New clocking mode for X-ray CCD detector

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X-ray CCD detector

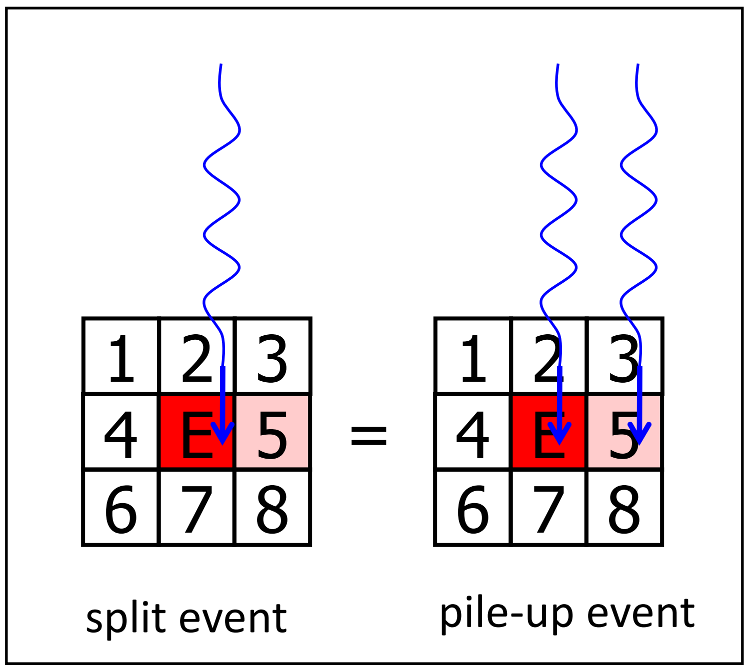
- Pros
  - small pixel size
  - large number of pixels with a few readout nodes
- Cons
  - <u>long exposure time</u> (to read many pixels in sequence)
  - (requires clocking signal)

CCDs exhibit good imaging quality and moderate time resolution

pile-up problem

- two (or more) photons enter to the same pixel or neighbor

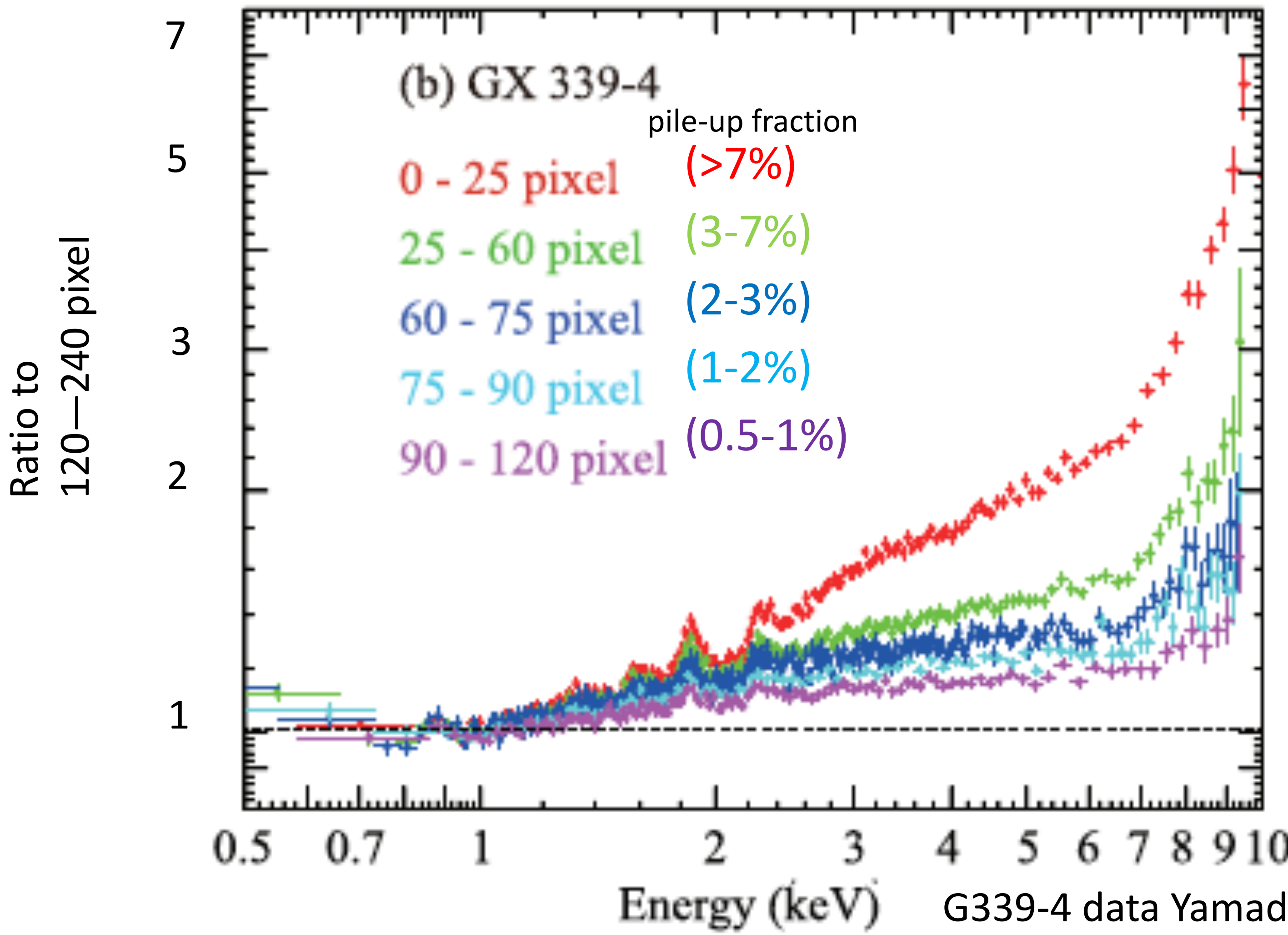
We cannot know incident X-ray energy of each photon



Pile-up effect（Suzaku/XIS0）

～550 mCrab in 0.3s burst 1/4window Suzaku/XIS0

(～3 mCrab for XRISM/Xtend 4s full window)



*) GX339-4 in this observation had softer spectrum than typical AGNs. The effect is thus enhacned.

G339-4 data Yamada et al. PASJ 64, p53, 2012

mitigation method

- Window mode: readout a certain region of CCD
  → reduced field of view
- Burst mode: use a part of exposure time
  → loose large fraction of X-ray events
- P-sum mode: continuous transfer
  → loose coordinate information of one direction

  Loose significant information

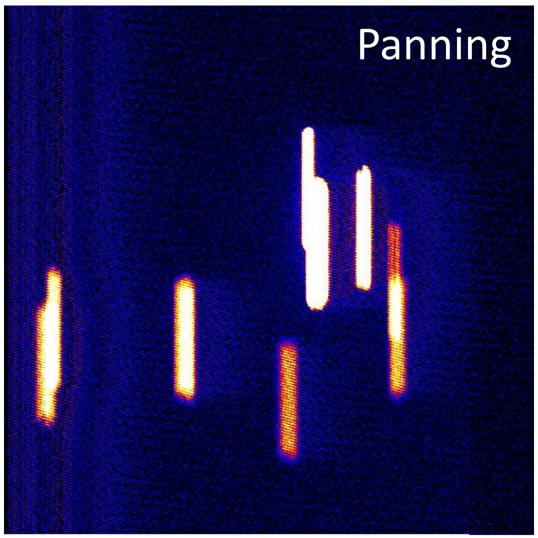
- New mode: intermediate of normal and P-sum (or full-frame) mode:

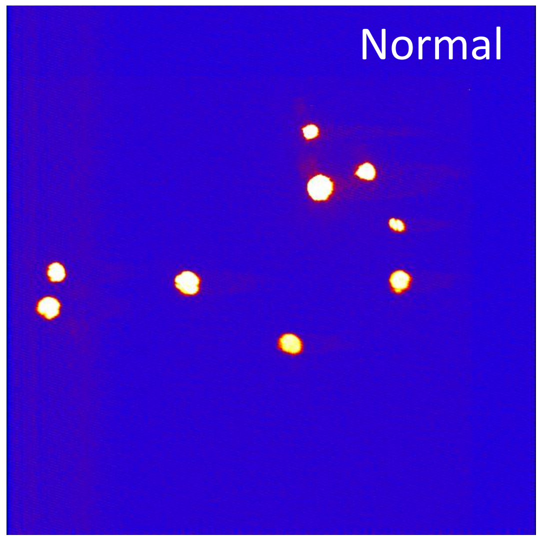
→ Reduce pile-up fraction without losing statistics nor information of position

New clocking mode: Panning mode

- A certain number of the vertical transfer is performed in the imaging area during each exposure. (We don't move satellite attitude or CCD camera)
- Readout in the storage area is the same as that in the normal mode.
- The number of the transfer (during exposure time) is a setting parameter (N_{pan})
- Shape of each event is unchanged. Accumulated image is elongated to vertical direction. → Reduce event rate of each pixel

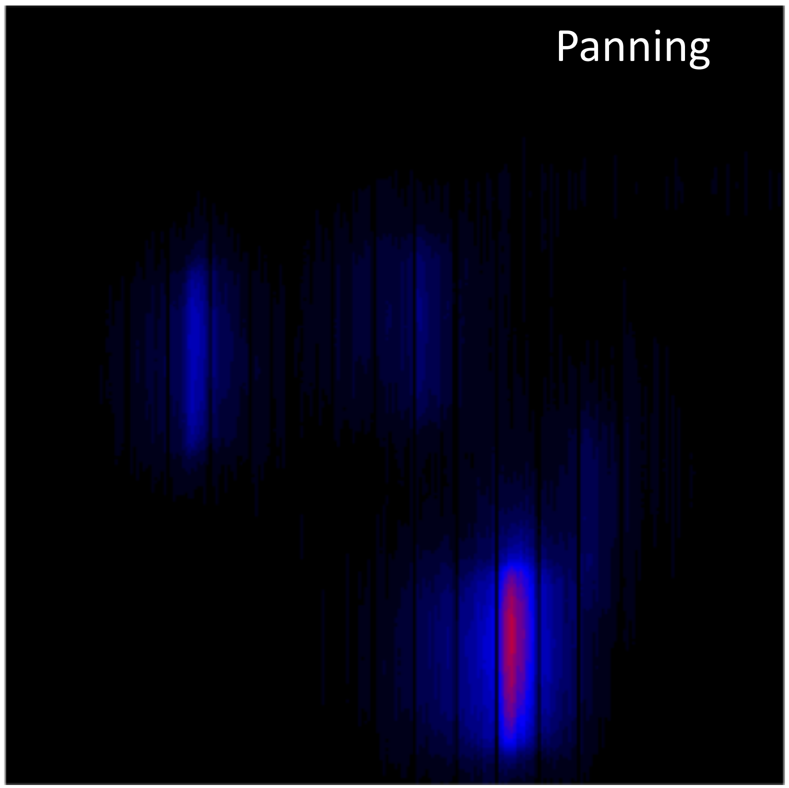
LED irradiation experiment performed with a CCD

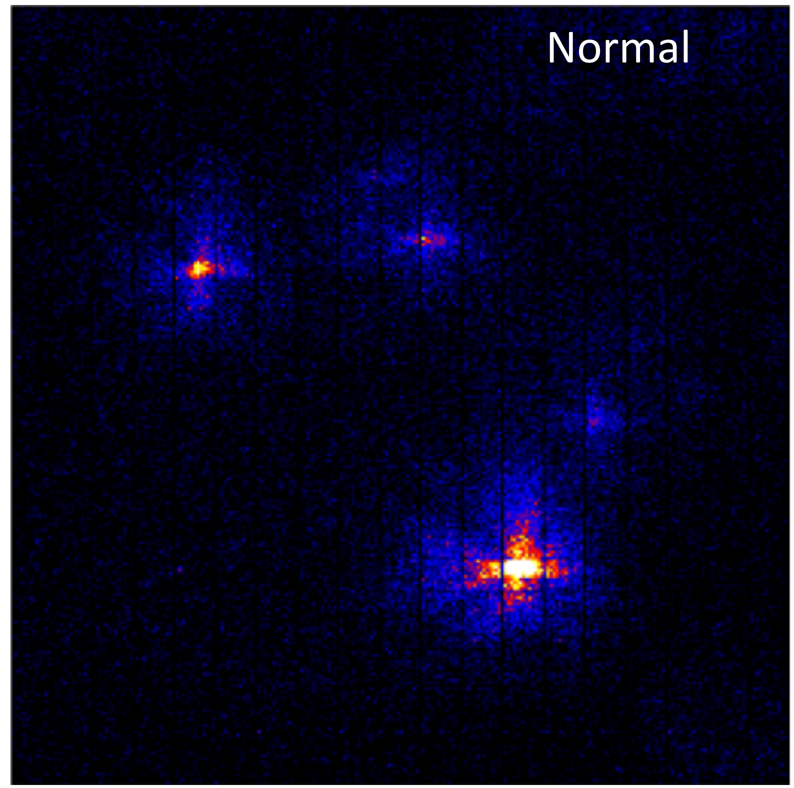




Umezu, R. et al. Review of Scientific Instruments 85, 075103 (2014)

Simulation (Suzaku observation)





Simulated panning image (N_{pan}=240)
(XIS observaion of Cyg OB2 region)

Tolerance of pile-up

Count rate per one pixel in one shot image becomes small with each mode → reduce pile-up fraction

- Window/Burst

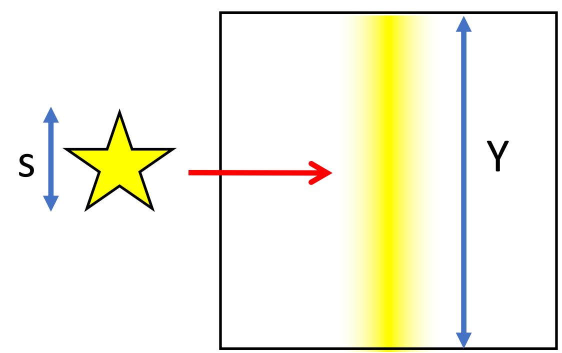
  Pixel rate of 1 shot image becomes small

  - $1/N_{win}$ window size → $1/N_{win}$
  - $1/N_{bst}$ snap shot time → $1/N_{bst}$

- P-sum mode

  point source image is extended to CCD size

  - image size s, CCD pixel size $X * Y$ → s/Y



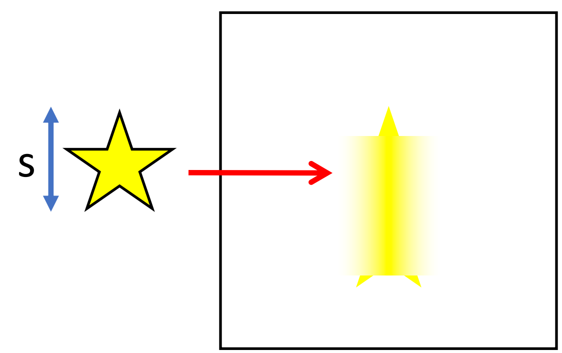
Tolerance of pile-up

Count rate per one pixel in one shot image becomes small with each mode → reduce pile-up fraction

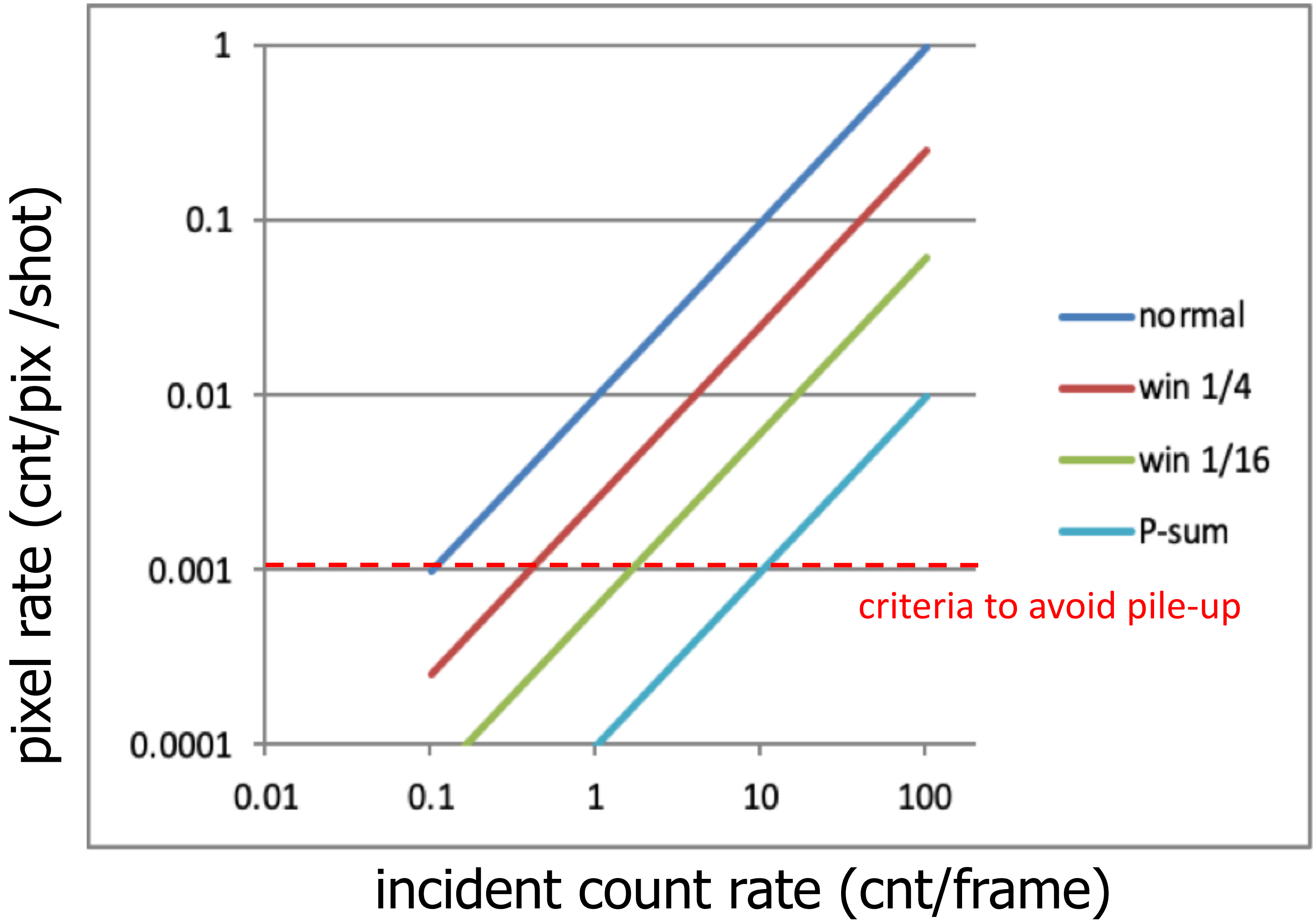
- Panning mode

The deformation of point source image is related to number of vertical transfer N_{pan}

  - image size s → s/N_{pan}

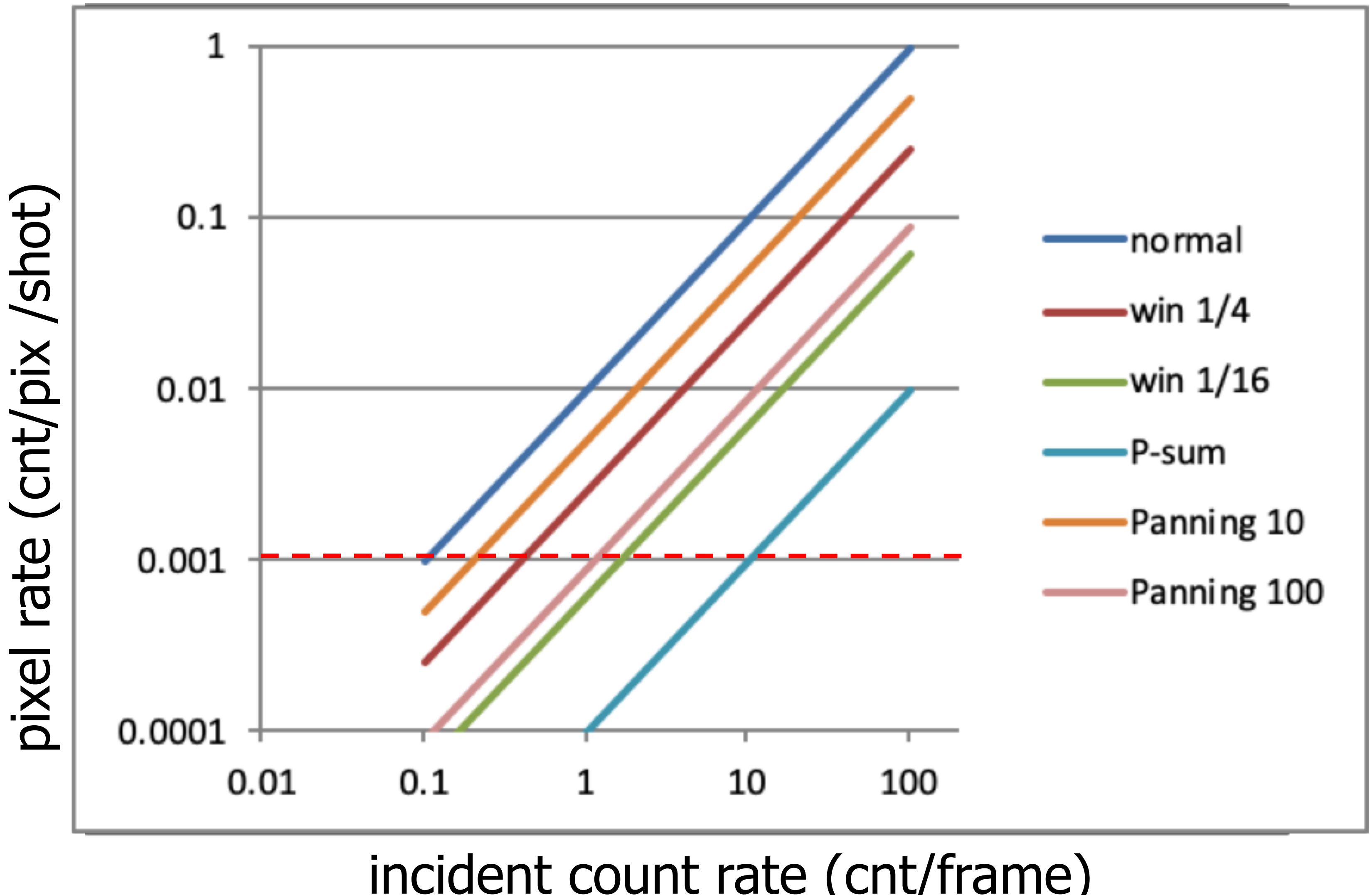


s = 10 pixel



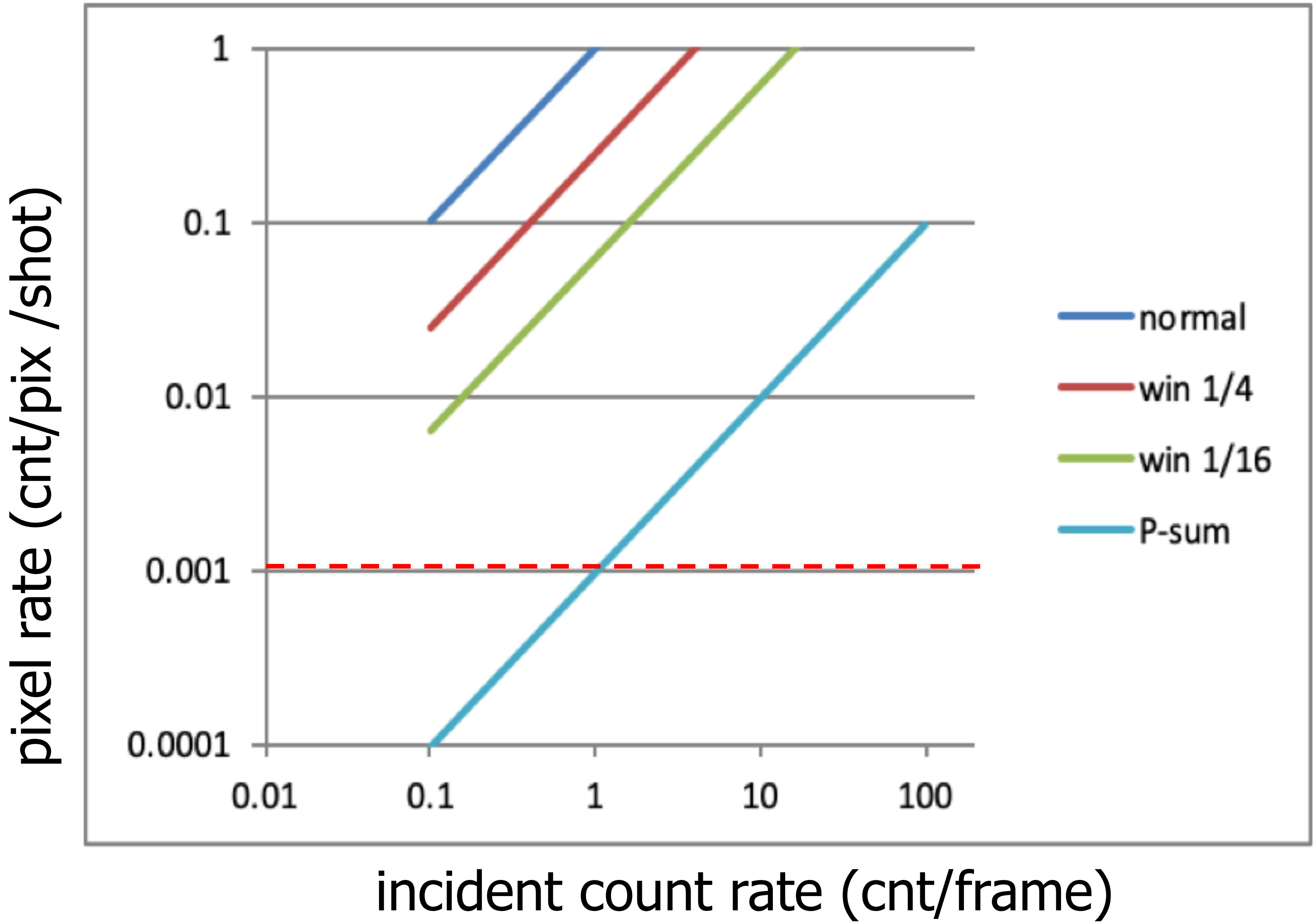
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100
normal
win 1/4
win 1/16
P-sum
criteria to avoid pile-up
pixel rate (cnt/pix /shot)
incident count rate (cnt/frame)

s = 10 pixel



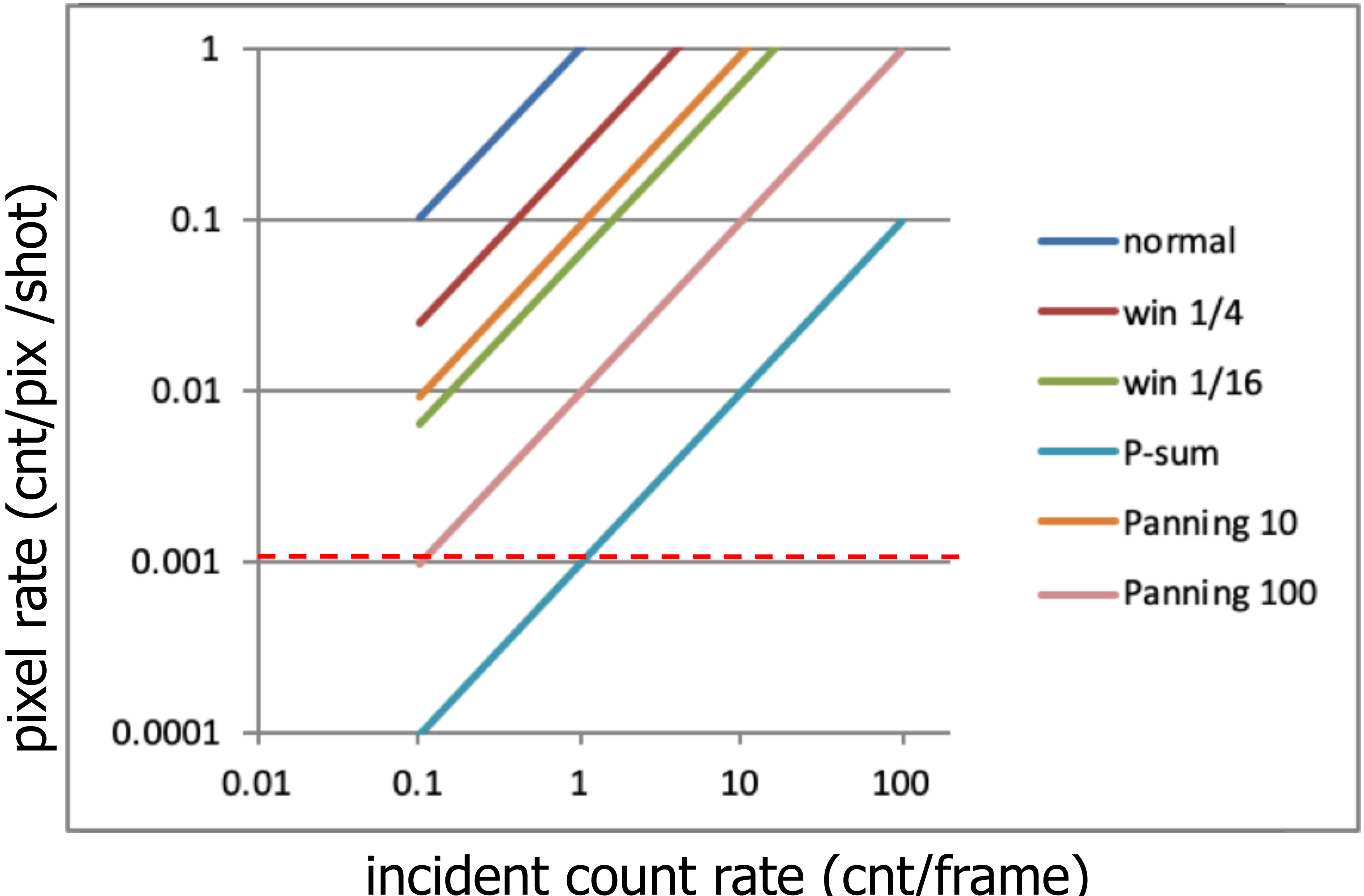
pixel rate (cnt/pix /shot)
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100
incident count rate (cnt/frame)
normal
win 1/4
win 1/16
P-sum
Panning 10
Panning 100

s = 1 pixel



1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100
normal
win 1/4
win 1/16
P-sum
pixel rate (cnt/pix /shot)
incident count rate (cnt/frame)

s = 1 pixel

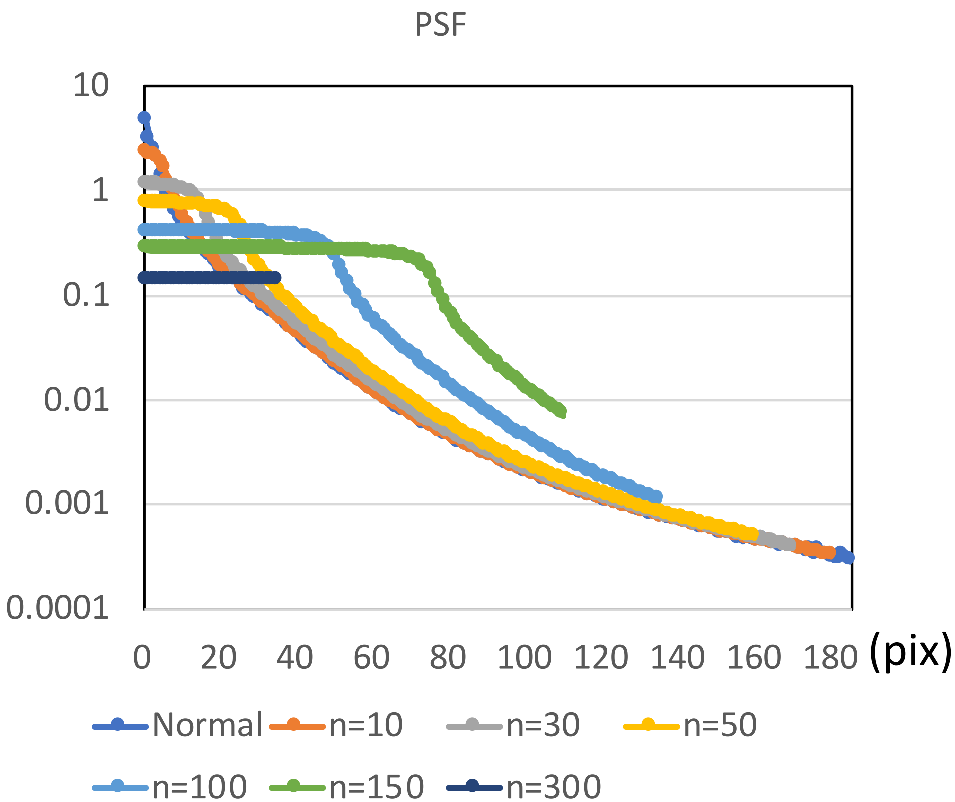


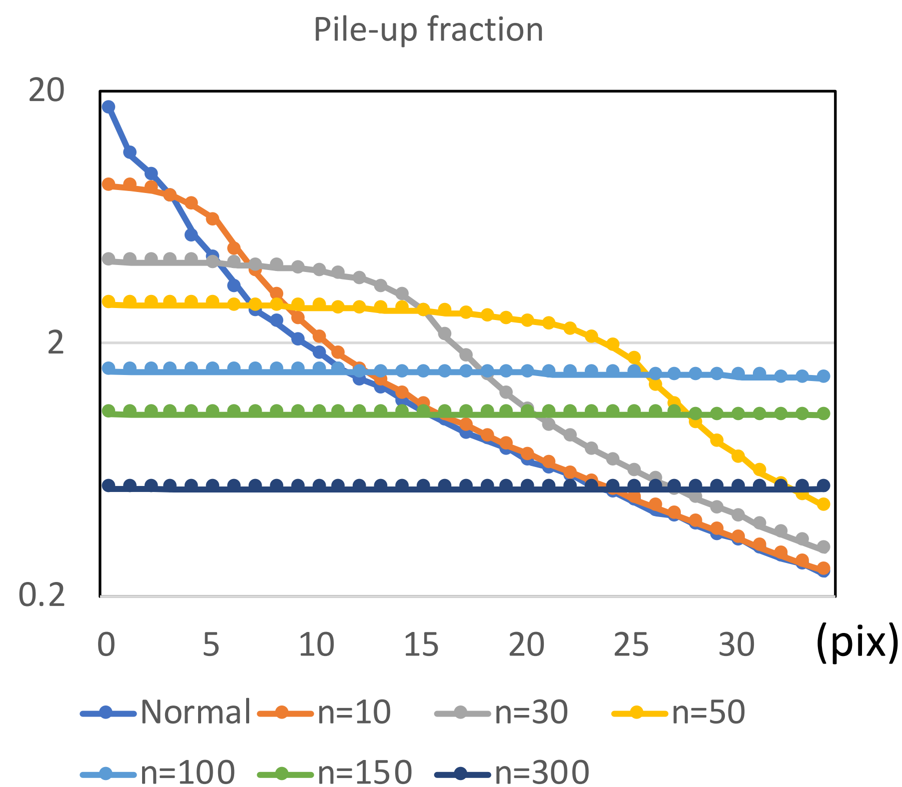
1
0.1
0.01
0.001
0.0001
0.01
0.1
1
10
100
pixel rate (cnt/pix /shot)
incident count rate (cnt/frame)
normal
win 1/4
win 1/16
P-sum
Panning 10
Panning 100

Decrease of pile-up fraction with realistic PSF (Xtend/XRISM)

- The peak of Point Spread Function becomes 1/16 with *n*=150 (bpix)

  → factor of 2 better than 1/8 window mode



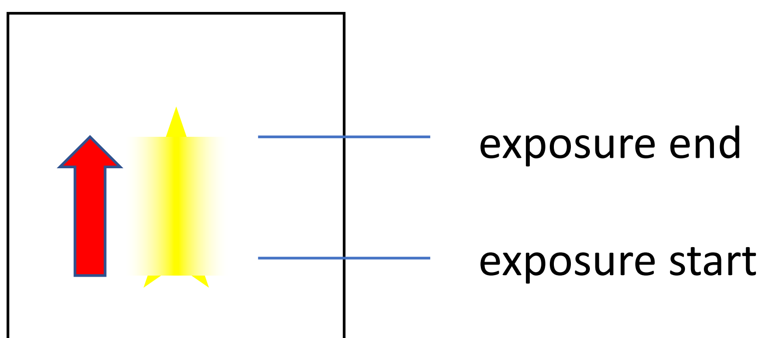


Time resolution

- The shift of the image is controlled by clocking signal

  → Fine time resolution can be archived by using position of X-ray event
- Light curve is smoothed by PSF

  (If PSF is equivalent to pixel size, time resolution becomes $1/\,N_{\mathrm{pan}}$)



Spectroscopic performance

- Comparison with normal mode;

  The difference is only a small number of vertical transfer ($0 \sim N_{pan}$)

  Little degradation of energy resolution is expected

cf. P-sum mode

Continuous clocking (with different voltage)

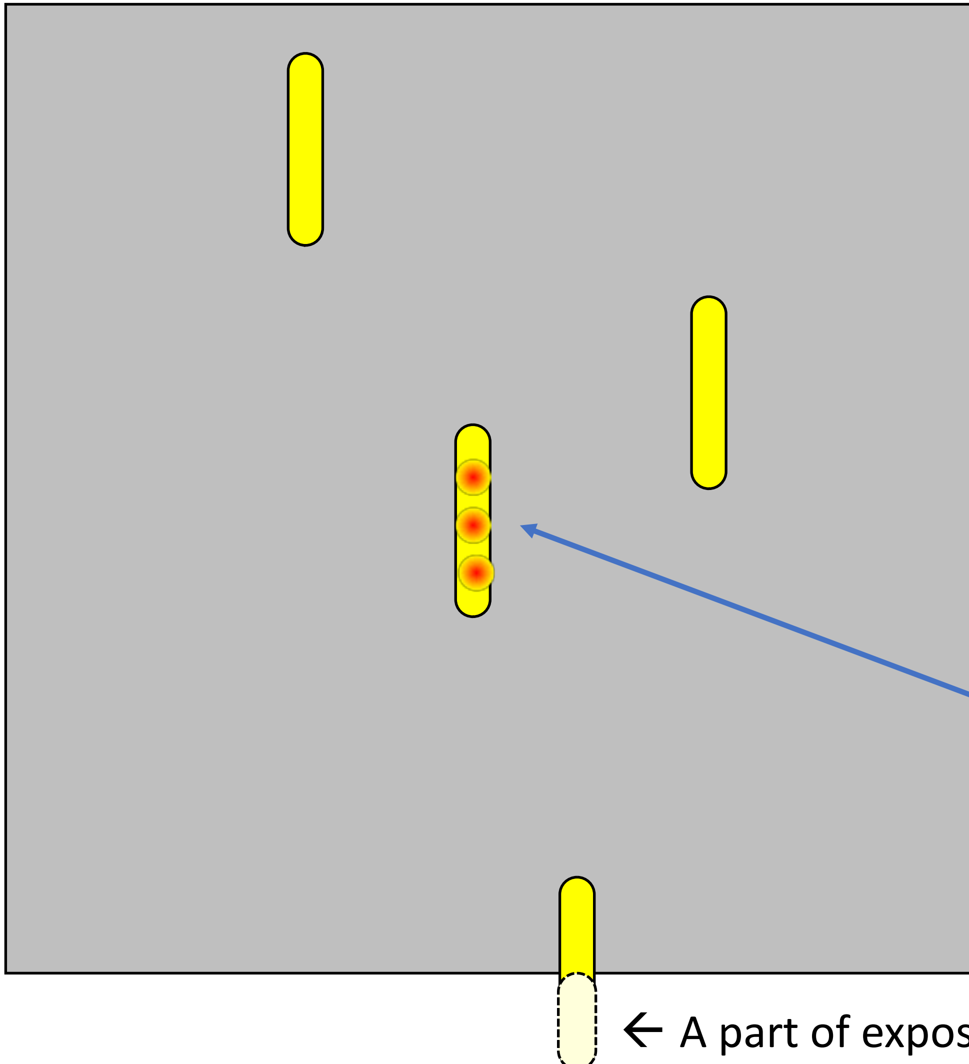
Different event extraction (split pattern is different)

Charge injection is impossible

→ large impact to energy resolution

Summary : Panning Mode Trade-off

- pros
  - Reduce pile-up fraction
  - Keep full region of imaging area
  - Exposure time is not lost in most of the imaging area
  - Possible improvement in time resolution
  - No change in hardware is needed, of course.
- cons
  - PSF is elongated
    - degradation of imaging capability
    - S/BGD ratio is reduced
  - The exposure time at the CCD boundary of the far side from the FOV center is reduced
  - Need additional calibration time (there would be little difference in spectroscopy)
  - Impact to processing software



- pixel count rate is reduced
- relative position indicates photon arriving time
  (not 1 to 1 relation smeared with PSF tail)

If a source has a variability within exposure time, the image should be different from the constant flux case. In principle, variability information can be extracted.

← A part of exposure is lost at the pixel boundary (far side of the FOV center)

supplemental slides

TABLE I: Characteristics of various modes, for the observation of point-like objects.

	Normal	Window	Burst	P-sum	Panning
Pile-up Tolerance	1	$N_{\rm window}$	$N_{\rm burst}$	$N_{\rm line}/N_{\rm image}$	$1\sim N_{\rm line}/N_{\rm image}$
Field of View	1	$N_{\rm window}^{-1}$	1	1	1
Photon Statistics	1	1	$N_{\rm burst}^{-1}$	1	1
Time Resolution	1	$N_{\rm window}^{-1}$	1	$1/N_{\rm line}$	$1\sim N_{\rm image}/N_{\rm line}$
Pattern Selection	○	○	○	△	○
Image Resolution	1	1	1	$N_{\rm line}/N_{\rm image}$	$1\sim N_{\rm line}/N_{\rm image}$

Pile-up limit of XRISM/Xtend scaled from Suzaku/XIS

		Suzaku/XIS	XRISM/Xtend
Frame integration time (sec)		8	4
Pixsel scale (arcsec)		1.04	1.74
Effective area (cm^2)	1.5 keV	390 (BI)	400
	8 keV	100 (BI)	300
HPD (arcmin)		2.0	1.26

pixel count rate ∝ (frame time) x (pixel scale)^2 x (HPD)$^{-2}$ x (Effective area)

→ 3.6 ～10.6 times larger than XIS

(1 keV: $(4/8)x(1.74/1.04)^2x(2.0/1.26)^2x(400/390)$~3.6

8 keV: $(4/8)x(1.74/1.04)^2x(2.0/1.26)^2x(300/100)$~10.6)

We use factor 7.7 in the following discussion to be consistent with Astro-H SWG discussion

Xtend will suffer a severer pile-up problem

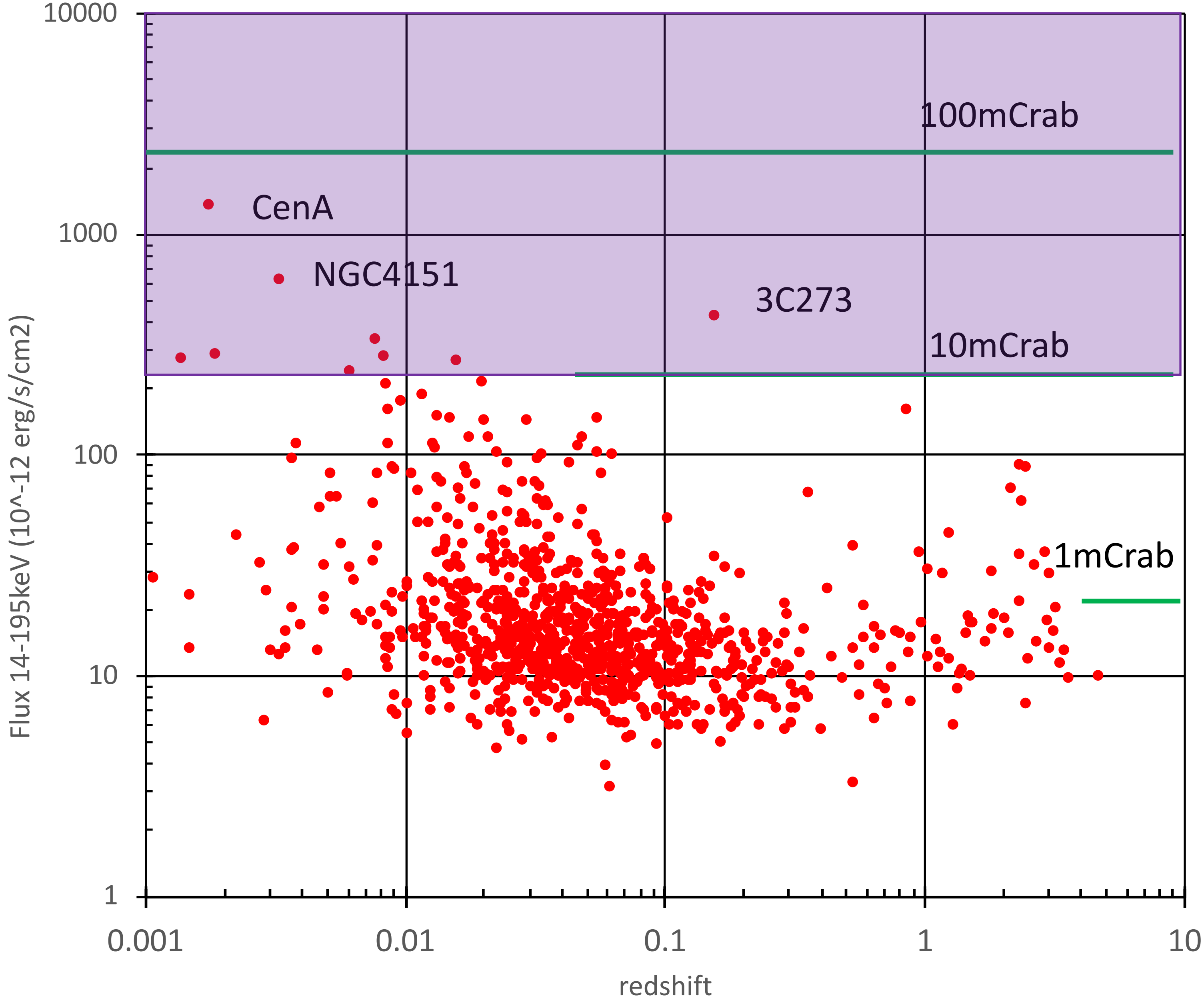
https://heasarc.gsfc.nasa.gov/docs/suzaku/prop_tools/suzaku_td/node10.html#SECTION00102210000000000000

Pile-up (3%) limit of XIS : 12 cts/sec ～10 mCrab

→ 1.3 mCrab in Hitomi/SXI and XRISM/Xtend

Data from https://swift.gsfc.nasa.gov/results/bs105mon/

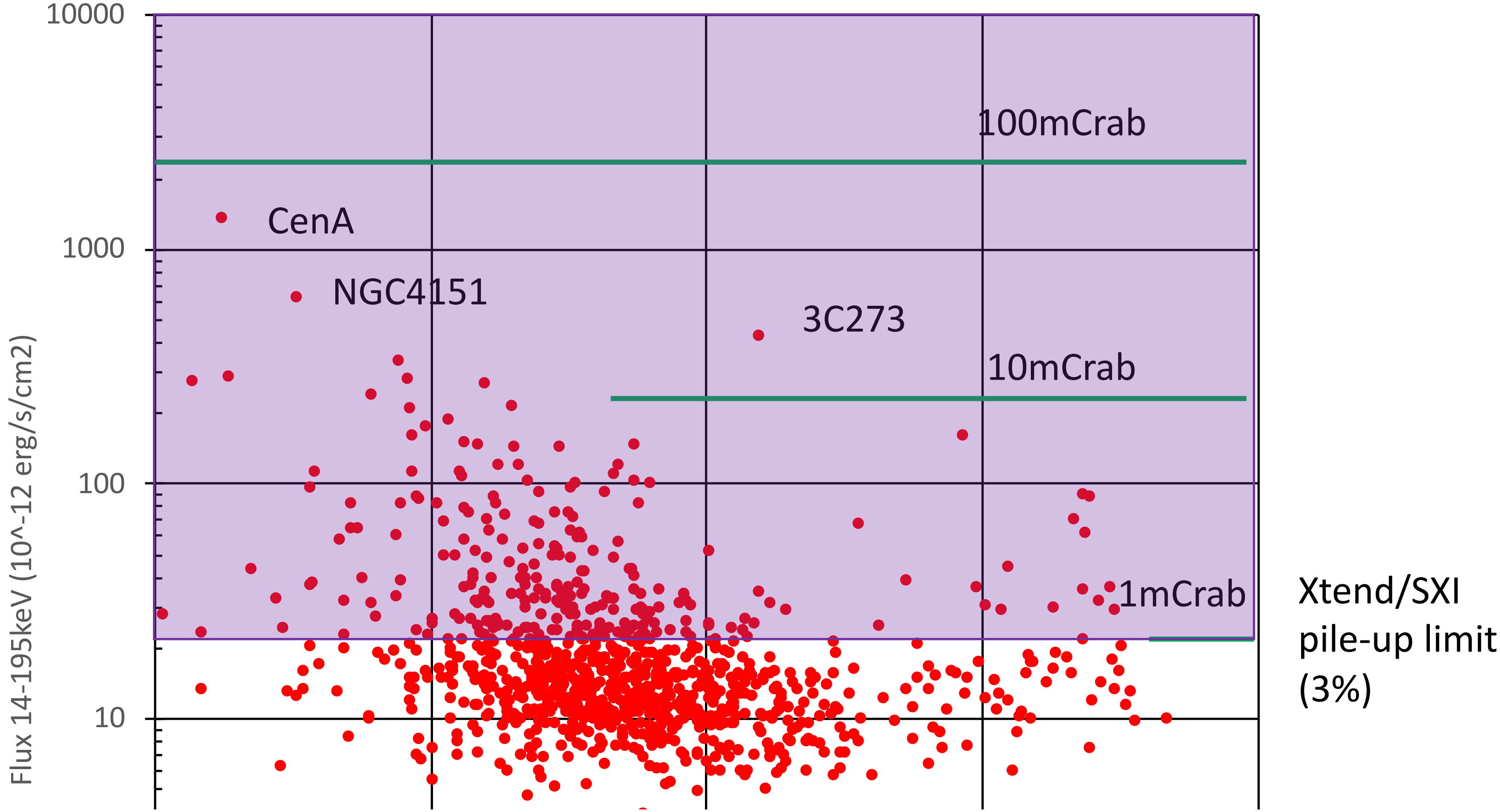
AGN in Swift BAT 105months Catalog



XIS
pile-up limit
(3%)

Data from https://swift.gsfc.nasa.gov/results/bs105mon/

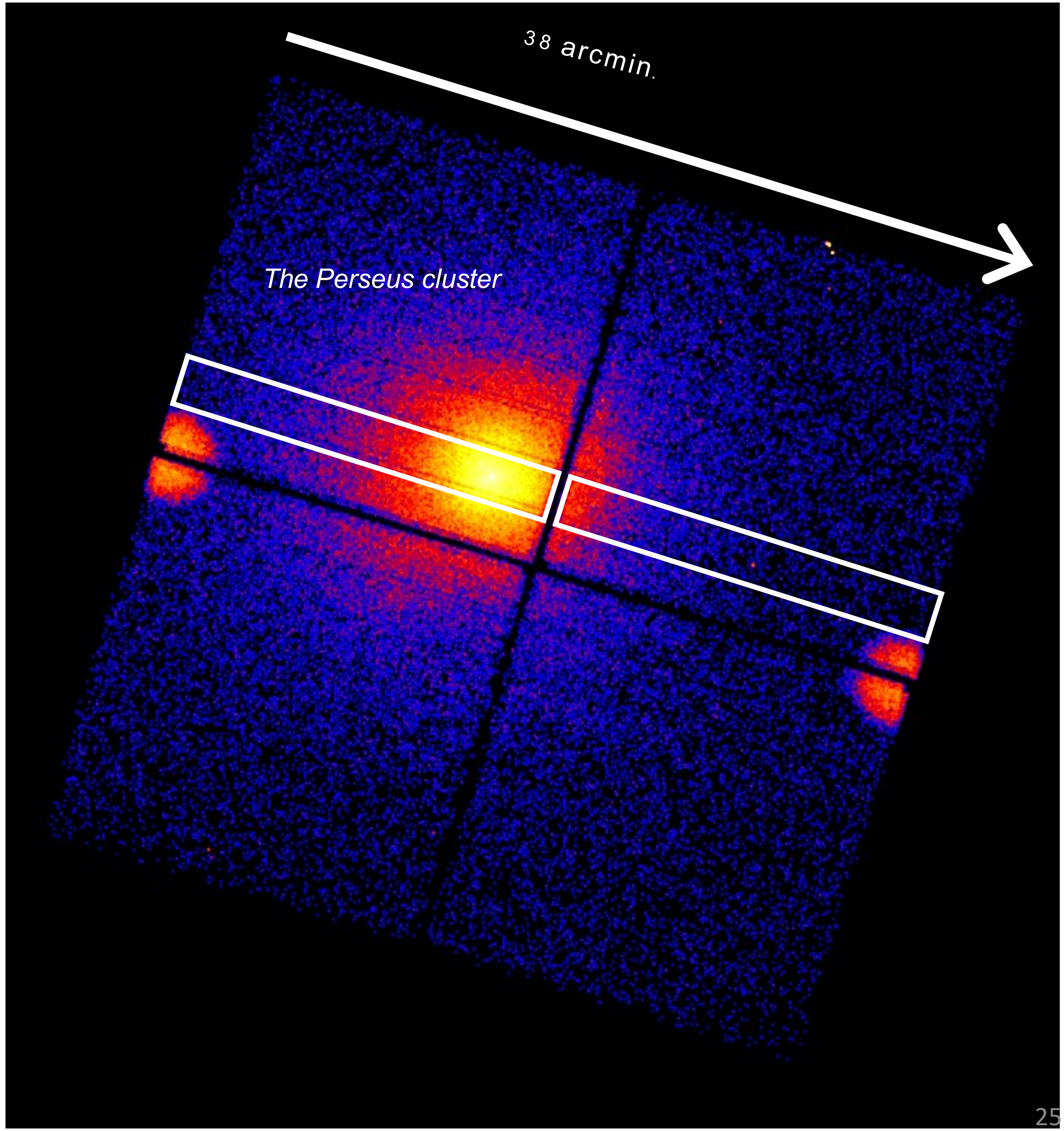
AGN in Swift BAT 105months Catalog



Pile-up is a problem not only for bright binary sources but also for a significant fraction of XRISM target AGNs

Perseus cluster observed with Hitomi SXI (Nakajima+2018)

Overlaid 1/8 window area (2.35’ width)

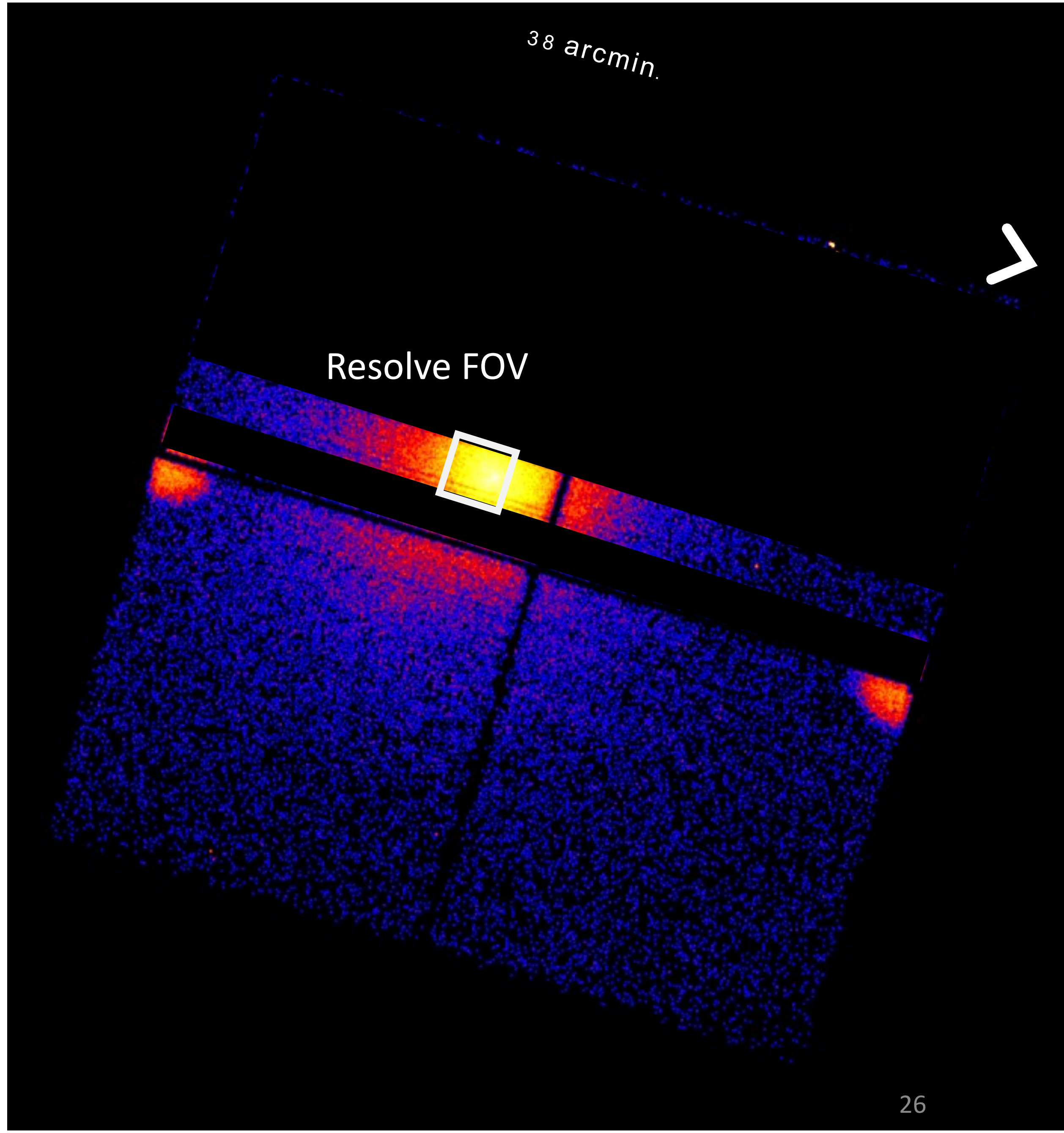


1/8 Window mode

- Mitigates pileup by factor of 8
- Lose Information of the Sky around the target (Some fraction of Resolve FOV is outside the window)
    - One of the role of Xtend is to estimate contamination into Resolve FOV.
- Periodic (every 0.5s) deadtime up to 10%

cf
Annular Extraction or
Burst Mode
can also mitigates pileup, but lead to loss of photons (dead area at the PSF core or deadtime)

1/16 window mode is not adequate, as its width is only 1.2’



pile up rateの計算

- 仮定する条件
  - 天体の明るさ: f (cnts/sec)
  - 露出 1sec (normal mode)
  - 天体の広がり (PSF): a x a ($pixel^2$), 一様
  - CCDの縦方向のpixel数: y = 1024 (pixel)

→ 1 pixel内に入る平均photon数を計算し、
pile upの指標とした

normal modeの場合:

(pile up rate) = f / a^2

modeごとのpile up rate

- normal mode

  f / a^2

- window (1/n size)

  $f / a^2 / n$

- P-sum

  $f / a / y = (f/a^2) \times a/y$

changes in software

item	change	impact
position	+1/2n	small
timing	---	0
	rawy-rawy$_0$ -> Δt	large
energy	$1/(1-c_{vs})^{n/2}$	small
	rawy-rawy$_0$ correction	large
	---	0
QE	x(0～1)?	small or 0
	---	0

If the process depends on the source position, impact becomes large

Changes in software (spectrum)

1. CTI correction：Additional 0 – n (very) slow transfer
   - A) Modified CTI correction (1): ΔE △
     1. Add CTI correction for (very) slow transfer of *n*/2 lines

$$\mathrm{PH} = \mathrm{PH}_0\,(1-c_f)^{\mathrm{Y}_0}\,(1-c_{f0})^{\mathrm{Y}_1}\,(1-c_a)^{\mathrm{Y}_2}\,(1-c_{a0})^{\mathrm{Y}_3}\,(1-c_s)^{\mathrm{Y}_4}\cdot(1-c_{vs})^{n/2}$$

   - B) Modified CTI correction (2): ΔE ○
     1. Reduce uncertainty of the number of very slow transfer by using "rawy-rawy$_0$"
   - C) No additional correction: ΔE △
     1. No change in software (sxipi)
     2. Calibrate energy gain (similar to window mode of Suzaku)

+ Prepare CTI parameters, response function for panning mode in all cases

*Sawtooth correction is identical to that of normal mode; relative position is preserved

**Unified correction may be possible by referring the number of transfer for all mode

prediction of energy resoltion

- CTI effect with additional 0-n bpix transfer

$$(1 - c_{vs})^{0\sim n}$$

ex. C_{vs} = 5x10^{-5}, n=150

→ 1〜0.9925

ΔE = 45 eV@6keV (maximum shift)

Degradation of energy resolution (overestimate)

$$\sqrt{(130^2 + 45^2)} = 137.6$$

※energy resolution of normal mode is assumed to be 130eV

Consider only photon statistics $\frac{1}{\sqrt{0.9925}} = 1.004$ times larger (under estimate)