Detector Development

making the invisible visible

A very personal selection

- **Collider Detectors**
  - silicon: from transparent to massive
- **Dark Matter Detectors**
  - searching for particles and waves over 50 orders of magnitude
- **Neutrino Detectors**
  - pixelizing light and charge

Collider Detectors

From Sand to Science

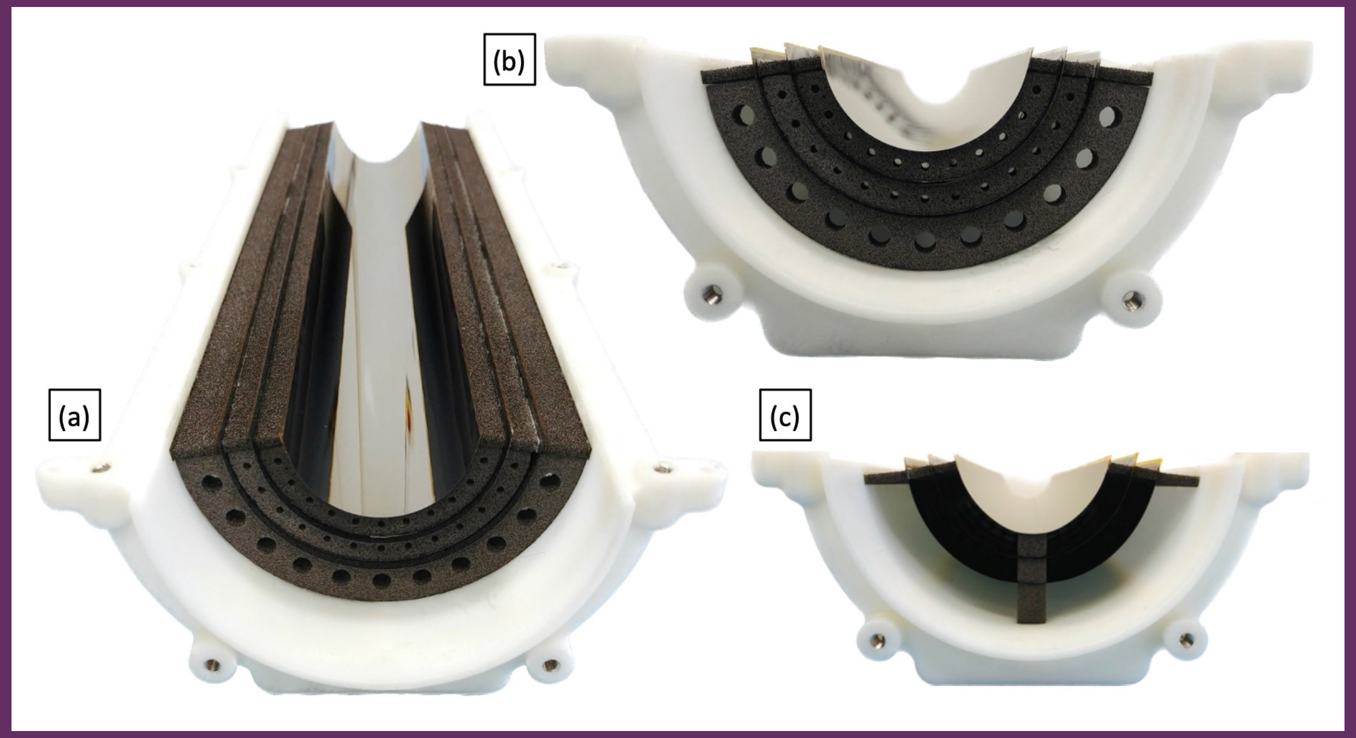
Silicon detectors are now the workhorse of collider detectors, spanning hundreds of m^2 from near transparent vertex detectors to massive calorimetry

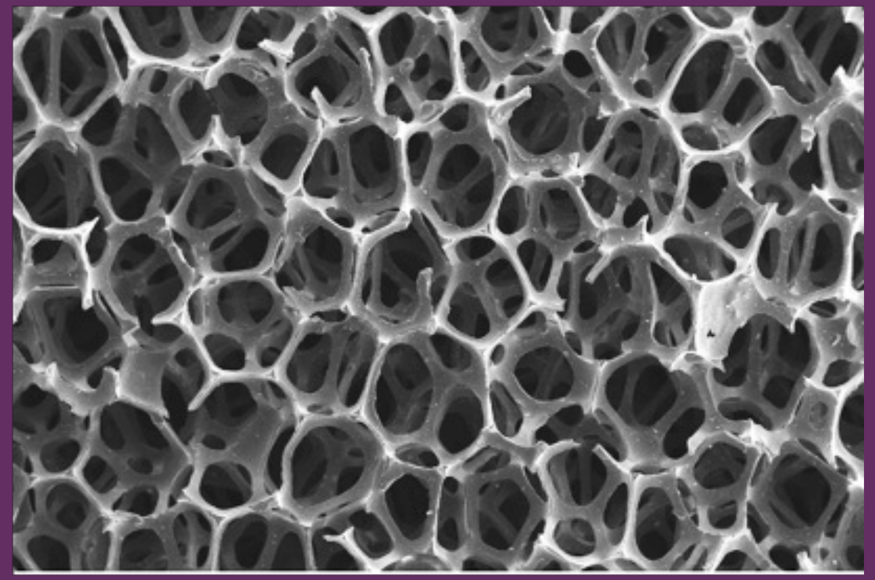
see talk by F. Schlepper

State-of-the-art: ALICE ITS3

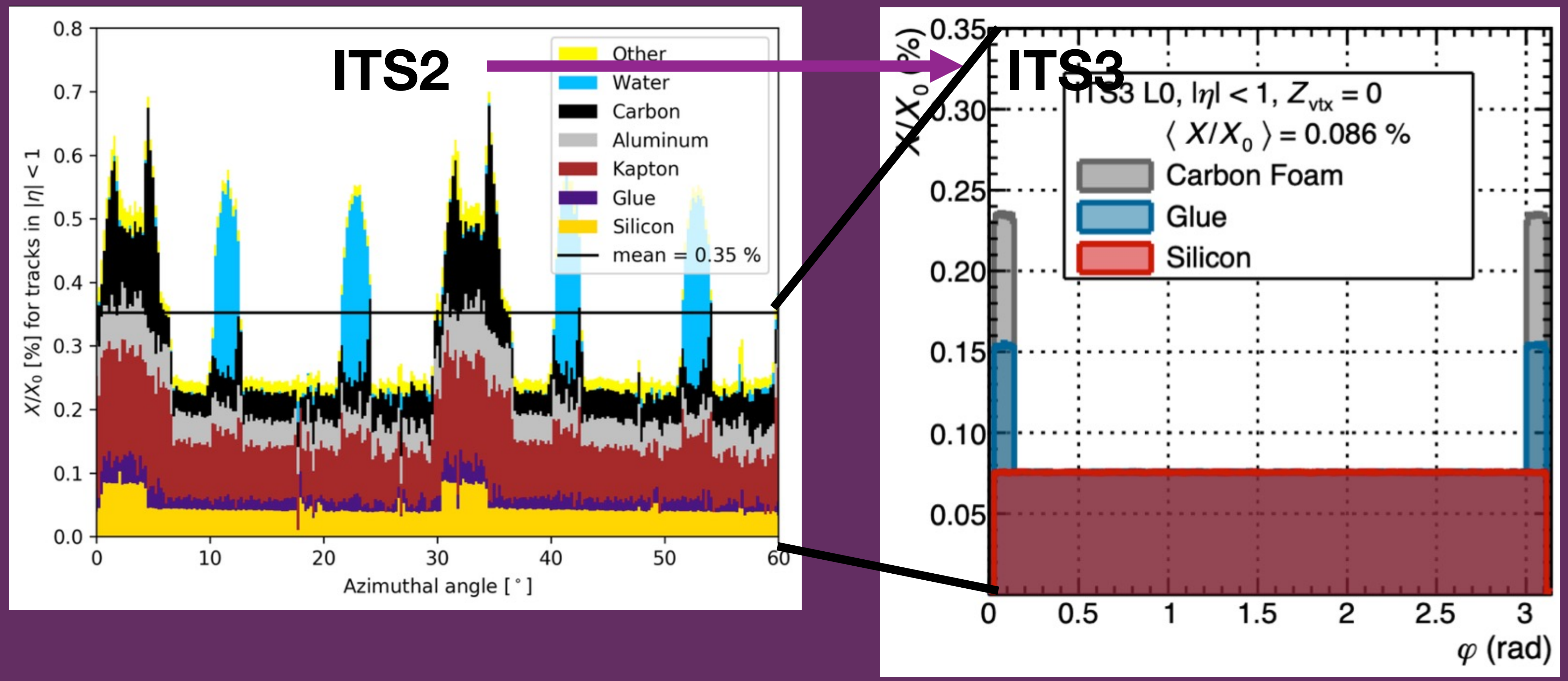
A truly cylindrical, near-transparent vertex detector

- 300mm wafer-scale CMOS MAPS fabricated from smaller chips using stitching
  - ✓ Silicon thinned down to ≤50μm making them flexible; bent to target radii
  - ✓ Power density <40mW/cm²
  - ✓ mechanically held in place by carbon foam
  - ✓ Planning to use air cooling (~8m/s)
- Extremely low material budget: <0.07% X_0, homogeneous material distribution





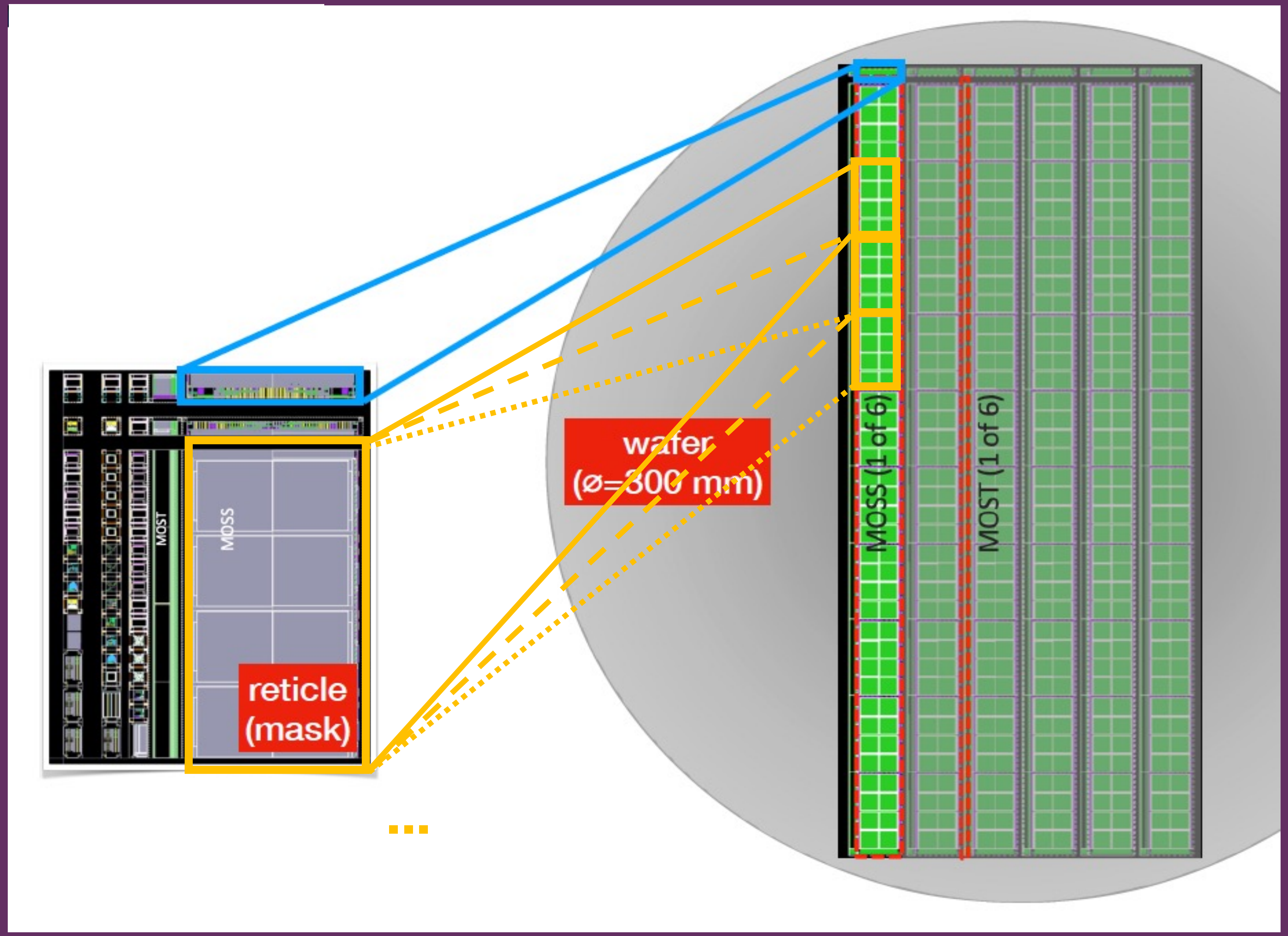
Carbon foam support + air cooling

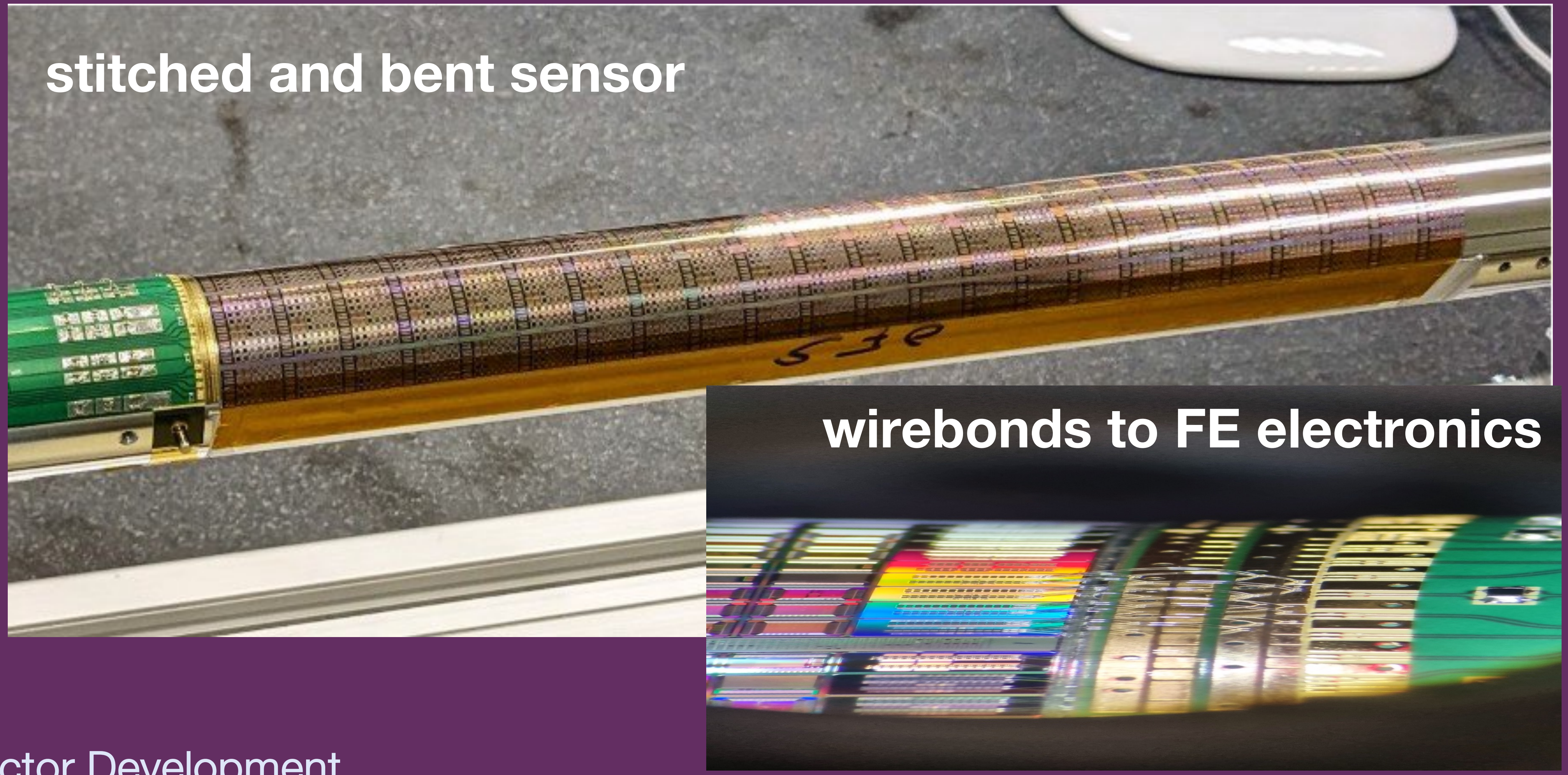


Sensor Stitching

- Chip size is traditionally limited by CMOS manufacturing (“reticle size”)
  - typical size of few cm^2
  - modules are tiled with chips connected to a flexible printed circuit board

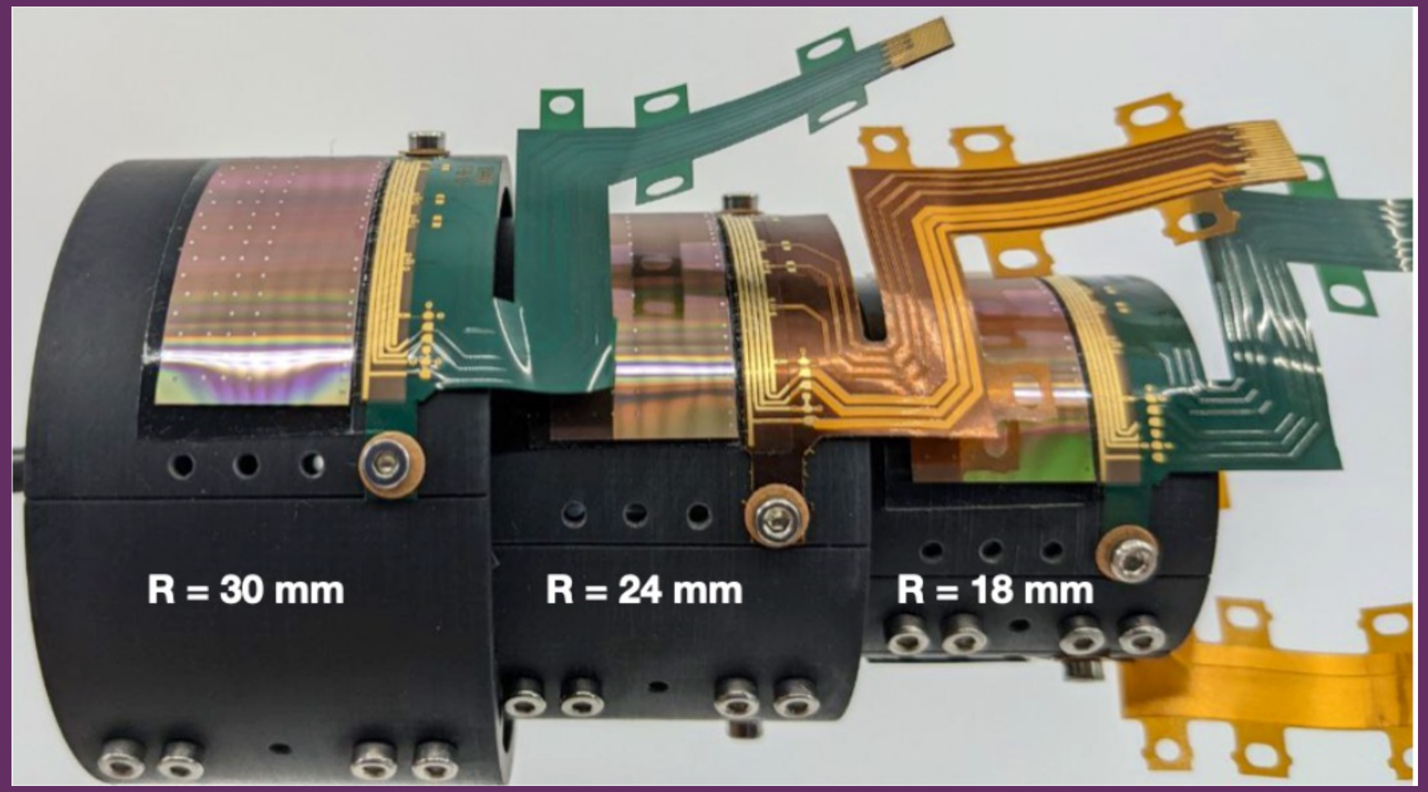
- New developments: stitching
  - aligned exposures of a reticle to produce larger circuits
    - actively used in industry
    - a 300mm wafer can house a chip to equip a full half-layer
    - requires dedicated chip design
- Final circuit is concatenation of different parts of the mask

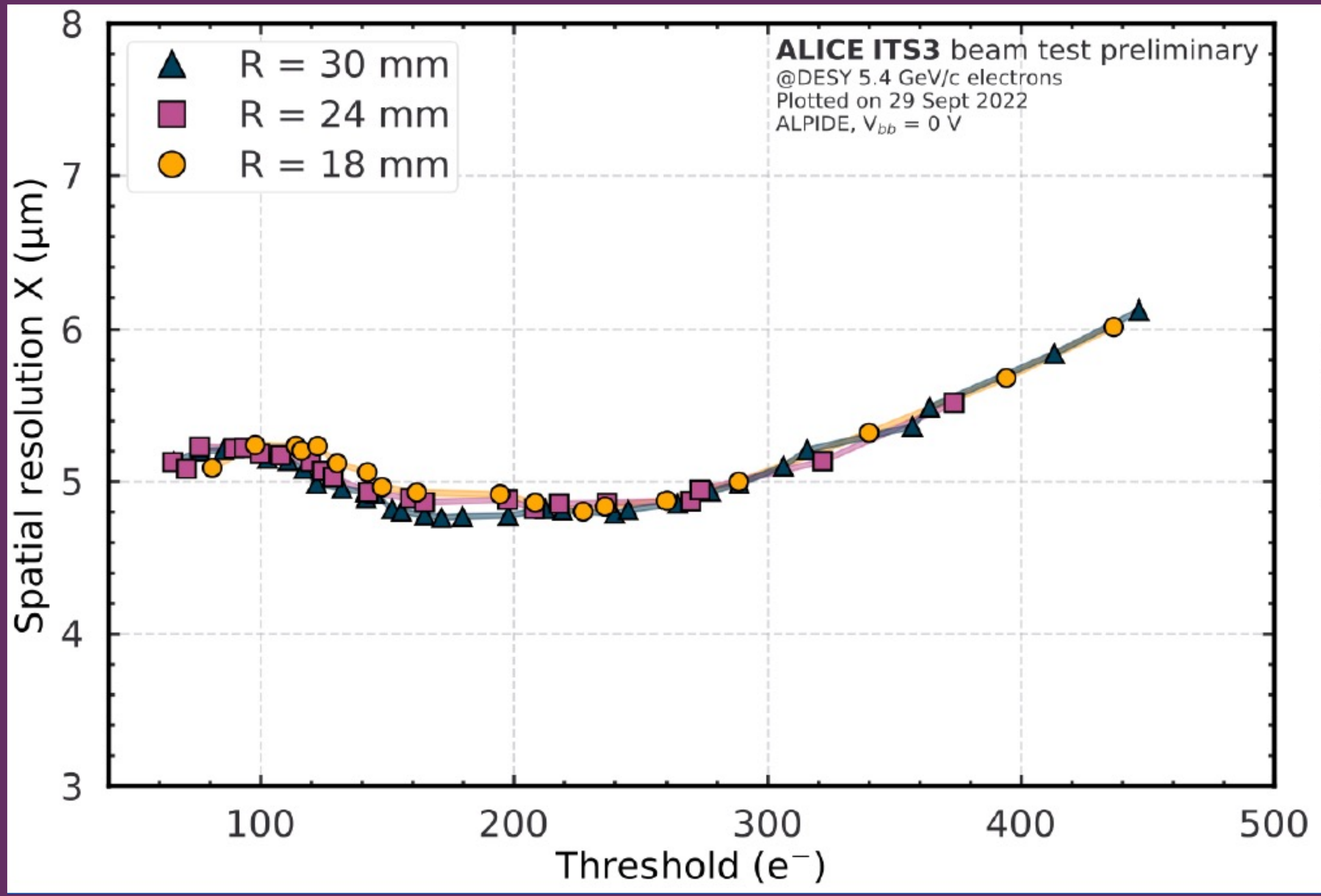


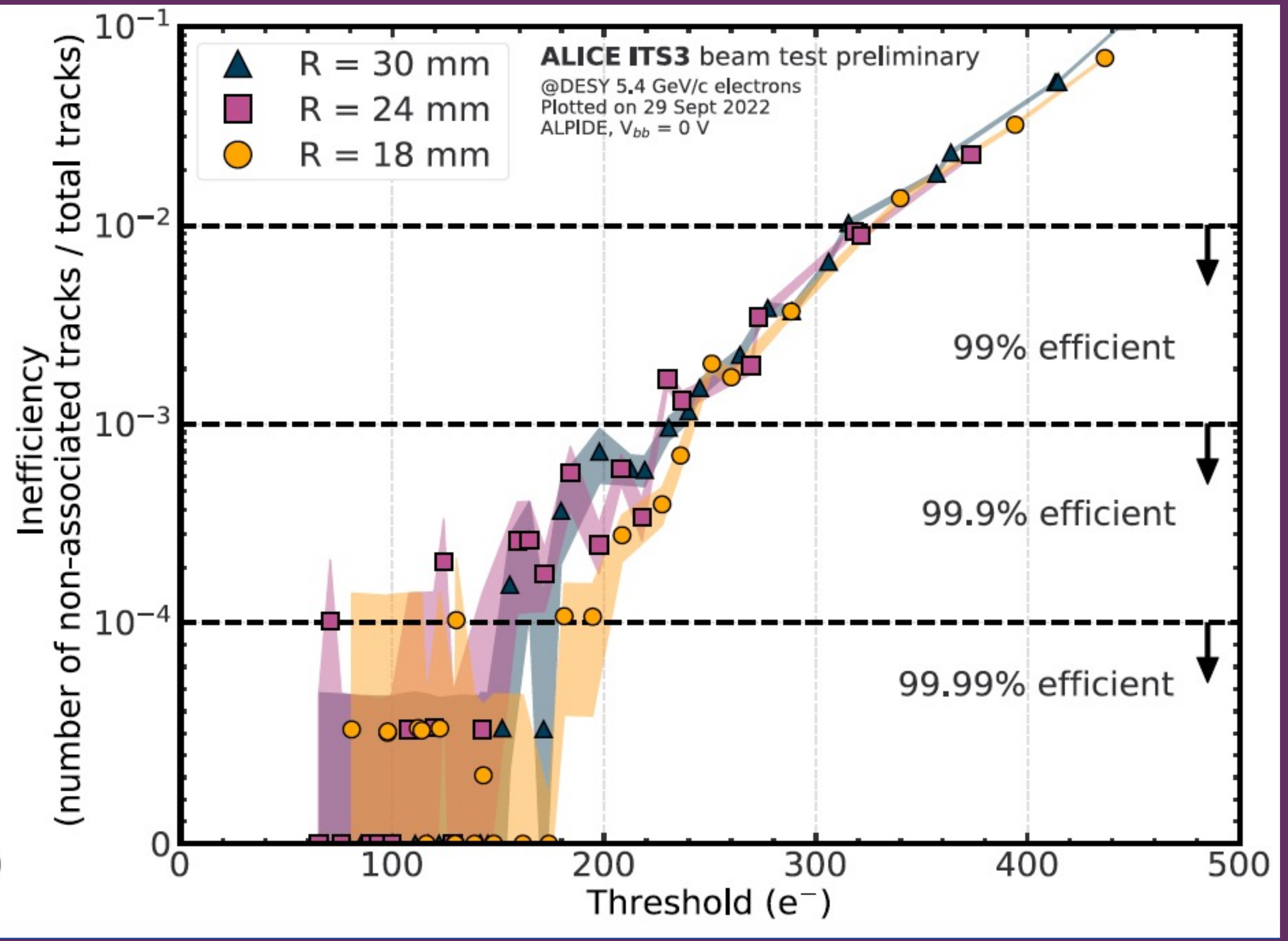


Performance of bent sensors

- Excellent performance, comparable to flat sensor
- Spatial resolution 5μm
- Efficiency >99.99%







More Intelligent Detectors

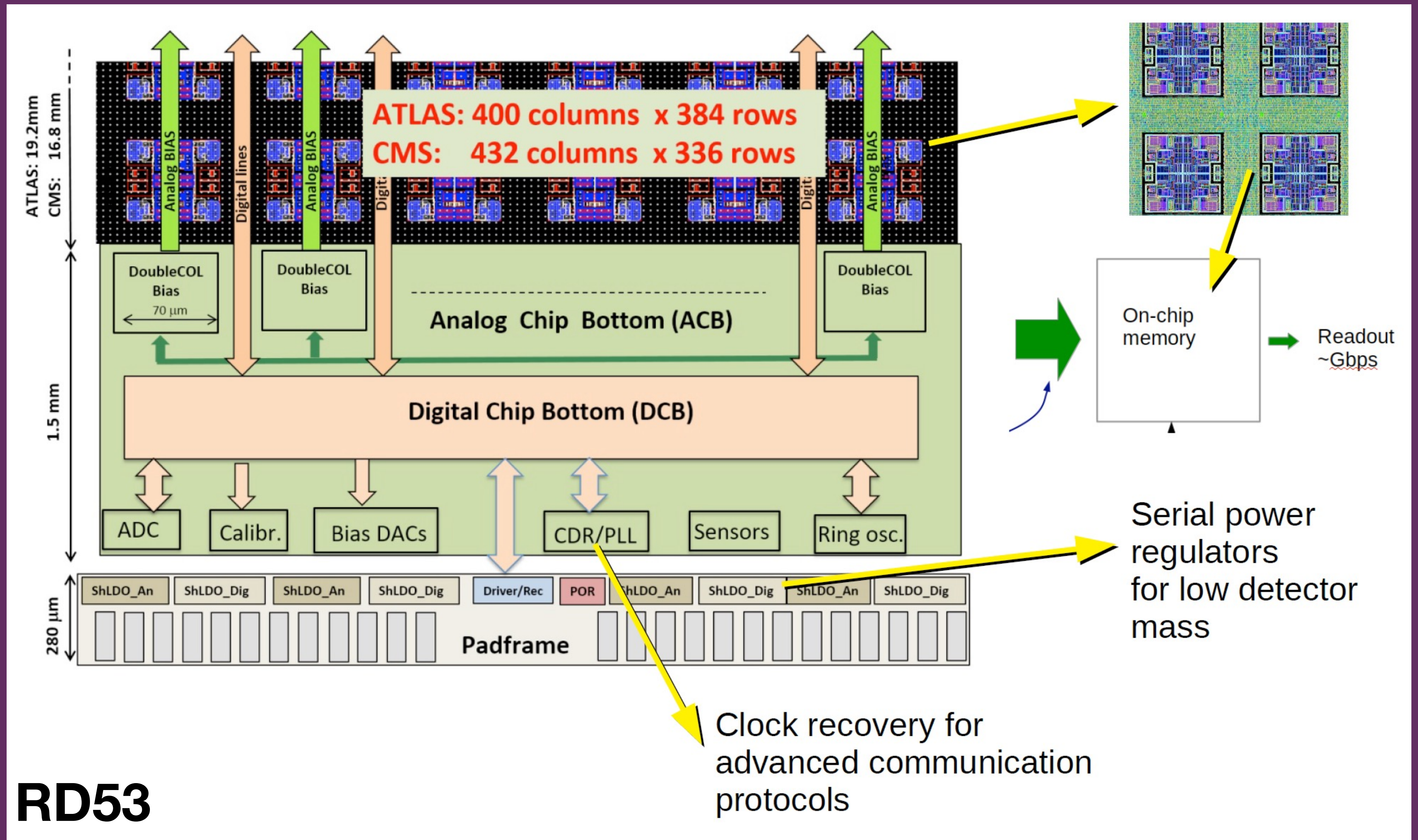
Pack more and more functionality onto chip

- communication, power distribution, monitoring
- optical and wireless
- FPGA and AI/ML functions now straightforward to include
- Big challenge: SEU tolerance, power consumption

→ Next-gen ASICs will be developed in 28nm technology

Use Machine Learning on ASIC for physics motivated data reduction on detector

- filter on e.g. incidence angle, pt, hit position, uncertainty, time information, etc.

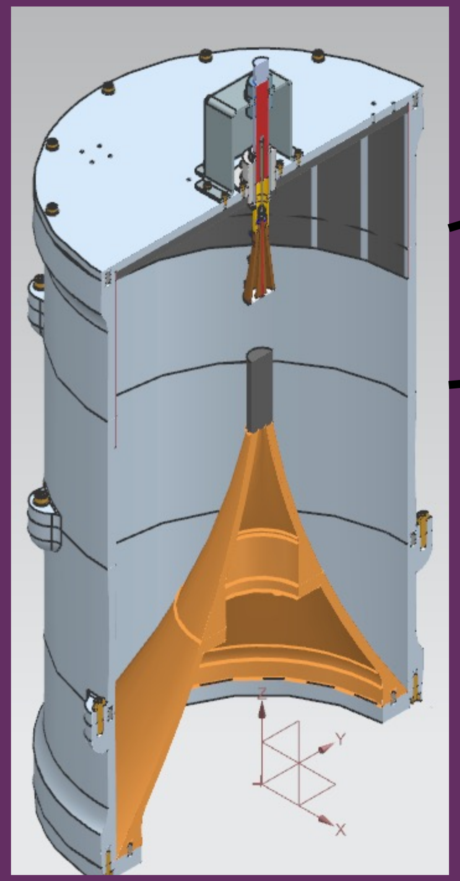


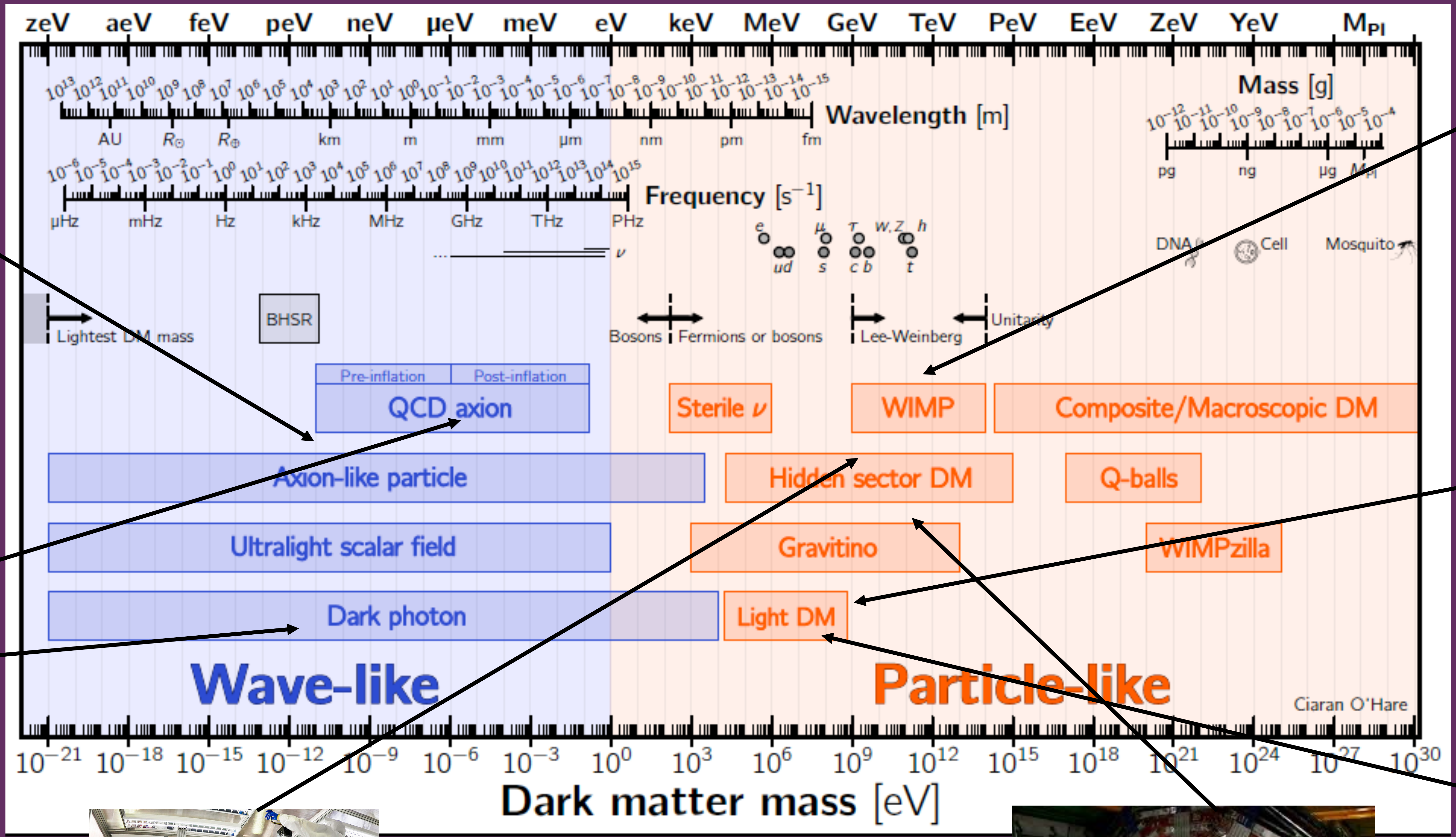
➔ **more complex systems have increased need for on-chip data storage**

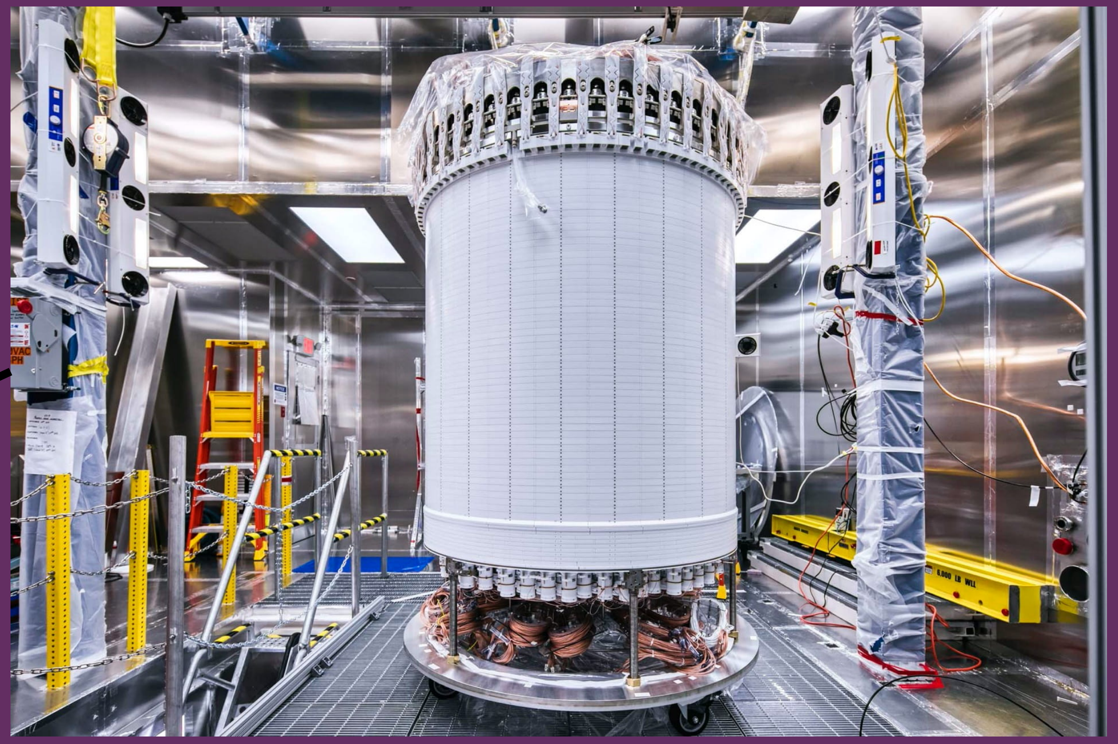
Synergies with Neutrino and DM Detectors and Medical Imaging

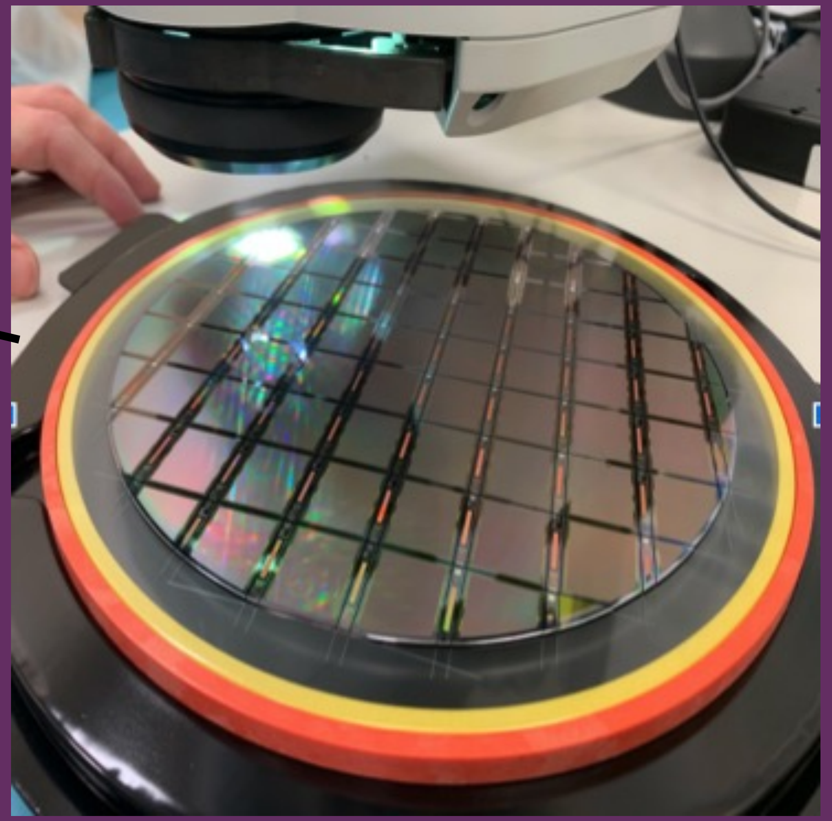
Dark Matter Detectors

50 orders of magnitude to hide in







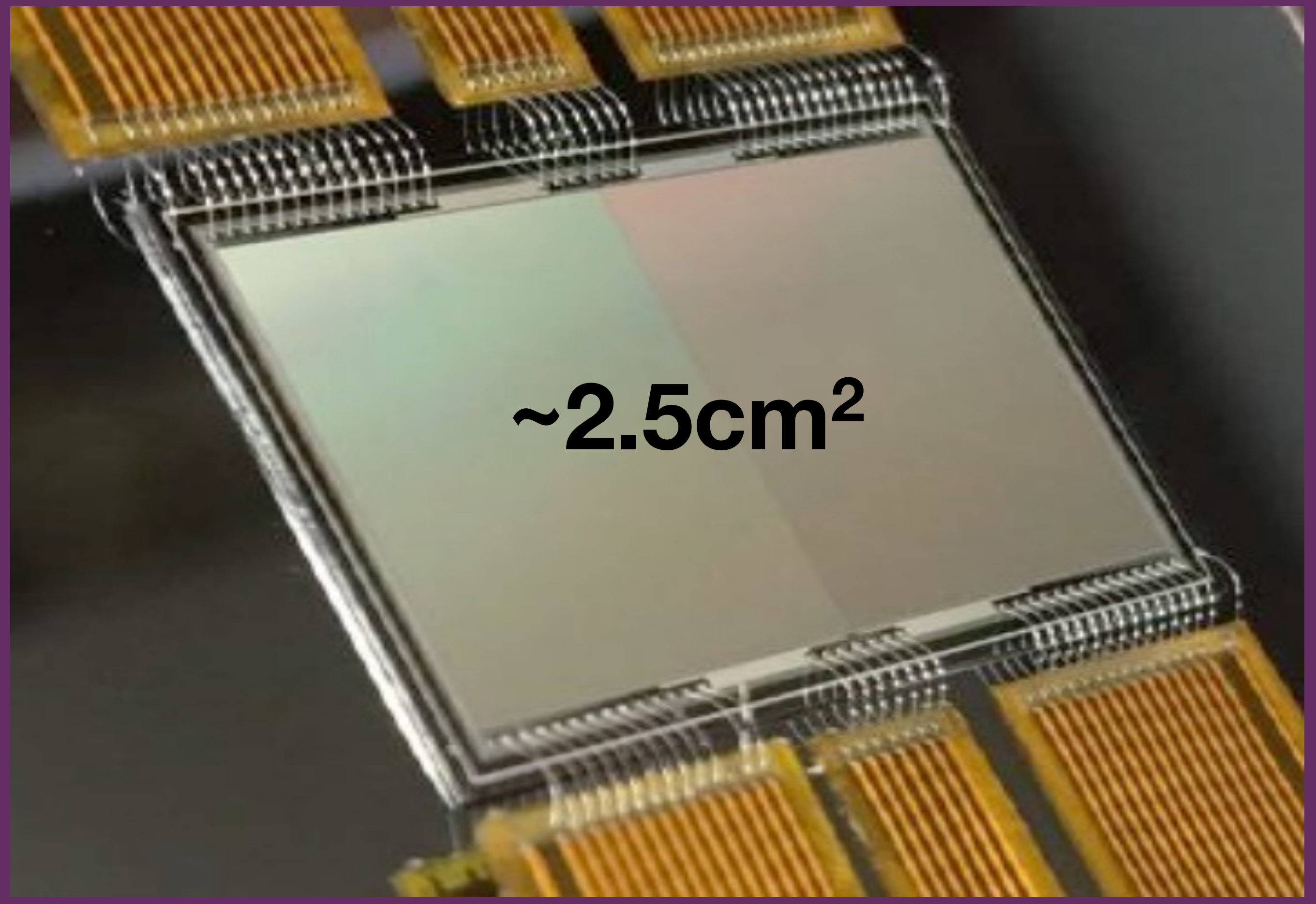


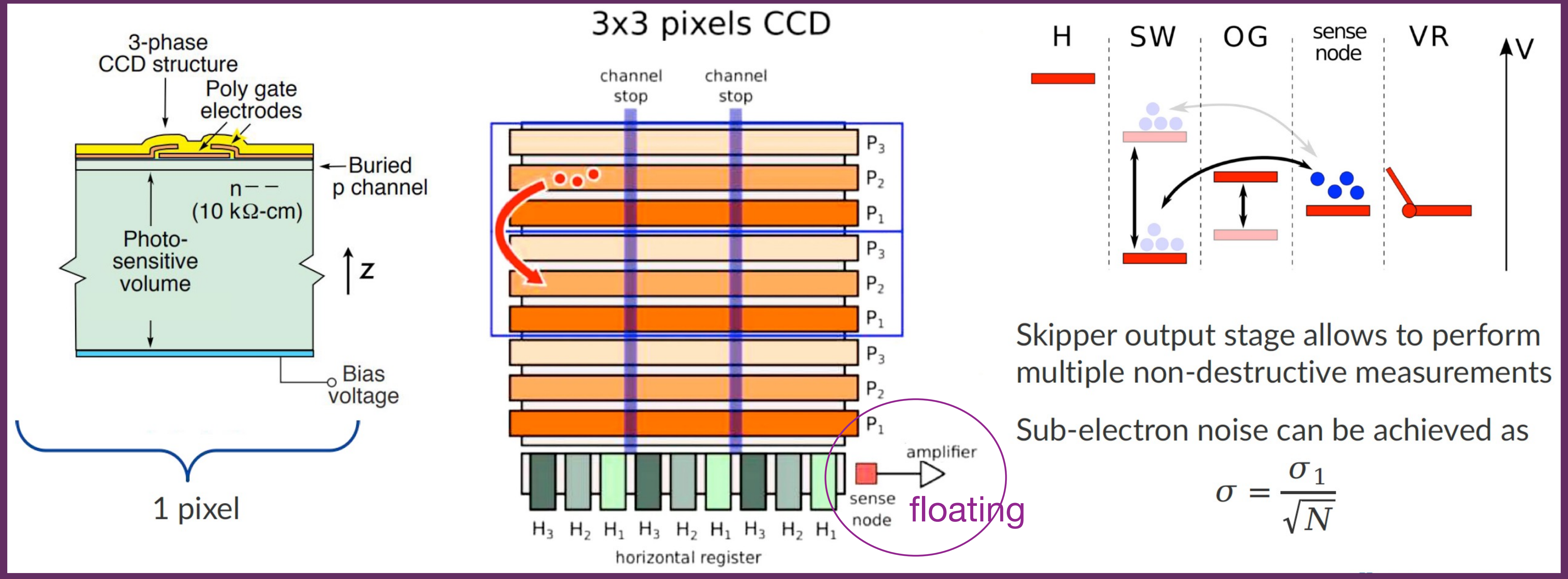
Detecting sub-GeV Particle-like DM

Low threshold technologies to explore the dark sector:

- Very promising: Skipper-CCDs
- Extremely low noise → single electron/photon counting
- Downside: slow readout

  → R&D to speed up, e.g. regional r/o, energy-dependent r/o, double-sided r/o, background suppression through masking or freezing



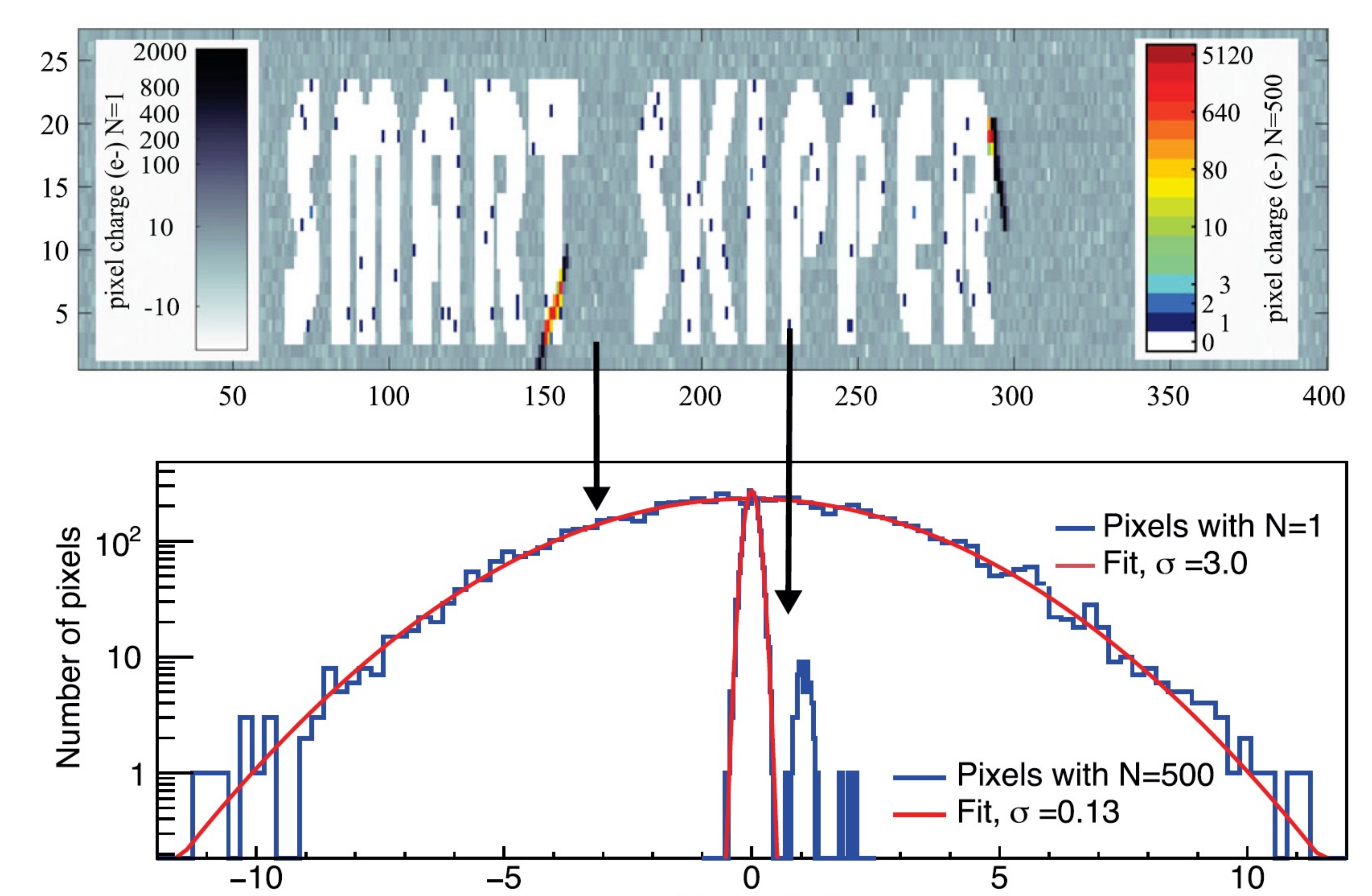


design by S.Holland, LBNL

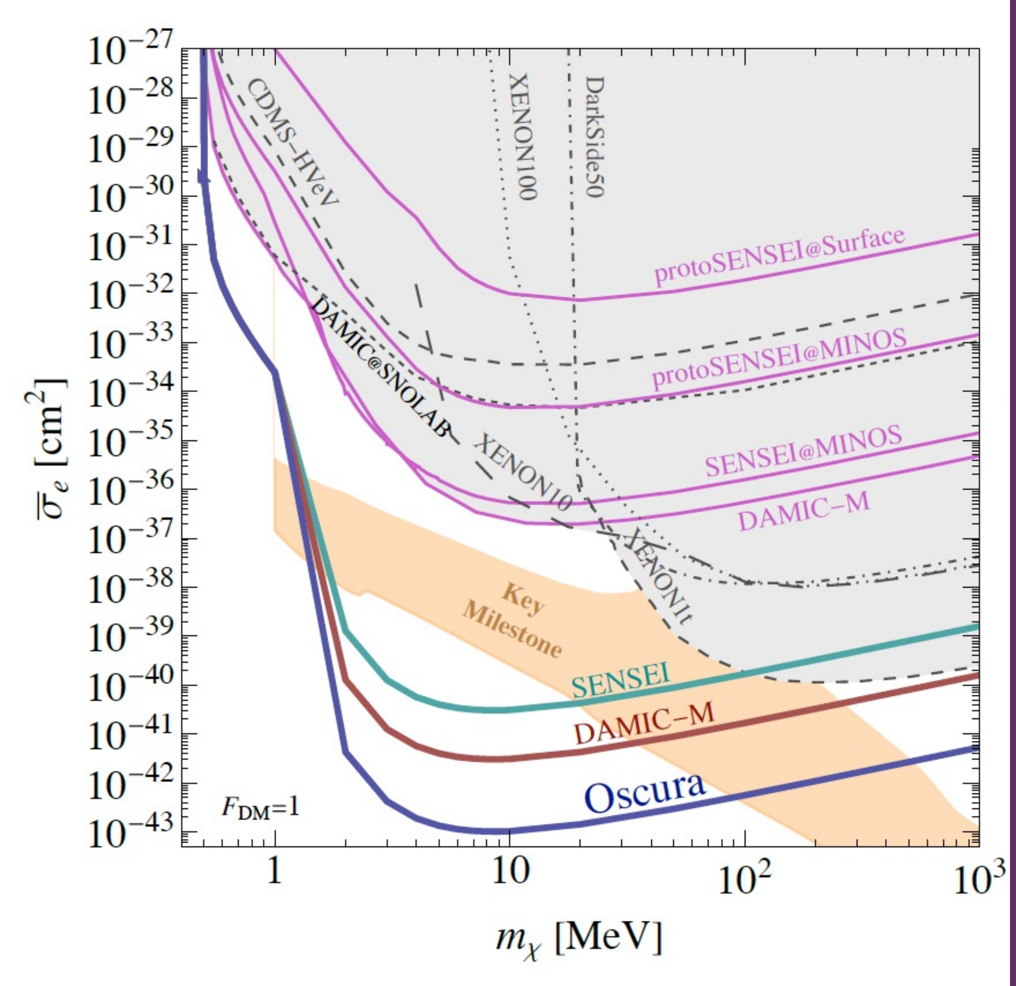
Exciting first Results

[Skipper-CCD ROI paper]

- Different applications call for different levels of noise or dynamic range sensitivities
- For low-mass DM low threshold and large target mass are key
- World-leading first science results from
  - SENSEI@MINOS (2g detector, shallow underground)
  - DAMIC-M (18g detector, 1700m deep@Modane)
  - SENSEI (100g, 2000m deep@SNOLAB)
  - DAMIC-M (1kg, 1700m deep@Modane)
  - OSCURA (10kg, 2000m deep@SNOLAB)
  - well motivated sub-GeV DM models



region of interest r/o



[DM projections with Skipper-CCDs]

Detecting wave-like DM

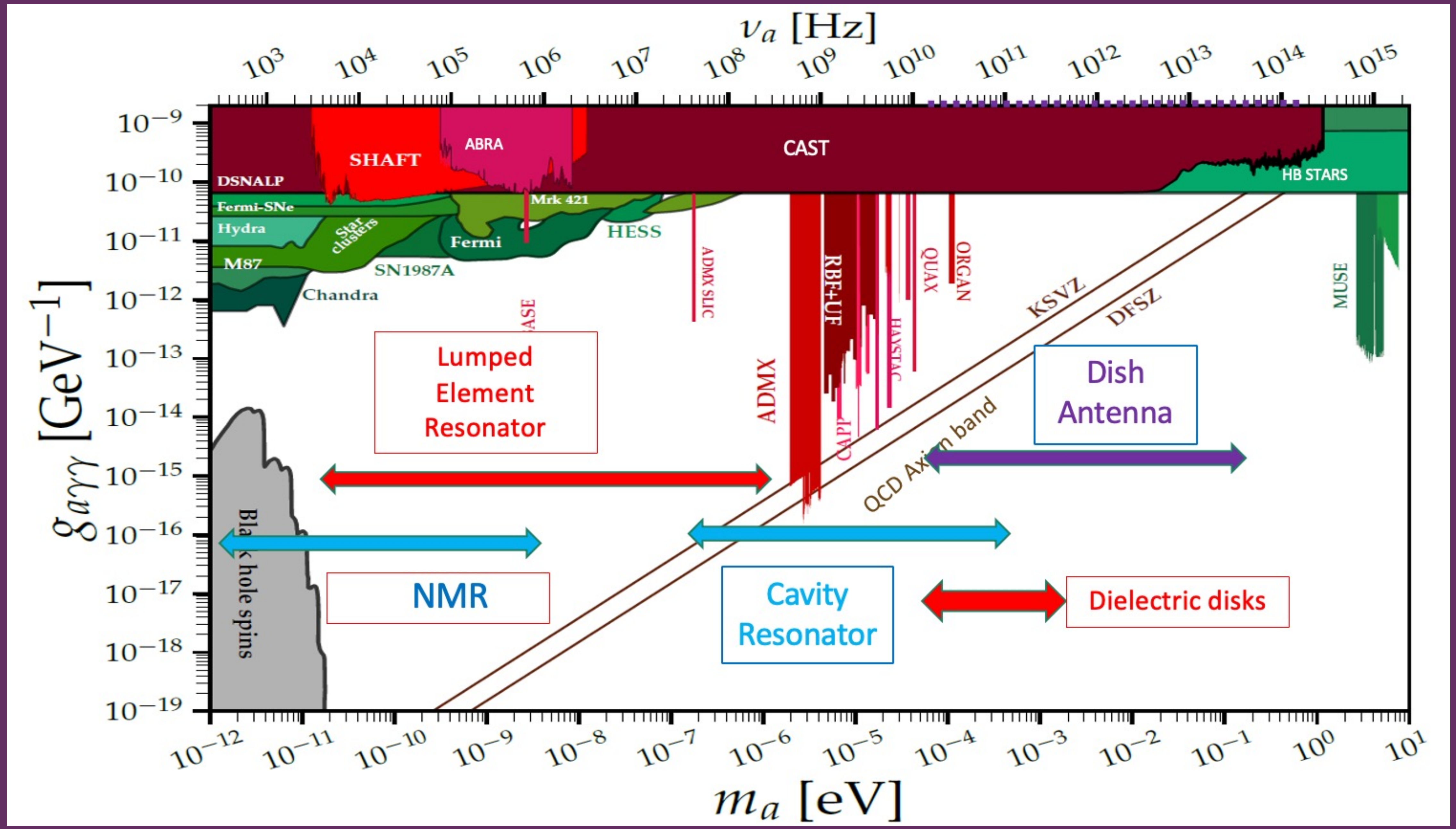
Suite of axion search experiments, based on resonant cavity detectors in strong magnetic fields

- cavity size matched to axion Compton wavelength

- Axion-to-photon conversion power proportional to volume

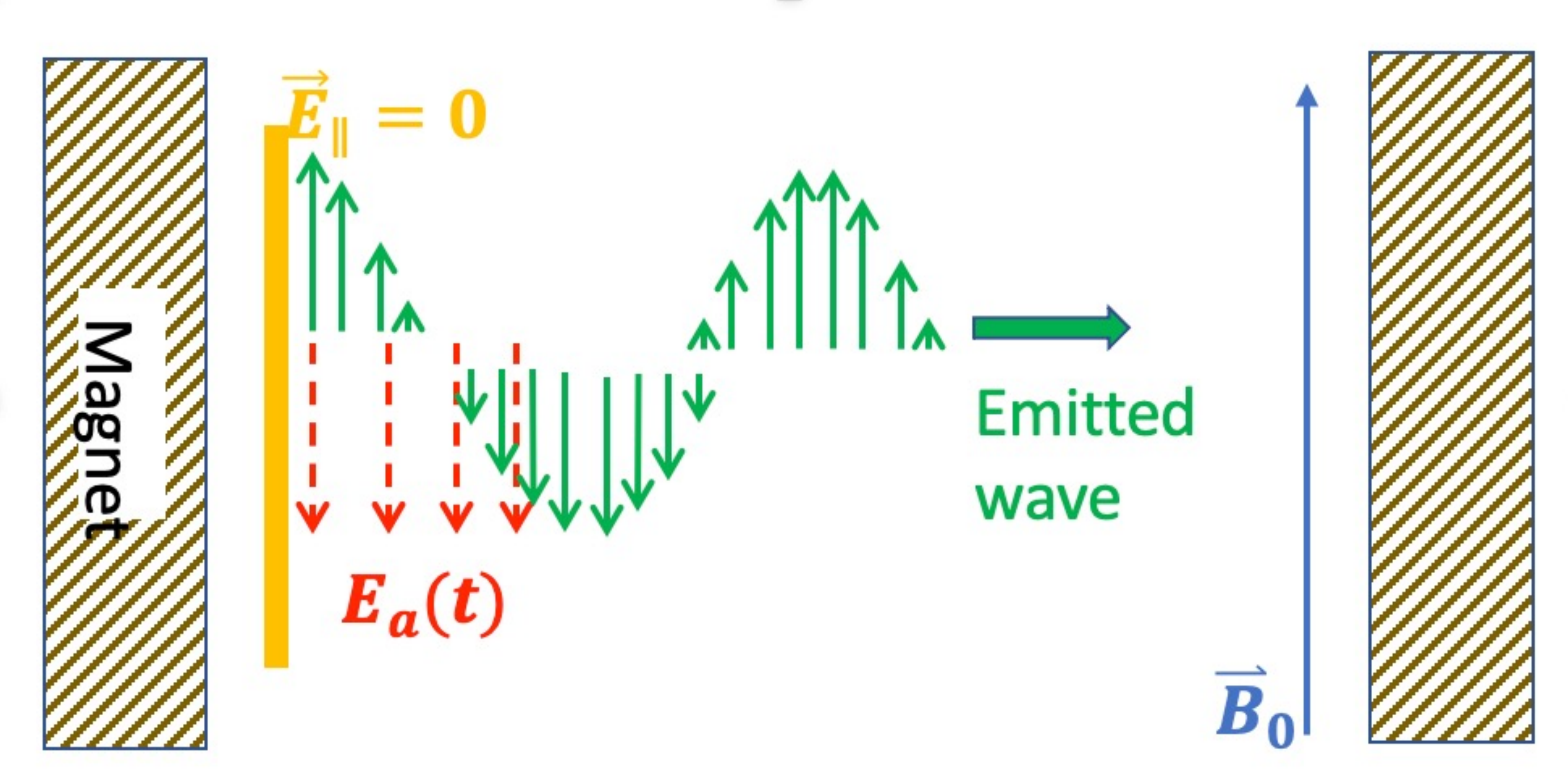
→each experiment limited to narrow frequency band in sensitivity, need for tuning rods or modular approach

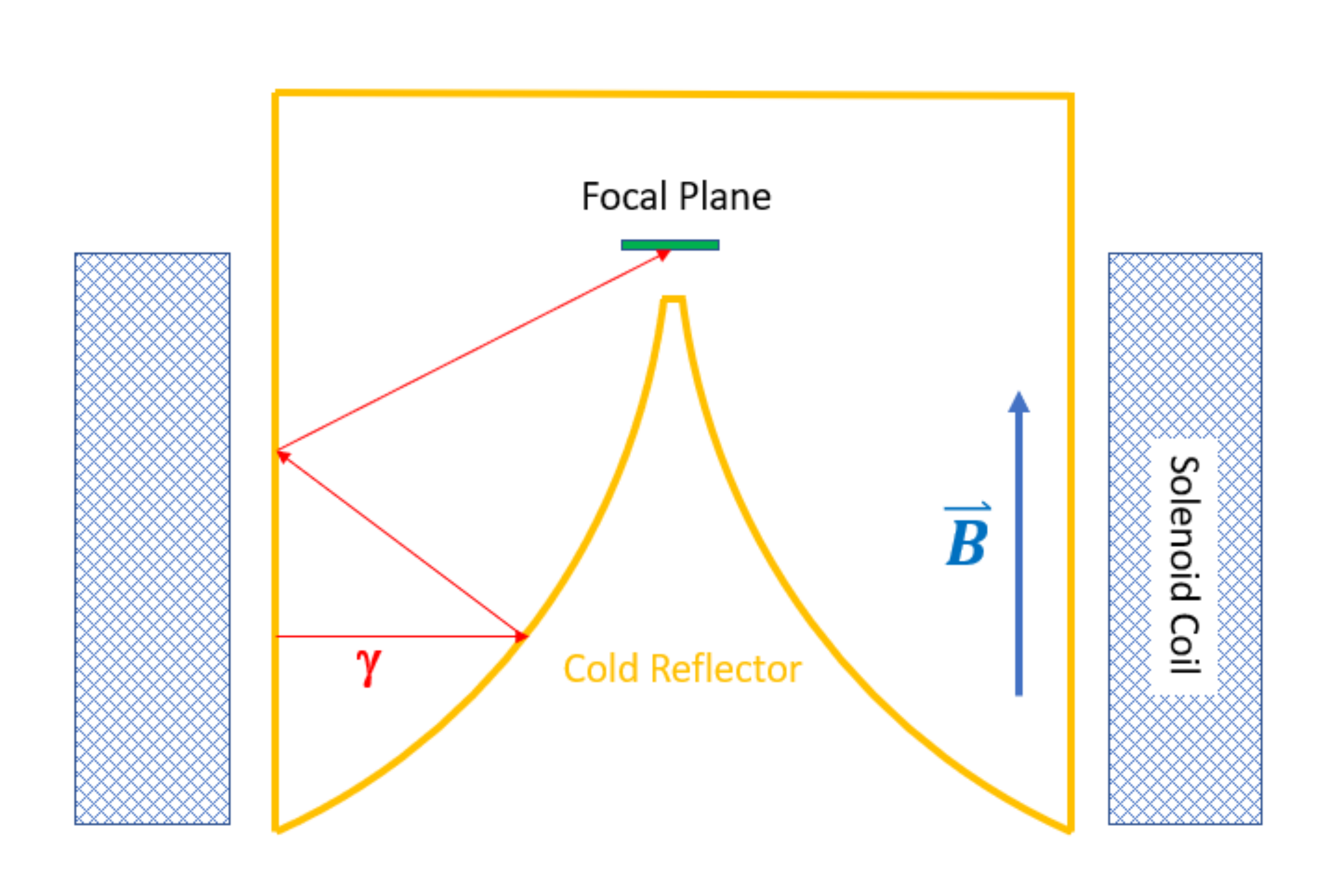
→this technology scales poorly to high mass



Idea: convert DM and count single photons

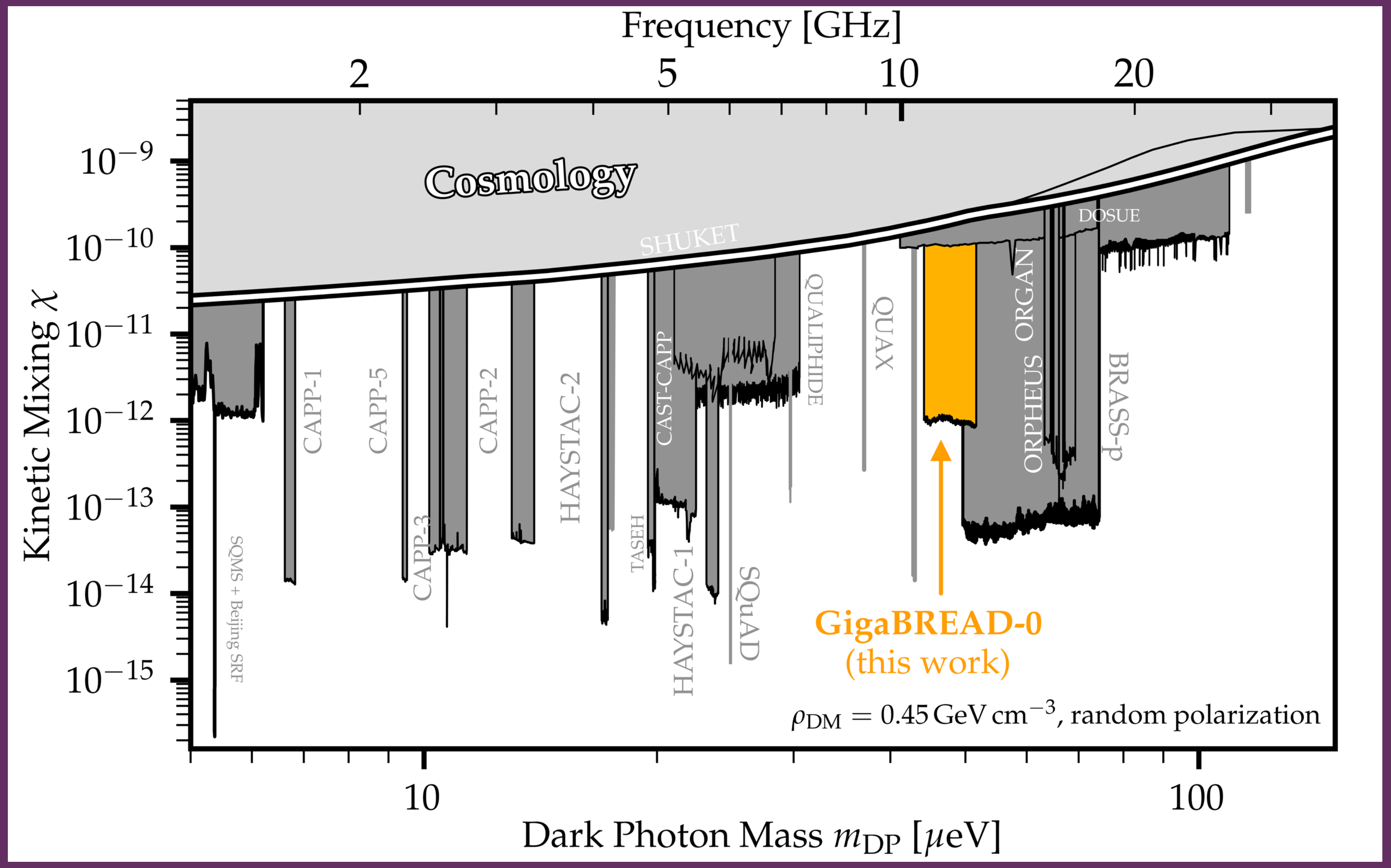
- Axions interact with a static magnetic field producing an oscillating parallel electric field in free space
- A conducting surface in this field emits a planar wave perpendicular to the surface
- Radiated power is low, but no detector tuning required!
- Need for powerful single photon sensors: e.g. SNSPD, KID, or Bolometers, Heterodyne, etc. for signal detection



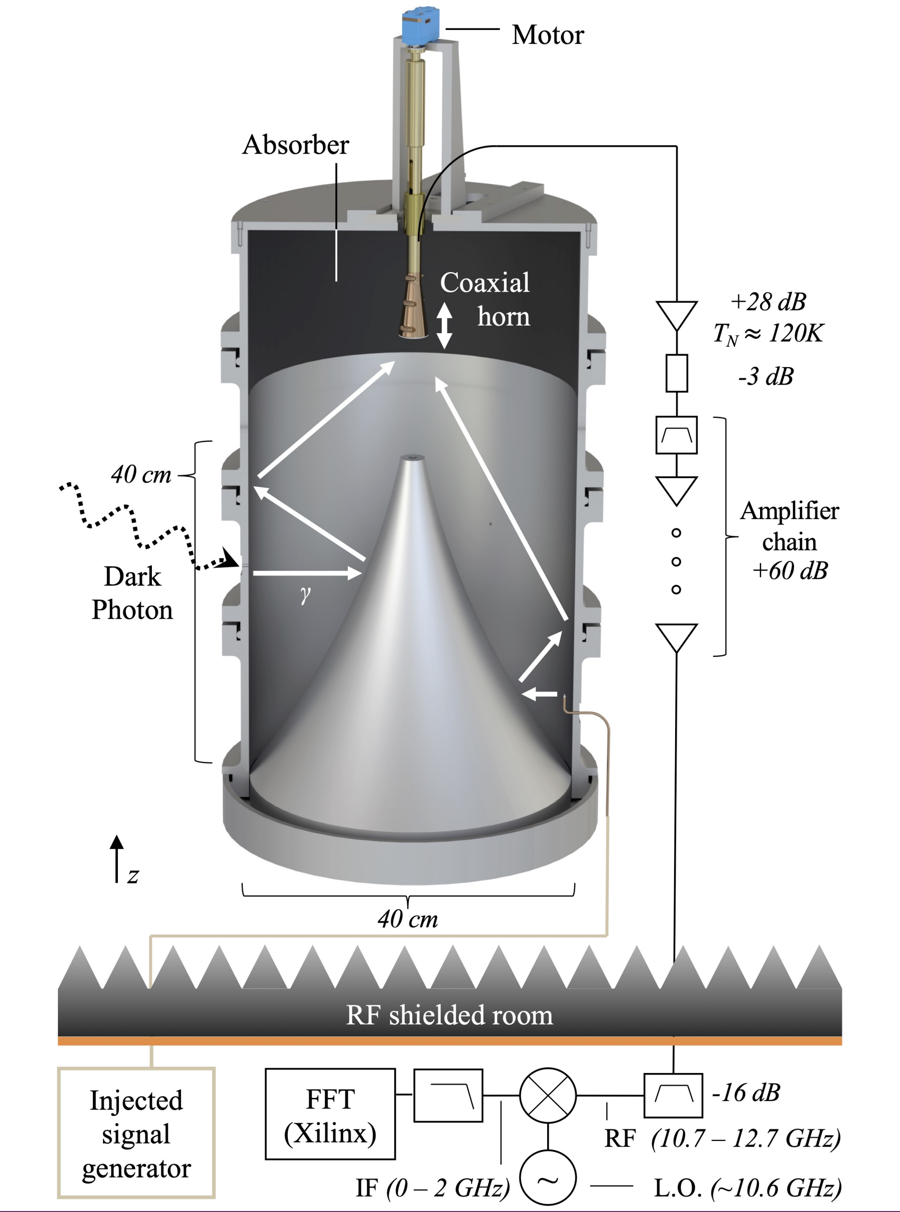


Broadband Coaxial Dish Antenna

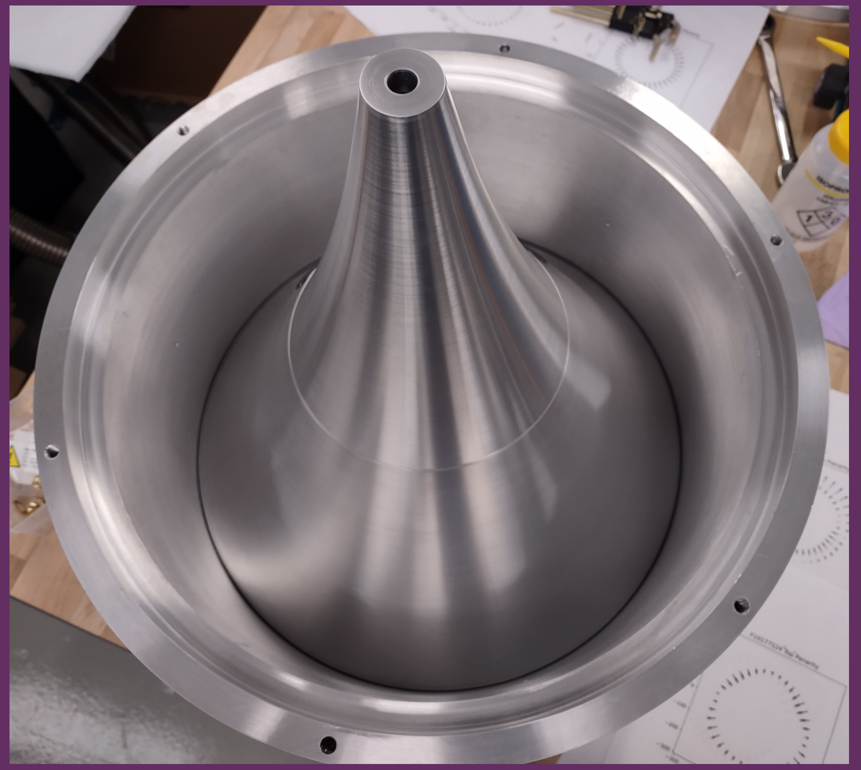
GigaBREAD: use coaxial dish antenna as optical concentrator for solenoid magnets



- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections



- Employ different single photon sensors to cover broad frequency range



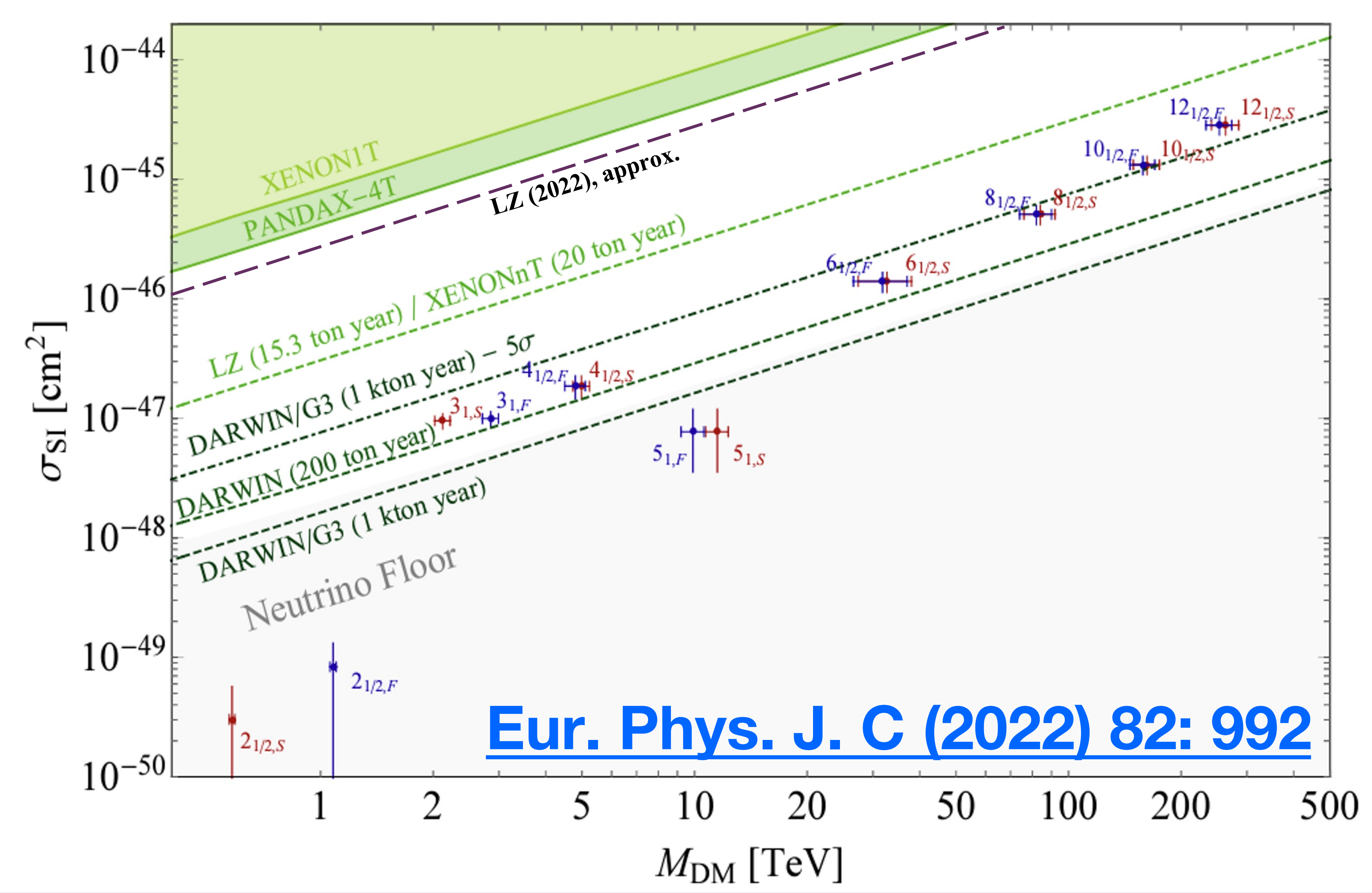
- First dark photon results: [arXiv: 2310.13891](https://arxiv.org/abs/2310.13891)

Large Mass Noble Element Detectors

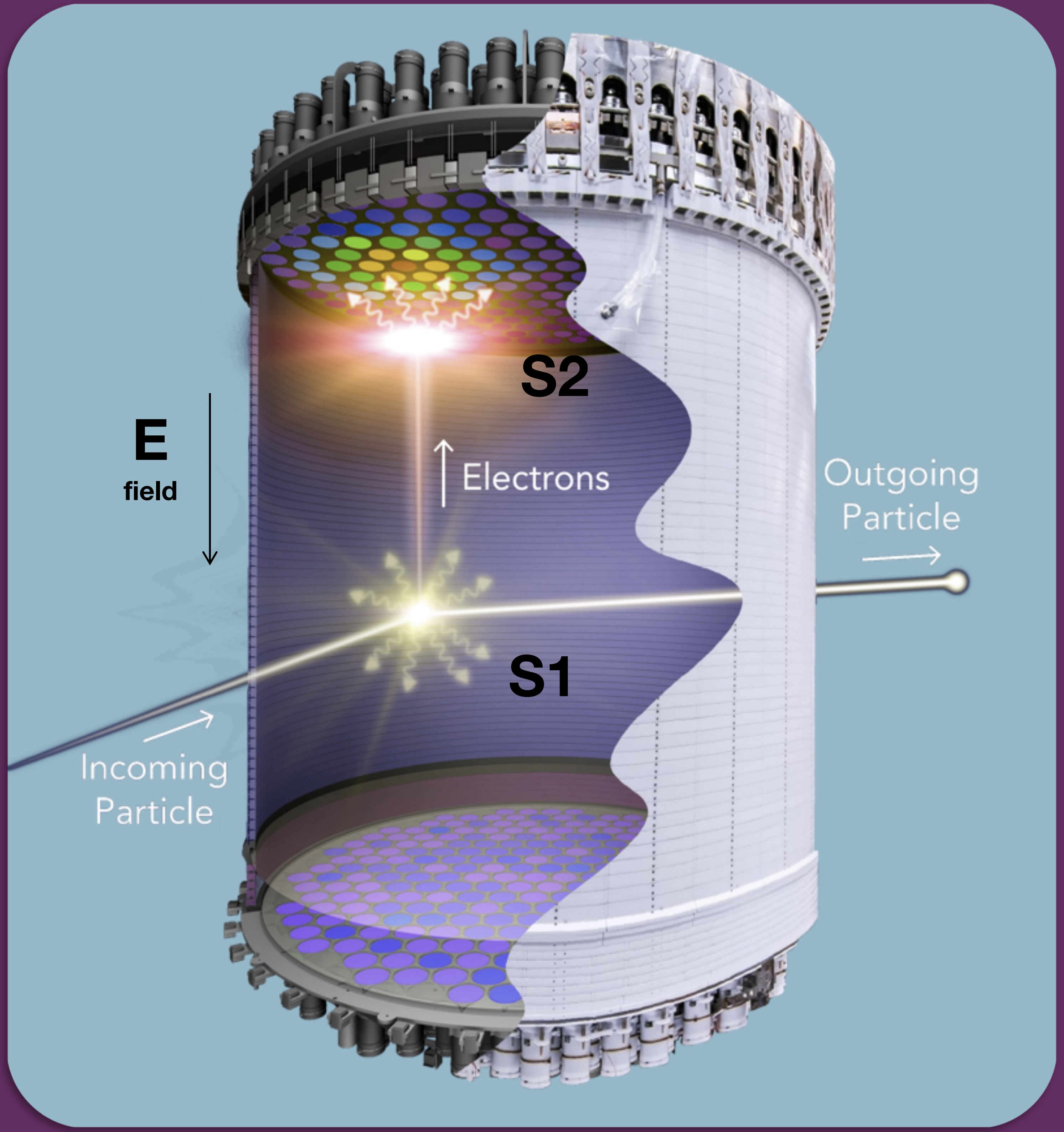
- Typical reconstruction data based on S1 (prompt scintillation light), S2 (ionization signal), x/y position (hit pattern), z position (Δt of S1 and S2), energy (S1+S2/weight), recoil type (S1/S2)

- Reaching Neutrino Floor requires massive new detectors (very limited supplies of ultra-pure Xenon)

- Worthwhile to look into alternative ideas



Eur. Phys. J. C (2022) 82: 992



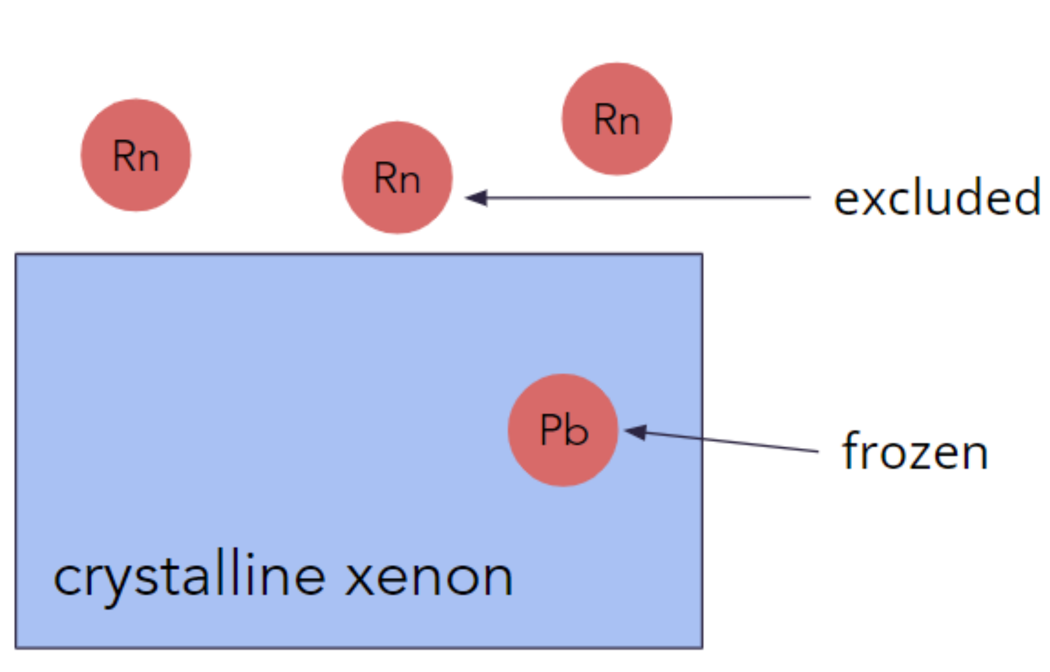
Synergies with Neutrino Detectors

Blue Sky R&D
Thinking outside the (Phase Diagram) Box

- Background limitations and Xe supply gave rise to smaller/more compact solid Xe detector: e.g. CrystaLiZe R&D (UT Austin, LBNL)

- Idea: crystalline Xe - solid/vapor two-phase TPC

→radon excluded from solid bulk (reduction of Rn-chain daughters x100); lead frozen in



Source	Expected Events	Fit Result
^{214}Pb	164 ± 35	-
^{212}Pb	18 ± 5	-
^{85}Kr*	32 ± 5	-
Det. ER	1.4 ± 0.4	-
β decays + Det. ER	215 ± 36	222 ± 16
ν ER	27.1 ± 1.6	27.2 ± 1.6
^{127}Xe**	9.2 ± 0.8	9.3 ± 0.8
^{124}Xe	5.0 ± 1.4	5.2 ± 1.4
^{136}Xe	15.1 ± 2.4	15.2 ± 2.4
^{8}B CEνNS	0.14 ± 0.01	0.15 ± 0.01
Accidentals	1.2 ± 0.3	1.2 ± 0.3
Subtotal	273 ± 36	280 ± 16
^{37}Ar	[0, 288]	$52.5^{+9.6}_{-8.9}$
Detector neutrons	$0.0^{+0.2}$	$0.0^{+0.2}$
$30\,\mathrm{GeV/c^2}$ WIMP	–	$0.0^{+0.6}$
Total	–	333 ± 17

Dominant! (^{214}Pb, ^{212}Pb)

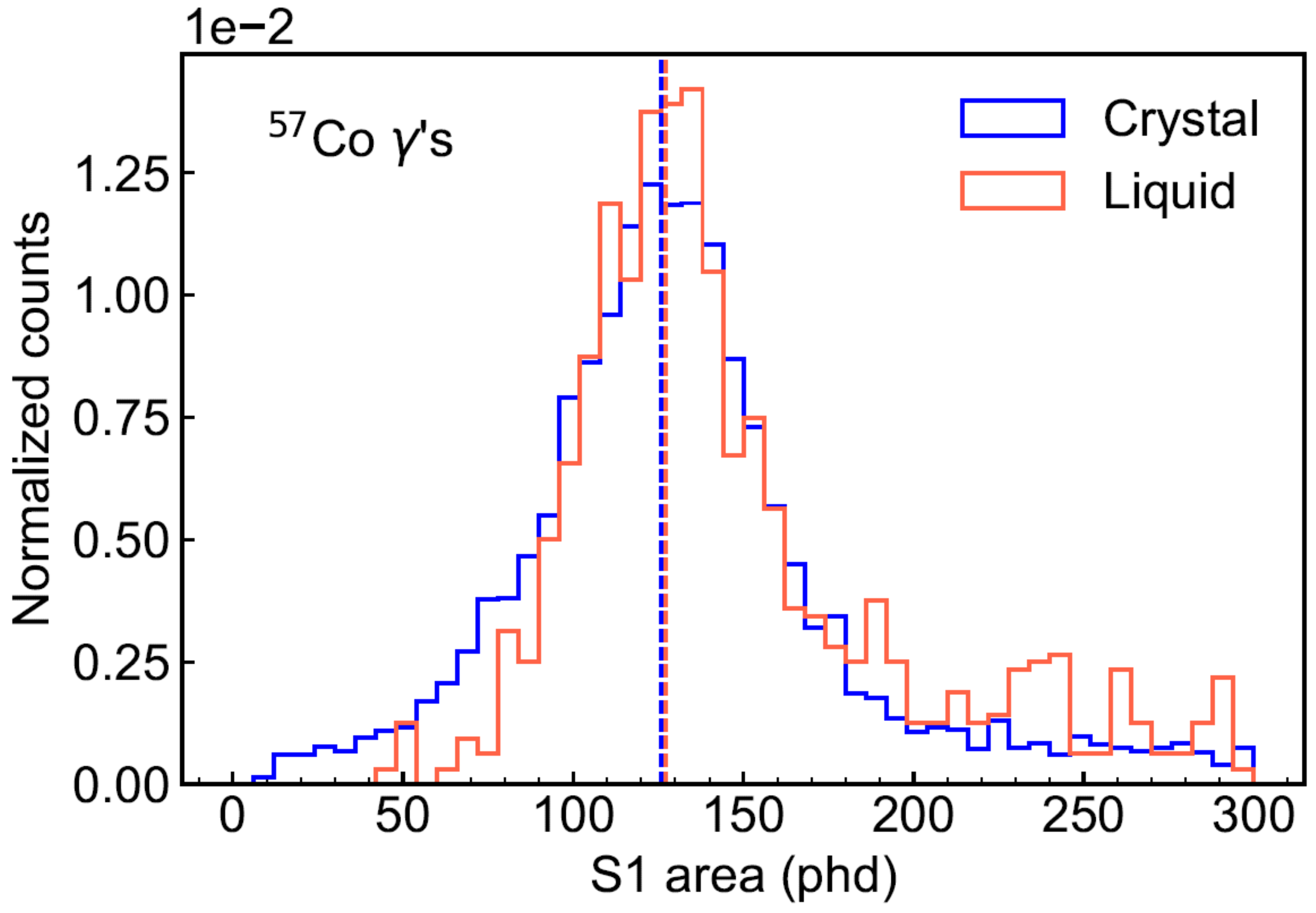
* Permanently removable w/ distillation

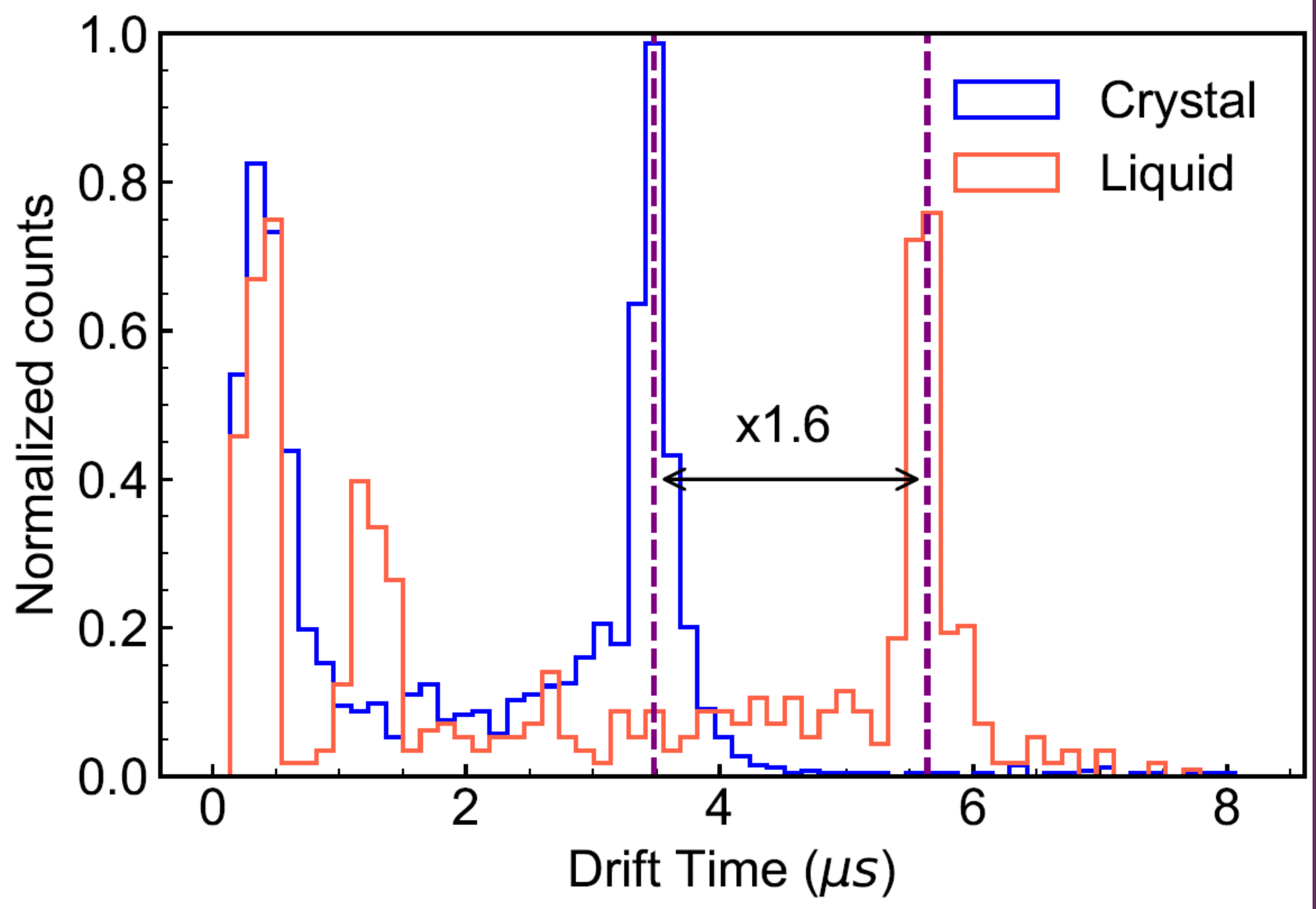
** Short half-life; negligible in latest science run

Slides from CPAD Workshop

Preliminary Results

- Operation ~20K below LXe
- Matching scintillation behavior, ionization works as well; hints at higher gain, but need calibration
- Drift speed is faster in crystal → less pileup
- Steady decay of Rn in crystal → demonstrated exclusion >x1000 of ^{220}Rn
- Promising start, but lots of open questions remain, especially of scaling up in size



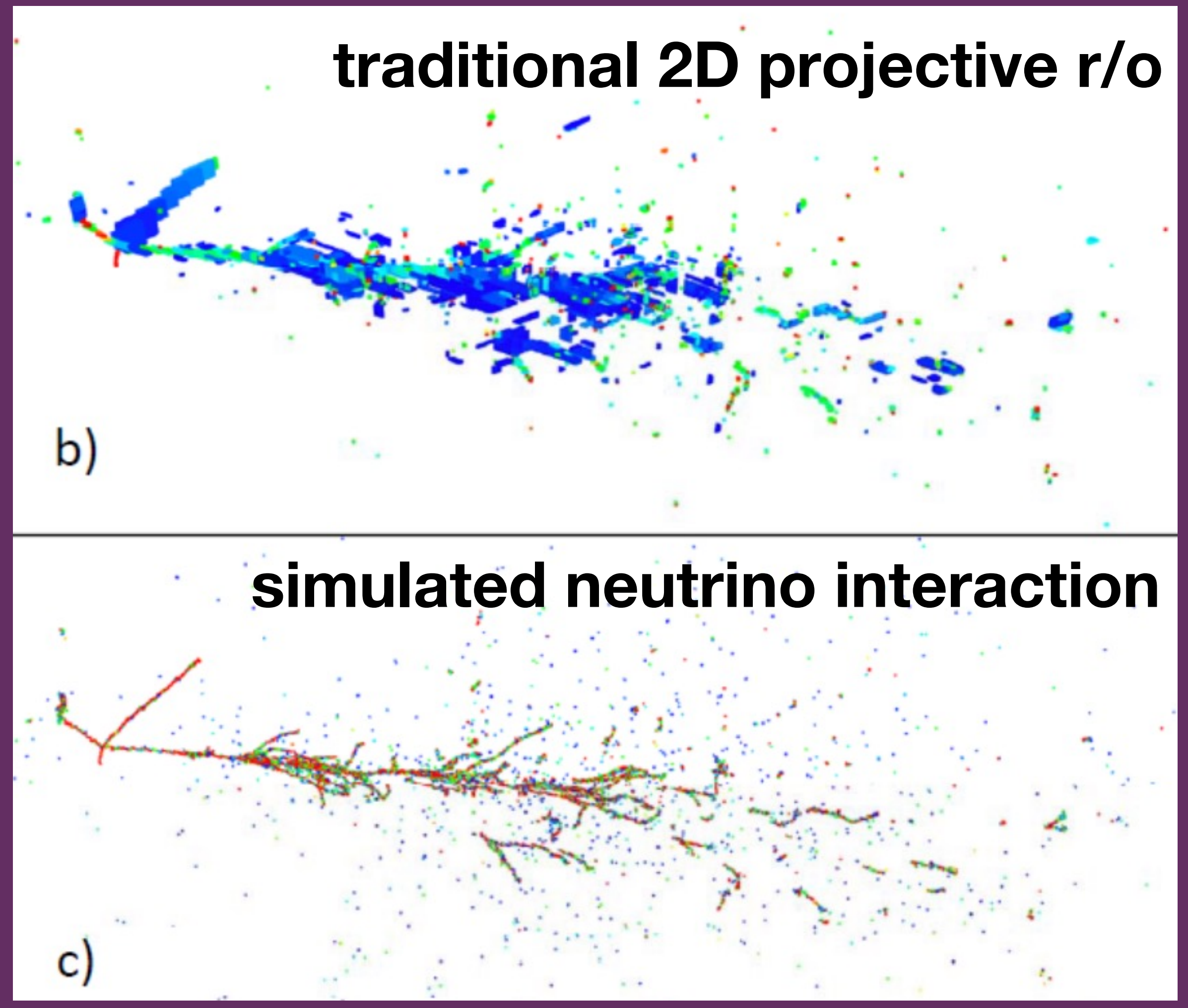


Neutrino Detectors

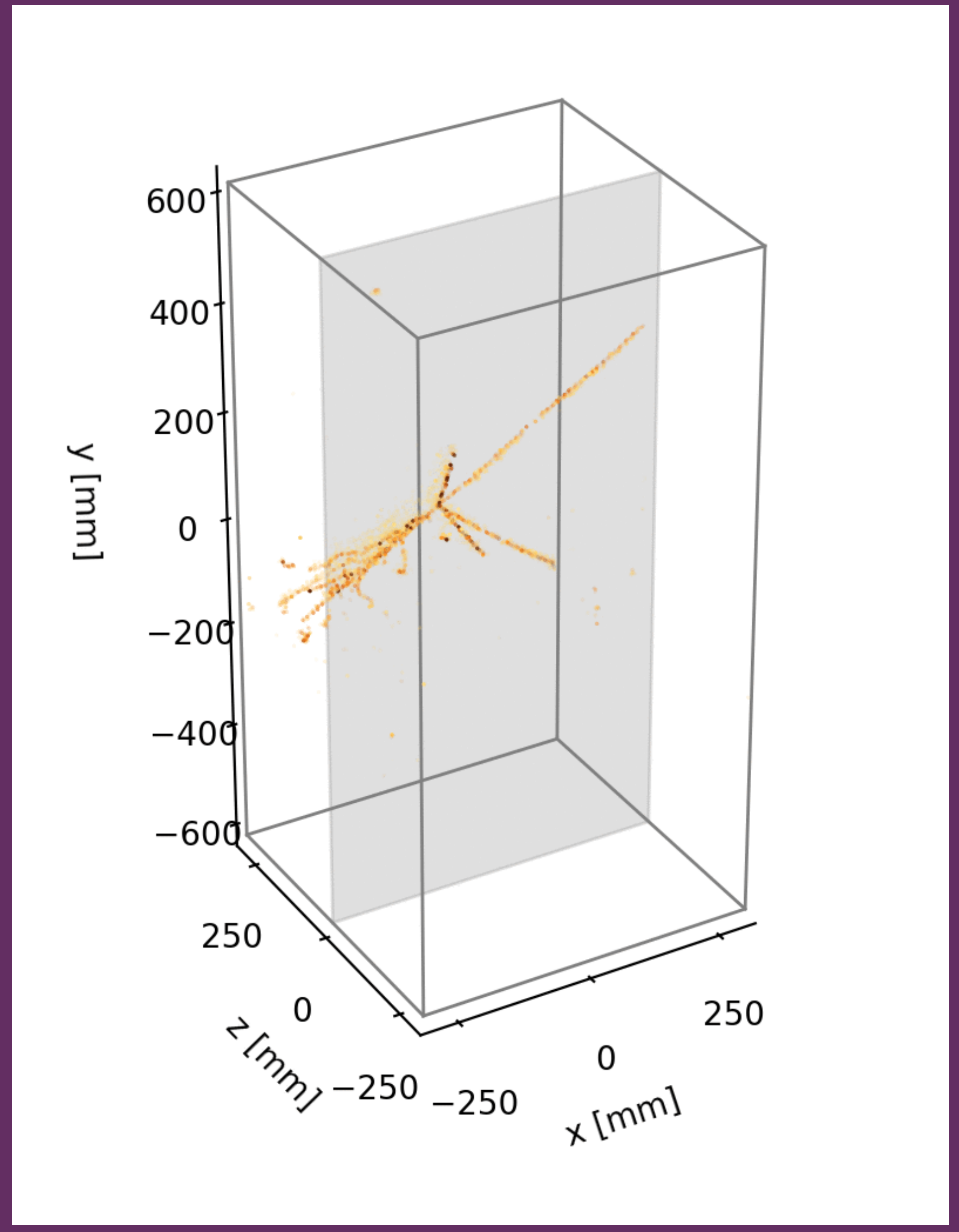
The DUNE Challenge

Need to achieve ~4mm spatial granularity for stadium-sized detectors (50,000m^3)
→ ~1 trillion spatial voxels

- LAr TPCs use traditionally projective 2D r/o through wire planes
- Achieve much higher spatial precision using pixelated r/o
  - true 3D imaging
  - continuous r/o, ~100% uptime
  - intrinsically sparse data, low data volume
  - improved signal fidelity (S/B)
  - enhanced low-energy program



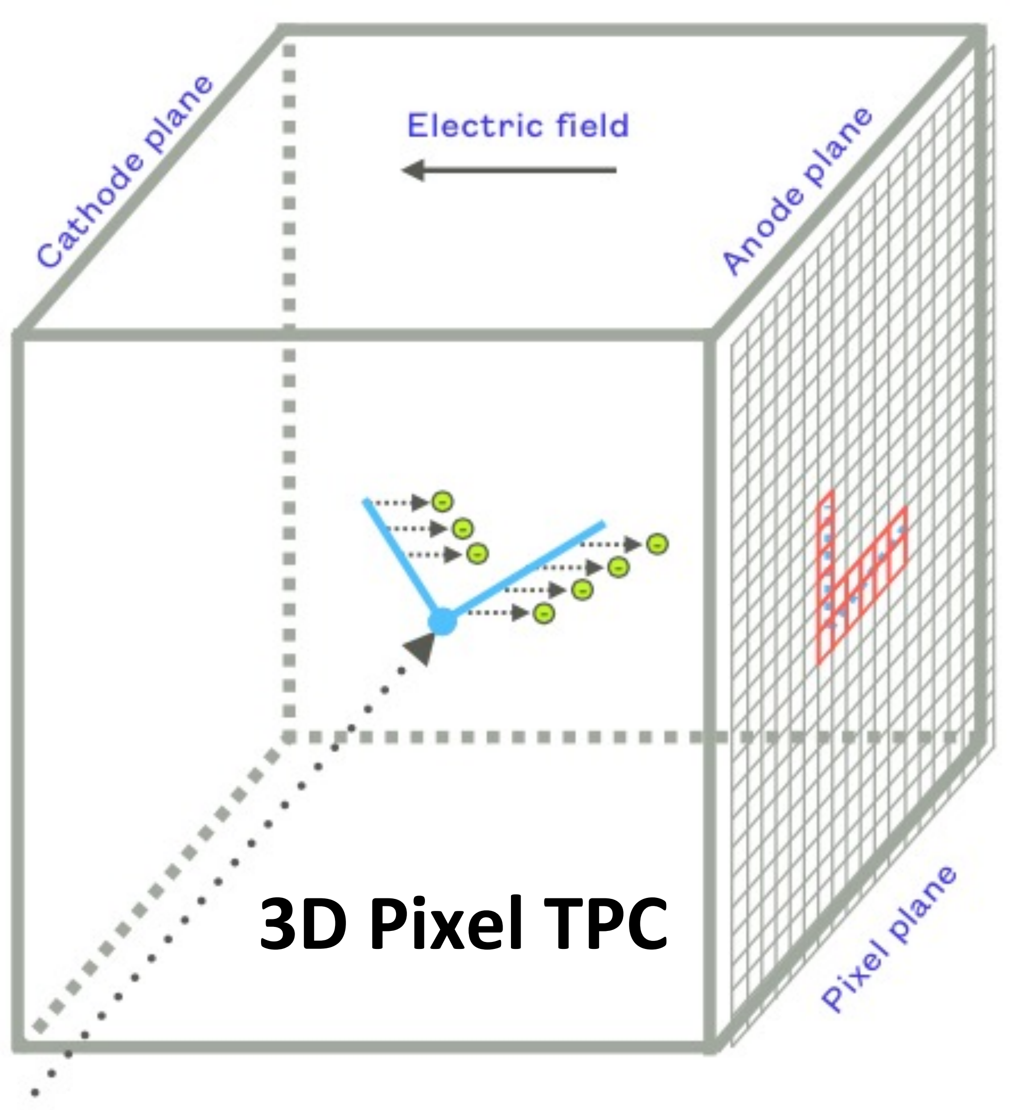
Example ambiguities for complex signals
JINST 13, P05032 (2018)

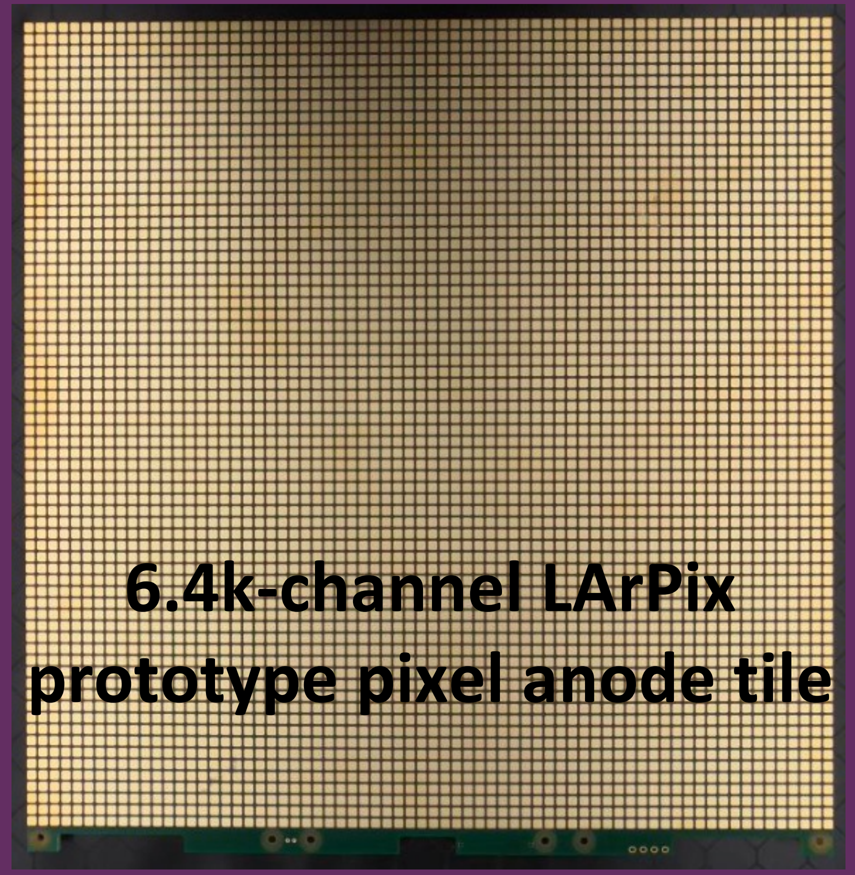


true 3D imaging using pixels
D.Dwyer, CPAD

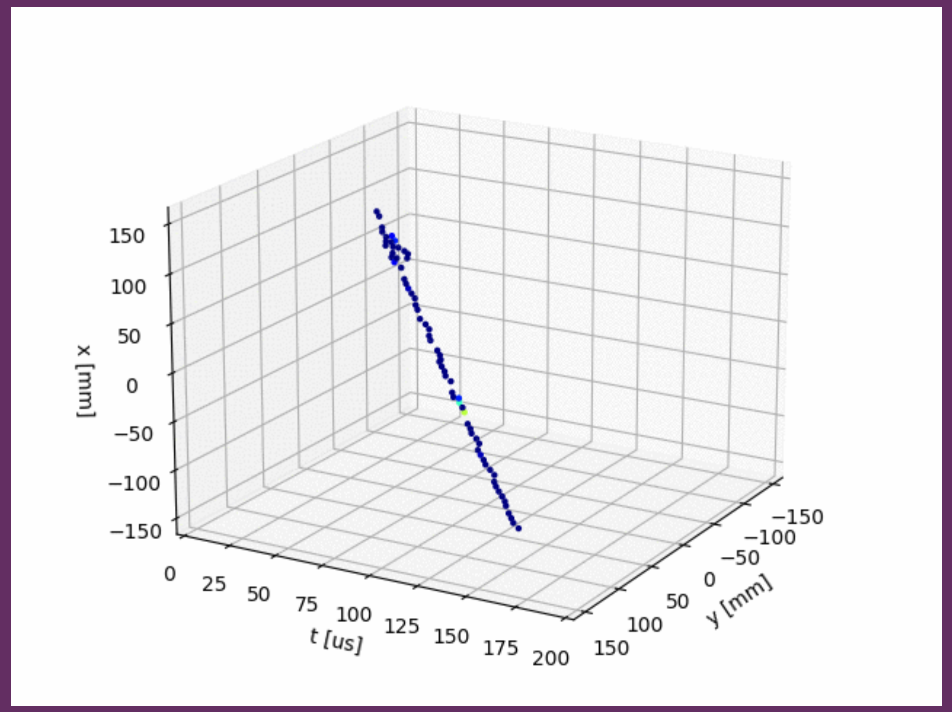
Intense R&D Phase

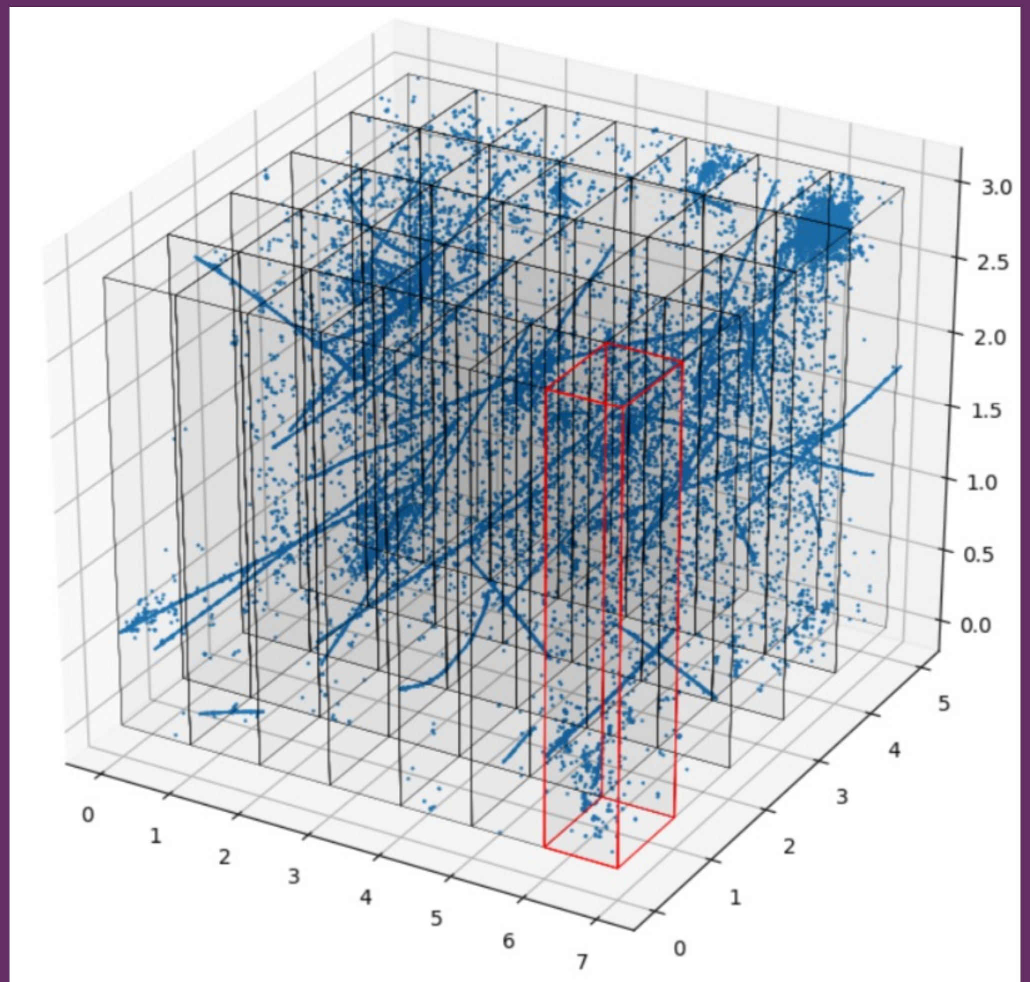
- For example: LarPix and Q-Pix R&D Collaborations
- Pixel r/o requires high channel density:
  - low noise (cryogenic-compatible amplifiers)
  - multiplexing (limited number of cables and feed-throughs)
  - extremely low-power electronics (limit heat)
  - reliability (largely inaccessible)
  - scalability (need to cover 100-1000m2, >107 pixels @ <$0.10/pixel)





Raw 3D Cosmic Ray images in LArPix prototype LArTPC





Simulation of one beam pulse in DUNE Near Detector LArTPC

(Pileup of ~50 neutrino interactions)

Summary

- Many R&D challenges to enable science at future colliders with near-transparent to very massive silicon detectors
- R&D of many different technologies crucial for combing through 50 orders of magnitude on the hunt for Dark Matter
- Crucial R&D into lowering thresholds, increased spatial resolution and background rejection to understand the nature of neutrinos

Lots of Synergies across the board of HEP and beyond. Most efficient if we all work together!