Resolving sites of particle acceleration with next-generation high-resolution hard X-ray observatories

Chien-Ting Chen (USRA/MSFC)

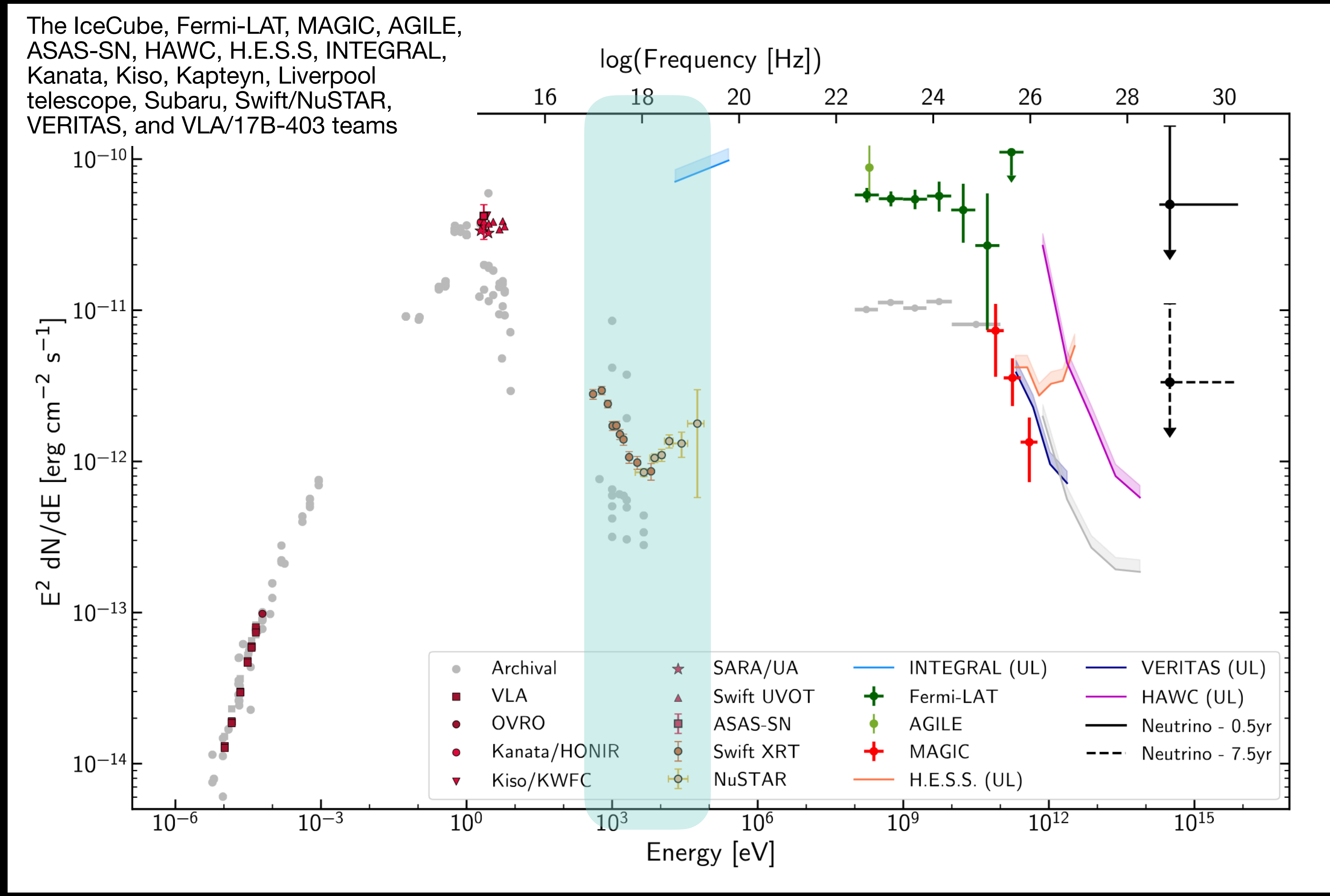
HEROIX - High EneRgy Observatory for Imaging X-rays

A concept of a high angular resolution hard X-ray MidEX mission

Chien-Ting Chen (USRA/NASA MSFC), on behalf of the HEROIX team

“High EneRgy” Observatory for Imaging X-rays

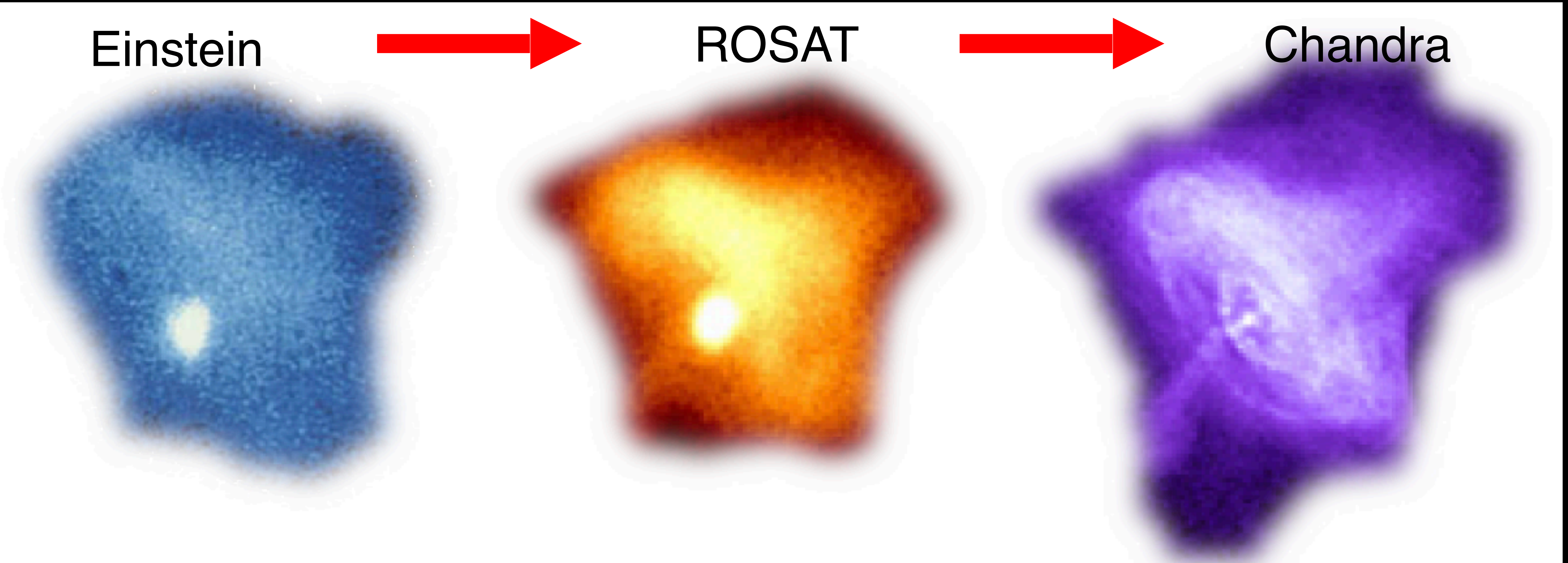
> 10 keV is considered “hard” and high energy for the X-ray community



- X-ray probes the regions where extreme physics dominates, such as accreting black holes, neutron stars, jets, and shock waves.
- X-ray provides key spatial information for extreme events with grazing-incidence angle optics (resolving structures as well as localization for multi-messenger analysis)
- X-ray is useful for studying in-situ particle cooling for its lower optical depth and versatility for probing both leptonic and hadronic dominated processes

High EneRgy Observatory for Imaging X-rays

- Hard X-ray probes photons generated by physical processes in extreme astrophysical environments, from accreting of stellar mass compact objects to shock waves and jets in galaxy clusters
- NuSTAR pioneered this field as the first focusing hard X-ray mission in orbit, albeit limited by its ~arcmin half power diameter
- An order-of-magnitude improvement in angular resolution will lead to exciting discoveries



HEROIX baseline mission

- 5 arcsec half-power-diameter
- 380 cm^2 @30keV effective area
- 12-arcmin FoV
- 30 shells per mirror module, with 4 mirror modules
- 2 to 80 keV bandpass via multilayer coatings
- 12-meter focal length
- Pixelated detectors with ~200 micron detector pitch, well-matched with the HPD
- Energy resolution 0.8 keV @ 60 keV, comparable with NuSTAR
- MSFC-led, PI: Nicholas Thomas, PS: CTC

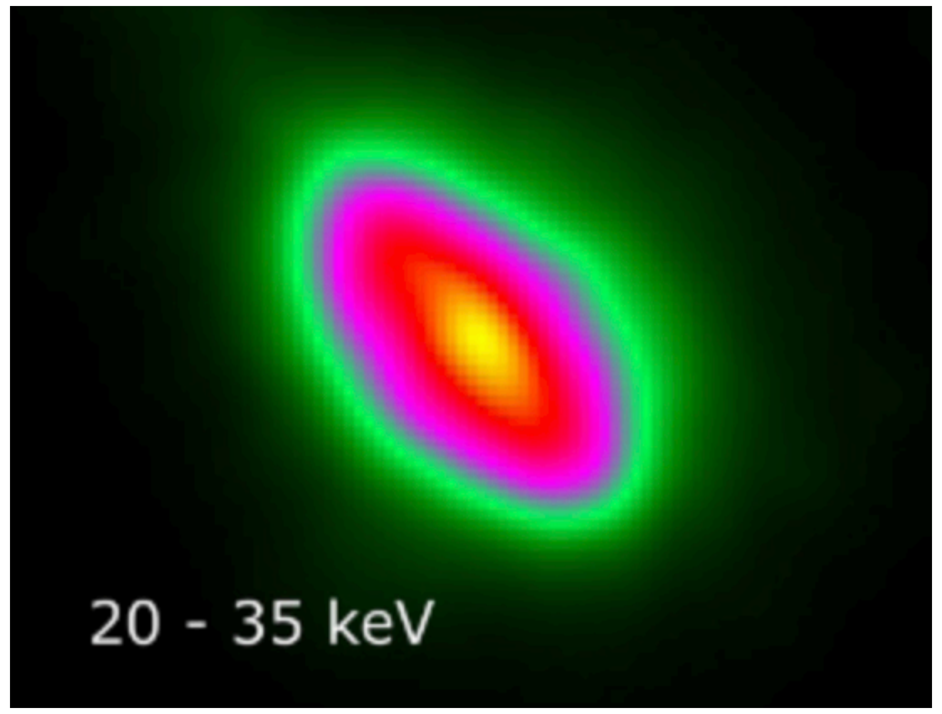
Baseline design can be tweaked based on scientific requirements

Secondary instrument can also be an option

SuperHERO Balloon mission

- PI: N. Thomas; PS: C. Chen. Optics Leads: S. Bongiorno (Alignment and Mounting), S. P. Panini (Design), D. Gurgew (Coating)
- Successor to the successful HERO/ HEROES missions
- Incorporates cutting-edge MSFC's NiCo shell x-ray optics
- Takes advantage of proven technologies from collaborating institutions (WashU, UNH, WFF, Kavli IPMU, & iMAGINE-X)
- Inaugural flight on 2028, with 7 MMA and two shells per MMA, primary science goal is to resolve the Crab nebula in 20-40 keV
- Future long-duration flights for surveying Galactic Center is under consideration

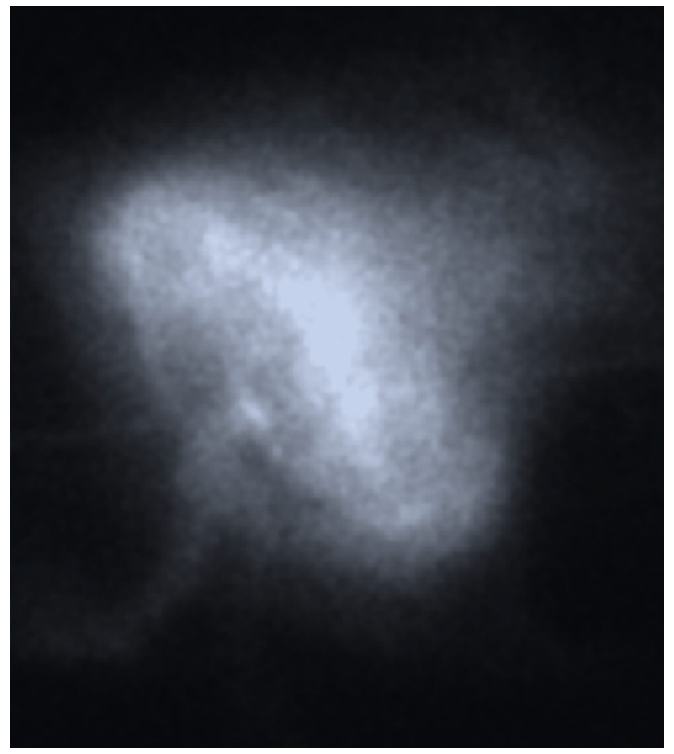
60 arcsec
State-of-art



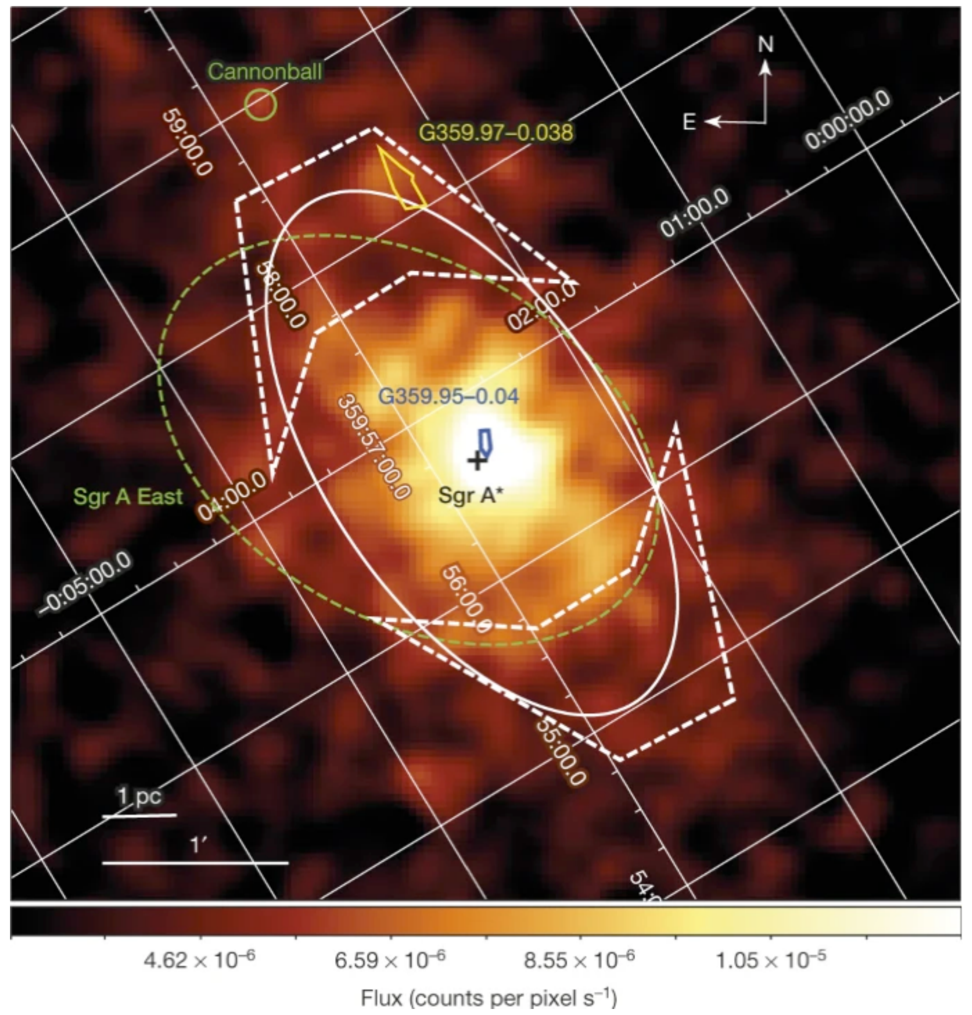
Harrison et al. 2013, Madsen et al. 2015

The Crab Nebula

10 arcsec
Future-mission

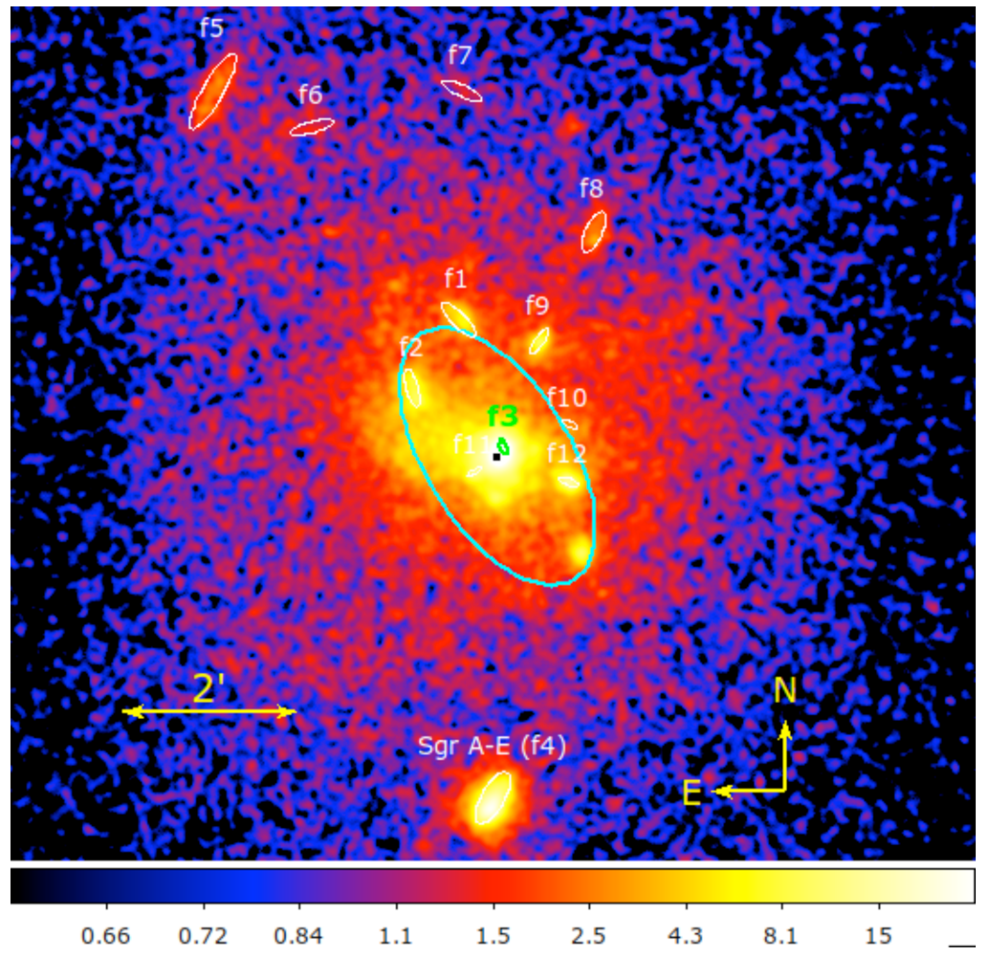


Projected by Chien-Ting Chen Chandra Data
Mori et al. 2002, Weisskopf et al. 2012



Perez et al. 2015

Sgr* Complex

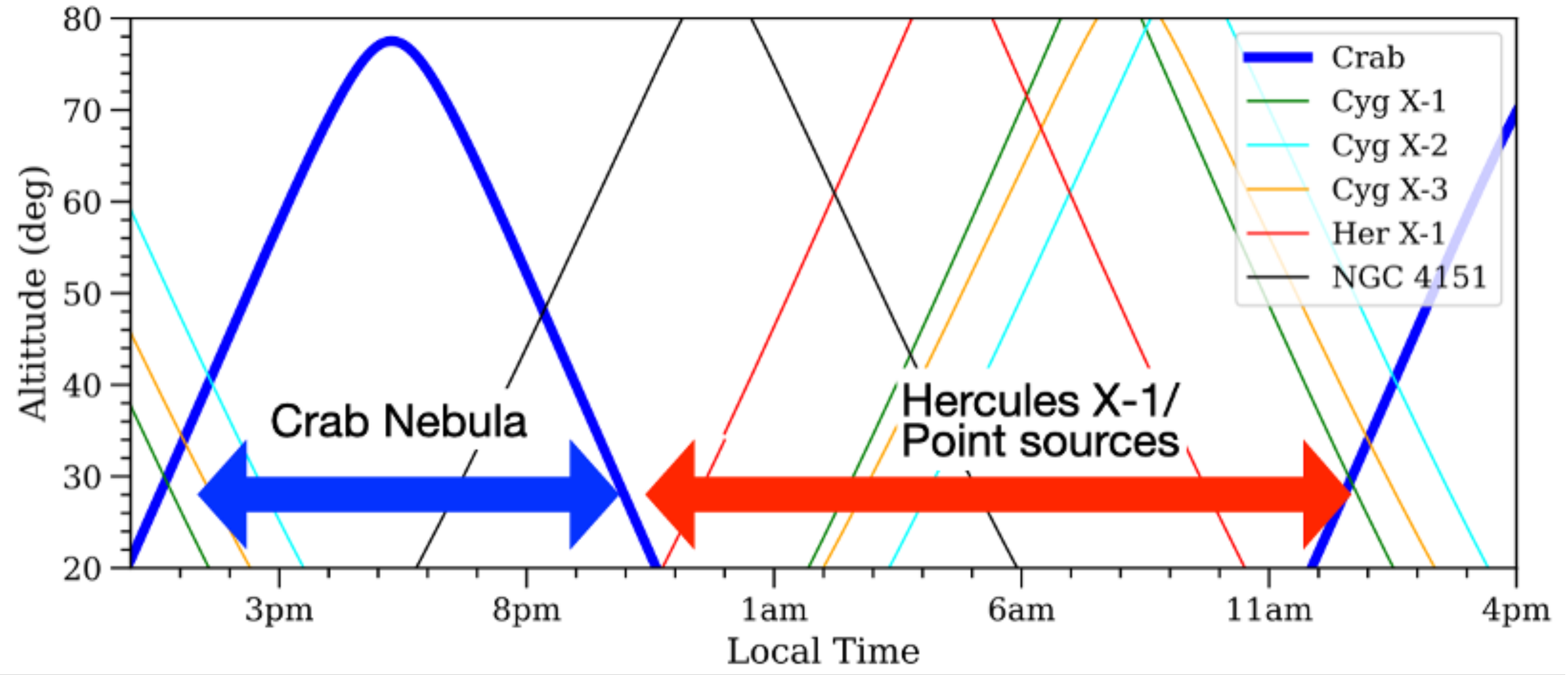


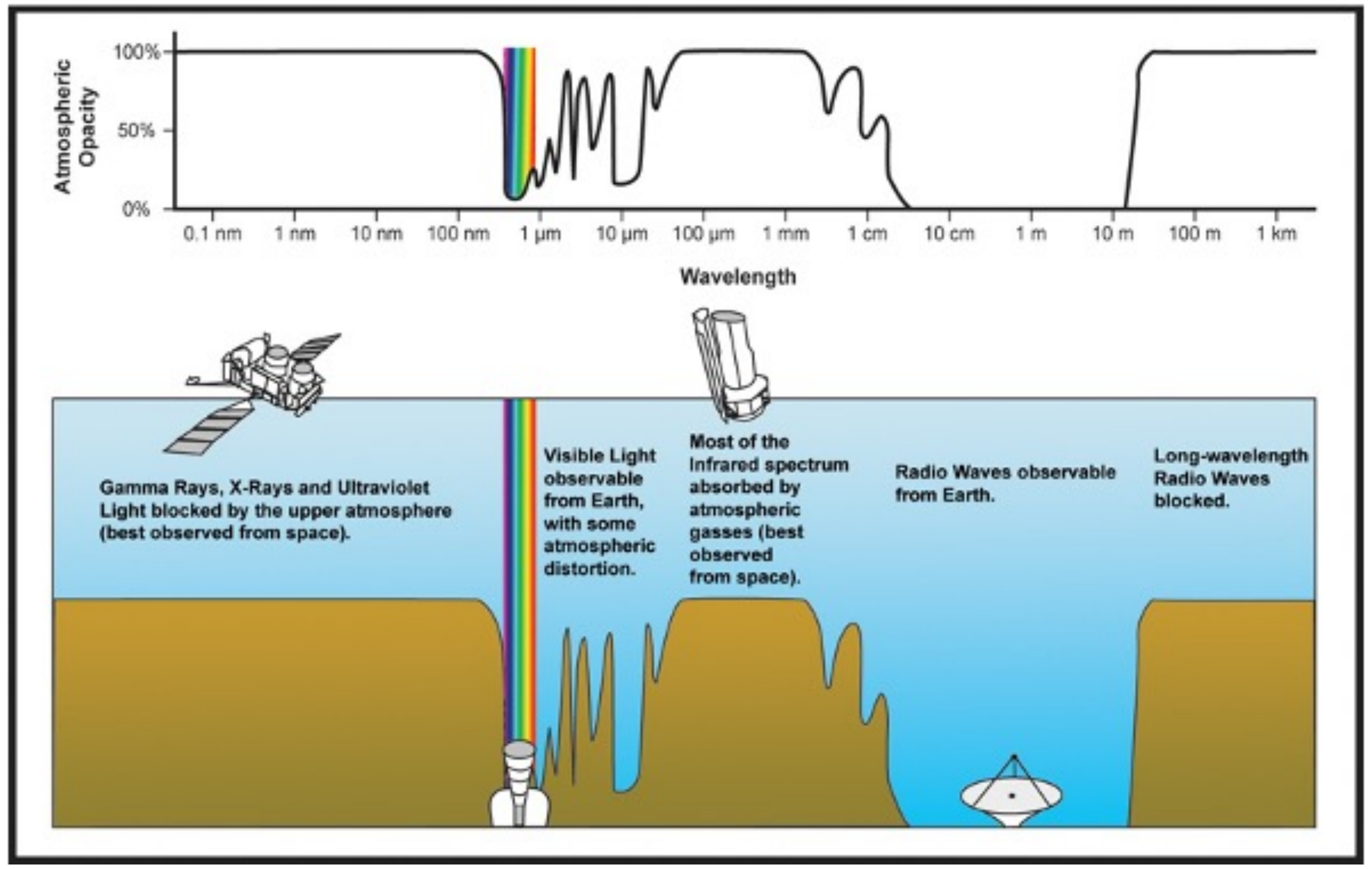
Mori et al. 2023

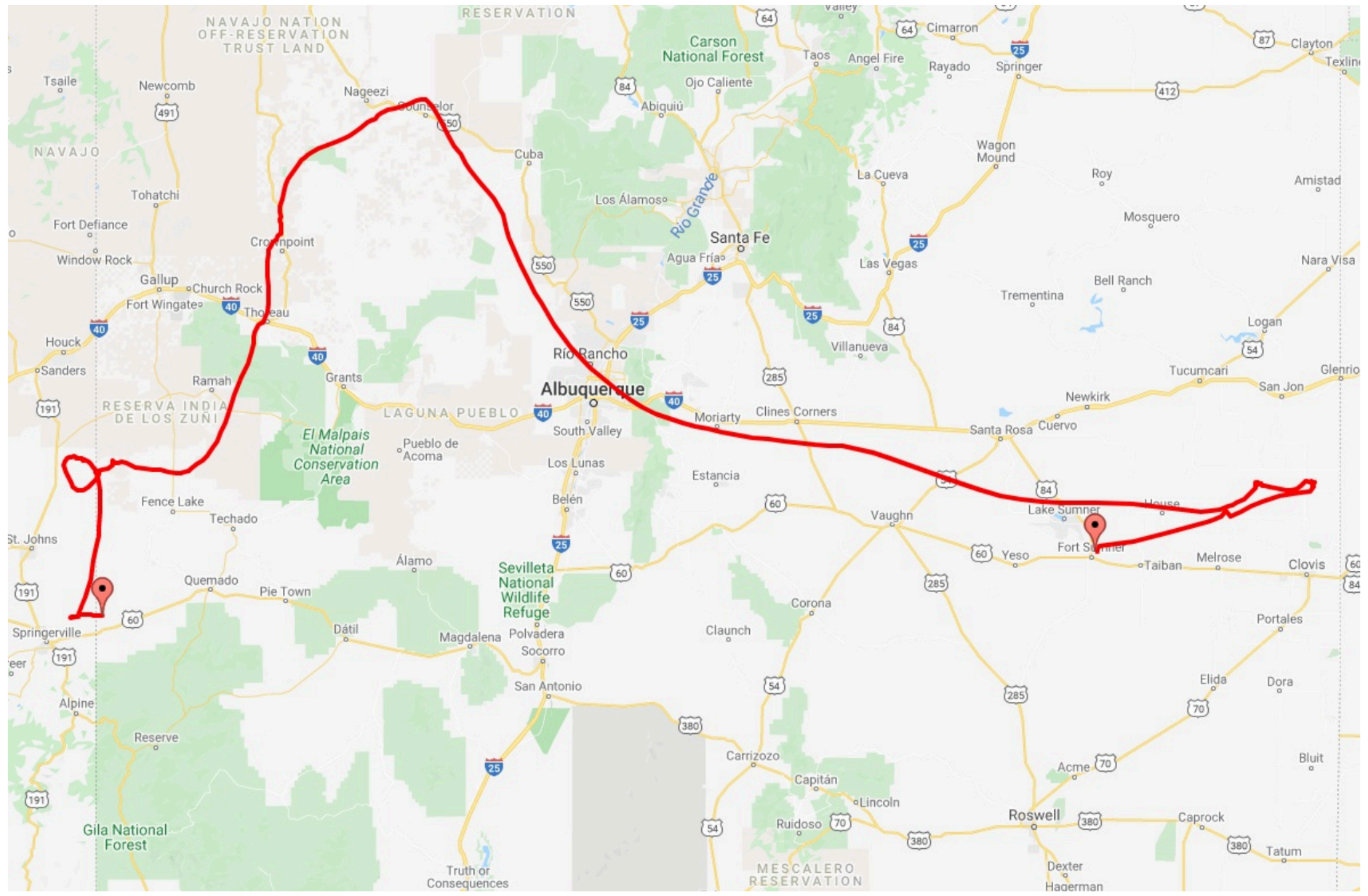
SuperHERO first flight in September, 2028

Turnaround flight, Fort Sumner

- Nominally planned for 8 hours
- Crab Nebular — point-source (4U 0614+091) — Crab Nebular — point-source (Her X1) — more Crab or point source observations (weather permitting)



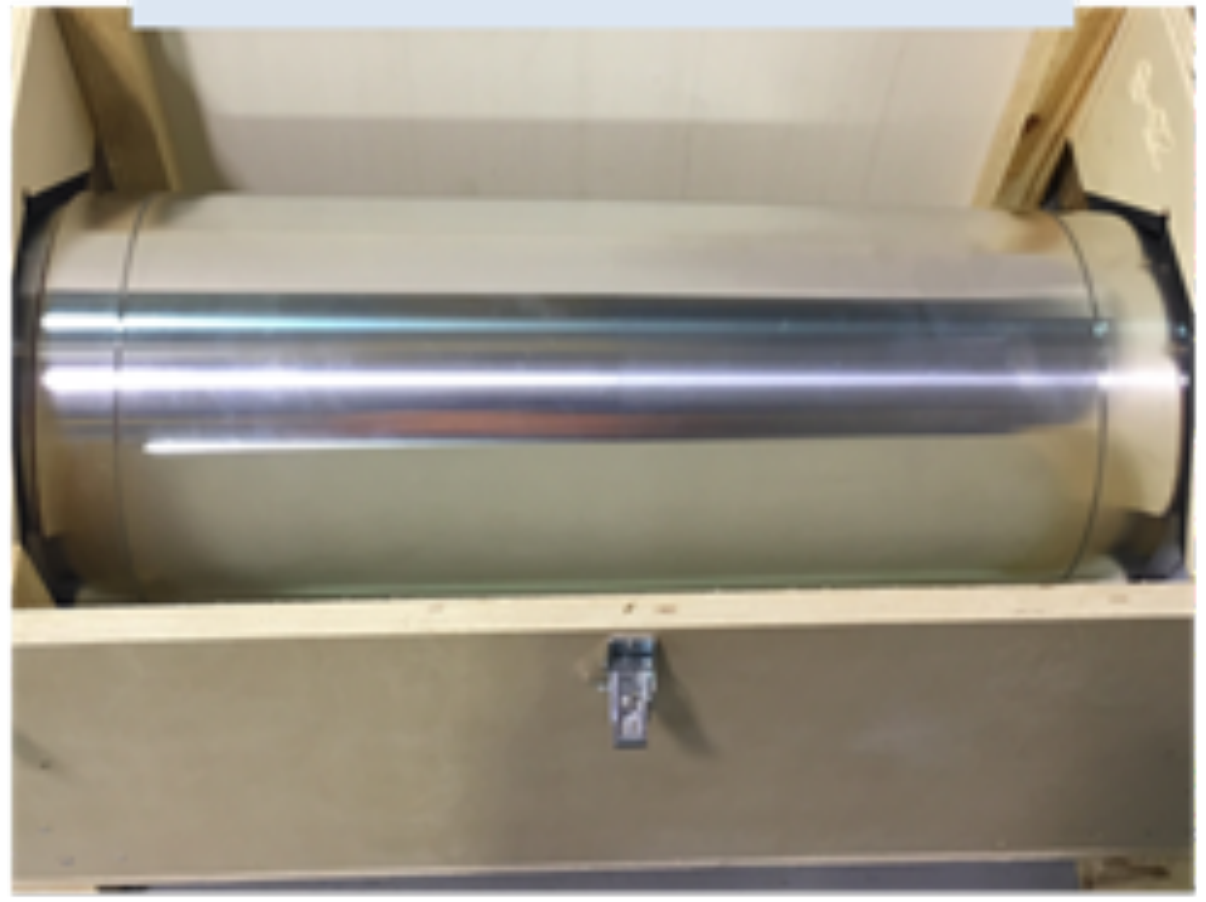




Balloon launched on: **9/17/2016 at 13:28 utc**
Launch site: **Scientific Flight Balloon Facility, Fort Sumner, (NM), US**
Balloon launched by: **Columbia Scientific Balloon Facility (CSBF)**
Balloon manufacturer/size/composition: **Zero Pressure Balloon Raven Aerostar - W39.57 (39.500.000 cuft)**
Flight identification number: **671N**
End of flight *(L for landing time, W for last contact, otherwise termination time)*: **9/18/2016 at 17:03 utc**
Balloon flight duration *(F: time at float only, otherwise total flight time in d:days / h:hours or m:minutes -)*: **28 h 15 m**
Landing site: **W of Red Hill, New Mexico, US**

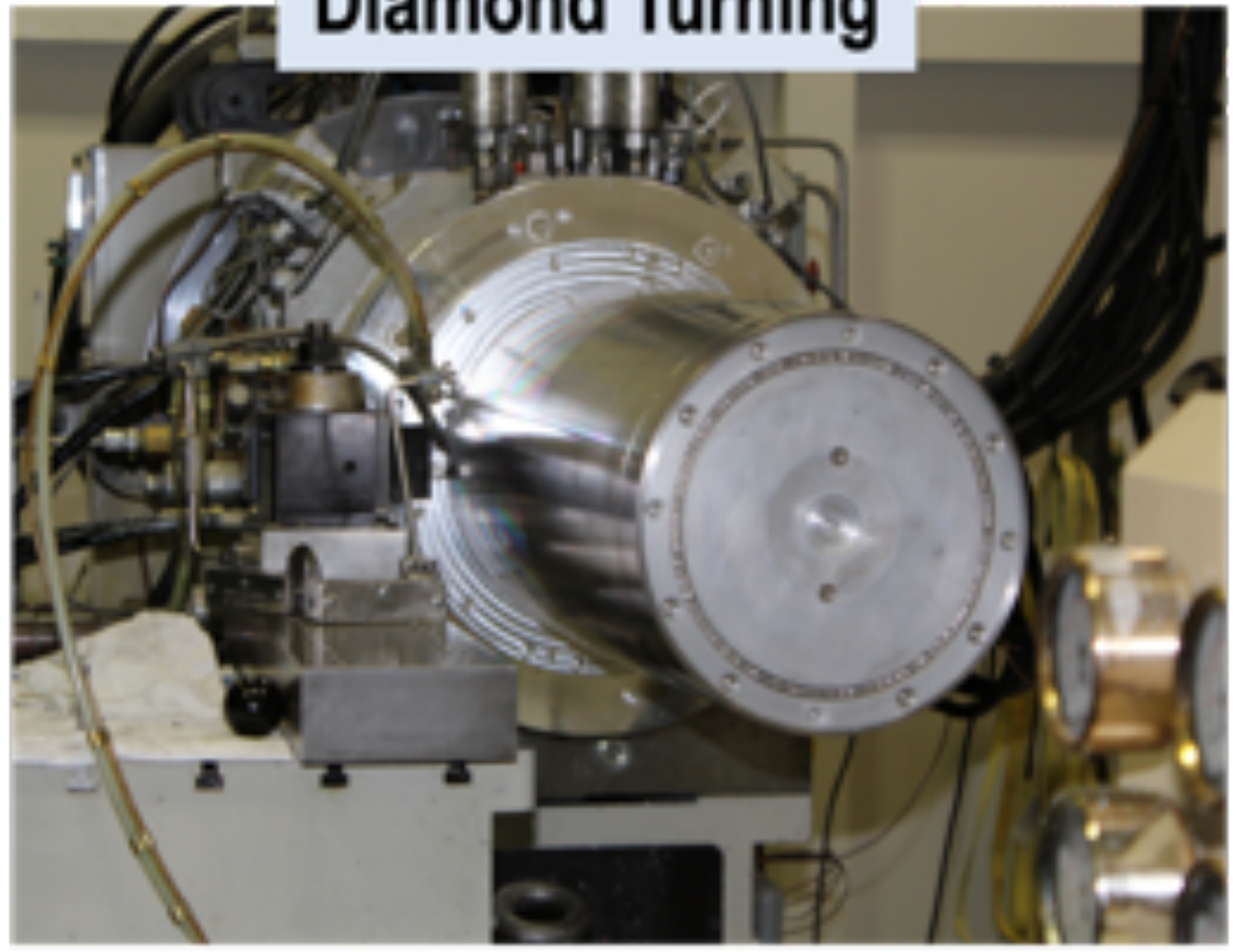
Electroformed Nickel-Cobalt Replicated Optics
Full Shell X-ray Optics

Aluminum Mandrel Blank



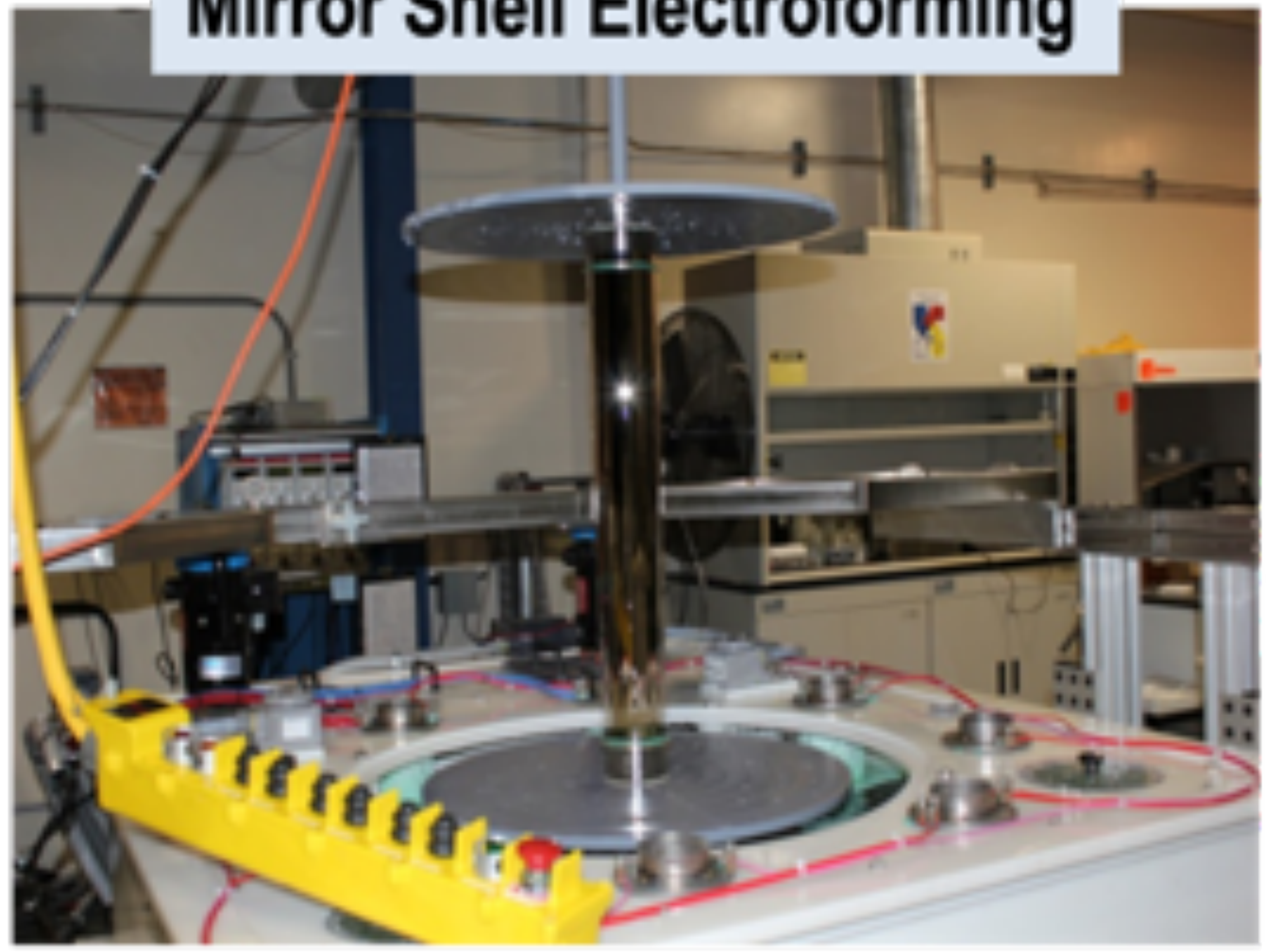
EN Plating

Diamond Turning

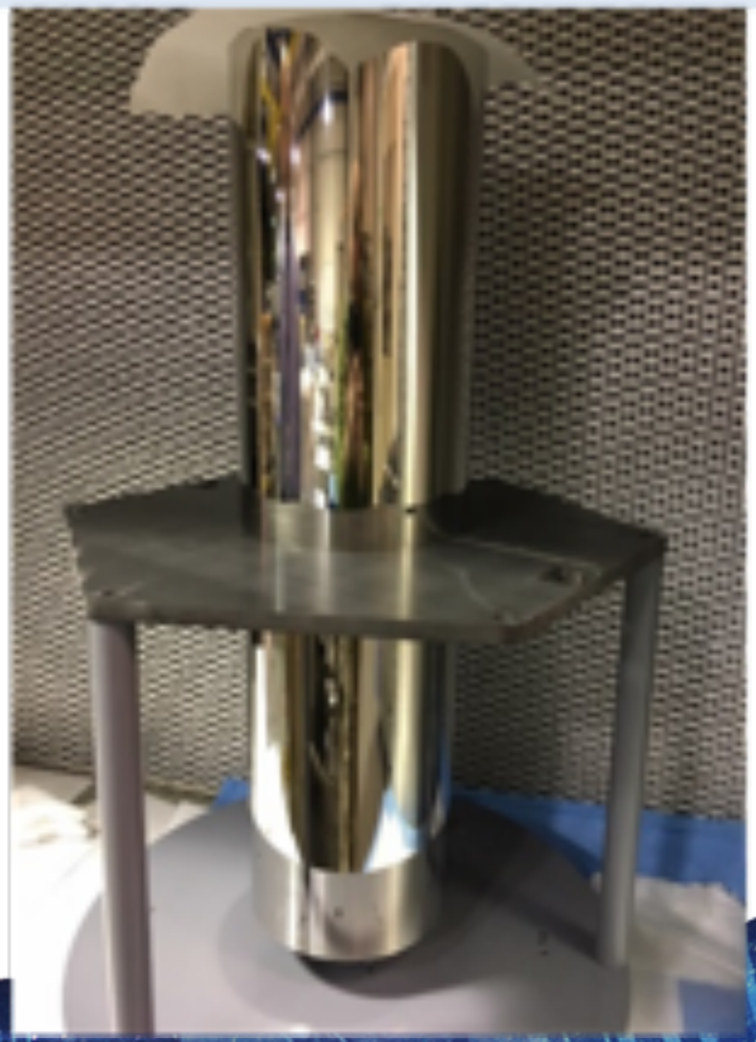


Mandrel Polishing

Mirror Shell Electroforming

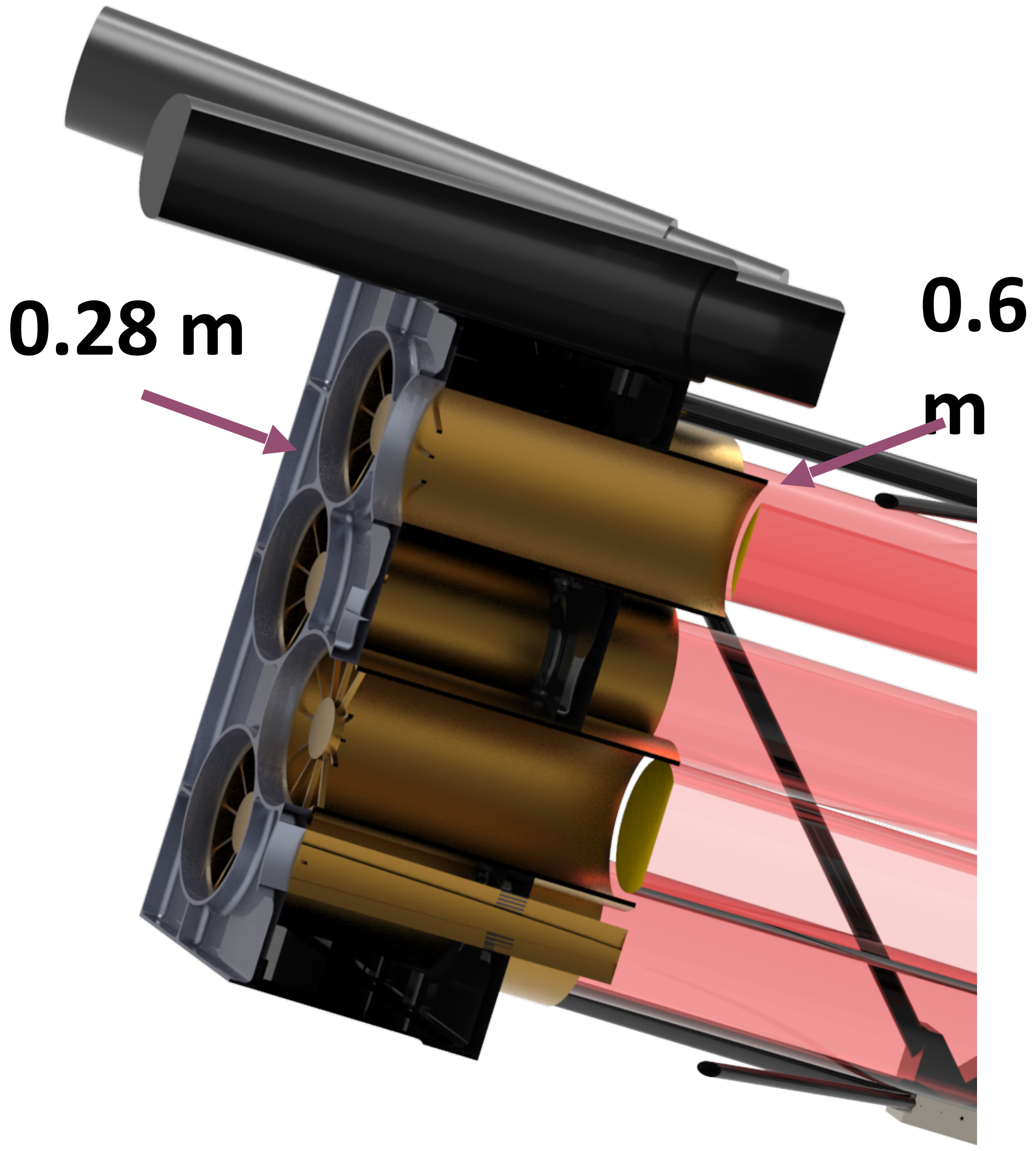


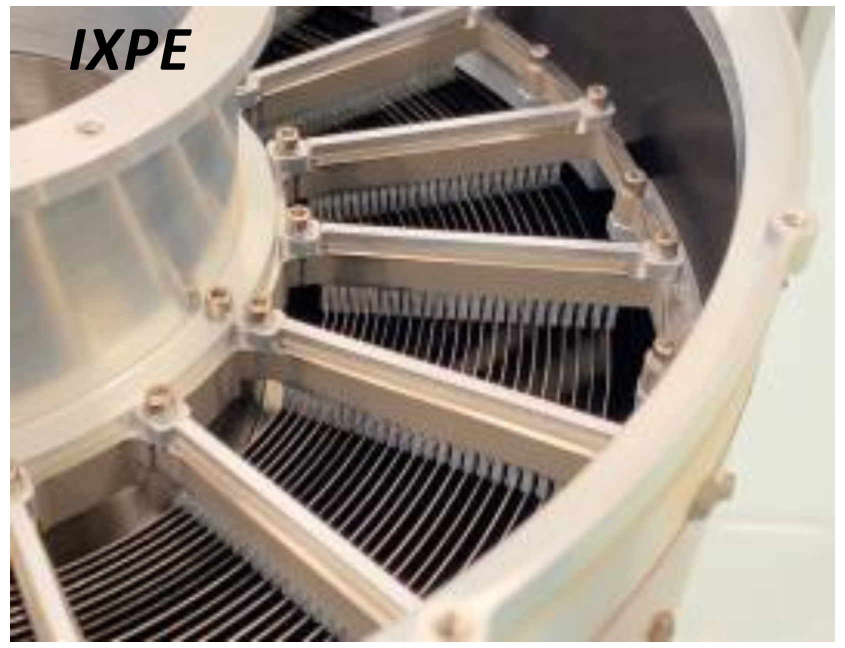
Mirror Shell After Separation

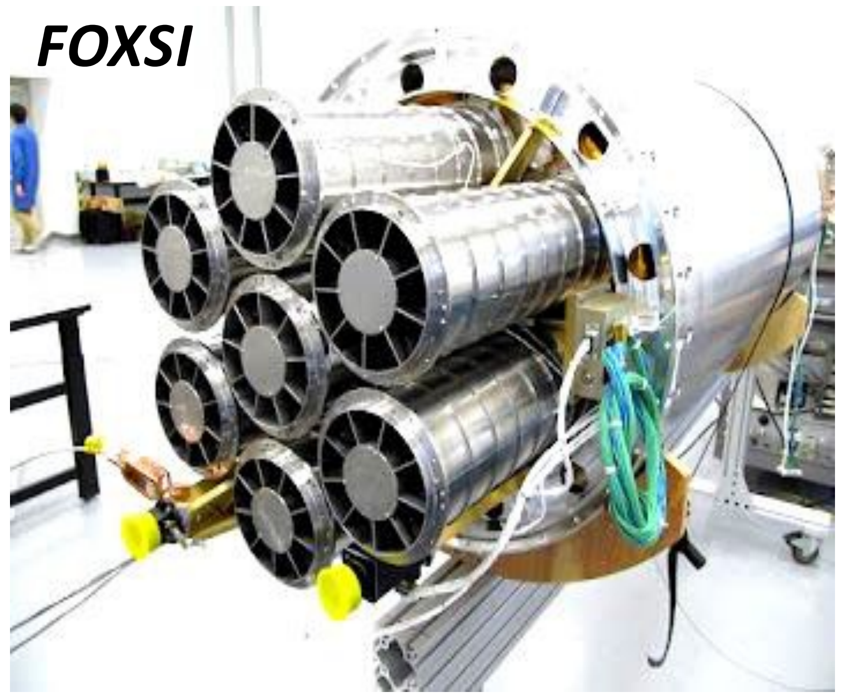


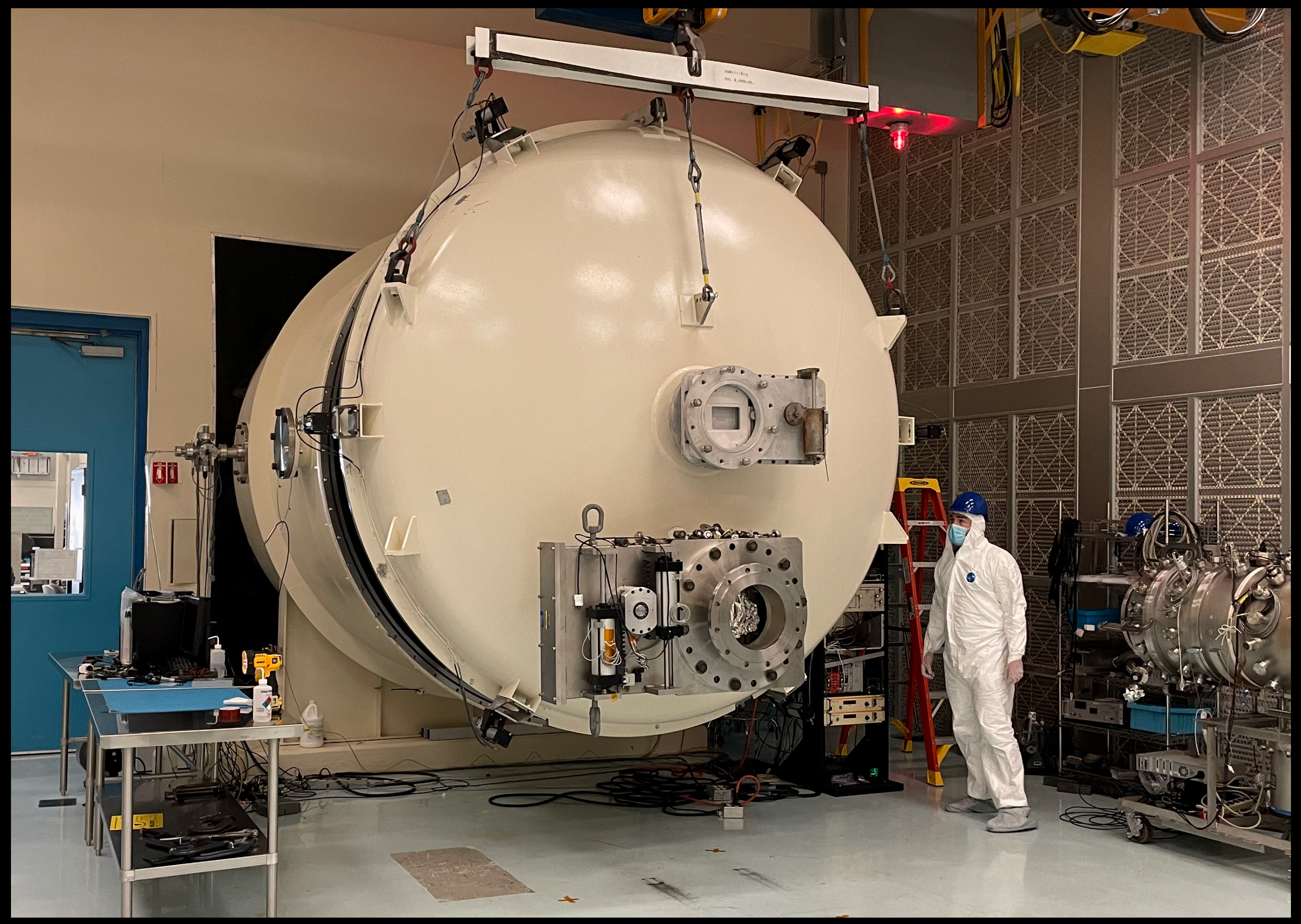
SuperHERO Mirror Module Assembly(MMA)

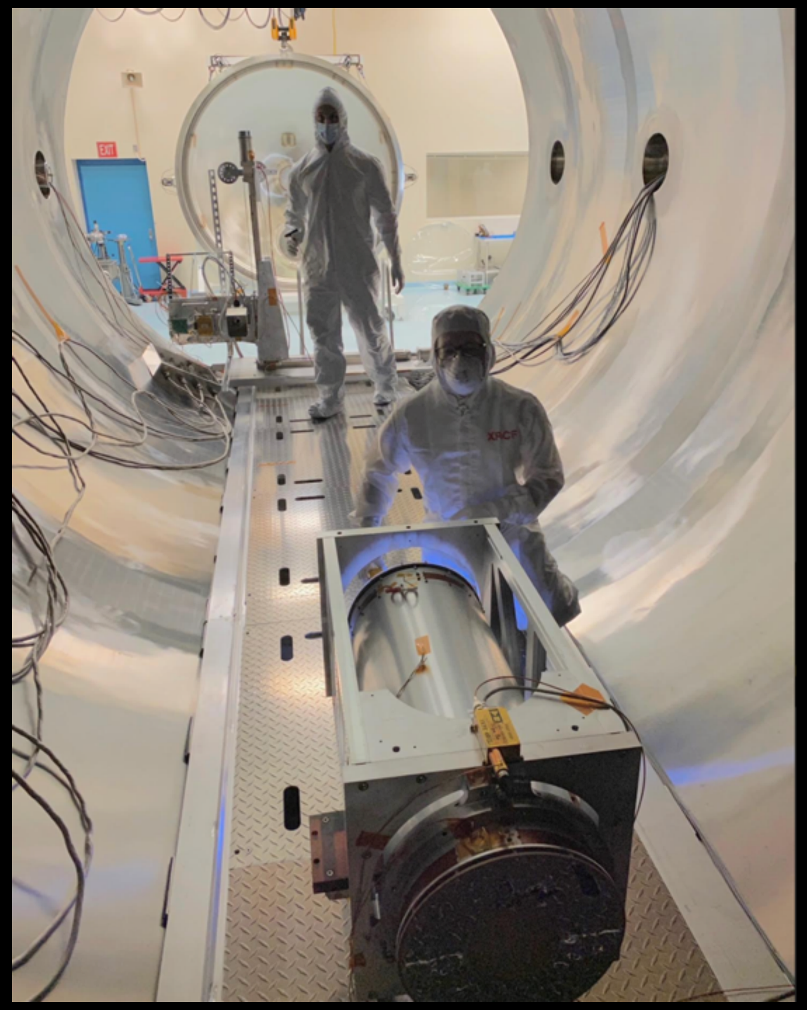
- Seven MMAs, requiring two super polished mandrels to produce two shells per MMA.
- MMAs to be enhanced for future missions.
- Calibration at Marshall 100-meter X-ray Beamline.





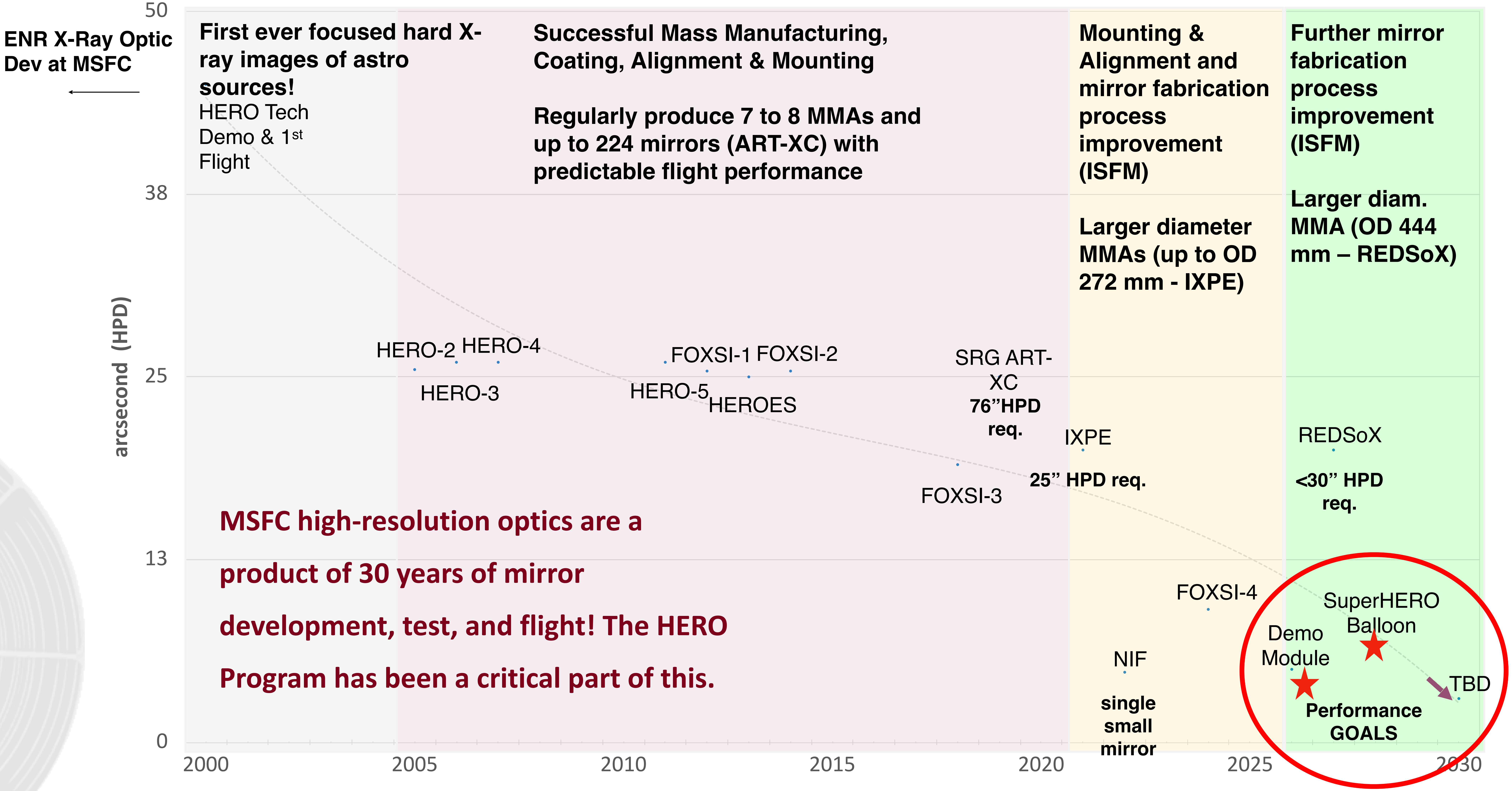






Marshall 100-m X-ray Beamline

MSFC X-Ray Mirror Module Performance



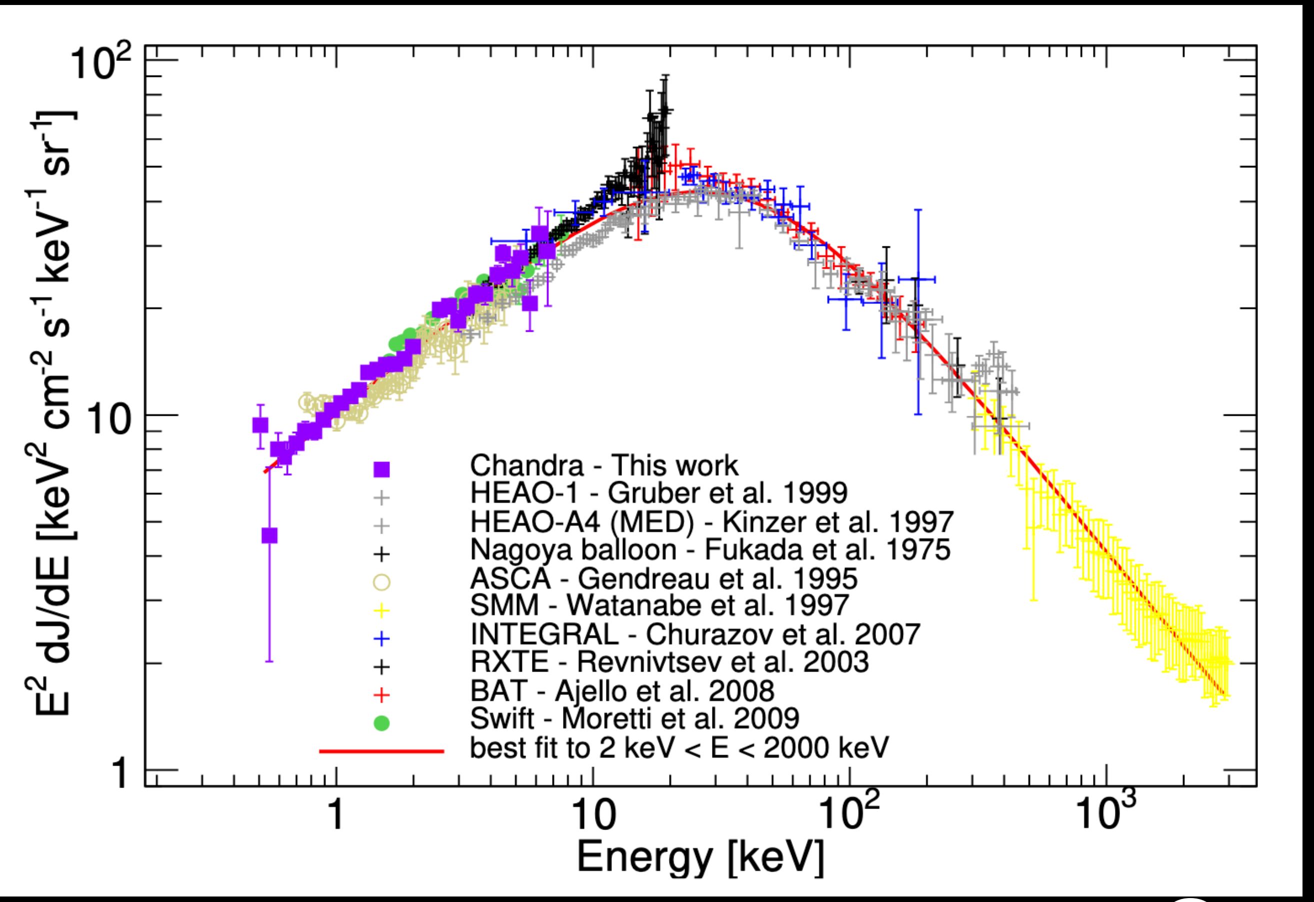
*All values are for Mirror Module Assemblies (MMAs), with the exception of the NIF optic.
*All values reflect X-ray test measurements or in-flight performance. Not all values are gravity subtracted.

HEROIX MidEx concept

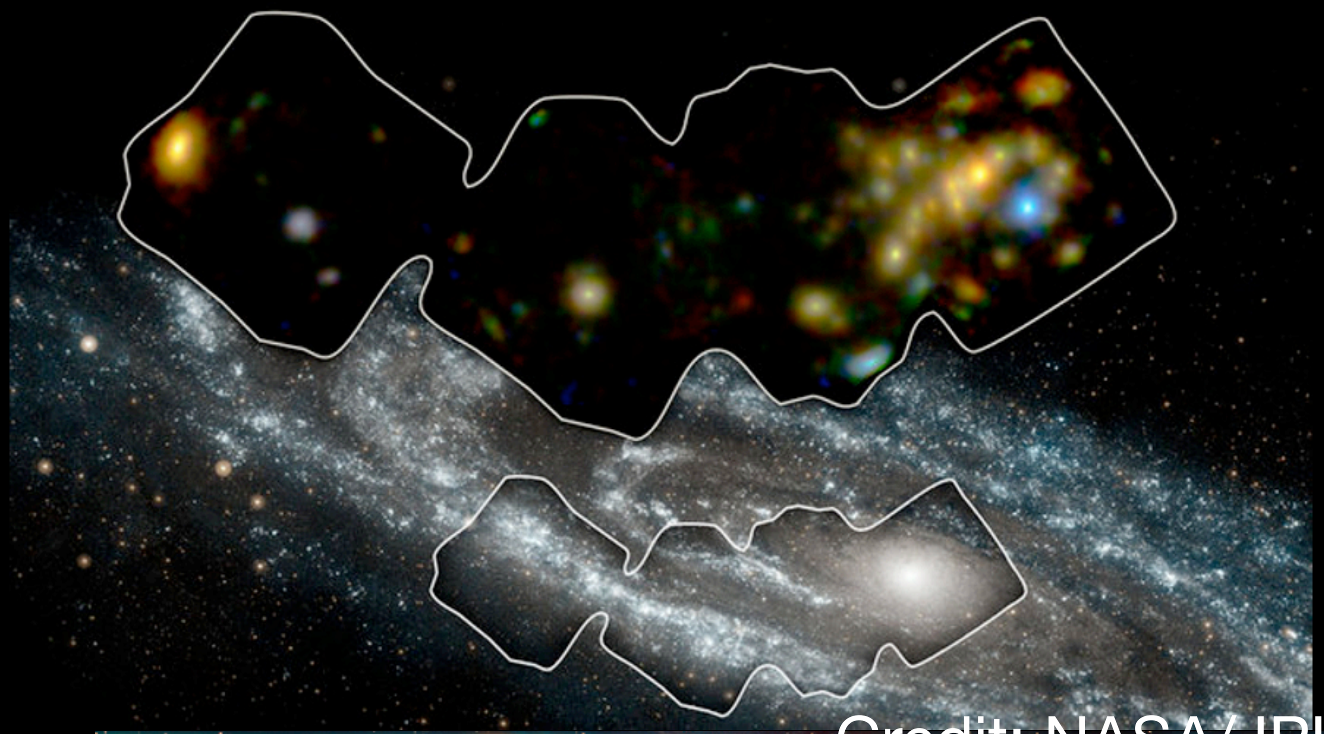
- A next-generation hard X-ray observatory with 5 arcsec resolution in ~2-80 keV
  - Resolving the Cosmic X-ray Background at its peak of ~30 keV
  - Understanding the dust-enshrouded X-ray population, including X-ray binaries and AGN
  - **Particle acceleration in extreme environments such as shock waves, jets, coronae from celestial objects of all sizes**
  - Accretion physics with broad-band X-ray spectroscopy
  - Additional science cases

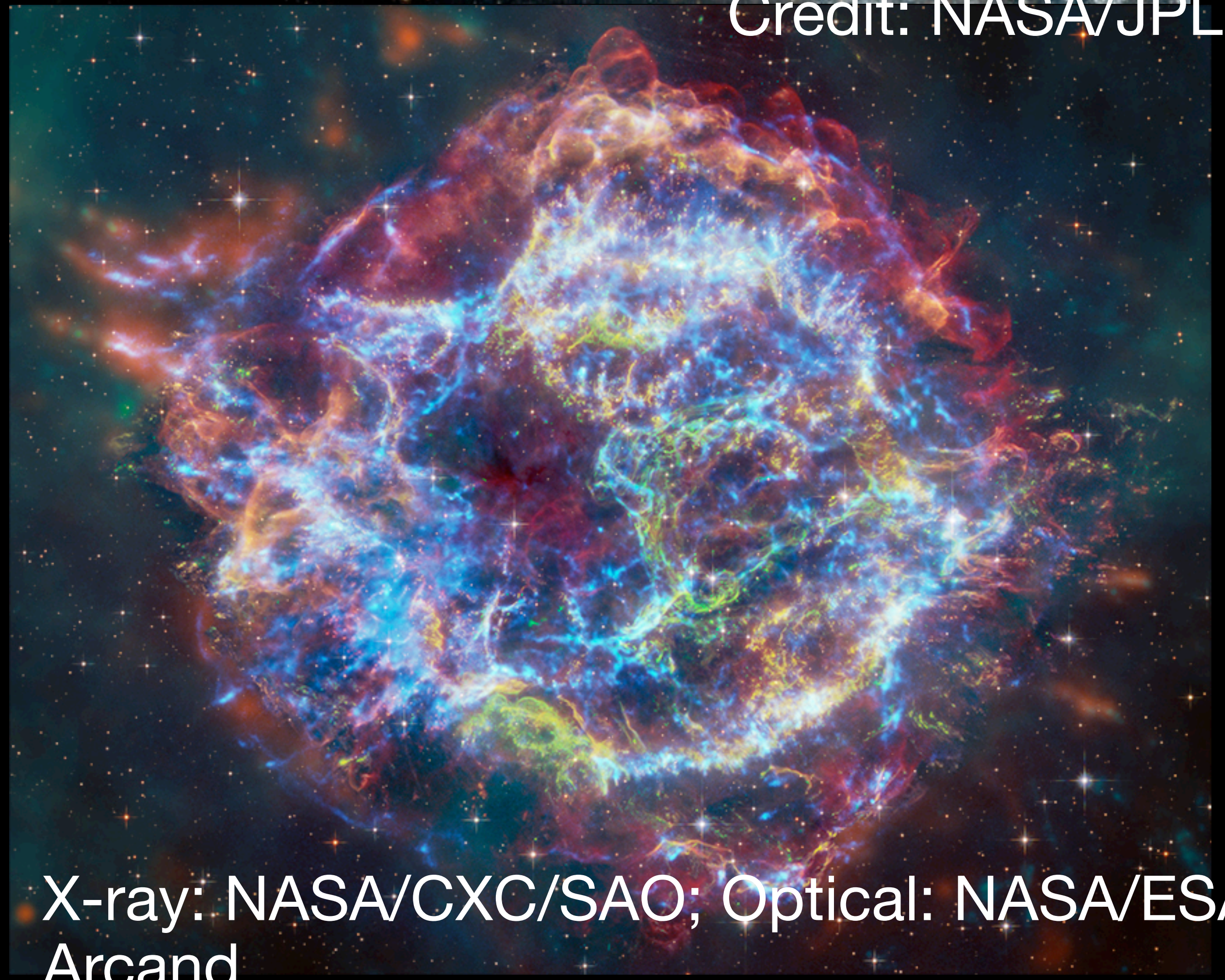
Astro2020: Drivers of galaxy growth

Astro2020: New windows on the dynamic universe



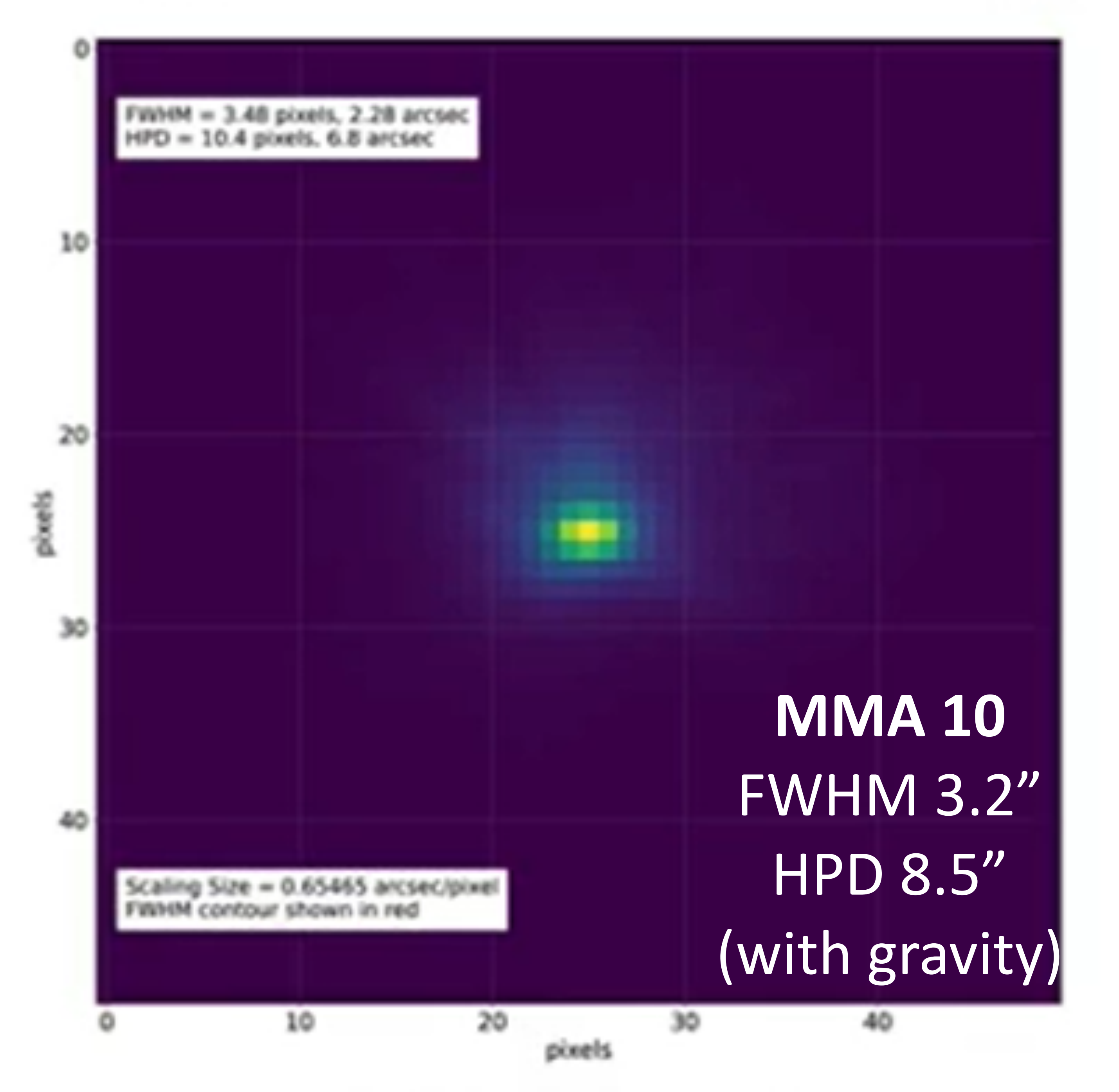
Capelluti+17


Credit: NASA/JPL-Caltech/GSFC


X-ray: NASA/CXC/SAO; Optical: NASA/ESA/STScI; IR: NAS
Arcand

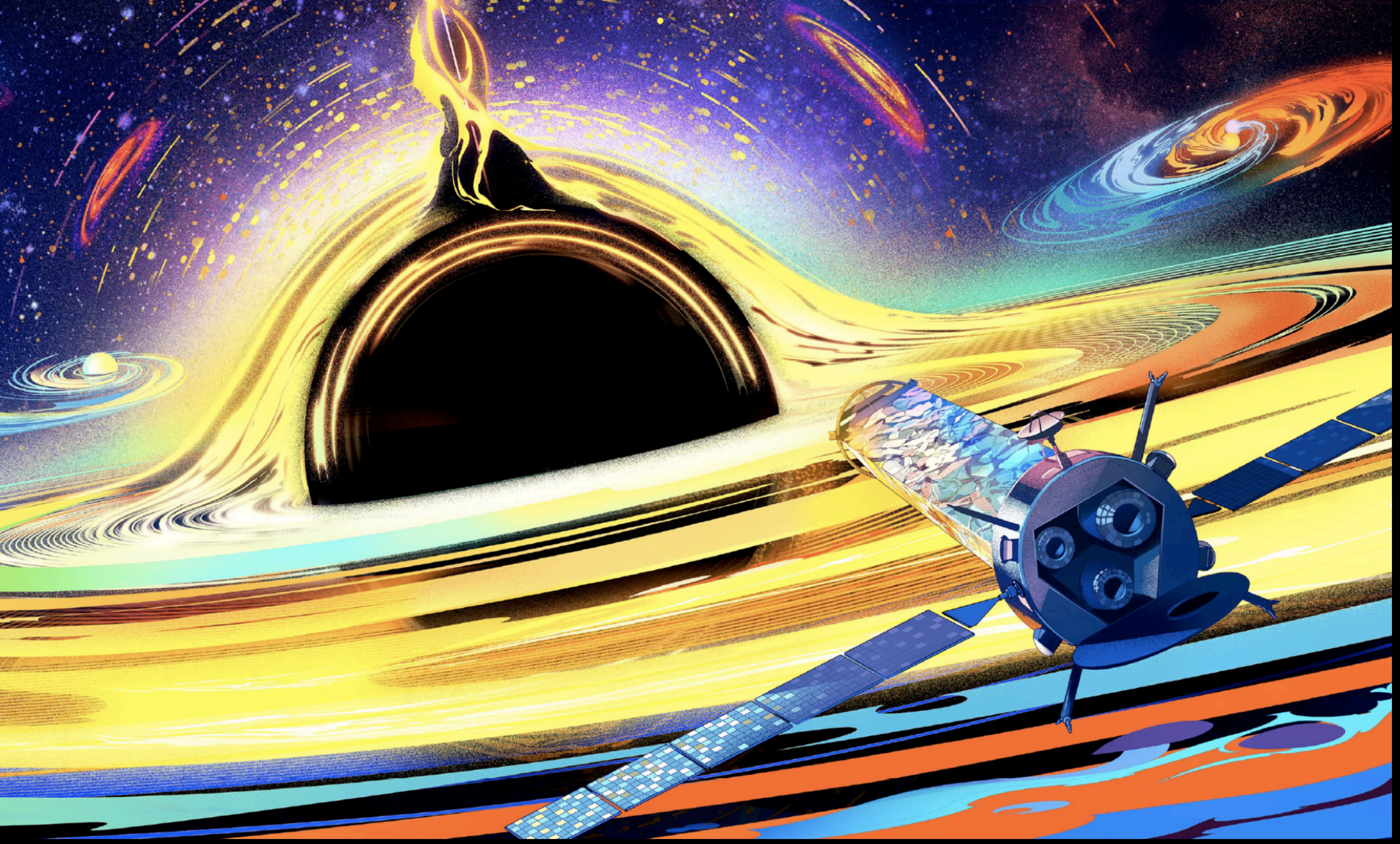
MSFC’s readiness for HEROIX

- MSFC's manufactured FOXSI-4 mirror module achieved better than 10 arcsec HPD during beamline calibration.
- SuperHERO (APRA, < $10M) technical goal is to demonstrate better than 10 arcsec HPD integrated for the entire observatory during its inaugural flight in the fall of 2028, while mitigating the combined effects of gravity induced error and the thermal environment encountered in stratospheric balloon flight.
- In parallel, the MSFC team is developing a dedicated high-resolution optics demonstrator module which aims to achieve 5 arcsec HPD (with gravity subtraction) in a X-ray beamline by late 2027.
- HEROIX manufacturing requirements are similar to IXPE and SuperHERO, requiring the use of existing MSFC hardware and capabilities.



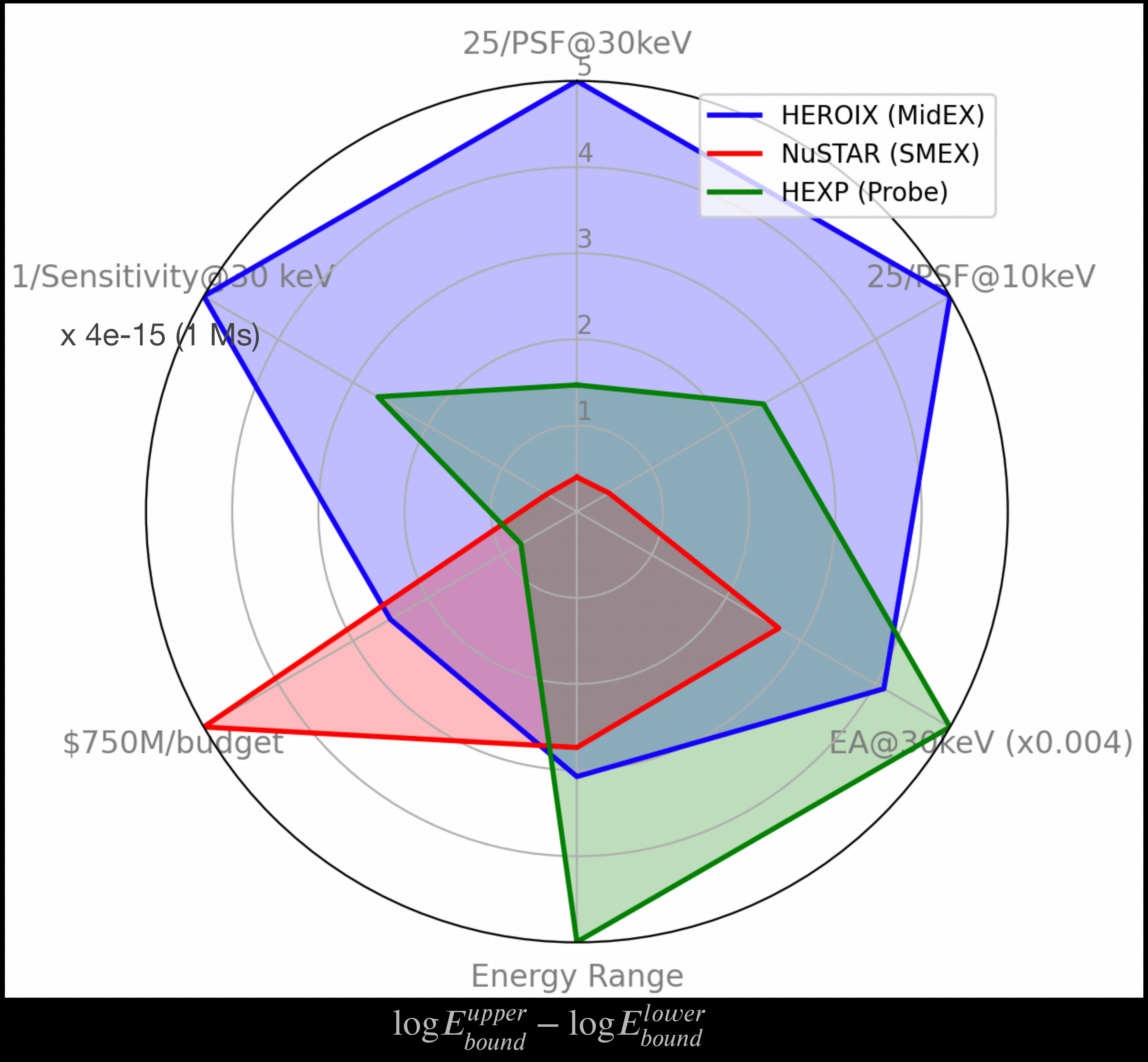
Wayne H. Baumgartner, Stephen Bongiorno, Jeffery Kolodziejczak, Srikanth Singam, Danielle Gurgew, Chet Speegle, David Banks, Patrick Champey, Nicholas Thomas, C. Grant Davis, "High resolution full shell replicated x-ray optics for FOXSI-4," Proc. SPIE 12679, Optics for EUV, X-Ray, and Gamma-Ray Astronomy XI, 126790C (6 October 2023); https://doi.org/10.1117/12.2680486

HEROIX ≠ HEX-P Light



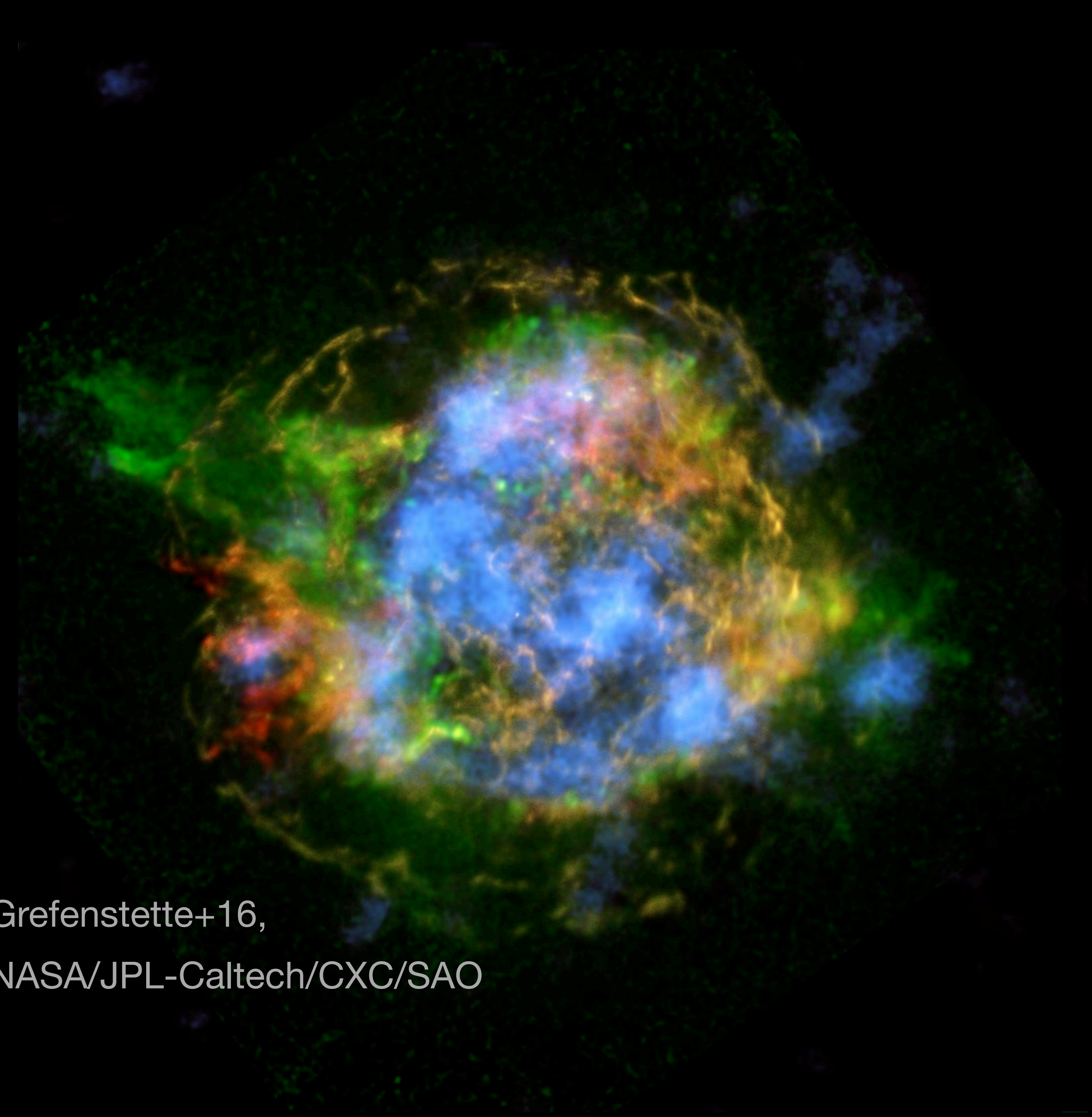
- HEX-P was a JPL-led probe concept in response to the 2023 Astrophysical Probe Explore call
- There were a total of four X-ray probe concepts, only AXIS was selected
- HEX-P emphasized on broad-band, large effective area capability with decent angular resolution in the soft X-rays (~3 arcsec HPD) and good angulare resolution in ~30 keV (~17 arcsec HPD), powered by GSFC's silicon segmented mirror technology (same as AXIS)
- The HEX-P proposal made a strong case for broad-band science and the strength of having high angular resolution at > 10 keV
- Many of HEROIX team members also contributed to the HEX-P proposal, but we are our own mission
- I strongly encourage everyone to read the special issue on HEXP for a very well-prepared set of white papers for broad-band X-ray science

A Comparison between Hard X-ray missions



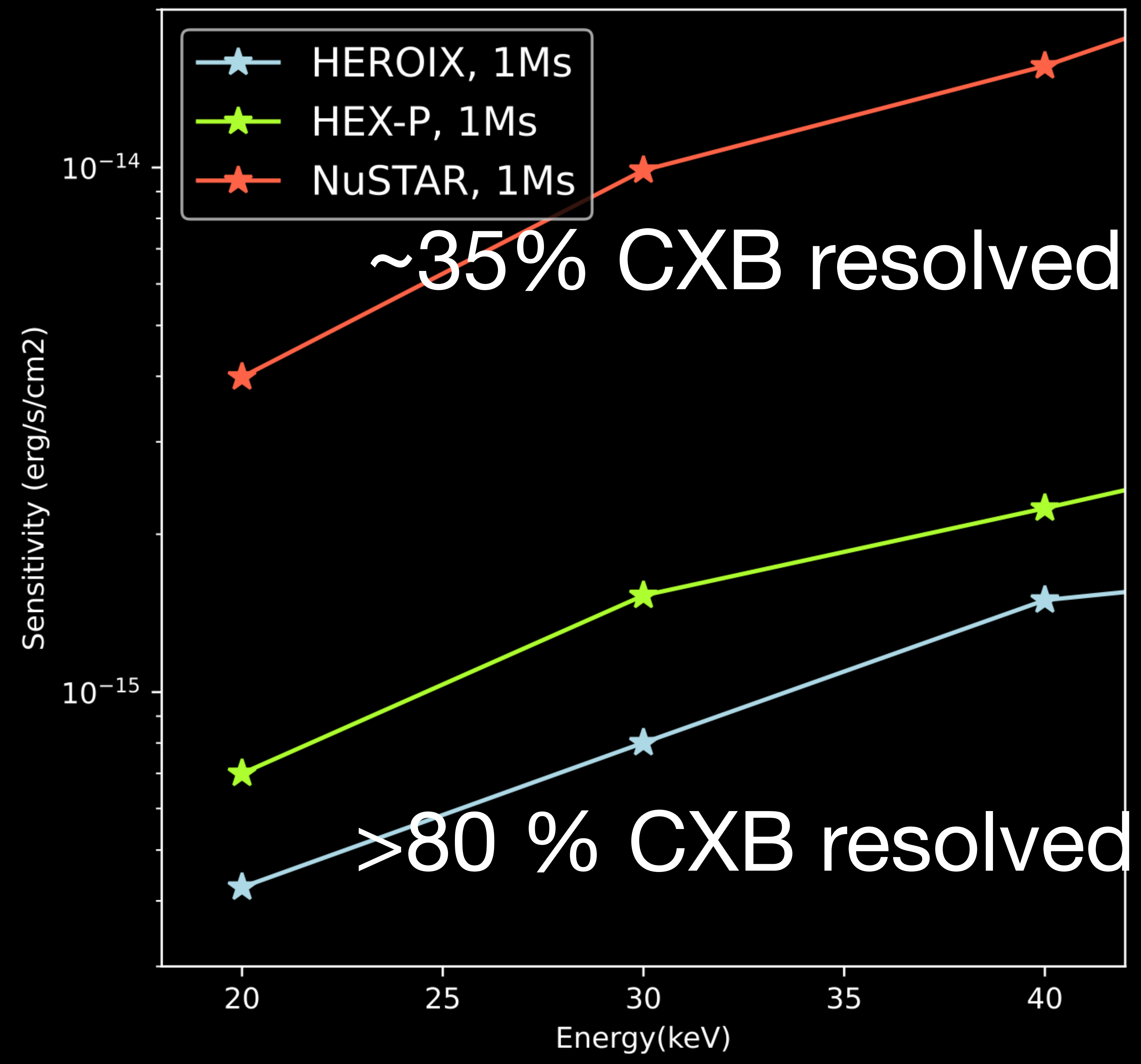
	NuSTAR	HEROIX	HEX-P
HPD@30 keV	58”	5”	17” (10”@10 keV)
Energy Range	3-80 keV	~2-80 keV*	0.2-80 keV
Effective Area@30 keV	250 cm2	380 cm2	462 cm2
Focal Length	10 m	12 m	20 m
Detector Pitch	600 micron	~200 micron	600 micron
Budget	SMEX (150M)	MidEX (3-400M)	Probe (1B)

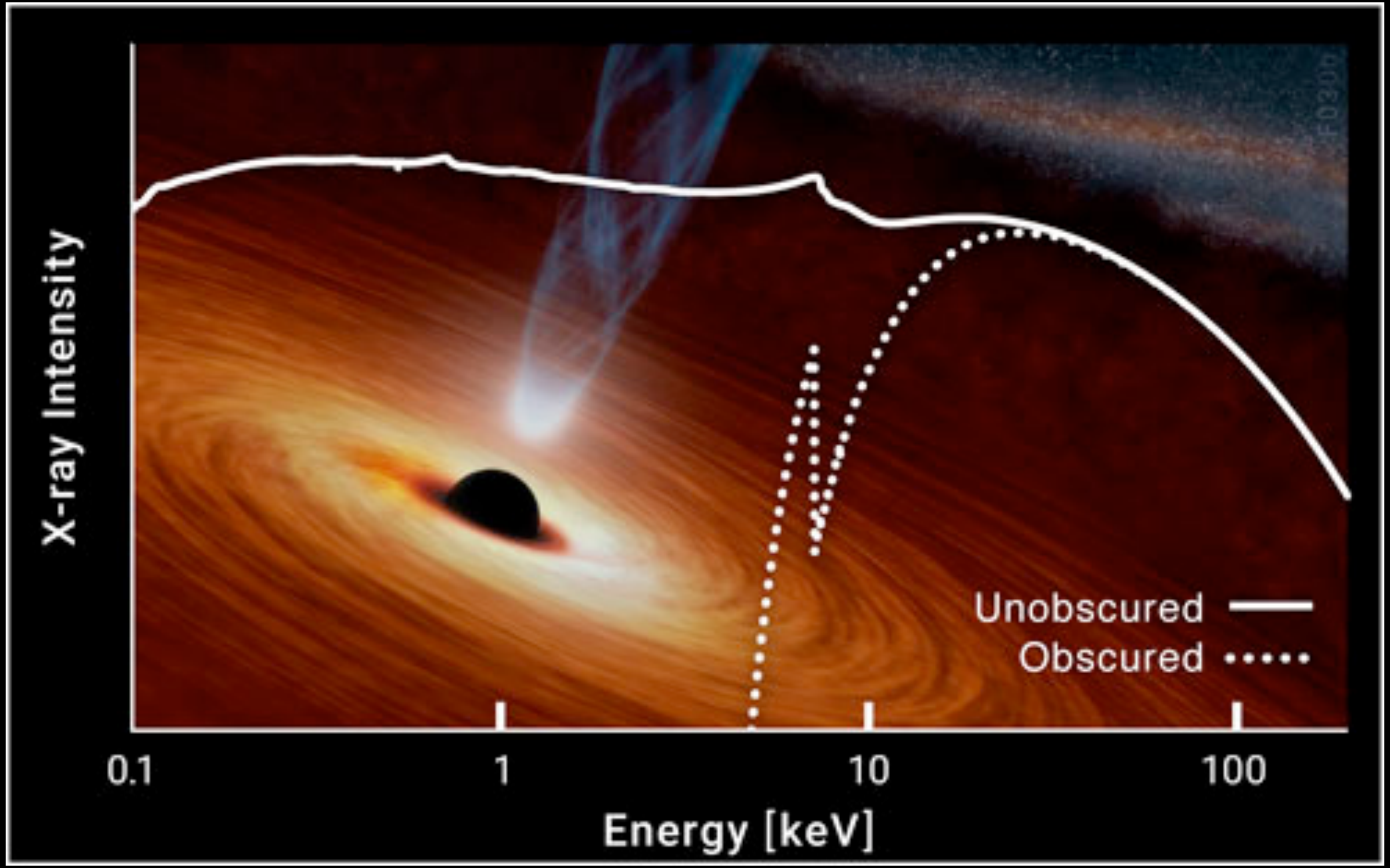
*Additional MMA for soft X-ray can be an option

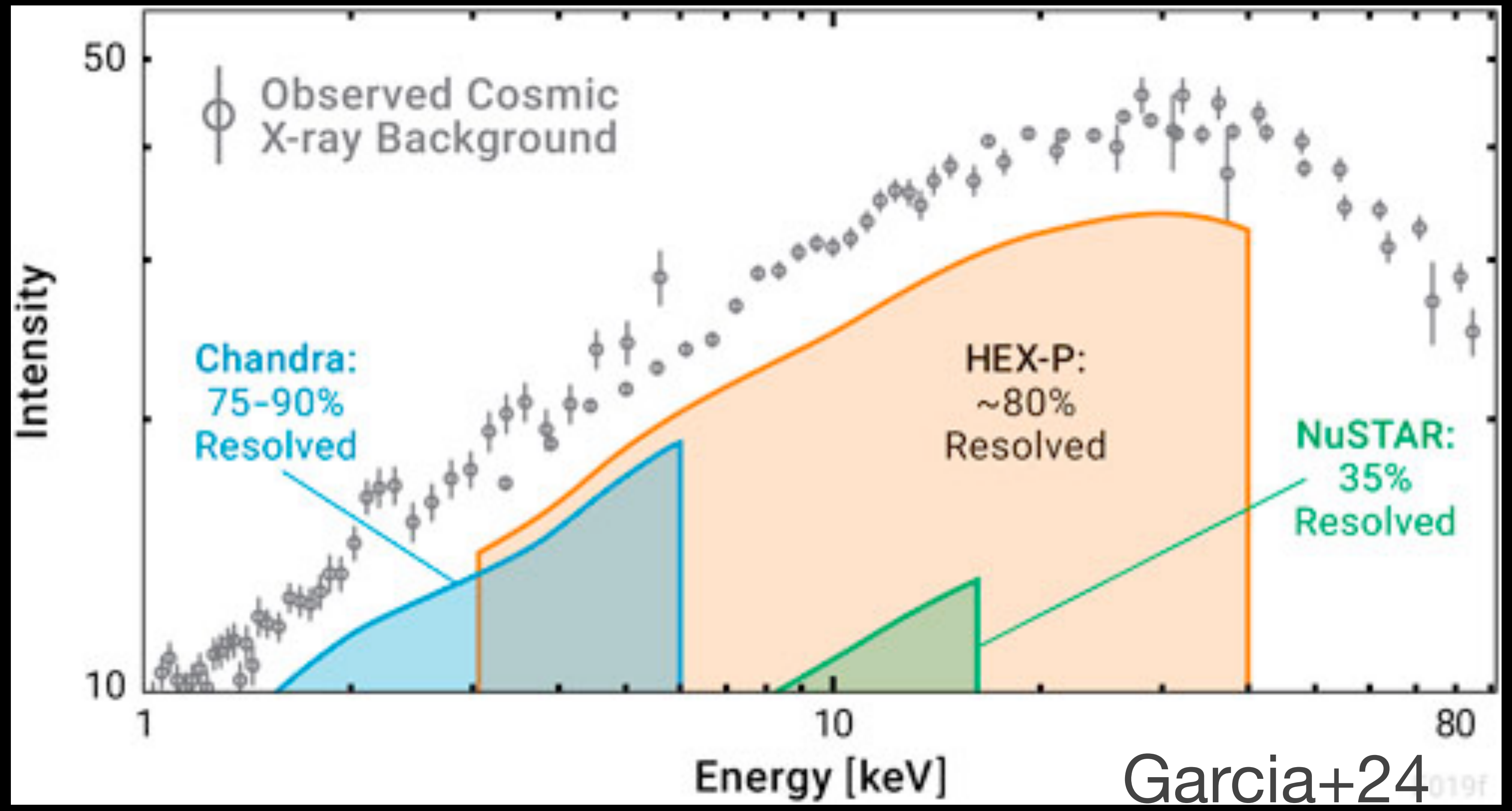


Grefenstette+16,
NASA/JPL-Caltech/CXC/SAO

Angular resolution improves sensitivity — crucial for resolving CXB, studying obscured X-ray sources, and elucidating spatial structures in extended emission



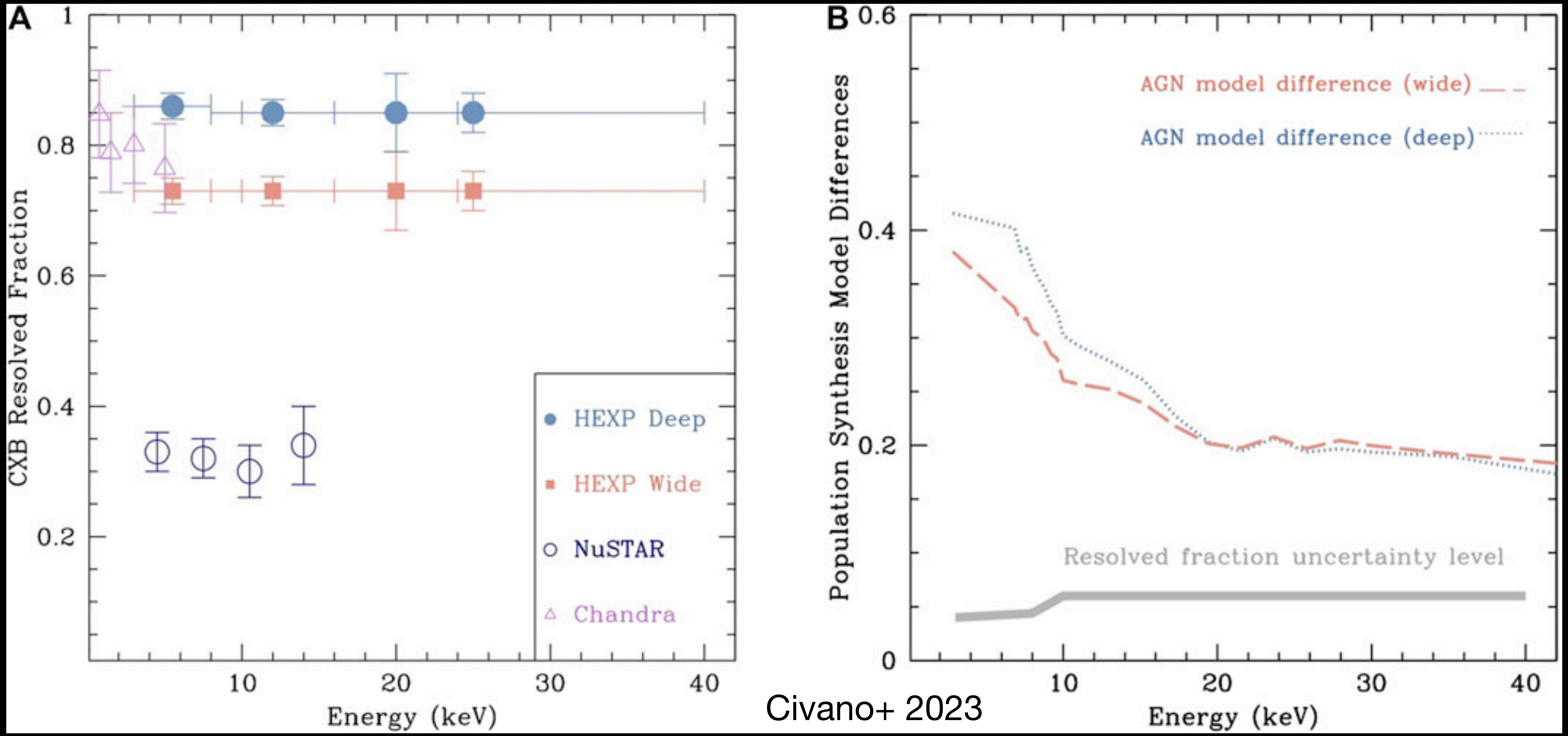




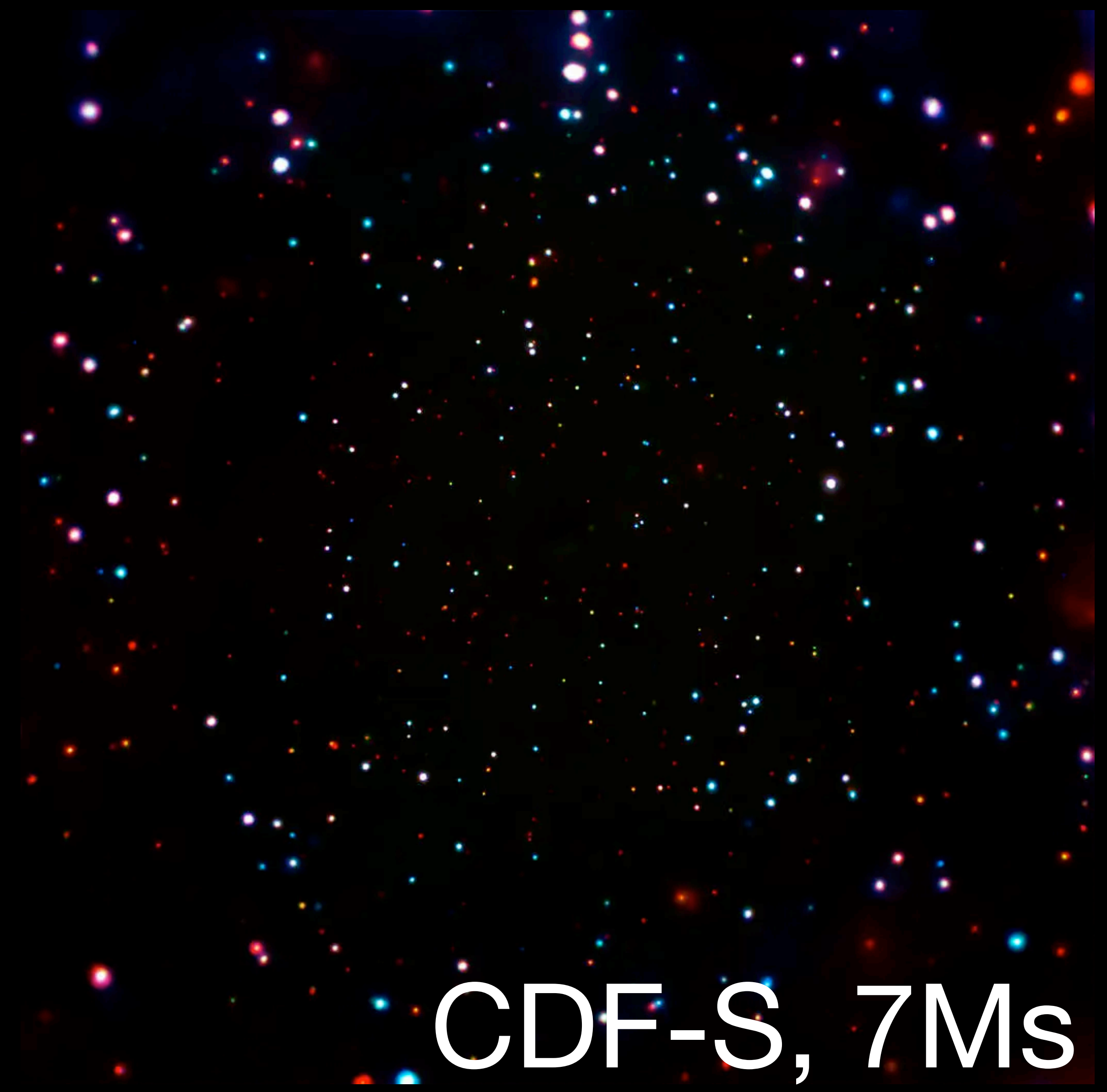
Garcia+24

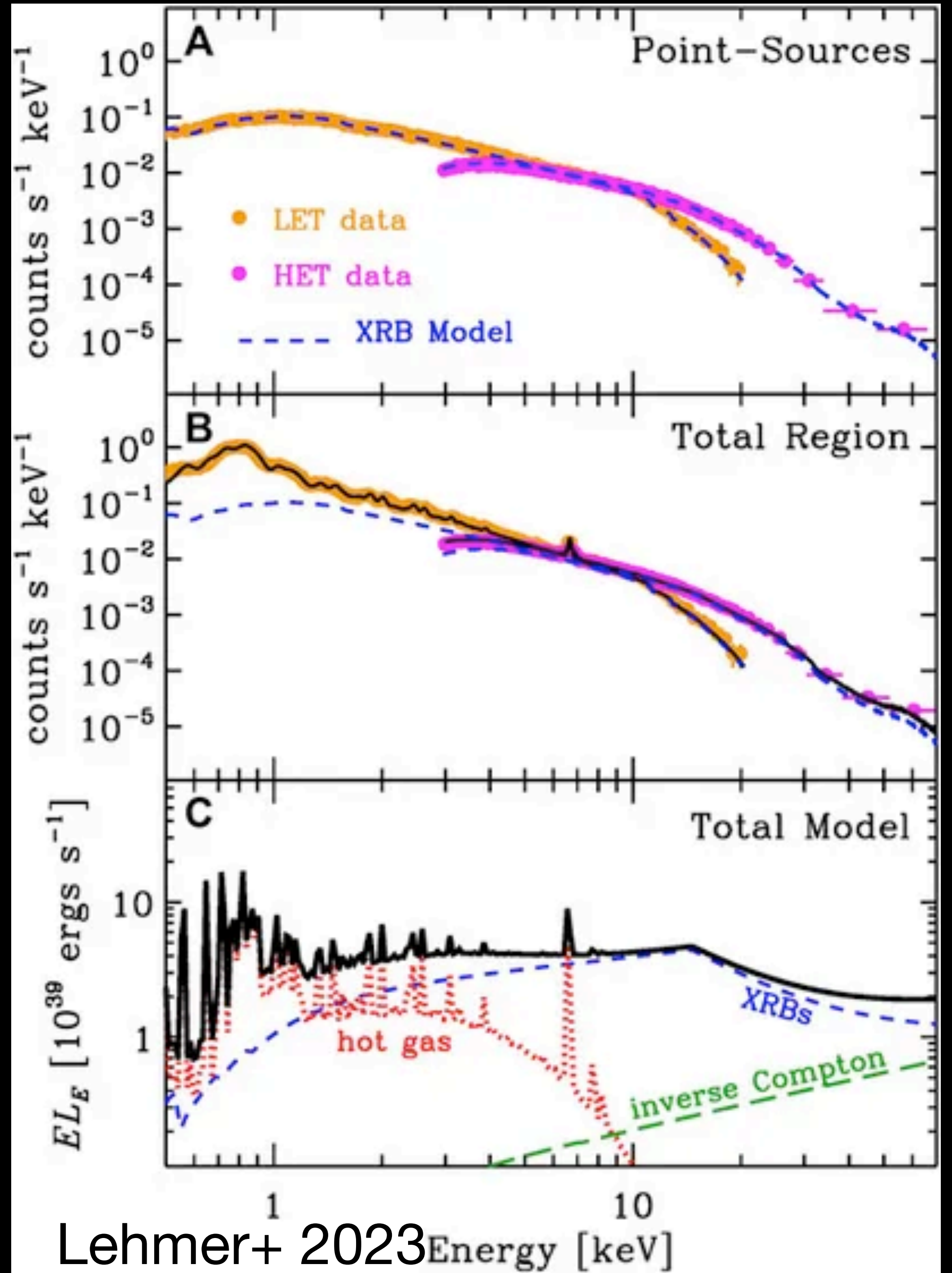
$$\mathrm{SNR} \propto \frac{Source Flux \times Time \times EA}{\sqrt{BG Flux * \times Time}}$$

Smaller PSF = less background
→ better SNR



Civano+ 2023





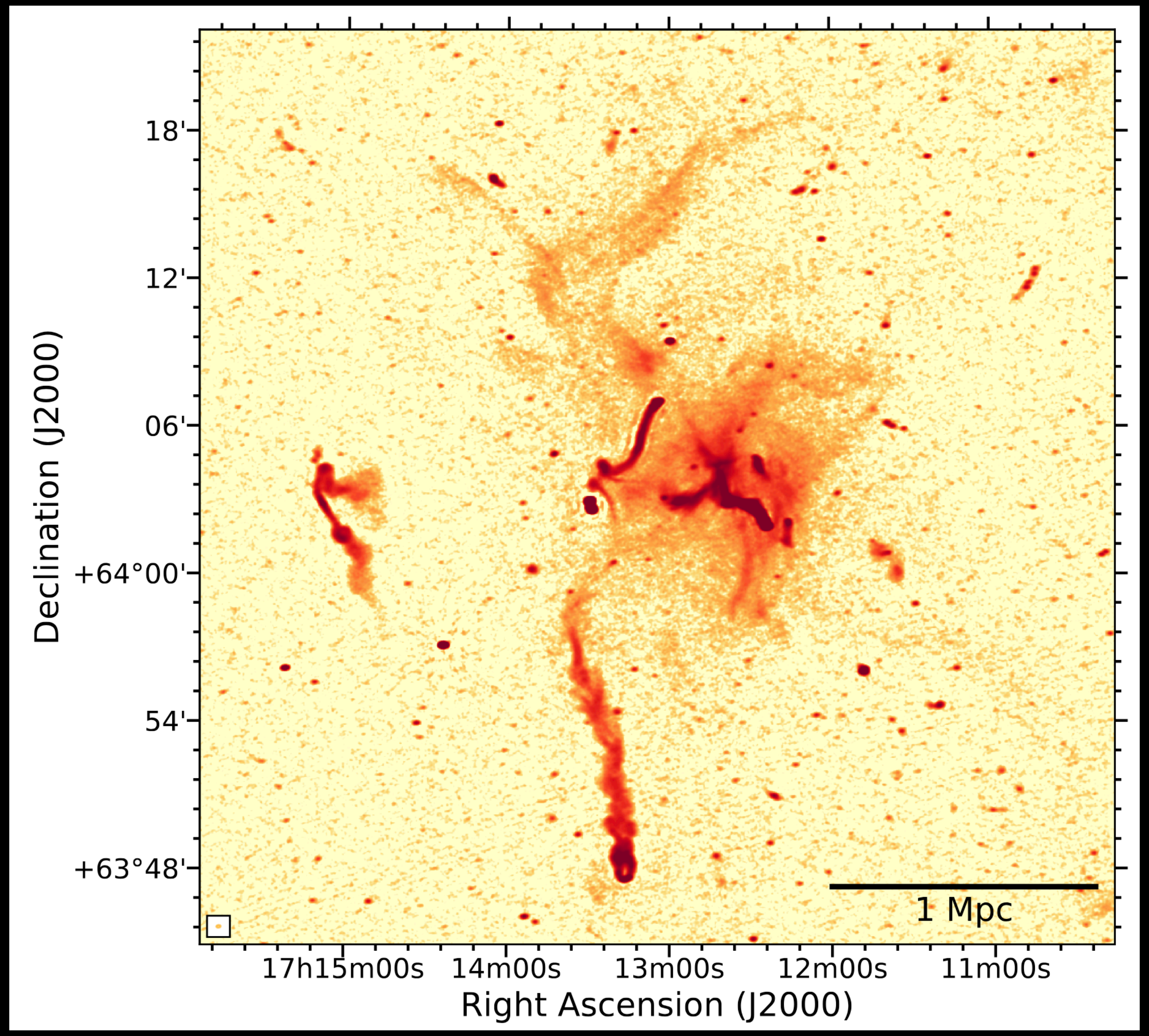
Lehmer+ 2023

- **Detecting unknown X-ray sources**
- **AGN population synthesis model: torus geometry, radiation efficiency**
- **Extragalactic X-ray Binary demographics, IC emission in starburst galaxies, redshift evolution of galaxy metallicity, etc.**

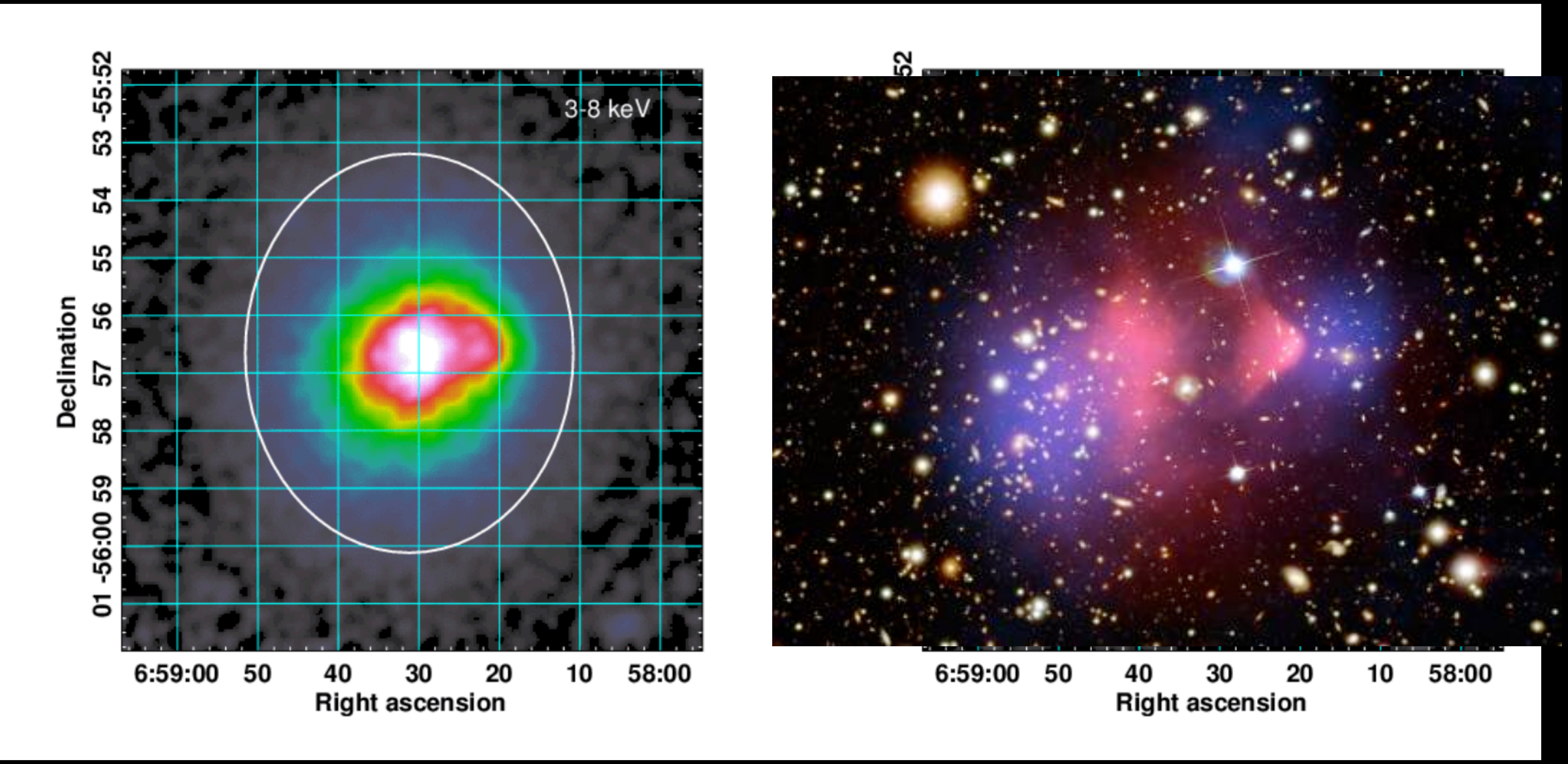
Merging galaxy clusters

- Merging galaxy clusters harbor the largest collisionless shocks in the Universe
- Long lifetime of the shocks due to the limited cooling channels (e.g., IC-CMB, adiabatic expansion, synchrotron)
- Shock heating via DSA is commonly adopted but it is hard to probe X-ray shocks with thermal emission from intracluster gas in the soft X-rays
- Hard X-ray can probe non-thermal X-ray emission from the shocks but requires excellent sensitivity and angular resolution

Also see Alvina's talk!



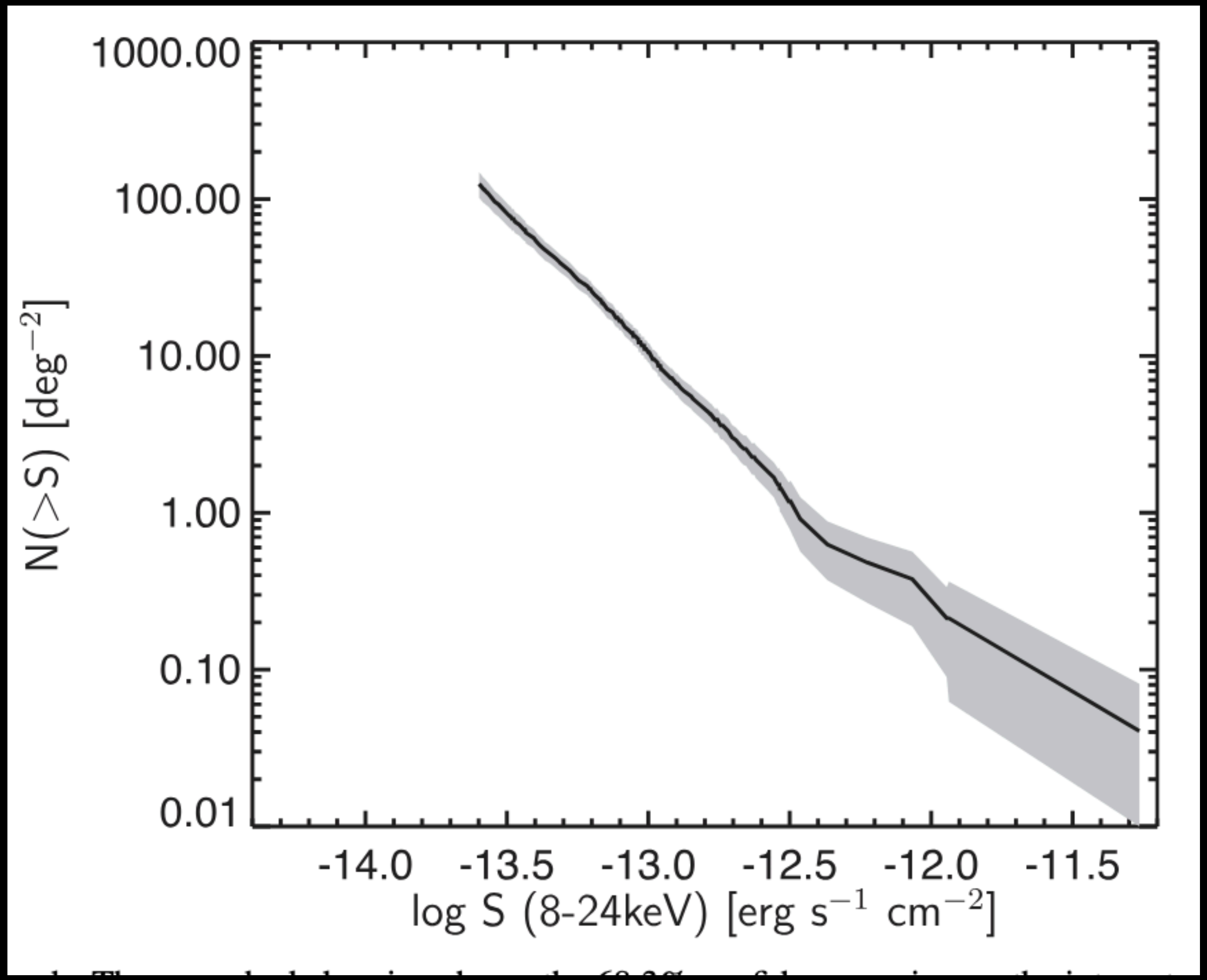
Radio relic for Abell 2255, Botteon+20 (LOFAR)



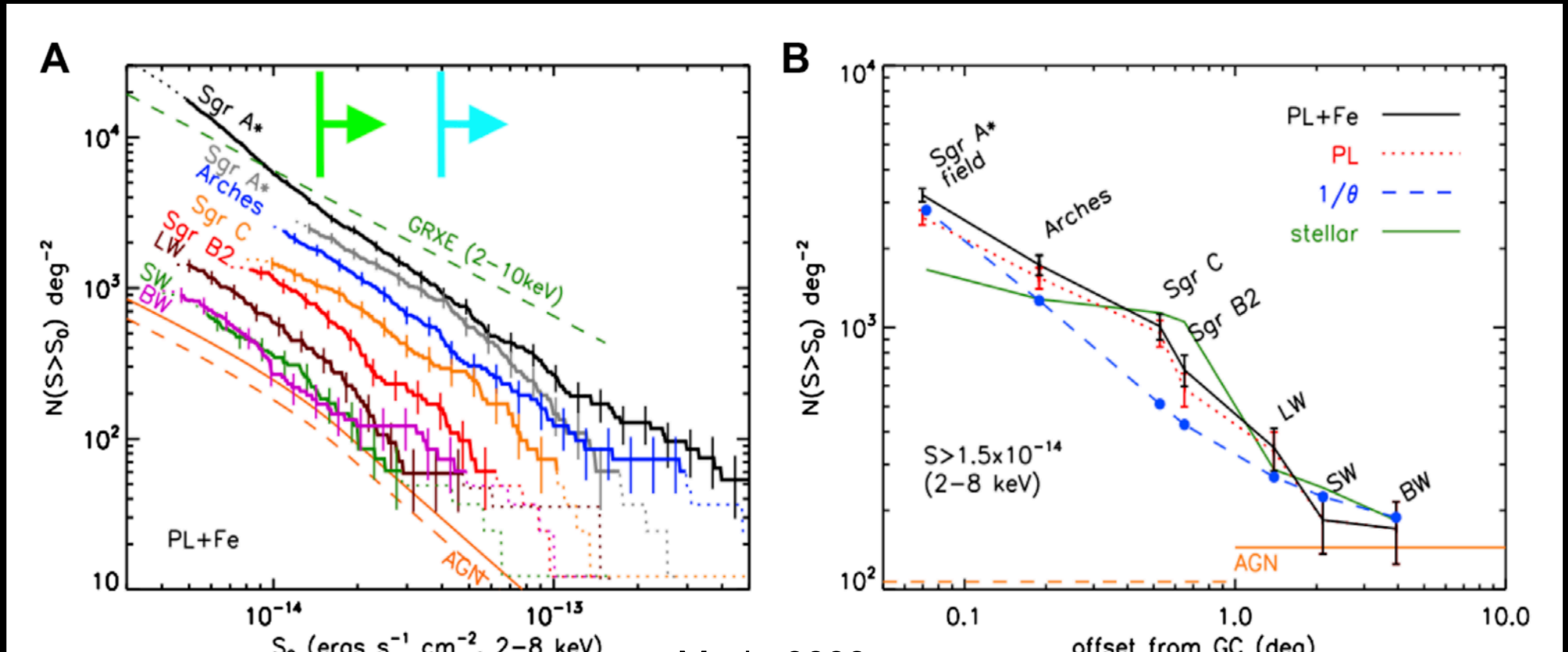
Bullet cluster, NuSTAR (Wik+2014)

Galactic Center Science

NuSATR 8-24 keV number count (Harrison+2016)



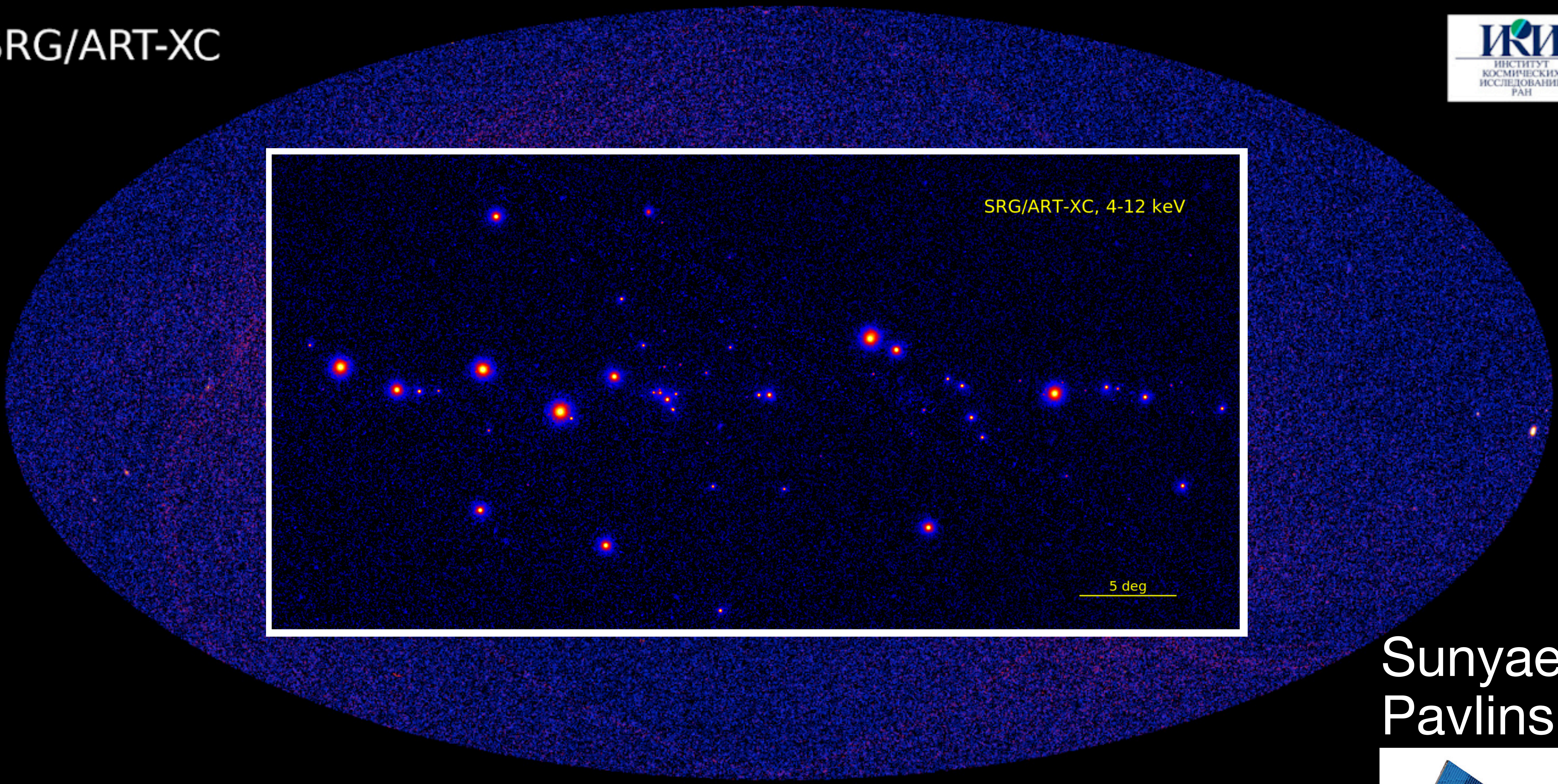
2 orders of magnitude difference between Chandra and NuSTAR in number counts



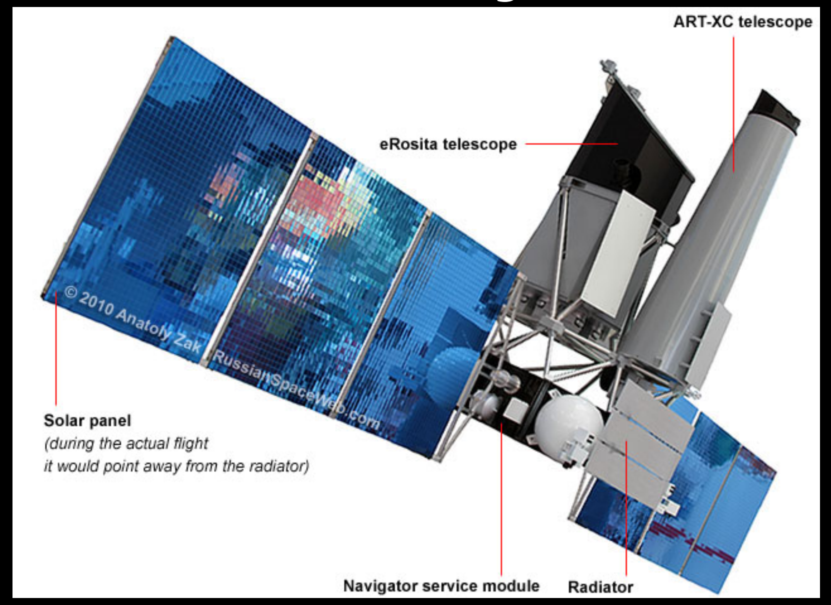
Mori+ 2023

Several talks focusing on GC (e.g., Abe-san on Tuesday, Ellis on Wednesday)

SRG/ART-XC



Sunyaev+2021,
Pavlinsky+2021

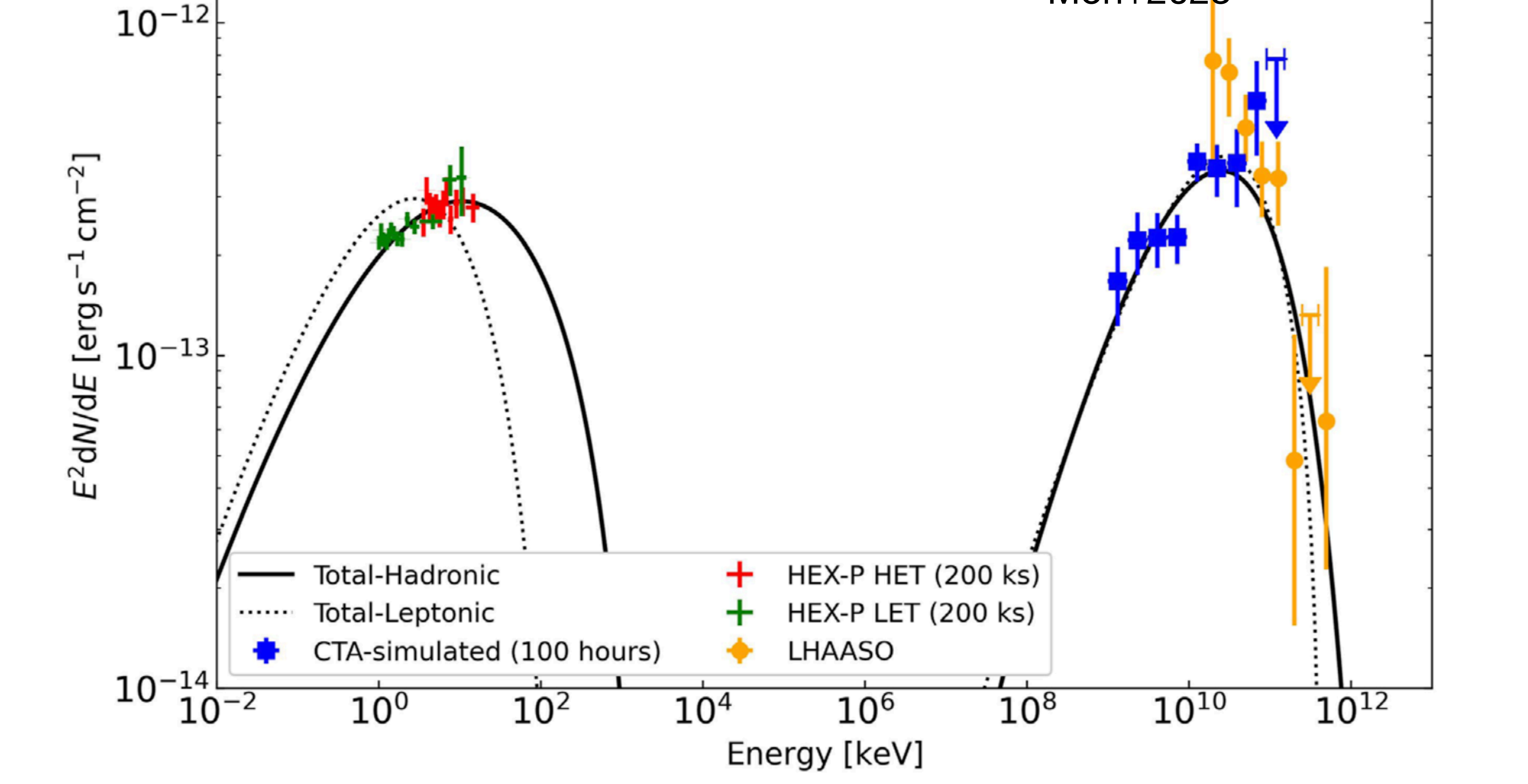


We need sensitive hard X-ray mission to pierce through dust and resolve crowded fields in the Galactic Center region.

Galactic Pevatron sources

- X-ray spectra can provide constrains on the leptonic vs hadronic models.
- Spatial resolution and the better sensitivity can detect faint features in micro-quasars such as SS 433.
- Also see the talks by Asano-san and Tsuji-san, Dmitriy-san, Kimura-san (sorry if I missed anyone here)

Simulation for HEX-P by Mori+2023



Conclusion

- MeV–PeV Frontiers: New Perspectives in Gamma-Ray Astronomy and Particle Acceleration.
- One of the primary science goals for HEROIX is to resolve and detect the sites of particle acceleration, with synergies between multi-messenger facilities.
- Please consider joining the HEROIX science team!

https://forms.gle/62LdpEnwSEZGQBYZ8

HEROIX Status updates

- Science Team:
  - Dan Wilkins, Lebani Malick, Kaya Mori, Dave Pooley, Fabio Pacucci, Francesca Civano, Paolo Coppi, Stefano Bianchi, Steven Ehlert, Ioannis Liodakis, Zorawar Wadiasingh
  - Approximately ~ 100 people in the current mailing list, 70 have joined the Slack channel.
  - We had a first in-person meeting at the 2025 HEAD, with a mixture of the SuperHERO and HEROIX team members
  - We have the critical mass to move forward now!

MidEX timeline

- The cadence of the Astro MIDEX Announcement of Opportunity (AO) tend to very depending on budget availability.
- We know that the SMEX AO release is set for no earlier than April 2026.
- MIDEX AO is currently projected for First Quarter of 2028… with some uncertainty. Very tentative dates to keep in the back of your mind include-
- Draft AO: Early to mid 2027
- Proposal Due: 90 days after release of final AO (Mid 2028)
- Selection for competitive Phase A Study: First Quarter 2029 (9 month long)
- Concept study report due: Third Quarter 2029
- Down-selection: First Quarter 2030

- - all of this is a guesstimation

Short-term goals (next ~ 6 months)

- Starting in January, we will have start having telecons with three main goals
    - Topics not covered or looked over by the HEX-P white papers due to its angular resolution limitations
    - Identifying transferrable science with updated parameters given the better angular resolution of HEROIX and the smaller effective area
    - Synergies between the primary and secondary instrument
    - First “actual” science discussion is planned to start in mid-January, but volunteers are strongly encouraged to contact me.
- Results of these science discussion will be reported at a upcoming SPIE meeting in July, 2026.

Mid-term goals (6-18 months)

- Aiming to release science white paper(s) in ~12 months.
- We're looking into having a meeting on science and technology for high angular resolution X-ray missions in Huntsville in September/October 2026.
- Science Traceability Matrix and Secondary Instruments will provide information for a Advanced Concepts Office (ACO) study.
  - ACO is a part of MSFC, they perform early-phase analyses and feasibility evaluations of space systems for planning purposes.
  - Secondary instrument will be driven by science, but feasibility and cost will help us down select if we have more than one truly competitive options.
  - Contributions from external space agencies will also be determined at this point.
- Proposal writing will commence as early as 2027, determine on the ACO's schedule.
- We will closely monitor the SMD's plan for the upcoming Astrophysics Explorer calls and adjust the mid-term goals to get the best possible mission possible.

Conclusion

- SMEX AO is being delayed to 2026. The MidEX proposal was anticipated to be due by the end of 2027, although it is less certain now.
- SuperHERO APRA is still on schedule for flight in 2028. We will be proposing for Long-Duration Balloon Flights for a Galactic Center Survey regardless. The high-resolution modules are also in active development.
- Our goal is to be technologically prepared to meet any opportunities available in 2027 and beyond.
- One of the primary science goals for HEROIX is to resolve the sites of particle acceleration.
- We need your help with building strong science cases that will define the future of high energy astrophysics in the next decades.

Join us!

Sign up to be a part of the HEROIX team!

https://forms.gle/62LdpEnwSEZGQBYZ8