HEMERA WORKSHOP

Advancing X-ray polarimetry through observations from the stratosphere

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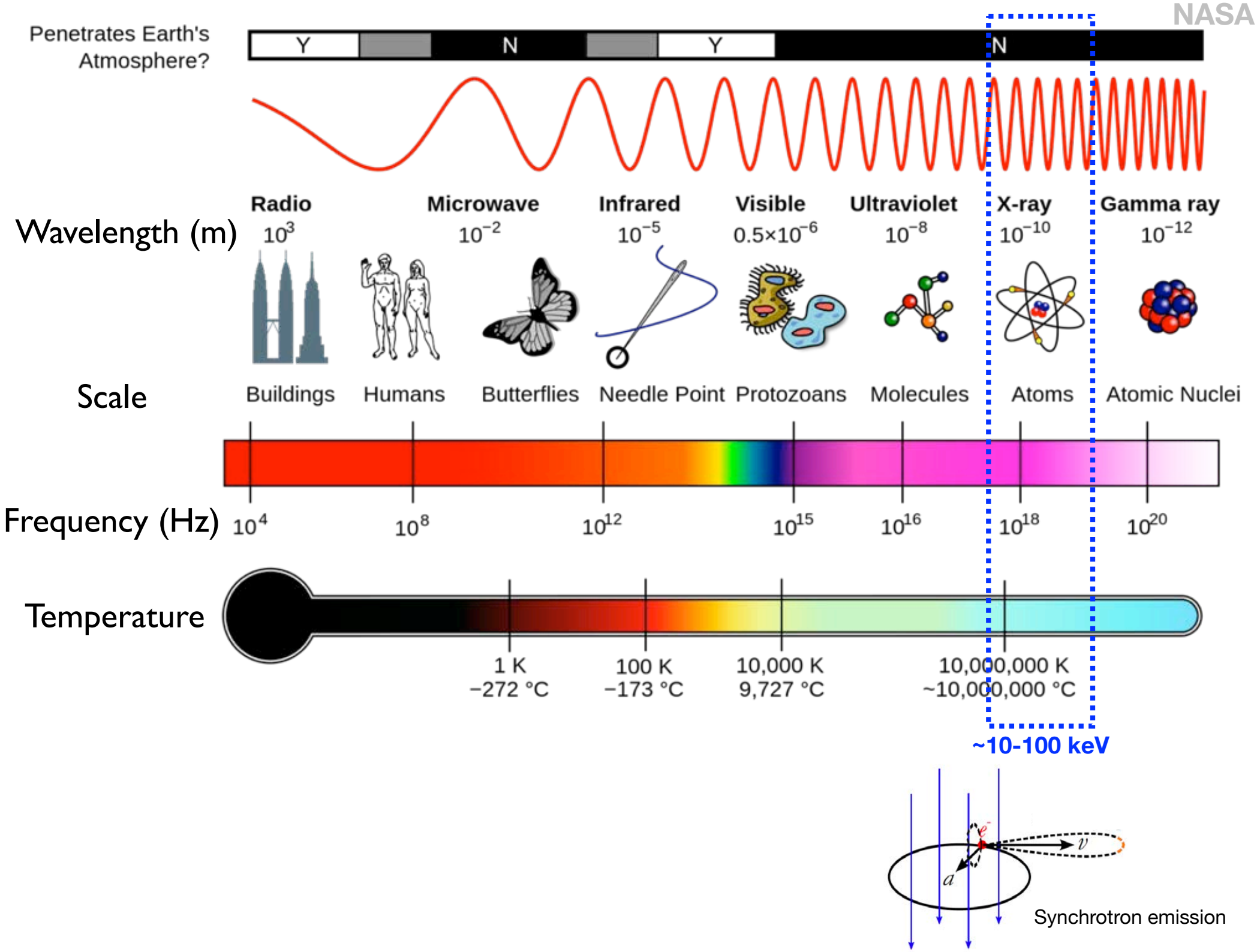
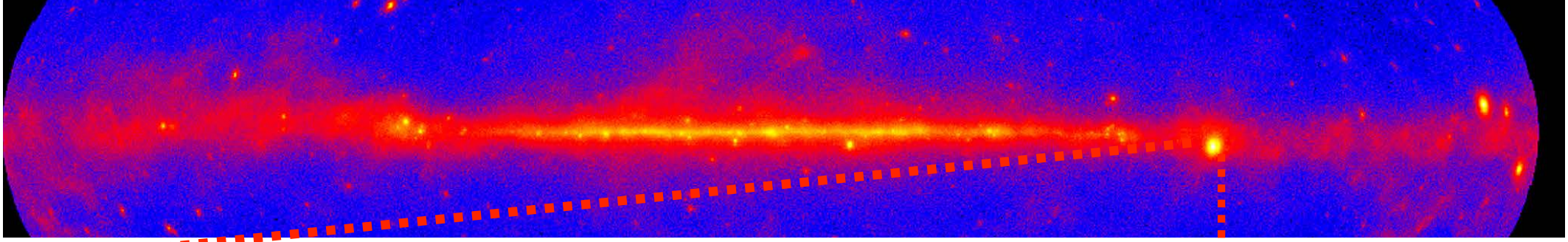
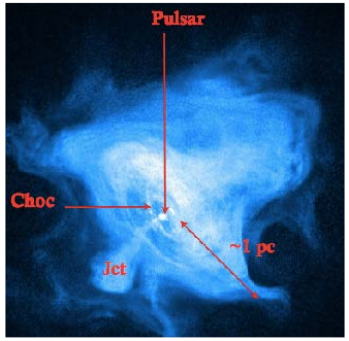
Esrange Space Centre

67° 53’ N, 21° 04’ E

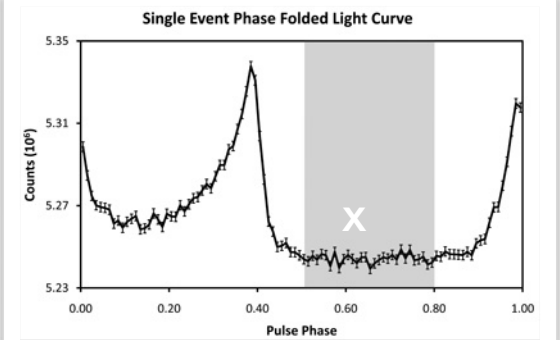
Washington University in St. Louis
McDonnell Center for the Space Sciences
WFF
University of New Hampshire
Goddard Space Flight Center
U.S. Naval Research Laboratory
Guarino
RICE
OSAKA UNIVERSITY
JAXA
HIROSHIMA
RIKEN
TOKYO UNIVERSITY OF SCIENCE since 1881
KYOTO UNIVERSITY FOUNDED 1897
OIST
Yamagata University
KTH VETENSKAP OCH KONST


NASA
Penetrates Earth's Atmosphere?
Y
N
Y
N
Wavelength (m)
Radio
10^{3}
Microwave
10^{-2}
Infrared
10^{-5}
Visible
0.5×10^{-6}
Ultraviolet
10^{-8}
X-ray
10^{-10}
Gamma ray
10^{-12}
Scale
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^{4}
10^{8}
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C
~10-100 keV
e
v
a
Synchrotron emission

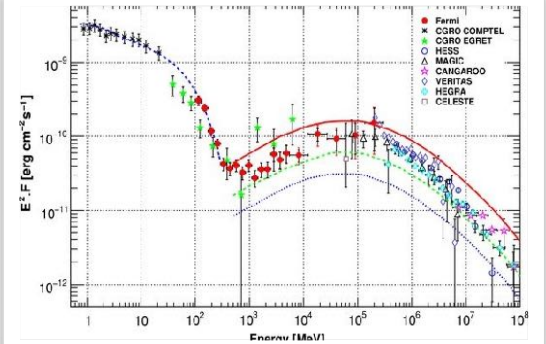




image



light curve

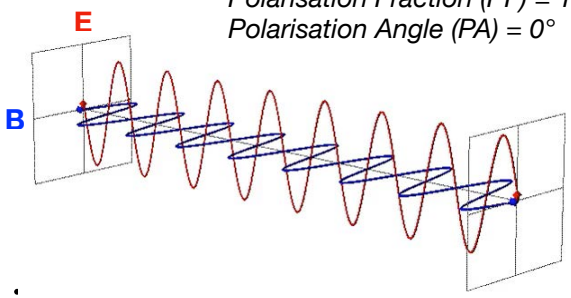


energy spectrum

?

polarisation

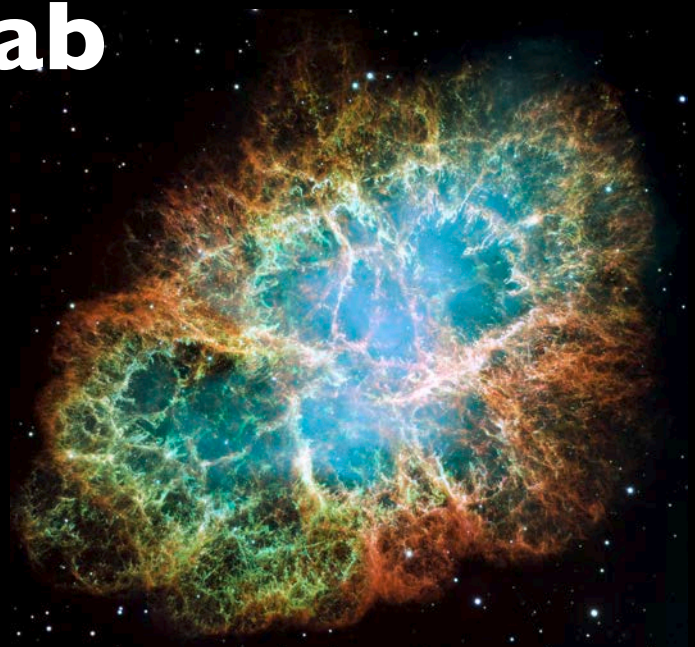
- Linear polarisation **constrains on source geometry**
  - **Polarisation Fraction:** symmetry of the source
  - **Polarisation Angle:** orientation of the source



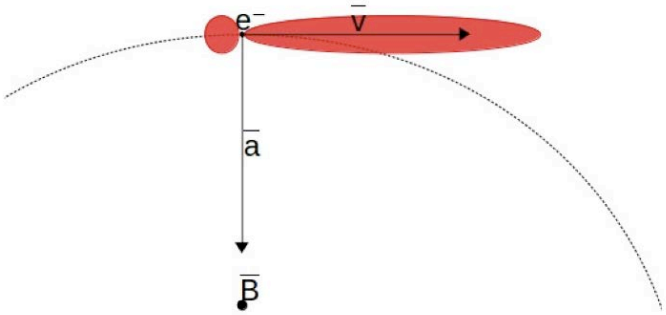
Polarisation Fraction (PF) = 100%
Polarisation Angle (PA) = 0°

- X-ray polarimetry provides a new window on high-energy universe
  - New purpose-built instrumentation is required

Crab



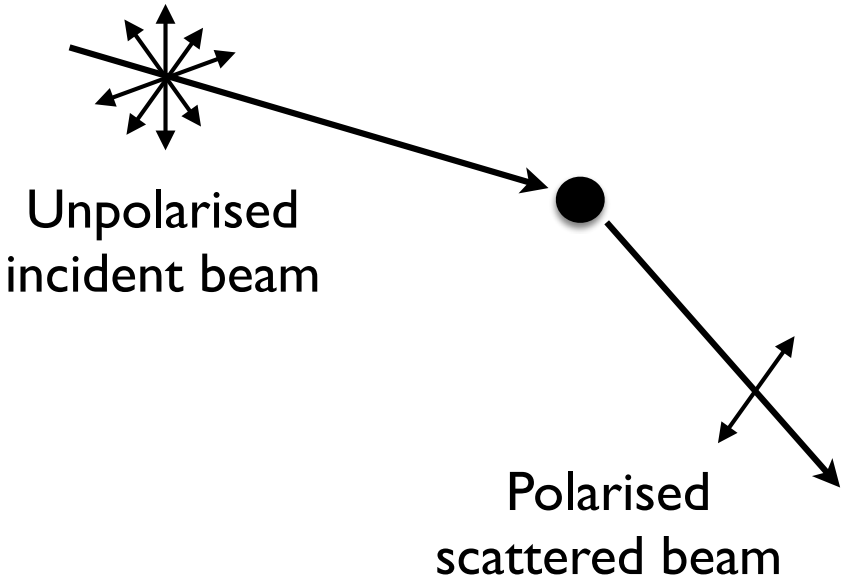
Synchrotron emission



- Polarisation angle determines the magnetic field direction
- Maximum polarisation fraction for synchrotron emission ~75%. Will be reduced for a disordered magnetic field.

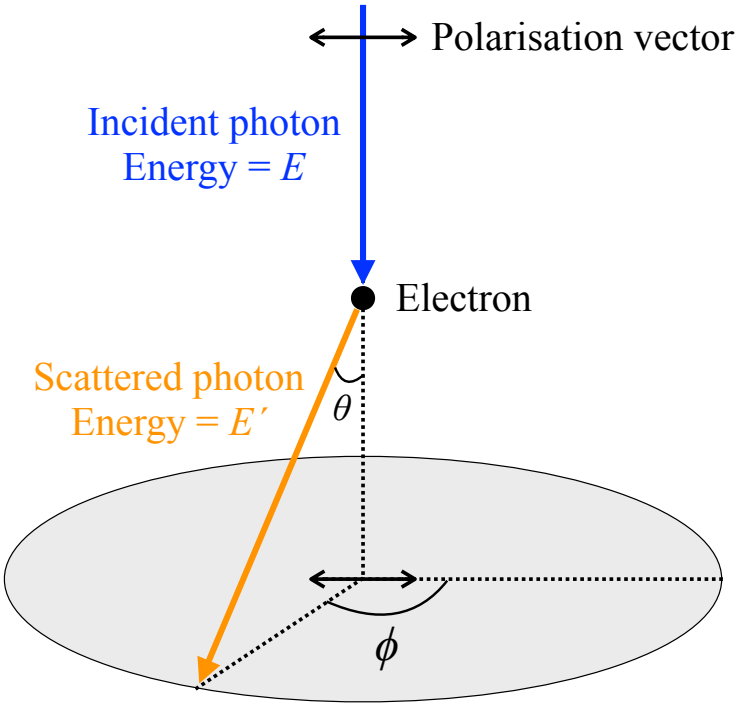
Cygnus X-1

Reflection

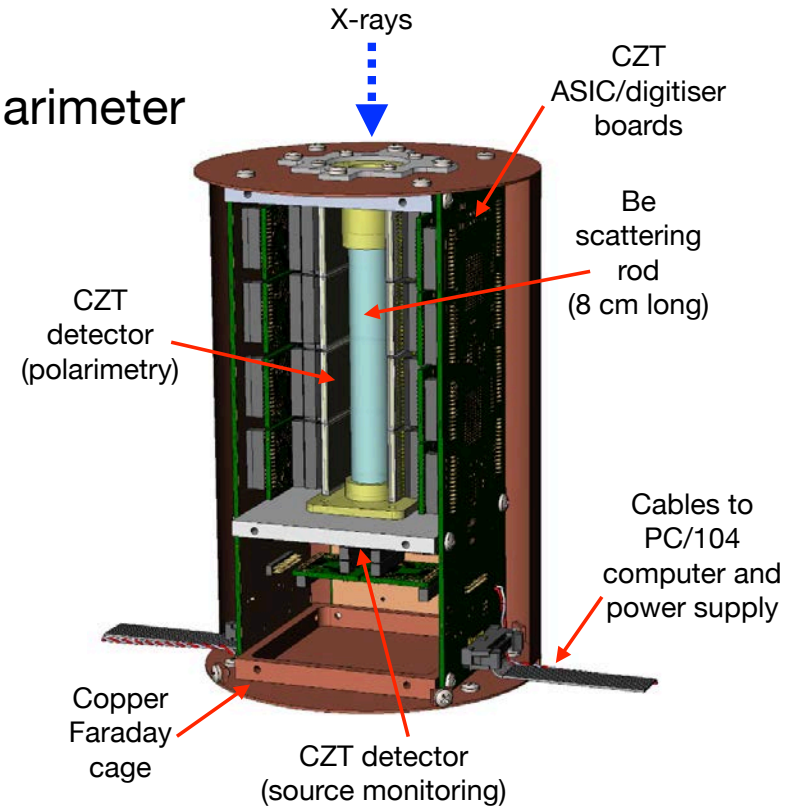


- Polarisation probes geometry

Method

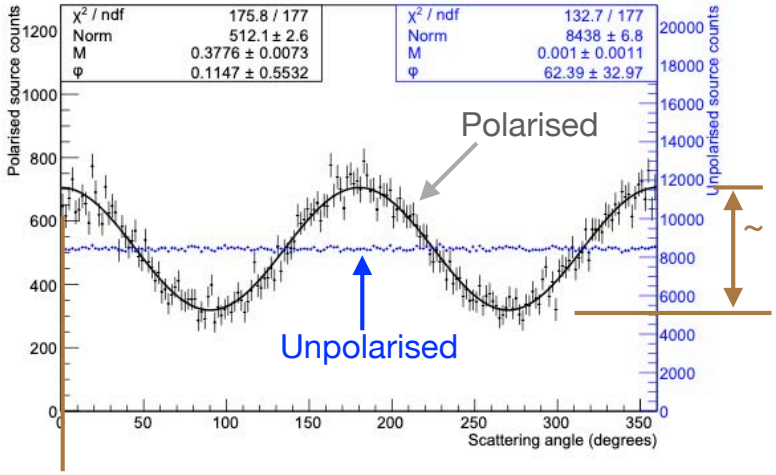


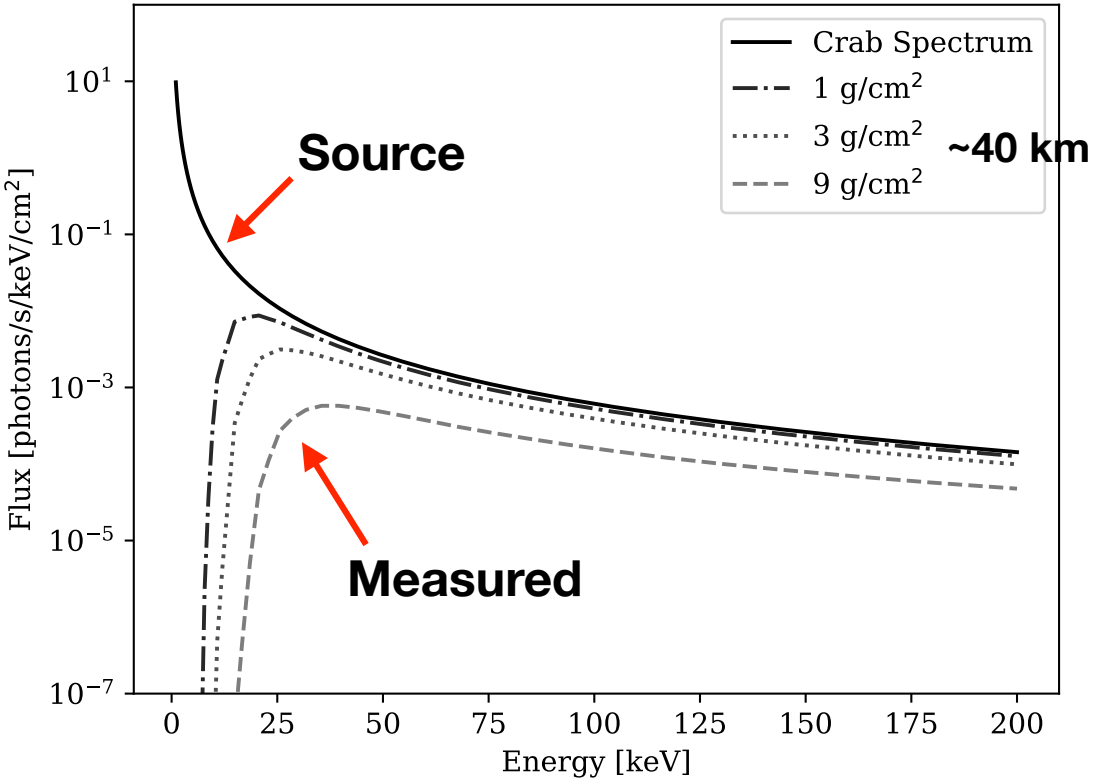
e.g. XL-Calibur polarimeter

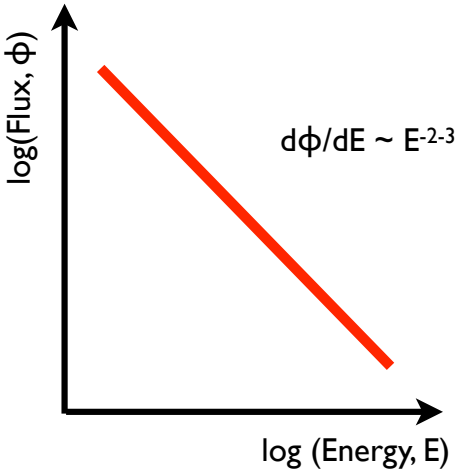


Compton scattering (Klein-Nishina):

$$\frac{d\sigma}{d\Omega} = \frac{3\sigma_T}{16\pi}\left(\frac{E'}{E}\right)^2\left(\frac{E}{E'}+\frac{E'}{E}-2\sin^2\theta\cos^2\phi\right)$$



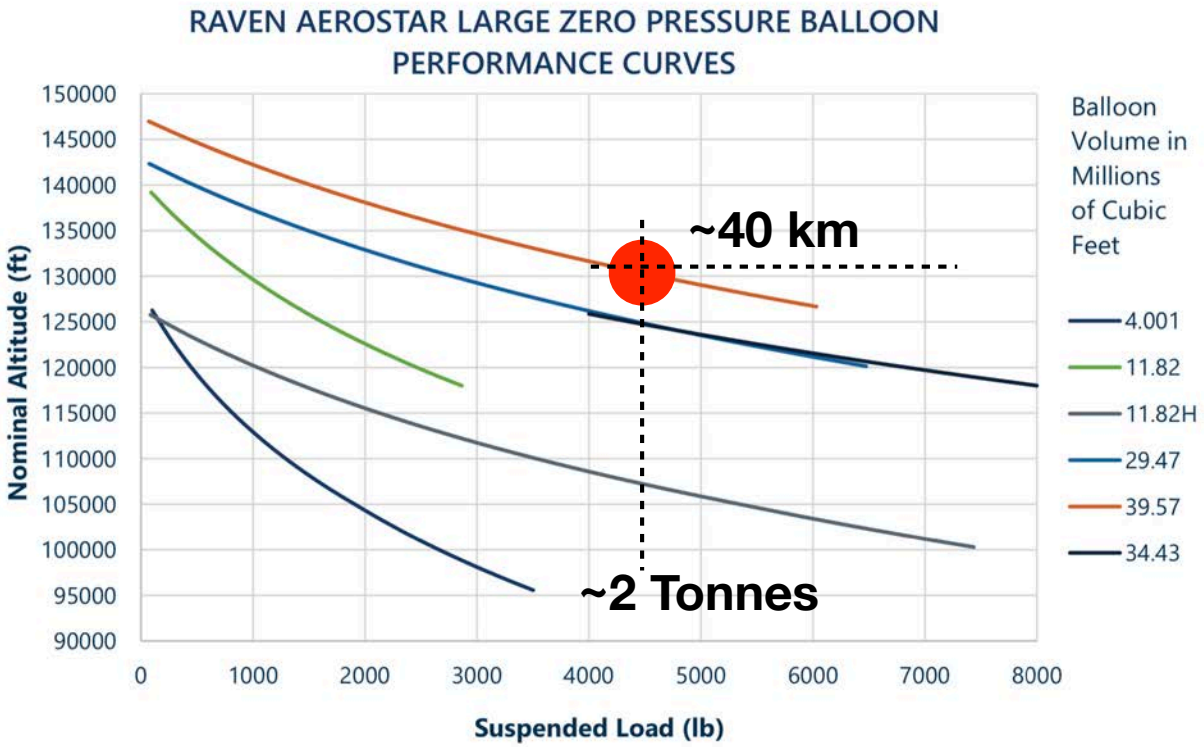




The flux ($m^{-2}s^{-1}E^{-1}$) of cosmic radiation typically follows an inverse power law

"As high as possible..."

...10^6 m^3 zero pressure balloon

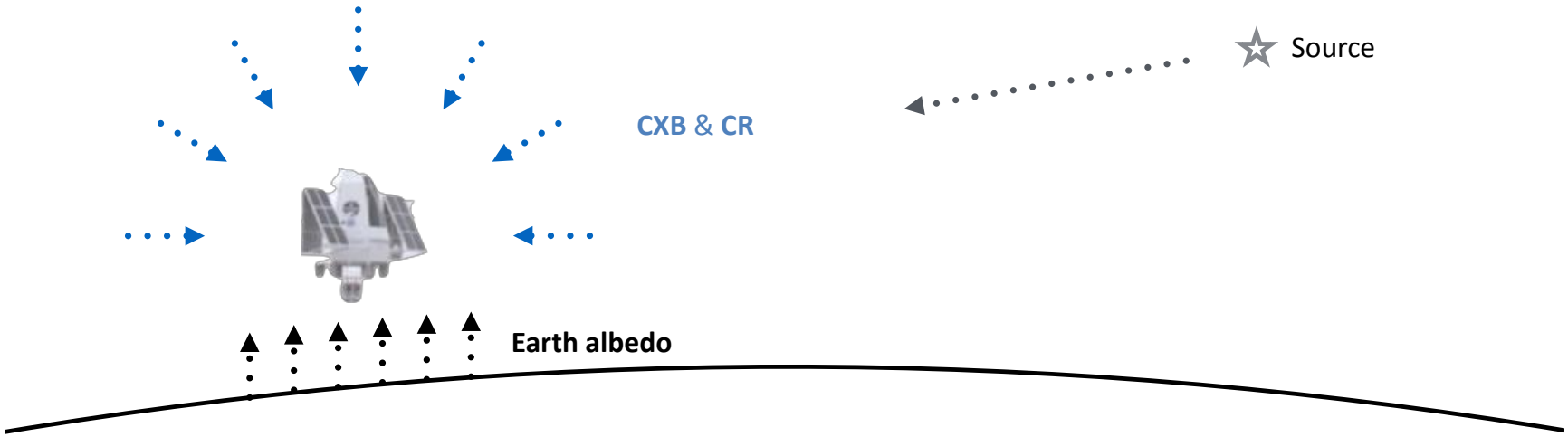


“… for as long as possible”

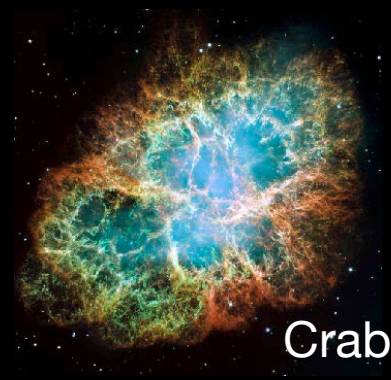
• Collecting area drives measurement sensitivity. Eventually limited by mass constraints.

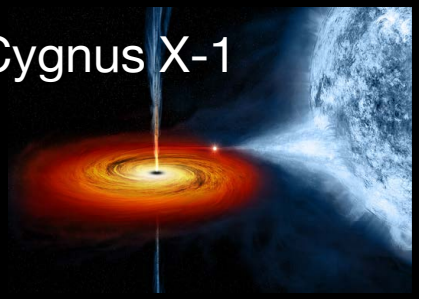
• Measurements are subject to significant non-isotropic background. Strong atmospheric albedo component. Neutrons and forward-scattering X-rays are troublesome. Anticoincidence systems are heavy.

• Multi-day flights are required



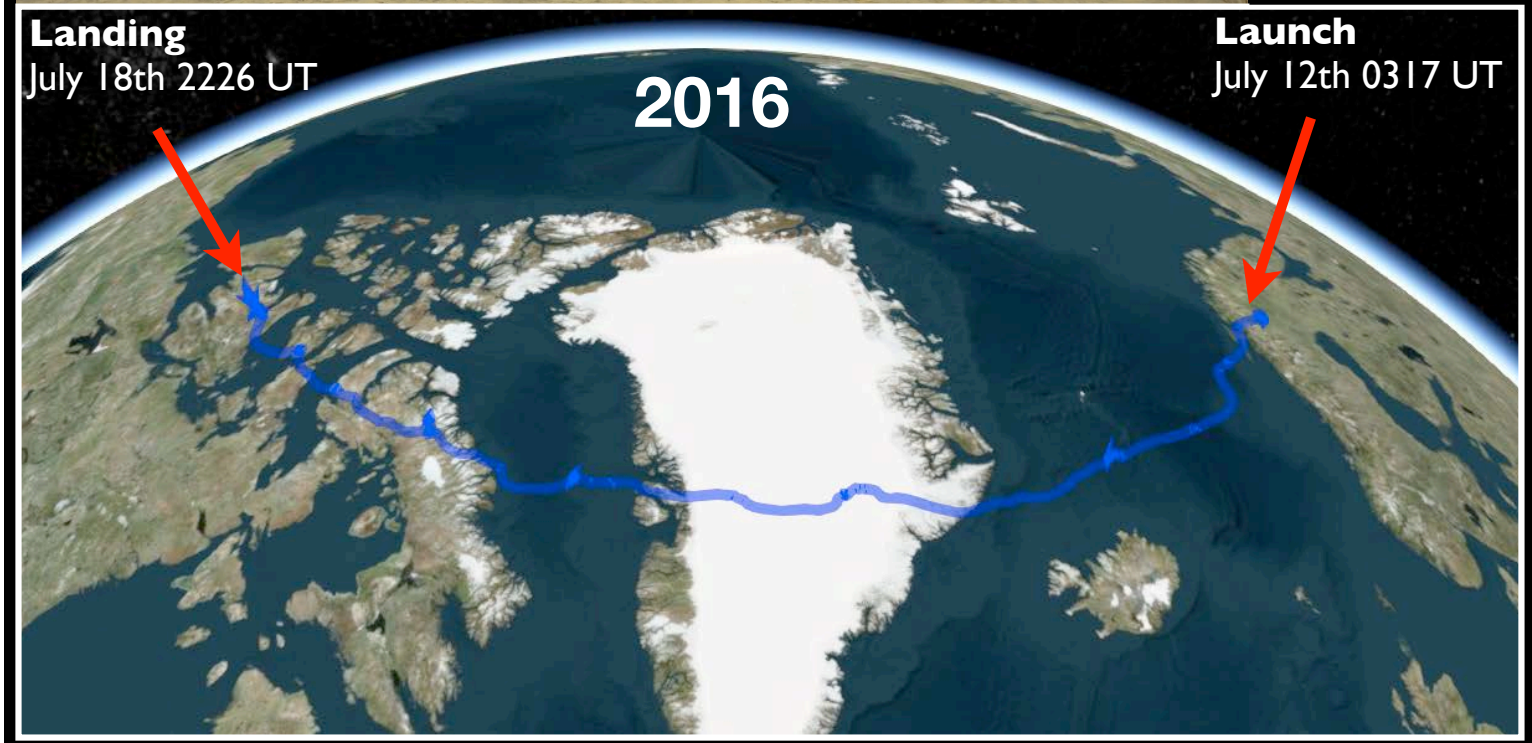
e.g. M. Chauvin et al., Nat. Sci. Rep. 7 (2017) 7816 / Nat. Astr. 2 (2018) 652 / MNRAS 477 (2018) L45/ MNRAS 483 (2019) L138.

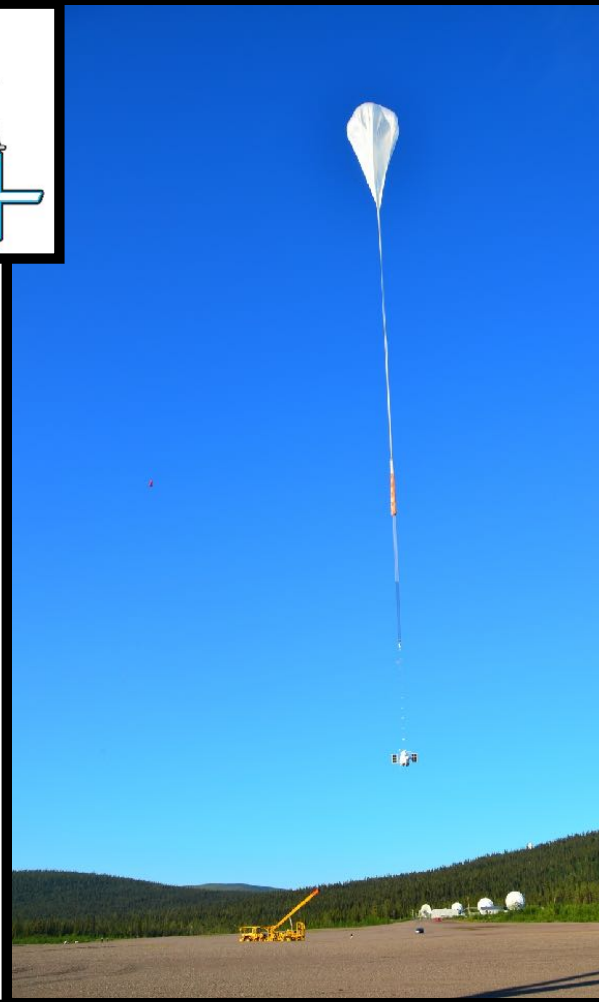


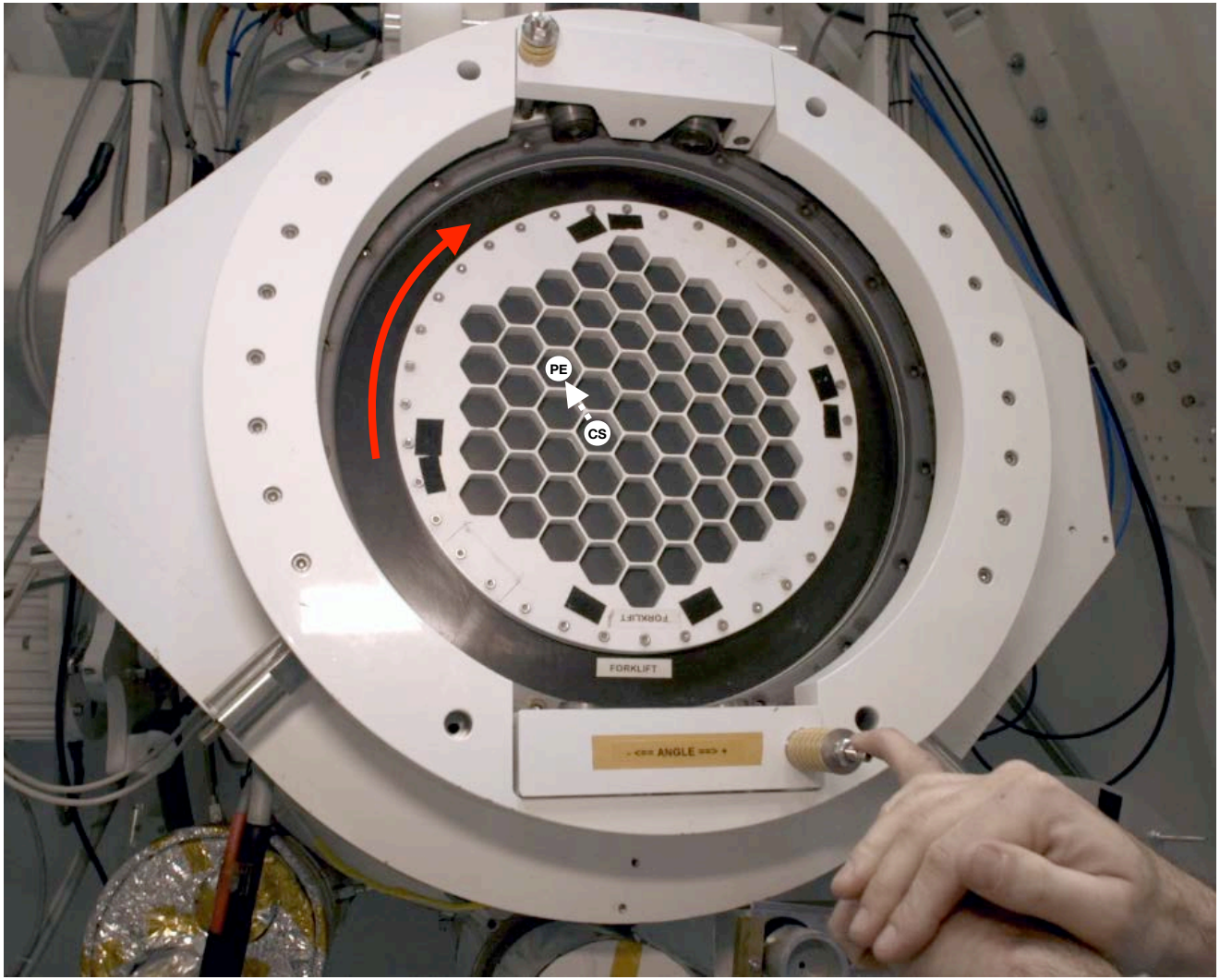


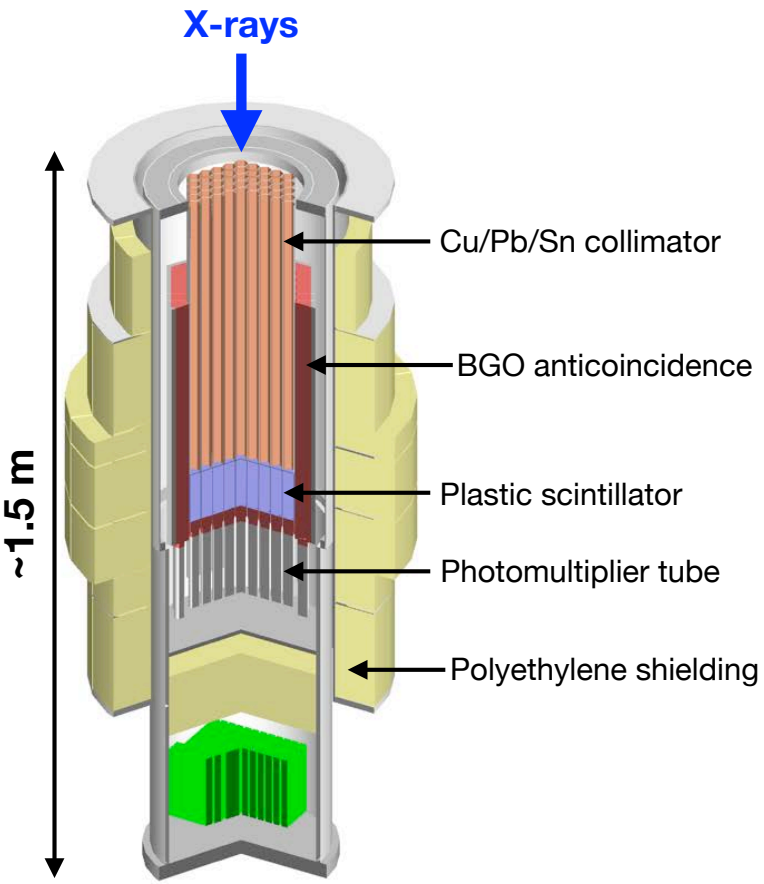
PoGO+: "MDP" ~10% (~1 week)

PoGO+

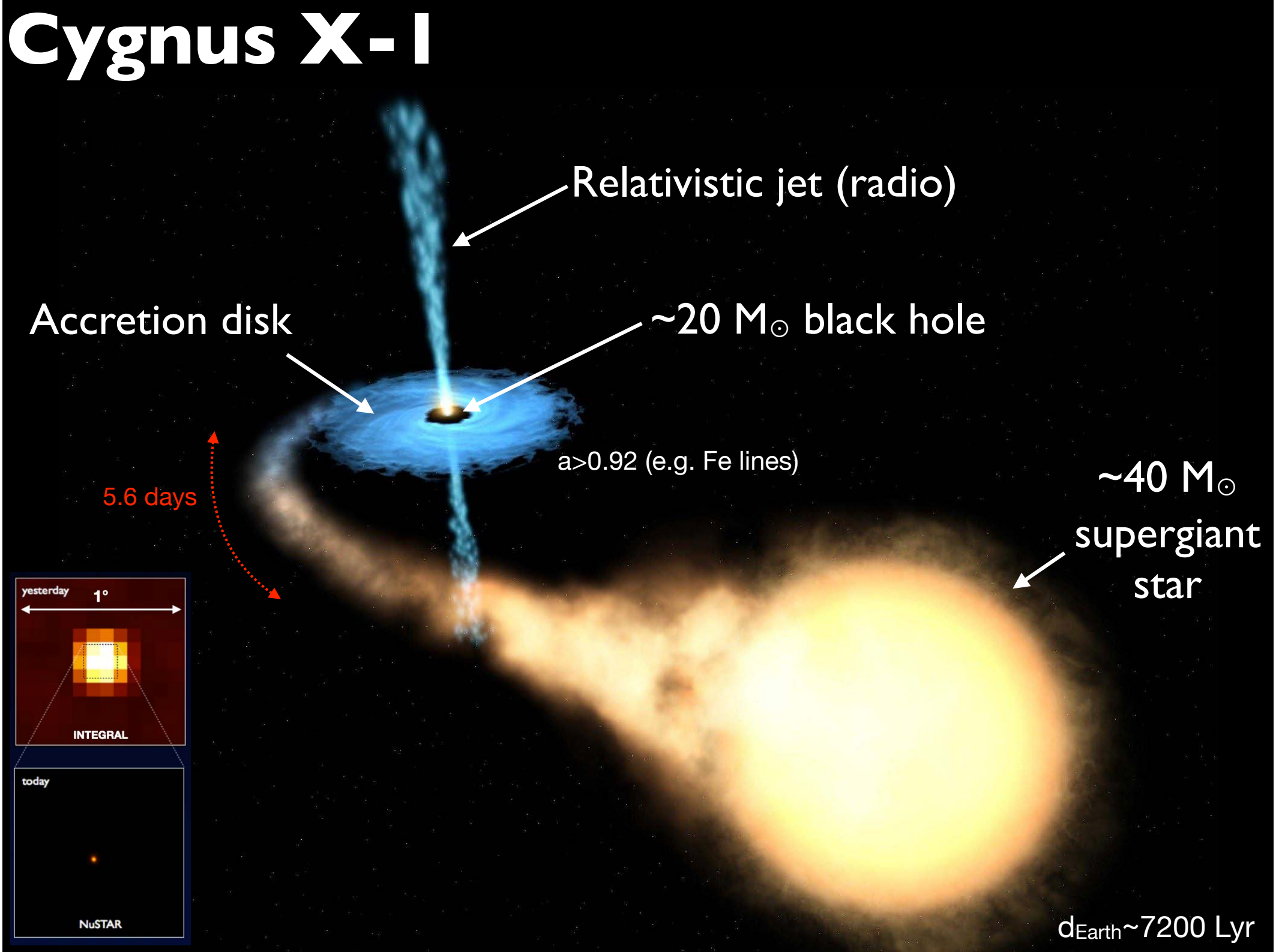


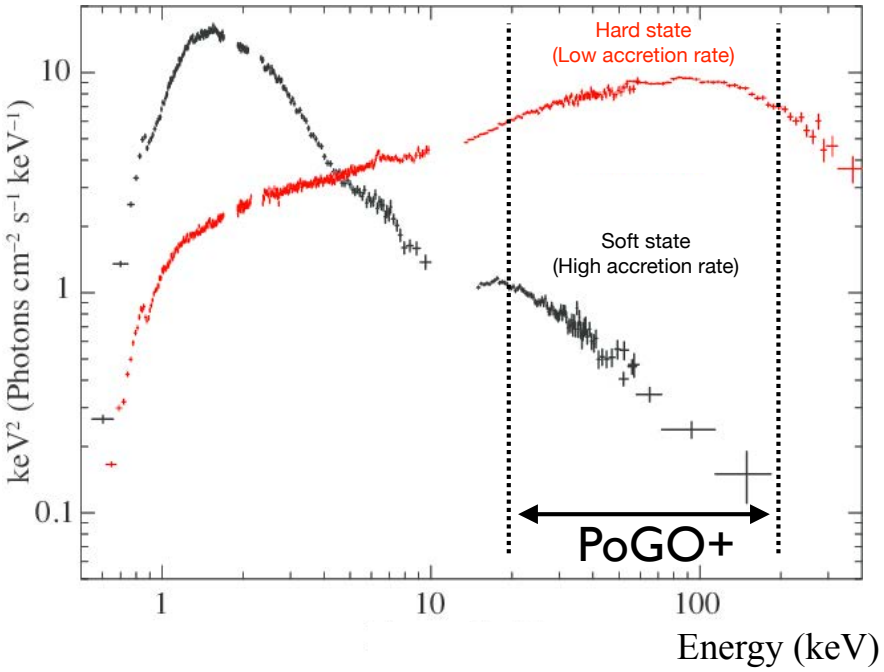


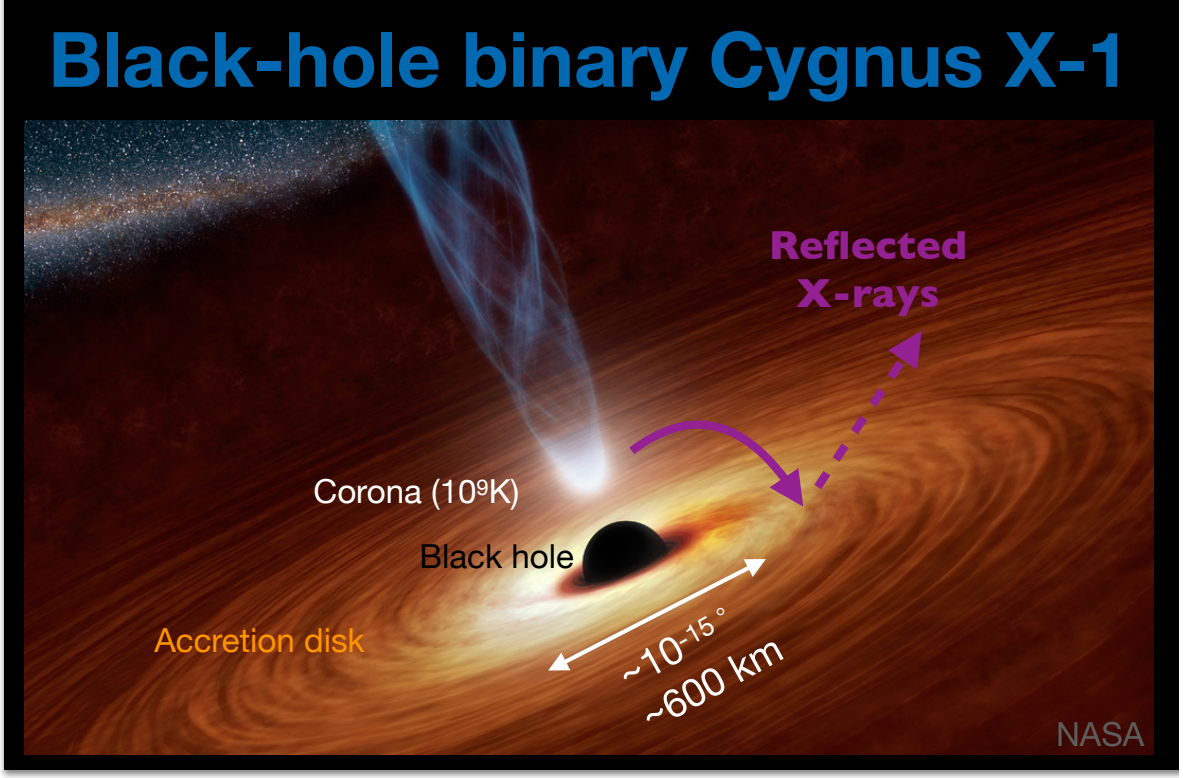

PE
CS
FORKLIFT
FORKLIFT
ANGLE

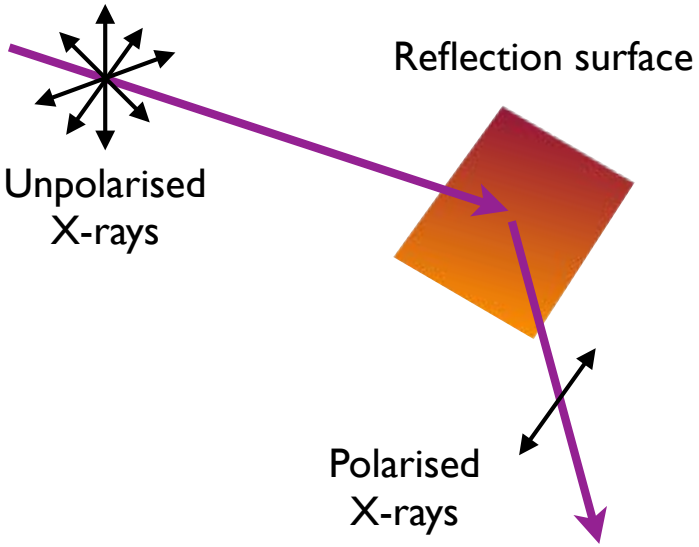

X-rays
~1.5 m
Cu/Pb/Sn collimator
BGO anticoincidence
Plastic scintillator
Photomultiplier tube
Polyethylene shielding

Cygnus X-1

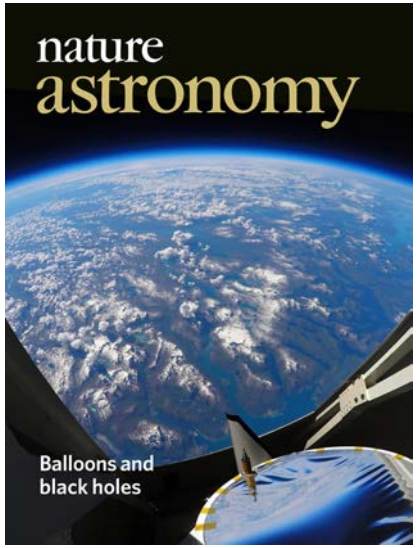

Relativistic jet (radio)
Accretion disk
~20 M⊙ black hole
a>0.92 (e.g. Fe lines)
5.6 days
~40 M⊙ supergiant star
yesterday
1°
INTEGRAL
today
NuSTAR
dEarth~7200 Lyr



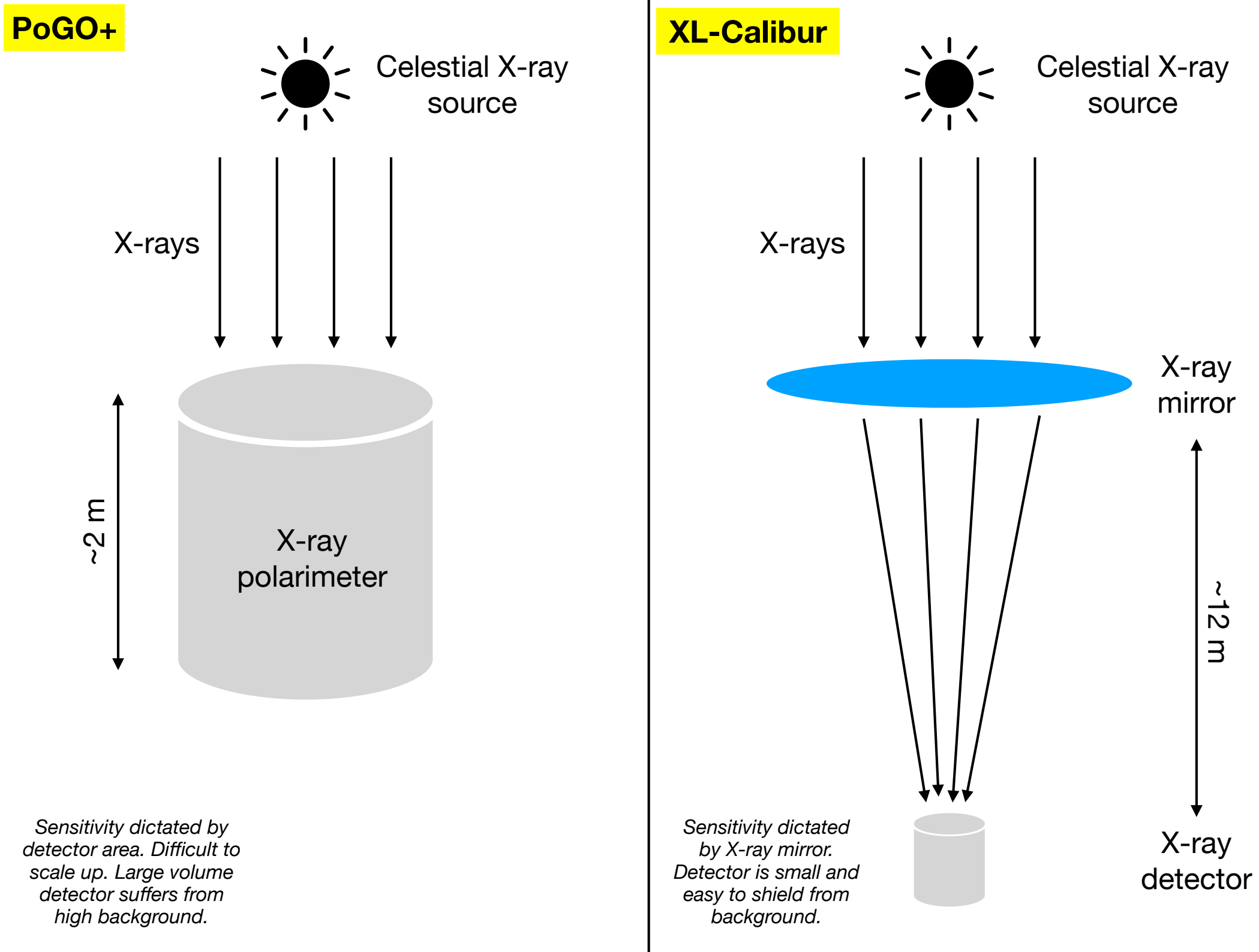


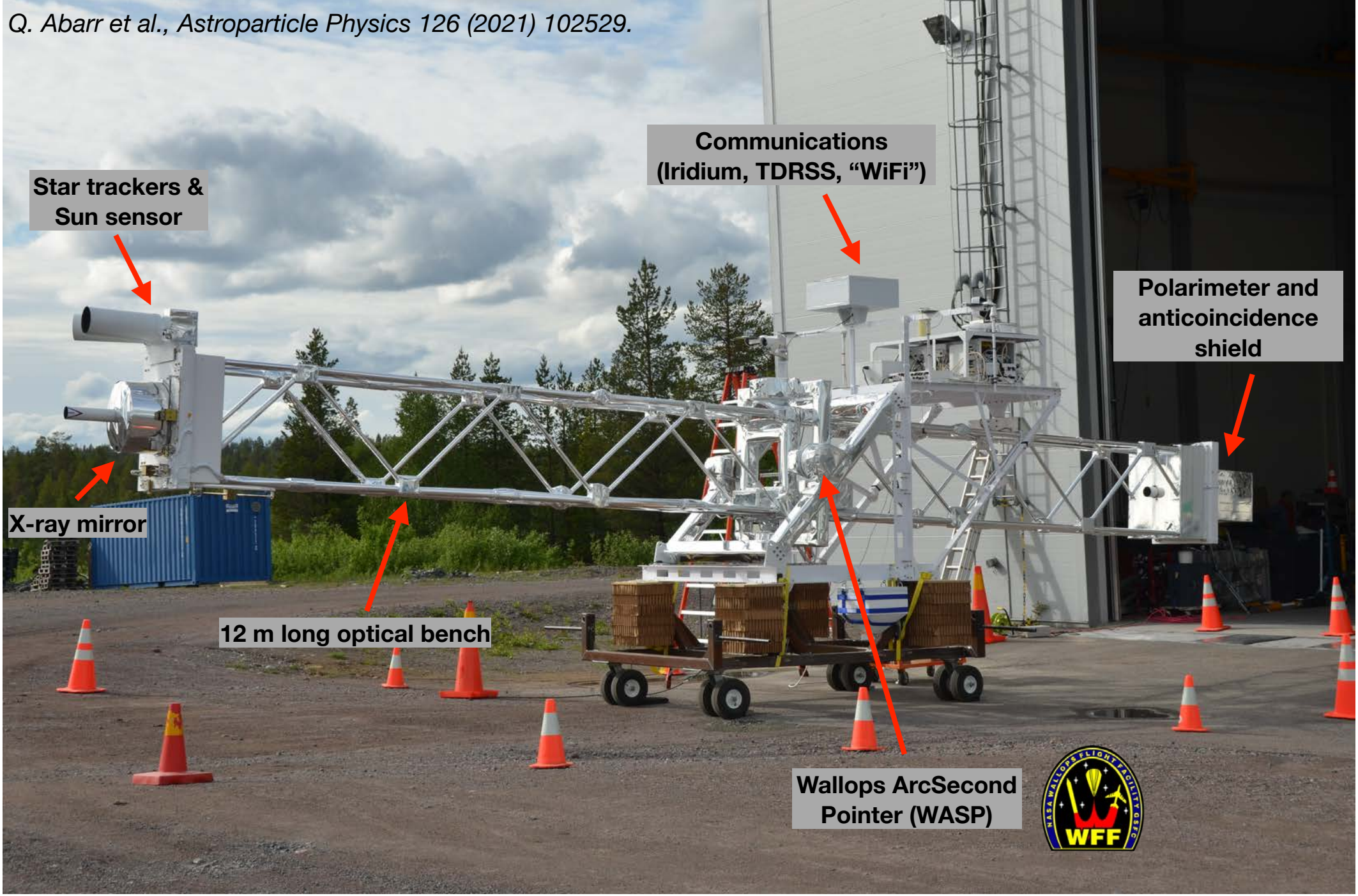


- PoGO+ observations (20-180 keV):
  - Emission weakly polarised (<8.6%, 90% CL)
  - Polarisation angle perpendicular to accretion disk
- **No indication of "strong gravity"**
  - Implies that the inner part of the accretion disk ("corona") is an extended object or lies far from the black hole
  - Geometric information without imaging ($10^{-15°}$!)
- Intriguing - a more sensitive mission is now required.



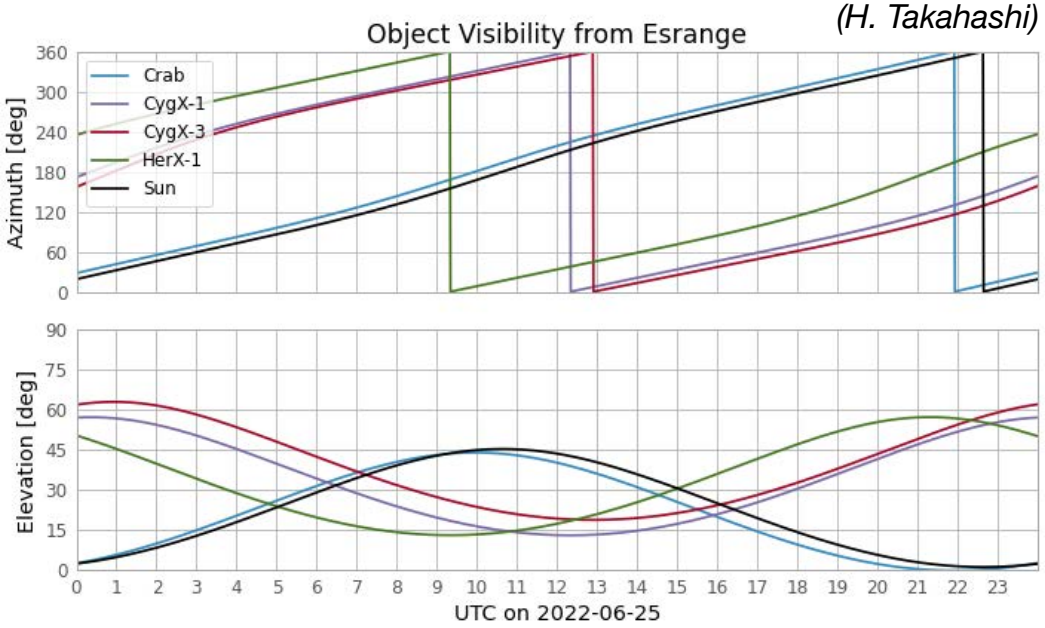
M. Chauvin et al. (PoGO+ Collaboration), Nature Astronomy 2 (2018) 652


PoGO+
Celestial X-ray source
X-rays
~2 m
X-ray polarimeter
Sensitivity dictated by detector area. Difficult to scale up. Large volume detector suffers from high background.
XL-Calibur
Celestial X-ray source
X-rays
X-ray mirror
~12 m
X-ray detector
Sensitivity dictated by X-ray mirror. Detector is small and easy to shield from background.



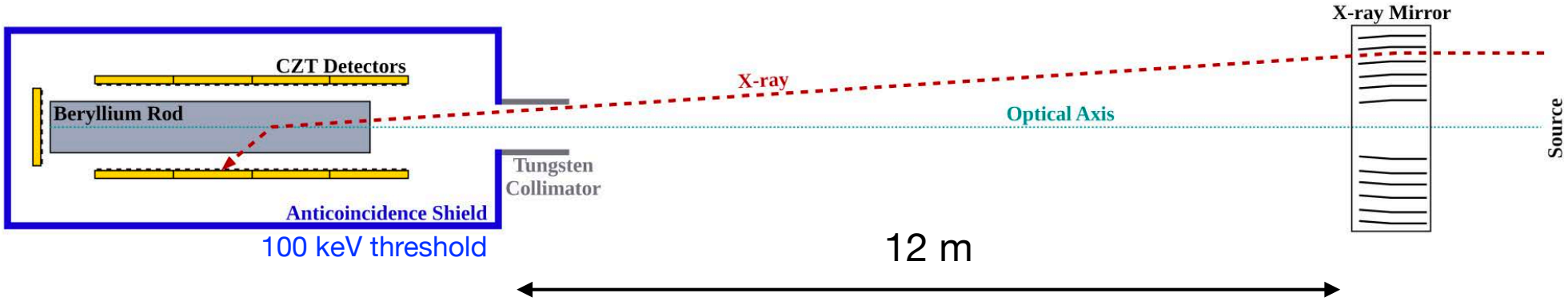
Pointing precision: 1 arcsec (RMS)
Pointing knowledge < 15 arcsec (3σ)

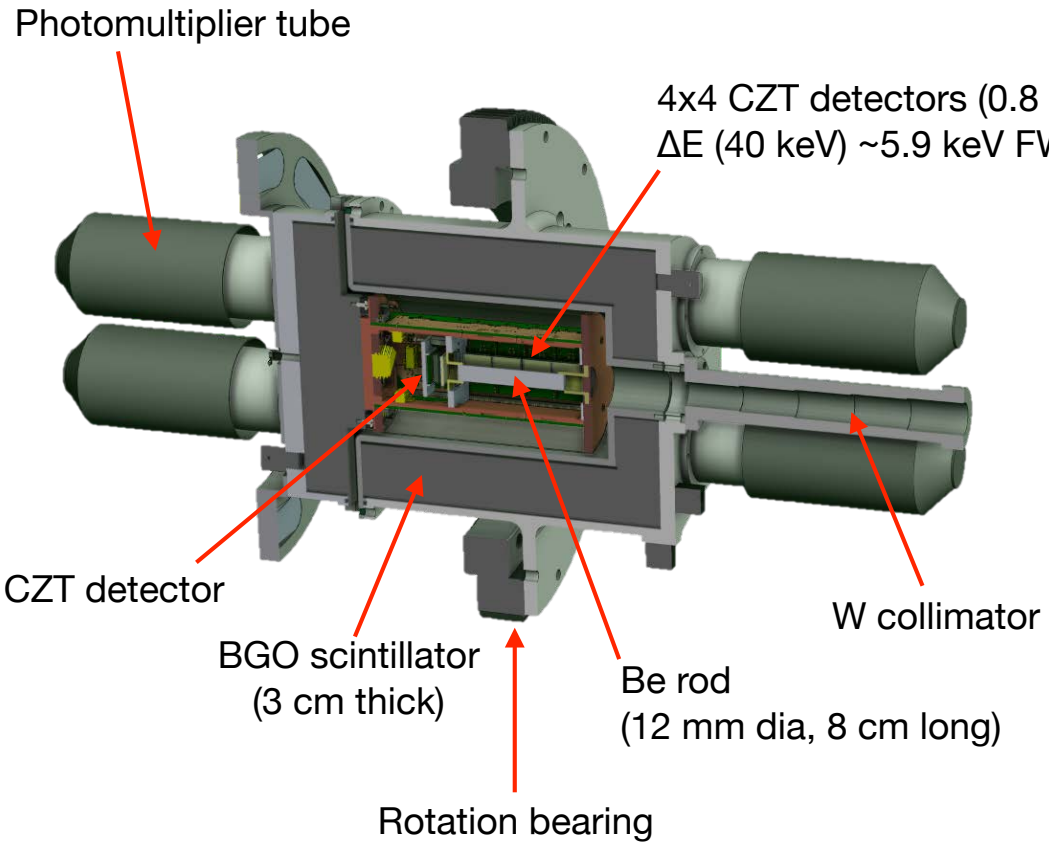
(H. Takahashi)



XL-Calibur tests at CSBF facilities, Palestine, USA

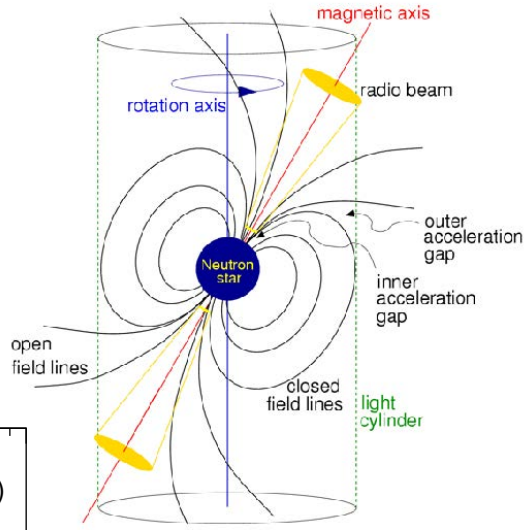
XL-Calibur: spectropolarimetry 15-80 keV. MDP ~2% / $\sqrt{t_{day}}$

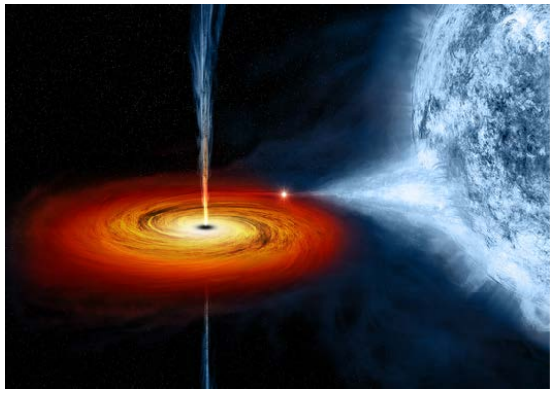


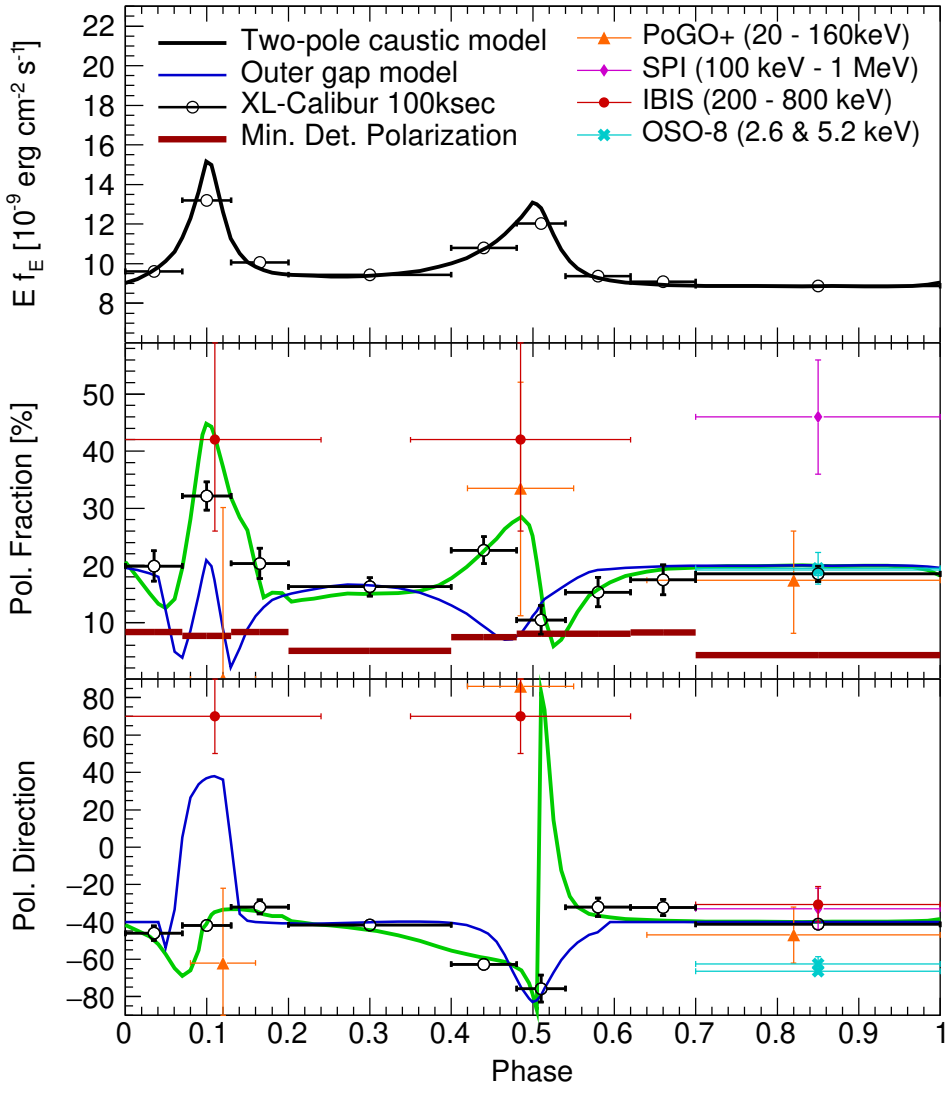


X-ray mirror (Hitomi spare)
213 nested Pt/C-coated shells (Wolter I)
Effective area: 180 cm^2 @ 30 keV

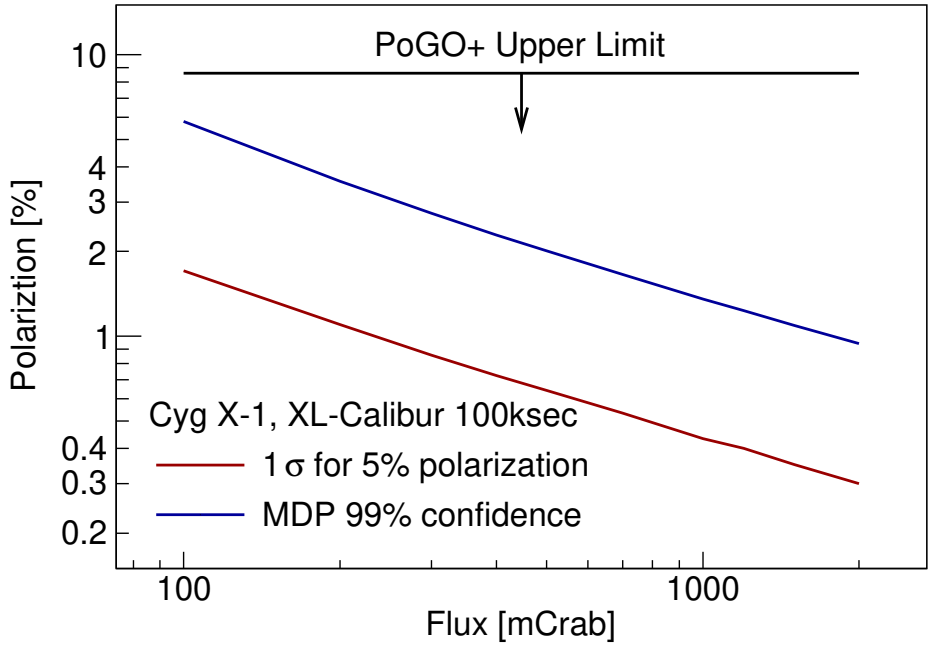
- **Crab pulsar**
  - Rotation powered pulsar
  - Phase-resolved polarimetry
  - Differentiate emission models



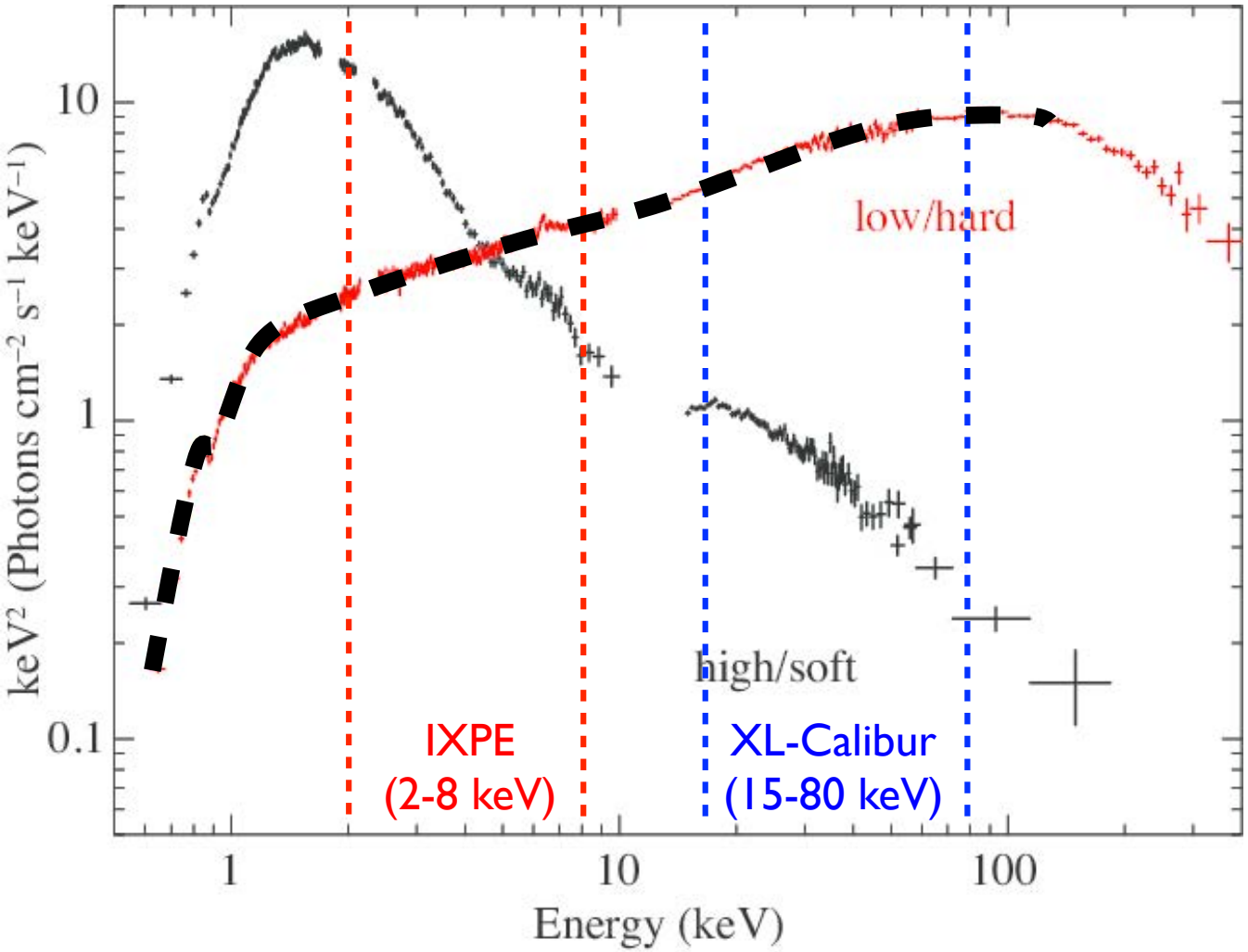


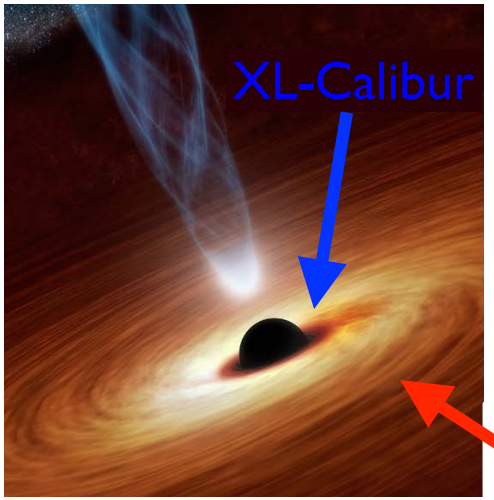


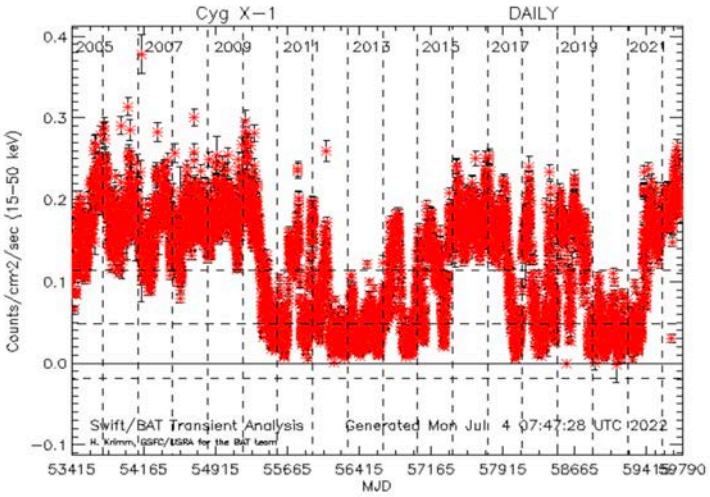
- **Cygnus X-1 (hard spectral state)**
  - Black hole binary
  - Discern geometry of X-ray bright black hole corona.



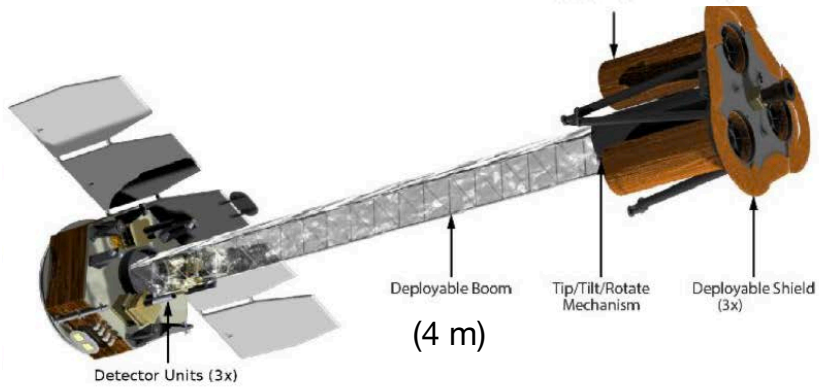
Balloon-satellite synergy





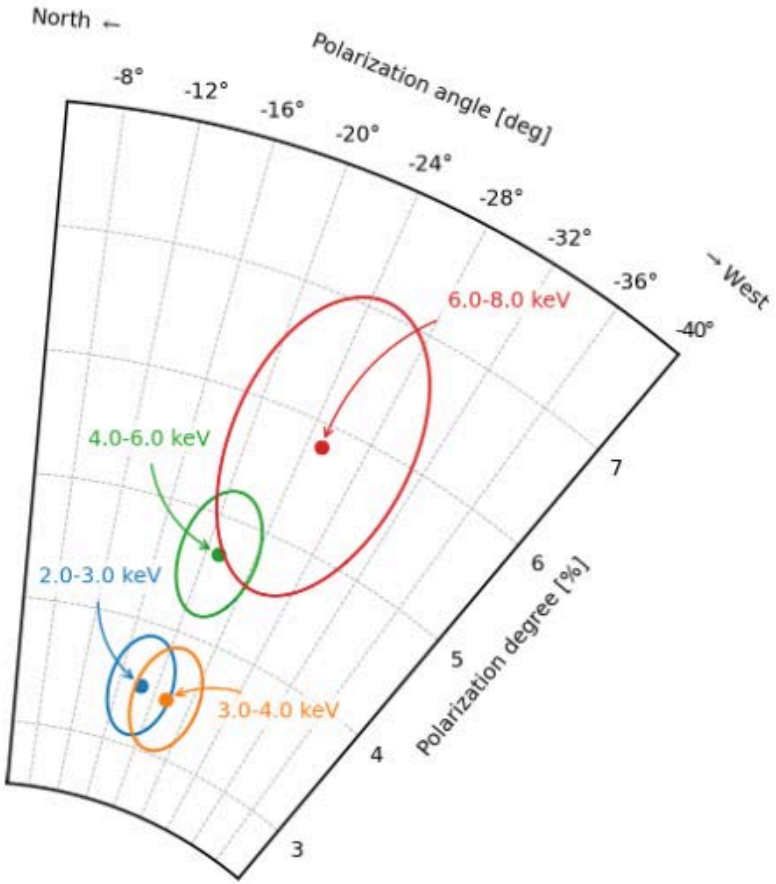


Swift / BAT (15-50 keV)



- **NASA Small Explorer mission, *IXPE***
- 2-8 keV (photoelectric polarimeter)
- 30” imaging
- **Launch December 9th 2021**

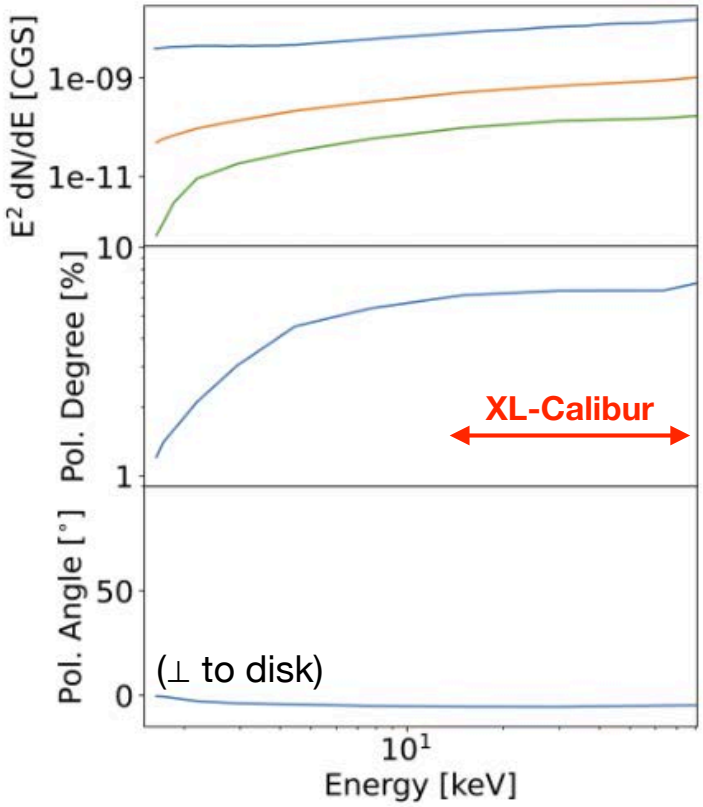
H. Krawczynski et al. (IXPE Collaboration)
arXiv:2206.09972
20th June 2022



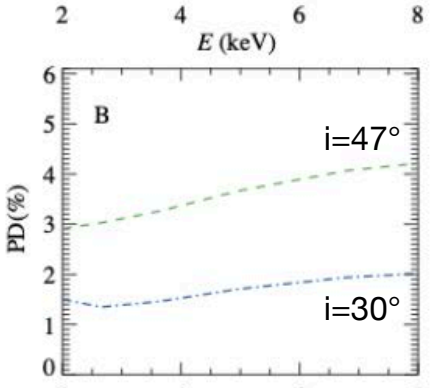
2-8 keV
PF=(4.0±0.2)% (20σ !)
PA=(-20.7±1.4)°

Clear support for a corona extended in the plane of the accretion disk

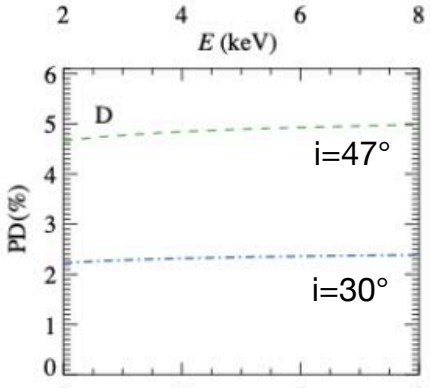
Wedge-shaped corona



Truncated disk+inner hot flow

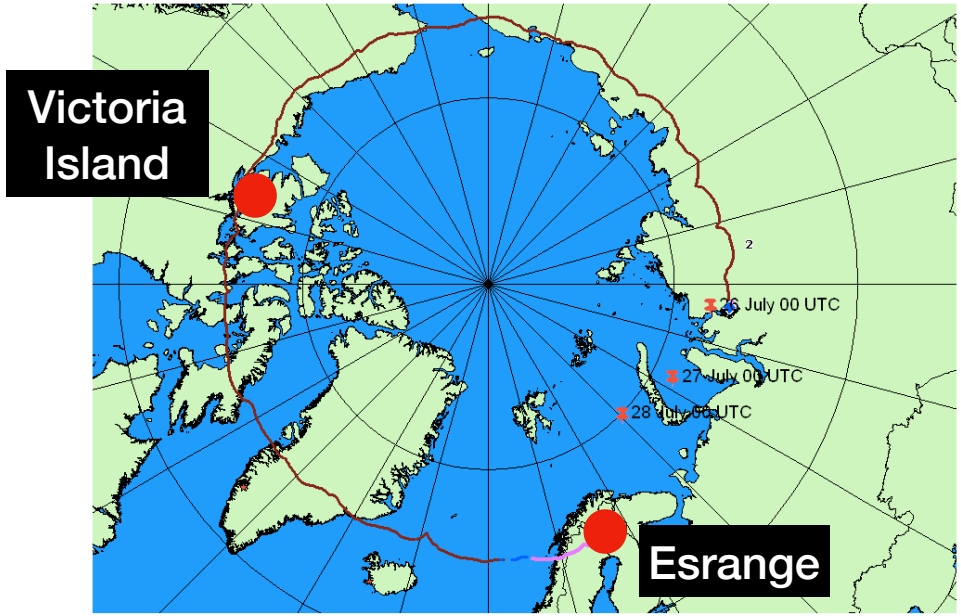


Seed photons from outer cool disk



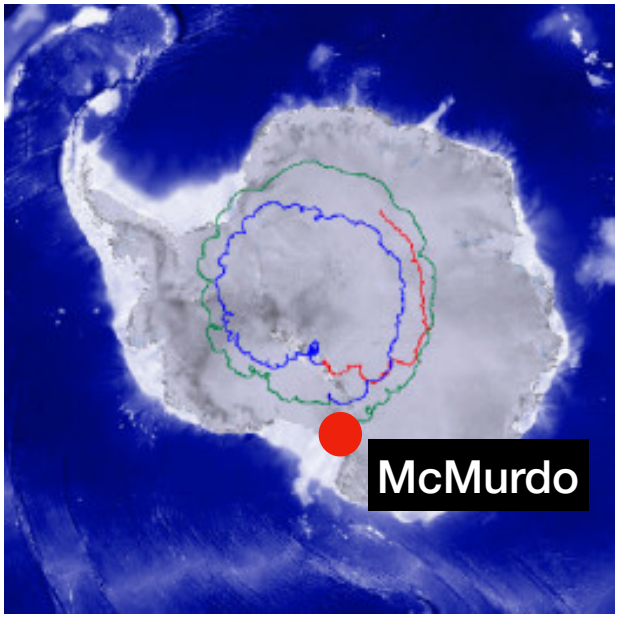
Synchrotron seed photons

XL-Calibur flights (NASA *APRA* programme)



~5-7 days

Launch attempts: 25/6, 30/6, 1/7, 2/7, (3/7), …



~8-55+ days

December/January

Planned for 2023/2024

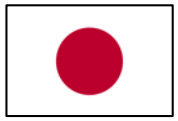
Hoping for better weather ...

... before the campaign ends on ~13 July

The XL-Calibur Collaboration

Q. Abarr,
H. Awaki,
R. Bose,
D. Braun,
G. De Geronimo,
P. Dowkontt,
T. Enoto,
M. Errando,
Y. Fukazawa,
A. Furusawa,
T. Gadson,
E. Gau,
V. Guarino,
S. Gunji
K. Hayashida,
S. Heatwole,
K. Ishibashi,
M. Ishida,
N.K. Iyer,
K. Harmon,
F. Kislat,
M. Kiss,
T. Kitaguchi,
H. Krawczynski (PI),
R.J. Lanzi,
L. Lisalda,
Y. Maeda,
H. Matake,
H. Matsumoto,
T. Miyazawa,
T. Mizuno,
T. Okajima,
M. Pearce,
Z. Peterson,
B. Rauch,
N. Rodriguez Cavero
F. Ryde,
Y. Saito,
S. Spooner
T.A. Stana,
D. Stuchlik,
H. Takahashi,
T. Takeda,
M. Takeo,
T. Tamagawa,
H. Tsunemi,
N. Uchida,
Y. Uchida,
K. Uchiyama,
A.T. West,
E.A. Wulf,
Y. Yoshida





PI: Henric Krawczynksi, Washington University in St. Louis