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

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Outline

• Sub-GeV/$c^2$ 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/c² dark matter
Several astronomical evidences for the existence of dark matter at different scales

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 $2\text{GeV}/c^2 .. 120\text{TeV}/c^2$
- Usual event signature in direct searches: nuclear recoils
- Dominated the direct searches until recently
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Landscape

[courtesy of F. Reindl]
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Landscape

No evidence for WIMPs yet

[courtesy of F. Reindl]
### Detection limit for nuclear recoils

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

\[
\Rightarrow E_N (m_{DM} = 100\text{MeV}/c^2) \approx 1\text{eV}
\]

[courtesy of F. Reindl]
Detection limit for electron recoils [JHEP05(2016)046]

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

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

Typical energy transfer to a bound outer-shell electron

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

Coherent Neutrino Scattering on CaWO$_4$
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/c^2 to GeV/c^2 scale
## Target materials for e\(^{-}\) scattering

<table>
<thead>
<tr>
<th>Active target</th>
<th>Detection threshold</th>
<th>DM mass threshold</th>
<th>Status</th>
<th>Time scale</th>
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</thead>
<tbody>
<tr>
<td>Noble liquids (e.g. Xe, Ar, Ne)</td>
<td>~ 10 eV</td>
<td>~ 5 MeV/c(^2)</td>
<td>Done with data; improvements possible</td>
<td>existing</td>
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<tr>
<td>Semiconductors (e.g. Ge, Si)</td>
<td>~ 1 eV</td>
<td>~ 200 keV/c(^2)</td>
<td>(E_{\text{th}} \sim 40) eV SuperCDMS, DAMIC (E_{\text{th}} \sim 1) eV SENSEI, DANAЕ R&amp;D</td>
<td>~ 1-2 yr</td>
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<td>Scintillators (e.g. CsI, NaI, …)</td>
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[arXiv:1608.08632]
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Single DM-e\(^{-}\) interactions: \(\rightarrow < 1\) e\(^{-}\) RMS noise level

[arXiv:1608.08632]
DEPFET-RNDR detectors
DEPFET-RNDR

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

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DEPFET-RNDR

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

DEPFET-RNDR

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

Start

Read 1: noise $\sigma$

Open transfer gate

Read 2: noise $\sigma$

Clear charges

End

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

DEPFET-RNDR

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


Effective noise: \( \sigma_{\text{eff}} = \frac{\sigma}{\sqrt{N}} \)
DEPFET-RNDR single pixel performance

![Graph showing Dependency of equivalent noise on number of readout cycles](Eur. Phys. J. C77.12(2017)279)
DEPFET-RNDR single pixel performance

\[ \sigma_{\text{eff}} \sim \frac{1}{\sqrt{N}} \text{ confirmed} \]
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DEPFET-RNDR single pixel performance

Minimal noise limited by leakage current @ 233K (-40°C)
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DEPFET-RNDR single pixel performance

Predicted temperature dependence (only DC from thermal excitation) - to be verified
DEPFET-RNDR single pixel performance

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

Stirling-cycle cryocooler

Vacuum chamber
Prototype test setup

Outer shielding & support

Inner shielding & cooling pad

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

[courtesy of H. Shi]

[courtesy of H. Shi]
Prototype test setup

@ HLL

Detected assembly: to be assembled in mid 2019

[Outer shielding & support]
[Inner shielding & cooling pad]

[courtesy of H. Shi]
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Detector control and readout electronics

Flexible PCB

Pitch adaptors

Readout board: gate-control and readout ASICs

[courtesy of H. Shi]

[courtesy of J. Treis]
Prototype detector matrix:

- 64 pixel x 64 pixel
- Single pixel: 75µm x 75µm x 450µm
- Sensitive volume: 24mg
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Readout & control

Vacuum  Air

~ -170°C

Al wire-bonding

Room temp.

Sequencer program

DAQ PC

Spectrum ADC

DC power supply

[courtesy of H. Shi]

[courtesy of H. Shi]

[courtesy of J. Treis]
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Components are ready

Vacuum → Air

~ -170°C

Room temp.

[courtesy of H. Shi]
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Read-out sequence

Simplified $5\times5$ matrix, $N=1$

One preamp per column → To preamps (VERTIAS multiplexer)
Read-out sequence
Simplified 5x5 matrix, N=1

Initial charges
Read-out sequence
Simplified 5x5 matrix, N=1

Initial transfer

To preamps
(VERTIAS multiplexer)

Gate 1
(Switcher multiplexer)
Read-out sequence
Simplified 5x5 matrix, N=1

Initial transfer

Transfer gate
Gate 1
Gate 2
(Switcher multiplexer)
To preamps
(VERTIAS multiplexer)
Read-out sequence

Simplified 5x5 matrix, N=1

Initial transfer
Read-out sequence
Simplified 5x5 matrix, N=1

Initial transfer

Transfer gate

Gate 1

Gate 2
(Switcher multiplexer)

To preamps
(VERTIAS multiplexer)
Read-out sequence
Simplified 5x5 matrix, N=1

Signal readout 1

To preamps
(VERTIAS multiplexer)
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

Transfer gate

To preamps
(VERTIAS multiplexer)

Gate 1
(Switcher multiplexer)

Gate 2
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Read-out sequence
Simplified 5x5 matrix, N=1

Signal transfer

Transfer gate
Gate 1
(Switcher multiplexer)
Gate 2
To preamps
(VERTIAS multiplexer)
Read-out sequence
Simplified 5x5 matrix, N=1

Baseline readout 1

To preamps
(VERTIAS multiplexer)

Gate 1
(Switcher multiplexer)
Read-out sequence
Simplified 5x5 matrix, N=1

Signal readout 2

To preamps (VERTIAS multiplexer)
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

Transfer gate

To preamps
(VERTIAS multiplexer)

Gate 1
(Switcher multiplexer)

Gate 2
Read-out sequence
Simplified 5x5 matrix, N=1

Baseline readout 2

Transfer gate

Gate 1
(Switcher multiplexer)

Gate 2

To preamps
(VERTIAS multiplexer)
Read-out sequence
Simplified 5x5 matrix, N=1

Repeat N-times
Go on to next row

Transfer gate

Gate 1
(Switcher multiplexer)

Gate 2

To preamps
(VERTIAS multiplexer)
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Simplified 5x5 matrix, N=2

Transfer gate

Gate 1 on

Gate 2 on

Clear gate

VERITAS sequence
read one row

Simulated waveform
(5 repetition cycle)
Read out sequence

Simulated waveform (5 repetition cycle)

Sequence tested on simulator

→ Next: test on running electronic
Physics perspective
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• 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

Initial goal: 0.9 g.yr

→ 40 matrices à 24mg
→ ~1g sensitves 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
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Expected 1 day exposure compared to SENSEI

[Graph showing expected exposure with SENSEI prototype physics run and DANAE prototype 24 mg one-day exposure with zero background expected reach (Preliminary)].

[Graph showing DM-electron cross section with Preliminary notes from SENSEI homepage].

[Courtesy of H. Shi (ICHEP2018)].
A comparison with skipper CCD

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

similar concepts of non-destructive readout, compatible performance; different architecture, different systematics; -> good complementary from experimental point of view

[courtesy of H. Shi (ICHEP2018)]
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DEPFET with RNDR

RNDR: repetitive non-destructive readout

structure of a basic DEPFET cell: a “subpixel”

structure of RNDR DEPFET “super-pixel”

Fully-depleted n-Si

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

[courtesy of H. Shi (ICHEP2018)]
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compact RNDR & blind
structure name RNDR_GPIX
chip size 8.5 x 8.0 mm²
format 64 x 64
pixel size 75 x 75 µm²
PXD7 chip D.03
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Cooling & shielding layout

- top-out
- bot-out
- top-inner
- window
- top out
- top inner

outer shielding : support structure
inner shielding : cooling contact

[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

<table>
<thead>
<tr>
<th>Switcher-S</th>
<th>64x2 channel analog multiplexer</th>
<th>Readout board</th>
</tr>
</thead>
<tbody>
<tr>
<td>switcher id</td>
<td>W</td>
<td>N</td>
</tr>
<tr>
<td><strong>function</strong></td>
<td>Gate 1 &amp; 2</td>
<td>Gate common</td>
</tr>
<tr>
<td>Voltage [V]</td>
<td>-2.5 ~ + 5</td>
<td>-0.5 ~ +20</td>
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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

[courtesy of H. Shi (ICHEP2018)]
Detector Structures – Matrix Devices

- **readout sequence**
  - DEPFET turned ON
  - CLEAR
  - DEPFET turned OFF

  Correlated double sampling:
  - 1st measurement: signal + baseline
  - clear: removal of signal charges
  - 2nd measurement: baseline
  - difference = signal
  - complete clear is mandatory!

- **matrix operation**

- **option to speed up (1)**
  - readout parallelisation
  - 2 x readout channels, 2 active rows

February 19, 2019