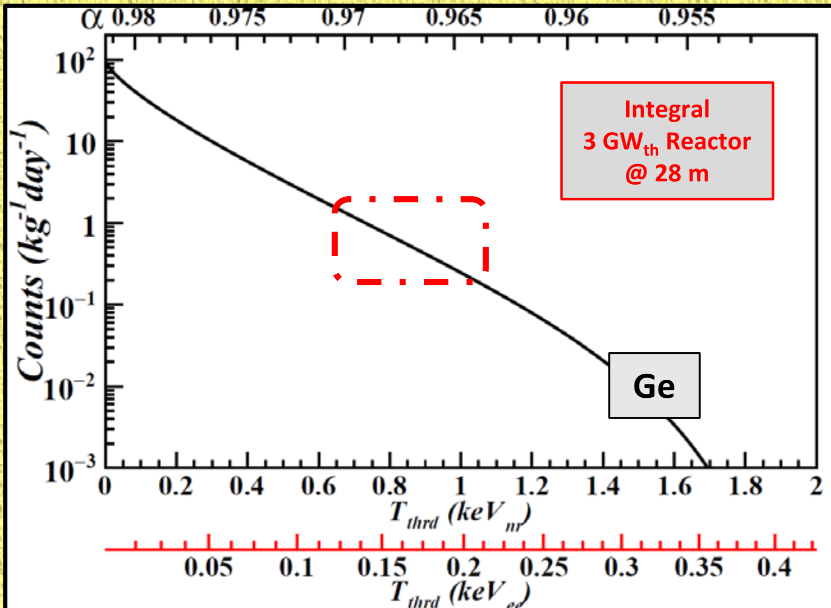
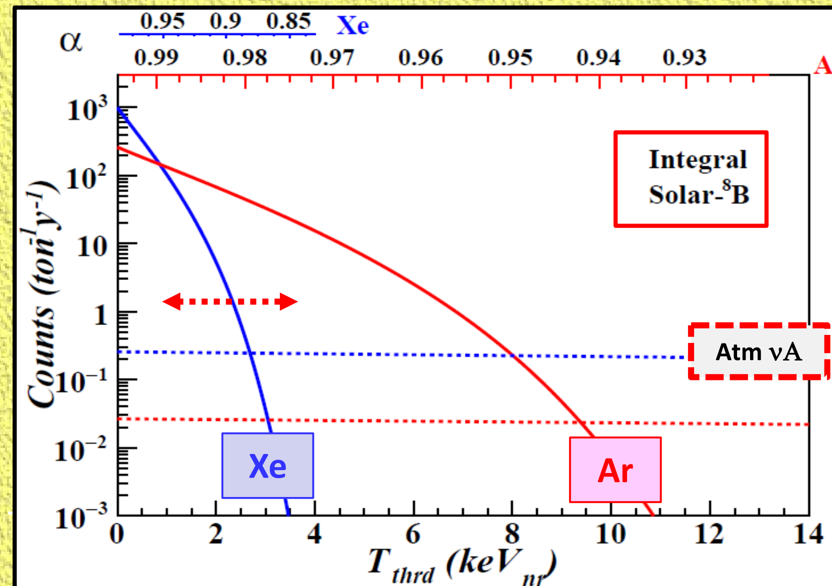


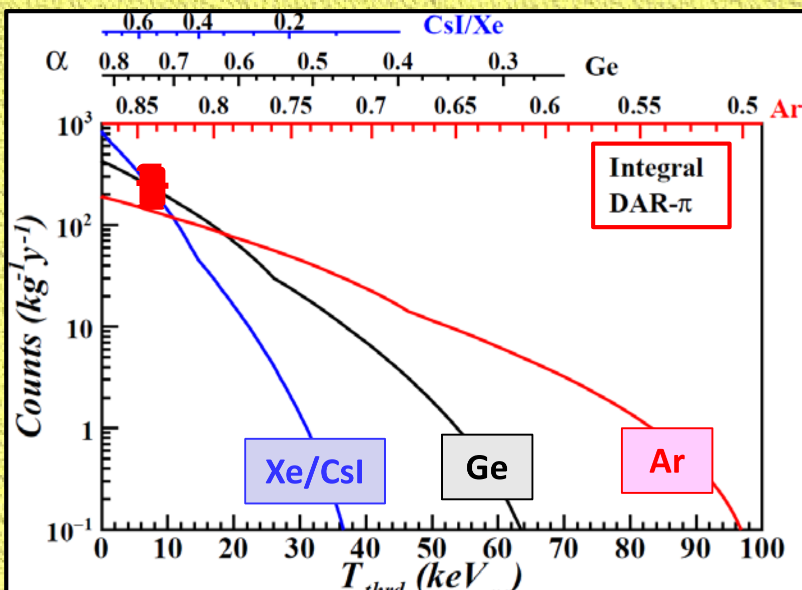
TABLE II: The half-maxima in the distributions of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$ at T_{min}=0 for the different neutrino sources, and the values of $\langle\alpha\rangle$ probed by the selected target nuclei. The ν_μ from DAR-π is mono-energetic.

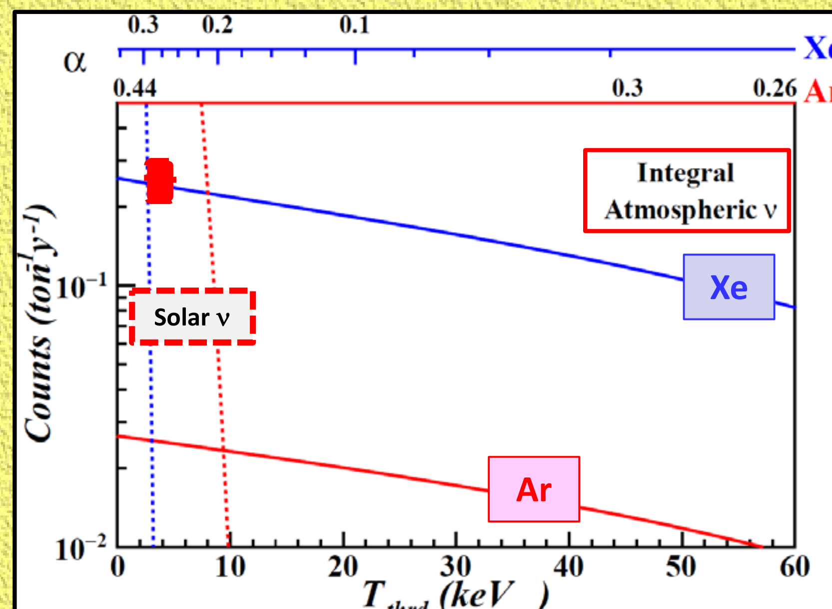
ν Source	Half-Maxima of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$ in E_ν(MeV)	$\langle\alpha\rangle$ with Ar	Ge	Xe
Reactor $\bar{\nu}_e$	0.96−4.82	1.00	1.00	1.00
Solar-^{8}B ν_e	5.6−11.9	0.99	0.99	0.98
DAR-π ν_μ	29.8	0.91	0.86	0.80
DAR-π ν_e	27.3−49.8	0.89	0.83	0.76
DAR-π $\bar{\nu}_\mu$	37.5−52.6	0.85	0.79	0.71

Measureable (Recoil Energy, Event Rate, α) Scales for νA_{el} from ν-Sources



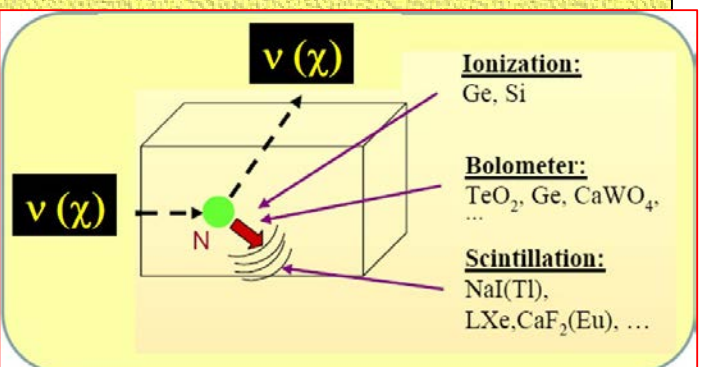


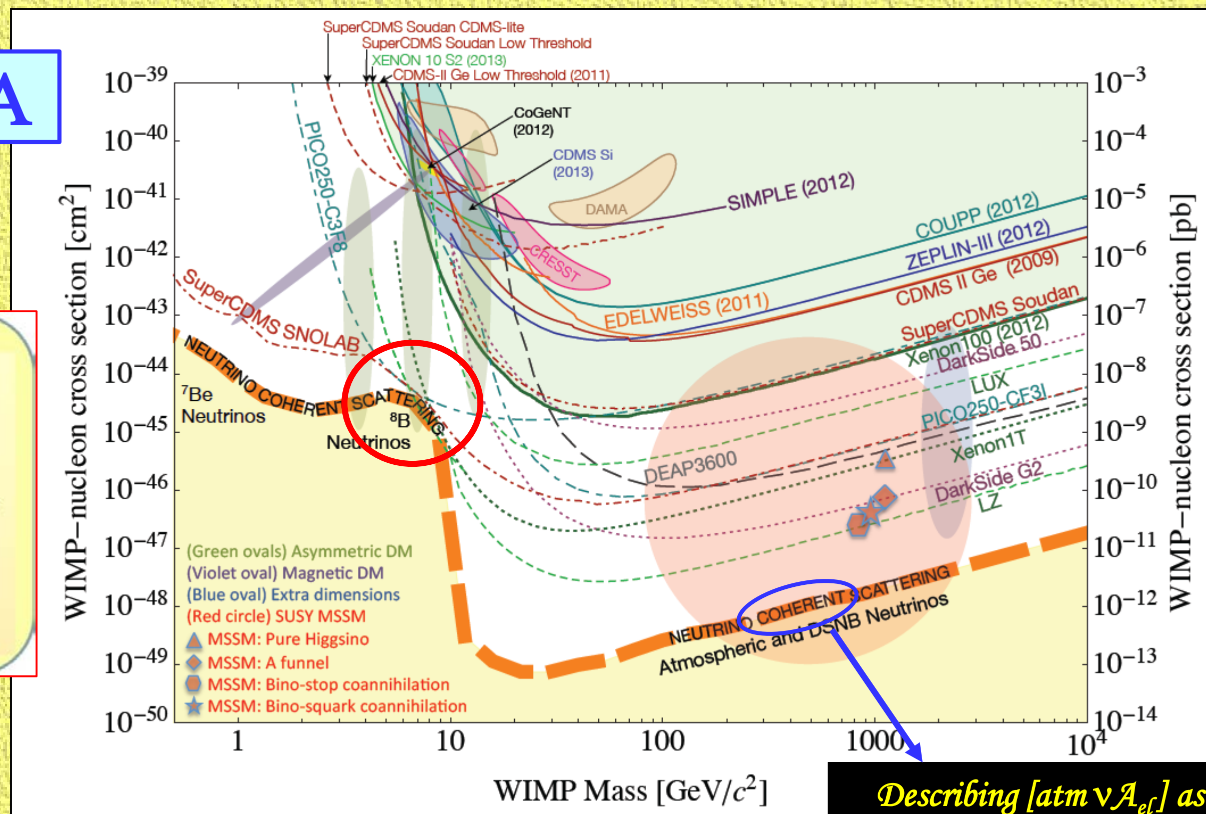




- νA_{el} from Solar & Atmospheric ν's constitute the "neutrino floor" (irreducible background) to WIMP searches
- νA & χA projects share common techniques and challenges
- Next(+) Generation (of LiqXe) Projects close to the required sensitivities for ^{8}B solar-ν
- Surmounting this "background" – directional sensitivities

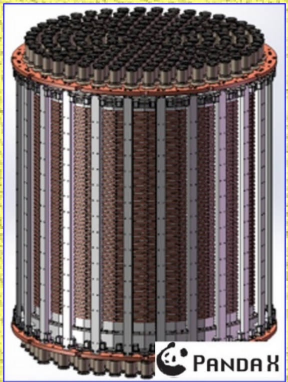
$$\nu(\chi) + A \rightarrow \nu(\chi) + A$$





Describing [atm νA_{el}] as "Coherent" is inaccurate

Next(+) Generation Large Liq-Xe Experiments …



Next: **PandaX-4T** (4-ton target)

- ☑ @ CJPL
- ☑ Fiducial mass 2.8 ton, threshold 5 keVnr,
- ☑ Background NR~1 /ton-year
- ☑ Neutrino CNNS: 0.3/ton-year
- ☑ On-site assembly and commissioning: 2019-2020

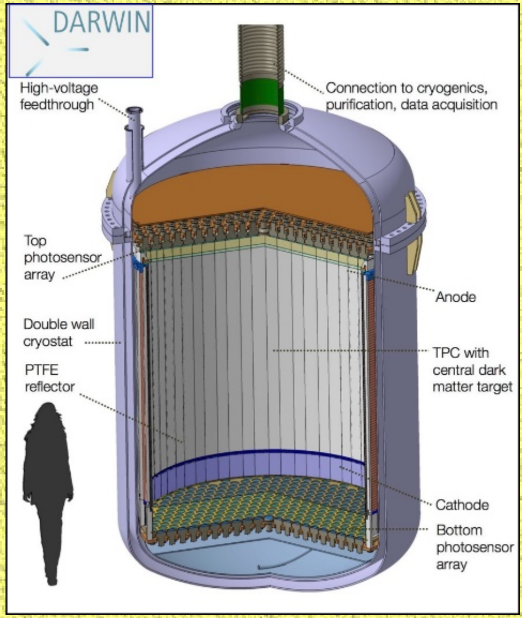
Poster ν–18

Total mass – 10 T
WIMP Active Mass – 7 T
WIMP Fiducial Mass – 5.6 T

- ☑ @ SURF
- ☑ threshold 6 keVnr,
- ☑ Background NR~0.6/1000days
- ☑ Neutrino CNNS: ~0.7/1000days
- ☑ Commissioning: 2019

144 cm drift TPC
Total: 8 000 kg
Target: **6 000** kg
Fiducial: 4 500 kg

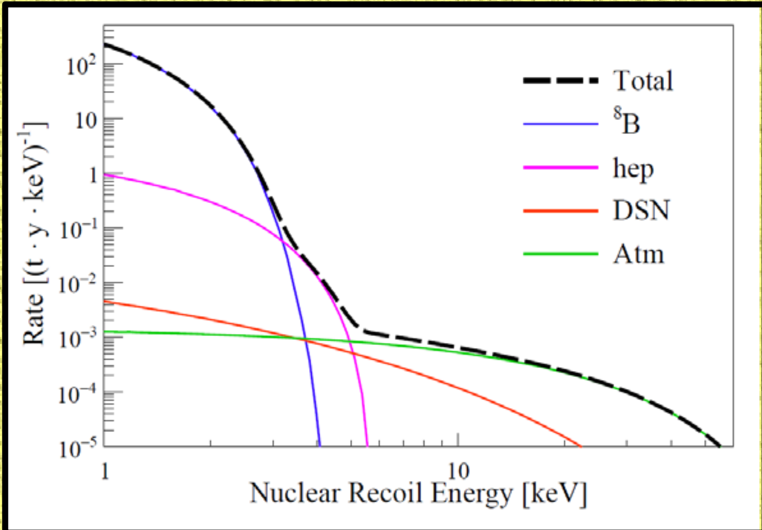
- ☑ @ Gran Sasso
- ☑ threshold 4 keVnr,
- ☑ Background NR~2.5/20 ton-yr
- ☑ Neutrino CNNS: ~4.7/20 ton-yr
- ☑ Operation: 2019-2025



DARWIN Project (2025+)

- ☑ Detector filled with 50 t LXe, 40 t in the TPC (2.6 m electron drift, 2.6 m diameter)
- ☑ Light sensors: PMTs, SiPM arrays, …
- ☑ Shields: large water Cherenkov, and neutron veto
- ☑ Background goal: dominated by neutrinos
- ☑ threshold 4 keVnr
- ☑ ~10 years data taking

Prospects of Observing solar νA_{el} in Xe …



Expectation values of events in XENONnT, in 20 t·y exposure	No discrimination	99.75% ER discrimination
Signal (μ_s)		
6 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	0.68	0.27
10 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	4.65	1.86
100 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-48}$ cm^2)	7.13	2.85
1 TeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	8.85	3.54
Background		
Total ER (μ_{bER})	1000	2.5
NR from neutrons	-	-
NR from CNNS (μ_{bNR})	11.8	4.7

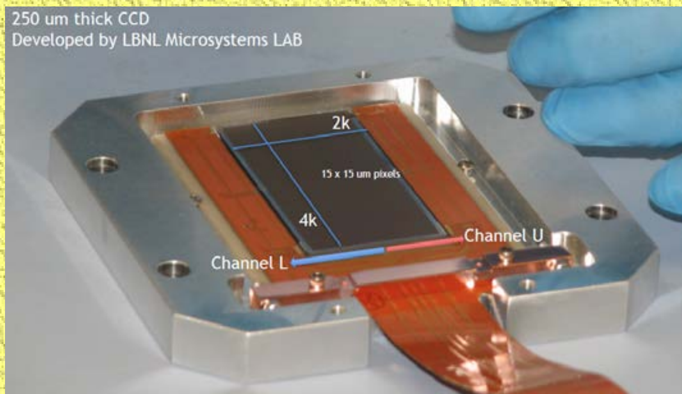
☑ Typical threshold for Liq-Xe experiments with "(S1,S2)" for ER/NR differentiation is light yield corresponding to "averaged" <~4 keVnr>, nominally too high for solar νA_{el}

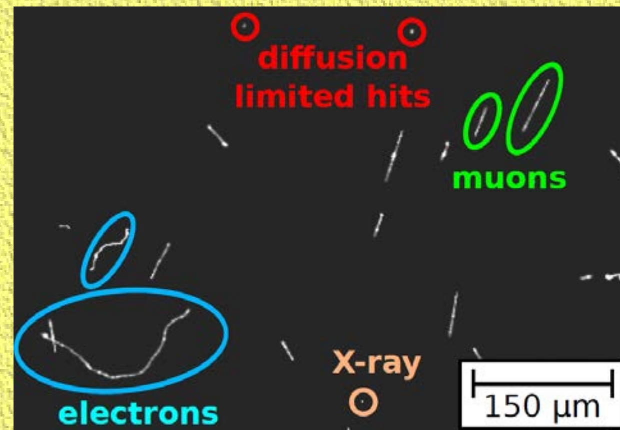
- ➢ Large spread in event-wise *keVnr⬄light yield* conversion (Poisson, energy resolution, fiducial non-uniformity) ⇒ thorough understanding necessary
- ➢ Observable 0.2-0.3 events / ton-year *(~5 events in 20 t-y XE-nT ; ~100 events in 400 t-y DARWIN)*

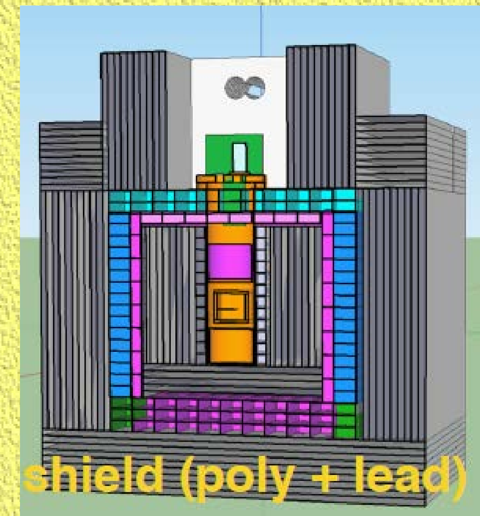
☑ "S2-Only" has lower "<~1 keVnr>" threshold , rates much larger *(~90 events / ton-year)* ; but no ER/NR discrimination ⇒ suppression & understanding of ER background crucial

Thanks: Consultation with K. Ni & L. Baudis

….. @ Angra II 3.8 GW Power Reactor







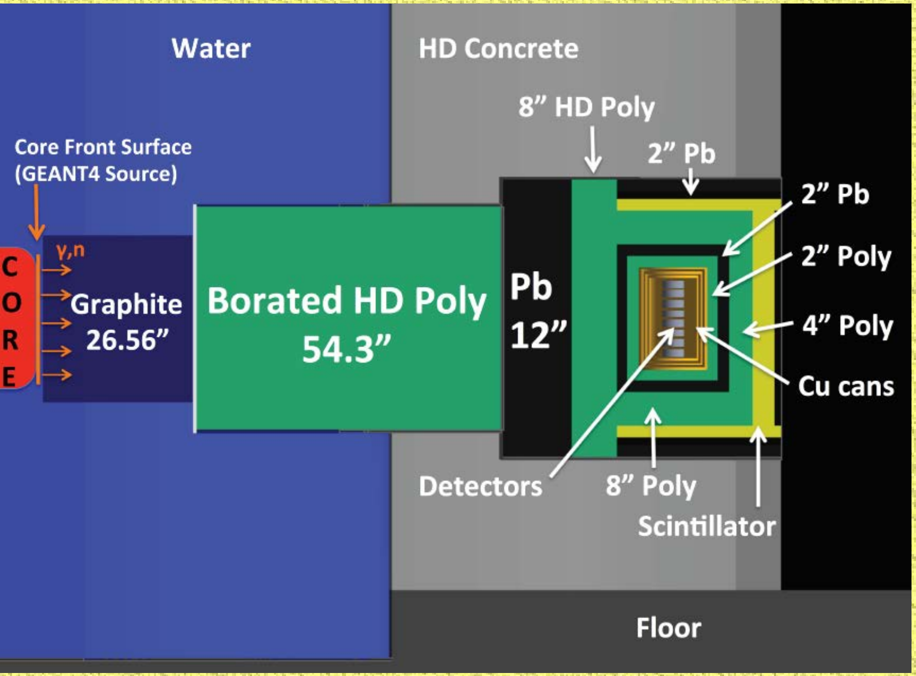
- ☑ 3.8 GW MW Research Reactor ; 30 m distance
- ☑ Advanced CCD (Si) detector ; ~40 eVee threshold ; Event ID capabiities

Expected number of events (event/kg/day)	
E_{th} = 5.5 eV (1σ_{RMS})	~ 28.3
E_{th} = 28 eV (5σ_{RMS})	~ 18.1

- ☑ Engineering Run, 1-g detector, completed and successful
- ☑ Data taking with O(100 g) detector.
- ☑ Challenges: Background, Long integration time, small mass …..

MIνER

….. @ TAMU ~MW Research Reactor

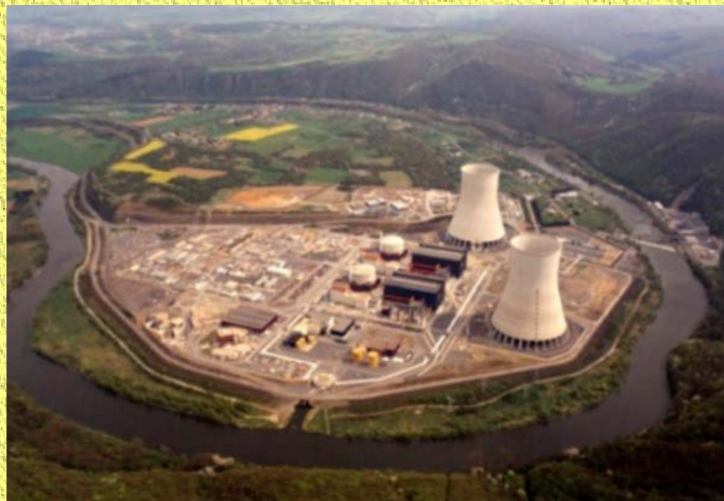


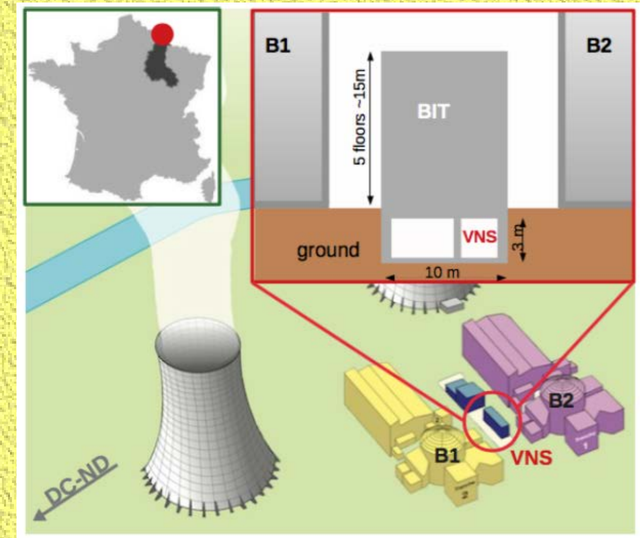
- ☑ 1 MW Research Reactor ; **2-3m distance!** ~15 mwe
- ☑ CDMSlite-type cryogenic detector (bolometric amplification); Ge/Si ; O(100 eVee) threshold demonstrated
- ☑ Rate: 1000 /kg-day at 10 eVnr threshold
- ☑ Moveable Core tests short baseline oscillation
- ☑ 10 kg payload with sensitivity to CNS in a month
- ☑ Challenges: Background, Long thermalization time …..

Status:

- Dilution fridge commissioned
- Have <1000/kg-keV-day in ROI. Goal ~ 100
- Engineering data taking late summer

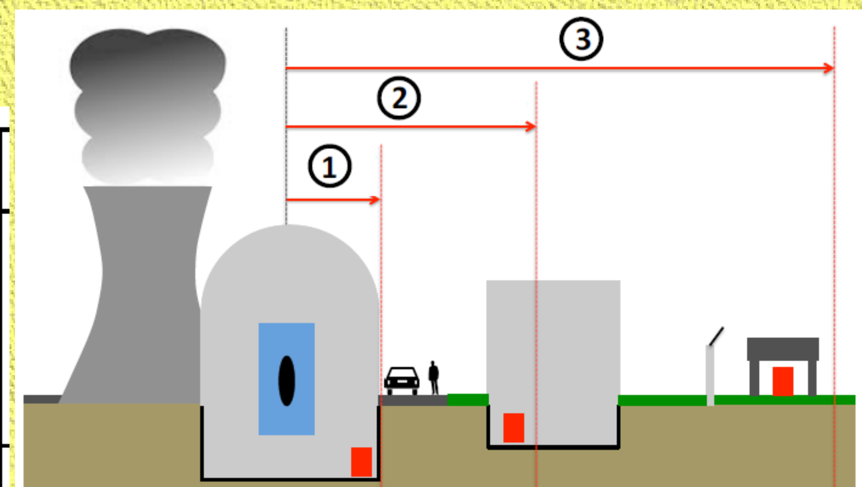
Initiatives at Chooz Reactors





	Strategy	Detector mass and E_{th} *
①	Short range (< 10 m)	O(10-100 g) E_{th} < 300 eV
②	Mid range (< 100 m)	O(0.1-1 kg) E_{th} < 100 eV
③	Long range (< 0.5-1 km)	O(1-10 kg) E_{th} < 50 eV

* to get $O(1\ d^{-1})$

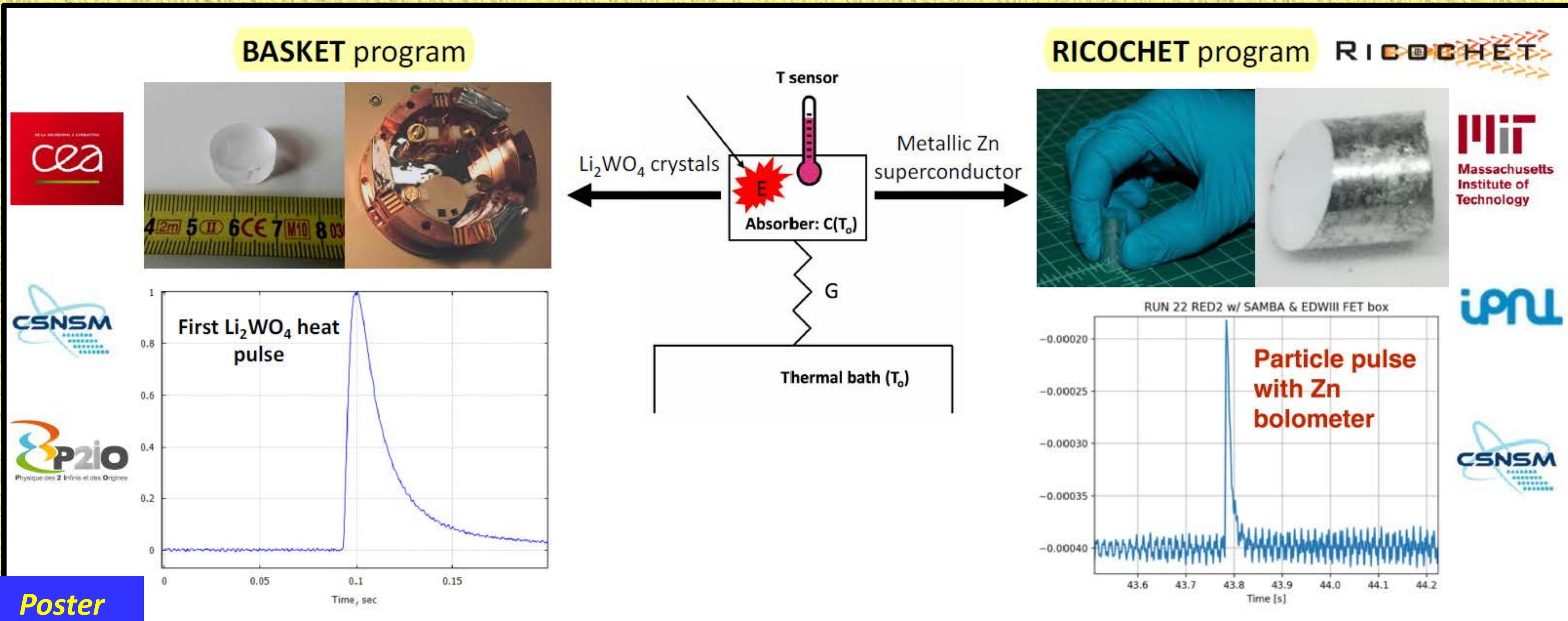


→ VNS at Chooz

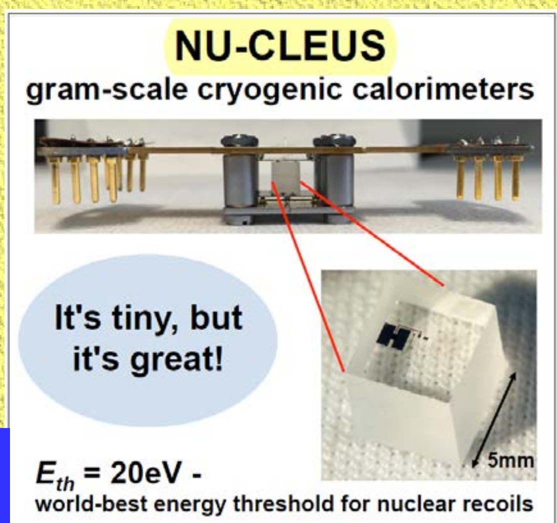
100 m/70 m

→ DC near lab

Candidate Detectors: *"to repurpose DM & $0\nu\beta\beta$ bolometers"*



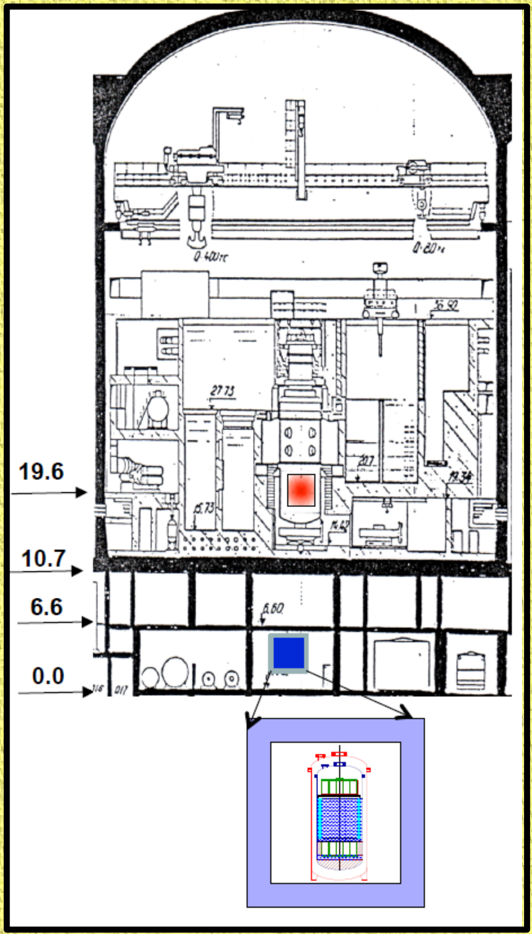
Poster ν–18

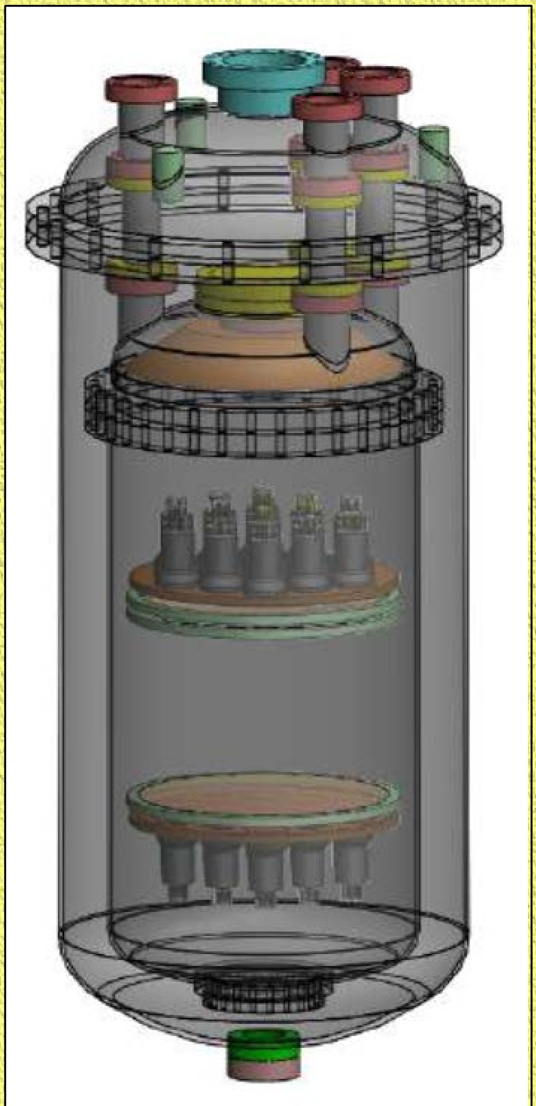


Poster ν–18

- ☑ a la CRESST ($CaWO_4$, Al_2O_3)
- ☑ Small modular mass O(1 g)
- ☑ Very low threshold ~ 20 eVnr **(!!)**
- ☑ 1-g demonstrator built

RED-100 @ Kalinin 3 GW Power Reactor





- ☑ Dual Phase Xenon Detector
- ☑ ~100 kg Fid. Vol.
- ☑ Threshold < 1 keVnr Xe-recoil
- ☑ 19 m from core KNPP
- ☑ O(100 events)/100-kg-day !
- ☑ Challenges: Background, Long drift time …
- ☑ Installation: late 2018

Poster
ν–18

νGeN @ Kalinin 3 GW Power Reactor

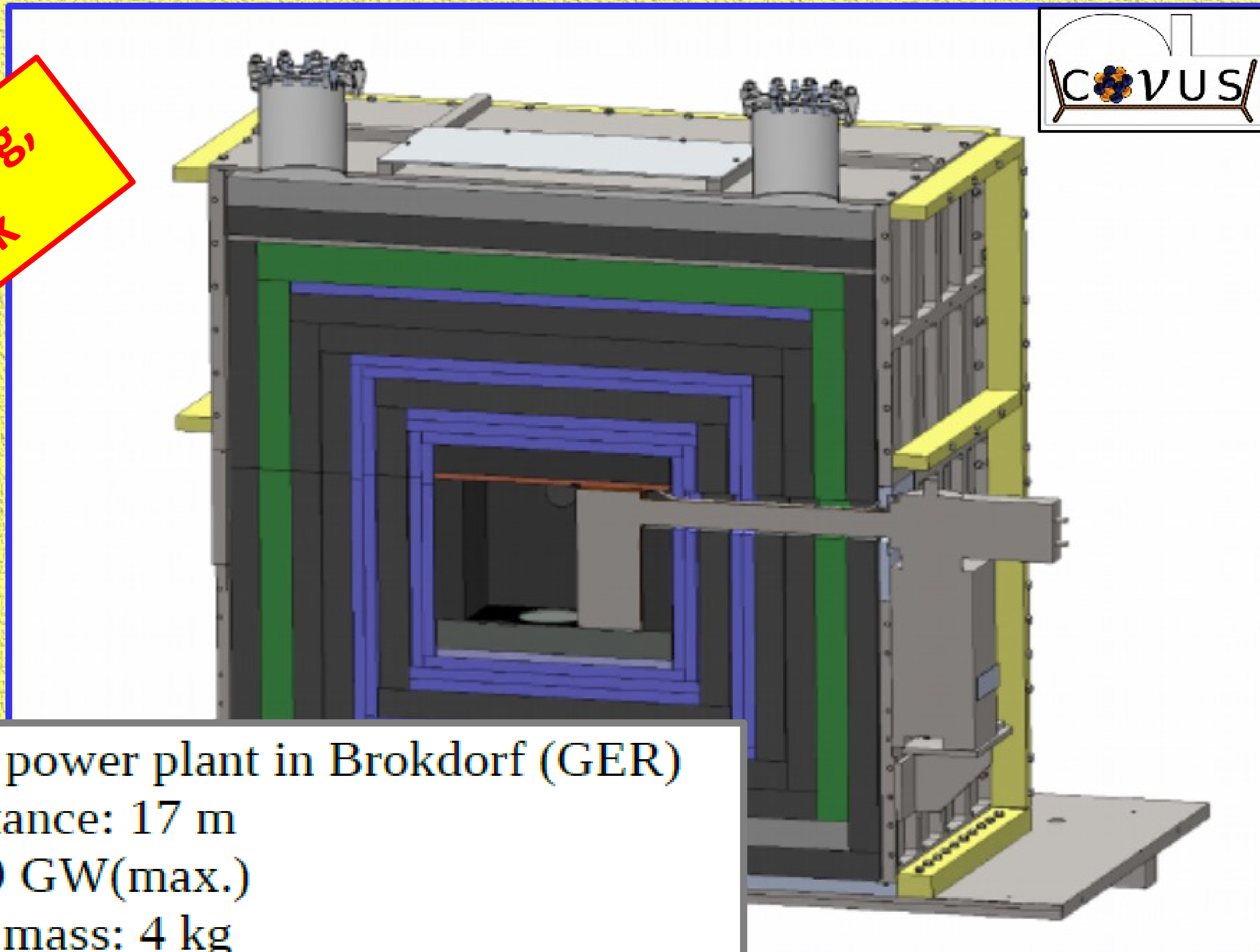
Passive shielding:
- 10 cm copper
- 8 cm borated polyethylene (3%)
- 10 cm lead
- 8 cm borated polyethylene

+ muon veto (5 cm)

νGEN (under the construction)
~ 4x0.4 kg HPGe,
threshold ~ 350 eV
10 m from reactor **!!**
bkg ~ 1 cts/(keV kg day) at LSM

☑ **Challenges:** **Threshold & Background …**

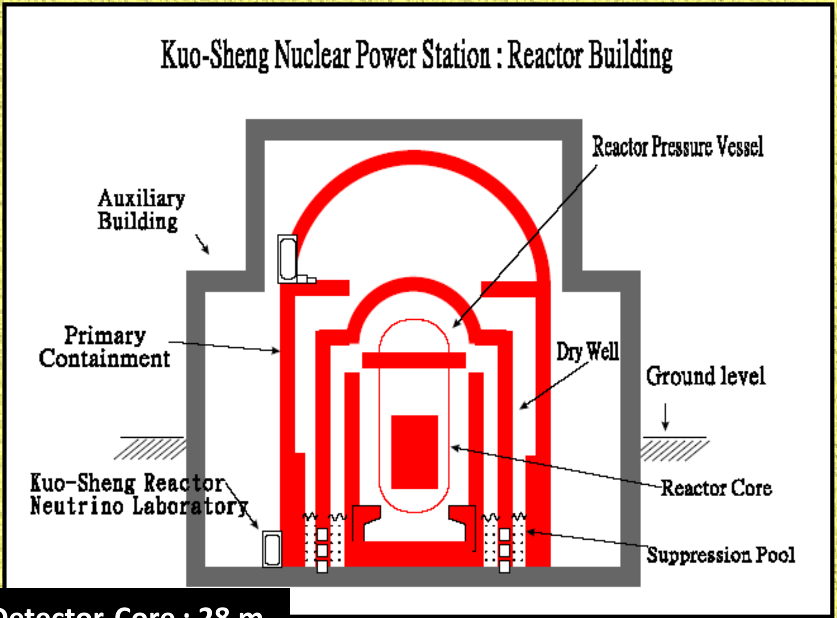
CONUS: Coherent Neutrino nUcleus Scattering



Werner Maneschg, previous talk

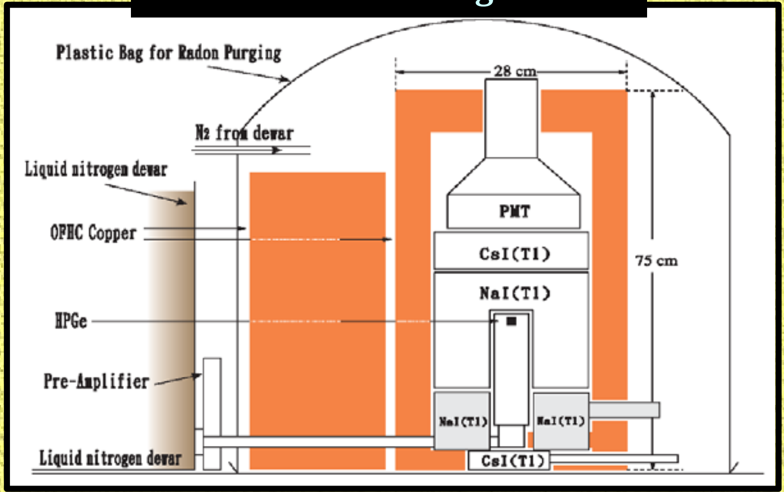
location: nuclear power plant in Brokdorf (GER)
detector core distance: 17 m
core strength: 3.9 GW(max.)
total Ge detector mass: 4 kg
goal noise threshold: <=300 eV
goal bg rates in ROI: O(bg) = 10 cts/(d*kg*keV)
commissioning/data collection: in progress

TEXONO at Kuo-Sheng Reactor



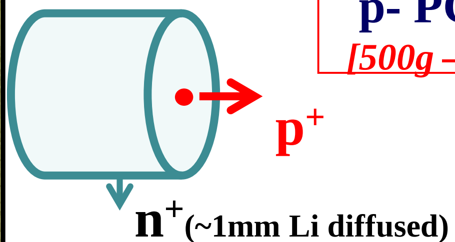
Detector-Core : 28 m

Baseline Design

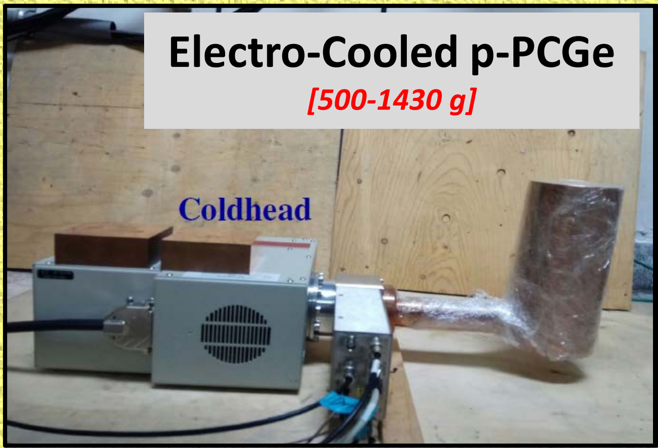


R&D on Pushing Threshold on Ge-Ionization Detectors

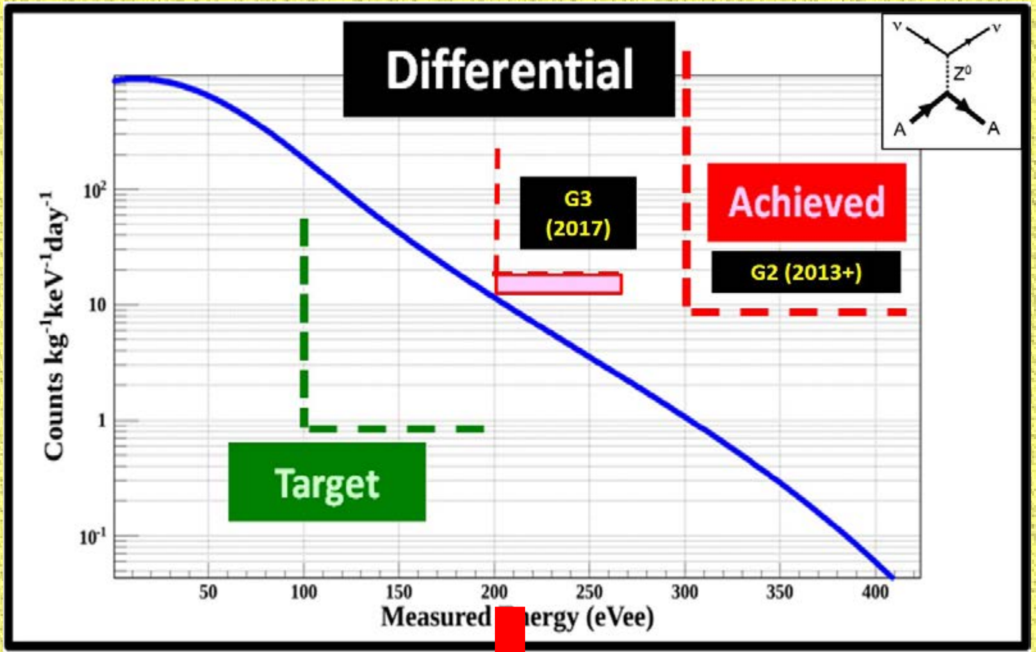
p- PCGe
[500g – 1 kg]

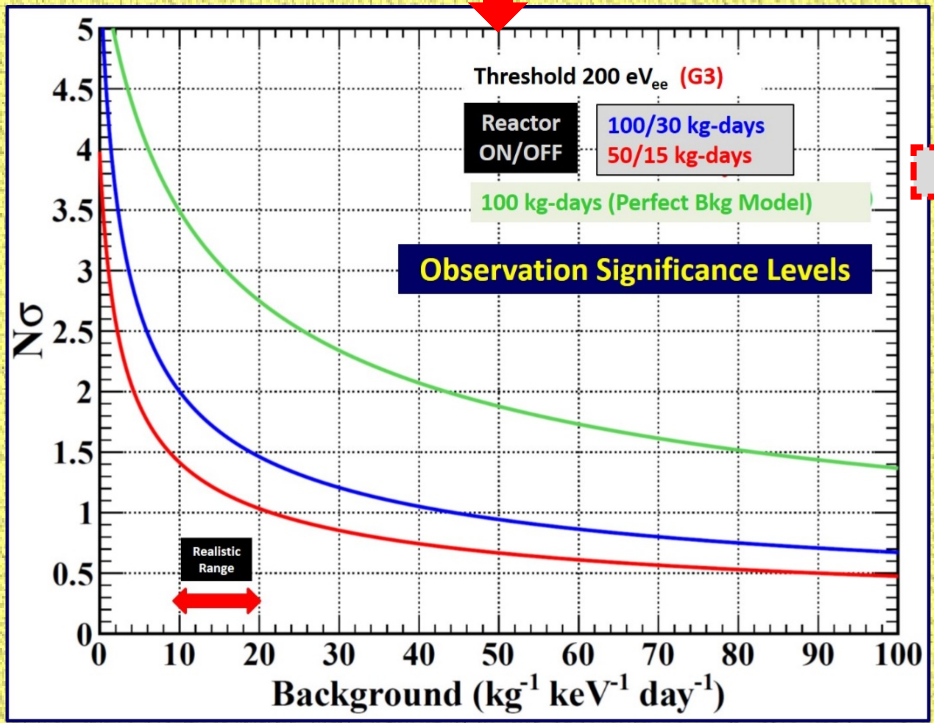


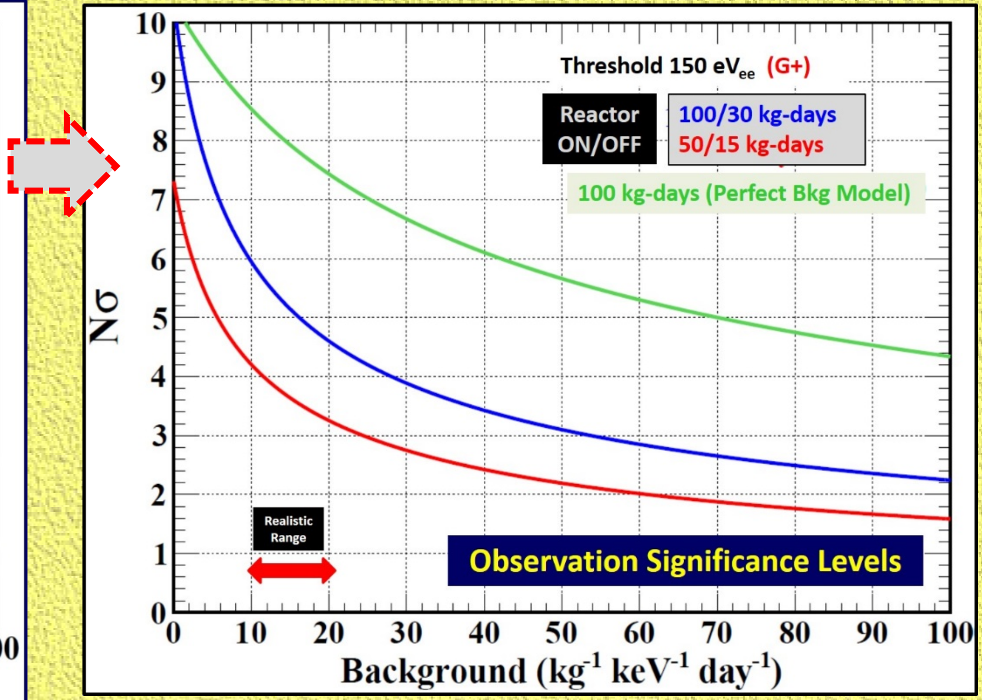
Electro-Cooled p-PCGe
[500-1430 g]



Projected Sensitivities: νA_{el} at KSNL





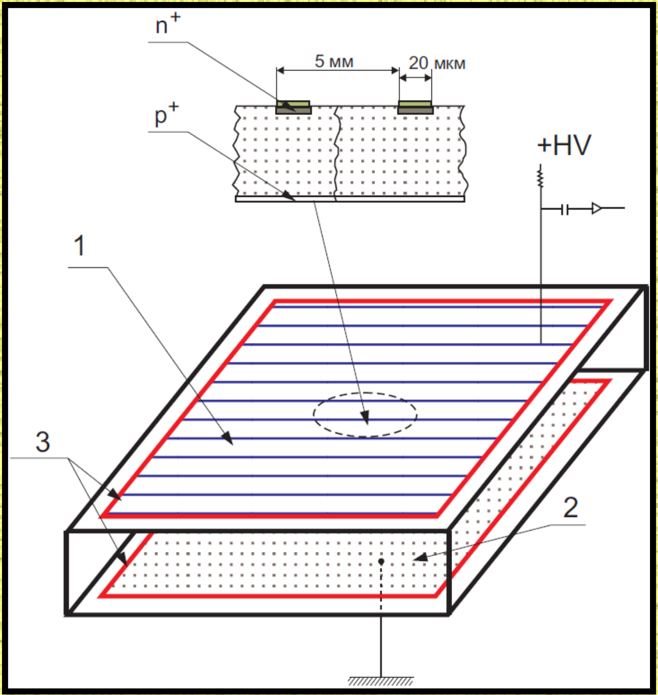


R&D on Ge-Ionization with Charge Amplification

GEMADARC

Germanium Materials and Detectors Advancement Research Consortium

- ☑ One of the R&D Projects of the NSF-GEMADARC Program
- ☑ Ge-IA, following concept paper of *[Starostin & Beda 2000]* on Ge planar strip detectors, extend to point-contact design.
- ☑ Expect Charge multiplication @ 10^5 V/m E-field
- ☑ Potentials: O(10 eVee) threshold, with Ge-Ionization, LN2 operation, fast ~μs signals
- ☑ Applications: νA_{el} & other ν-physics at reactor, dark matter searches
- ☑ Groups: USD (US), AS (Taiwan), BHU (India) ….
- ☑ Start: early 2018.



Starostin & Beda 2000

- Avalanche with V=4000 V ; E~105 V/m at O(10 mm)

Prospects & Outlook

- Probe *finer questions* on νA_{el} after 1st observation, both theory & experiments

[Recommend: *Decouple C from ENNS in writing, not to suppress the richness in C*]

- A natural *Portal for Synergy* between Neutrino and Dark Matter programs
- **Reactor νA_{el} –**
  - ☑ Diverse techniques to *reduce detector threshold*, potentials applications in other areas
  - ☑ *Small(er) scale projects* complementing large experimental facilities
- **Solar νA_{el} –**
  - ☑ From *Irreducible background* to a potentially important *physics output* for future DM direct searches projects

Back Up + Web Archive Technical Materials

Coherency in Neutrino-Nucleus Elastic Scattering

[PRD16]

- Quantify transitions between Coherency & Decoherency
- Complementarity between different Sources & Target

$$\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2, E_\nu) = \frac{1}{2}\left[\frac{G_F^2}{4\pi}\right]\left[1 - \frac{q^2}{4{E_\nu}^2}\right] \left[\varepsilon Z F_Z(q^2) - N F_N(q^2)\right]^2$$

$$\alpha \equiv \cos\langle\phi\rangle \in [0,1]$$

<ϕ> : averaged decoherence angle

Cross-section Ratio relative to neutron

$$\frac{\sigma_{\nu A_{el}}(Z,N)}{\sigma_{\nu A_{el}}(0,1)} = \{\ Z\varepsilon^2[1+\alpha(Z-1)] + N[1+\alpha(N-1)] - 2\alpha\varepsilon Z N\ \}$$

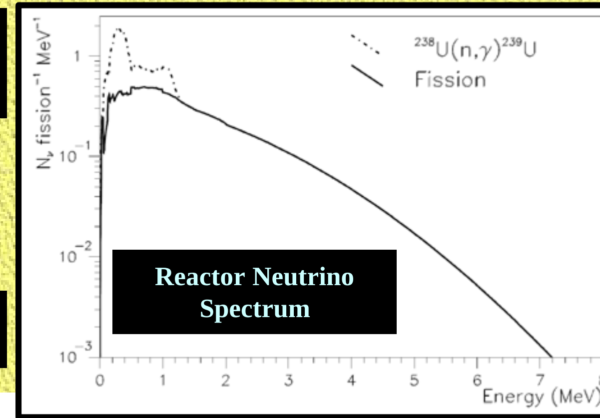
Cross-section Ratio relative to Full Coherency

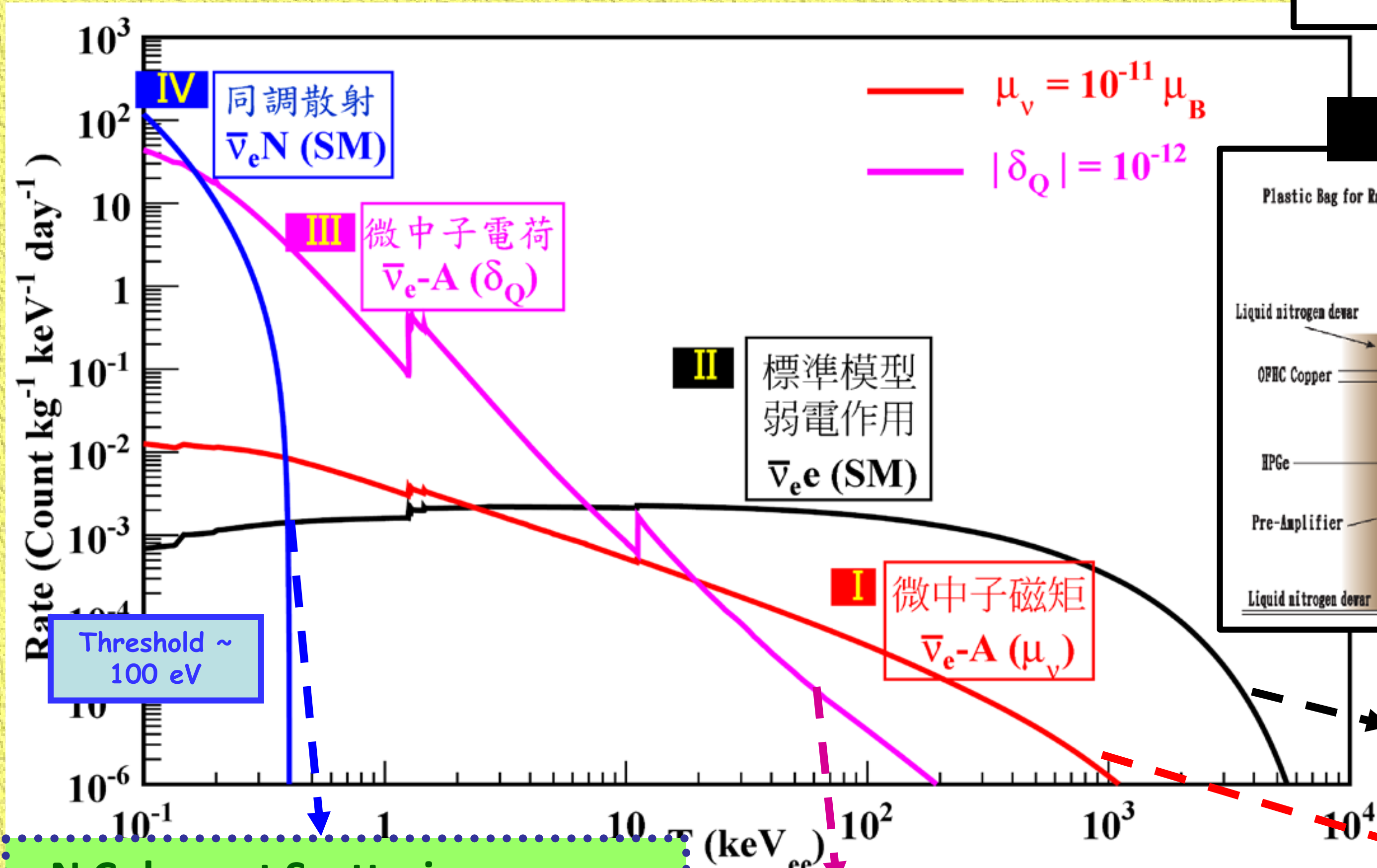
$$\xi \equiv \frac{\sigma_{\nu A_{el}}(\alpha)}{\sigma_{\nu A_{el}}(\alpha=1)} = \alpha + (1-\alpha)\left[\frac{(\varepsilon^2 Z + N)}{(\varepsilon Z - N)^2}\right]$$

TEXONO at Kuo-Sheng Reactor

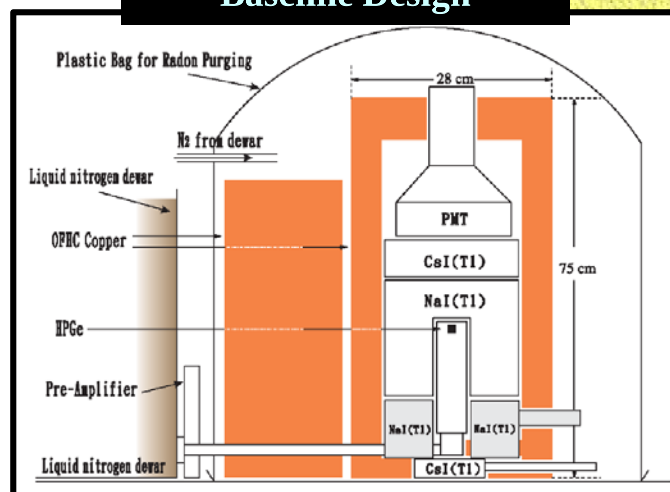
Observable Spectra with Reactor Neutrino "Beam"

quality ← Detector requirements → mass





Baseline Design



ν-e Scattering SM
⇨ 200 kg CsI(Tl) *[PRD10]*

νN Coherent Scattering
⇨ sub-keV O(kg) PCGe
⇨ Light WIMP searches *[PRL13 ….]*

Neutrino Milli-charge
⇨ sub-keV O(kg) PCGe *[PRD14]*

Magnetic Moments
⇨ 1 kg HPGe *[PRL03 ….]*

$$\nu + \mathrm{N} \rightarrow \nu + \mathrm{N}$$

Standard Model Cross-Sections at KSNL

[with Quenching Function for Ge for nuclear recoils]

$$\left(\frac{d\sigma}{dT}\right)^{coh}_{SM} = \frac{G_F^2}{4\pi} m_N [Z(1 - 4\sin^2\theta_W) - N]^2 \left[1 - \frac{m_N T_N}{2E_\nu^2}\right]$$

- **Needs Background < 10 cpkkd, Target → 1 cpkkd**

Current Focus !!

- **Needs Threshold < 200 eV_{ee}, Target → 100 eV_{ee}**

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi} [Z(1 - 4\sin^2\theta_W) - N]^2$$