20190912_X-ray Astronomy 2019 @Bologna

Multiple Image X-ray Interferometer Modules (MIXIM) and their Scalable Mission Plans from Sub-arcsecond to μ-arcsecond Resolution

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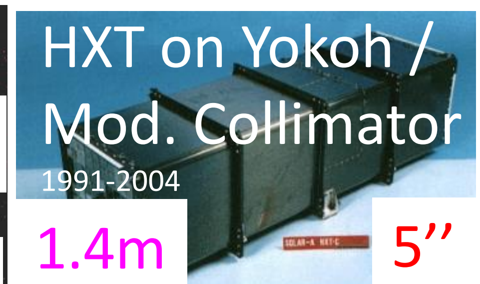
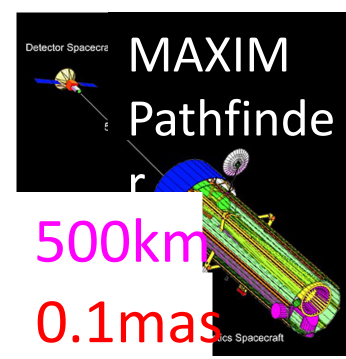
-Instruments of X-ray Astronomy-

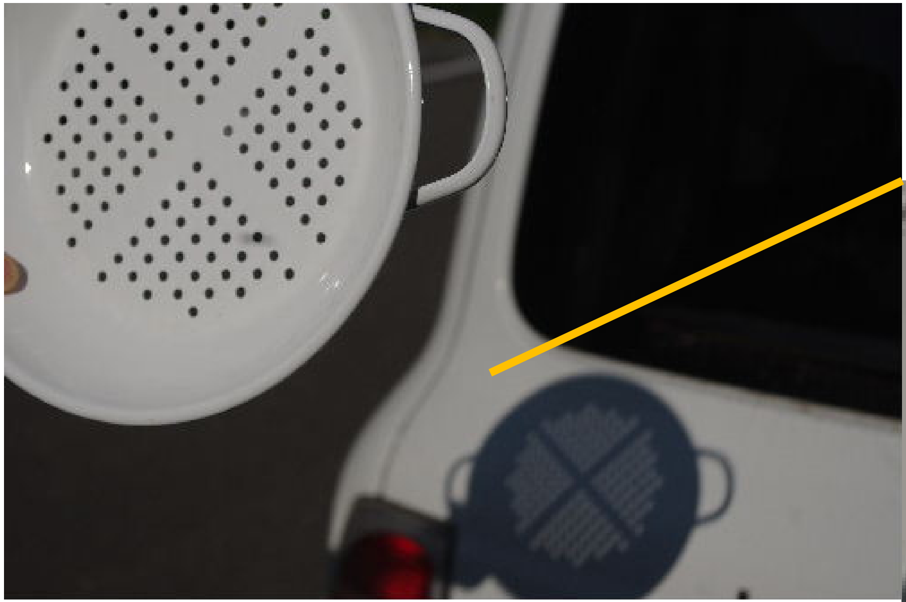
1. Telescopes are build with Grazing Incidence Mirrors with FL of 3-12m plus Pixel Detectors.
2. 0.5’’ resolution mirror is exceptional. It is very much difficult to reproduce it now.
3. Slits, Masks or Collimators are used primarily for wide FOV surveys, in which angular resolution is limited to ~arcminutes.
4. Interferometers have been proposed. Some function in lab, but application in orbit are even more difficult.





A Challenge to these to obtain High Angular Resolution, which is essential in many cases from Galileo Galilei to EHT

Multi-Pinhole(Slit) Camera is the baseline

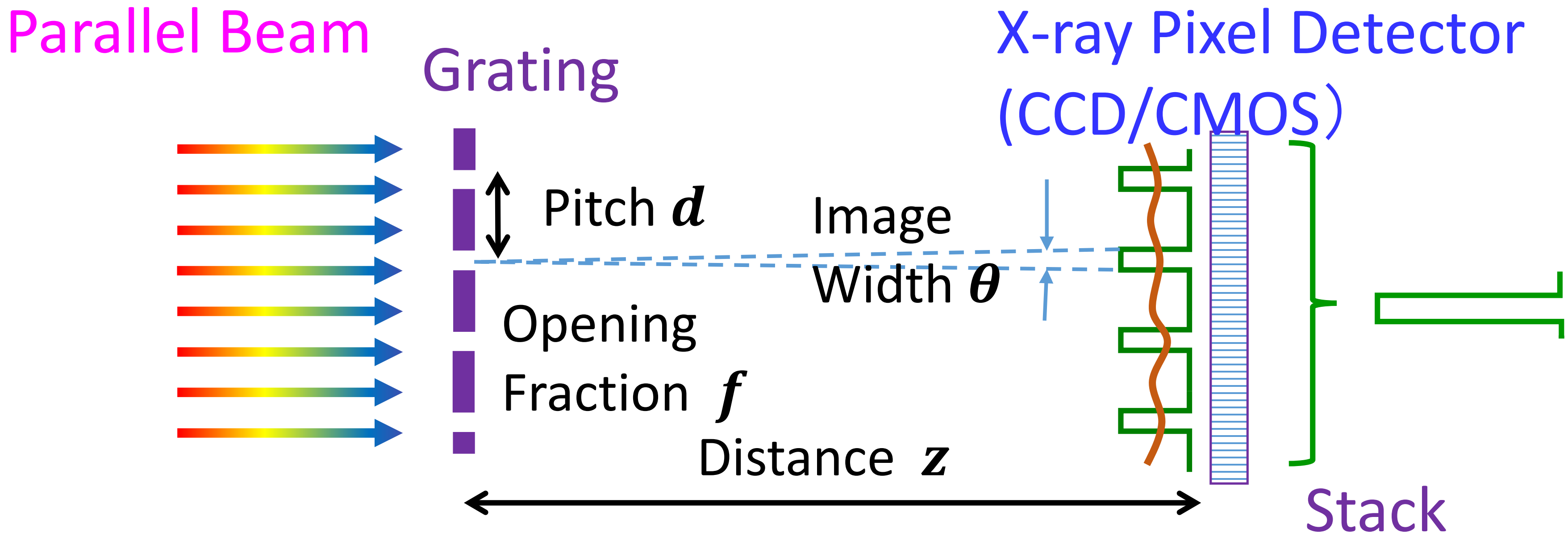


http://blog.goo.ne.jp/hanahanaharu04/e/a8ef27218dee3713136a89943109a431

STACK these multiple images in the analysis

Hayashida+2016

Multi Image X-ray Interferometer/Imager



- Only employ a Grating and an X-ray Pixel Detector
- Image profile detected reflects the profile of the X-ray source.
- Stacking the image with a period of d in the analysis, accurate source profile is obtained.
- Image Width $\theta = fd/z = 0.4'' \left(\frac{f}{0.2}\right)\left(\frac{d}{5\mu m}\right) / \left(\frac{z}{50cm}\right)$

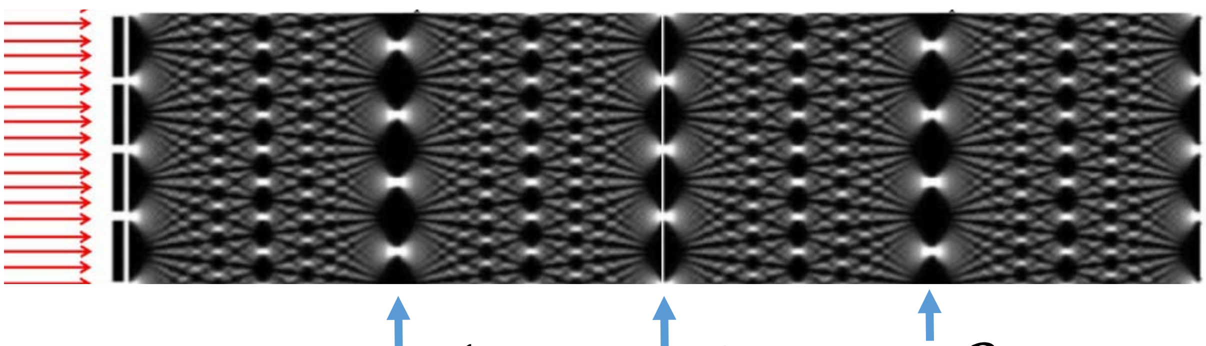
Chandra Resolution with a 50cm size satellite ?

But, diffraction blurs the image significantly.

But, but, Talbot Effect can be employed

- **Talbot Effect**
  - Parallel Light through a grating makes **Self Image** of the grating at periodic distances. (H.F.Talbot, 1836)
  - Explained with **Diffraction** and **Interference** (Rayleigh, 1881)
  - Hard X-ray Talbot Effect in experiment (P. Cloetens, 1997)
- **Talbot Distance** $z_T = m\frac{d^2}{\lambda}$

Plain Wave Light



$m = 1$ $m = 2$ $m = 3$

Talbot Carpet

Image from Wen et al. Advances in Optics and Photonics 5, 83-130 (2013)

For λ=0.1nm(12keV) X-rays and a d=5µm pitch grating, Talbot distance z_T of m=2 is 50cm

Multi Image X-ray Interferometer Module (or Method,Mission) = MIXIM

Hayashida+ 2016,2018

- X-ray Grating with >a few μm pitch and X-ray Imaging Spectrometer
- Select X-ray Events of which energy is within specific band around the Talbot condition $z = m\frac{d^2}{\lambda}$
  - Band-pass of about 10% (for m=2; 20% for m=1) can be utilized. Wider than Si-detector energy resolution of 2~3%. Good for X-ray CCD and X-ray CMOS.
- Stacked Image tell us the X-ray source profile

c.f. **X-ray Talbot (-Lau) Interferometer** Momose+(2003), Pfeiffer+(2006) for Phase Contrast X-ray Imaging of Light Material

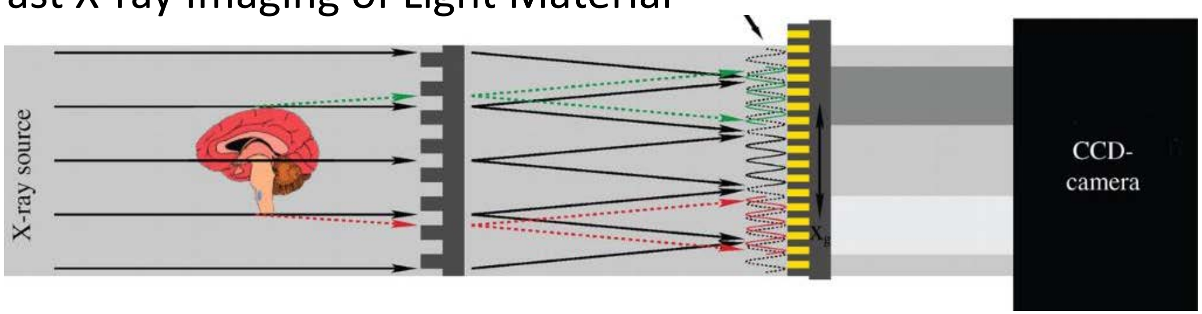
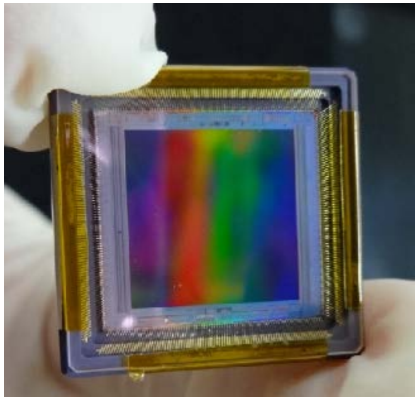
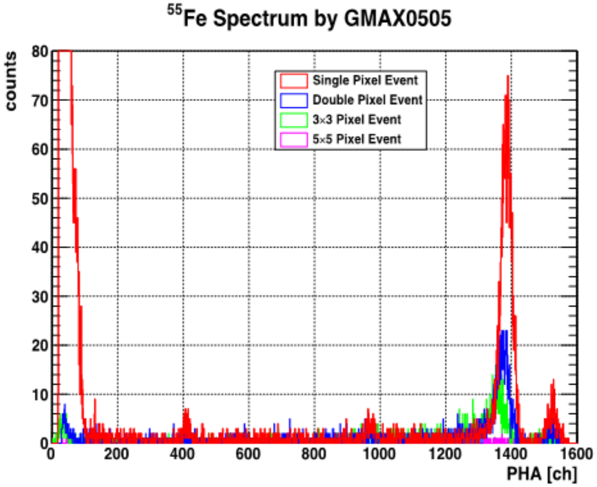


Figure from http://rsif.royalsocietypublishing.org/content/7/53/1665

Hoshino+ 2014 KONICA MINOLTA TECHNOLOGY REPORT Vol11

- X-ray Gratings of a few μm pitch are fabricated and purchased.
- Pixel size of the detectors should be a few μm or smaller, while X-ray CCDs pixel is 24μm or larger.
- Variety of CMOS pixel detectors designed for optical light.
- Some groups (Einstein Probe, FOXSI-3) succeeded in detecting X-rays with optical CMOS with 11μm pixel.
- We employed GSENSE5130 4.25μm pixel in 2017 and GMAX0505 2.5μm pixel in 2018, both from Gpixel Co.





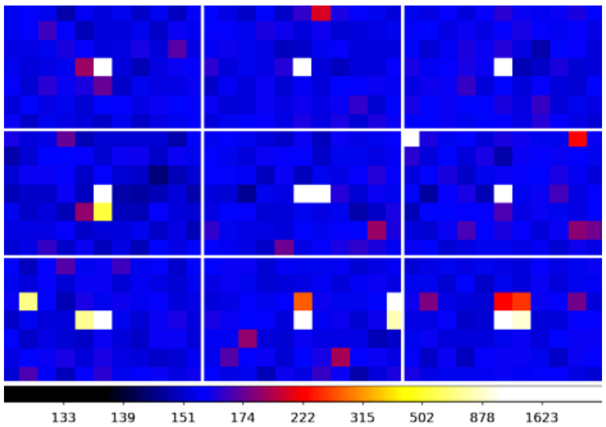
FWHM=170eV@5.9keV
at Room Temperature!!!
In Open Air

Detection Layer ~ 5μm Thick

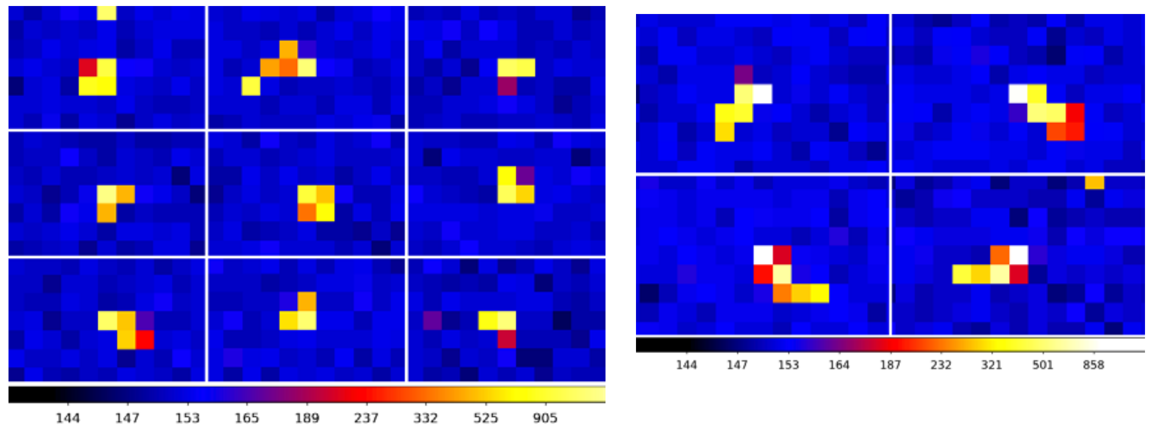
Small pixel size enables us to detect X-ray polarization
See Asakura+ 2019, JATIS, 5(3) and Poster #501

Small Pixel→Photo-electron-Track→X-ray polarimetry

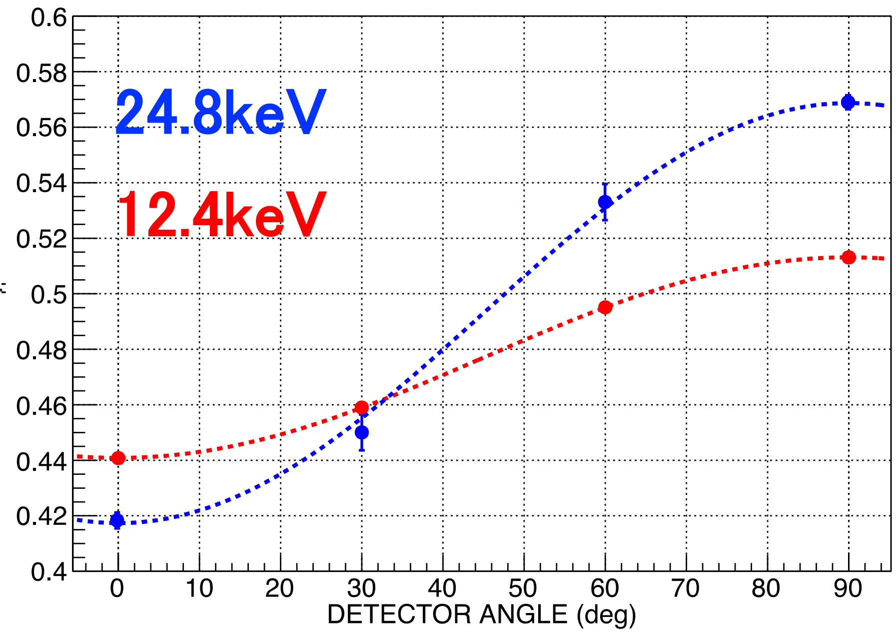
12.4keV



24.8keV



$$r_H(\varphi) = \frac{N_H(\varphi)}{N_H(\varphi) + N_V(\varphi)}$$



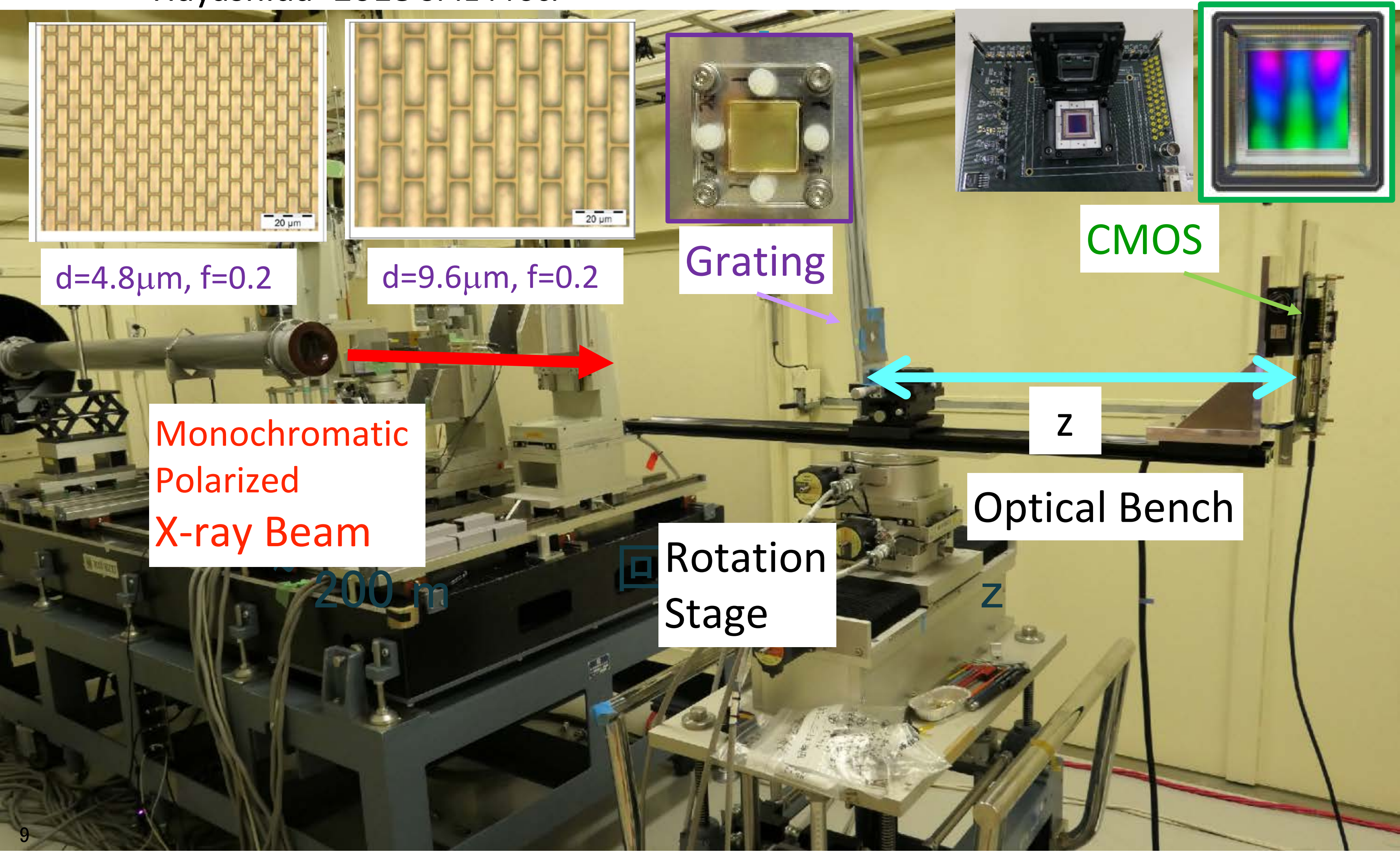
Asakura+2019
JATIS, 5(3)

MF=
7.63±0.07%@12.4keV
15.5±0.4%@24.8keV

SPring-8 BL20B2 200m beam line

2017 Nov,Dec 2018 May, Jun (4.25μm) 2018 Oct,Dec (2.5μm)

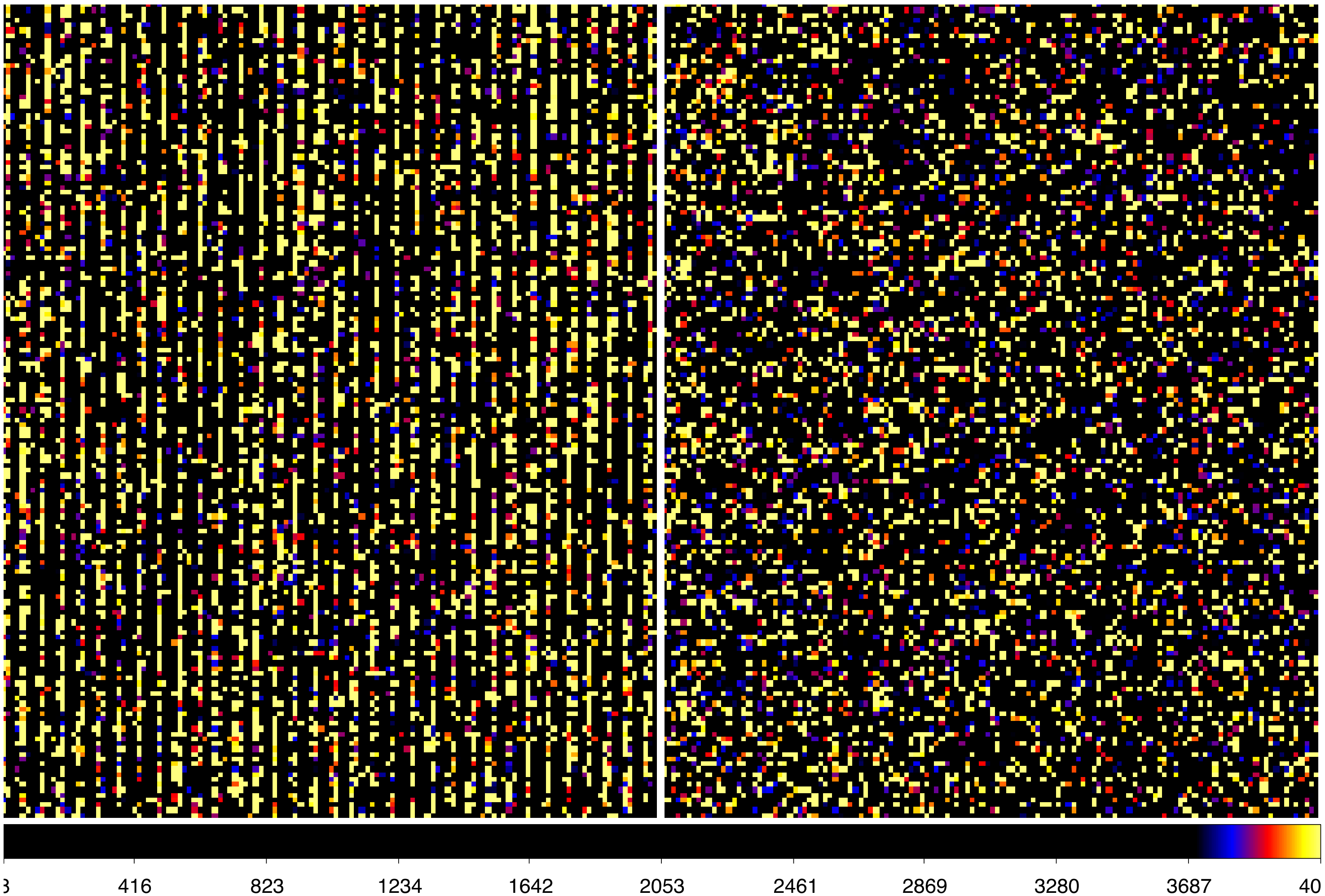
Hayashida+2018 SPIE Proc.



d=9.6μm,f=0.2,z=92cm Raw Frame Image 6s-exposure

Ex=12.4keV
(m=1.0; meet Talbot condition)

Ex=10.0keV
(m=1.24; NOT meet)

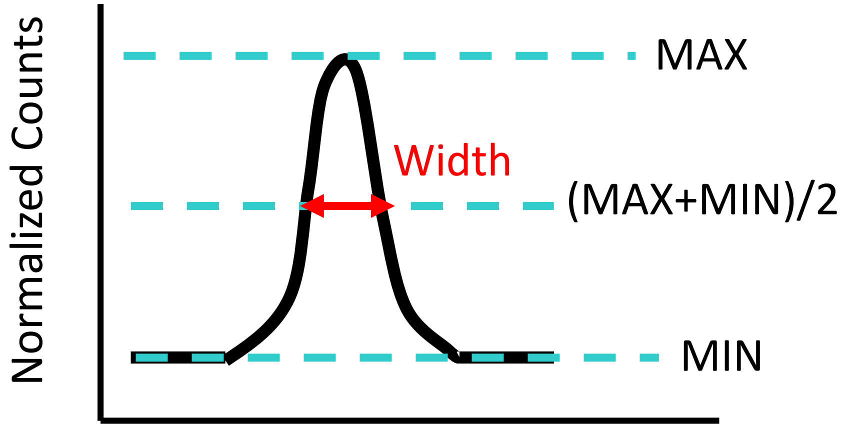


Following data were taken with exposure/frame of 0.1-1s with attenuator to prevent pileup

Event Extraction→Projection→Folding Ex=12.4keV

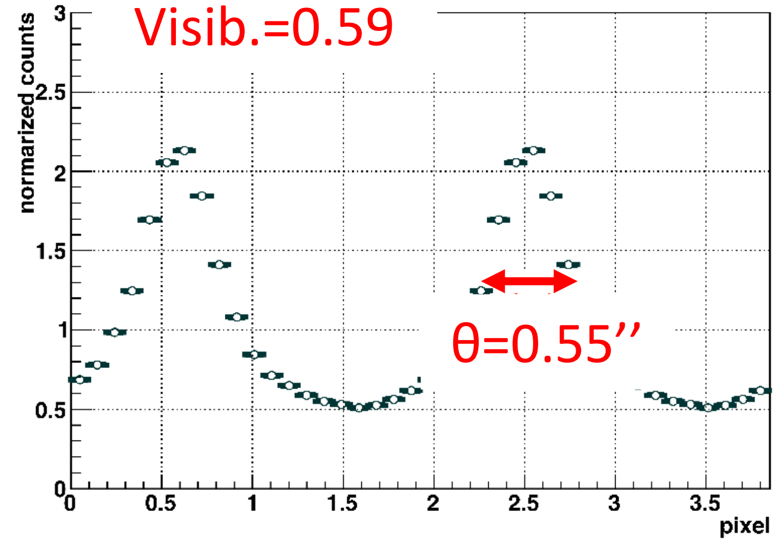
Folded Profile

Visibility=(MAX-MIN)/(MAX+MIN)

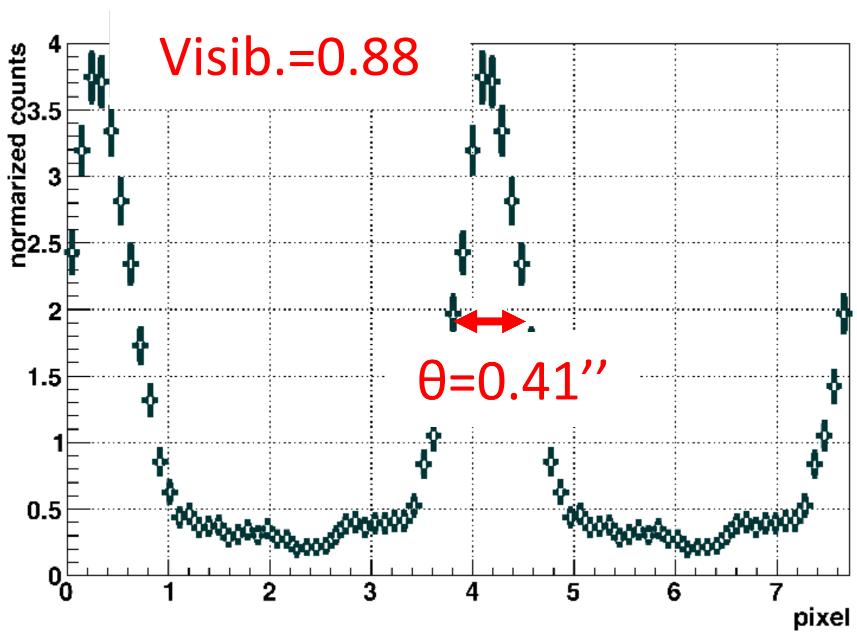


*) Two periods are plotted for display purpose

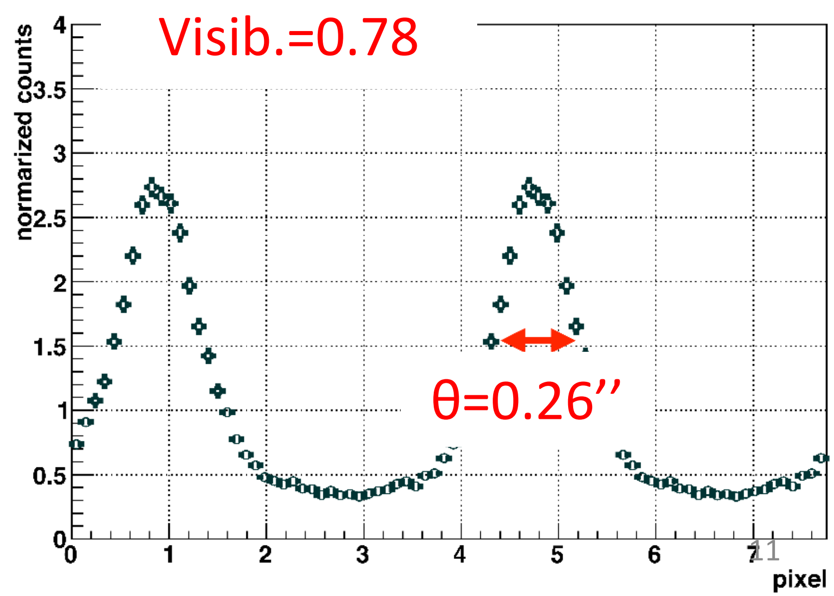
d=4.8μm, z=46cm



d=9.6μm, z=92cm

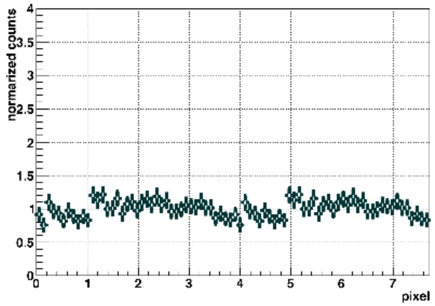


d=9.6μm, z=184cm

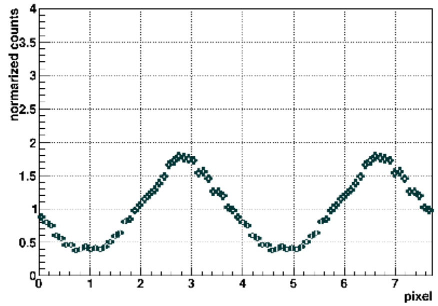


Energy Dependence of Visibility

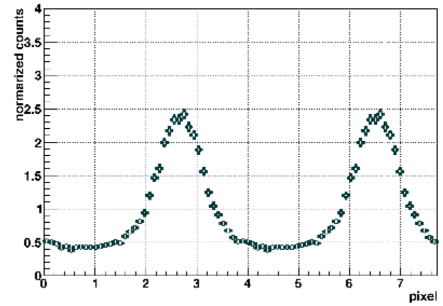
E = 10.0 keV



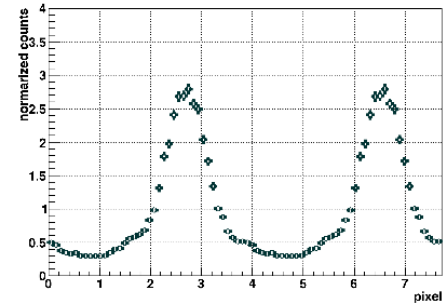
E = 11.6 keV



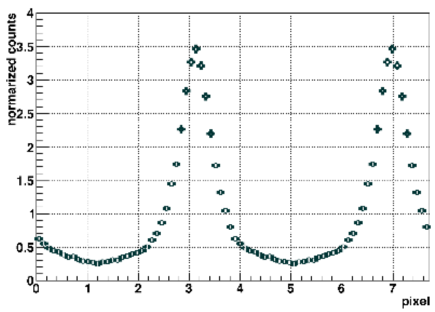
E = 11.8 keV



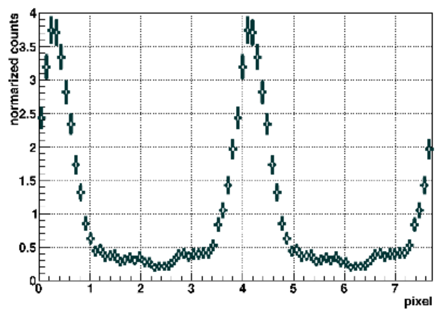
E = 12.0 keV



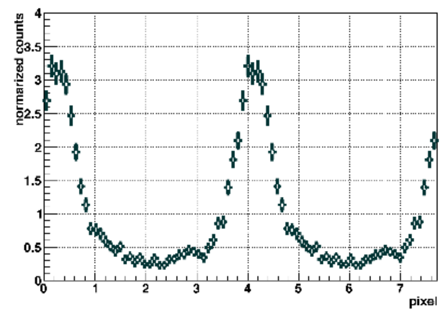
E = 12.2 keV



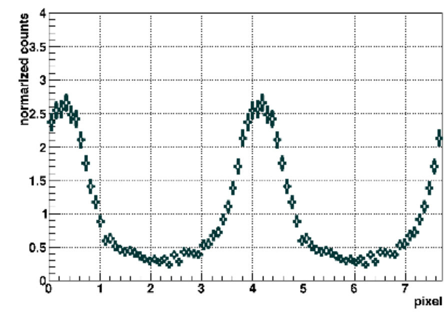
E = 12.4 keV



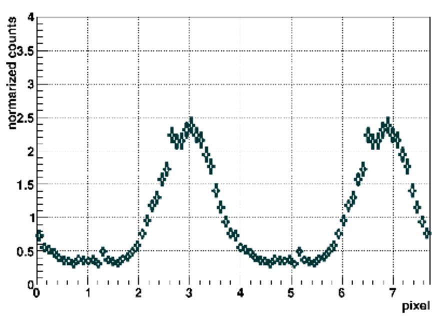
E = 12.6 keV



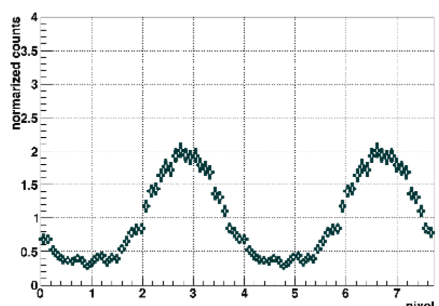
E = 12.8 keV



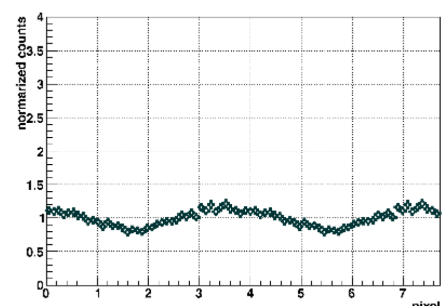
E = 13.0 keV



E = 13.2 keV

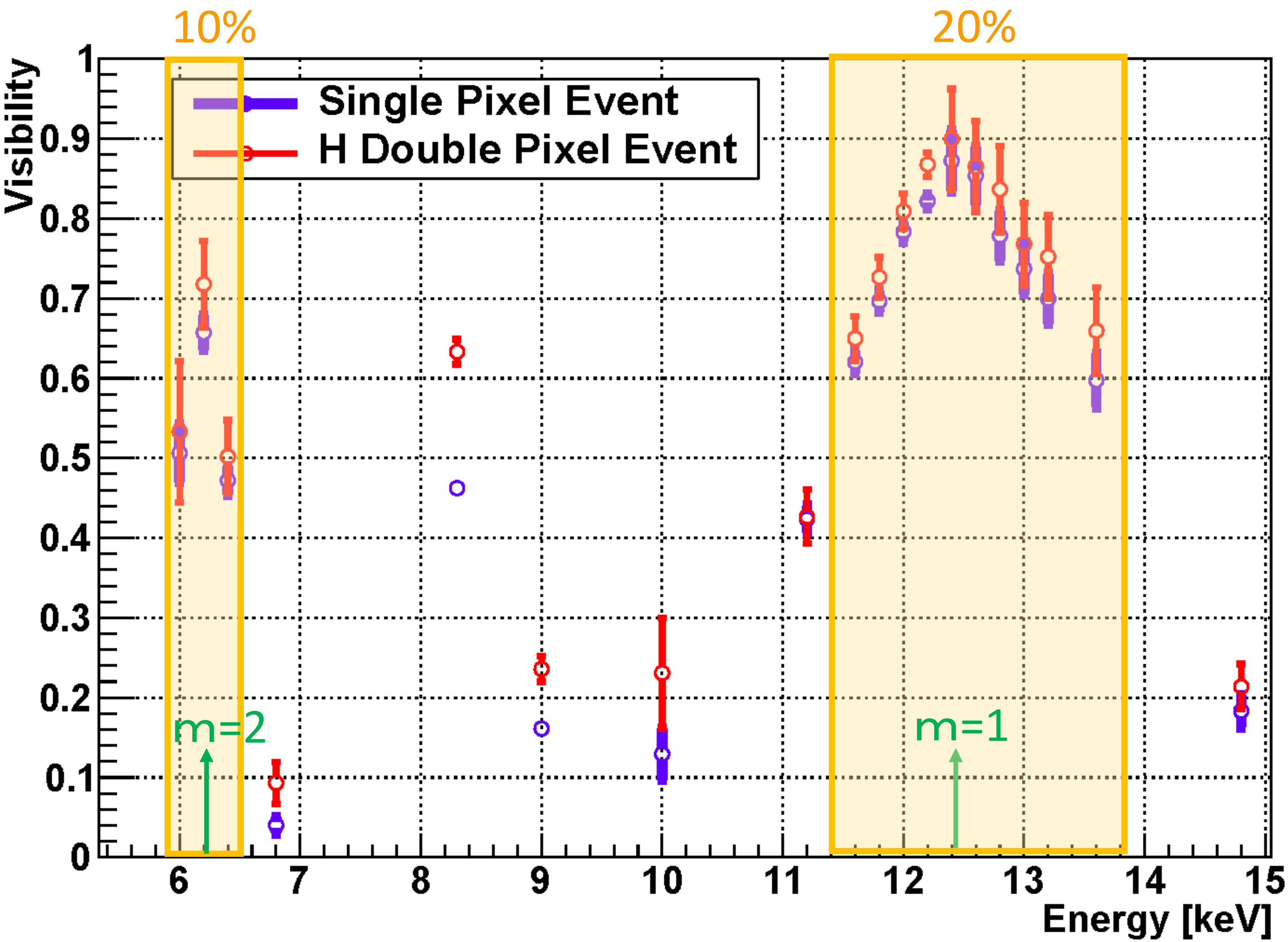


E = 14.8 keV



Energy Dependence of Visibility→Band Width

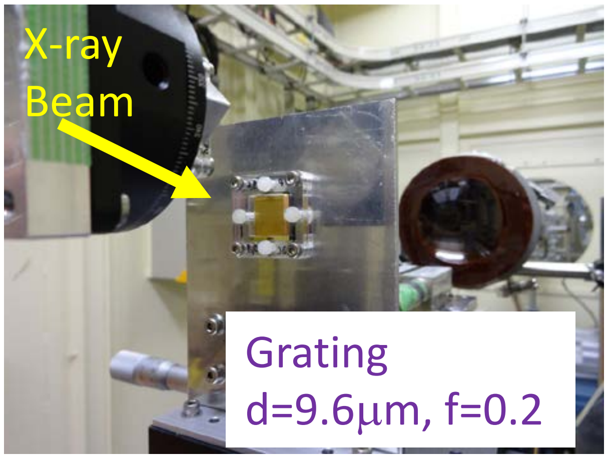
d=9.6μm,f=0.2, z=92cm

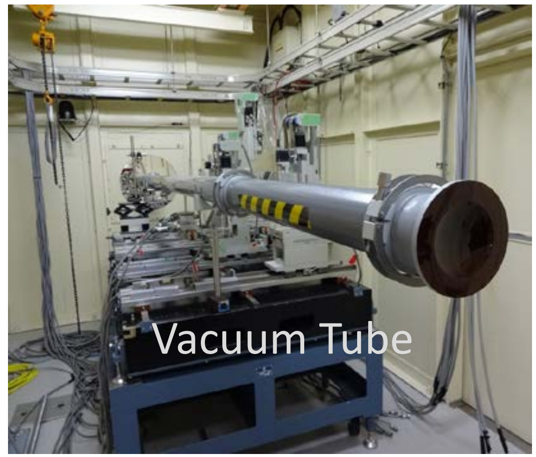


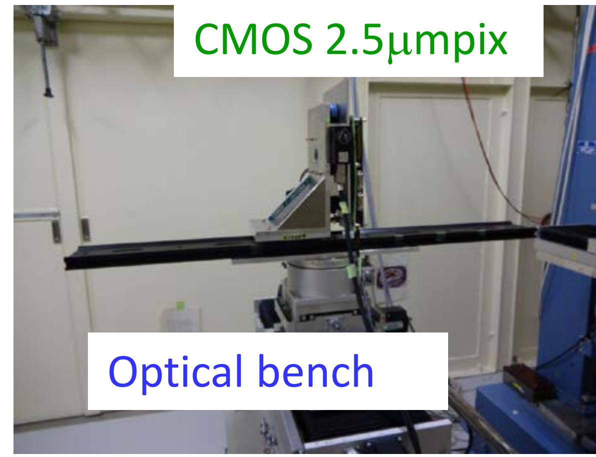
SPring-8 BL20B2 2019 Jul

1. Test large z case to obtain smaller (better) Image width <0.1’’
2. First 2D imaging by stacking two 1D gratings diagonally

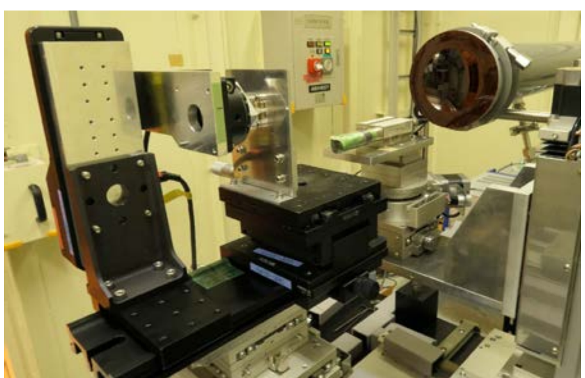
z=8.67m



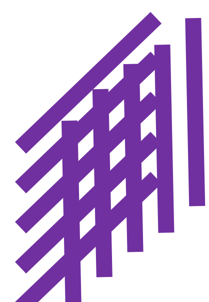




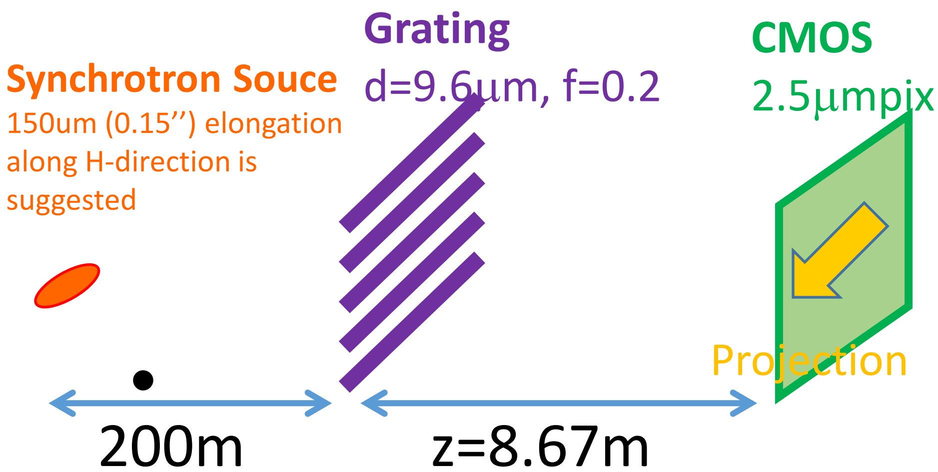
This Image is flipped horizontally to explain the configuration

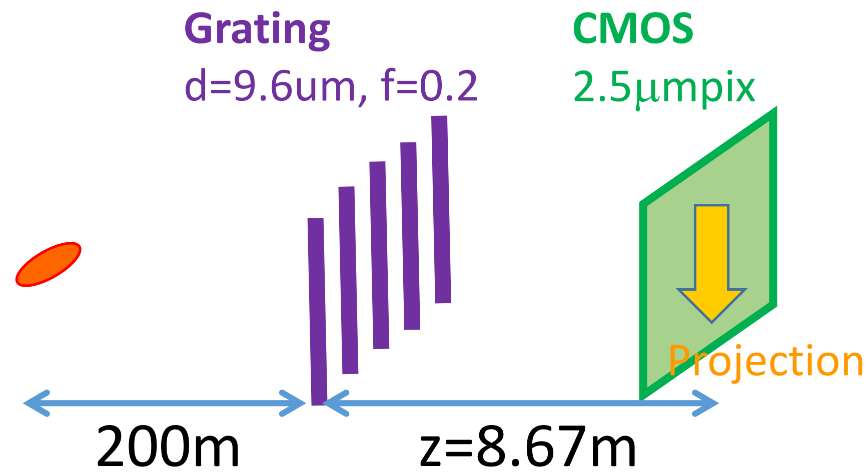


This Image is flipped horizontally to explain the configuration

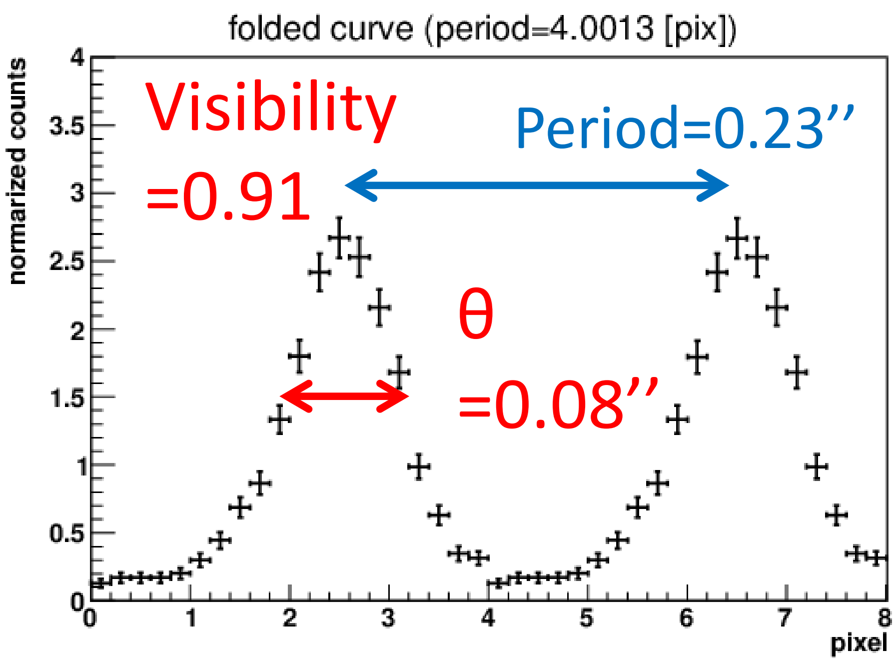


<0.1'' Image was obtained !

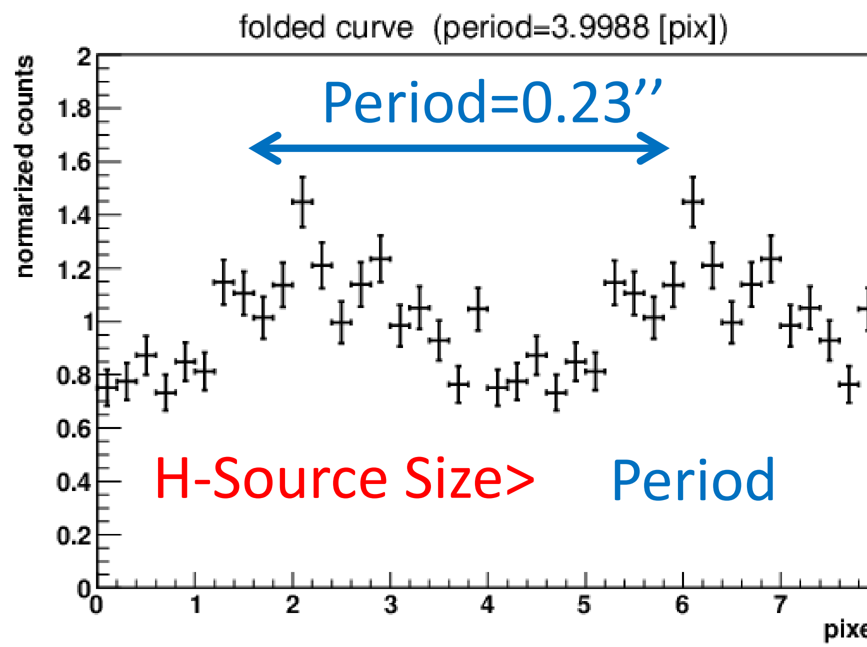




Ex=12.4keV



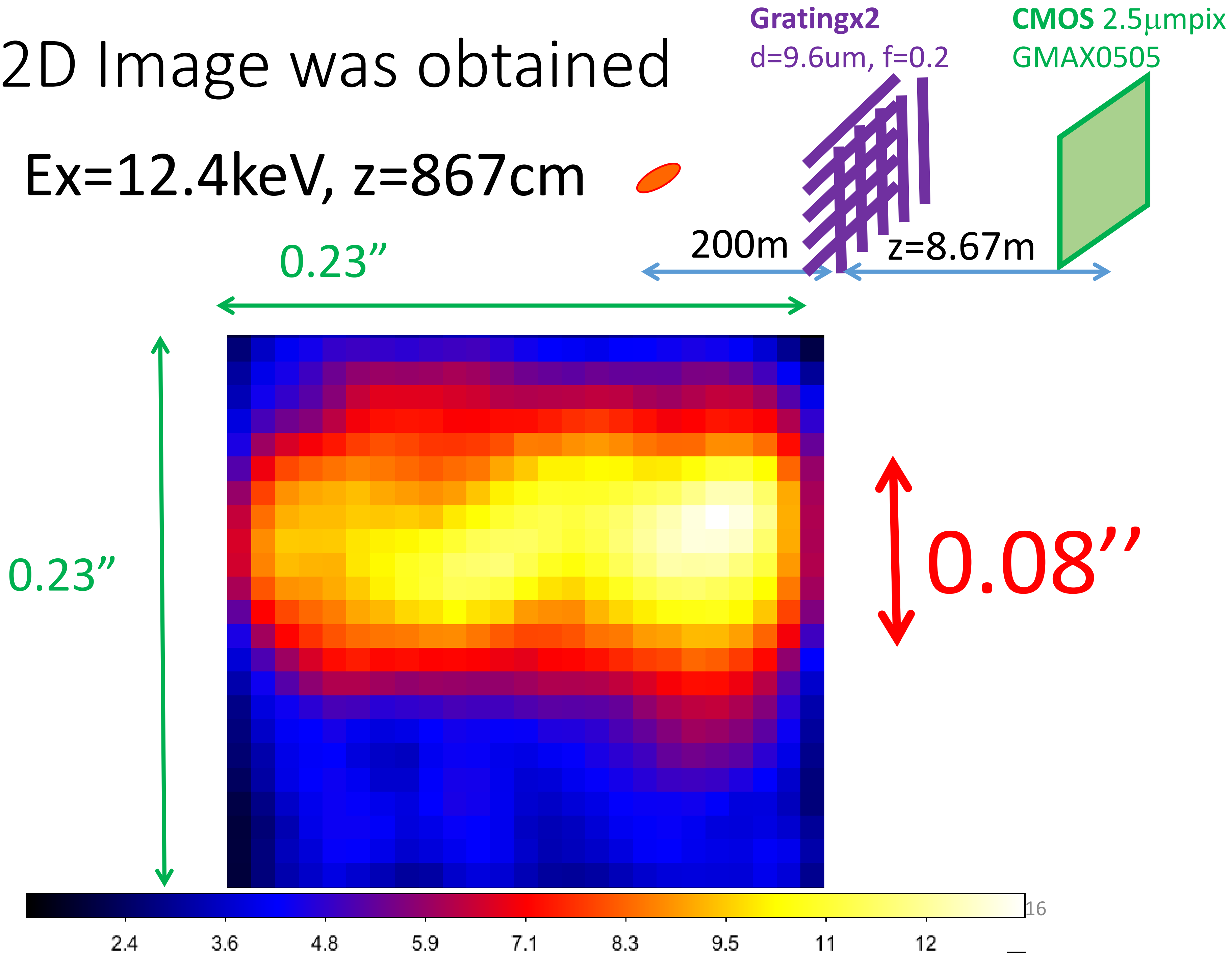
Ex=12.4keV



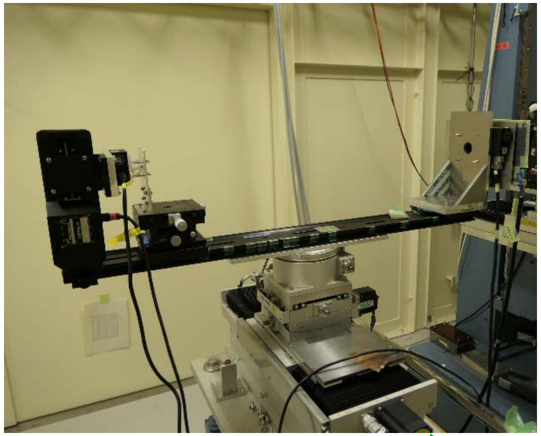
1pixelは2.5um

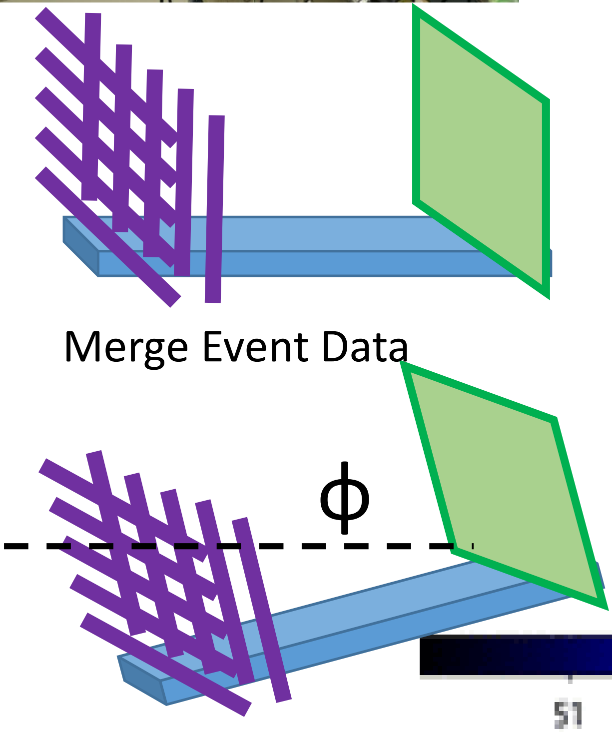
2D Image was obtained

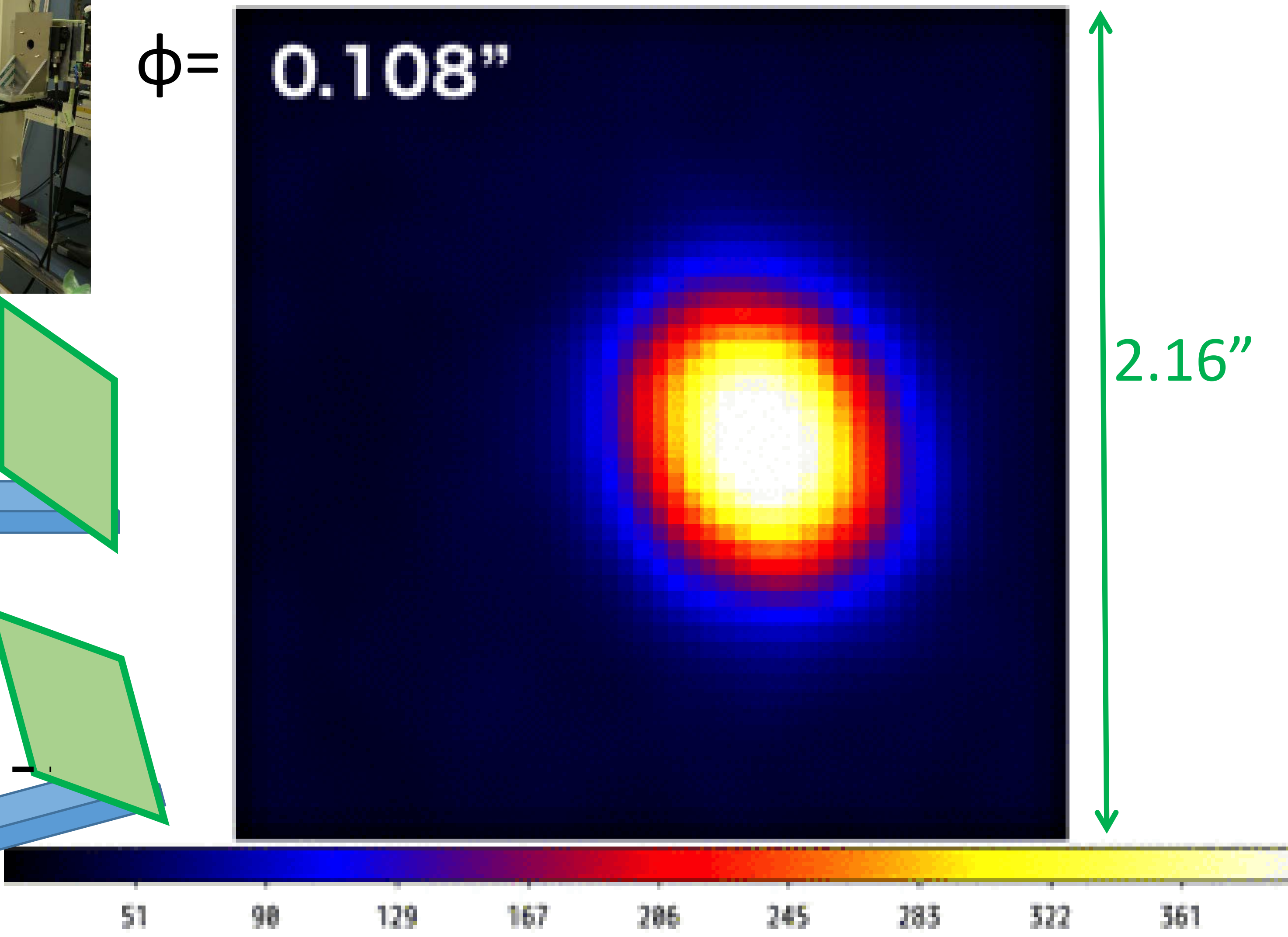
Ex=12.4keV, z=867cm



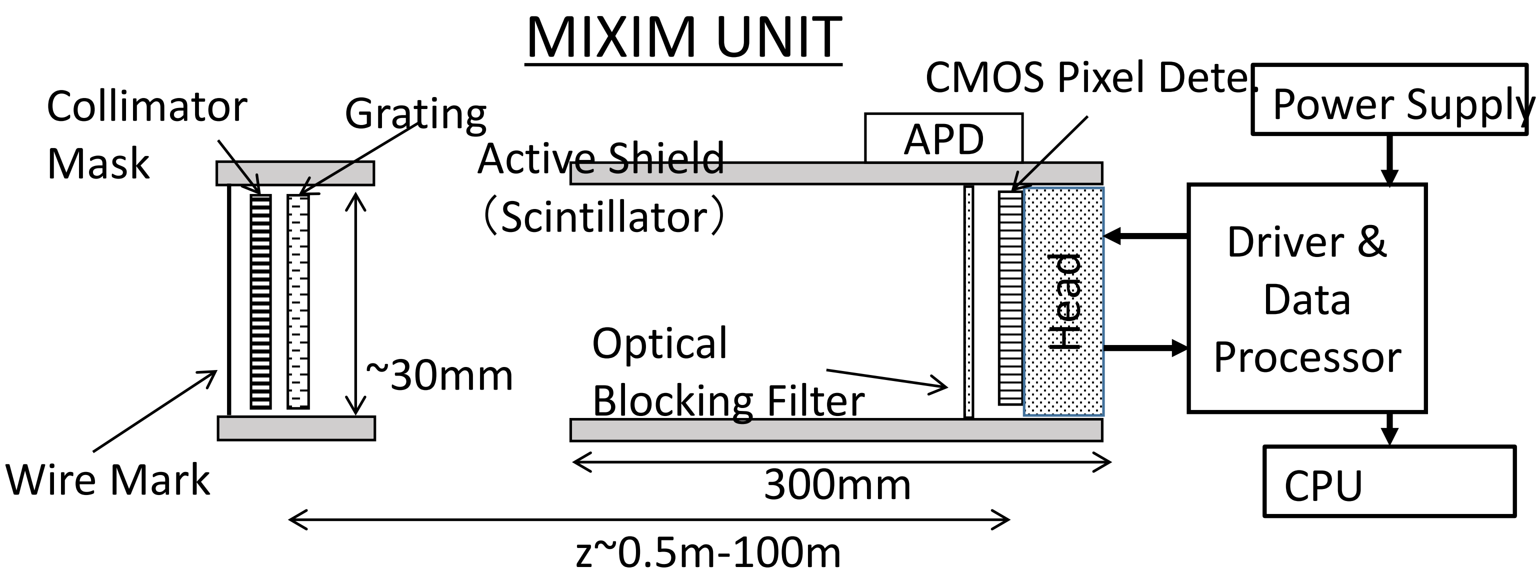
“Experimental” Simulation of Two Sources
z=92cm, Rotate the Optical Bench



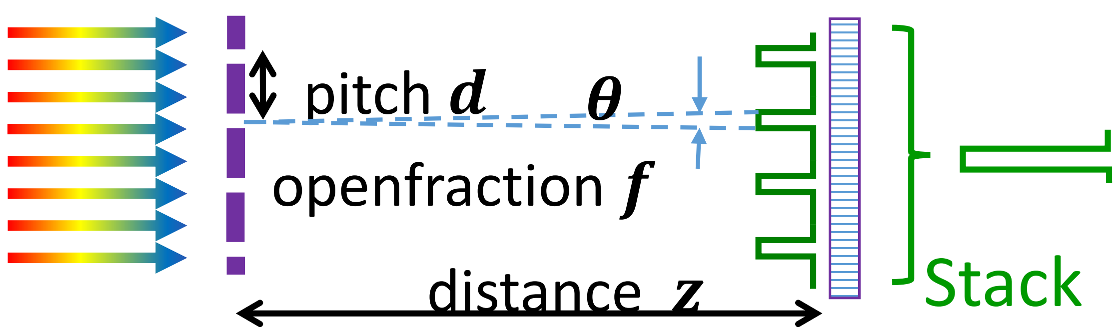


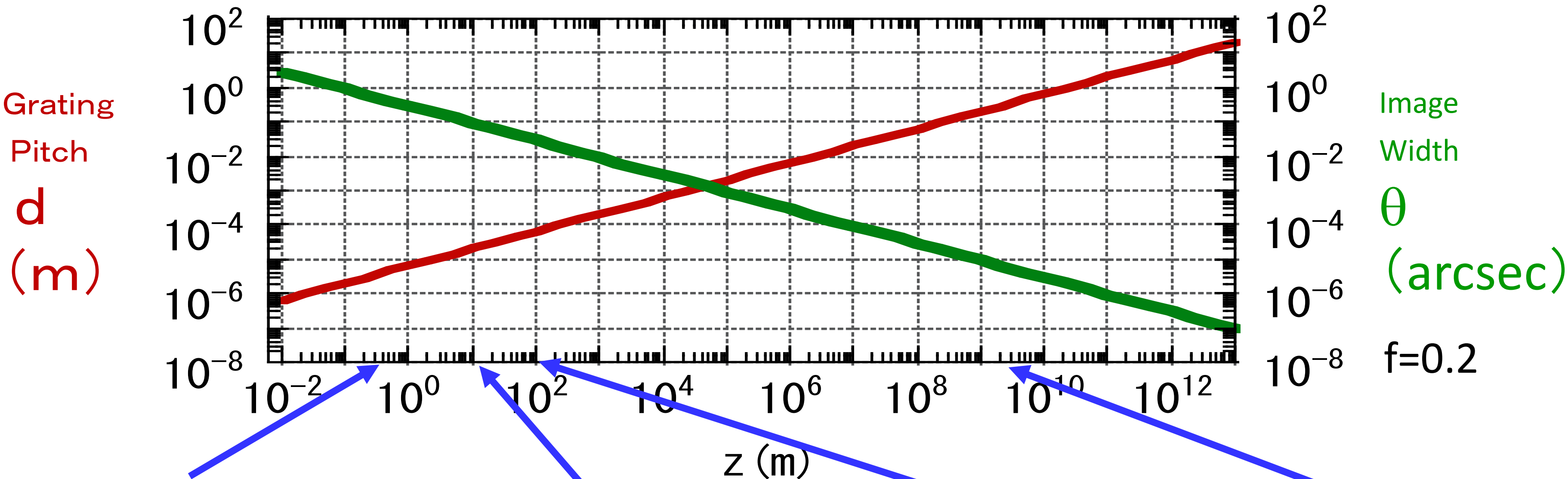


MIXIM is scalable in unit no and in d&z



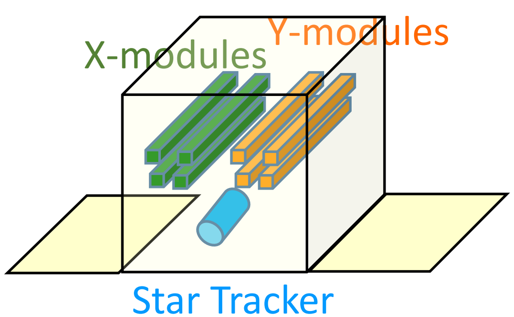
- $z = md^2/\lambda = 50\text{cm}\left(\frac{m}{2}\right)\left(\frac{d}{5\mu m}\right)^2 / \left(\frac{\lambda}{0.1nm}\right)$
- $\theta = \frac{fd}{z} = f\lambda/dm = 0.4''\left(\frac{f}{0.2}\right)\left(\frac{\lambda}{0.1nm}\right) / \left(\frac{d}{5\mu m}\right)\left(\frac{m}{2}\right)$

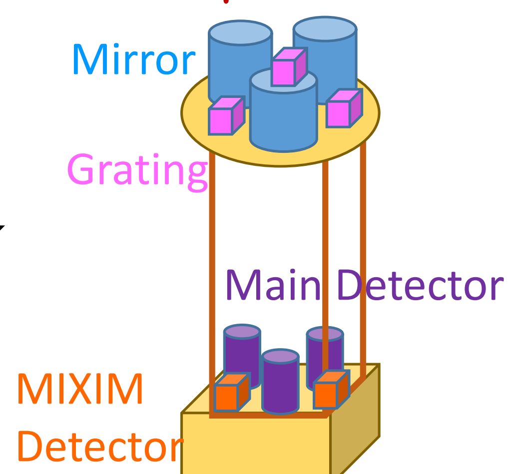


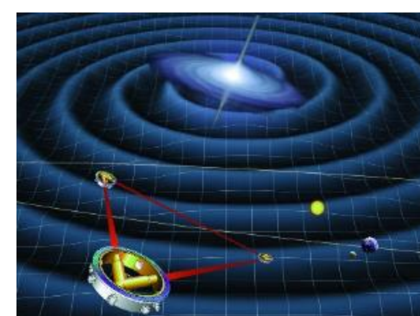


MIXIM-S (Small) -P (Parasite) -Z (Zoom) -L (Large/LISA)

MIXIM-S (Small)	-P (Parasite)	-Z (Zoom)	-L (Large/LISA)
z=50cm	z=10m	z=10~100m	z=2.5x10^6km
θ=0.4''	θ=0.09''	θ=0.1''~0.01''	θ=3μarcsec
d=5μm,f=0.2	d=22μm, f=0.2	d=100μm,f=0.1	d=35cm, f=0.1





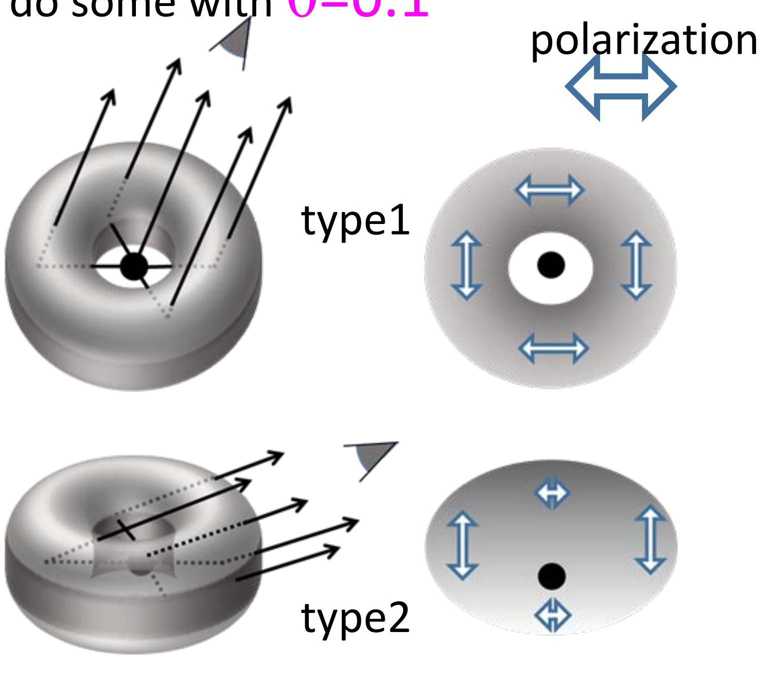


Targets >mCrab apparently point-like sources, e.g., nearby AGNs

X-ray Imaging and Polarimetry of AGN putative Torus

→Final Answer to AGN Unified Model

θ=0.01'' is goal but we can do some with θ=0.1''



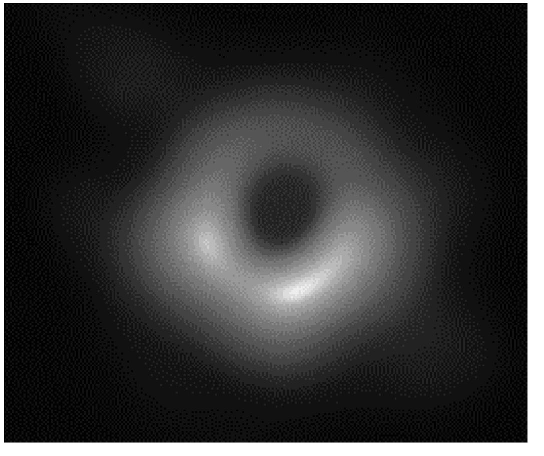
X-ray Image of EH

(Temperature/Abundance/Polrarization)

First Color Image of EH

θ=μarcsec

c.f. EHT image is B/W



Limitations Not like Mirrors

- No Collecting Power
  - Additional Collimator (0.1-1deg) is needed.
  - Eff. Area=Geo. Area x f x Det. Efficiency
  - Non Xray Background will be those for conventional collimator detectors
- Narrow “1-period” FOV

We should consider >mCrab apparently point-like targets with long exposures.

Many Technical Issues

- Attitude Determination must be better than the image resolution.
  - Conventional Star Trackers are not enough.
  - Techniques used in Astrometry may help.
  - Common Issue for super high angular resolution instruments
- Note: Attitude Control is not as severe as
  - X-rays through Grating goes Detector; tolerance of mm is allowed.
  - Formation flight case, fuel needed to control the grating satellite orbit may be a problem.
- Optical CMOS detection layer is currently thin, e.g. 5um.
- .....

MIXIM FAQ

1. Is MIXIM interferometer?
   - In the sense that the Talbot Interference condition is the key. Multi slit camera employing the Talbot interference may be appropriate.
2. What is the FOV of MIXIM.
   - Folded image within the (additional) collimator is obtained. FOV is thus 0.1-1deg, while 1-folding-period is very narrow. If we use f=0.2 grating, just 5 times of θ.
   - One bright point-like source within 0.1-1deg FOV is expected.
3. Effective Area of several cm^2 is too small, isn't it?
   - People observe >μCrab (Suzaku) >10nCrab (Chandra) sources with Telescopes with 100-1000cm^2 effective area.
   - For MIXIM targets >mCrab, it should be enough
   - cf. We roughly estimate 0.1 c/MIXIM-unit/Crab with technical enhancement in next few years. 5 units, 5mCrab source need 0.5Ms to collect 10^3 counts.

Detection layer→10um,
Geo. Area of 1 CMOS→20mmx20mm
New mask with Opening fraction of 0.5 keeping image width as 0.2

4. How can you obtain 2D image? Muti-Pin-Hole?
   - 1D units placed X and Y are baseline. 2D mask with larger opening is being designed.