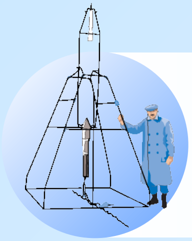


Future NASA X-ray Astronomy Missions and Concepts

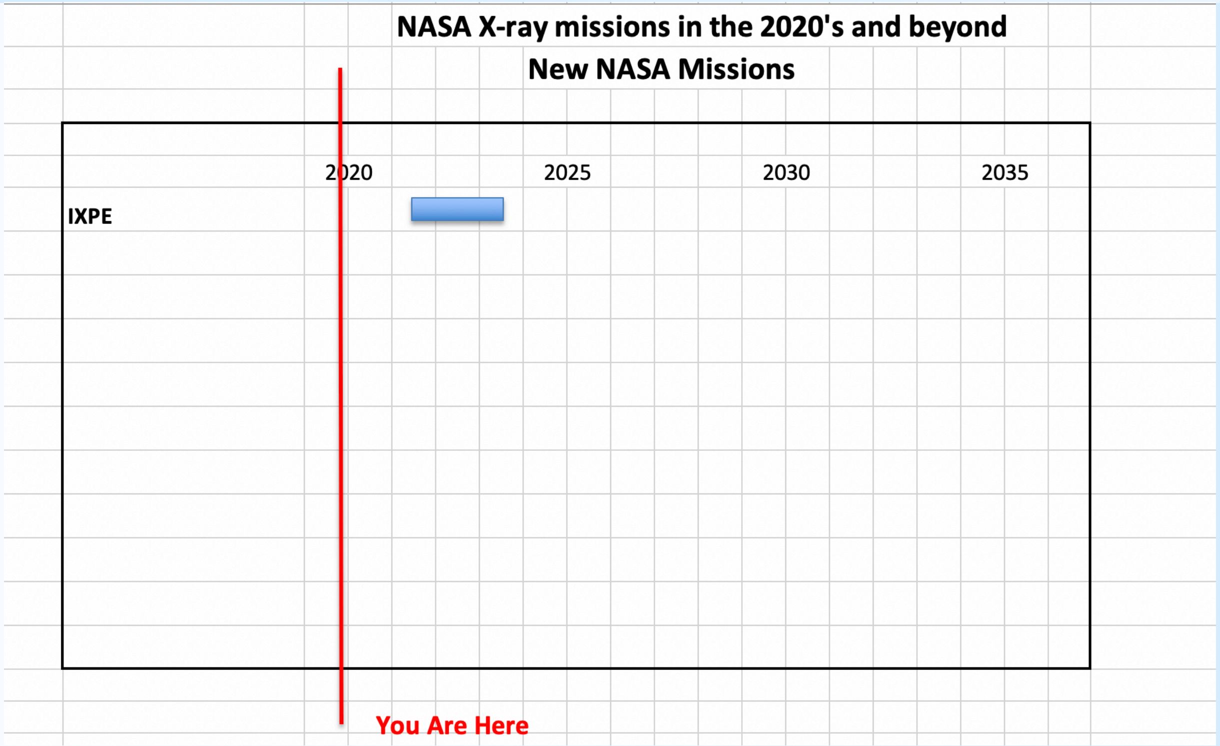
Rob Petre
Director of Astrophysics
NASA / Goddard Space Flight Center

Presented by Azita Valinia
Deputy Director, Astrophysics Flight Projects
NASA Goddard Space Flight Center

NASA X-ray missions in the 2020's: Takeaways

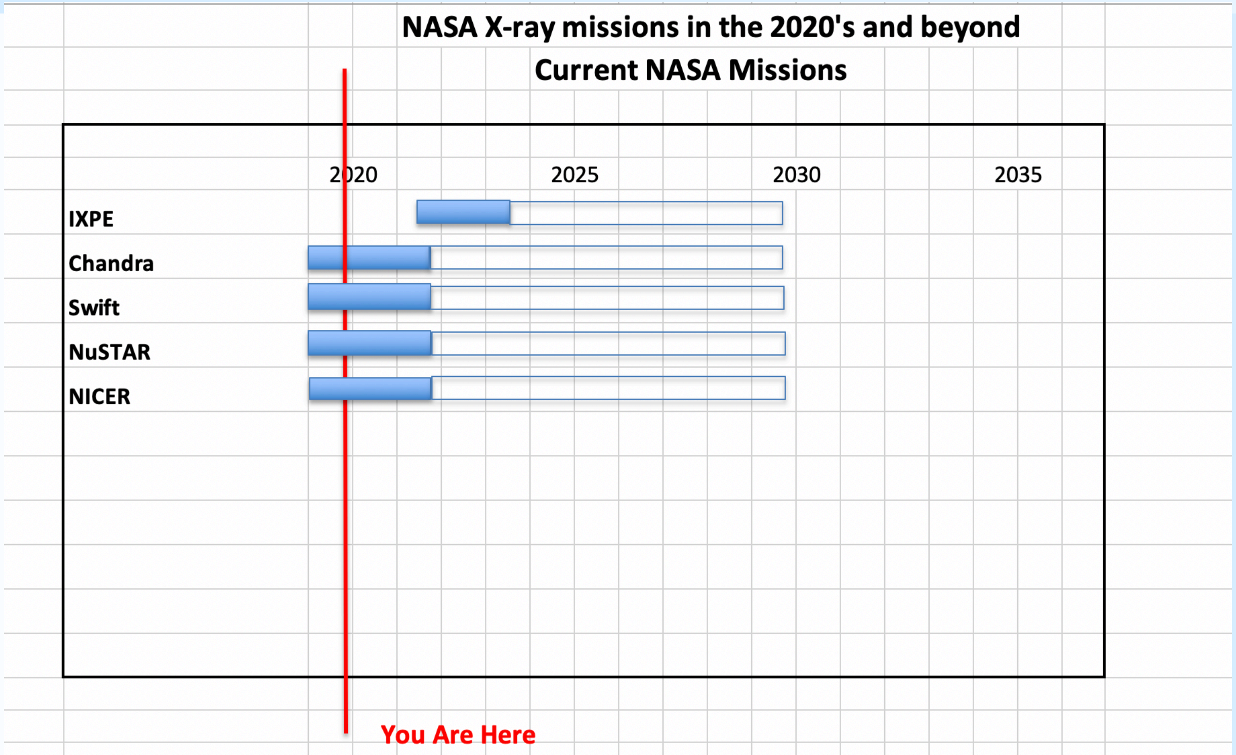
- NASA has one new X-ray mission under development for 2020's – IXPE (Weisskopf talk)
- NASA is relying primarily on its existing fleet of missions and on collaborations with ESA and JAXA to advance X-ray astronomy
- Promising concepts exist for MIDEX class X-ray missions for the latter half of the decade
- CubeSats and SmallSats are emerging as a new opportunity
- NASA funded X-ray instrumentation has made substantial progress over the past decade
- The future of large NASA X-ray missions depends on the outcome of the 2020 decadal survey, now underway
  - Lynx
  - X-ray probe-class missions

NASA led X-ray missions under development



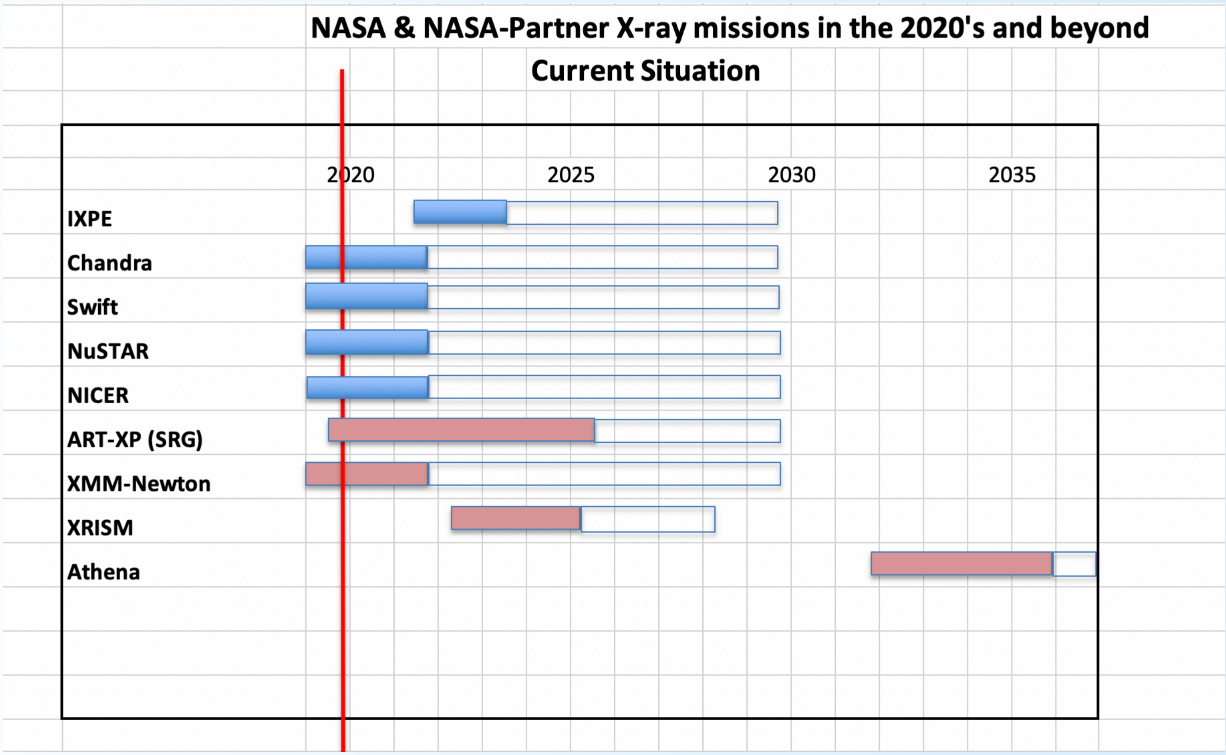
- NASA has only one X-ray mission under development – IXPE, scheduled for a 2021 launch and a two-year nominal mission
- Mission extension likely if the baseline mission is successful
- See M. Weisskopf talk

NASA X-ray missions in the early 2020's



- NASA has four X-ray missions in extended operations – Chandra, Swift, NuSTAR, NICER
- All were awarded three-year extensions until 2022 in 2019 Senior Review
- Fleet is aging: Chandra is 20 years old, Swift is 15

NASA is relying on foreign partnerships



- NASA relies on its successful partnerships with foreign space agencies like ESA and JAXA
- Partnerships on XRISM and Athena allow NASA to fulfill 2010 Decadal Survey goals related to IXO

Potential NASA missions in the 2020's

- NASA's astrophysics portfolio consists of competed and directed missions
- Competed missions are SMEX (~$145M), MIDEX (~$250M), MOO's (~$70M), and SmallSats
  - Two SMEX and two MIDEX calls per decade, with accompanying MOO/SmallSat call
- Directed missions are large missions (e.g., Chandra) or medium ("probe-class") missions (e.g., Fermi)
  - Directed missions are strategic, defined through the decadal survey process
- Any future NASA X-ray mission must be selected through either a MIDEX/SMEX call or by the decadal survey

Potential NASA missions - MIDEX

- NASA solicits Explorer mission proposals every 2.5 years
- One mission selected per solicitation
- Next call is for a MIDEX (PI led; ~$250M cost cap) in late 2021
- Several X-ray missions are likely to be proposed
- Two X-ray missions did well (but were not selected) in the 2016 round:
  - Arcus – high resolution grating spectroscopy in 0.2-1.5 keV band
  - STAR-X – 1 degree field of view, 5 arcsec imager for transient followup and surveys

Proposed Mission: *Arcus*

Exploring the Formation and Evolution of Clusters, Galaxies, and Stars

SAO-led effort with an experienced team of institutions, scientists, and engineers:

Key Hardware Institutions

NASA/Ames, MIT, Penn State, MPE & FAU

Why Arcus?

An Order of Magnitude Improvement in X-ray High-Resolution Spectroscopy

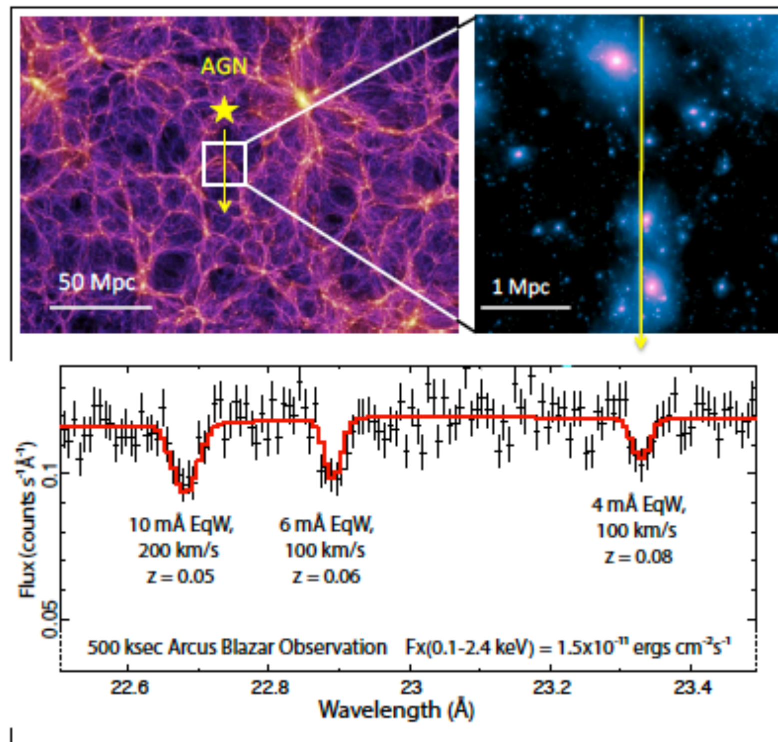
•2010 Decadal Review made X-ray spectroscopy high priority.

•Key science requires gratings; next large X-ray mission (ESA's *Athena,* 2028) has *no* gratings

•Uses Silicon Pore Optics developed for Athena together with nanotech Critical Angle Transmission gratings to achieve efficient high-resolution X-ray spectroscopy.

Science Objectives

- Where are the 'missing baryons,' and more generally, how does matter cycle in and out of galaxies?
- What powers the black hole winds that can impact entire galaxies and clusters?
- How do stars & circumstellar disks form and evolve?



Arcus will find the 'missing matter' at and beyond the edges of galaxies & clusters of galaxies

Potential MIDEX – STAR-X

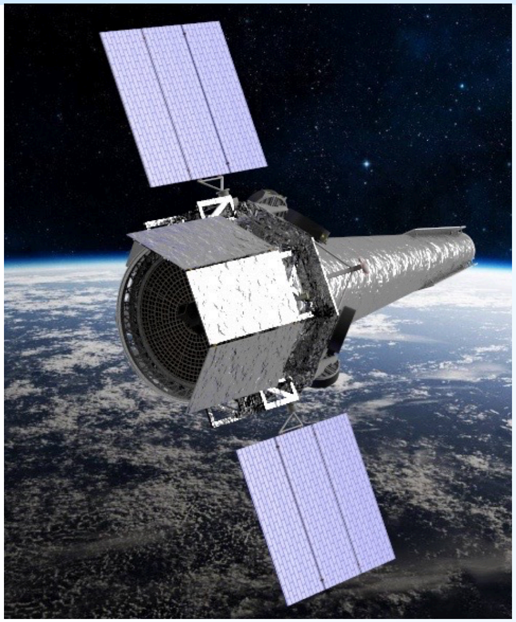
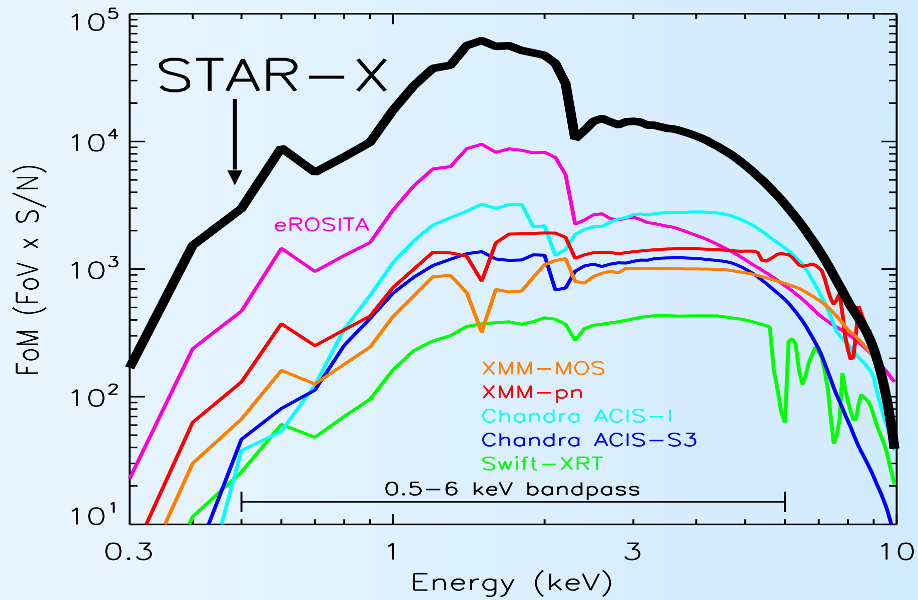
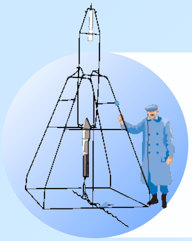


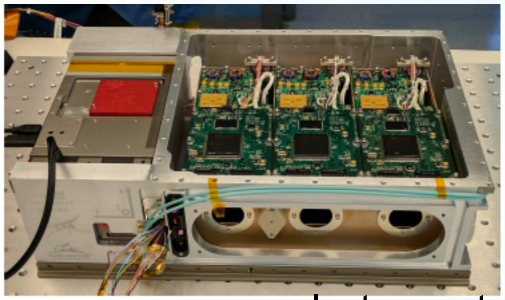
Figure of merit for finding transients



- Powerful telescope for discovering faint transients
- Mirror has 1º diameter FOV with uniform 5 arcsec HPD;1,800 cm^2@ 1keV and 1,270 cm^2@ 0.5 keV – best figure of merit for finding transients (like GW events)
- Fast slewing spacecraft to enable high cadence observations and fast response to ToO
- Low inclination orbit for low background and fast uplink

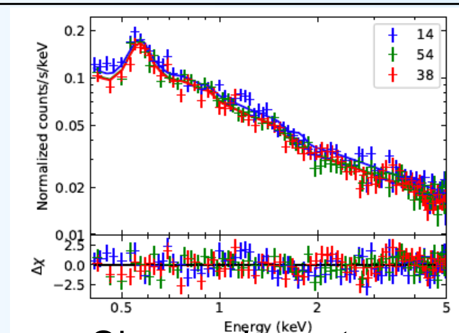


Smallsats and Cubesats

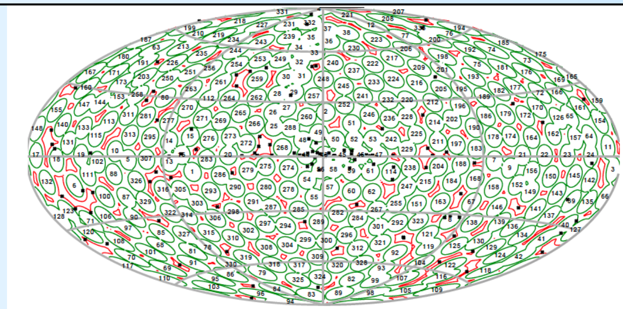


HaloSat

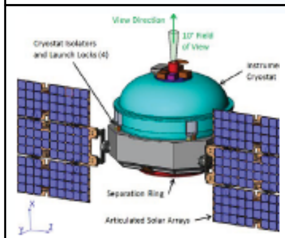
Instrument



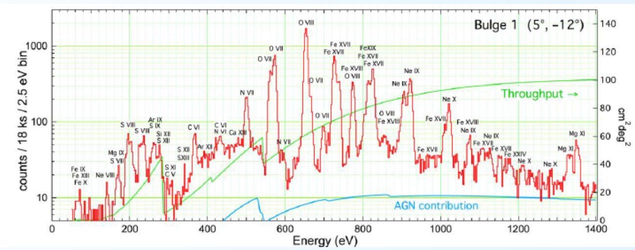
Observed spectrum



Sky coverage

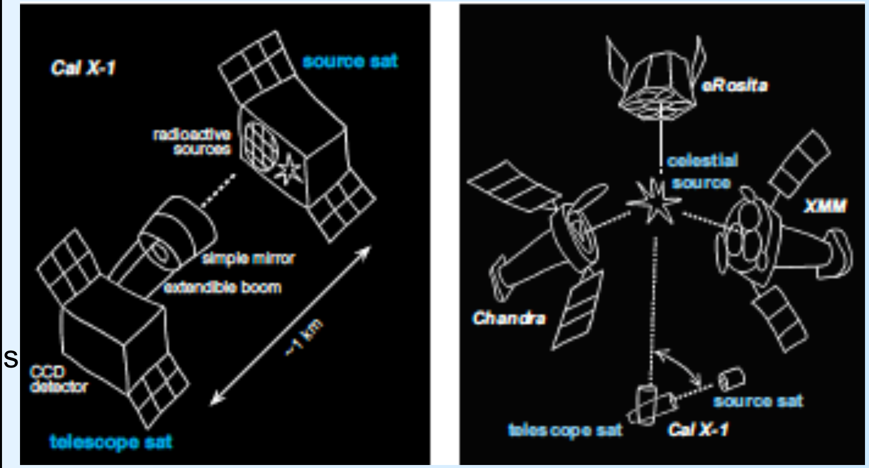


XQCSat



Simulated spectrum

- CubeSats (<$5M) and SmallSats (<$35M) have become attractive throughout NASA – highly focused science objectives with modest mission lifetime at low cost
- X-ray astrophysics examples include:
  - HaloSat: CubeSat mapping the Galactic halo in OVII (deployed July 2018)
  - Cal X-1: SmallSat to provide absolute on orbit calibration of X-ray observatories
    XQCSat: Calorimeter based SmallSat to study IGM



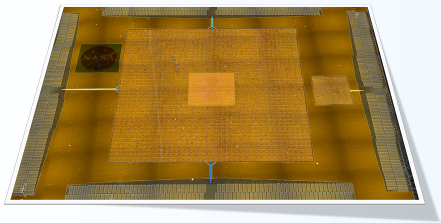
Operations concept

Cal X-1

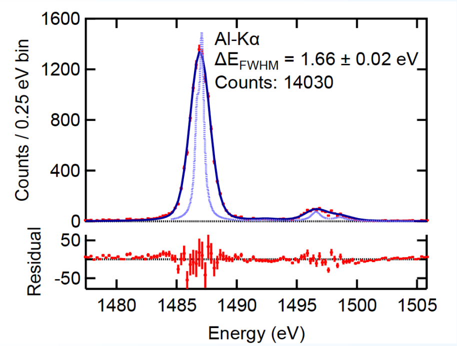
Technology development towards a strategic NASA X-ray mission

- NASA has invested in technology development that can be used on a future strategic X-ray mission – met goals for IXO set in 2010

Calorimeters

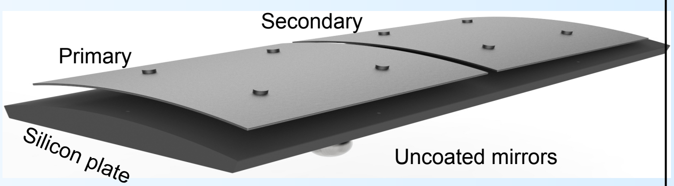


Lynx prototype array (GSFC)

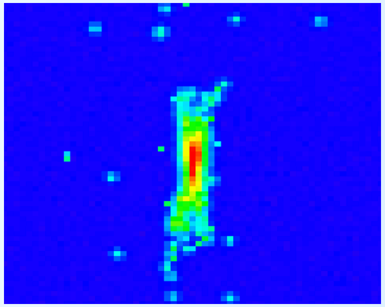


Resolution of ≤ 1 eV achieved

Mirrors

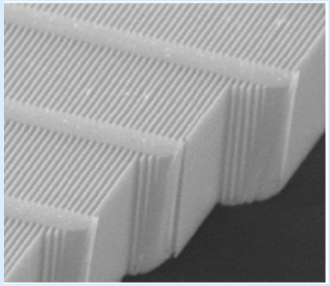


Single crystal Si mirror testbed (GSFC)

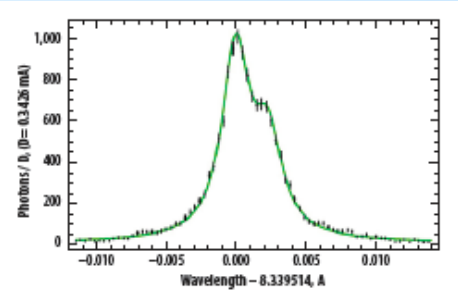


1.2” HPD measured

Gratings



CAT gratings (MIT)

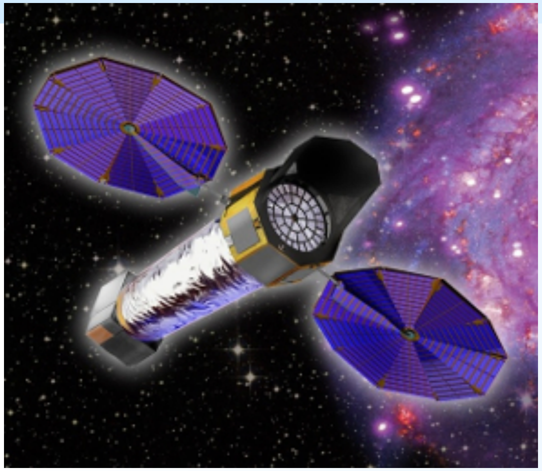


Resolution of 10,000 achieved

Prospects for a strategic NASA X-ray mission

- Beyond the Explorer program and international partnerships, the future of NASA X-ray astronomy in the 2020's depends on the outcome of the 2020 Decadal Survey of Astronomy and Astrophysics
- The 2020 Decadal Survey of Astronomy and Astrophysics is underway
- Report expected in late 2020
- The report will rank large (>$1B) and medium (~$0.5B-$1B) space and ground facilities
- Previous top ranked large missions include WFIRST (2010), JWST (2000), Spitzer (1990), Chandra (1980)
- NASA instituted studies for four large mission candidates:
    - Origins Space Telescope – large far IR observatory
    - LUVOIR – very large successor to HST with substantial terrestrial planet finding component
    - HabEx – terrestrial planet finder
    - Lynx – successor to Chandra
- NASA also instituted studies of 10 "Probe-class" (<$1B) missions, including two X-ray missions (AXIS, STROBE-X) and a multiband mission with an X-ray telescope (TAP)

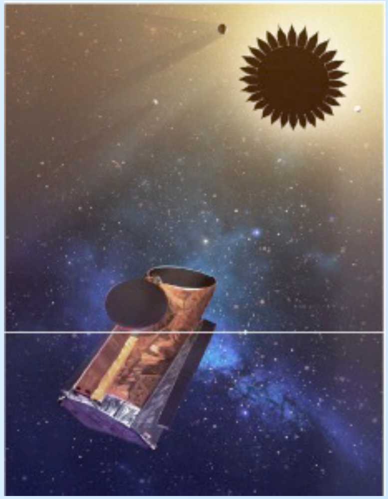
Candidate Large NASA Missions for 2020 Decadal

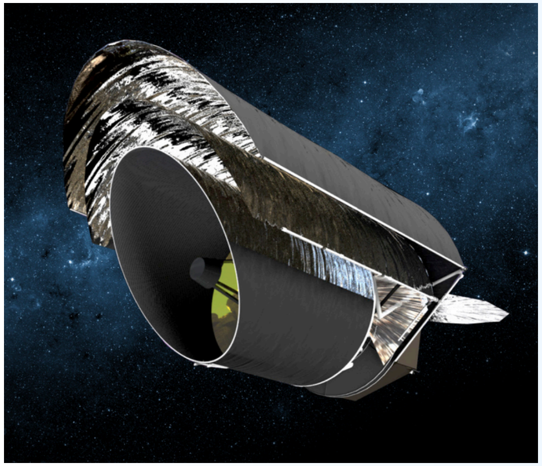


Lynx (X-rays)

- NASA supported thorough studies of four large missions.
- The 2020 decadal will prioritize these
- Each mission costs ≥$5B

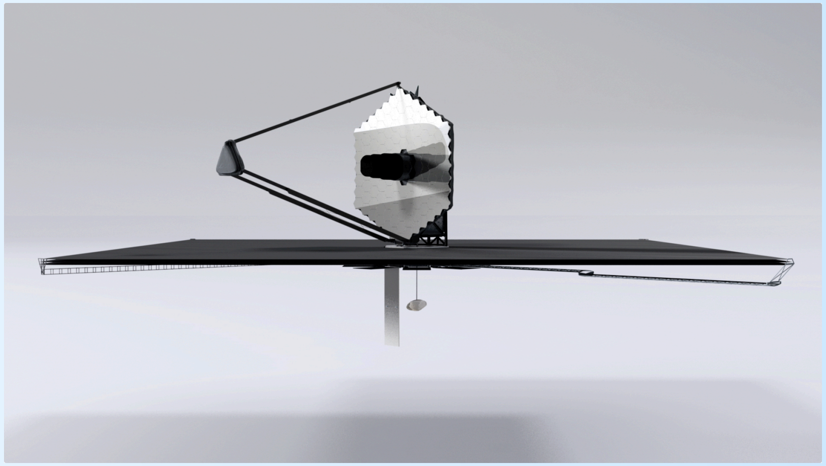
Habitable Planet Explorer



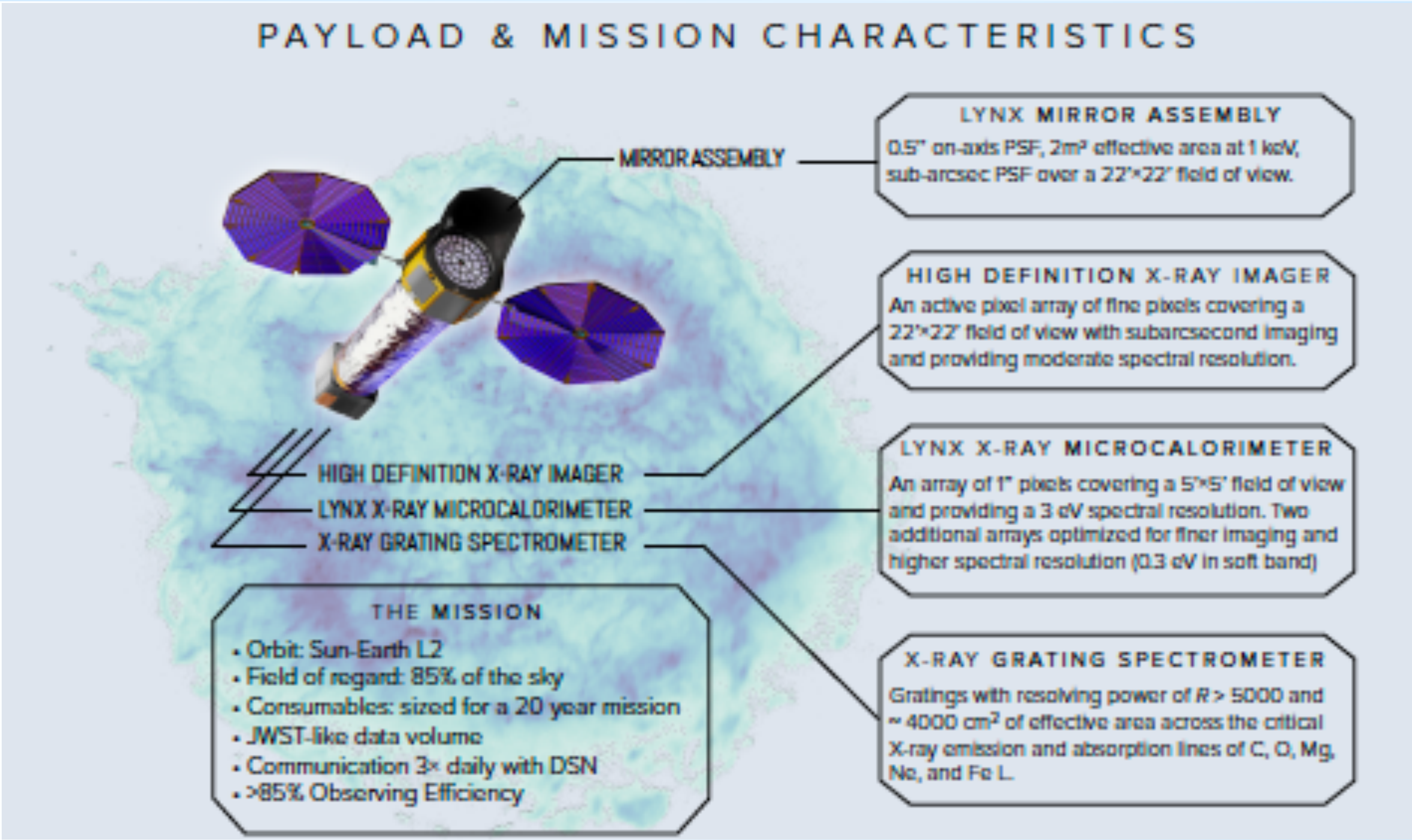


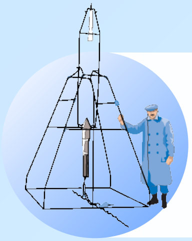
Origins Space Telescope (far IR)

Large UV Optical Infrared Telescope



Lynx Capabilities





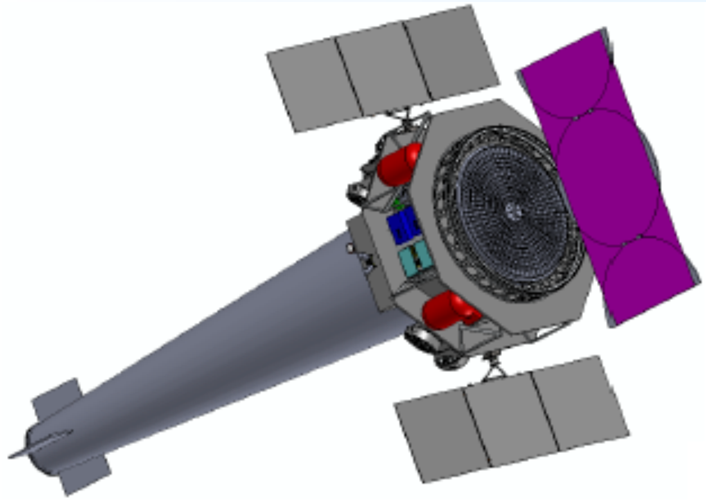
X-ray Probe Concepts

- NASA funded 10 probe studies (out of >25 proposed)
- Two are X-ray specific; a third is multiband, including X-ray
- Several other X-ray probe concepts were submitted in white papers to decadal
- All probe missions will be considered equally

Probe Study	Band	Closest Predecessor
AXIS	X-ray	Chandra
CDIM	Near-mid-IR	SPHEREx, JWST
CETUS	UV	GALEX, HST
Earthfinder	Near-IR	Ground-based radial velocity
GEP	Mid-IR, Far-IR	Herschel, Spitzer
PICO	CMB	Planck
POEMMA	Cosmic rays, neutrinos	Auger
Starshade	Optical/NIR	WFIRST
STROBE-X	X-ray	RXTE, NICER
TAP	X-ray, IR, gamma	Swift
Farside[#]	Radio	LWA,MWA , LOFAR, SunRISE
Exo-C*	Optical/NIR	WFIRST
Exo-S*	Optical/NIR	WFIRST

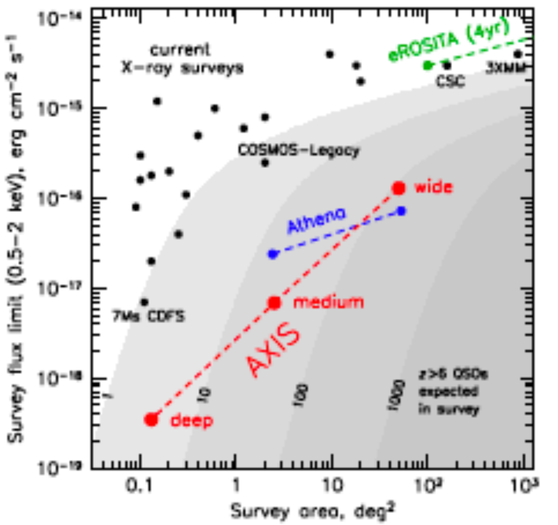
(From M. Elvis white paper)

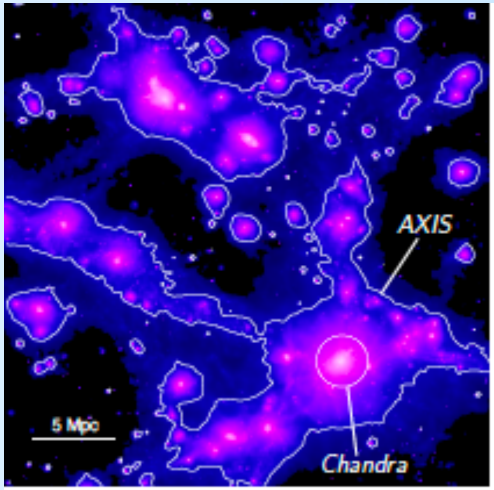
Advanced X-ray Imaging Satellite (AXIS)



Parameter		Value	*AXIS* vs. *Chandra*
Angular resolution (HPD, at 1 keV)	on-axis 15′ off-axis	0.4″ 1″	2× sharper 28× sharper
Energy band		0.2-12 keV	Similar
Effective area (mirror + detector)	at 0.5 keV at 6.0 keV	7000 cm^2 1500 cm^2	15× more collecting area 6× more collecting area
Energy Resolution	at 1.0 (6.0) keV	60 (150) eV	Similar
Timing Resolution		< 50 ms	6× brighter pile-up limit
Field of View (FoV)	HPD $\lesssim 1''$	$24' \times 24'$	70× better for < 1″ imaging
Detector Background	at 1 keV	2×10^{-4} ct/s/keV/arcmin^2	50× better sky/background
Slew Rate		120° /5 min	Comparable to *Swift*

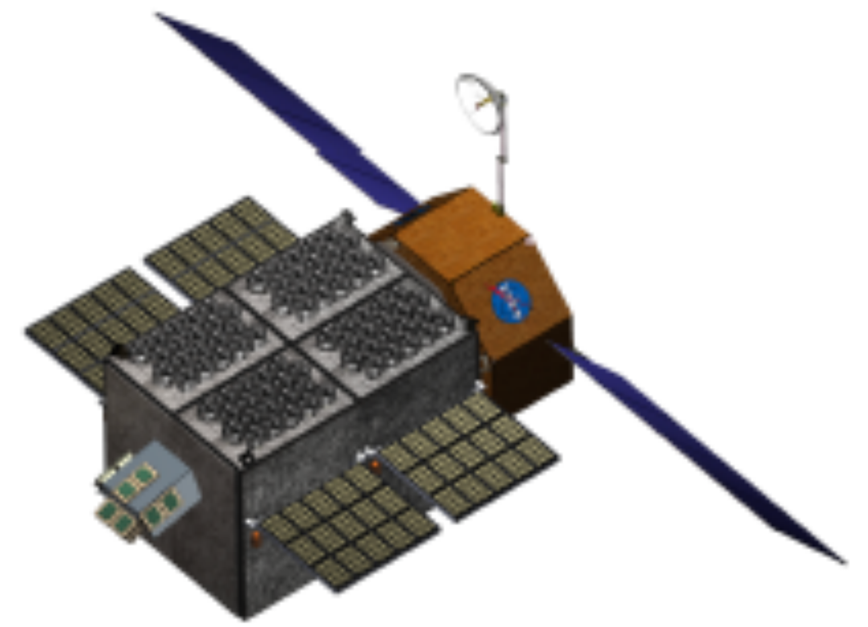
- X-ray imager with 10x Chandra area, much larger field of view
- Low earth orbit, low background for surface brightness studies; rapid response for transient studies



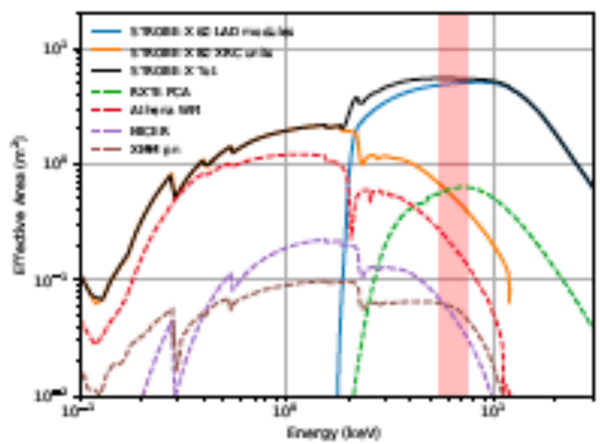


AXIS concept study at https://arxiv.org/abs/1807.02122

STROBE-X



STROBE-X Mission	
Instrument Mass (kg)	2,706
Spacecraft Bus Mass (kg)	1,737
Propellant (kg)	555
Total Mass (kg)	4,998
Orbit	LEO, 550 km altitude
Launcher	Falcon 9 FT
Launcher Capacity to LEO (kg)	5180 kg to 10° inclination
Instrument Power (W)	1,918
Spacecraft Power (W)	1,228
Attitude Control	3-axis stabilized, slew 15°/min
Solar Avoidance	< 45 deg
Data Gen/Orbit (raw, Gb)	36.0
Duration	5+ years



- Combines huge collecting area, high X-ray throughput, broad energy coverage, and excellent spectral and temporal resolution in a single facility.
- Characterize the behavior of X-ray sources over an unprecedentedly vast range of time scales.

STROBE-X concept study at https://arxiv.org/abs/1903.03035

Transient Astrophysics Probe (TAP)

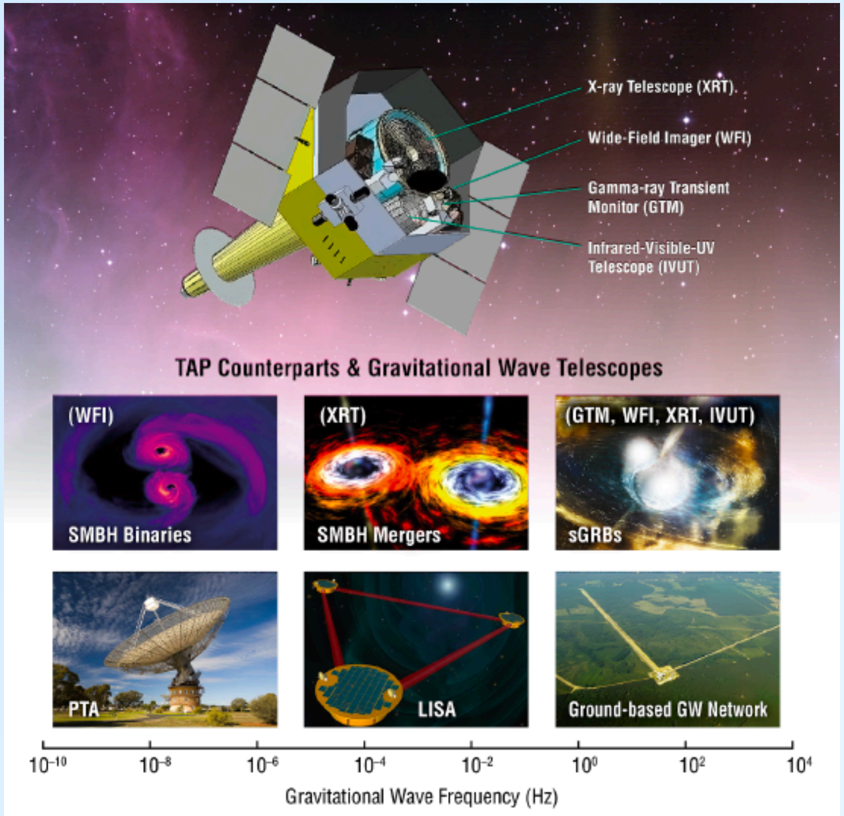


Table 2: *Estimated rates of sources discovered by the TAP instruments.*

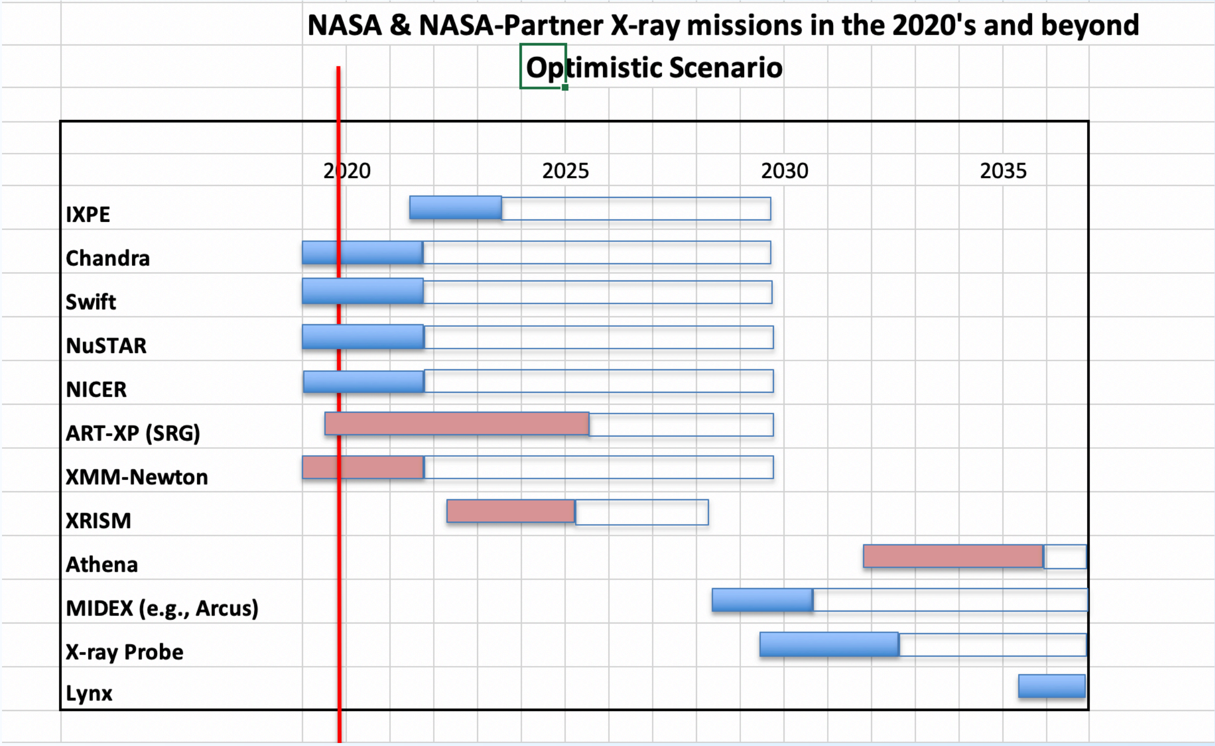
Transient Type	WFI Rate (yr^{-1})	XRT Rate (yr^{-1})	IVUT Rate		GTM rate (yr^{-1})
			IR (yr^{-1})	UV (yr^{-1})	
Objective 1 – X-ray, UV and IR Counterparts to Gravitational Wave Sources					
GW NS-NS (on-axis)	20	14	--	--	20
GW NS-NS (off-axis)	--	7	70	56	2
GW SMBH-SMBH (10^6 $M_\odot$)	--	≥ 1	--	--	--
GW SMBH-SMBH (10^9 $M_\odot$)	Several in 5 yr	--	--	--	--
Objective 2 - Highest Sensitivity Time-Domain Survey of the Transient Soft X-ray / UV Sky					
ccSN shock breakout	1	19	--	6	--
Jetted TDEs	106	1	--	--	--
Non-jetted TDEs	1	48	--	40	--
AGN (daily / weekly)	120 / 660	1600 / 8700		--	--
High-z GRBs (z>5)	25	--	22	--	--

- Rapid response, multi-band observatory for following up GW sources and other transients
- X-ray telescope and X-ray Lobster-eye, along with gamma-ray transient monitor and UVOIR telescope

Other X-ray Probes

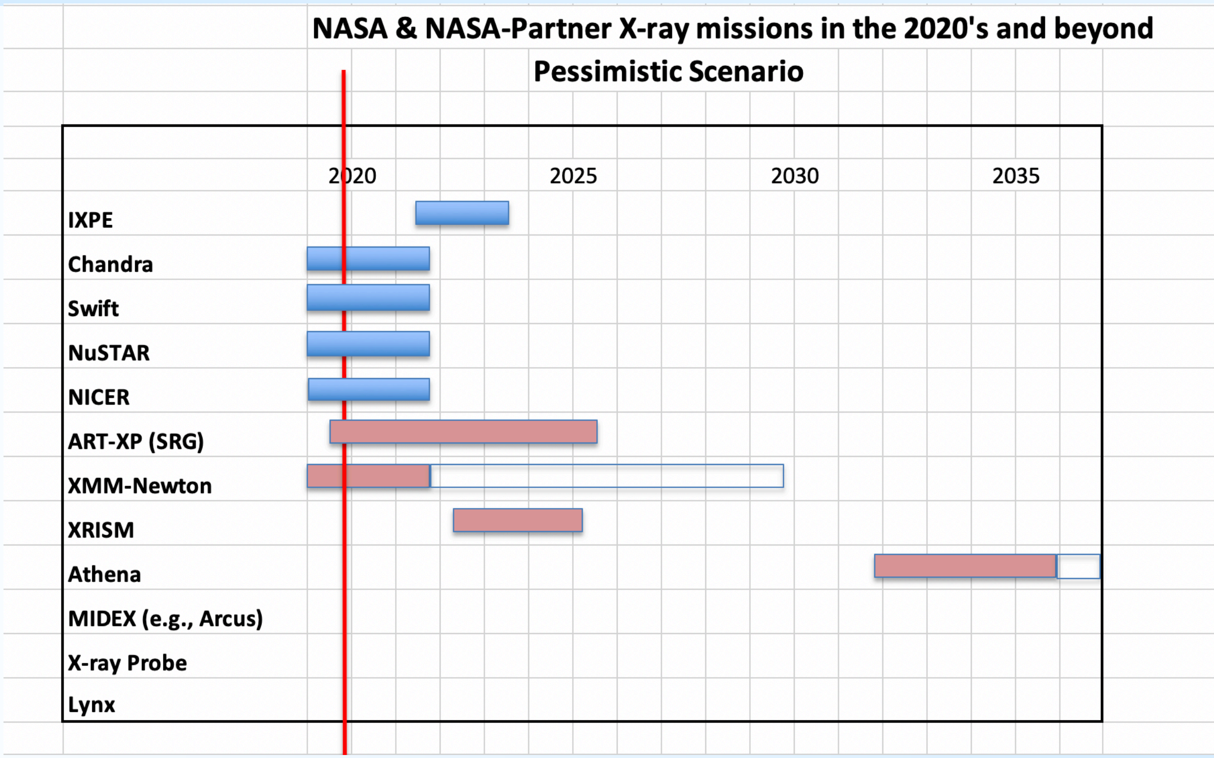
- White papers for a number of other probe concepts were submitted for consideration by the decadal survey.
- Submitted concepts include:
  - The X-ray Grating Spectroscopy Probe
    - Similar science to Arcus – missing baryons, AGN outflows, stellar coronae
    - $\lambda/\Delta\lambda > 5000$, effective area > 1000 cm2, at 653 eV, OVIII Lyα
  - The High-Energy X-ray Probe
    - Successor to NuSTAR
    - Response 40 times that of any previous mission in the 10-80 keV band and > 100 times in the 80-200 keV band.
    - Science goals: Black hole growth over cosmic time; probing accreting compact object power sources; constraining stellar evolution endpoints
  - X-ray Polarization Probe
    - Successor to IXPE
    - Science goals: structure of inner accretion flow onto black holes; use neutron stars as fundamental physics laboratories; probe how cosmic particle accelerators work
    - Broadband polarimetery over the wide 0.2-60 keV bandpass in addition to imaging polarimetry from 2-8 keV

Prospects for Future NASA X-ray Missions - 1



- An optimistic scenario leads to a healthy NASA X-ray astrophysics program for decades to come – long-lived extended missions, a MIDEX, a Probe, and Lynx
- Still a worrisome gap in the late 2020's…

Prospects for Future NASA X-ray Missions - 2



- A pessimistic scenario sees current fleet turned off in 2022, no X-ray MIDEX, no X-ray Probe, and Lynx deferred to a future decade.
- A more realistic scenario lies in between these two.

Summary

- Prospects for 2020's not unlike prospects for 2010's. Then we were:
  - Relying heavily on operating missions
  - Waiting on small explorers (NuSTAR and GEMS)
  - Relying on strong international partnerships (e.g., Astro-H)
  - Waiting on decadal survey to recommend IXO
- Technology advances over the decade improve the prospects for NASA X-ray missions to make major advances
- New mission classes make possible a broader range of investigations
  - Astrophysics Probes (assuming Decadal Survey recommendation)
  - SmallSats/CubeSats
- NASA will continue to rely on a mix of operating missions, small, medium and large new missions and strong international partnerships to maintain a strong X-ray astronomy program
- Final note: X-ray astronomy is visible at the highest levels of NASA: weekly report by the Administrator highlighted a NuSTAR image of NGC 6946 featuring a flaring ULX