Reactor CEνNS Detection with MIMAC

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Sino-French Collaboration Team

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CPPM (Centre de Physique des Particules de Marseille, Marseille): C. Tao

IRSN- LMDN (Cadarache): M. Petit, T. Vinchon (neutron spectroscopy)

SYSU (Sun Yat-sen University, Shenzhen): Tao Yi

THU (Tsinghua University, Beijing): Gao Fei (A prototype hosted in THU now)

USTC (University of Science and Technology of China, Hefei): Zhang Zhiyong

SJTU (Shanghai Jiao-Tong University): Wang Shaobo, Han Ke

SHAO (Shanghai Astronomical Observatory): Shan Huanyuan

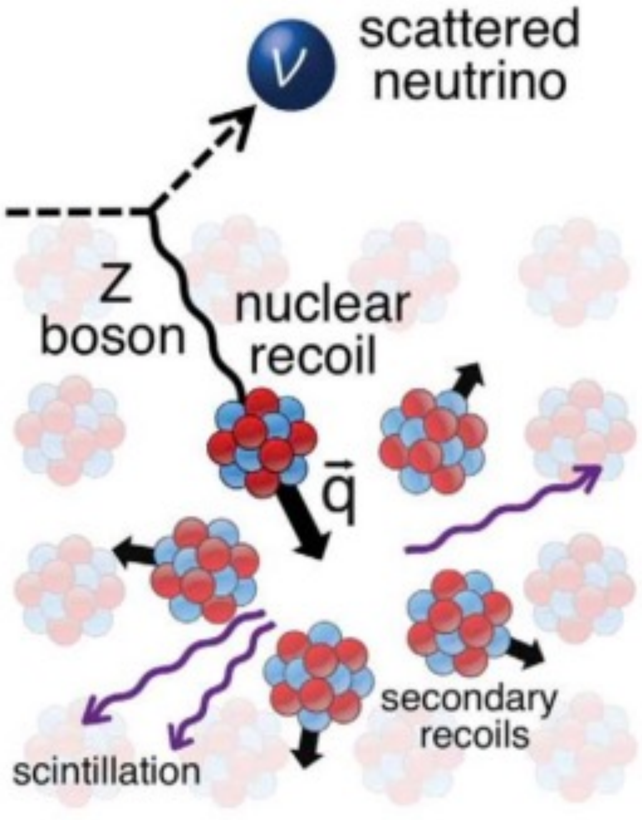
Joint goal: Develop directional detection of CEνNS using the MIMAC gaseous TPC.

CEνNS (Coherent Elastic ν-Nucleus Scattering)

A long-awaited neutral-current process …

- Proposed by **D. Freedman in 1974** — *PRD* ***9***, 1389 (1974)
- First observed by **COHERENT in 2017** — *Science* **357**, 1123-1126 (2017)
- The neutrino **scatters coherently** from the entire nucleus when $qR \lesssim 1$

$$\nu + A \rightarrow \nu + A \qquad \boxed{\frac{d\sigma}{dE_r} \propto Q_W^2 \simeq N^2}$$



10.1126/science.aao0990

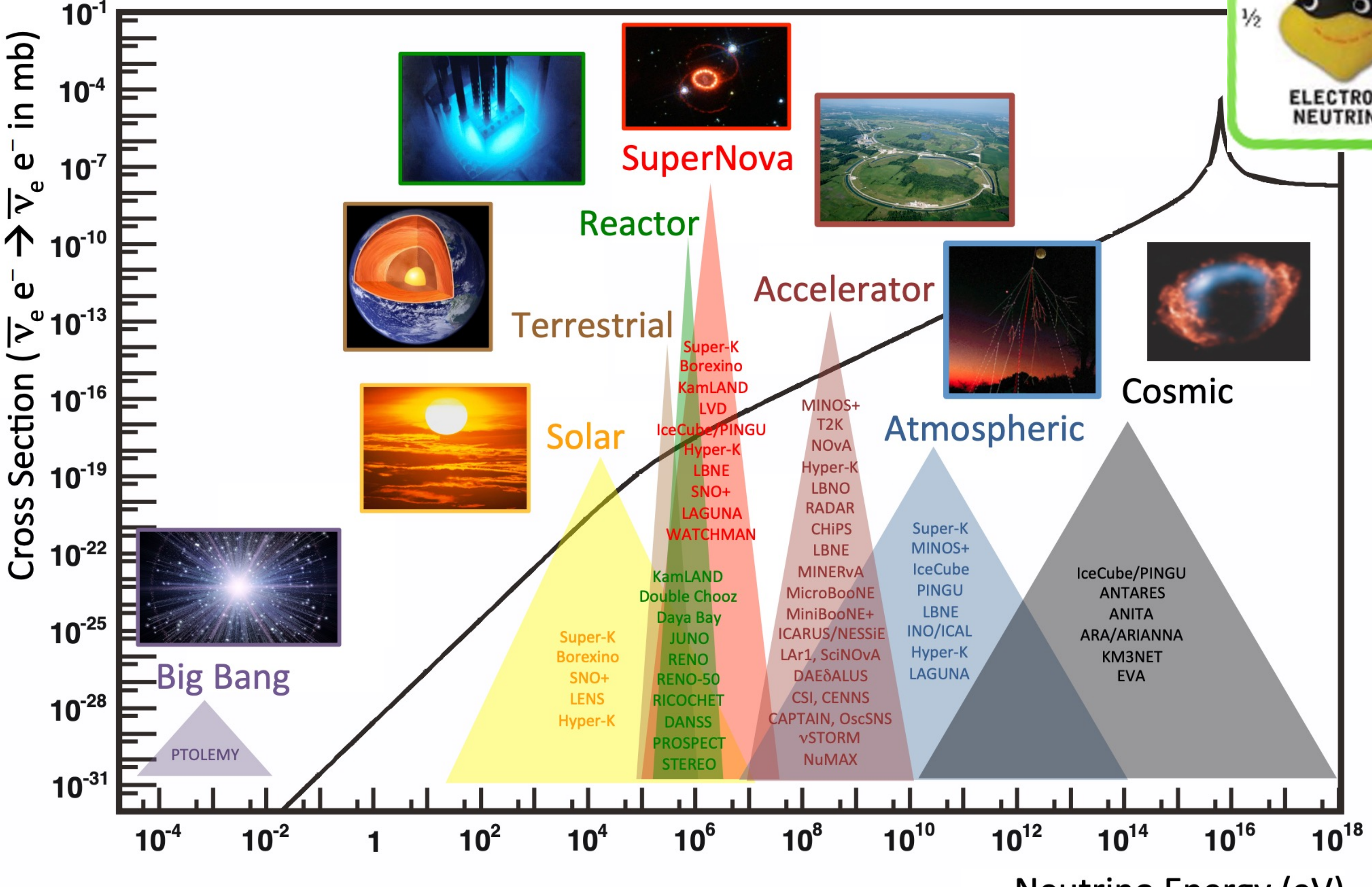
Why is CEνNS important?

- Largest neutrino-nucleus cross section at low energies
- Sensitive test of the Standard Model weak interaction
- Probe of light mediators and non-standard neutrino interactions
- Relevant to reactor monitoring and the neutrino background in dark-matter searches

Experimental challenge

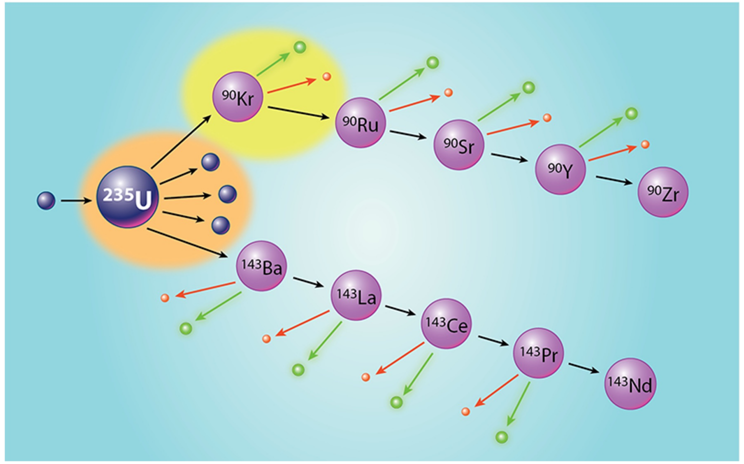
- Signal is a tiny nuclear recoil, typically at the sub-keV to few-keV scale.

(Anti-)Neutrinos from Reactor



Snowmass 2013; Rev. Mod. Phys. 84, 1307

- Neutrinos come from many natural and artificial sources
- For CEvNS, reactor antineutrinos provide an intense, continuous, and controllable MeV-scale source.



Planned Experiment On-site

- **Samen Nuclear Power Plant, Taizhou, China (share with RELICS)**
- Reactor Power **~3.4 GW**, Distance to Core **~25 m**
- Neutrino flux **$\sim 10^{13}\ \nu/cm^2/s$**

Detection Challenges

- **ER/NR discrimination:** reject X/γ-ray and muon-induced electron recoils from the active volume
- **ν-NR / neutron-NR separation:** distinguish CEνNS NRs from reactor and atmospheric neutron recoils
- **Ionization quenching:** low-energy IQF strongly affects NR threshold and expected CEνNS yield

3D track topology and detector observables

Recoil directionality

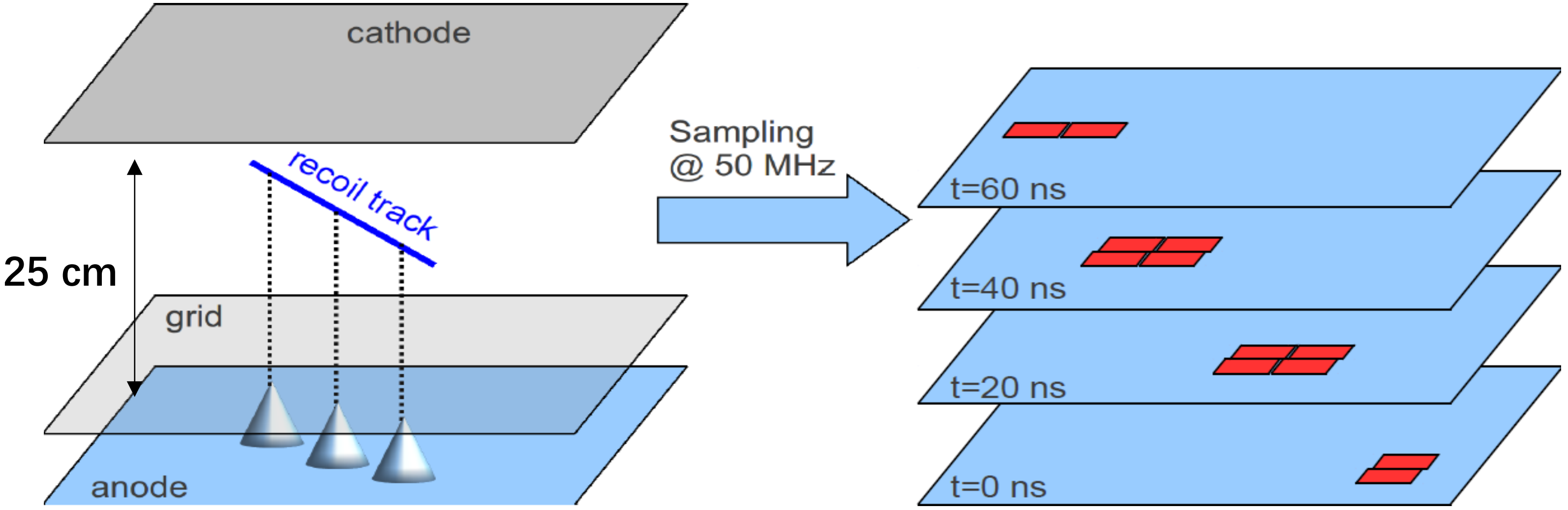
Calibrated with IQF measurements

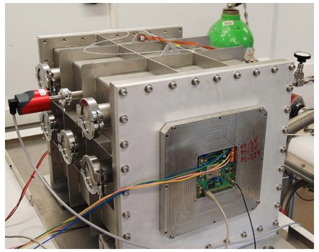
→ **MIMAC detection strategy**

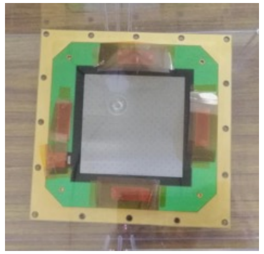
MIMAC Detector

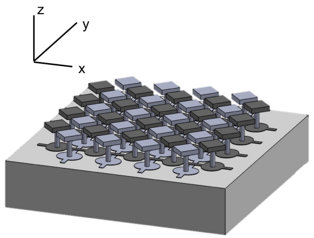
MIMAC: MIcro-TPC **MA**trix of **C**hambers = TPC + Micromegas

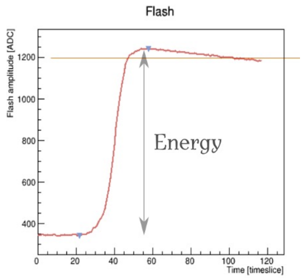
- ✓ **TPC**: **T**ime **P**rojection **C**hamber
- ✓ **Micromegas**: **Micro Me**sh **Ga**seous **S**tructure

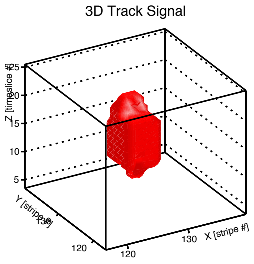












Advantages

- ➢ Energy Measurement
- ➢ 3D Track Reconstruction

➢ **Working Gas Mixture:**

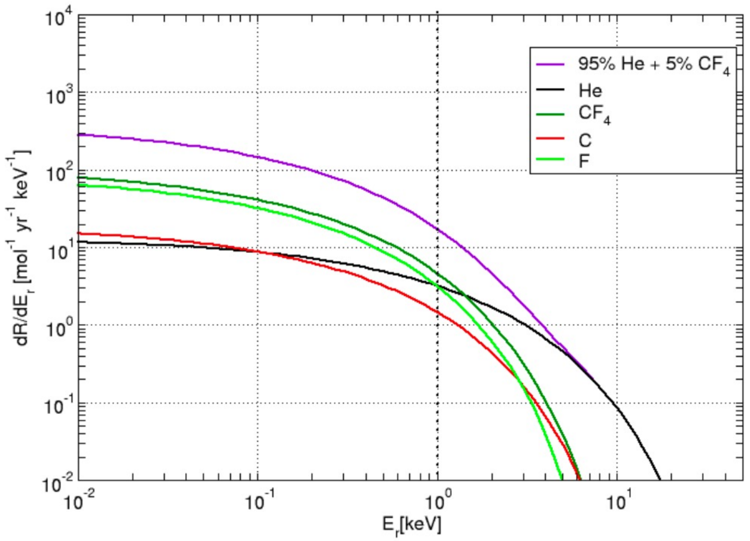
- (80 - x) % ^{4}He
- (20 - y) % CF_4
- (x + y) % C_4H_{10}

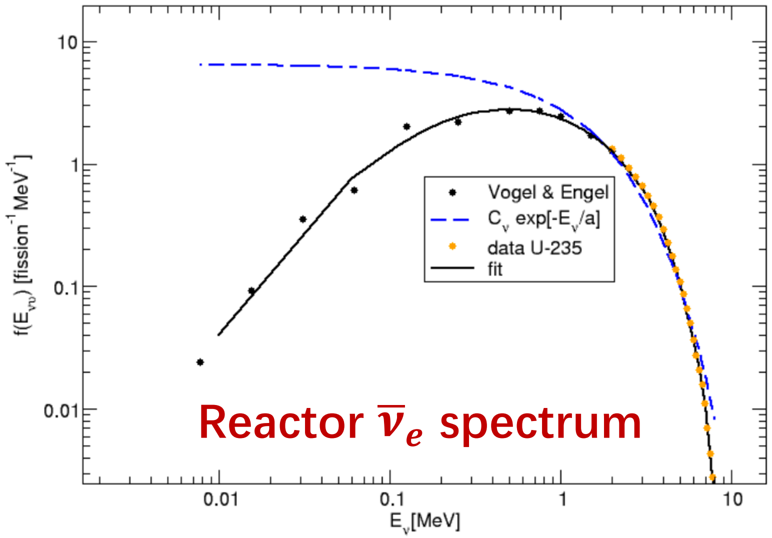
(x: ~0; y: ~1)

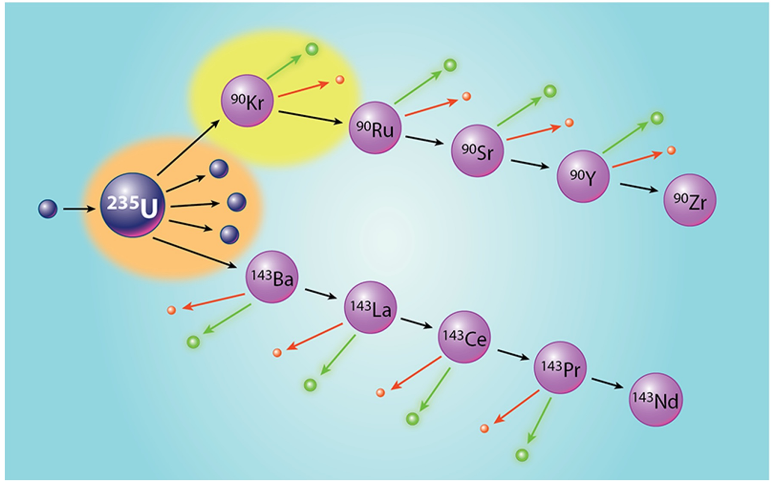
➢ **Goal: 16 bi-chambers to achieve 1 m^3 volume.**

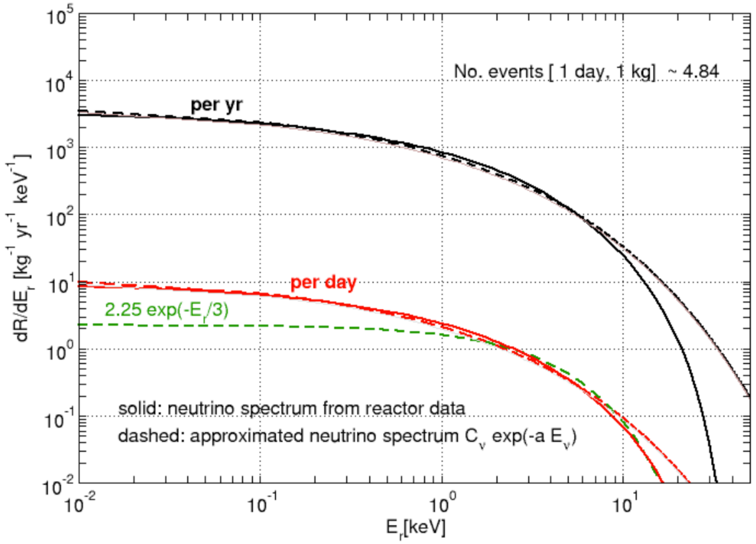
CEvNS Signals

- The empirical exponential approximation reproduces the main behavior well enough for rate estimates.
- Folding the spectrum with CEvNS cross section gives the He recoil spectrum, with high-E_r events strongly suppressed.
- In a 95% He + 5% CF_4 gas mixture: **He** dominates the signal, while **C** and **F** still add non-negligible events.
- **Expected yield: 400-700 events/year for 1 m^3.**





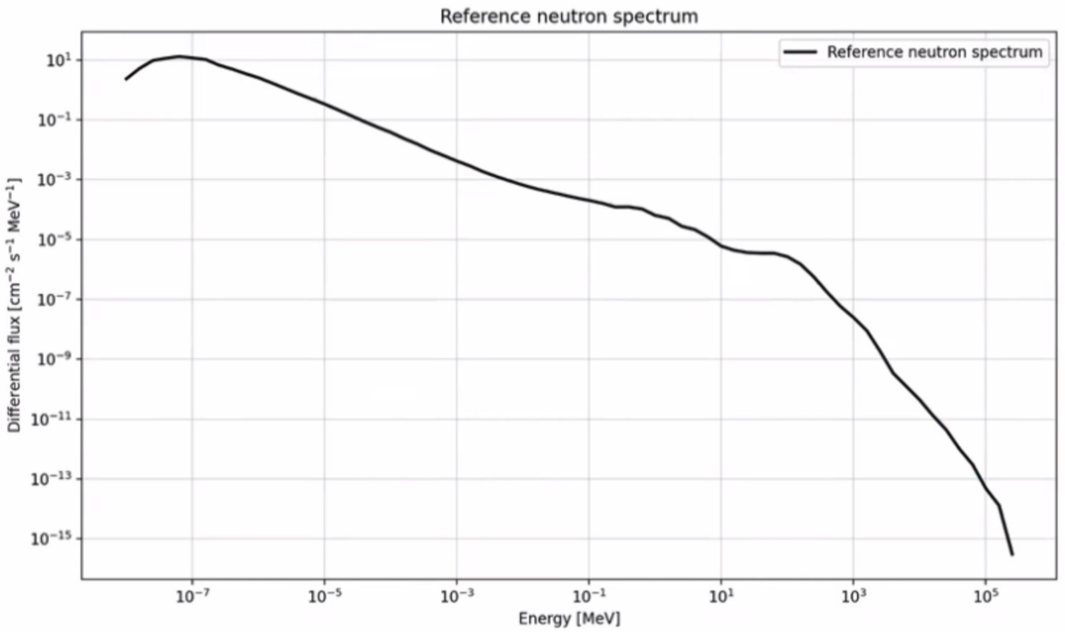




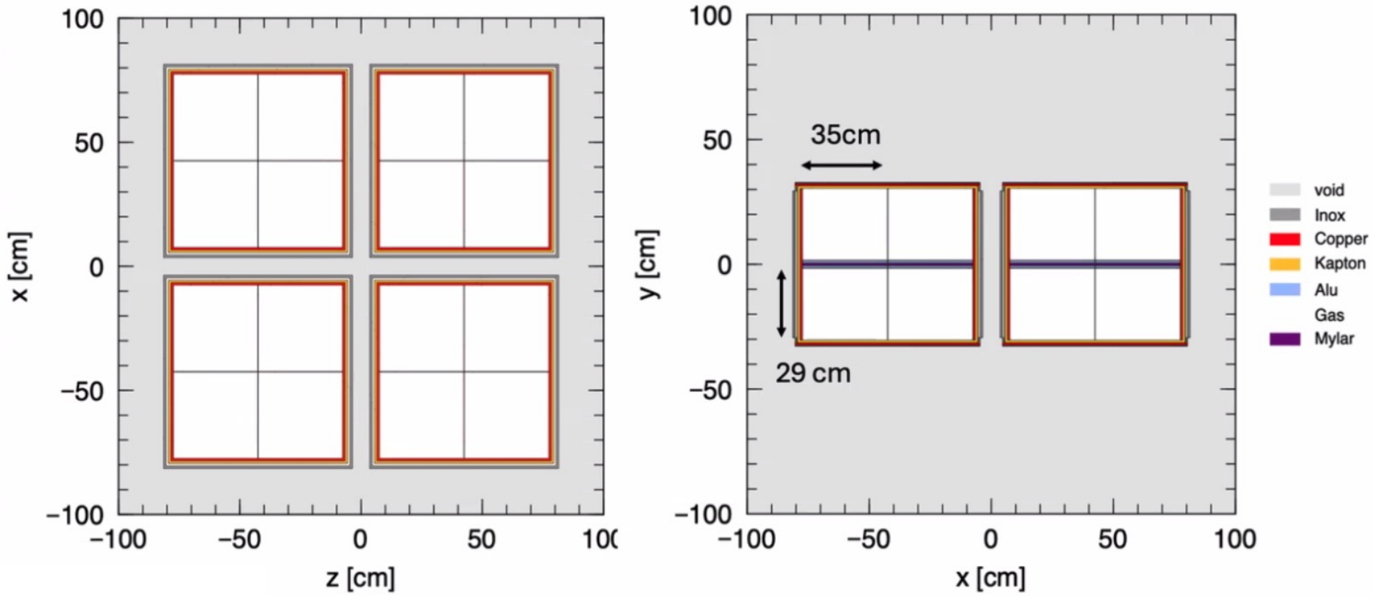
Dominant Background: Atmospheric Neutron

➢ Monte-Carlo Simulation (CRY + PHITS):

- CRY (Cosmic-ray Shower Library) → Generate atmospheric neutrons (w/ angular + energy distributions)
- PHITS (Particle and Heavy Ion Transport code System) → Detector response & background estimation & shielding optimization

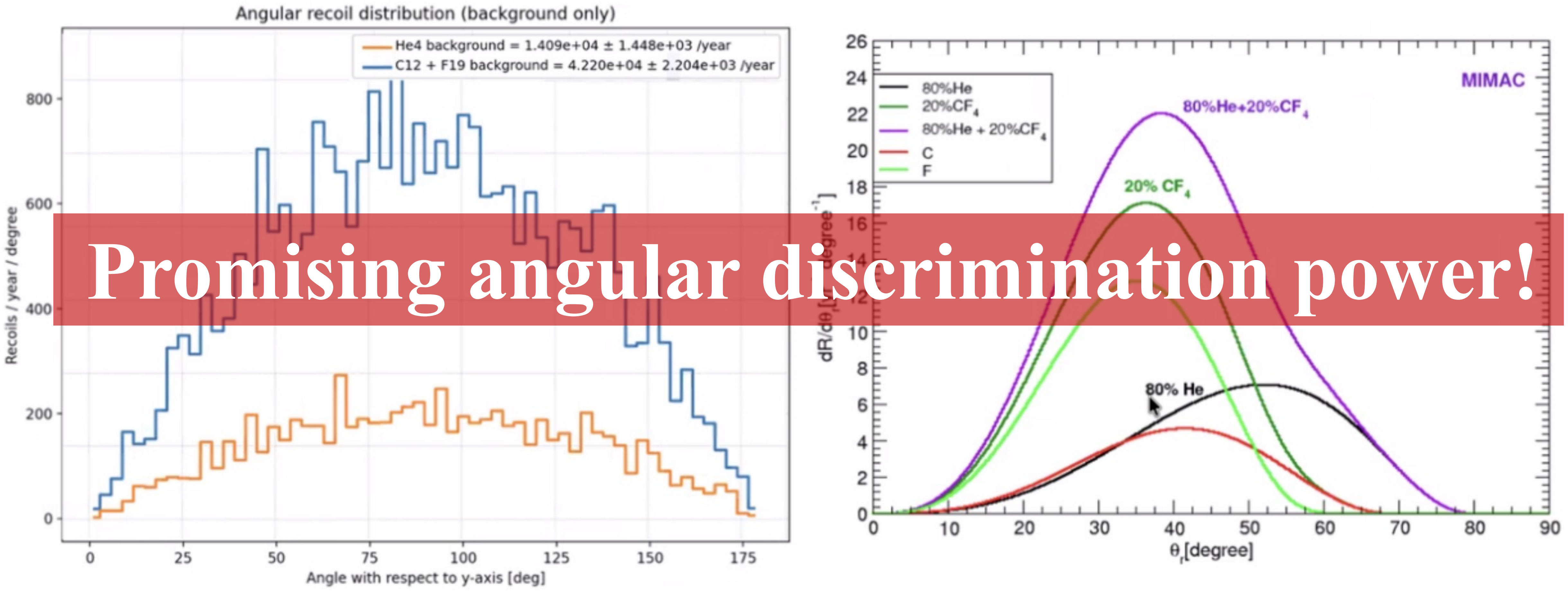


1 m^3 detector 16 MIMAC bi-chambers



Dominant Background: Atmospheric Neutron

- Major advantage: Directionality!
- Preliminary results from MC: Background (L) vs. Signal (R)



How do we reduce such a significant background?

- Background study:
  - With 1.5 m of HDPE shielding, ~ 6×10^4 recoils/yr
  - Introduce hydrogen (H) as an internal neutron monitor

Gas Mixture:
80 % ^4He + 19 % CF_4
+ 1 % C_4H_{10}

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{\pi}\boxed{Q_W^2}M_A\left(1-\frac{E_r}{E_r^{\max}}\right)F(q)^2 \propto Q_W^2 \simeq N^2$$

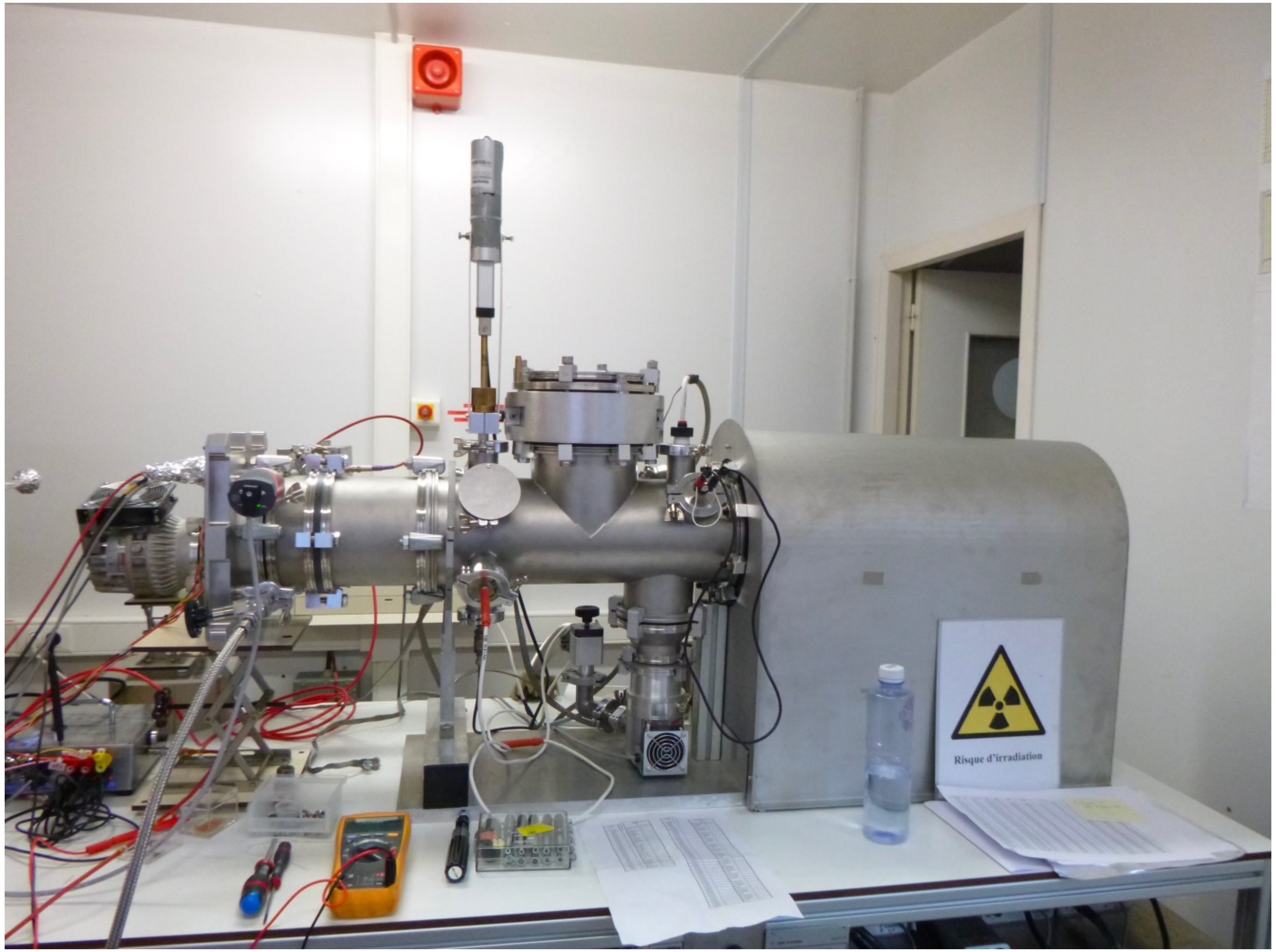
where $Q_W = Z\left(2\sin^2\theta_W - \frac{1}{2}\right) + \frac{N}{2} \simeq 0.5N - 0.04Z$

  - Reactor-Off data could give direct validation

Ionization Quenching Measurement with COMIMAC

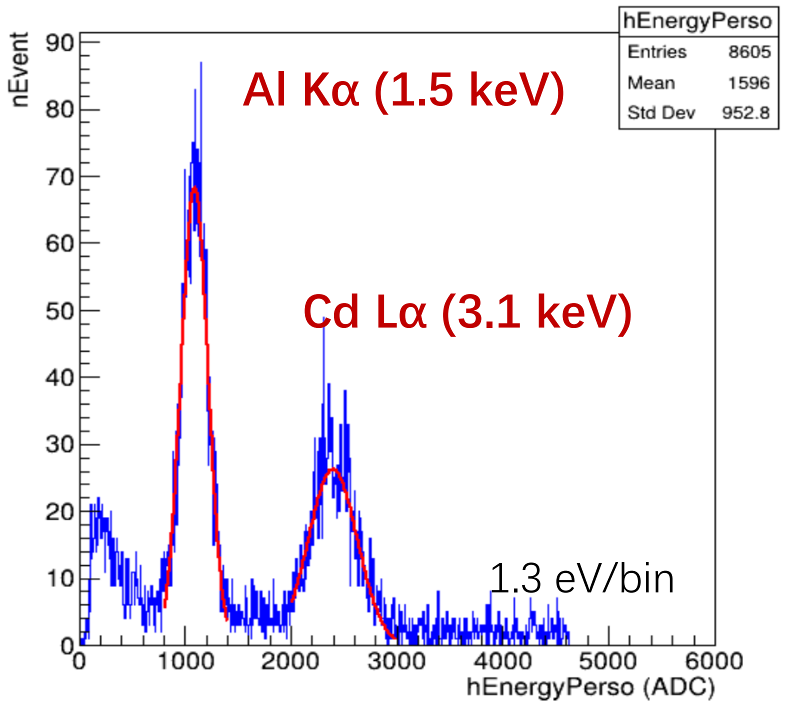
COMIMAC @ LPSC

- Portable table-top facility for low-energy detector calibration
- Delivers calibrated ion/electron beams up to **50 keV**
- Uses COMIC ECR source + Wien filter for particle selection
- Measures ion response and IQF in gas detectors
- Flexible choice of target particles, (including e^-)



New Micromegas from USTC

- Several Key Parameters:
  - Sensitive area: 35 × 35 cm^2;
  - Avalanche gas gap: 512 µm;
  - Strip pitch: 200 µm;
  - Withstands HV: ~1800 V @air pressure.



Tests at LPSC

- X-ray Generator with the Al, Cd & Cu foils
- Test gas mixture:
  - 70% C_4H_{10}
  - 30% CHF_3
  - Pressure 30 mbar
- Energy resolution (FWHM):
  - 27.4% @ 1.5 keV
  - 22.6% @ 3.1 keV

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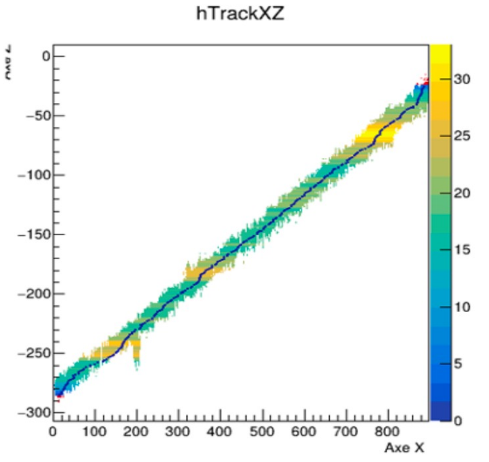
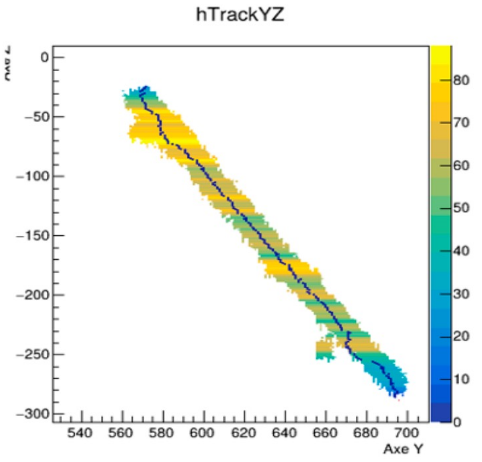
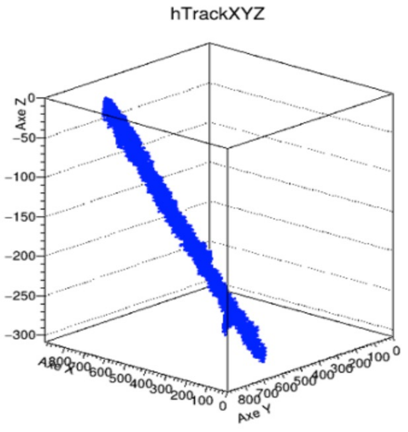
Tests at LPSC

- Clear 3D alpha track reconstruction!





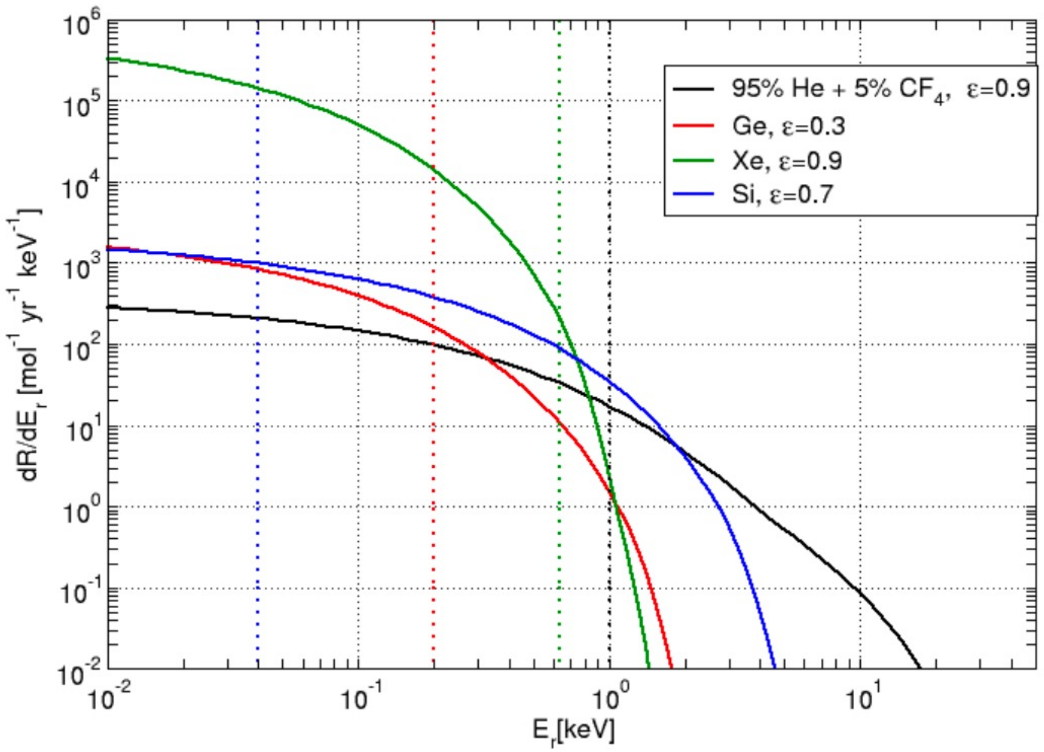


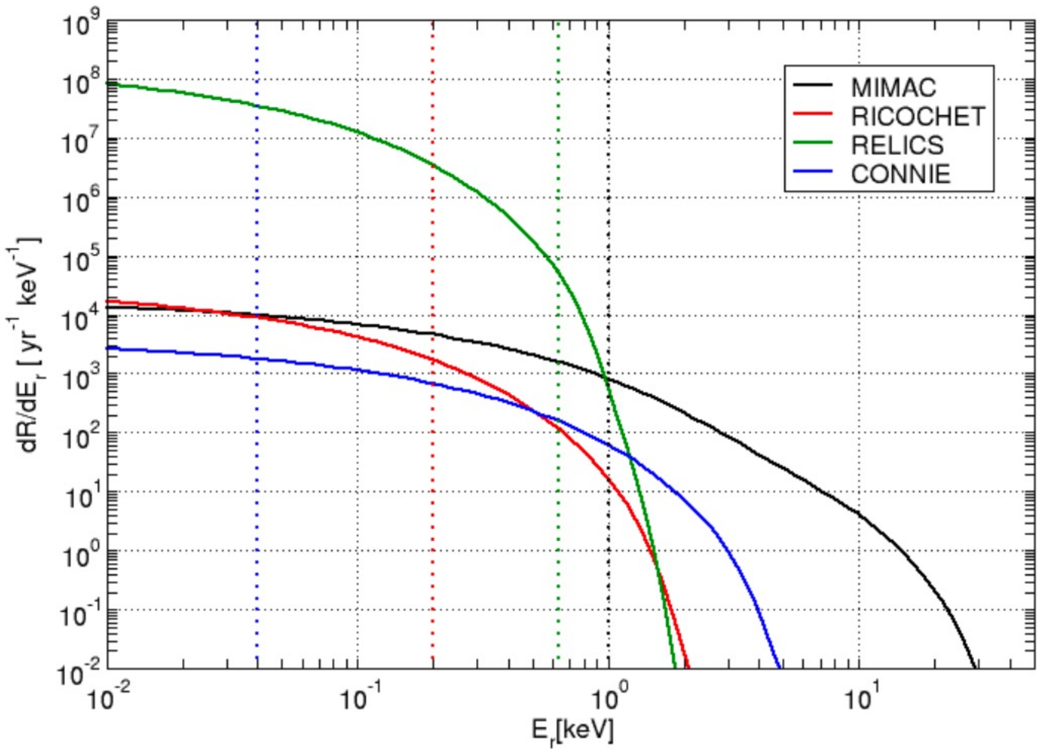
Summary

Thanks for your attention!

Backups

➢ **Differential rate per mol per year**





Backups

➢ 25 cm3 drift distance for each chamber