Future Technology for Astroparticle Physics

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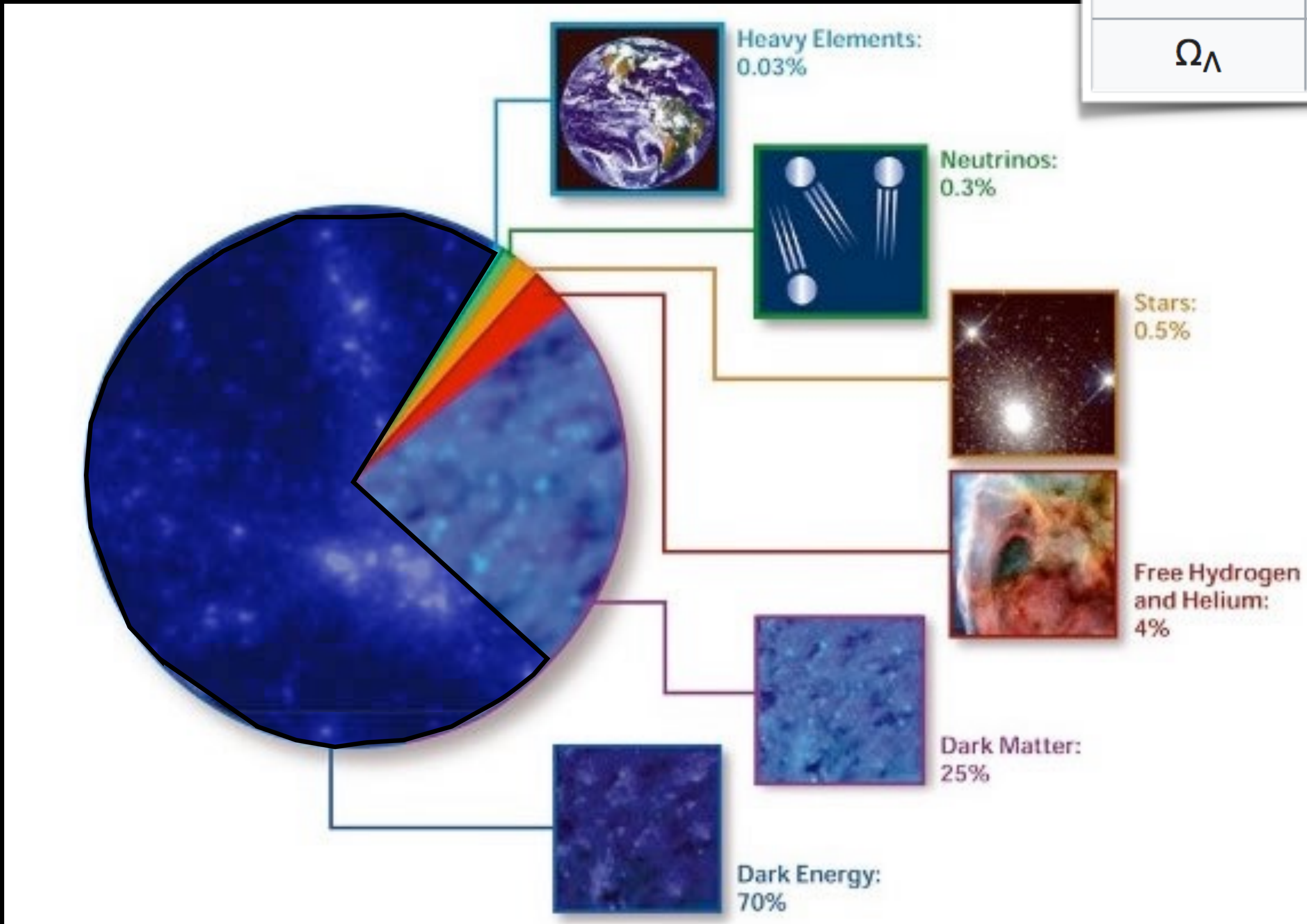
TRIUMF Science Week

July 21, 2022

The Standard Model of Cosmology

Ω_b	0.0486 ±0.0010[e]
Ω_c	0.2589 ±0.0057[f]
Ω_m	0.3089 ±0.0062
Ω_Λ	0.6911 ±0.0062

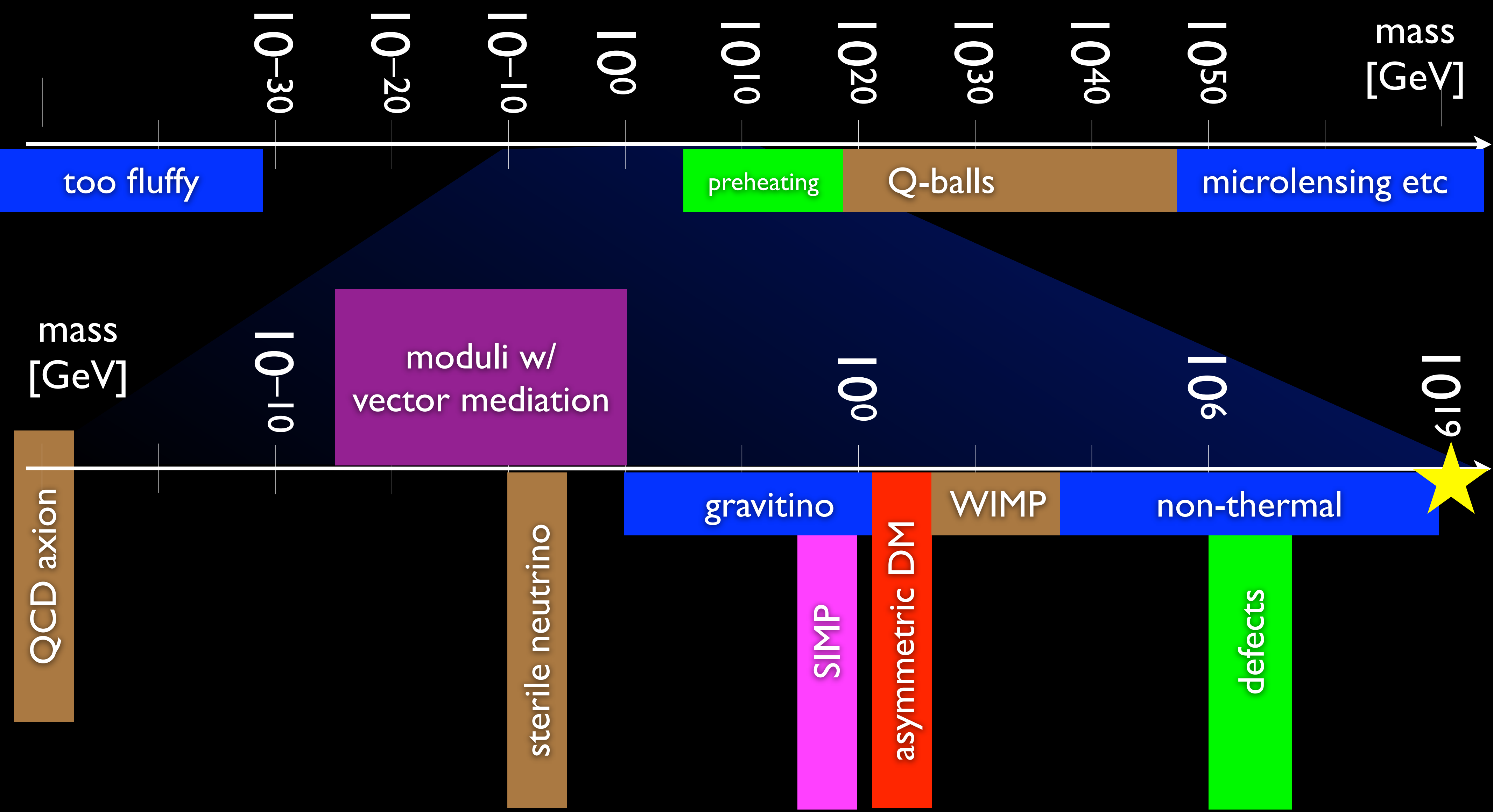
Planck (2016). Astronomy & Astrophysics. 594 (13): A13



Dark Matter is ~25% of the universe.

Model Space: Theorist's View

(thanks to H. Murayama)



New sociology: dark matter definitely exists, naturalness problem may be optional? Need to explain dark matter on its own.

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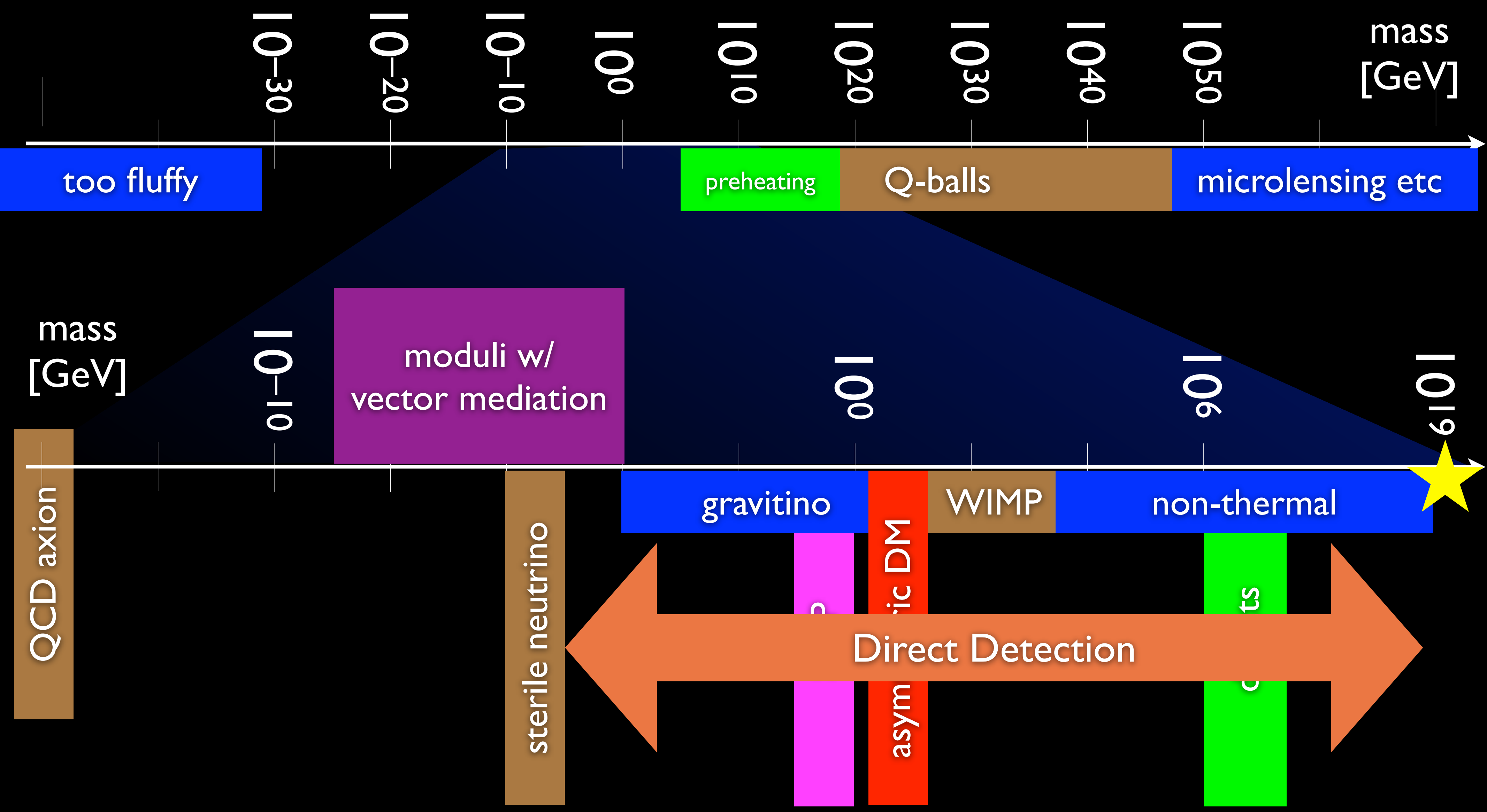

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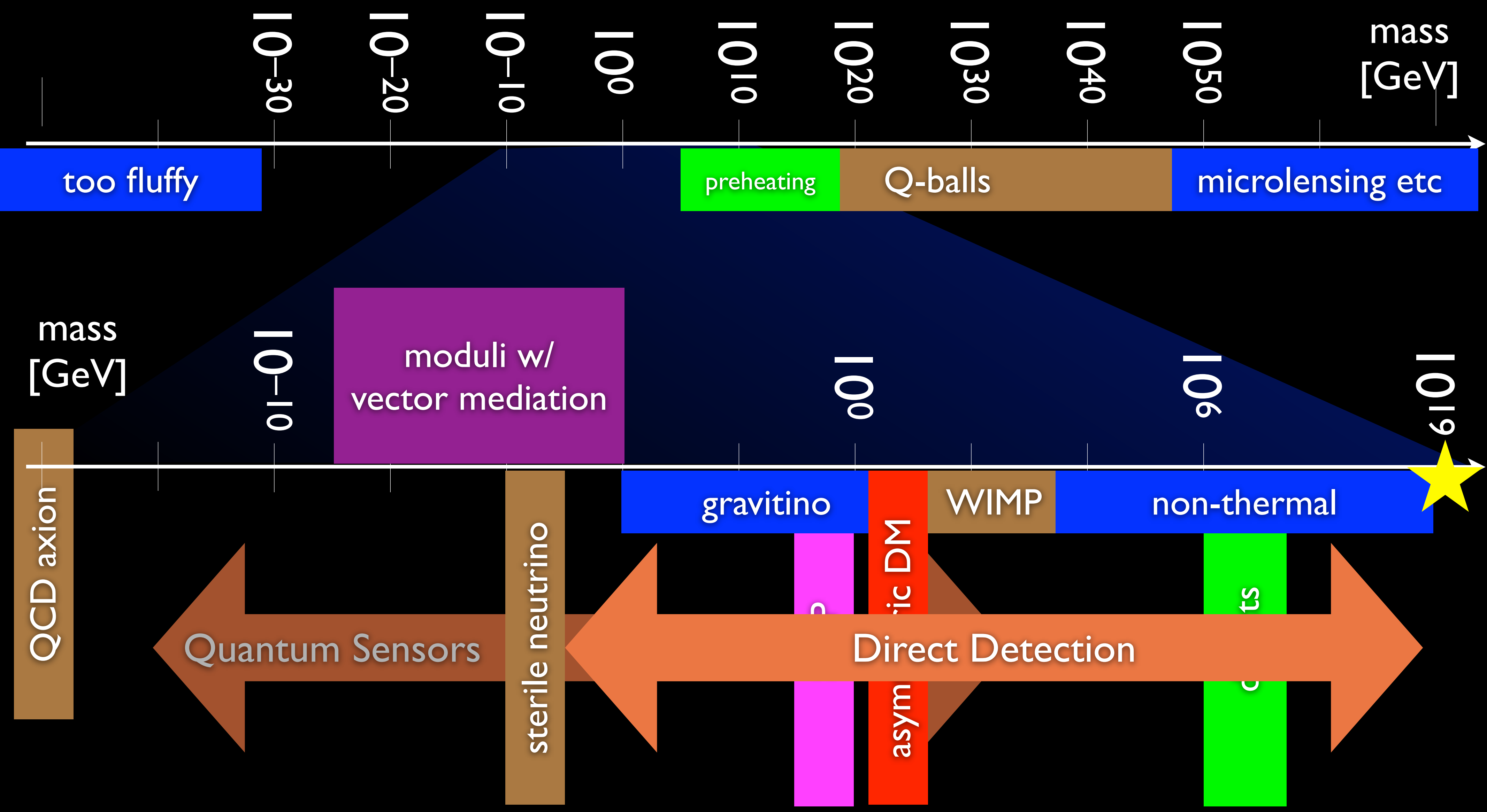

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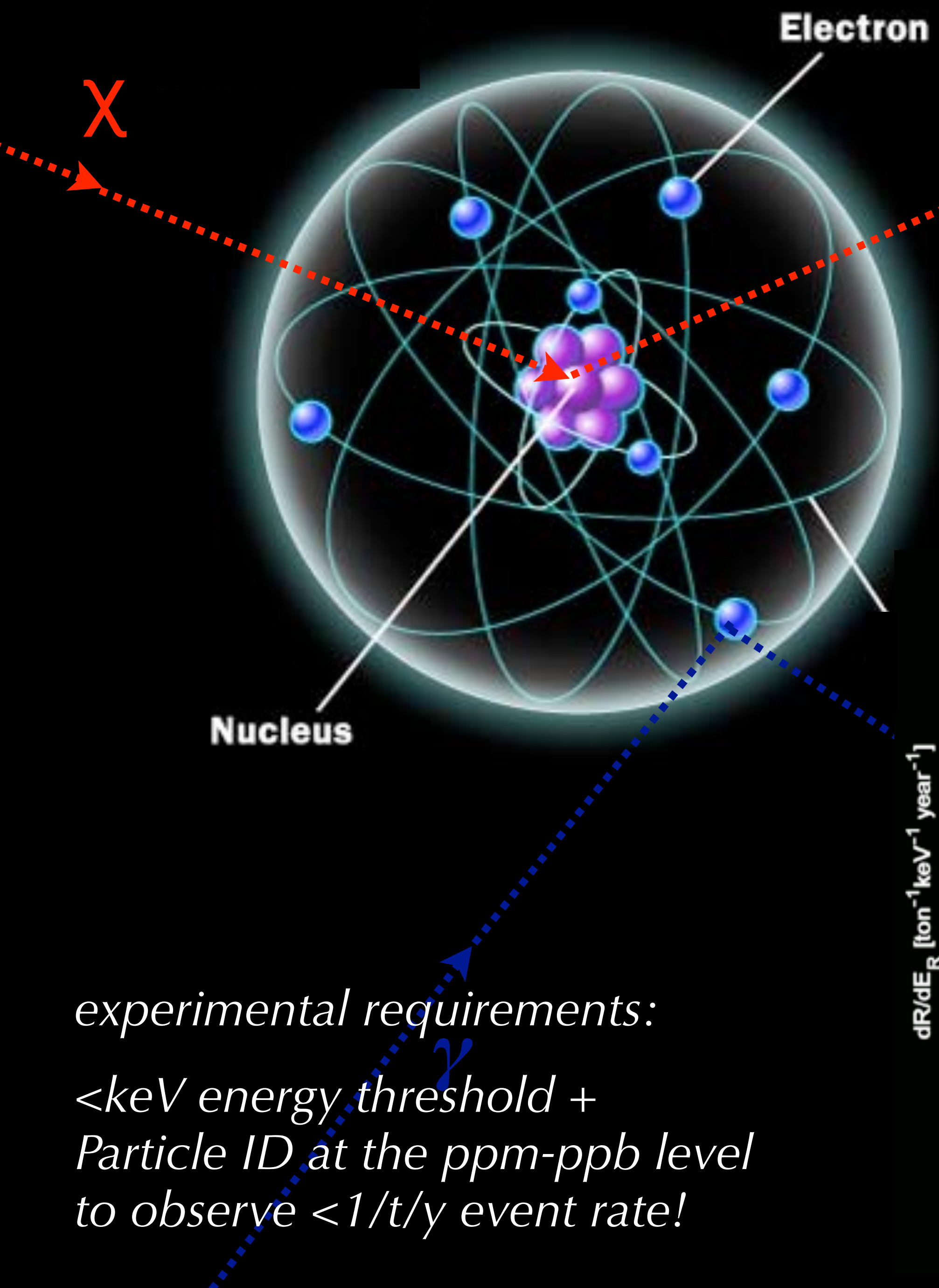
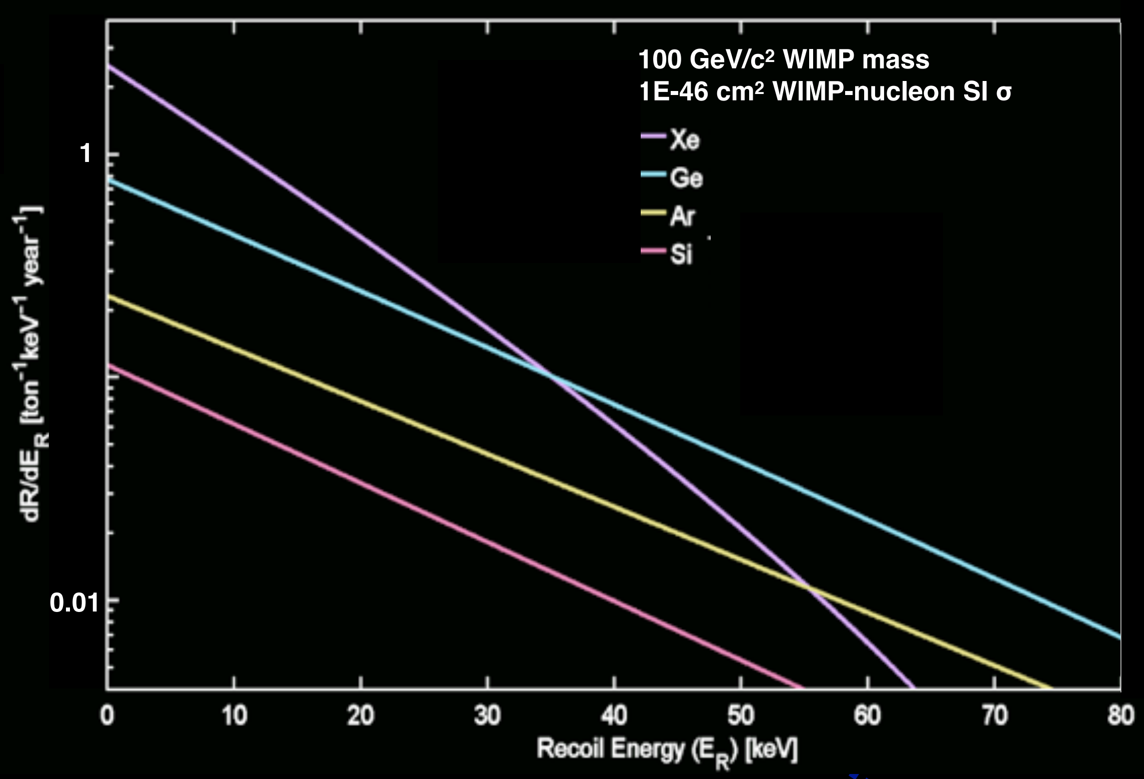
Direct Detection: Experimentalist's View



Signal: $\chi N \rightarrow \chi N$ (or $\chi e^- \rightarrow \chi e^-$)



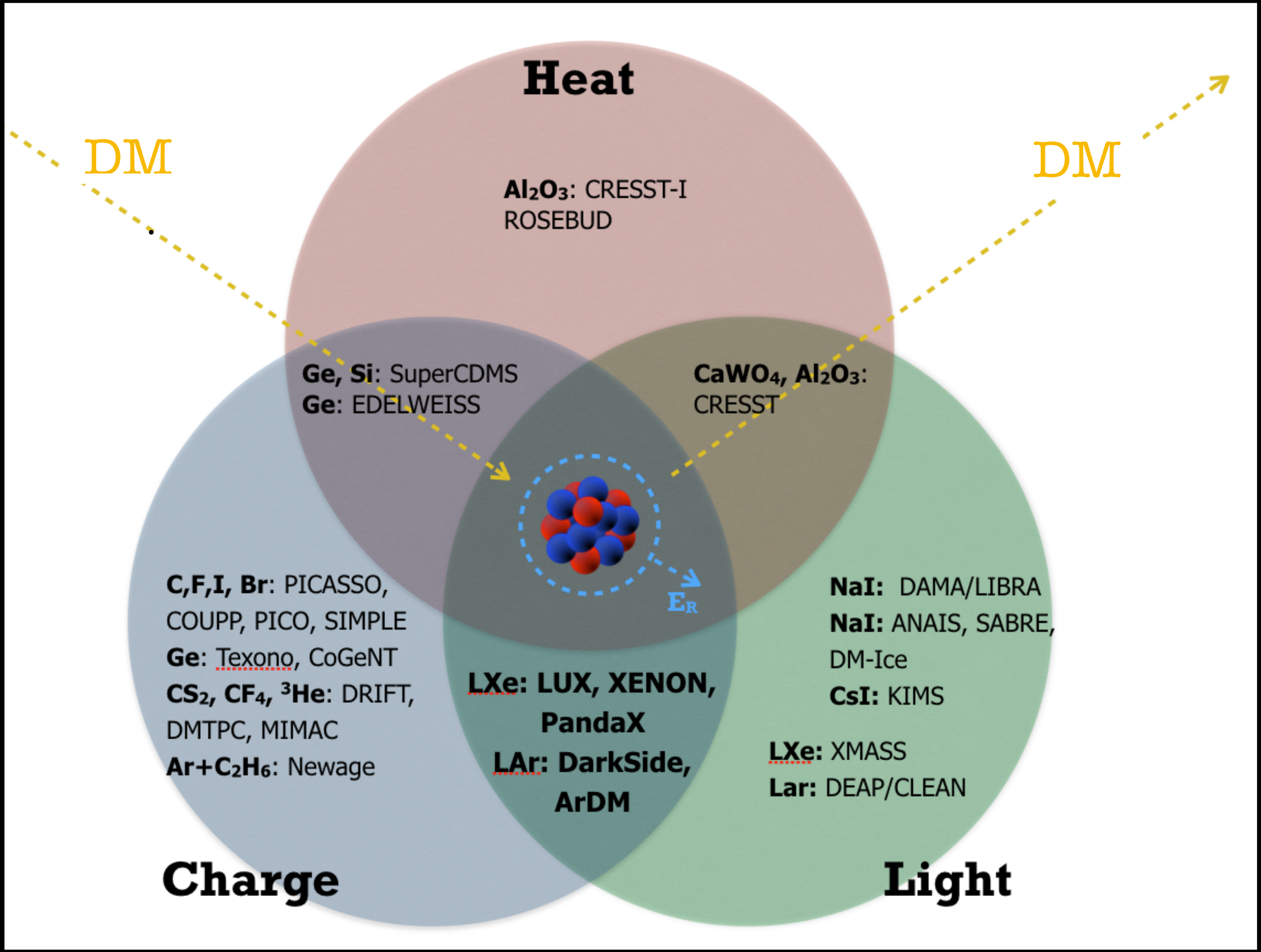
experimental requirements:

<keV energy threshold +
Particle ID at the ppm-ppb level
to observe <1/t/y event rate!

Observables

Nuclear recoil $E_R \sim 1E\text{-}6 \times m_{DM}$

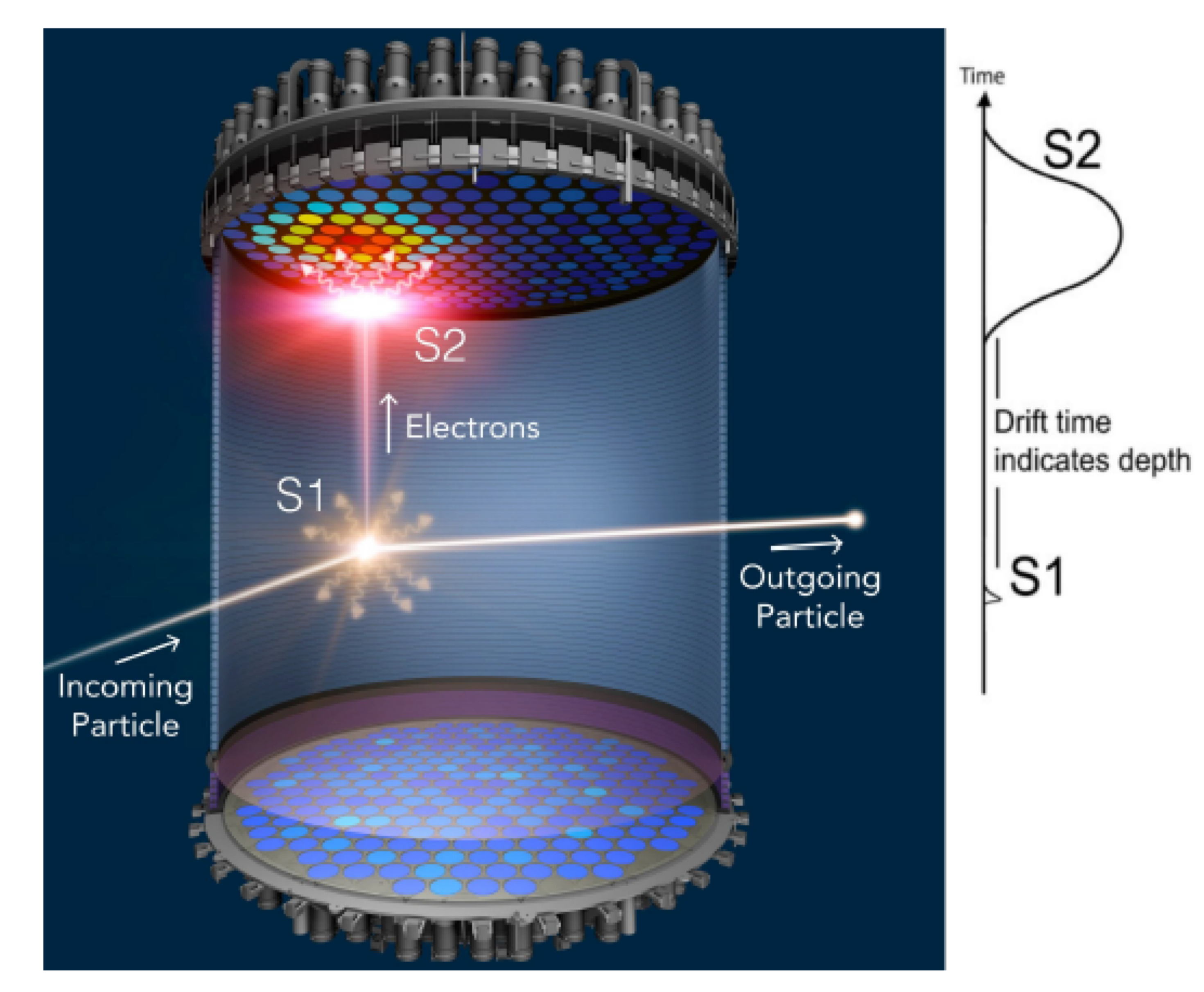
E_R threshold now O(10s eV), potential to reach meV



E_R threshold now O(10 eV), potential to reach eV

E_R threshold now O(keV), potential to reach 10 eV

Charge + Light: Detected with Photosensors



https://lz.slac.stanford.edu/our-research/lz-research

Detector Technology:
dual-phase Time Projection Chambers with multi-tonne liquid Xe, Ar targets

read out primary scintillation: “S1” + proportional gas scintillation from drifted electrons: “S2”

Goal: reach the neutrino floor!

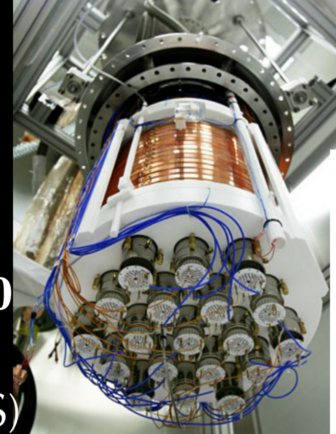
Argon Detectors

Astropart.Phys. 22 (2005) 355-368
New Astron.Rev. 49 (2005) 265-269

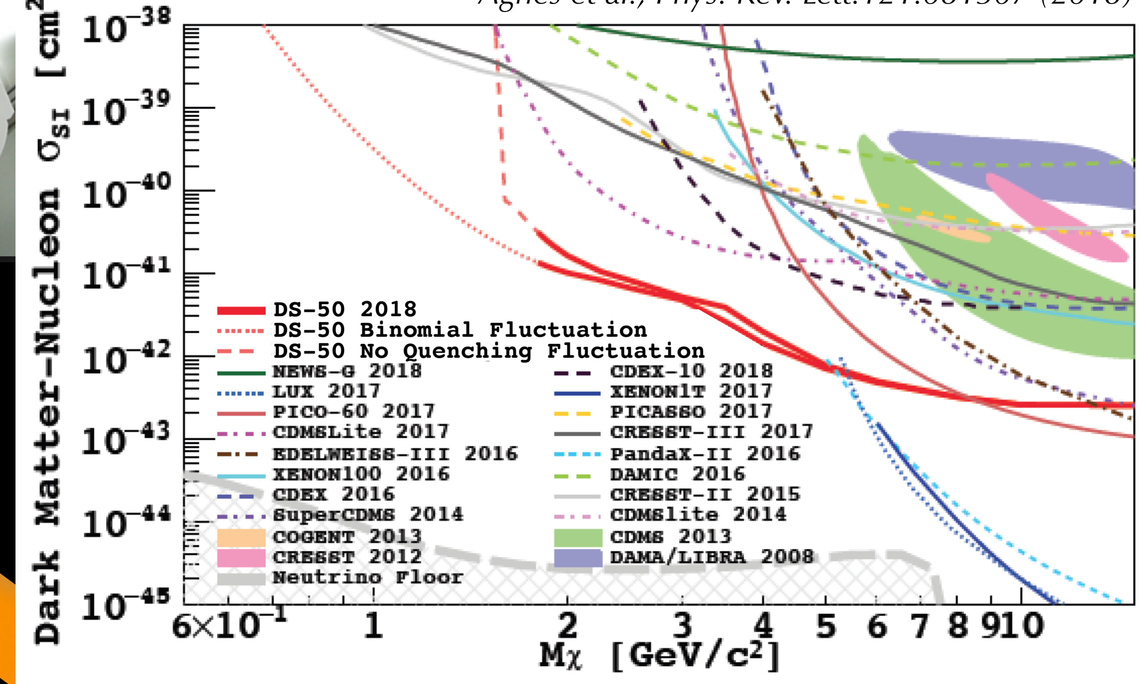
2010

10 kg

DarkSide-50 (50 kg, LNGS)



DS-50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering



Agnes et al., Phys. Rev. Lett.121.081307 (2018)

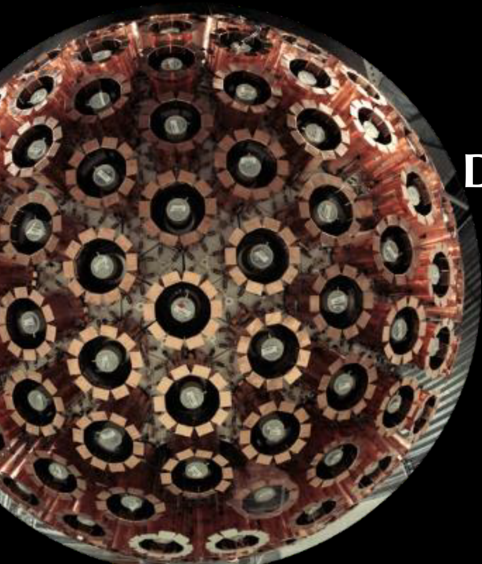
100 kg

ArDM (1t, LSC)

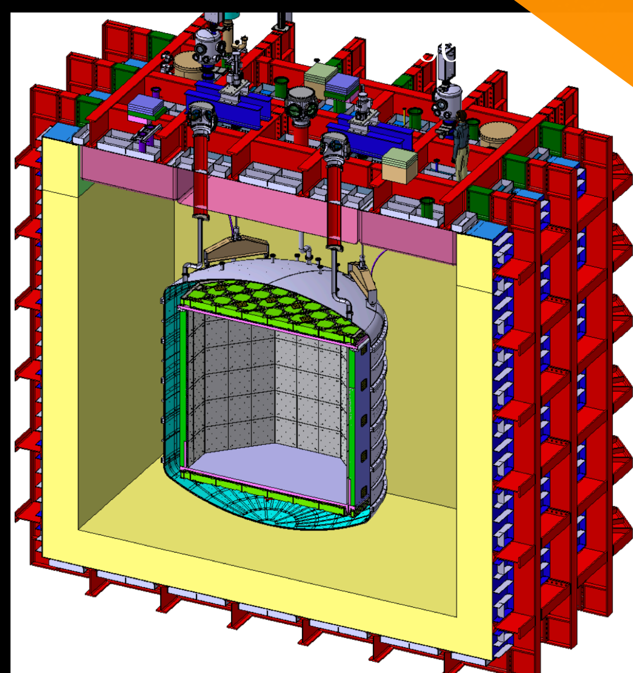
1,000 kg

2015

DEAP-3600 (3.6t, SNOLAB)



DEAP-3600: demonstrated "S1" particle ID, and ultrapure acrylic cryostat



Global Argon Dark Matter Collaboration formed

10,000 kg

2020

APPEC

100,000 kg

DarkSide-20k (50t, LNGS)

Future: ARGO kt-scale

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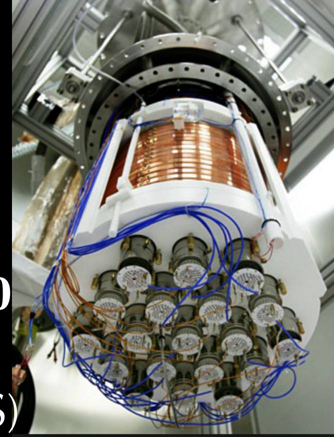

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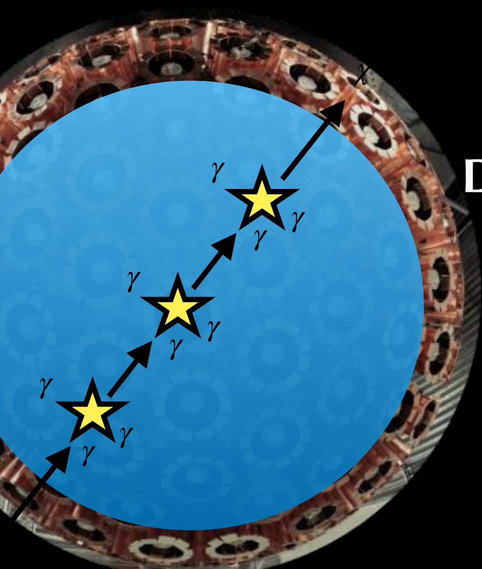
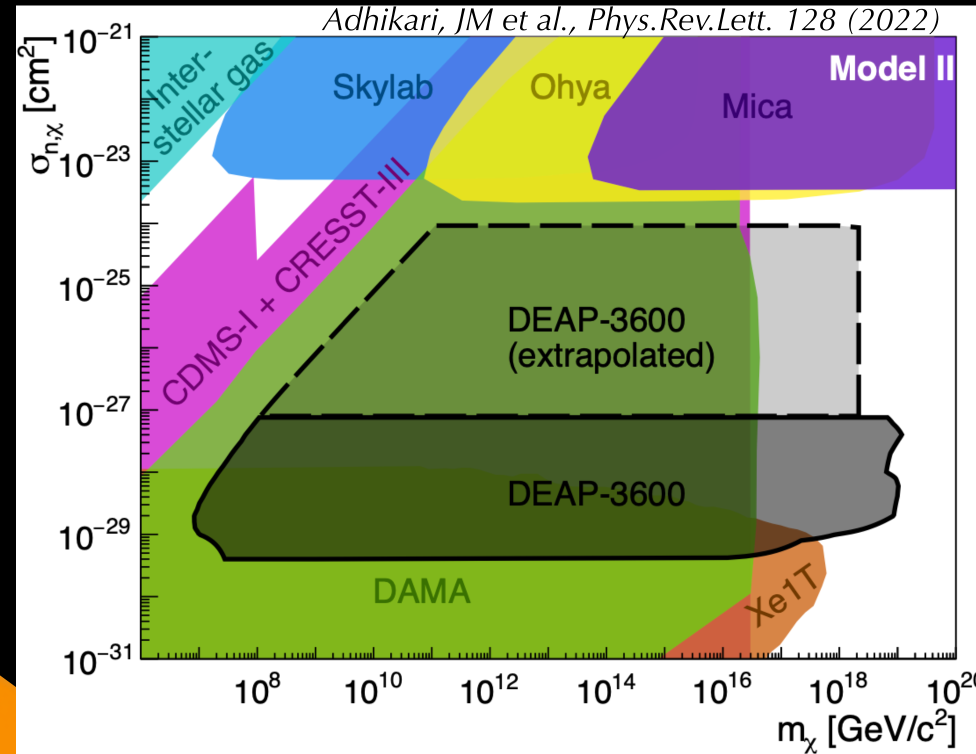


DEAP-3600: leading Planck-scale dark matter search result (can be produced in GUTs, PBHs …)



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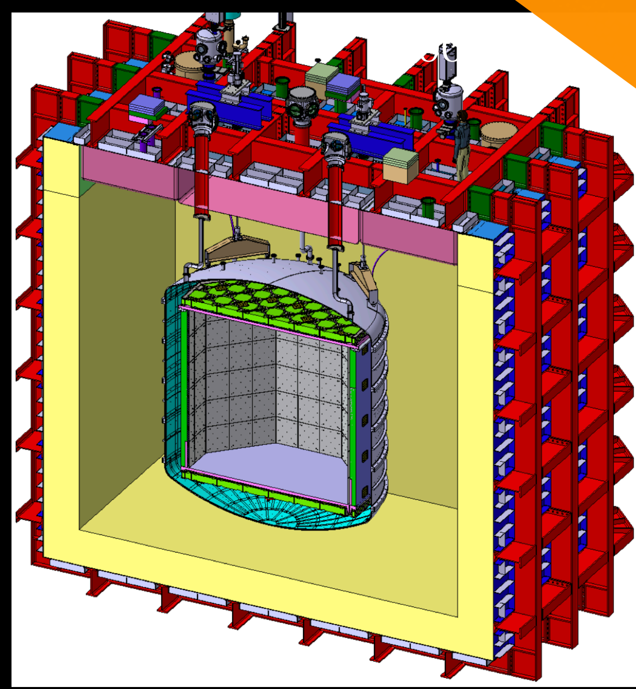

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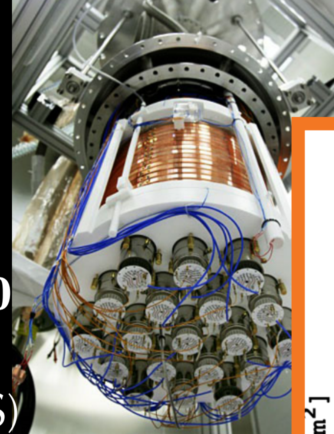

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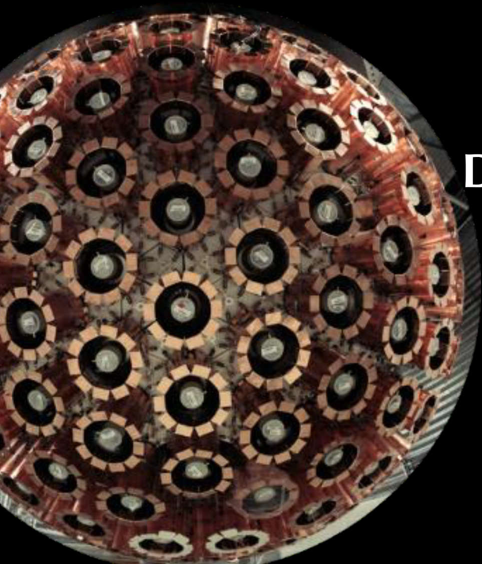
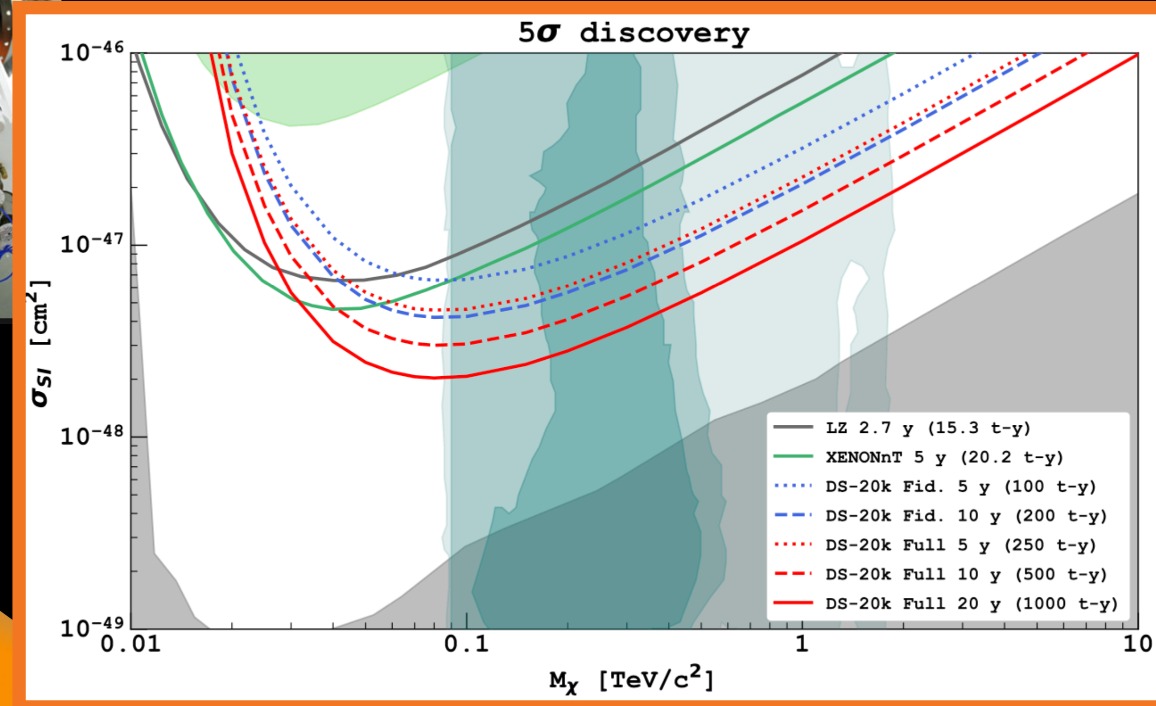


DarkSide-20k: observatory for dark matter and **ν**



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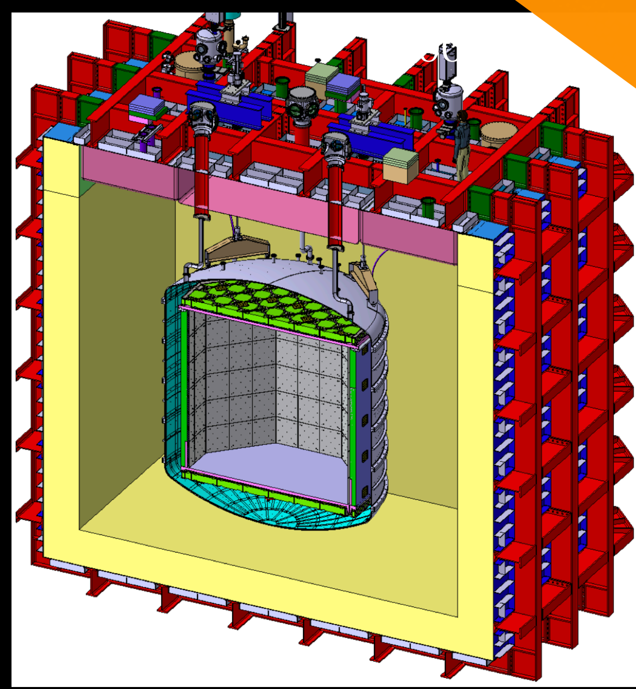

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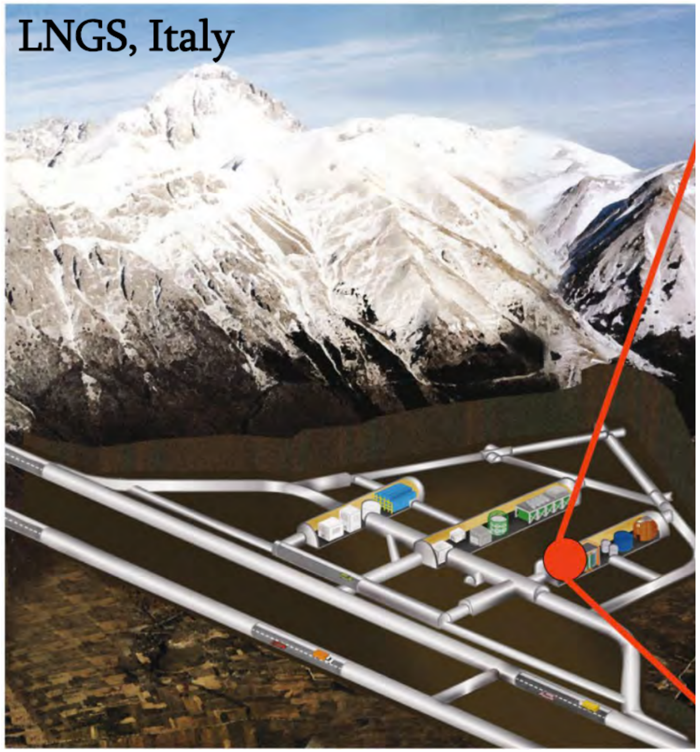
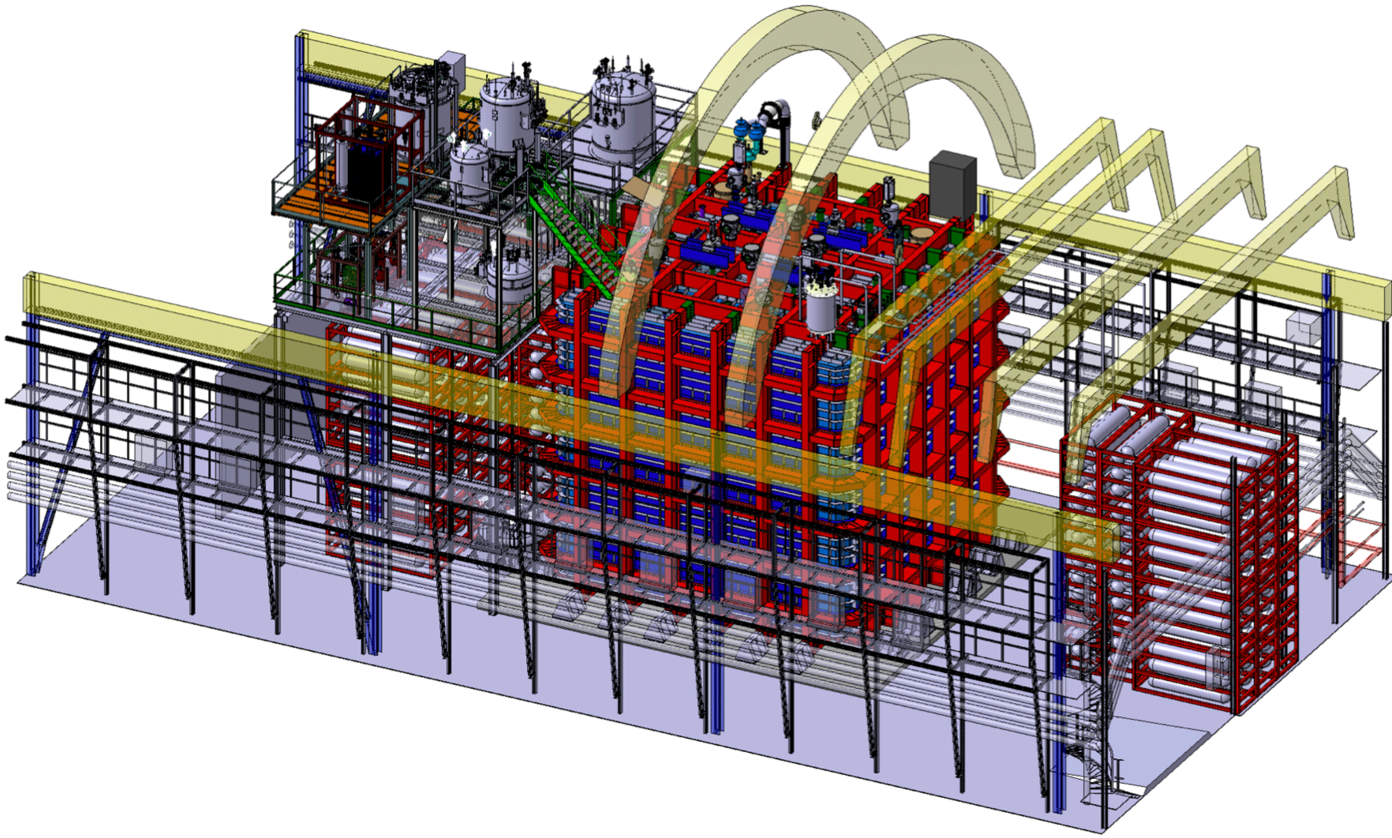




11 countries
>100 institutions
>400 collaborators
INFN, CFI, NSF, DOE, STFC, IHEP, European Commission, Horizon 2020

New Technologies: DarkSide-20k

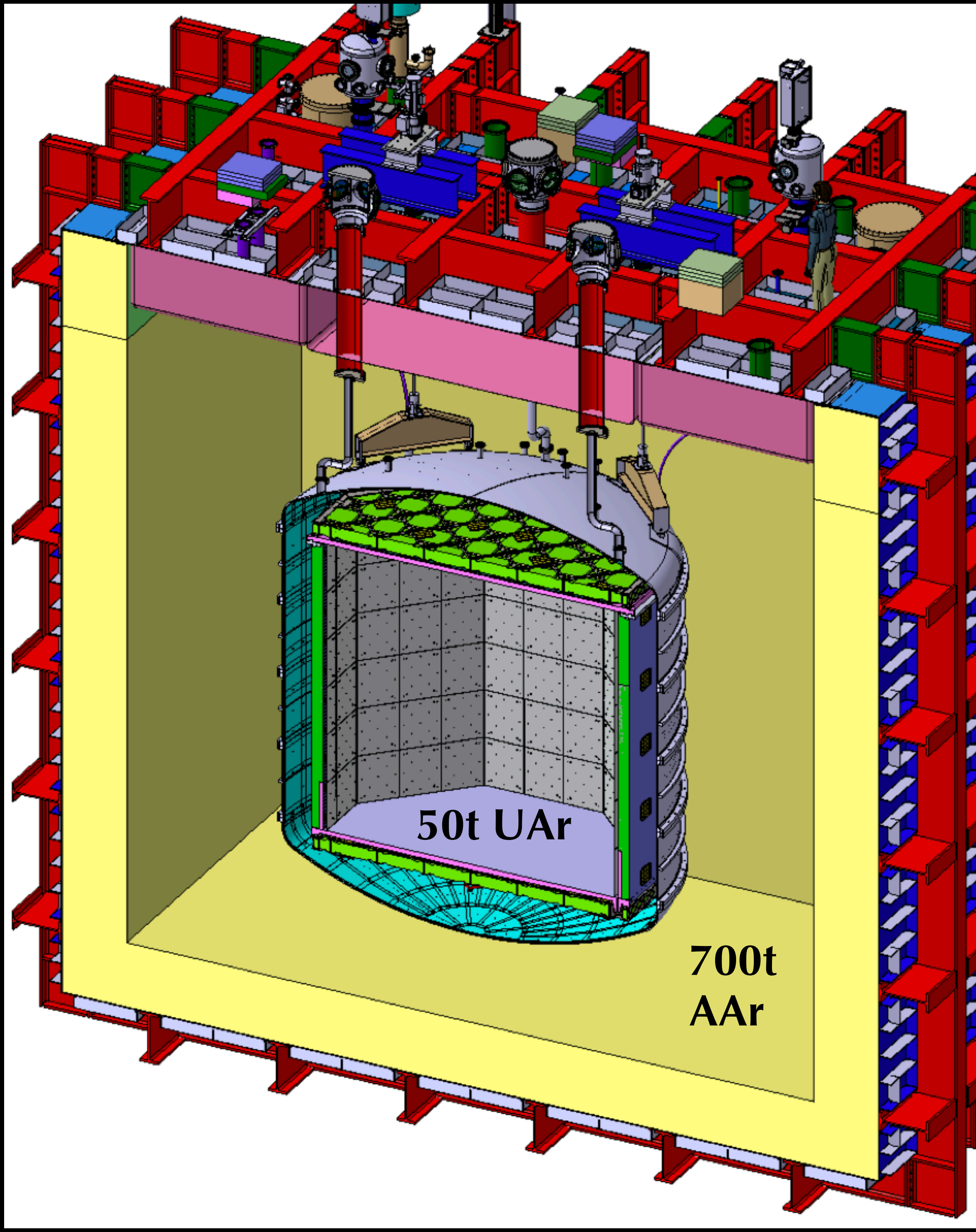
50 t liquid Underground Ar (UAr) dark matter target, walls coated with wavelength shifter, inside a 700 t liquid Atmospheric Ar (AAr) outer detector

Gran Sasso Underground Laboratory (LNGS) (outside L'Aquila, IT)

Two key innovations:

1. first large-scale use of large-area cryogenic Si photon detection modules (PDMs) instead of PMTs.

2. liquid AAr outer detector to veto the limiting background: neutrons



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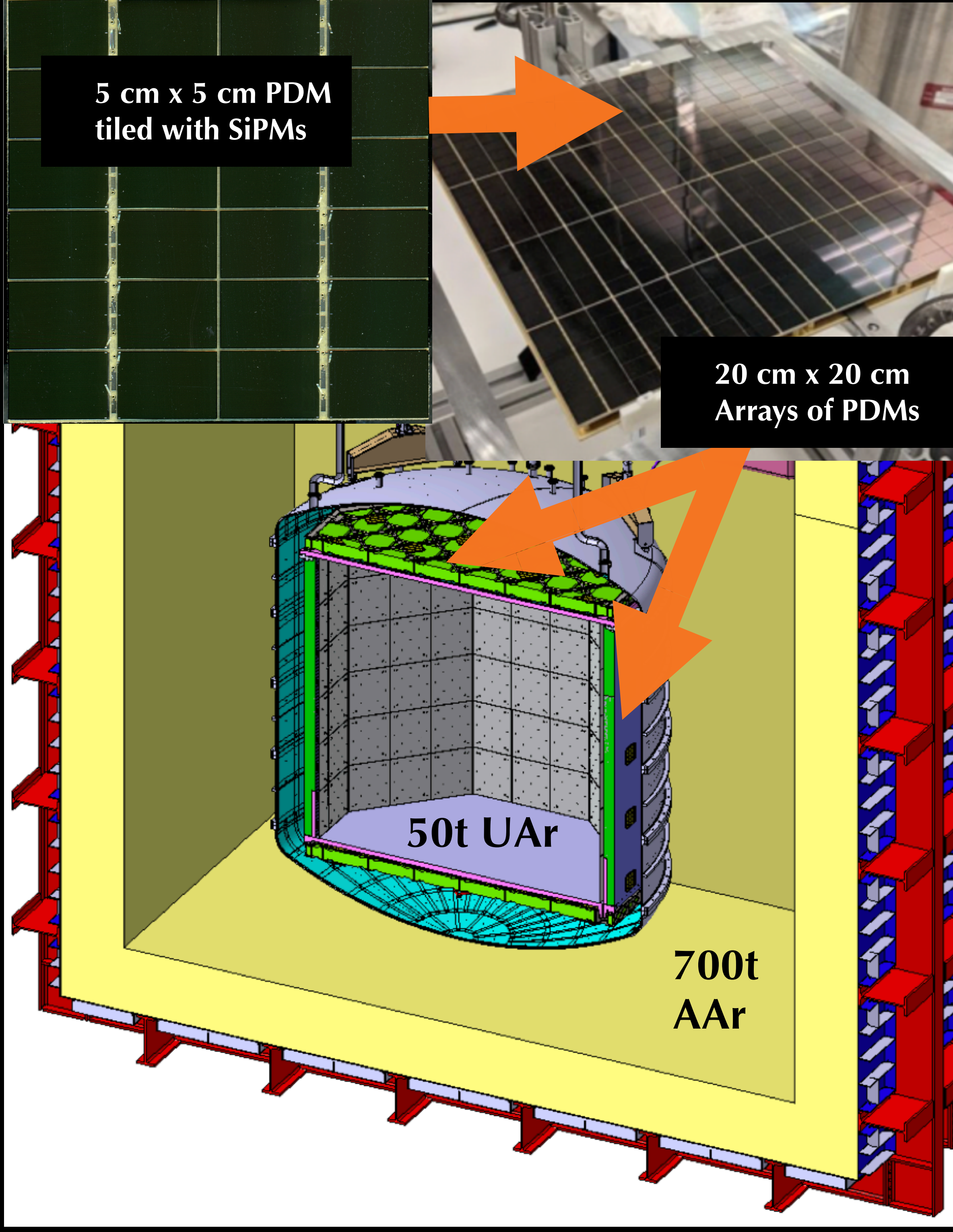
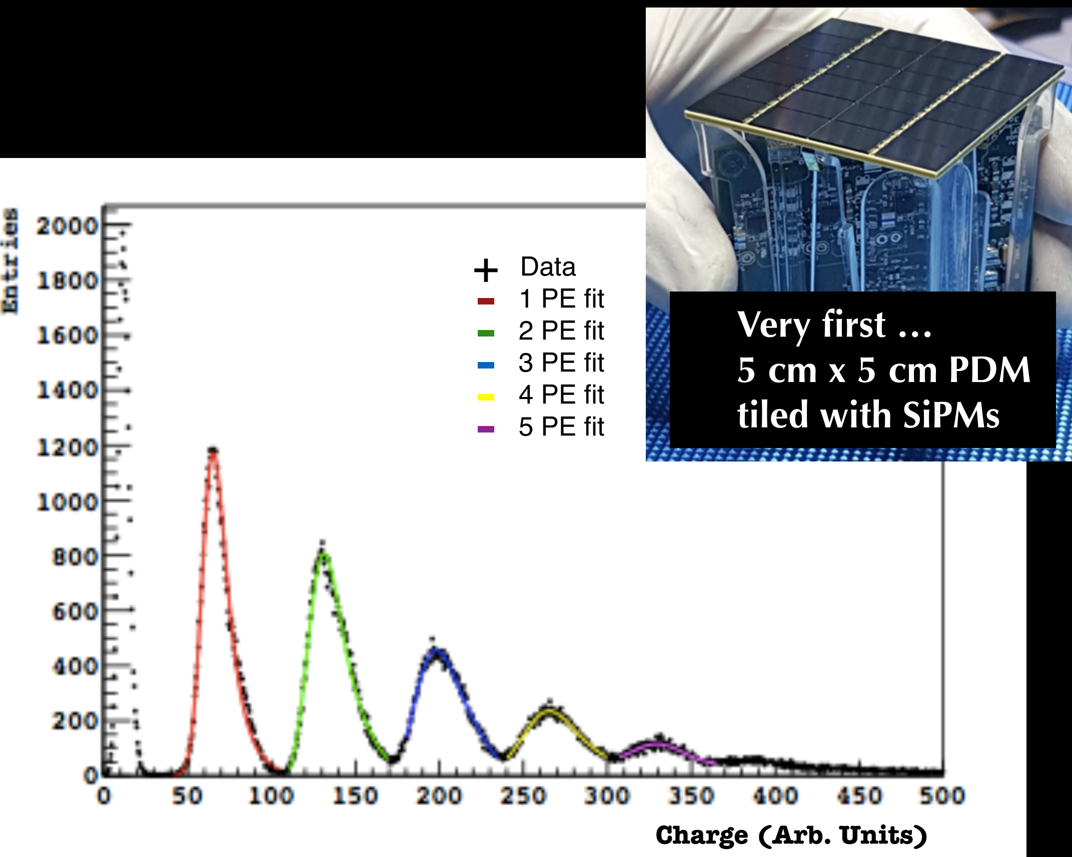


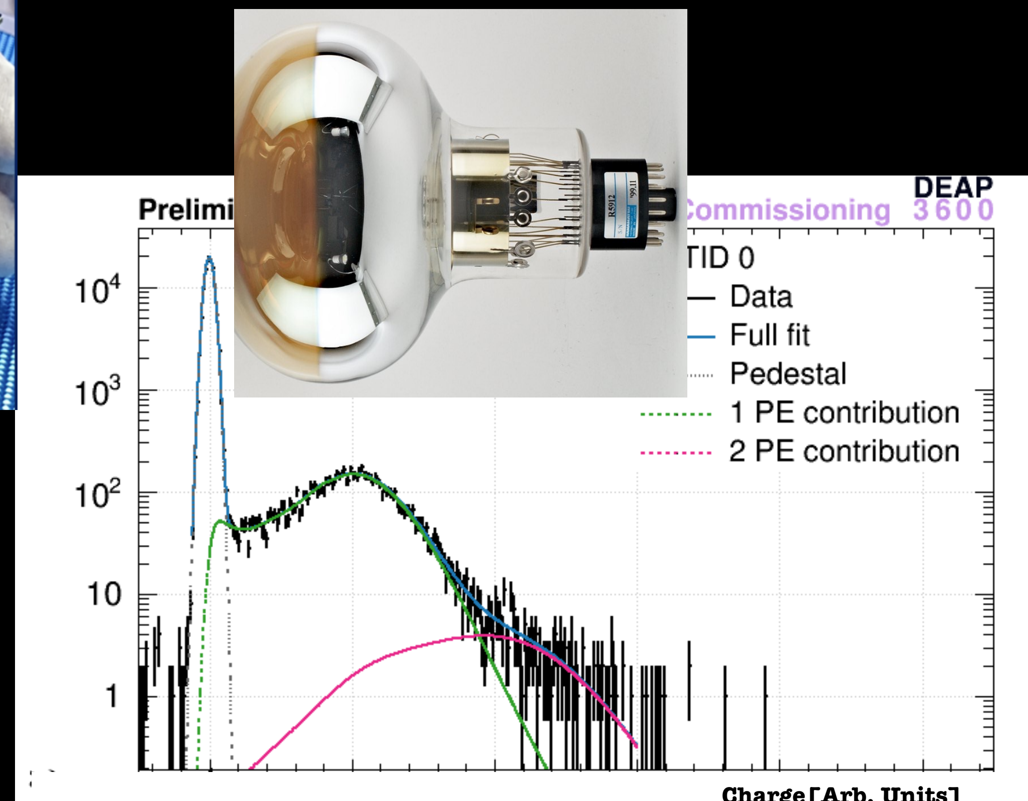
New Technology Collaborations

Photon Sensors: low noise, high efficiency, tiled arrays of cryogenic Si sensors developed in collaboration with FBK, achieving >45% PDE and 1 mHz/mm² dark noise



Aalseth, JM, et al. JINST 12 (2017) no.09, P09030

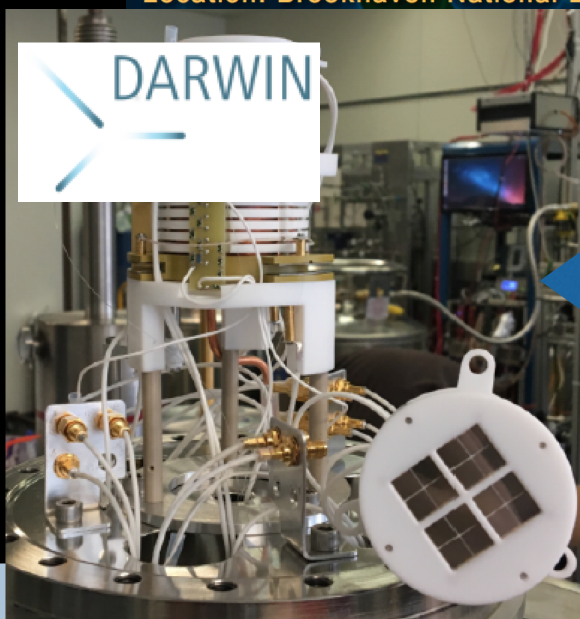
compared with:

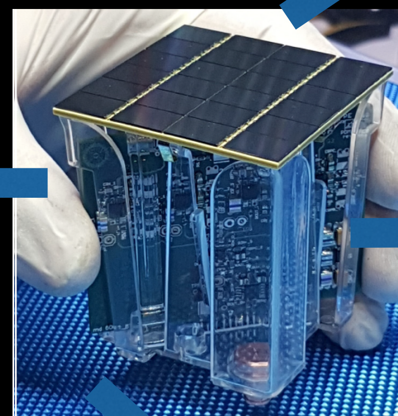


Amaudruz, JM, et al. NIM A 922 (2019) 373

>3x photon detection efficiency, 10x lower noise, >50x lower radiogenic backgrounds than PMTs.

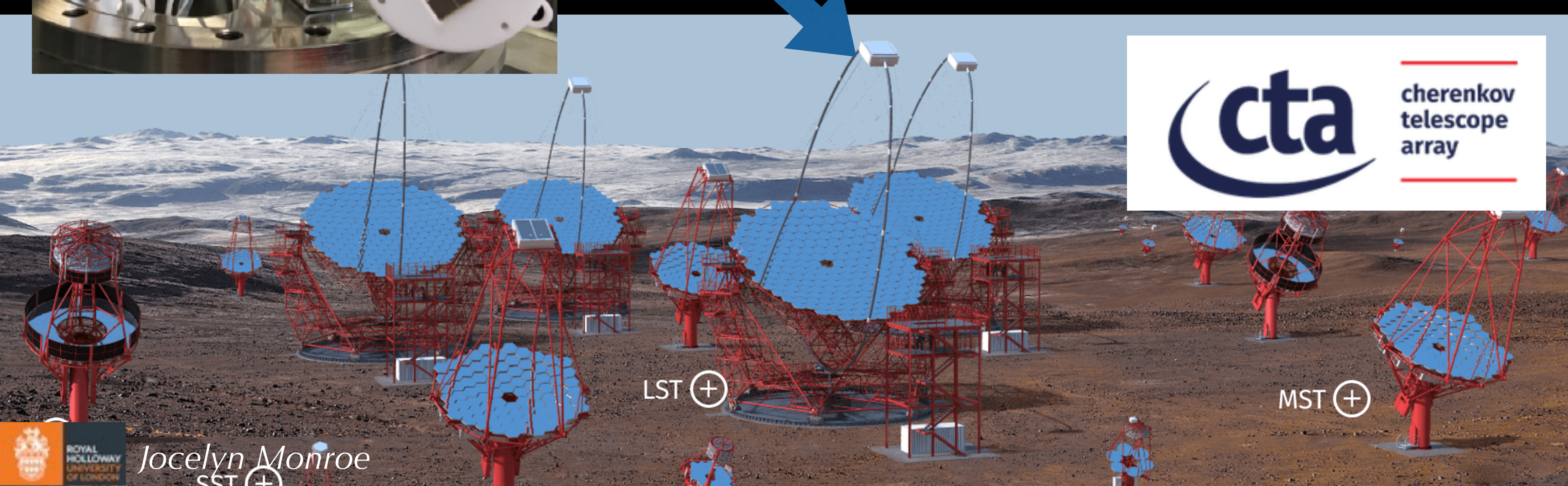
Experiments Exploring Cryogenic SiPM Technology





LEGEND

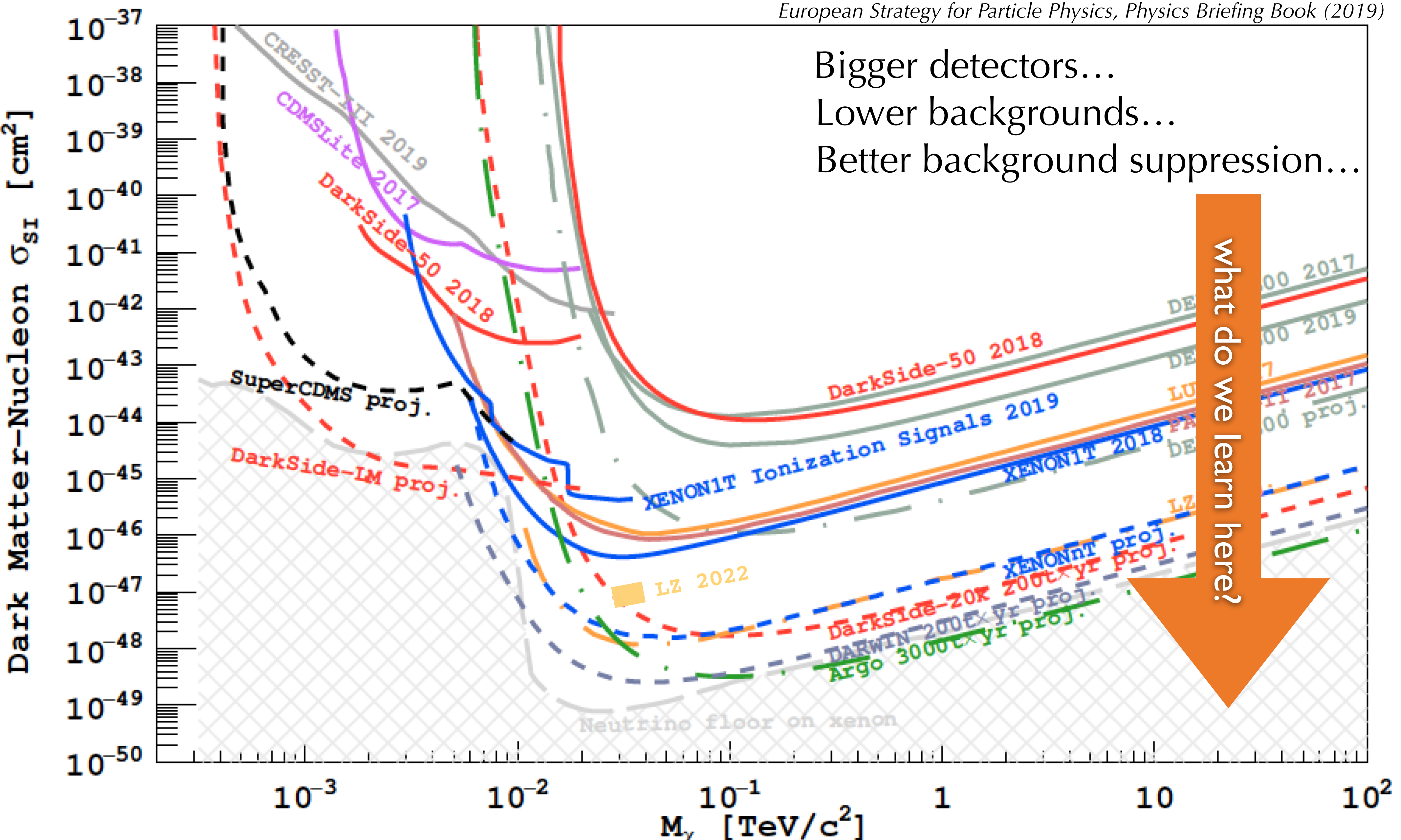
Large Enriched Germanium Experiment for Neutrinoless ββ Decay



+ environmental monitoring, medical imaging, automated navigation (LIDAR) …

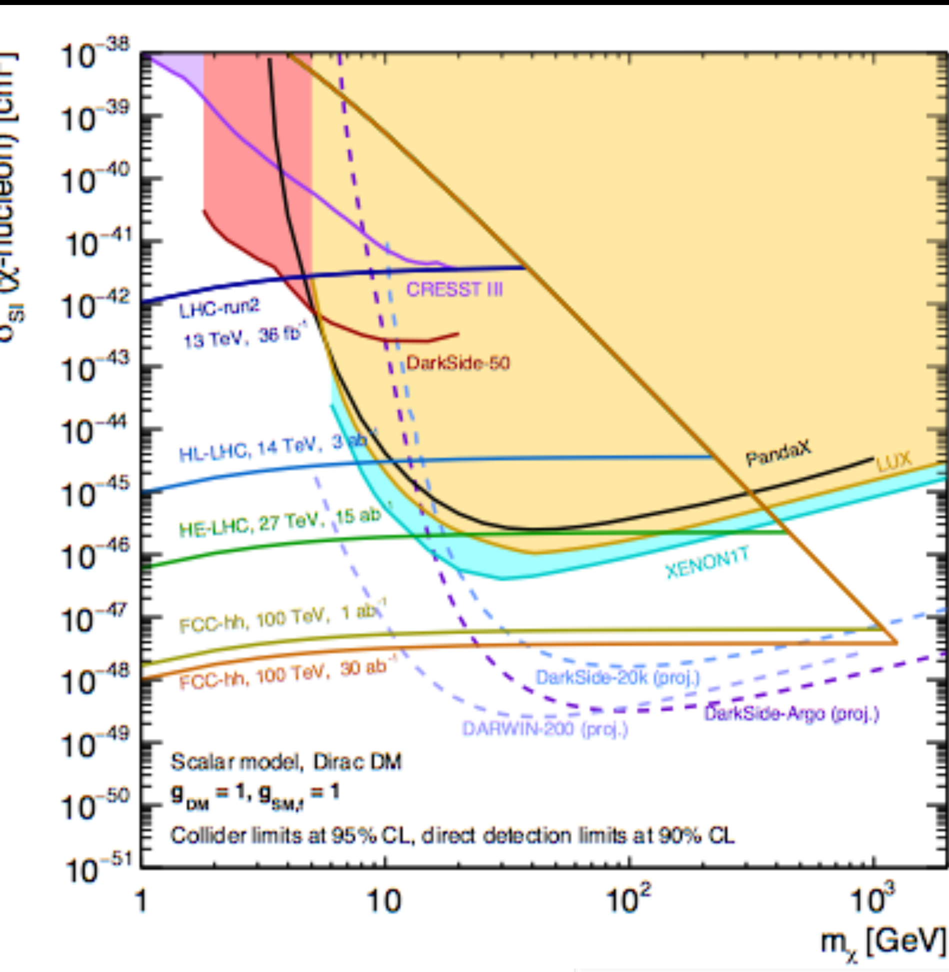
Quo Vadis?

European Strategy for Particle Physics, Physics Briefing Book (2019)

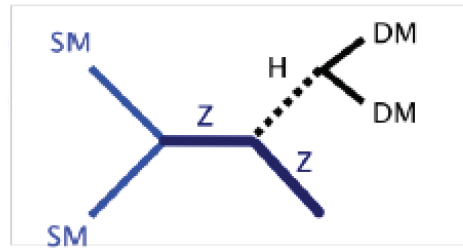


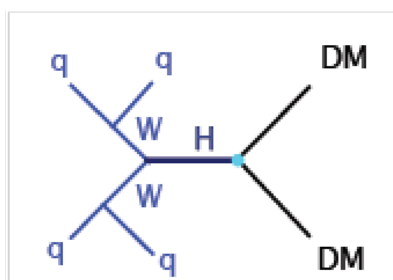
Is it interesting to measure zero?

Ellis, JM et al., ESPPU Physics Briefing Book, CERN-ESU-004 (2019)

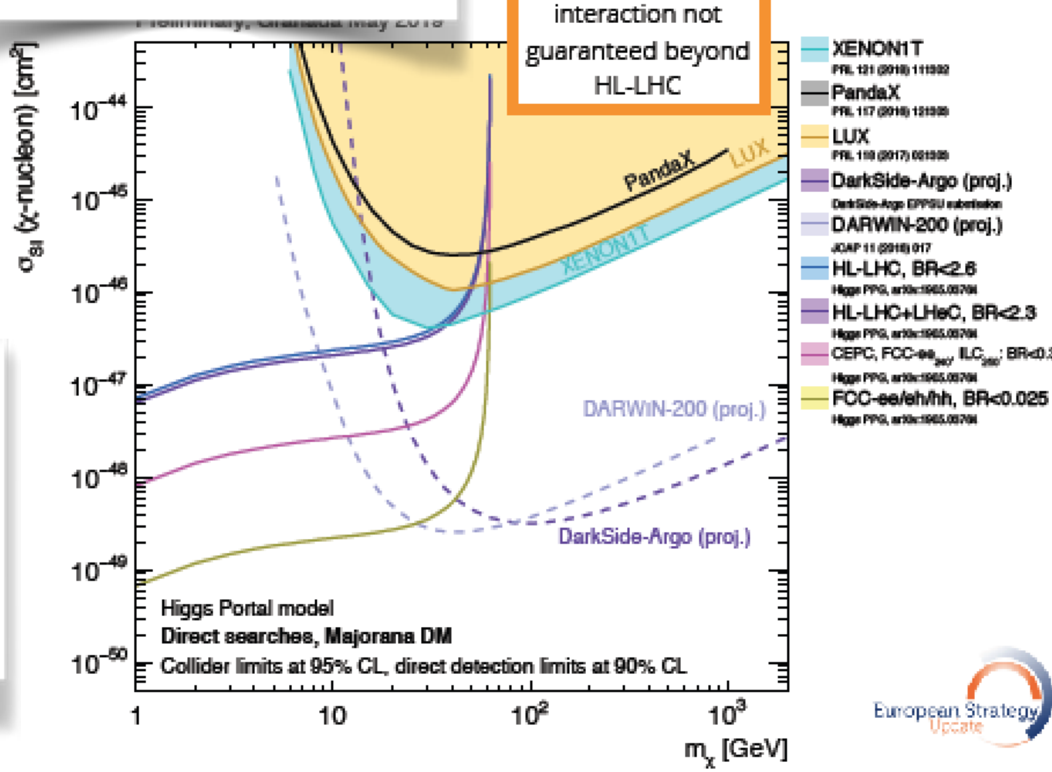


limits on branching ratio translated to limits on cross section vs. mass

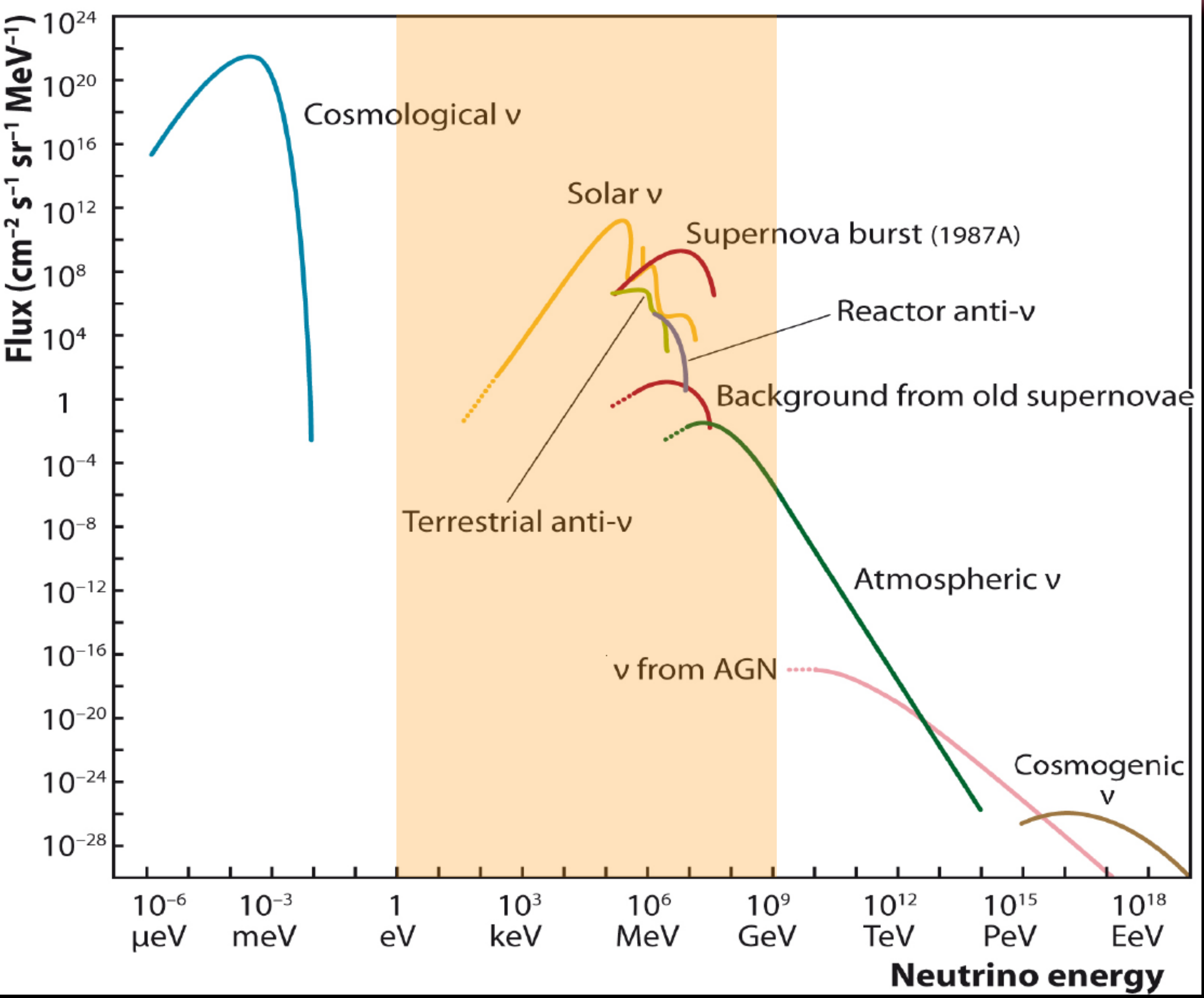


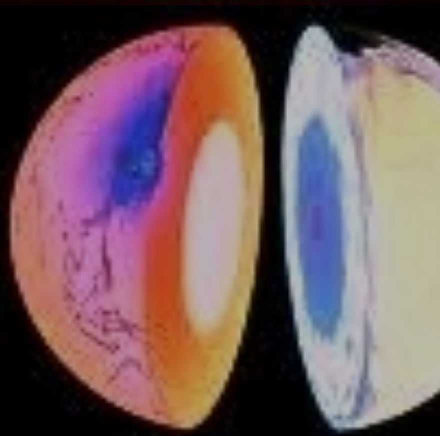


Caveat: EFT validity in Higgs-DM interaction not guaranteed beyond HL-LHC



What ν sources can dark matter detectors see?





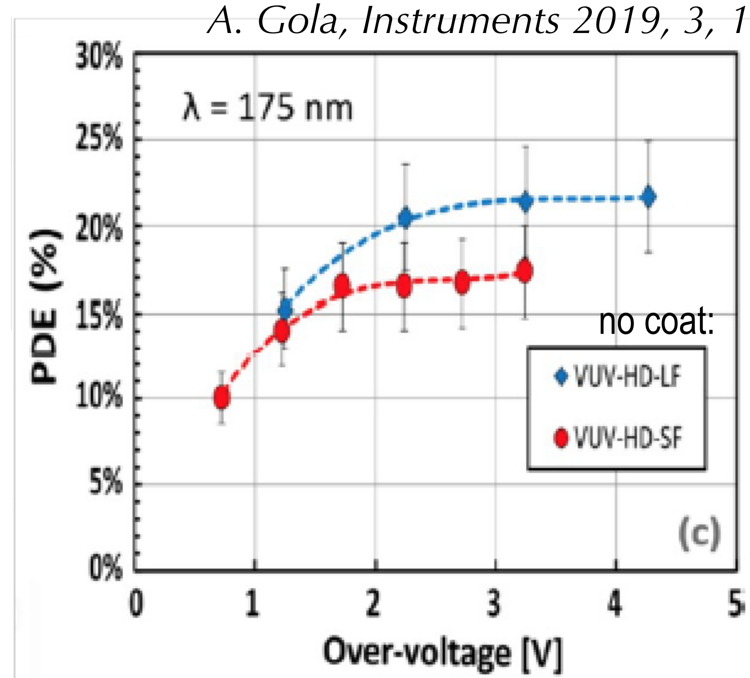
https://masterclass.icecube.wisc.edu/en/learn/detecting-neutrinos

Horizon Scanning: Enabling Technologies

1) VUV-Sensitive SiPMs for 100 m² readouts

Building on advances in SiPMs (nEXO) and coatings (OU/e2v) for CCDs, aim for 20%-50% @ 128-178 nm

A. Gola, Instruments 2019, 3, 15



J. Heymes et al., IEEE NSS 2019, DOI: 10.1109/TNS.2020.3001622

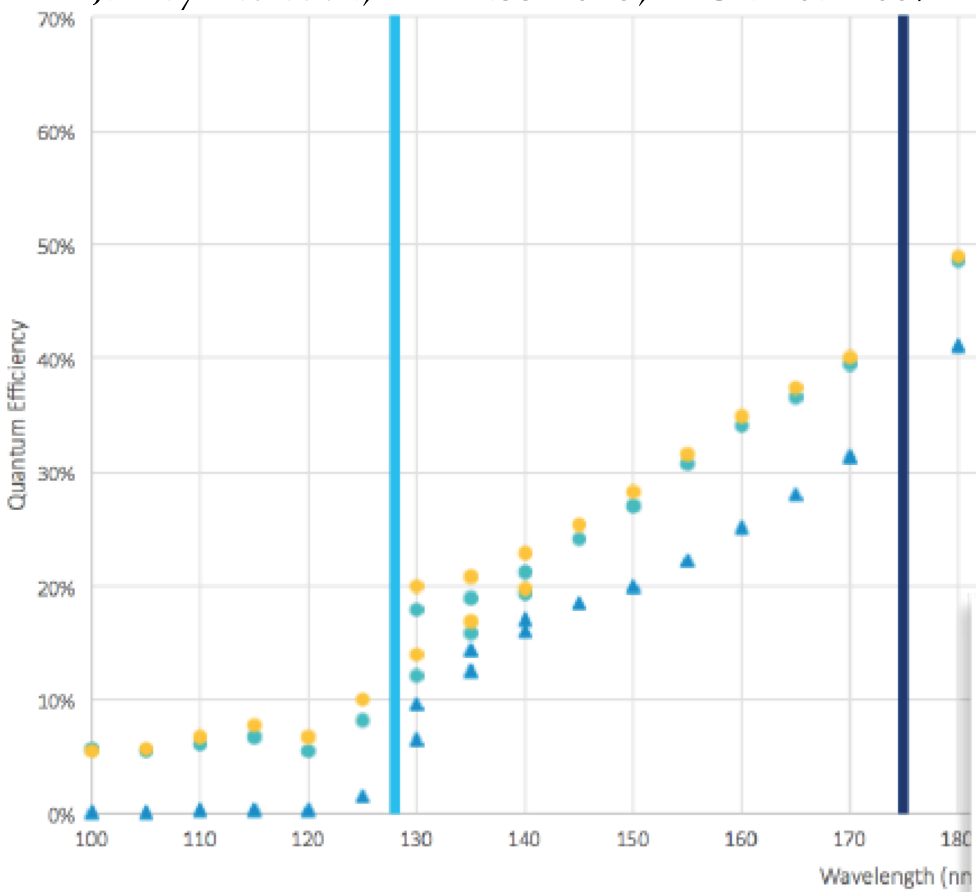
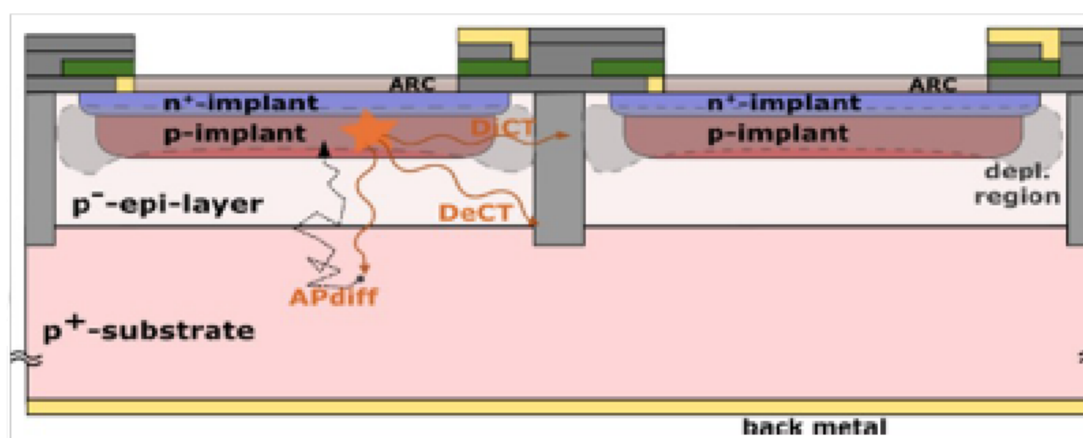


Figure 6: Measurement of photon detection efficien

this coating is optimised for **193 nm**

*normal incidence



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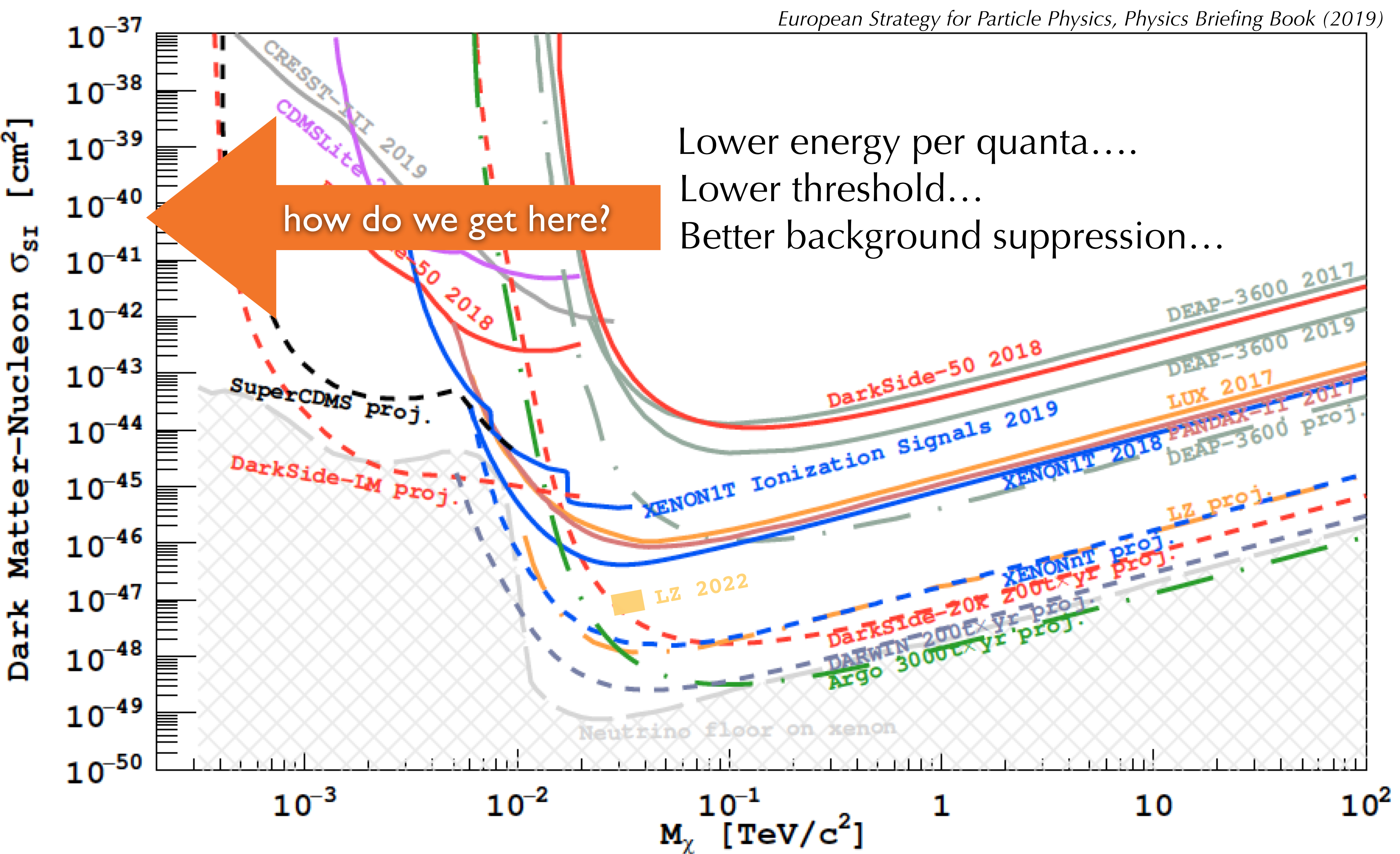


European Strategy for Particle Physics, Physics Briefing Book (2019)
how do we get here?
Lower energy per quanta….
Lower threshold…
Better background suppression…
CRESST-III 2019
CDMSLite
DarkSide-50 2018
DEAP-3600 2017
DEAP-3600 2019
LUX 2017
PANDAX-II 2017
DEAP-3600 proj.
XENON1T Ionization Signals 2019
XENON1T 2018
XENON1T
SuperCDMS proj.
DarkSide-1M proj.
LZ proj.
LZ 2022
XENONnT proj.
DarkSide-20K 200t×yr proj.
DARWIN 200t×yr proj.
Argo 3000t×yr proj.
Neutrino floor on xenon
Dark Matter-Nucleon σ_{SI} [cm^2]
M_χ [TeV/c^2]

Lighter Targets

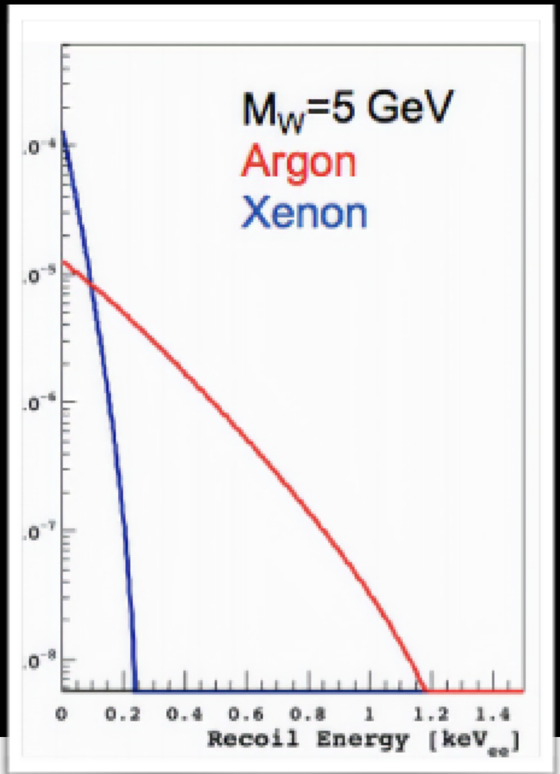
kinematic advantage to detect low-mass dark matter scattering on a lighter target…

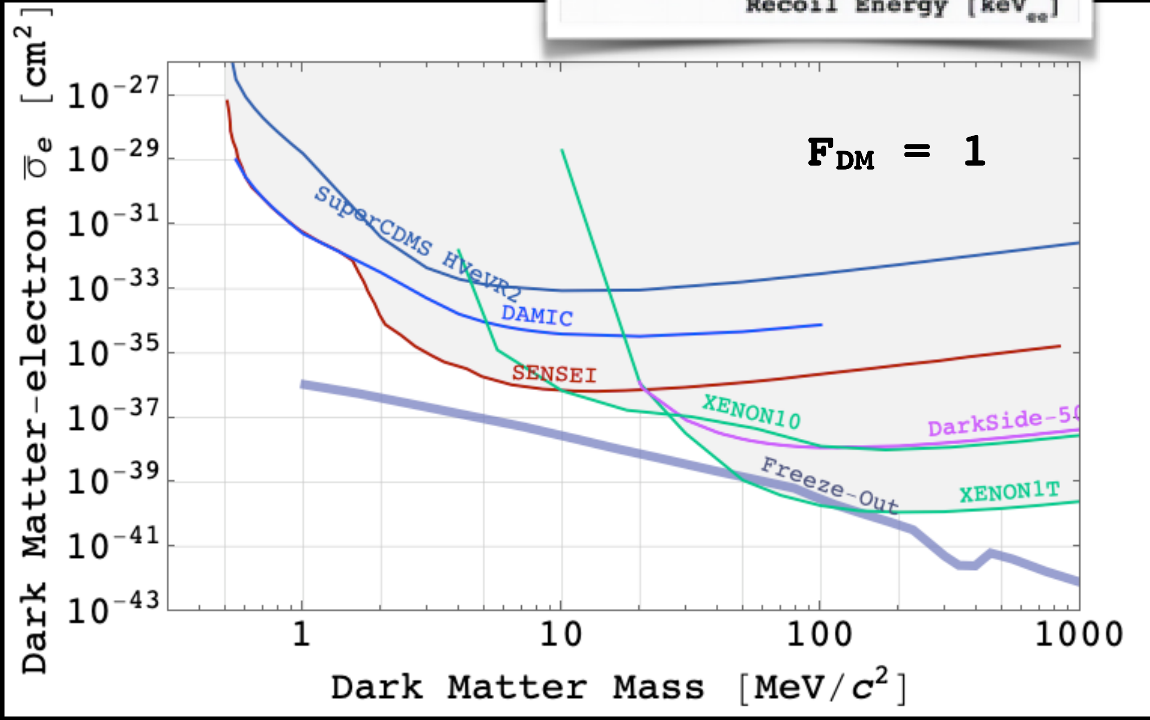
Use the lighter species as the target:

- **Silicon:**

—can reach MeV dark matter mass sensitivity because of low threshold to liberate an e- (~2 eV cf. ~23 in Ar)

—e.g. DAMIC, SENSEI lead limits on vector DM with *O(100 gm-day) exposures*





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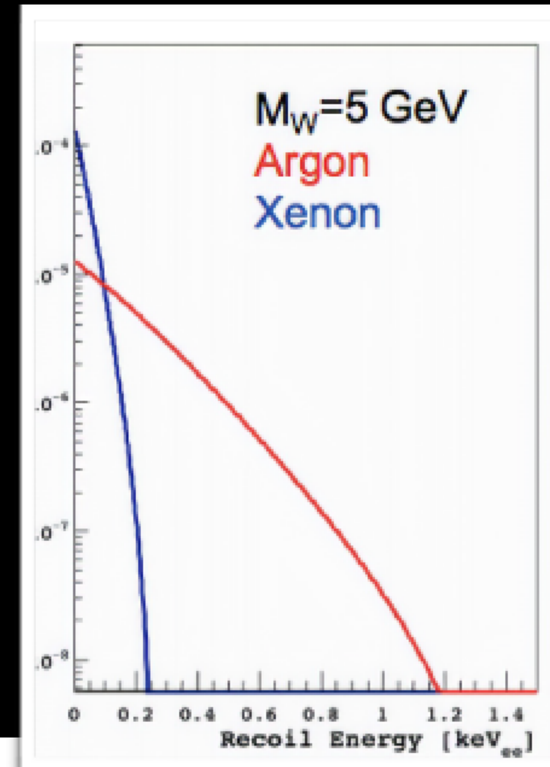
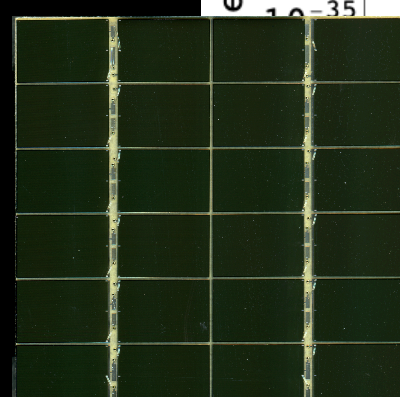
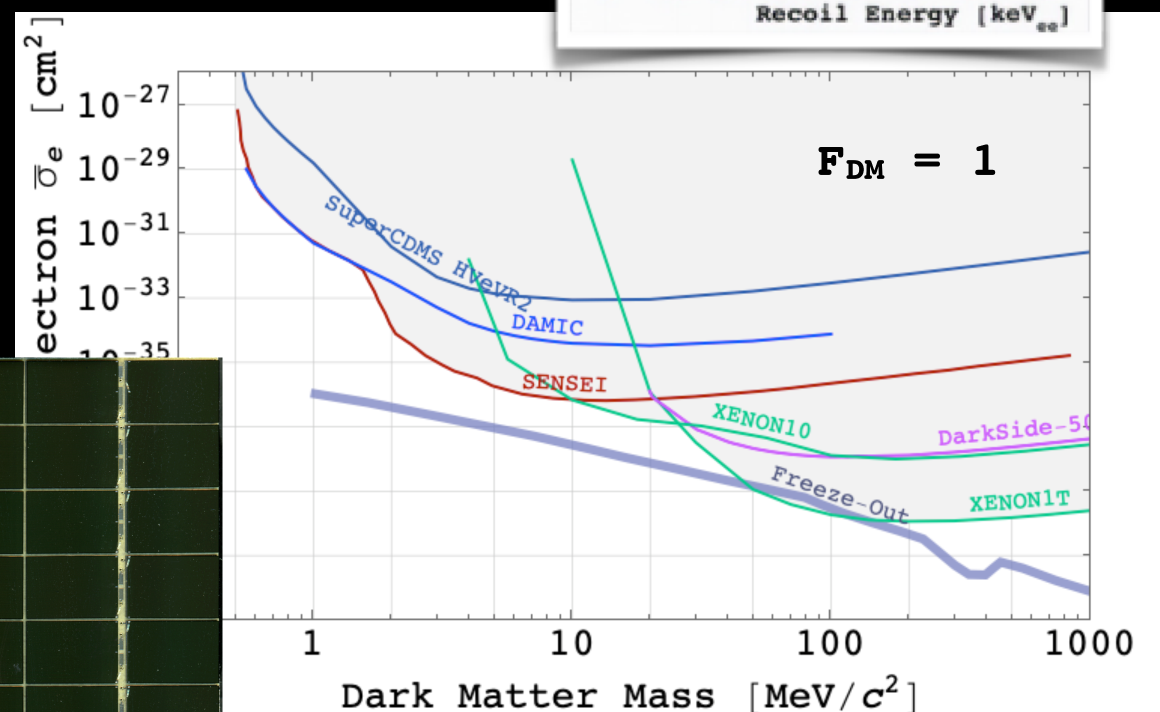


27 kg of radiopure Si in Dark**Si**de-20k SiPM array! ~10x more in ARGO….

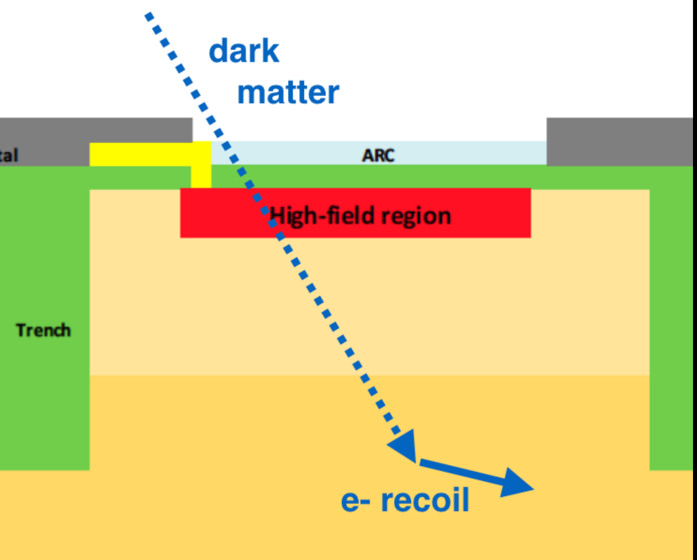
single electron noise comparable to DAMIC, 0.3 e-/pixel/day

(Gola et al., Sensors 2020)





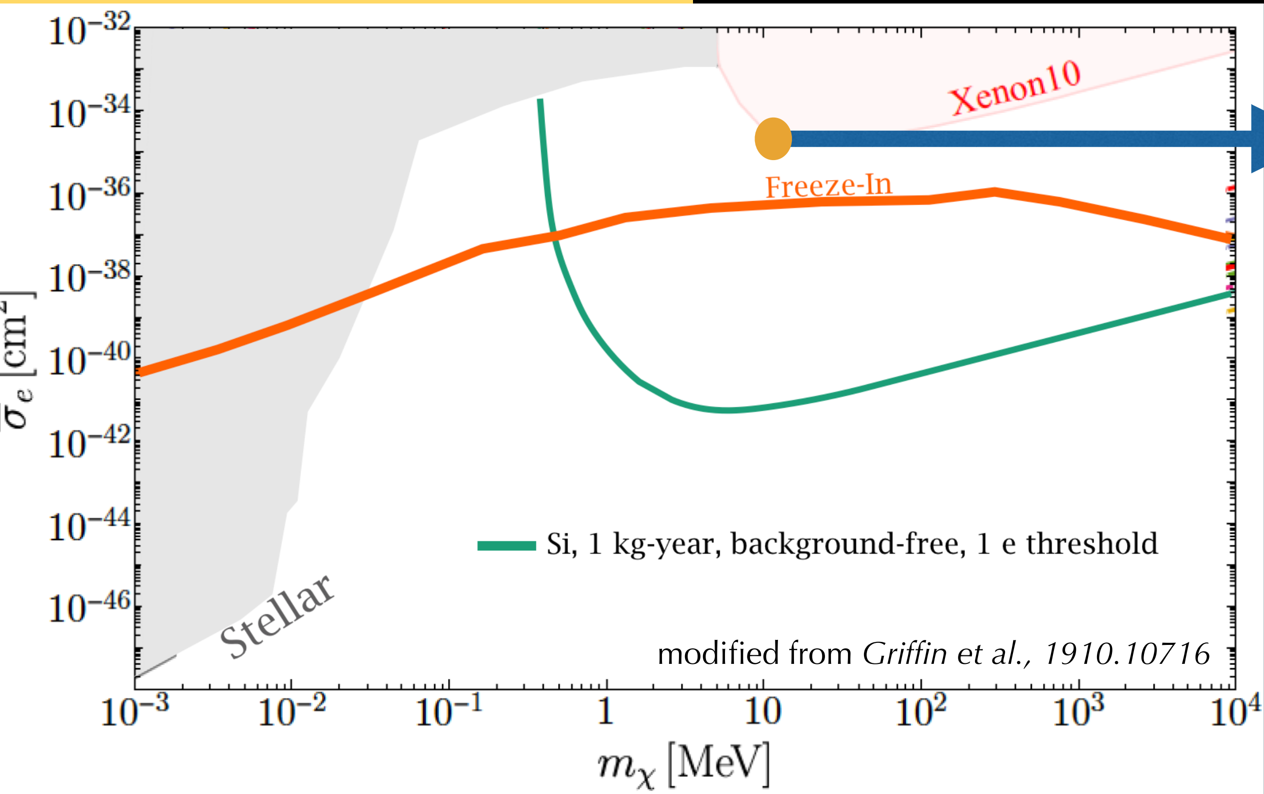
R&D: Detector as Target

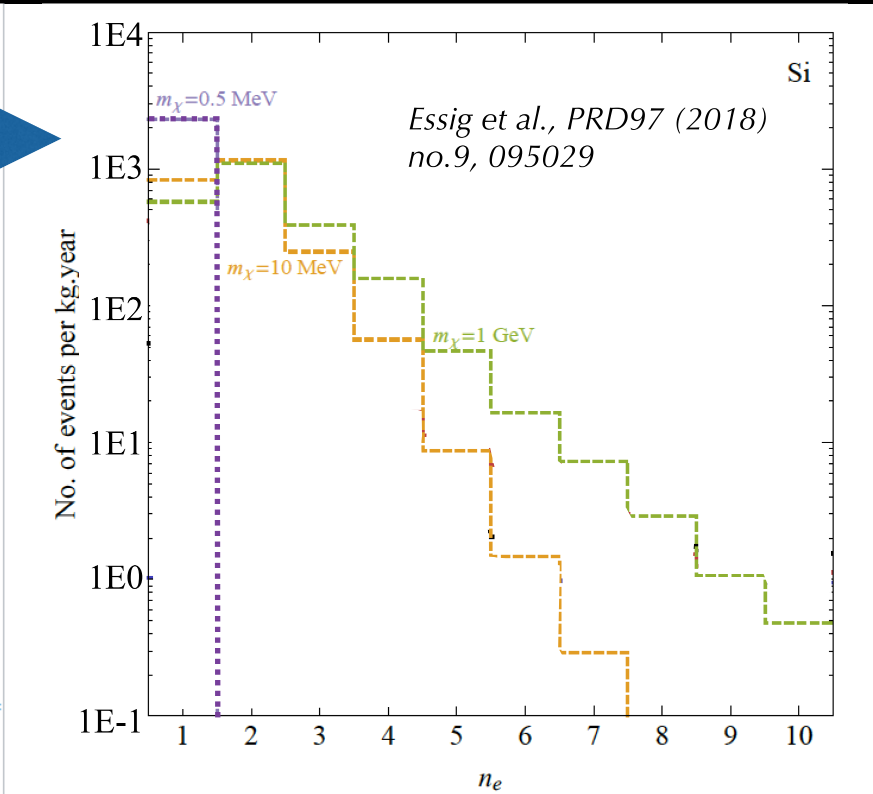


TRIUMF-led R&D effort (JADDE) underway:

1) to measure:
—hole lifetime in the bulk, determines the 'active mass'
—energy resolution: diffusion produces n_pixels ~ n_e

2) optimized sensor R&D underway for full depletion + pixel readout (builds on 3DdSiPM project)





Marie Skłodowska-Curie Actions

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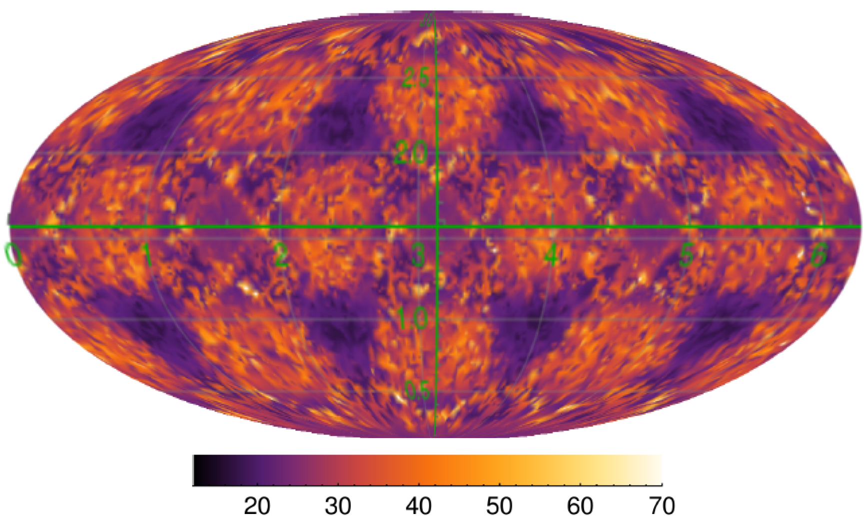
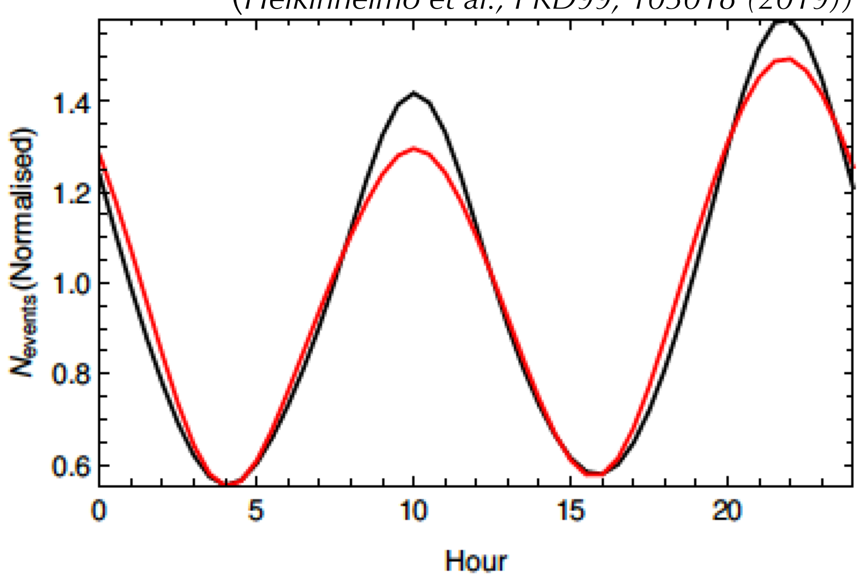
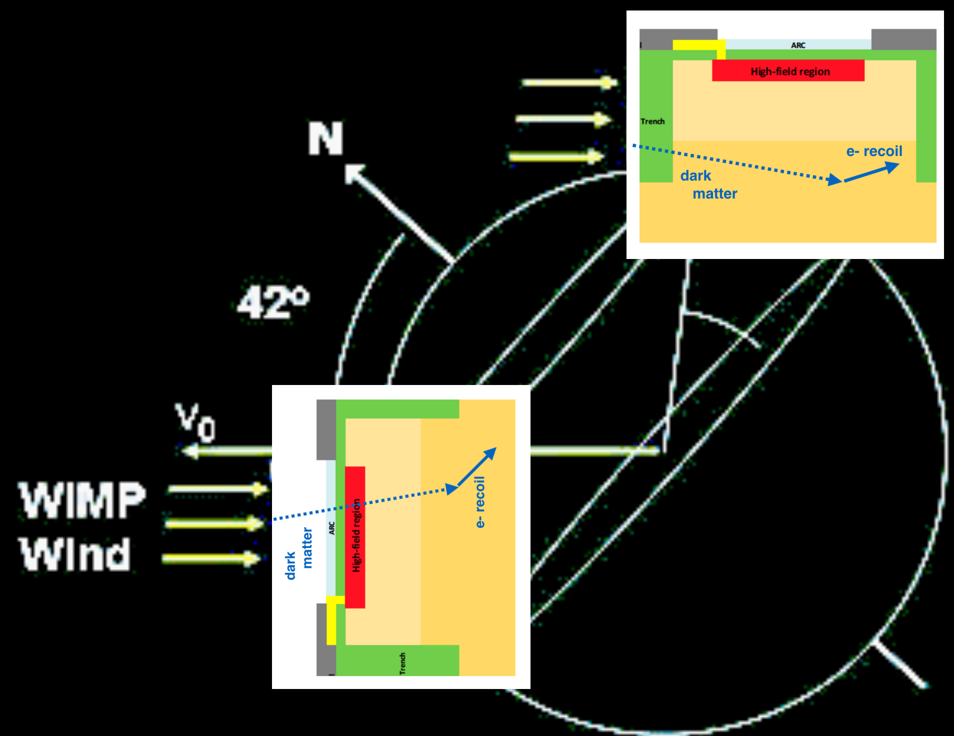


(*Heikinheimo et al., PRD99, 103018 (2019)*)

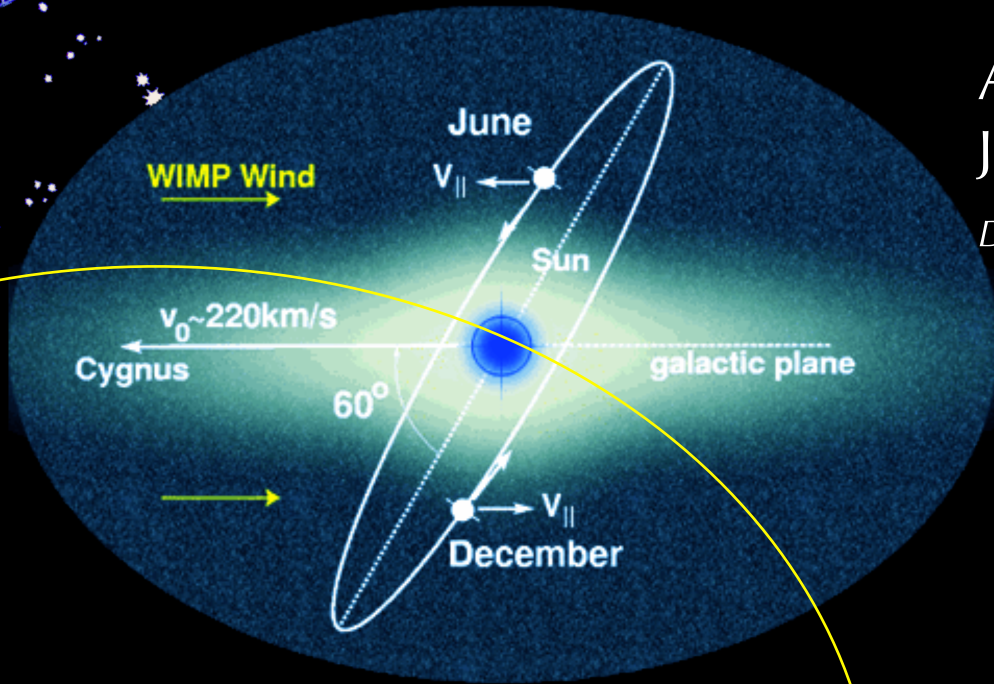


- interesting potential in Si: energy threshold to liberate a charge carrier in Si depends on orientation relative to crystal symmetry axis — sidereal modulation in dark matter signal rate

- planar geometry of crystal could enable *directional* identification of signal vs. backgrounds

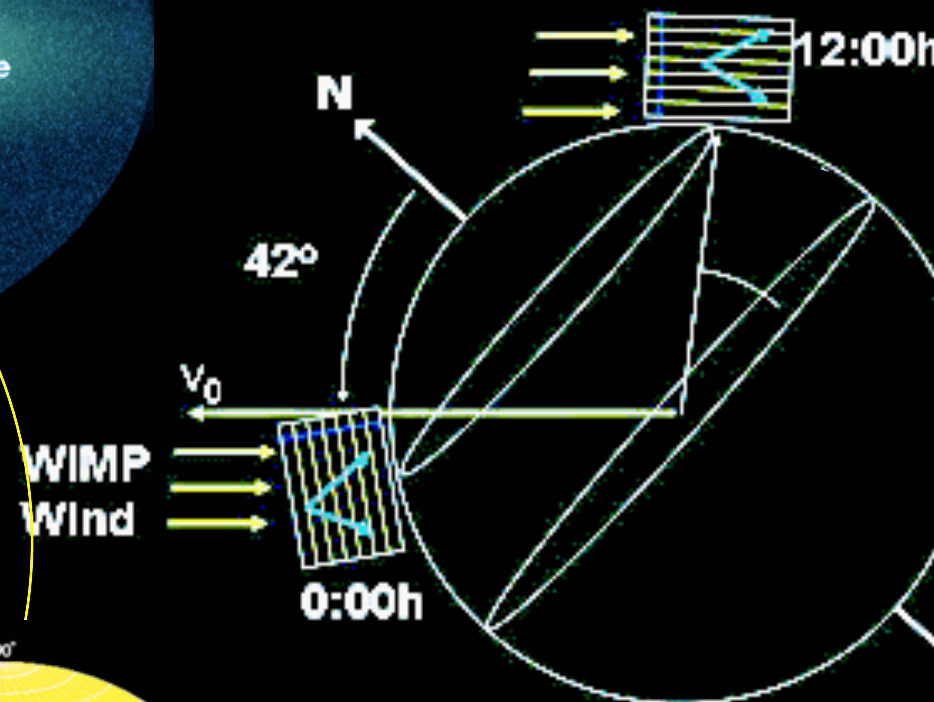


Direction Signatures in Dark Matter Searches



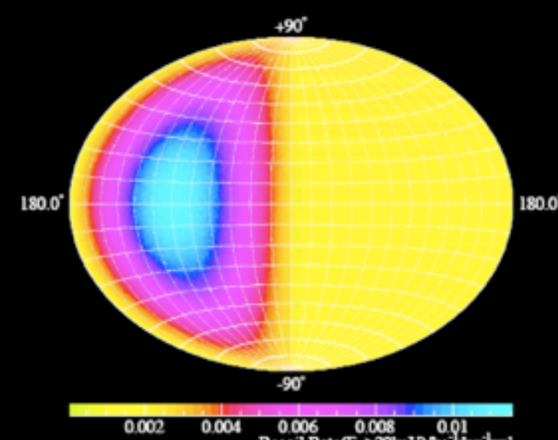
Annual event rate modulation:
June-December asymmetry ~2%.

Drukier, Freese, Spergel, Phys. Rev. D33:3495 (1986)



Sidereal direction modulation:
asymmetry ~ 20-100% in
forward-backward event rate.

Spergel, Phys. Rev. D36:1353 (1988)



Ultimate goal:
dark matter skymap

Horizon Scanning: Enabling Technologies

2) develop back-side illuminated SPAD, for full depletion, to expand reach

Building on **3DdSiPM** project's advances in FSI-SPAD readout

Photon to Digital Converter

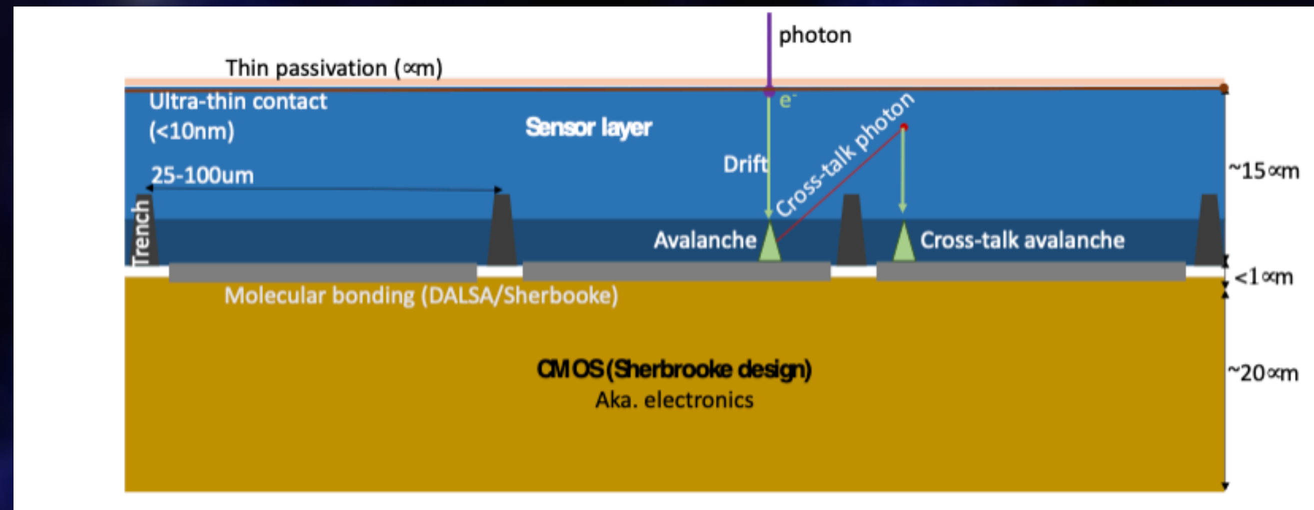
- Back-side illumination R&D for enhanced performance and versatility (search in **Si**!)

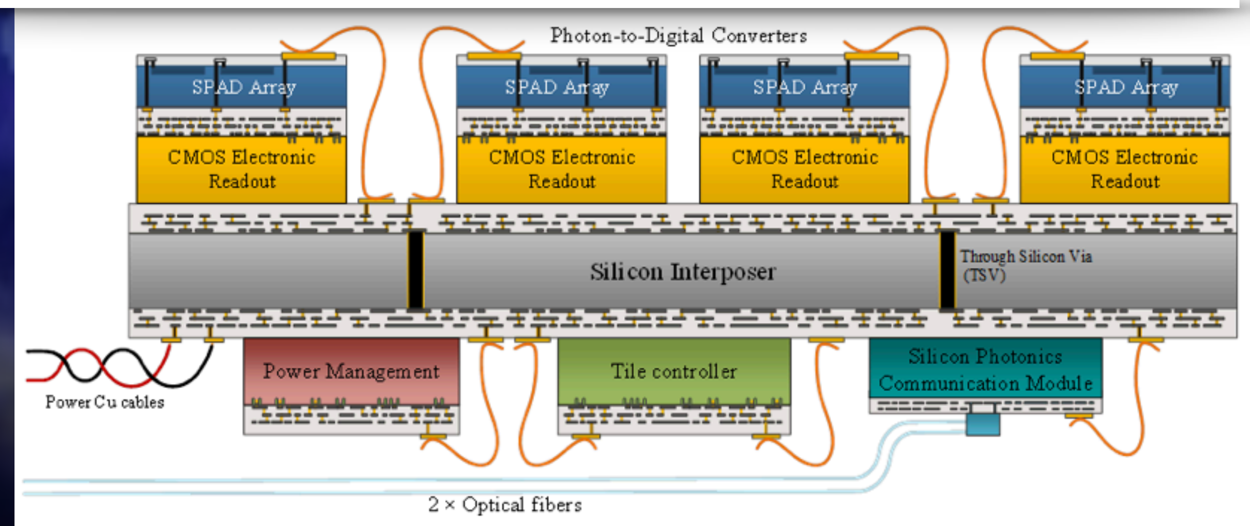
Silicon interposer

- In collaboration with Fraunhofer IZM

Photonic communication

- Data encoding by light modulation - no light source





U. Sherbrooke, TRIUMF, Carleton U. with implementation at Teledyne-DALSA

Ultra-low radioactivity photon detector module for ARGO

Conclusions & Outlook

Exciting prospects at the low background frontier are driving technology development in inspiring directions.

Direct detection searches are rapidly expanding physics reach.

Experiments running now or under construction aim to continue to beat Moore's Law by 2x….

… detector development is the engine of progress!