The high energy universe at ultra-high resolution
The power and promise of X-ray interferometry

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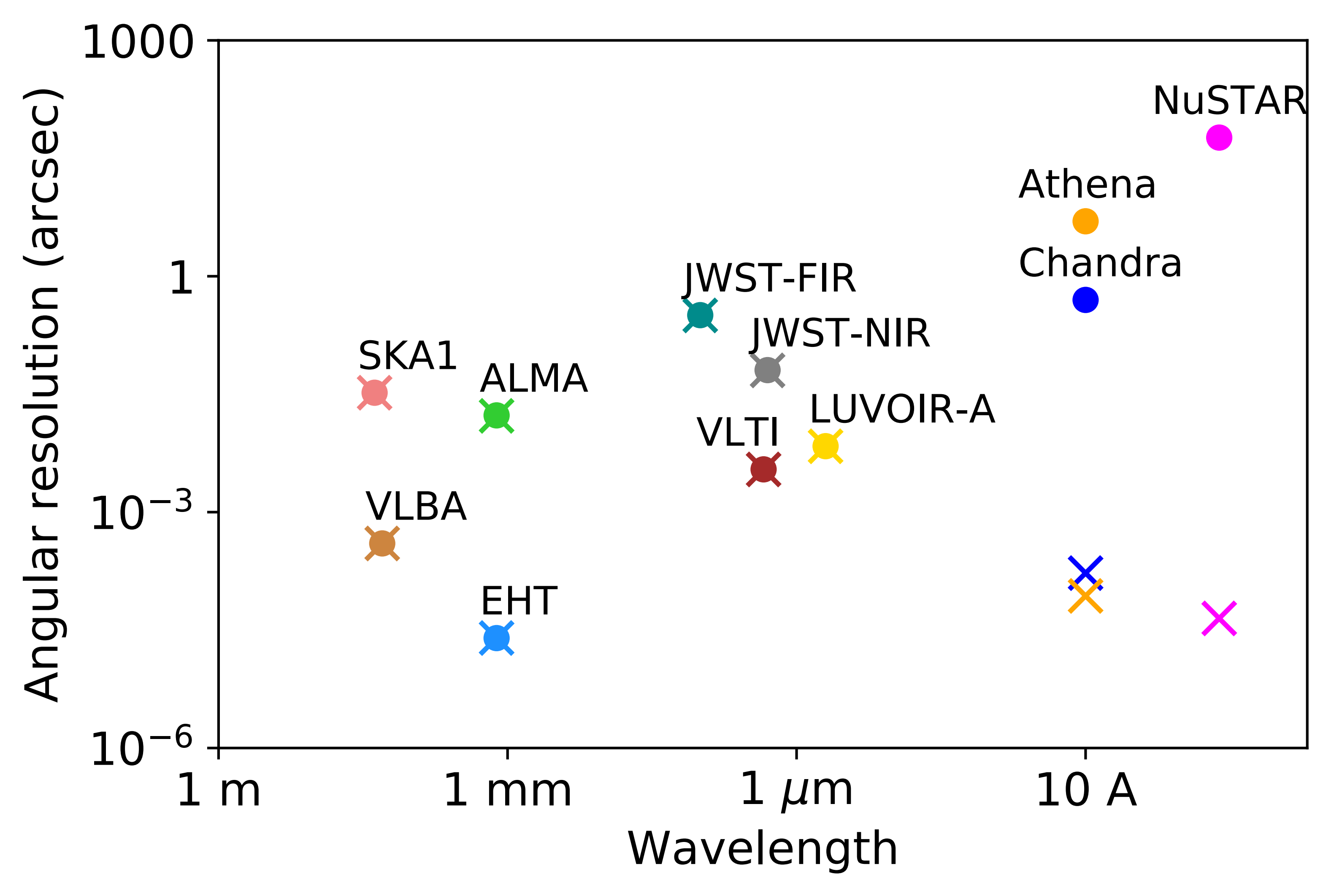
https://arxiv.org/abs/1908.03144

Angular resolution across the EM spectrum

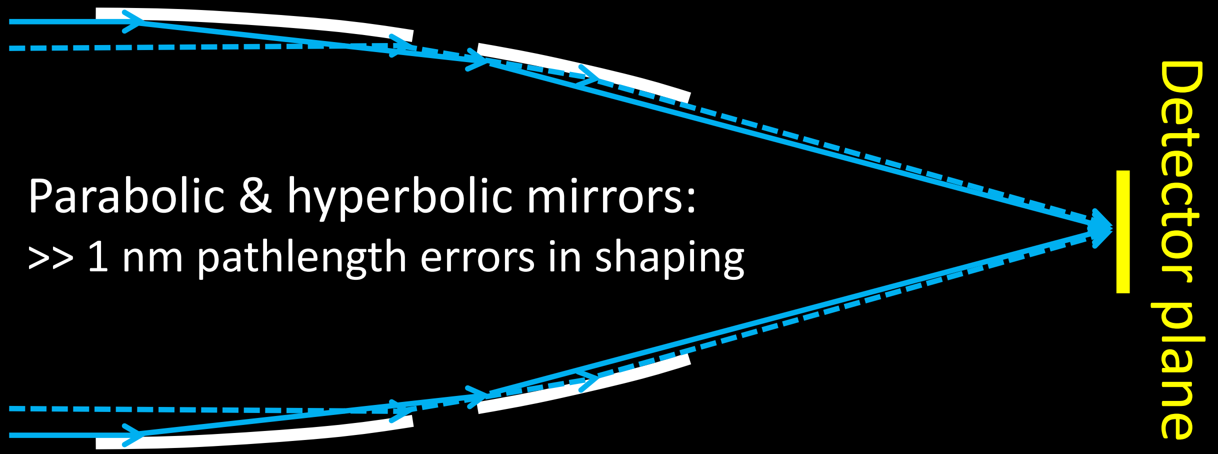
● Actual image quality

× Diffraction limit (λ/D) for effective instrument aperture D and wavelength λ

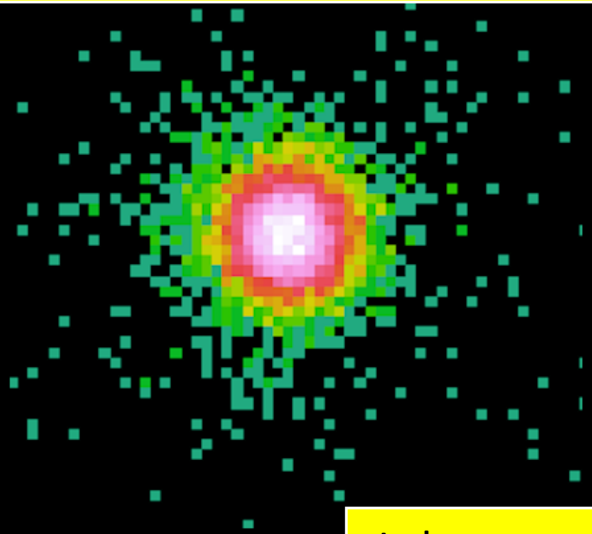


X-ray focussing optics (Wolter-I)

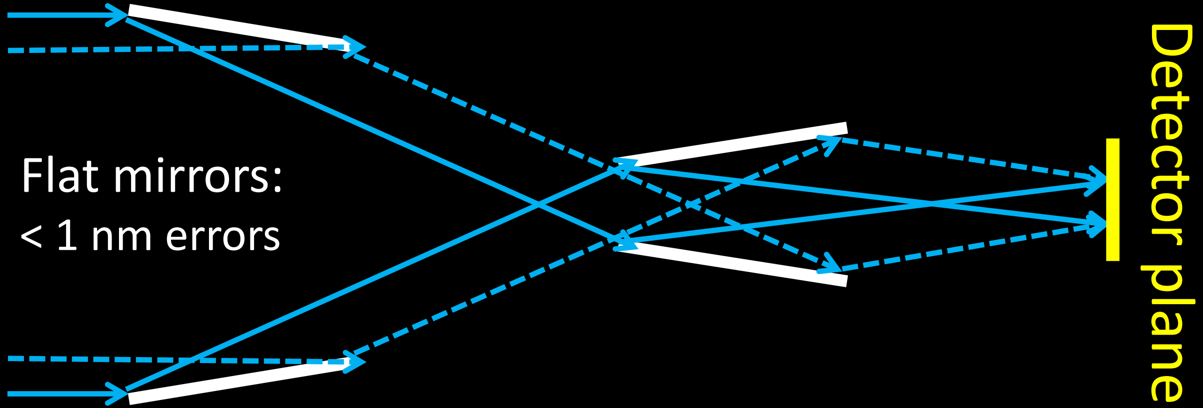
Chandra point-spread function:
0.5 arcsec (half-energy width)



Parabolic & hyperbolic mirrors:
>> 1 nm pathlength errors in shaping

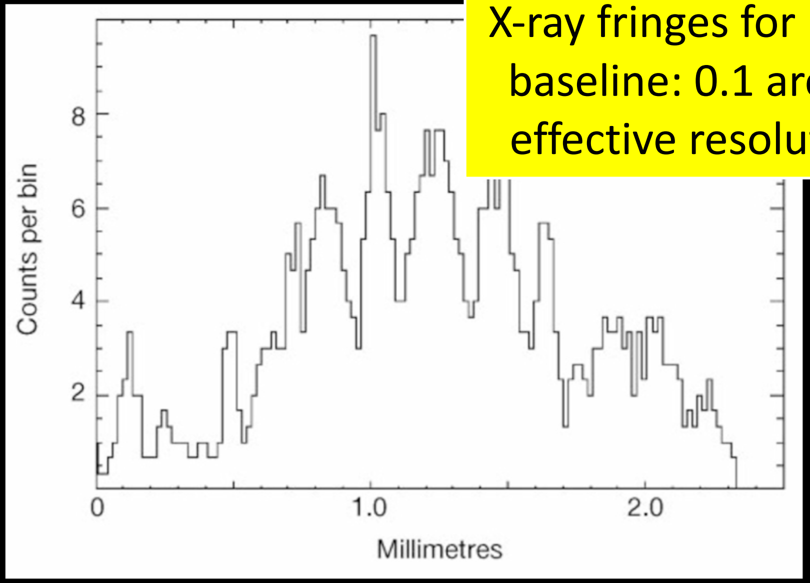


X-ray Michelson interferometer



Flat mirrors:
< 1 nm errors

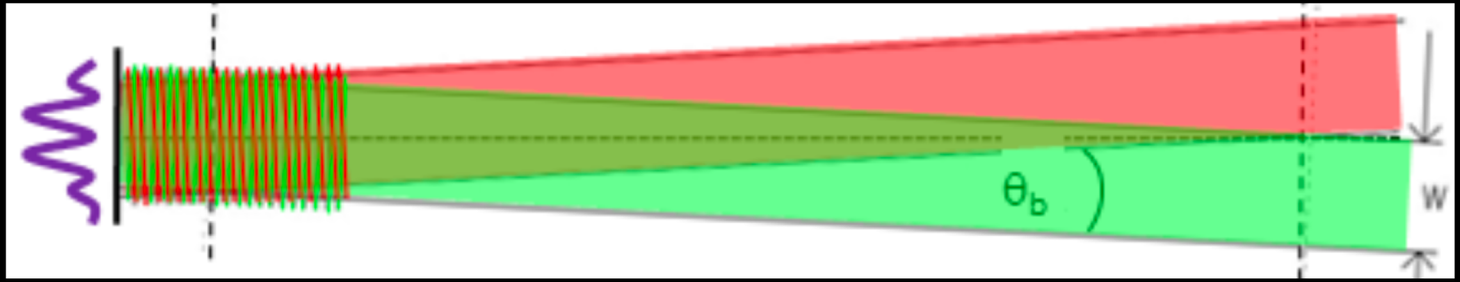
Lab measurement of X-ray fringes for 1mm baseline: 0.1 arcsec effective resolution



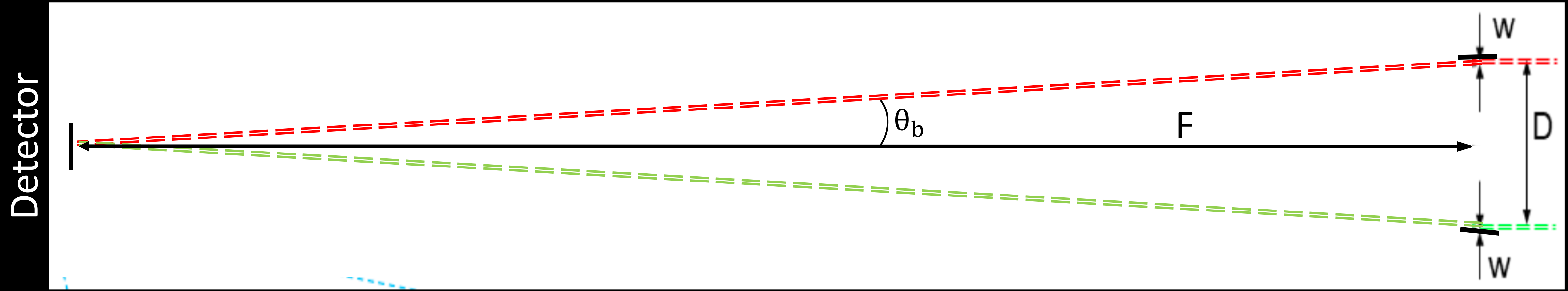
Cash et al. 2000

A compact interferometer design

For 5-10 μm detector pixels to resolve fringes, angle between beams < 10 arcsec:

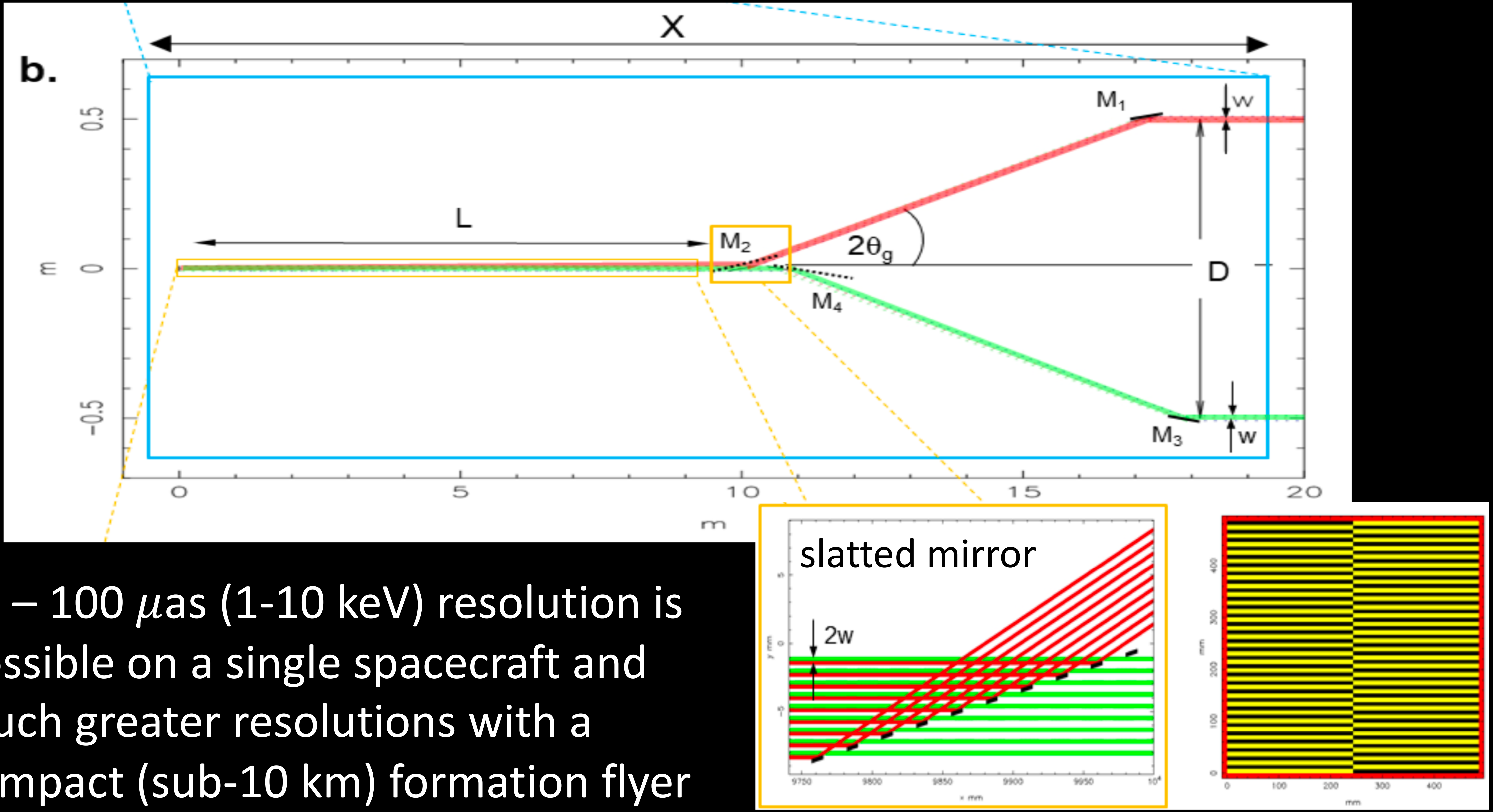


The required focal length $F = D/\theta_b \approx \left(4000/\theta_{\mu as}\right)$ km! Such mirror-detector seperations were used by original NASA formation-flyer concepts (Cash, Gendreau, 2003-2010)



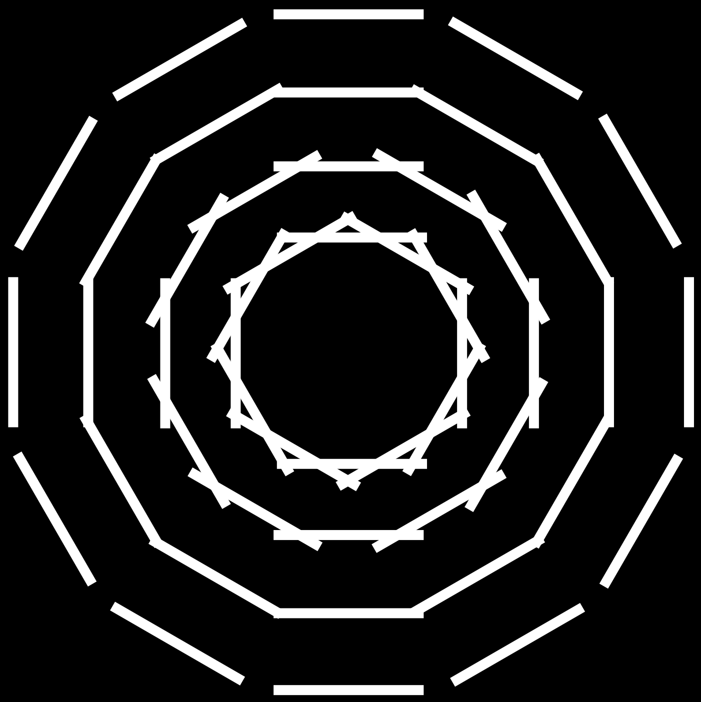
The interferometer can be made **much** more compact (factor 2000!) using a 'telephoto' mirror arrangement (Willingale 2004)

(based on Willingale 2004)



10 – 100 μas (1-10 keV) resolution is possible on a single spacecraft and much greater resolutions with a compact (sub-10 km) formation flyer

Imaging capability and sensitivity



Spacecraft aperture can be 'tiled' with pairs of mirrors to form different baselines

UV plane can be effectively filled simply by rotating the spacecraft around the optical axis

Sensitivity:

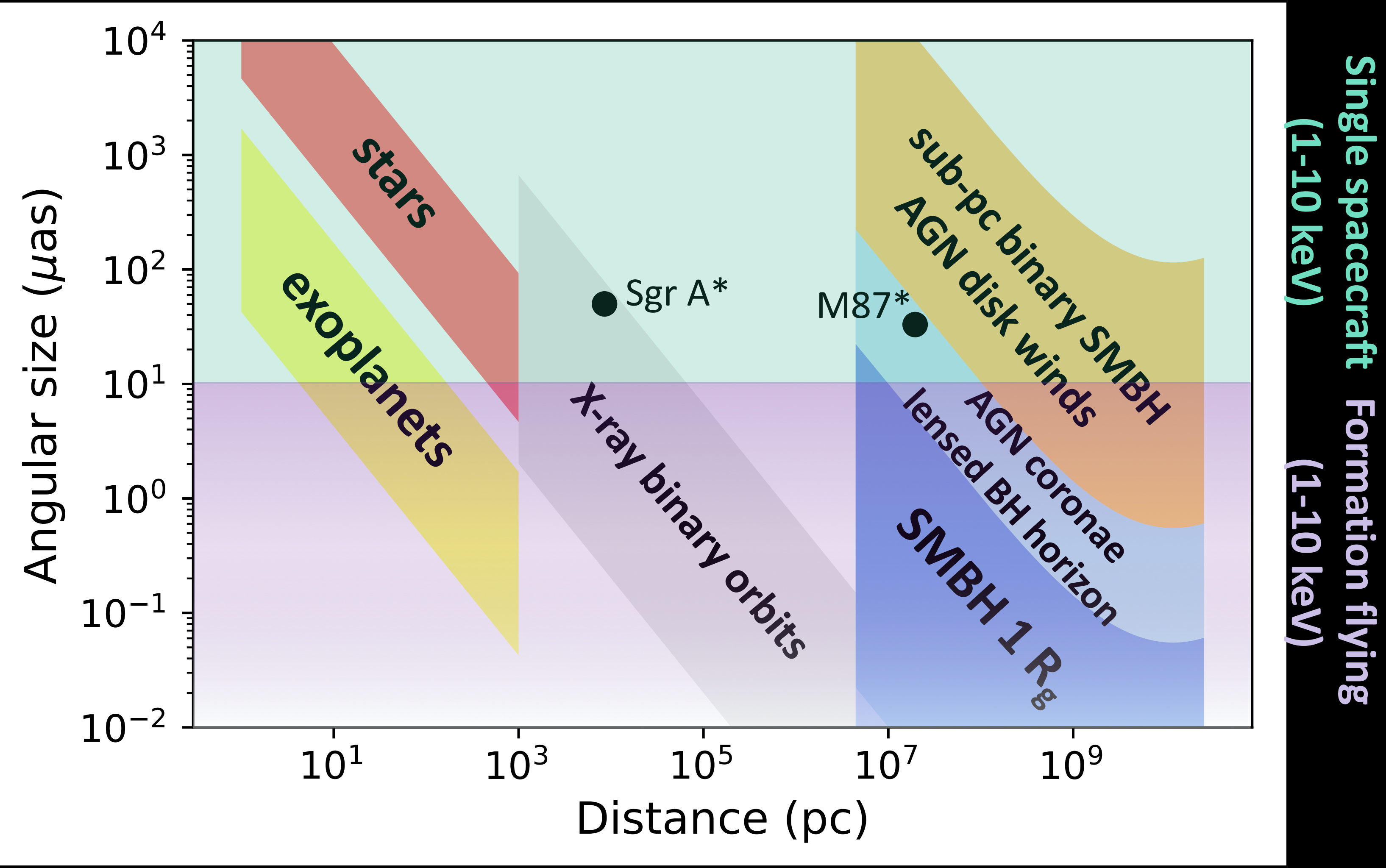
$$\sigma_{rms} = \sqrt{counts/2}$$

In principle point sources can be detected with few photons, complex images require many photons ($>10^5$) for high contrast.

Stray light from non-imaged sources can significantly reduce sensitivity (collimator/baffle requirement).

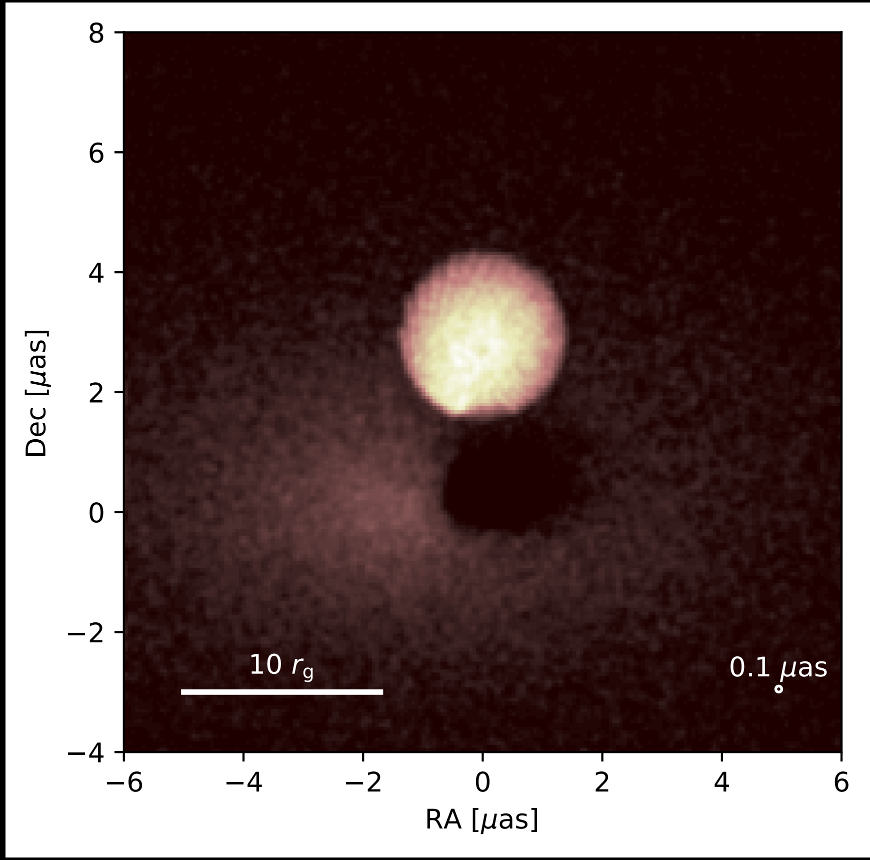
The high-energy universe at μas resolution

X-ray interferometers can image the emission from a wide variety of energetic processes from compact X-ray sources (thermal, non-thermal plasmas, fluorescent emission and other atomic processes…)



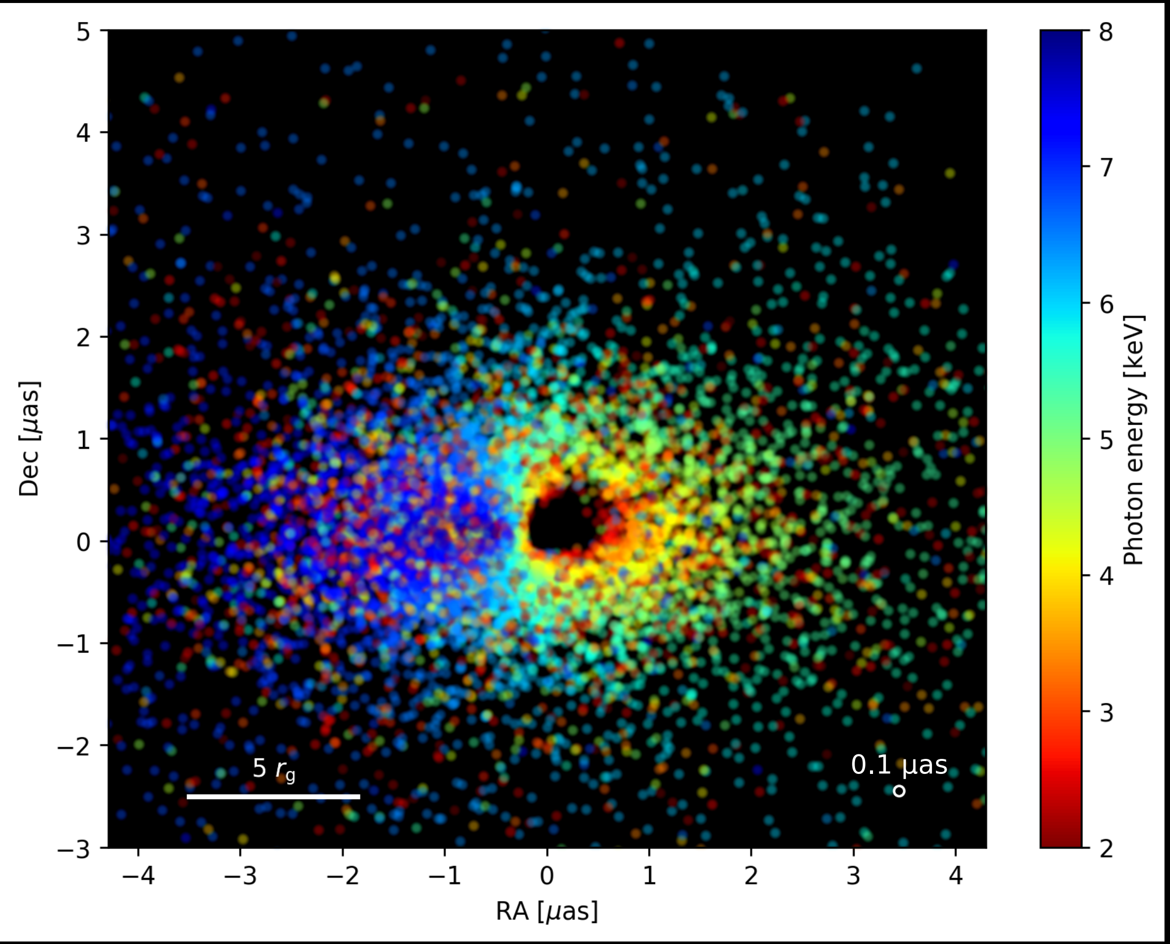
XRI science: supermassive black hole accretion flows and event horizons

- A single-spacecraft XRI can match EHT resolution, to image BH ‘shadow’, accretion flows and X-ray coronae for the closest SMBH
- Image outer disks/disk winds/Broad Line Regions in nearby AGN
- A multi-spacecraft ‘constellation’ could image disk and coronal geometry in detail in more distant AGN (see right).



XRI science: (hydro)dynamics in strong-field gravity

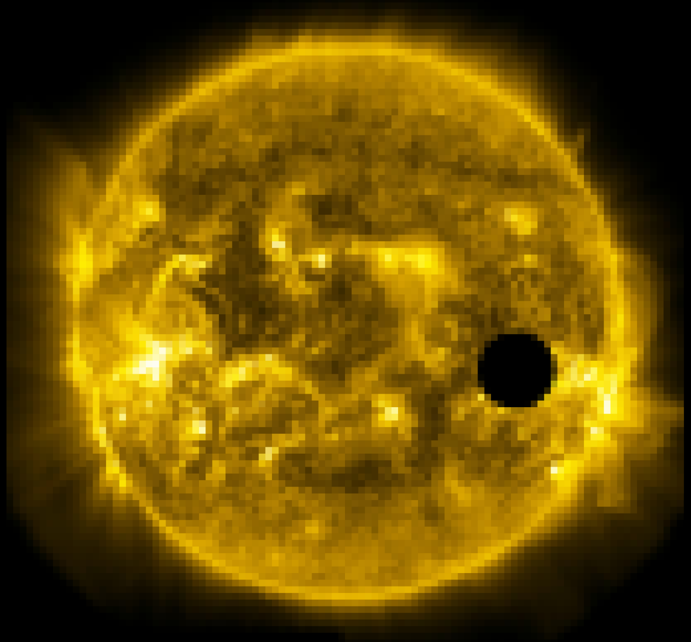
- Imaging spectroscopy of black hole accretion disks
- Detailed measurement of relativistic dynamics of plasma close to the black hole.
- For bright variable processes, we can image X-ray reverberation effects directly -> 4-D dynamics/geometry of plasma and light motion in strong-field gravity.
- Tests of the spacetime metric and crucial validation of our understanding of relativistic effects on X-ray spectra.



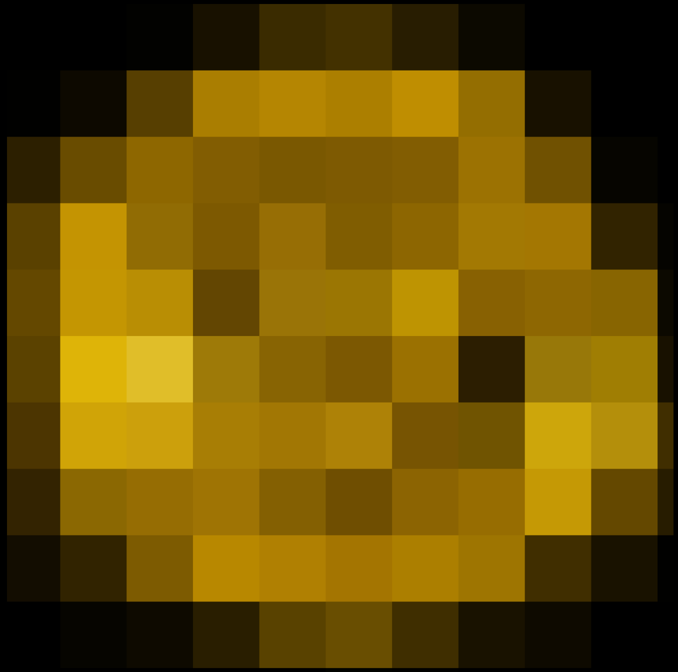
Stellar coronae and exoplanets

- Completely new understanding of coronal structure in a variety of stars
- Transiting exoplanet ‘shadows’ will be resolved: detailed transmission spectroscopy of exoplanet atmospheres
- Star-planet coronal interactions?

Solar type star AU Mic and its transiting exoplanet



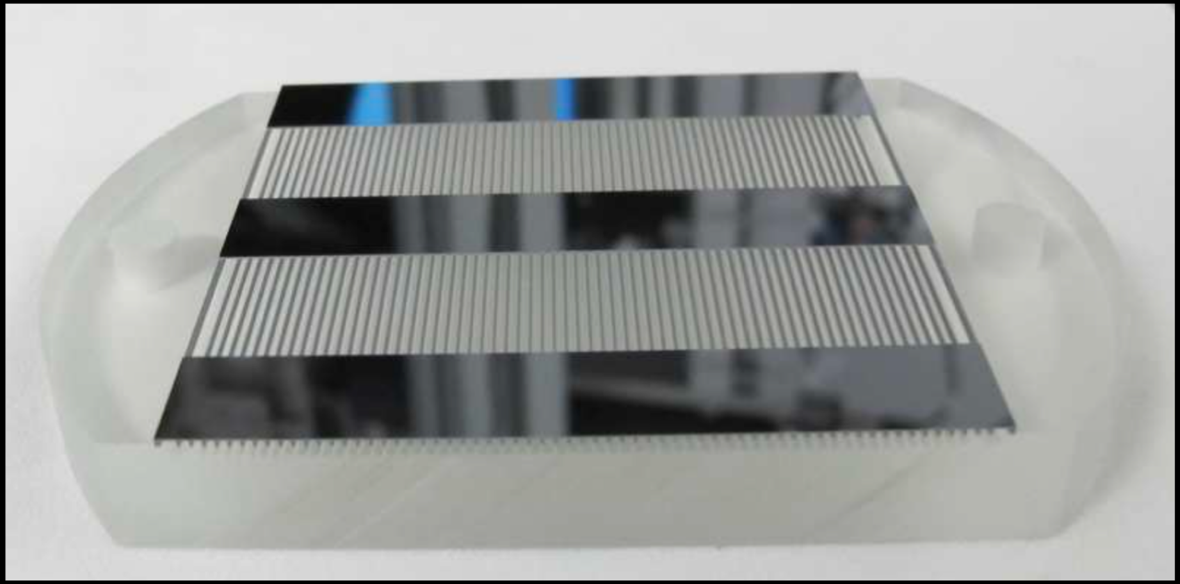
10 μas resolution



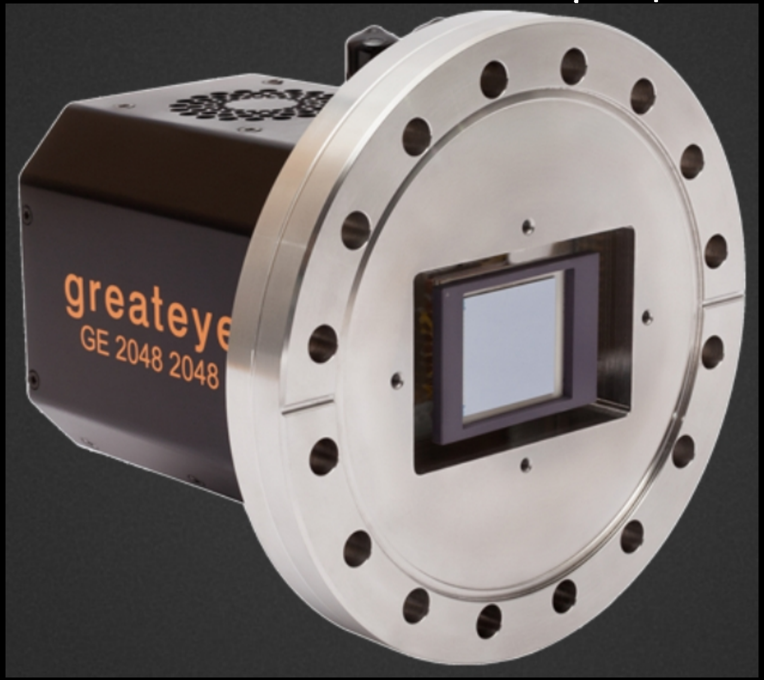
100 μas resolution

Feasibility: mirrors and detectors

2048 x 2048 13.5 μm pixels



Credit: Willingale (U. Leicester), Cosine



- Si-pore ultra-flat mirrors can already be made with close to required projected surface roughness (source: Cosine)
- Slatted mirror prototype shown above (and see Willingale et al., 2013).

- Large-area Si detectors can now be bought ‘off-the-shelf’.
- Nice to have: increased spectral resolution with large area (10 eV?)
- Spatial resolution only needed in 1 dimension.

Challenges

Interferometric testbed

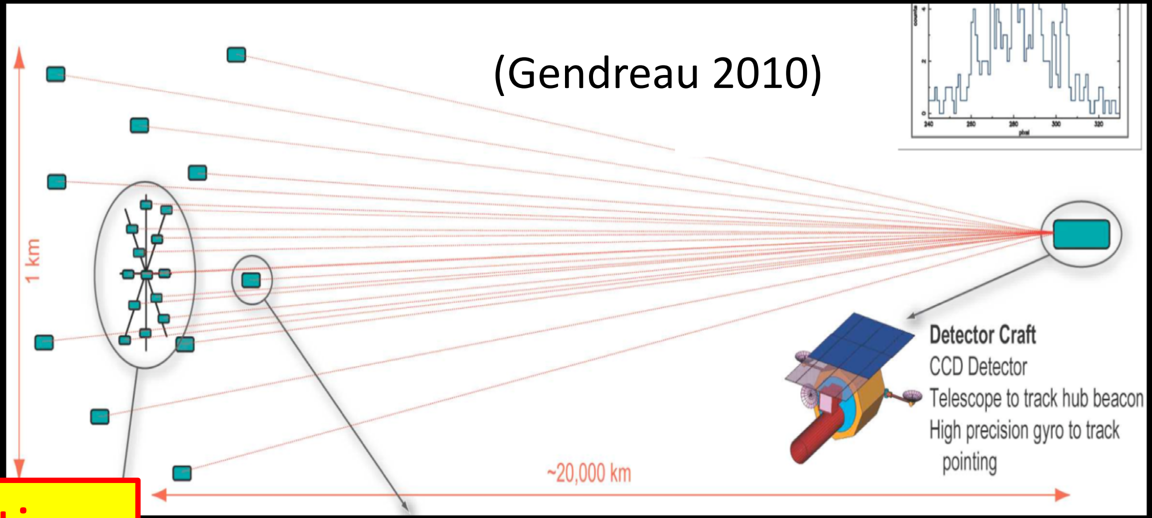
- How to test interferometric optics to μas precision?
- May require 'inverse telephoto' design to produce ~parallel rays.
- High fluence: may need special testbed extension for existing synchrotron sources.

Pointing/source-localization

- For bright sources, direct fringe-finding tracking possible on large-area CCD (1 arcsec localization/pointing required).
- Faint sources require sub-100 μas localization and pointing accuracy.
- Can be mitigated with 'periscope' mirror design and good (sub-10 μas) pointing knowledge.

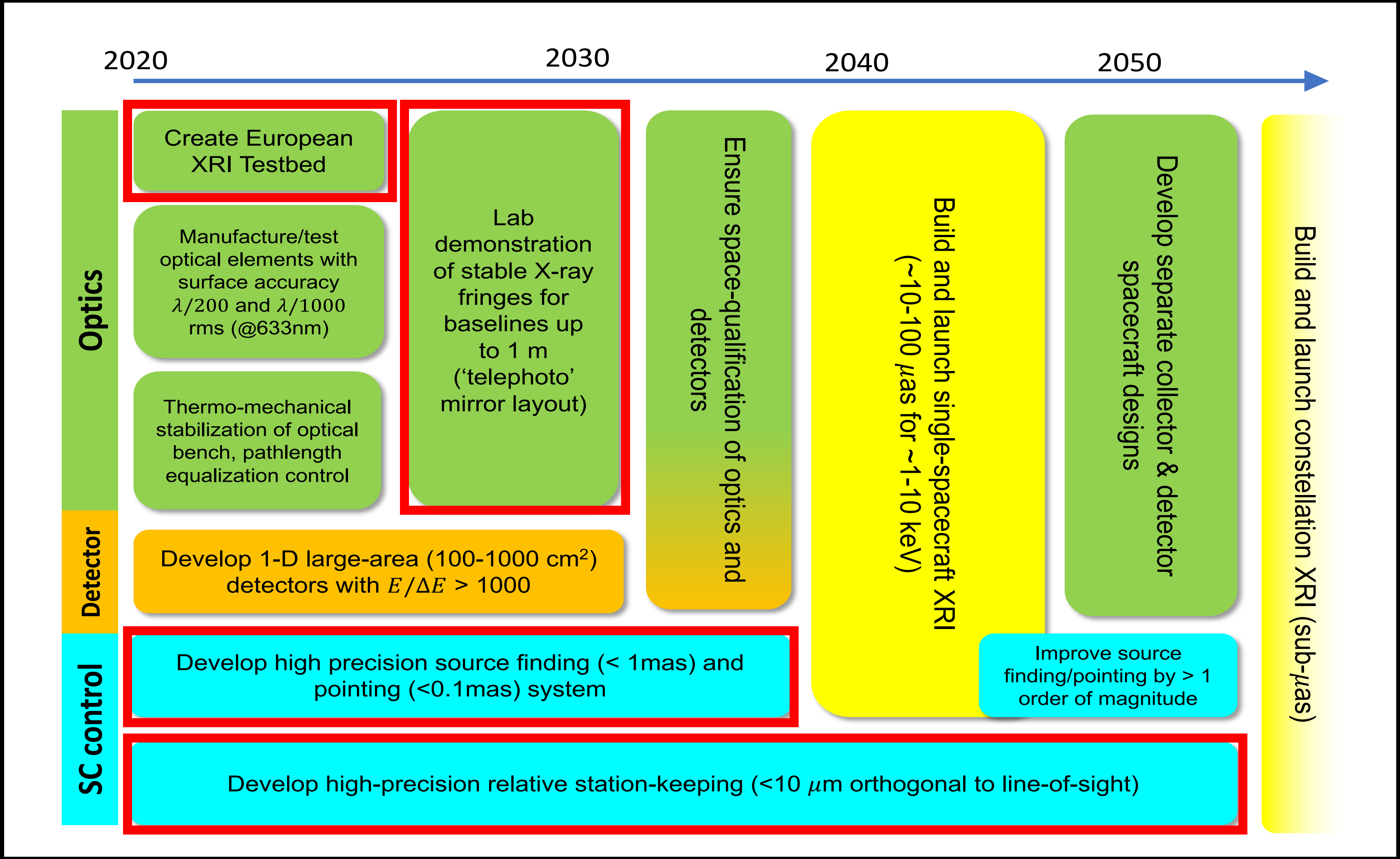
Formation flying

- NASA studies: collector spacecraft need 10 μm precision lateral station keeping. Roll/yaw offsets can be ~arcsec
- Strong synergies with other missions (interferometric, GW)



All would benefit from ESA support/co-ordination

A roadmap towards sub-μas X-ray imaging



Outlook: removing the limits of resolution