DANAE

A new effort to directly search for Dark Matter with DEPFET-RNDR detectors

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15TH VIENNA CONFERENCE ON INSTRUMENTATION

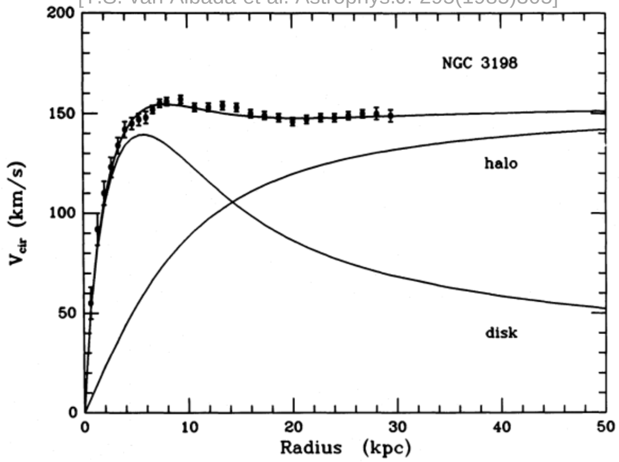
February 19, 2019

Outline

- Sub-GeV/c² dark matter:
  why is it attractive
- DEPFT-RNDR detectors:
  how do they work
- The DANAE project:
  its current status
- Physics perspective:
  what we aim for

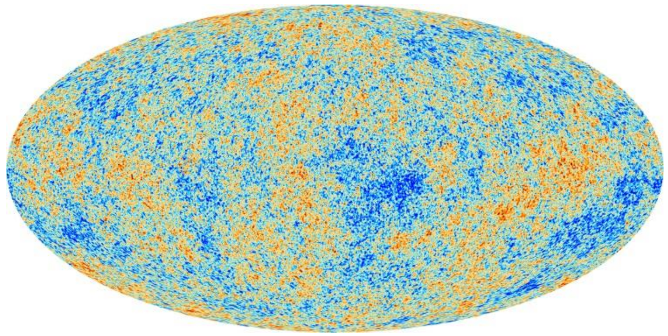
Sub-GeV/c^2 dark matter

[T.S. van Albada et al. Astrophys.J. 295(1985)305]



Several astronomical evidences for the existence of dark matter at different scales

[NASA/CXC/SAO]



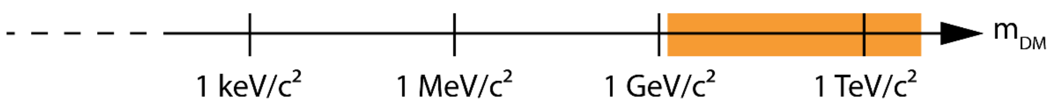
[ESA and the Planck Collaboration]

Cosmic Microwave Background
+ Big Bang Nucleosynthesis

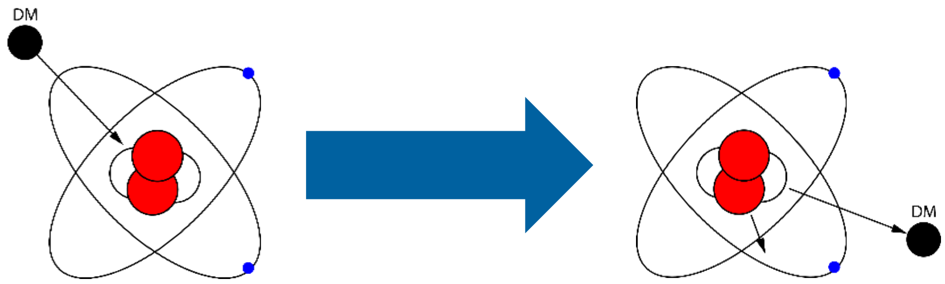
→ ~20% of Universe is Dark Matter
but no unambiguous particle candidate

WIMP dark matter

- WIMP is a classic particle candidate for DM
- Predicted particle mass 2GeV/c² .. 120TeV/c²

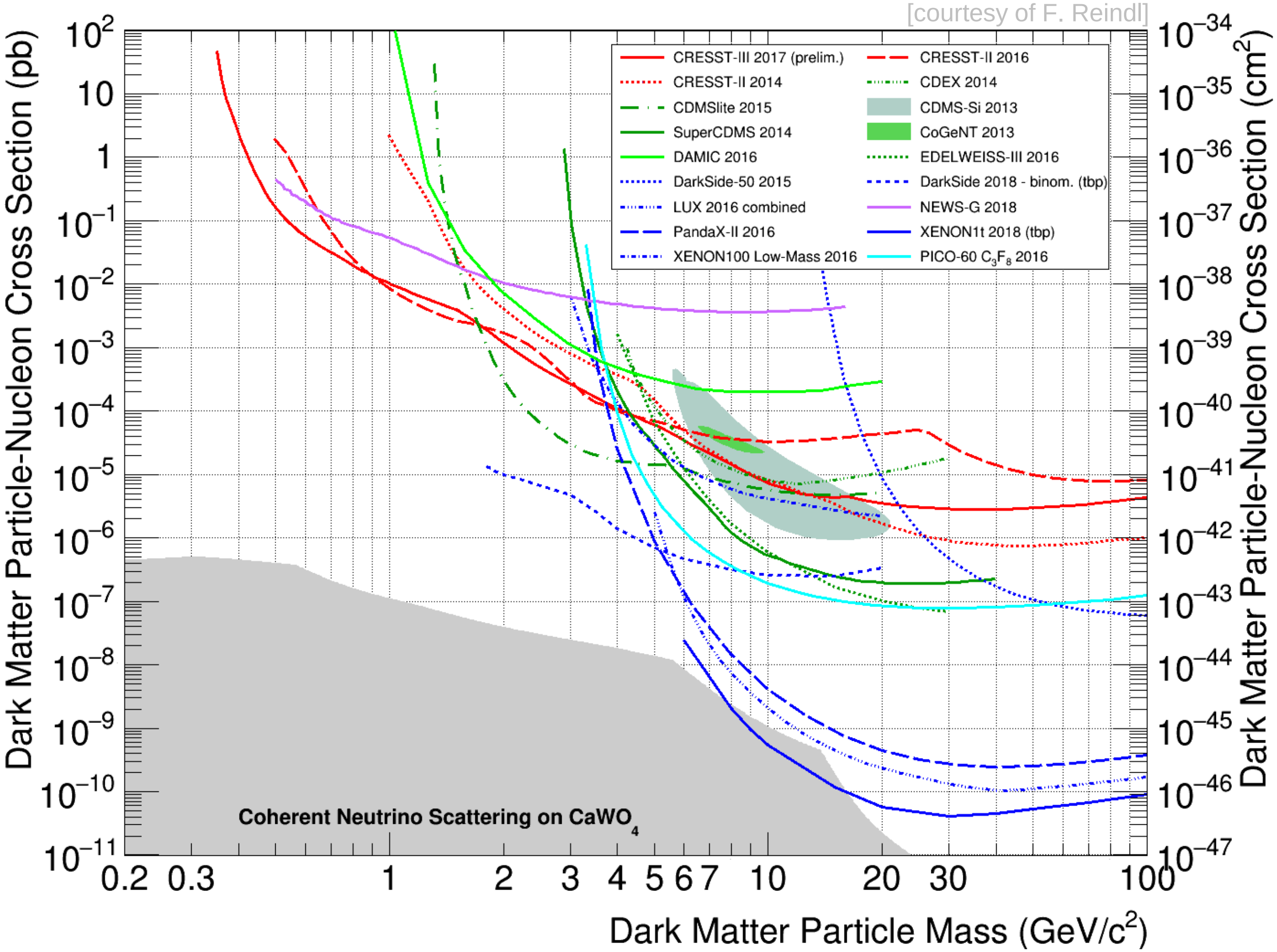


- Usual event signature in direct searches: nuclear recoils

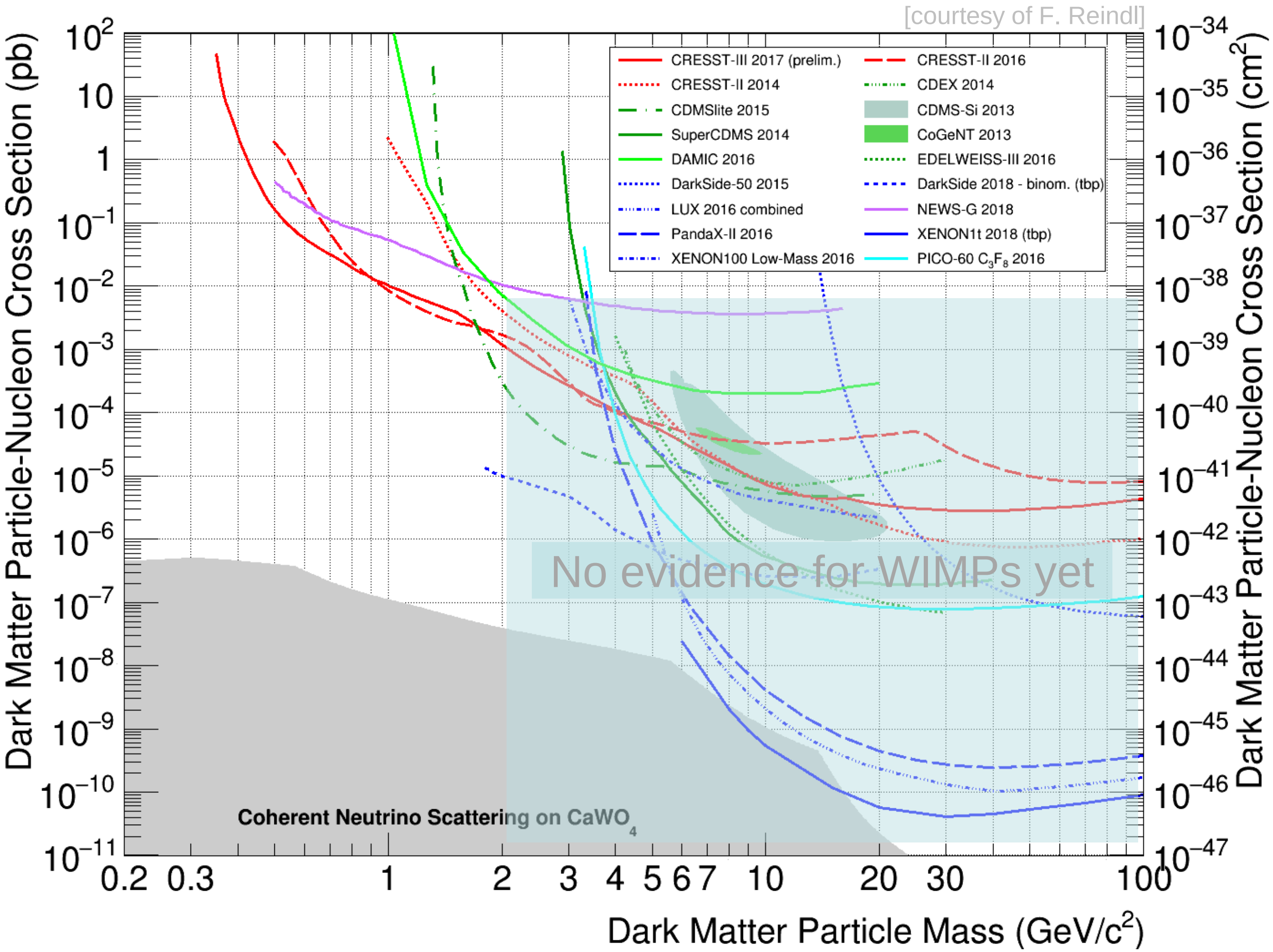


- Dominated the direct searches until recently

Landscape


[courtesy of F. Reindl]
Dark Matter Particle-Nucleon Cross Section (pb)
Dark Matter Particle-Nucleon Cross Section (cm²)
Dark Matter Particle Mass (GeV/c²)
CRESST-III 2017 (prelim.)
CRESST-II 2016
CRESST-II 2014
CDEX 2014
CDMSlite 2015
CDMS-Si 2013
SuperCDMS 2014
CoGeNT 2013
DAMIC 2016
EDELWEISS-III 2016
DarkSide-50 2015
DarkSide 2018 - binom. (tbp)
LUX 2016 combined
NEWS-G 2018
PandaX-II 2016
XENON1t 2018 (tbp)
XENON100 Low-Mass 2016
PICO-60 C3F8 2016
Coherent Neutrino Scattering on CaWO4

Landscape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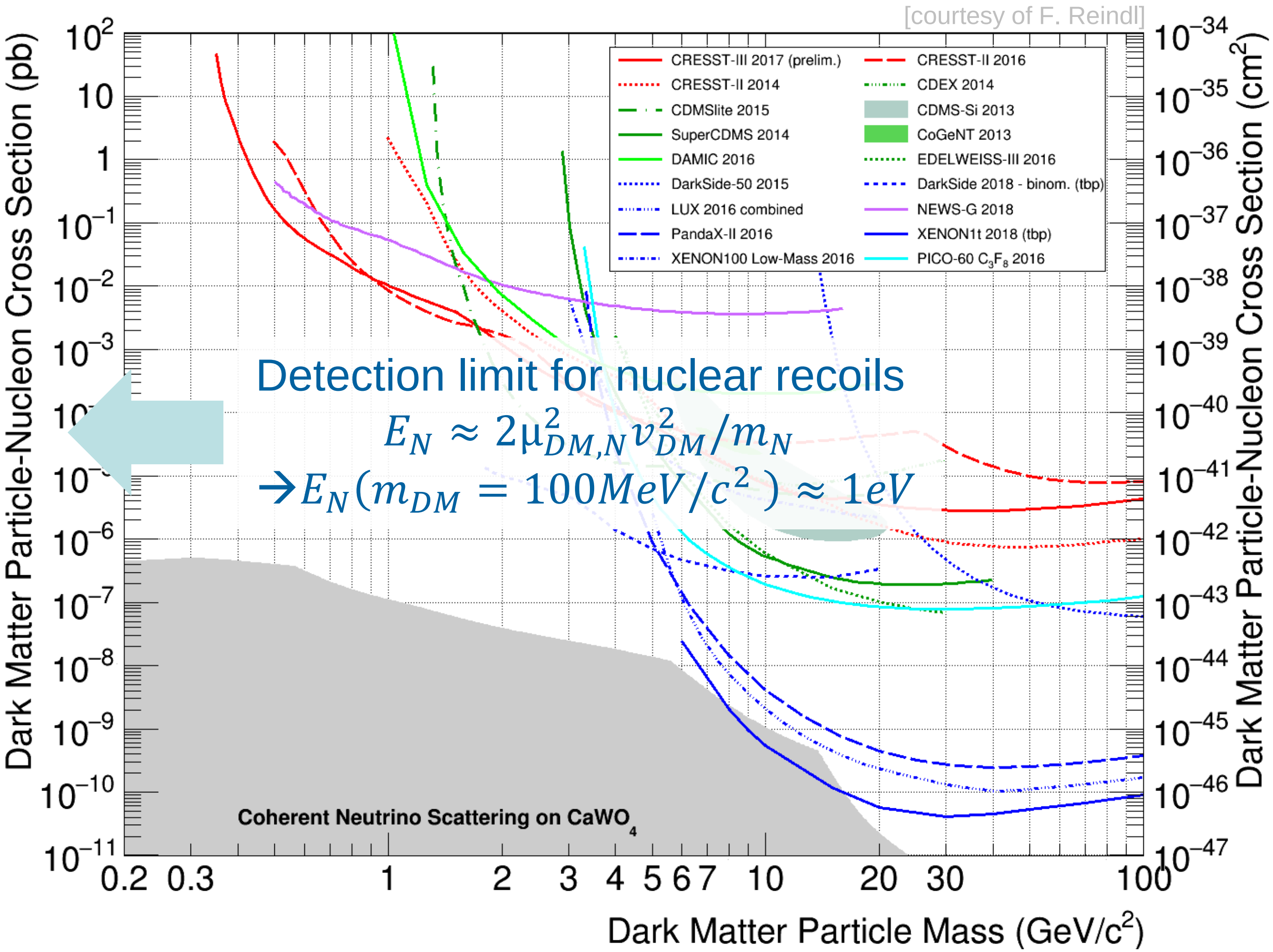
No evidence for WIMPs yet
Coherent Neutrino Scattering on CaWO4

Landscape

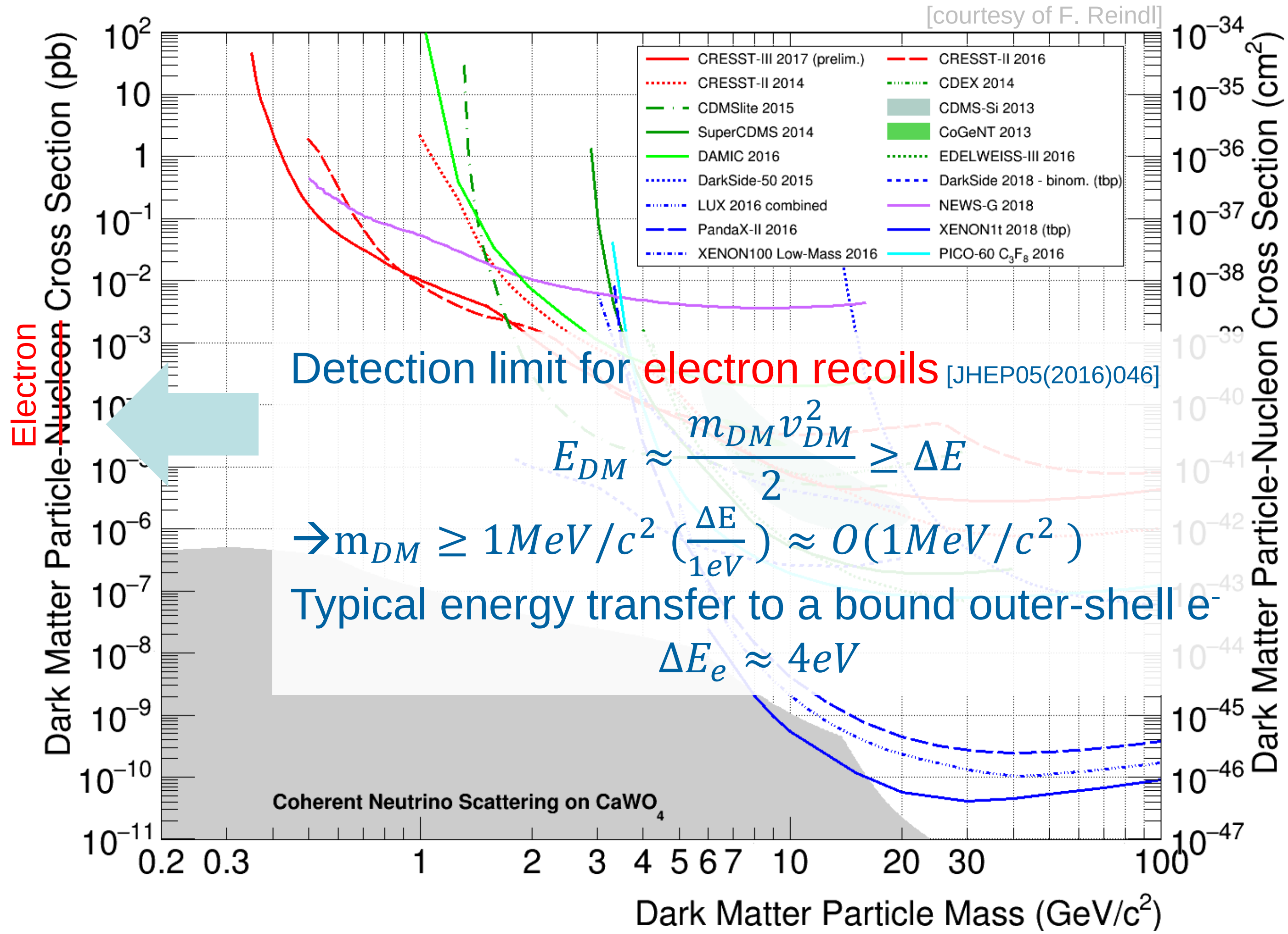


Detection limit for nuclear recoils

$$E_N \approx 2\mu_{DM,N}^2 v_{DM}^2 / m_N$$

$$\rightarrow E_N(m_{DM} = 100 MeV/c^2) \approx 1eV$$

Landscape



Detection limit for electron recoils [JHEP05(2016)046]

$$E_{DM} \approx \frac{m_{DM} v_{DM}^2}{2} \geq \Delta E$$

$$\rightarrow m_{DM} \geq 1MeV/c^2 \left(\frac{\Delta E}{1eV}\right) \approx O(1MeV/c^2)$$

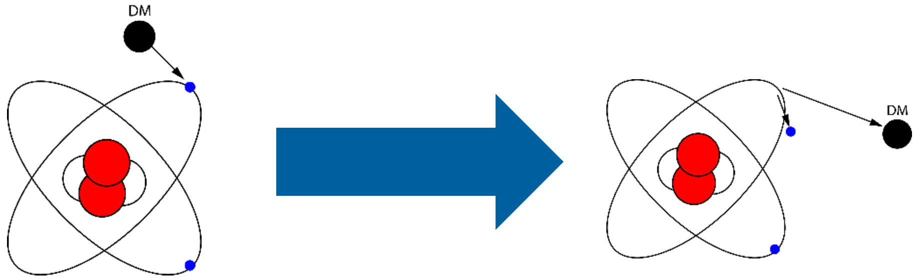
Typical energy transfer to a bound outer-shell e^-

$$\Delta E_e \approx 4eV$$

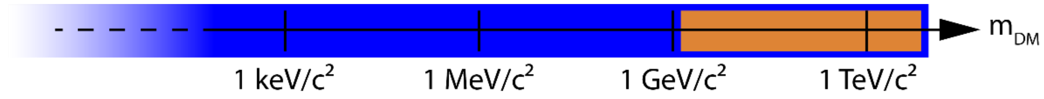
Dark sector and light dark matter

- Dark sector: interaction between DM and SM mediated by new particle(s), e.g. dark photons

- Possible event signature in direct searches: electron scattering



- Mass prediction from several models (e.g. freeze-out, asymmetric DM, freeze-in, SIMP, ELDER) including keV/c² to GeV/c² scale



Target materials for e^- scattering

Active target	Detection threshold	DM mass threshold	Status	Time scale
Noble liquids (e.g. Xe, Ar, Ne)	~ 10 eV	~ 5 MeV/c^2	Done with data; improvements possible	existing
Semiconductors (e.g. Ge, Si)	~ 1 eV	~ 200 keV/c^2	(E_{th} ~ 40 eV SuperCDMS, DAMIC) E_{th} ~ 1eV SENSEI, DANAE R&D	~ 1-2 yr
Scintillators (e.g. CsI, NaI, …)	~ 1 eV	~ 200 keV/c^2	R&D required	$\lesssim$ 5 yr
Superfluid (e.g. He)	~ 1 eV	~ 1 MeV/c^2	R&D required unknown background	$\lesssim$ 5 yr
Superconductor (e.g. Al)	~ 1 meV	~ 1 keV/c^2	R&D required unknown background	~ 10-15 yr

[arXiv:1608.08632]

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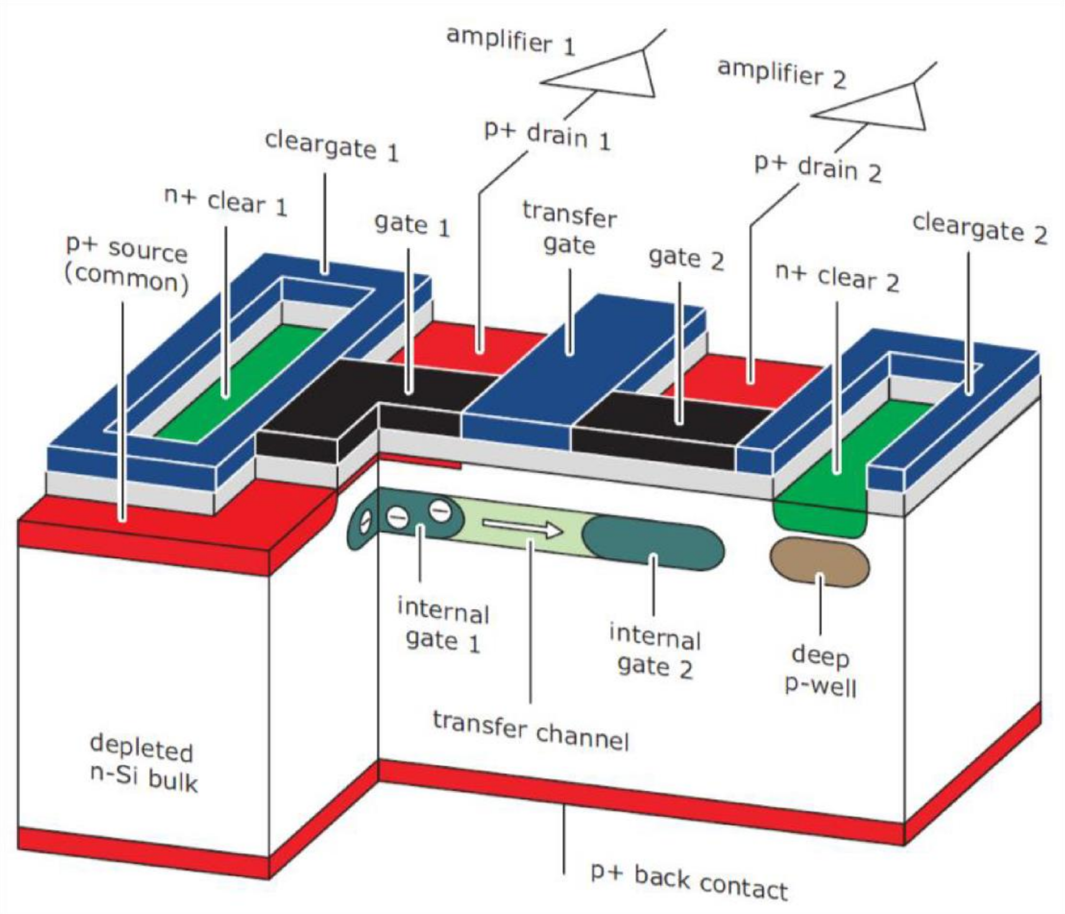
Single DM-e^- interactions:
→ < $1e^-$ RMS noise level

[arXiv:1608.08632]

DEPFET-RNDR detectors

DEPFET-RNDR

Depleted **P**-channel **F**ield **E**ffect **T**ransistor with **R**epetitive **N**on **D**estructive **R**eadout



DEPFET-RNDR „super-pixel“ [Eur. Phys. J. C77.12(2017)279]

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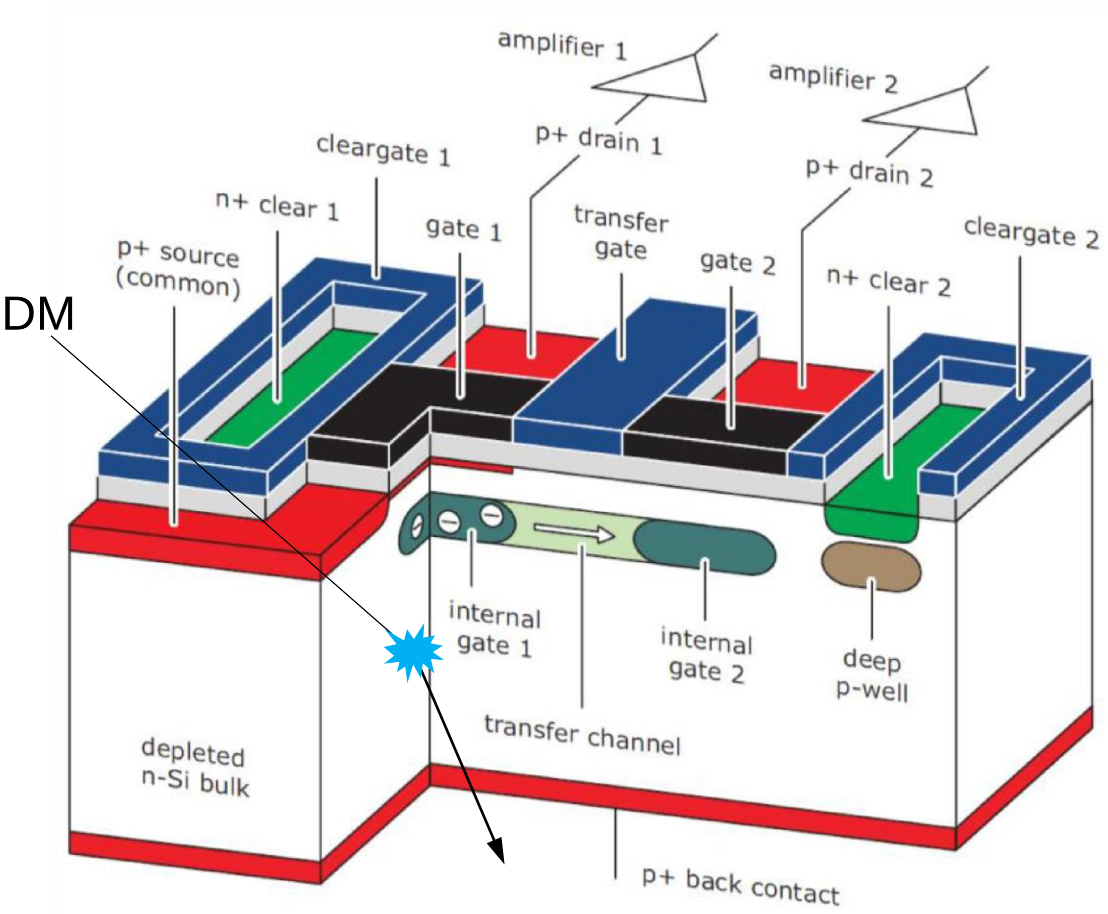
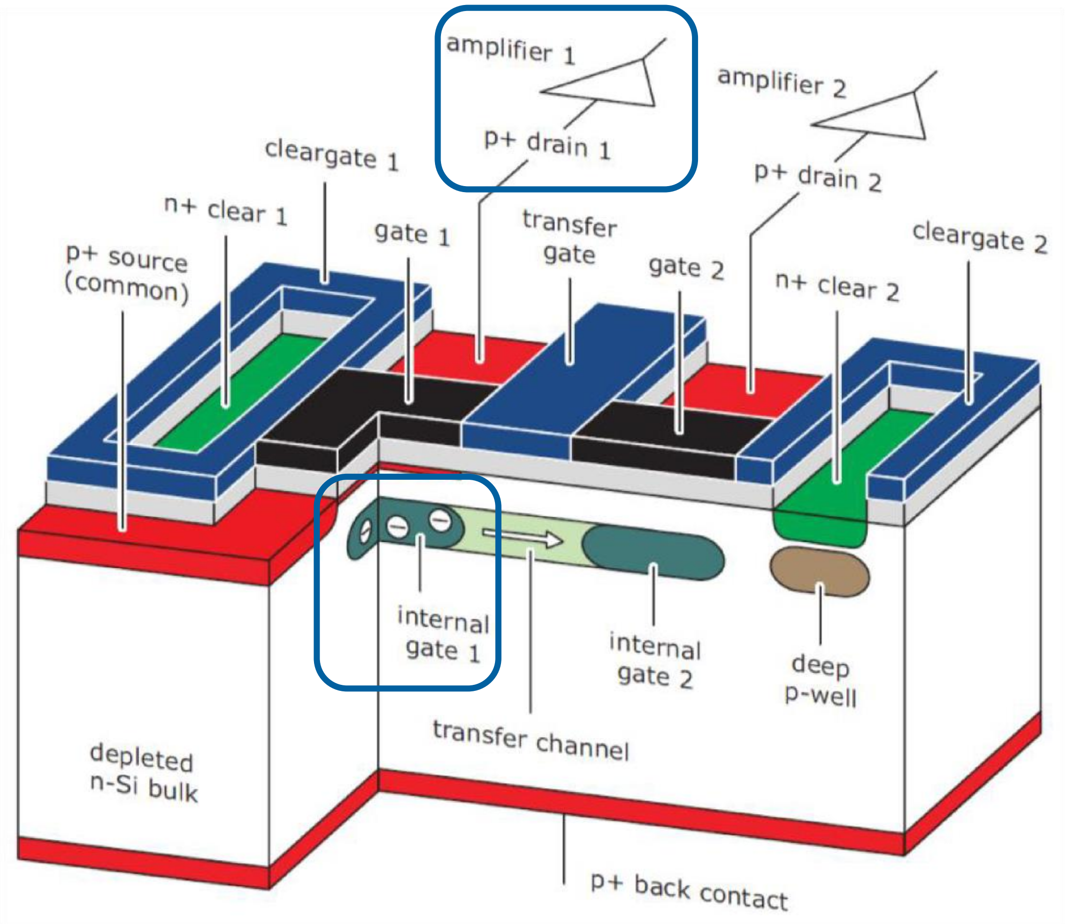
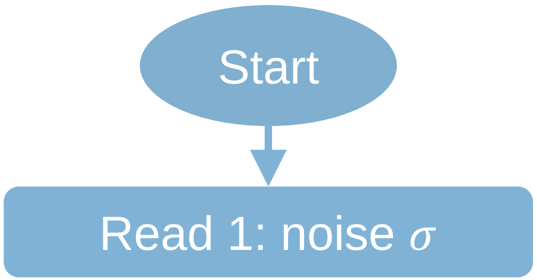


DEPFET-RNDR „super-pixel" [Eur. Phys. J. C77.12(2017)279]

DEPFET-RNDR

Depleted P-channel Field Effect Transistor with Repetitive Non Destructive Readout





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DEPFET-RNDR

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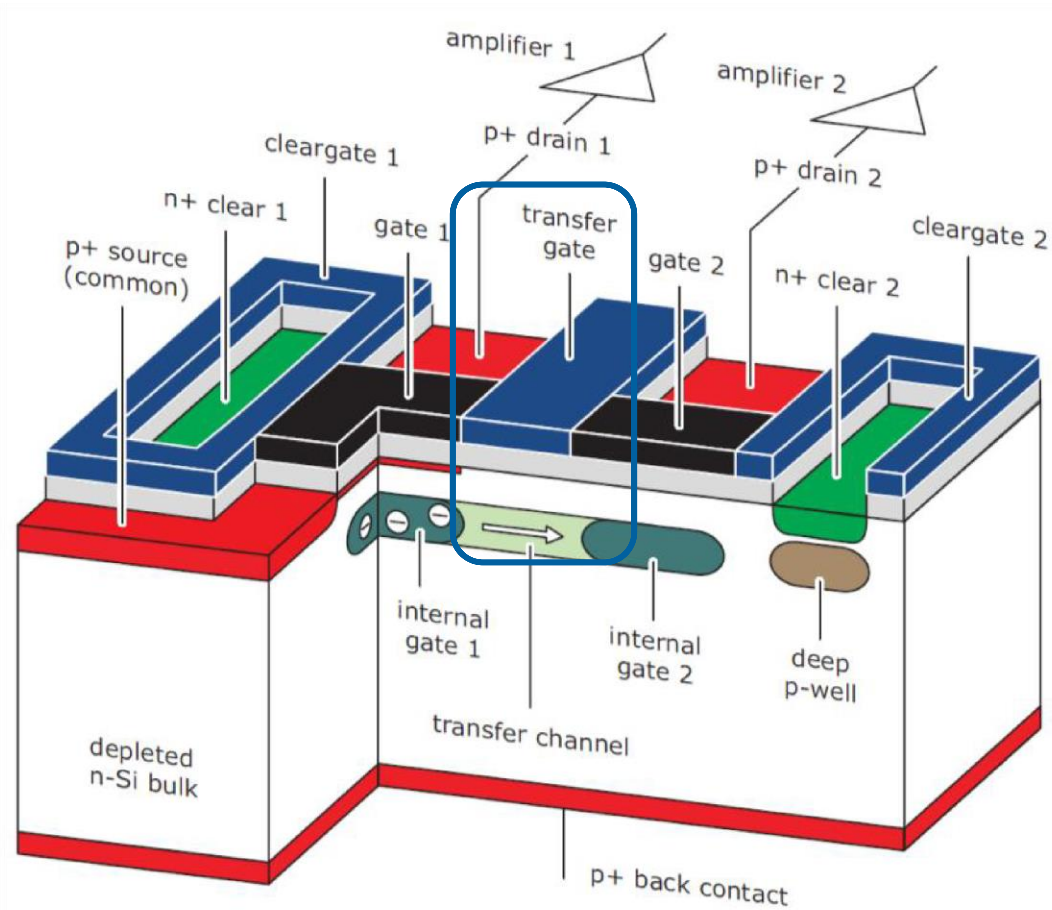

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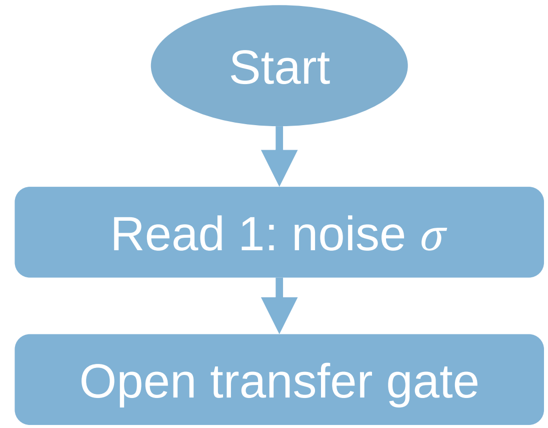
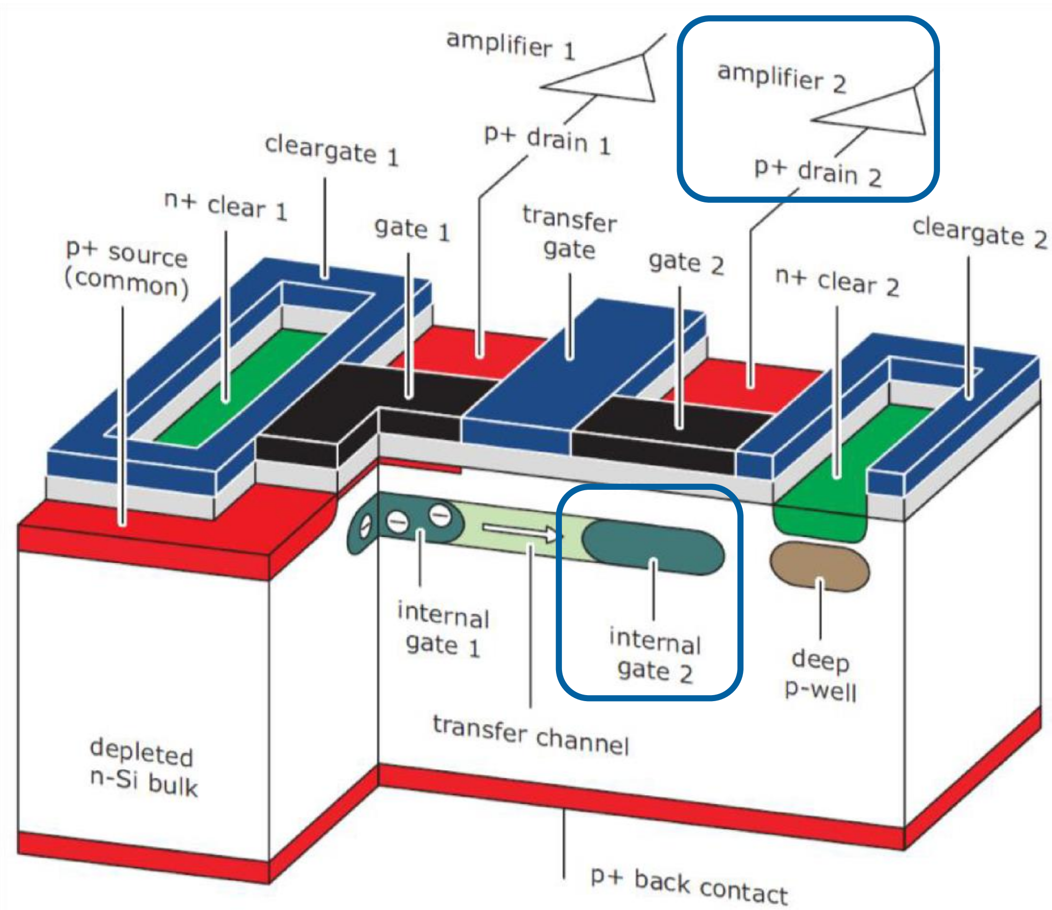
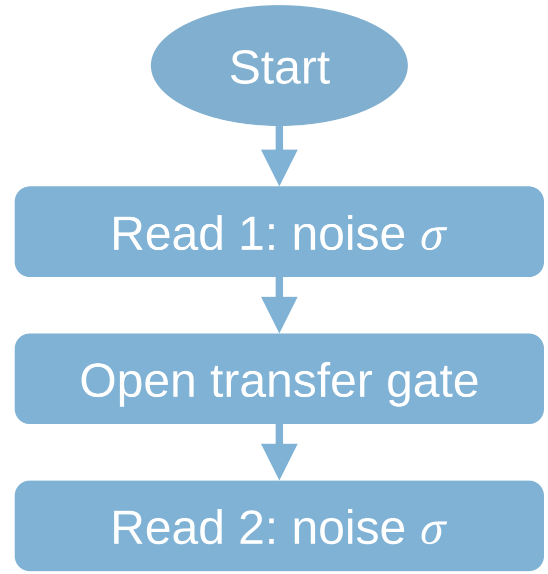


DEPFET-RNDR

<u>De</u>pleted <u>P</u>-channel <u>F</u>ield <u>E</u>ffect <u>T</u>ransistor with <u>R</u>epetitive <u>N</u>on <u>D</u>estructive <u>R</u>eadout





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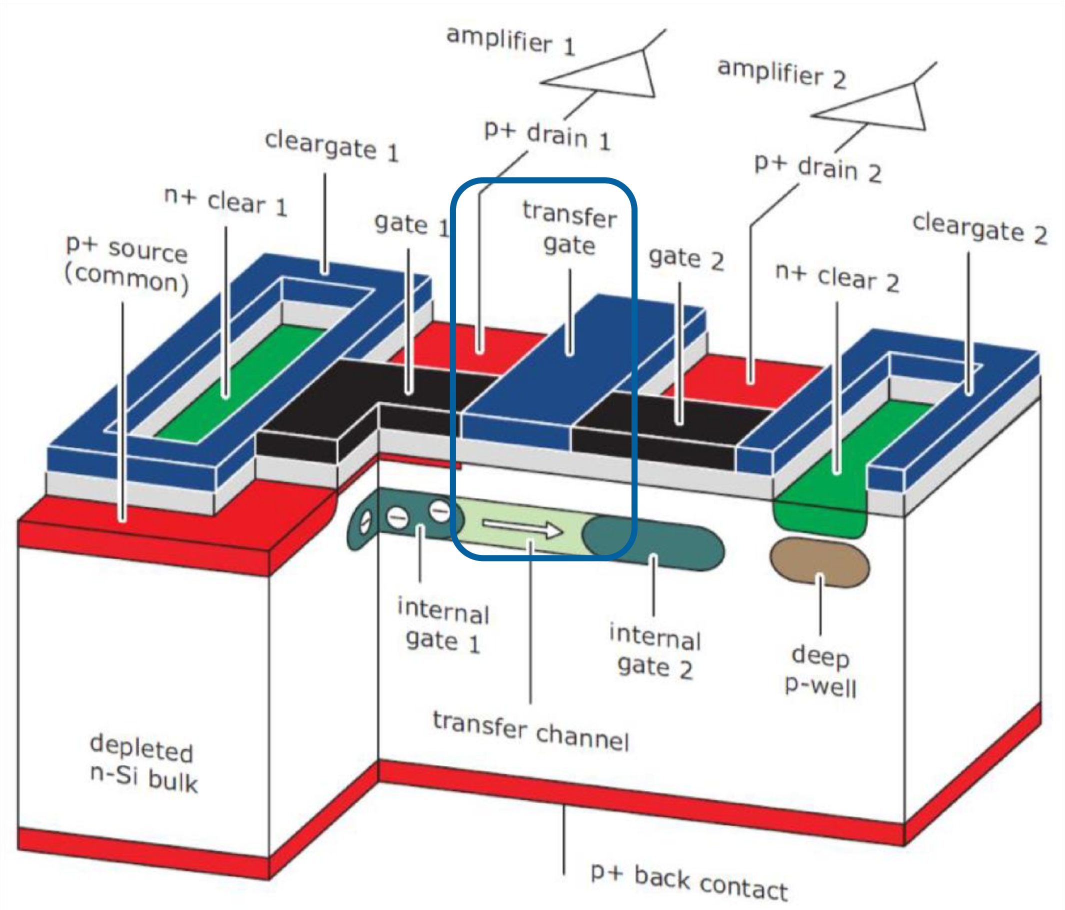

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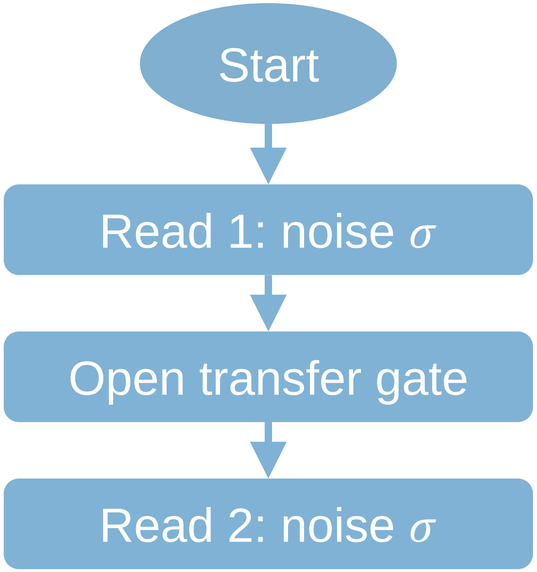

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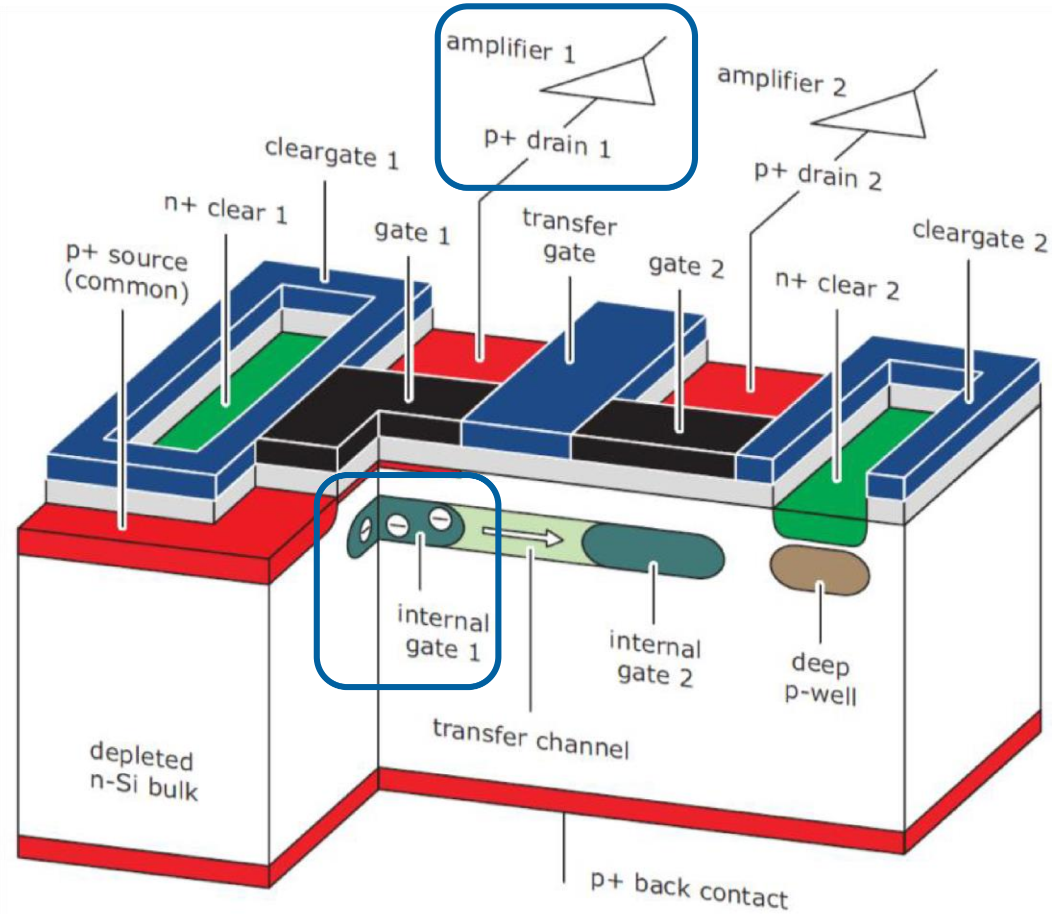

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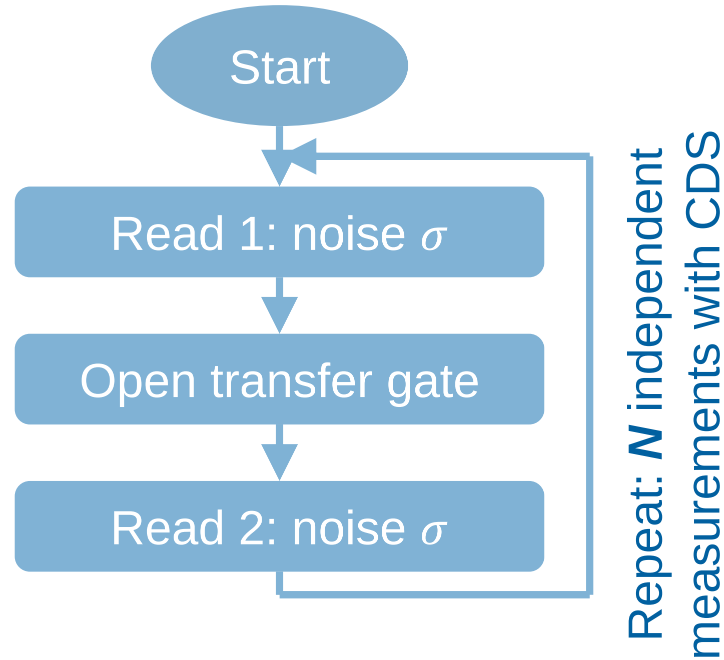

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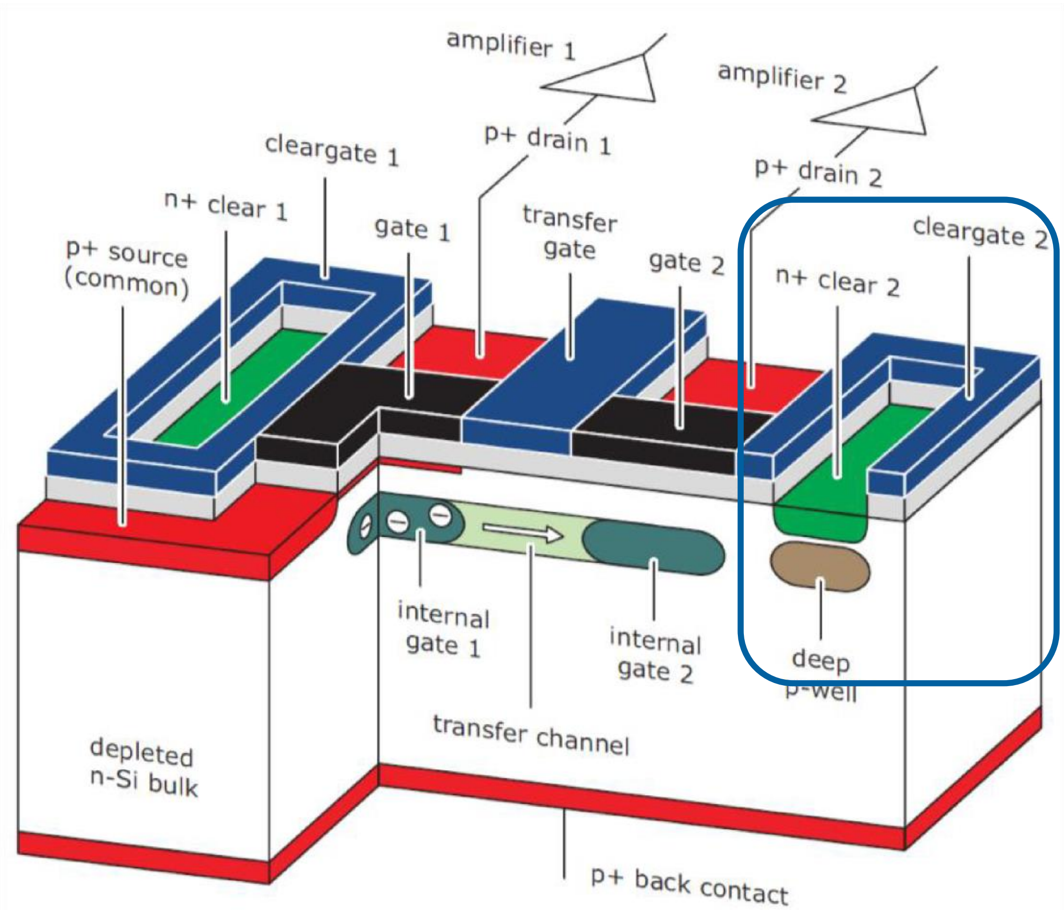

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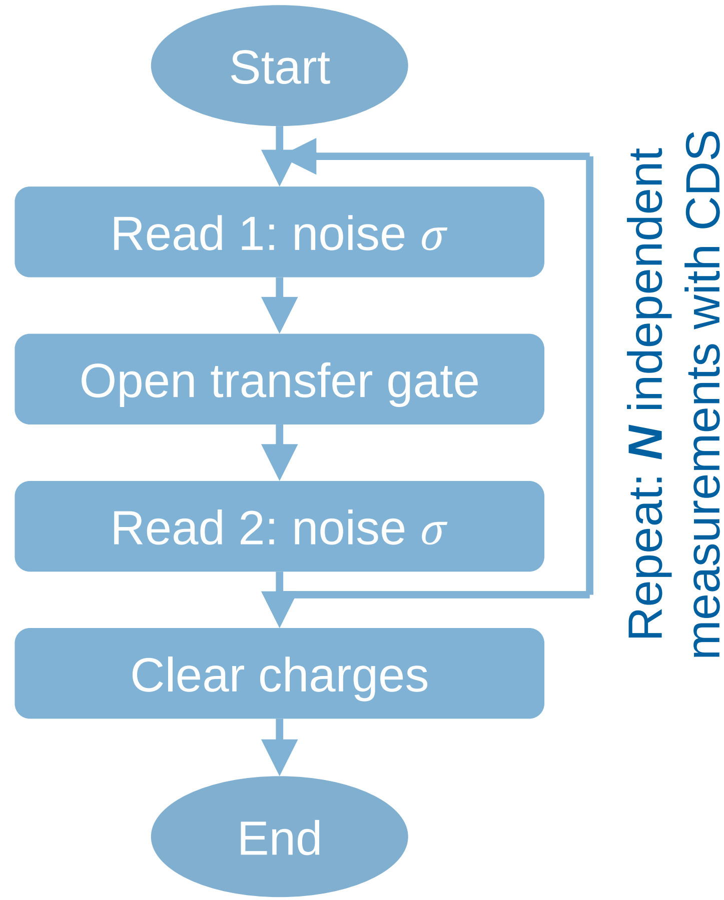

Effective noise: $\sigma_{eff} = \sigma/\sqrt{N}$

DEPFET-RNDR

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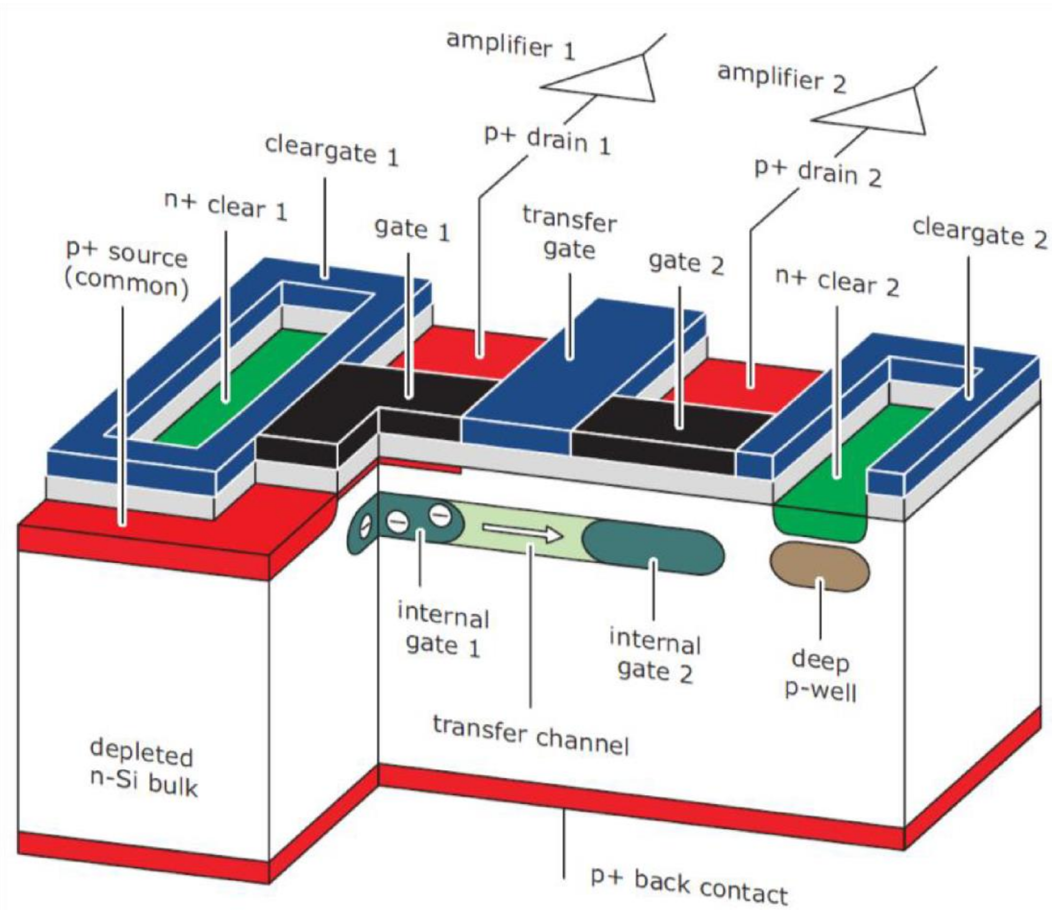

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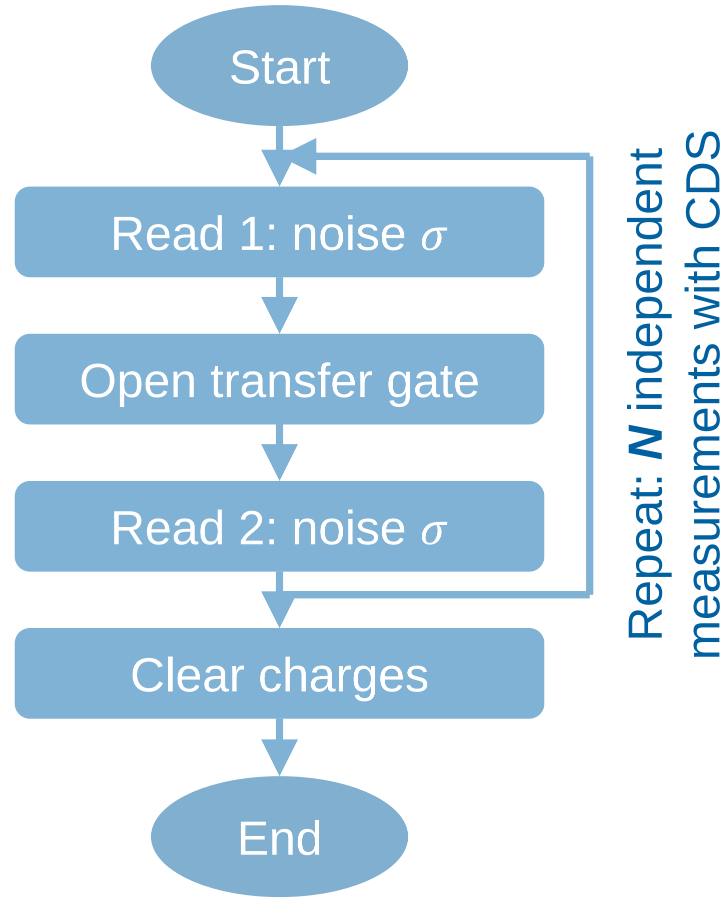
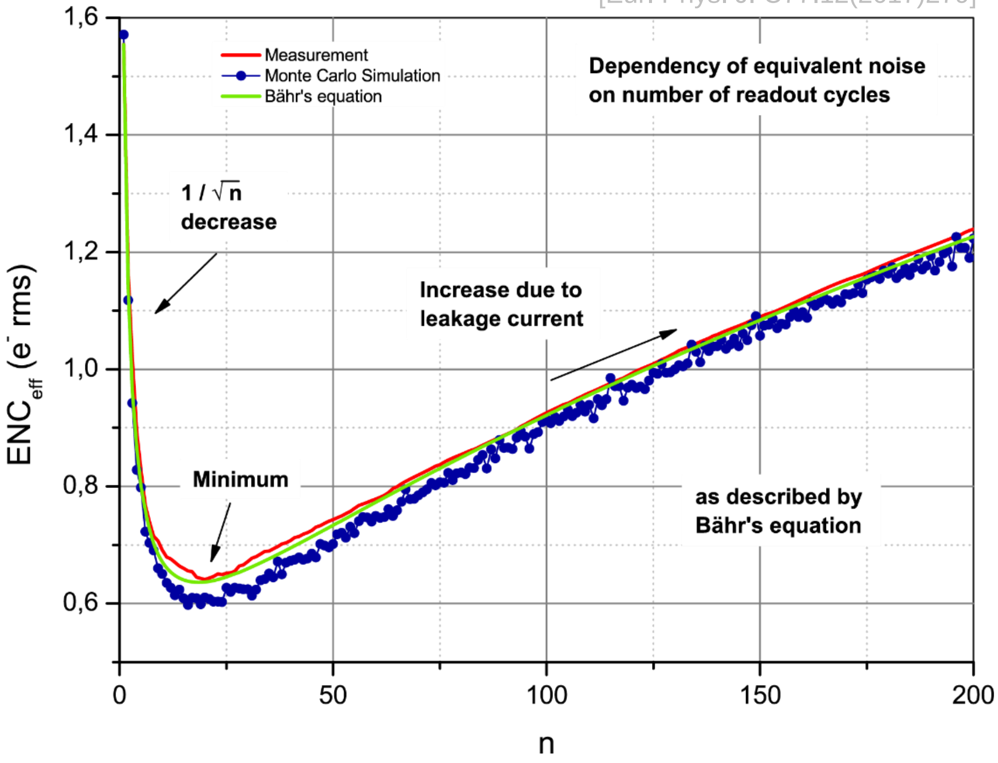


Effective noise: $\sigma_{eff} = \sigma/\sqrt{N}$

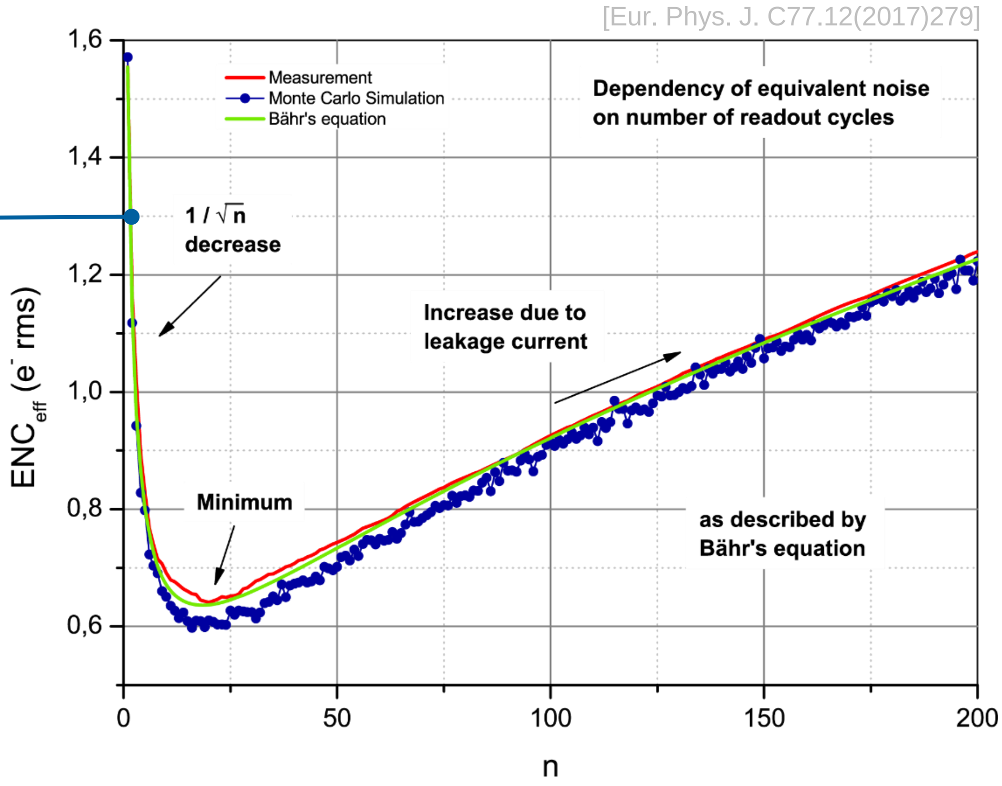
DEPFET-RNDR single pixel performance

[Eur. Phys. J. C77.12(2017)279]



DEPFET-RNDR single pixel performance

$\sigma_{eff} \sim 1/\sqrt{N}$ confirmed



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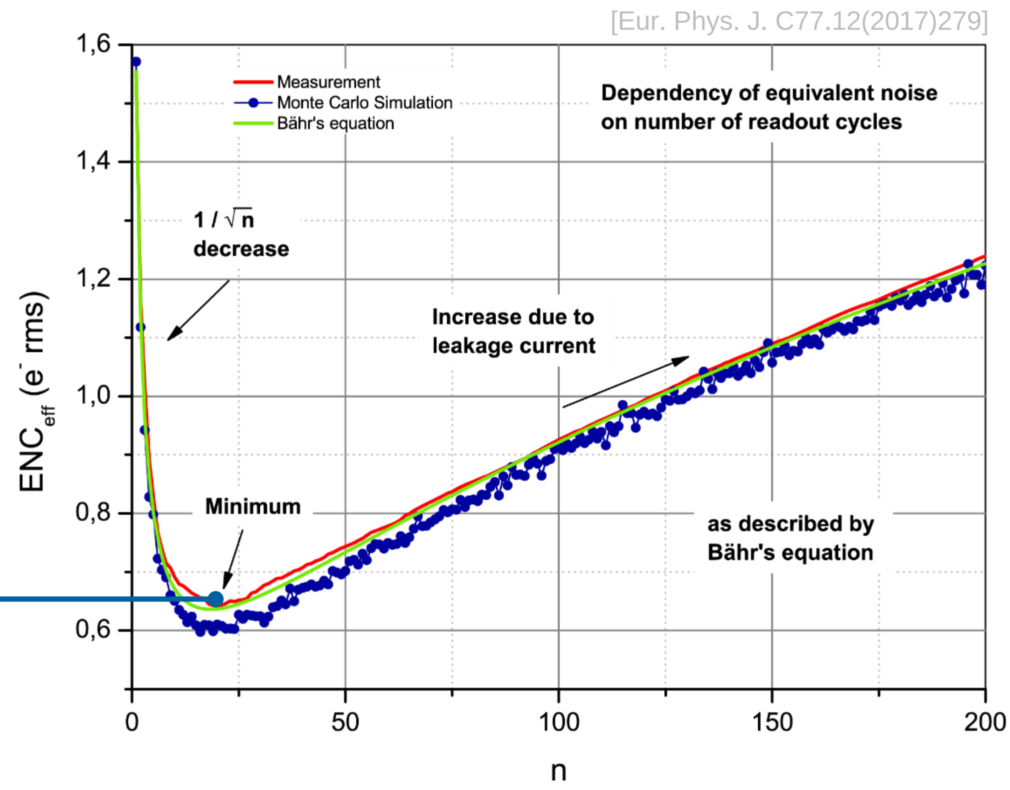
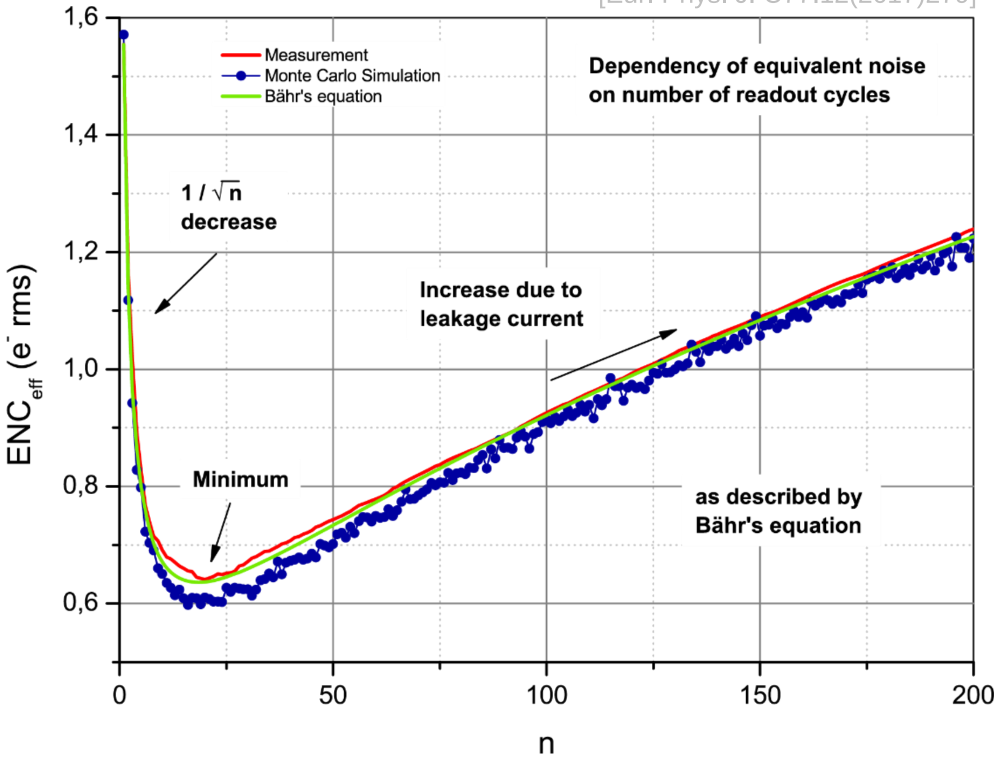


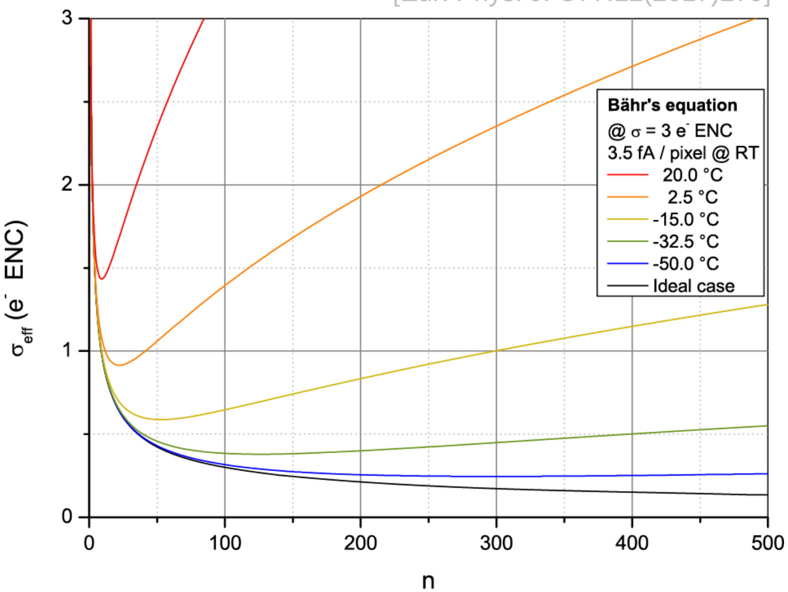
Minimal noise limited by leakage current @ 233K (-40°C)

DEPFET-RNDR single pixel performance

[Eur. Phys. J. C77.12(2017)279]



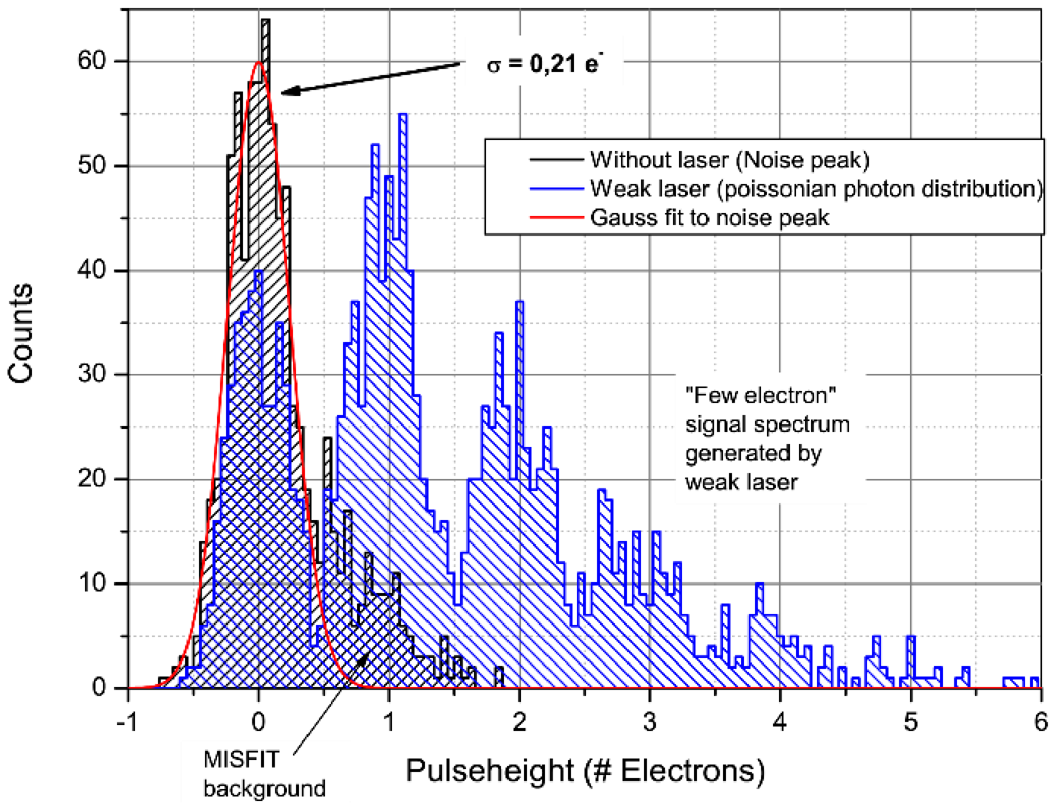
[Eur. Phys. J. C77.12(2017)279]



Predicted temperature dependence (only DC from thermal excitation)
- to be verified

DEPFET-RNDR single pixel performance

[Eur. Phys. J. C77.12(2017)279]



Single pixel DEPFET-RNDR effective noise:

$0.2e^-$ RMS @ 203K(-70°C)

→ Capable to distinguish **single electron** charge

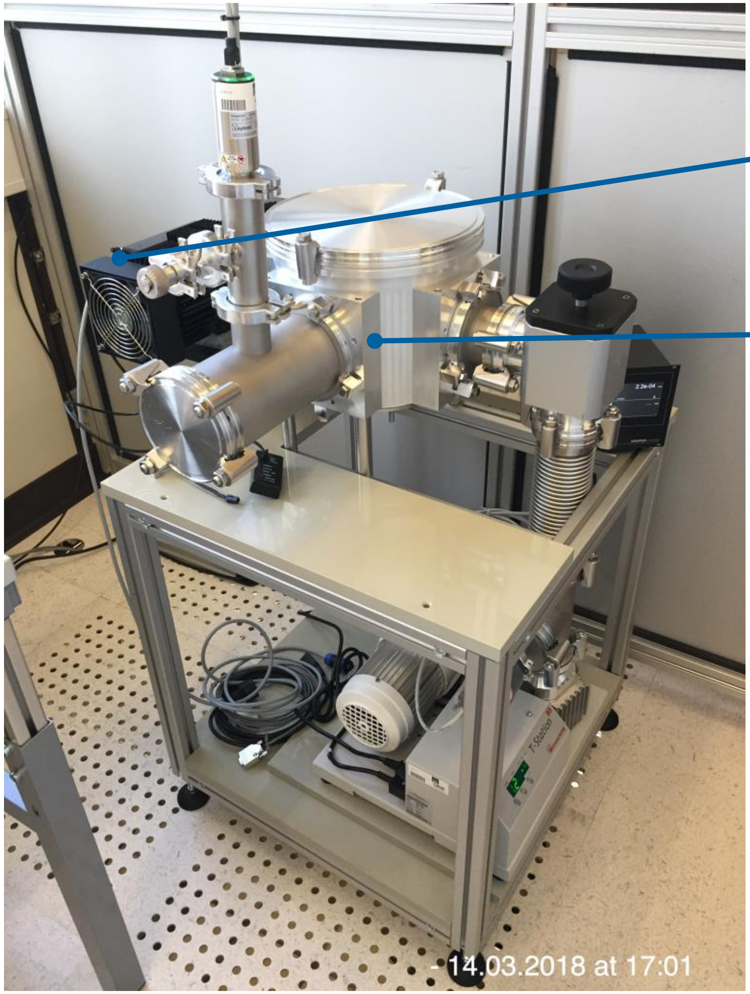
The DANAE project

Direct dArk matter search using DEPFET with repetitive-Non-destructive-readout Application Experiment

Prototype test setup

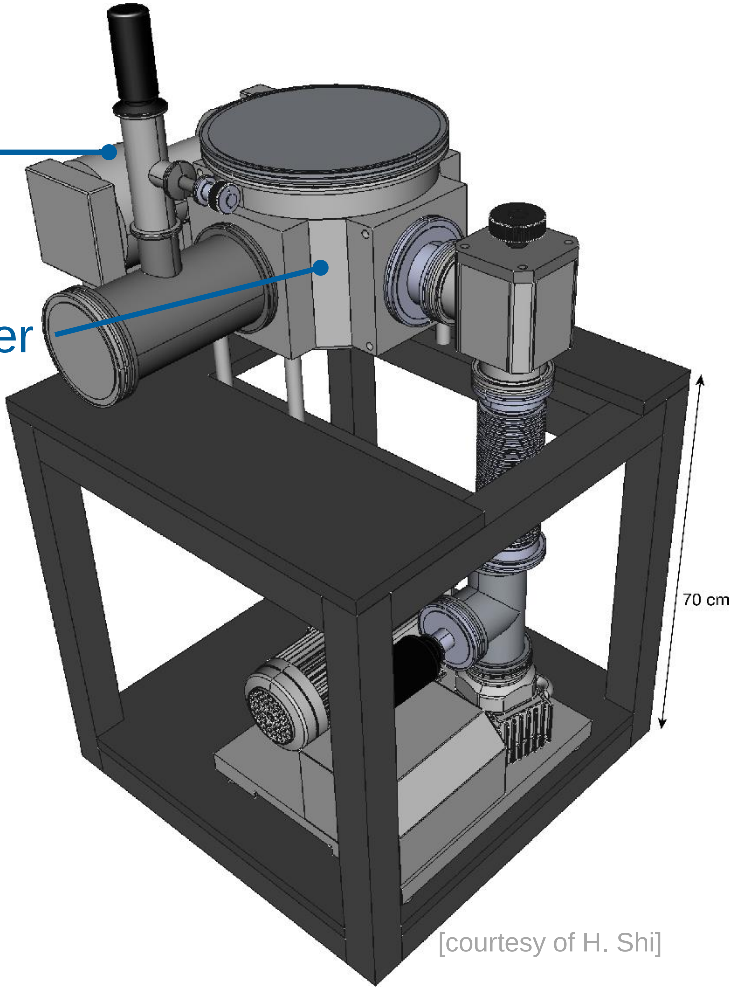
@ HLL

[courtesy of H. Shi]



Stirling-cycle cryocooler

Vacuum chamber



[courtesy of H. Shi]

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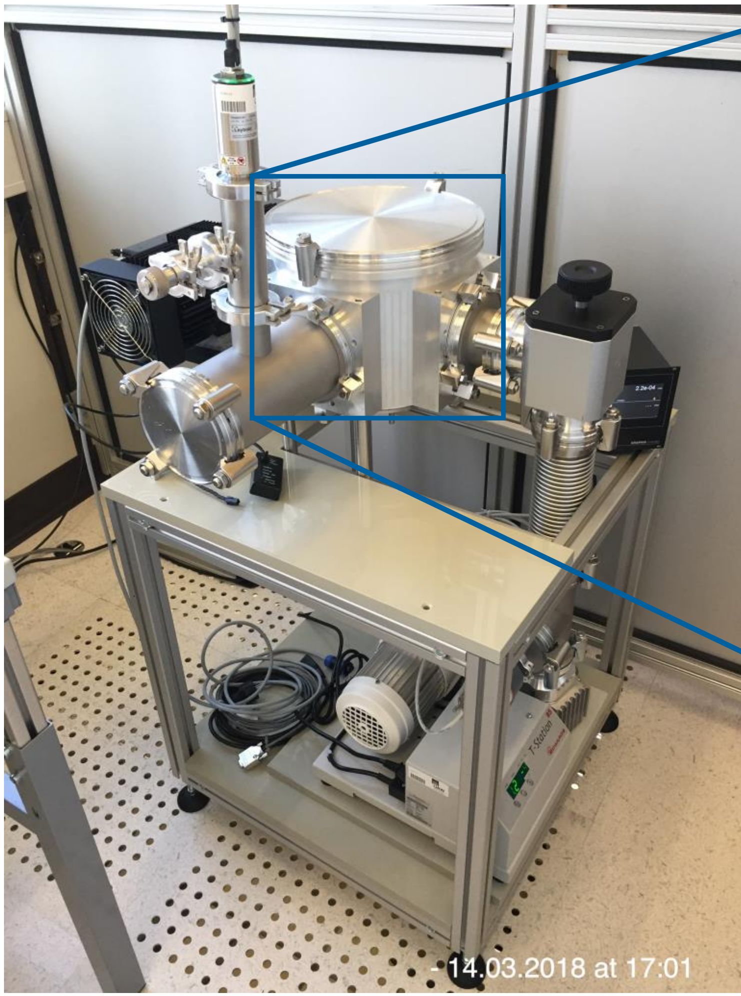
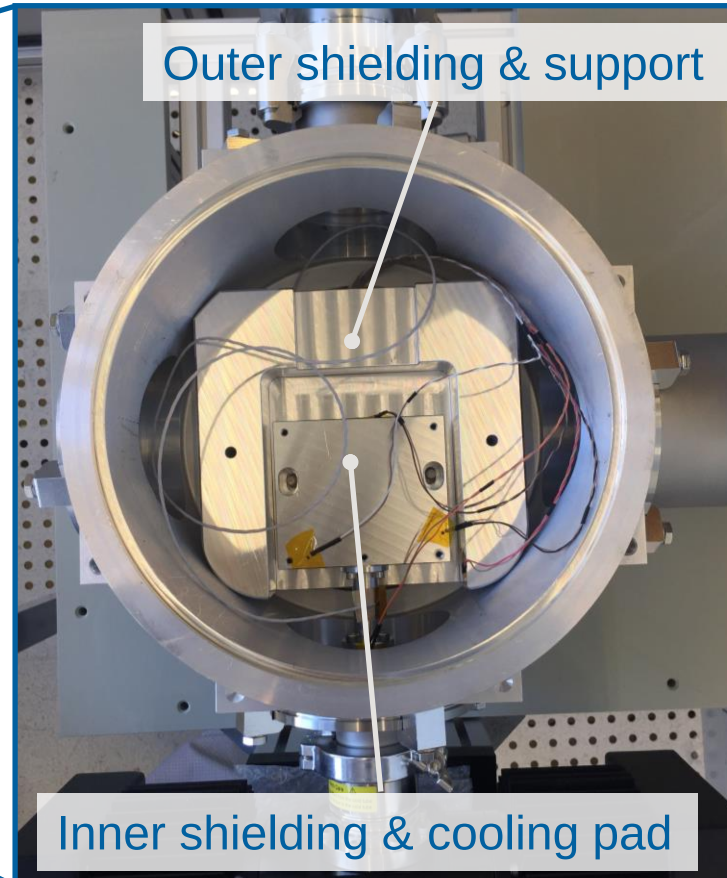




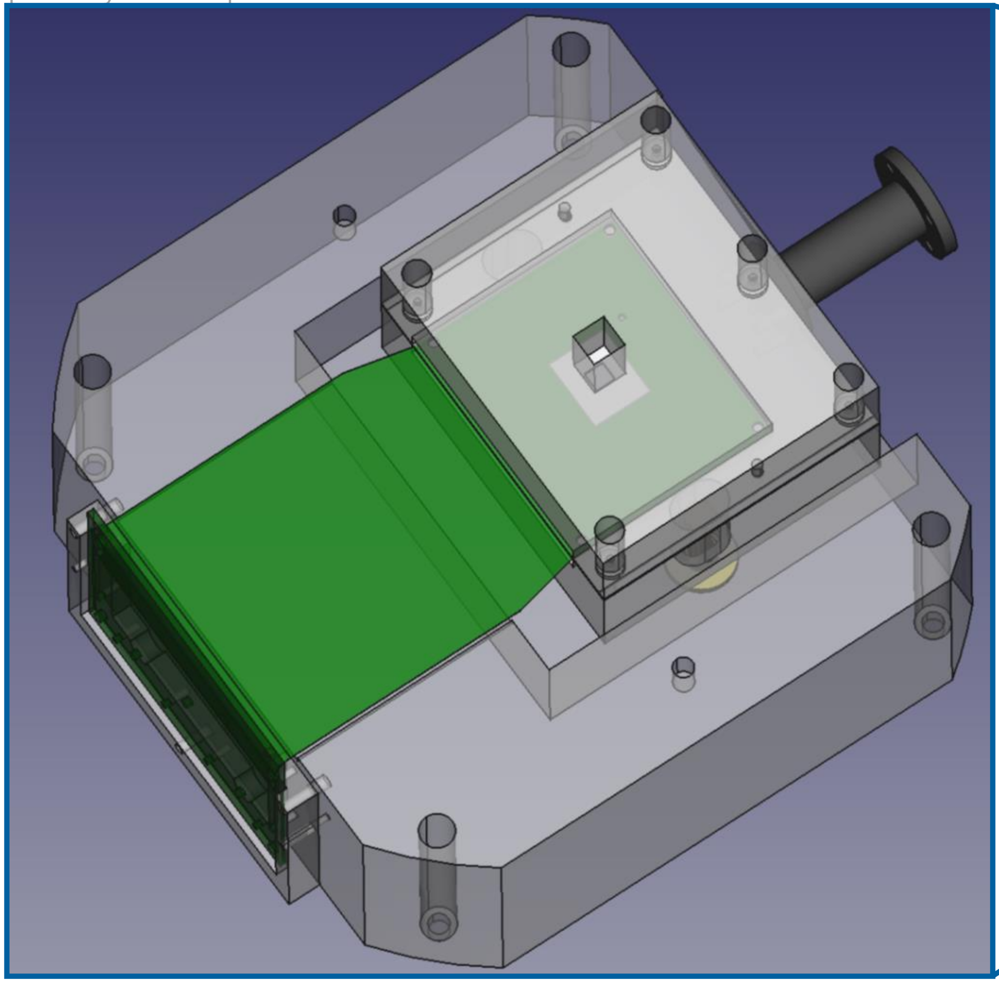
[courtesy of H. Shi]

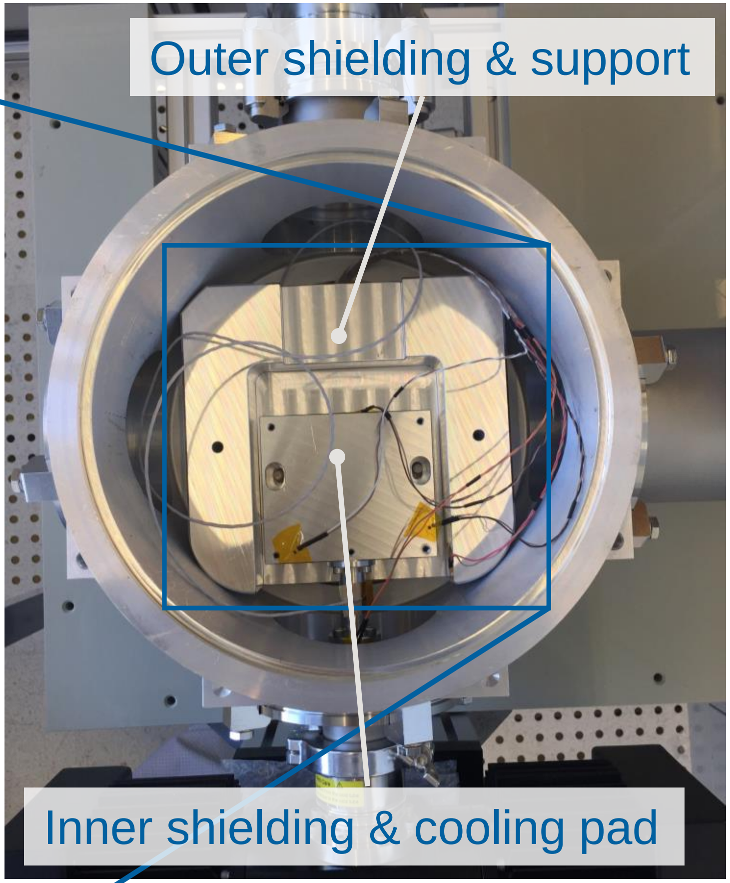
Vacuum and cooling test in March 2018:
reached 150K @ cooling pad

Prototype test setup

@ HLL

[courtesy of H. Shi]

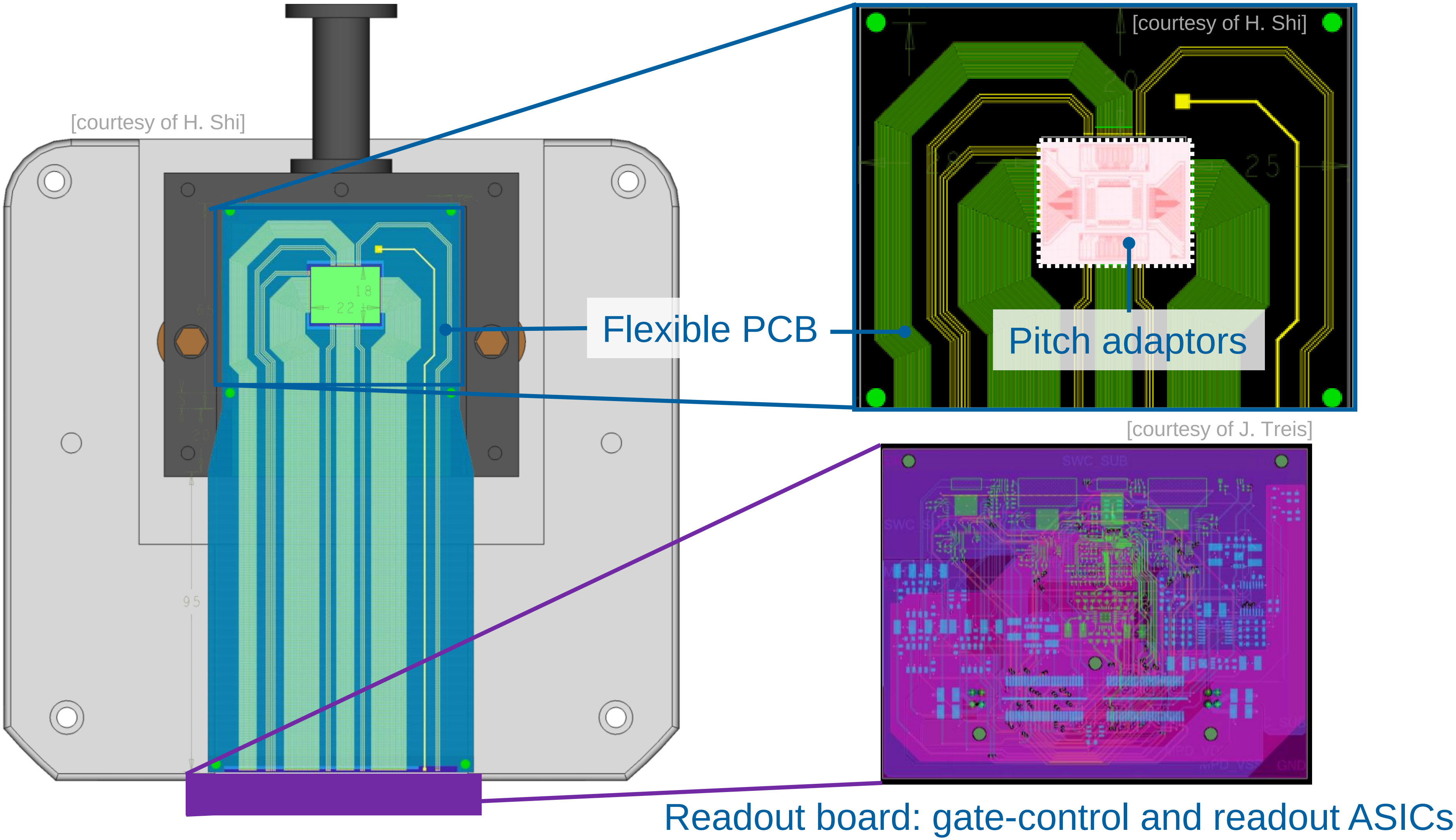




[courtesy of H. Shi]

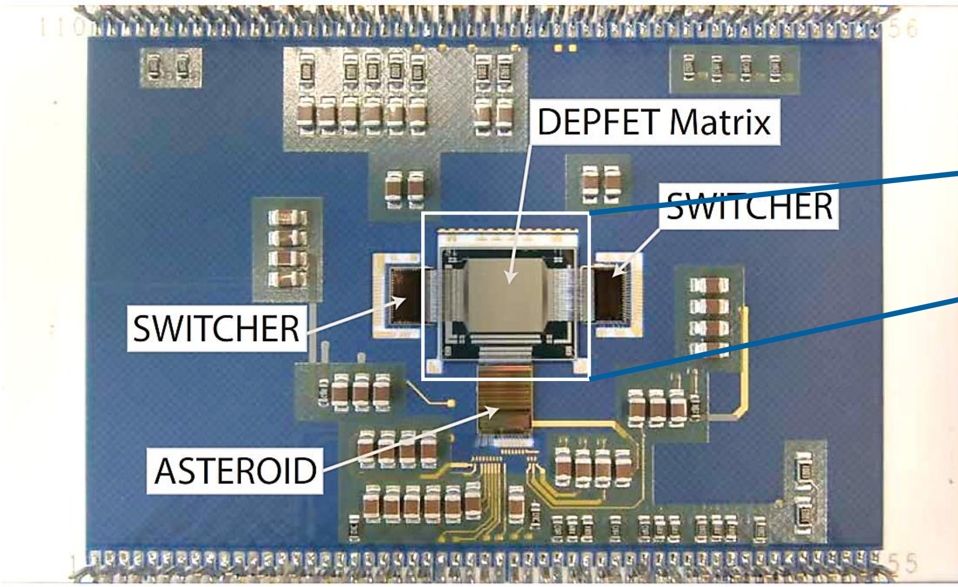
Detector assembly:
to be assembled in mid 2019

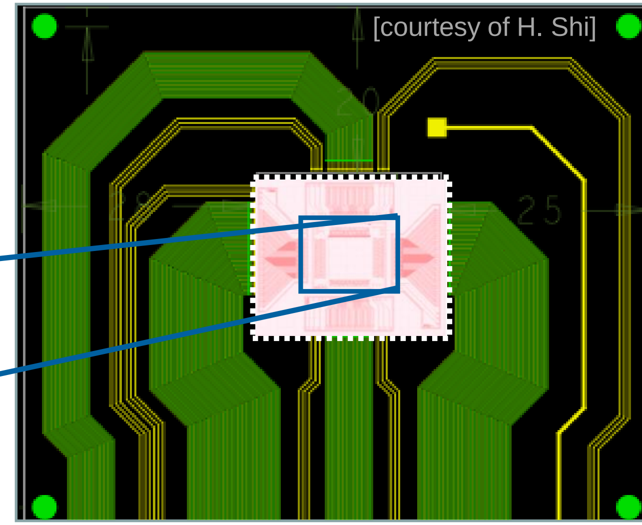
Detector control and readout electronics



Prototype detector matrix

[courtesy of J. Treis]

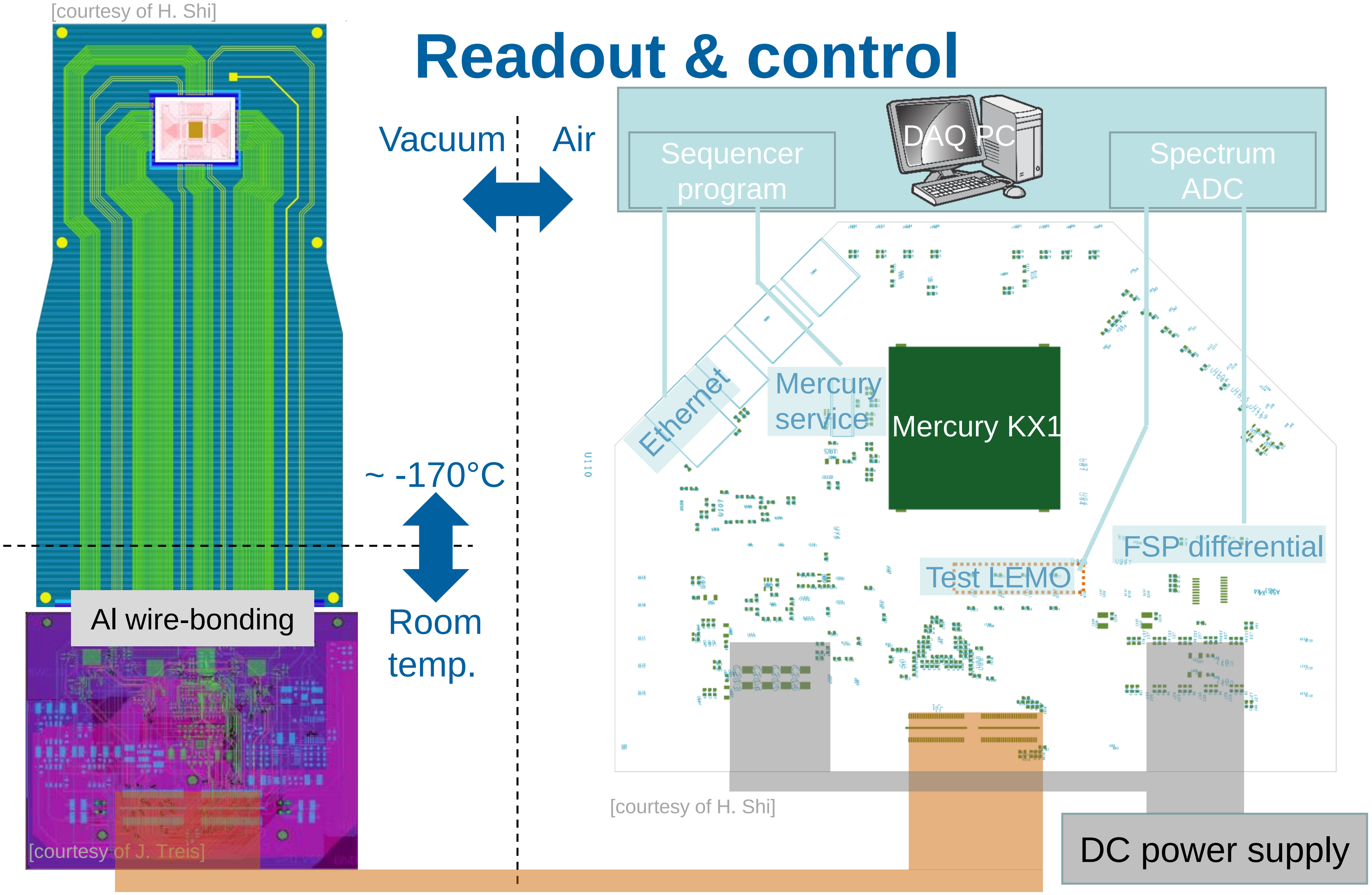



[courtesy of H. Shi]

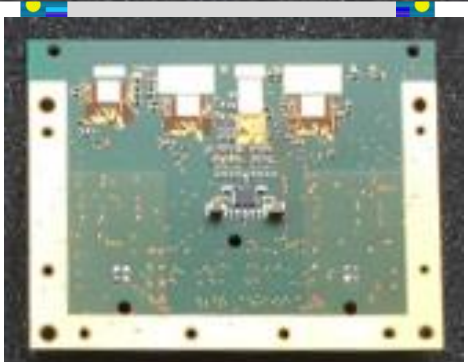
Prototype detector matrix:

- 64pixel x 64pixel
- Single pixel: 75µm x 75µm x 450µm
- Sensitive volume: **24mg**

Readout & control



Components are ready



Vacuum

Air

~ -170°C

Room temp.

Sequencer program

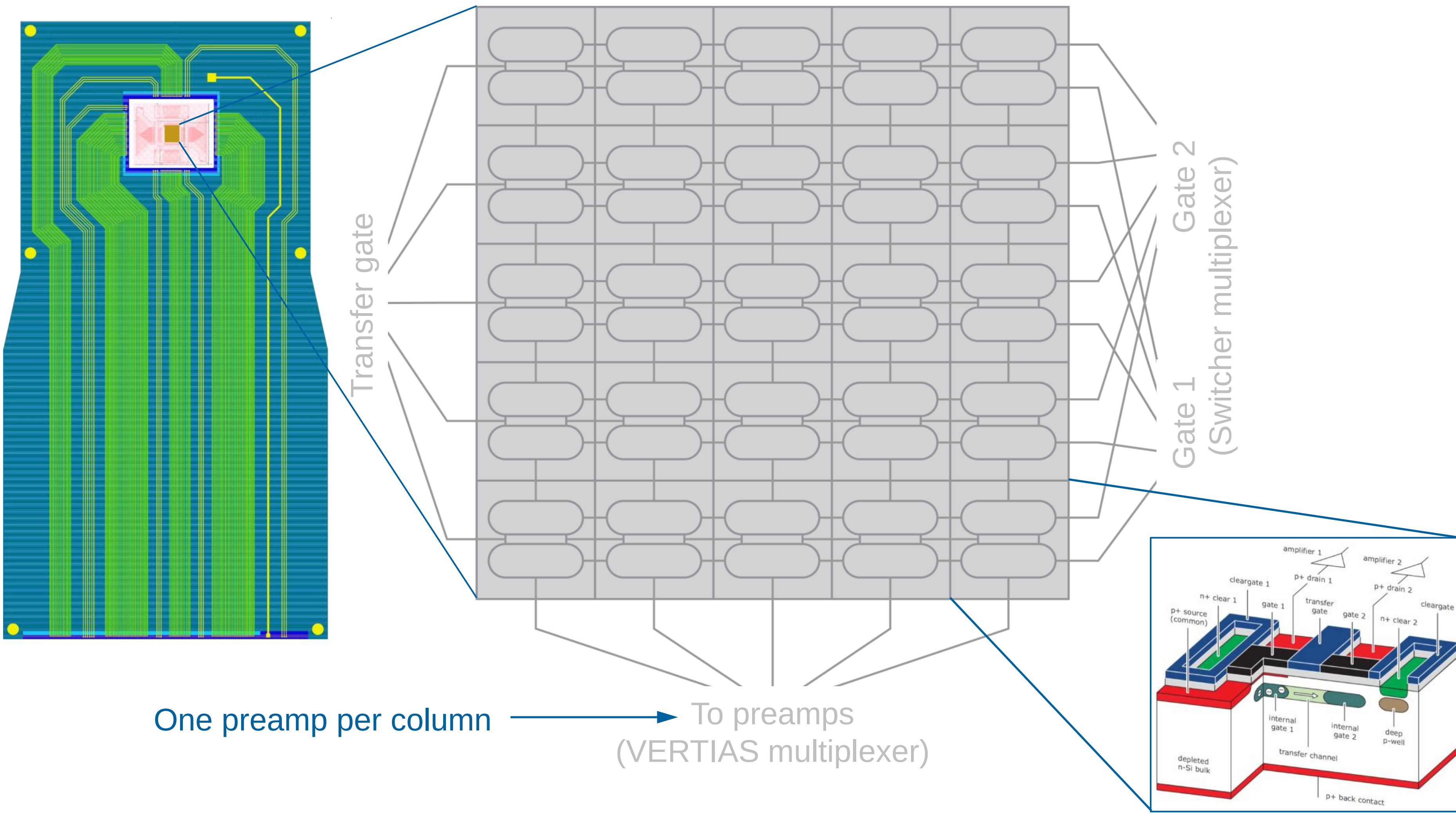
Spectrum ADC

DC

[courtesy of H. Shi]

Read-out sequence

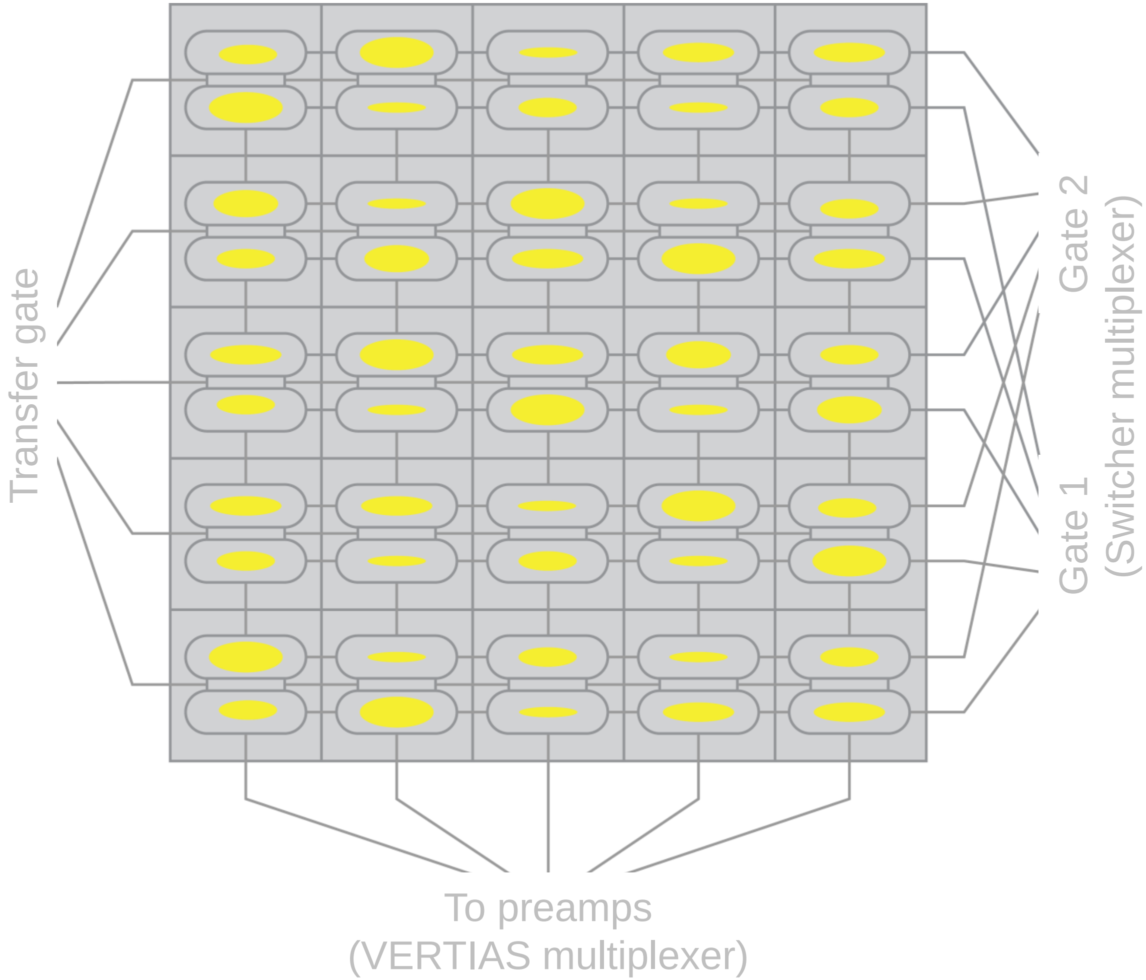
Simplified 5x5 matrix, N=1



Read-out sequence

Simplified 5x5 matrix, N=1

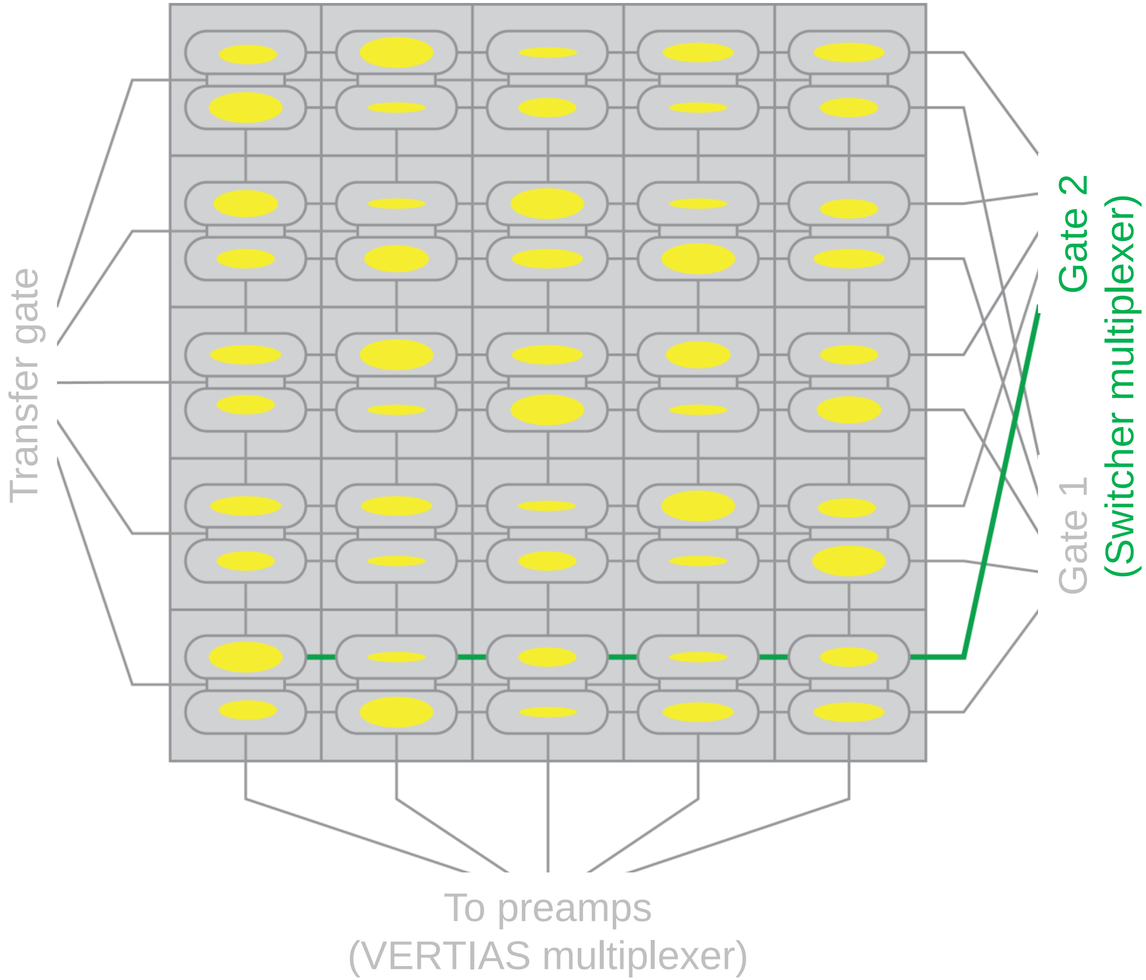
Initial charges



Read-out sequence

Simplified 5x5 matrix, N=1

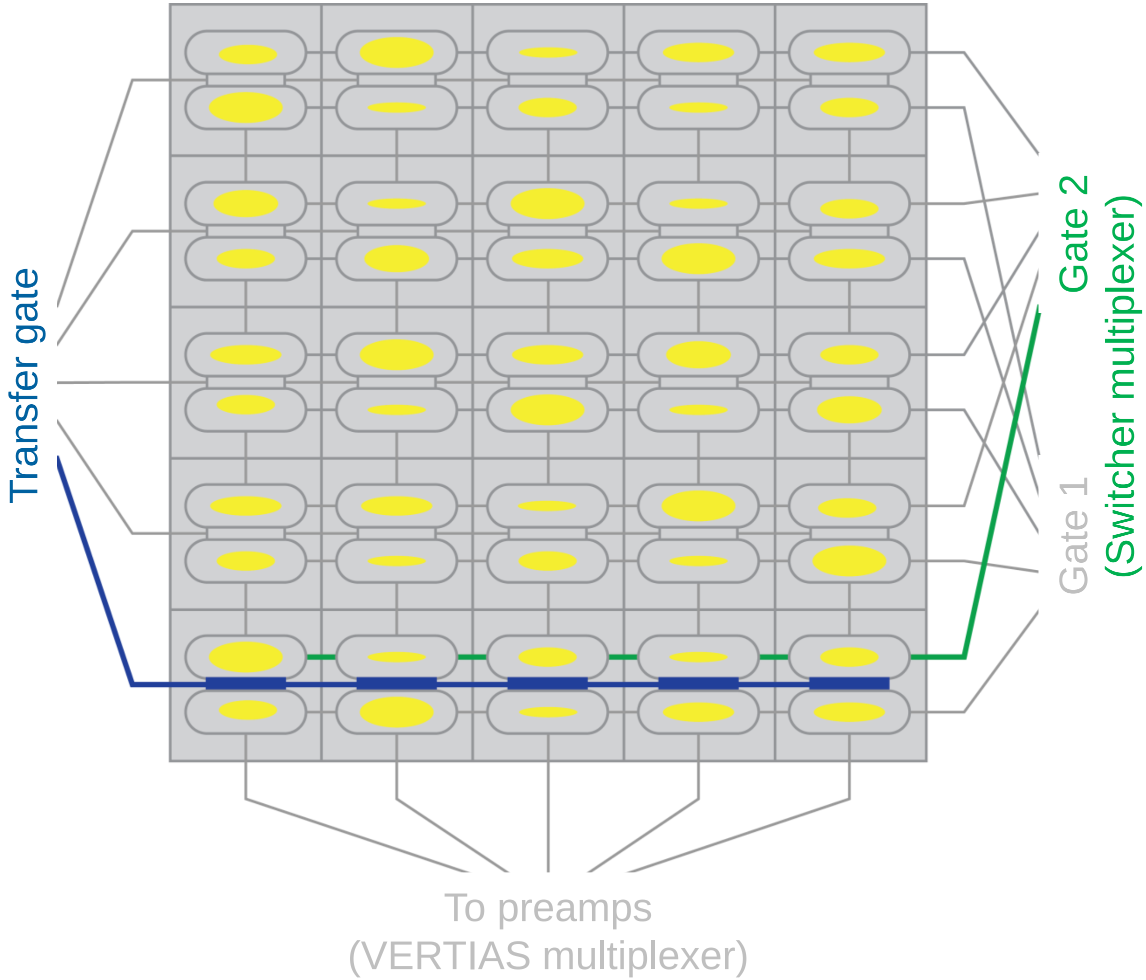
Initial transfer



Read-out sequence

Simplified 5x5 matrix, N=1

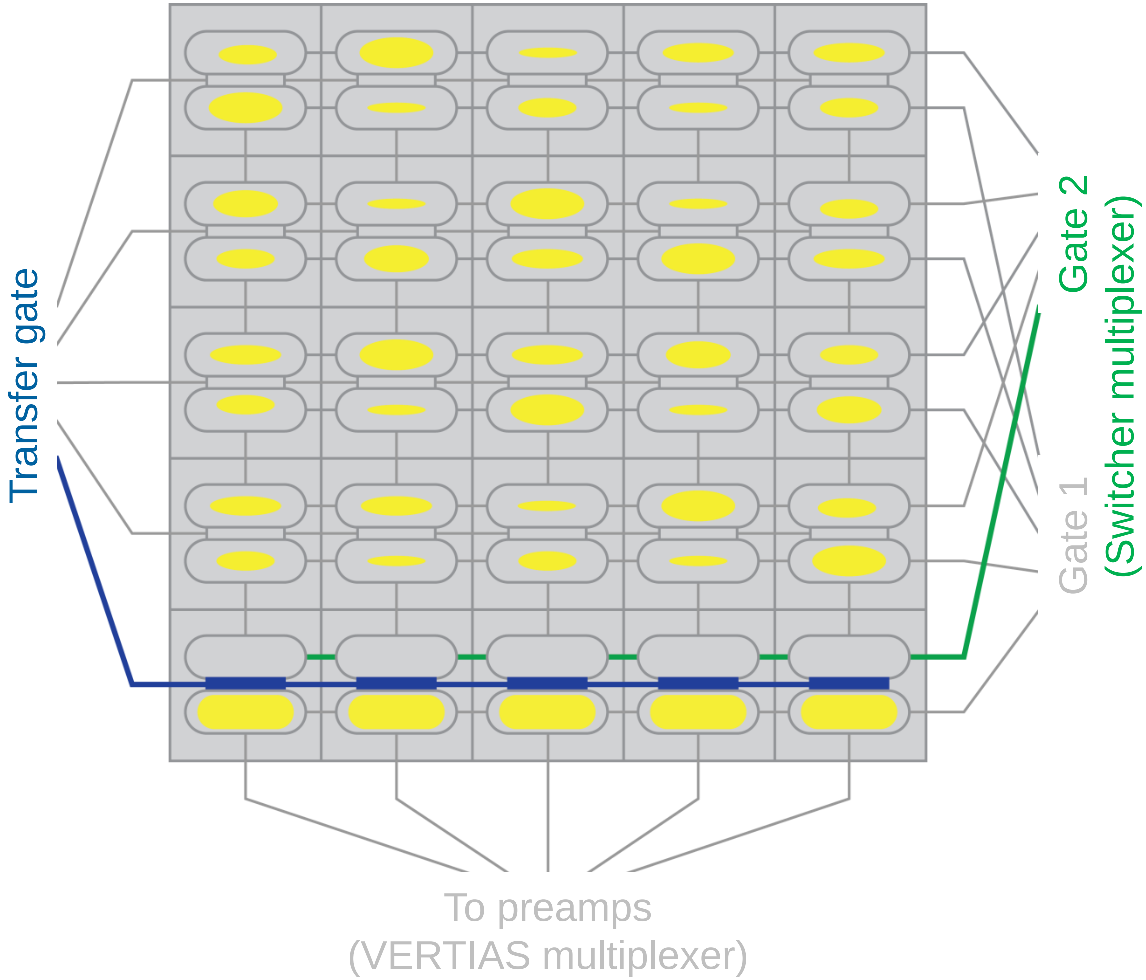
Initial transfer



Read-out sequence

Simplified 5x5 matrix, N=1

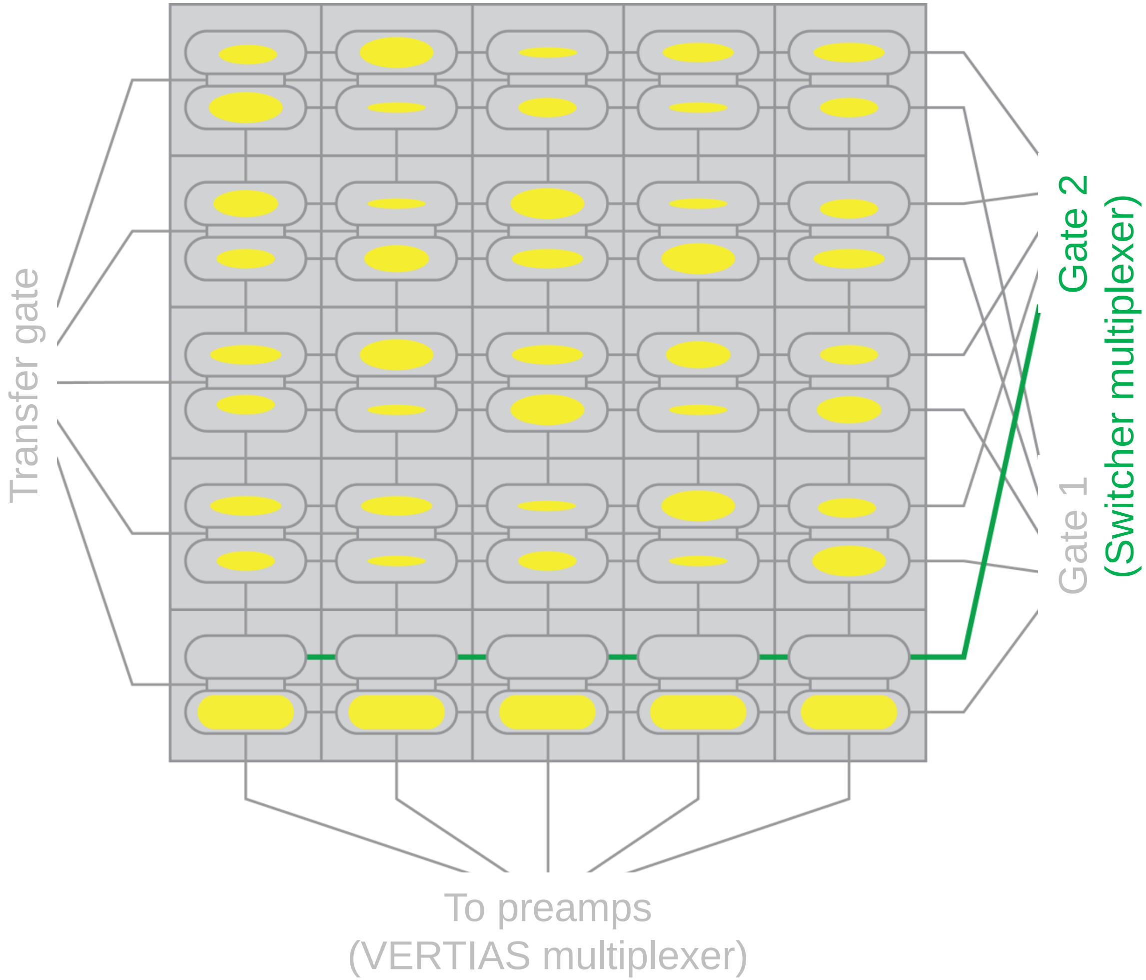
Initial transfer



Read-out sequence

Simplified 5x5 matrix, N=1

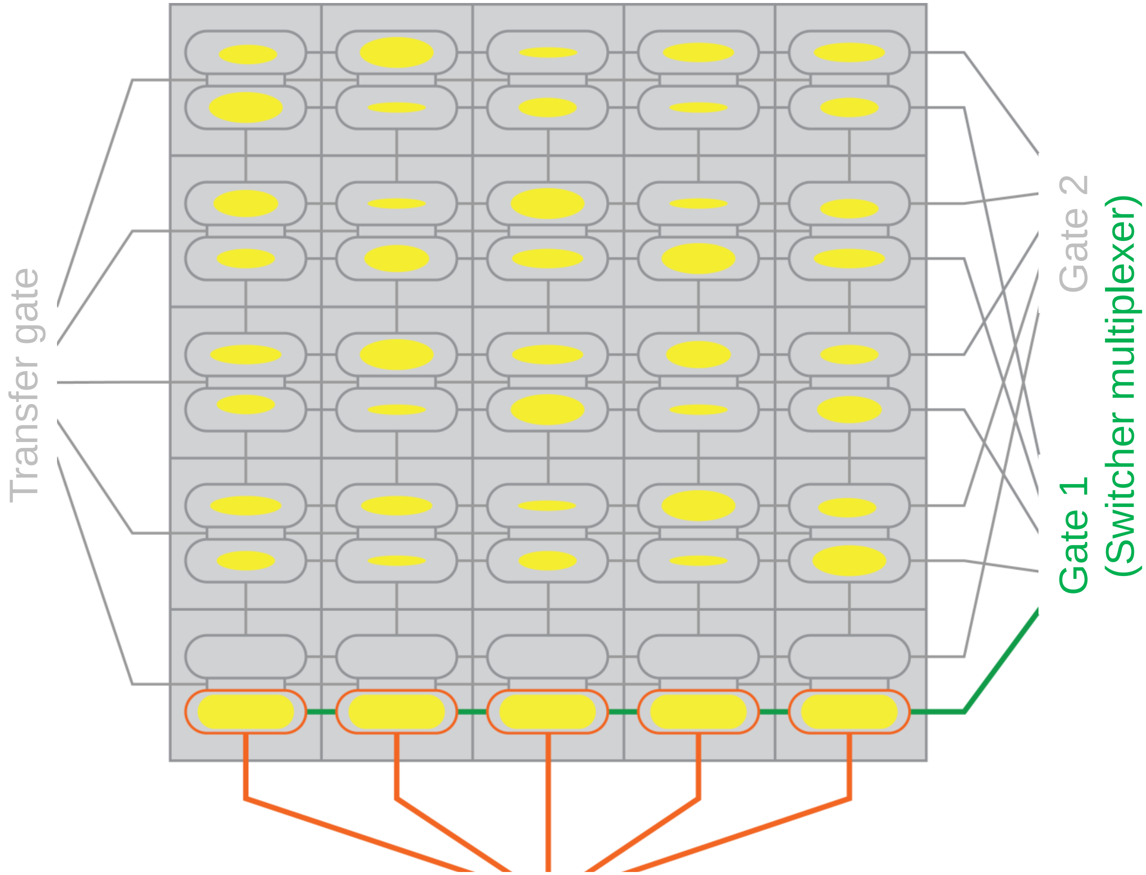
Initial transfer



Read-out sequence

Simplified 5x5 matrix, N=1

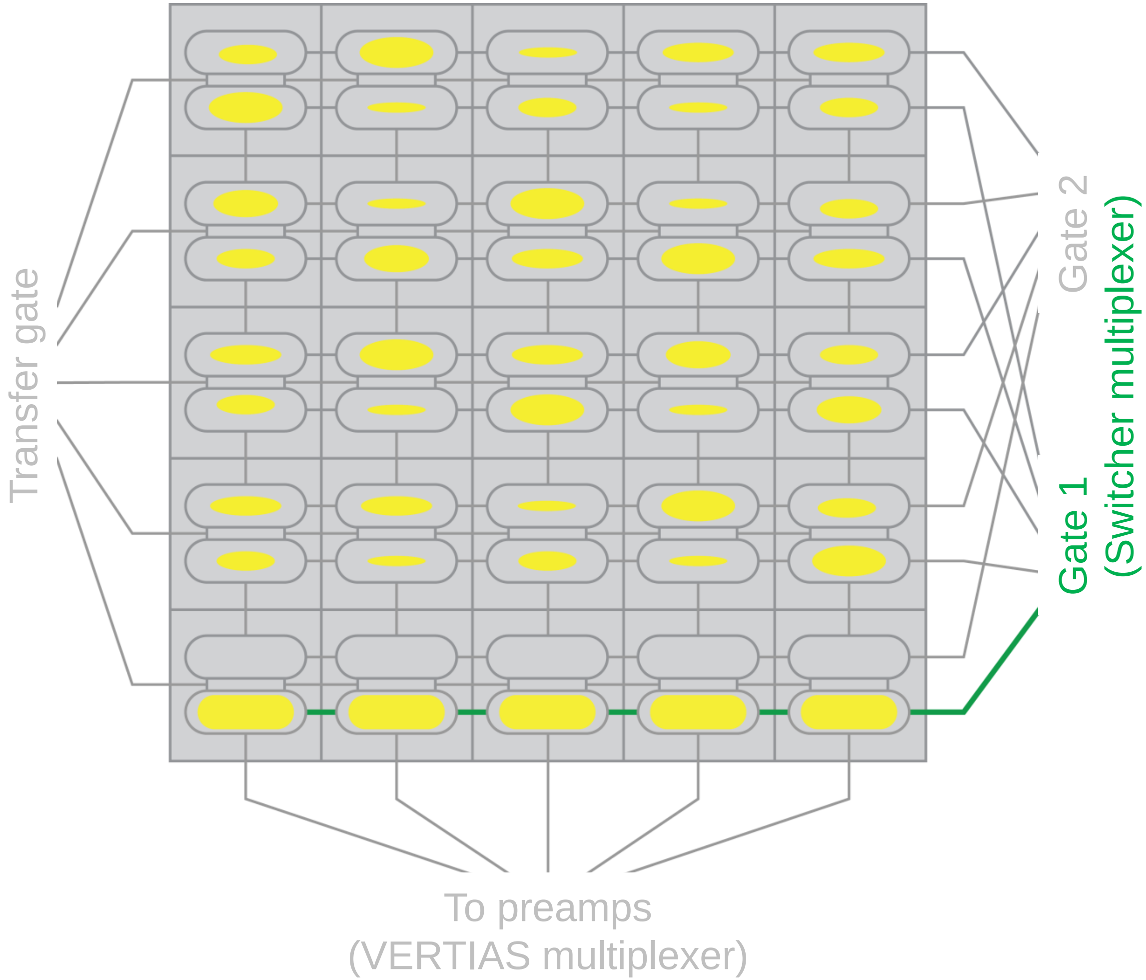
Signal readout 1



Read-out sequence

Simplified 5x5 matrix, N=1

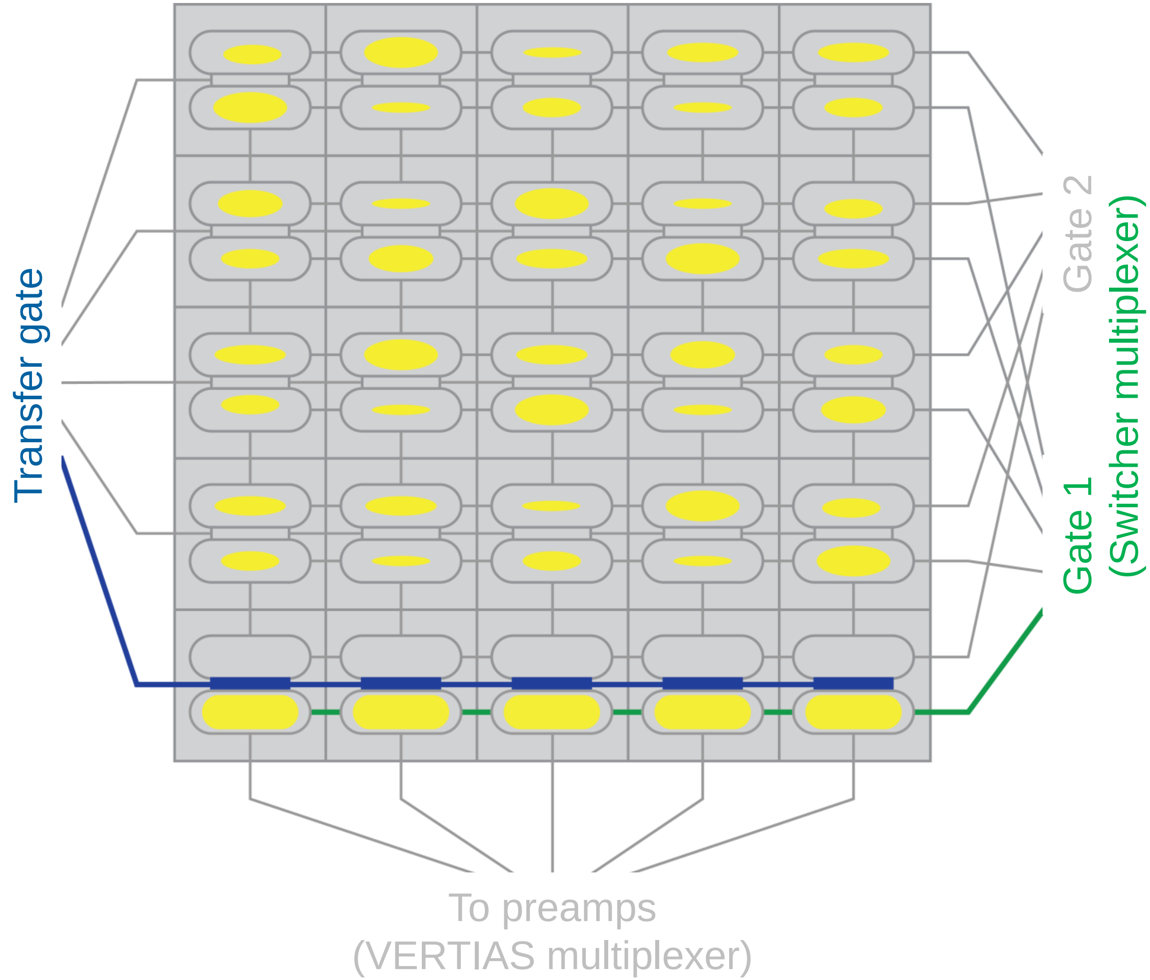
Signal transfer



Read-out sequence

Simplified 5x5 matrix, N=1

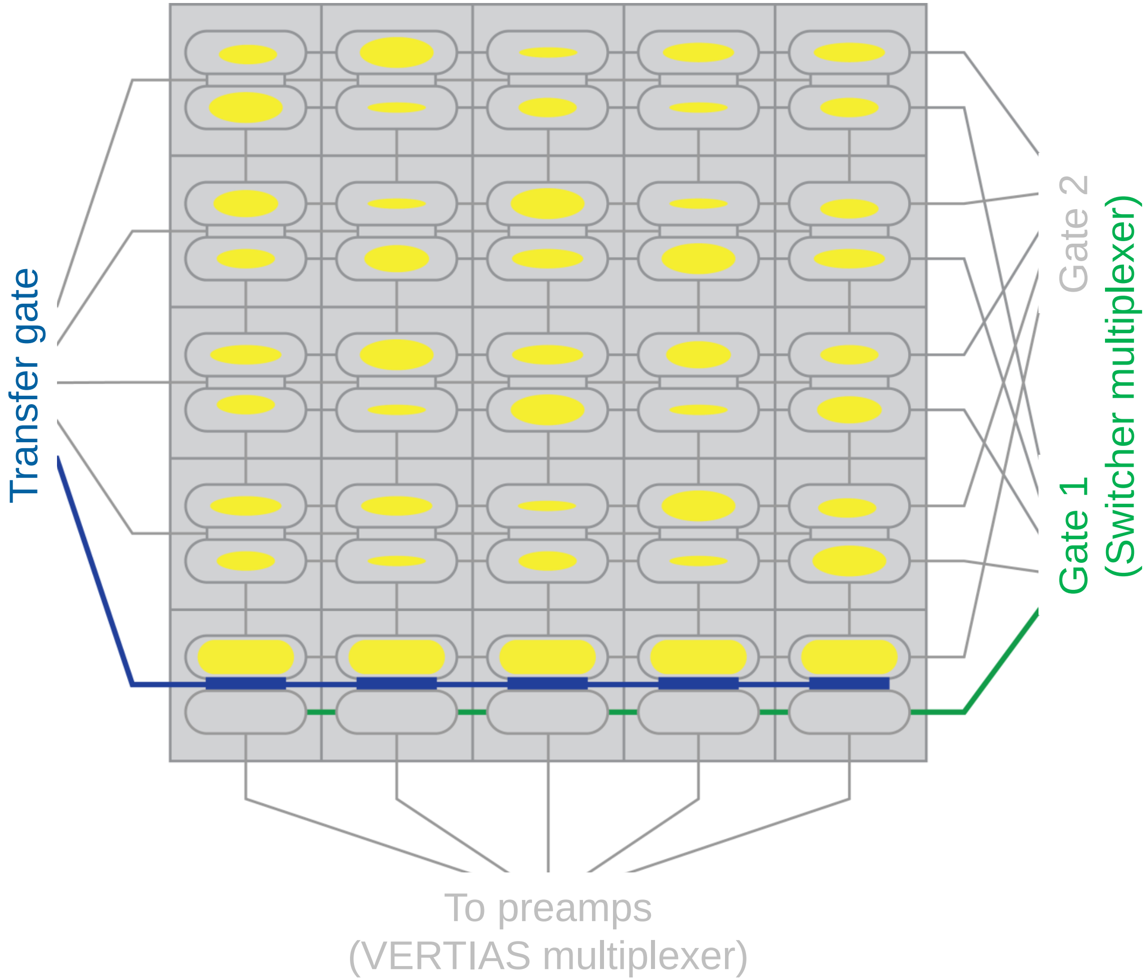
Signal transfer



Read-out sequence

Simplified 5x5 matrix, N=1

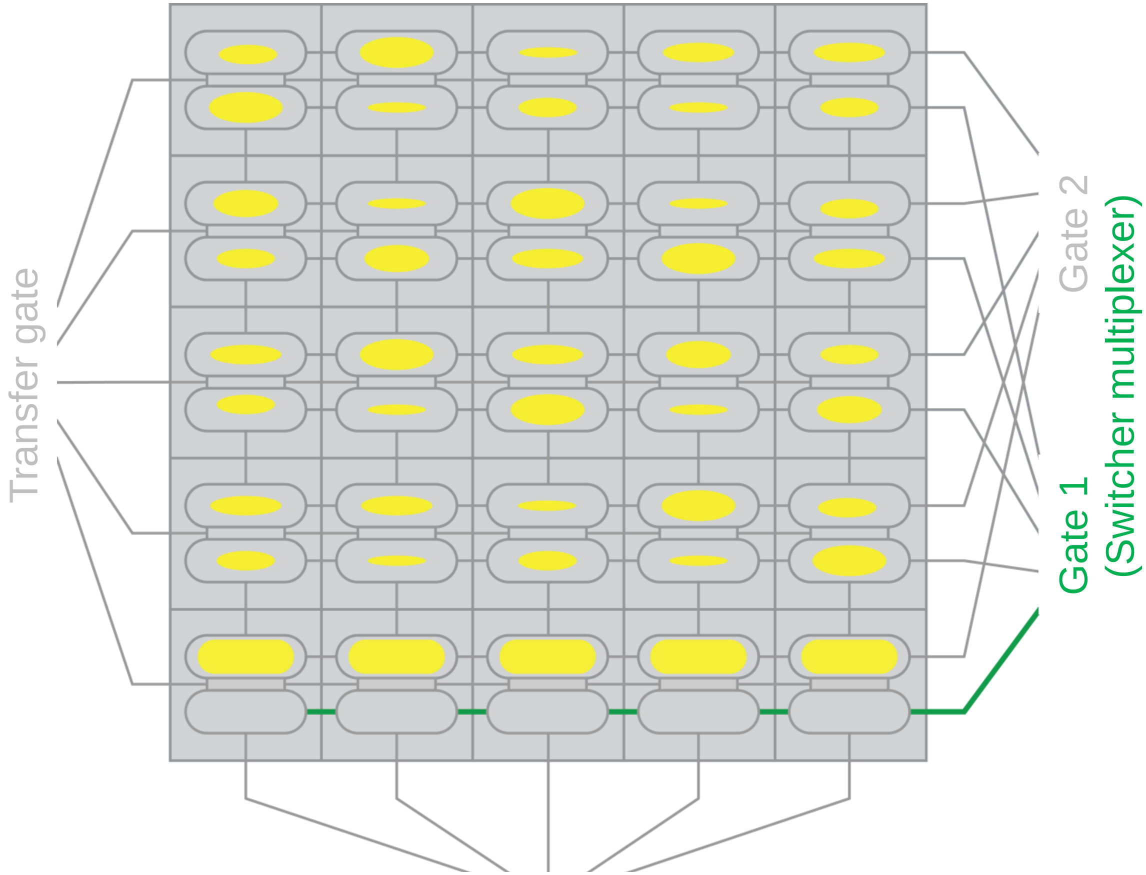
Signal transfer



Read-out sequence

Simplified 5x5 matrix, N=1

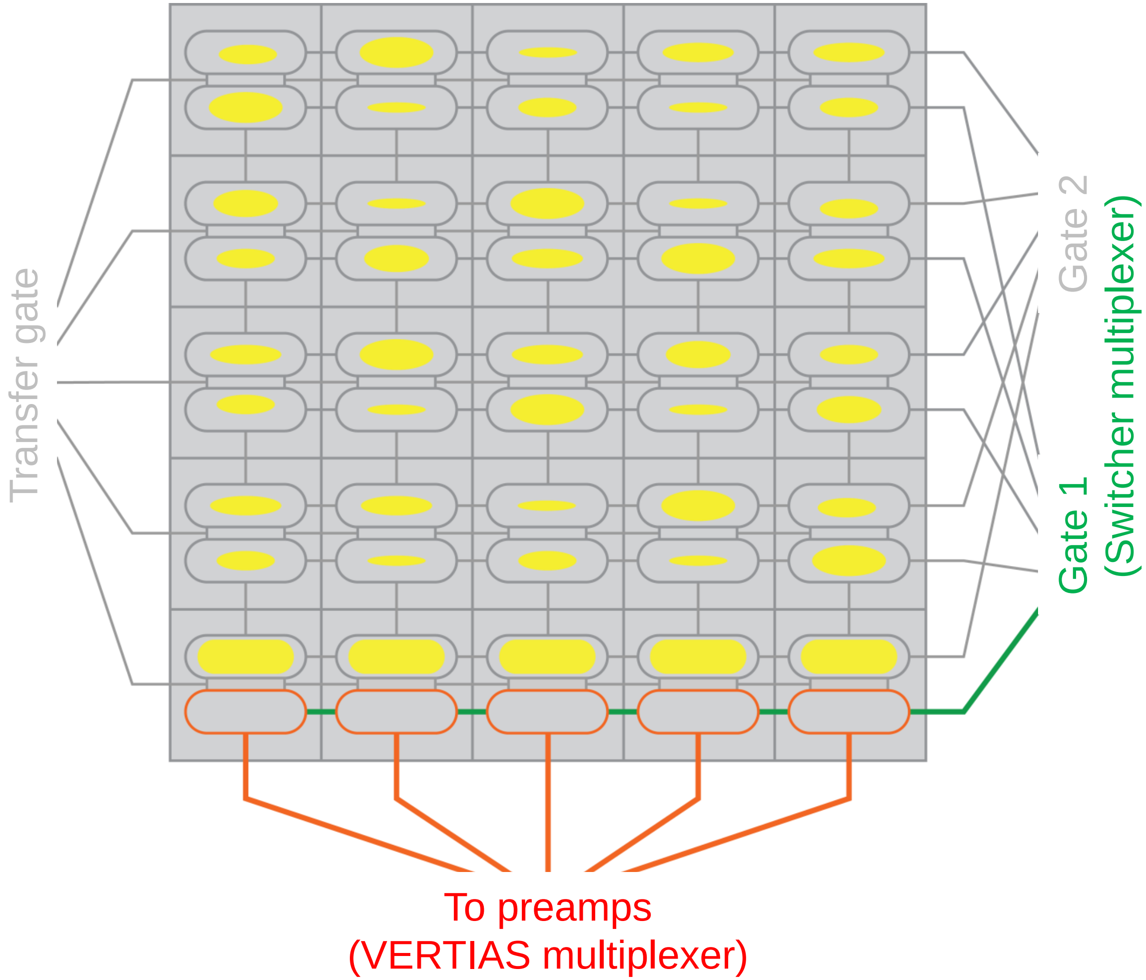
Signal transfer



Read-out sequence

Simplified 5x5 matrix, N=1

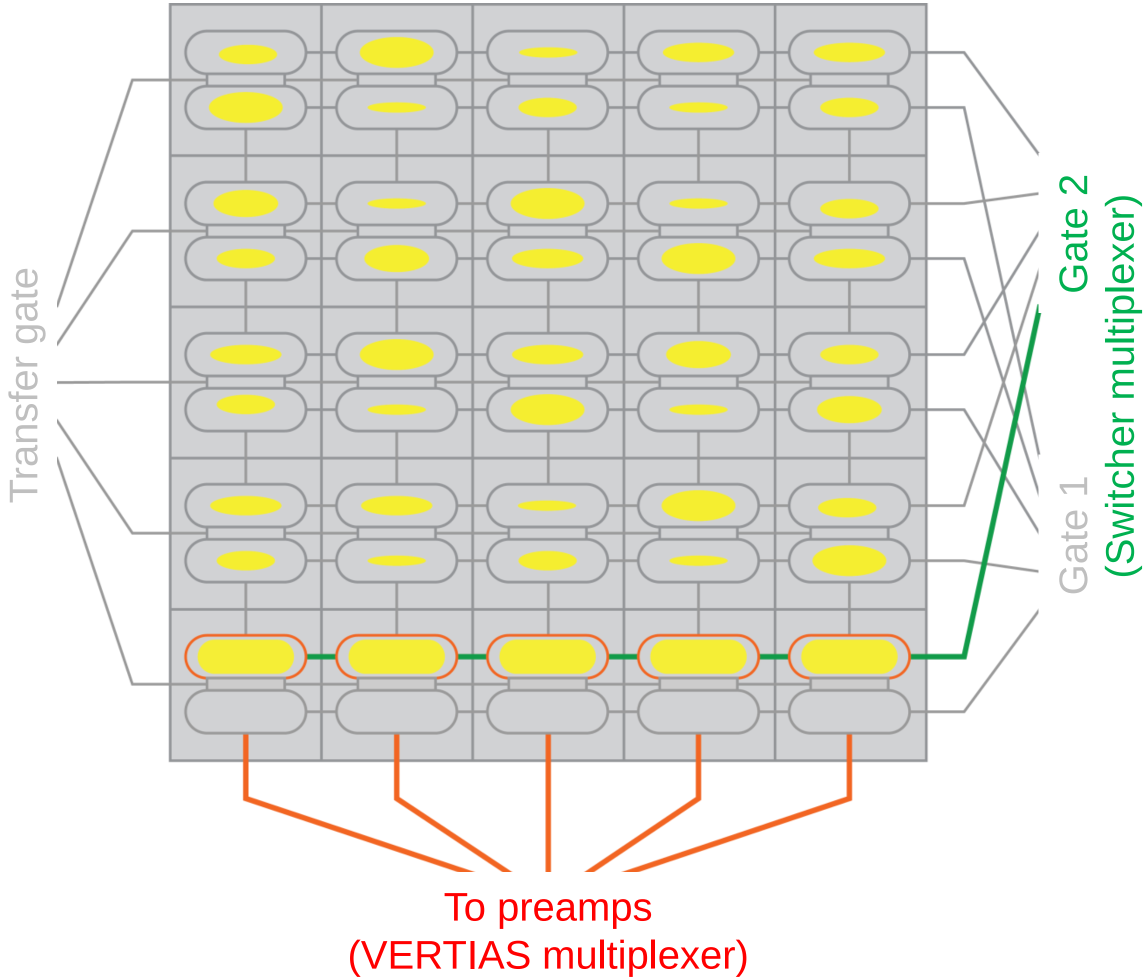
Baseline readout 1



Read-out sequence

Simplified 5x5 matrix, N=1

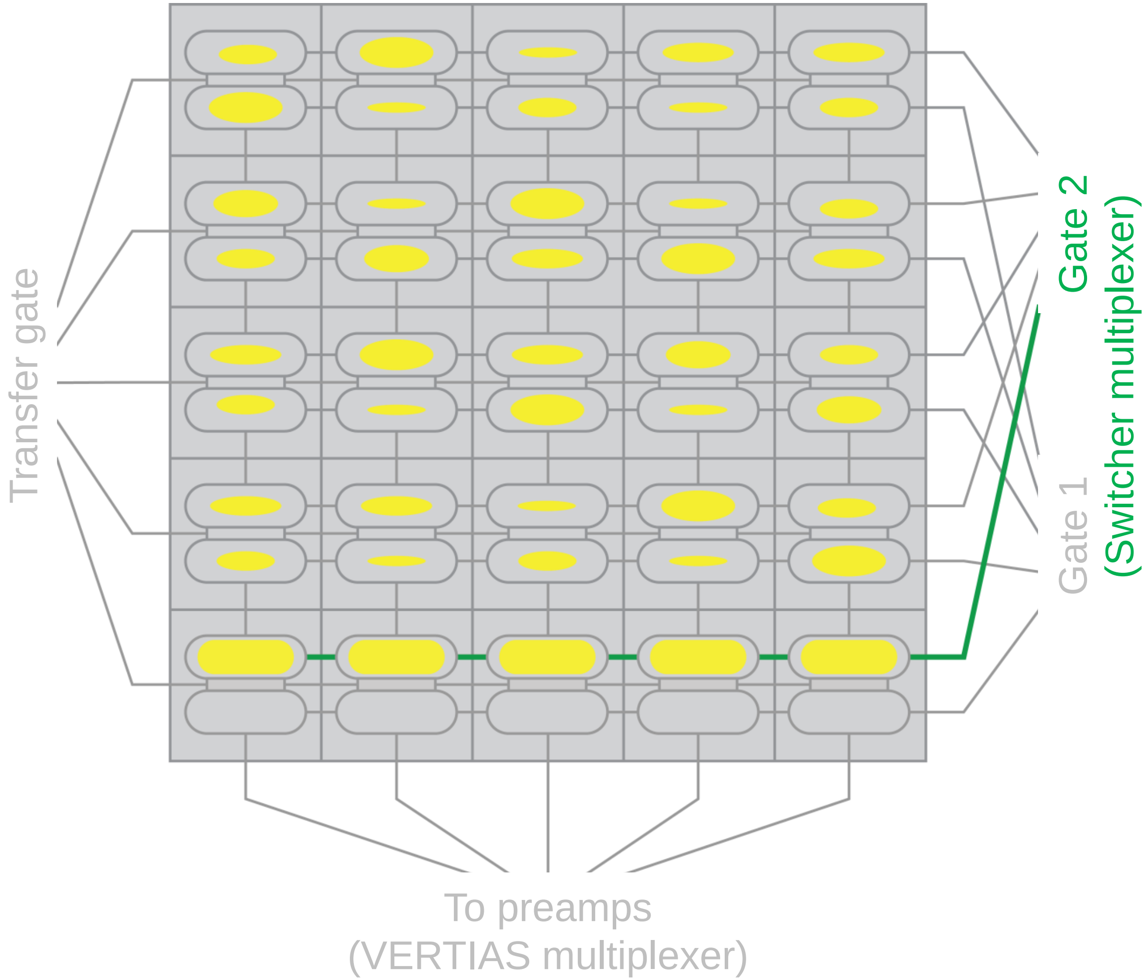
Signal readout 2



Read-out sequence

Simplified 5x5 matrix, N=1

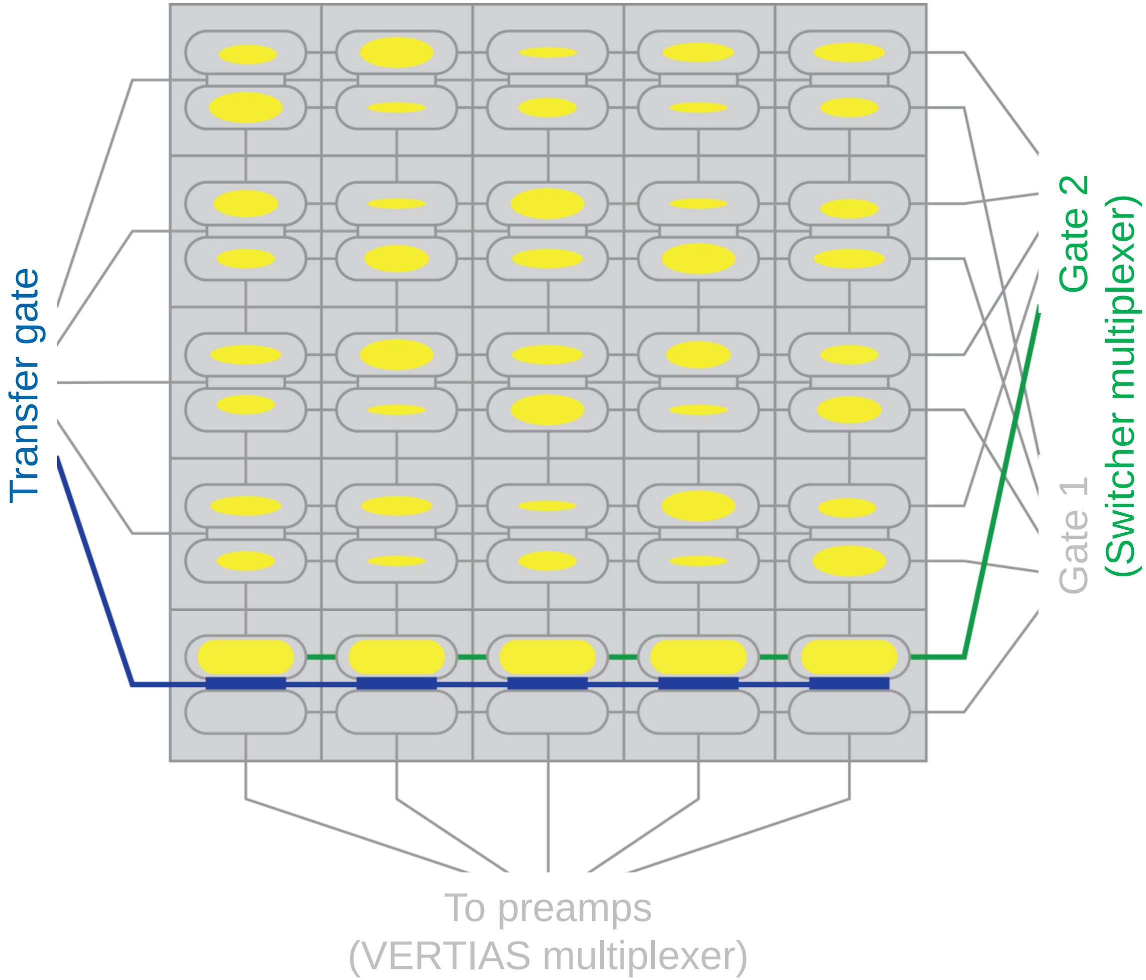
Signal transfer



Read-out sequence

Simplified 5x5 matrix, N=1

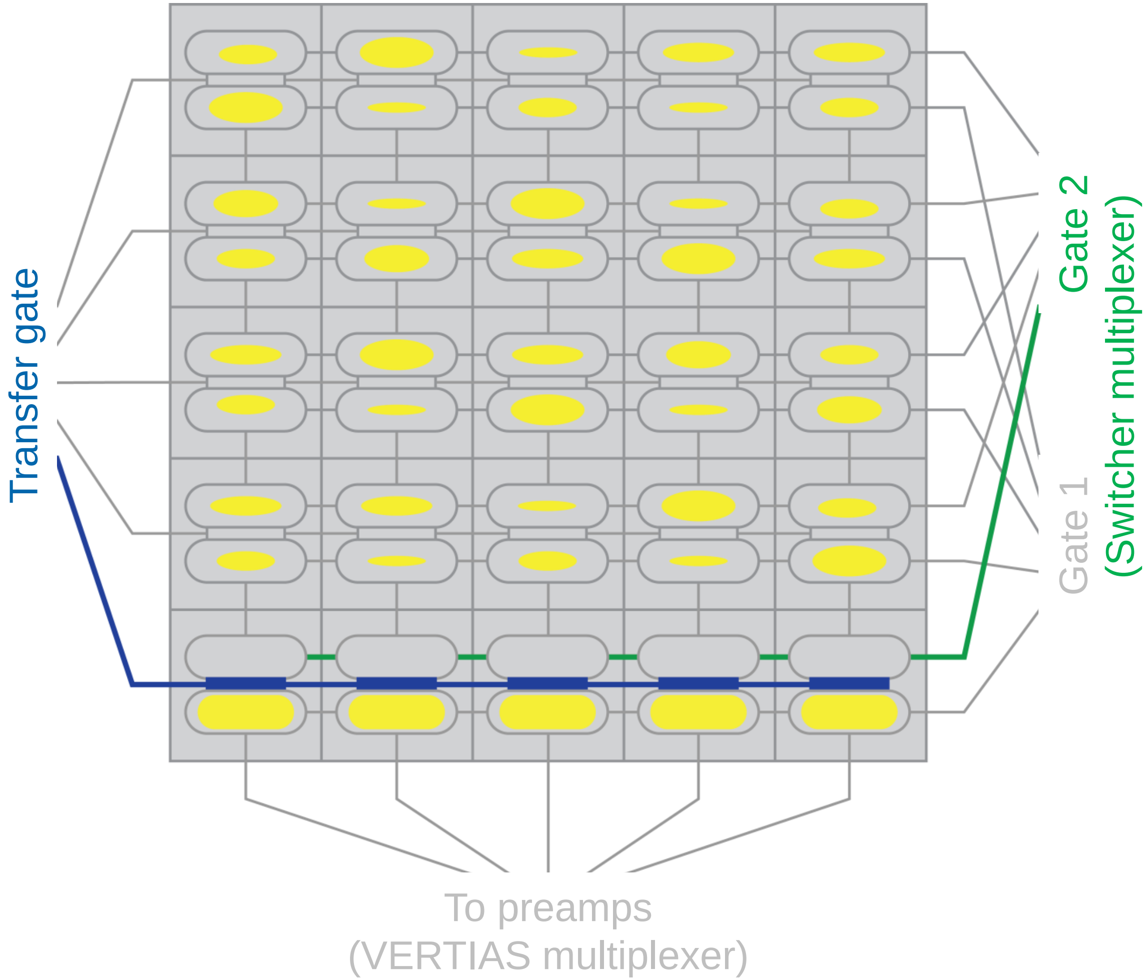
Signal transfer



Read-out sequence

Simplified 5x5 matrix, N=1

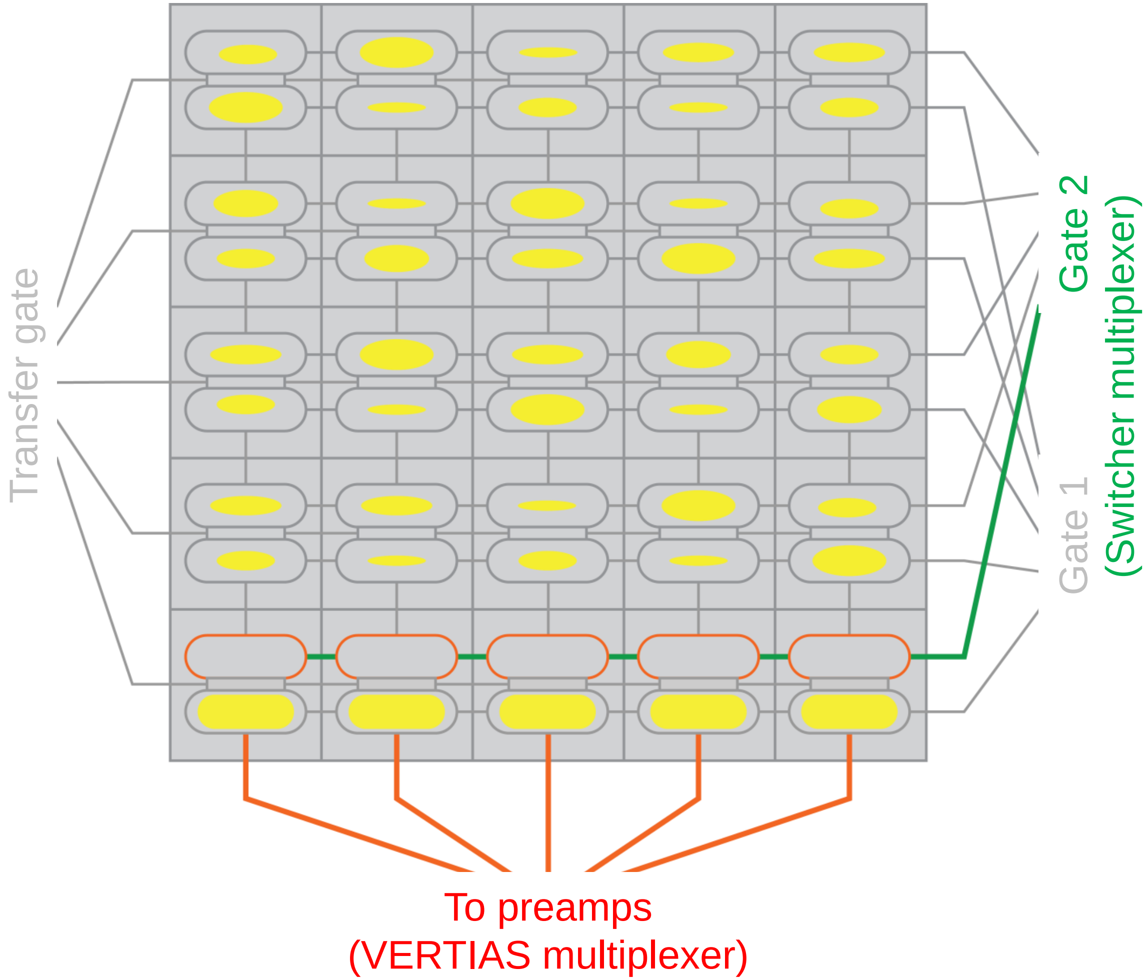
Signal transfer



Read-out sequence

Simplified 5x5 matrix, N=1

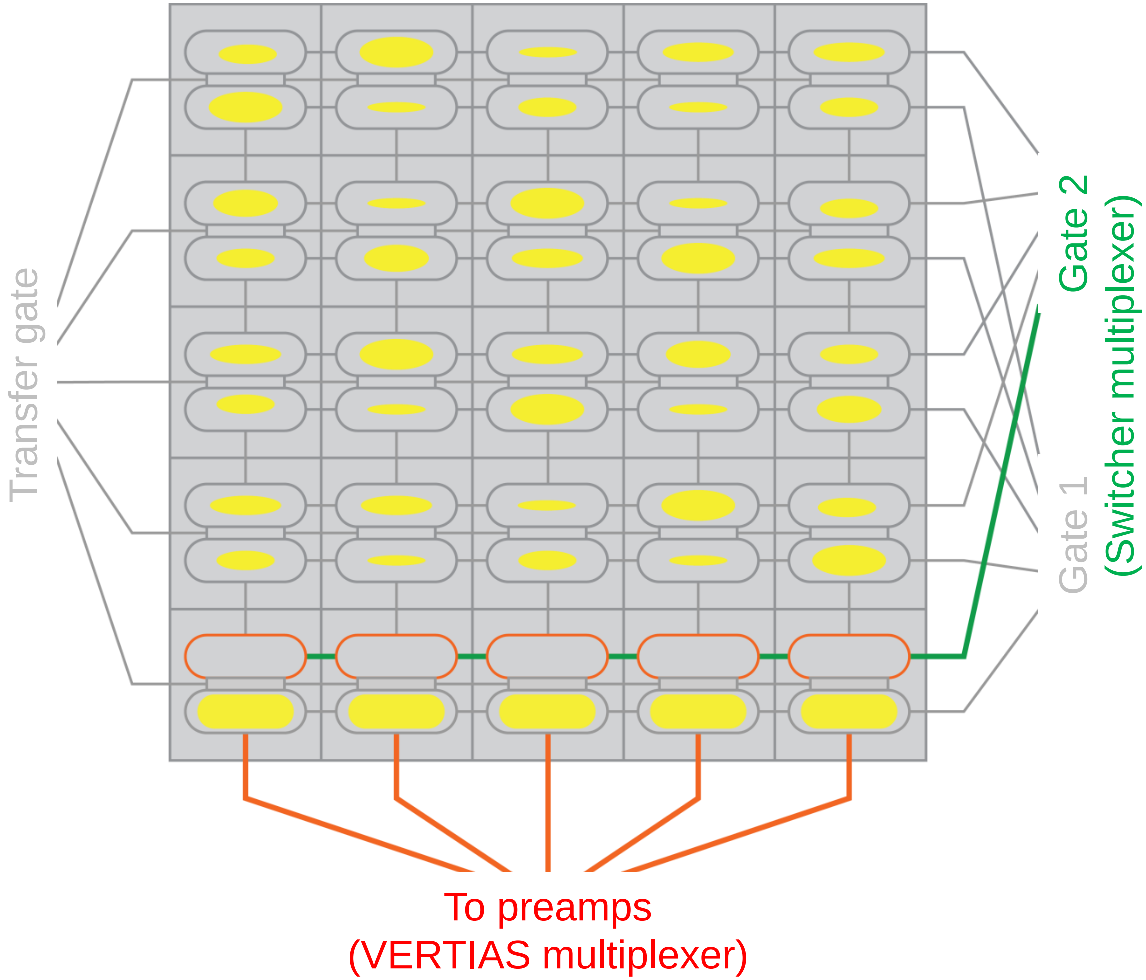
Baseline readout 2



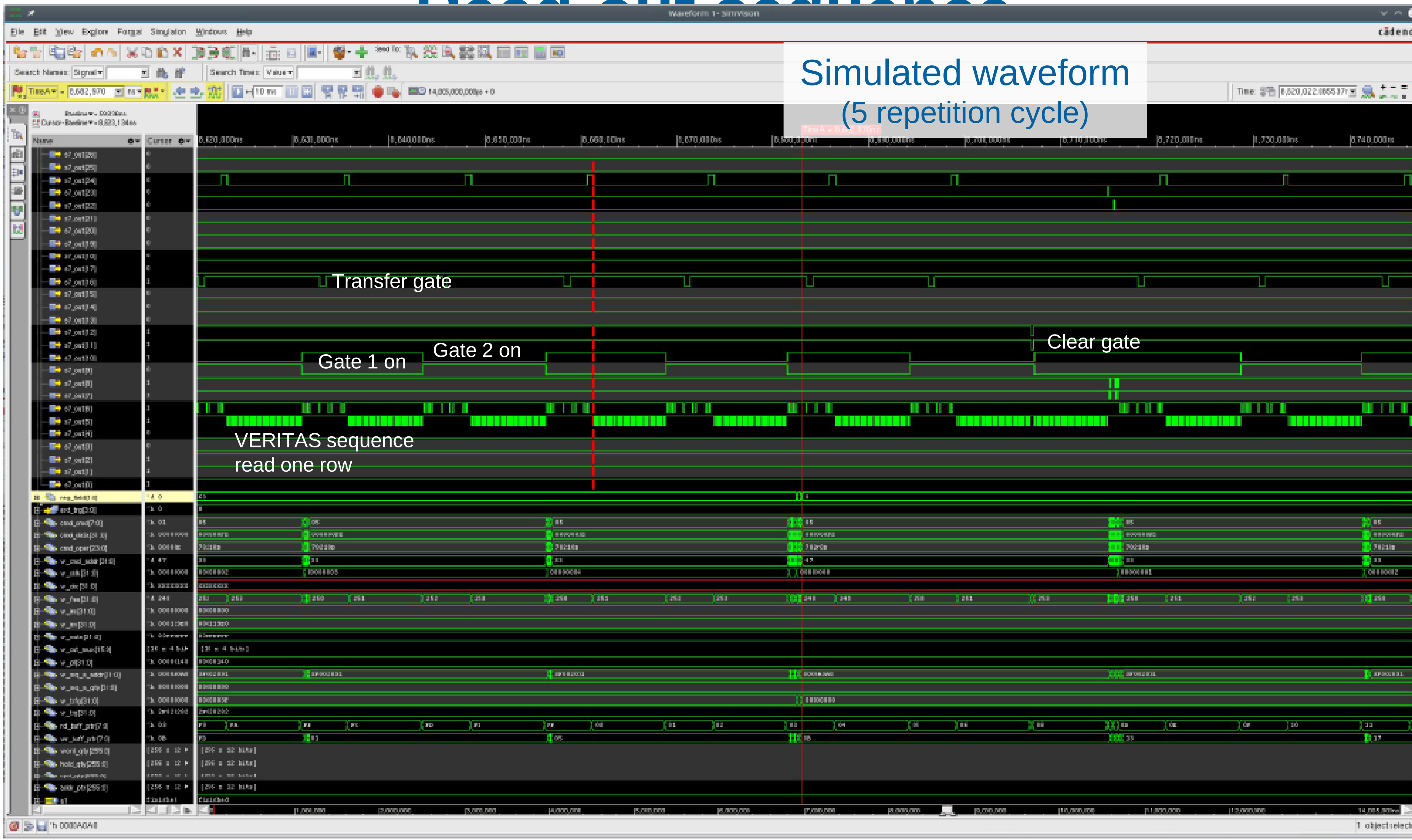
Read-out sequence

Simplified 5x5 matrix, N=1

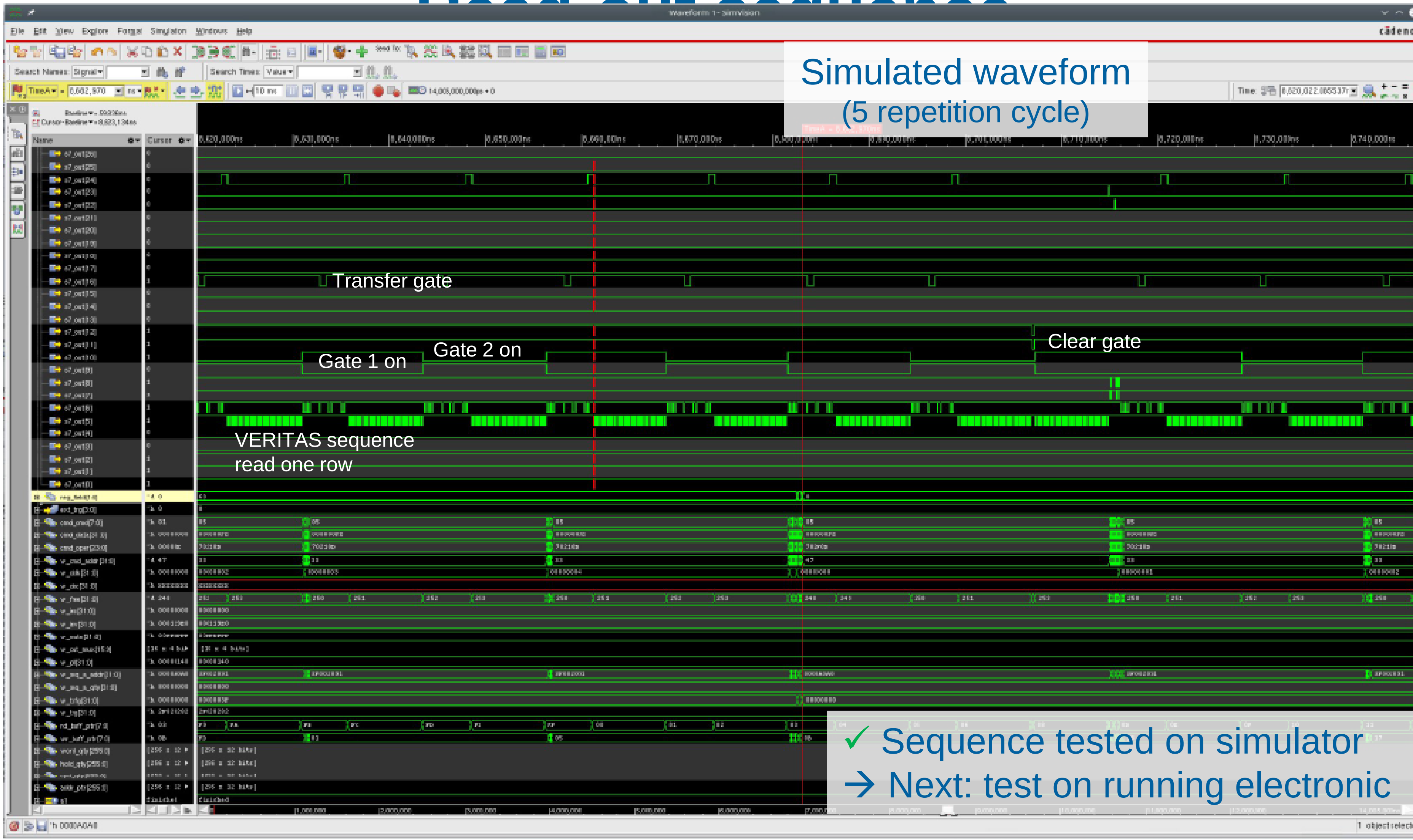
Repeat N-times
Go on to next row



Read-out sequence

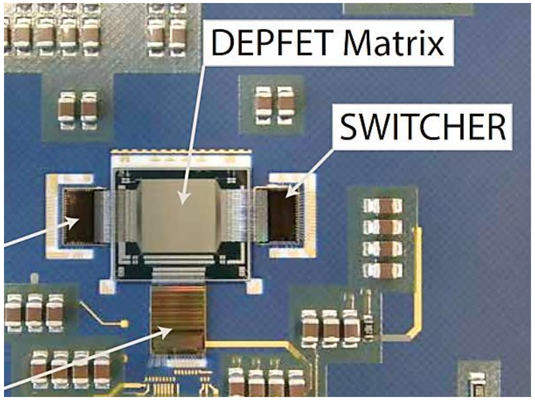


Read-out sequence



Physics perspective

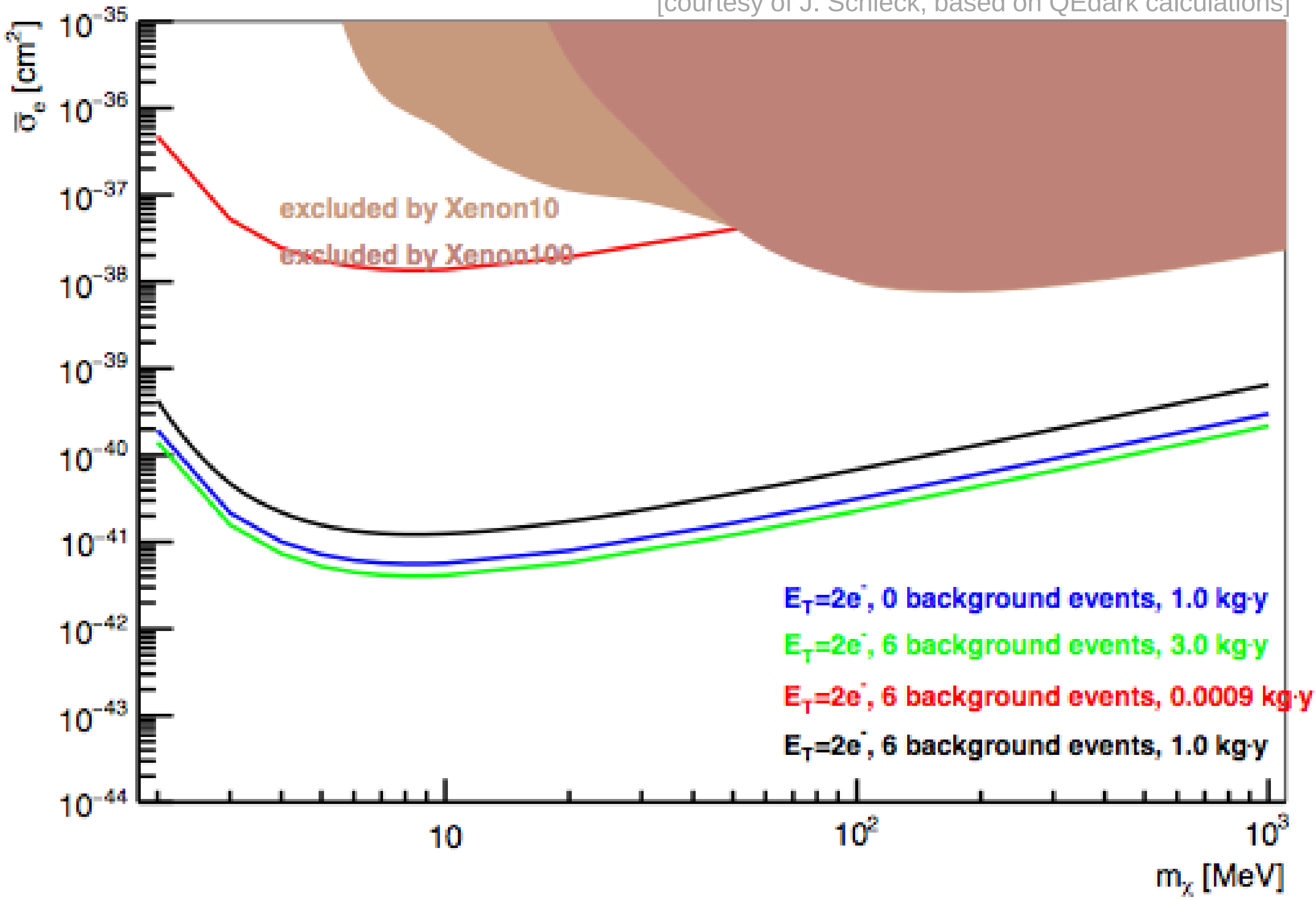
- Expect preliminary results from the prototype setup (24 mg sensitive volume) in late 2019

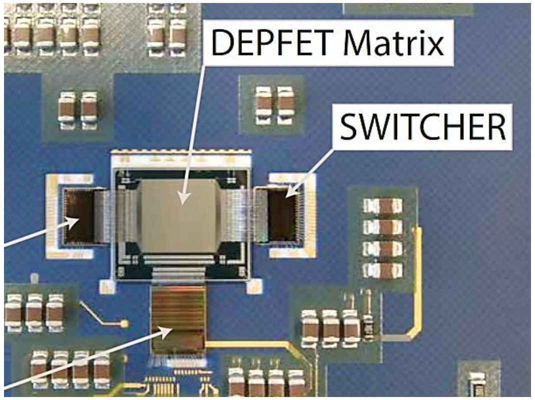


[courtesy of J. Treis]

- Expect preliminary results from the prototype setup (24 mg sensitive volume) in late 2019
- Physics run with significant result requires more matrices

[courtesy of J. Schieck, based on QEdark calculations]





[courtesy of J. Treis]

Initial goal: 0.9 g.yr

→ 40 matrices à 24mg
→ ~1g sensitives volume

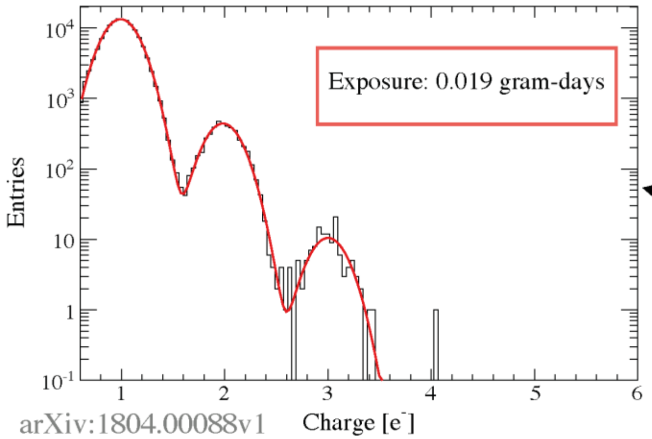
Summary

- **Sub-GeV/c²** dark matter is a **attractive alternative** to classic WIMPs
- Potential signature: **electron scattering**
- Require semiconductor detectors with **sub-e^- RMS noise level**
- **DEPFET-RNDR successfully demonstrate** such a low noise level
- **DANAE** is a new project aiming to **utilizing DEPFET-RNDR to search for sub-GeV/c² dark matter** interactions in silicon
- Under construction: **DANAE prototype** with 64pixel x 64pixel detector matrix
- Expect **first test-of-principle** measurement in **late 2019**

→ **Stay tuned** for future results!

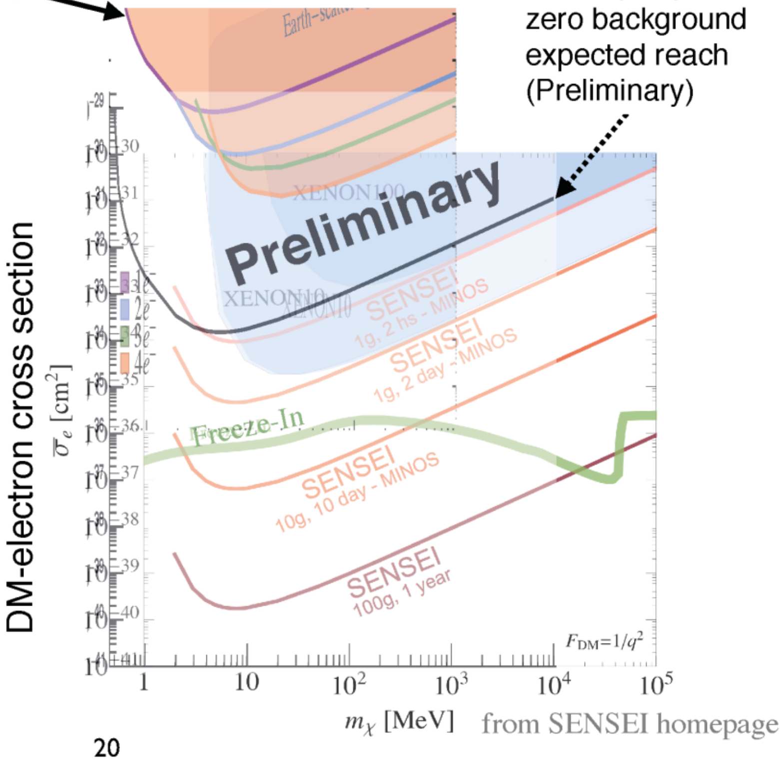
Additional slides

Expected 1day exposure compared to SENSEI



SENSEI prototype physics run

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



[courtesy of H. Shi (ICHEP2018)]

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

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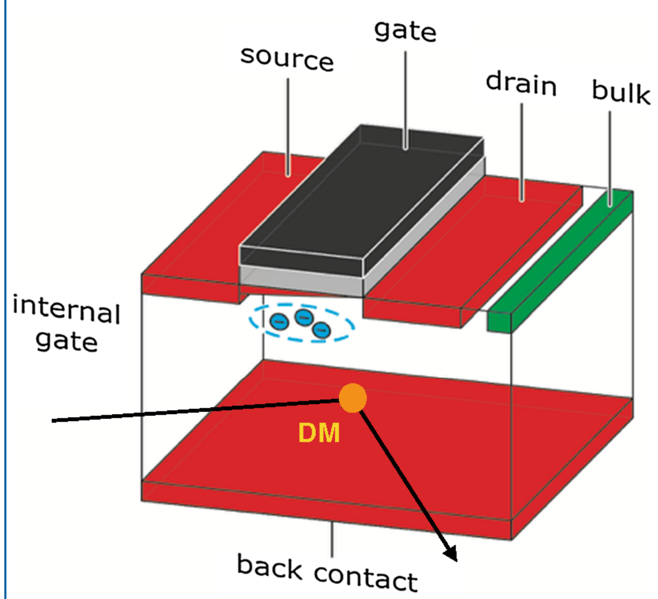
[courtesy of H. Shi (ICHEP2018)]

DEPFET with RNDR

RNDR : repetitive non-destructive readout

structure of a basic DEPFET cell :

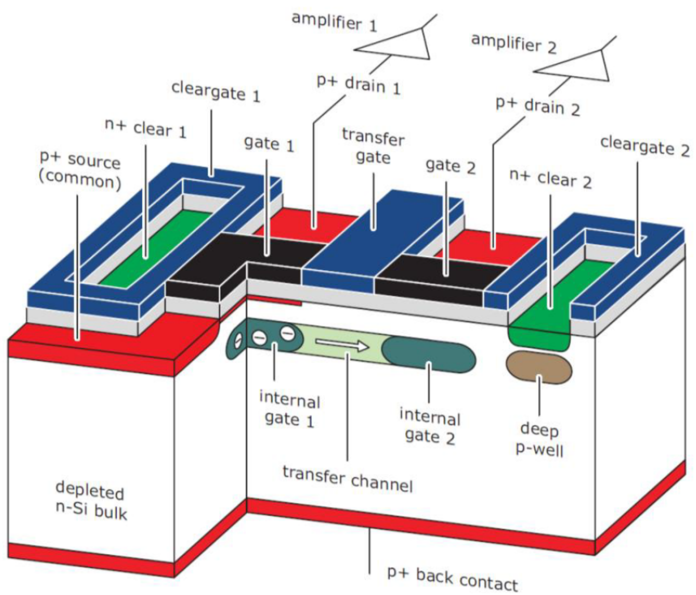
a "subpixel"



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

fully-depleted n-Si

structure of RNDR DEPFET "super-pixel"



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

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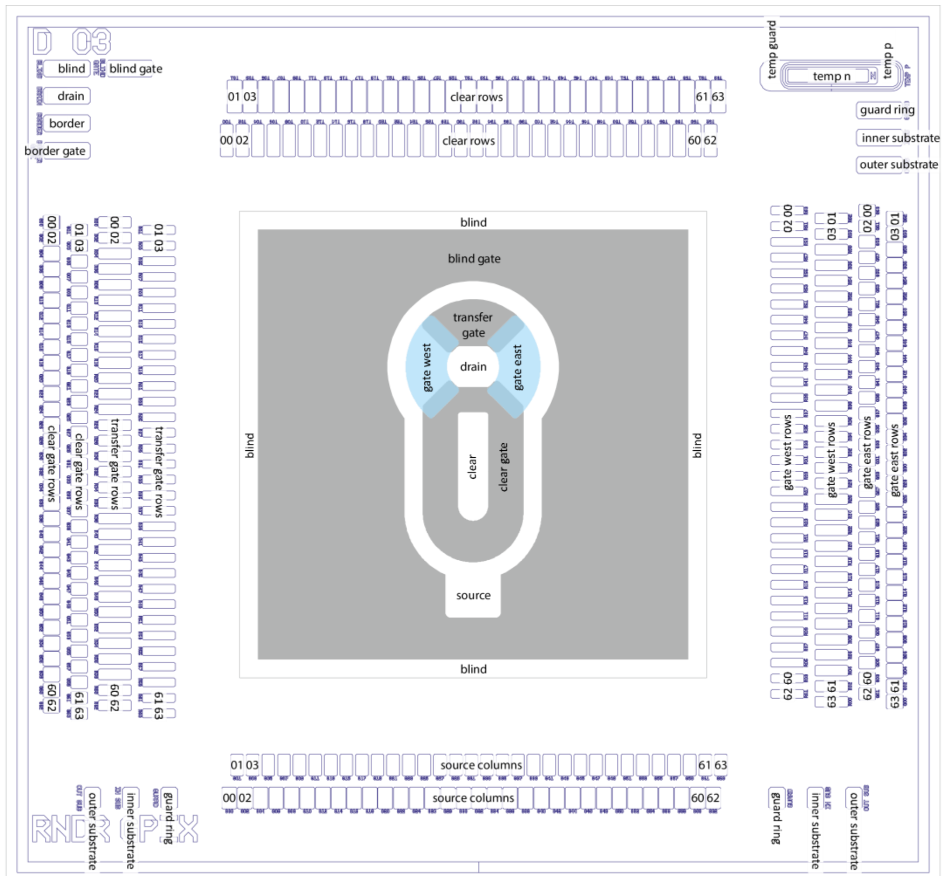
[courtesy of H. Shi (ICHEP2018)]

DANAE - A new effort to directly search for Dark Matter with DEPFET-RNDR detectors

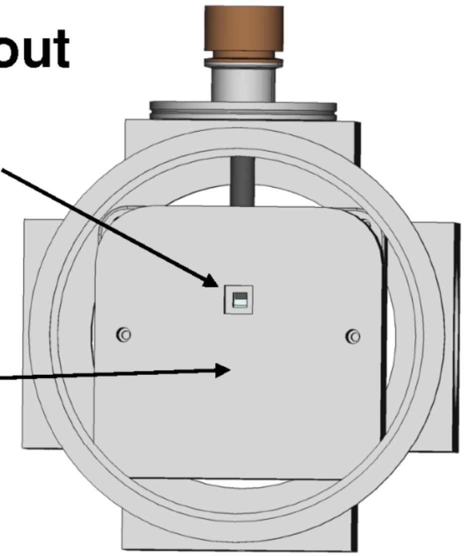


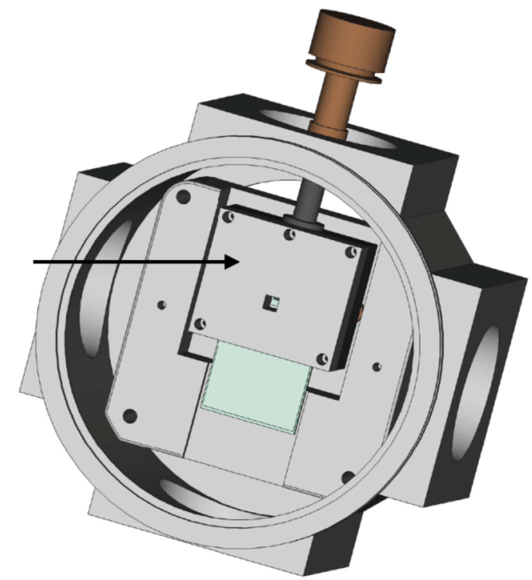
compact RNDR & blind
structure name RNDR_GPIX
chip size 8.5 x 8.0 mm^2
format 64 x 64
pixel size 75 x 75 μm^2
PXD7 chip D.03

MPG HLL HALBLEITERLABOR DER MAX-PLANCK-GESELLSCHAFT

Peter Lechner, 29.11.18

Cooling & shielding layout





outer shielding : support structure
inner shielding : cooling contact

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[courtesy of H. Shi (ICHEP2018)]

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

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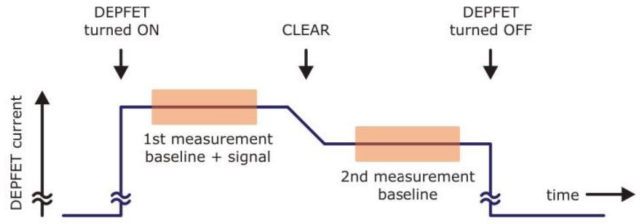
[courtesy of H. Shi (ICHEP2018)]

Detector Structures – Matrix Devices

- **readout sequence**



Correlated double sampling:

1st measurement: signal + baseline

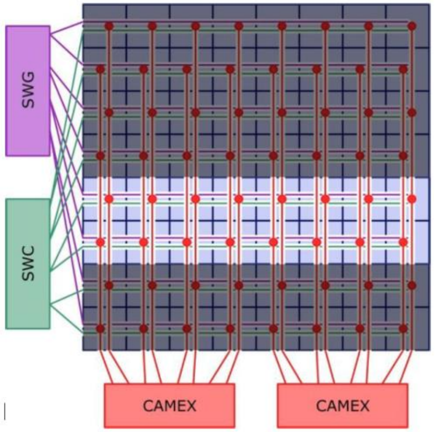
clear: removal of signal charges

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

Johannes Treis / Halbleiterlabor der MPG