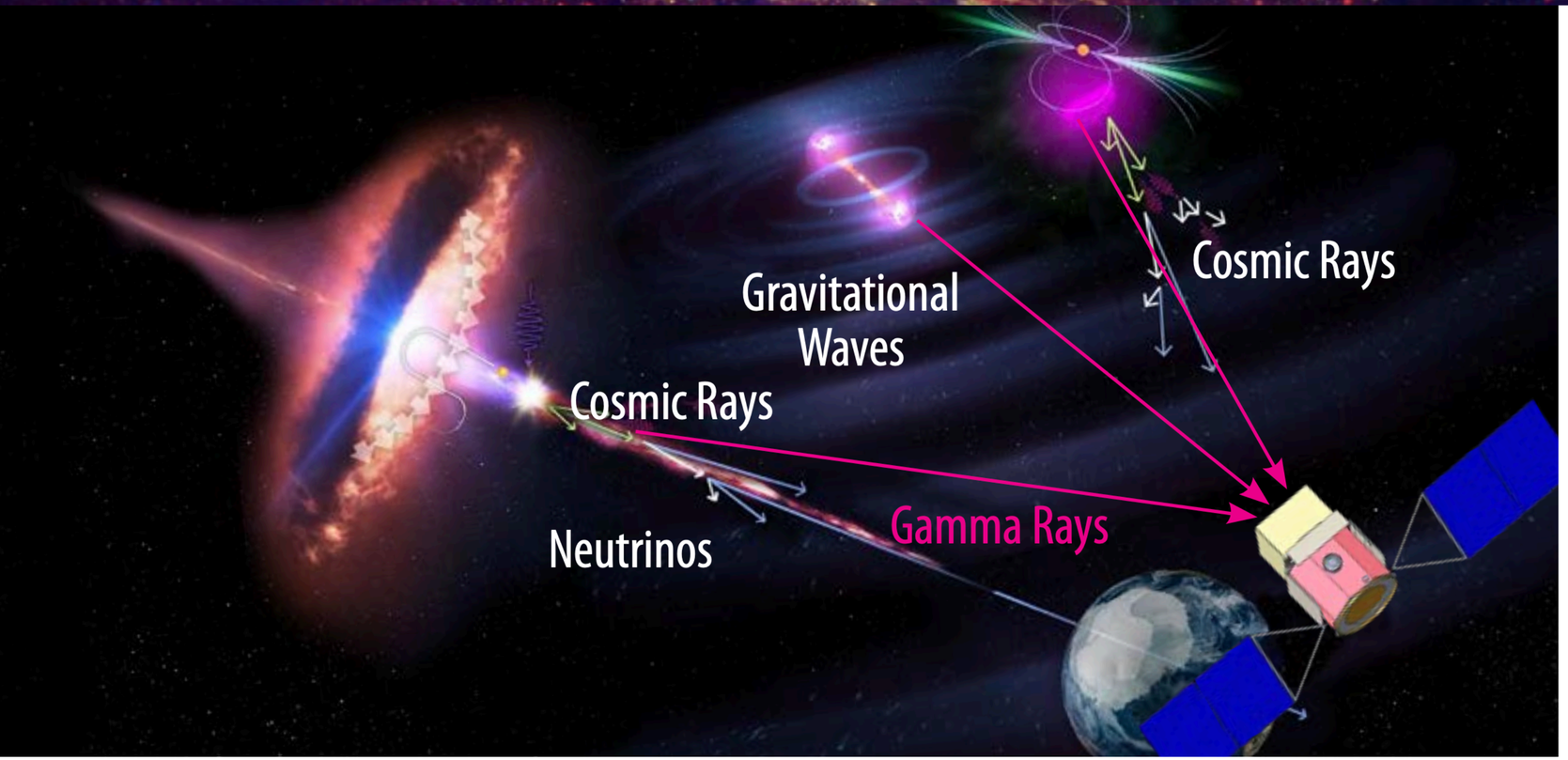
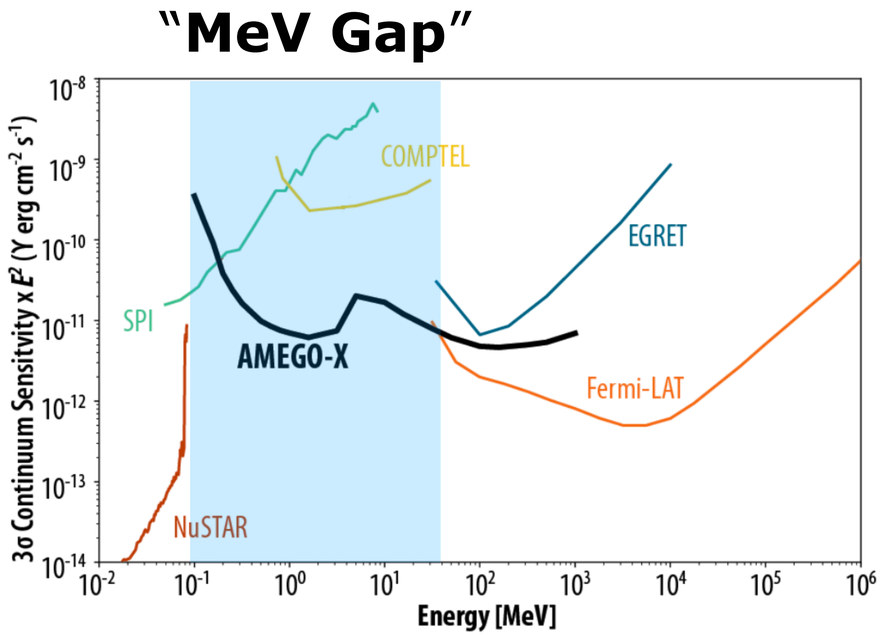
次世代宇宙ガンマ線衛星に向けた 大面積ピクセルを持つピクセル検出器の開発

須田祐介（広島大学）

SOIPIX量子イメージング研究会2025
石川県政記念　しいのき迎賓館 @金沢
Dec 2, 2025

AMEGO-X: All-Sky MeV Gamma Satellite

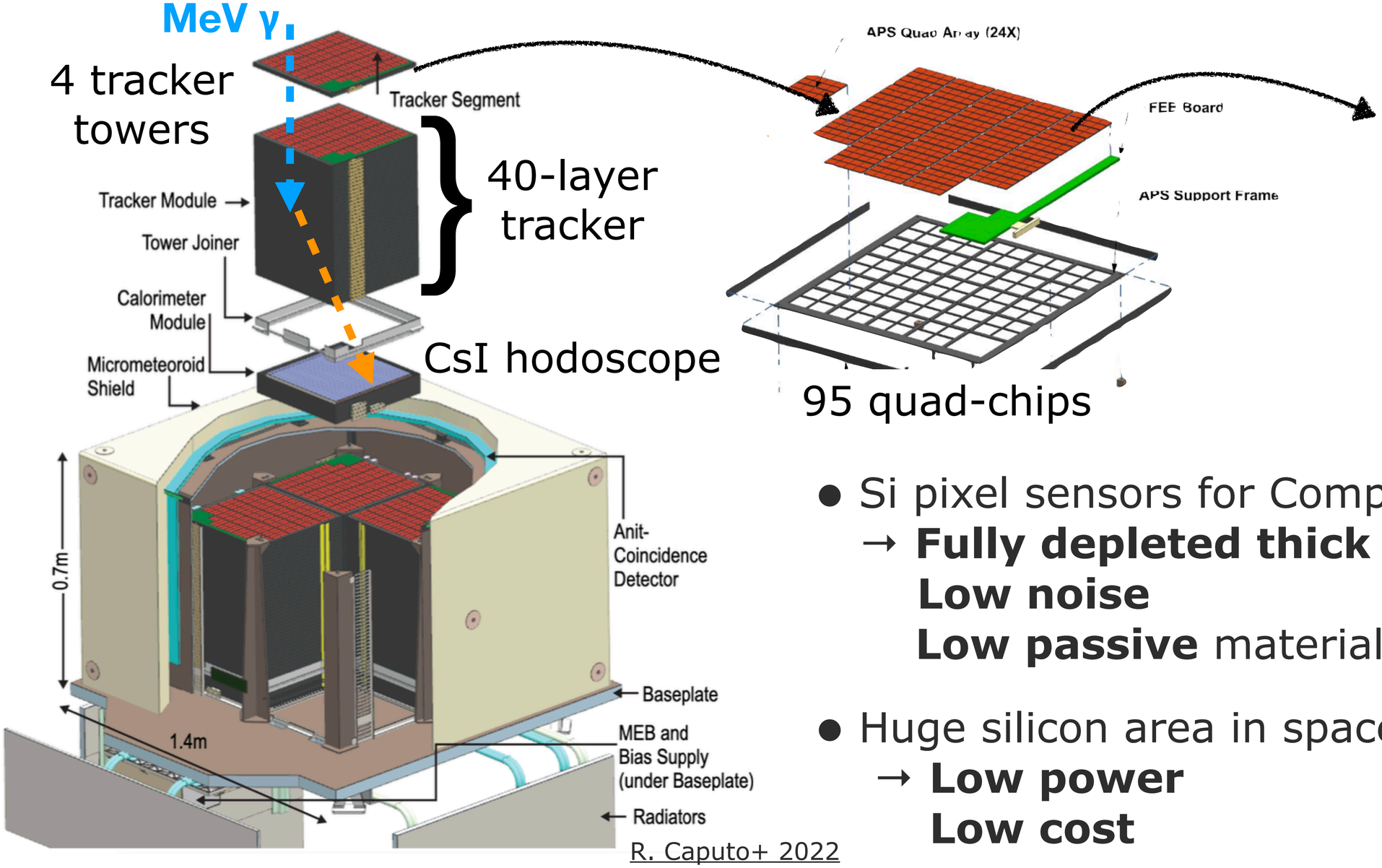




R. Caputo+ 2022

- **A**ll-sky **M**edium **E**nergy **G**amma-ray **O**bservatory e**X**plorer (PI: R. Caputo, GSFC/NASA) is a proposed MeV gamma-ray mission
  - Supermassive black holes: ~150 blazar flares/year
  - Neutron star mergers: >200 short gamma-ray bursts per year
  - Galactic cosmic ray origin, multi-messenger astronomy, etc.

AMEGO-X Gamma-Ray Telescope



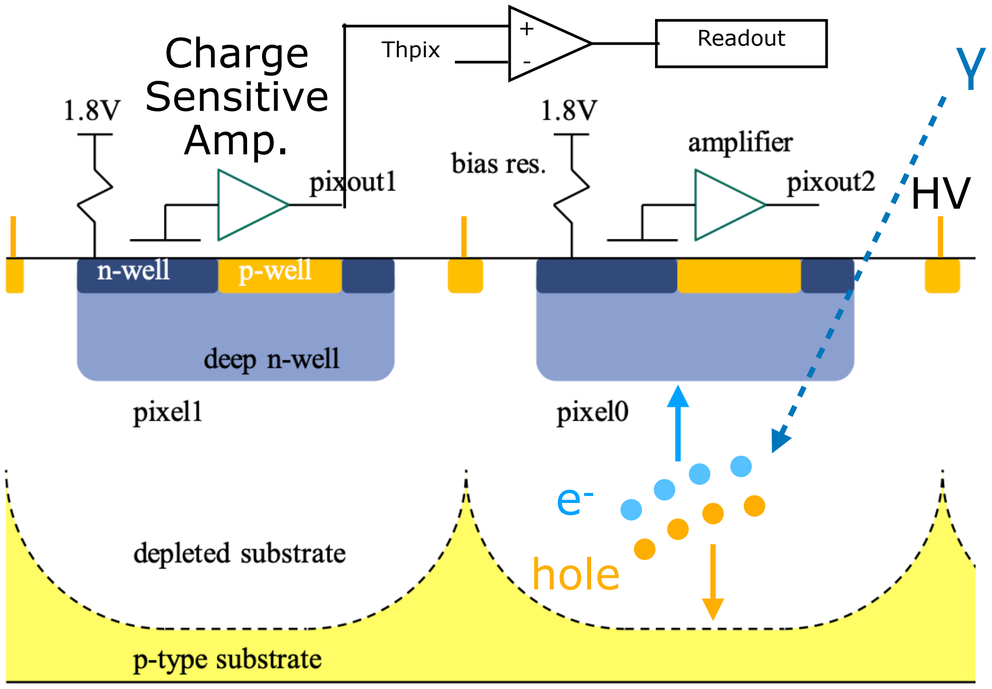
R. Caputo+ 2022

- Si pixel sensors for Compton camera
  → **Fully depleted thick sensor**
  Low noise
  Low passive material quantity

- Huge silicon area in space (24 m², 74M pixels)
  → **Low power**
  Low cost

AstroPix

HV-CMOS pixel sensor

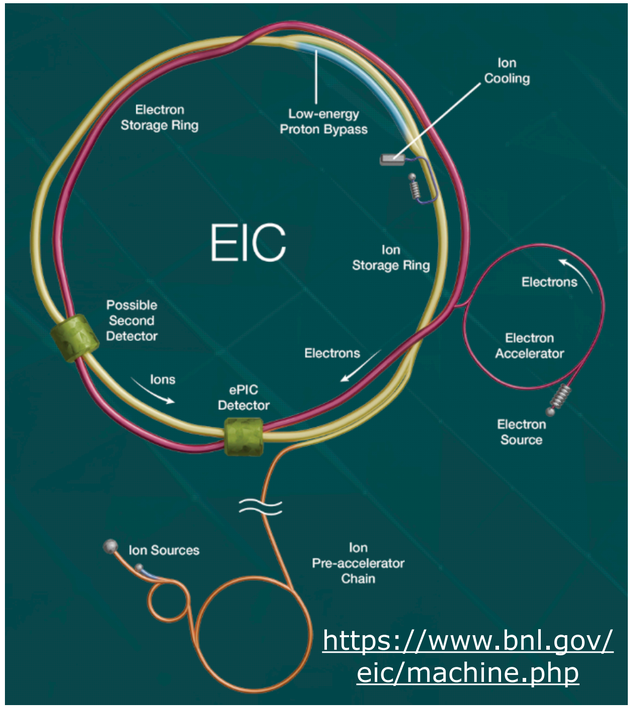


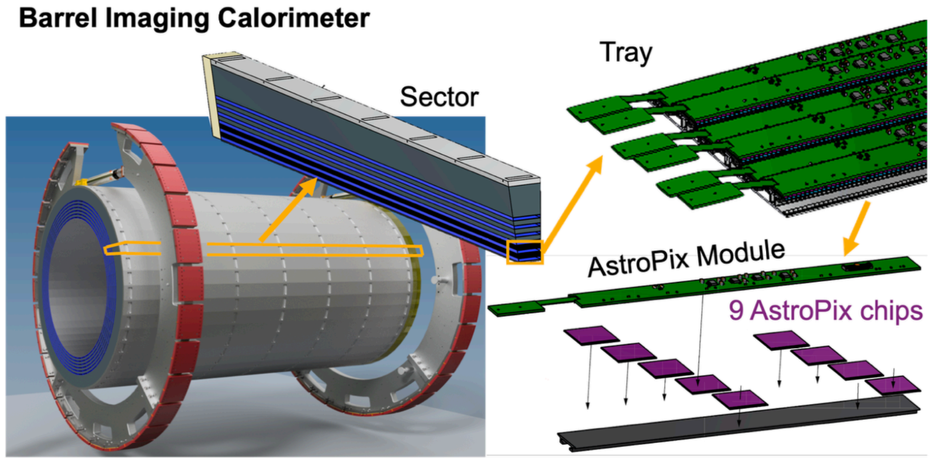
I.Peric+'07 with modifications

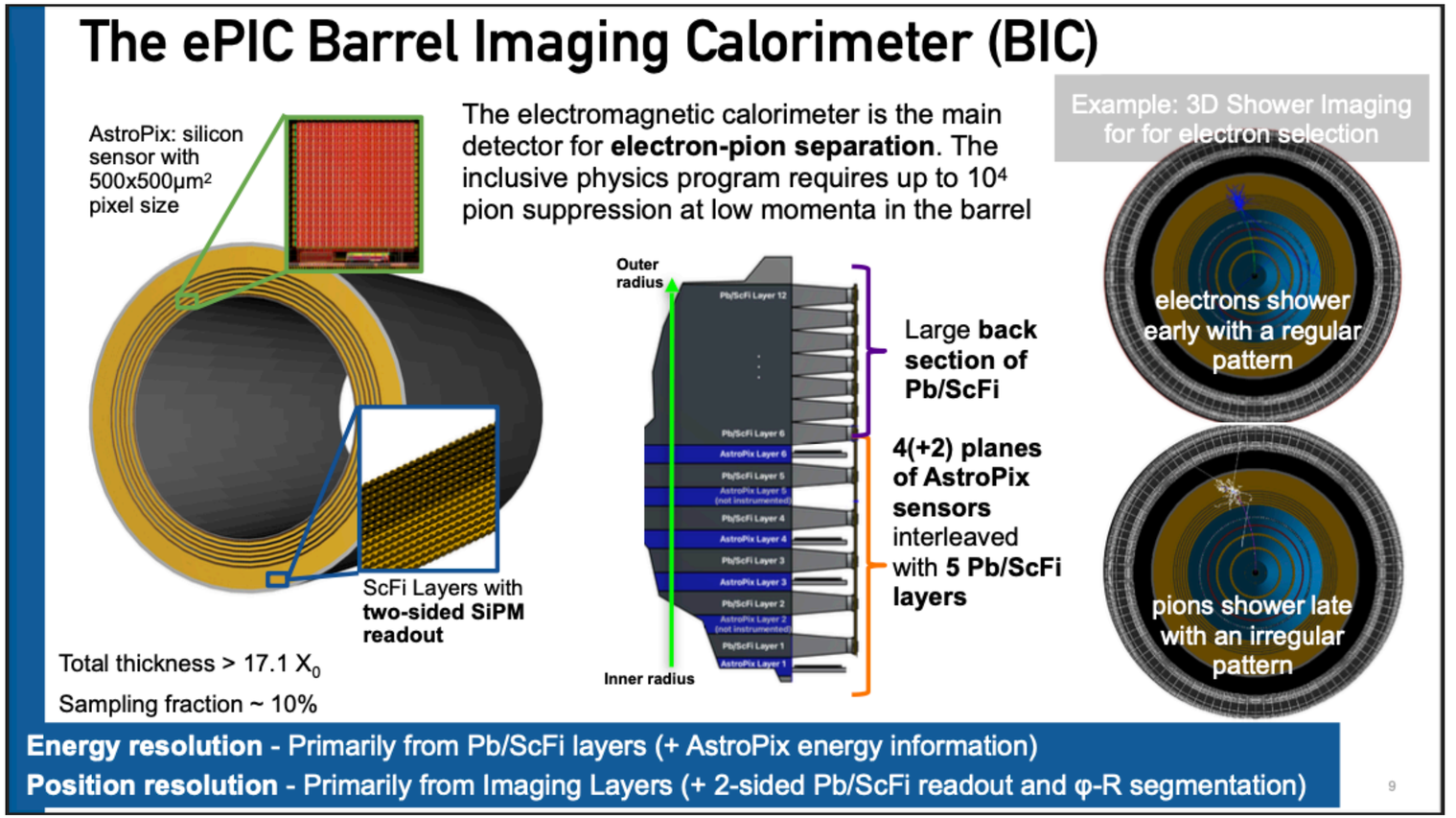
- Monolithic active pixel sensor (MAPS) = Detector + CMOS
  - On-pixel charge amplification and on-chip digitization
    → **Low noise**
    → **Low passive** material quantity
  - Typical CMOS wafer process & high yield
    → **Low cost**
- HV-CMOS MAPS
  → **Fully depleted thick sensor**
- Low pixel density allowing a large pixel pitch
  → **Low power**
- Time-over-Threshold measurement
  → Energy & timing

	Pixel pitch	Full depletion	Dynamic range	Energy resolution (FWHM at 122 keV)	Power
Goal	500 × 500 μm^2	500 μm	25 - 700 keV	12.2 keV	< 1.5 mW/cm^2

AstroPix @ Electron-Ion Collider







M.Jadhav (ANL) @ PIXEL 2024

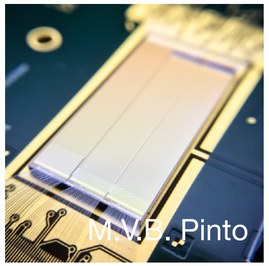
B.Kim+2025, PoS(VERTEX2025)

AstroPix Series

2020 | 2021 | 2022 | 2023 | 2024 | 2026

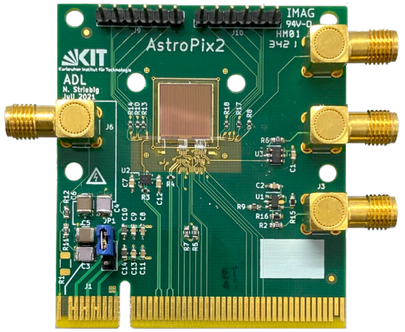
MuPix

ATLASPix



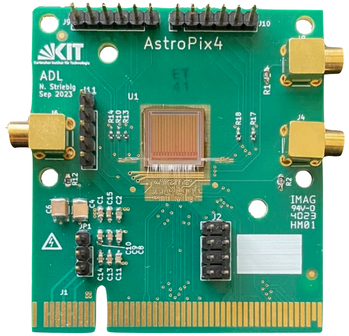
AstroPix v1

v2



v3

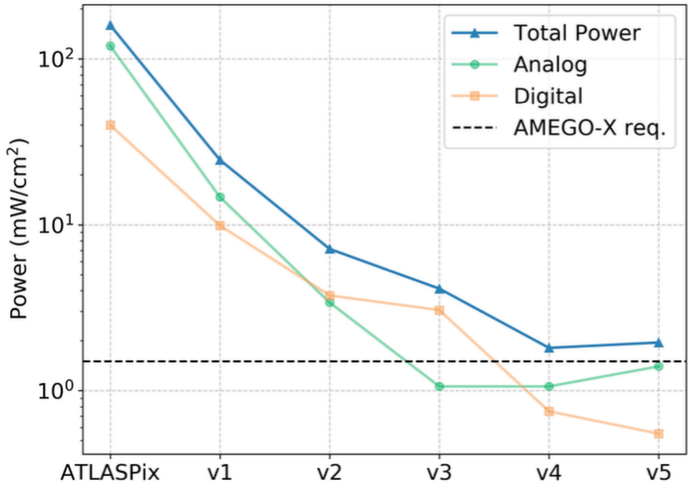
v4



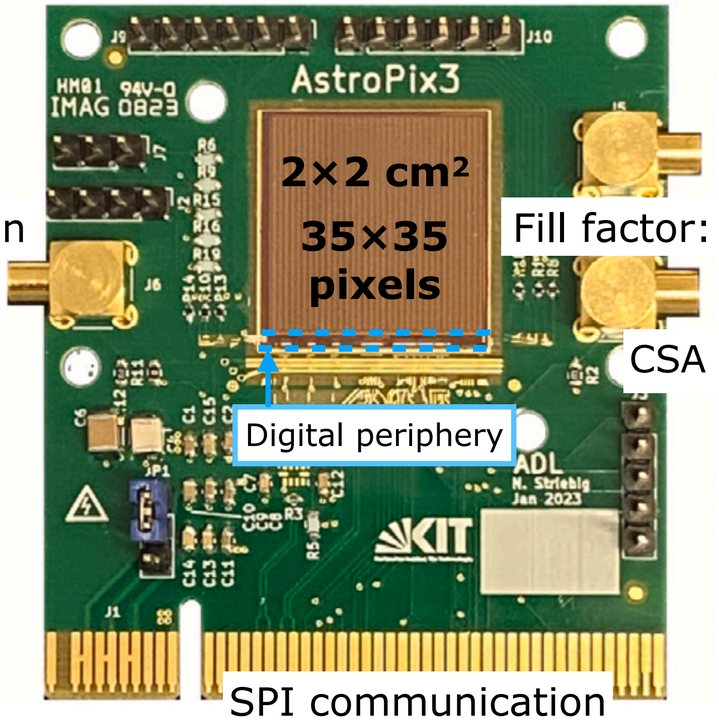
v5

	ATLASPix	AstroPix v1	v2	v3	v4	v5
Pitch:	150 x 50 µm	175 x 175 µm	250 x 250 µm	500 x 500 µm	500 x 500 µm	
Power:	160 mW/cm²	24.6 mW/cm²	7.2 mW/cm²	4.1 mW/cm²	2 mW/cm²	

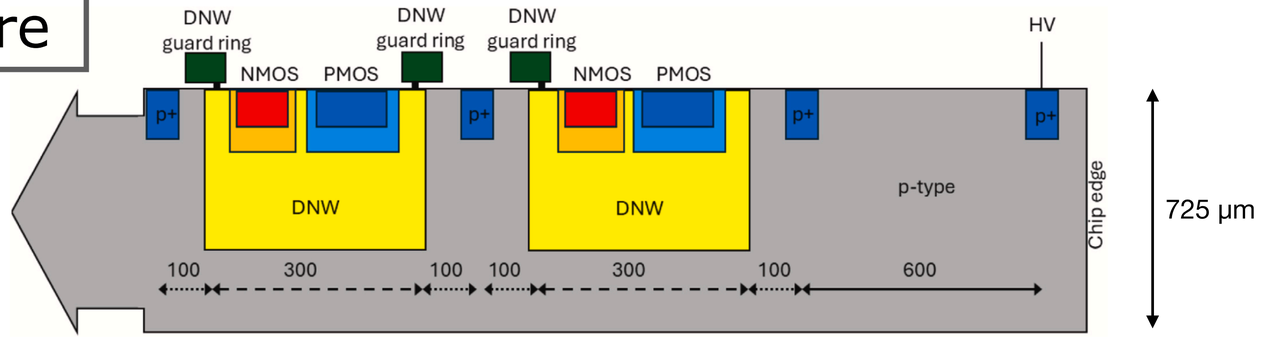
- PI: R. Caputo (GSFC/NASA)
- Design: Karlsruhe Institute of Technology based on ~20 years of experience in HV-MAPS
- AstroPix1: First prototype. Analog readout only
- AstroPix2: Digital readout capability
- AstroPix3: Full reticle chip, 2 x 2 cm². Large pixel pitch, 500 µm
- AstroPix4, AstroPix5, …



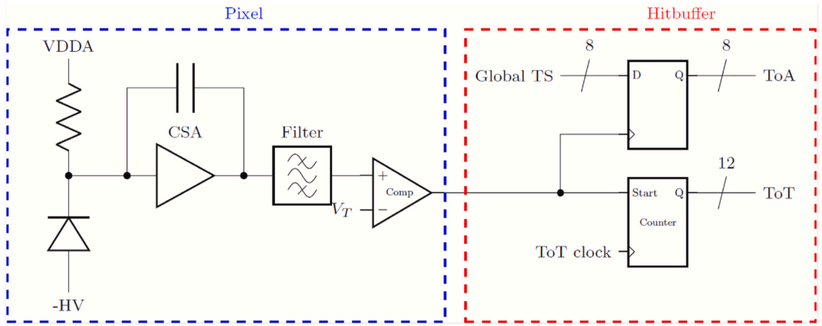
AstroPix3

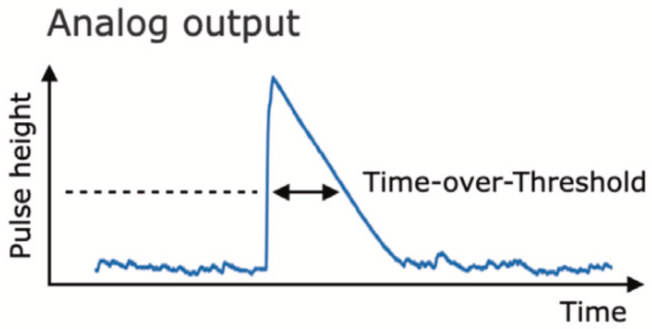


Structure

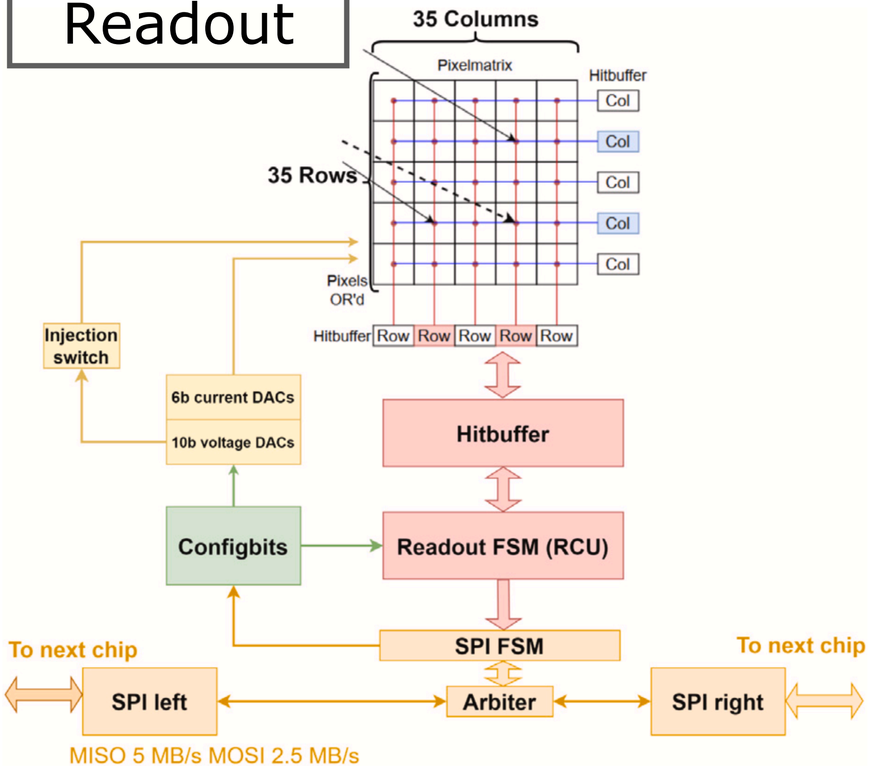


Electronics





Readout

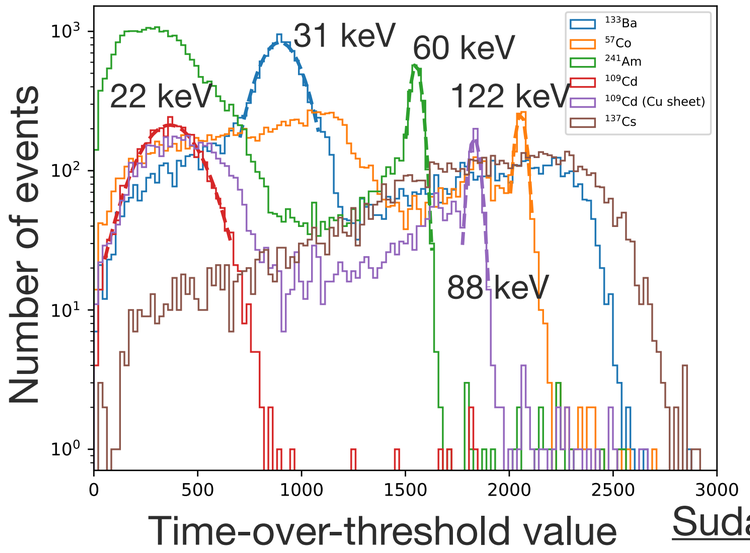


	ATLASPix [5,6]	v1 [7]	v2 [7,8]	v3 [9–11]	Goal [12]
E_{res} [keV] (FWHM)	7.3 ± 1.2% at 30.1	20 ± 7.4%* at 30.1	15 ± 3% at 30.1	10.4 ± 3.2%◊ at 59.5	10% at 122
Pitch [µm]	150 × 50	175 × 175	250 × 250	500 × 500	500 × 500
Thick [µm]	100	725	725	725	525
Dep. [µm]	48■	N.M.	N.M.	94 ± 6△	500
Range [keV]	5-32	14-122	14-80	22-200	25-700
Analog [mW/cm²]	120	14.7	3.4	1.06	1.0
Digital [mW/cm²]	40	9.9	3.75	3.06	0.5

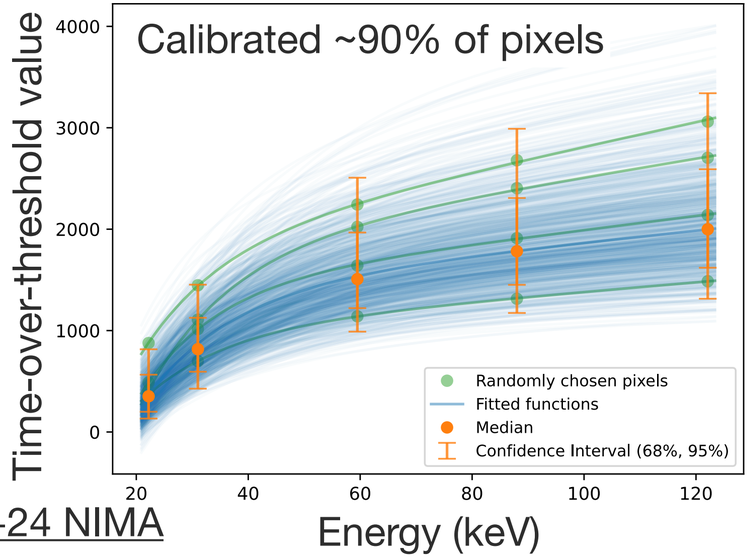
Steinhebel+25 NIMA

AstroPix3: Performance

ToT spectra

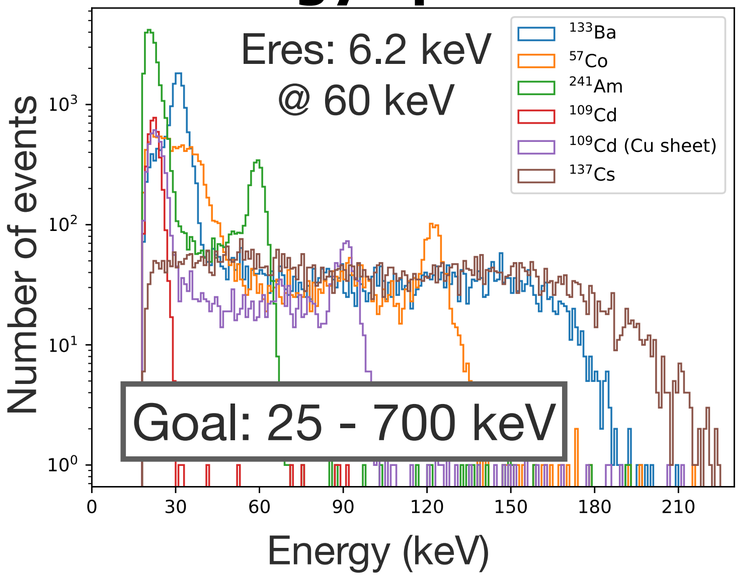


Calibration curves

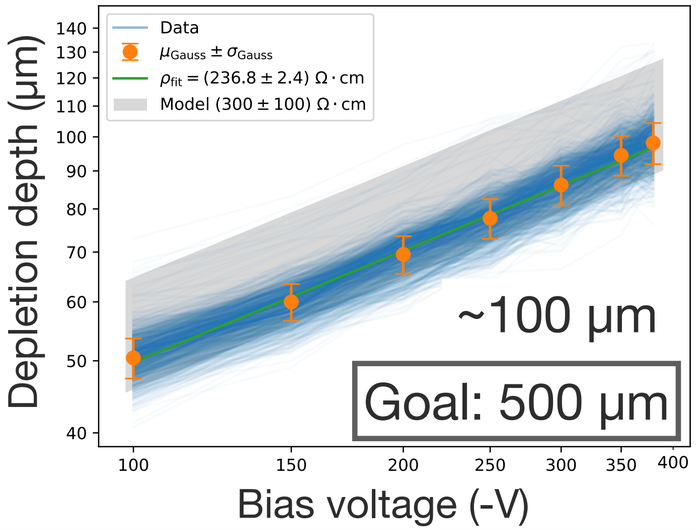


Suda+24 NIMA

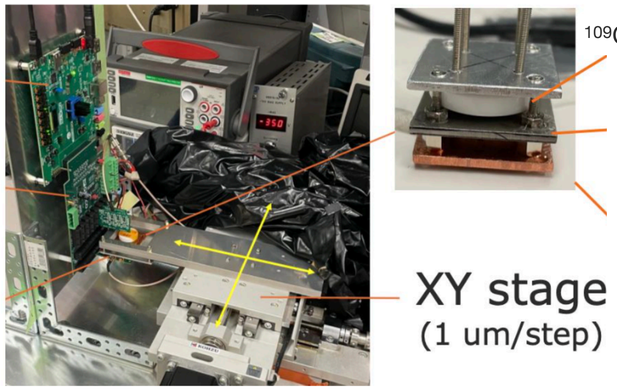
Energy spectra

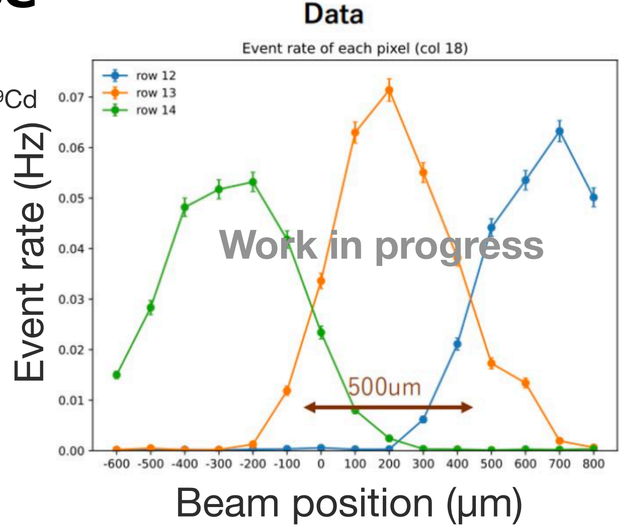


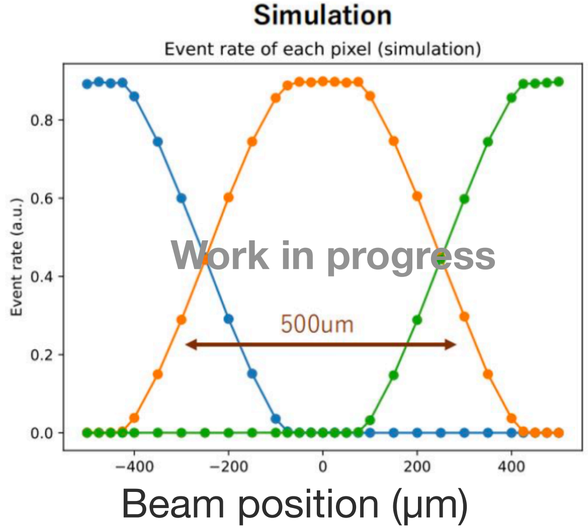
Depletion depth



Sub-pixel response







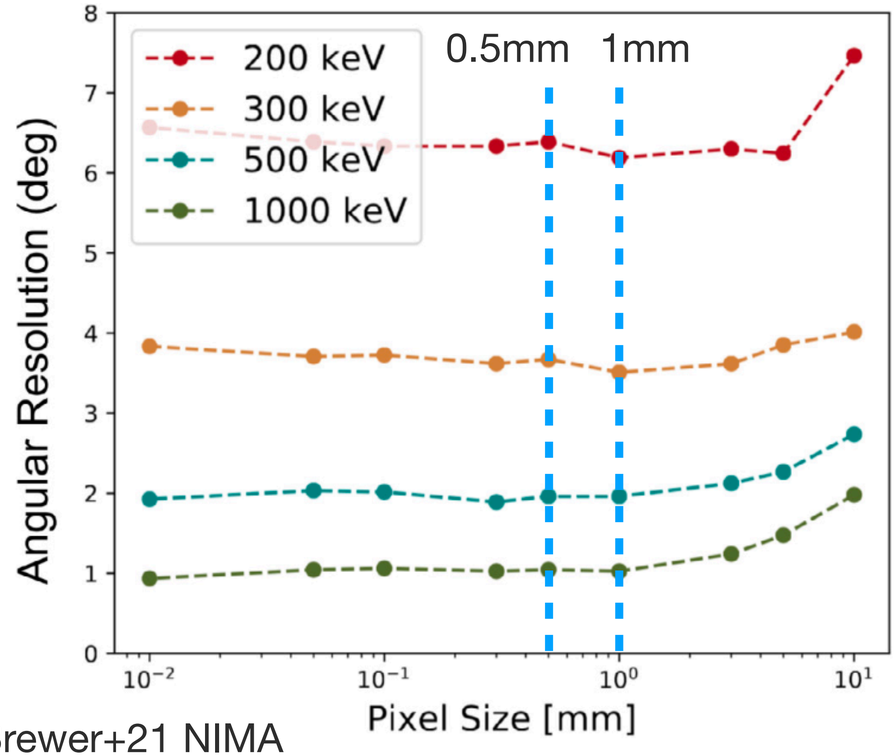
国産低消費電力ピクセルセンサ

- CubeSat・素核実験・医療・月面なども視野に国産で持っておきたい

⇩

- 完全空乏実績のあるXRPIXをベースに低消費電力チップを作ろう！
- ピクセルの巨大化（36 um→ 500 um）
  - 消費電力：~140 mW/cm^2 @XR10 → 1 mW/cm^2 ?
  - 電子飛跡は追えないのでパターン判定不要
- 電荷収集が不安
- 実はMeVガンマ衛星的には1mmでも良い

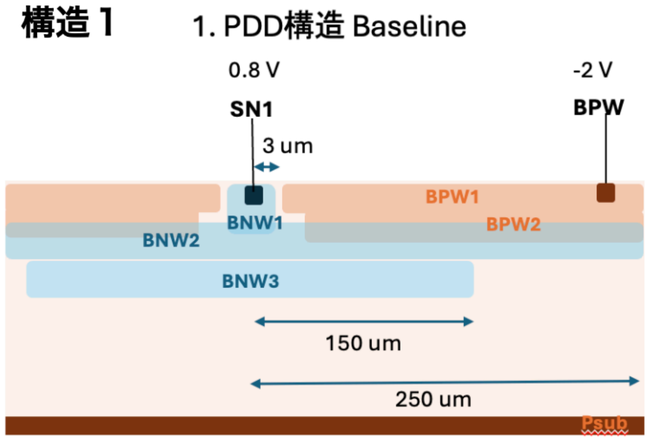
コンプトンカメラの角度分解能
vs. ピクセルピッチ

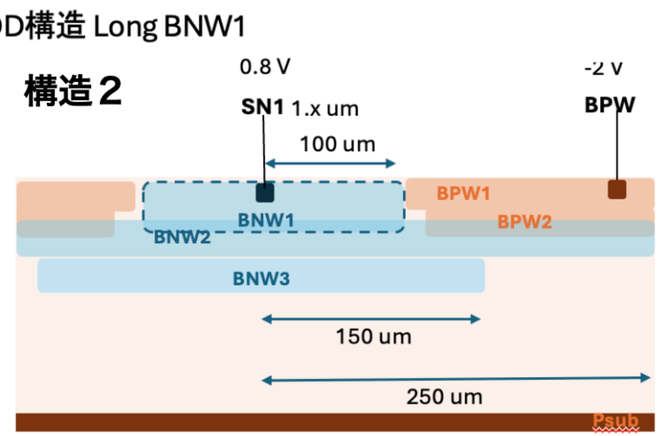


Brewer+21 NIMA

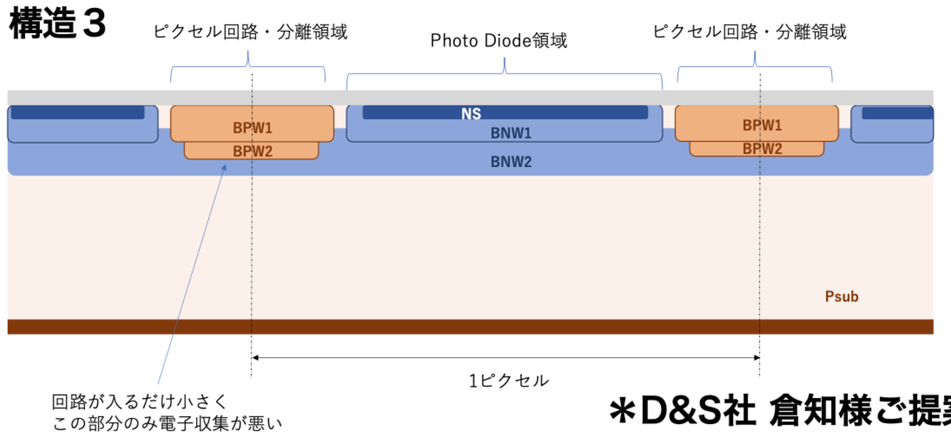
OROCHI

- 提案＆出資：須田（広大）
- 設計：武田さん（宮大）
- PD設計サポート：倉知様（D&S）
- アドバイザー：鶴さん（京大），
  森さん（宮大），新井先生（KEK)



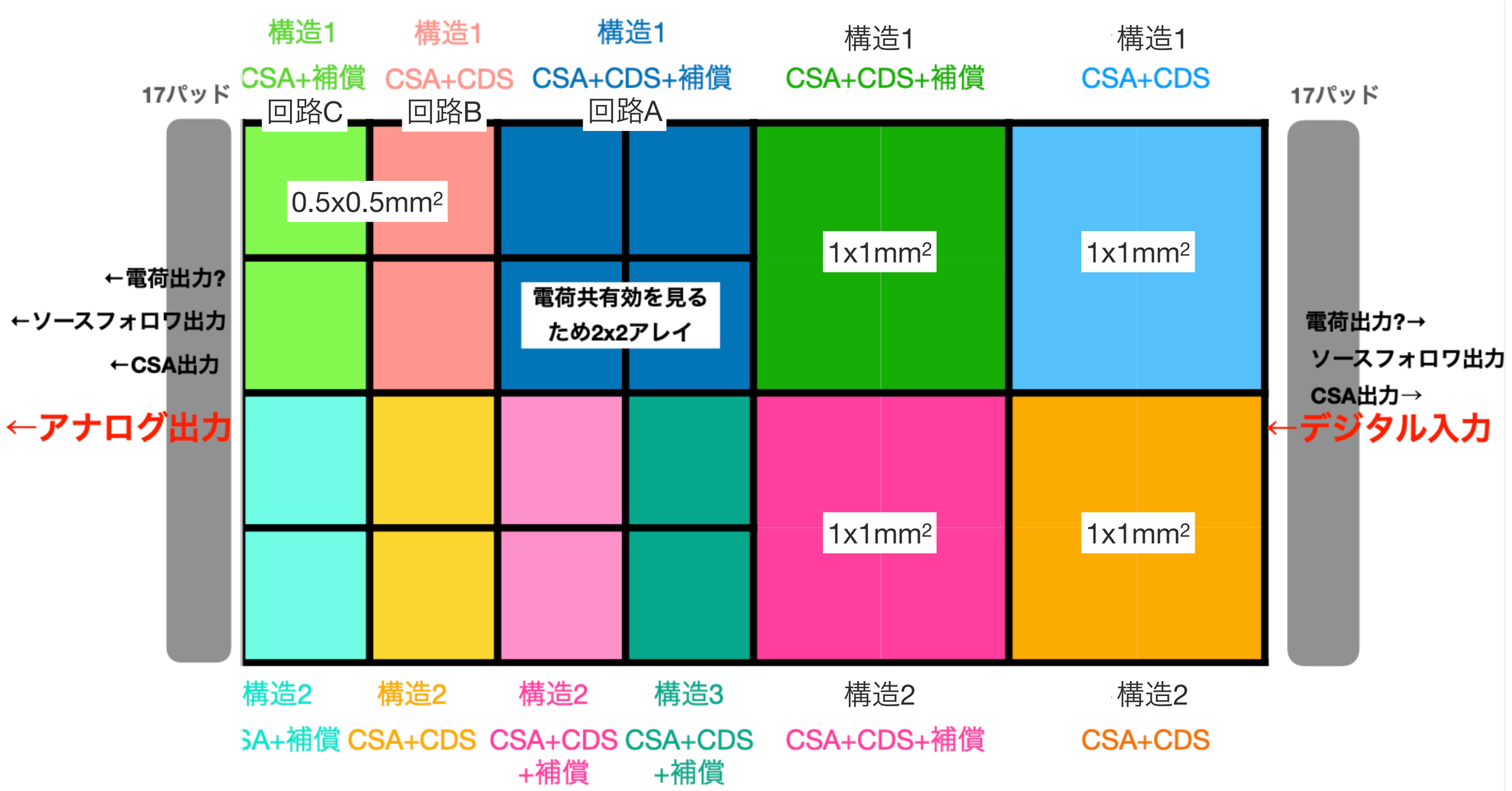


- OROCHI1: 2.9 x 6mm^2 chip
- XRPIXのPDD構造を拡張した構造2つと
  全面センスノード構造の３種で電荷収集効率を評価する
  - TCAD sim. by 吉田大雅さん（宮大）
- ラピス25年度MPWランにsubmit. 来月納品



＊D&S社 倉知様ご提案の構造

OROCHI1 構成


構造1
CSA+補償
回路C
構造1
CSA+CDS
回路B
構造1
CSA+CDS+補償
回路A
構造1
CSA+CDS+補償
構造1
CSA+CDS
17パッド
17パッド
0.5x0.5mm2
1x1mm2
1x1mm2
電荷共有効を見る
ため2x2アレイ
←電荷出力?
←ソースフォロワ出力
←CSA出力
←アナログ出力
電荷出力?→
ソースフォロワ出力
CSA出力→
←デジタル入力
1x1mm2
1x1mm2
構造2
構造2
構造2
構造3
構造2
構造2
CSA+補償
CSA+CDS
CSA+CDS
+補償
CSA+CDS
+補償
CSA+CDS+補償
CSA+CDS