A new era of high-resolution spectroscopy in X-ray astronomy

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Tsinghua University

HEACOSS-2024, Yerevan, Armenia

Looking back

Riccardo Giacconi

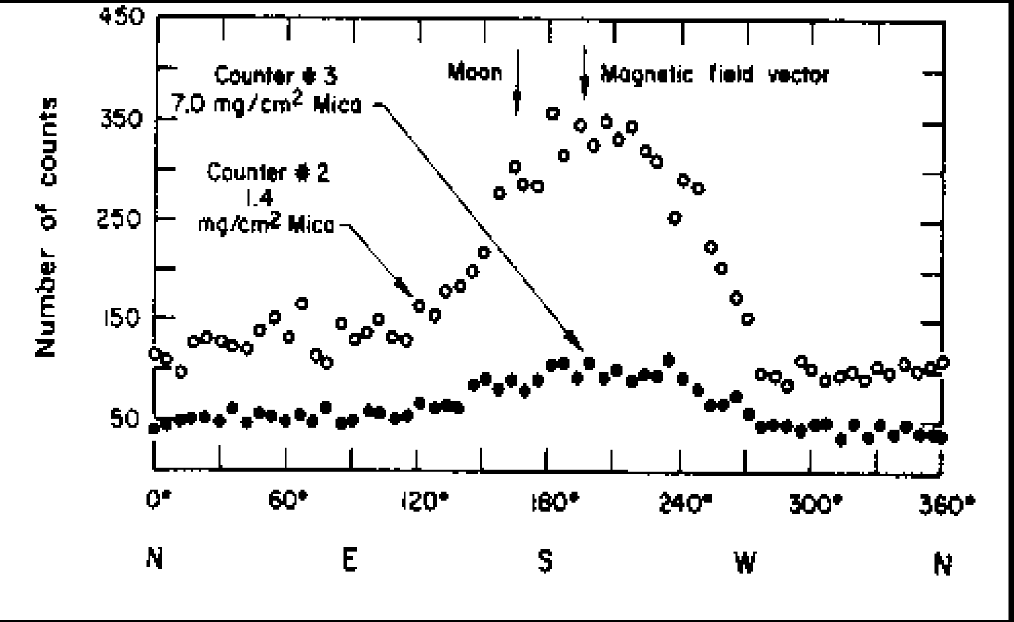
"In 1963, Herbert Gursky and I submitted a plan for X-ray astronomy to NASA that outlined a program from rocket experiments, to a dedicated satellite, to imaging X-ray telescopes, and finally, to a 1.2 meter X-ray telescope. "

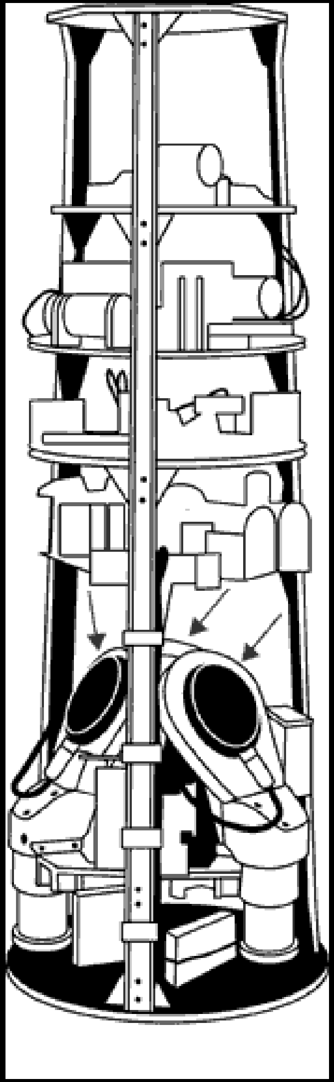
https://ecuip.lib.uchicago.edu/multiwavelength-astronomy/x-ray/impact

“Rocket Experiments”

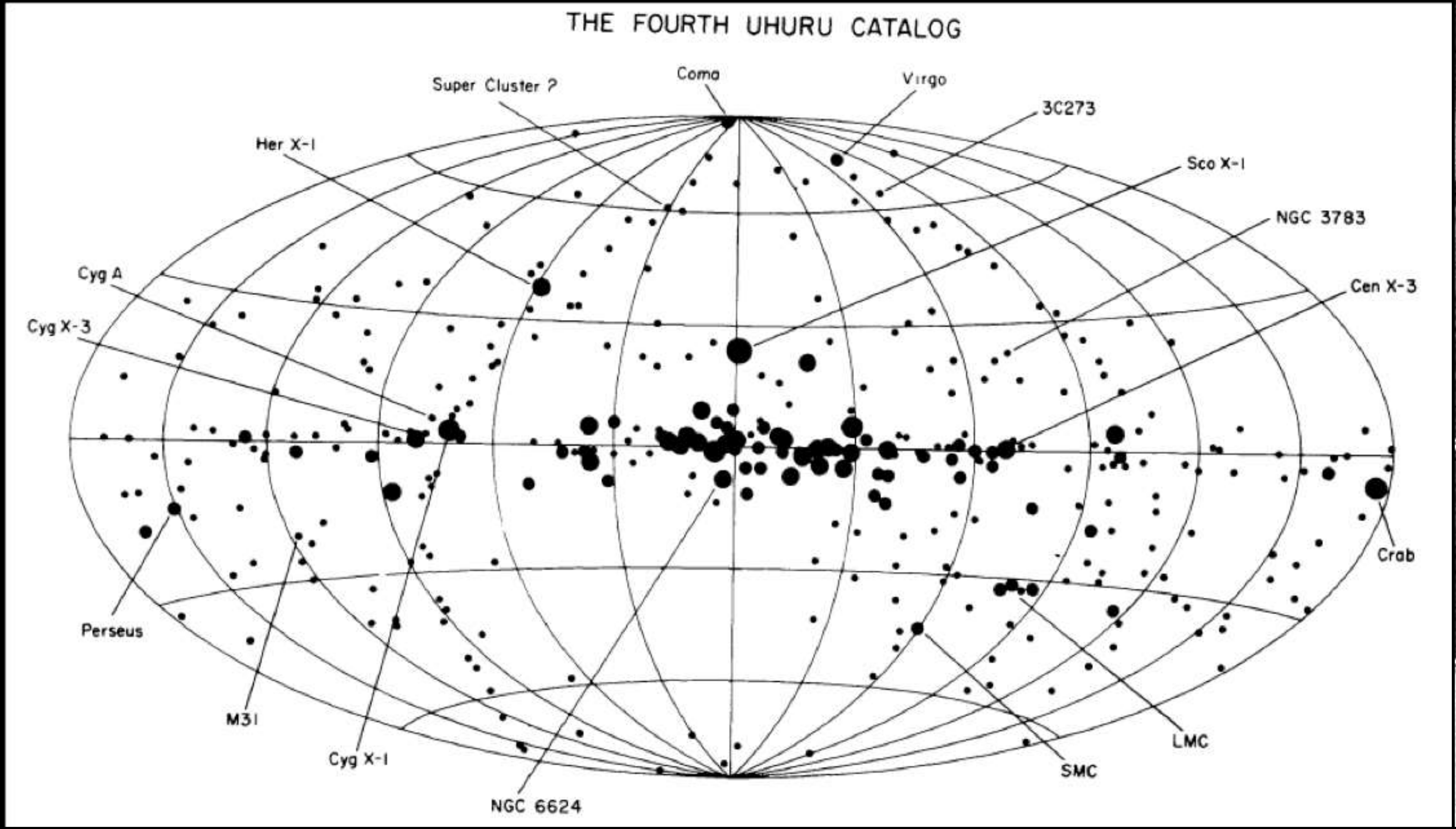
- **Aerobee rockets**
  - Led by Bruno Rossi and Riccardo Giaconni;
  - As the rocket rotates, an unexpectedly bright X-ray source, now known as Scorpius X-1, appeared in the field of view, marking the discovery of the first X-ray source other than the Sun;
  - Confirmed by the NRL group using a larger detector with better angular resolution;
  - Subsequet flights detected other X-ray binaries in the Milky Way.

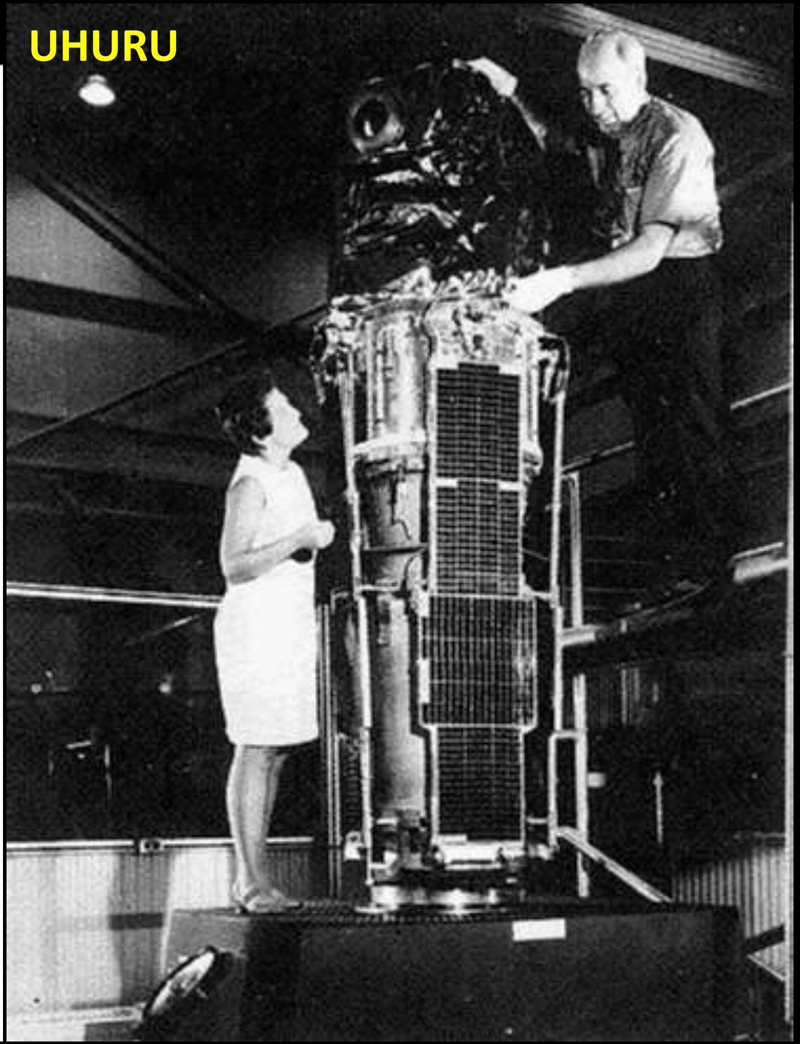
“The Nature is more imaginative in many case than we suspect!! ” -Bruno Rossi





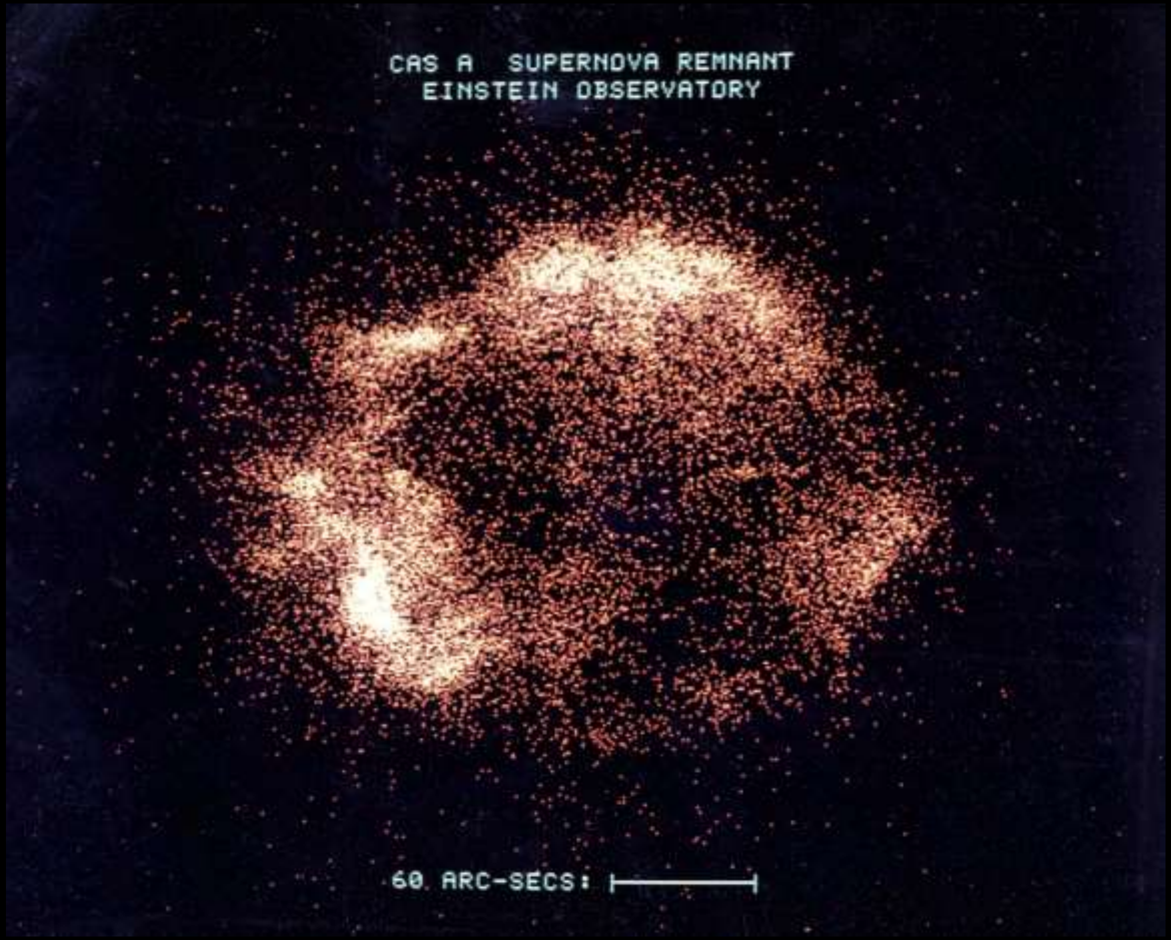
“A Dedicated Satellite”

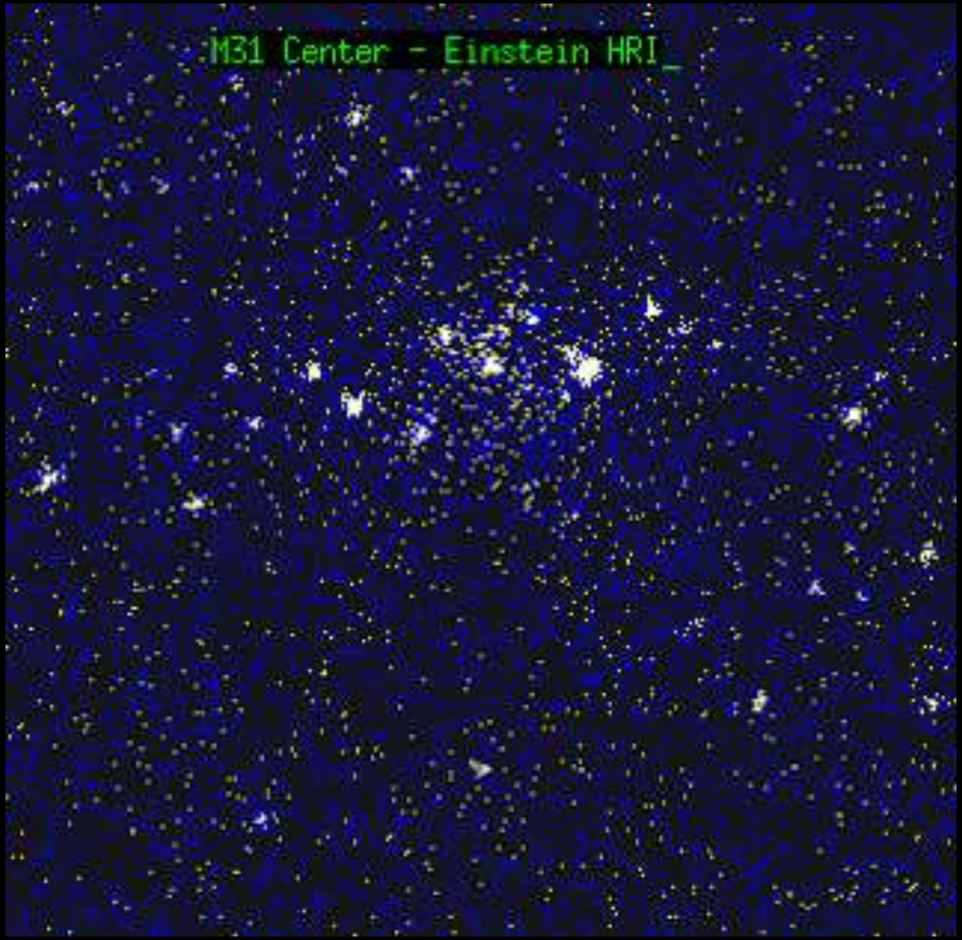




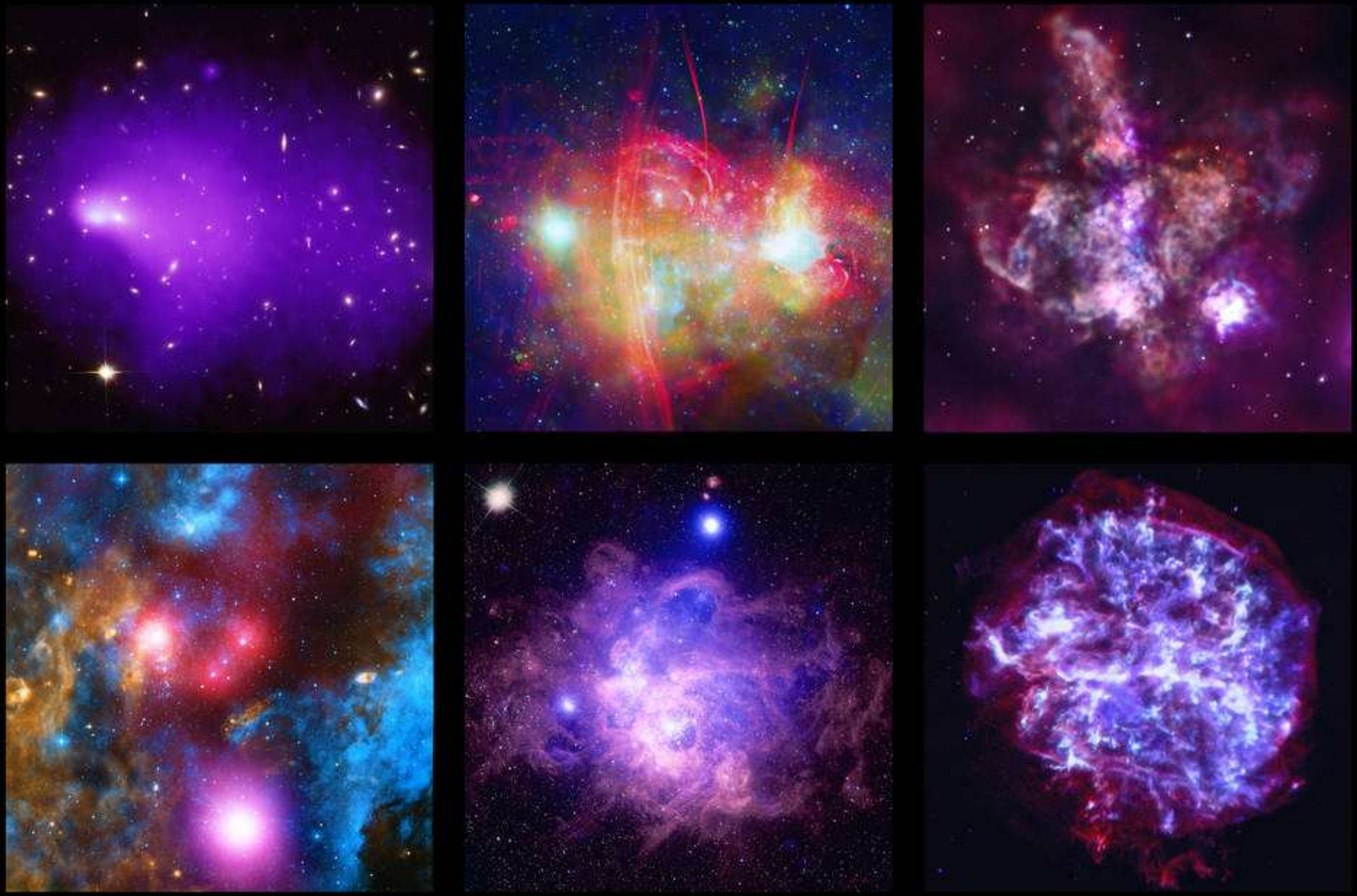
“Imaging X-ray Telescope”

Einstein Observatory





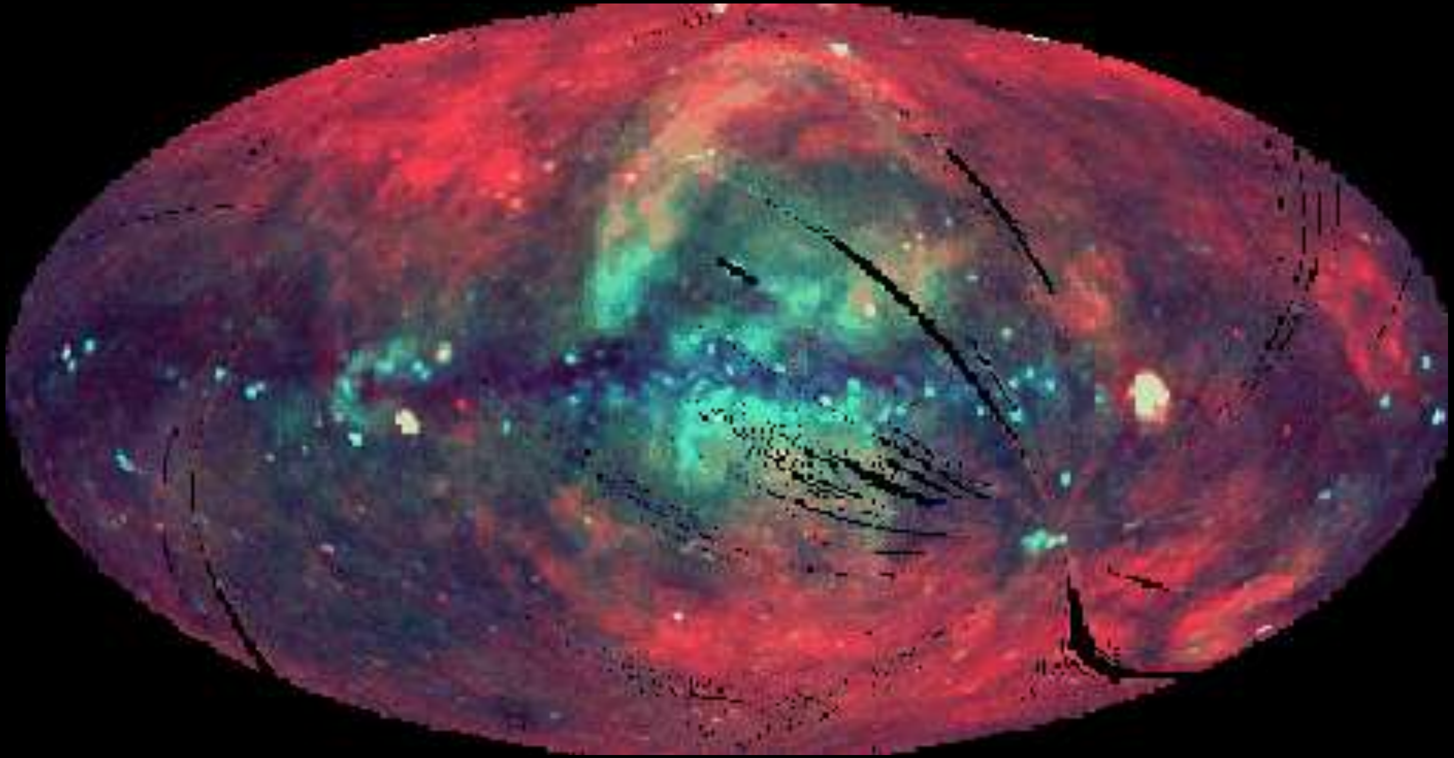
“A 1.2-Meter X-ray Telescope”

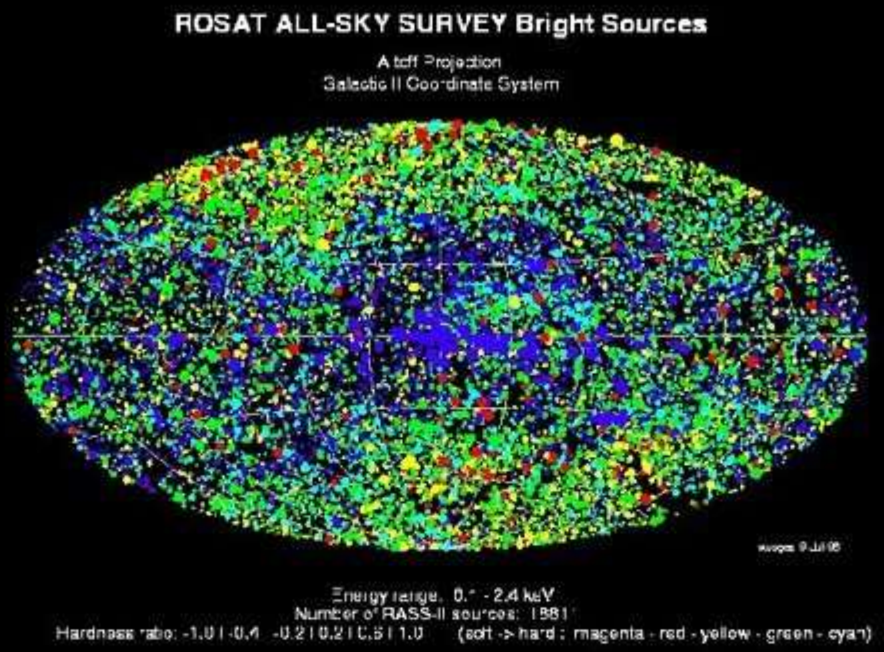


Chandra X-ray Observatory

All-Sky Survey

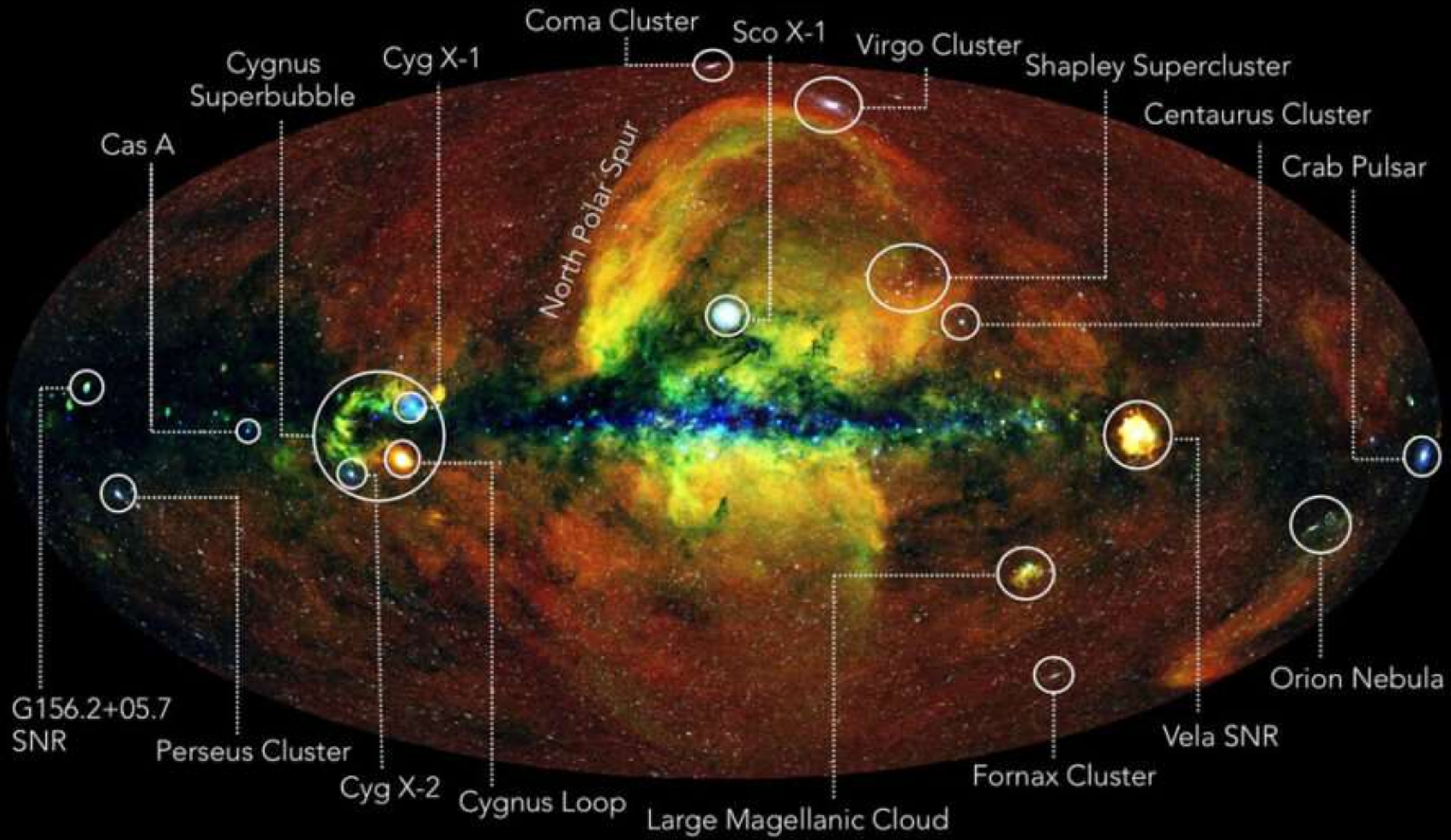
Hot Gas and Diffuse X-ray Background





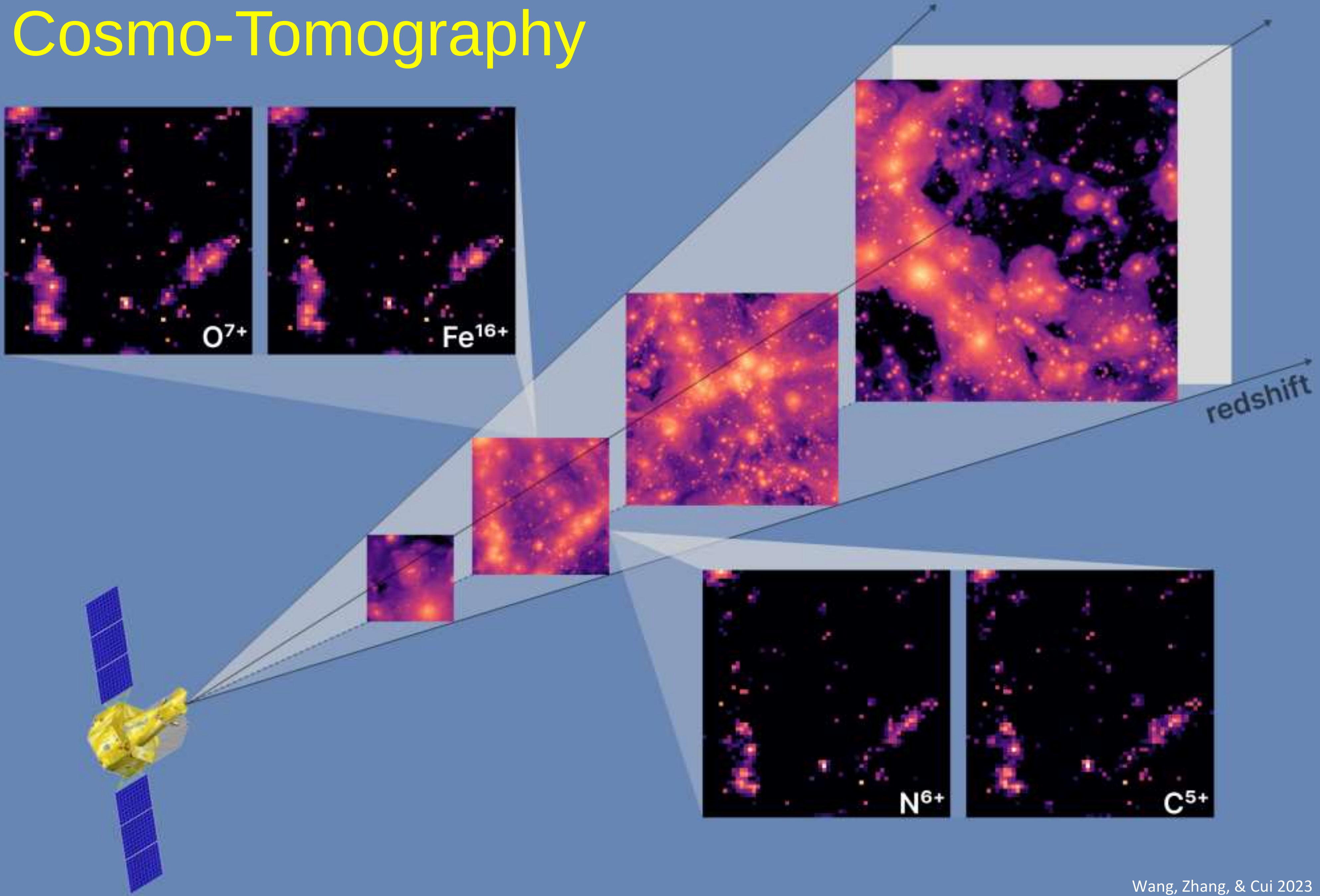
What’s Next?

https://www.mpe.mpg.de/7719713/news20210705



Ultimately, we would need a new detector to replace CCD, to carry out CT scans of the universe!

Cosmo-Tomography



Wang, Zhang, & Cui 2023

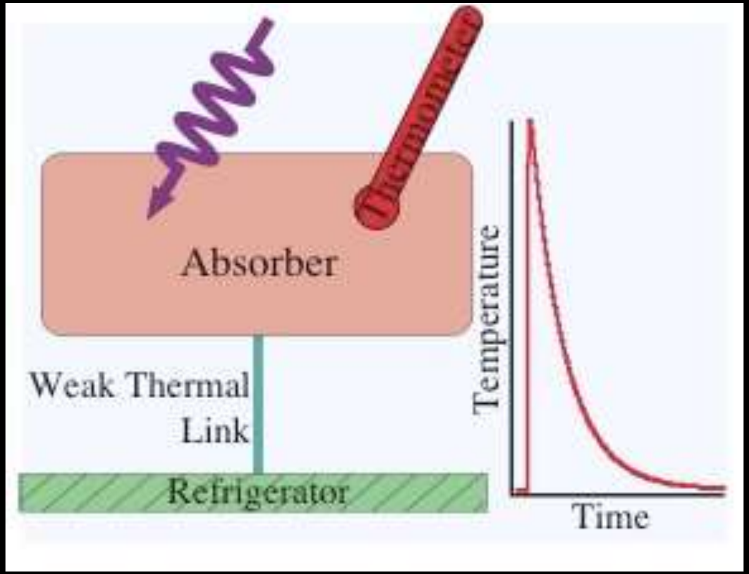
Enabling Technology

Non-dispersive, high-resolution X-ray spectrometer

Microcalorimeter:

- A material to absorb X-ray photons
- A sensitive thermometer to measure temperature rise
- A weak link to the heat sink to remove excess heat, getting ready for another X-ray photon.

Every X-ray photon produces a temperature pulse!



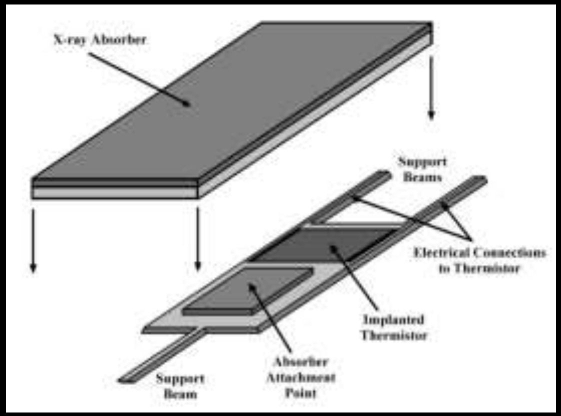
Energy resolution:

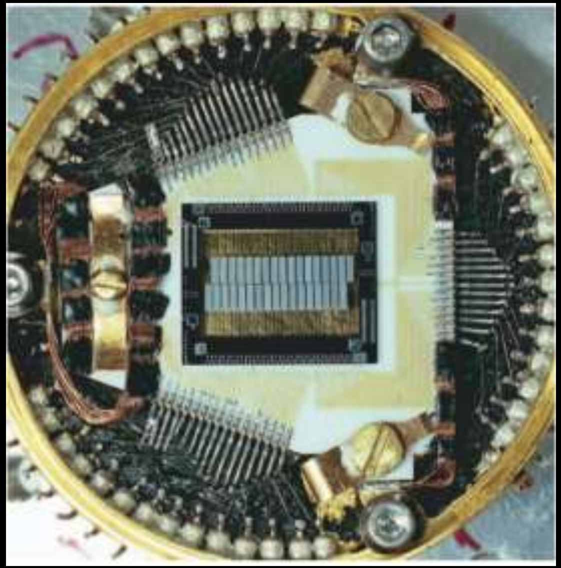
$$\Delta E = \xi \sqrt{\frac{k_B T^2 C}{\alpha}}$$

$$\alpha \equiv \frac{dlogR}{dlogT}$$

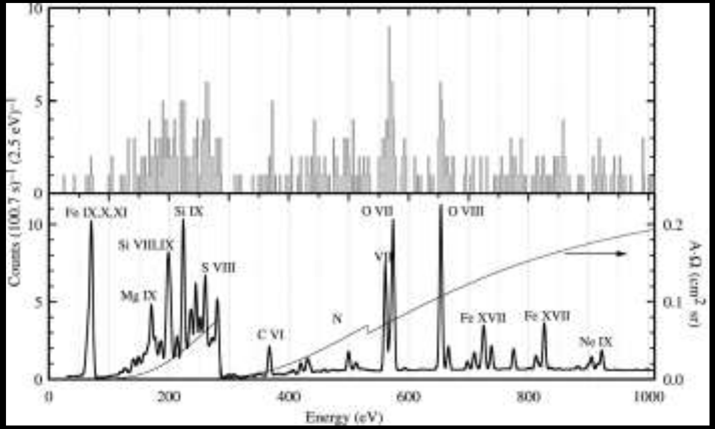
Development of Microcalorimeter

~1990

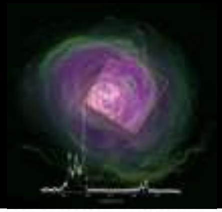




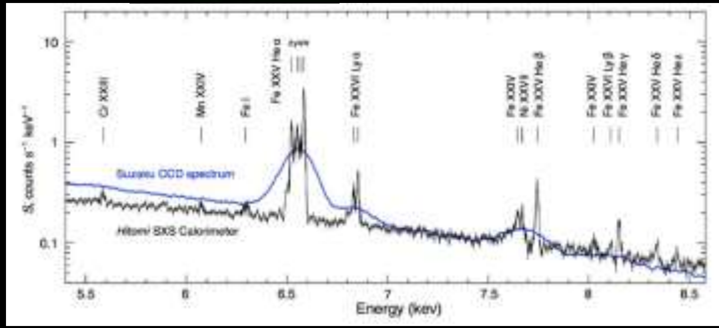
1995-2022: XQC



D. McCammon + 2002

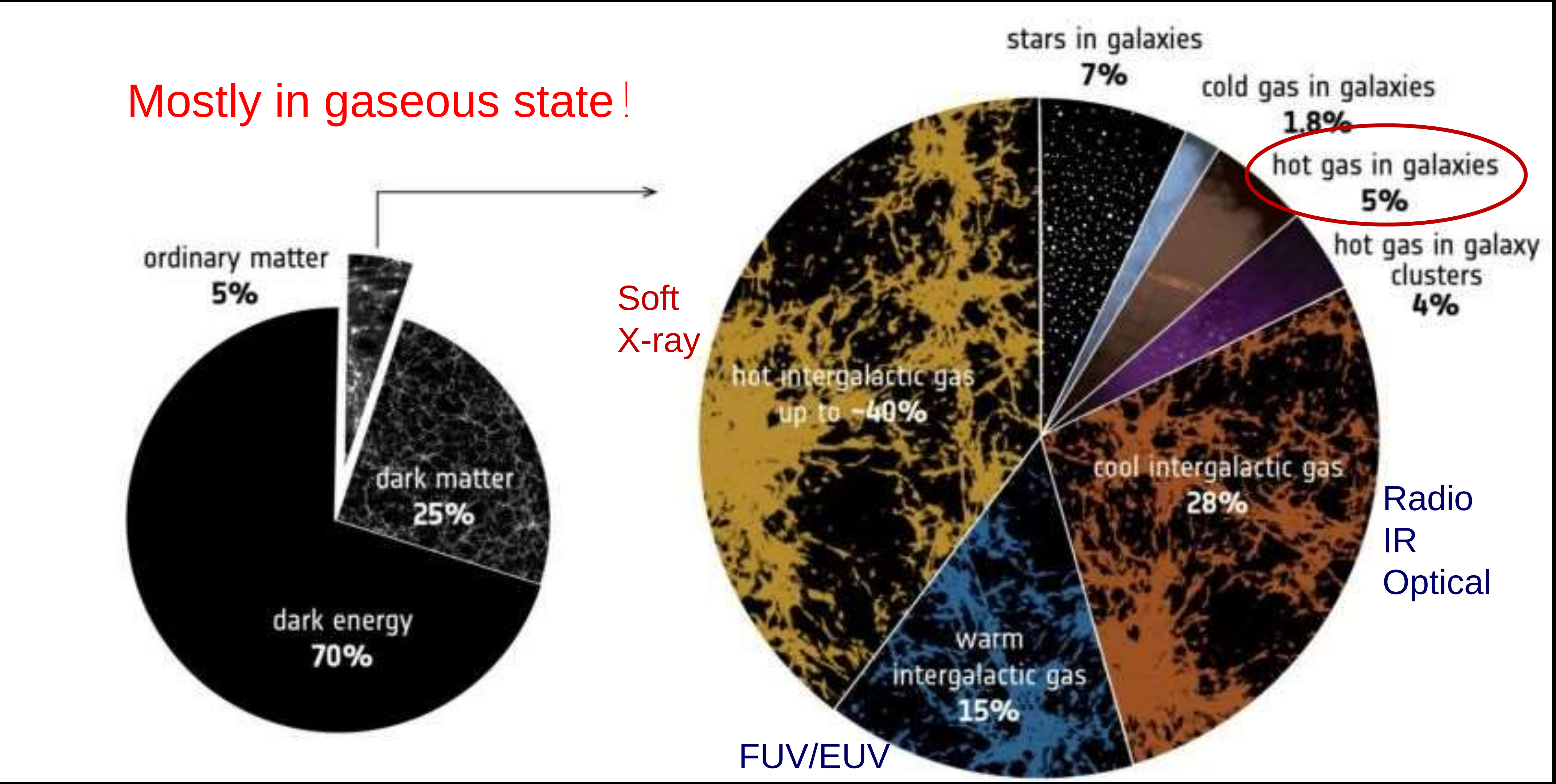


Hitomi Collaboration 2016



2000- : Astro-E's, Hitomi, XRISM

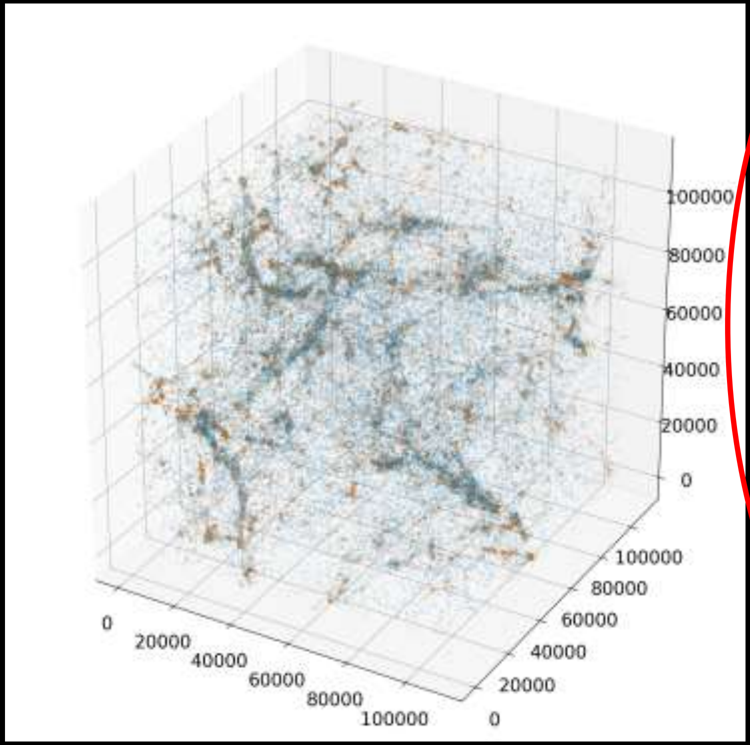
Cosmic Baryons



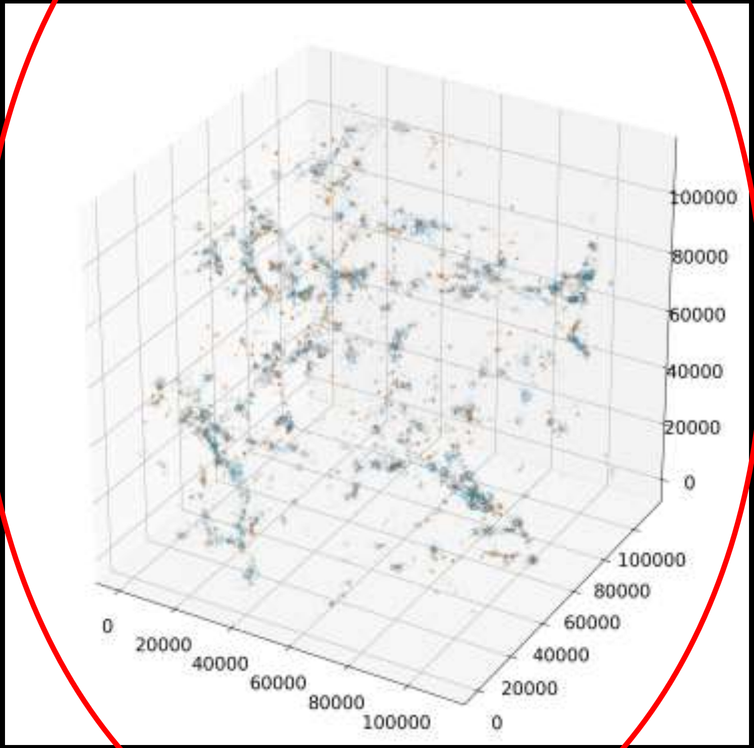
Credit: ESA, https://sci.esa.int/web/xmm-newton/-/60430-the-cosmic-budget-of-ordinary-matter

Hot Baryons in the Cosmic Web

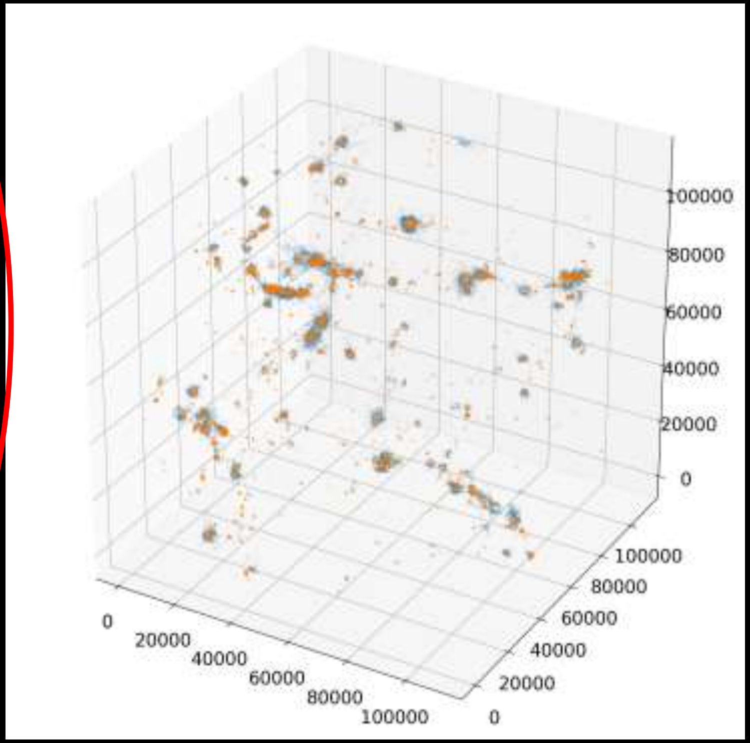
All T



$T = 10^{6} - 10^{6.5}$ K



$T = 10^{6.5} - 10^{7}$ K



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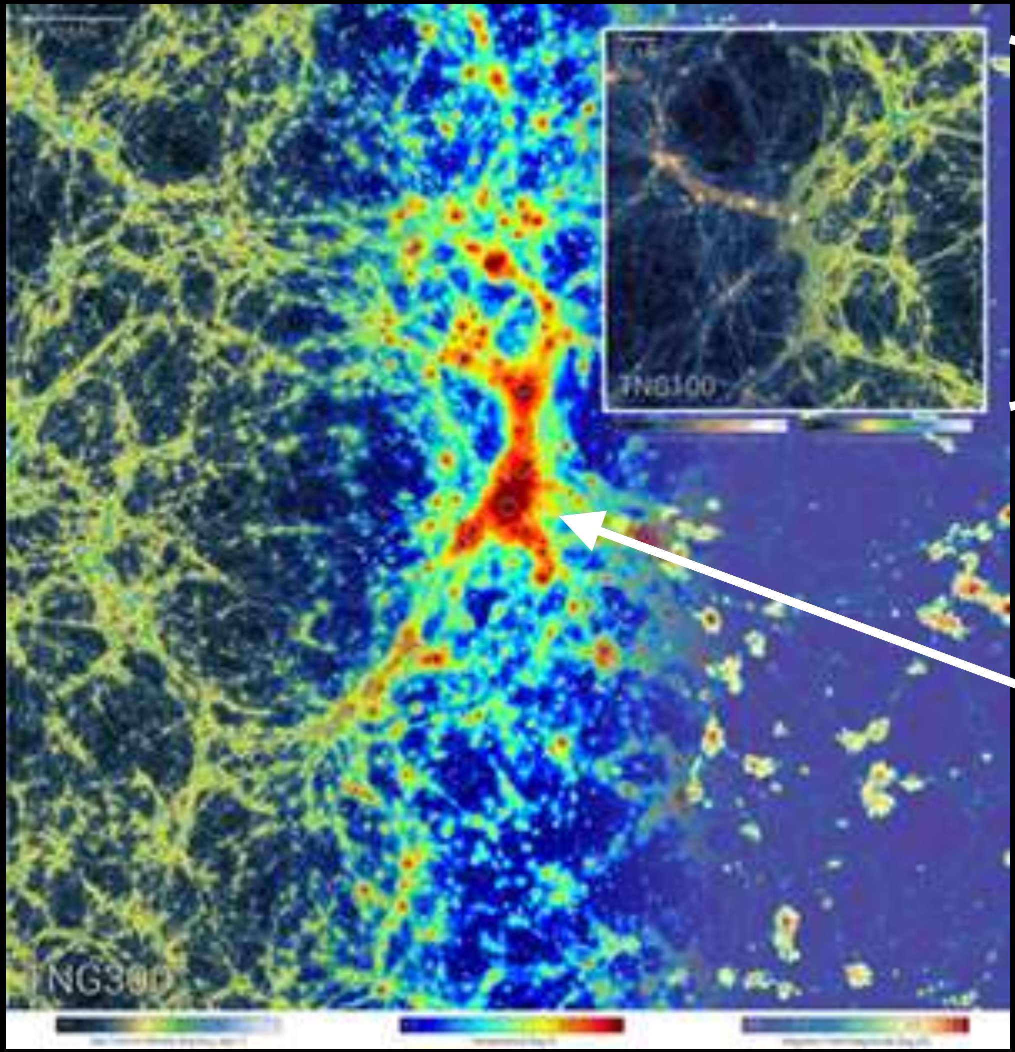
Key Tracer Paricles



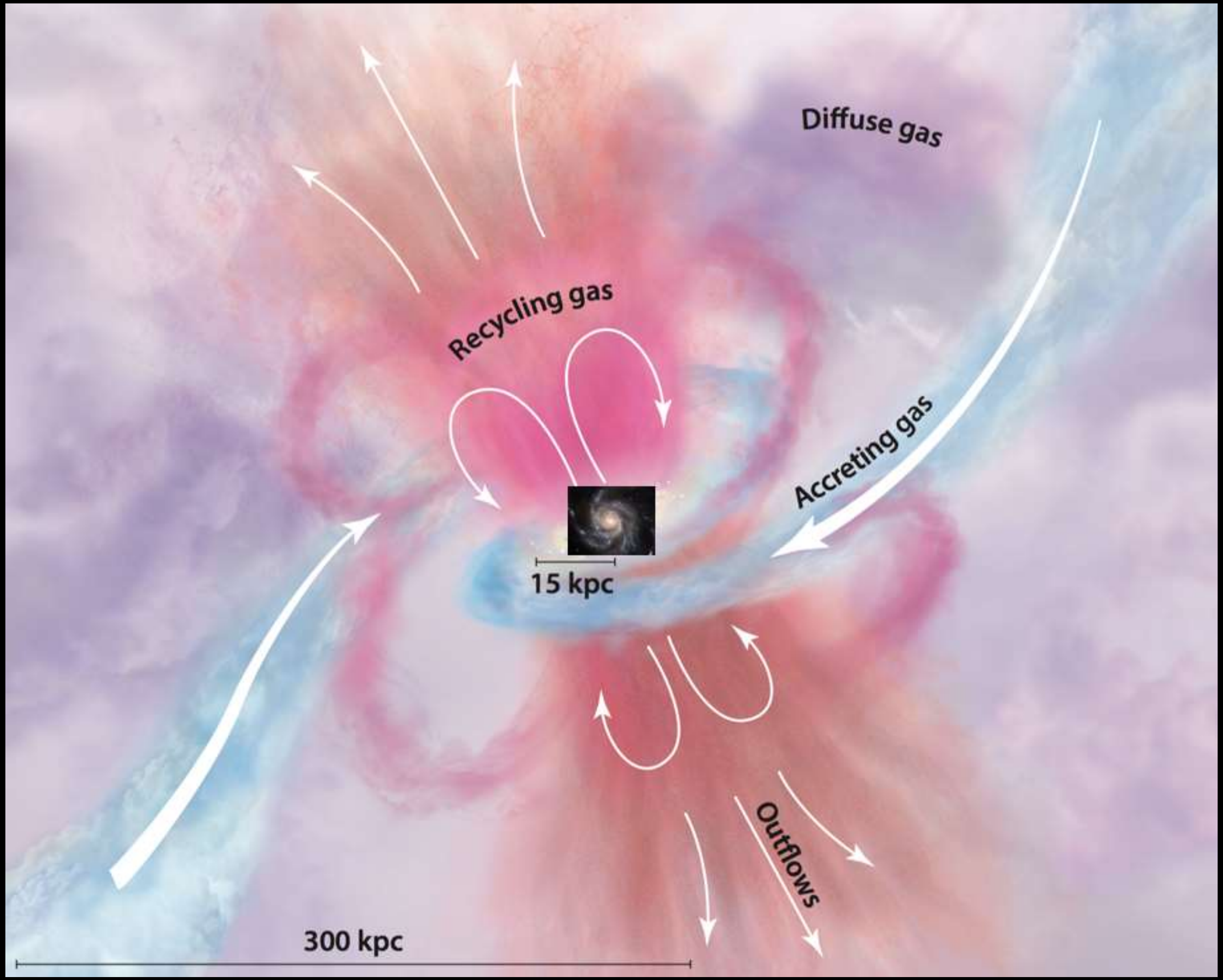
From https://www.tng-project.org/static/tng/media/

Baryonic feedback

Shock-heated baryons in the cosmic web

"Missing" baryons?

Key Tracer Paricles



Adapted from Tumlinson, Peeples, & Werk 2017

Baryons cycling in and out of galaxies

Galaxy evolution

Realizing the Astro2020 Program: Pathways From Foundations to Frontiers

Explore the Cosmos

- Worlds and Suns in Context
- New Messengers and New Physics
- Cosmic Ecosystems
- Pathways to Habitable Worlds
- New Windows on the Dynamic Universe
- Unveiling the Drivers of Galaxy Growth

Forge the Frontiers

- Enable U.S. community participation in ELT program
- Develop and Implement Cosmic microwave Background S4 (joint DOE)
- Begin ngVLA design, technical demonstration, construction
- Upgrade IceCube to Gen2 (NSF/PHY)
- Begin implementation of an Infrared/Optical/Ultraviolet large strategic mission for exoplanet exploration and general astrophysics after a successful maturation program

Enable Future Visions

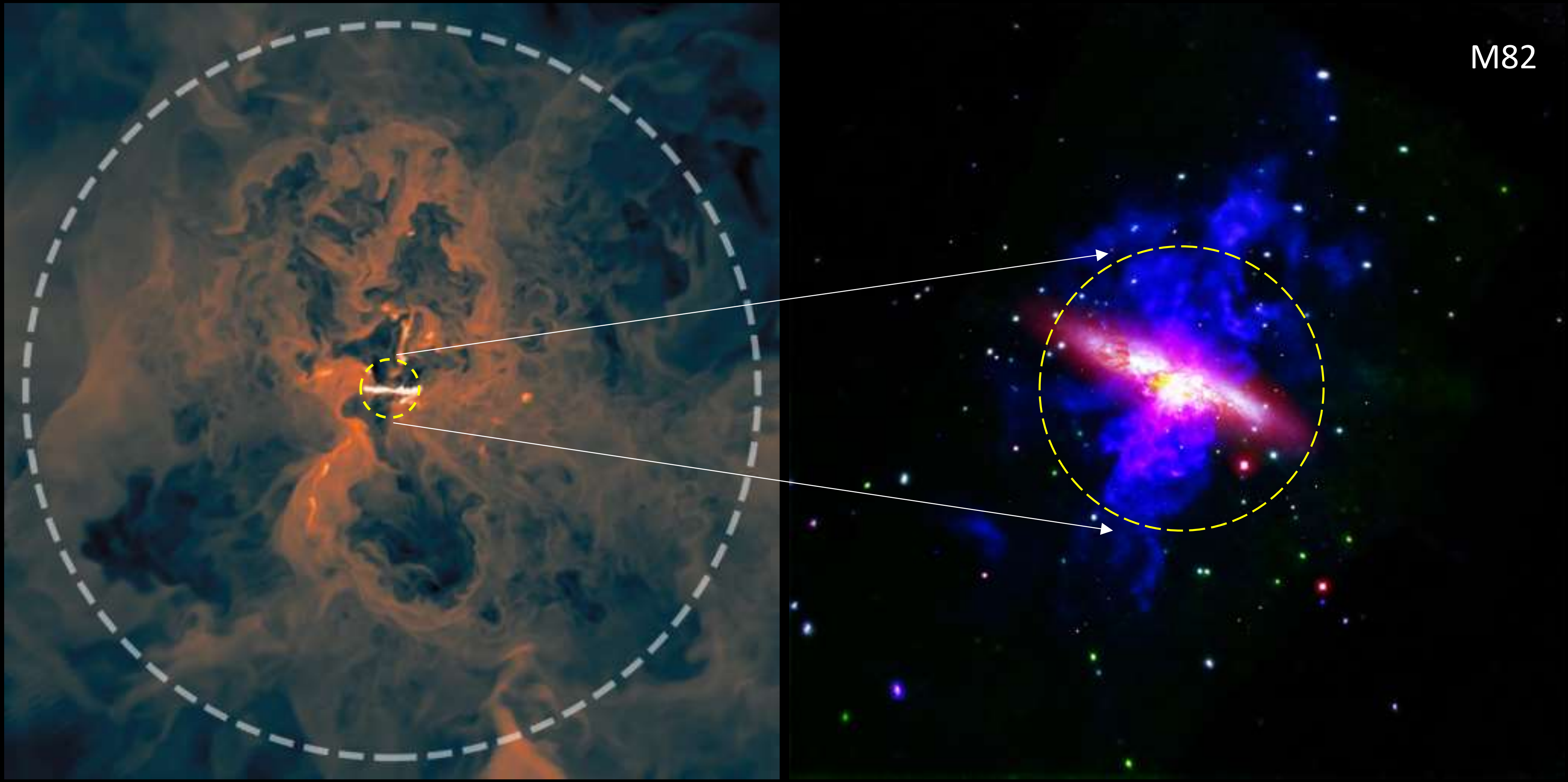
- Develop technology for future gravitational wave upgrades and observatories (NSF/PHY)
- Commence Great Observatories Missions and Technology Maturation Program

First entrant: IR/O/UV missions

Ground-Based

Space-Based

Gap between Theory and Observation

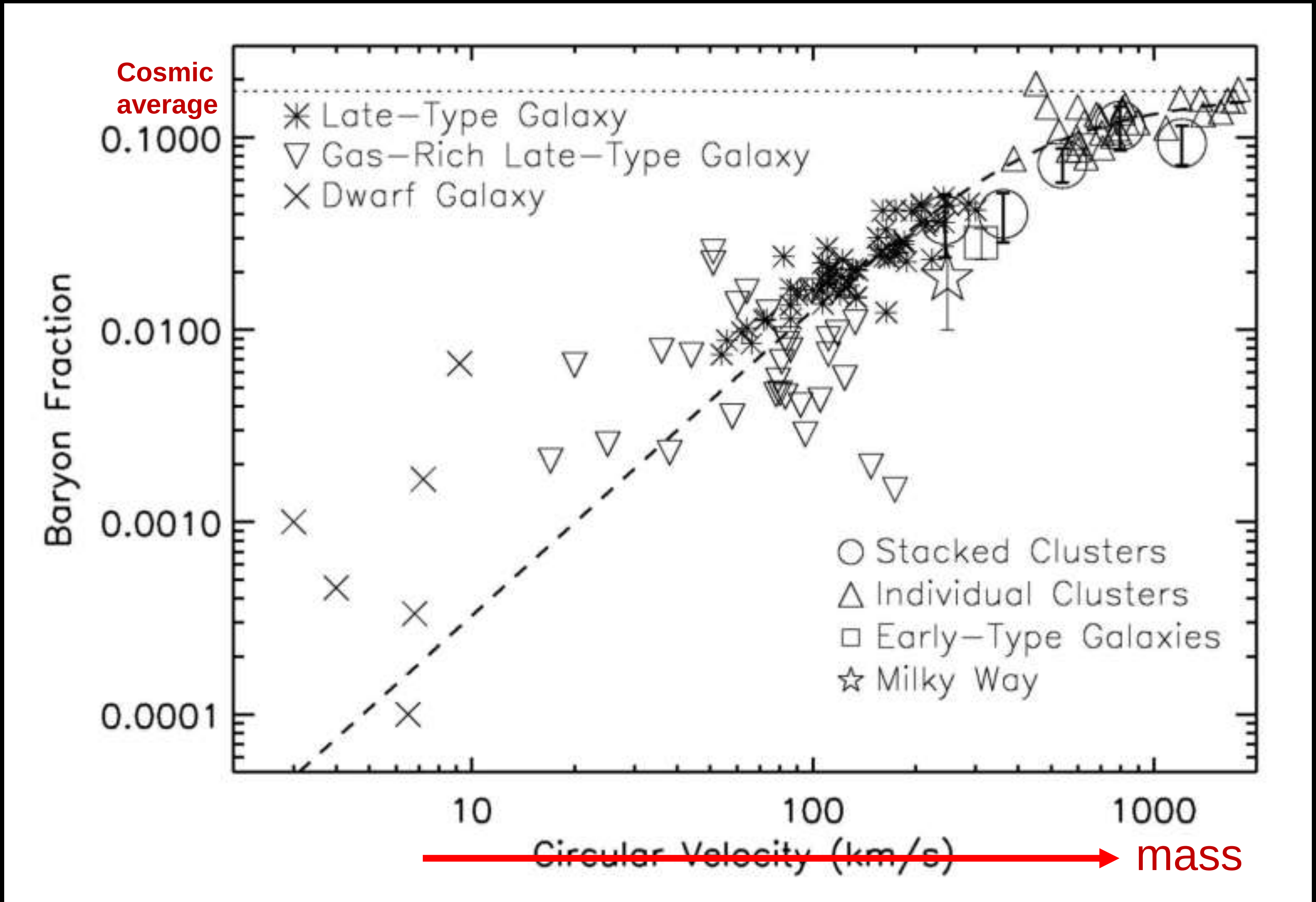


From https://www.itp.ucsb.edu/activities/halo21

From https://chandra.harvard.edu/photo/2011/m82/

Baryon Deficit in Galaxies

X. Dai + 2010

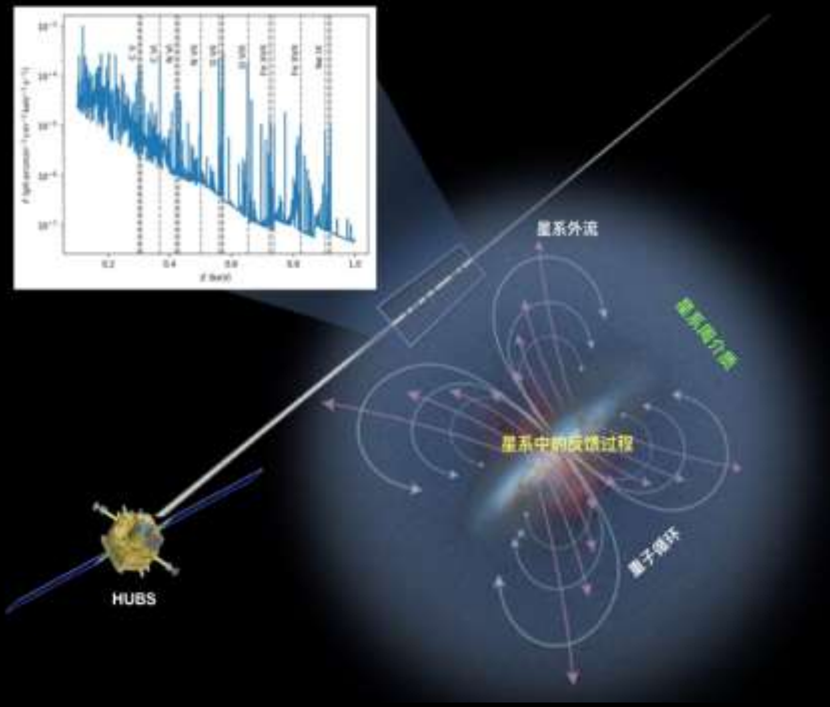


Hidden baryons in the hot halo?

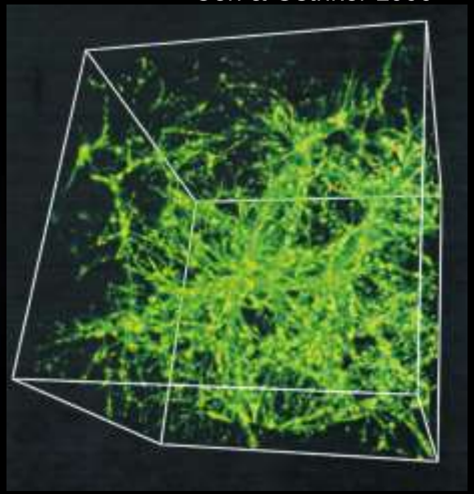
HUBS Concept

- An imaging spectrometer optimized for the soft X-ray band
  - Energy range: 0.1-2 keV
  - Detector: TES microcalorimeter array
    - Main array: 60x60, 2 eV resolution
    - Central sub-array: 12x12, 0.6 eV resolution
- X-ray telescope with large FoV
  - Peak collecting area: $A_{col} > 1000\ cm^2$
  - Field of view (FoV): $\Omega_{FoV} \sim 1\ deg^2$
  - Angular resolution: $< 1'$

- Unseen baryons in galaxy ecosystems and large-scale structures
- High-resolution spectroscopy in the soft X-ray band



Cen & Ostriker 1999



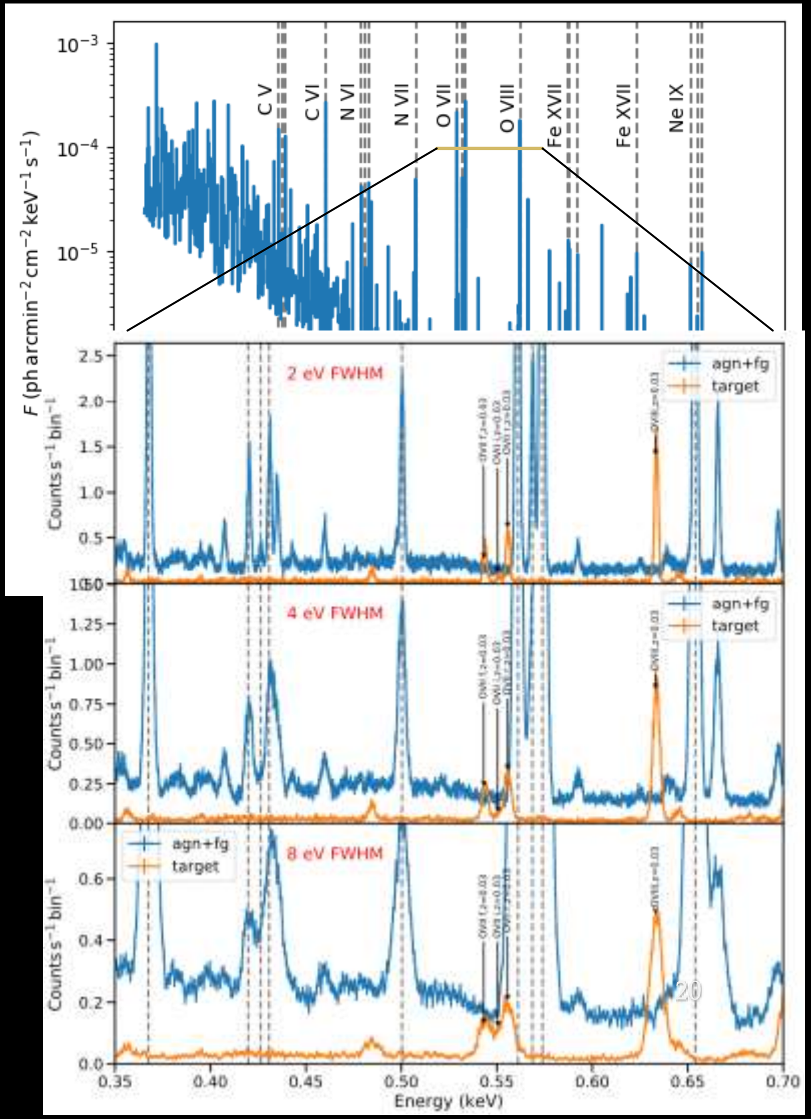
W. Cui + 2020, SPIE Astronomical Telescopes+Instrumentation

HUBS website: https://hubs.phys.tsinghua.edu.cn/en

High-Resolution X-ray Spectroscopy

- Strong foreground
  - Local Bubble+halo+SWCX
  - E.g., ROSAT, XQC
  - Need to separate redshifted lines
- Enhance S/N in imaging
  - Narrow-band imaging around isolated emission lines
- Plasma diagnostics
  - Imaging shows spatial distribution.
  - High-resolution X-ray spectroscopy provides diagnostics of density, temperature, and abundance

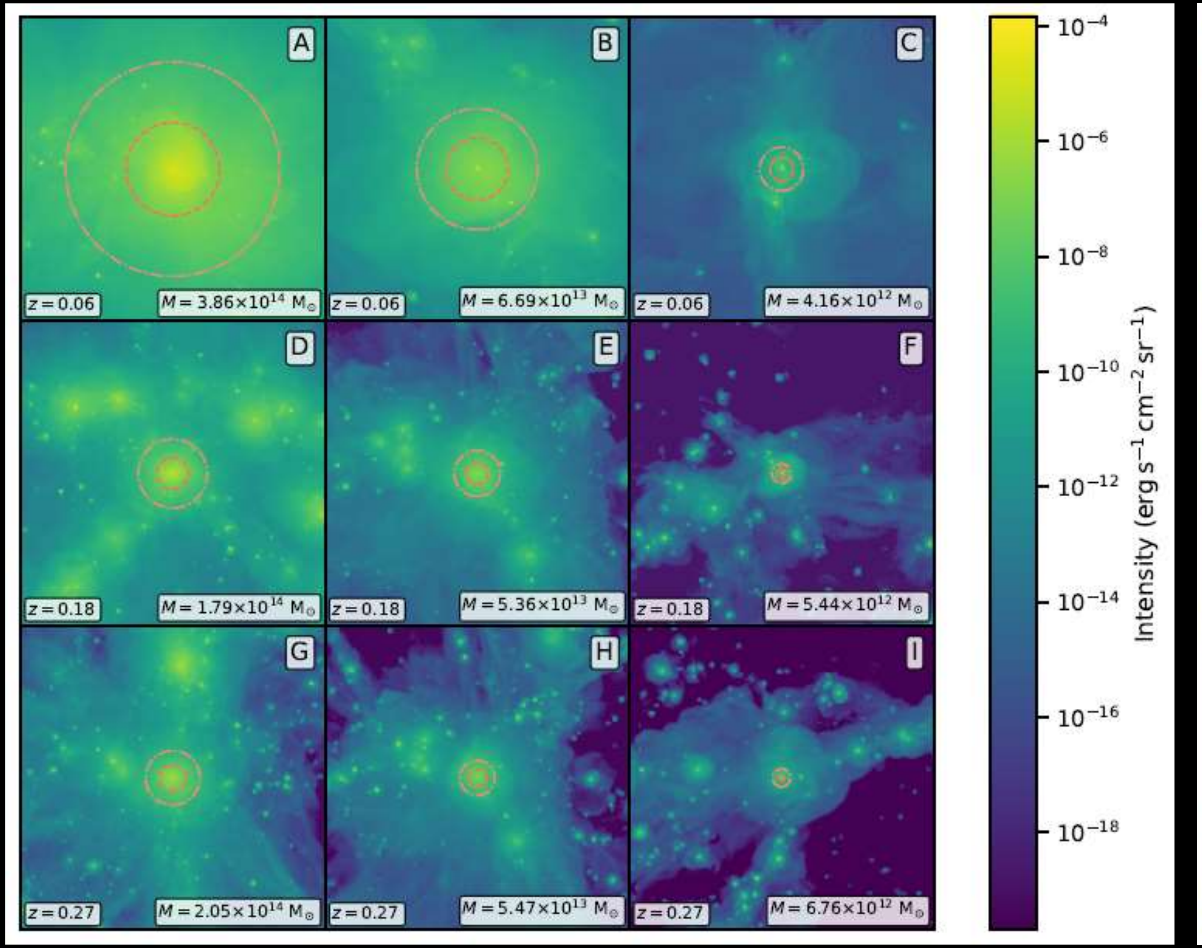
W. Cui + 2020

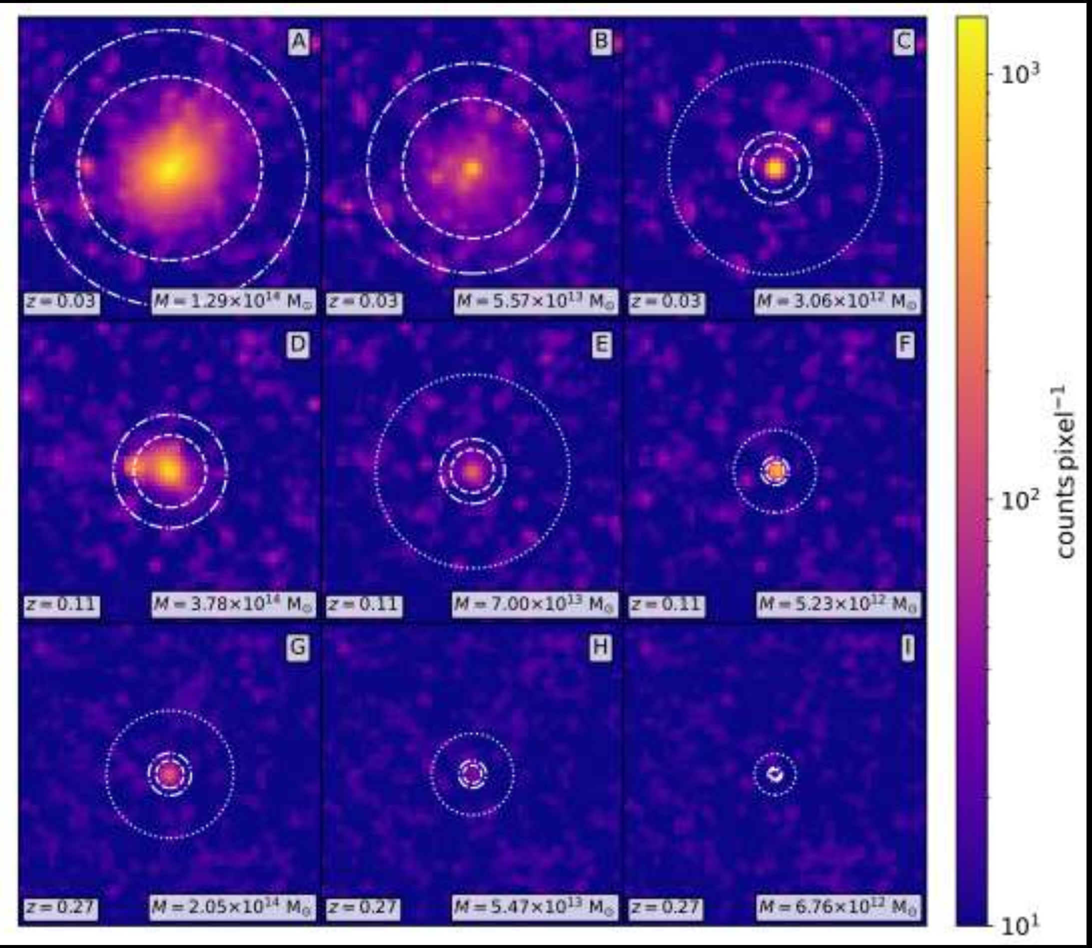


Mock HUBS Images

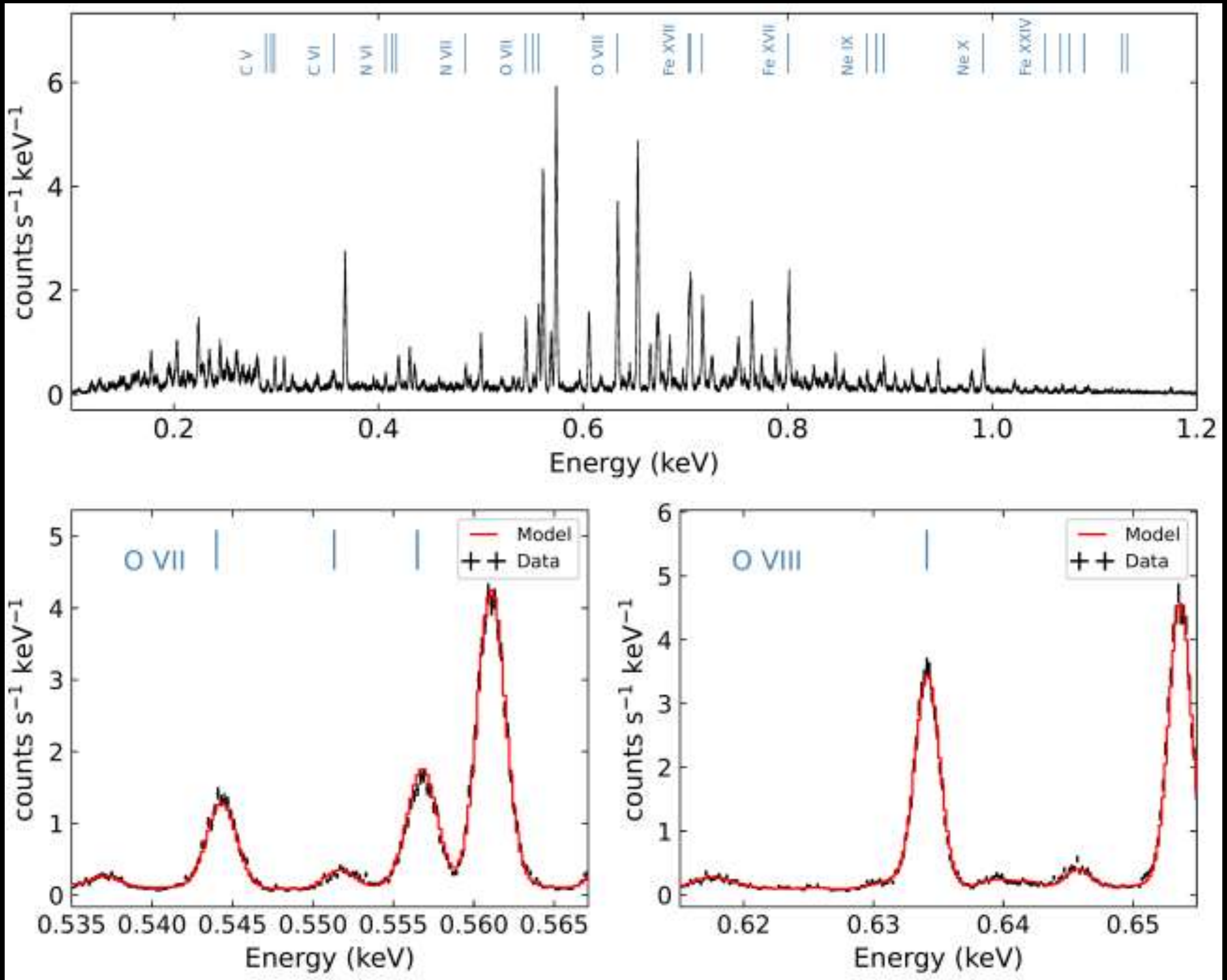
clusters groups galaxies

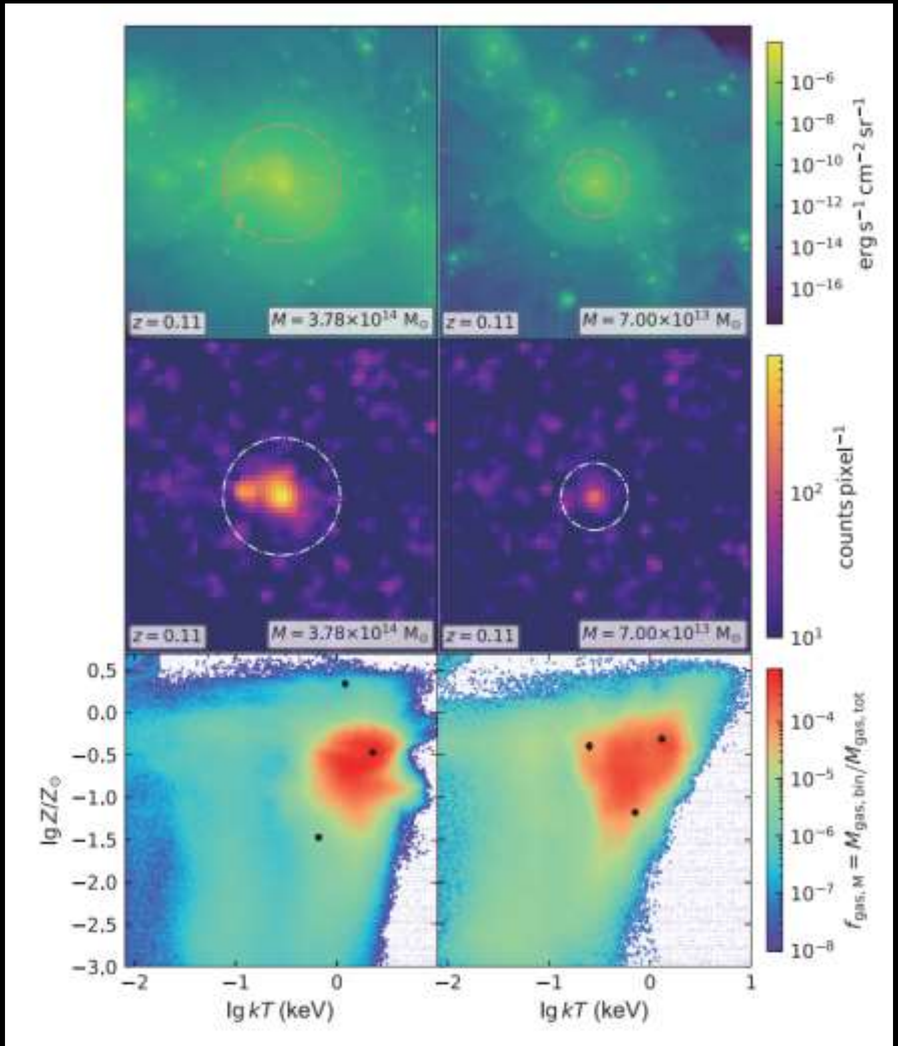
Y.N. Zhang + 2022





Mock HUBS Spectrum





Y.N. Zhang +, 2022

Complementarity: Large vs Small FoV

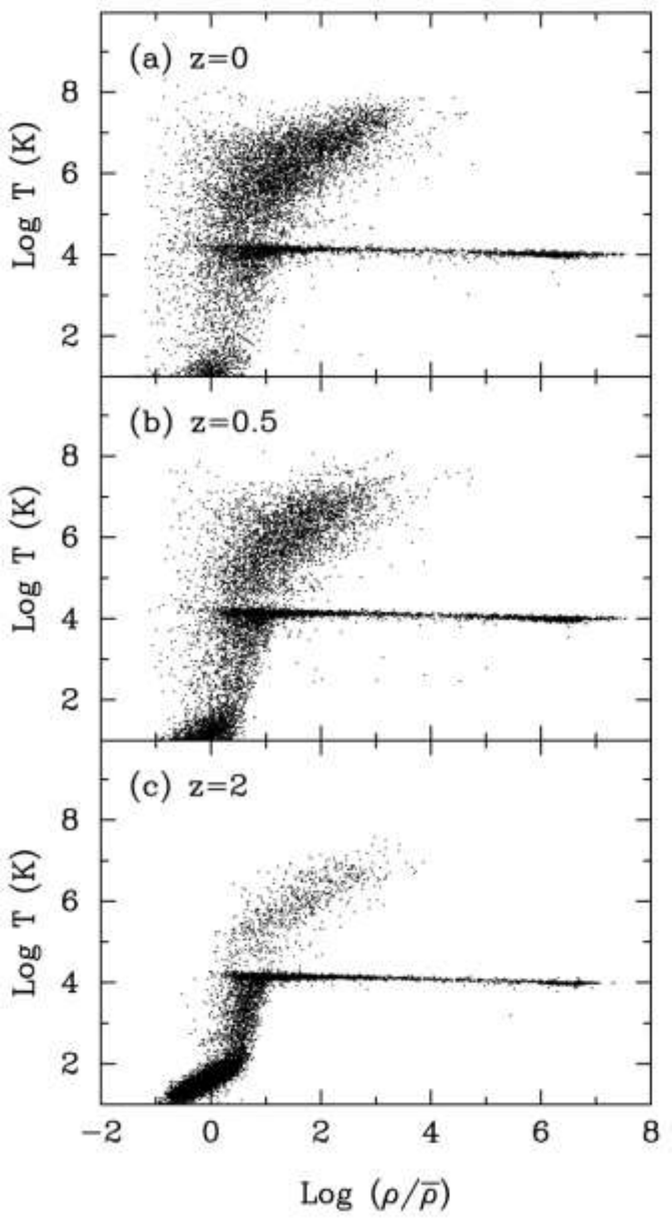
For detecting the spectral lines of diffuse emission, the figure of merit is

$$FoM = RA_{eff}\Omega_{FOV}$$

Mission	Instrument	Launch Date	R @1 keV	A_{eff} @1 keV (cm^2)	Ω_{FOV} (deg^2)	FoM
NewATHENA	X-IFU	~2037	<333	<8500	0.0069	<19530
HUBS		~2031	500	500	1	250000

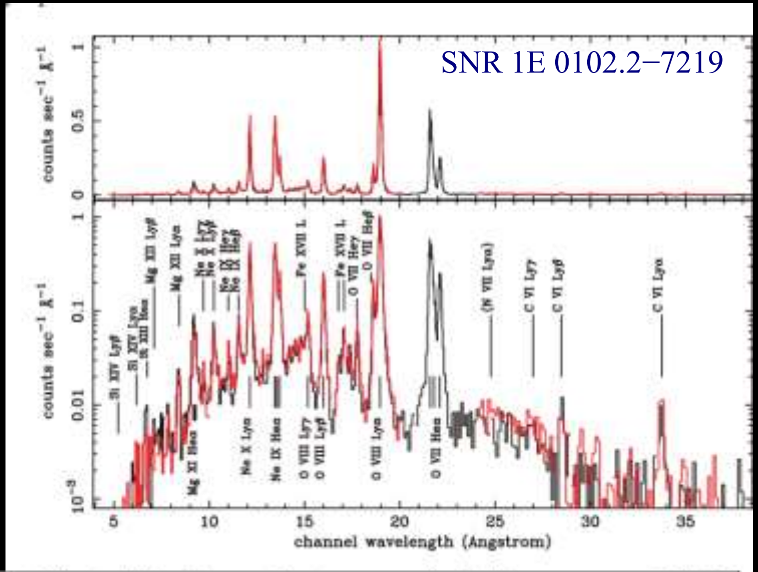
HUBS is highly optimized for detecting hot baryons in the present-day universe!

Croft + 2001

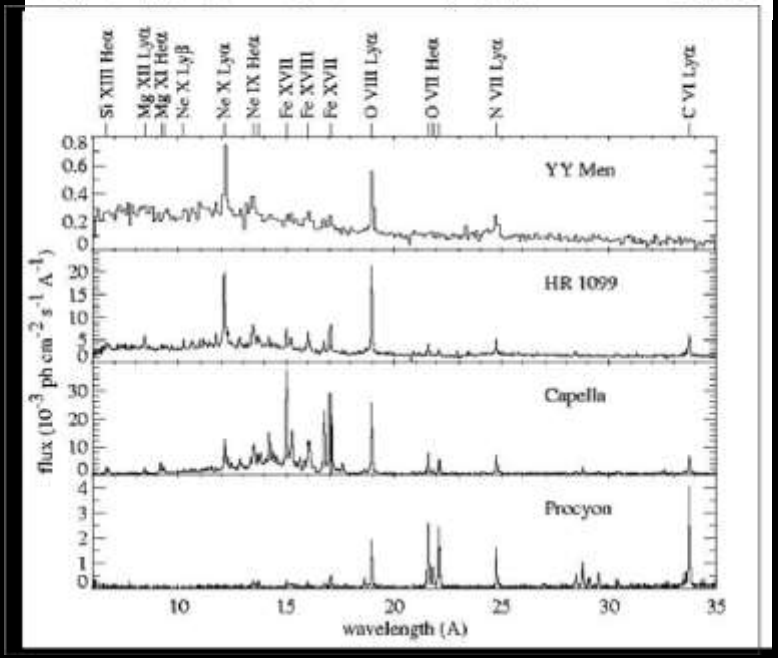


HUBS Science Programs

- Key science drivers
  - CGM/IGM
  - Black hole and stellar feedback
  - Large-scale accretion
- Broader science reach
  - Diffuse X-ray background
  - Local Bubble/halo
  - Solar-wind charge exchange
  - Supernova remnants, ISM
  - X-ray binaries
  - X-ray transients
  - Neutron star and GR
  - Active stars and stellar coronae
  - Light dark matter



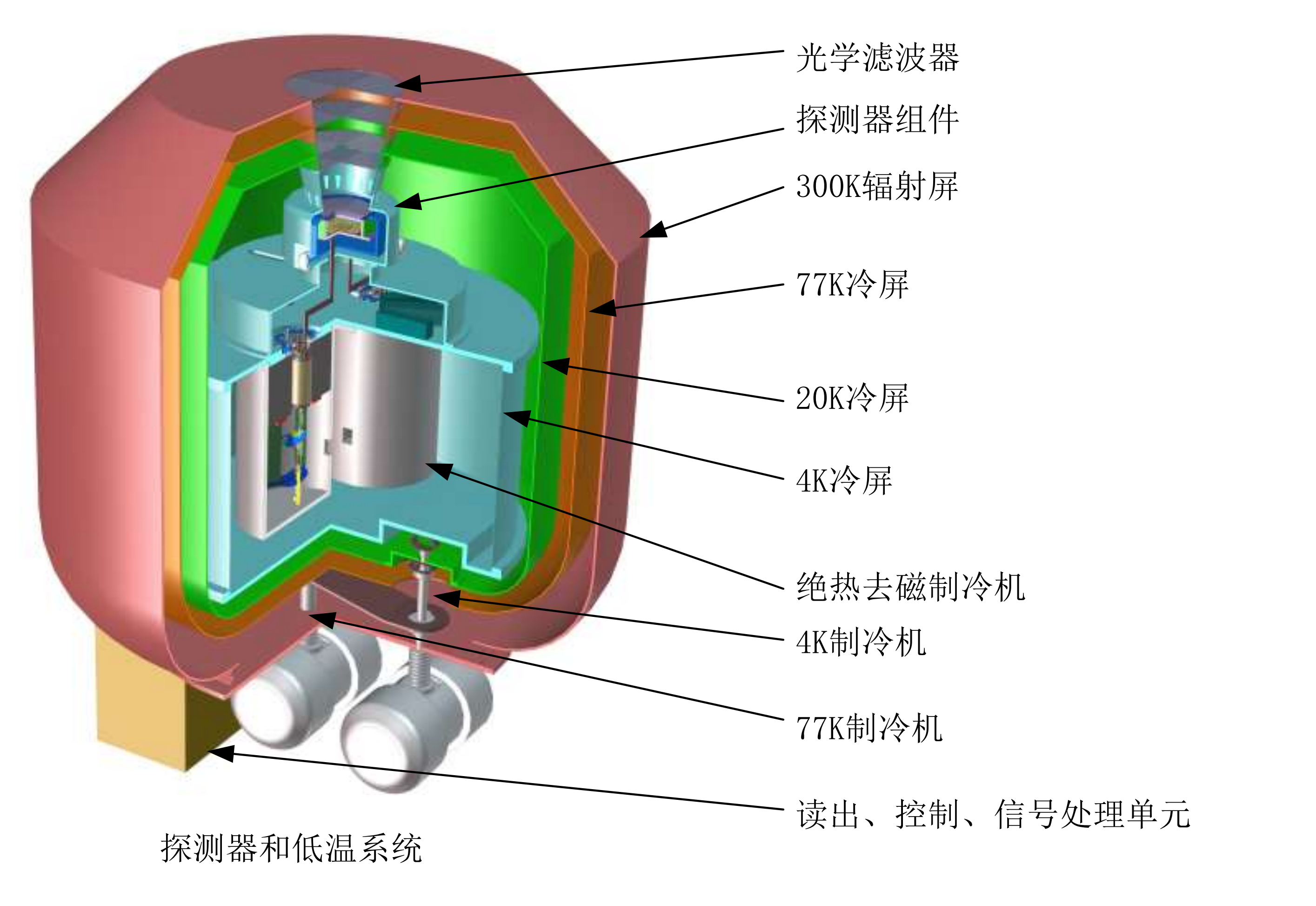
Supernova remnants

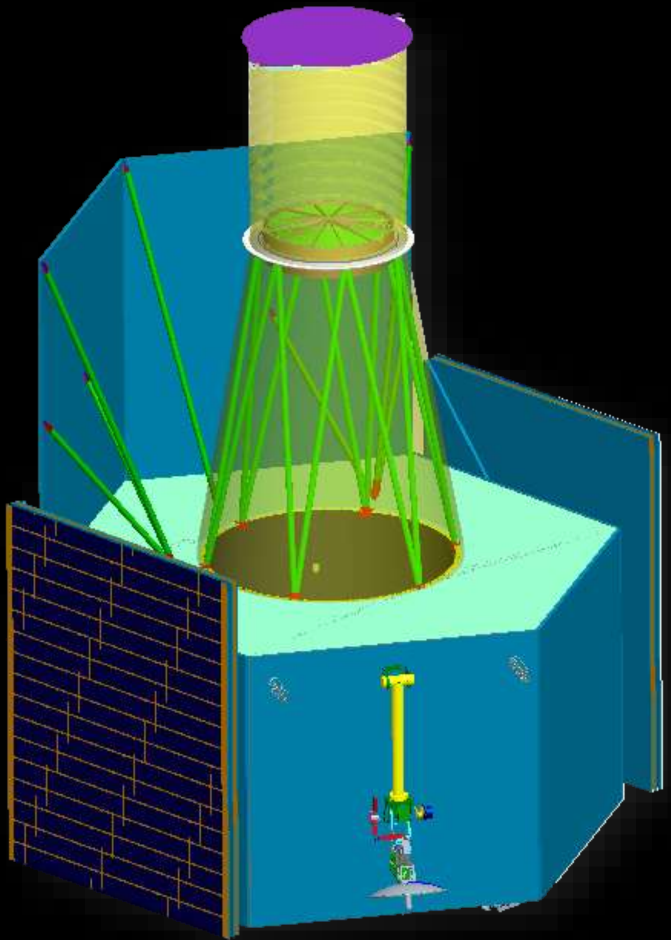


Stars

HUBS Design

Low-earth orbit：~550km, <30° incl.





HUBS Status and Future Plans

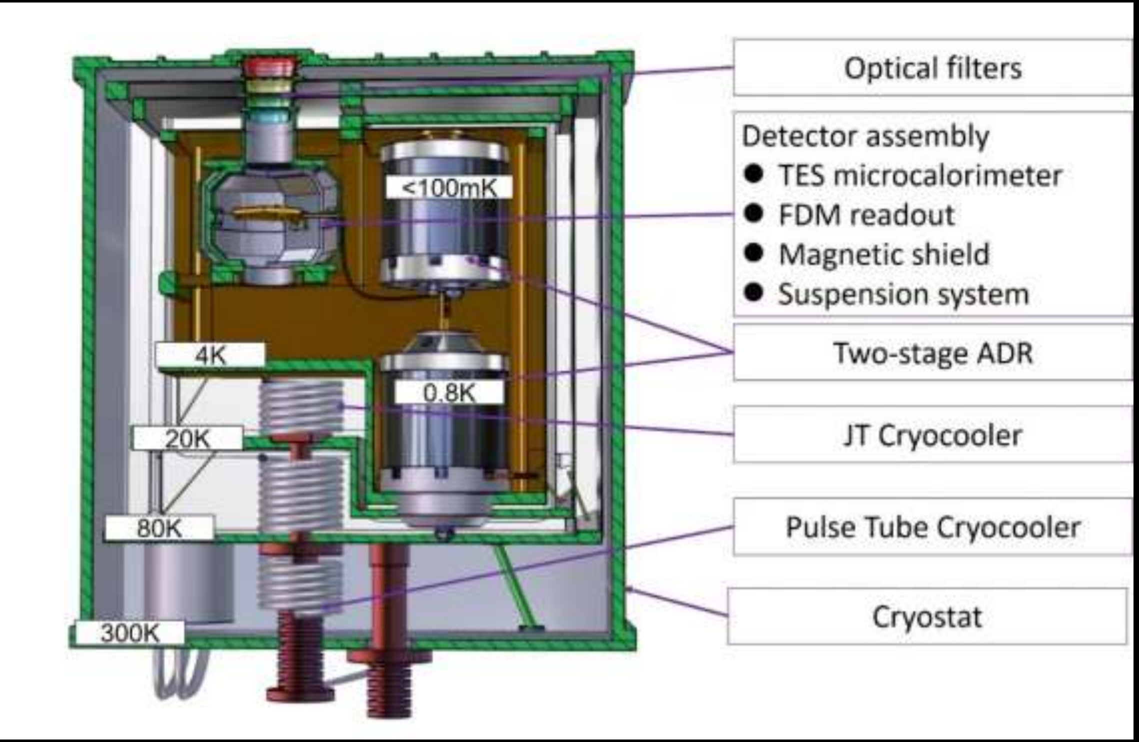
- ## Concept studies
  - First collaboration meeting in Beijing, 2017
  - Focus meeting at the IAU General Assembly meeting in Vienna, 2018
  - First HUBS Workshop in Shanghai, 2018
- ## Concept development
  - Preliminary development, CAS, 2018-2021
  - Key technology development, CNSA, 2022-2023
- ## Path forward
  - Preliminary design and technology completion, 2024-2026
  - Construction, 2026-2031
  - Science operation, 2031-2036

A Survey Experiment

Diffuse X-ray Explorer (DIXE) is proposed for the China Space Station.

DIXE web site: https://dixe-css.cn/en

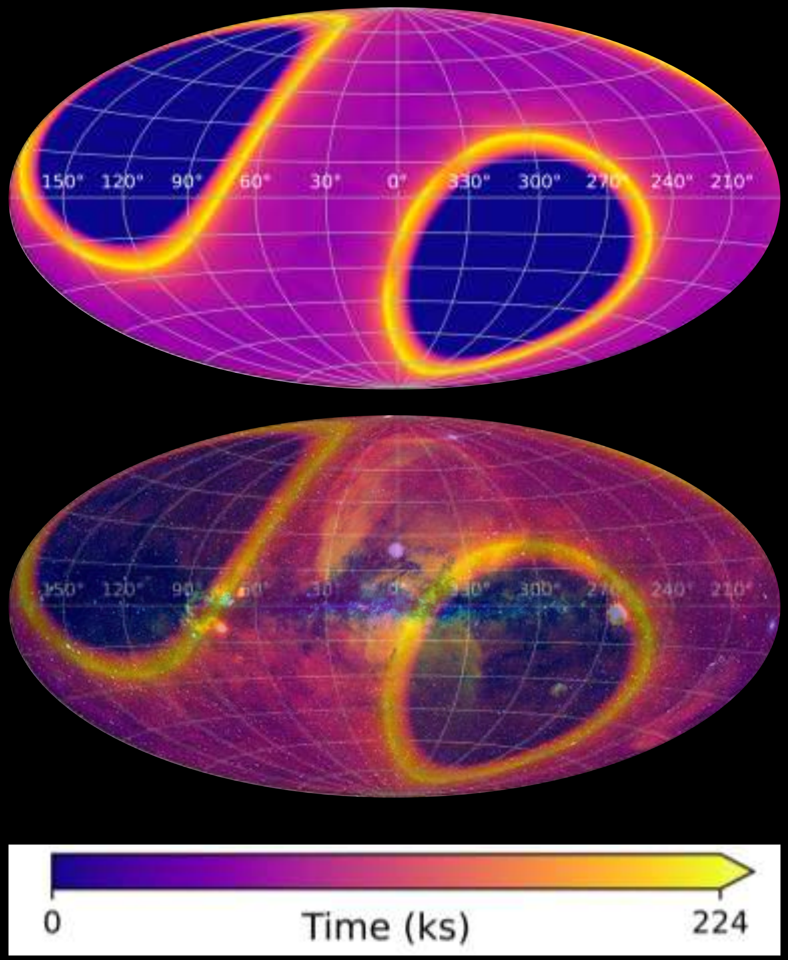
- Energy range： 0.1-10 keV
- Energy resolution: < 6 eV
- Field of view： 10° (collimated)
- Effective area： > 0.5 cm^2
- Grasp： > 50 cm^2 deg^2
- Observing mode： scanning survey
- Period of operation: 2027-2029



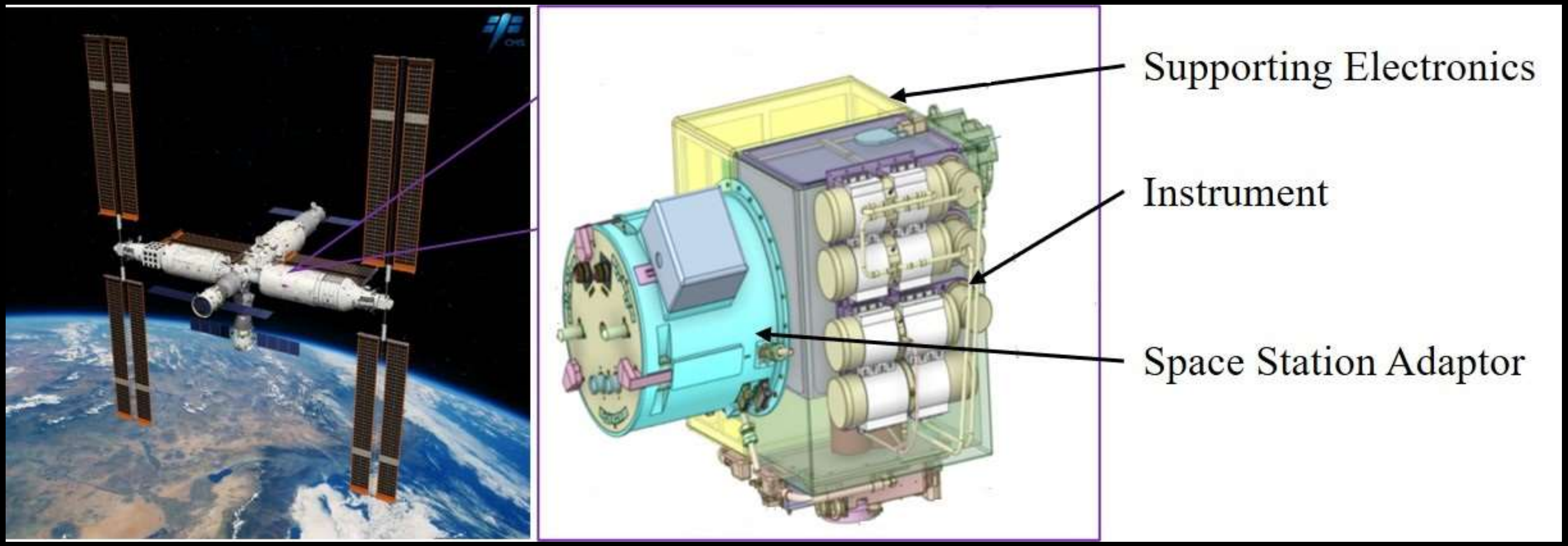
Jin, Mao + 2024

Bring high-resolution X-ray spectroscopy to the whole sky!

DIXE Sky Coverage



Courtesy J.J. Mao

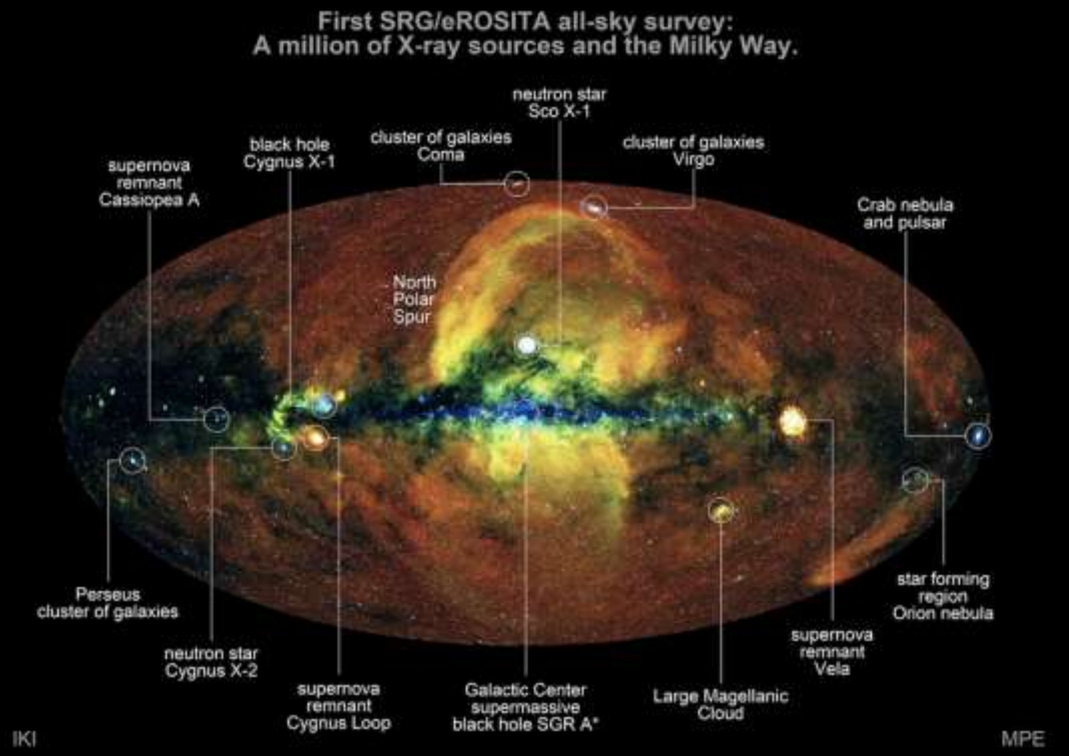


Jin, Mao +. 2024

The payload is fixed to CSS. There are significant holes in the coverage. But, cumulated exposure time still exceeds 150 ks on the eROSITA Bubble, Cygnus Superbubble, and others.

DIXE Scientific Objectives

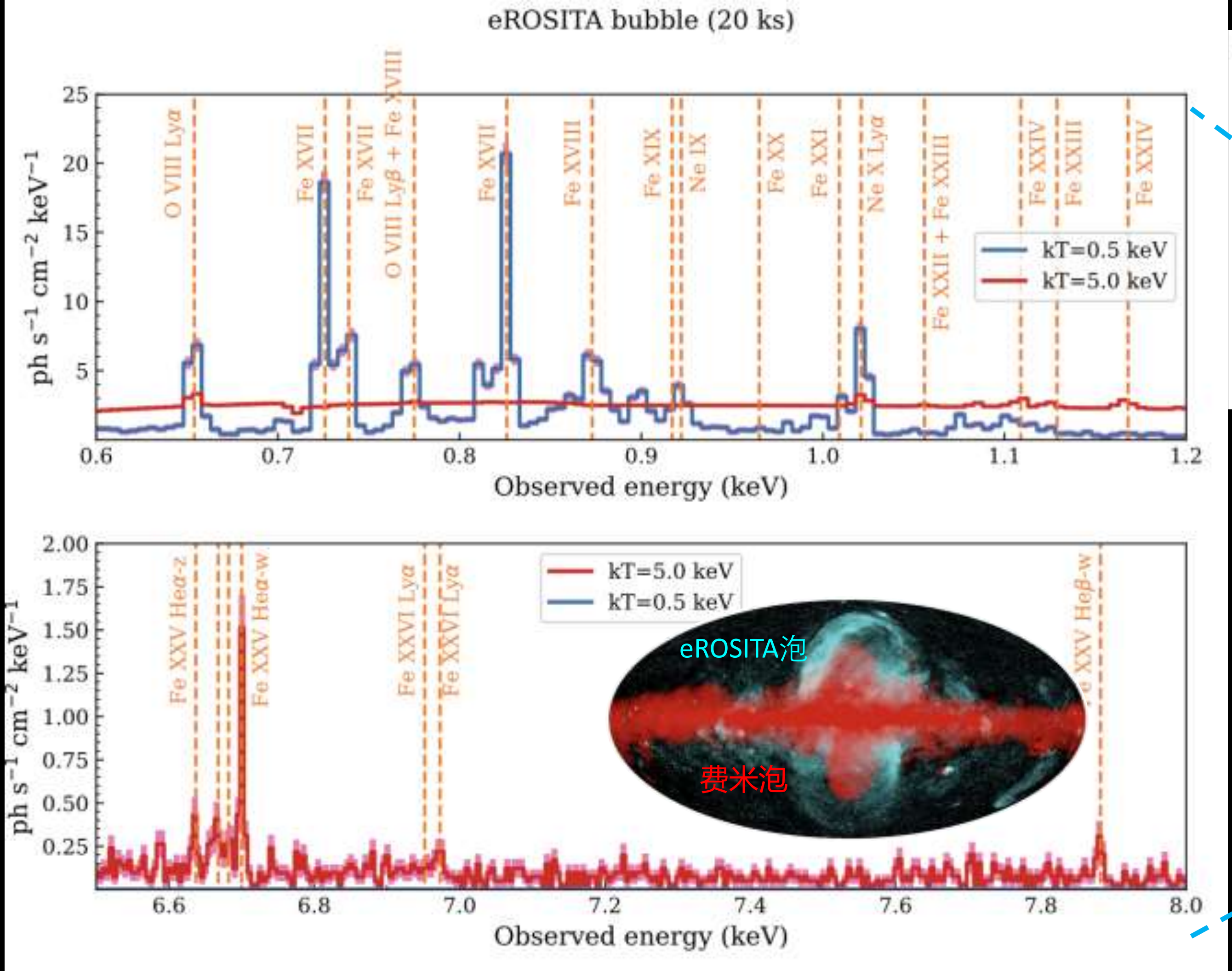
- Origin of the soft diffuse X-ray background
  - Local Bubble
  - Halo
  - Solar wind charge exchange
- Origin of X-ray structures in the Milky Way
  - eROSITA Bubble
  - Superbubbles
  - ISM
- Origin of Galactic halo
  - Stellar and black hole feedback
  - Accretion from large-scale structures



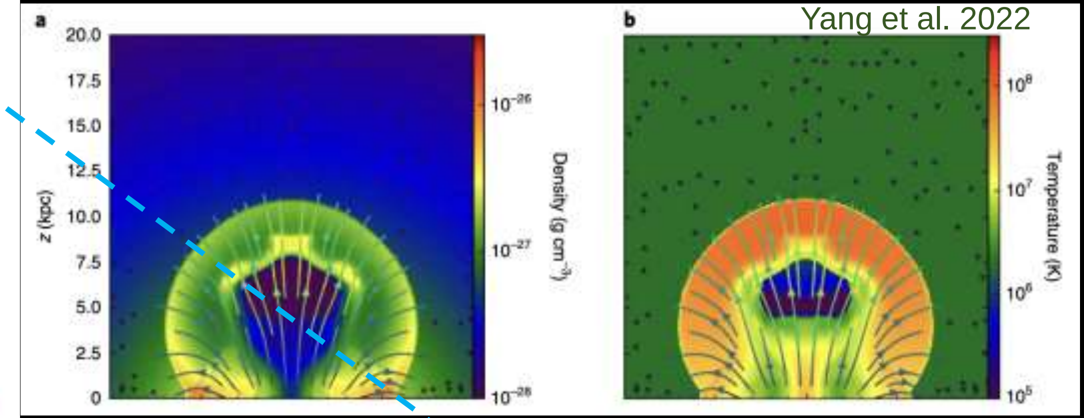
Building upon state-of-the-art imaging survey, DIXE enables high-resolution spectroscopic studies of hot gas in the Milky Way.

Simulated DIXE Spectrum

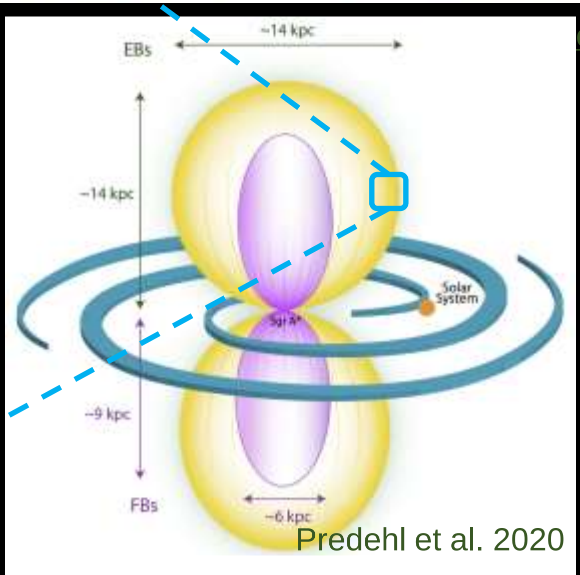
Credits: Junjie Mao



Theoretical model



e Astronomy



Summary

- New era of technologies
  - Striving for ever higher sensitivity!
  - Developing low-temperature detectors
  - Needing space-qualified mK coolers and other supporting technologies
- New era of X-ray spectroscopy.
  - Perfect marriage of astrophysics, plasma physics, and atomic physics
  - Laboratory astrophysics
  - Novel spectral analysis and plasma diagnostic techniques
- New era of scientific breakthroughs
  - Kinematics, chemical composition and evolution
  - From planets, stars to galaxies, clusters, further to cosmic web