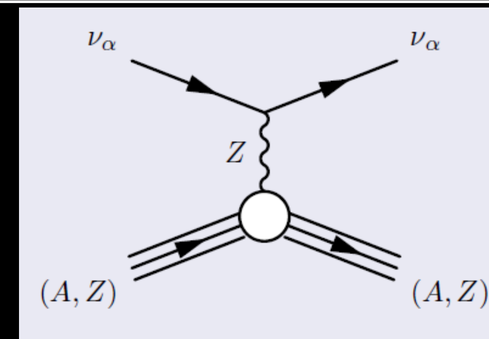
Coherent Neutrino-Nucleus Elastic Scattering

- Broad νA_{el} Physics Landscape
- Complementarities in νA_{el} among ν-sources
  - ☑ QM Coherency as a Qualifier
- "Applications"
- Experimental Projects
  - ☑ Accelerator, Reactor and Solar ν's
  - ☑ TEXONO: how we get to and from here
- Prospects & Outlook



Henry T. Wong / 王子敬
Academia Sinica / 中央研究院

September 2019

@

My Sources :

- ☑ **Workshop on this Subject at Chicago, November 2018**
  https://kicp-workshops.uchicago.edu/2018-CEvNS/presentations.php

- ☑ **Related Talks (4) at Neutrino 2018 at Heidelberg**
  https://www.mpi-hd.mpg.de/nu2018/programme

- ☑ **Recent Review Talk, K. Scholberg, Pheno-Symposium, Pittsburg, May 2019**
  https://indico.cern.ch/event/777988/contributions/3409119/attachments/1839130/3015019/pheno19.pdf

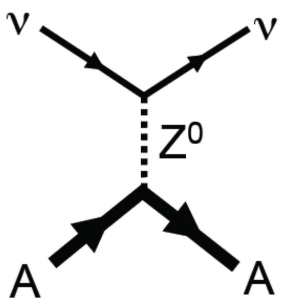
- ☑ **Individual Journal Papers**

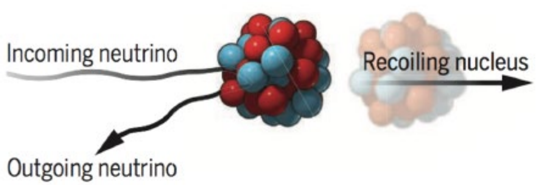
- ☑ **Communications from Experiments**

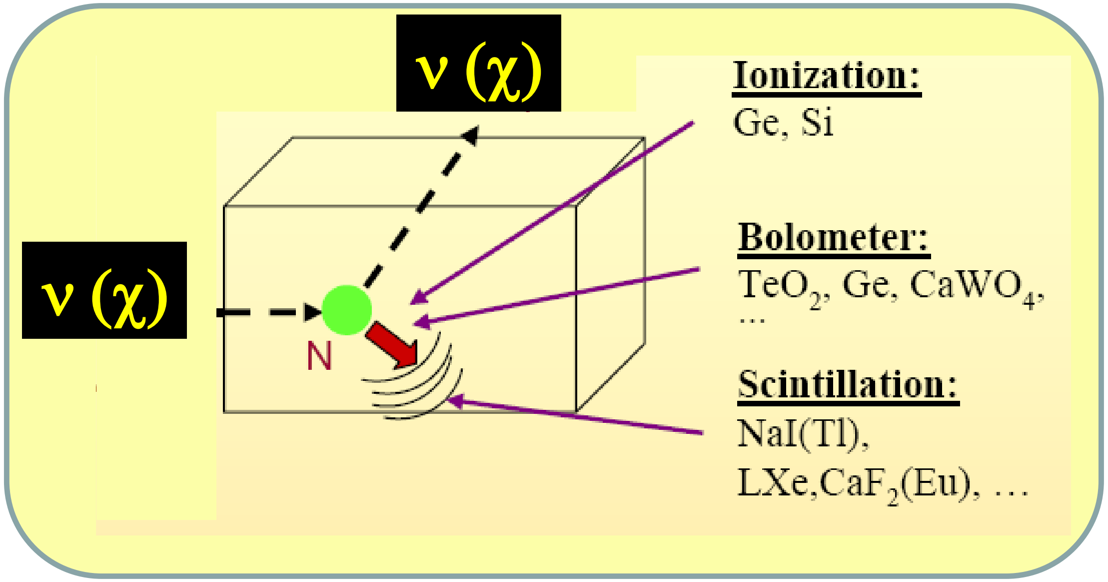
Neutrino-Nucleus Coherent Scattering (Panoramic)

Standard Model allowed and predicted processes :

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







- Neutral current process (same for all ν-flavor)
- $\sigma \propto N^2$ @ $E_\nu < 50$ MeV
  - ⇒ *"Coherent" [probe "sees" the whole nucleus]*
  - ⇒ *No!* Physics Threshold
- sensitive probe for BSM ; interest in reactor monitoring
- important process in stellar collapse & supernova explosion
- analogous interaction used in dark matter detection

Two Different Conditions *[Appearing Everywhere in Physics, May or May Not be Simultaneous]*:

☑ **Elastic –**

Total kinetic energy of the system is *conserved* ⇔ Kinetic energy is *constant* in center of mass frame

☑ **Coherent –**

Outgoing wavelets from different scattering centers have *non-random relative phase* in *direction of interest*

i.e. with matter of extent/degree/distributions.

Notation:

- **Acronyms like CNS, CNNS, CENNS, CEνNS are used in Literature**
- **I would explicitly state "Coherent" νA_{el}**
  - ☑ **A=Z+N denoting the nucleus**
  - ☑ **Be reminded on the richness and continuous aspect of "C"**

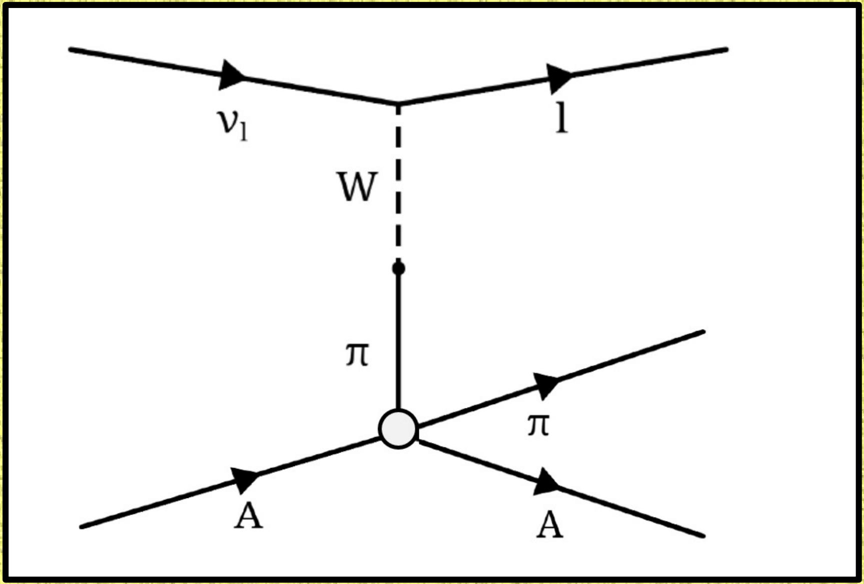
Different Process as :
neutrino-induced "coherent" pion production

[Next Talk ; NOT discussed in THIS ONE]

☑ **Coherent π Production**

$$\nu_\mu A \rightarrow \nu_\mu A \pi^0, \qquad \bar{\nu}_\mu A \rightarrow \bar{\nu}_\mu A \pi^0,$$

$$\nu_\mu A \rightarrow \mu^- A \pi^+, \qquad \bar{\nu}_\mu A \rightarrow \mu^+ A \pi^- .$$



- **Apply to high energy (> GeV) accelerator neutrinos**
- **Low Q^2**
- **No nuclear recoil**
- **Forward Final state π**
- **Coherency in a strong interaction vertex -- σ scales as A^2**
- **important background to ν_e CC detection**

Early Literature ....

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)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

ISOTOPIC AND CHIRAL STRUCTURE OF NEUTRAL CURRENT

V. B. Kopeliovich and L. L. Frankfurt
Leningrad Institute of Nuclear Physics, USSR Academy of Sciences
Submitted 7 January 1974
ZhETF Pis. Red. 19, No. 4, 236 - 239 (20 February 1974)

Relations are obtained between the cross sections for ν and ν̄ scattering by nuclei; these relations explain the isotopic and chiral structure of the neutral current. It is show that the cross section for the interaction of low-energy neutrinos is enhanced by the coherence effect, and processes in which charged current participates are suppressed by virtue of the Pauli principle.

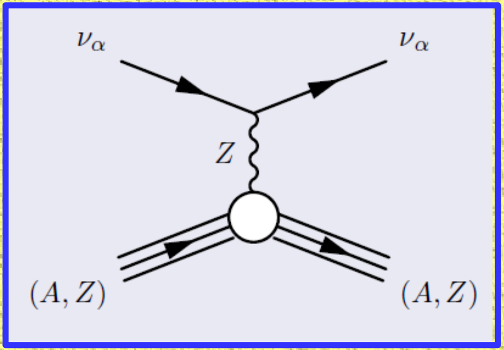
THE WEAK NEUTRAL CURRENT AND ITS EFFECTS IN STELLAR COLLAPSE

Ann. Rev. Nucl. Sci. 1977. 27 : 167–207

Daniel Z. Freedman
Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, New York 11790

David N. Schramm[1] *and David L. Tubbs*[2]
Enrico Fermi Institute (LASR), University of Chicago, Chicago, Illinois 60637

Standard Model Description



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

M is the nucleus mass;
T recoil nucleus energy (from 0 to $T_{max} = 2E_\nu^2/(M+2E_\nu)$);
E_ν neutrino energy;
$qR << 1$, $q \simeq \sqrt{2MT}$;
J. Barranco, OGM, T. I. Rashba JHEP 0512 (2005) 021

Vector:

$$G_V = \left[F_Z^V(q^2) g_V^p Z + F_N^V(q^2) g_V^n N\right]$$

Axial Vector:

$$G_A = [F_Z{}^A(q^2) g^p{}_A \Sigma_Z + F_N{}^A(q^2) g^n{}_A \Sigma_N]$$

$$g_V^p = 0.0298$$
$$g_V^n = -0.5117$$
$$g_A^p = 0.4955$$
$$g_A^n = -0.5121.$$

Simplifications:

- ☑ Vector Component dominant
- ☑ Neutron component dominant
- ☑ Single Nuclear Form Factor

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{\left[F_Z^V(q^2) Z g_V^p + F_N^V(q^2) N g_V^n\right]^2\right\}$$

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

$$\varepsilon \equiv (1\text{–}4\sin^2\theta_W) = 0.045$$

At $q^2 \to 0$ and $F(q^2) \simeq 1$

$$\sigma_{\nu A_{el}}(T_{\min} = 0) = \frac{G_F^2 {E_\nu}^2}{4\pi}[\varepsilon Z - N]^2$$

... at low E_ν (< 10 MeV)

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

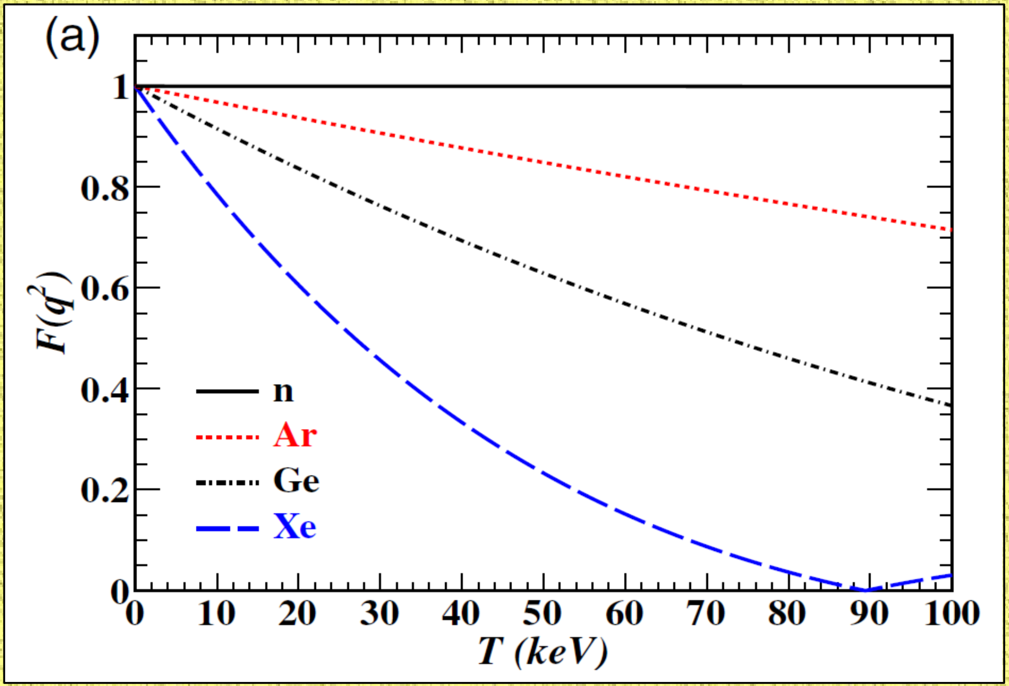
$$T_{max} = \frac{2\,{E_\nu}^2}{(M+2E_\nu)} \sim \frac{2{E_\nu}^2}{M}$$

$$\frac{d\sigma_{\nu A_{el}}}{dT}(T \to 0) \simeq \left[\frac{G_F^2 M}{4\pi}\right][\varepsilon Z - N]^2$$

... independent of E_ν

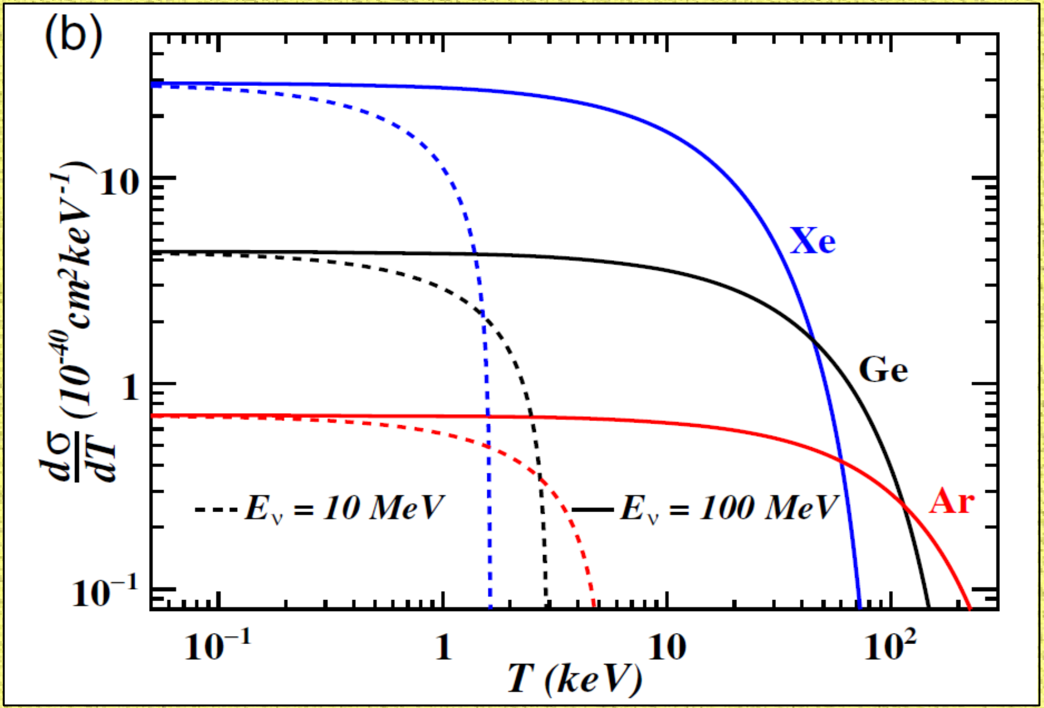
Form Factors
(a typical parametrizaiton)

$$F(q^2) = \left[\frac{3}{qR_0}\right] J_1(qR_0) \exp\left[-\frac{1}{2} q^2 s^2\right]$$

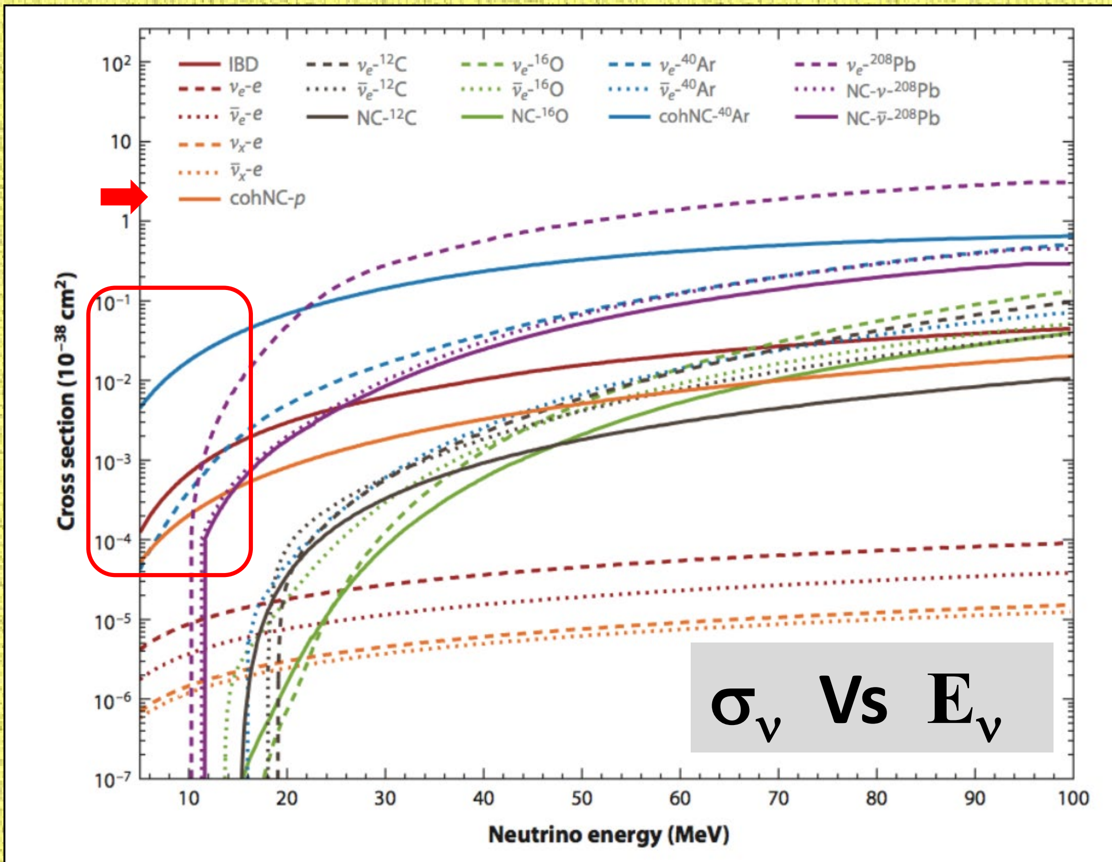


Differential σ

$$T_{max} = \frac{2\,E_\nu^{\,2}}{(M+2E_\nu)} \sim \frac{2E_\nu^{\,2}}{M}$$



νA_{el} within context of ν-Interactions

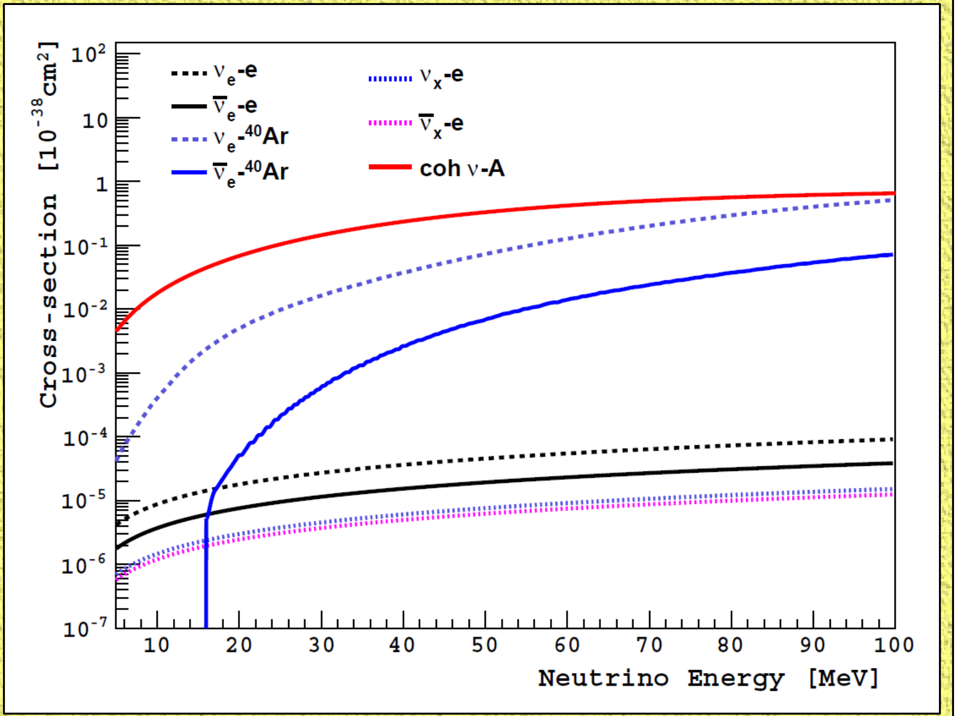


Process	Threshold (typical)
$\nu N \to \nu N$ (elastic)	none
$\nu_e n \to e^- p$	None for free neutron & some other nuclei.
$\nu e \to \nu e$ (elastic)	~ 10eV – 100 keV
anti-$\nu_e p \to e^+ n$	1.8 MeV (free p). More in nuclei.
$\nu_\ell n \to \ell^- p$ (quasielastic)	~ 10s MeV for ν_e +~100 MeV for ν_μ
$\nu_\ell N \to \ell^- X$ (inelastic)	~ 200 MeV for ν_e +~100 MeV for ν_μ

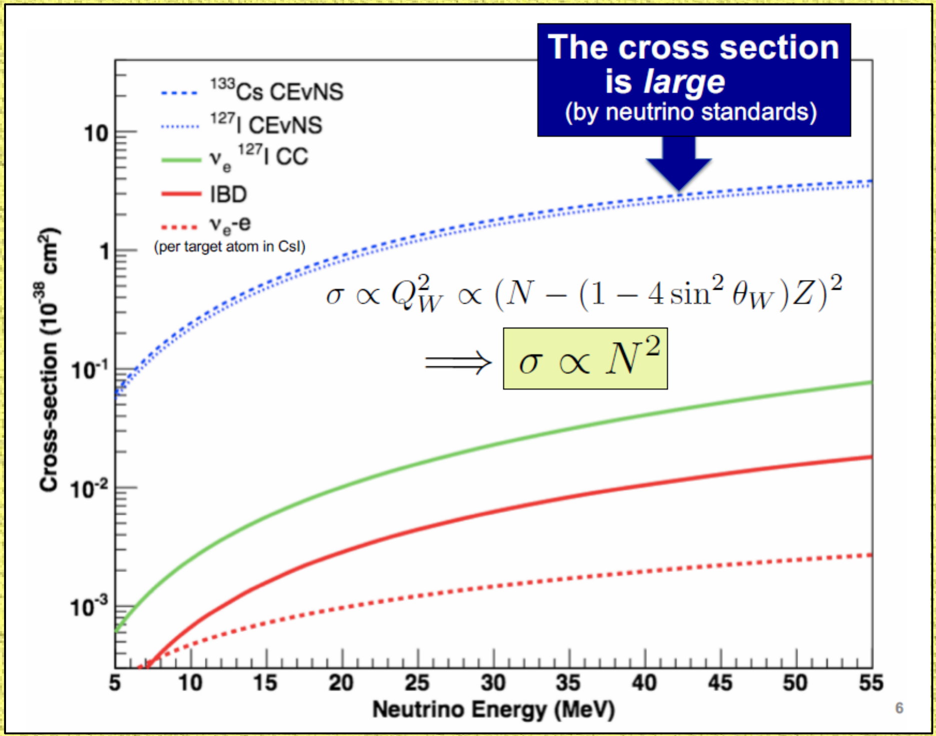
General Features (point-like weak interactions << M_W ~ 100 GeV

- ☑ $d\sigma_{TOT}/dT \sim$ constant @ $T \ll E_\nu$
- ☑ $\sigma_{TOT} \sim O\,[\,G_F^2\,(\,Q_{max}^2 - Q_{min}^2\,)\,]$
- ☑ $\Delta Q^2 \sim E_\nu^2$ for ν-N elastic & $\sim m_e E_\nu$ for ν-e elastic
- ☑ σ_{TOT} (ν : anti-ν) ~ 1 : 1/3 (for helicity-dependent processes)
- ☑ Nucleus/Nucleon-Target add "Form Factor" corrections.

Specific Target : Ar

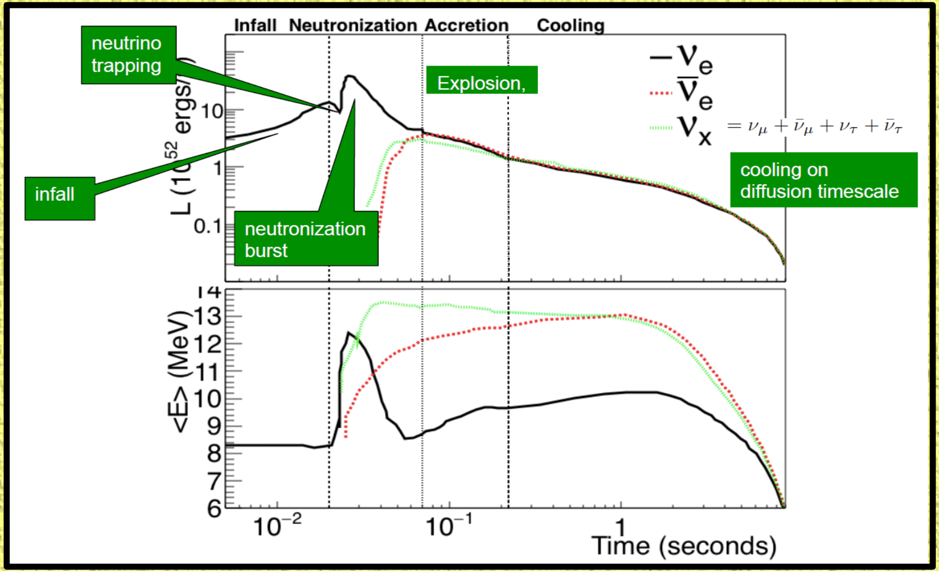


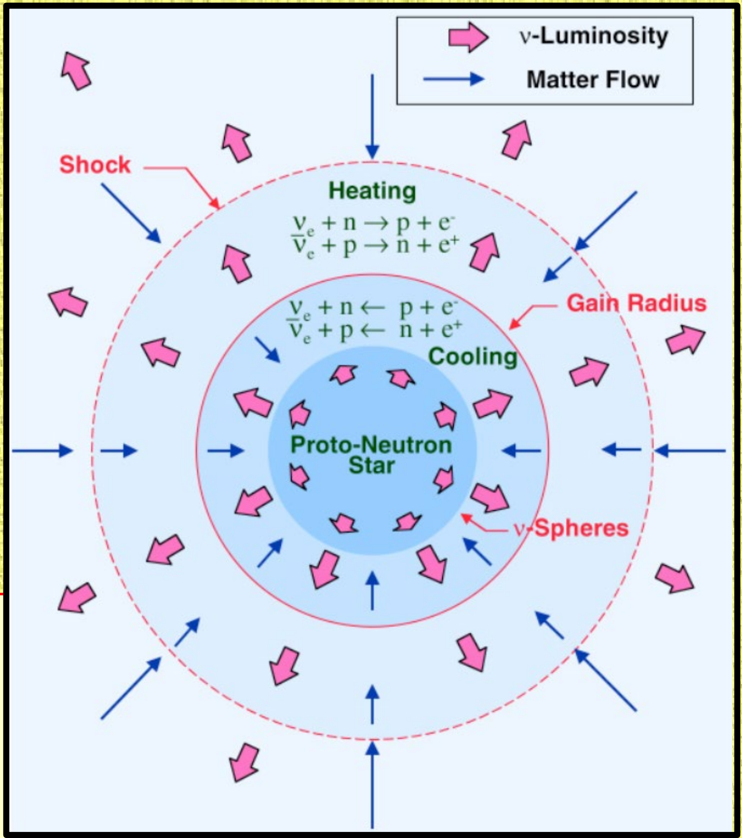
Specific Target : I / Xe / Cs



νA_{el} in Astrophysics

An Example: Neutrino Trapping in Supernova *[e.g. Bethe, RMP 62, 801 (1990)]*





At SN collapse with $\rho \sim 10^{12}$ g/cc, R ~ 30 km

- ⇨ $\lambda_\nu (\nu A_{el}) \sim 2\,[10/E_\nu]^2$ km ~ 0.4 km << R
- ⇨ ν diffusion time (s) >> SN Collapse time
- ⇨ ν trapping in SN core

Long time ⇒ allows ν-e inelastic scattering with degenerate electrons, despite smaller cross-section

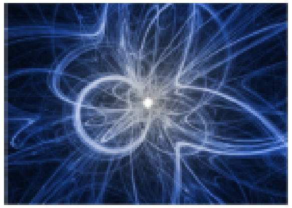
- ⇨ ν loses energy
- ⇨ Lower E_ν ⇒ reduced σ, enable ν to escape
- ⇨ loss of leptons & energy from SN

CEvNS: what's it good for?

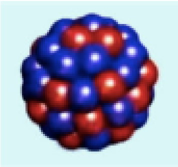
1. So
2. Many
3. Things

! (not a complete list!)

CEvNS as a **signal**
for signatures of *new physics*

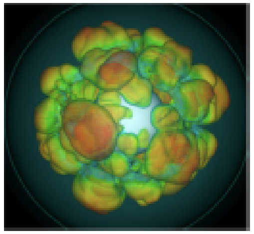


CEvNS as a **signal**
for understanding of "old" physics

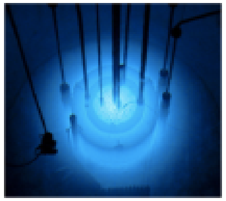


CEvNS as a **background**
for signatures of new physics

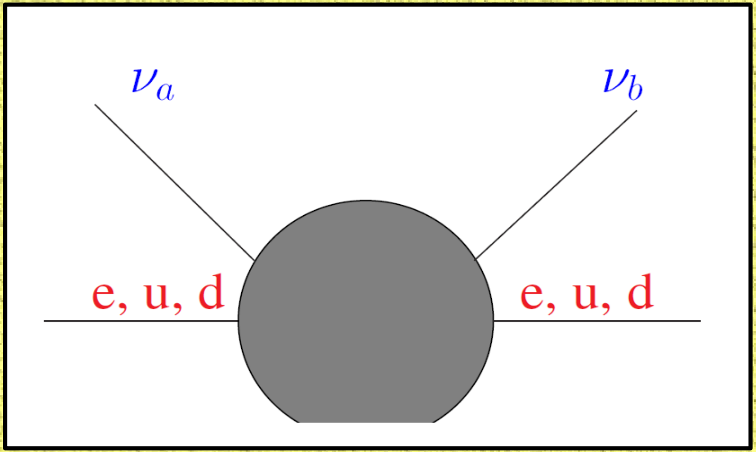
CEvNS as a **signal** for *astrophysics*



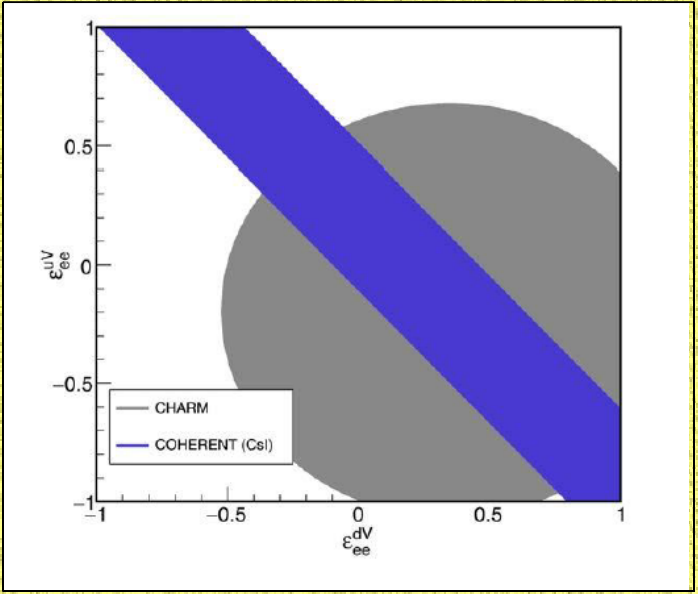
CEvNS as a **practical tool**



νA_{el} as Probe of NSI & BSM



NSI can be *both* Neutrino-
***Flavor-Conserving* and**
Flavor-Changing



$$
\begin{aligned}
\frac{d\sigma}{dT}(E_\nu, T) &= \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \mathrm{F}(q^2) \\
&\times \left\{\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \right. \\
&+ \left. \sum_{\alpha=\mu,\tau}\left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2\right\}
\end{aligned}
$$

BSMs Probed by νA_{el}

Analysis in the Literature:

- ☑ NSI parameters
- ☑ Light Mediators

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

- ☑ Leptoquarks
- ☑ Neutrino Magnetic Moments

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

- ☑ Neutrino Charge Radius
- ☑ Sterile Neutrino Oscillations
- ☑ …..

Challenges:

- ☑ Complex Degeneracies
- ☑ Uncertainties of SM "Predictions"

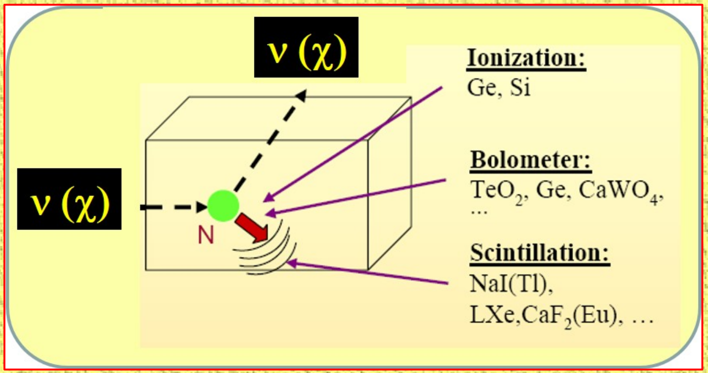
Experimental Handles:

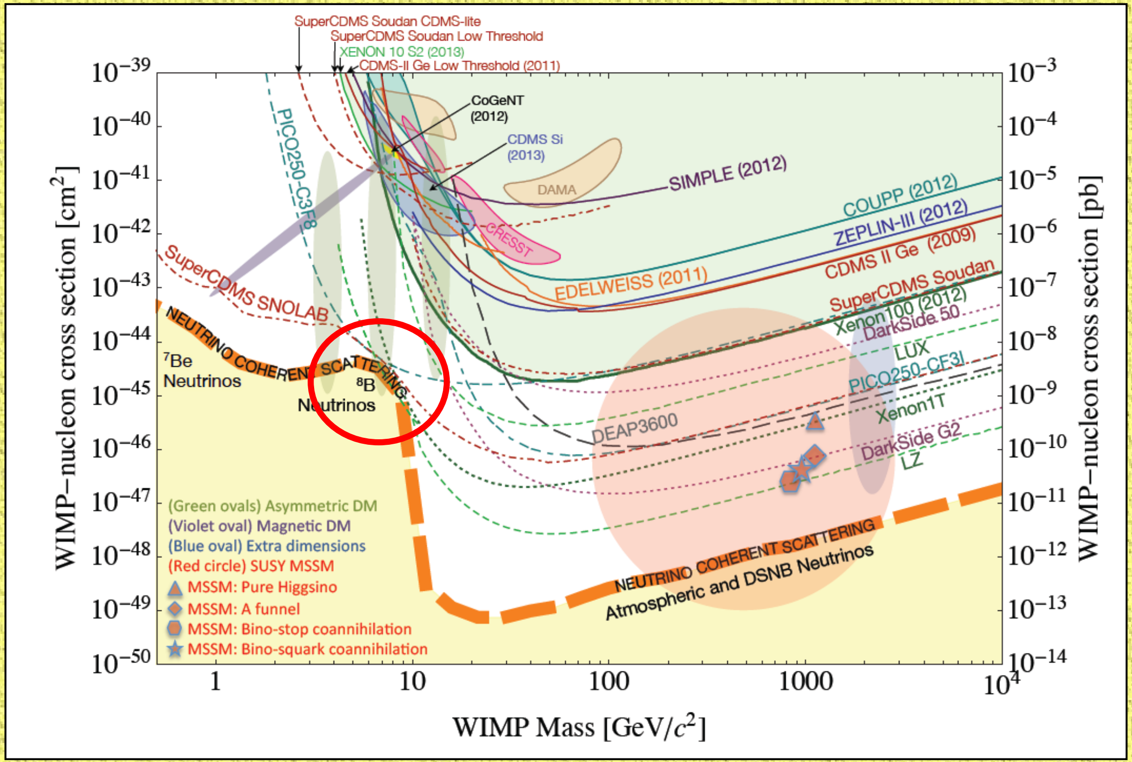
- ☑ Different q^2 dependence *[i.e. spectral distortion]*
- ☑ Different (A,Z,N) dependence *[e.g. NMM scales as Z^2]*

νA_{el} as "Background" to WIMP Searches

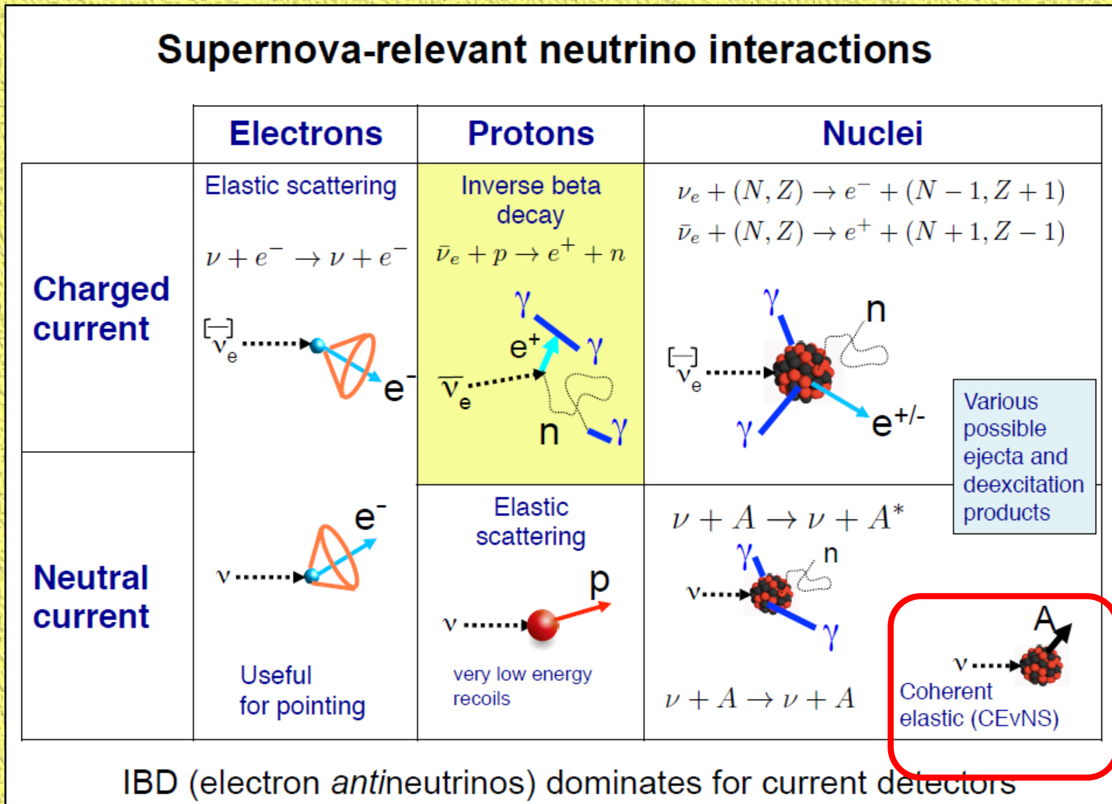
- νA_{el} from Solar & Atmospheric ν's constitute the "neutrino floor" (irreducible background) to WIMP searches
- νA & χA projects share common techniques and challenges
- Next(+) Generation (of LiqXe) Projects close to the required sensitivities for ^{8}B solar-ν
- Surmounting this "background" – directional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

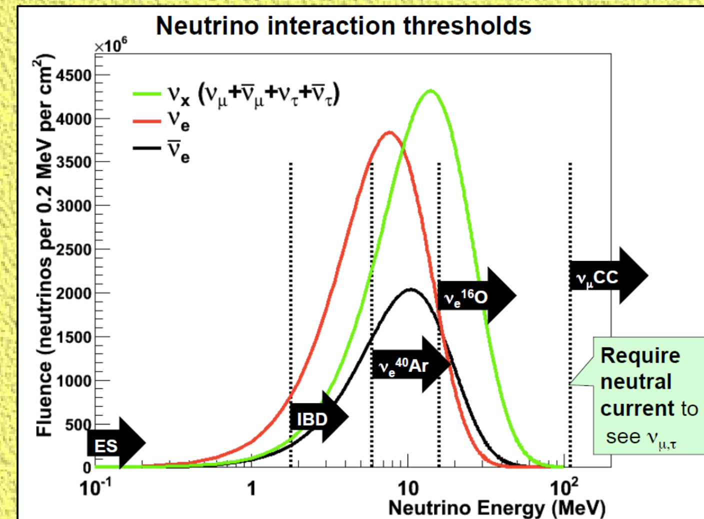
$$\nu(\chi) + A \rightarrow \nu(\chi) + A$$





νA_{el} as Detection Channel e.g. Supernova





Complementarities / Merits :

☑ Low (No) Detection Threshold in principle

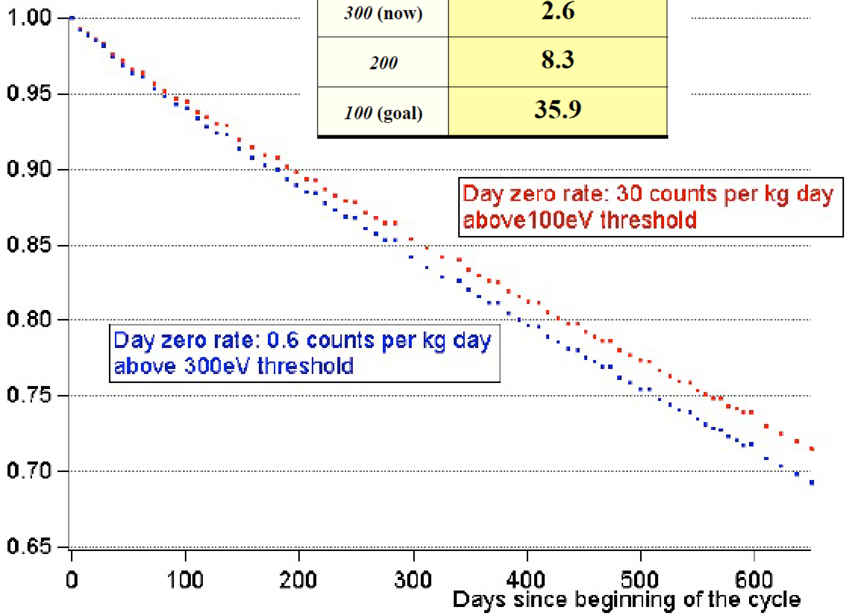
☑ Sensitive to all Neutrino Flavors

BUT ….

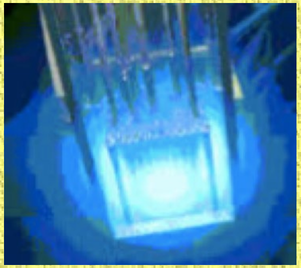
Need LARGE Target Mass *Yet* Low Threshold Detector Systems

νA_{el} in Practical Application e.g. Reactor Monitoring

Ge detector Threshold (eV)	Signal counts / day kg at 20m from reactor core
300 (now)	2.6
200	8.3
100 (goal)	35.9



- About 25% variation in total events during NPP cycle
- anti-NCS has better sensitivity to fuel composition than inverse beta
- Percentage variation reduced with threshold but overall signal increases significantly



Potential Merits :

☑ (Relatively) Compact system, potentially mobile …..

☑ Low threshold and large rates

Coherency as a Qualifier for νA_{el} *[PRD 93, 113006 (2016)]*

Dependence of νA_{el} on q^2, E_ν & Target (Z,N)

Complementary Characterization:

☑ **$FF(q^2) < 1$**

⇨ connected to other nuclear physics measurements

⇨ describe transitions between *nucleus* and *nucleons*

☑ **Cross-sections "do not scale as $[N-Z(1-4\sin^2\theta_w)]^2 \sim N^2$"**

⇨ direct experimental observables

☑ **QM coherency transition**

Quantify with "decoherence angle $<\phi>$ " *[PRD16]*

$(\alpha \equiv \cos <\phi> \in [0,1])$

⇨ Unified Description for all A(Z,N)

Coherency in Neutrino-Nucleus Elastic Scattering

⚐ Quantify transitions between Coherency & Decoherency

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

<ϕ> : averaged decoherence angle

Cross-section Ratio relative to neutron

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

Full Coherency $\alpha=1$:

$$\sigma_{\nu A_{el}} \propto [\varepsilon Z - N]^2$$

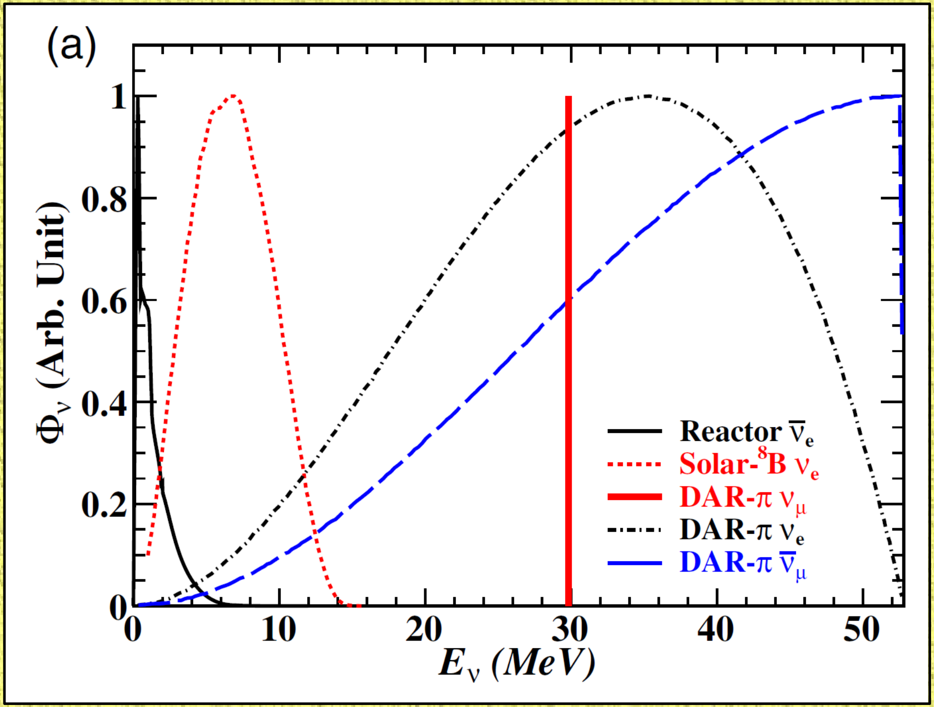
Total Incoherency $\alpha=0$:

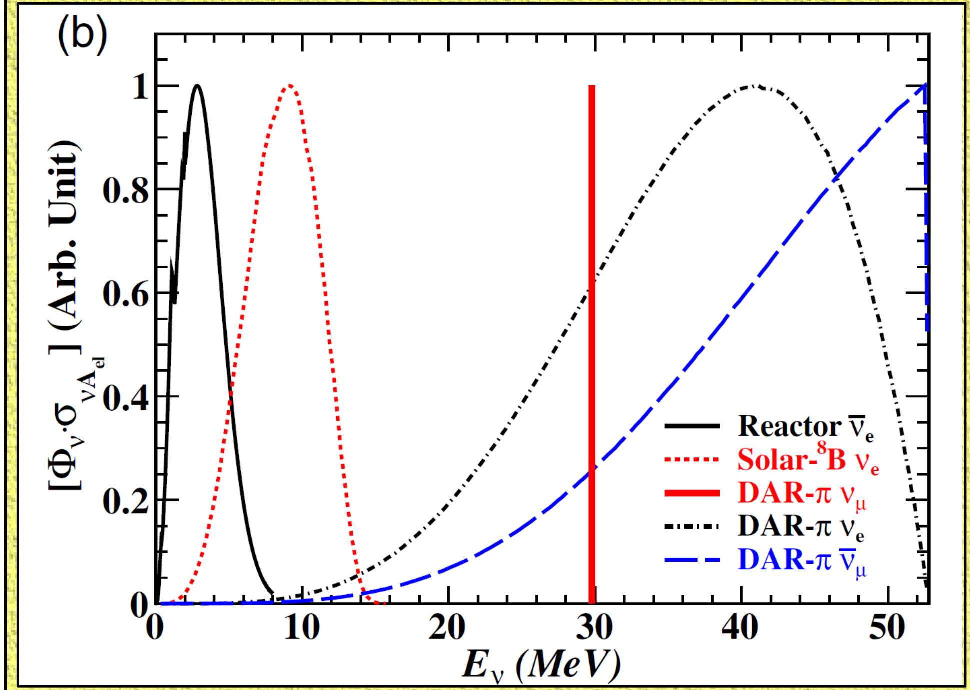
$$\sigma_{\nu A_{el}} \propto [\varepsilon^2 Z + N]$$

Cross-section Ratio relative to Full Coherency

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

Different ν-Sources (E_ν) Probe Complementary Kinematical Regions

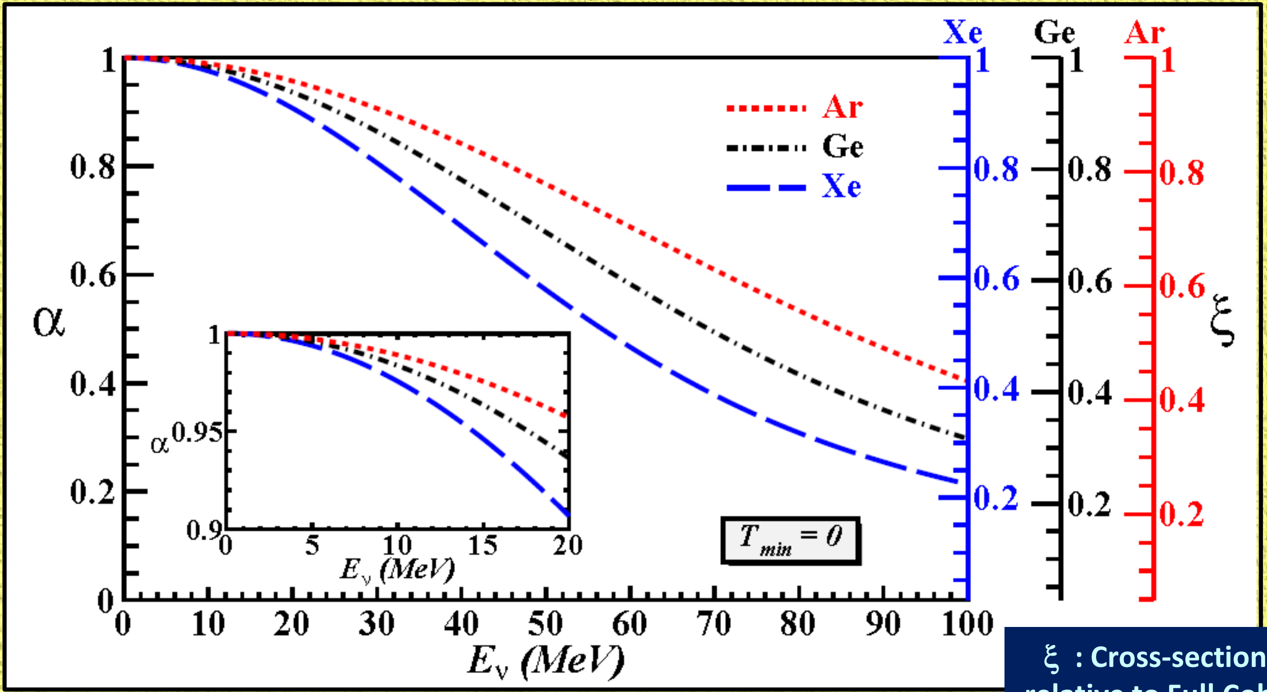




ν-Spectra

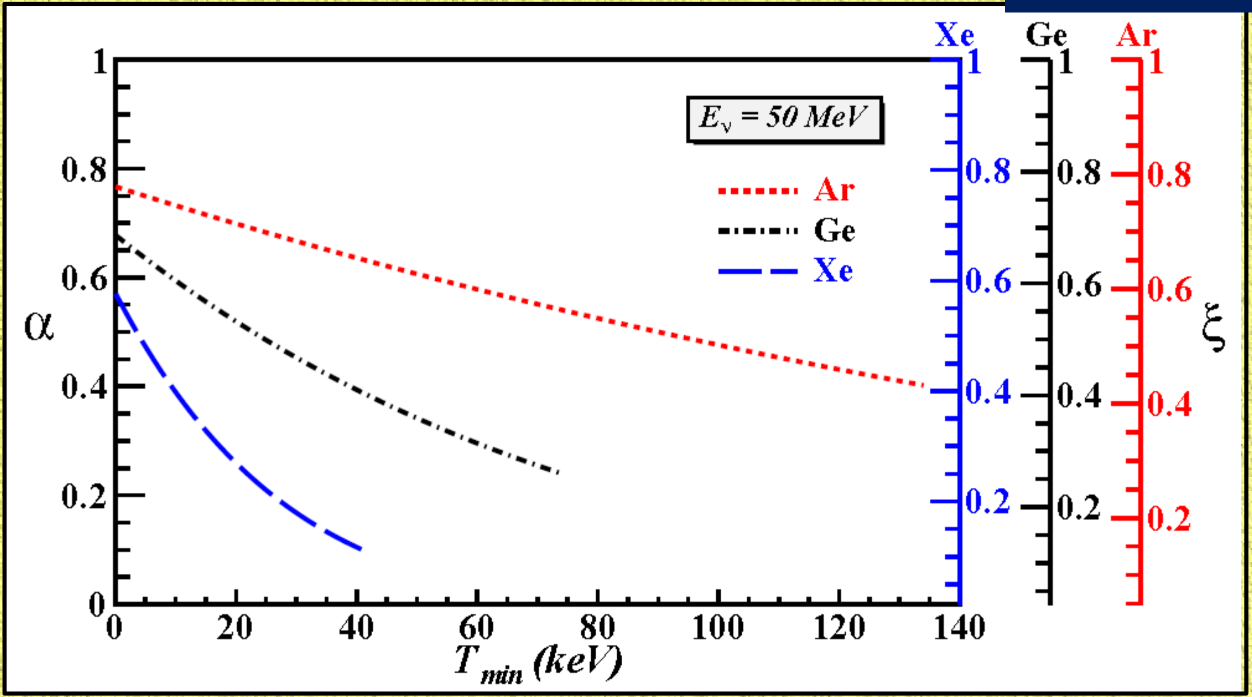
$\sigma(\nu A_{el})$ weighted ν-Spectra

ν-Energy Dependence at Zero Detector Threshold



ξ : Cross-section Ratio relative to Full Coherency

Detector Threshold Dependence at ν-Energy = 50 MeV



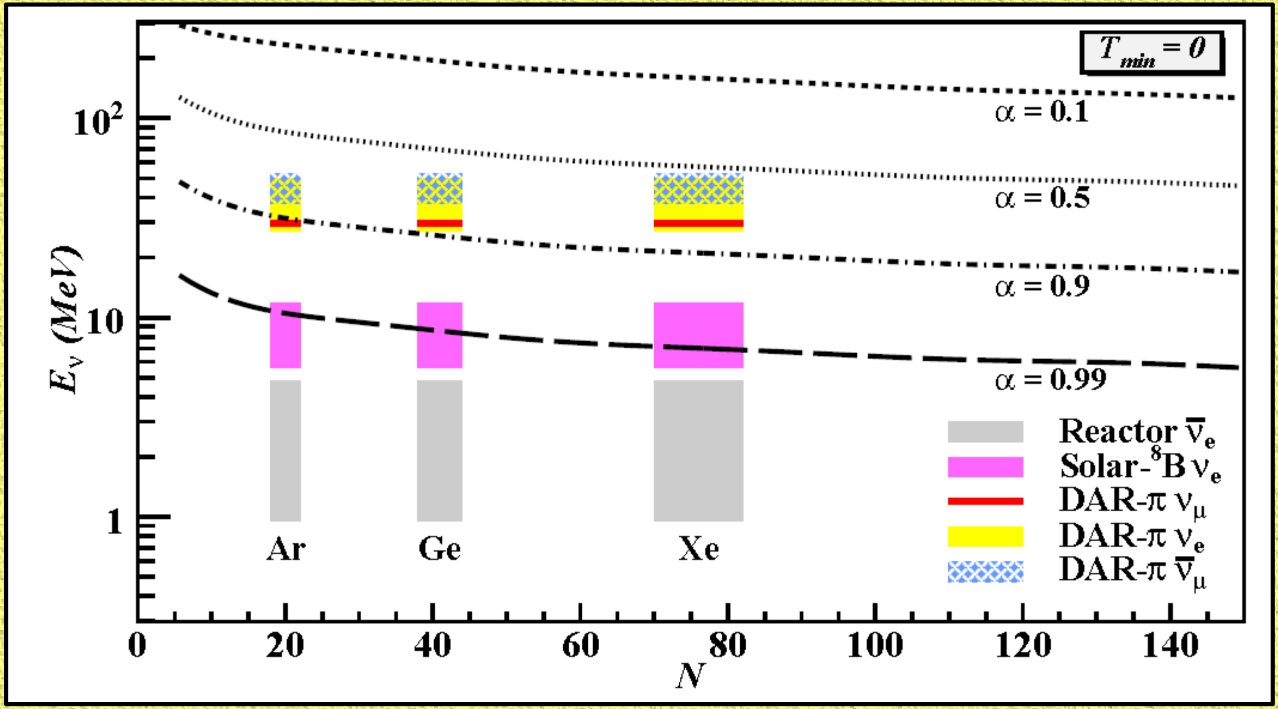


TABLE II: The half-maxima in the distributions of $[\Phi_\nu \cdot \sigma_{\nu A_{el}}]$ at T_{min}=0 for the different neutrino sources, and the values of $\langle\alpha\rangle$ probed by the selected target nuclei. The ν_μ from DAR-π is mono-energetic.

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

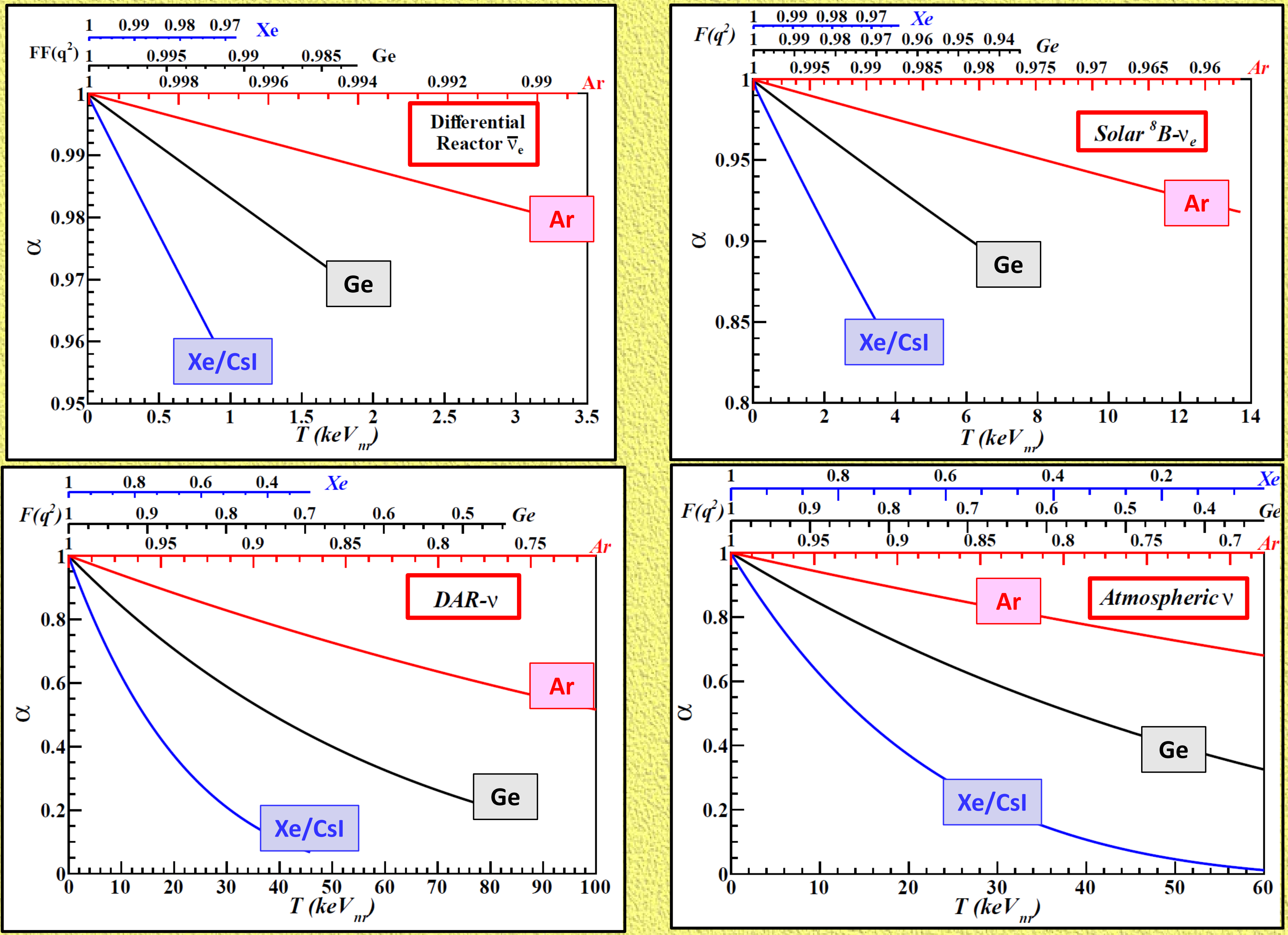
TABLE III. Maximum neutrino energy (E_ν) with which coherency is maintained among the constituents, as characterized by the parameters $F(q^2_{\max})$, α and ξ being > 0.95.

Parameter > 0.95	Maximum E_ν (MeV) for Ar	Ge	Xe
$F(q^2_{\max})$	17.2	14.1	11.6
α at $T_{\min} = 0$	21.1	17.4	14.3
ξ at $T_{\min} = 0$	21.6	17.6	14.4

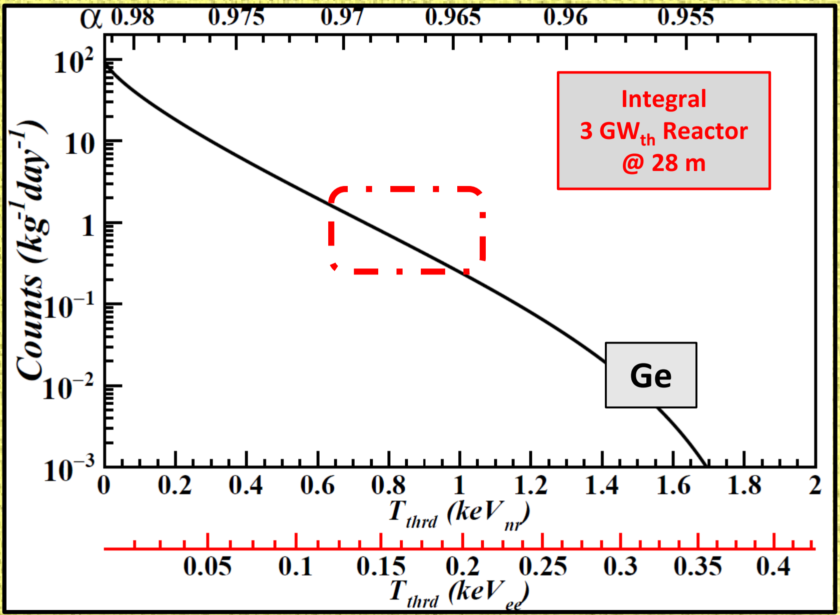
⟨α⟩ from different ν-Sources

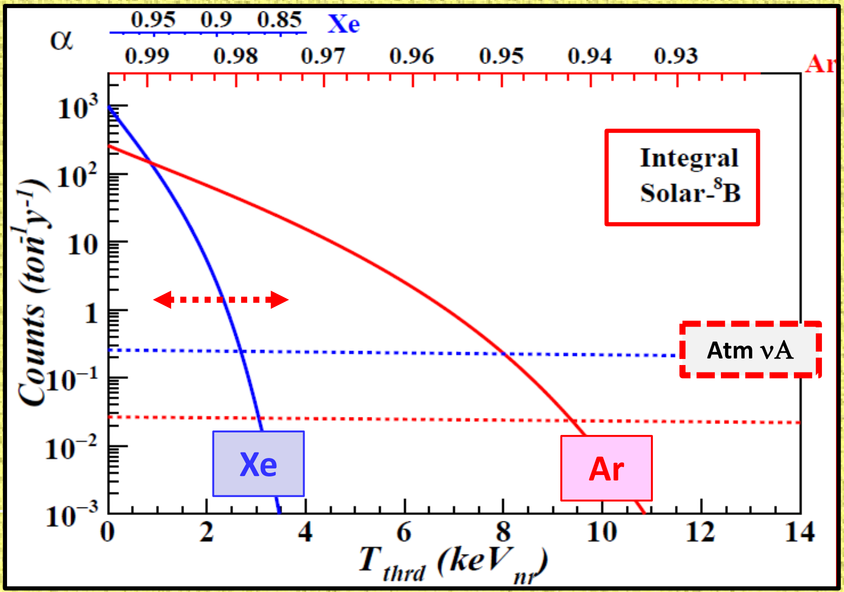
Full Coherency Conditions

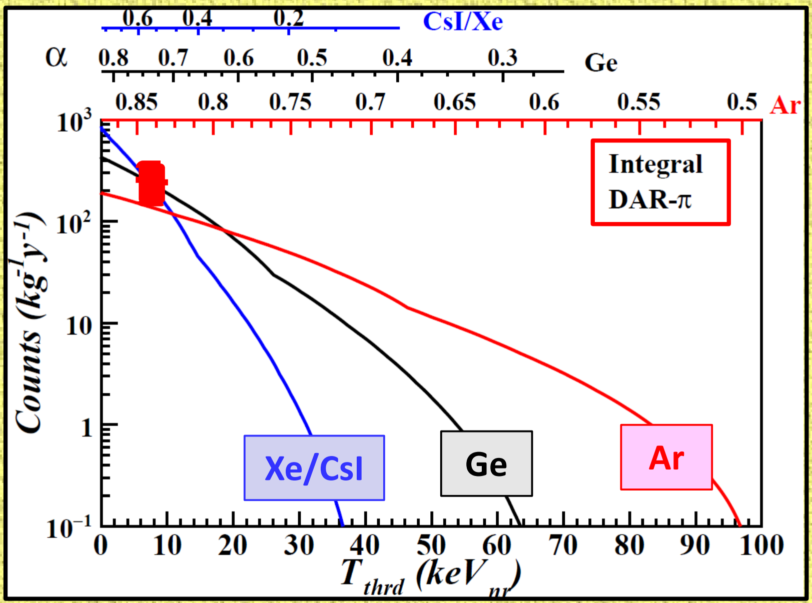
Relating (Recoil Energy, Form Factor, α) in νA_{el} from ν-Sources

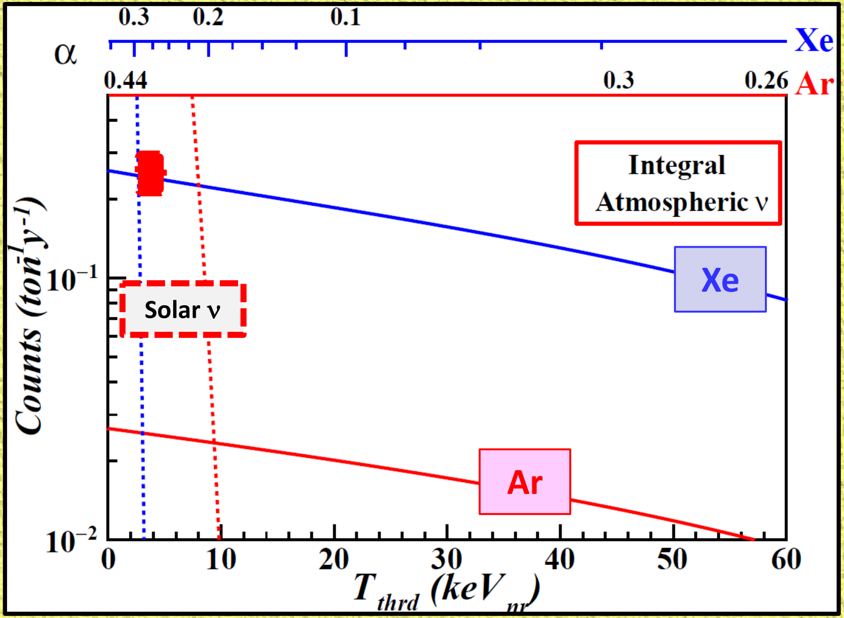


Measureables (Energy Threshold, Integral Event Rate, $\langle\alpha\rangle$) in νA_{el} from ν-Sources

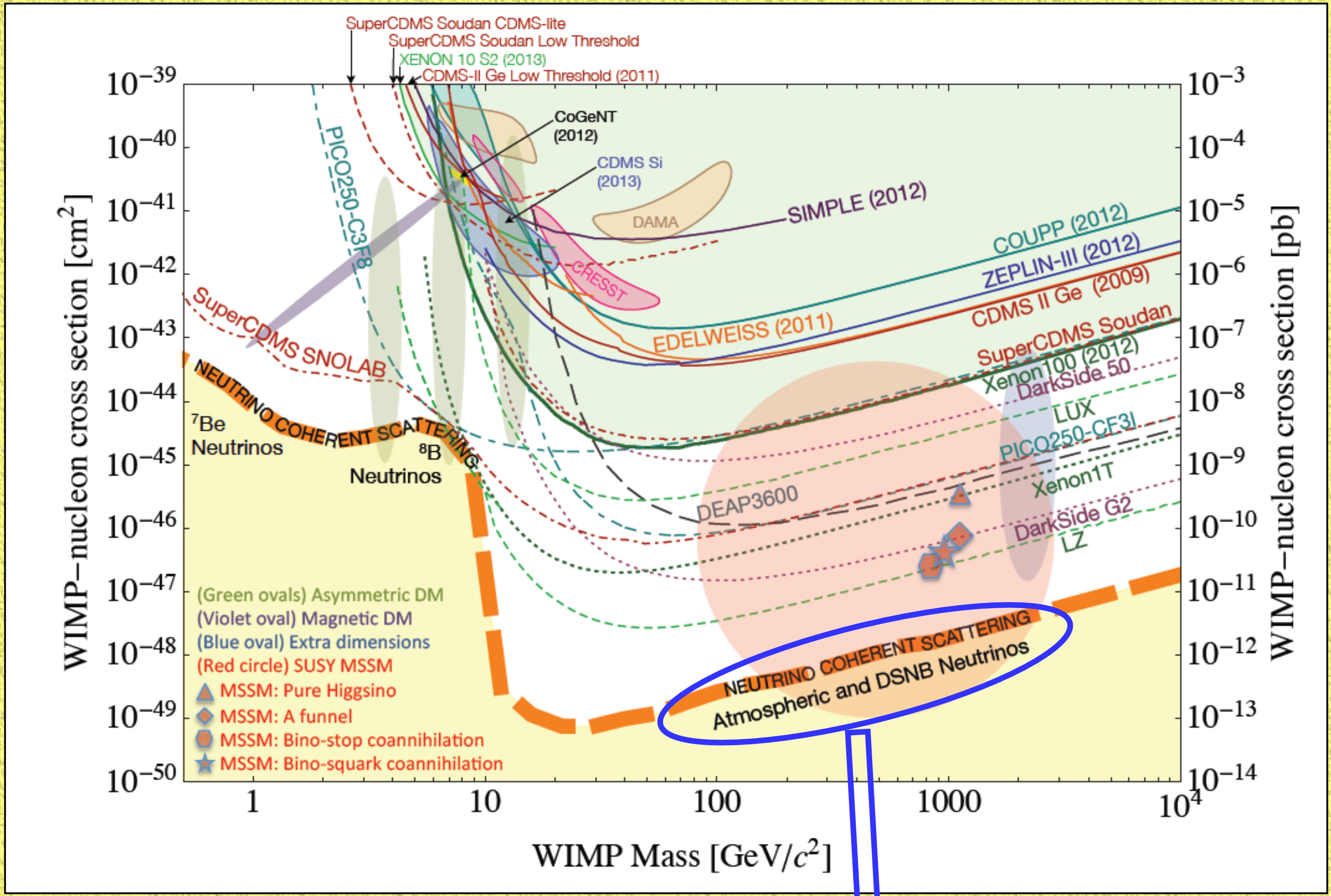






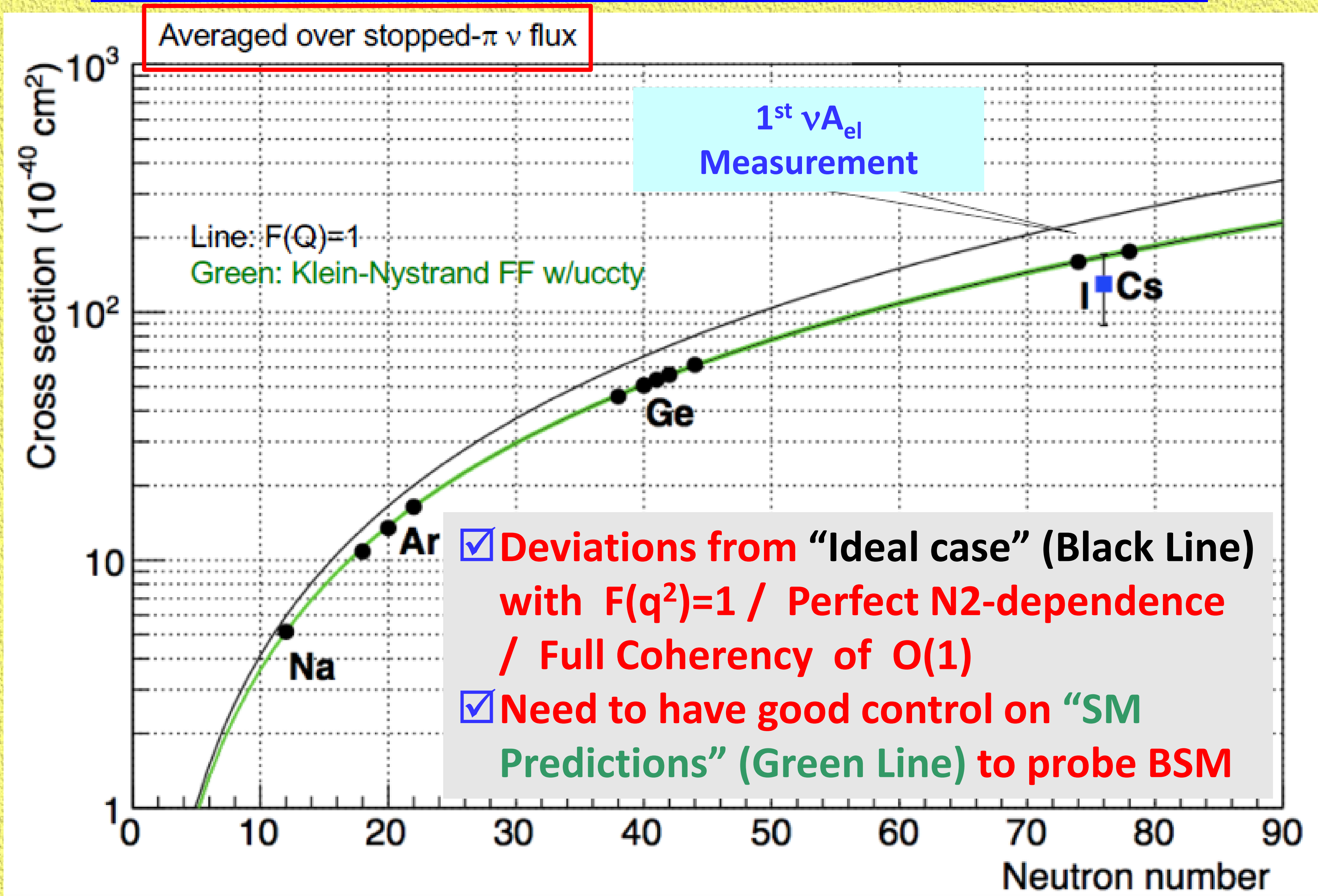


$\nu(\chi) + A \rightarrow \nu(\chi) + A$



- ☑ $\alpha < 0.3$ for Xe
- ☑ Describing Neutrino Floor at large WIMP-mass as due to [atm νA_{el}] "Coherent" scattering is *Inaccurate !!*

Standard Model "Predictions" for νA_{el}



☑ Deviations from "Ideal case" (Black Line) with $F(q^2)=1$ / Perfect N2-dependence / Full Coherency of O(1)

☑ Need to have good control on "SM Predictions" (Green Line) to probe BSM

Complications / Twists / Opportunities ……..

Nuclear Physics Form Factor:

- ☑ *i.e.* density distributions of nucleons in nucleus
- ☑ esp. relevant to **O(10 MeV) DAR-π ν-beam**
- ☑ O(1) Correction to cross-sections

  e.g. ***ξ~0.55*** *@ E_ν~50 MeV ; Thr=0*
- ☑ Different formulations to $F(q^2)$, and ranges for parameter choices.
- ☑ *Expect:* **~few%** uncertainties, from existing NP data
- ☑ *Reverse:* future ton-scale projects measure "neutron/nucleus RMS-radius" to **~few%** *[assuming no BSM ….]*

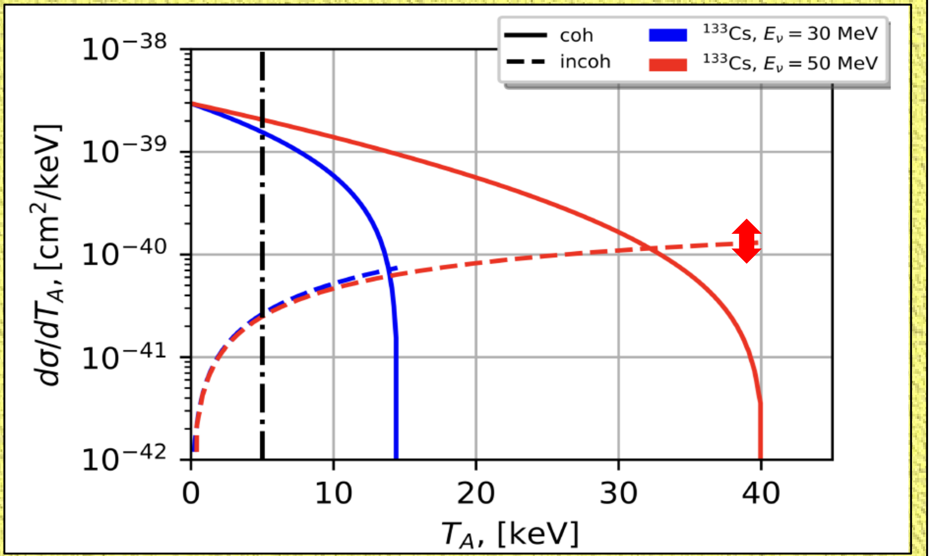
Background with Incoherent Interactions *[PRD 98, 053004 (2018)]*:

☑ Inelastic Channel contaminating the Elastic Nuclear Recoil signals *(beam-related single pulses in anti-coincidence with other detector-systems)*

$\Rightarrow$ Incoherent Component $\propto A$

☑ esp. relevant to O(10 MeV) DAR-π ν-beam

☑ estimated ~10-20% for Cs133 at realistic thresholds



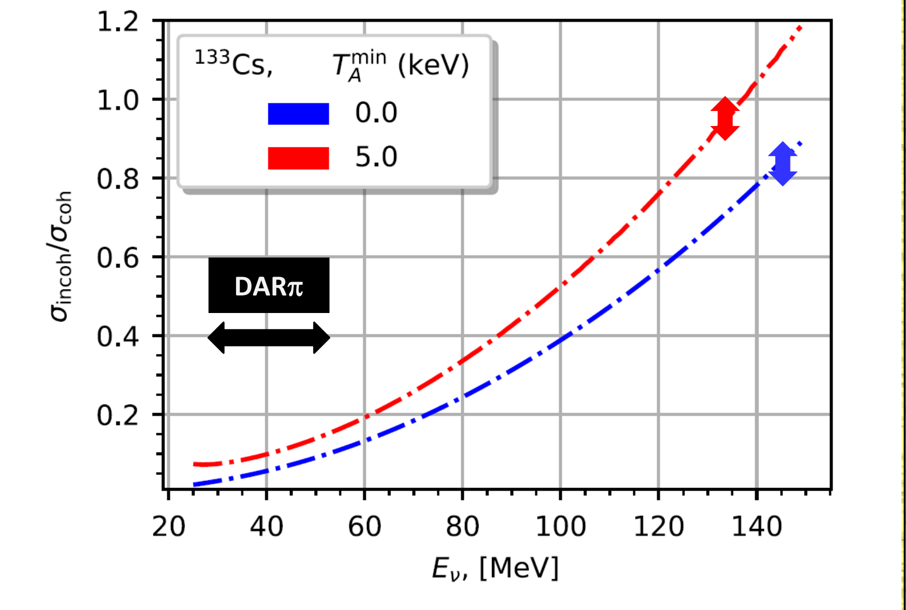
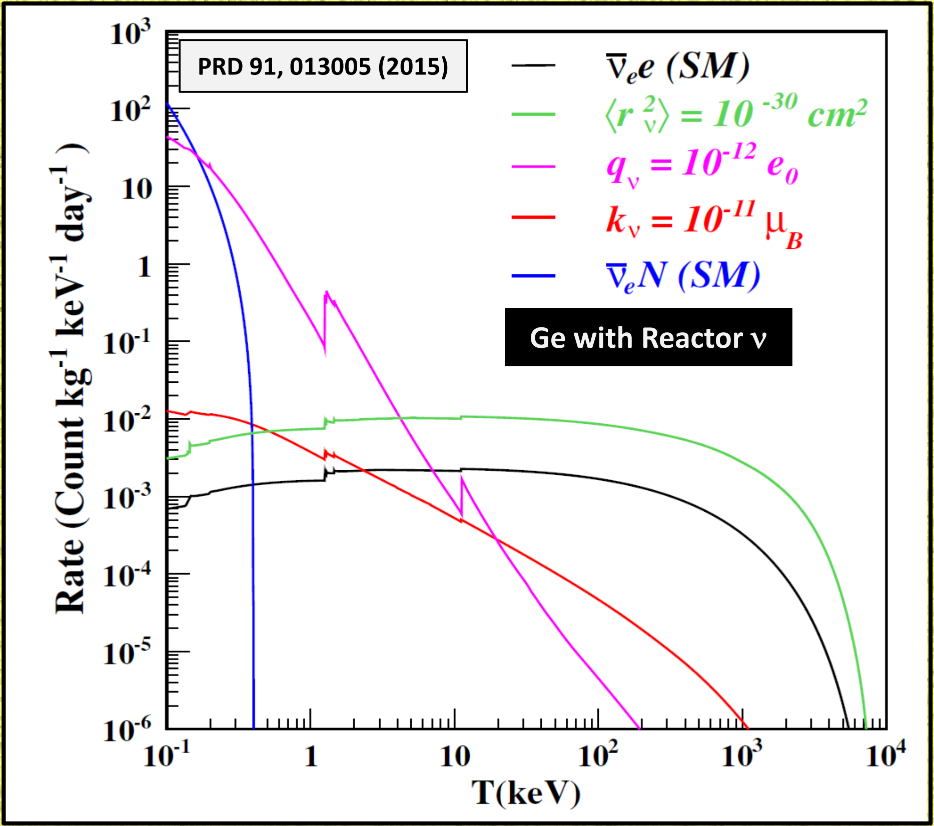
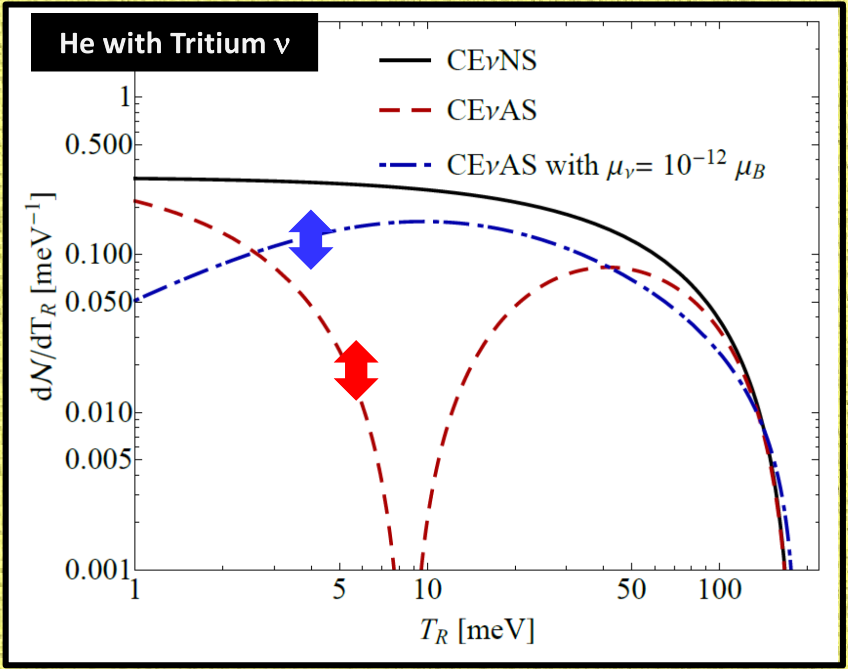


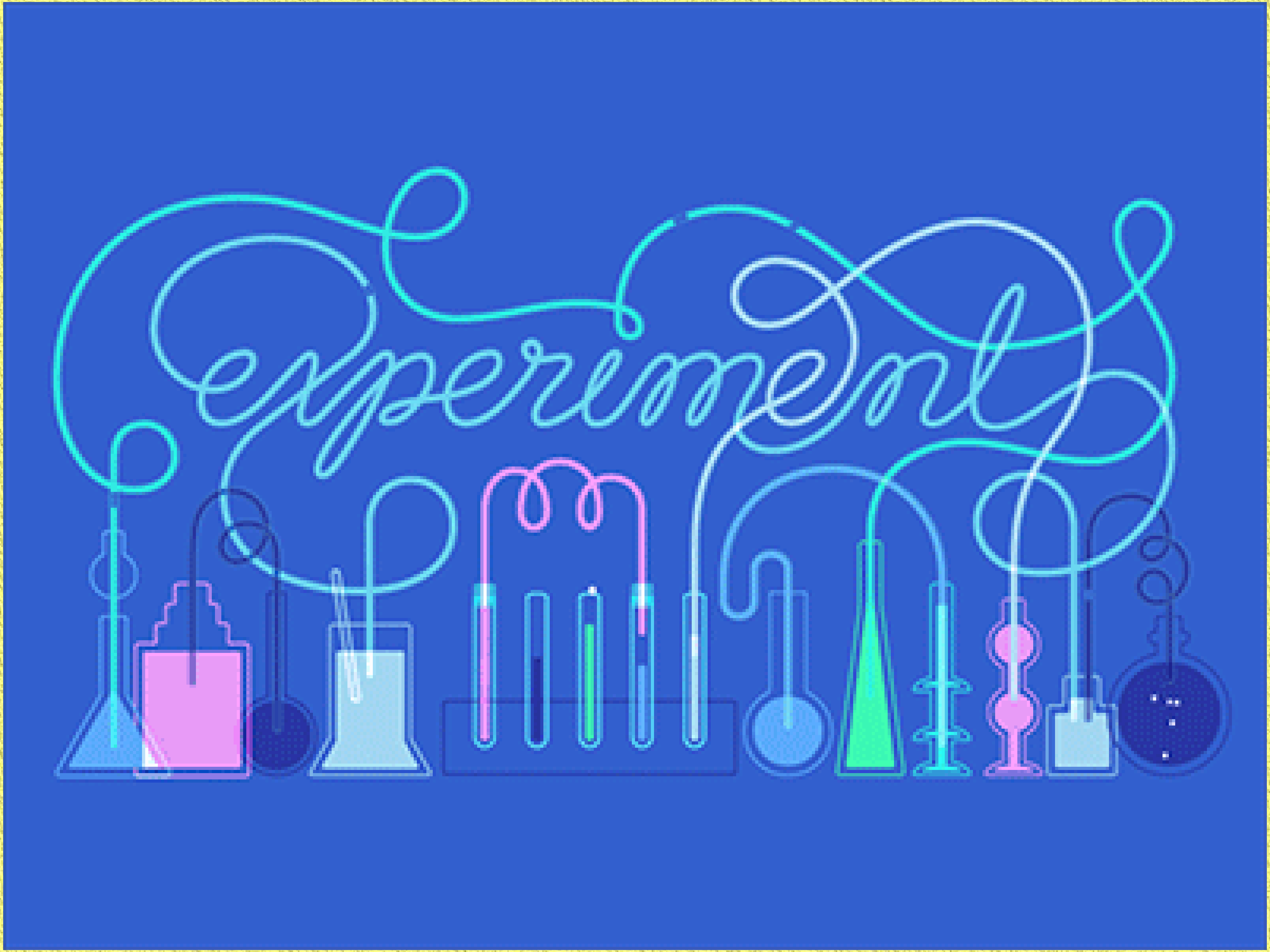
FIG. 8. Ratio $\sigma_{incoh}/\sigma_{coh}$ for neutrino scattering off of a ^{133}Cs nucleus as a function of E_ν. The two curves correspond to a $T_A^{min} = 0(5)$ keV detection threshold.

νA_{el} Atomic Effects at Very Low q^2 [arXiv:1907.03302]:

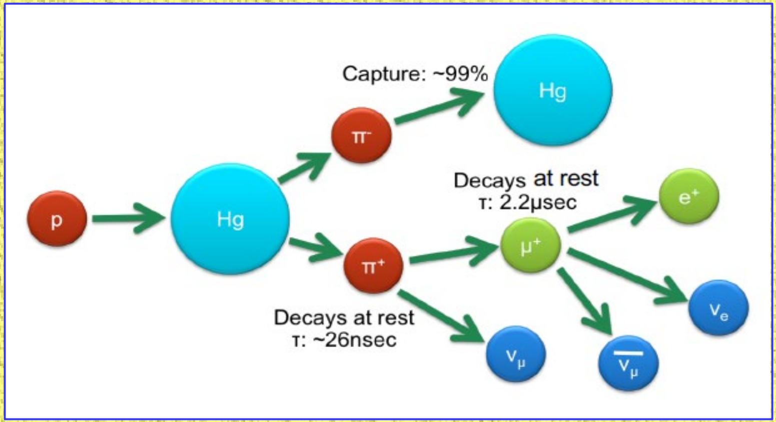
- ☑ Atomic effects known for νe-EW & EM processes
- ☑ Screening by atomic electrons / Enhancement by $q^2 \to 0$
- ☑ νA: Expect --
  - ⇨ effect relevant at Recoil Energy ~ O(10 meV)
  - ⇒ not relevant to current projects






experiment

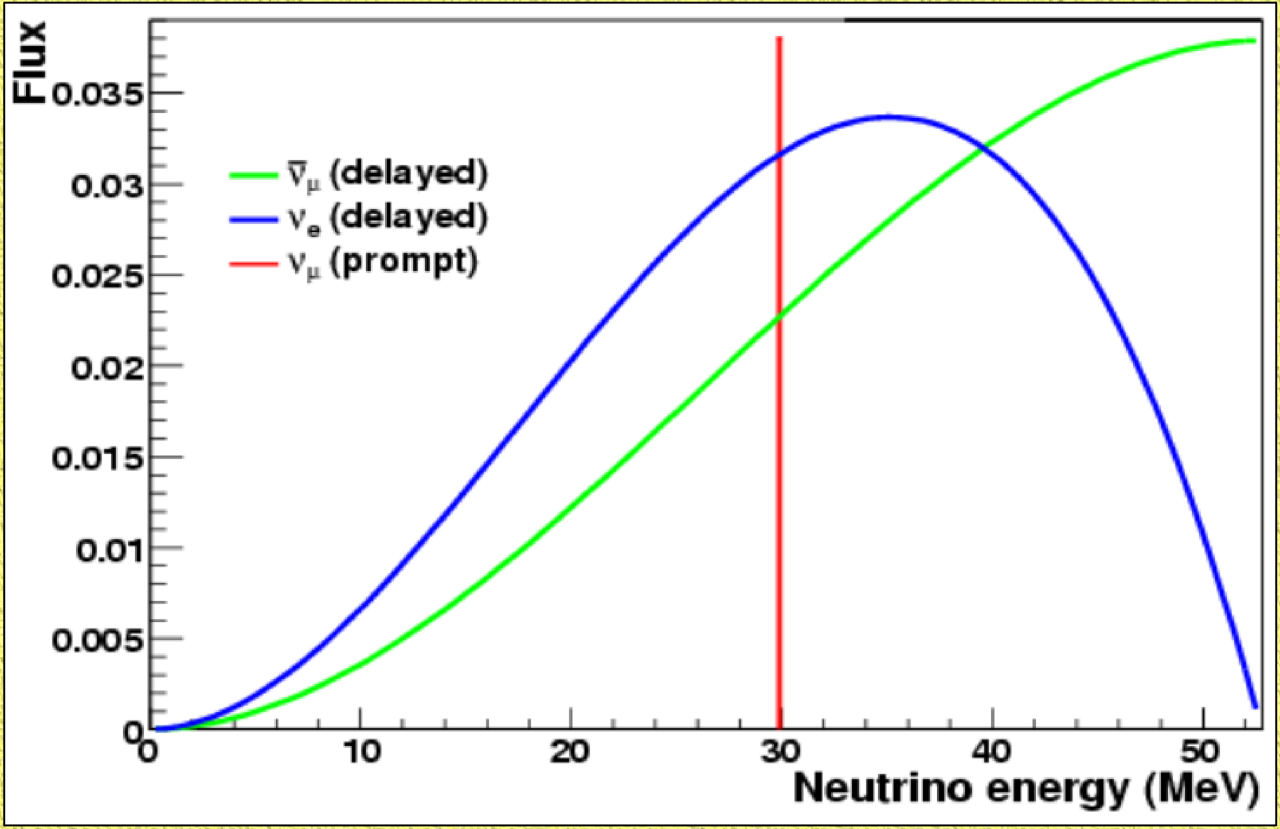
Stopped-Pion (πDAR) Neutrinos



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$ 2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

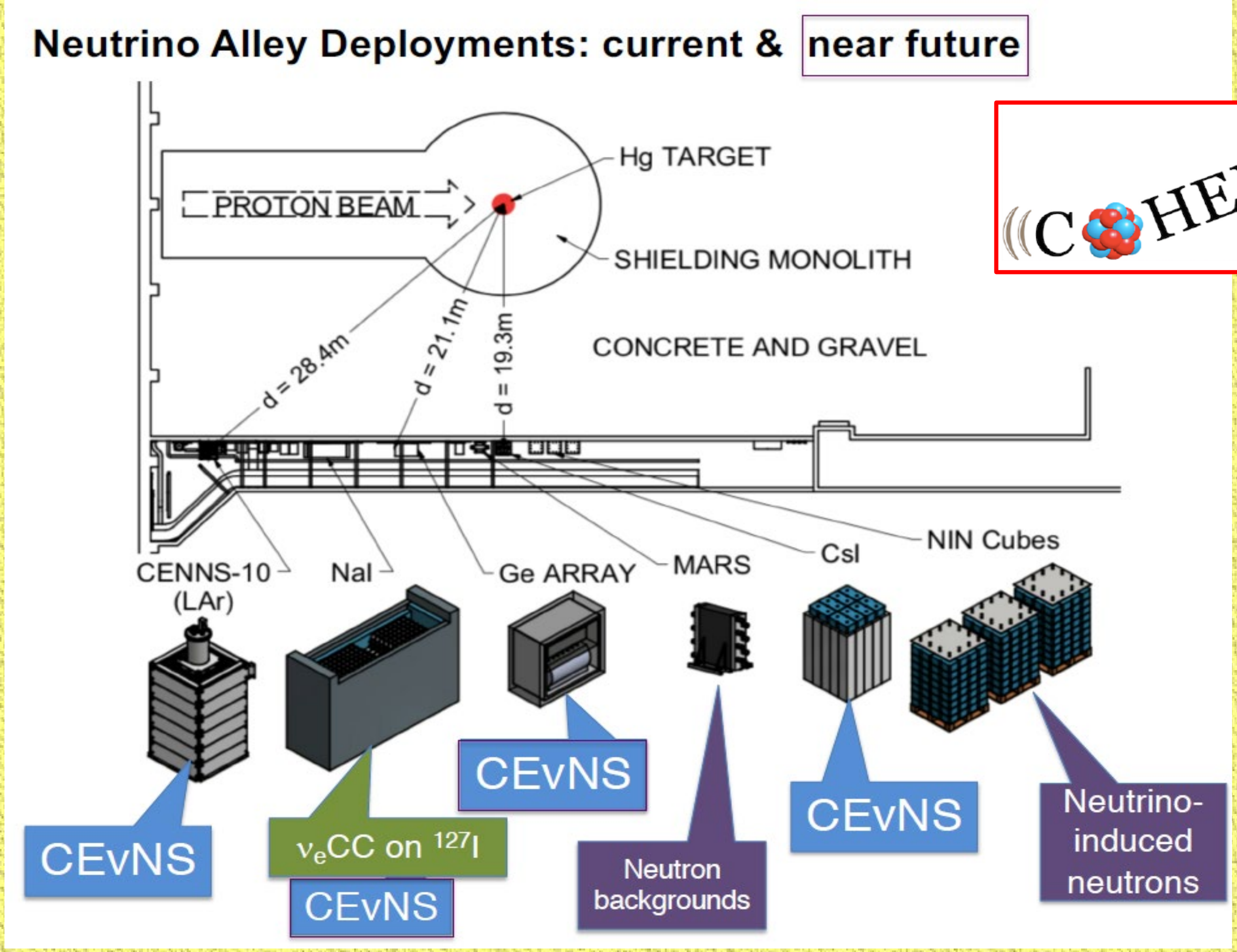
$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$ 3-body decay: range of energies between 0 and $m_\mu/2$ DELAYED (2.2 μs)



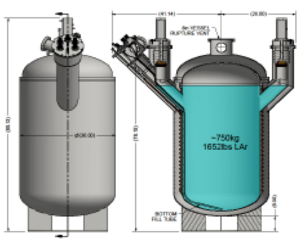
Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz
Liquid mercury target

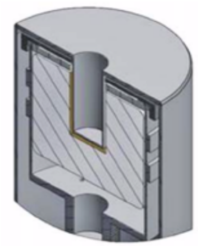
The neutrinos are free!

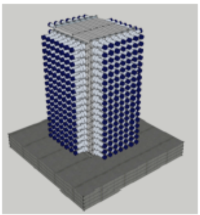


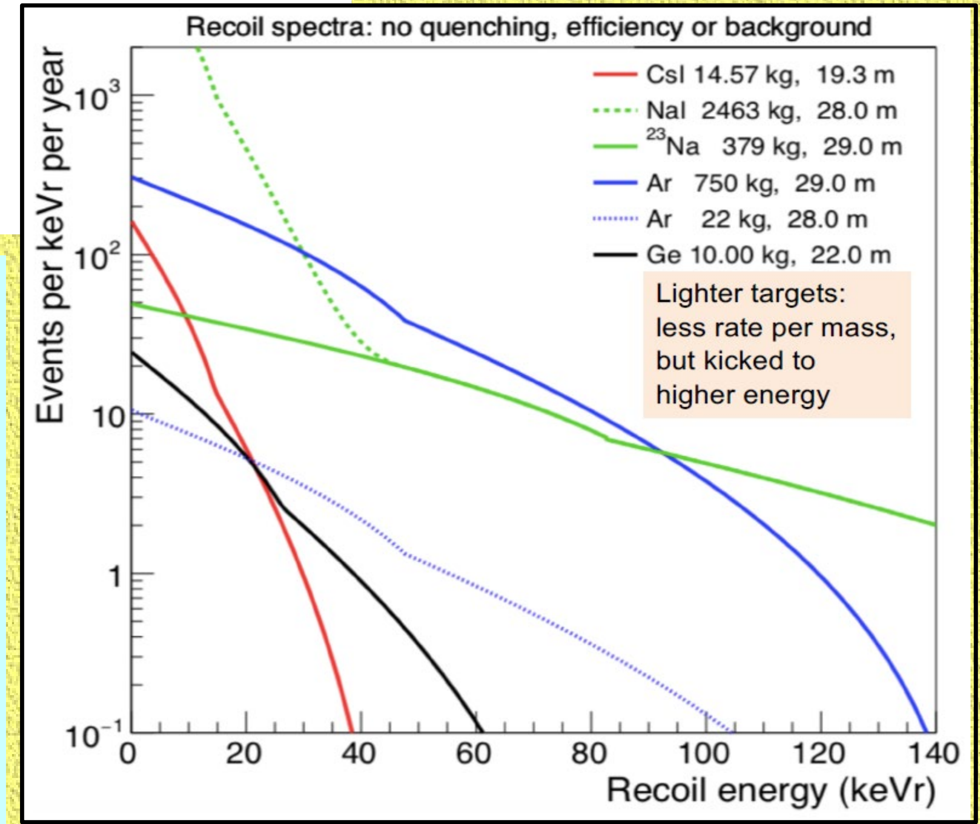
COHERENT

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015	Finishing data-taking
Ge	HPGe PPC	16	22	<few	2019	
LAr	Single-phase	22	29	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	28	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes









Merits:

- ☑ Beam ON/OFF
- ☑ High(er) Energy ν/Signals ; Detector Technologies Exist

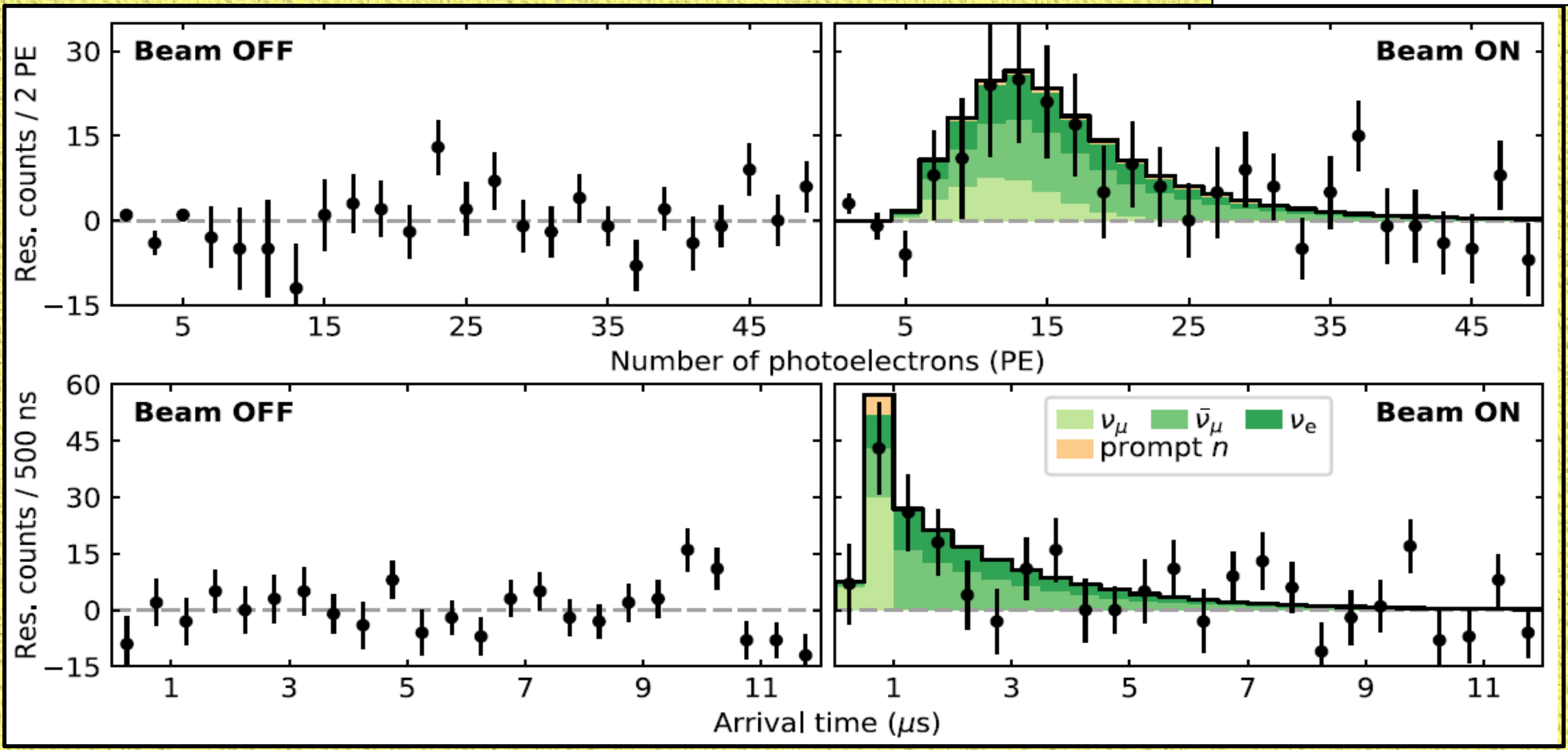
Challenges:

- ☑ $F(q^2)<1$; Coherency Partial
- ☑ Beam-Associated Neutrons
- ☑ ν-Induced Neutrons

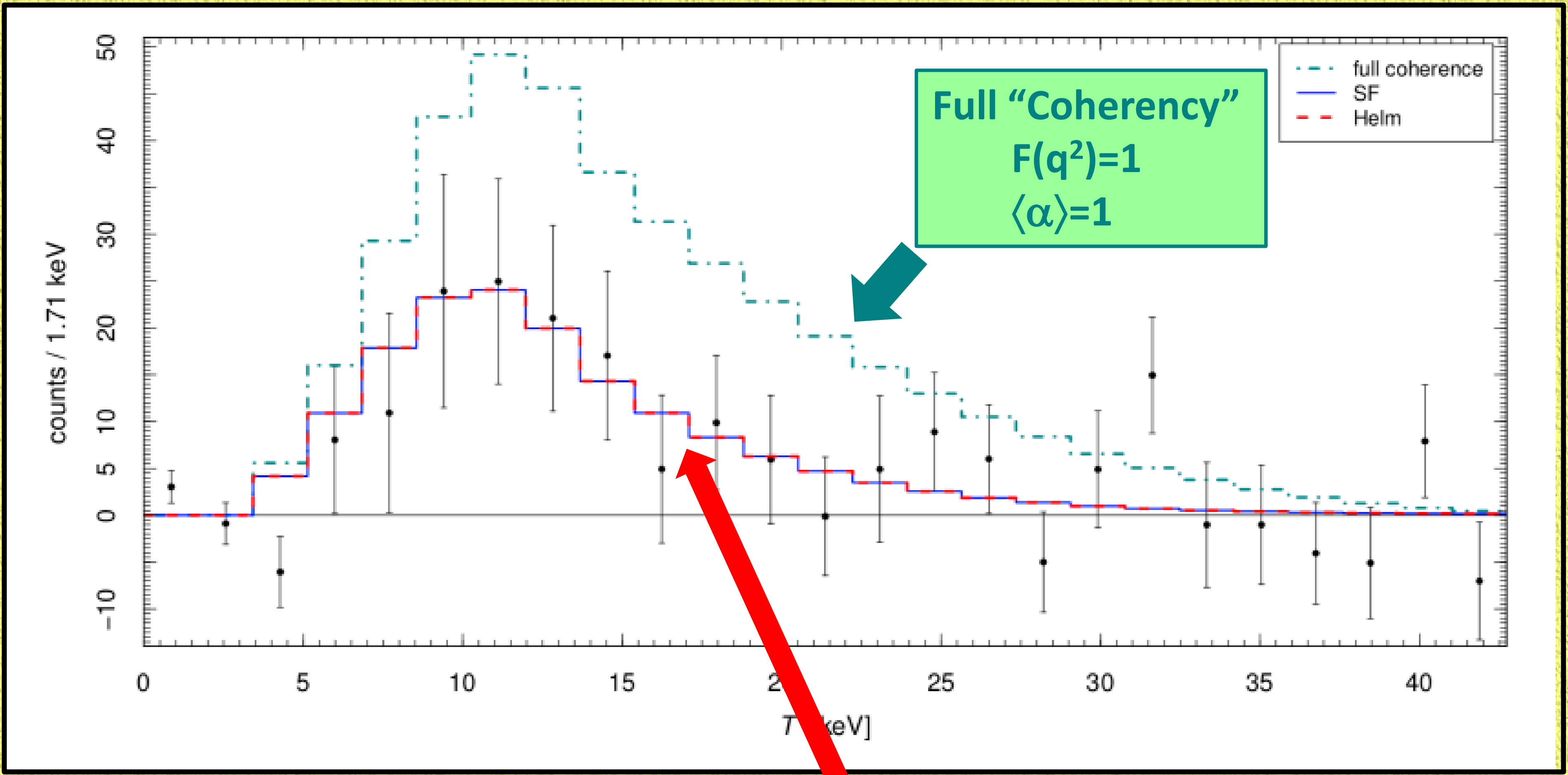
COHERENT CsI(Na) :

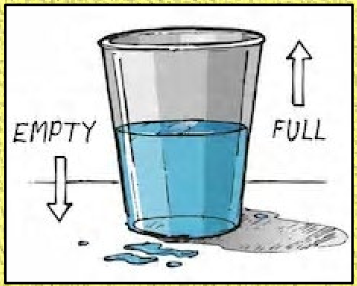
- ☑ ORNL-SNS Beam ~6 GWh ; 1.4 X 10^{23} PoT ; spill 360 ns FWHM
- ☑ ν-flux ~1.7 X 10^{11} /cm2-s
- ☑ DAQ Real Time ~15 months
- ☑ CsI(Na) target 14.6 kg ; 19.3 m from target ;
- ☑ Physics Threshold **5 p.e. (~4.5 keVnr)**
- ☑ SM Prediction: **173 events**
- ☑ Best Fit: **134 ± 22 events**
- ☑ Null Hypothesis Rejected at **6.7 σ**

Cite as: D. Akimov *et al*., *Science* 10.1126/science.aao0990 (2017).



COHERENT CsI(Na) 2017 Beam-On Data





$F(q^2) < 1 \Rightarrow$

Derive parameters in selected FF models

⇨ *assuming no BSM effects of this scale*

⇨ *e.g. Neutron RMS radii to ~20%*

$\langle\alpha\rangle \sim 0.65$

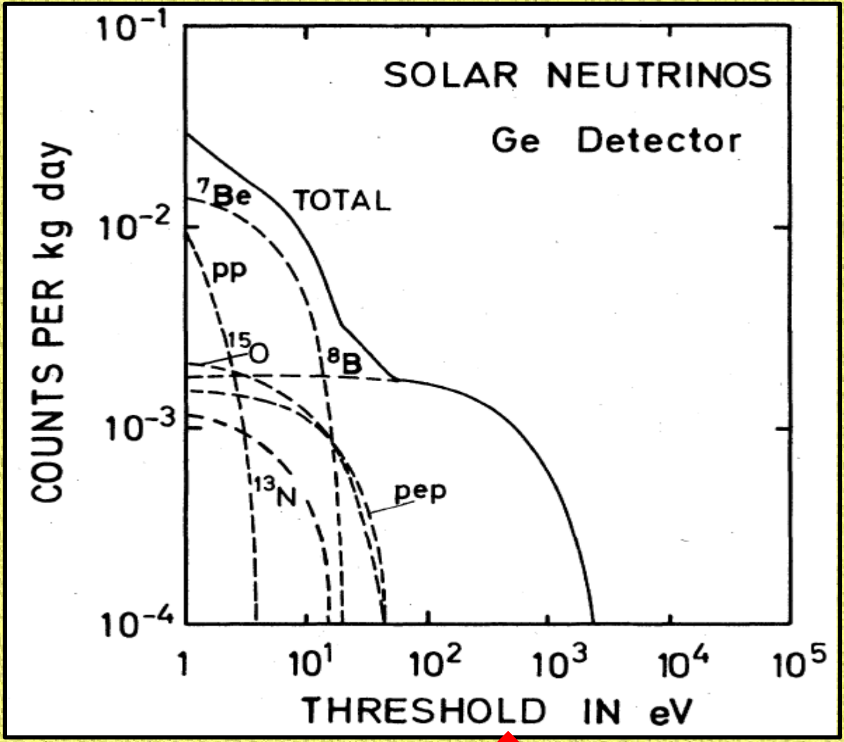
Solar Neutrinos with νA_{el}

- Drukier & Stodolsky, PRD 30, 2295 (1984)
- Cabrera, Krauss & Wilczek, PRL 55, 25 (1985)

ν ⇨ Early Motivations for "Cryogenic" Detectors !!

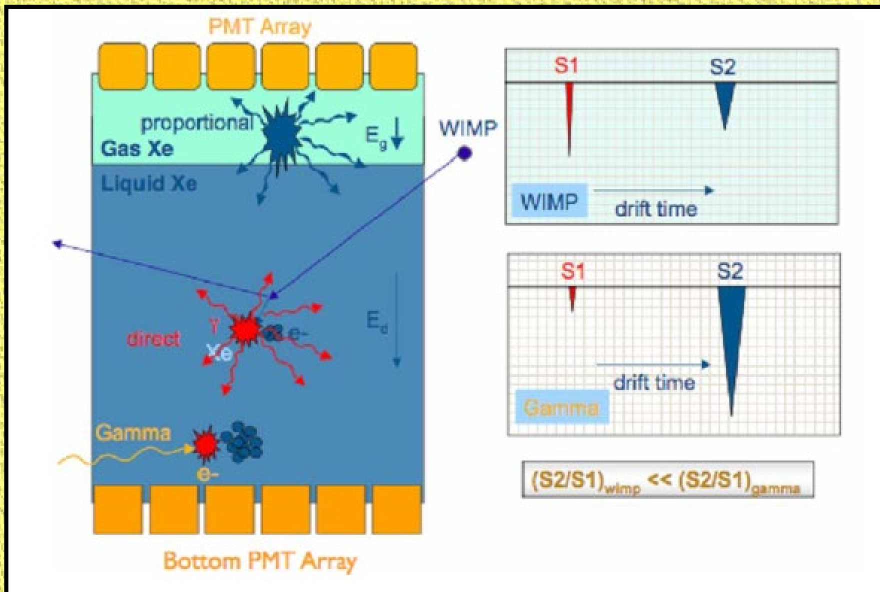
BUT …. Power manifested in Dark Matter Searches, CMB Telescopes …..

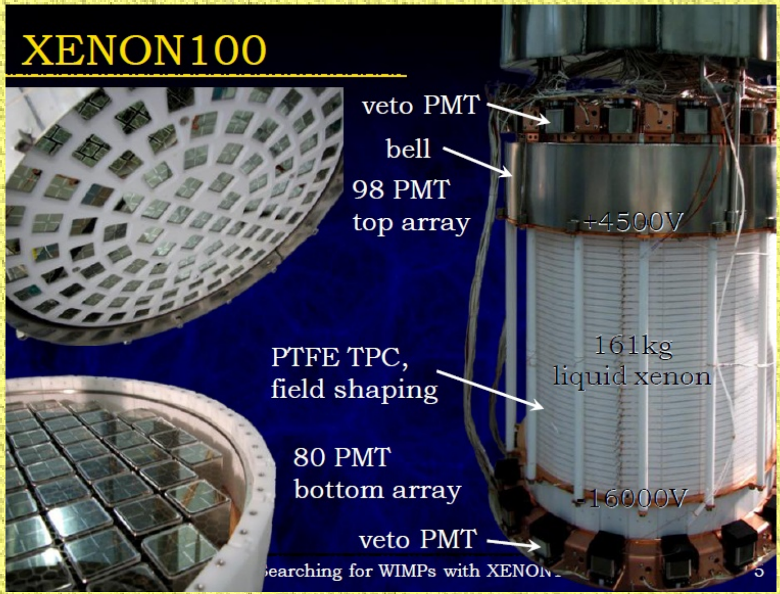
>Ton Scale Detectors

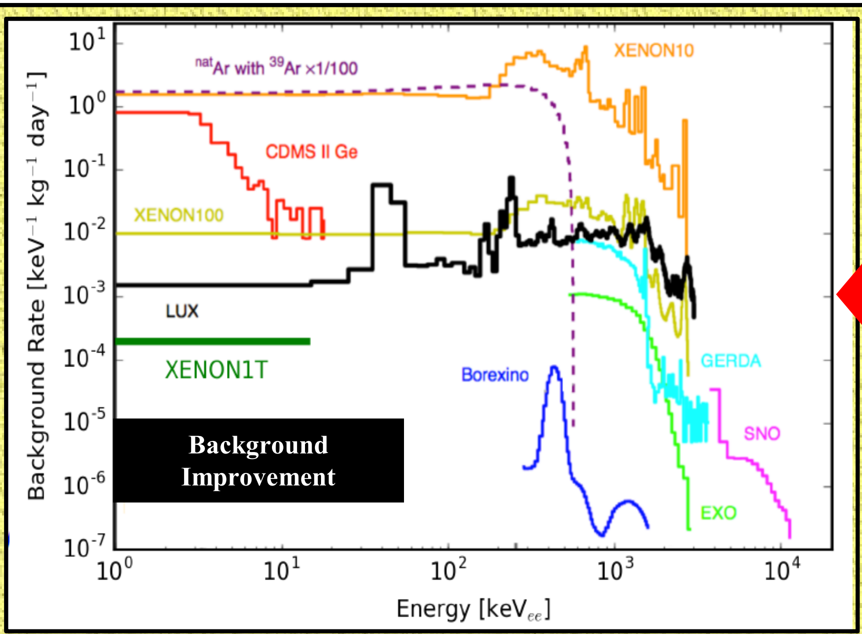


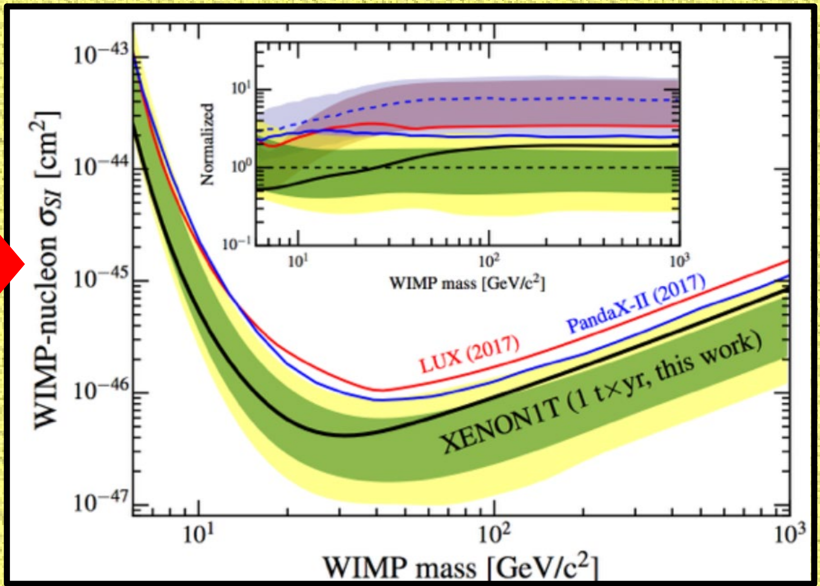
Sub-keV Sensitivity

Two-Phase Liquid Xenon Techniques Dominates the $\sigma_{\chi N}$(SI) Sensitivity Plots at m_χ > 10 GeV

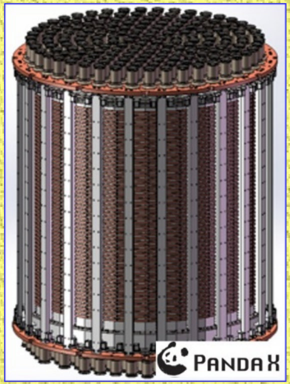








Next(+) Generation Large Liq-Xe Experiments …



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

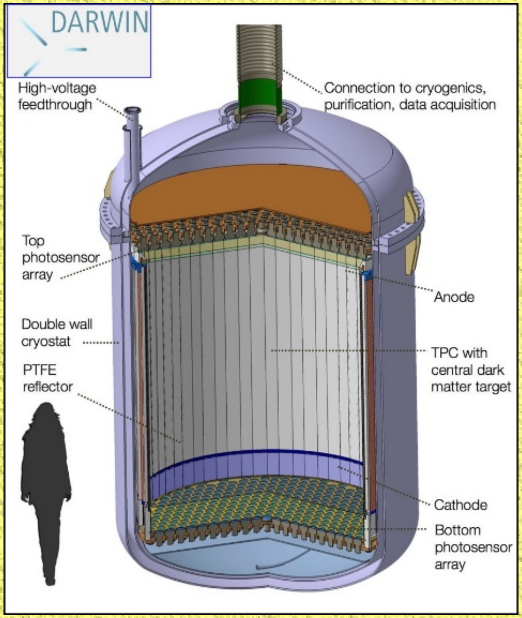
- ☑ @ CJPL
- ☑ Fiducial mass 2.8 ton, threshold 5 keVnr,
- ☑ Background NR~1 /ton-year
- ☑ Neutrino CNNS: 0.3/ton-year
- ☑ On-site assembly and commissioning: 2019-2020

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

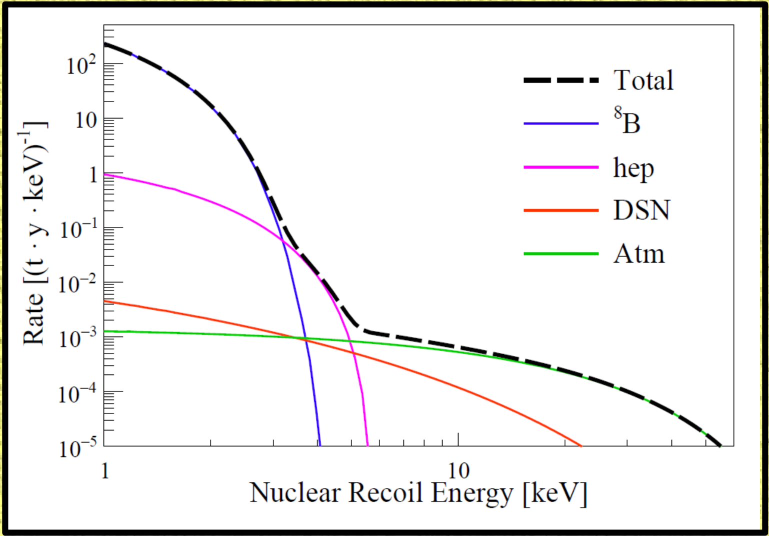
- ☑ @ Gran Sasso
- ☑ threshold 4 keVnr,
- ☑ Background NR~2.5/20 ton-yr
- ☑ Neutrino CNNS: ~4.7/20 ton-yr
- ☑ Operation: 2019-2025



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 …



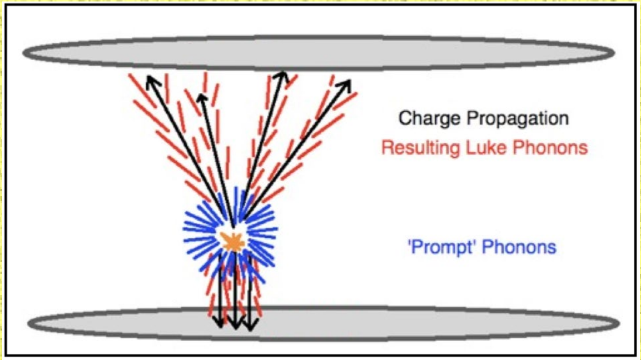
Expectation values of events in XENONnT, in 20 t·y exposure

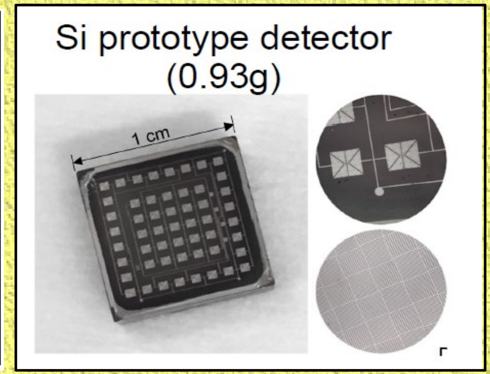
	No discrimination	99.75% ER discrimination
Signal (μ_s)		
6 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-46}$ cm^2)	0.68	0.27
10 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	4.65	1.86
100 GeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-48}$ cm^2)	7.13	2.85
1 TeV/c^2 WIMP ($\sigma = 2 \cdot 10^{-47}$ cm^2)	8.85	3.54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

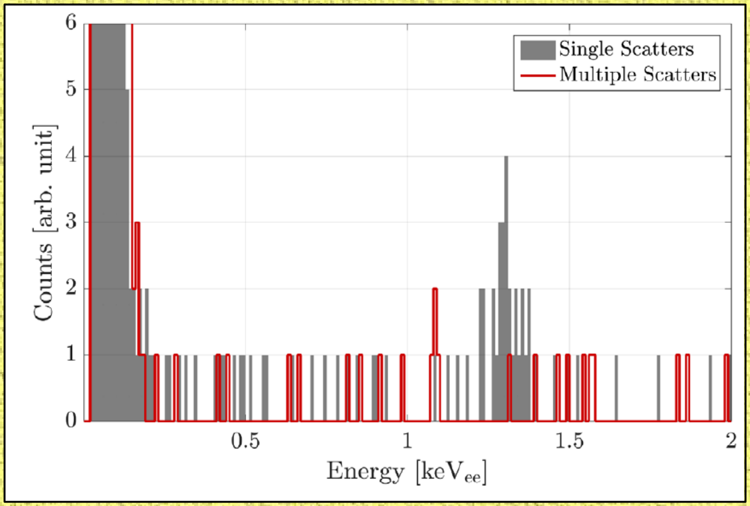
- ☑ Typical threshold for Liq-Xe experiments with **"(S1,S2)" for ER/NR differentiation** is light yield corresponding to "averaged" <~4 keVnr>, nominally too high for solar νA_{el}
  - ➢ Large spread in event-wise ***keVnr ⇔ light yield*** conversion (Poisson, energy resolution, fiducial non-uniformity) ⇒ 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

Consultation with K. Ni & L. Baudis

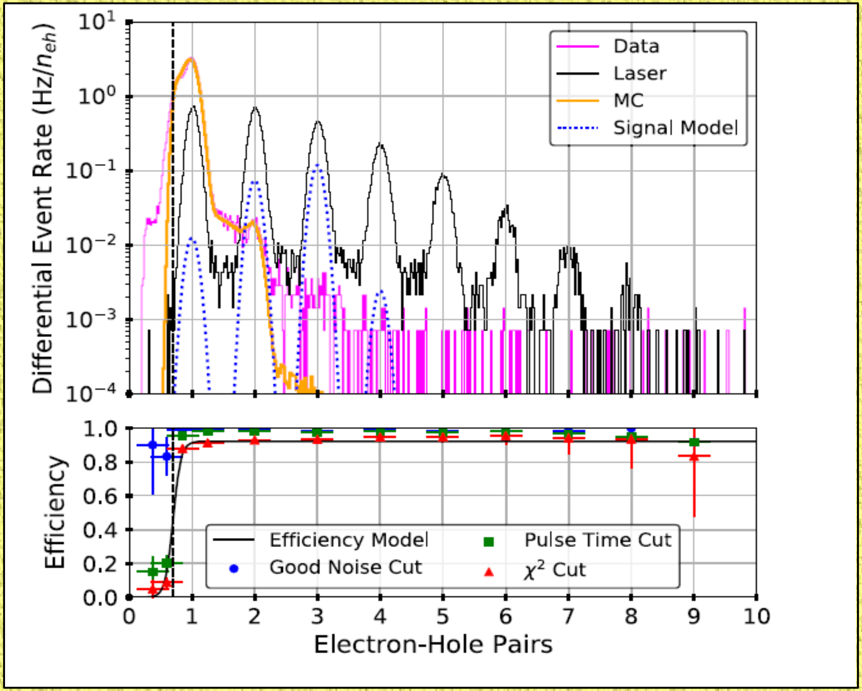
SuperCDMS ["Neganov-Trofimov-Luke Effects" (Bolometric Amplification)]



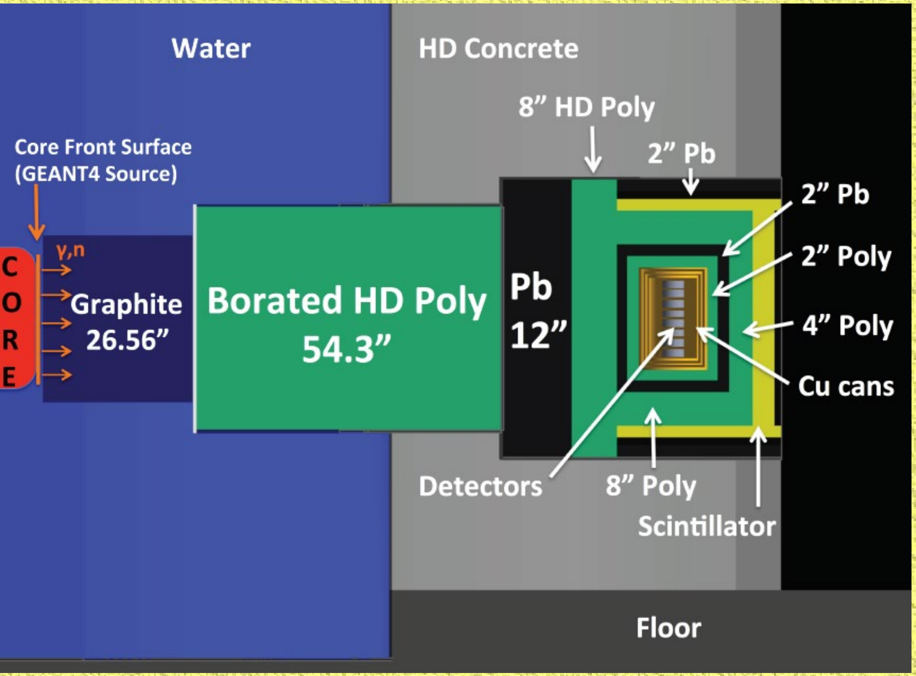




- **CDMSlite @ Soudan** *[PRD18]*
  - ☑ **600 g Ge target,**
  - ☑ **R2: 70.1 kg-d**
  - ☑ **DM-N Threshold ~56 eVee**
- **HVeV @ SNOLab** *[PRL18]*
  - ☑ **0.93 g Si @ 33 mK, 140 V**
  - ☑ **0.49 g-d data**
  - ☑ **Threshold~1 eh (3 eV)**
  - ☑ **DM-electron scattering Probe m_{DM}~1 MeV**
  - ☑ ***Also dark photon constraints***



MIνER ….. @ TAMU ~MW Research Reactor

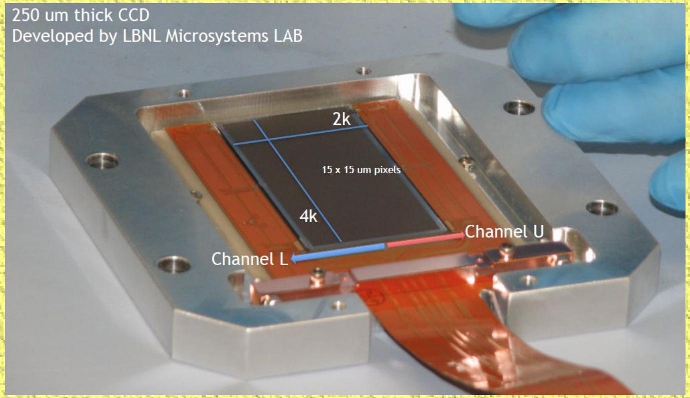


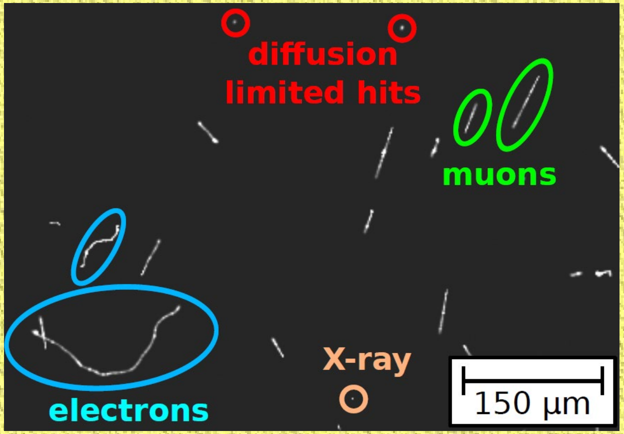
- ☑ 1 MW Research Reactor ; **2-3m distance!** ~15 mwe
- ☑ CDMSlite-type cryogenic detector (bolometric amplification); Ge/Si ; O(100 eVee) threshold demonstrated
- ☑ Rate: 1000 /kg-day at 10 eVnr threshold
- ☑ Moveable Core tests short baseline oscillation
- ☑ 10 kg payload with sensitivity to CNS in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

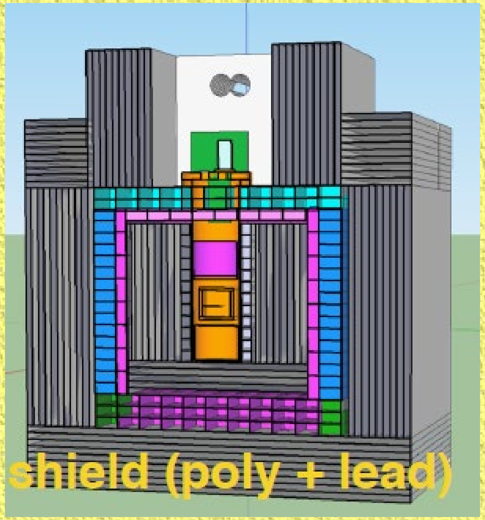
Status:

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

….. @ Angra II 3.8 GW Power Reactor





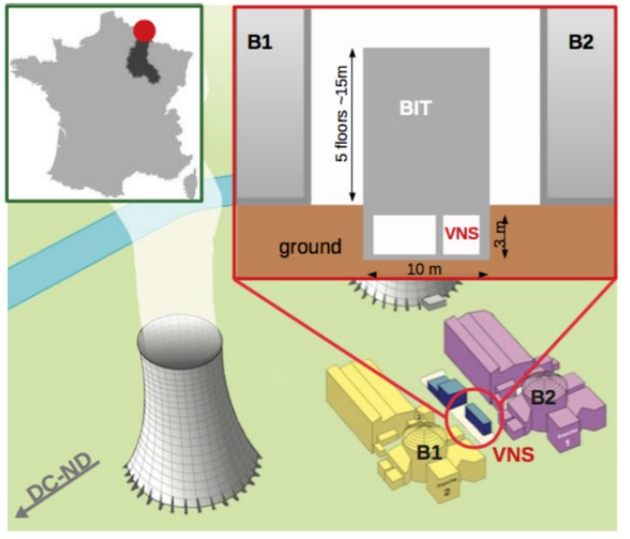


- ☑ 3.8 GW MW Research Reactor ; 30 m distance
- ☑ Advanced CCD (Si) detector ; ~40 eVee threshold ; Event ID capabiities

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

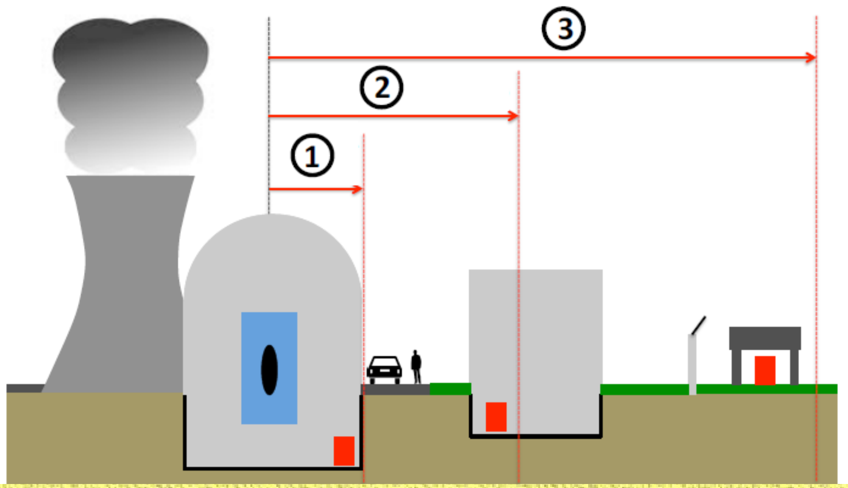
- ☑ Engineering Run, 1-g detector, completed and successful
- ☑ Data taking with O(100 g) detector.
- ☑ Challenges: Background, Long integration time, small mass …..

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 $O(1\ d^{-1})$



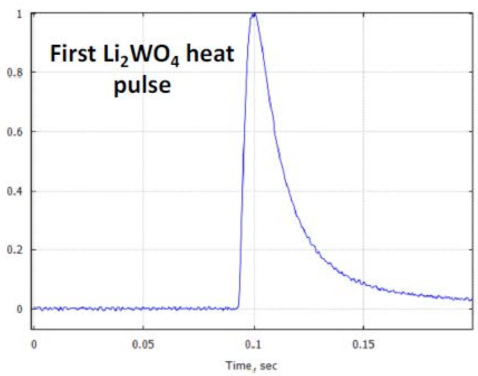
→ **VNS at Chooz**

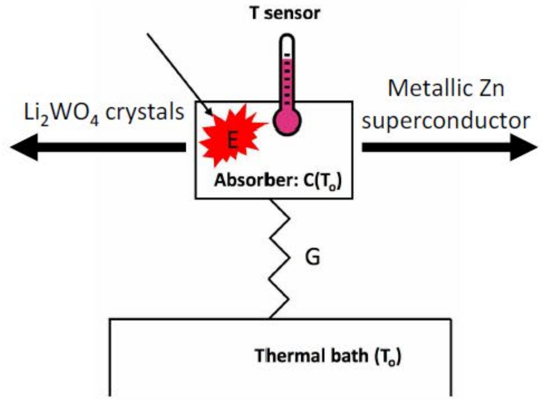
100 m/70 m

→ **DC near lab**

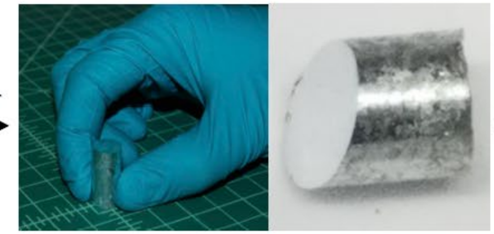
Candidate Detectors: *“to repurpose DM & 0νββ bolometers”*

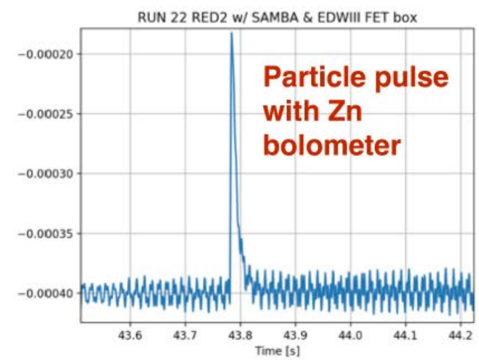
BASKET program





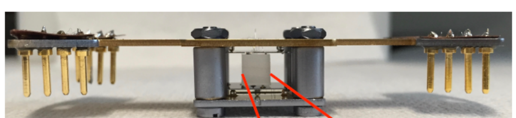
RICOCHET program



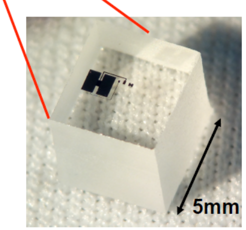


NU-CLEUS

gram-scale cryogenic calorimeters



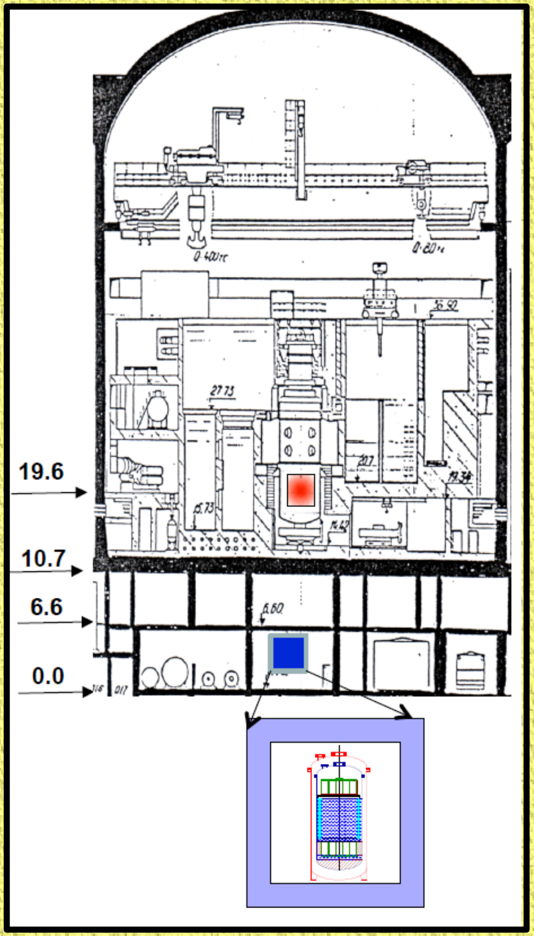
It's tiny, but it's great!

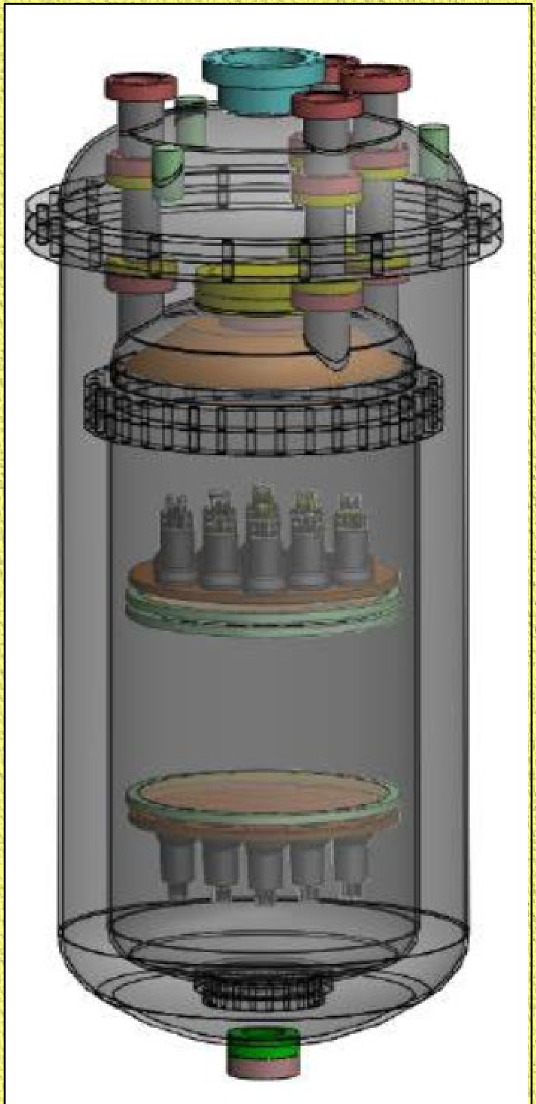


E_{th} = 20eV -
world-best energy threshold for nuclear recoils

- ☑ 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

νGeN @ Kalinin 3 GW Power Reactor

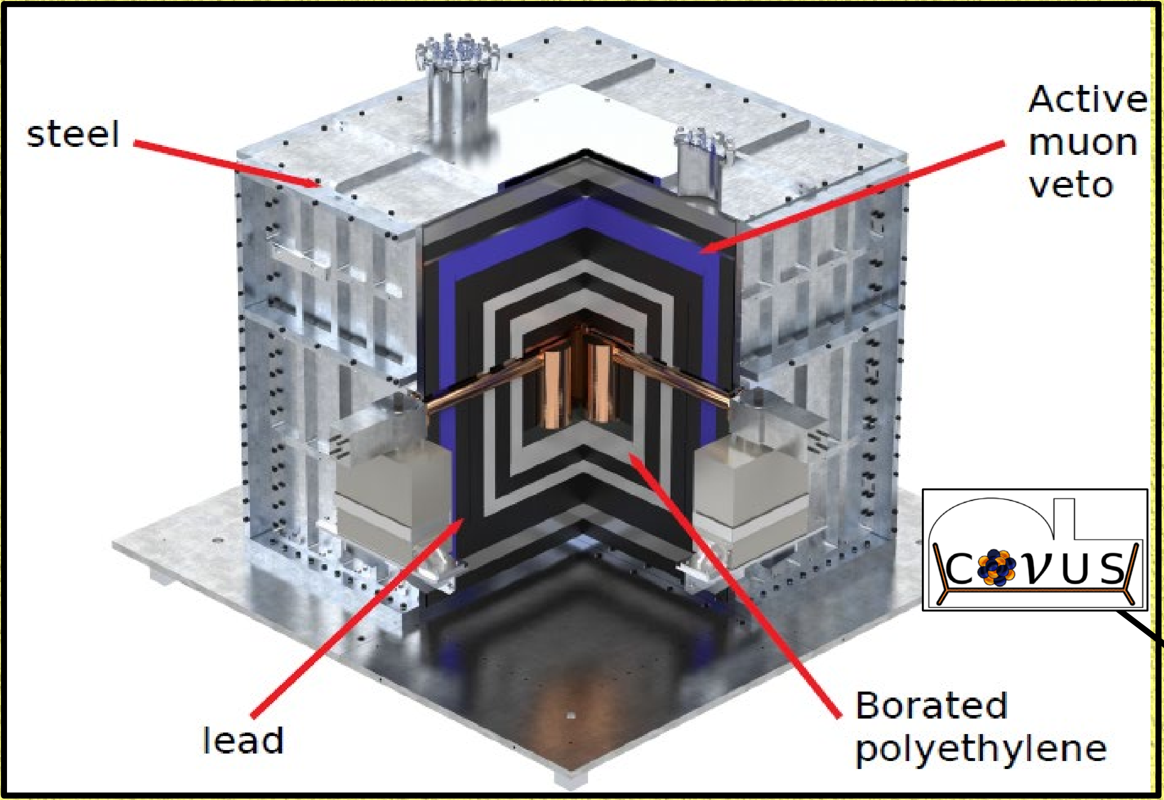
Passive shielding:
- 10 cm copper
- 8 cm borated polyethylene (3%)
- 10 cm lead
- 8 cm borated polyethylene

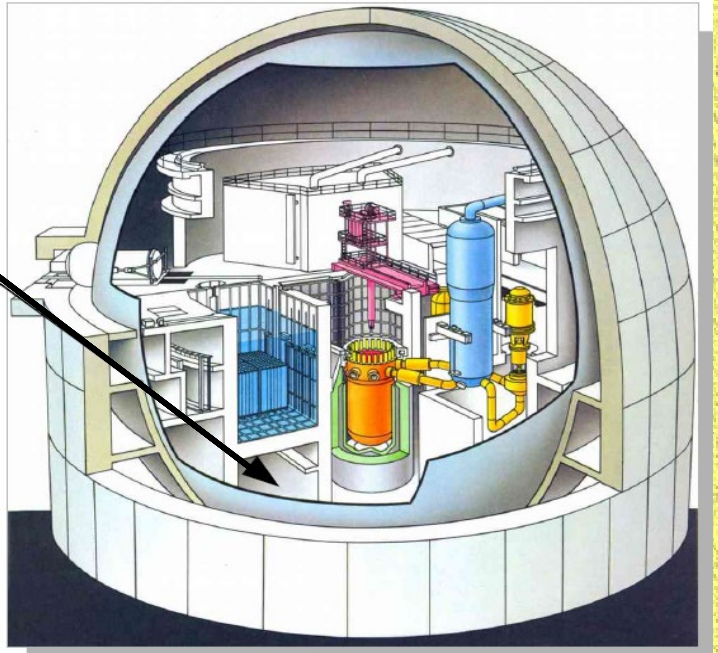
+ muon veto (5 cm)

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

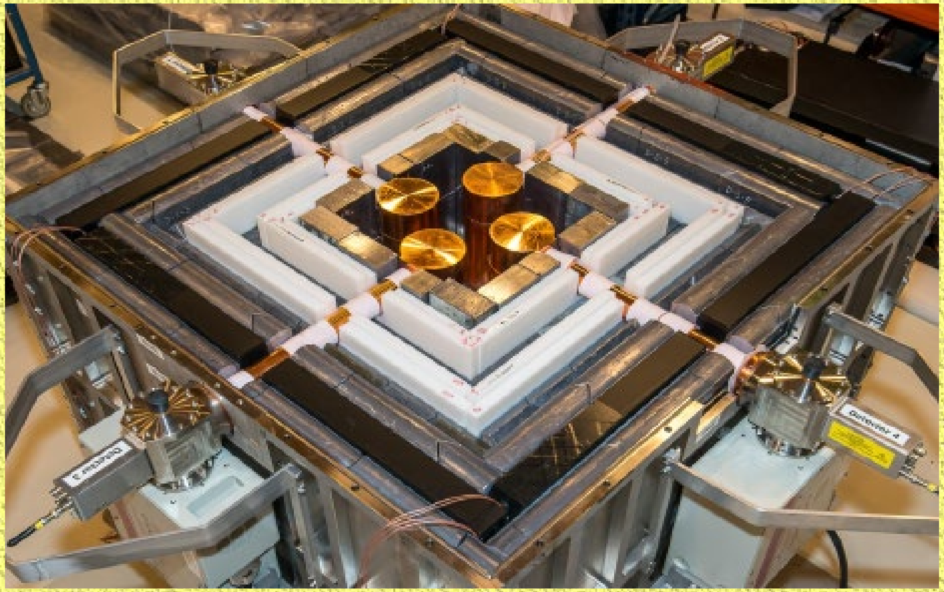
☑ **Challenges:** **Threshold & Background …**

CONUS: Coherent Neutrino nUcleus Scattering



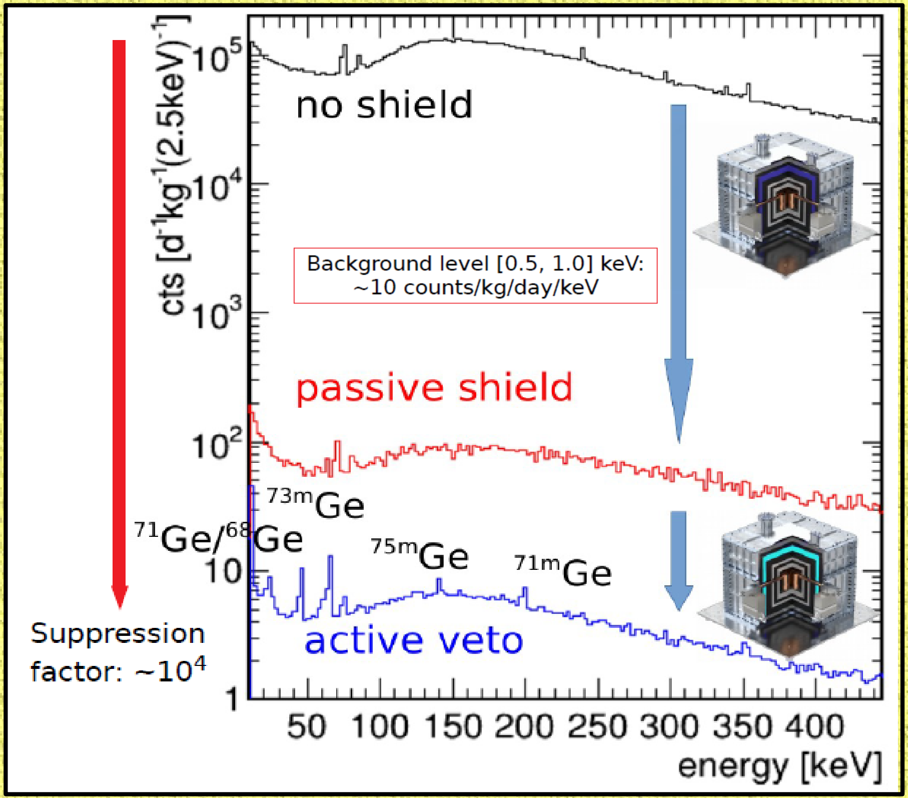


location: nuclear power plant in Brokdorf (GER)
detector core distance: 17 m
core strength: 3.9 GW(max.)
total Ge detector mass: 4 kg
goal noise threshold: <=300 eV
goal bg rates in ROI: O(bg) = 10 cts/(d*kg*keV)
commissioning/data collection: in progress



Detector performance under lab conditions

detector	Pulser FWHM [eV_{ee}]
C1	74 ± 1
C2	75 ± 1
C3	59 ± 1
C4	74 ± 1

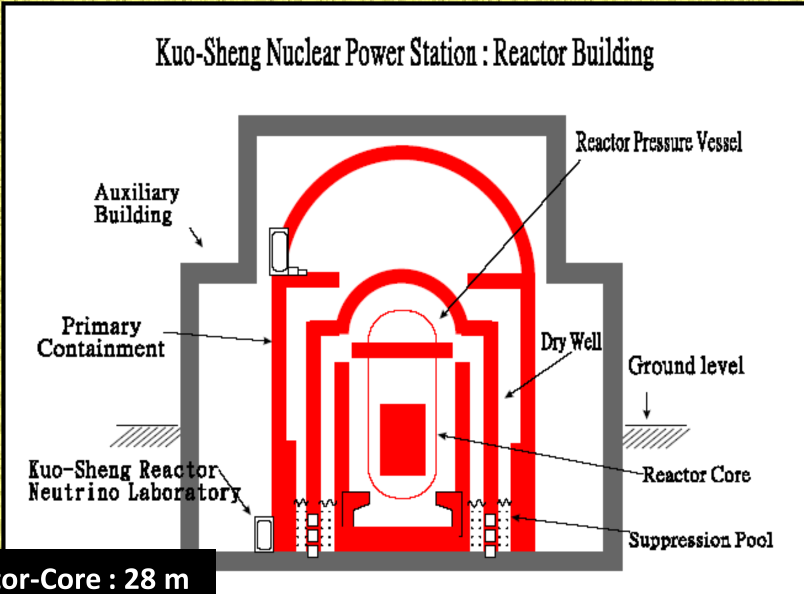


Summer 2019

Preliminary result (only 3 detectors)

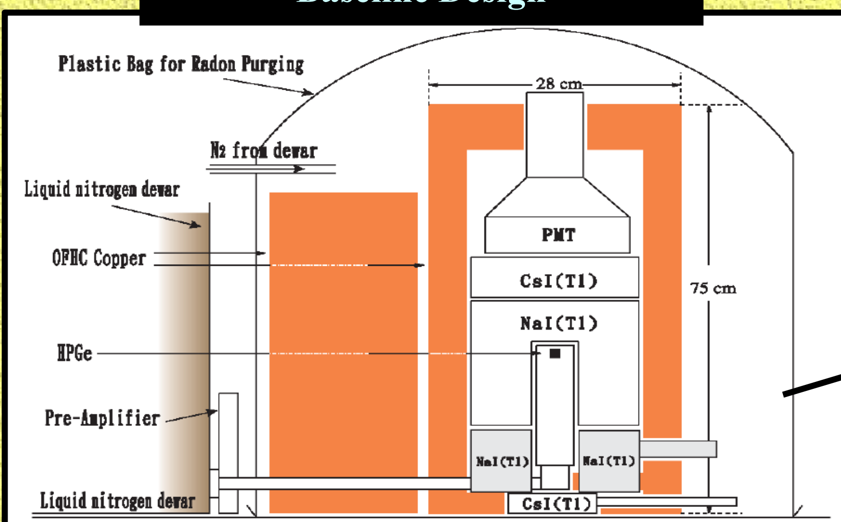
Analysis [300; 550] eV_{ee}	**counts**
Reactor OFF (65 kg*d)	354 ± 19
Reactor ON (417 kg*d)	2405 ± 49
Residual ON-OFF	133 ± 130

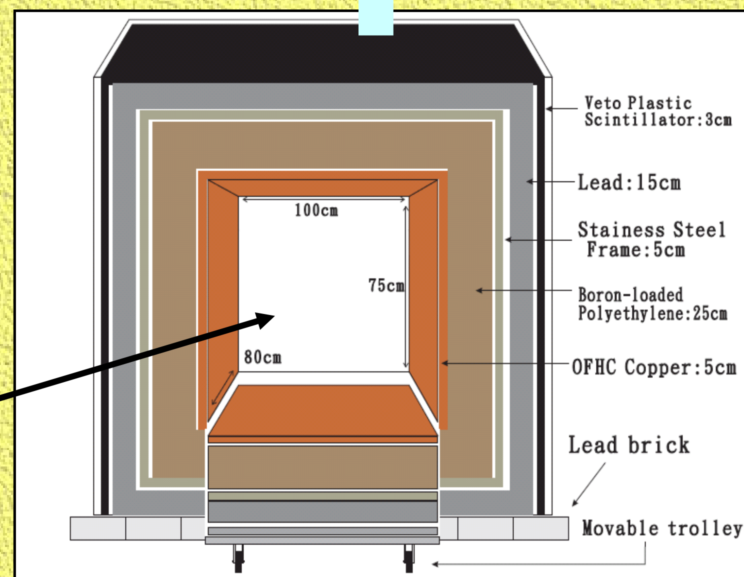
TEXONO at Kuo-Sheng Reactor Neutrino Laboratory (KSNL) in Taiwan



Detector-Core : 28 m

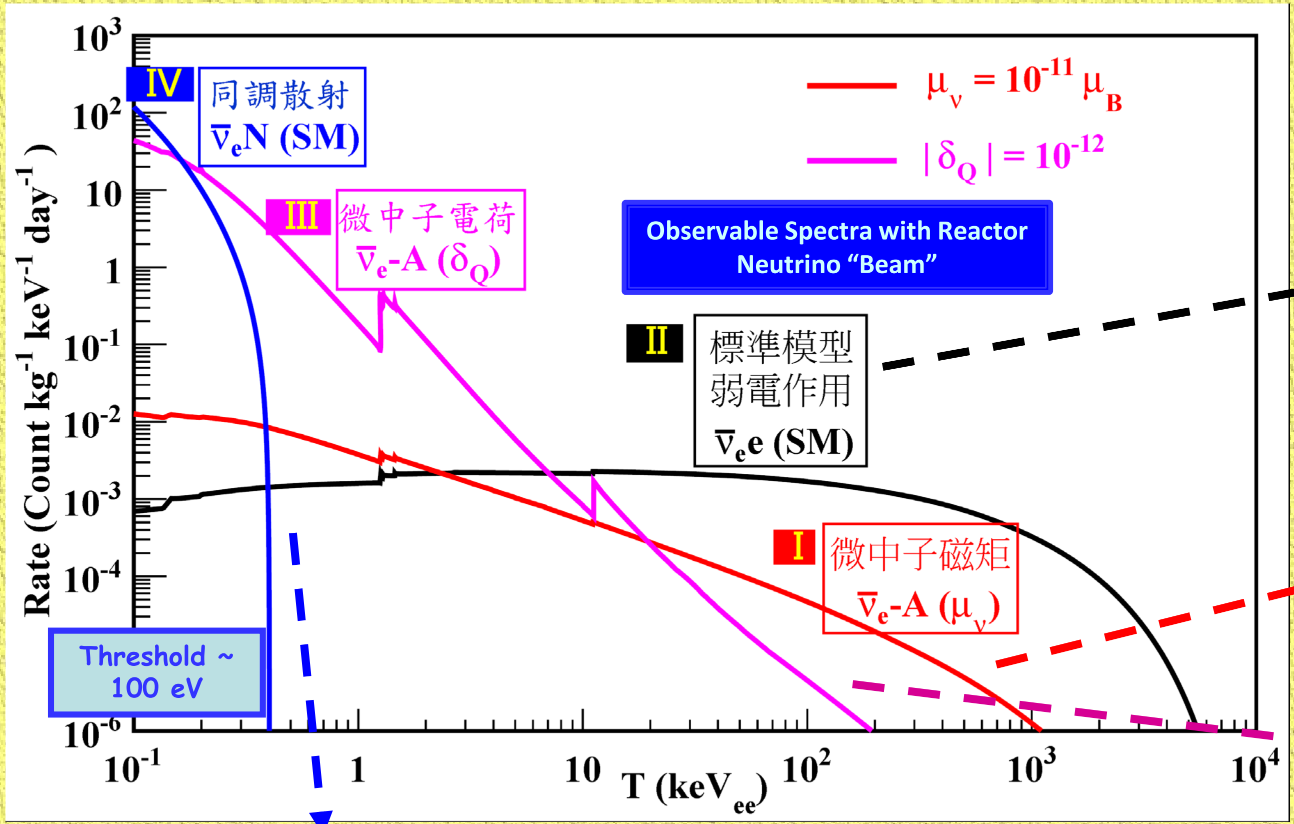
Baseline Design

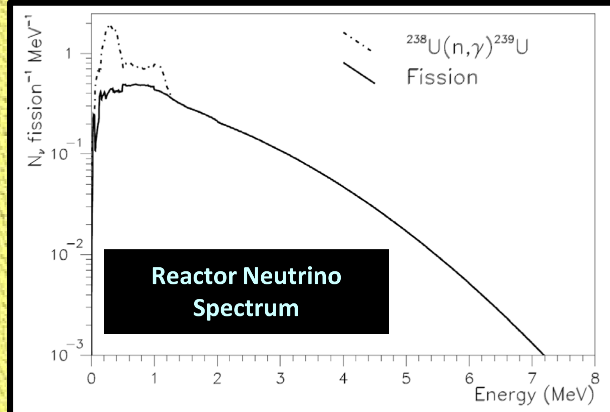




Neutrino Properties & Interactions at Reactor

quality ← **Detector requirements** → **mass**





ν-e Scattering SM *[PRD10]*
& NSI/BSM
[PRD10,PRD12,PRD15,PRD17]
⇨ **200 kg CsI(Tl)**

Magnetic Moments
[PRL03,PRD05,PRD07]
⇨ **1 kg HPGe**

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

νN Coherent Scattering *[Current Theme;PRD16]*

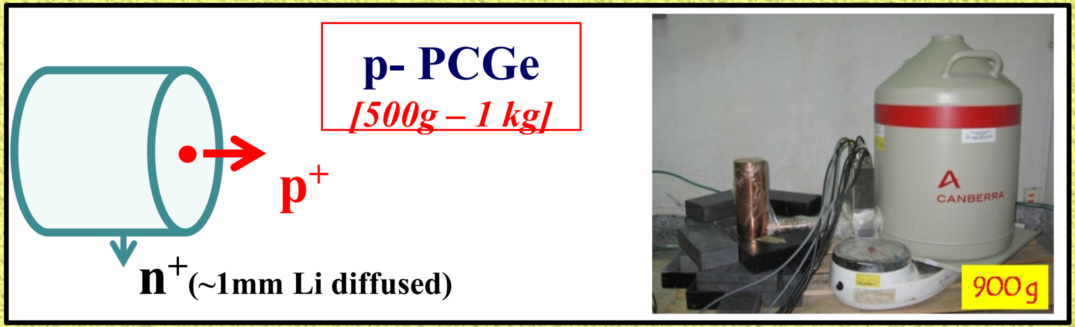
⇨ **sub-keV O(kg) ULEGe / PCGe**

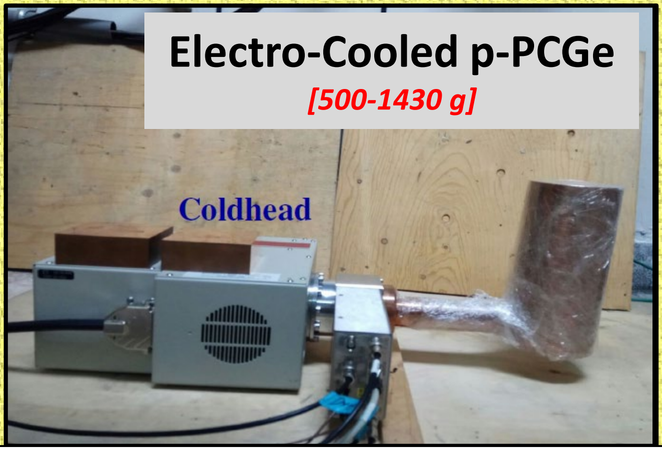
↳ **Dark Matter Searches @ KSNL** *[PRD09,PRL13,AP14]*

↳ **CDEX Dark Matter @ China Jinping Underground Laboratory (CJPL)** *[PRD13,2XPRD14,PRD16,PRD17,PC17,PRL18]*

➡ **Future Ge-based Projects at CJPL :**
DM & 0νββ

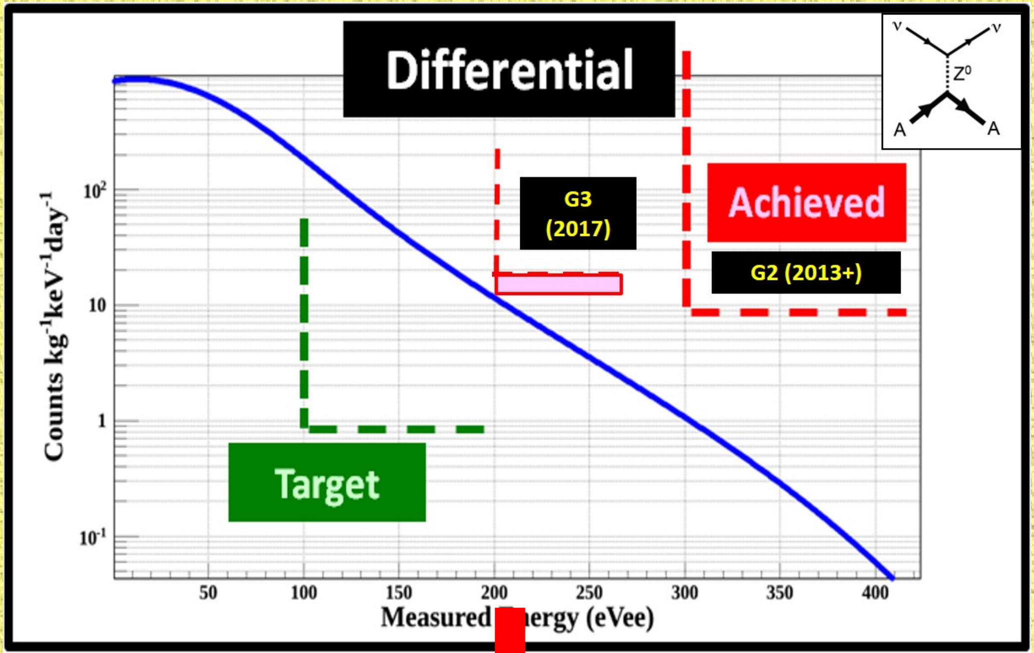
Sub-keV Ge Detector Techniques : Hardware/Software Development

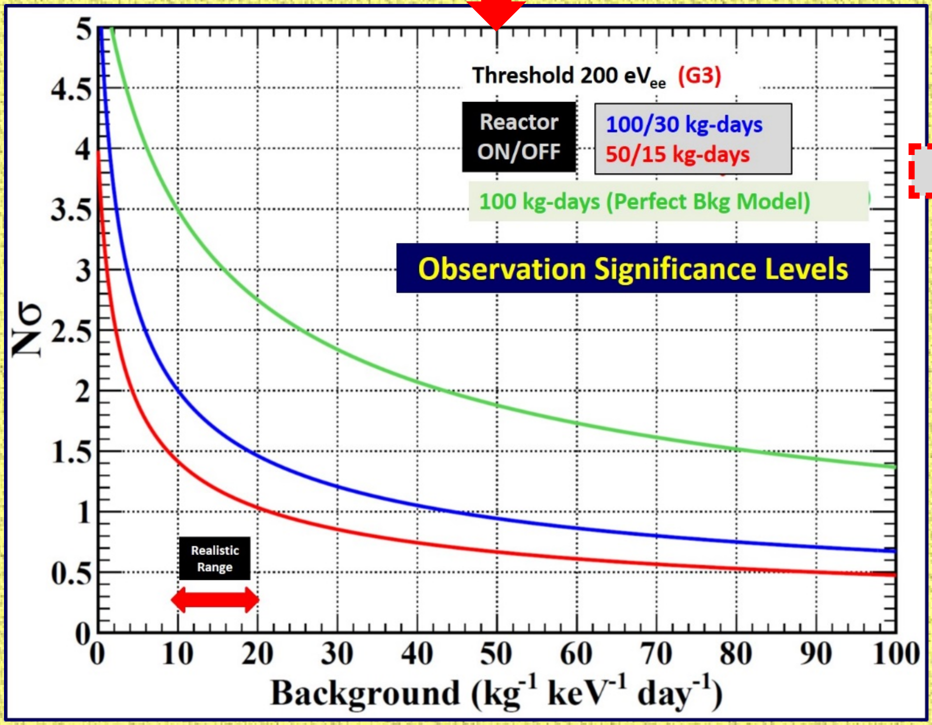


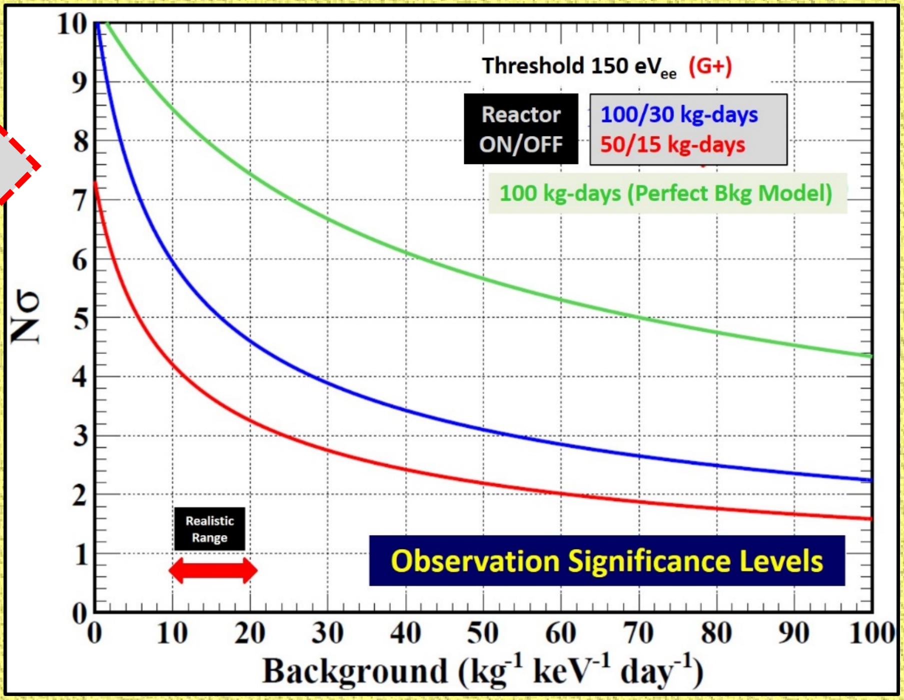


- Quenching Factors -- nuclear recoils' Ionization Yields
- Energy Definition & Calibration
- Trigger Efficiencies near threshold
- Bulk Vs Surface Events Selection – algorithms & efficiencies
- Physics Vs Noise Pulse-Shape Selection -- algorithms & efficiencies

Projected Sensitivities: νA_{el} at KSNL



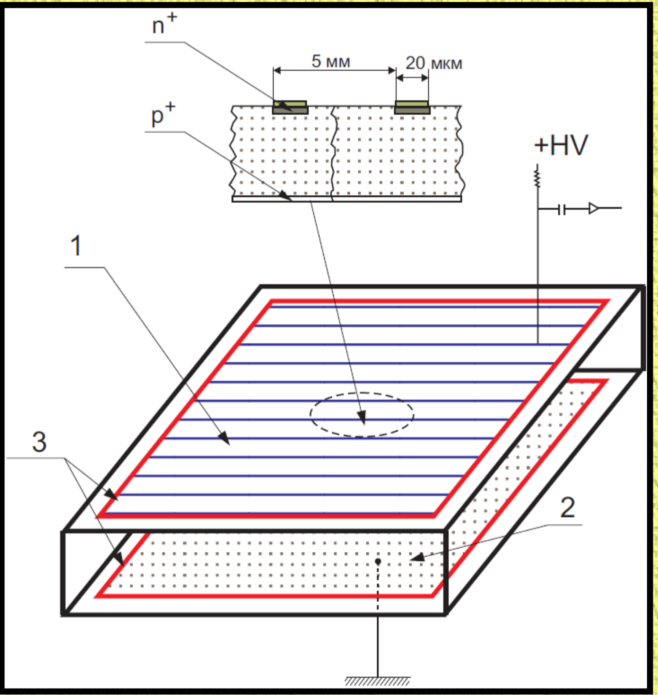




R&D on Ge-Ionization with Charge Amplification

GEMADARC
Germanium Materials and Detectors Advancement Research Consortium

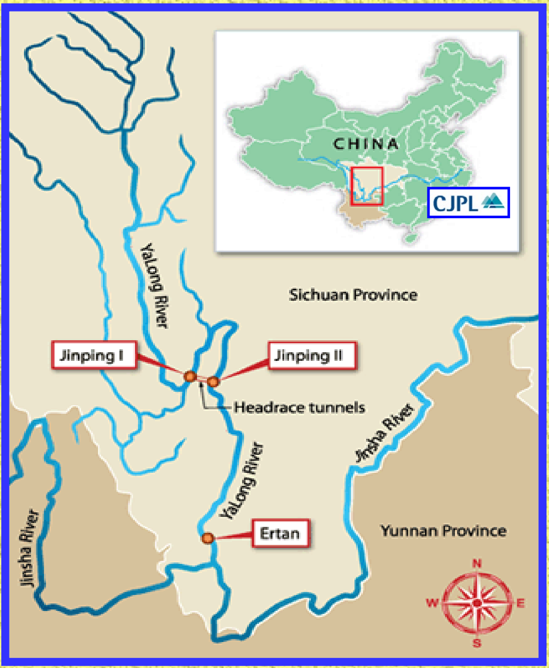
- ☑ One of the R&D Projects of the NSF-GEMADARC Program
- ☑ Ge-IA, following concept paper of *[Starostin & Beda 2000]* on Ge planar strip detectors, extend to point-contact design.
- ☑ Expect Charge multiplication @ 10^5 V/m E-field
- ☑ Potentials: O(10 eVee) threshold, with Ge-Ionization, LN2 operation,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



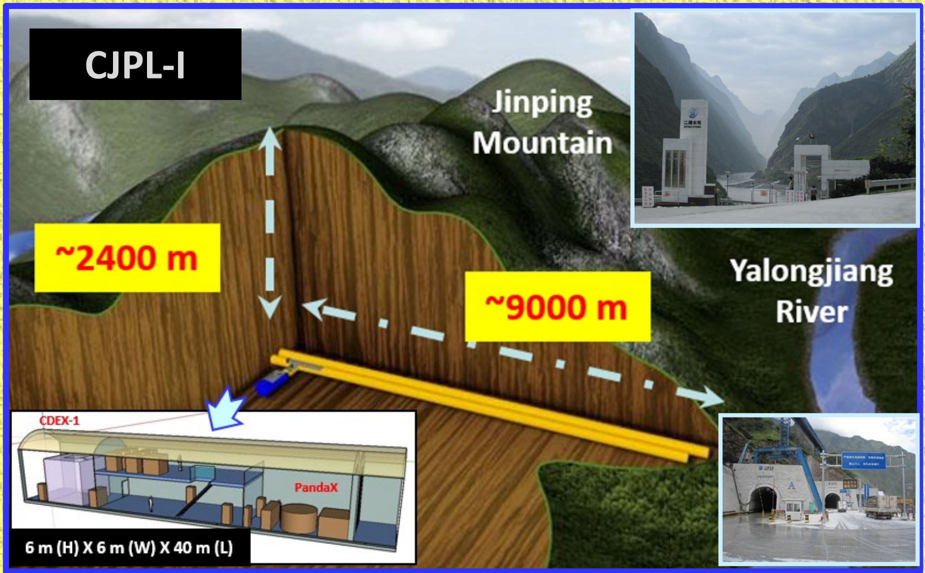
Starostin & Beda 2000

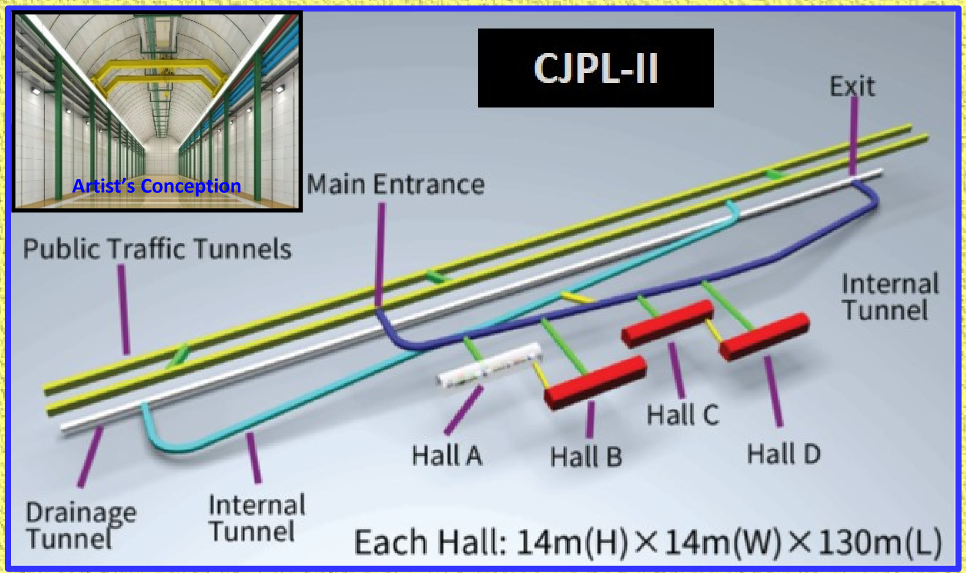
- Avalanche with V=4000 V ;
  E~105 V/m at O(10 mm)

CJPL 中国锦屏地下实验室 China Jinping Underground Laboratory



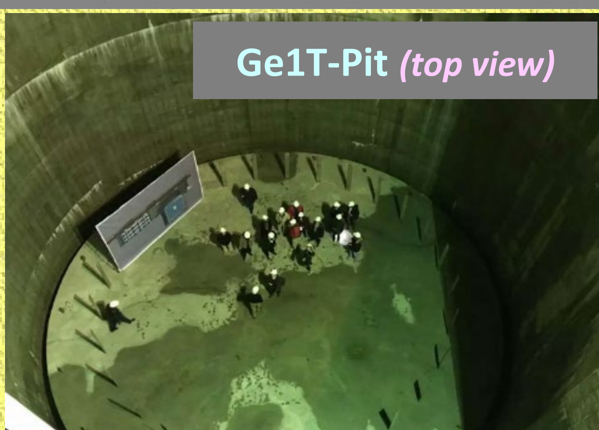
- **Location:** Sichuan Province, China
- **Merits:** 2400+ m rock overburden ; drive-in road tunnel access ; superb supporting infrastructures
- *CJPL-I (2010):* 6X6X40 m cavern
  CJPL-II (2017+): [4X(14X14X130 m) Halls]+Pits
- The *Deepest* & *Largest* Underground Research Facility in the World





Future Prospects @ CJPL-II: CDEX-Ge1T (0νββ+DM) Project

- LEGEND-1T is a natural and excellent candidate for Ge1T@CJPL2



LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

- ☑ **Towards Ton-scale enriched-Ge76 experiment for neutrinoless double beta decay experiment to *cover the "Inverted Hierarchy"***
- ☑ **Main Cast : mainly GERDA, Majorana, CDEX groups *[i.e. world's expertise teams in ultra-low-background Ge-detector experiments]***

LEGEND — Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Mission: "The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results."

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

First phase:

- up to 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal 0.6 c /(FWMH t y)
- start by 2021

Subsequent stages:

- staged 1000 kg
- timeline connected to U.S. DOE down select process
- BG: goal 0.1 c /(FWHM t y)
- Location: TBD
- Required depth (Ge-77m) under investigation

⚐ **CDEX groups ⇨ building a case to host this experiment at CJPL-II**

Prospects & Outlook

- νA_{el} has been observed in experiment with ν from ORNL-SNS DAR-π
- Probe *finer questions* after 1st observation, both theory & experiments
- SM, BSM, Nuclear, QM Coherency, Applications ………
- A natural *Portal for Synergy* between Neutrino and Dark Matter programs – both Physics & Techniques
  - ⇨ Catalyzed CJPL & CDEX-DM program (& beyond …)

Prospects & Outlook

- **DAR-π νA_{el} –**
  - ☑ Advances Made in *"Taming of the Beam"* 🏆🏆🏆
  - ☑ *Controlled Experiments* are Feasible
  - ☑ To be Studied in *more Target*
  - ☑ *Partial Coherency* – Attend Degeneracy to extract Physics
  - ☑ SM Uncertainties relevant when measurement errors reach <10%
- **Reactor νA_{el} –**
  - ☑ Diverse techniques to *reduce Detector Threshold*, potentials applications *[e.g. Light DM Searches]*
  - ☑ *Small(er) scale projects* complementing large facilities
- **Solar νA_{el} –**
  - ☑ From *Irreducible background* to a potentially important *physics output* for future DM direct searches projects
    - ⇨ Background → Discovery *[c/f Atm.ν]*