Low-level impurity measurements in Xenon with cold traps

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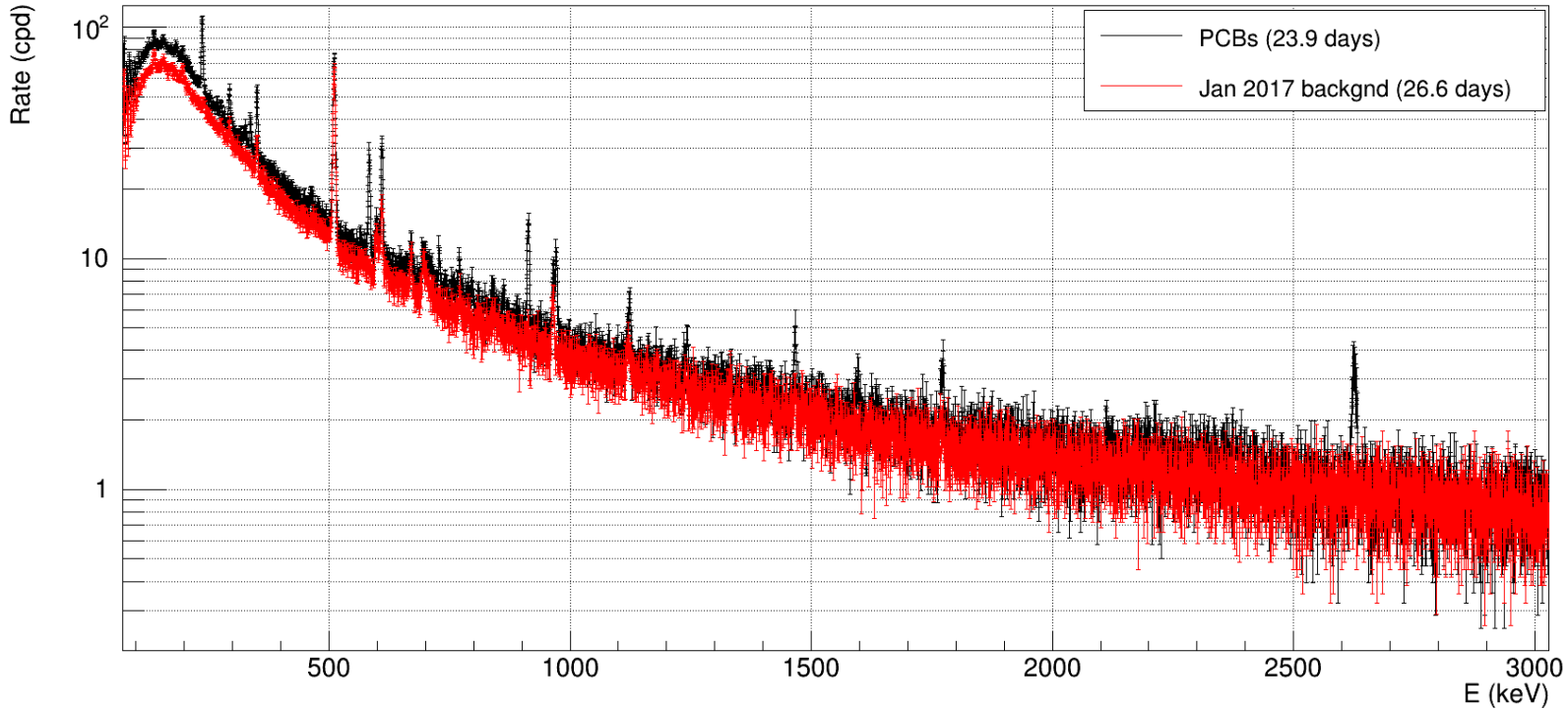
The problem

- Low-level radioactive impurities are ubiquitous
- Rare event searches need materials extremely low in radioactive impurities
  - 1 decay/year = 31.7 nBq (after discrimination)
  - (τ=)10^{9} years X 1 decay/year = 10^{-15} mols
- Either measure extremely low level radioactivities or concentrate the impurities.
  - Extremely low radioactivity means large samples and lots of patience
  - Low level radioactivity measurements best suited for non-sensitive materials

Low level γ spectroscopy

- 2 setups:
- underground (CJPL)
  - Main worry: Rn
- Above ground (SJTU)
  - Main worry: CR



- O(10) l capacity (32 l – cryostat – cold finger)
- 1 mBq = 86.4 dpd
- If O(10%) efficiency ⇒ O(10) cpd
- O(10) d measurements for 10% poissonian error

^{85}Kr in sensitive detector volume

- $\tau_{1/2}$ 10.76 a, τ 15.52 a, ^{85}Kr/^{nat}Kr: 20 ppt, ^{nat}Kr/Xe: 1 ppb – 1 ppm
  - O(400) – O(4 x 10^5) dec/a/mol Xe
  - ^{85}Kr/Xe measurable via radiation if ~8 kg sample
- But backgnd requirement of a DM search for the sensitive material is (after discr.) O(1) dec/a/ton, so purified Xe gets close to this…
- Measure 1 ton sample for 100 years?!
- Measuring the ^{nat}Kr/Xe directly may offer 11 orders of magnitude better chances.
- BTW, if you can see substantial ^{85}Kr radiation from a sample, your detector will see it too

The trick

See, e.g., Dobi et al., NIM A 665 (2011) 1

- A standard RGA with EM can measure $<10^{-9}$ Pa
- 10^{-9} Pa Kr in 1 bar Xe = 10 ppq
- “Just” get rid of the Xe and measure the Kr… easy, right?
- A way of removing the Xe is by freezing it to LN temperature
  - At 1 atm: T_{fus}^{Xe} = 161 K; T_{boil}^{Kr} = 116 K
- But P_{vap}^{Xe} @ 77 K is ~0.25 Pa. An RGA (EM on) can take 1 mPa
  - Response is linear up to 0.1 mPa
- Decreasing the pressure by 10^2-10^3 shifts the 10 ppq up to 1-10 ppt
  - But can push by increasing sample size. E.g., 10 bar Xe can allow for 0.1-1 ppt

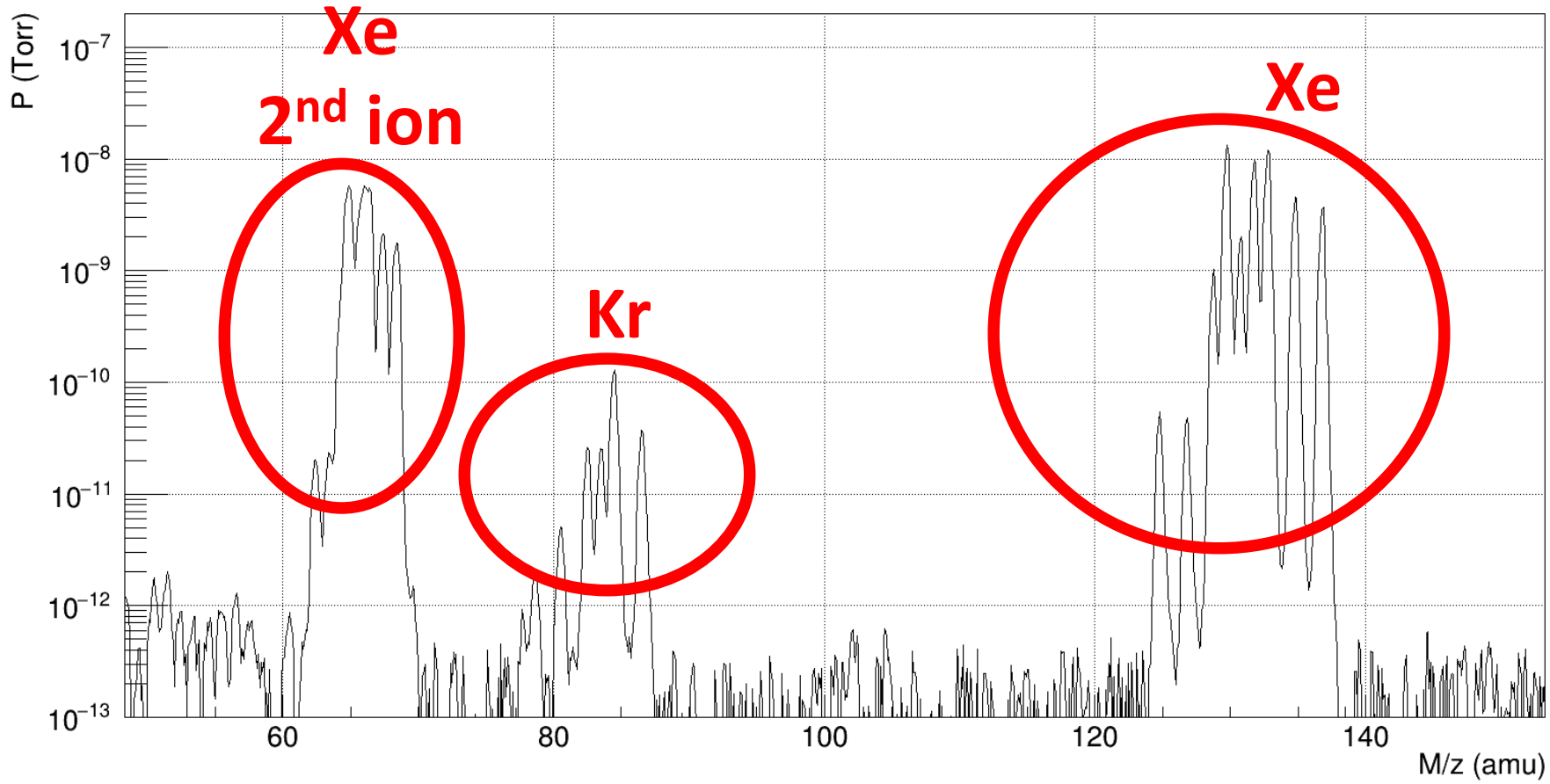
Safe trap volume

- Perfect gas is “conservative”
- @ 300 K, 1 mol ~25 bar-l
- If up to 1.3 kg Xe in trap allowed to reach 300 K, this is 250 bar-l
- Setting max safe P to 50 bar, this requires a 5 l trap.
- What about cold clogging?
- ρ_{sol}^{Xe} = 3.65 g/cm^3, so 1.3 kg < 0.4 l < 10% of 5 l.

How does a cold trap setup look like?

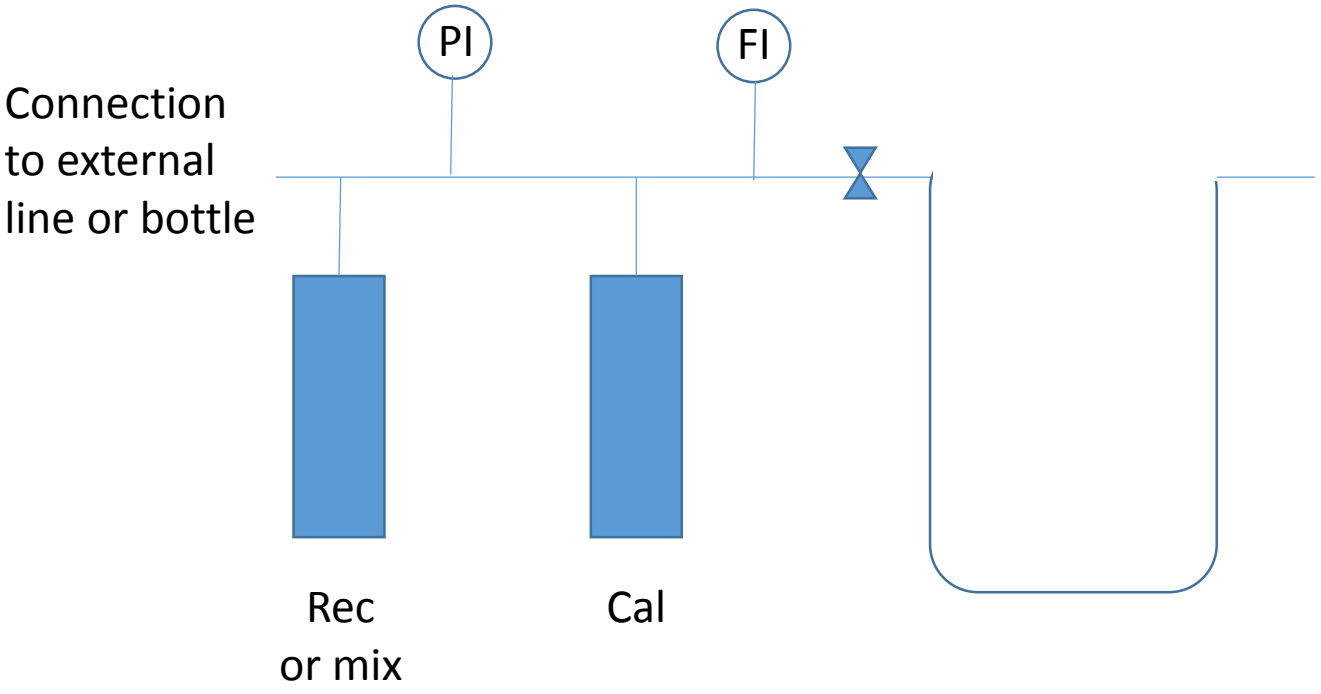
- 1st rule: don't add air to your sample
  - A gas purity setup is a vacuum setup!
- E.g., 10 μPa of residual air, contain up to 10 pPa Kr. If inject 1 bar Xe, 10^{-1} ppq Kr added
- But the pressures of the sample bottles hooked to the setup can be 10s of bars or more
- Old setup in photo currently reaches O(0.1) ppb

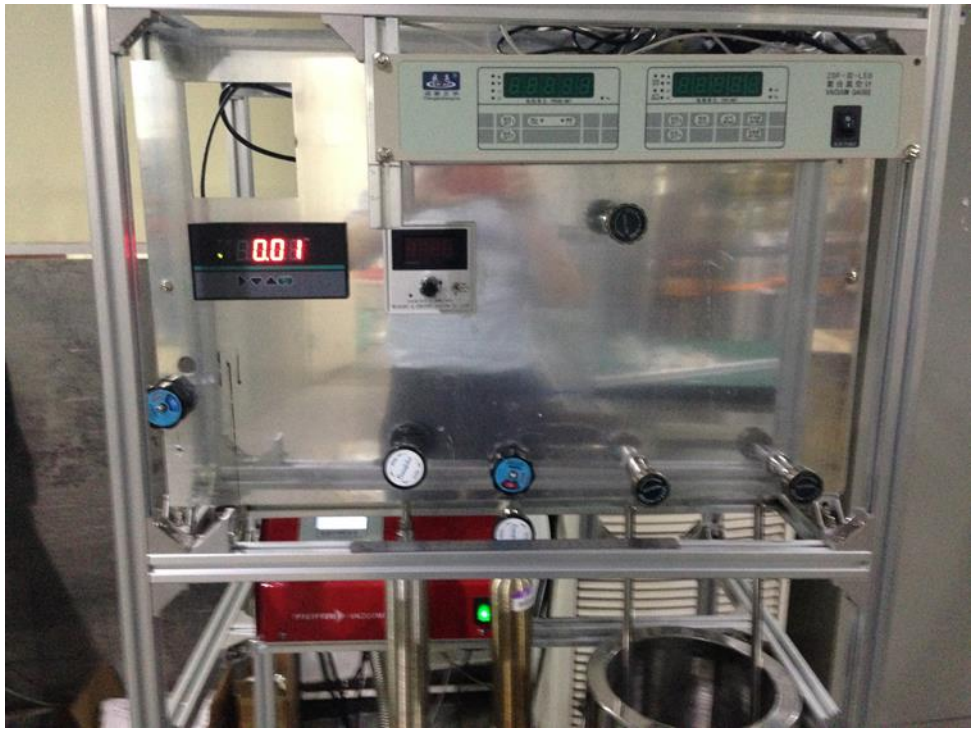
Example mass spectrum



New setup coming online

- Goal: 10 ppq sensitivity
- To be hooked to Xe distillation tower in CJPL
- Stay tuned…





Summary

- If you can accurately measure the radioactivity of the impurities in a material, this material is unsuited as the sensitive material of a detector for a rare event searches (DM, $0\nu\beta\beta$, …)
- For Xe-based detectors, this means Xe's radiopurity should be measured with non-radiation based methods, in particular cold traps or gas chromatography
- The PandaX collaboration has two cold trap-based setups:
  - One is operative, in CJPL and has currently O(0.1) ppb sensitivity (improvable)
  - The second is coming online, dedicated to monitor the product of Xe distillation, aimed at 10 ppq sensitivity

BACKUP

Is a single trap enough?

- If we trap 10 mols (1.3 kg), 10 ppq Kr means 2.5×10^{-7} Pa-l in trap
- This translates to O(10^{-10} - 10^{-9}) Pa-l.
  - May require high sensitivity RGA or several kg sample

Can we go beyond?

- What about using 2 traps? (main advantage: we already have a working single trap)
- E.g.:
  - sample has 1 ppq Kr
  - both traps concentrate by 10^5.
- 2^{nd} trap has 0.25 Pa of Xe with 10 ppm Kr
- If P_{RGA} = 0.25 mPa, @ RGA P_{Kr} ~ 2.5×10^{-9} Pa
- But to make in 2^{nd} trap 0.25 Pa-l of Xe with 10 ppm Kr from a 0.1 ppb sample, we need 0.25 bar-l from 1^{st} trap. This, in turn, needs 25000 bar-l from the 1 ppq sample. @ RT, this is O(100) mols = O(130) kg sample.
- Its price? O($200k)… but the Xe is recoverable

Any alternative?

- Limitation comes from Xe P_{vap} @ 77 K
- Use other type of trap, e.g. adsorption, may allow to further reduce the P_{Xe} without reducing P_{Kr} too much
- Lindemann et al (Eur. Phys. J. C (2014) 74:2746) recently used gas chromatography with 3 traps in series, reaching 8 ppq detection limit
- Adsorption is boosted by low T
- Mg-ma>P/rog=RT-arog