20200121_AGN Jet Workshop @Tohoku Univ.

Sub-arcsecond to μ-arcsecond Resolution X-ray Imaging of SMBH with a novel method MIXIM

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+

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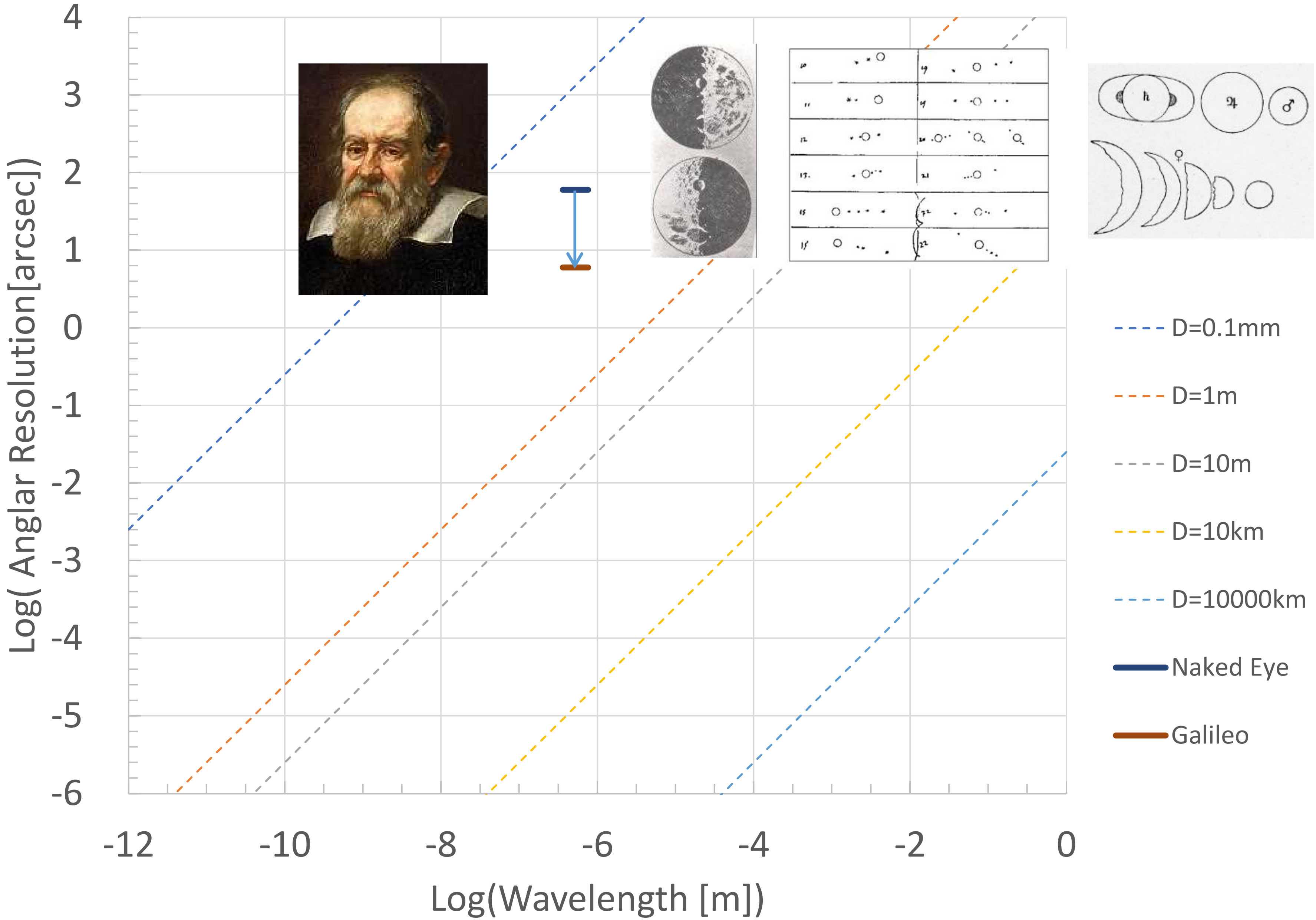
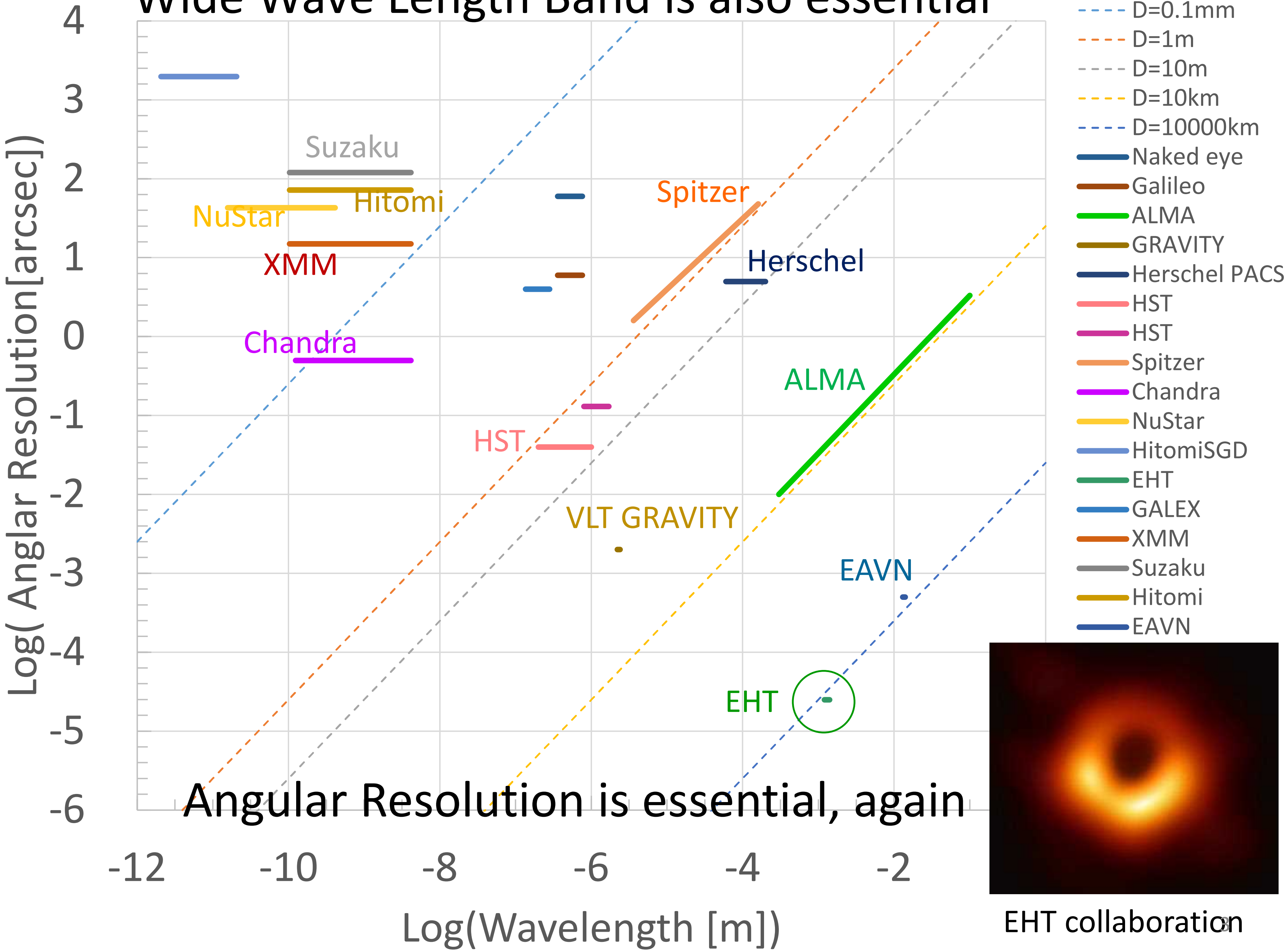
J.S. Hiraga (Kwansei-Gakuin Univ.)

Angular Resolution is essential



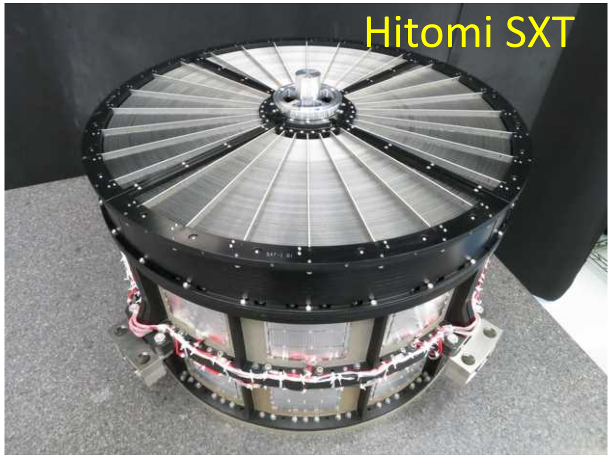
Wide Wave Length Band is also essential

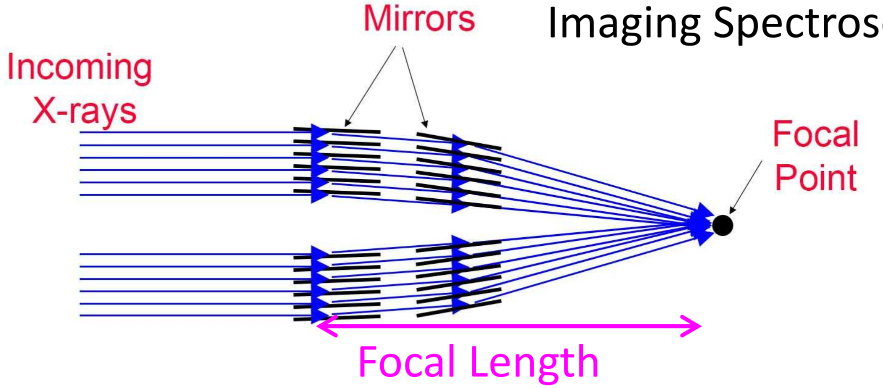


Angular Resolution is essential, again

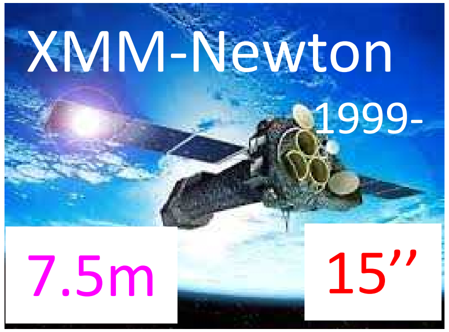
EHT collaboration

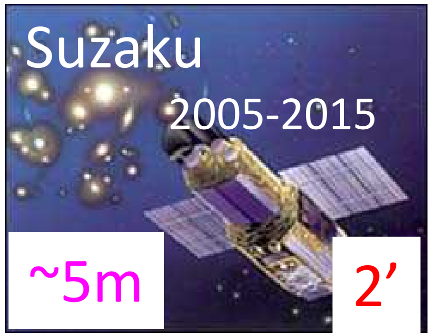
Grazing Incidence Mirror + X-ray CCD is the de facto standard of X-ray Observatories since ASCA (1993)





Photon Counting
Imaging Spectroscopy

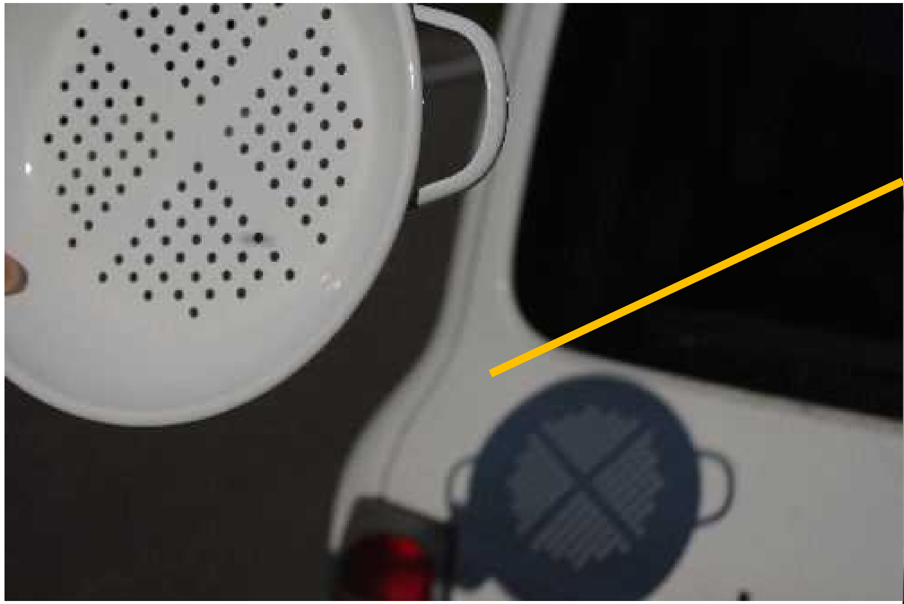




- Angular resolution is exceptionally good for Chandra, 0.5''.
- Better or similar resolution mirror is very difficult to make (cost etc).
- Satellites must be big when grazing incidence mirrors are employed.

Our challenge to this field consensus →MIXIM

Multi-Pinhole(Slit) Camera is the baseline

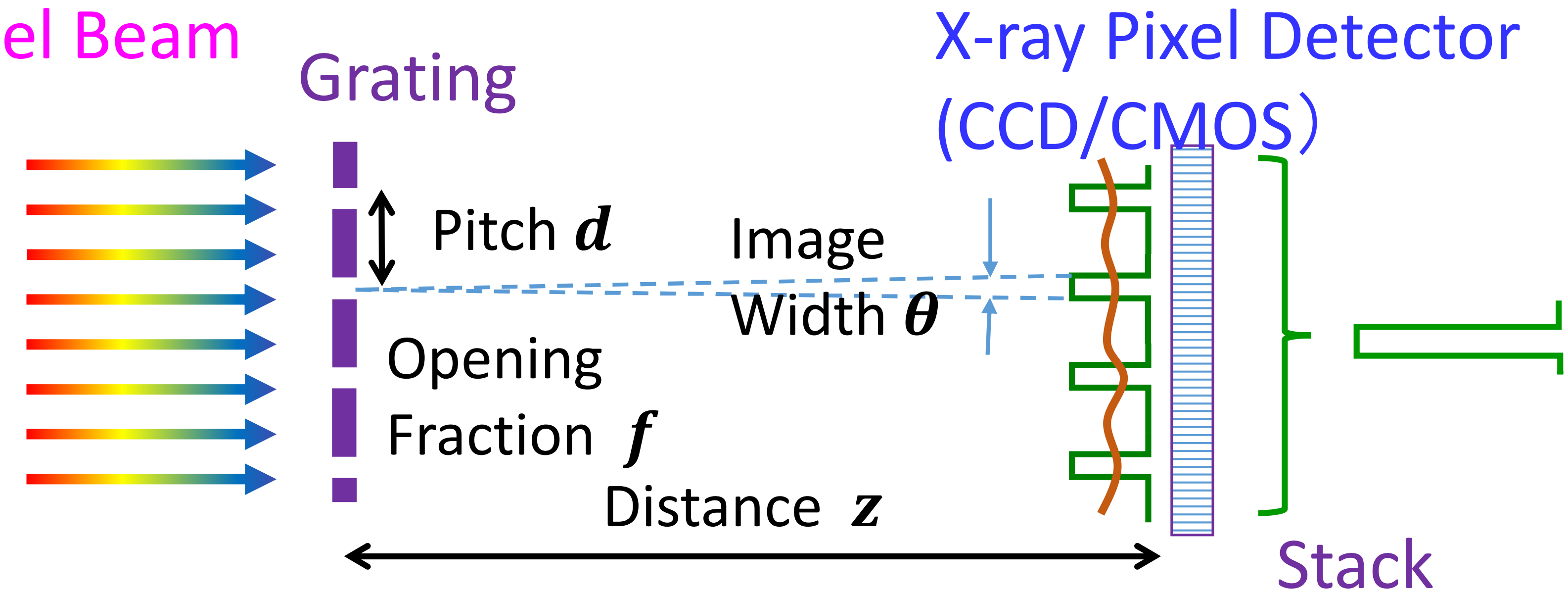


http://blog.goo.ne.jp/hanahanaharu04/e/a8ef27218dee3713136a89943109a431

STACK
these multiple
images in the
analysis

Multi Image X-ray Interferometer/Imager

Hayashida+2016



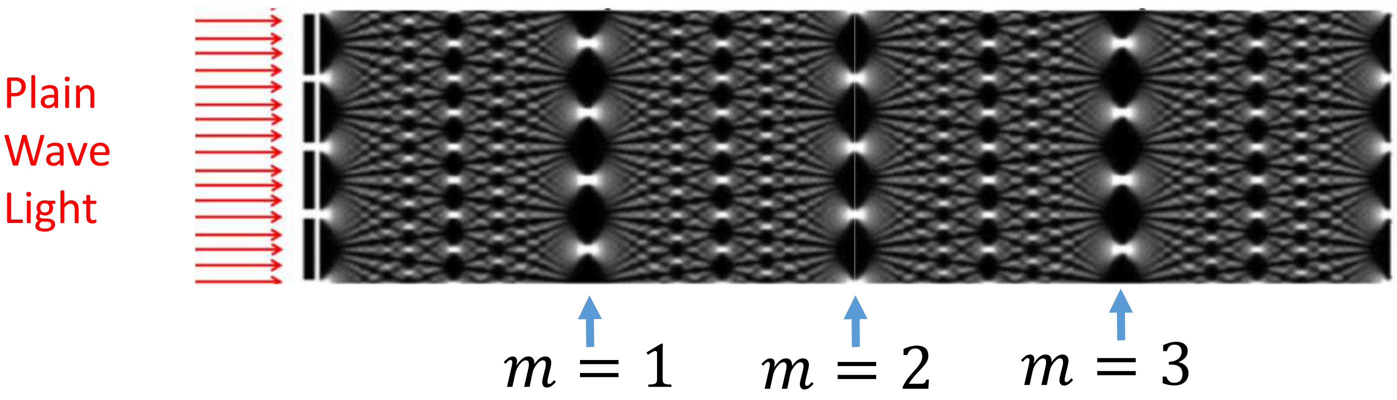
- Only employ a Grating and an X-ray Pixel Detector
- Image profile detected reflects the profile of the X-ray source.
- Stacking the image with a period of d in the analysis, accurate source profile is obtained.
- Image Width $\theta = fd/z = 0.4'' \left(\frac{f}{0.2}\right)\left(\frac{d}{5\mu m}\right)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

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** $z_T = m\frac{d^2}{\lambda}$



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

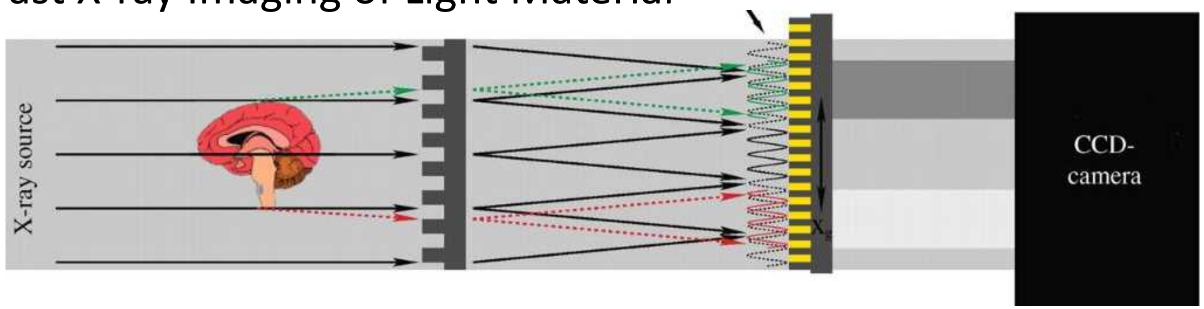
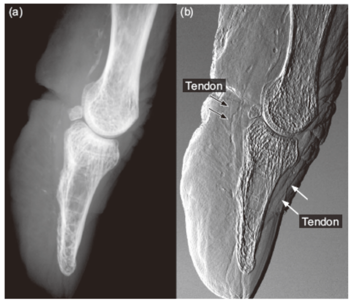
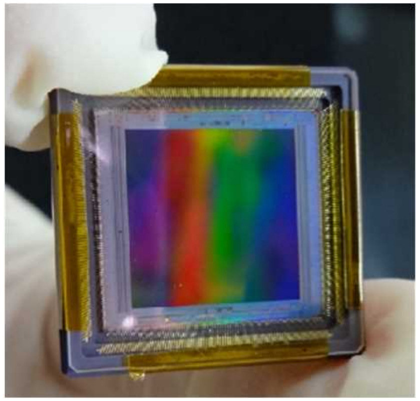


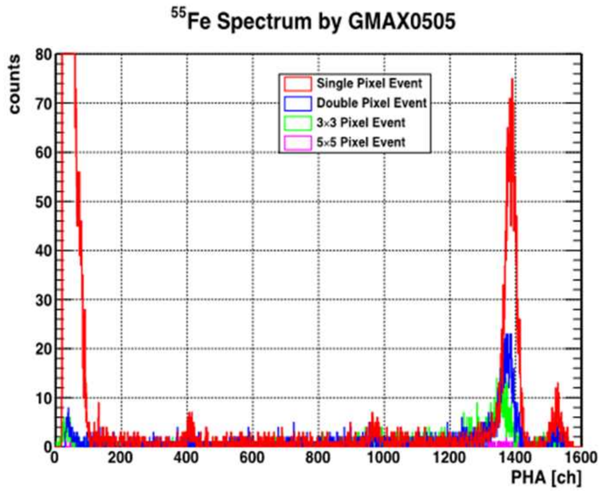
Figure from http://rsif.royalsocietypublishing.org/content/7/53/1665



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.





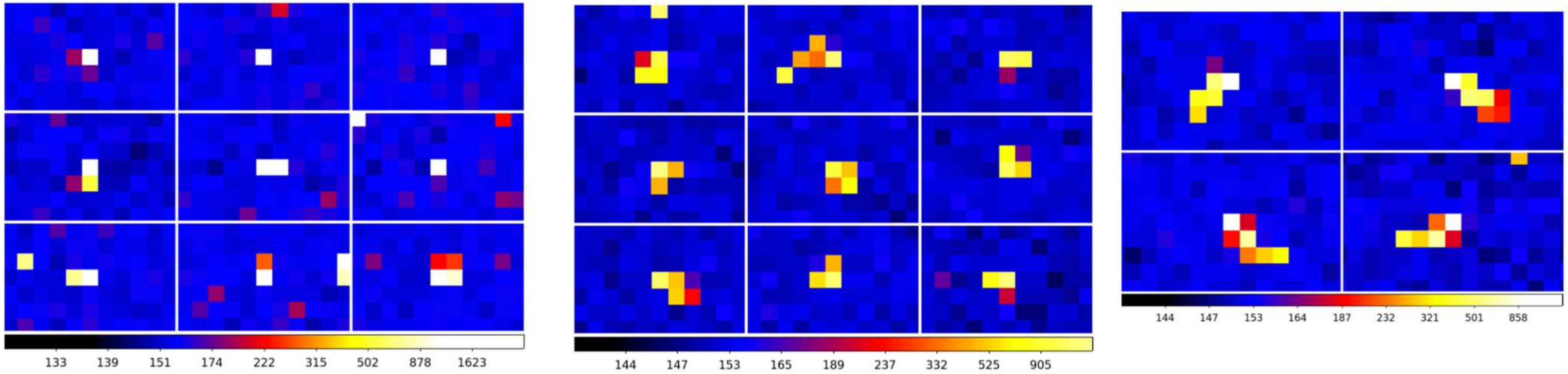
FWHM=170eV@5.9keV
at Room Temperature!!!
In Open Air

Detection Layer ~ 5μm Thick

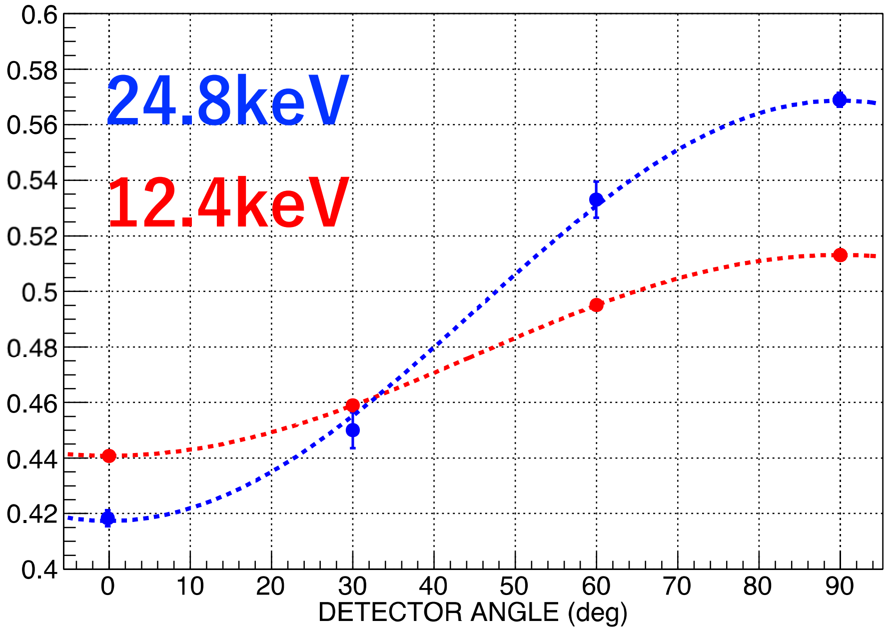
Small pixel size enables us to detect X-ray polarization
See Asakura+ 2019, JATIS, 5(3) and Poster #501

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

12.4keV **24.8keV**



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



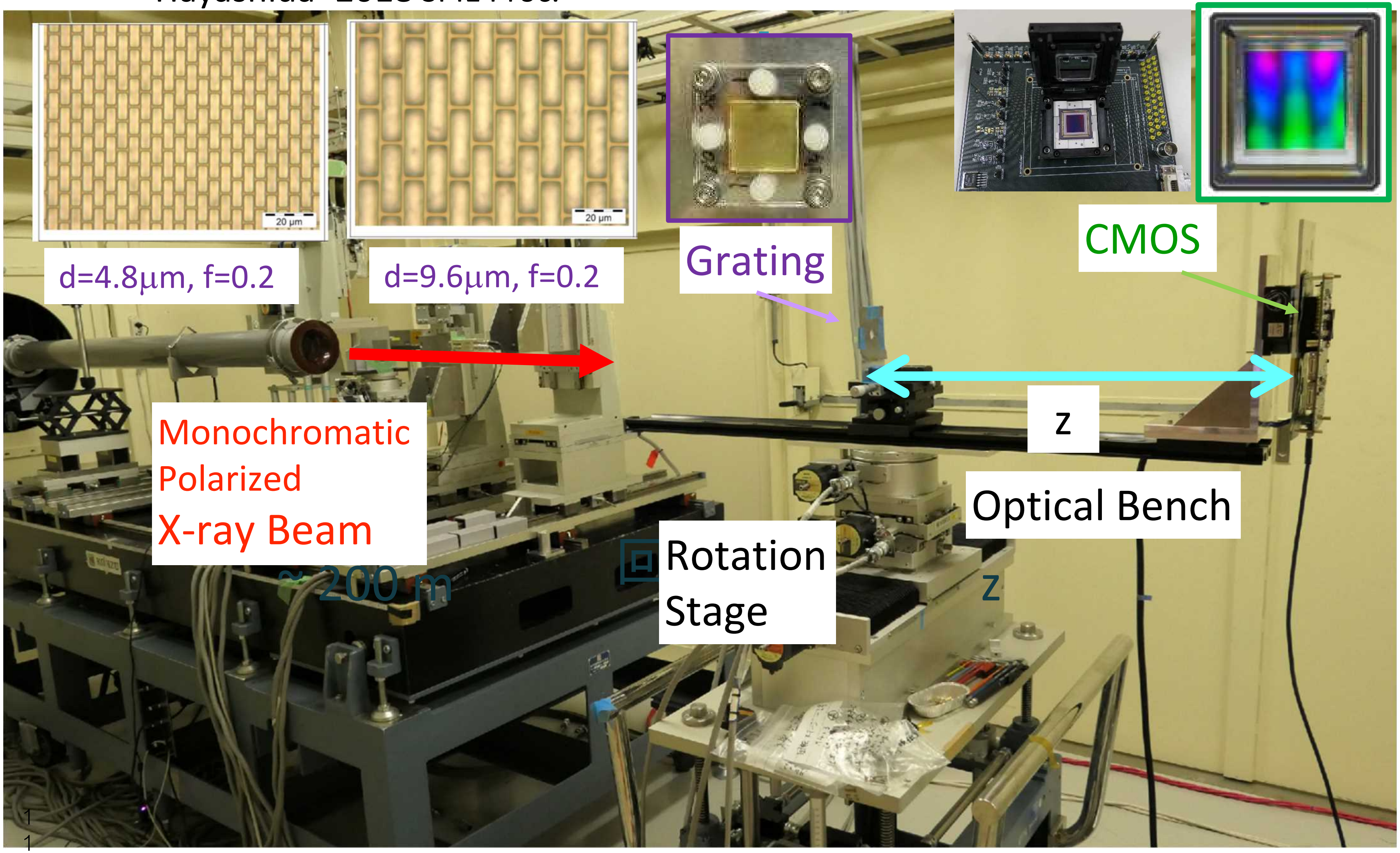
Asakura+2019
JATIS, 5(3)

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)

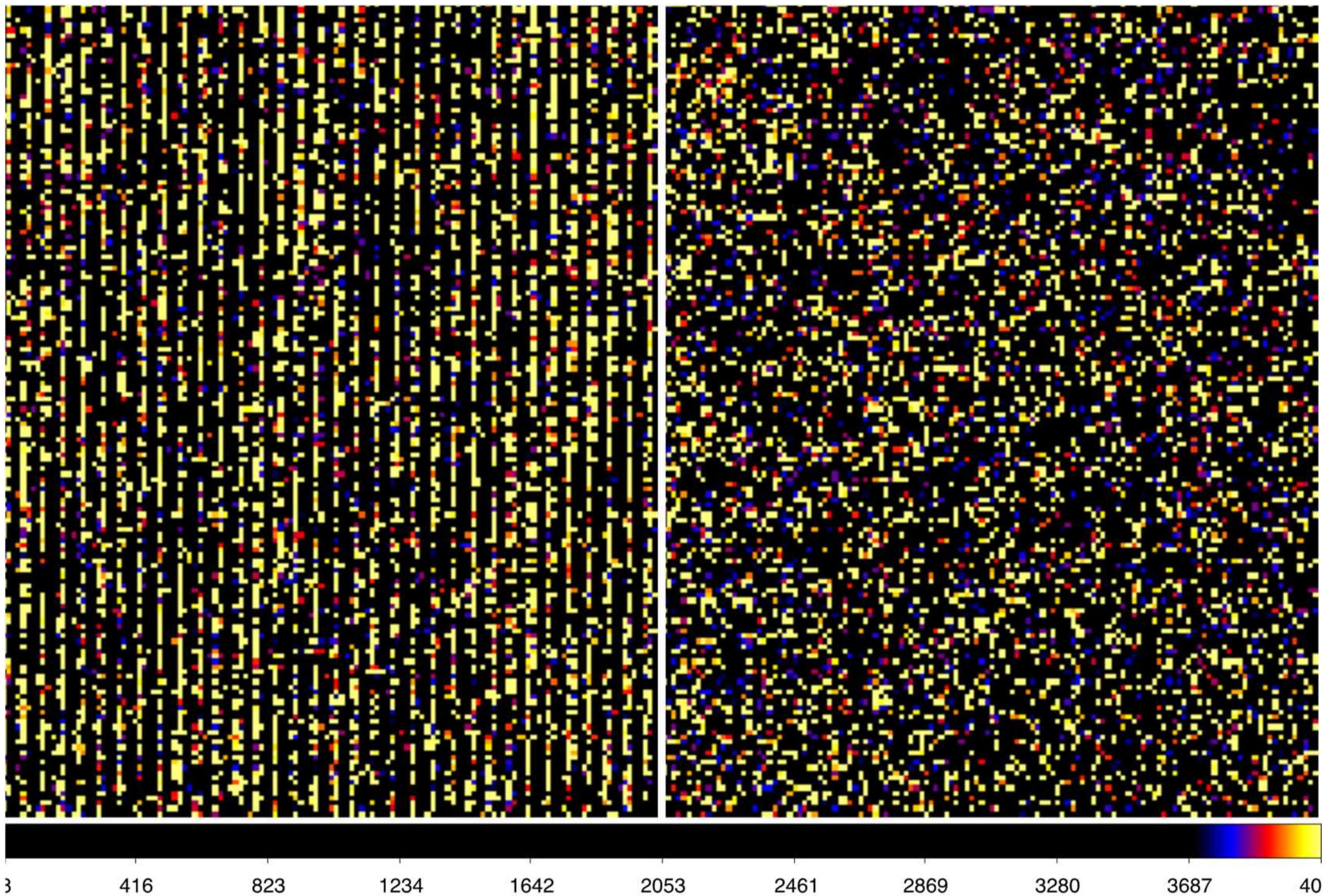
Hayashida+2018 SPIE Proc.



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

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

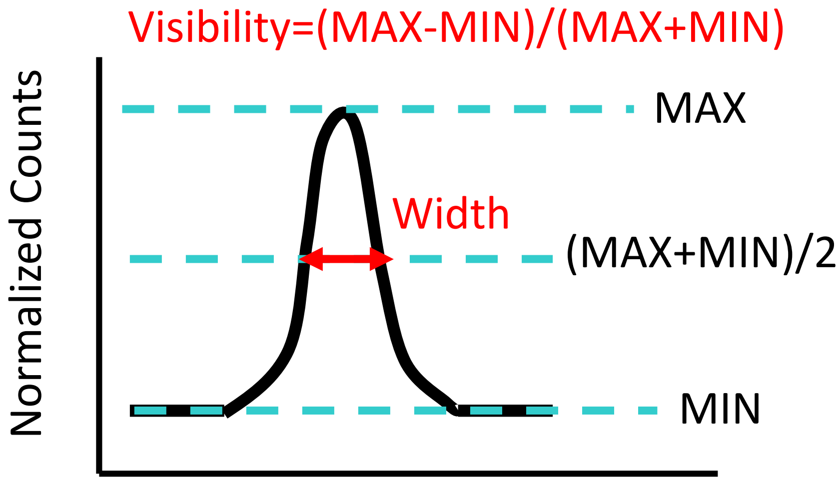
Ex=10.0keV (m=1.24; NOT meet)



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

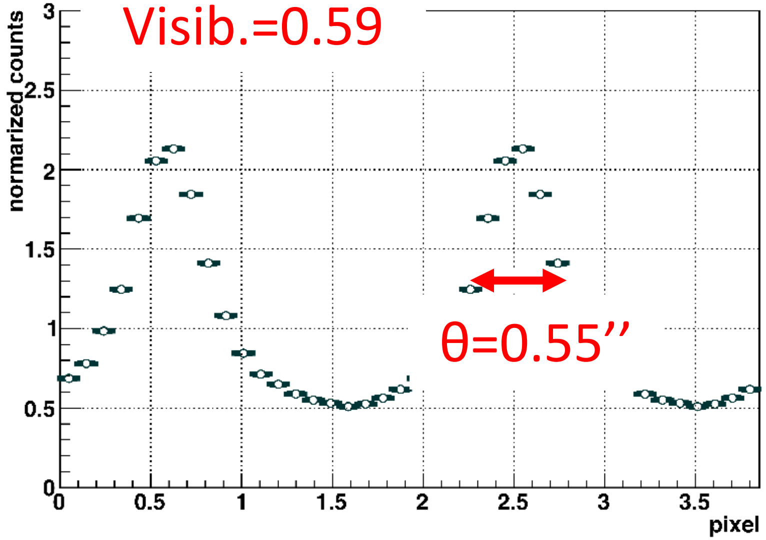
Event Extraction→Projection→Folding Ex=12.4keV

Folded Profile

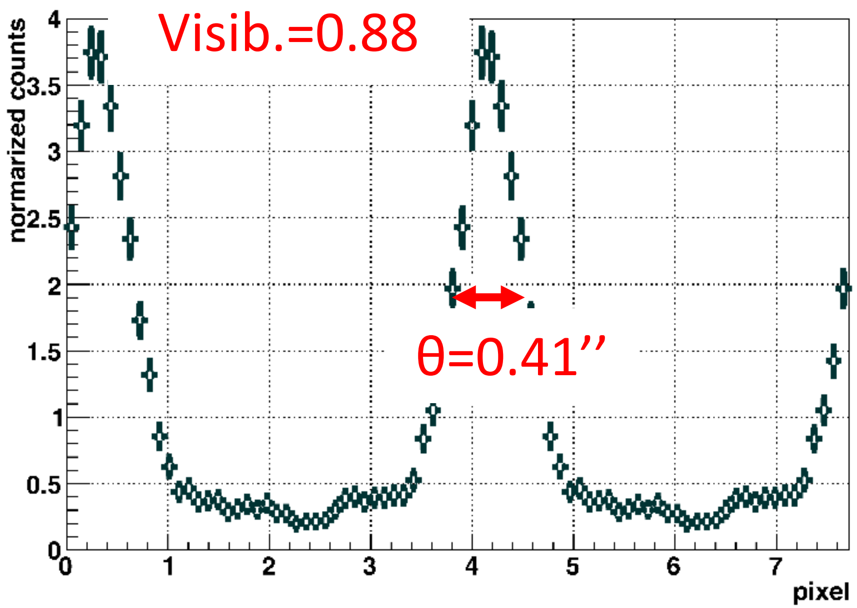


*) Two periods are plotted for display purpose

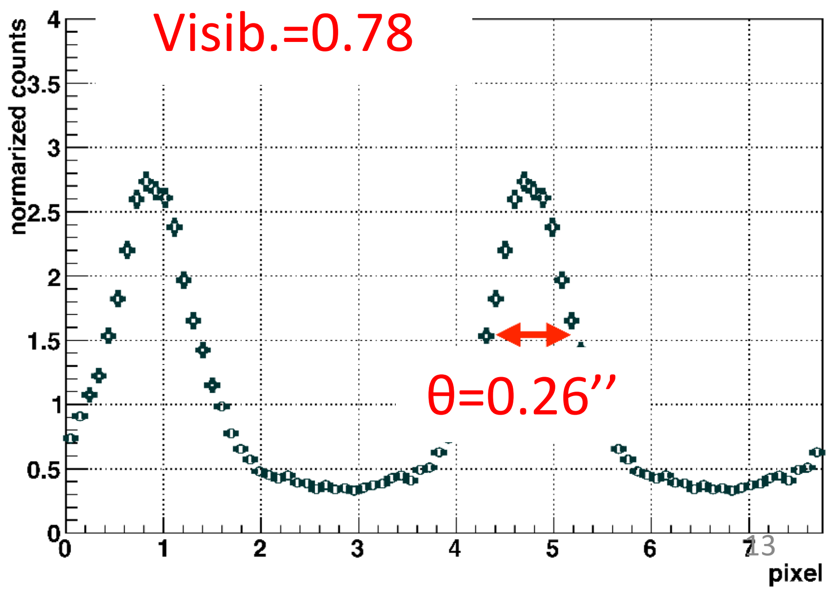
d=4.8μm, z=46cm



d=9.6μm, z=92cm

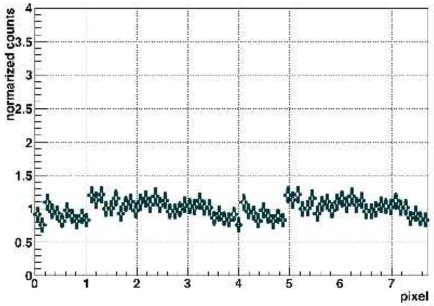


d=9.6μm, z=184cm

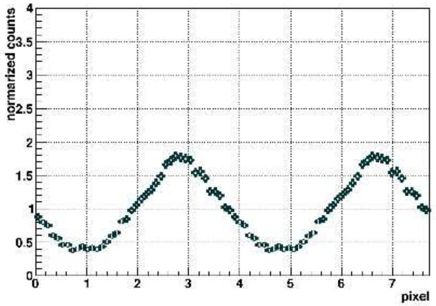


Energy Dependence of Visibility

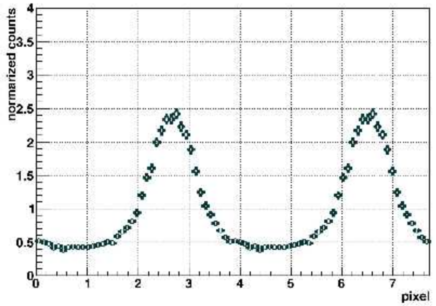
E = 10.0 keV



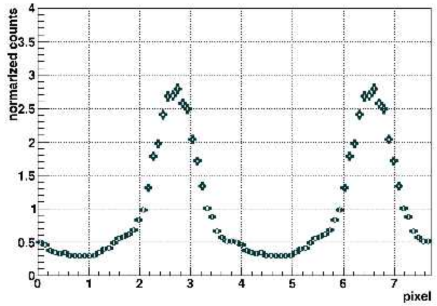
E = 11.6 keV



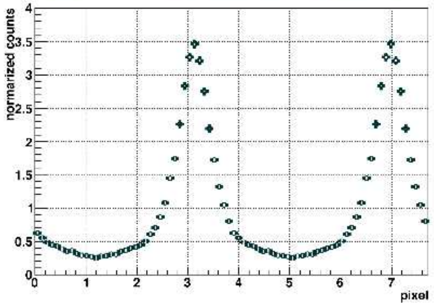
E = 11.8 keV



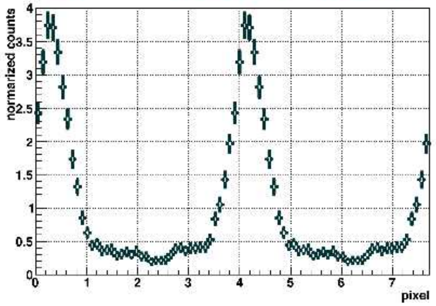
E = 12.0 keV



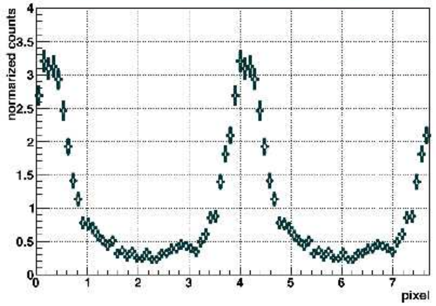
E = 12.2 keV



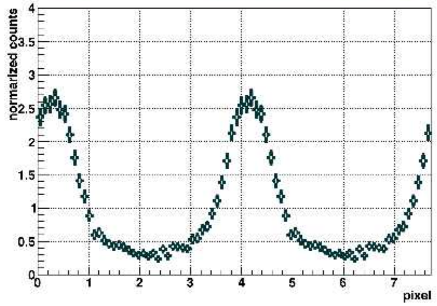
E = 12.4 keV



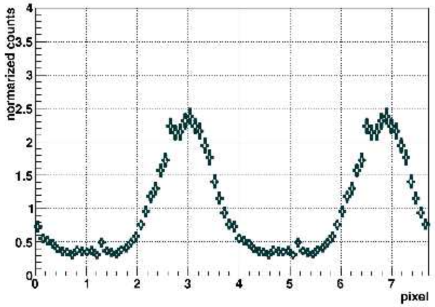
E = 12.6 keV



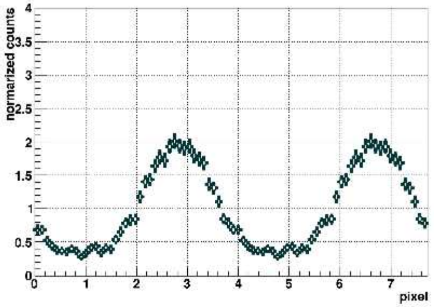
E = 12.8 keV



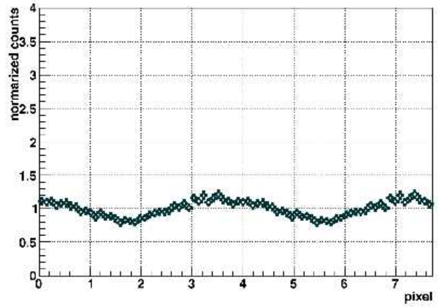
E = 13.0 keV



E = 13.2 keV

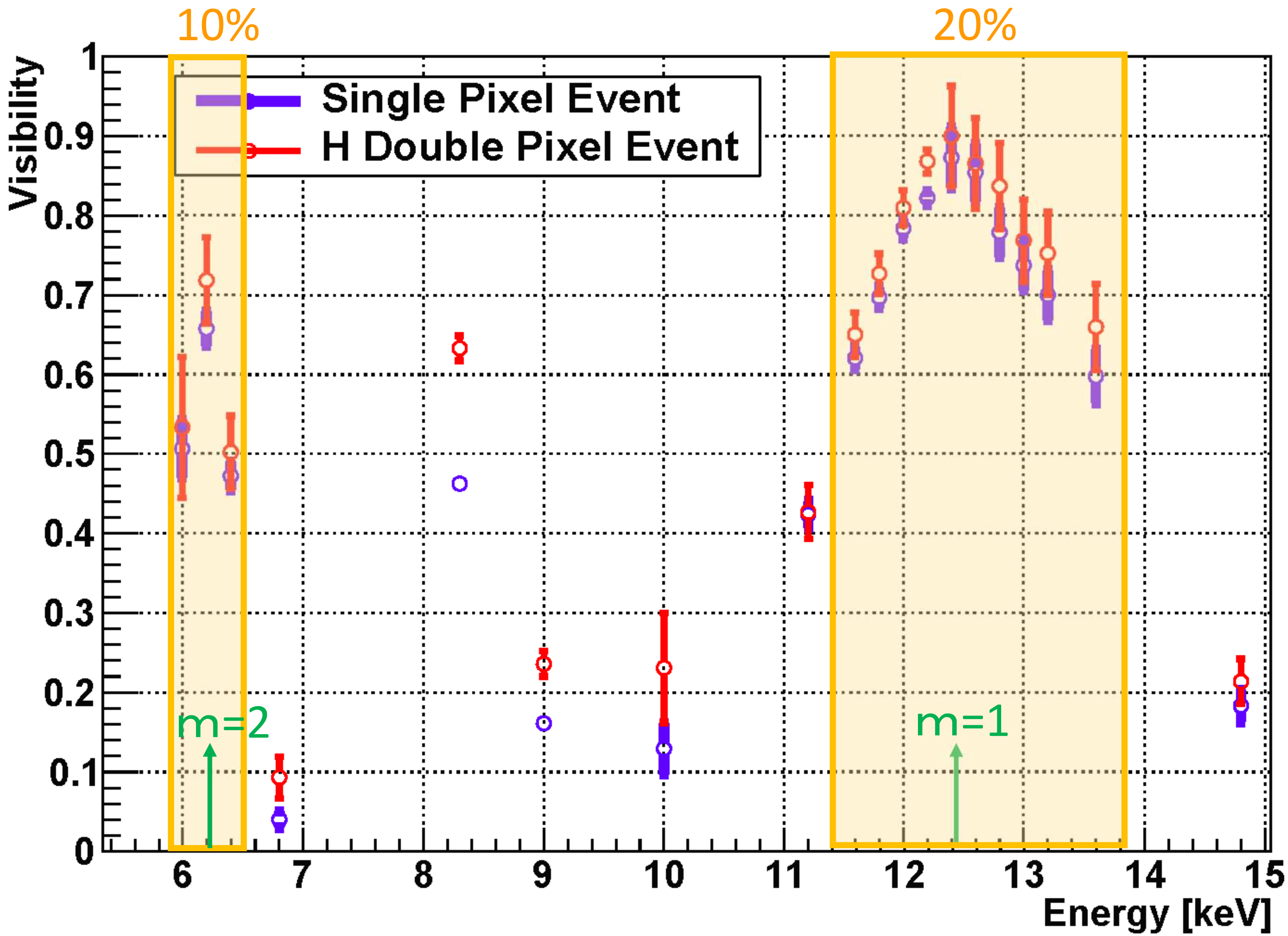


E = 14.8 keV



Energy Dependence of Visibility→Band Width

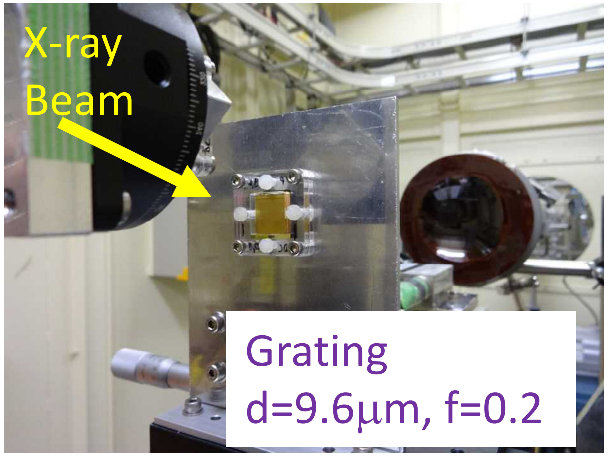
d=9.6μm,f=0.2, z=92cm



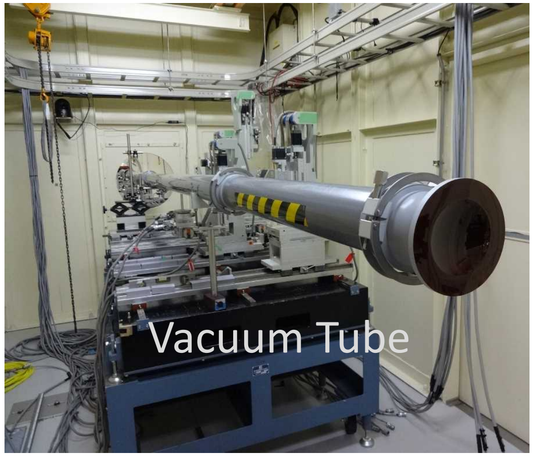
SPring-8 BL20B2 2019 Jul

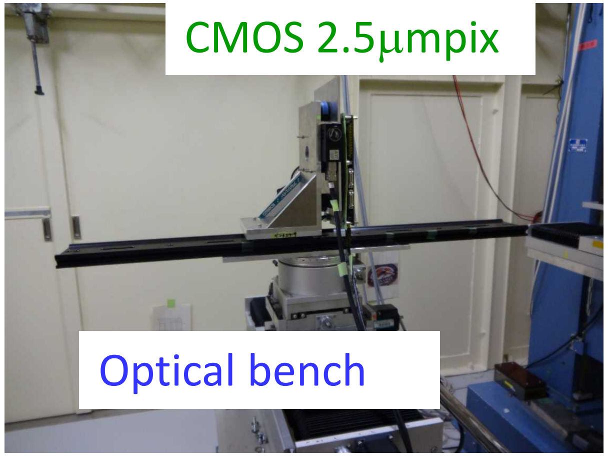
1. Test large z case to obtain smaller (better) Image width <0.1’’
2. First 2D imaging by stacking two 1D gratings diagonally

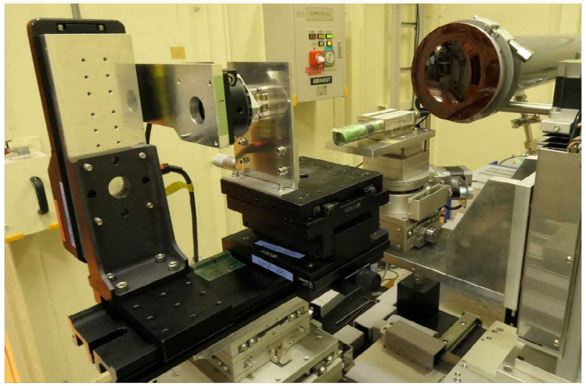
z=8.67m



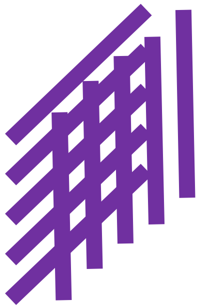
This Image is flipped horizontally to explain the configuration



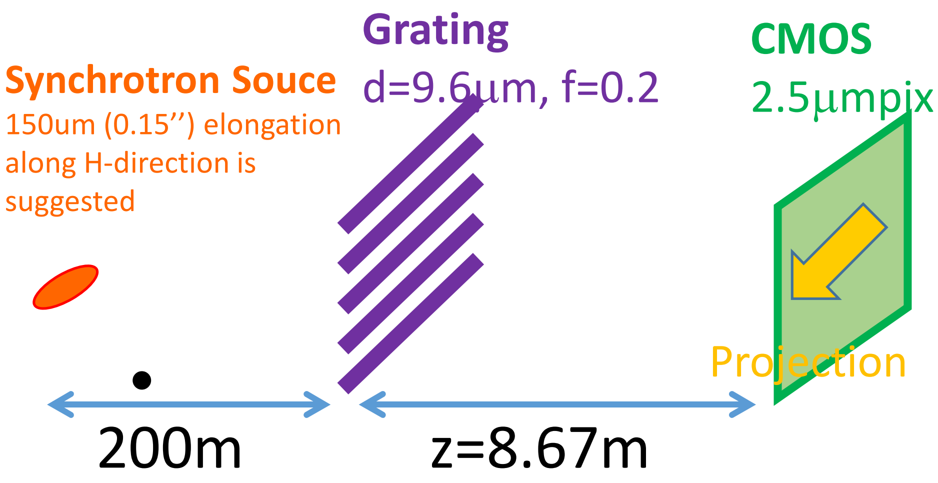


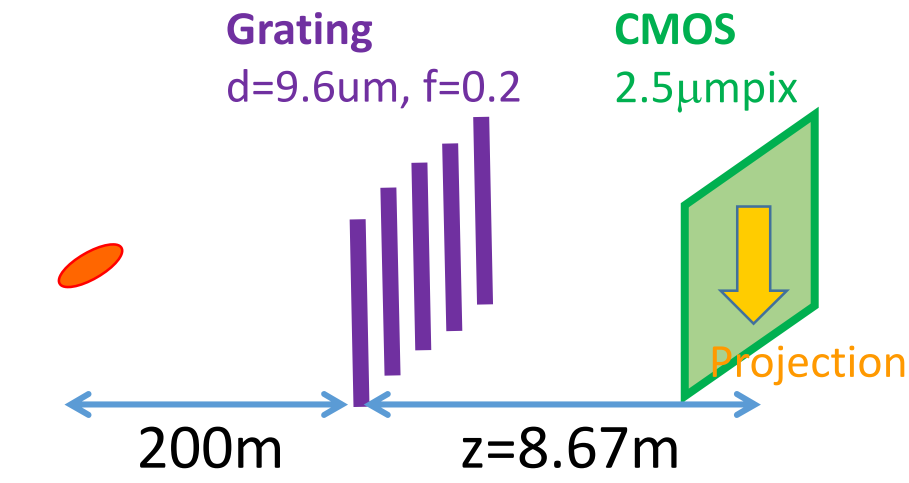


This Image is flipped horizontally to explain the configuration

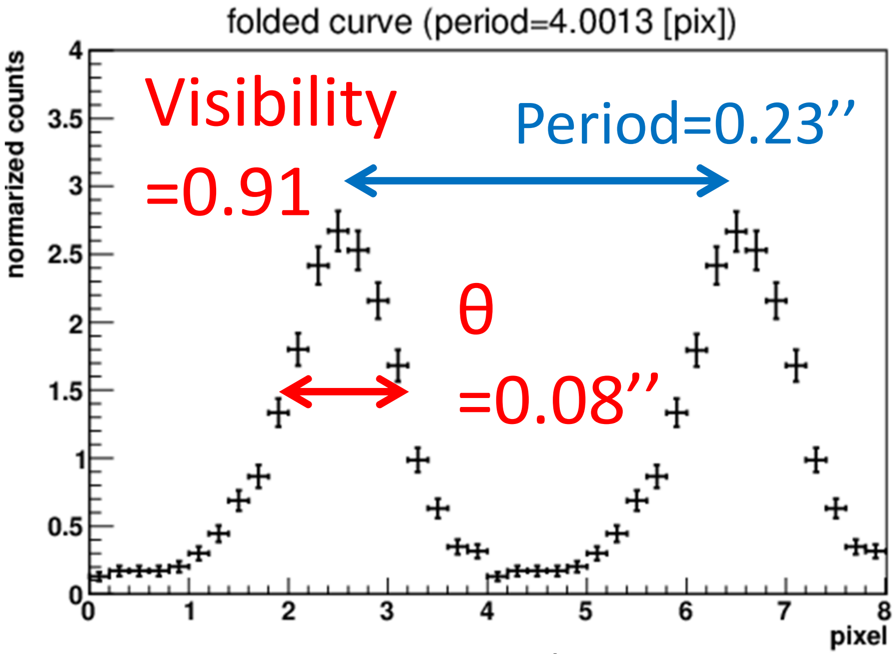


Resolution <0.1'' , best ever achieved with X-ray astronomical imagers

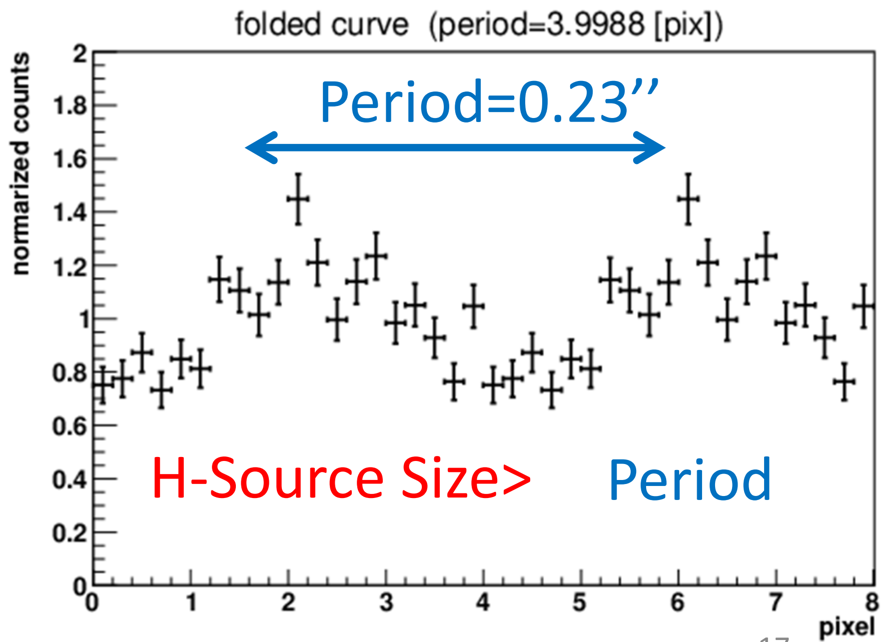




Ex=12.4keV



Ex=12.4keV

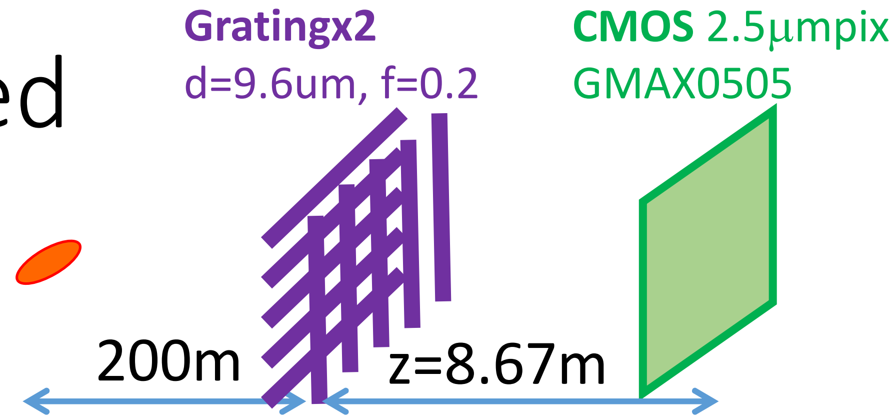


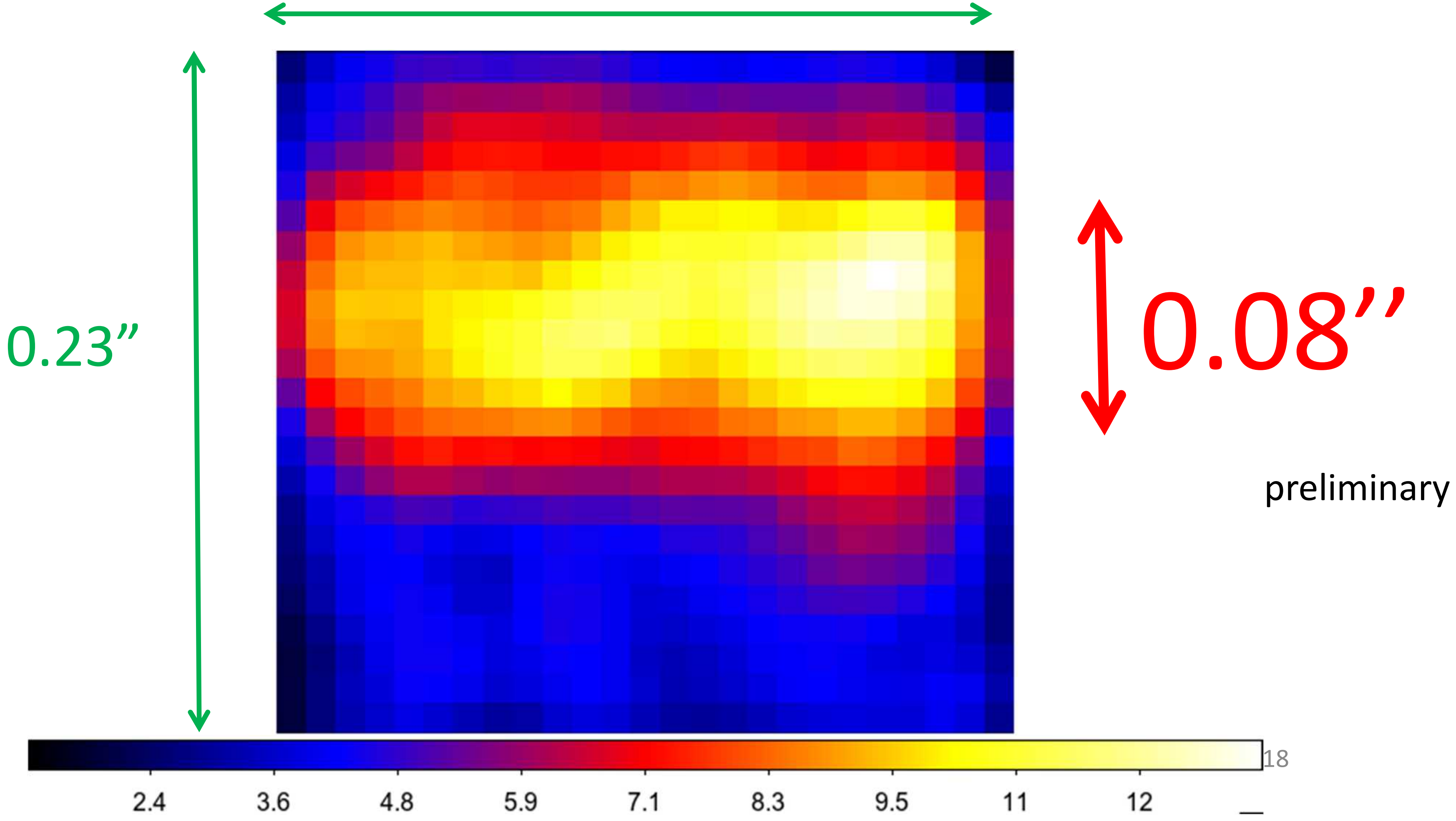
preliminary

1pixel=2.5um

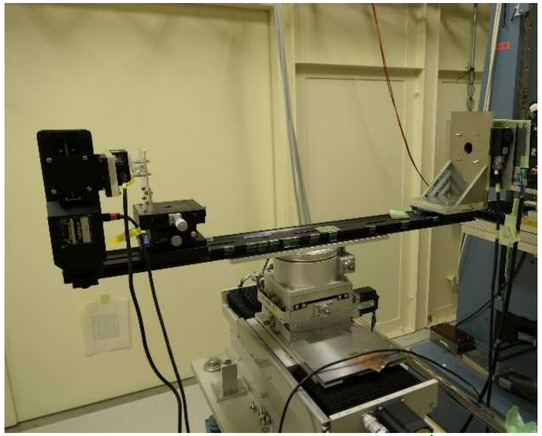
2D Image was obtained

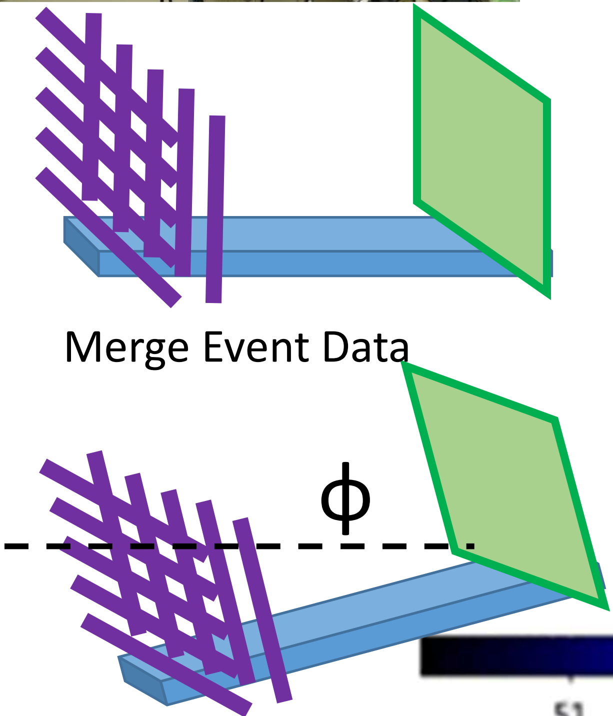
Ex=12.4keV, z=867cm



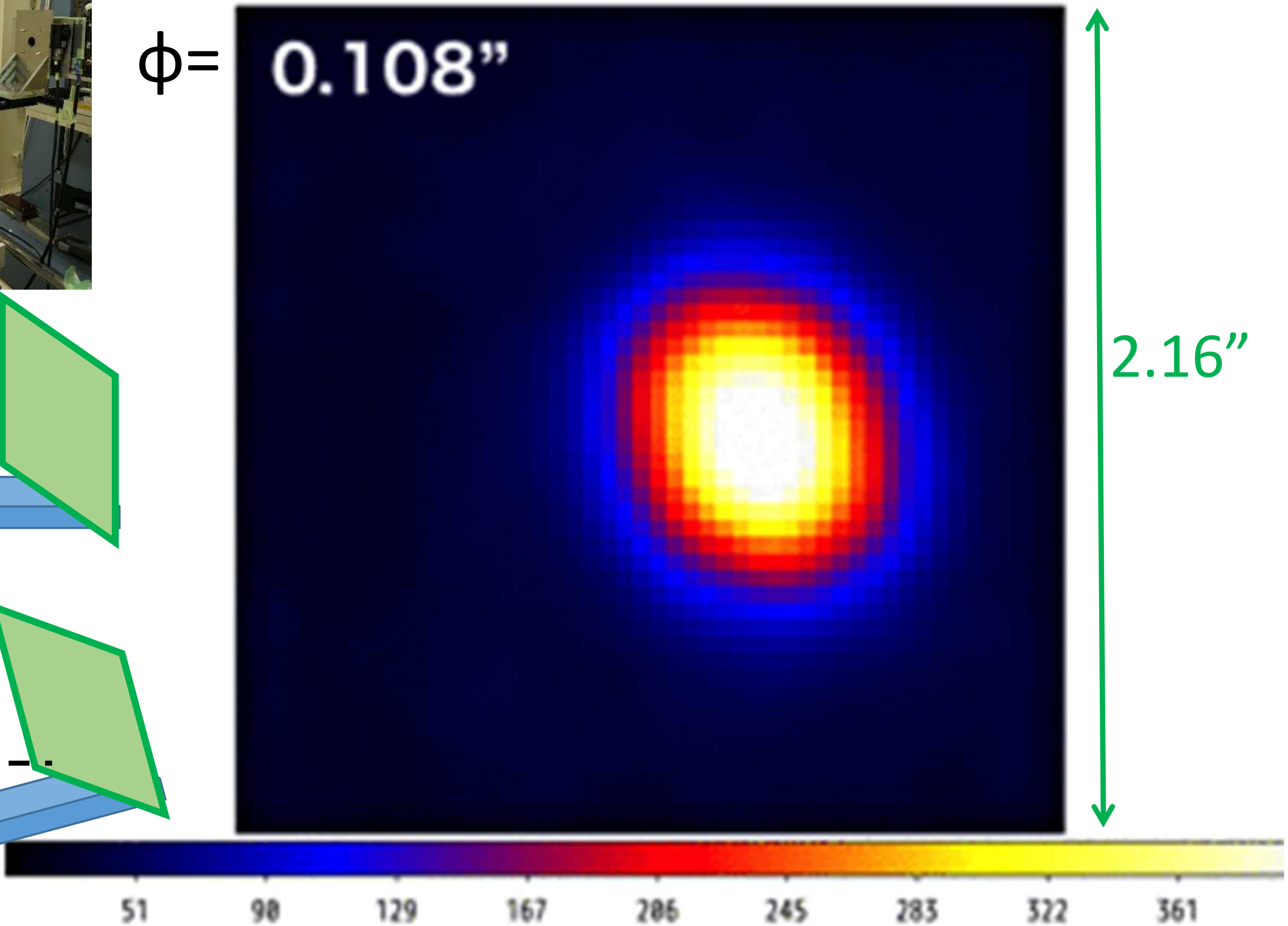


“Experimental” Simulation of Two Sources
z=92cm, Rotate the Optical Bench

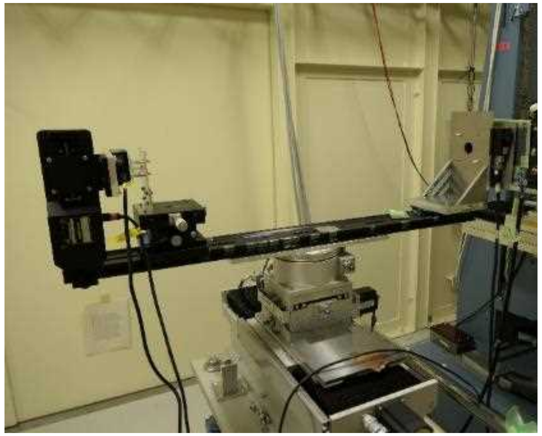


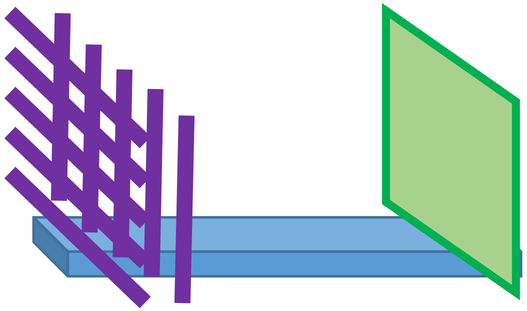


Real Observations of a 8GeV Jet on the Earth

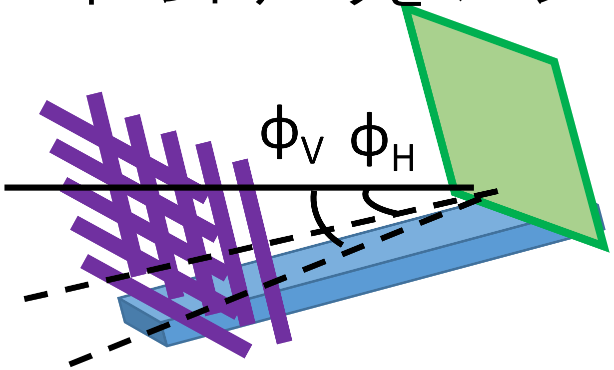


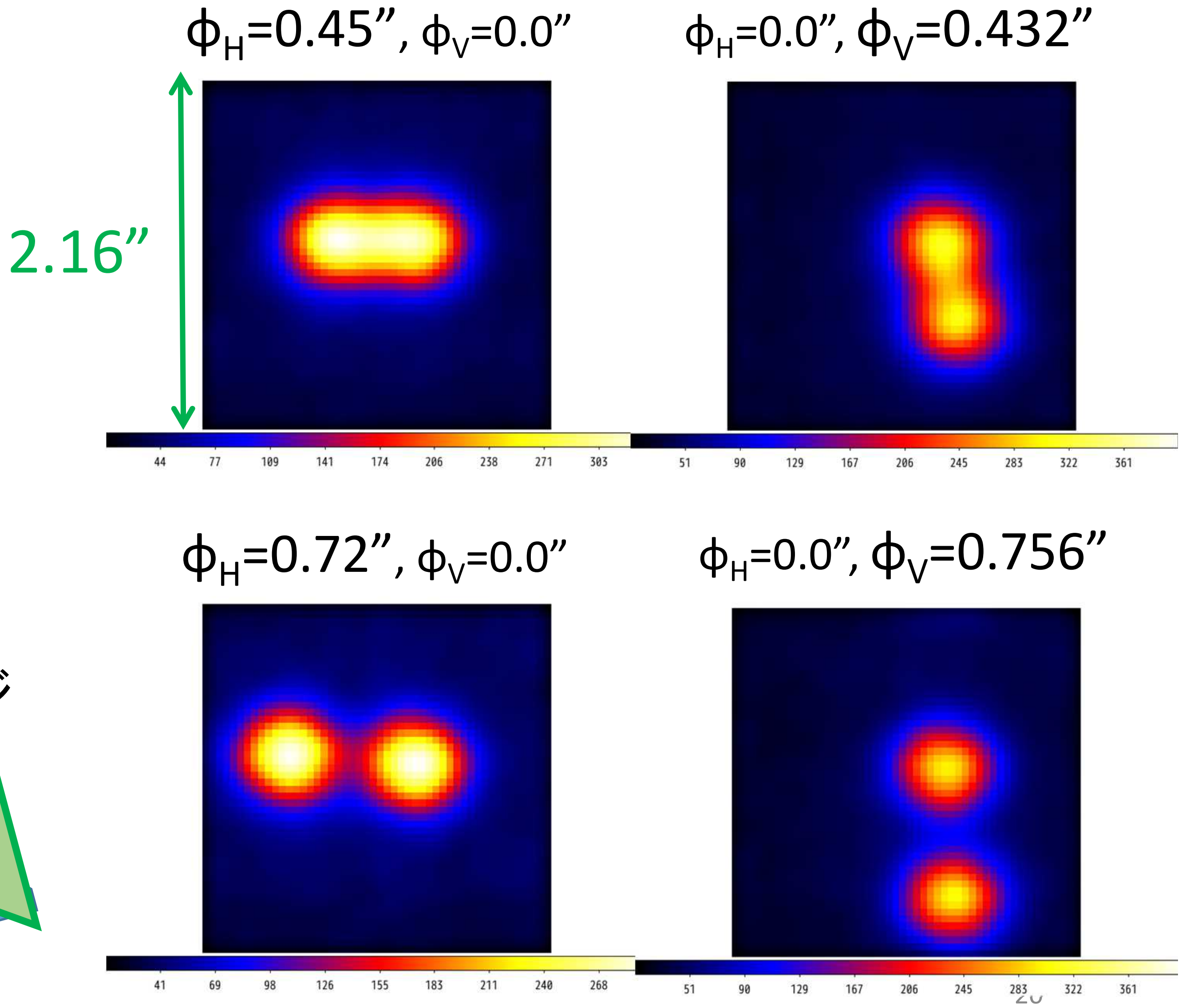
z=0.92m　光学台の向きを変えてデータ取得
イベントデータをマージ=2個の天体の観測模擬



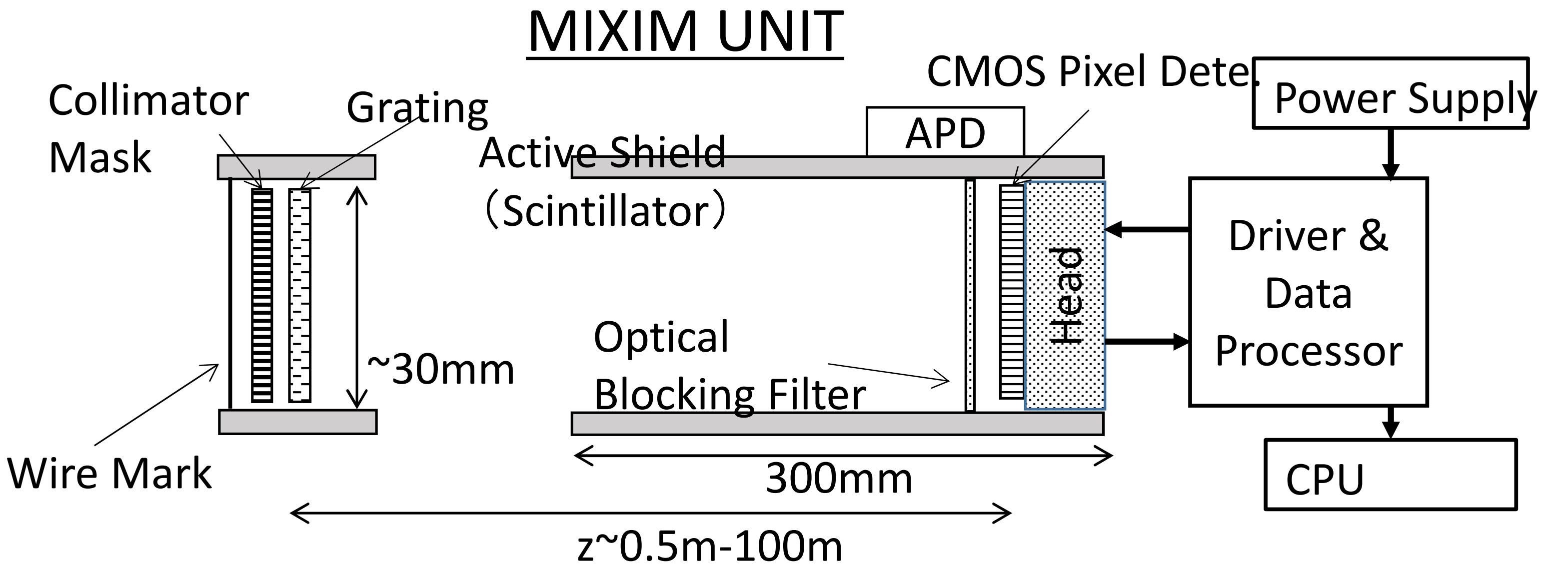


イベントデータをマージ

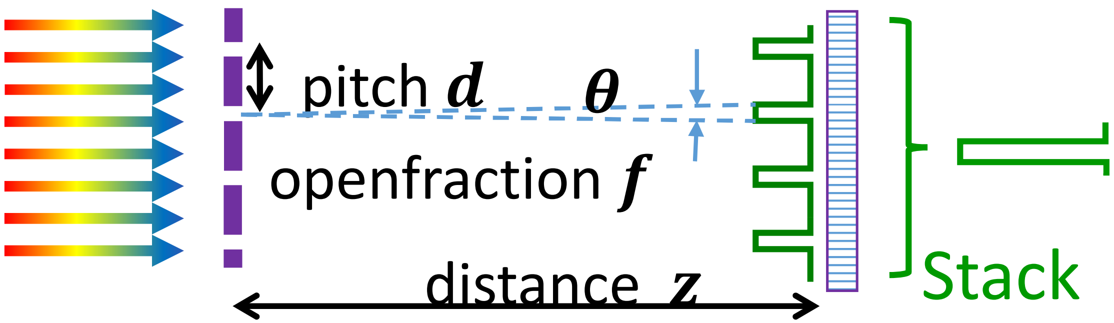


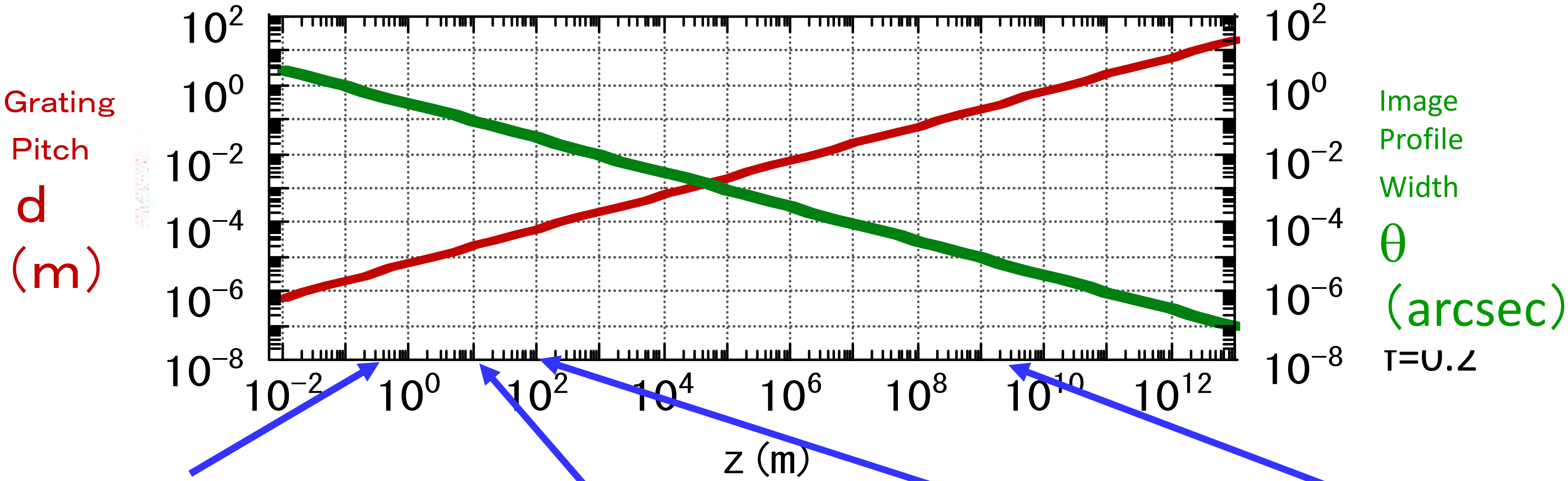


MIXIM is scalable in unit no and in d&z

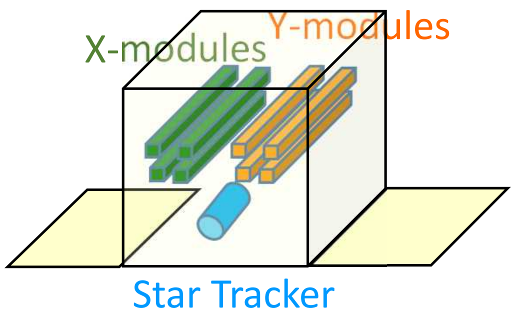


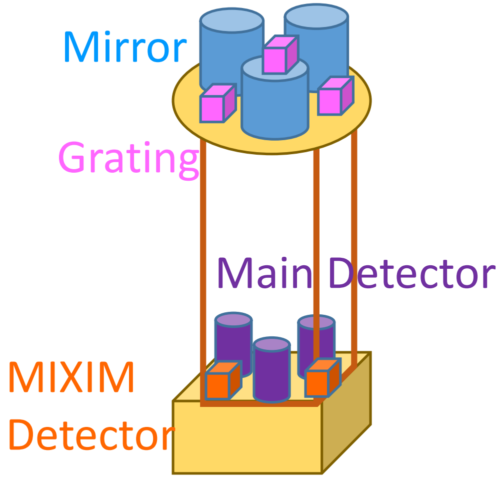
- $z = md^2/\lambda = 50\text{cm}\left(\frac{m}{2}\right)\left(\frac{d}{5\mu m}\right)^2 / \left(\frac{\lambda}{0.1nm}\right)$
- $\theta = \frac{fd}{z} = f\lambda/dm = 0.4''\left(\frac{f}{0.2}\right)\left(\frac{\lambda}{0.1nm}\right) / \left(\frac{d}{5\mu m}\right)\left(\frac{m}{2}\right)$

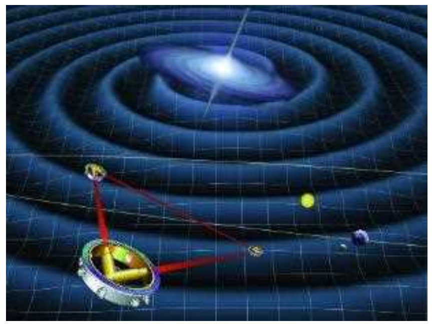


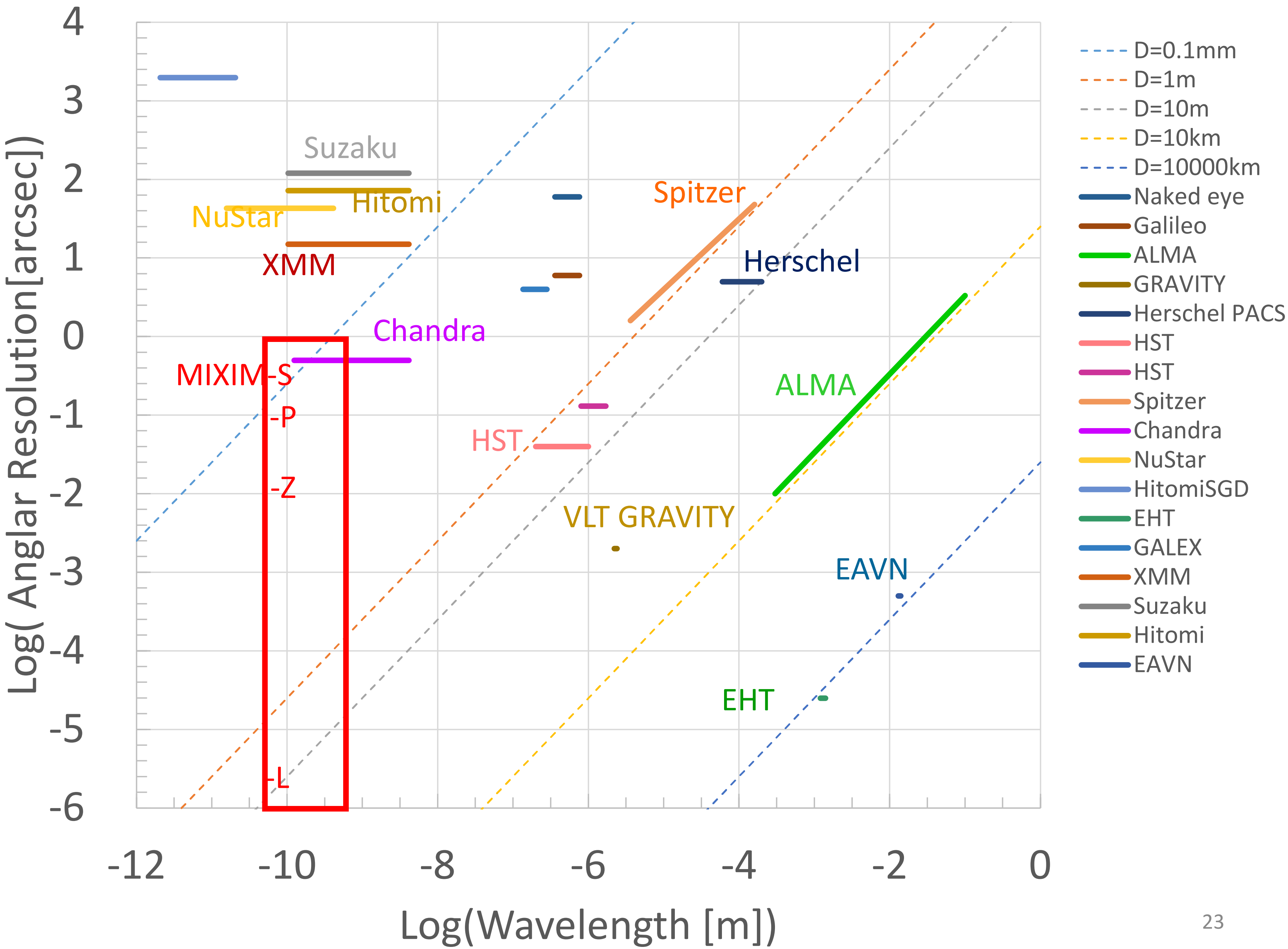


MIXIM-S (Small)	-P (Parasite)	-Z (Zoom)	-L (Large/LISA)
z=50cm	z=10m	z=10~100m	$z=2.5\text{x}10^{6}$km
θ=0.4''	θ=0.09''	θ=0.1''~0.01''	θ=3μarcsec
d=5μm,f=0.2	d=22μm, f=0.2	d=71μm,f=0.1	d=35cm, f=0.1



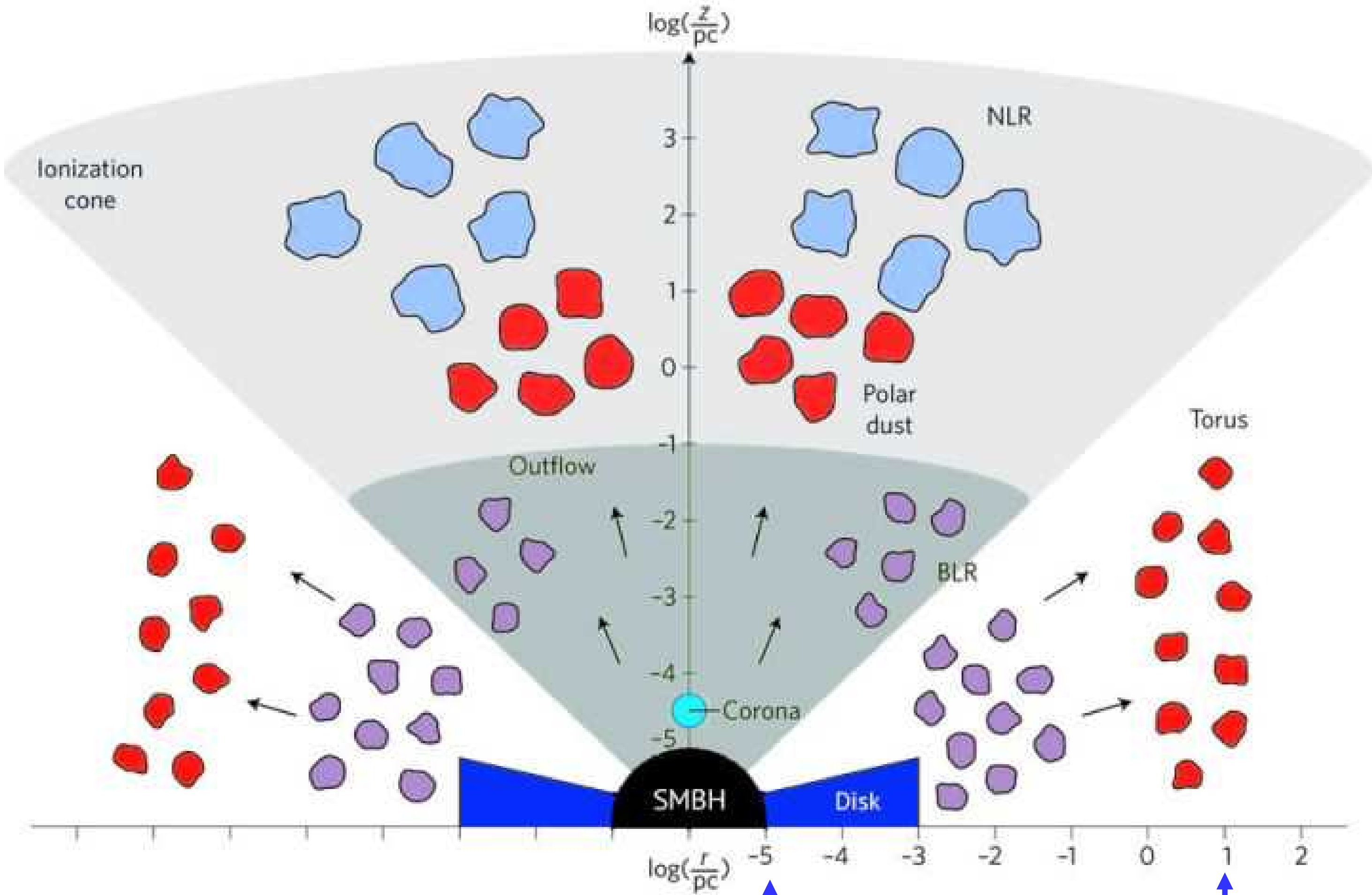






Log(Anglar Resolution[arcsec])
Log(Wavelength [m])
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-12
-10
-8
-6
-4
-2
0
Suzaku
Hitomi
NuStar
XMM
Chandra
MIXIM-S
-P
-Z
-L
Spitzer
Herschel
HST
ALMA
VLT GRAVITY
EAVN
EHT
D=0.1mm
D=1m
D=10m
D=10km
D=10000km
Naked eye
Galileo
ALMA
GRAVITY
Herschel PACS
HST
HST
Spitzer
Chandra
NuStar
HitomiSGD
EHT
GALEX
XMM
Suzaku
Hitomi
EAVN

Primary Target >mCrab almost Point-like Sources e.g. Nearby AGNs



Ryan C. Hickox and David M. Alexander
https://ned.ipac.caltech.edu/level5/March18/Hickox/Hickox1.html

0.5uarcsec 0.5'' @4Mpc

Everything included in this 6 decades would be target of MIXIM

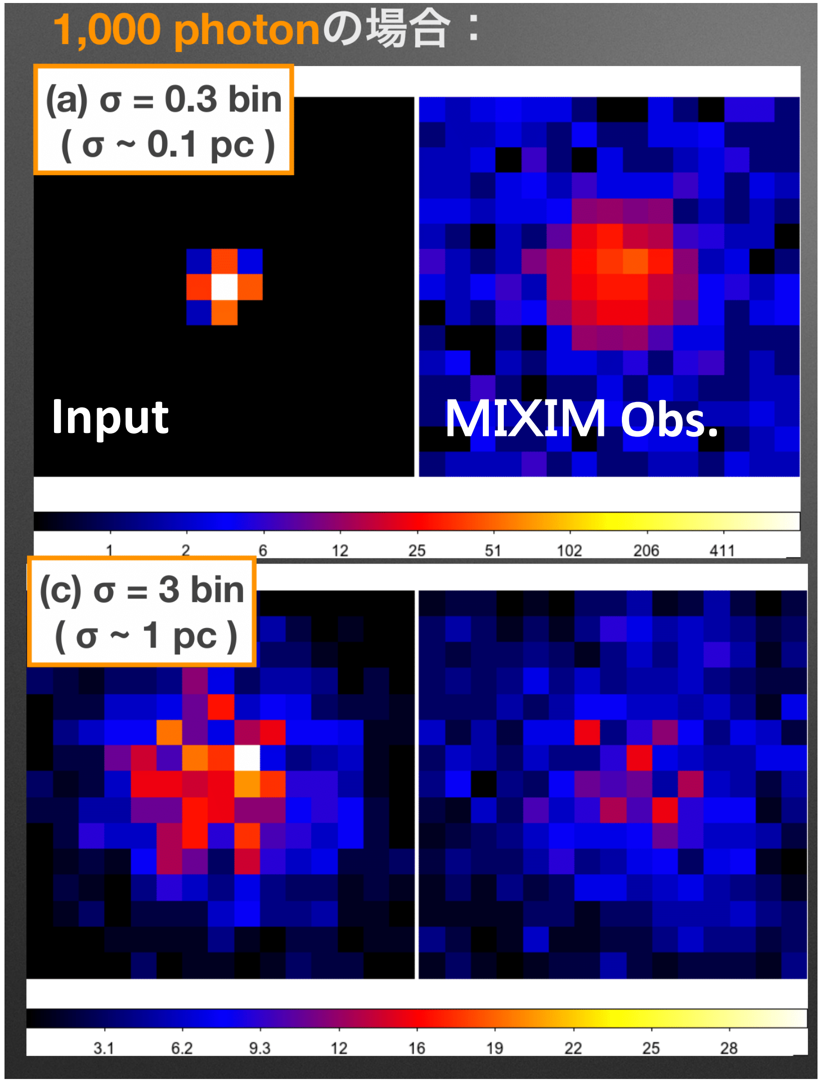
Very Preliminary by K. Asakura

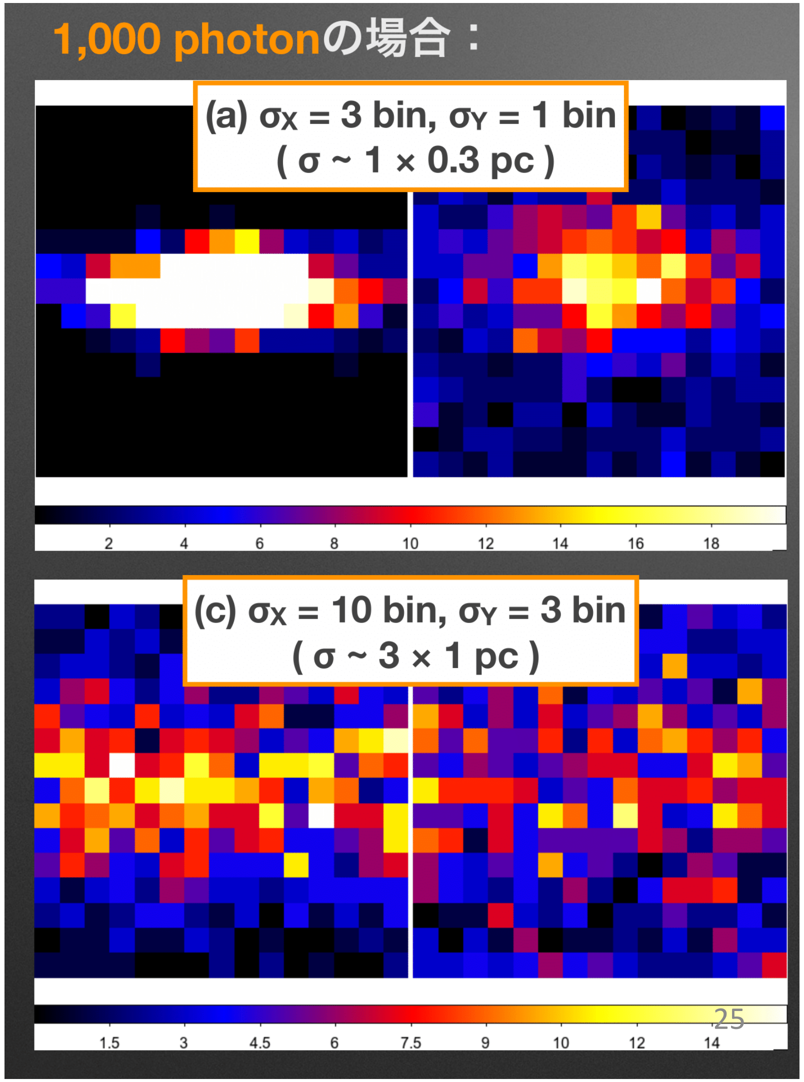
Circinus Galaxy(Sy2) Fe-Ka line simulation

Background is not included

A_{eff}=10 cm^2 (If we get Det. Layer of 20μm, A_{geo}=24cm^2) 、Texp～1Ms

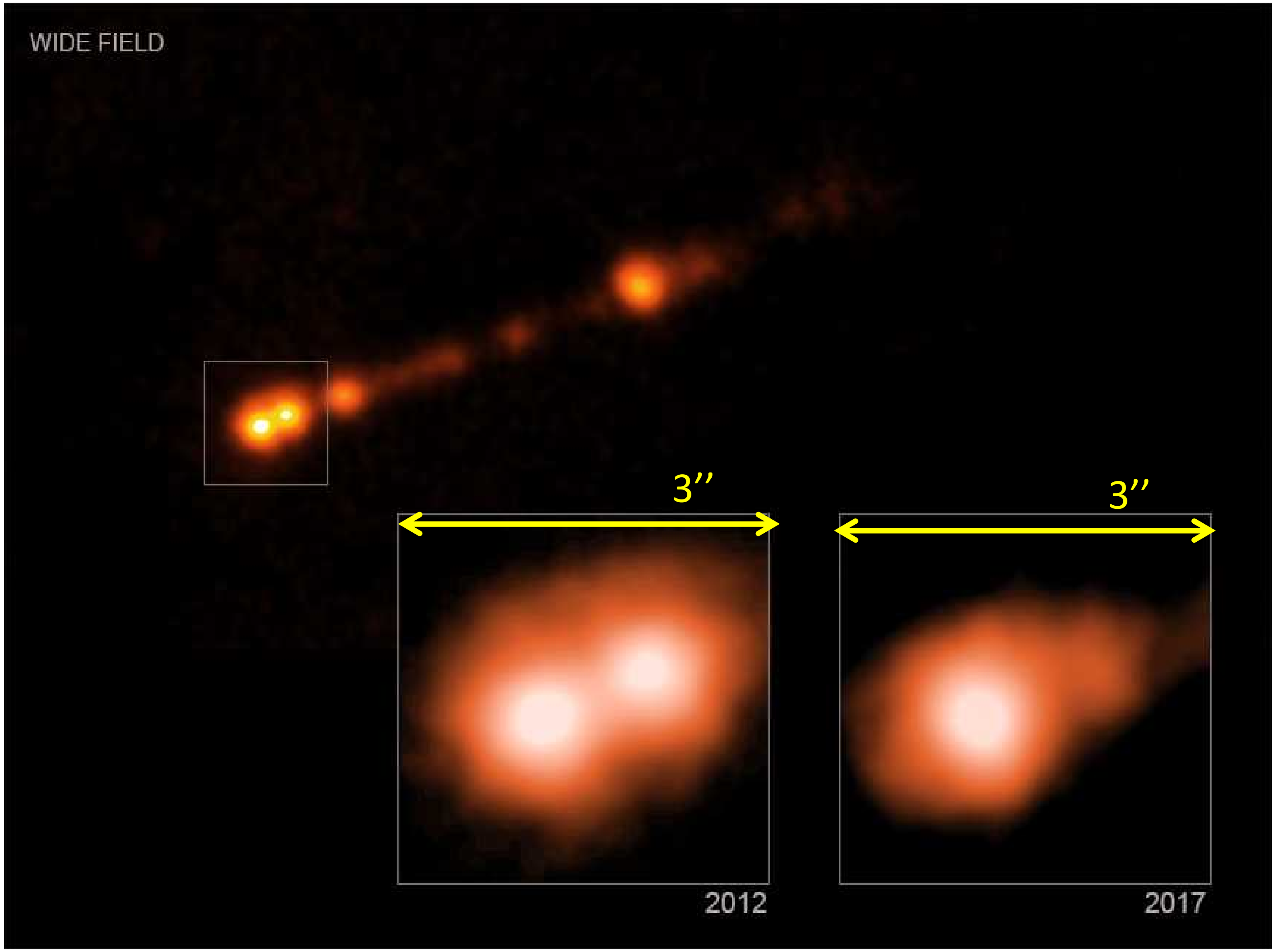
Opening Fraction 0.5、Minimum Patter 0.2 Mask z=8.67m





Jets are important target, of course.

Chandra X-ray Images of M87 from Press Release 2019
(Credit: NASA/CXC/SAO/B.Sinos)



Do we need X-ray observations around the Event Horizon after EHT?

- X-ray vs Radio

Thanks inputs from Kawashima-san, Tazaki-san

  - Penetration power is highest for (hard) X-rays.
    - Optically thick gas in radio can be optically thin in X-rays.
    - AGNs with high accretion rate (not RIAF) can be targets for X-rays but not for radio (?).
    - Inner edge of a (standard) accretion disk, which is sensitive to BH spin, can be imaged only with X-rays (?). Coronae, too.
  - (Color) Temperature of the accreting matter can be measured only with X-rays.
  - Elemental Abundance and Doppler Motion (through Fe fluorescent lines) can also be measured with X-rays.
  - Enough room to diffraction limit for X-rays but not so for radio.
  - The event horizon was resolved in Radio but not yet in X-rays.

X-ray would be complementary to Radio, at least

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.