# Development of Kyoto's X-ray Astronomical SOI pixel sensor

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for experiment of XRPIX1b-CZ-FI/BI

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## Publication

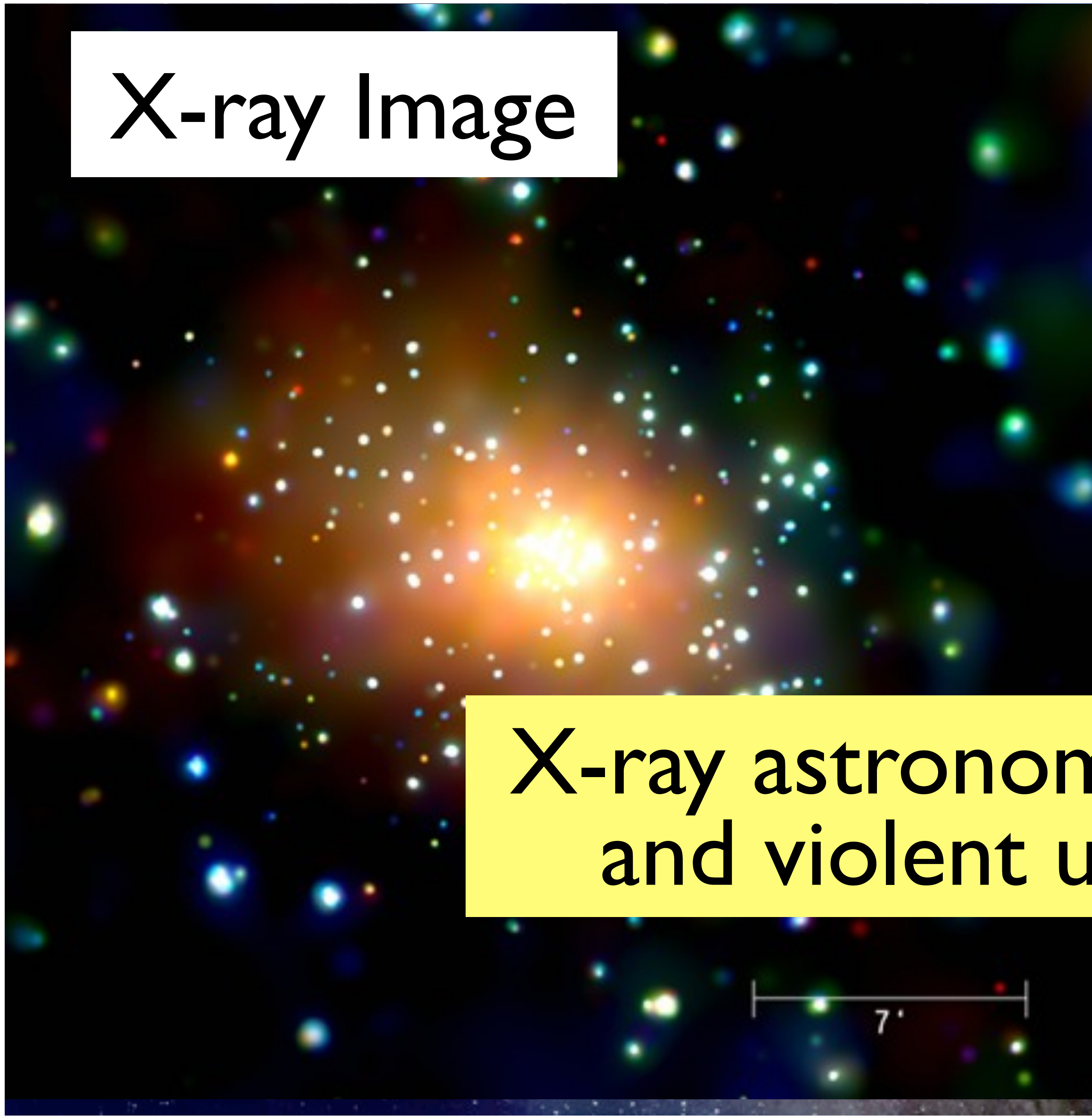
| | | |
|---|---|---|
| Ryu et al. | IEEE NSS 2010, Conf. Record | XRPIX1-CZ -FI |
| Ryu et al. | IEEE TNS 58, 2528 (2011) | XRPIX1-CZ-FI |
| Tsuru et al. | IEEE NSS 2011 | Review |
| Ryu et al. | IEEE NSS 2011, Conf. Record | Event-Driven Readout system |
| Nakashima et al. | IEEE NSS 2011, Conf. Record | XRPIX-ADC1 |
| Nakashima et al. | Physics Procedia 37, 1373 (2012) | XRPIX1-FZ-FI |
| Ryu et al. | IEEE TNS 60, 465 (2013) | XRPIX1b-CZ-FI, Inter-pixel cross-talk |
| Takeda et al. | IEEE TNS 60, 586 (2013) | Event-Driven Readout with XRPIX1b-CZ-FI |
| Tsuru et al. | SPIE Astro2012 | Review |
| Nakashima et al. | NIM A, Accepted (2013) | XRPIX2 |

# Talk Plan

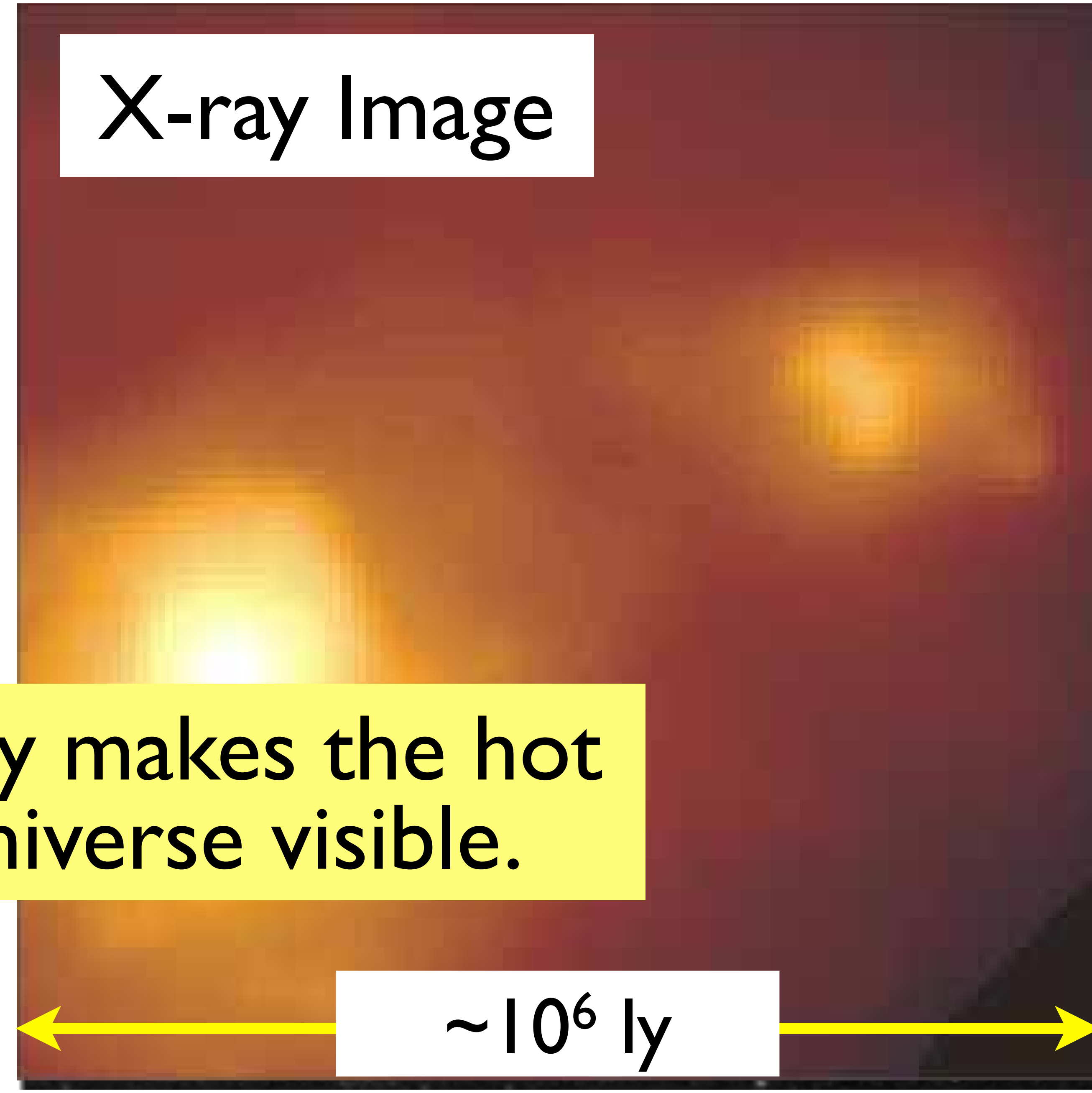
- X-ray Astronomy
- "XRPIX"
  Kyoto's X-ray Astronomical SOI pixel sensor
- Depletion Layer and Dark current
    - FZ of 2010 and 2012
- Spectral Performance
- Back Illumination
- Coming Soon

# Why X-ray Astronomy ?

## The Andromeda Galaxy




## Cluster of Galaxies



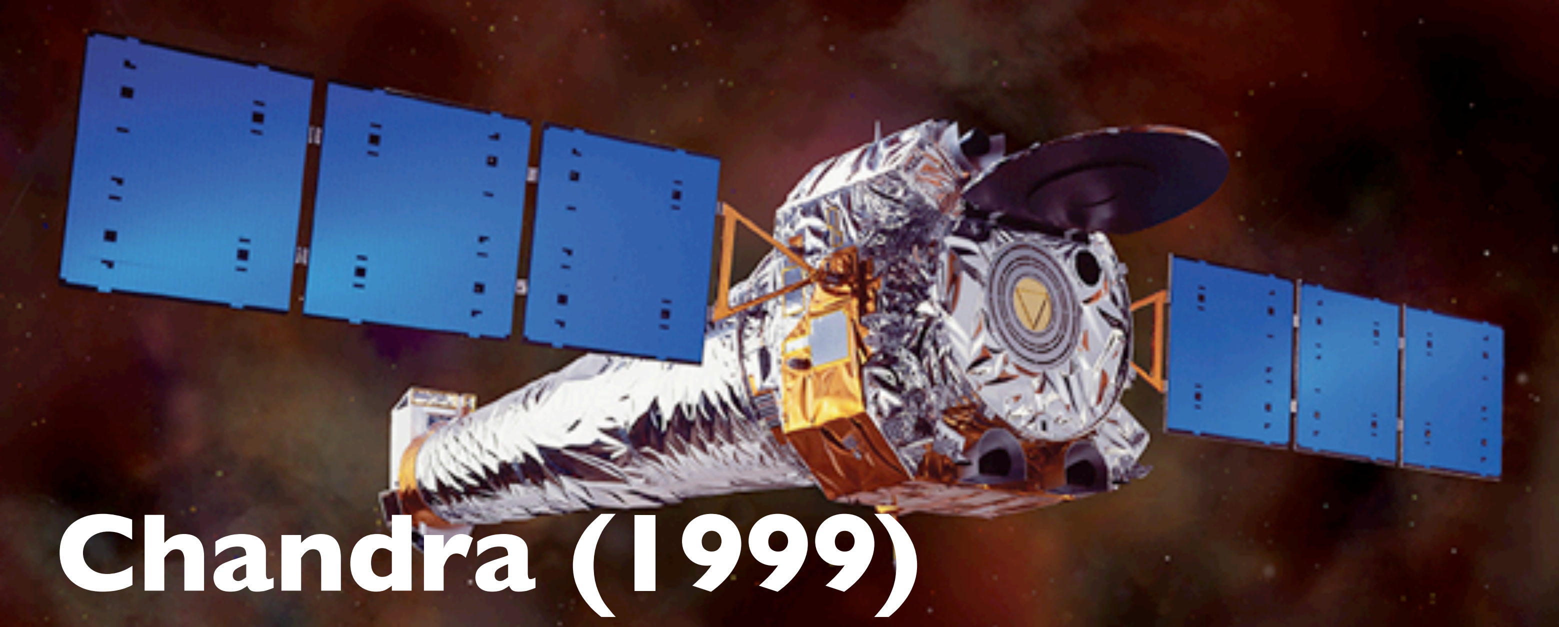

**X-ray astronomy makes the hot and violent universe visible.**

- Stars likes the sun in the optical.
- Blackholes and neutron stars in X-ray.

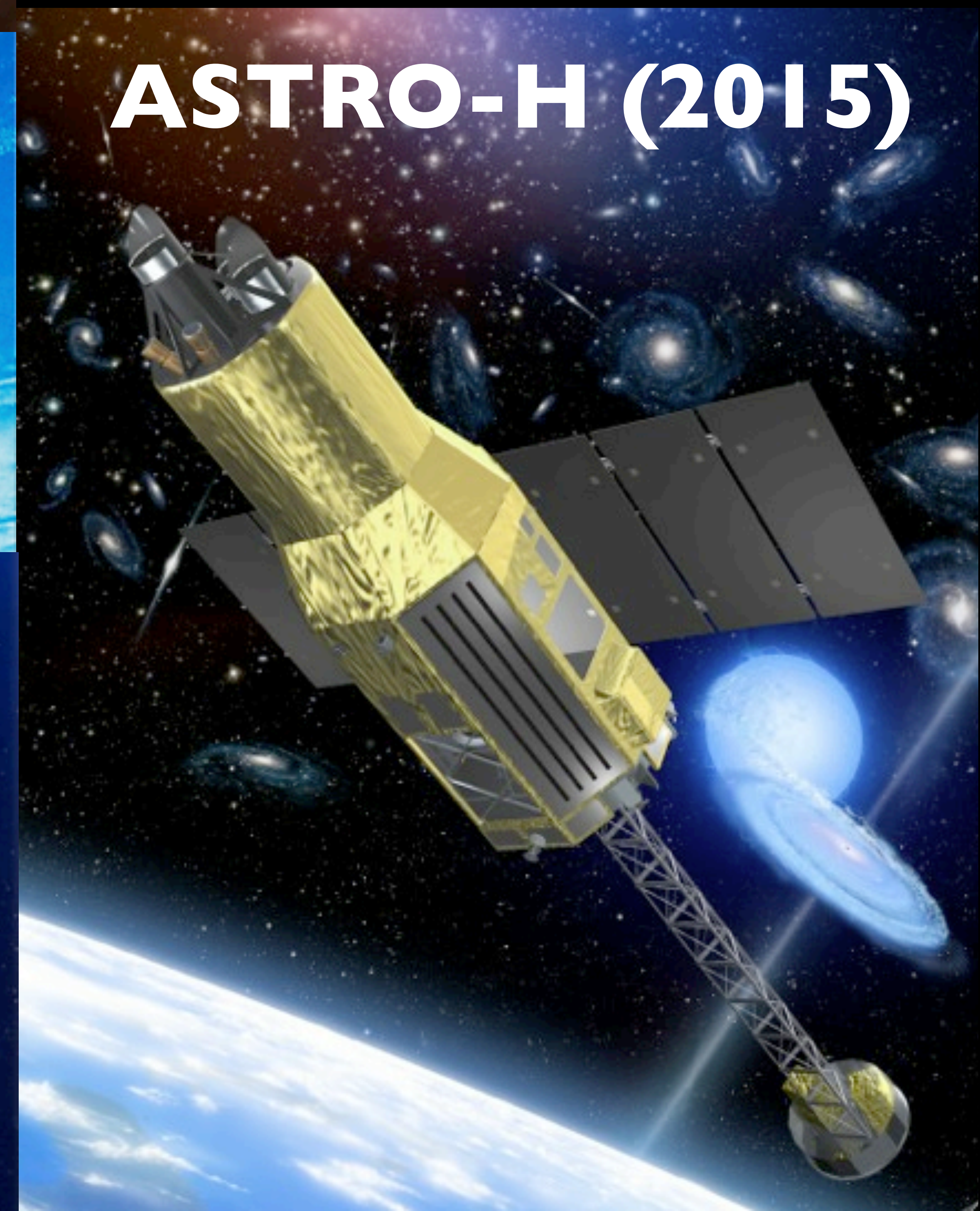
- Hot plasma = several x sum of galaxies.
- Most of normal (baryonic) matter in the universe is visible ONLY in X-ray.

# X-ray CCD

"The" standard Imaging Spectrometer

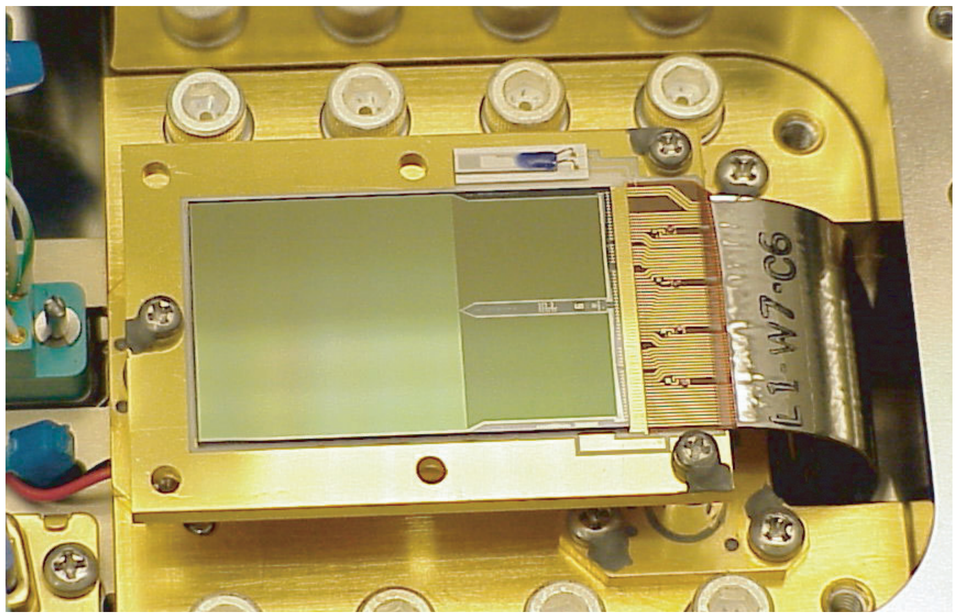




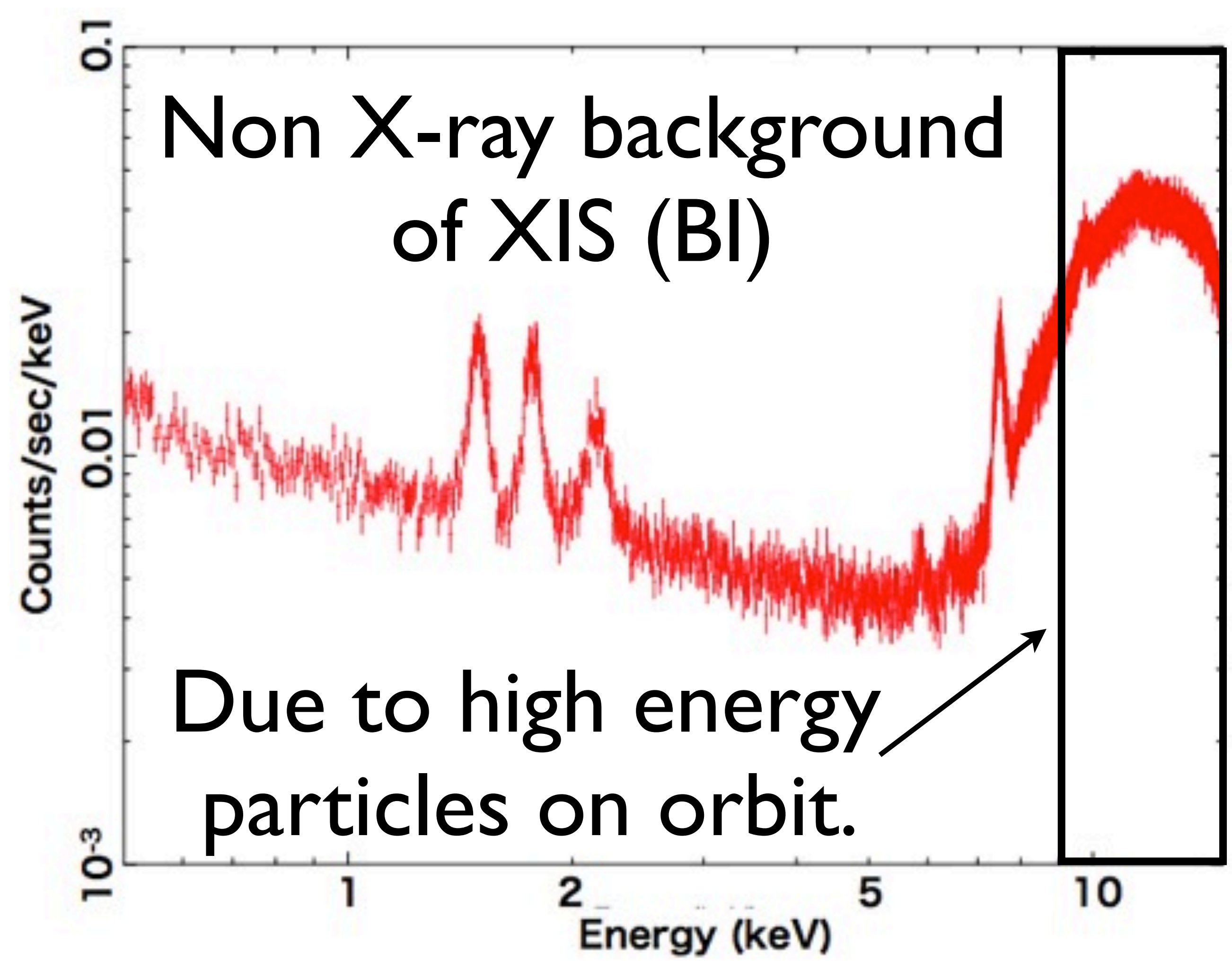



# The standard Imaging Spectrometer of modern X-ray astronomical satellites → X-ray CCD

## Suzaku「すざく」 XIS

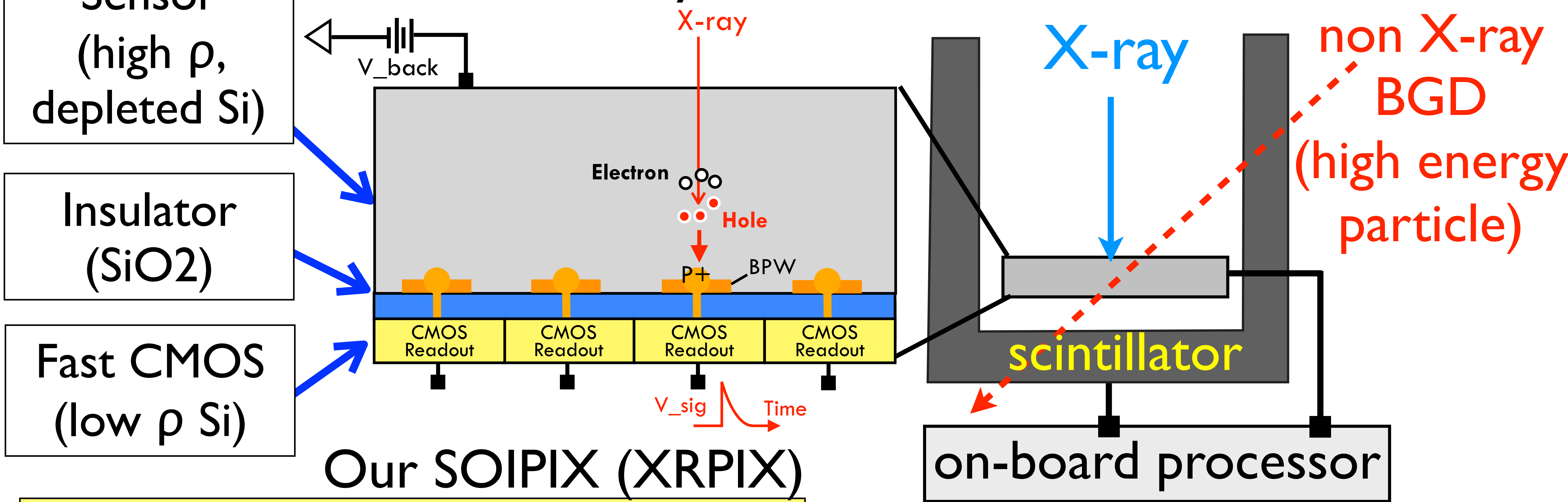


- Fano limited spectroscopy with the readout noise ~3e- (rms).
- Wide and fine imaging with the sensor size of ~20-30mm pixel size of ~30μm□




- Non X-ray background above 10keV is too high to study faint sources.
- The time resolution is too poor (~sec) to make fast timing obervation of time variable sources.

# “XRPIX” = **Monolithic** SOI pixel sensor for future X-ray astronomical satellites



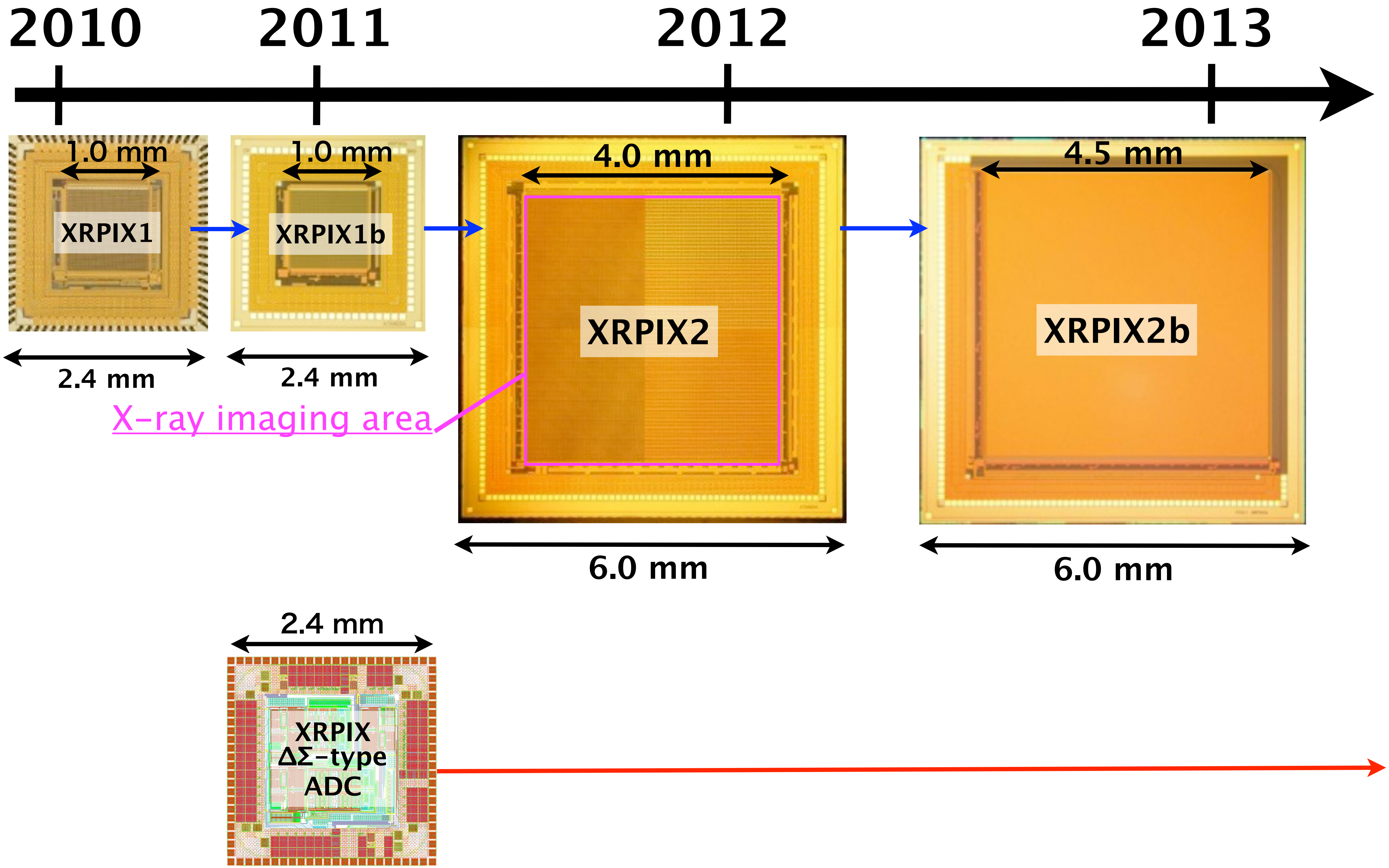

Our SOIPIX (XRPIX)

<u>Each pixel</u> has its own trigger and analogue readout CMOS circuit.

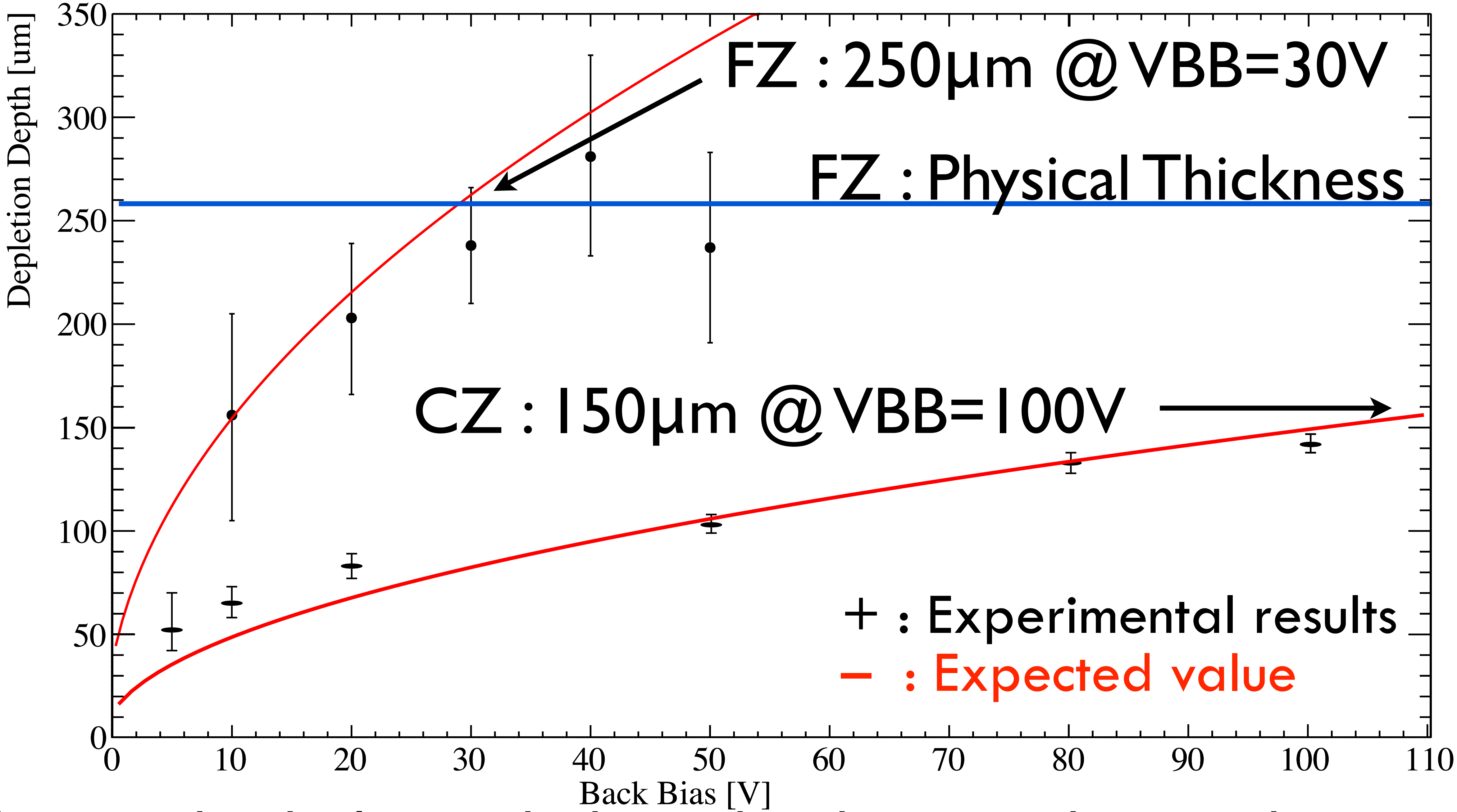
Very low BGD by anti-coincidence (1/100 of CCD at 20keV)

| | | |
|---|---|---|
| Target Spec. | Imaging | area > 25x25mm2, pixel ~ 30-60μm□ (1” @ F=9m) |
| | Energy Band | 0.3-40keV with BI (<0.1μm), and thick depletion (>250μm) |
| | Spectroscopy | ΔE < 140eV @ 6keV, Fano limit (Req.<10e-, Goal < 3e-) |
| | Timing | <1μsec |
| | Dark Current | <2pA/cm2 (assuming working T = -40℃) |
| | Function | Trigger signal & pixel address output, built-in ADC |
| | Non X-ray BGD | 5e-5 c/s/keV/10x10mm2 at 20keV (1/100 of CCD) |

# XRPIX Series – Road Map –



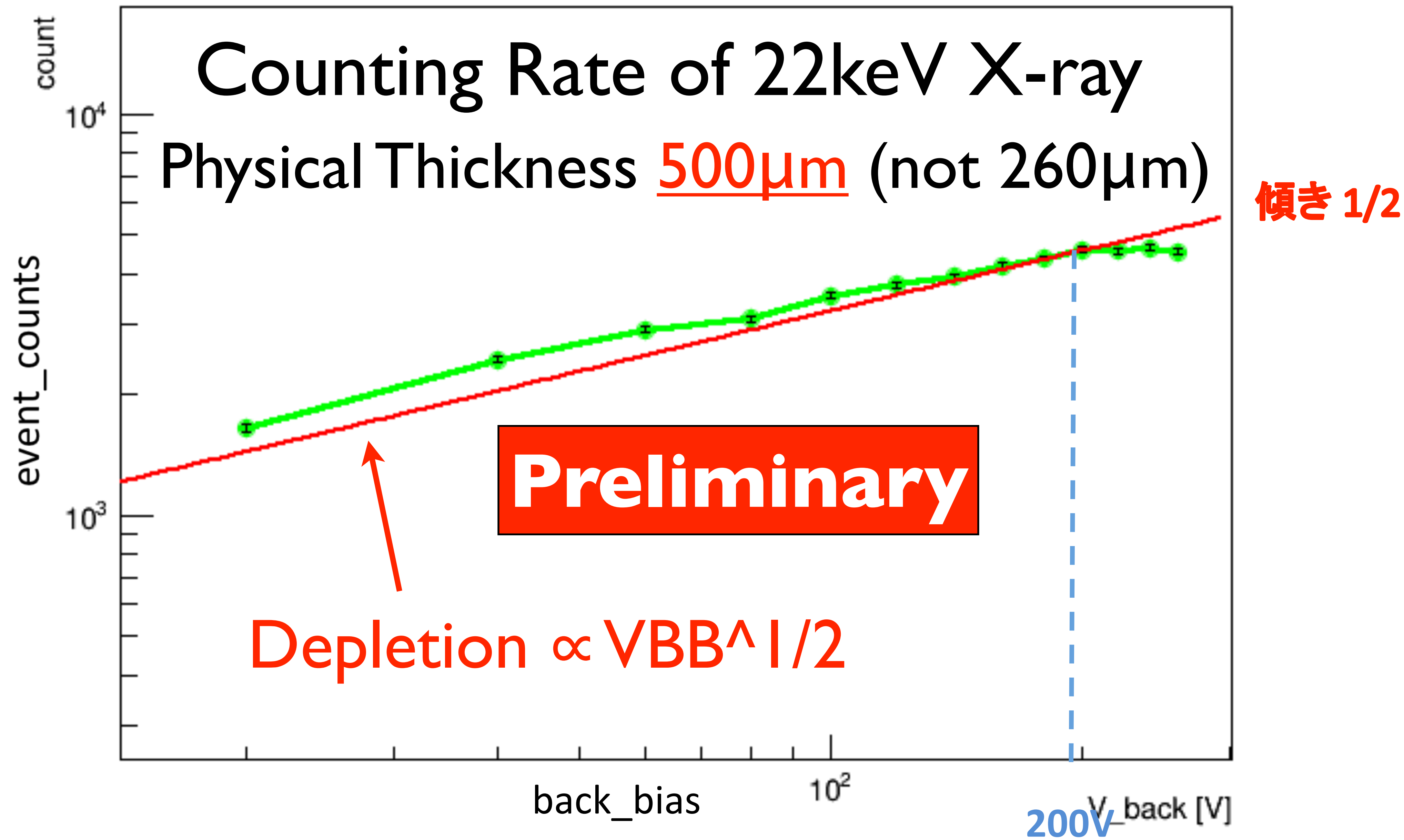
# XRPIX1-CZ (0.7kΩcm), -FZ(2010) (7kΩcm): Depletion Depth




- Measure the depletion thickness by observing the ratio between the counting rates of two energies X-rays having different attenuation lengths.
- CZ: Depletion thickness of 150μm at VBB=100V.
- FZ: Full depletion of 250μm is achieved at VBB=30V.

*Nakashima et al., 2012, Physics Procedia 37, 1373*

# XRPIX1b-FZ(2012)-FI (7kΩcm) : Depletion Depth



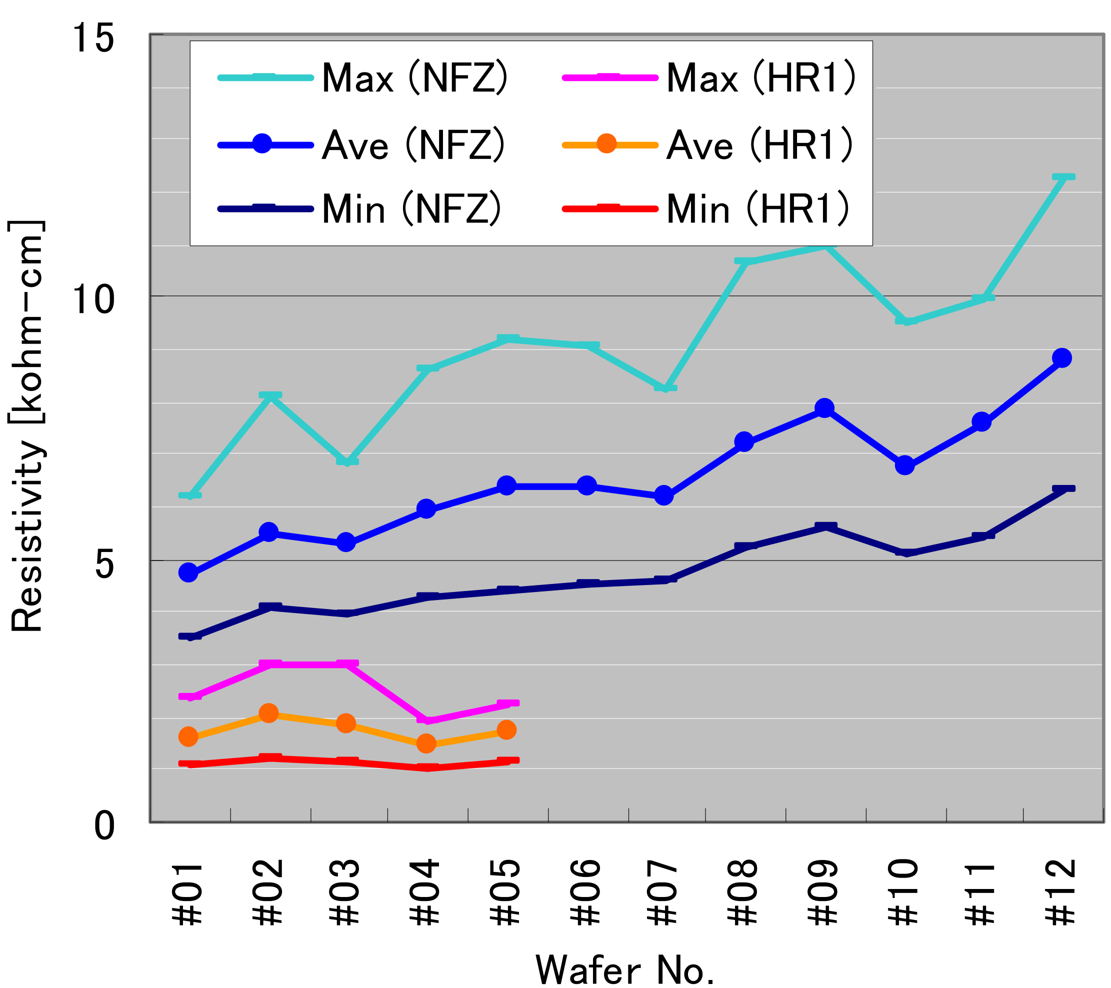

- Counting Rate of 22keV X-ray (Cd-109) as a function of VBB. (Attenuation Length = 1200μm > Physical Thickness = 500μm.)
- The data follow the expected slope of depletion ∝ VBB^1/2.
- Full Depletion is reached at VBB=200V.

*20130502_matsumura.pdf*

# XRPIX1b-FZ(2012)-FI (7kΩcm) : Depletion Depth

- 500μm @ VBB=200V
  → ρ=4kΩcm < average (7kΩcm)
- ρ is different from position to position on a wafer.
- Check which wafer used in this device.

**b) 比抵抗のウェハバラツキ**




**b) MX1542-002JA (N型FZ)**

#01

| | | | | |
|---|---|---|---|---|
| | 4.8 | 4.6 | | |
| 4.8 | 3.5 | 3.8 | 4.1 | |
| 4.6 | 4.1 | 3.7 | 3.6 | 5.3 |
| 4.2 | 5.1 | 4.2 | 3.9 | 5.8 |
| 4.6 | 4.7 | 4.2 | 4.3 | 6.2 |
| 5.6 | 5.2 | 5.0 | 5.6 | |
| | 5.7 | 6.0 | | |

#12

| | | | | |
|---|---|---|---|---|
| | 8.5 | 8.8 | | |
| 8.2 | 6.9 | 6.8 | 8.2 | |
| 7.8 | 6.3 | 6.9 | 9.2 | 11.1 |
| 8.0 | 7.3 | 7.1 | 8.2 | 10.9 |
| 8.8 | 7.8 | 7.8 | 8.7 | 12.2 |
| 10.5 | 9.9 | 9.7 | 10.8 | |
| | 11.2 | 10.5 | | |

*121001_MX1542_Lapis.pdf*

# XRPIX1/1b-FZ(2010/12)-FI (7kΩcm) : Dark (Leak) Current



- XRPIX1-FZ(2010)
  - Wafer Thickness 260μm

Consists of two components.

(1) Depend on T and VBB.

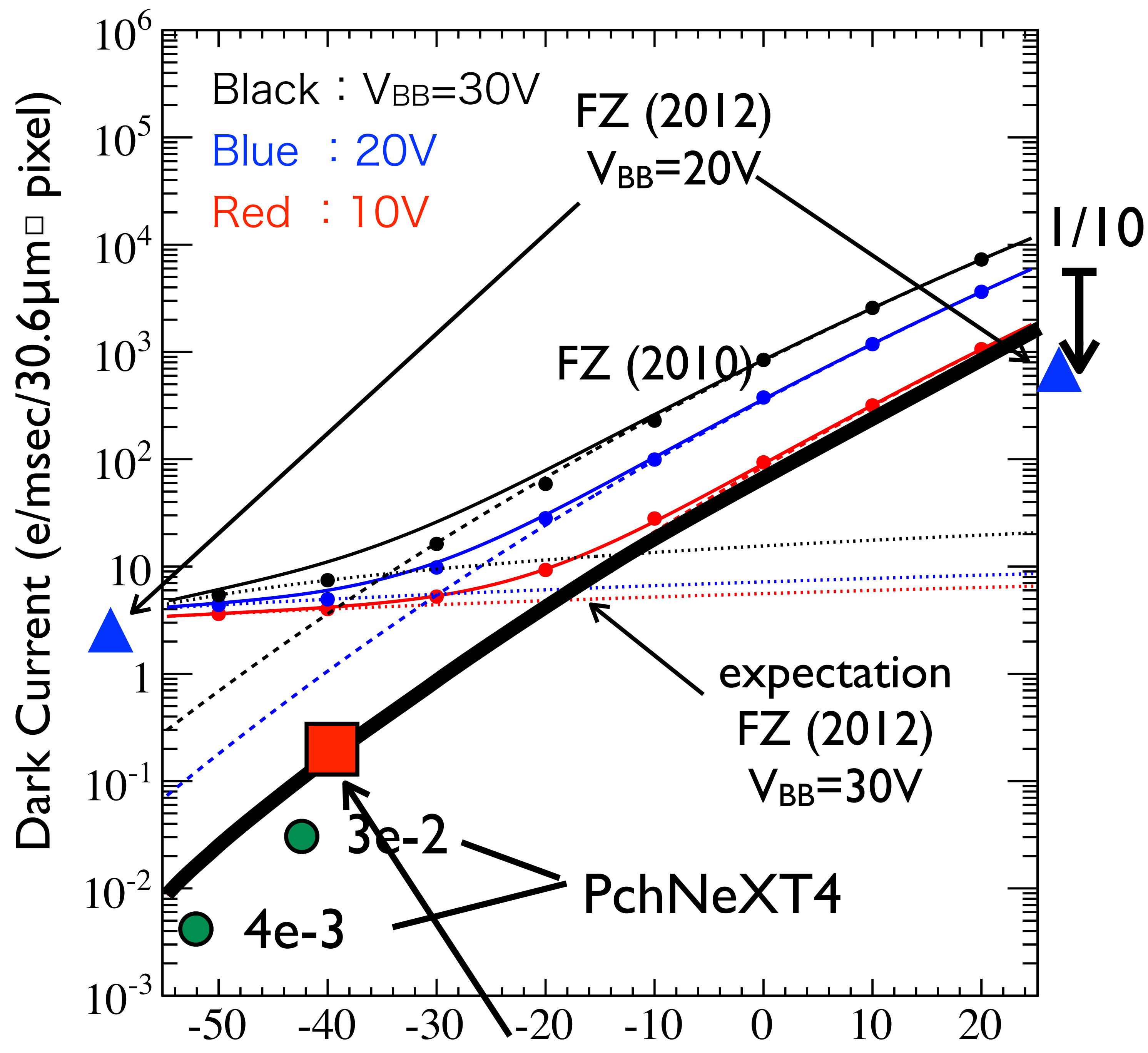
generation in depletion layer.

(2) Almost Constant.

10e/msec = 1.6fA

⇒ Next Slide

- XRPIX1b-FZ(2012)
  - Dark is 1/10 of FZ(2010) (at the same VBB)




Eliminating the constant component

⇒ reach the target specification.

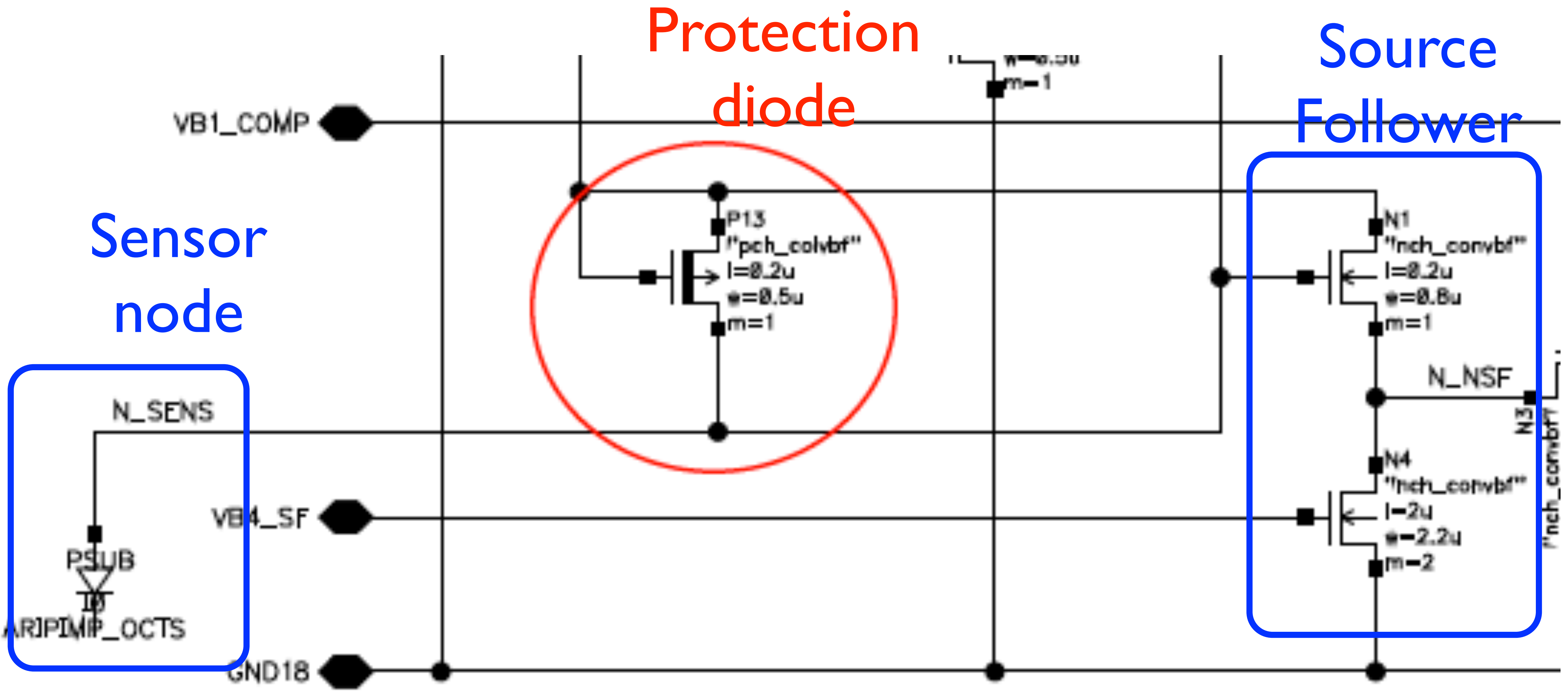
Target Spec. at -40C (depletion 250μm)

= 0.1e/1msec/30.6μm□ =2pA/cm2

From 20110516_OKImeeting_SOI_Dark_v5

# Leak Current from Protection Diode (Arai-sensei)

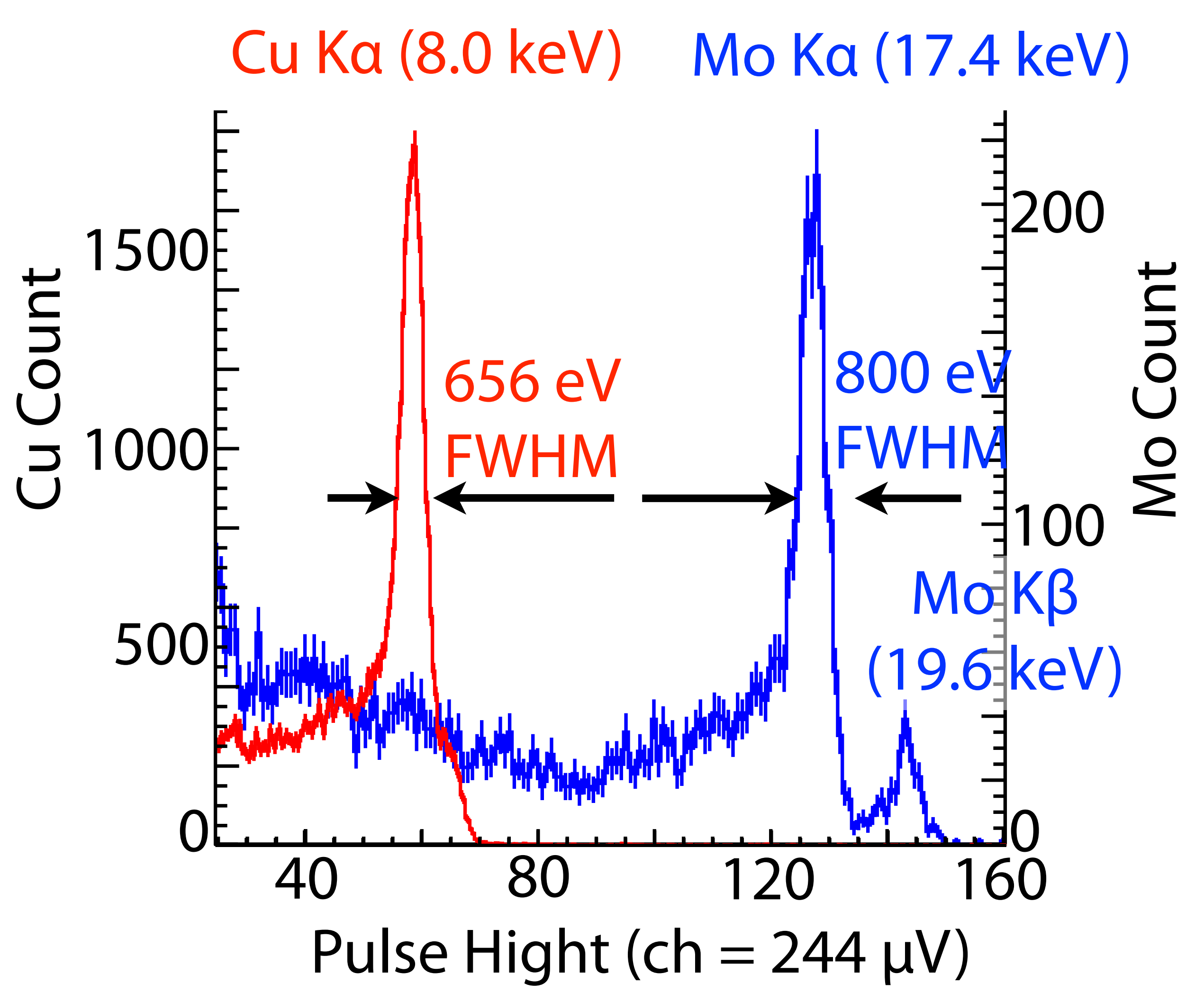


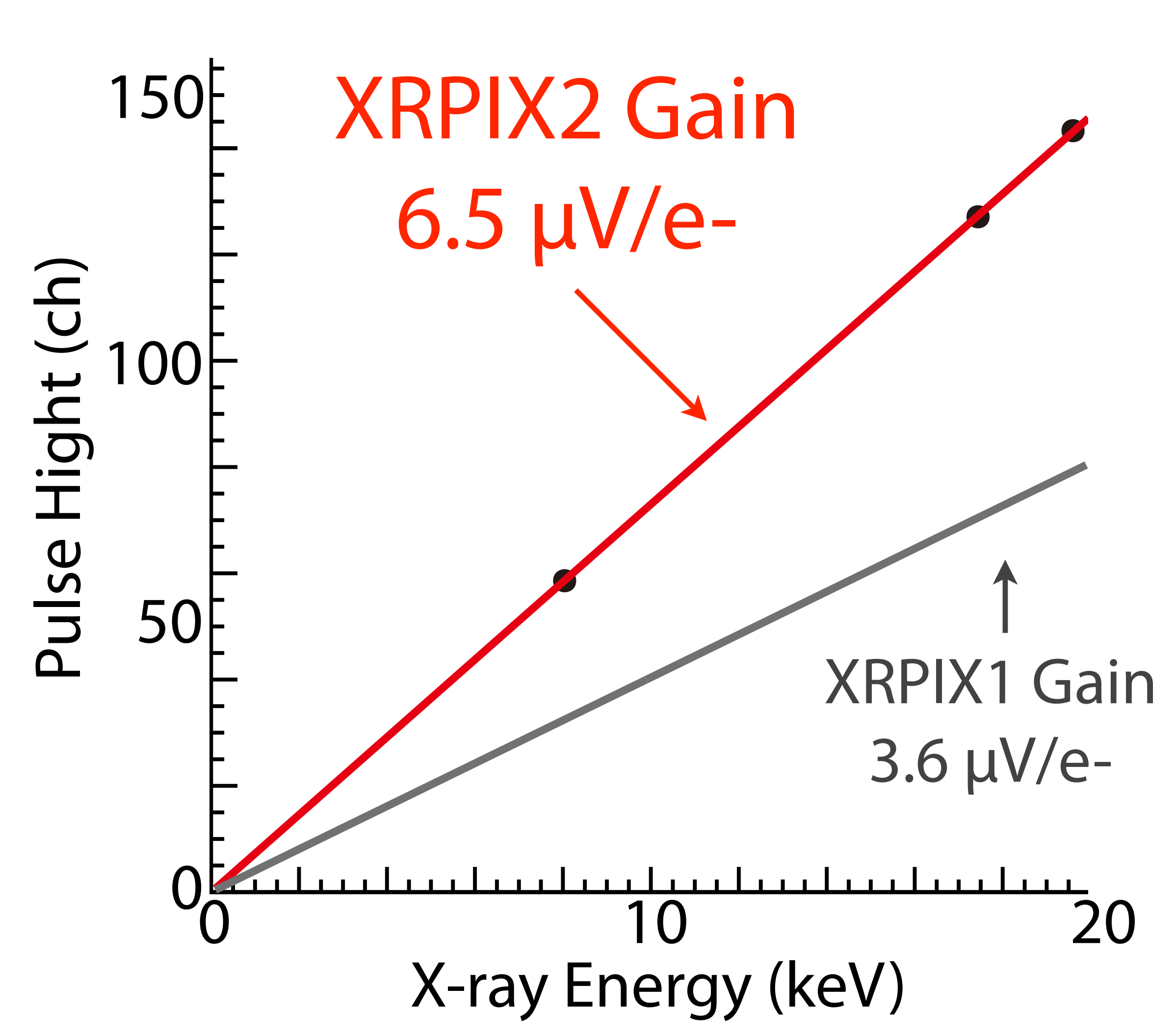



- Simulation shows leak current from PMOS used as a protection diode at the sensor node is 2fA = 12.5e/msec.
- Possibly explains the constant component.
- Gate length of the PMOS = 0.2μm → 1μm.
  ⇒ Reduce leak current 2fA → 0.02fA.

# XRPIX2-CZ-FI (Small Pixel) : Spectrum



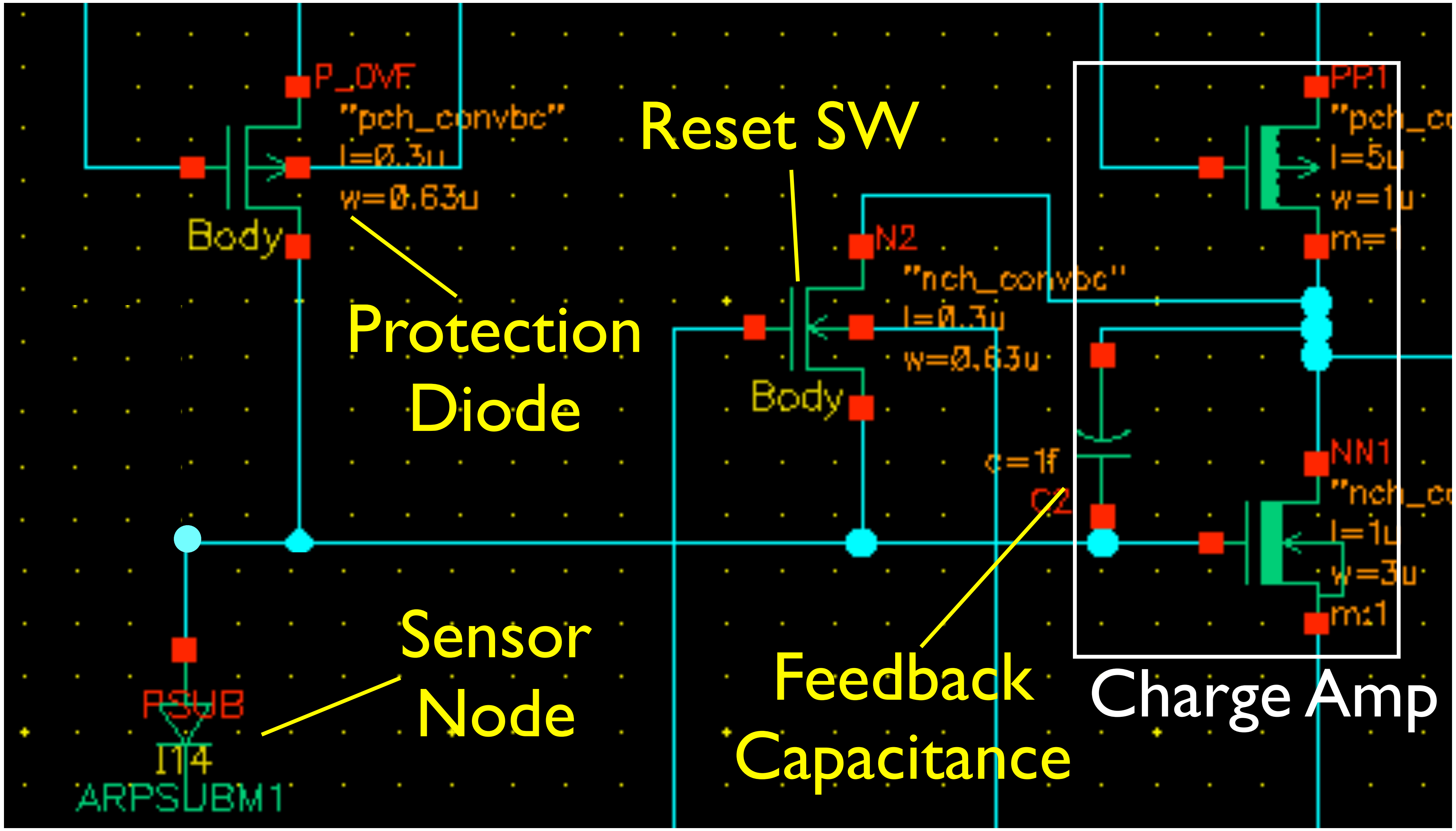



| | Observed | Readout Noise | Fano Noise | Pixel-Pixel Gain Dispersion 1% | Sum |
|---|---|---|---|---|---|
| Cu Kα | 656 eV | 548 eV (FWHM) 64 e-(rms) | 139 eV | 255 eV | 620 eV |
| Mo Kα | 800 eV | | 205 eV | 553 eV | 805 eV |

*Nakashima et al., 2012, NIM A submitted*

# Coming Soon 1 / Pre Amp in Each Pixel



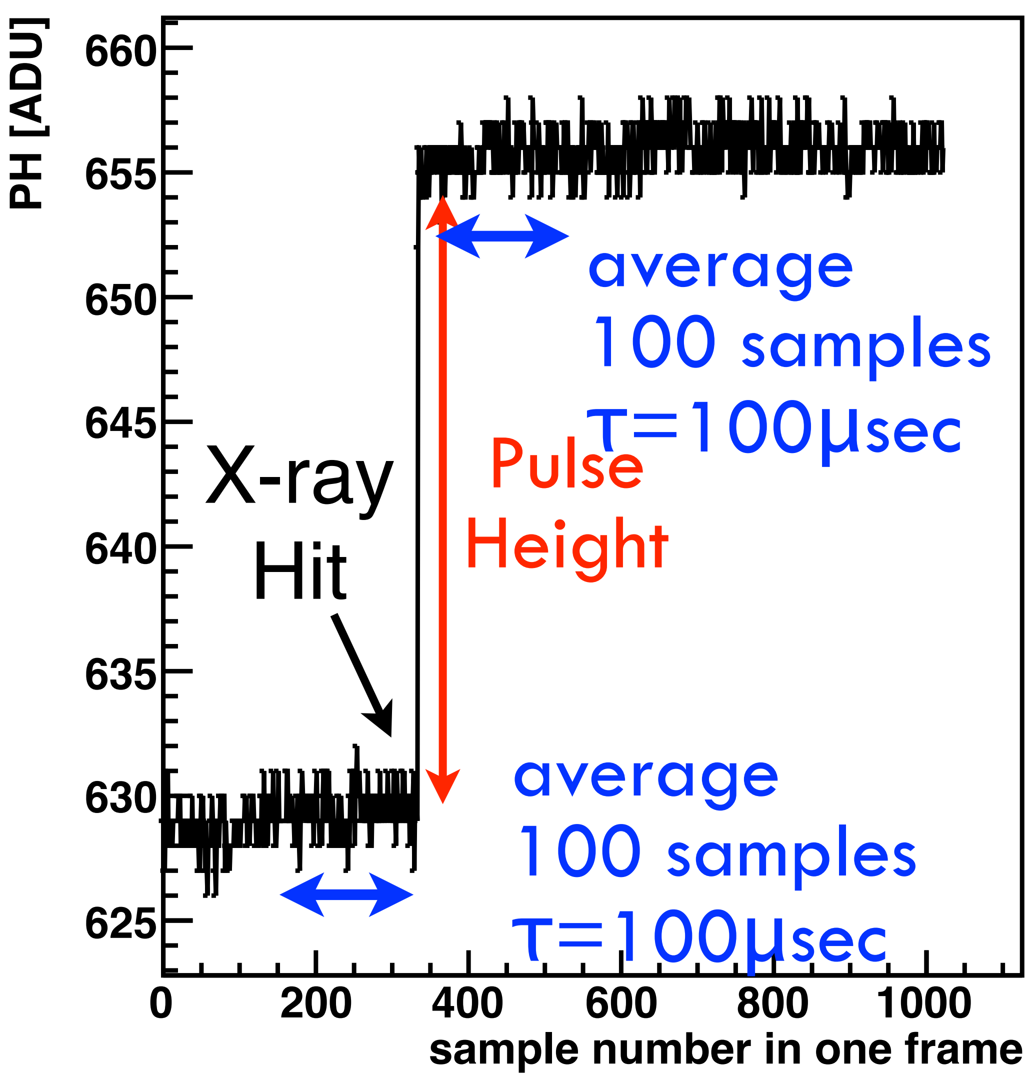

## XRPIX3

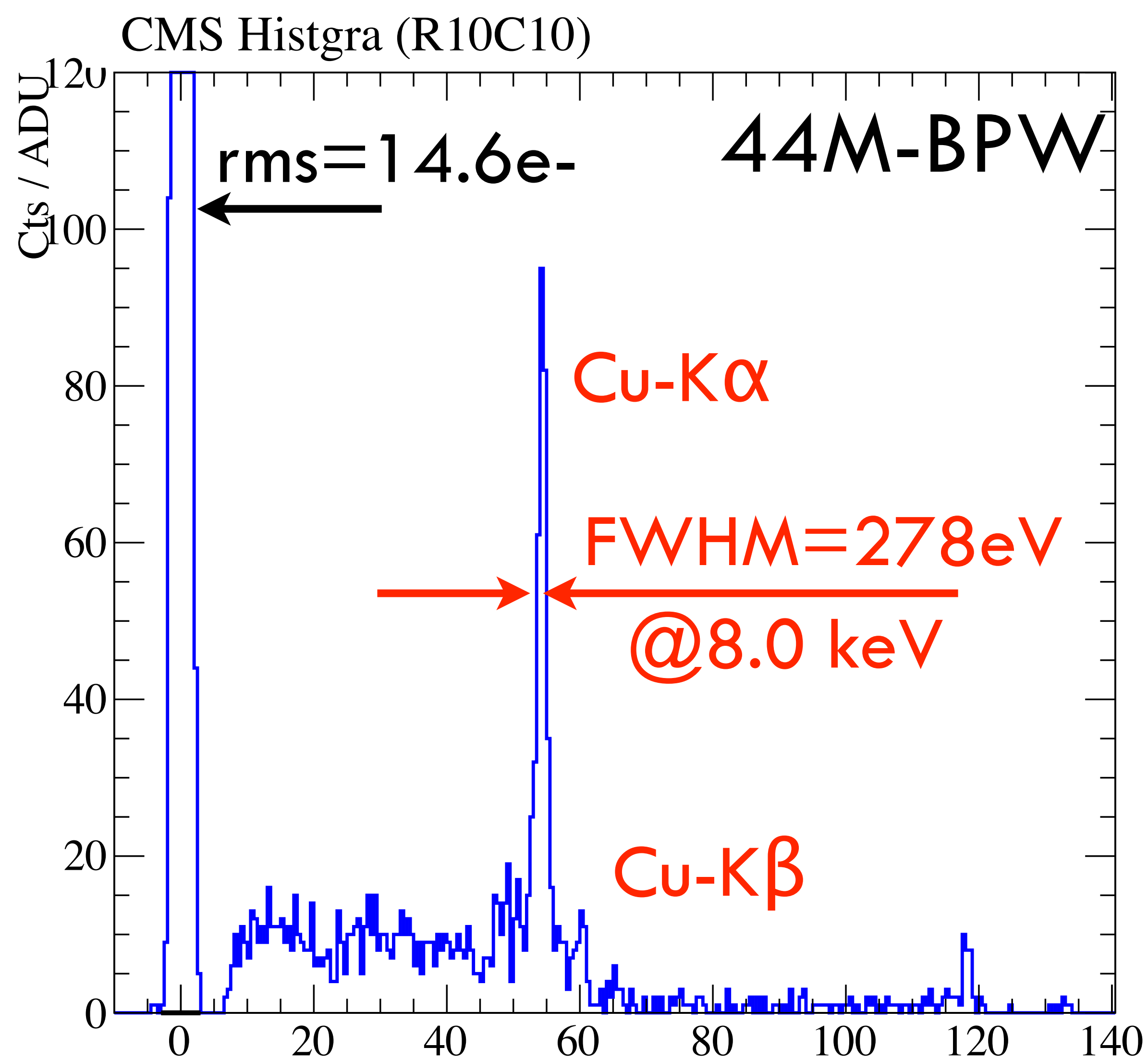
- A charge sensitive amp in every pixel in order to increase the gain.
- This is basically the same amp used in PIXOR.
- Gain ~100 μV/e, higher by a factor of ~15.
- Readout noise = 64e (rms) → ~4e (rms).

# XRPIX1b-CZ : Single Pixel Readout



- In order to study the soft X-ray performance.
- Observe the waveform of analogue output from a single pixel by fixing the readout address without clocking (Single Pixel Readout like a SSD).
- Detect an X-ray as a "step" and measure the pulse height. → X-ray spectrum.
- No reset during the measurement → Free from the reset noise
- Reduce noises other than the reset noise by introducing LPF.
  high_v(100 samples average) - low_v(100 samples average) → LPF with τ=100μs



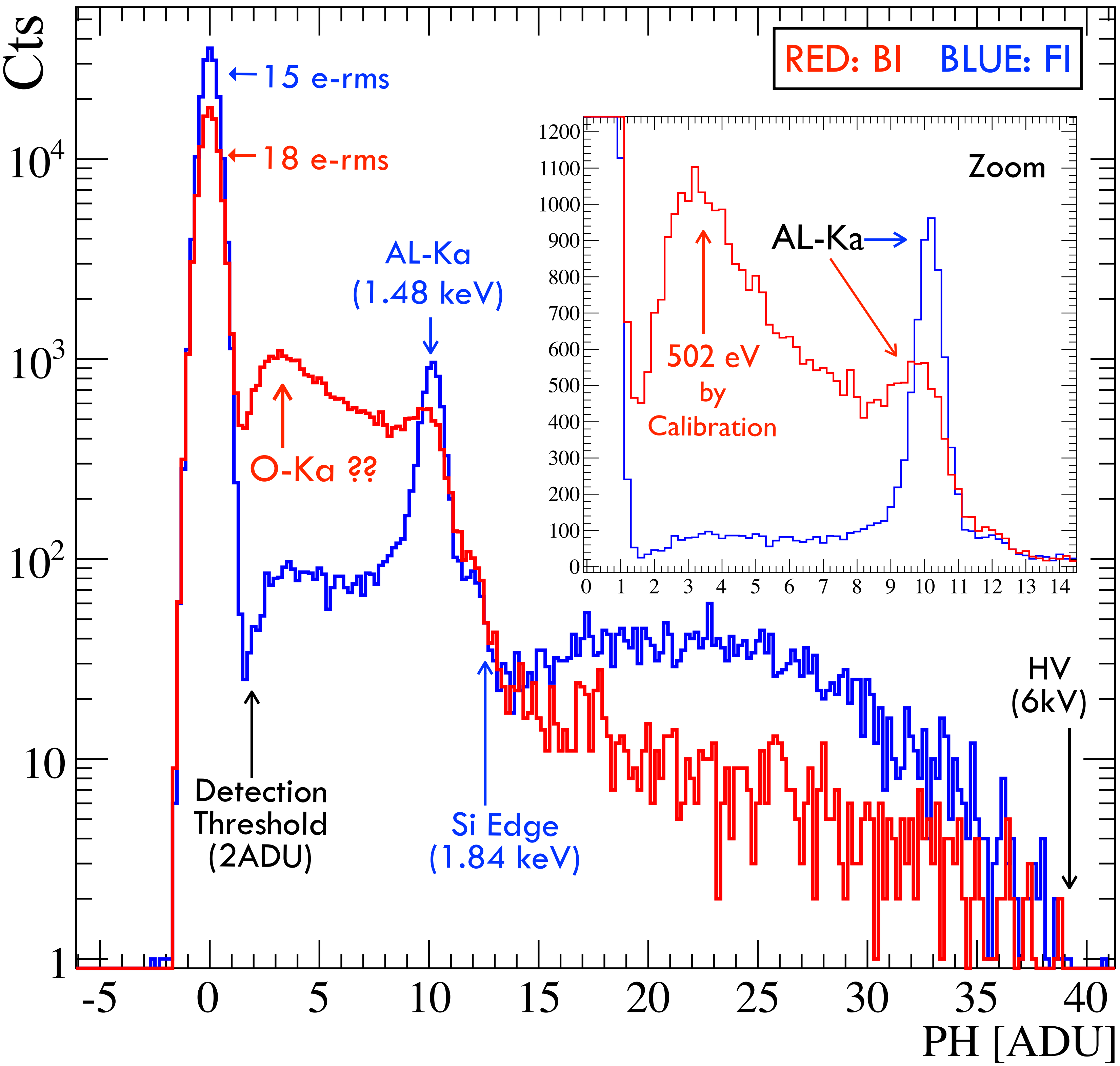




*Nakashima et al., 2012, Physics Procedia 37, 1373*
*Ryu et all, 2013, IEEE TNS 60, 465*

**ΔE = 278eV @ 8.0keV (FWHM), readout noise = 14.6e (rms)**

# XRPIX1b-CZ-FI/BI (100μm): Spectra in Single Pixel Readout (2011.11.22)

Target= $Al_2O_3$ , Front-I, Back-I, V_tube=6 kV,
V_bais = 100V, Temp=–50°C, Hit Threshold= 2 ADU, Exposure=400 sec, PIX=R10C10, 2us_sample, 300 μs_ave



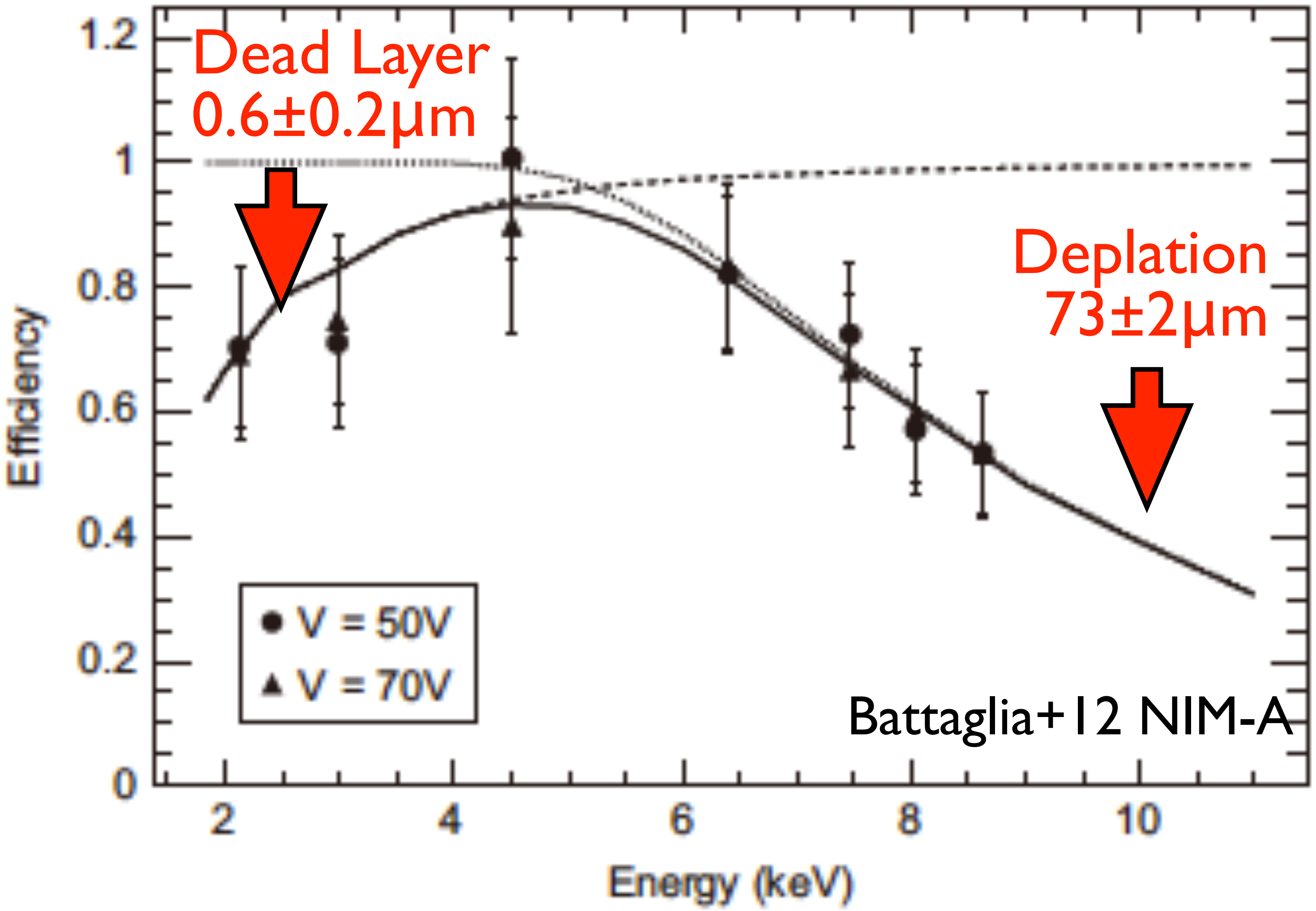

- Back illumination type.
- X-ray generator (target = Al, 6kV).
- Al-K + Bremss (+O-K from Al2O3?)
- ΔE (FI) = 188eV, ΔE (BI) = 351eV (if line)
- Absolute and relative X-ray Fluxes are uncalibrated. → QE and dead layer thickness are unknown.

*Results on FI : Ryu et al., IEEE TNS 60, 465 (2013)*

# Coming Soon 2 / "Pizza Process"

- Pizza Proc. is the back side process developed by LBNL.
- CZ-BI with Back-thinned to 70μm.
- A thin phosphor layer is implanted.
- Dead Layer : 0.6±0.2μm

QE of LBNL's BI-SOIPIX / SOImager-2-CZ-BI




## Pizza Process to FZ devices of XRPIX

- The Pizza proc. is now being made at LBNL.
- Evaluation of low energy X-ray spectral performance.

# Summary

- We have been developing monolithic SOI sensor 'XRPIX' for future X-ray Astronomical Satellites.
- It contains the function of trigger signal output for the anti-coincidence, which realizes very low non-X-ray BGD.
- We successfully developed the test devices with the depletion thickness of ~250μm.
- Under going
  - Improvement of the readout noise.
  - Reduction of dark current.
  - Test with new back side process (Pizza Proc.).