DANAE - a new experiment for direct dark matter detection with DEPFET silicon detector

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ÖAW

25 June 2018
DSU 2018
Annecy

DANAE (DANAË)
Direct dArk matter search using DEPFET with repetitive-Non-destructive-readout Application Experiment

OeAW funding for detector technology

“Danae” by G. Klimt

Collaboration

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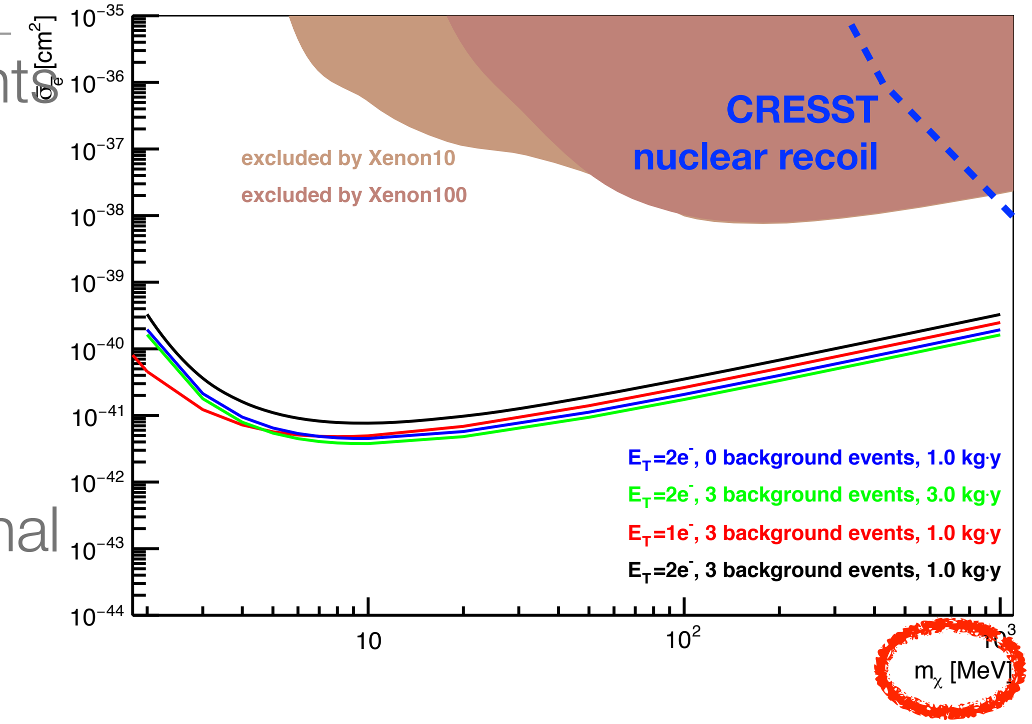
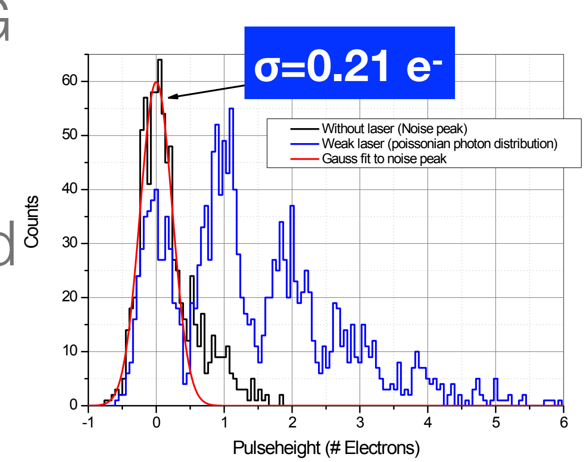
Atominstitut, Technische Universität Wien, Vienna, Austria [C]

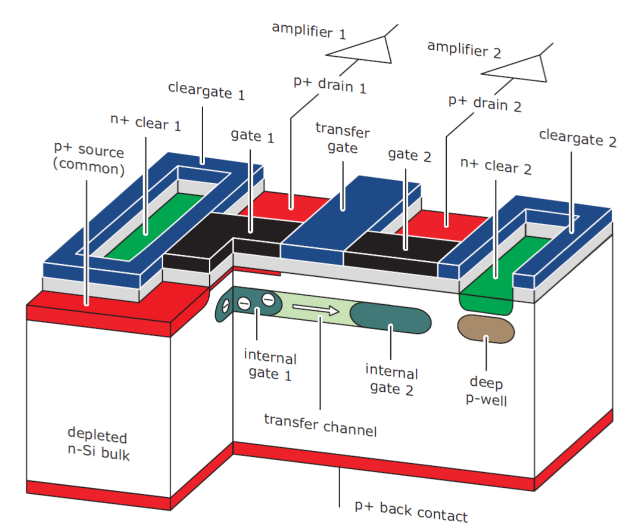
The project overview

Direct Dark Matter Detection with DEPFET

- minimal reach for nuclear recoil experiments about few 100 MeV
- dark matter electron scattering offers **reach towards MeV dark matter**
- measurement of **low noise** ionisation signal in **low background** environment
- RNDR* DEPFET sensors developed by semiconductor laboratory of MPG
- setup for **proof-of-principle measurement** currently prepared
- expect first results early 2019







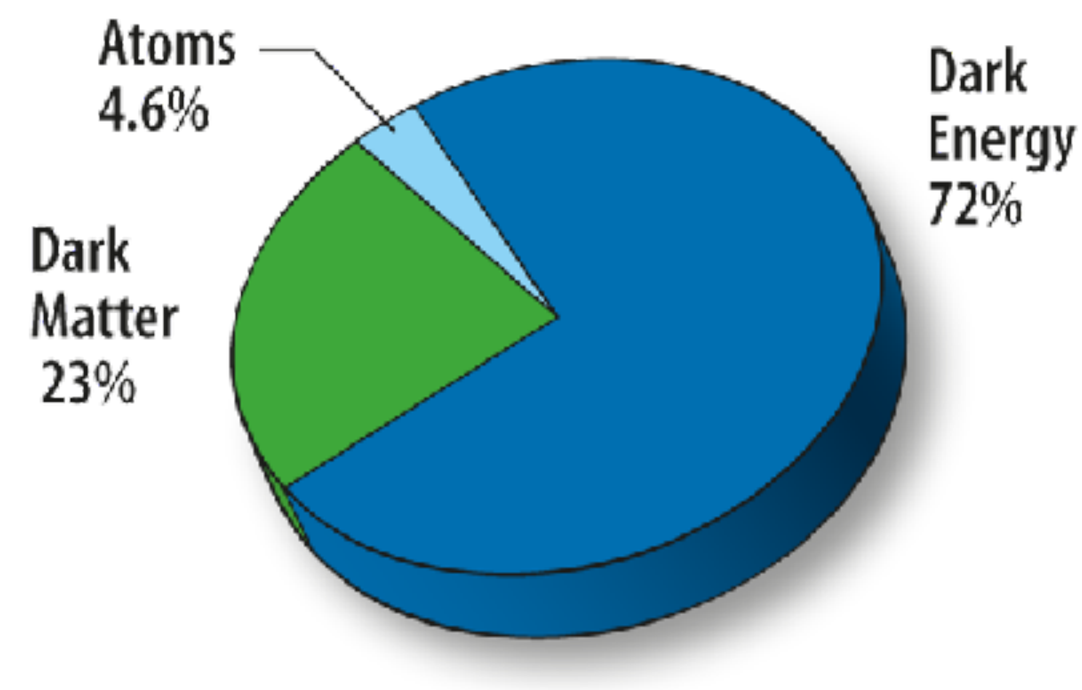
EPJ C, 77(12), 279 (2017)

*Repetitive Non-Destructive Readout

from Jochen Schieck "Experimental Dark Matter Search at HEPHY"

Dark matter landscape - partly

Over 80% of the mass in the universe is invisible dark matter

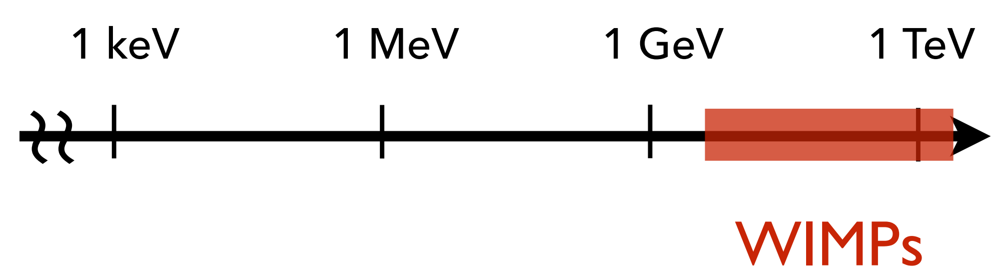


Credit: NASA / WMAP Science Team

"WIMP" as a dark matter candidate :

- weakly interacting with matter
  $<\sigma_{WIMP} \cdot v> \sim G_F^2 \cdot m_X^2 \sim 1/\Omega_X$
- fits the Hubble constant and "relic" density of dark matter

predicts dark matter WIMP mass between 2 GeV and 120 TeV



dominated the direct detection experiments until recently

WIMP direct detection method

look for nuclear recoils from WIMP-nucleus scattering

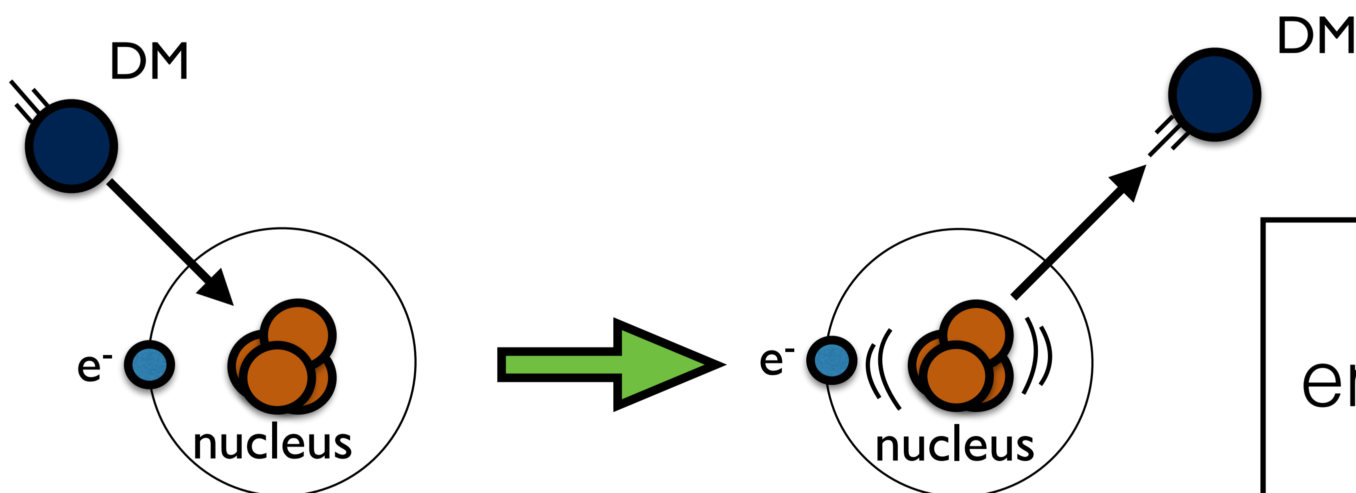


image credit R. Essig

Energy deposit in target material in forms of :
- light
- phonon
- electric charge

<u>Detection limitation :</u>

energy deposit from nucleus recoil

$E_{NR} \sim 2\mu_{\chi,N}^2 . v_\chi/m_N$

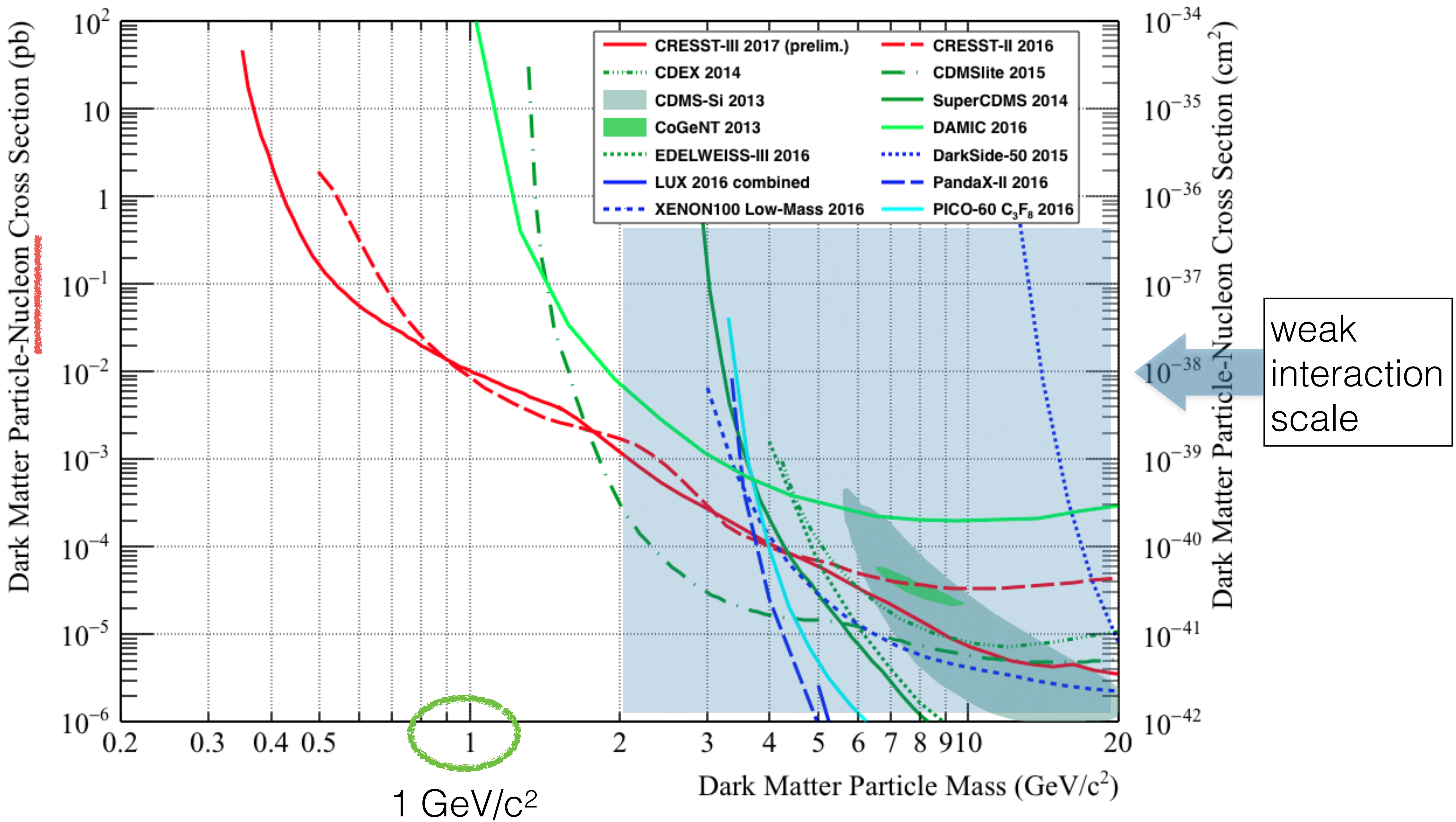
-> for 100 MeV m_χ, $E_{NR} \sim 1$ eV *

plus quenching factors and noise level of the detectors

typical DM velocity $v_\chi \lesssim 800$ km/s

*for silicon

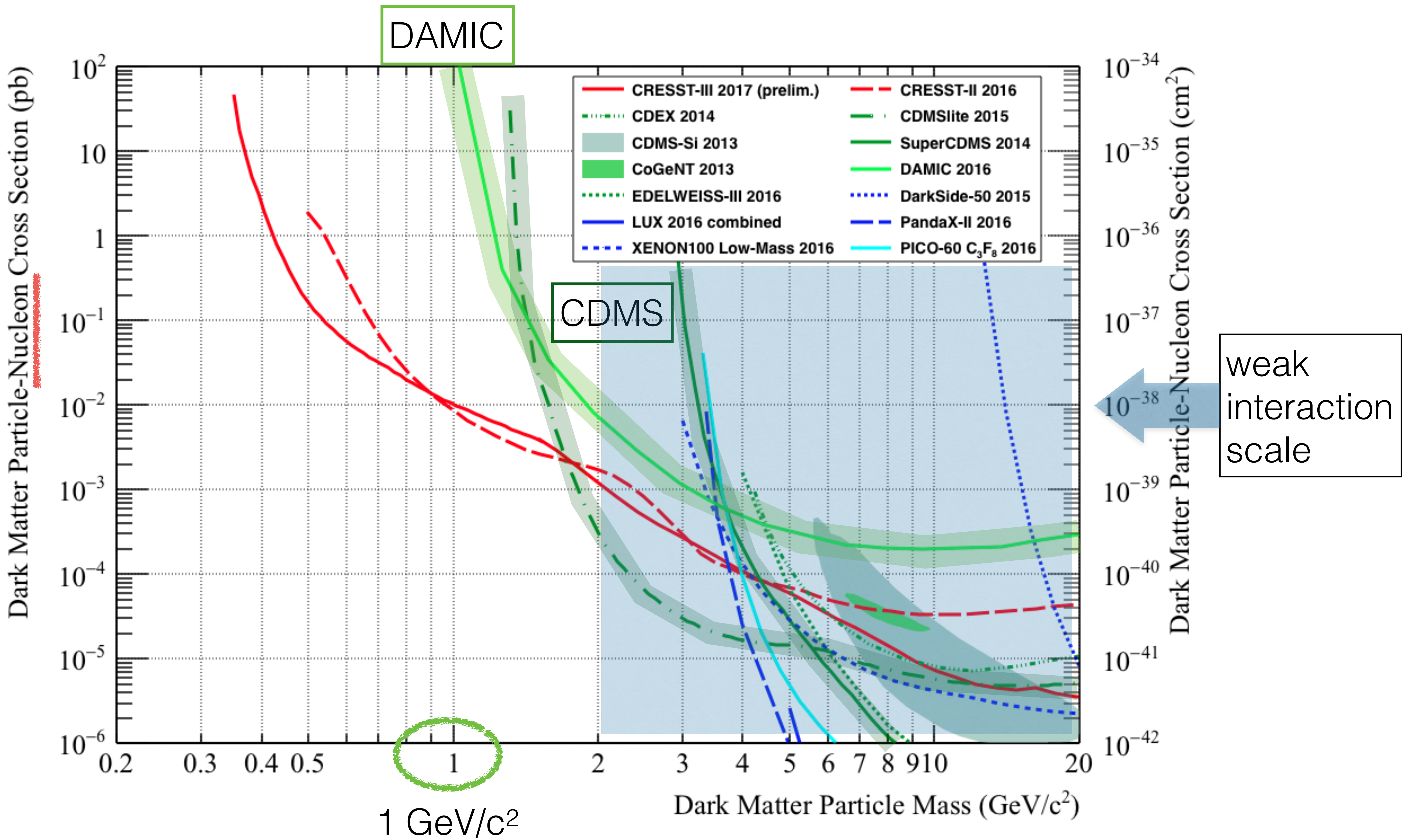
DM-nucleus scattering direct search status



no evidence for WIMP yet

arXiv:1711.07692

DM-nucleus scattering direct search status



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Dark Sector and Light Dark Matter

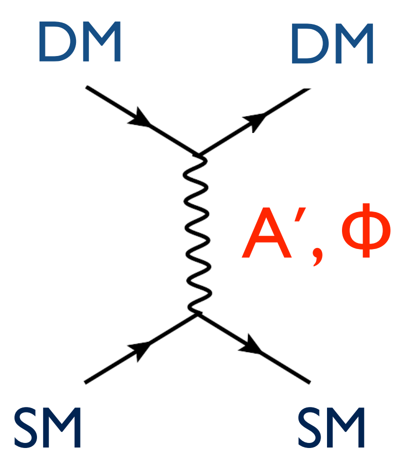
Dark sectors

(DM + new mediators)

WIMPs

several sharp "theory" targets

(freeze-out, asymmetric, freeze-in, SIMP, ELDER)



DM scattering

image credit R. Essig

Dark sector :
interaction between DM and standard model particle mediated by a dark photon
(one example of mediators)

clear predictions from multiple models over wide DM mass region, including keV ~ GeV range
-> comparable observables in experiments

DM-electron scattering

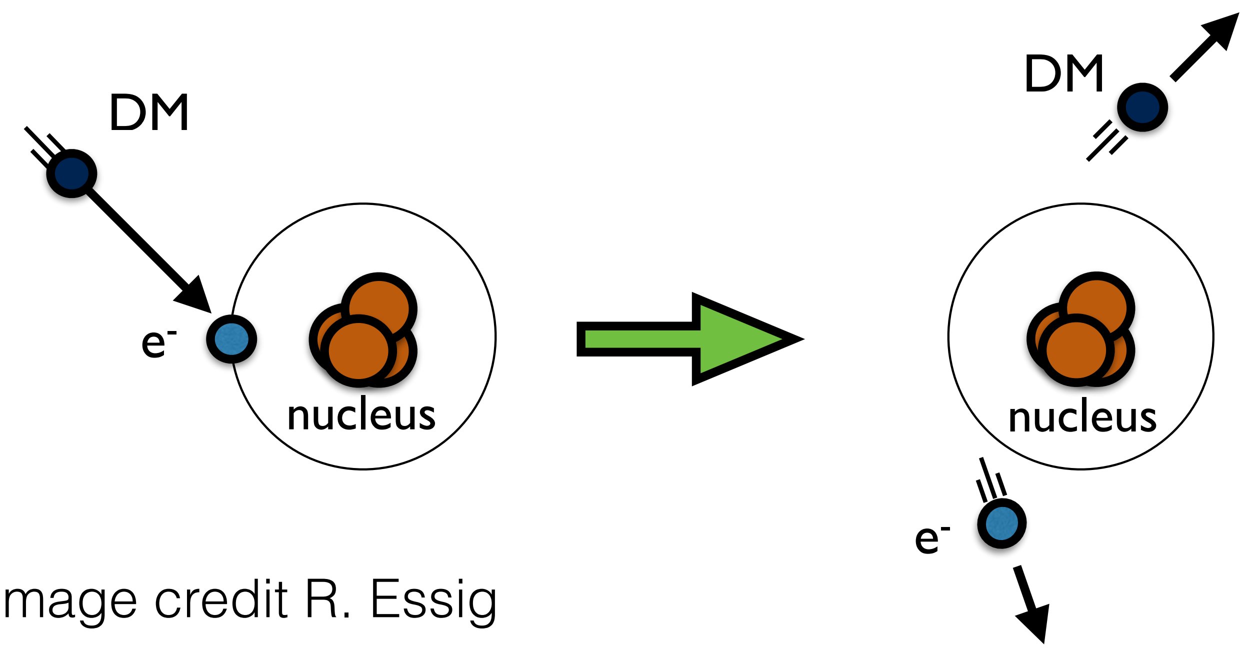


image credit R. Essig

kinematically

to overcome binding energy ΔE

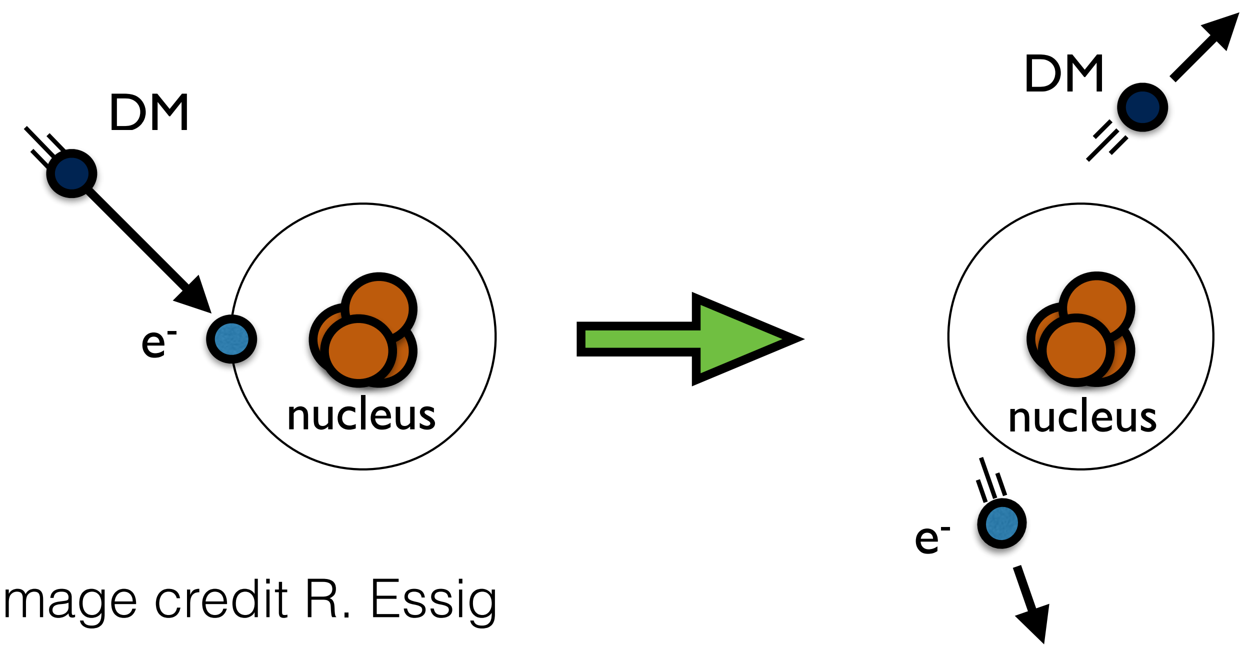
need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$

$$v_{\rm DM} \lesssim 800 \text{ km/s} \Longrightarrow \boxed{m_{\rm DM} \gtrsim 300 \text{ keV} \left(\frac{\Delta E}{1 \text{ eV}}\right)}$$

O(100 keV)

JHEP05(2016)046

DM-electron scattering



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kinematically
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need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 > \Delta E$

$$v_{\rm DM} \lesssim 800 \text{ km/s} \implies m_{\rm DM} \gtrsim 300 \text{ keV} \left(\frac{\Delta E}{1 \text{ eV}}\right)$$

O(100 keV)

bound e- does not have definite momentum,
typical momentum transfer is set by e- not by DM.

$$q_{\rm typ} \sim \alpha m_e \sim 4 \text{ keV}$$ (for outer shell electron)

transferred energy: $\Delta E_e \sim \vec{q} \cdot \vec{v}_{\rm DM}$

$$\Delta E_e \sim 4 \text{ eV}$$

typical recoil energy

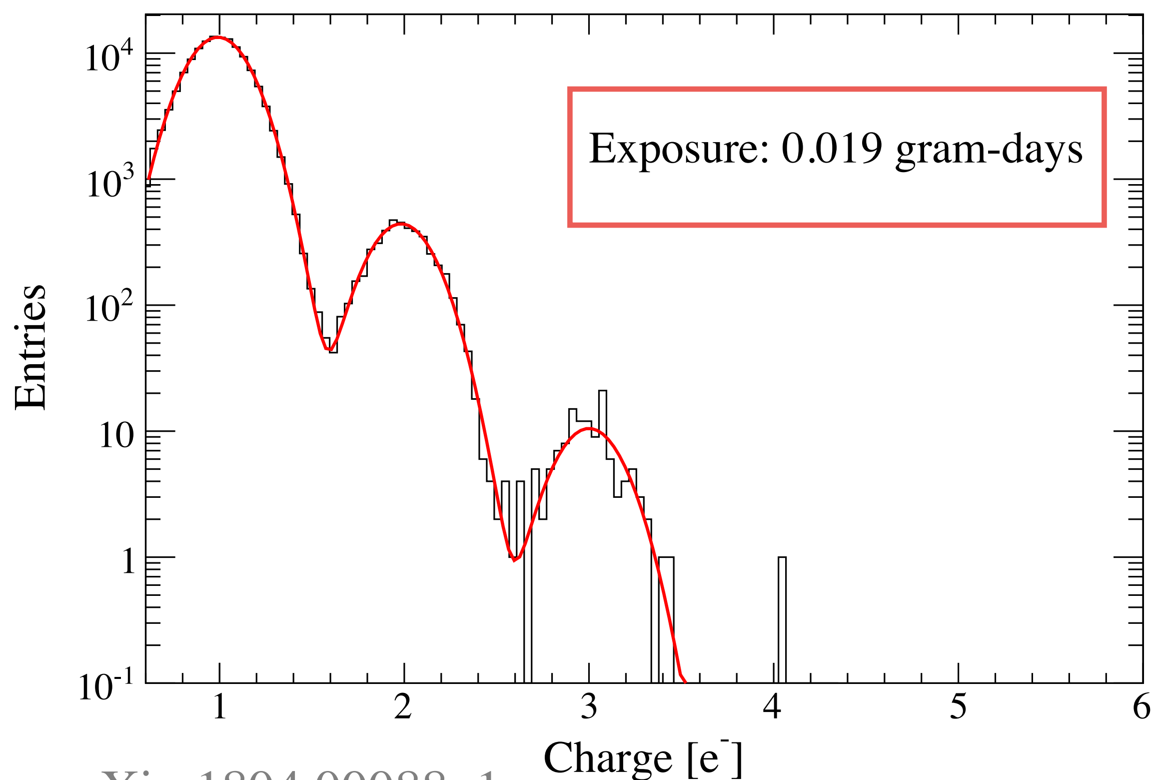
JHEP05(2016)046

Target materials for electron recoils

Target Type	Examples	E_{th}	m_χ threshold	Status	Timescale
Noble liquids	Xe, Ar, He	~ 10 eV	~ 5 MeV	Done w data; improvements possible	existing
Semi-conductors	Ge, **Si**	~ 1 eV	~ 200 keV	(E_{th} ~ 40 eV SuperCDMS, **DAMIC**) E_{th} ~ 1eV **SENSEI**, **DEPFET** R&D	~ 1-2 years
Scintillators	GaAs, NaI, CsI, …	~ 1 eV	~ 200 keV	R&D required	≲ 5 years
Supferfluid	He	~ 1 eV	~ 1 MeV	R&D required unknown background	≲ 5 years
Super-conductor	Al	~ 1 meV	~ 1 keV	R&D required unknown background	~ 10 - 15 years

arXiv:1608.08632

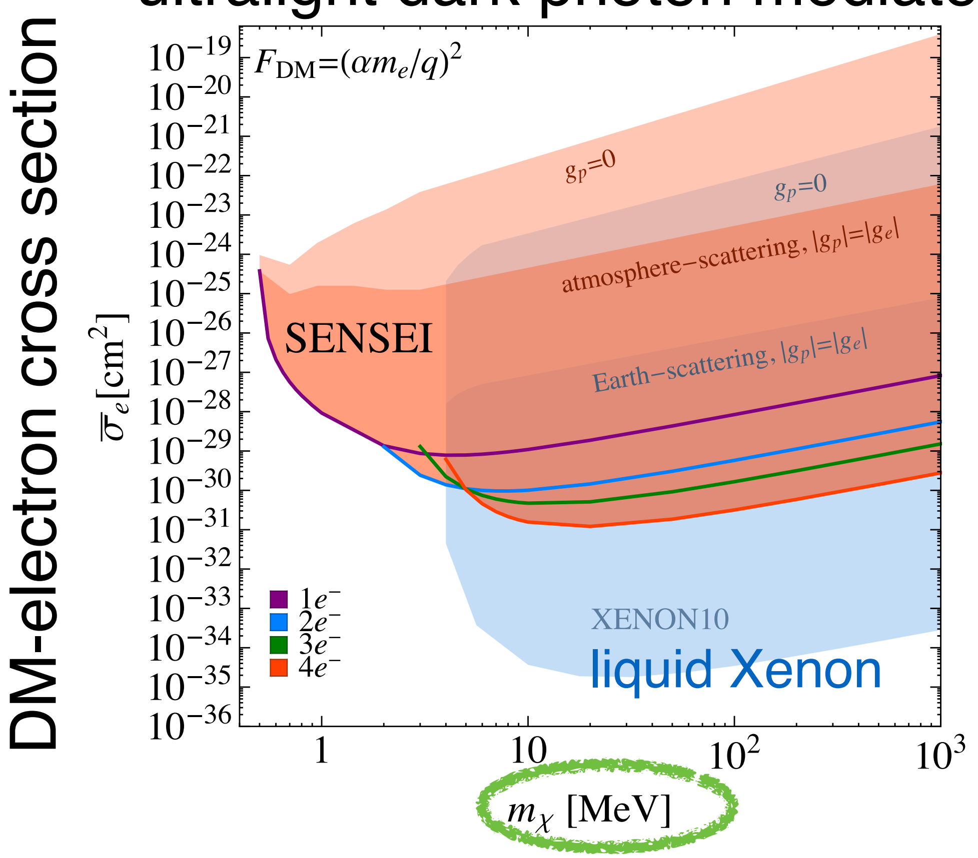
SENSEI first result with “skipper” CCD



arXiv:1804.00088v1

Active mass : 0.071 grams
427 minutes exposure (0.33 g-hr)
above sea level 220 m
single read noise : ~ 4 e-
effective noise : ~ 0.14 e- (800 repetitions)
dark current : ~1.14 e-/pixel/day
assume all events DM induced
-> conservative limit

ultralight dark photon mediator



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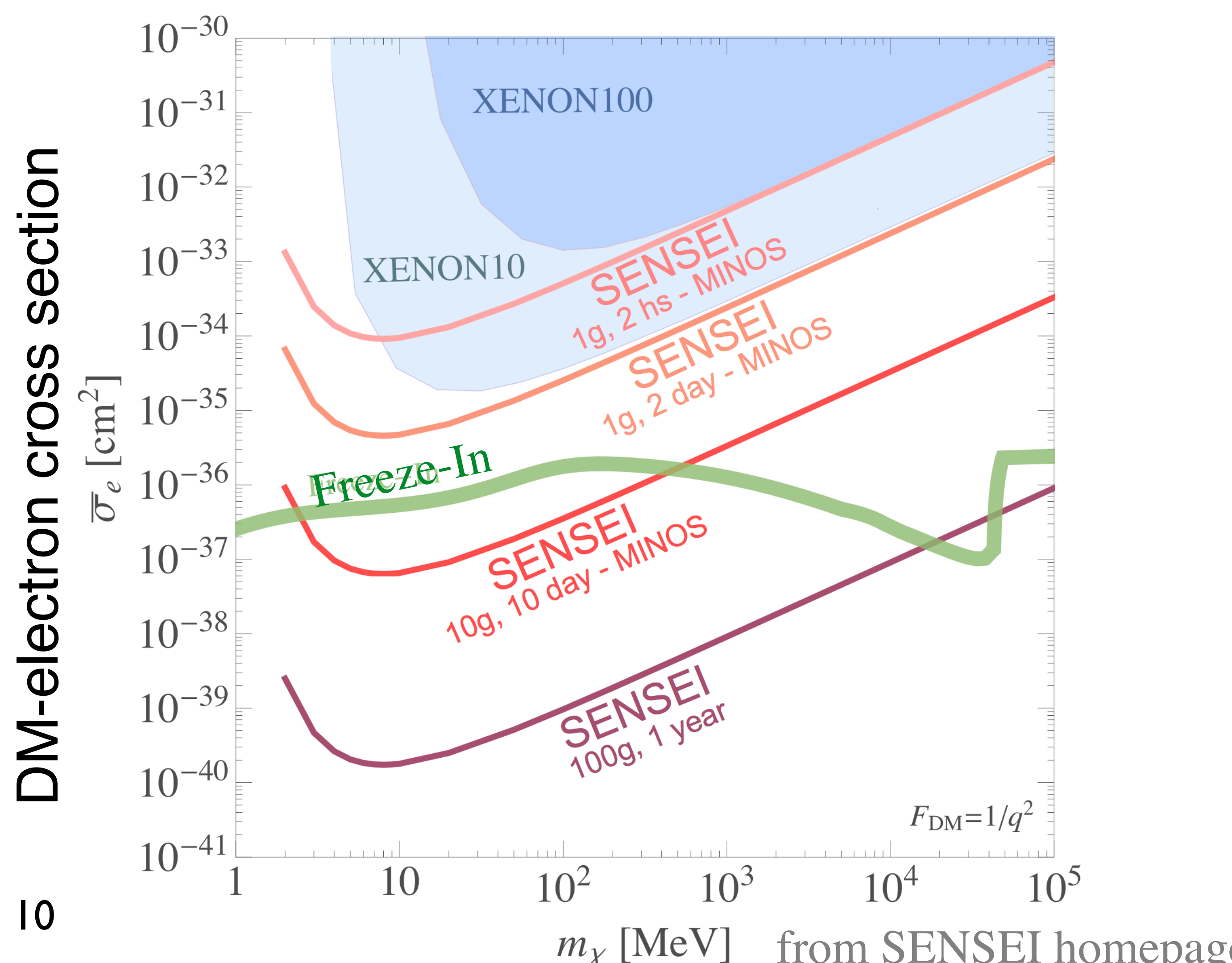
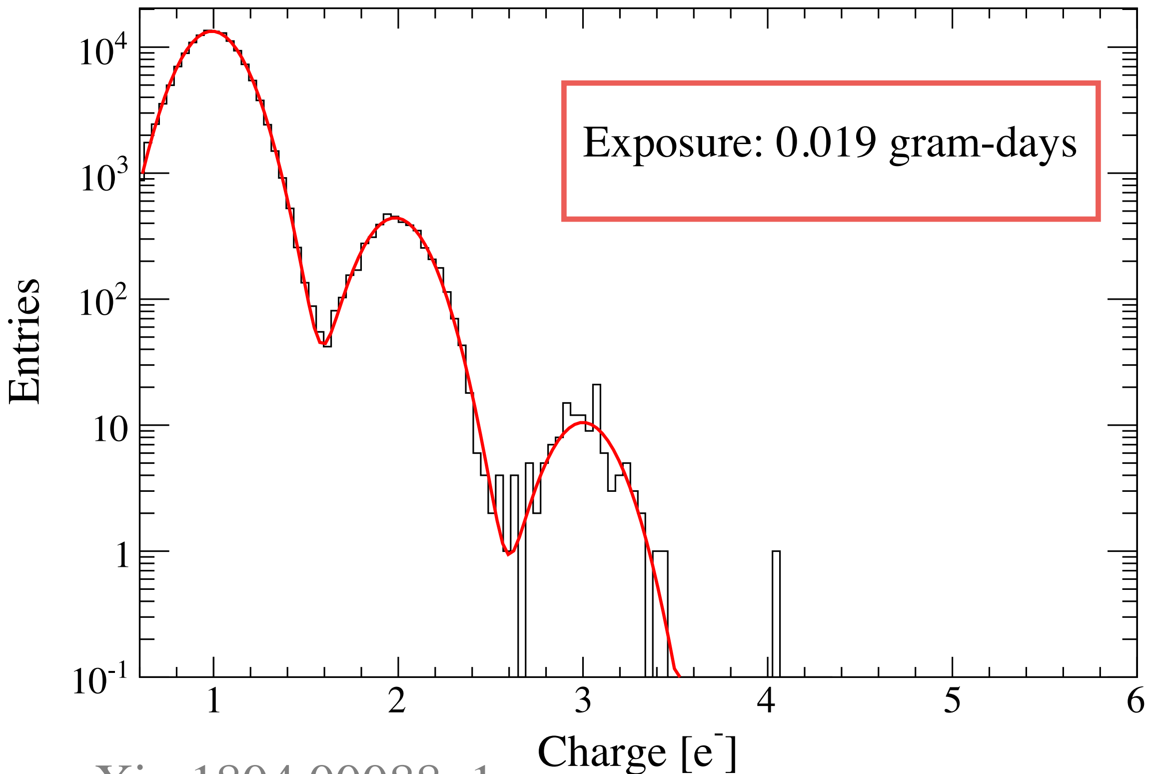


from SENSEI homepage

SENSEI first result with “skipper” CCD



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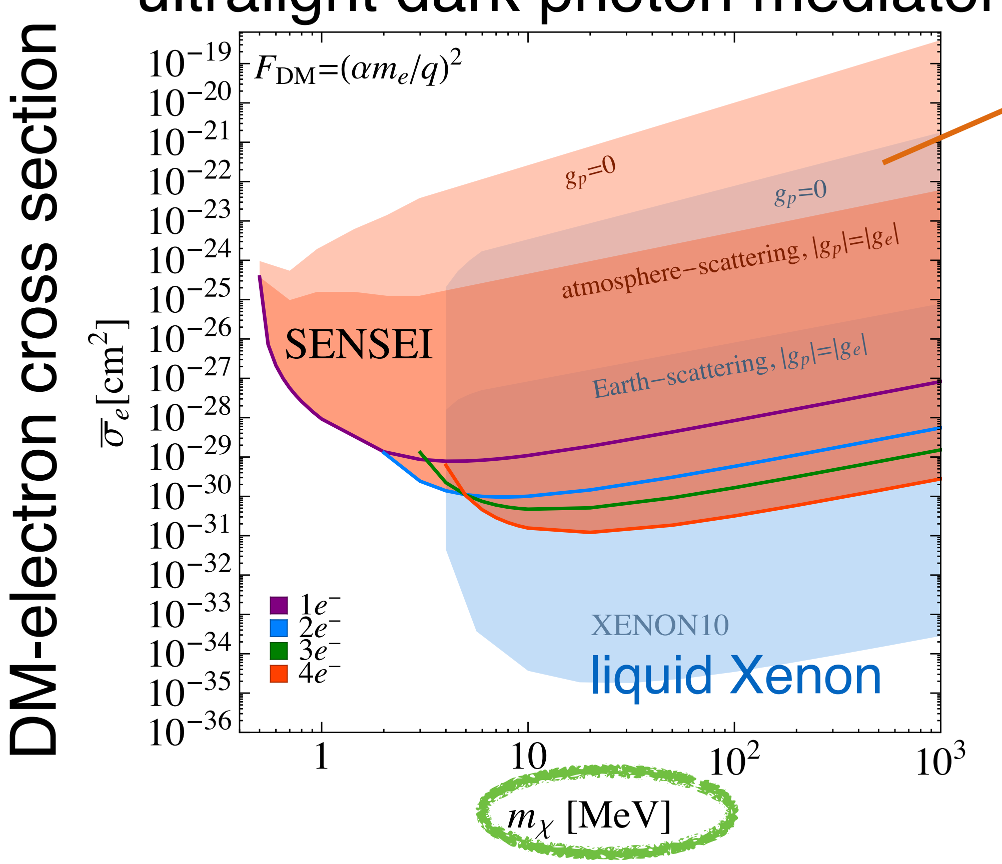

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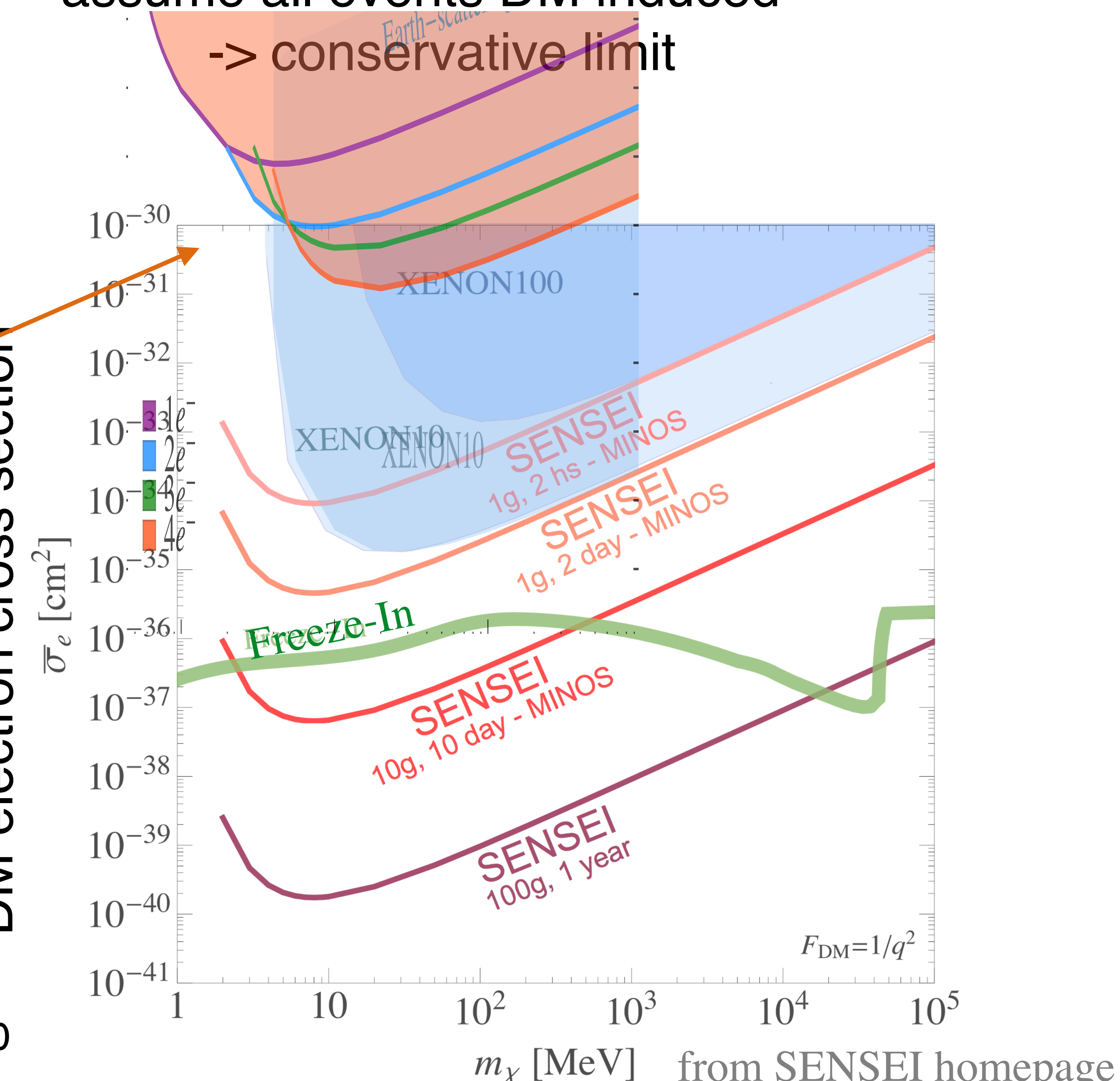


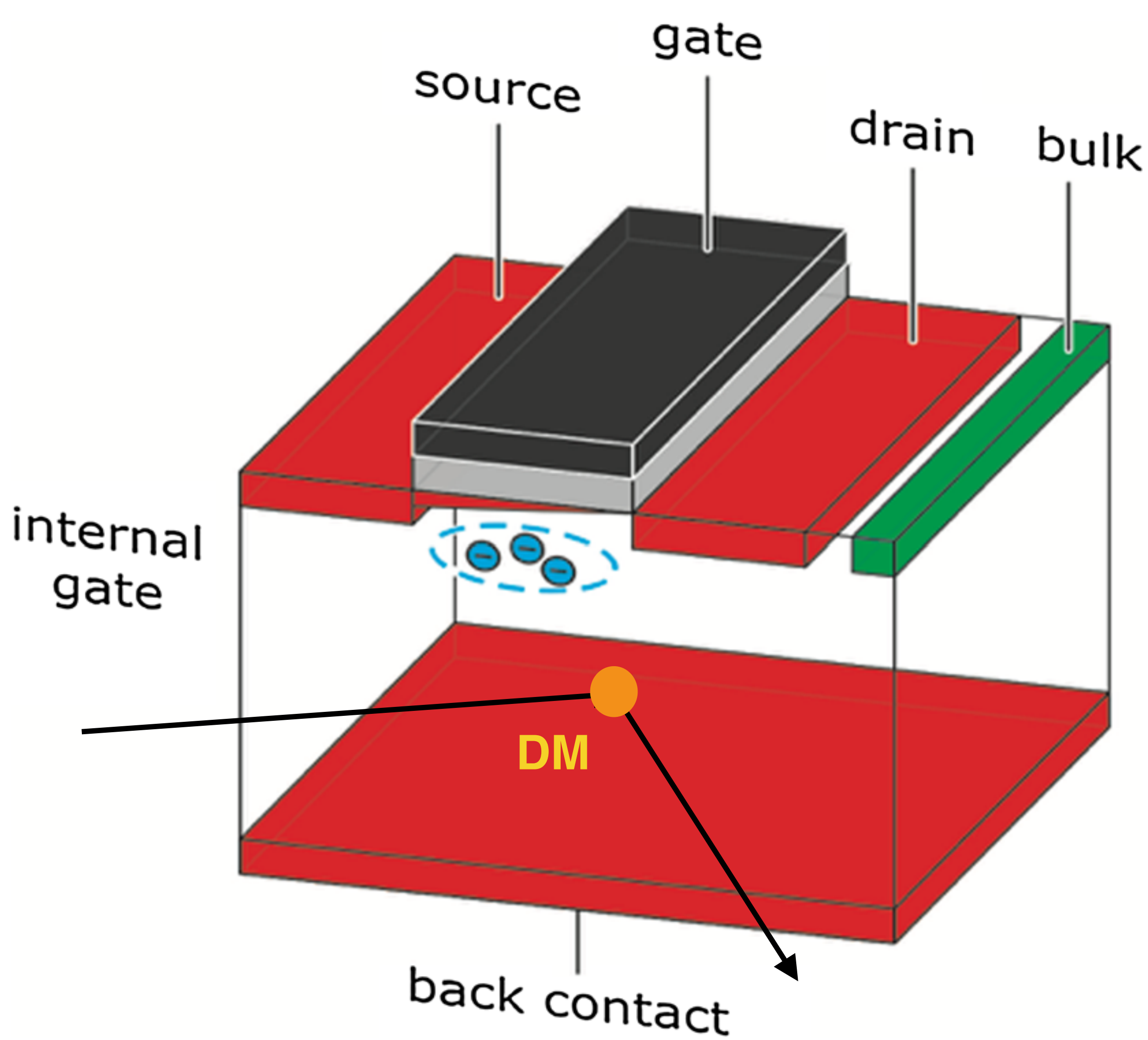
from SENSEI homepage

DEPFET with RNDR

RNDR : repetitive non-destructive readout

structure of a basic DEPFET cell :

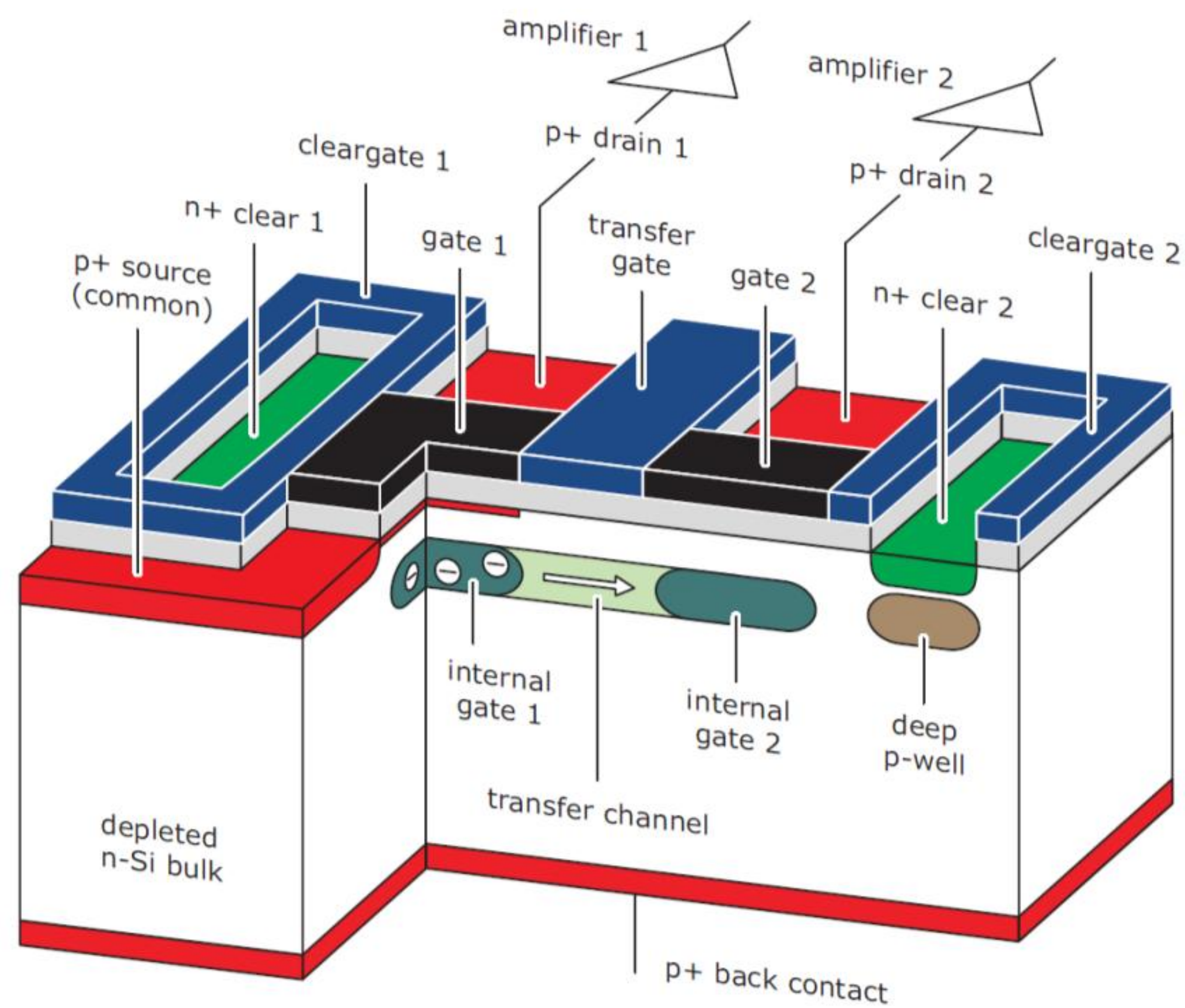
a “subpixel”



EPJ C, 77(12), 279 (2017)

fully-depleted n-Si

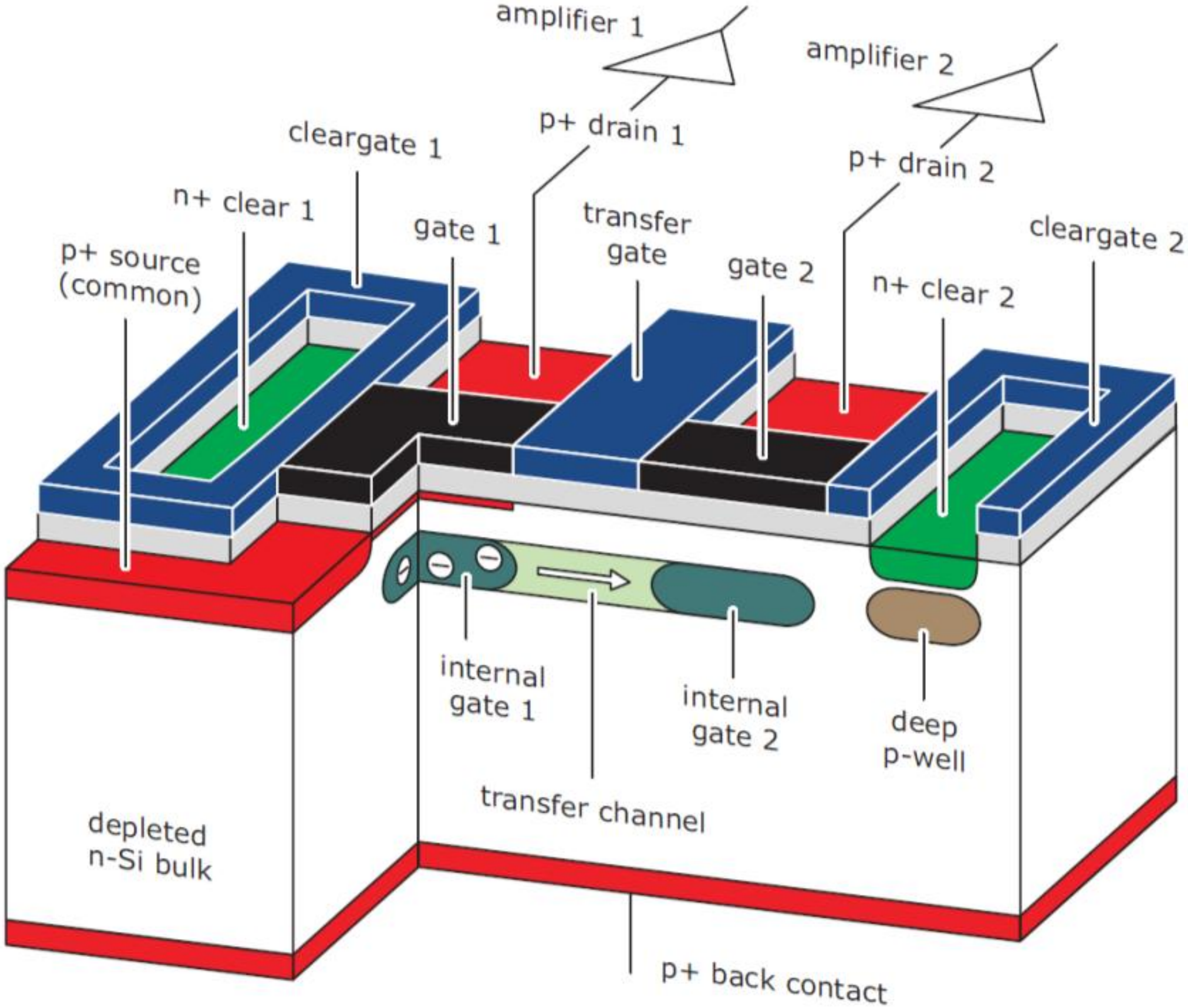
structure of RNDR DEPFET “super-pixel”



EPJ C, 77(12), 279 (2017)

RNDR

RNDR readout

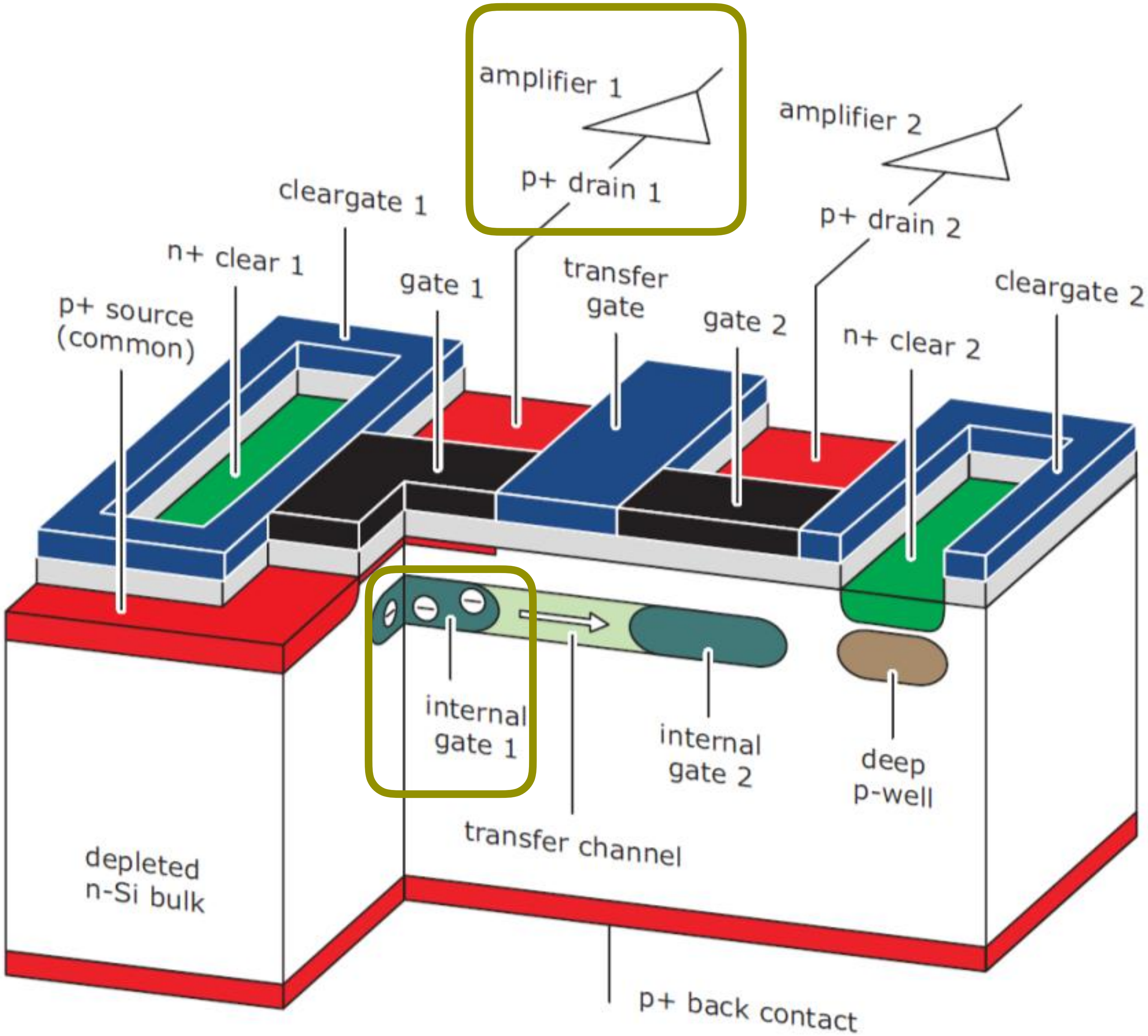


EPJ C, 77(12), 279 (2017)

read N times *effective noise* :

$$\sigma_{eff} = \sigma/(\sqrt{N})$$

RNDR



EPJ C, 77(12), 279 (2017)

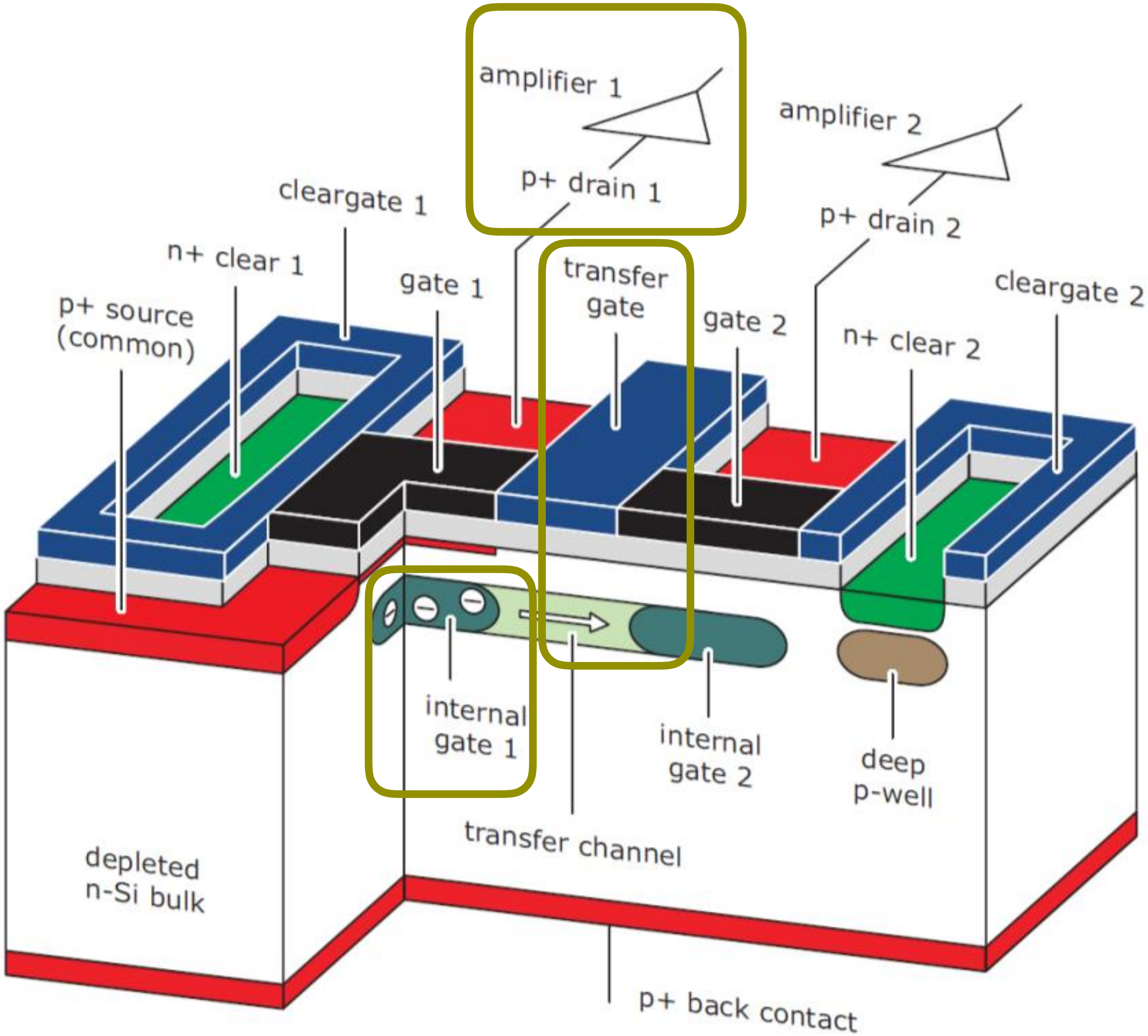
RNDR readout

read **1** : noise **σ**

read N times *effective noise* :

$$\boldsymbol{\sigma_{eff} = \sigma/(\sqrt{N})}$$

RNDR



EPJ C, 77(12), 279 (2017)

RNDR readout

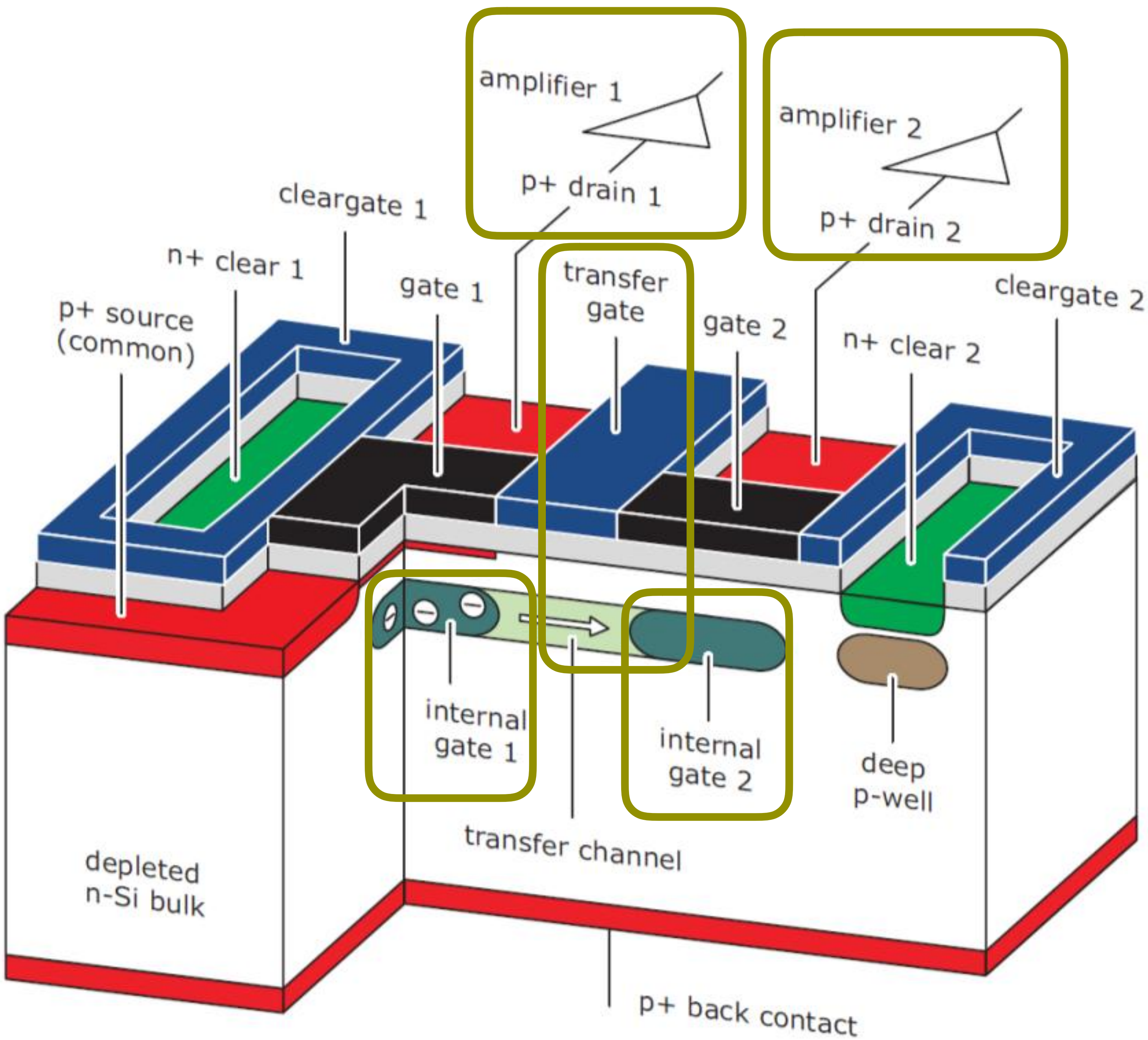
read **1** : noise **σ**

transfer gate open

read N times *effective noise* :

$\boldsymbol{\sigma_{eff} = \sigma/(\sqrt{N})}$

RNDR



EPJ C, 77(12), 279 (2017)

RNDR readout

read **1** : noise **σ**

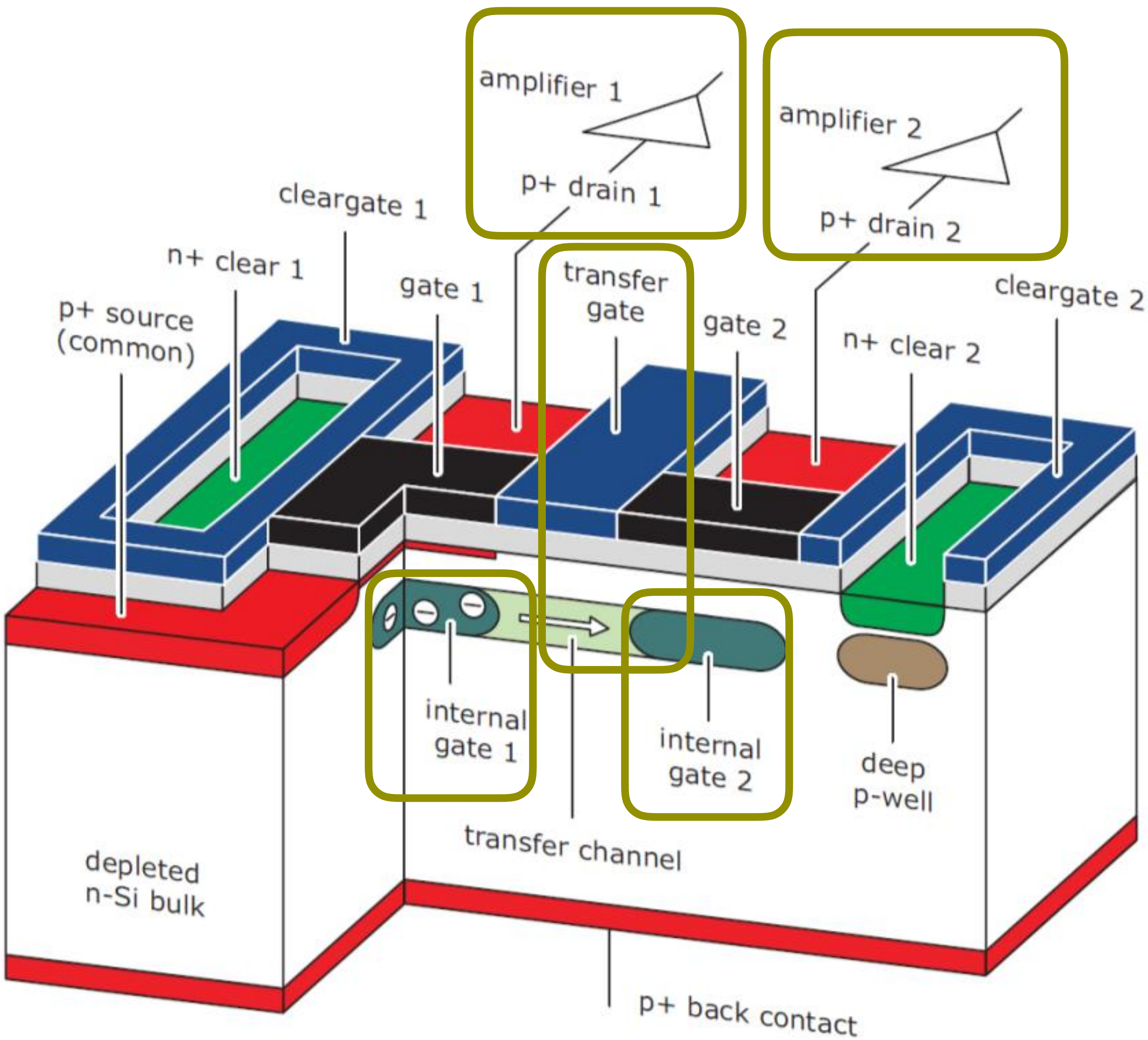
transfer gate open

read **2** : noise **σ**

read N times *effective noise* :

$\boldsymbol{\sigma_{eff} = \sigma/(\sqrt{N})}$

RNDR



EPJ C, 77(12), 279 (2017)

RNDR readout

read **1** : noise **σ**

transfer gate open

read **2** : noise **σ**

: repeat **N** times
independent measurements

clear charges

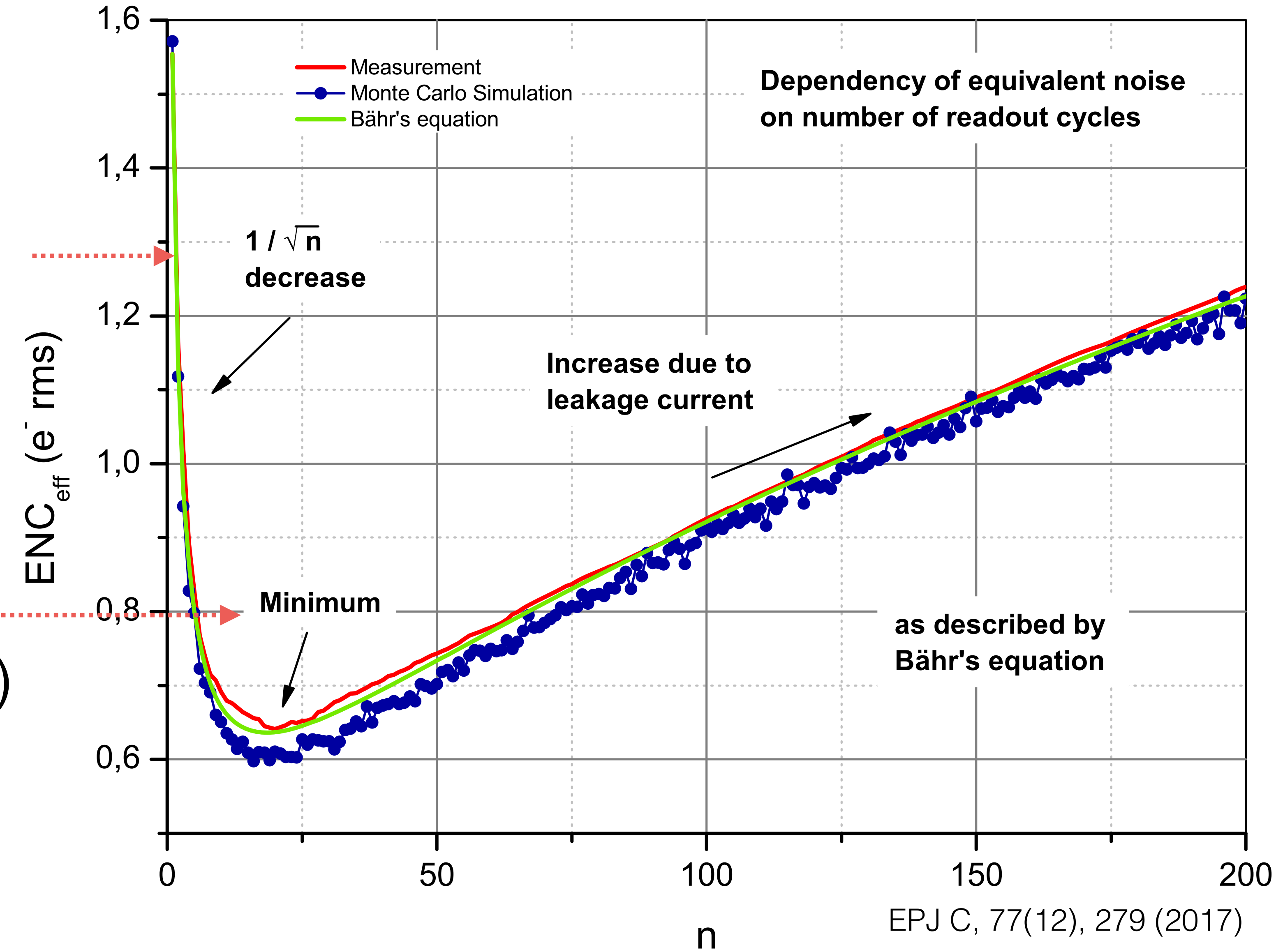
read N times *effective noise* :

$\boldsymbol{\sigma_{eff} = \sigma/(\sqrt{N})}$

DEPFET RNDR single pixel performance

confirmed the 1/√N decrease of σ_{eff}

minimal noise level limited by leakage current at 230 K (-40 °C)



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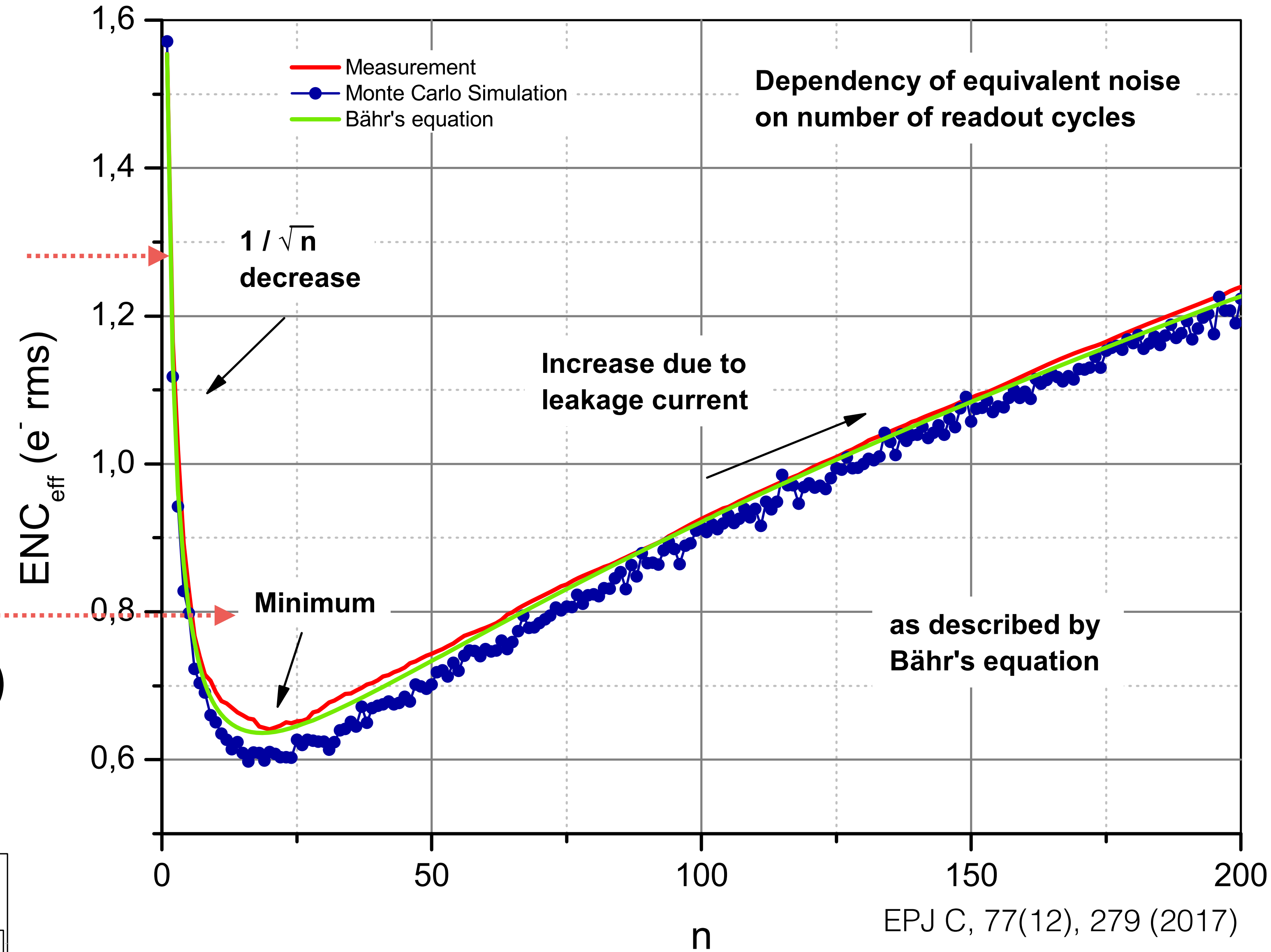
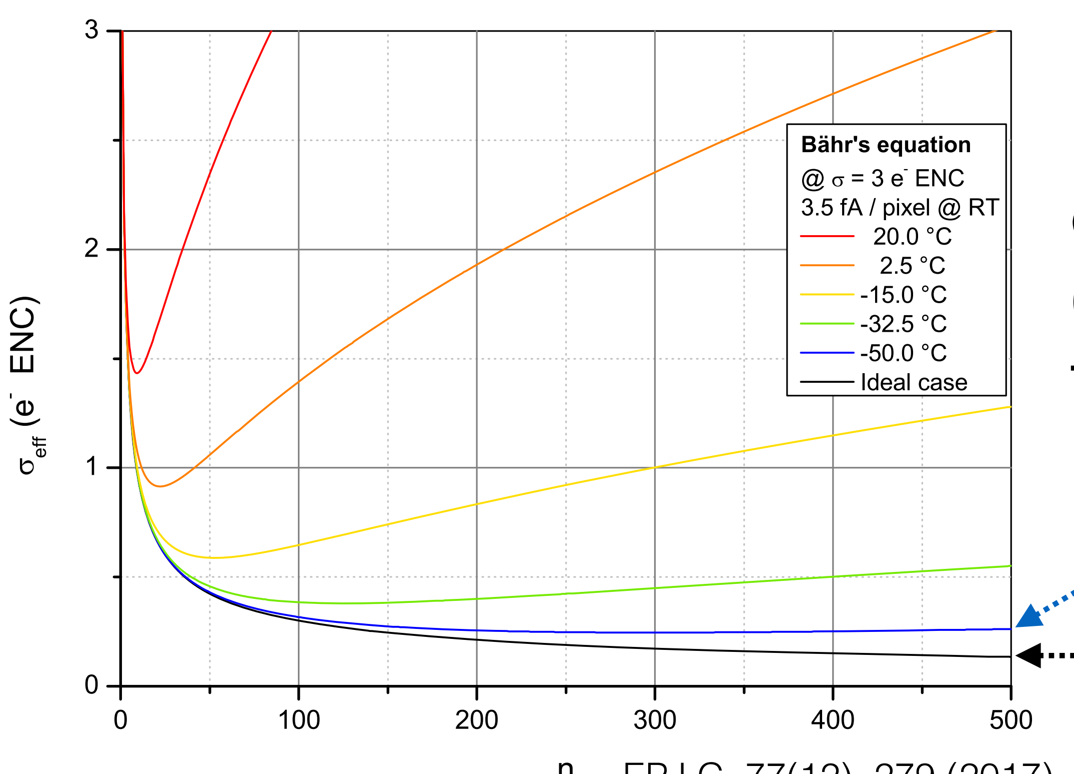


EPJ C, 77(12), 279 (2017)

confirmed the $1/\sqrt{N}$ decrease of σ_{eff}

minimal noise level limited by leakage current at 230 K (-40 °C)



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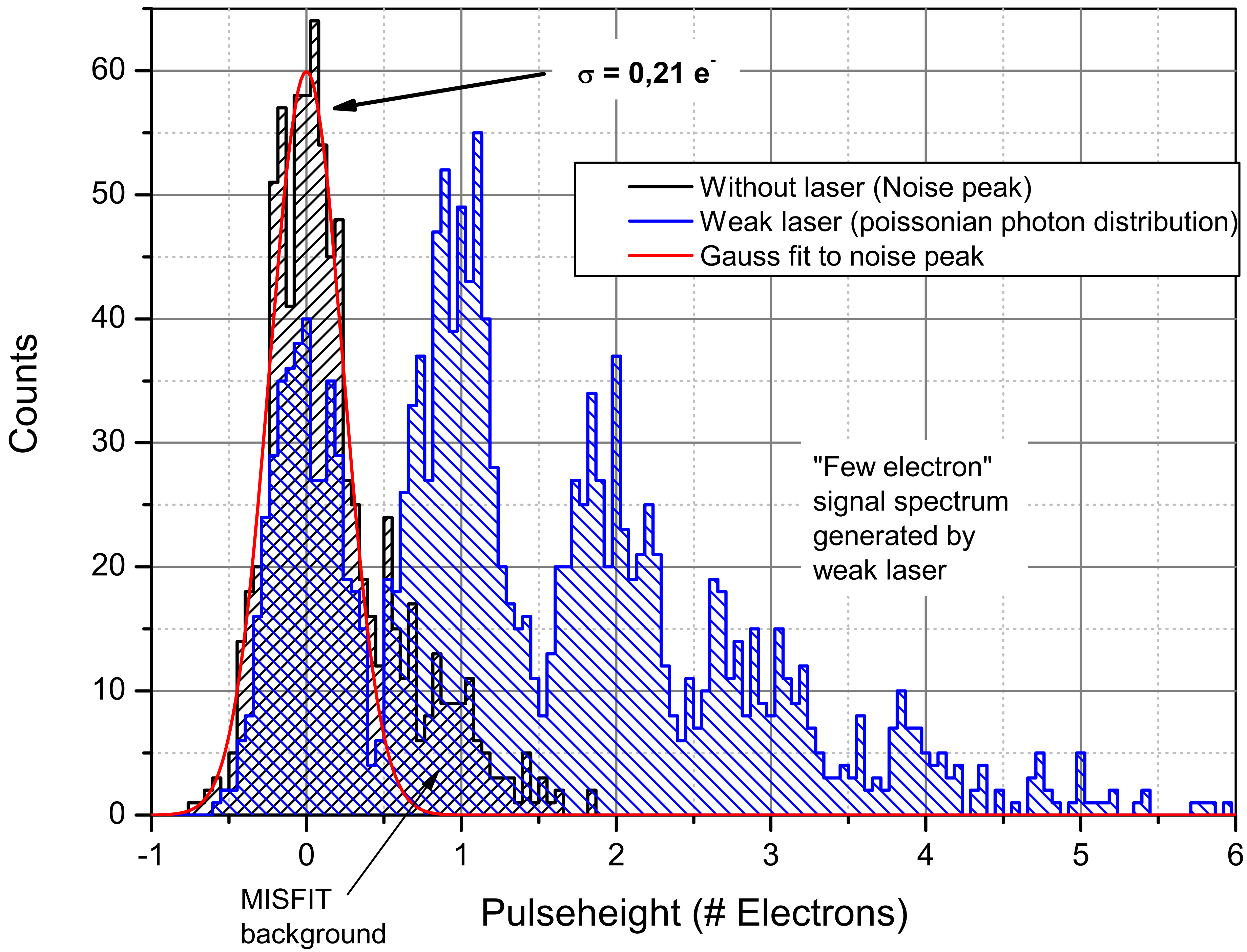
estimated temperature dependence (only DC from thermal excitation) to be testified in measurement

- 50 °C

ideal case

DEPFET RNDR single pixel performance



single pixel RNDR DEPFET effective noise :

$0.2\ e^{-}$ RMS at 200 K

capable of distinguish single electron charge

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A comparison with skipper CCD

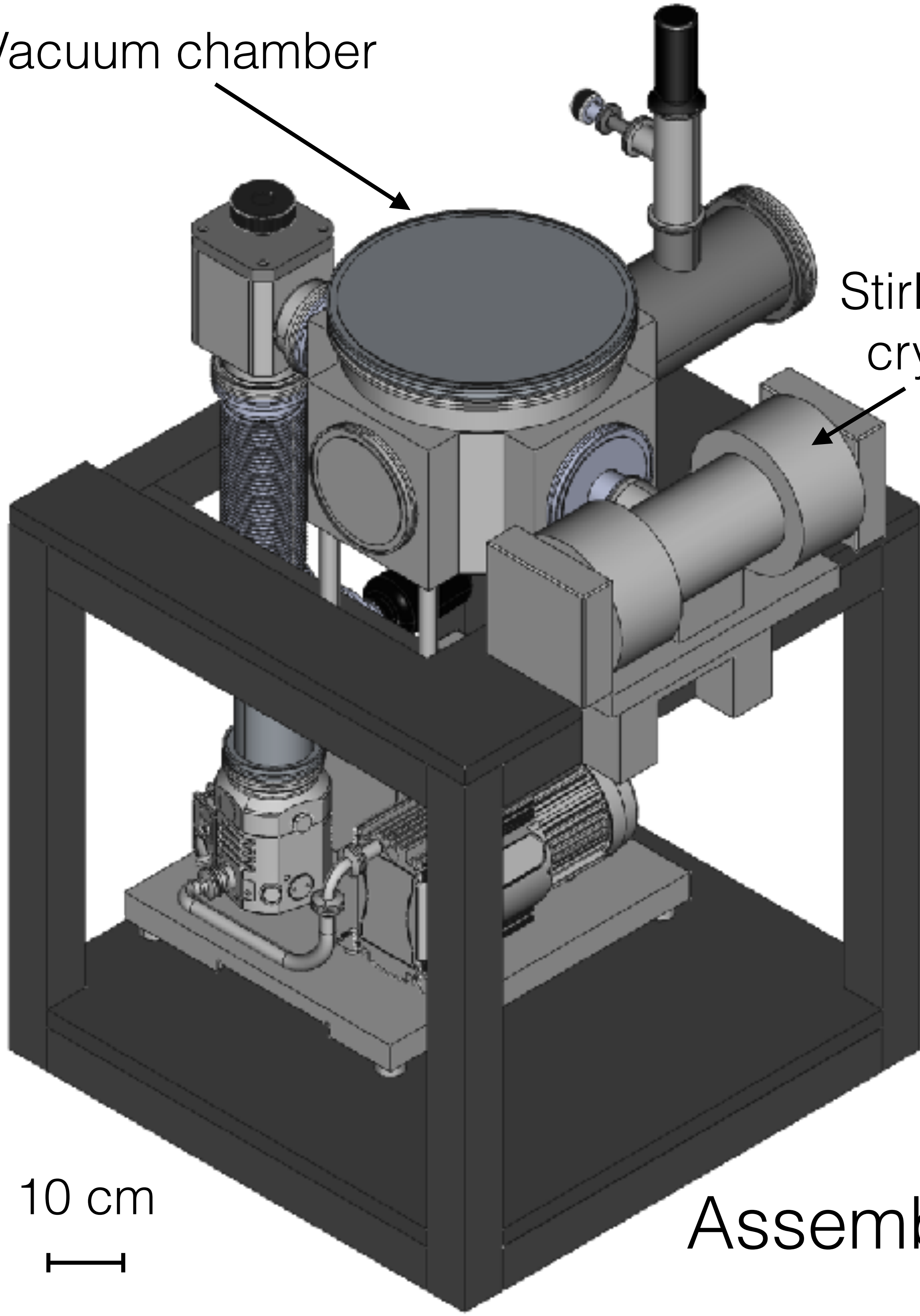
Type	Pixel format [μm]	prototype mass	operating temp	dark current	readout time (1sample)	readout noise (optimal)
skipper CCD	15 x 15 x 200	0.071 g	140 K	< ~1.14 e-/pix/day	10 μs/pix/ amplifier	0.068 e-rms/pix
RNDR DEPFET	75 x 75 x 450	0.024 g	≲ 200 K	< 1 e-/pix/day	4 μs/ 64 pix	0.2 e-rms/pix

similar concepts of non-destructive readout, compatible performance;

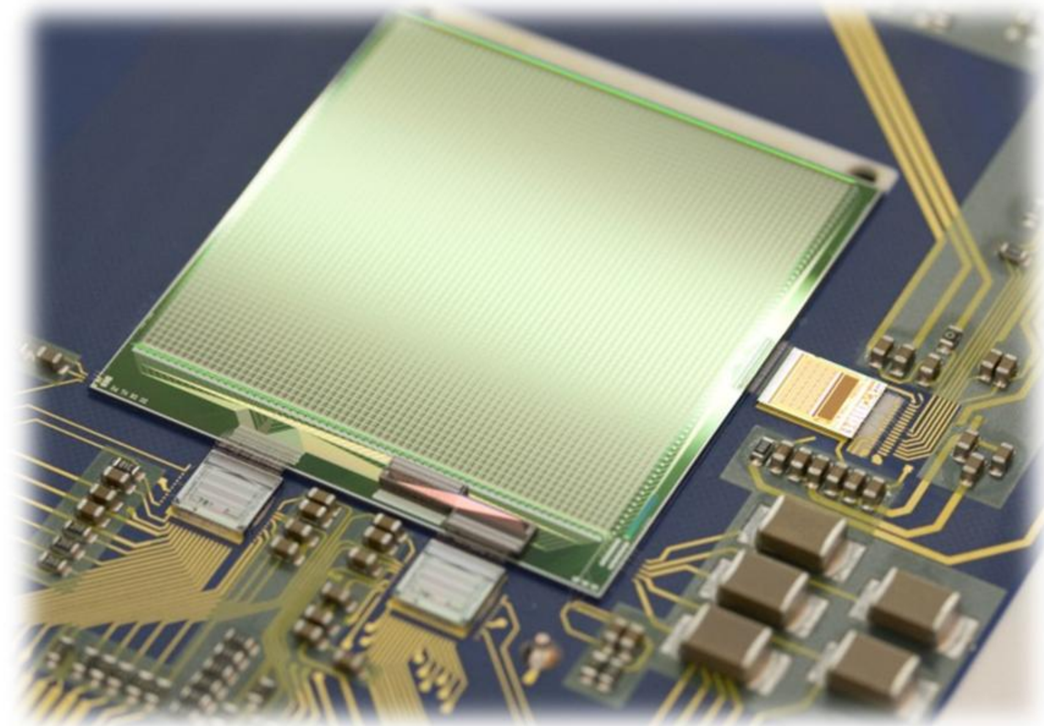
different architecture, different systematics;

-> good complementary from experimental point of view

DANAE prototype test setup



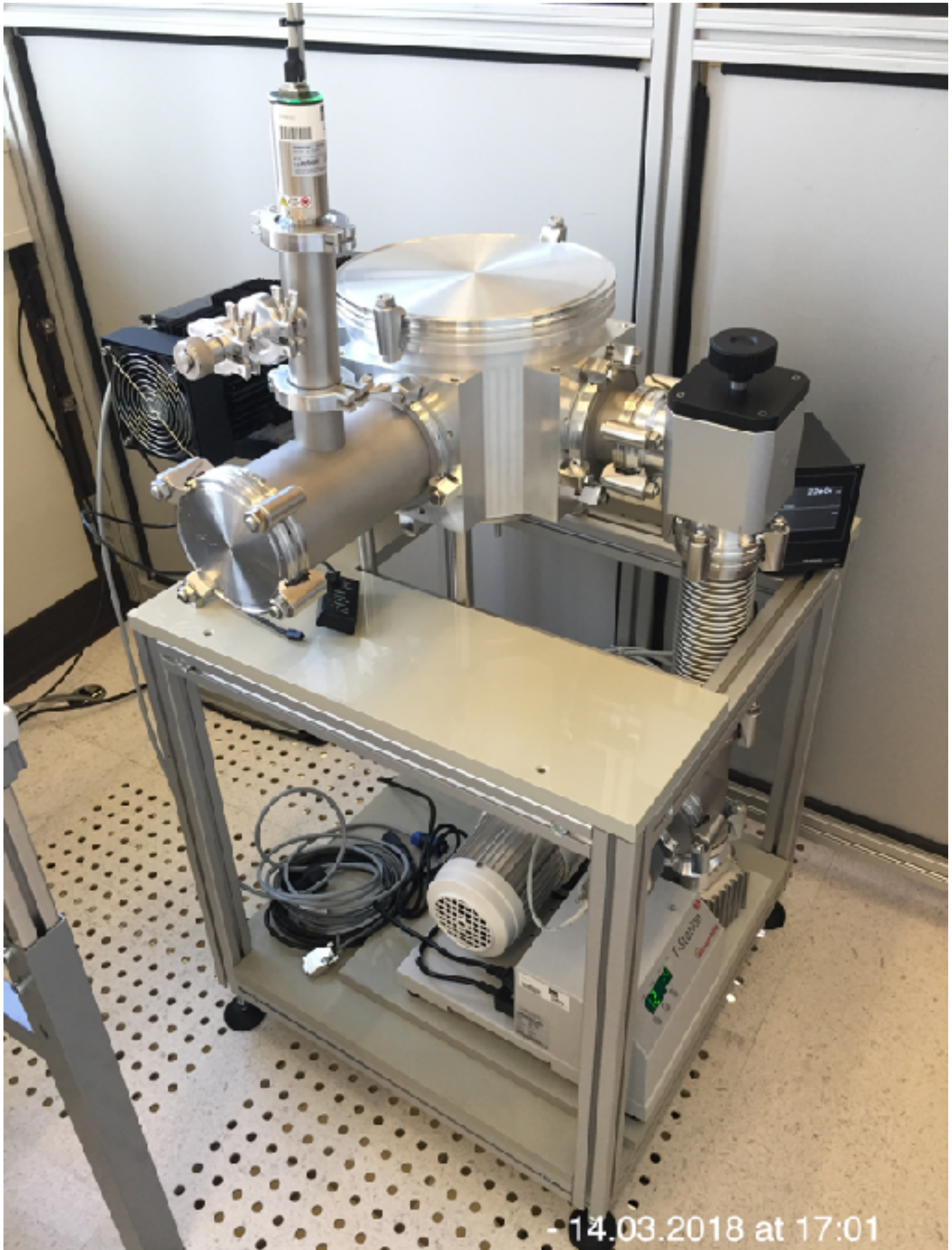
Assembly at HLL

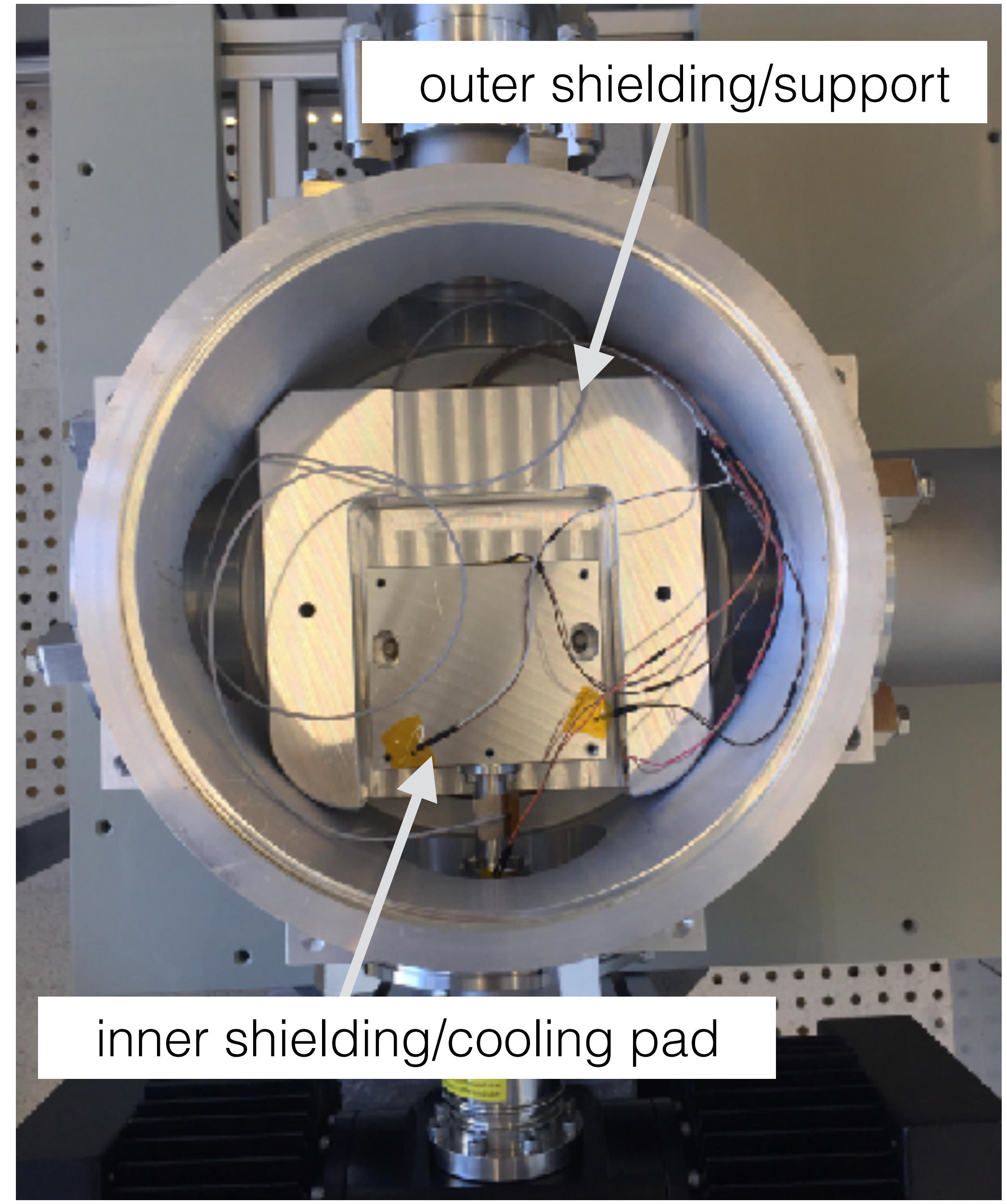


Detector prototype at HLL-MPG
courtesy of J. Treis

proto-type :
75 um x 75 um x 450 um single pixel,
64 x 64 matrix
sensitive volume **0.024 g**

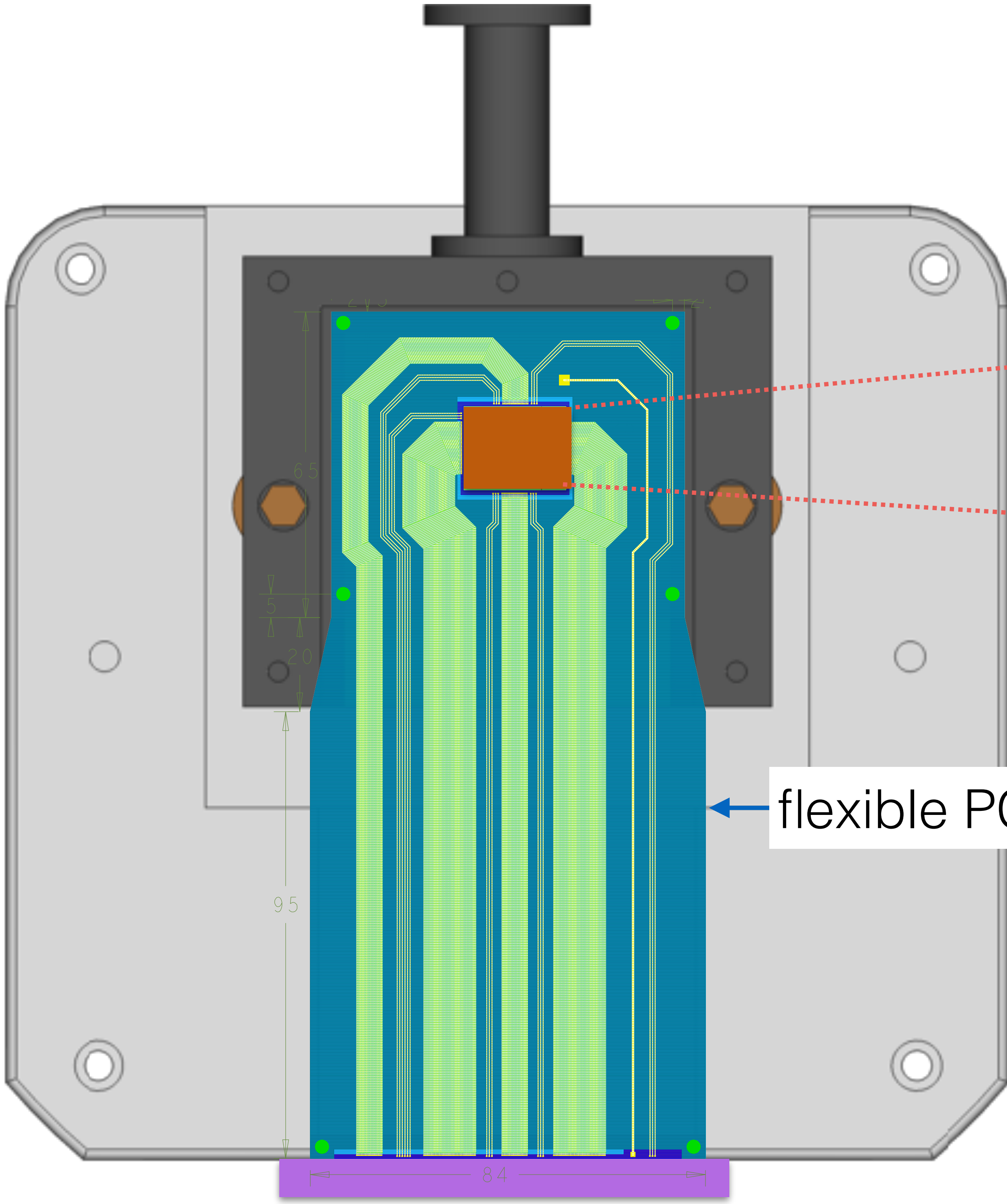
Setup at HLL

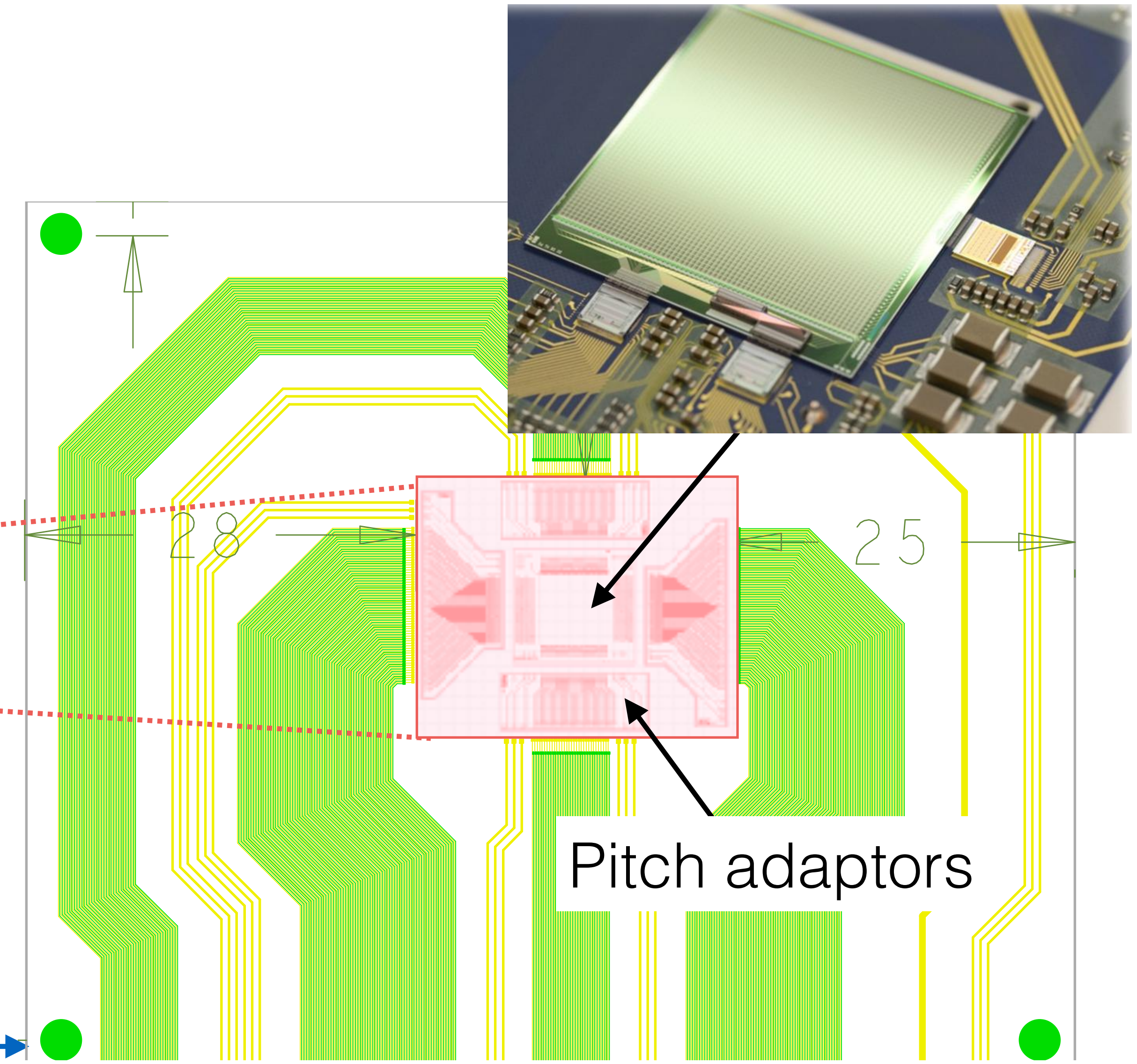




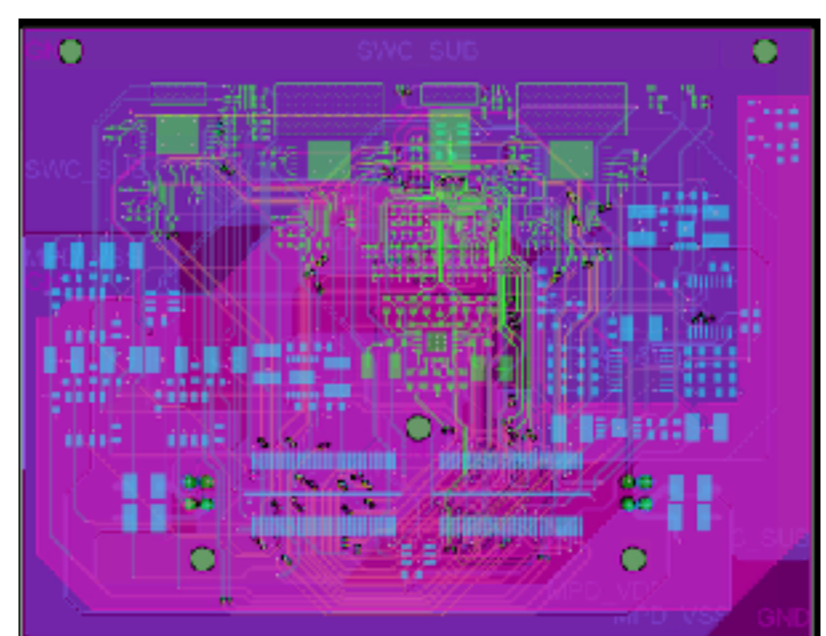
Vacuum and cooling test in March 2018
cooling pad reached 150 K

Detector control and readout electronics





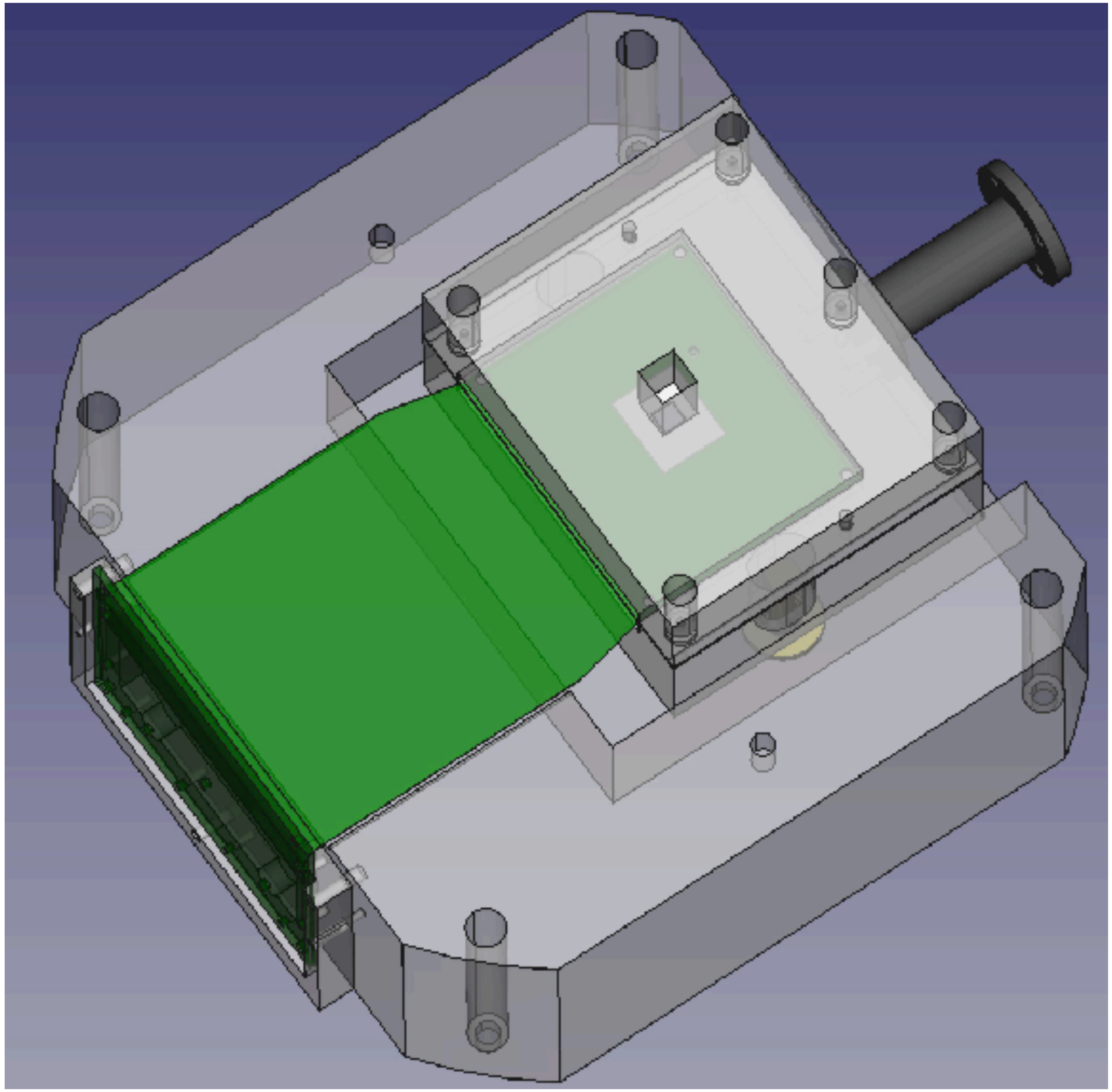
flexible PCB



Readout board
(consists of gate-control
and readout ASICs)

J. Treis
HLL

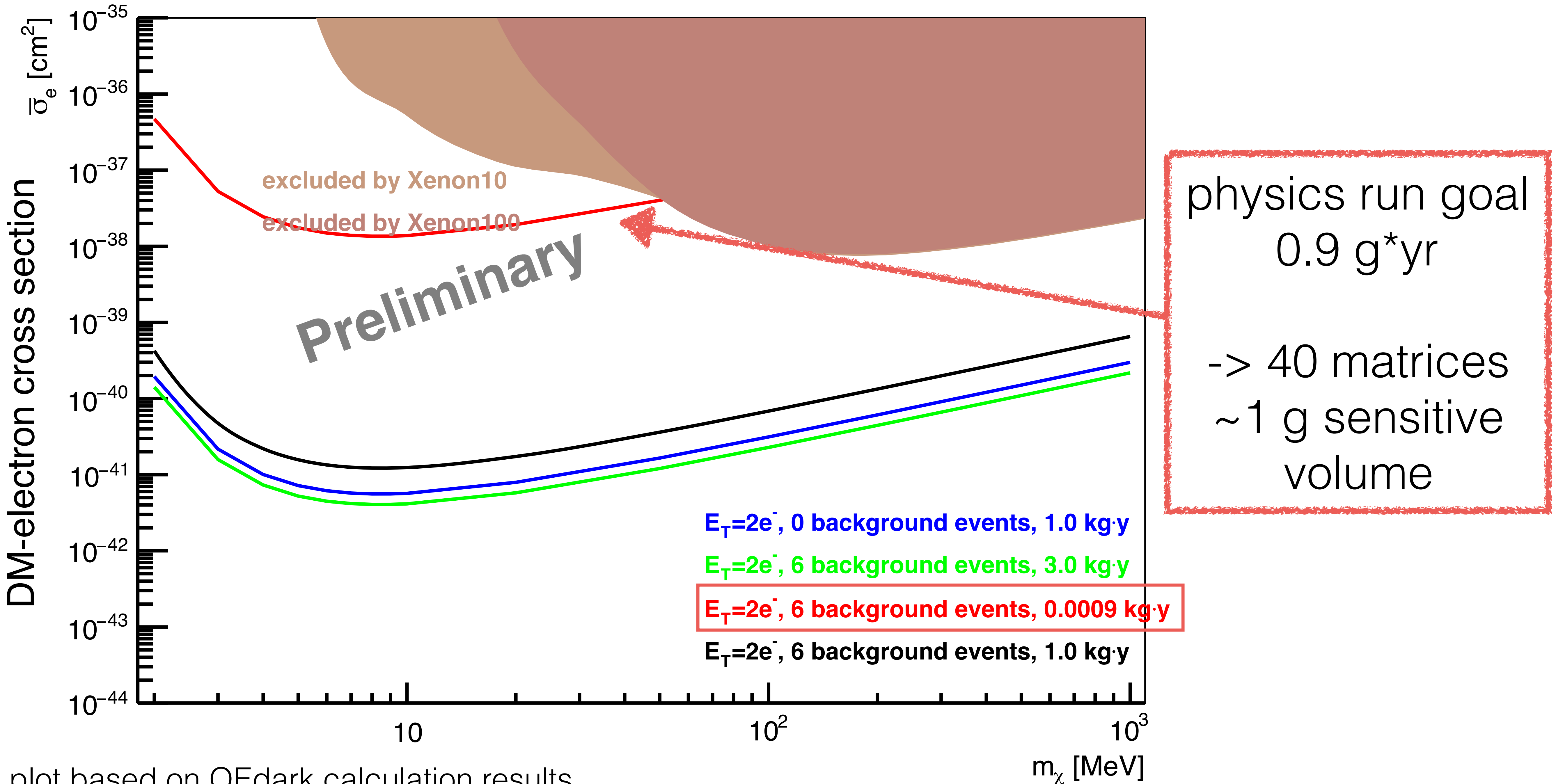
Image of the detector assembly



To be assembled in July-August 2018

Physics run perspective

- Expect preliminary results from the prototype setup (0.024 g sensitive volume) in late 2018
- physics run with significant result requires more matrices



plot based on QEdark calculation results

JHEP05(2016)046

Summary

- sub e^- ENC low noise semiconductor detector capable of detecting the energy deposit from sub-GeV DM-electron recoil;

- DANAE prototype for test-of-principle measurement with 64 x 64 pixel matrix in preparation;

- one of the first generation experiments using non-destructive repetitive readout method.

DANAE (DANAË)
Direct dArk matter search using DEPFET with repetitive-Non-destructive-readout Application Experiment

OeAW funding for detector technology

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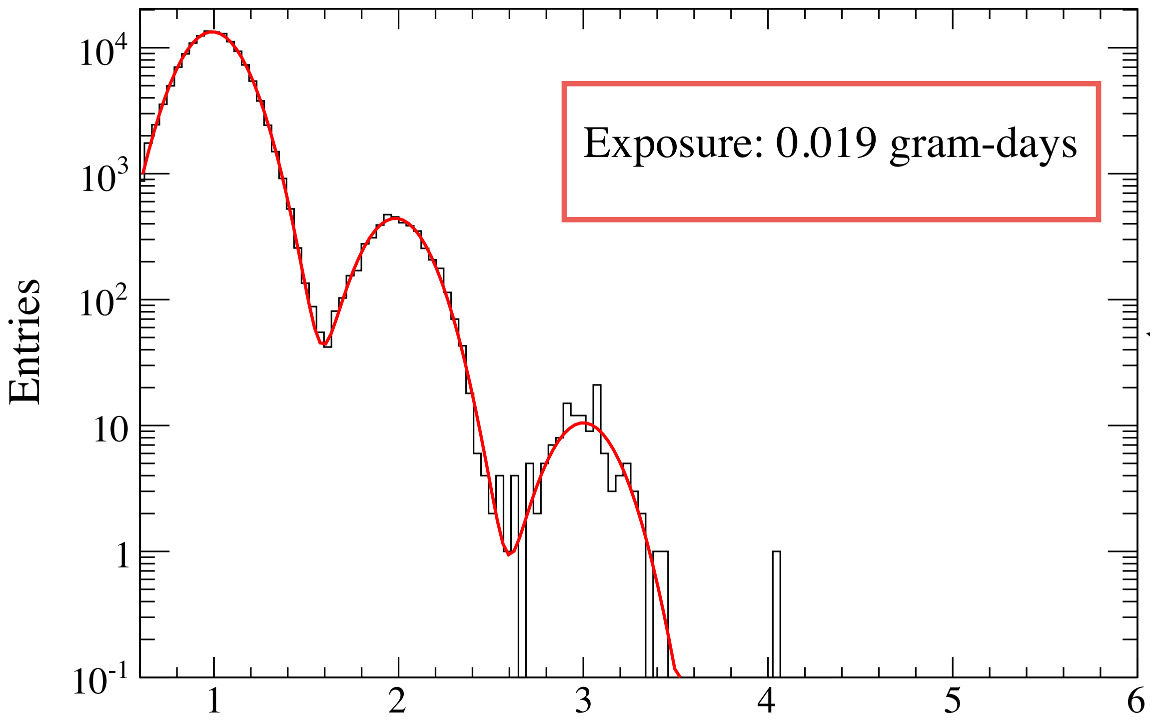
Atominstitut, Technische Universität Wien, Vienna, Austria [C]

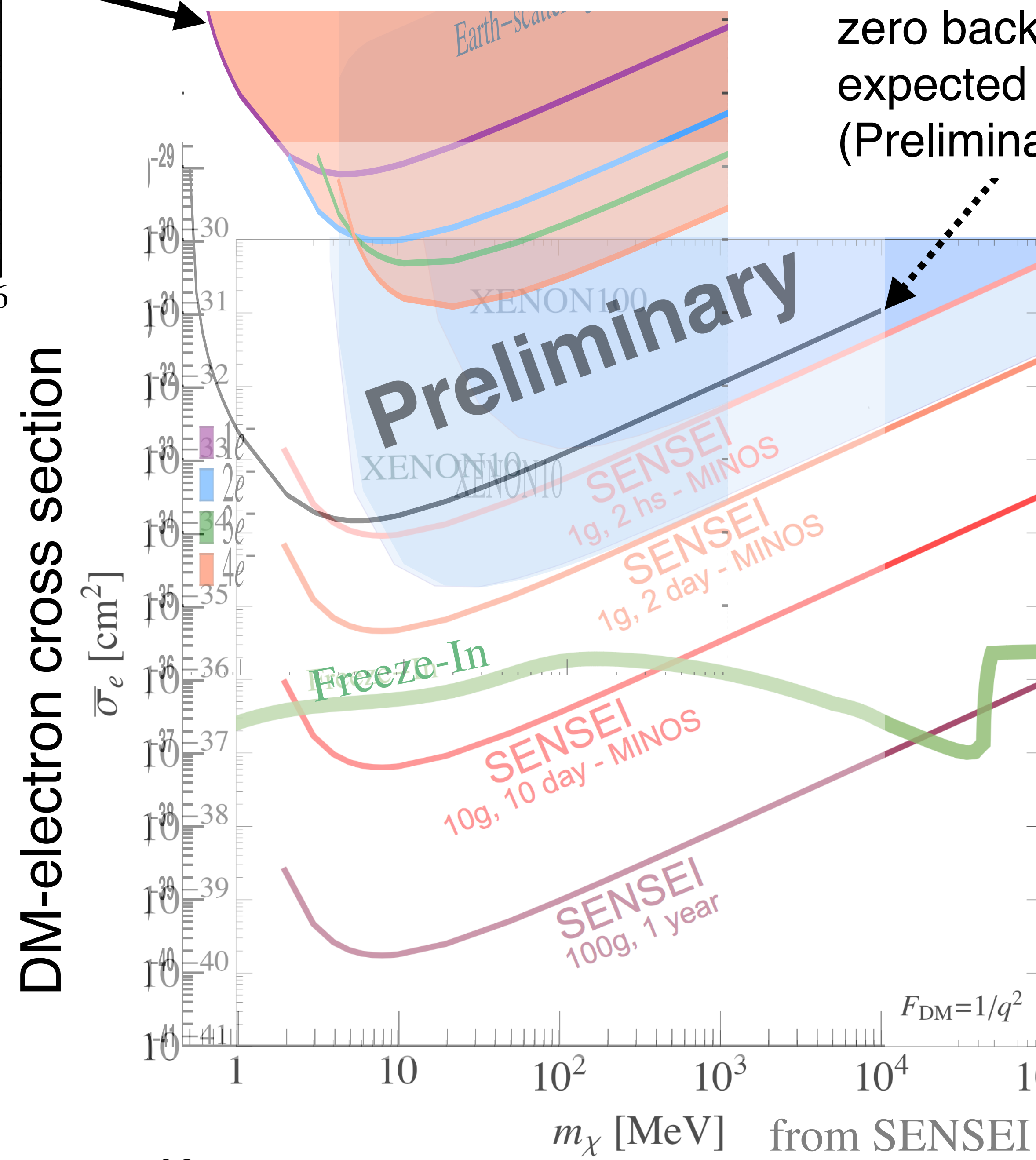
Expected 1day exposure compared to SENSEI



arXiv:1804.00088v1

SENSEI prototype physics run

DANAE prototype 24 mg one-day exposure zero background expected reach (Preliminary)

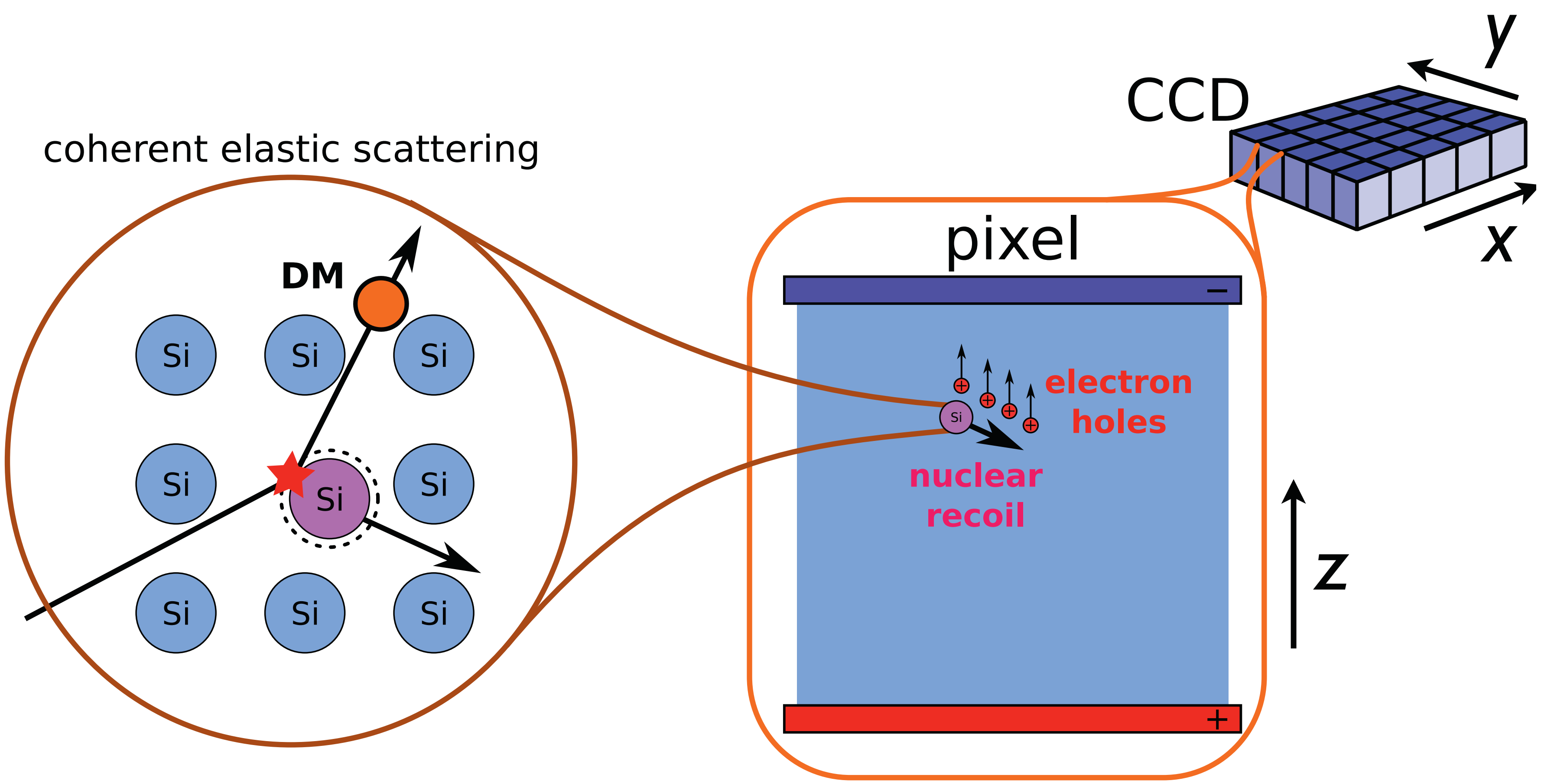


from SENSEI homepage

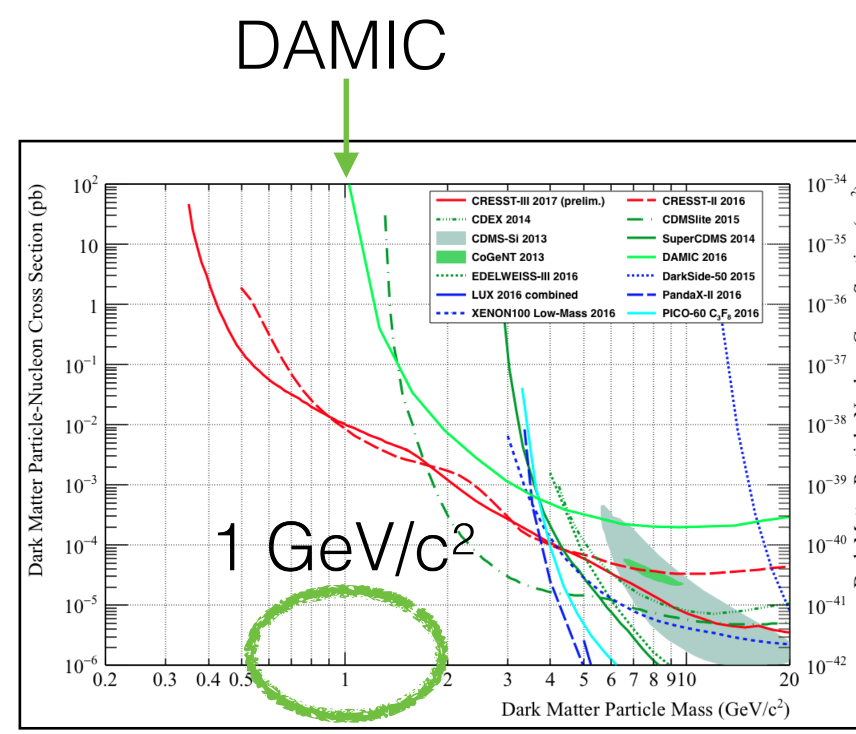
Application of Silicon detector

DAMIC

nucleus recoil   CCD, with physics results



Physics Procedia 61 (2015) 21 – 33

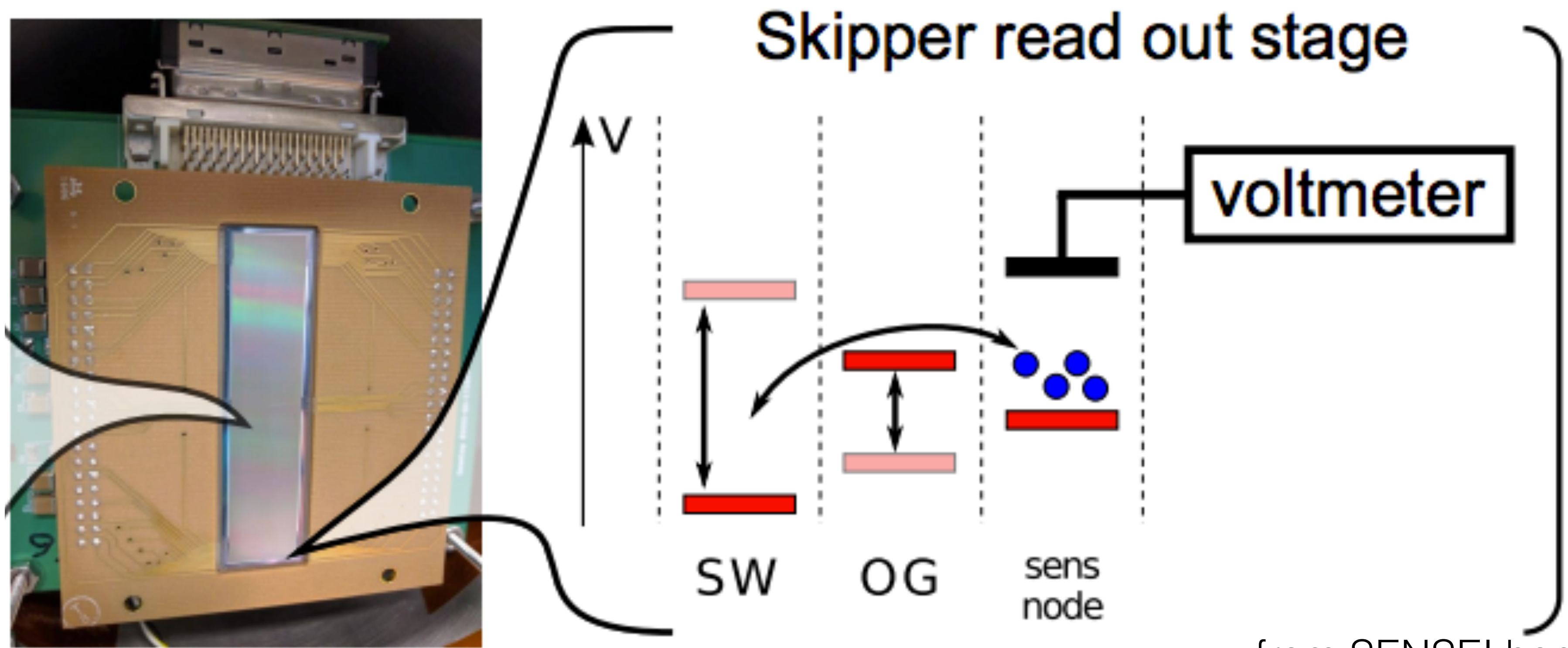


Readout noise determines threshold of ~ 11 e^- (or ~ 40 eV)

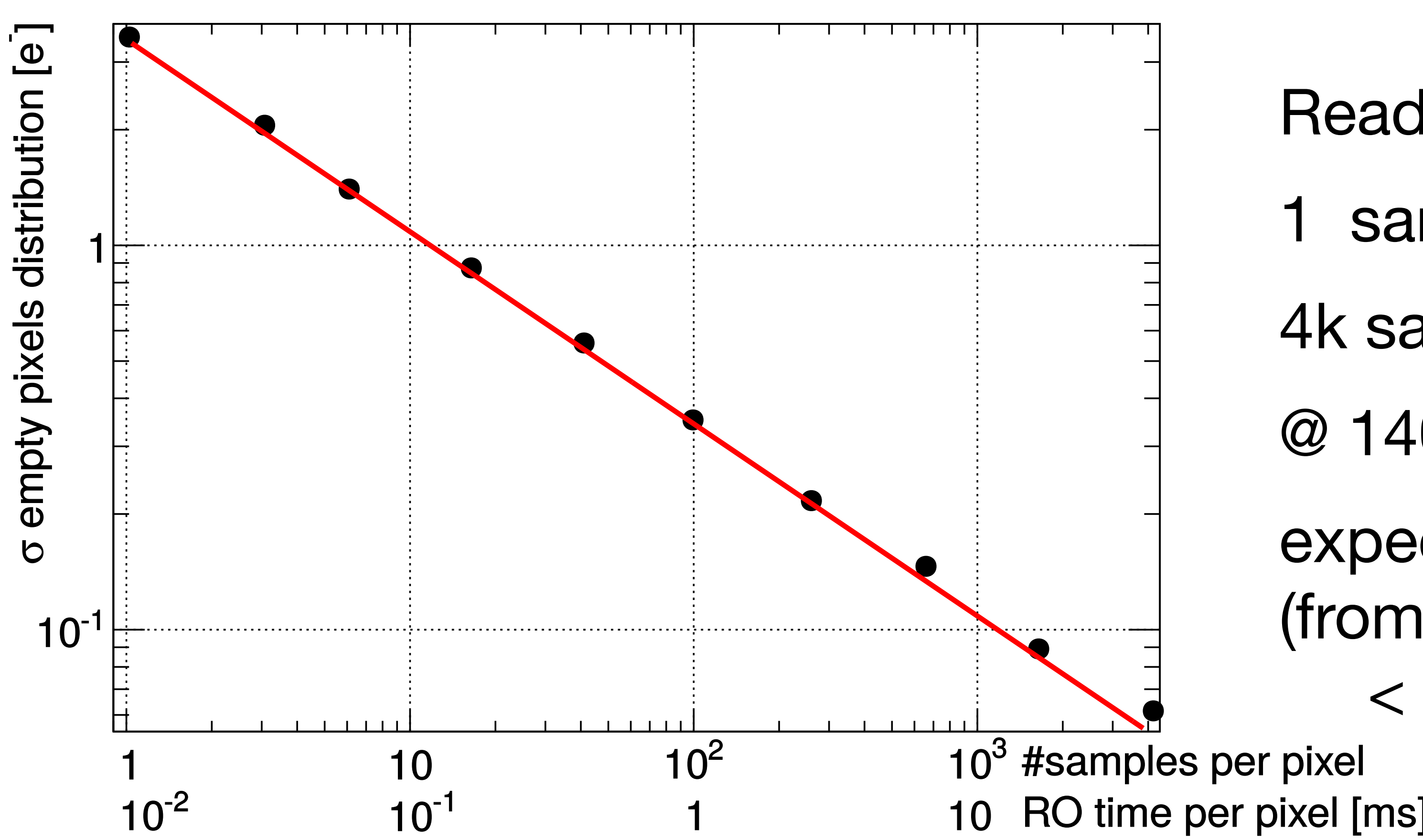
For O(MeV) DM-electron scattering, required threshold : O(e^-)
Sub-electron noise level necessary

Skipper CCD for SENSEI

DAMIC CCD with **repetitive readout**



from SENSEI homepage



PRL 119(1) 131802 (2017)

Readout noise :

1 sample : 3.55 e^- rms

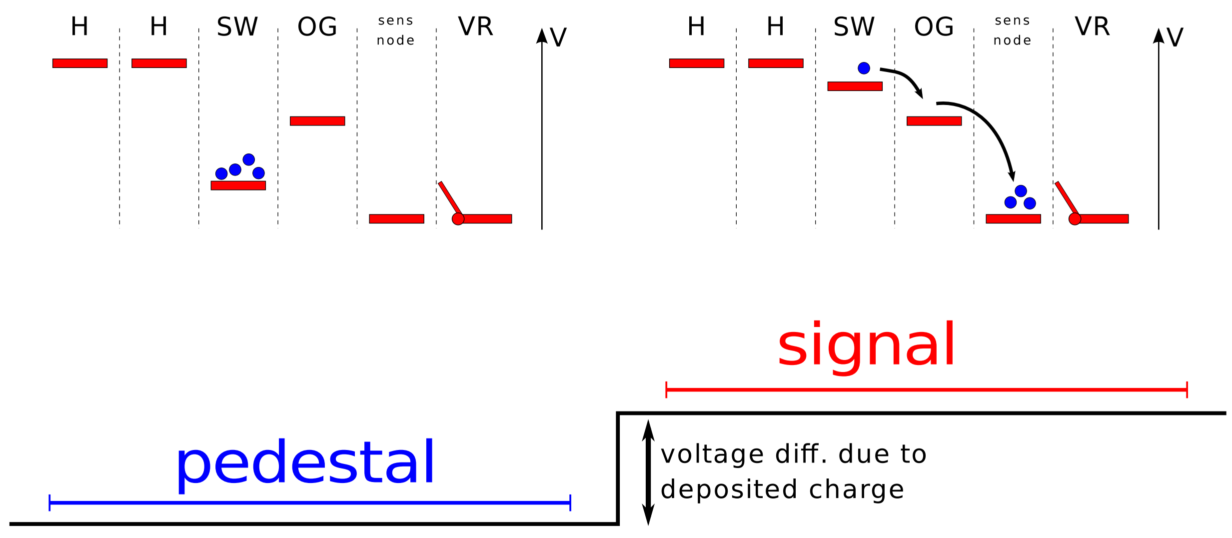
4k samples : 0.068 e^- rms

@ 140 K

expected dark current (from DAMIC CCD) :
< 10^{-3} e^-/pix/day

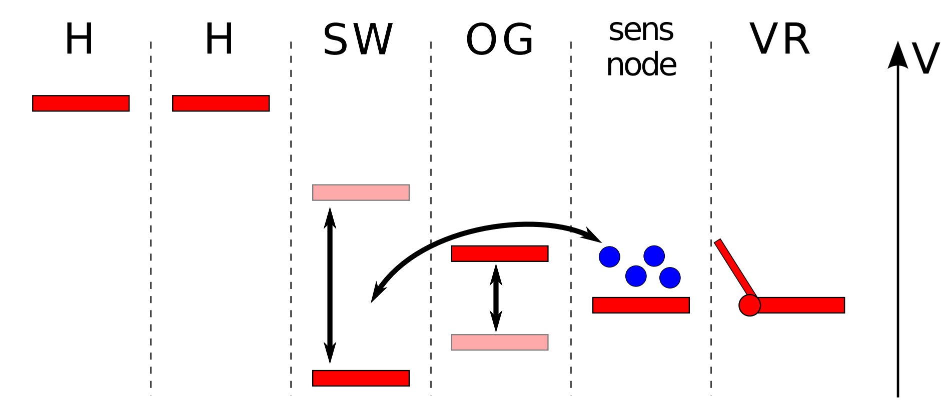
CCD (skipper) readout

CCD: readout



Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  Pixel value $= \frac{1}{N}\Sigma_i^N$ **(pixel sample)**$_i$



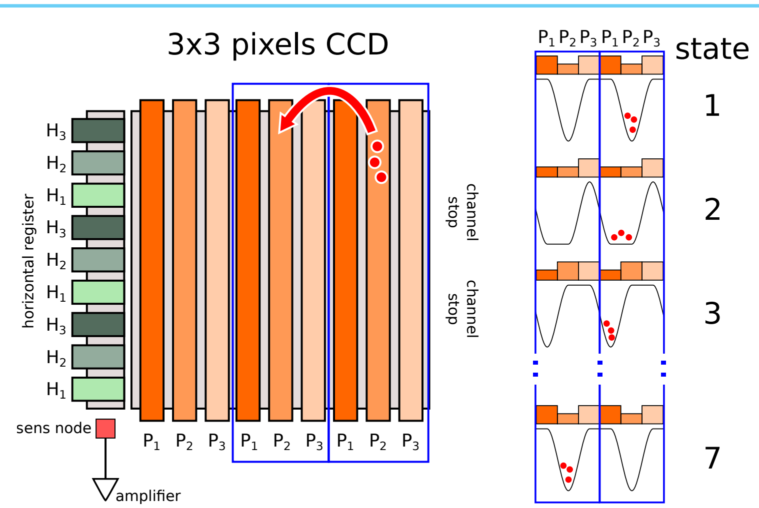
SW : summing-well gate

OG : output gate

RG : reset gate

VR : V_ref

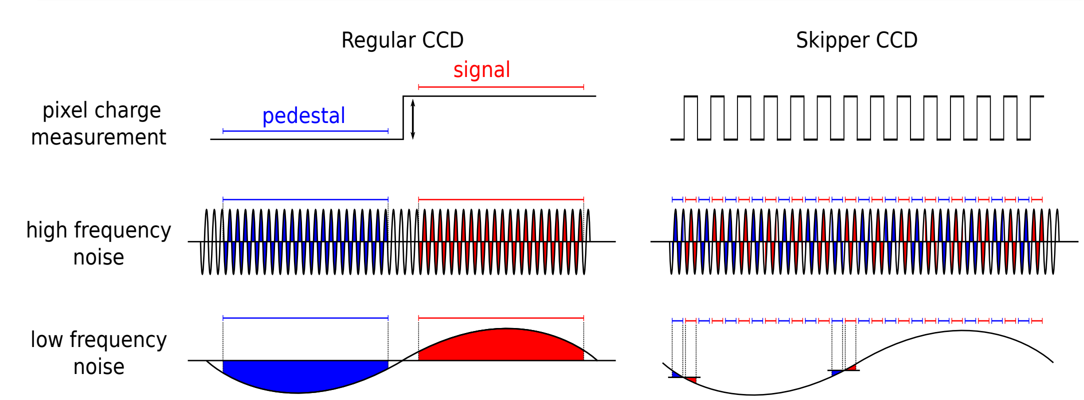
CCD: readout



capacitance of the system is set by the SN: C=0.05pF→ 3μV/e

Lowering the noise: Skipper CCD

- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  Pixel value $= \frac{1}{N}\Sigma_i^N$ **(pixel sample)**$_i$

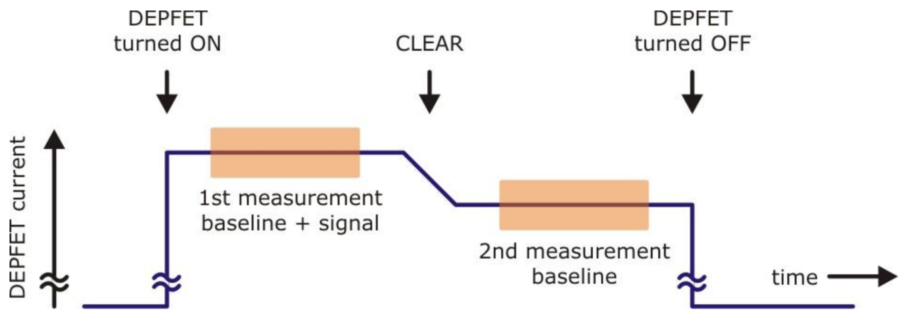


Javier Tiffenberg

DEPFET CDS circle

Detector Structures – Matrix Devices

- **readout sequence**

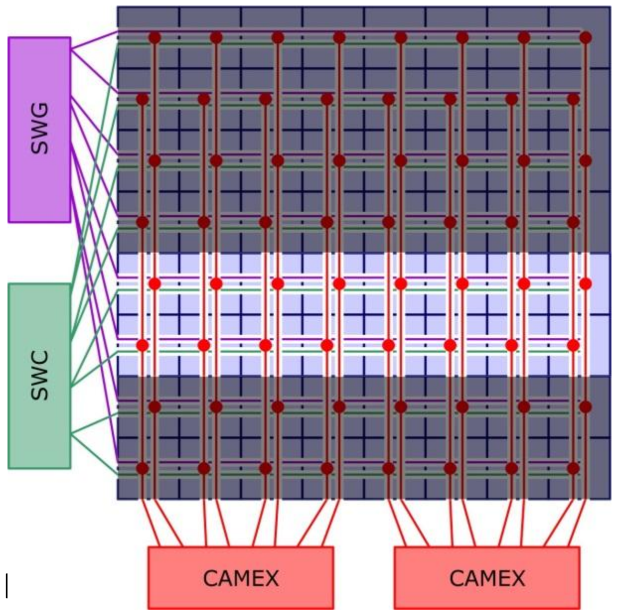


Correlated double sampling:

1st measurement: signal + baseline
clear: removal of signal charges
2nd measurement: baseline

difference = signal
complete clear is mandatory!

- **matrix operation**

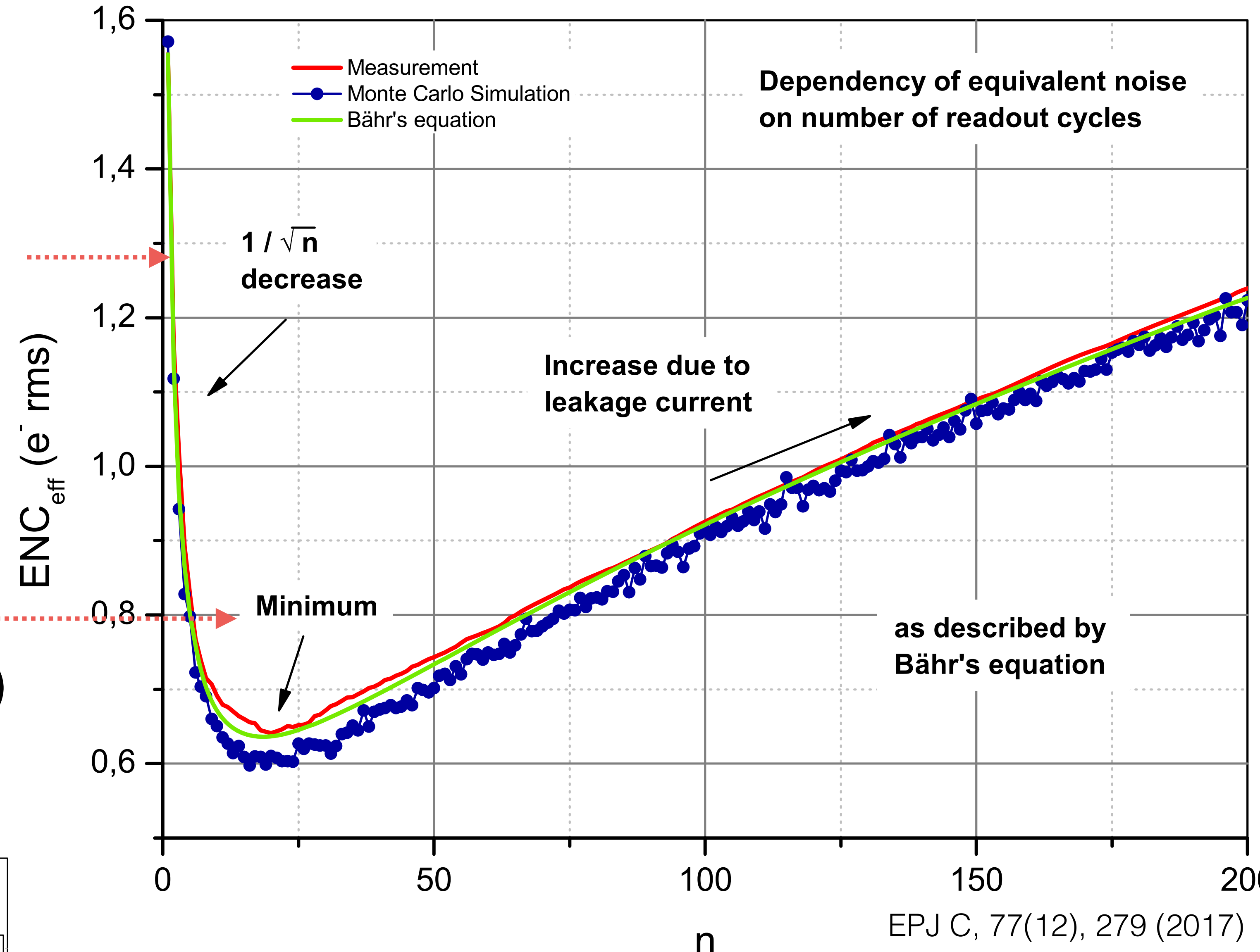


vertical signal lines
1 active row, other pixels integrating

- **option to speed up (1)**

readout parallelisation
2 x readout channels, 2 active rows

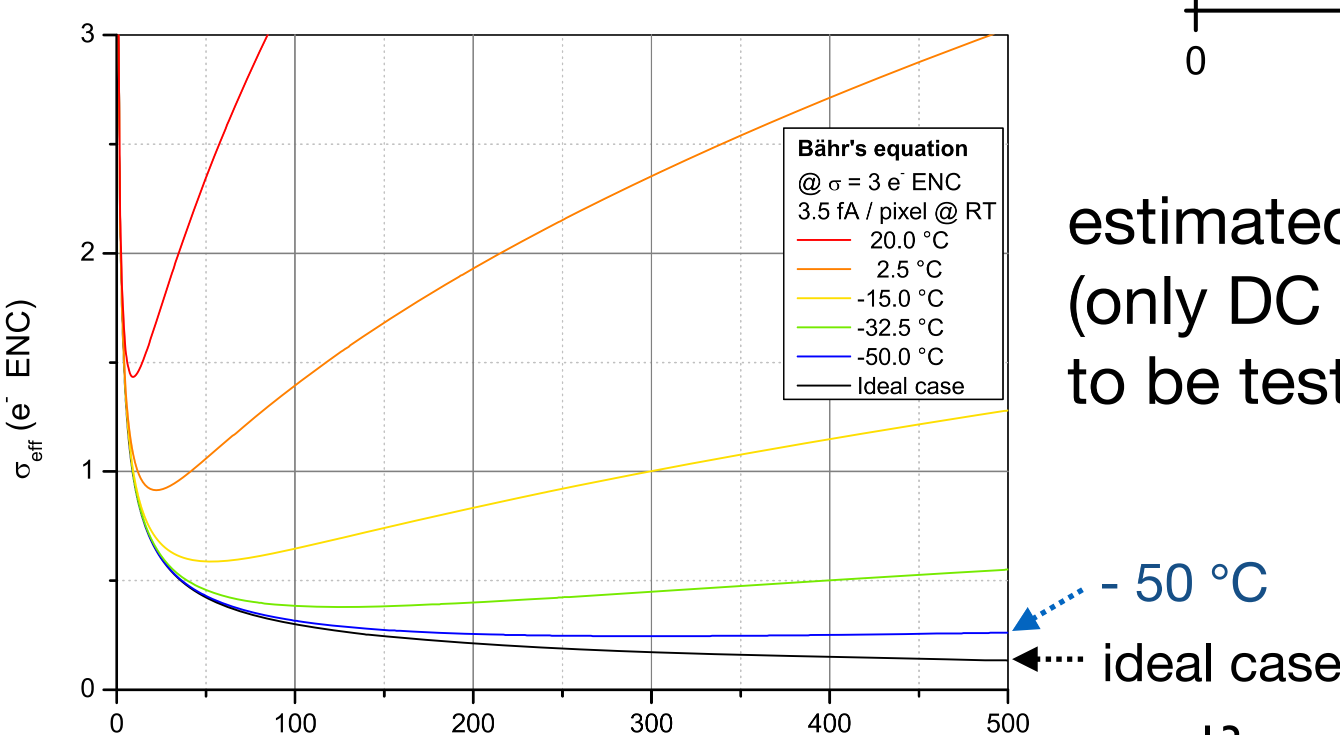
DEPFET RNDR single pixel performance



EPJ C, 77(12), 279 (2017)

confirmed the 1/√N decrease of σ_{eff}

minimal noise level limited by leakage current at 230 K (-40 °C)



EPJ C, 77(12), 279 (2017)

estimated temperature dependence (only DC from thermal excitation) to be testified in measurement

new architecture with “blind-gate” possibility of reducing leakage current during readout