Prospects for X-ray Interferometry from the Moon

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NASA's Moon to Mars Objectives - 2022

LPS-4: Advance understanding of the origin of life in the solar system by identifying where and when potentially habitable environments exist(ed), what processes led to their formation, how planetary environments and habitable conditions have co-evolved over time, and whether there is evidence of past or present life in the solar system beyond Earth.

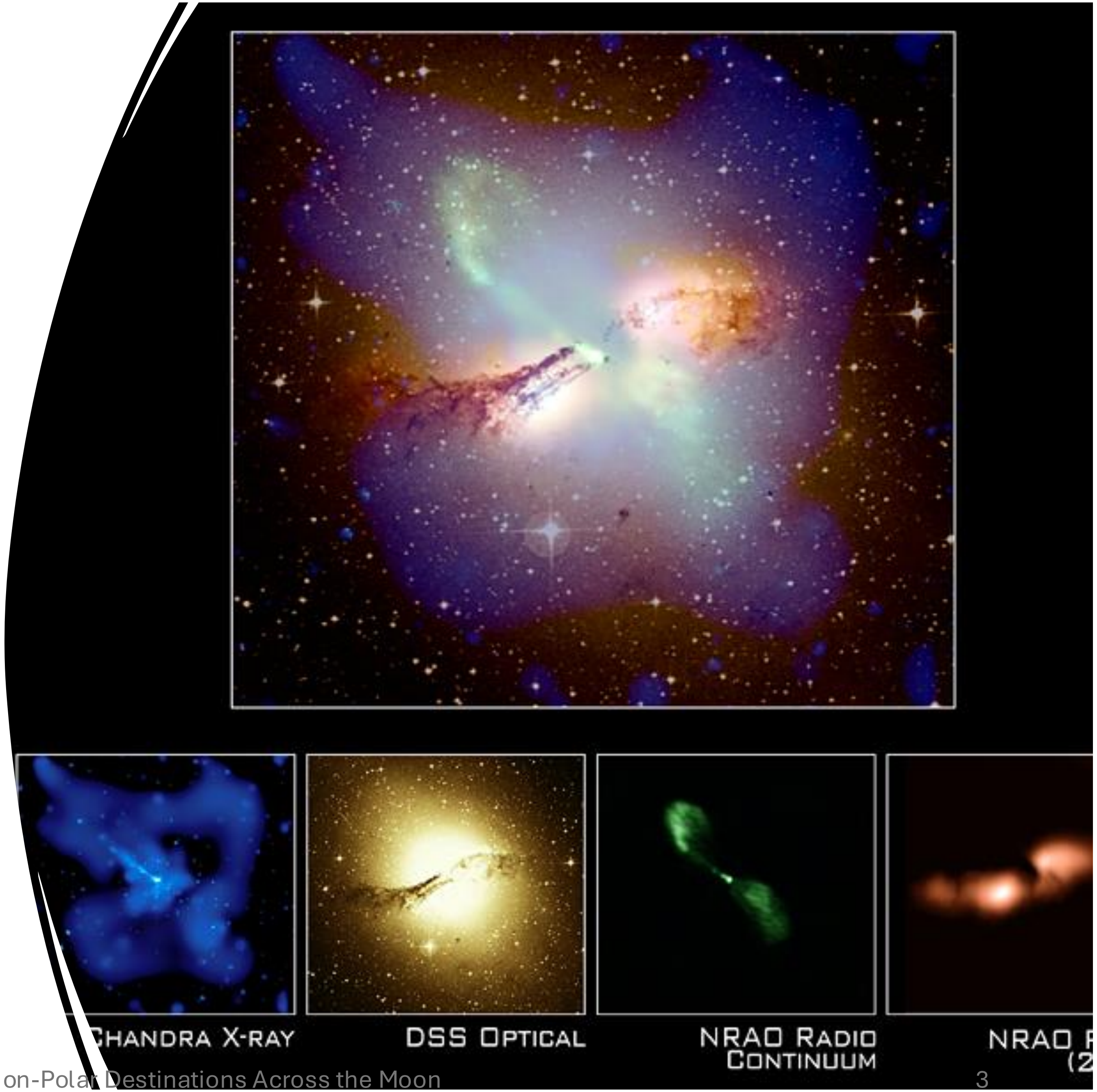
PPS-2: Advance understanding of physical systems and fundamental physics by utilizing the unique environments of the Moon, Mars, and deep space.

National Academy Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020):

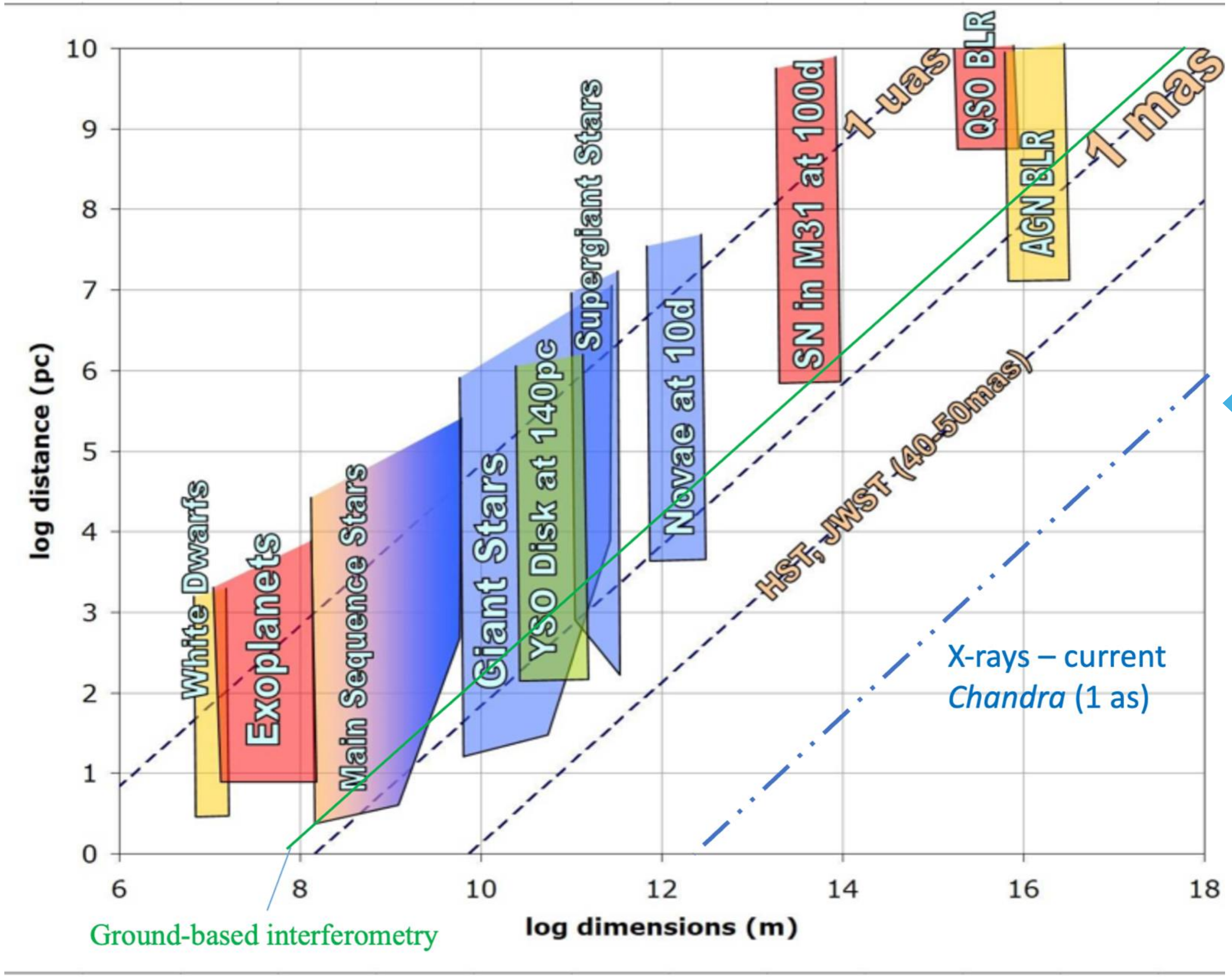
- Themes: Cosmic Ecosystems and New Messengers and New Physics.
- Priority science areas: Unveiling the Hidden drivers of galaxy growth and opening New Windows on the Dynamic Universe through the goal of Understanding black hole accretion and feedback.
- Questions: (1) How do gas, metals, and dust flow into, through, and out of galaxies?, (2) How do supermassive black holes form?, and (3) ***How is [supermassive black hole] growth coupled to the evolution of their host galaxies?***
- Habitable Worlds objectives require: ***A high spatial and spectral resolution X-ray space observatory*** *to probe stellar activity across the entire range of stellar types, including host stars of potentially life-sustaining exoplanets.*
- Astro 2020 recommends development toward a "**high spatial and spectral resolution X-ray strategic mission**" with **imaging resolution goal of < 0.5 arcsec**

Why X-rays?

- X-rays signal extreme events
- High temperatures, intense magnetic activity, photoionized plasmas
- Accreting black holes shine brightly in X-rays; regions are small
- Accretion regions often hidden at longer wavelengths
- Observing primary sources of the X-ray continuum near supermassive black holes and where jets are launched requires *at least* milli-arcsecond (mas) resolution
- X-rays probe stellar flare activity in systems hosting exoplanets

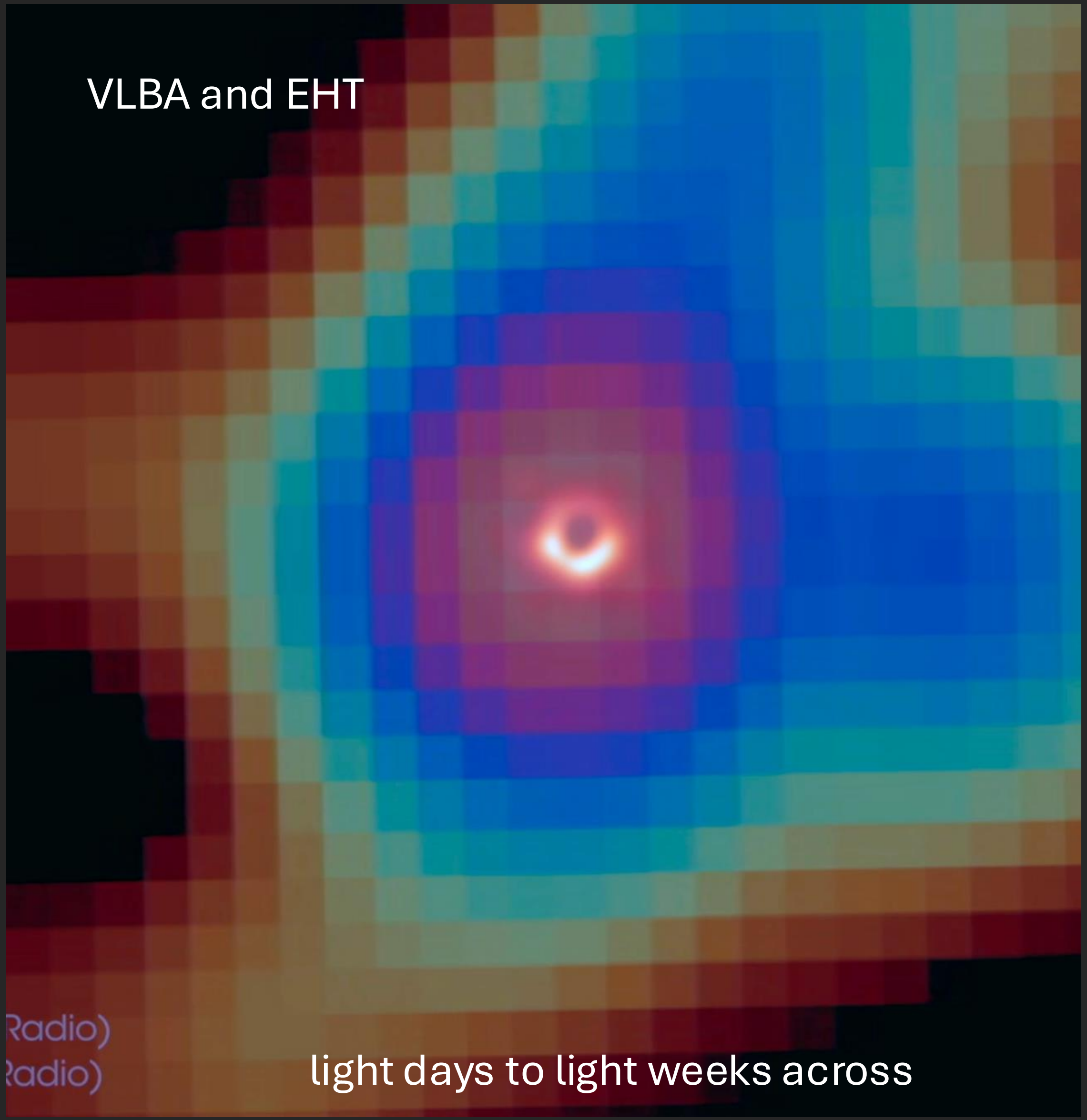


X-ray imaging has fallen orders of magnitudes behind other bands



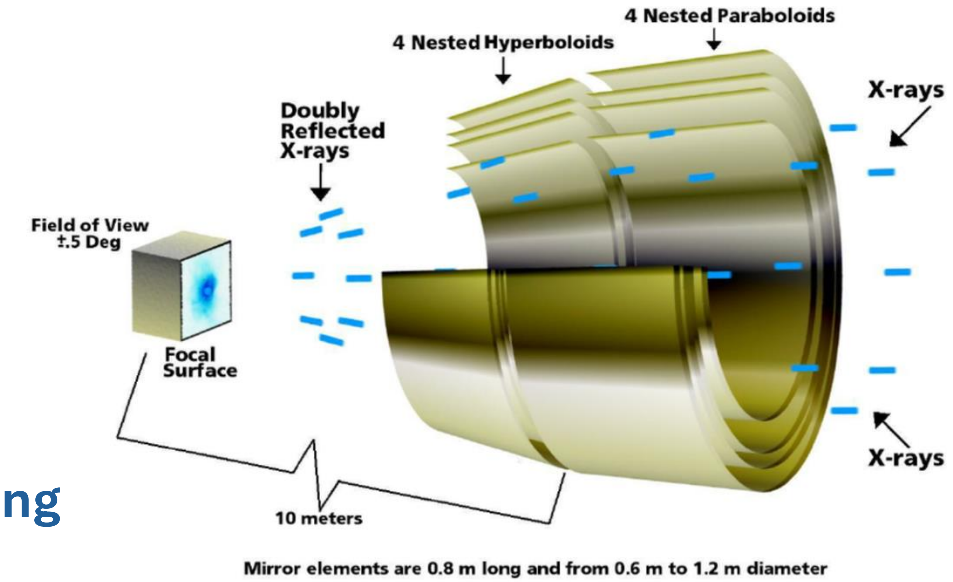
(adapted from Rinehart et al. 2020 Astrophysics Decadal Whitepaper).


M87; HST and Chandra
e (Visible)
tory (X-ray)
100s to 1000s of light years across


VLBA and EHT
Radio)
Radio)
light days to light weeks across

Categories of diffraction-limited X-ray telescopes

- Diffractive Fresnel zone plate
- Refractive Fresnel zone plate
- Refractive + diffractive zone plate
- Normal incidence mirrors with multilayer coatings
- Wolter-Schwarzschild Type 2 telescope
- **Flat mirrors at grazing incidence in sparse formation flying**

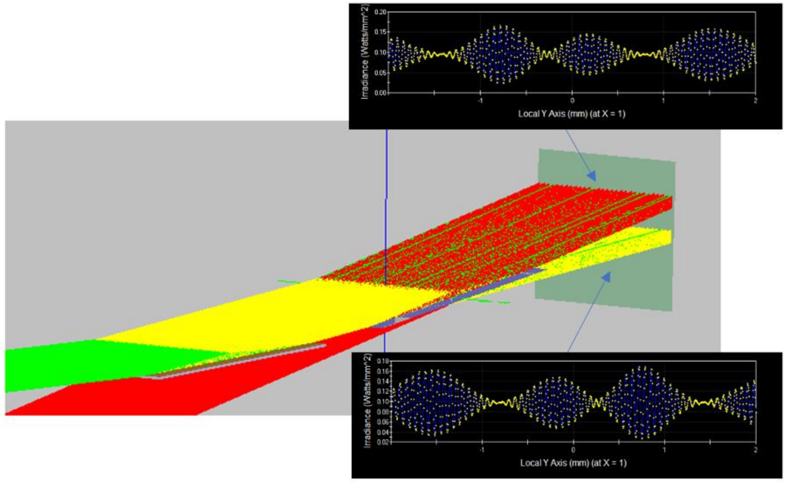


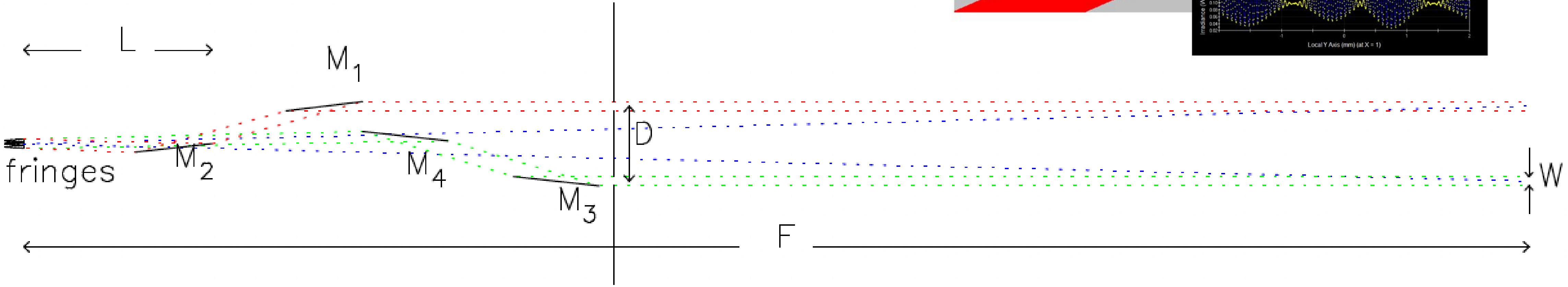
Work in the science community is currently being done to advance all of these technologies, but it is an <u>extremely</u> sparse funding environment.

Chandra grazing incidence Wolter Type 1 telescope
0.5-1 arcsec; not diffraction limited

Basic X-ray interferometer

Willingale R., 2004, SPIE, 5488, 581. doi:10.1117/12.552917





- X-ray waves are short, only ~ 0.2 – 5 nm in wavelength.
- Minimum angular separation required to distinguish two point sources: $\theta r = 1.22\lambda/D$
- 1 milli-arcsecond interferometer baseline ~ 1 – 2 m
- micro-arcsecond interferometer baseline ~ 20 – 200 m
- compare with radio (VLBA) up to ~8,000 km; can get to milli-arcsecond scales

How is supermassive black hole growth coupled to the evolution of their host galaxies?

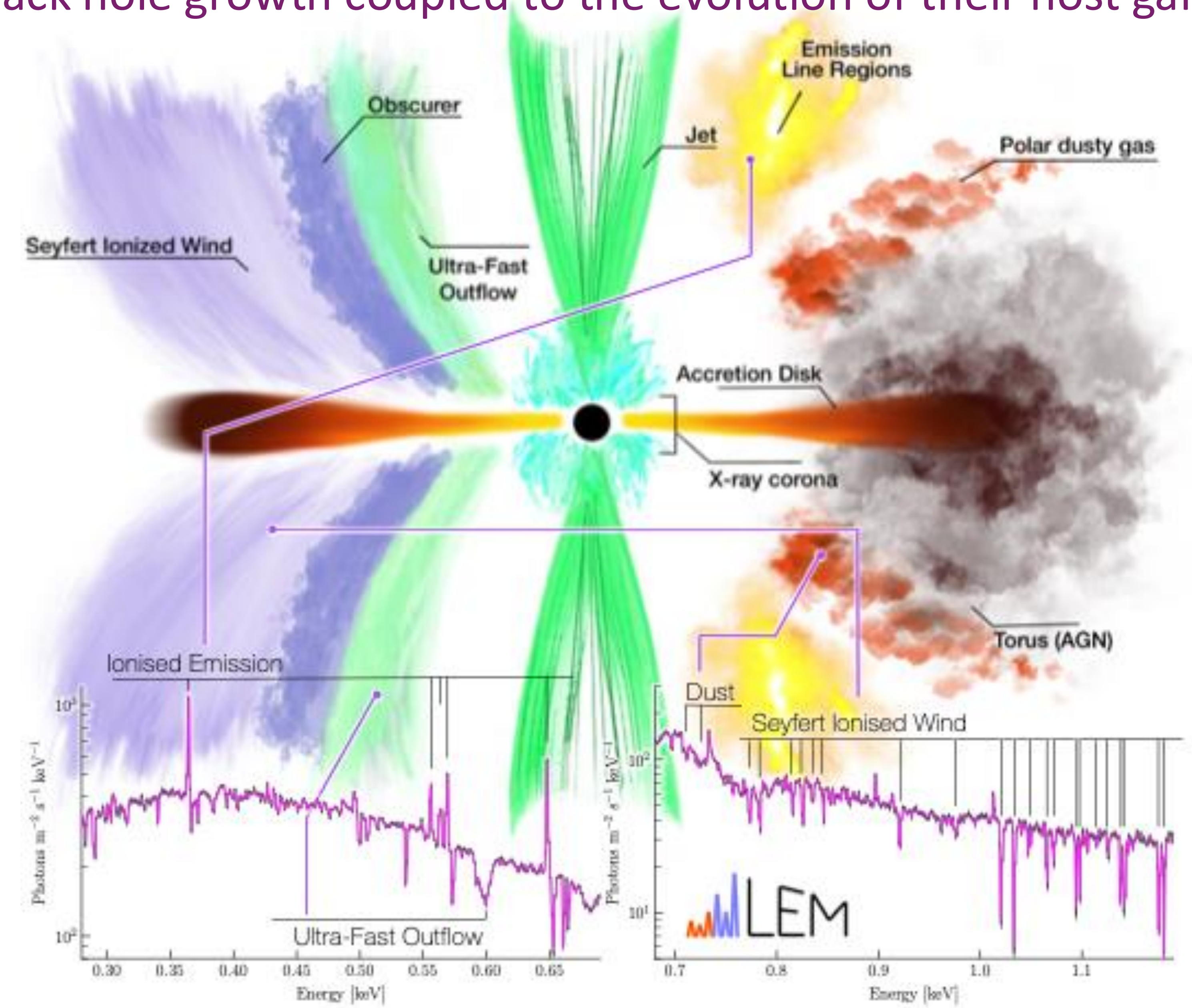
Active Galactic Nucleus (AGN)

L_X ~10^{42} □ 10^{47} erg/s

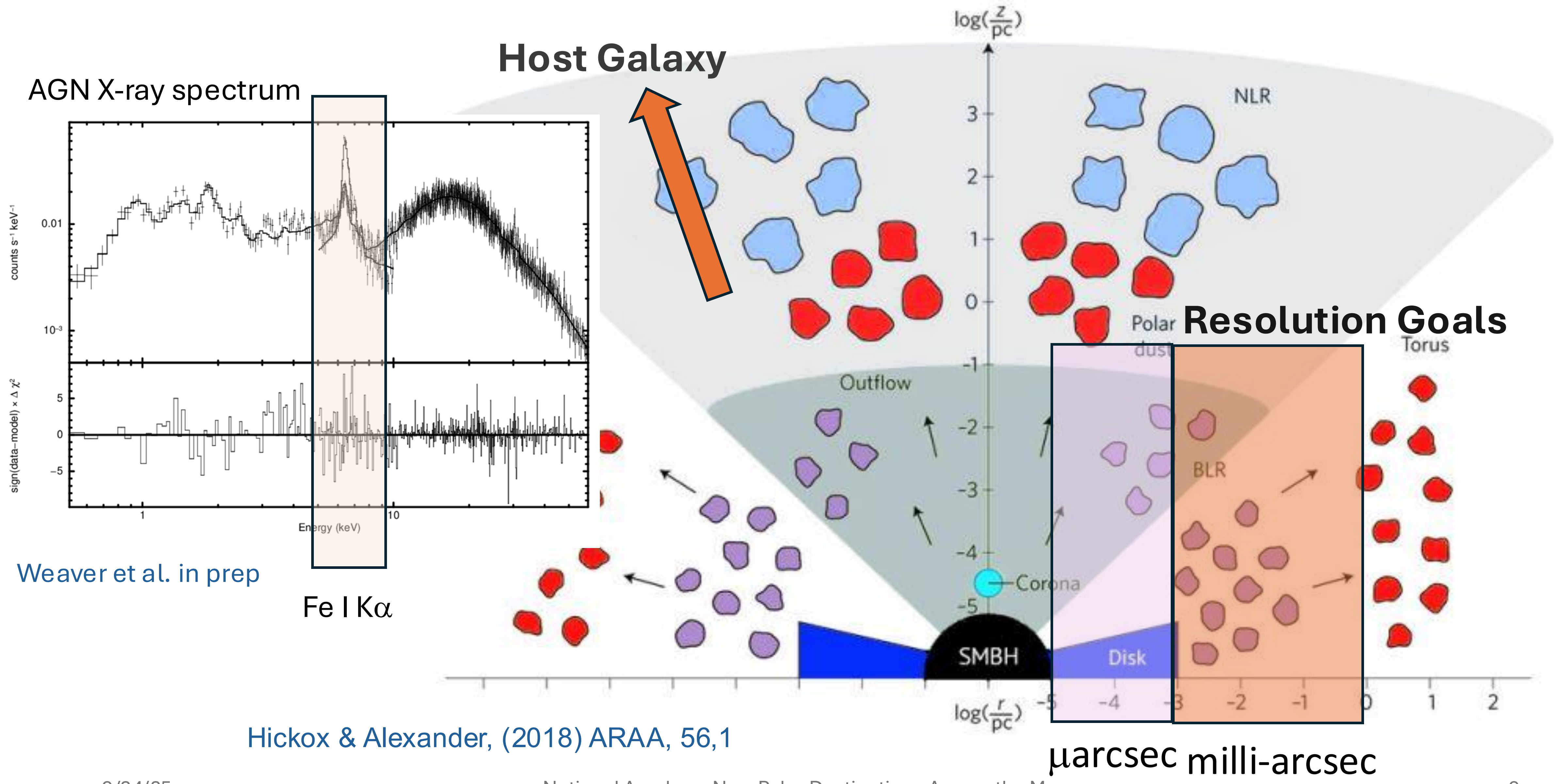
Supermassive black hole (SMBH)

M_{BH}~10^6 –10^9 M_{Sol}

Weaver et al. (2024) "Active Galaxy Science with the Line Emission Mapper"
doi: 10.48550/arXiv.2406.18743

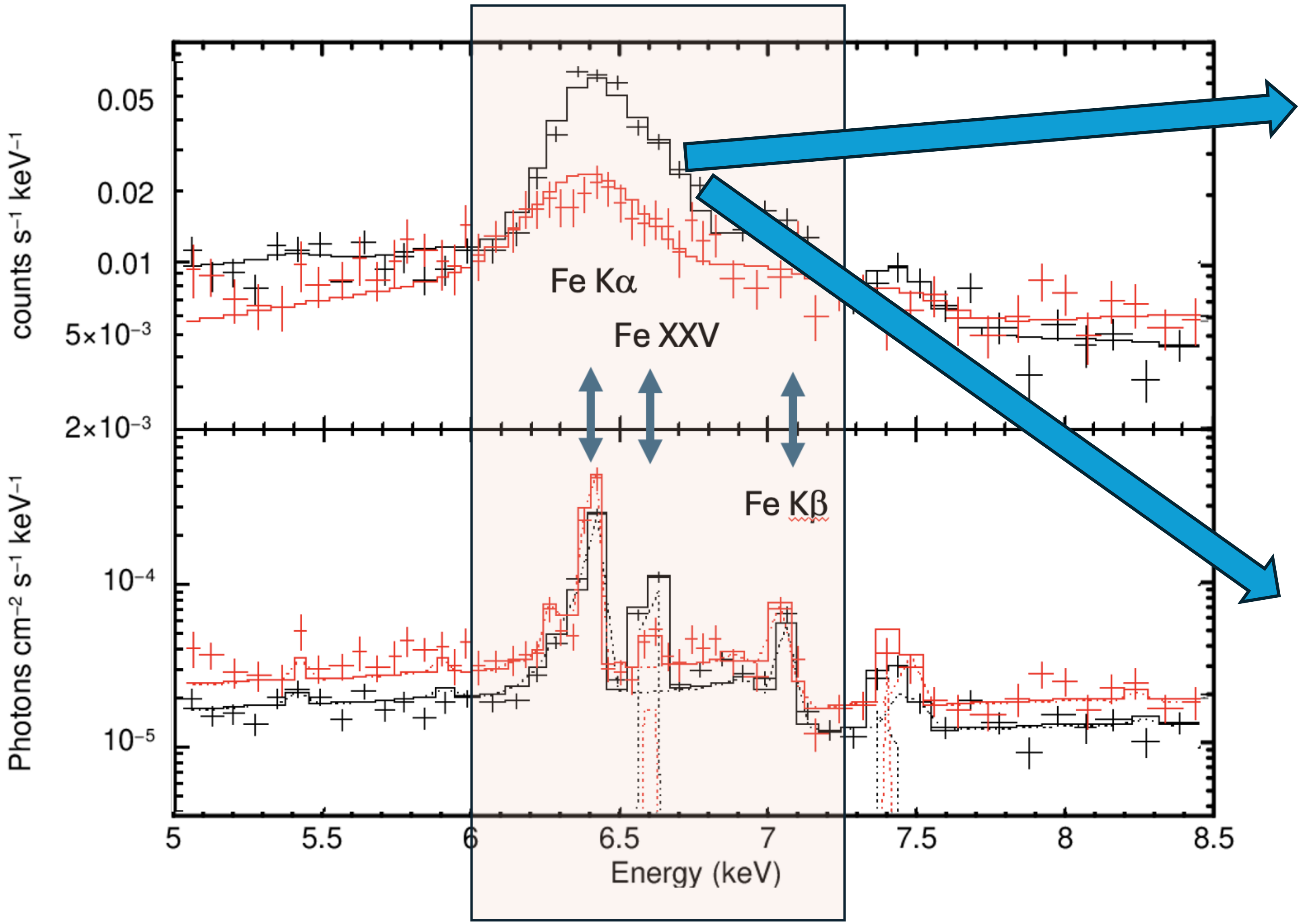


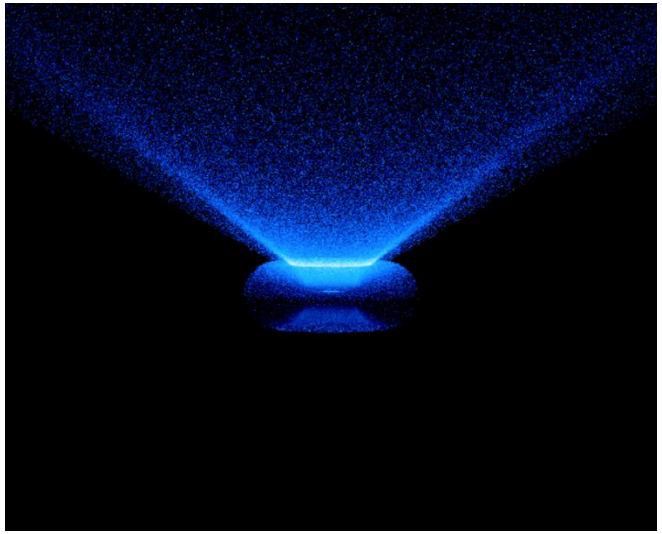
How is supermassive black hole growth coupled to the evolution of their host galaxies?



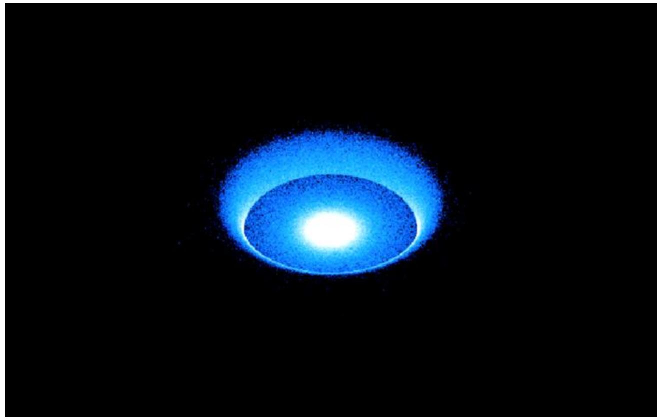
Weaver et al. in prep

Hickox & Alexander, (2018) ARAA, 56,1



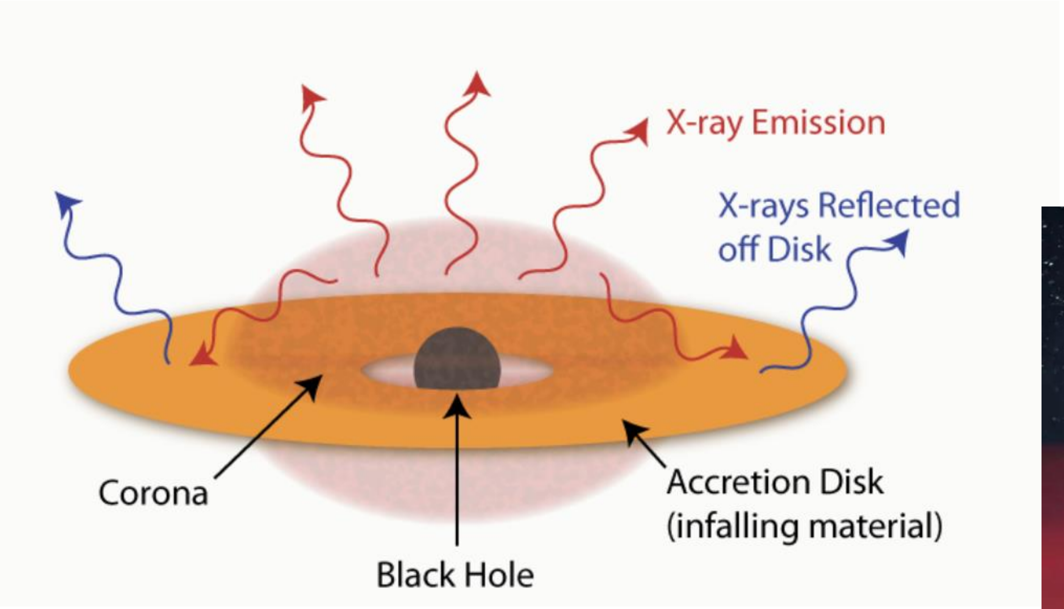


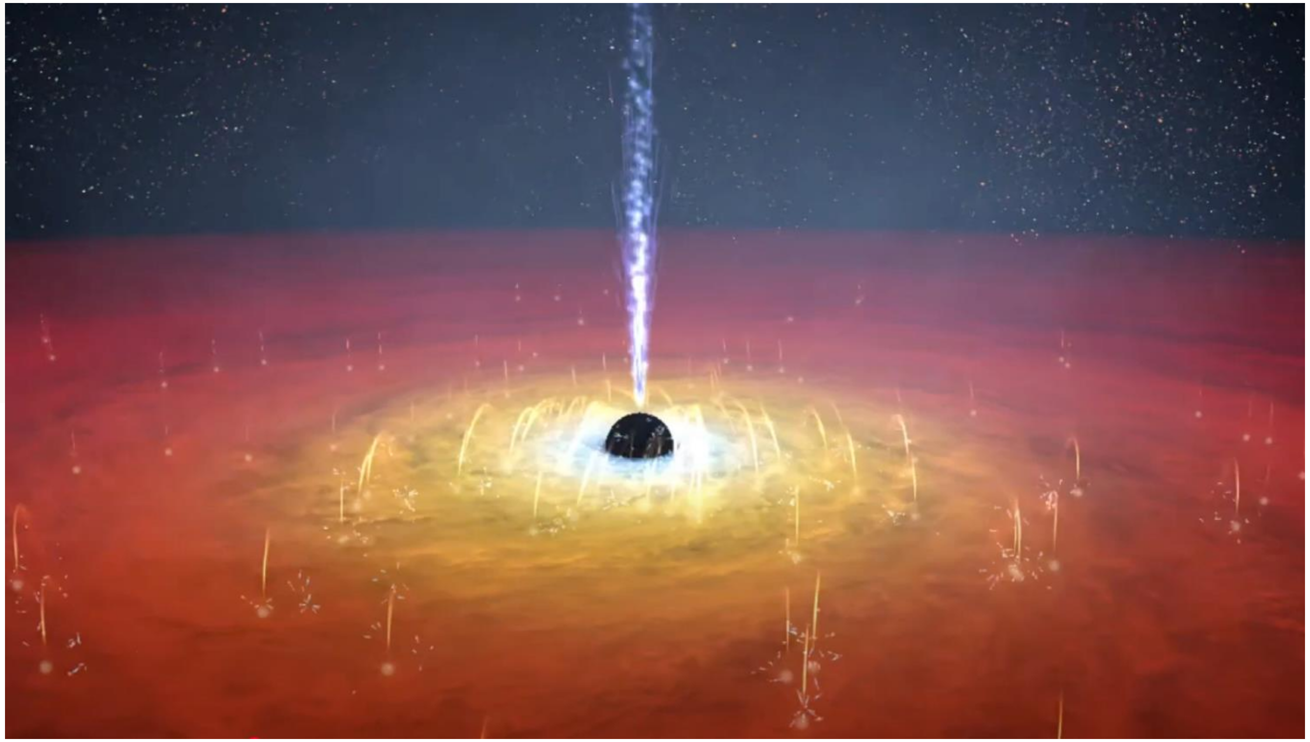
torus



broad line region

Measuring Black hole accretion



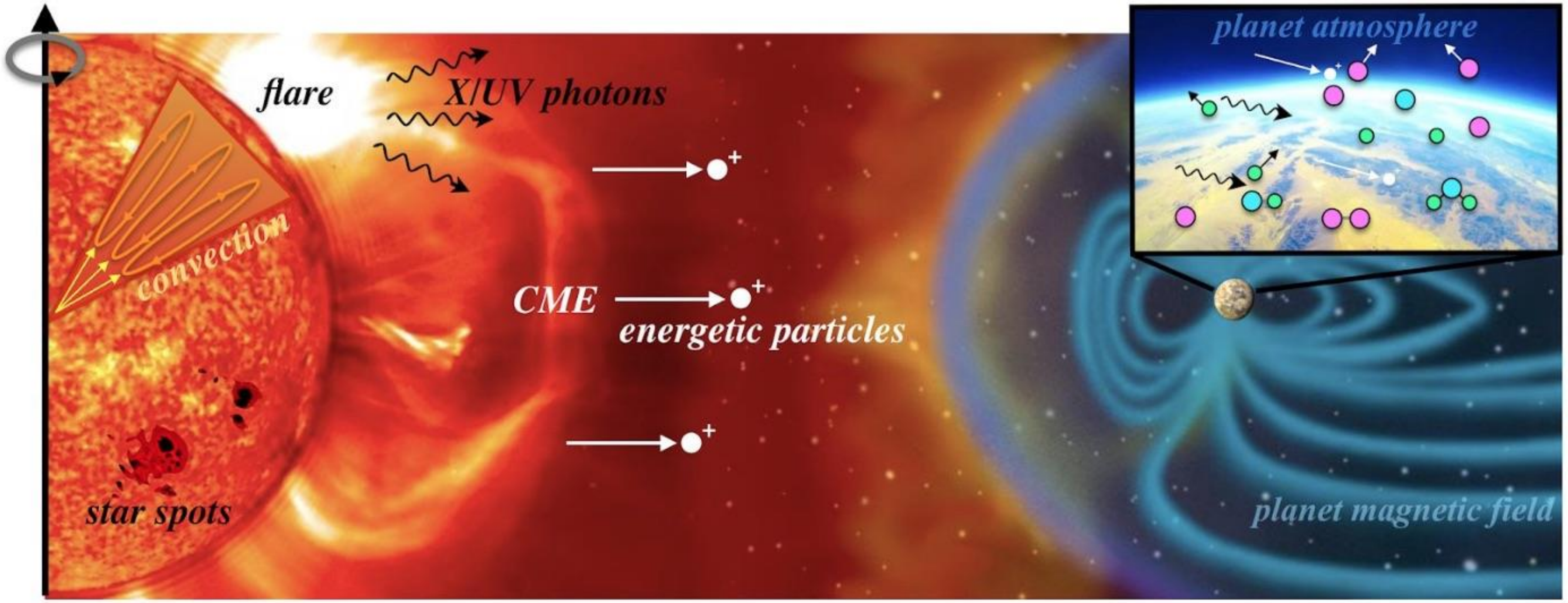


Tr'Ehnl & Brandt 2017

Required Parameters & Observations

- **SMBH:** Constrain the geometry of the inner regions of the AGN, and how it changes with fundamental parameters (e.g., BH mass, accretion rate, etc.). Constrain outflows.
- **Angular resolution:** To observe in proximity to the AGN X-ray emission line regions & torus, need 1x10-3 pc sizes in local AGN (1x10-3 arcsec).
- To observe in proximity to the accretion disk need 1x 10-5 to 1x 10-6 pc size scales in local AGN (this is 1x10-5 to 1x10-6 arcsec).
- **Bandpass:** Observe energies from 6-7 keV; 0.5-1.5 keV.
- **Sensitivity:** At least to 10^(-14) erg s-1 cm-2. Ideally per resolution element.
- **Spectral Resolution:** CCD quality or rough band passes are sufficient
- **Observation exposure times:** ~week+
- **Other Requirements:** Ability to tile/mosaic across regions

Astro2020: Probe stellar activity across the entire range of stellar types, including host stars of potentially life-sustaining exoplanets



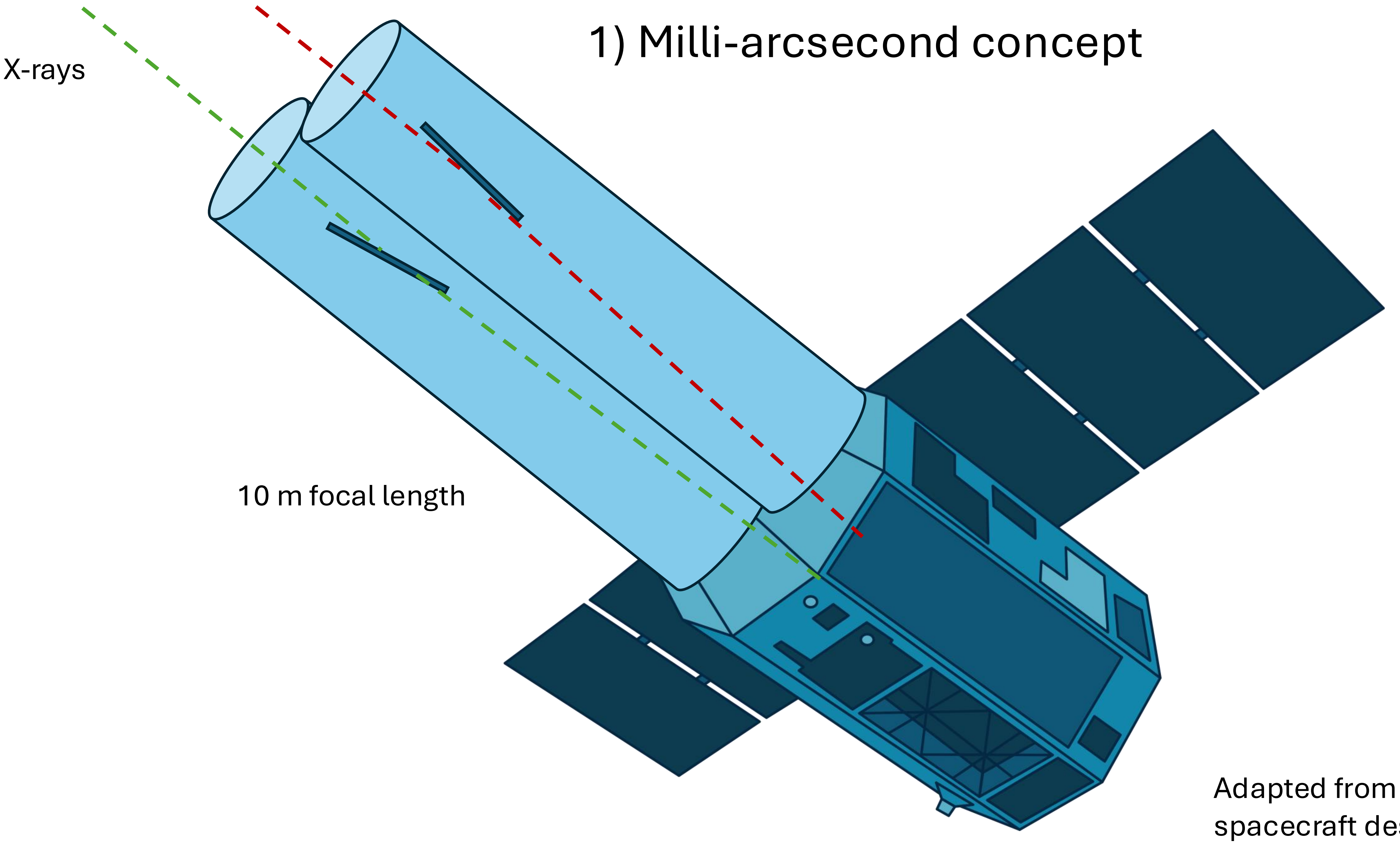
- High-resolution X-ray images would help assess extreme conditions on exoplanets orbiting solar-like stars.
- mechanisms of rotation and convection drive flares in low-mass stars.
- High-energy photons and energetic particles generated by flares and CMEs interact with planetary atmospheres (upper right inset) and lead to photochemistry, atmospheric loss, and impacts on habitability.
- No water likely means no life

Required Parameters & Observations

- **Stellar science/flares:** How does the spatial distribution and morphology of stellar flare and magnetic activity affect atmospheric escape and planetary habitability?
- **Angular resolution: ~**μas will spatially resolve stellar flares for a significant population. mas-accessible targets also available for flares.
- **Bandpass:** Soft X-rays
- **Sensitivity:** To study both quiescent and flaring activity for stars, the instrument should achieve a sensitivity of ~10^(-12) to 10^(-13) erg s-1 cm-2 with time averaging on the order of seconds to minutes.
- **Observation exposure time:** ~couple of days
- **Other Requirements:** Timing resolutions on the order of seconds/minutes

Free-flying X-ray interferometers

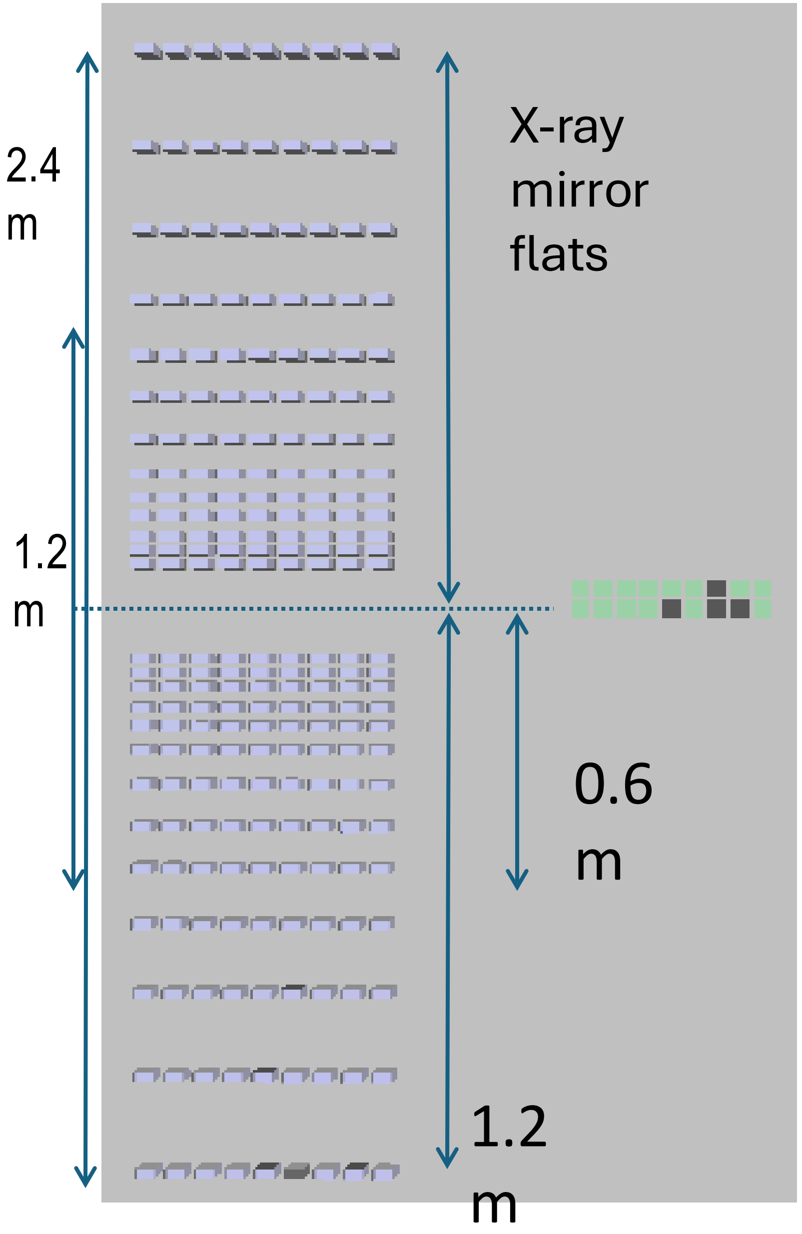
1) Milli-arcsecond concept

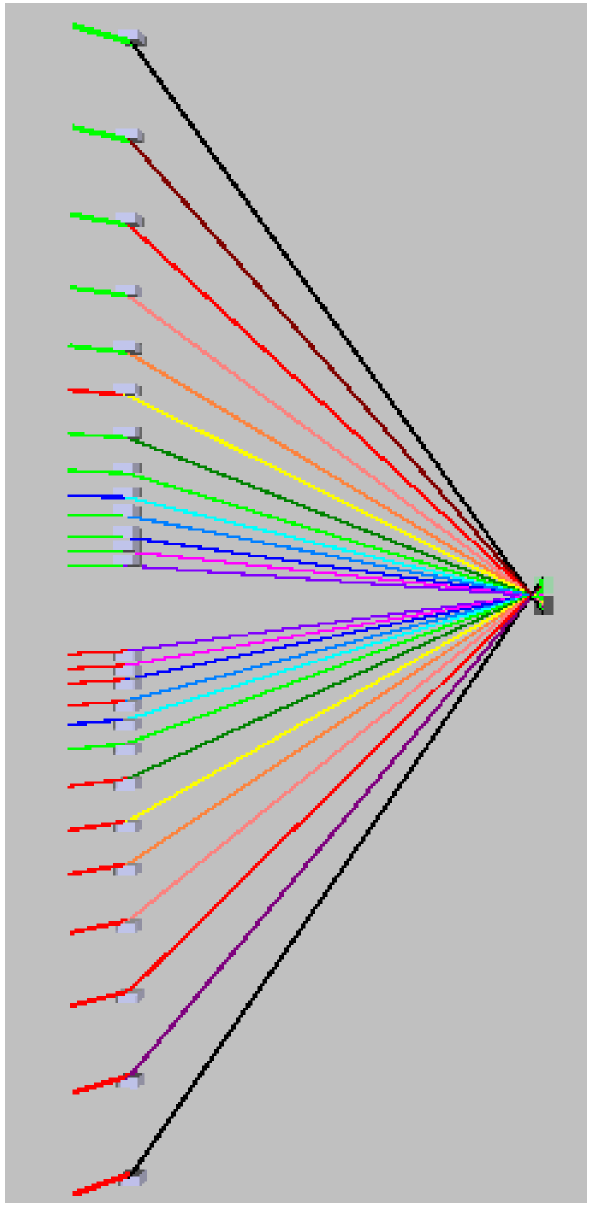


Adapted from the XRISM spacecraft design

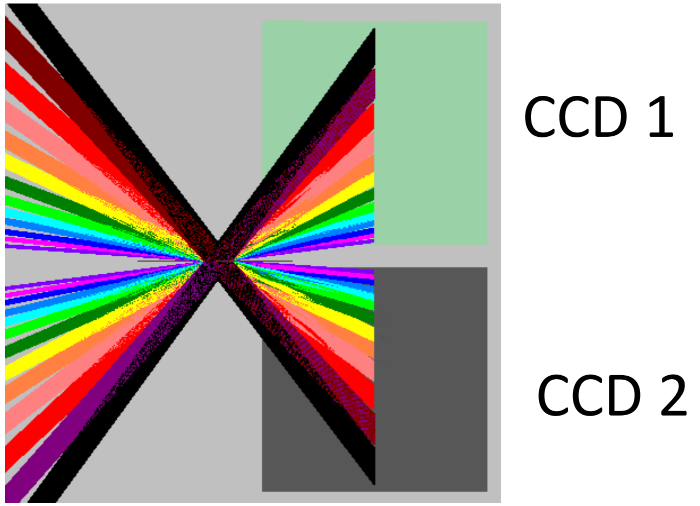
High-Level Mission Description

- mas resolution requires a focal length of ~10 meters and a diameter (baseline) of 2.4 meters.
- Doable today with a more compact interferometer (Willingale 2004; Uttley et al. 2020) and a compact X-ray beamsplitter optic.
- X-rays must bounce off flat mirrors at grazing angles of <2 degrees. The innermost mirror pair has a graze angle of 0.3 degrees and can collect photons of energy up ~8 keV
- We can stack, or “nest” mirrors packed tightly together. Filling 50% of the side-to-side entrance aperture, each energy channel could reach ~10% of Chandra’s collecting area.
- Having a fleet in relative formation flying could provide the full Chandra effective area or more.





Looking “down the barrel”



- X-ray CCDs with 15 micron pixels located 400 nm from the center of the beamsplitter.
- Separate energy channels. Inner pairs collect higher energy X-rays. Outer pairs collect soft X-rays.
- Narrow band imaging.
- Can design a sparse or filled aperture.

2) NASA Innovative Advanced Concepts study

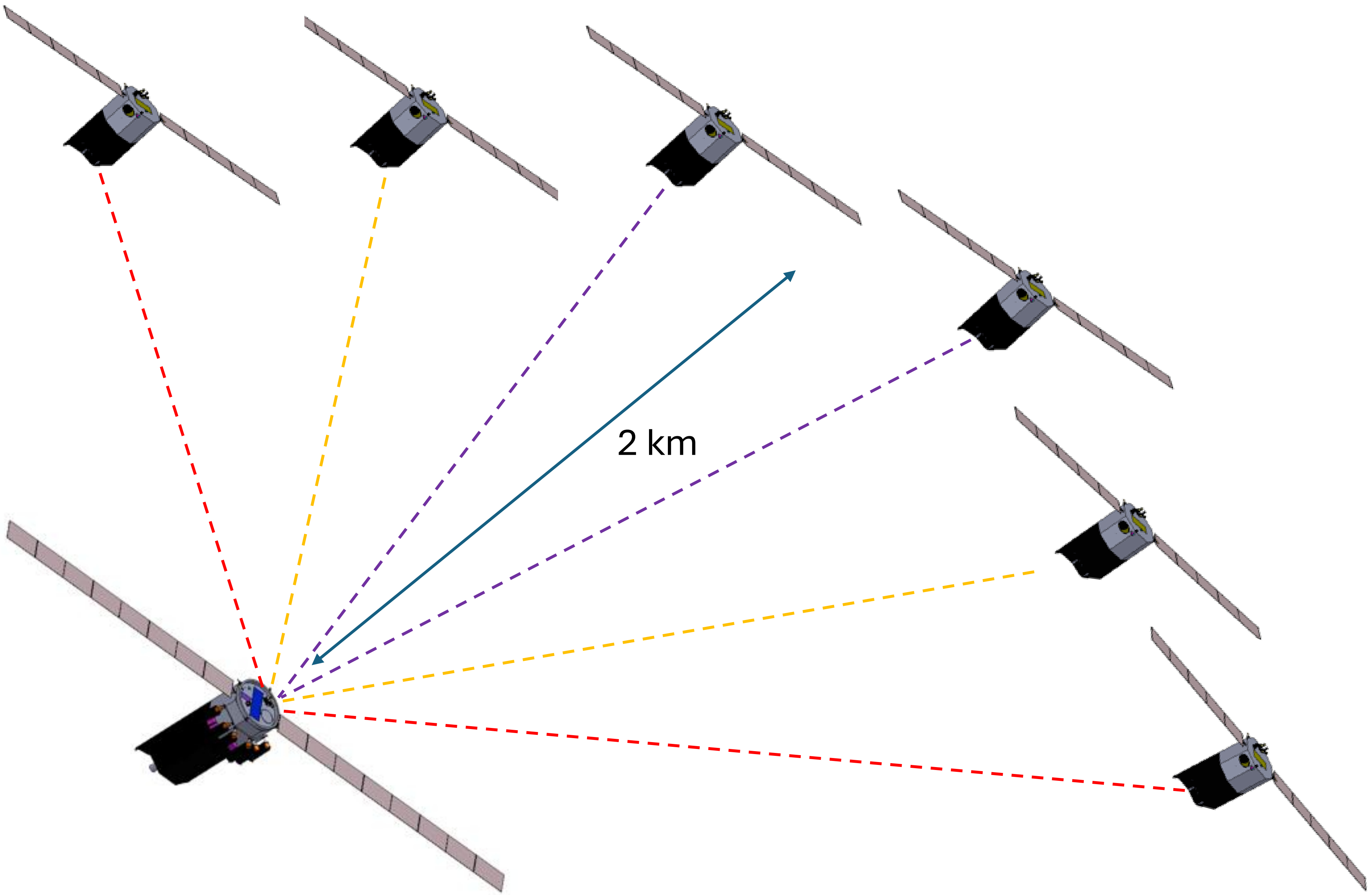
(PI: Weaver)

a plan to achieve micro-arcsecond (μas) resolution at X-ray energies

precision formation flying X-ray interferometer with a ~20 m to ~280 m baseline and 2 km “focal length”

FY25 Progress:

- preliminary satellite designs created for a complete mission architecture
- multiple X-ray finder telescopes required
- **formation flying problem solved for this architecture**
- L2 orbit
- total launch mass feasible, propulsion system trades, delta v estimates
- pointing knowledge requirements can be reached.
- observation exposure times: ~week+ (long stares required on target)
- LISA telescopes / lasers baselined on all satellites for 100 picometer stability


2 km

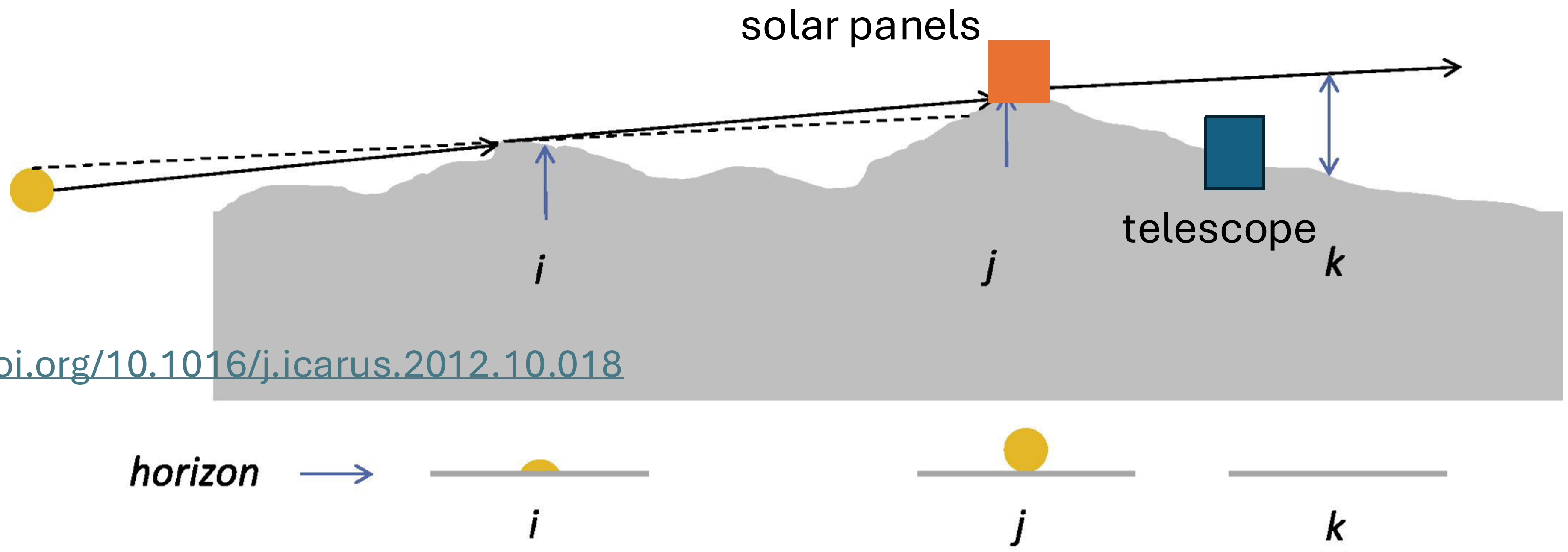
Lunar surface – milli-arcsec capability

- Can translate the mas telescope to the lunar surface.
- Would require installing the telescope and a pointing system.
- Likely will require more than one finder scope, to be able to lock onto the target and stare for several days.
- Could add more telescopes with time to increase sensitivity.
- The moon rotates at about 0.5 arcsecond per second near its equator. Targets would need to be stably tracked at speed.
- This argues for being closer to a lunar pole.
- Various options for pathfinders are likely available with more infusion into the technologies.

Panel Considerations

Does this science require a specific site, multiple sites, or can it be done anywhere on the lunar surface?

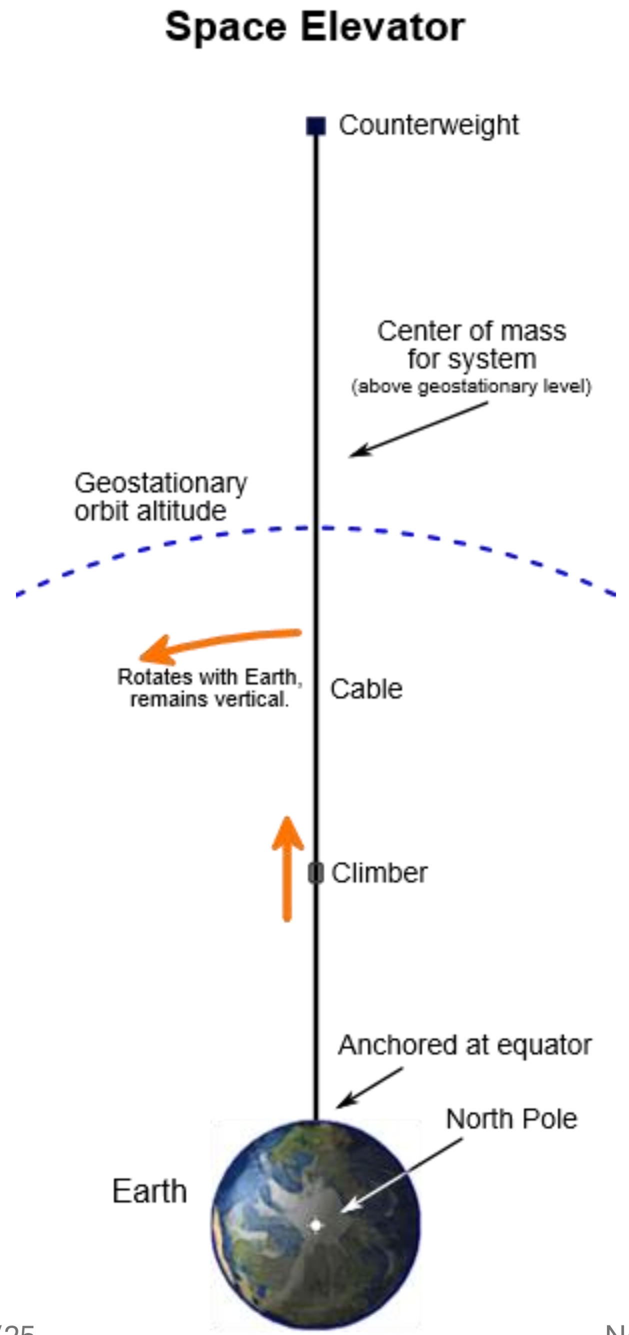
- No specific site. Holding steady on target within the moon's rotation and source inclination should be a significant consideration.
- Site should have access for some human / robotic assistance. If the observatory is powered by solar arrays and batteries, the ideal site would have the telescope (s) in shadow to avoid Sun exposure, solar arrays could be located on a nearby hill.

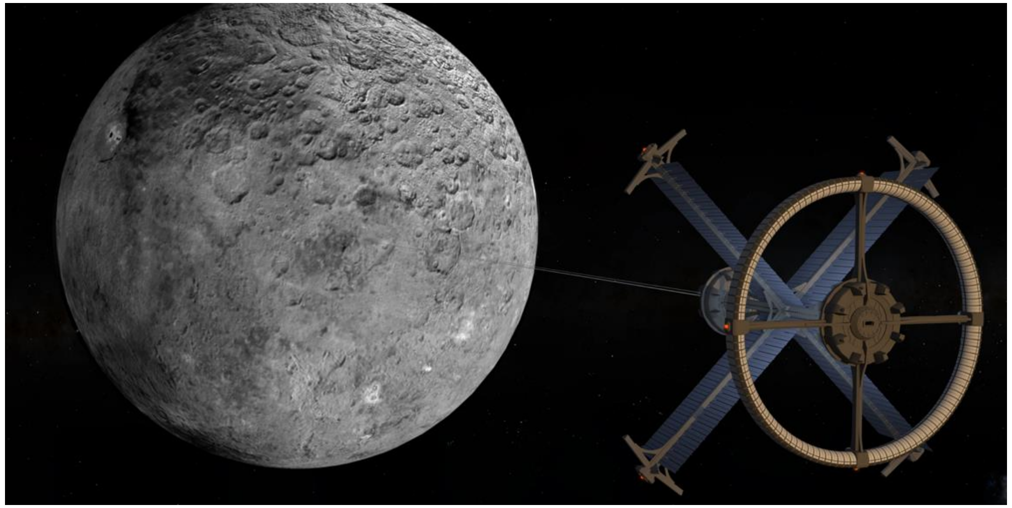


https://doi.org/10.1016/j.icarus.2012.10.018

Lunar surface micro-arcsecond capability

- Need stable km-length distances or longer.
- Science requires hard X-rays. At grazing incidence for flat mirrors this is not directly possible from an array on the lunar surface (although zone plates may offer a future solution).
- A soft X-ray interferometer built along the lunar surface is possible with multilayer technology allowing these photons to bounce at 45-degree angles.
- Possible to service the L2 free-flyer from lunar orbit. Due to the intricate formation flying operations and delta-v requirements, this design has a maximum two-year mission. If we can refuel regularly, we can extend this mission.
- NIAC concept is micro-arcsec pathfinder
- May be able to couple surface and space units (Dr. Gyula Greschik, private comm.)
- Translate to lunar surface by using a space elevator concept and placing the detector assembly on the surface and the collector satellites, tethered, in orbit.
- Derek J. Pearson (2022). "The Steep Climb to Low Earth Orbit: A History of the Space Elevator Community's Battle Against the Rocket Paradigm".





Ceres asteroid space elevator concept

- Anchor a satellite to a planet's surface and the satellite hovers above because the cable doesn't let it fly away, which it would otherwise.
- But the satellite must be over the equator above geostationary orbit, and at a high altitude.
- Problem is moon's rotation and large orbital velocities. Can't keep the satellites aligned with the hub.
- There may be variants of this idea to be studied.

By Skyway and User:Booyabazooka –
This is an improved diagram of a Space Elevator.
https://commons.wikimedia.org/w/index.php?curid=42947438

Panel Considerations

How can this science be accomplished on the Moon? Are there particular advantages to a non-polar lunar site?

- X-ray astronomy can be done from the lunar surface similarly to flying in space due to the lack of a significant atmosphere. Non-polar locations increase challenges of acquiring and holding targets compared to polar locations, depending on distance from the poles.

What measurements are needed to accomplish this objective?

- Discrete band passes including 6-7 keV X-ray band.
- Soft X-ray capability.
- Imaging down to at least milli-arcsecond scales
- Eventual micro-arcsecond imaging for critical back hole accretion and jet science.

Panel Considerations

What will the site, or site type, need to ensure that the science objective can be accomplished (e.g. radio quiet, geological properties, other)?

- Dark environment for telescope. Little scattered light or other reflections.

Is there a pathfinder to advance the scientific objective?

- Optics technology is being developed.
- A pathfinder free-flying mission is being studied.
- Could have a pathfinder for lunar to demonstrate the basic technology and performance.

How does a human onsite enable or improve the quality of the measurement(s)? (e.g., Judgement? Reaction? Adaptability?)

- Human interaction is important to test and operate the system if we build some on site.
- Proper alignment of optics is crucial. If we perform alignment and testing on the surface, human judgement and reaction is critical for proper optics alignment for fringes.

Are new capabilities and/or pre-placed assets necessary to ensure the human can do the measurement or collect the sample? If so, what?

- Requires a long term or permanent observing platform.