ASIC based readout electronics for high-purity Germanium detectors in LEGEND 1000

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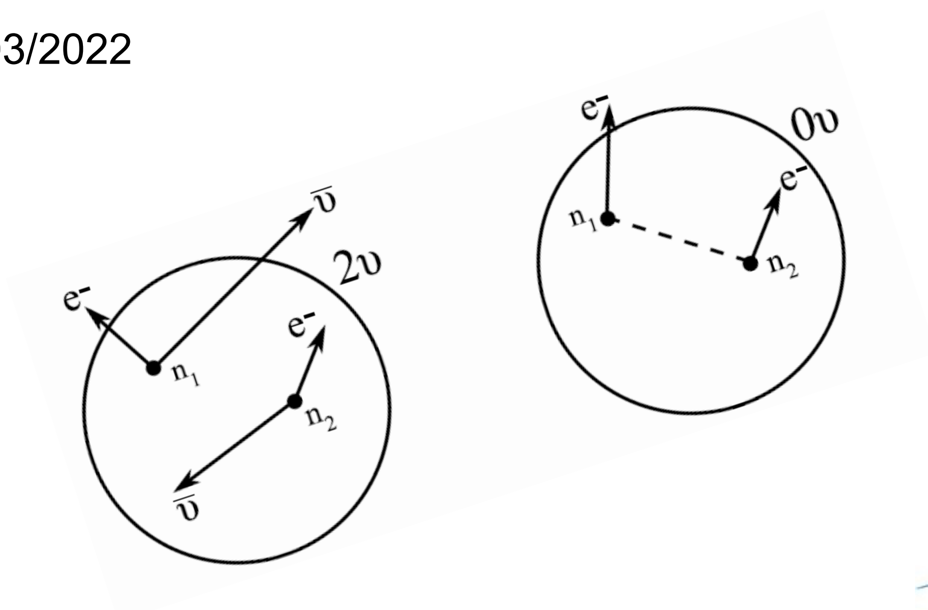
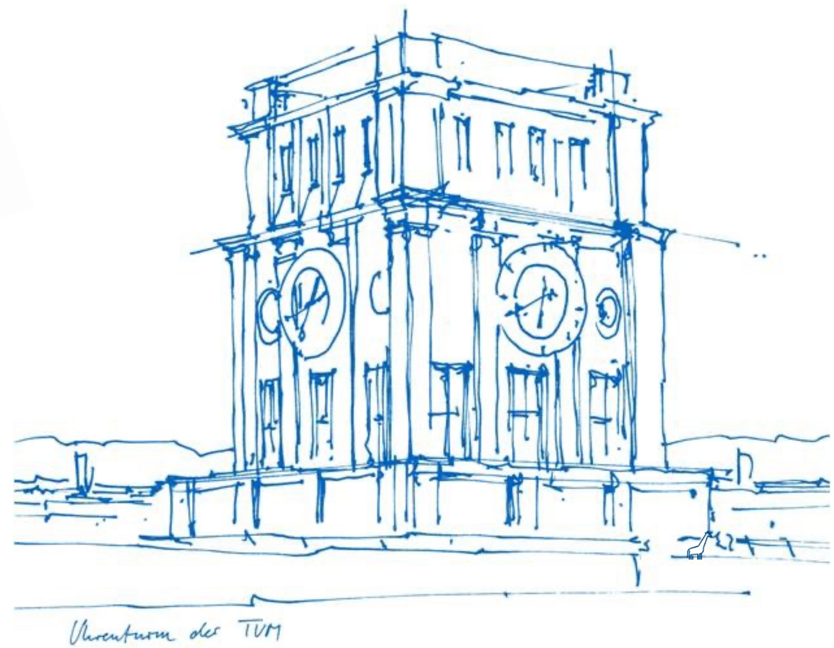
24/03/2022





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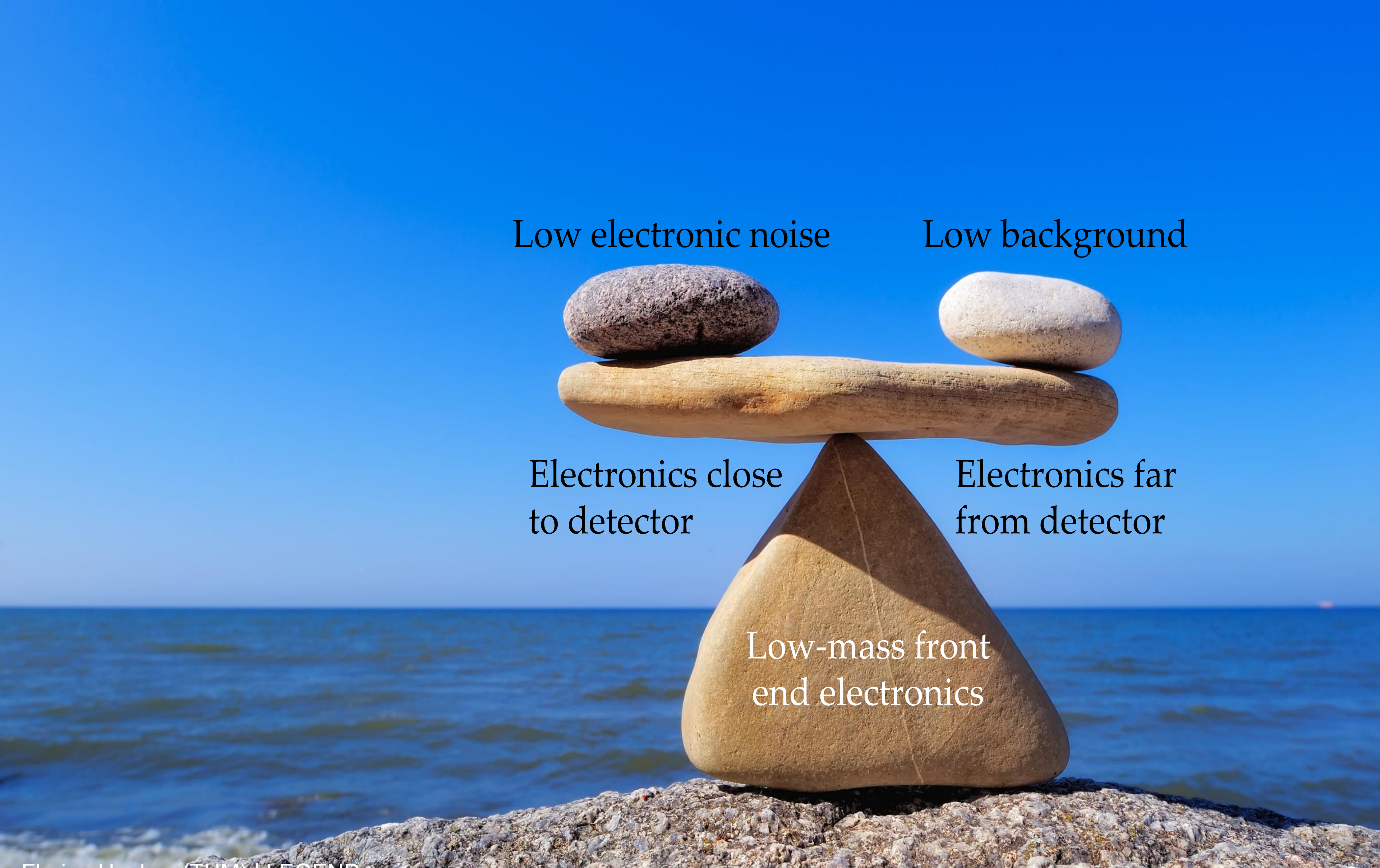
Motivation – Readout Electronics for $0\nu\beta\beta$ Experiments

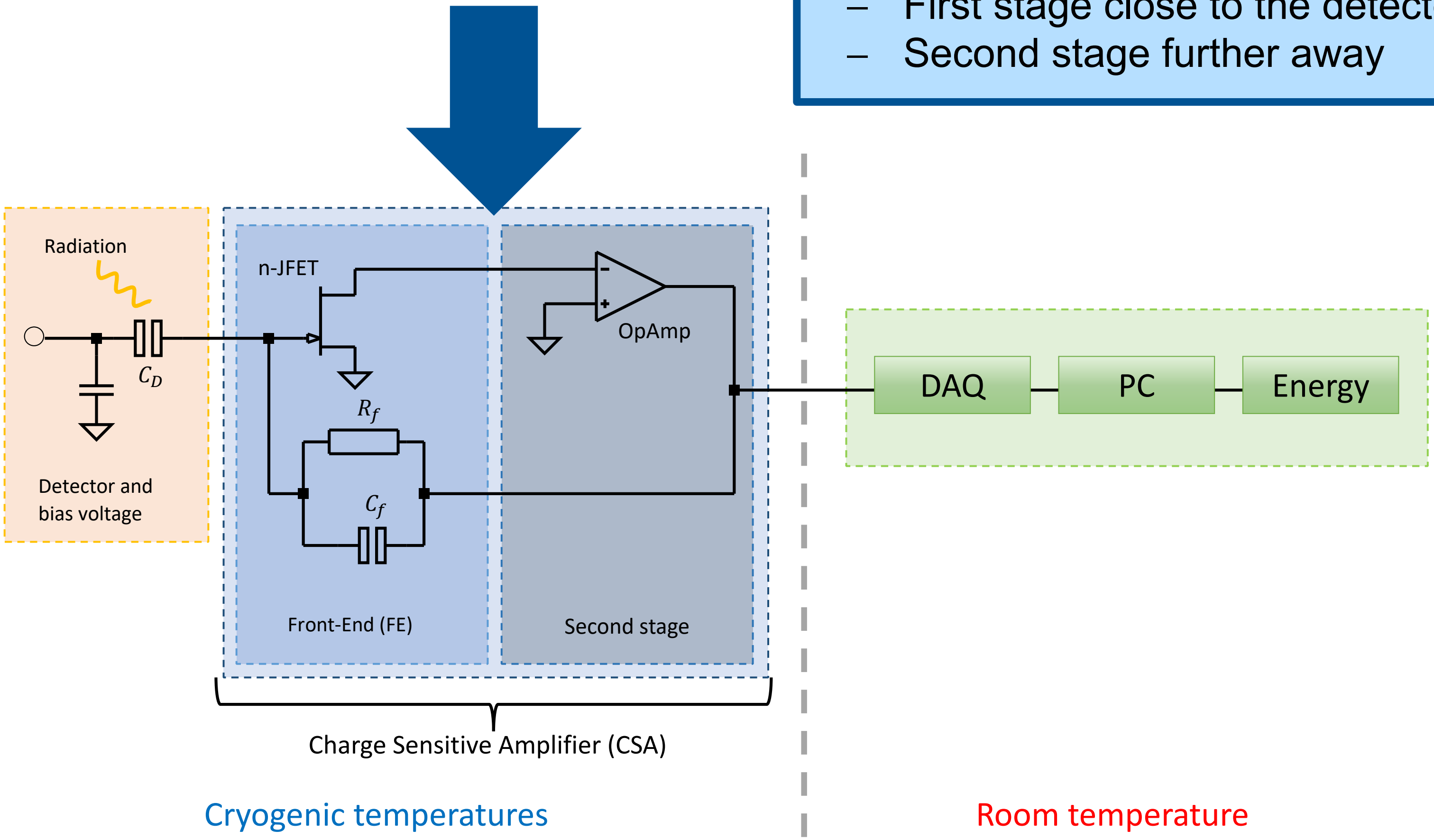


Signal readout in HPGe detectors

Readout chain

- HPGe detector with HV reverse bias voltage
- p^+ contact connected to Charge Sensitive Amplifier (CSA), typically:
  - First stage close to the detector
  - Second stage further away

LEGEND-200



Charge Sensitive Amplifier – LEGEND-1000

LEGEND-1000 Electronics

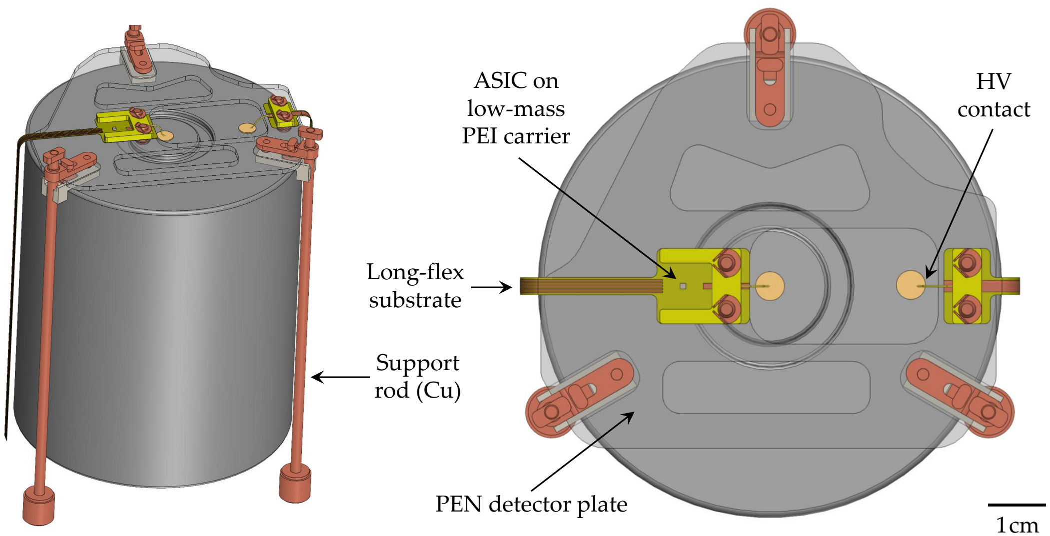
Application-**S**pecific **I**ntegrated **C**ircuit (ASIC) technology

- Combine all CSA components into low-mass chip ➡ ASIC technology
- Enables excellent noise performance

CSA Requirements for LEGEND-1000

- Very low electronic noise
- Large dynamic range (up to 10 MeV) and high linearity
- Important constraint radiopurity (ASIC + everything supporting the chip!)
- Continuous (exponential) reset, decay time $\gtrsim \mathcal{O}(100\mu s)$
- Fast rise times: $\mathcal{O}$(10 ns), bandwidth 50MHz

Cryogenic temperatures

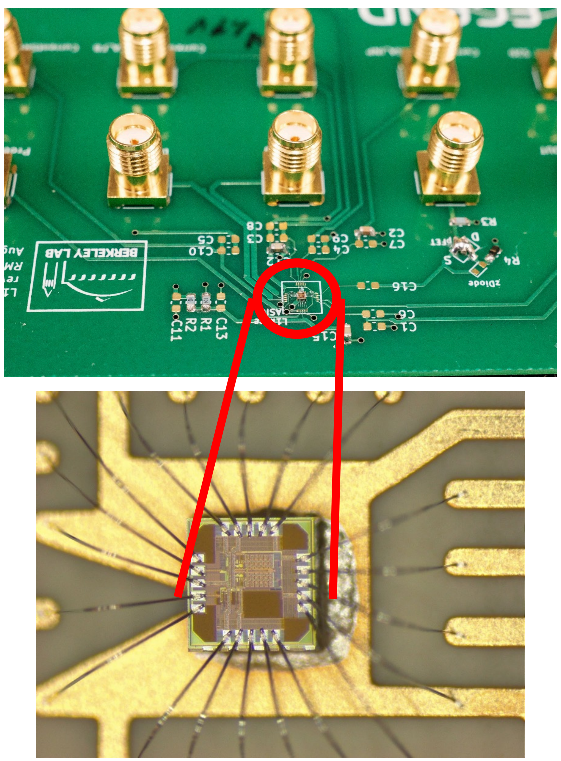


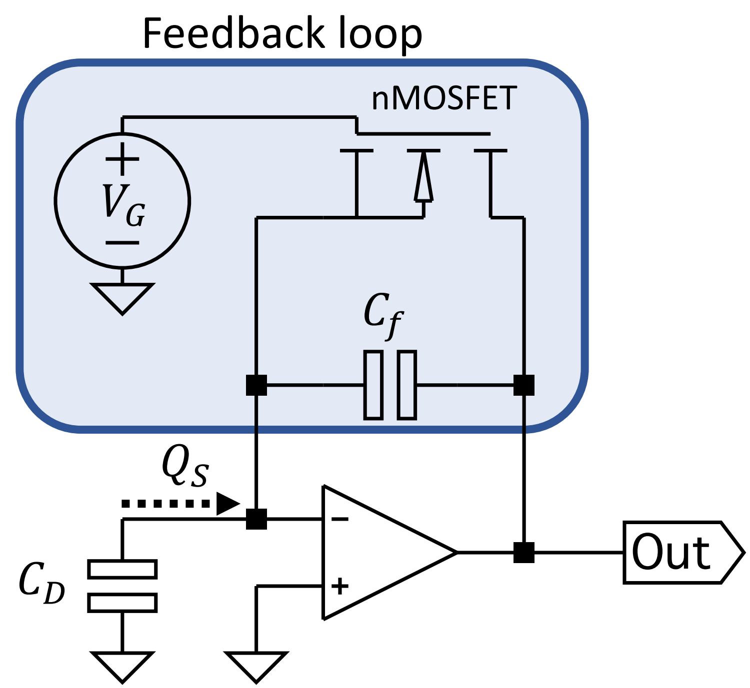
The L1k Berkeley ASIC (LBNL ASIC)

L1k preliminary ASIC

ASIC built by Berkeley lab in 2020 and tested @ TUM

- Internal, continuous reset with semiconductor technology
- Differential output
- Detector load: $\sim 1 - 5$ pF
- $C_F = 500 f$F
- Feedback loop: effectively a capacitor and a transistor (*n-MOSFET*) in parallel





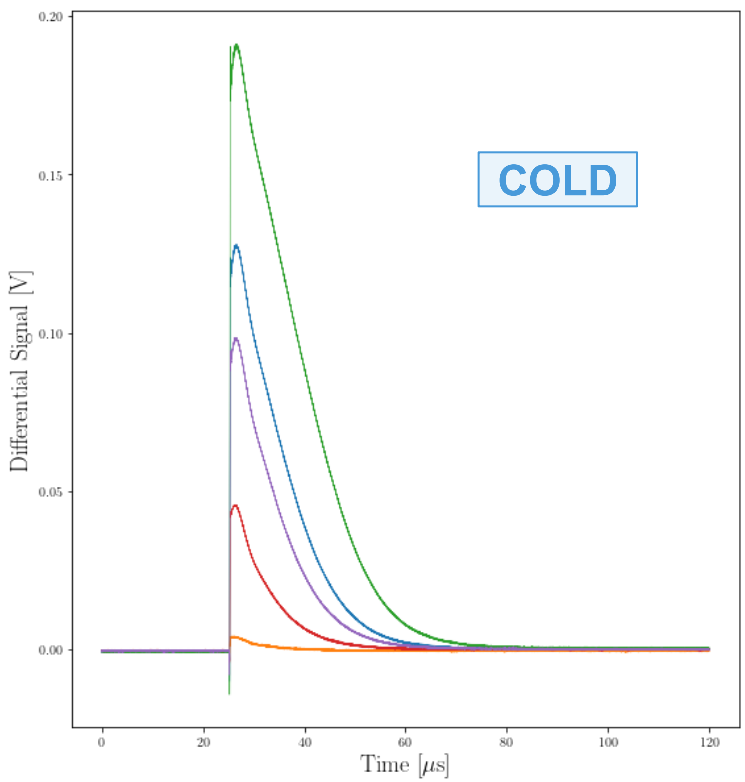
The L1k Berkeley ASIC (LBNL ASIC)

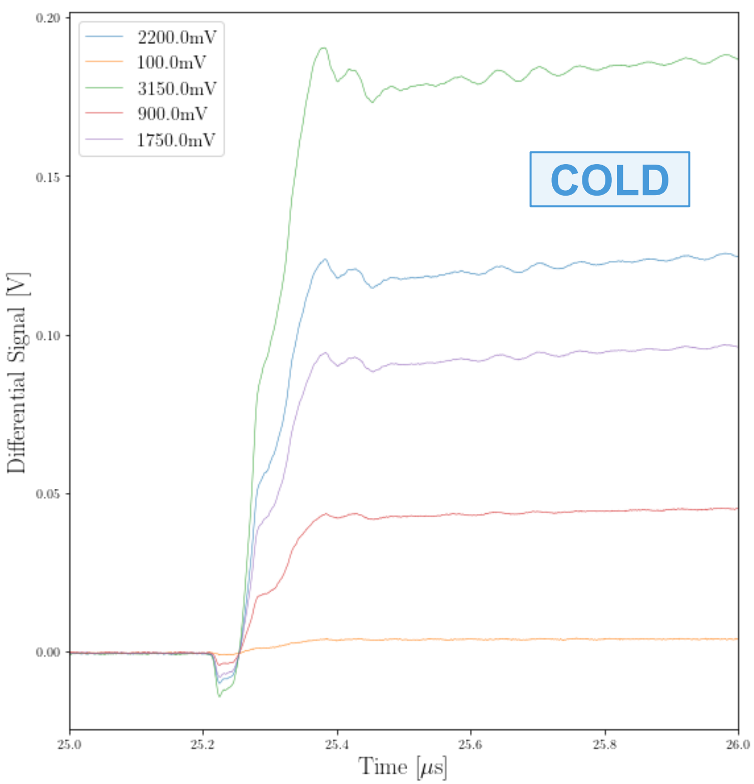
L1k preliminary ASIC

- Two different regions in the decay tail
  - "Linear" region in the beginning of the tail
  - "Exponential" region in the end of the tail

- Good linearity
- Cold and warm almost similar

➡ Under- and overshoot in the rise unclear

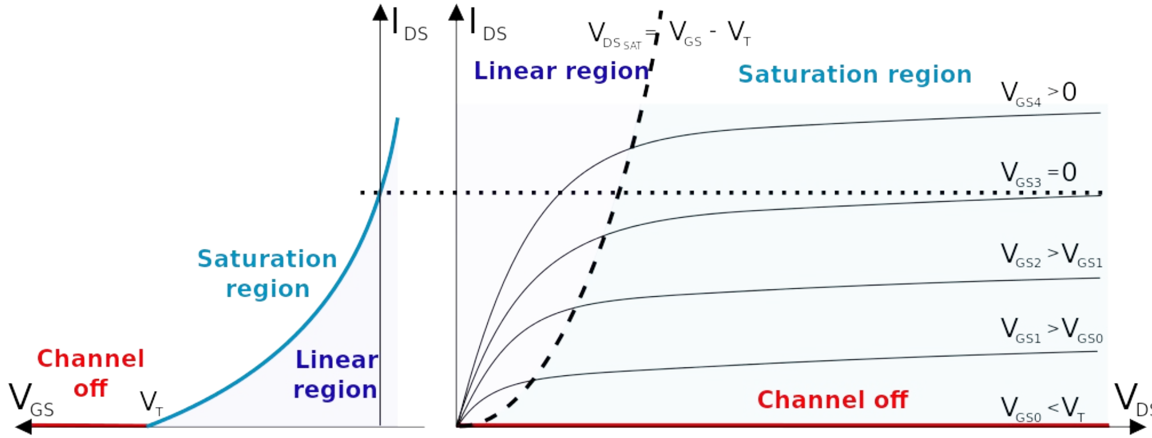


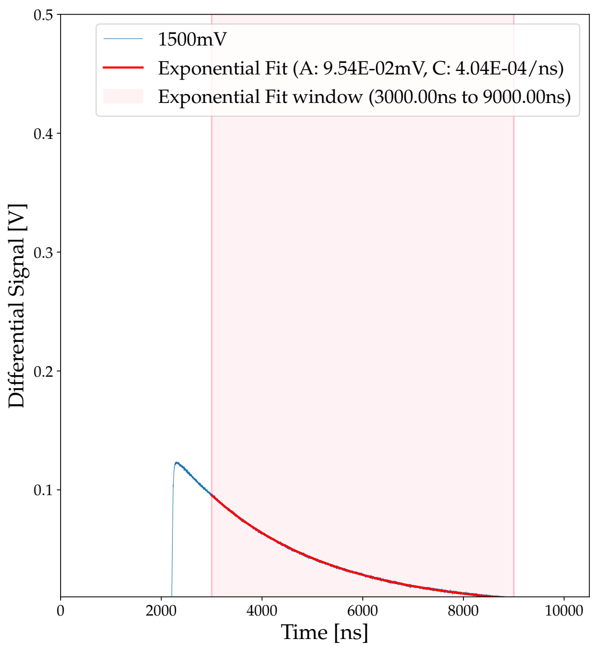


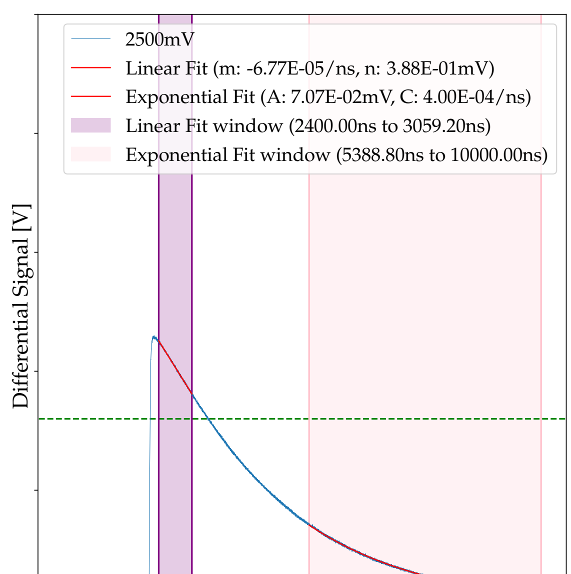
The L1k Berkeley ASIC (LBNL ASIC)

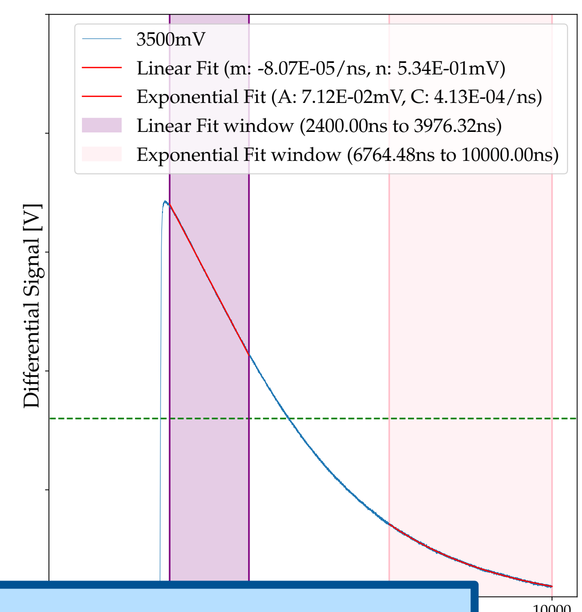
"Saturated region" ($V_{DS} > V_{sat}$)

- $i_D \approx \text{const}$
  $\Rightarrow$ "$R_{equiv.}$" $\approx k \cdot V_{DS}$
- $h(t) \approx m \cdot t + n$









Problems:

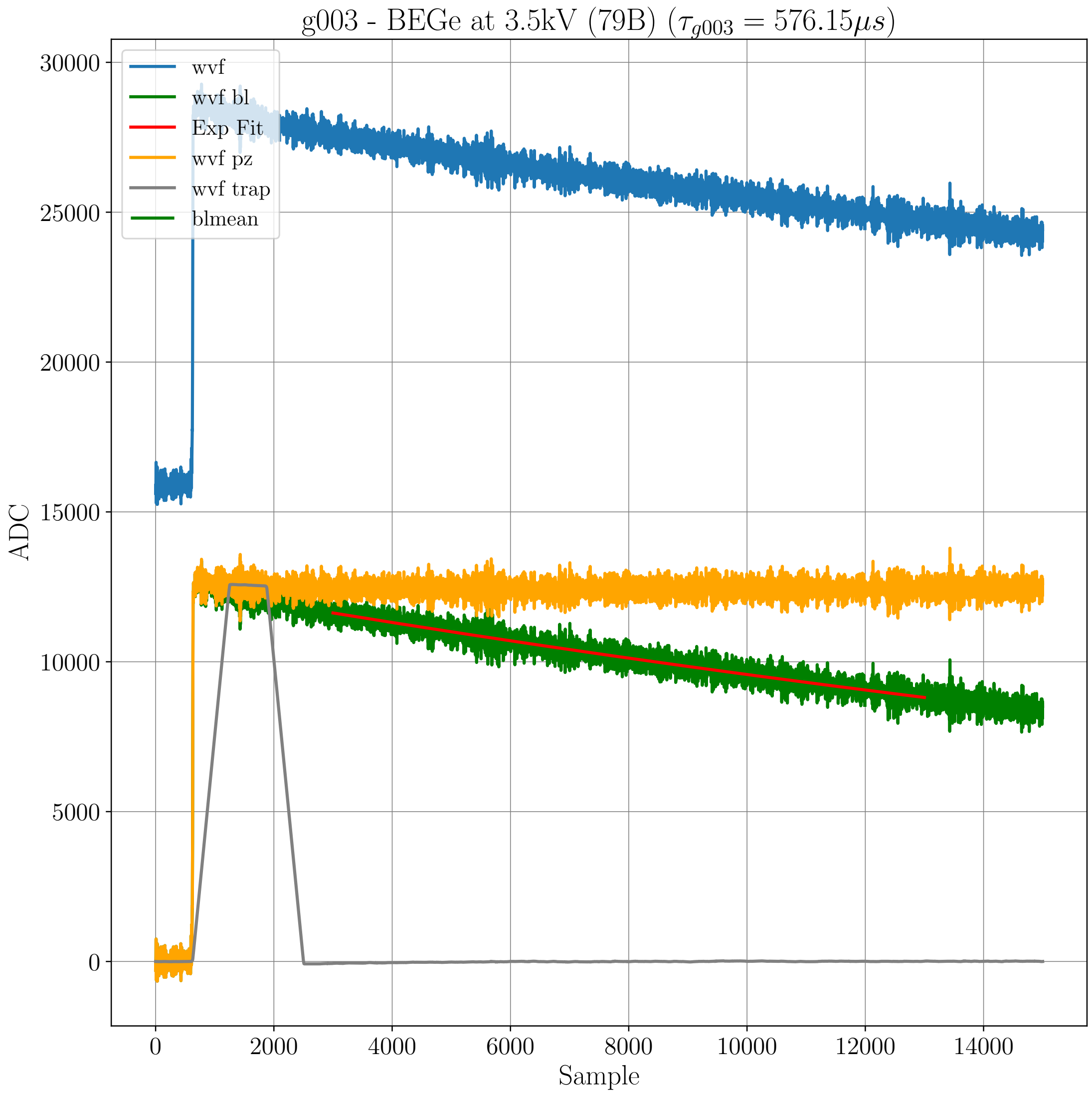
- Regions in the *beginning*, *between* and *end* of the tail?
- Pulse shape is energy dependent (!)

LEGEND Signal Processing

LEGEND DSP

Most important steps for raw data

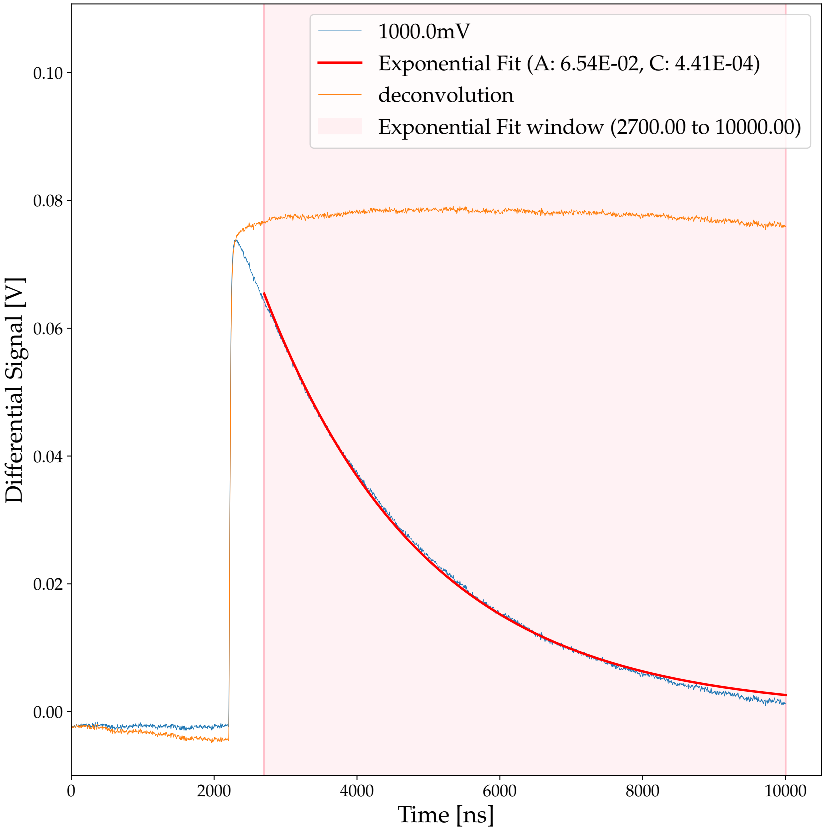
- Baseline subtraction
- Exponential fit
- Deconvolution
- Trapezoidal filtering

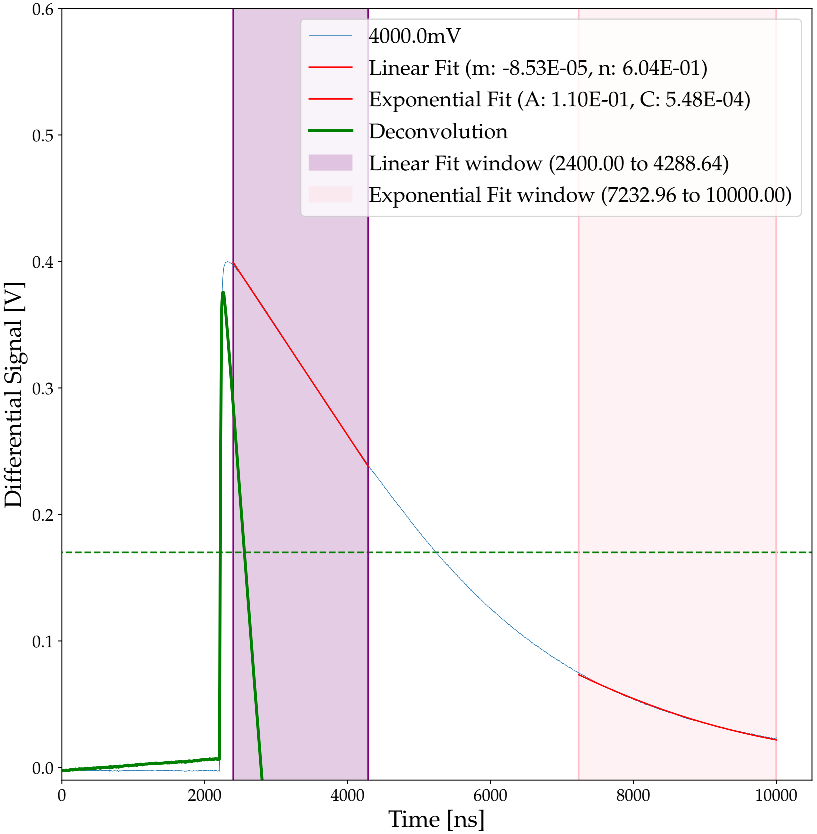


The L1k Berkeley ASIC (LBNL ASIC)

L1k preliminary ASIC – Deconvolution

- No full analytical $h(t)$ for the MOSFET feedback of the ASIC
  - ➡ every energy ⇒ different shape
  - ➡ higher rates: circuit not fully discharged ⇒ different shape
  - ➡ For pulses only in the "linear" region ⇒ model also not precise enough





The L1k Berkeley ASIC (LBNL ASIC)

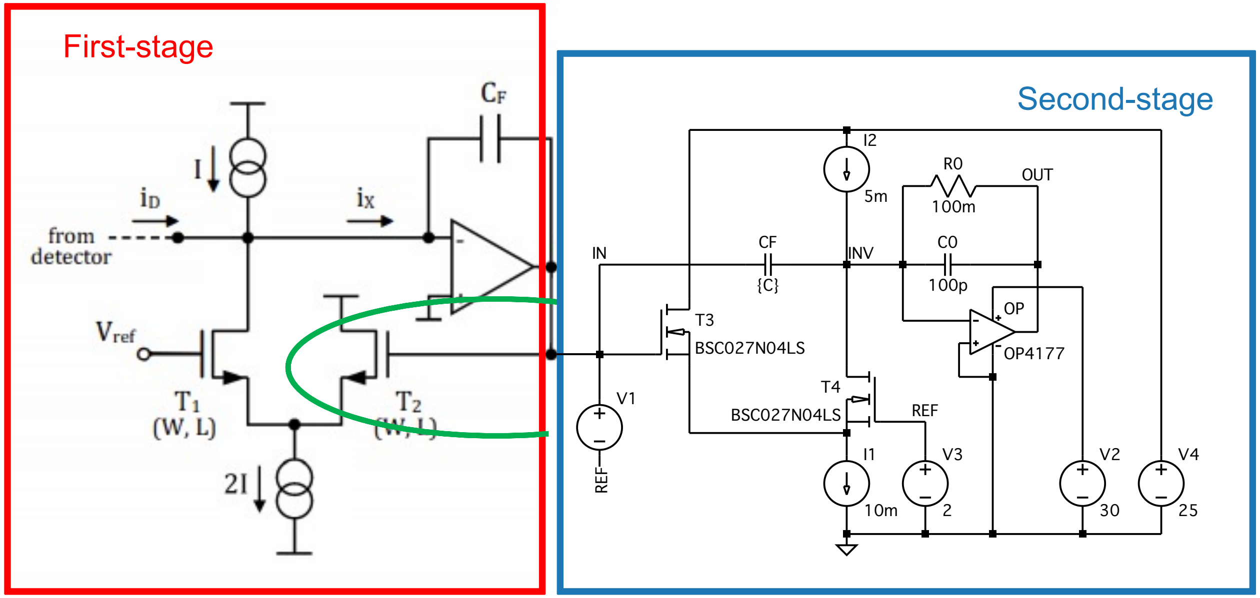
L1k preliminary ASIC – What can be done?

- Current ASIC setup **NOT** suitable for DSP
- One possible approach:

Second stage circuit according to Pullia et.al. Paper (DOI: 10.1109/NSSMIC.2012.6551066)

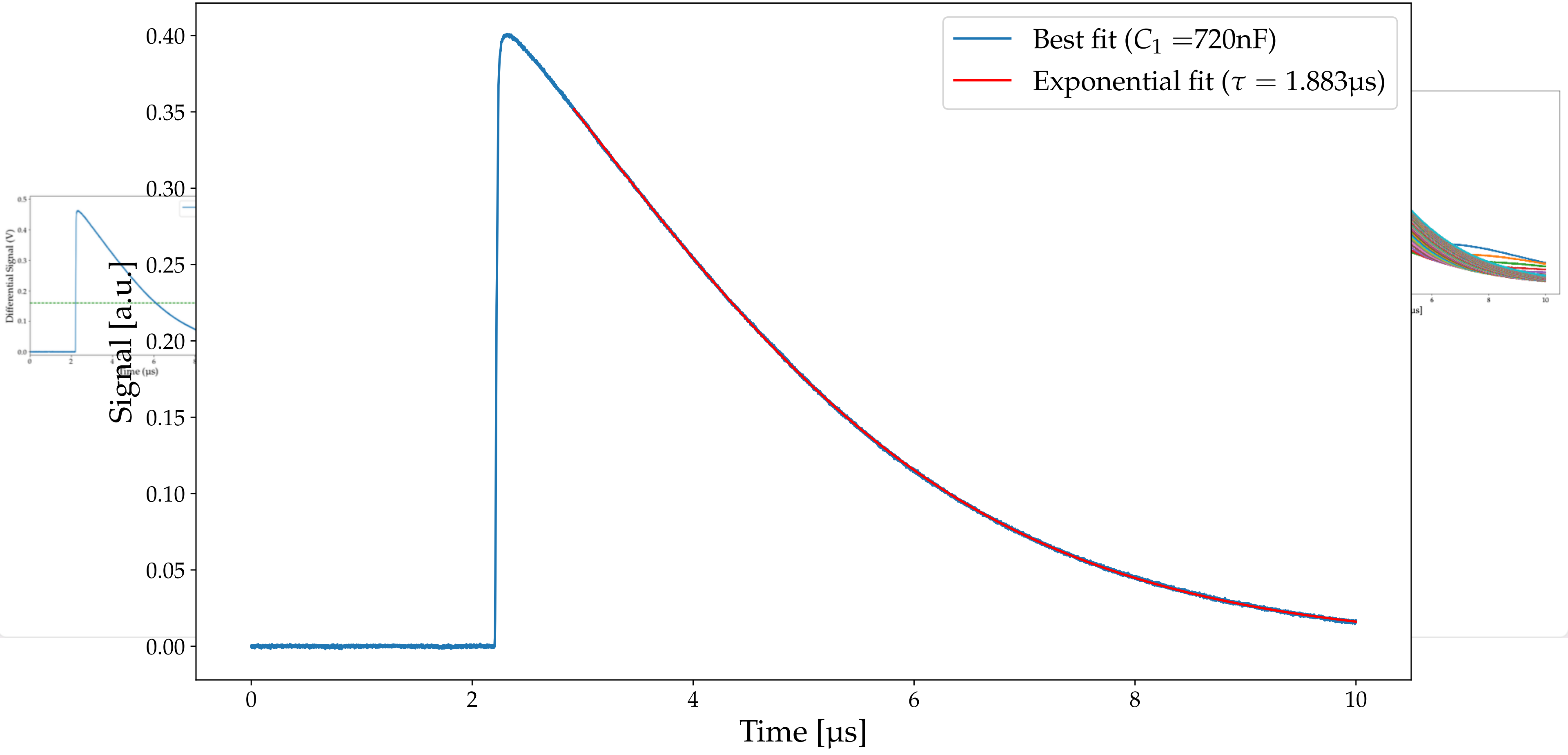
– On-chip second-stage circuits to cancel ”non-linear behavior” by coupling a second MOSFET to the first stage circuit

– Tested with LTSpice simulation for second-stage circuit and real data for the first stage circuit



The L1k Berkeley ASIC (LBNL ASIC)

L1k preliminary ASIC – Second stage circuit

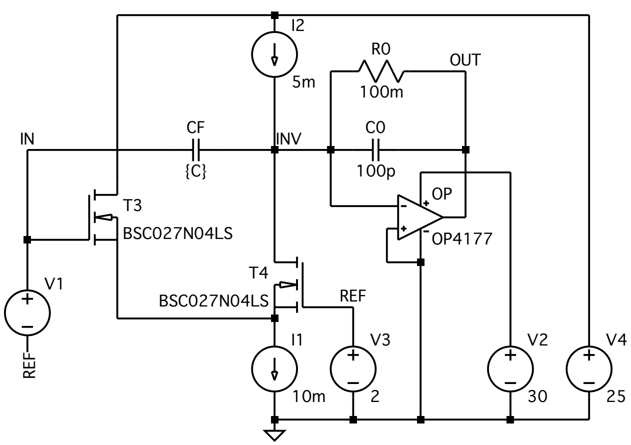


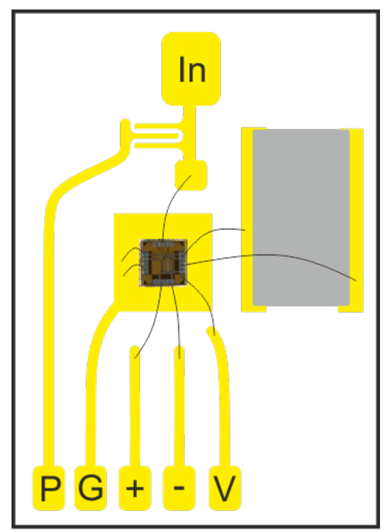
Summary and Outlook

L1k ASIC - Outlook

- What comes next?
  - Collaboration with *LBNL*
  - Collaboration with *Politecnico di Milano* (Prof. Carlo Fiorini) → **TUM ASIC**
    - New design with second-stage circuit approach or/and
    - New design with external aGe resistor

➡ Most important: Evaluation of physics performance in LAr with ICPC





SFB 1258 | Neutrinos Dark Matter Messengers

Thanks for the attention!

BACKUP

L1k ASIC – Summary Table

	XGLab	LBNL	Future TUM ASIC
External components	Too many	Only one supply voltage (but filter capacitor needed!)	Low drop-out regulator Clean external capacitors
Reset mode	Pulsed reset	Continuous reset (but non-uniform waveforms)	• Second stage • Int. high-ohm feedback • External resistor
Suitable for long cables	no	yes	yes
Detector capacitance	Only up to 3 pF	Up to 5 pF	Up to 10 pF

Charge Sensitive Amplifier – LEGEND-1000

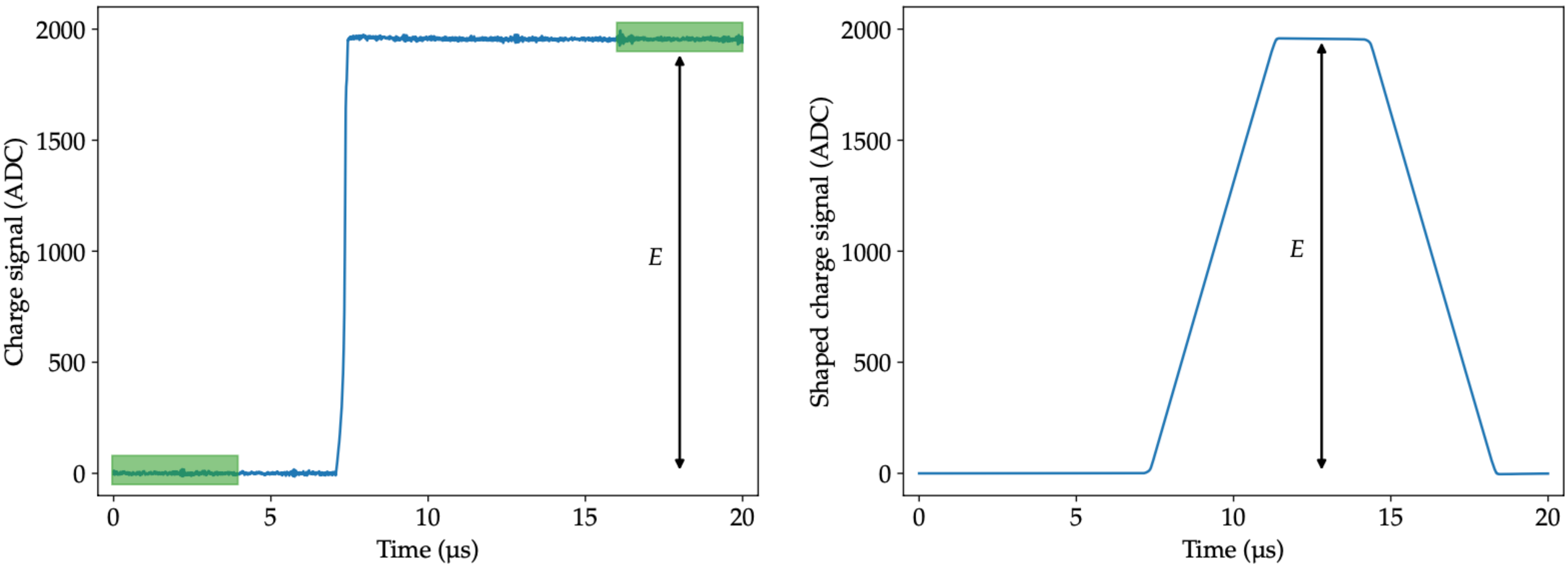
CSA Requirements for LEGEND

- Very low electronic noise: < 1 keV FWHM pulser $\approx 10e^-$ RMS
- Large dynamic range (up to 10 MeV) and high linearity
- Primary constraint ➡ radiopurity (ASIC + everything supporting the chip!)
  - Small volume ($\lesssim 0.4$mm^3), bare die, wire-bondable
  - No external components: single power supply, no (close) bypass capacitors, on-chip LDO
  - Ideally no external feedback components
- Continuous (exponential) reset, decay time $\geqslant \mathcal{O}(100\mu s)$
- Fast rise times: $\mathcal{O}$(10 ns), bandwidth 50MHz
- Suited for detector capacitances in range $\sim 1 - 10$ pF
- Operational in liquid argon at 87 K
- Low power consumption (avoid bubbling of cryostatic liquid)
- Driving differential signal over distance of ~ 10 m
- Robustness to electrostatic discharges (ESD protection *VS* noise)

DSP for LEGEND

Digital Signal Processing – Why we need certain decay shape?

- DSP for LEGEND:
  - Baseline correction
  - Waveform smoothing
  - Pole-Zero correction
  - Signal shaping (trapezoidal)
  - Energy reconstruction
  - Further analysis:
    - Pulse-Shape Analysis, Drift-Time correction etc.



(a) Charge signal.

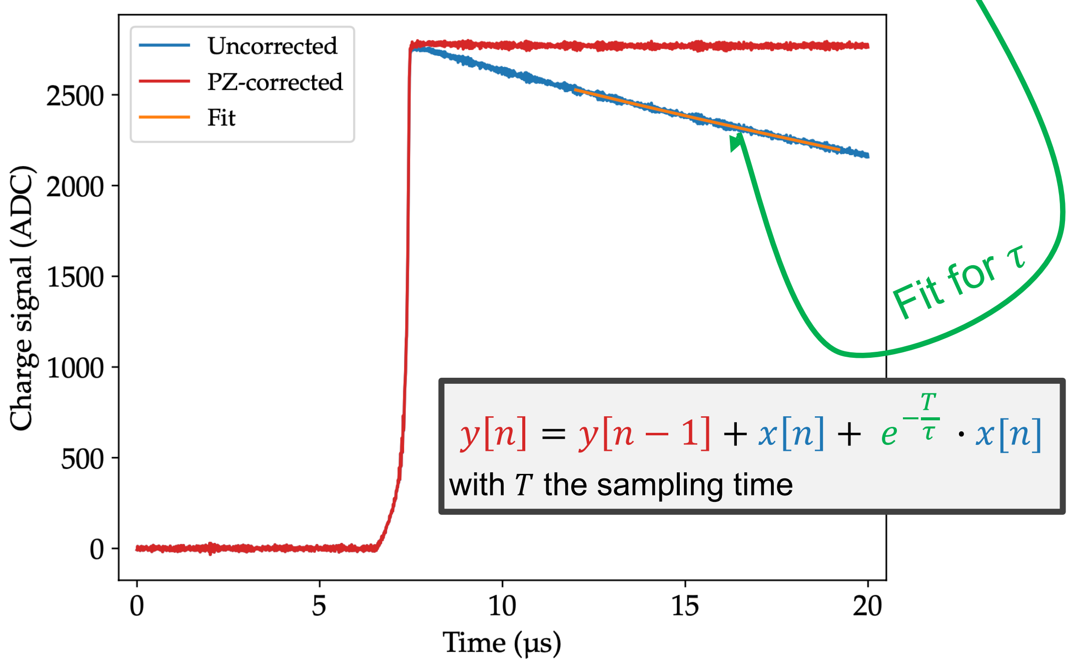
(b) Shaped charge signal (trapezoid).

Deconvolution

Digital Signal Processing – Deconvolution

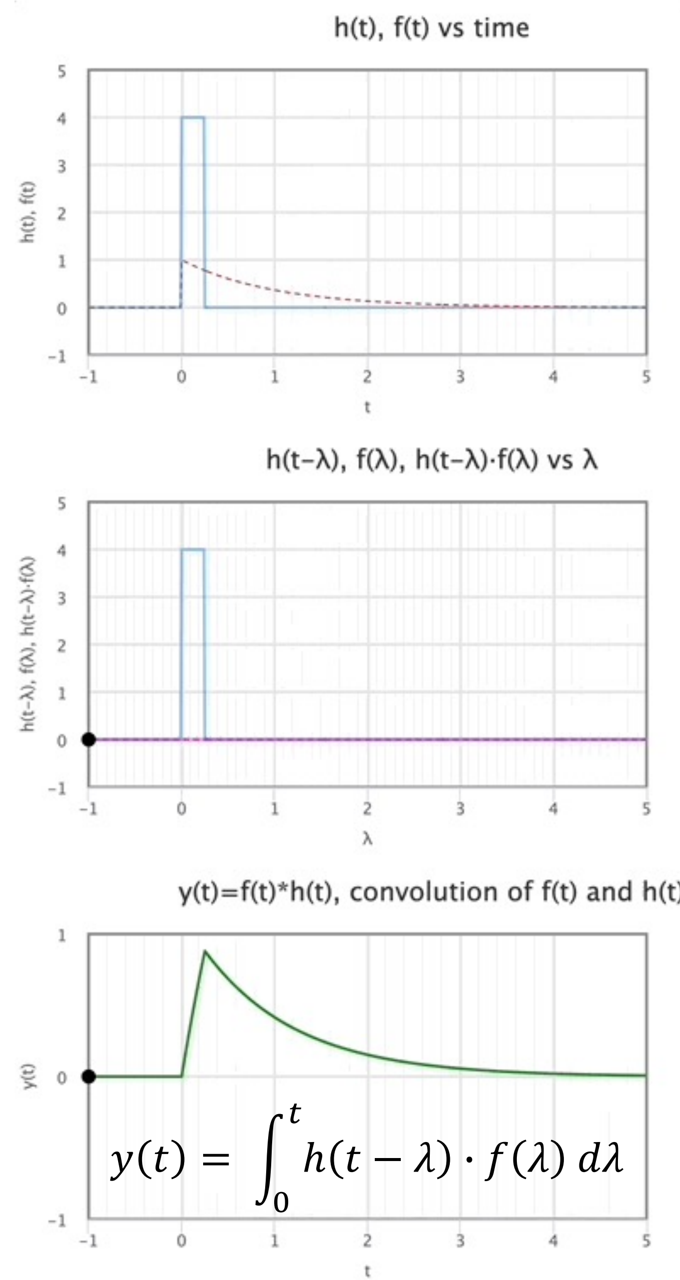
Convolution
Every waveform = convolution of the charge input signal coming from the detector with the response function of the RC-feedback (*and gained according to the CSA properties).*

Deconvolution
Infinite-Impulse-Response Filter (IIR) which corresponds to the inverse transfer function of the CSA while only require the decay time $\tau = RC$



$$y[n] = y[n-1] + x[n] + e^{-\frac{T}{\tau}} \cdot x[n]$$

with T the sampling time



$$y(t) = \int_0^t h(t-\lambda) \cdot f(\lambda)\, d\lambda$$

Charge Sensitive Amplifier (CSA)

Simple CSA

Consists of:

- Feedback capacity combined with Operational Amplifier ("Integrator")
- Input voltage: $V_{in} = \frac{Q_s}{C_{det}+C_i}$

1. Output voltage of amplifier: $v_o = -Av_i$
2. „Node rule

$$v_i = v_f + v_O$$

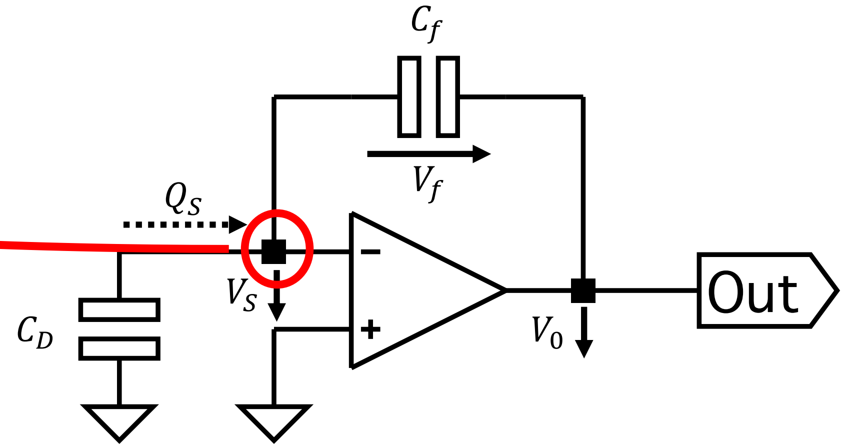
$$\Longrightarrow v_f = (A+1) \cdot v_i$$

3. "Ideal no current in OpAmp":

$$Q_i(= Q_f) = C_f v_f = C_f(A+1) \cdot v_i$$

$$\Longrightarrow v_o = \frac{-A}{C_f \cdot (A+1)} Q_i$$

$$\Longrightarrow v_o \approx \frac{Q_i}{C_f}$$



Charge Sensitive Amplifier (CSA)

What is the problem?

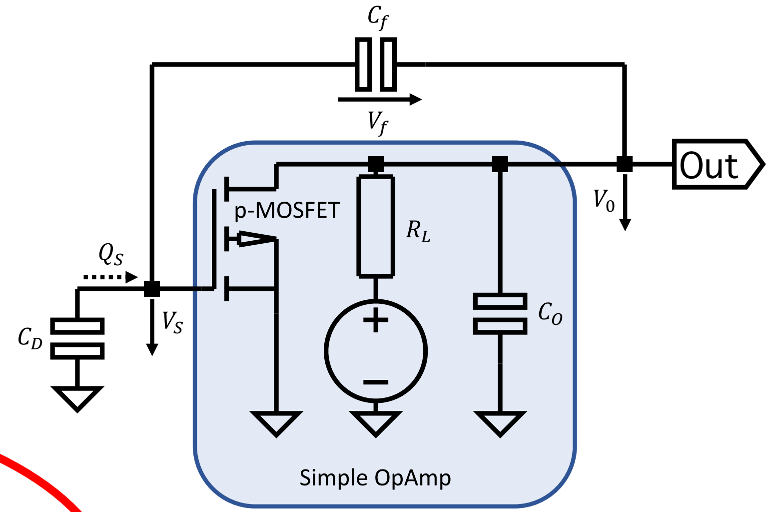
Realistic CSAs are frequency dependent:

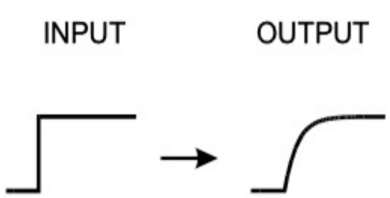
- $A_\omega = g_m \left(\frac{1}{R_L} + i\omega C_0\right)^{-1}$
  A_ω: gain
  g_m: transconductance
  R_L: series resistance
  C_0: parallel capacity

➢ For low frequencies: gain constant
➢ For high frequencies: drops off linearly
First need to “load the capacitance”

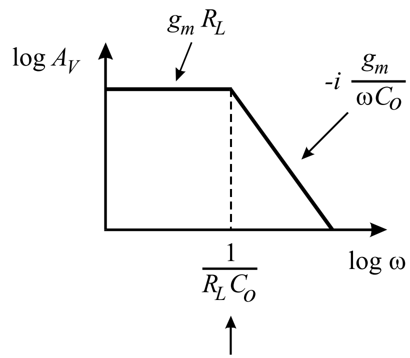
- A JFET before the OpAmp cancels this out
  - At high frequencies:

➡ JFET helds voltage ”constant” while following the current coming from the detector
➡ Acts as a “current source” for OpAmp
➡ Lowest shot noise of all available components





OUTPUT: $V = V_o(1 - e^{-t/\tau})$



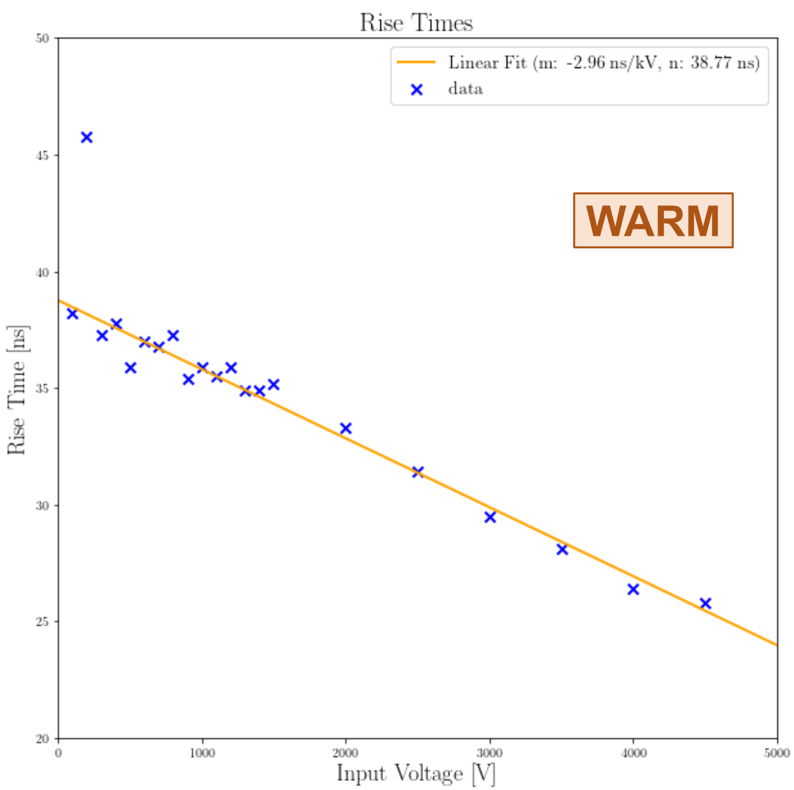
$$\left(\frac{S}{N}\right)^2 = \left(\frac{S}{N_1}\right)^2 \frac{1}{1 + (\frac{N_2}{A_1 N_1})^2}$$

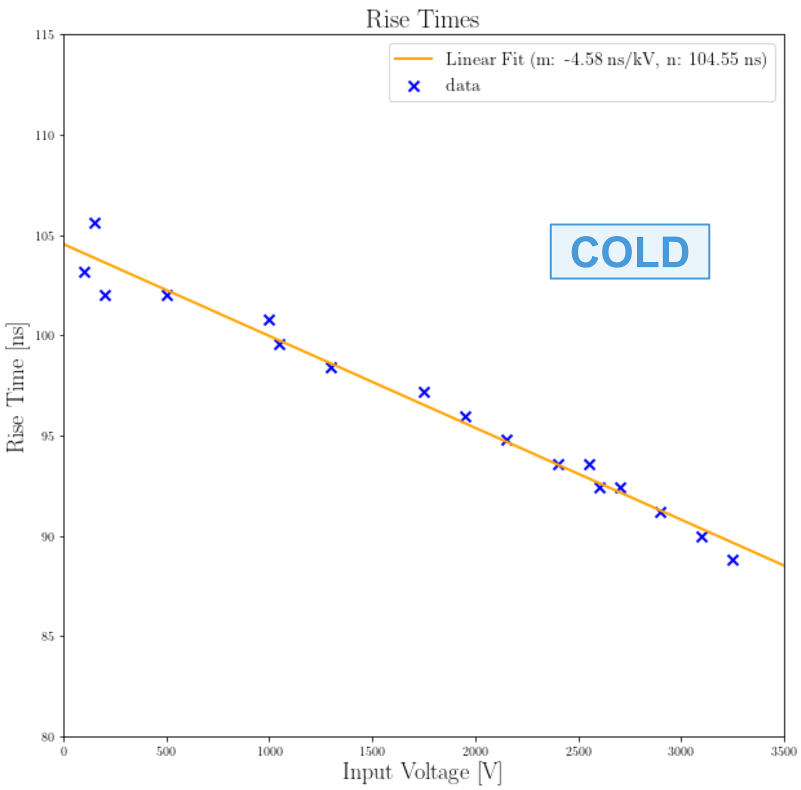
$$\mathrm{ENC}^2 = \underbrace{\alpha \frac{1}{\tau_s} \frac{2k_B T}{g_m} C_{tot}^2}_{\text{series: } \mathrm{ENC}_p^2} + \underbrace{\beta A_f C_{tot}^2}_{1/\text{f: } \mathrm{ENC}_s^2} + \underbrace{\gamma \left(e I_{tot} + \frac{k_B T}{R_F}\right) \tau_s}_{\text{parallel: } \mathrm{ENC}_{1/f}^2}$$

The L1k Berkeley ASIC (LBNL ASIC)

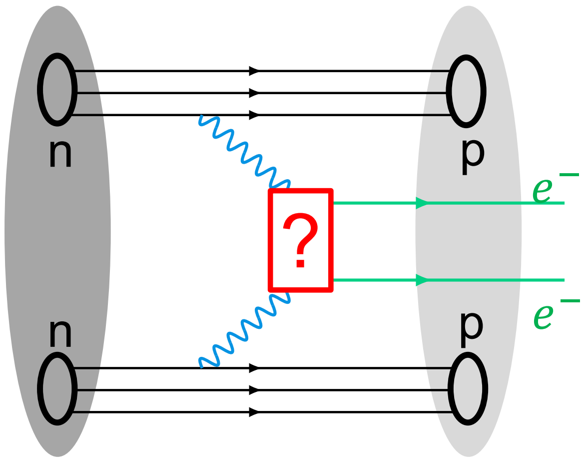
L1k preliminary ASIC – Rise Times

- Rise Times (10%-90%) in the desired range (< 100ns) for the warm and the cold setup
- Rise Time depends linear on the input voltage (~ energy)





Neutrinloess double beta ($0\nu\beta\beta$) decay



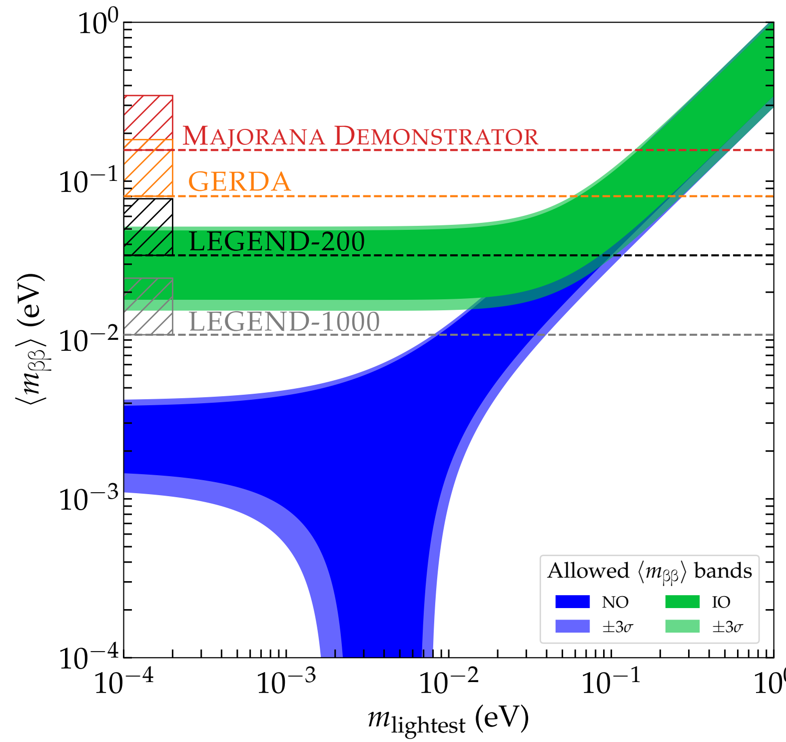
$$\langle m_{\beta\beta}\rangle \propto \frac{1}{g_A^2\,|M^{0\nu}|}\sqrt{\frac{1}{T_{1/2}^{0\nu}\,G^{0\nu}}}$$

$\langle m_{\beta\beta}\rangle$: Effective Majorana mass
$T_{1/2}^{0\nu}$: Decay half-life
$M^{0\nu}$: Nuclear matrix element
$G^{0\nu}$: Phase space factor

$$\langle m_{\beta\beta}\rangle = |\sum_i \mathcal{U}_{ij}^2 m_i|$$
$$= |\cos^2\theta_{12}\cos^2\theta_{13}\,m_1 + e^{2i\alpha}\,\sin^2\theta_{12}\,\cos^2\theta_{13}\,m_2 + e^{2i\beta}\,\sin^2\theta_{13}m_3|$$

Neutrinoless double-beta decay

Double beta decay <u>without</u> emission of two anti-neutrinos
→ Neutrinoless double beta decay (0vββ decay)



LEGEND Sensitivity

$$T_{1/2}^{0\nu}(3\sigma\,\mathrm{DS}) \propto \begin{cases} f_{\mathrm{enr}} \cdot \epsilon_{\mathrm{det}} \cdot \sqrt{\frac{M \cdot t}{BI \cdot \Delta E}} & \text{with background} \\ f_{\mathrm{enr}} \cdot \epsilon_{\mathrm{det}} \cdot M \cdot t & \text{background} - \text{free} \end{cases}$$