DANAE - a new experiment for direct dark matter detection using RNDR DEPFET detectors

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ÖAW

11 April 2018
DEPFET workshop
Schloss Ringberg

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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HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK

MPG HLL HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT

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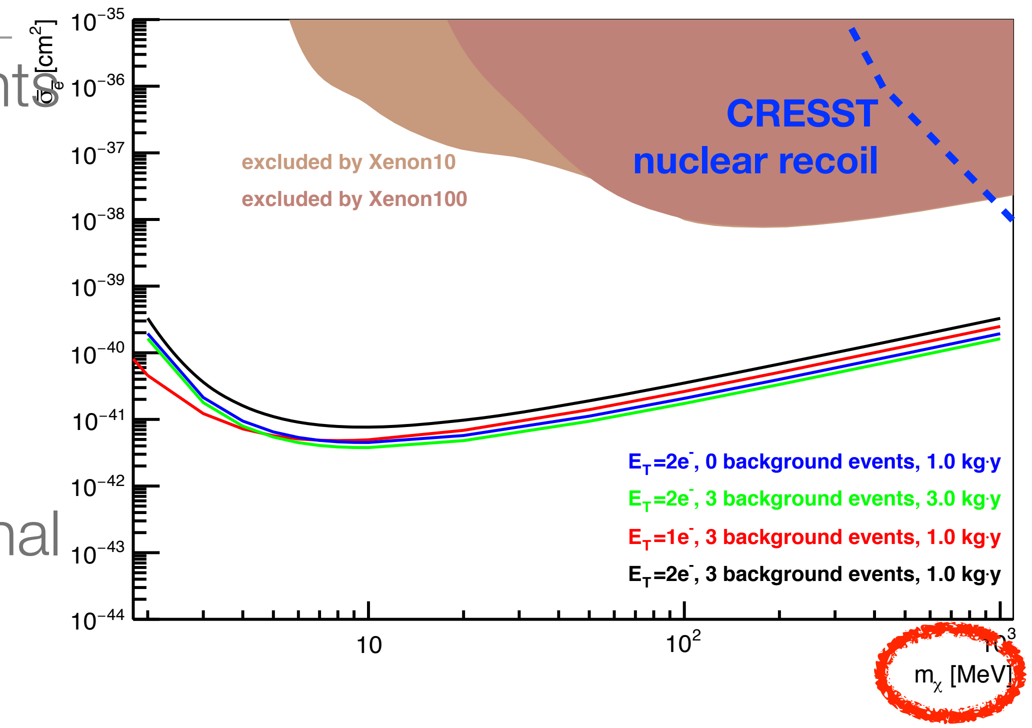
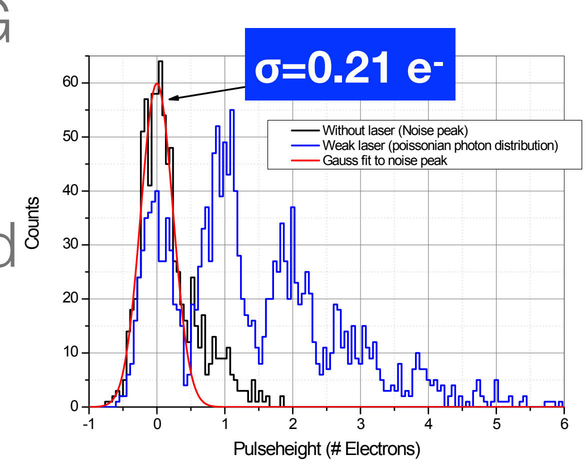
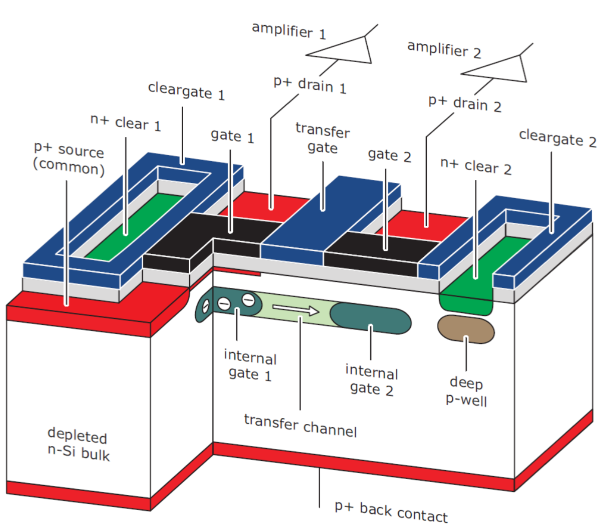
The project overview

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







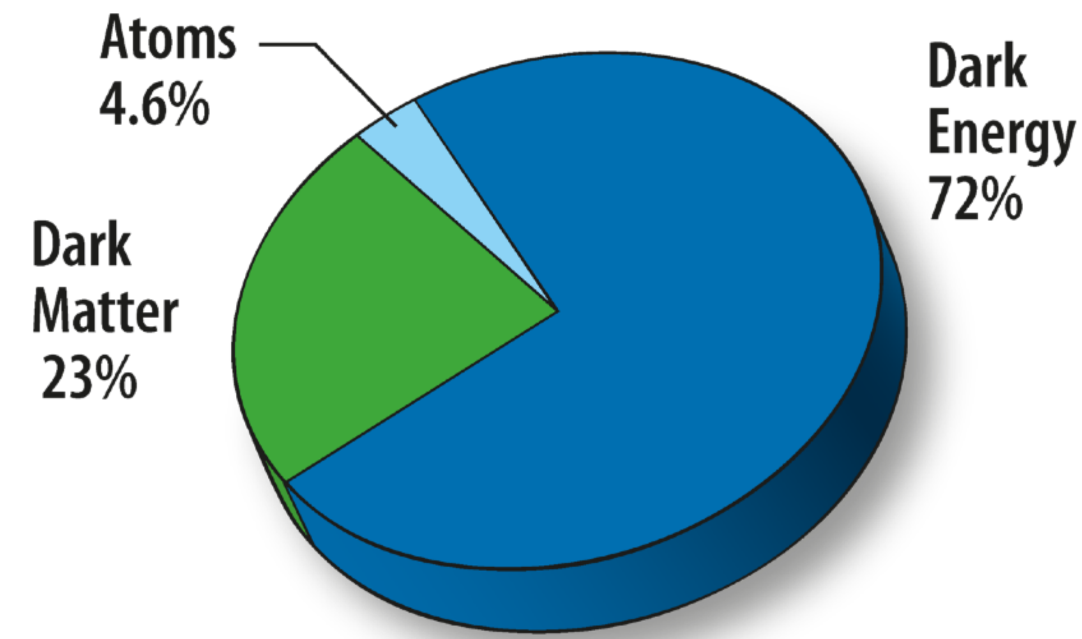
EPJ C, 77(12), 279 (2017)

*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

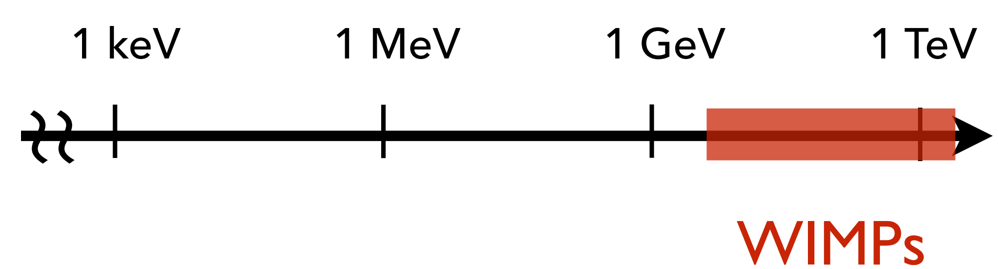


TODAY

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

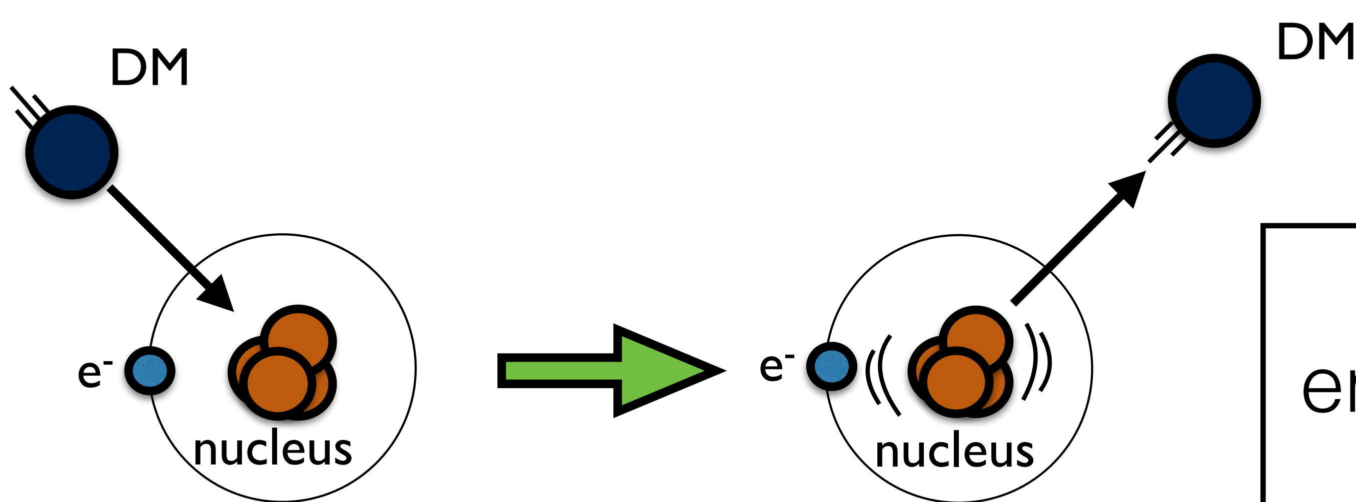


image credit R. Essig

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

<u>Detection limitation :</u>

energy deposit from nucleus recoil

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

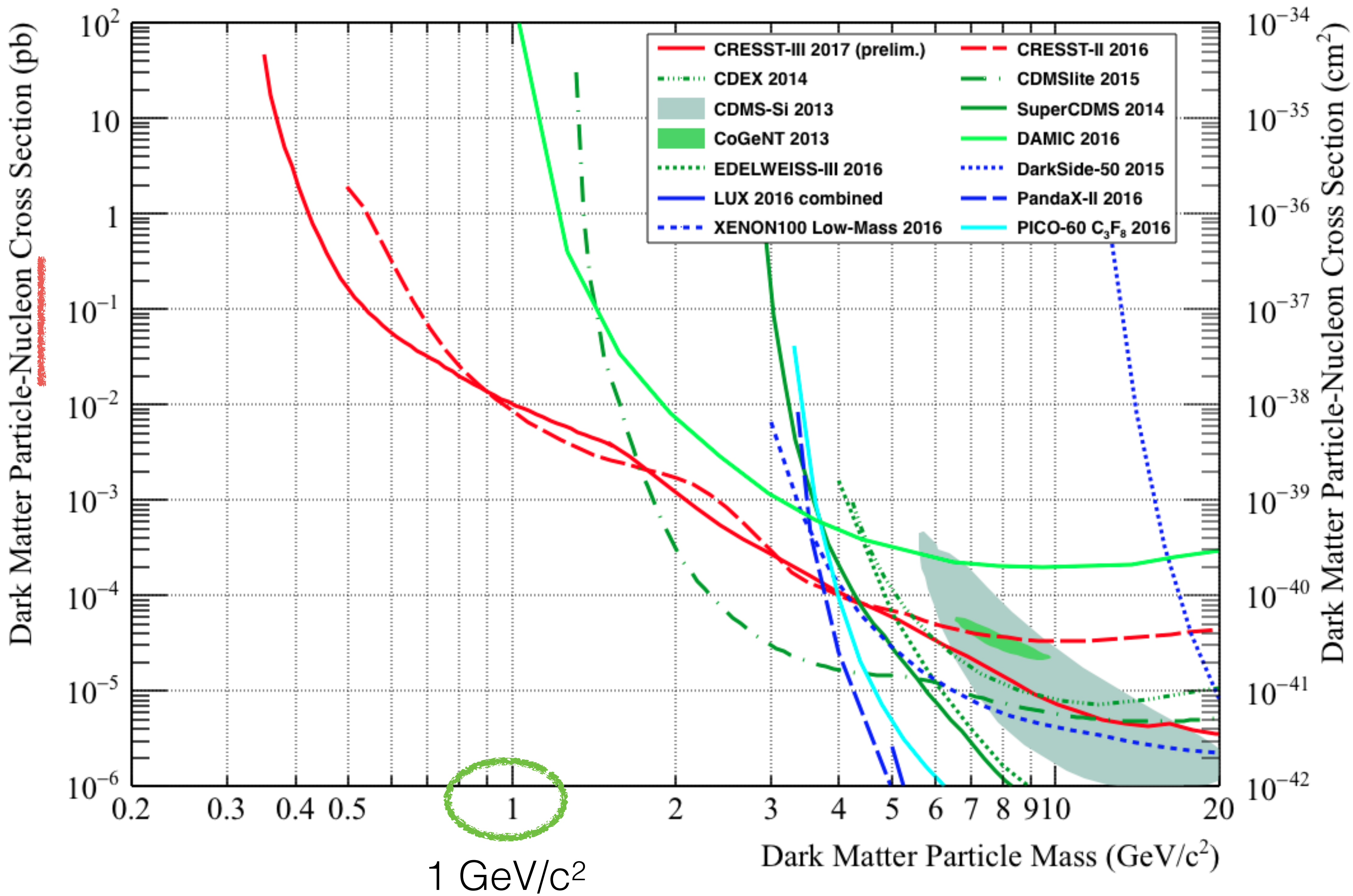
-> for 100 MeV m_χ, $E_{NR} \sim 1$ eV *

plus quenching factors and
noise level of the detectors

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

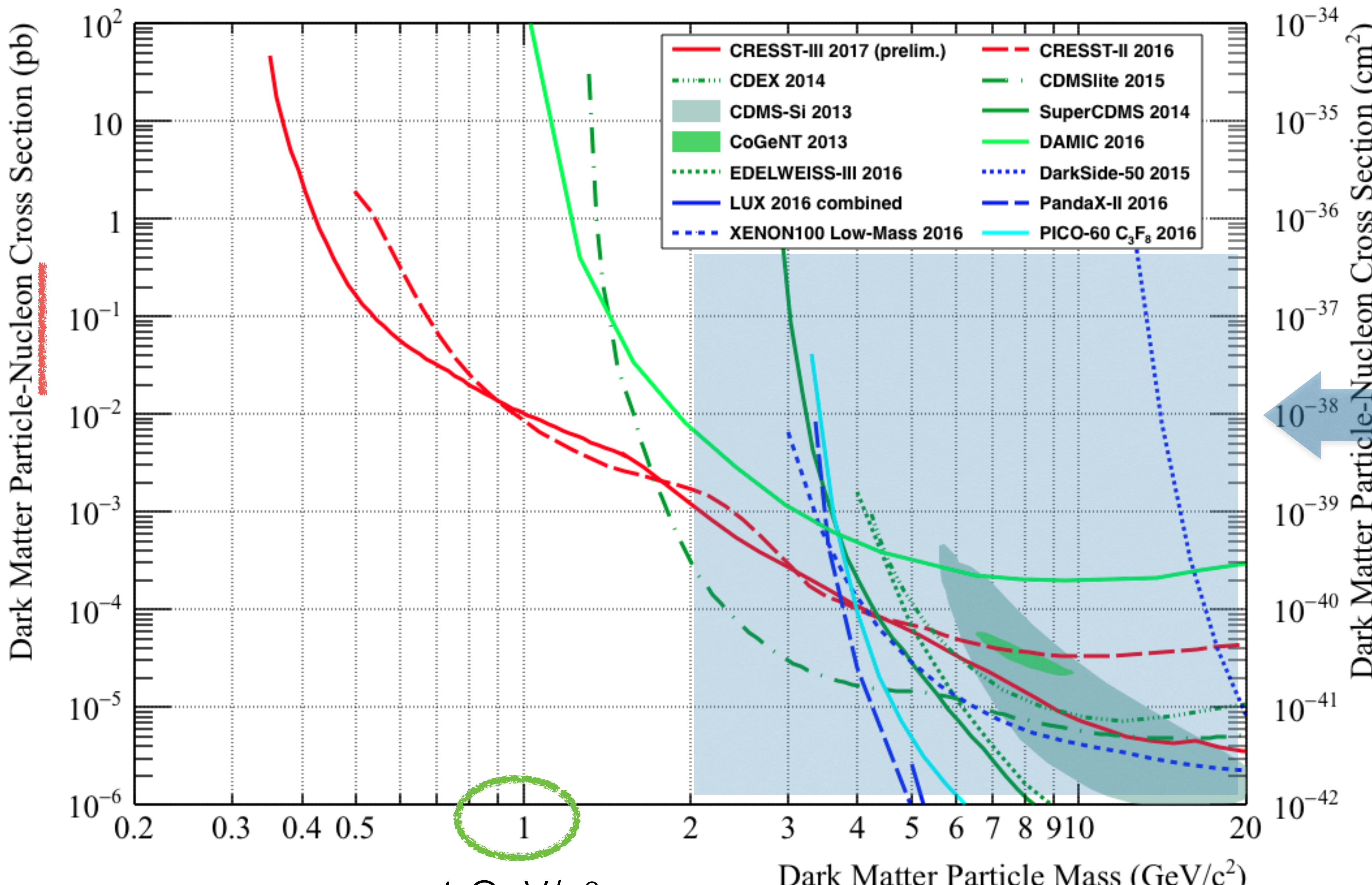
*for silicon

DM-nucleus scattering direct search status



arXiv:1711.07692

DM-nucleus scattering direct search status



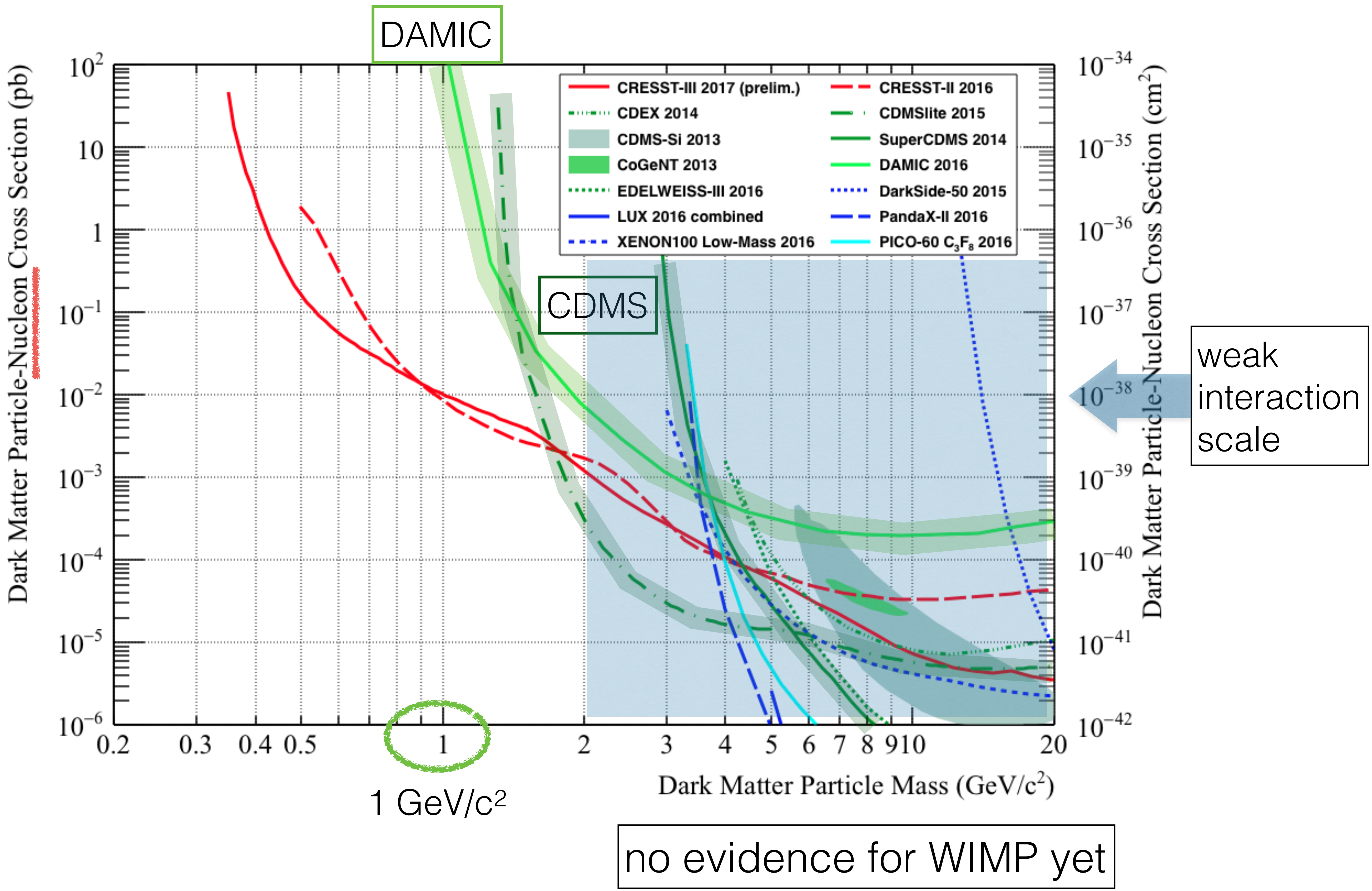
weak interaction scale

1 GeV/c^2

no evidence for WIMP yet

arXiv:1711.07692

DM-nucleus scattering direct search status



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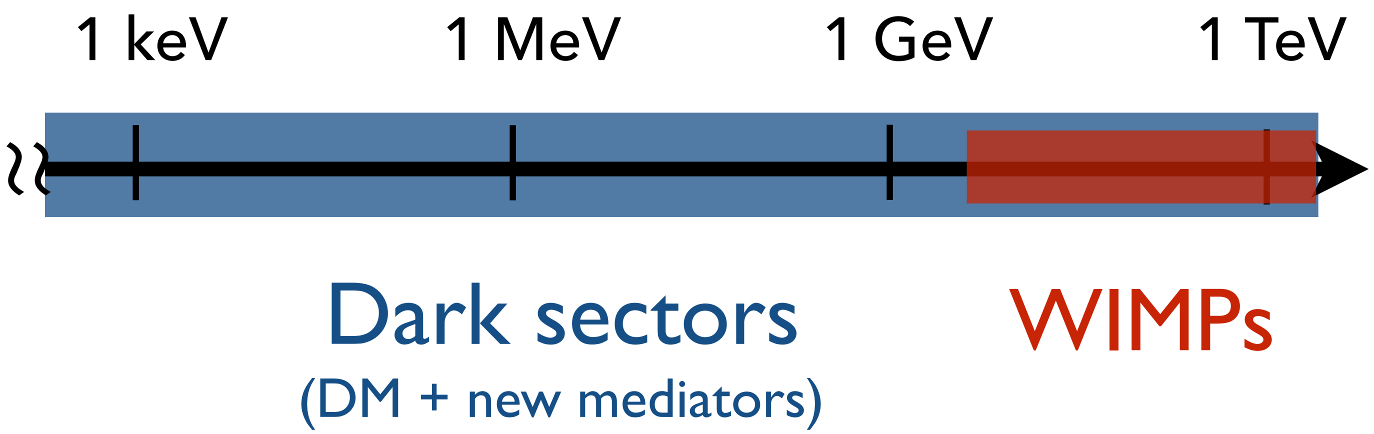
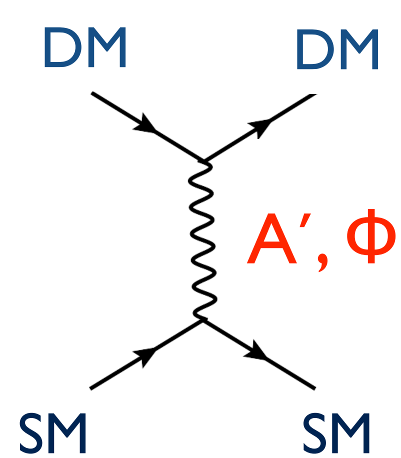
Dark Sector and Light Dark Matter



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

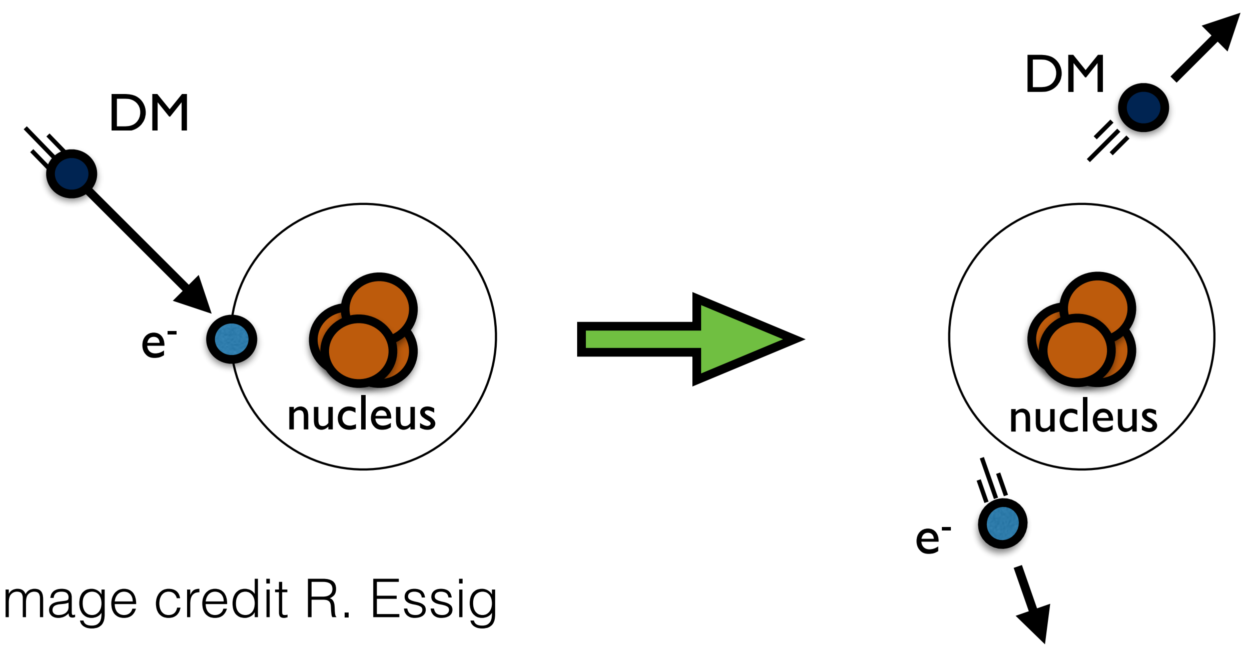


image credit R. Essig

kinematically

to overcome binding energy ΔE

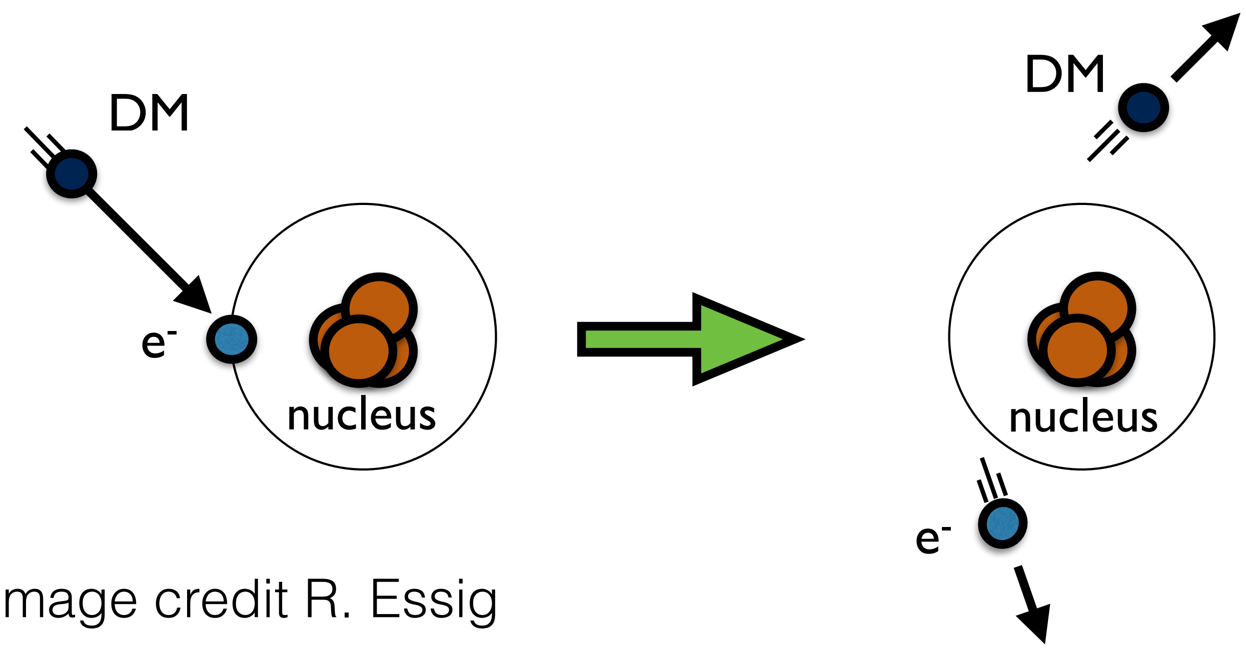
need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$

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

O(100 keV)

JHEP05(2016)046

DM-electron scattering



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kinematically

to overcome binding energy *ΔE*

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

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

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

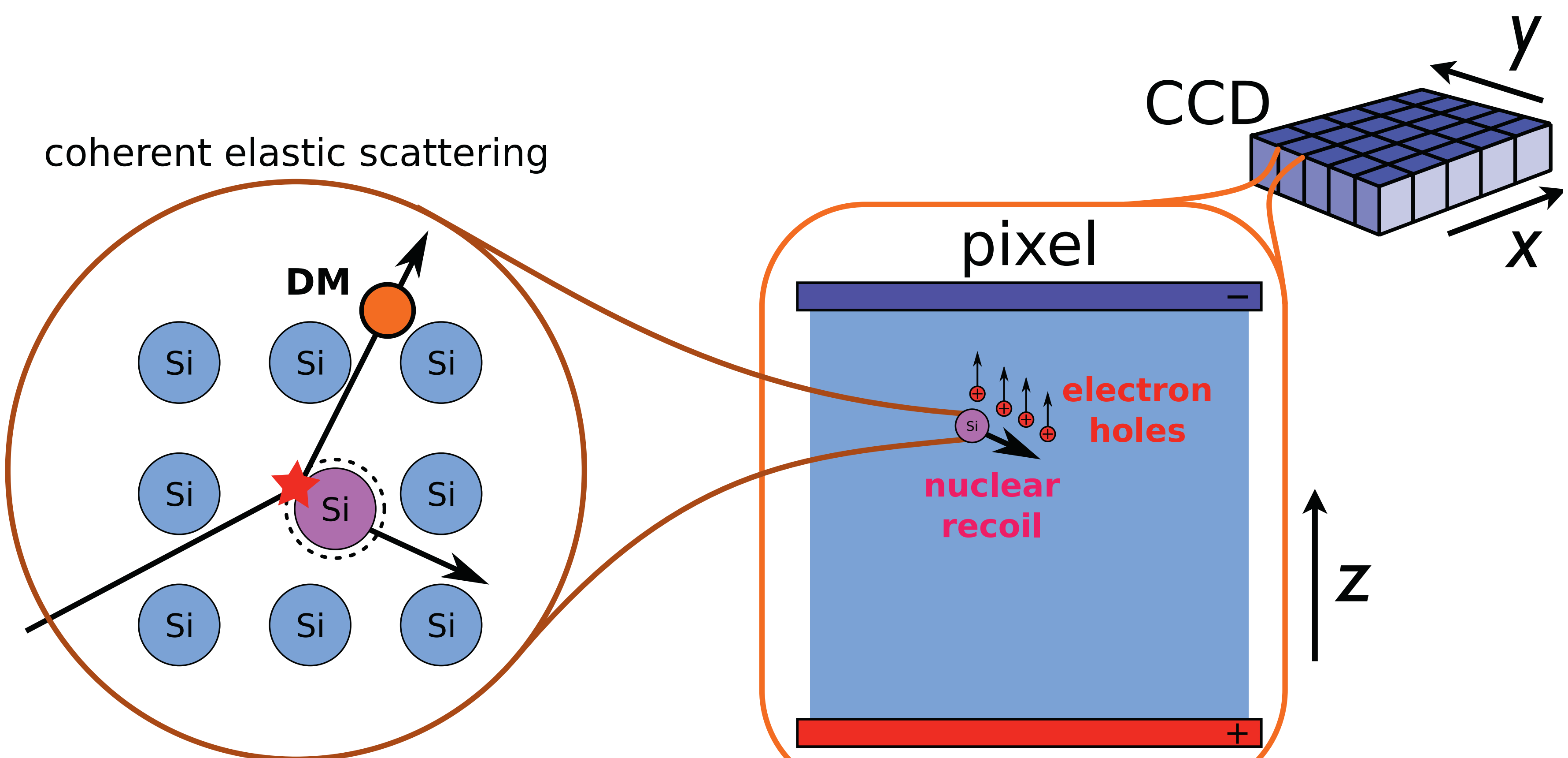
Target Type	Examples	E_{th}	m_χ threshold	Status	Timescale
Noble liquids	Xe, Ar, He	~ 10 eV	~ 5 MeV	Done w data; improvements possible	existing
Semi-conductors	Ge, Si	~ 1 eV	~ 200 keV	(E_{th} ~ 40 eV SuperCDMS, **DAMIC**) E_{th} ~ 1eV **SENSEI**, **DEPFET** R&D	~ 1-2 years
Scintillators	GaAs, NaI, CsI,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

Application of Silicon detector

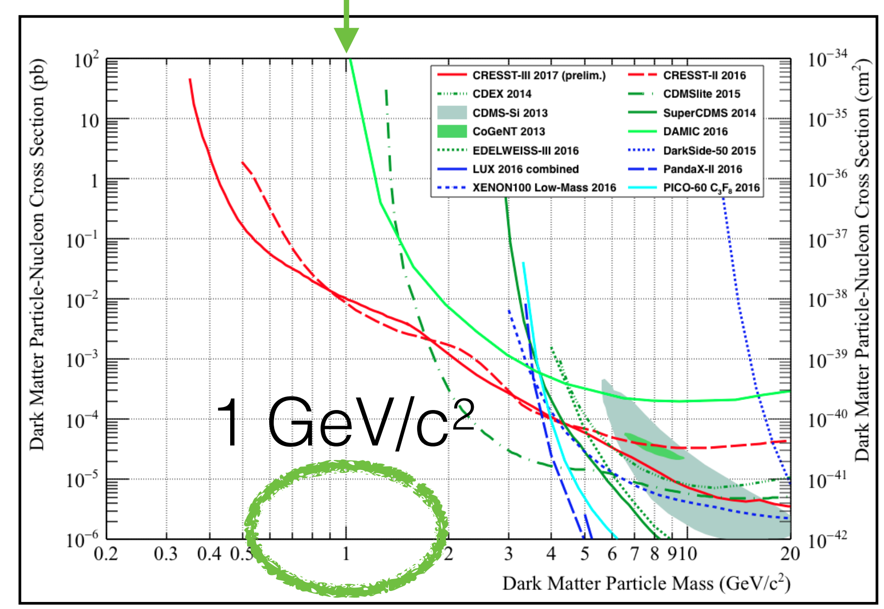
DAMIC

nucleus recoil   CCD, with physics results



Physics Procedia 61 (2015) 21 – 33

DAMIC



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

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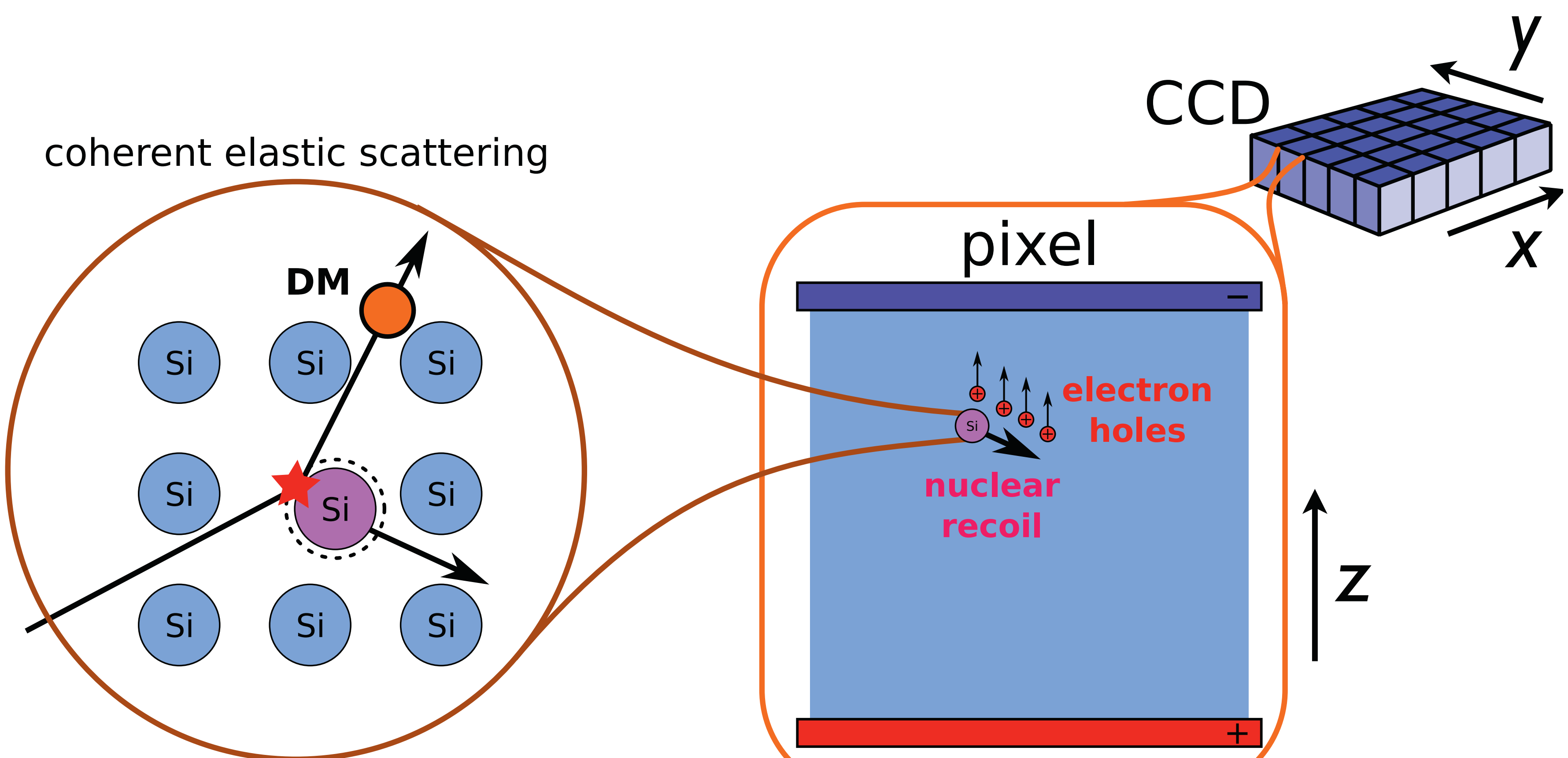

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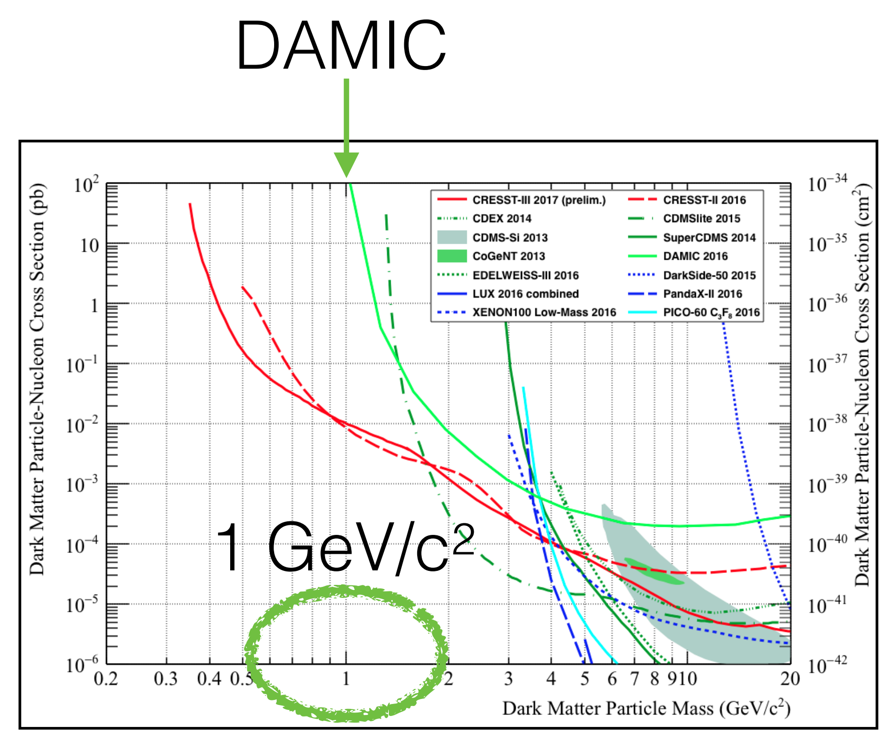
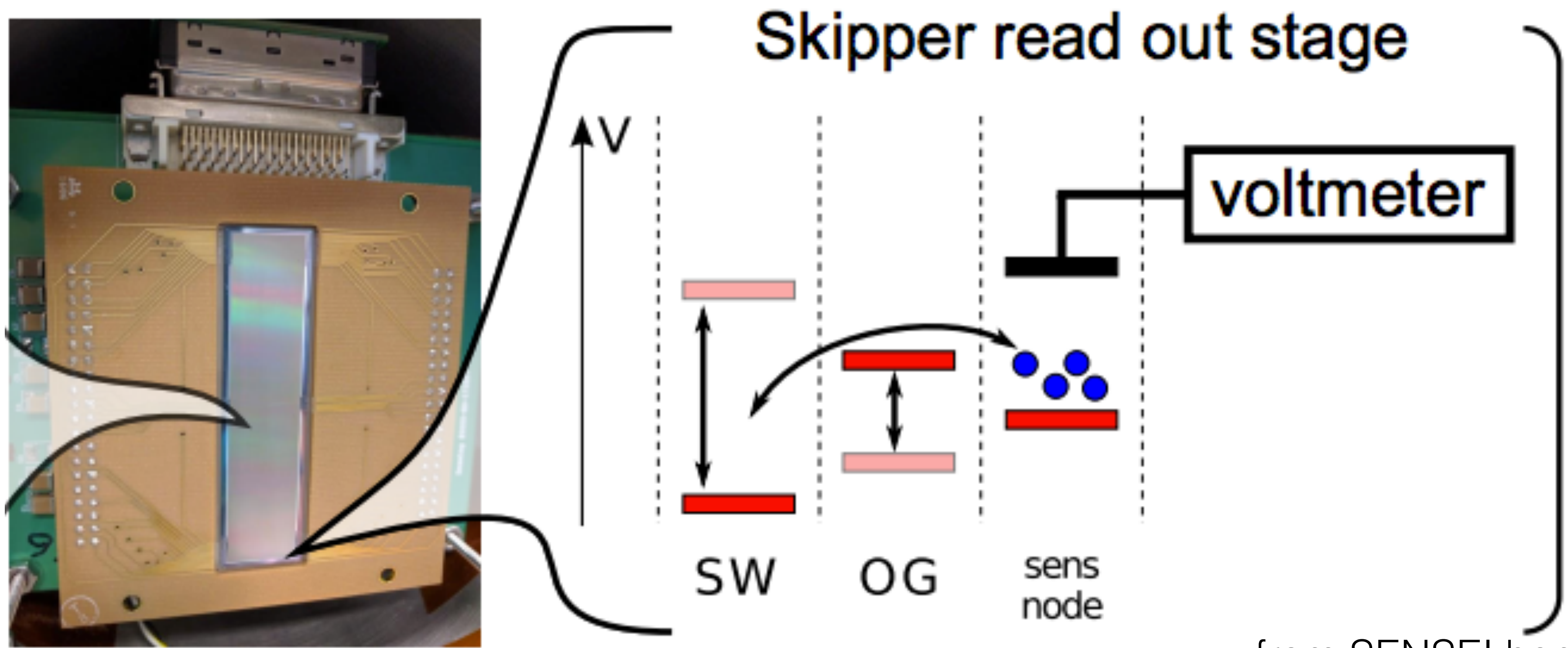


Readout noise determines threshold of ~ 11 e^- (or ~ 40 eV)

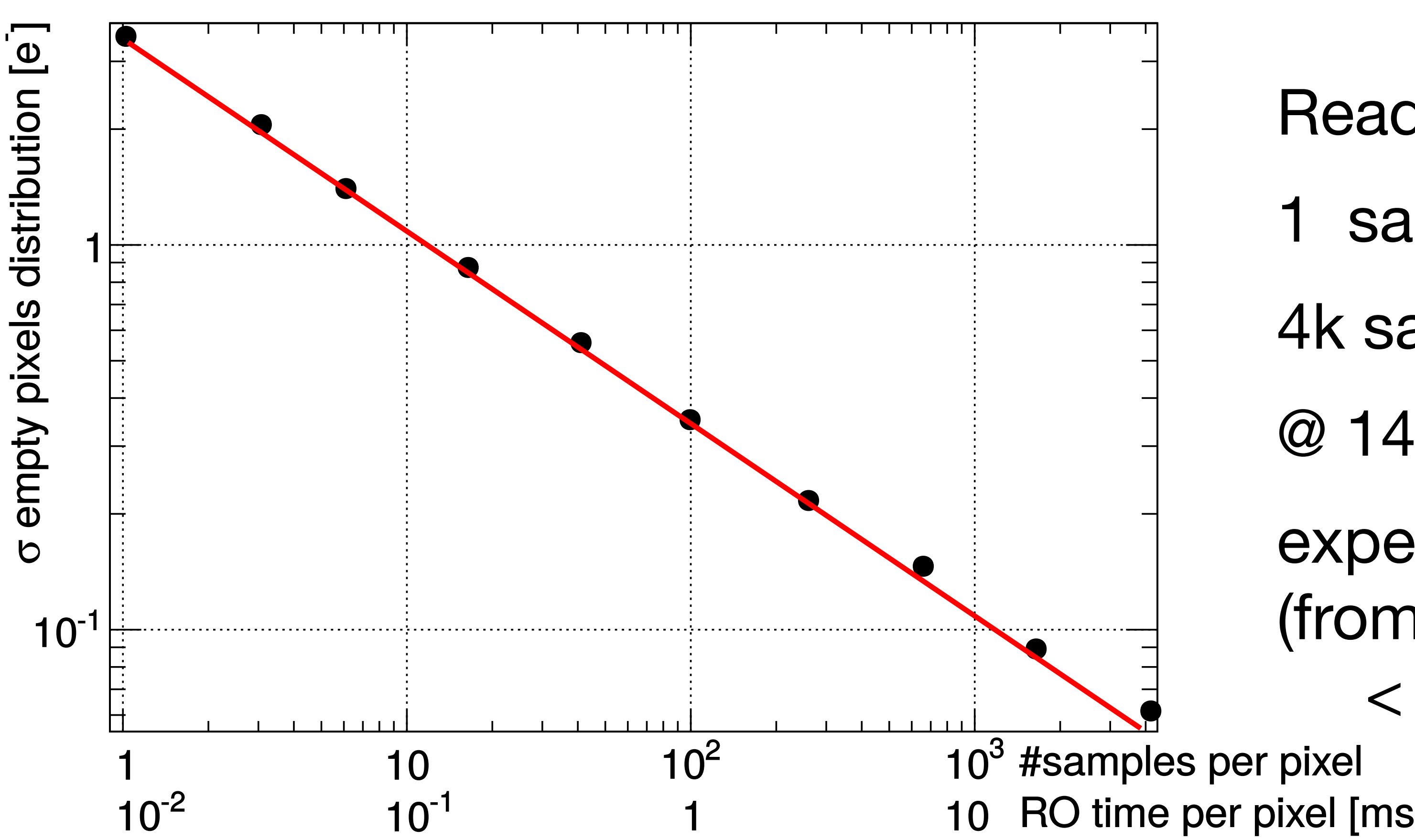
For O(MeV) DM-electron scattering, required threshold : O(e^-)
Sub-electron noise level necessary

Skipper CCD for SENSEI

DAMIC CCD with **repetitive readout**



from SENSEI homepage



PRL 119(1) 131802 (2017)

Readout noise :

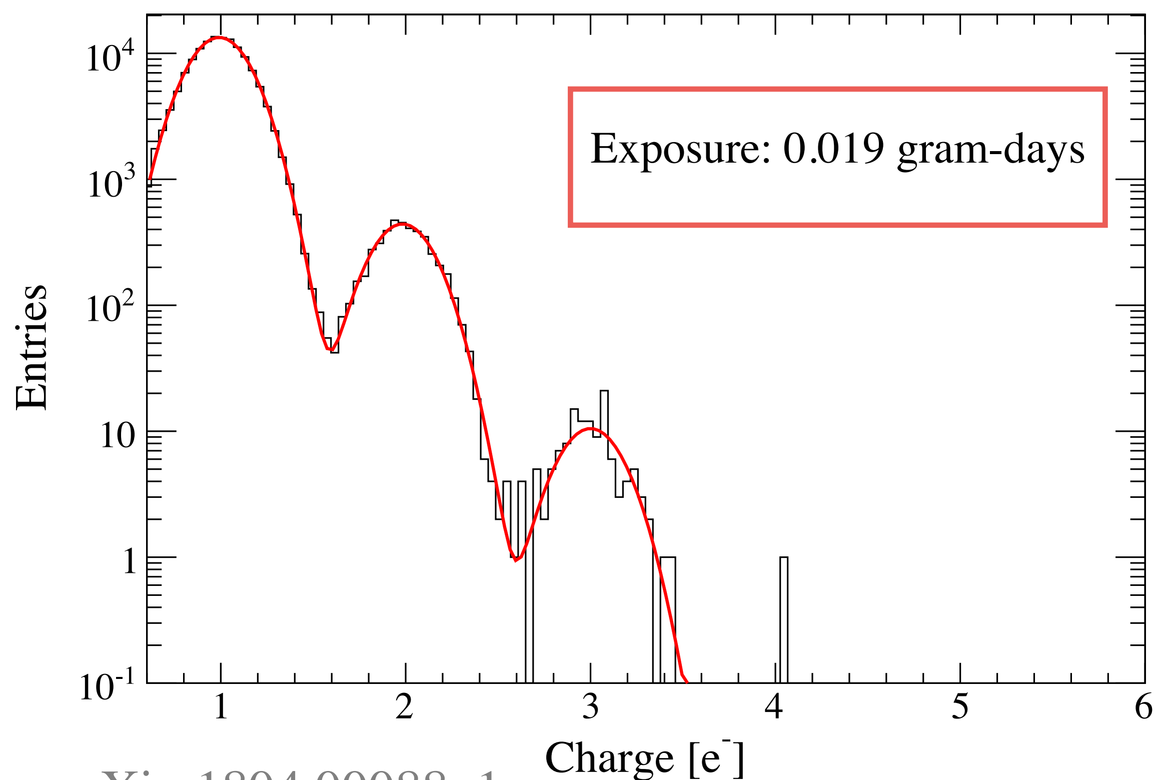
1 sample : 3.55 e^- rms

4k samples : 0.068 e^- rms

@ 140 K

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

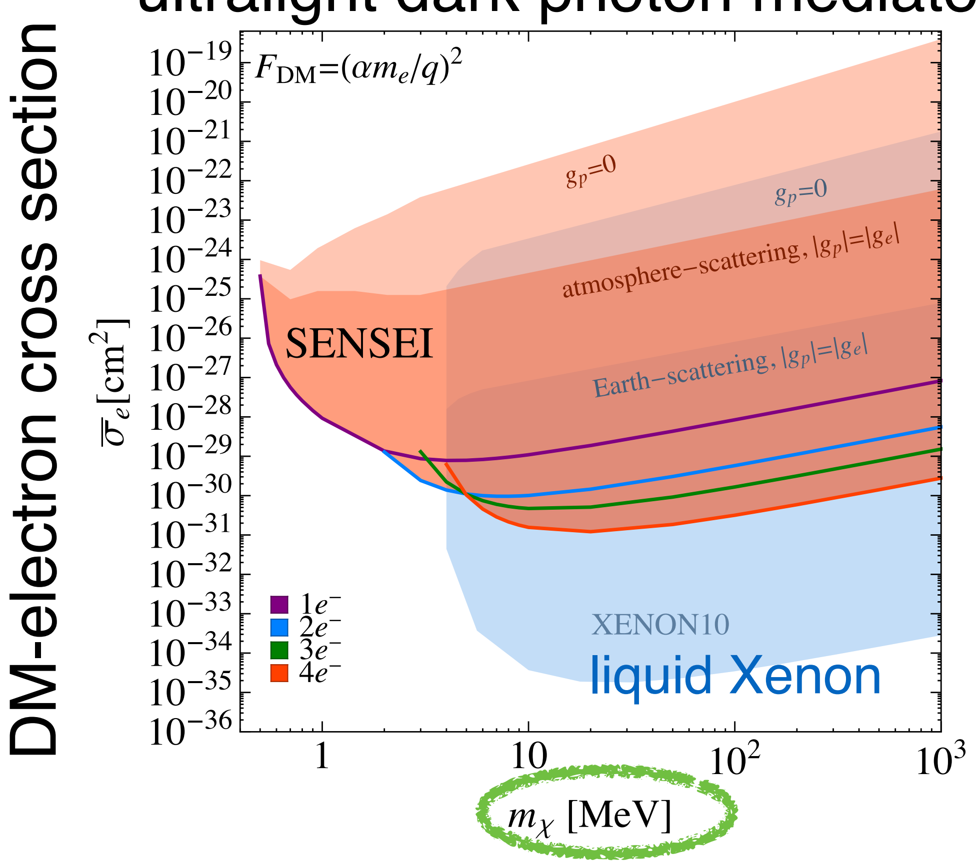
SENSEI first result from a surface run



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



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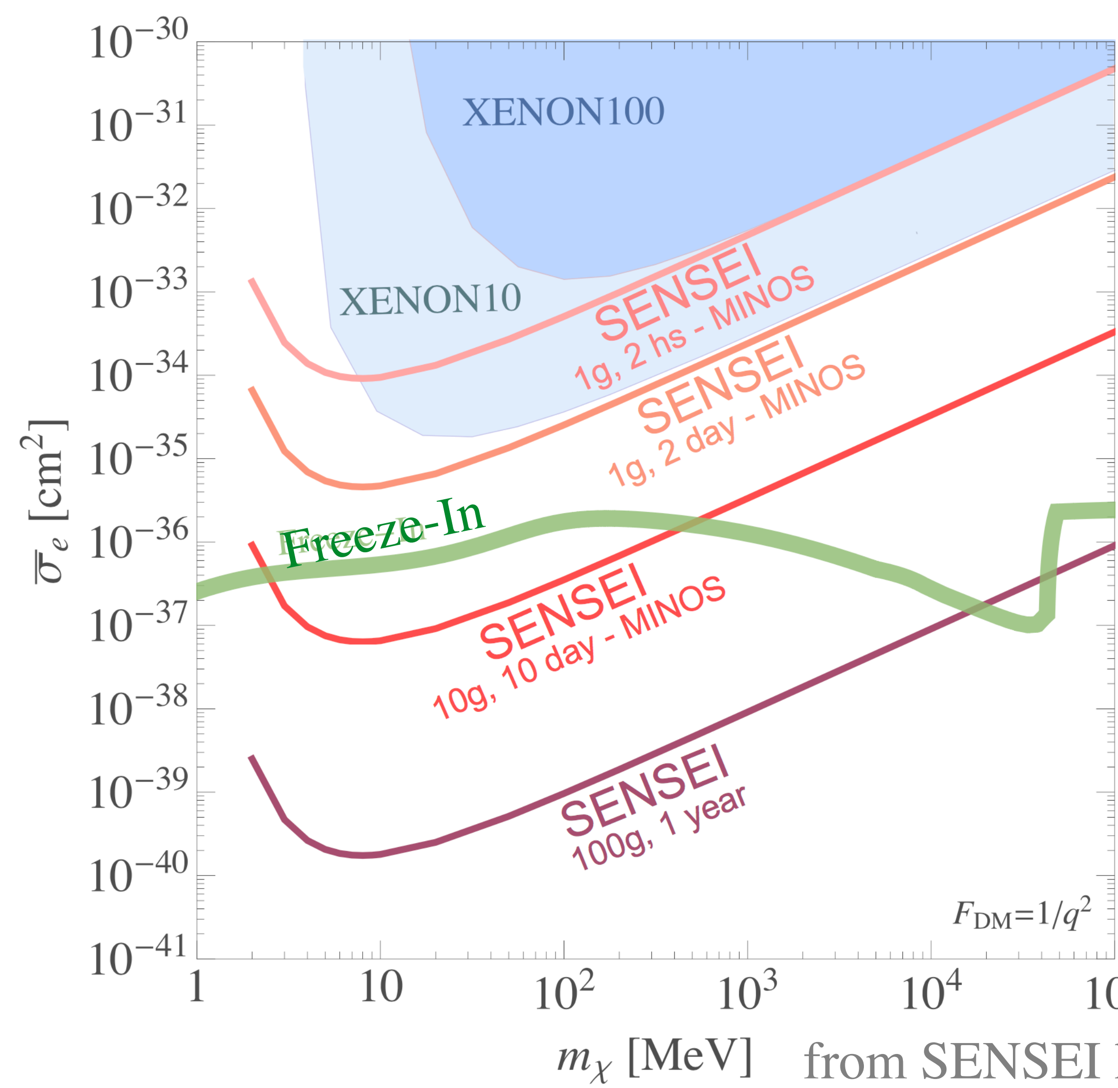

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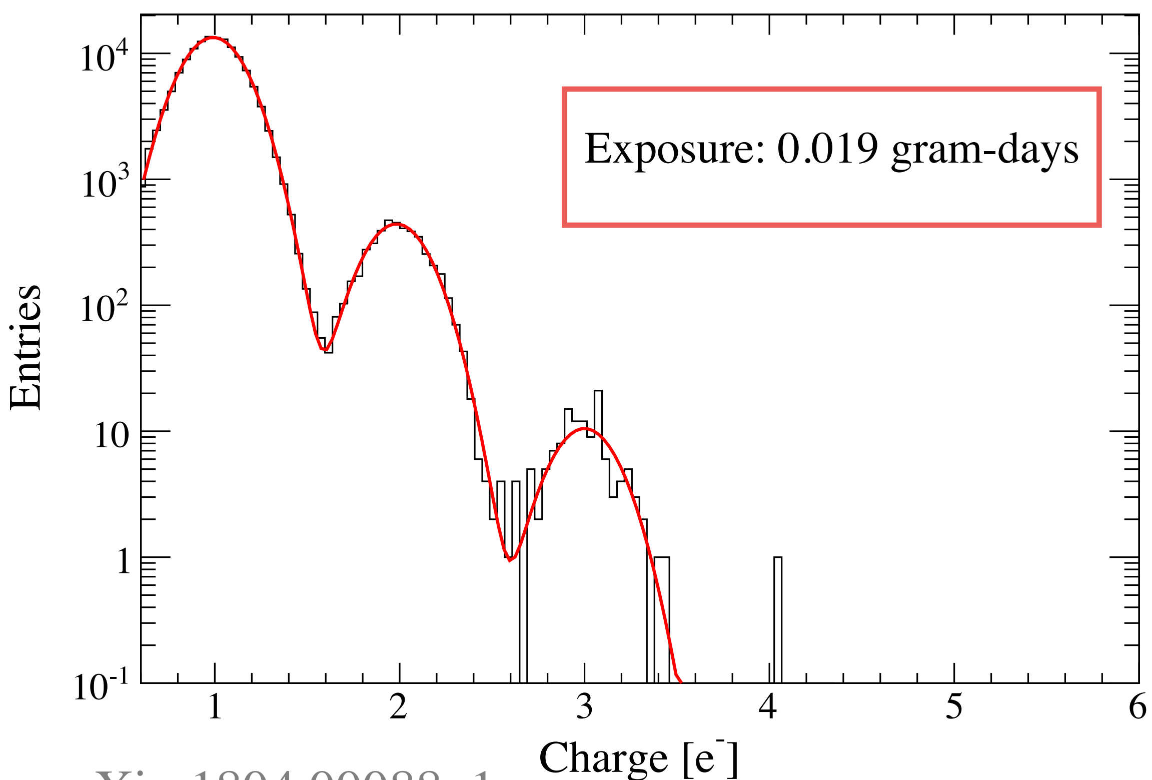

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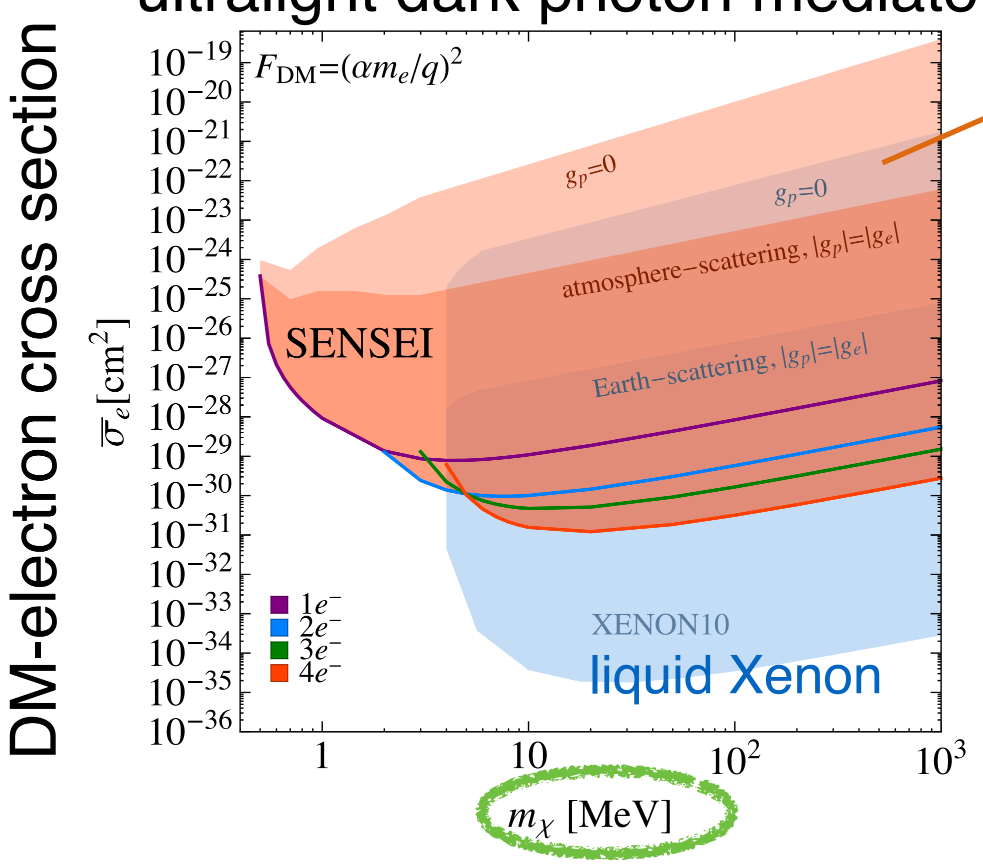

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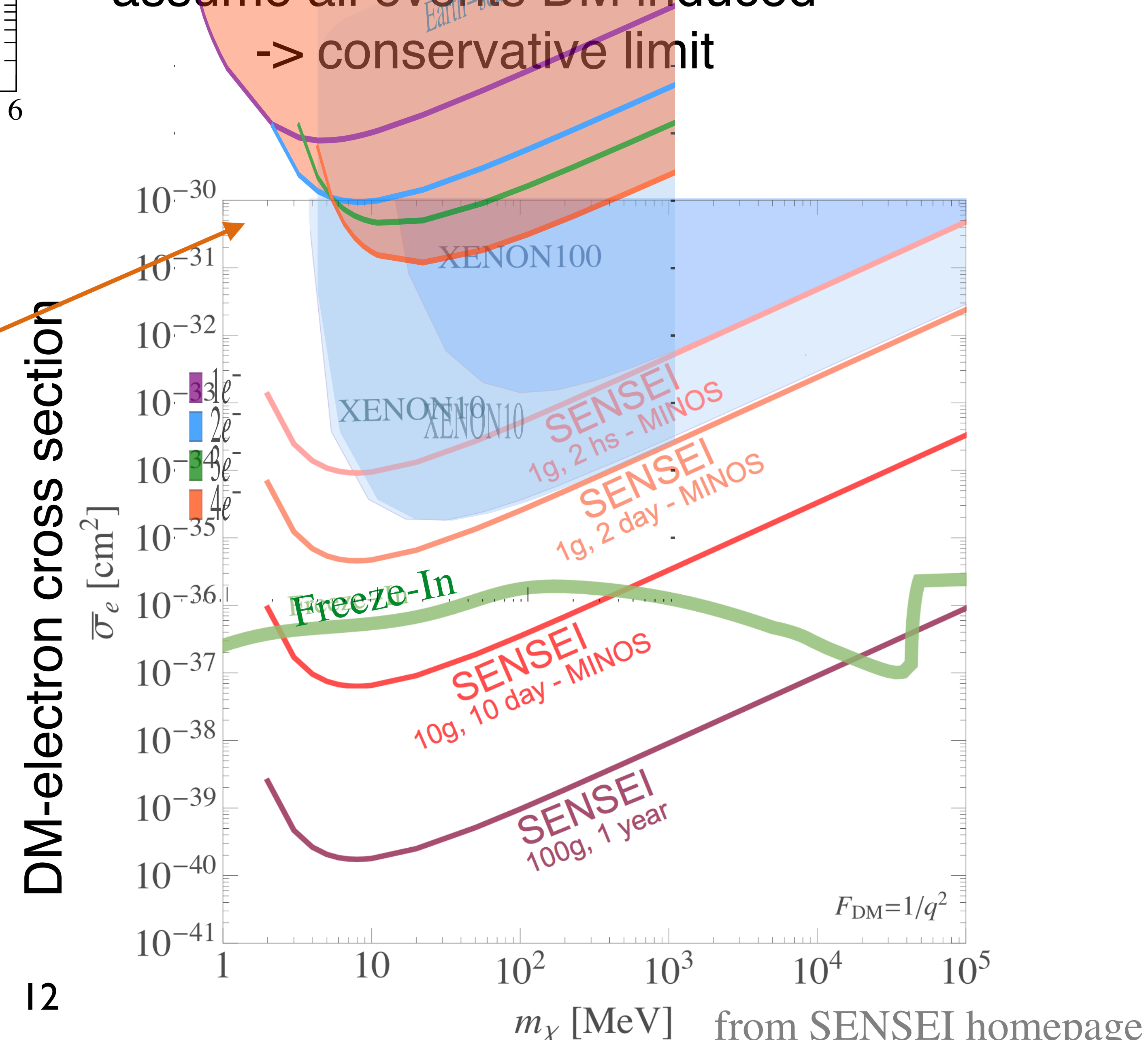


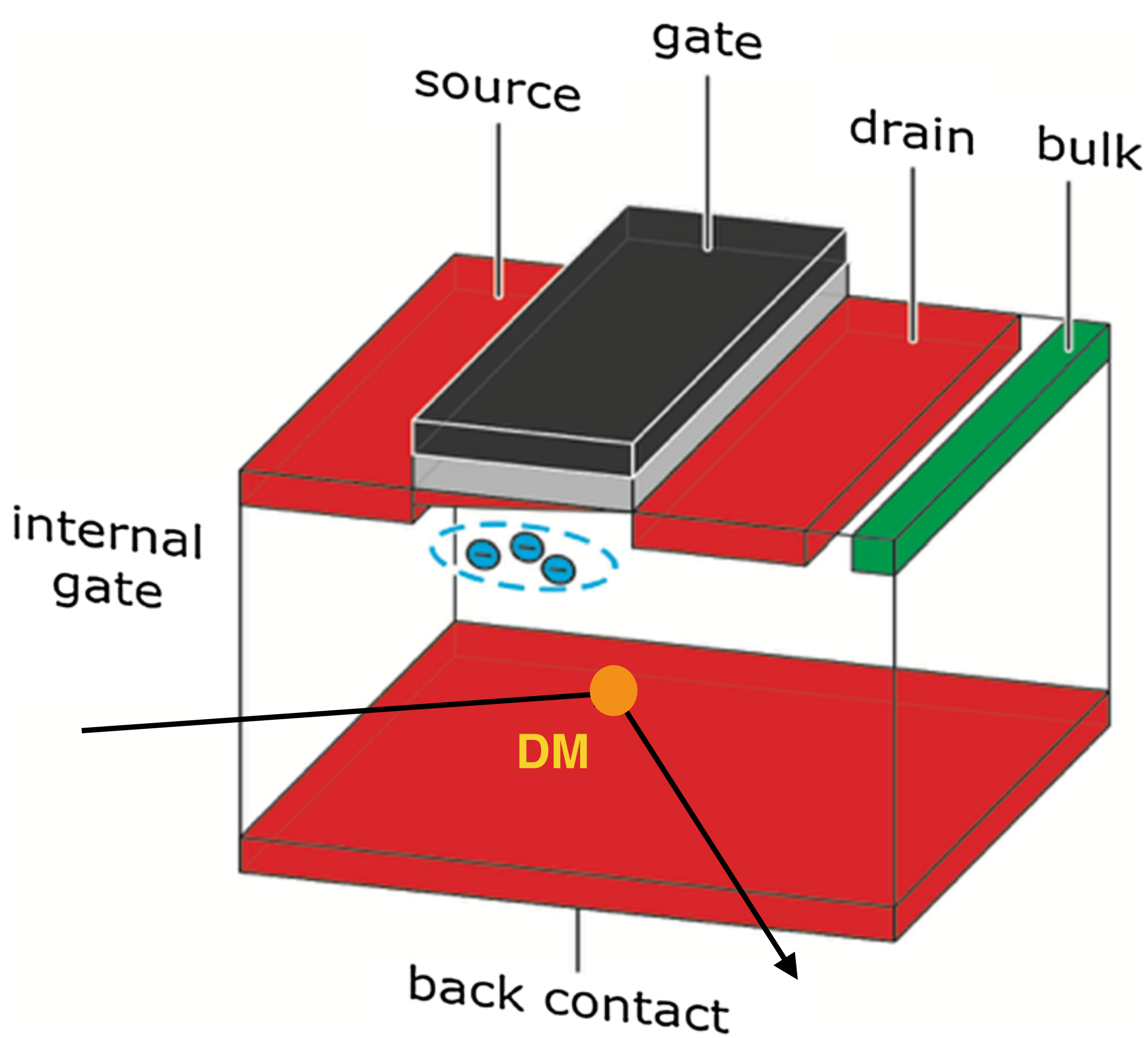
from SENSEI homepage

DEPFET with RNDR

RNDR : repetitive non-destructive readout

structure of a basic DEPFET cell :

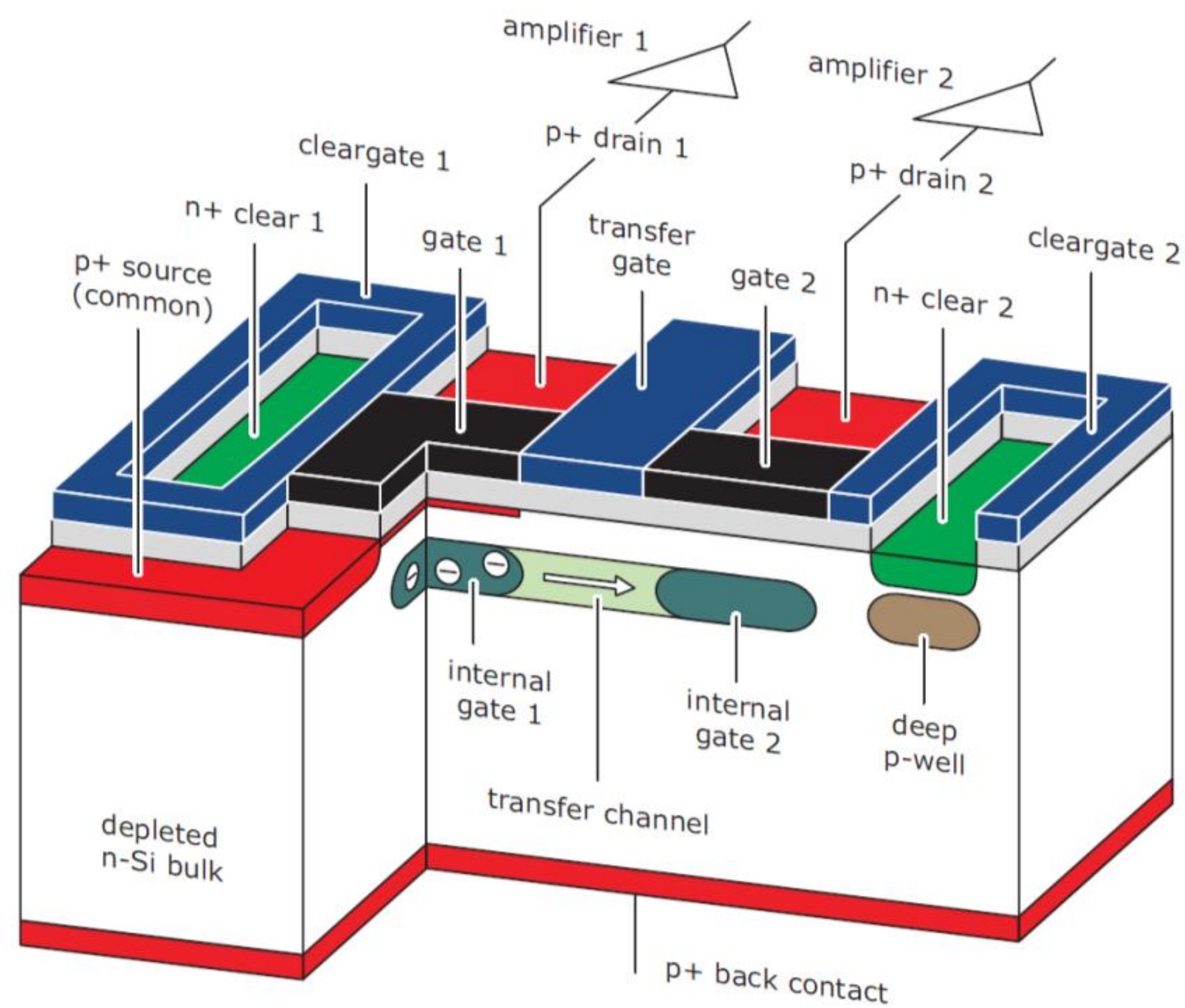
a “subpixel”



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

fully-depleted n-Si

structure of RNDR DEPFET “super-pixel”



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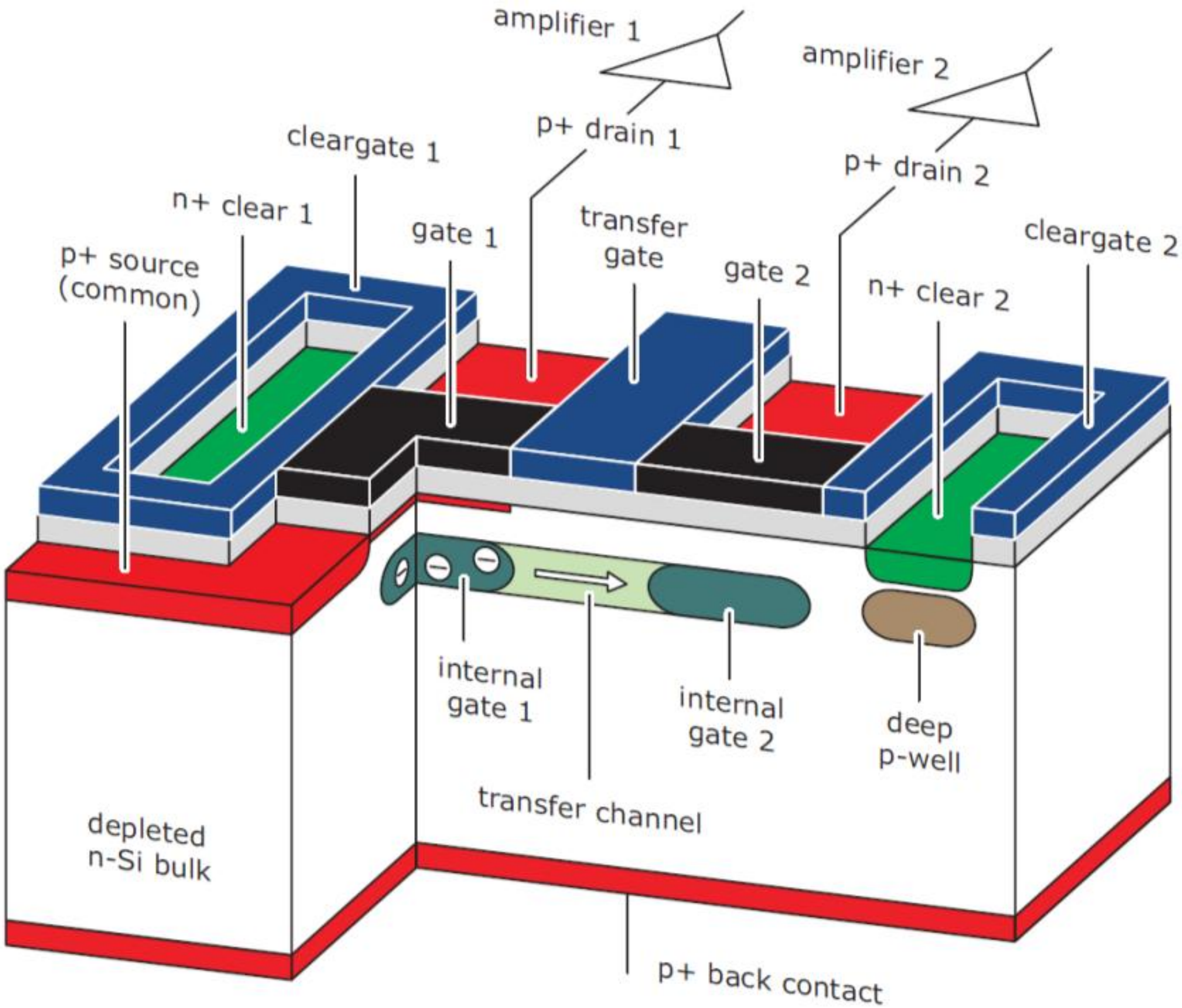
RNDR



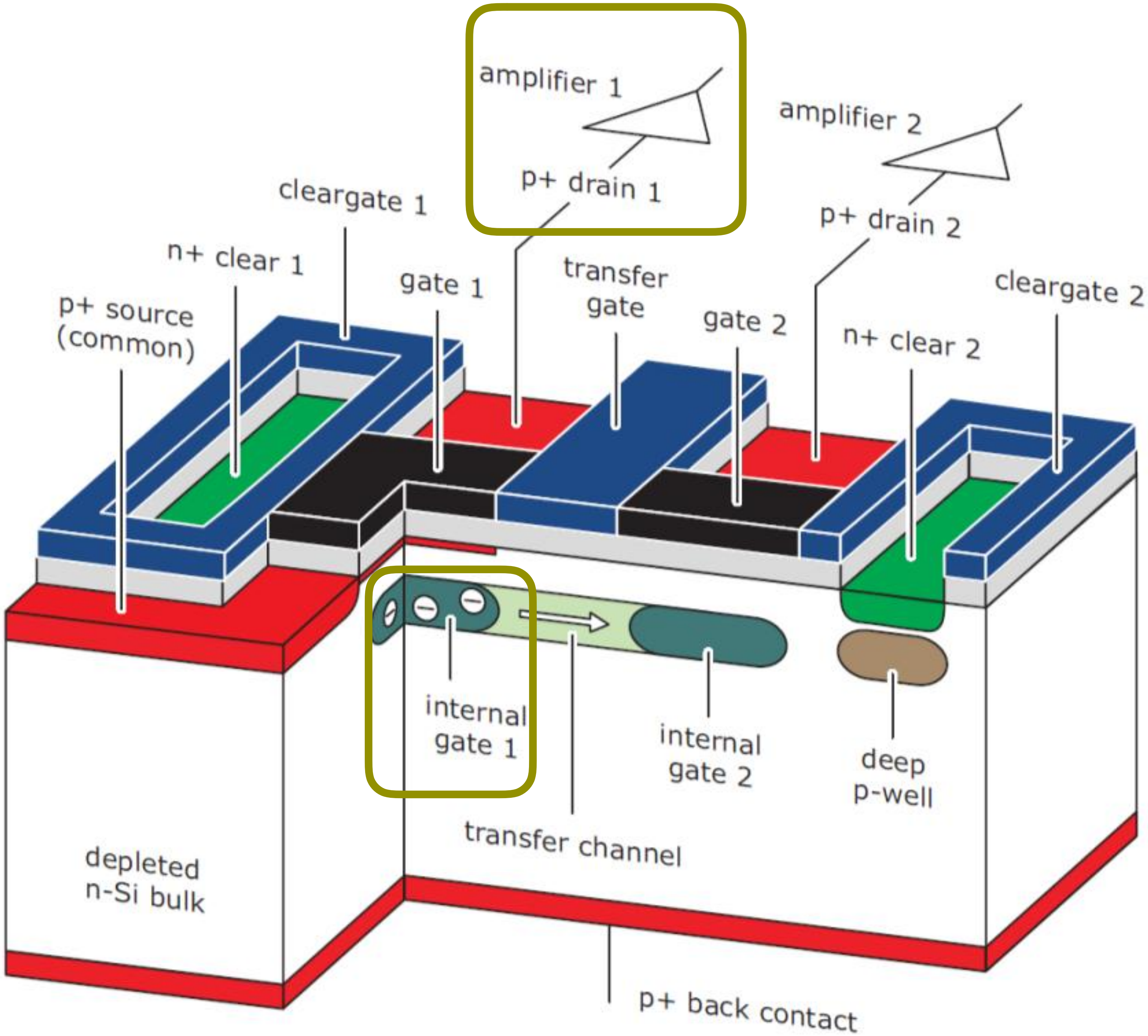
EPJ C, 77(12), 279 (2017)

RNDR readout

read N times effective noise :

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

RNDR



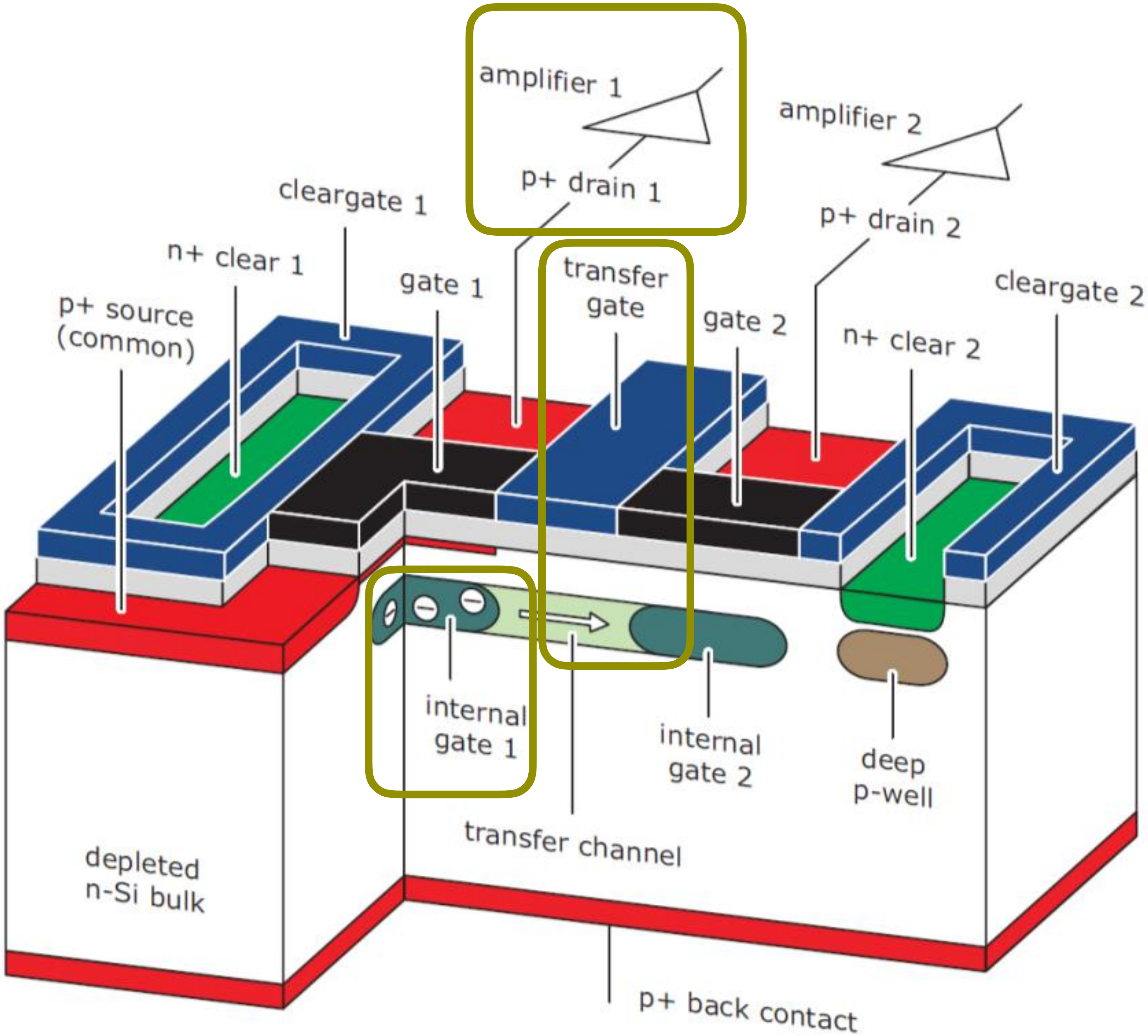
EPJ C, 77(12), 279 (2017)

RNDR readout

read 1 : noise σ

read N times effective noise :
$\sigma_{eff} = \sigma/(\sqrt{N})$

RNDR



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RNDR readout

read 1 : noise σ

transfer gate open

read N times effective noise :

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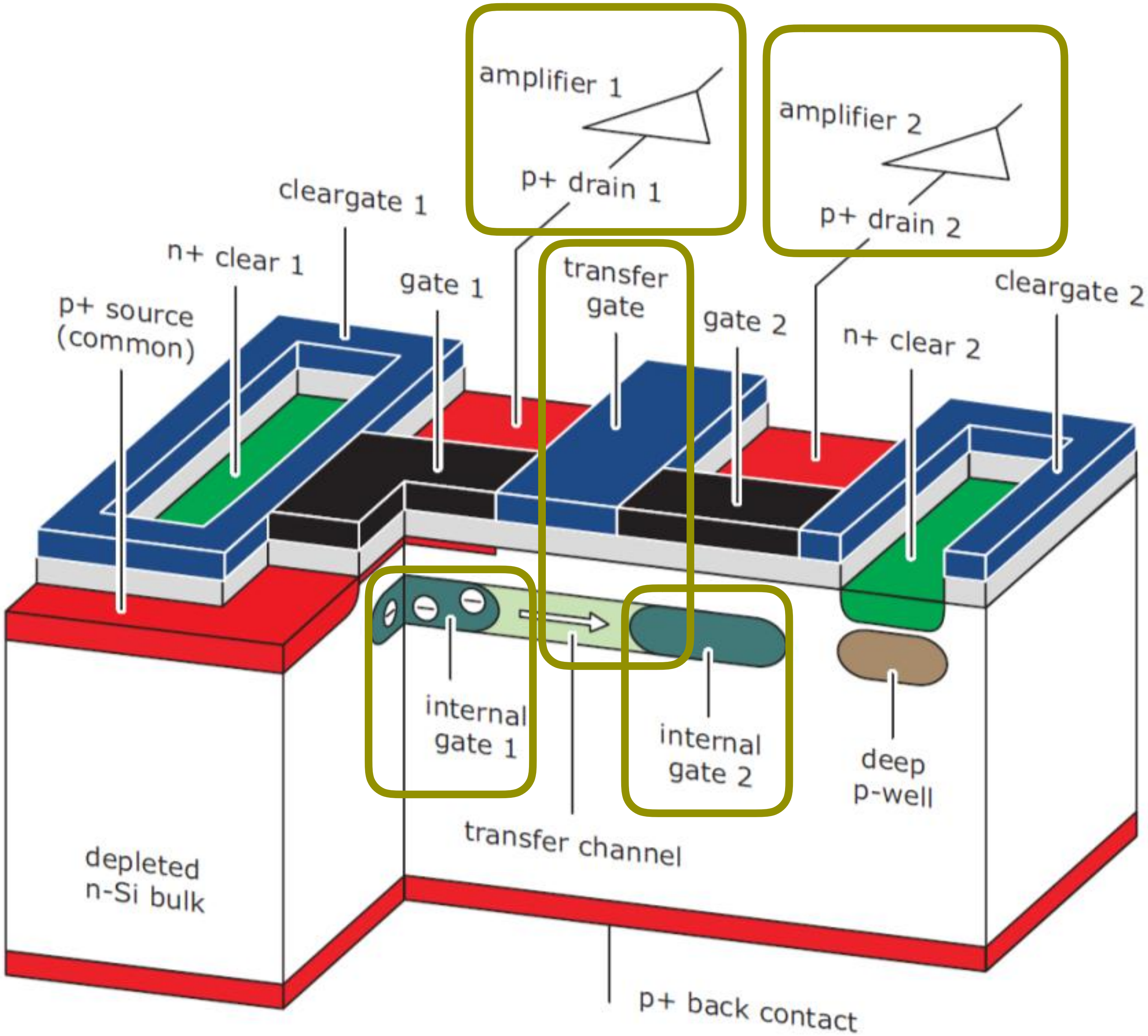
RNDR



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

RNDR readout

read 1 : noise σ

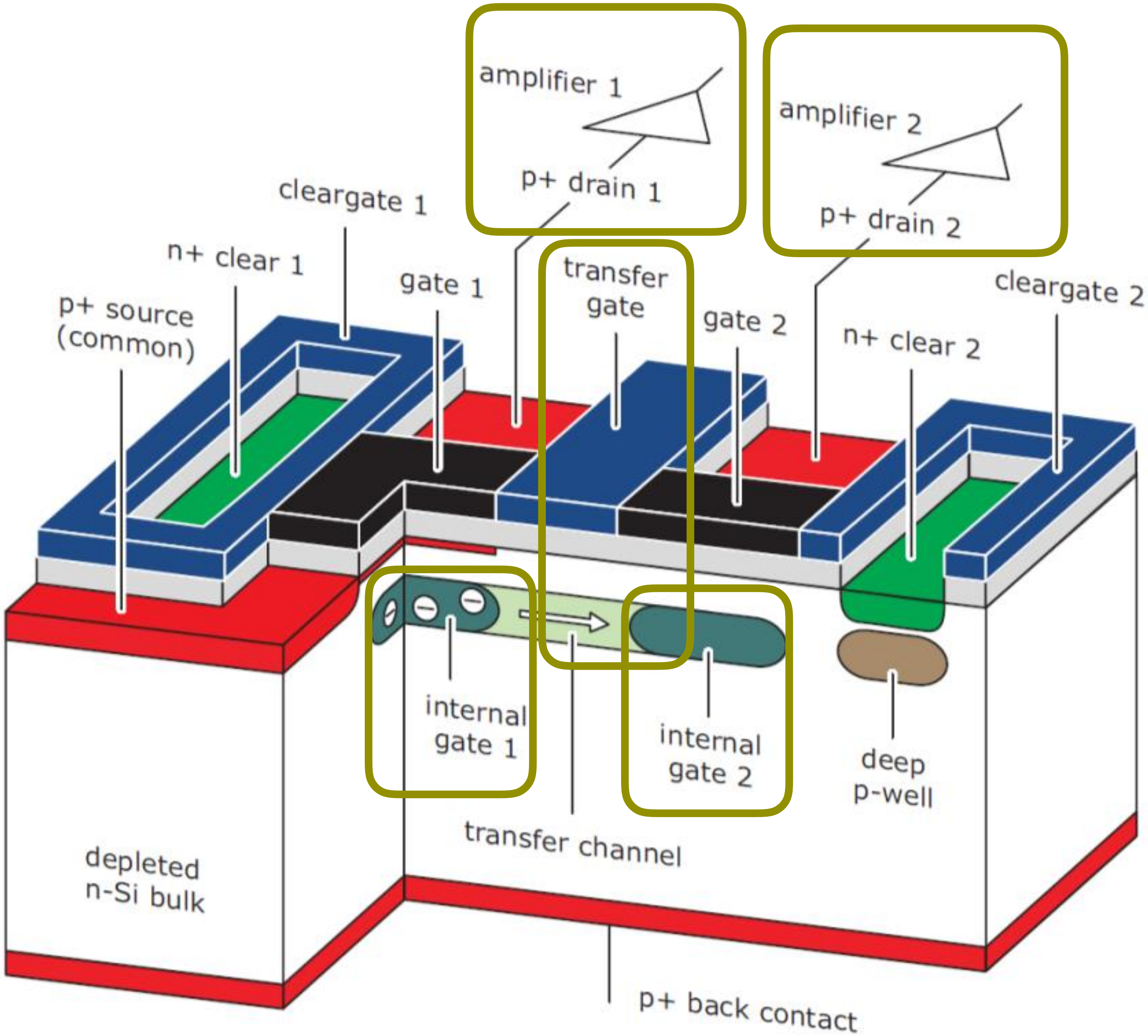
transfer gate open

read 2 : noise σ

read N times effective noise :

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

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

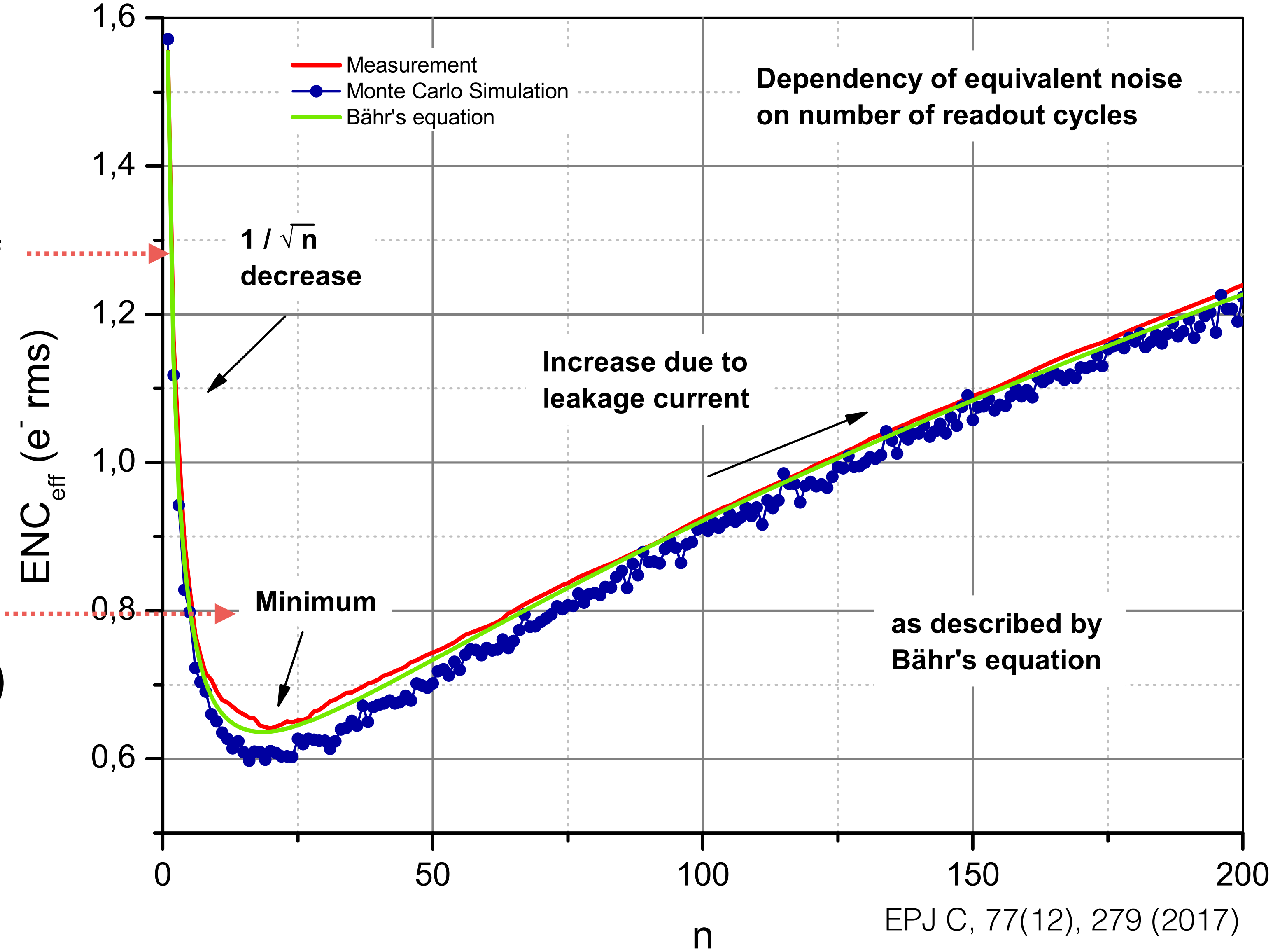
read N times effective noise :

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

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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DEPFET RNDR single pixel performance

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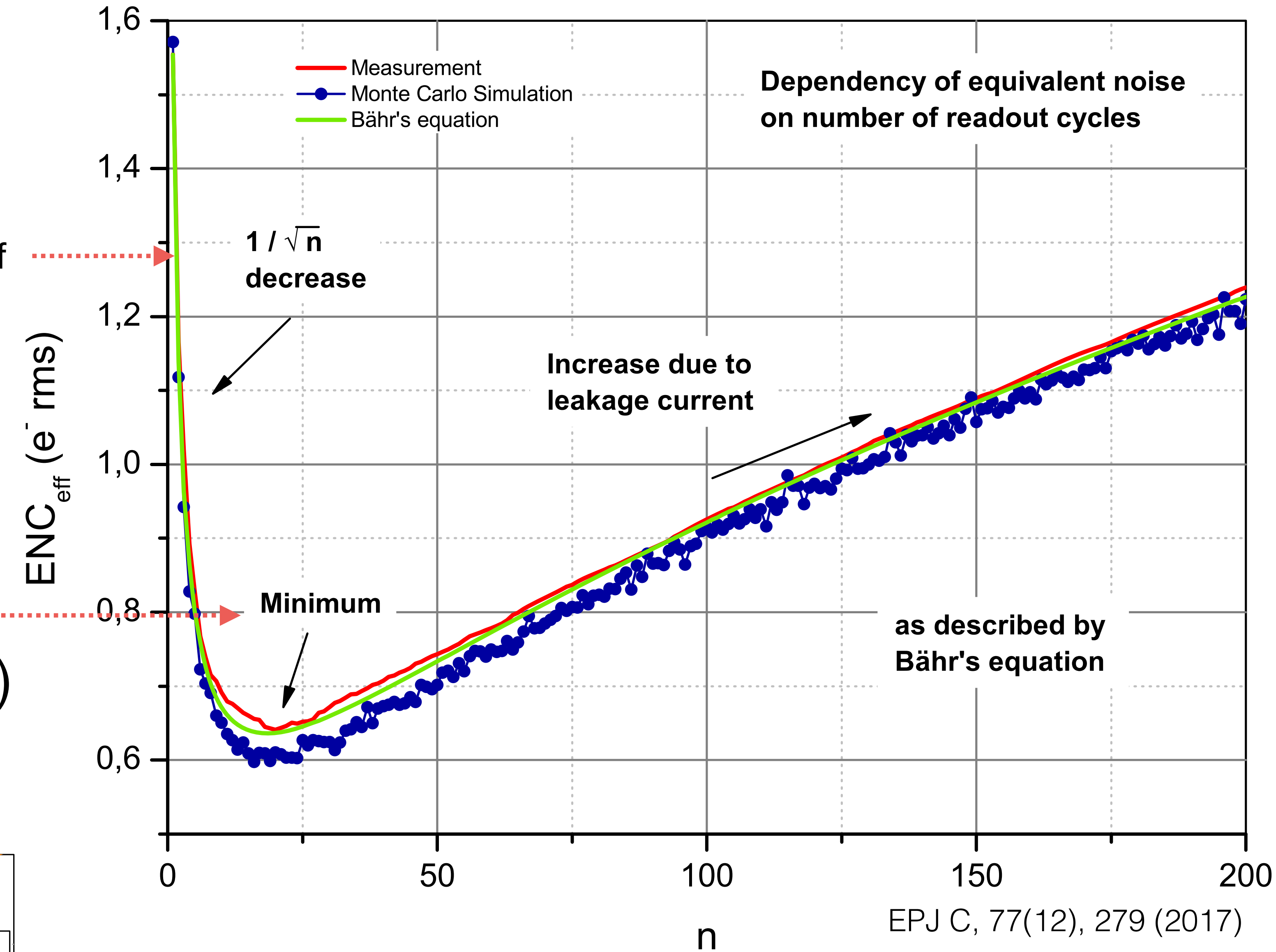

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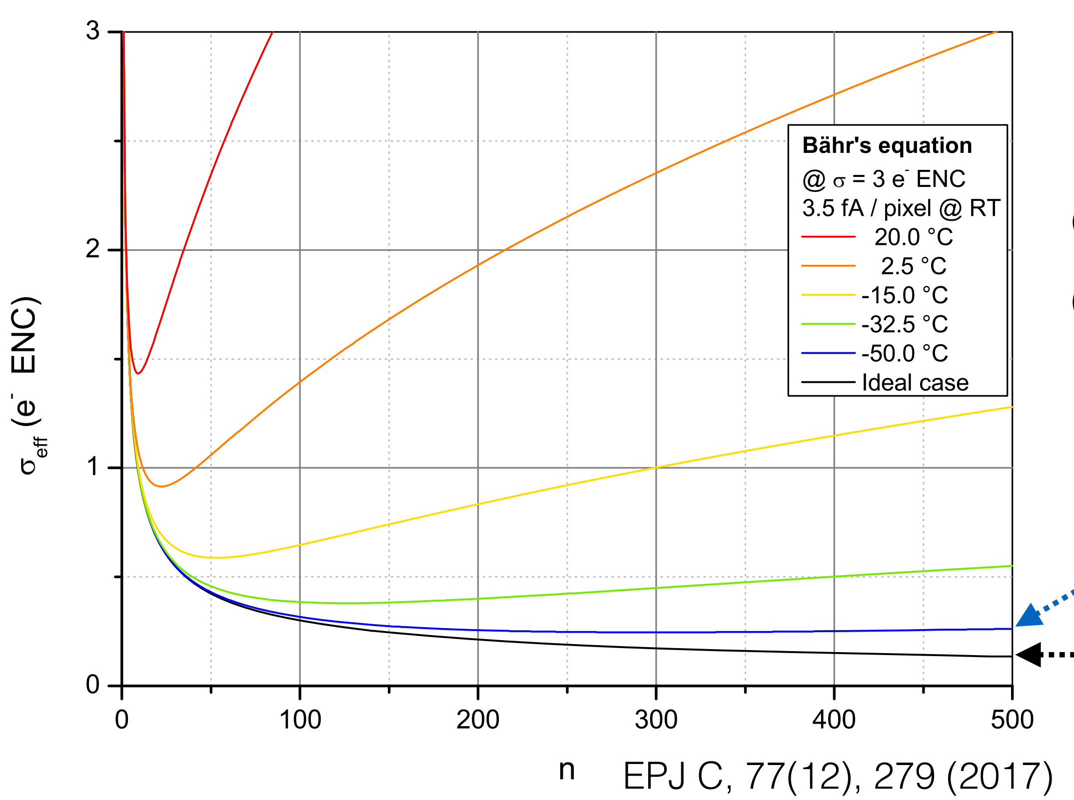

estimated temperature dependence, to be testified in measurement

- 50 °C

ideal case

DEPFET RNDR single pixel performance

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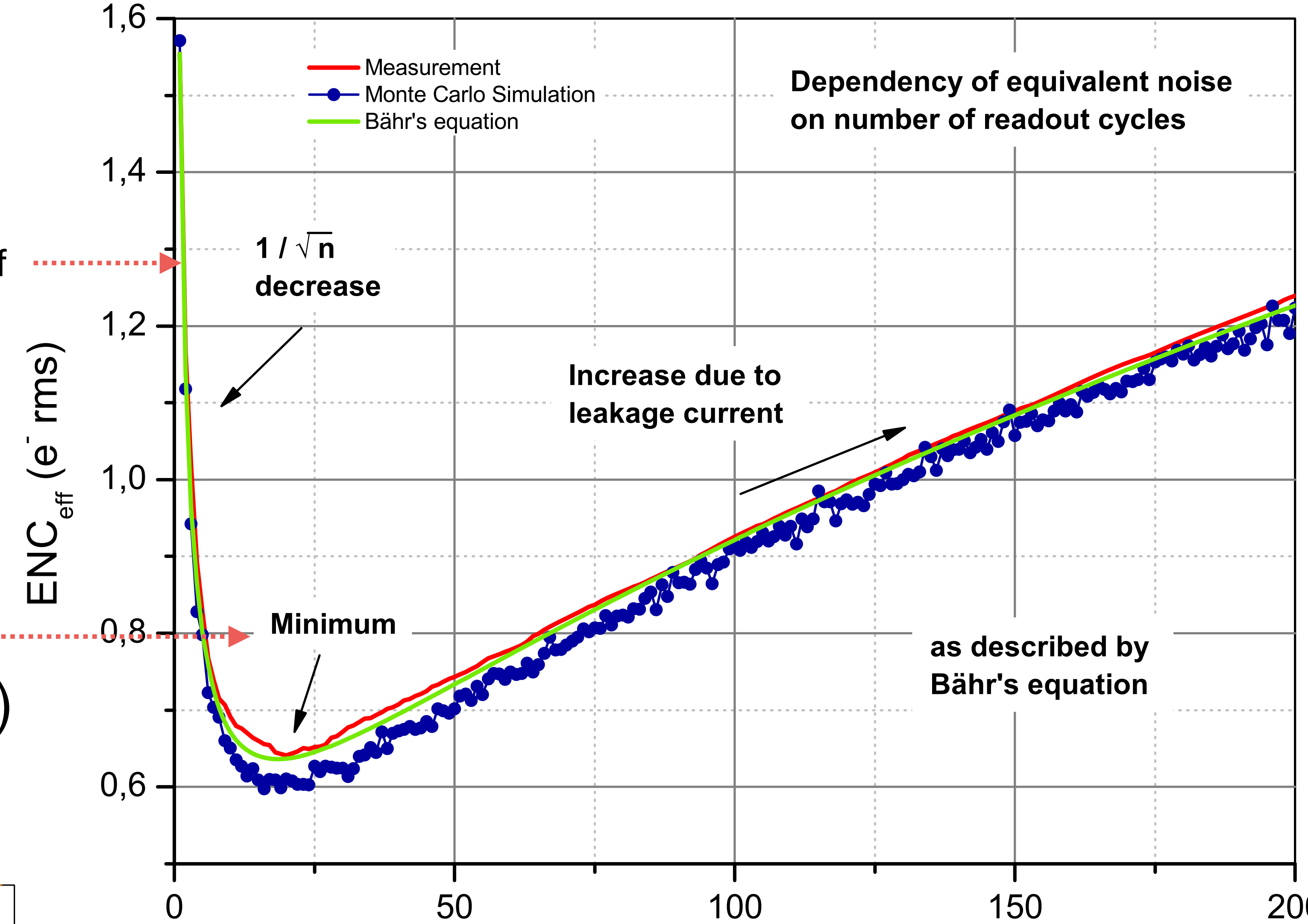

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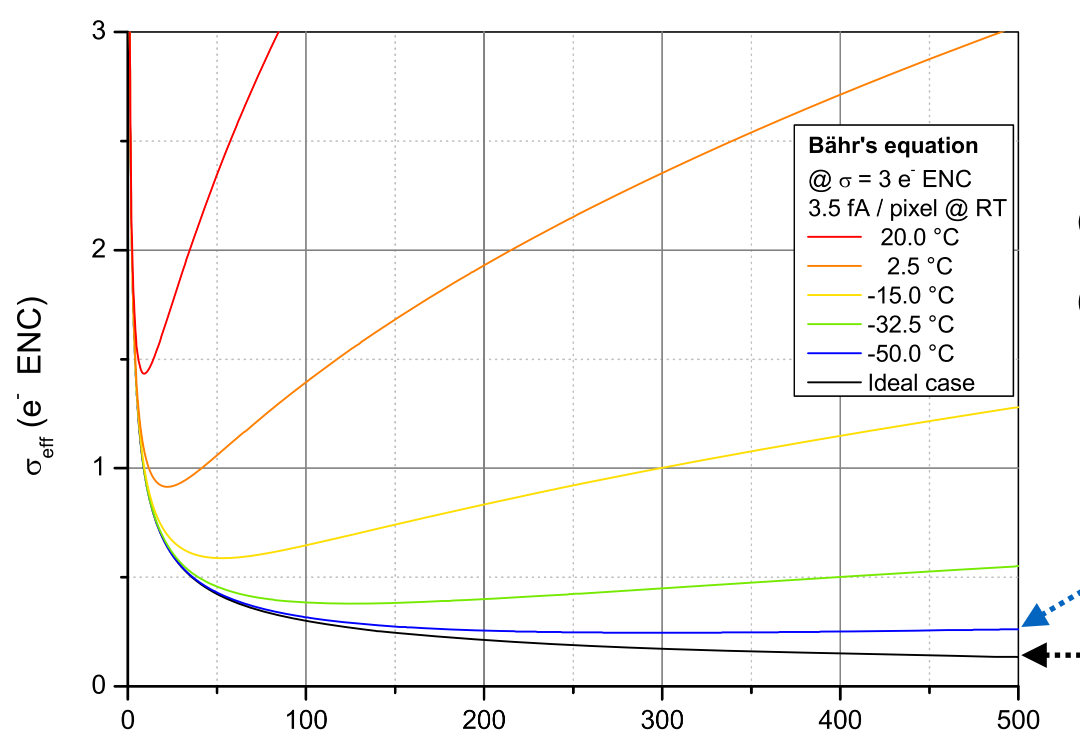


EPJ C, 77(12), 279 (2017)

- 50 °C

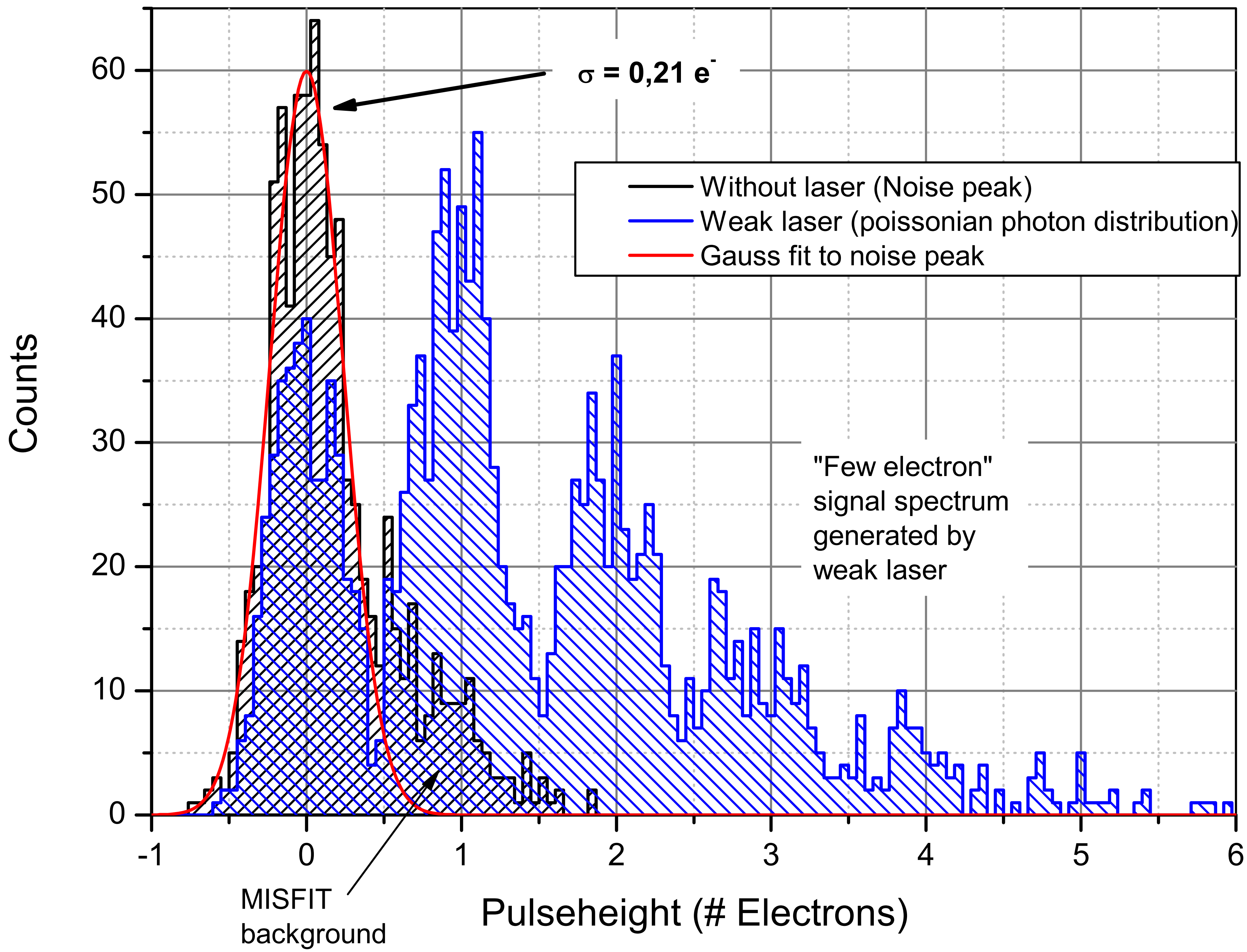
ideal case

estimated temperature dependence, to be testified in measurement

new architecture with “blind-gate”

possibility of reducing leakage current during readout

DEPFET RNDR single pixel performance



single pixel RNDR DEPFET effective noise :

0.2 e^- RMS at 200 K

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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

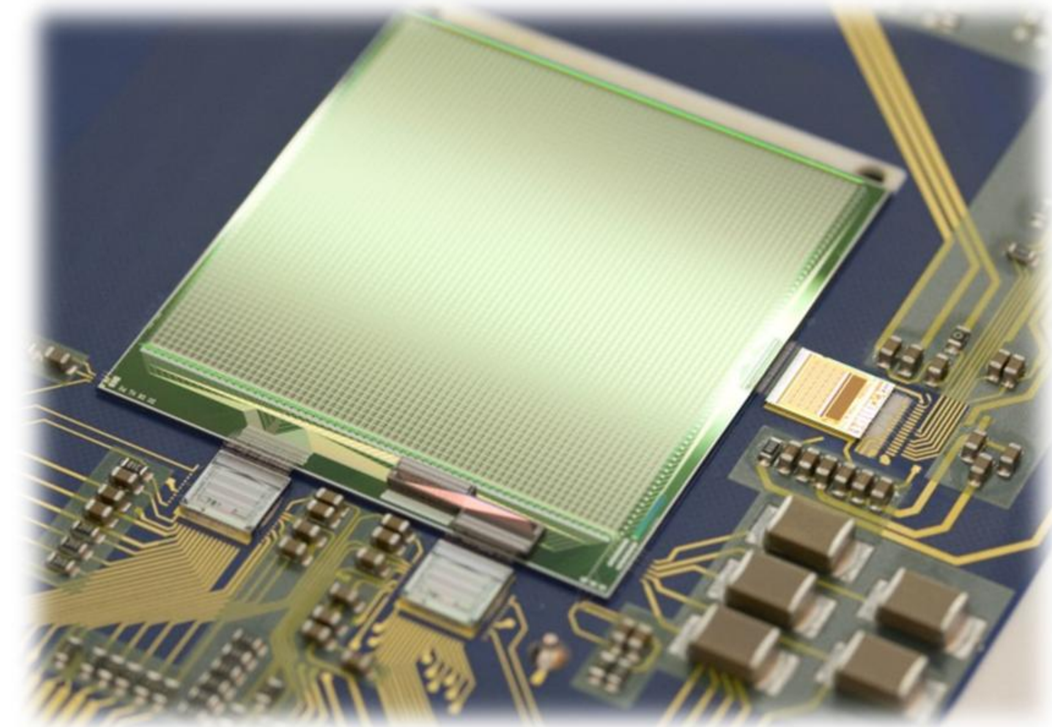
similar concepts of non-destructive readout, compatible performance;

different architecture, different systematics;

-> good complementary from experimental point of view

DANAE proof-of-principle measurement

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



Detector prototype at HLL-MPG
courtesy of J. Treis

At HLL :

matrix readout

optimization for operational/readout parameters

temperature dependence of leakage current

In Vienna:

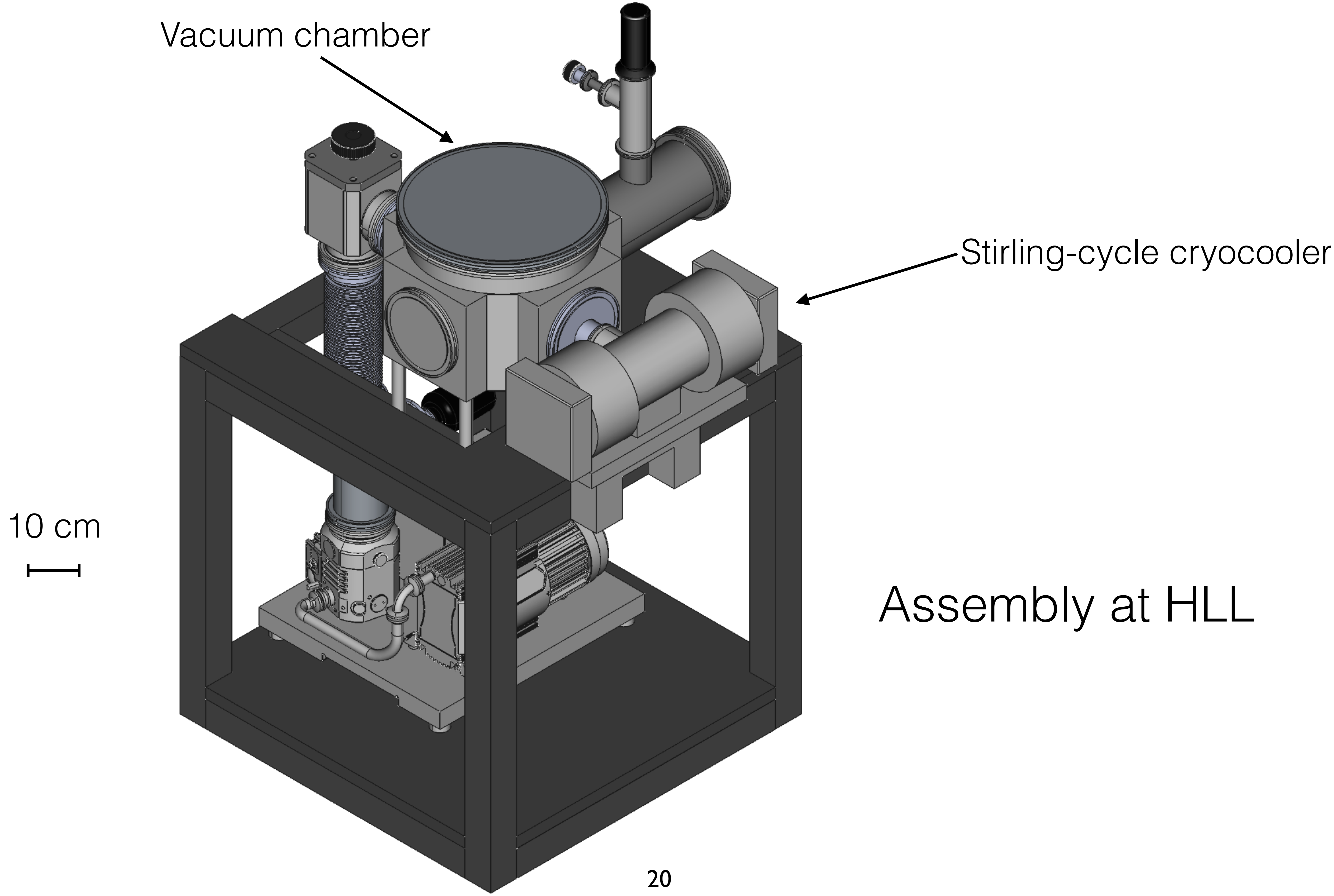
low background environment measurement
or surface measurement with veto

MC simulation for background budget

Expect to have operating matrix by the second half of 2018

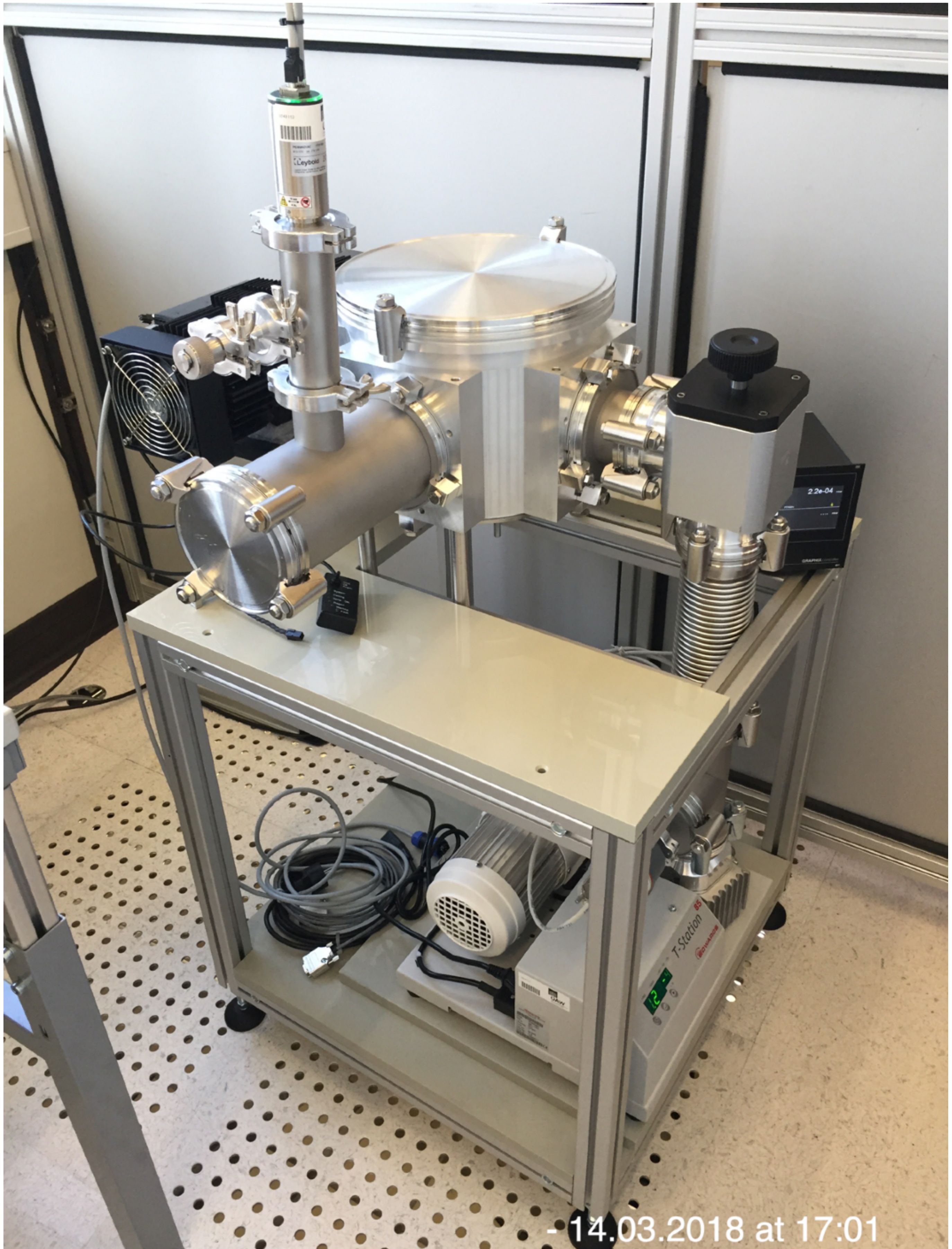
DANAE preparation status

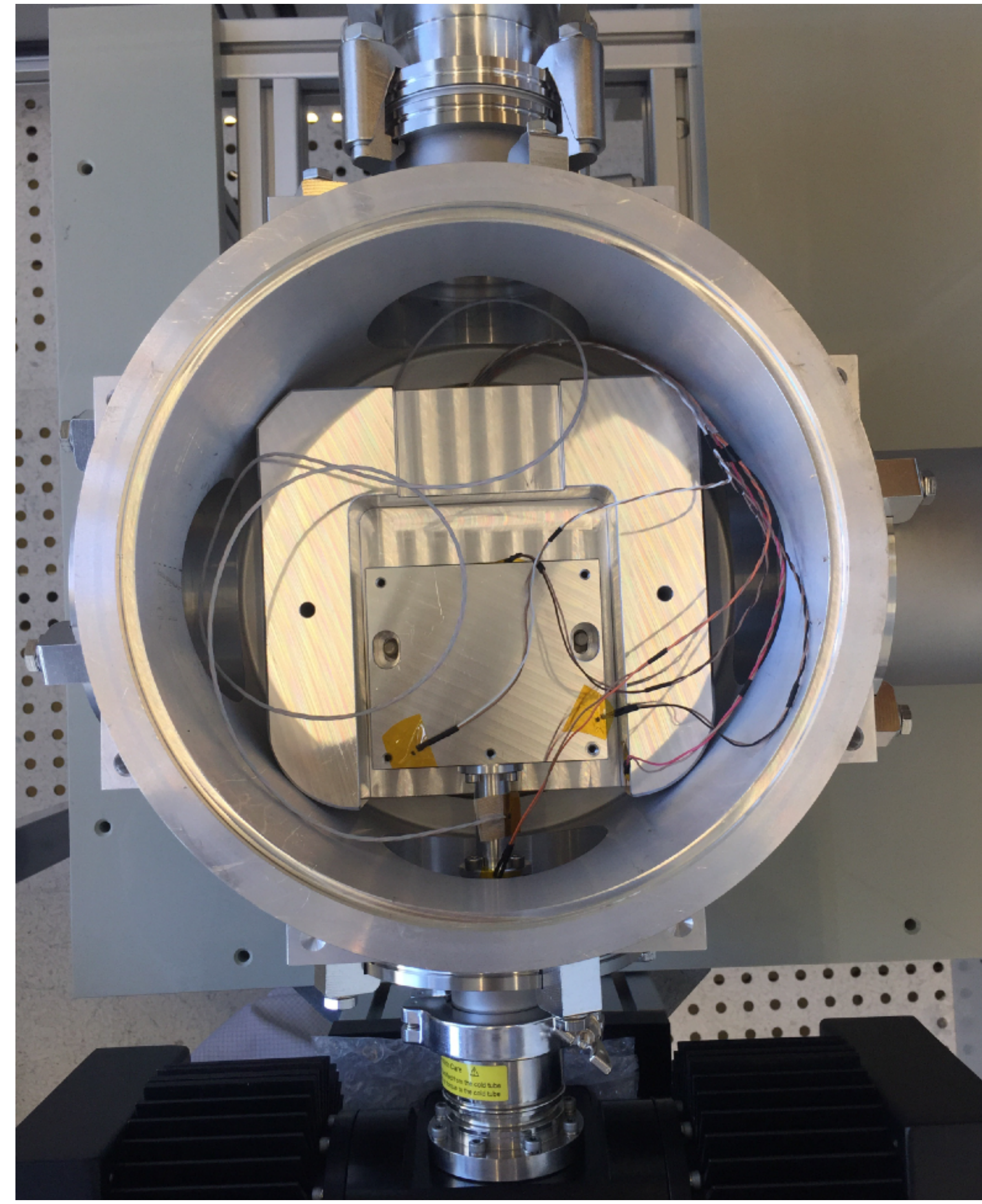
DANAE test setup - design image



Assembly at HLL

Setup at HLL

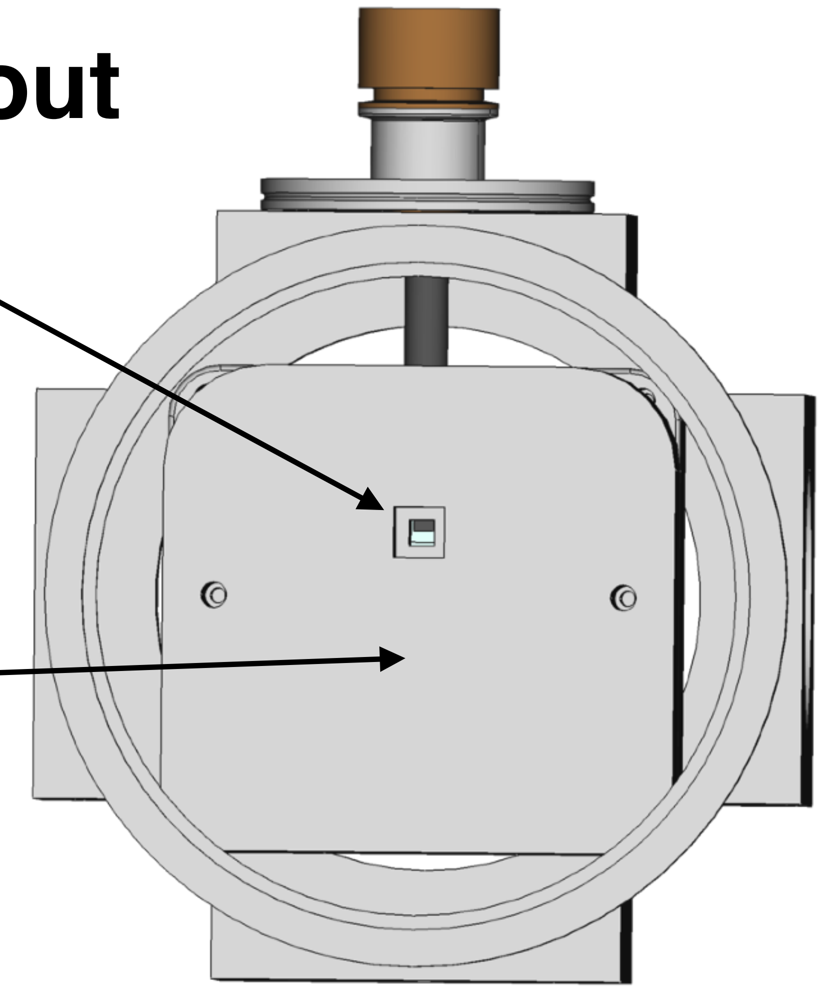


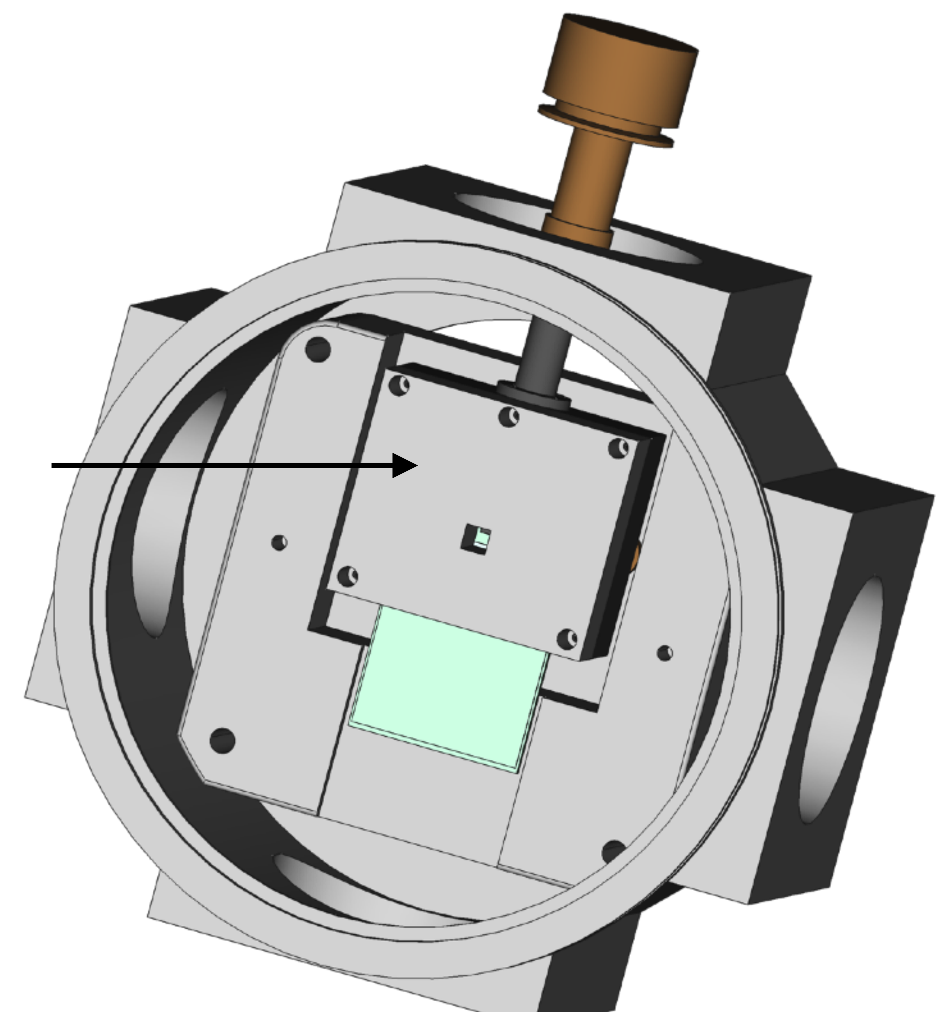


Vacuum and cooling tests done in March 2018

cooling pad reached 150 K

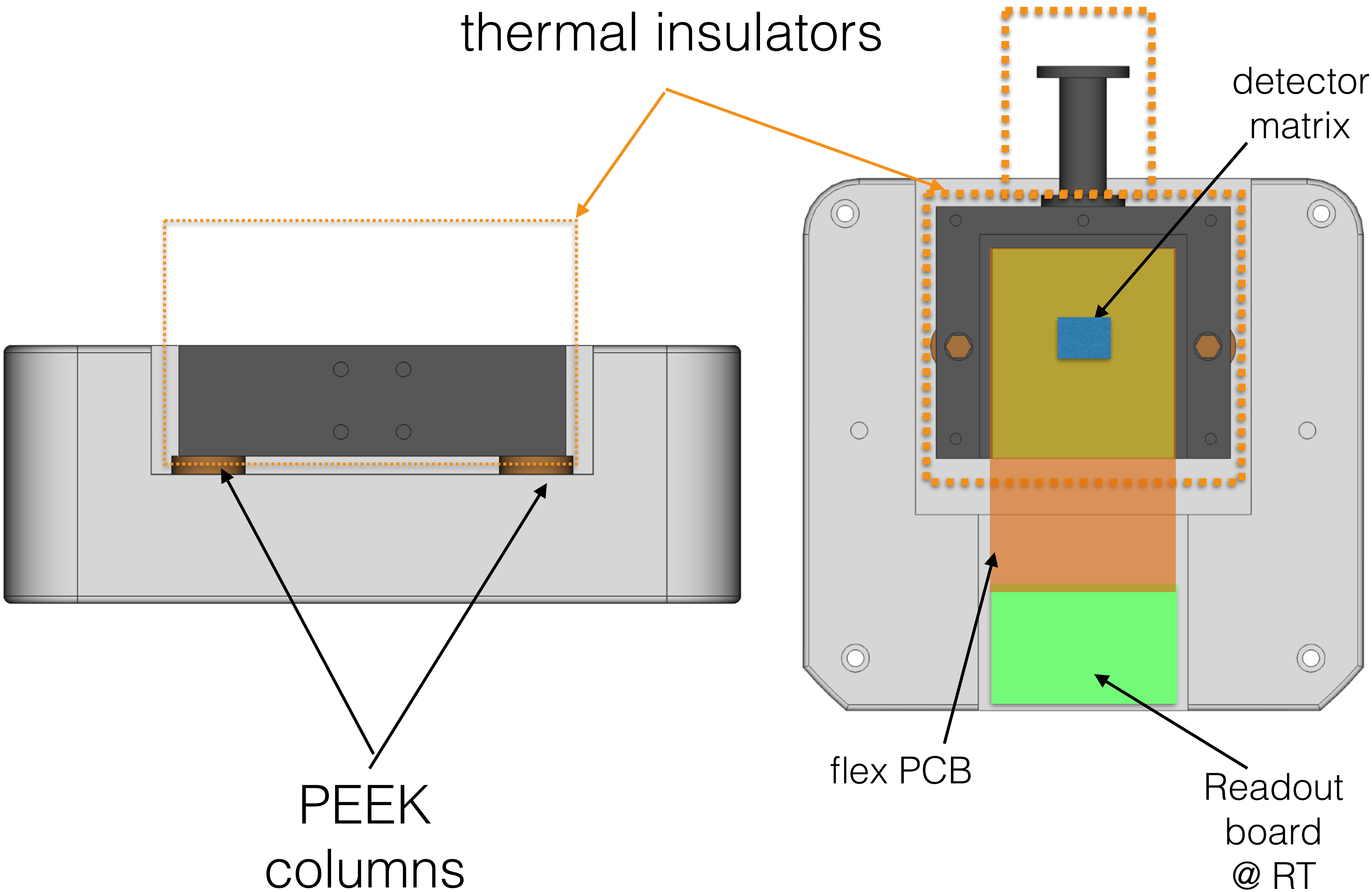
Cooling & shielding layout





outer shielding : support structure
inner shielding : cooling contact

Cooling of the detector and electronics



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

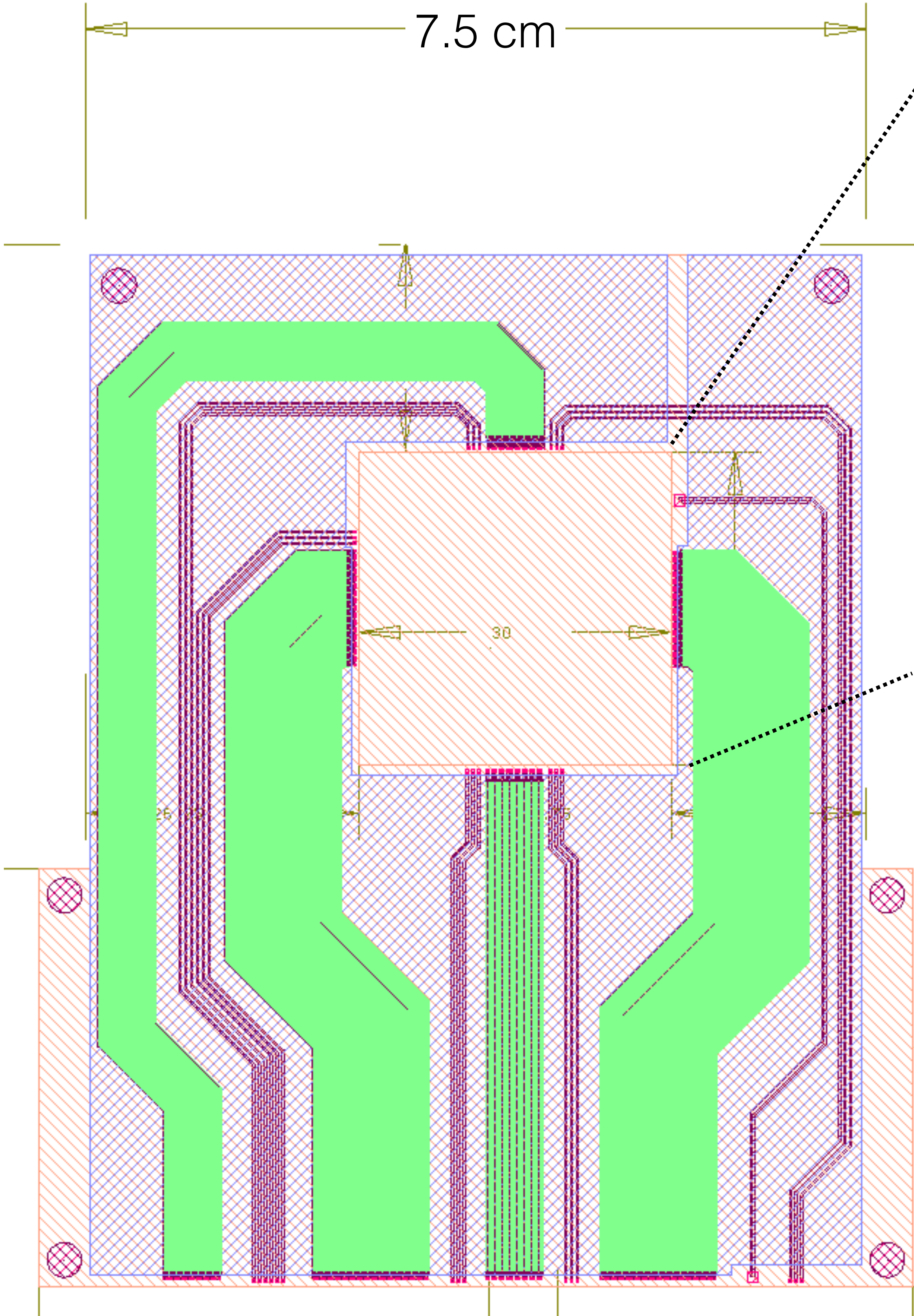
VERITAS

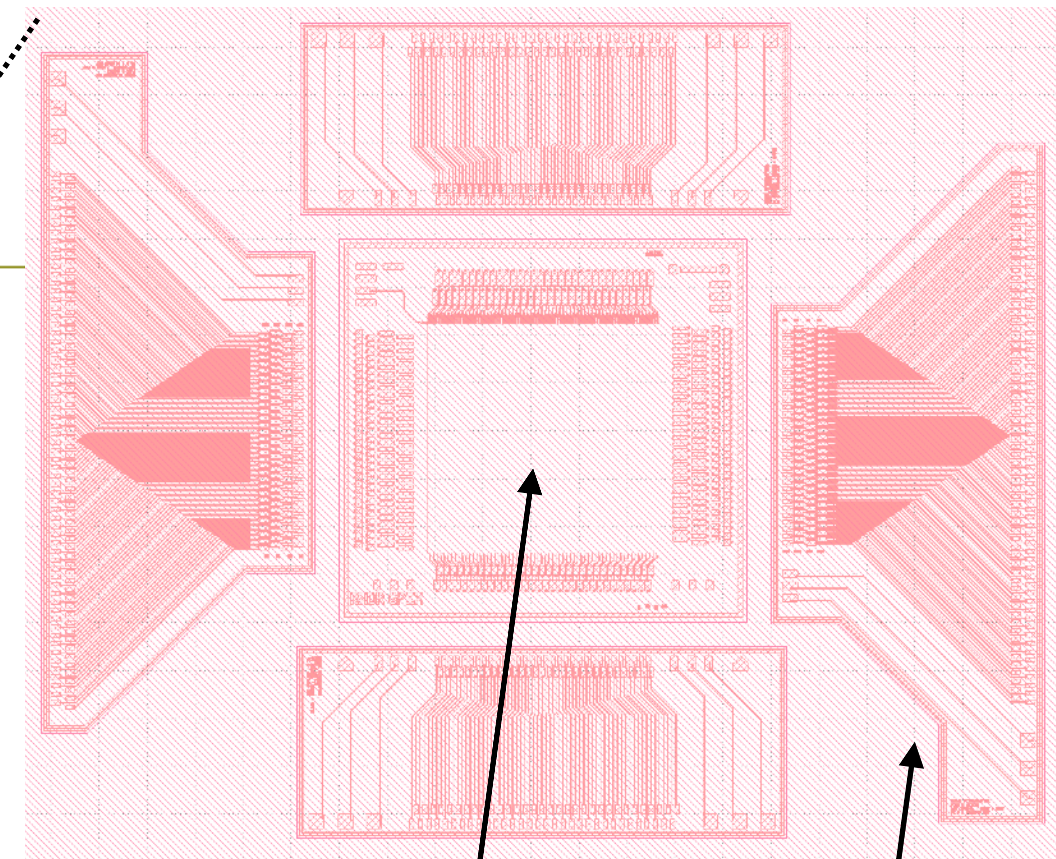
- VERITAS 2 ASIC in the AMS 0.35 μm CMOS 3.3 V technology
- 64 analog readout channels able to process in parallel the **signals coming from 64 DEPFET devices**.

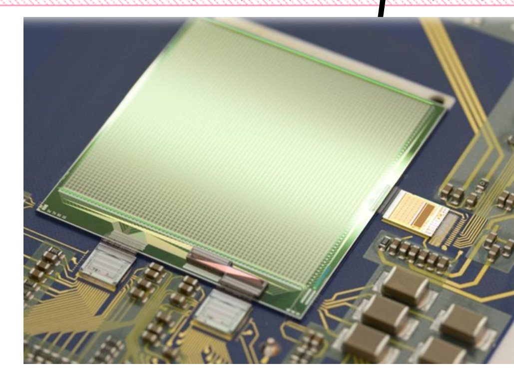
ADC

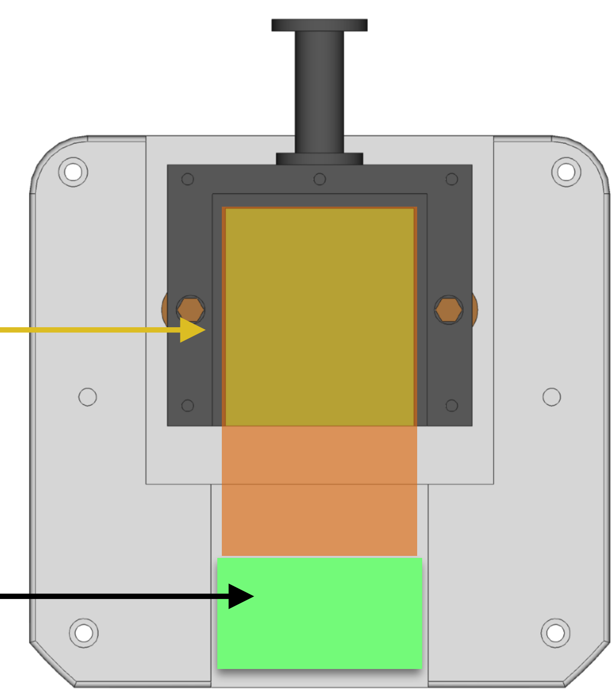
FADC type digitizer

Readout electronics designs



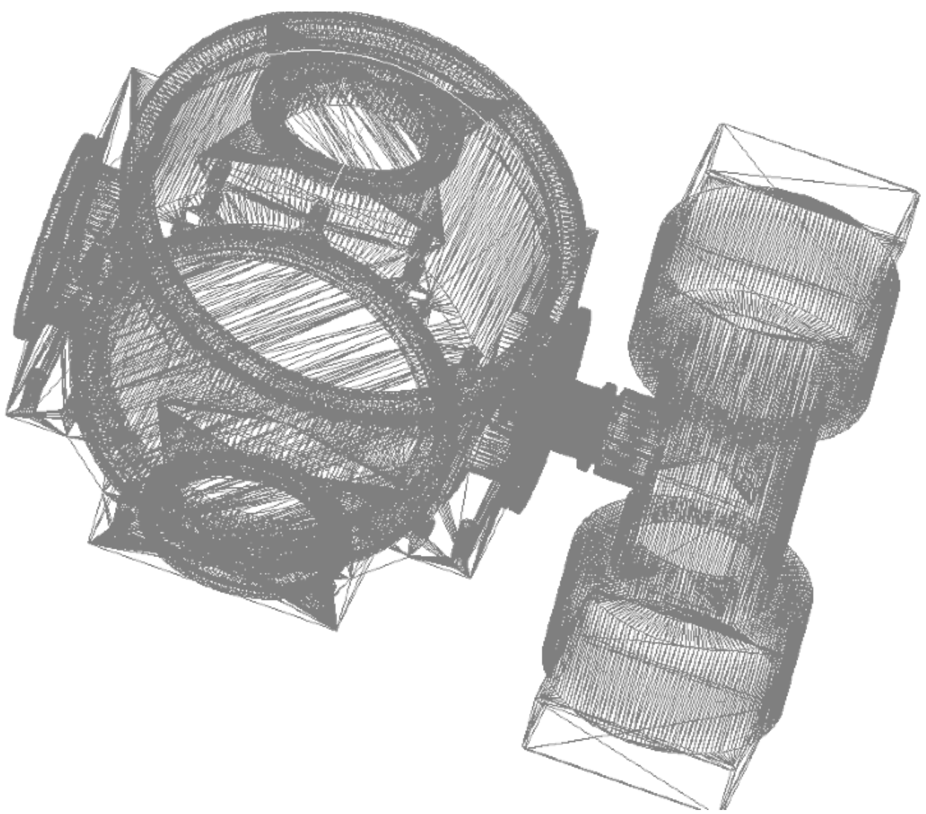


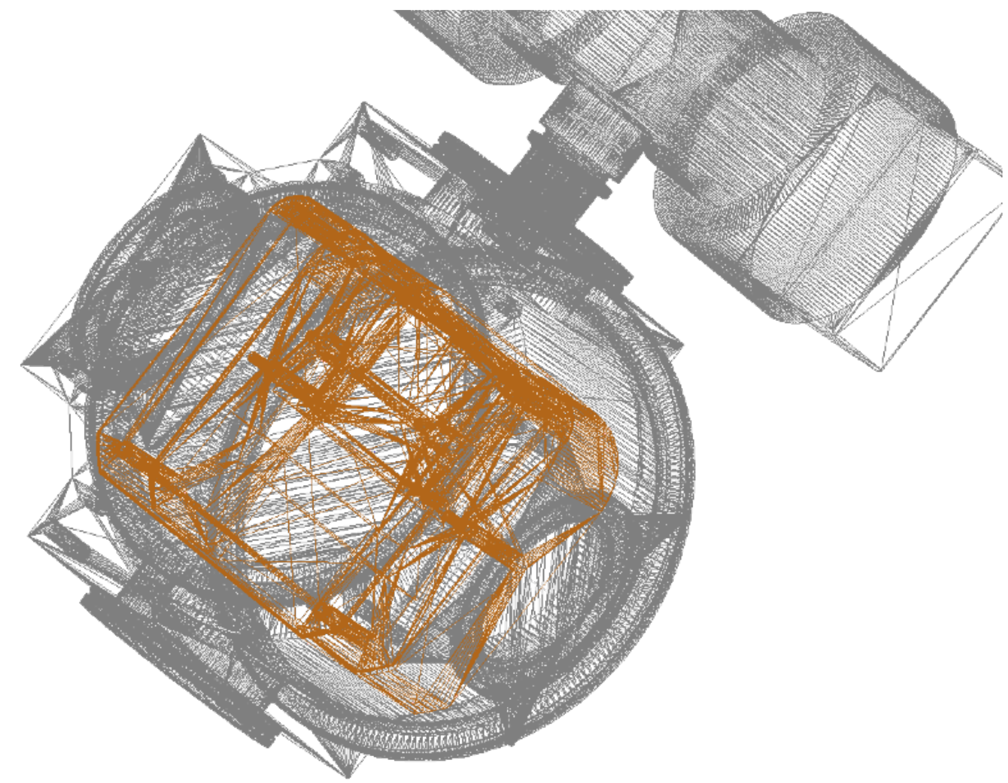




Monte Carlo simulation with Geant4

- to have a guideline of particle tracks and hit pattern, prepare the library of analysis routine;
- for future design of VETO counters and calibration layout.

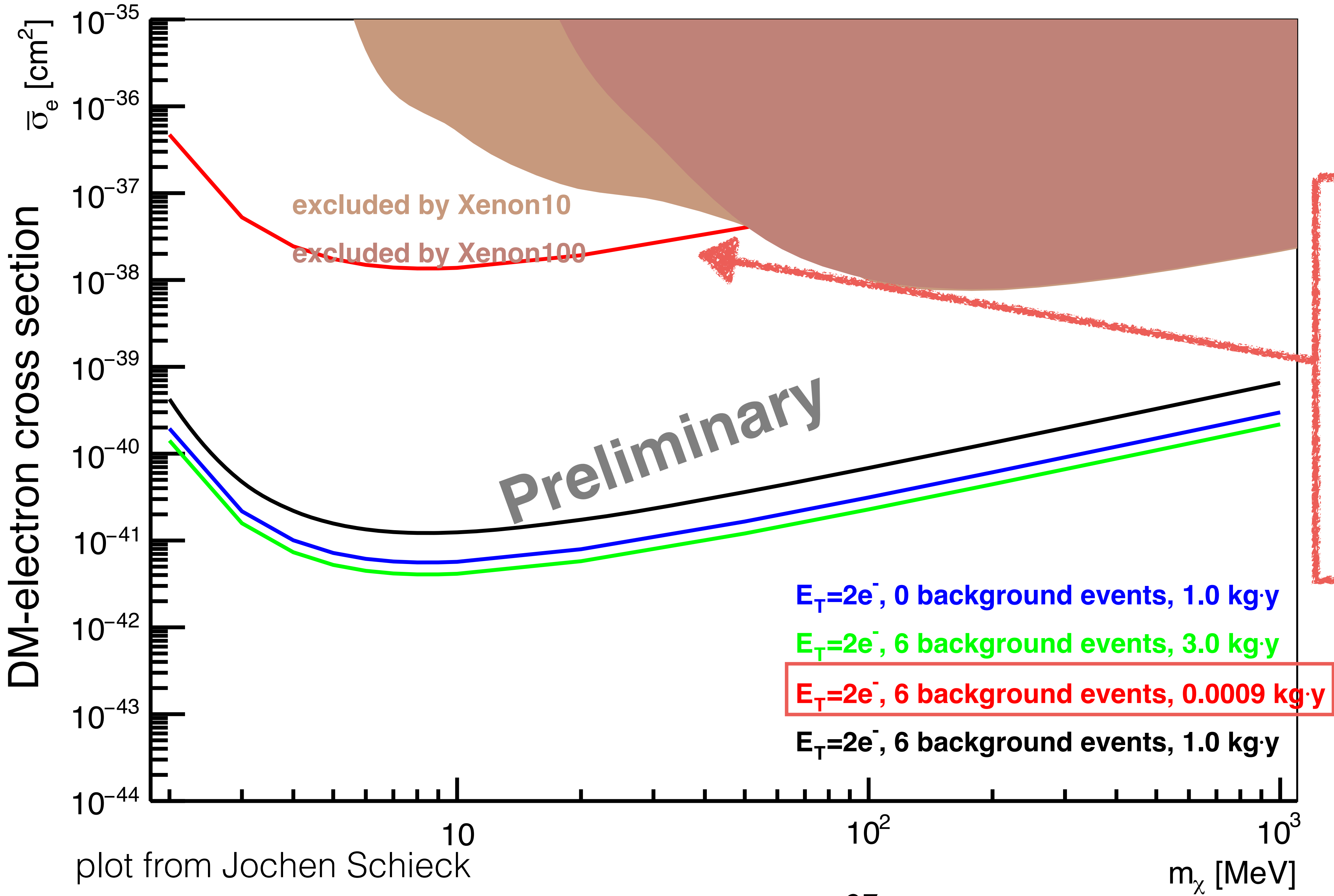




- geometry of the setup from vacuum parts 3D model;
- primitive geometrical shape for DEPFET :
  75 um x 75 um x 450 um bulk pixel, 64 by 64 matrix;
- to check response to X-rays, ambient gamma, cosmic charged particles, and neutrons;

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



physics run goal
0.9 g*y

-> 40 matrices
~1 g sensitive volume

plot from Jochen Schieck

Summary

- sub e^- ENC low noise semiconductor detector provides the possibility to detect the energy deposit from sub-GeV DM-electron recoil;
- DANAE prototype for test-of-principle measurement with single matrix in preparation;
- one of the first generation experiments using non-destructive repetitive readout method.

Future tasks & topics

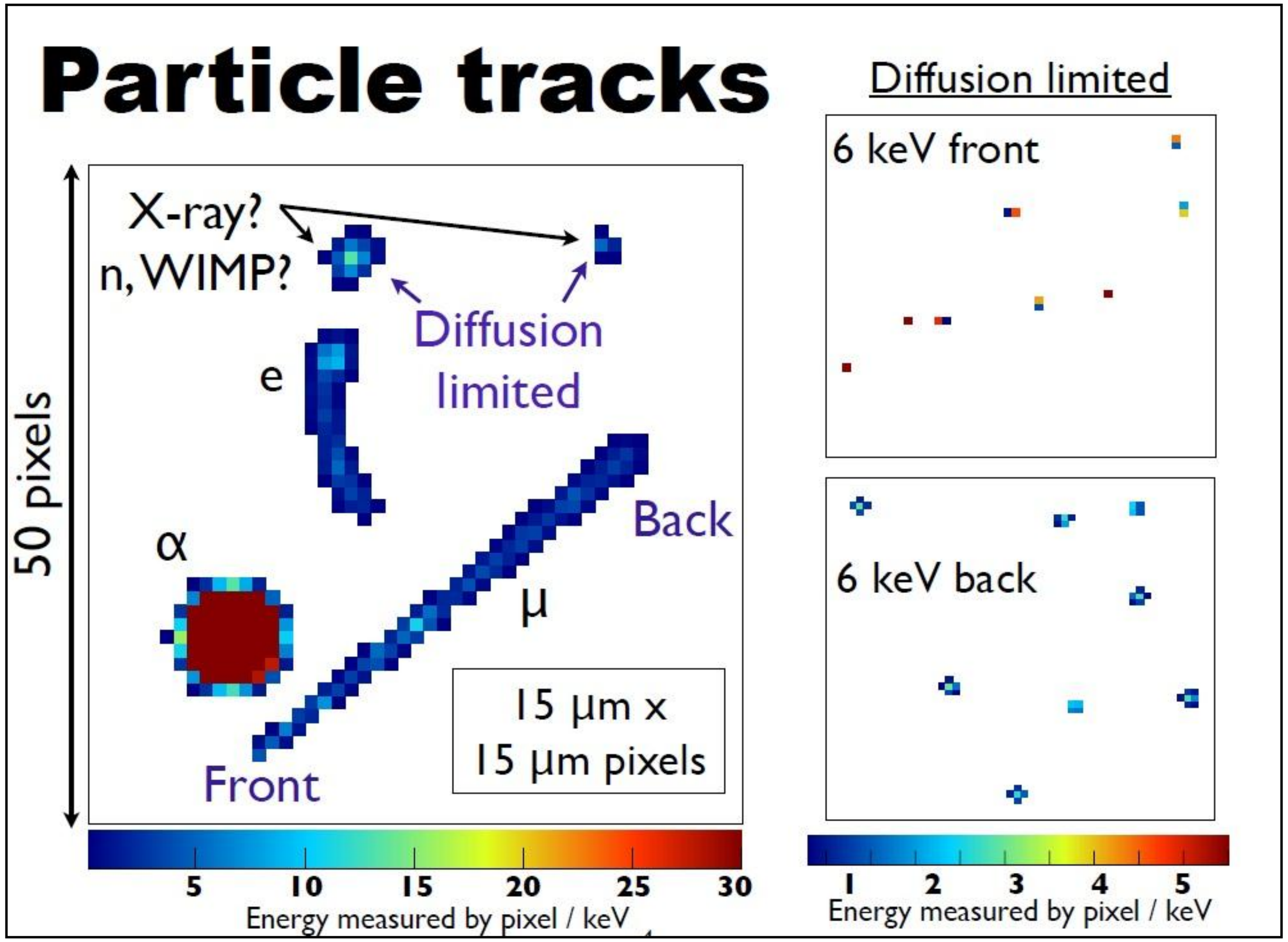
- readout electronics, DAQ in preparation;
- readout test, leakage current test;
- calibration regime and configuration;
- simulation for background;
- design for further shielding - passive and active.

Let us put DANAE into the landscape of direct DM detection experiments!!

Hit pattern simulation with Geant4

- to have a guideline of particle tracks and hit pattern, prepare the library of analysis routine;
- for future design of VETO counters and calibration layout.

Results from DAMIC experiment



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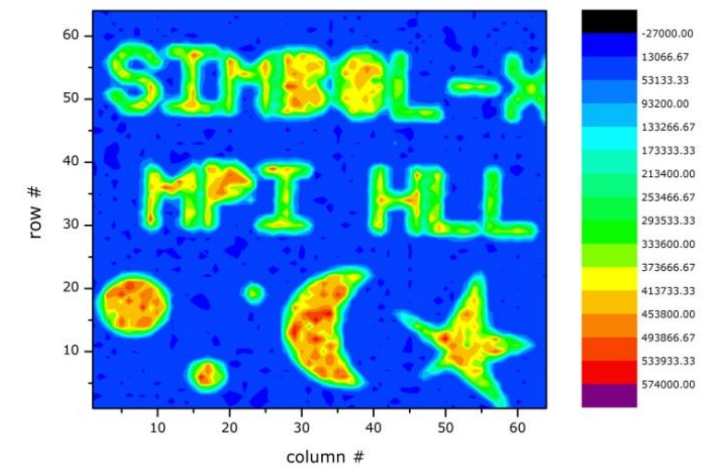
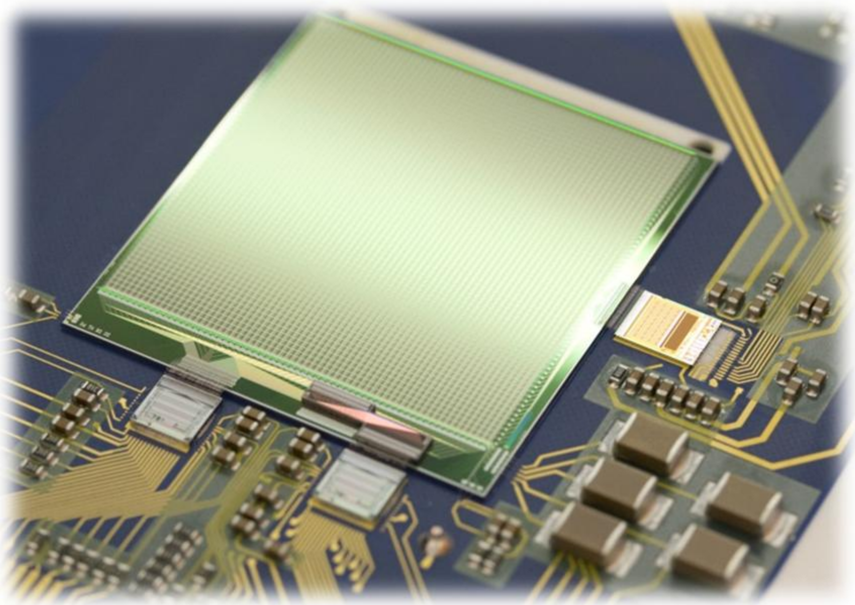
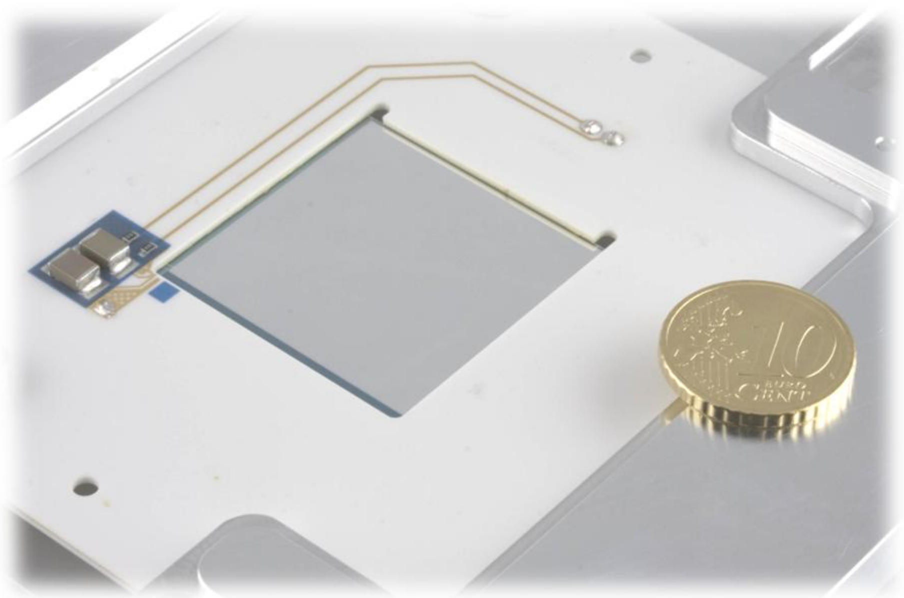
Detector Structures

Macropixel sensors

- Prototypes
  - 64 x 64 pixels (500 µm & 300 µm)
  - 3.2 x 3.2 cm²
  - high framerate (4 kHz)
  - near Fano-Limited energy resolution

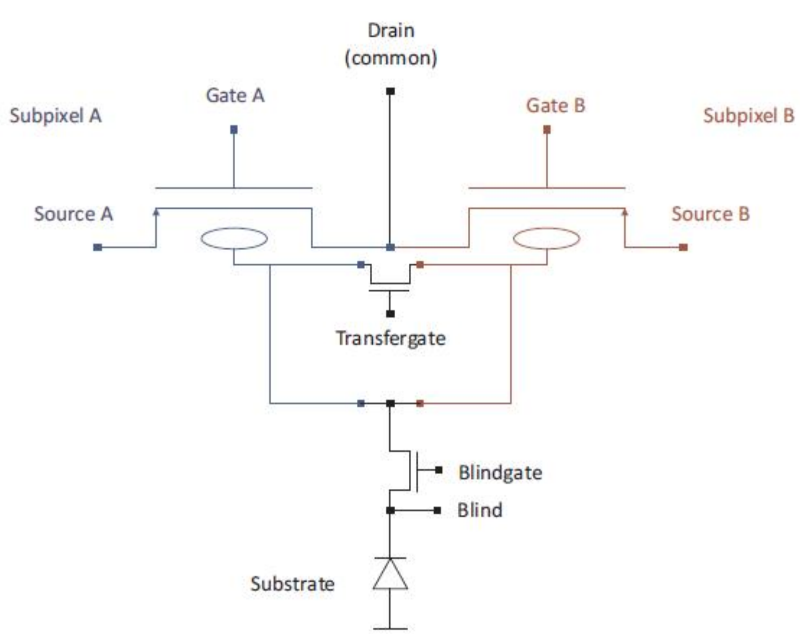


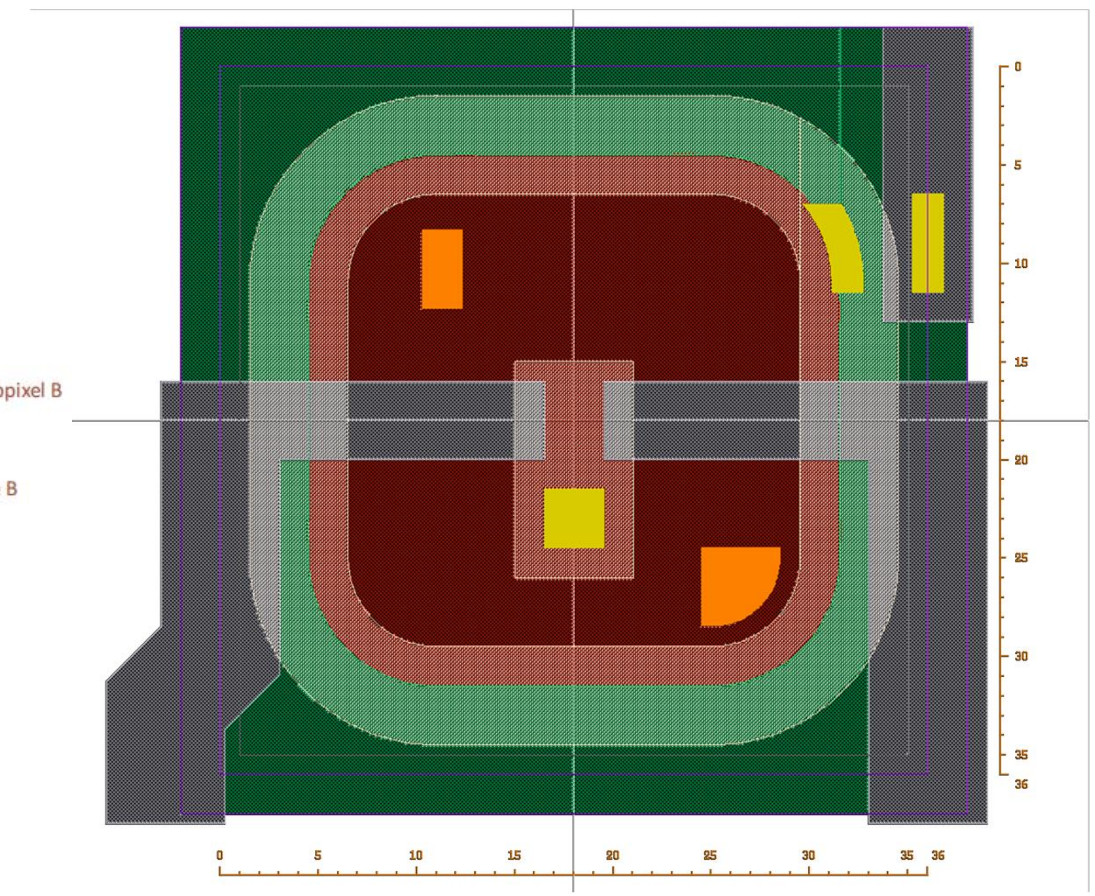




Small pixel device layouts

- Global Clear variant
- Blinds also used for clearing
- 36 x 36 mm^2



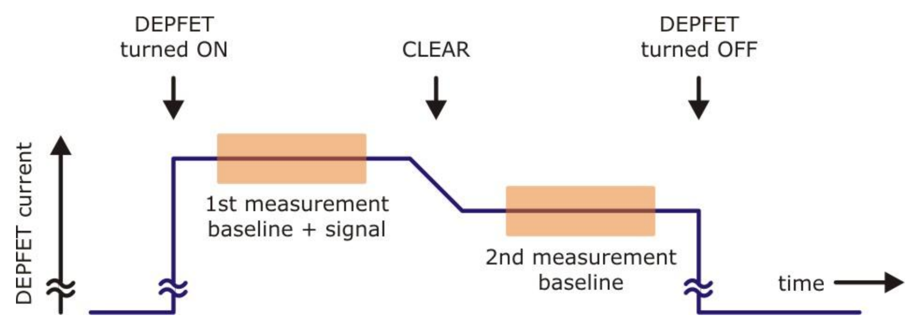


Johannes Treis / Halbleiterlabor der MPG

DEPFET CDS circle

Detector Structures – Matrix Devices

- **readout sequence**

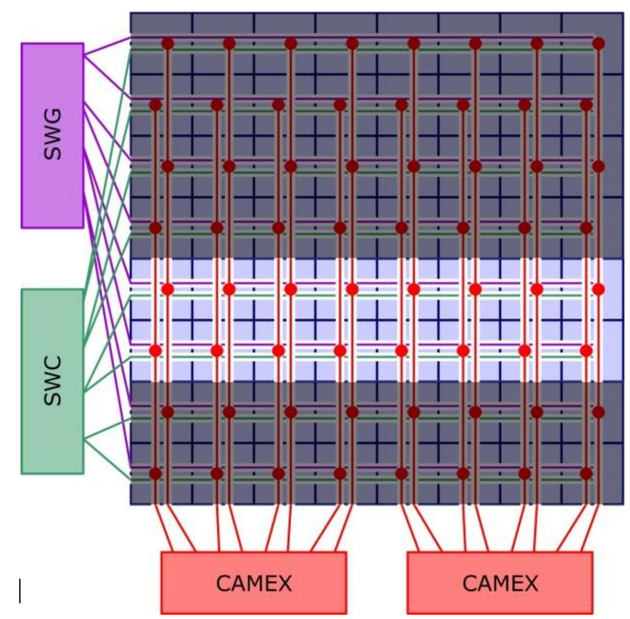


Correlated double sampling:

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

difference = signal
complete clear is mandatory!

- **matrix operation**



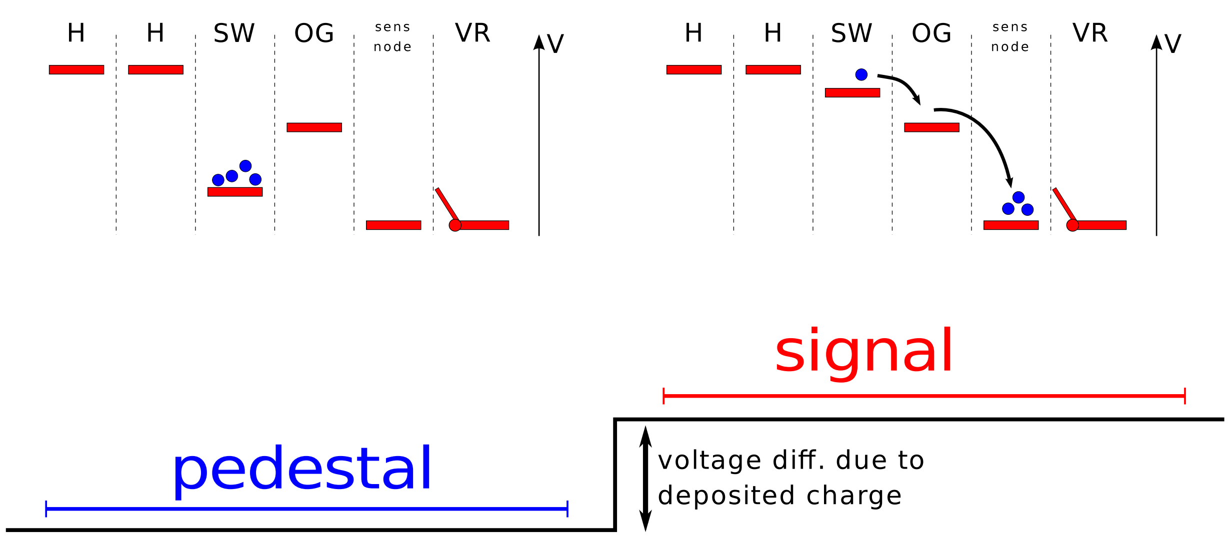
vertical signal lines
1 active row, other pixels integrating

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

readout parallelisation
2 x readout channels, 2 active rows

CCD (skipper) readout

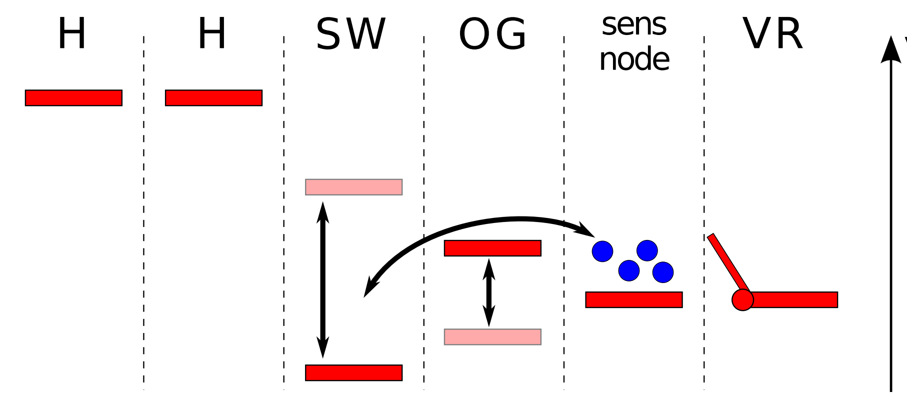
CCD: readout



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

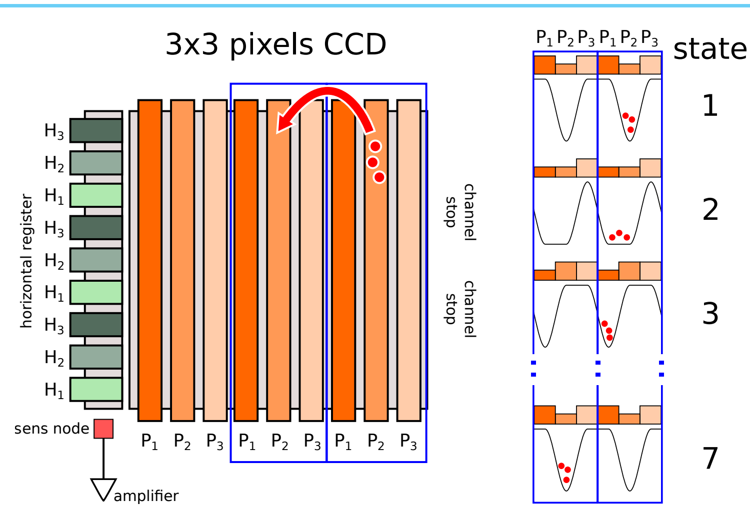
SW : summing-well gate

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

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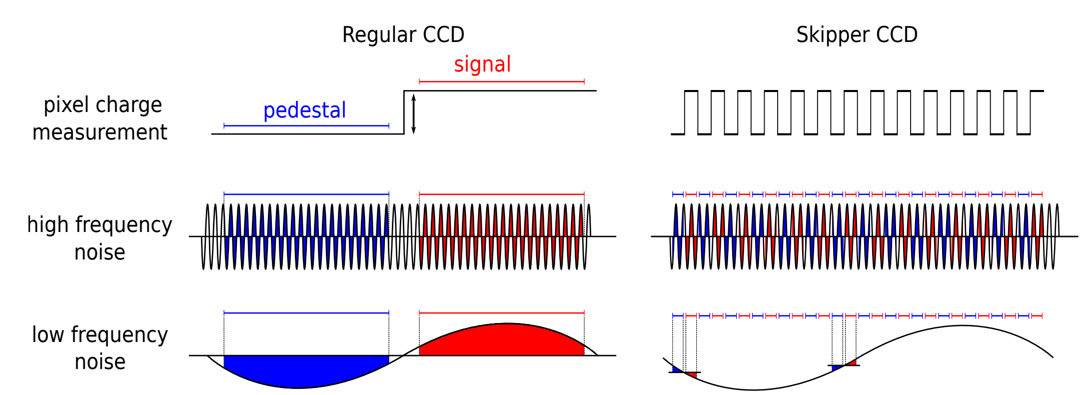
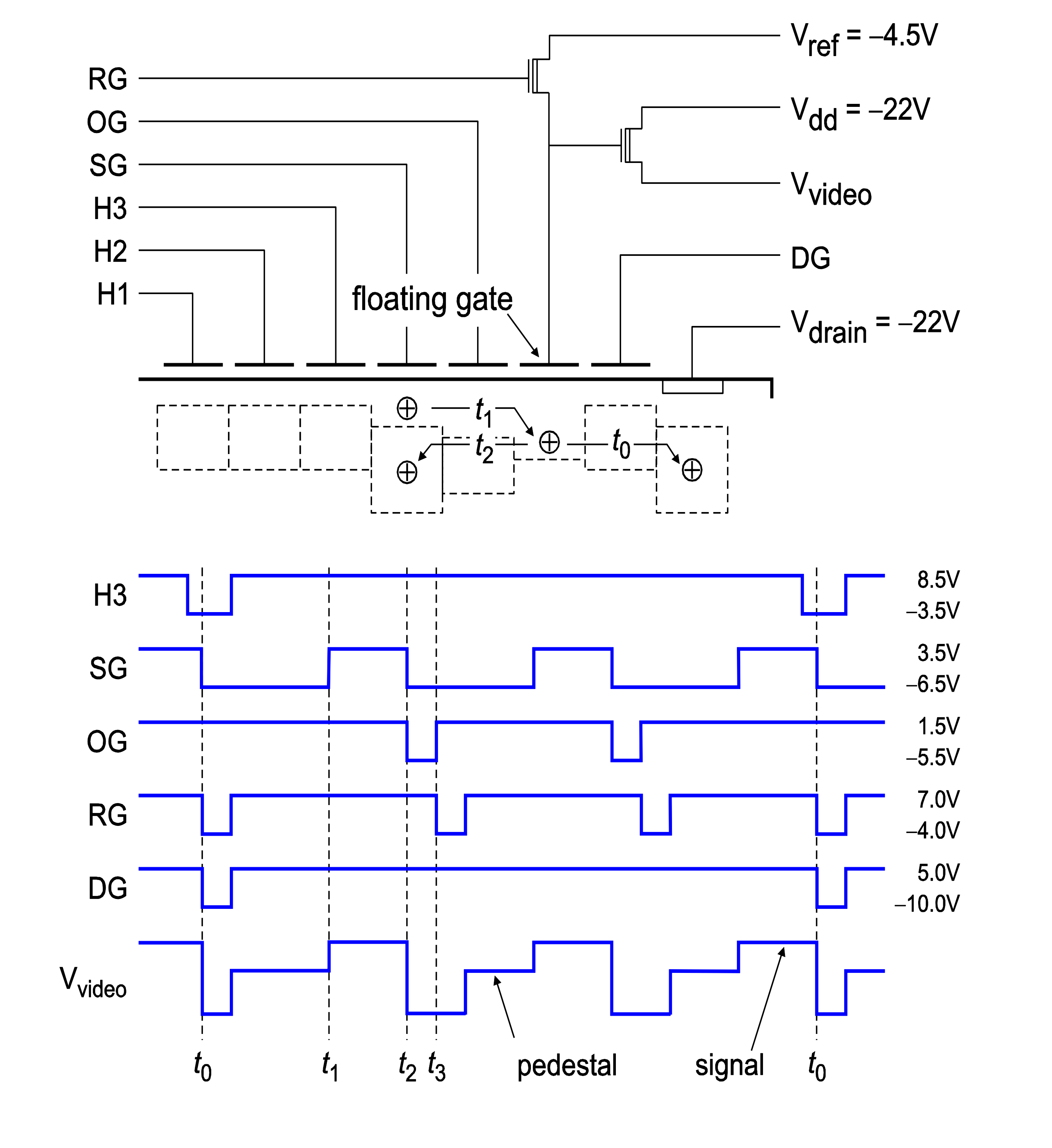


Fermilab

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.