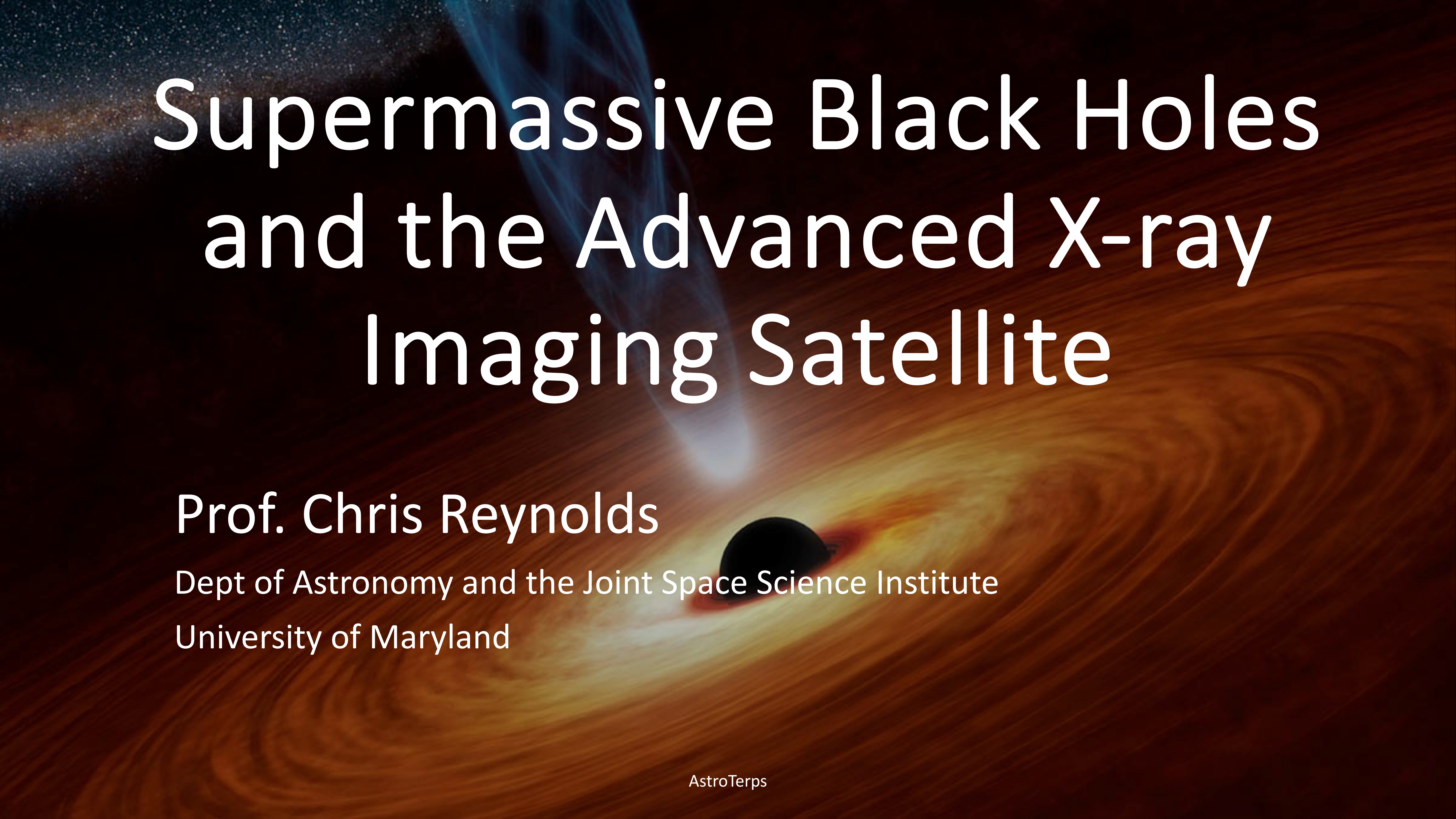
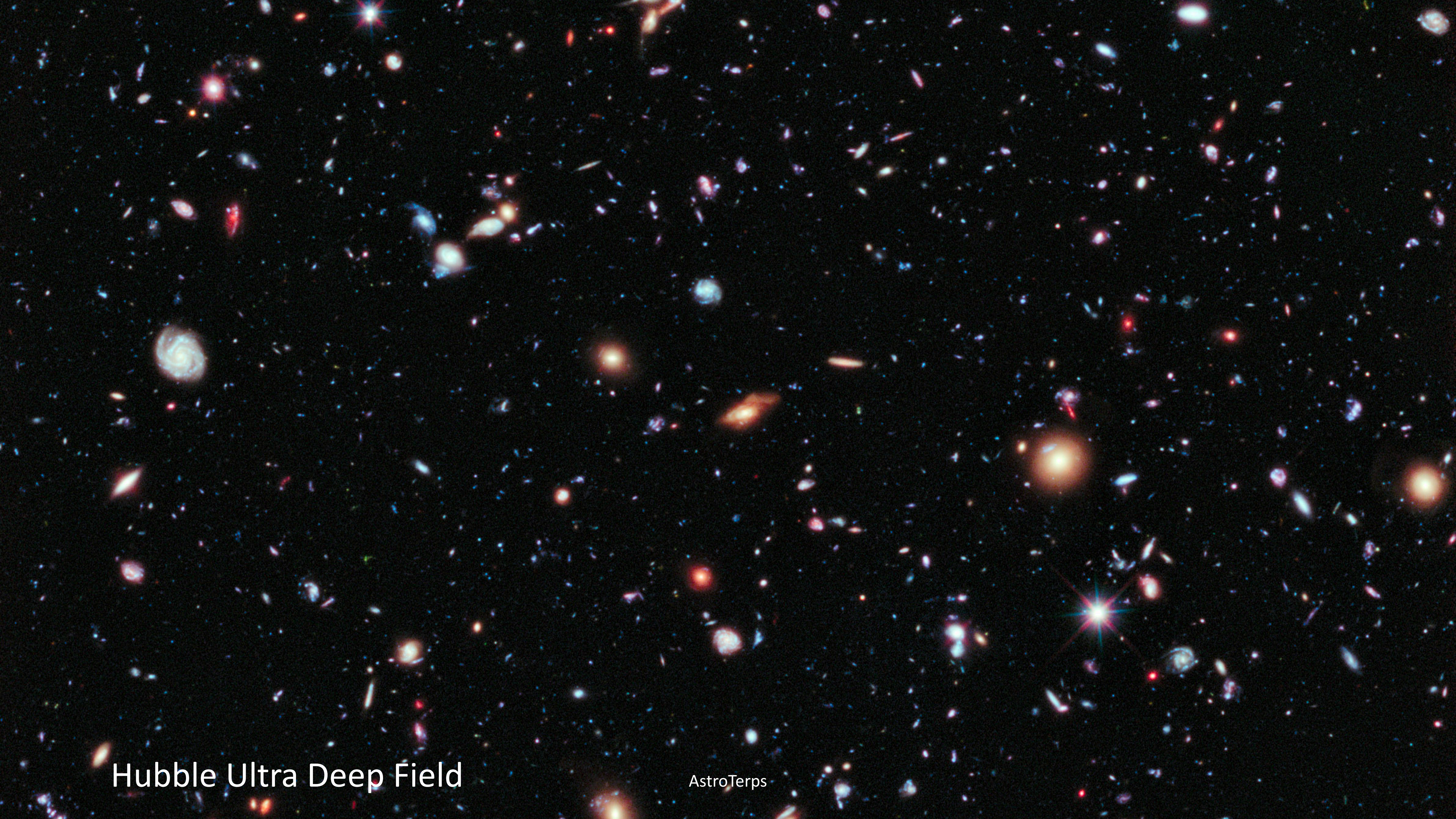


Supermassive Black Holes and the Advanced X-ray Imaging Satellite

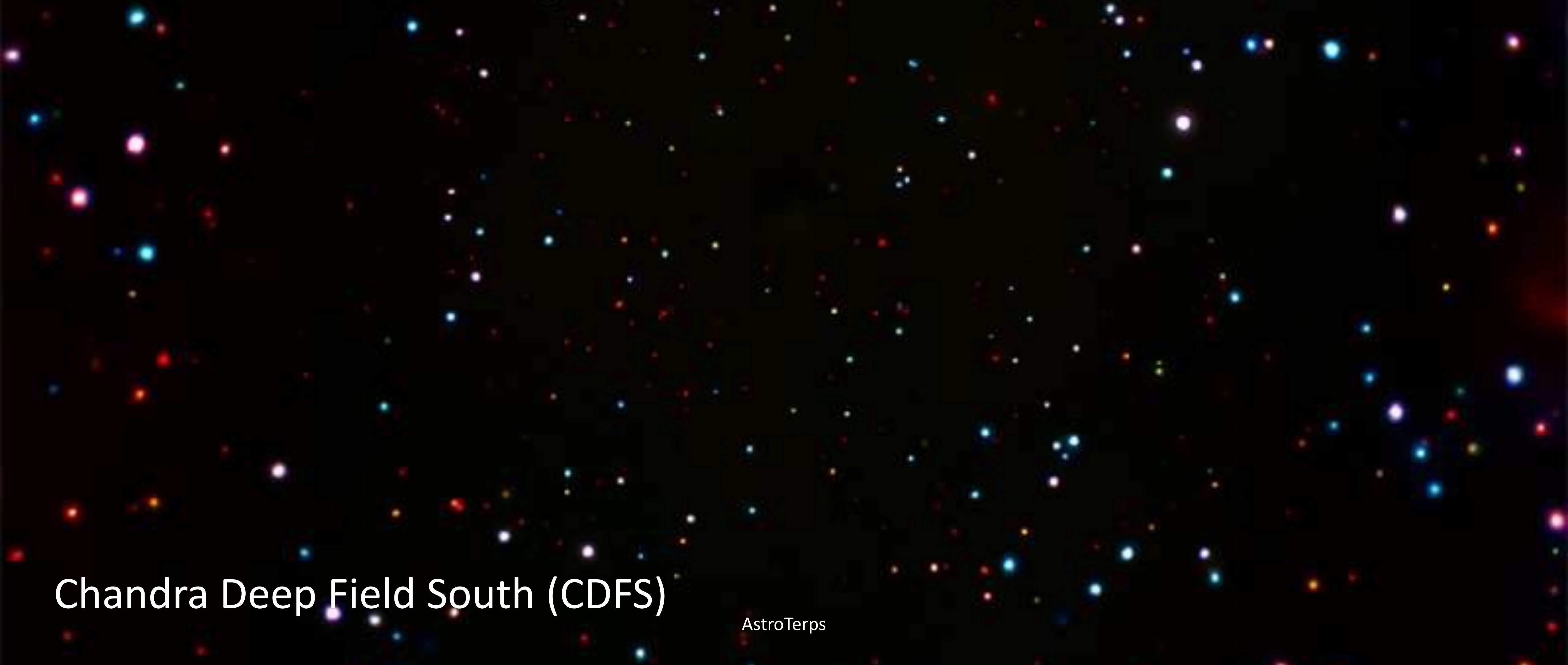
Prof. Chris Reynolds

Dept of Astronomy and the Joint Space Science Institute

University of Maryland

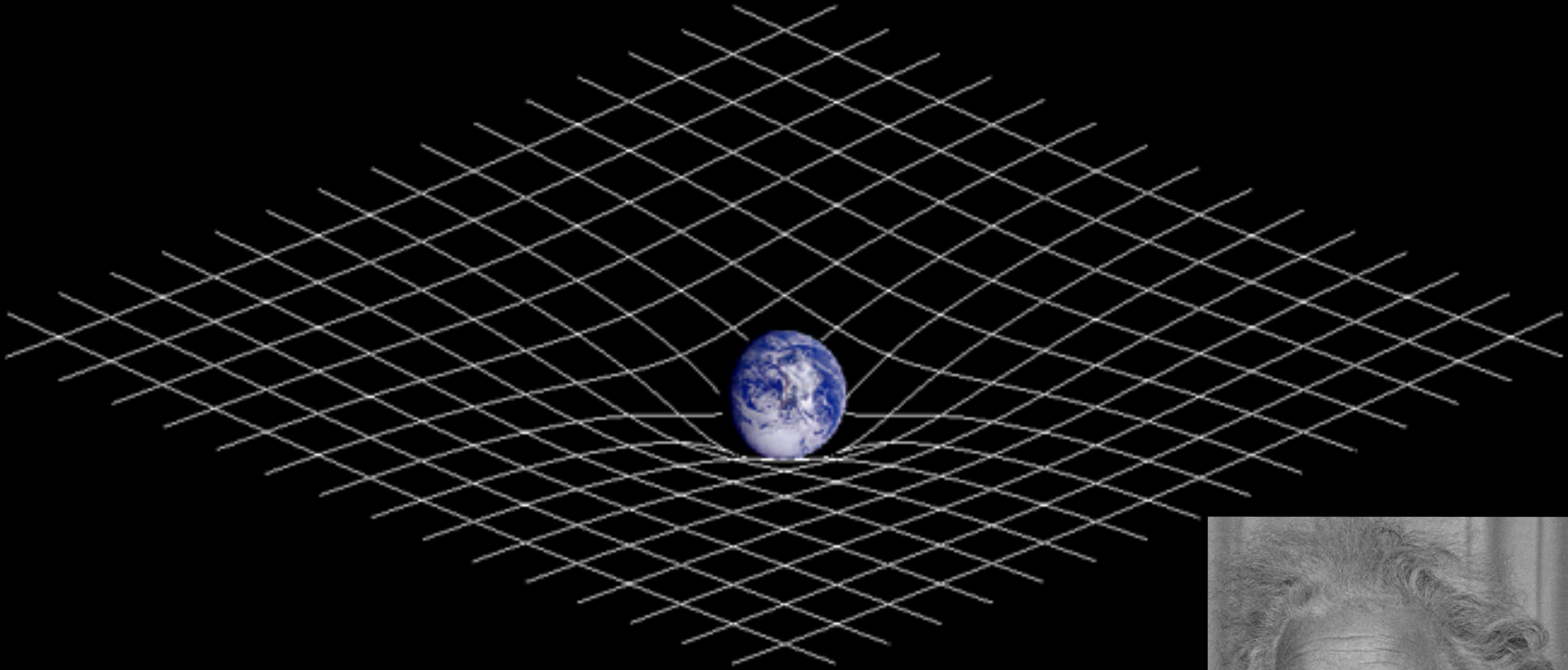


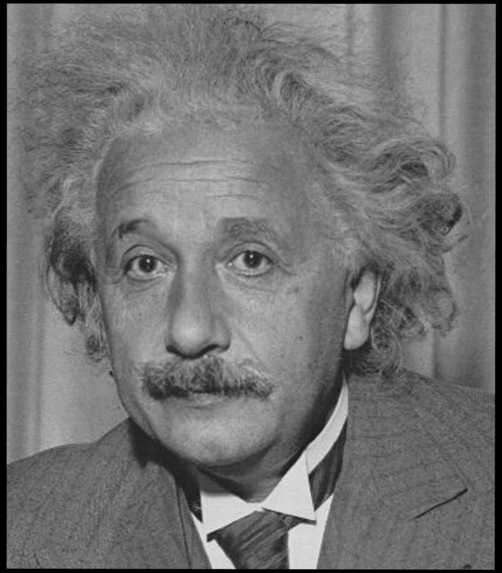
Hubble Ultra Deep Field



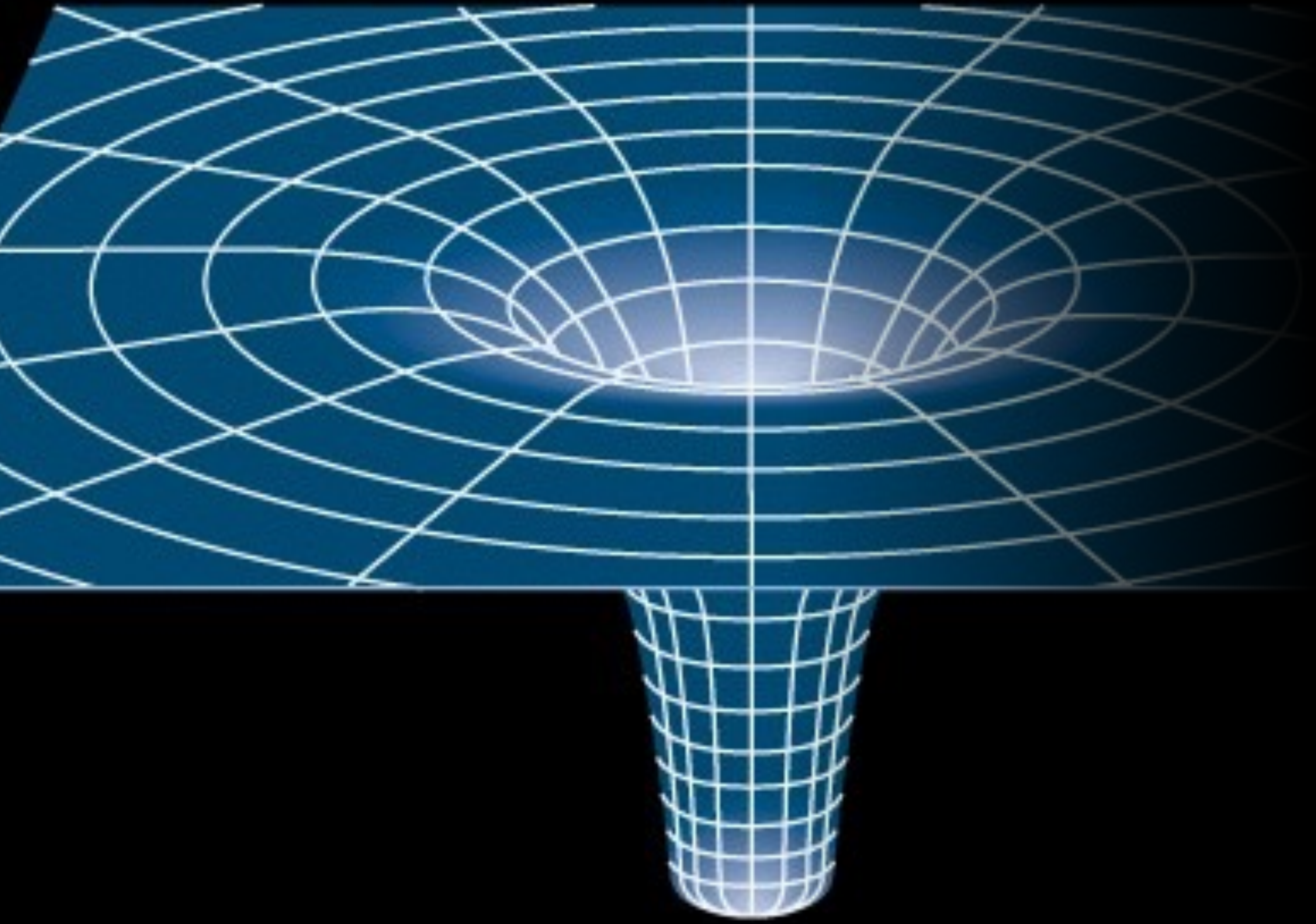
Chandra Deep Field South (CDFS)

- What are black holes?
- How do we see them?
- Where do we find them?
- When/how were they formed?





Einstein's "General Theory of Relativity"… attributes gravity to the curvature of space and time (1915)

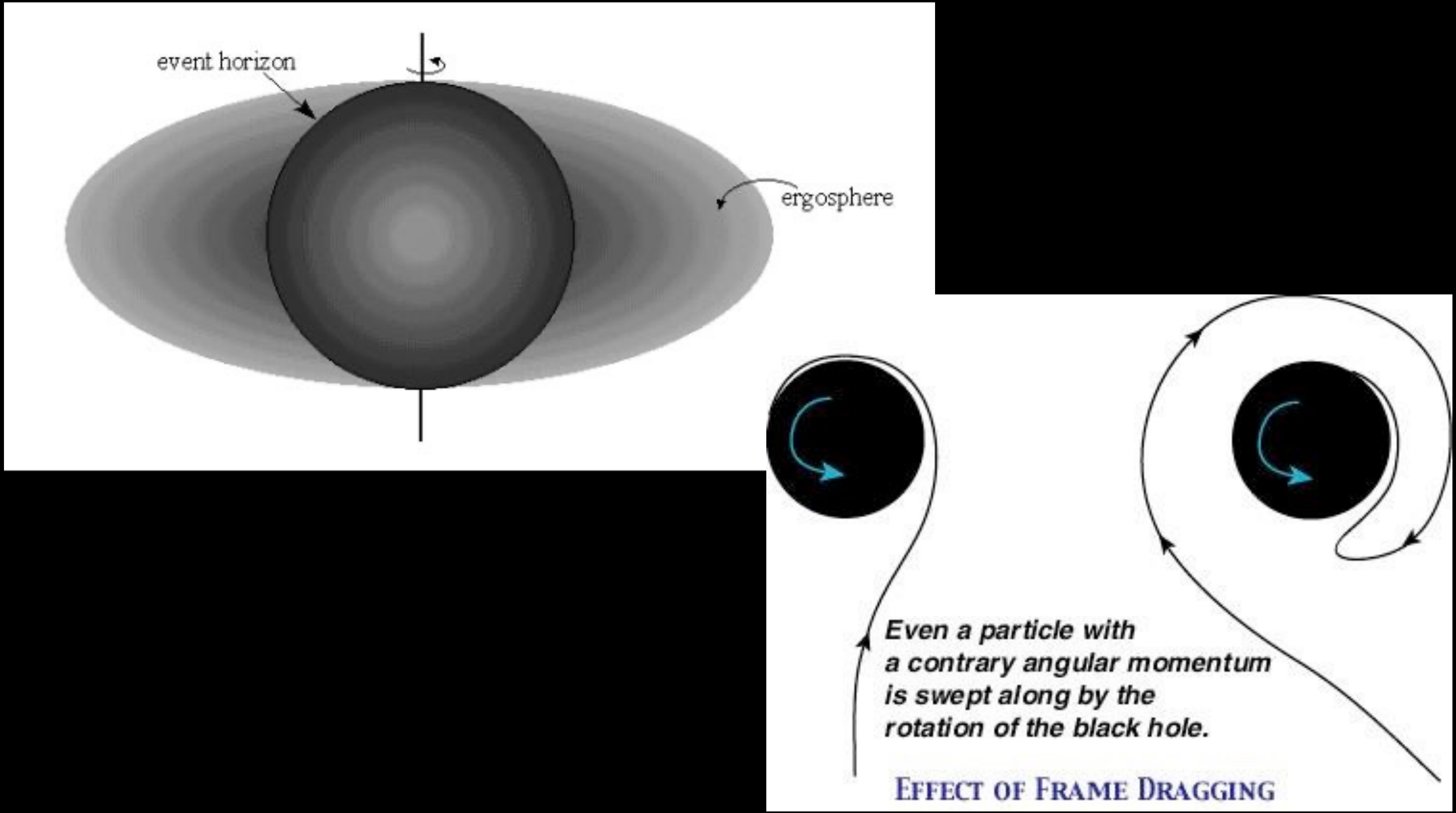


“Gravity always wins”
(Fake Plastic Trees, Radiohead)

Credit : Cetin Bal

AstroTerps

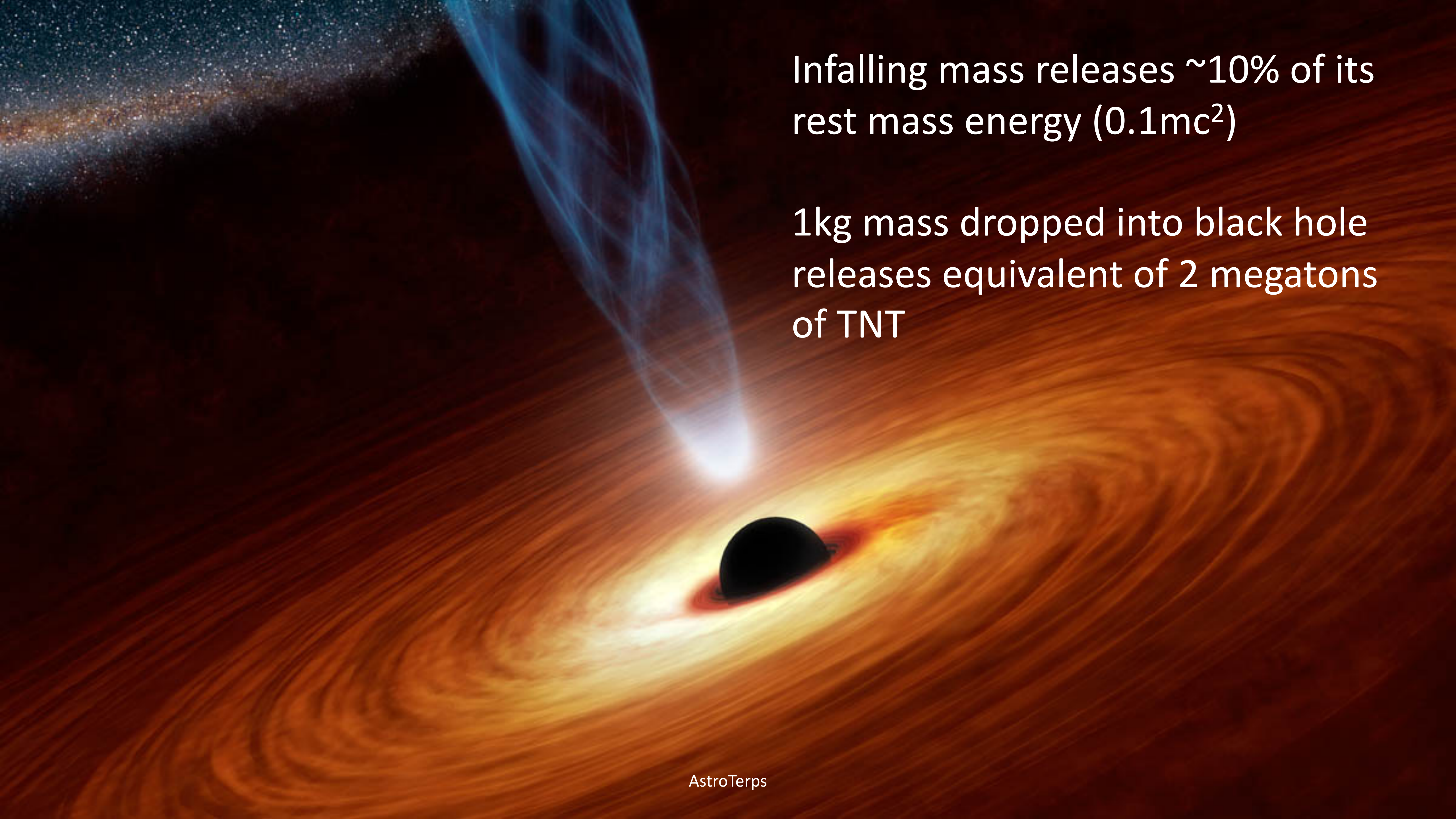
Frame dragging and the ergosphere



Even a particle with a contrary angular momentum is swept along by the rotation of the black hole.

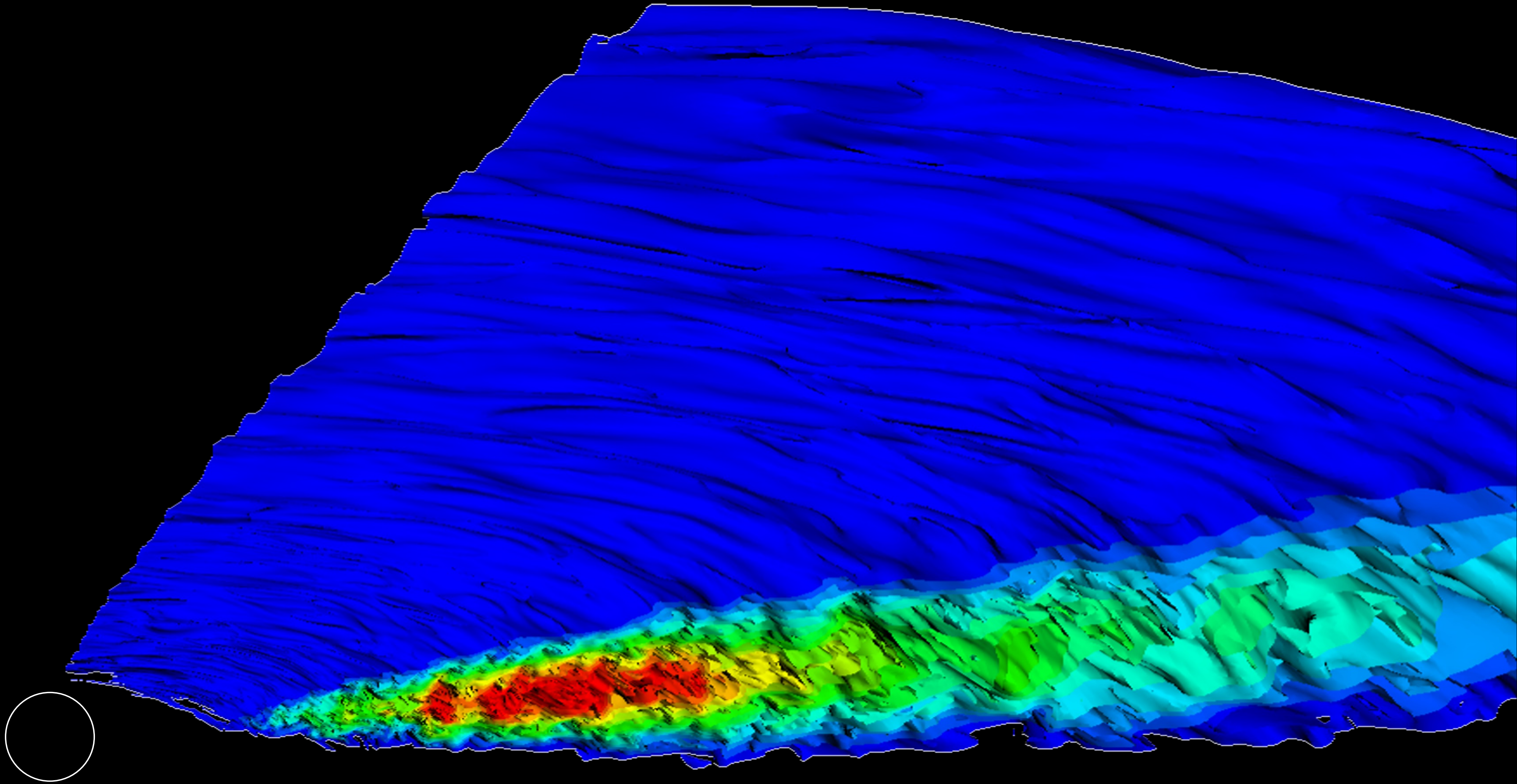
EFFECT OF FRAME DRAGGING

Graphics: University of Winnipeg, Physics Dept.

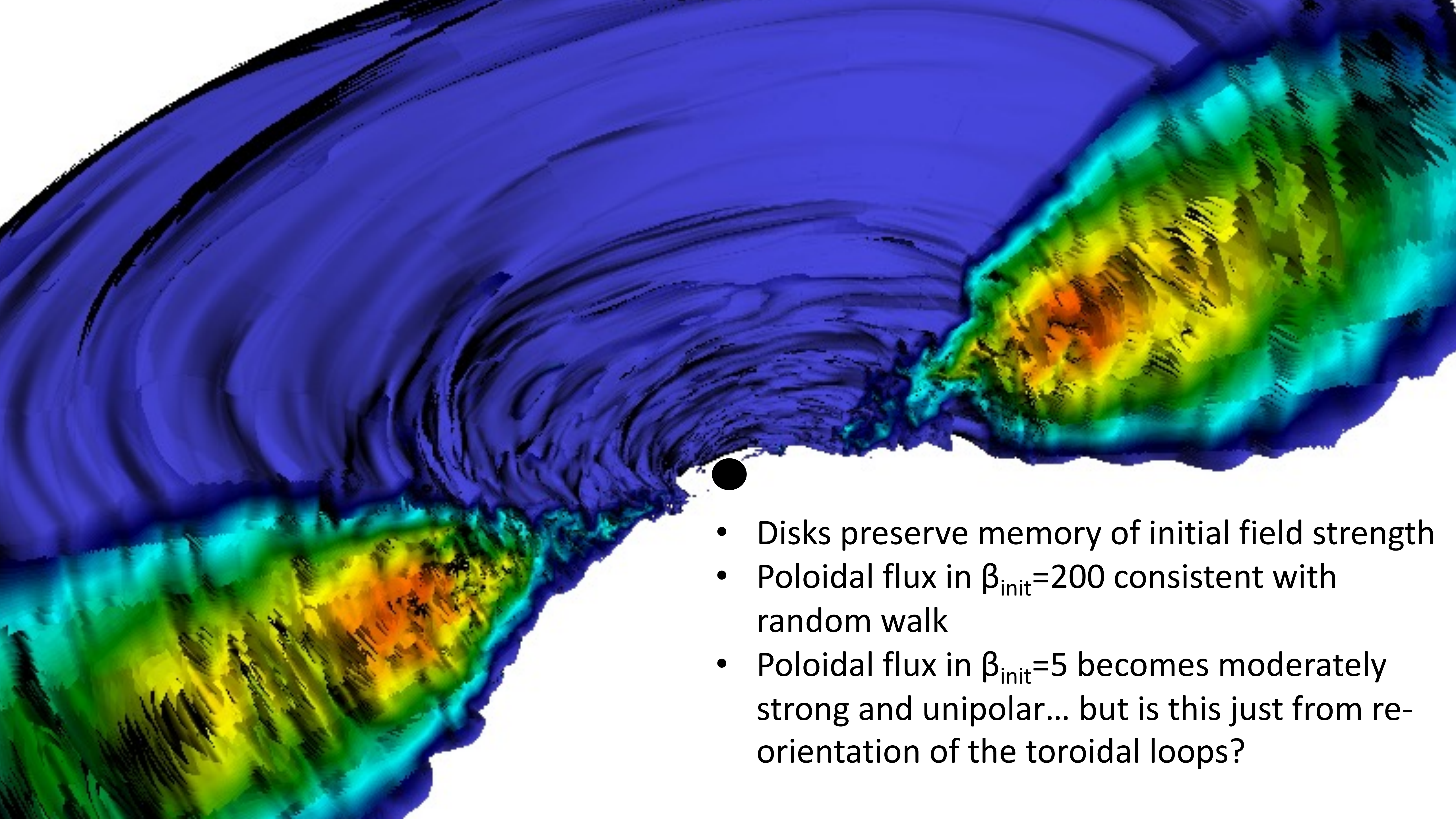


Infalling mass releases ~10% of its rest mass energy ($0.1mc^2$)

1kg mass dropped into black hole releases equivalent of 2 megatons of TNT



Hogg & Reynolds (2018)

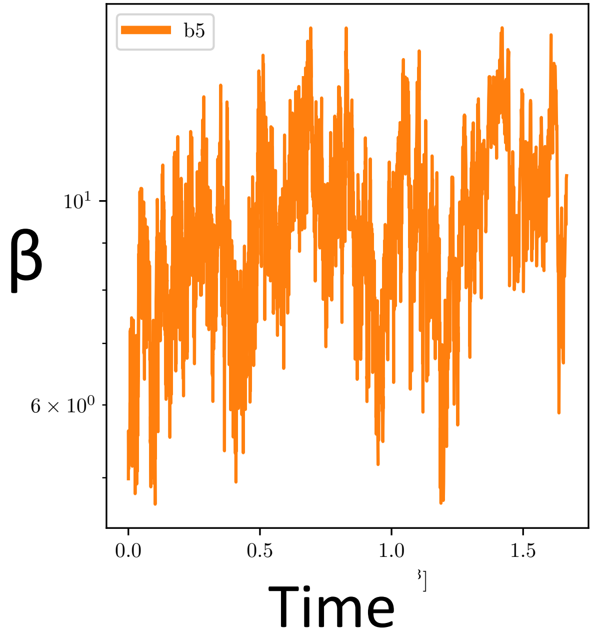


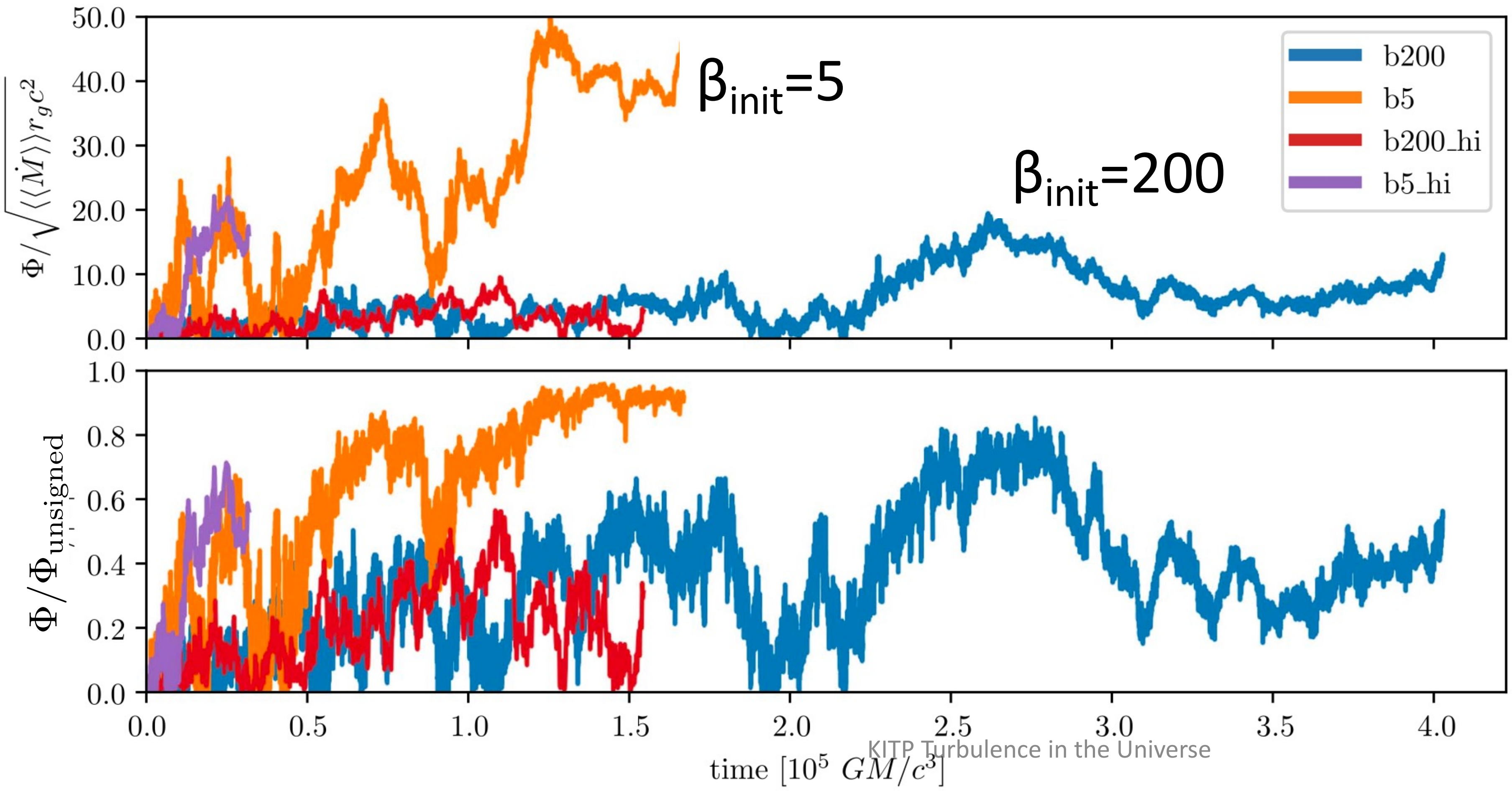
- Disks preserve memory of initial field strength
- Poloidal flux in $\beta_{init}=200$ consistent with random walk
- Poloidal flux in $\beta_{init}=5$ becomes moderately strong and unipolar… but is this just from re-orientation of the toroidal loops?

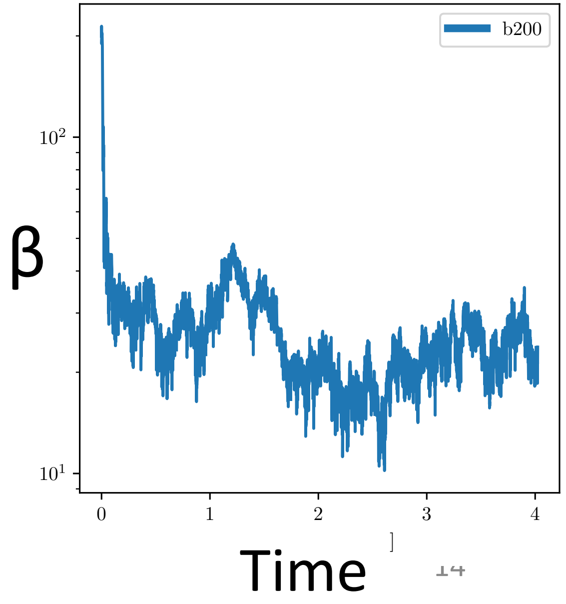
Growth of large-scale fields?

Rodman & Reynolds (2024)

Radiatively-inefficient h/r ~ 0.3 disk
Non-relativistic MHD, pseudo-Newtonian potential
Initially poloidal field (β=5 and β=200 cases)





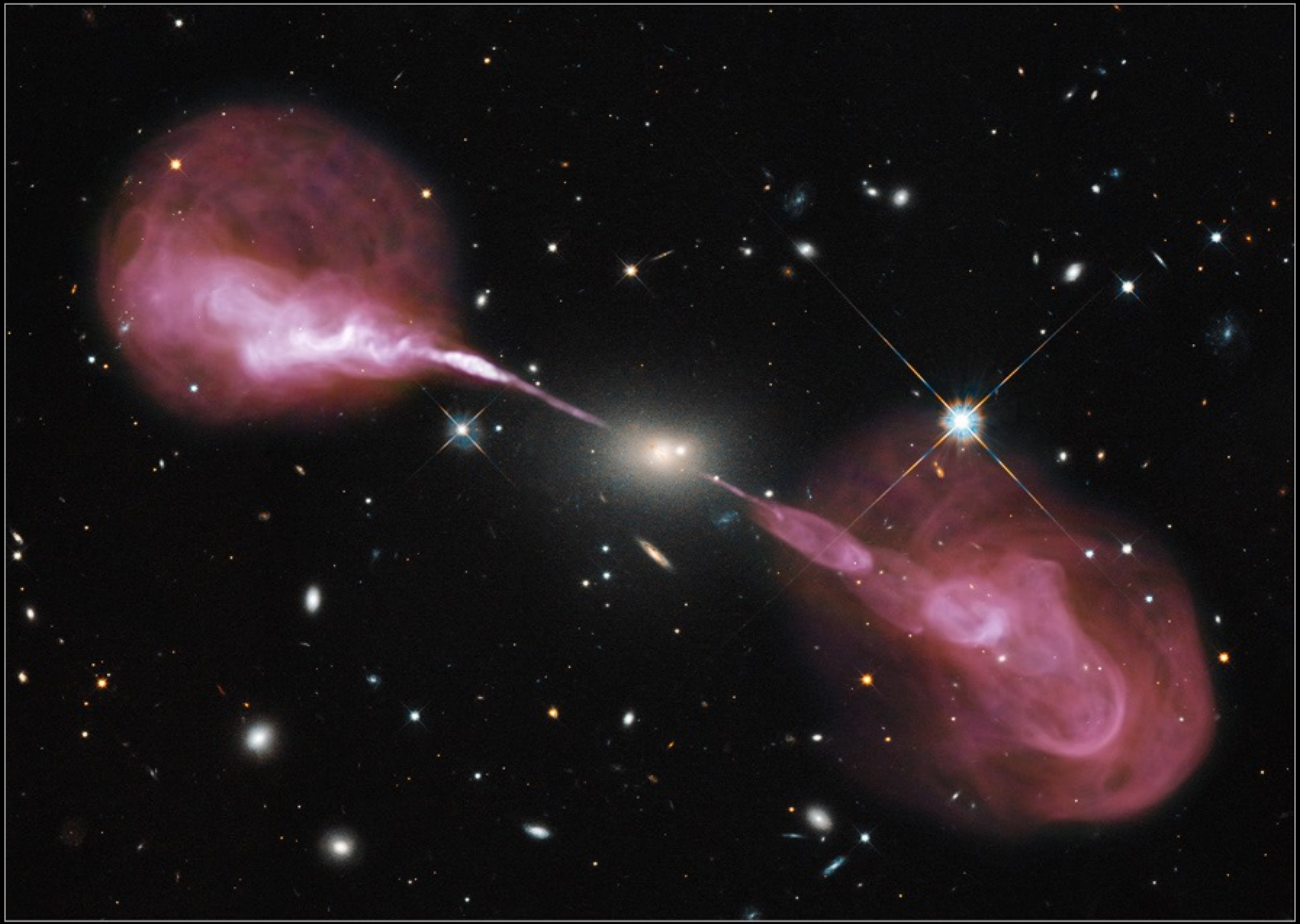


How do we find and study supermassive black holes?


AstroTerps

Centaurus-A

Radio Galaxy Hercules A



Hubble Heritage

NASA, ESA, NRAO • *HST* WFC3/UVIS • VLA • STScI-PRC12-47

AstroTerps

NGC 1365

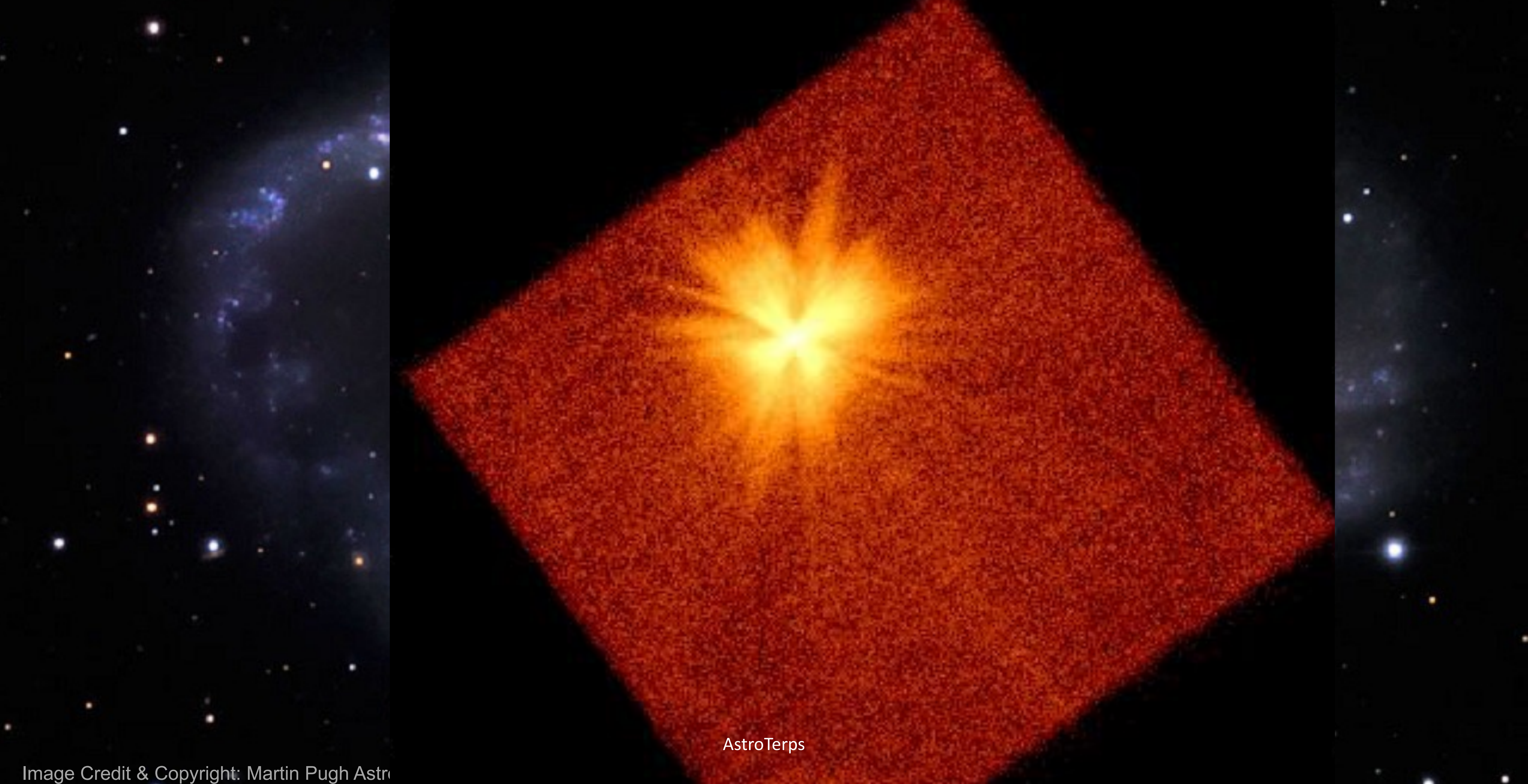
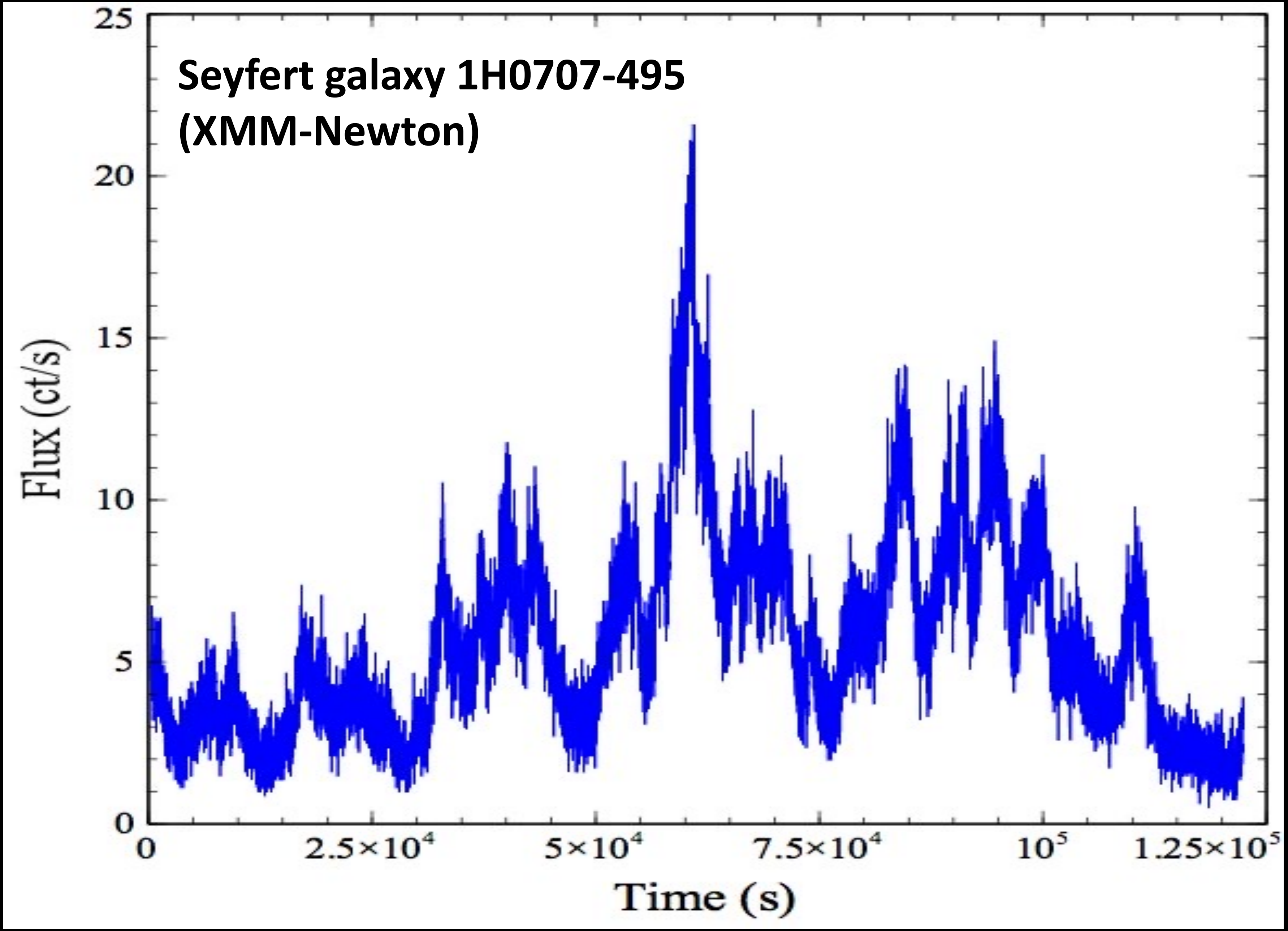
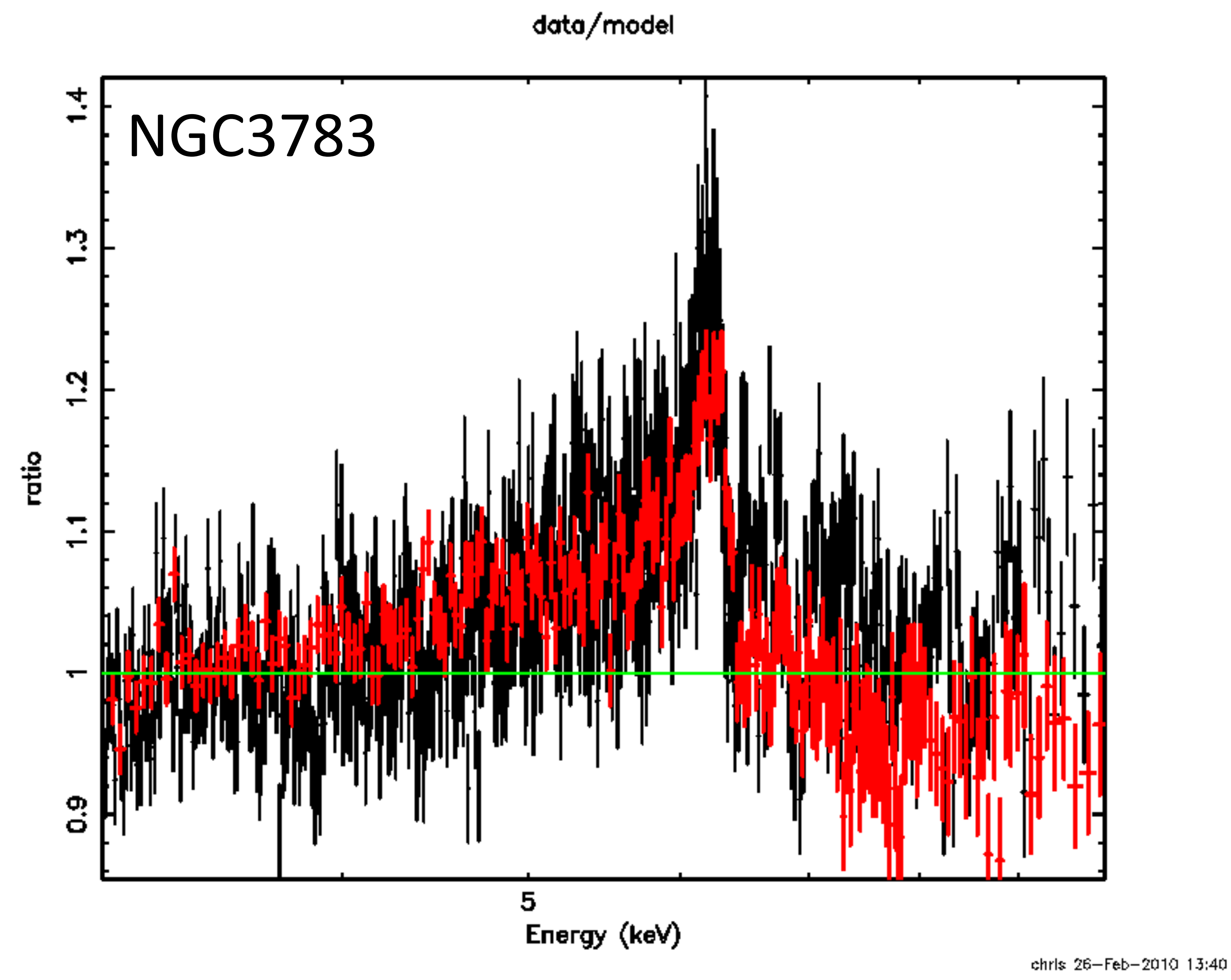
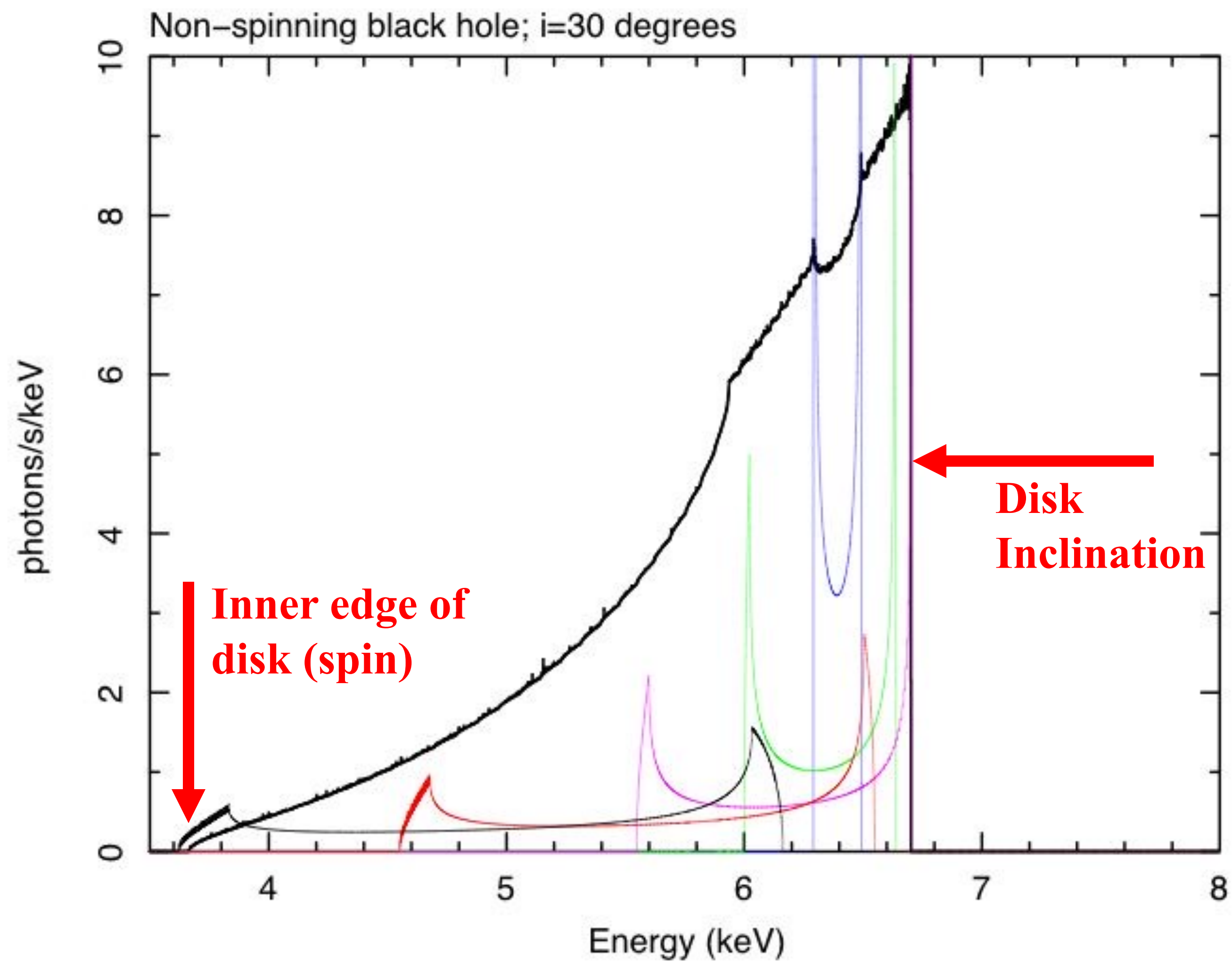


Image Credit & Copyright: Martin Pugh Astr


Seyfert galaxy 1H0707-495
(XMM-Newton)
Flux (ct/s)
25
20
15
10
5
0
Time (s)
0
2.5×10⁴
5×10⁴
7.5×10⁴
10⁵
1.25×10⁵

AstroTerps

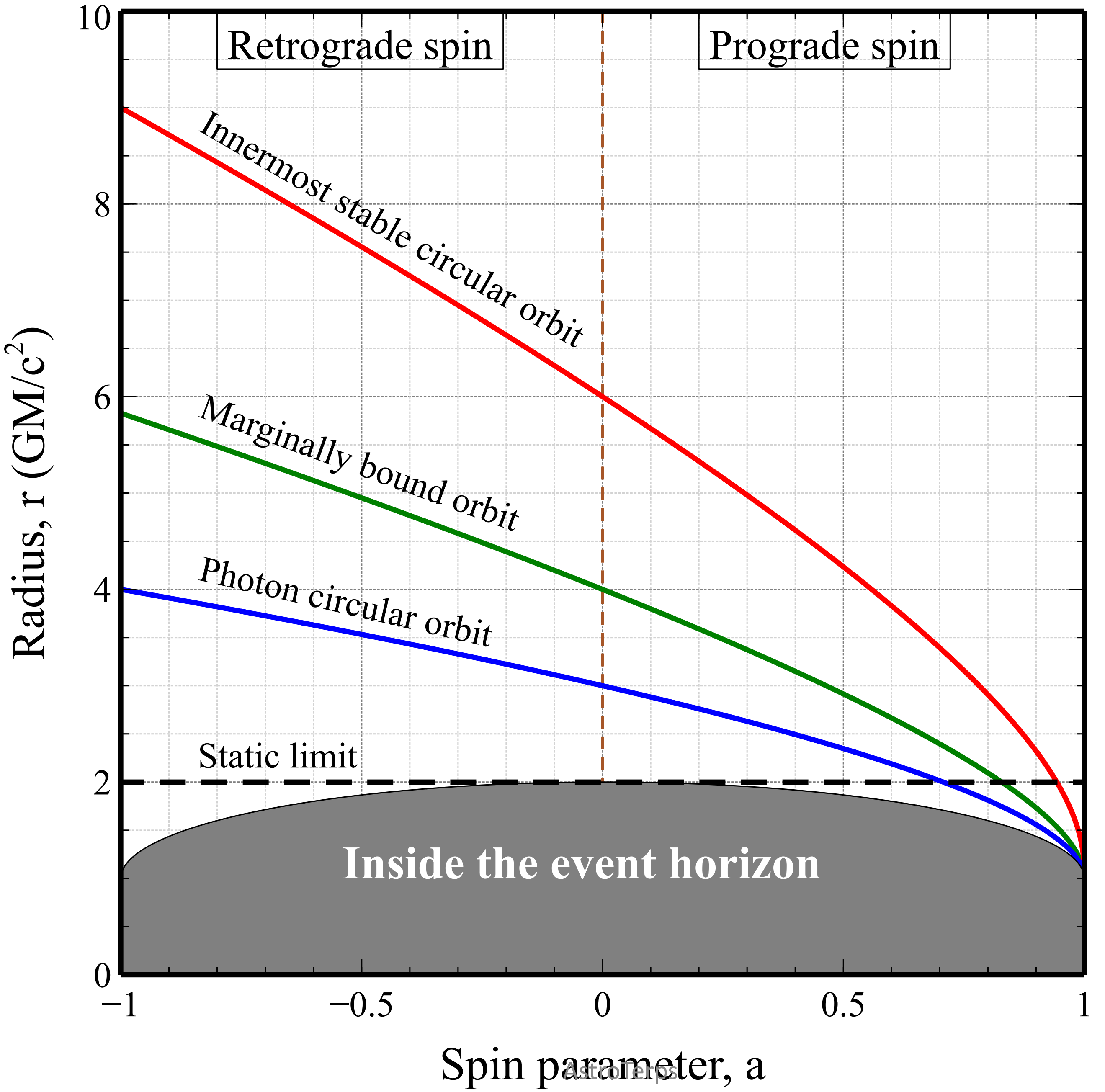

data/model
NGC3783
ratio
1.4
1.3
1.2
1.1
1
0.9
5
Energy (keV)
chris 26-Feb-2010 13:40



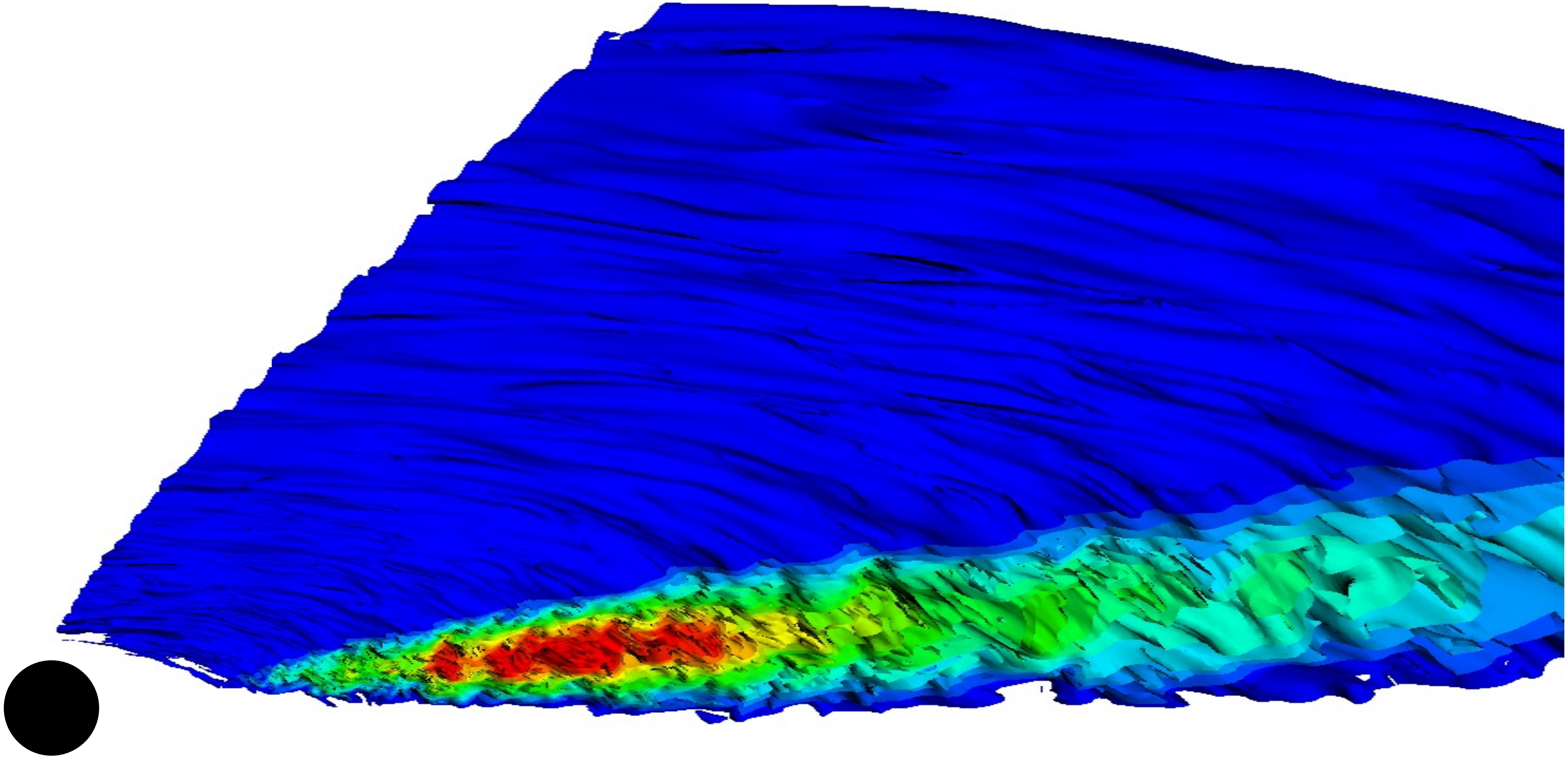
Inner edge of disk (spin)

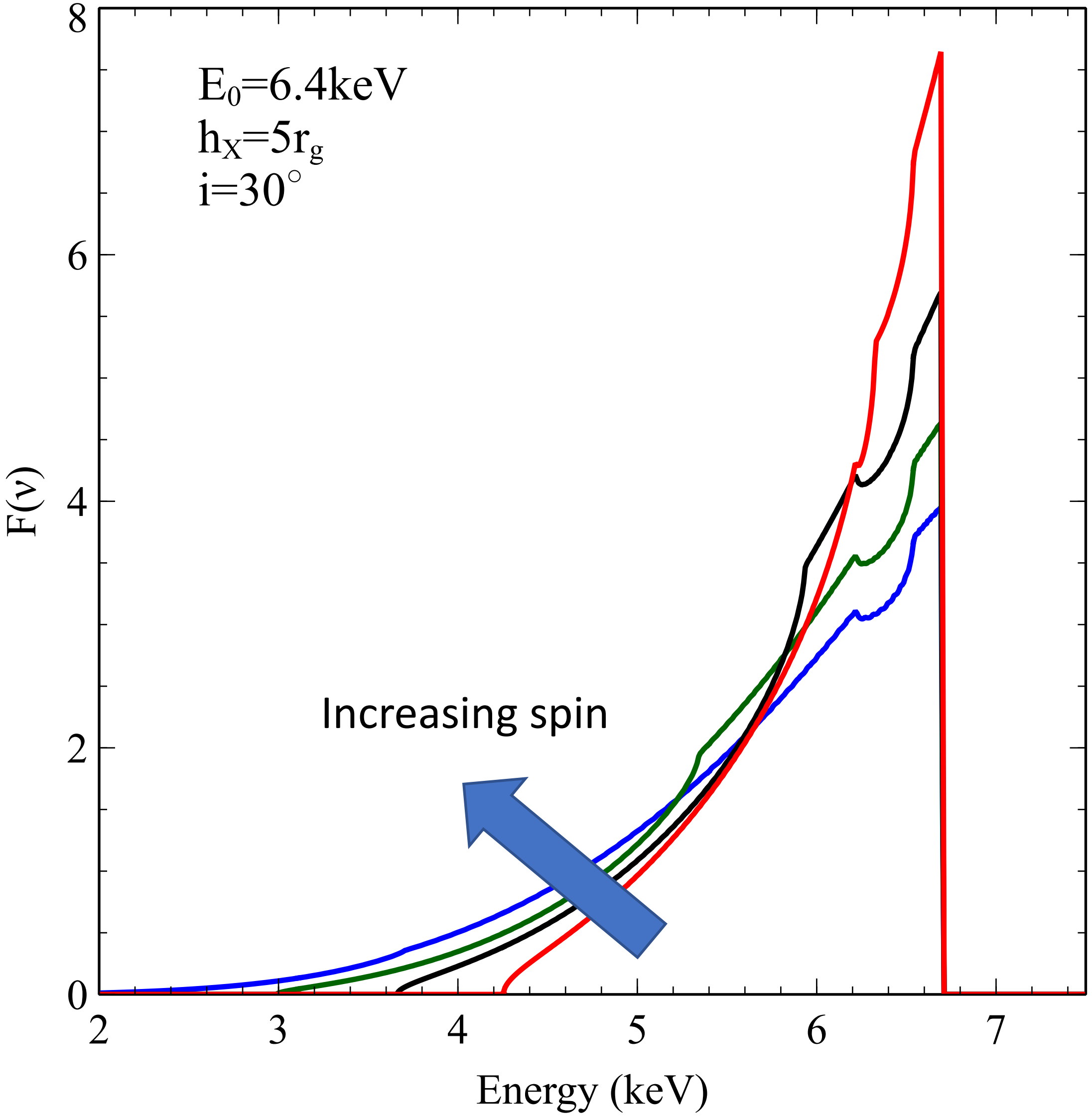
Disk Inclination

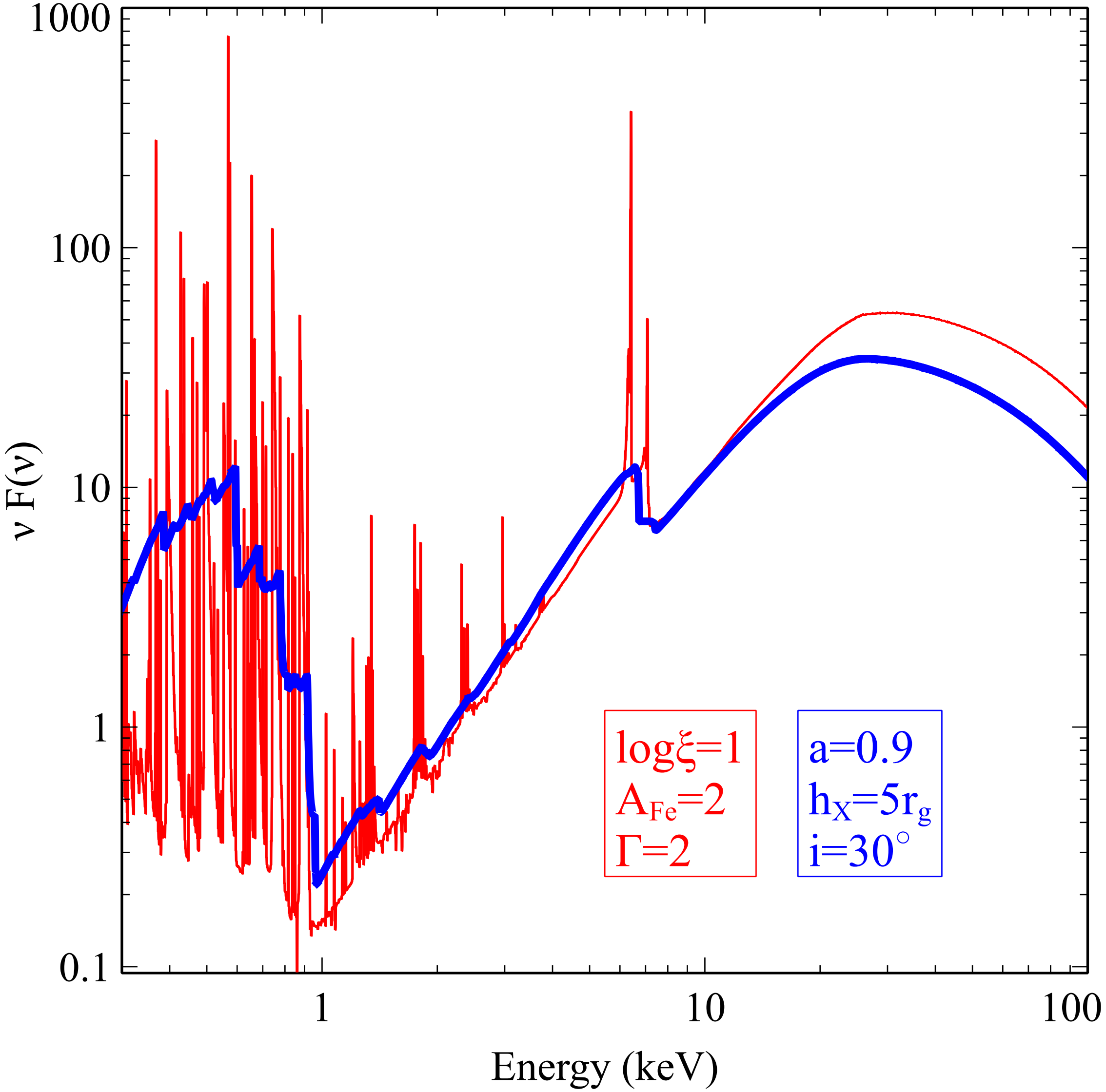
AstroTerps

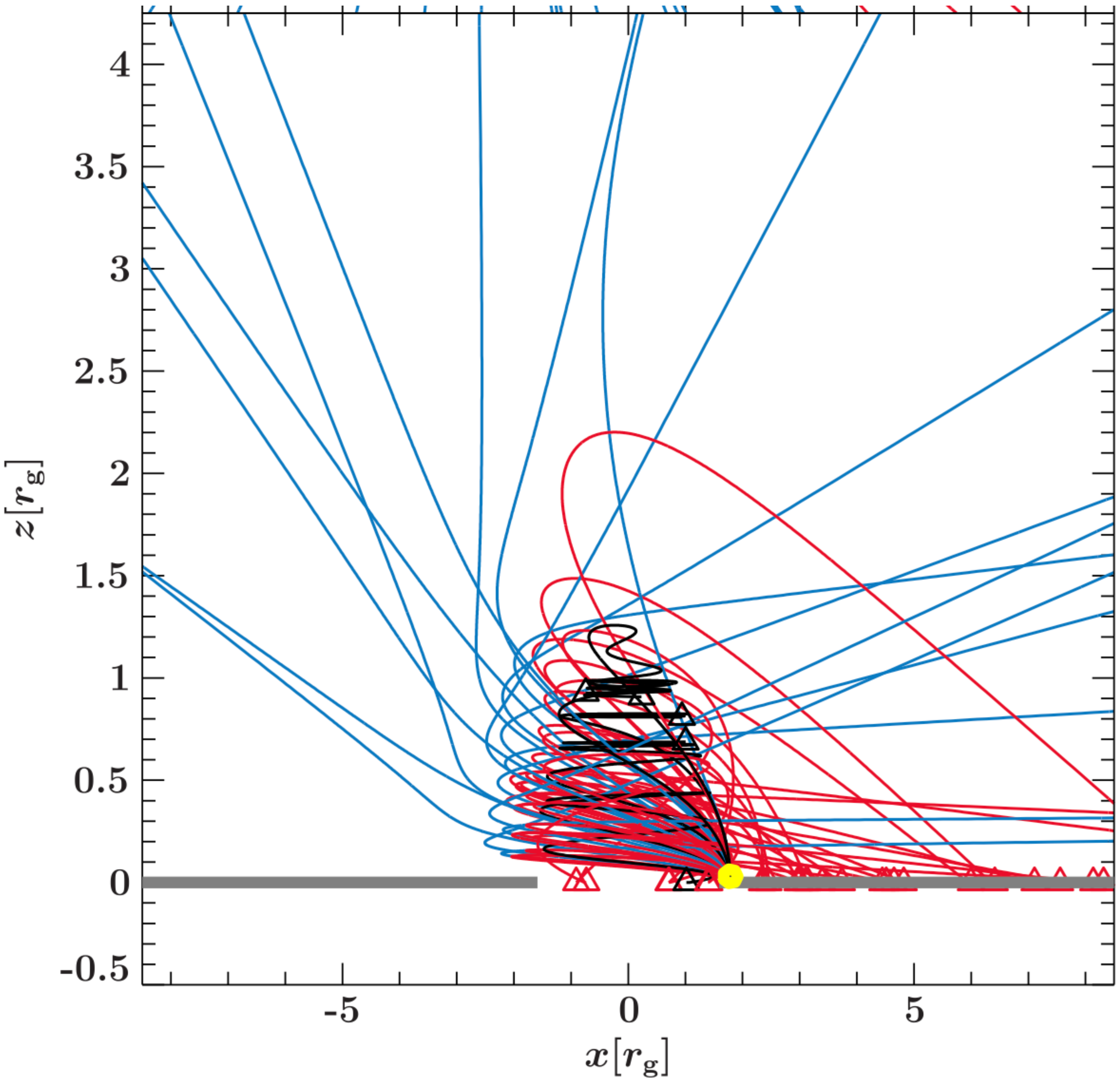

Retrograde spin
Prograde spin
Innermost stable circular orbit
Marginally bound orbit
Photon circular orbit
Static limit
Inside the event horizon
Radius, r (GM/c²)
Spin parameter, a
10
8
6
4
2
0
−1
−0.5
0
0.5
1

AstroTerps



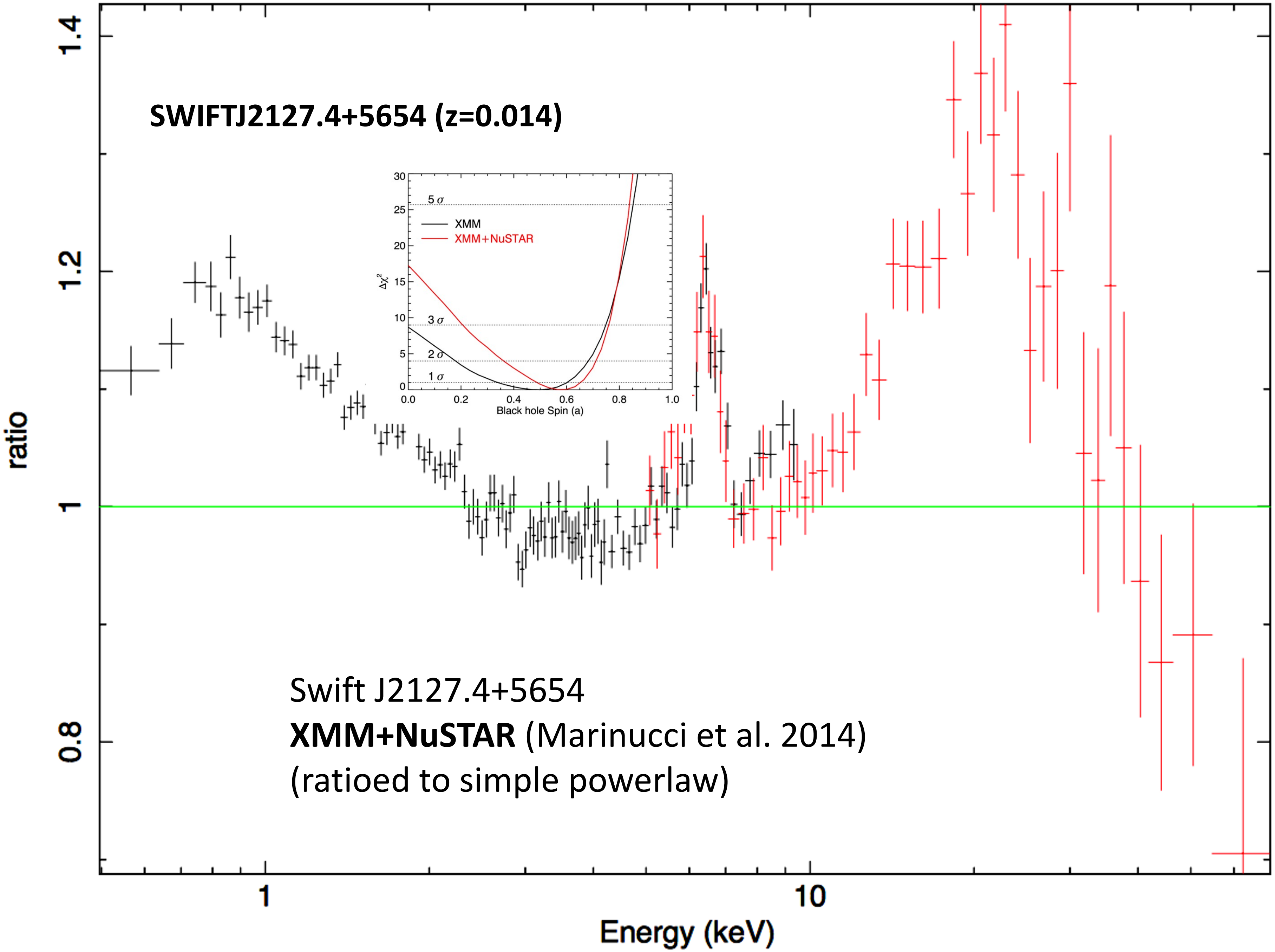

E_0=6.4keV
h_X=5r_g
i=30°
Increasing spin
F(ν)
8
6
4
2
0
2
3
4
5
6
7
Energy (keV)


ν F(ν)
1000
100
10
1
0.1
1
10
100
Energy (keV)
logξ=1
A_{Fe}=2
Γ=2
a=0.9
h_X=5r_g
i=30°

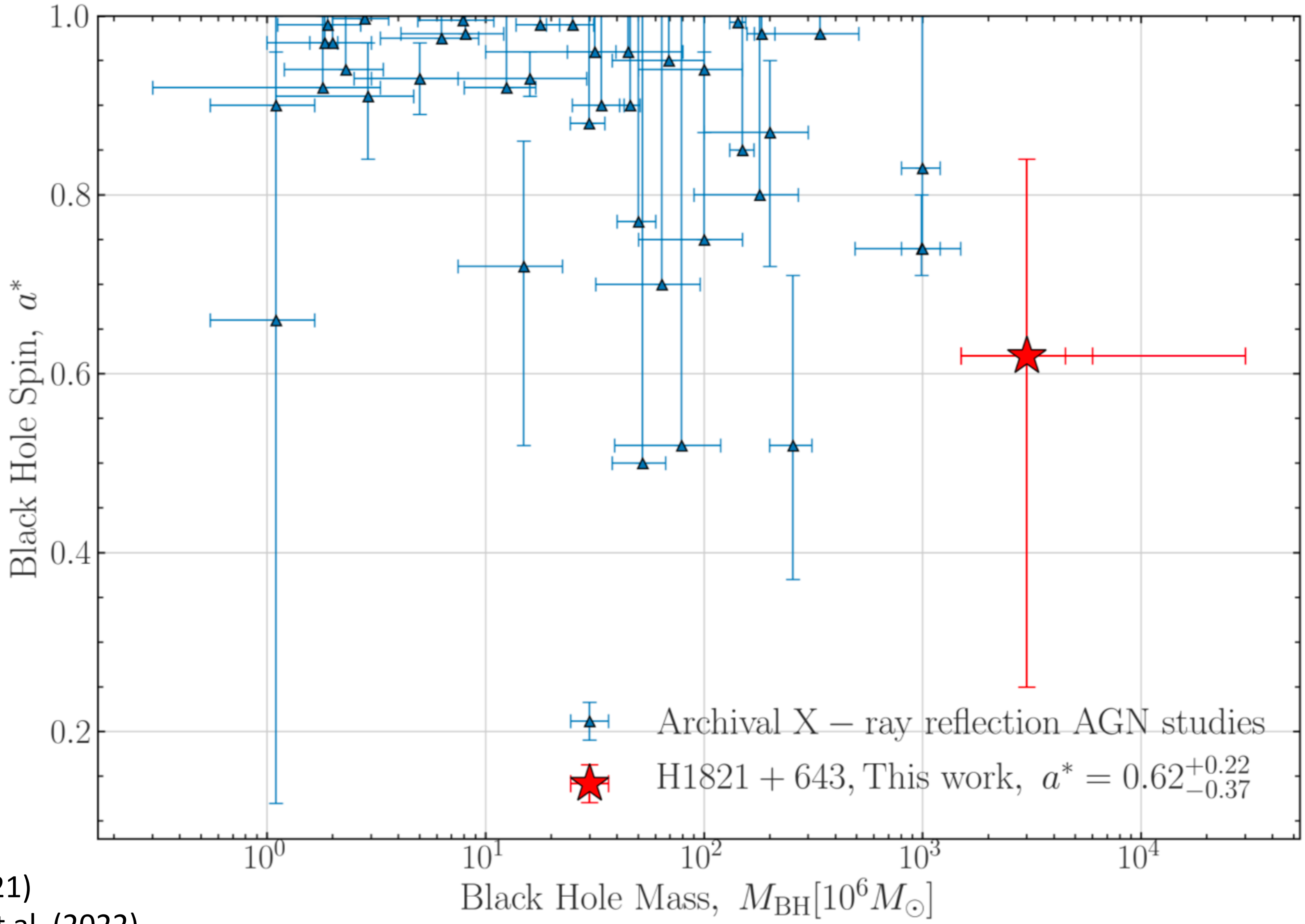


4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
$z[r_g]$
-5
0
5
$x[r_g]$

SWIFTJ2127.4+5654 (z=0.014)

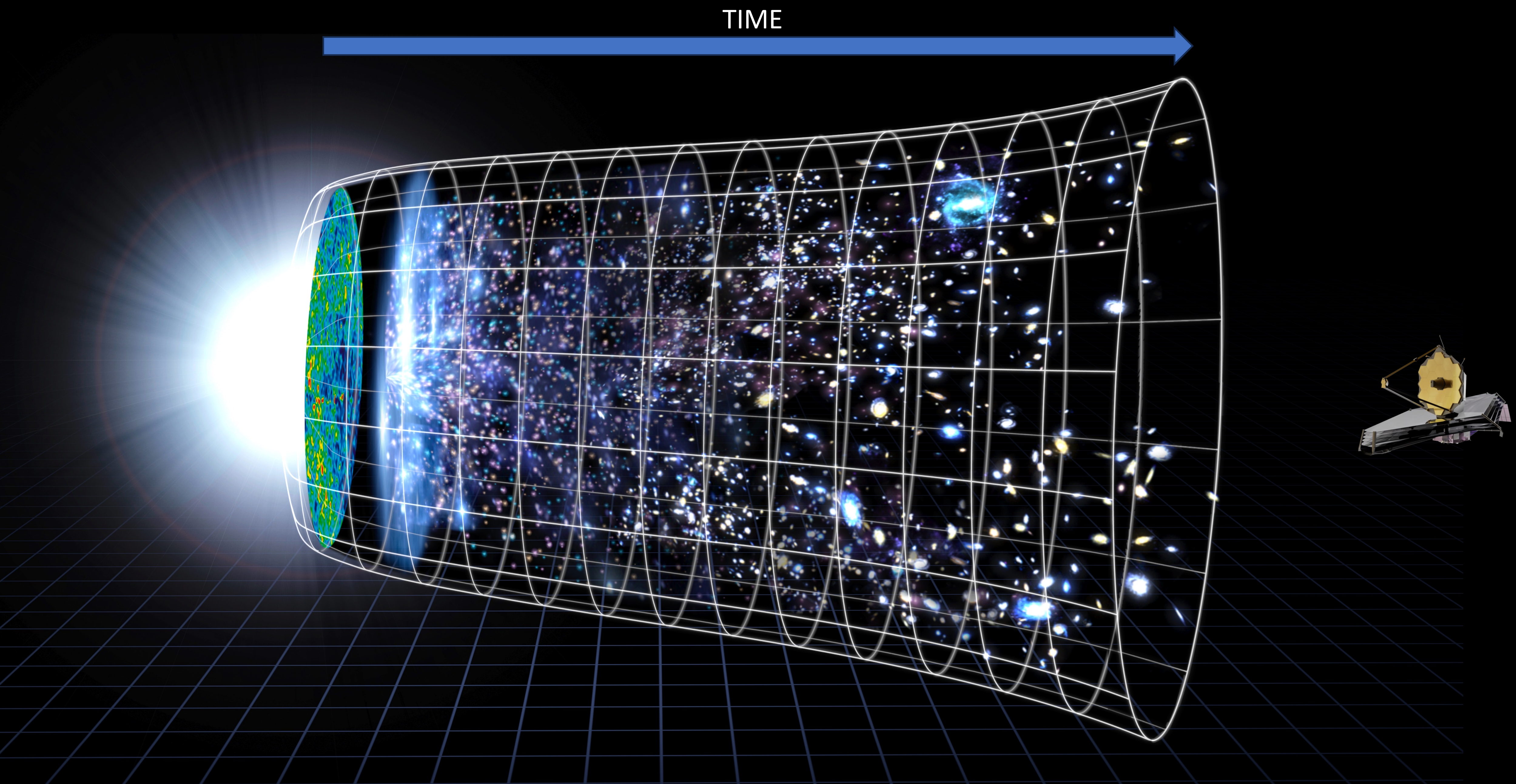


Swift J2127.4+5654
XMM+NuSTAR (Marinucci et al. 2014)
(ratioed to simple powerlaw)



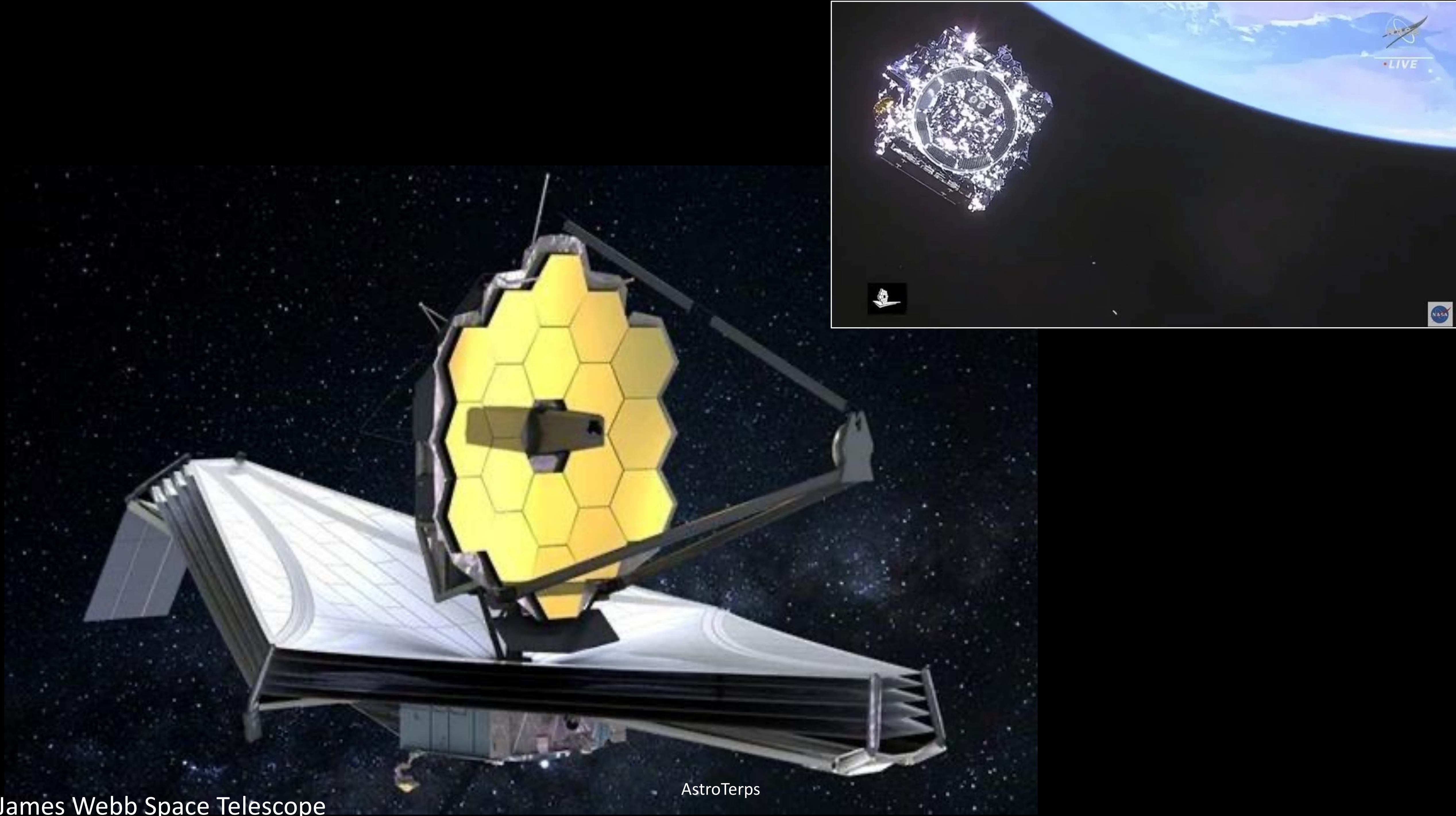
Reynolds (2021)
Sisk-Reynes et al. (2022)

When/where did supermassive black holes form? ($1B question)



AstroTerps

SA

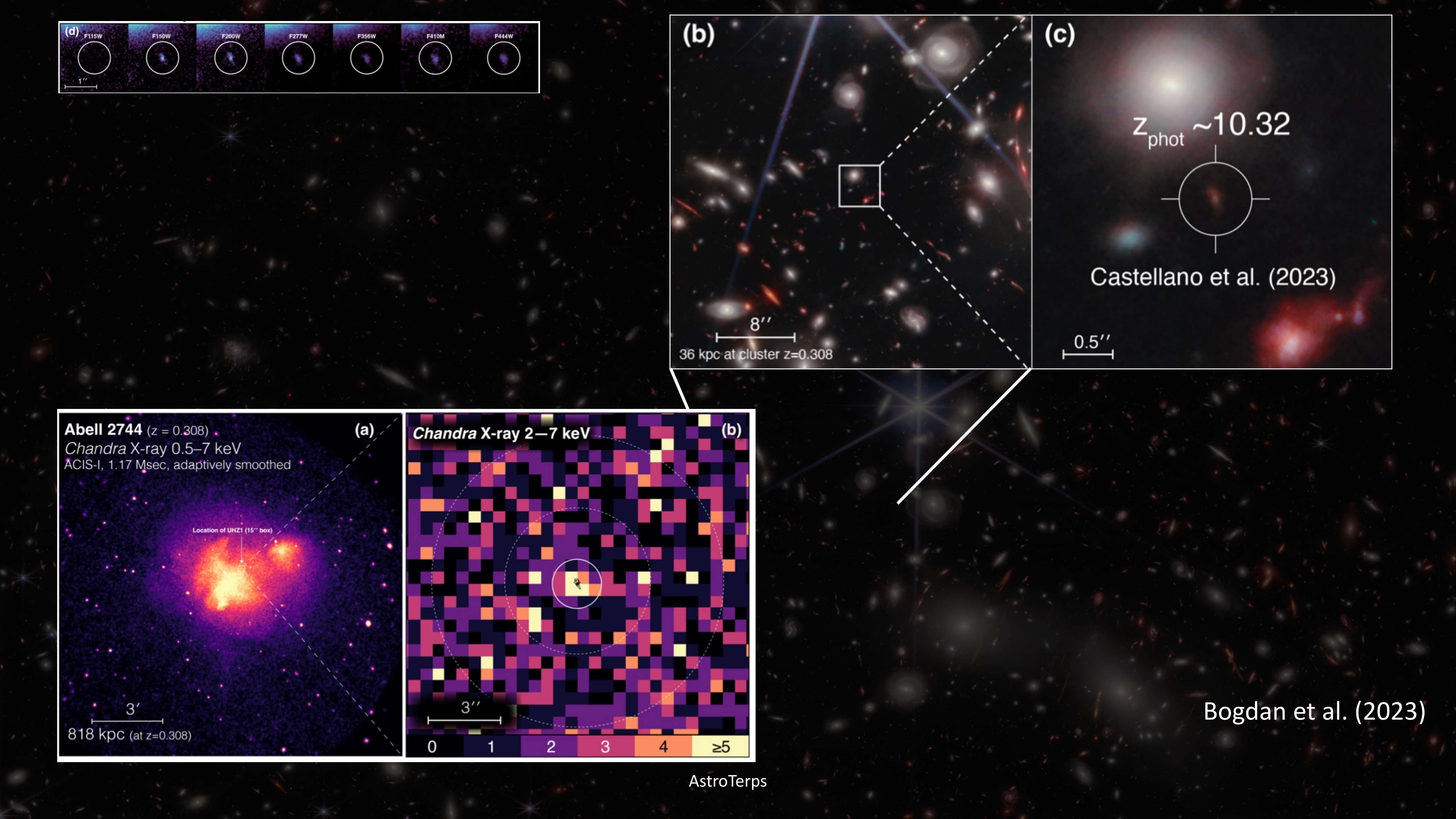


AstroTerps

James Webb Space Telescope

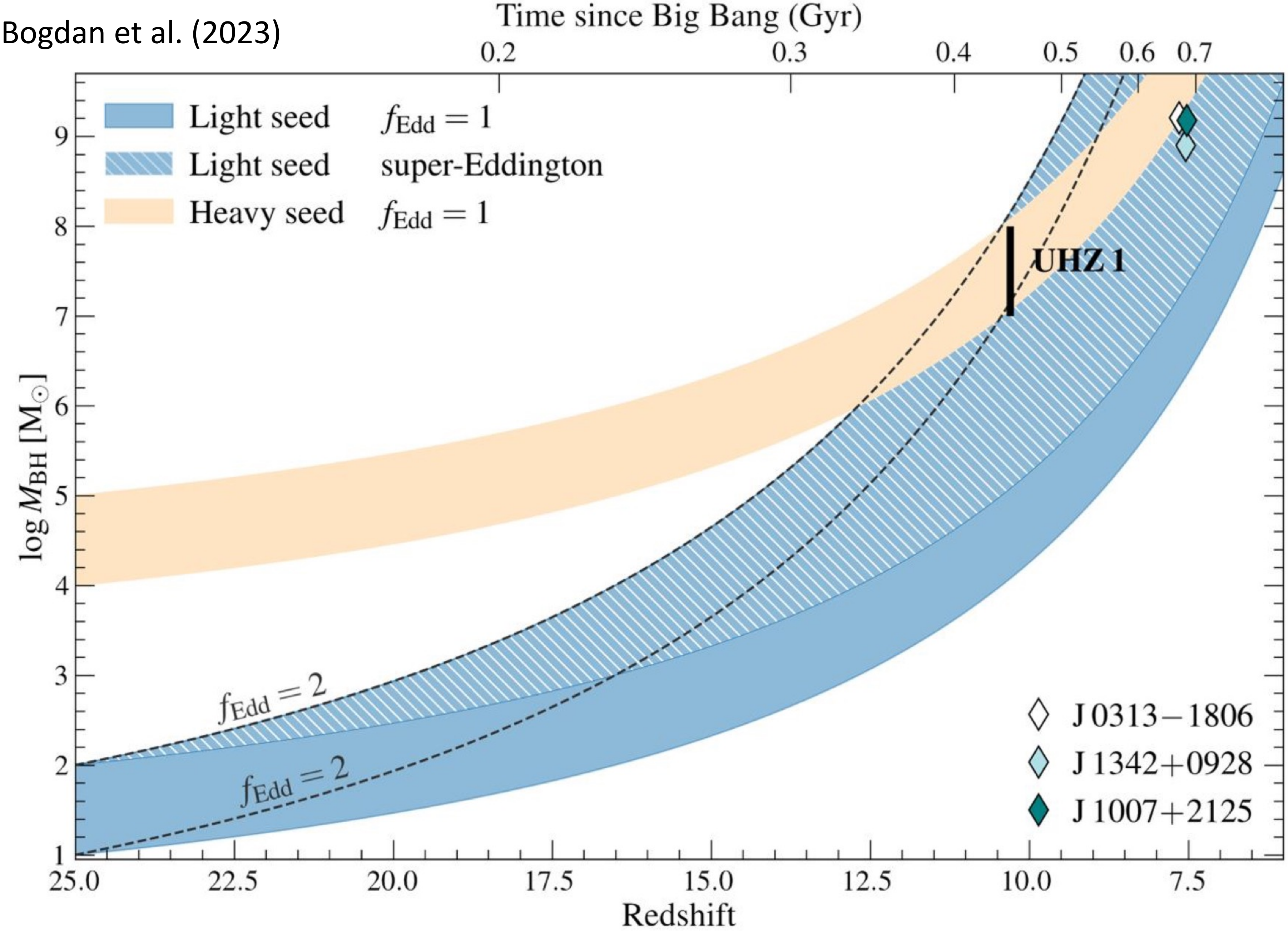
Bogdan et al. (2023)

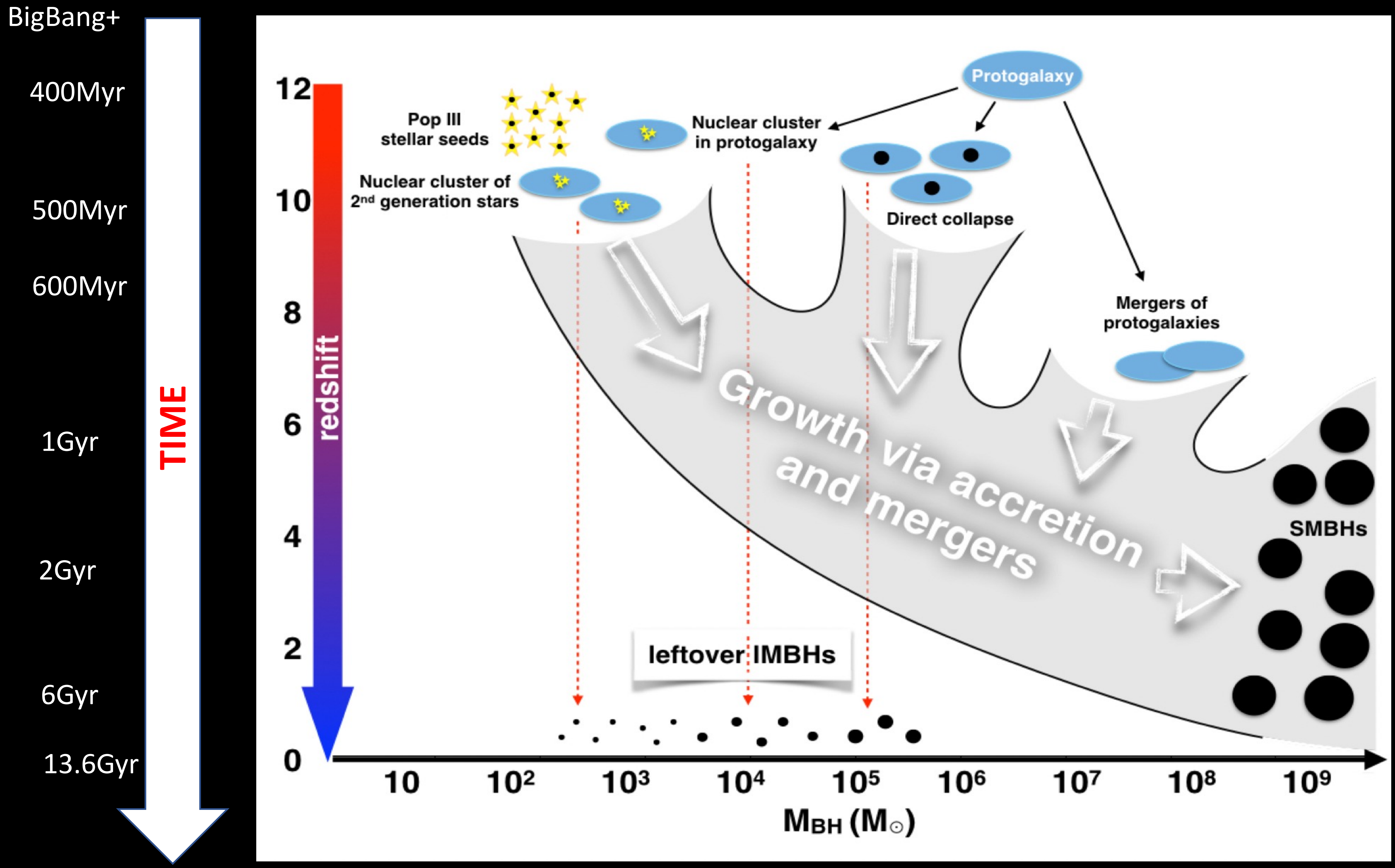
AstroTerps



Bogdan et al. (2023)

AstroTerps


Bogdan et al. (2023)

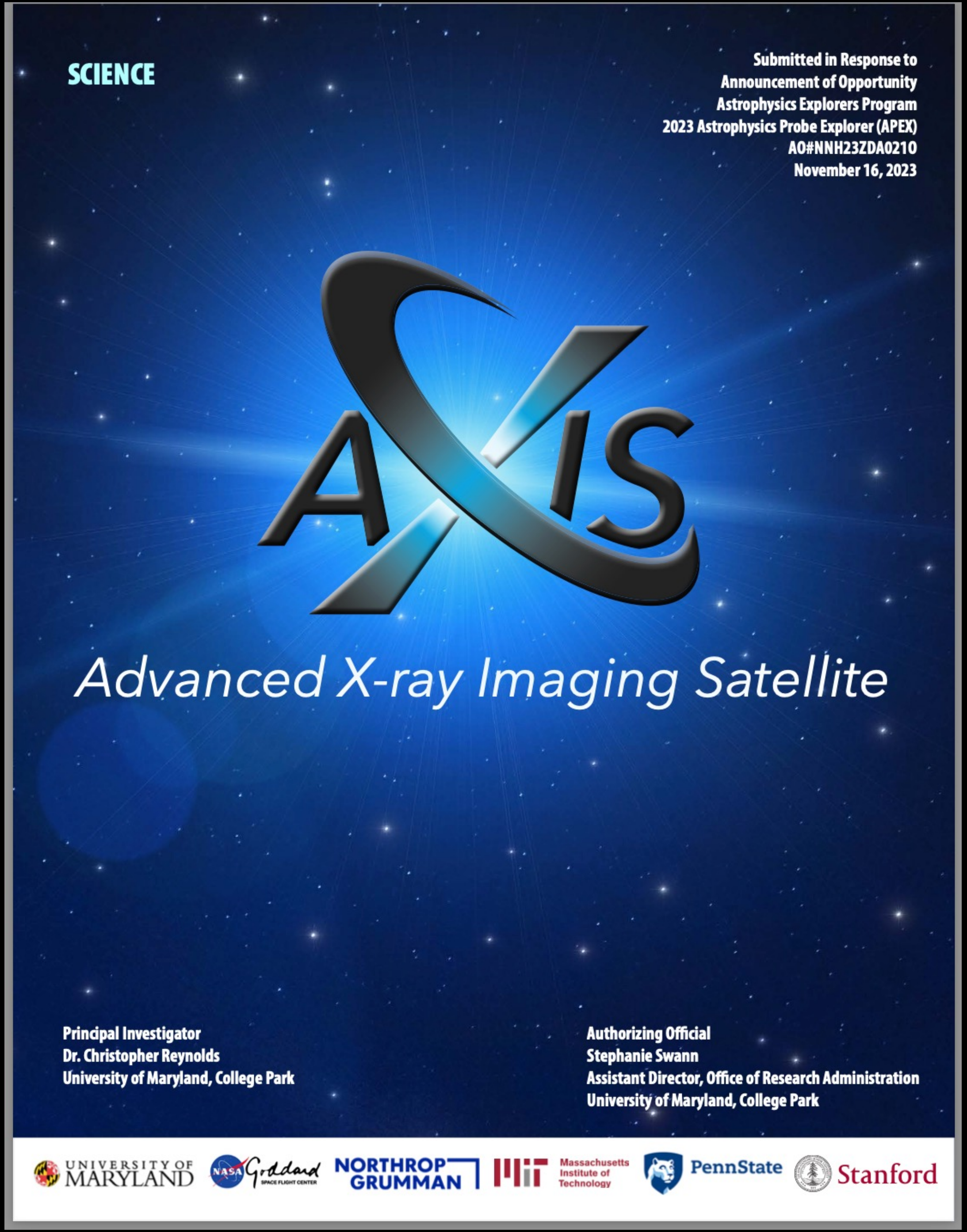

BigBang+
400Myr
500Myr
600Myr
1Gyr
2Gyr
6Gyr
13.6Gyr
TIME

Advanced CCD Imaging Spectrometer

Chandra Deep Field South (CDFS; 7Ms)

AstroTerps

Launch of Chandra X-ray Observatory (23rd July 1999)



SCIENCE

Submitted in Response to
Announcement of Opportunity
Astrophysics Explorers Program
2023 Astrophysics Probe Explorer (APEX)
AO#NNH23ZDA0210
November 16, 2023

AXIS

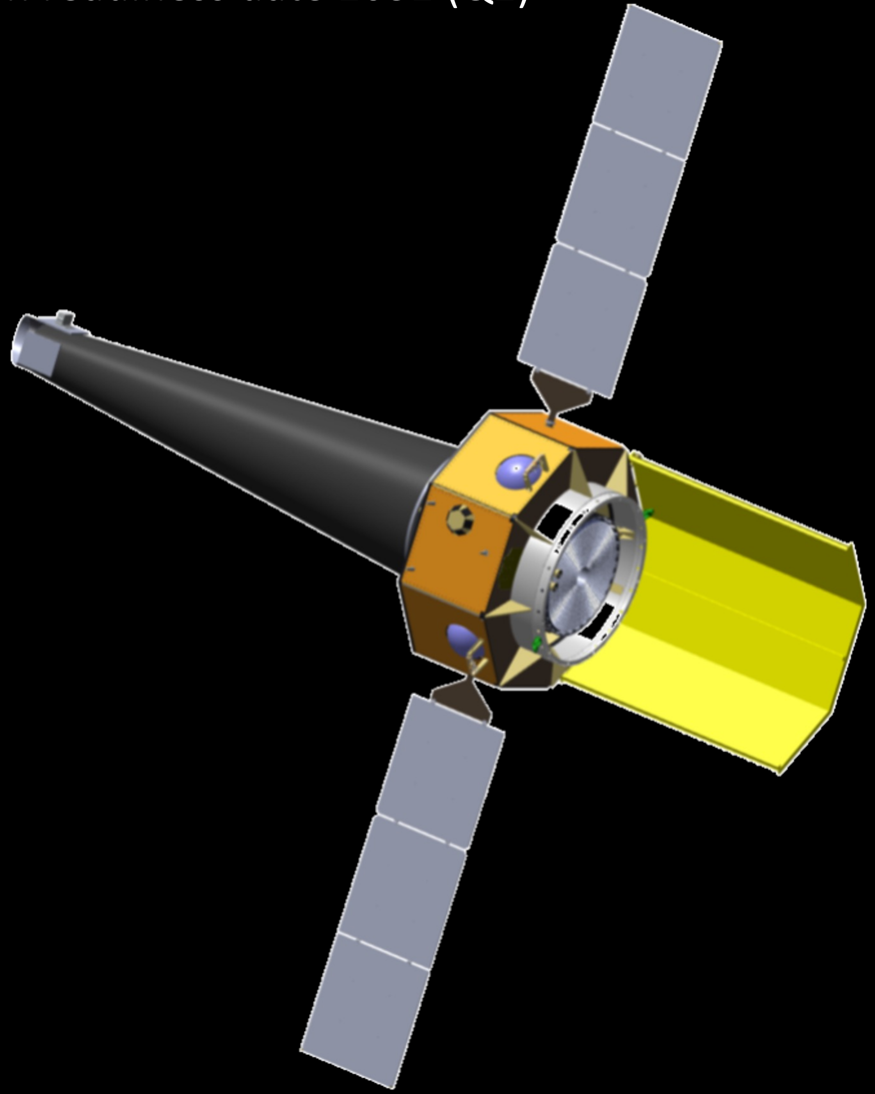
Advanced X-ray Imaging Satellite

Principal Investigator
Dr. Christopher Reynolds
University of Maryland, College Park

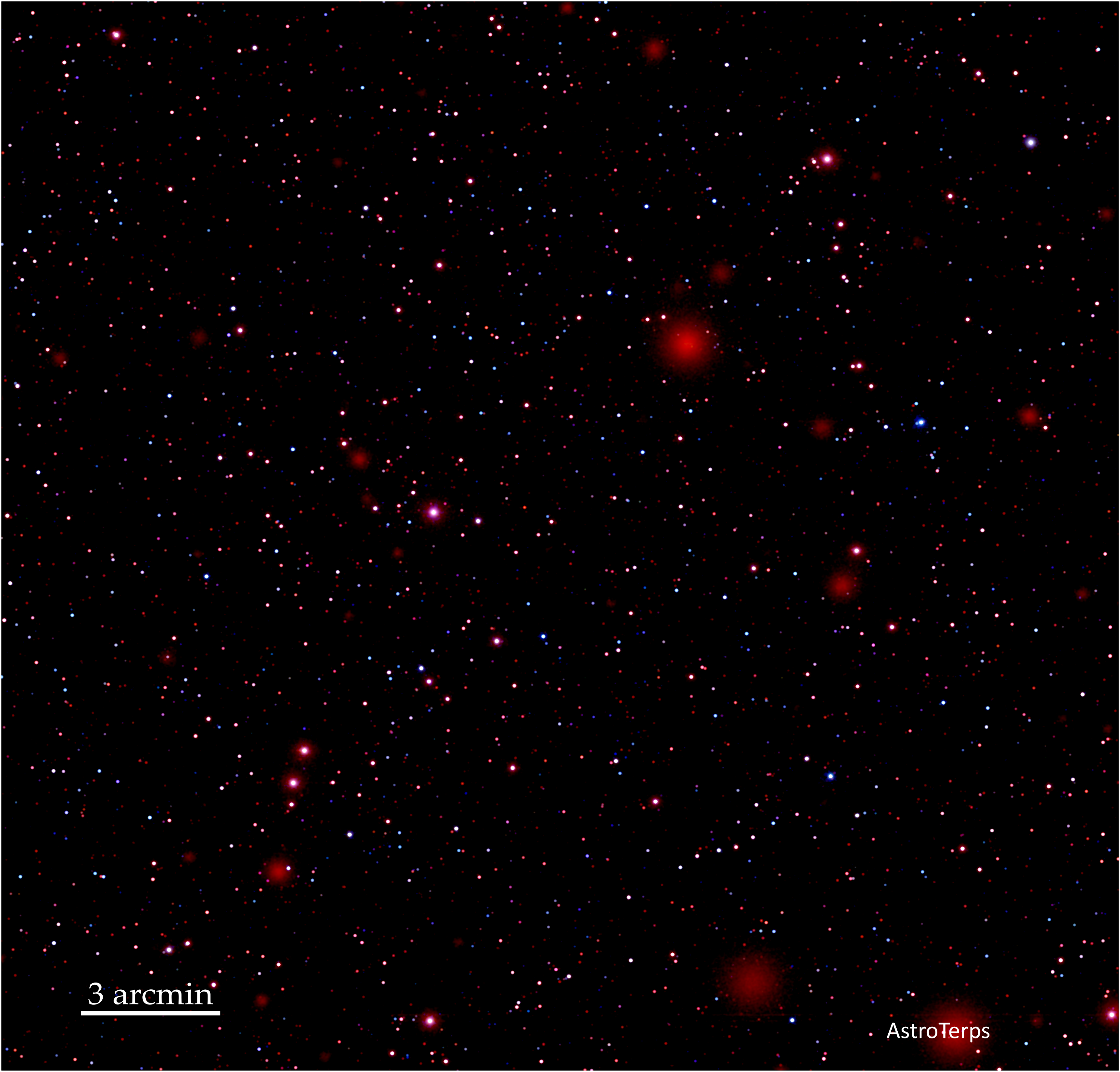
Authorizing Official
Stephanie Swann
Assistant Director, Office of Research Administration
University of Maryland, College Park

UNIVERSITY OF MARYLAND · NASA Goddard Space Flight Center · NORTHROP GRUMMAN · MIT Massachusetts Institute of Technology · PennState · Stanford

Response to NASA Astrophysics Probe call
Cost cap FY23$1B
Launch readiness date 2032 (Q2)



AstroTerps



Courtesy of Stefano Marchesi
(update of Marchesi et al. 2022)

AXIS Deep Field (7Ms, 0.16deg^2)

Sensitivity in 0.5-2.0keV band,

- 1.9x10-18 erg/s/cm^2 (20% field, 90arcmin^2)
- 3.7x10-18 erg/s/cm^2 (80% field, 360arcmin^2)

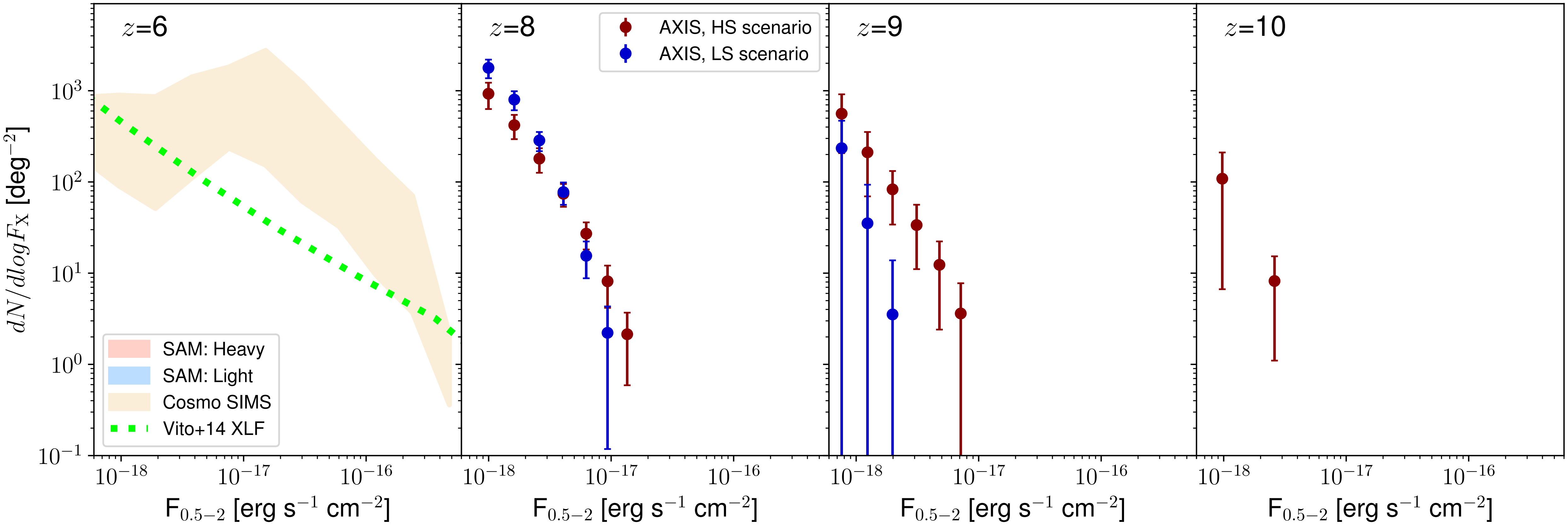
AXIS Intermediate Field (300ks / 2.0 deg^2)

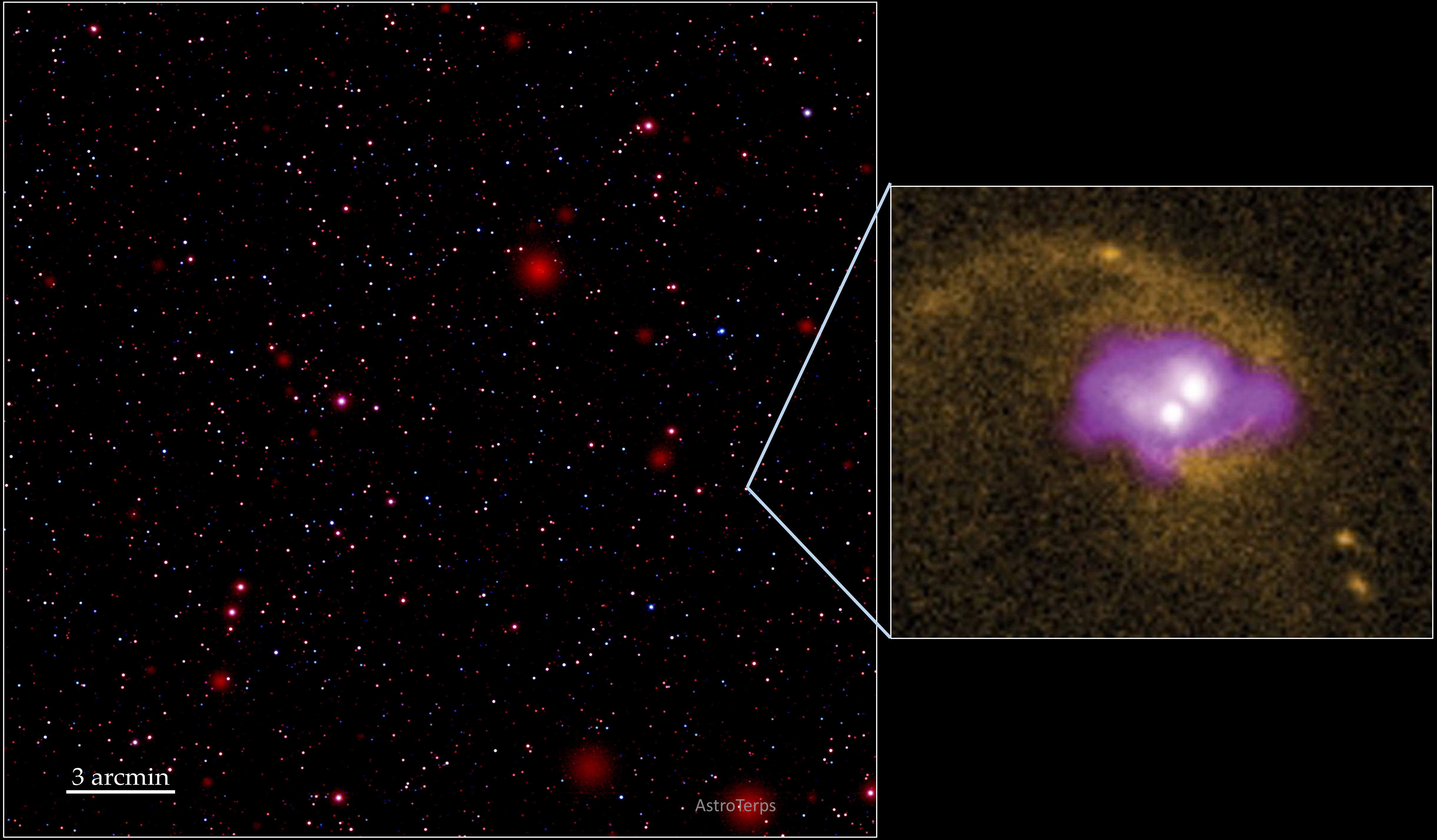
Sensitivity in 0.5-2.0keV band,

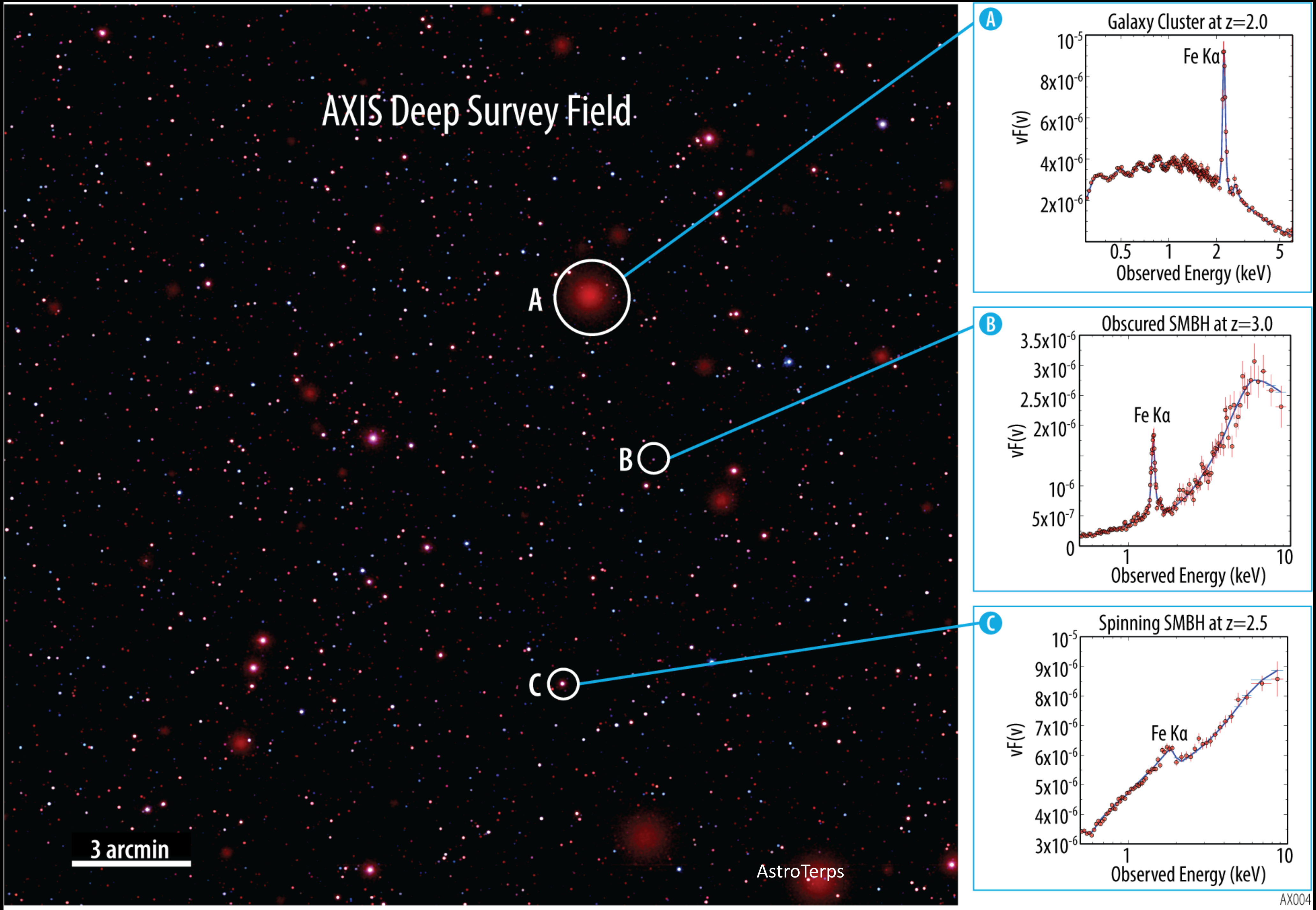
- 1.1x10-17 erg/s/cm^2 (20% field, 0.4deg^2)
- 3.7x10-17 erg/s/cm^2 (80% field, 1.6deg^2)

Marchesi et al. (2020) mock catalogues:

- >2800 AGN (AXIS Deep Field)
- >22,000 AGN (AXIS Intermediate Field)


z=6
z=8
z=9
z=10
AXIS, HS scenario
AXIS, LS scenario
SAM: Heavy
SAM: Light
Cosmo SIMS
Vito+14 XLF
$dN/dlogF_X$ [deg^{-2}]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{-18}
10^{-17}
10^{-16}
F$_{0.5-2}$ [erg s^{-1} cm^{-2}]

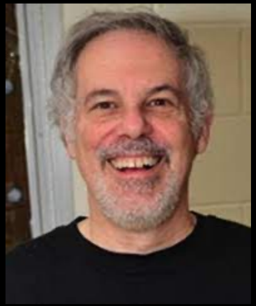

3 arcmin
AstroTerps


AXIS Deep Survey Field
A
B
C
3 arcmin
AstroTerps
A
Galaxy Cluster at z=2.0
10^{-5}
8×10^{-6}
6×10^{-6}
4×10^{-6}
2×10^{-6}
$\nu F(\nu)$
Fe Kα
0.5
1
2
5
Observed Energy (keV)
B
Obscured SMBH at z=3.0
3.5×10^{-6}
3×10^{-6}
2.5×10^{-6}
2×10^{-6}
10^{-6}
5×10^{-7}
0
$\nu F(\nu)$
Fe Kα
1
10
Observed Energy (keV)
C
Spinning SMBH at z=2.5
10^{-5}
9×10^{-6}
8×10^{-6}
7×10^{-6}
6×10^{-6}
5×10^{-6}
4×10^{-6}
3×10^{-6}
$\nu F(\nu)$
Fe Kα
1
10
Observed Energy (keV)
AX004

AXIS Science Leadership Team


Chris Reynolds
PI


Erin Kara
Deputy PI


Richard Mushotzky
PI of 2018 Study
Chair of AXIS-SAB


Eileen Meyer
Synergies Lead


Mike Koss


Brian Williams

Associate PIs for Science


Andy Ptak
Project Scientist


Adi Foord


Nico Cappelluti

AGN/SMBH SWG


Samar Safi-Herb


Kevin Burdge

Compact Object & SNR SWG


Helen Russell


Laura Lopez

Galaxies & Feedback SWG

AstroTerps


Lia Corrales


Keivan Stassun

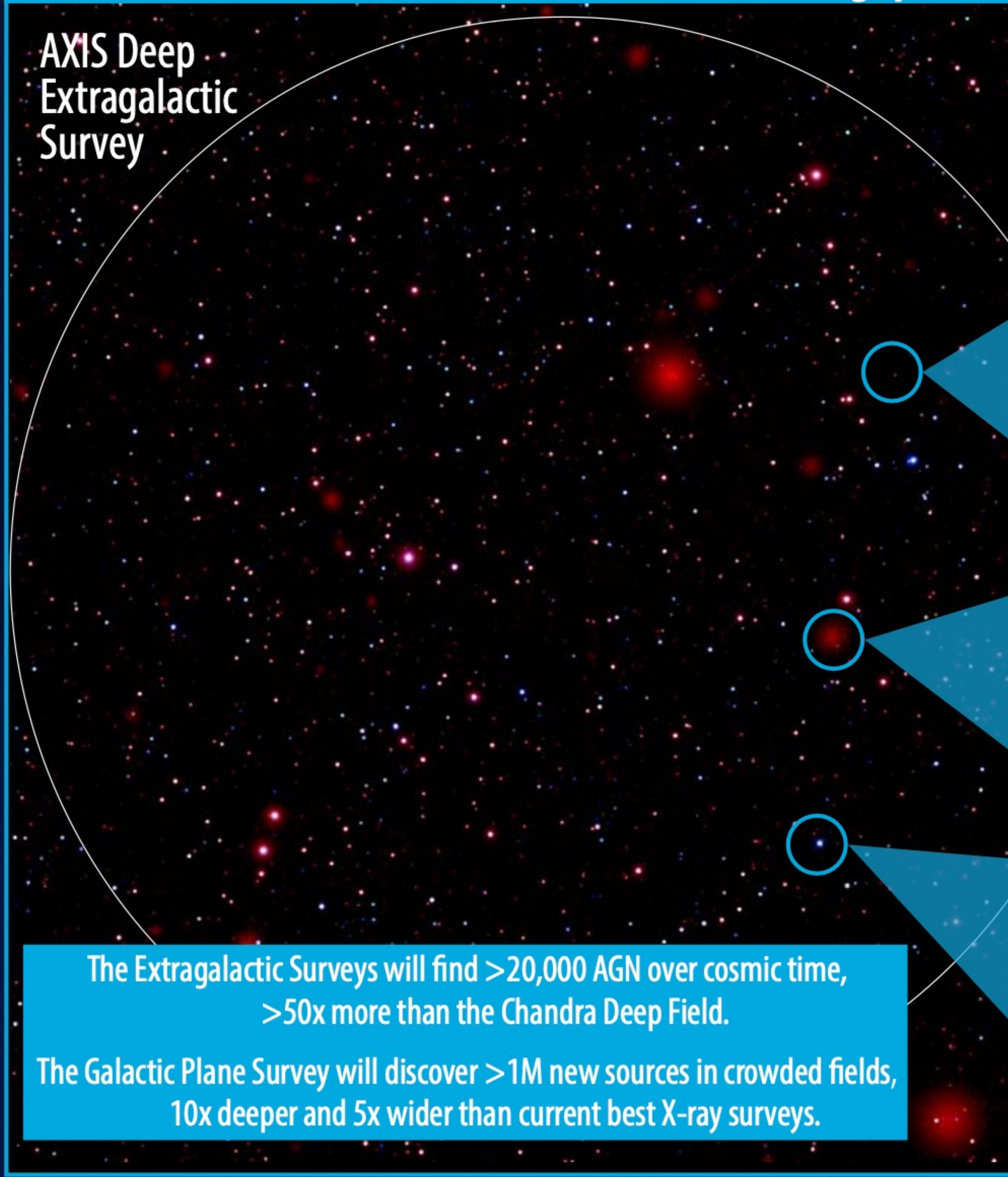
Stars and Exoplanets SWG


Daryl Haggard


Brad Cenko

Time-domain and MMA SWG

AXIS answers the big questions posed by the Astro2020 Decadal Survey



The Extragalactic Surveys will find >20,000 AGN over cosmic time, >50x more than the Chandra Deep Field.

The Galactic Plane Survey will discover >1M new sources in crowded fields, 10x deeper and 5x wider than current best X-ray surveys.

The AXIS Science Pillars

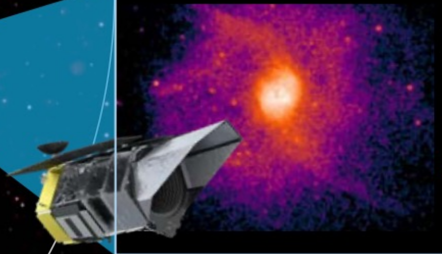
Astro 2020 asks...	...AXIS answers
Why X-rays?	Why AXIS?

Pillar 1: "What seeds supermassive black holes and how do they grow?"

AXIS determines the origin of massive black holes

X-rays identify clean census of black holes in distant JWST galaxies

AXIS' PSF and large area enable imaging of distant, faint sources

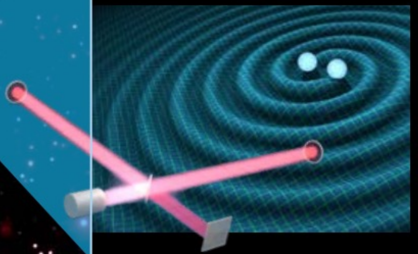


Pillar 2: "How do gas, metals, and dust flow into, through, and out of galaxies?"

AXIS shows how supernovae and AGN transform galaxies

X-rays uniquely probe the million-degree gas that drives gas flows

High contrast imaging separates diffuse gas and bright sources



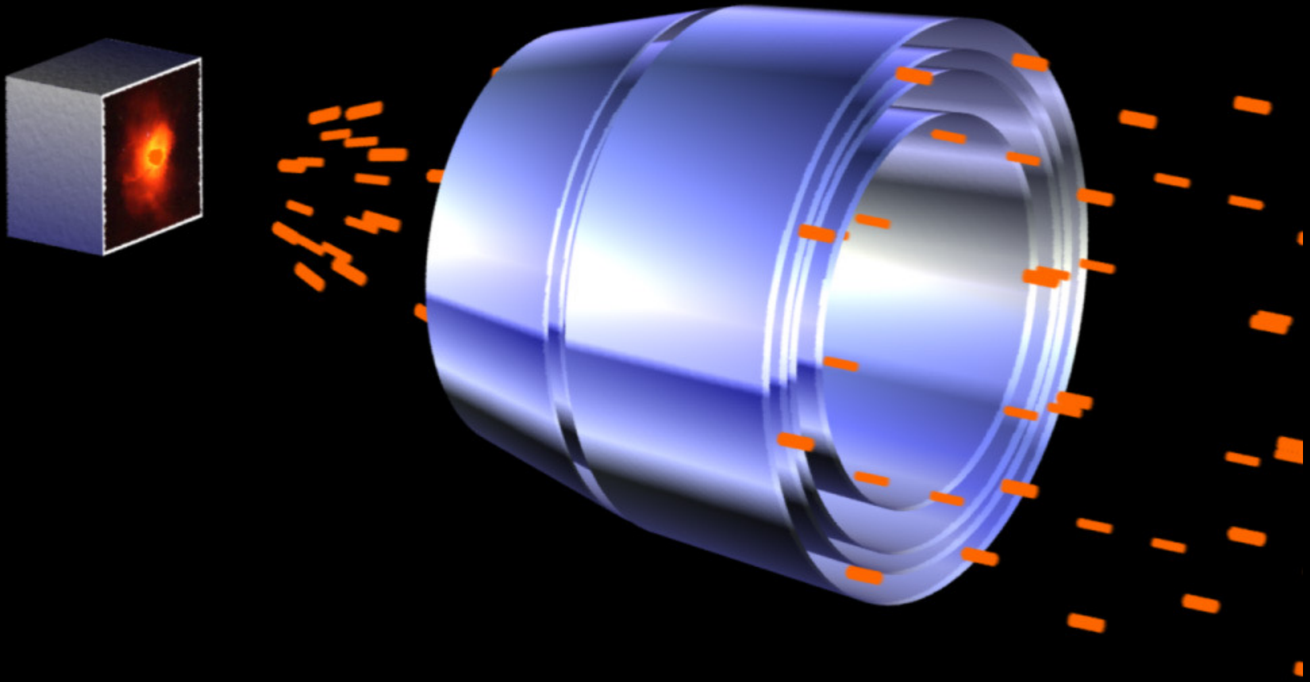
Pillar 3: "What powers the diversity of explosive phenomena across the electromagnetic spectrum?"

AXIS discovers explosive transients both near and distant

X-rays uniquely encode information on transient progenitors

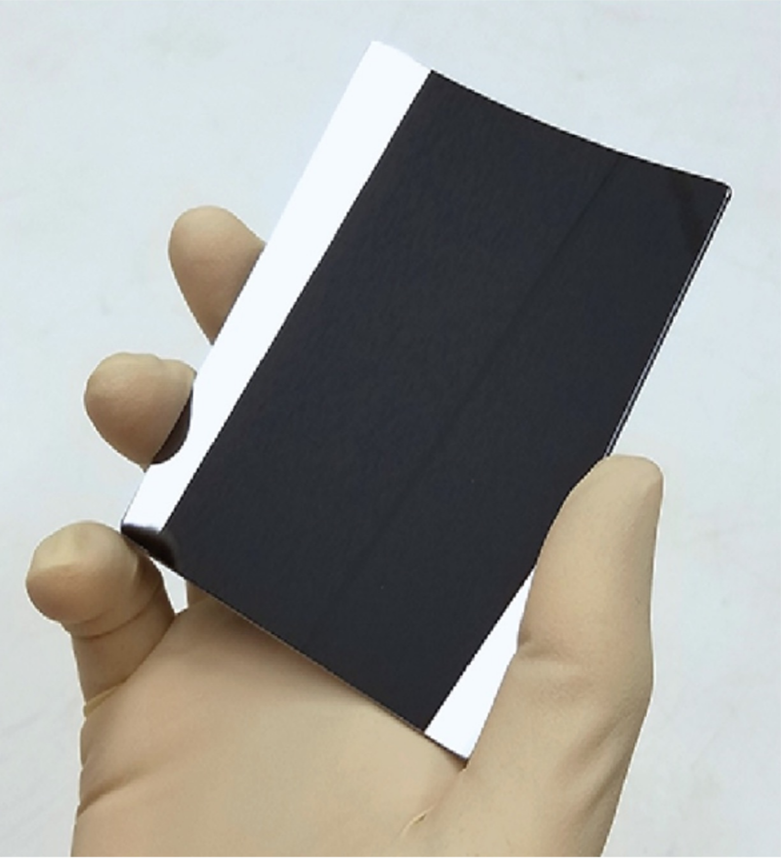
AXIS enables transient alerts, TDAMM surveys and fast followup

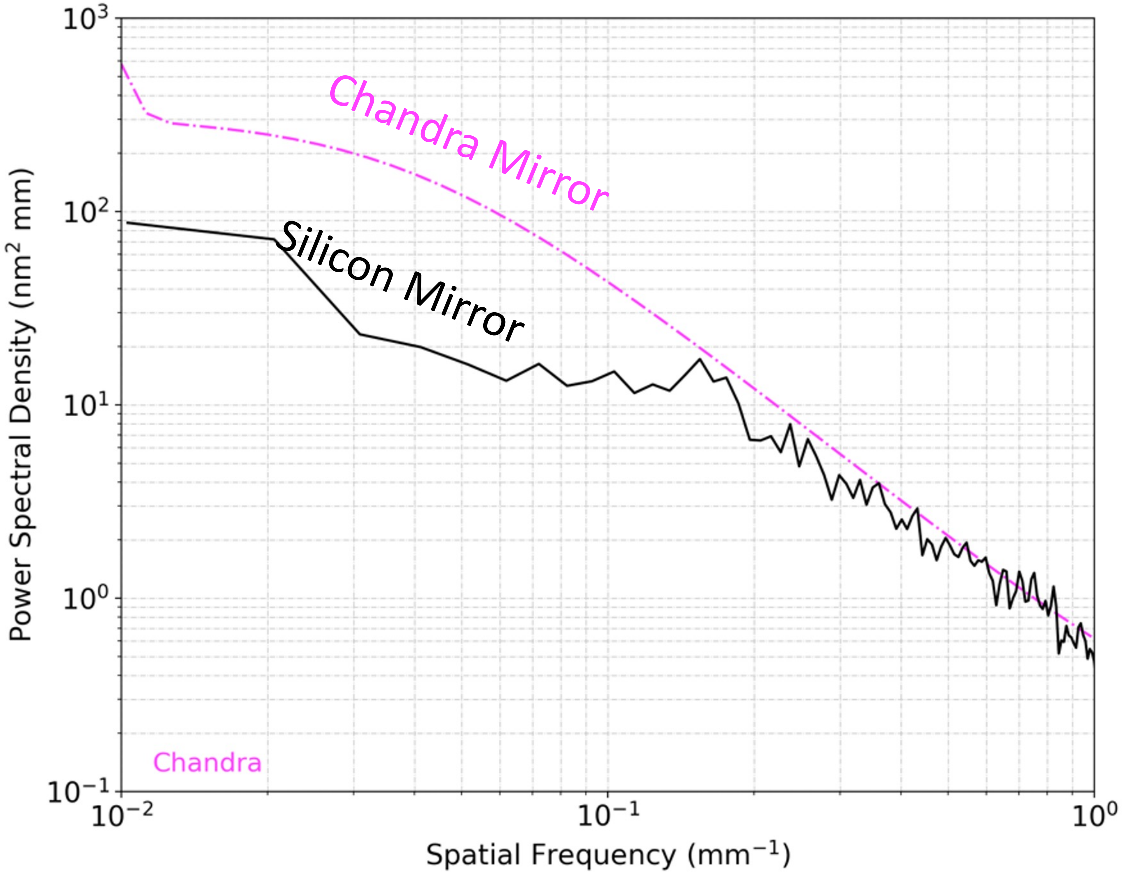
Chandra High-Resolution Mirror Assembly



AstroTerps

Mirror Segment



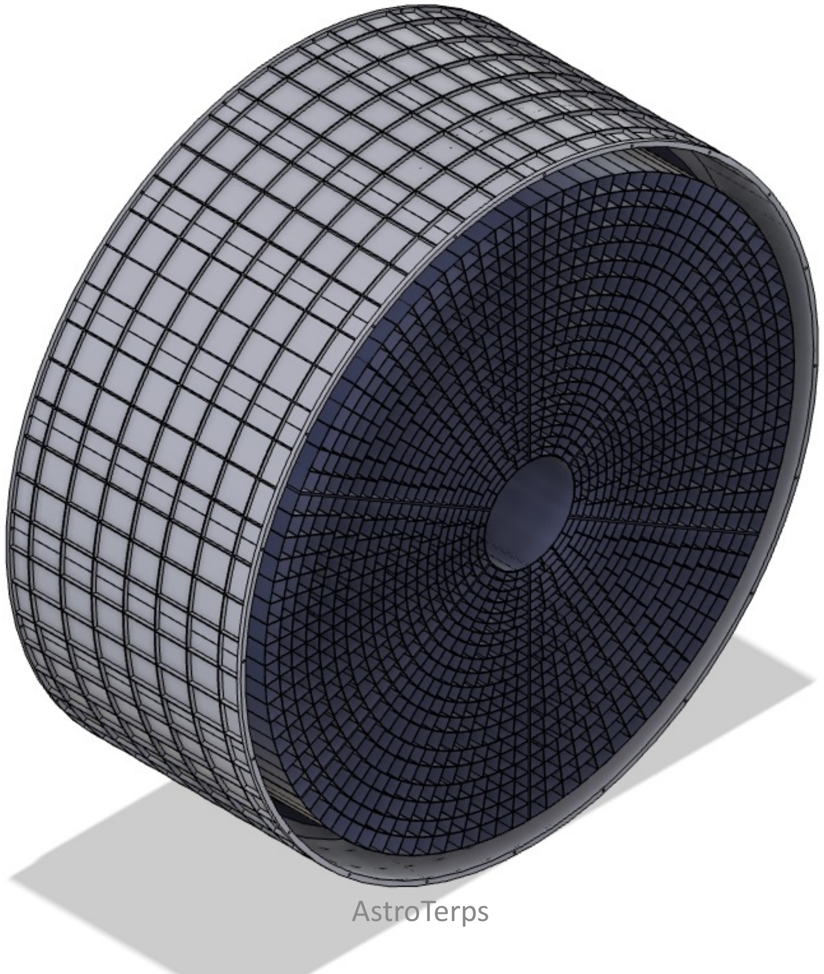


3X Better, 20X Lighter (thinner), 30X Cheaper than Chandra's Mirror Elements.

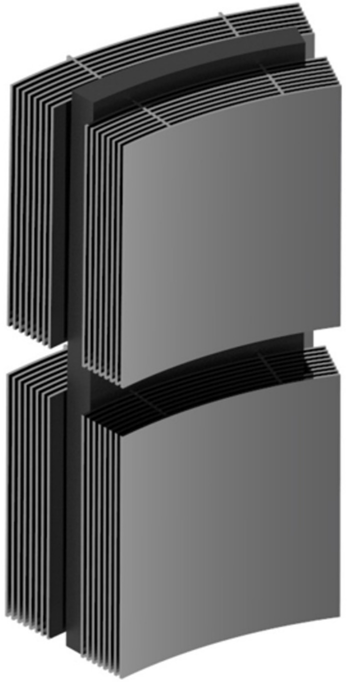
AXIS Mirror Assembly

~17000 iridium-coated monocrystalline silicon shells
Forming 8500 mirror pairs
Packed into 312 modules

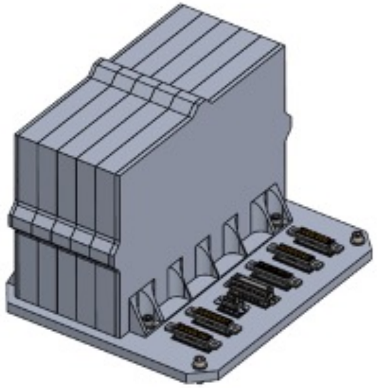
Diameter 1.86m
Focal length 9.0m

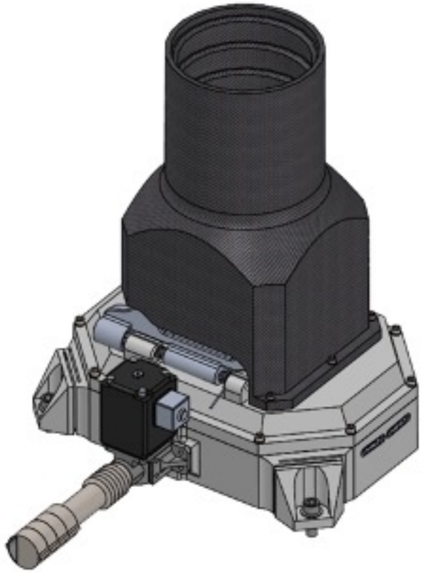


AstroTerps



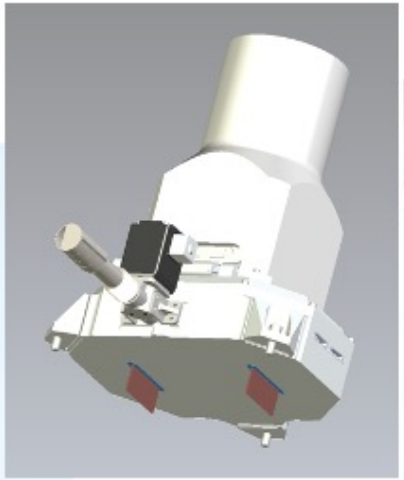
Focal Plane Assembly

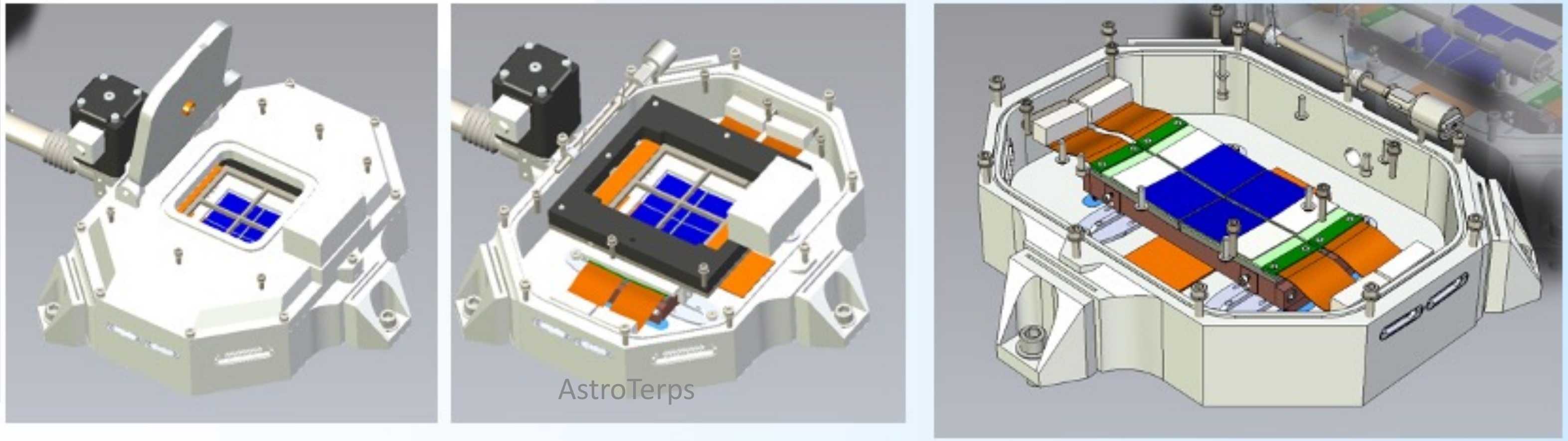

Front-End Electronics


Camera Assembly

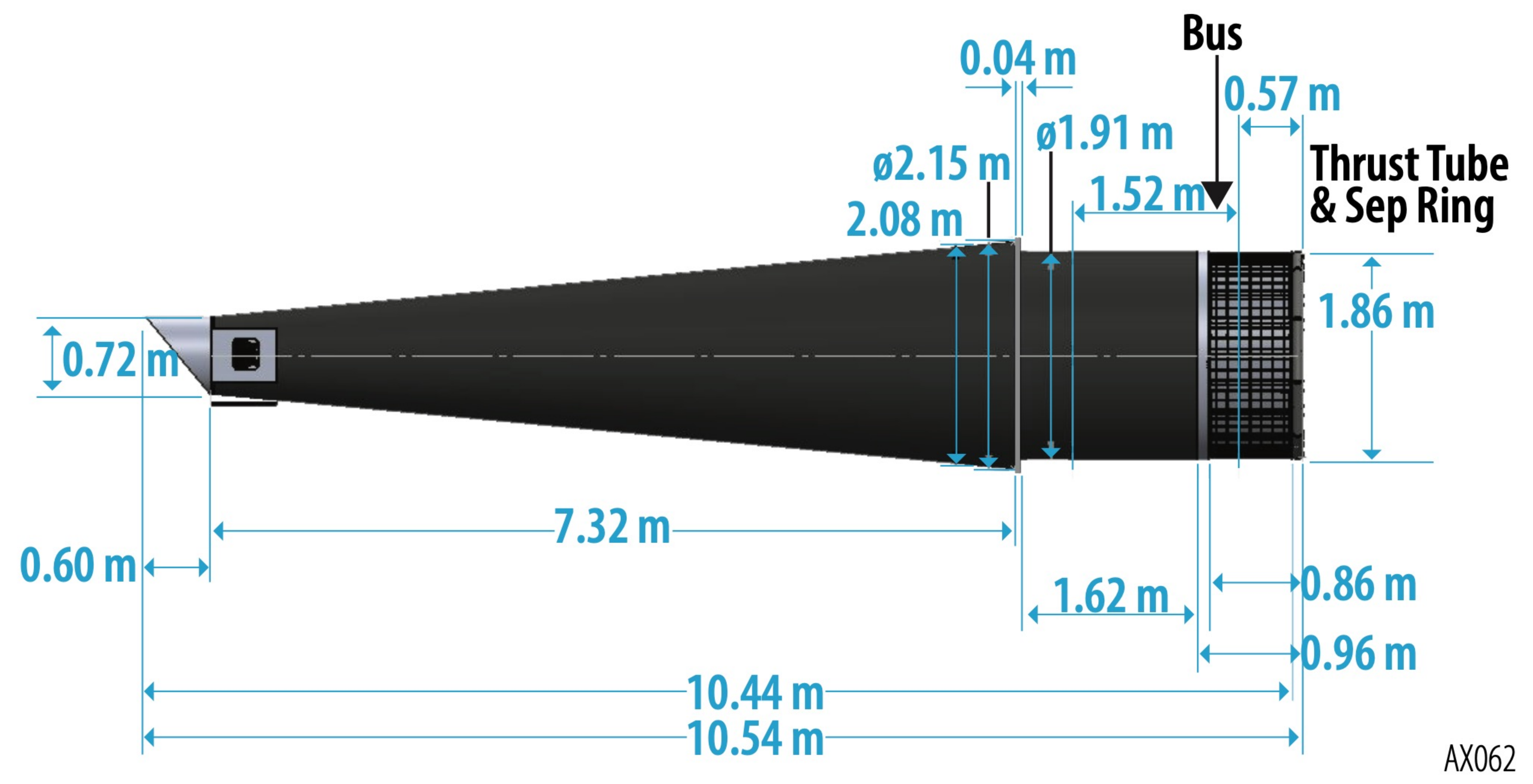
Focal Plane Assembly (FPA) comprises:

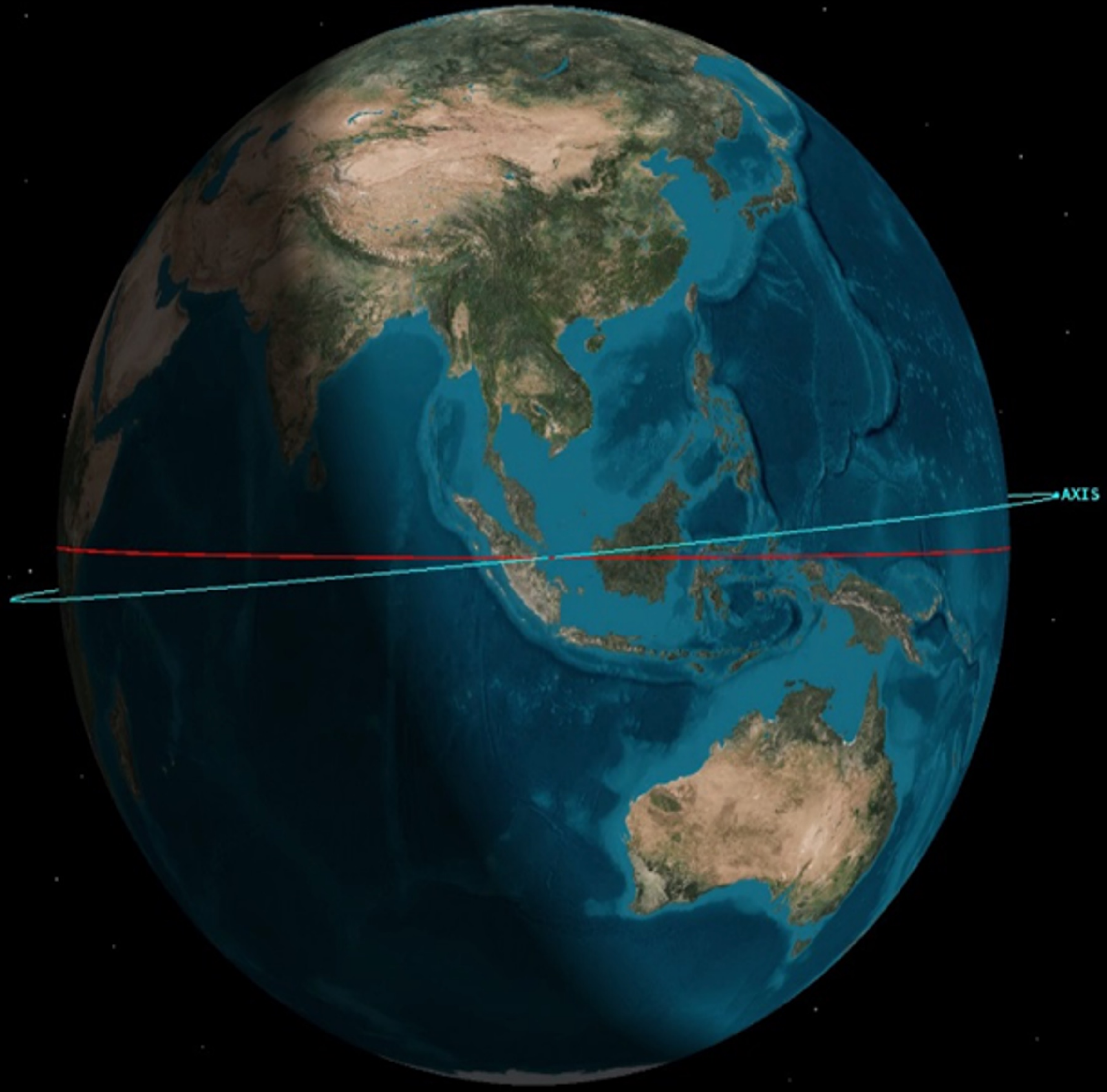
- Camera Assembly
    - Baffle
    - Bonnet Assembly
        - Bonnet Housing
        - Door Assembly
        - Contamination Blocking Filter Assembly
    - Detector Assembly
        - Detector Housing
        - Detector Array (CCD package)
- Front-End Electronics (FEE)

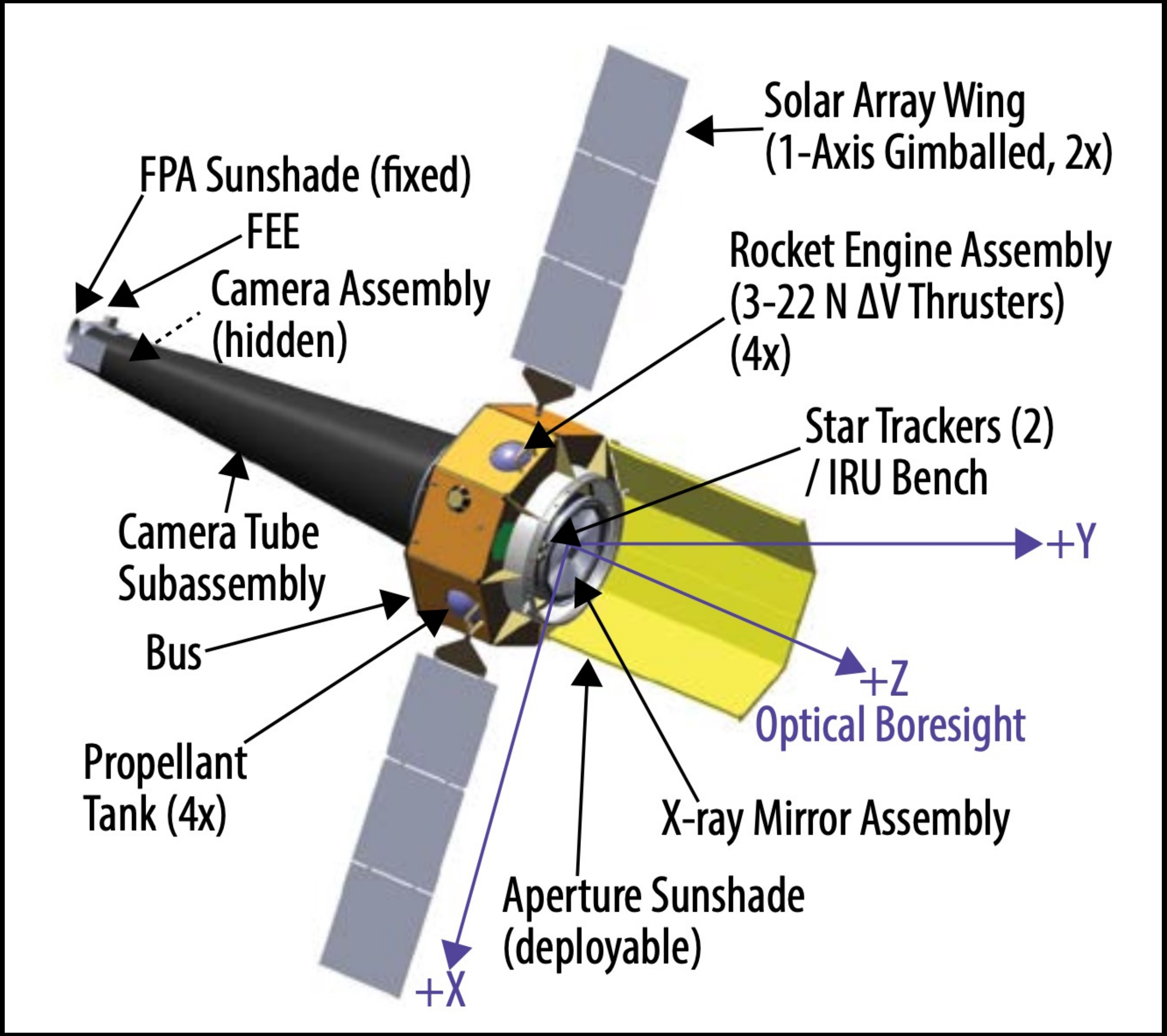




AstroTerps

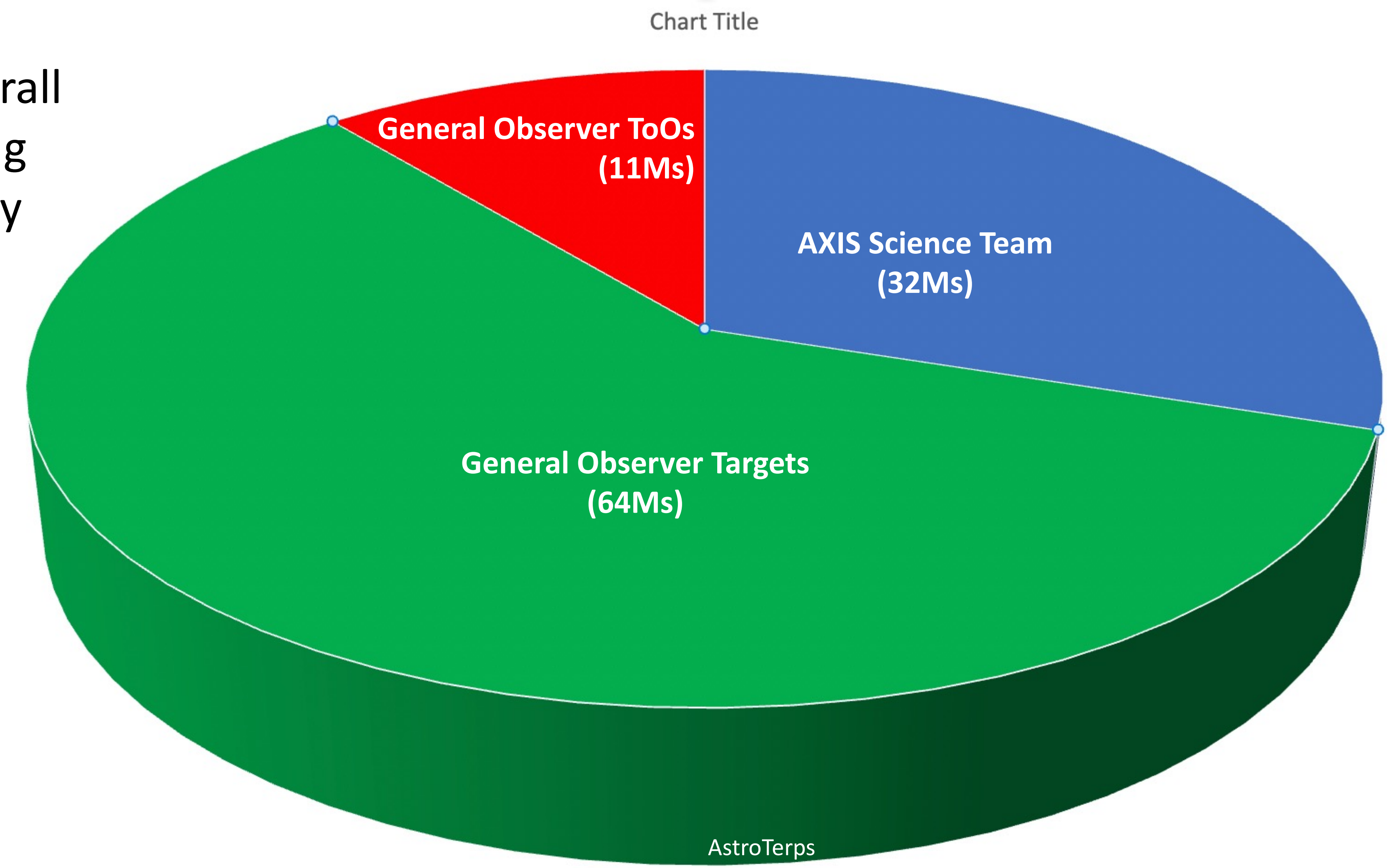

Bus
0.04 m
0.57 m
ø1.91 m
ø2.15 m
Thrust Tube
& Sep Ring
1.52 m
2.08 m
1.86 m
0.72 m
7.32 m
0.60 m
0.86 m
1.62 m
0.96 m
10.44 m
10.54 m
AX062


AXIS


Solar Array Wing
(1-Axis Gimballed, 2x)
FPA Sunshade (fixed)
FEE
Camera Assembly
(hidden)
Rocket Engine Assembly
(3-22 N ΔV Thrusters)
(4x)
Star Trackers (2)
/ IRU Bench
+Y
Camera Tube
Subassembly
Bus
+Z
Optical Boresight
Propellant
Tank (4x)
X-ray Mirror Assembly
Aperture Sunshade
(deployable)
+X

Prime Mission (5 year) Observing Time Budget

68% overall observing efficiency (via fast slewing)



The Reach of AXIS Science

- Cosmology
    - Cluster mass functions
    - Cluster baryonic mass fractions
    - Probes of DM / axion-sector physics
- Active Galactic Nuclei
    - Nature of SMBH seeds
    - Accretion vs merger SMBH growth
    - Obscured accretion at high-z
    - SMBH spin across cosmic time
    - Resolved studies of jets at low+high-z
    - SMBH feeding / Bondi flows
    - AGN winds at low- and high-z
    - Strongly lensed quasars as probes of strong gravity
- Galactic structure formation
    - AGN-galaxy interactions
    - AGN-feedback in galaxy clusters
    - Stellar feedback in galaxies
    - Hot CGM of field ellipticals and massive spirals
- Galaxy clusters
    - Micro/plasma physics of the ICM
    - Cooling instabilities in cool cores
    - Merging clusters and cluster shocks
    - Cluster outskirts and accretion shocks
- Stellar physics
    - Activity as function of type, age, time
    - Temperature/metallicity of stellar coronae
    - Progenitors of core-collapse SNs
    - Progenitors of SN1a
    - Mapping the solar wind via solar system CX
    - Astrospheres of nearby stars
    - Evolution and physics of supernova remnants
    - Pulsars and pulsar wind nebulae
- Exoplanets
    - X-ray transits as probe of photoevaporation
    - Impact of stellar activity on atmospheric chemisty
- Solar system
    - Mapping the solar wind via solar system CX
    - CX associated solar system objects as probe of solar wind
    - Coronal activity on Jupiter
- Time-domain and multi-messenger
    - Tidal disruption events
    - Follow-up of GW counterparts (ground-based and LISA)
    - Supernova shock breakouts
    - Magnetars
    - Ultracompact binaries

- AND SO MUCH MORE!