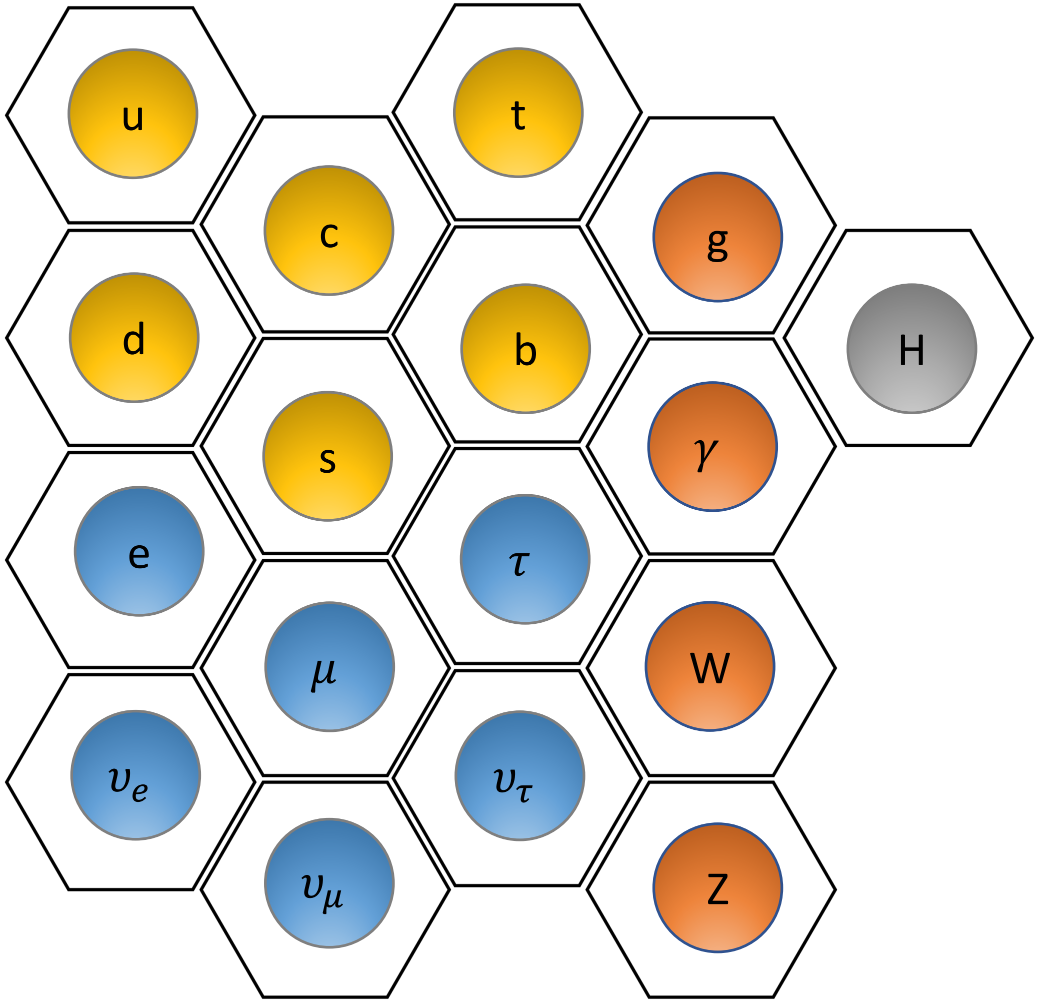
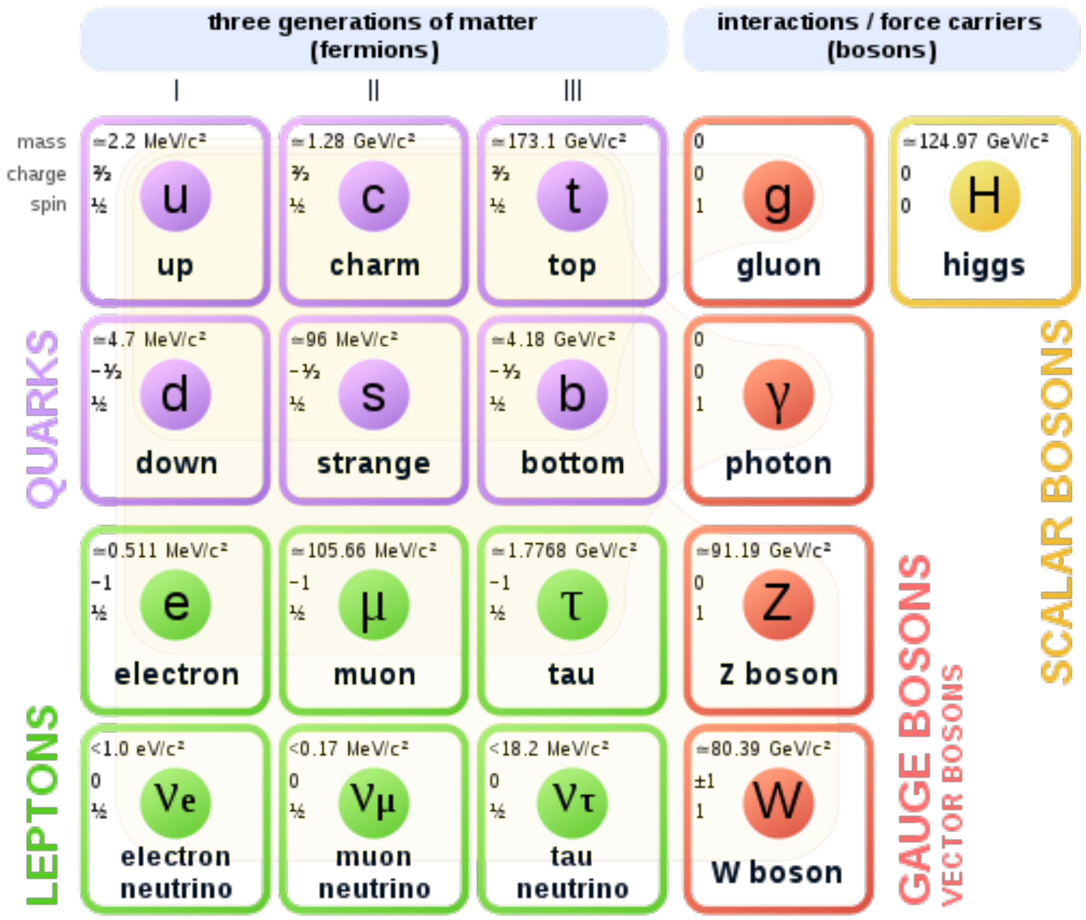
Silicon Detectors in (low energy) Particle Physics

Susanne Mertens, MPP/TUM

30.9.2021



Standard Model of Particle Physics (SM)



- SM describes most phenomena observed
- But, we know that is cannot be complete
  - Theoretical problems: e.g. prediction of the Higgs mass (hierarchy problem)
  - Tensions between theory and high-precision experiments (e.g. magnetic moment of the muon)
  - **Most pressing problem:** it does not provide a suitable dark matter candidate
- Goal find physics beyond the SM!

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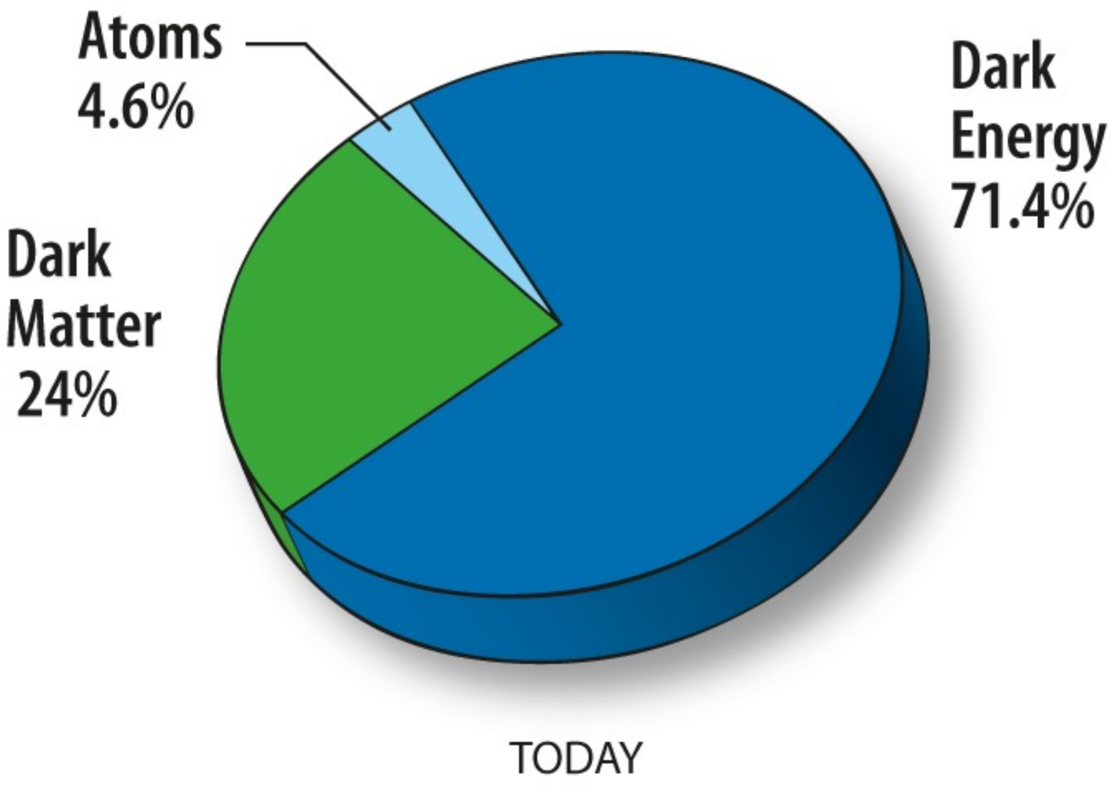

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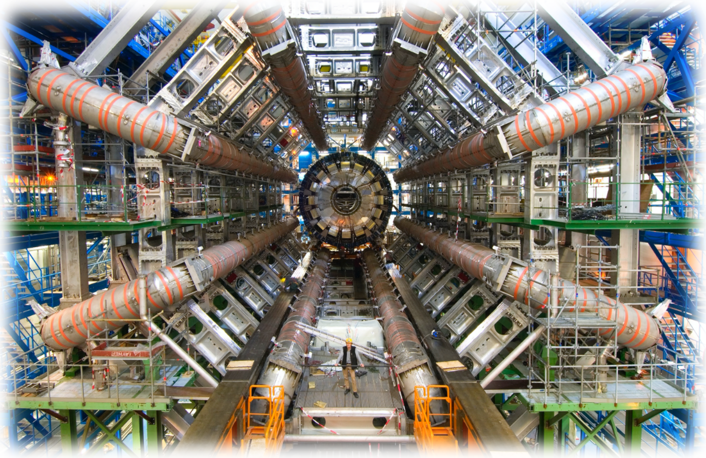
Beyond the Standard Model (SM)

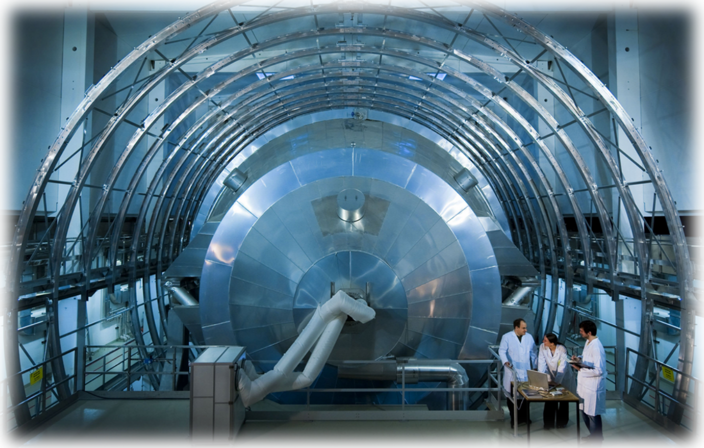
"High Energy" Frontier

Idea: produce a new particle at a collider



"Low-Energy" Frontier

Idea: find a small signal of new physics in a high-precision or low background measurement



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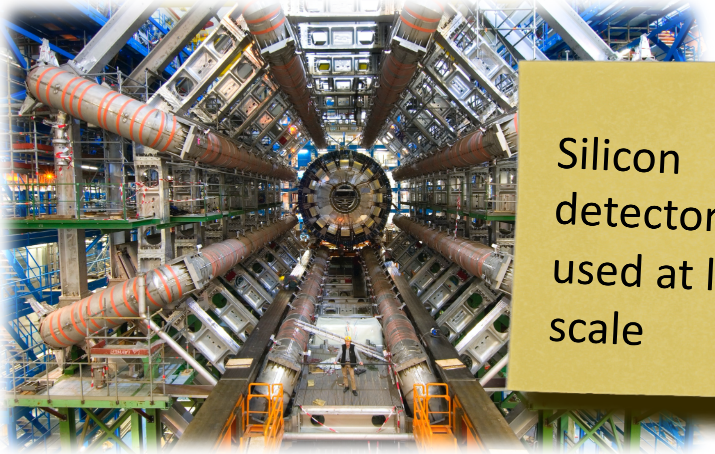

Silicon detectors used at large scale

“Low-Energy” Frontier

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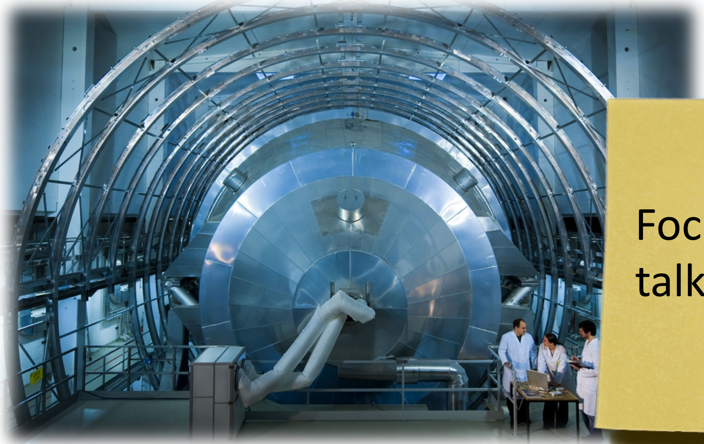
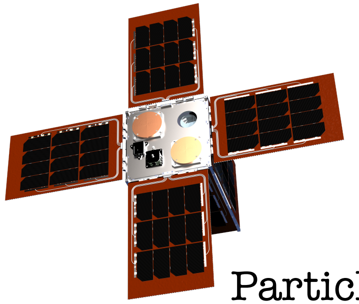


Focus of this talk

Examples (my personal choice)



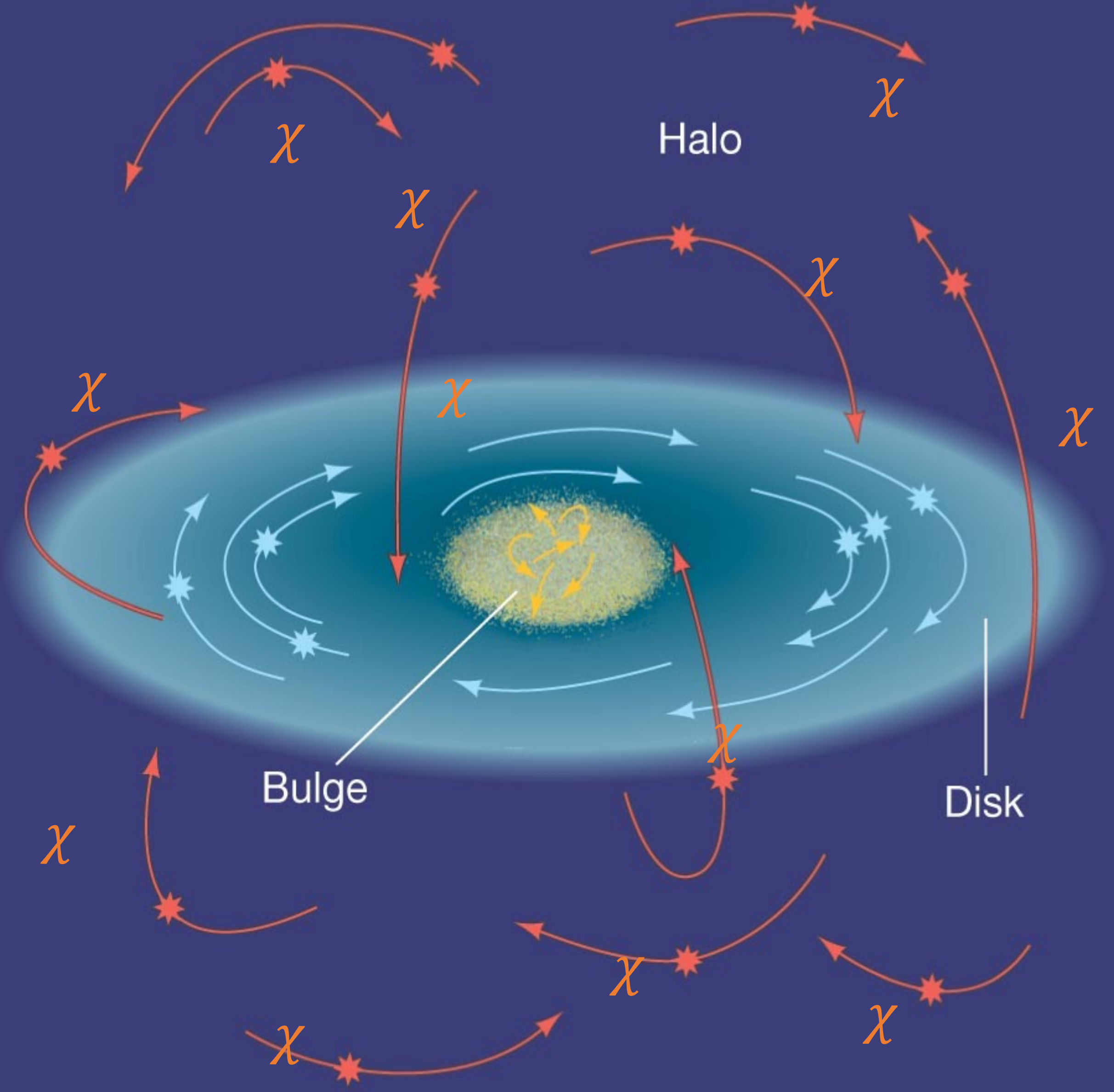
Particles as messengers

Low-background
Rare-event search

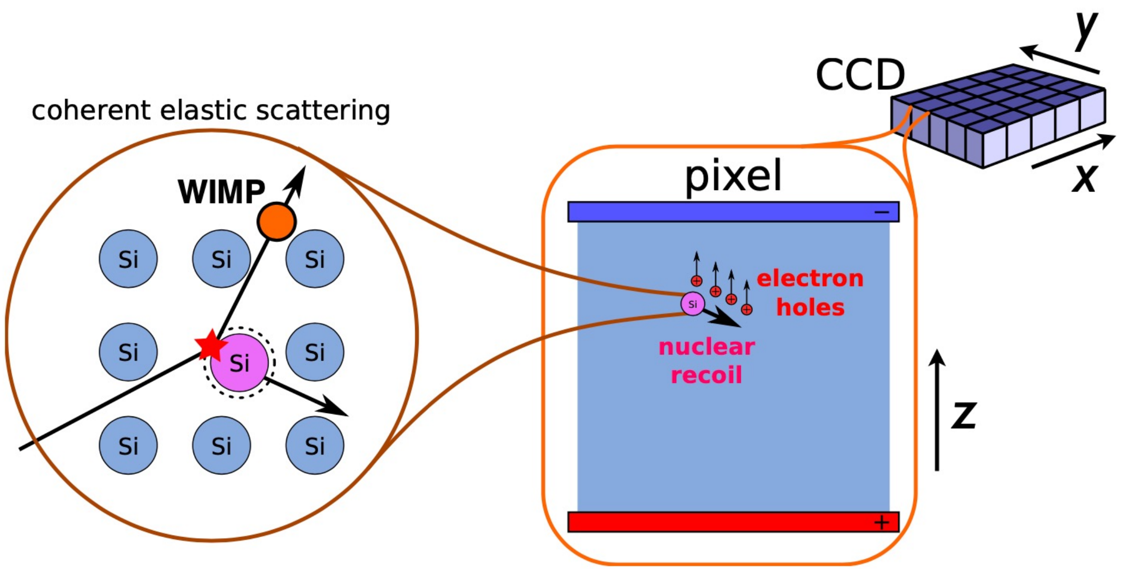
The Selena Neutrino Experiment

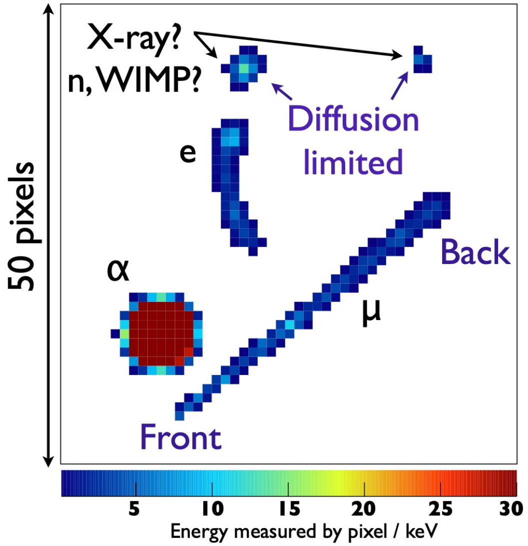
High precision
measurement

- Direct Dark Matter experiment
- Our galaxy is filled with dark matter (0.3 GeV/cm^3)
- Goal: direct detection of dark matter particle on earth



- Dark matter search with CCDs at SNOLAB and later at Modane
- Dark matter particle (WIMP) scatters off a nucleus, recoil energy (~ keV) is detected (1 event/kg/year for 100 GeV WIMP)
- Advantages of CCDs:
    - low energy threshold (~eV) allows to detect small recoil energies (low mass WIMPs)
    - High spatial resolution allows for particle identification
- Challenge:
    - Low background
    - Large mass (~ kg)

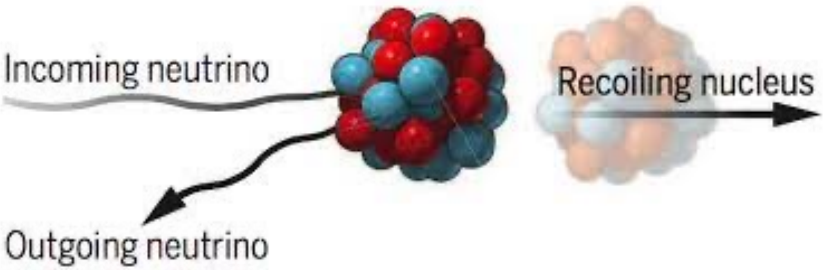


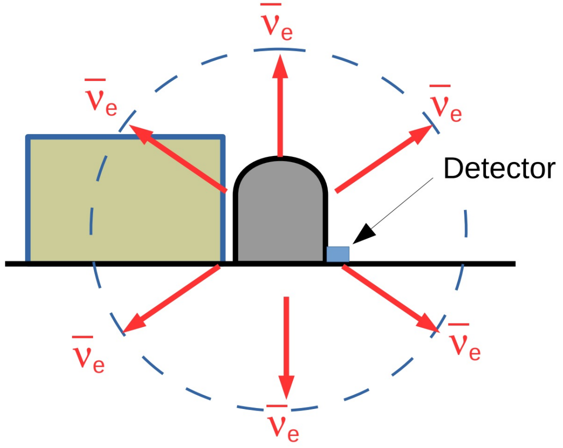


- 16 Mpixel (15 μm x 15 μm)
- 675 μm thick (high-resistivity Si and low donor density for depletion at low voltage)
- Operated at 140 K
- 40-g total mass
- Produced at LBNL

Phys. Rev. Lett. 125 (2020) 241803

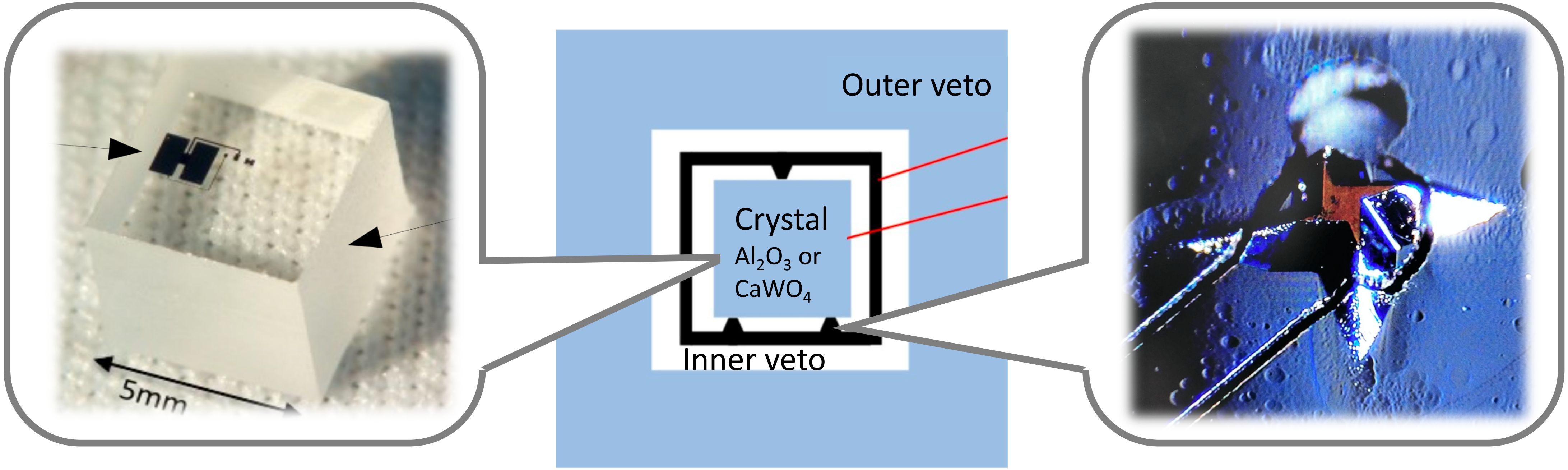
- Coherent Elastic Neutrino-Nucleus Scattering (CEνENS)
- Process first detected in 2017.
  Now, very topical field!
- CONNIE: Detection of CEνENS of reactor neutrinos with CCD detectors
  (< 1 count/day/10g)
- Challenge (similar as for DM search):
  - **Low threshold** (~ 10 eV)
  - Large mass (~ kg)
  - Low background
- So far, no detection. Upgrades are planned





Phys.Rev.D 100 (2019)

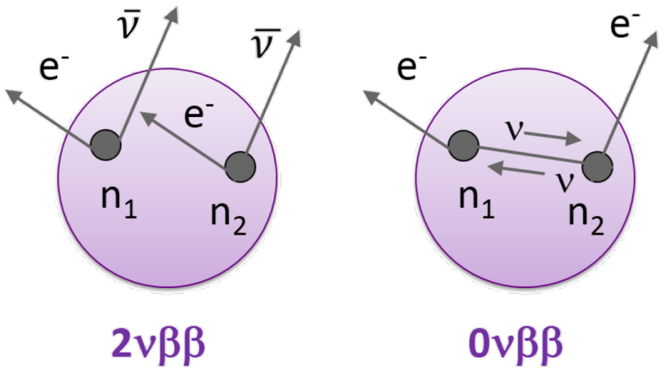
- Coherent neutrino scattering experiment with reactor neutrinos and **cryogenic detectors**
- Active inner veto made of Si
  with pyramidic holding structures produced via wet chemical etching at HLL

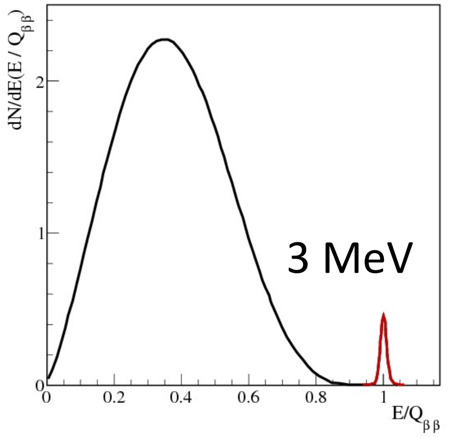


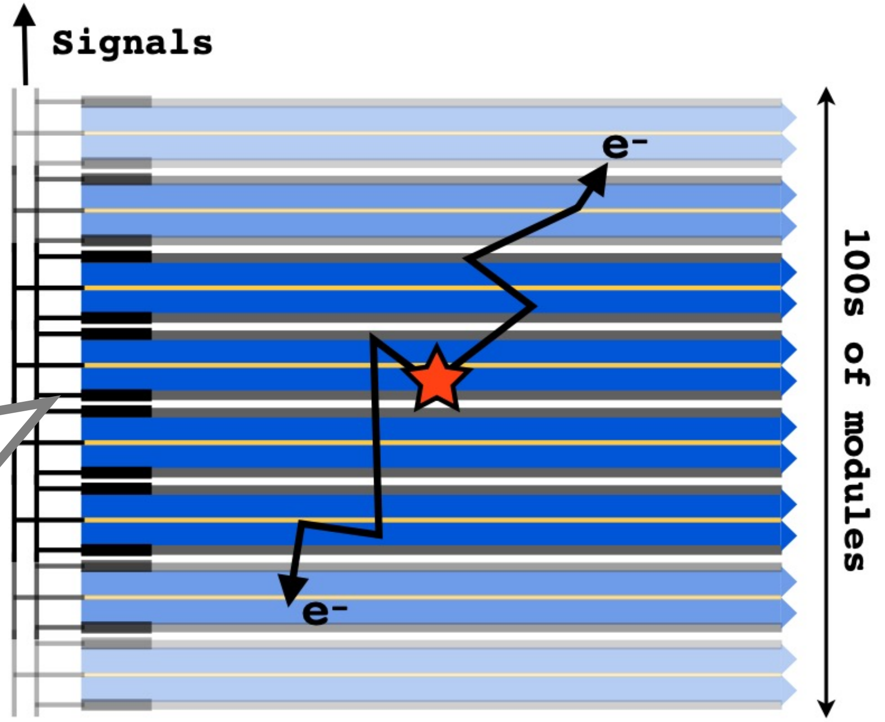
Eur. Phys. J. C 77 (2017) 506

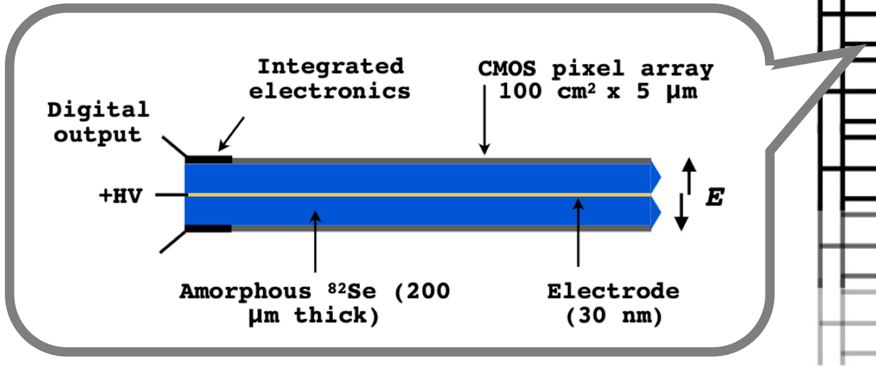
SELENA Experiment

- Search for neutrinoless double beta decay
  (< 1 event/tonne/year)
- One of the most fundamental open questions in physics
- SELENA: Search for $0\nu\beta\beta$ in ^{82}Se with CMOS pixel array
- Advantages of CMOS pixel arrays:
  - Energy resolution
  - Spatial resolution → signal identification
- Challenge:
  - Low background
  - Large mass
    (tonne scale)

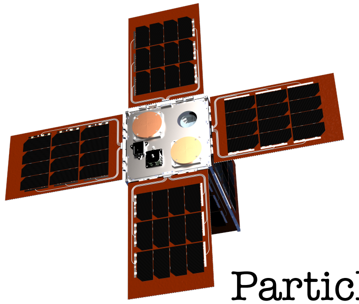








Examples (my personal choice)



Particles as messengers

CONNIE

nucleus EXPERIMENT

DAMIC-M

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IAXO

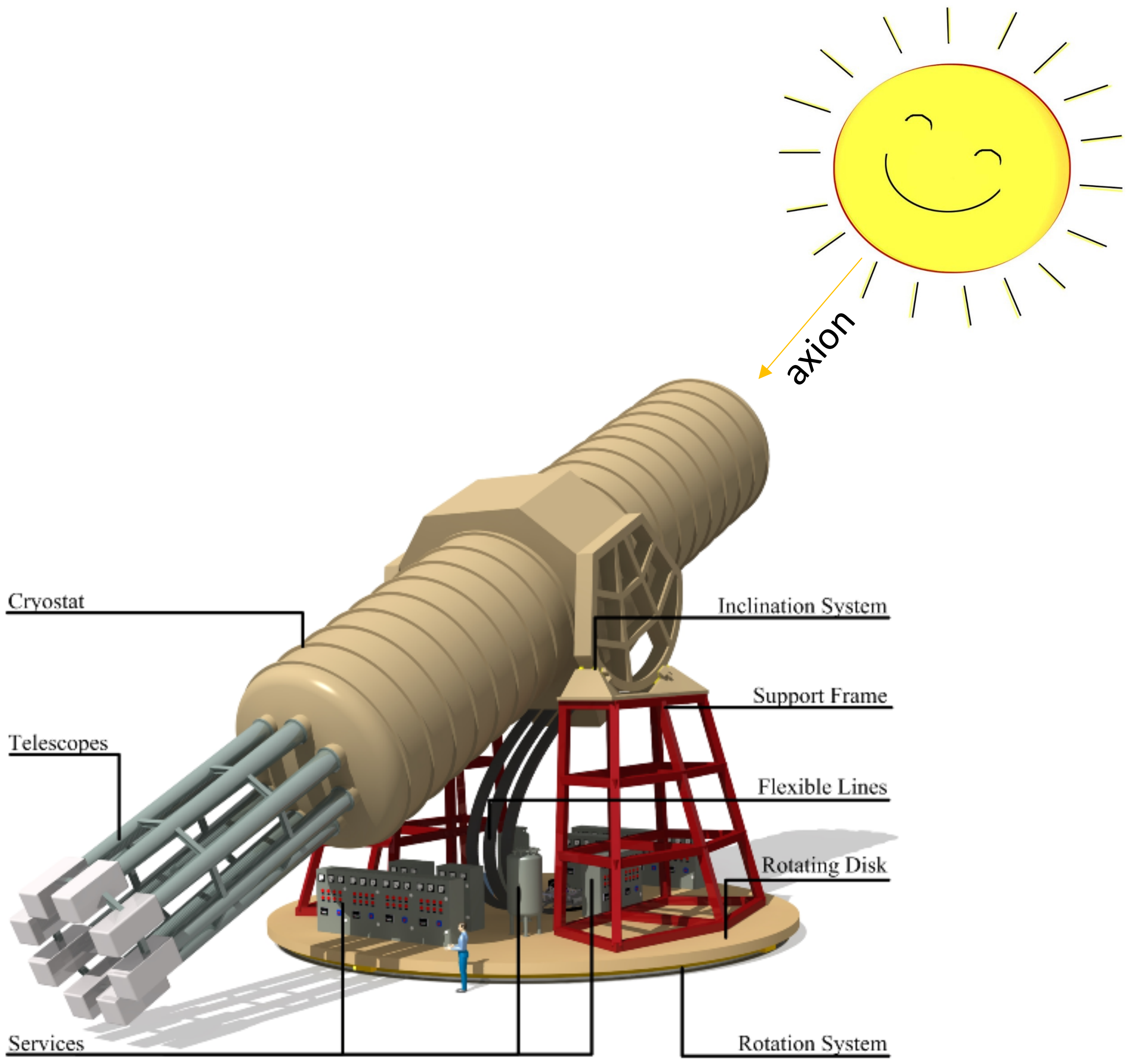
Belle II

High precision
measurement

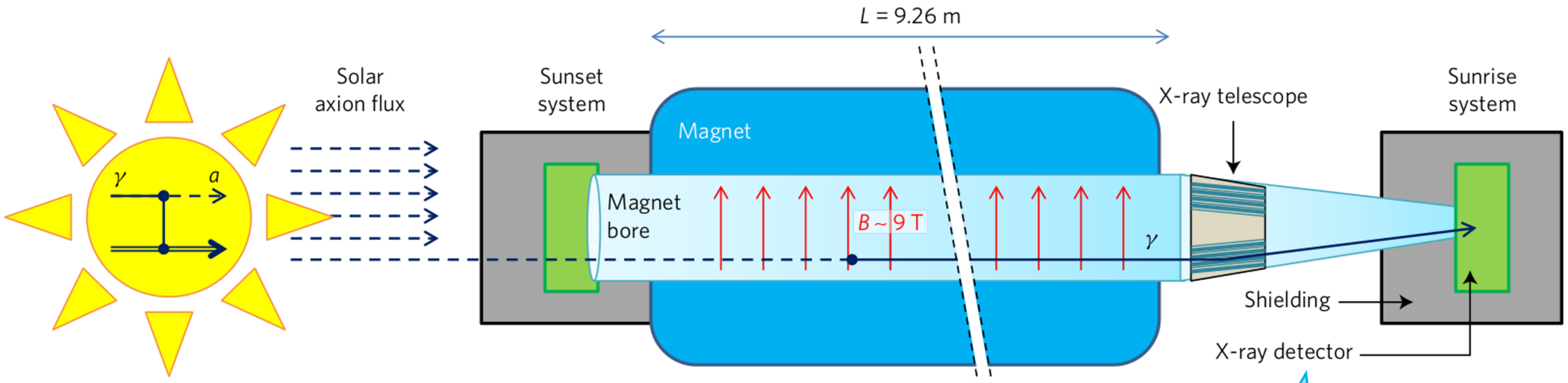
PERC

TRISTAN

* Next-generation solar axion search
* Axion = dark matter candidate
* Successor of successful CAST experiment
  * Used CCD detectors from HLL



IAXO - working principle

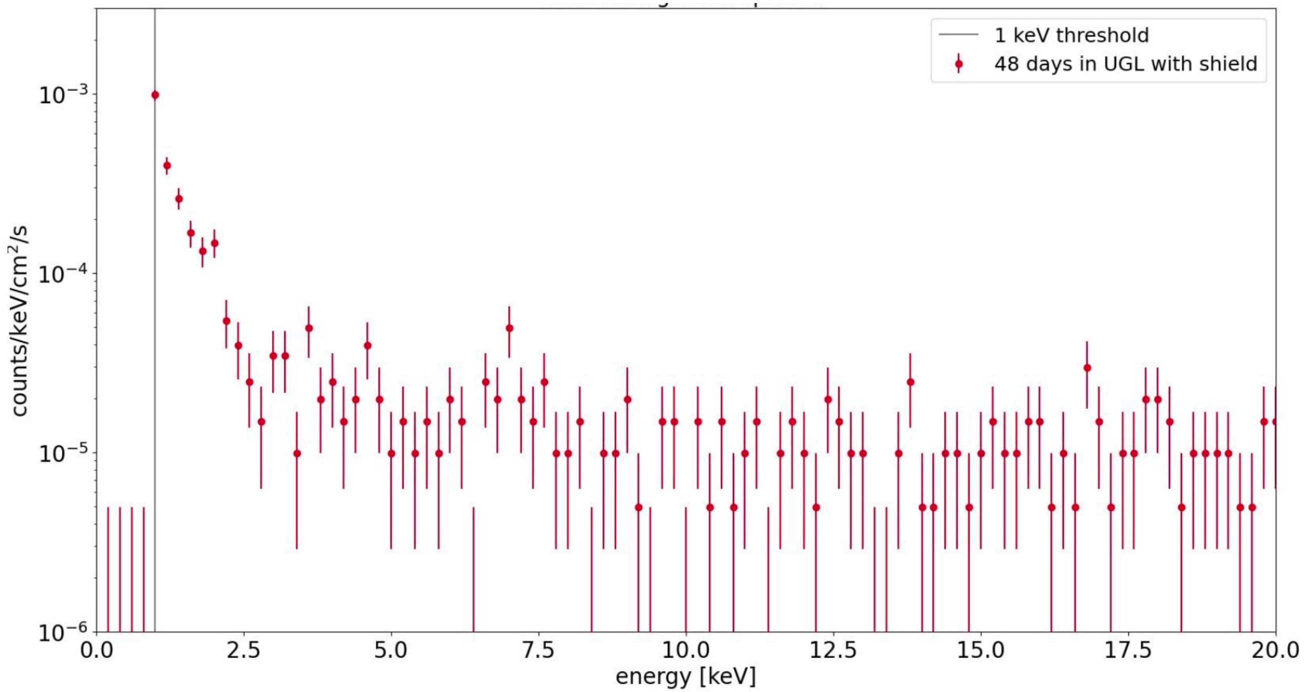


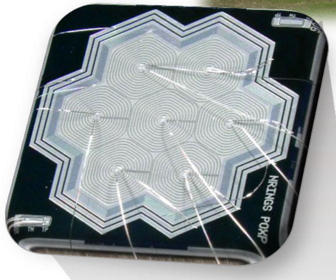
- Advantages
  - Good energy resolution and linearity
  - High quantum efficiency up to 10 keV (would be nice to cover 15 keV x-rays)
  - Operation at room temperature
  - Radiopure material
- Challenge:
  - Expect 1 count/year/keV/cm^2 → low background

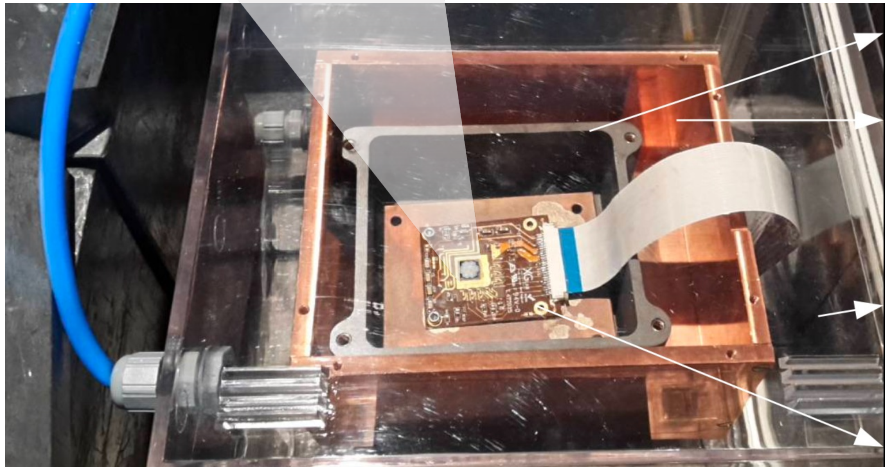
Possible solution:
Silicon Drift Detector

First measurements

- 7-pixel prototype detector on kapton PCB in shallow underground lab
- Bg: 1.2x10^{-5} counts/s/keV/cm^2 (ROI: 2.5 – 20 keV)

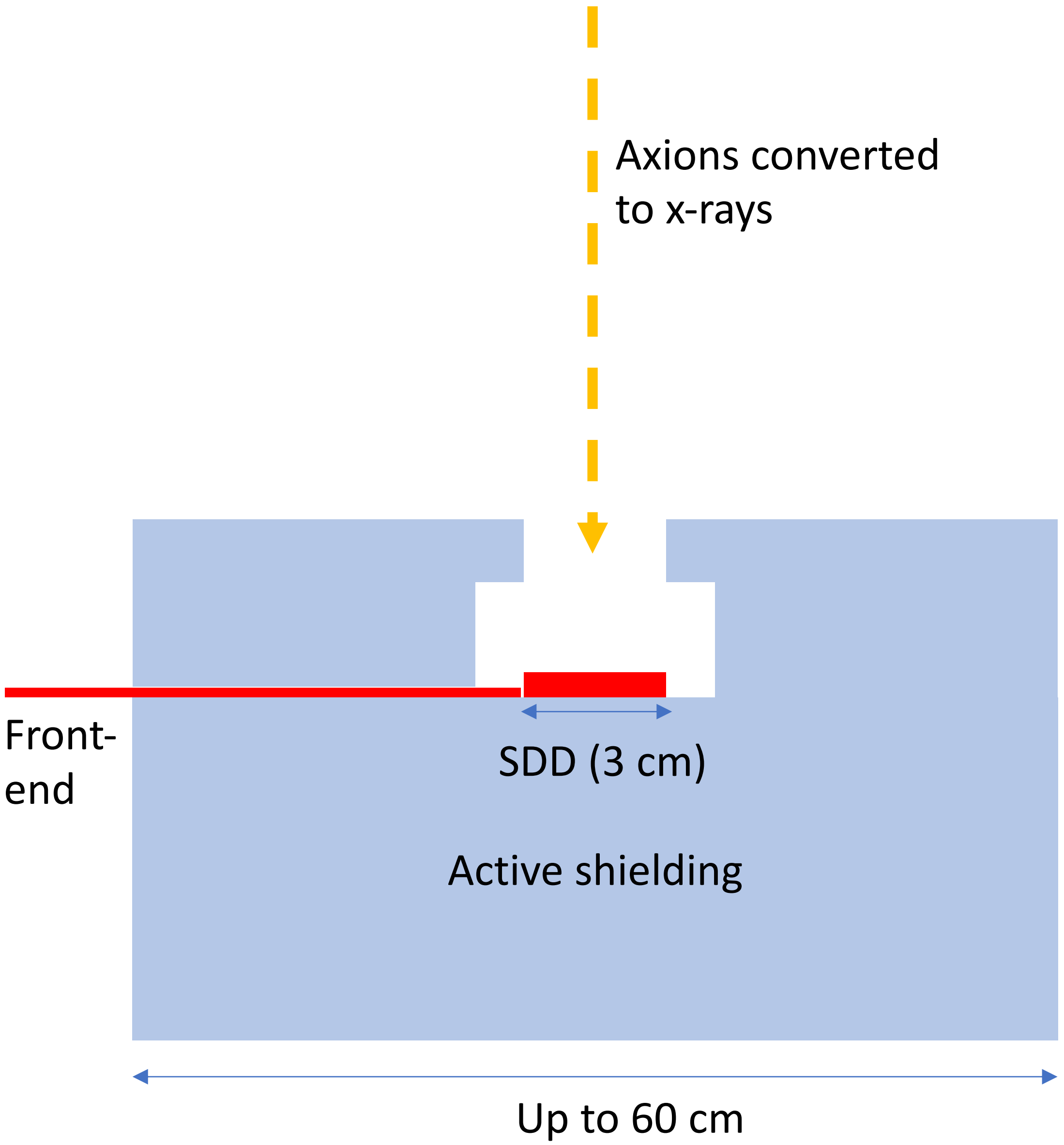






Next steps

- Optimize SDD layout (with integrated FET)
- Develop shielding concept
- Discussion with HLL ongoing



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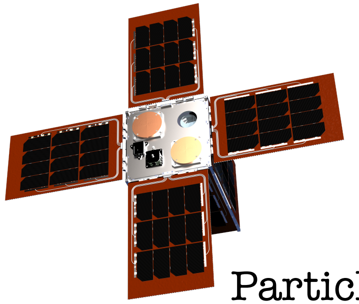

Particles as messengers

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Belle II

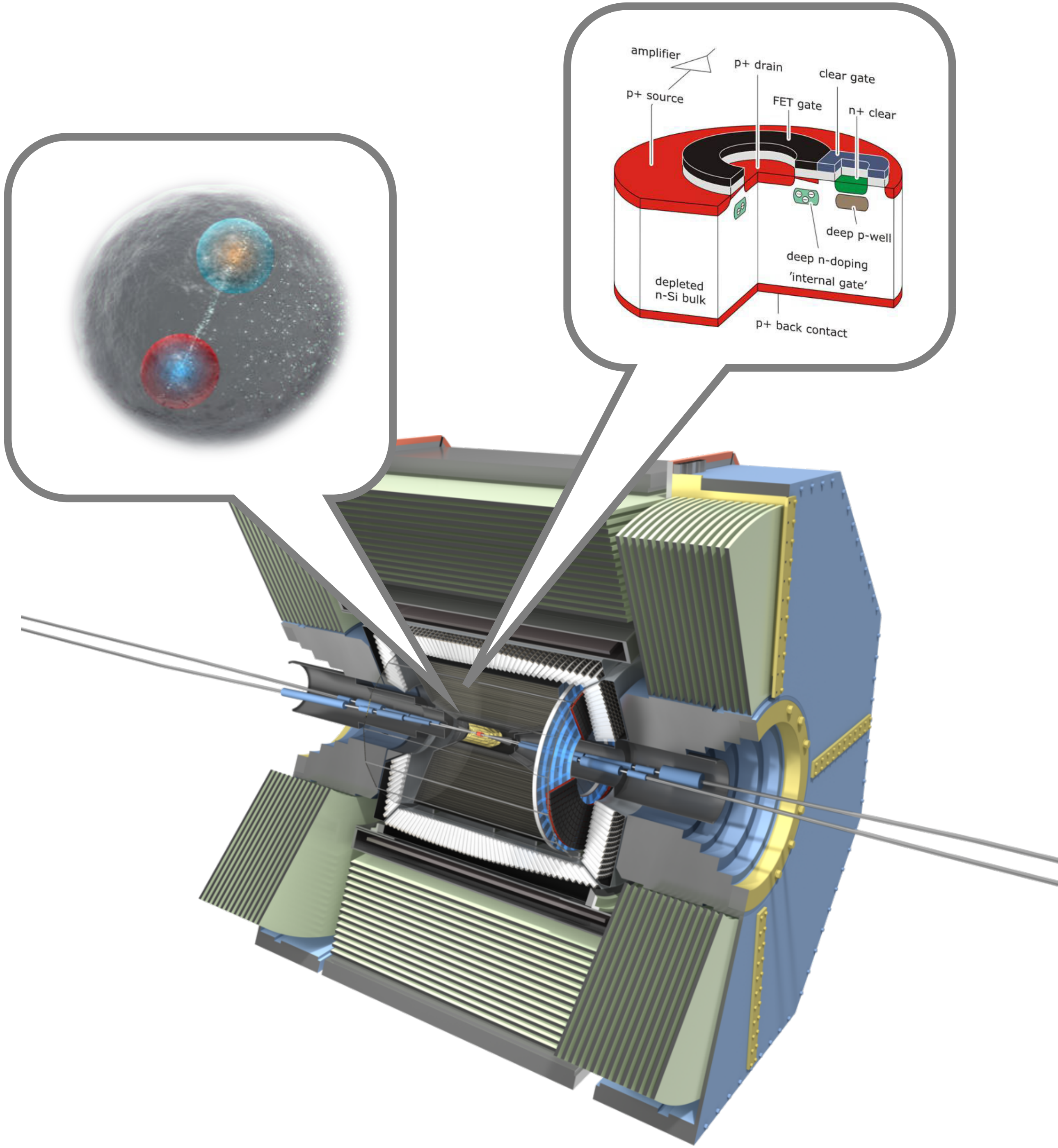
High precision
measurement

PERC

TRISTAN

Belle II - experiment

- SuperKEKB (e+ e- collider) in Japan
- B-Factory (heavy particle with b-quark)
- Ultra-precise measurement of weak interaction parameters to find new physics
- Inner vertex detector system made of DePFET detectors from HLL
- Advantages:
  - Chip on sensor concept
  - Low mass, all-silicon device
  - High pixelization
  - Suitable for high rate application
- Started data taking in 2018/2019



NIM-A 936 (2019), *NIM-A* 958 (2020)

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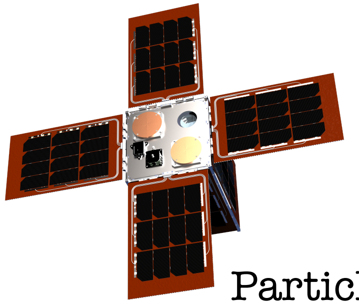

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High precision measurement

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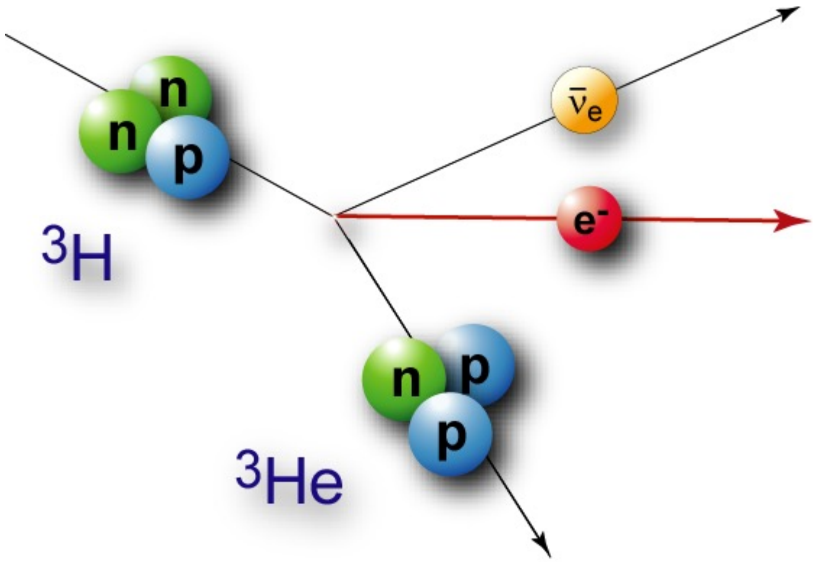
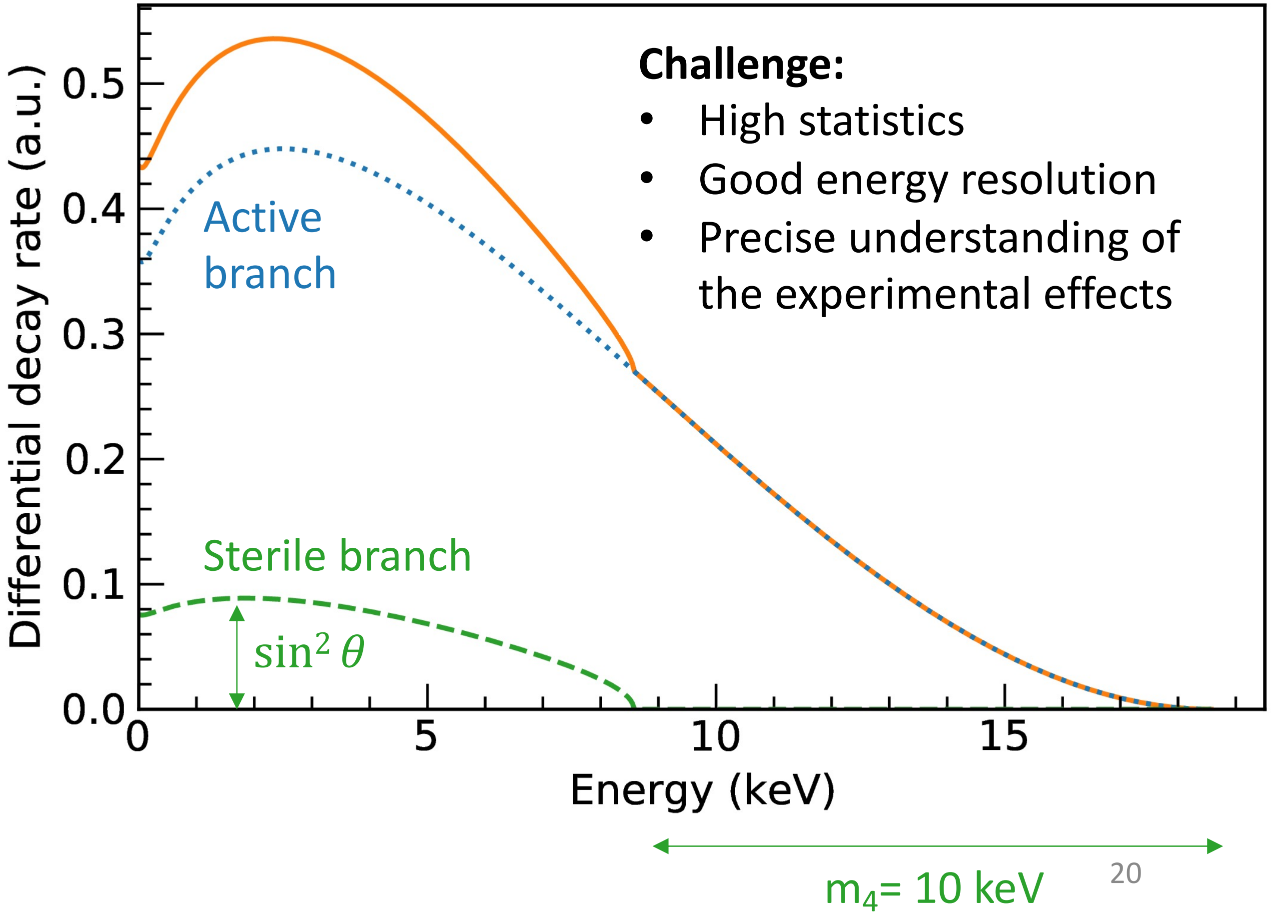
- Search for ***sterile neutrinos*** is ultra-high precision beta spectroscopy of tritium
- Sterile neutrinos = dark matter candidate





Mertens et. al. Phys. Rev. D91 (2015)
Mertens et. al. JCAP 1502 (2015)

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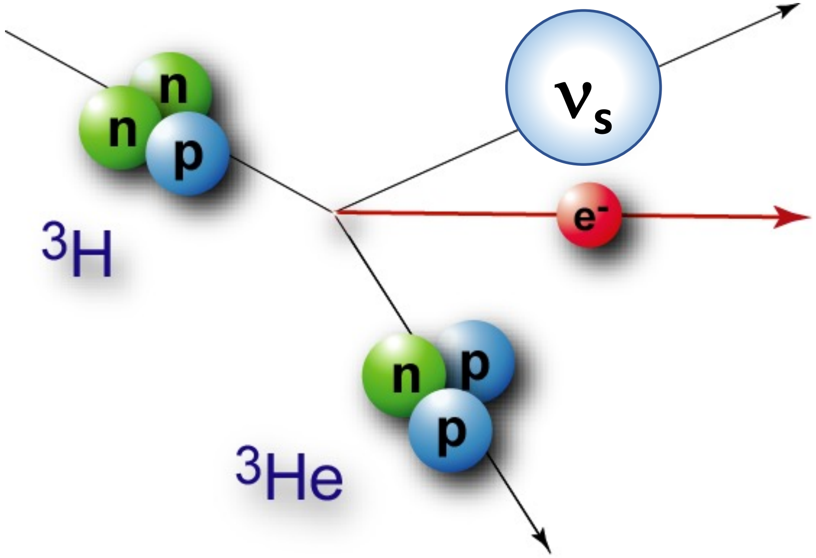

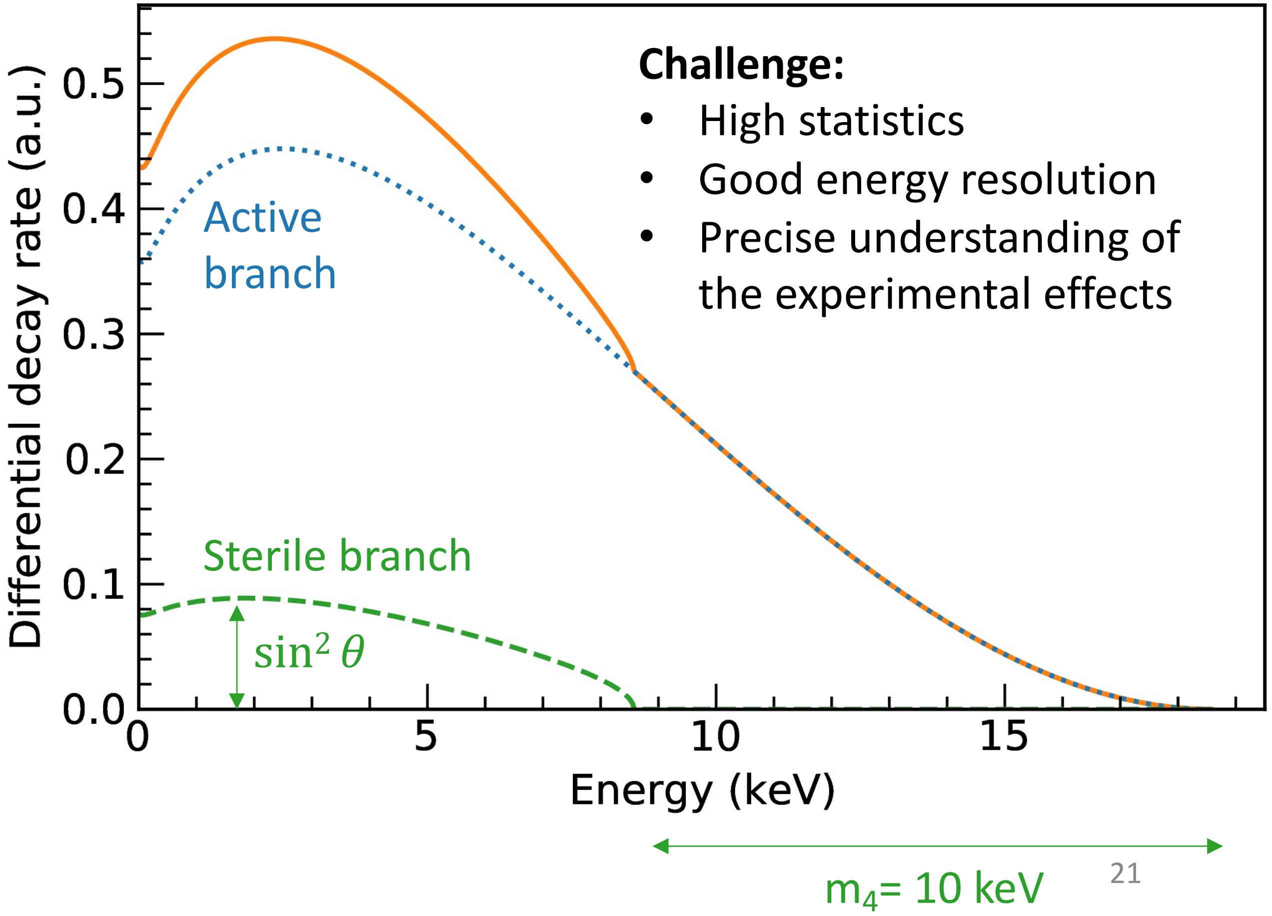

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The world's strongest tritium source @ KATRIN

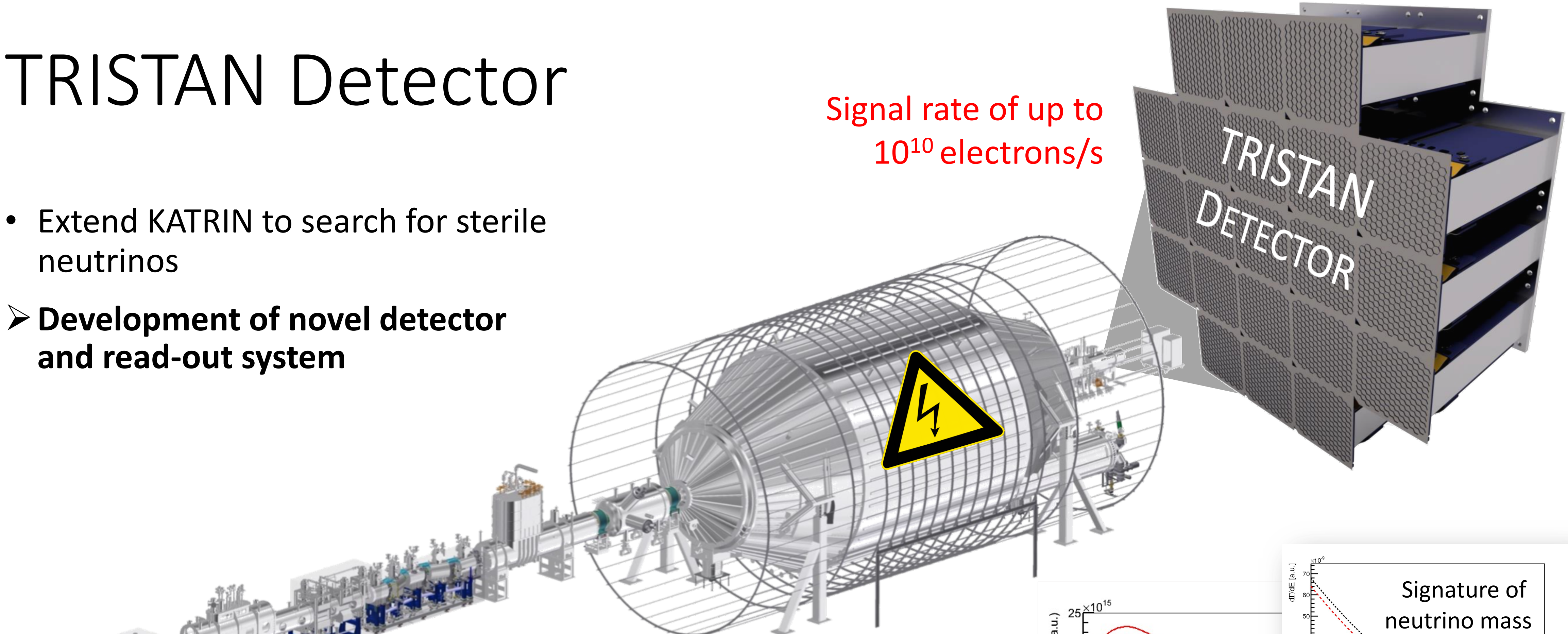
The world's strongest tritium source @ KATRIN

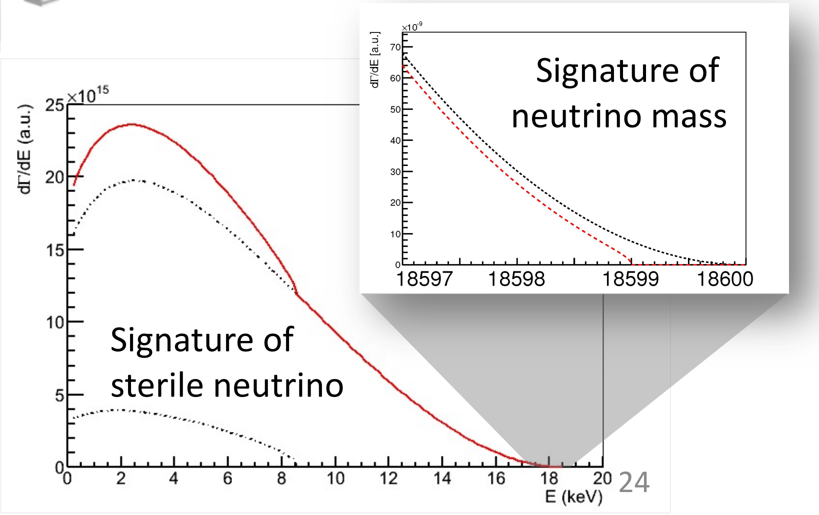
- ➢KATRIN is designed to measure the neutrino mass (200 meV @ 90% CL)
- ➢First sub-eV limit published recently
  (PRL 123 (2019), PRL 126 (2021), PRD 104 (2021), arXiv:2105.08533 (2021))

TRISTAN Detector

- Extend KATRIN to search for sterile neutrinos

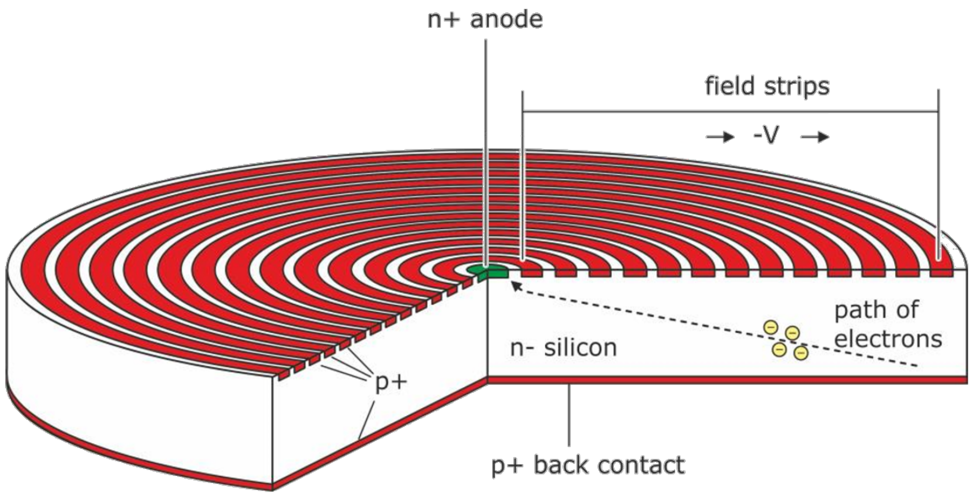
➢ **Development of novel detector and read-out system**

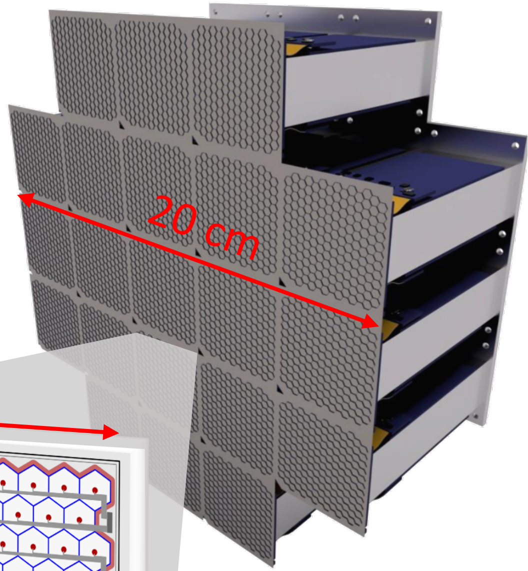




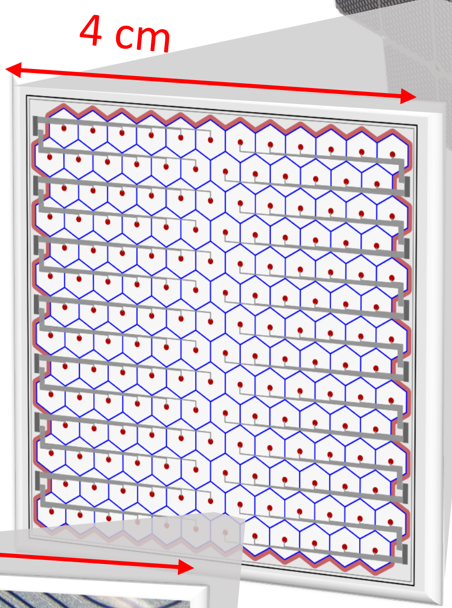
TRISTAN detector design

- Silicon drift detector (SDD) technology
- Advantages:
  - Capability of handling high rates (> 10^8 cps)
  - Excellent energy resolution (300 eV @ 20 keV for electrons)
- Challenge:
  - Application to electrons (thin deadlayer, understanding of response)
  - Large-scale focal plane array

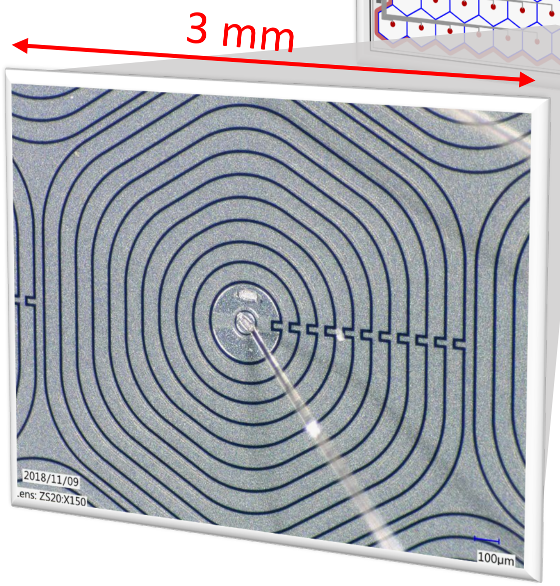




Full detector
21 x 166 pixels
= 3486 pixels



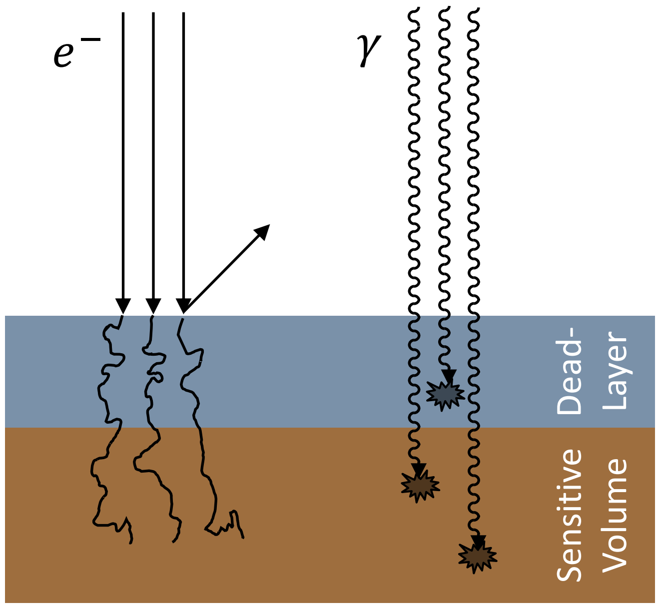
Detector module
166 pixels



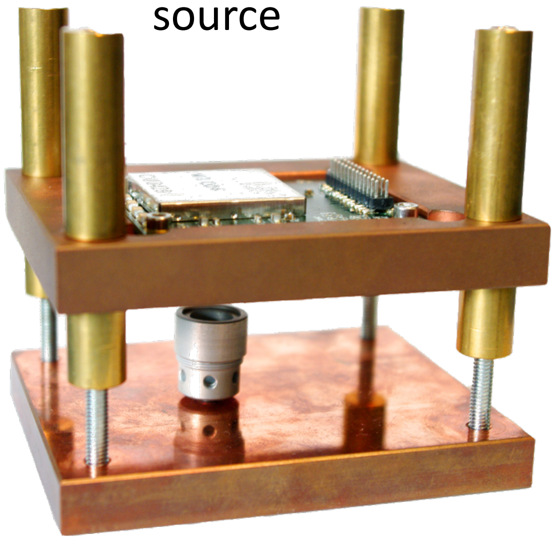
Detector pixel

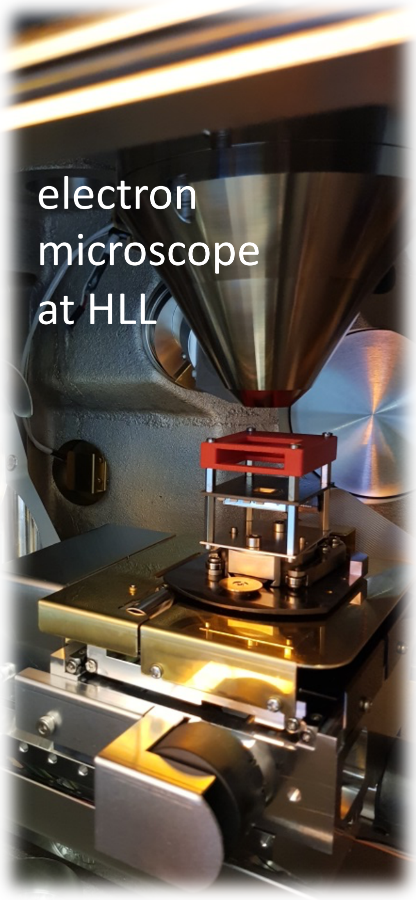
Characterization with electrons

- detailed characterization of entrance window + backscattering
- scanning electron microscope + evaporated krypton source



^{83}Rb/^{83m}Kr source

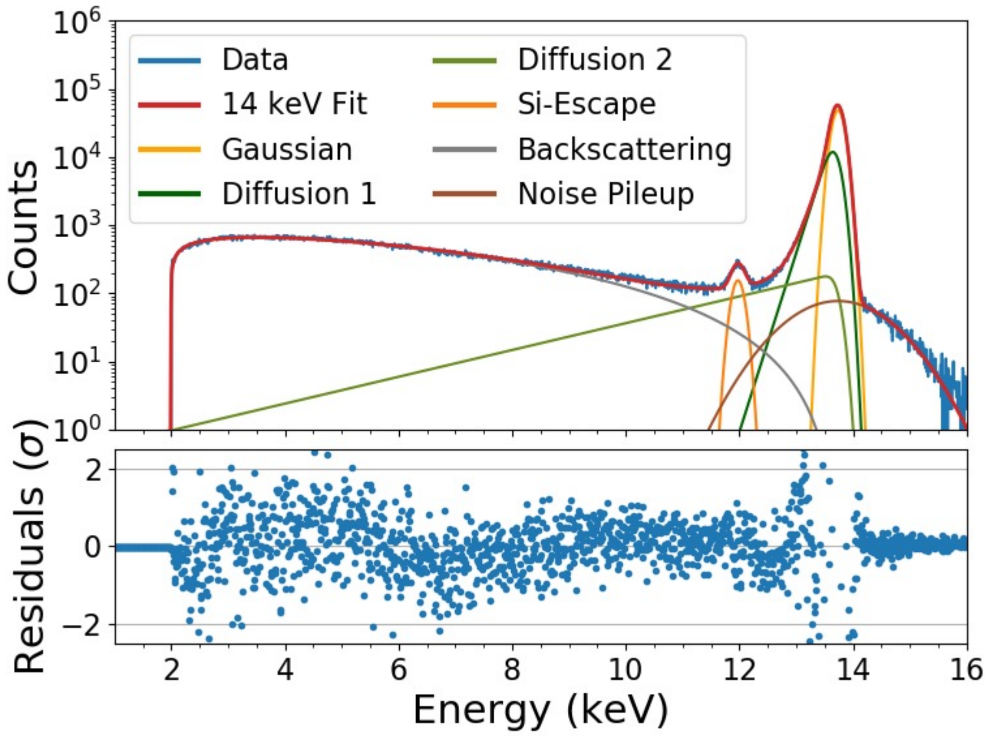


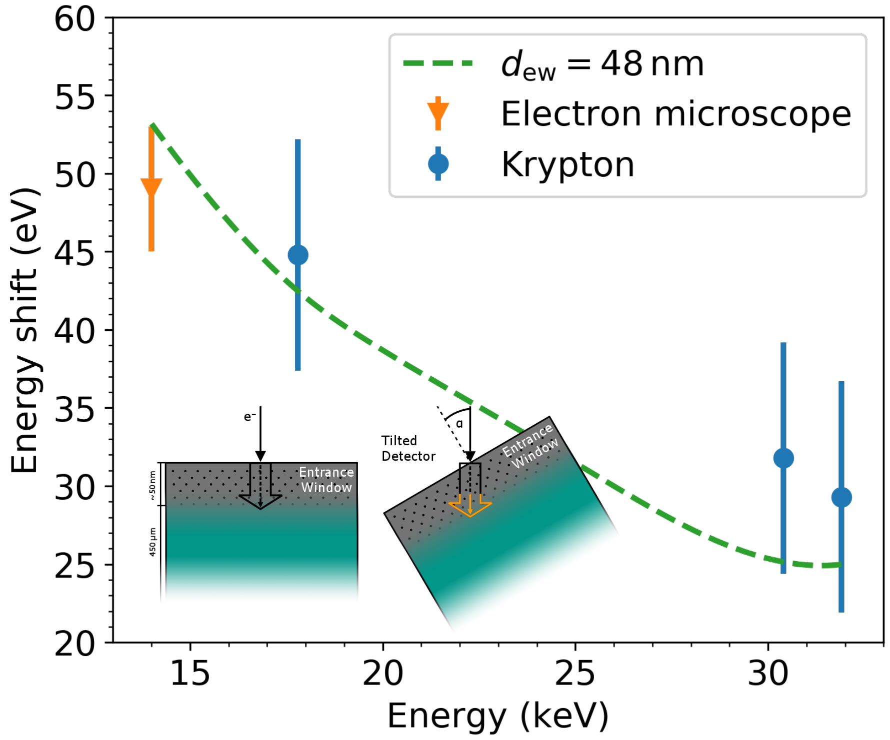


Characterization with electrons

✓ good understanding and modelling of electron response

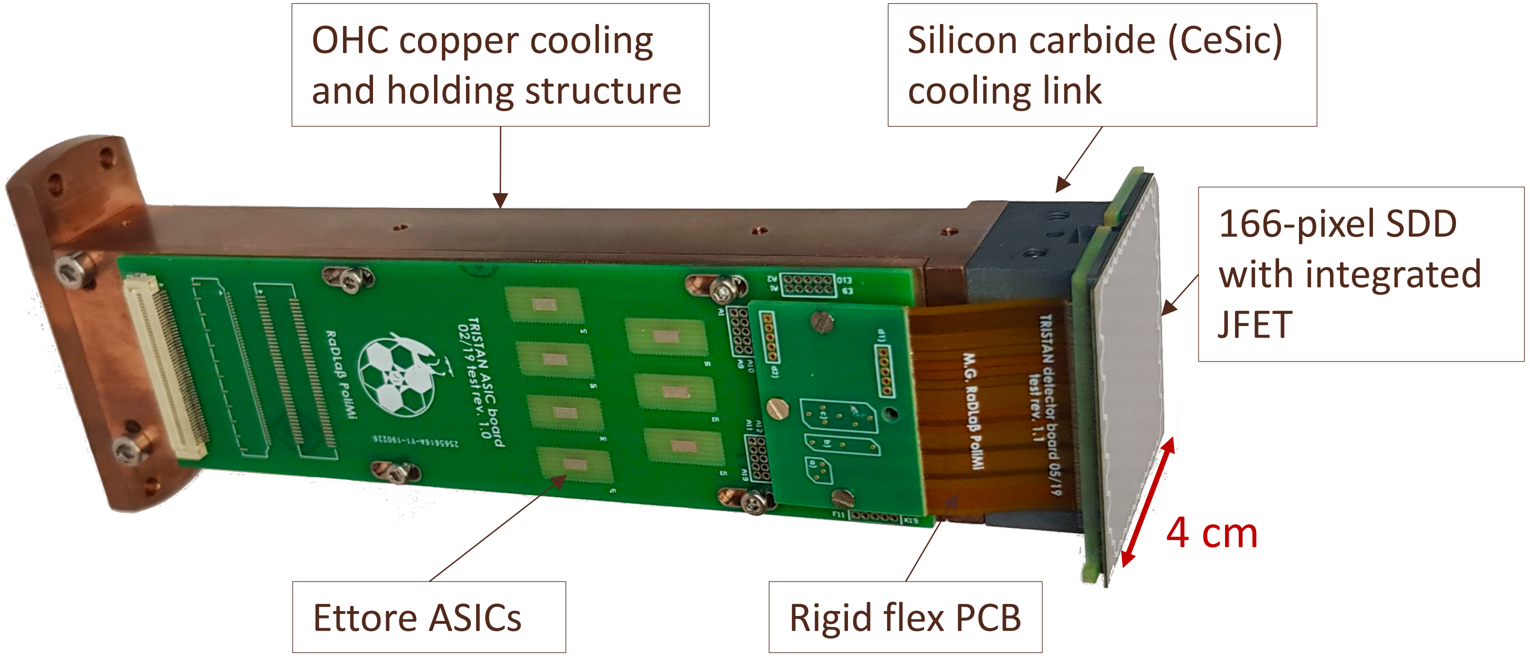
✓ thin effective entrance window: < 50 nm → new technology under investigation



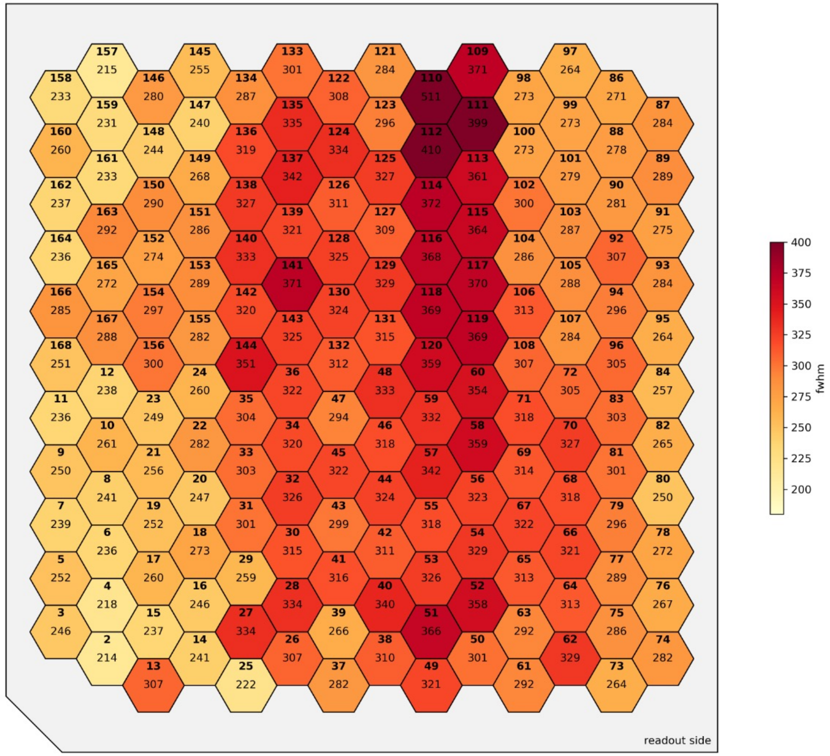


S. Mertens et al, J. Phys. G (2020)

TRISTAN module



166-pixel spectra

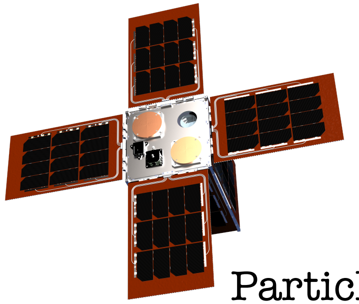


- Module (47 channel) is operating in KATRIN setup
- First 166-pixel spectra recorded @ Polimi
- Implementation of 9-modules in KATRIN in 2024

POLITECNICO
MILANO 1863

doi: 10.1109/NSS/MIC42677.2020.9507856

Examples (my personal choice)



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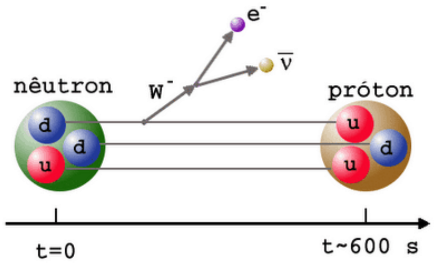
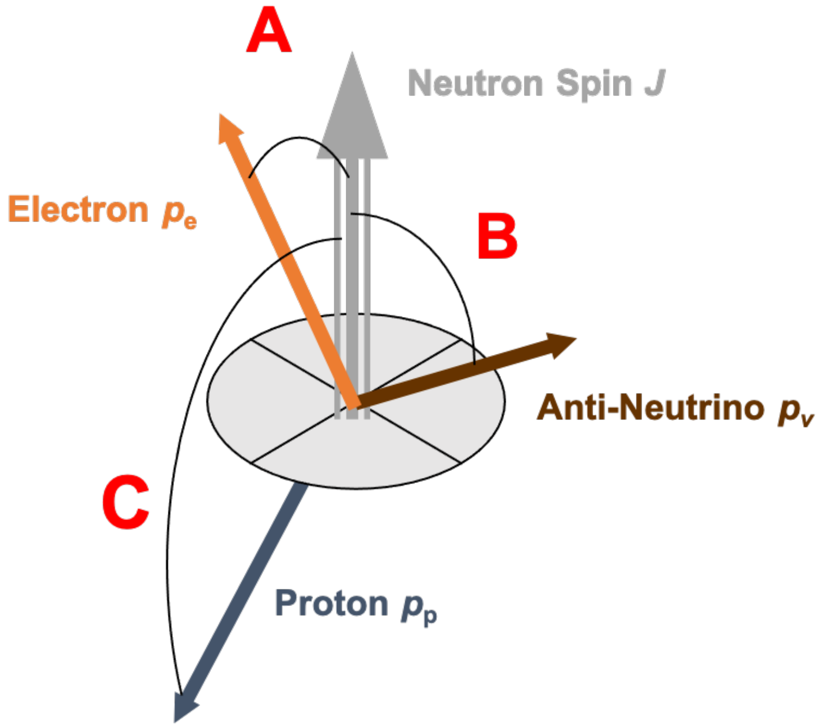
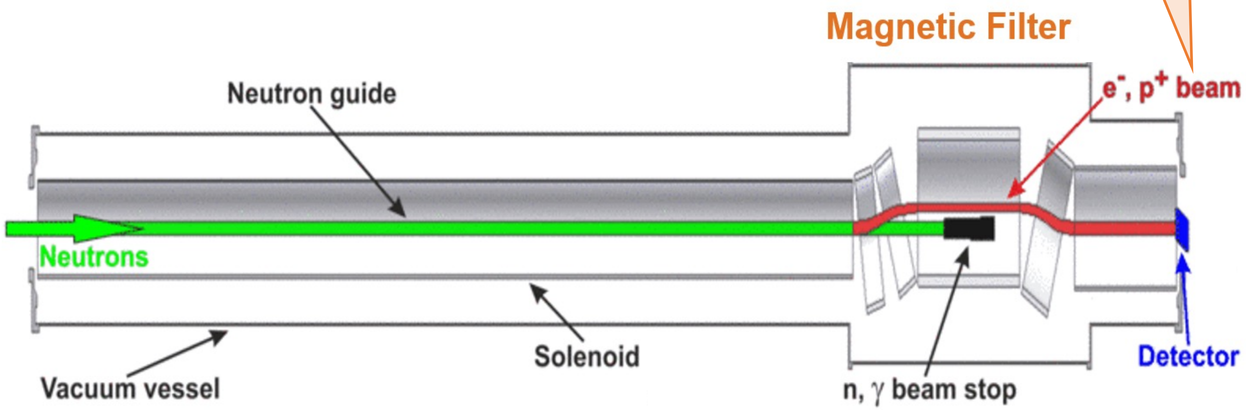


- Precision measurements of neutron decay parameters (lifetime, correlations of spin and momentum)
- Theoretically extremely well understood – search for deviations from SM prediction
- Advantages of Si-detector
  - Energy resolution
  - Energy linearity
- Challenges
  - Detection of e^- with up to 1 MeV (Si-detector with ~mm thickness are needed)
  - ns timing resolution is important
  - Proton detection (e.g. via post-acceleration) (very thin deadlayer)



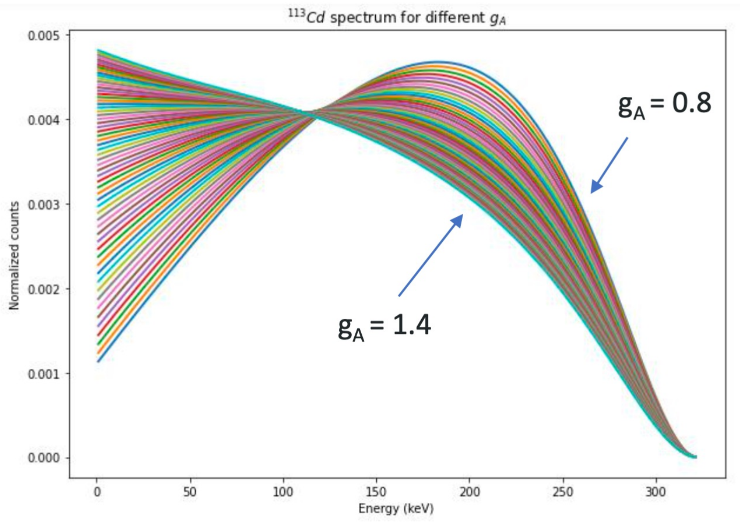
So far:
scintillator
Future:
Si-detector



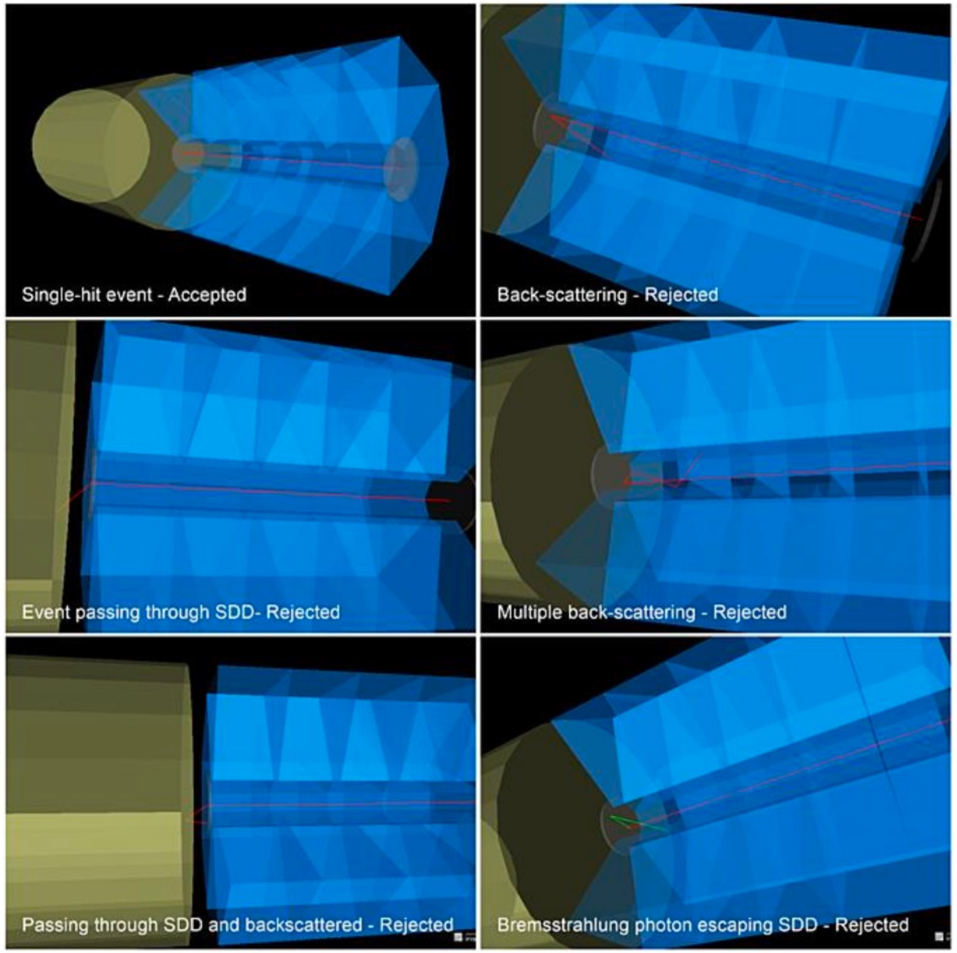
Forbidden beta decays

- Precision beta-spectroscopy of forbidden beta decays
- Access to parameters of importance for neutrino physics
- Challenges:
  - thick silicon detectors (mm-scale)
  - thin entrance window

M. Biassoni et al,
arXiv:1905.12087



SDD with veto system



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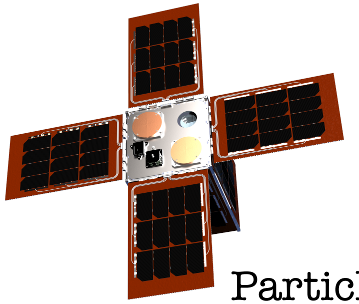

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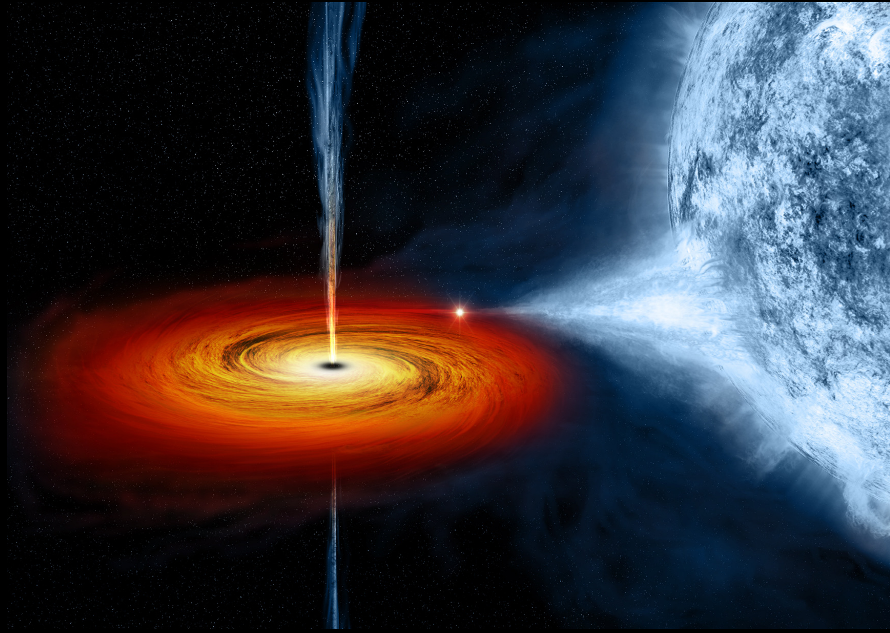
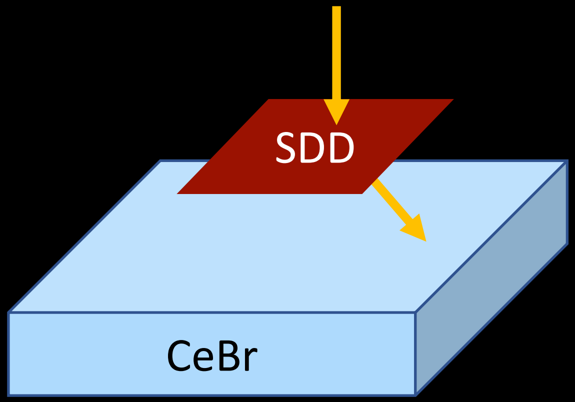


- Compton Telescope (SDD + Scintillator) in a Cube Sat
- Goal: measure level of polarization of x-rays from Cygnus X-1



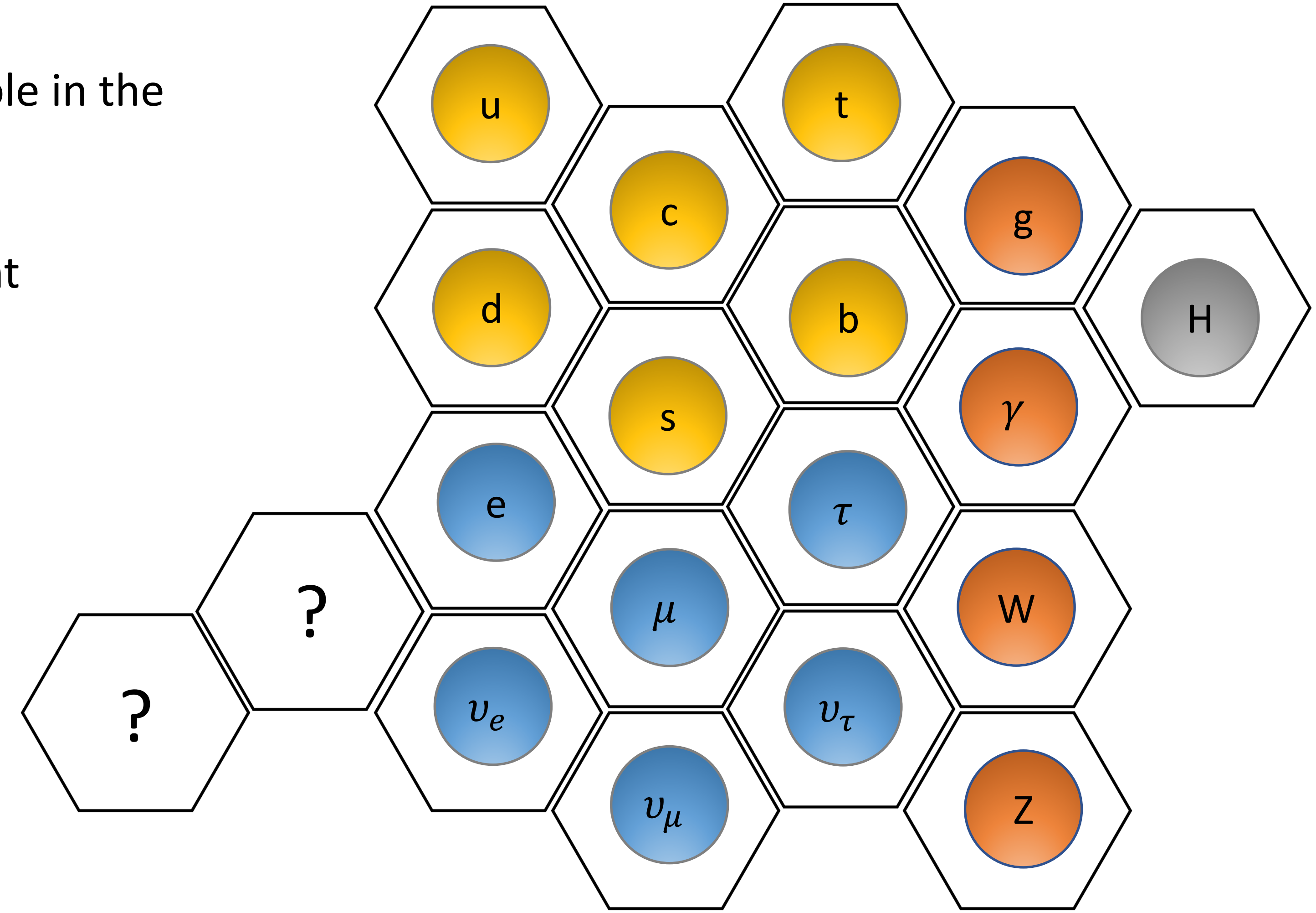
- Balloon flight in 2017
- Test launch to ISS planned for 2022 in the framework of the ORIGNS Laboratory of Rapid Space Missions (LRSM)

Summary

Type	**Example**	**Requirements**	**Technology**
Rare event search	CONNIE, DAMIC, SELENA, IAXO	**Low background, low threshold, particle identification**	CCD, CMOS, or SDD
High-precision at collider	Belle-II	Low mass, high rates, high pixelization	DePFET
High-precision beta-spectrocopy	TRISTAN, PERC, forbidden beta decays	**Thin entrance window, thick detectors, timing resolution**	SDD or other?
Astroparticle physics	ComPol Cube-Satellite	Space proof, energy resolution, etc.	SDD

Conclusion

- Si-detectors (of all kinds) play a key role in the search for physics beyond the SM
  - Collider experiments
  - Direct Dark Matter and rare-event searches
  - High-precision spectroscopy
  - Astroparticle physics
- We look forward to working with advanced Si-detector technologies to advance particle physics



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