Neutrino Electro-Magnetic Properties with Reactor Neutrinos

- ☑ **Broad Landscape & Overviews**
- ☑ **Experiments** *[TEXONO, GEMMA ….]*
- ☑ **Physics** *[μ_ν, δ_Q …..]*
- ☑ **Atomic effects at ~keV**
- ☑ **Prospects**

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Mini Workshop: Neutrino Electromagnetic Properties

August 12, 2020
US/Central timezone

Neutrino Electromagnetic Interactions

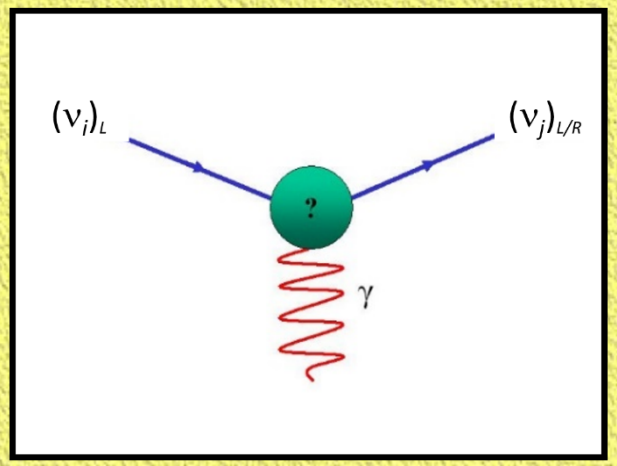
[Theory & Phenomenology (Miranda's Talk)]

Neutrino Electromagnetic Form Factors

$$\Gamma^{\mu}_{\rm em} \equiv F_1 \cdot \gamma^{\mu} + F_2 \cdot \sigma^{\mu\nu} \cdot q_{\nu}$$

$$F_1 = \delta_{\rm Q} \cdot e_0 + \frac{1}{6} \cdot q^2 \cdot \langle r_{\nu}^2 \rangle,$$

$$F_2 = (-i) \cdot \frac{\mu_{\nu}}{2 \cdot m_e},$$



$$\left(\frac{d\sigma}{dT}\right)_{\rm FEA} = \delta_{\rm Q}^2 \left[\frac{2\pi\alpha_{\rm em}^2}{m_e}\right]\left[\frac{1}{T^2}\right],$$

Helicity Conserved : Milli-Charge

$$\frac{d\sigma}{dT}(\nu e)_{\mu} = \frac{\pi\alpha^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E_{\nu}}\right]\mu_{\nu}^{\ 2}$$

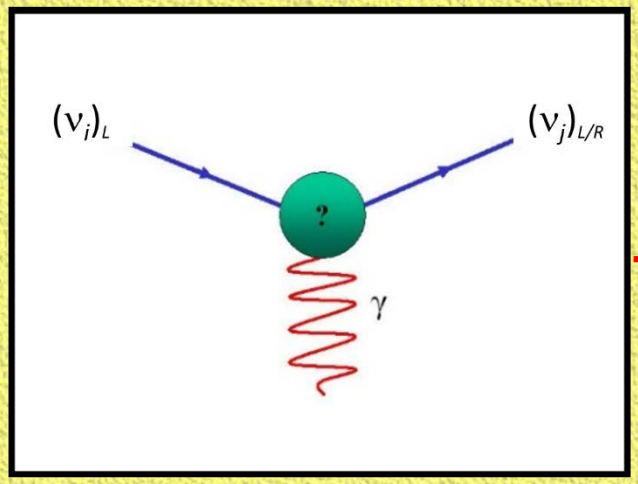
Helicity Flipped : Magnetic Moments

$$\sin^2\theta_{\rm W} \rightarrow \sin^2\theta_{\rm W} + \left(\frac{\sqrt{2}\pi\alpha_{em}}{3G_F}\right)\langle r_{\bar{\nu}_e}^2 \rangle,$$

Helicity Conserved : Charge Radius

- Tree-Level Radiative Corrections
- SM "predictions" : O(10^{-33}) cm^2

Motivations



requires $m_\nu \neq 0$

e.g. BSM

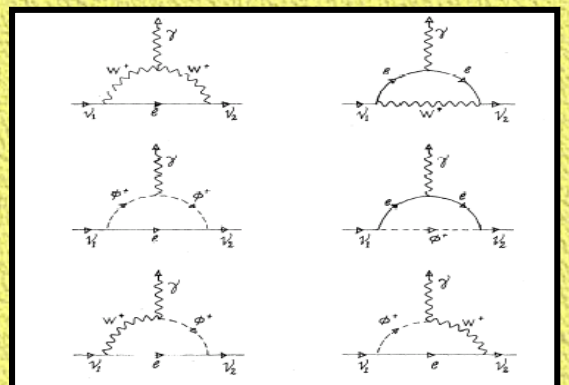


FIG. 1. Lowest-order diagrams for $\nu_1 \to \nu_2 + \gamma$ in the Dirac case, in the SU(2)×U(1) model with right-handed singlet neutrinos. ϕ is the standard Higgs doublet and e stands for a generic charged-lepton field.

- ☑ fundamental *BSM* neutrino properties & interactions ; can differentiate Dirac/Majorana neutrinos (ν_D/ν_M)
- ☑ Sensitivities enhanced at low (~keV) measureable recoil energy
- ☑ inspire low energy & techniques & theory advances (atomic effects)
- ☑ Inspire studies of roles of neutrinos in astrophysics *[Studenikin's Talk]*
- ☑ ~(1990-2010) dedicated experiments ; Present : popular BSM "by-product" subjects

For completeness/historical footnote ……

Magnetic Moments & Solar Neutrinos

- ν_e produced in the Sun interact with $B_\odot$ to become $\nu_x(x \neq e)$, via spin-flavor precession(SFP), with or without resonance effects in solar medium.
- used to explain anti-correlation of Cl-$\nu_\odot$ data with Sun-spot cycles in late 80's
- scenario compatible with *all* solar neutrino data
- KamLAND independently confirms LMA as *the* solution for solar neutrino problem $\Rightarrow$ SFP cannot be the dominant contribution
- $\therefore$ [$\nu_\odot$ data + LMA allowed region + no $\bar{\nu}_e$]

  → constrain $\int \mu_\nu B_{\odot\perp}\, dr$:

  ranges of $\mu_\nu(solar) < 10^{-10} - 10^{-12}\ \mu_B$ (after $B_{\odot\perp}$ modeling)

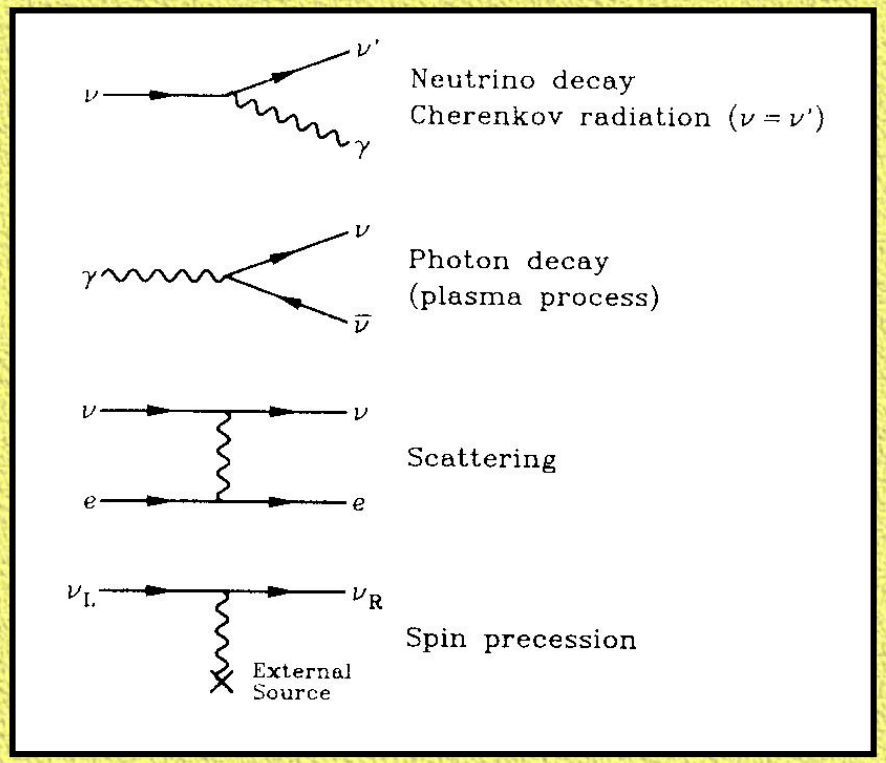
Experimental Manifestations

- **Minimally-Extended Standard Model with ν_D : μ_ν *VERY* small**

$$\mu_\nu = \frac{3G_F m_e m_\nu}{4\sqrt{2}\pi^2} = 3.2\times 10^{-19}\left[\frac{m_\nu}{1\ \text{eV}}\right]$$

☑ **many ways to significantly enhance it (ν_M, W_R …..)**

☑ **If observed : $\mu_\nu > 10^{-15}\ \mu_B \Rightarrow \nu_M$**



e.g. neutrino radiative decays

$$\Gamma(\nu_i \to \nu_j \gamma) = \frac{1}{8\pi}\frac{(\Delta m_{ij}^2)^3}{m_i^3}\mu_\nu^2$$

☑ Indirect constraints from μ_ν typically more stringent then direct bounds.

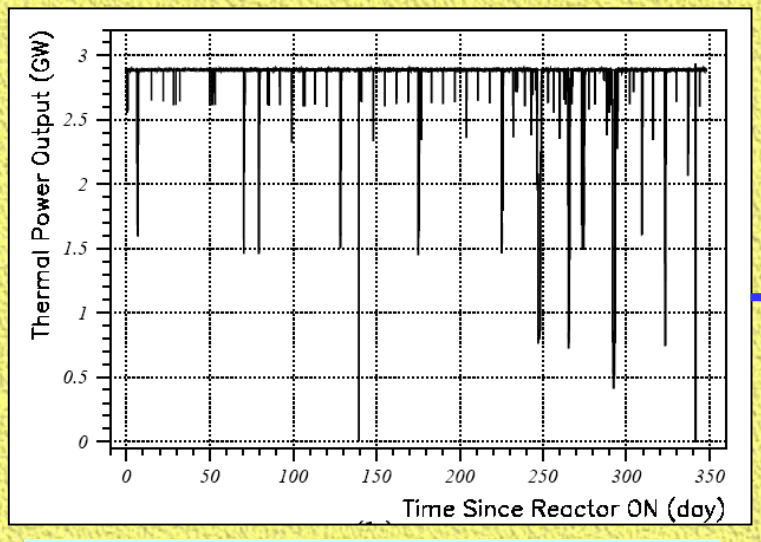
Direct Experiments

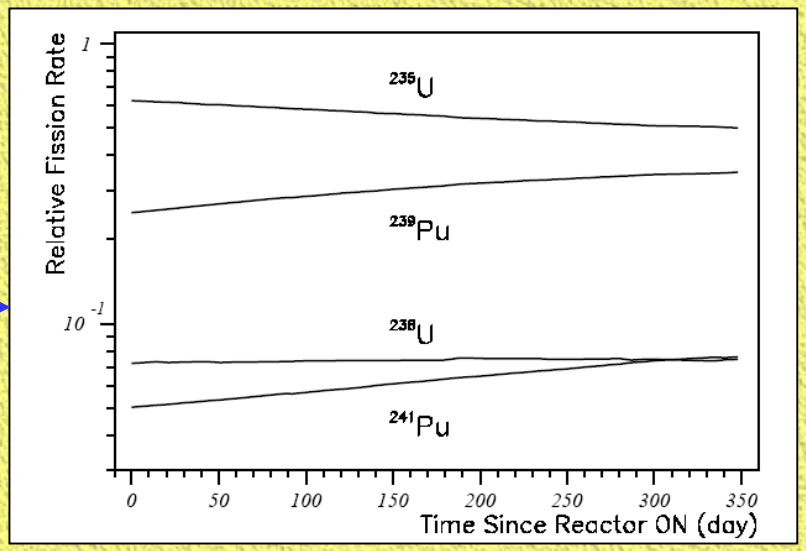
- **using sources understood by independent means : reactor ν , accelerator ν , $\nu_\odot$ at detector , ν–sources (discussed)**
- **look for excess due to ν–e scattering background over Standard Model processes**
- **interpretation of results : need to take into account mass eigenstates composition $|\nu\rangle_{initial}$ at detector**

$$\mu_\nu{}^2(\nu_l, L, E_\nu) = \sum_j \left| \sum_i U_{li} e^{-iE_\nu L} \mu_{ij} \right|^2$$

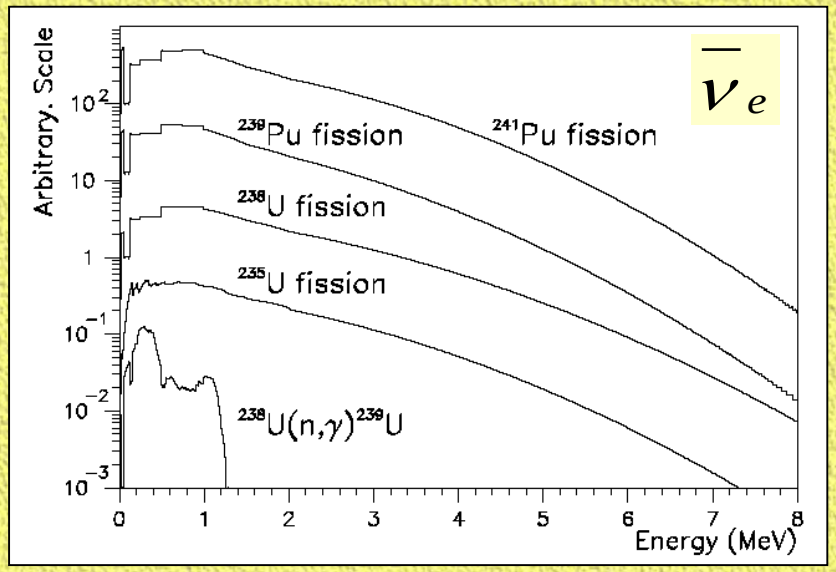
- **limits independent of $|\nu\rangle_{final}$: valid for ν_D/ν_M & diag./tran. moments -- no modeling involved**
- **reactor ν : controlled laboratory experiments ; reactor ON/OFF to filter out background uncertainties ; typically more sensitive than accelerator bounds** ***[from low-T & high-ϕ_ν but E_ν-independent ; note $|\nu\rangle$ differences]***
- **$\nu_\odot$:** ***[Papoulias's talk in connection with Xe1T results]***

Reactor Neutrino Spectra





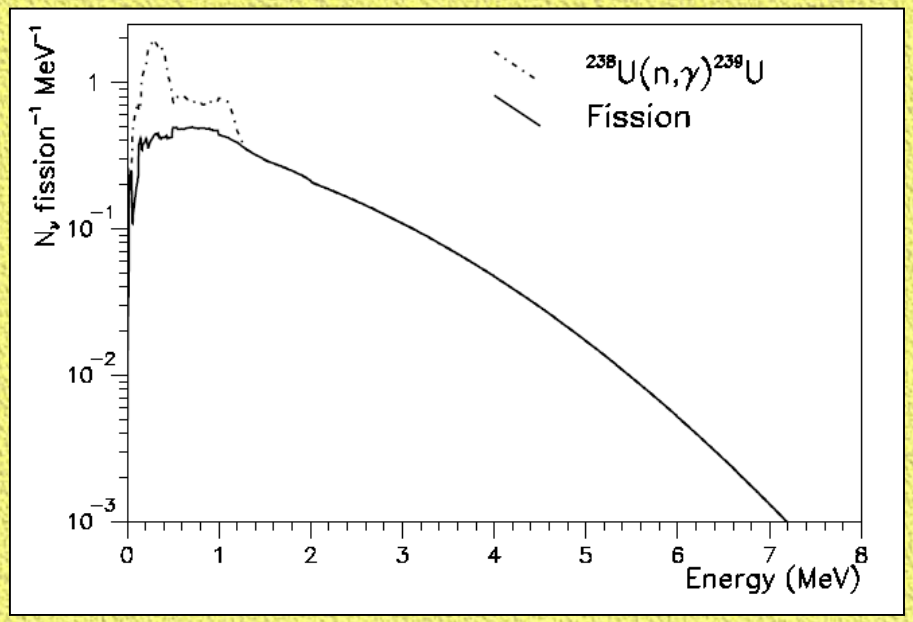
Reactor Operation Data

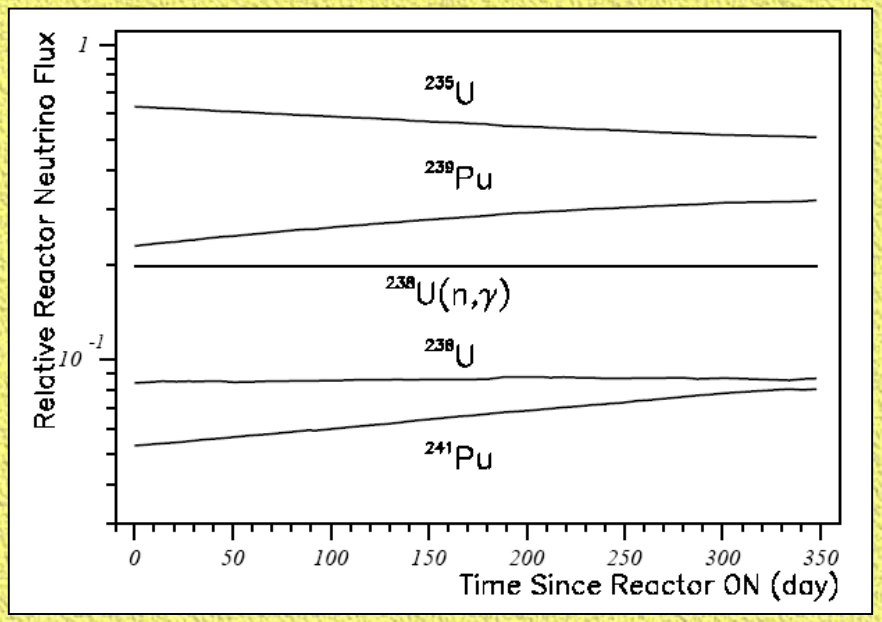


Nuclear Physics

TABLE II: Fractional mass compositions, relative fission contributions and neutrino yield per fission for the four fissile isotopes and the ^{238}U neutron capture. All values are time-dependent and only typical levels are given.

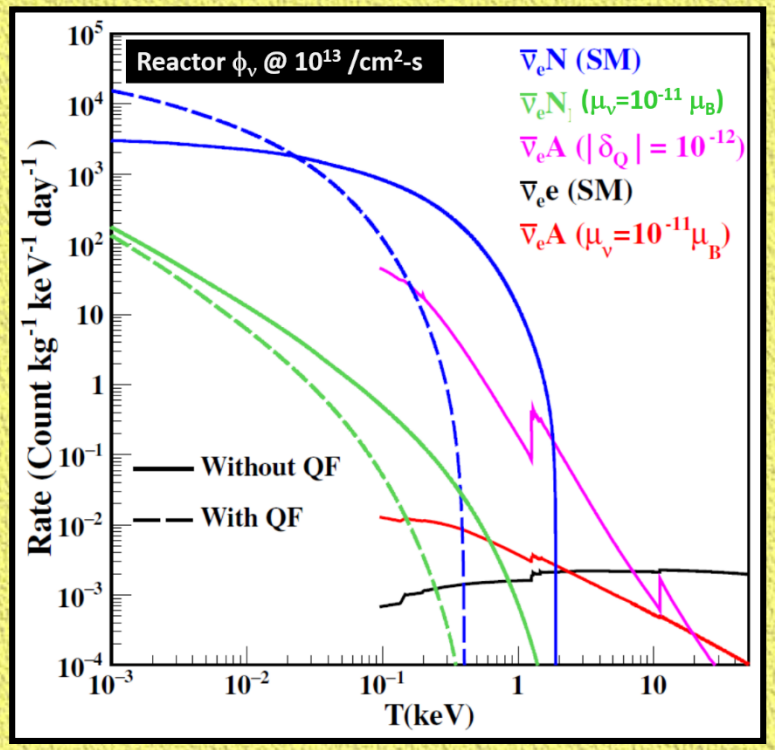
Channels	Fractional Compositions by Mass (%)	Relative Rates per Fission	Neutrino Yield per Event	Neutrino Yield per Fission
^{235}U Fission	1.5	0.55	6.14	3.4
^{238}U Fission	98.0	0.07	7.08	0.5
^{239}Pu Fission	0.4	0.32	5.58	1.8
^{241}Pu Fission	<0.1	0.06	6.42	0.4
^{238}U (n,γ) ^{239}U	–	0.60	2.00	1.2
Total	–	–	–	7.3

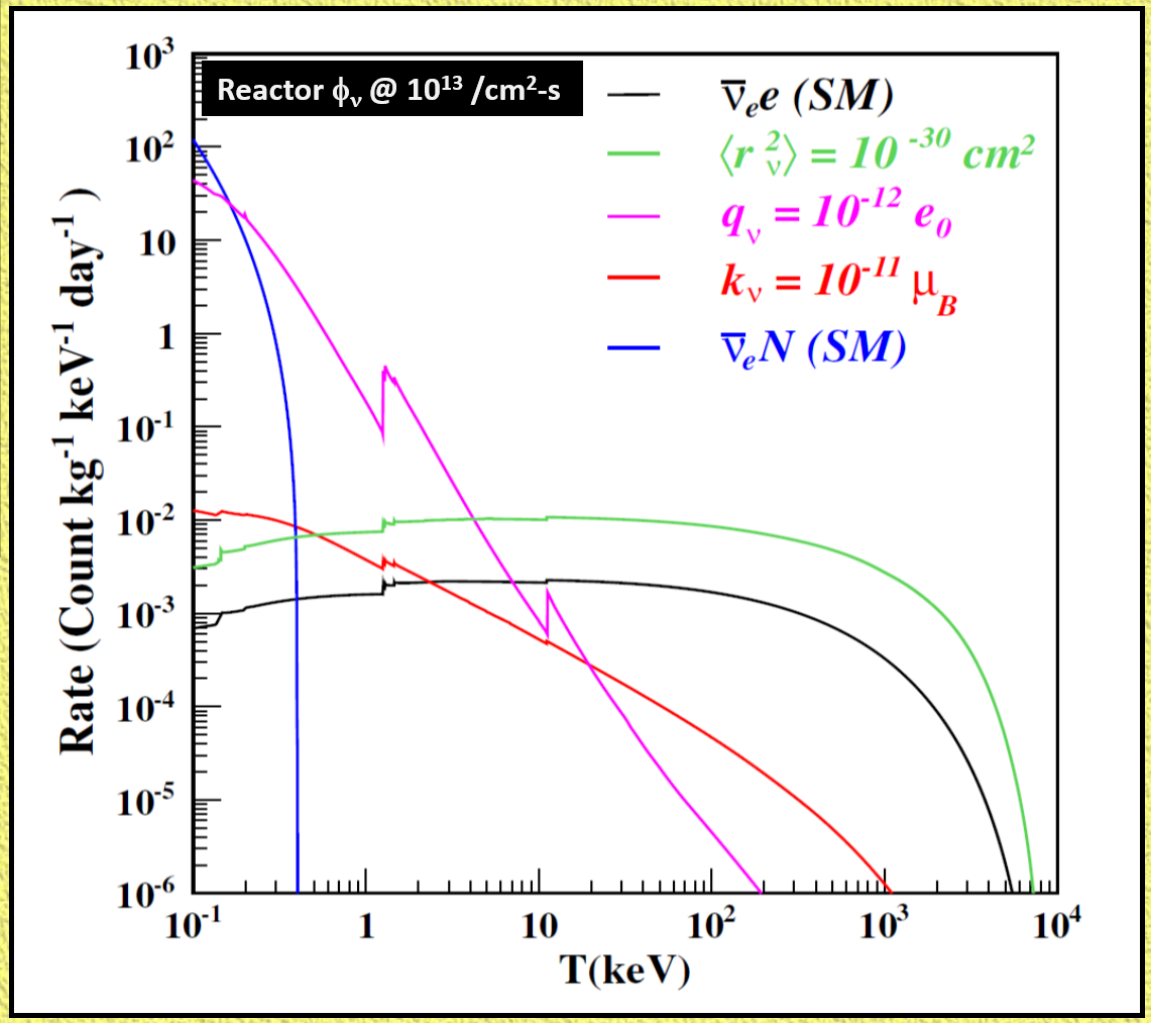




Typically ~10^{13} ν / cm ^{2} -s @ ~ 20 m for 3 GeV Thermal Power

Typically Measureable Spectra for Ge-Ionization @ ~10^{13} ν / cm ^{2} -s



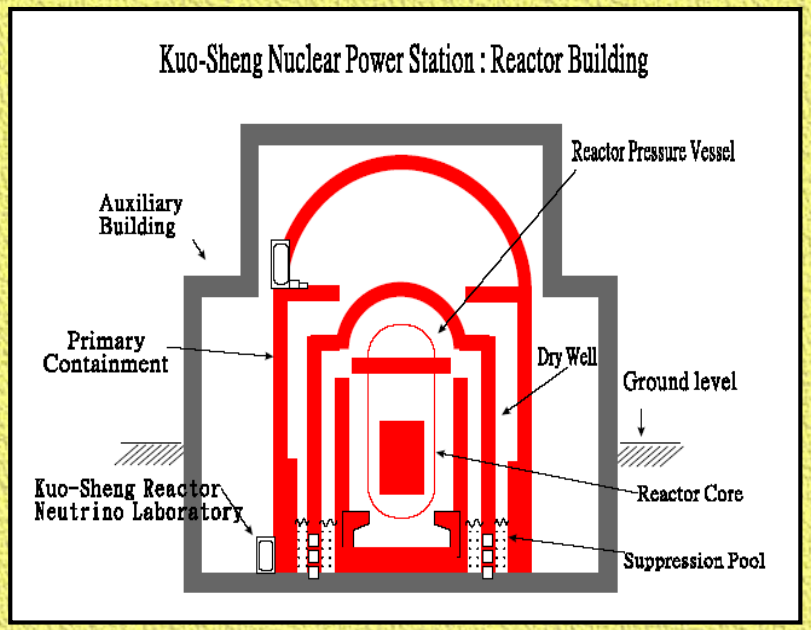


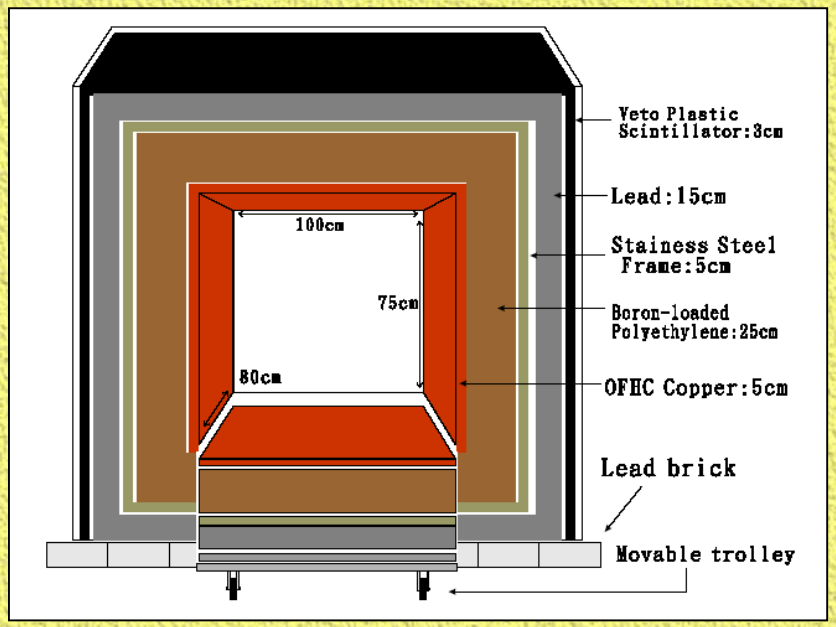
Previous Reactor Experiments

$$\frac{d\sigma}{dT}(\nu e)_{\mu} = \frac{\pi\alpha^2}{m_e^2}\left[\frac{1}{T} - \frac{1}{E_\nu}\right]\mu_\nu{}^2$$

- **Savannah River** *[PRL 1976]*
  - ***first observation of the ν-e***
  - **~ 16 kg plastic scintillator ; ON/OFF 64/61 days**
  - ***revised analysis*** *[Vogel & Engel PRD 1989]*
    - ⇨ μ_ν **~ (2 – 4) × 10 $^{-10}$ μ_B**
- **Krasnoyarsk** *[JETP Lett 1992]*
  - **~ 100 kg liquid scintillator C_6F_6,**
  - **ON/OFF 254/78 days**
  - $\mu_\nu \leq$ **2.4 × 10 $^{-10}$ μ_B (90% C.L.)**
- **Rovno** *[JETP Lett 1993]*
  - **75 kg silicon multi-detector, 600 Si(Li) cells,**
  - **ON/OFF 30 /17 days**
  - $\mu_\nu \leq$ **1 .9 × 10 $^{-10}$ μ_B (95% C.L.)**
- **MUNU@ Bugey** *[PLB 2003]*
  - **CF_4 TPC**
  - **mass 11.4 kg; 66.6 d ON/16.7 d OFF ; T > 900 keV**
  - **$\mu_\nu(\nu_e)$ < 1.0 X 10^{-10} m_B (90% CL)**

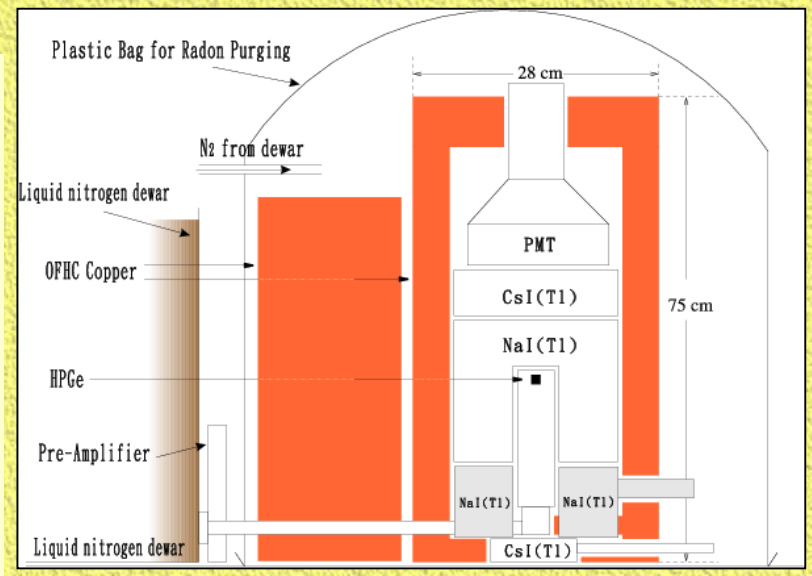
TEXONO @ Kuo-Sheng (KSNL) – 28 m & 2.9 GW

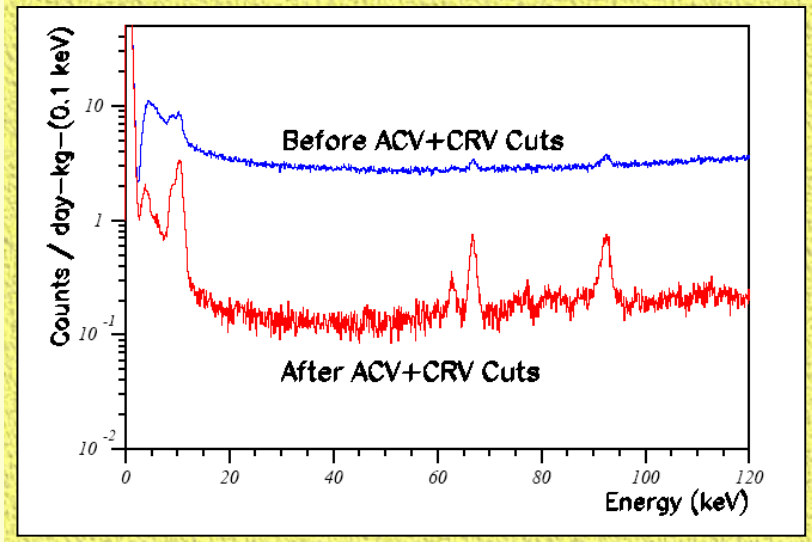




Magnetic Moment Searches @ KSNL

- simple compact *all-solid* proton-free: HPGe (mass 1 kg) enclosed by active NaI/CsI anti-Compton, further by passive shieldings & cosmic veto
- selection: single-event after cosmic-veto, anti-Comp., PSD
- TEXONO data (571/128 days) ON/OFF) *[PRL 2003 ; PRD 2007]*
  - background comparable to underground CDM experiment : ~ 1 $day^{-1}keV^{-1}kg^{-1}$ (cpd)
  - DAQ threshold 5 keV analysis threshold 12 keV

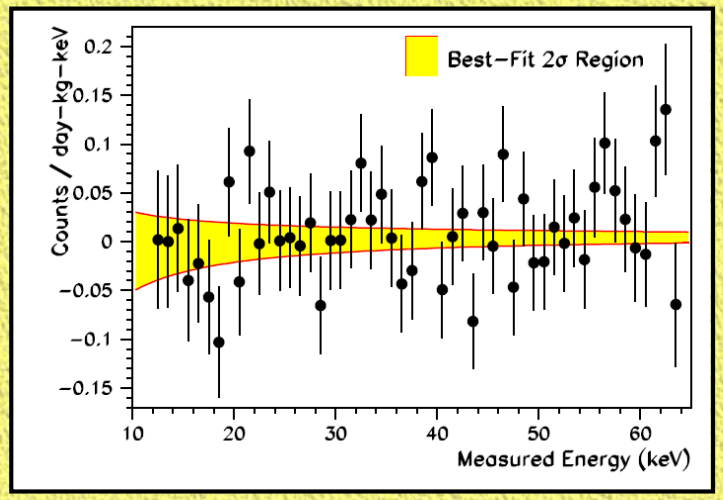


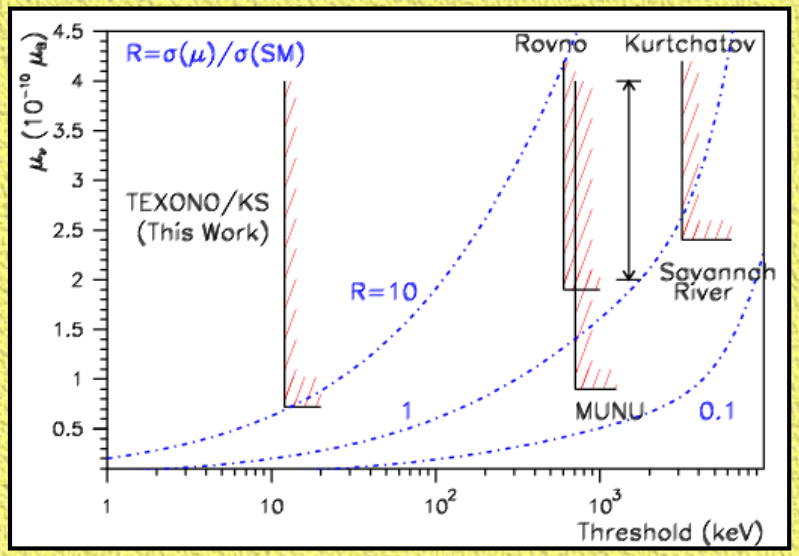


Search of μ_ν at low energy with Reactor νe scattering

⇒ high signal rate & robustness:

- μ_ν>>SM [decouple irreducible bkg ⊕ unknown sources]
- T << E_ν ⇒ $d\sigma/dT$ depends on total ϕ_ν flux but *NOT* spectral shape [flux well known : ~6 fission-ν ⊕ ~1.2 ^{238}U capture-ν per fission]





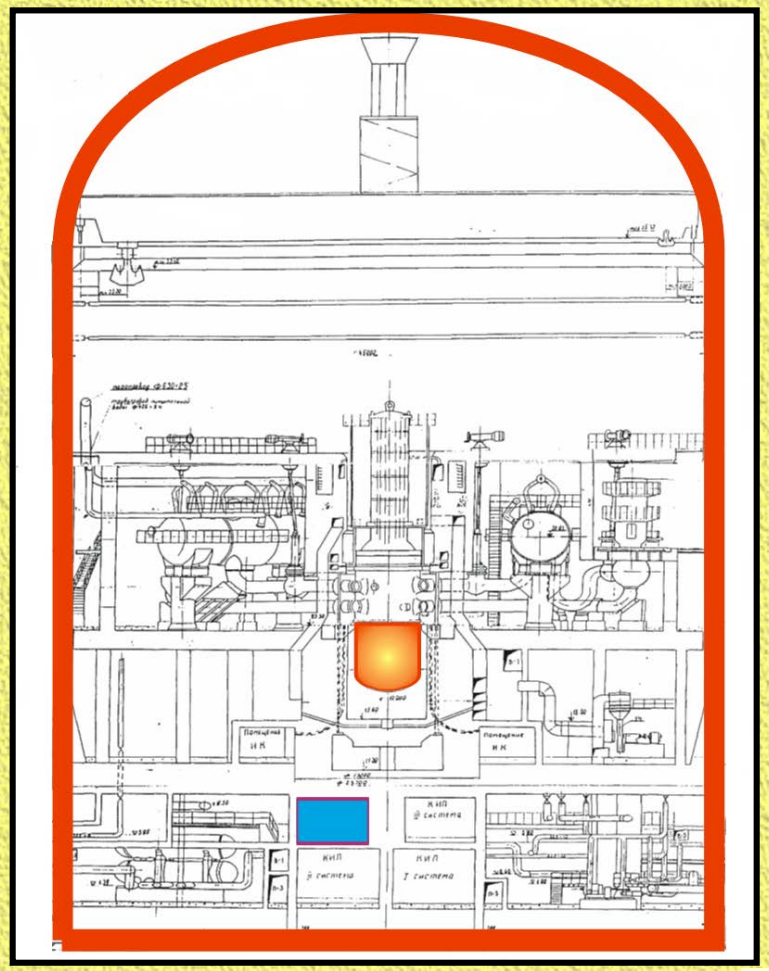
$\mu_\nu(\nu_e) < 7.2 \times 10^{-11}\ \mu_B$ [PRL03,PRD07]

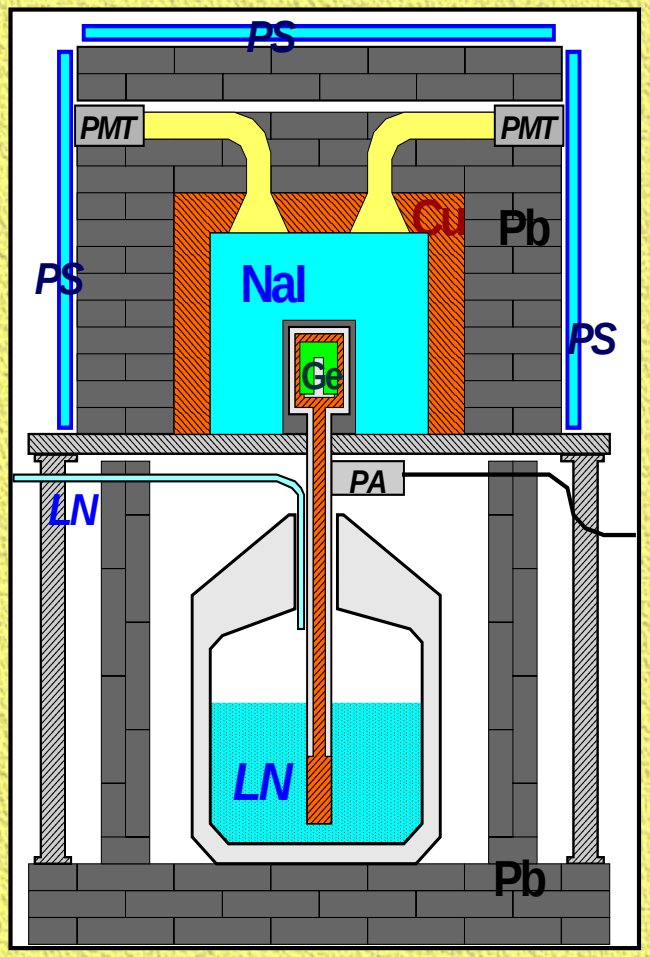
⚐ TEXONO dedicated μ_ν program completed 2007.

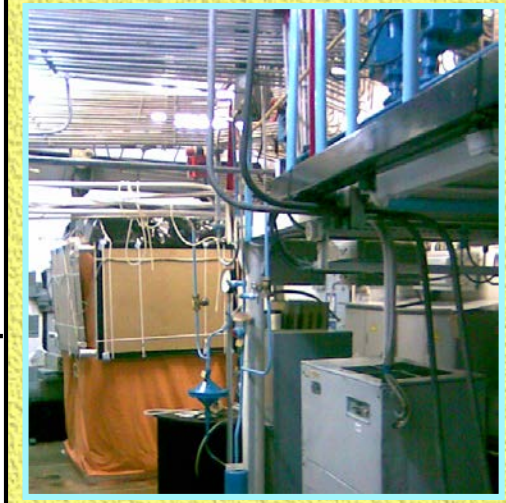
⚐ ……. Similar approach continuing in GEMMA @ Kalinin, Russia

⇨ $\mu_\nu(\nu_e) < 2.9 \times 10^{-11}\ \mu_B$ *[AHEP 2012]*

GEMMA @ Kalinin – 14 m (!!) & 3 GW

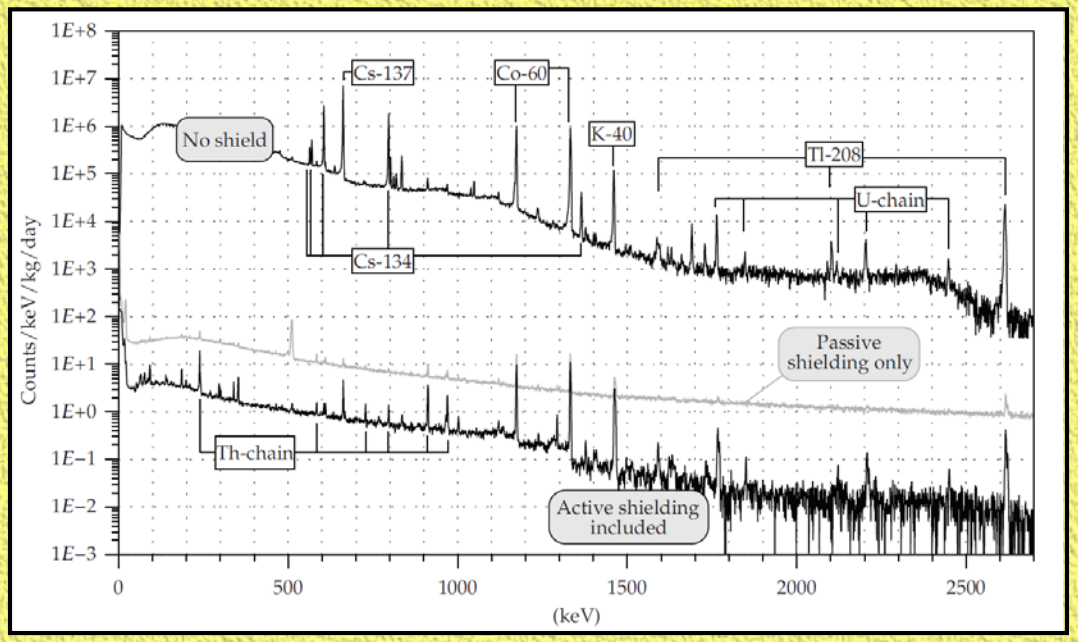


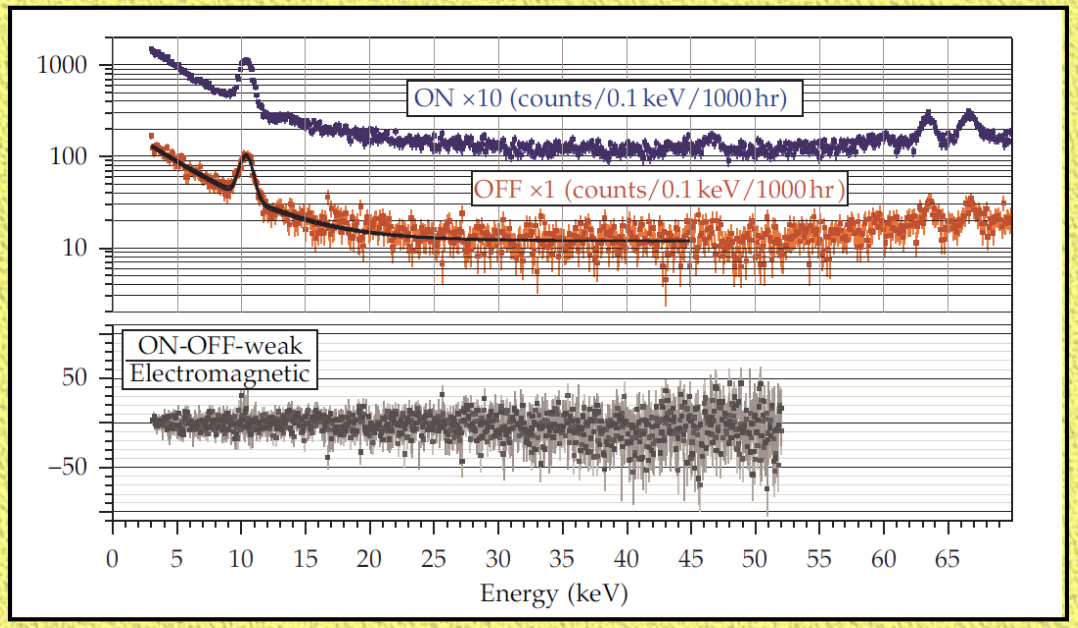




Lab just under Reactor Core
14 m only!
2.7×10^{13} ν/cm²-s

- **HPGe detector of 1.5 kg within NaI(Tl) active shielding. surrounded with multi-layer passive shielding of copper & lead + cosmic veto plastic scintillator**





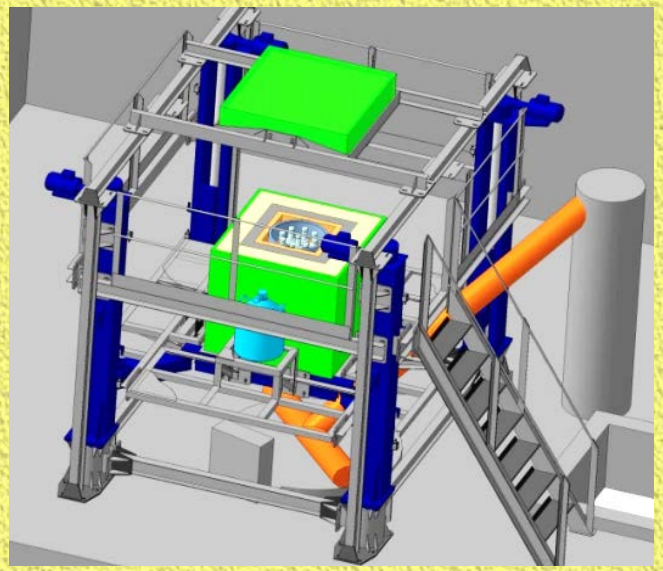
- ☑ **Comparable background levels as TEXONO**
- ☑ **Flux X4**
- ☑ **3 Phases – ON/OFF 754/187 days (~ +50%)**

2012 AHEP:

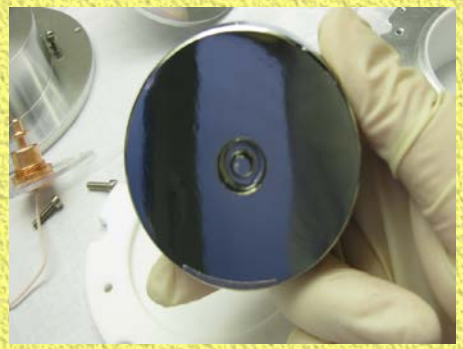
$$\mu_\nu < 2.9 \text{ X } 10^{-11} \mu_B$$

Experiment GEMMA II

- Preparation of the experiment GEMMA II is in progress now.
- The measurements will be performed at third unit of KNPP. The detector is installed directly under the core of an industrial 3.1 GW reactor
- The distance to the core center as low as 10.7 m (!!) can be reached by means of a movable platform.
- At that distance the density of the antineutrino flow is 5.4×10^{13} см$^{-2}$s^{-1}.
- Four point-contact HPGe detectors (~400 g. each detector) produced at LNP JINR will be used for antineutrino registration. The energy threshold is 300-350 eV
- Sensitivity down to $\mu_\nu \leq 1 \times 10^{-11}\ \mu_B$ is expected to be achieved within 2 years of operating



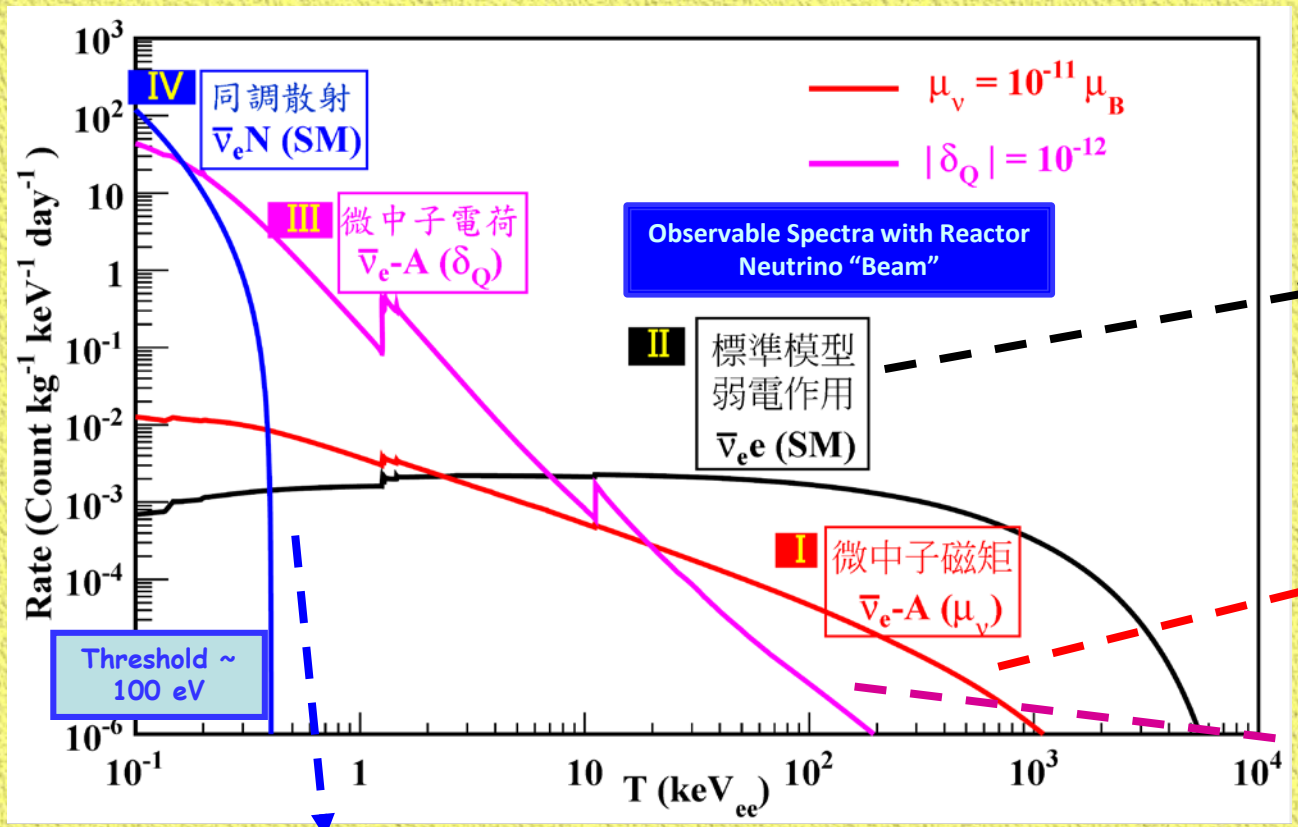
GEMMA II at movable platform

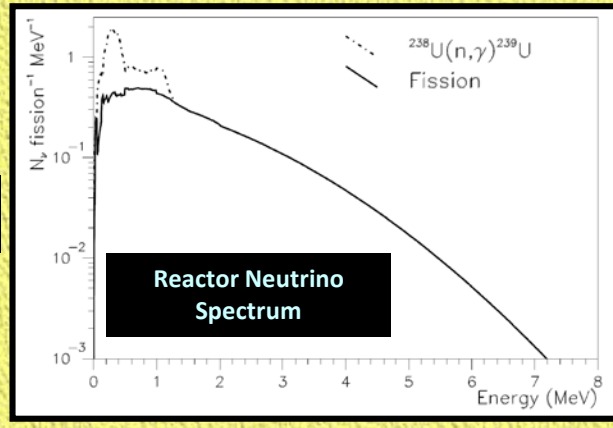


Point contact HPGe detector produced at JINR (Dubna) (~400 g. each detector). The energy threshold from 300-350 eV

TEXONO@KSNL – Beyond μ_ν (ν_e)

quality ← Detector requirements → mass





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

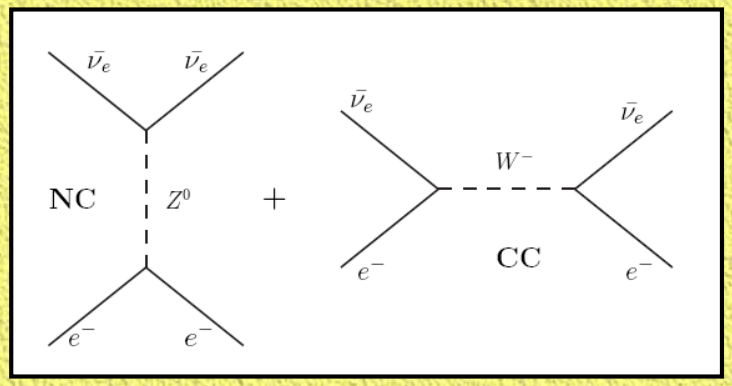
Magnetic Moments
[PRL03,PRD05,PRD07]
⇨ **1 kg HPGe**

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

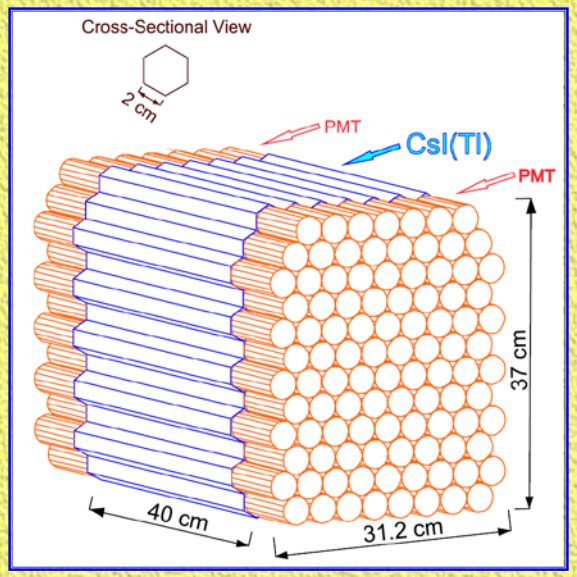
νN Coherent Scattering *[Current Theme;PRD16]*
⇨ **sub-keV O(kg) ULEGe / PCGe**
- ↳ **Dark Matter Searches @ KSNL** *[PRD09,PRL13,AP14]*
- ↳ **CDEX Program@CJPL** *[PRD13 ..... PRL2020]*
- ↳ **Theory Program** *[+ atomic physics ... etc] [PRD14.....]*

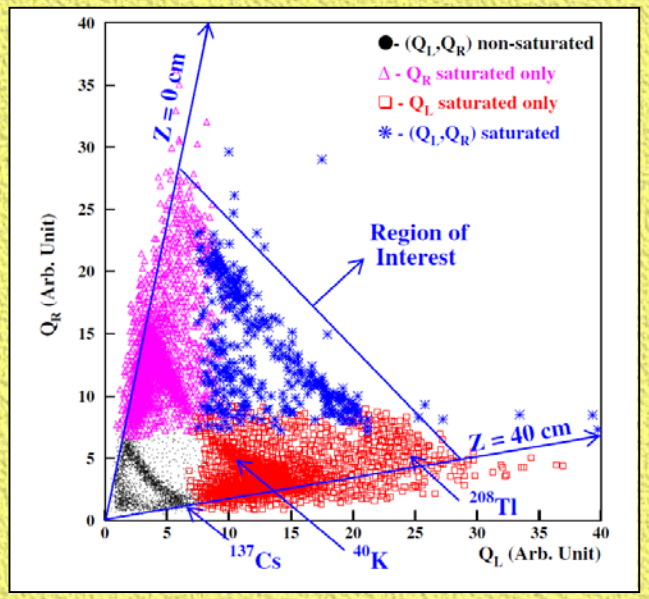
sub-keV PCGe

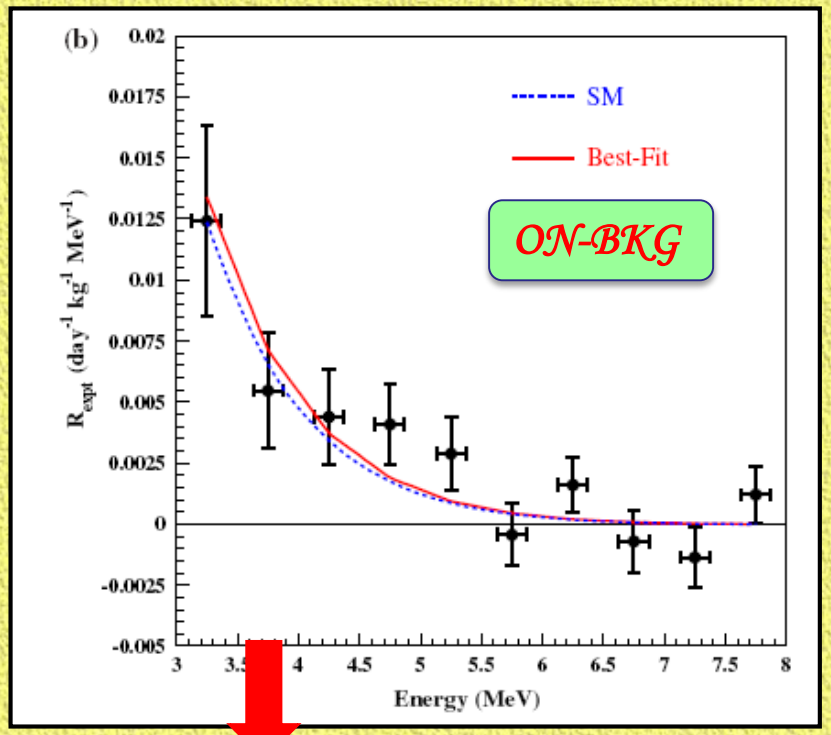
$\bar{\nu}_e$-e Scattering - CsI(Tl) 200 kg : Probe Electroweak Physics & BSM *[PRD10+]*



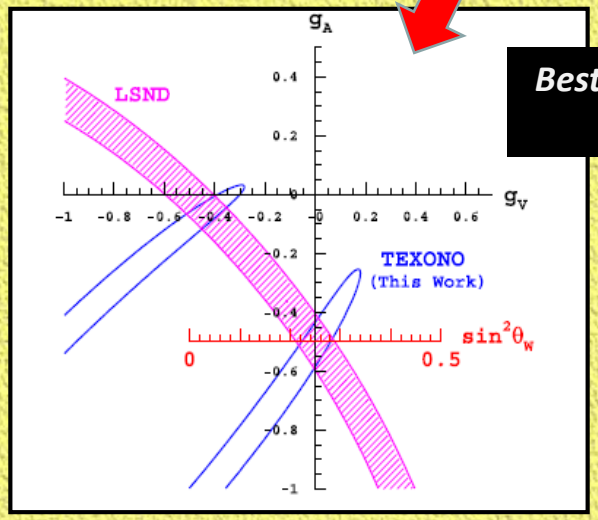
$$\left[\frac{d\sigma}{dT}(\bar{\nu}_e e)\right]_{\rm SM} = \frac{G_F^2 m_e}{2\pi}\cdot\Big\{4(\sin^2\theta_{\rm W})^2 \times\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_e T}{E_\nu^2}\right] + 4\sin^2\theta_W\left[\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_e T}{2E_\nu^2}\right] + \left(1-\frac{T}{E_\nu}\right)^2\Big\}.$$







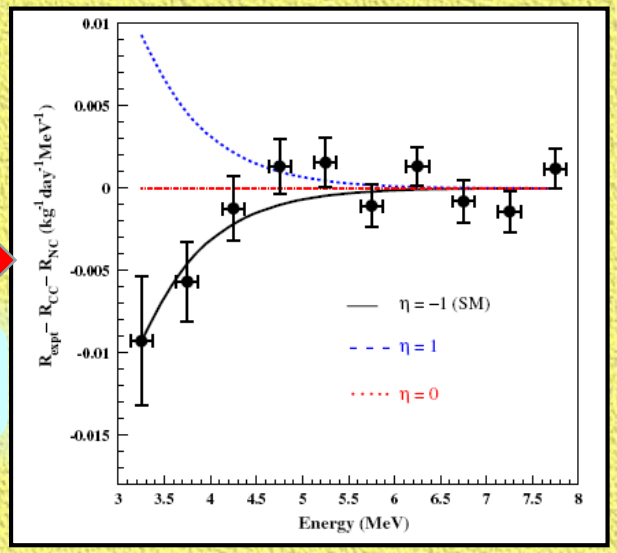
$$\sin^2\theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$



Best Measurement in ν_e !

$$R = [1.08 \pm 0.21(stat) \pm 0.16(sys)] \times R_{SM}$$

Verify SM Destructive Interference



⊕ Constraints on Various Beyond SM Effects *[PRD10;PRD12;PRD15]*

BSM "Charge Radius" *[coupled to $\sin^2\theta_w$ sensitivity]* **:**

$$\sin^2\theta_W \rightarrow \sin^2\theta_W + \left(\frac{\sqrt{2}\pi\alpha_{em}}{3G_F}\right)\langle r^2_{\bar{\nu}_e}\rangle,$$

$$-2.1 \times 10^{-32}\ \mathrm{cm}^2 < \langle r^2_{\bar{\nu}_e}\rangle < 3.3 \times 10^{-32}\ \mathrm{cm}^2$$

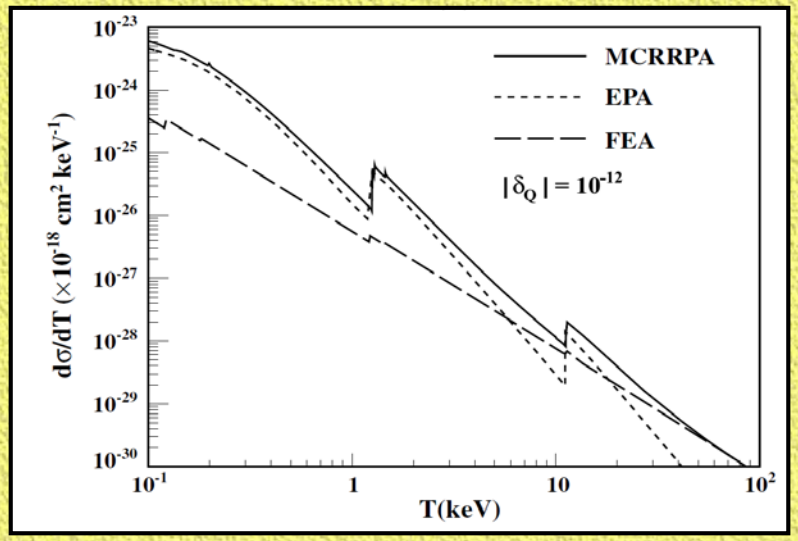
.. Among the most stringent in ν_e

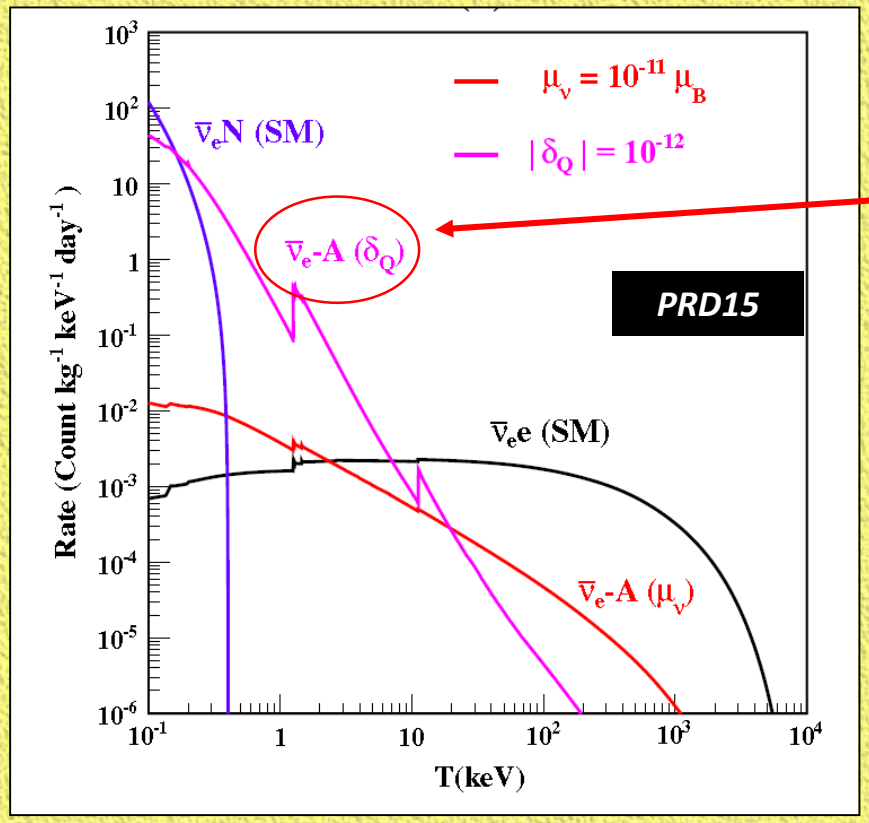
Neutrino "Milli-charge"

[PRD14]

$$\overline{\nu_e} + A \rightarrow \overline{\nu_e} + A^+ + e^-,$$

Atomic Ionization Differential Cross-Section with full atomic physics many-body "MCRRPA" calculation, improved over: EPA (Equivalent Photon Approximation) & FEA (Free Electron Approximation) *[PRD15]*

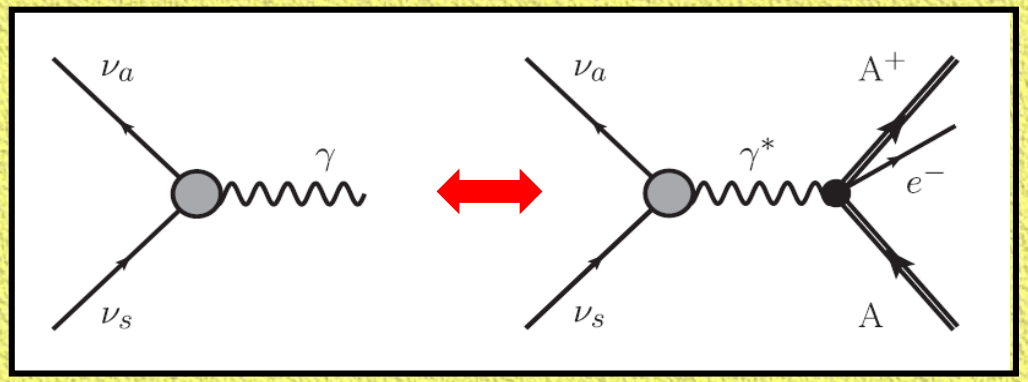


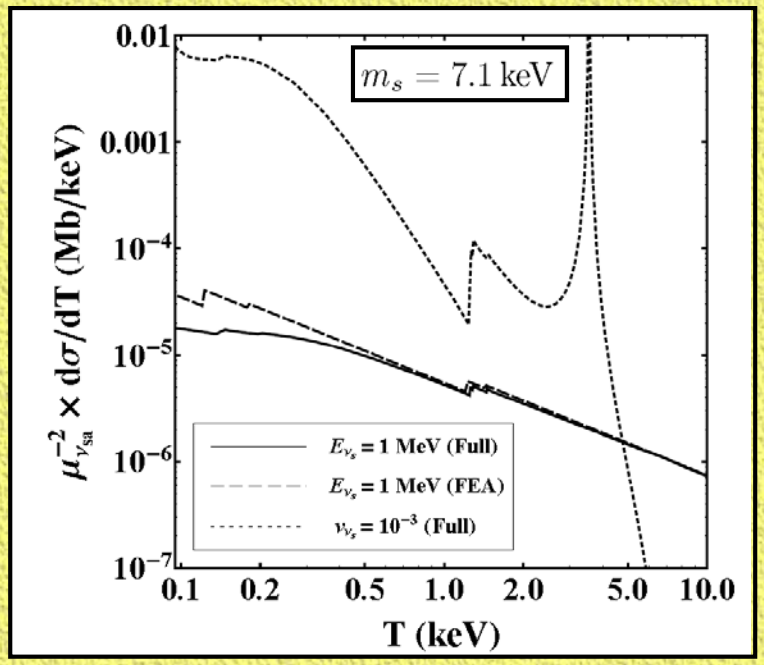


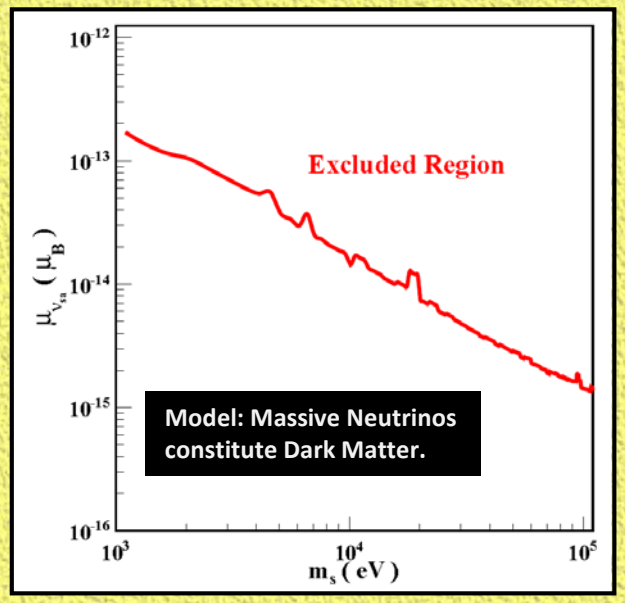
- ☑ **New Twist - Cross-section enhanced at low energy transfer ("minimum ionizing") with atomic physics incorporated.**
- ☑ **Smoking-gun signatures for positive signals: peaks at known K/L binding energy at known ratios *[different from cosmic-activation electron-capture background]***
- ☑ **Present Bound (combined TEXONO+GEMMA) : $\delta_Q < 10^{-12}$**
- ☑ **Steeper ~$1/T^2$ rise ; >10^4 SM-ν_e @ T~100 eV *[c.f ~1/T & >10 for μ_ν]***

Non-Relativistic Massive Sterile Neutrino to Light SM Neutrinos Radiative Decays Via Transition Magnetic Moment Atomic Ionization *[PRD16]*

- Pole structure at differential cross-section at $m_\nu/2$ ($q^2 \sim 0$)







- ☑ Direct Search of Sterile Neutrinos as Dark Matter
- ☑ Probe transition μ_ν ($\nu_s \to \nu_{SM}$)
- ☑ Pole enhancement ⇒ Probe into $\mu_\nu < 10^{-13}\ \mu_B$ below the SM-ν_e background for m_ν > keV
- ☑ Still…. many orders less sensitive than astro-bounds (equivalent < $10^{-20}\ \mu_B$)

Prospects on Sensitivity Improvement @ Reactors

Scaling:

$$\mu_\nu(\delta_Q) \propto \frac{1}{\sqrt{N_\nu}}\left(\frac{B}{mt}\right)^{\frac{1}{4}}$$

- N_ν : signal events
- B : background level
- m : target mass
- t : measurement time

$N_\nu \propto \phi_\nu$ (neutrino flux) & related to T-threshold

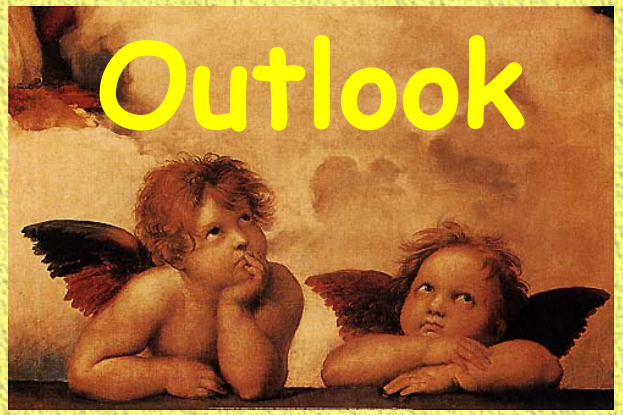
μ_ν *[Current ~ 3X10^{-11} μ_B] :*

- ☑ ~1/T ⇨ ~sqrt{2.3} every ~1/10 in threshold
- ☑ $\mu_\nu(\nu N) < SM(\nu N)$ @ $\mu_\nu < 10^{-11}\ \mu_B$
- ☑ $\mu_\nu(\nu e) \sim SM(\nu e)$ @ [T~400 eV , $\mu_\nu \sim 3X10^{-12}\ \mu_B$]
- ☑ T < 400 eV ⇨ < SM(νN) Bkg *[unless n/e recoil differentiation]*
- ☑ Challenging < 10^{-11} ; Need new ideas *["appearance expts."]* for ≤ 10^{-12}

δ_Q *[Current ~ 10^{-12}] :*

- ☑ ~1/T^2 ⇨ ~sqrt{10} every ~1/10 in threshold
- ☑ $\delta_Q(\nu e) \sim SM(\nu e)$ @ [T~200 eV , $\delta_Q \sim 10^{-14}$]
- ☑ T < 200 eV ⇨ < SM(νN) Bkg *[unless n/e recoil differentiation]*
- ☑ Can expect probing → ~10^{-13} *[with χN & νN O(10-eV)-threshold grade detectors at reactor, + n/e]*

$\langle r^2_{\nu_e} \rangle$ *[Current $\delta(\sin^2\theta_W)$~16%] : require <5% to reach "SM-levels"*



- **Neutrino EM properties:** a ***conceptually*** **rich BSM subject ; much physics & astrophysics can be explored, based on known electro-weak & electro-magnetic physics & hardware/software tools; interesting twists along the way ….**
- ***practical*** **consequences remain to be seen ;** ***NO*** **hints or indications on BSM-scales.**
- **experimental studies push on** ***new neutrino sources & detection techniques/ranges/channels***
  - **incorporate into ⊕ contribute to other "driving" research subjects**
  - **Good as first BSM searches** ***(before the more exotics)***
- **Further improvement in δ_Q can be expected ; μ_ν-searches soon constrained by SM-background-scales unless circumvented with new ideas; $\langle r^2_\nu \rangle$ depends on precision in** ***$\sin^2\theta_W$ [+ theoretical uncertainties]***