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

Hexi Shi
HEPHY ÖAW

Seminar organized within the project :

"*Hunt for the `impossible atoms'*:
the quest for a tiny violation of the Pauli Exclusion Principle. Implications for physics, cosmology and philosophy,"

ID 58158, funded by the John Templeton Foundation

28 June 2018
Frascati

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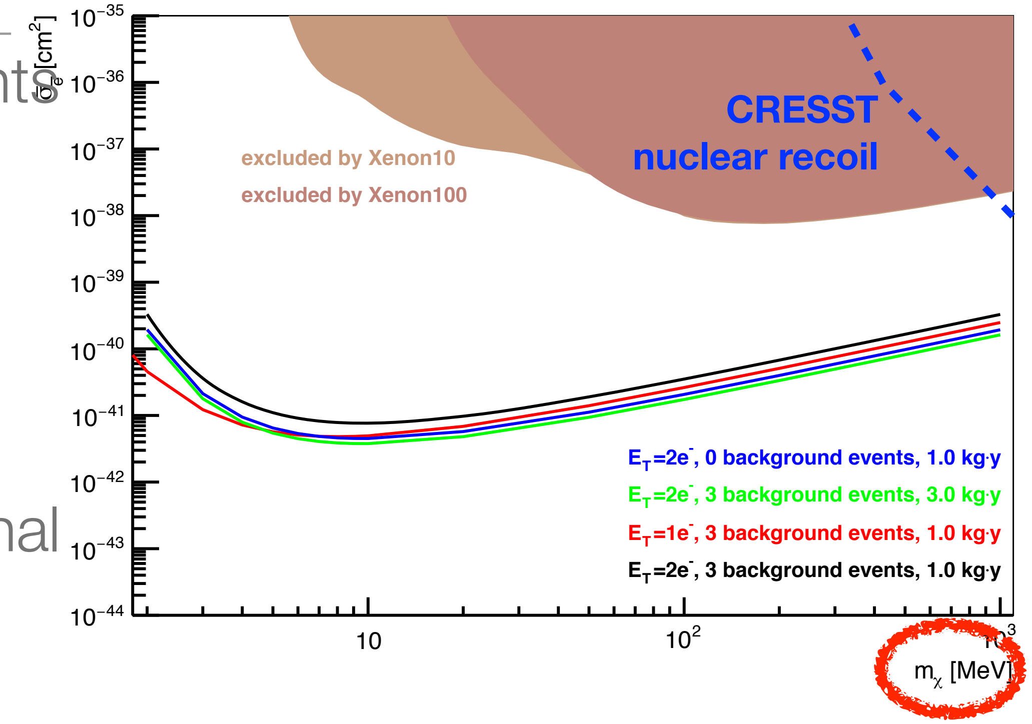
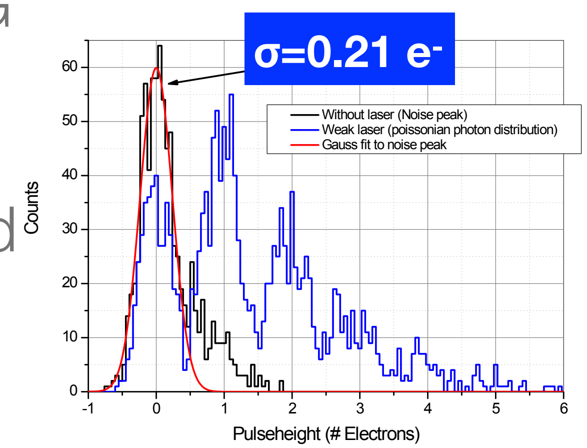
Atominstitut, Technische Universität Wien, Vienna, Austria [C]

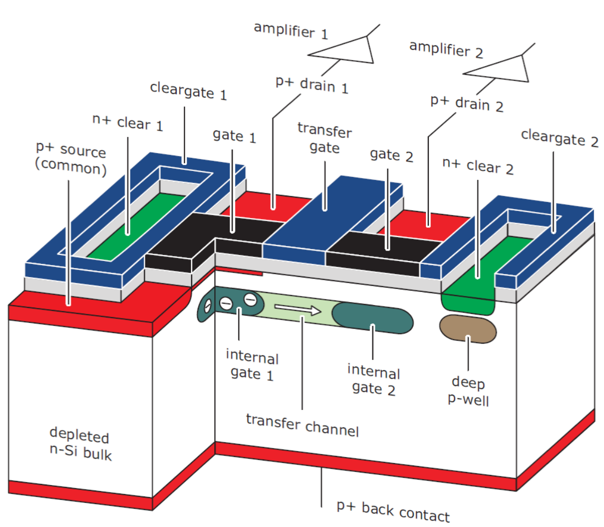
The project overview

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







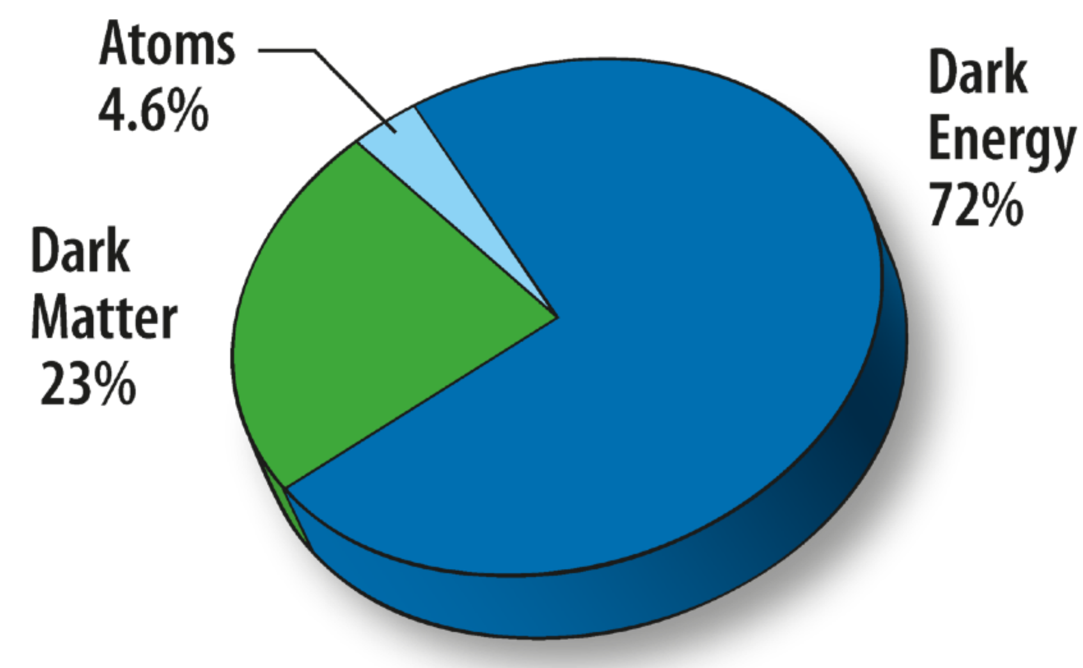
EPJ C, 77(12), 279 (2017)

*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



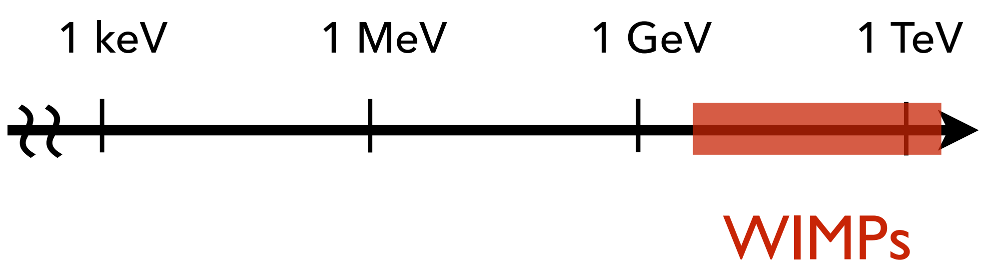
TODAY

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

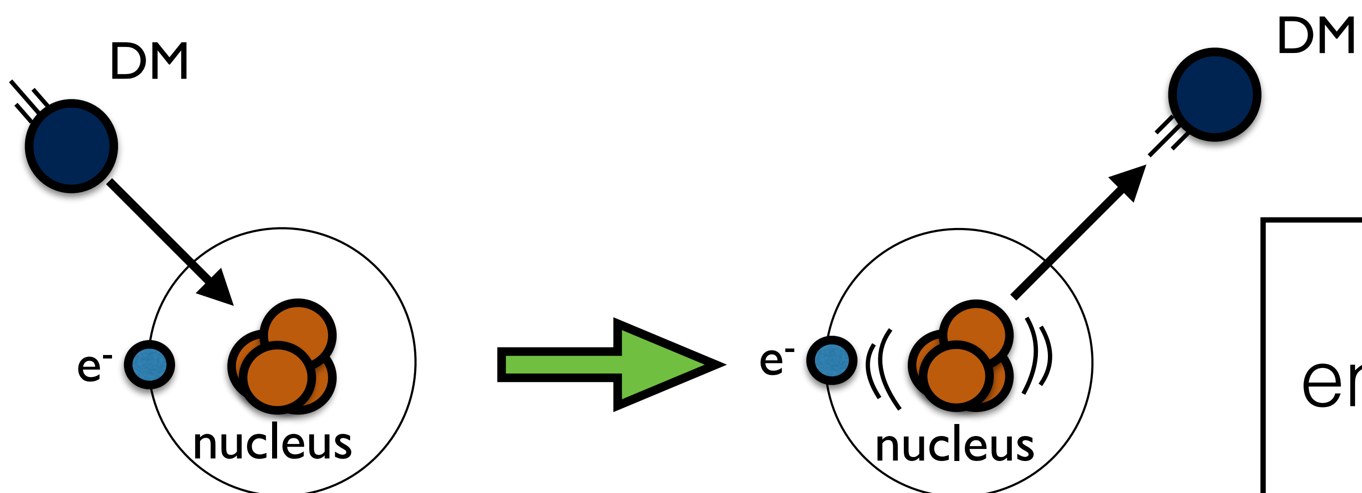


image credit R. Essig

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

<u>Detection limitation :</u>

energy deposit from nucleus recoil

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

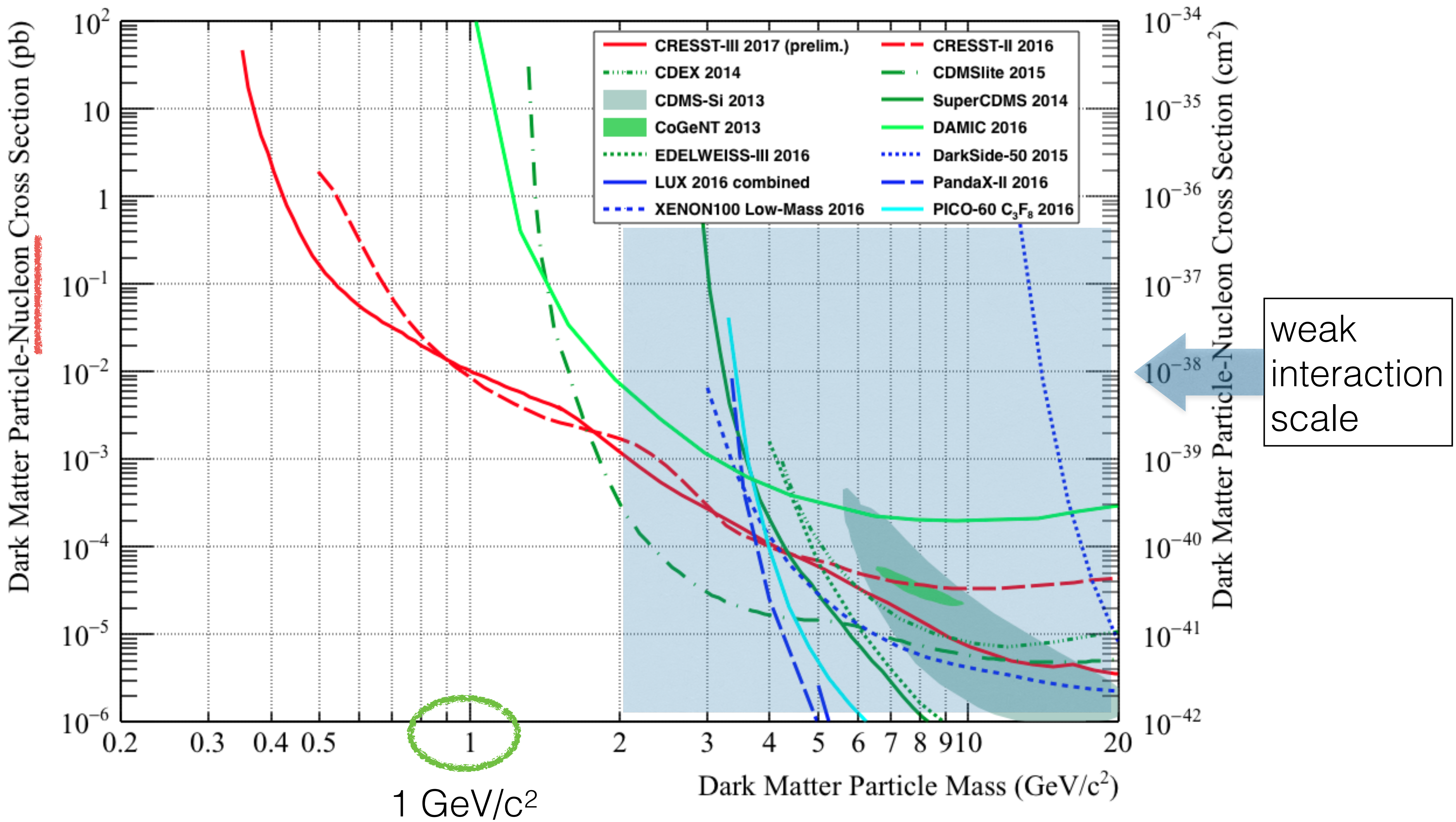
-> for 100 MeV m_χ, $E_{NR} \sim 1$ eV *

plus quenching factors and noise level of the detectors

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

*for silicon

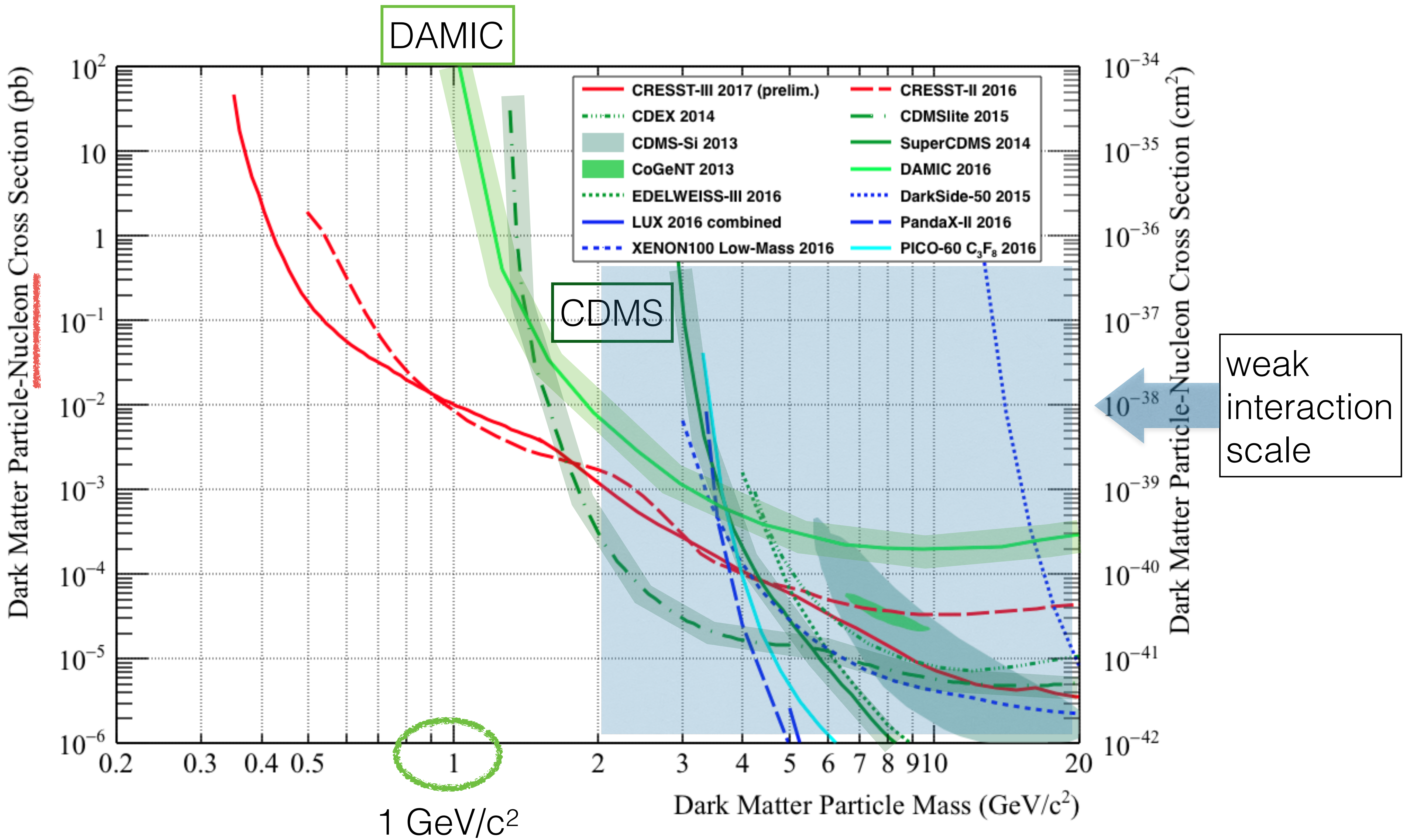
DM-nucleus scattering direct search status



no evidence for WIMP yet

arXiv:1711.07692

DM-nucleus scattering direct search status



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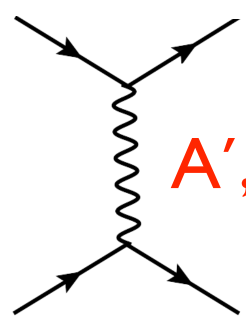
Dark Sector and Light Dark Matter

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

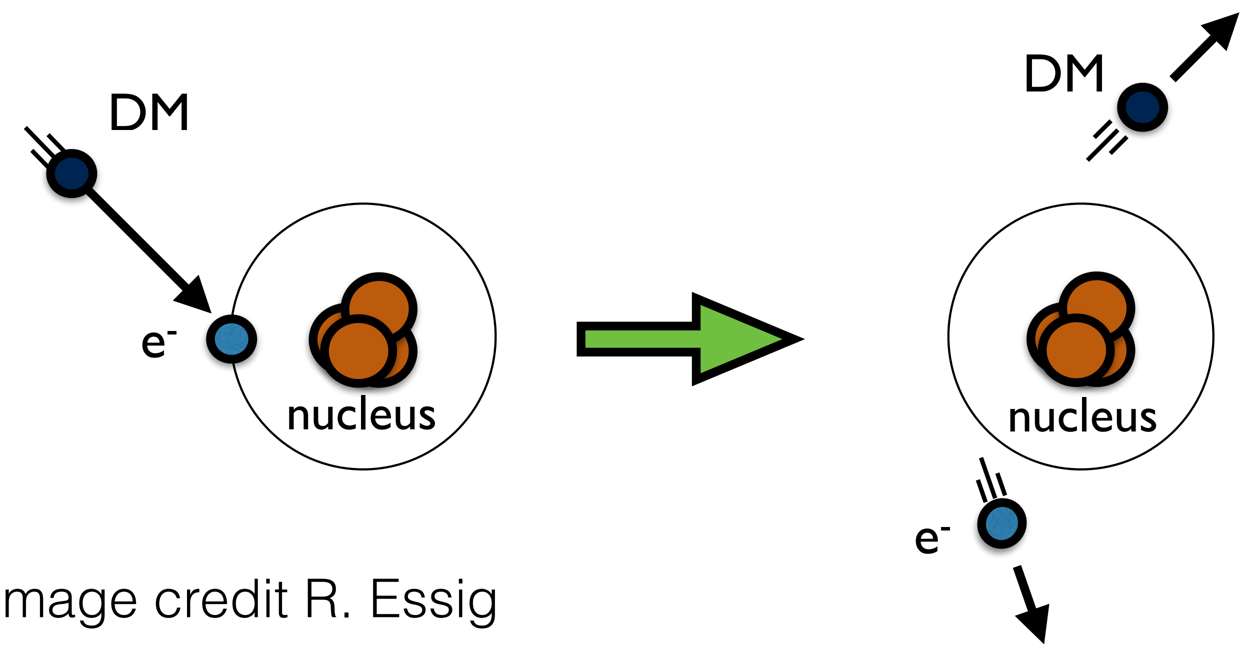


image credit R. Essig

kinematically

to overcome binding energy *ΔE*

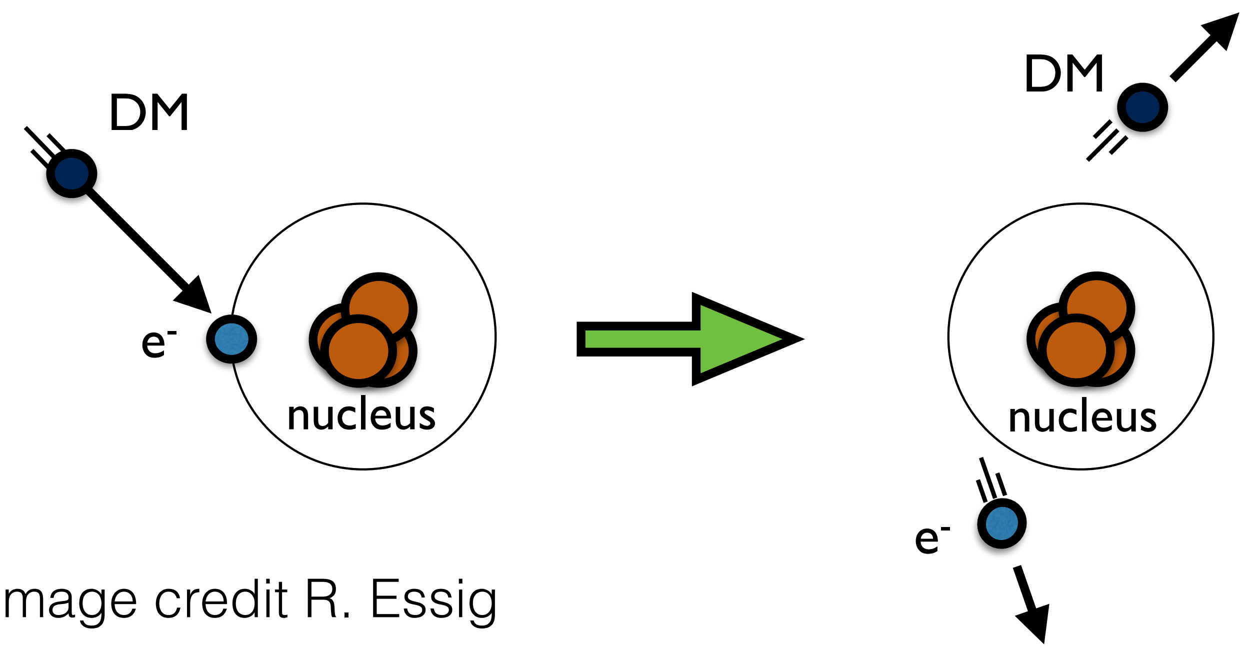
need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$

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

O(100 keV)

JHEP05(2016)046

DM-electron scattering



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

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

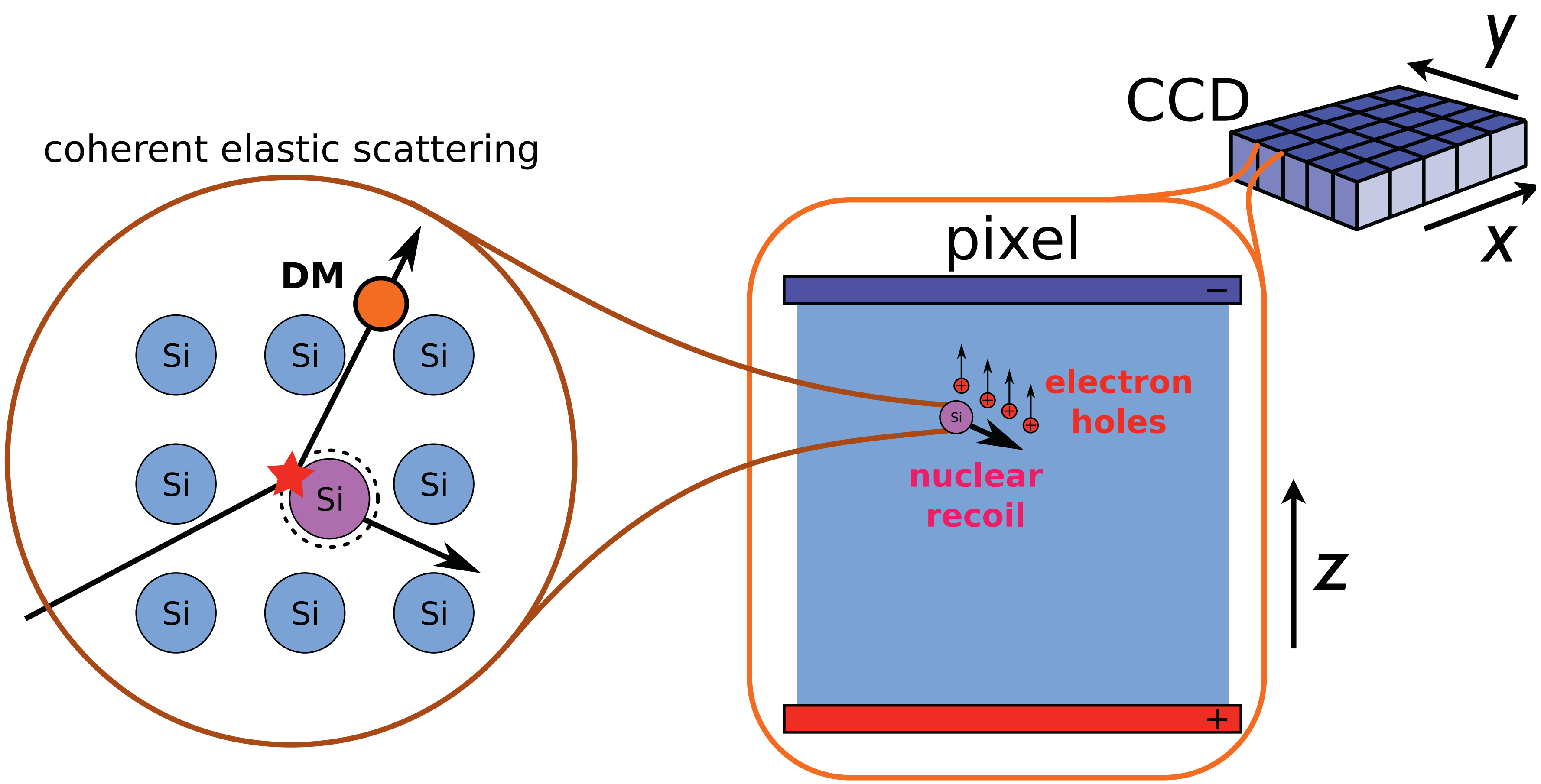
Target Type	Examples	E_{th}	m_χ threshold	Status	Timescale
Noble liquids	Xe, Ar, He	~ 10 eV	~ 5 MeV	Done w data; improvements possible	existing
Semi-conductors	Ge, **Si**	~ 1 eV	~ 200 keV	(E_{th} ~ 40 eV SuperCDMS, **DAMIC**) E_{th} ~ 1eV **SENSEI**, **DEPFET** R&D	~ 1-2 years
Scintillators	GaAs, NaI,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

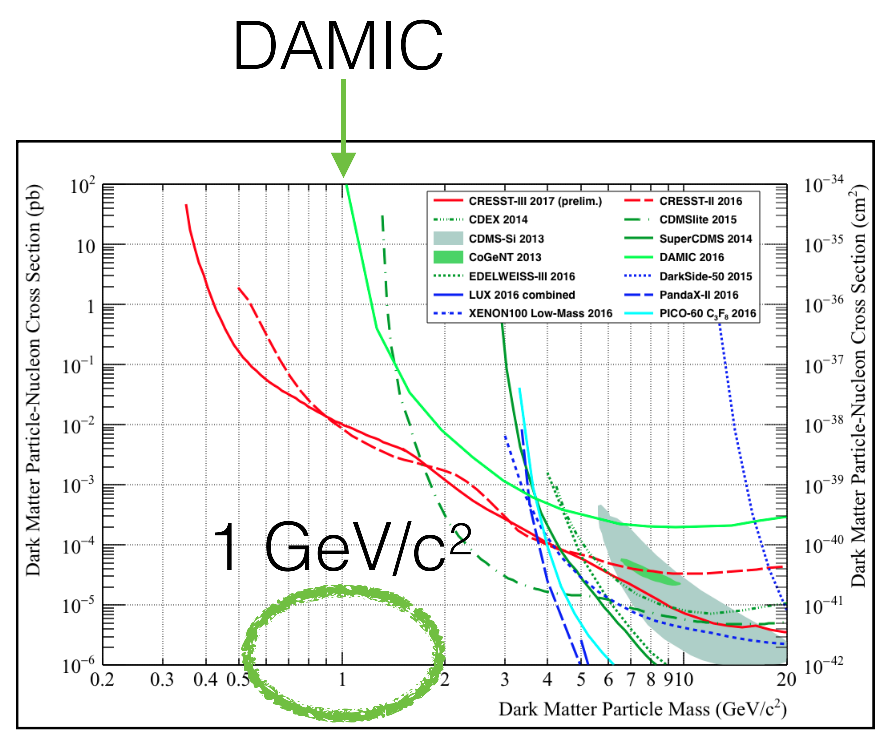
Application of Silicon detector

DAMIC

<u>nucleus</u> recoil CCD, with physics results



Physics Procedia 61 (2015) 21 – 33

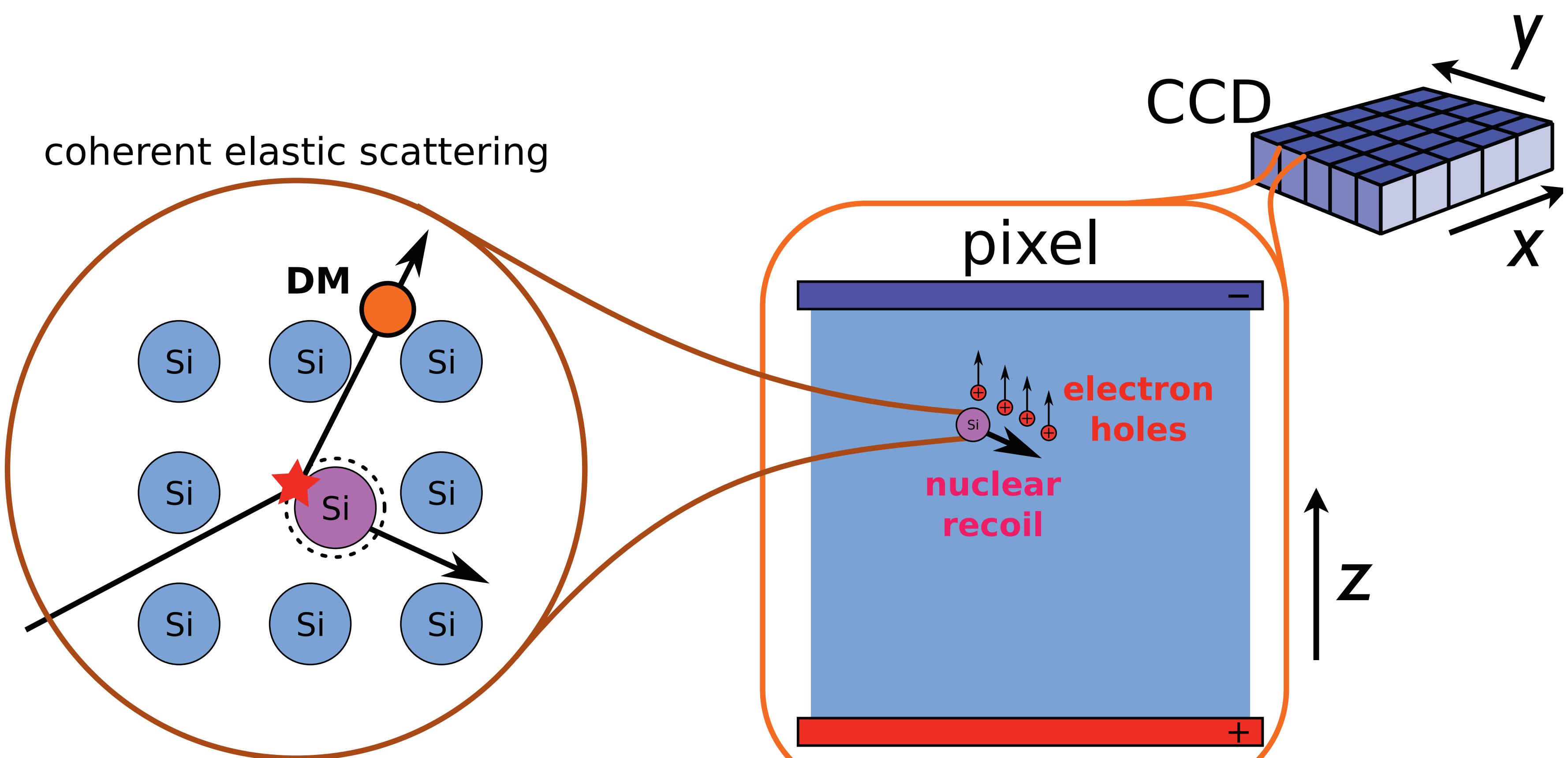


Readout noise determines threshold of ~ 11 e⁻ (or ~ 40 eV)

Application of Silicon detector

DAMIC

<u>nucleus</u> recoil   CCD, with physics results



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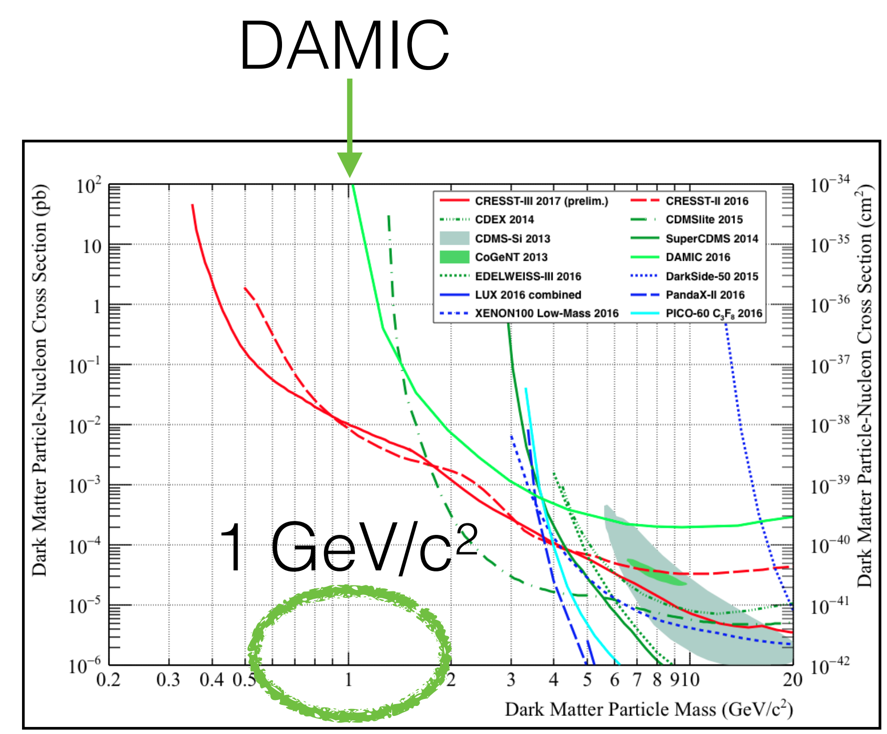
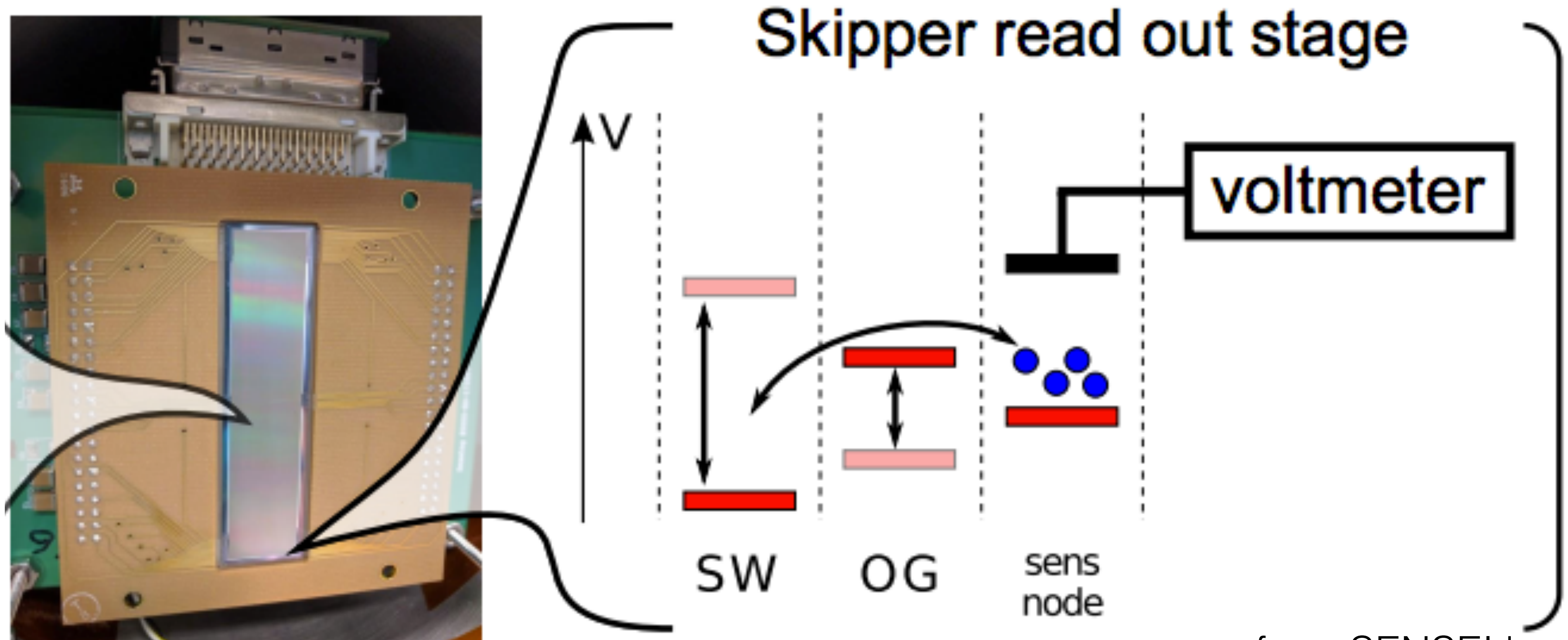


Readout noise determines threshold of ~ 11 e^-
(or ~ 40 eV)

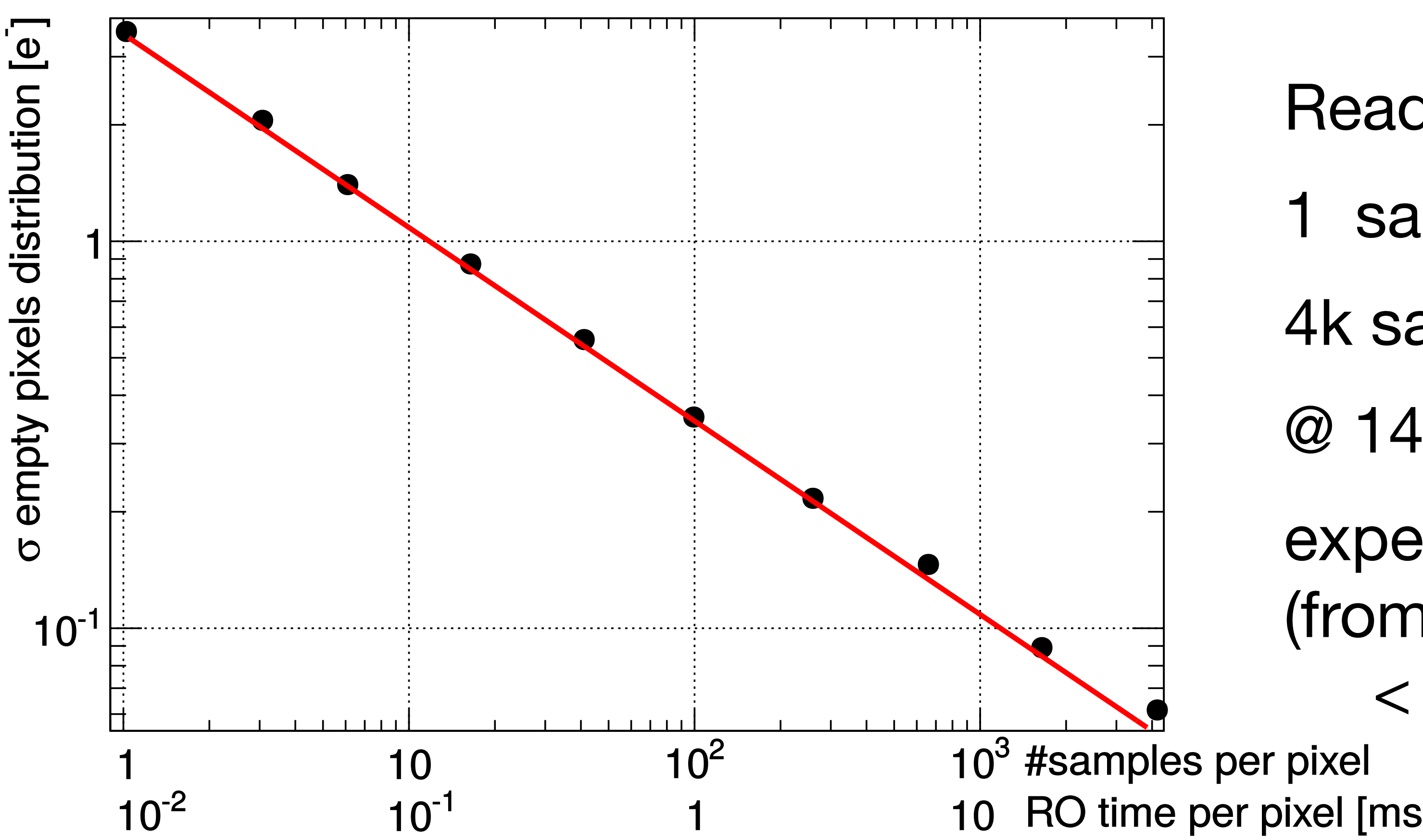
For O(MeV) DM-electron scattering, required threshold : O(e^-)
Sub-electron noise level necessary

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

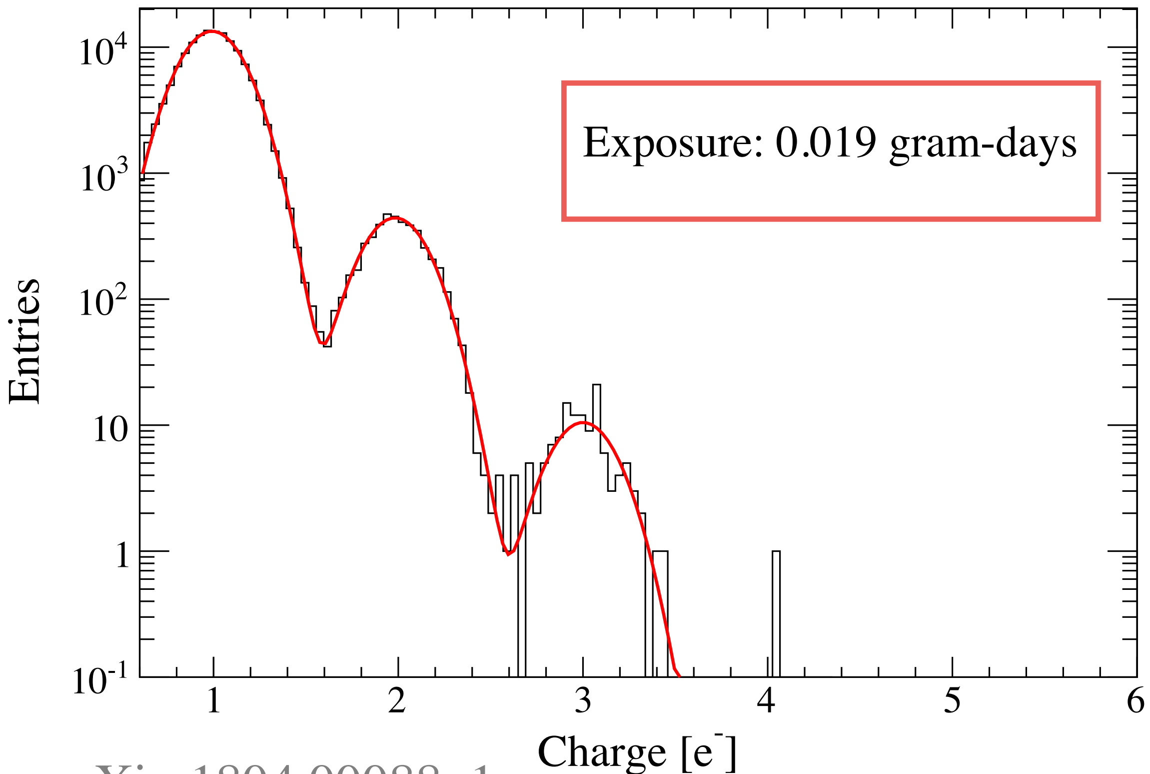
4k samples : 0.068 e^- rms

@ 140 K

expected dark current (from DAMIC CCD) :

< 10^{-3} e^-/pix/day

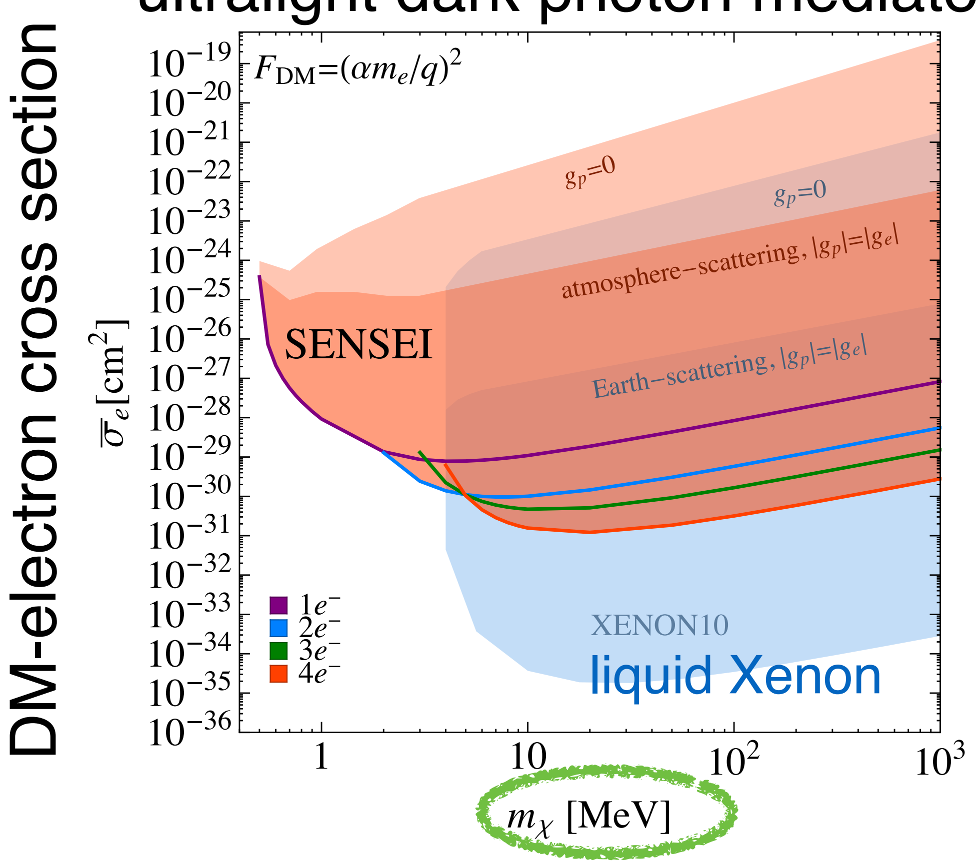
SENSEI first result from a surface run



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-
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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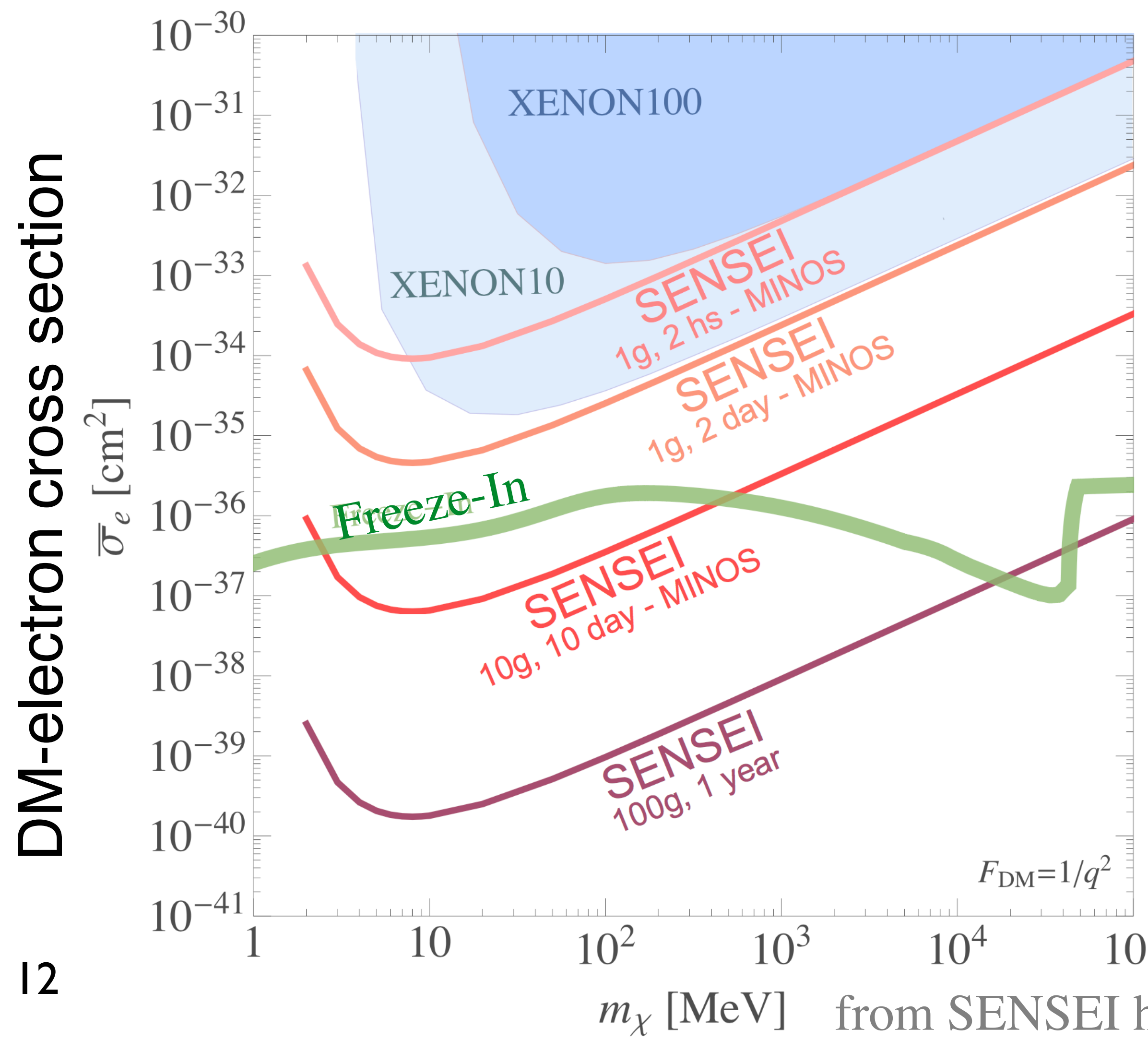

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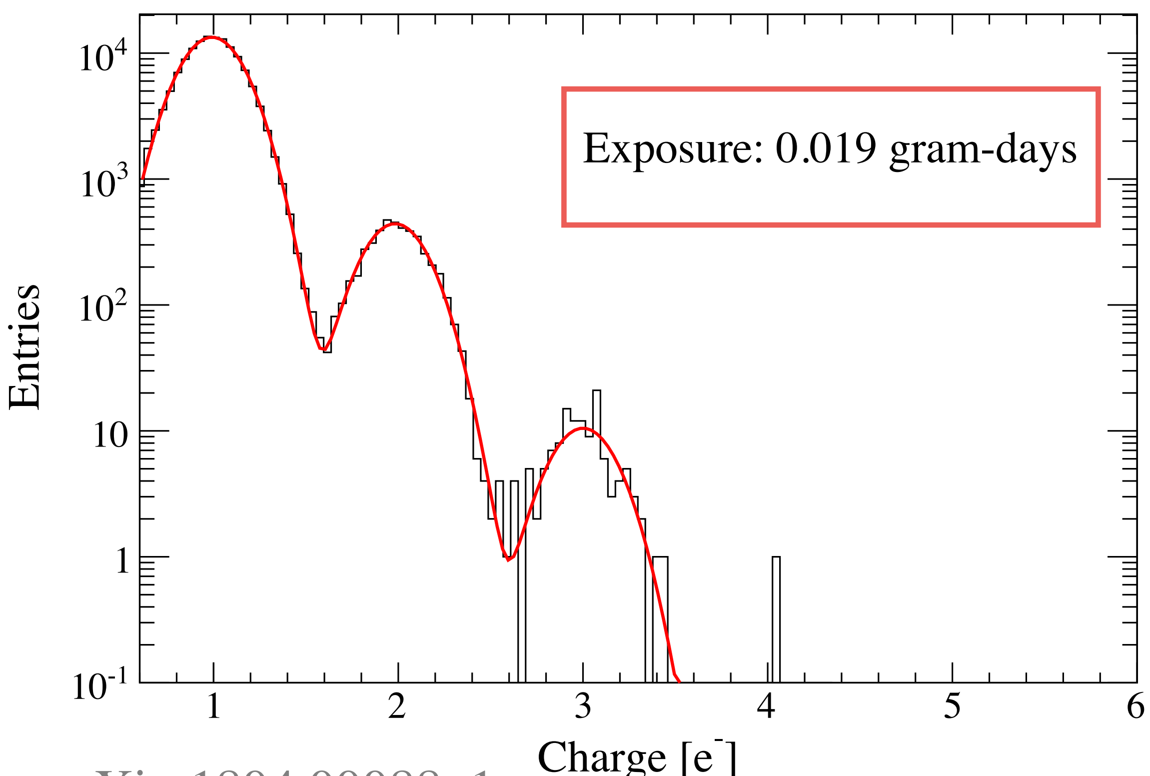

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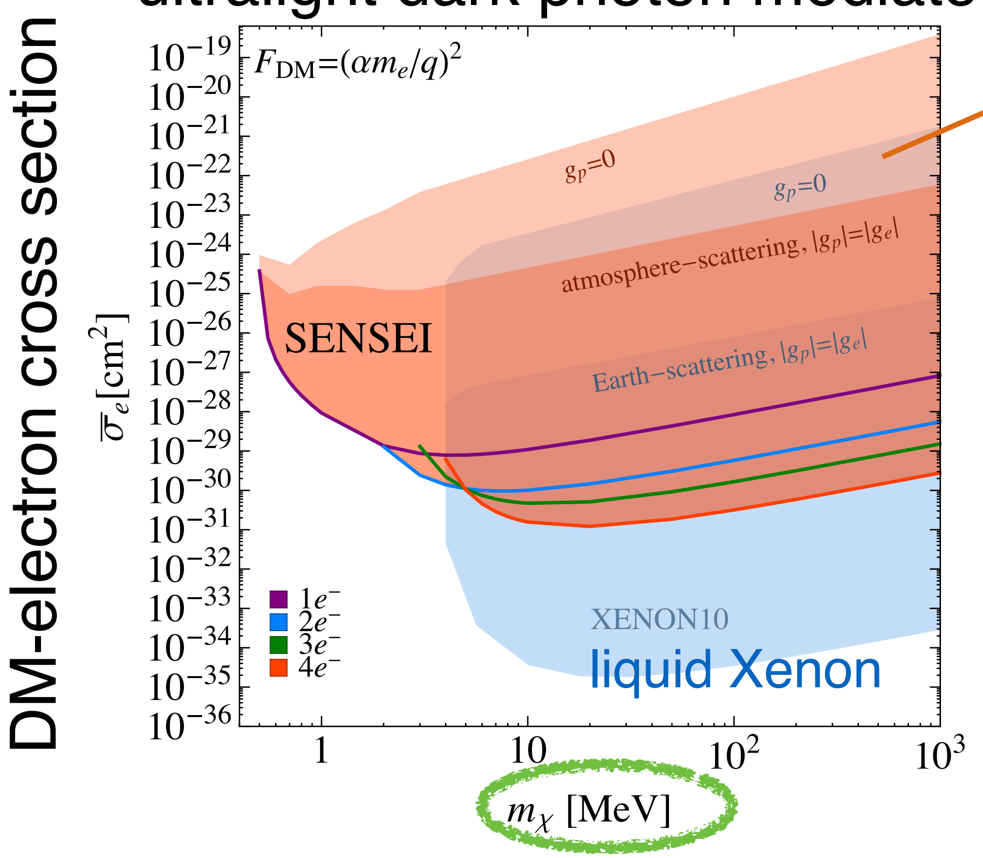
- dark current : ~1.14 e$^-$/pixel/day
- assume all events DM induced
  - -> conservative limit

ultralight dark photon mediator



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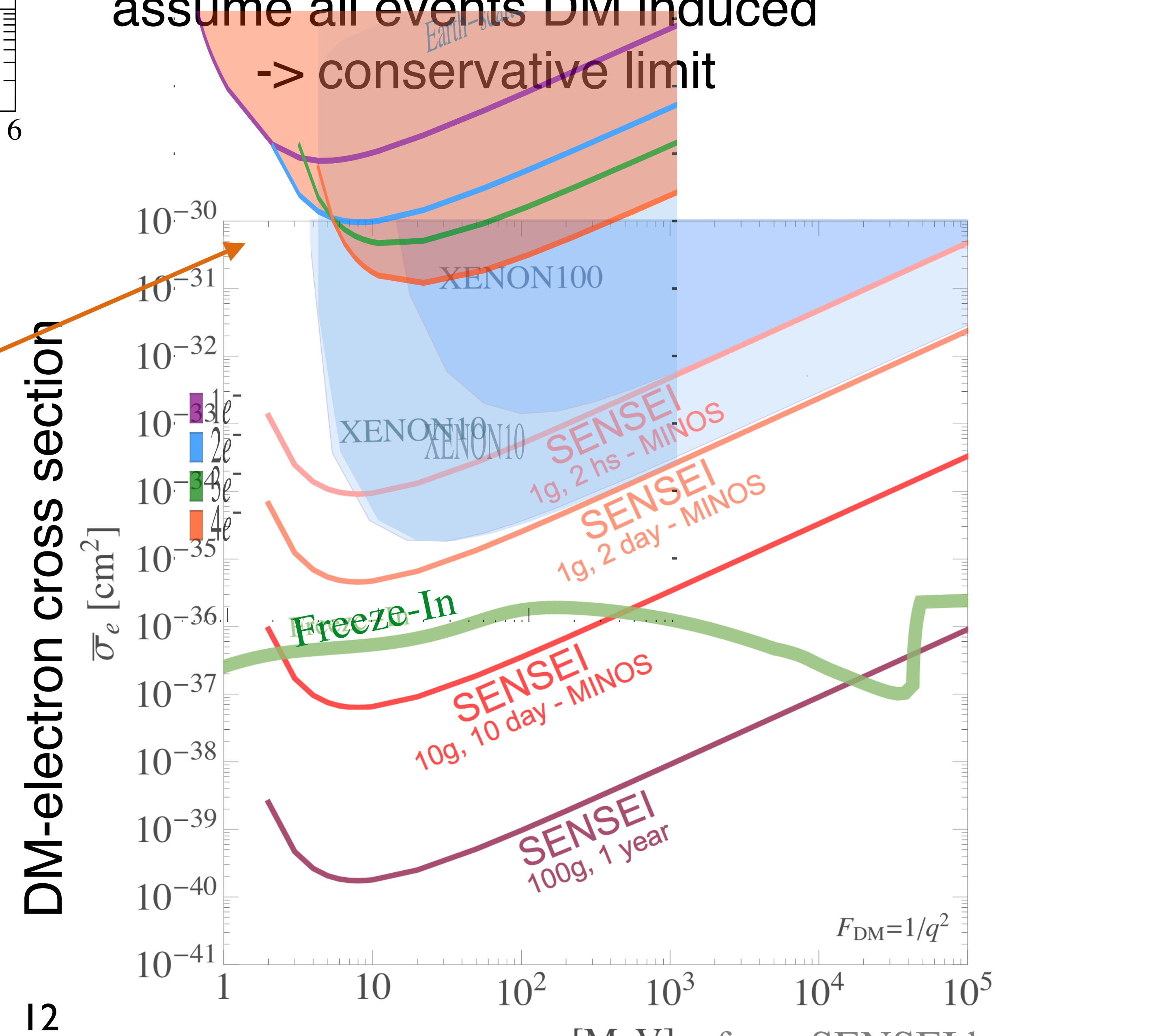


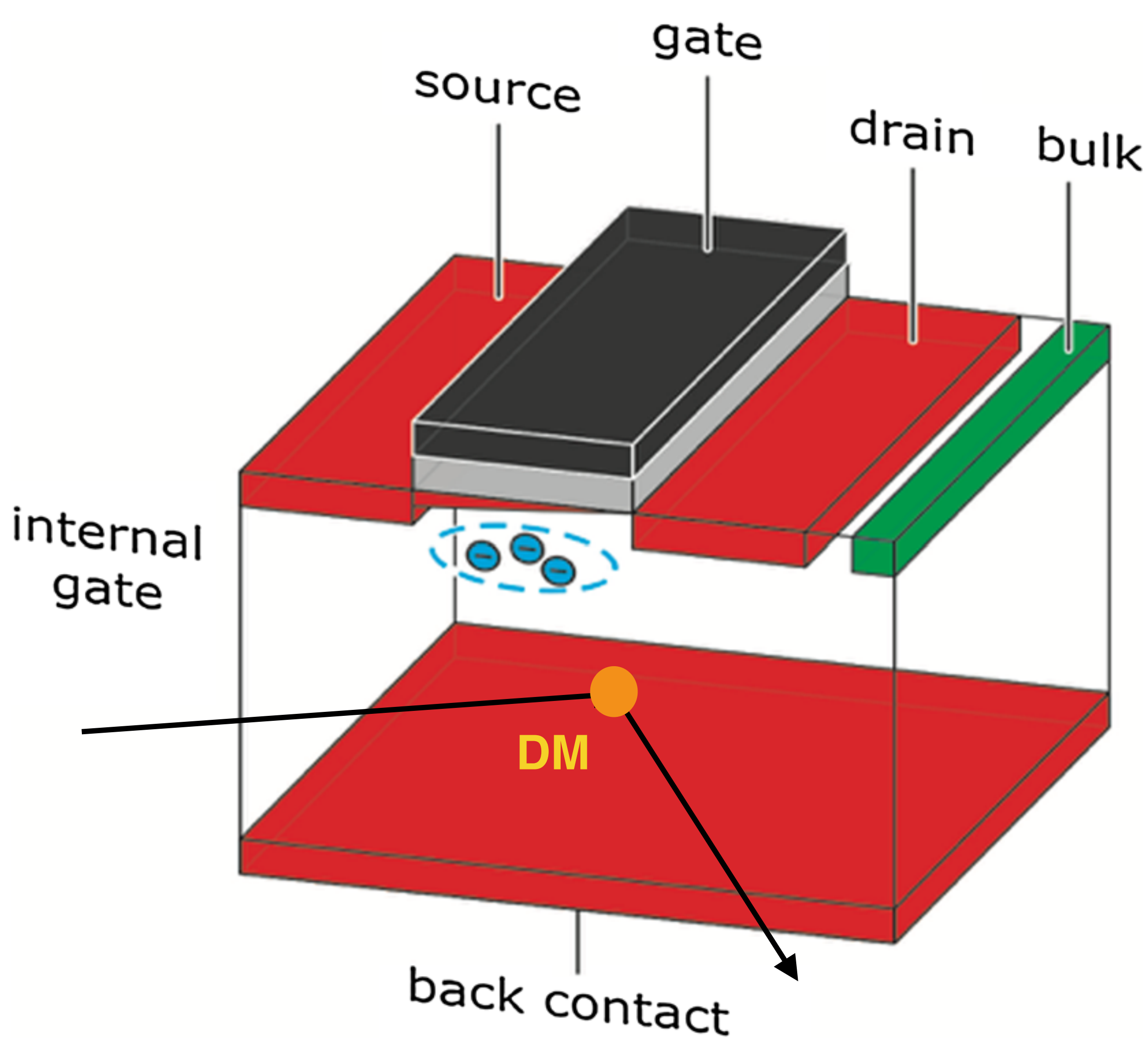
from SENSEI homepage

DEPFET with RNDR

RNDR : repetitive non-destructive readout

structure of a basic DEPFET cell :

a “subpixel”



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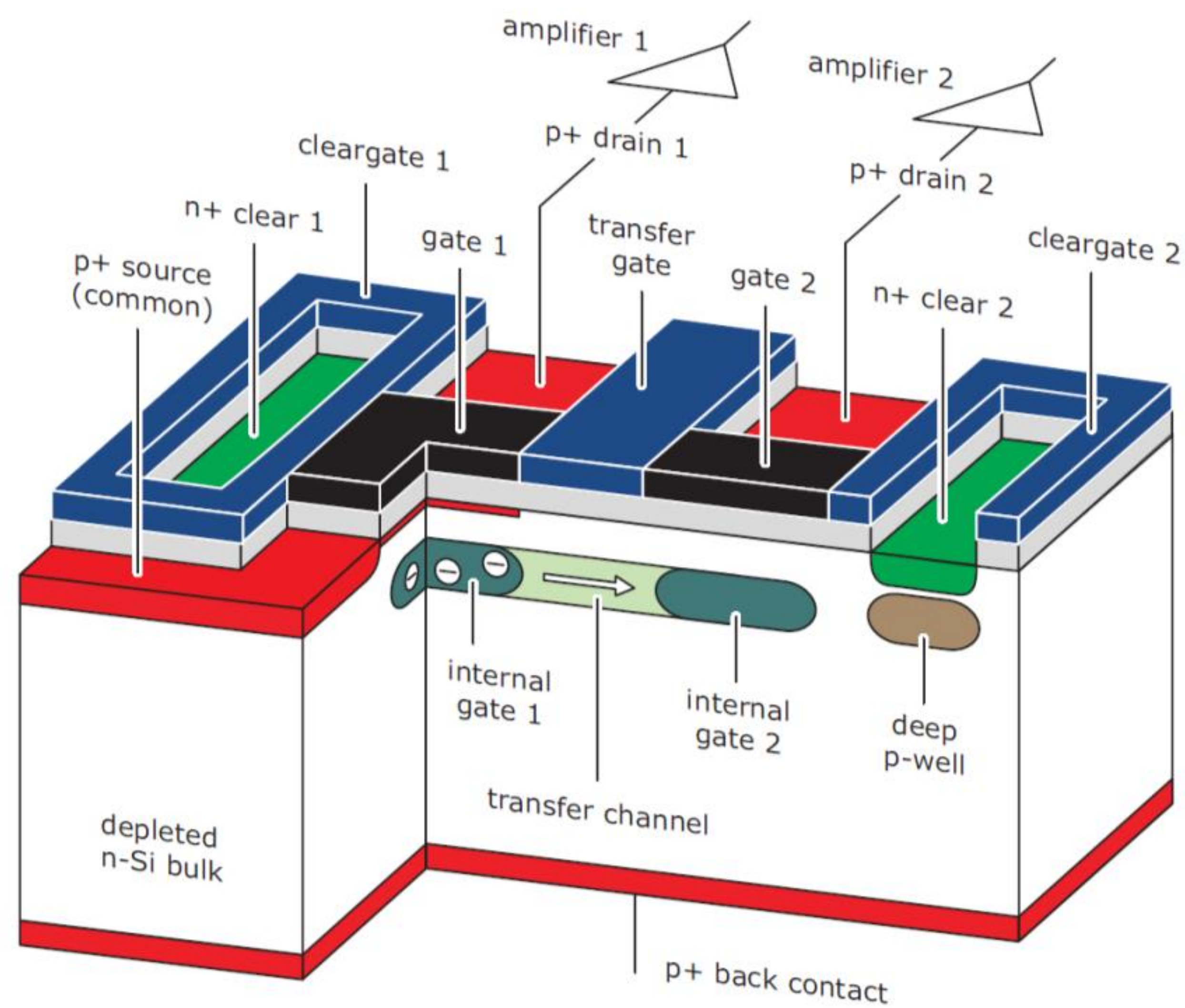
fully-depleted n-Si

structure of RNDR DEPFET “super-pixel”



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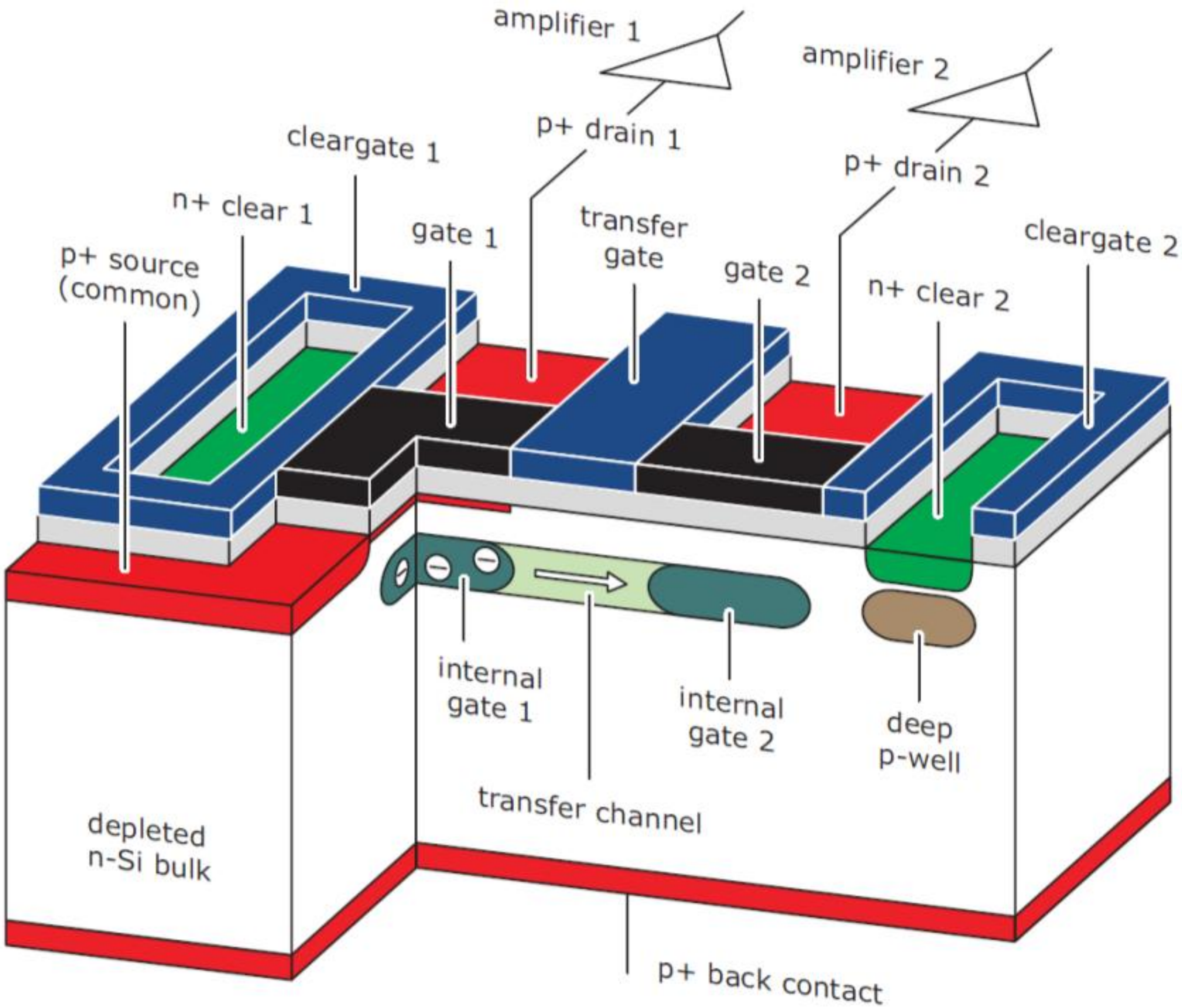
RNDR



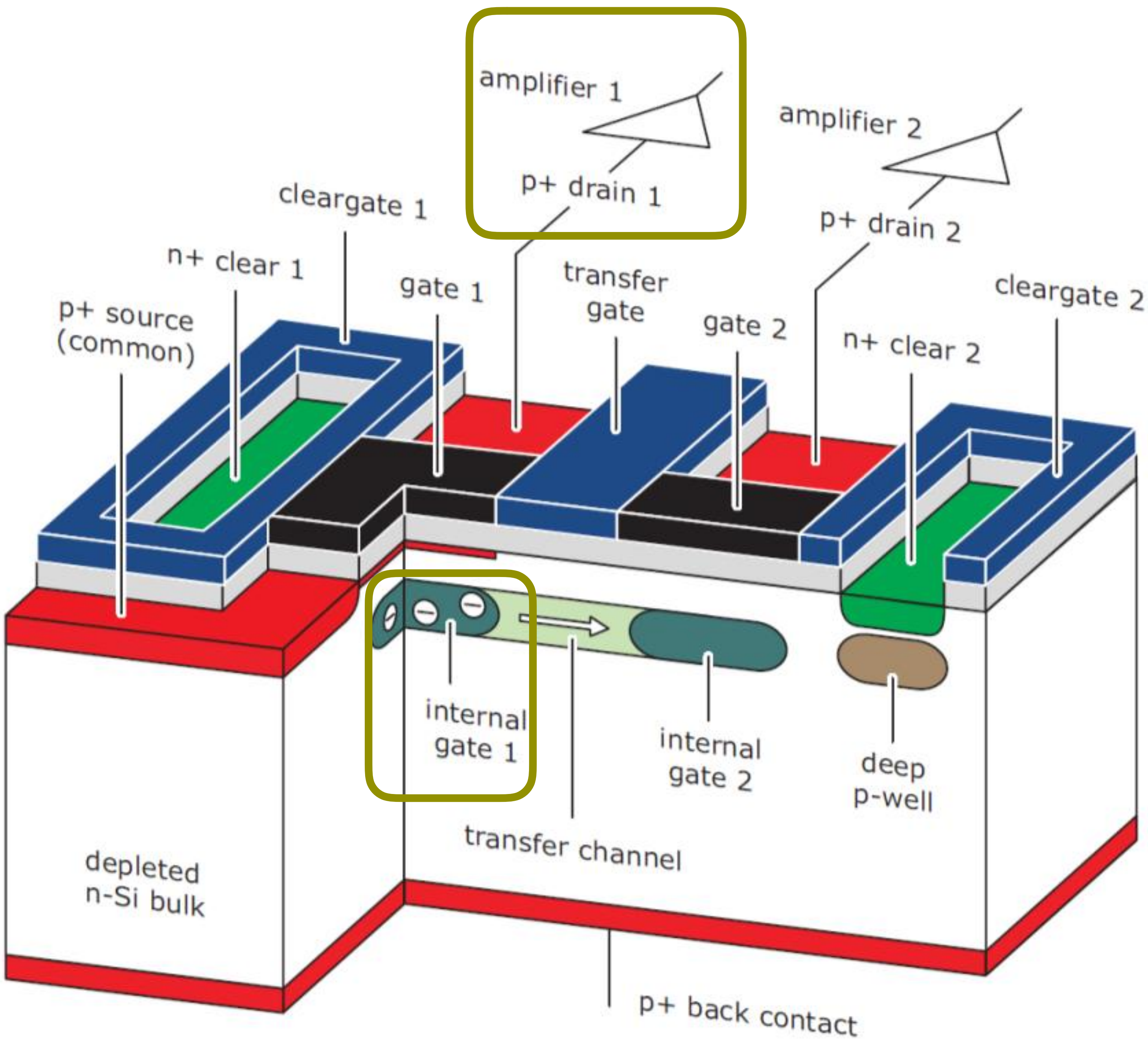
EPJ C, 77(12), 279 (2017)

RNDR readout

read N times *effective noise* :

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

RNDR



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

RNDR readout

read **1** : noise **σ**

read N times *effective noise* :

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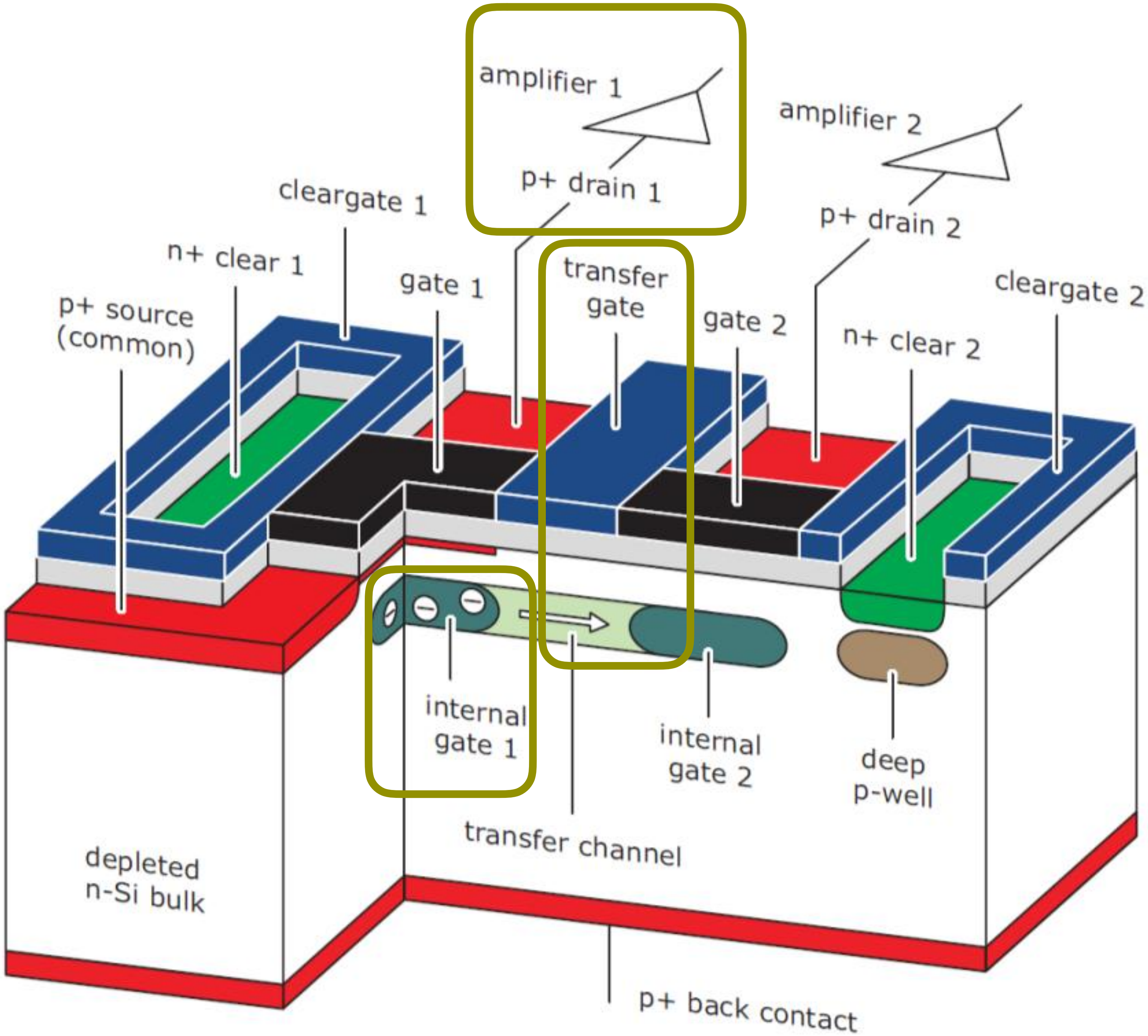
RNDR



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

RNDR readout

read **1** : noise **σ**

transfer gate open

read N times *effective noise* :

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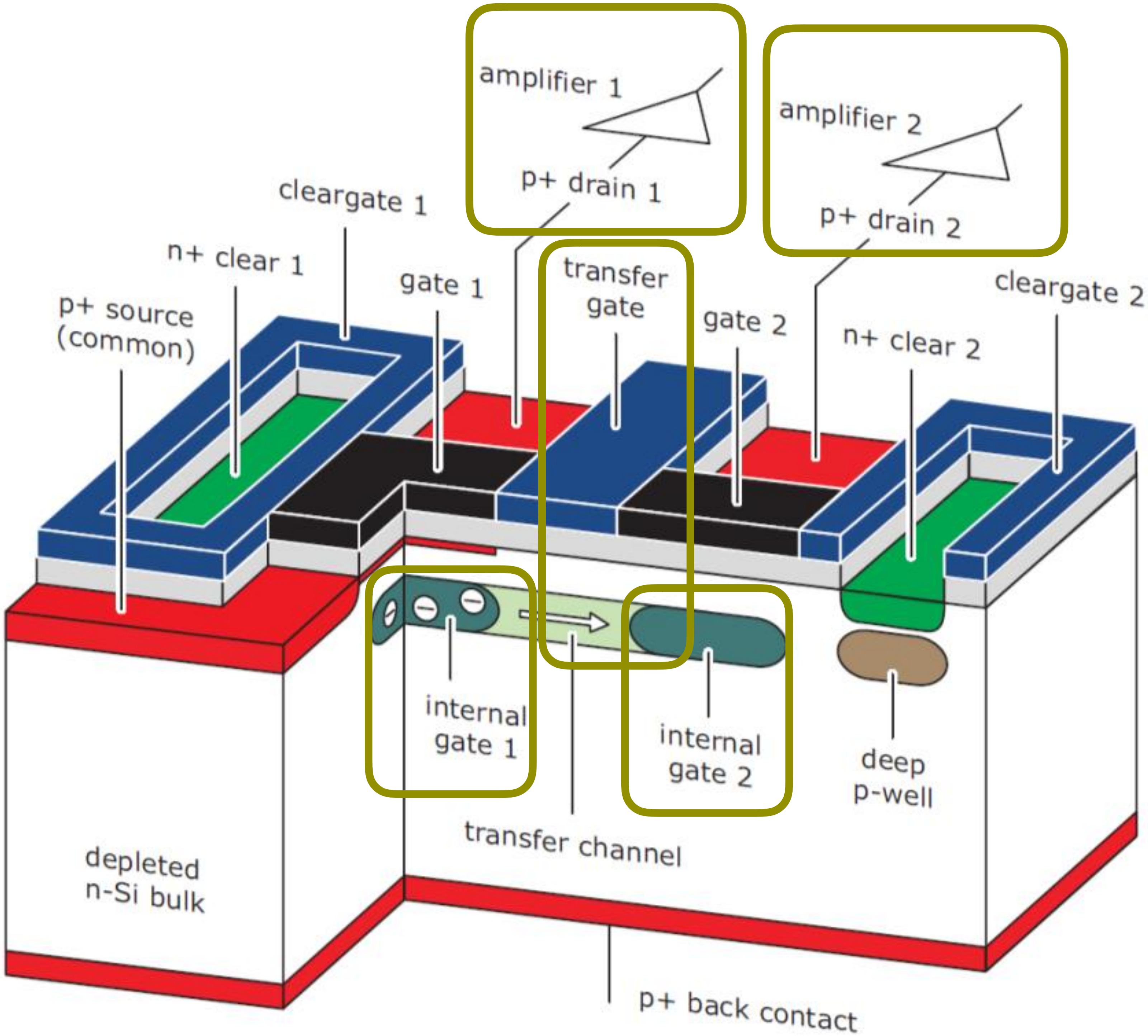
RNDR



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

RNDR readout

read **1** : noise **σ**

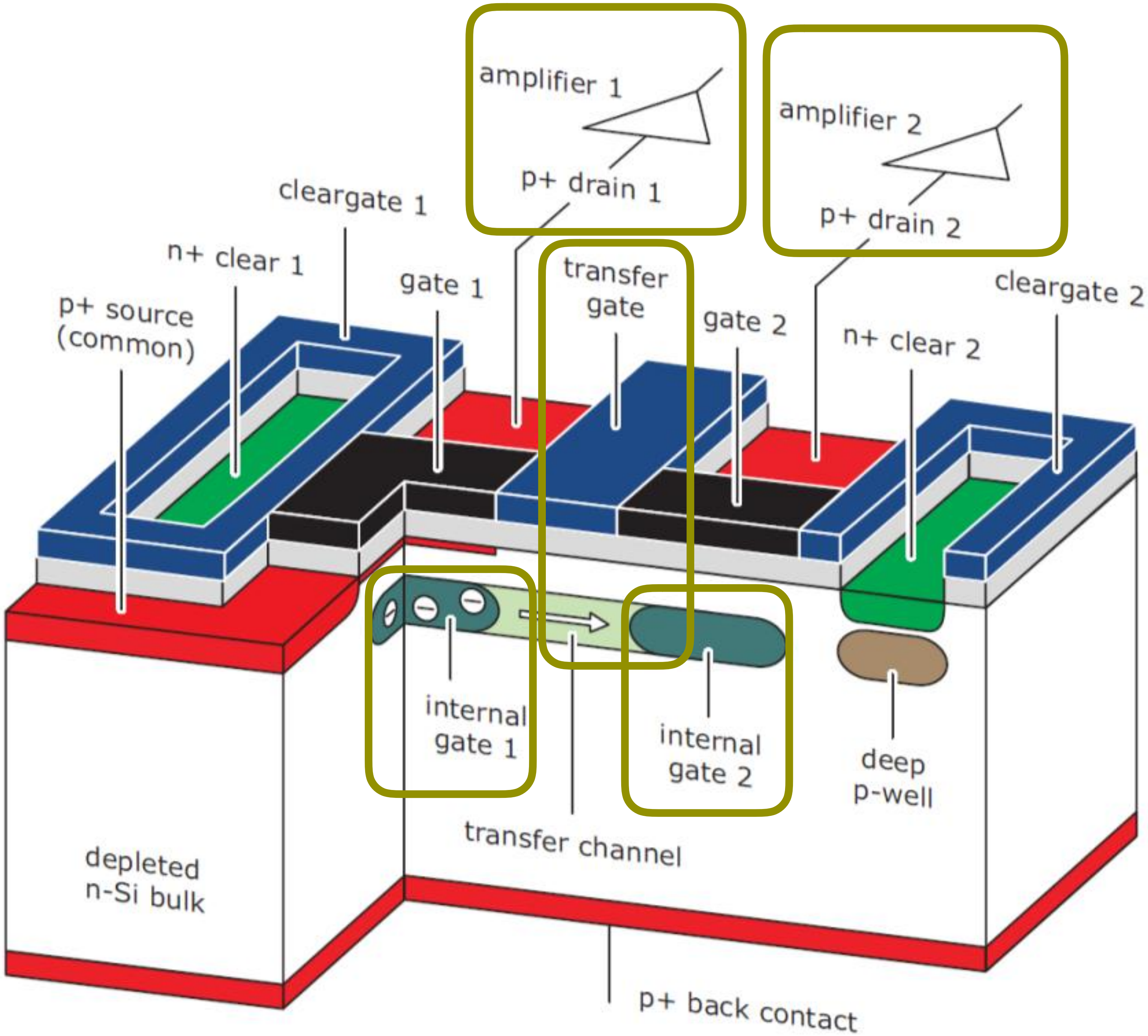
transfer gate open

read **2** : noise **σ**

read N times *effective noise* :

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

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

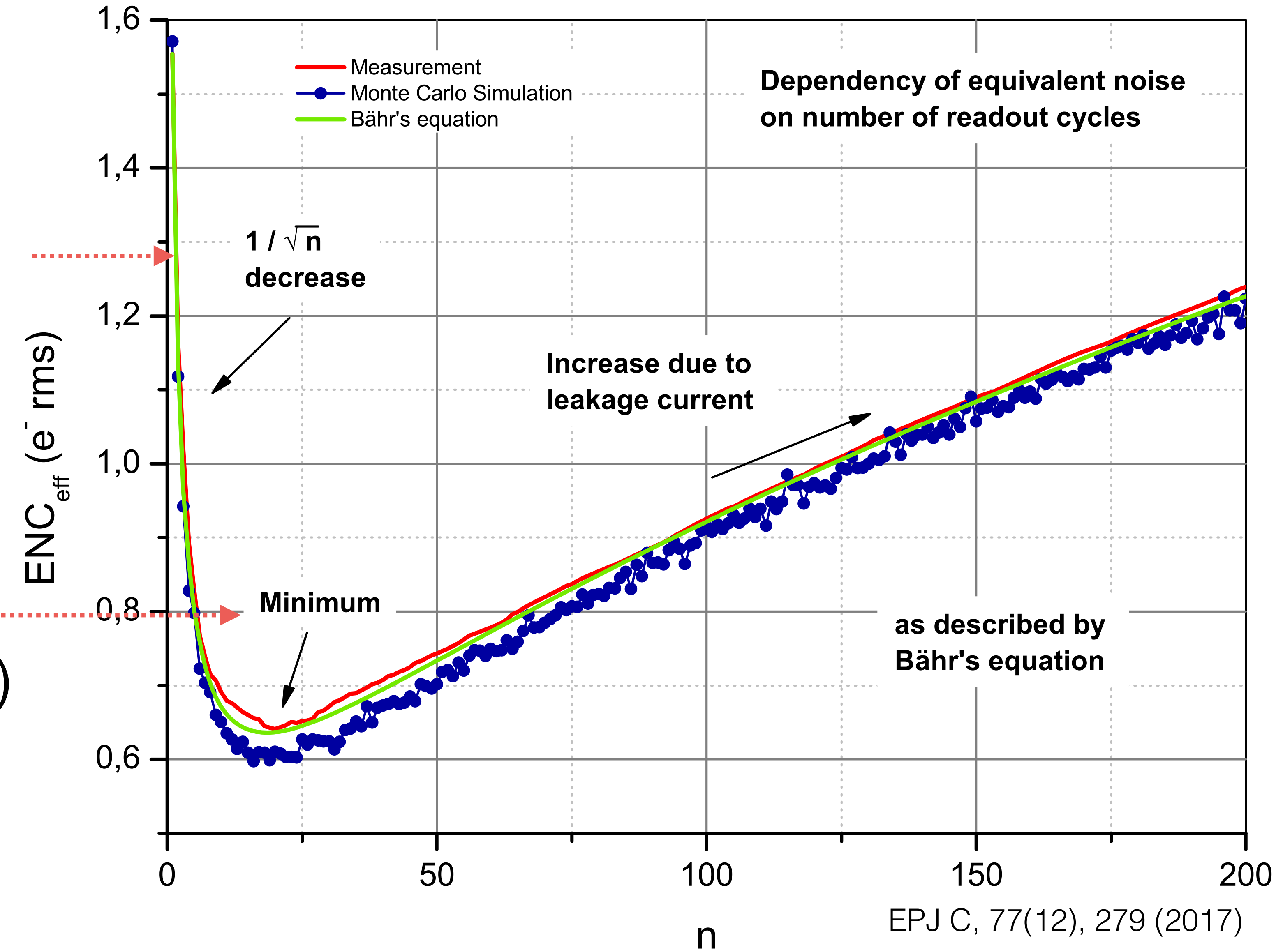
read N times *effective noise* :

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

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)



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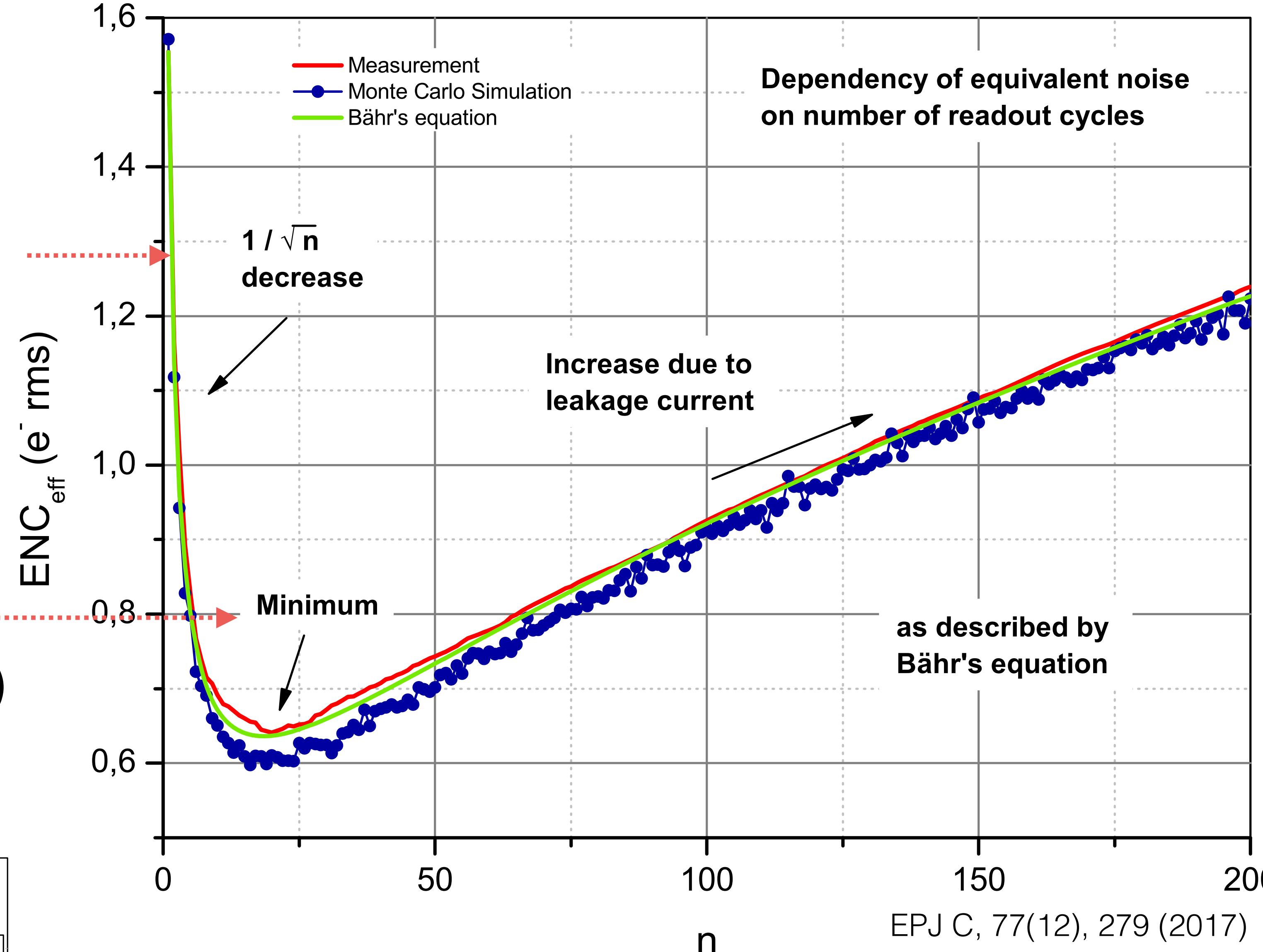

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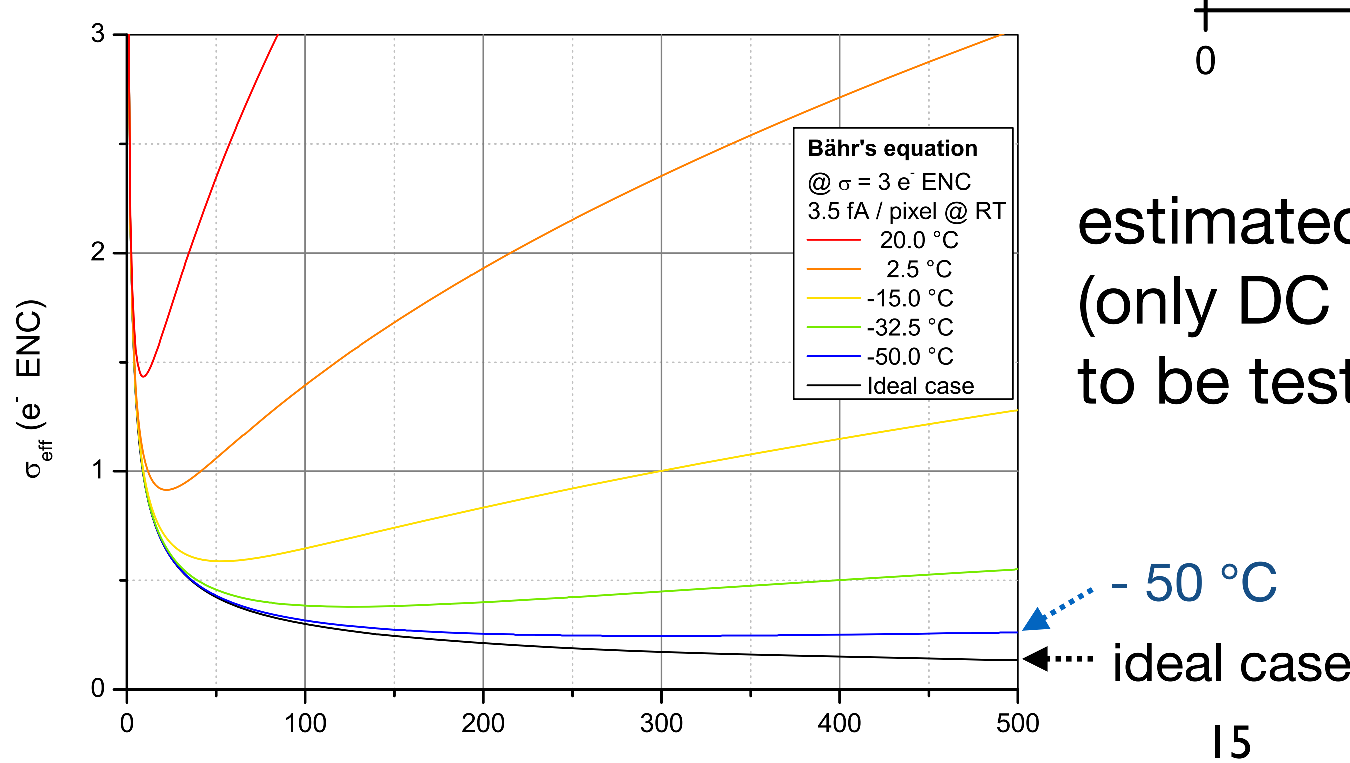

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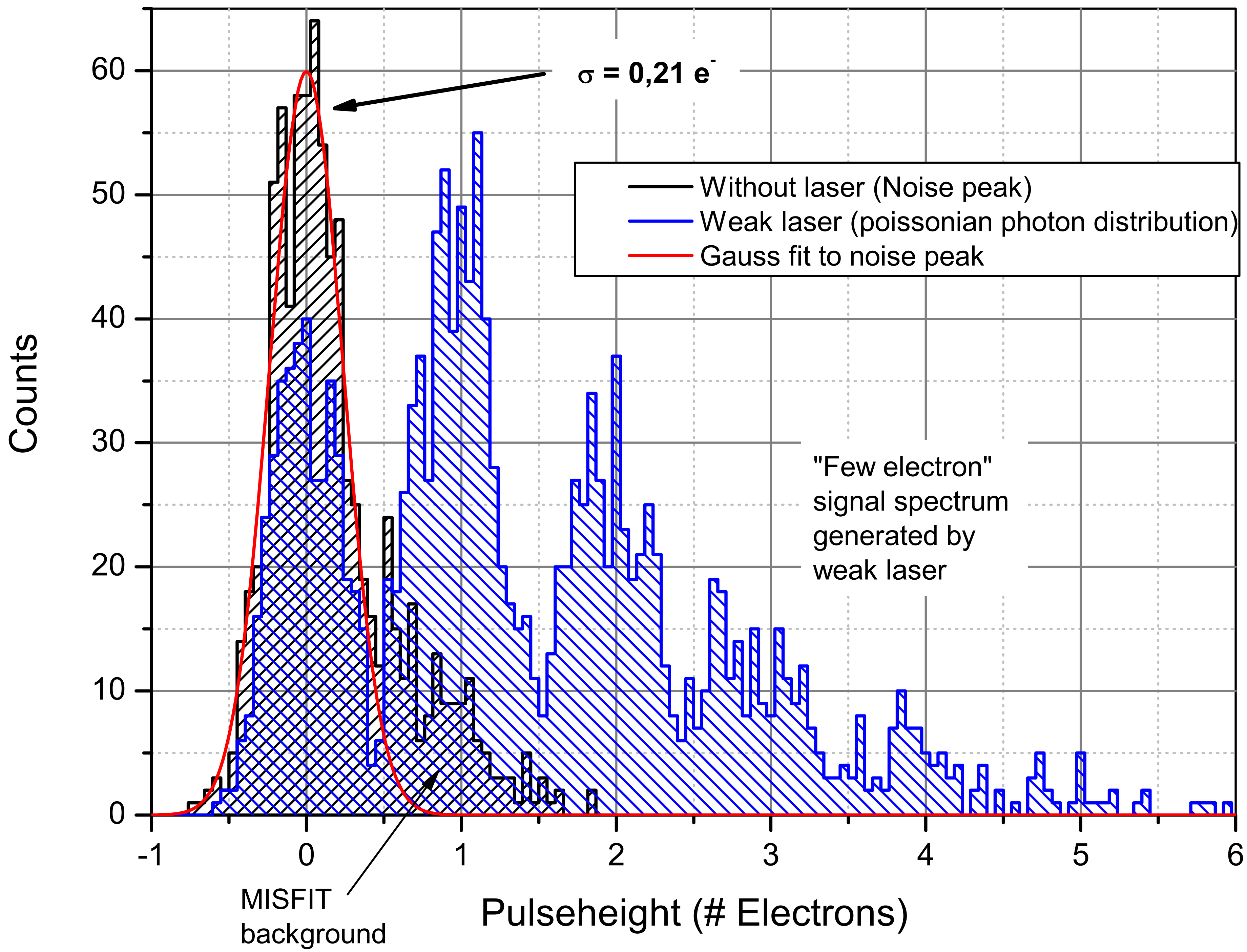
estimated temperature dependence (only DC from thermal excitation) to be testified in measurement

new architecture with “blind-gate”

possibility of reducing leakage current during readout

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

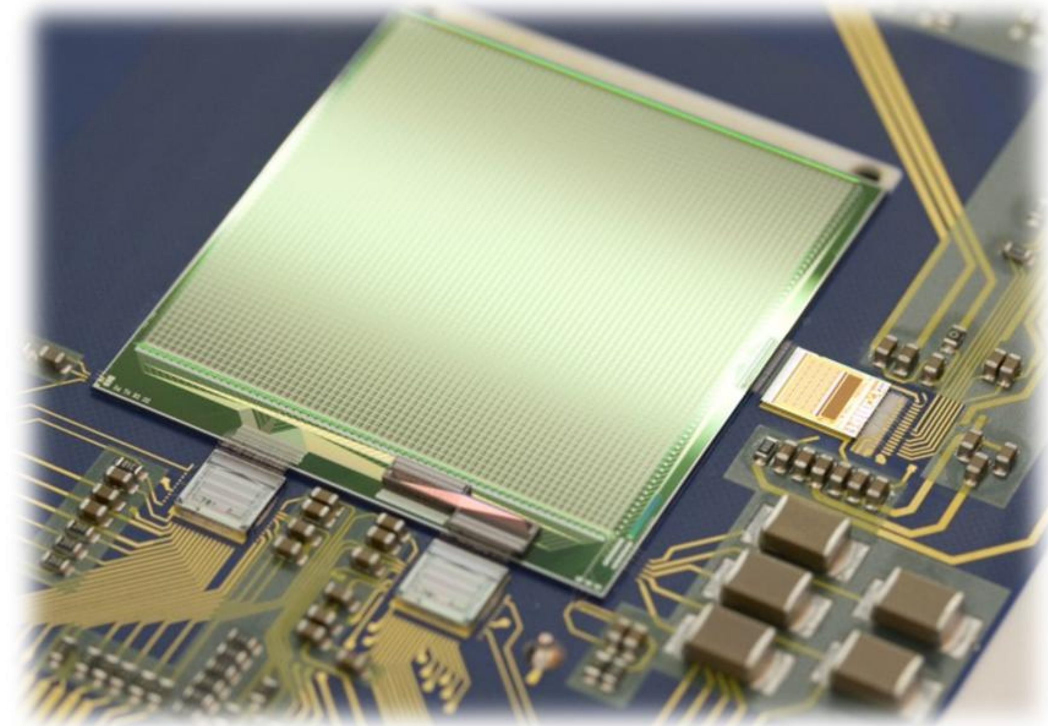
similar concepts of non-destructive readout, compatible performance;

different architecture, different systematics;

-> good complementary from experimental point of view

DANAE 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

Expect to have operating matrix by the end of 2018

In Vienna:

low background environment measurement
or surface measurement with veto

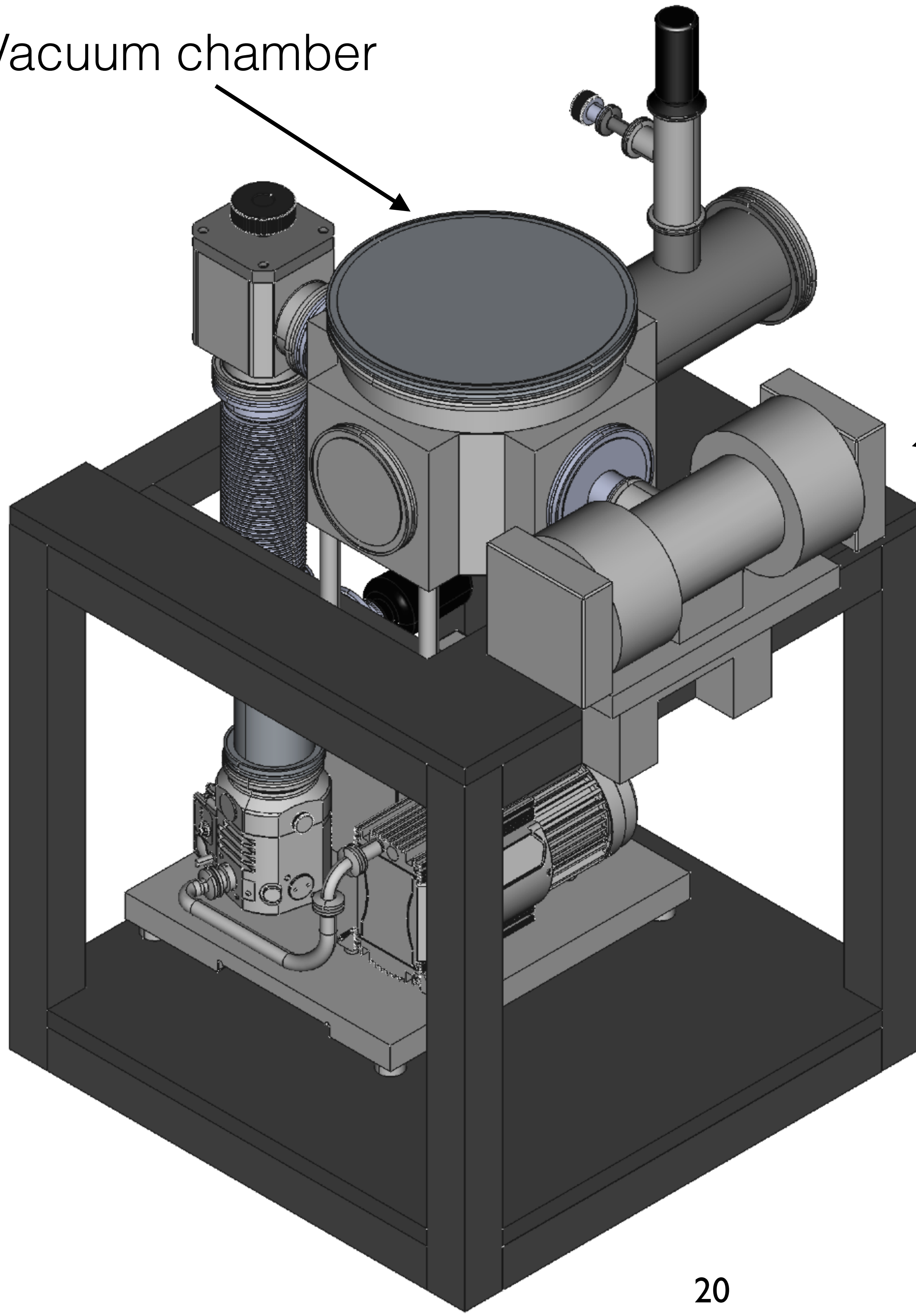
MC simulation for background budget

DANAE preparation status

DANAE test setup - design image

Vacuum chamber

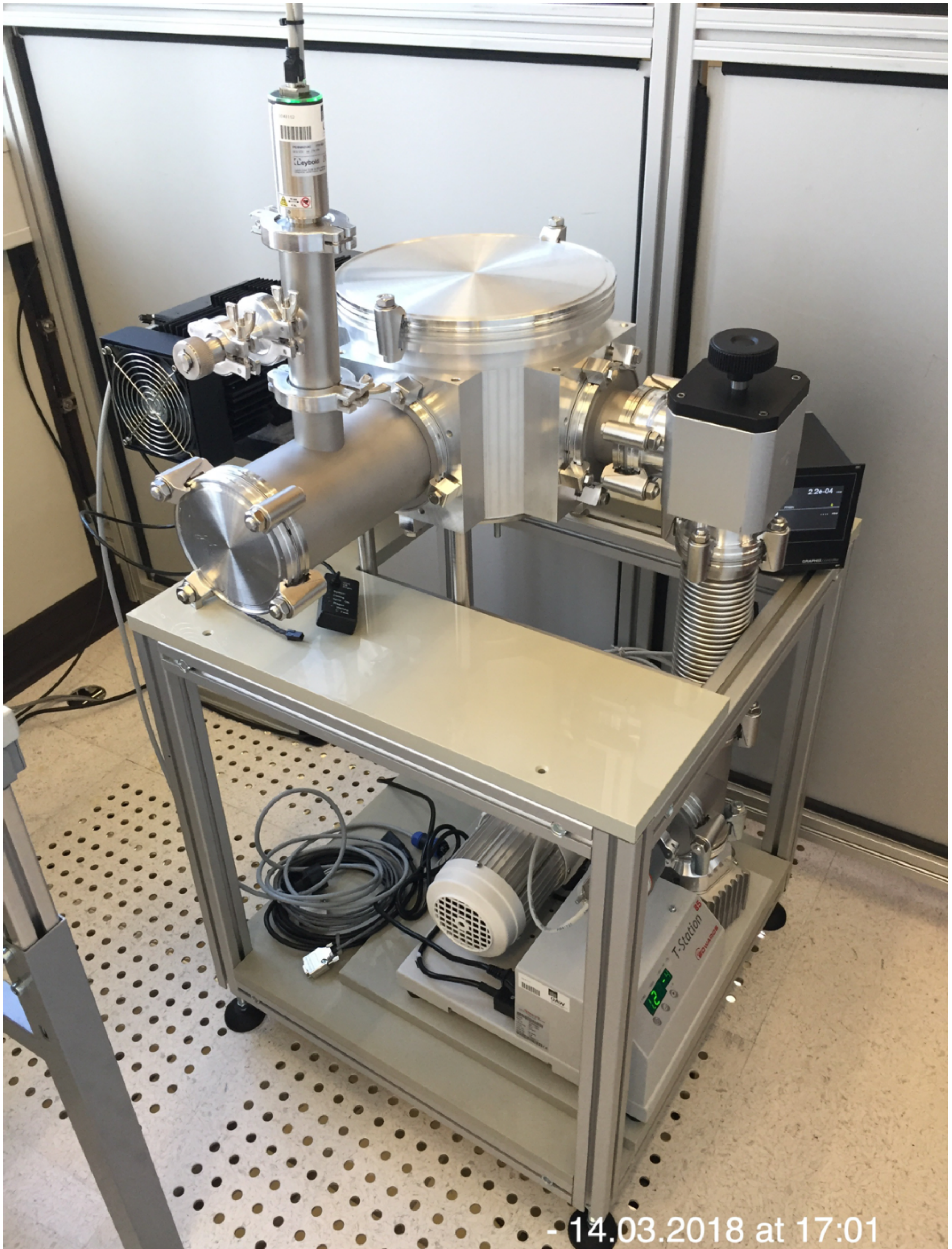
Stirling-cycle cryocooler

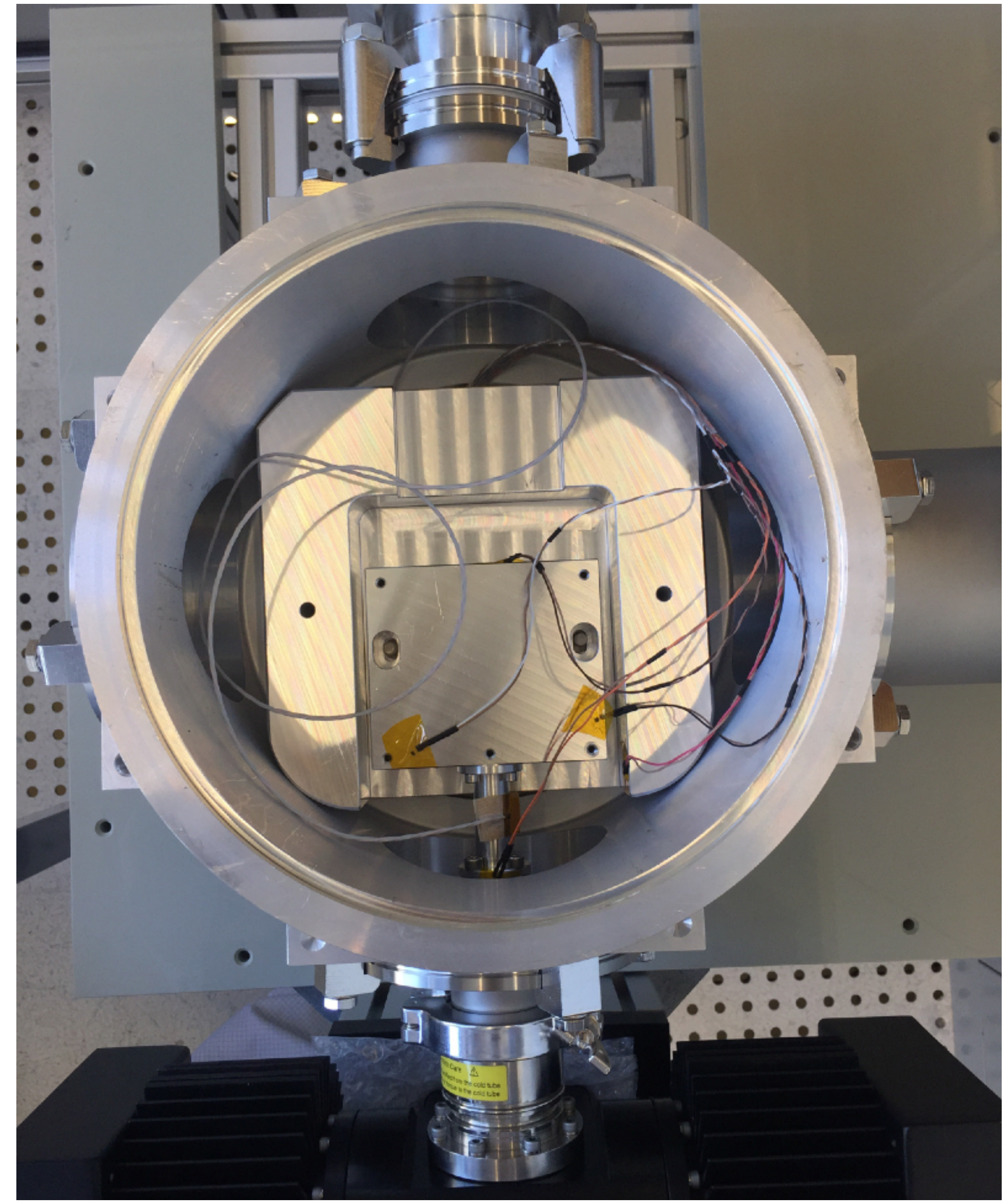


10 cm

Assembly at HLL

Setup at HLL

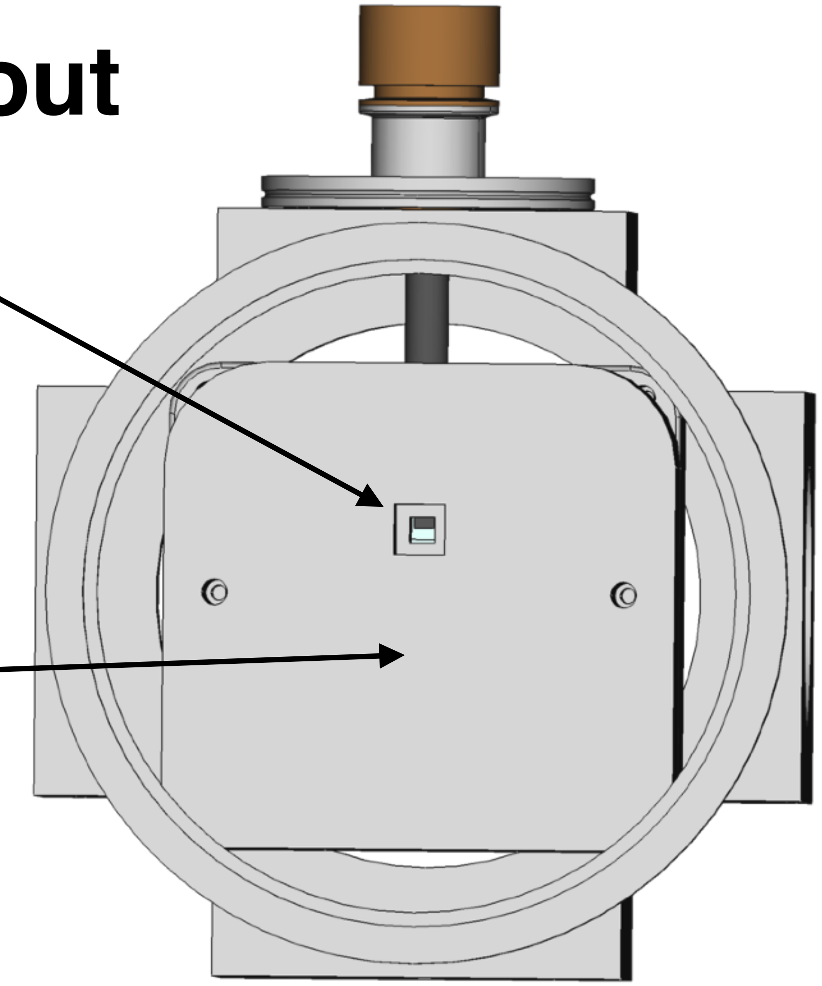


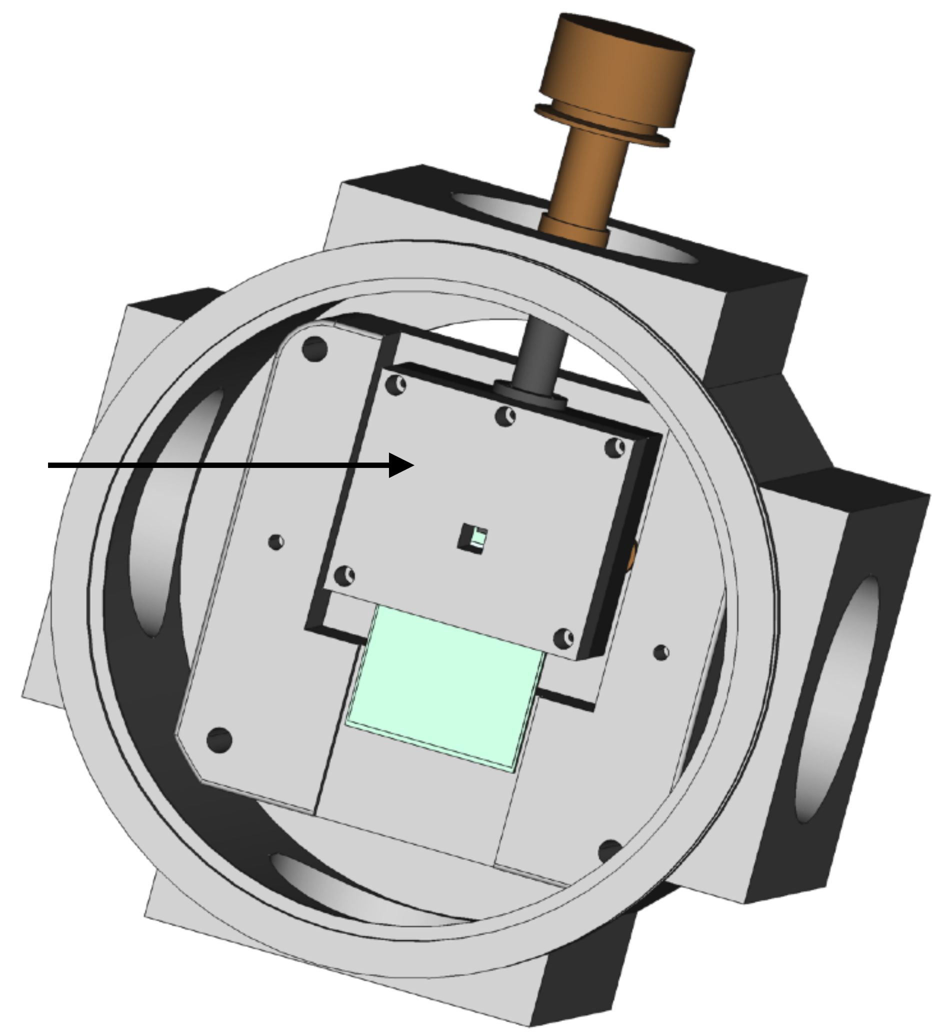


Vacuum and cooling tests done in March 2018

cooling pad reached 150 K

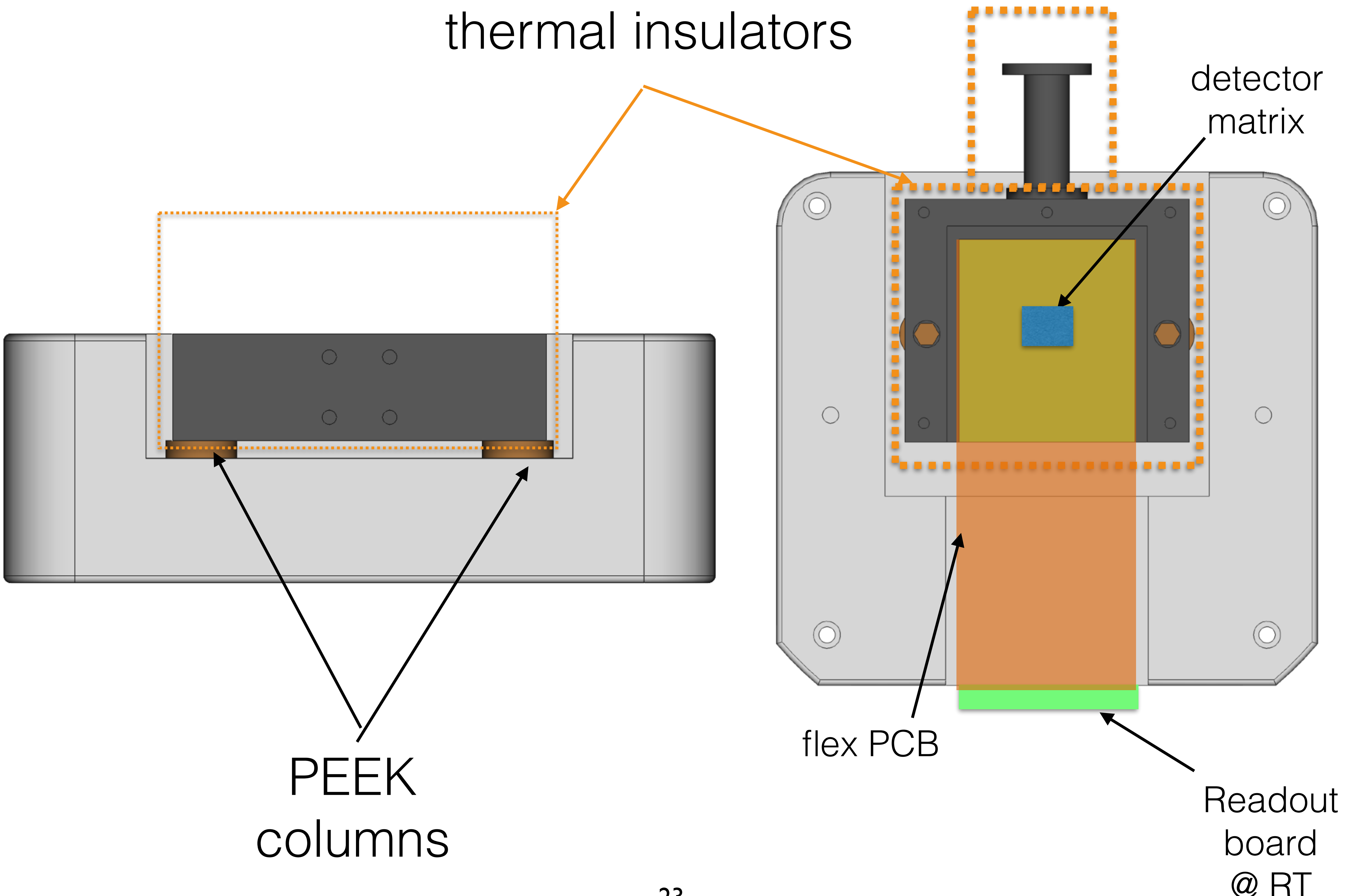
Cooling & shielding layout





outer shielding : support structure
inner shielding : cooling contact

Cooling of the detector and electronics



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 matrix control & readout electronics

Detector matrix

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ADC

FADC type digitizer

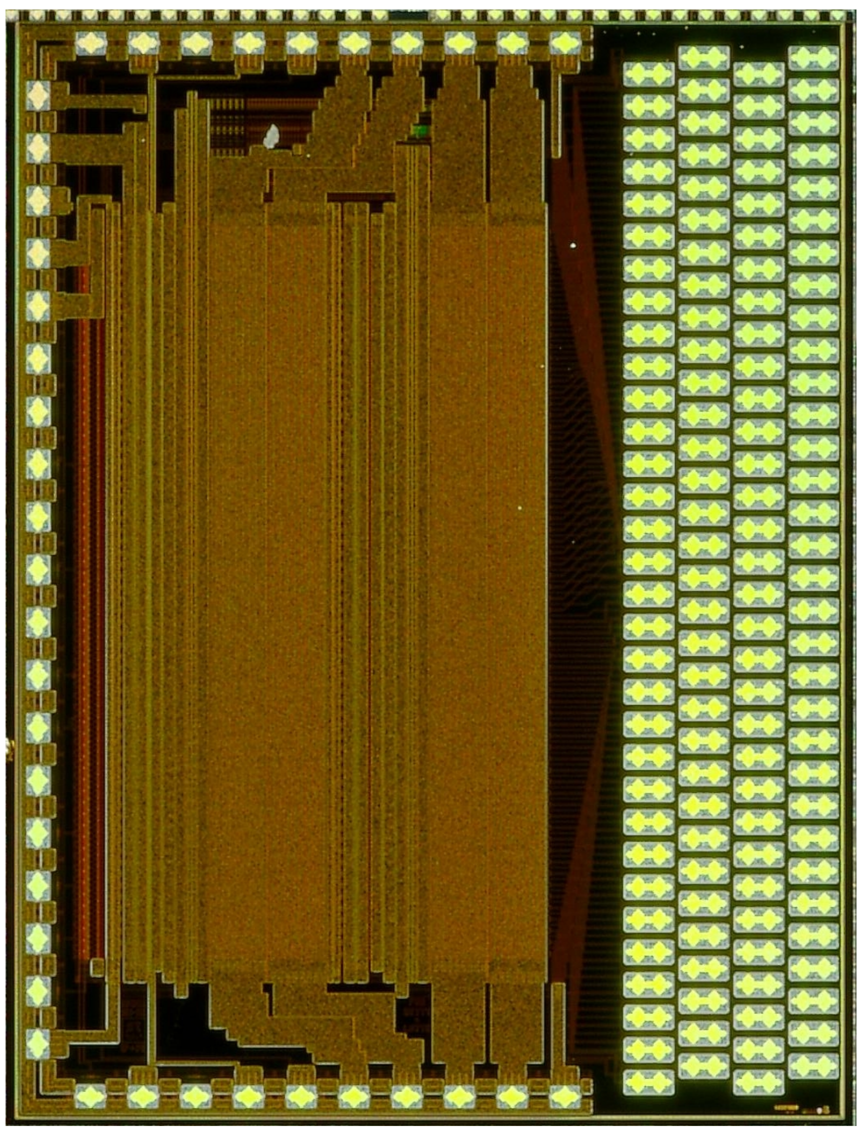
Switcher-S

Switcher-S, a HV Switch ASIC for DEPFET Matrix Control

Peter Fischer, STZ Microelectronics & Sensor Systems

Steinbeis-Transferzentrum
Microelectronics and
Sensor Systems

Chip Manual, Version 3.2



64 x 2 channel analogue multiplexer ASIC for the row steering of DEPFET sensor matrices

for RNDR operation

- 3 chips
- programable sequence

applications in BELLE DEPFET

DEPFET matrix control & readout electronics

Detector matrix

Front-end ASICS for the 64x64 matrix
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Readout board

Switcher-S

64x2 channel analog multiplexer

switcher id	W	N	E
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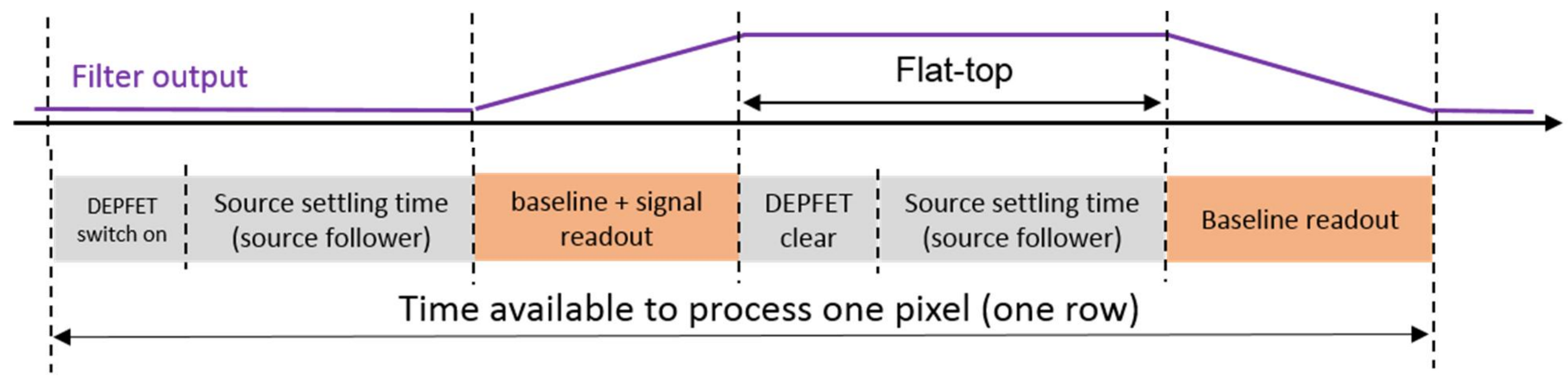
- 64 analog readout channels able to process in parallel the **signals coming from 64 DEPFET devices**.

ADC

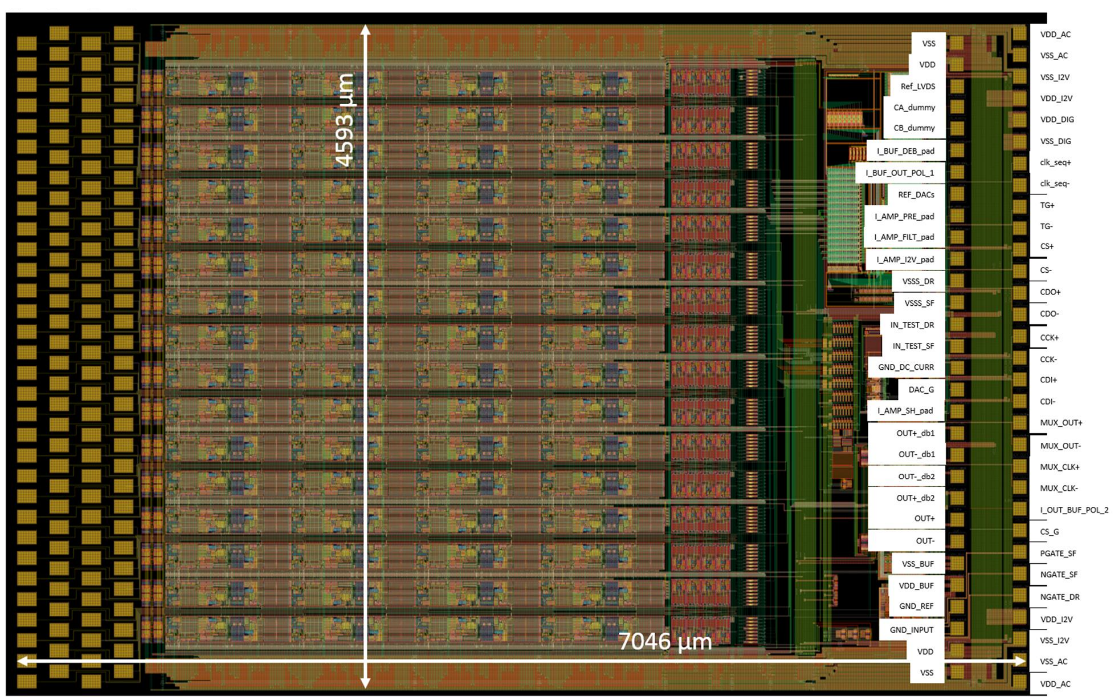
FADC type digitizer

VERITAS 2.1

- VERITAS 2.1 (Versatile Readout based on Integrated Trapezoidal Analog Shapers)
- 64-channel readout ASIC for DEPFET pixel arrays
- source-follower readout of DEPFET
- each channel implements a trapezoidal weighting function
- CDS : Correlated Double Sampling for signal



layout dimensions and pad stack chip developed by MPE



time diagram of the filter operation with a trapezoidal weighting function

Correlated Double Sampling mode:

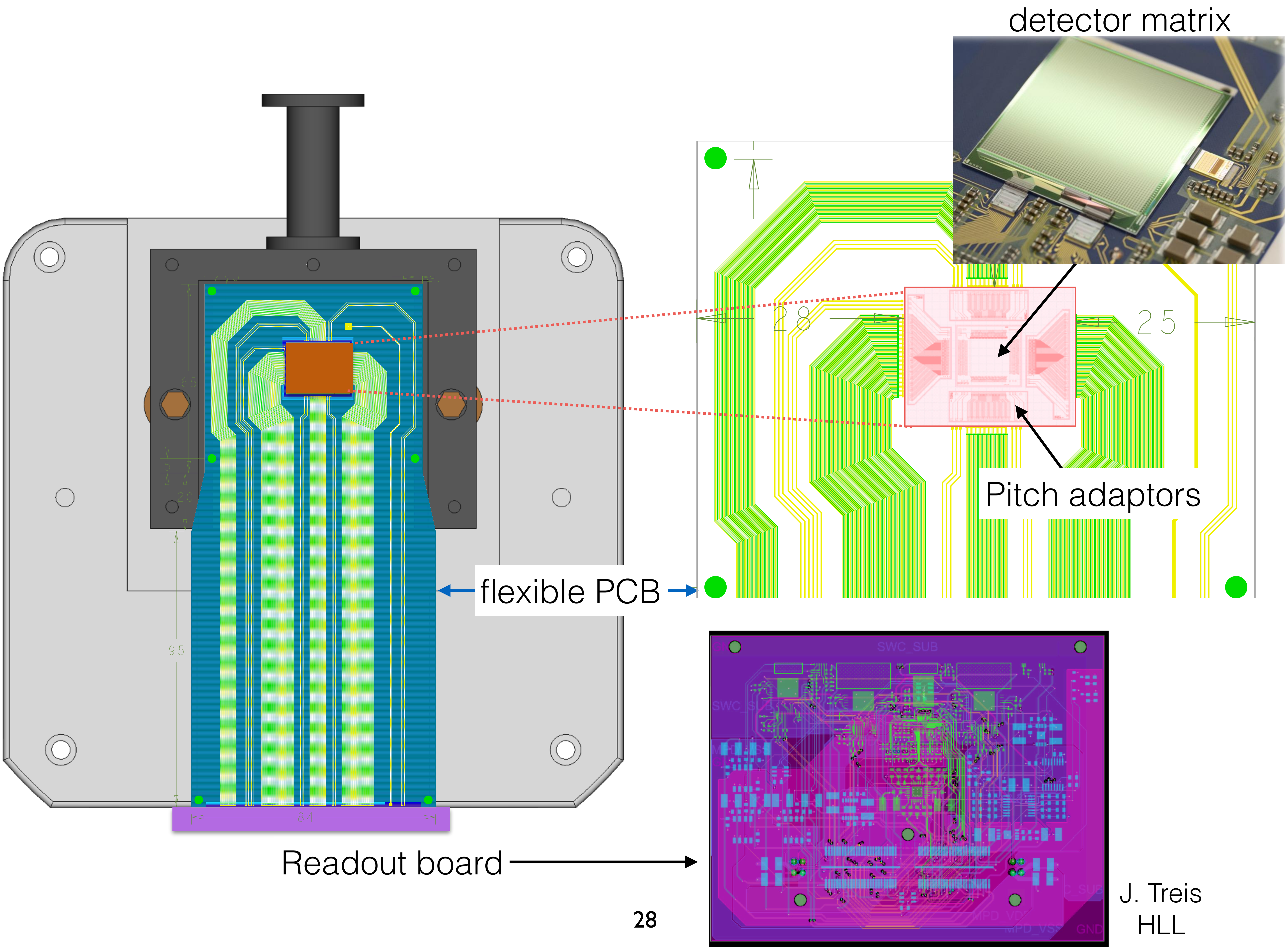
1st measurement : **baseline + signal**;

DEPFET CLEAR

2nd measurement : **baseline** ;

<u>signal</u> = difference

Detector control and readout electronics



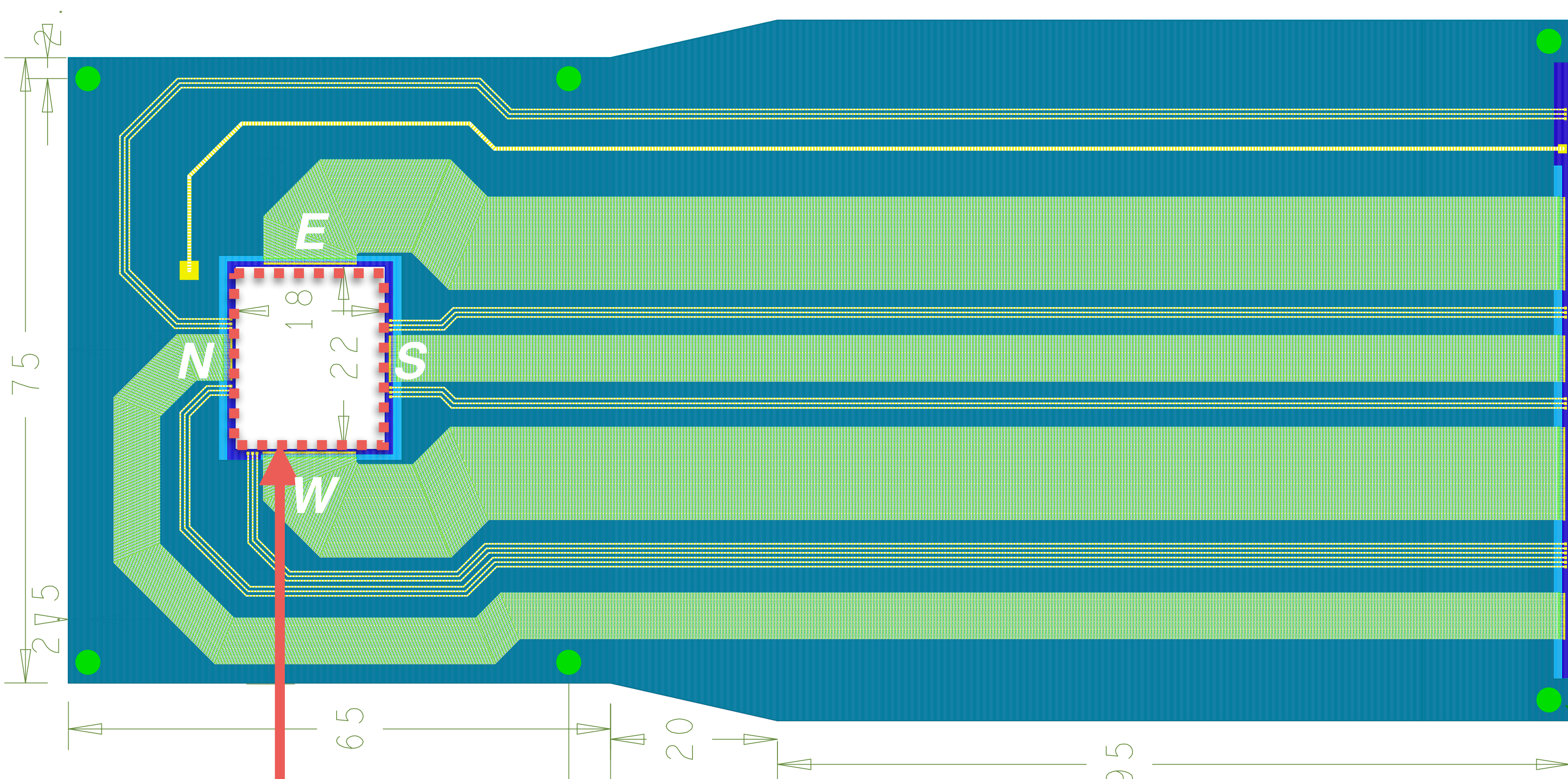
Readout PCB and Flex PCB

design using CADENCE 16.6

submitted to the manufactures

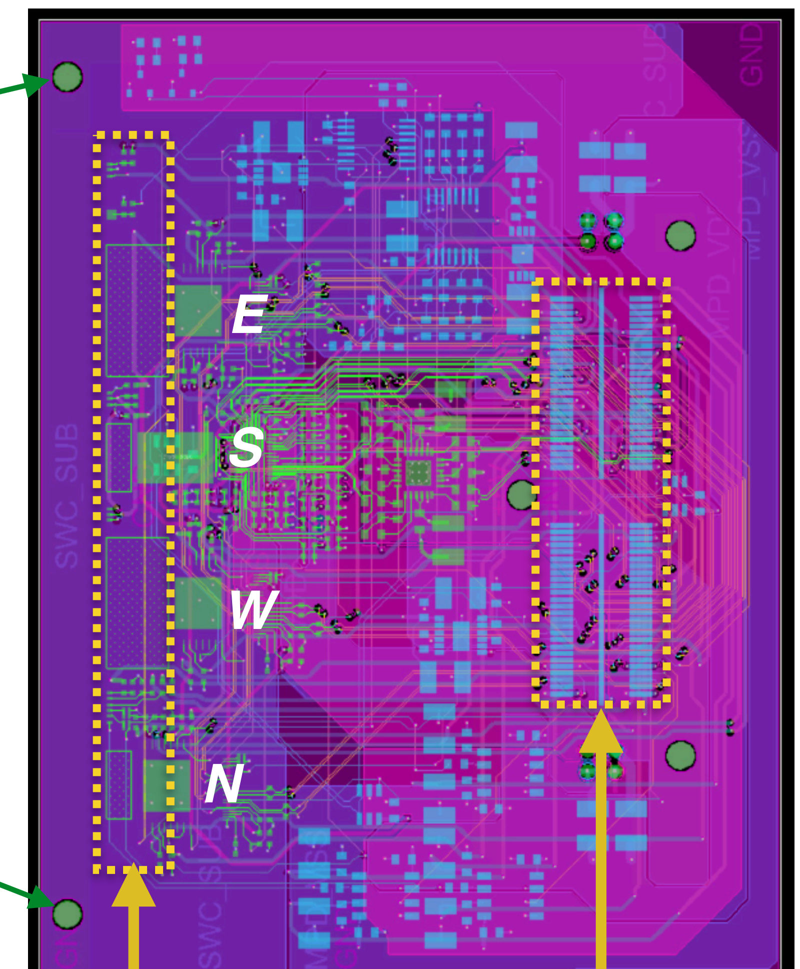
H. Shi
HEPHY

Flexible PCB



RO PCB

J. Treis
HLL



detector matrix

120 mm
flexible part

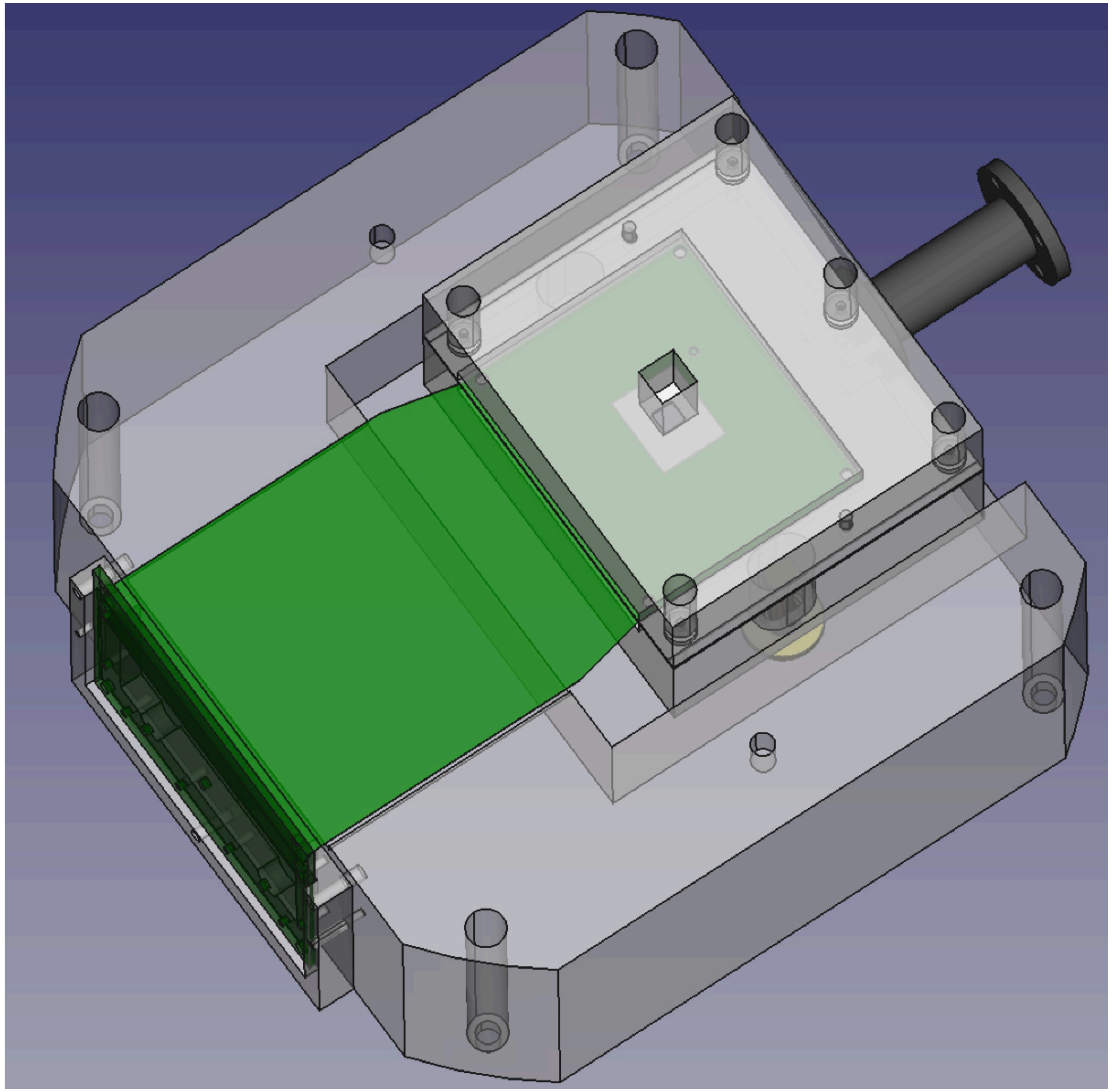
65 mm
glue to the ceramics

interface w flex
Al wire bonding

connector to
flange feedthrough

E, W, N : Switcher-S
S : VERITAS 2.1

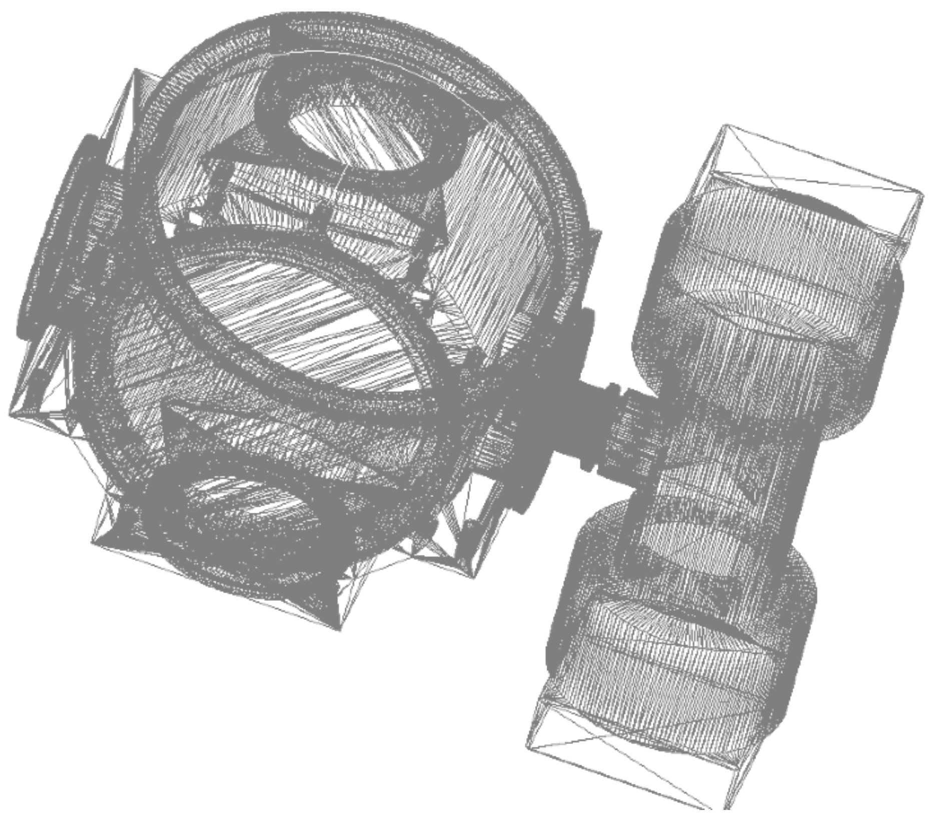
Image of the detector assembly

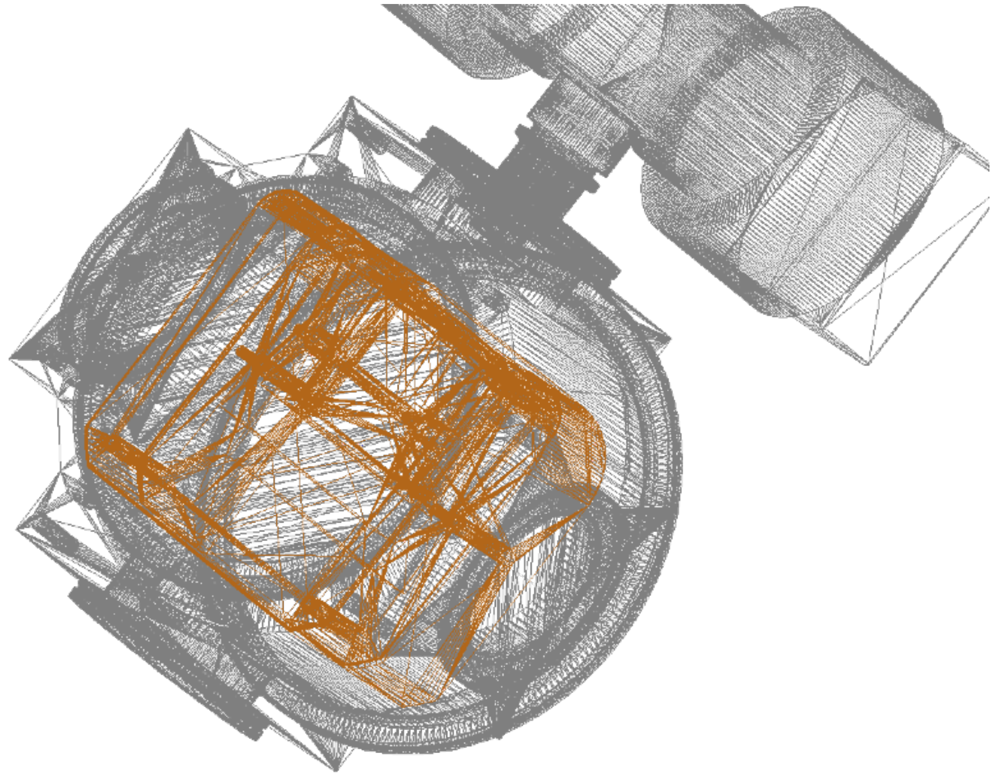


To be assembled in July-August 2018

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.

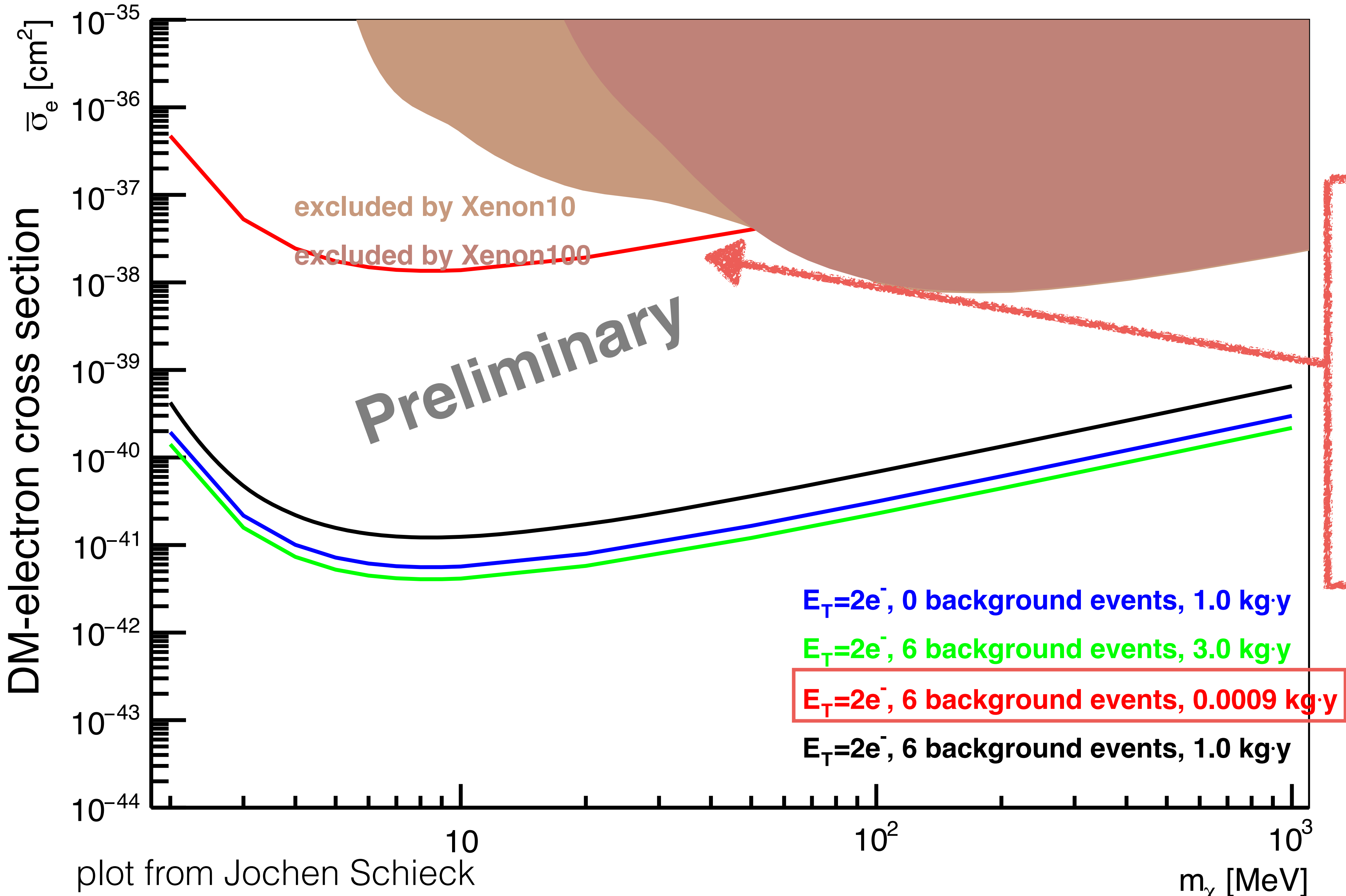




- geometry of the setup from vacuum parts 3D model;
- primitive geometrical shape for DEPFET :
  75 um x 75 um x 450 um bulk pixel, 64 by 64 matrix;
- to check response to X-rays, ambient gamma, cosmic charged particles, and neutrons;

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

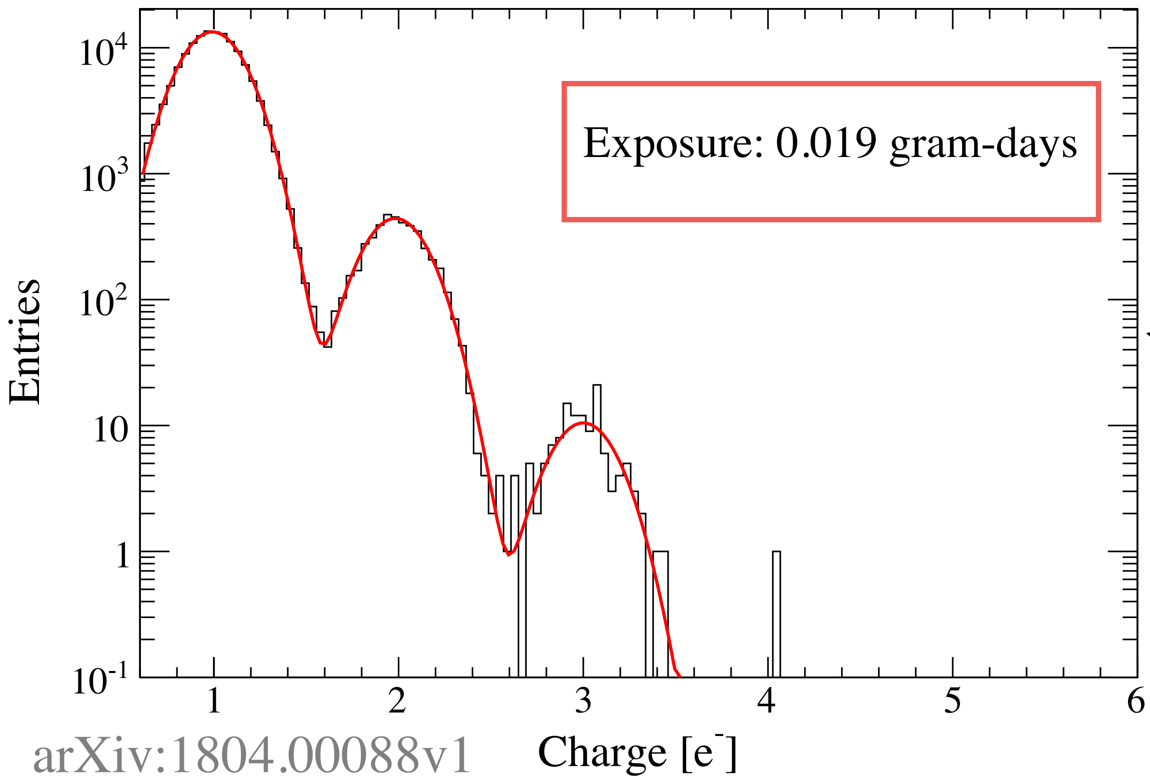


physics run goal
0.9 g*y

-> 40 matrices
~1 g sensitive volume

plot from Jochen Schieck

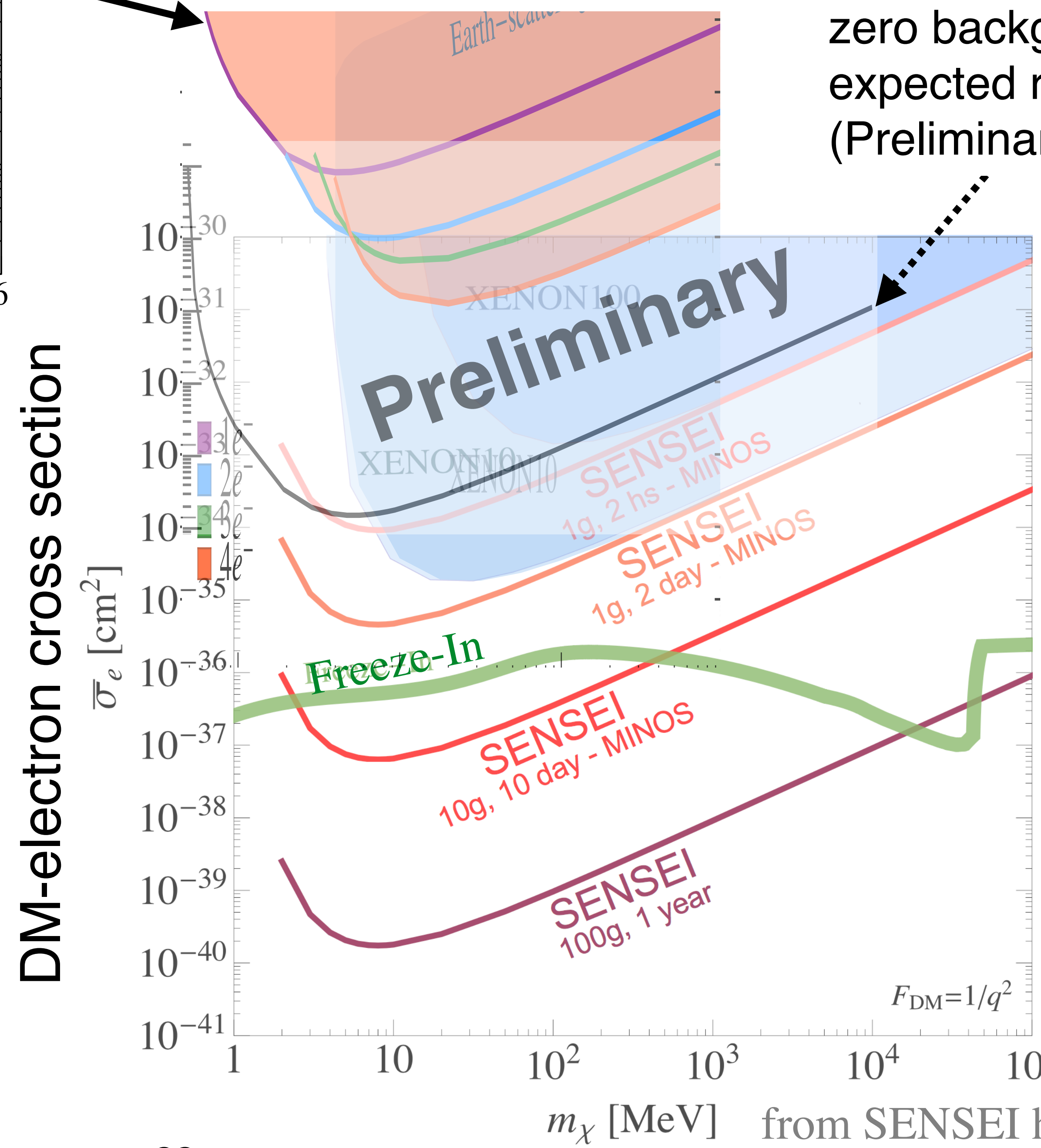
Expected 1day exposure compared to SENSEI



arXiv:1804.00088v1

SENSEI prototype physics run

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



from SENSEI homepage

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

Other topics for discussion

- connection/collaboration with VIP-2?
- VIP CCD data for DM search?
- possible application of low-noise detector

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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