Neutrino physics with the TEXONO Program at the KSNL and Dark Matter Search at CJPL

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TEXONO Taiwan EXperiment On NeutrinO (since 1997)

Neutrino Physics at Kuo-Sheng Reactor Neutrino Laboratory (KSNL)

CDEX China Dark Matter Experiment (birth 2009)

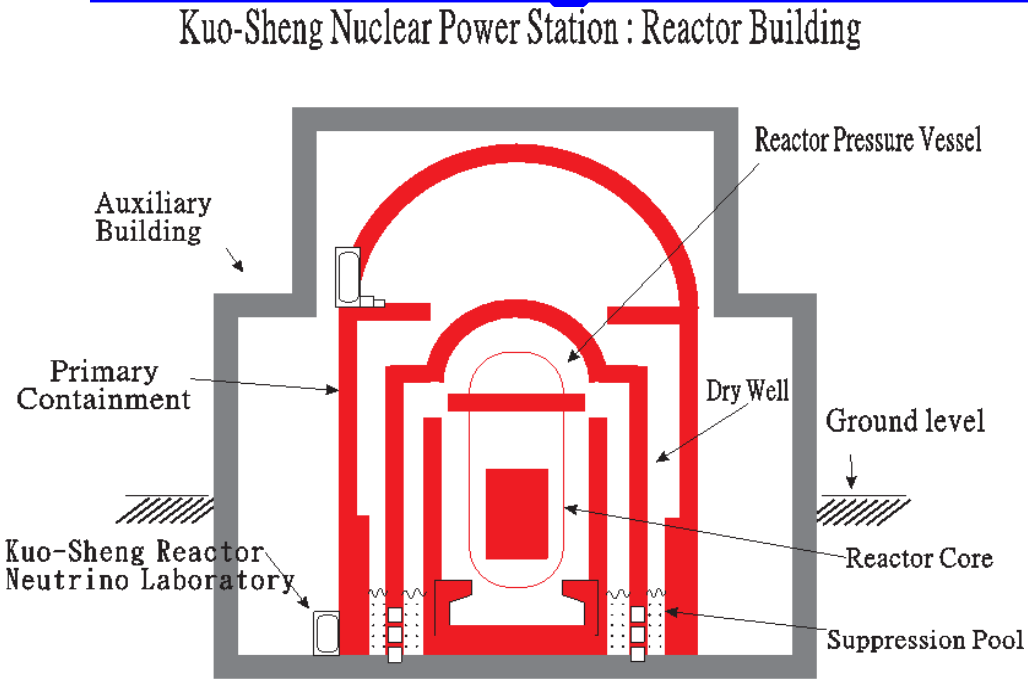
Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)

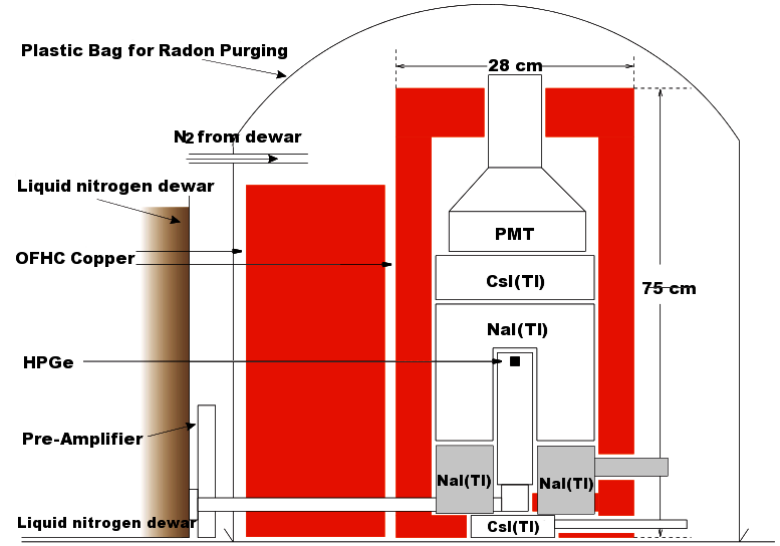
- Overview :KSNL
- Neutrino programs at KSNL & Germanium detectors
- Dark Matter searches at KSNL & CJPL
- Summary

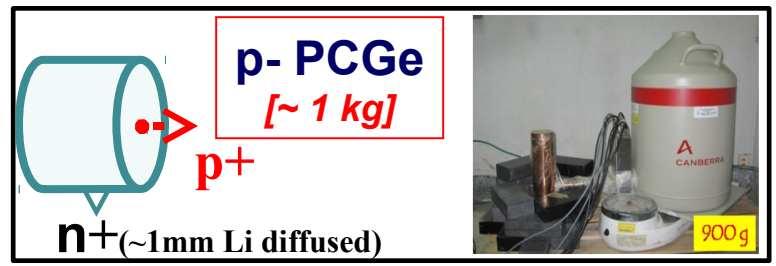
The 26th International Workshop on Weak Interactions and Neutrinos (WIN2017)

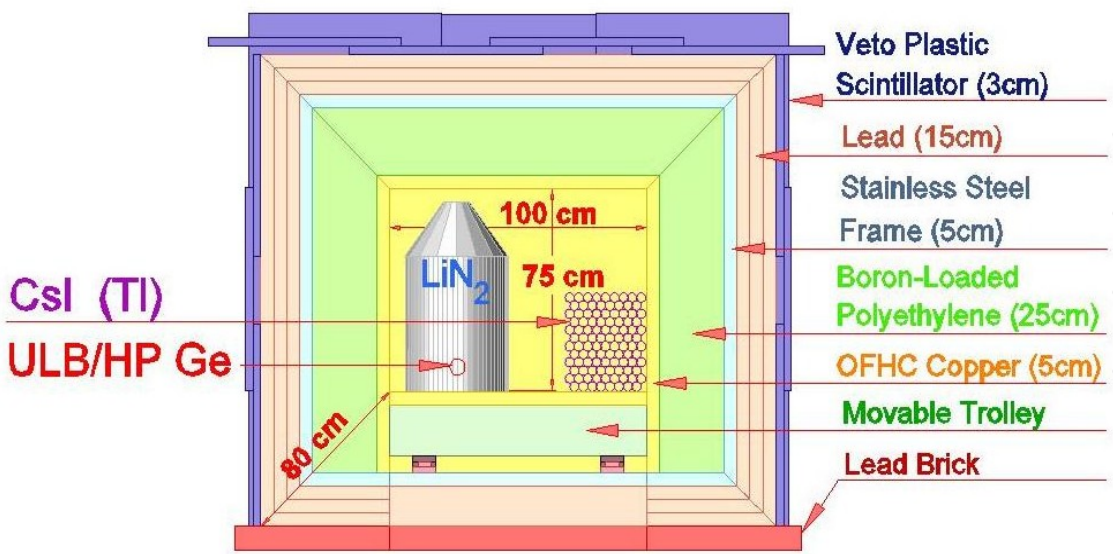
18-24 June 2017 UC Irvine, Irvine, CA, USA

Kuo Sheng Reactor Neutrino Laboratory



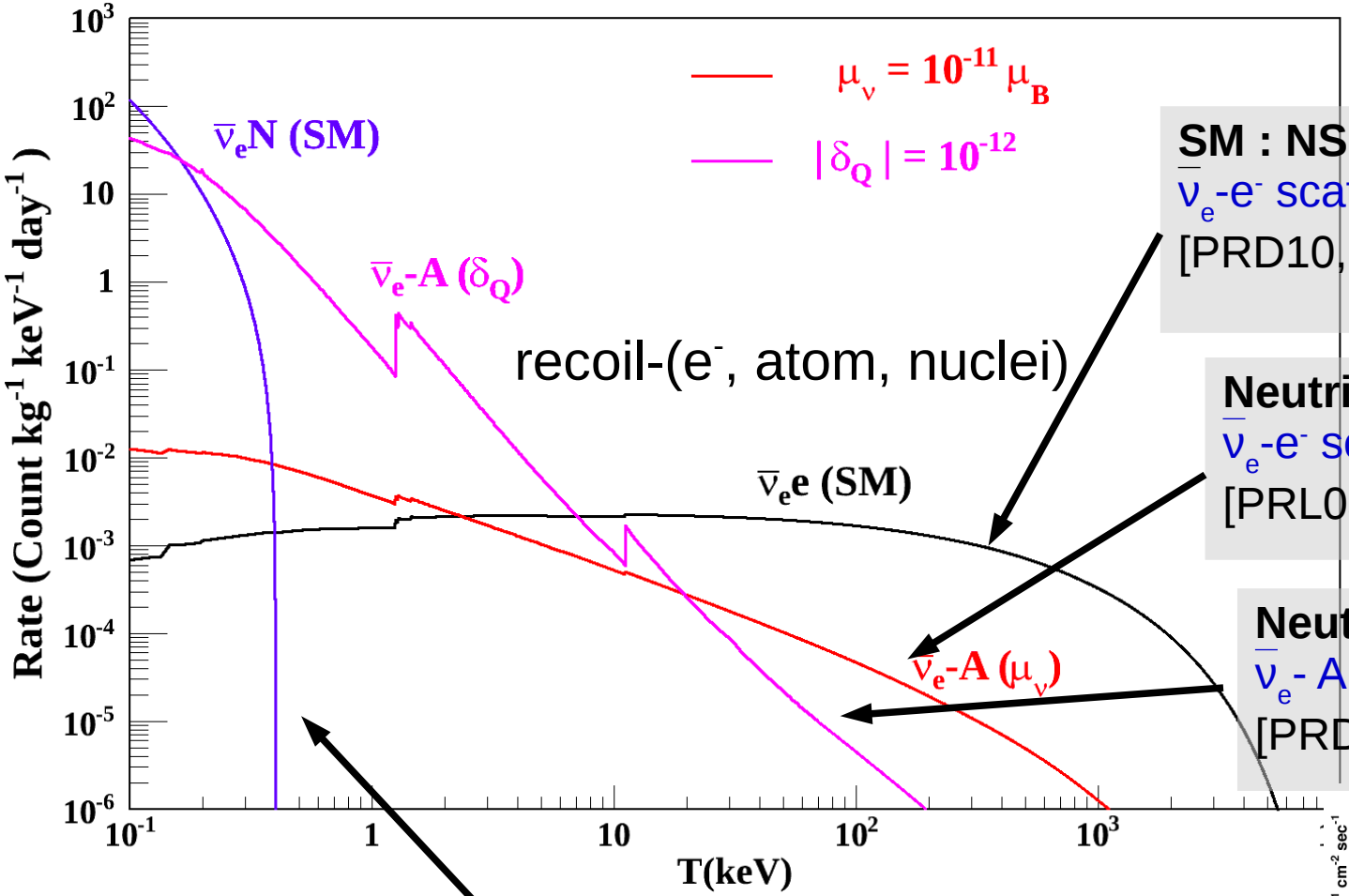






- 2 reactor core, 2 GW.
- Lab. : 28 m from nearest core.
- 30mwe concrete over burden.
- Flexible Design:
  Allows different detectors conf. for different physics

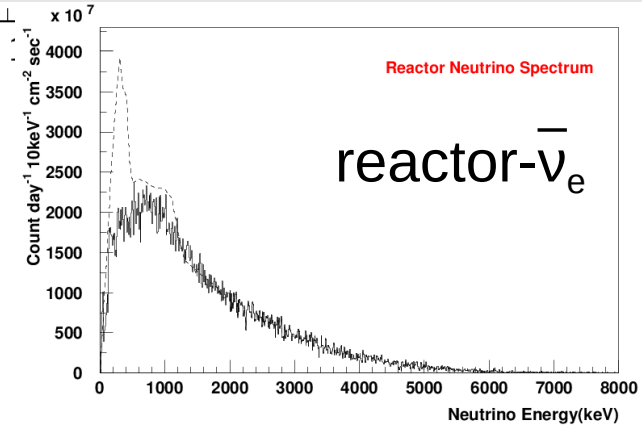
TEXONO Physics Program : interactions by neutrino at reactor



SM : NSI/BSM
$\bar{\nu}_e$-e$^-$ scattering with 200 kg CsI
[PRD10,PRD10,PRD12]

Neutrino Magnetic Moment
$\bar{\nu}_e$-e$^-$ scattering with 1 kg HPGe
[PRL03,PRD05,PRD07,PRD15]

Neutrino milli-charge
$\bar{\nu}_e$- A with sub-keV ULEGe, PCGe
[PRD14,PRD15]



ν-Nuclei Coherent Scattering [goal] [PRD2016]
sub-keV ULGe, PCGe
Dark Matter Searches at KSNL [PRD09,PRL13,AP14]
at CDEX(CJPL) [PRD13,PRD14,PRD14,PRD16]
Axion at CJPL [PRD17]

Ge detector & sub-keV challenge

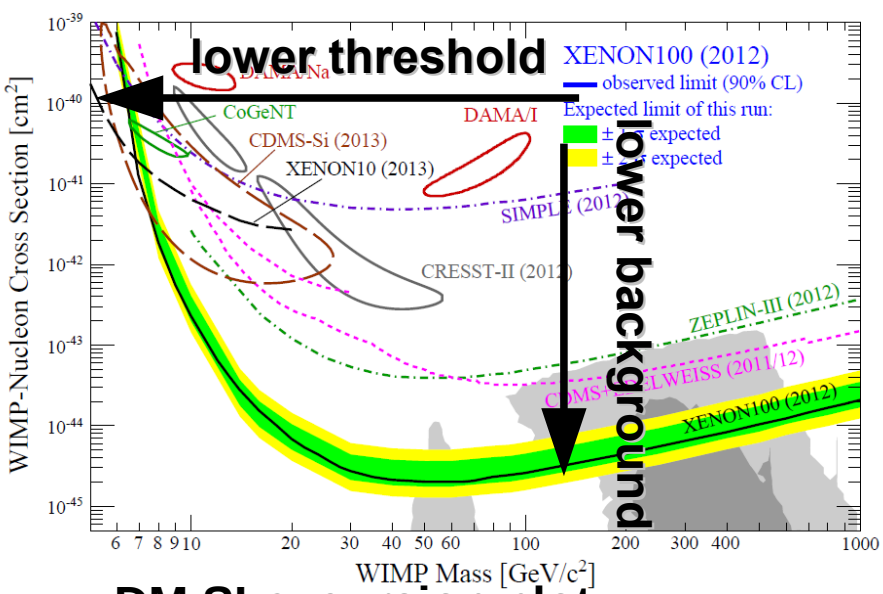
mass ~1kg : threshold ~few×100 eV : bgk ~few cpkkd

- Neutrino physics at sub-keV :

  neutrino electro-magnetic properties, vN-coherent scattering

- Low-mass (~10 Gev) **WIMP Search**.

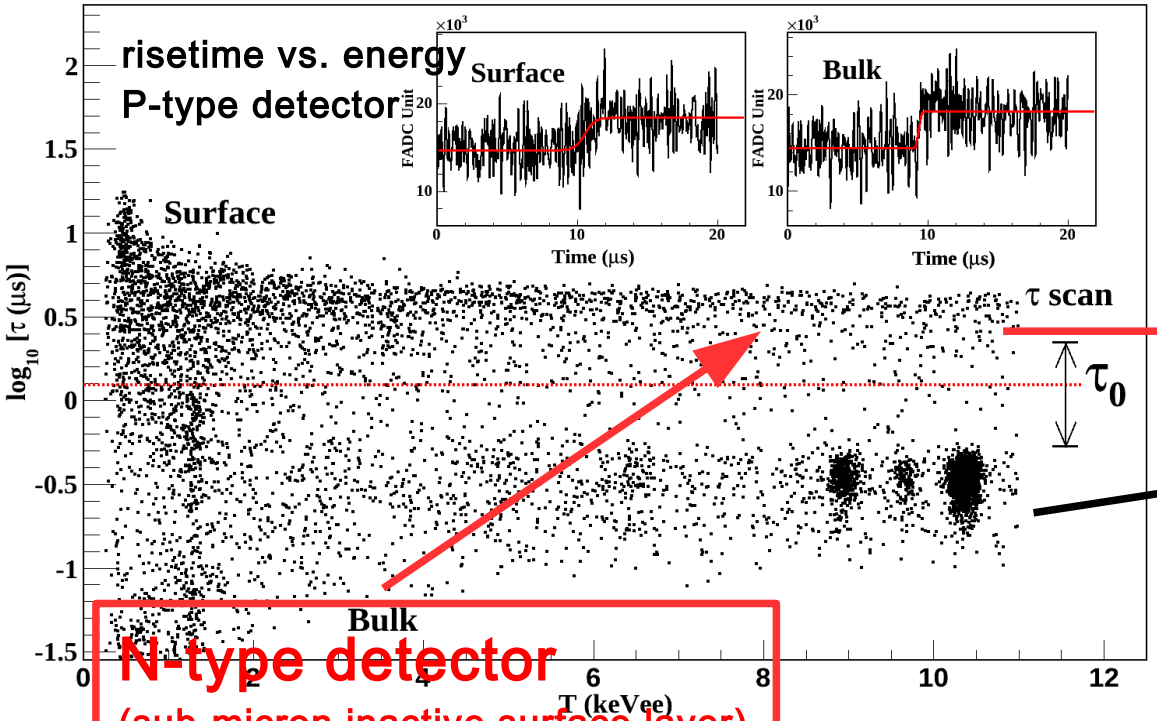
- Allow Low Threshold Measurements(~100eV)

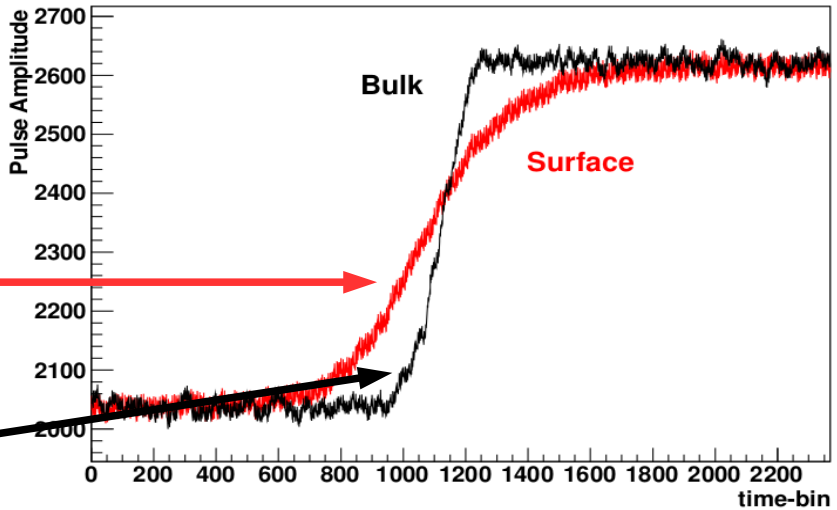


DM SI-excursion plot

- **Near threshold :**
  energy spectrum : noise leakage.
  pulse : noise comparable to signal.
- Quenching Factors : not well measured
- Energy Calibration :
  non-linearity of energy definition.
- Trigger Efficiencies near threshold :
  noise survive hardware threshold.
- Physics vs. Noise : PSD, eff.
- Bulk vs. Surface : algorithms, bulk-efficiency and surface-leakage at low energy.
- Background understanding :
  contributions from background and cosmic-induced isotopes at low energy.

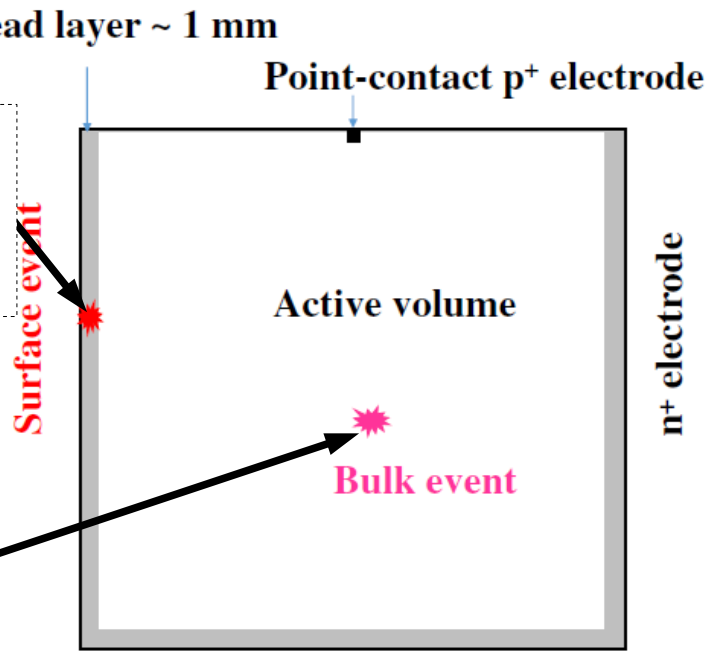
Special feature of PCGe : Bulk/Surface





N-type detector
(sub-micron inactive surface layer)
do not show these anomalous surface events

surface
- partial energy deposit
- diffuse and drift → slow

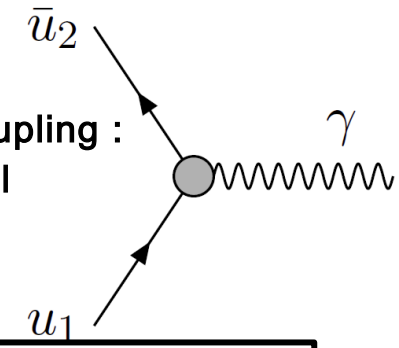


- a bless (most background are surface) and a curse.
- need to measure (at low E): efficiency ε leakage 1-λ

bulk
- full energy deposit
- drift → fast

Neutrino interaction with atoms

high energy : $\nu_e + e^- \rightarrow \nu_e + e^-$

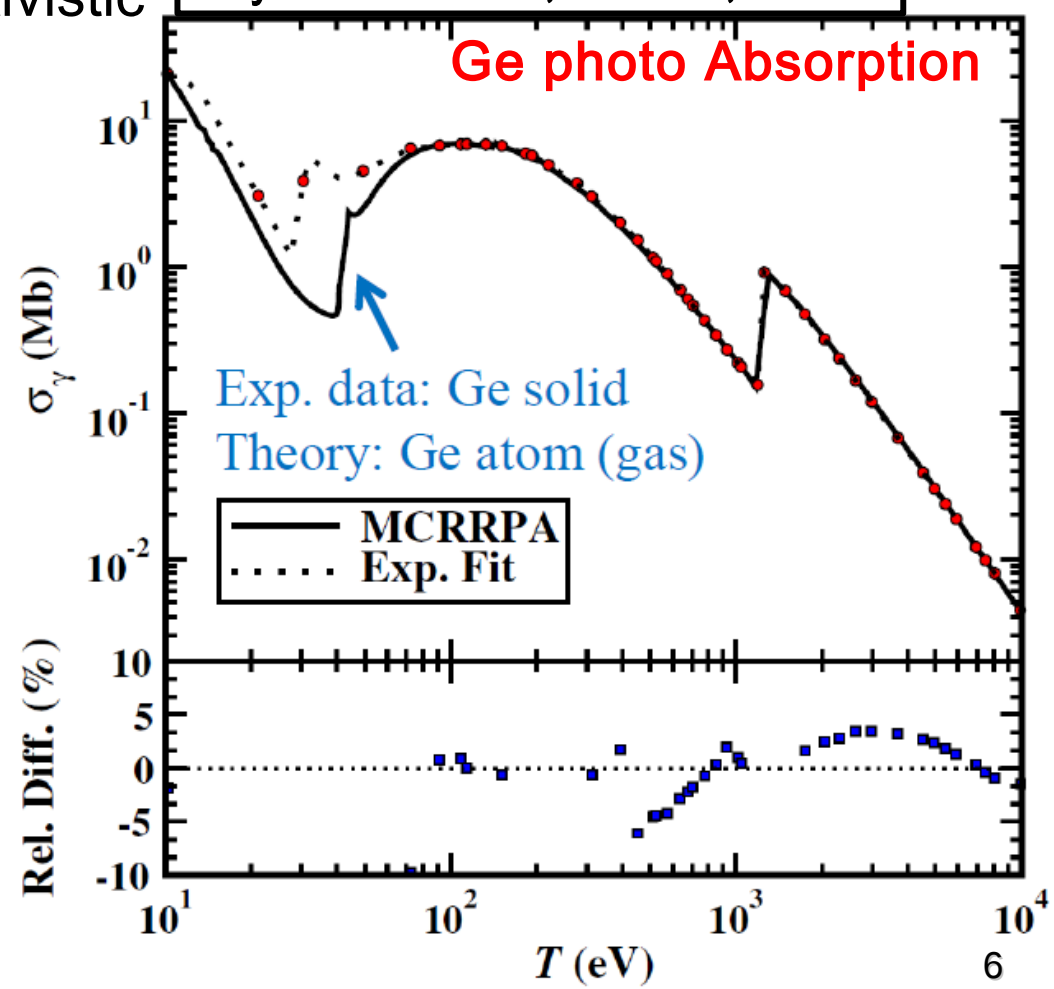


neutrino-photon coupling :
non-standard model

when transfer energy < binding energy of e⁻ , $\nu_e + A \rightarrow \nu_e + A^+ + e^-$ **:**

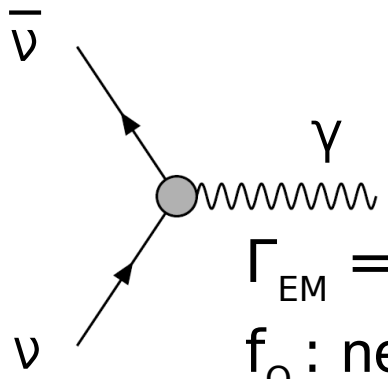
MCRRPA: Multi Configuration Relativistic Random Phase Approximation

Phys. Rev. D 91, 013005, 2015.



- MCRRPA describes well Ge response function up to 80 eV
- Above 80eV Ge-crystal can treated as atom-like
- Below 80eV condense state should considered.
- Above 80 eV, error < 5 %

Neutrino milli-charge



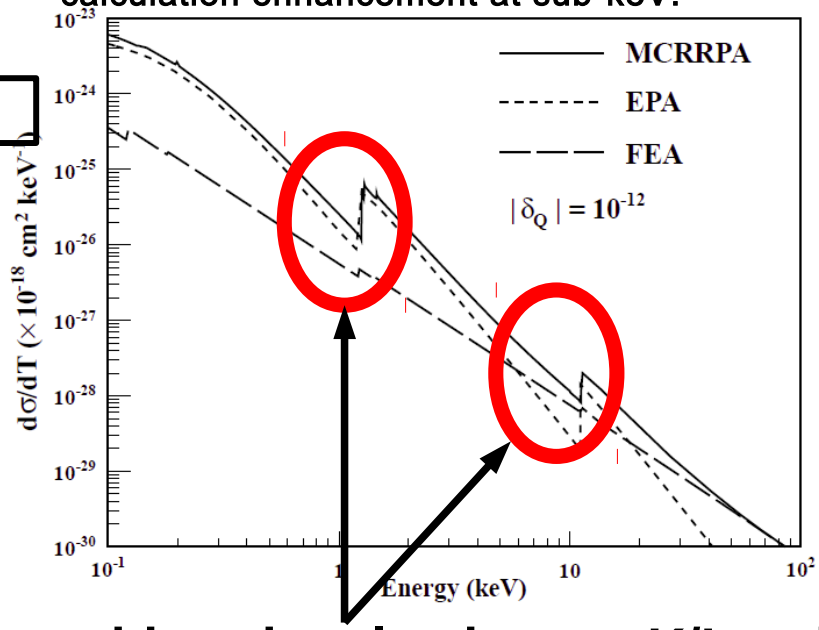
$\Gamma_{EM} = f_Q \gamma_\mu + \ldots$

f_Q : neutrino milli-charge

free electron :

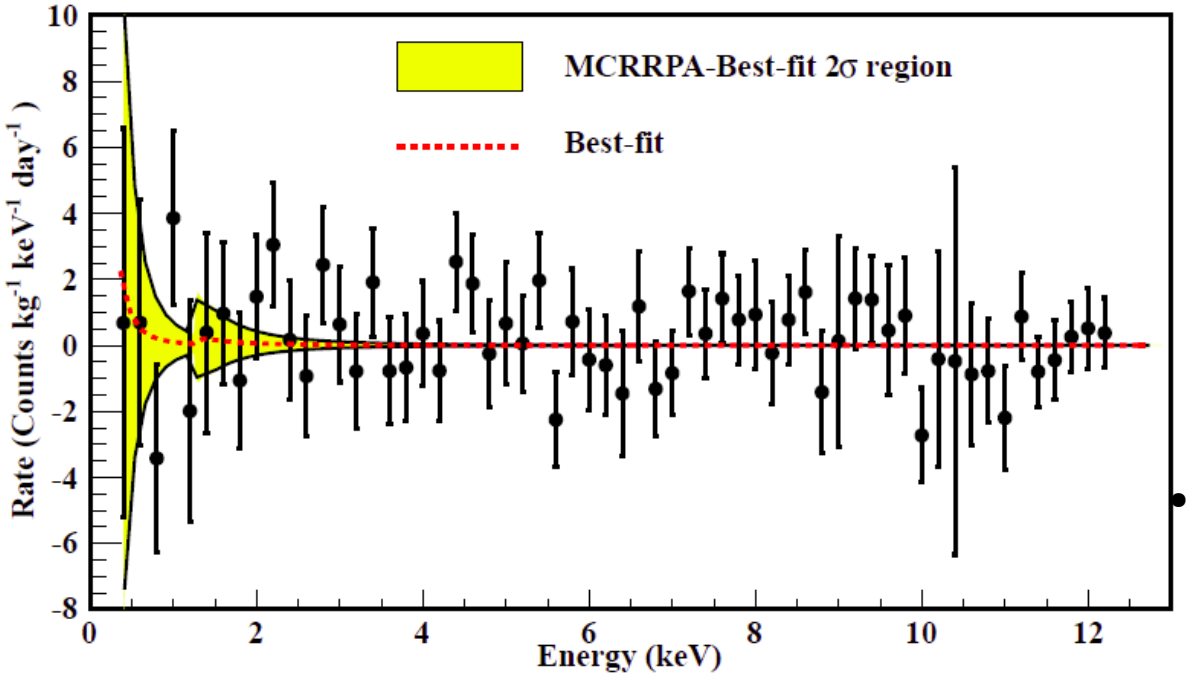
$$\left(\frac{d\sigma_{\delta_Q}}{dT}\right)_{FEA} = \delta_Q^2 \left[\frac{2\pi\alpha_{em}^2}{m_e}\right] \frac{1}{T^2},$$

Atomic Ionization Differential Cross-Section with full atomic physics many-body "MCRRPA" calculation enhancement at sub-keV.



best-fit results on 0.5 kg PCGe
threshold = 300 eV

Phys. Rev. D 91, 012005, 2015.



- **positive signals : known K/L ratio (different from cosmic-activation electron-capture background)**

→ **$\delta_Q < 2.1 \times 10^{-12}$e at 90 % C. L.**

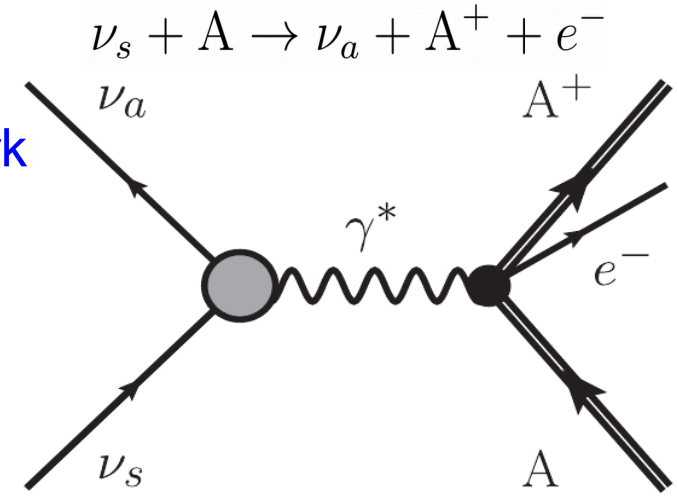
- **goal $\delta_Q \sim 10^{-14}$e at 100 eV threshold**

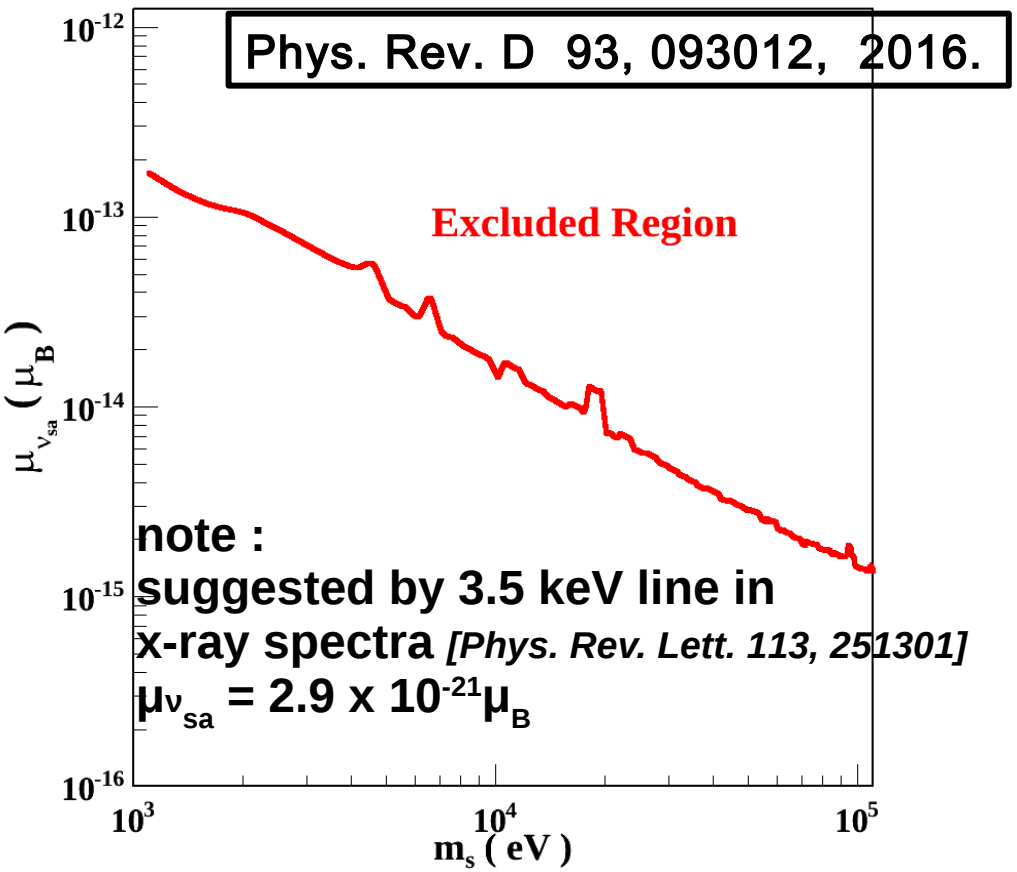
Sterile Neutrino Magnetic Moment

In Radiative Decay $\nu_a, \nu_s \rightarrow \nu_a + \gamma$

Under the assumption of sterile neutrino as cold dark matter, following parameters are adopted,

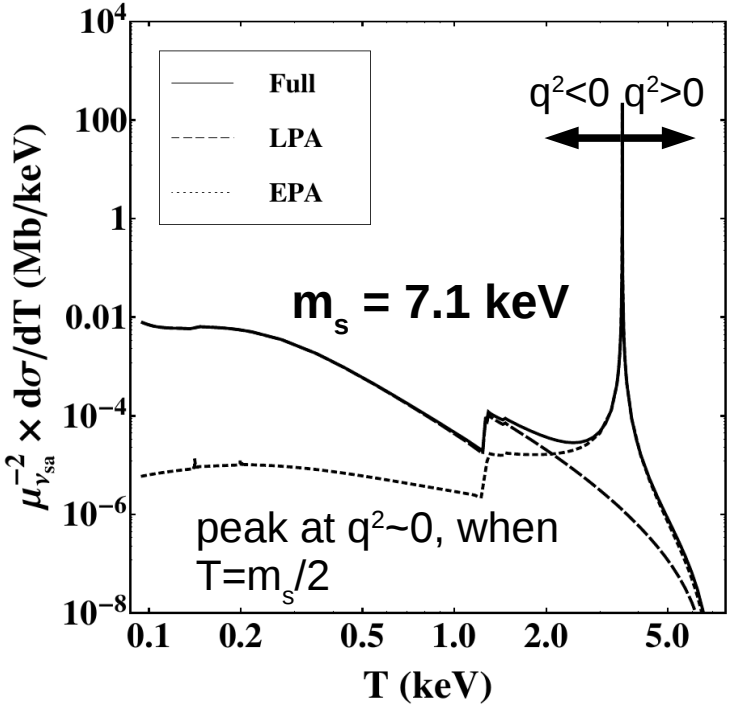
- Dark matter density = 0.4 GeVcm^{-3} ,
- Maxwellian velocity distribution with
- mean velocity = 220.0 km/s and V_{esc} = 533 km/s





$q^2>0$: forward scattering $\nu_s + A \rightarrow \nu_a + A^+ + e^-$, $T>m_s/2$

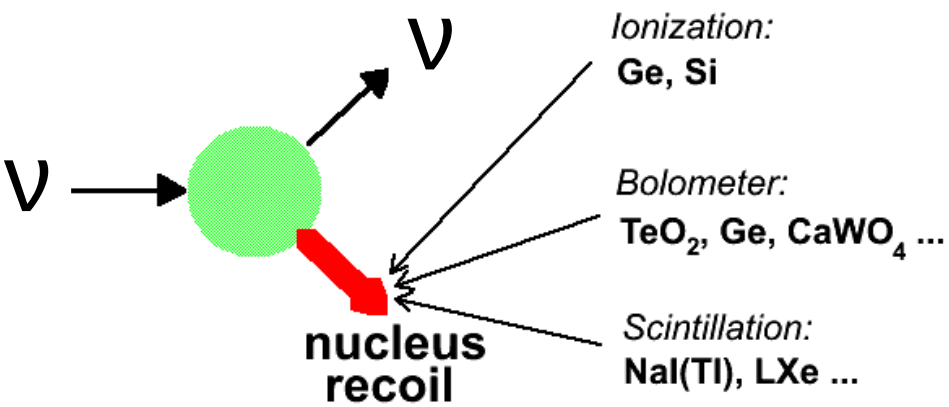
$q^2<0$: $\nu_a + A \rightarrow \nu_a + A^+ + e^-$, for all T



νN coherent scattering

- ν+A→ν+A : Never been experimental observed.
- $\frac{d\sigma}{dT} = \frac{G_F^2}{m_N}\left[(1-4sin^2\theta_W)-N\right]^2\left[1-\frac{m_N T_N}{2E^2}\right]$
- Neutral current process.
- $\sigma \propto N^2$ for E_ν<50MeV (Coherent)
- sensitive probe for BSM
- reactor monitoring
- important process in stellar collapse & supernova explosio
- for reactor neutrino on Ge, T_{max} ~ 2 keV

  T_{max} ~ 500 eV (Q. F. ~ 0.2)



νN coherent scattering

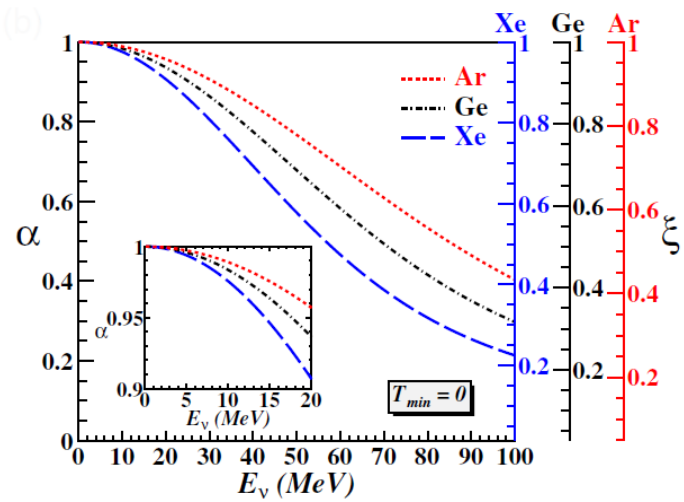
Partial coherency: when wavelength < nucleus-size

The cross-section ratio between nucleus and neutron & partial-coherency and full-coherency :

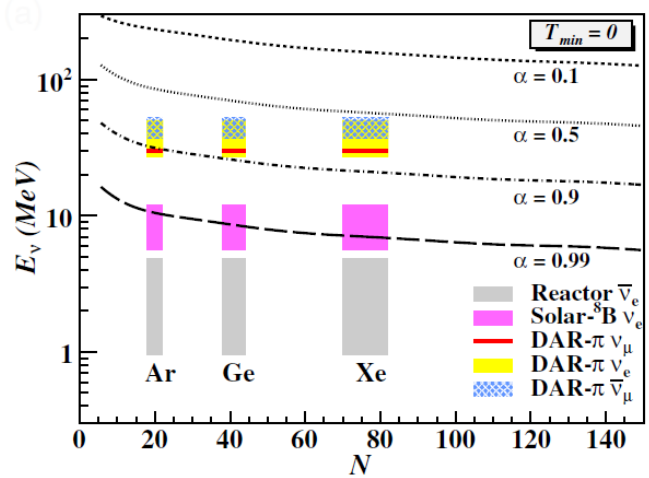
$$\frac{\sigma_{\nu A_{el}}(Z,N)}{\sigma_{\nu A_{el}}(0,1)} = Z\epsilon^2[1+\alpha(Z-1)] + N[1+\alpha(N-1)] - 2\alpha\epsilon ZN$$

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

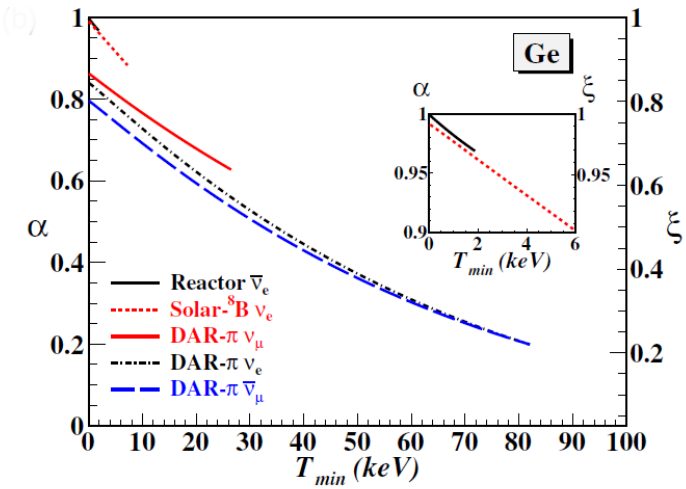
Phys. Rev. D 93, 113006, 2016.



coherency vs. E_ν



equal coherency line at E_ν and N

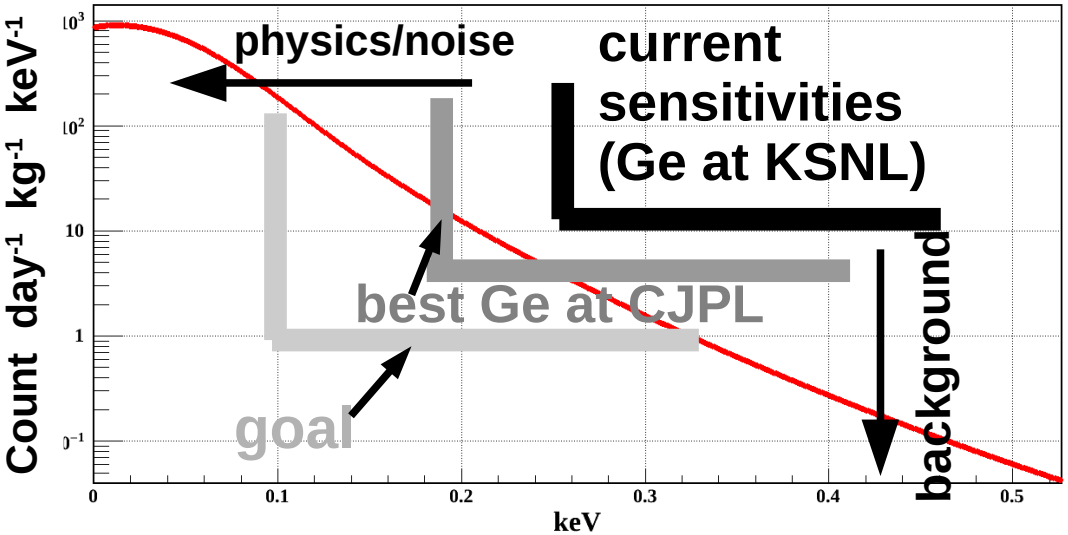


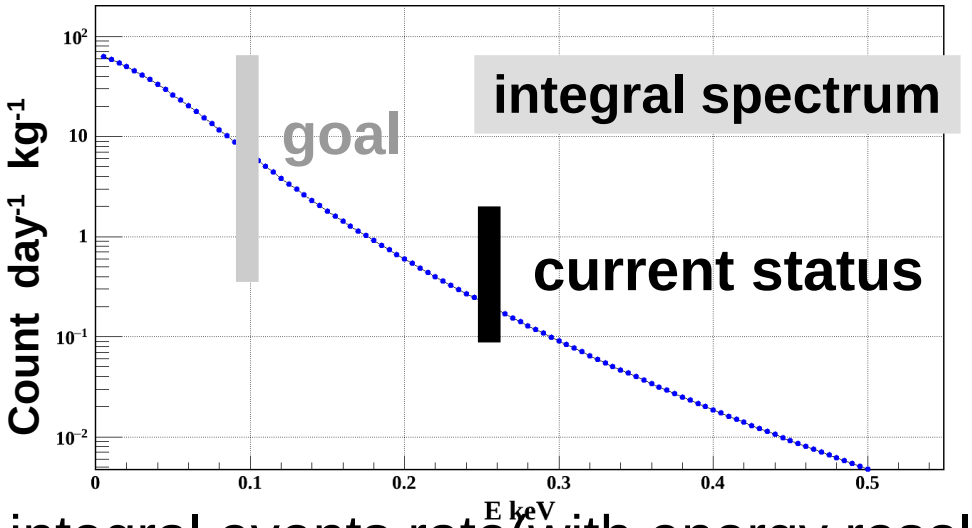
coherency vs. thorehold

- reactor neutrino is fully coherent.

νN coherent scattering

estimated events rate at KSNL





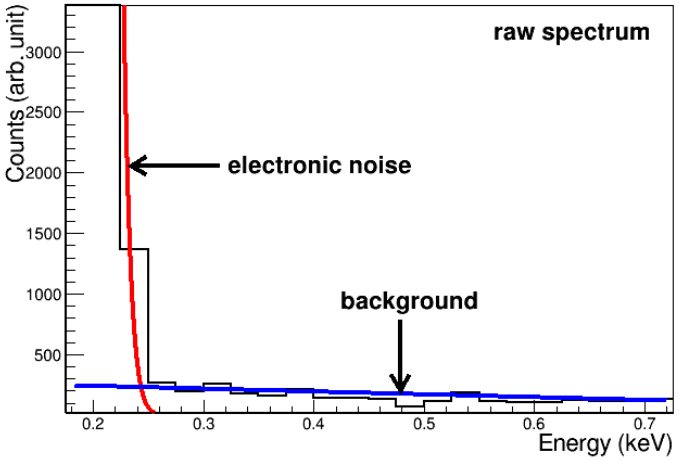
integral events rate(with energy resolution) :

6.6 count day^{-1} kg^{-1} at 100 eV threshold

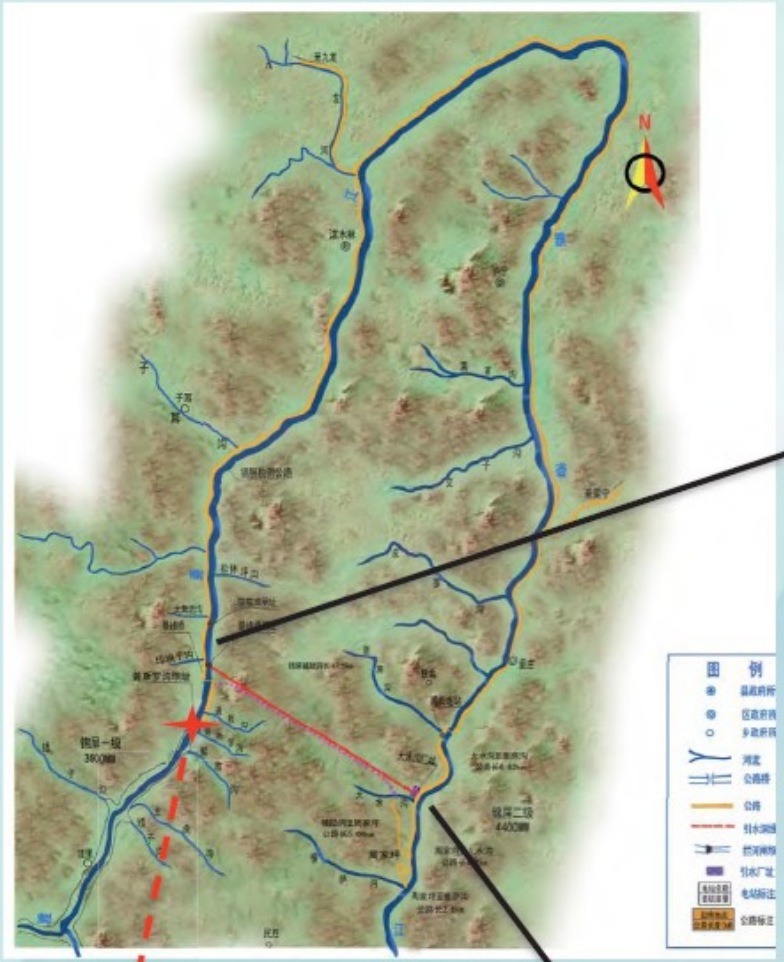
0.59 count day^{-1} kg^{-1} at 200 eV threshold

improvements (plan) **:**

- **background :**
  cosmic correction,
  B/S correction,
  known sources,
  understanding (simulation).
- **phys/noise :**
  hardware improvement :
  cooling, electronic.
  PSD, noise-simulation.



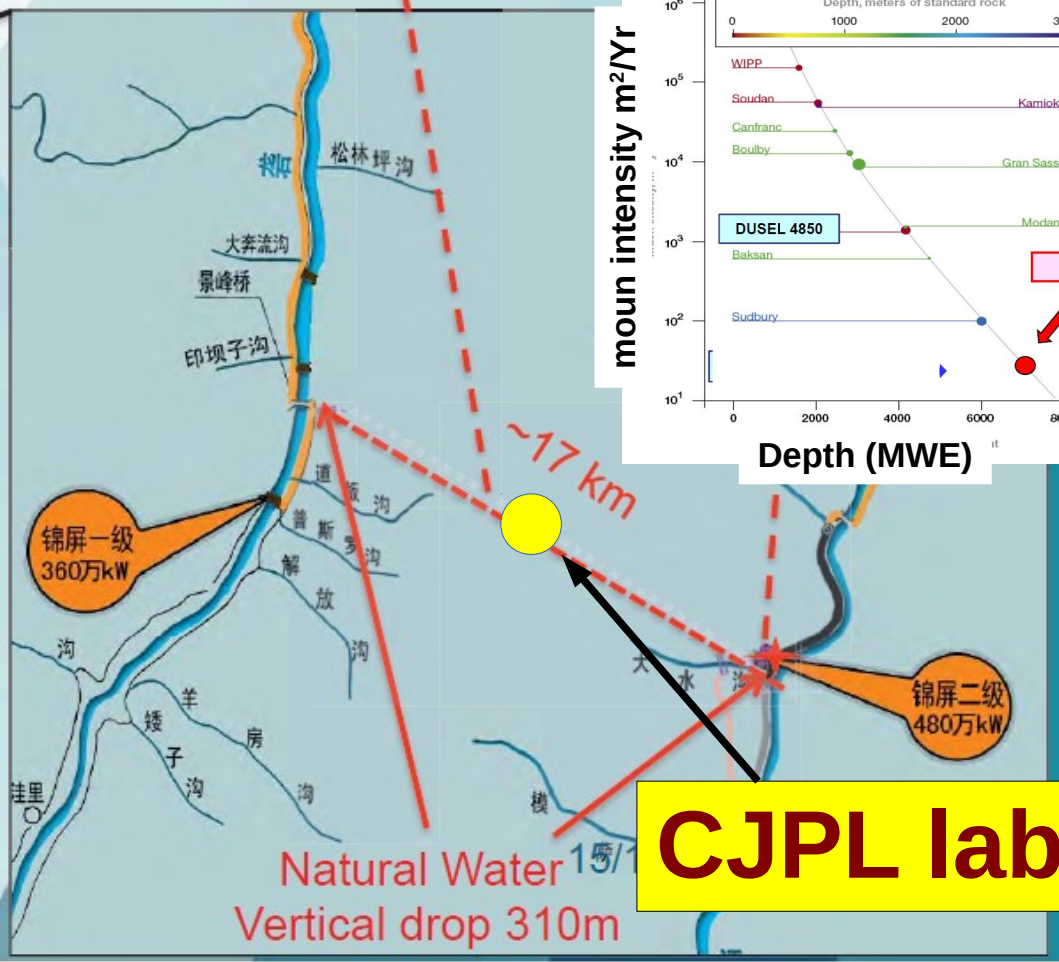
Jinping Hydroelectric Power Plants

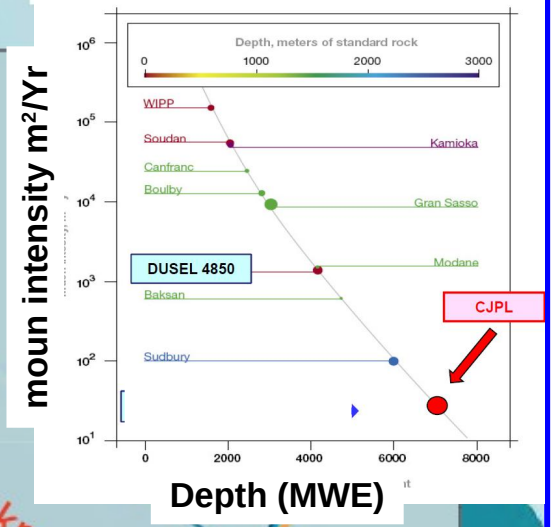


4 hydraulic tunnels
Φ13m×16.6km

Jinping-II Power Plant
4800MW
(8×600MW)

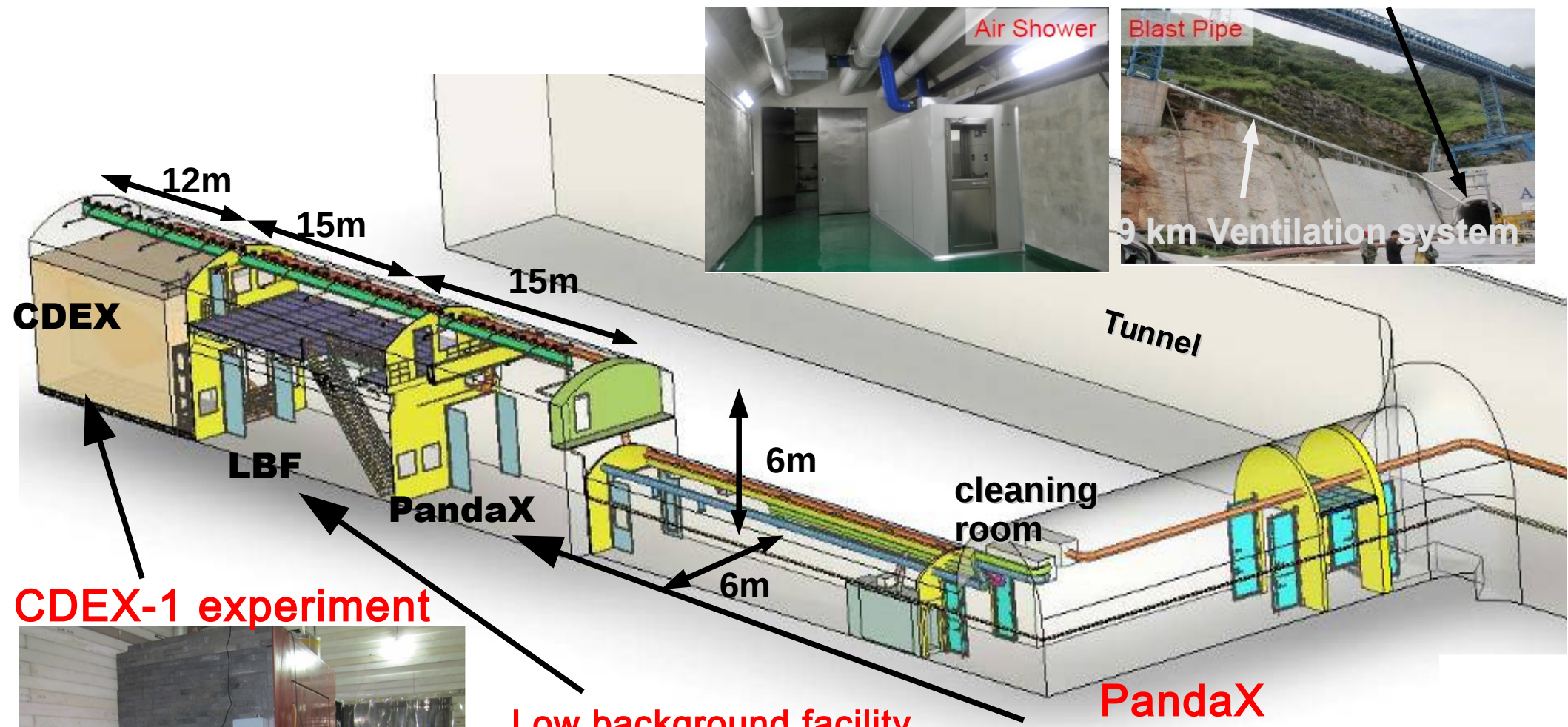
Jinping-I Power Plant
3600MW
(6×600MW)





CJPL lab.

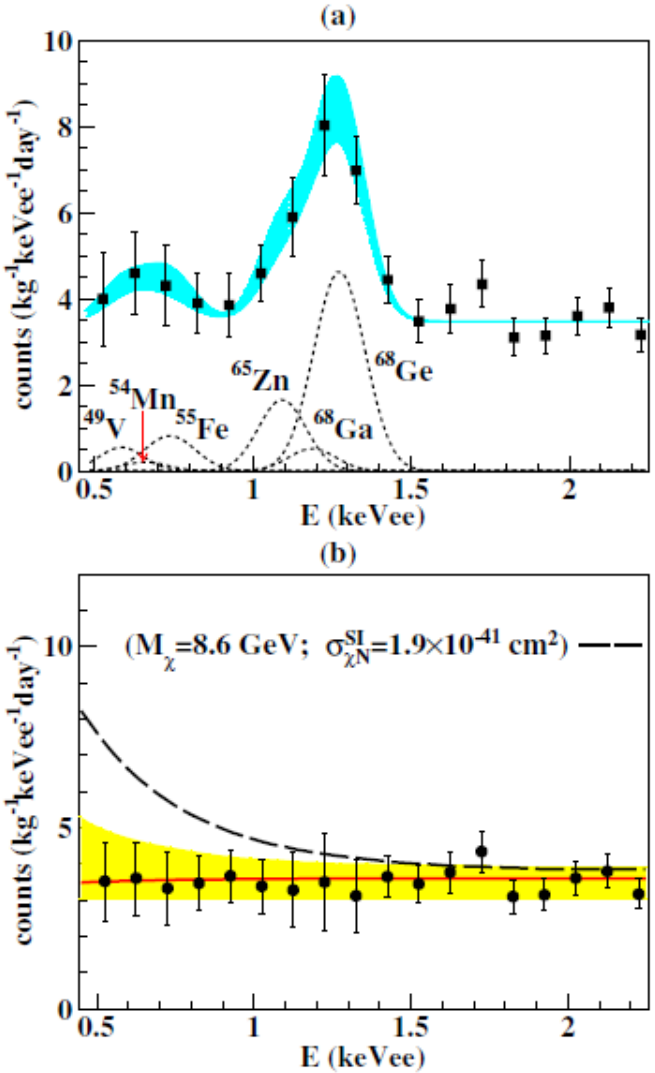
CDEX & CJPL-I

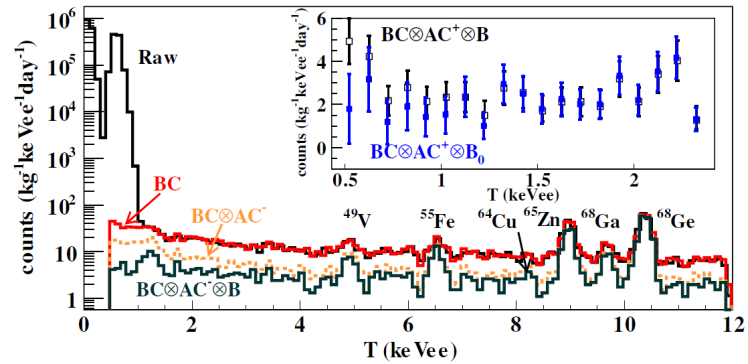


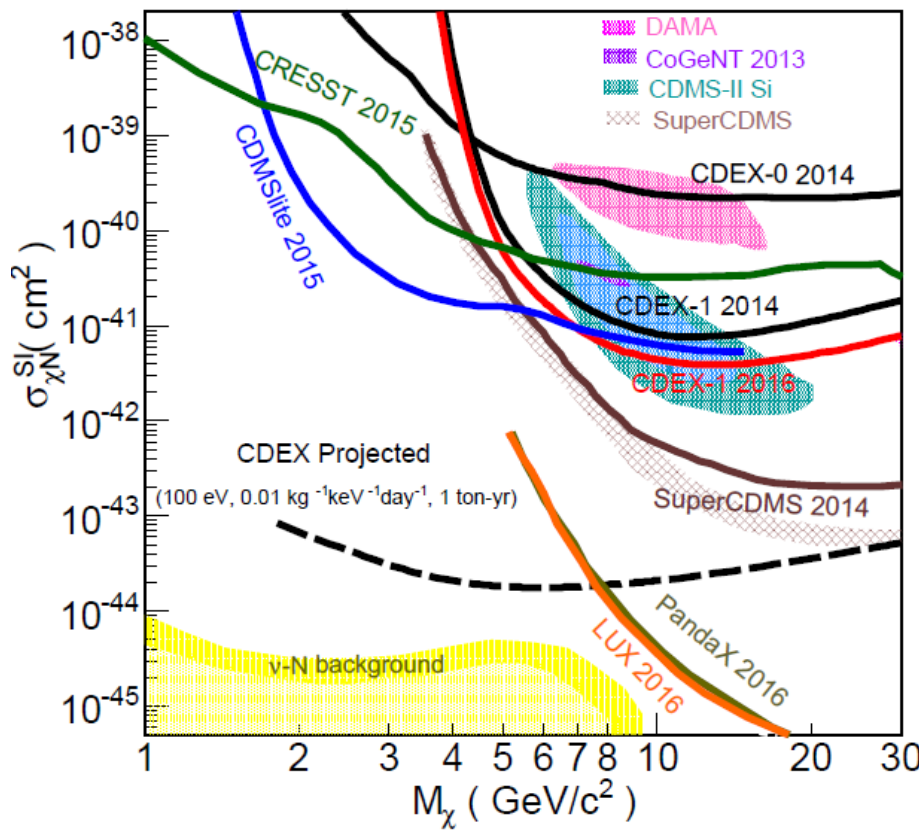
Low background facility

CDEX-1 Dark Matter Search

[PRD 93 092003 (2016)]







335 kg-days of data
Baseline design with NaI(Tl)
Fiducial mass : 915 g, Analysis threshold ~ 475 eV
Q.F. adopted by TRIM software with 10% systematic uncertainty

CDEX-1 : Axion

Phys. Rev. D 95, 052006, 2017.

M1 transition from ^{57}Fe from Sun: $^{57}Fe^{*} \rightarrow {}^{57}Fe + a$ [g_{AN}]

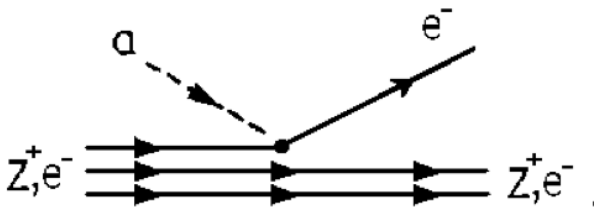
axion(a) from sun [g_{Ae}]

Compton(C): $\gamma + e \rightarrow e + a$

bremsstrahlung(B): $e + Q \rightarrow e + Q + a$

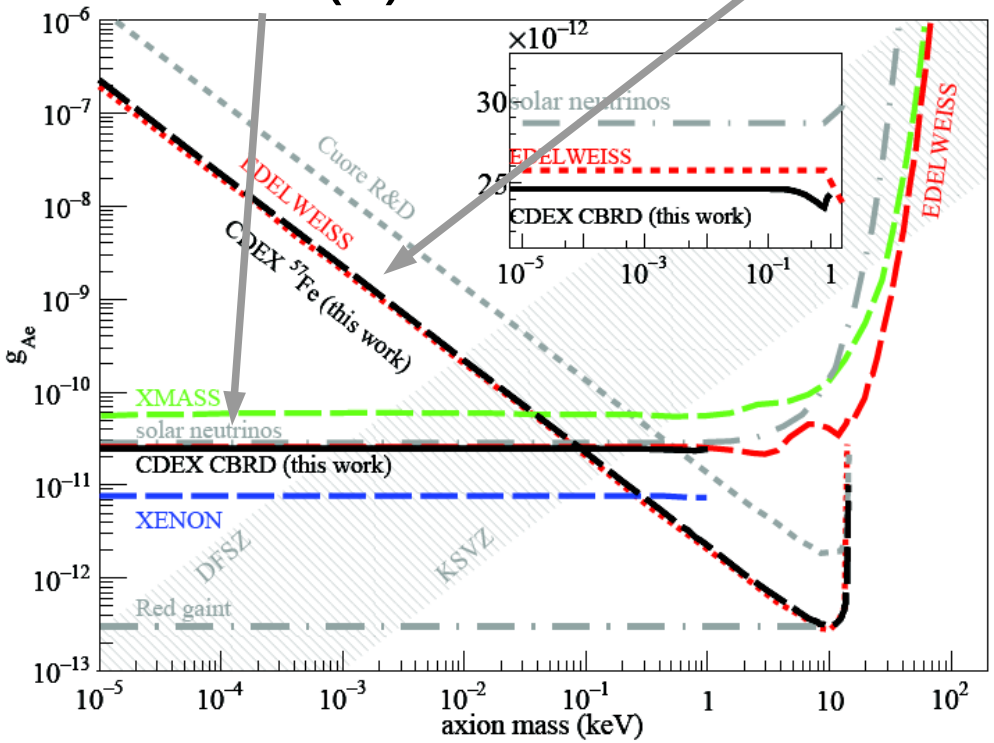
recombination(R): $e + I \rightarrow I^{-} + a$

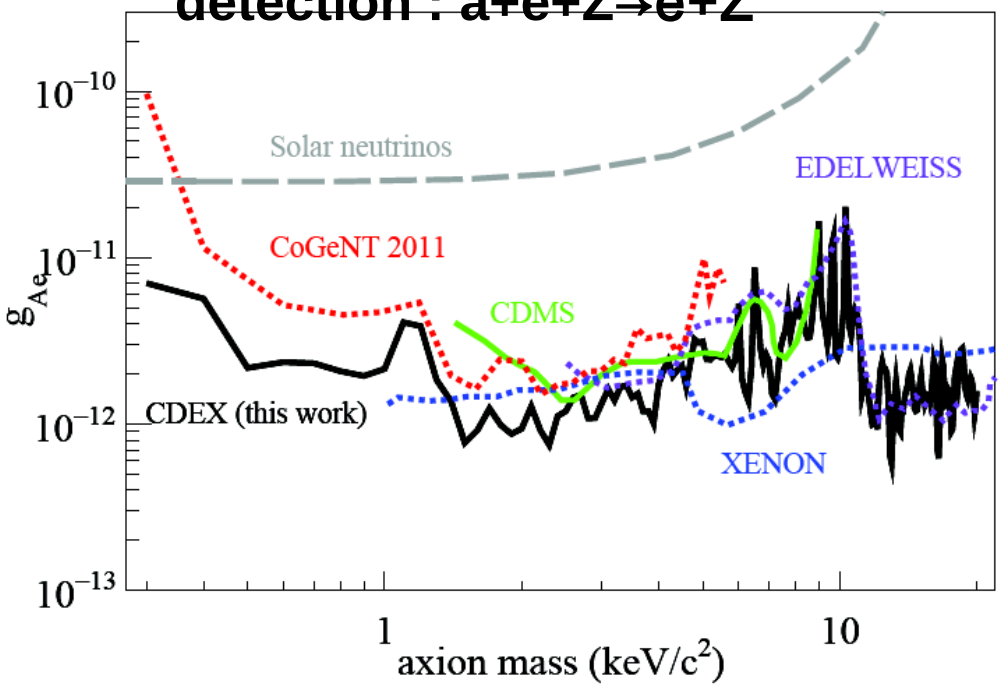
de-excitaion(D): $I^{*} \rightarrow I + a$



Axioelectric
or Photoelectric-like

galatical axion(DM) : axioelectric detection : $a + e + Z \rightarrow e + Z$

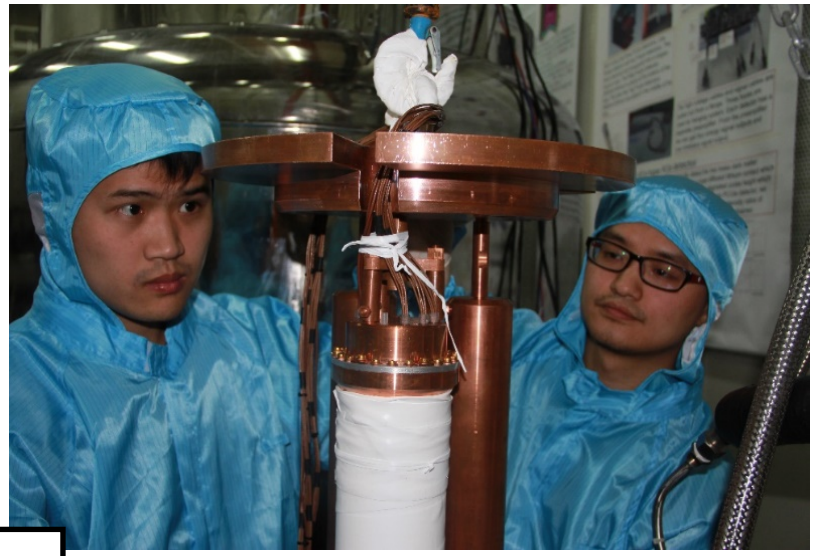


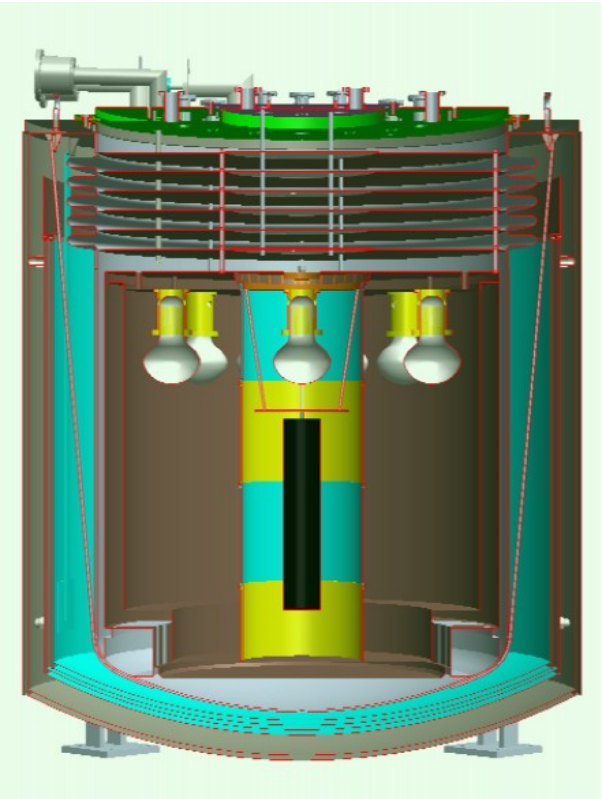


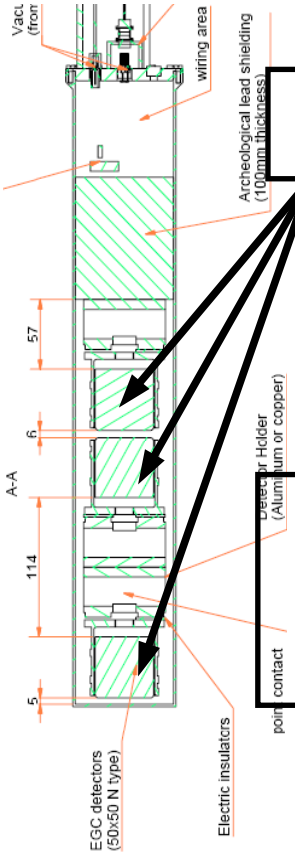
Competitive results for DM axion below the axion mass of 1 keV.

next step : CDEX-10 Array detectors

- Test of cryogenic system has been done and shipped to CJPL in March 2016.
- A germanium array with LN in cryogenic system is commissioning.
- The performance of LAr is under study.







PCGe

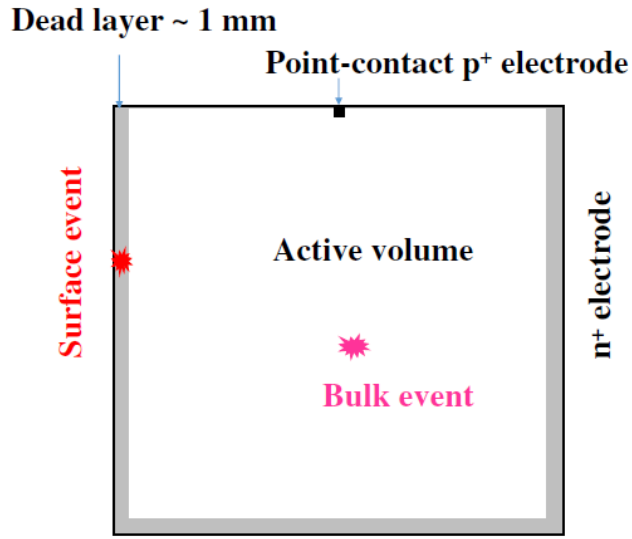
~9 kg of PCGe
&
1.5 T of LN/LAr

3 kg + 3 kg prototype: ready to take data, threshold < 250 eV

CDEX-1 : status & plans

Physics results :

- DM results
- axion results
- DM annual modulation (plan)

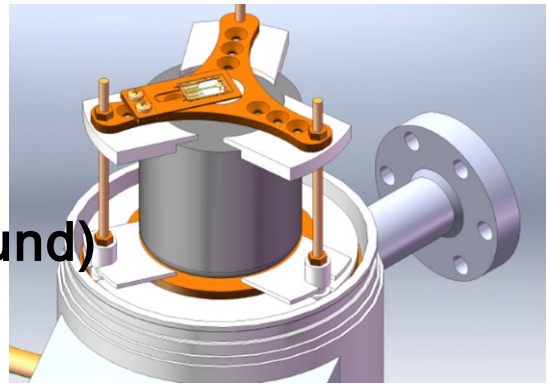


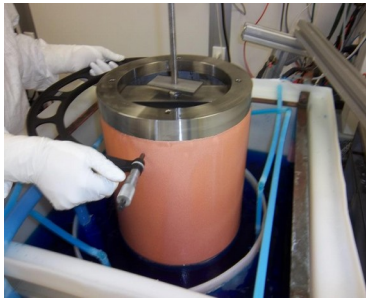
Analysis :

- new B/S method
- dead layer measurement
- background understanding: experiment and simulation

Detector R&D :

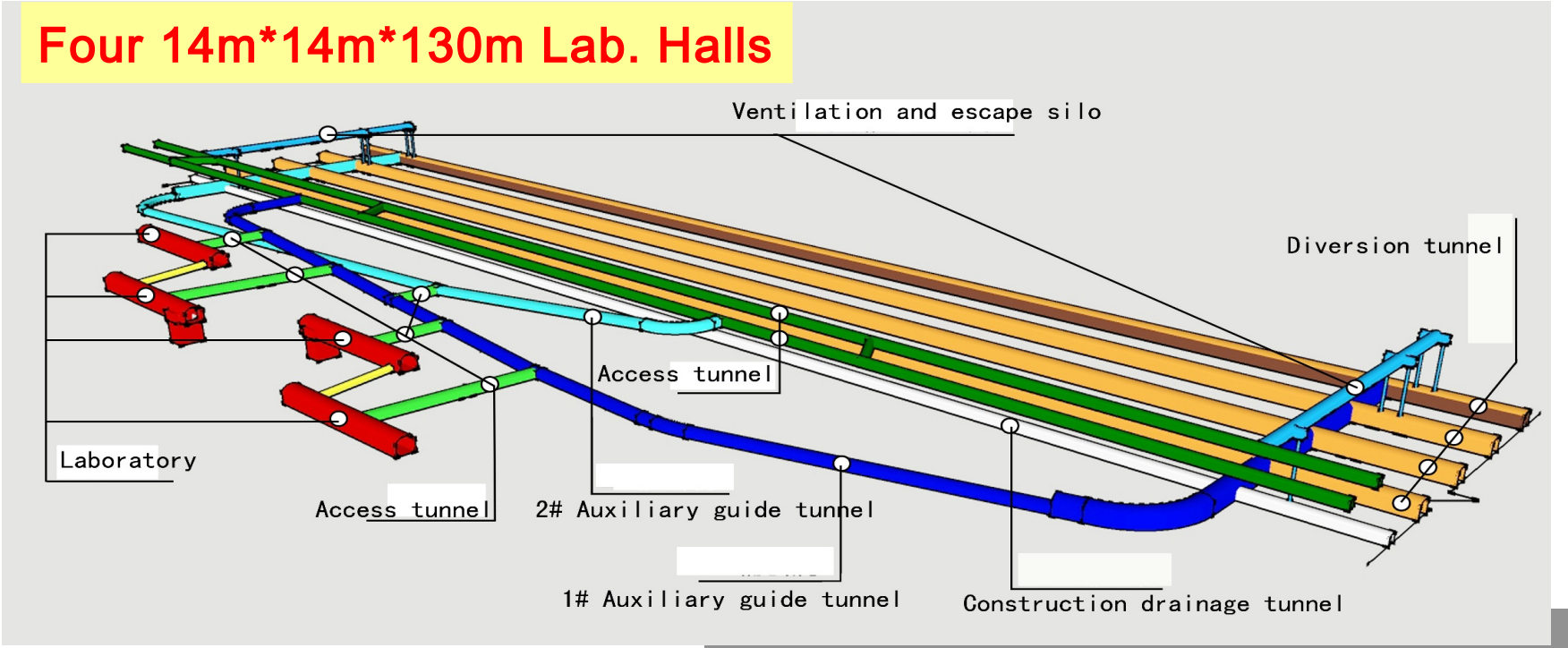
- homemade Ge crystal
- detector fabrication
- low background electronics
- homemade electroformed Cu material (plan for underground)
- liquid-N for shielding and cooling



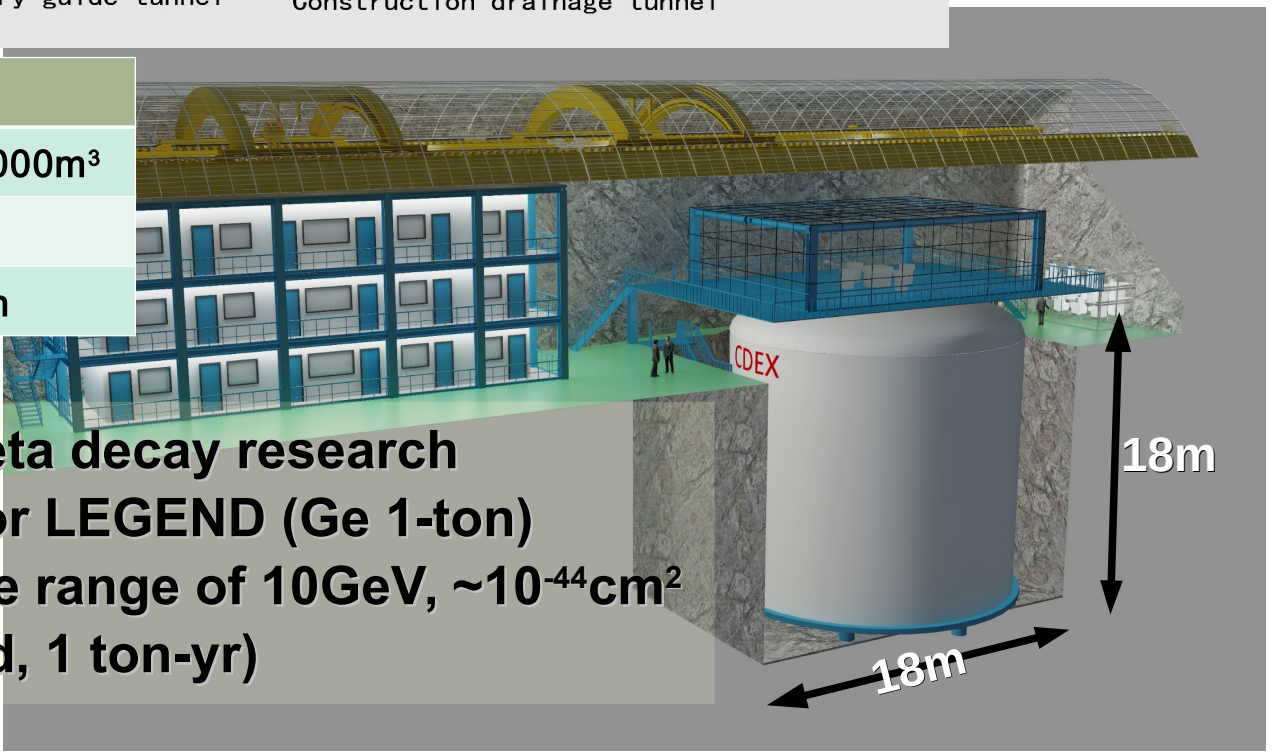


CJPL-II : construction & Ge-1t (plan)

Four 14m*14m*130m Lab. Halls



	CJPL-I	CJPL-II
Rock Work	4100 m^3	210000+151000m^3
Electric Power	70x2 kVA	10x2 MVA
Fresh Air	2400 m^3/h	15000x3 m^3/h



- plan : Ge-1t ^{76}Ge double beta decay research
- CJPL-II : a candidate site for LEGEND (Ge 1-ton)
- DM search : Sensitive in the range of 10GeV, ~$10^{-44}cm^2$ (based on 100eV, 0.01cpkkd, 1 ton-yr)

summary

- **sub-keV Ge R&D and ongoing plan :**

  Backgrond understanding.

  Detector properties near noise edge.

  Noise simulation.

  B/S calibration schemes.
- **Neutrino at KSNL:**

  Neutrino-atoms interaction : MCRRPA.

  Results on neutrino electromagnetic properties.

  goal : νN coherent scattering, ~100 eV threshold & ~ cpkkd.
- **Dark Matter Searches at CJPL:**

  Competitive results on light WIMPs with sub-keV Ge.

  CDEX-1 Axion results (competitive for DM-axion at sub-keV mass).

  1-ton for 0νββ at CJPL-II ?

Thank you

TEXONO Collaboration

TEXONO Taiwan EXperiment On NeutrinO (since 1997)

Neutrino Physics at Kuo-Sheng Reactor Neutrino Laboratory (KSNL)

- **Taiwan (AS, INER, KSNPS)**
- **Turkey (METU, DEU)**
- **India (BHU)**

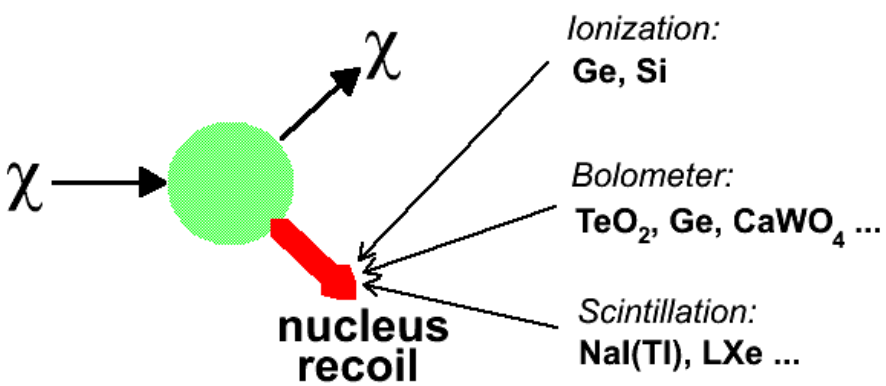
Partner : CDEX Collaboration

CJPL

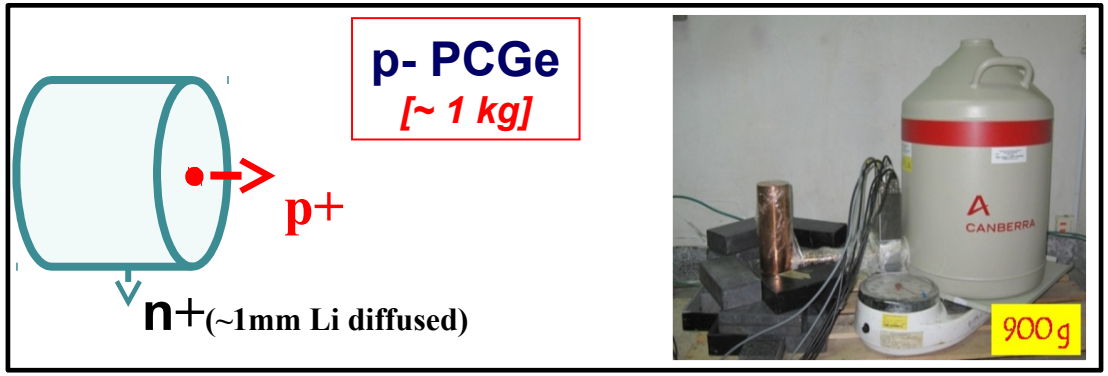
CDEX China Dark Matter Experiment (birth 2009)

Dark Matter Searches at China Jin-Ping Underground Laboratory (CJPL)

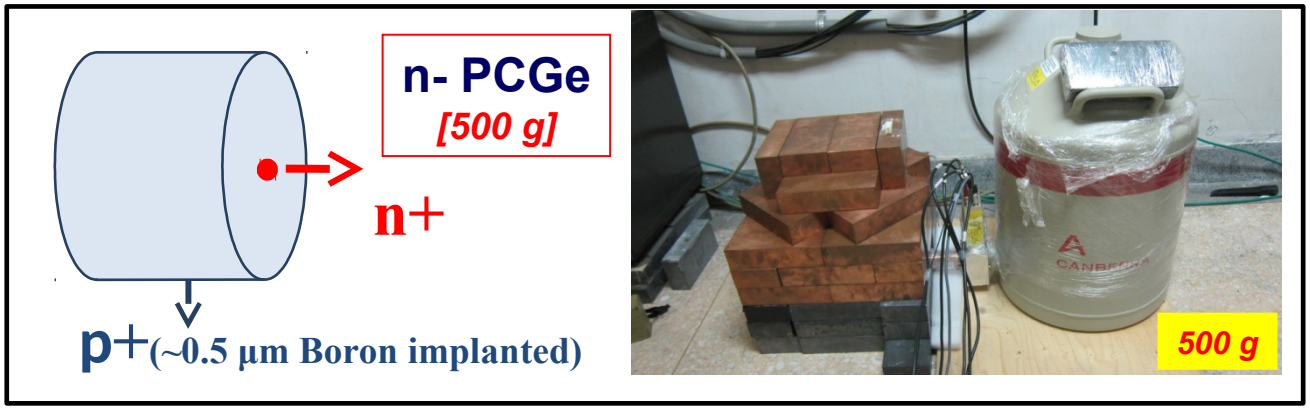
- China (THU, CIAE, NKU, SCU,YLJHD)
- Ge as primary detector.
- same detector technique, i. e. bulk/surface seperation, phys/noise seperation.



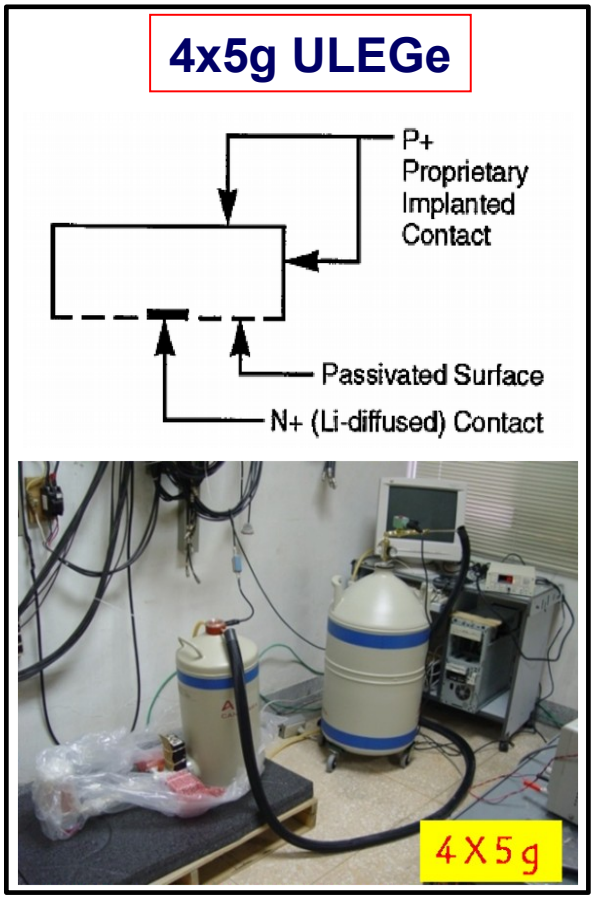
Various Ge detectors



p-PCGe : ~kg, threshold ~300 eV with bulk/surface feature

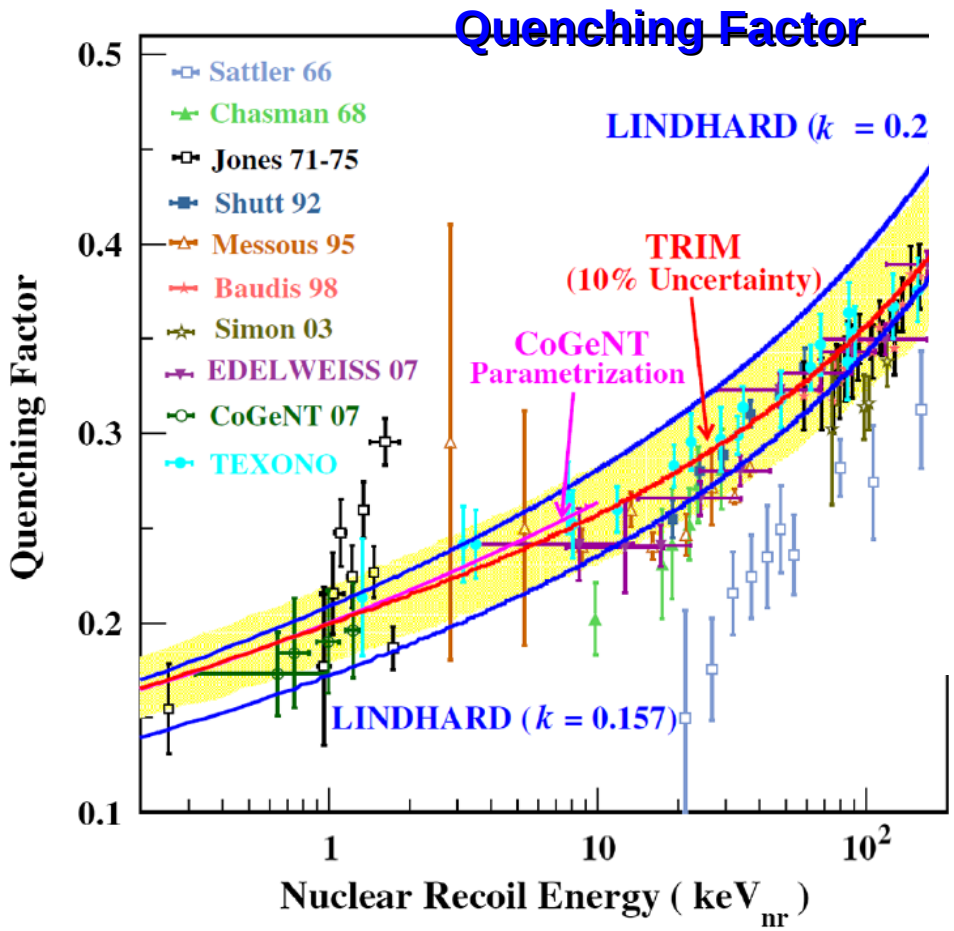


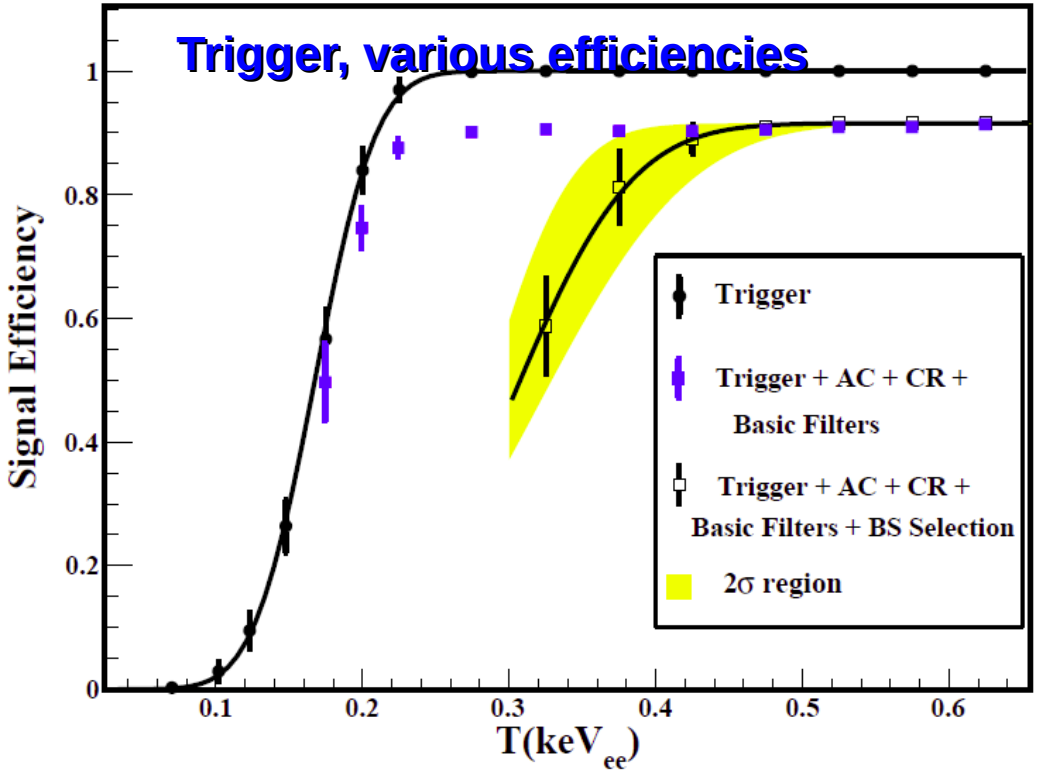
n-PCGe : ~kg, threshold ~300 eV without bulk/surface feature

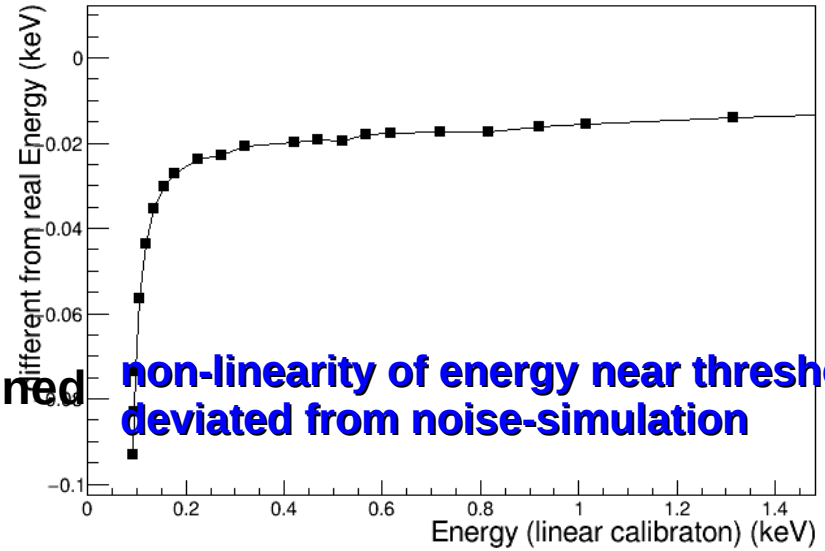


ULEGe : ~g, threshold ~100 eV

Challenge for sub-keV Ge





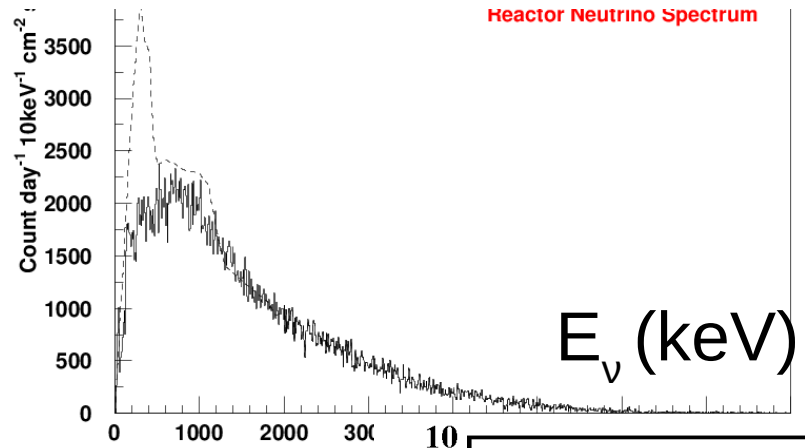


non-linearity of energy near threshold deviated from noise-simulation

- Quenching factor at sub-keV are not well known.
- Energy and efficiencies should be measured/defined carefully at sub-keV range.
- non-linearity had been checked.

Neutrino magnetic moment

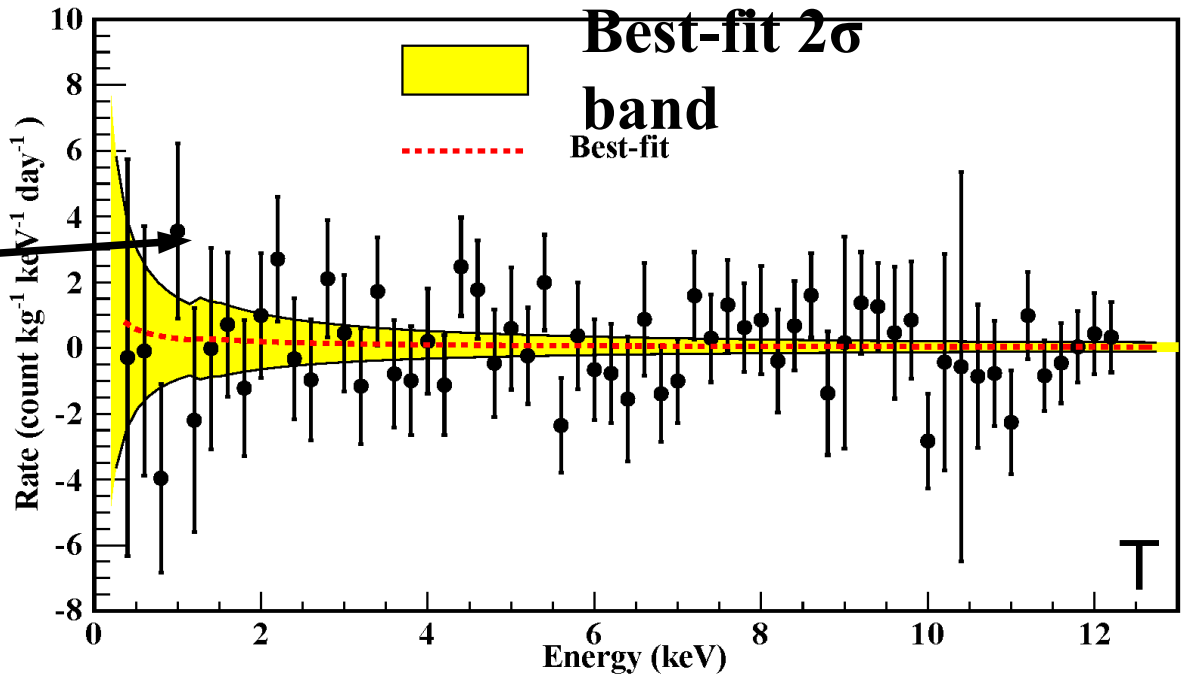
Data	Data Strength (kg-day)	Threshold (keV)	μ_ν 90% CL Limits ($< \times 10^{-11}$) FEA	MCRRPA
TEXONO 1 kg Ge	570/127.8	12	< 7.4	< 7.4
GEMMA 1.5 kg Ge	755.6/187	2.8	< 2.9	< 2.9
TEXONO Point-Contact Ge	124.2/70.3	0.3	< 26.0	< 26.0
Point-Contact Ge Projected	800/200	0.1	< 1.5	< 1.7



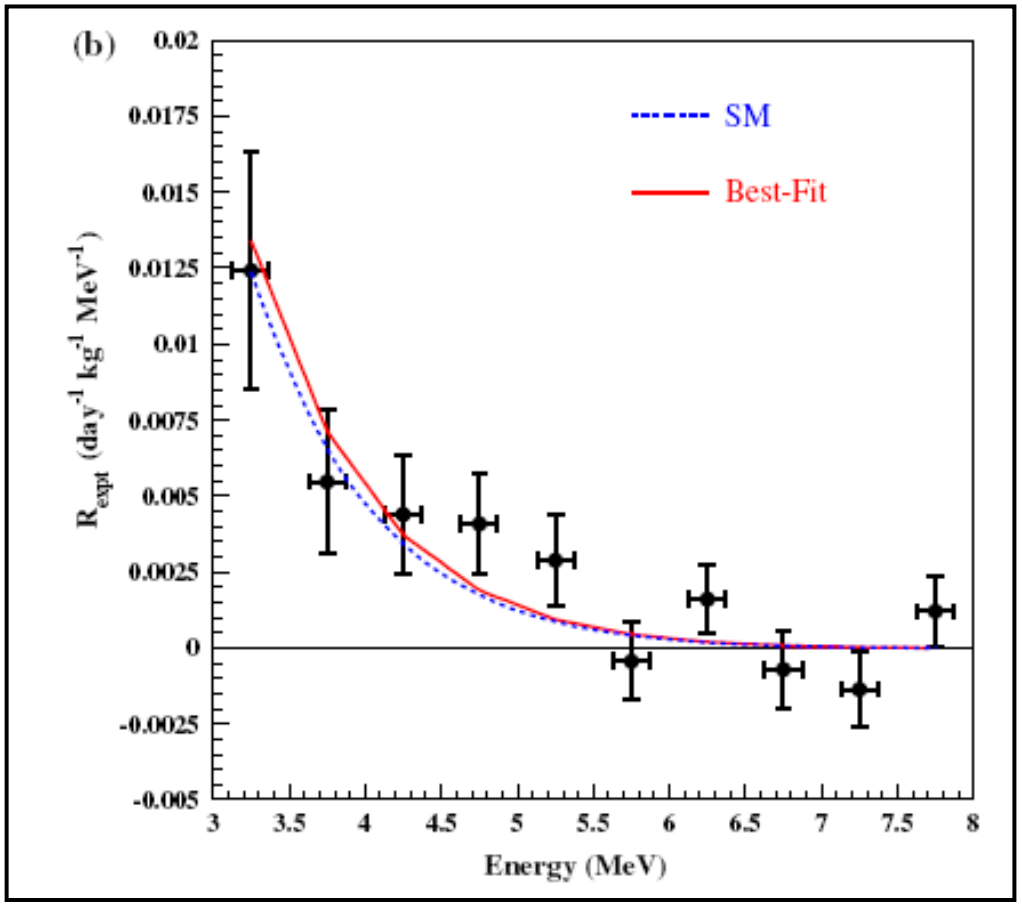
$$+ (d\sigma/dT)_{mm} \sim 1/T - 1/E_\nu$$

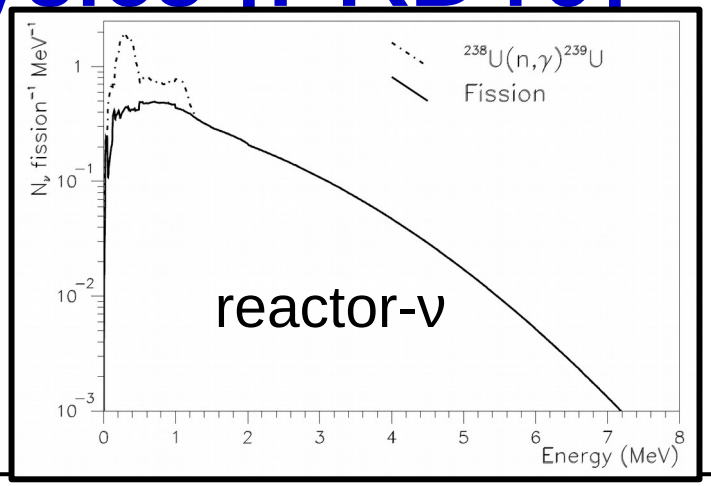
minimize effect of uncertainties of E_ν at low T

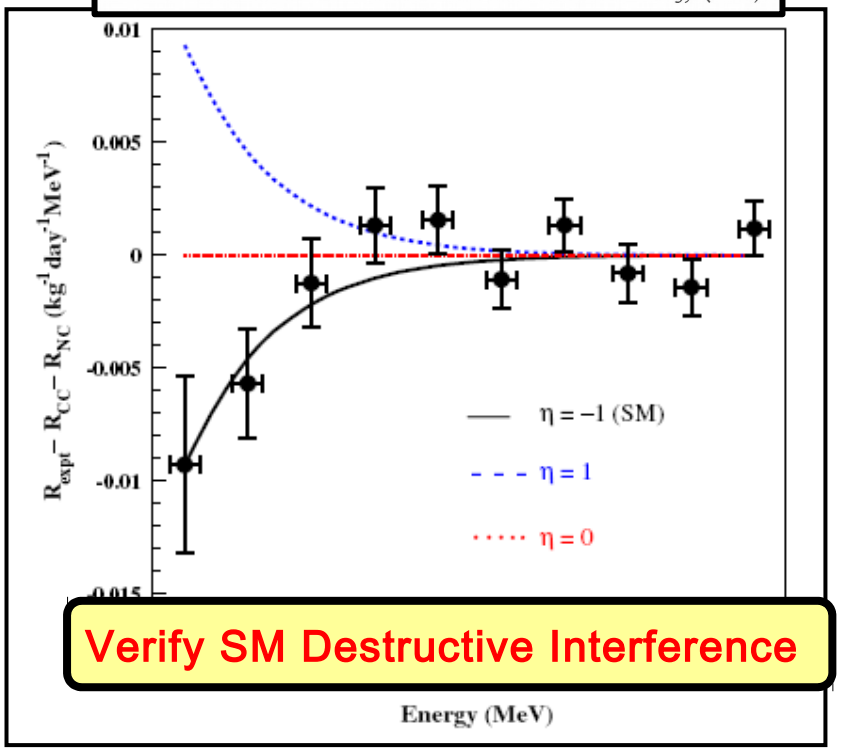
ON-OFF data



CsI(Tl) 200 kg :
Probe Electroweak Physics [PRD10]







Verify SM Destructive Interference

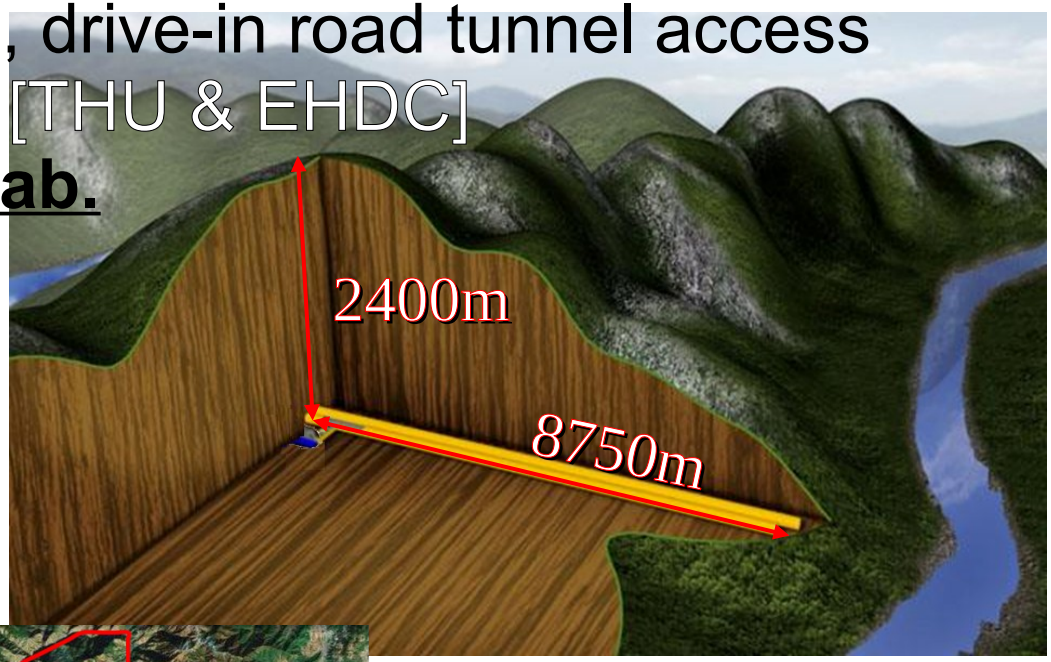
$$R = [1.08 \pm 0.21(stat) \pm 0.16(sys)] \times R_{SM}$$

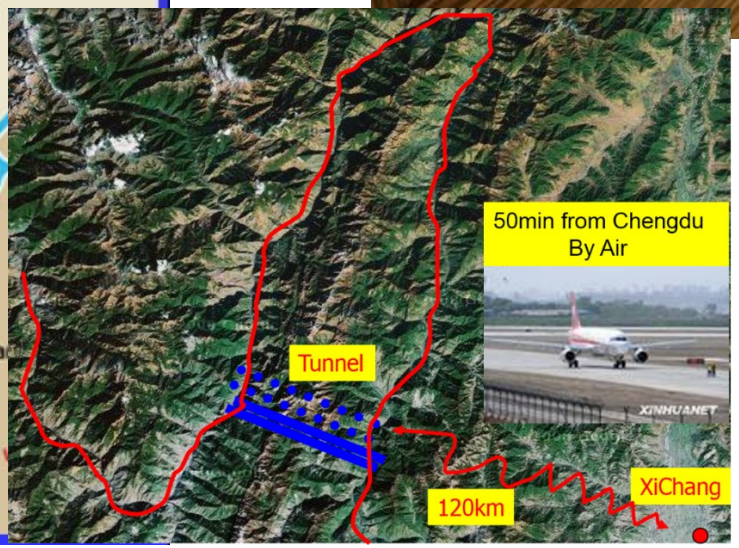
$$\sin^2\theta_W = 0.251 \pm 0.031(stat) \pm 0.024(sys)$$

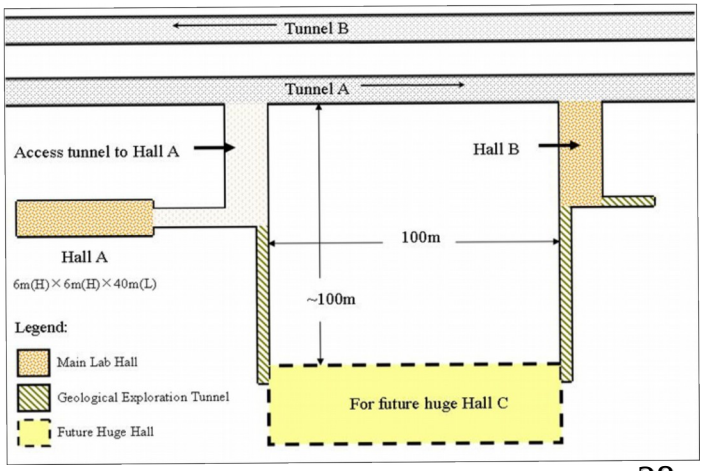
China Jin-Ping Underground Laboratory (CJPL)

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

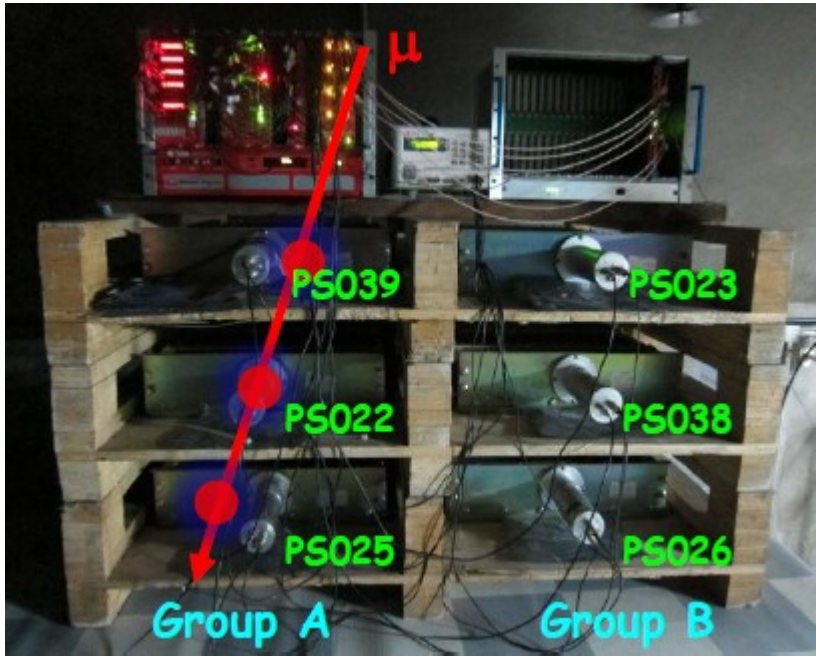
- 2400+ m rock overburden, drive-in road tunnel access
- 6x6x40 m cavern ready [THU & EHDC]
- **Deepest Underground Lab.**

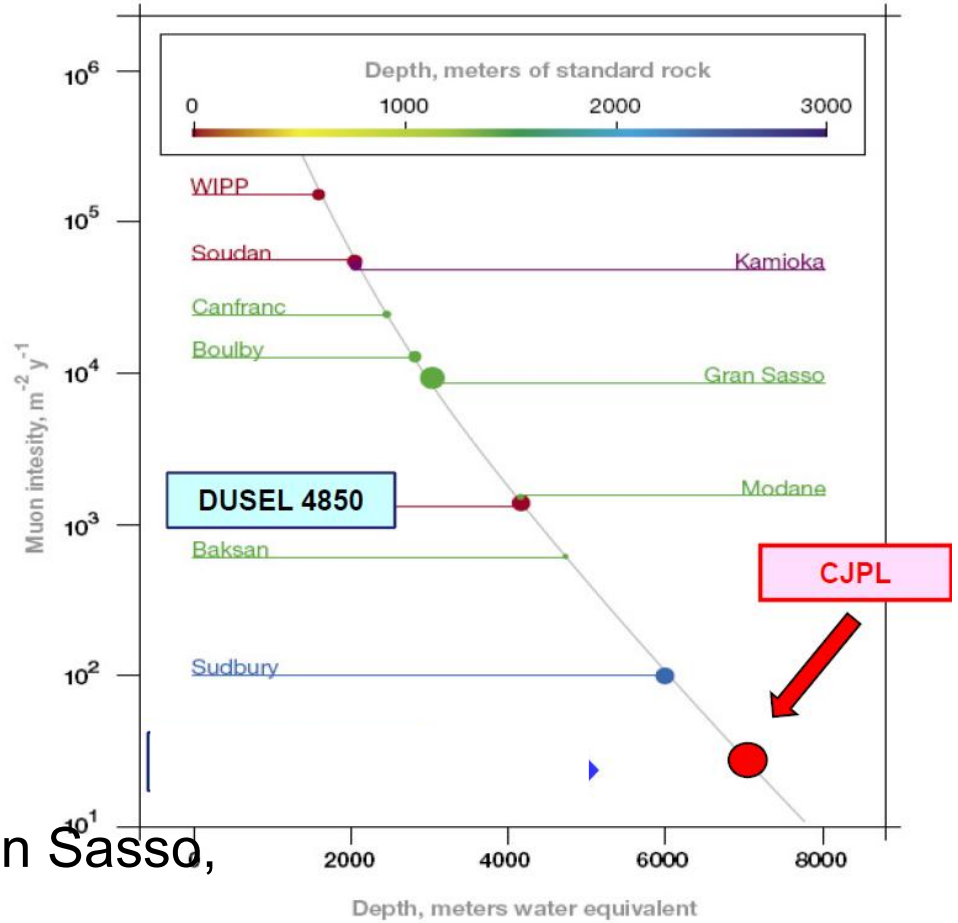






Cosmic flux at CJPL





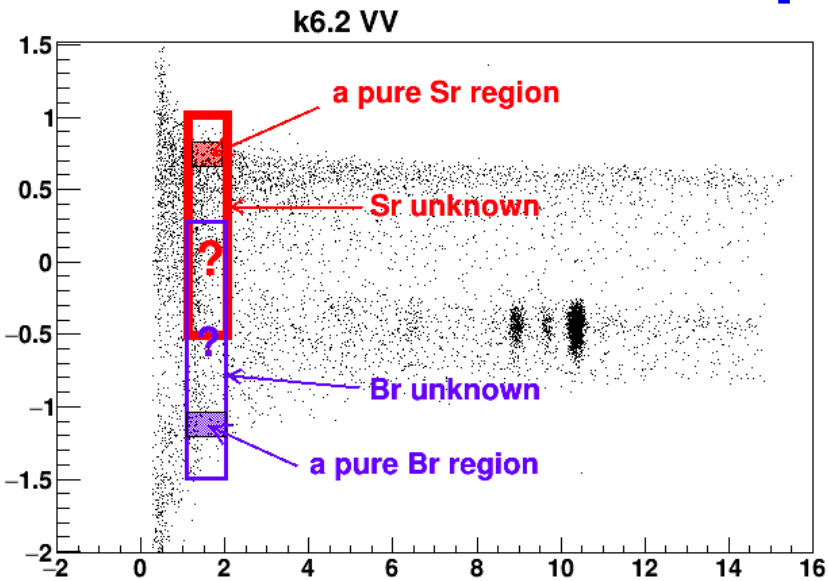
- 61.7 ± 11.7 /(m²·yr) [~8000/(m²·yr) at Gran Sasso, ~950 /(m²·yr) at Homestake]

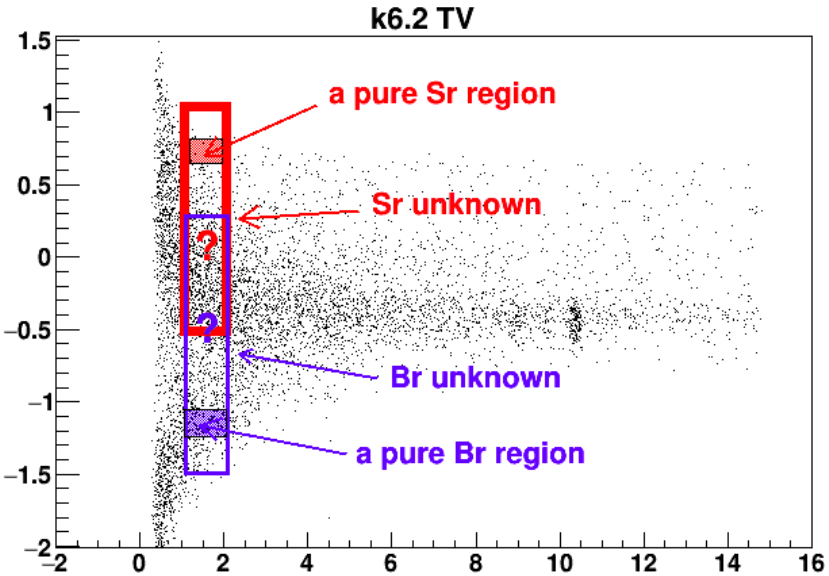
  ref : *arXiv:1305.0899*
- Consistent with expectation : $^{10}cm^{-2}s^{-1}$

  ≈ 10^{-8} of ground level

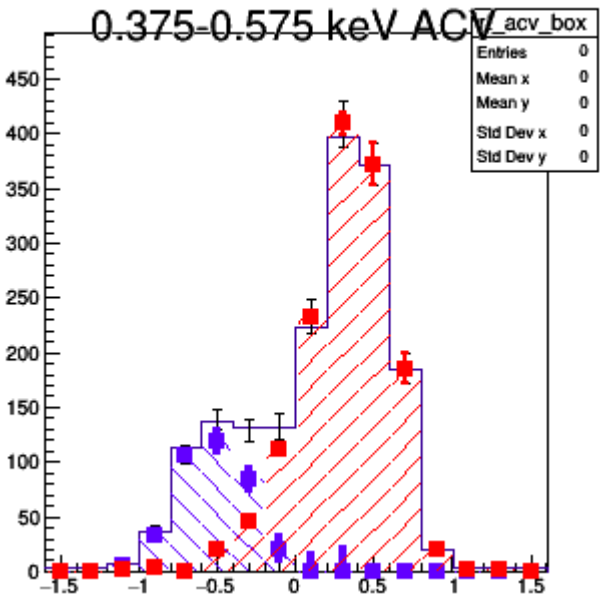
(Unit : Bq/kg)	K-40	Ra-226 (609keV)	Th-232 (911keV)
Rock Sample	< 1.1	1.8±0.2	< 0.27
Ground Level (Beijing)	~600	~25	~50

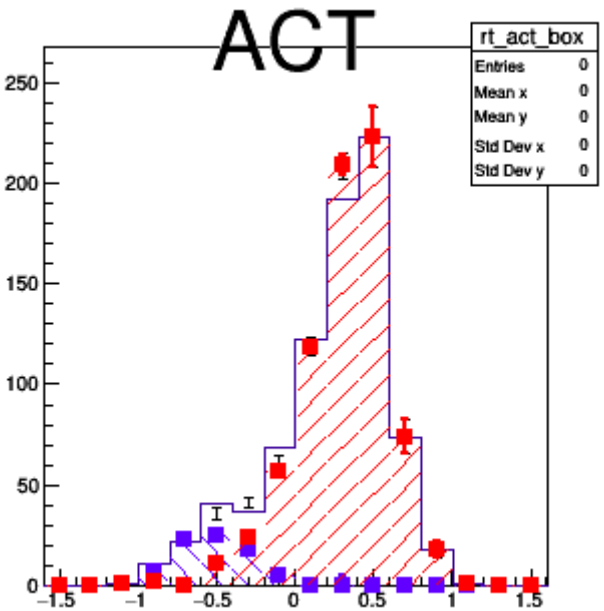
Bulk/Surface separation : a better way

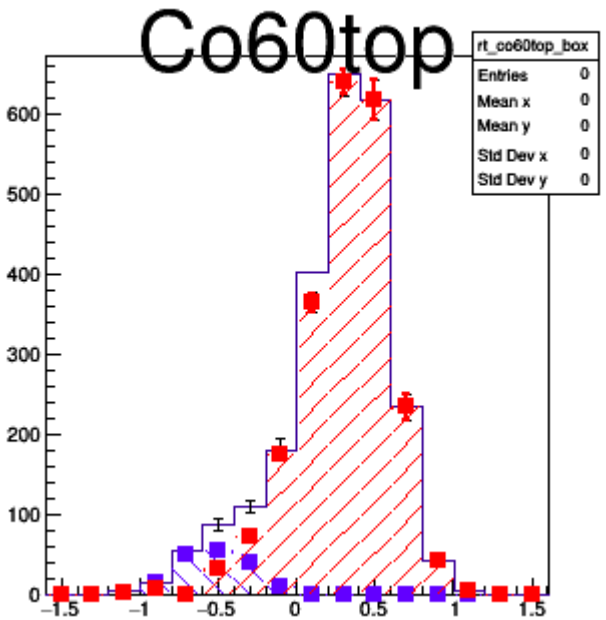




using bulk-ratio and surface ratio to solve the distribution :







Ge Crystal Growth Facilities at THU

Zone refining machine

Czochralski machine

Cutting & Polishing

Grown samples Ge single crystal

Ge Detector Fabrication at THU

Vacuum Coating Machine

Magnetron Sputtering Device

Boron Implant Accelerator

10g Planar-Ge

500g PCGe (testing)

Front -electronics

main considerations : cost and cosmic activation

CDEX-1t at CJPL-II

- Best sensitive in the range of 10GeV, ~10^{-44}cm^2
- ^{76}Ge double beta decay research