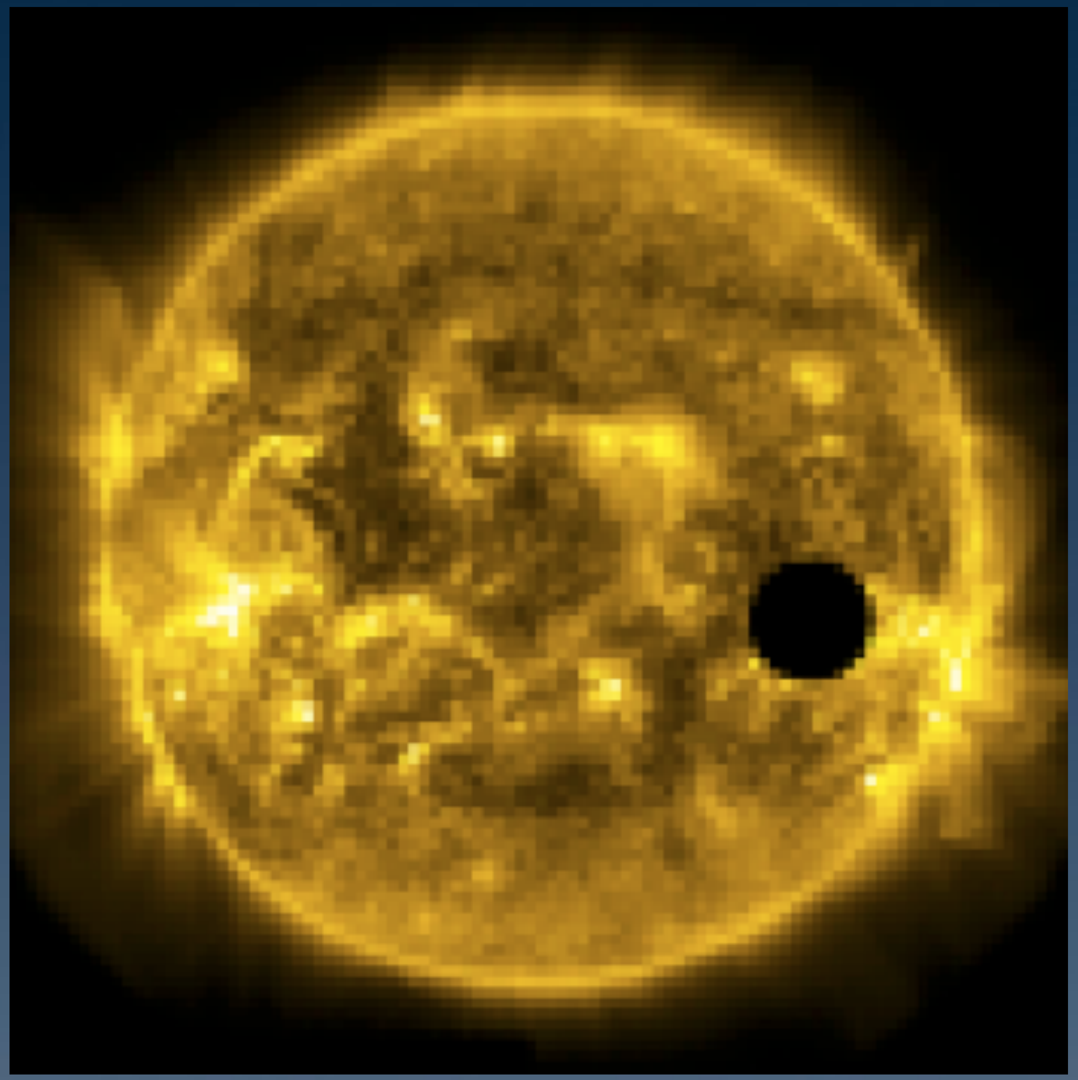
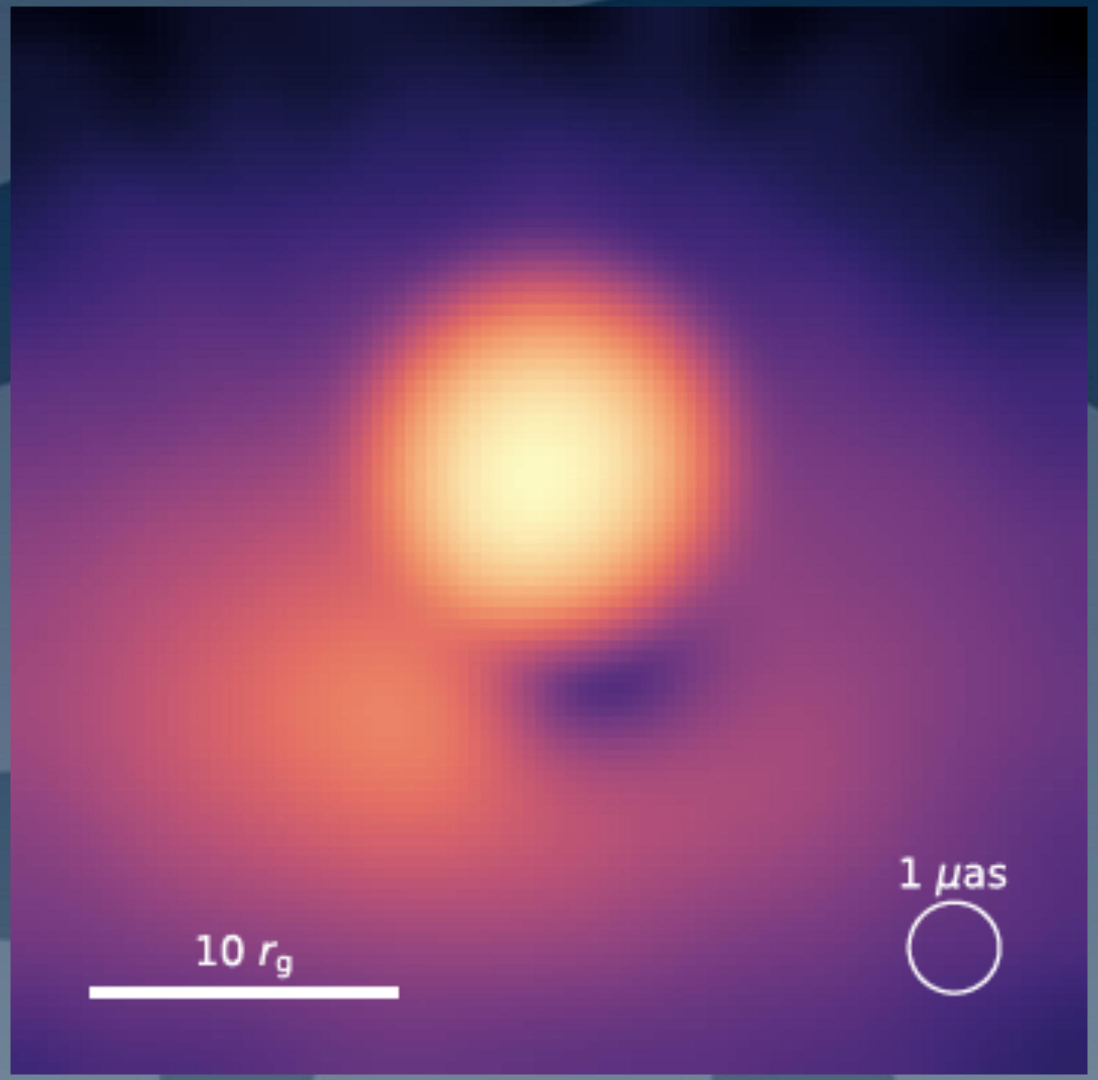
Astrophysics with Diffraction-Limited X-ray Optics



MAXIM (Cash+ ’00) and MAXIM Pathfinder (Gendreau+ ’02)
Multilayer-based, normal incidence optics (Windt & Kahn ’03)
MASSIM diffraction/refraction optics (Skinner+ ’08)
New: Micro-Arcsecond X-ray Optics Concept: (Chalifoux+, in prep.)
X-ray Interferometry for ESA Vision 2050: (Uttley et al. ’19)

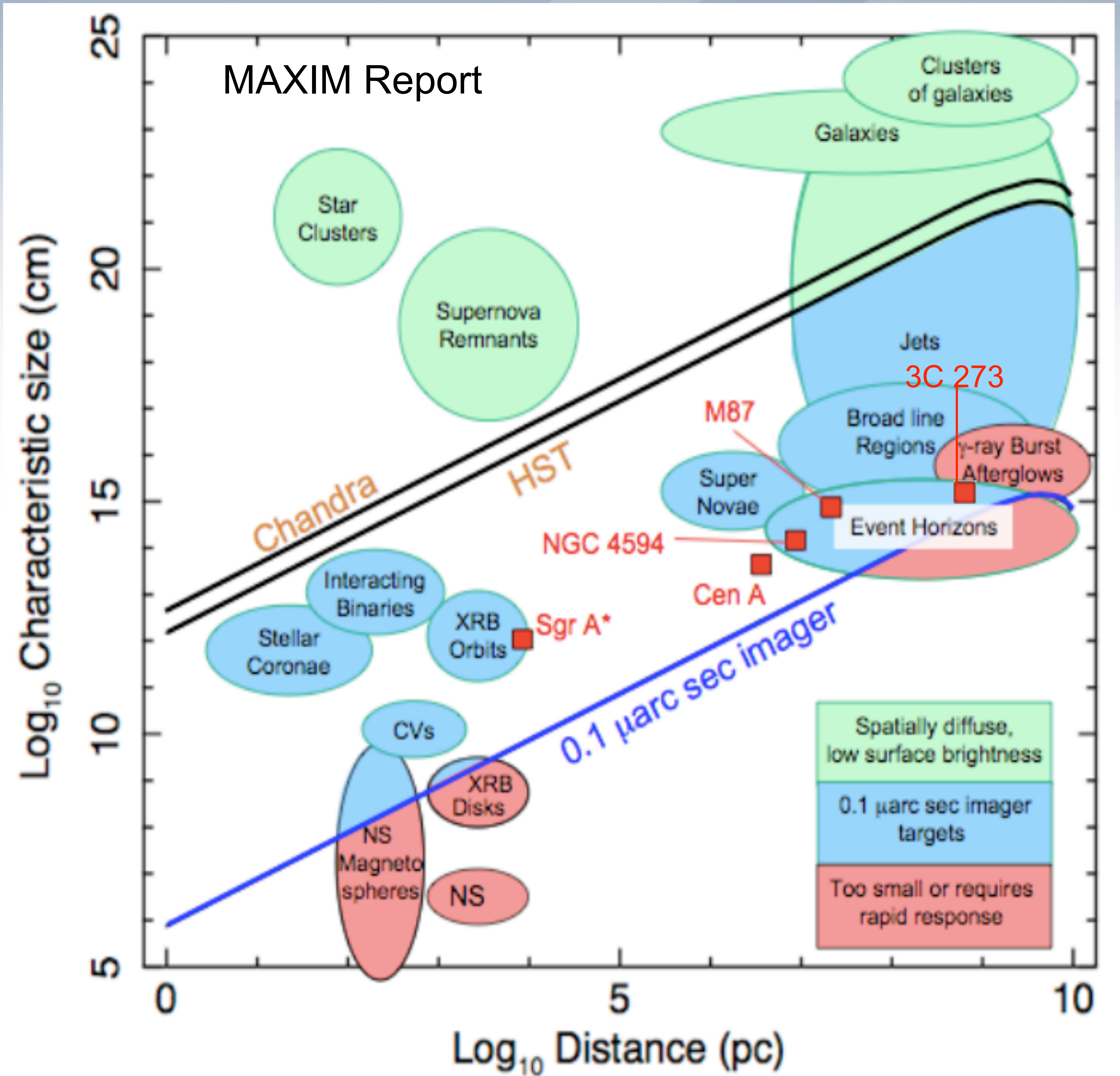
H.L. Marshall, M. Schattenburg, B. Chalifoux, R. Heilmann — Jan. 8, 2020

The Plan

- Scientific Motive
  - Imaging AGN and XRB black hole accretion disks, planetary systems
  - High temperatures mean high brightness and small angular sizes
- Technical Issues
  - Diffraction-limited optics
  - Formation flying
  - Small pixel detectors
  - System metrology & active alignment
  - Attitude control and knowledge
- Strategy and Progress
  - EUV lithography yields diffraction-limited optics
  - Si mirrors are nearly there for X-ray optics
  - CMOS detectors reduce formation flying requirements
  - Active alignment and mas-level control being tested in small systems
  - Staged development: 0.05” ⇨ 0.000,1” ⇨ 0.000,000,1”

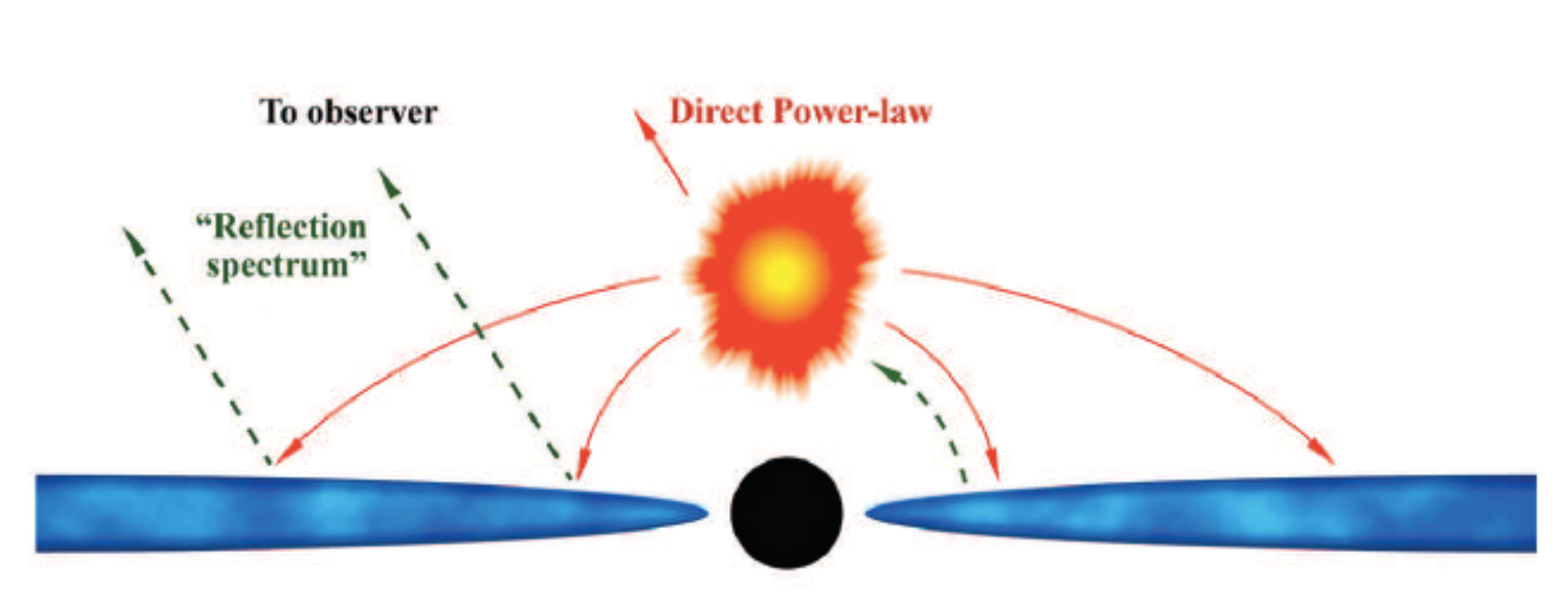
Scale sizes of Typical X-ray Sources

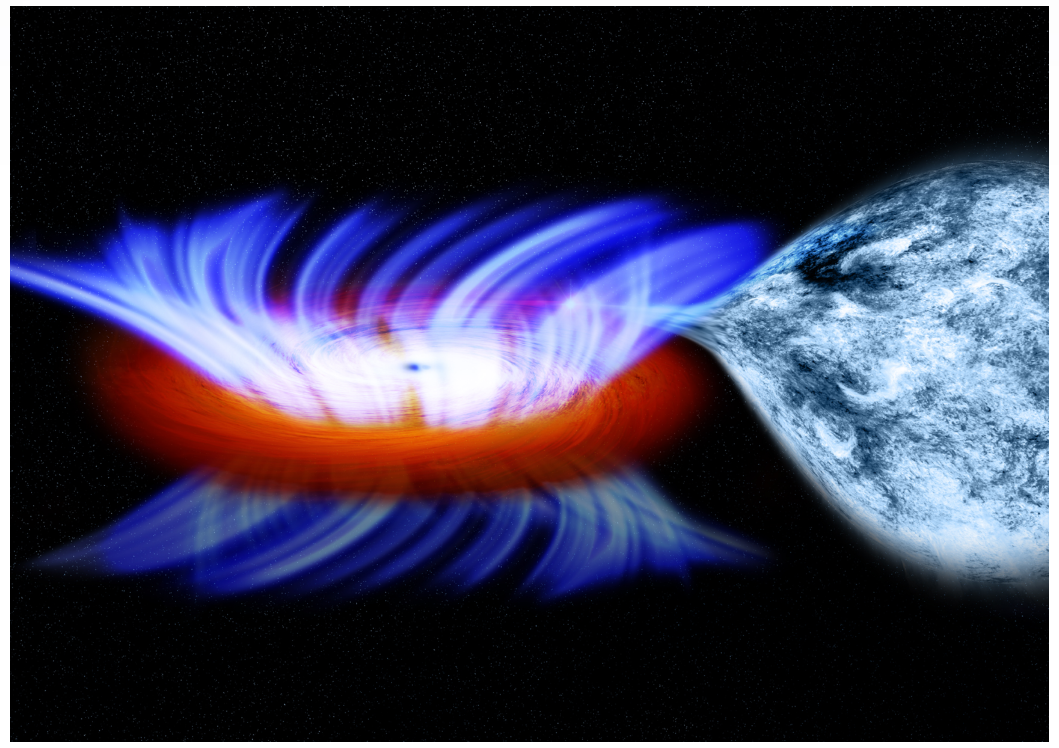
- Milli-arcsecond size
  - AGN jets
  - XRB jets, orbital scales
  - Stellar coronae
  - Gravitional Lenses
- Micro-arcsecond size
  - SMBH event horizons
  - AGN BLRs
  - Extragalactic SNRs
  - CV disks
  - XRB orbits
  - Pulsar light cylinders
  - Exoplanetary systems
  - Protoplanetary disks



Some Science Goals of a Micro-ArcSecond Imager

- Supermassive Black Holes in Active Galaxies
  - Test ‘lamp post' model of coronae
  - Velocity mapping in Fe-K from reflection off disk
  - Image blazar jets — aligned with BH spin or disk?
  - Resolve gravitational microlensing
  - Resolve BH binaries in AGN (before merger and GW emission)
  - Address ‘final parsec’ problem (1 pc > 0.1 mas everywhere)
  - Resolve outflows, photo-excited gas, and BLRs at 1-100 pc scales
- Measure GRB fireball expansion & jet speed
- Resolve XRB populations in galaxy bulges
- Resolve BH X-ray binaries to < 10^7 km at 10 kpc
  - Image accretion disk and separate irradiated companion
  - Image jets from SS 433, Cyg X-1, etc.
  - Locate globular cluster sources
- Stars
  - Stellar coronae, prominences, winds, CMEs
  - Resolve interacting binaries, disks (CVs, Dwarf Novae)
  - Planetary systems, transiting exoplanets, star forming regions

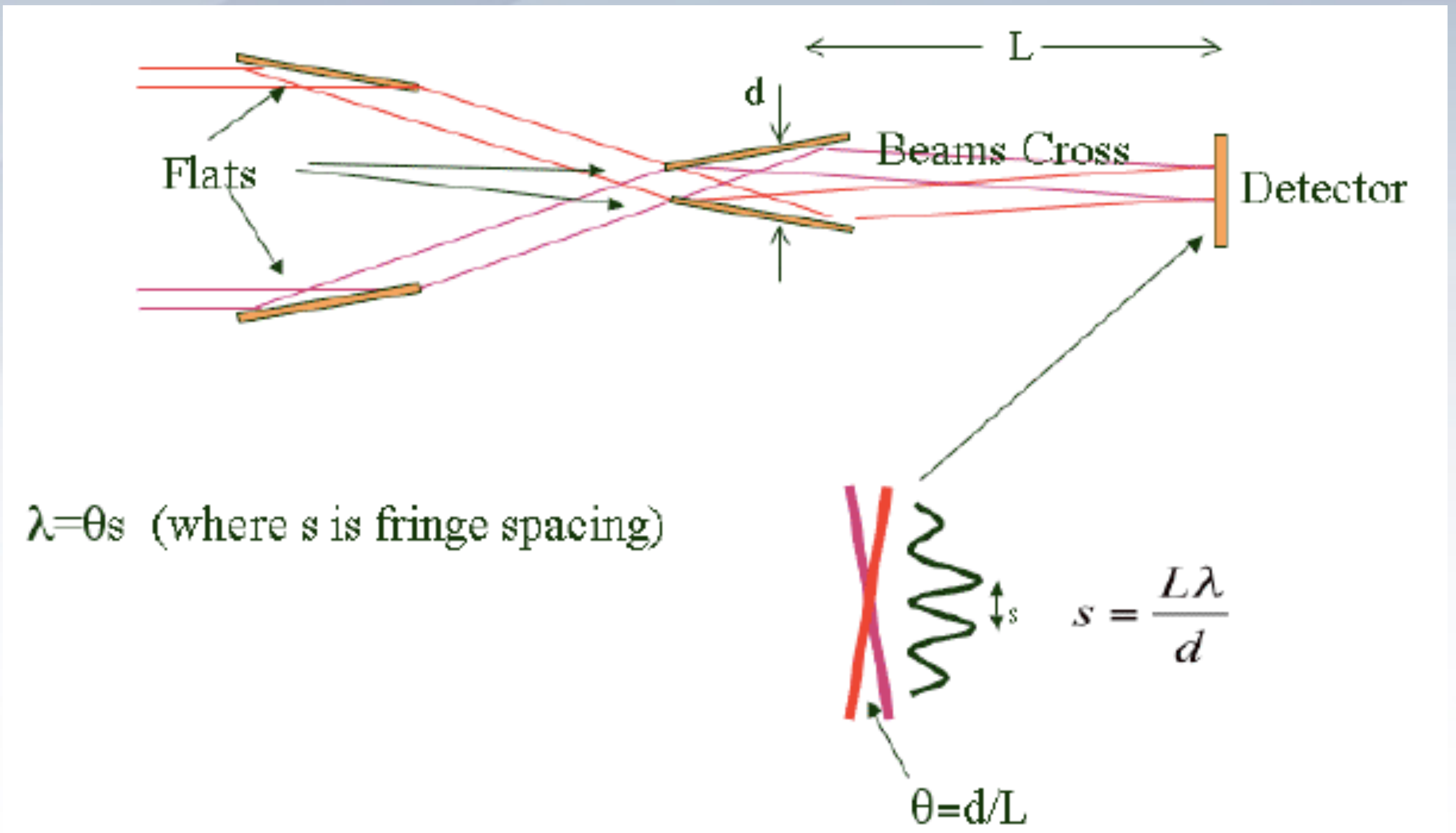


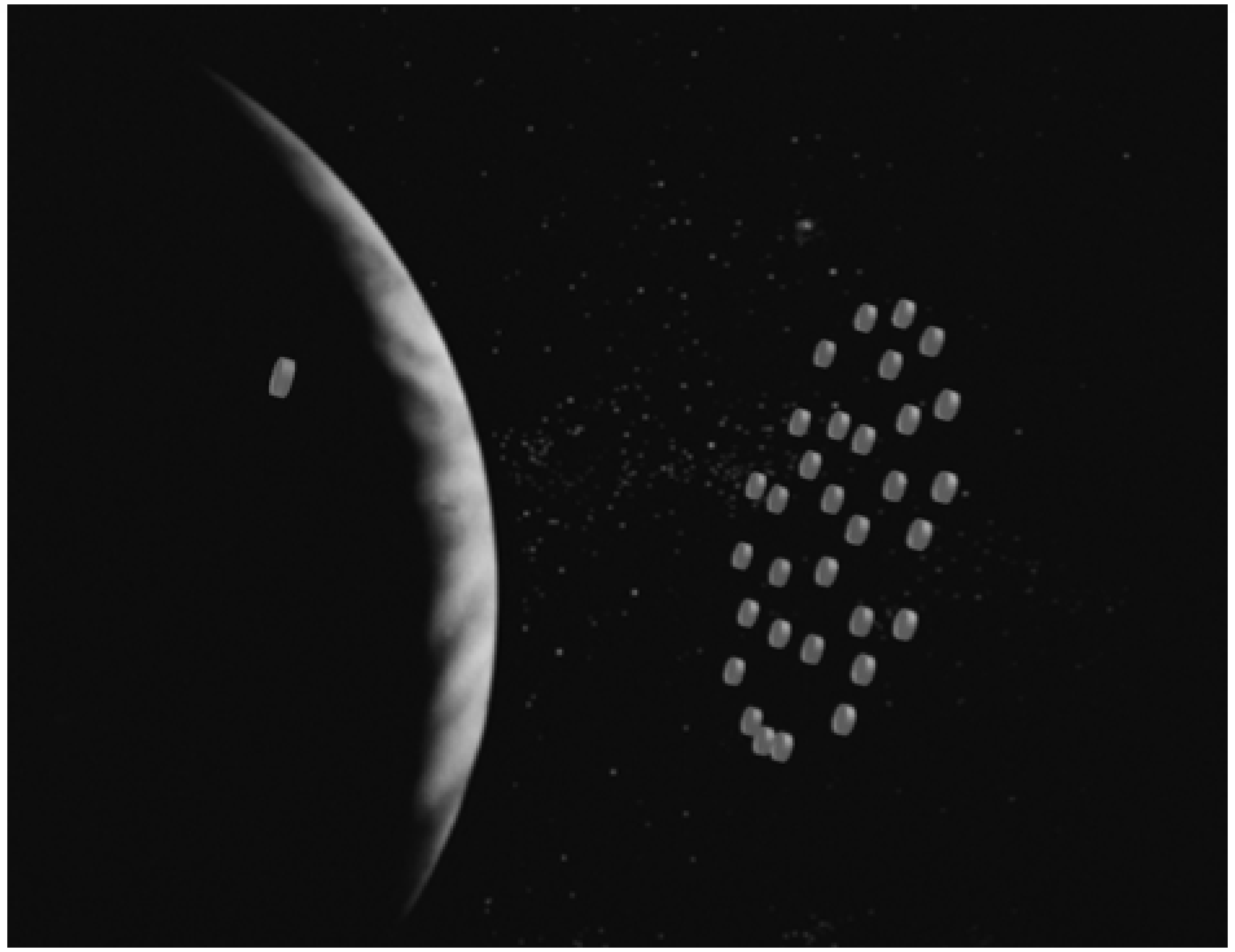


η Carina

Previous Suggstions for Improving X-ray Imaging

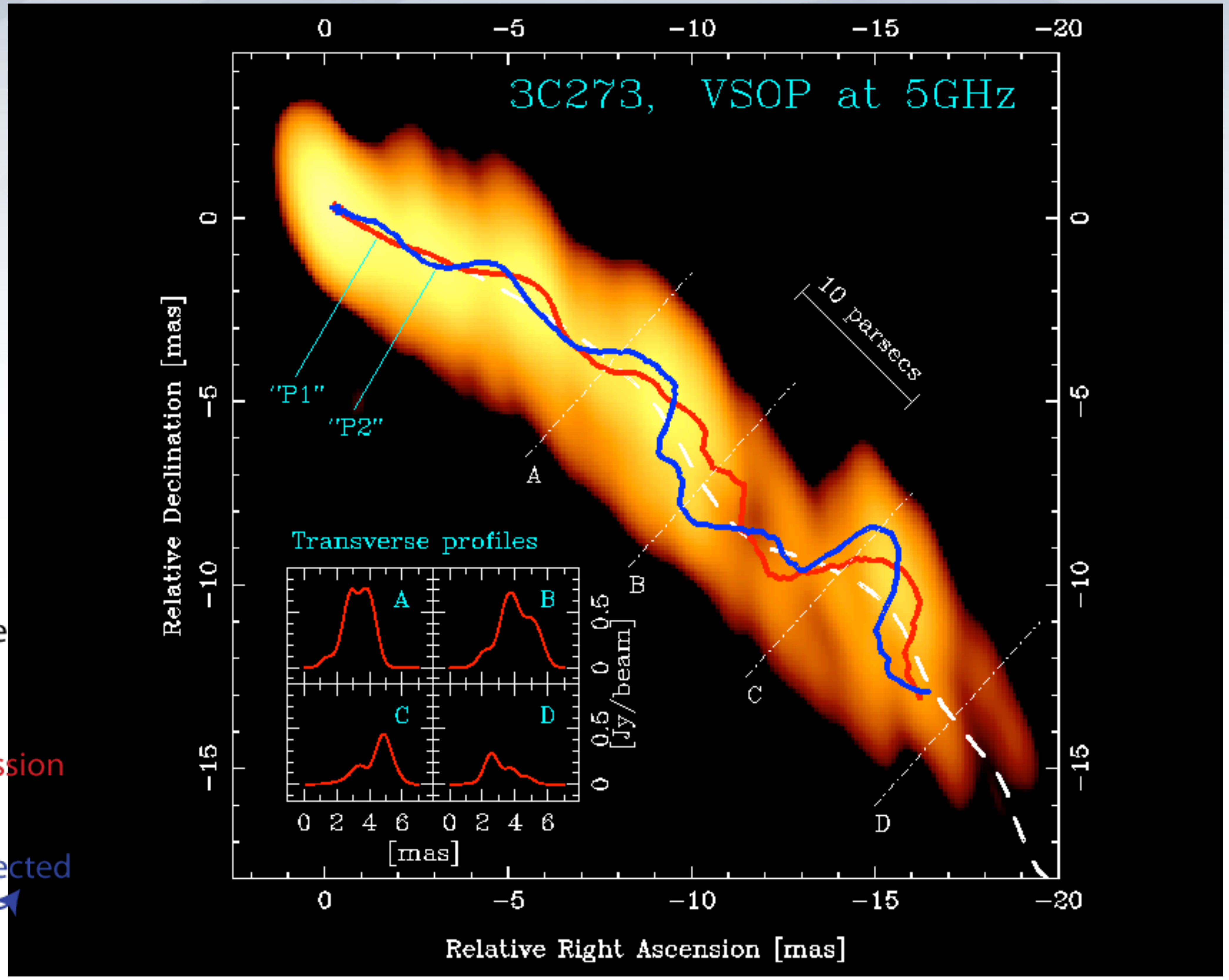
- NASA Beyond Einstein "Vision Mission": a black hole imager
  - Science goal: image BHs in nearby AGN
  - Instrument goal: 0.000,000,1" angular resolution
  - MAXIM: X-ray interferometry with 100+ m baseline
  - Pathfinder: 0.000,1" resolution, 0.14 m primary size, 2 spacecraft 450 m apart
- One alternative: normal incidence telescope with multilayer (ML) coatings
  - Proposed by Windt and Kahn (2003)
  - Tune MLs to lines of ions in 17-35Å range
  - Distribute 2.5m mirrors over 50m aperture
  - Pathfinder: 0.000,3", 2.5 m diam primary, Cassegrain design, 10 m focal length
- Another alternative: combine diffractive & refractive optics
  - See Skinner (2001, 2002), Gorenstein (2007)
  - Good option for γ-ray imaging

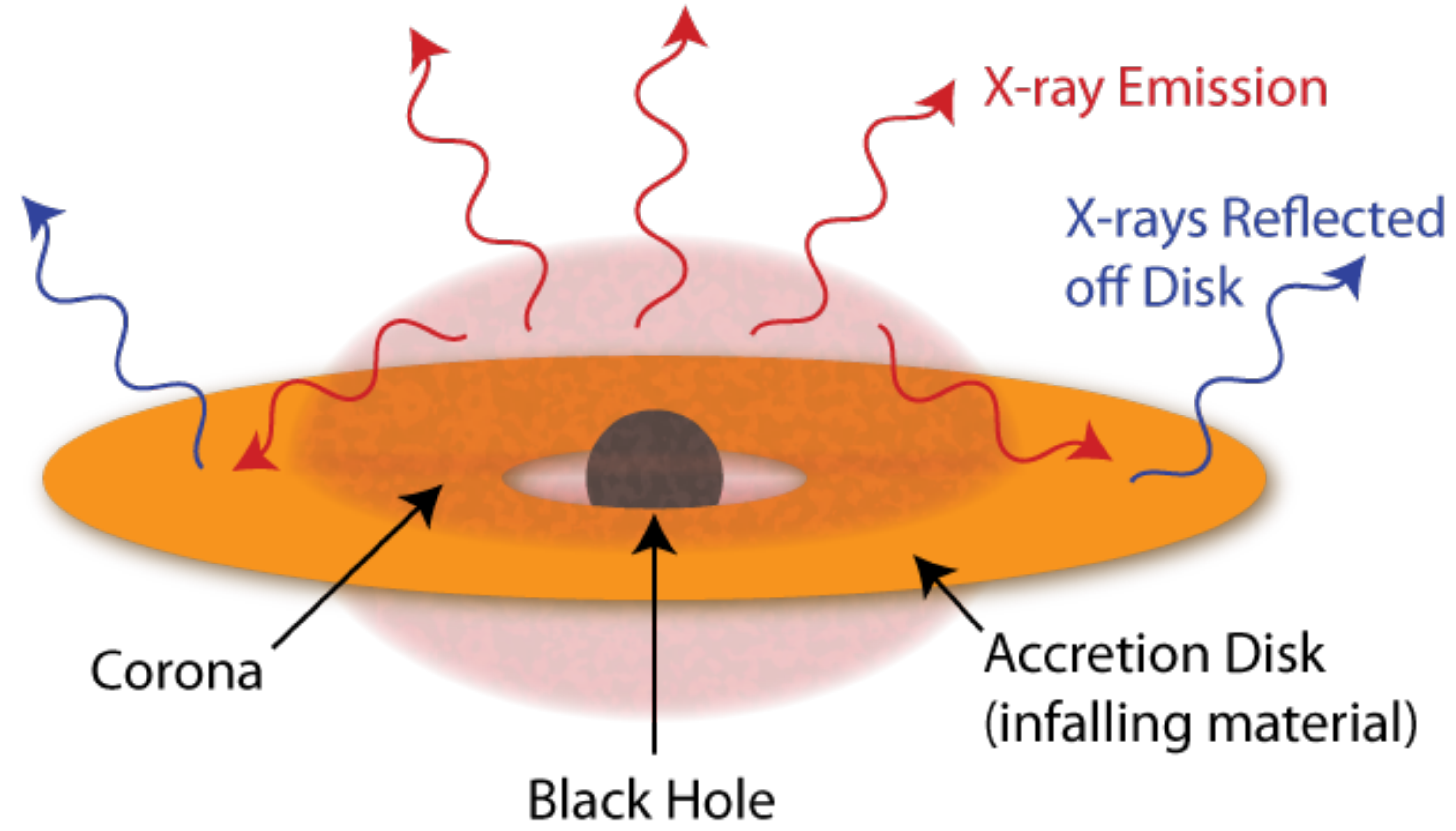


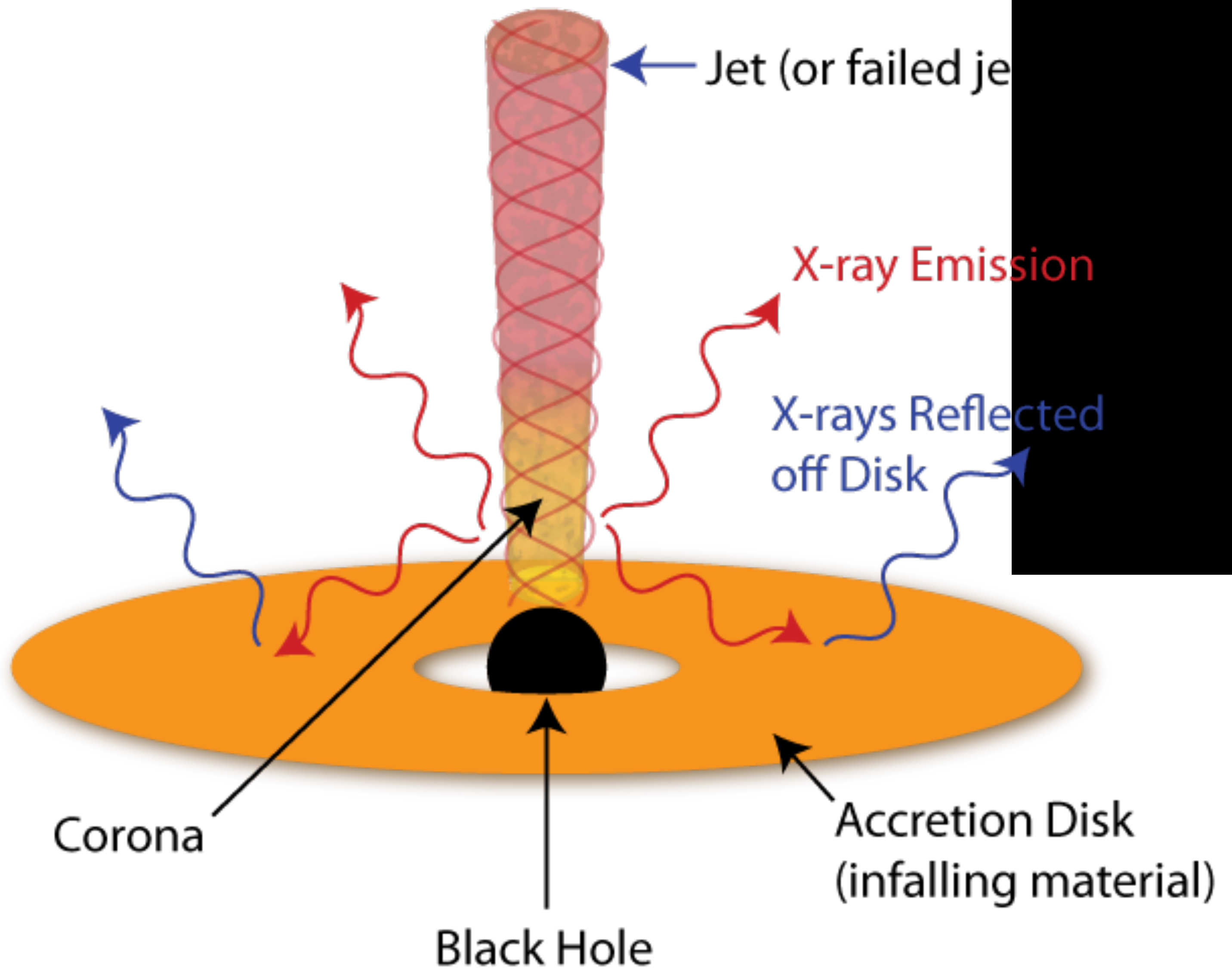


Imaging AGN Cores: 3C 273

- Discern between jet and coronal models
- VLBI shows core is a jet about 25 mas long
- Core flux is 0.15 ph/cm^2/s/keV at 0.4 keV
- Requires imaging < 0.01”
- A ML-based mirror can get 100 cnt/PSF in 10^5 s



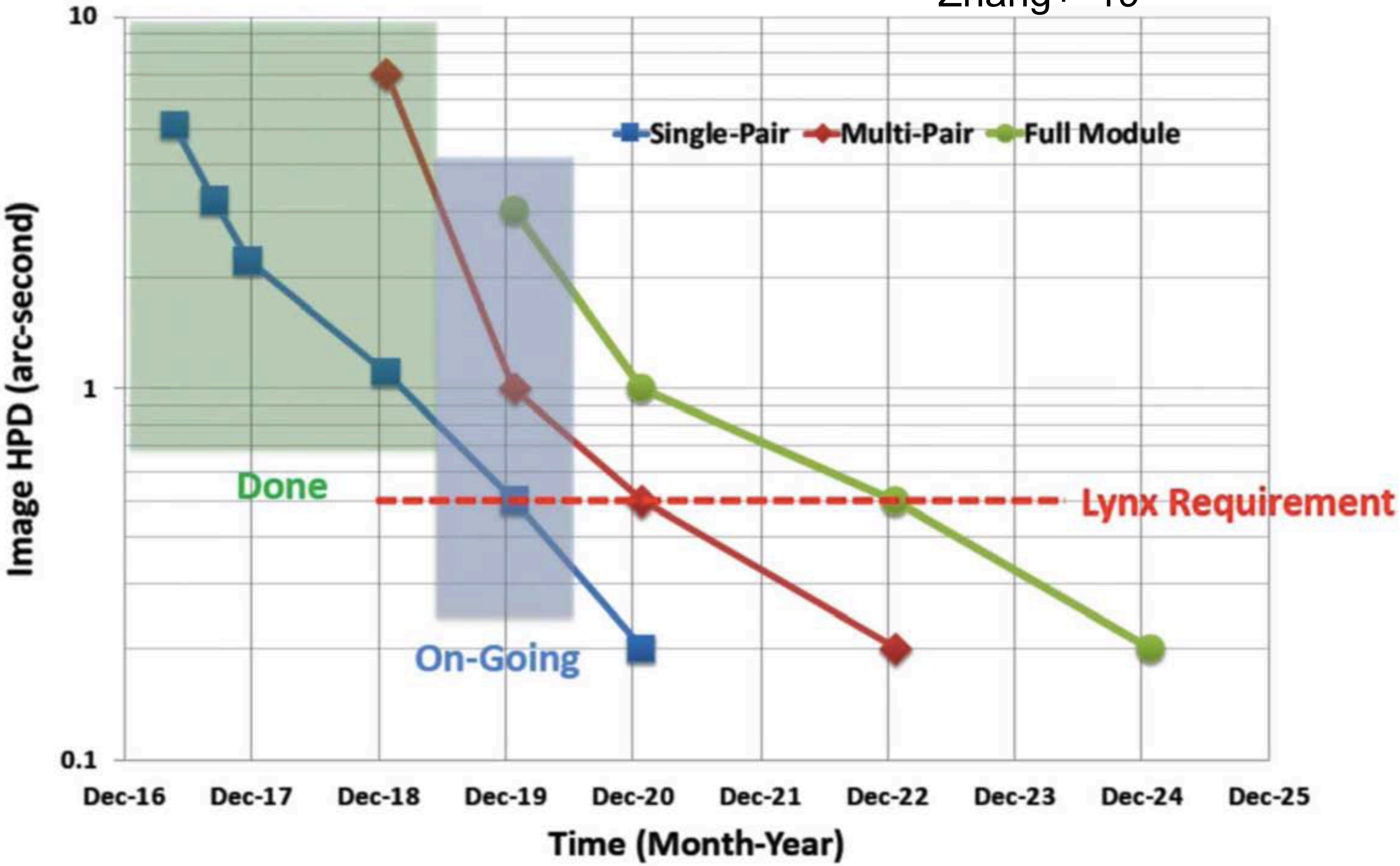




Diffraction Limited Si Mirrors

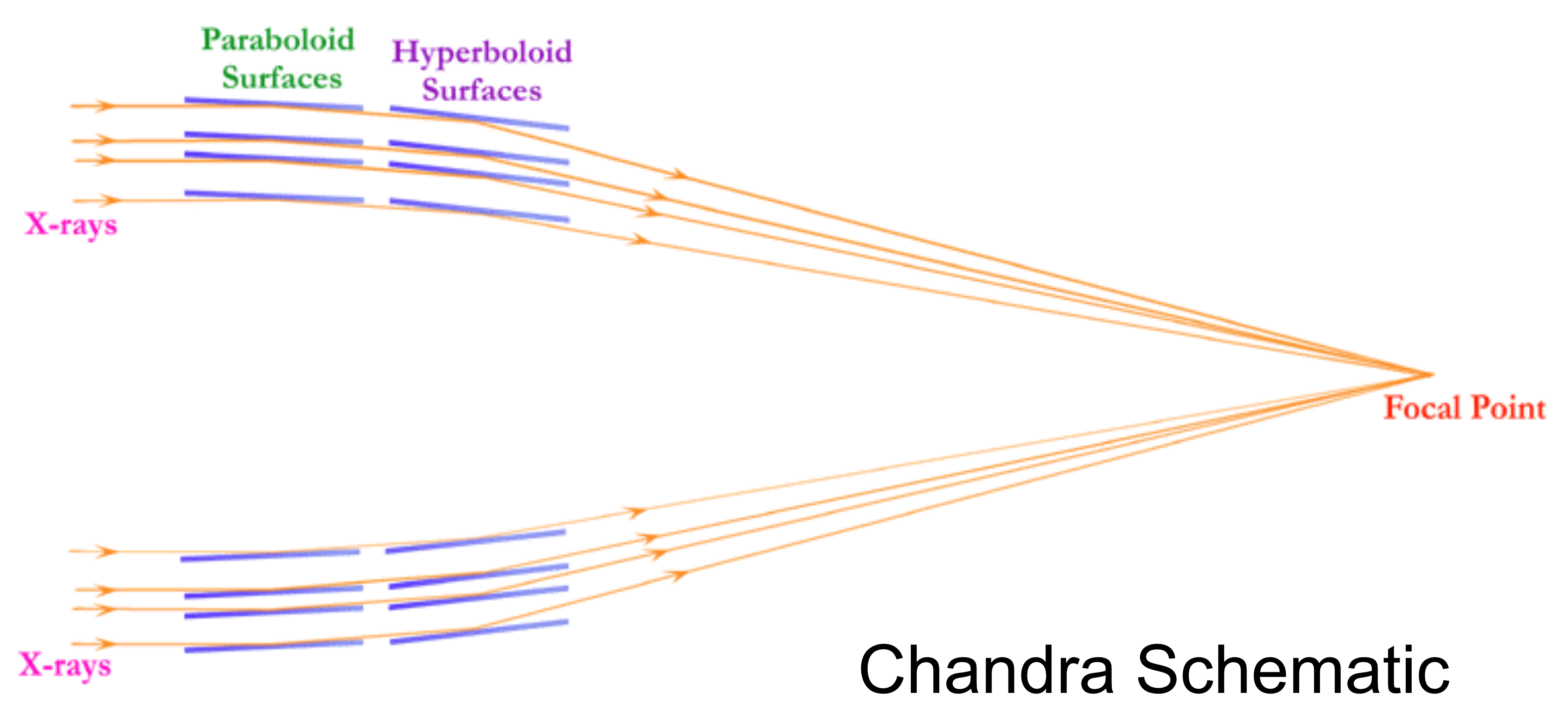
- Now near diffraction limit per mirror at grazing incidence
- $\delta\theta = \lambda/D = \lambda/(L \sin \alpha)$
  - α = graze angle (0.2-0.5°)
  - L = mirror length (0.1 m)
  - $\delta\theta$ = 0.4-0.9” @ 1 keV
  - $\delta\theta$ = 0.1-0.2” @ 5 keV
- Development timetable achieves diffraction limit for mirror modules

Zhang+ ‘19

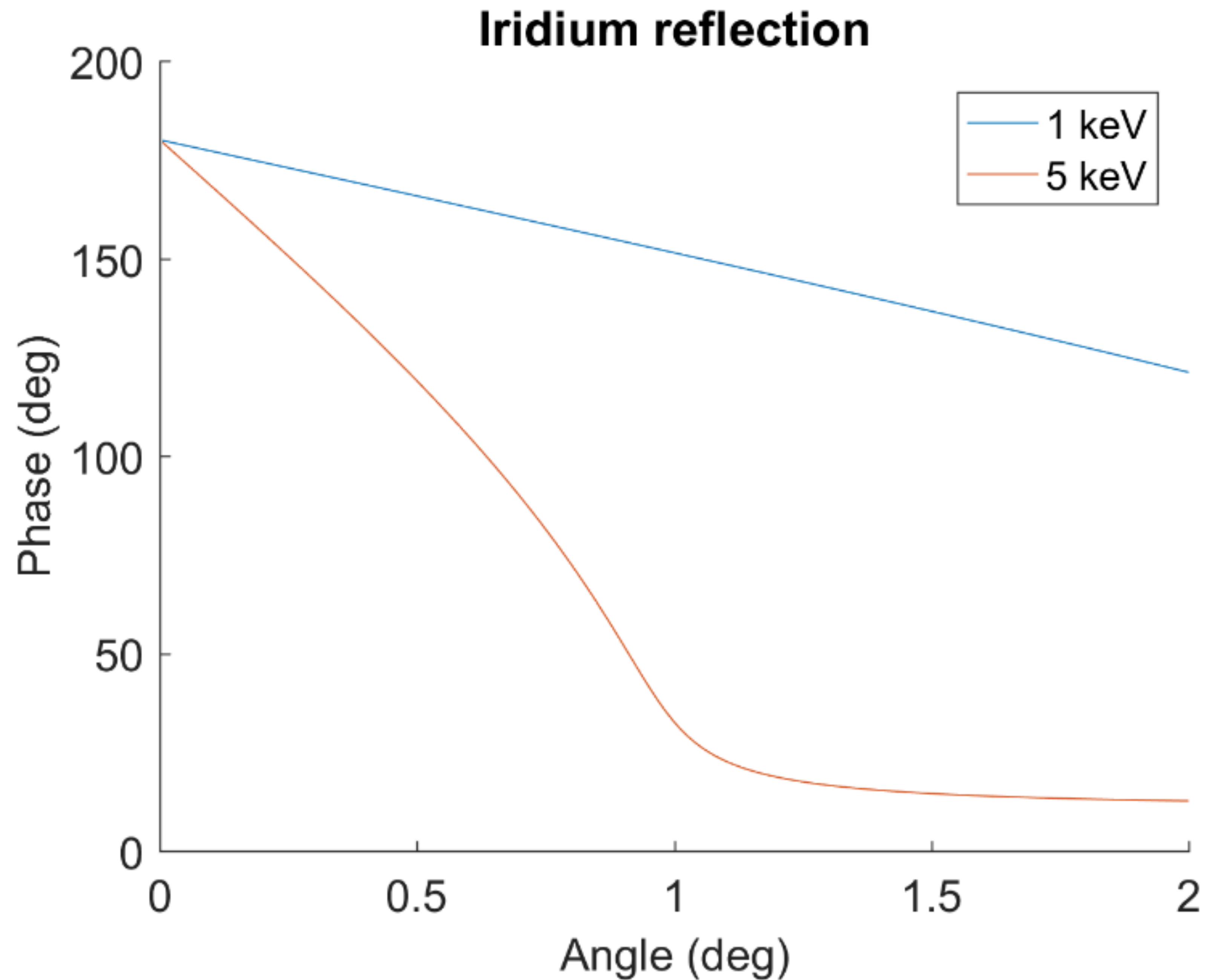


AAA Optical Design for Grazing Incidence Optics

- Aplanatic Wolter type 2
  - Obeys Abbe sine rule: constant magnification
  - Eliminates 1st order spherical or coma aberration
- Achronat
  - Obeys Fermat's principle: all rays have the same optical path length (OPL) to focus
  - Wolter I assemblies have large OPL differences (Chandra: >10 mm >> λ)
  - Fermat's principle is constraint of new design
- Achromat
  - Indices of refraction are f(E): photon phase depends on graze angle across aperture
  - WS I telescopes are not phase coherent
  - Achromaticity verified numerically a posteriori

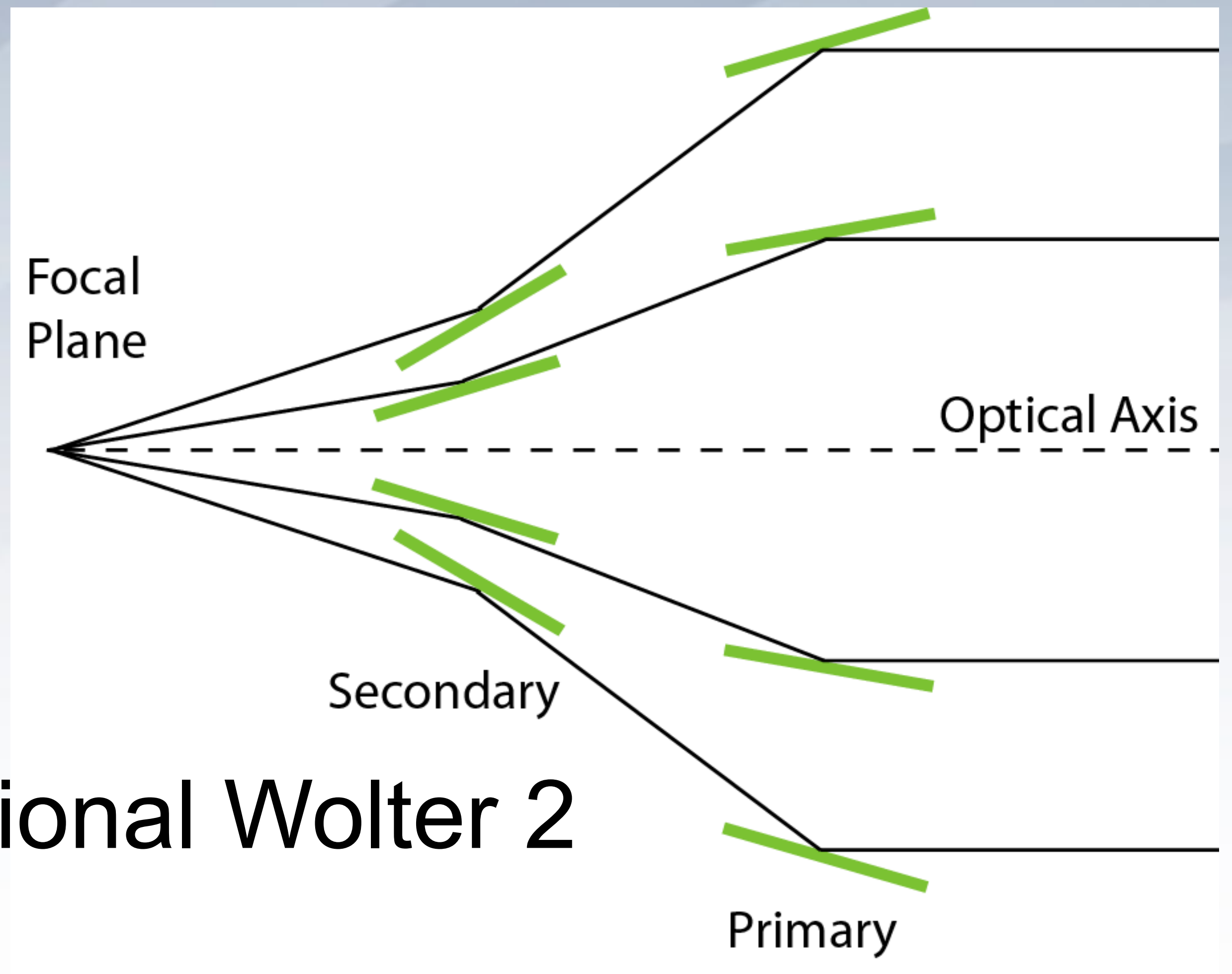


Chandra Schematic

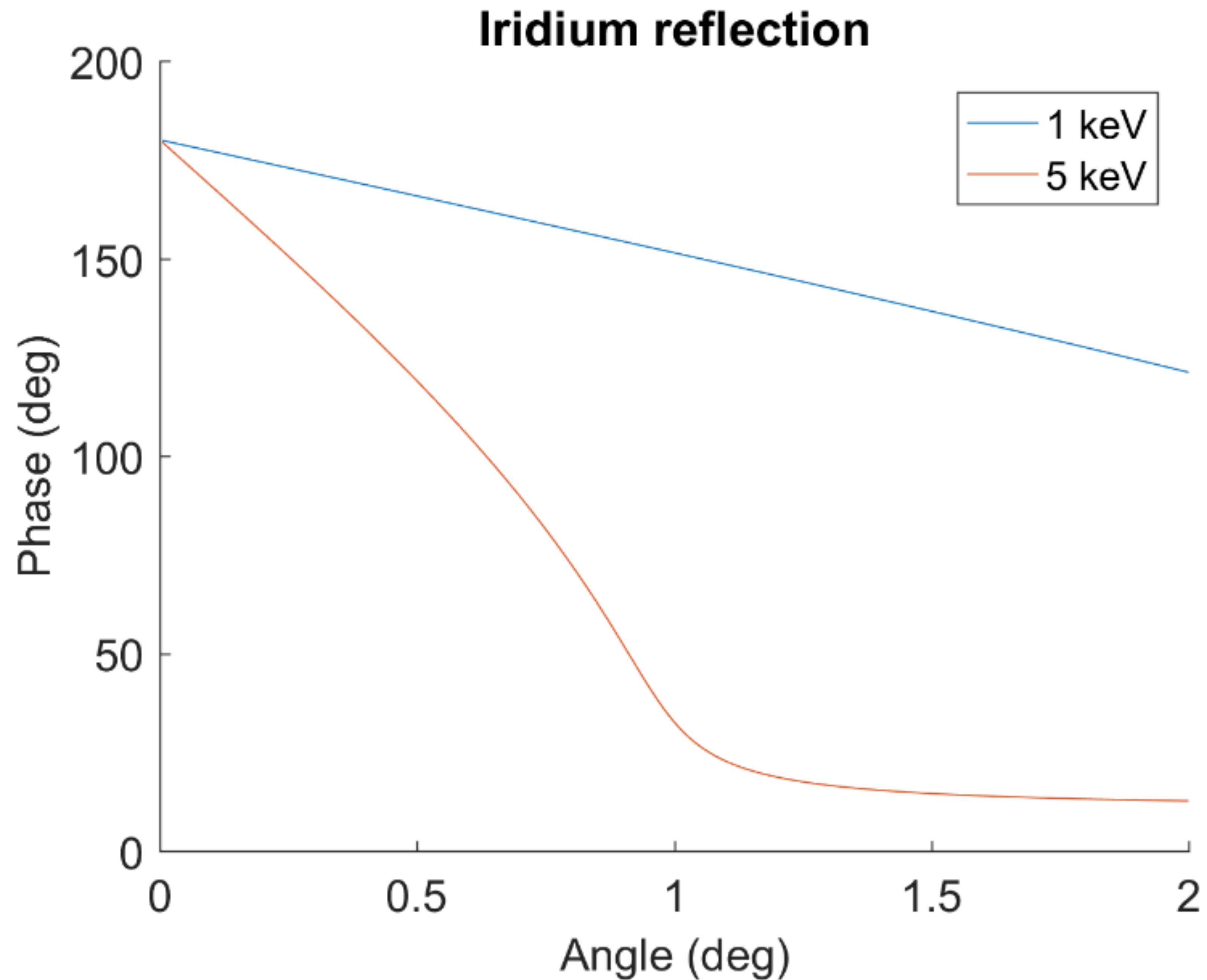


AAA Optical Design for Grazing Incidence Optics

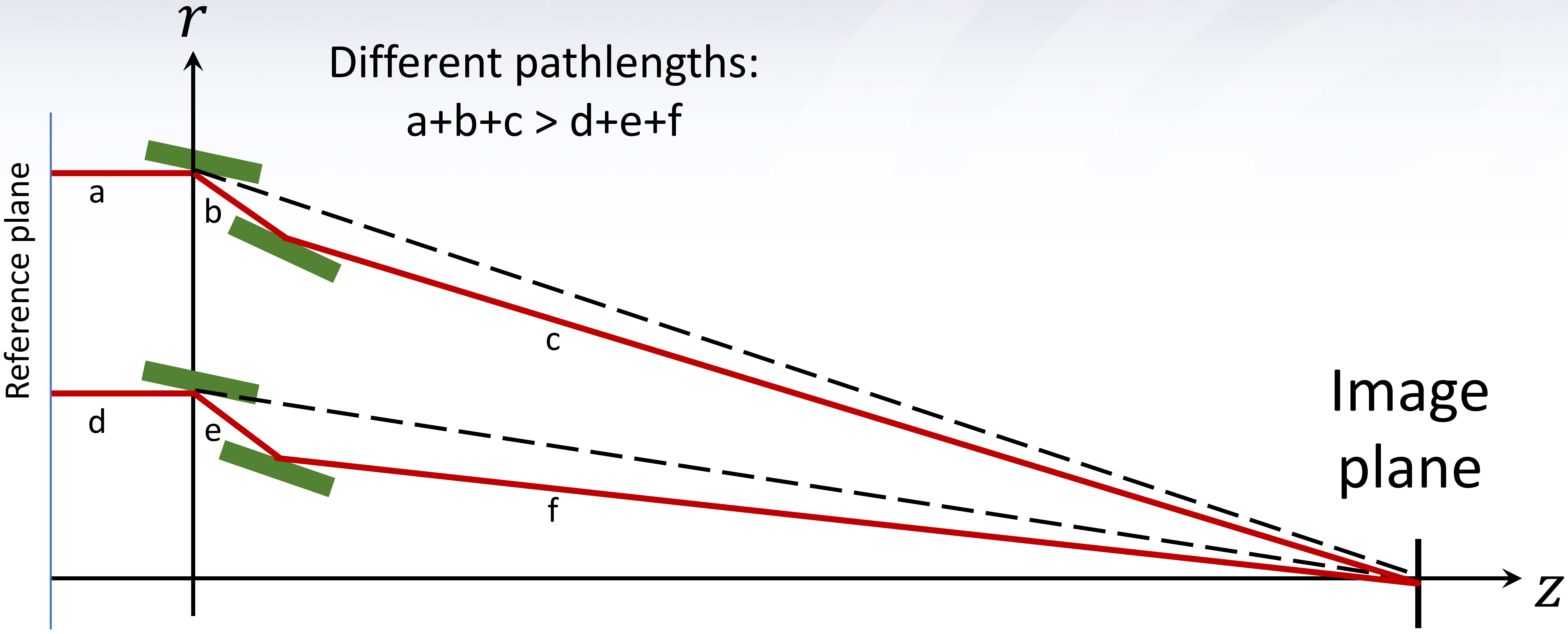
- Aplanatic Wolter type 2
  - Obeys Abbe sine rule: constant magnification
  - Eliminates 1st order spherical or coma aberration
- Achronat
  - Obeys Fermat's principle: all rays have the same optical path length (OPL) to focus
  - Wolter I assemblies have large OPL differences (Chandra: >10 mm >> λ)
  - Fermat's principle is constraint of new design
- Achromat
  - Indices of refraction are f(E): photon phase depends on graze angle across aperture
  - WS I telescopes are not phase coherent
  - Achromaticity verified numerically a posteriori



Traditional Wolter 2

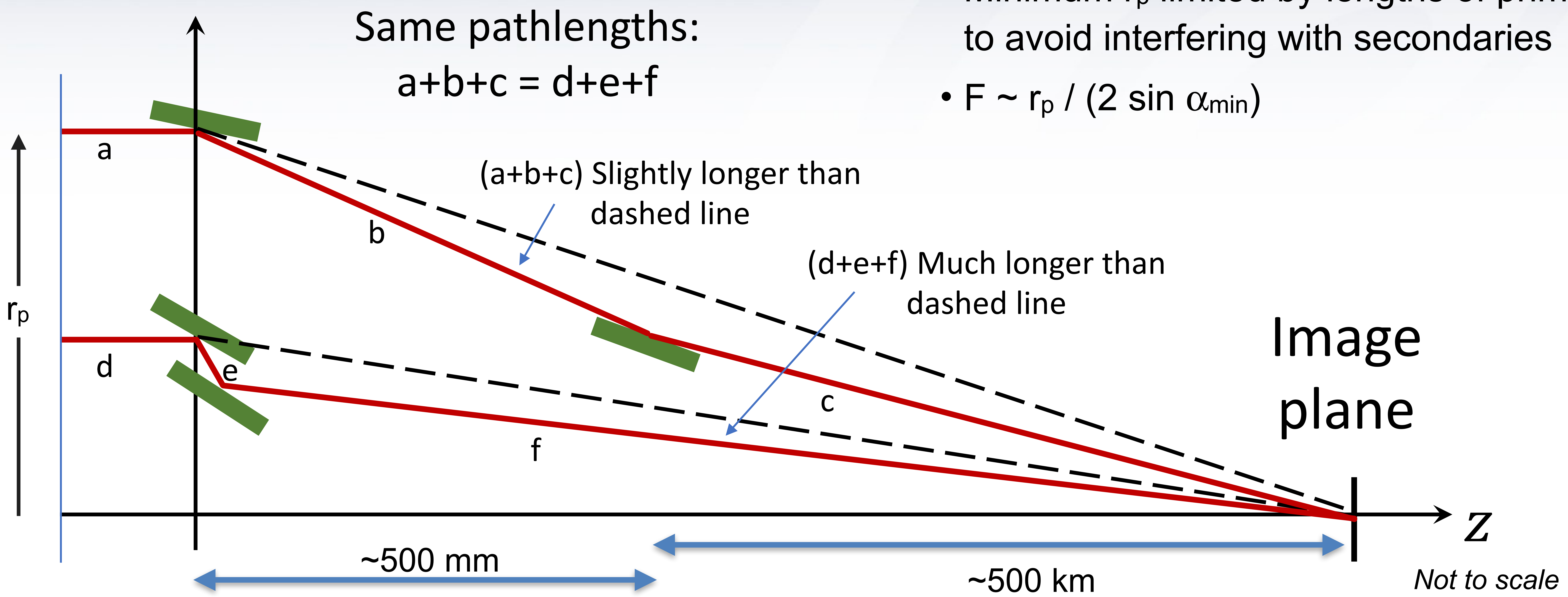


How to Fix Grazing Incidence Optics for Interferometry



Schematic of a Design for Grazing Incidence Interferometry

- Graze angle α <u>decreases</u> with r_p
- Secondary <u>farther</u> from aperture with r_p
- Minimum r_p limited by lengths of primaries to avoid interfering with secondaries
- $F \sim r_p / (2 \sin \alpha_{min})$

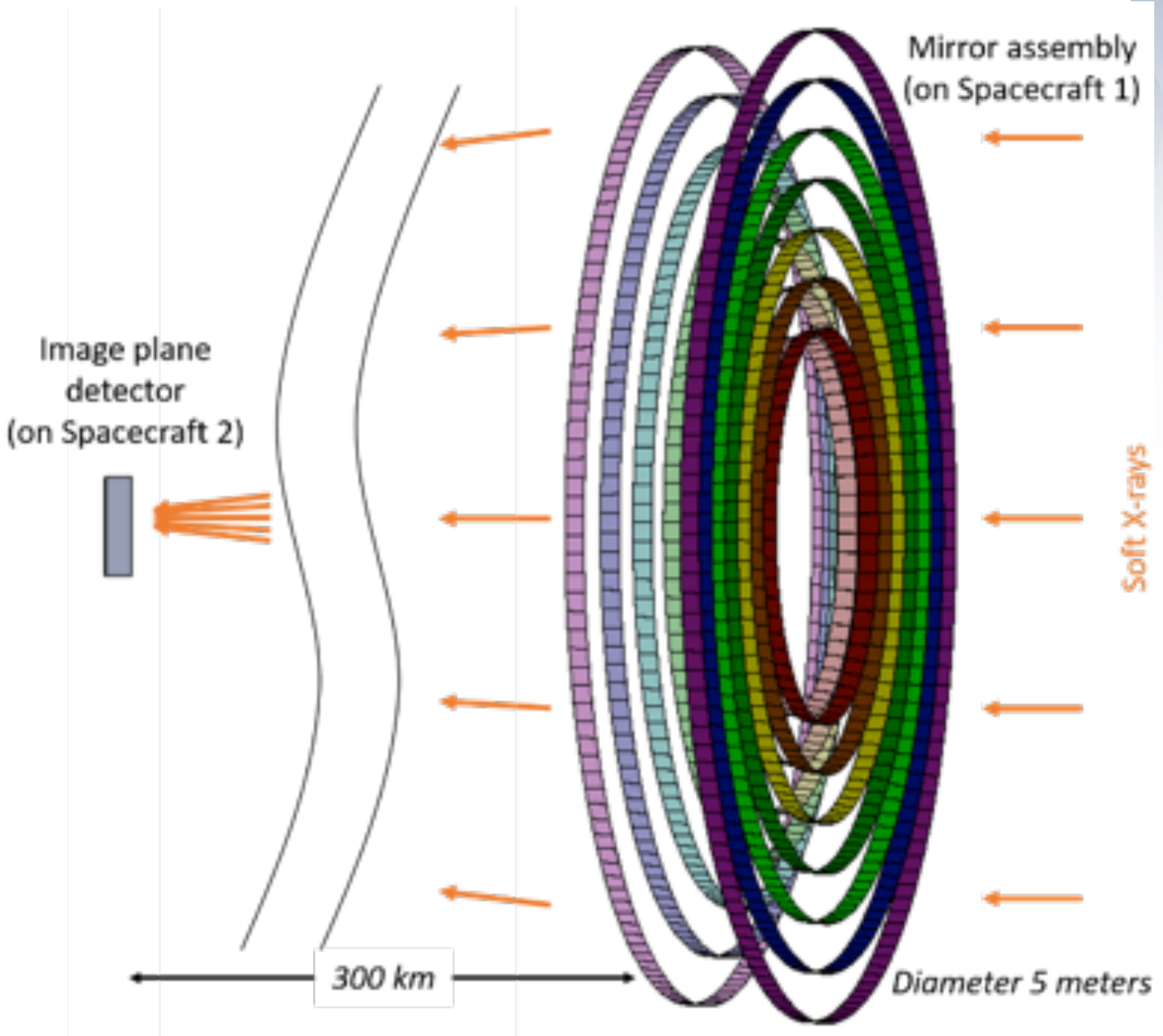


Sample Design

Fixed $L = L^*$, variable $h_0 - h_2, z_2, i_0$

Focal length	500 km
Shell radii	1.25 m to 2.50 m
Graze angles	0.50° to 0.17°
Mirror size	100 mm long, 1 mm thick
Reflective coating	Iridium (5 Å roughness)

PSF	17 μas HPD @ 5 keV (40 μm at image plane)
Effective area	2.77 m² @ 5 keV
Total mirror surface area	1500 m² (~4x Lynx)
Total mirror mass	3500 kg (~8x Lynx)



Sample Design

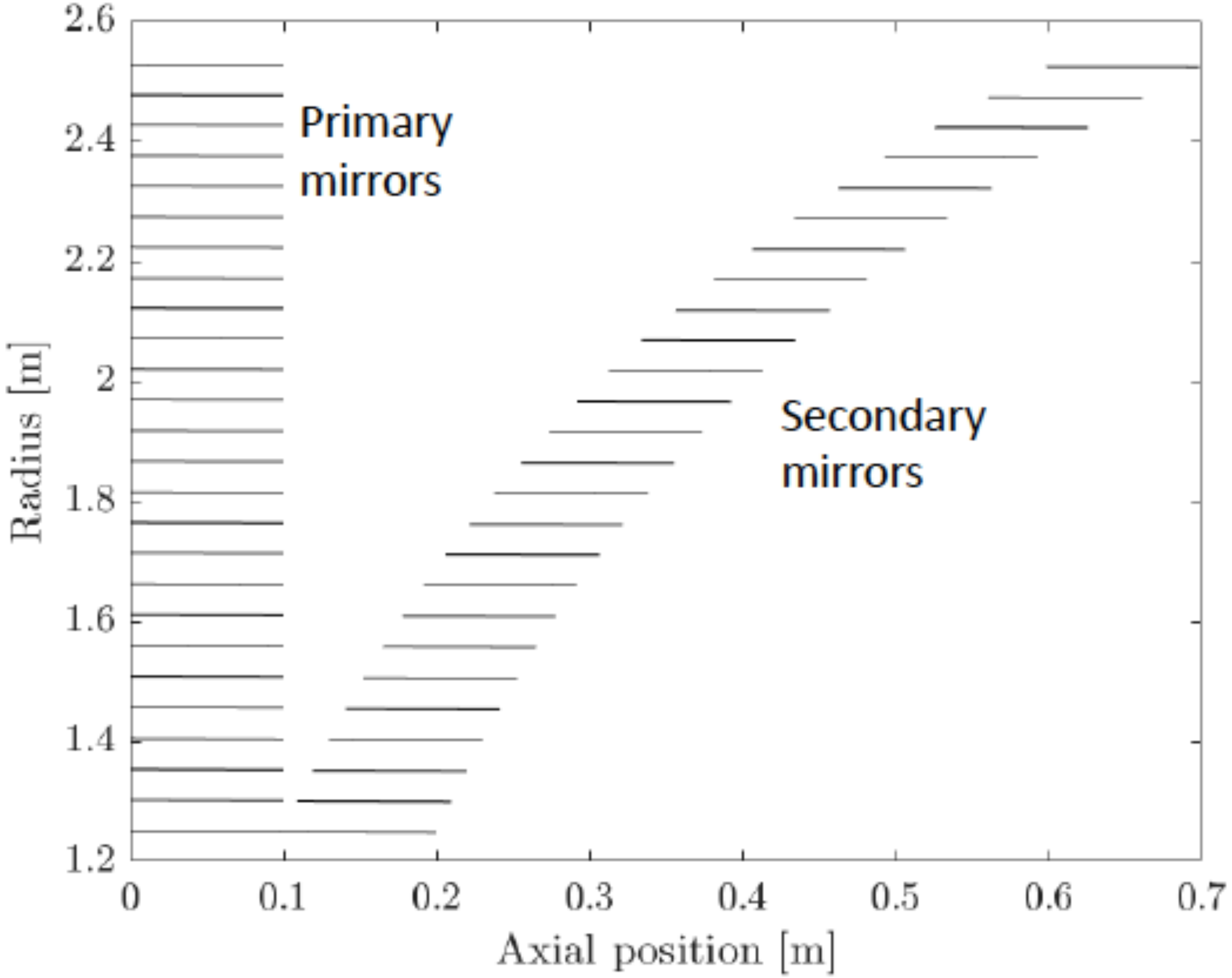
Fixed $L = L^*$, variable $h_0 - h_2, z_2, i_0$

Focal length	500 km
Shell radii	1.25 m to 2.50 m
Graze angles	0.50° to 0.17°
Mirror size	100 mm long, 1 mm thick
Reflective coating	Iridium (5 Å roughness)

PSF	17 μas HPD @ 5 keV (40 μm at image plane)
Effective area	2.77 m² @ 5 keV
Total mirror surface area	1500 m² (~4x Lynx)
Total mirror mass	3500 kg (~8x Lynx)

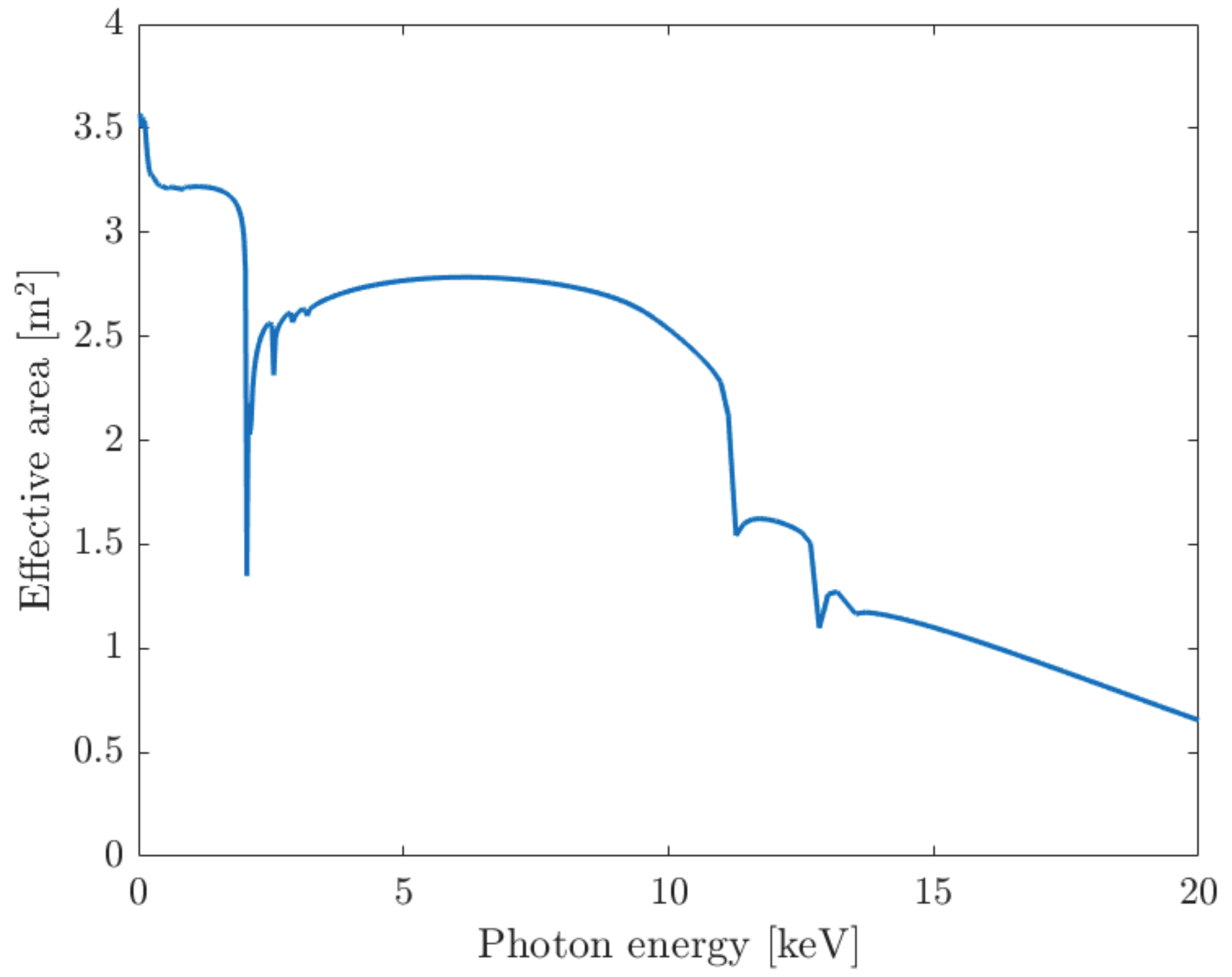
Mirror assembly layout

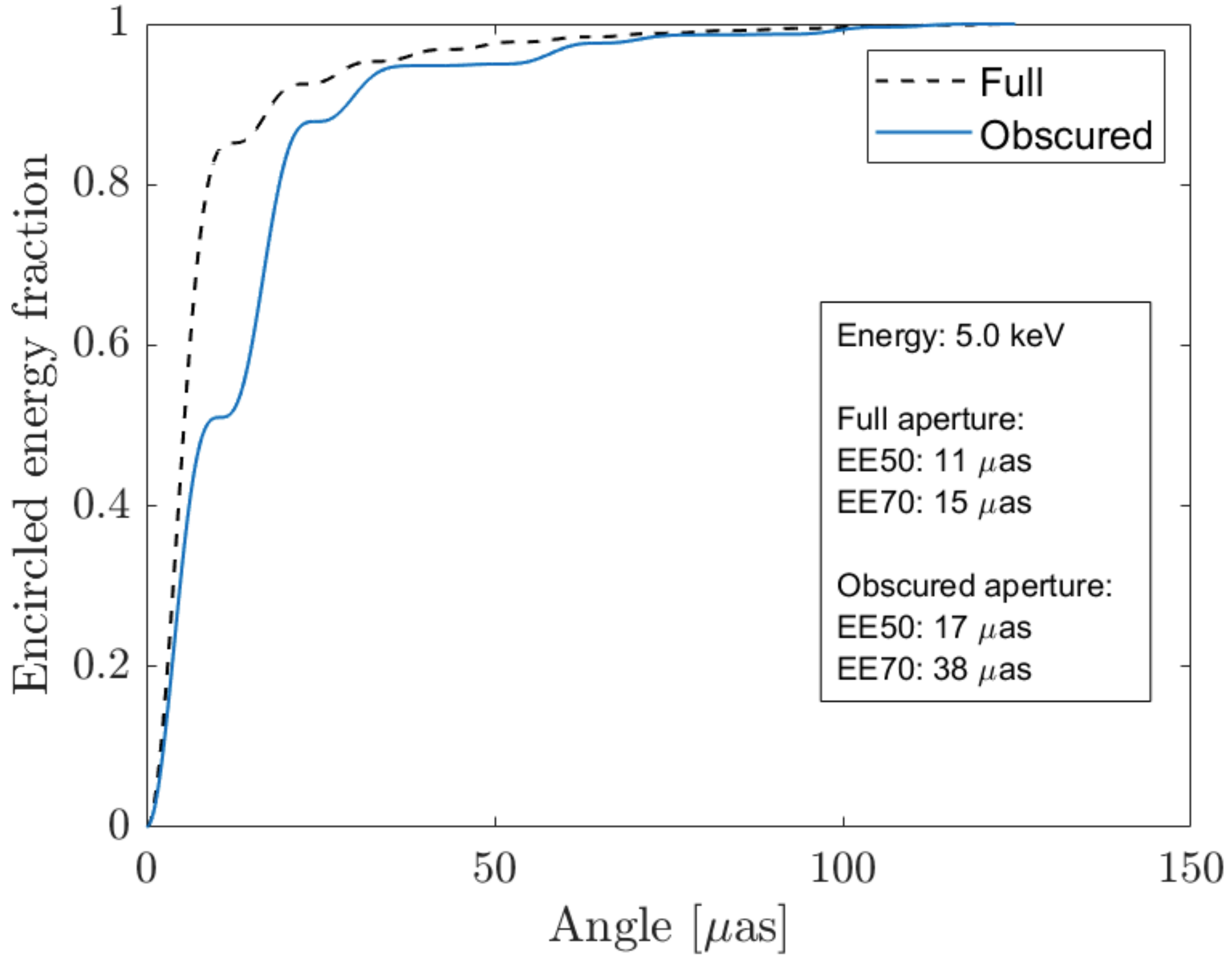
Low-density aperture fill shown for illustration clarity



Sample Telescope Performance

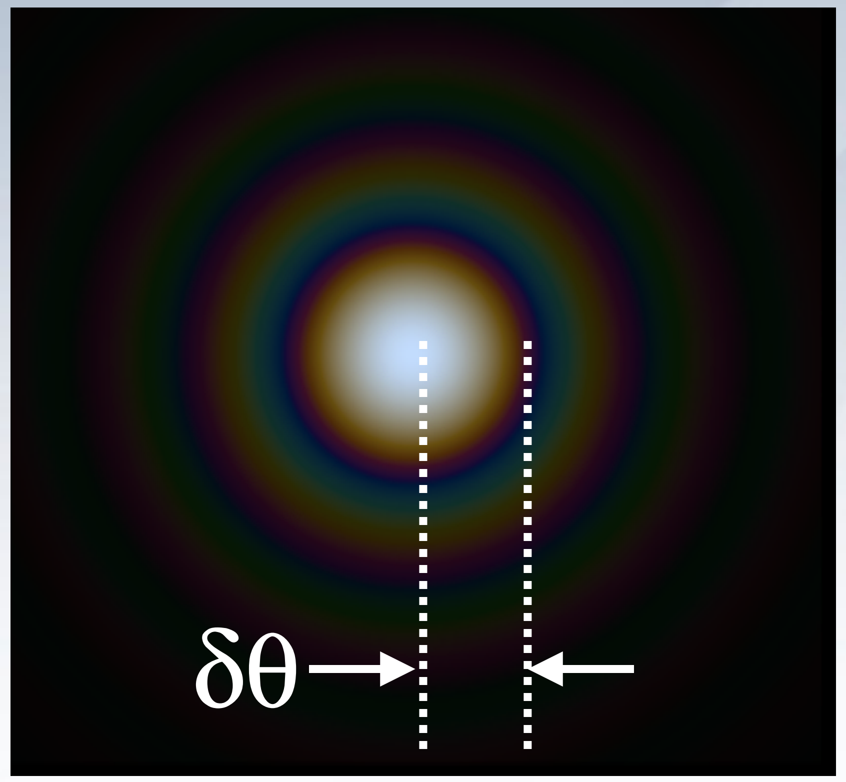
- Effective area at high E <u>increases</u> with shell diameter
- Obscuration (by shell thicknesses) & unfilled aperture increases HPD





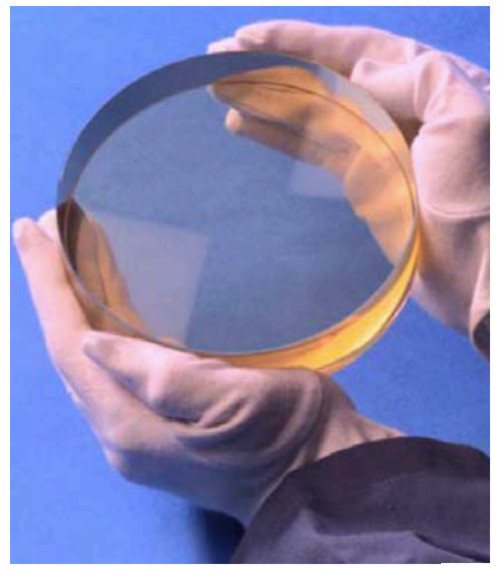
Resolution Drives Aperture Size
Pixel Size Drives Telescope Length

- Imaging resolution ($\delta\theta$, Rayleigh criterion)
  - $\delta\theta = 1.22\ \lambda/D = 0.25$ mas (λ/nm) / (D/m)
  - 2 mas @ 3 nm ⇨ D = 0.4 m
  - 0.1 μas @ 0.1 nm ⇨ D = 250 m



White light Airy disk

- Effective focal length (F)
  - $F = \delta x/\delta\theta = 410$ m ($\delta x/\mu$) / ($\delta\theta$/mas)

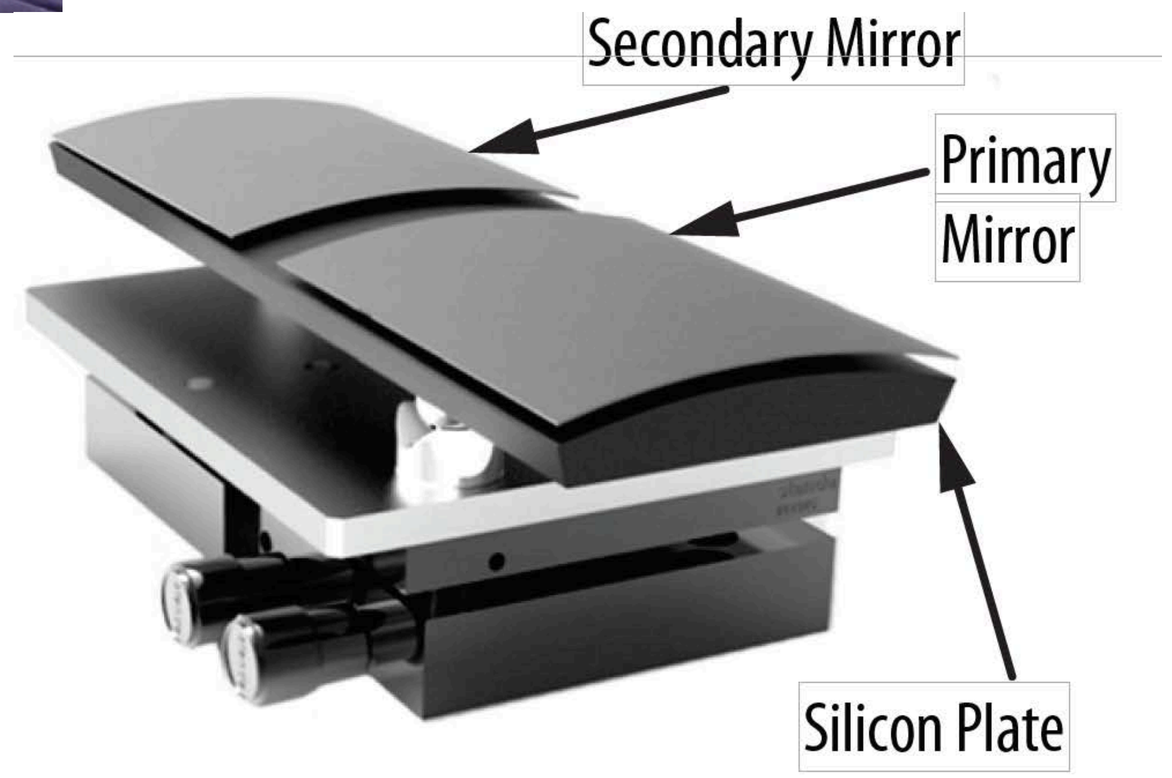


  - 50 mas, 5 nm, $\delta x = 3\ \mu$ ⇨ F = 25 m
  - 2 mas, 3 nm, $\delta x = 2\ \mu$ ⇨ F = 410 m

} Normal Incidence

  - 0.1 mas @ 1 nm, $\delta x = 1\ \mu$ ⇨ F = 4.1 km
  - 0.1 mas @ 0.1 nm, $\delta x = 0.2\ \mu$ ⇨ F=820 km

} Grazing Incidence



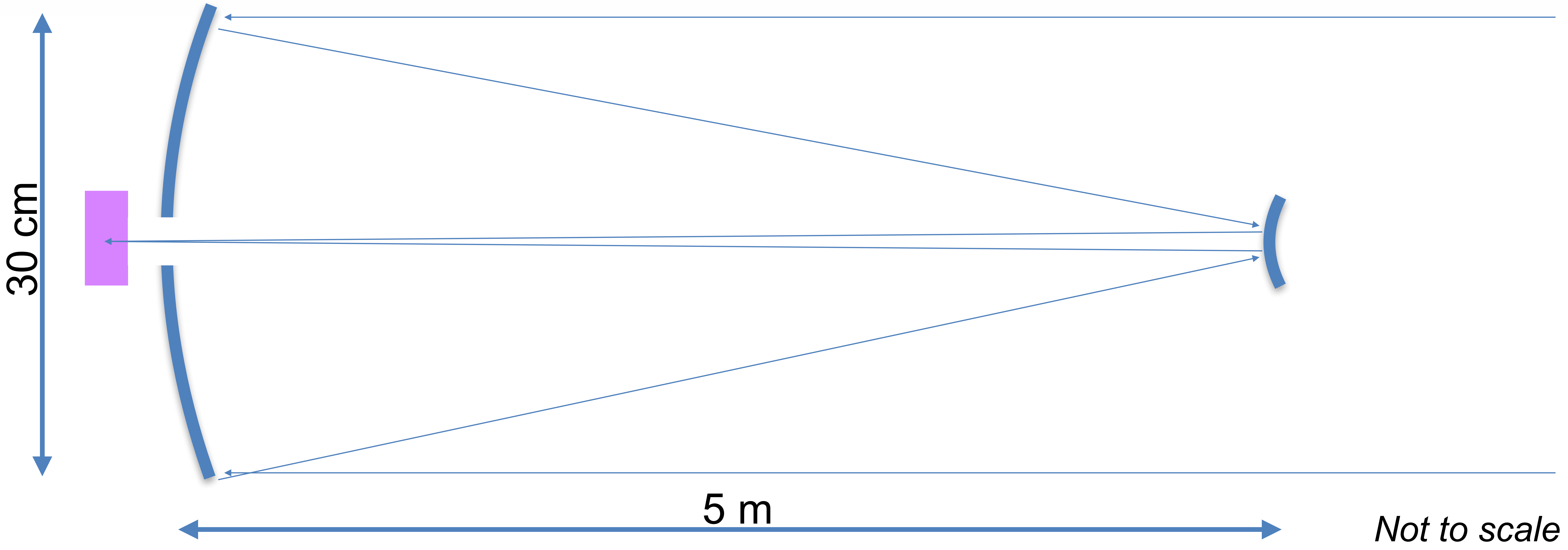
Zhang+ '19

A Near-Term Option:
Normal Incidence Milliarcsecond X-ray Imager

- **Approach**: Normal Incidence Multilayer optics
  - Diffraction-limited mirror at 0.25-0.40 keV (3-5 nm)
  - ML coatings give 10-20% reflectivity, 2% band
  - 1-2 μ localization drives 100 m effective focal length
  - Cassegrain optical design for 2 mas
- **Technologies:** Mirror figure to 0.05 nm and ML coatings, high resolution X-ray detectors, structure stability, mirror verification at X-rays, attitude knowledge

Timetable:

- **Stage 1 (5 yr):** imaging to 50 mas
- **Stage 2 (10 yr):** imaging to 2 mas
- **Long-term**: finder scope for micro-arcsecond imager?
- **Science**: Quasar & XRB jet imaging, astrometry to 10 microarcsecond, resolving binaries, planets, etc.



Steps to a Black Hole Imager

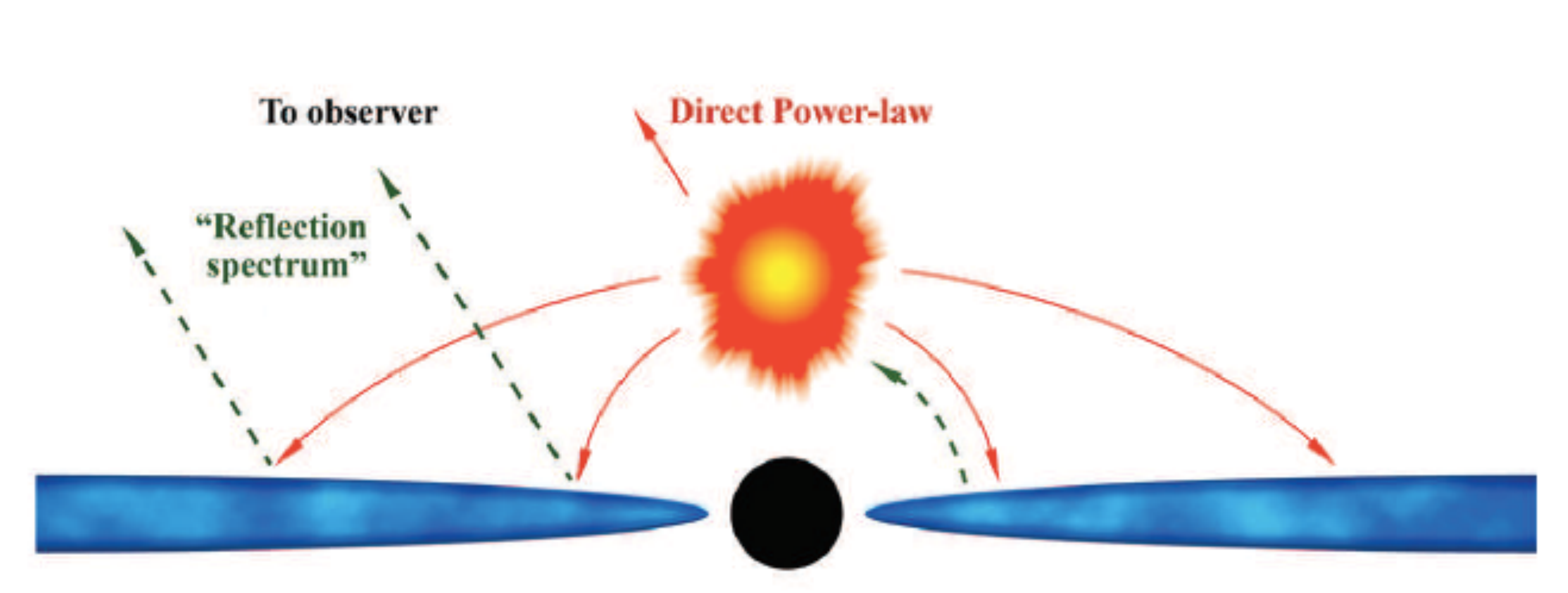
- 0.05” in a ML-based SmallSat
  - 10 mas knowledge
  - small pixel detectors
- 0.002” in a ML-based SMEX
  - sub-mas knowledge
  - folded beam, active secondary
  - X-ray ref. frame
- 0.0001” in a grazing-incidence Probe (single s/c mirror)
  - μ” knowledge
  - formation flying detector
  - ground X-ray testing
- 0.000,003” grazing-incidence Flagship
  - mirrors in formation flying
  - sub-μ” knowledge
- 0.000,000,1” grazing-incidence Black Hole Imager

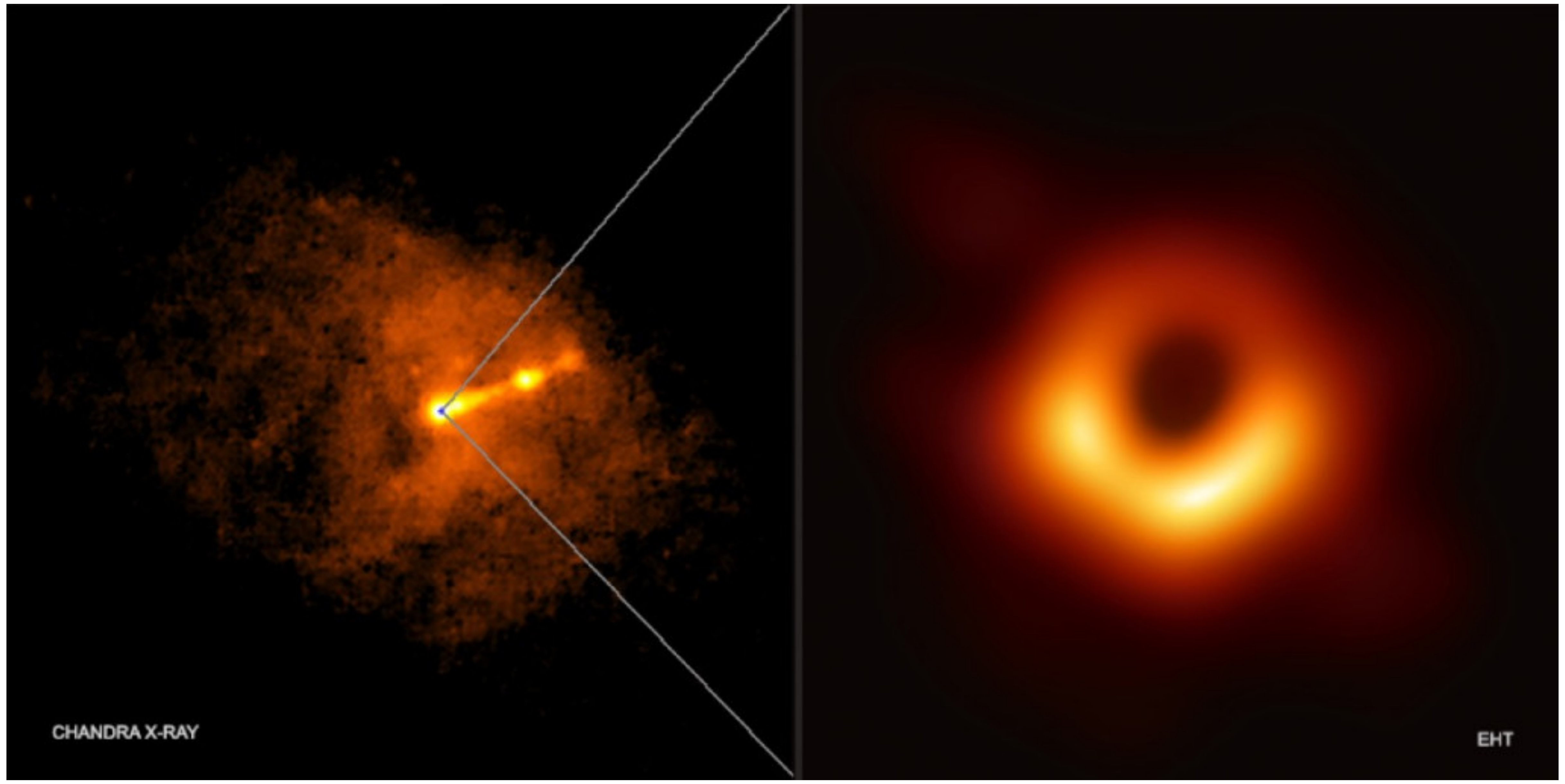
Micro-ArcSecond Imager Actions

- Science team
  - Set long-term and intermediate objectives
  - Establish priorities
  - Foster theory
    - Event horizon accretion
    - Relativistic jets
    - Accretion disk outflows
    - Stellar flare effects on planets
  - Explore!
- Engineering development timetable
  - Attitude knowledge, reference frame
  - Metrology and dynamic structures
  - Formation flying
    - Several detector spacecraft?
    - Add optics to expand u-v coverage and area

Some Science Goals of a Micro-ArcSecond Imager

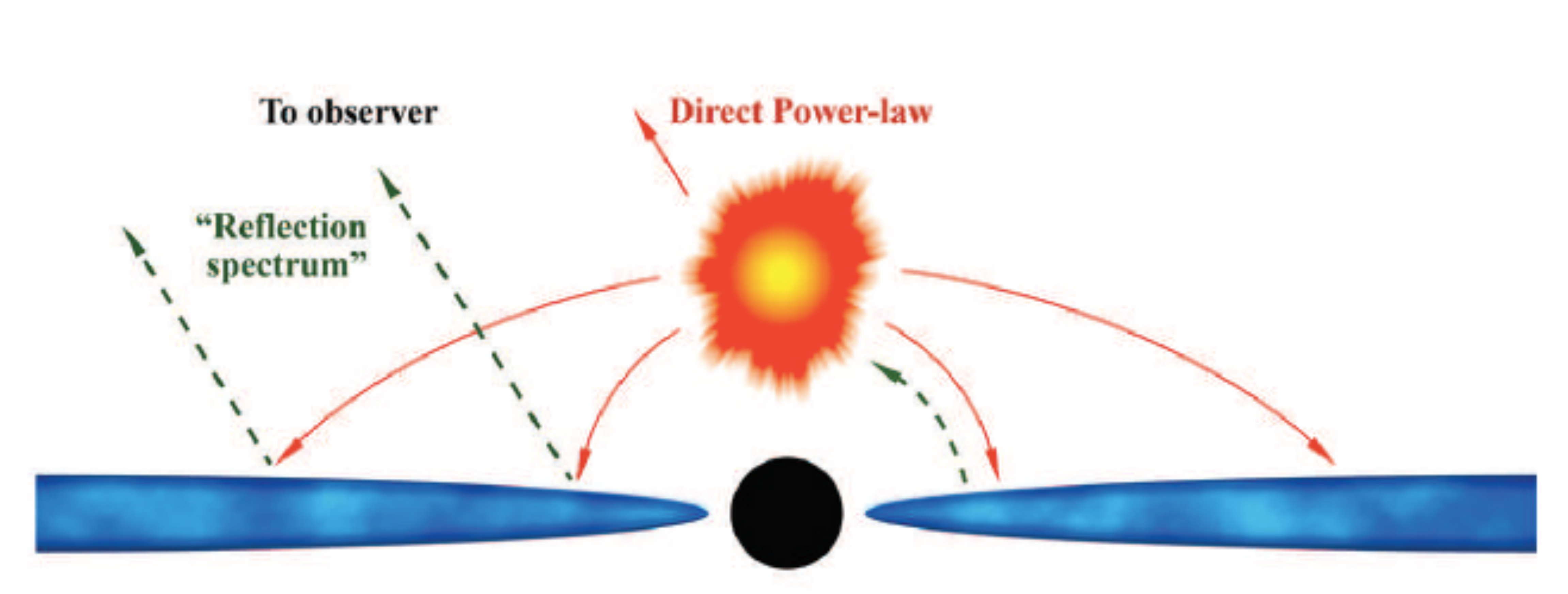
- Supermassive Black Holes in Active Galaxies
  - Test ‘lamp post' model of coronae
  - Velocity mapping in Fe-K from reflection off disk
  - Image blazar jets — aligned with BH spin or disk?
  - Resolve gravitational microlensing
  - Resolve BH binaries in AGN (before merger and GW emission)
  - Address ‘final parsec’ problem (1 pc > 0.1 mas everywhere)
  - Resolve outflows, photo-excited gas, and BLRs at 1-100 pc scales
- Measure GRB fireball expansion & jet speed
- Resolve XRB populations in galaxy bulges
- Resolve BH X-ray binaries to < 107 km at 10 kpc
  - Image accretion disk and separate irradiated companion
  - Image jets from SS 433, Cyg X-1, etc.
  - Locate globular cluster sources
- Stars
  - Stellar coronae, prominences, winds, CMEs
  - Resolve interacting binaries, disks (CVs, Dwarf Novae)
  - Planetary systems, transiting exoplanets, star forming regions

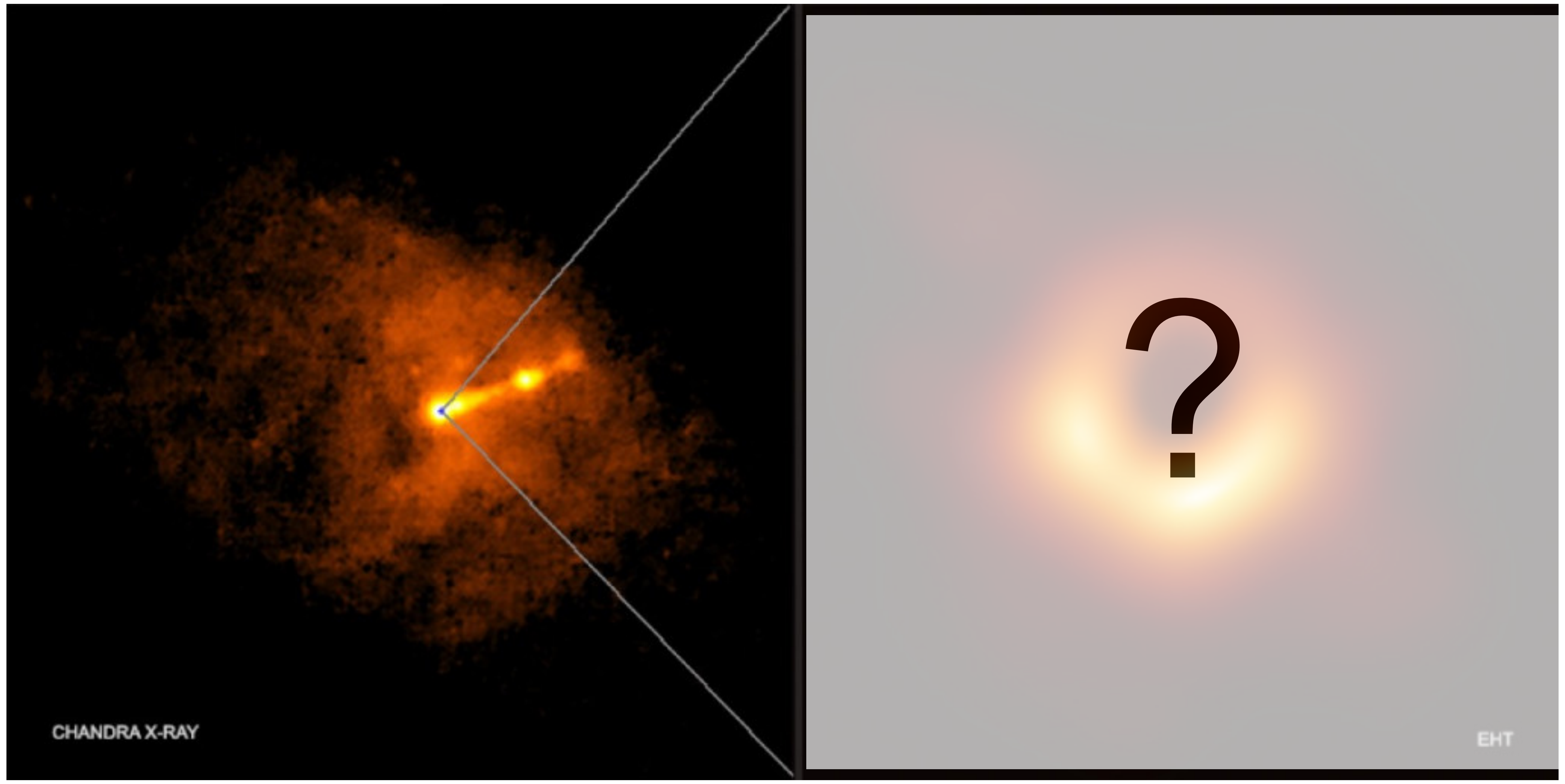




Some Science Goals of a Micro-ArcSecond Imager

- Supermassive Black Holes in Active Galaxies
  - Test ‘lamp post' model of coronae
  - Velocity mapping in Fe-K from reflection off disk
  - Image blazar jets — aligned with BH spin or disk?
  - Resolve gravitational microlensing
  - Resolve BH binaries in AGN (before merger and GW emission)
  - Address ‘final parsec’ problem (1 pc > 0.1 mas everywhere)
  - Resolve outflows, photo-excited gas, and BLRs at 1-100 pc scales
- Measure GRB fireball expansion & jet speed
- Resolve XRB populations in galaxy bulges
- Resolve BH X-ray binaries to < 107 km at 10 kpc
  - Image accretion disk and separate irradiated companion
  - Image jets from SS 433, Cyg X-1, etc.
  - Locate globular cluster sources
- Stars
  - Stellar coronae, prominences, winds, CMEs
  - Resolve interacting binaries, disks (CVs, Dwarf Novae)
  - Planetary systems, transiting exoplanets, star forming regions



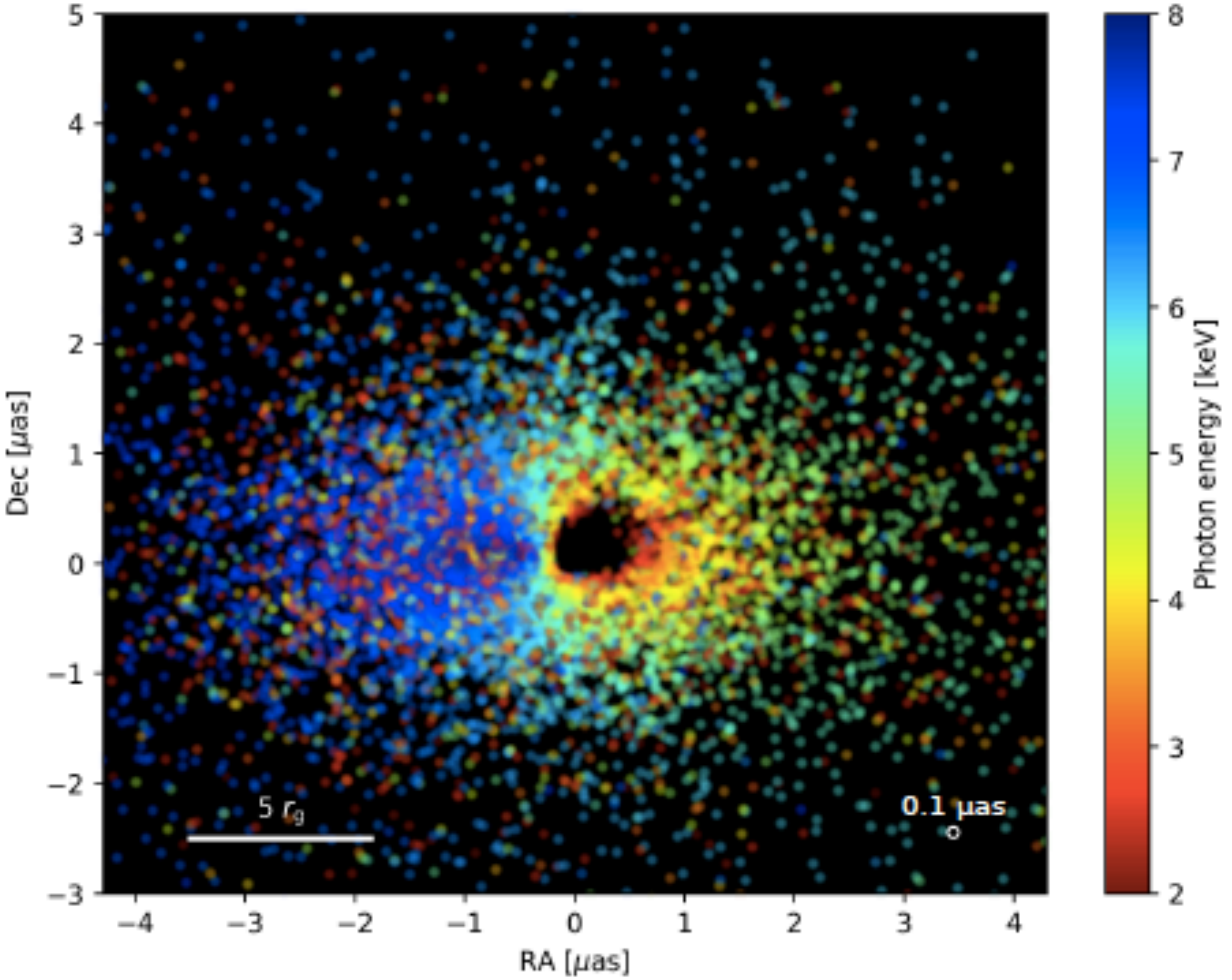


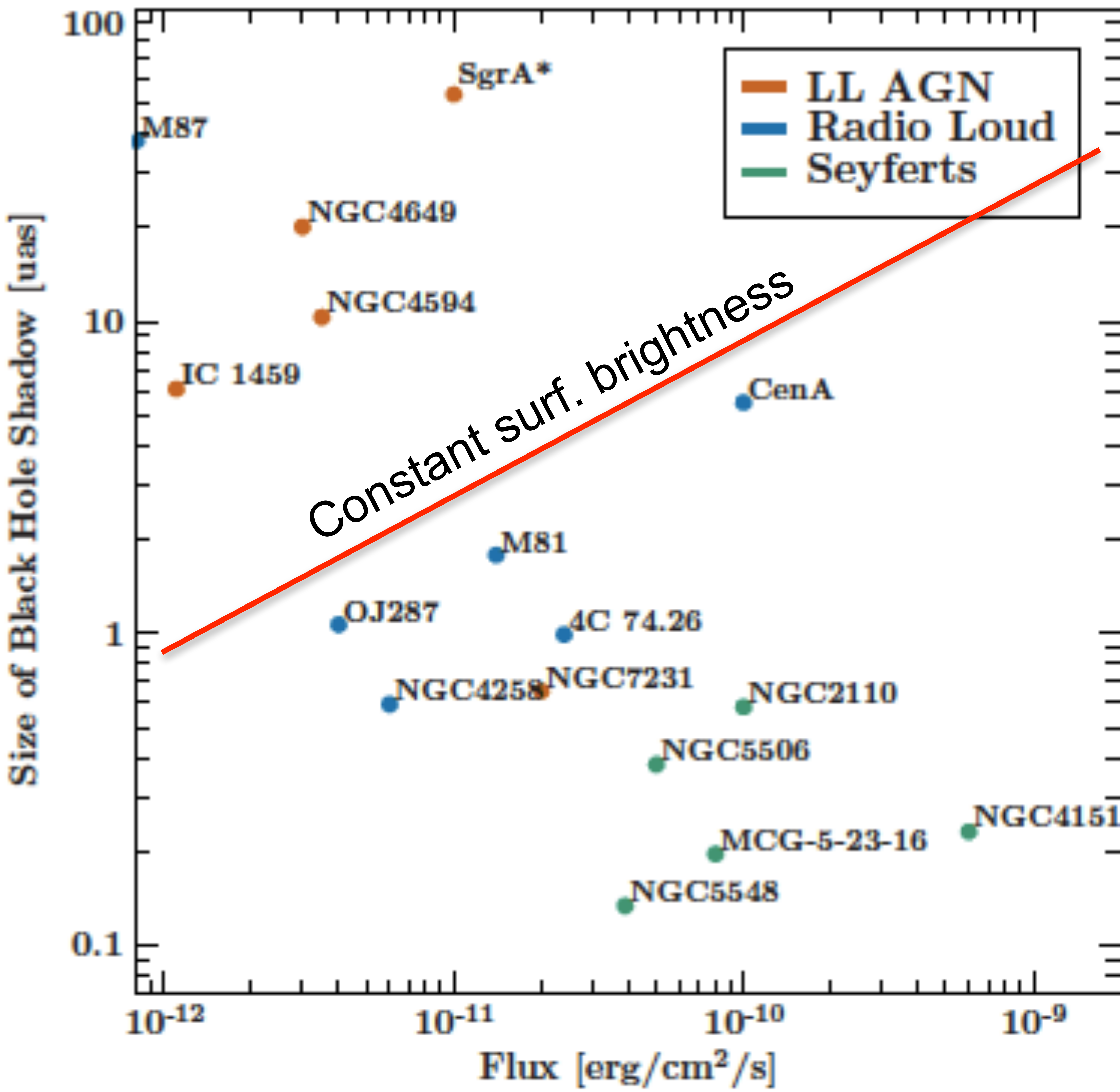
Backup Slides

Prospects for Normal Incidence Imaging

- Development needed
  - Substrate stiffness for 1g testing ➪ Zerodur, 1 cm thick
  - Detector: 1-2 μ imaging resolution
  - X-ray testing of optics: 2 μ source at 500 m = 0.8 mas
  - Optics placement and attitude
    - need 1 m optical mirror! ➪ embed X-ray mirror
    - optical feedback for active focus/pointing control
  - Optical bench metrology for other missions
  - 2 year development to high TRL for stage 1
  - 5 year development for stage 2
- Roadmap toward a Micro-Arcsecond X-ray Imager
  - Need a “finder/guide scope” with larger field of view
  - Establish an X-ray reference frame

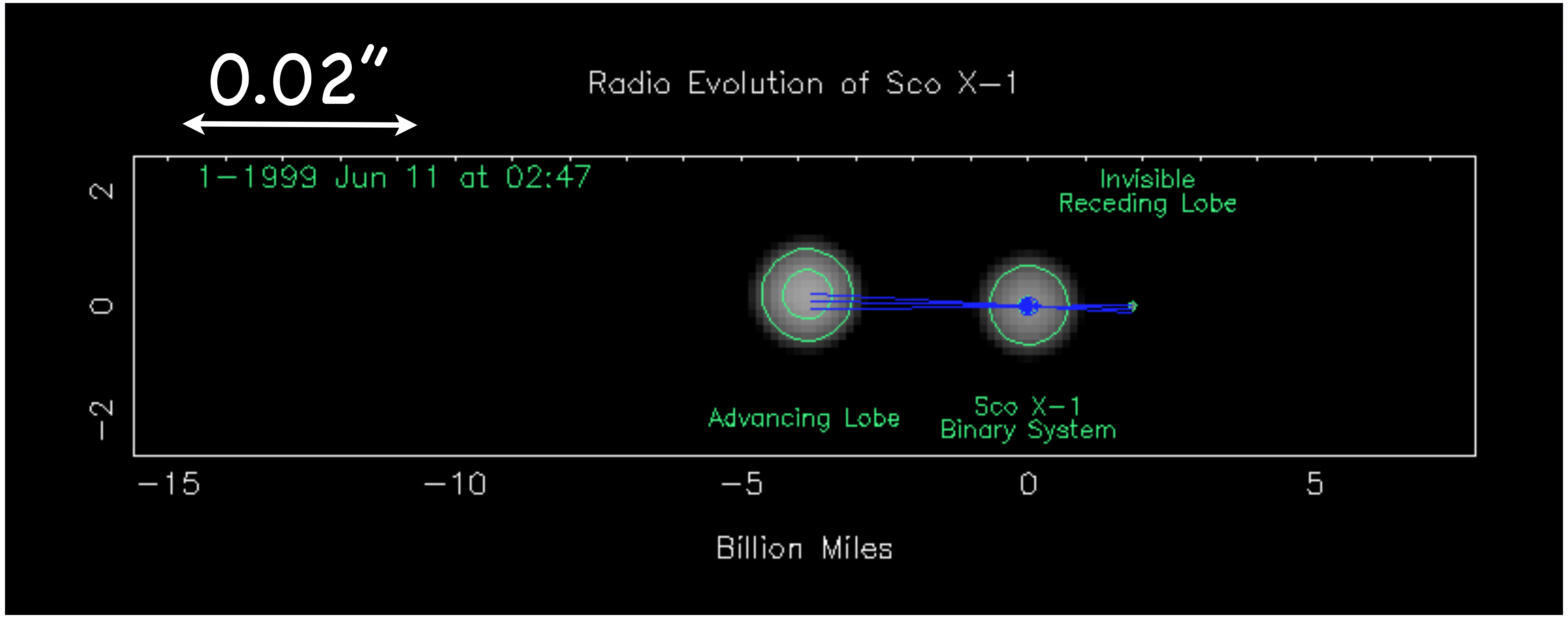
X-rays from AGN

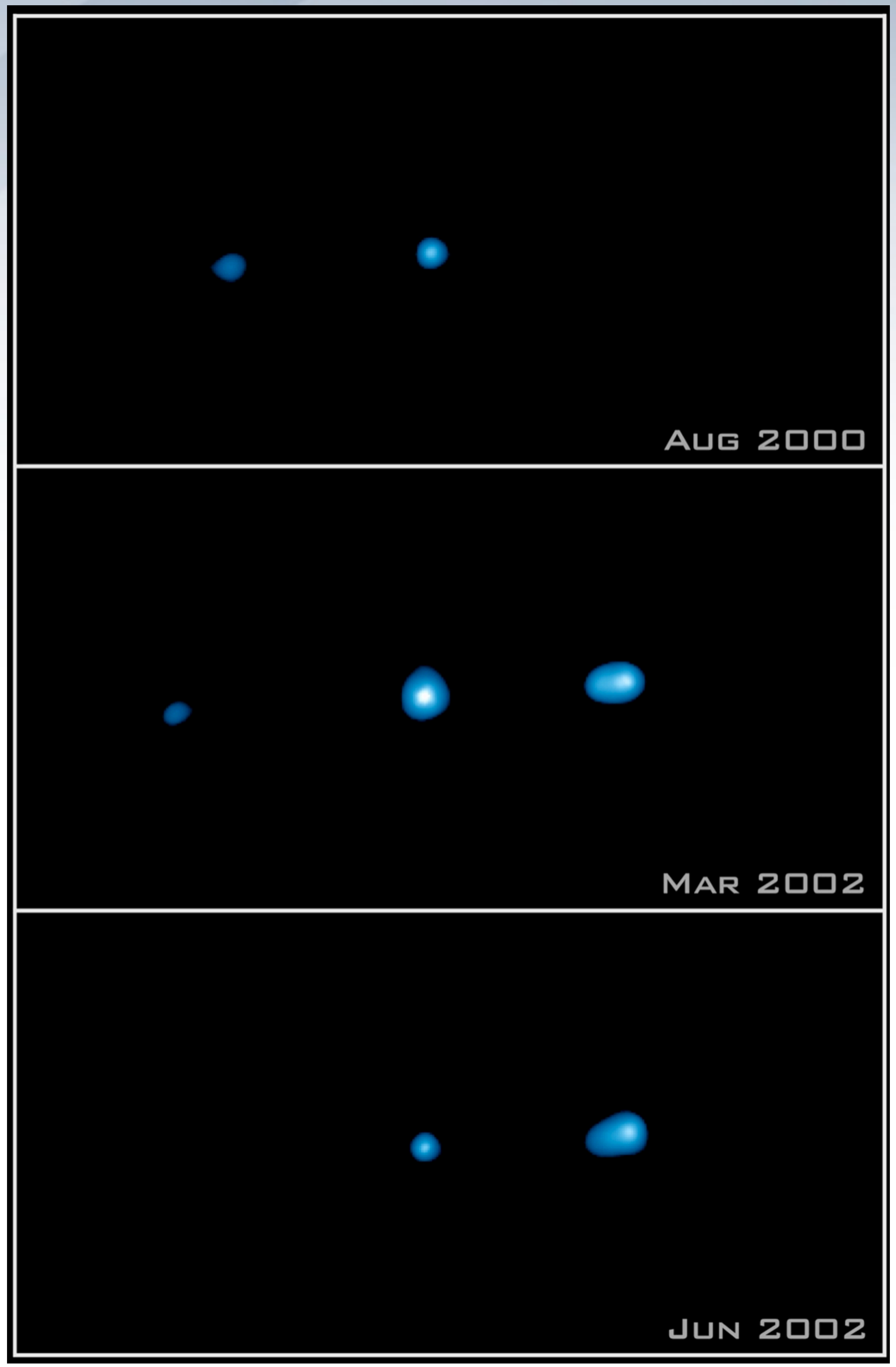




X-ray Binary Jets

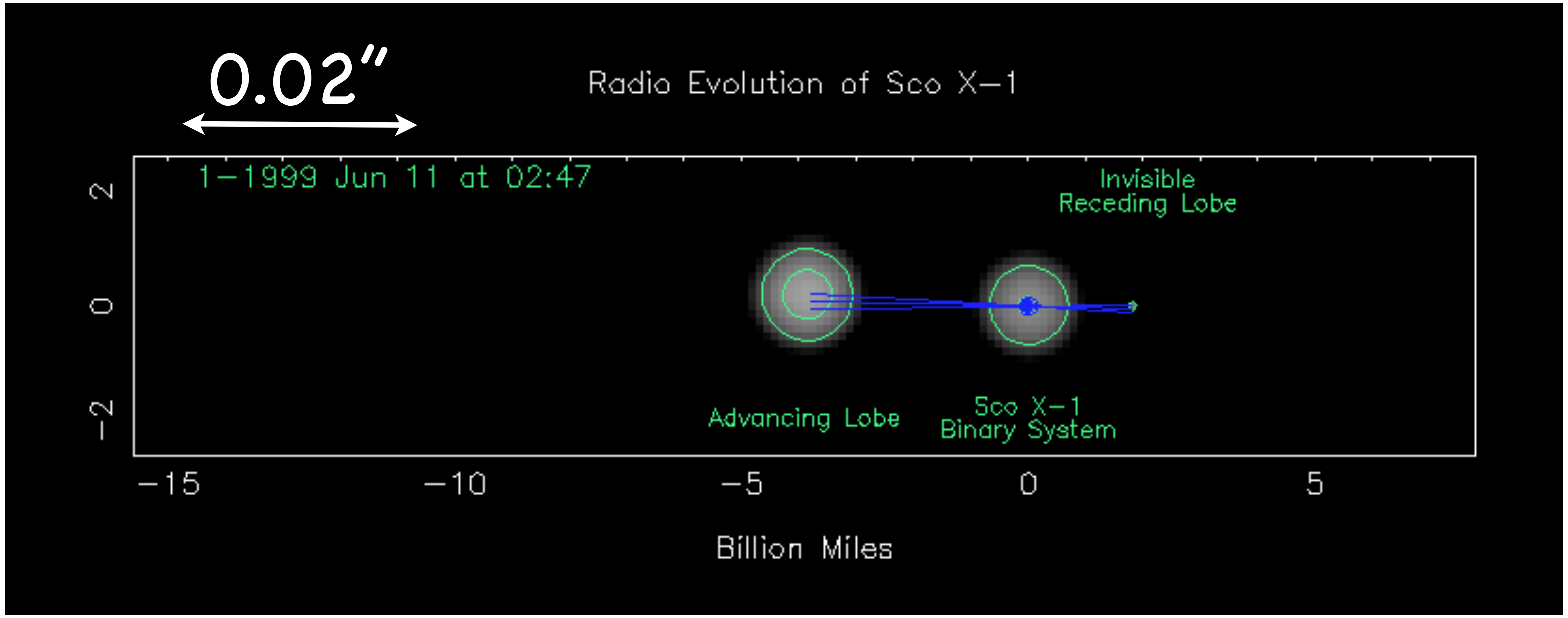
- X-ray jets discovered using Chandra
- Proper motion observed — speeds are relativistic
- Radio maps of Sco X-1 indicate high speed knots at 10-30 mas scales

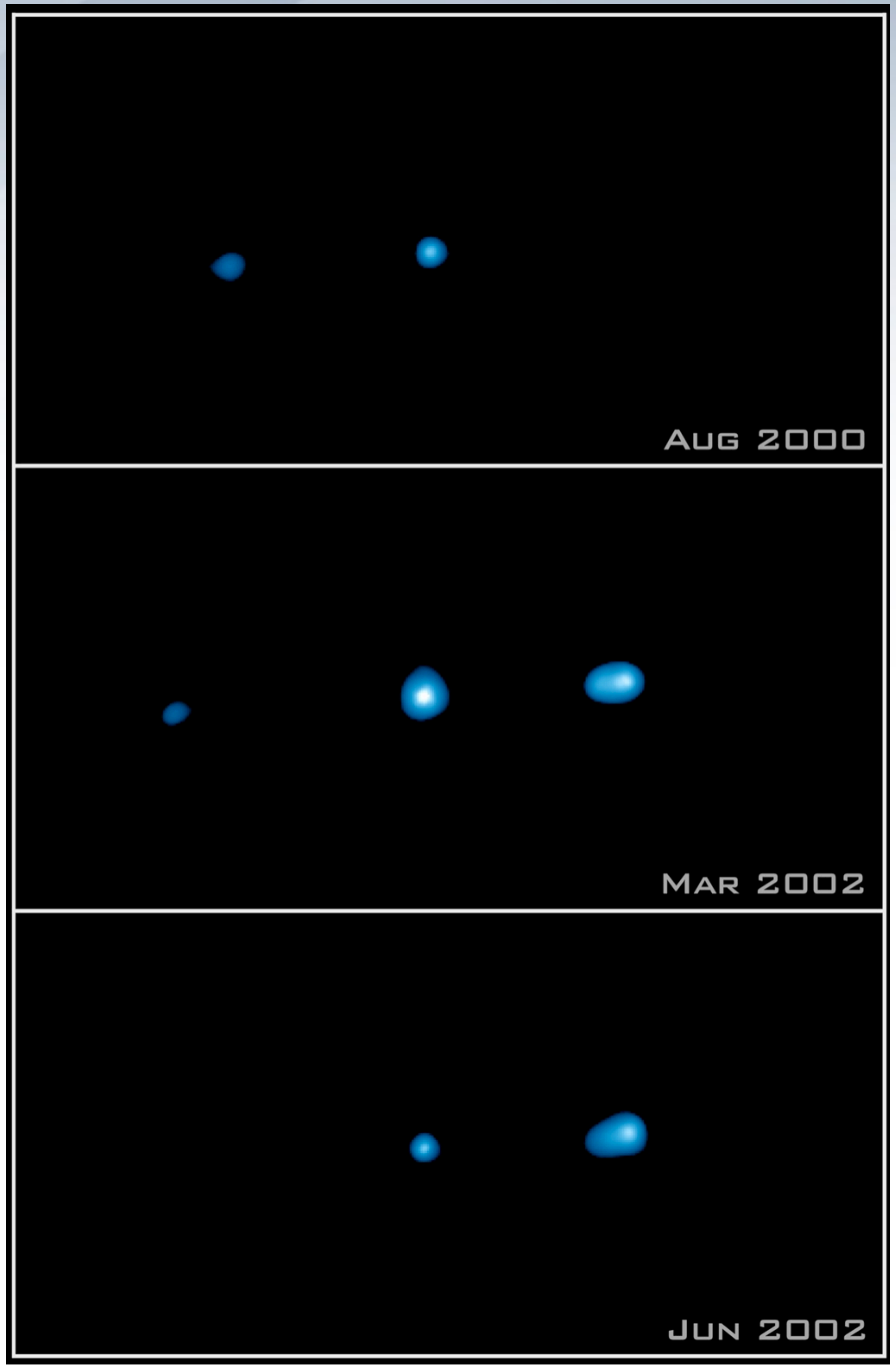




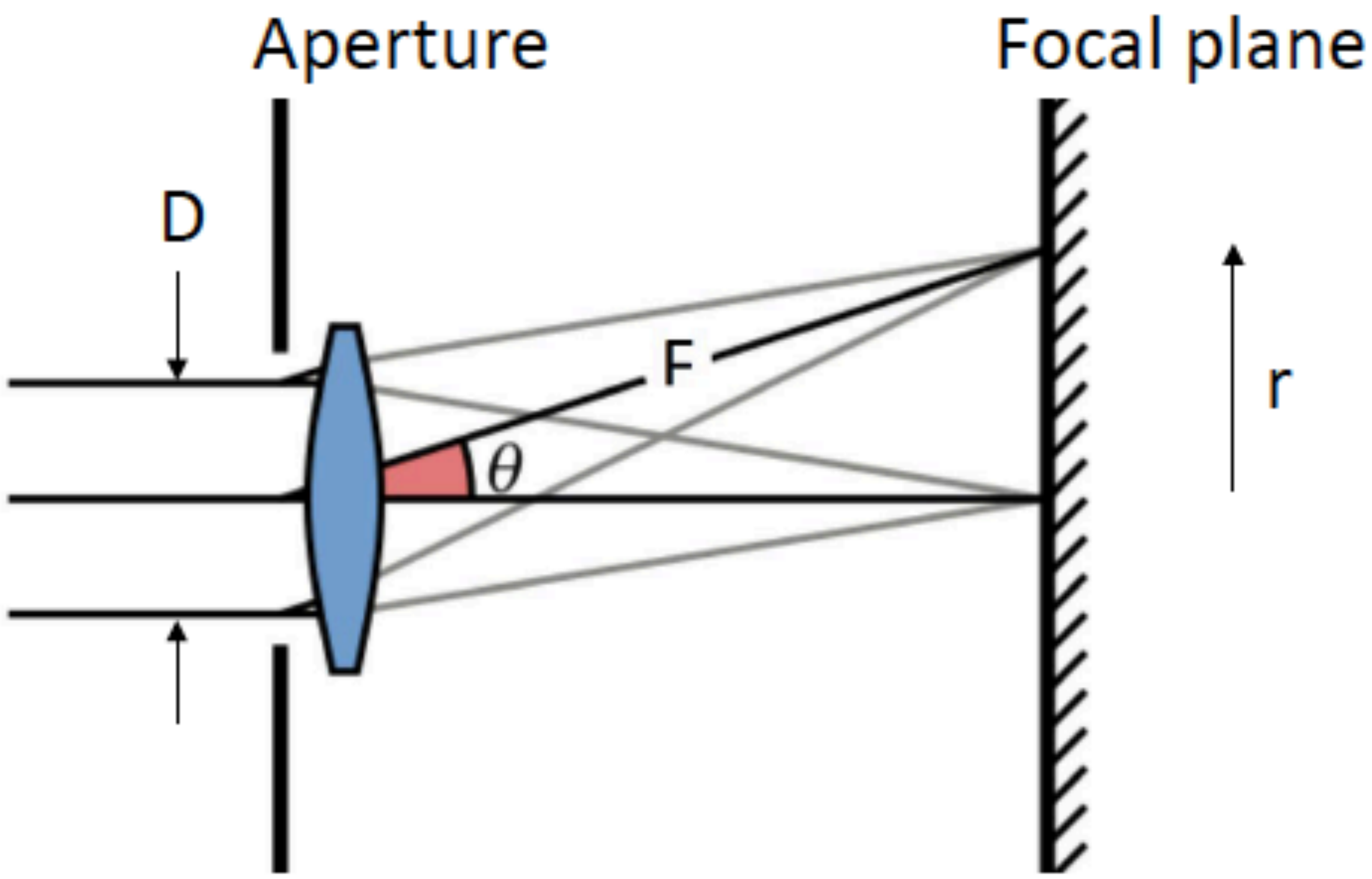
X-ray Binary Jets

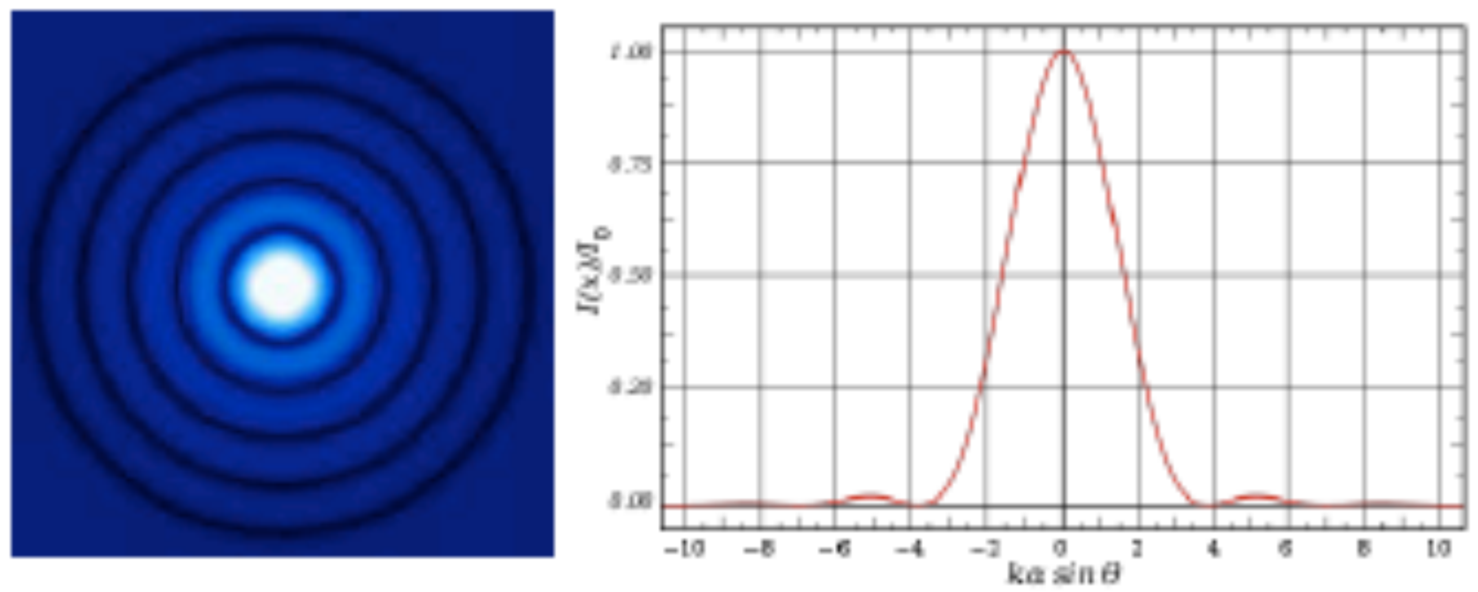
- X-ray jets discovered using Chandra
- Proper motion observed — speeds are relativistic
- Radio maps of Sco X-1 indicate high speed knots at 10-30 mas scales





PSF of a Diffraction Limited Telescope





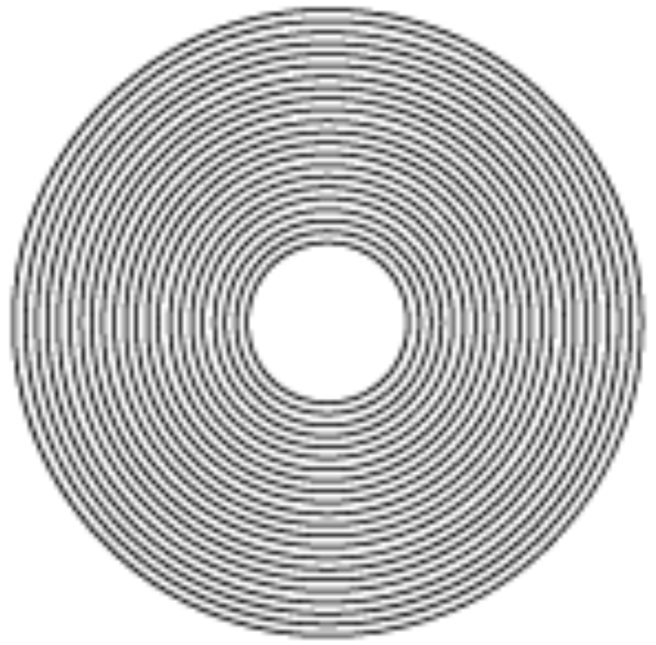
A diffraction-limited telescope will generate a point spread function (PSF) at the focal plane described by an *Airy disk*

$$I(\theta) = I_0 \left(\frac{2J_1(x)}{x}\right)^2 ,$$

where J_1 is a Bessel function, $x = k\frac{D}{2}\frac{r}{F}$, $k = 2\pi/\lambda$, D is the aperture diameter, *F* is the focal length, and $r = F\sin\theta$ is the radial observation point at the focal plane.

The disk's half power diameter (HPD) is given by

$$\mathrm{HPD} \cong \lambda/D$$



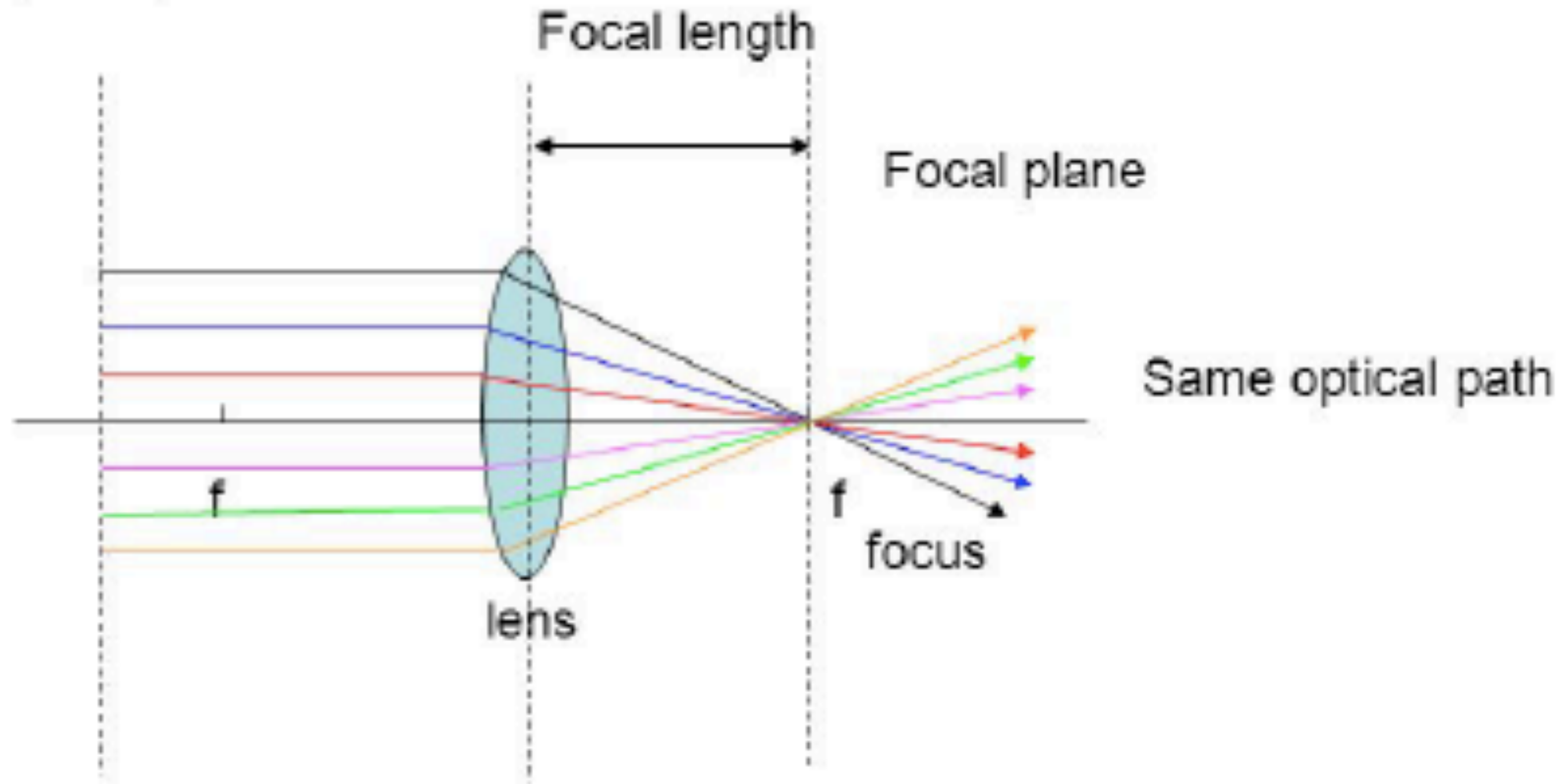
For an "annulated" aperture the telescope HPD is only mildly degraded

30

Fermat's Principle

- Telescope figure must be "perfect," which enables …
- All waves through the telescope aperture to arrive in-phase at telescope focus with a tolerance of $<2\pi/10$
- In other words, the optical path difference (OPD) of all rays from source to focus need to be identical to a small fraction of the λ, i.e., OPD $< \lambda/10$
- At 5 keV, λ = 0.2 nm, $\lambda/10$ = 20 pm

Fermat's Principle

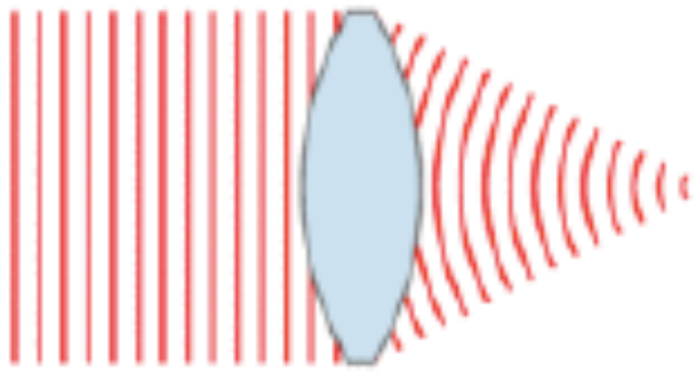


Pierre de Fermat
(1607 – 1665)

Diffraction limited resolution requires all rays to have the same optical path length

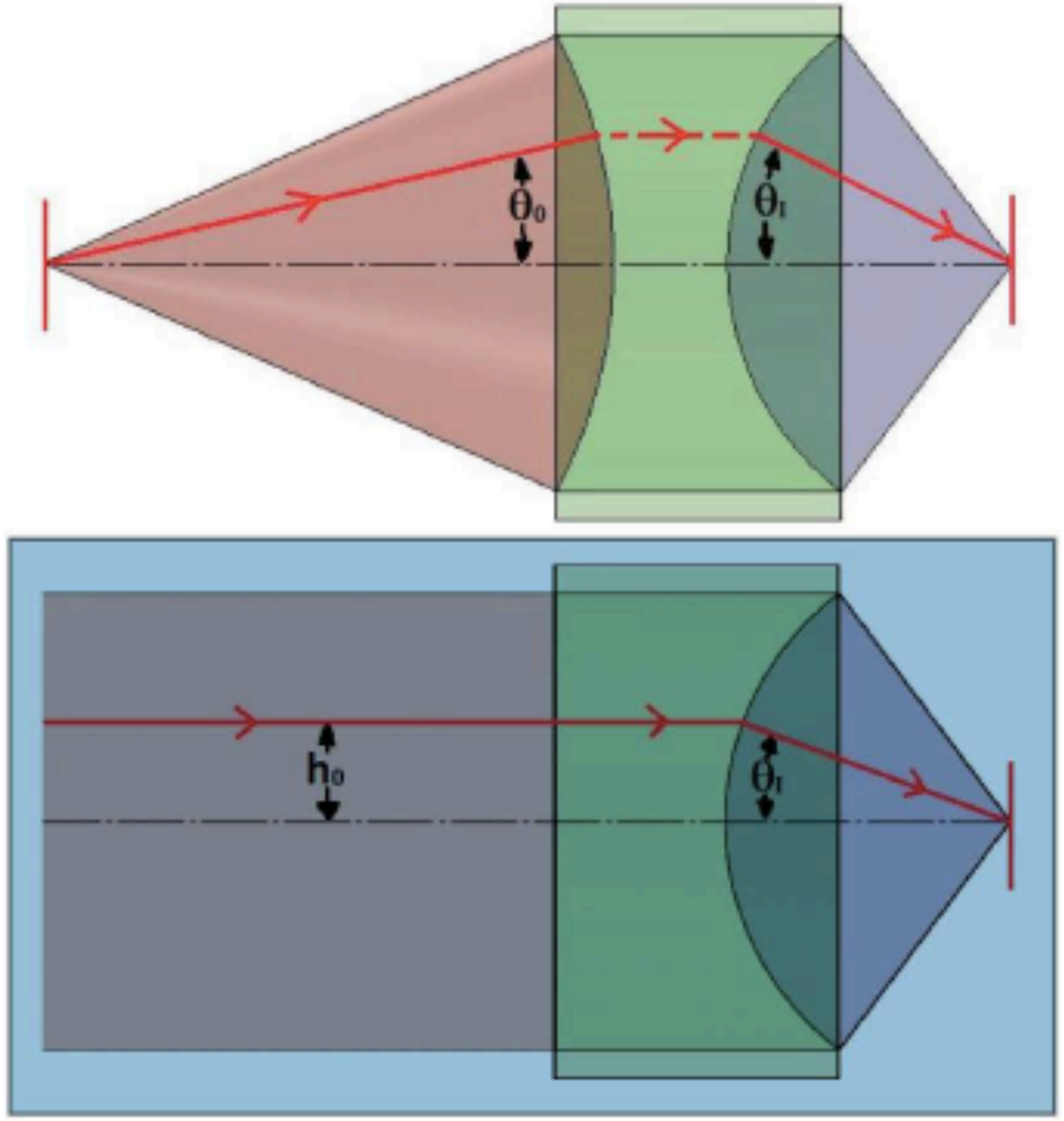
$$OPL = \int_a^b n(z)dz$$

where $n(z)$ is refractive index



All waves must arrive in phase at the focal plane

Abbe Sine Condition



Ernst Karl Abbe
(1840-1905)

- Enforces constant telescope magnification across the aperture
- Eliminates first-order spherical and coma aberration (aplanatic)

<u>**Coma free images**</u> as long as

$$\frac{\sin\theta_O}{\sin\theta_I} = \text{Constant}$$

$$\frac{h_O}{\sin\theta_I} = \text{Constant}$$

for all rays

Matching Mirror Shell Path Lengths

- There are two parameters common to all shells: $\Delta s, f$
- There are five design parameters for each shell: h_0, L, h_2, z_2, i_0
- Typically h_0 is chosen as the independent variable.

There are three equations (derived from Saha 1987, simplified for P-H telescope) that connect the four design parameters:

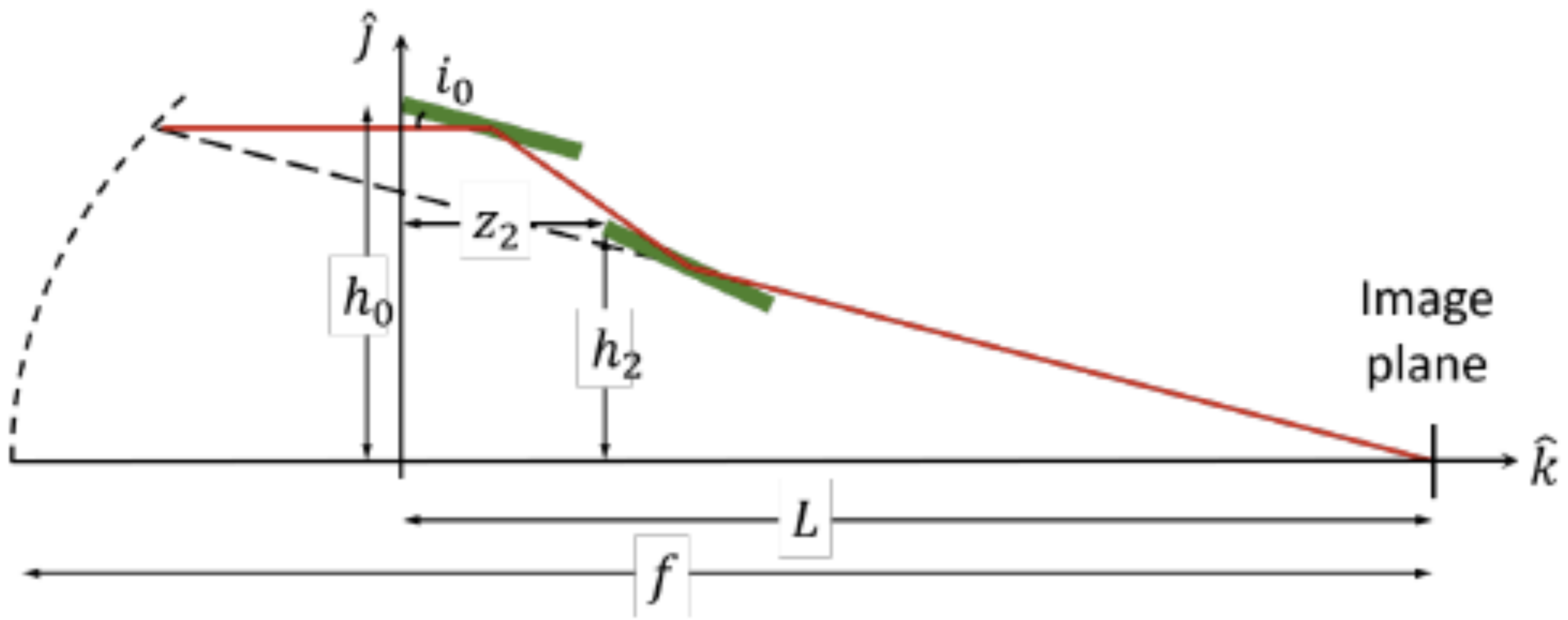
$$\Delta s = \sqrt{(h_0 - h_2)^2 + \left(L - \frac{h_2 f}{h_0}\left(1 - \frac{h_0^2}{4f^2}\right)\right)^2} + \frac{h_2 f}{h_0}\left(1 + \frac{h_0^2}{4f^2}\right) - L$$

$$\tan i_0 = \frac{2f\Delta s - h_0^2}{(2f - \Delta s - 2L)h_0}$$

$$h_0 - h_2 = z_2 \tan 2i_0$$

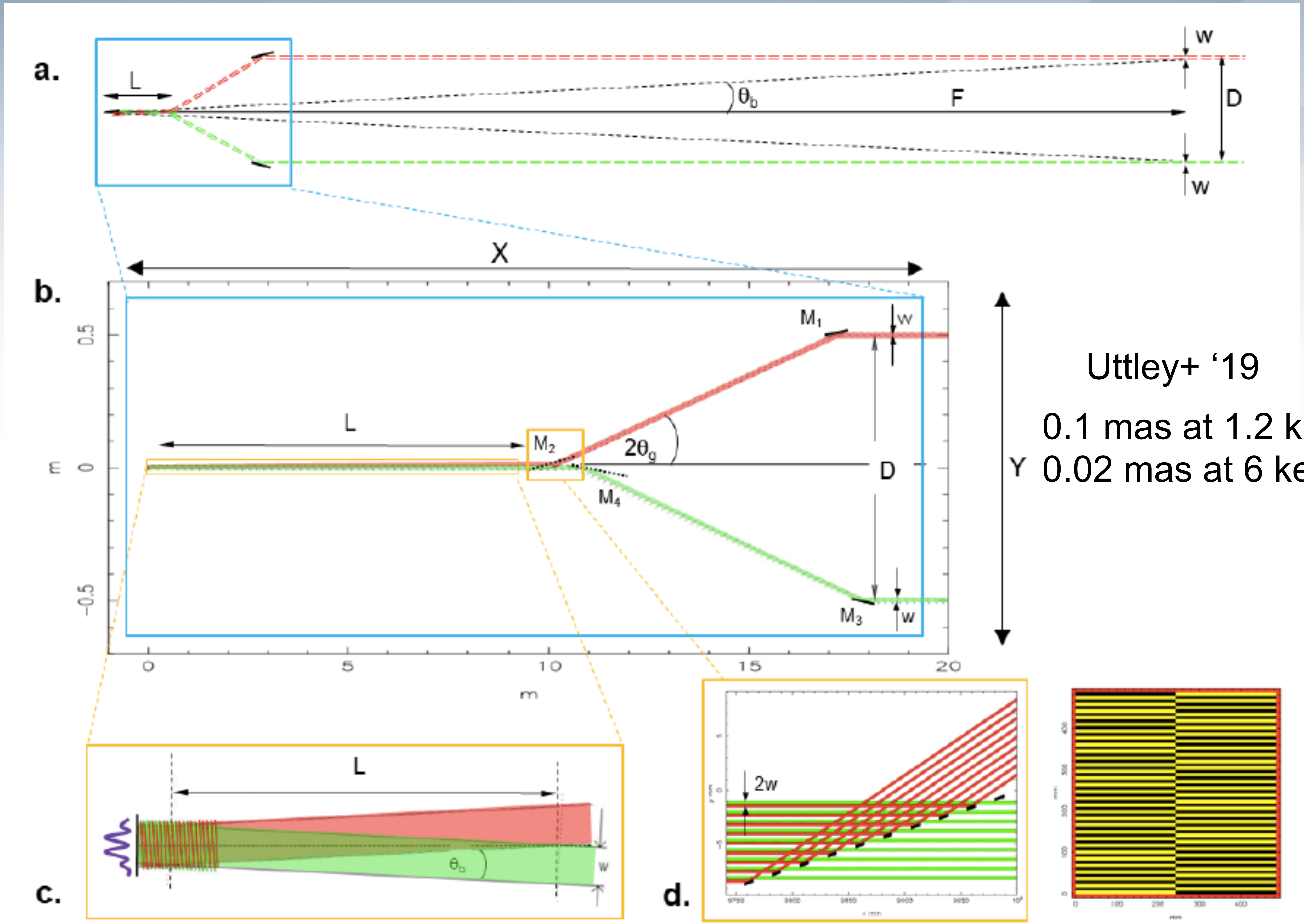
Determining Δs requires choosing two design parameters of a reference shell. The length of a shell with z_2^* and i_0^* is approximately,

$$L^* = f\left(1 - \frac{z_2^*}{h_0^*}\tan 2i_0^*\right) + z_2^*$$ *(* indicates parameter of ref. shell)*



- There is one free design parameter.
- These equations can be solved and evaluated exactly using a symbolic solver and quad-precision arithmetic (since f is large and Δs is small).
- Approximate solutions provide intuition and capture trends.

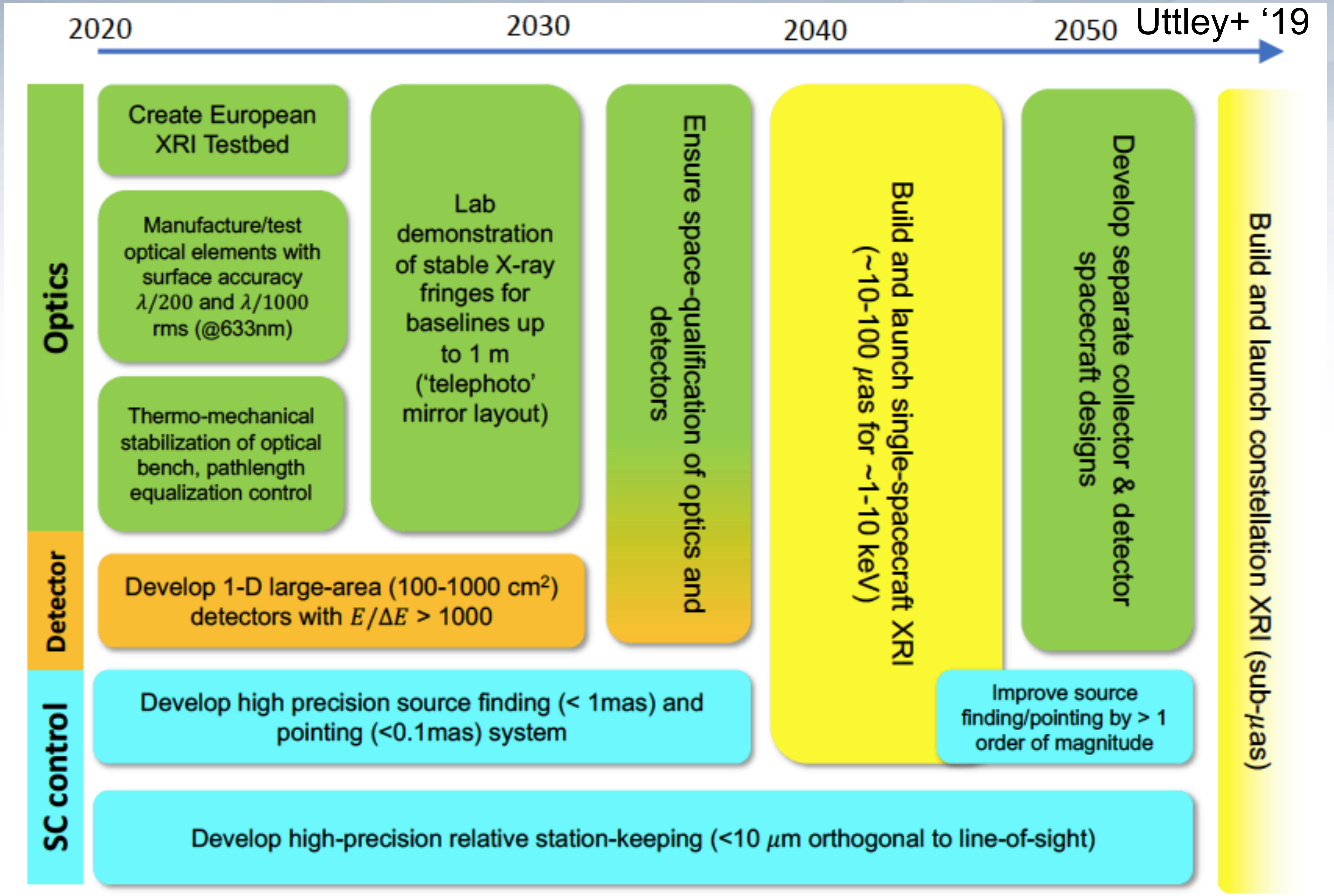
A Michelson X-ray Interferometer (XRI)



Uttley+ ‘19

0.1 mas at 1.2 keV
0.02 mas at 6 keV

ESA 2050 Vision Roadmap



Diffraction Limited Aspherical Optics Are Critical to the Success of EUV Lithography

- λ_{euv}/50 figure
- Low flare
- Ultrasmooth finish
- 10 µm departure from a sphere

Tinsley Sample C
Zerodur-M
150 mm diameter

Courtesy of John Taylor, LLNL.

Professor David Attwood
AST 210/EECS 213
Univ. California Berkeley

Ch10_DiffrLtdAsph.ppt

Current Status of EUV Lithography