Modelization, characterization and optimization of HEMT-based charge readout pre-amplifier

for the RICOCHET collaboration

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presenter

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RICOCHET: *A future low-energy neutrino observatory*

RICOCHET is a **France, USA and Russia** wide collaboration accounting for about 50 physicists, engineers, and technicians, aiming at building the **first low-energy neutrino observatory**

RICOCHET
A Coherent Neutrino Scattering Program

History of CEνNS

CEνNS → Coherent Elastic neutrino-Nucleus Scattering

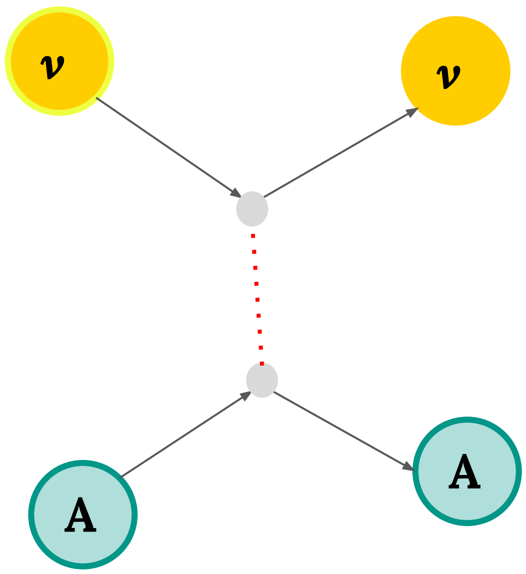
Predicted by Freedman in 1973 *Physical Review D*, *9*(5), 1389.

Measured for the first time in 2017 *Science*, *357*(6356), 1123-1126.

- COHERENT collaboration
- E^{ν}_{mean} ~30 MeV (spallation source)

What's next ?

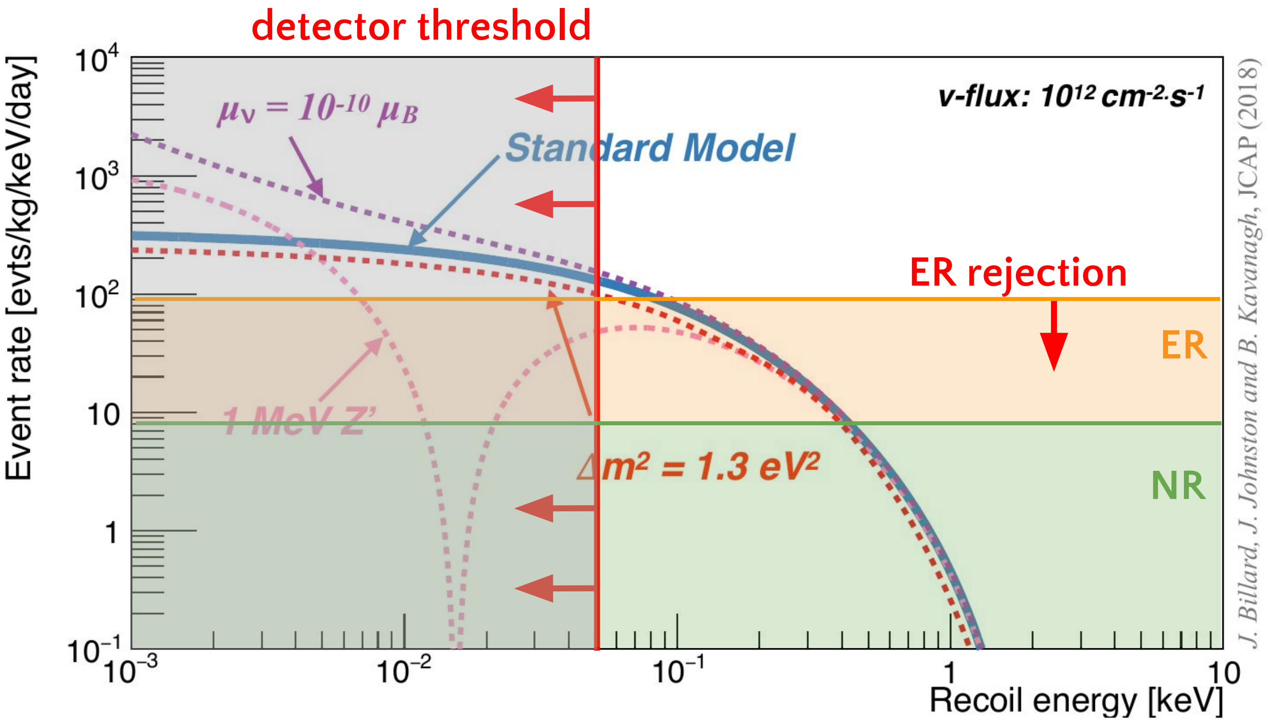
- Measuring CEνNS at reactor (lower E^{ν}_{mean})
- Lowering detection threshold
- Increasing precision -> % level (stat)
- Constraining new physics models



CEνNS allows small detector (~kg) to be competitive with large scale ν physics experiment

RICOCHET signal/noise goal

threshold 50 eV
→ **12.8 evt.kg^{-1}.day^{-1}**



Particle identification

NR/ER discrimination
Event by event tagging
Heat & Ionization
Heat pulse timing

Performances goal

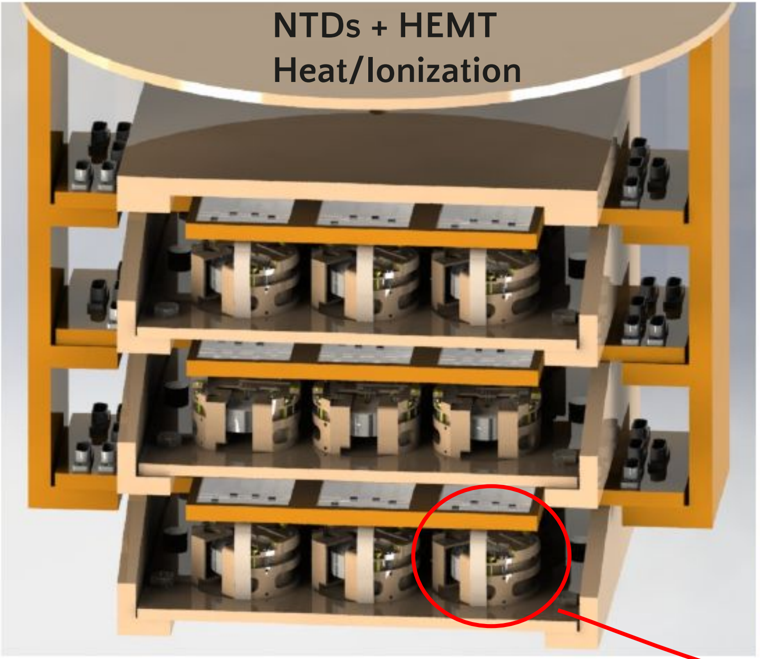
σ_{Heat} ≃ 10 eV

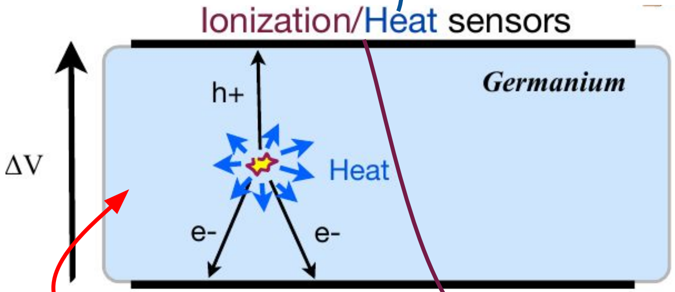
σ_{Ion} ≃ 20 eV

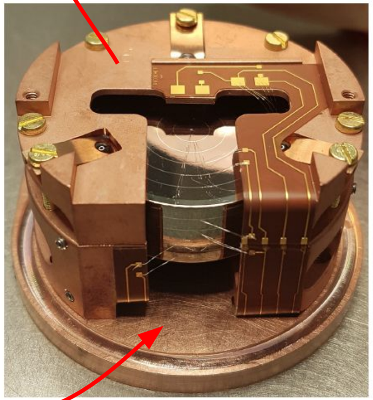
Exposure

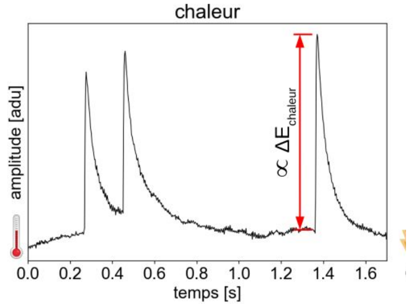
kg scale target mass

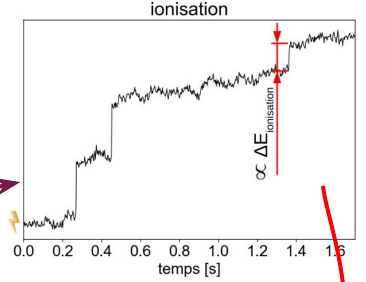
The CryoCube detector

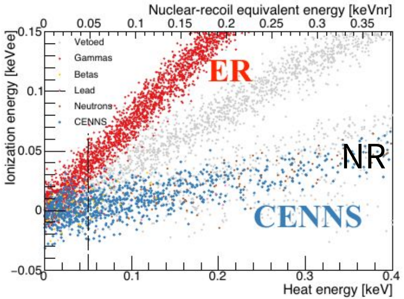










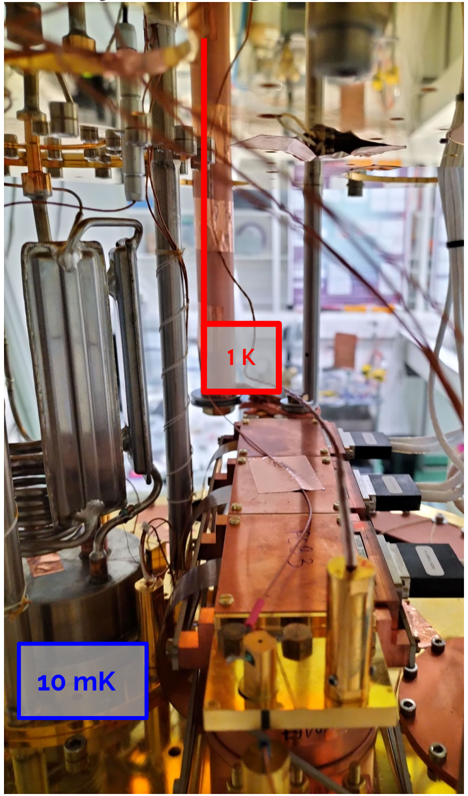


Misiak PhD Thesis

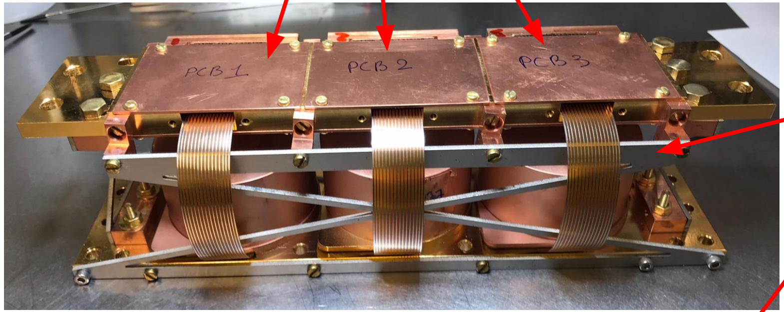
Salagnac & al: arXiv:2111.12438

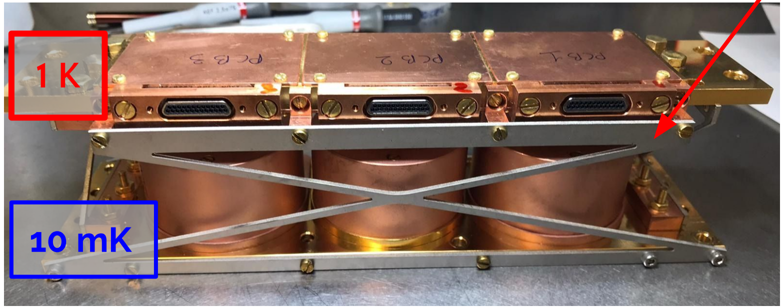
The mini-CryoCube

Cryostat integration

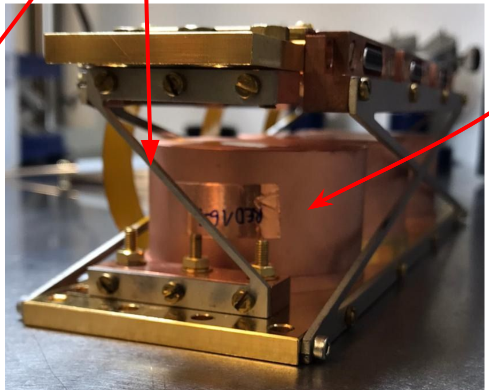


HEMT pre-amplifiers



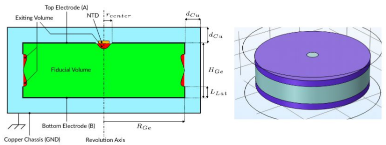


Timetal
(1μW dissipated power)

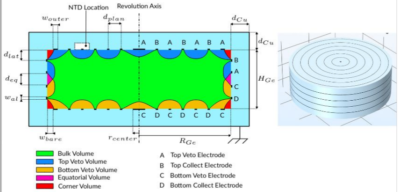


Two type of detectors
PL38 / FID38 → Two 'type' of pre-amplifiers

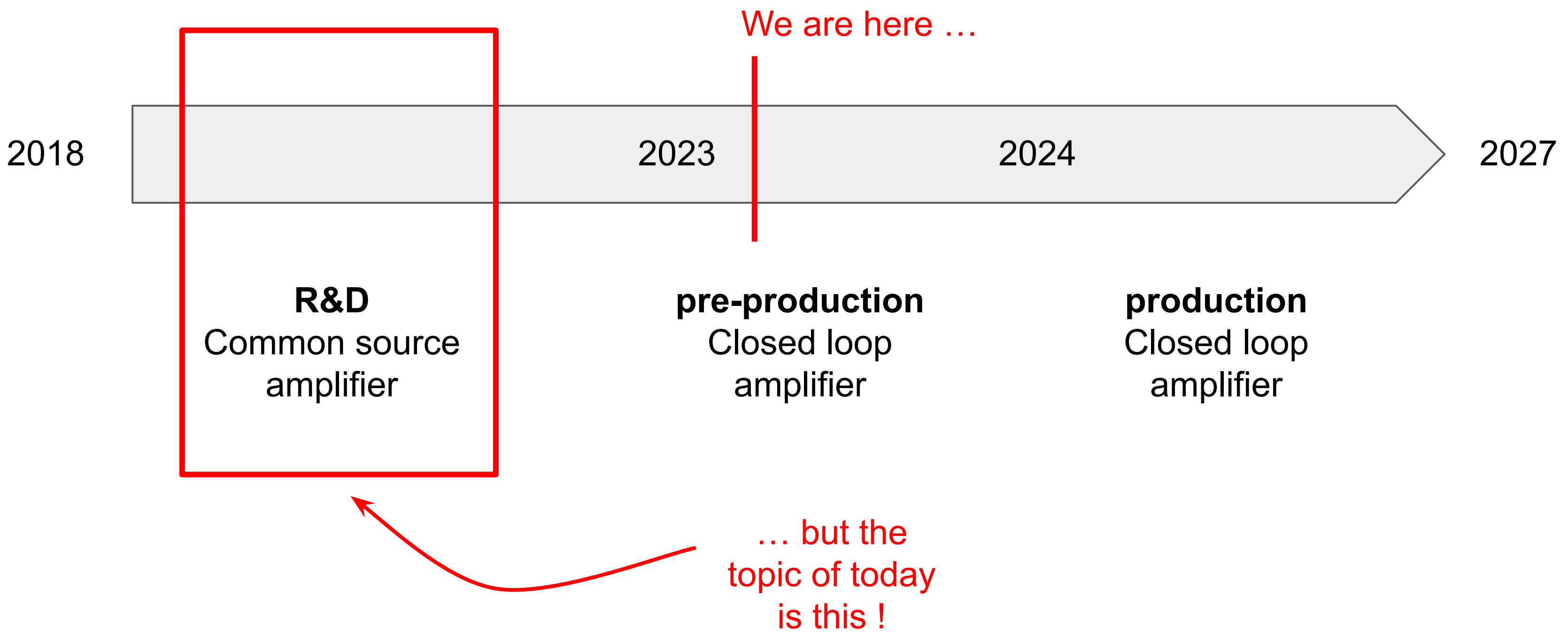
PL38: 2 Planar electrodes extended over the corners on the lateral surface



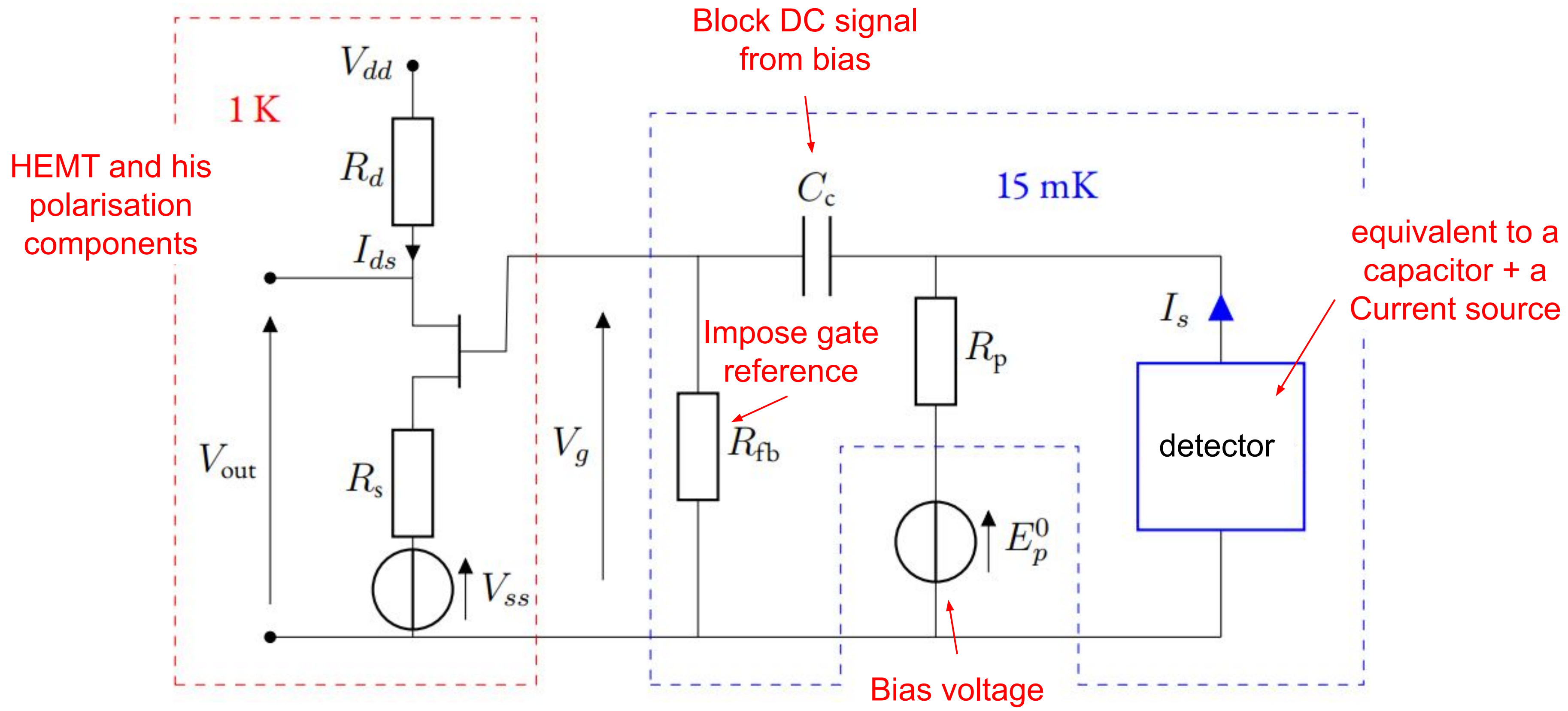
FID38: 4 Fully Interdigitized electrodes



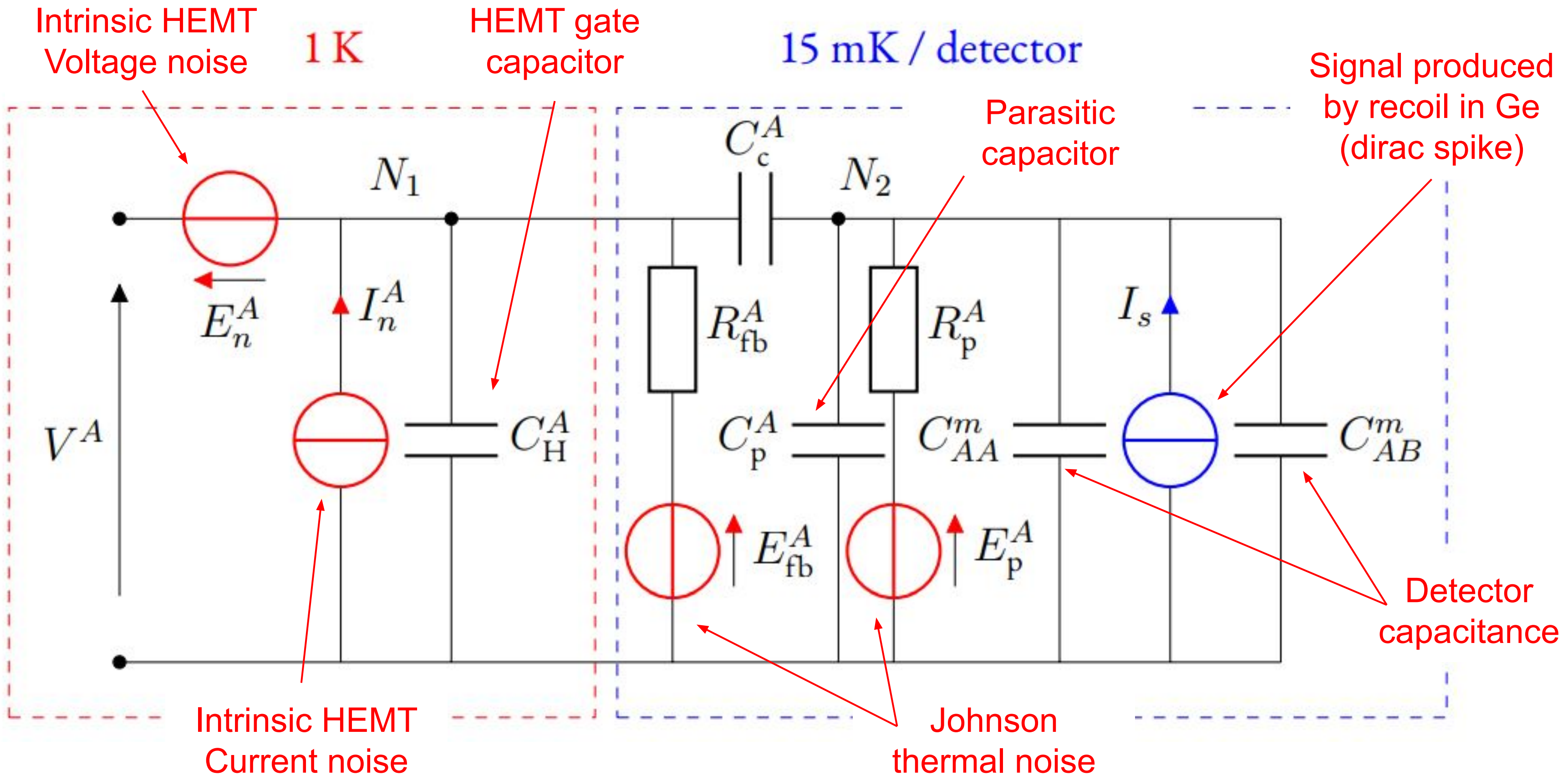
We have multiple HEMT-based ionization readout



The common source amplifier is simple



The common source amplifier model, for one channel



Signal/Noise propagation

1. In **any case** one can write :

$$V^A(f) = h_1(f)E_n^A(f) + h_2(f)E_{fb}^A(f) + h_3(f)I_n^A(f) + \dots$$
$$= \sum_i h_i(f)U_i(f)$$

Obtained using generalized Millman's equations

2. If we suppose **independent sources** :

$$|V^A(f)|^2 = \sum_i |h_i(f)|^2 |U_i(f)|^2$$

Power Spectral Density of noise sources and signals

3. Then we **impose the signal/noise sources** :

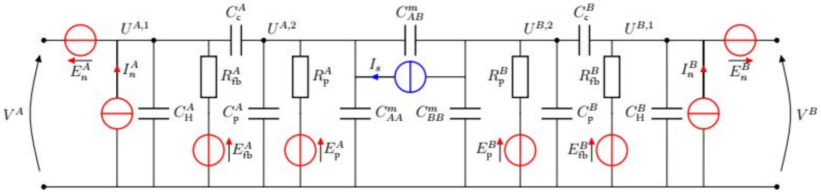
$$|E_p(f)|^2 = 4k_bT_pR_p$$
$$|E_{fb}(f)|^2 = 4k_bT_{fb}R_{fb}$$

$$|I_n(f)|^2 = i_0^2 + i_a^2 f$$
$$|E_n(f)|^2 = e_0^2 + (e_a^2/f) + (e_b/f)^2$$

$$|I_s(f)|^2 = 333q$$

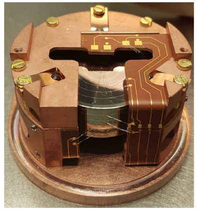
Common source models for planar and FID detectors

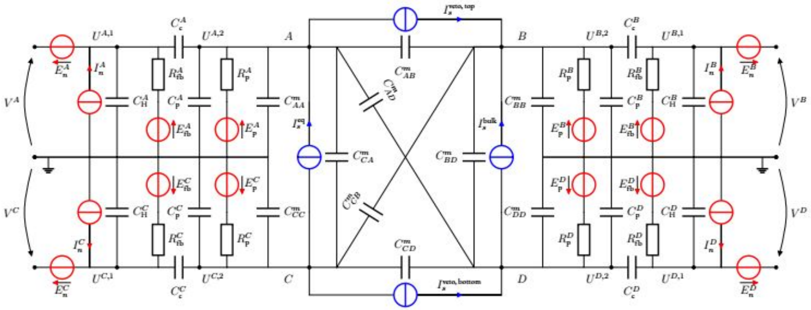
PL38



$$C^{m}_{\mathrm{PL38}} = \begin{bmatrix} C^{m}_{AA} & C^{m}_{AB} \\ C^{m}_{BA} & C^{m}_{BB} \end{bmatrix} = \begin{bmatrix} 4.06 & 10.86 \\ 10.86 & 4.06 \end{bmatrix} \mathrm{pF}$$

FID38





$$C^{m}_{\mathrm{FID38}} = \begin{bmatrix} C^{m}_{AA} & C^{m}_{AB} & C^{m}_{AC} & C^{m}_{AD} \\ C^{m}_{BA} & C^{m}_{BB} & C^{m}_{BC} & C^{m}_{BD} \\ C^{m}_{CA} & C^{m}_{CB} & C^{m}_{CC} & C^{m}_{CD} \\ C^{m}_{DA} & C^{m}_{DB} & C^{m}_{CD} & C^{m}_{DD} \end{bmatrix} = \begin{bmatrix} 1.46 & 10.19 & 4.02 & 2.58 \\ 10.19 & 1.18 & 2.58 & 1.98 \\ 4.02 & 2.58 & 1.46 & 10.19 \\ 2.58 & 1.98 & 10.19 & 1.18 \end{bmatrix} \mathrm{pF}$$

Using Sympy for symbolic solving of Millman equation system is convenient and versatile

SymPy

Full pipeline representation

$$N_1 = \frac{\frac{E_{fb}^A}{R_{fb}^A} + N_2 j\omega C_c^A + I_n^A}{j\omega(C_H^A + C_c^A) + \frac{1}{R_{fb}^A}}$$

$$N_2 = \frac{\frac{E_p^A}{R_p^A} + N_1 j\omega C_c^A + I_s + N_3 j\omega C_{AB}^m}{j\omega(C_p^A + C_{AA}^m + C_{AB}^m + C_c^A) + \frac{1}{R_p^A}}$$

$$N_3 = \frac{\frac{E_p^B}{R_p^B} + N_4 j\omega C_c^B - I_s + N_2 j\omega C_{AB}^m}{j\omega(C_p^B + C_{BB}^m + C_{AB}^m + C_c^B) + \frac{1}{R_p^B}}$$

$$N_4 = \frac{\frac{E_{fb}^B}{R_{fb}^B} + N_3 j\omega C_c^B + I_n^B}{j\omega(C_H^B + C_c^B) + \frac{1}{R_{fb}^B}}$$

SymPy

$$N_1 = \frac{\frac{E_{fb}^A}{R_{fb}^A} + N_2 j\omega C_c^A + I_n^A}{j\omega(C_H^A + C_c^A) + \frac{1}{R_{fb}^A}}$$

$$N_4 = \frac{\frac{E_{fb}^B}{R_{fb}^B} + N_3 j\omega C_c^B + I_n^B}{j\omega(C_H^B + C_c^B) + \frac{1}{R_{fb}^B}}$$

$$N_5 = \frac{\frac{E_{fb}^C}{R_{fb}^C} + N_6 j\omega C_c^C + I_n^C}{j\omega(C_H^C + C_c^C) + \frac{1}{R_{fb}^C}}$$

$$N_8 = \frac{\frac{E_{fb}^D}{R_{fb}^D} + N_7 j\omega C_c^D + I_n^D}{j\omega(C_H^D + C_c^D) + \frac{1}{R_{fb}^D}}$$

$$N_2 = \frac{\frac{E_p^A}{R_p^A} + N_1 j\omega C_c^A + N_3 j\omega C_{AB}^m + N_6 j\omega C_{CA}^m + N_7 j\omega C_{AD}^m + I_e - I_v^{top}}{j\omega(C_p^A + C_{AA}^m + C_{AB}^m + C_{AD}^m + C_{CA}^m + C_c^A) + \frac{1}{R_p^A}}$$

$$N_3 = \frac{\frac{E_p^B}{R_p^B} + N_4 j\omega C_c^B + N_2 j\omega C_{AB}^m + N_6 j\omega C_{CB}^m + N_7 j\omega C_{BD}^m + I_b + I_v^{top}}{j\omega(C_p^B + C_{BB}^m + C_{AB}^m + C_{BD}^m + C_{CB}^m + C_c^B) + \frac{1}{R_p^B}}$$

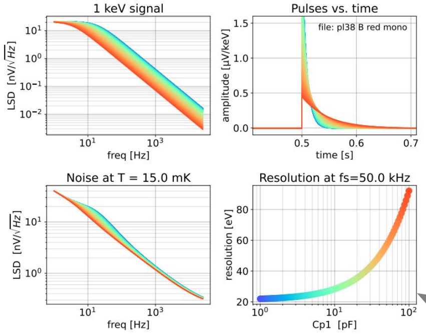
$$N_6 = \frac{\frac{E_p^C}{R_p^C} + N_5 j\omega C_c^C + N_2 j\omega C_{CA}^m + N_3 j\omega C_{CB}^m + N_7 j\omega C_{CD}^m - I_e - I_v^{bottom}}{j\omega(C_p^C + C_{CC}^m + C_{CA}^m + C_{CD}^m + C_{CB}^m + C_c^C) + \frac{1}{R_p^C}}$$

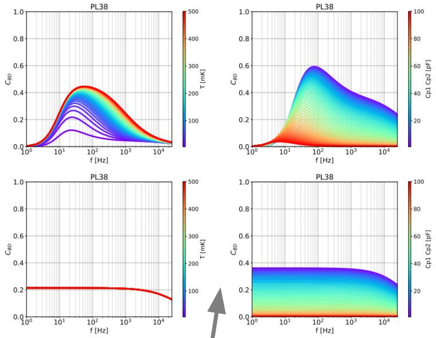
$$N_7 = \frac{\frac{E_p^D}{R_p^D} + N_8 j\omega C_c^D + N_2 j\omega C_{AD}^m + N_6 j\omega C_{CD}^m + N_3 j\omega C_{BD}^m - I_b + I_v^{bottom}}{j\omega(C_p^D + C_{DD}^m + C_{AD}^m + C_{BD}^m + C_{CD}^m + C_c^D) + \frac{1}{R_p^D}}$$

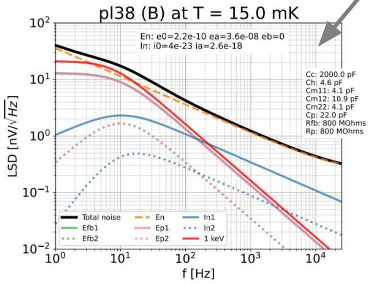
Solver → model.txt → **Scanner** → scan.zarr → **Plotter**

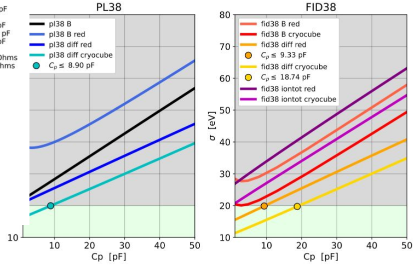
Electrical parameters + Noises

```
1.4142135623731*En +
(-Cc1**2*Cc2*Cc3**2*Cc4**2*Ep2*Rfb1*Rfb2*Rfb3*Rfb4*Rp1*Rp3*Rp4*s**7/(
(Rfb1*s*(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3) +
1)*(Rfb4*s*(Cc4 + Ch4) + 1)*(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) + 1)
*(Rp2*s*(Cc2 + Cm12 + Cm23 + Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 + Cm23
+ Cm34 + Cp3) + 1)*(Rp4*s*(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) -
Cc1**2*Cc2*Cc3**2*Cc4**2*Ib*Rfb1*Rfb2*Rfb3*Rfb4*Rp1*Rp2*Rp3*Rp4*s**7/(
(Rfb1*s*(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3) +
1)*(Rfb4*s*(Cc4 + Ch4) + 1)*(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) + 1)
*(Rp2*s*(Cc2 + Cm12 + Cm23 + Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 + Cm23
+ Cm34 + Cp3) + 1)*(Rp4*s*(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) -
Cc1**2*Cc2*Cc3**2*Cc4**2*Iv*Rfb1*Rfb2*Rfb3*Rfb4*Rp1*Rp2*Rp3*Rp4*s**7/(
(Rfb1*s*(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3) +
1)*(Rfb4*s*(Cc4 + Ch4) + 1)*(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) + 1)
*(Rp2*s*(Cc2 + Cm12 + Cm23 + Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 + Cm23
+ Cm34 + Cp3) + 1)*(Rp4*s*(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) +
Cc1**2*Cc2*Cc3**2*Cc4*Cm24*Efb4*Rfb1*Rfb2*Rfb3*Rp1*Rp2*Rp3*Rp4*s**7/(
(Rfb1*s*(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3) +
1)*(Rfb4*s*(Cc4 + Ch4) + 1)*(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) + 1)
*(Rp2*s*(Cc2 + Cm12 + Cm23 + Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 + Cm23
+ Cm34 + Cp3) + 1)*(Rp4*s*(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) +
Cc1**2*Cc2*Cc3**2*Cc4*Cm24*In4*Rfb1*Rfb2*Rfb3*Rfb4*Rp1*Rp2*Rp3*Rp4*s**7/
((Rfb1*s*(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3)
+ 1)*(Rfb4*s*(Cc4 + Ch4) + 1)*(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) +
1)*(Rp2*s*(Cc2 + Cm12 + Cm23 + Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 +
Cm23 + Cm34 + Cp3) + 1)*(Rp4*s*(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) +
Cc1**2*Cc2*Cc3**2*Cm24*Ep4*Rfb1*Rfb2*Rfb3*Rp1*Rp2*Rp3*s**6/((Rfb1*s*
(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3) + 1)*
(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) + 1)*(Rp2*s*(Cc2 + Cm12 + Cm23
+ Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 + Cm23 + Cm34 + Cp3) + 1)*(Rp4*s*
(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) -
Cc1**2*Cc2*Cc3**2*Cm24*Ib*Rfb1*Rfb2*Rfb3*Rp1*Rp2*Rp3*Rp4*s**6/((Rfb1*s*
(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3) + 1)*
(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) + 1)*(Rp2*s*(Cc2 + Cm12 + Cm23
+ Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 + Cm23 + Cm34 + Cp3) + 1)*(Rp4*s*
(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) -
Cc1**2*Cc2*Cc3**2*Cm24*Iv2*Rfb1*Rfb2*Rfb3*Rp1*Rp2*Rp3*Rp4*s**6/((Rfb1*s*
(Cc1 + Ch1) + 1)*(Rfb2*s*(Cc2 + Ch2) + 1)*(Rfb3*s*(Cc3 + Ch3) + 1)*
(Rp1*s*(Cc1 + Cm12 + Cm13 + Cm14 + Cp1) + 1)*(Rp2*s*(Cc2 + Cm12 + Cm23
+ Cm24 + Cp2) + 1)*(Rp3*s*(Cc3 + Cm13 + Cm23 + Cm34 + Cp3) + 1)*(Rp4*s*
(Cc4 + Cm14 + Cm24 + Cm34 + Cp4) + 1)) +
Cc1**2*Cc2*Cc3**2*Ep2*Rfb1*Rfb2*Rfb3*Rp1*Rp3*s**5/((Rfb1*s*(Cc1 + Ch1)
```

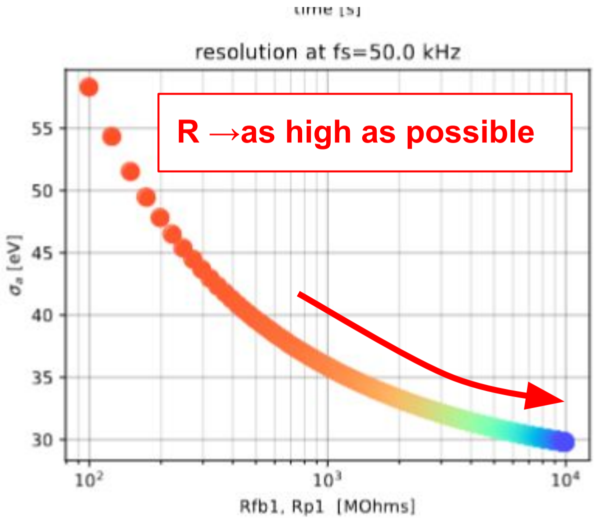


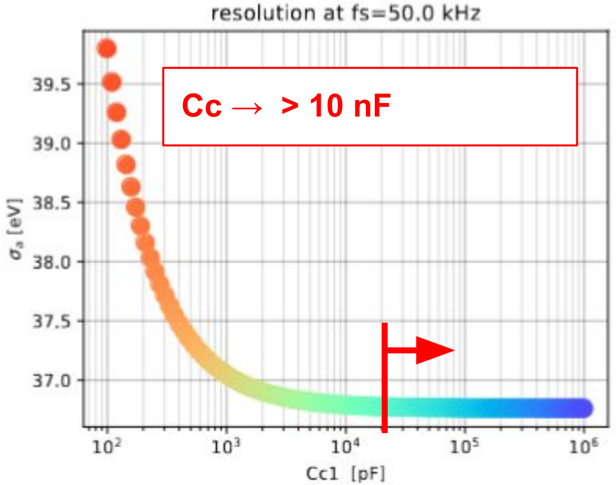


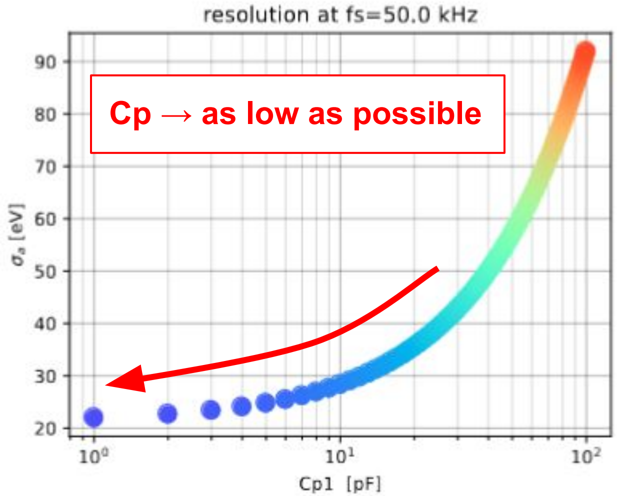




Resolution optimization (RMS)







Stable high value resistor at ~10 mK difficult to find

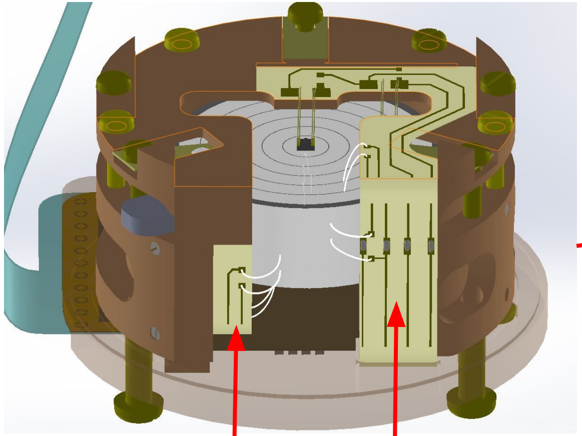
→ Maxed at ~800 MOhms

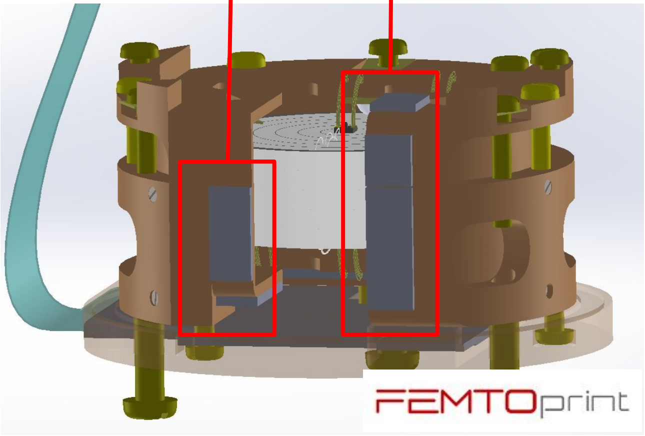
2 nF capacitor validated at 10 mK

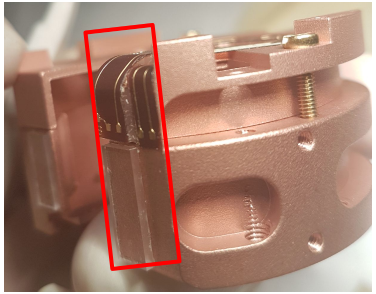
→ Low impact on resolution between 2 nF and 10 nF…

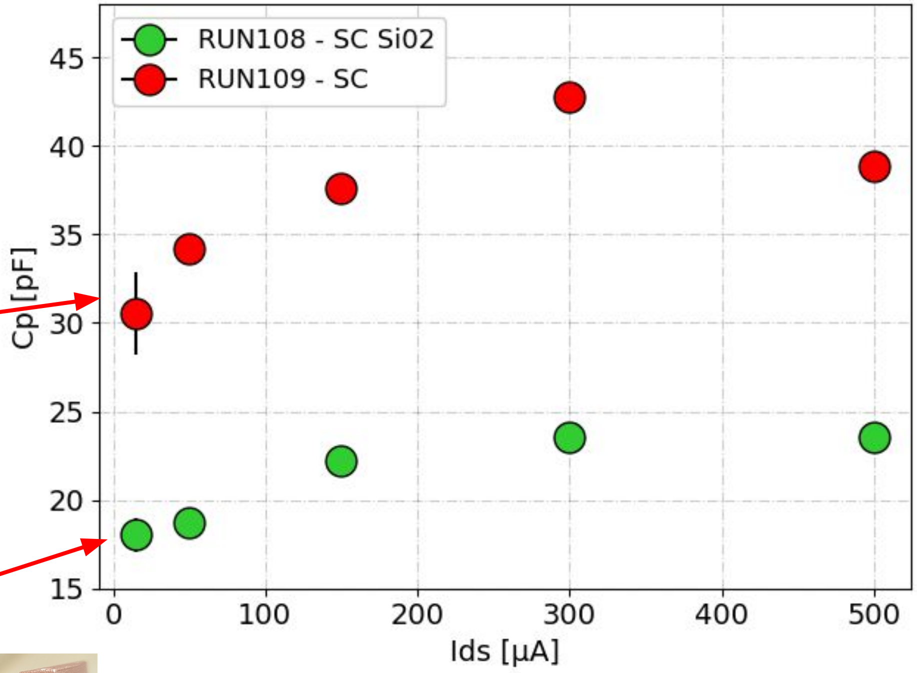
Main way to improve resolution !

Cp reduction using glass

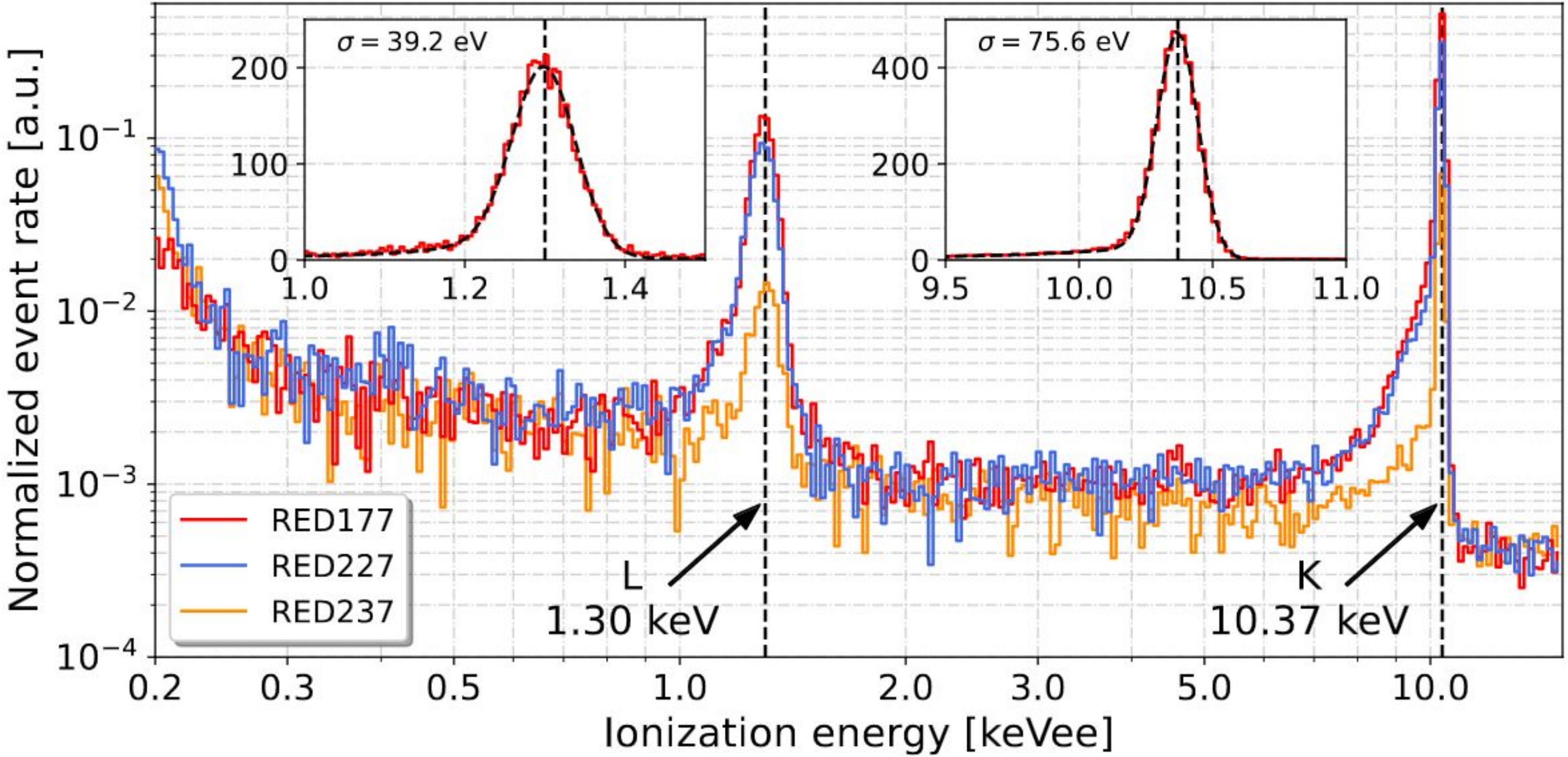








Experimental data with mini-CryoCube (Cp = 30 pF)



Take away message

1) Modelization allows for **components optimization**

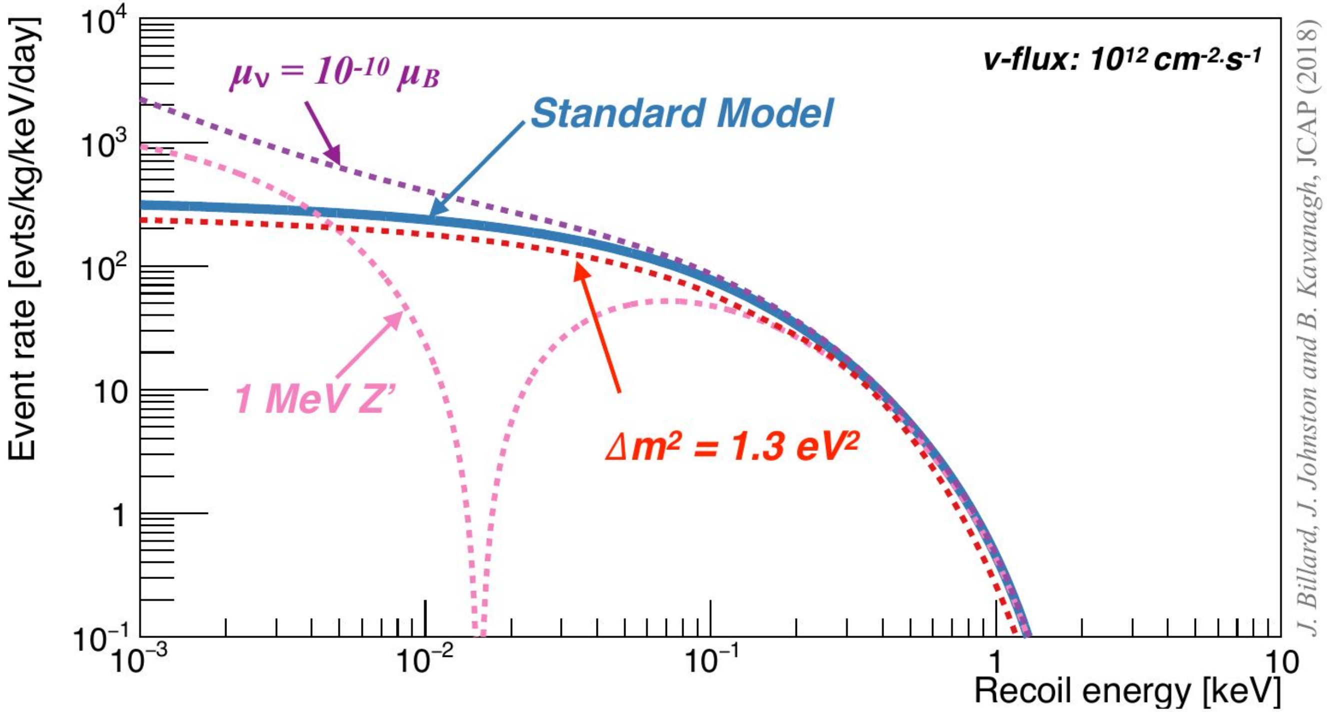
2) **20 eVee achievable** with PL38 and FID38 detector topology

3) This approach is **suitable for other detectors** : we only need the C^m matrix !

4) **R&D to reduce Cp still ongoing** (thermalization issues, …)

5) **~30 eVee RMS resolution achieved** already using common source !

Using CEνNS as a probe for new physics searches



CEvNS is a great probe of the standard model of particle physics in the electroweak region
Needs low energy neutrinos to increase new physics detection significance
Complementary to the Coherent science program

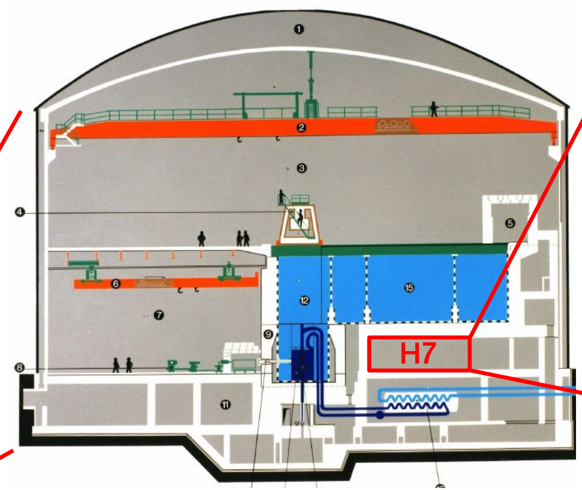
C. Augier & al: 2208.01760

RICOCHET at ILL research reactor

The H7 site

- Power: 58 MW
- Baseline: 8.8 m
- Flux: 10^{12} cm^{-2}.s^{-1}
- E^{ν}_{mean}: ~3 MeV
- ~13 CEnNS evt/kg/day
- ~15 m.w.e

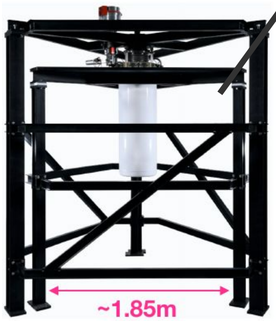
Elevation view of reactor building



Environment

- Magnetic fields
- Vibrations
- Reactogenic backgrounds
- On/Off modulation

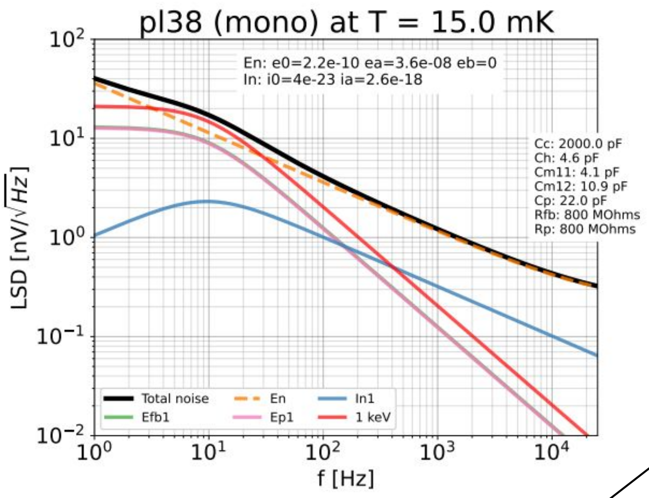
Repurposing of STEREO casemate



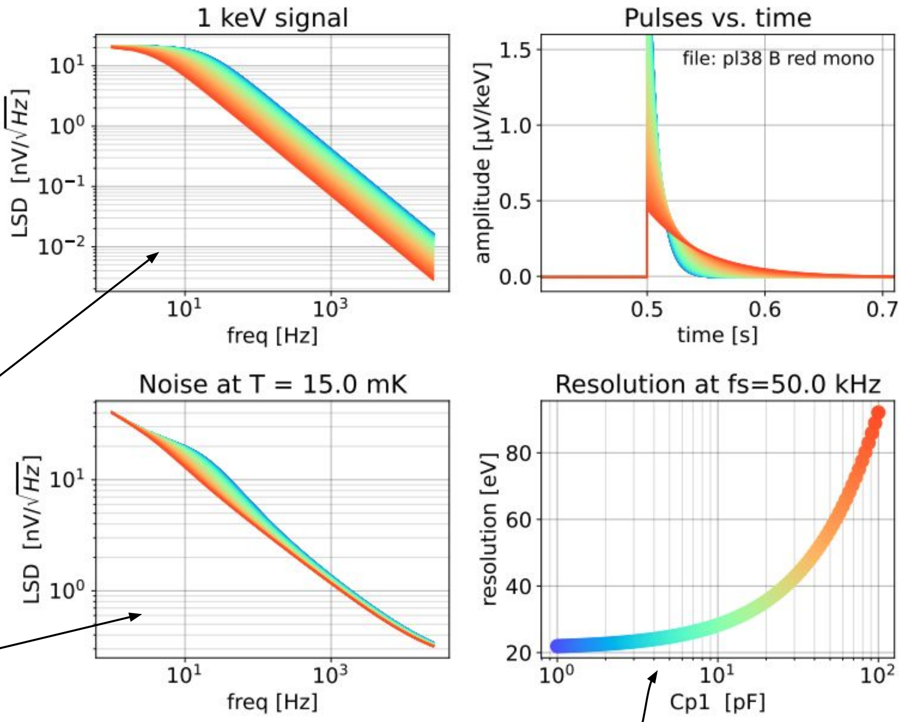
Cryostat

- CryoConcept HEXA-DRY 200
- Ultra quiet
- Low radioactivity

Get all separate contributions



Vary parameters



Compute resolution

$$\sigma_a = \sqrt{\left[\int_{-\infty}^{\infty} \frac{S(f)}{J(f)} df\right]^{-1}}$$