차세대 암흑물질 탐색 실험 제안

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IBS, Sep. 20, 2019

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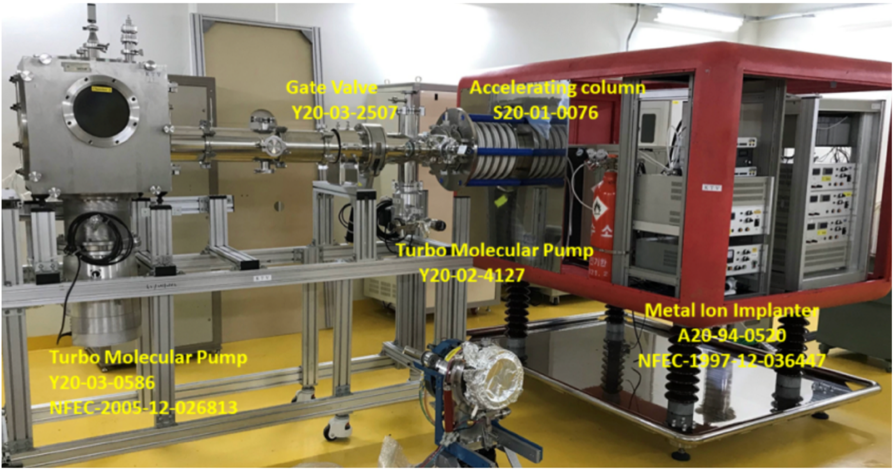
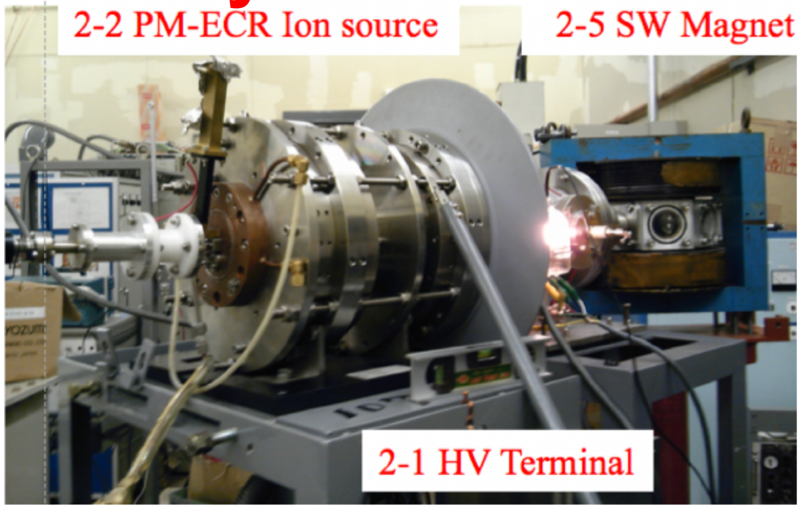
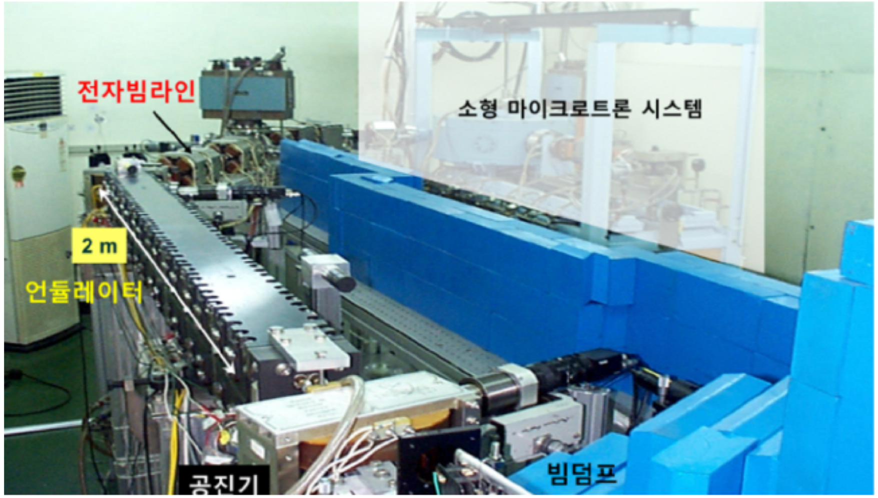
Proton

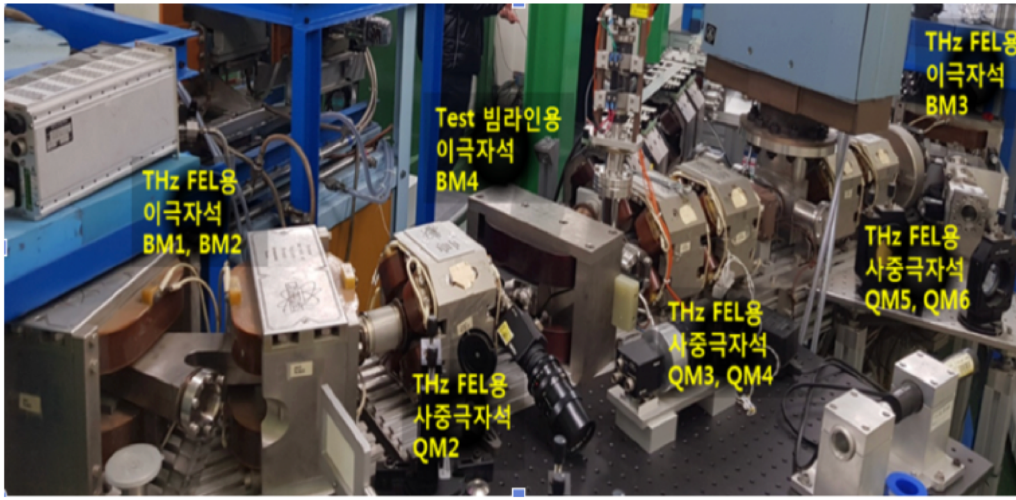


Heavy Ion



Electron & THZ Free Electron Laser





We are welcoming proposals !

Model for Dark Photon and Dark Matter

- **A simple model to include the dark matter**
  - **Contains Dark photon (A') and Dark matter**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'^2 - \sum_f q_f e(A_\mu + \varepsilon A'_\mu)\bar{f}\gamma^\mu f + \mathcal{L}_{DM},$$

Dark matter sector:

$$\mathcal{L}_{DM} = \begin{cases} \bar{\chi}(i\not{D} - m_\chi)\chi, & \text{fermionic DM } (\chi), \\ |D_\mu\varphi|^2 - m^2_\varphi\varphi^*\varphi, & \text{bosonic DM } (\varphi), \end{cases}$$

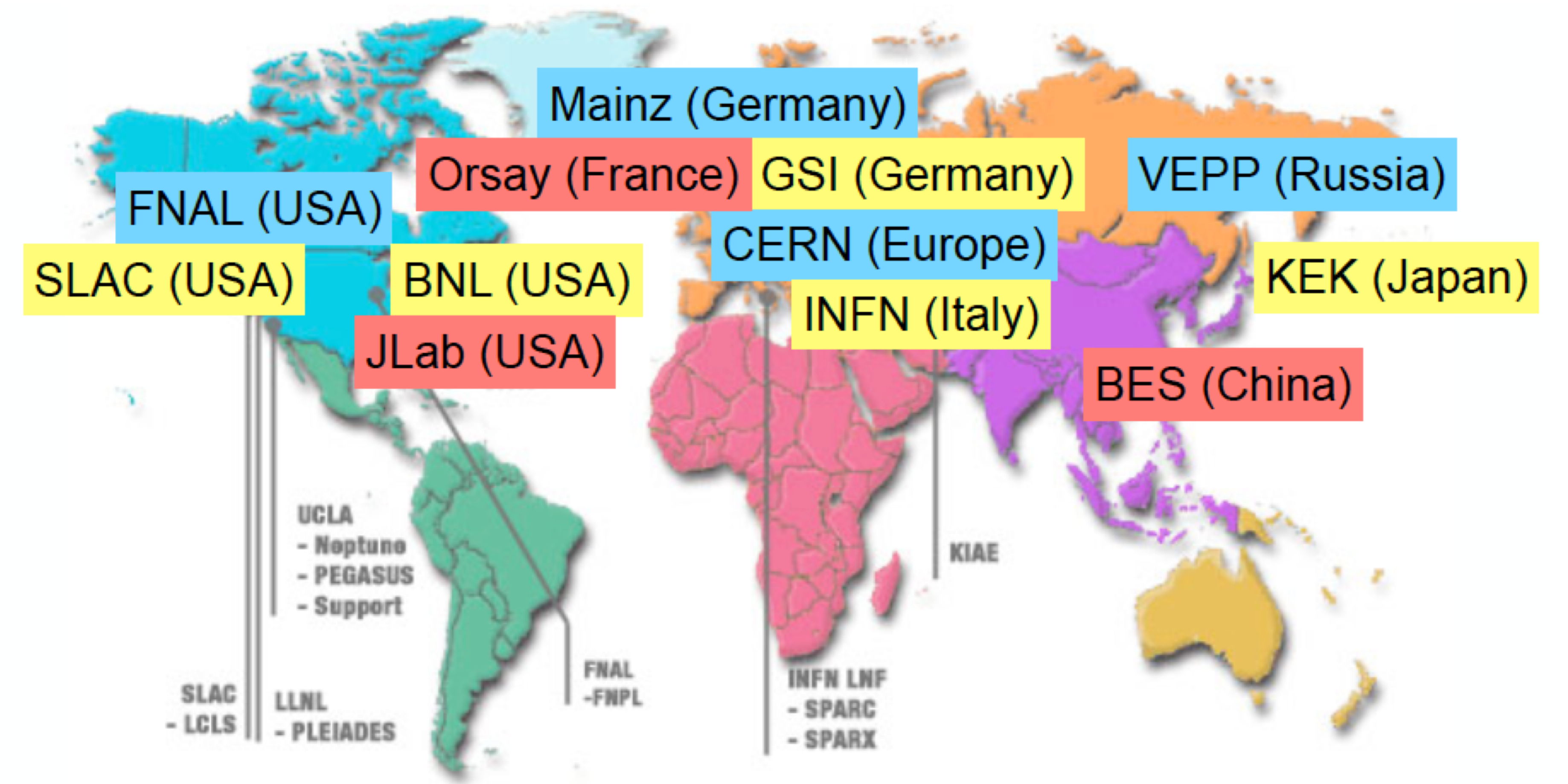
$$D_\mu = \partial_\mu + ig'A'_\mu$$

- Dark Photon and DM coupling: *g'* (*U(1)'* charge)

- Dark Photon and EM charged matter coupling: εe

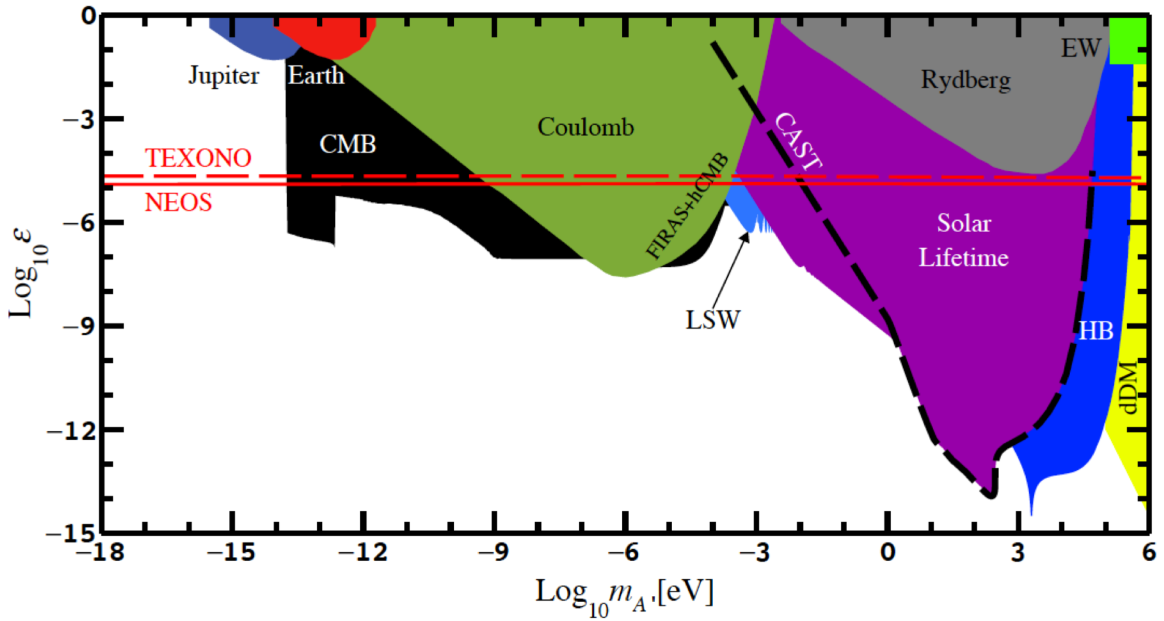
Worldwide map for Dark photon search

Ongoing and proposed accelerator-based experiments

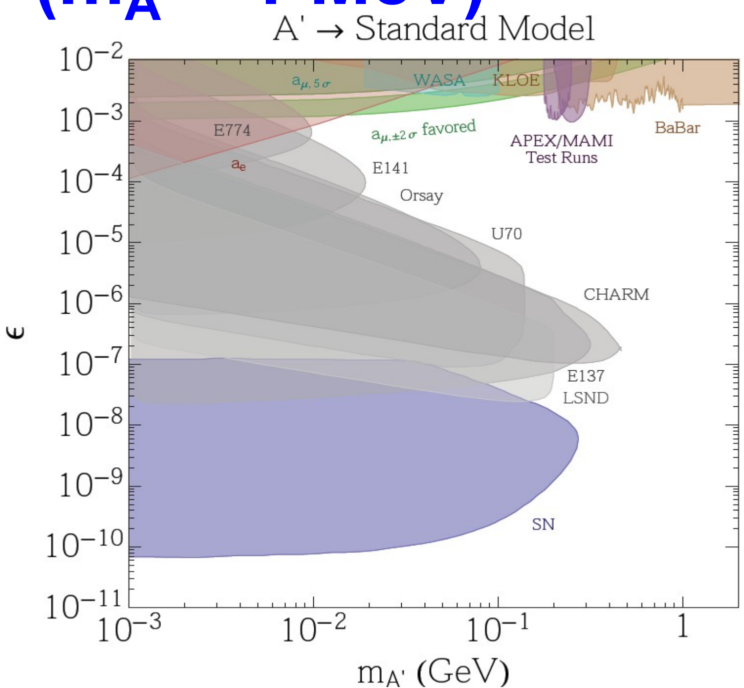


Constraints for A'

Astrophysics and other non-accelerator exps. ($m_{A'}$ < 1 MeV)

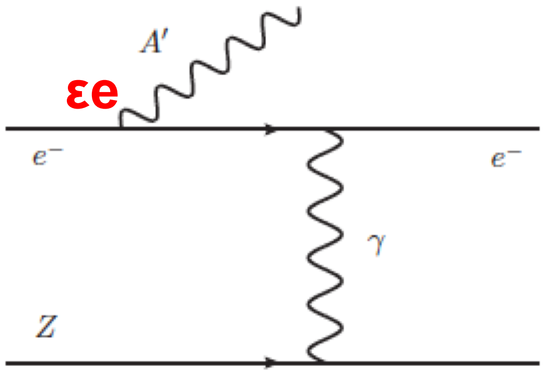


Accelerator exps. ($m_{A'}$ > 1 MeV)



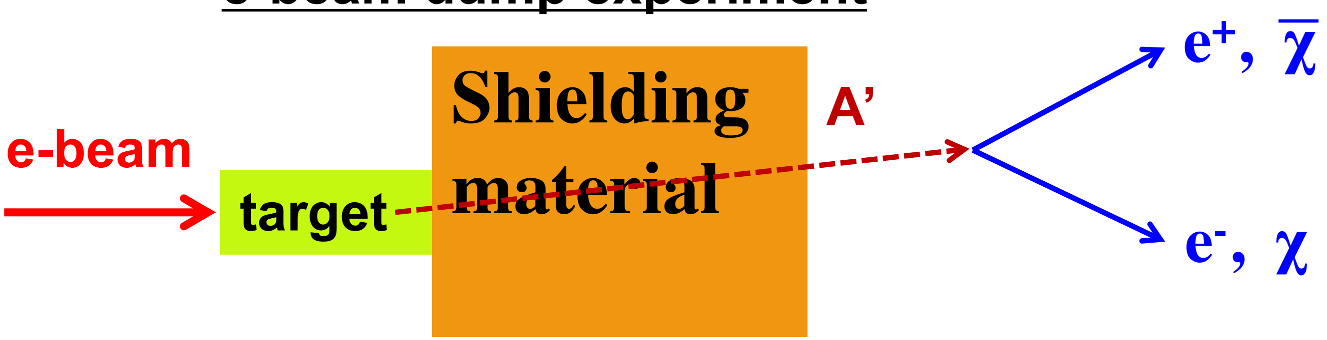
Usually look for A' decays:
Ex) A' -> $e^+ e^-$

A' production with electron accelerator (I)



Production rate: ~ $\varepsilon^2\sigma_{brem}$

<u>e-beam dump experiment</u>



- $m_{A'} > 2\,m_e$: A' -> e+ e-
- $m_{A'} < 2\,m_e$: A' -> 3 γ (Highly suppressed)

~ 10 keV < $m_{A'}$ < 1 MeV -> Dark-Photon Dark Matter

A' production with electron accelerator (II)

- **A' production rate in a thick target approximation:**

$$N_{A'} \sim 10 \times N_e \epsilon^2 \frac{m_e^2}{m_{A'}^2}$$

N_e: No. of incident electrons on target

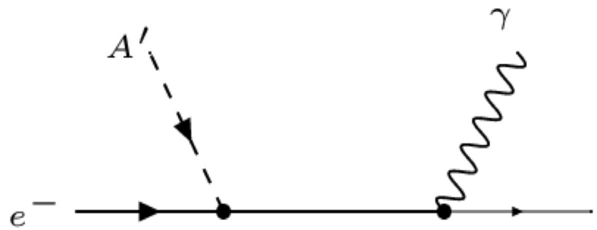
- **Decay length of A' for $m_{A'} > 2\, m_e$**

$$L_{dec} \sim 10^{-3}\ \mathrm{m}(\gamma/10)(10^{-4}/\epsilon)^2(100\mathrm{MeV}/m_{A'})$$

For $m_{A'}$=1 MeV and $\varepsilon=10^{-7}$, L_{dec} > 10 km

A' and Dark matter detection@Underground Lab.

- A' detection with Compton-like process

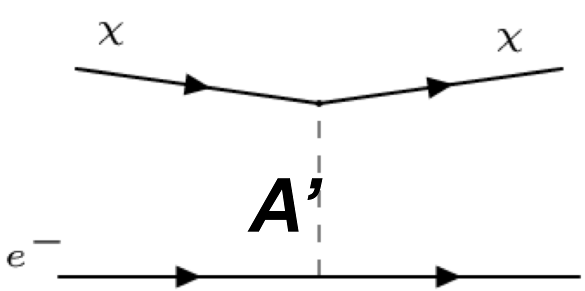


- $\sigma \sim \alpha^2 \varepsilon^2$

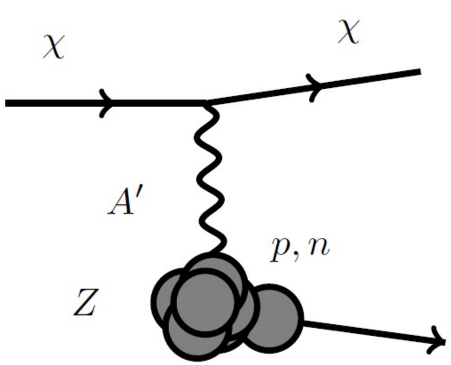
- X-section is dominant in ~ 100 keV - MeV

- Dark matter detection

electron recoil



nuclear recoil

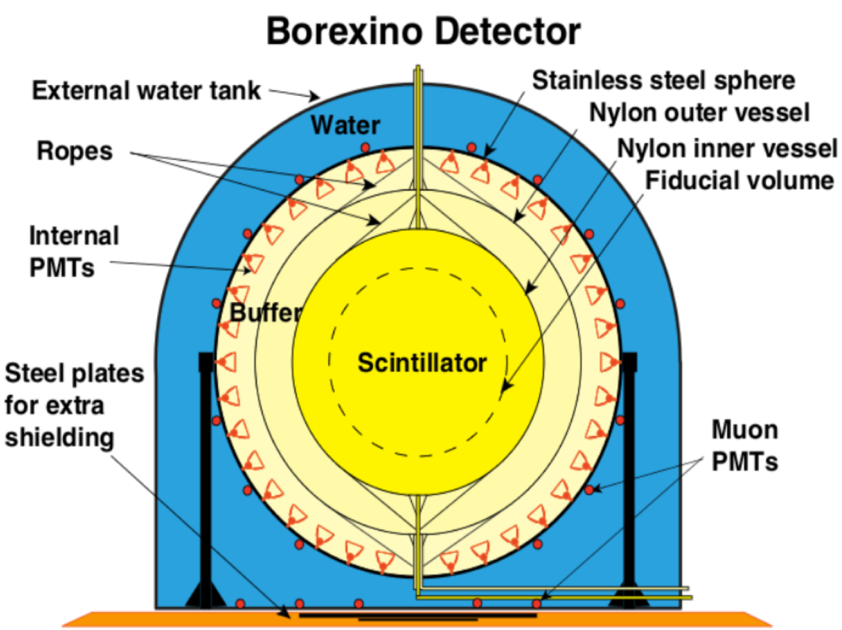


A Proposal for A' and Dark matter searches(I)

We are considering the following features for the proposal,

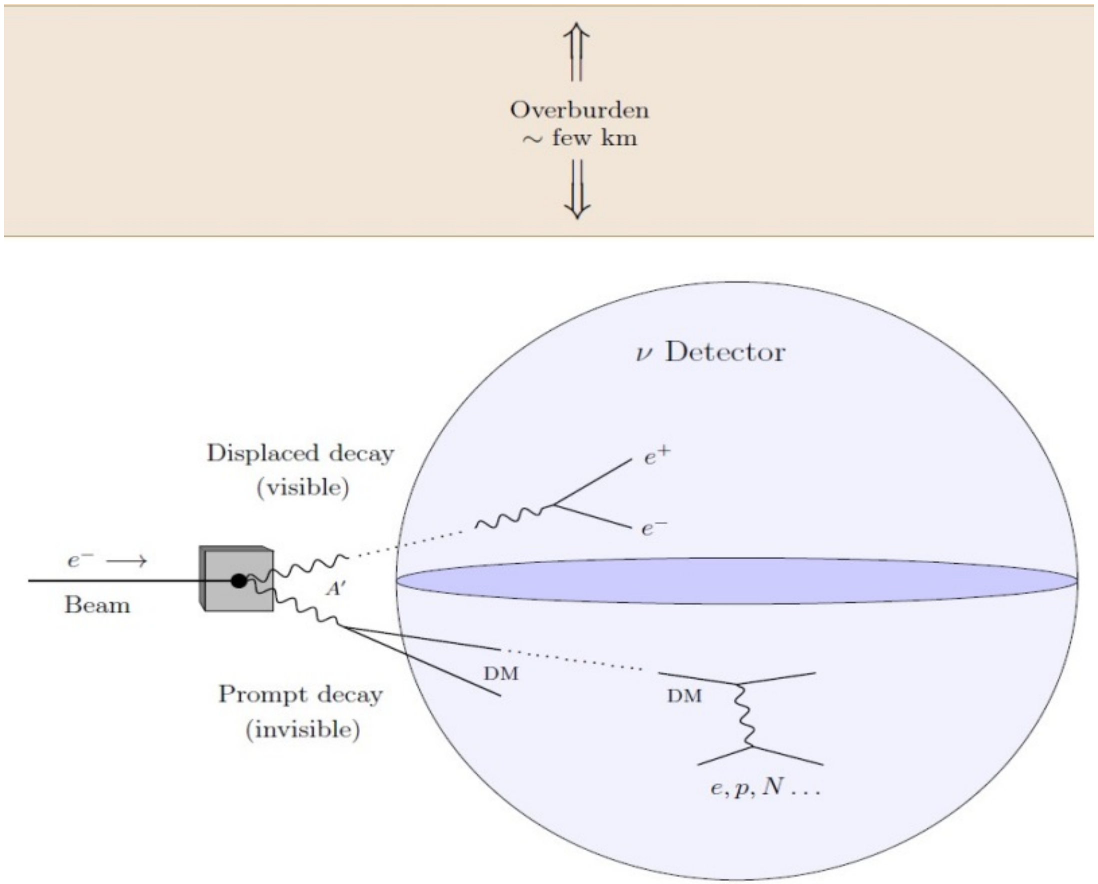
- A large scale multipurpose detector at a deep underground lab.
  - 2 kton of Liquid Scintillator
  - Energy threshold: ~ 200 keV
  - Radiopurity: $^{238}U < \sim 10^{-20}$ g/g, $^{232}Th < \sim 10^{-19}$ g/g

Note: Borexino: 278 tonnes



A Proposal for A’ and Dark matter searches(II)

- **Electron accelerator near by the LS detector**
  - **100 kW power with continuous beam**
  - **e-beam energy: 20 MeV -> 100 MeV upgrde.**

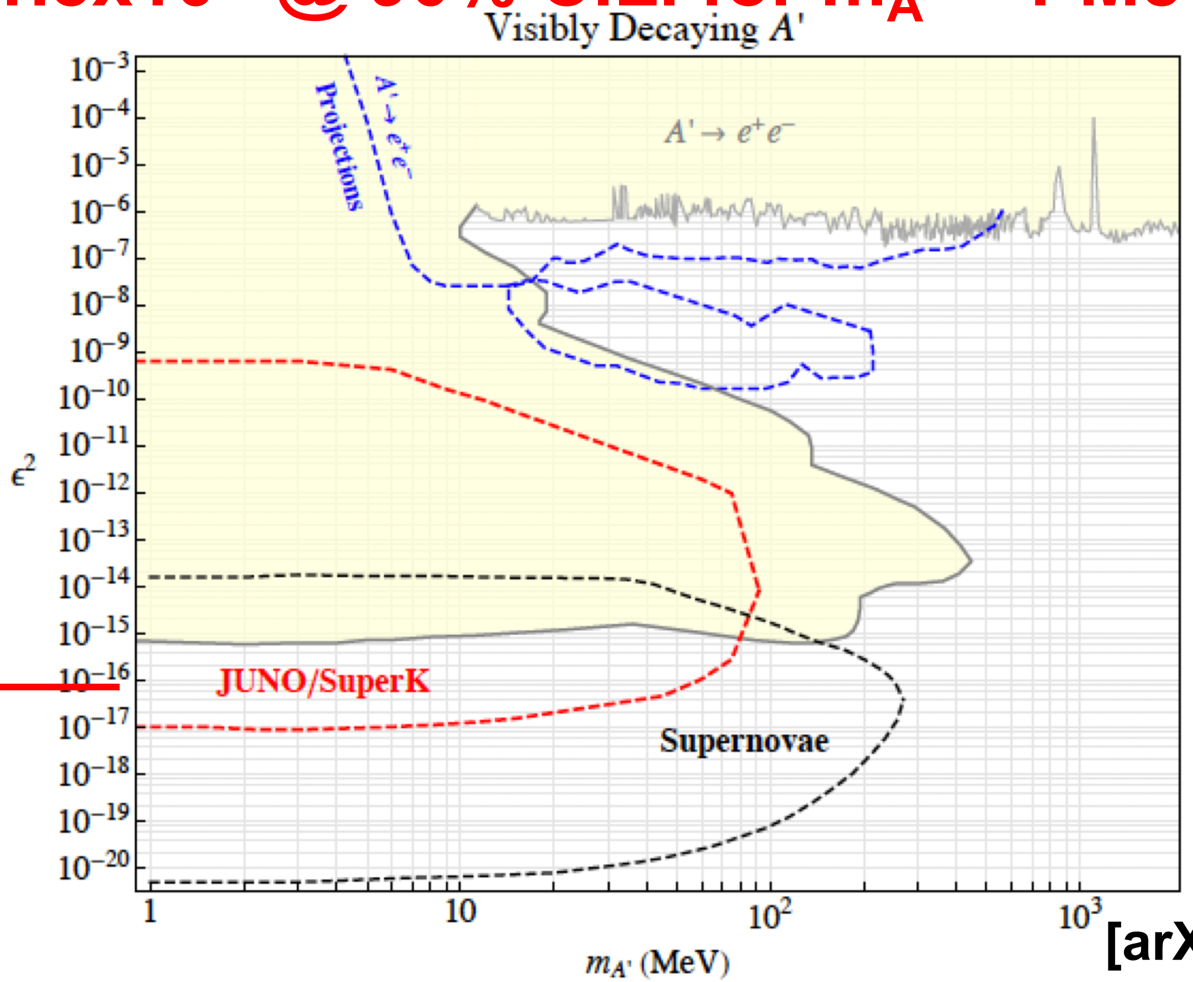


Sensitivity for A' search

- $m_{A'}$ < 1 MeV search with 100 kW and 20 MeV e-beam
  - Using Compton-like process for stable A'

$\varepsilon < 1.8\times10^{-8}$ @ 90% C.L. for $m_{A'}$ < 1 MeV

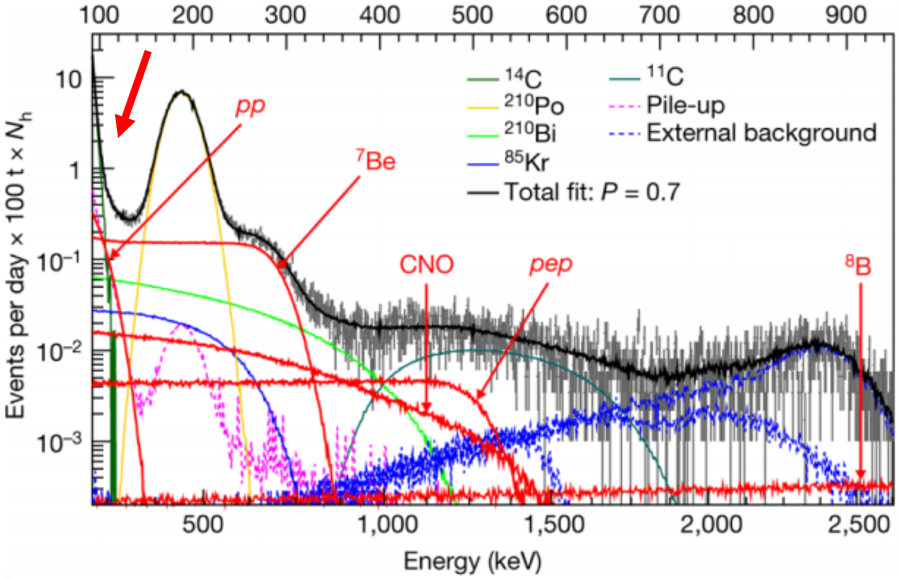
Our limit

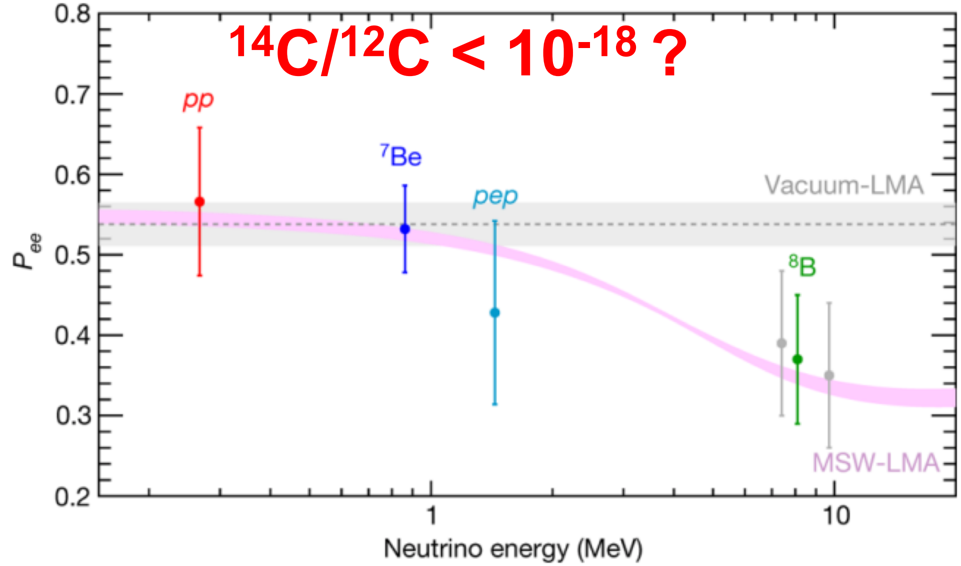


[arXiv:1507.0268]

Several Phases of the Experiment

- **Phase I: Solar Neutrino / Reactor Neutrino**



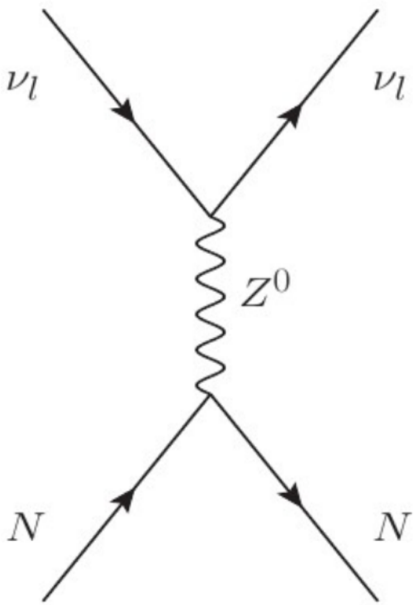


- **Phase II:**
  - **Dark-Photon and Dark Matter search with e-accelerator**
- **Phase III: Neutrinoless Double Beta Decay**
  - **Loading 10 tones of ^{nat}Mo (9.7%) or other one**

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- **Recent observation with 14.6 kg CsI crystals: (D. Akimov et al., Science, 2017)**

It takes 43 years !



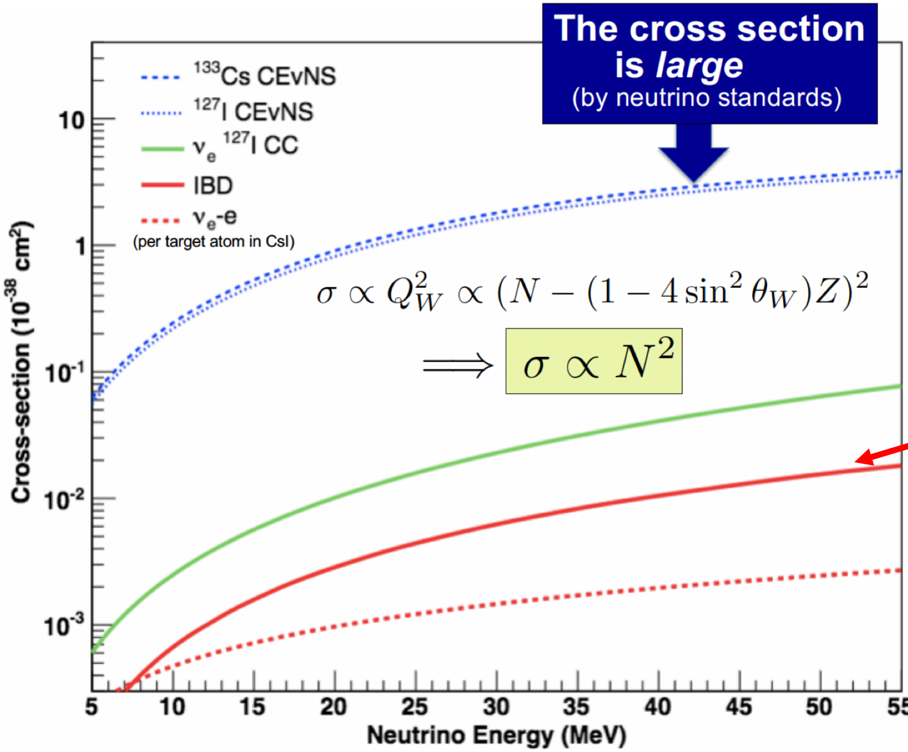
$$\frac{d\sigma_{\nu A_{el}}}{dq^2}(q^2, E_\nu) = \frac{1}{2}\left[\frac{G_F^2}{4\pi}\right]\left[1 - \frac{q^2}{4E_\nu^2}\right][\varepsilon Z - N]^2 F(q^2)$$

N: number of neutron in nucleus

$\sigma \propto N^2$ (or A^2)

X-sections are same for all nu flavors

Cross section and Recoil energy



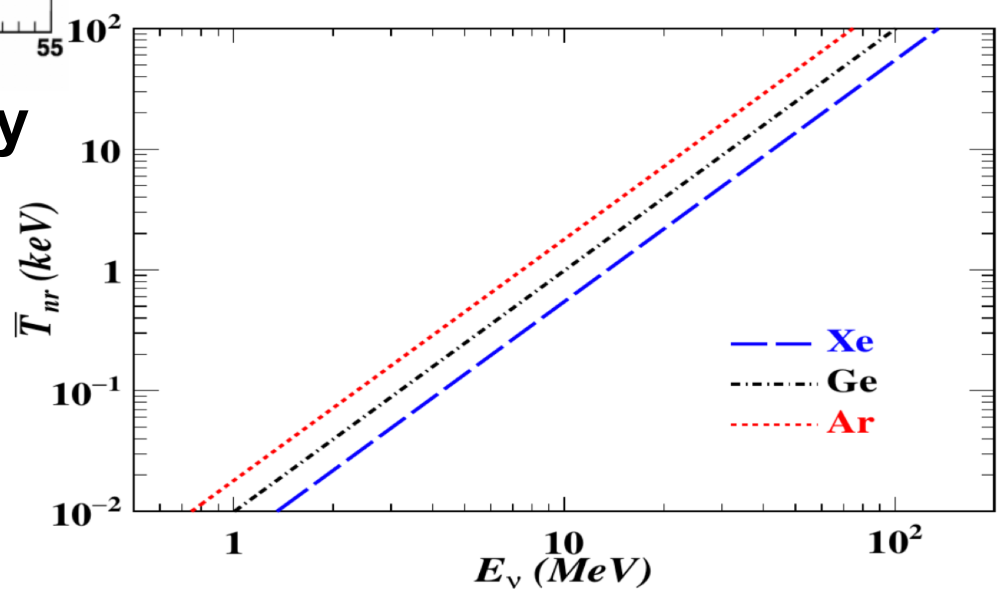
- X-section is coherent: < 50 MeV
- X-section is ~1,000 times larger than IBD.

$\bar{\nu}\, p \longrightarrow n\, e^+$

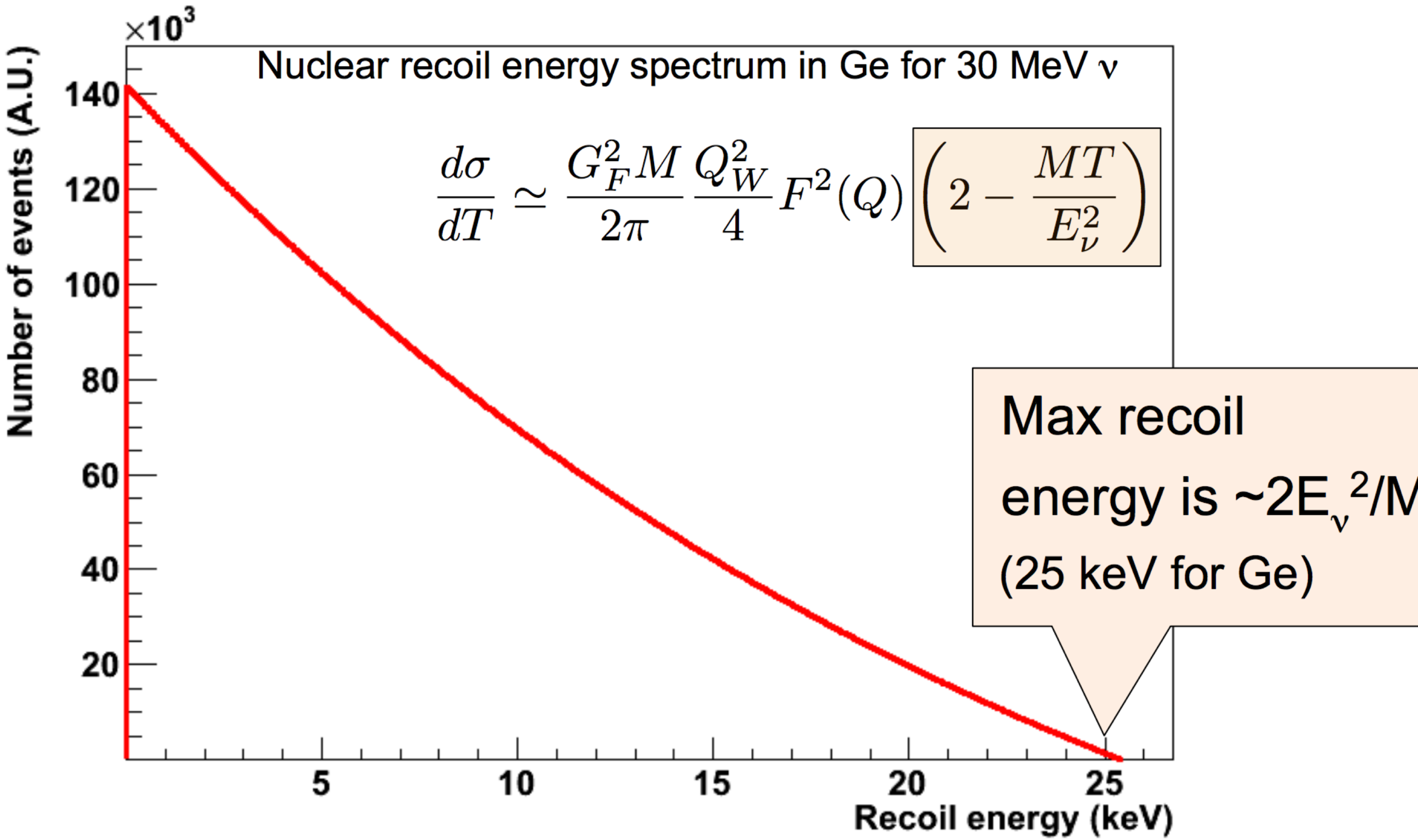
Average nuclear recoil energy

$$\bar{T}_{nr} = \frac{2}{3} T_{max} \simeq \frac{2E_\nu^2}{3M}$$

~ keV



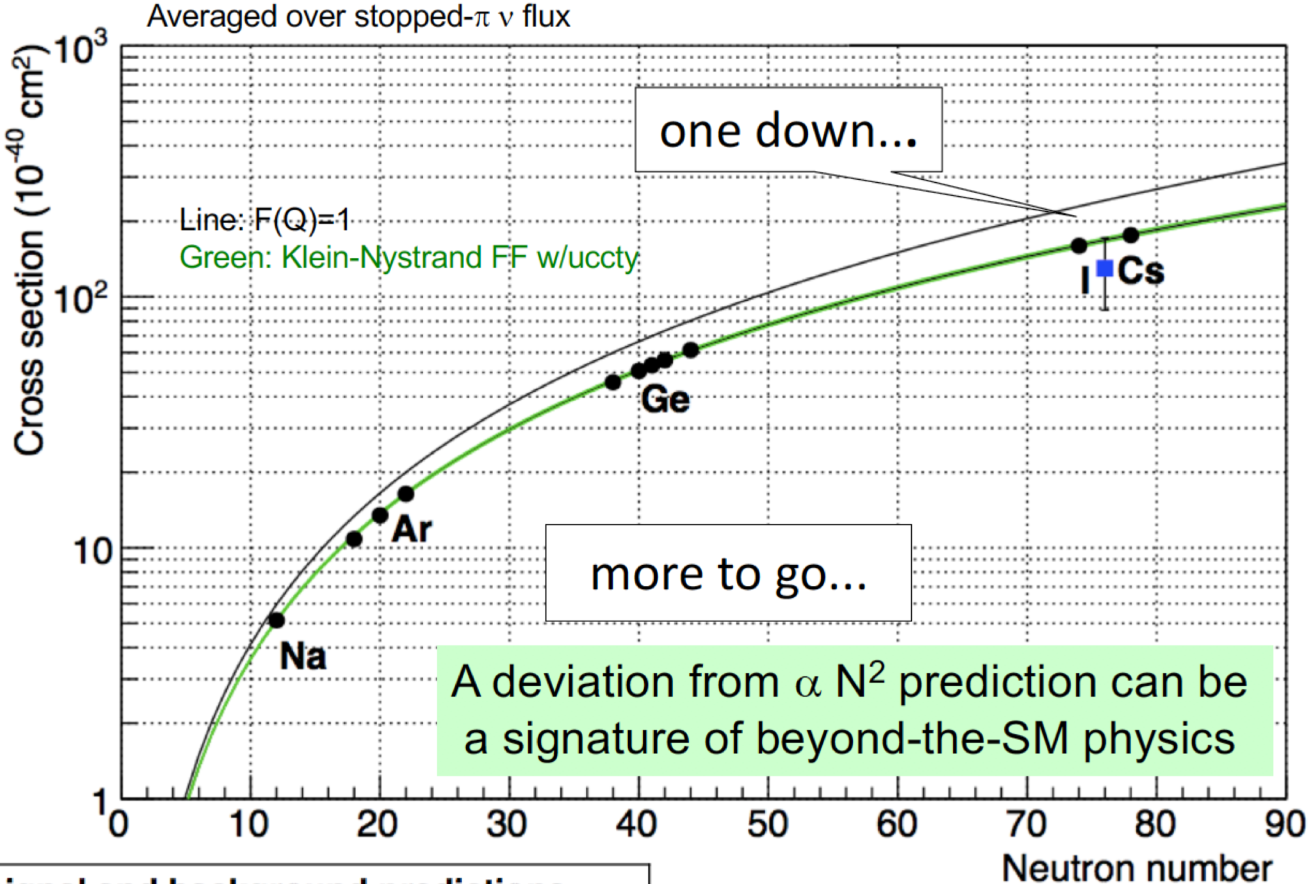
Number of events & Recoil energy



Lowering threshold is better.

X-section and systematics

Prospect

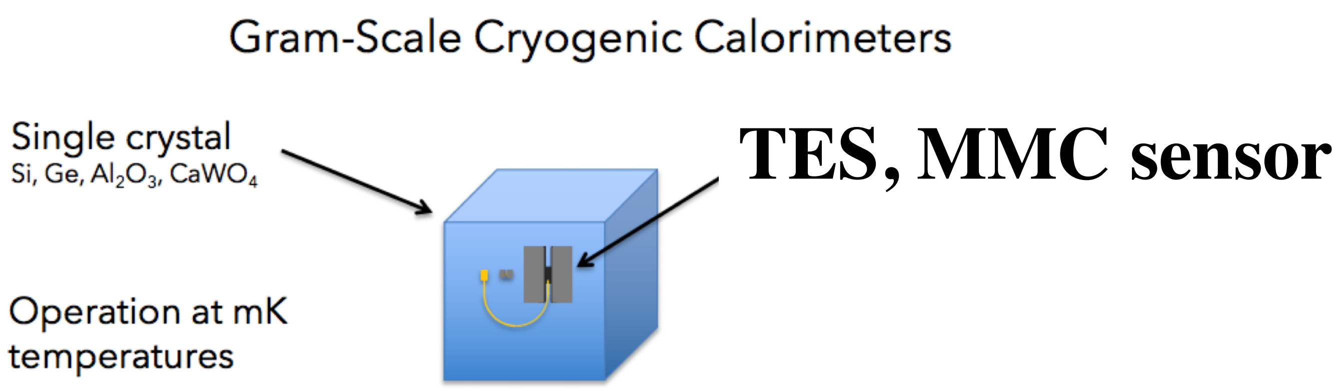


Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

Unavoidable for Scintillating detector

R&D for CEνNS

- **Cryogenic calorimeter with low threshold (< 100 eV)**



- **Growing various ultra-pure target crystals:**
  - **-> Low A to High A:**
    LiF crystal… $CaWO_4$ crystal

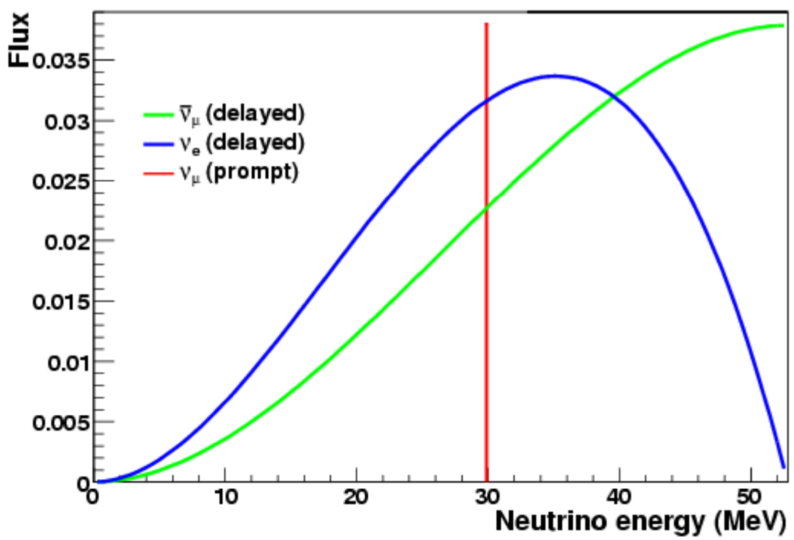
- **Find out neutrino source elsewhere**
  - ✓ **J-PARC, SNS, RAON…**
  - ✓ **Mci source of ^{51}Cr**

Neutrino sources

- **Reactor neutrino:**
  - High flux: ~$10^{14}/cm^2/s$ at 10 m
  - up to ~ 10 MeV
  - Difficult to manage experiment at a site
  - Need very good shielding
- **Accelerator:** Stopped pion

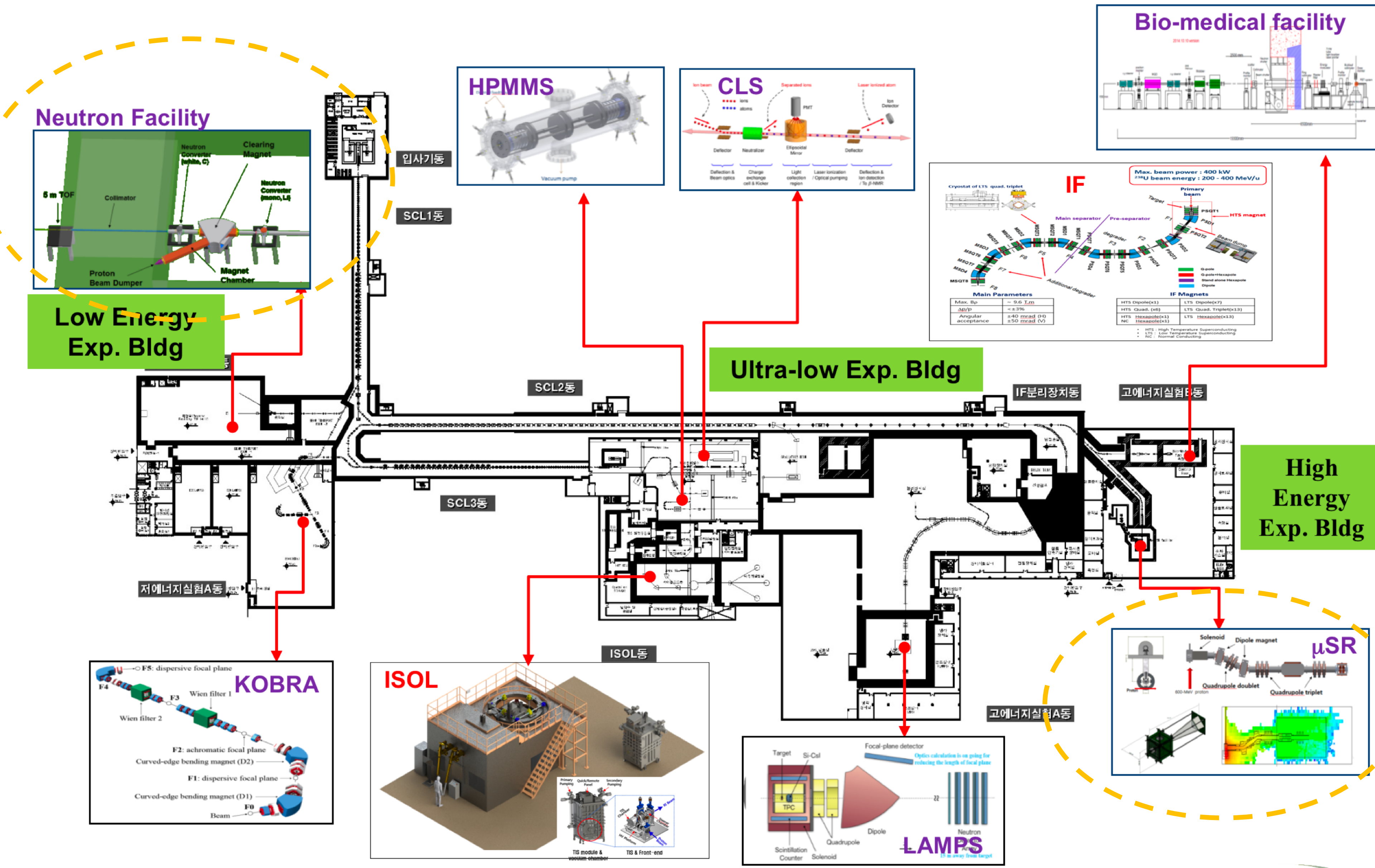
$$\pi^+ \longrightarrow \mu^+ \nu_\mu, \ \mu^+ \longrightarrow e^+ \bar{\nu}_e \nu_\mu$$

  - High energy ν
  - Pulsed beam:
    Good background rejection
  - Lower flux than reactor



- Proton(Deuteron) & IsoDAR target
- Mci of ^{51}Cr source

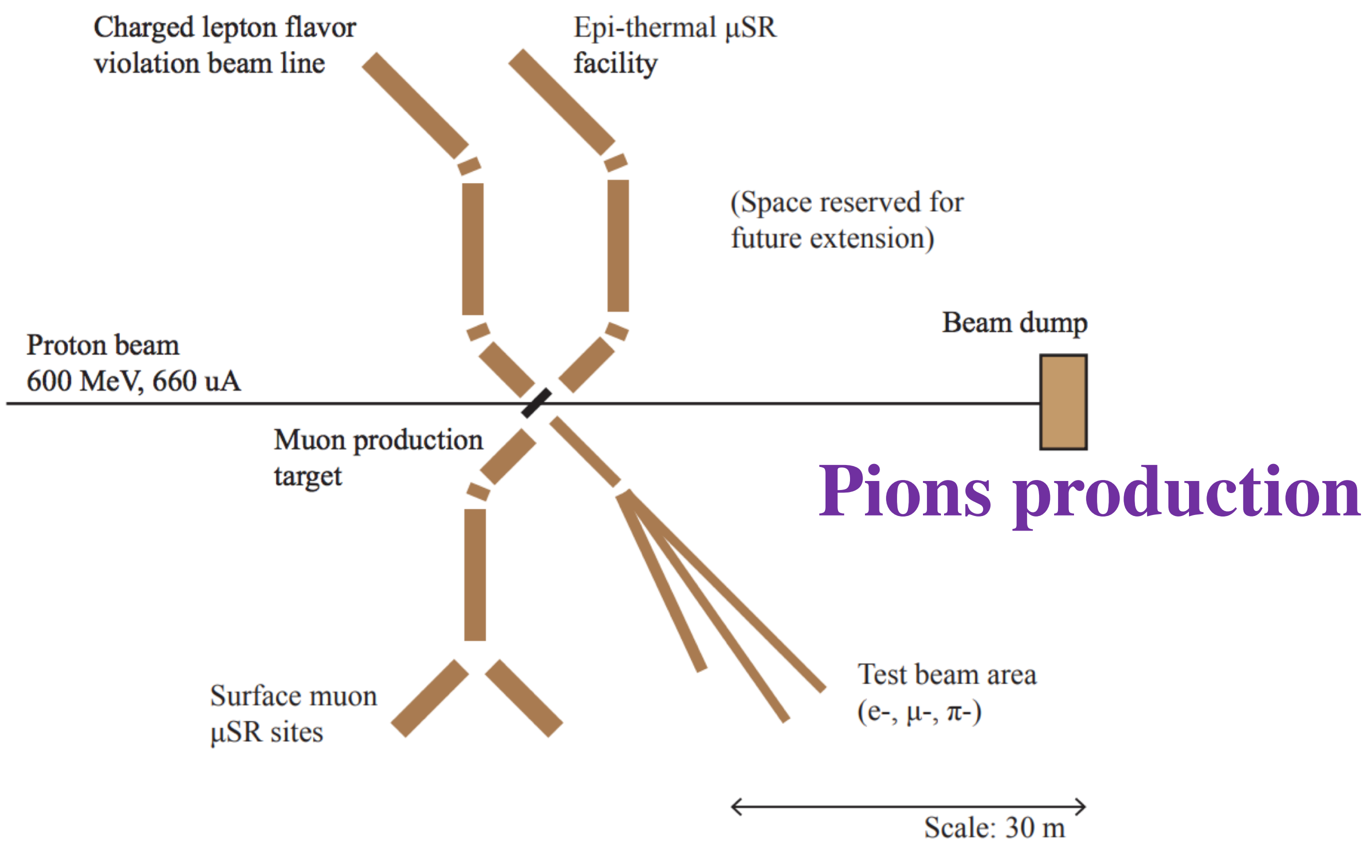
RAON Layout



Neutron Facility
Low Energy Exp. Bldg
HPMMS
CLS
Bio-medical facility
IF
Ultra-low Exp. Bldg
High Energy Exp. Bldg
입사기동
SCL1동
SCL2동
SCL3동
IF분리장치동
고에너지실험B동
고에너지실험A동
저에너지실험A동
ISOL동
KOBRA
ISOL
LAMPS
μSR

μSR beam line in RAON

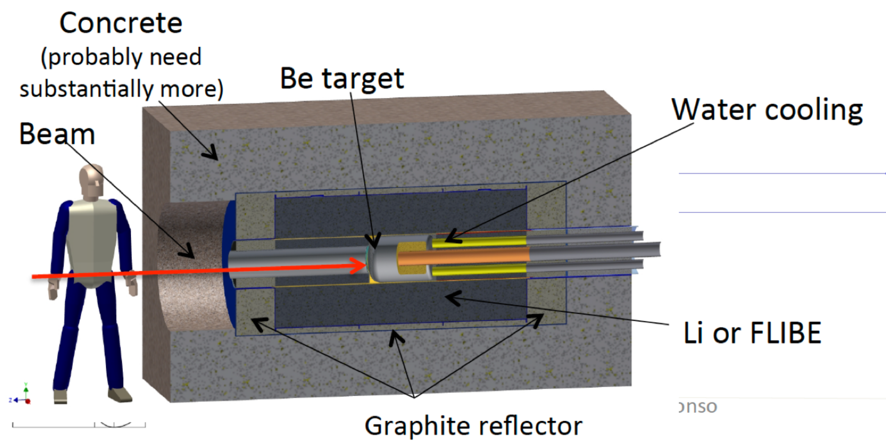
- **400 kW of 600 MeV proton on target**
- **Propose a dedicated target and beam line for coherent neutrino scattering.**

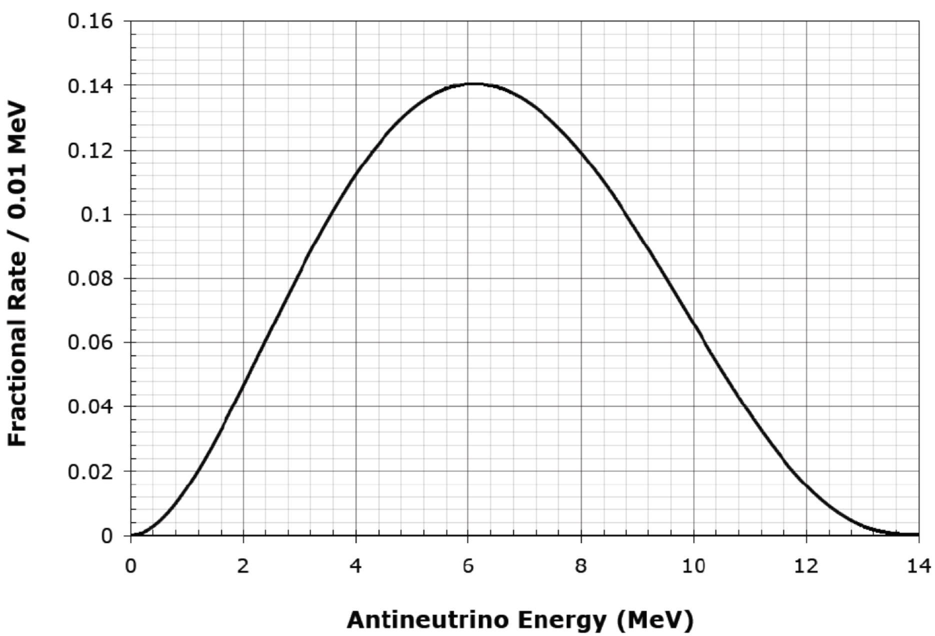


Neutrino source at RAON

- **Proton Cyclotron: 70 MeV & 0.75 mA**

p + Be-target
$\rightarrow$ n ^{7}Li $\rightarrow$ ^{8}Li $\rightarrow$ ^{8}Be e^{-} $\bar{\nu}_e$



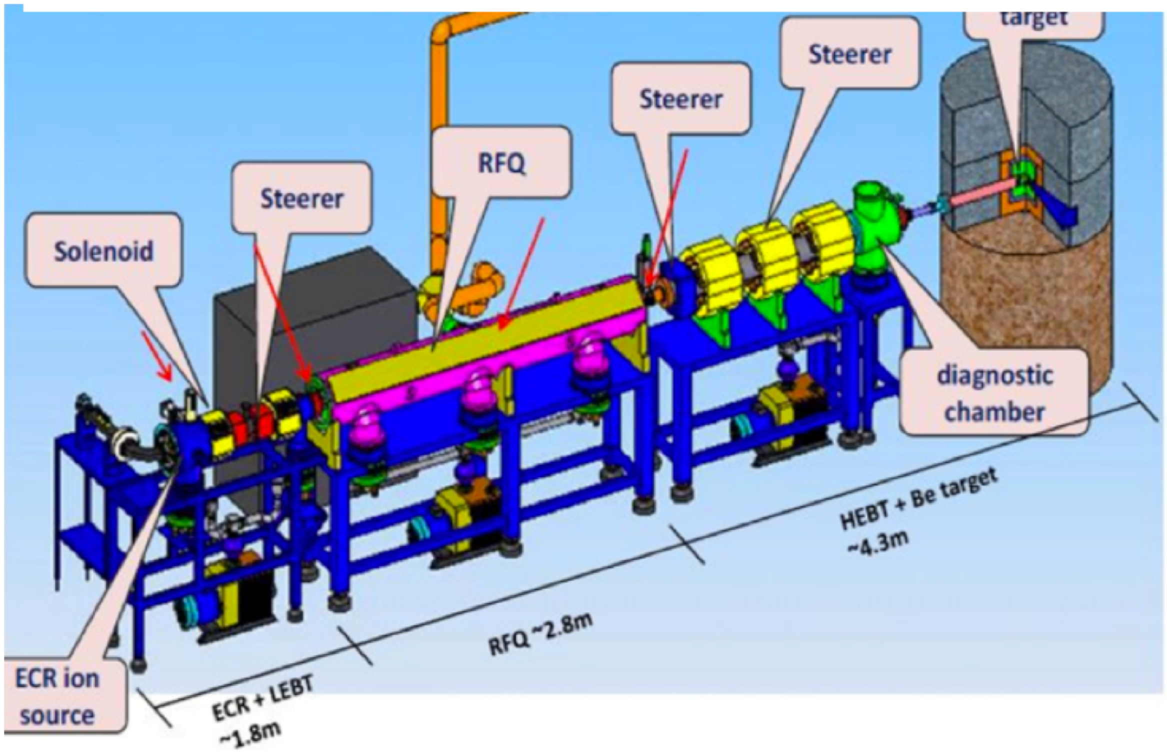


Very pure $\bar{\nu}_e$
~ 13 MeV endpoint

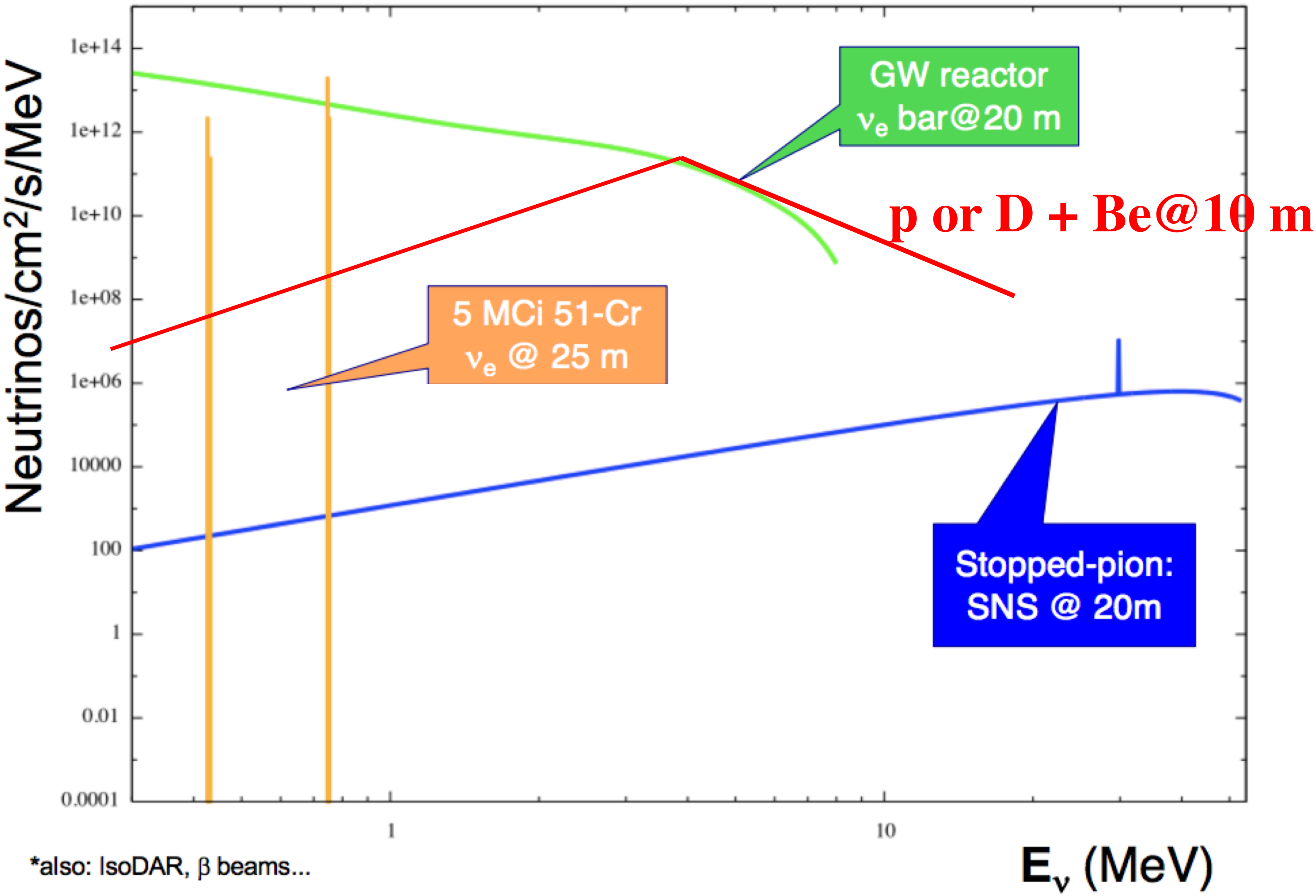
Neutrino source with Deuteron-beam

- **Build Compact Deuteron accelerator**
  - **ECR ion source, RFQ and Target**
  - **Beam energy and current: ~3 MeV and > 10 mA**

  D + Be-target → n ^{7}Li → ^{8}Li → ^{8}Be e^{-} ν_e



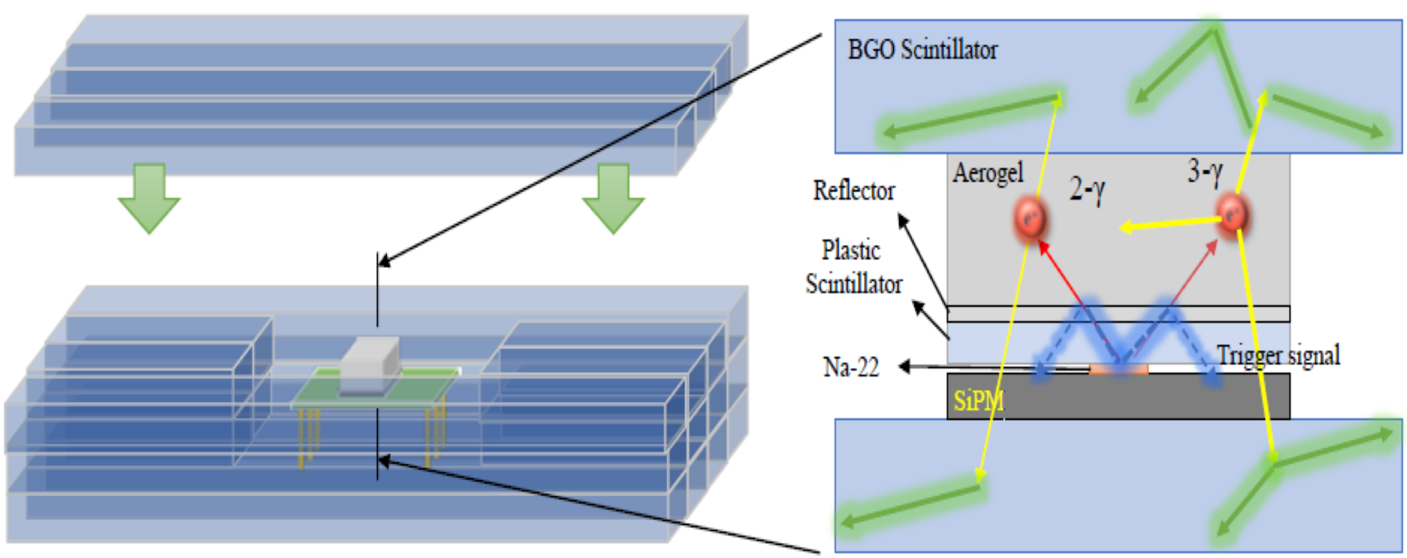
Neutrino flux for each neutrino source



*also: IsoDAR, β beams...

KNU Advanced Positronium Annihilation Experiment

- **Positronium annihilation physics:**
  - **New particle search (Hidden sector dark mater, Dark photon, axion), C,CP,CPT violation in lepton sector**
- **Experiment design & concept :**
  4π segmented BGO calorimeter / ^{22}Na radiation source
- **Status and prospect**
  - **Under construction / one order better than previous experiment.**



Summary

- **We should prepare several R&Ds**
  - Ultra-low-background LS production

    (Need purification technique)
  - Low-temperature detector with low-threshold
  - High-power accelerator system and target system

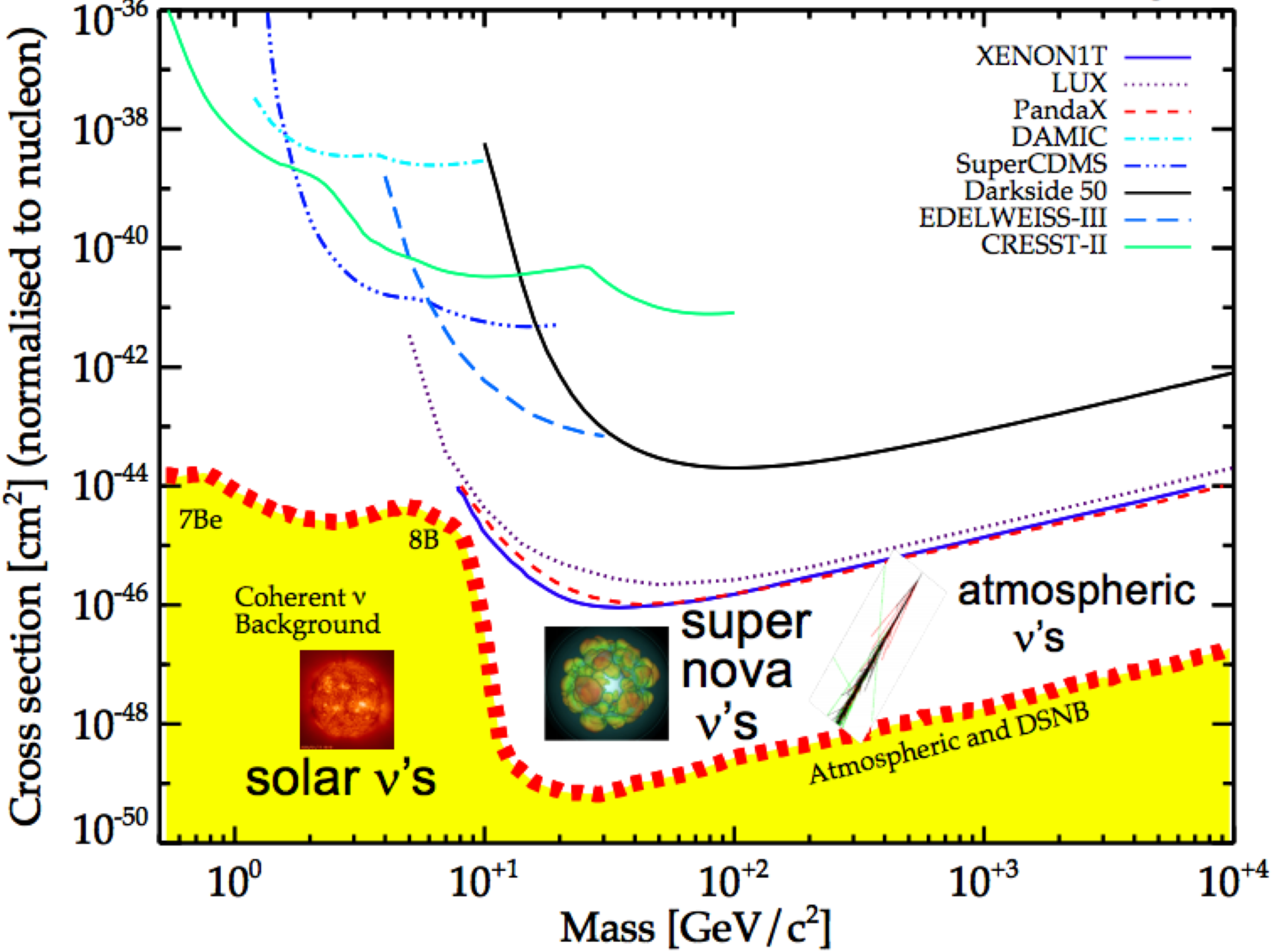
    electron, proton, deuteron
- **We should pursue on neutrino coherent scattering**
  - Look for possible neutrino sources elsewhere

Let’s build a neutrino source domestic !

Backup

J. Monroe & P. Fisher, 2007 J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



Back-of-envelope estimation for A’ search

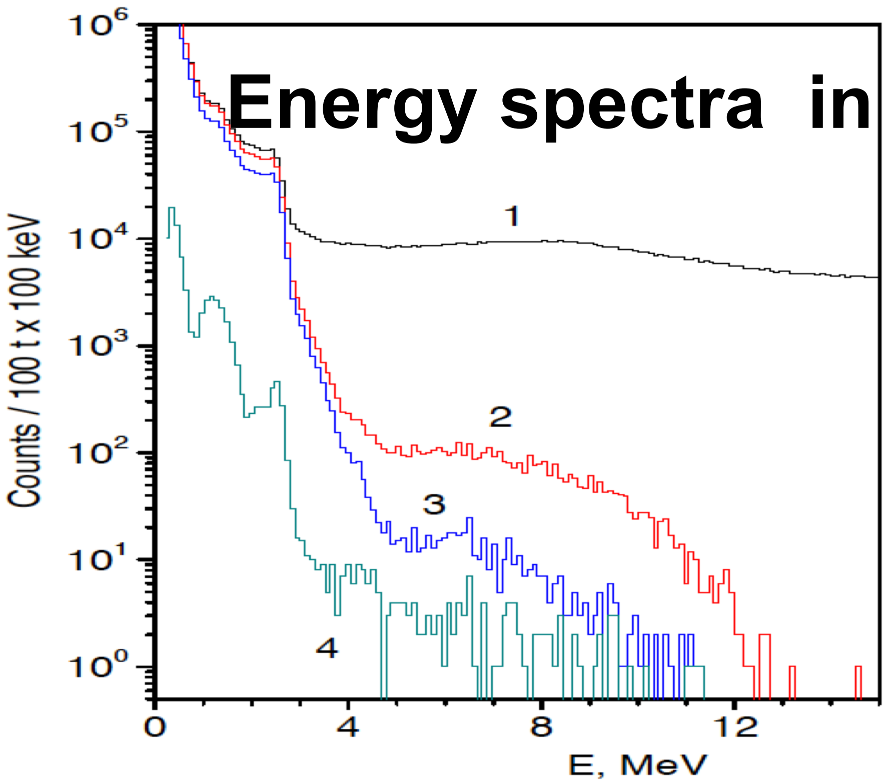
$m_{A'}$ < 1 MeV search with 100 kW and 20 MeV e-beam

•**Sensitivity for 1 year running:**

$N_{A'} \times \sigma_{comp} \times N_e \sim \varepsilon^4 \rightarrow \varepsilon < 1.8 \times 10^{-8}$ @ 90% C.L.

N_e : number of electron in fiducial mass (2 kton) of LS.

Energy spectra in Borexino

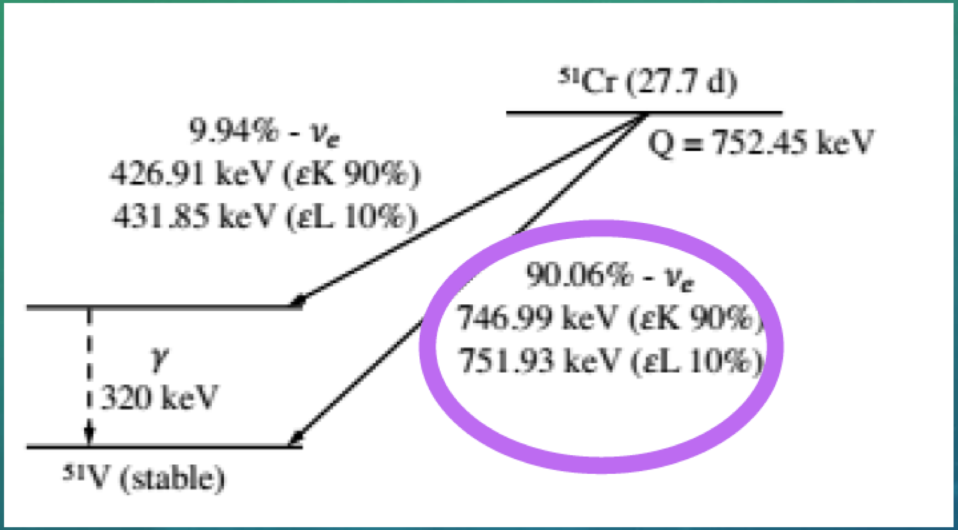


1: Raw spectrum

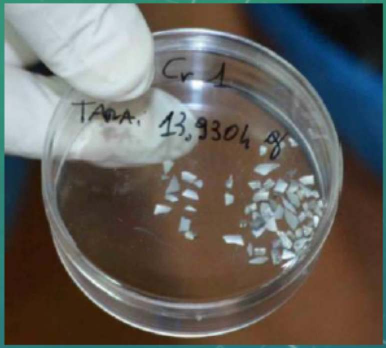
4:Fiducial Cut

THE ^{51}CR NEUTRINO SOURCE

The **neutrino** spectrum consists in four mono-energetic lines:



THE SOURCE PRODUCTION



The GALLEX (INFN) sample:

Mass: 36 kg

Volume: 2 dm^3

with 3.6 g/cm^3 effective density in metallic chips of 1-5 mm

Isotopic composition: ^{50}Cr 38.6% ^{52}Cr 60,7% ^{53}Cr 0,7% ^{54}Cr < 0,3%
enriched in ^{50}Cr and depleted in isotope ^{53}Cr (high neutron capture cross section)

Activation of the sample at reactor

GALLEX:
Siloé reactor in Grenoble with an *estimated* neutron flux 2 10^{14} neutrons cm^{-2} s^{-1}
23.8 Days of irradiation
Final activity of ^{51}Cr: 1.7 MCi

→

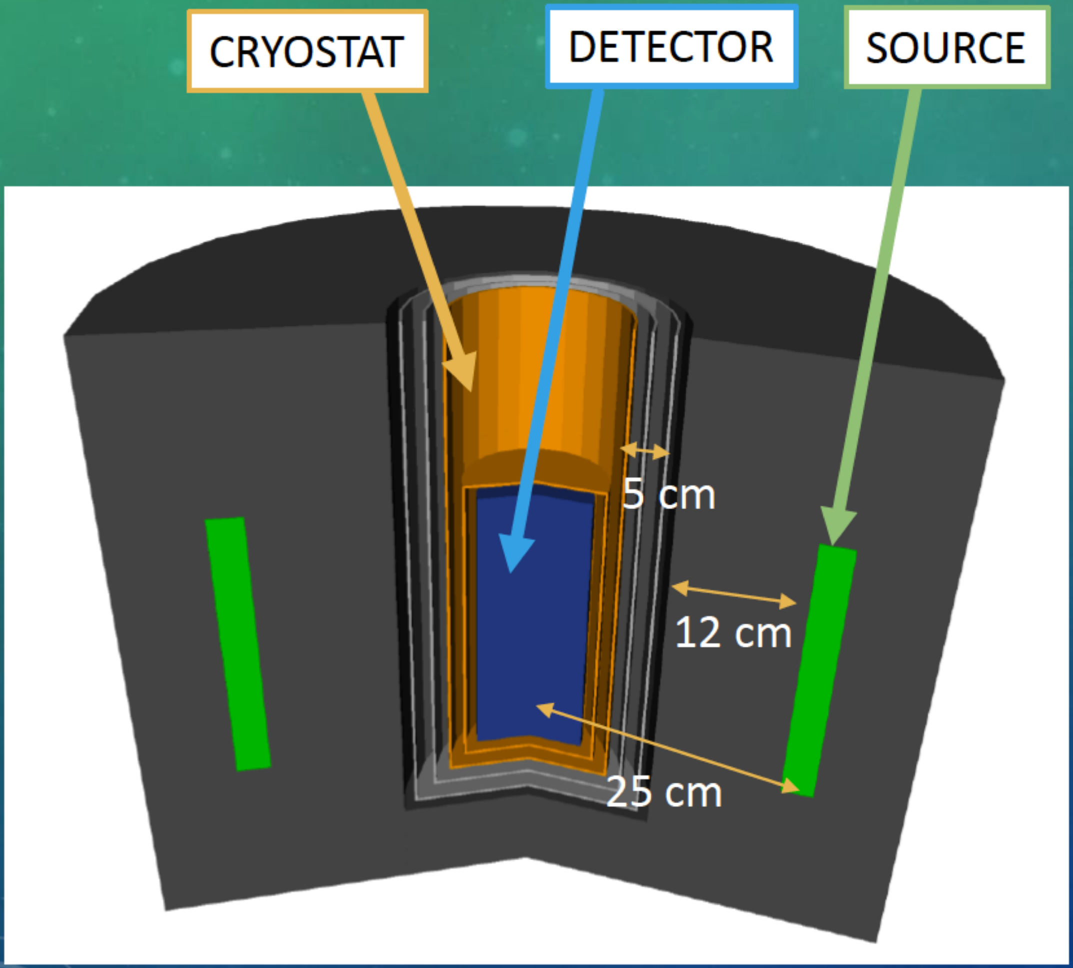
Challenging numbers:
neutron flux 5 10^{14} neutrons cm^{-2} s^{-1}
24 days of irradiation
Final activity of ^{51}Cr: 3.5-7 MCi

Recently a new ^{51}Cr source has been produced in Russia (Dimitrovgrad)!!!

By BEST experiment (3.2MCi) 5th July 2019

THE PROPOSED LAYOUT

for maximizing the detected event



Tungsten shield:
12 cm between source and detector

Ag gamma flux (GBq):
reduced of 10^{-6}

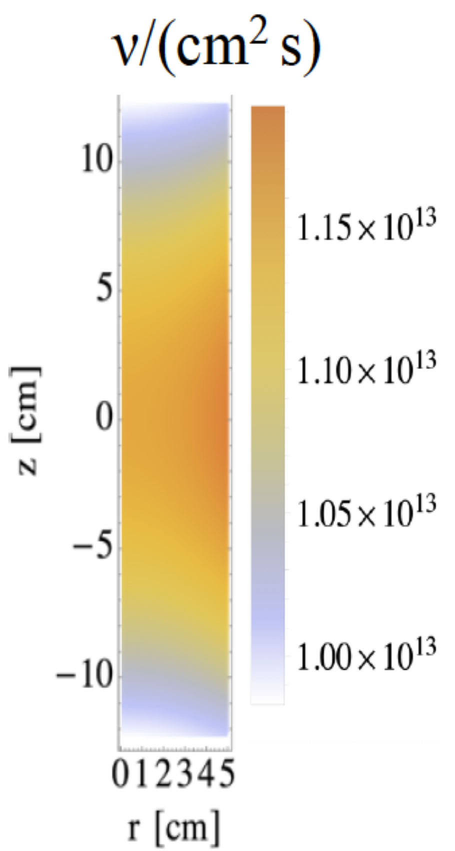
Cr Bremsstrahlung (PBq):
reduced of 10^{-11}

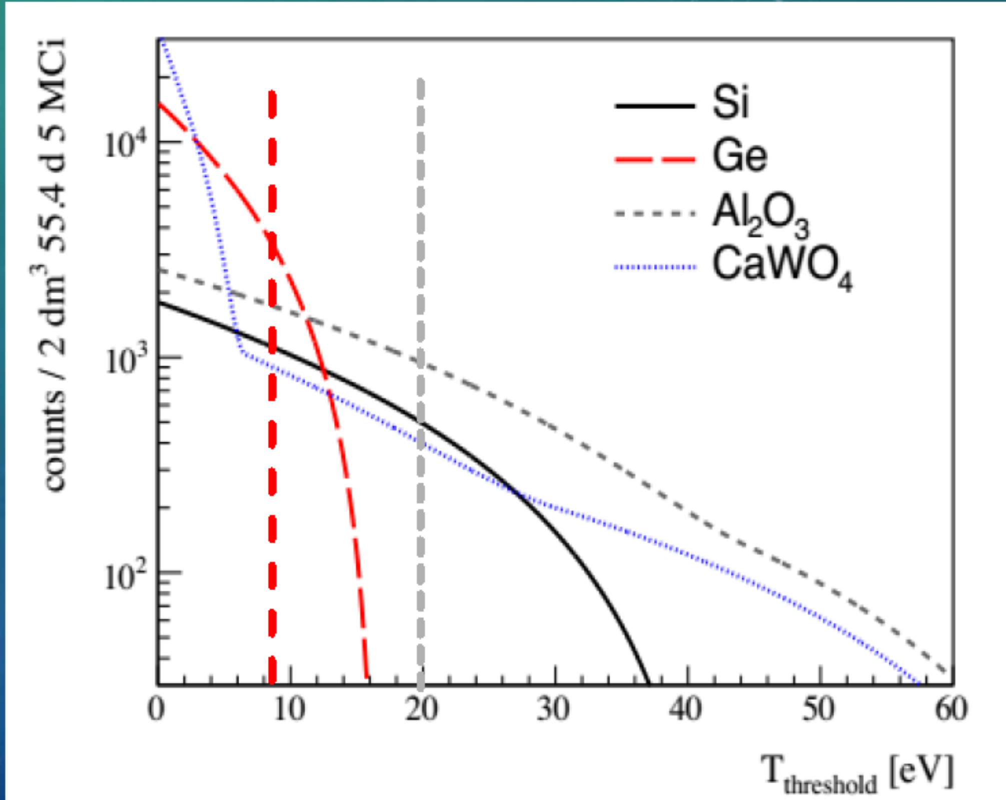
THE SIMULATION RESULTS

Initial activity: 5 MCi
Detector volume: 2 dm^3
Exposure: 55 days (2 half lives)

Detector	Threshold [eV]	Counts in 55 days
Sapphire	20	900
Ge	8	3900

Neutrino flux in the detector

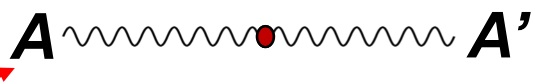




Average neutrino flux: $1\ 10^{13}\ \nu/cm^2s$

Minimal extension of SM

- **The SM allows a new massive or massless *U(1)'* field (A') coupled to the SM *U(1)* field (A) via the kinetic mixing.**

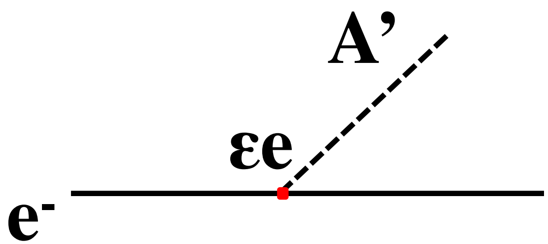


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 + eJ^{\mu}_{em}A_{\mu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \qquad F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$$

- **By rotation of A and A' fields and redefine the fields, one can get as follows,**

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2 + e(A_\mu + \epsilon A'_\mu)J^{\mu}_{em}$$

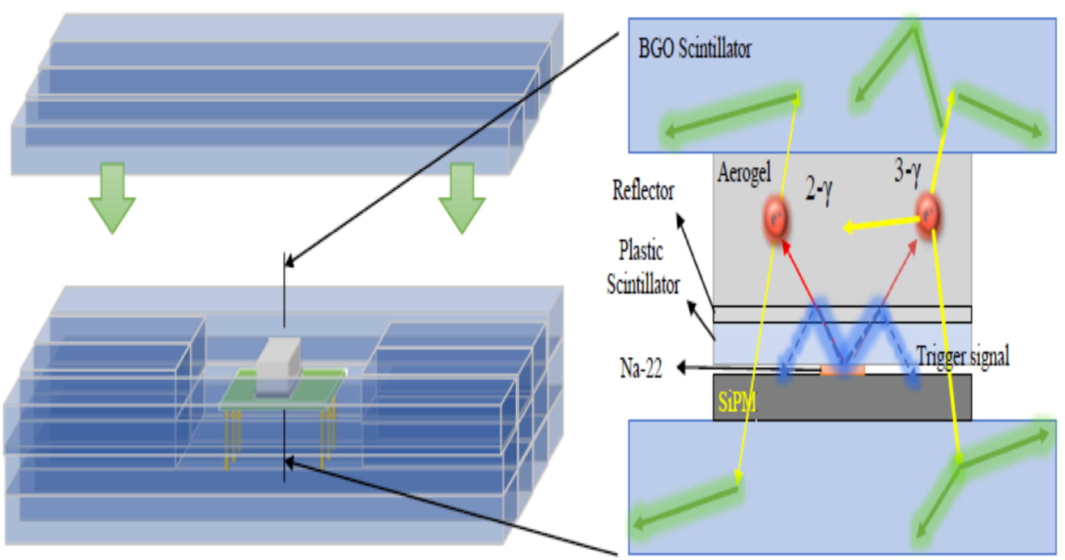


KNU Advanced Positronium Annihilation Experiment

- Positronium annihilation physics : New particle search (Hidden sector dark mater, Dark photon, axion), C,CP,CPT violation in lepton sector search and rare decay measurement [p-Ps (2γ) : 4 γ, o-Ps (3γ) : 5 γ]

- Experiment design & concept : 4π segmented BGO calorimeter
  Actual experiments consist of SiPM, ^{22}Na radiation isotopes, plastic scintillators(Ej-296 or PEN film), reflectors(3M VM2000), Aerogels, 14x14 BGO crystal scintillators (7.5x7.5x150 mm).

- Status and prospect : Under construction. It will give one order better sensitivity than previous experiments.
  In phase 2, BGO thickness can be increased from 4 to 15 cm (2 order better sensitivity)



- For dual readout both sides of the BGO scintillators are coupled with 7 x 7 arrangement of 2 x 2 arrays for a total of 14 x 14 SiPMs