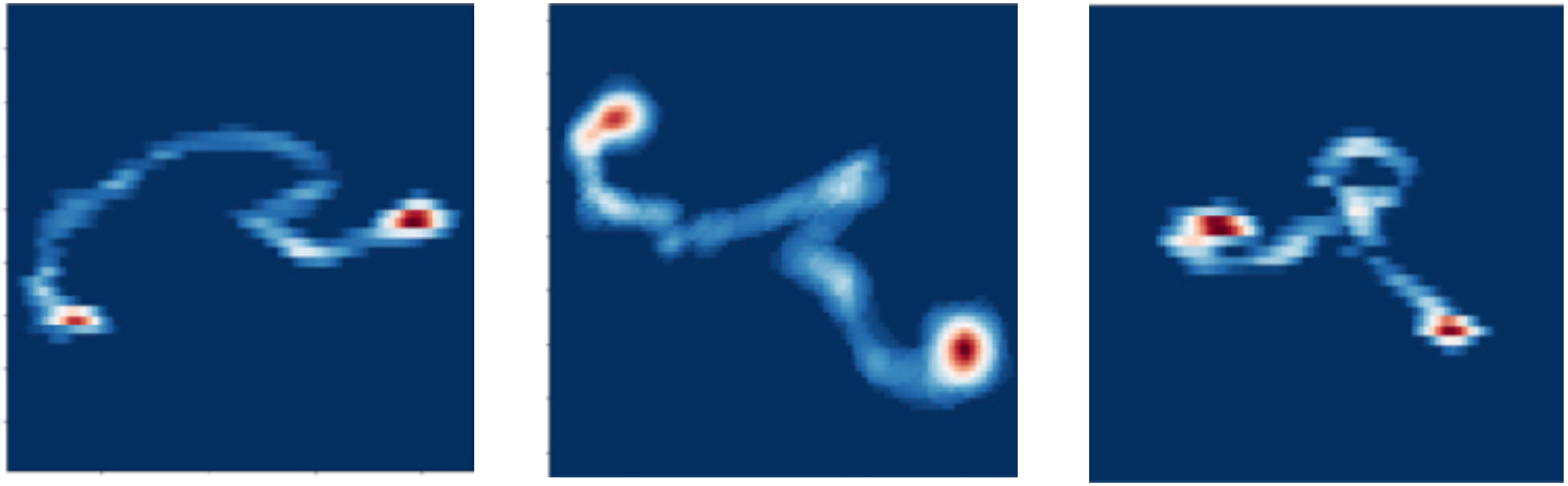


Scalability and optical enhancement of tracking planes for beyond the ton-scale experiments

Roxanne Guenette

MANCHESTER 1824

The University of Manchester

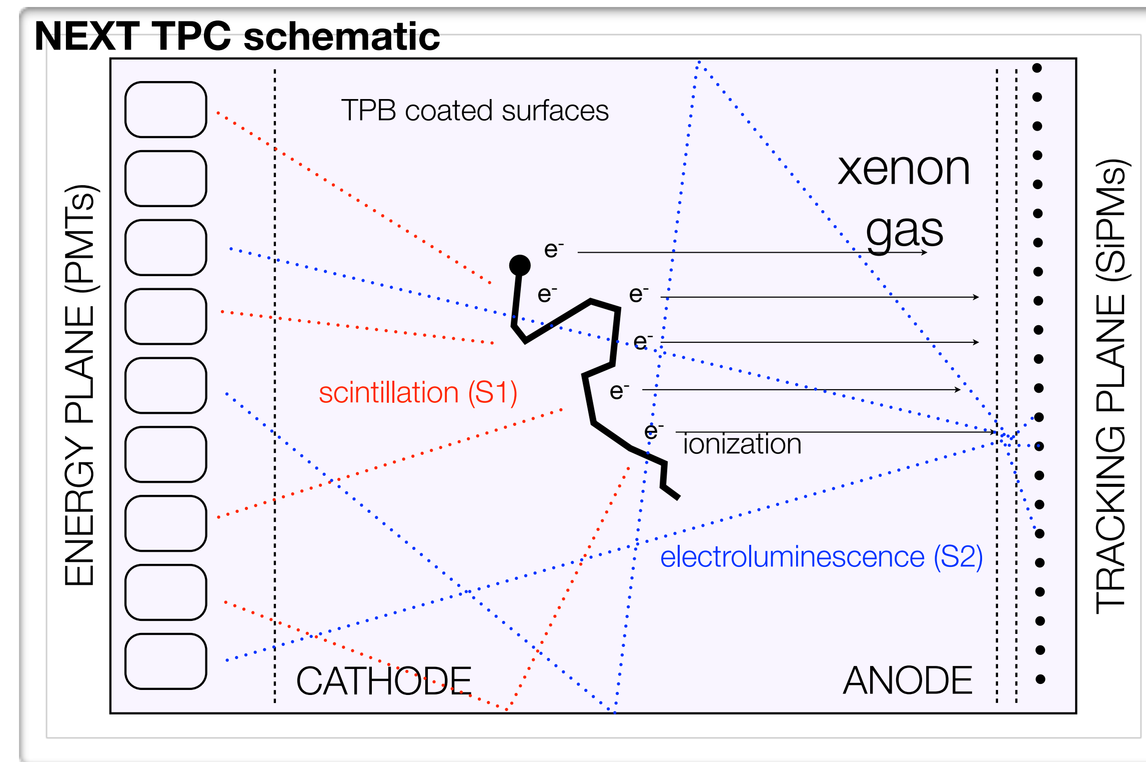
Workshop on Xenon Detector 0νββ searches: Steps towards the kilotonne scale

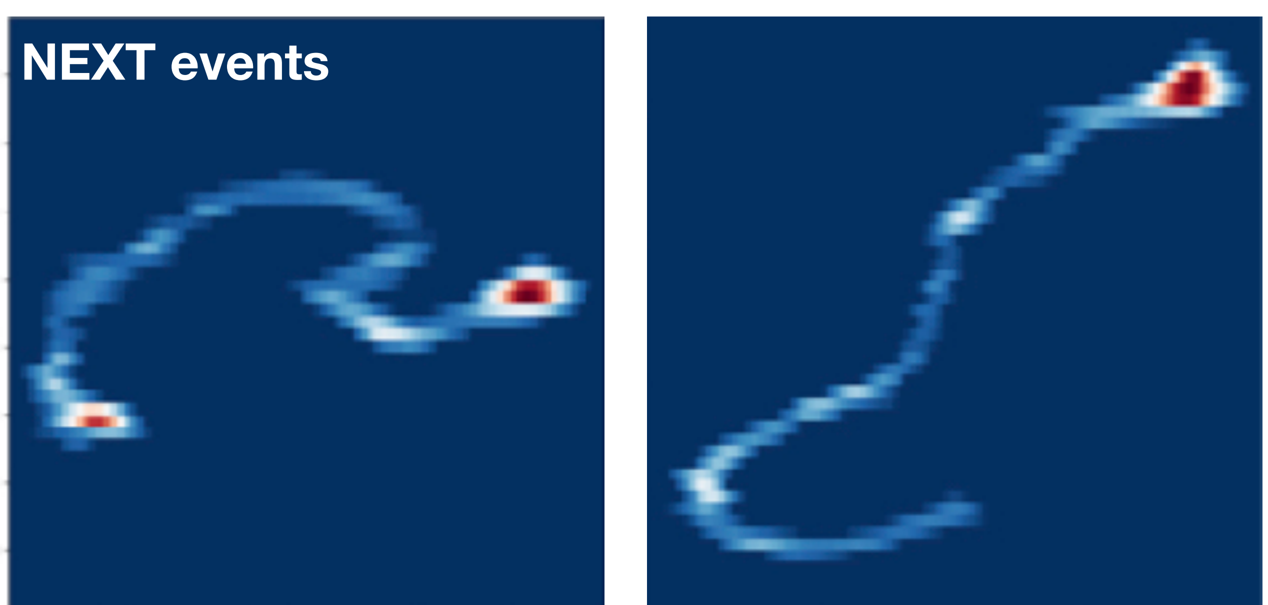
25-27 October 2023

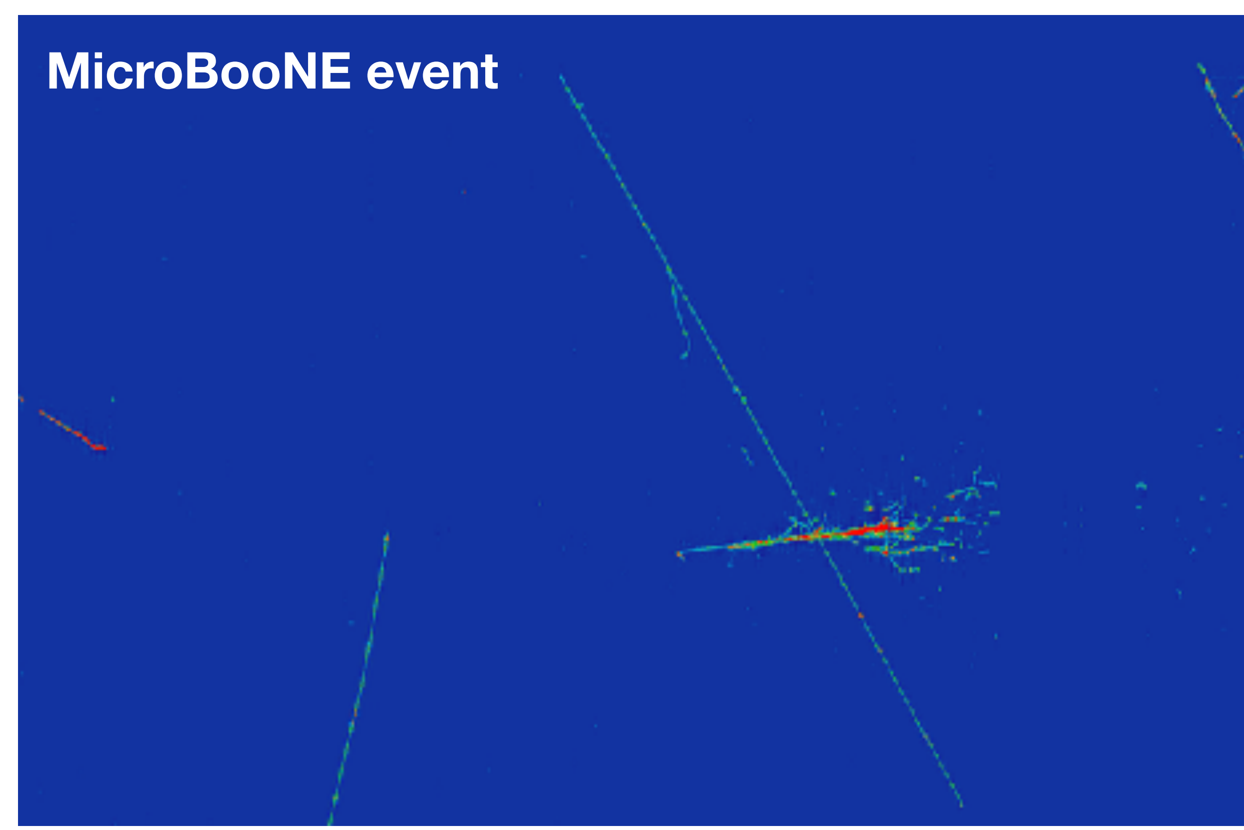
Imaging capabilities in TPCs

- The principle of TPC inherently allows for imaging

- Imaging plane provides 1D or 2D information while time provides the 3rd coordinate

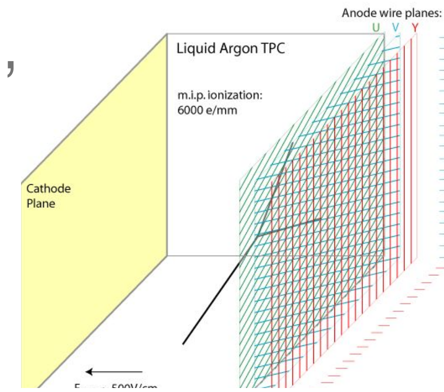


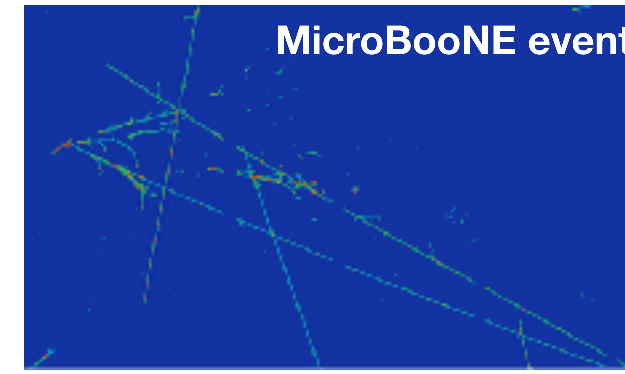




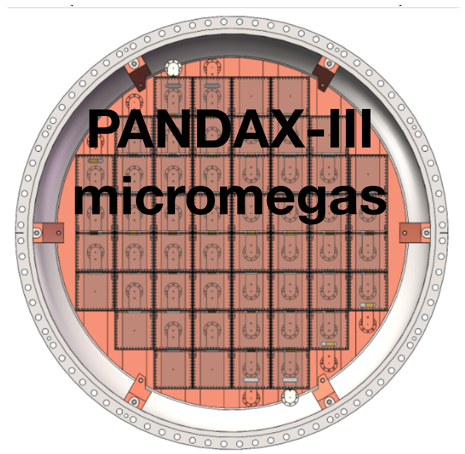
Few examples of imaging planes

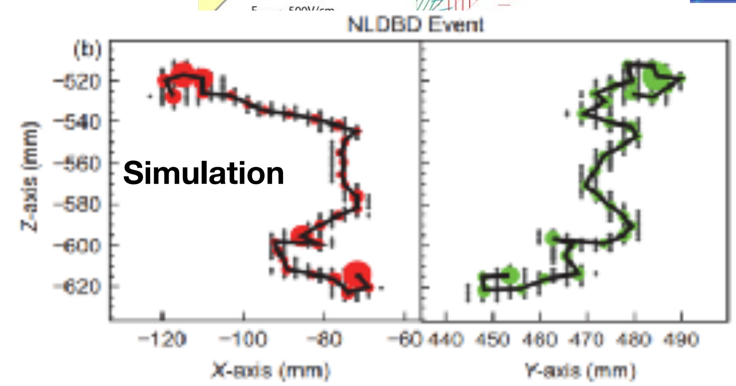
- Wire-based charge readouts (e.g. MicroBooNE, SBND, DUNE…)





- PANDAX-III micromegas

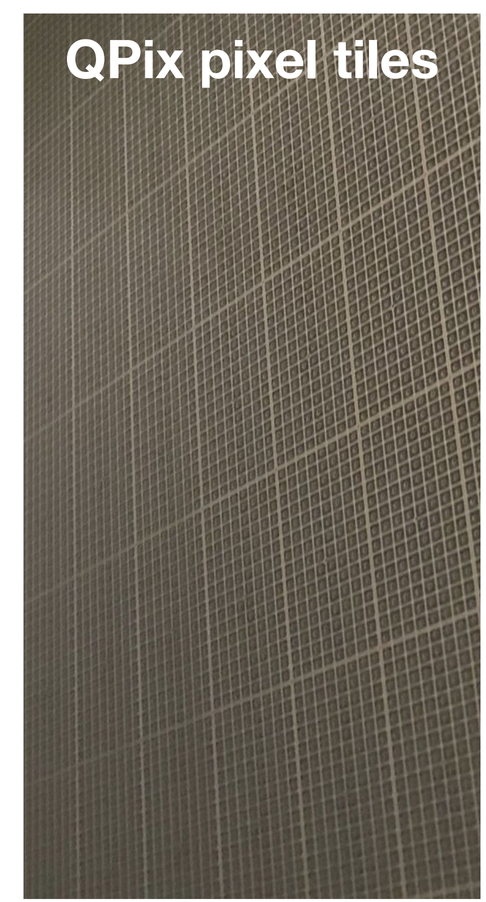




- NEXT: Electroluminescence light readout by SiPMs

- CRAB: Fast camera electroluminescence readout
  See L. Rogers' talk later in this session

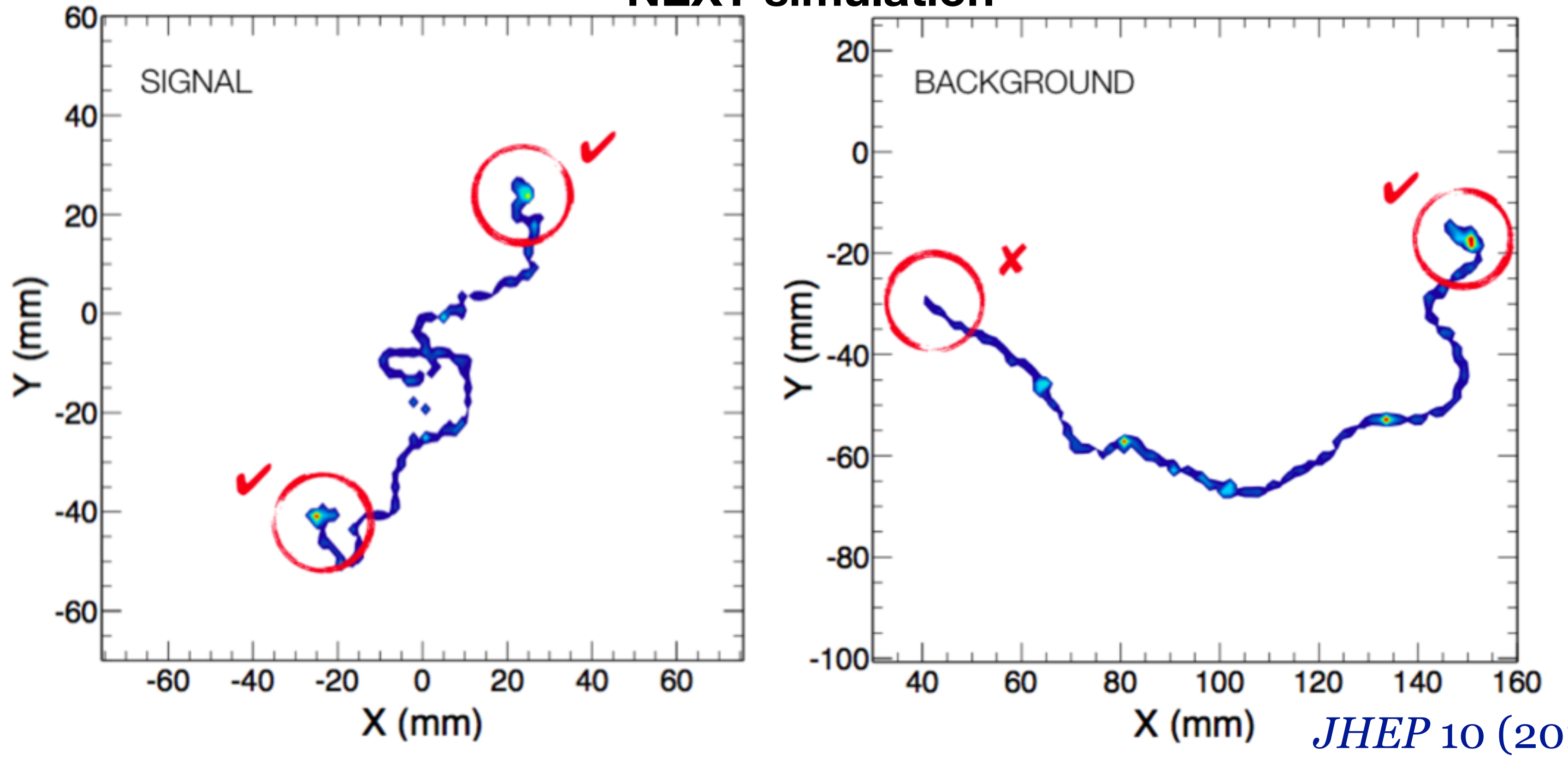
- QPix: direct charge readout (4mm x 4mm pixels)



Current topological capabilities of imaging planes

- Principle: signal (ββ) and backgrounds (β or γ) look different

NEXT simulation

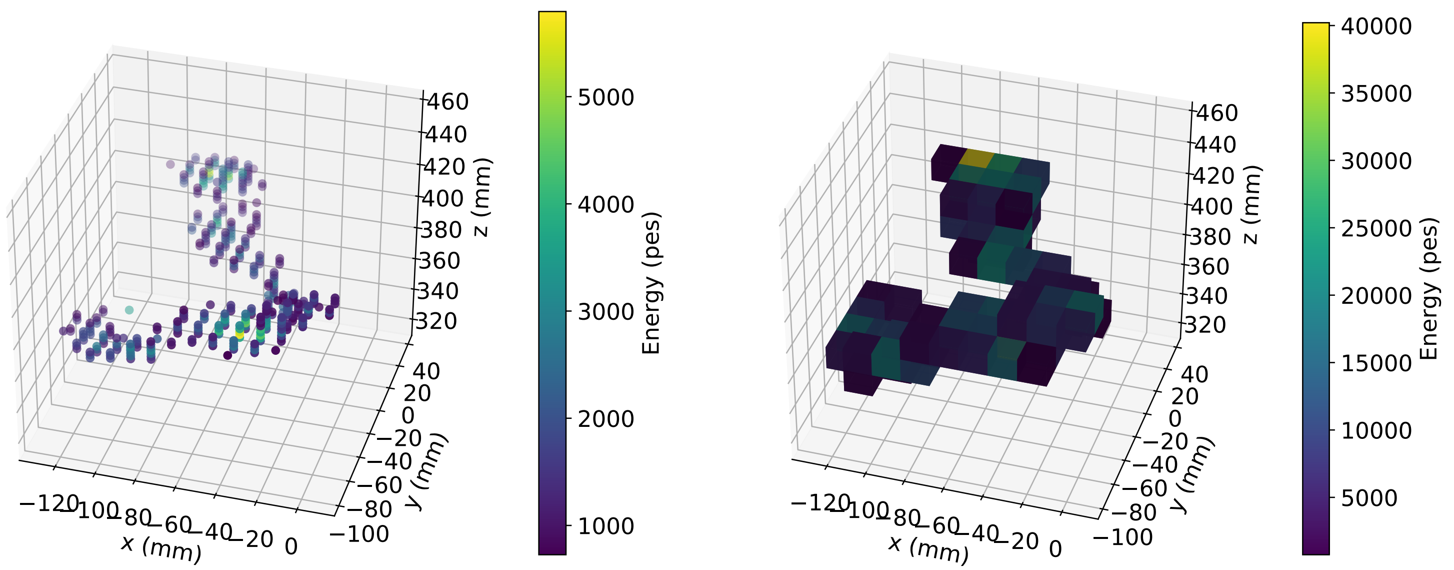


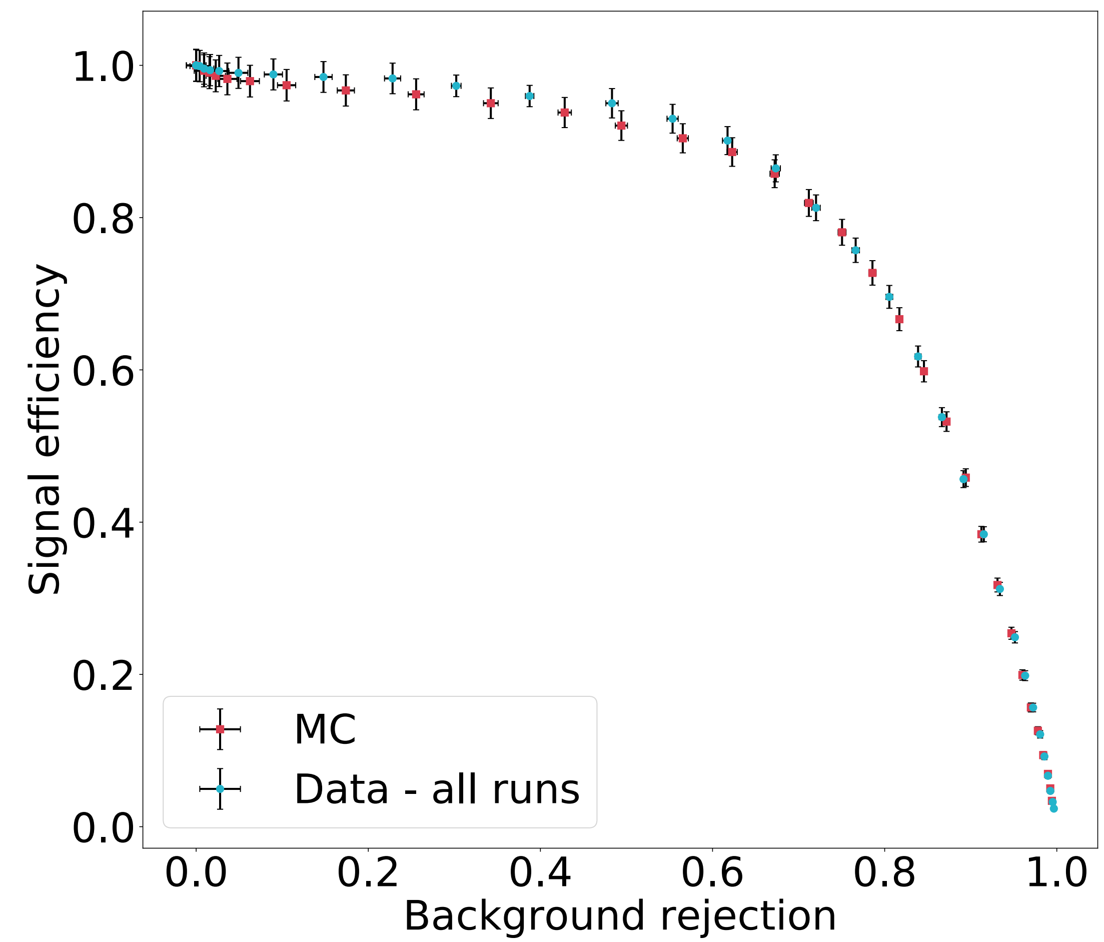
JHEP 10 (2019) 052

Current topological capabilities of imaging planes

Topological separation with NEXT-White

- Cut-based analysis





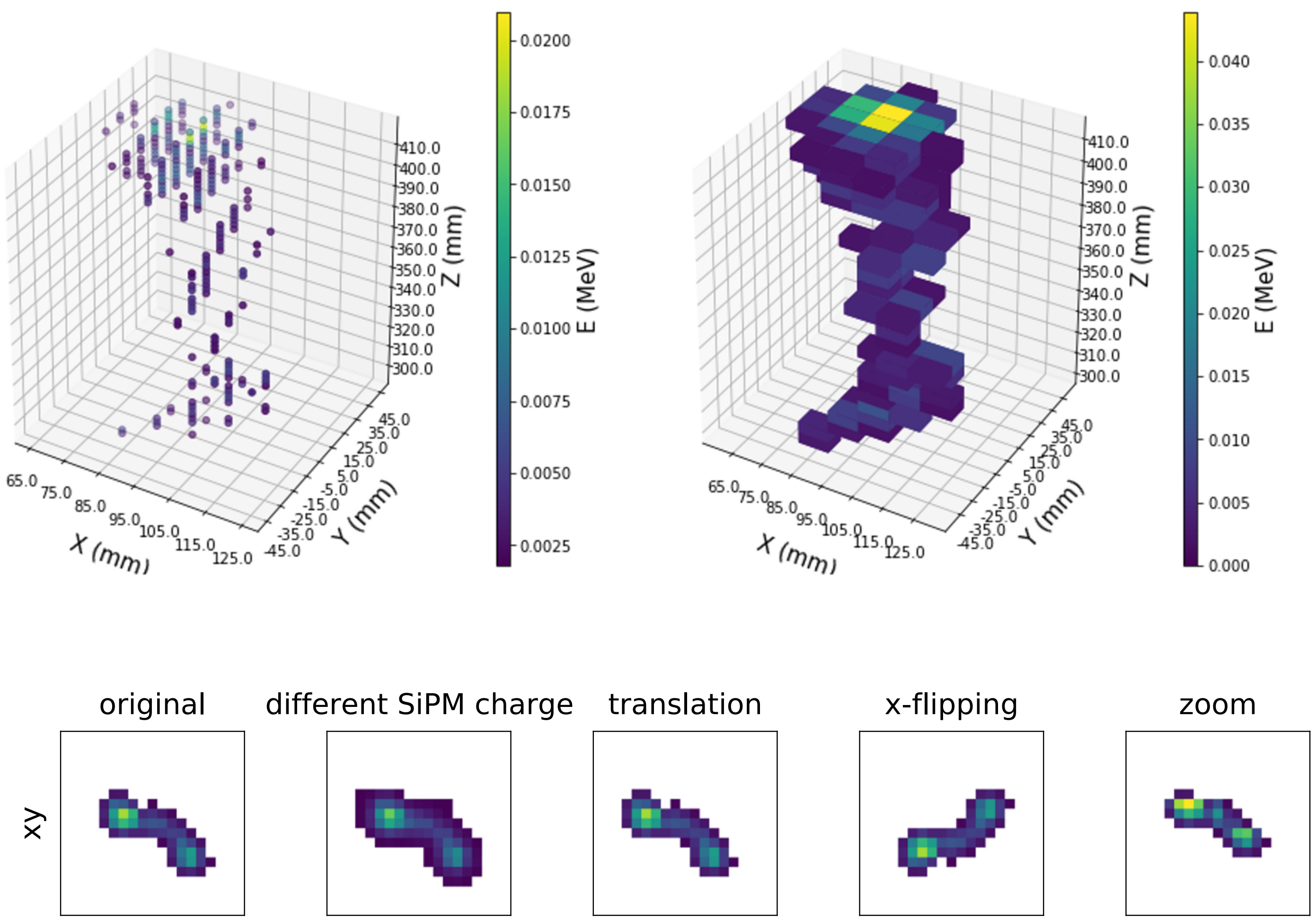
NEXT Collaboration, "*Demonstration of the event identification capabilities of the NEXT-White detector*" *JHEP* 10 (2019) 052

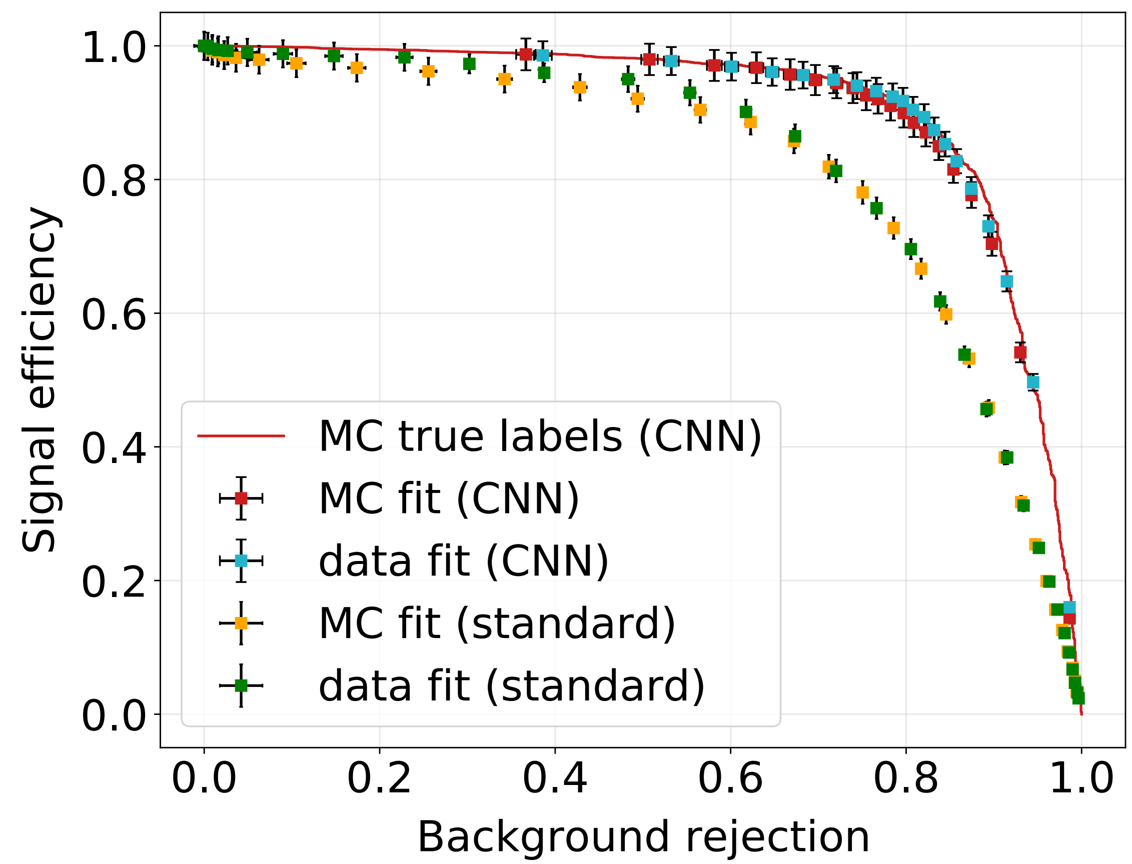
~70% efficiency
~20% bkg contamination

Current topological capabilities of imaging planes

Topological separation with NEXT-White

- DNN analysis





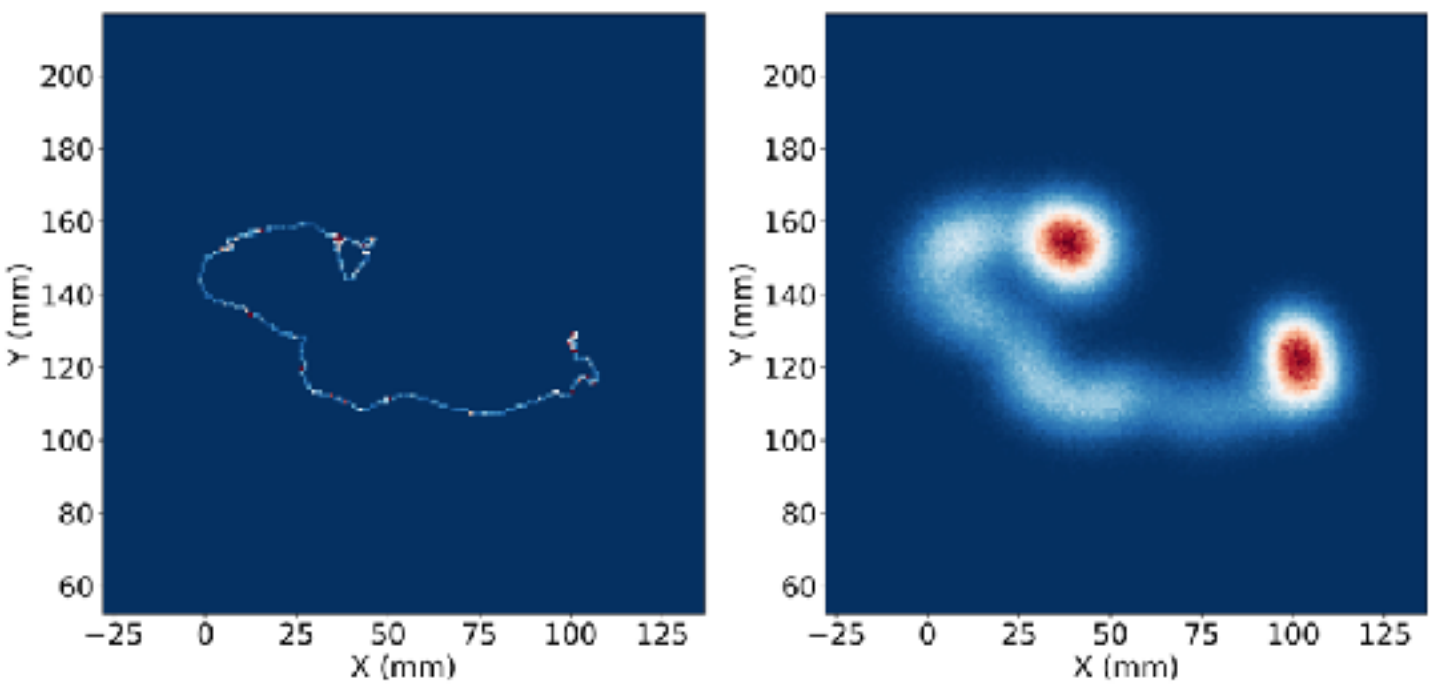
NEXT Collaboration, "*Demonstration of background rejection using deep convolutional neural networks in the NEXT experiment* ", *JHEP* 01 (2021) 189

~65% efficiency
~10% bkg contamination

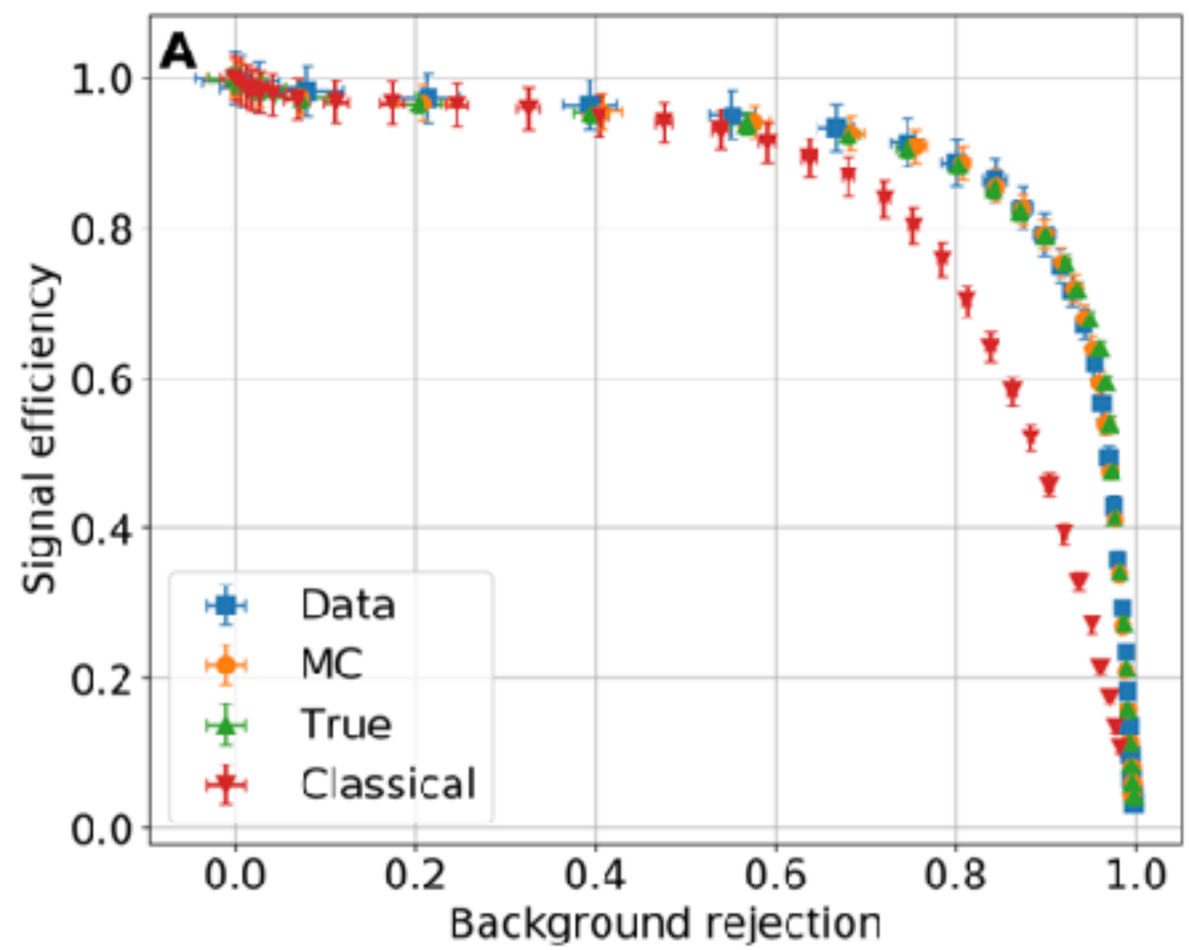
Current topological capabilities of imaging planes

Topological separation with NEXT-White

- Richardson-Lucy deconvolution analysis



NEXT Collaboration, "*Boosting background suppression in the NEXT experiment through Richardson-Lucy deconvolution*", *JHEP* 07 (2021) 146



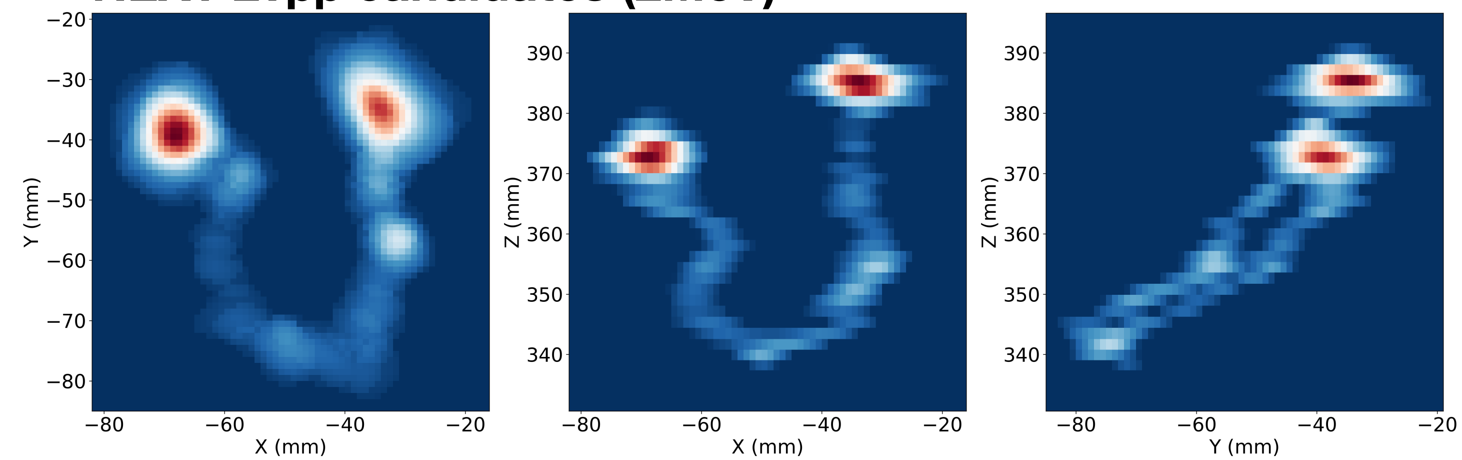
~56% efficiency
~4% bkg contamination

Why aim to keep imaging capabilities

- Powerful visual tool for discovery of few events

NEXT 2νββ candidates (2MeV)

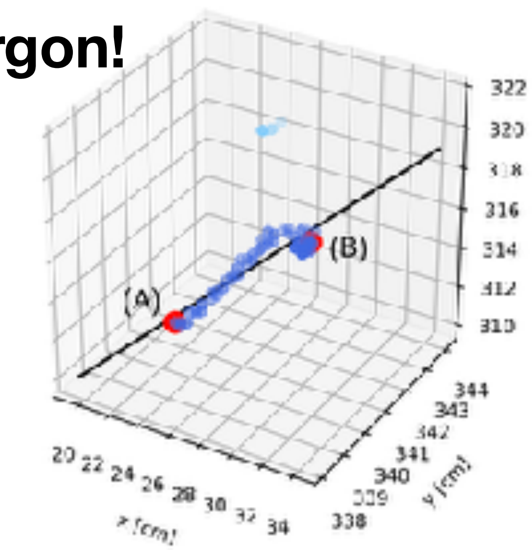
JHEP 07 (2021) 146

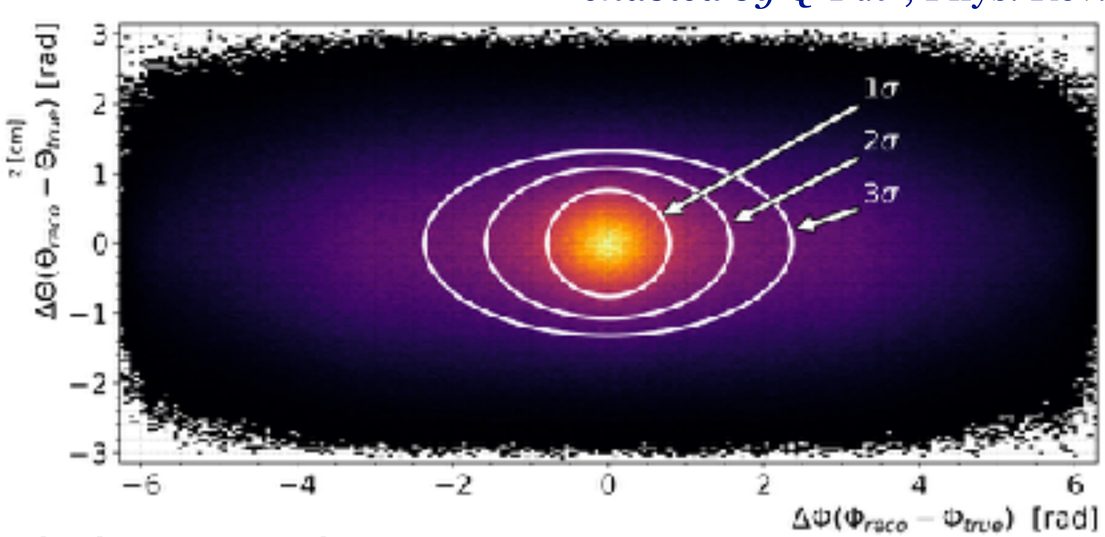


- Directionality (e.g. solar neutrino rejection)

S. Kubota et al., "*Enhanced low-energy supernova burst detection in large liquid argon time projection chambers enabled by Q-Pix*", Phys. Rev. D 106, 032011 (2022)

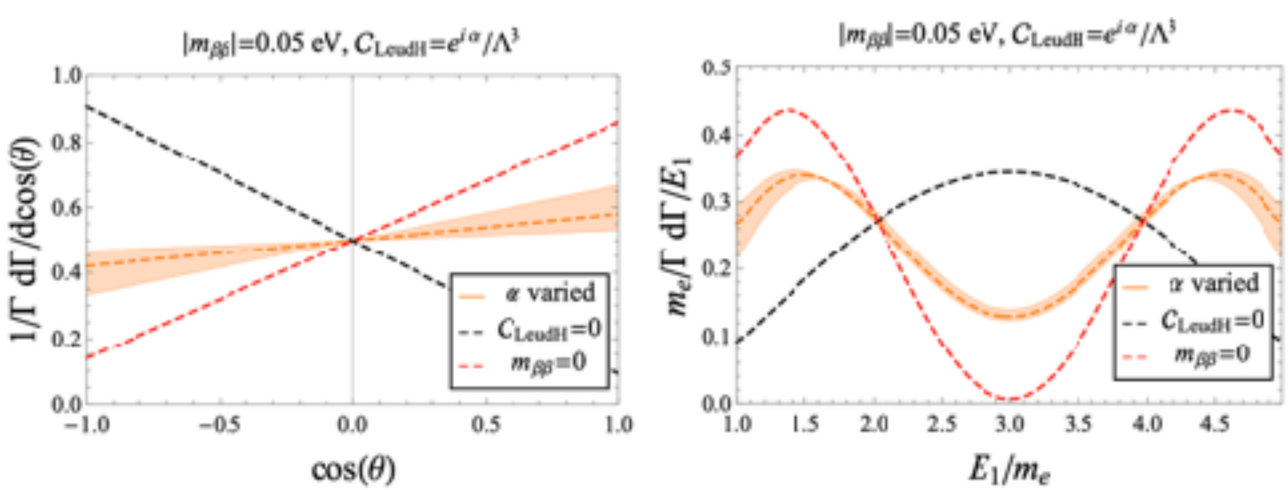
In Liquid Argon!





Similar conclusions for solar neutrinos in LAr (paper in prep.)

- Beyond the Standard Model searches



Cirigliano, V. et al., "Neutrinoless double beta decay in chiral effective field theory: lepton number violation at dimension seven", *JHEP* 12 (2017) 082

Desires for future imaging planes

- Highest possible granularity is desired (higher precision)

- Diffusion limited! (depends on drift length, pressure, gas composition)

Example: Diffusion at 10bar:

✳ 0.50m drift: 1.7cm

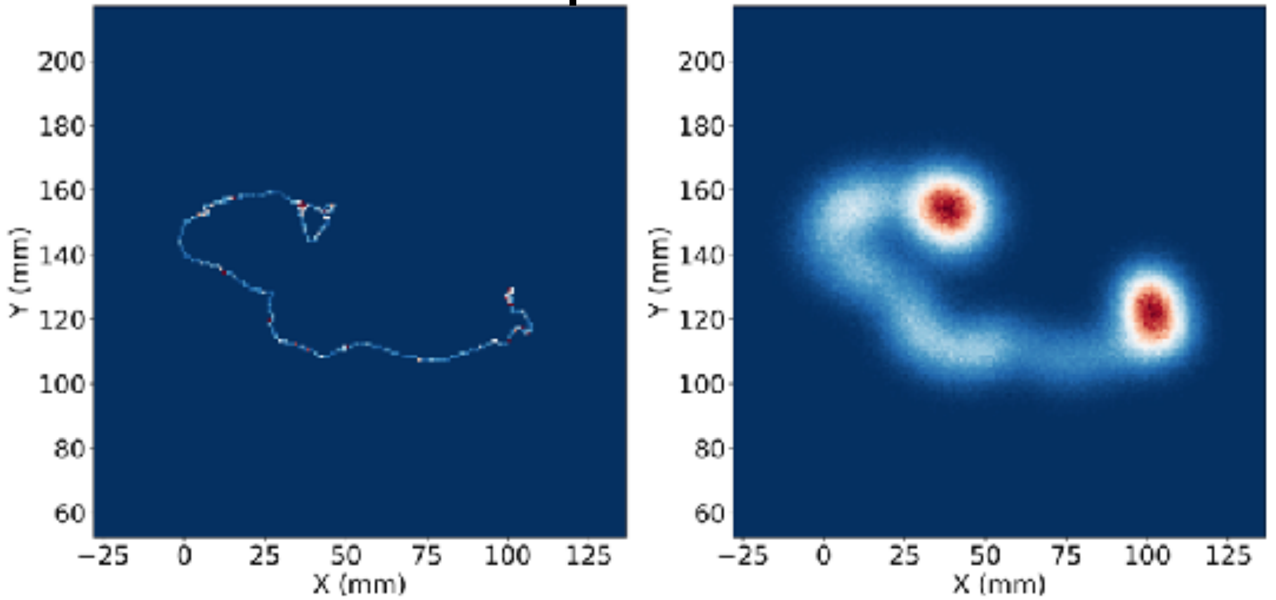
✳ 1.00m drift: 2.4cm

✳ 1.50m drift: 3.0cm

✳ 2.00m drift: 3.5cm

✳ Xe-He mixture, 2.0m drift: 0.7 cm

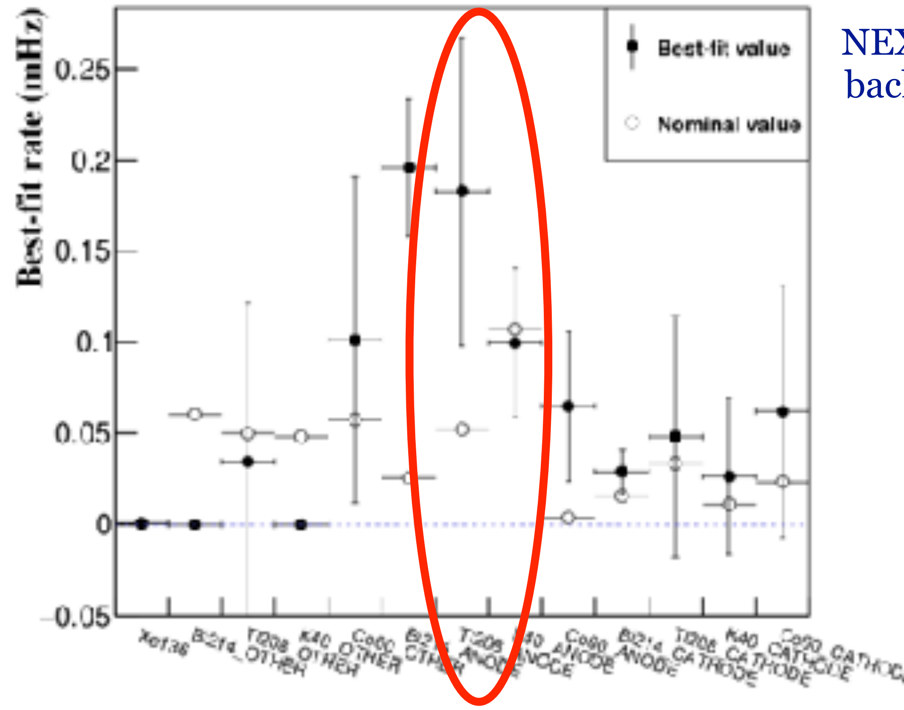
Example for 40cm drift



JHEP 07 (2021) 146

Desires for future imaging planes

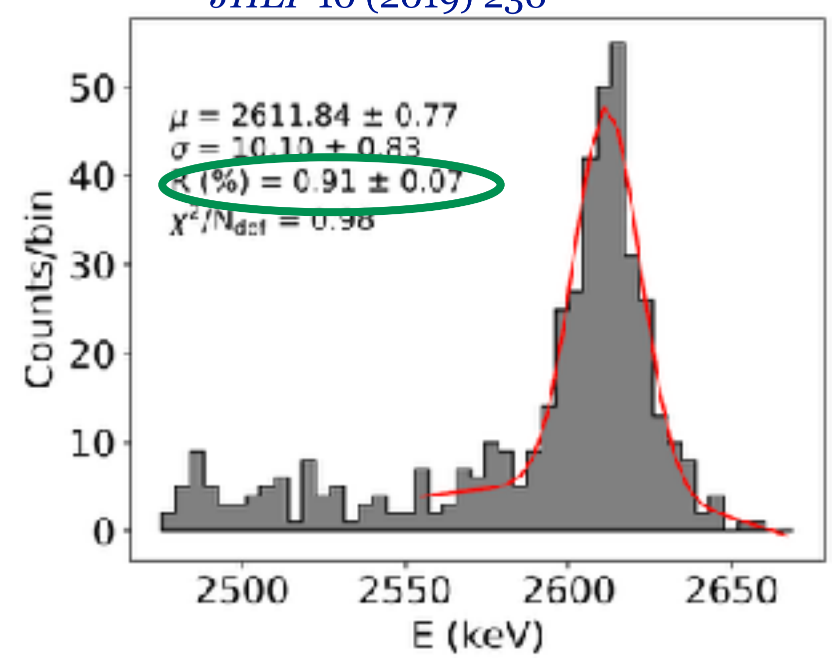
- Low radioactivity:
  - ✓ Need radiopure substrate
  - ✓ Need radiopure cables
  - ✓ Need radiopure SiPMs



NEXT Collaboration, "Radiogenic backgrounds in the NEXT double beta decay experiment" *JHEP* 10 (2019) 51

- Provides excellent energy resolution:
  - ✓ NEXT demonstrated sub-percent (FWHM) Eres (PMTs)
  - ✓ Need to use SiPMs (can they provide same Eres?)

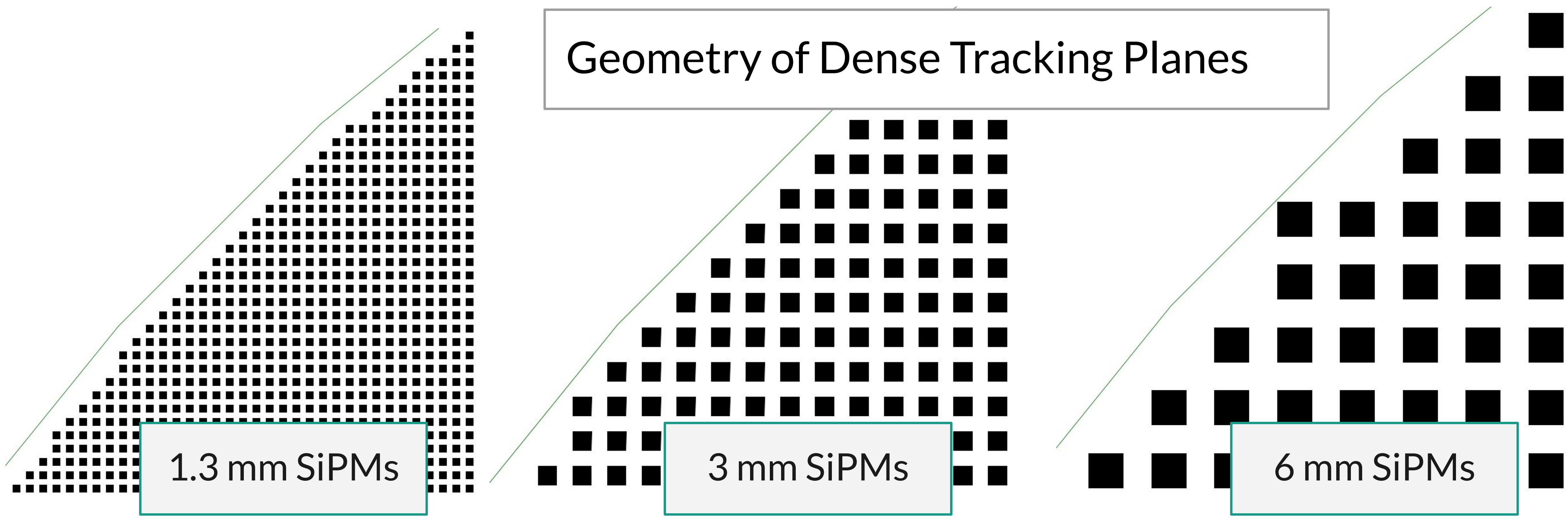
NEXT Collaboration, "Energy calibration of the NEXT-White detector with 1% resolution near $Q_{\beta\beta}$ of ^{136}Xe", *JHEP* 10 (2019) 230



- Allows for detection of S1 light
  - ✓ Need to use SiPMs (already demonstrated with PMTs)
  - ✓ Depends on SiPMs type (dark count rate), coverage, energy, readout electronics

Potential for future dense tracking plane

- Dense plane offers high granularity and high light detection coverage



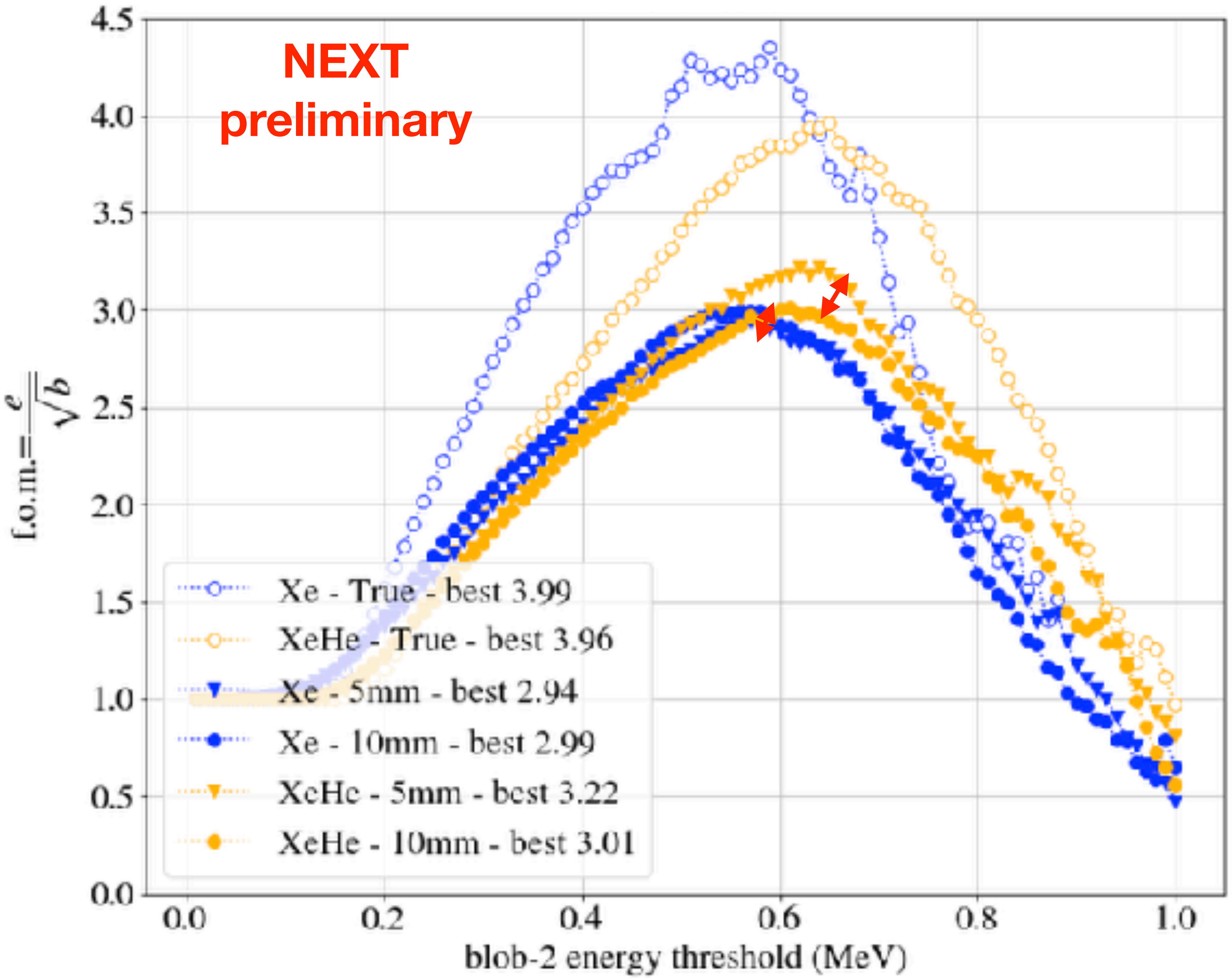
SiPM Size	Pitch	Coverage	**# of SiPMs** (ton scale, 2m diam)
1.3 mm x 1.3 mm	2.4 mm	30%	540,979
3 mm x 3 mm	5.5 mm	30%	103,074
6mm x 6mm	11 mm	30 %	25,956

Potential for future dense tracking plane

Imaging capabilities:

- Denser planes give better topology (diffusion limit)

Example at 15bar
1.5m drift
Pure Xe and He-Xe mixture

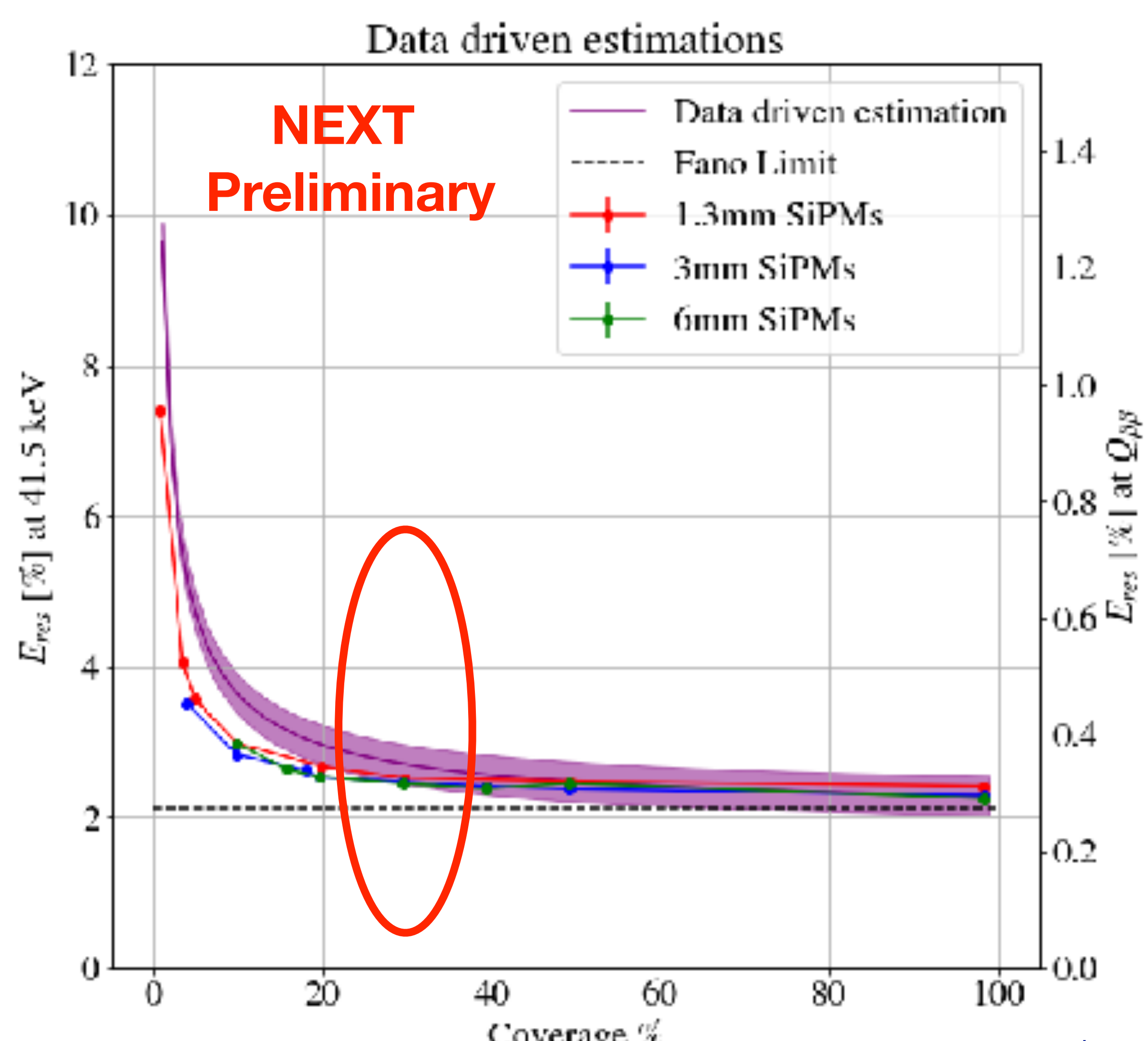


Work from Helena Almazan (U. Of Manchester)

Potential for future dense tracking plane

Energy resolution:

- Preliminary NEXT studies for dense tracking planes have shown that a 30% photocoverage would allow for sub-percent Eres
- Preliminary NEXT-White data analysis for Eres with SiPMs supports the 30% coverage



paper in preparation

Work from Taylor Contreras(Harvard)

Potential for future dense tracking plane

Detection of S1:

- Depends on:
  - ✓ Energy of events (e.g. 40keV Kr event produces ~10pes in NEXT PMTs)
  - ✓ Dark rate of SiPMs (vs temperature)
  - ✓ Readout window
- Very challenging for low-energy events like ^{83m}Kr (~40keV)
- Diffusion can be leveraged to find the position

Demonstration of Event Position Reconstruction based on Diffusion in the NEXT-White Detector

Coming soon!

J. Haefner,[1] K.E. Navarro,[2,*] R. Guenette,[3] B.J.P. Jones,[2] A. Tripathi,[2] C. Adams,[4]

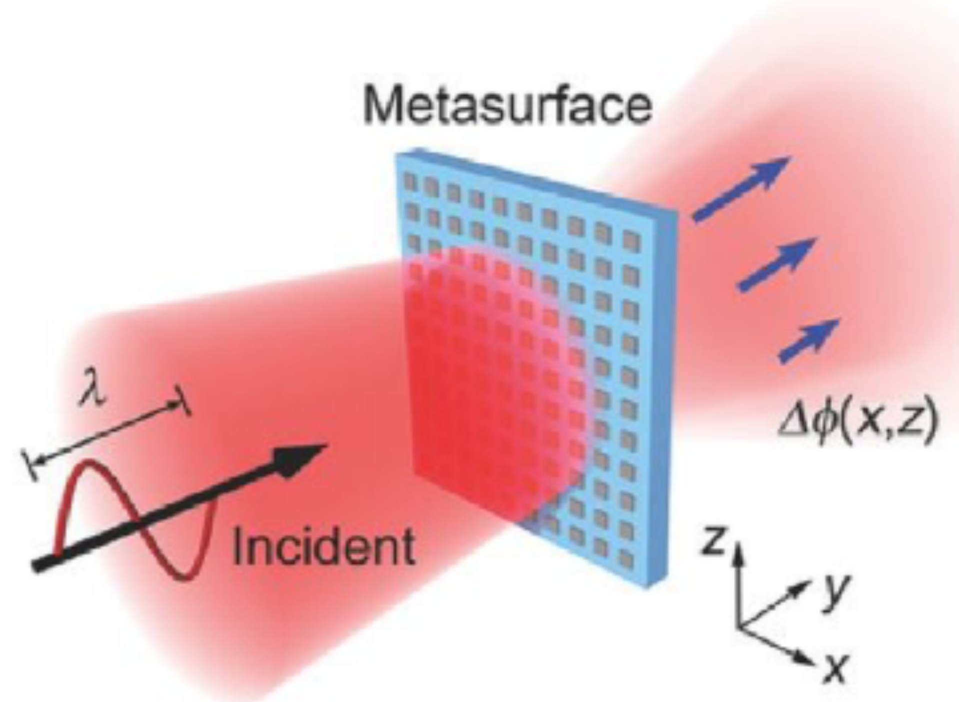
Potential for future dense tracking plane

Summary:

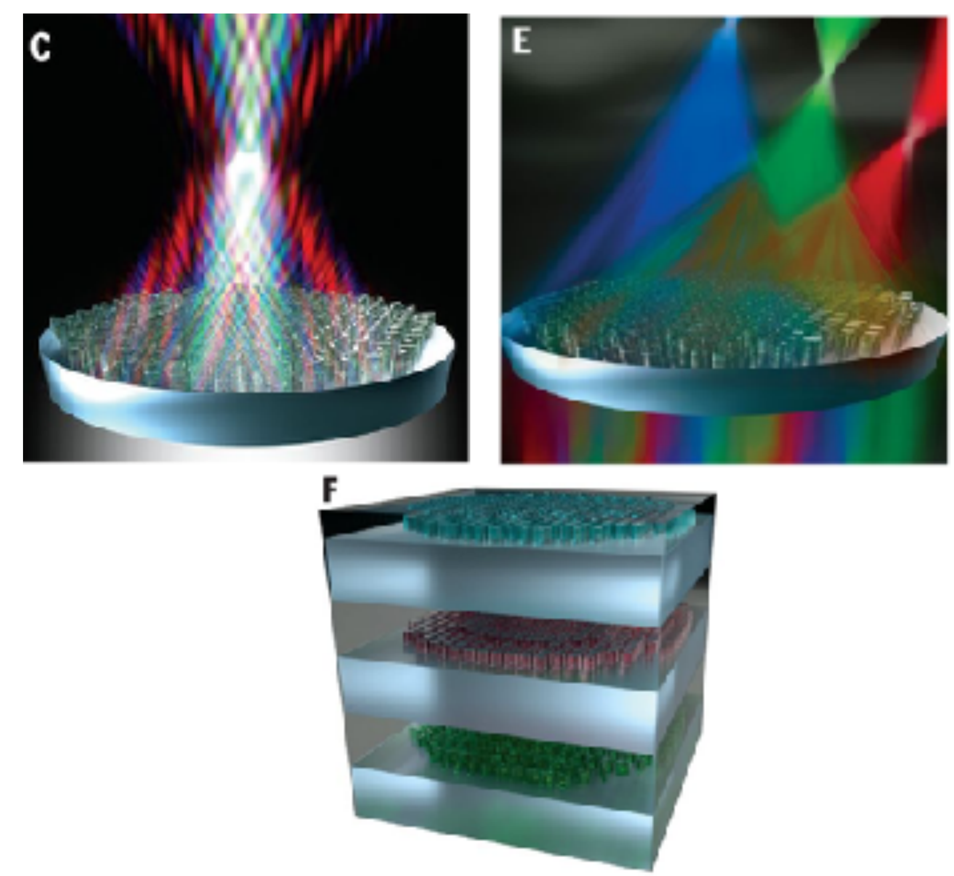
- High granularity imaging plane is desired
- Eres seem achievable with high (30%) coverage SiPMs plane
- S1 detection remains challenging for low energy events
- Electronics readout challenges for very high number of channels ($\mathcal{O}$(25k-0.5M)) **See interesting solution with PDCs from S. Charlebois' talk**

Increasing the light collected with metasurfaces

- Arrays of sub-wavelength spaced nanostructure that can manipulate light wavefronts
- Can control phase, amplitude and polarization state of transmitted light
- Optically **thin and light**
- **Low cost**, mass production (e-beam lithography or nano-imprints)
- Extremely versatile (which requires **dedicated design** for different applications)



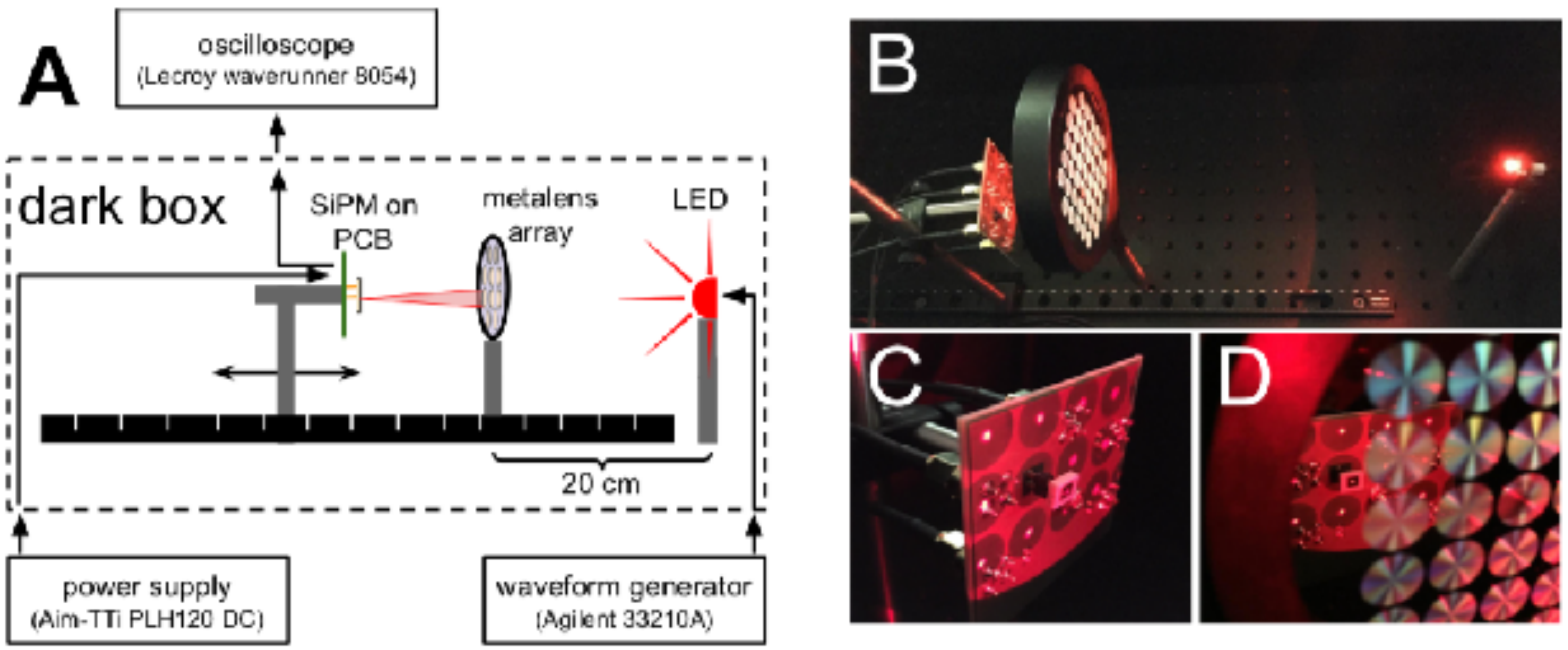
Kim, K.-H., Jung, G.-H., Lee, S.-J., Park, H.-G. and Park, Q.-H. (2016), Ultrathin Capacitive Metasurfaces for Strong Electric Response. Advanced Optical Materials, 4: 1501-1506. https://doi.org/10.1002/adom.201600146



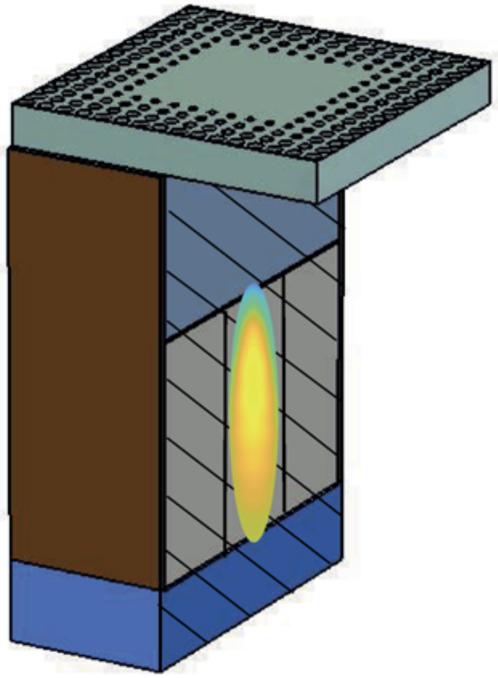
M. Khorasaninejad & F. Capasso, Science 358, 6367 (2017)

Increasing the light collected with metasurfaces

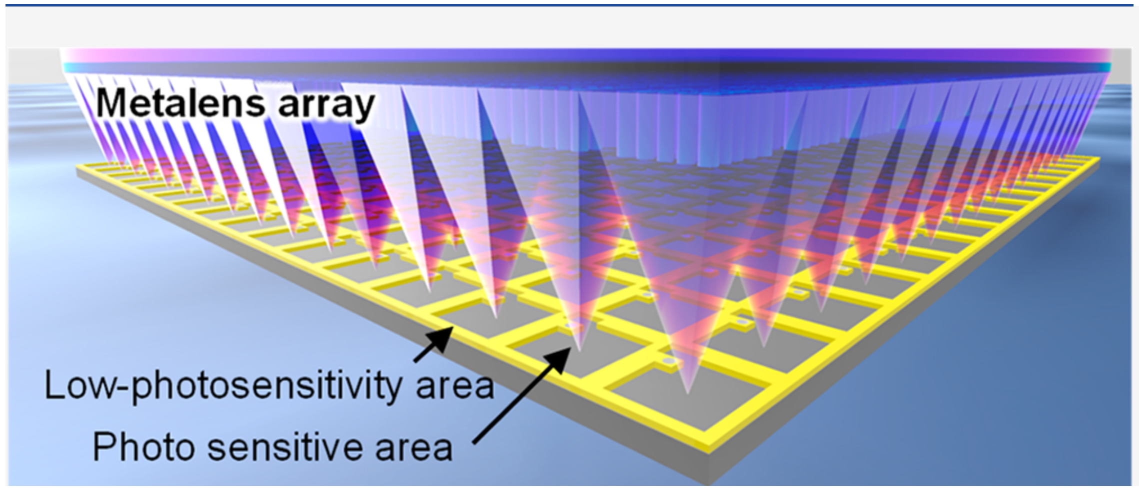
- Combining metalenses to SiPMs (to increase light collection with small SiPMs and/or to correct for dead-space)



A.A. Loya Villalpando et al., (2020), JINST 15, P11021.



E. Mikheva et al., APL Photonics 5, 116105 (2020)
FBK+CERN

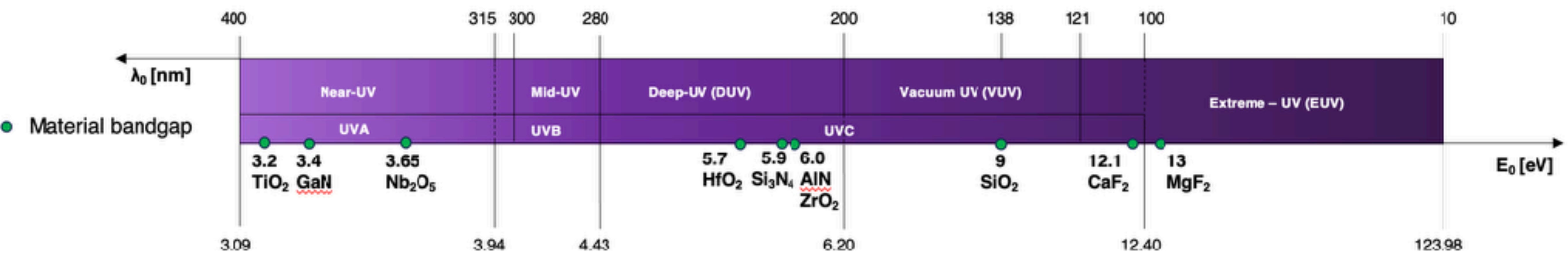


S. Uenoyama et al., ACS Photonics 8 (2021)
Hamamatsu

Metasurfaces in xenon

- Scintillation light is in VUV

- Challenges in UV meta optics:
  - Material absorption – most materials are absorbing (see green dots in the spectrum below)
  - Subwavelength features – fabrication difficulties
  - Few experimental demonstrations in the literature

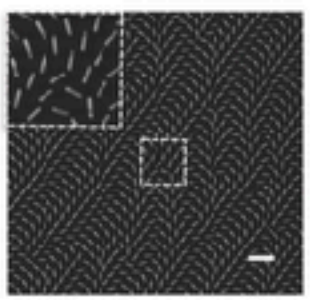


A.Martins, Optica Imaging Conference (14/08/2023)

Metasurfaces in xenon

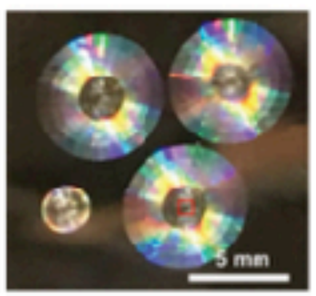
- Scintillation light is in VUV

- **380 nm**
  - c-Si
  - PB phase
  - Holograms
  - Efficiency: 15%



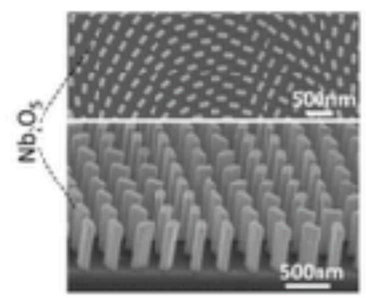
Advanced Materials, 1802632 (2018)

- **360 nm**
  - SiO_2/Polymer
  - Fresnel/metagratings
  - Metalenses (NA=0.9)
  - Efficiency: 13.9%



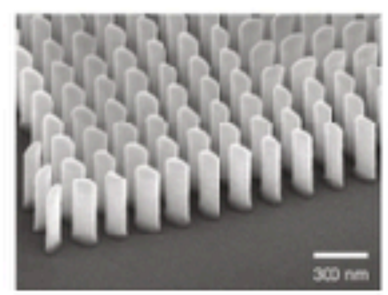
Adv. Optical Mater. 2023, 2300852.

- **355 nm**
  - Nb_2O_5
  - PB-Phase
  - Holograms
  - Efficiency: 79.6%



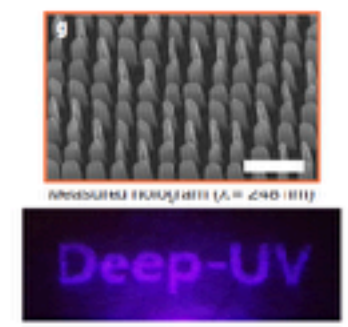
Laser & Photonics Reviews **13**, 1800289 (2019).

- **364, 325 and 266 nm**
  - HfO_2
  - PB-Phase
  - Holograms/metalenses (NA=0.6)
  - Efficiency: [55%,60%]



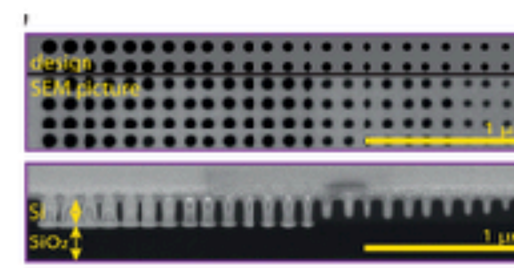
Light: Science & Applications **9**, 55 (2020).

- **325 and 248 nm**
  - ZrO_2
  - PB-Phase
  - Holograms
  - Efficiency: [72% and 48%]

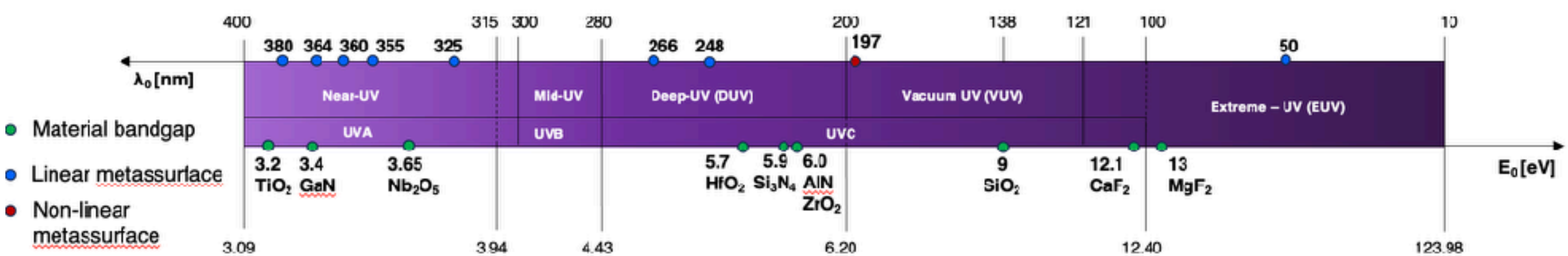


Light Sci Appl 12, 68 (2023).

- **50nm**
  - Nanoholes in c-Si
  - Vacuum guiding
  - Metalens (NA=0.05)
  - Efficiency: 5%



Science **380**, 59-63 (2023)



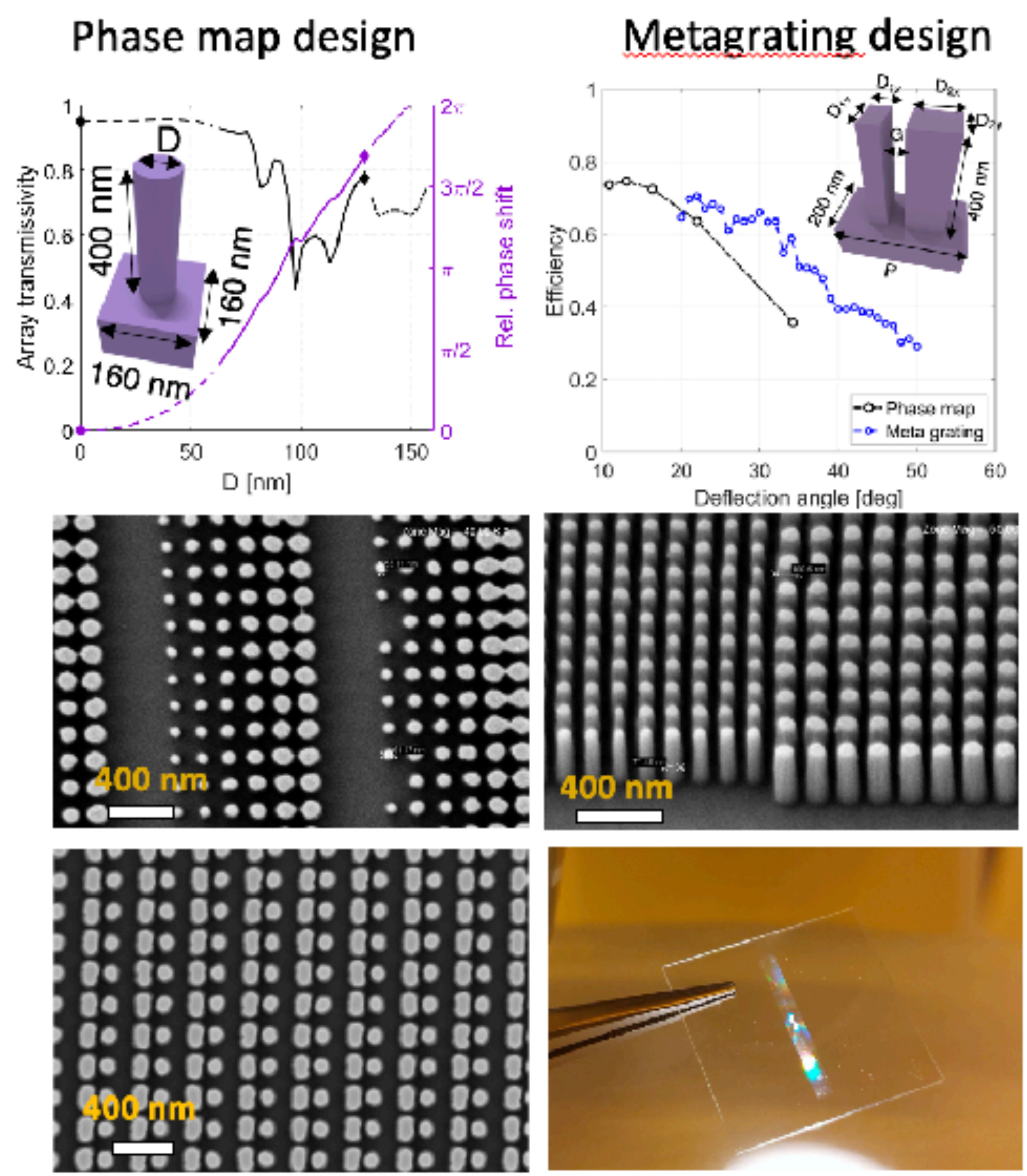
A.Martins, Optica Imaging Conference (14/08/2023)

First VUV metalens

- Metalens for 175nm

Metalens Parameters

- Focal length=9 mm
- NA = 0.65
- Metalens dimensions: 1.7 mm × 15.39 mm
- Simulated focusing efficiency: 68%



Work led by Augusto Martins (U. Of Manchester)

First VUV metalens

- Metalens for 175nm

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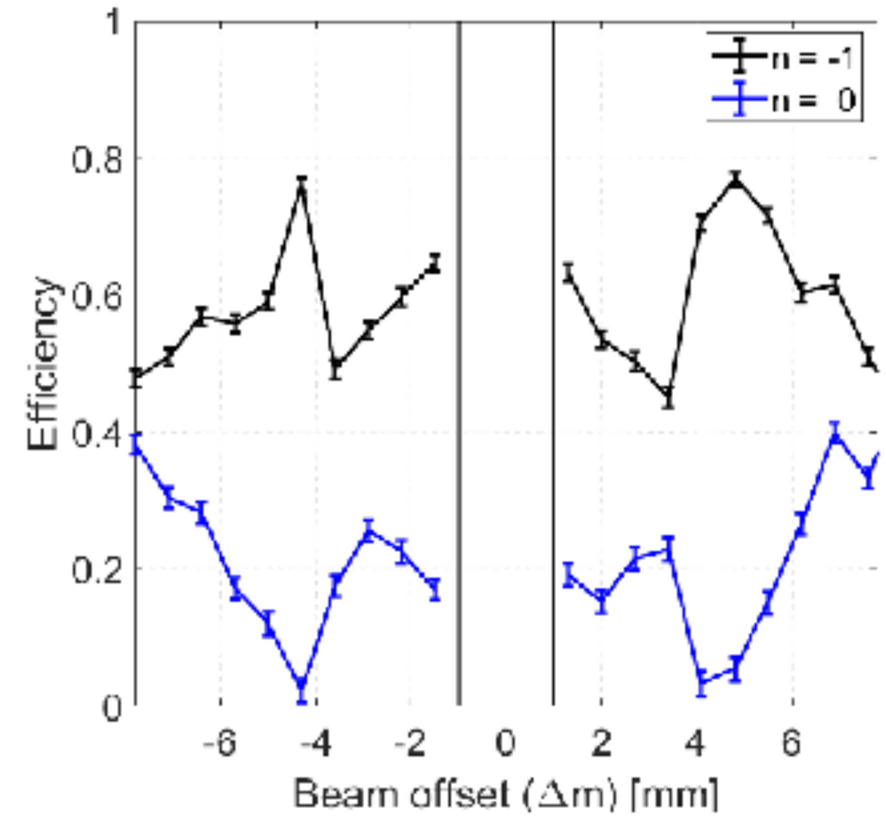
- Simulated focusing efficiency: 68%

λ_0 =175 nm



175 nm	(63.68±1.19) %

Reasonable efficiency (>30%) up to 25° from normal

Work led by Augusto Martins (U. Of Manchester)

First VUV metalens

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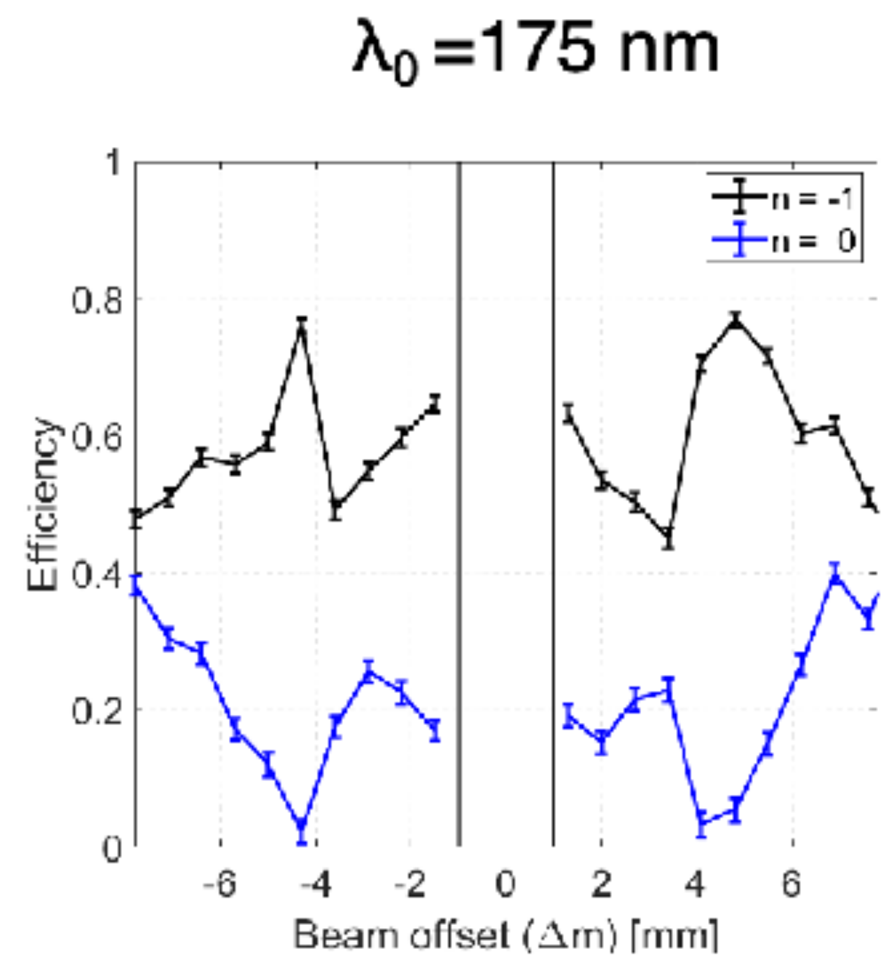


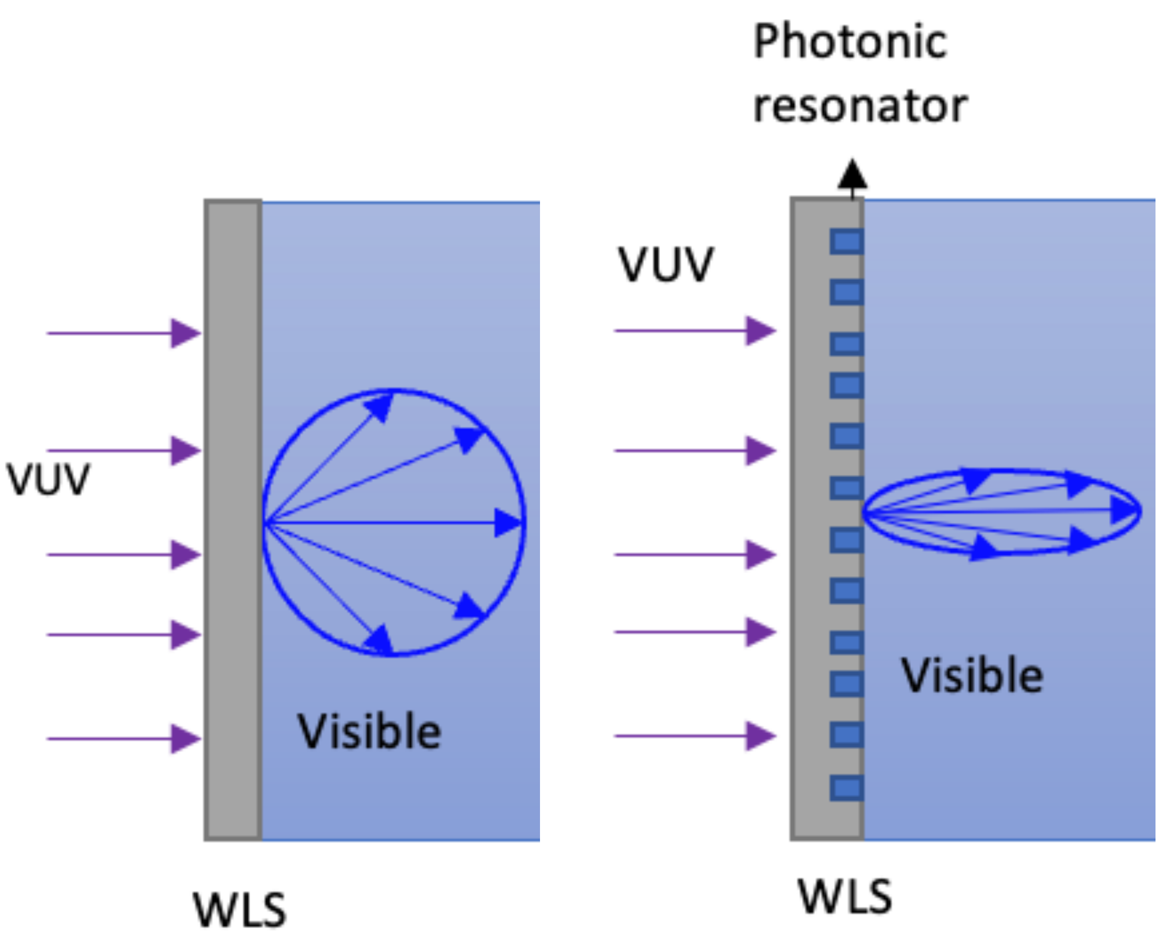
175 nm	(63.68±1.19) %

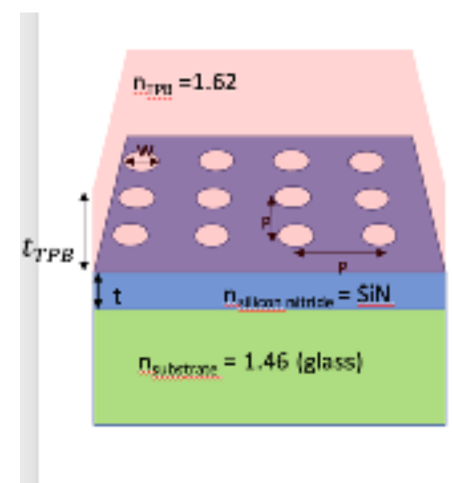
Reasonable efficiency (>30%) up to 25° from normal

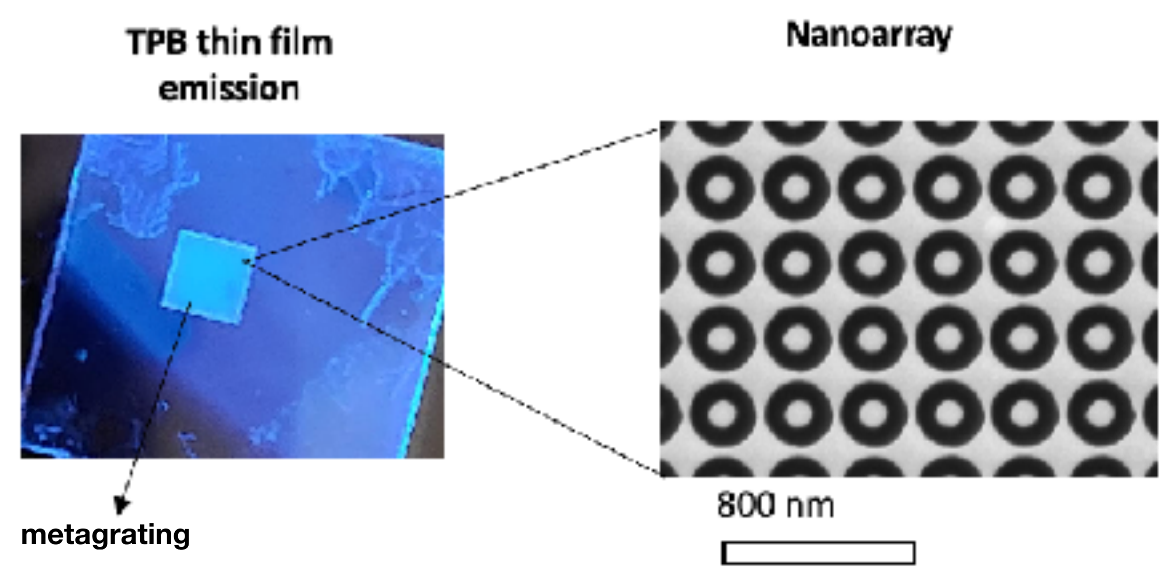
First demonstration of VUV metaoptics could be useful for future tracking planes

Alternative solution with wavelength shifters

- Much higher quantum efficiencies for SiPMs in visible
- Use of TPB introduces issues (loss of light due to isotropic emission, degradation, dissolution…)
- Use a metasurface to reshape the TPB emission profile



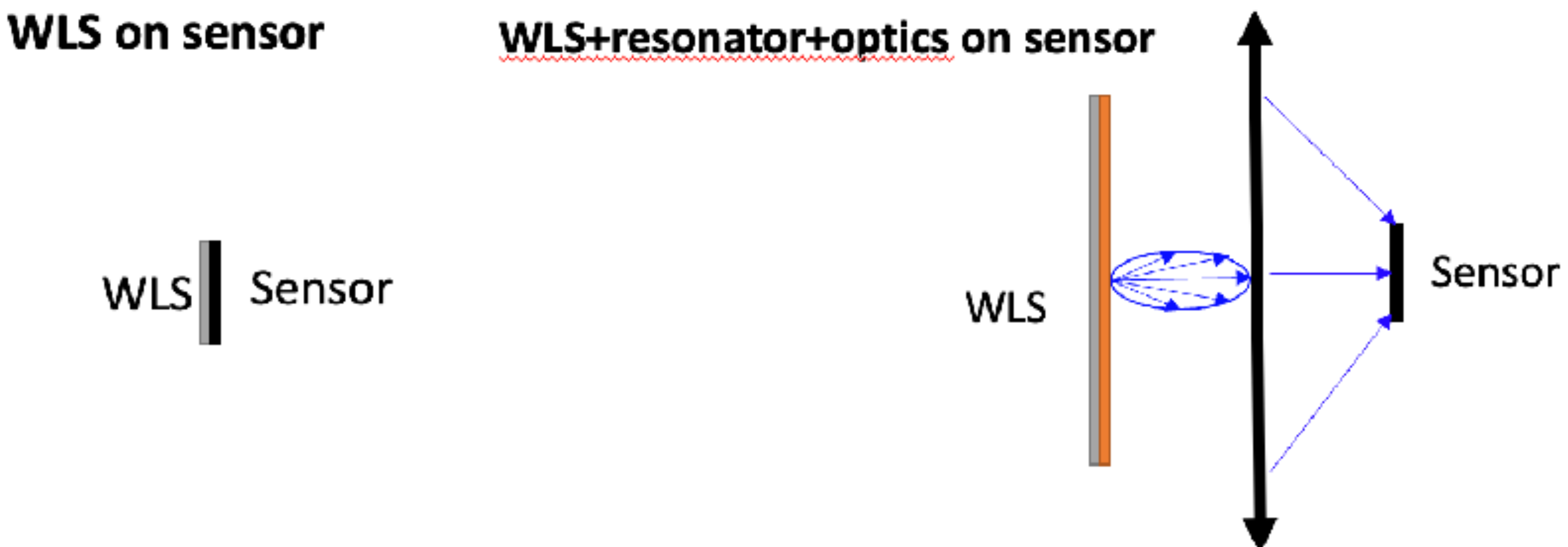




Work led by Augusto Martins (U. Of Manchester)

Alternative solution with wavelength shifters

- Much higher quantum efficiencies for SiPMs in visible
- Use of TPB introduces issues (loss of light due to isotropic emission, degradation, dissolution…)
- Use a metasurface to reshape the TPB emission profile
- Add metalens to increase area!



Work led by Augusto Martins (U. Of Manchester)

Summary

- Dense SiPMs plane used in EL-TPC could offer:
  - ✓ High granularity imaging capabilities
  - ✓ Excellent energy resolution
- Need good electronics readout solutions
- Addition of metasurfaces could enhance the amount of light collected

Thank You!