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

Hexi Shi
HEPHY ÖAW

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

ÖAW

07 July 2018
ICHEP2018
Seoul, South Korea

DANAE (DANAË)

<u>D</u>irect d<u>A</u>rk matter search using DEPFET with repetitive-<u>N</u>on-destructive-readout <u>A</u>pplication <u>E</u>xperiment

OeAW funding for detector technology

“Danae” by G. Klimt

Collaboration

A. Bähr [A], J. Ninkovic [A], J. Treis [A],
H. Kluck [B,C], J. Schieck [B,C], H. Shi [B],

Austria

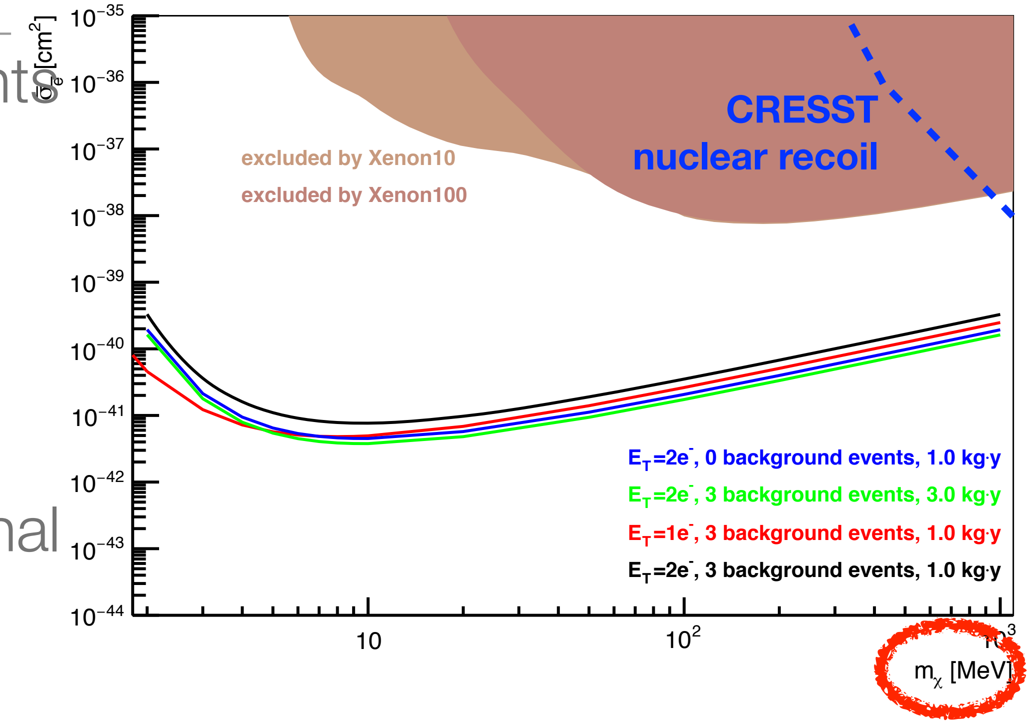
Germany

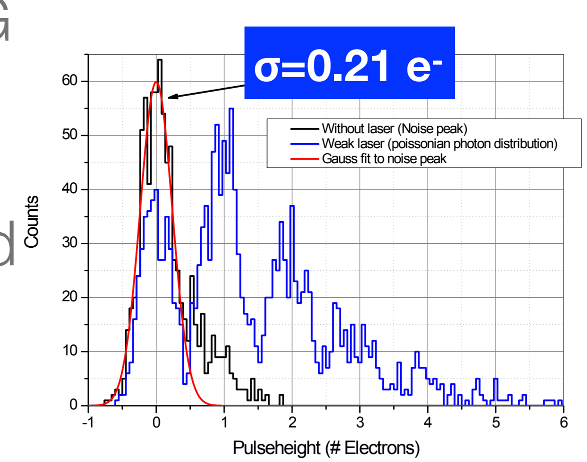
Max-Planck-Gesellschaft Halbleiterlabor, Germany [A],
Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, Vienna, Austria [B],
Atominstitut, Technische Universität Wien, Vienna, Austria [C]

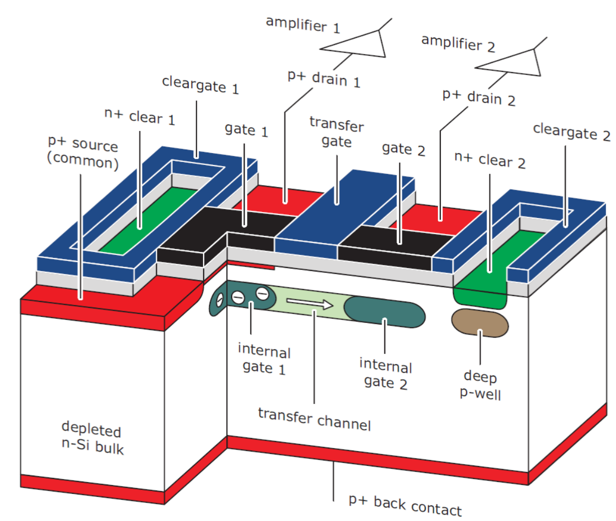
The project overview

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







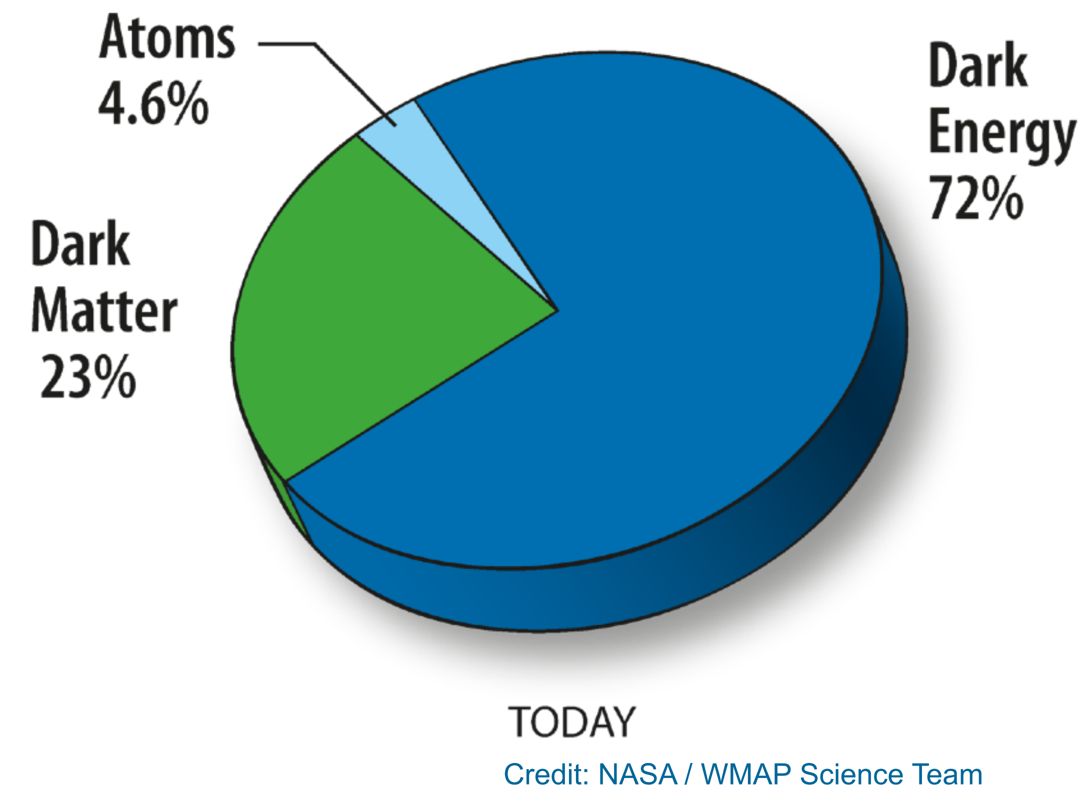
EPJ C, 77(12), 279 (2017)

*Repetitive Non-Destructive Readout

from Jochen Schieck "Experimental Dark Matter Search at HEPHY"

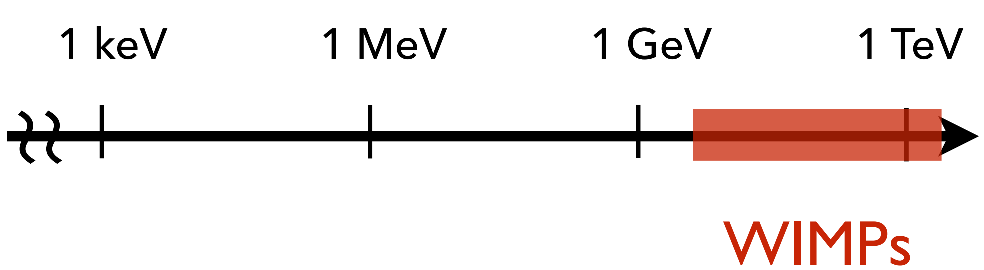
Dark matter landscape - partly

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



"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

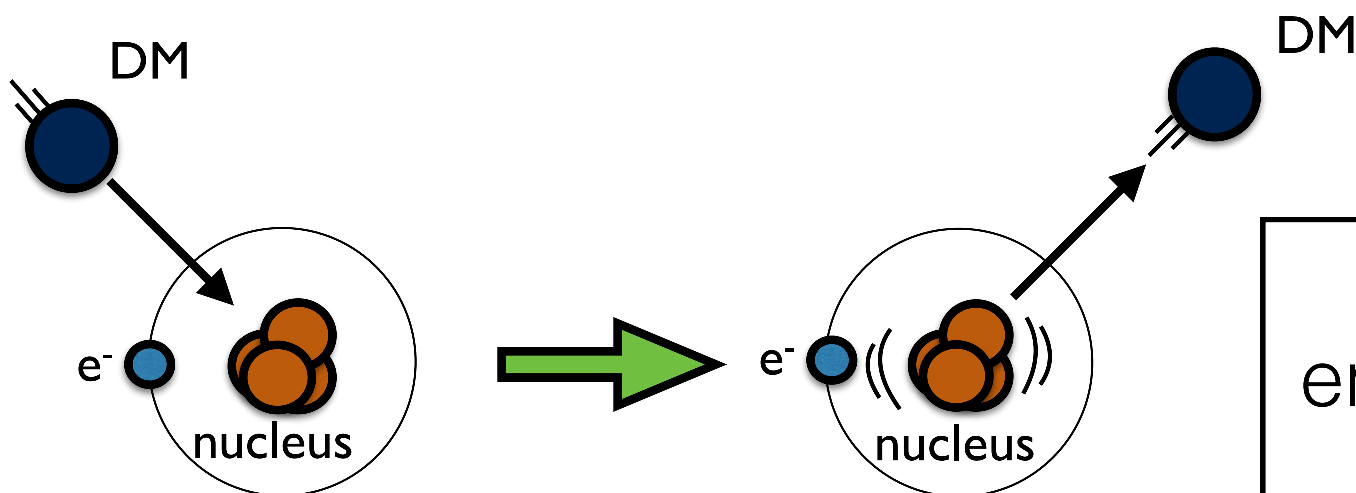


image credit R. Essig

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

<u>Detection limitation :</u>
energy deposit from nucleus recoil
$E_{NR} \sim 2\mu_{\chi,N}^2 . v_\chi / m_N$

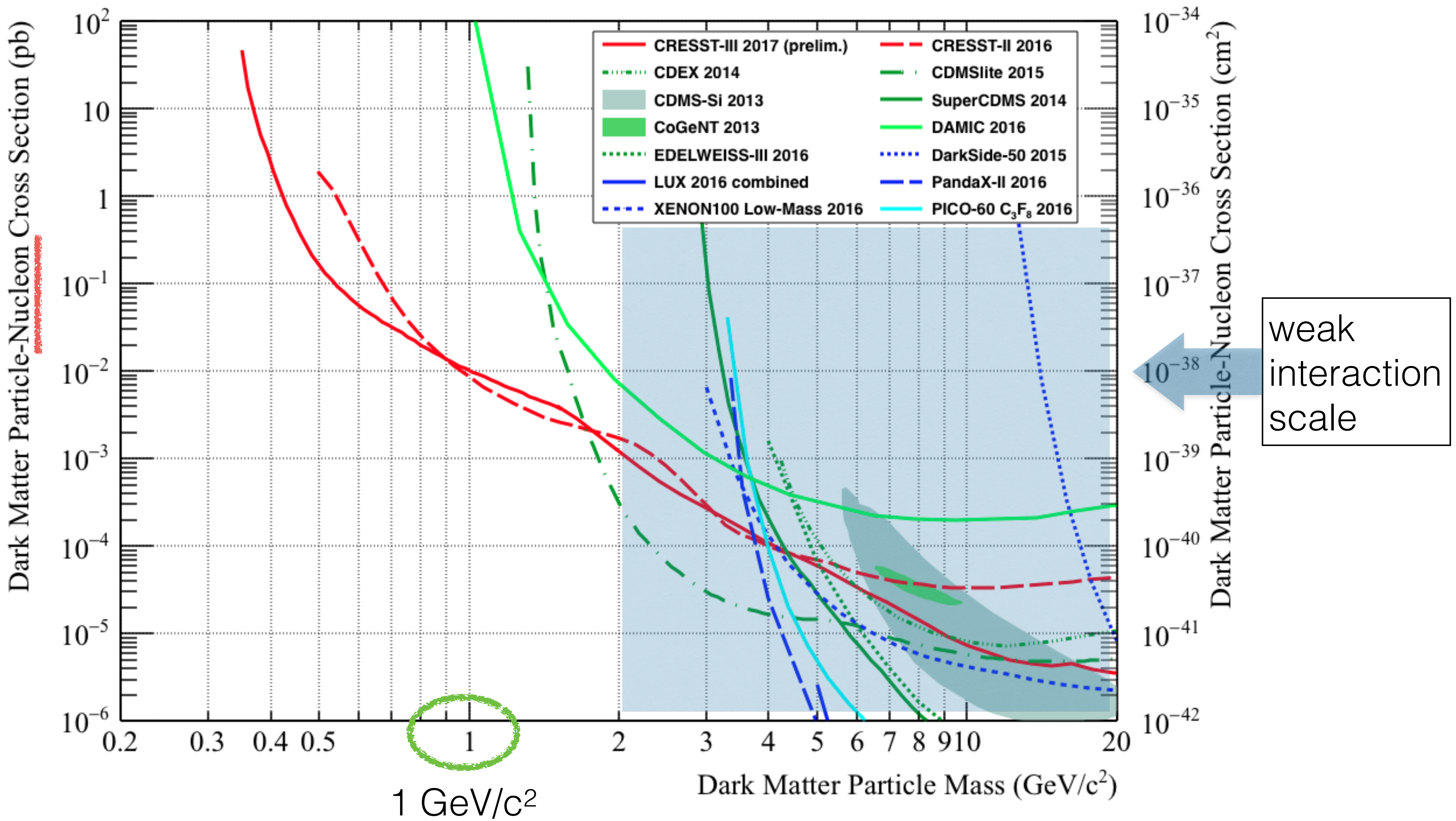
-> for 100 MeV m_χ, $E_{NR} \sim 1$ eV *

plus quenching factors and noise level of the detectors

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

*for silicon

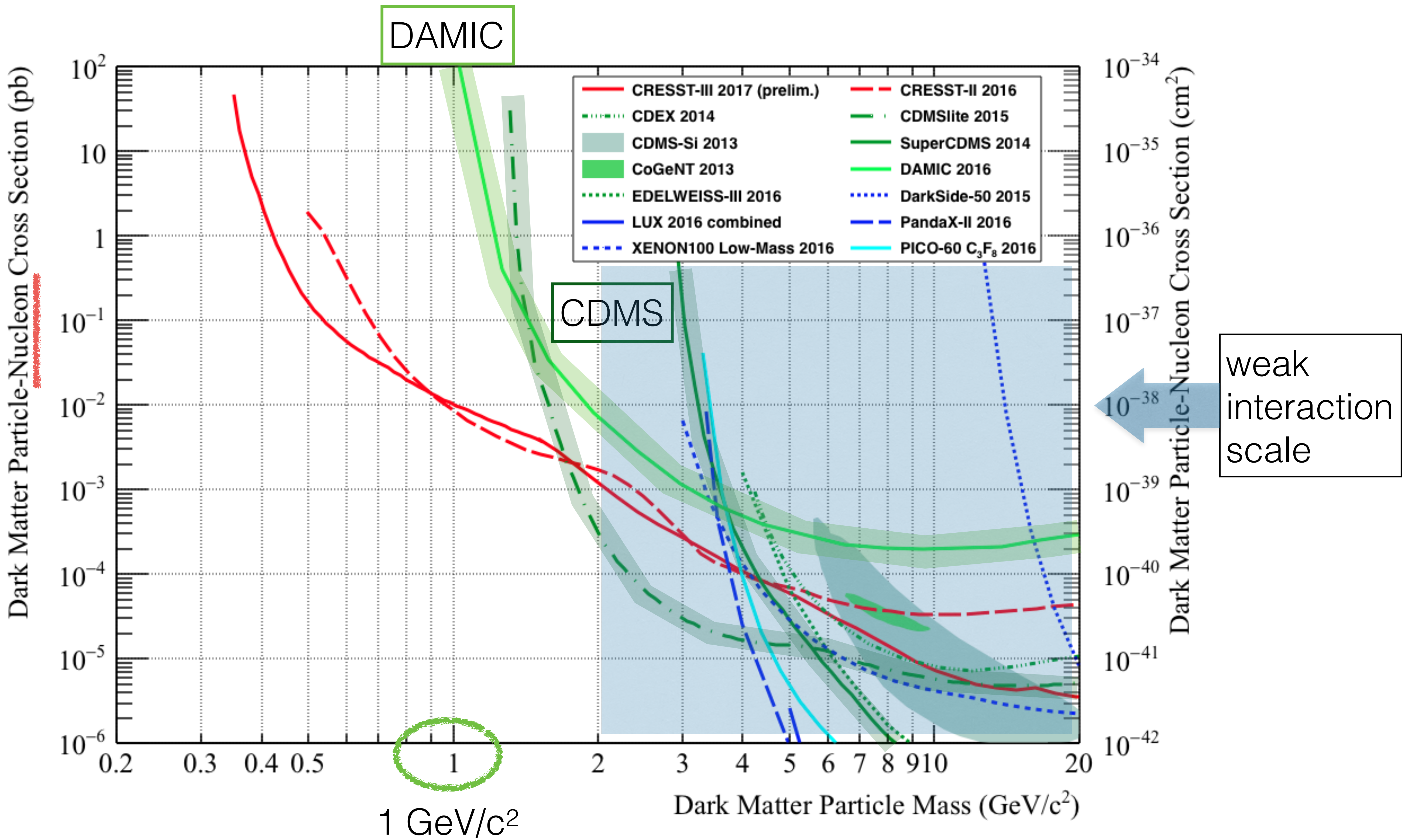
DM-nucleus scattering direct search status



no evidence for WIMP yet

arXiv:1711.07692

DM-nucleus scattering direct search status



no evidence for WIMP yet

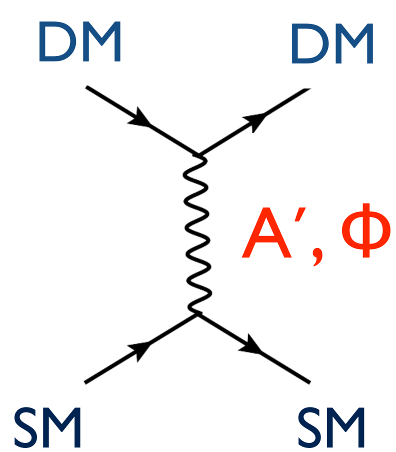
arXiv:1711.07692

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**
-> comparable observables in experiments

DM-electron scattering

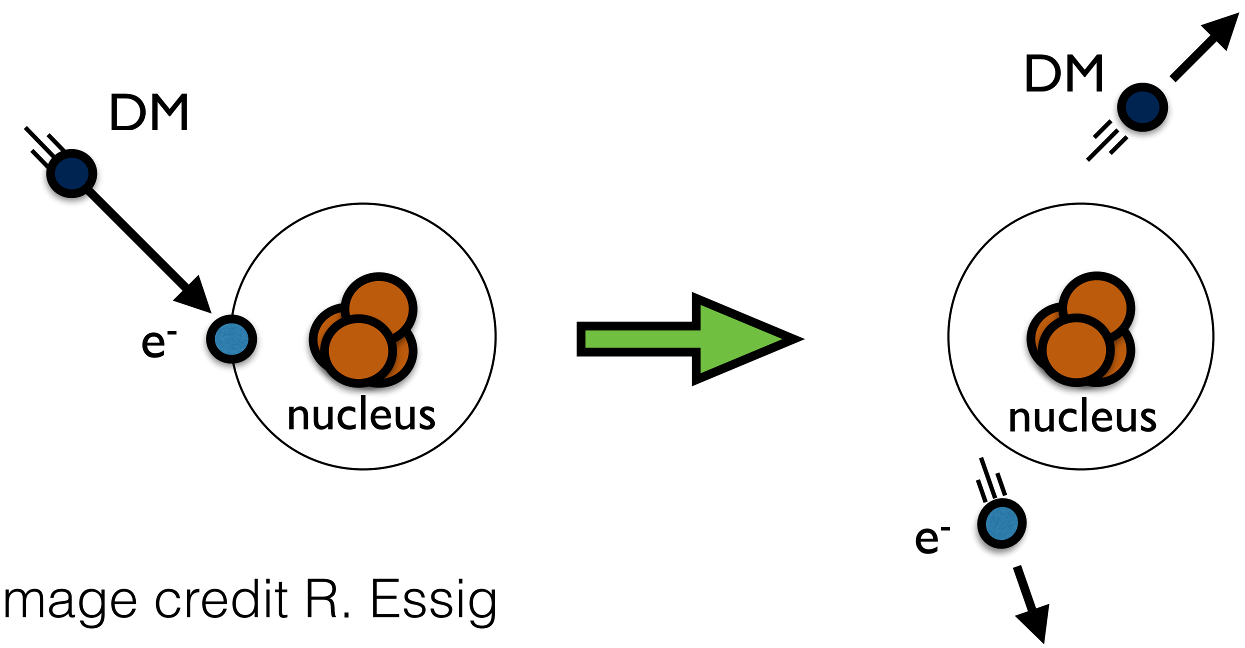


image credit R. Essig

kinematically

to overcome binding energy ΔE

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

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

O(100 keV)

JHEP05(2016)046

DM-electron scattering

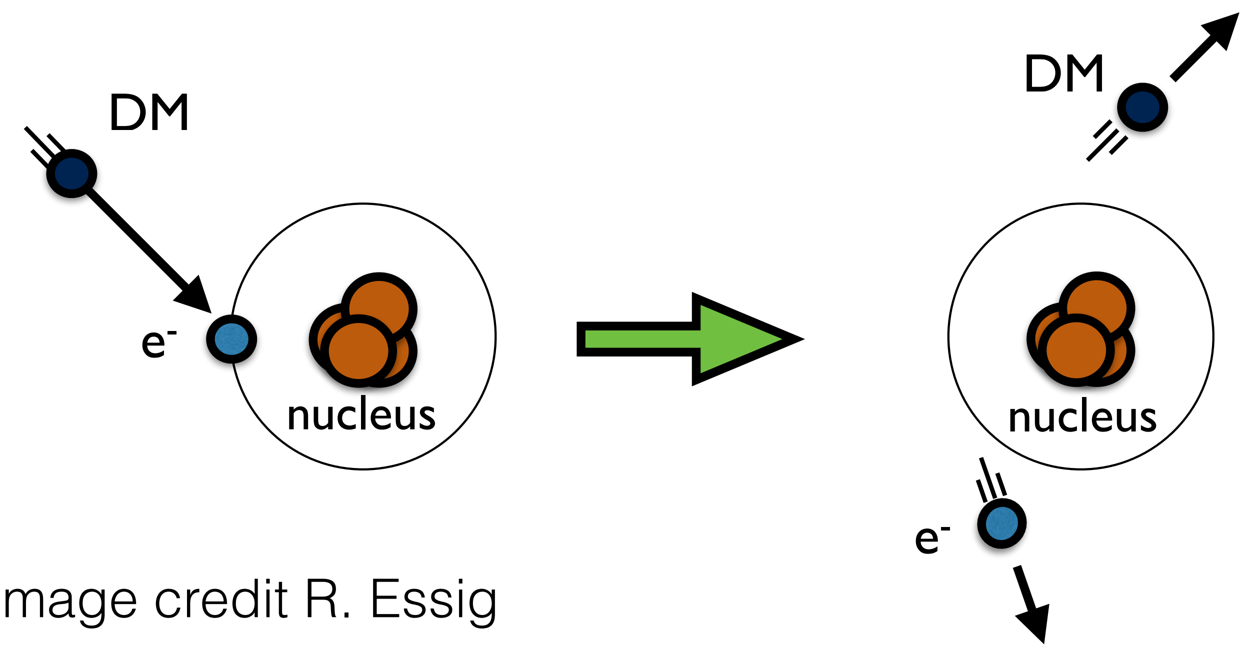


image credit R. Essig

kinematically

to overcome binding energy ΔE

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

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

O(100 keV)

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

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

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

$\Delta E_e \sim 4 \ {\rm eV}$ typical recoil energy

JHEP05(2016)046

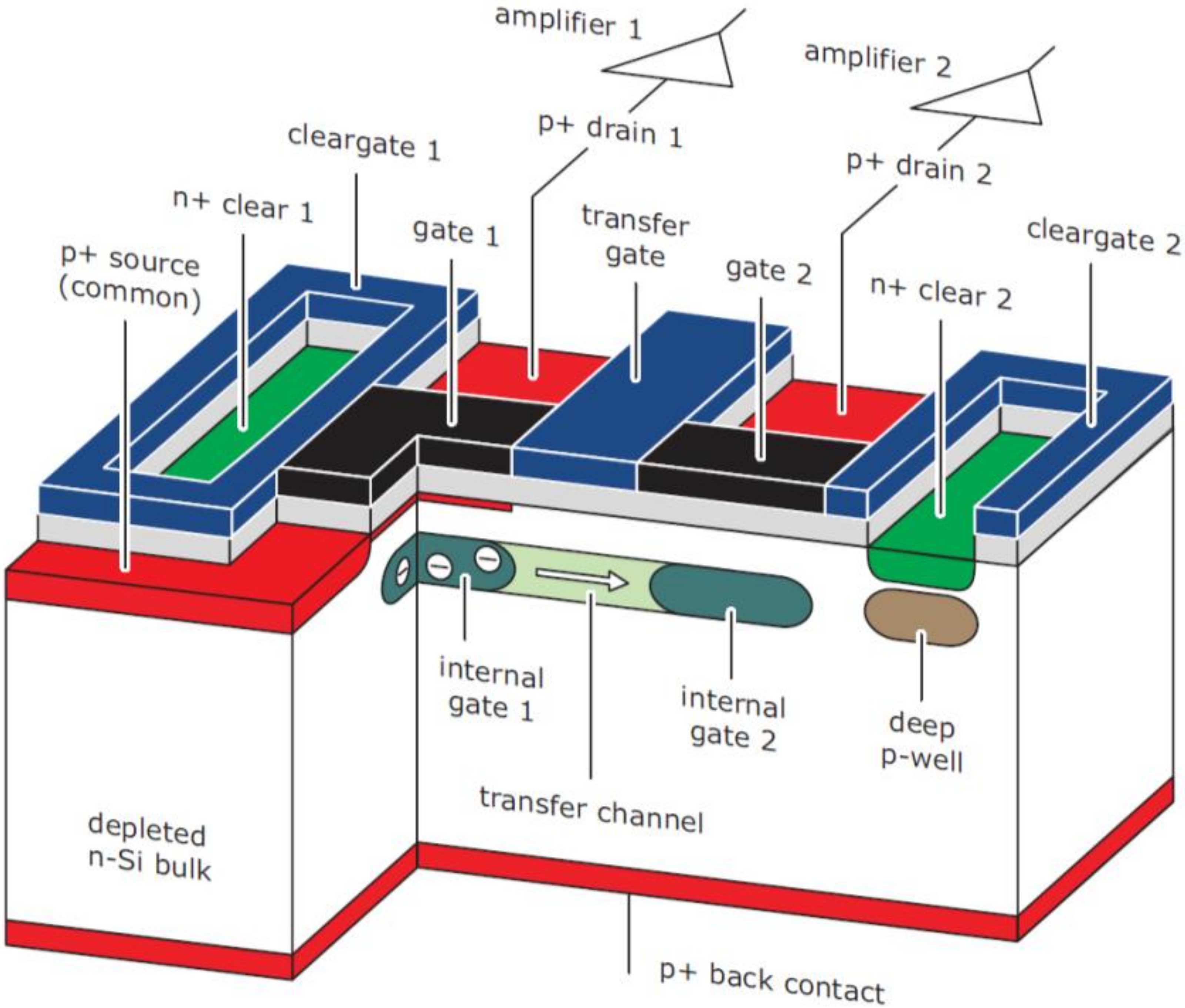
Target materials for electron recoils

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

DEPFET with RNDR

structure of RNDR DEPFET "super-pixel"



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

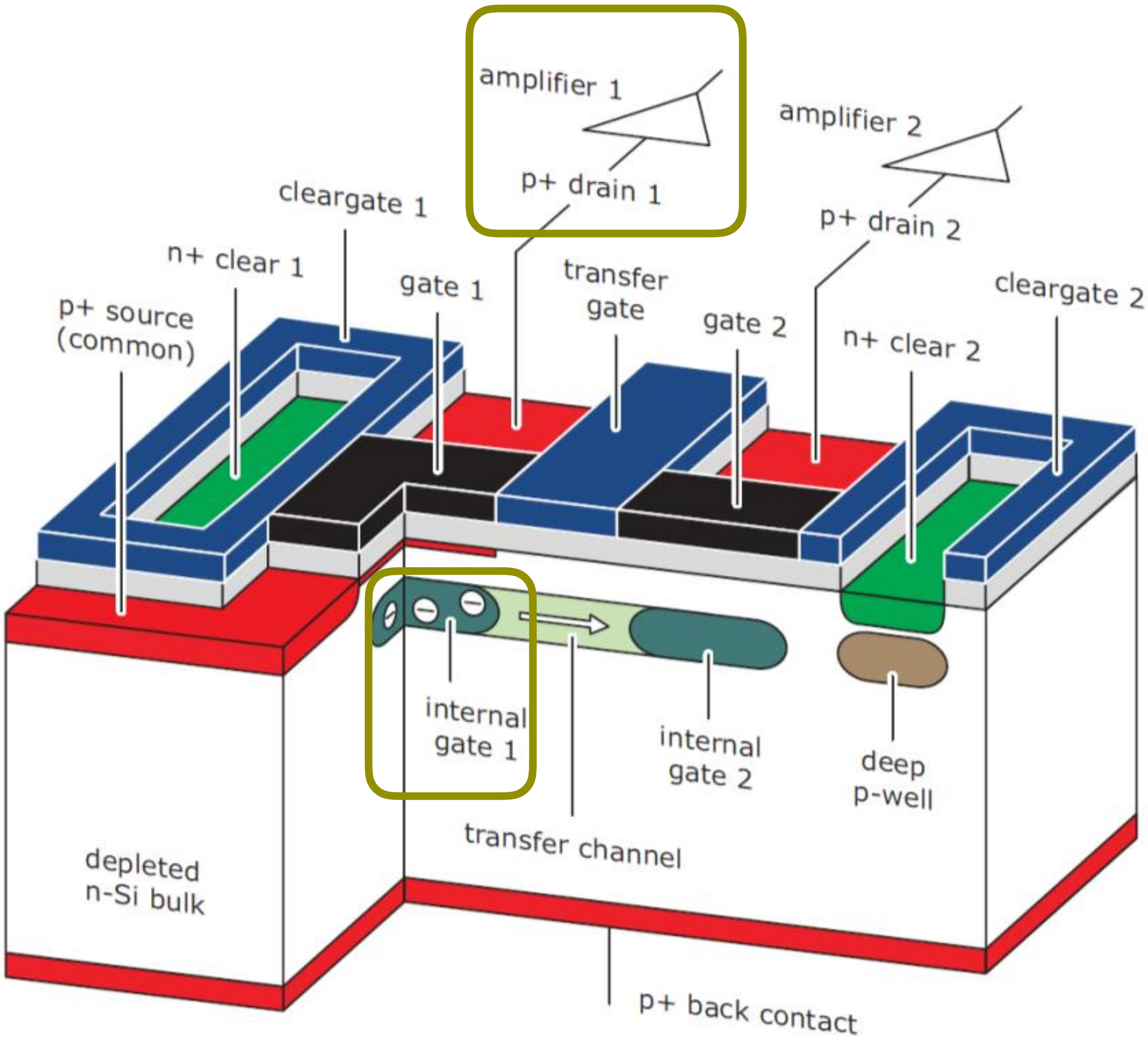
RNDR readout

read N times *effective noise* :

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

DEPFET with RNDR

structure of RNDR DEPFET "super-pixel"



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

RNDR readout

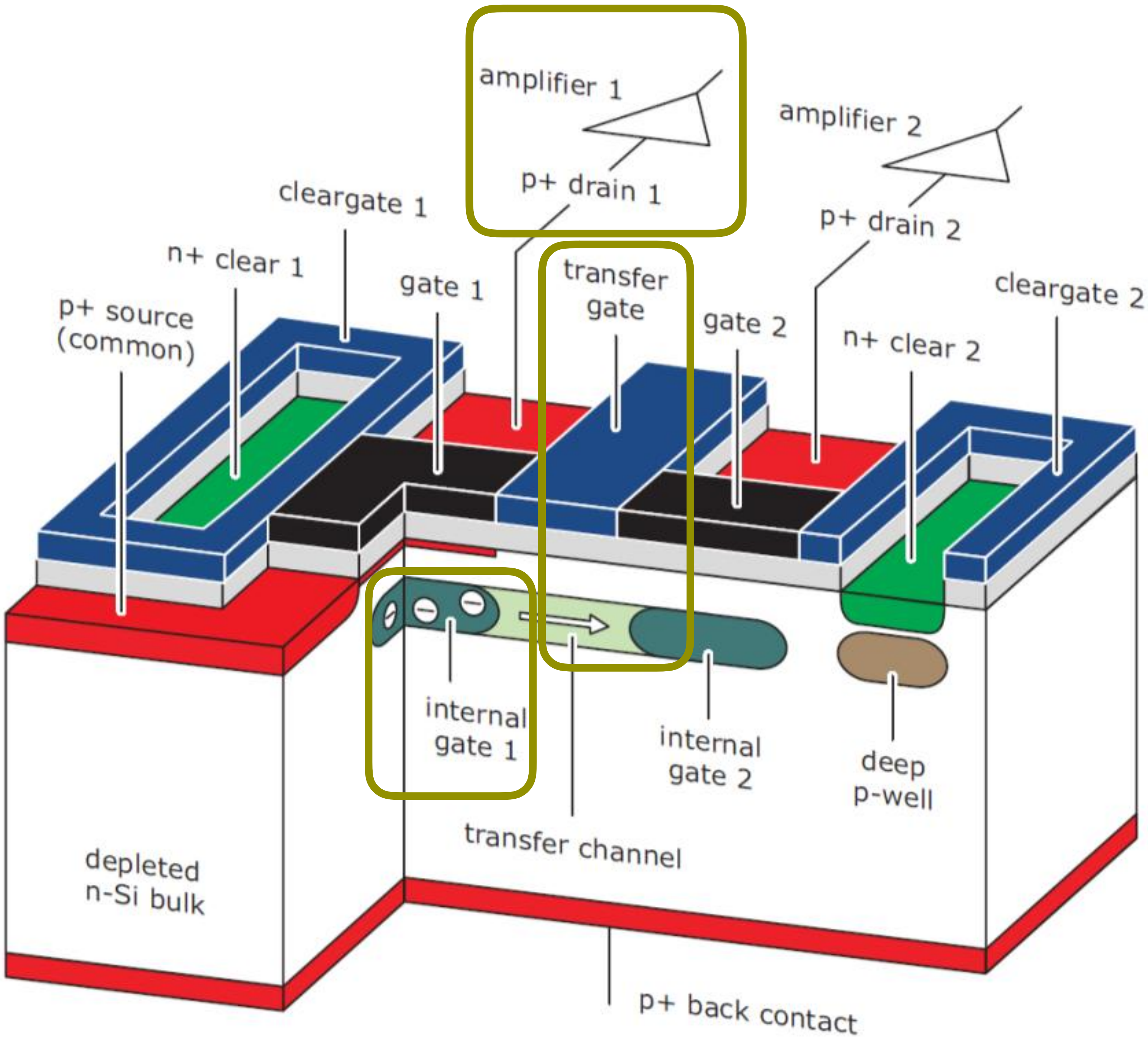
read **1** : noise **σ**

read N times *effective noise* :

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

DEPFET with RNDR

structure of RNDR DEPFET "super-pixel"



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

RNDR readout

read **1** : noise **σ**

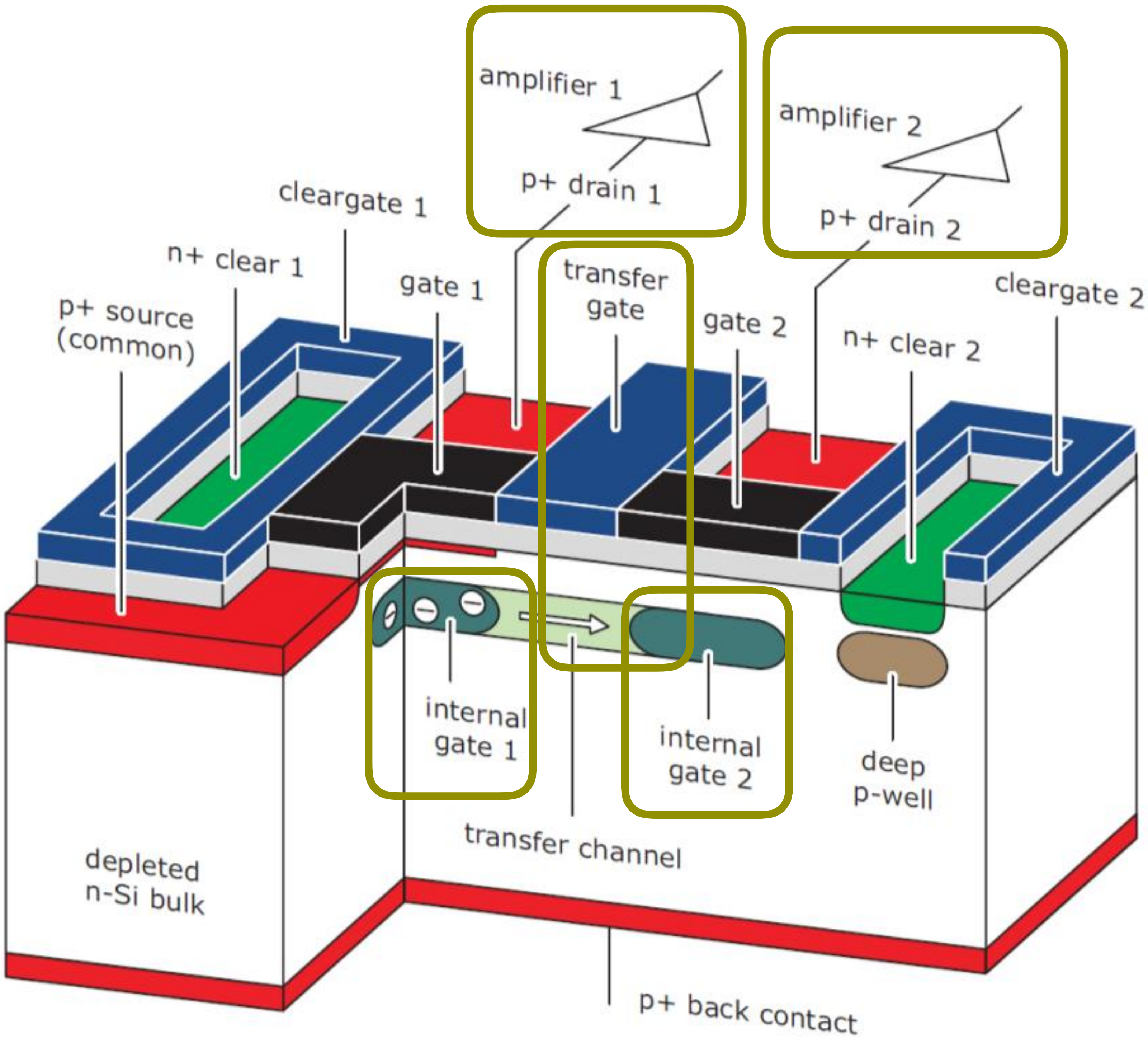
transfer gate open

read N times *effective noise* :

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

DEPFET with RNDR

structure of RNDR DEPFET “super-pixel”



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

RNDR readout

read **1** : noise **σ**

transfer gate open

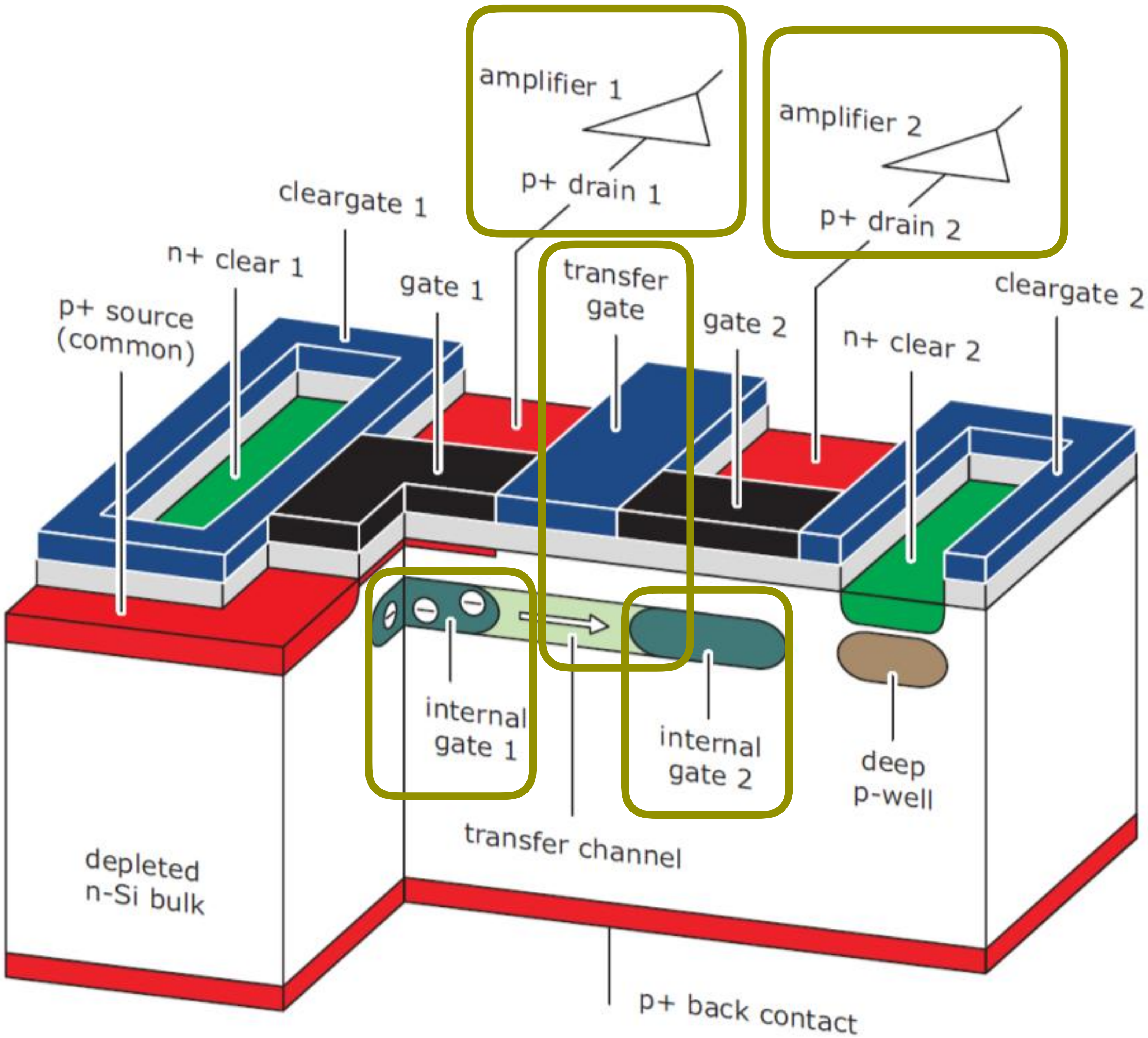
read **2** : noise **σ**

read N times *effective noise* :

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

DEPFET with RNDR

structure of RNDR DEPFET “super-pixel”



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

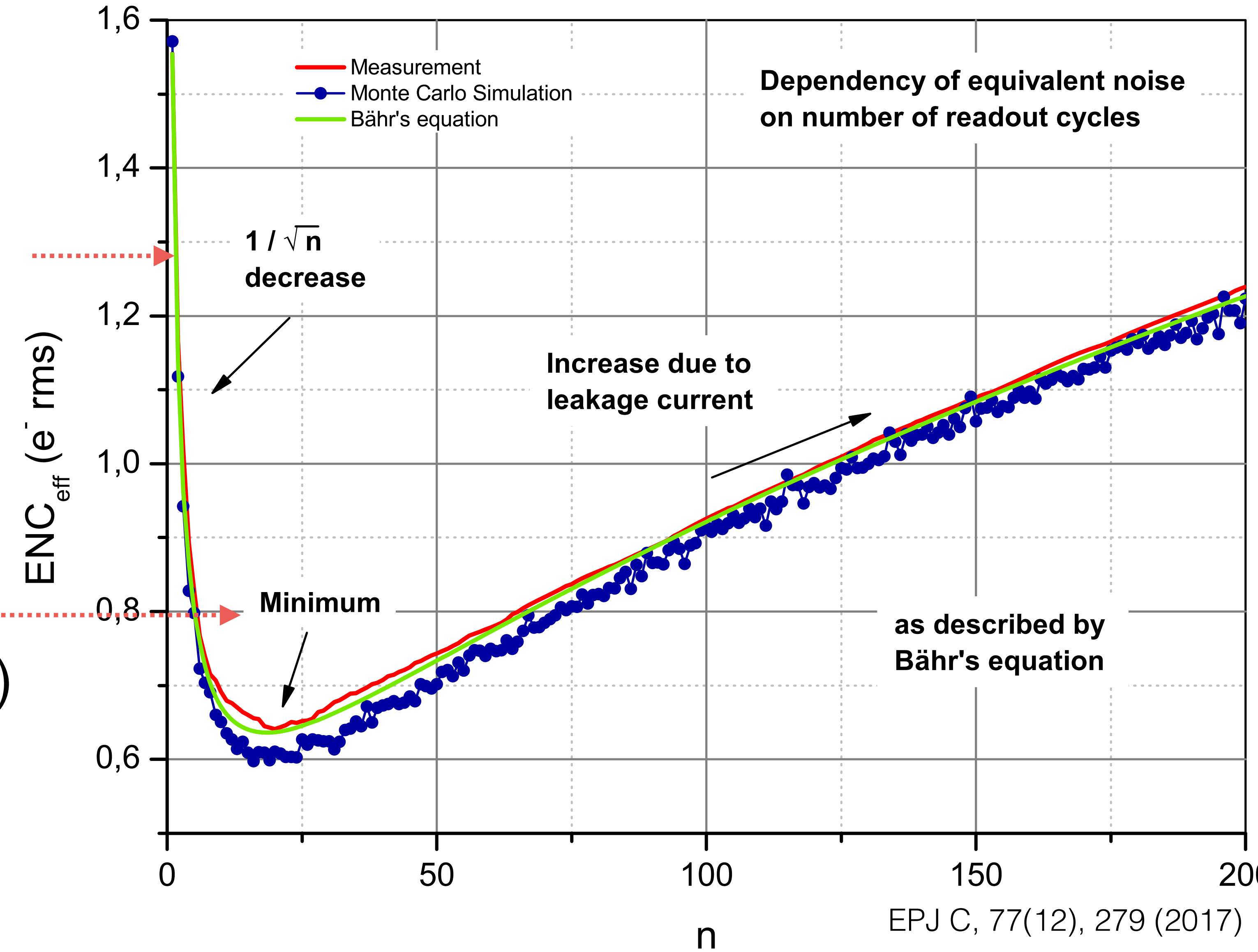
read N times *effective noise* :

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

DEPFET RNDR single pixel performance

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

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

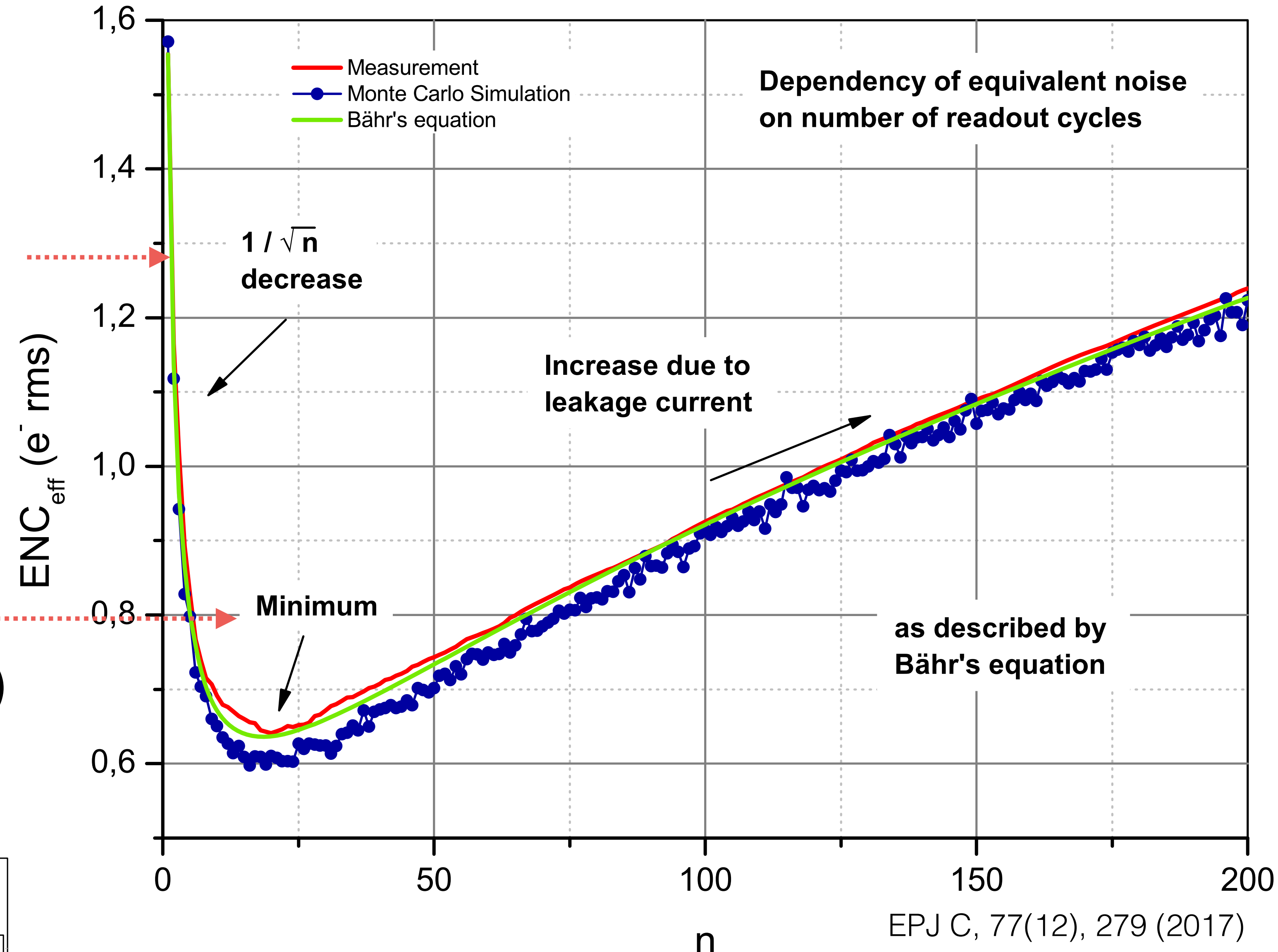


EPJ C, 77(12), 279 (2017)

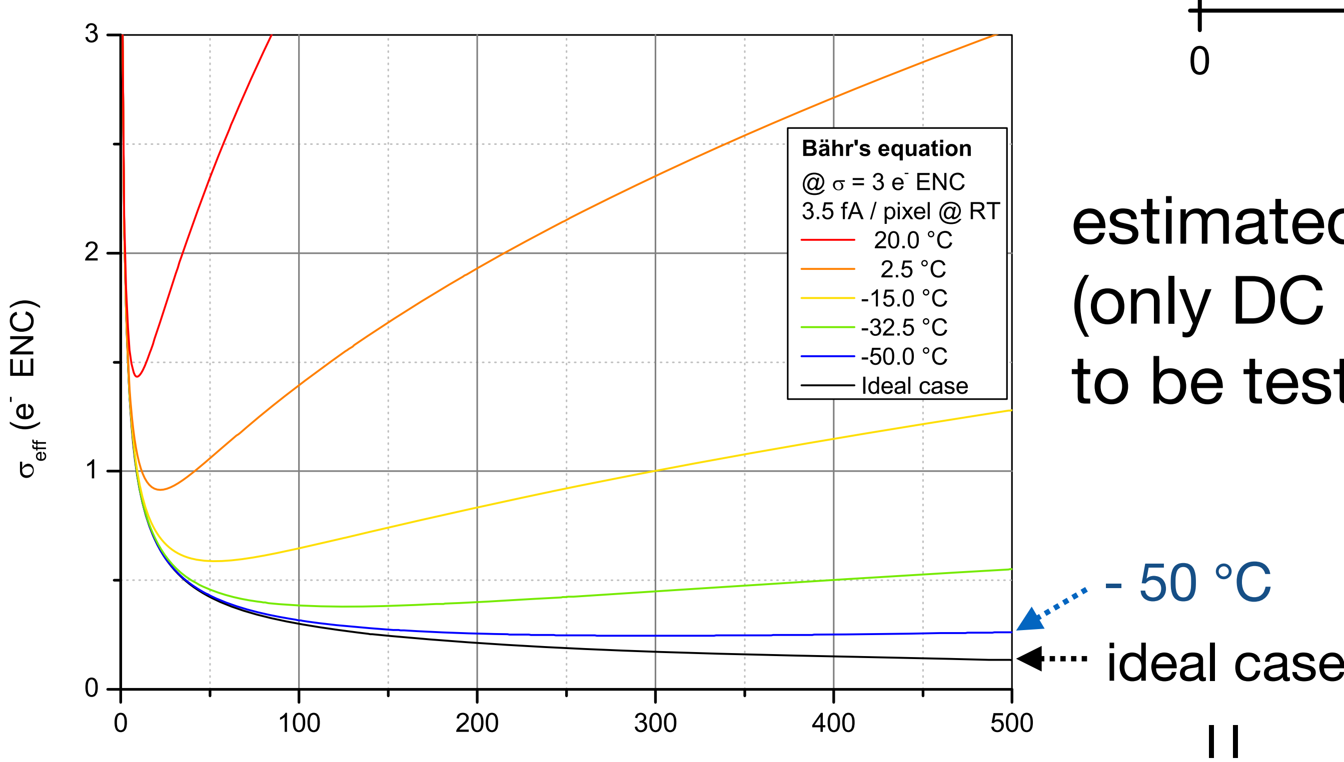
DEPFET RNDR single pixel performance

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

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



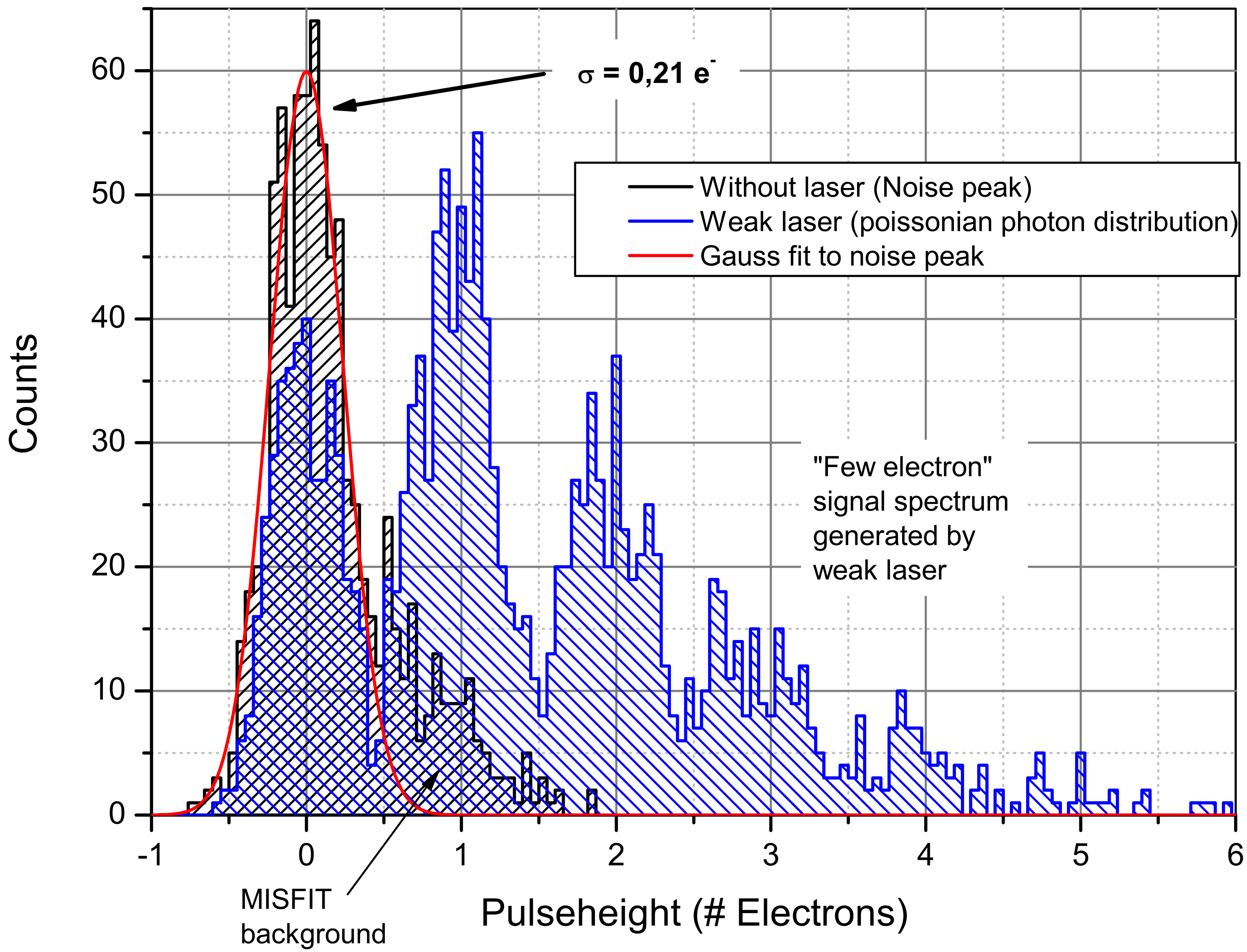
EPJ C, 77(12), 279 (2017)



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

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

DEPFET RNDR single pixel performance



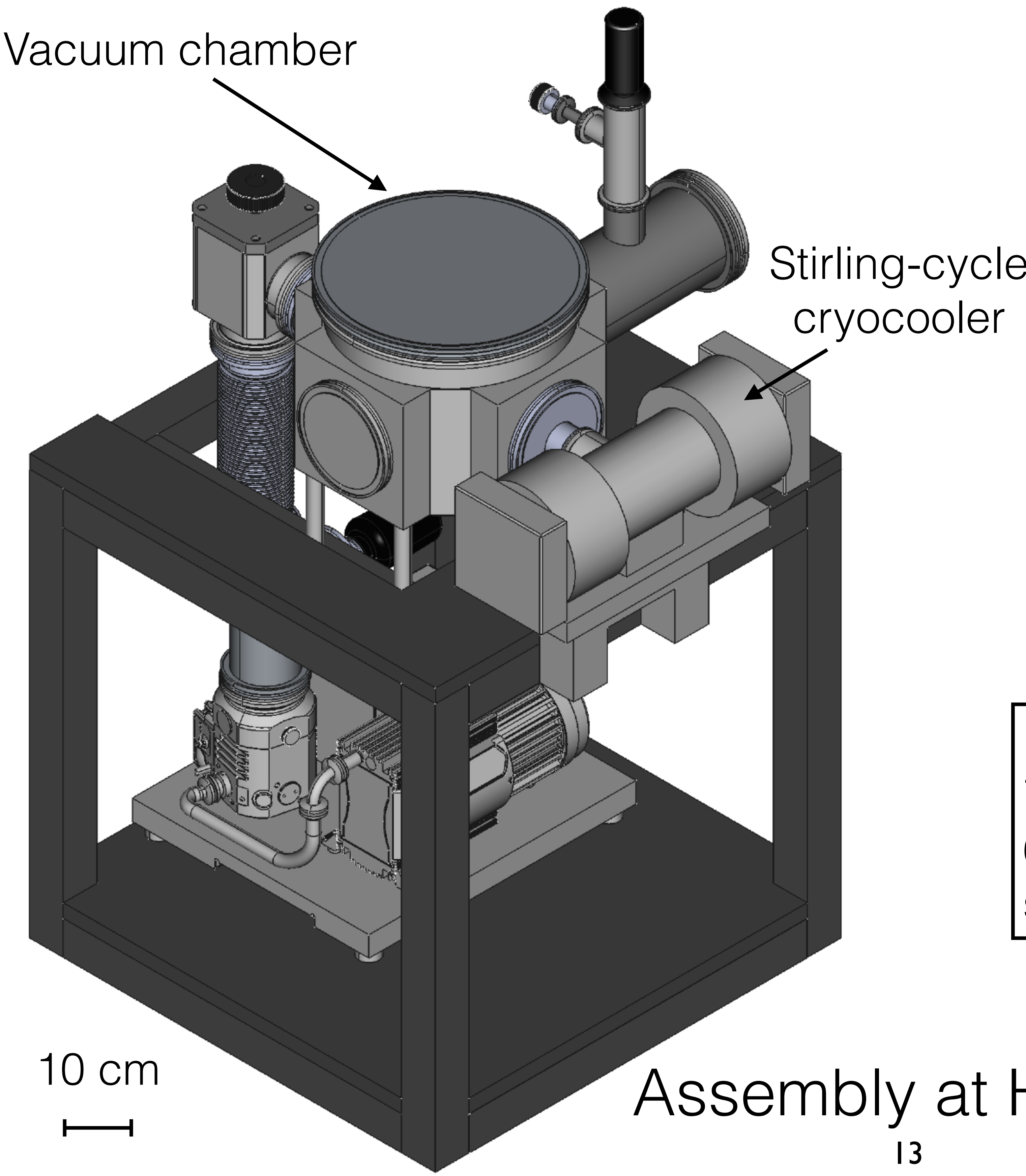
single pixel RNDR DEPFET effective noise :

0.2 e^{-} RMS at 200 K

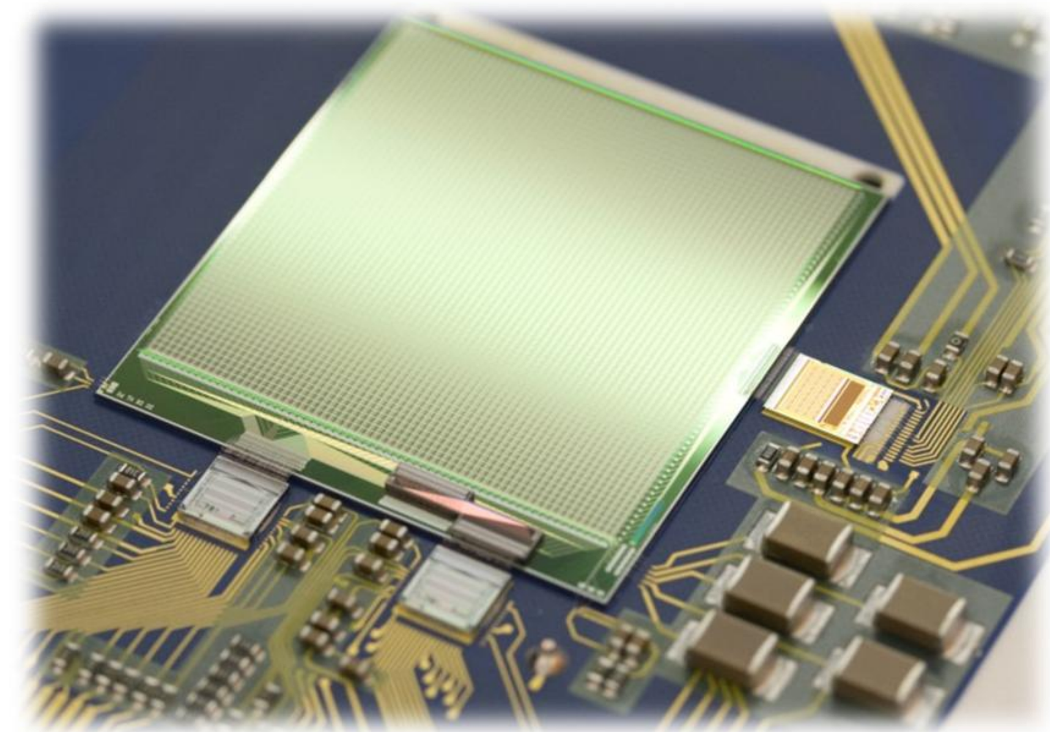
capable of distinguish single electron charge

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

DANAE prototype test setup



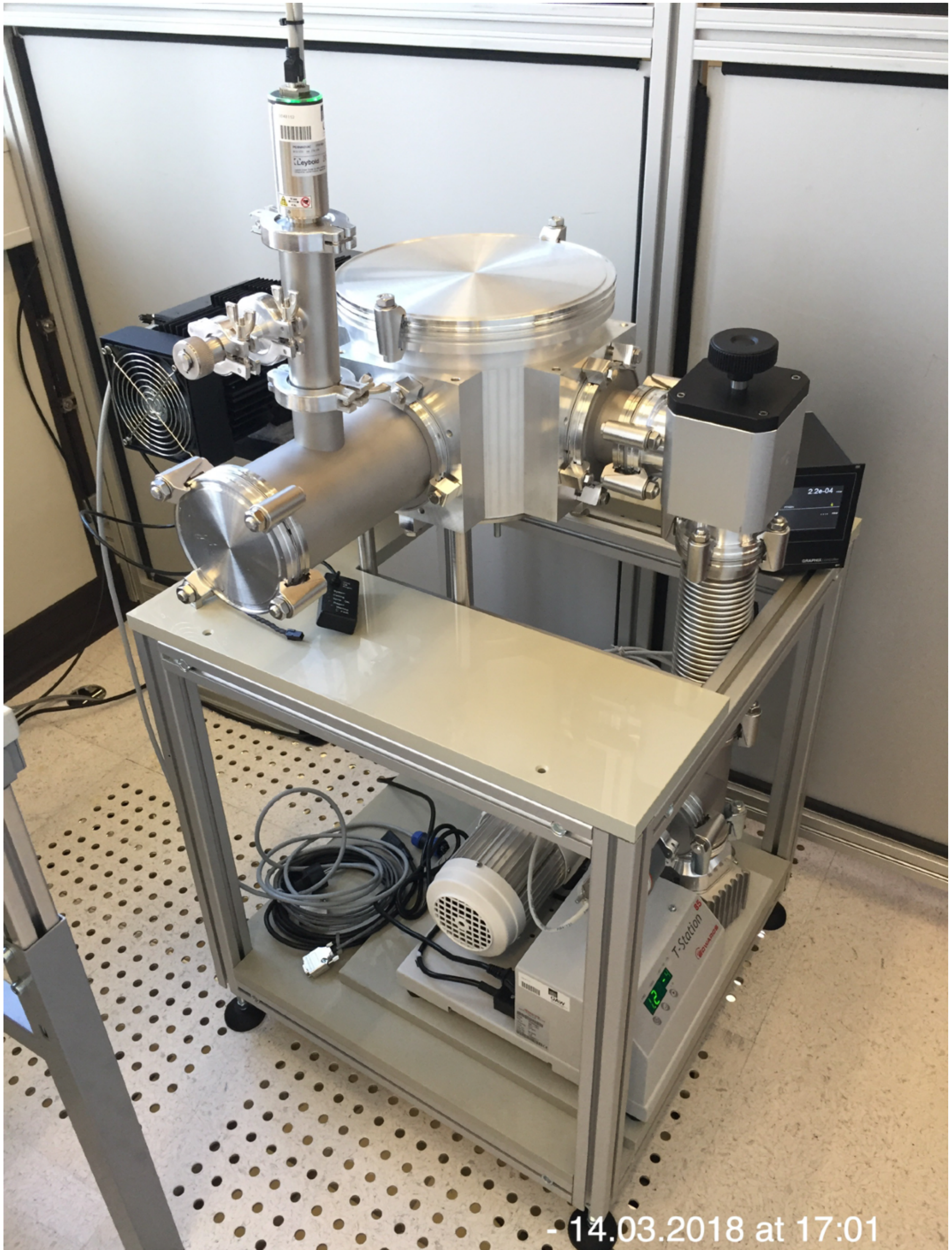
Assembly at HLL

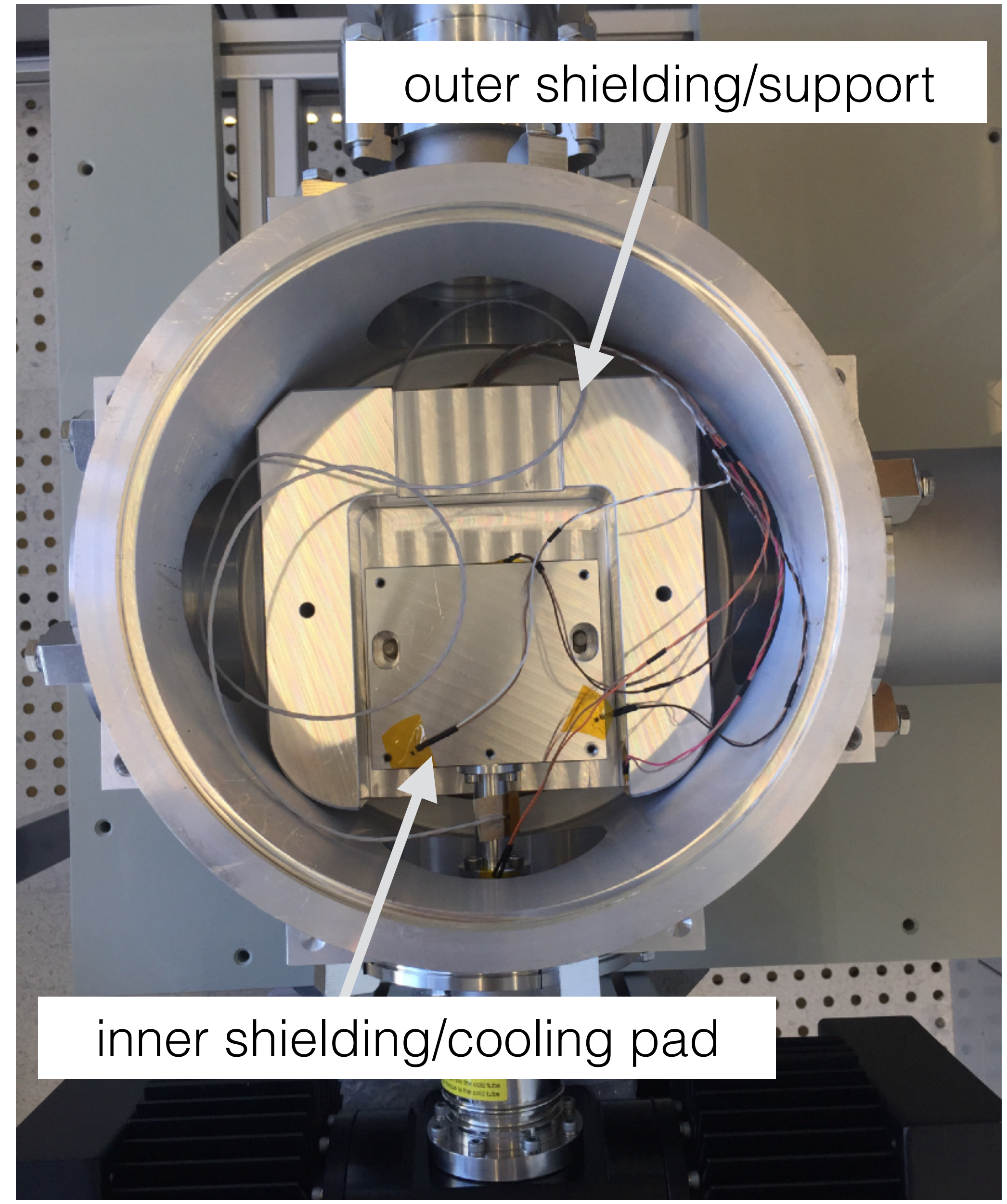


Detector prototype at HLL-MPG
courtesy of J. Treis

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

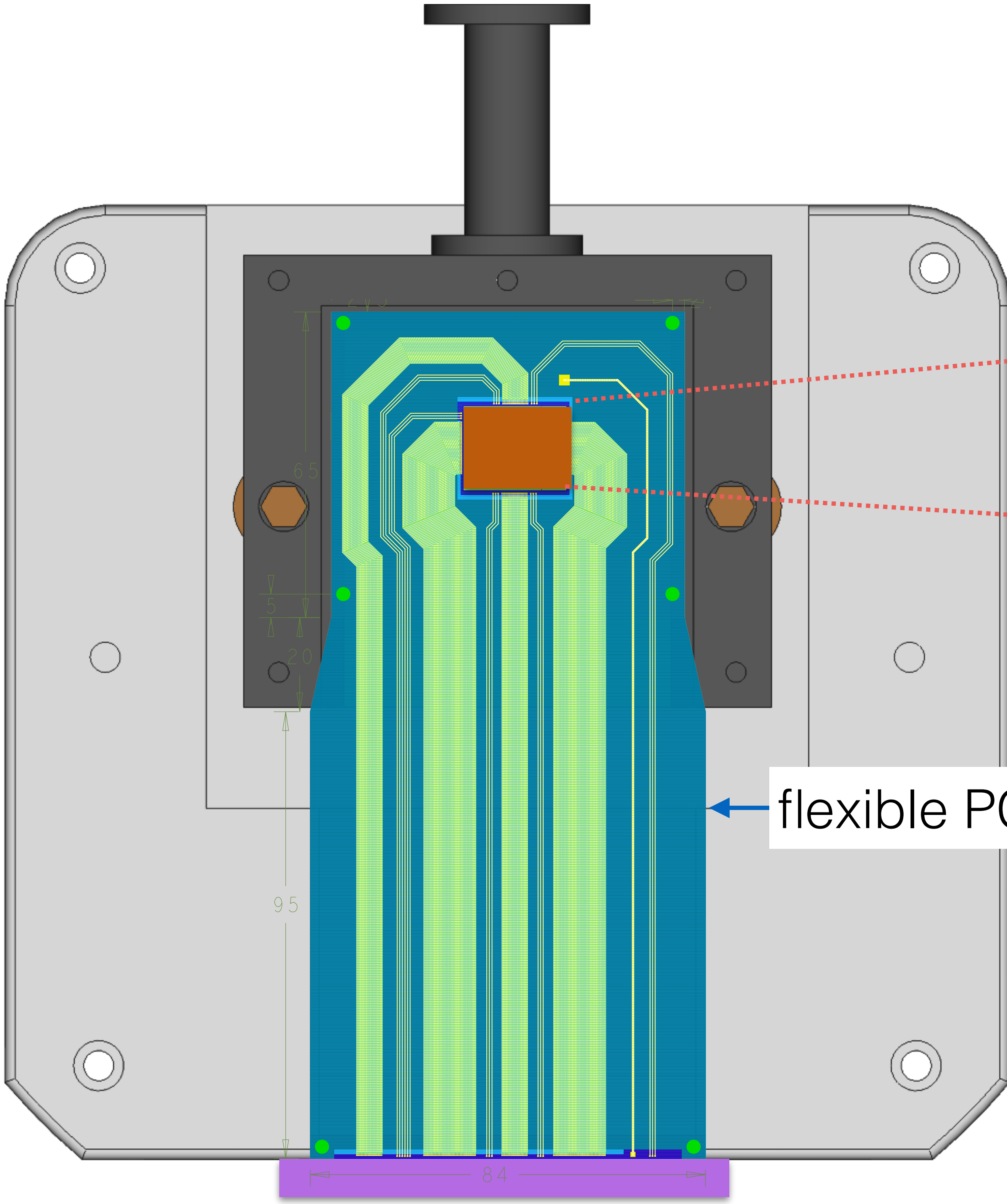
Setup at HLL

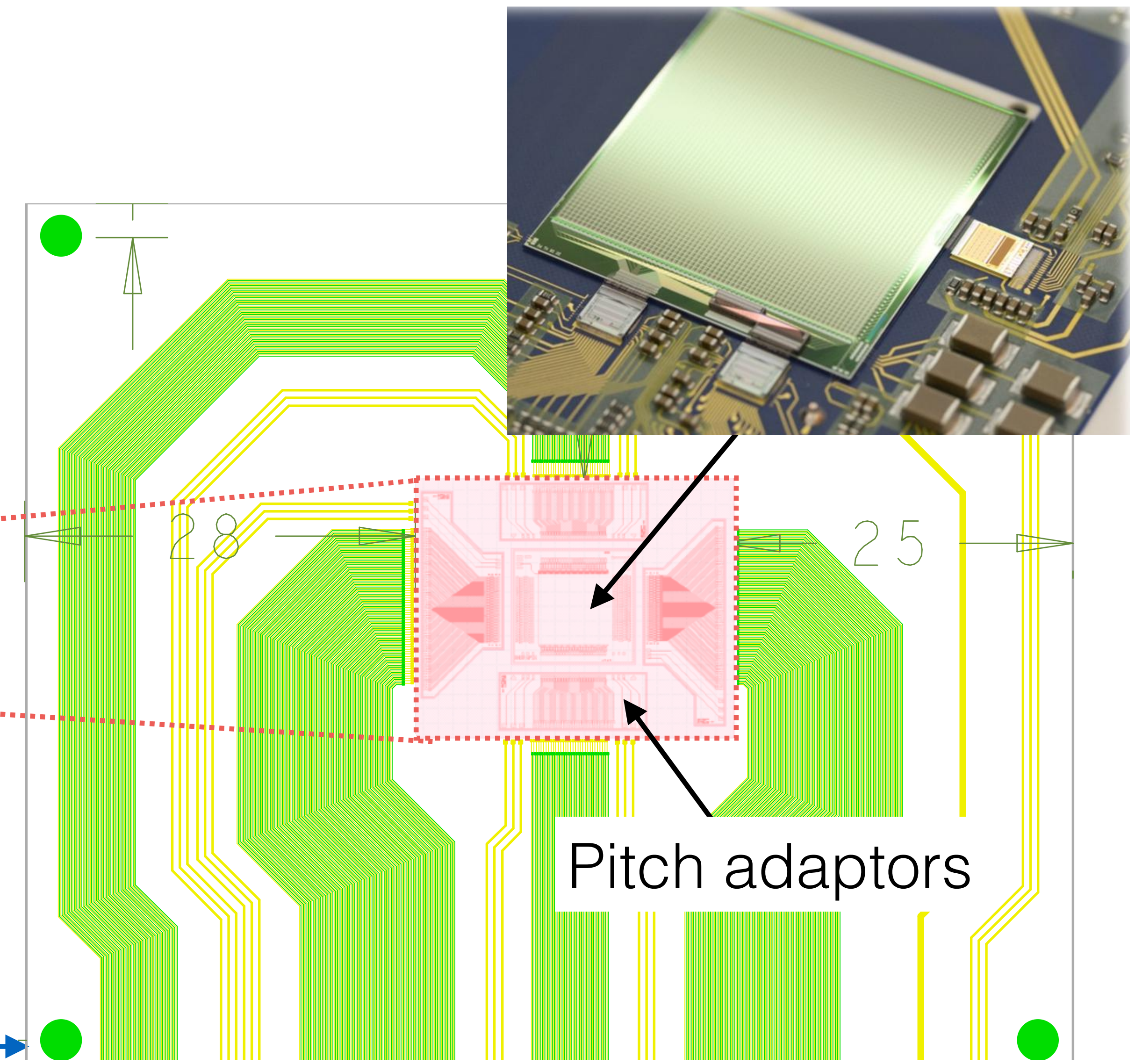




Vacuum and cooling test in March 2018
cooling pad reached 150 K

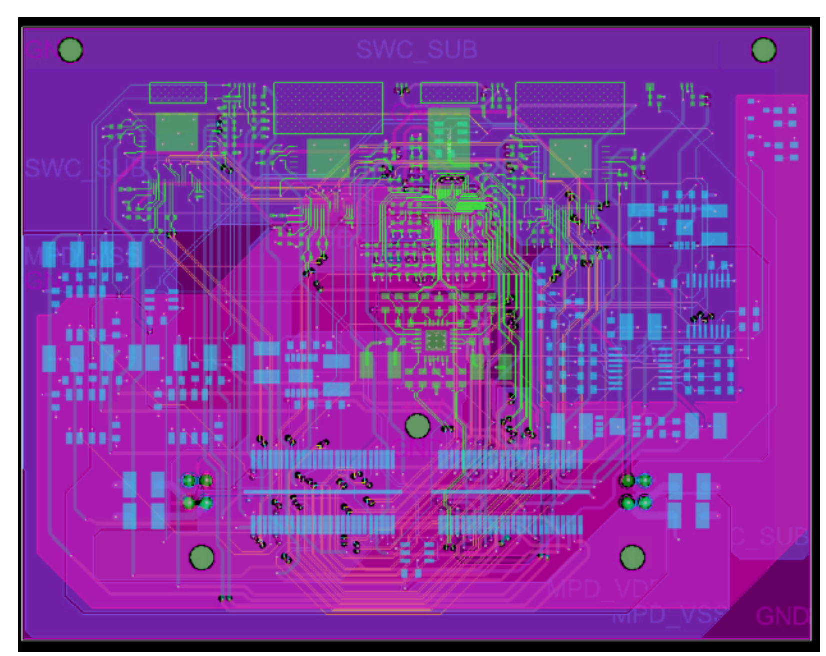
Detector control and readout electronics





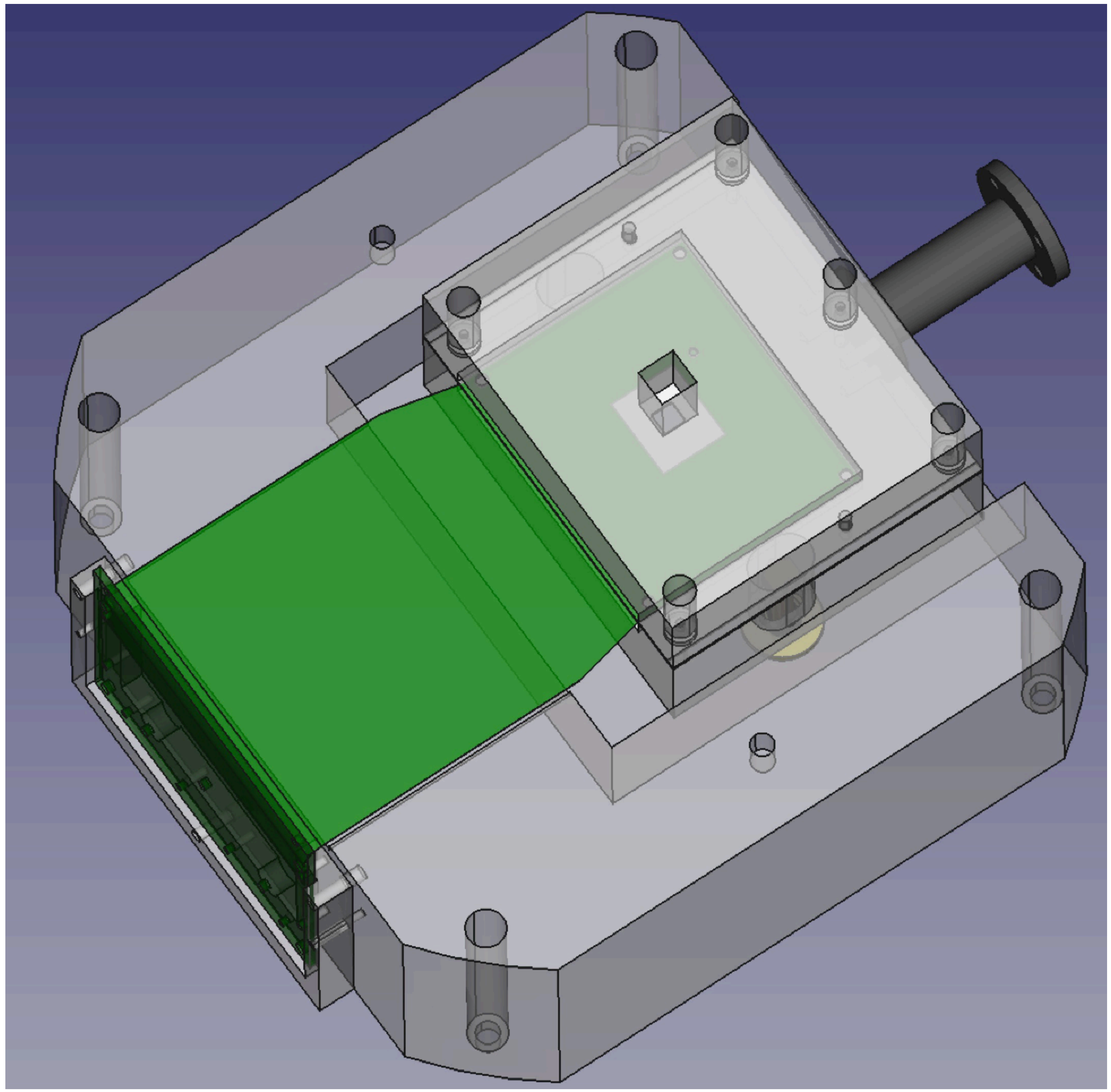
flexible PCB

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



J. Treis
HLL

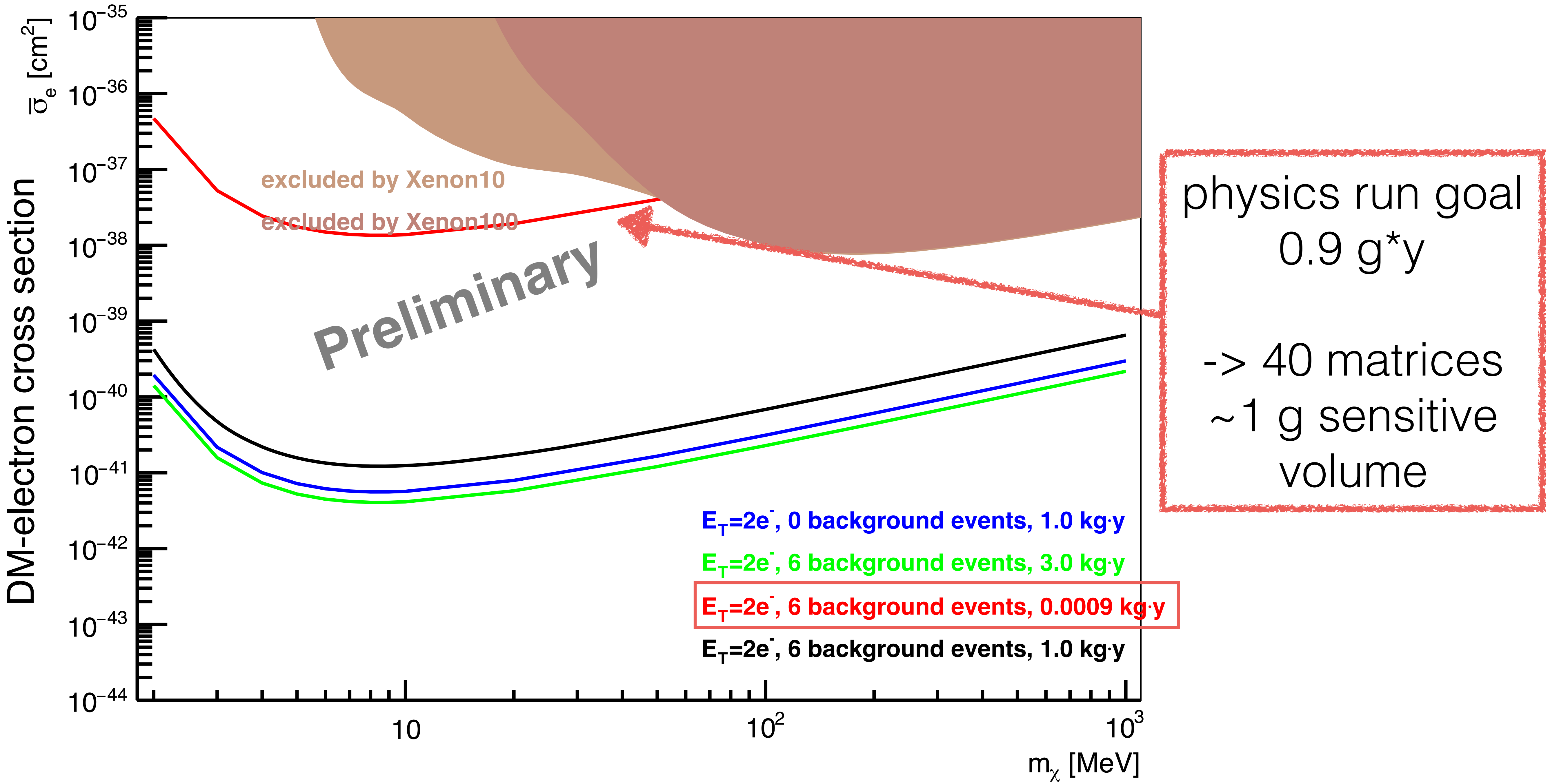
Image of the detector assembly



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

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

“Danae” by G. Klimt

Collaboration

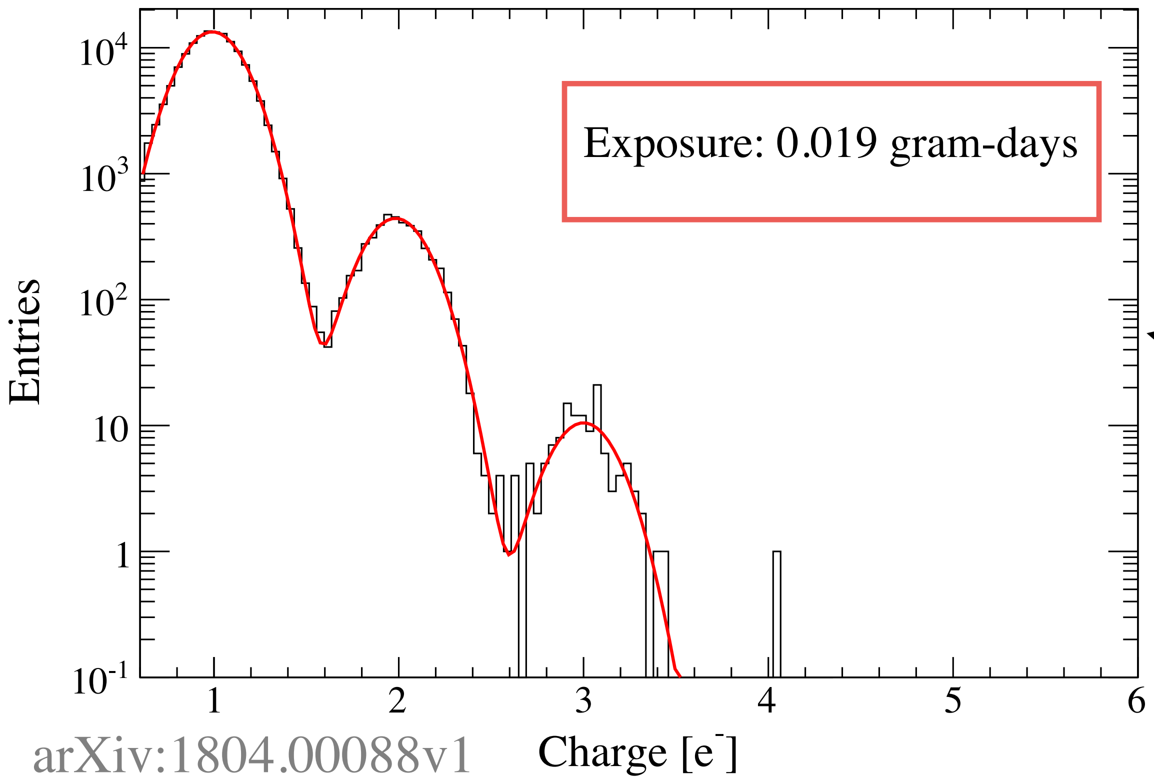
A. Bähr [A], J. Ninkovic [A], J. Treis [A],
H. Kluck [B,C], J. Schieck [B,C], H. Shi [B],

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK
Austria

HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT
Germany

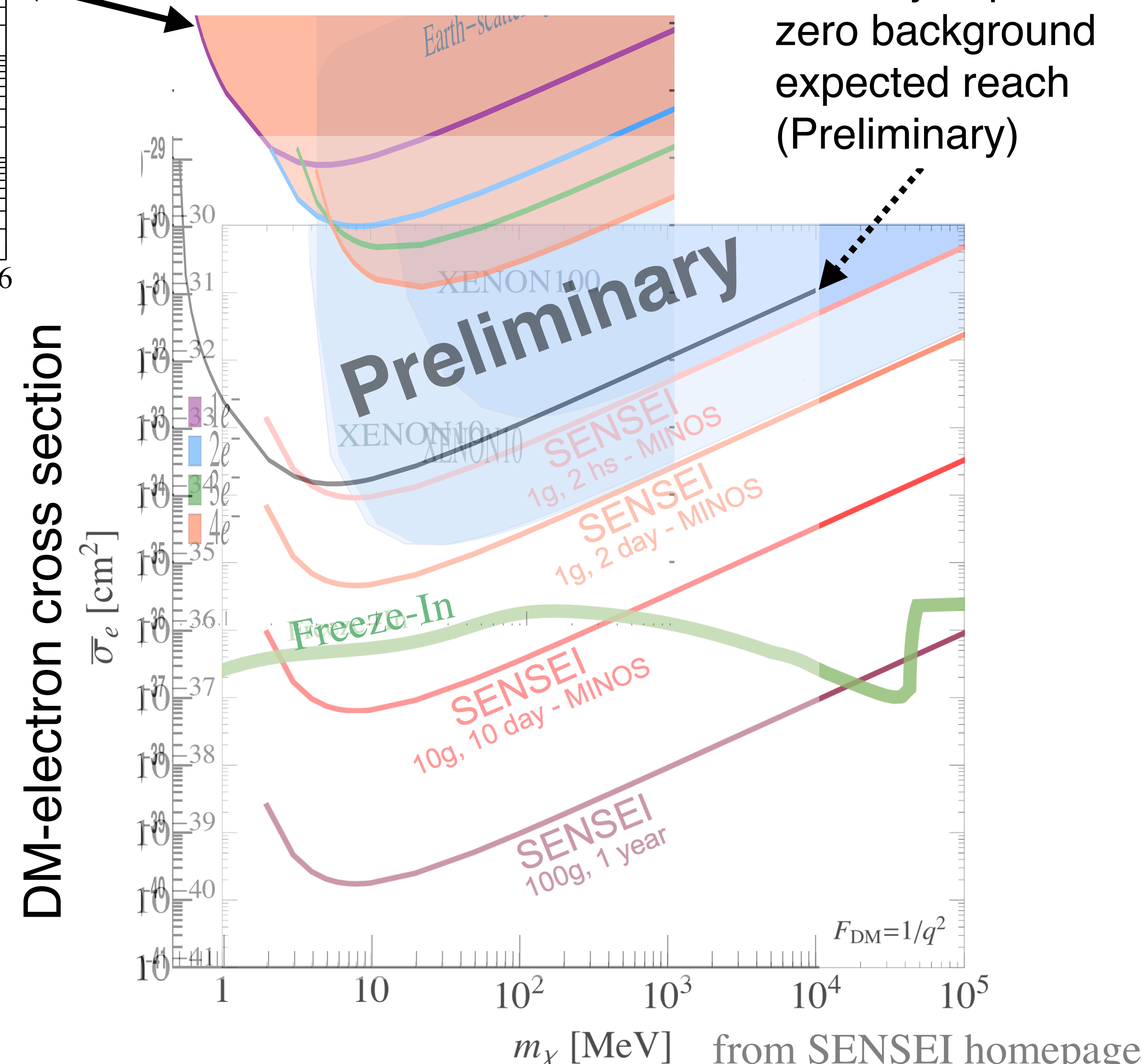
Max-Planck-Gesellschaft Halbleiterlabor, Germany [A],
Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, Vienna, Austria [B],
Atominstitut, Technische Universität Wien, Vienna, Austria [C]

Expected 1day exposure compared to SENSEI



SENSEI prototype physics run

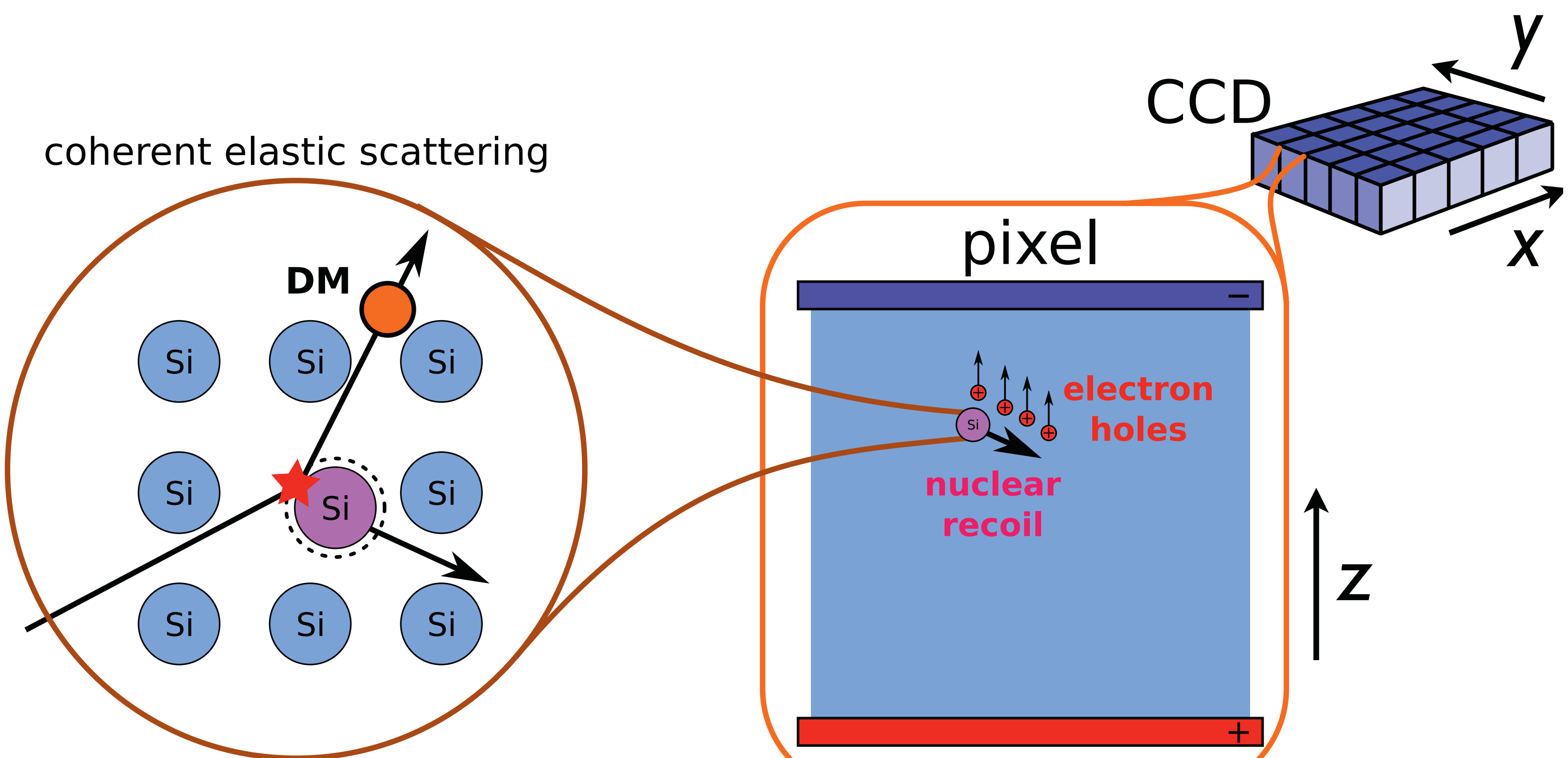
DANAE prototype 24 mg one-day exposure zero background expected reach (Preliminary)



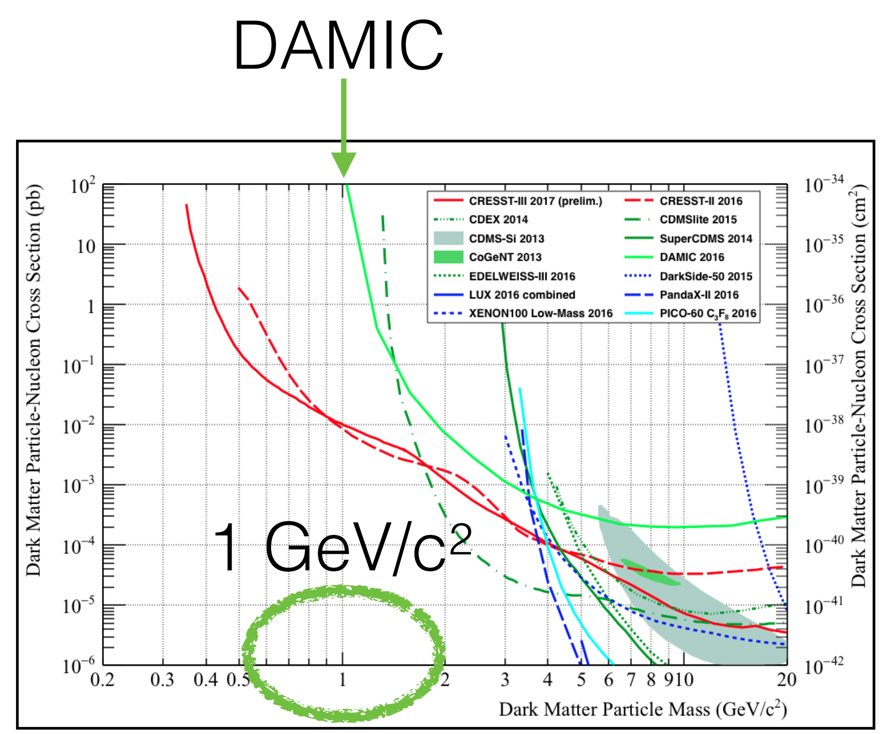
Application of Silicon detector

DAMIC

nucleus recoil   CCD, with physics results



Physics Procedia 61 (2015) 21 – 33

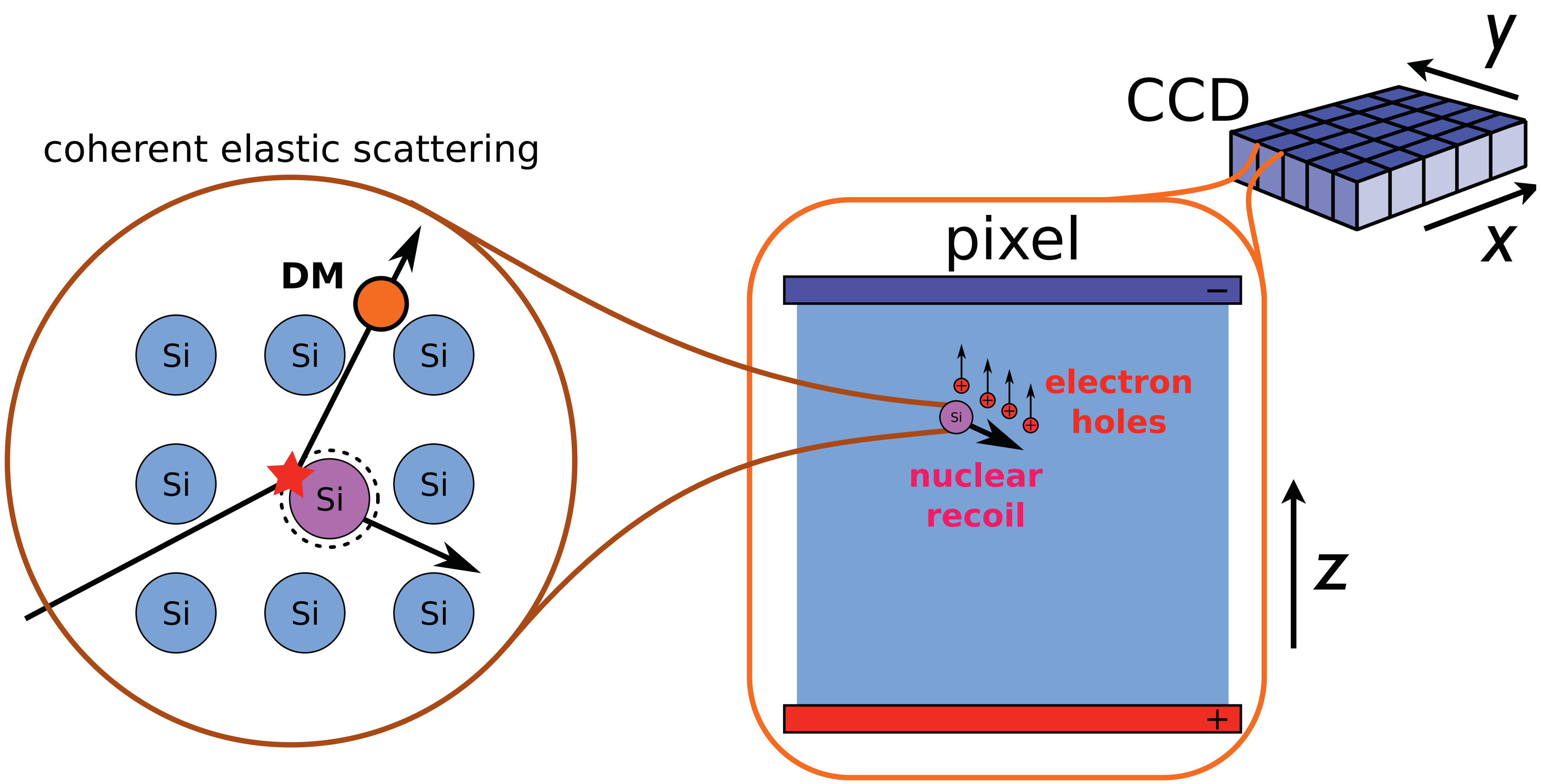


Readout noise determines threshold of ~ 11 e⁻
(or ~ 40 eV)

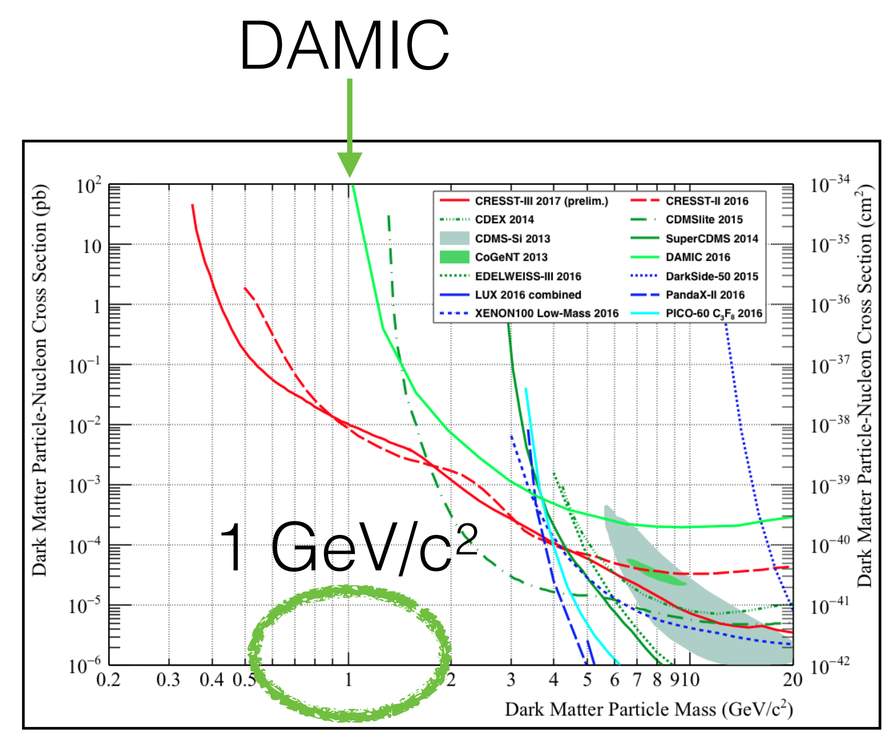
Application of Silicon detector

DAMIC

nucleus recoil   CCD, with physics results



Physics Procedia 61 (2015) 21 – 33

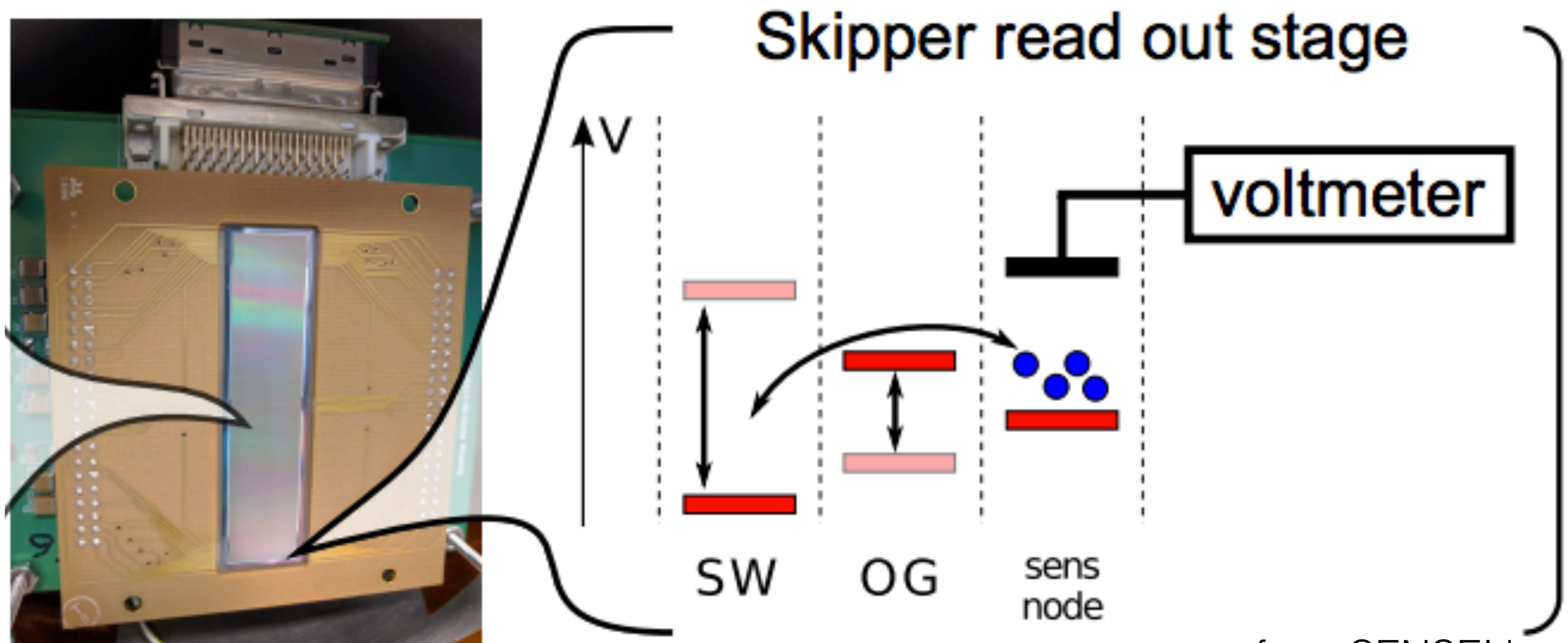


Readout noise determines threshold of ~ 11 e^-
(or ~ 40 eV)

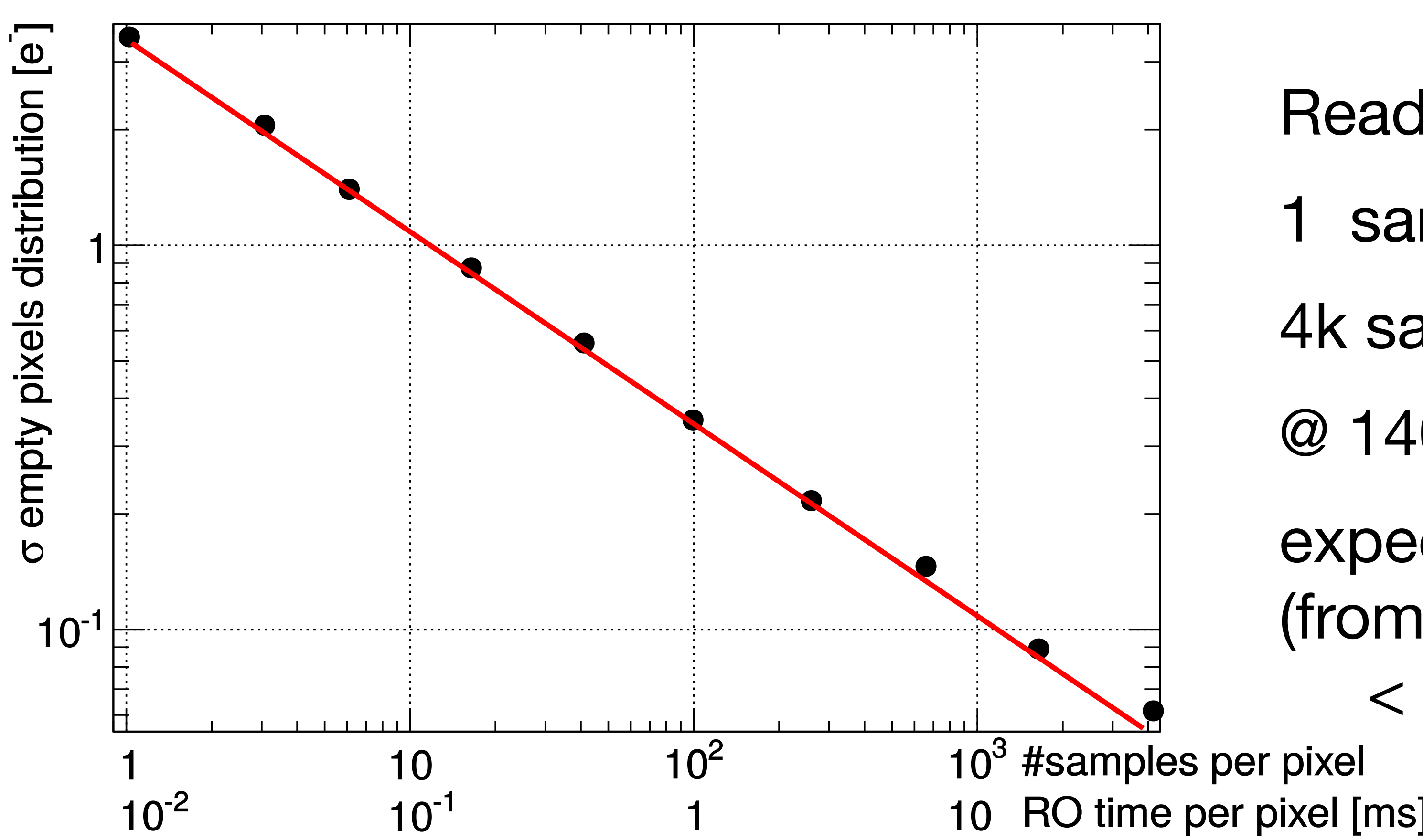
For O(MeV) DM-electron scattering, required threshold : O(e^-) Sub-electron noise level necessary

Skipper CCD for SENSEI

DAMIC CCD with **repetitive readout**



from SENSEI homepage



PRL 119(1) 131802 (2017)

Readout noise :

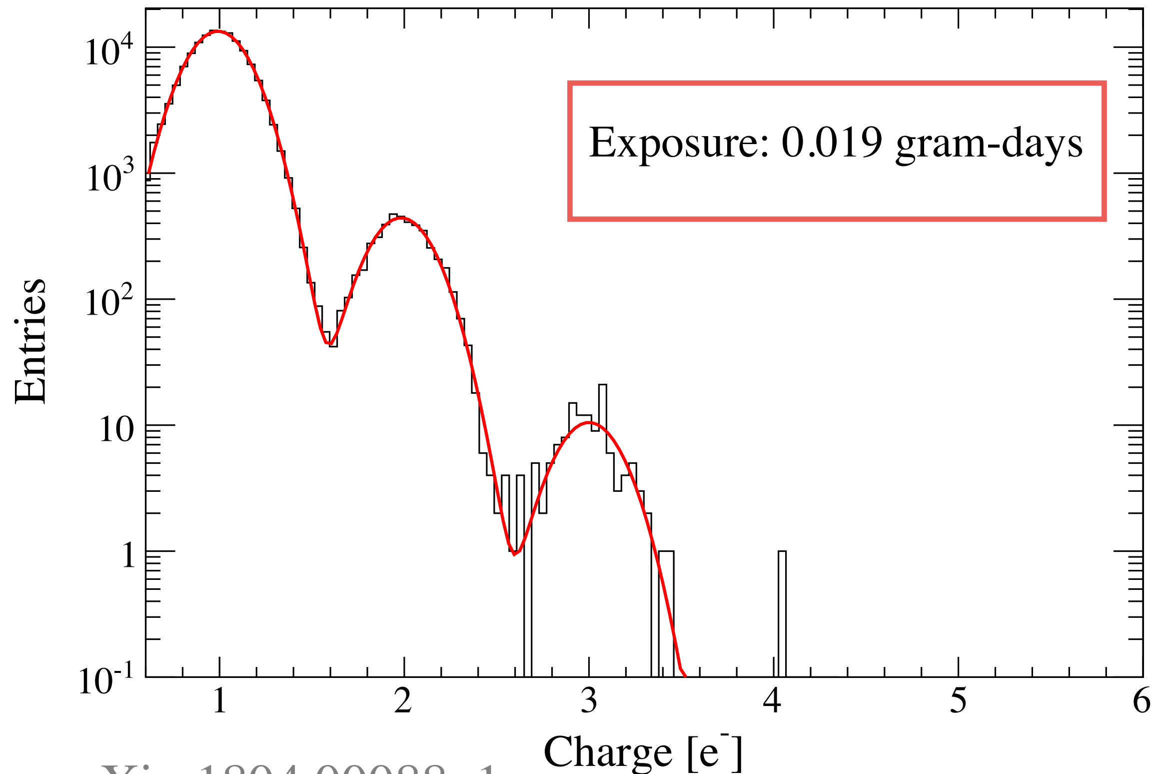
1 sample : 3.55 e^- rms

4k samples : 0.068 e^- rms

@ 140 K

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

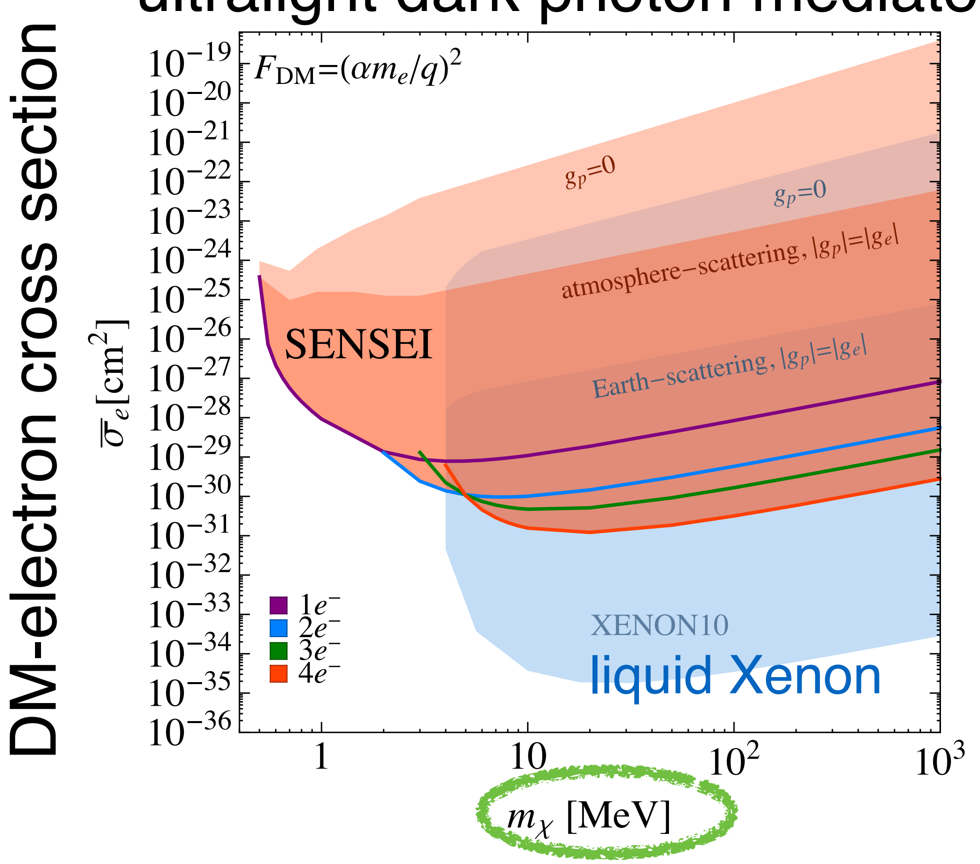
SENSEI first result with "skipper" CCD



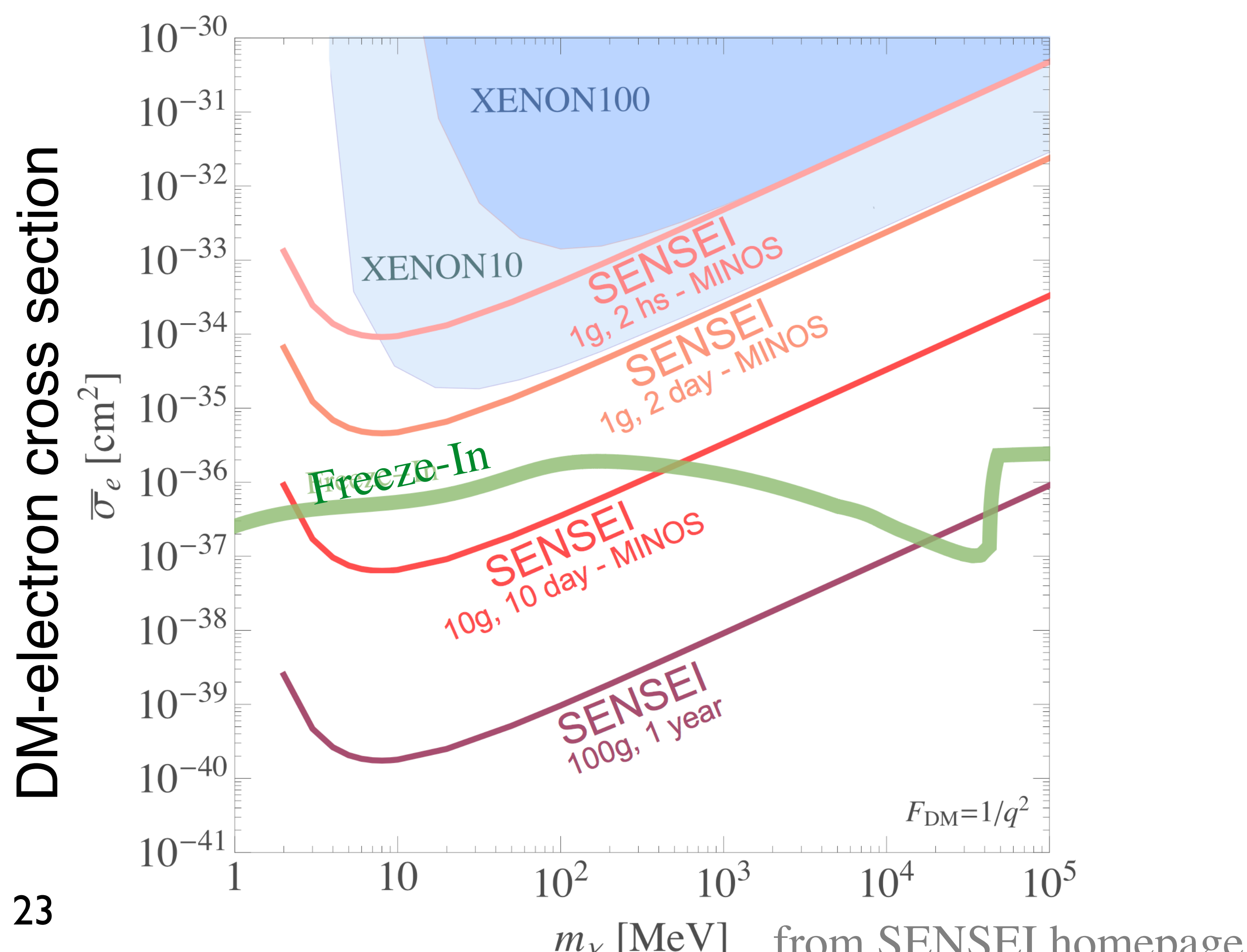
arXiv:1804.00088v1

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

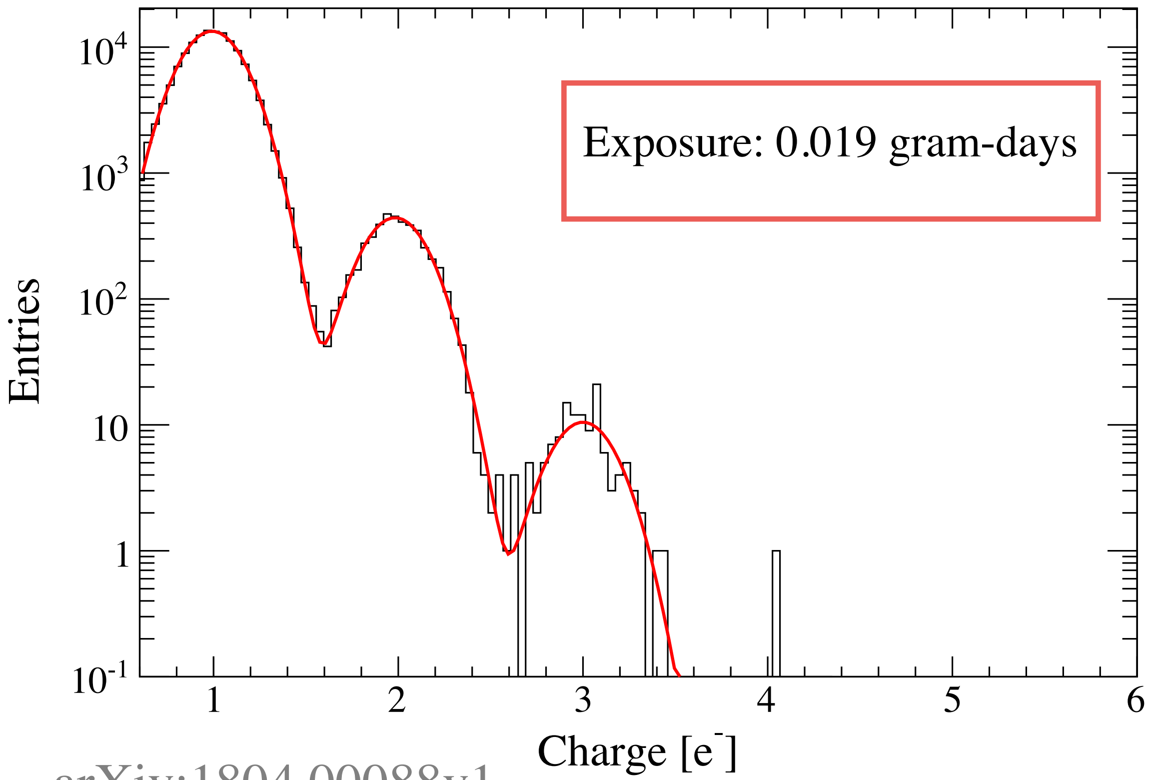


arXiv:1804.00088v1



from SENSEI homepage

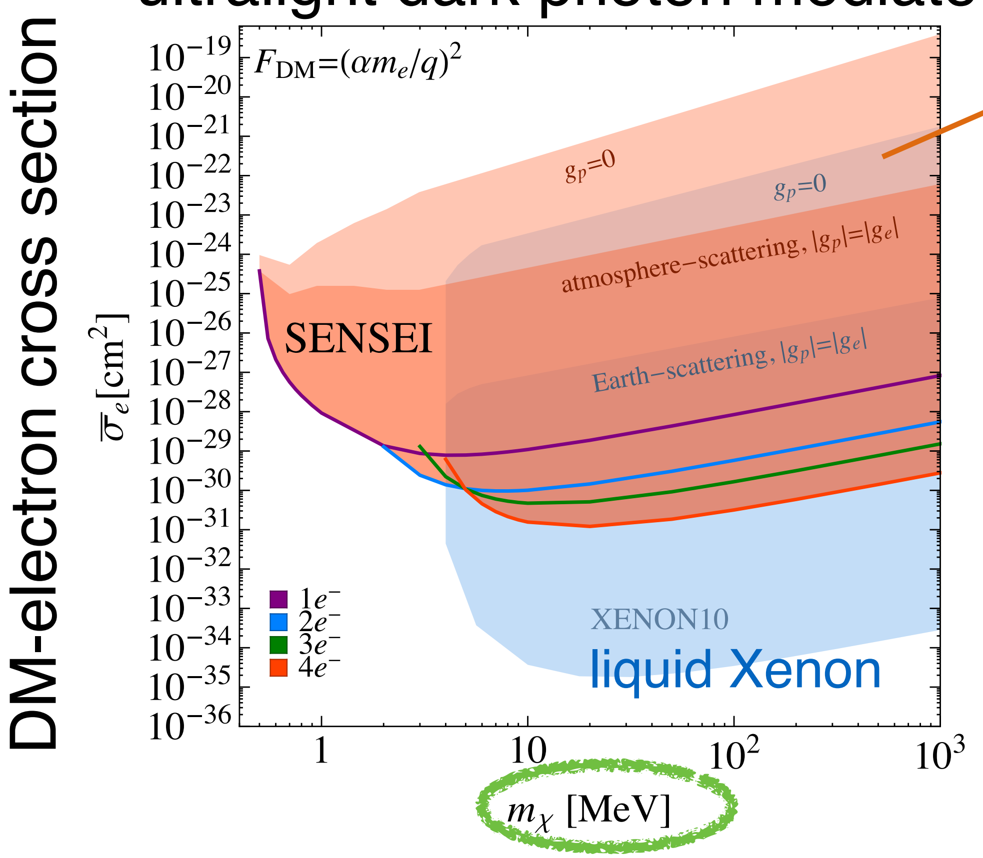
SENSEI first result with “skipper” CCD



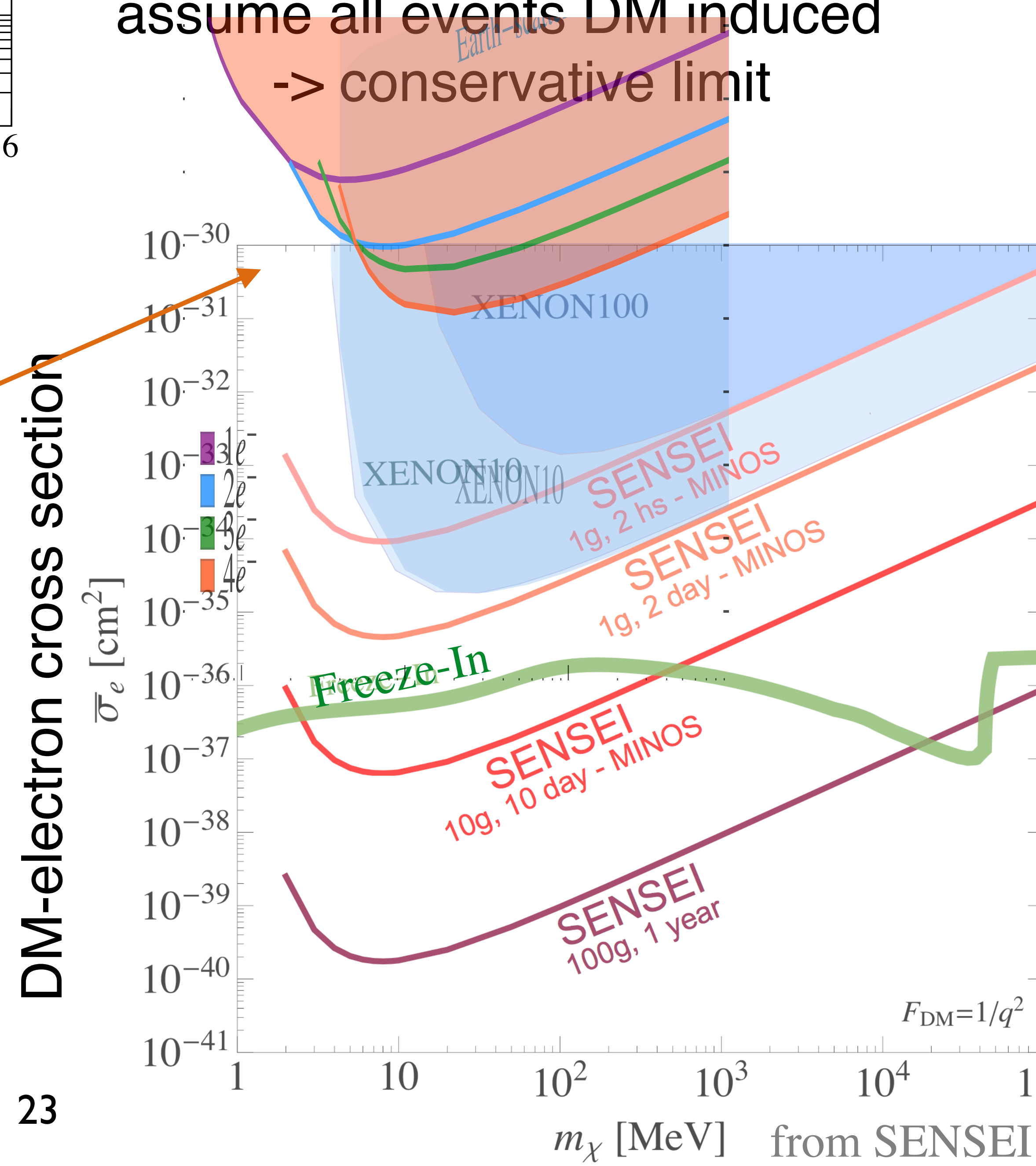
arXiv:1804.00088v1

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

ultralight dark photon mediator



arXiv:1804.00088v1



from SENSEI homepage

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;

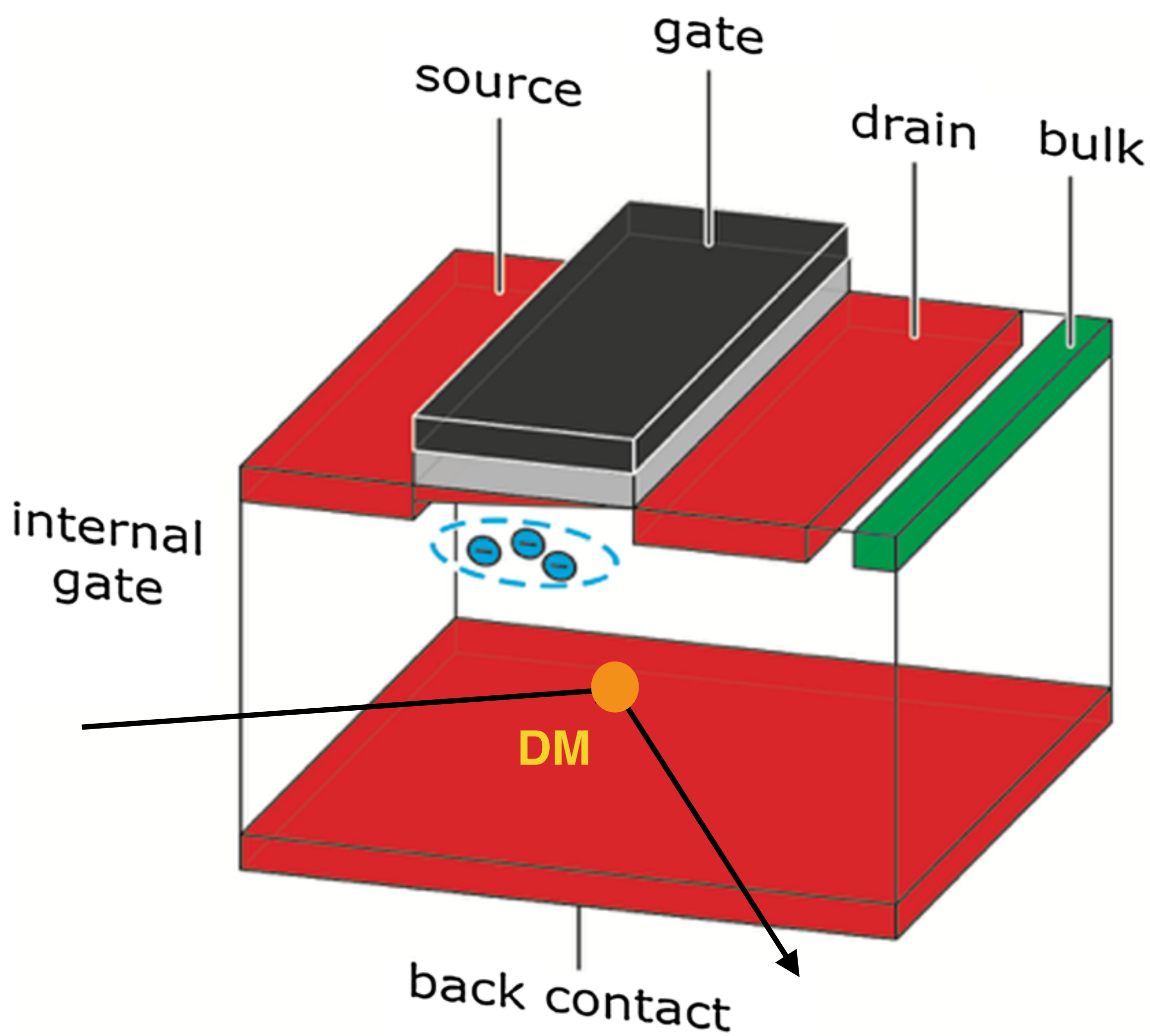
-> good complementary from experimental point of view

DEPFET with RNDR

RNDR : repetitive non-destructive readout

structure of a basic DEPFET cell :

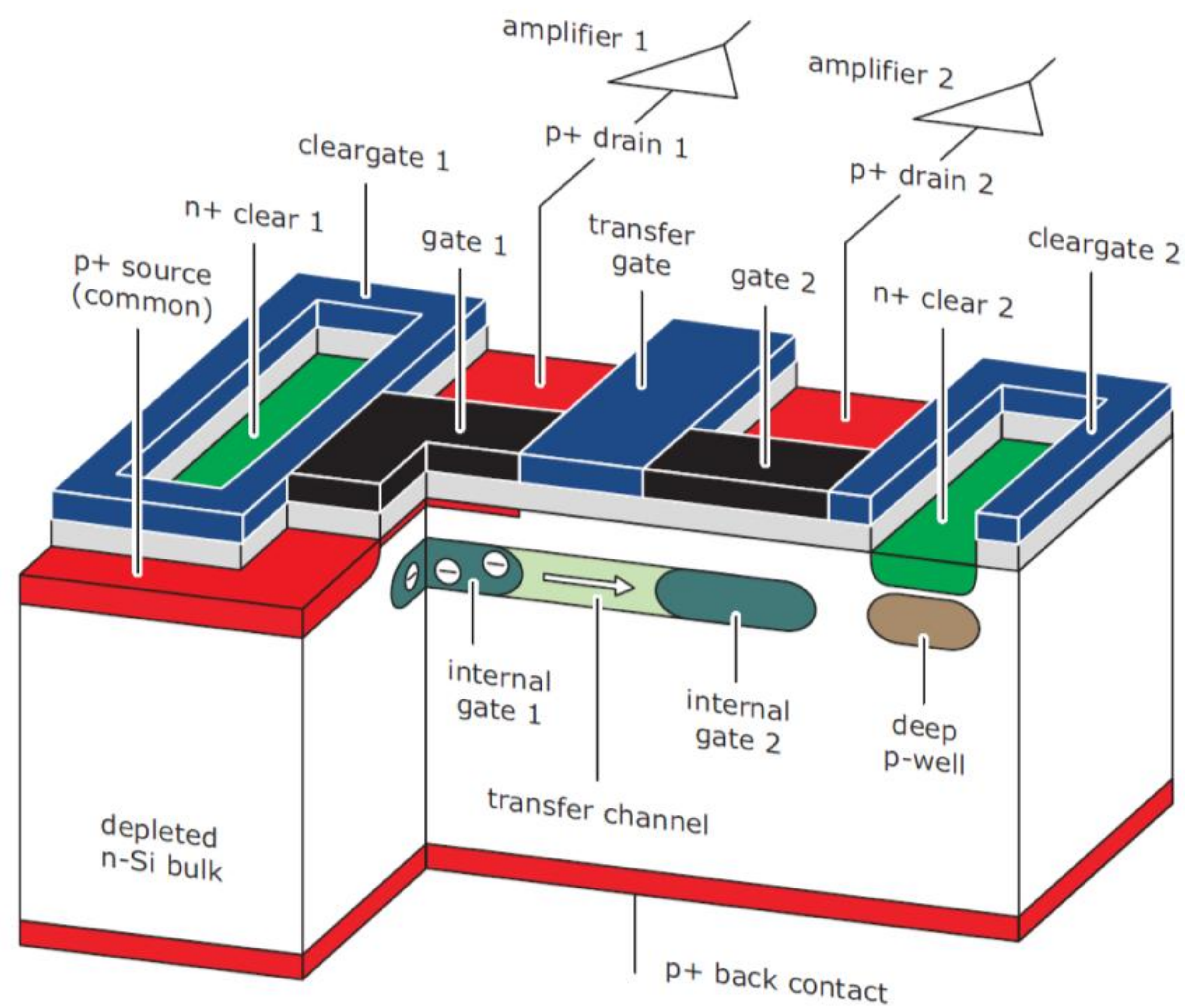
a "subpixel"



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

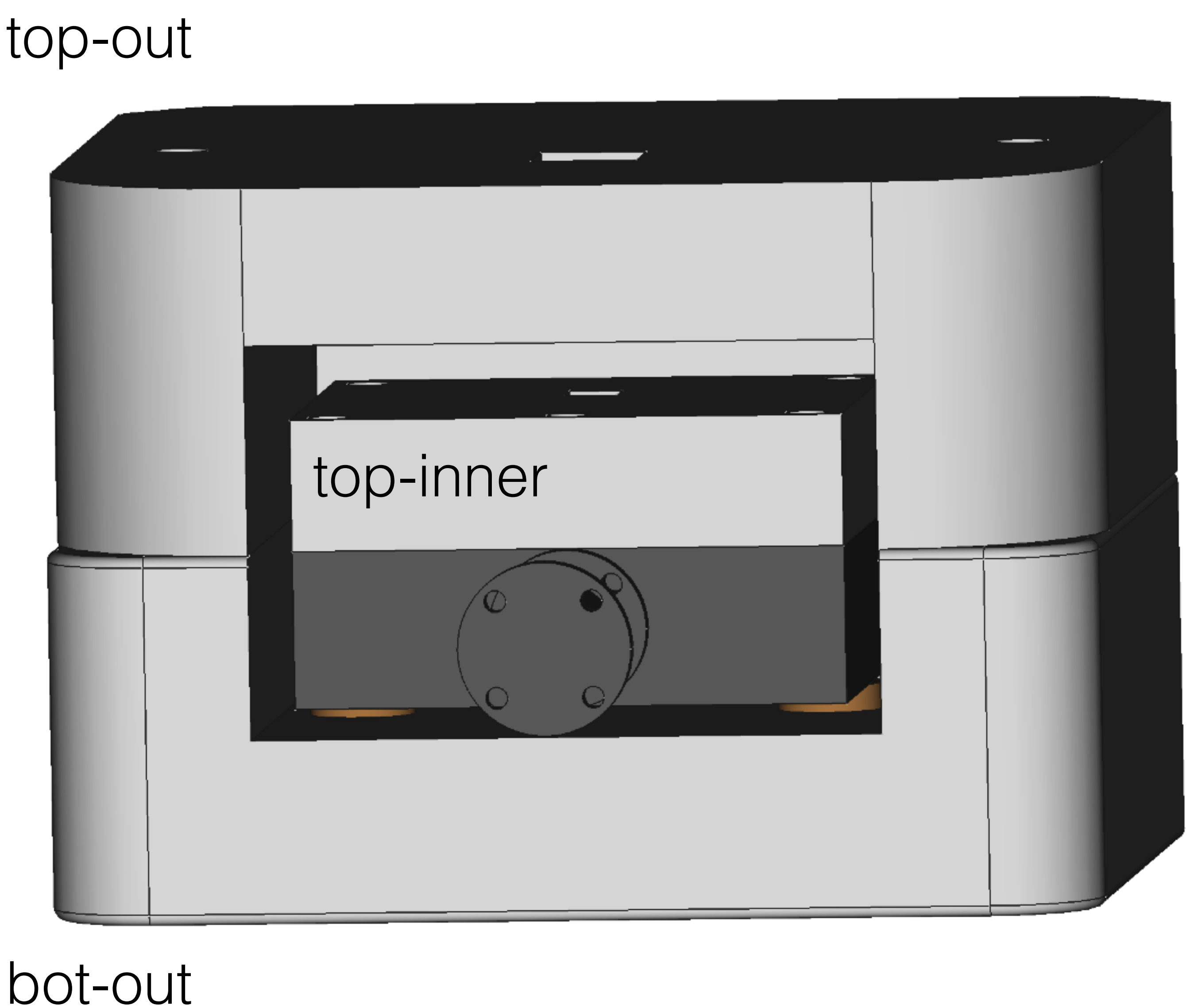
fully-depleted n-Si

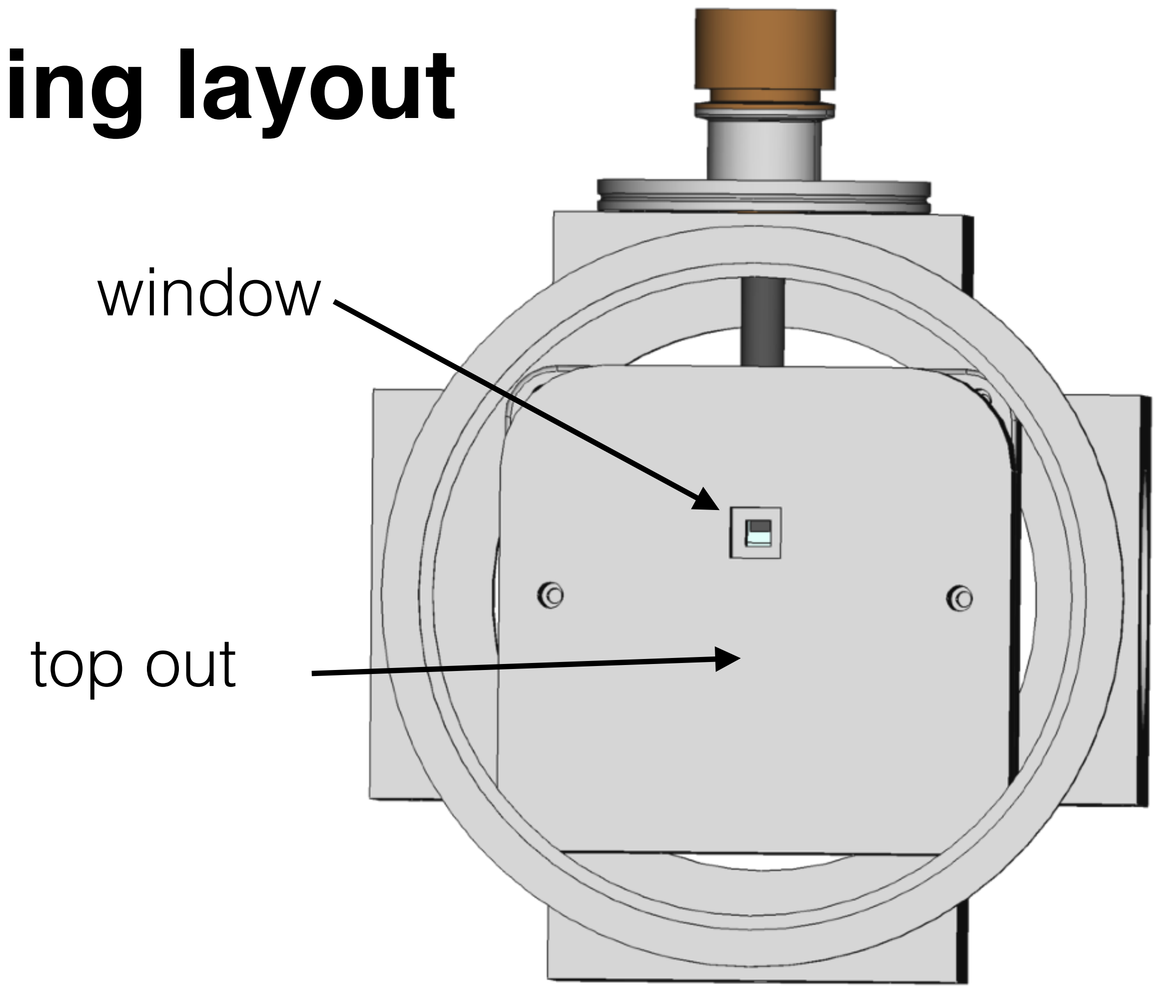
structure of RNDR DEPFET "super-pixel"

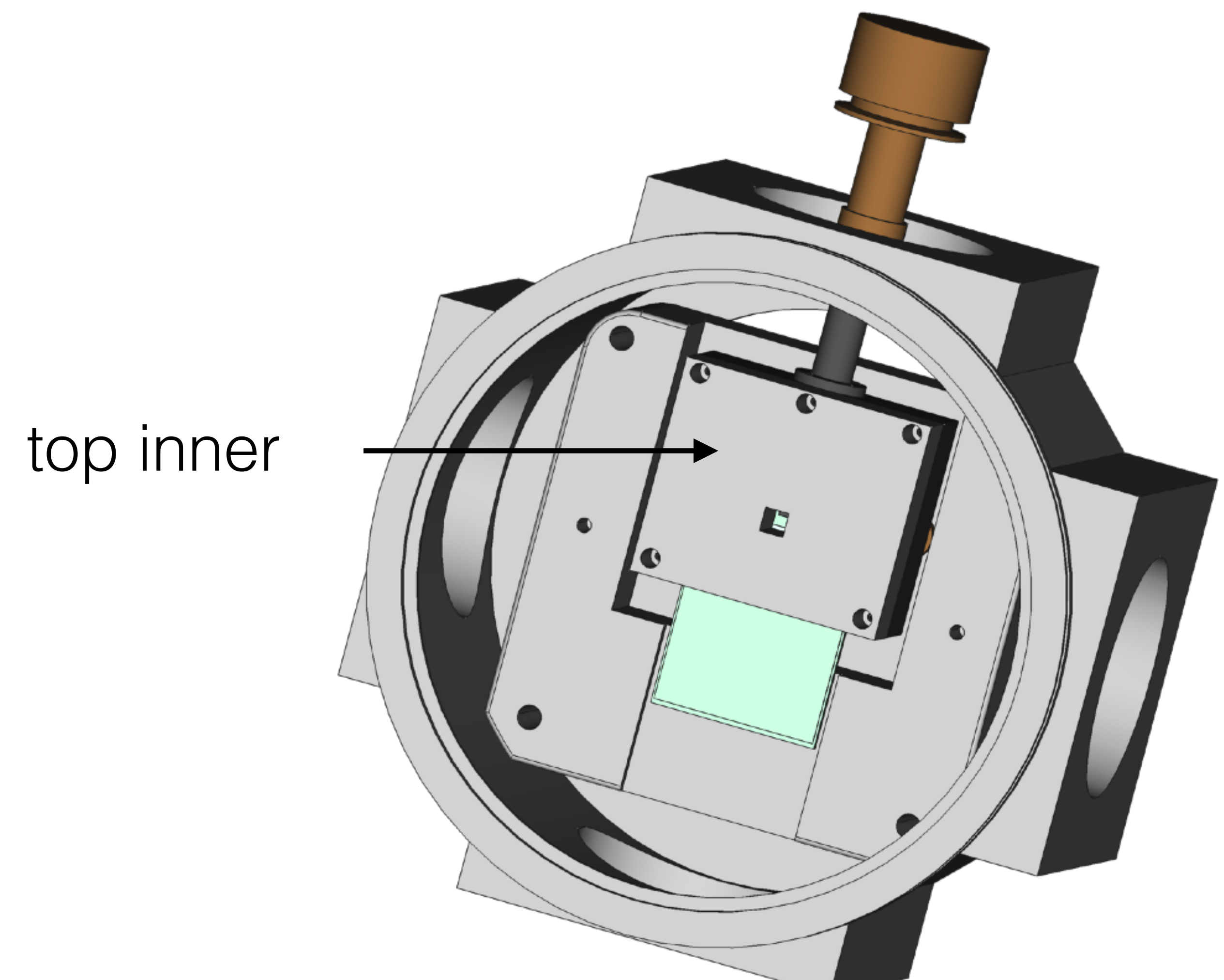


EPJ C, 77(12), 279 (2017)

Cooling & shielding layout







outer shielding : support structure
inner shielding : cooling contact

DEPFET matrix control & readout electronics

Detector matrix

Front-end ASICS for the 64x64 matrix
with interface to Switcher-S, VERITAS

Readout board

Switcher-S

64x2 channel analog multiplexer

switcher id	W	N	E
function	**Gate 1 & 2**	**Gate common**	**clear & transfer gate**
Voltage [V]	-2.5 ~ + 5	-0.5 ~ +20	-0.5 ~ + 20/25

VERITAS

- VERITAS 2.1 ASIC in the AMS 0.35 μm CMOS 3.3 V technology
- 64 analog readout channels able to process in parallel the **signals coming from 64 DEPFET devices**.

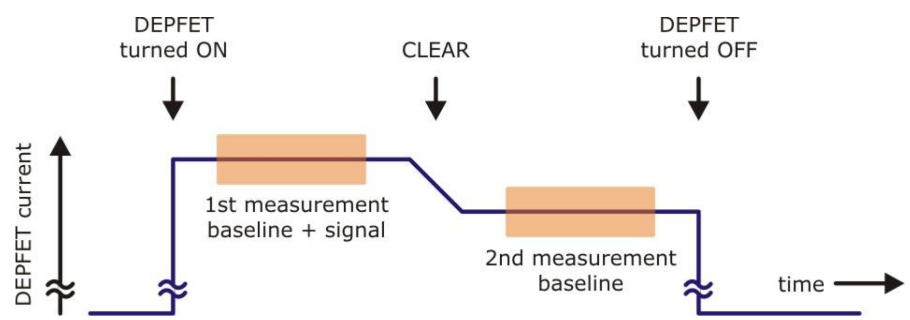
ADC

FADC type digitizer

DEPFET CDS circle

Detector Structures – Matrix Devices

- **readout sequence**



Correlated double sampling:

1st measurement: signal + baseline

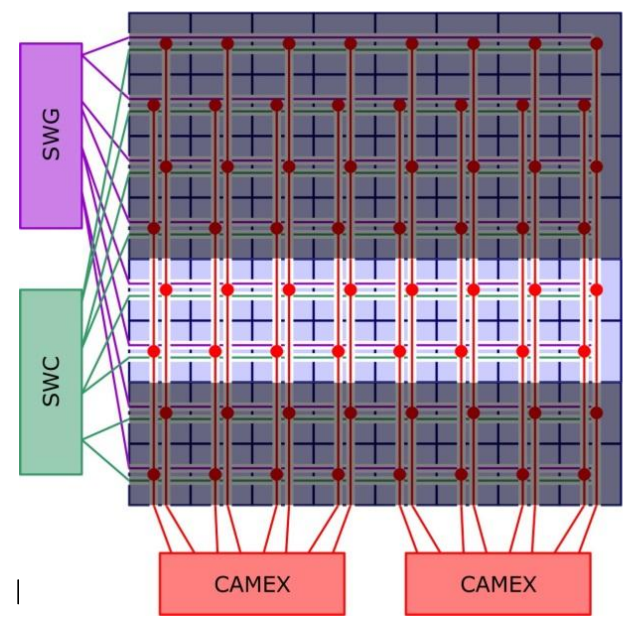
clear: removal of signal charges

2nd measurement: baseline

difference = signal

complete clear is mandatory!

- **matrix operation**



vertical signal lines

1 active row, other pixels integrating

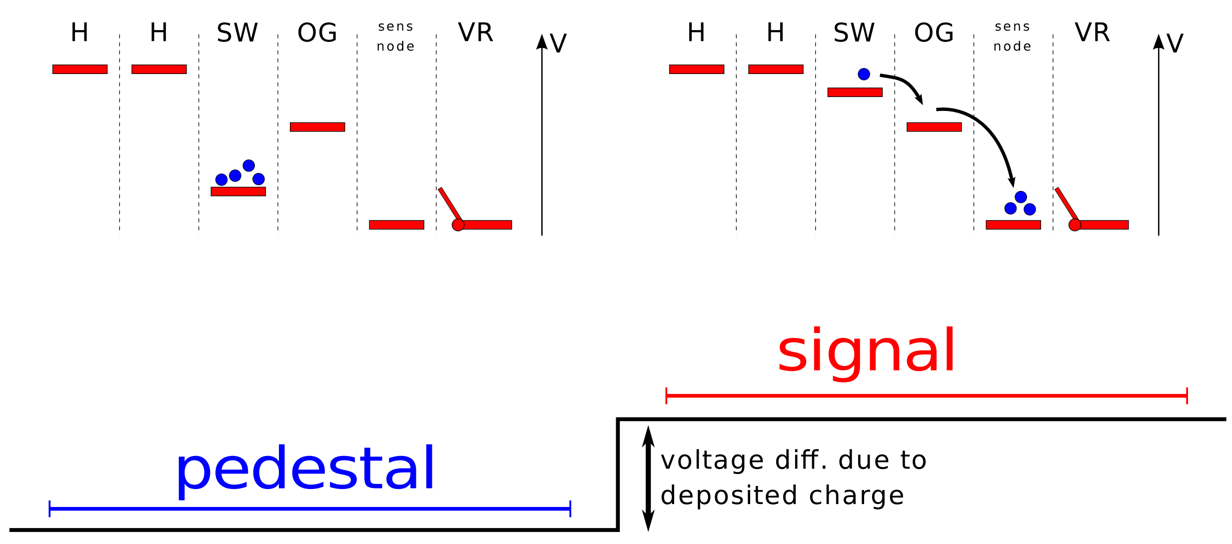
- **option to speed up (1)**

readout parallelisation

2 x readout channels, 2 active rows

CCD (skipper) readout

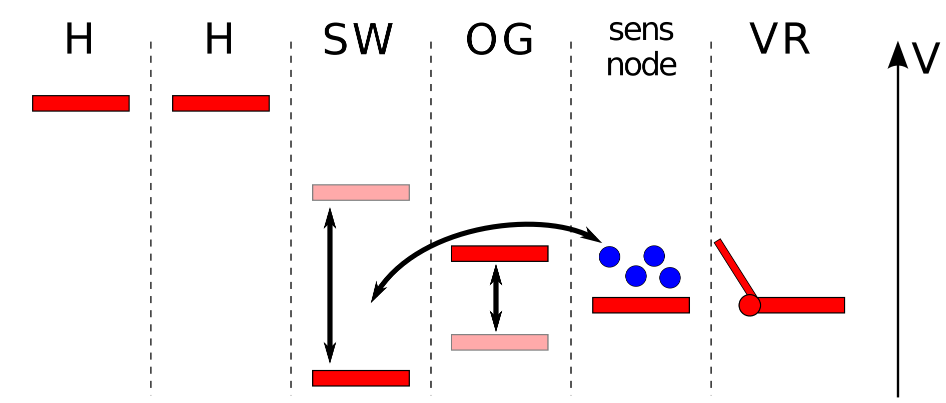
CCD: readout



Fermilab

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)**$_i$



Fermilab

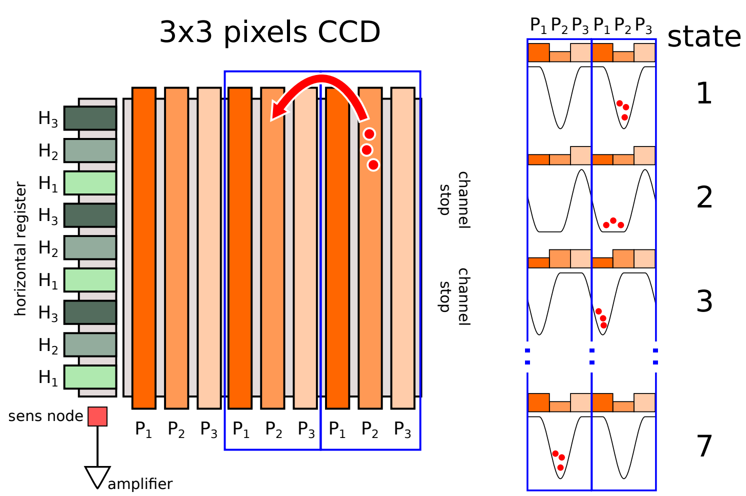
SW : summing-well gate

OG : output gate

RG : reset gate

VR : V_ref

CCD: readout

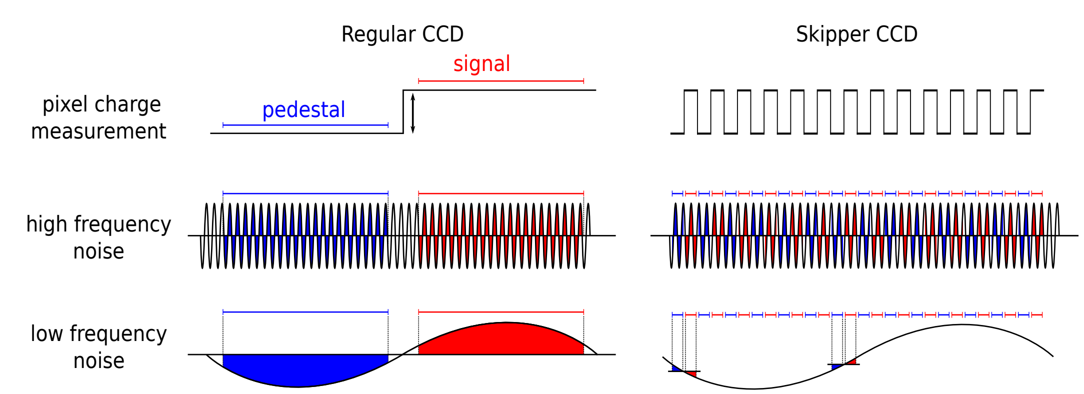


capacitance of the system is set by the SN: C=0.05pF$\rightarrow$ 3μV/e

Fermilab

Lowering the noise: Skipper CCD

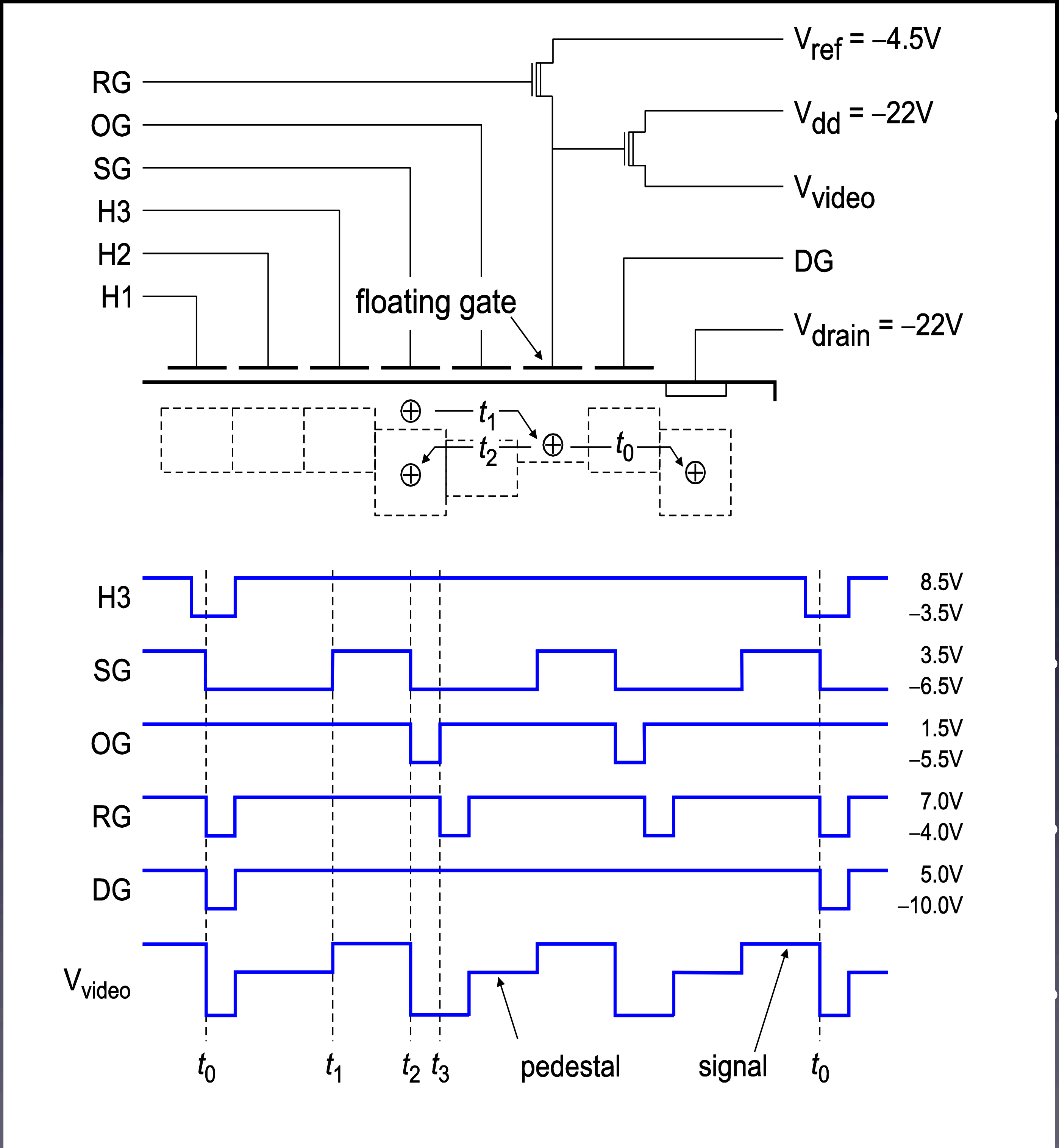
- **Main difference:** the Skipper CCD allows multiple sampling of the same pixel without corrupting the charge packet.
- The final pixel value is the average of the samples
  Pixel value $= \frac{1}{N}\Sigma_i^N$ **(pixel sample)**$_i$



Fermilab

Javier Tiffenberg

Skipper CCD



- The "skipper" allow multiple readouts of the charge in each pixel.
  - Floating gate output instead of floating diffusion output used in regular CCDs.
  - The charge can be moved back and forth between
- Each readout integration time is kept short to make 1/f noise negligible.
- A noise reduction of 1/sqrt(N) is achieved for N reads.
- The total readout time per pixel increases linearly with N.