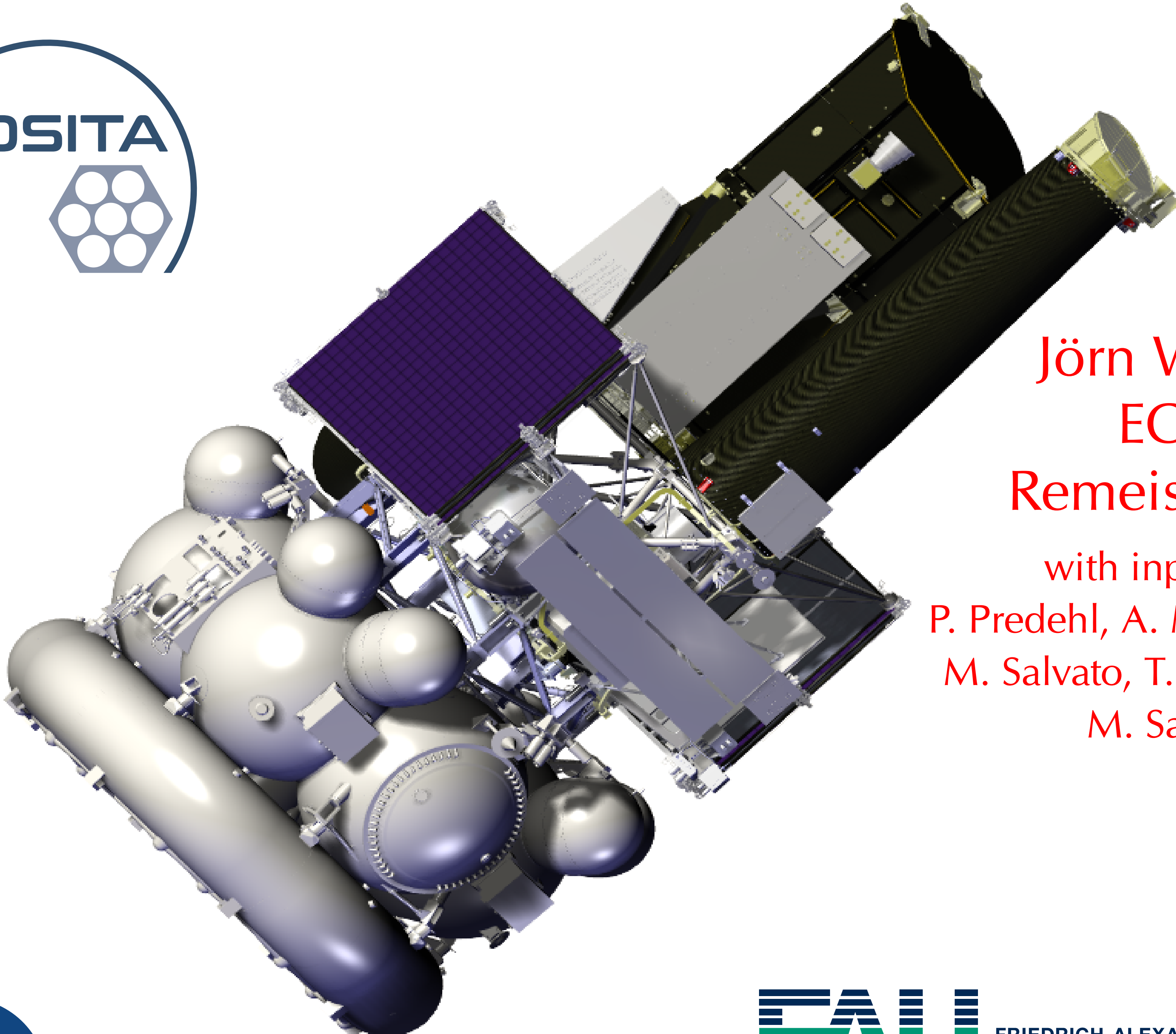
eROSITA

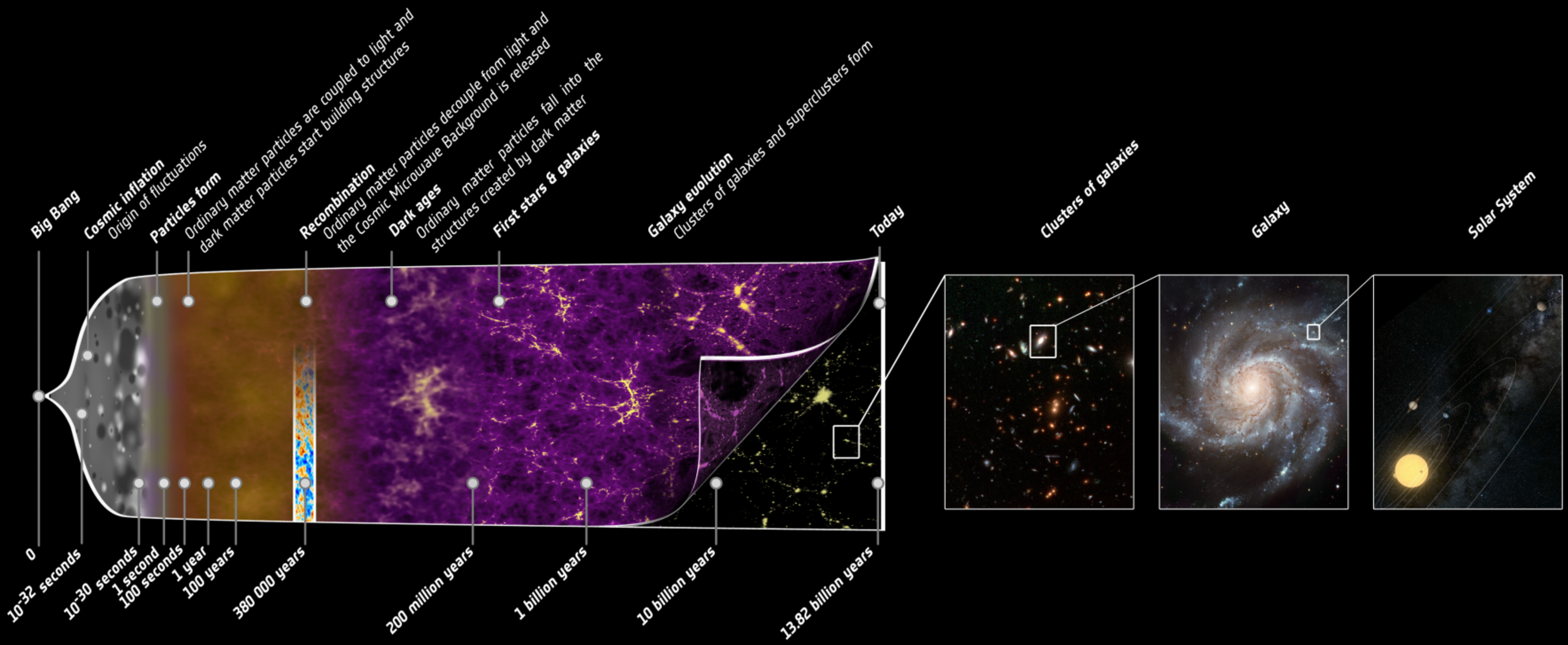


Jörn Wilms
ECAP &
Remeis-Obs.

with input from
P. Predehl, A. Merloni,
M. Salvato, T. Dauser,
M. Sasaki,...

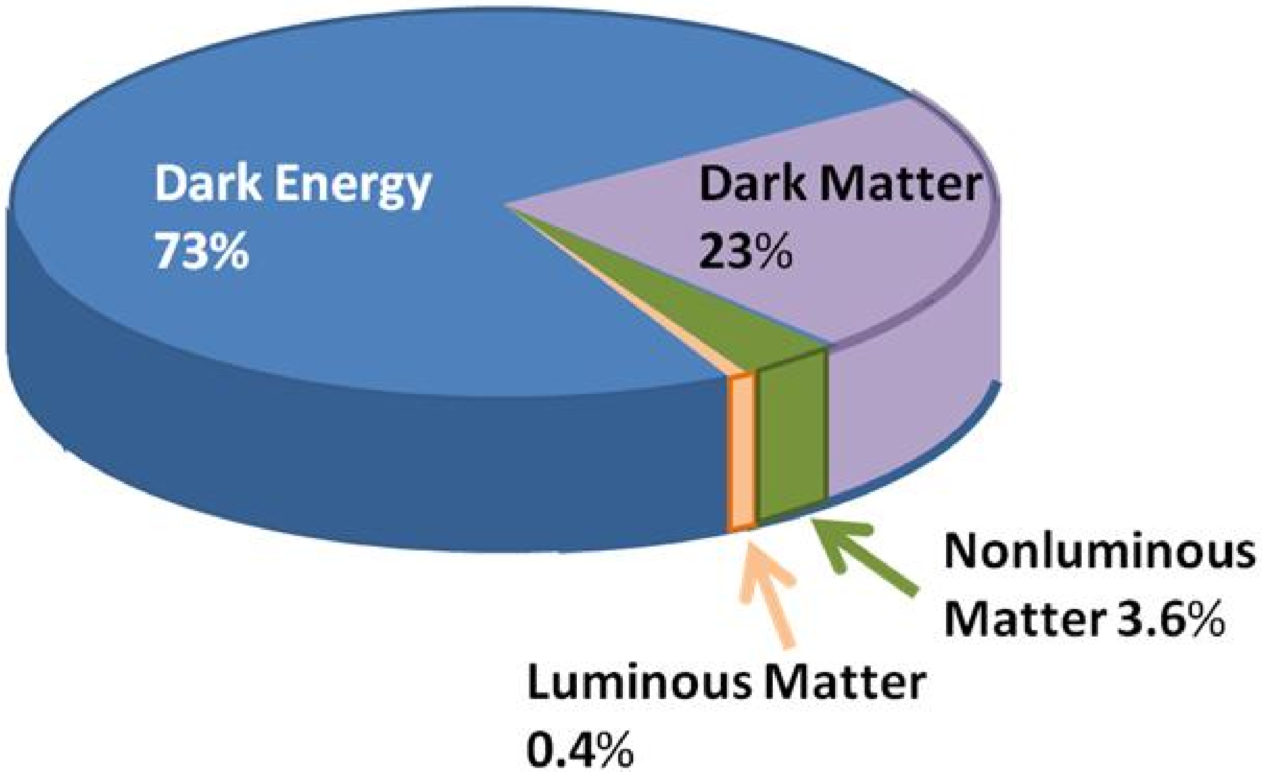
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE FAKULTÄT


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
Clusters of galaxies
Galaxy
Solar System
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

NASA

Cosmological Constant



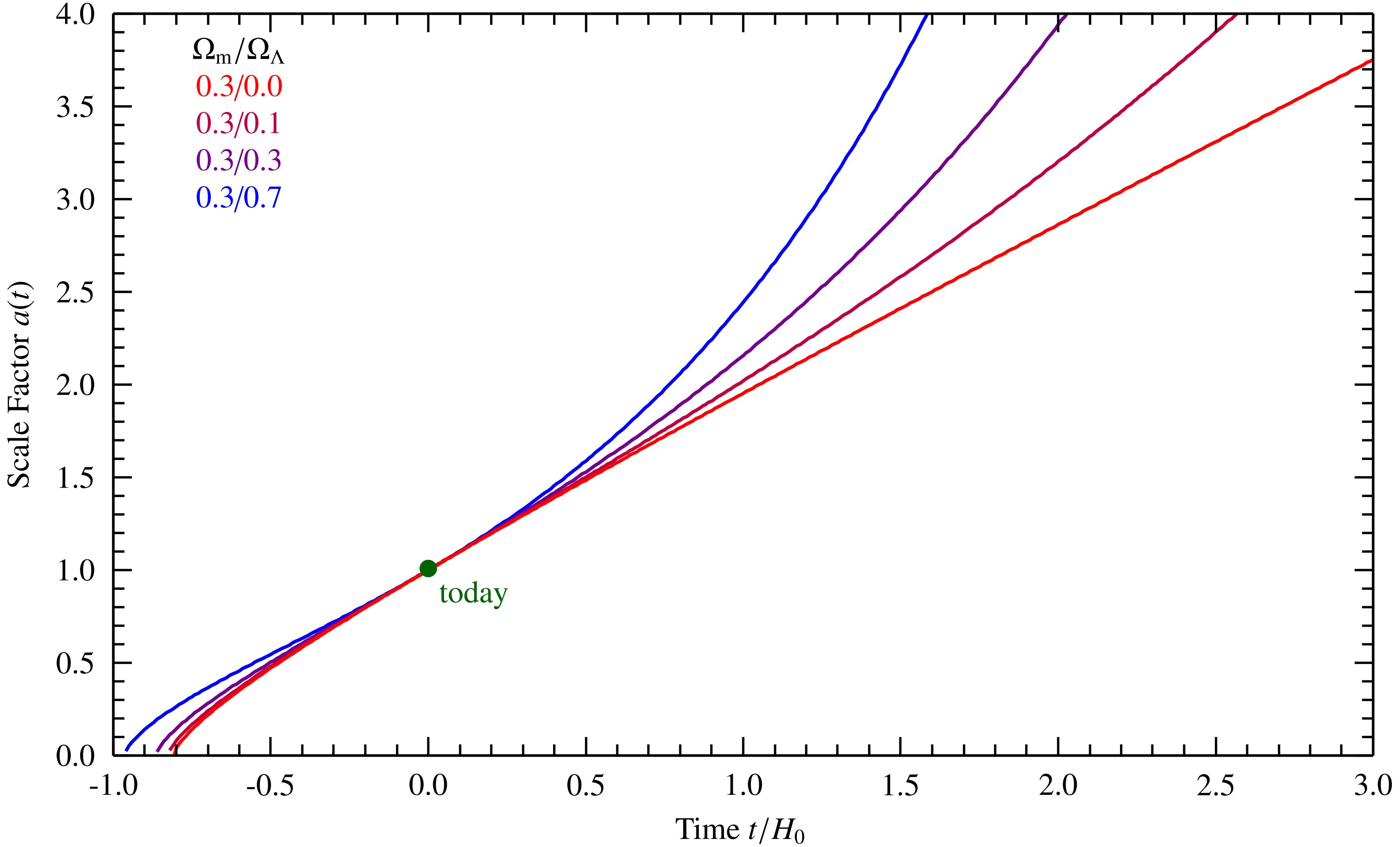
Expansion of the universe depends on its constituents:

- normal matter ("Baryons")
  - visible (Stars, galaxies)
  - not yet observed (hot gas between galaxies)
- dark matter

  exotic particles of unknown nature
- cosmological constant ("Dark Energy")

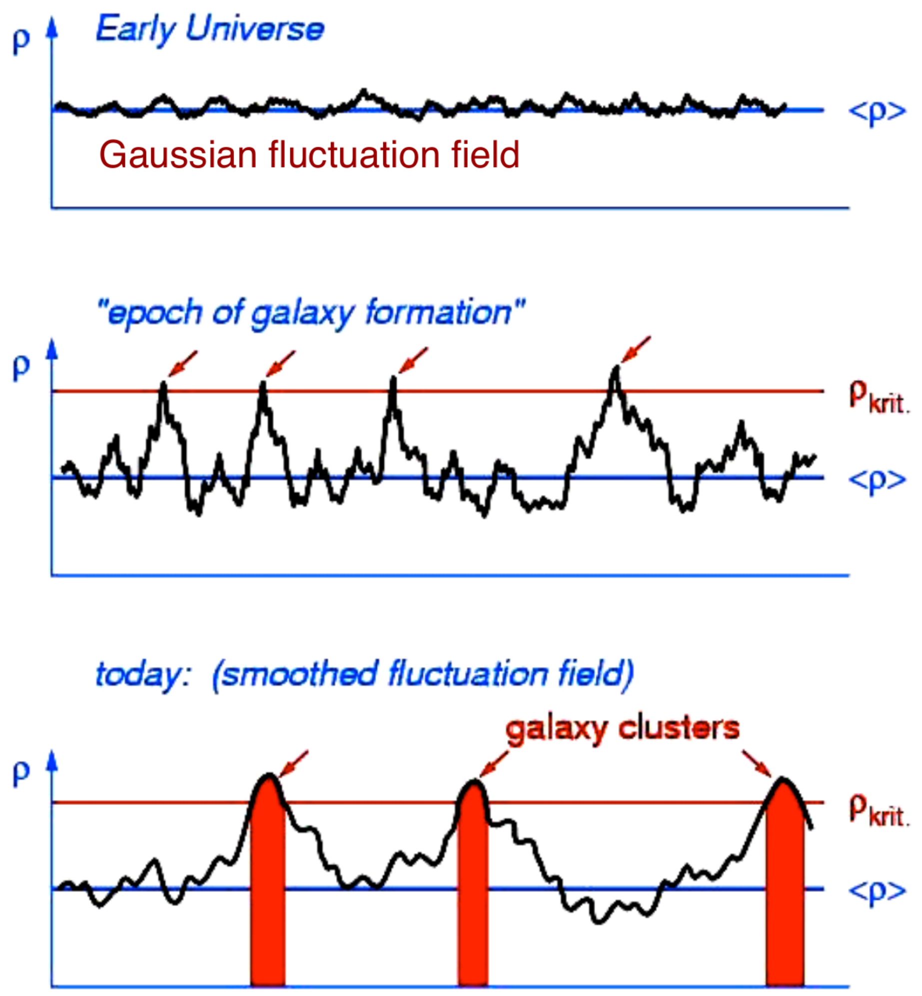
  property of space [energy density]

Cosmological Constant

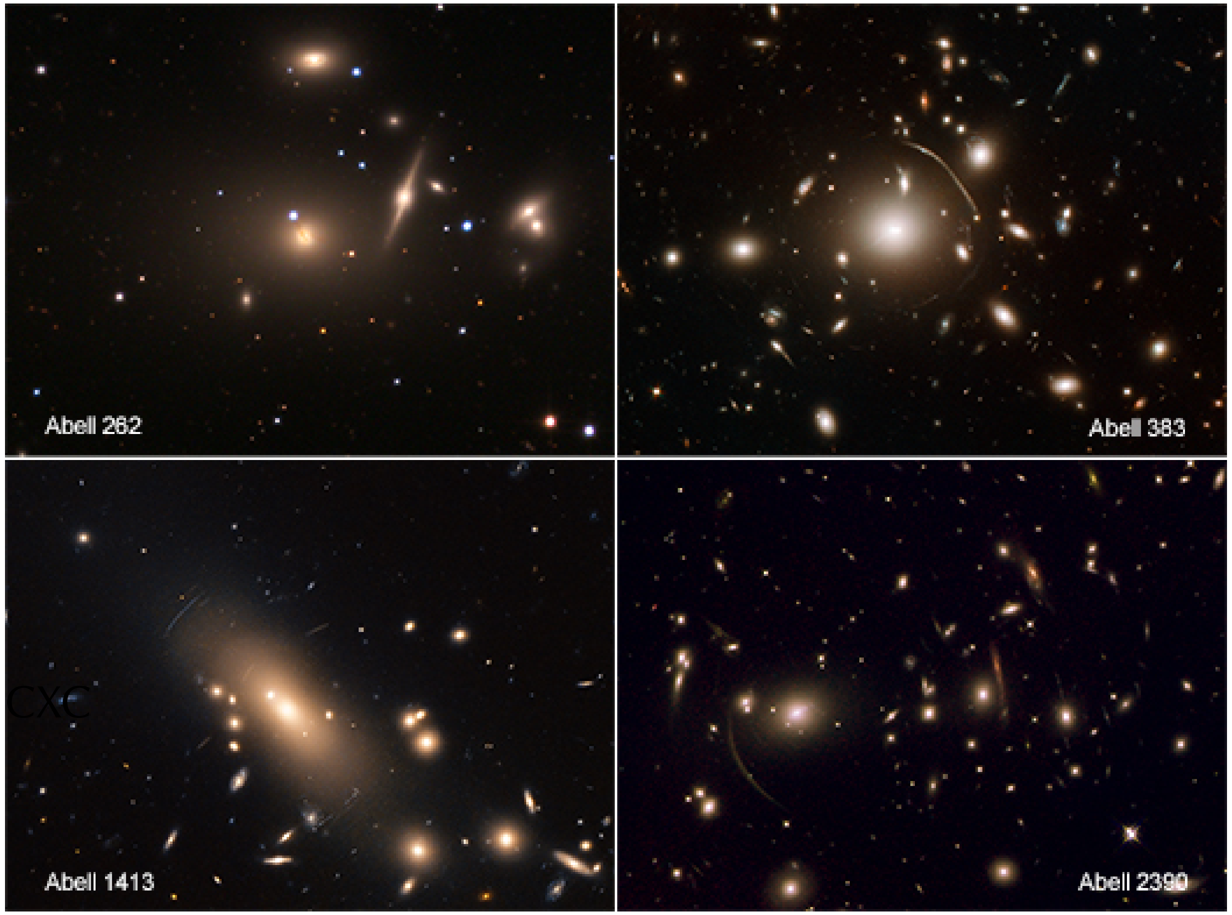


Ω_Λ: accelerated expansion of the universe

Evolution of Structures

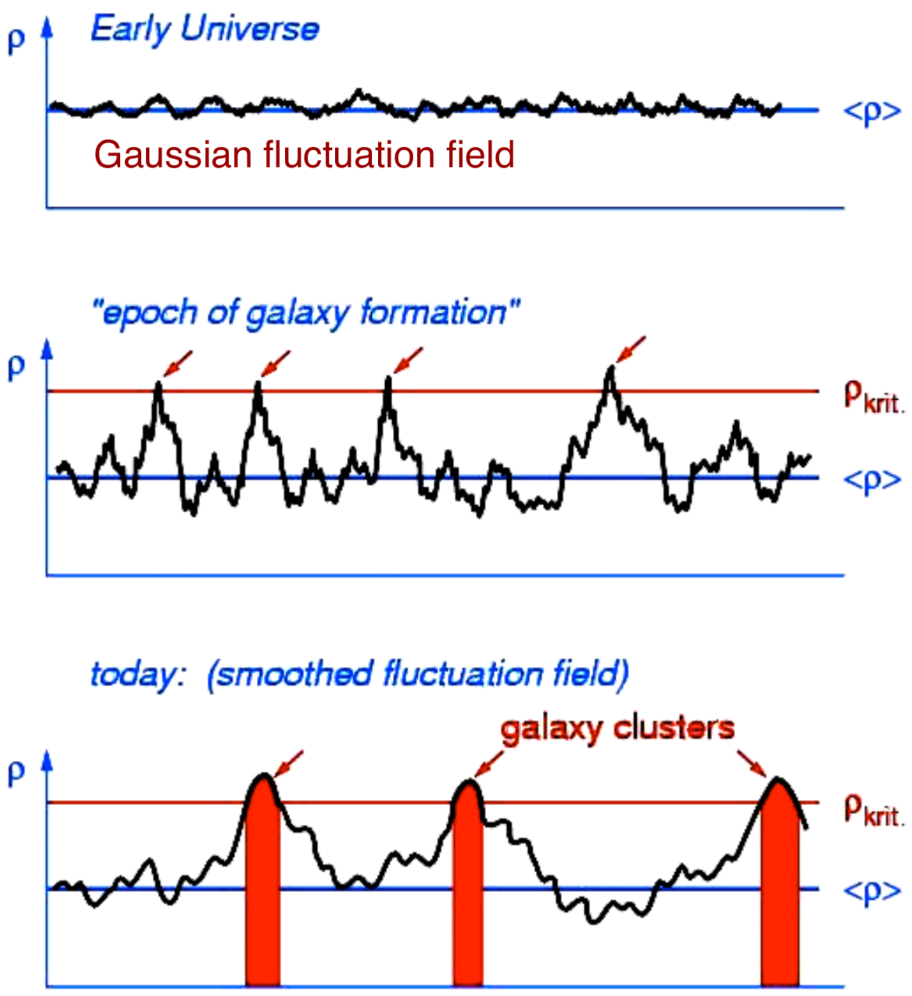


mass of galaxy clusters ~ 10^{14} – 10^{15} M_{sun}



Formation and growth of galaxies and galaxy clusters since the big bang

Evolution of Structures



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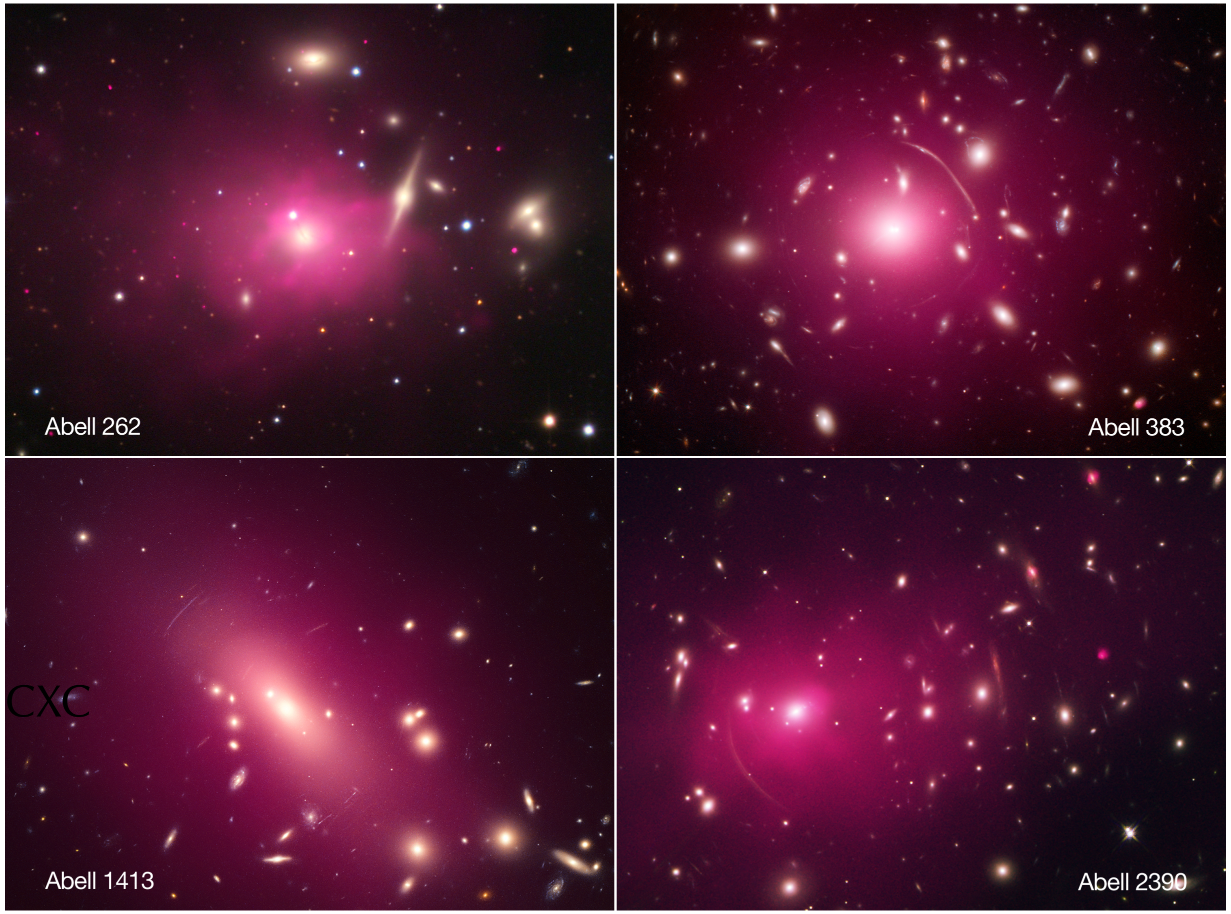

Formation and growth of galaxies and galaxy clusters since the big bang

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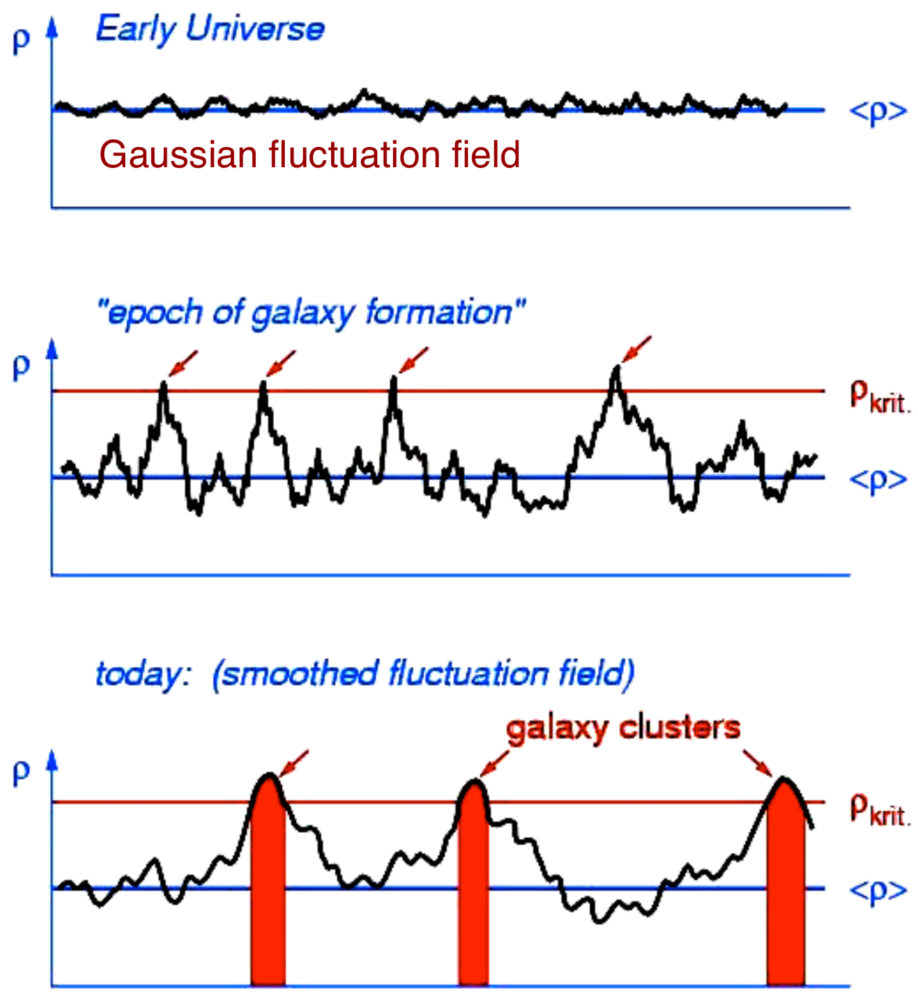

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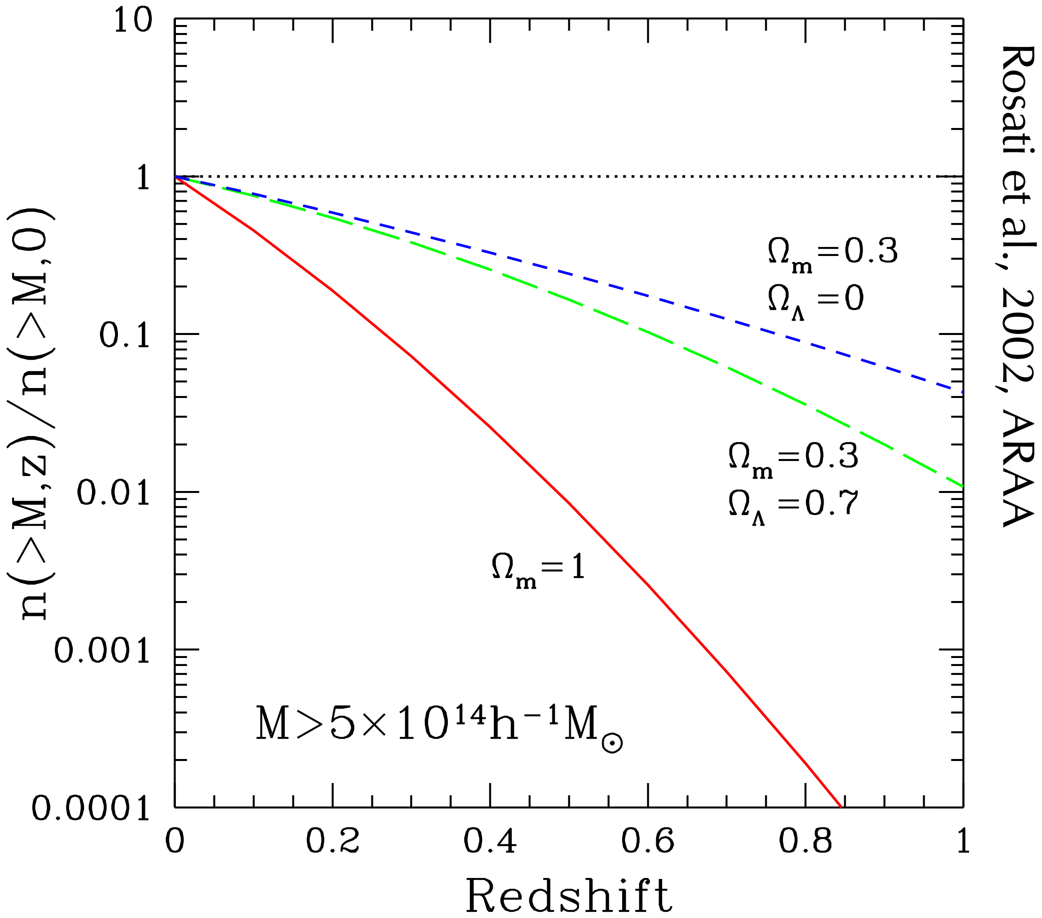
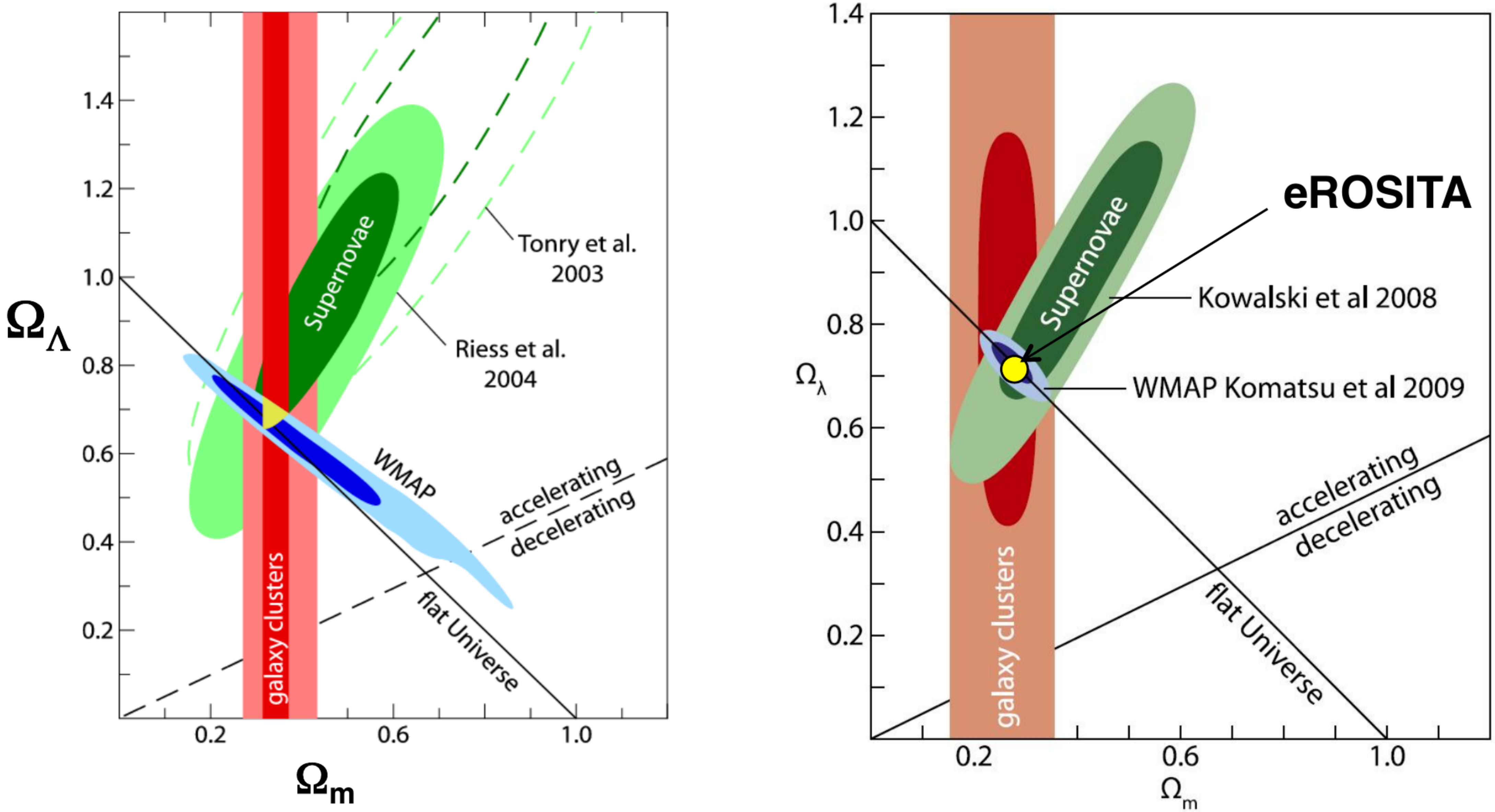


Formation and growth of galaxies and galaxy clusters since the big bang

Evolution of Structures



Böhringer

How to make X-rays

Astrophysical energy sources:

1. Nuclear fusion (stars)

Reactions à la

$$4p \longrightarrow {}^4\mathrm{He} + \Delta E_{nuc}$$

Energy released:

Fusion produces $\sim 6 \times 10^{11}\,\mathrm{J\,g^{-1}}$

(i.e., $\Delta E_{nuc} \sim 0.007 m_p c^2$)

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2. Gravitation (X-ray astro)

Accretion of mass m from ∞ to R_S on black hole with mass M gives

$$\Delta E_{\mathrm{acc}} = \frac{GMm}{R_S} \text{ where } R_S = \frac{2GM}{c^2}$$

Accretion produces $\sim 10^{13}\,\mathrm{J\,g^{-1}}$

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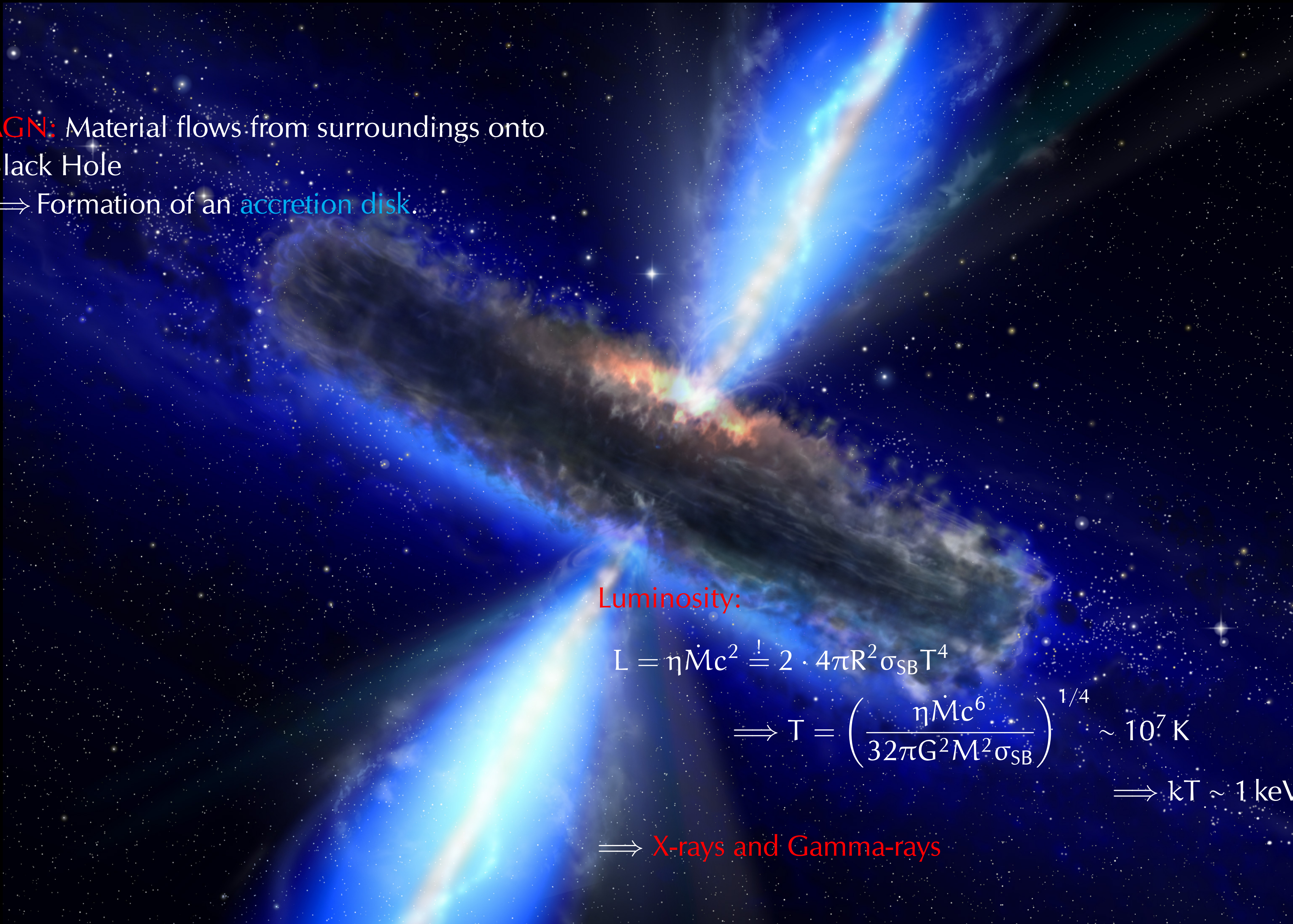
$\Longrightarrow$ Accretion of material is the most efficient astrophysical energy source.

…thus accreting objects are the most luminous in the whole universe, and crucial for its evolution.

Note: energy gets radiated away from *outside* the Schwarzschild radius!



AGN: Material flows from surroundings onto Black Hole

$\Longrightarrow$ Formation of an accretion disk.

Luminosity:

$$L = \eta \dot{M} c^2 \stackrel{!}{=} 2 \cdot 4\pi R^2 \sigma_{SB} T^4$$

$$\Longrightarrow T = \left(\frac{\eta \dot{M} c^6}{32\pi G^2 M^2 \sigma_{SB}} \right)^{1/4} \sim 10^7 \text{ K}$$

$$\Longrightarrow kT \sim 1 \text{ keV}$$

$\Longrightarrow$ X-rays and Gamma-rays

How to make X-rays

Typical mass accretion rate for a black hole in an Active Galactic Nucleus:

$$\dot{M} = 0.1\,M_\odot\,\mathrm{yr}^{-1}$$

Therefore:

$$L_{AGN} \sim 10^{44}\,\mathrm{erg\,s^{-1}} \sim 10^{10}\,L_\odot$$

about the same as a whole galaxy

$\Longrightarrow$ for nearby AGN at $d = 1\,\mathrm{Mpc}$, 1 % in X-rays:

$$N_{ph,X,AGN} = \frac{1}{\langle E_X \rangle} \cdot \frac{0.01 \cdot L_{AGN}}{4\pi d^2} \sim 8\,\mathrm{ph\,cm^{-2}\,s^{-1}}$$

assuming $\langle E_X \rangle = 1\,\mathrm{keV} = 1.06 \times 10^{-9}\,\mathrm{erg}$; in reality count rates are lower due to spectral shape.

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Therefore:

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abo

Many astronomical objects are luminous – X-ray and gamma-ray astronomy necessary to understand Universe

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How to make X-rays

AGN produce large amounts of energy over timescales of $\gtrsim 10^8$ years and they strongly interact with their environment.

10–20% of all energy radiated since the birth of the Universe comes from AGN.

Questions:

- What galaxies harbor AGN?
- Are these galaxies different from others?
- How do galaxies with AGN evolve?
- How do AGN form?

To answer these questions:

- need to model AGN evolution
- contrast models and statistical properties of AGN and their hosts, both among morphological type and with time $\Longrightarrow$ AGN surveys

How to make X-rays

How do we grow the black holes in AGN?

Eddington limit limits growth:

$$\dot{M} = \frac{L_{acc}}{\eta c^2} \leqslant \frac{4\pi G M m_p}{\eta c \sigma_T} \tag{1}$$

such that

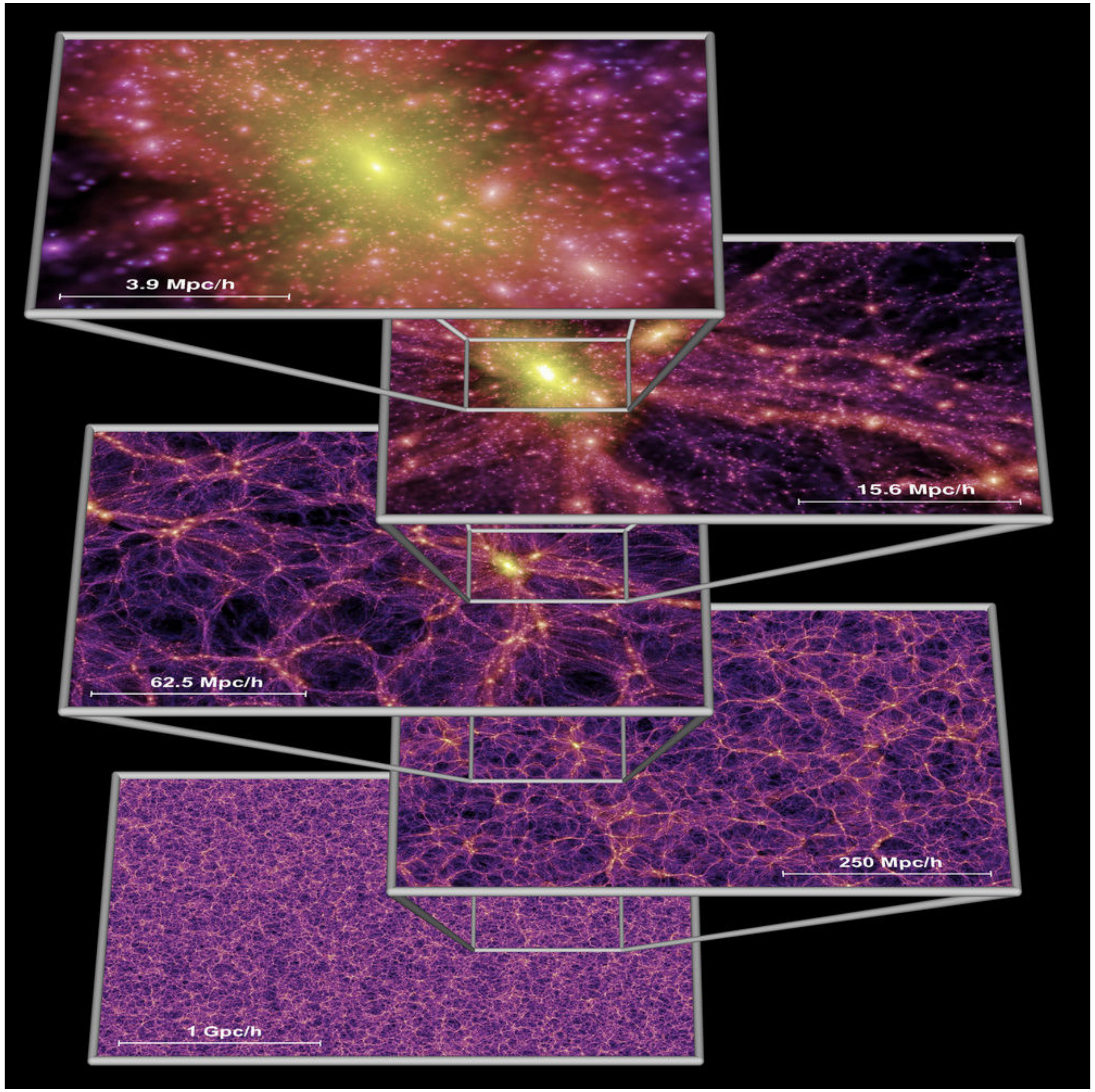
$$M(t) \leqslant M_0 e^{t/\tau} \quad \text{where} \quad \tau = \frac{\eta c \sigma_T}{4\pi G m_p} \sim 5 \times 10^7 \, \text{yr} \tag{2}$$

Soltan argument (Soltan et al., 1982):

> If supermassive black holes grow primarily by accretion, then the integral of the accretion rate across cosmic time should be equal to their present mass.

Generally found to be true, yields BH mass density $\rho_{BH} \sim 4 \times 10^{-5} \, M_\odot \, \text{Mpc}^{-3}$.

How to make X-rays

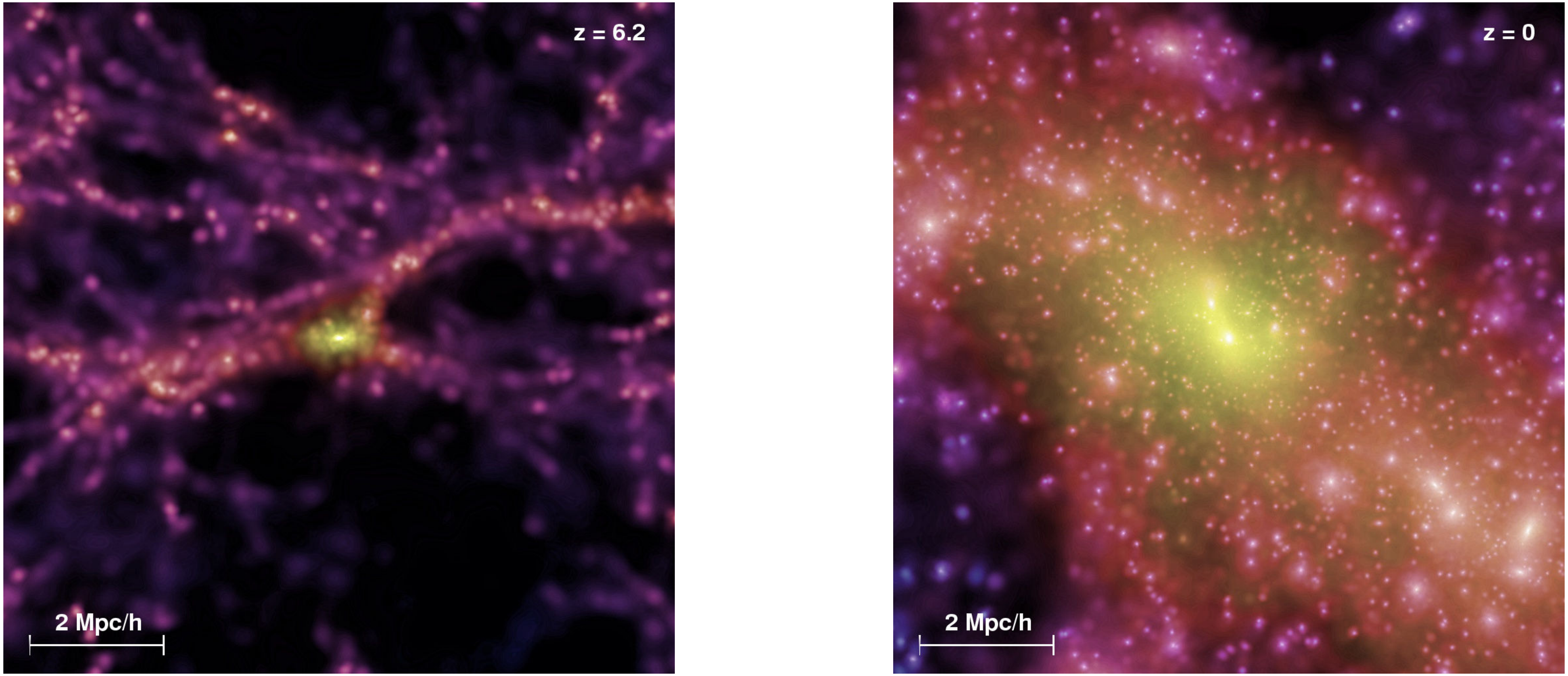


See Springel et al. (2005) for details.

Millenium simulation: numerical simulation of galaxy evolution in a ΛCDM universe

Baseline: semi-analytical evolution formalism adjusted to yield galaxy parameters (luminosity-color evolution, morphology, gas content, BH mass) consistent with observations. Covers galaxies down to SMC size, includes AGN formation and growth.

How to make X-rays

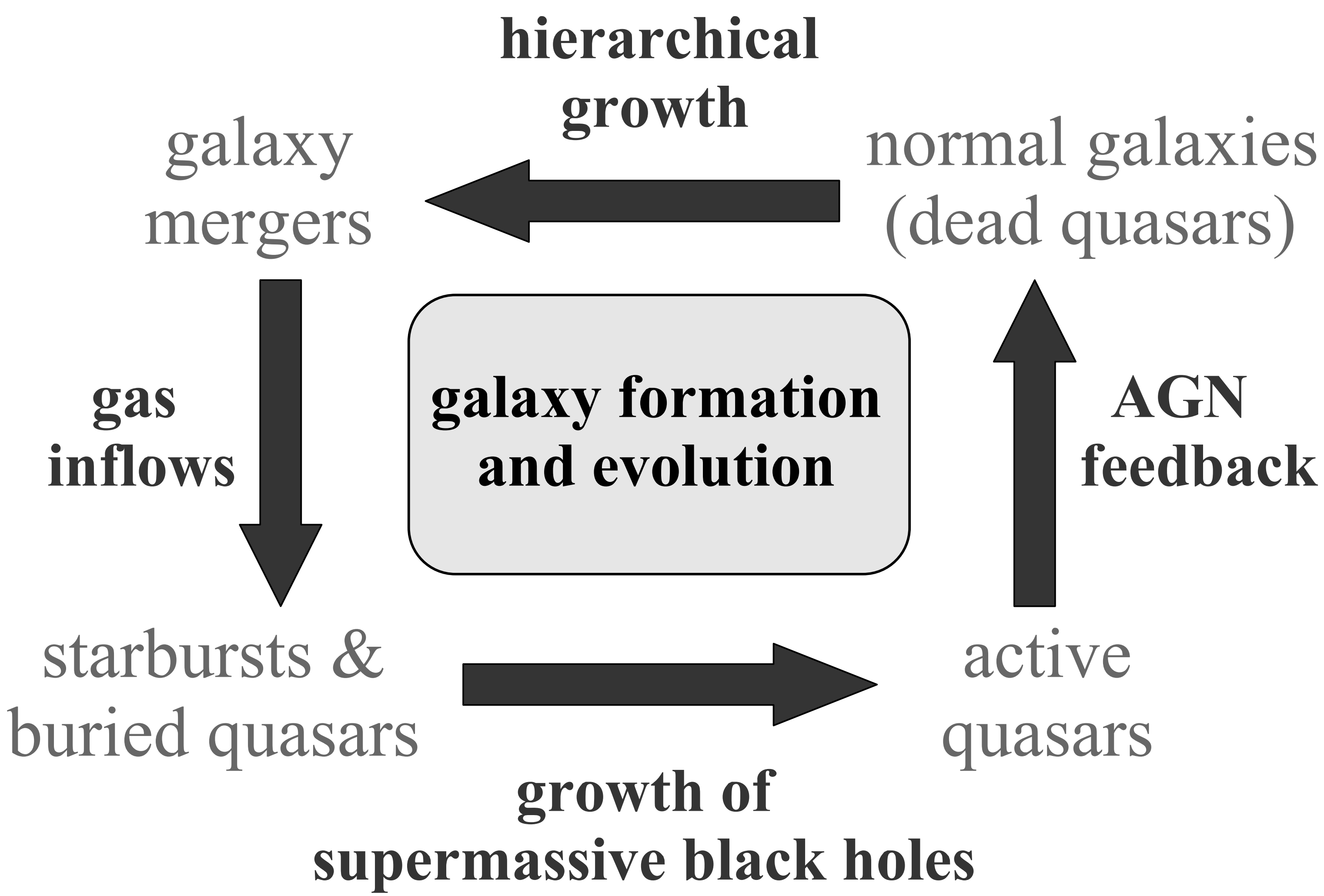


Springel et al. (2005)

Volume of Millenium simulation is too small to contain more than a few quasar candidates.

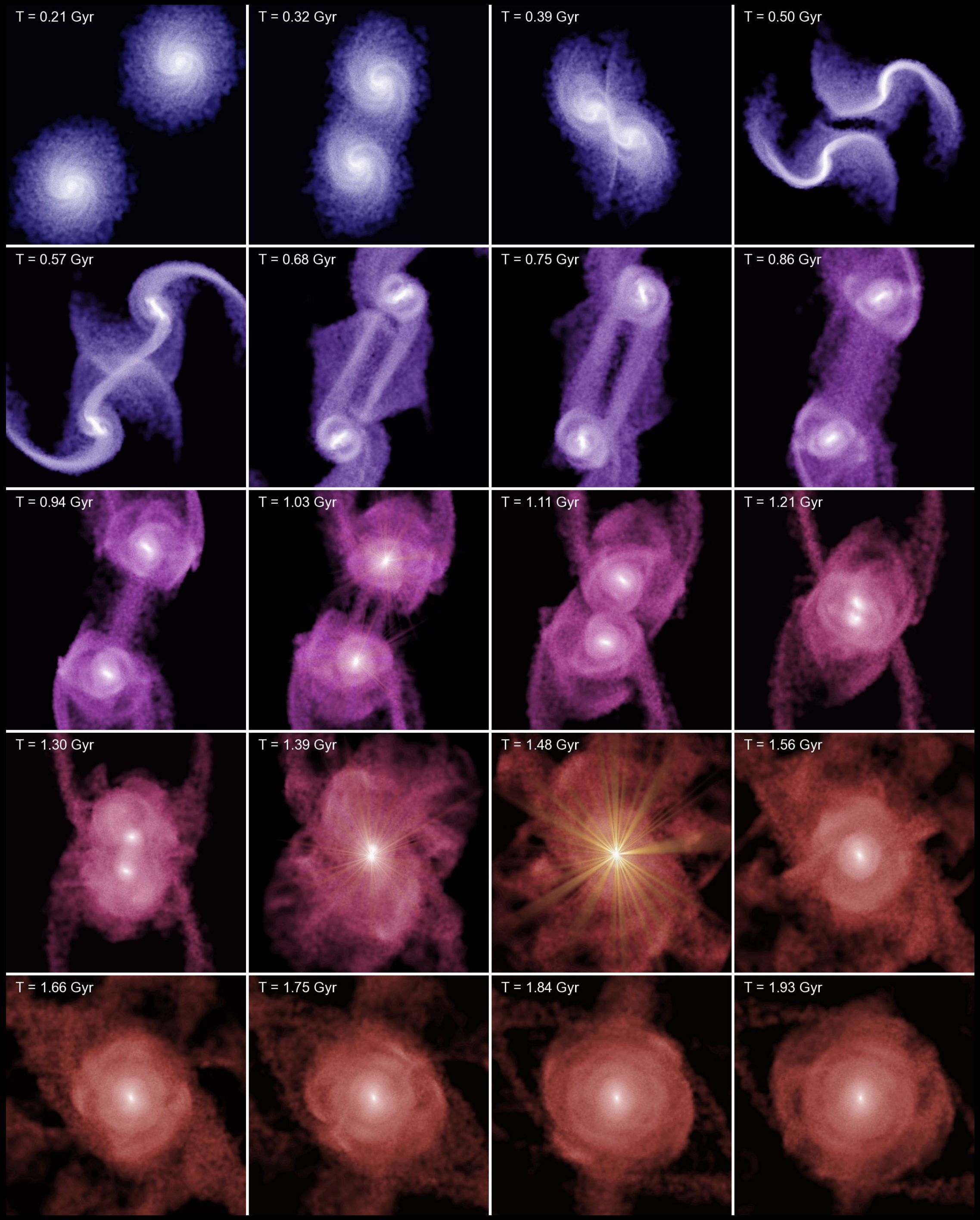
Here: Evolution of largest mass object, from halo dark matter mass $1.8 \times 10^{10}\ M_\odot$ at $z = 16.7$ to now $3.9 \times 10^{12}\ M_\odot$ in DM, $6.8 \times 10^{10}\ M_\odot$ normal matter, and a star formation rate of $235\ M_\odot\ \mathrm{year}^{-1}$.

How to make X-rays



(Hopkins et al., 2006)

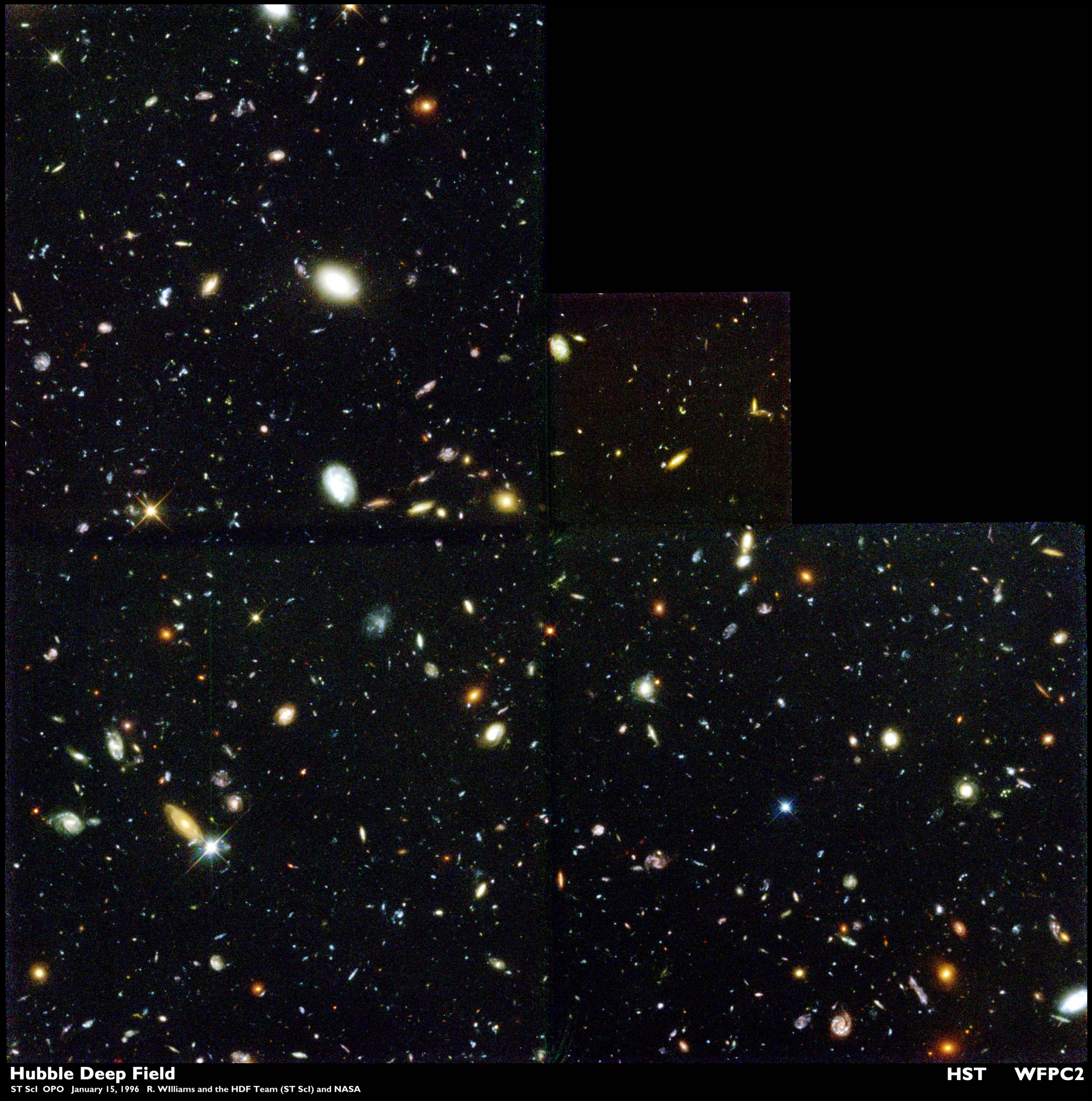
AGN formation and evolution are linked to galaxy mergers: “co-evolution”.



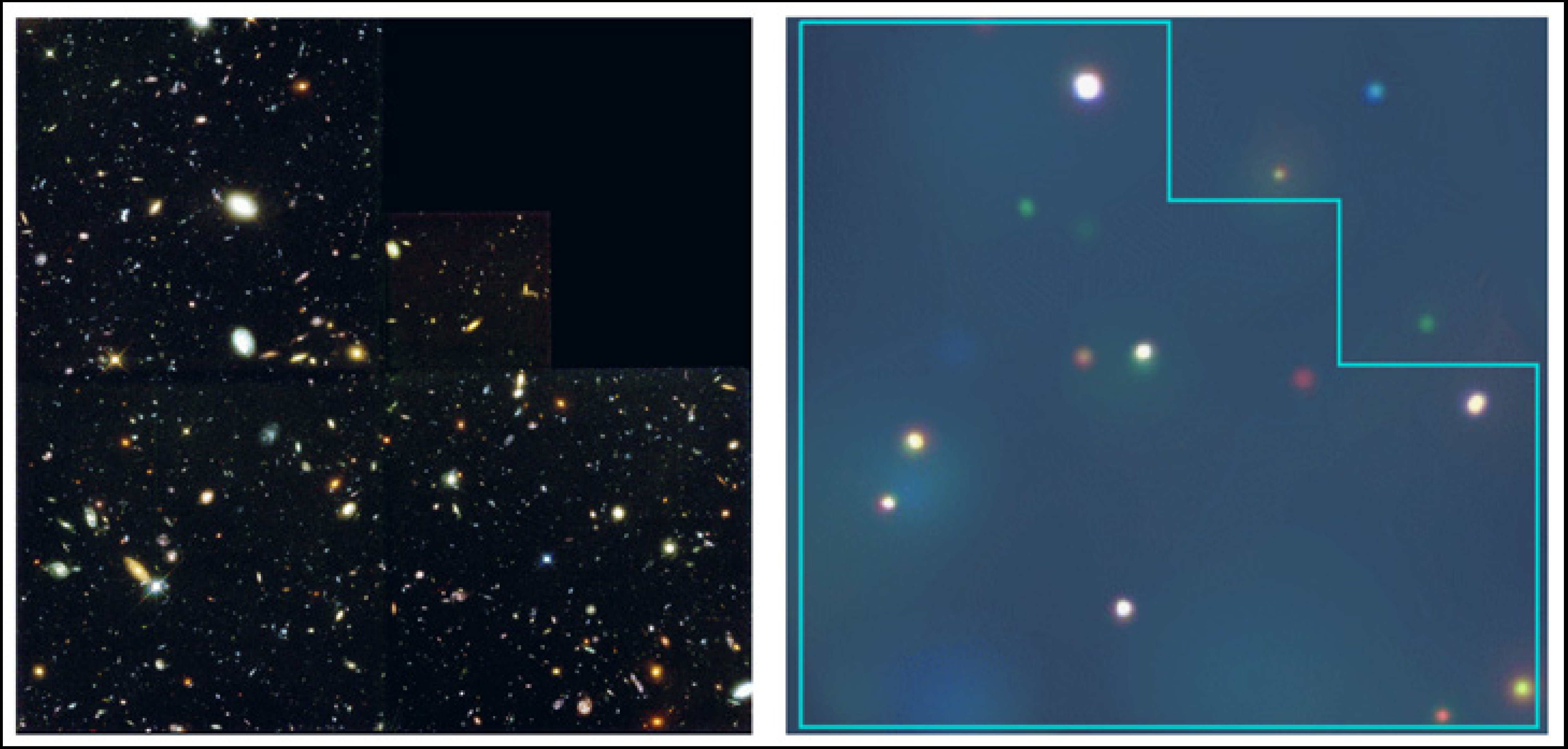
Evolution of a merger in a $80h^{-1}$ kpc wide box: blue: baryonic mass fraction 20%, red: $< 5\%$. Point sources shown when quasar activity would be observable.

(Hopkins et al., 2006, Fig. 2)

JWST deep field



1995 December: Hubble Deep Field: 8 d exposure
"weird galaxies" $\Longrightarrow$ proto galaxies!
redshifts: $z \in [0.5, 5.3]$ (Fernández-Soto et al., 1999)

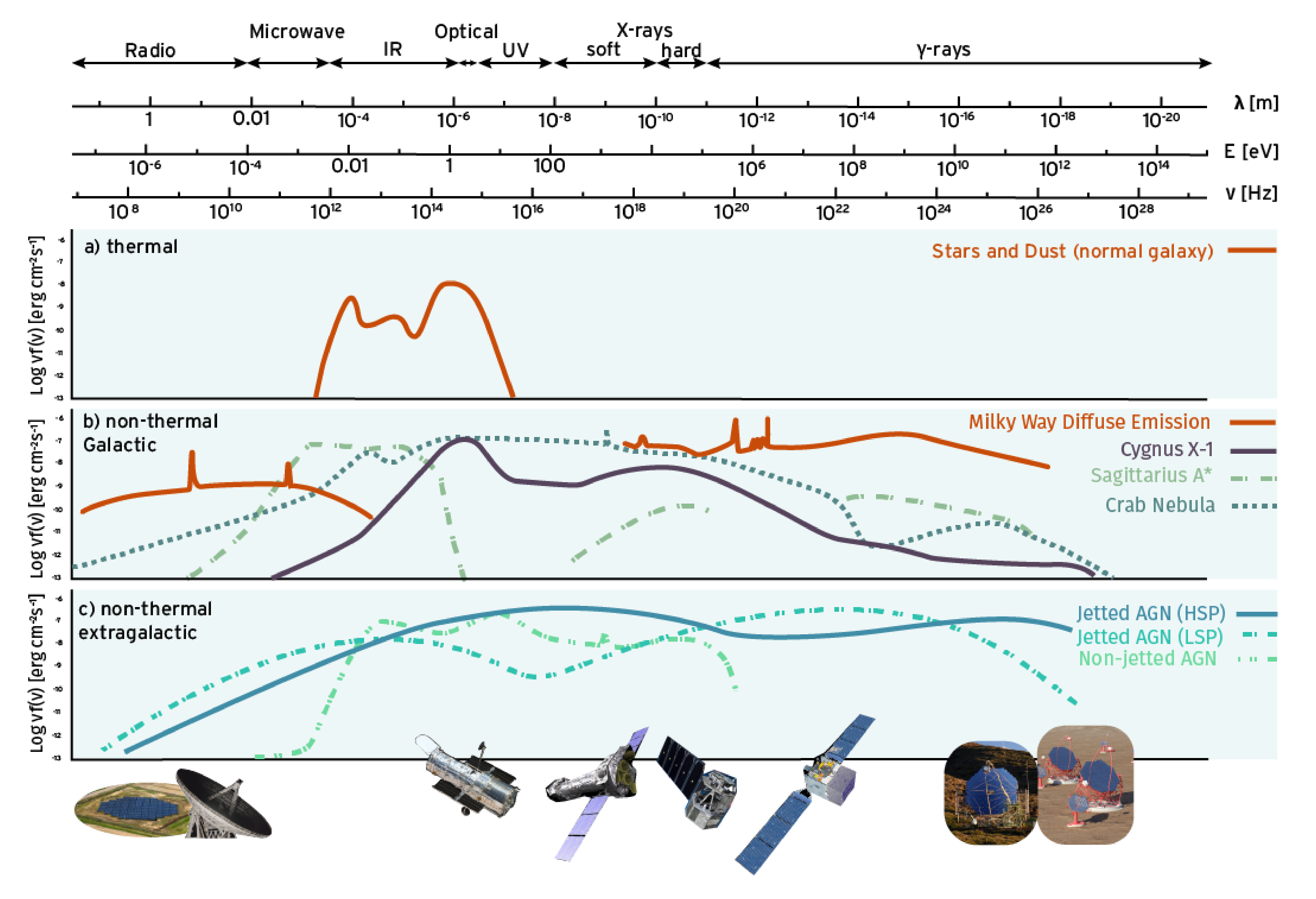


HST

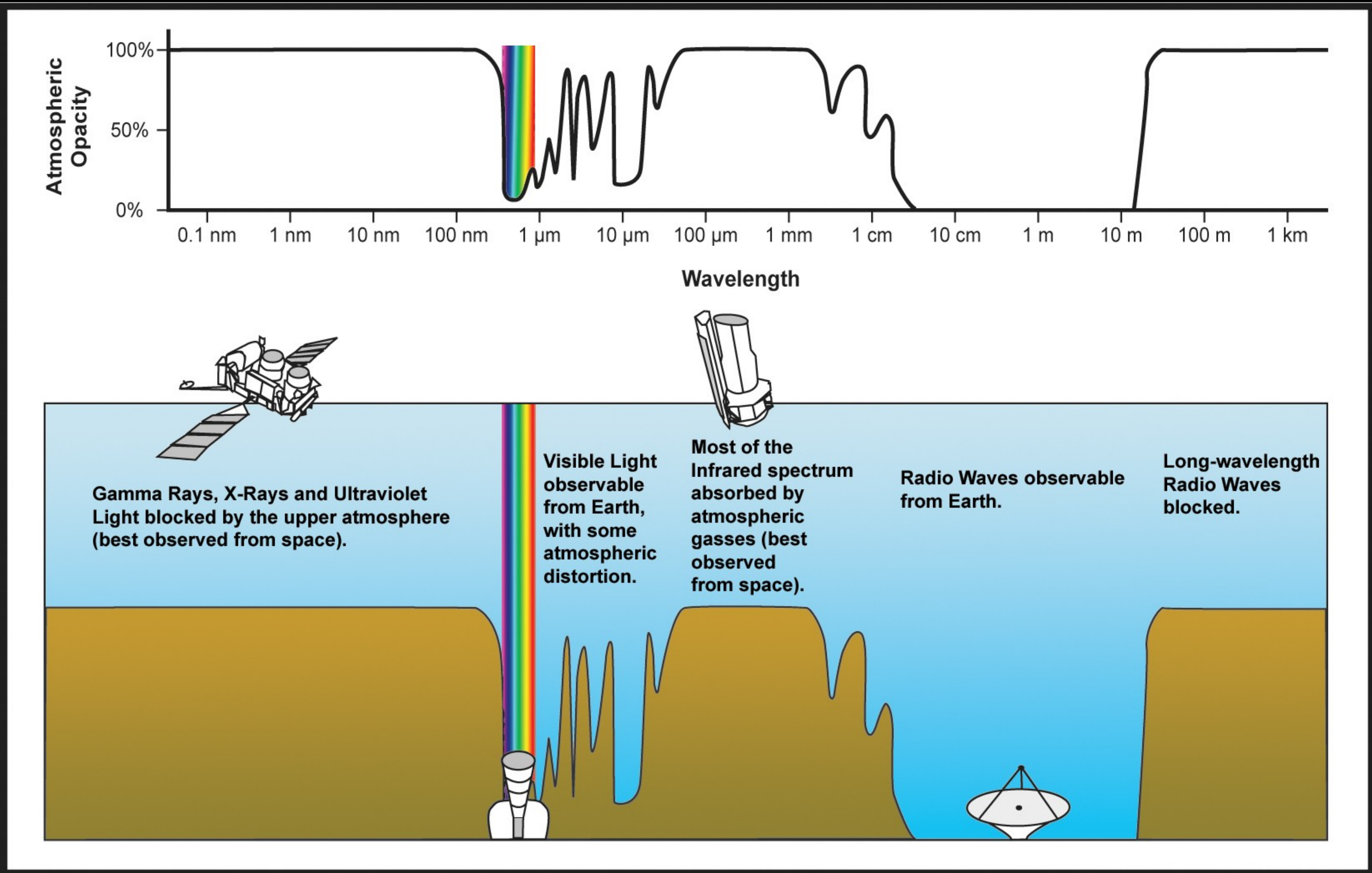
Chandra

Chandra/HST image of Hubble Deep Field North; 500 ks

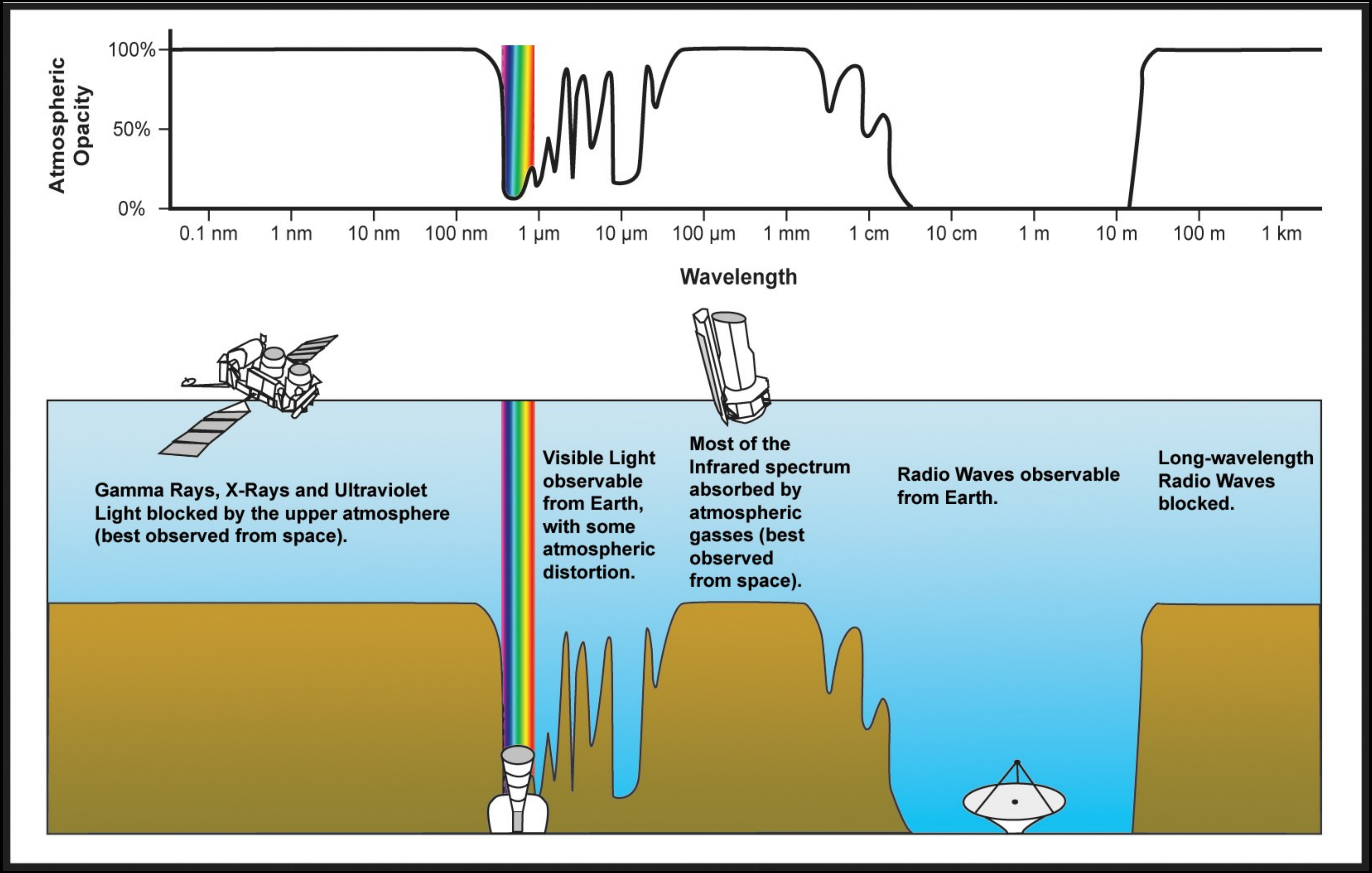
Multi Wavelength astronomy: different views onto the Universe



A. Kreikenbohm et al.

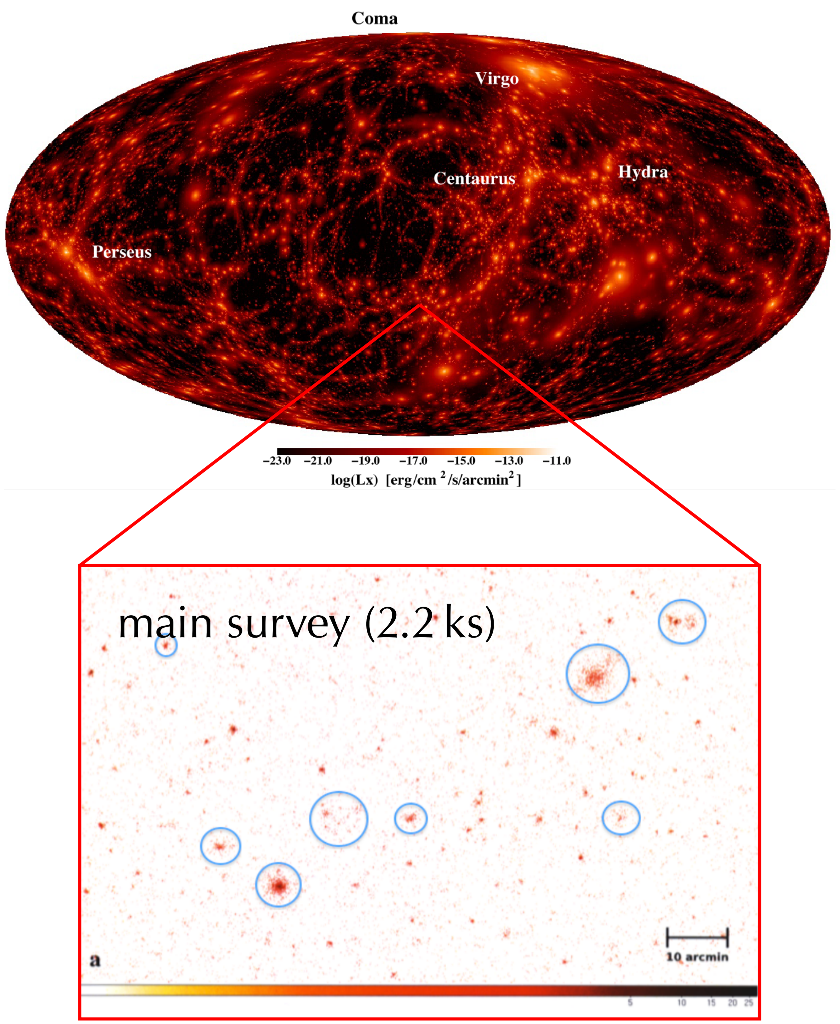


Earth's atmosphere is opaque for all radiation except for optical light and radio



$\Longrightarrow$ If you want to observe the sky in other wavebands,
you *must* go into space!

eROSITA at a glance



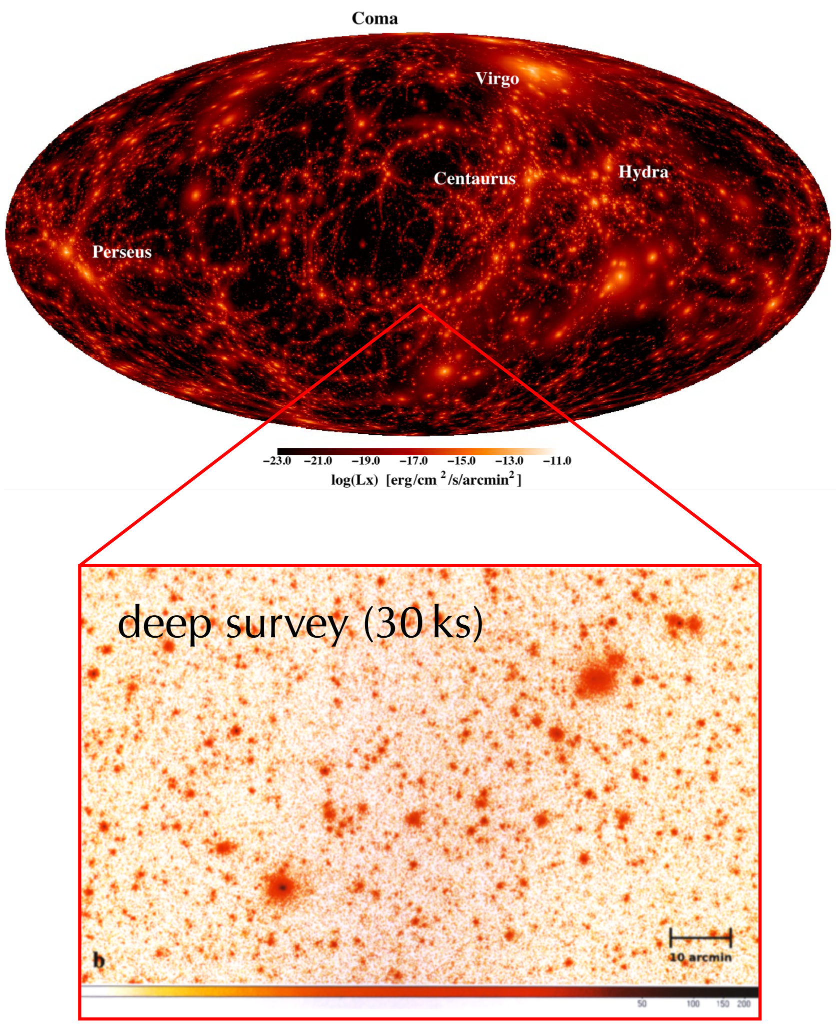
Main scientific goals:

- Search for galaxy clusters
  100000 clusters
- Evolution of Black Holes
  2×10^6 active galaxies

Strategy:

- sky survey
  down to 6×10^{-14} cgs
- deep survey
  ($\sim 100\,\square^\circ$) to 10^{-14} cgs
- 1° FoV, moderate angular resolution
  ($< 28''$ avg.)
- large collecting area
  ($>2000\,\mathrm{cm}^2$ at 1 keV)
- good spectral resolution
  155 eV at 6.4 keV

eROSITA at a glance



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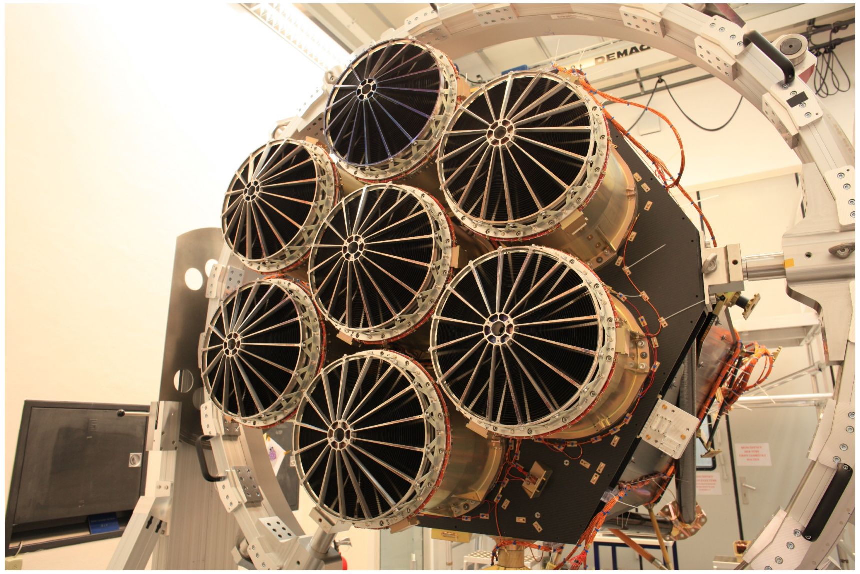
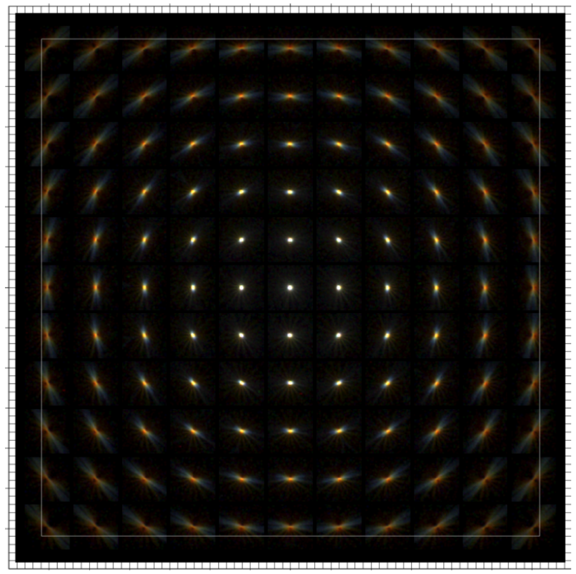
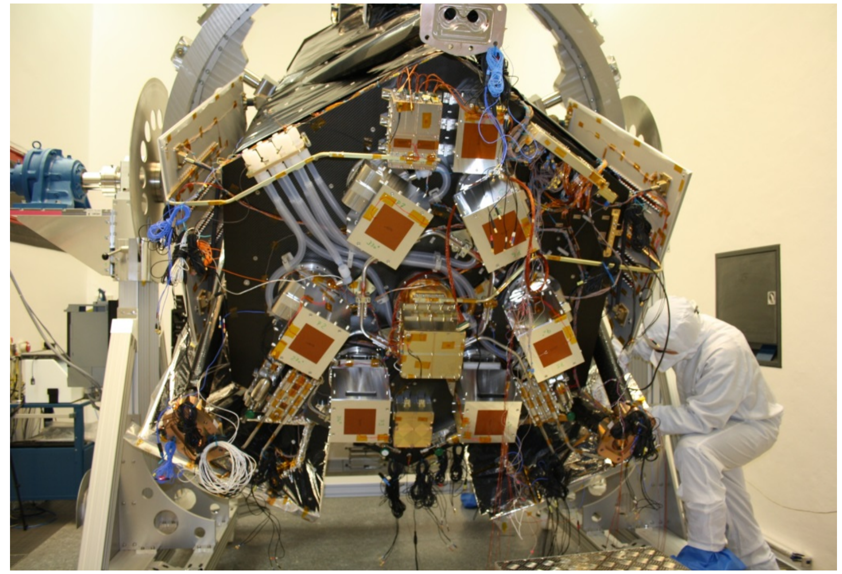
eROSITA







Large Effective area (~ 1300 cm^2 at 1 keV, ~XMM-Newton)
Large Field of view: 1° diameter
Half-Energy width (HEW) ~18″ (on-axis, point.); ~30″ (FoV avg., survey)
Positional accuracy: ~4.5″ (1σ)
X-ray baffle: 92% stray light reduction
pnCCD with framestore: $384 \times 384 \times 7 \sim 10^6$ pxl (9.4″), no chip gaps, no “out of time” events,
Spectral resolution at all measured energies within specs (~80 eV at 1.5 keV)

J. Wilms

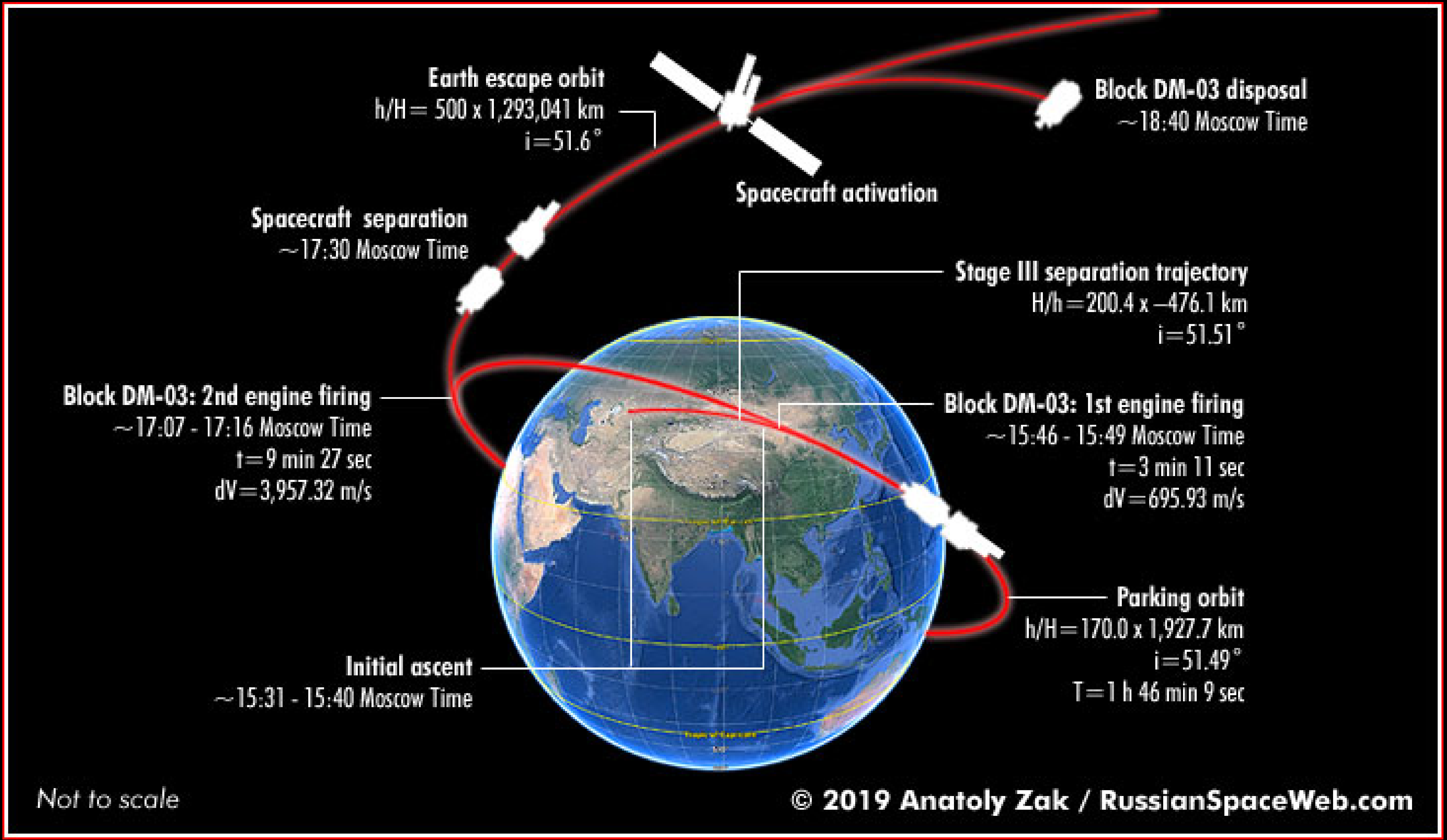
J. Wilms

C. Grossberger

Roscosmos

Roscosmos

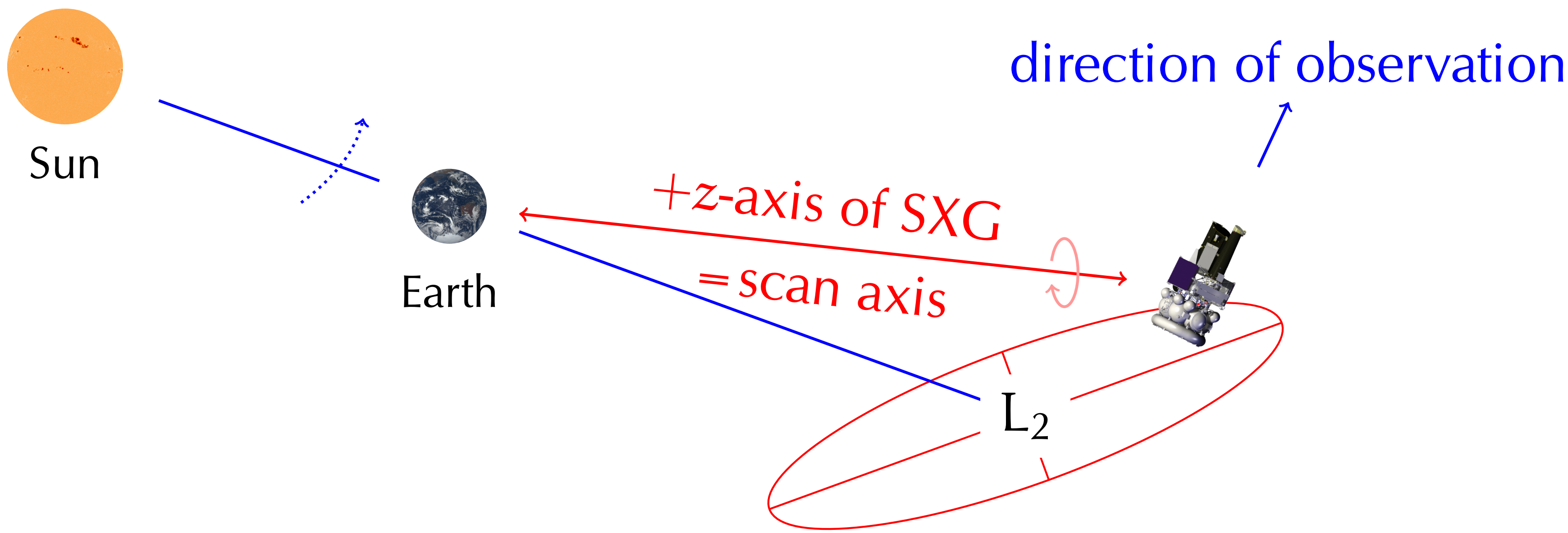
V. Burwitz



Russian Space Web

T. Dauser

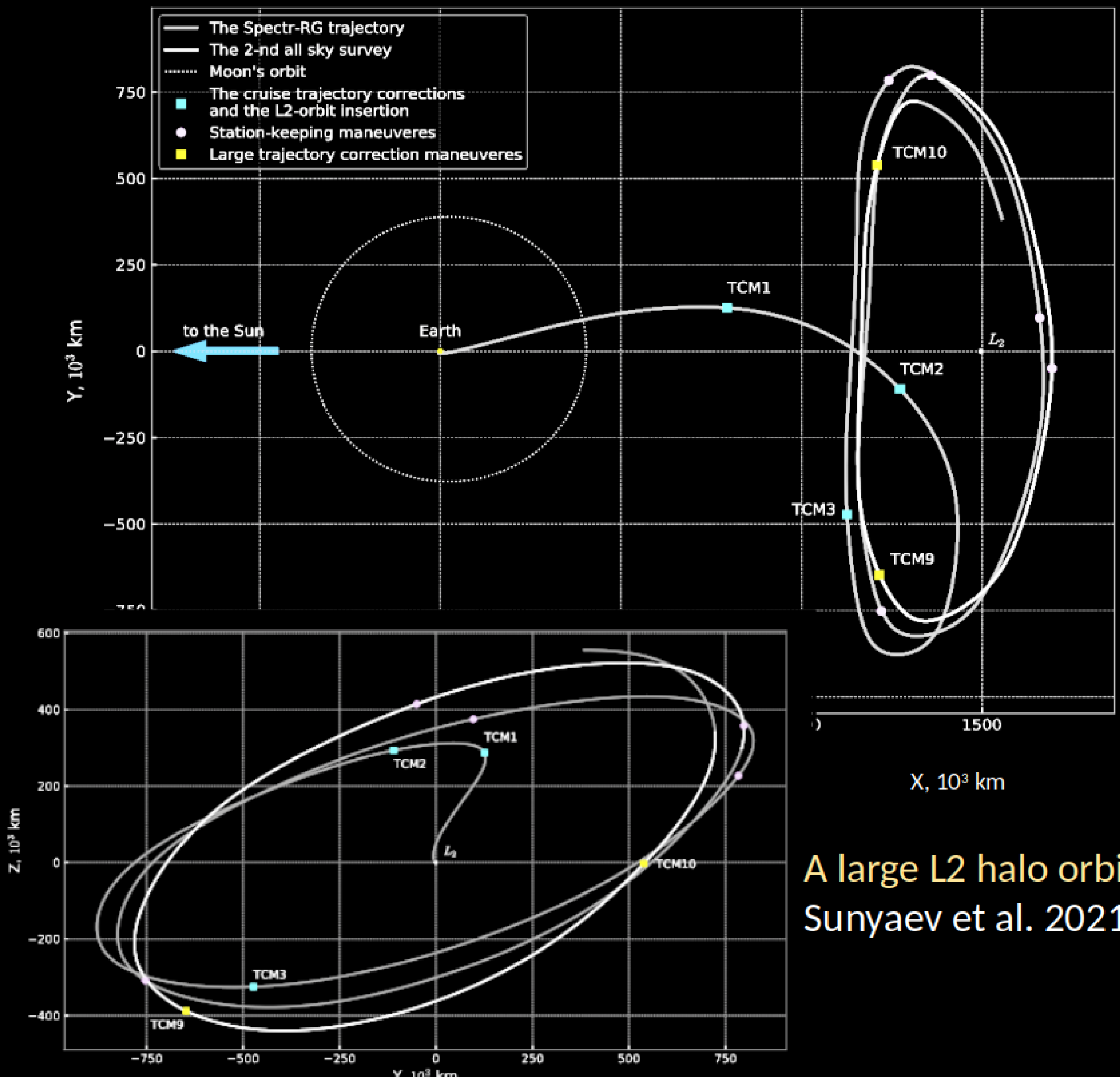
Launch



mission profile:

- L_2-Orbit (1.5 Mio km from Earth)
- scan axis points towards Earth (~4 h/Rotation)

4 years survey (modulo Ukraine war)
3 years pointed phase



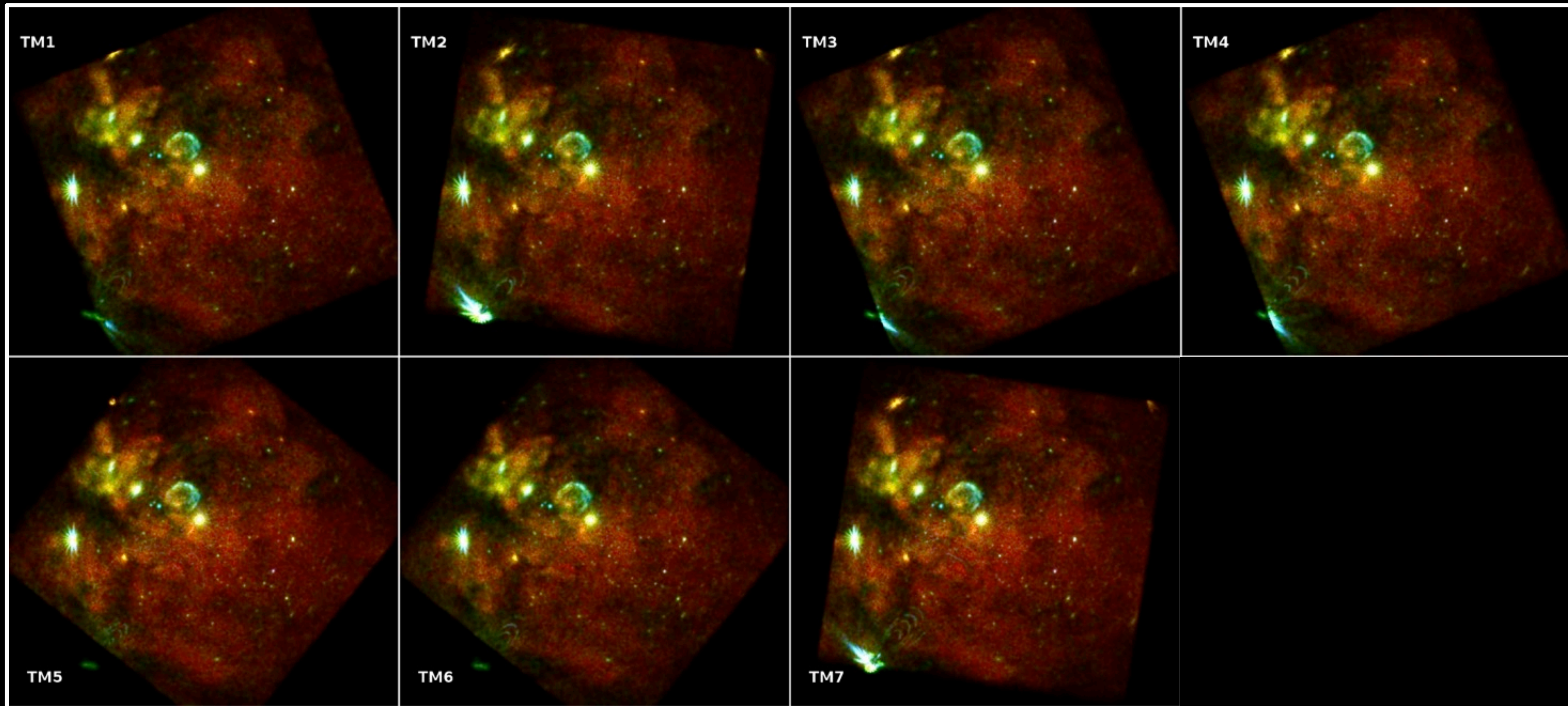
A large L2 halo orbit
Sunyaev et al. 2021

Orbit in the first 6 months

eROSITA Consortium: MPE Garching, AIP Potsdam, U Hamburg, FAU Erlangen-Nürnberg, U Tübingen, U Bonn, LMU München

First light: Large Magellanic Cloud

SRG/eROSITA (0.2-4.5 keV)

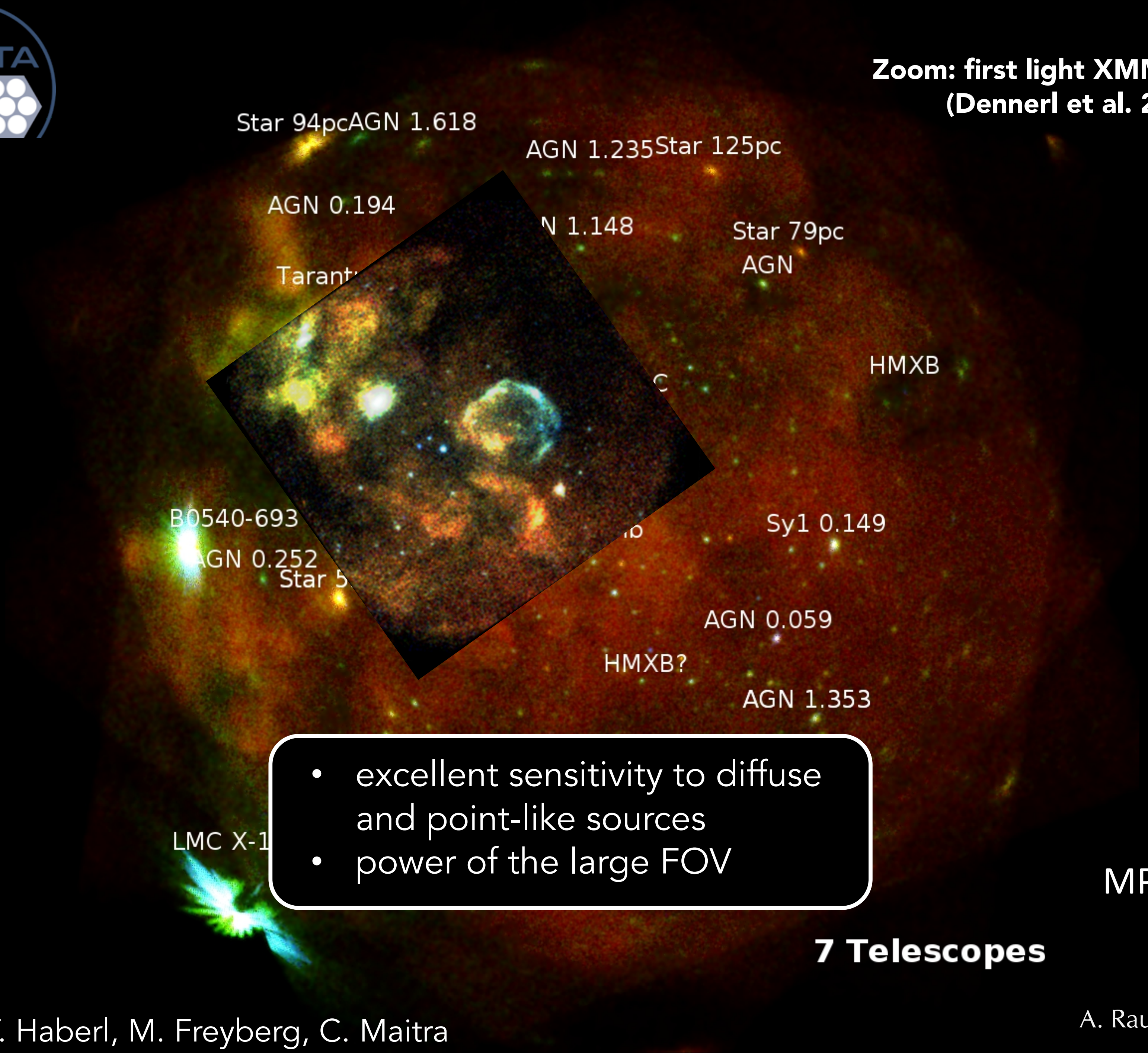


LMC/SN1987A

MPE/IKI

Credit: F. Haberl, M. Freyberg, C. Maitra

Zoom: first light XMM-Newton
(Dennerl et al. 2001)



- excellent sensitivity to diffuse and point-like sources
- power of the large FOV

MPE/IKI

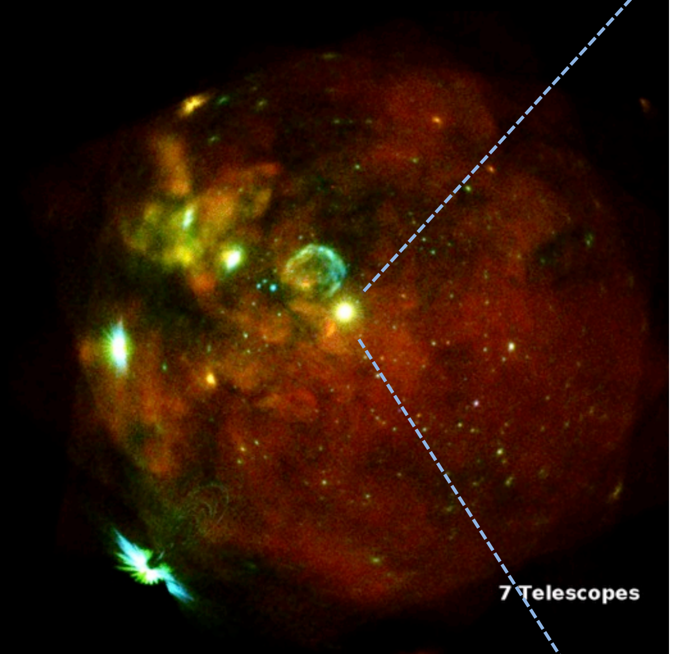
7 Telescopes

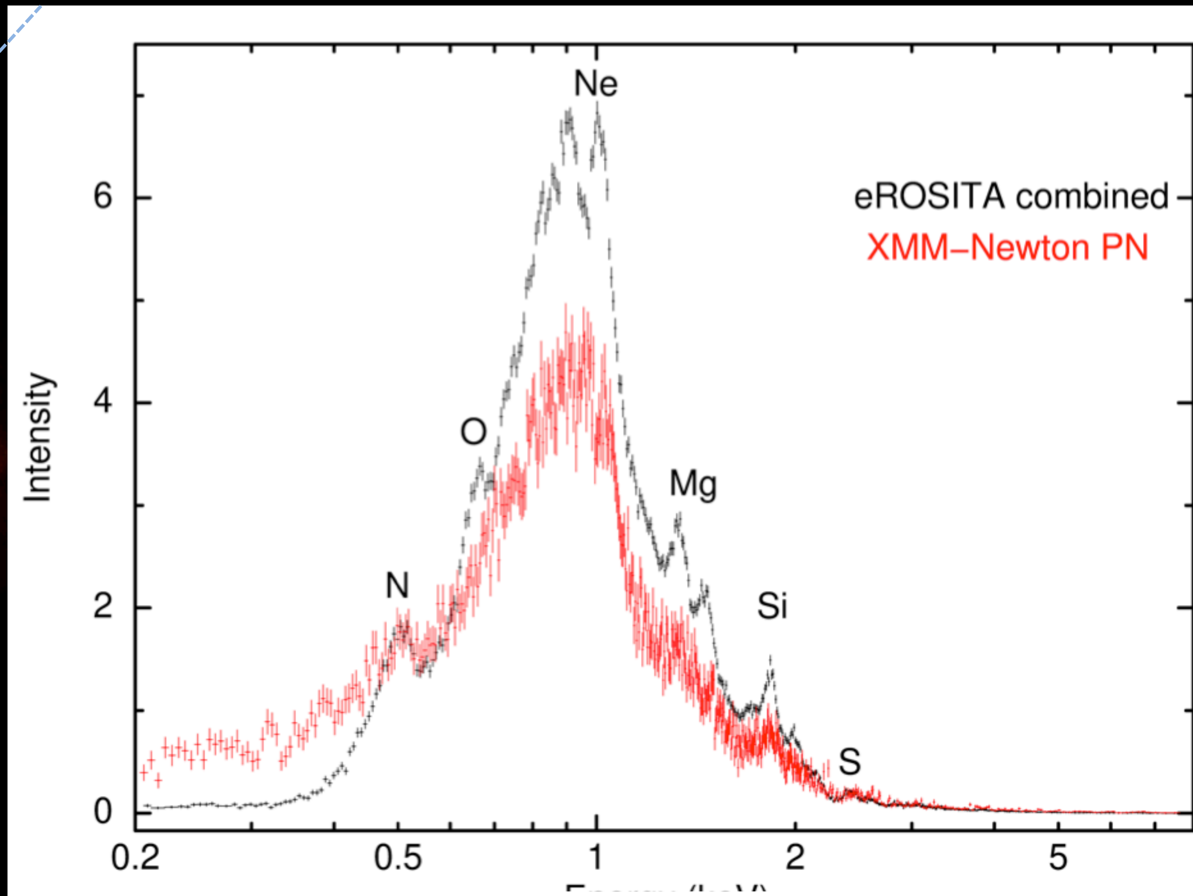
Credit: F. Haberl, M. Freyberg, C. Maitra

A. Rau

SN 1987A in the LMC

SRG/eROSITA



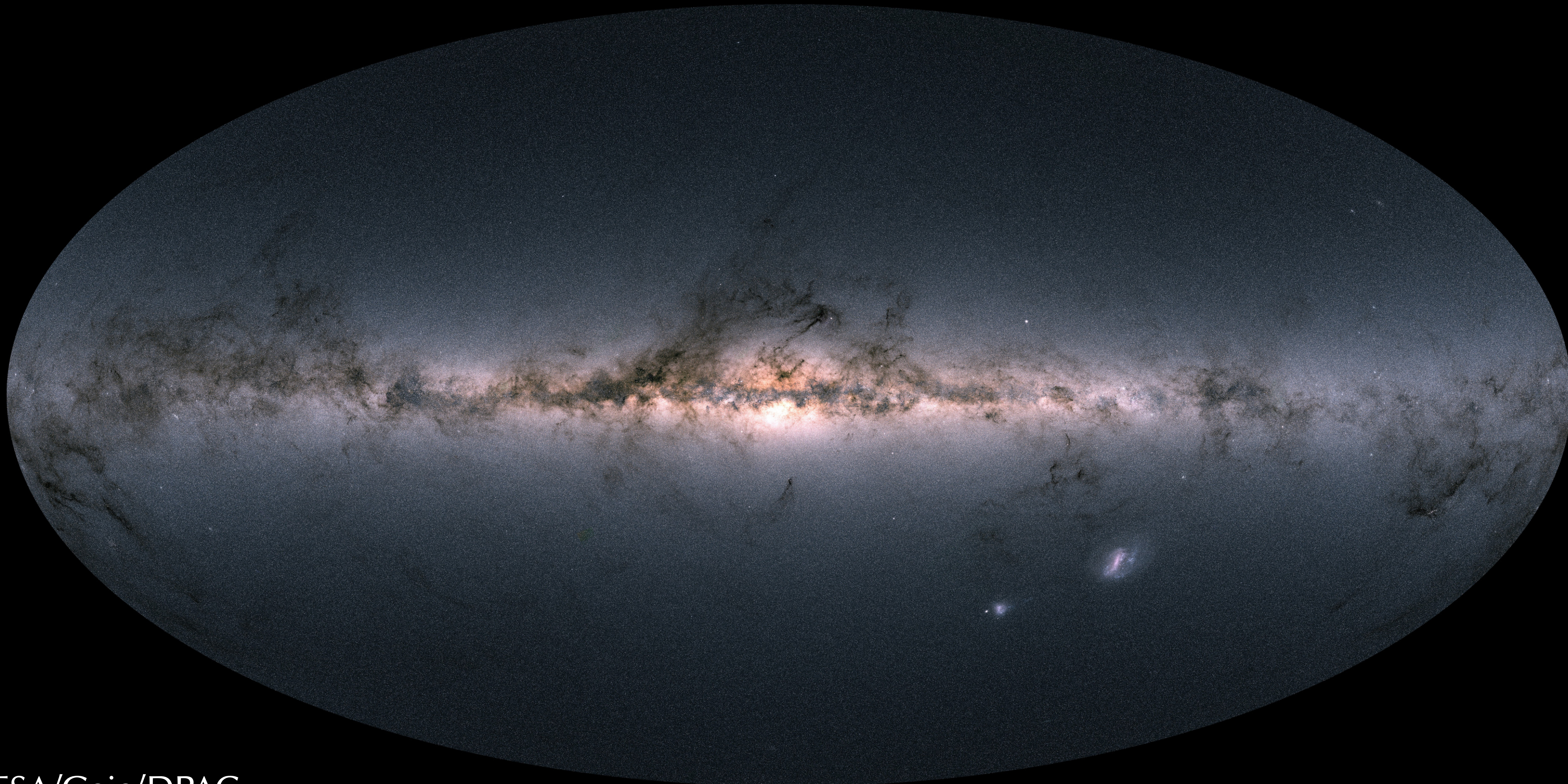


- higher throughput than XMM-Newton PN
- spectral resolution: best CCD-camera in space
  50 eV@0.3 keV, 77 eV@1.5 keV

Haberl, Maitra, Freyberg. MPE

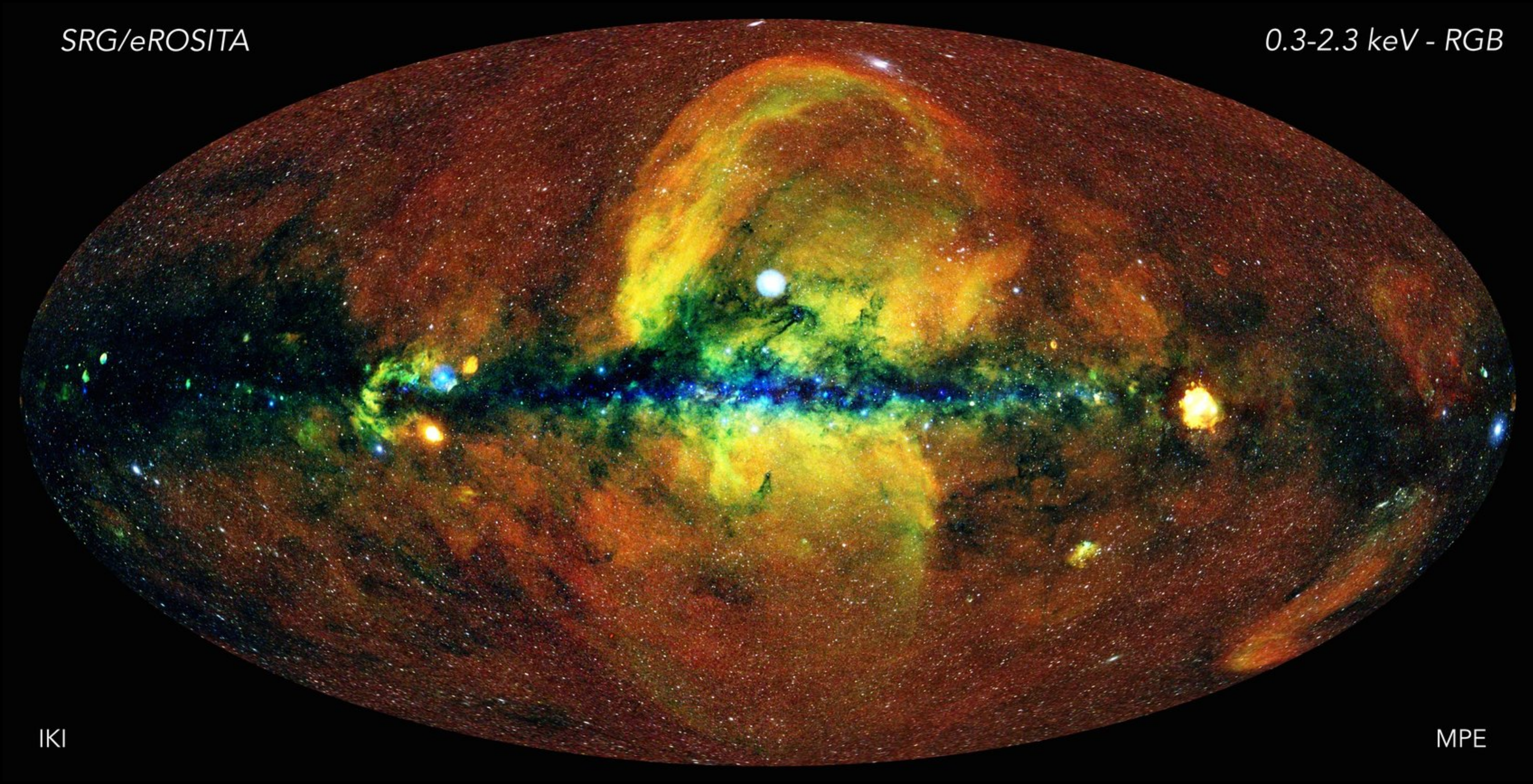
A. Rau

The visual Sky

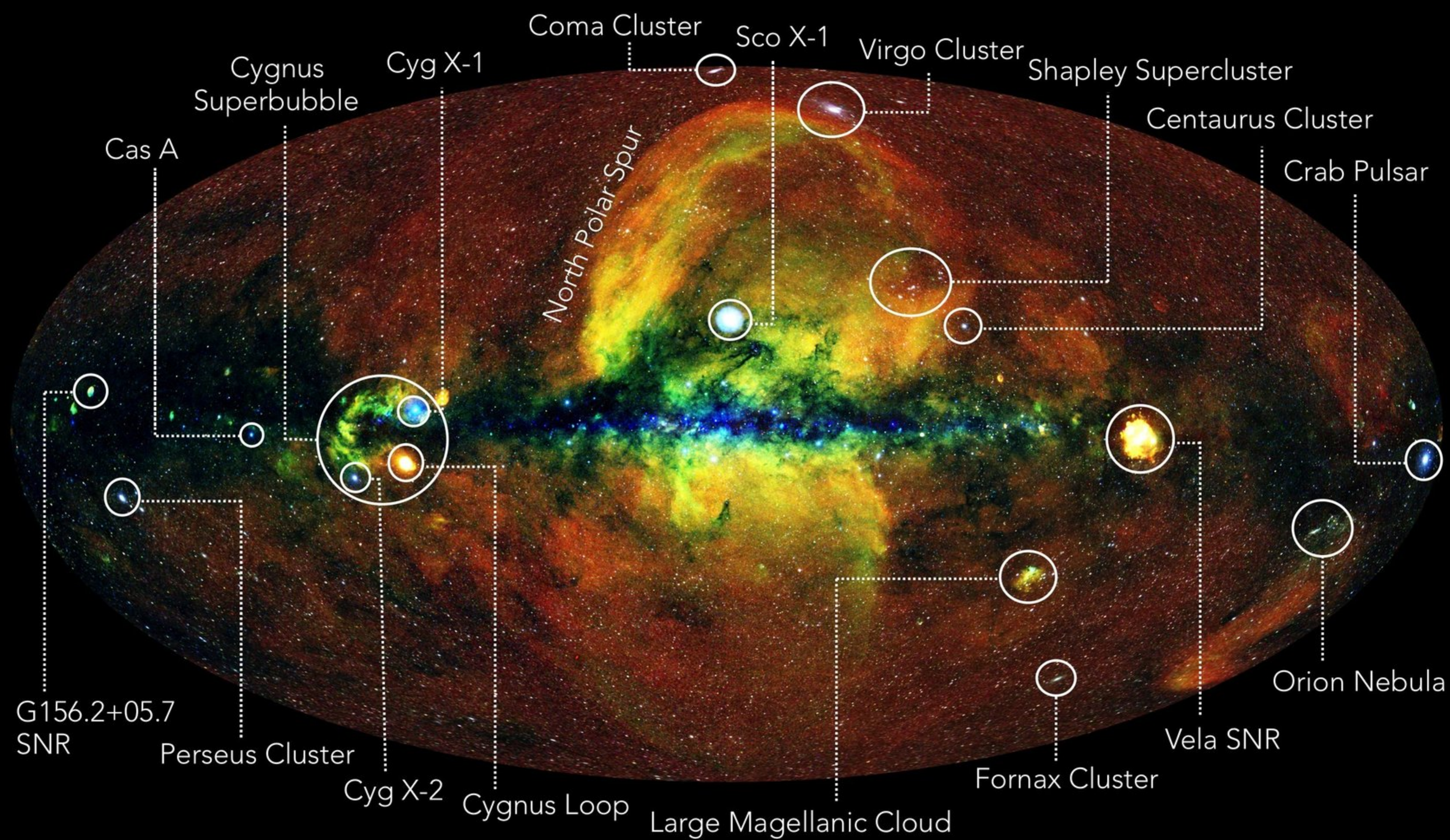


ESA/Gaia/DPAC

The first eROSITA All Sky Survey

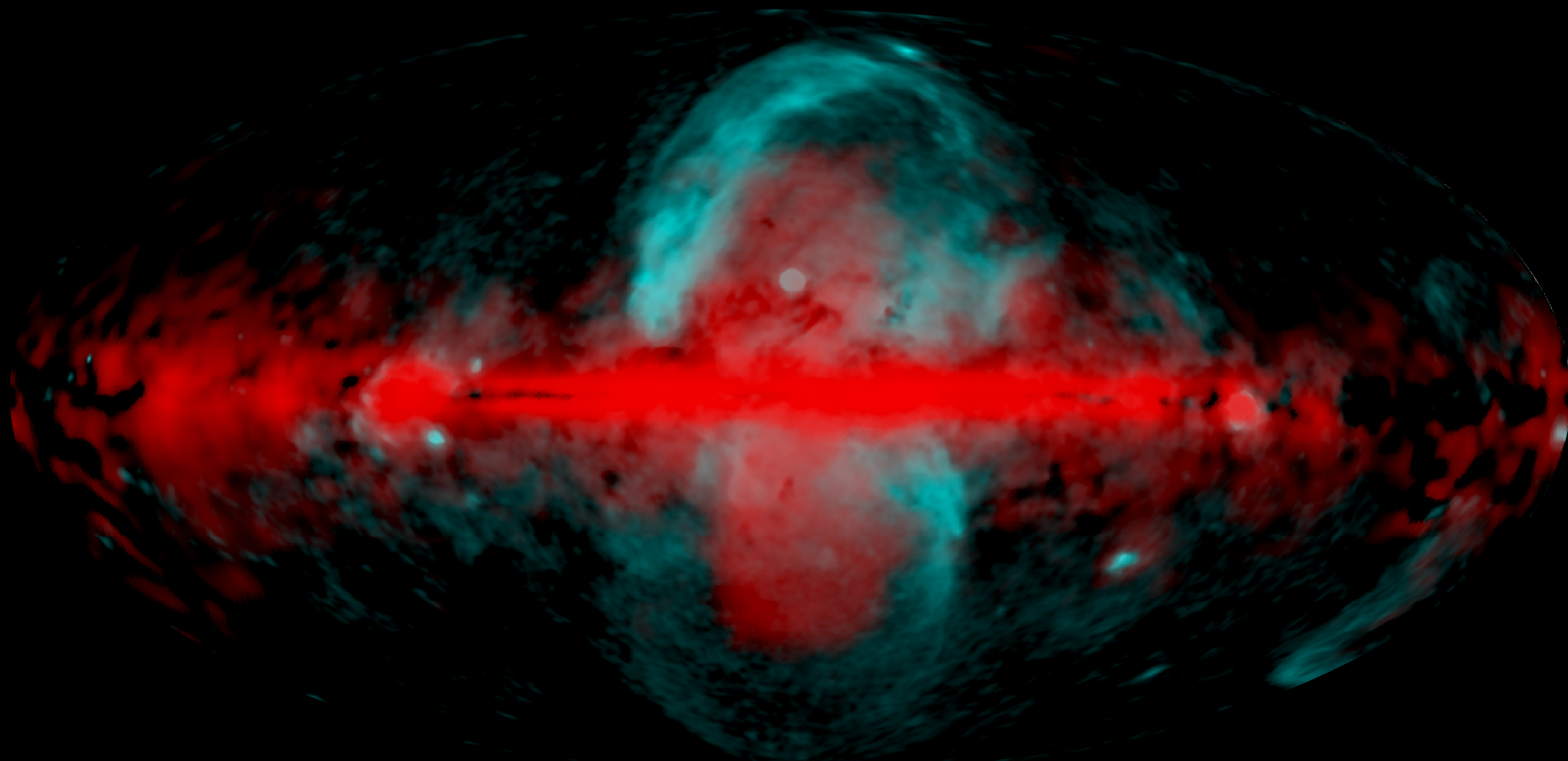


Navigating the eROSITA X-ray sky



- 1.1 M sources
- >10k clusters
- 130 000 stars

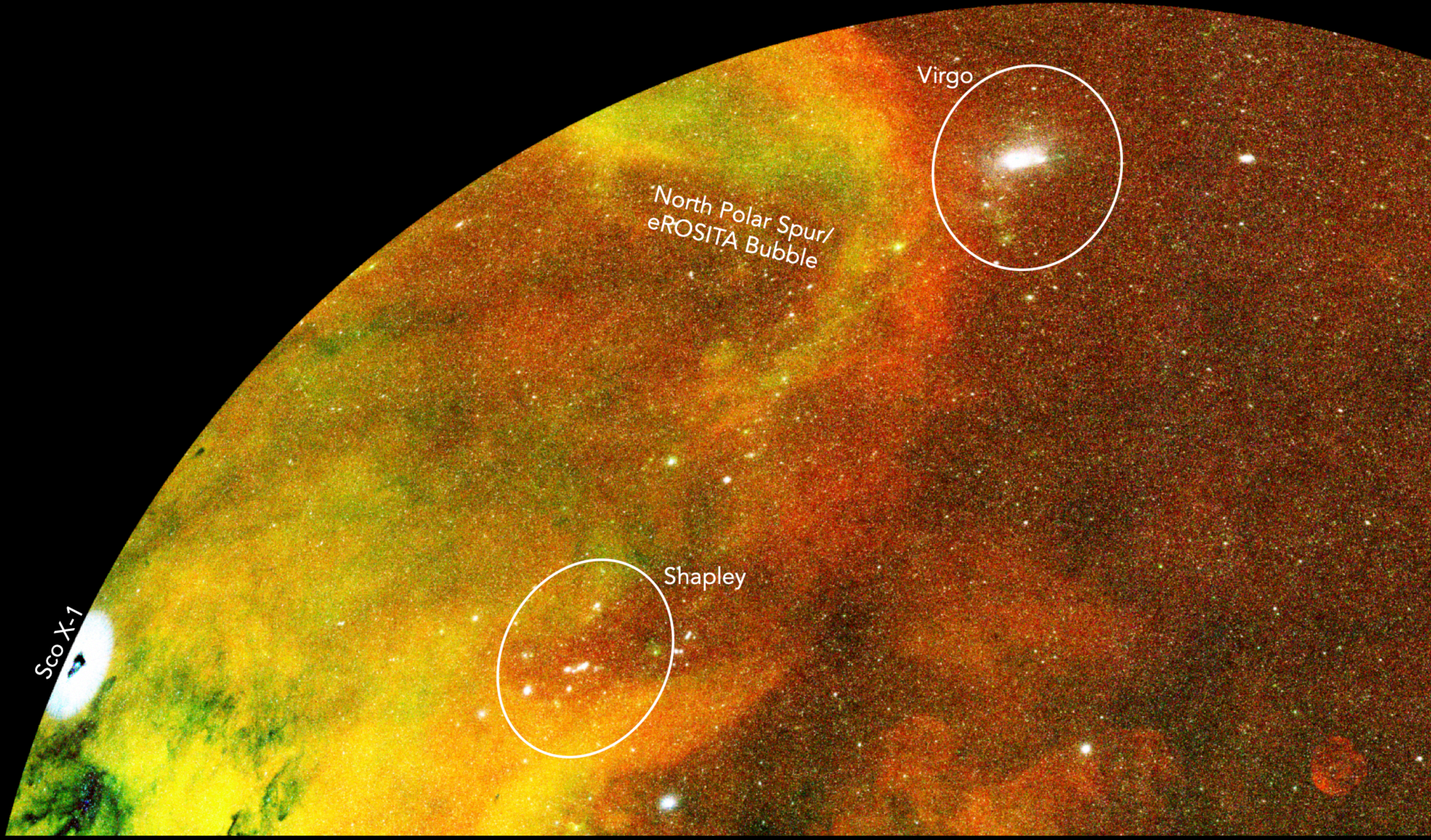
eROSITA and the Fermi bubbles



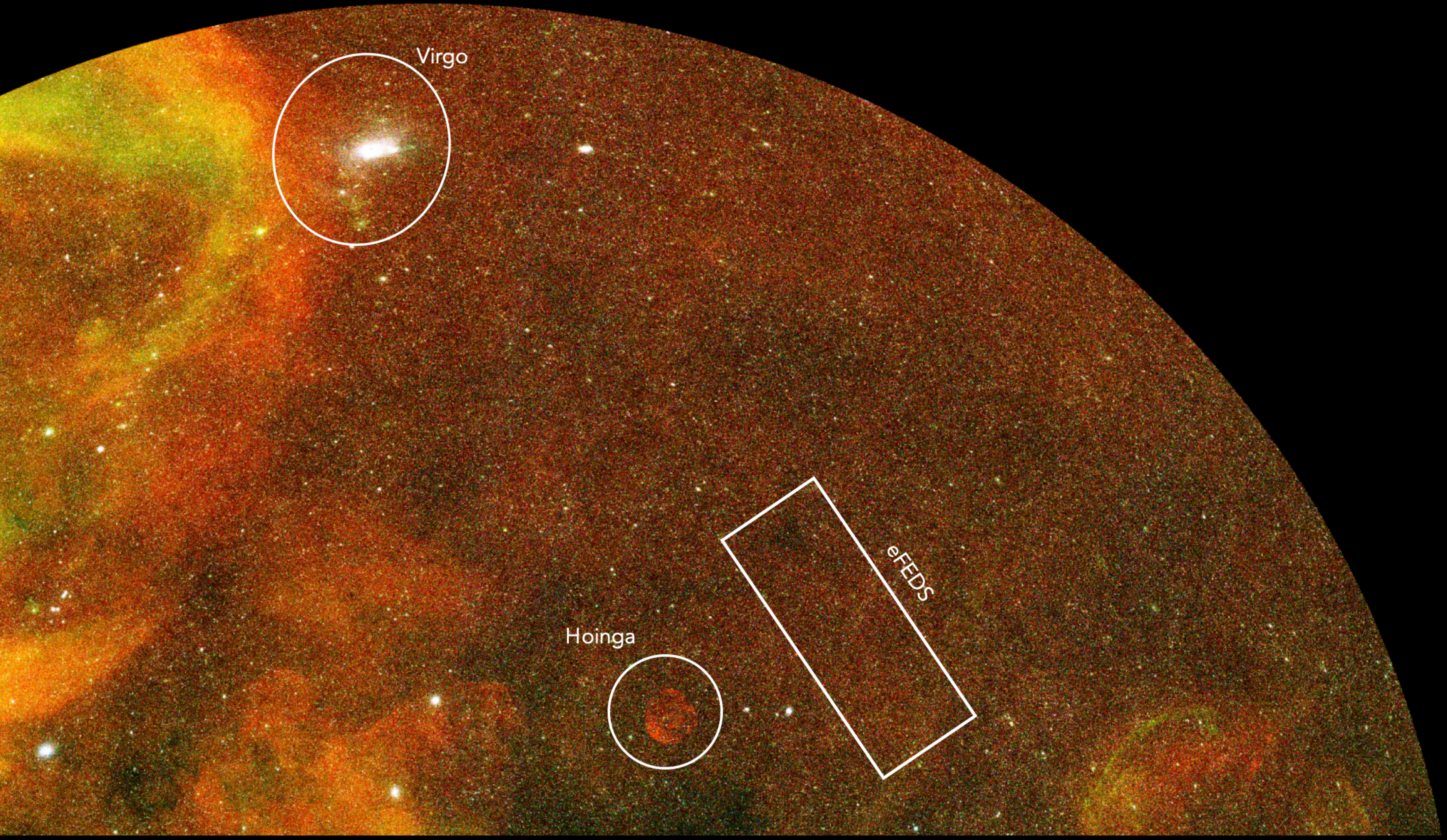
Predehl et al., 2020, Nature 588, 227 blue: X-rays (0.3–2.3 keV), red: γ-rays (20 MeV–300 GeV)

$L_X \sim 1 \times 10^{39}\,\mathrm{erg\,s^{-1}}$

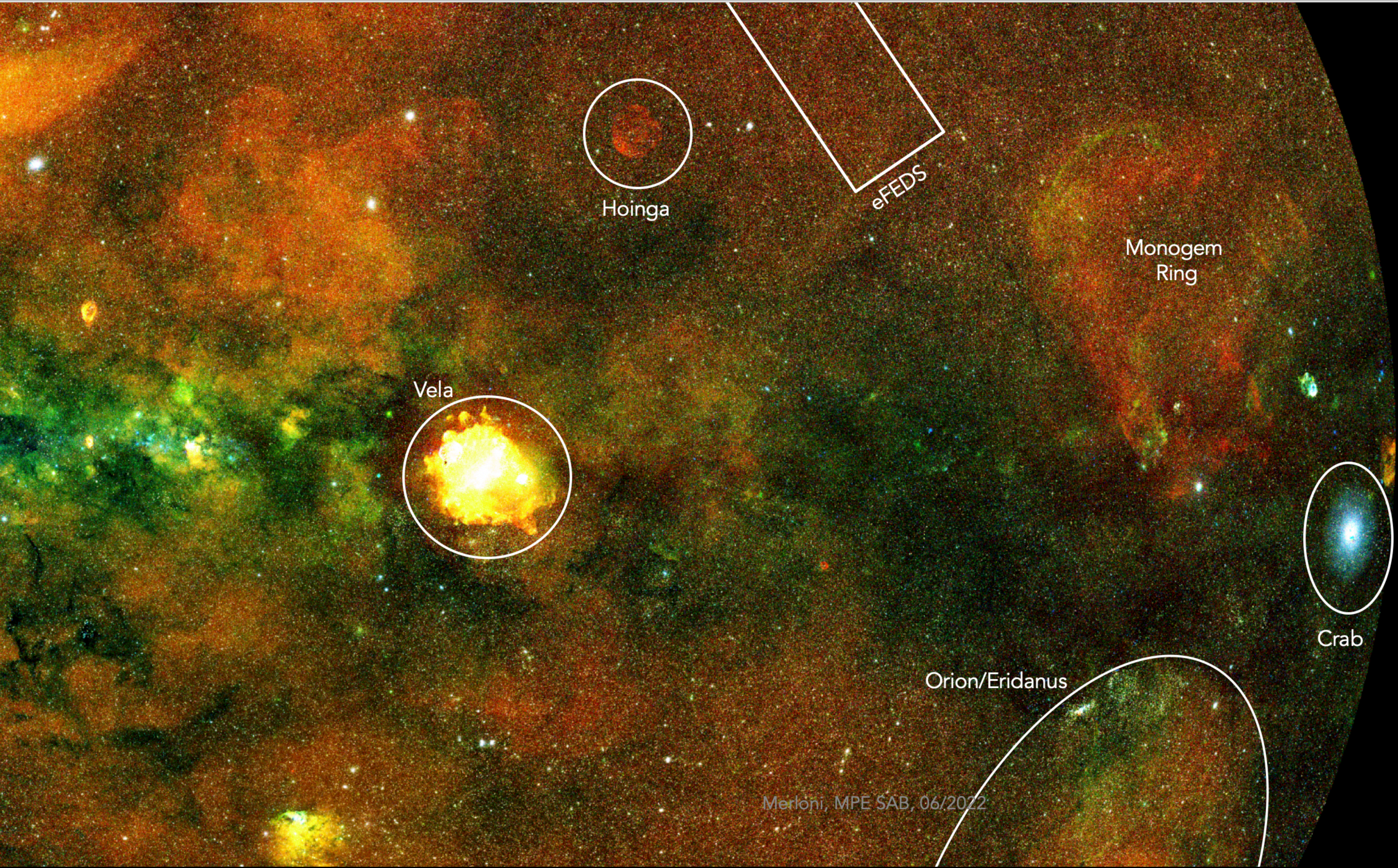
needs $10^{41}\,\mathrm{erg\,s^{-1}}$ for a few Myr, due to star burst or black hole activity in Sgr A* (similar to other radio galaxies).

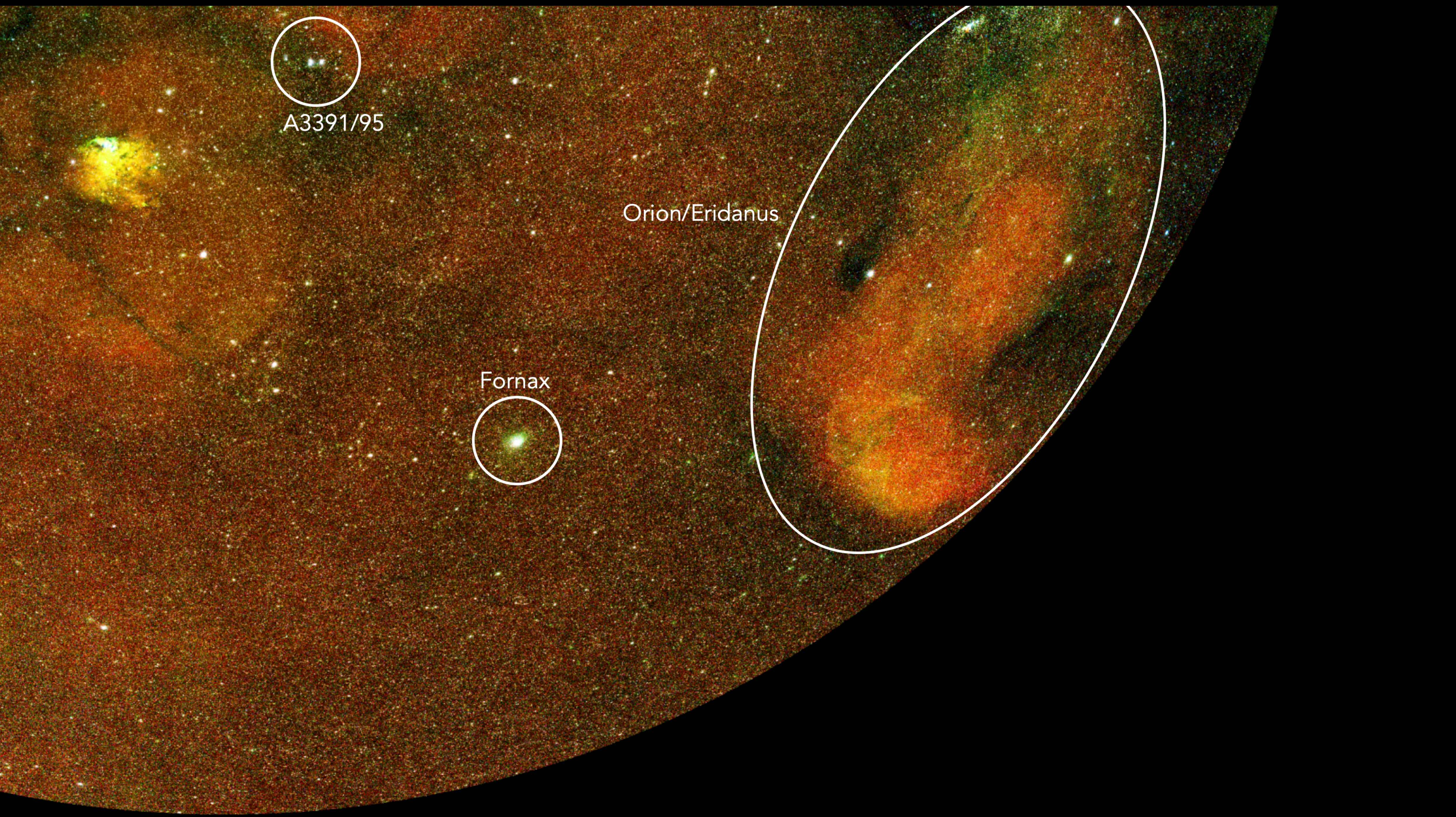


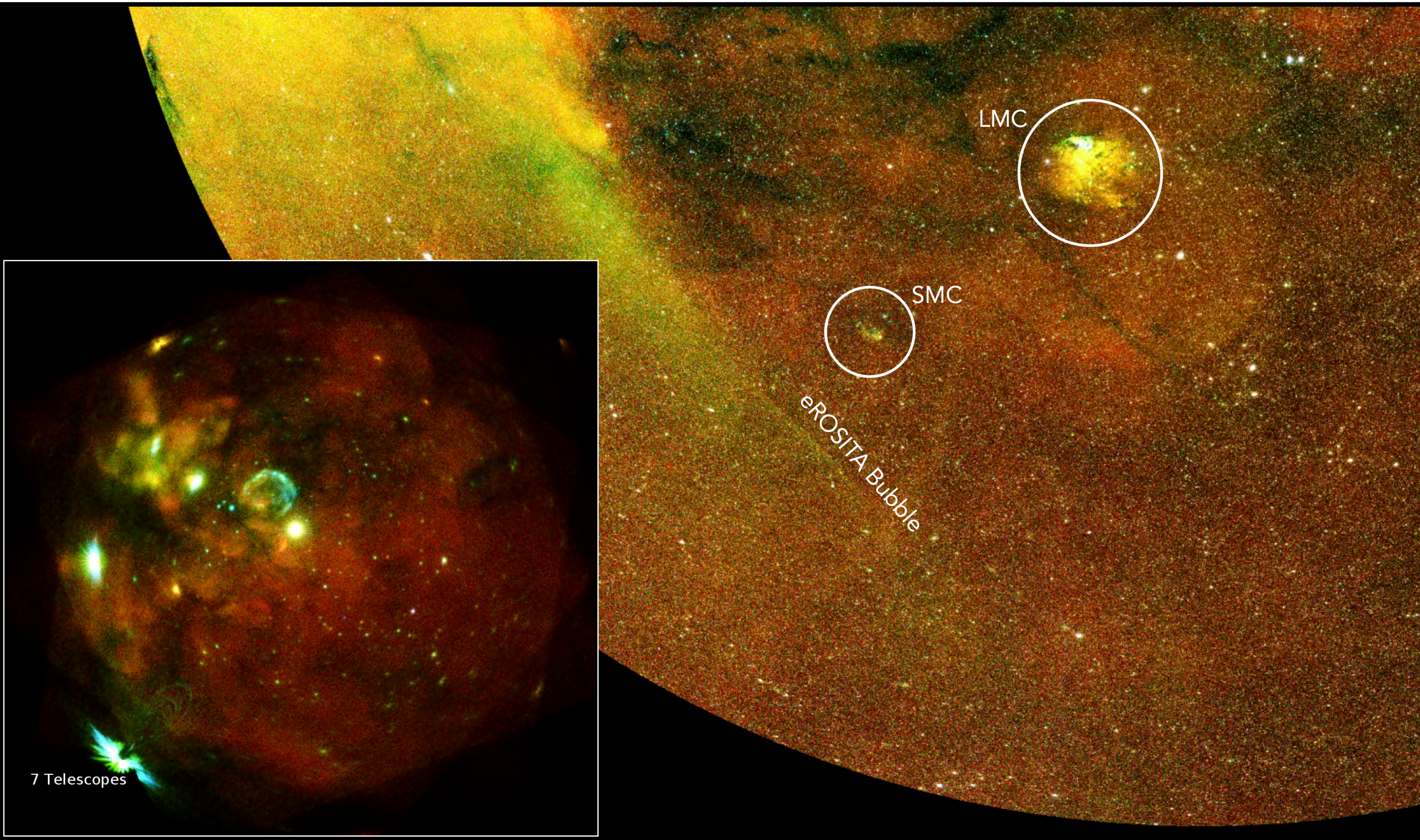
Virgo
North Polar Spur/
eROSITA Bubble
Shapley
Sco X-1

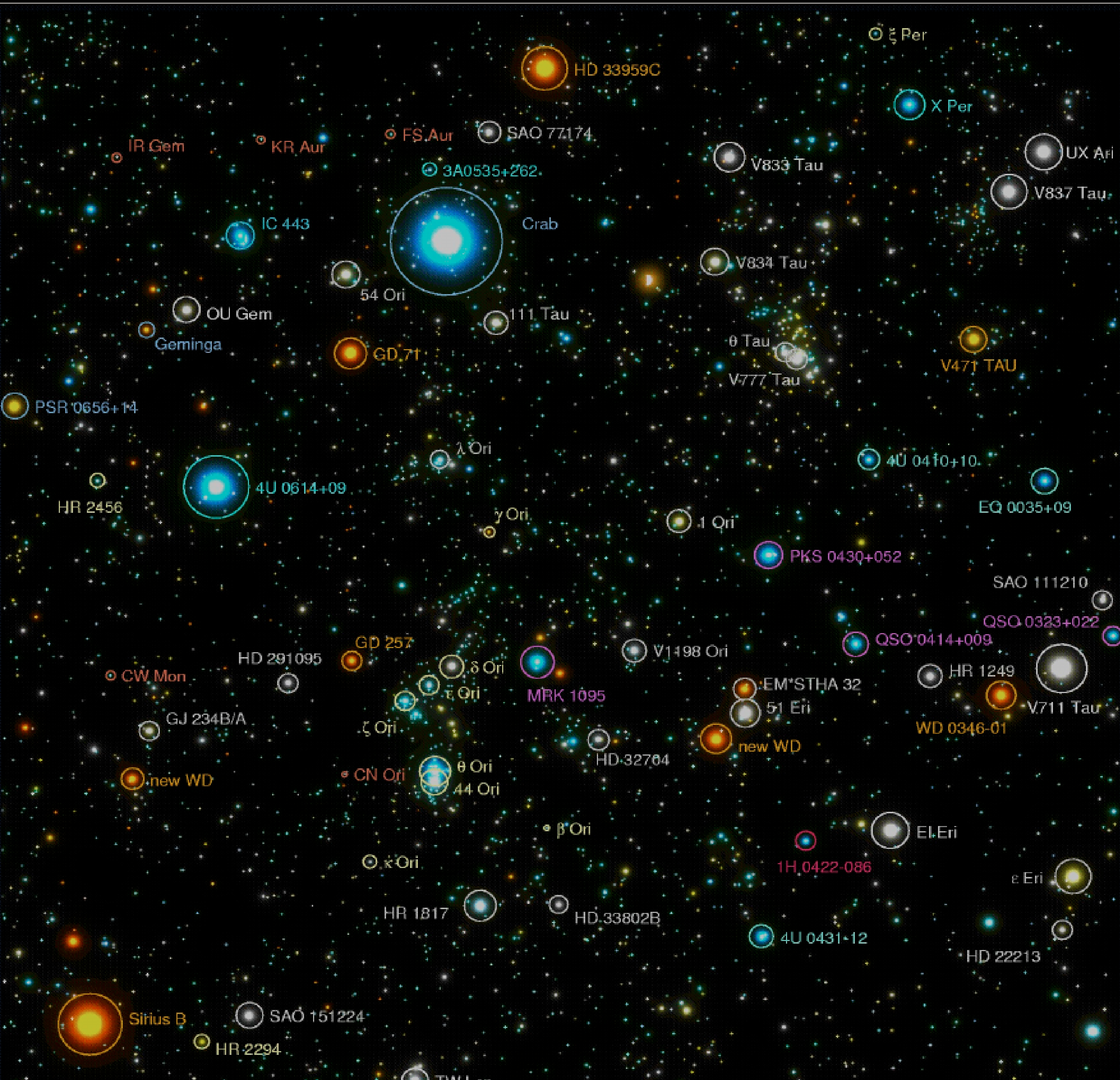

Virgo
eFEDS
Hoinga

Galactic Anti-center




A3391/95
Orion/Eridanus
Fornax


LMC
SMC
eROSITA Bubble
7 Telescopes



K. Dennerl

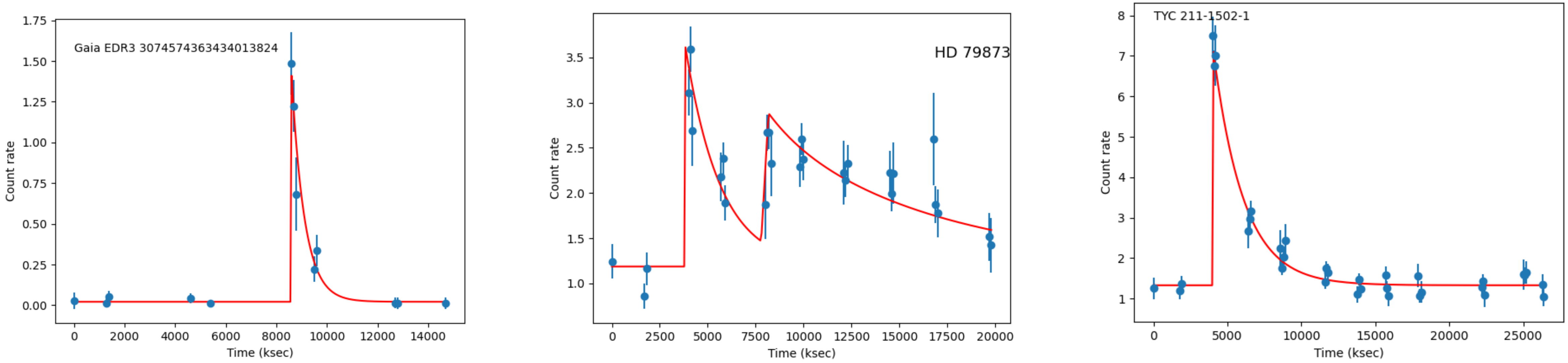
log L_X	stars	distance limit
26.0	late M dwarf	10 pc
26.5	active VLM (M9) star	20 pc
27.0	Sun, Altair (A7), Prox Cen (M5)	30 pc
28.0	Procyon (F5), Eps Eri (K2)	100 pc
29.0	low-mass CTTS, active M dwarf	300 pc
30.0	EK Dra (active G2)	1 kpc
31.0	Algol, bright TTS, early B star	3 kpc
32.0	WR1, O type star	10 kpc
33.0	θ^1 Ori C (mag. O5)	30 kpc

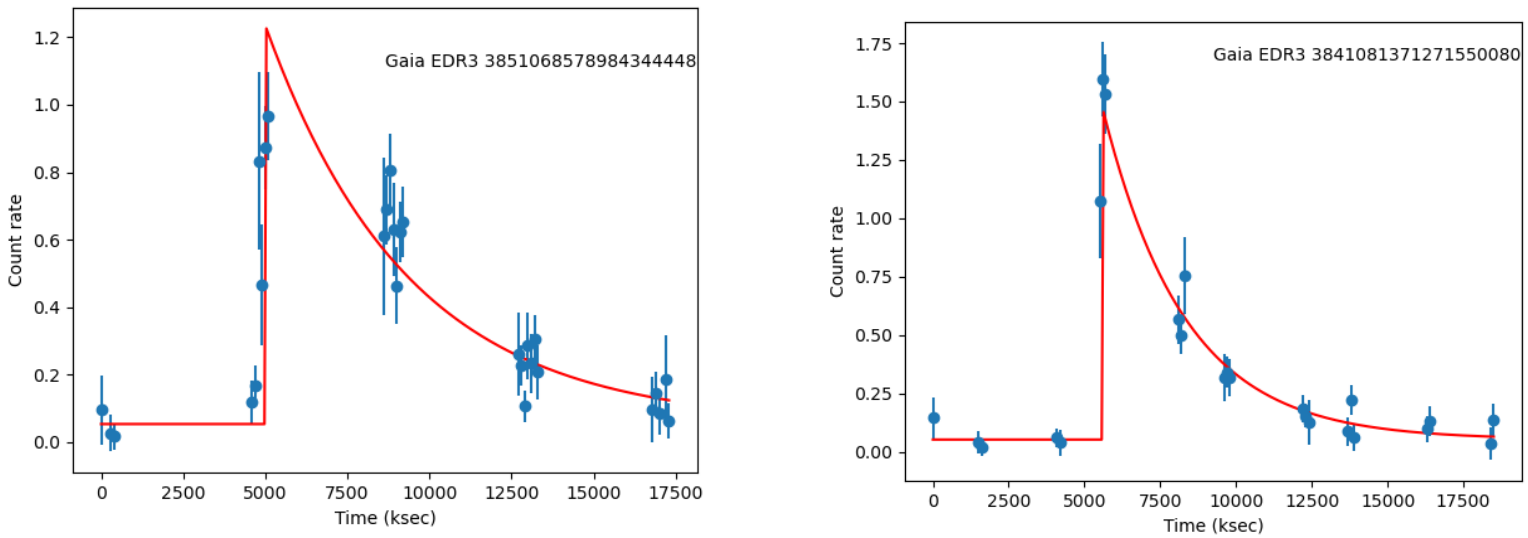
Stellar science:

- Stellar population studies
  activity vs. age, rotation, M, T…
- Dynamo theory
  saturation effects, L_X/L_{bol} evolution, transition at convective boundary
- Local SFH, gal. structure
  young nearby stars
- properties of the SFR in various regions
  masses, IMF, SFH,…

Robrade, Schmitt

Stars

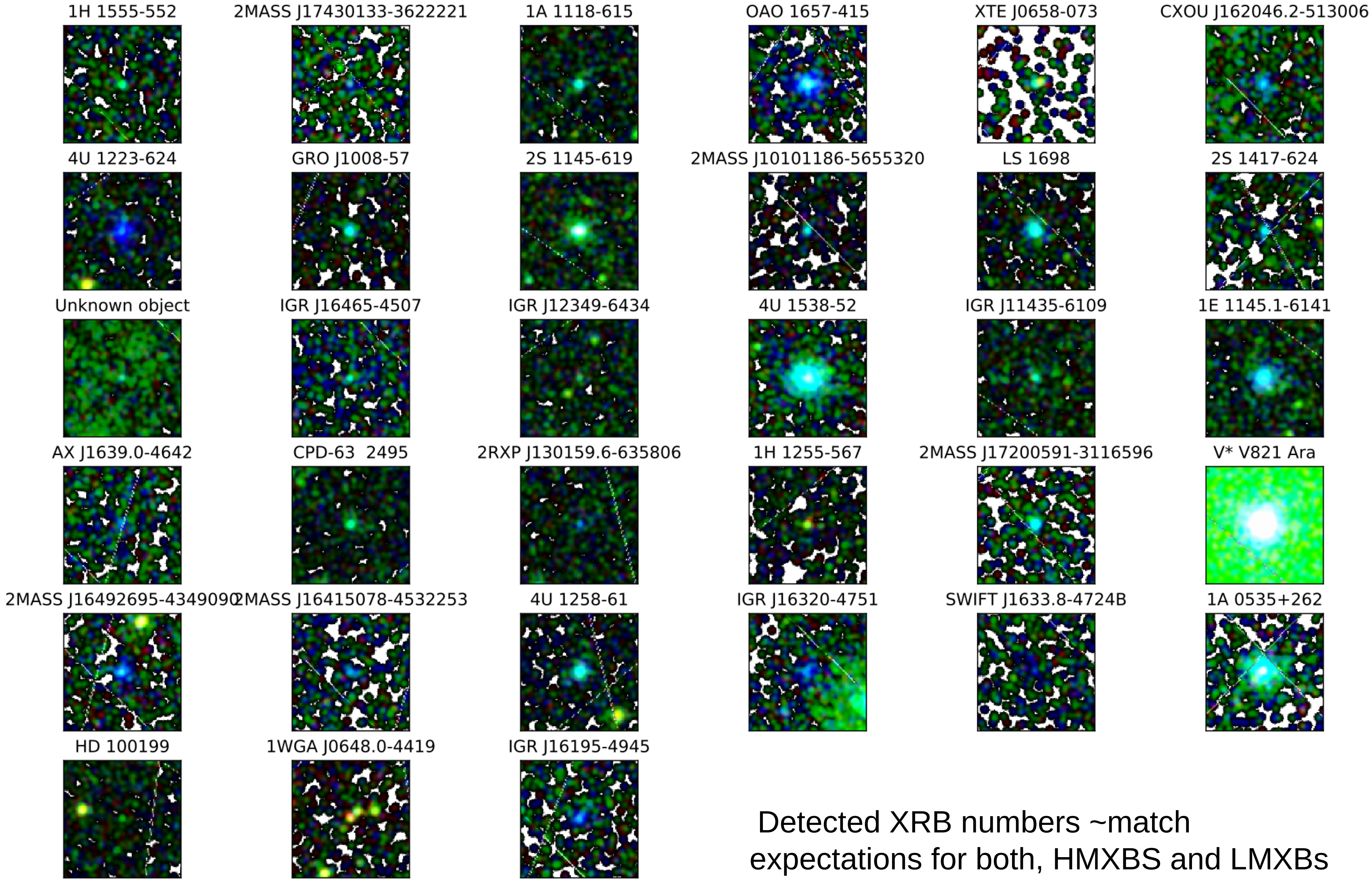




eFEDS field: strong stellar variability

eRASS provides extension to the whole sky (trigger on multiple stellar flares per day)

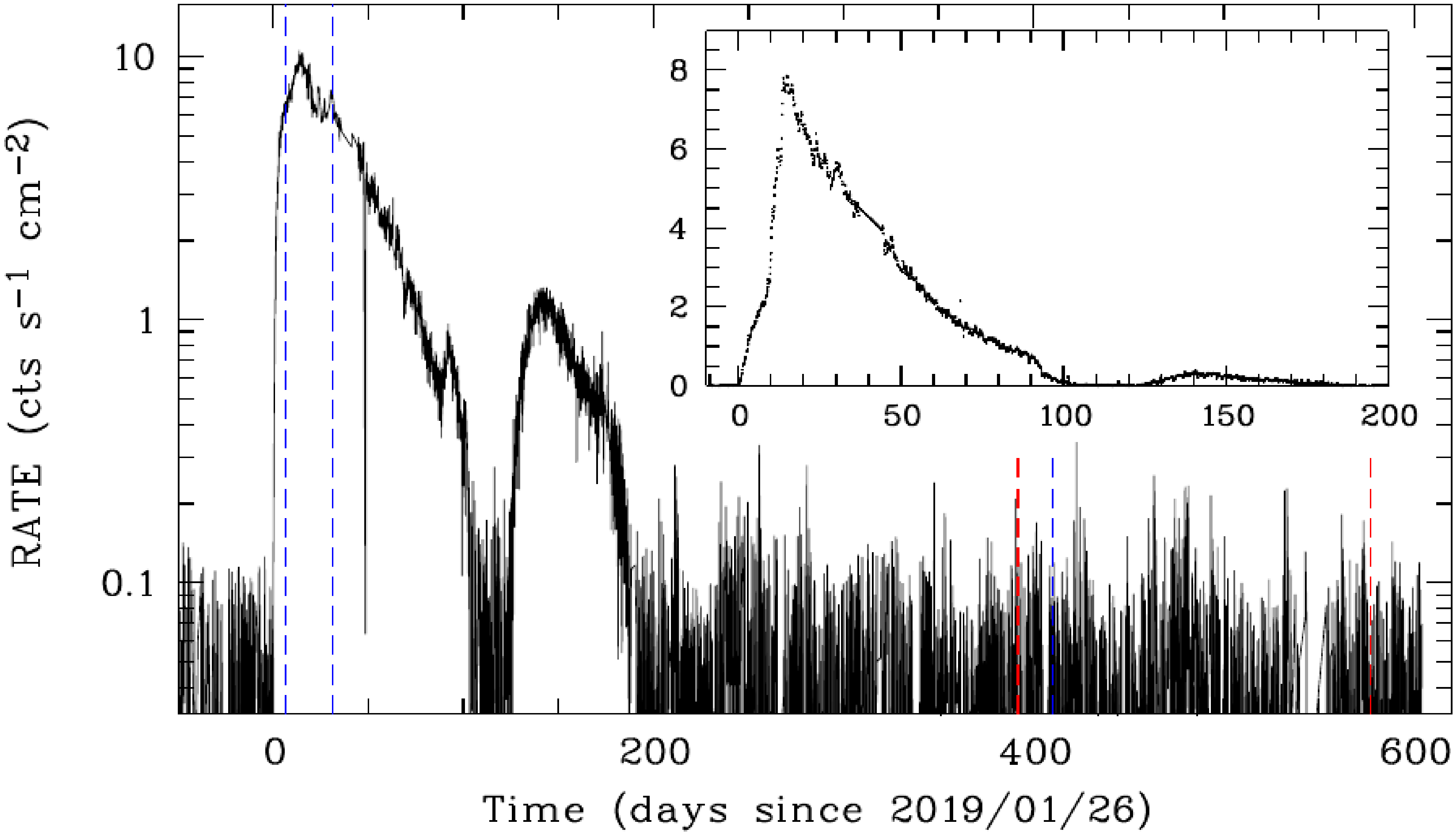
Some of the known HMXBs in eRASS (family portrait)



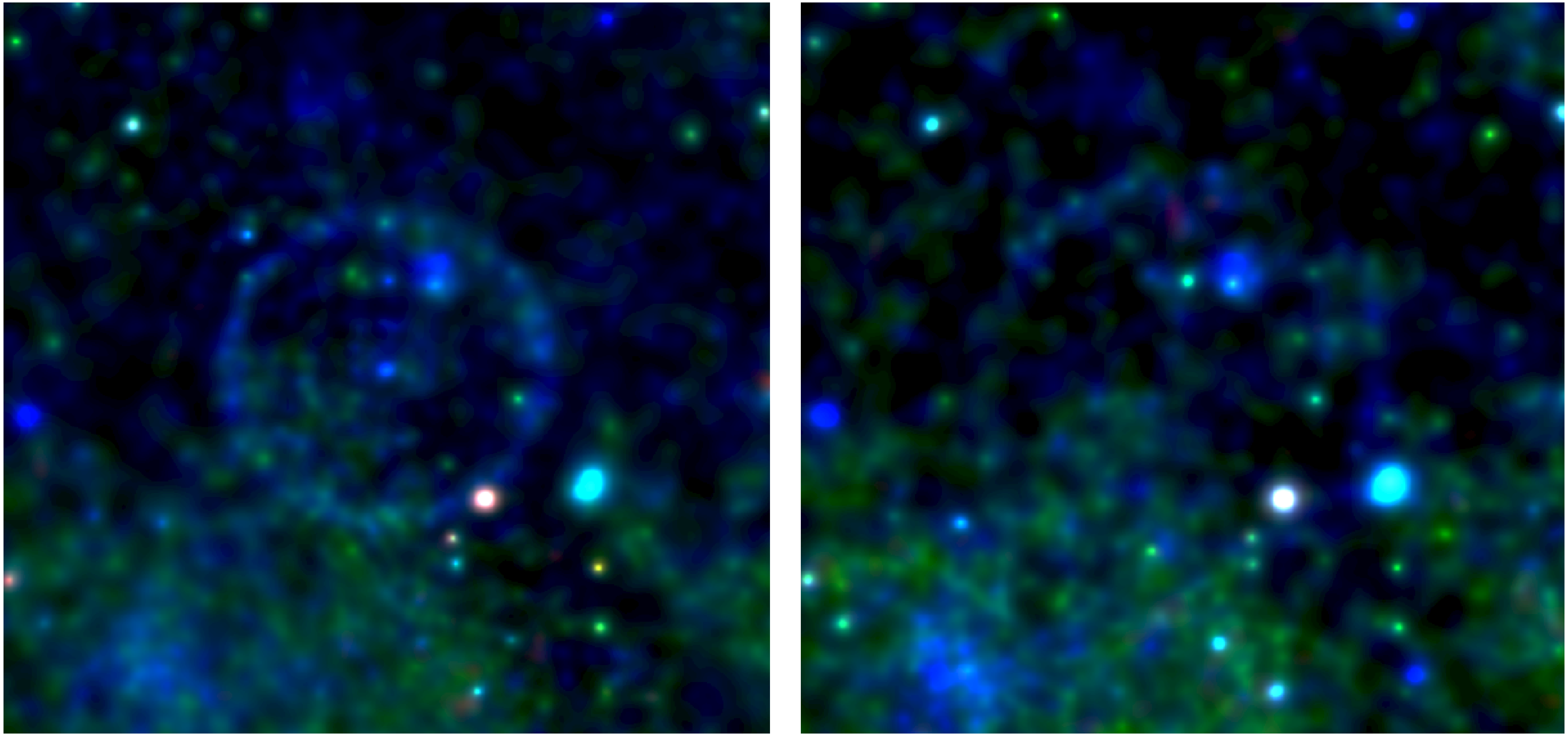
Detected XRB numbers ~match expectations for both, HMXBS and LMXBs

V. Doroshenko

Distance to MAXI J1348−630

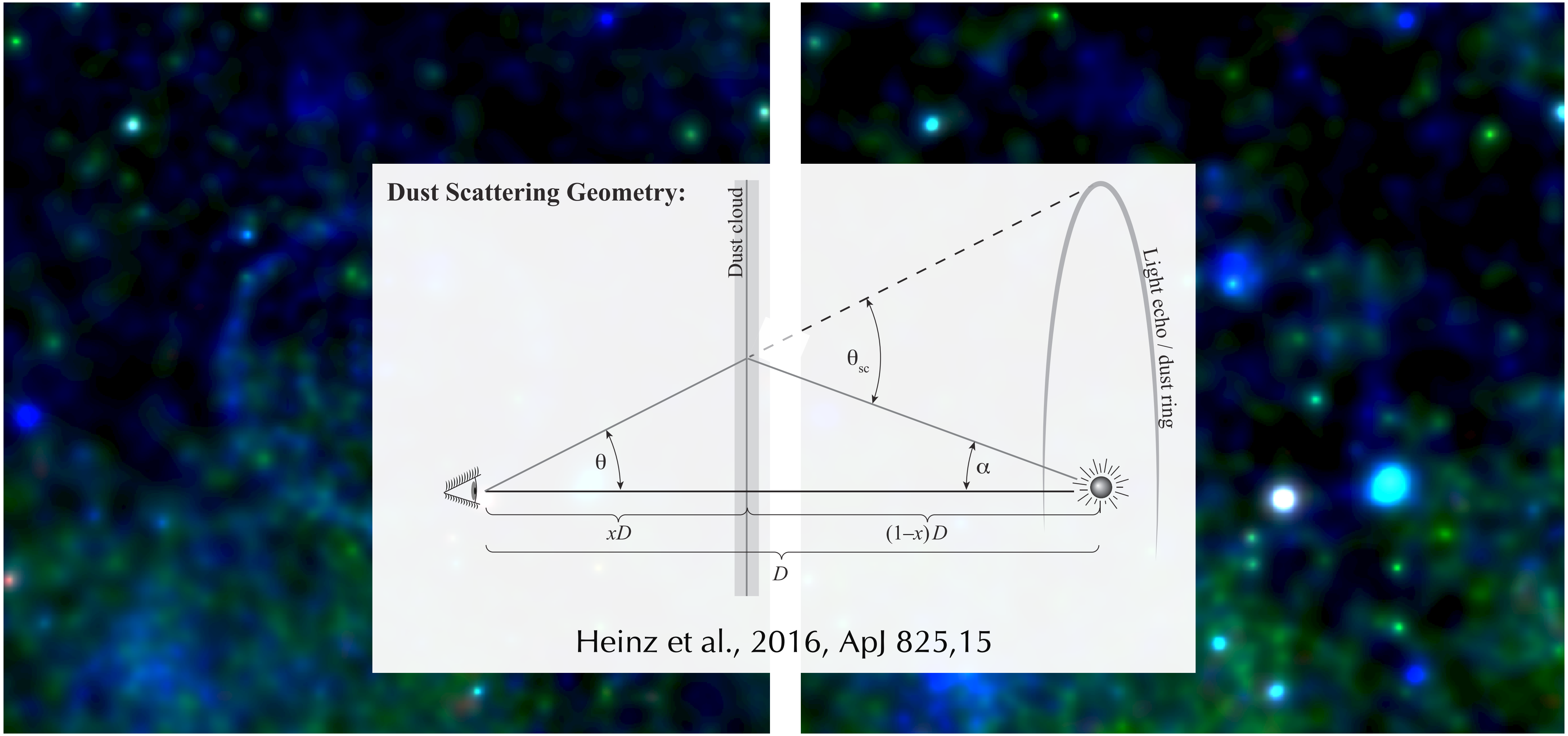


Distance to MAXI J1348−630



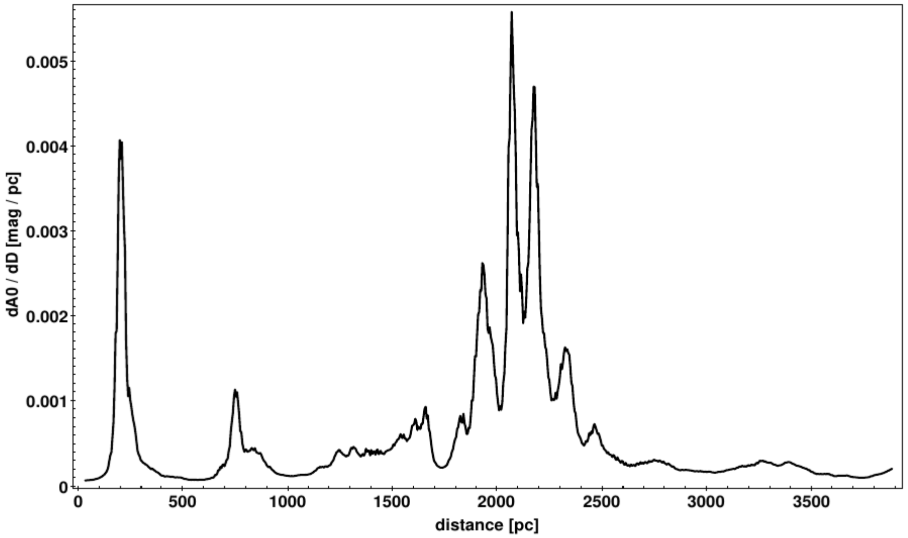
eRASS1 $3^\circ \times 3^\circ$; Lamer et al. (2021, A&A 647, 7) eRASS2

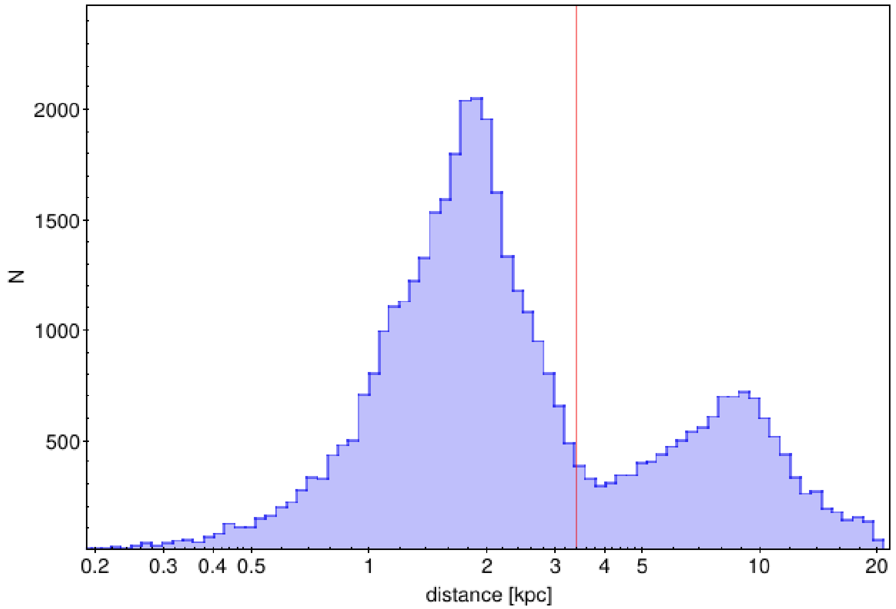
Distance to MAXI J1348−630

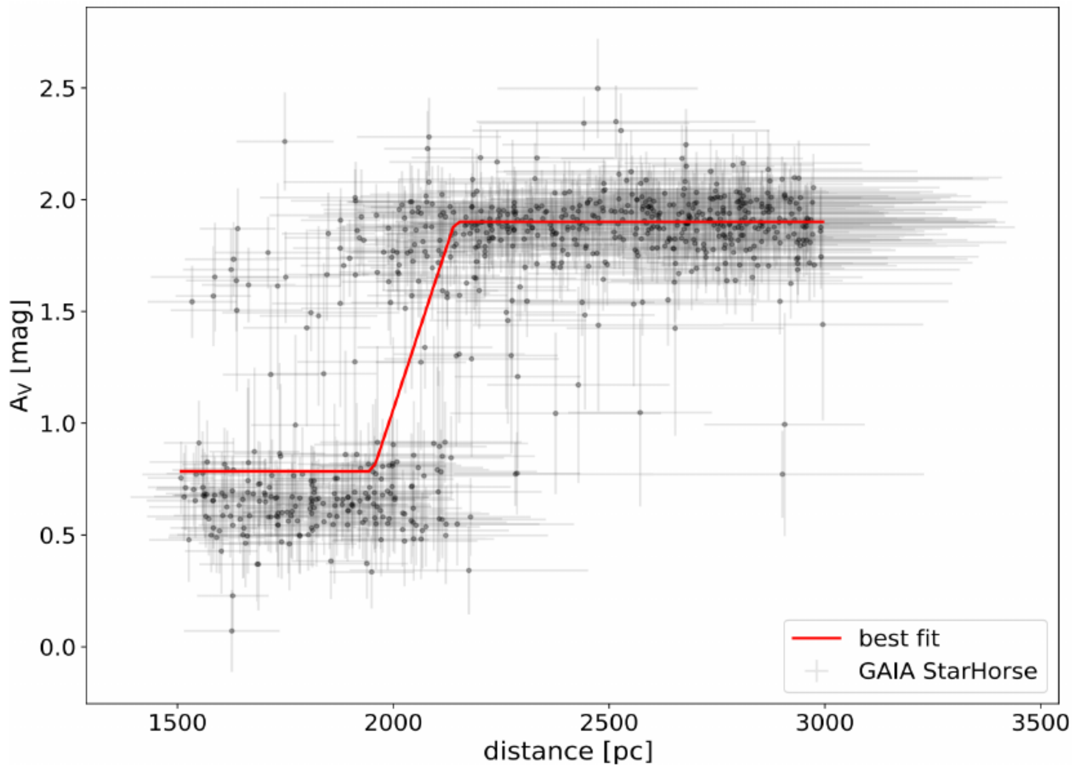


eRASS1 $3^\circ \times 3^\circ$; Lamer et al. (2021, A&A 647, 7) eRASS2

Distance to MAXI J1348−630



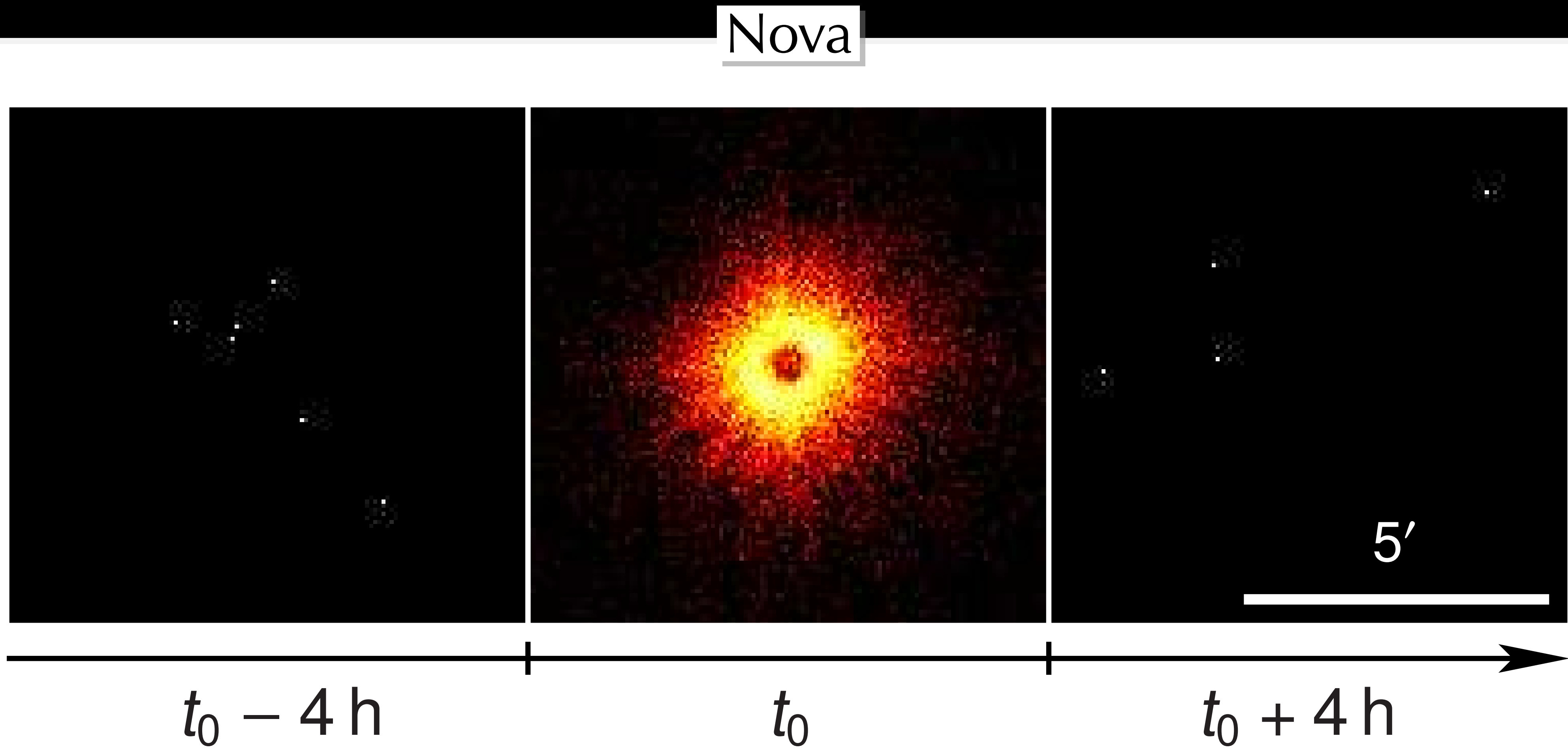




Gaia: dust cloud at 2047 ± 22 pc

$\Longrightarrow$ Geometrical distance of BH: 3390^{+46}_{-43} pc

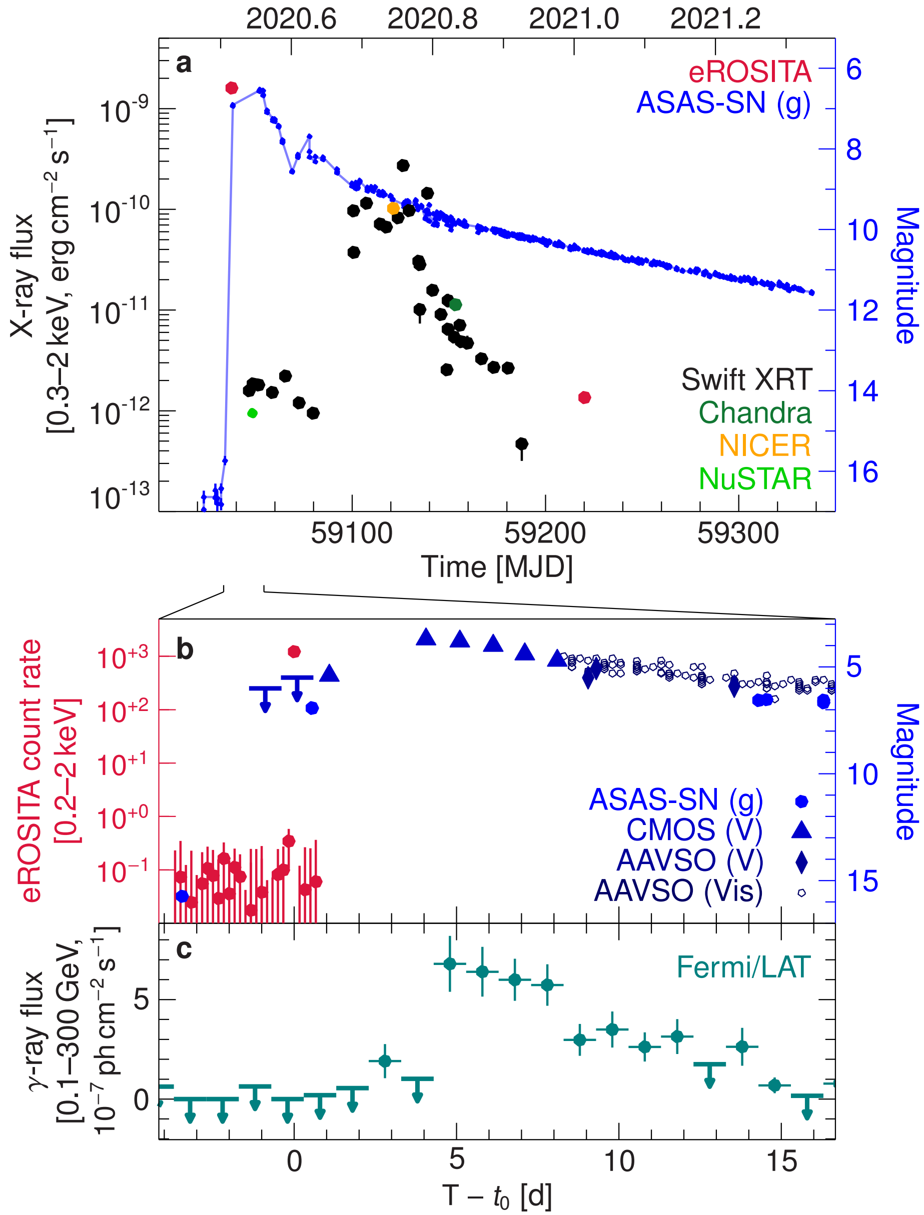
(syst. ± 339 pc [Gaia])

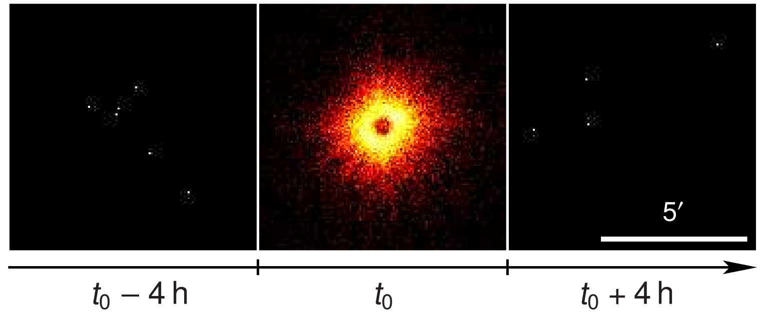


YZ Ret (Nova Reticuli 2020): Extremely bright source seen 2020-07-07, 16:47; no detection 4 h before or after

Nova

König et al. (2022, Nature)



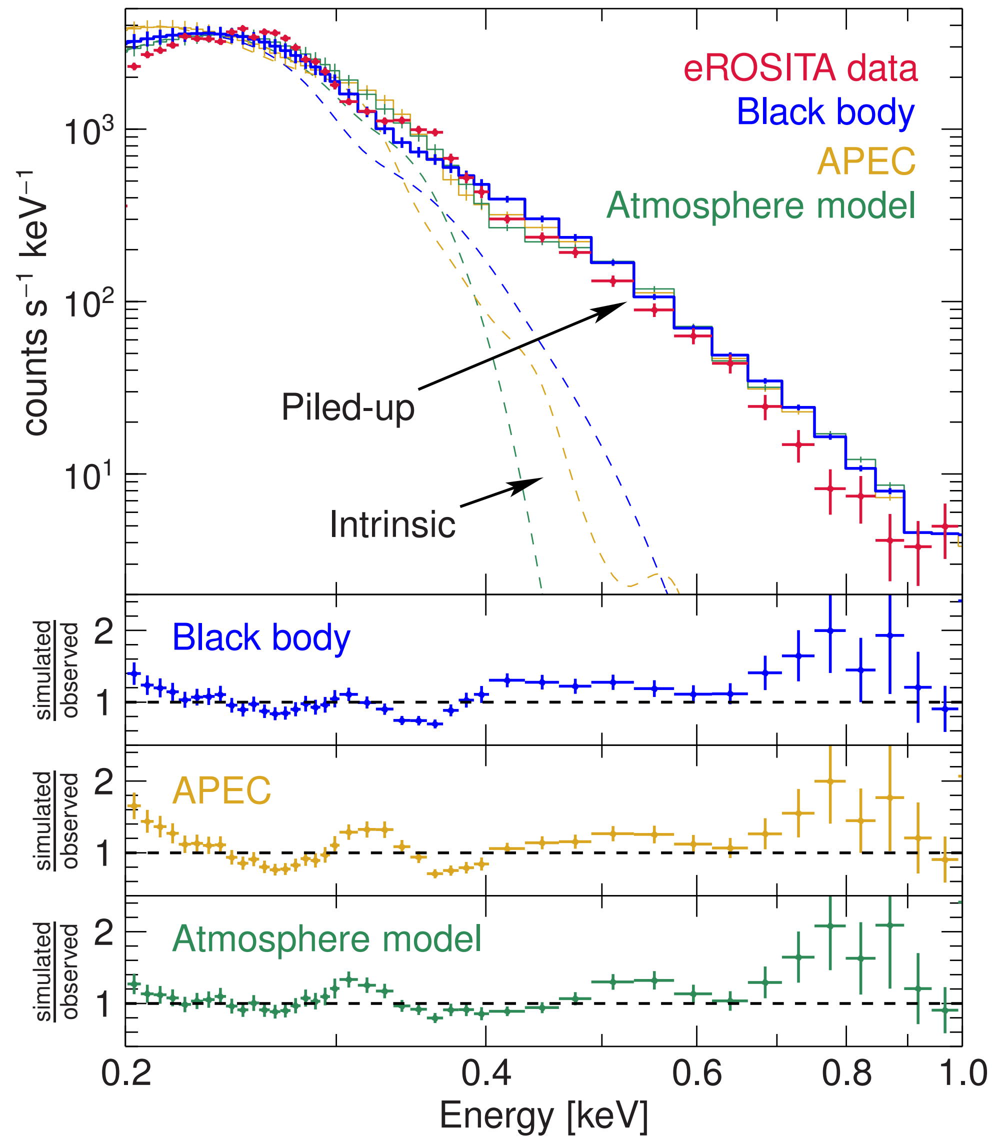


X-ray seen *before* optical

First detection of an X-ray flash

30 yr after prediction (Starrfield et al., 1990).

Nova



König et al. (2022, Nature)

Spectrum "piled up"

($F_{0.2-10\,\mathrm{keV}} = 1.86^{+0.38}_{-0.23} \times 10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$)

Modeling: extremely difficult because of detector effects

- black body

  $kT = 28.2^{+0.9}_{-2.8}\,\mathrm{eV}$, $L = 2.0(1.2) \times 10^{38}\,\mathrm{erg\,s^{-1}}$, $R = 50000 \pm 18000\,\mathrm{km}$

- atmosphere model

  $kT = 27.1^{+1.2}_{-0.5}\,\mathrm{eV}$, $L = 0.98(22) \times 10^{38}\,\mathrm{erg\,s^{-1}}$, $R = 37000 \pm 2900\,\mathrm{km}$, $\log g = 6.97 \pm 0.17$

atmosphere yields

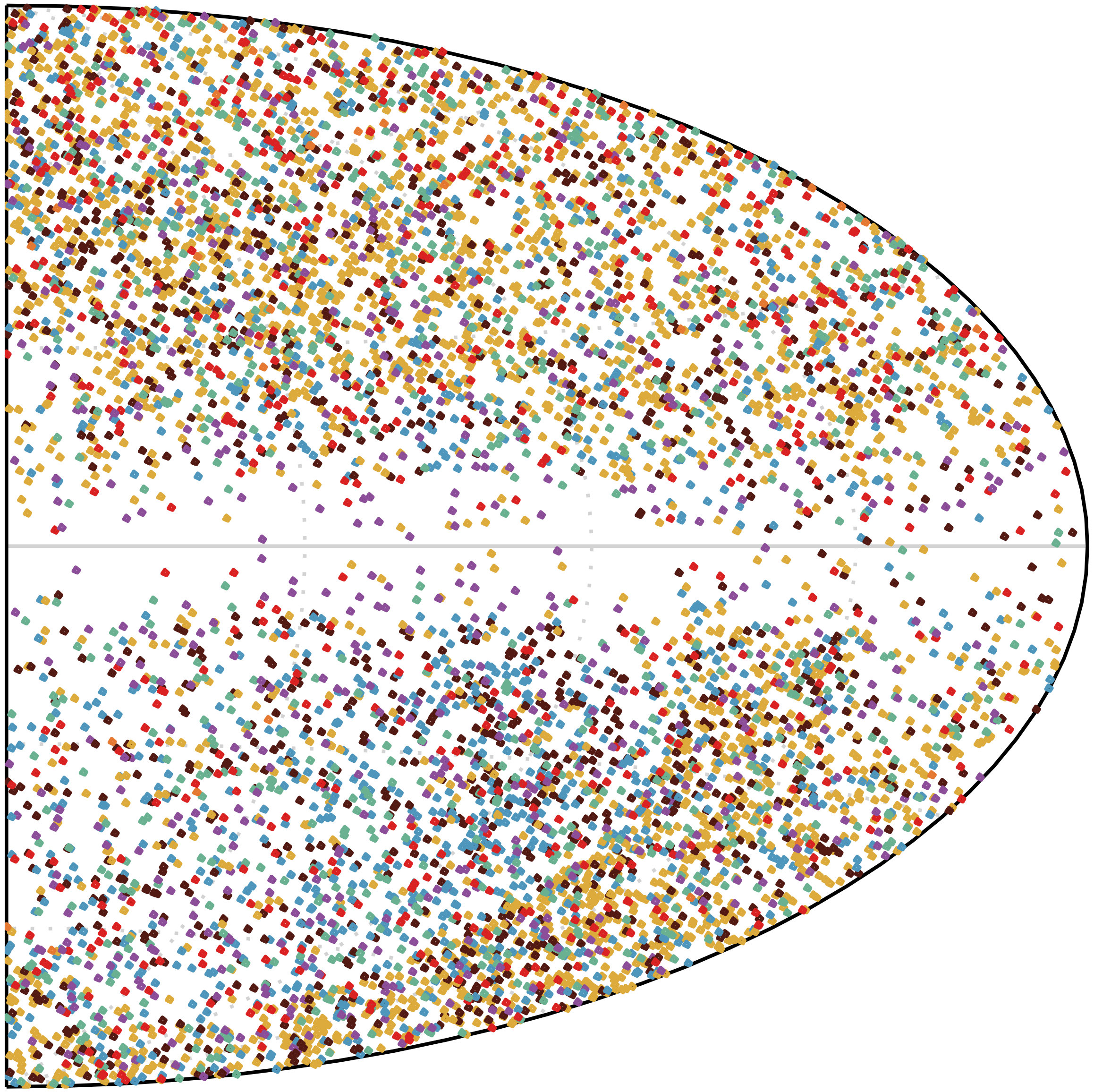
$M_{WD} = (0.98 \pm 0.23)\,M_{\odot}$

consistent w/explosion models; Hillman et al. (2014)


The international journal of science / 12 May 2022
nature
NOVA FIREBALL
Short burst of X-rays reveals early stage of an explosion on a white dwarf
Lunar ambitions
The countries and companies gearing up for a trip to the Moon
Financial risks
Find and protect vulnerable parts of the global economy
Origins of life
RNA and amino acids work together on early Earth
König et al. (2022, Nature)
counts s⁻¹ keV⁻¹
Piled
Int
Black body
APEC
Atmosphere
simulated observed
0.2
10⁻⁸ erg cm⁻² s⁻¹)
difficult because of
= 2.0(1.2) ×
00 ± 18000 km
= 0.98(22) ×
7000 ± 2900 km,
M☉
models; Hillman et al.

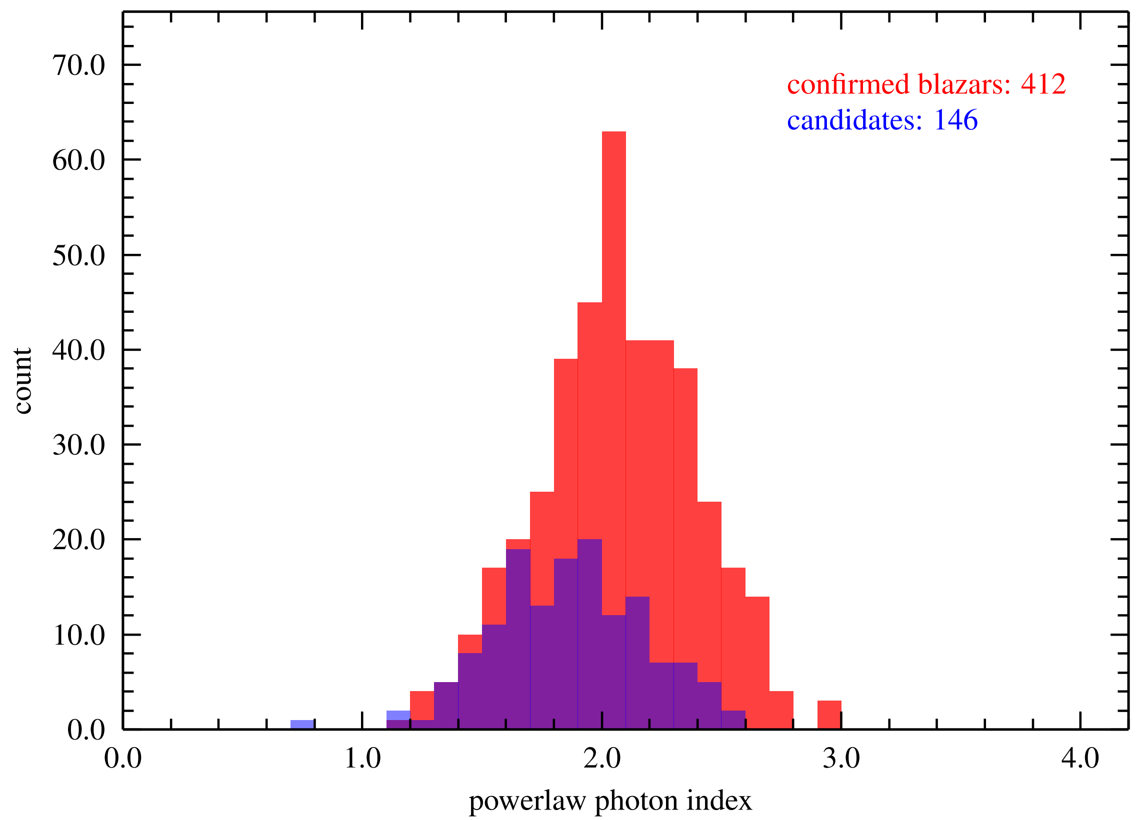
Blazars

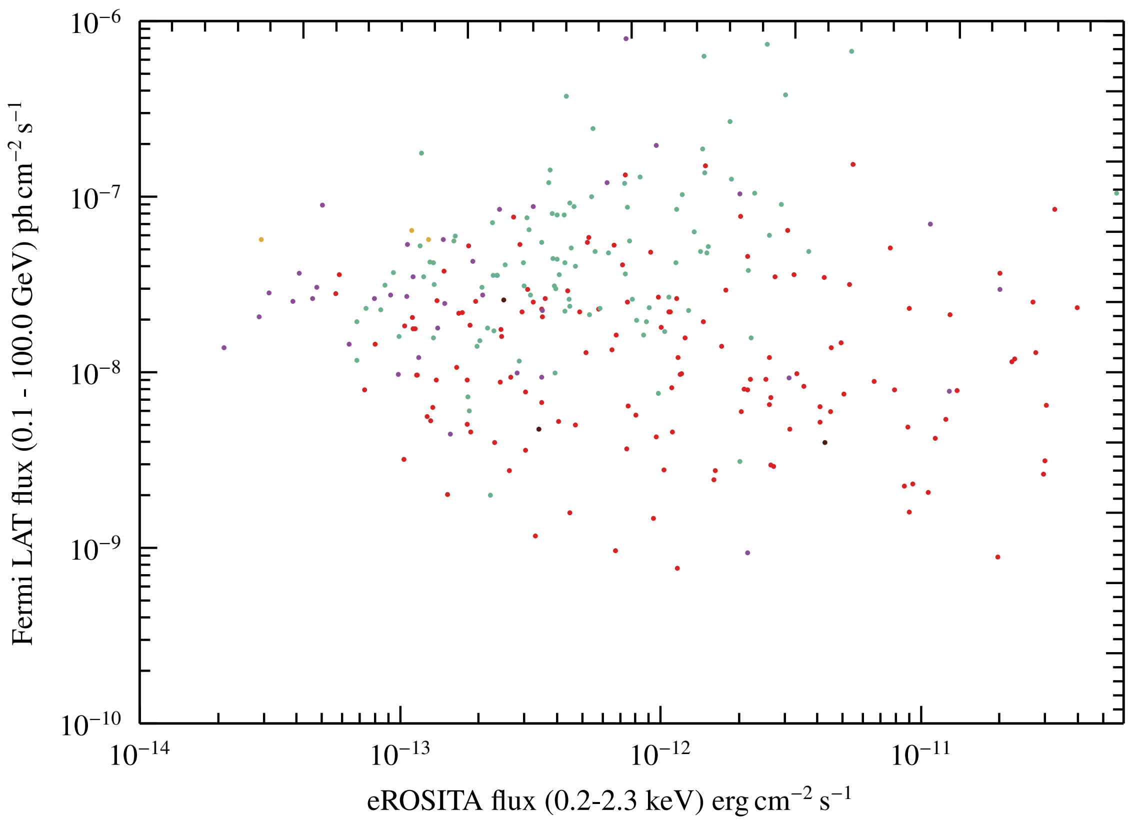
total matches: 7344 within 8 arcsec
uncertain blazar type: 661
BL Lac-galaxy dominated: 44
BL Lac candidates: 1192
FSRQ candidates: 1182
BL Lac: 666
uncertain blazar type candidates: 2758
FSRQ: 841



S. Hämmerich, A. Gokus, J. Wilms, et al.

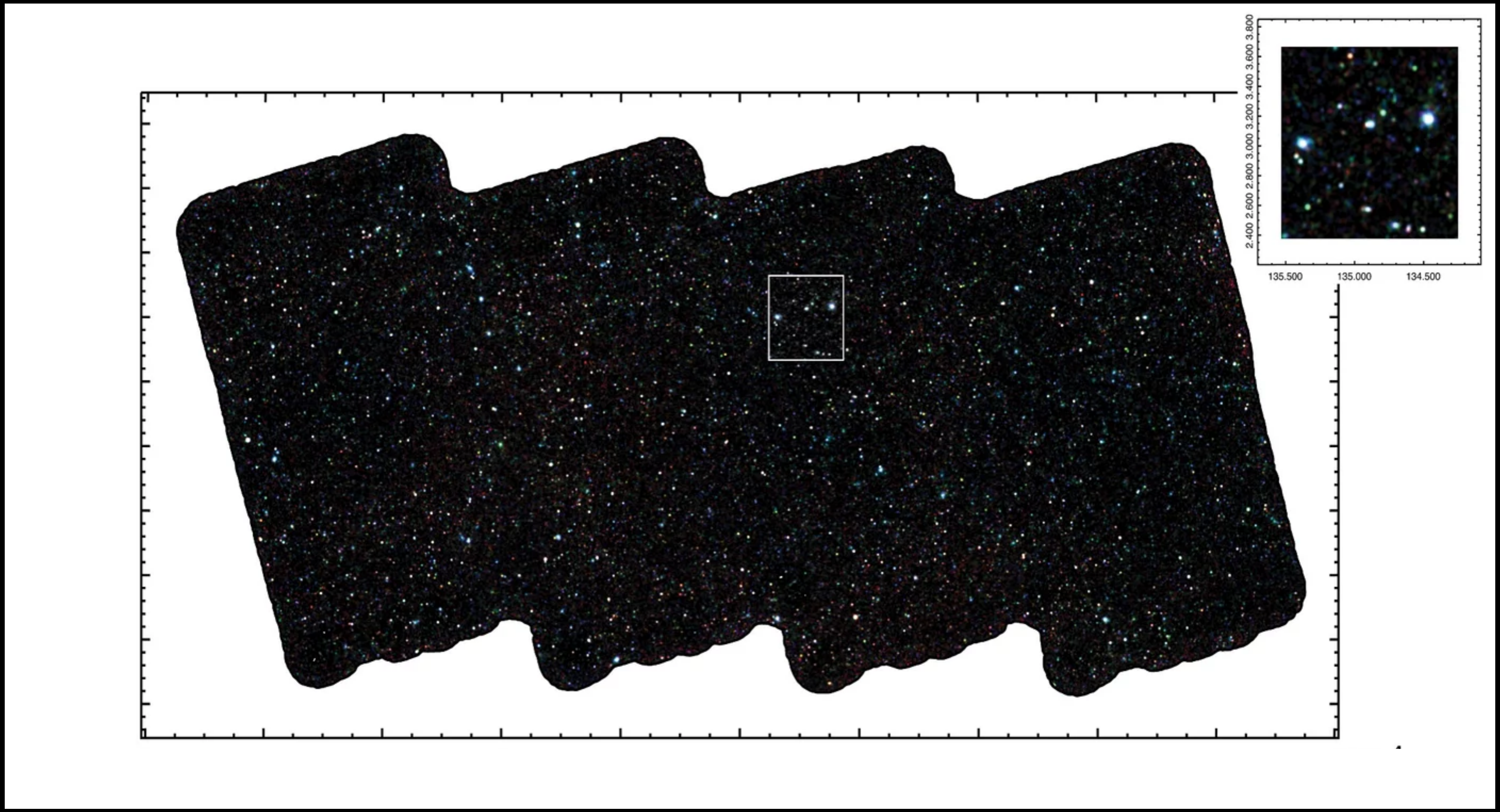
Blazars





S. Hämmerich, A. Gokus, J. Wilms, et al.

eROSITA Final Equatorial-Depth Survey (eFEDS)

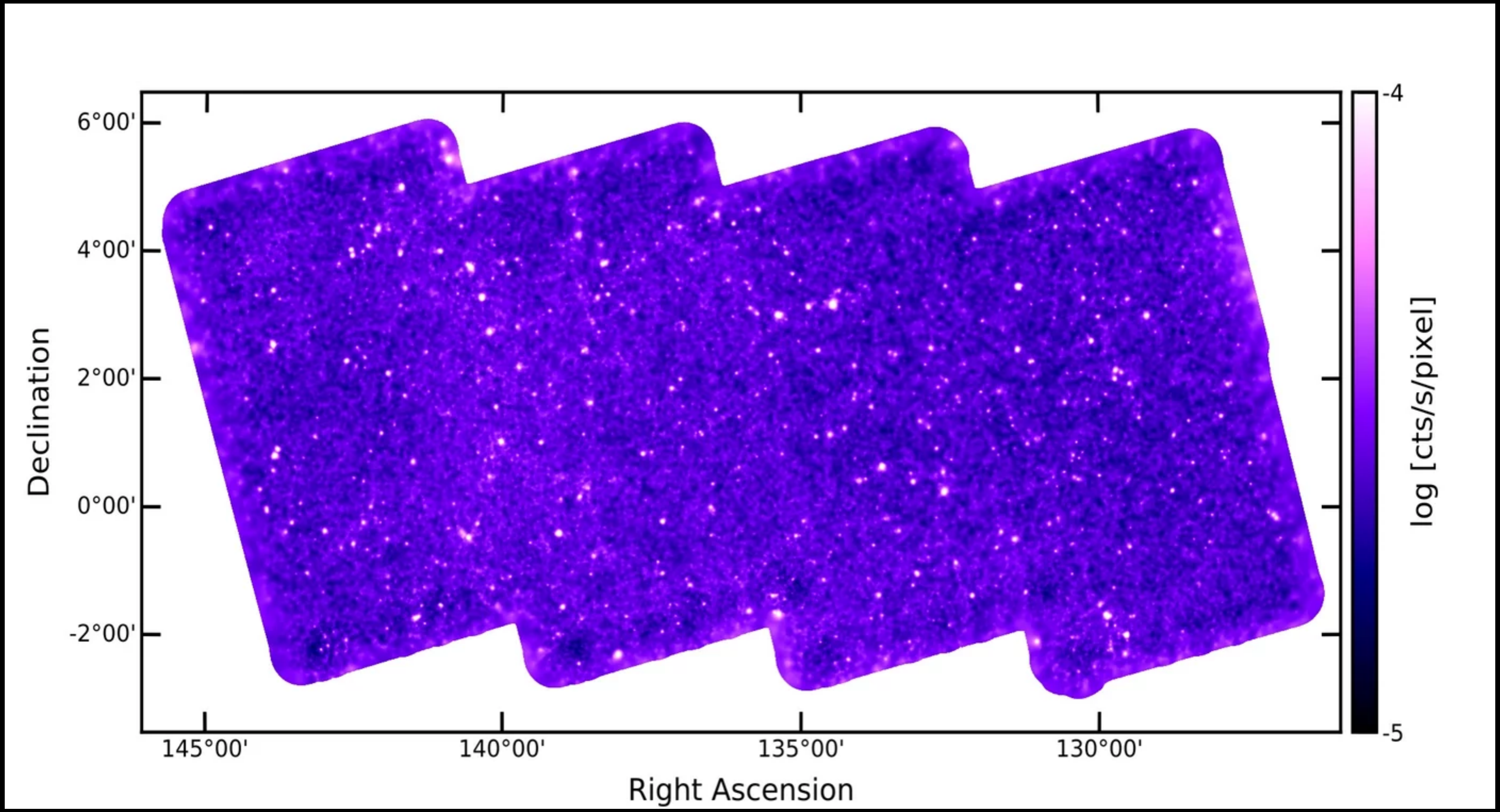


Brunner et al. (2021, A&A, arXiv:2106.14517)

PV-phase, representative for eRASS:8 – 130 □°

- covered w/opt. surveys (HSC, GAMA, DeCALS), radio (LOFAR, GMRT)

eROSITA Final Equatorial-Depth Survey (eFEDS)



Brunner et al. (2021, A&A, arXiv:2106.14517)

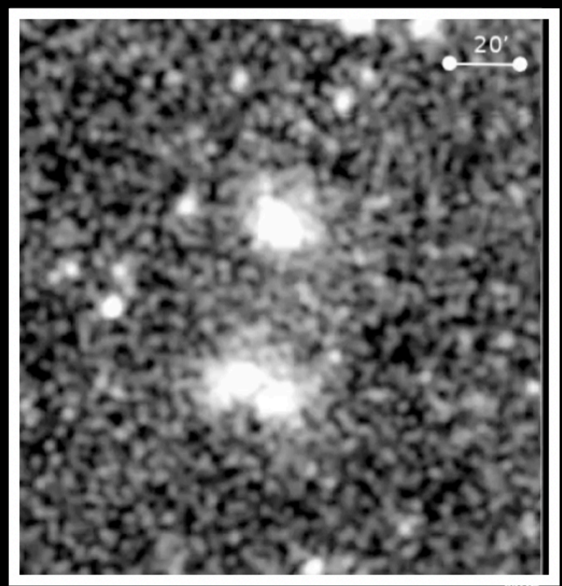
PV-phase, representative for eRASS:8 – 130 □°

- covered w/opt. surveys (HSC, GAMA, DeCALS), radio (LOFAR, GMRT)
- 400 clusters (3 per □°)
- M: $10^{13} \ldots 10^{15}\,M_\odot$, $z \leqslant 1.1$
- spectra: 12 SDSS-IV plates (~11 k spectra)

ROSAT → XMM-Newton → eROSITA →

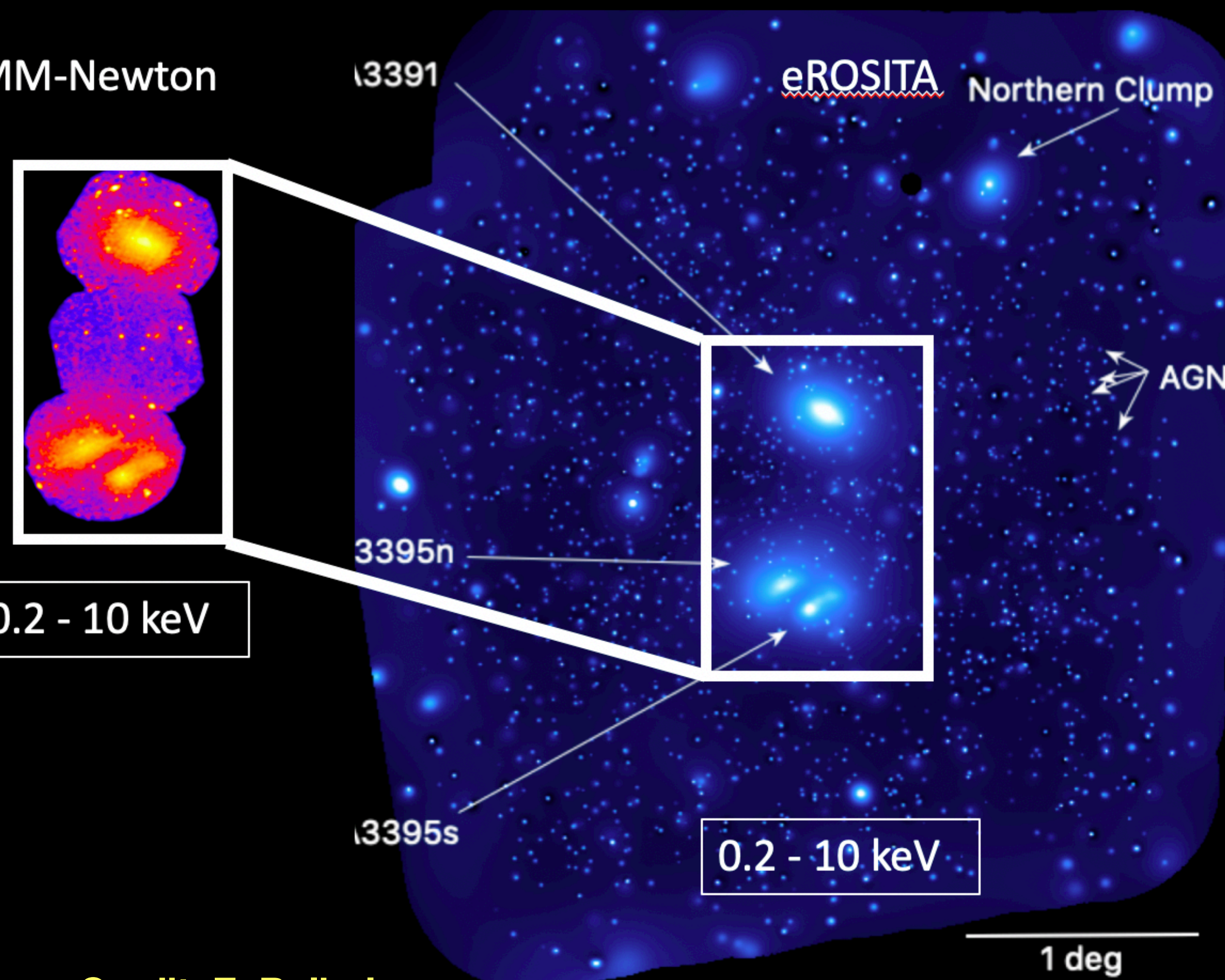
1990 → 2000 → 2019 →

ROSAT



0.2 - 2 keV

XMM-Newton

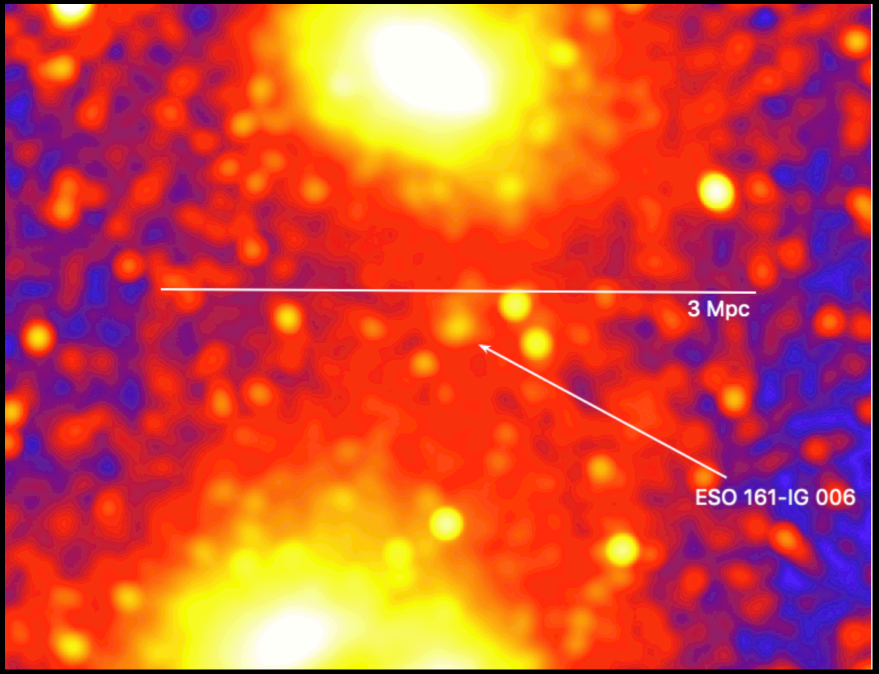


Reiprich et al. 2021, A&A, 647, A2
Brueggen et al. 2021, A&A, 647, A3

Credit: E. Bulbul

The Abell 3391/95 galaxy cluster system

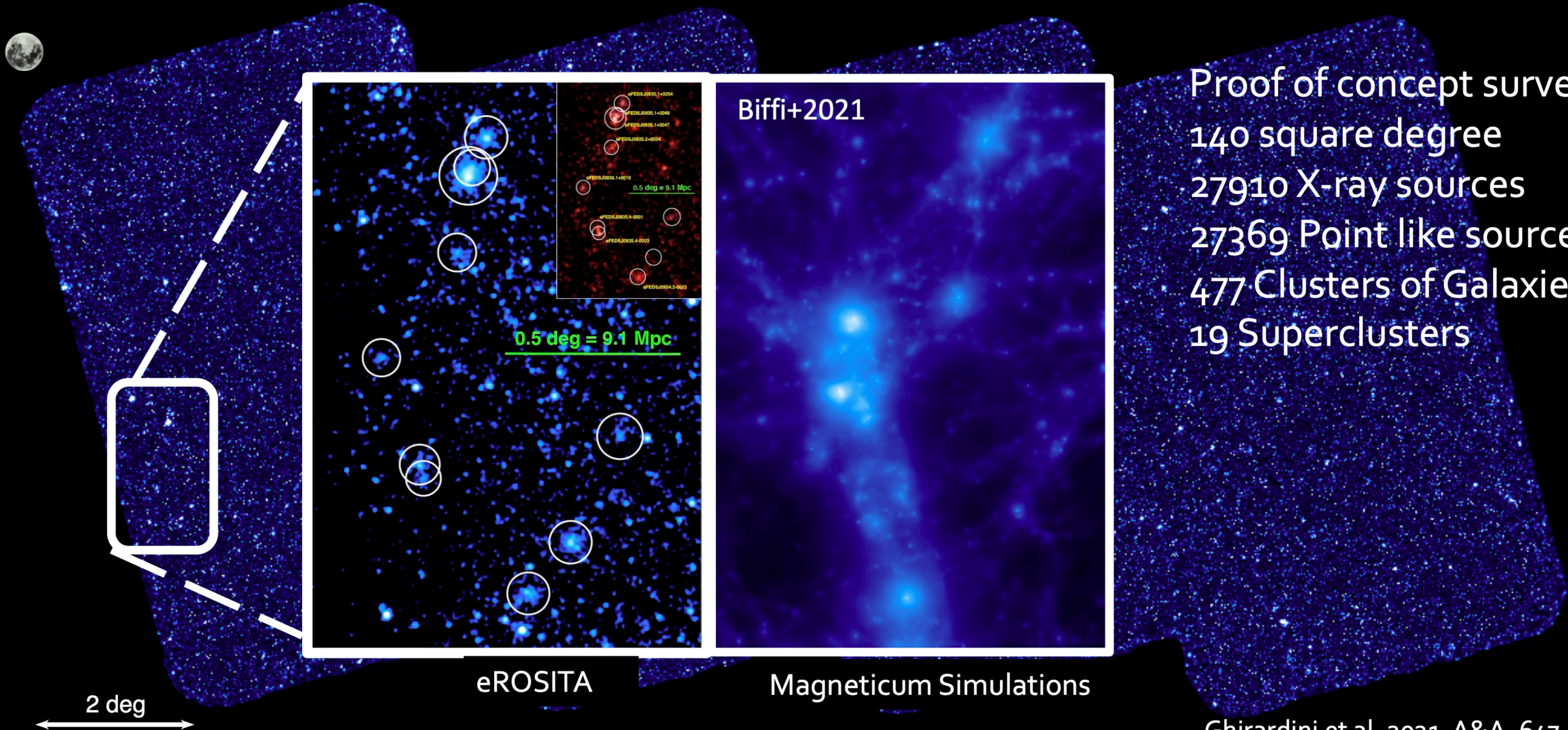
A 15 Mpc intergalactic medium emission filament, a warm gas bridge, infalling matter clumps, and (re-) accelerated plasma discovered by combining SRG/eROSITA data with ASKAP/EMU and DECam data



Reiprich et al 2022,A&A special Issue

eROSITA

Mapping Large Scale Structure with eROSITA



Proof of concept survey
140 square degree
27910 X-ray sources
27369 Point like sources
477 Clusters of Galaxies
19 Superclusters

Ghirardini et al. 2021, A&A, 647, A4

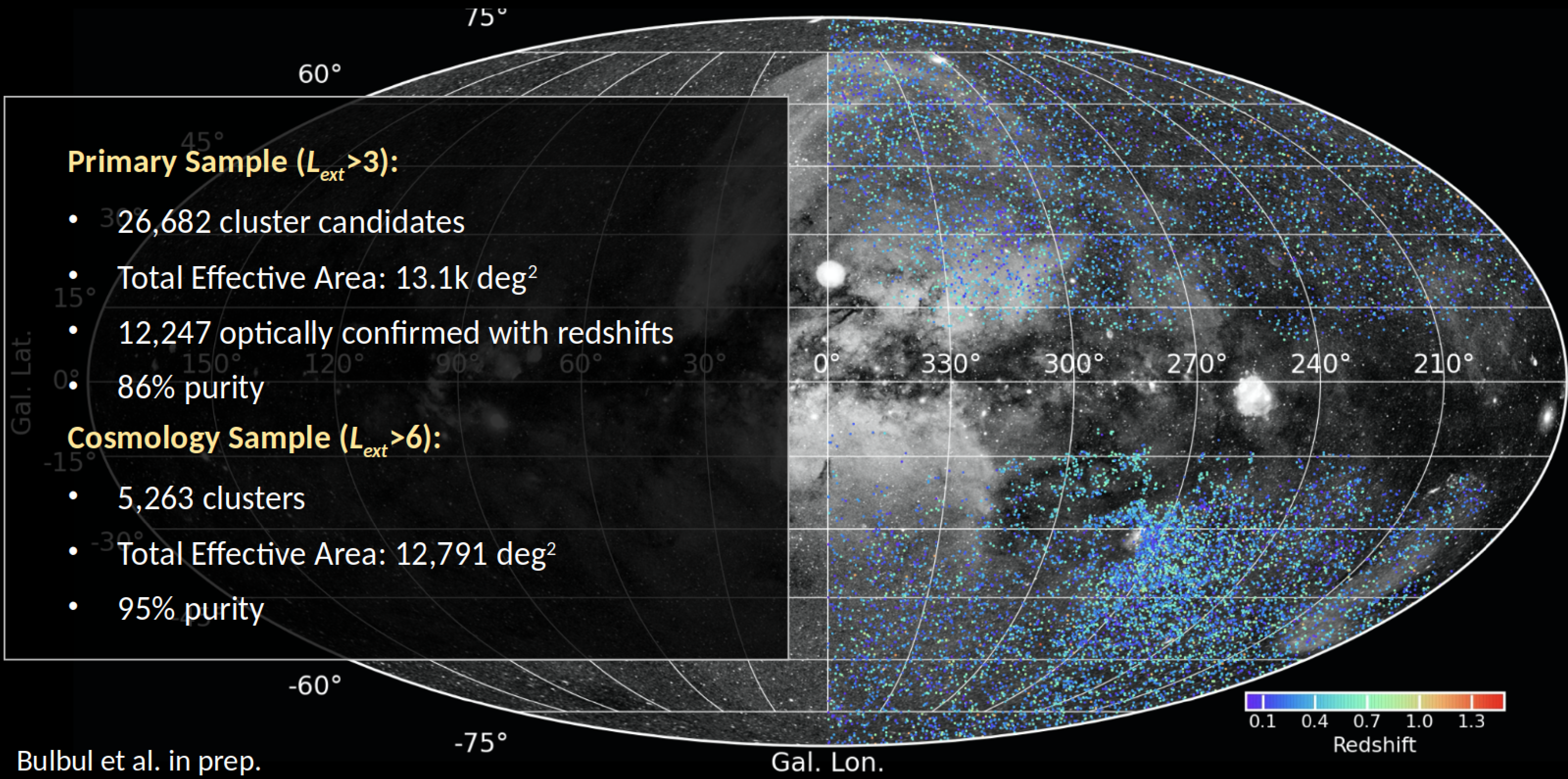
Clusters and Groups from eRASS1

Primary Sample (L_{ext}>3):

- 26,682 cluster candidates
- Total Effective Area: 13.1k deg^2
- 12,247 optically confirmed with redshifts
- 86% purity

Cosmology Sample (L_{ext}>6):

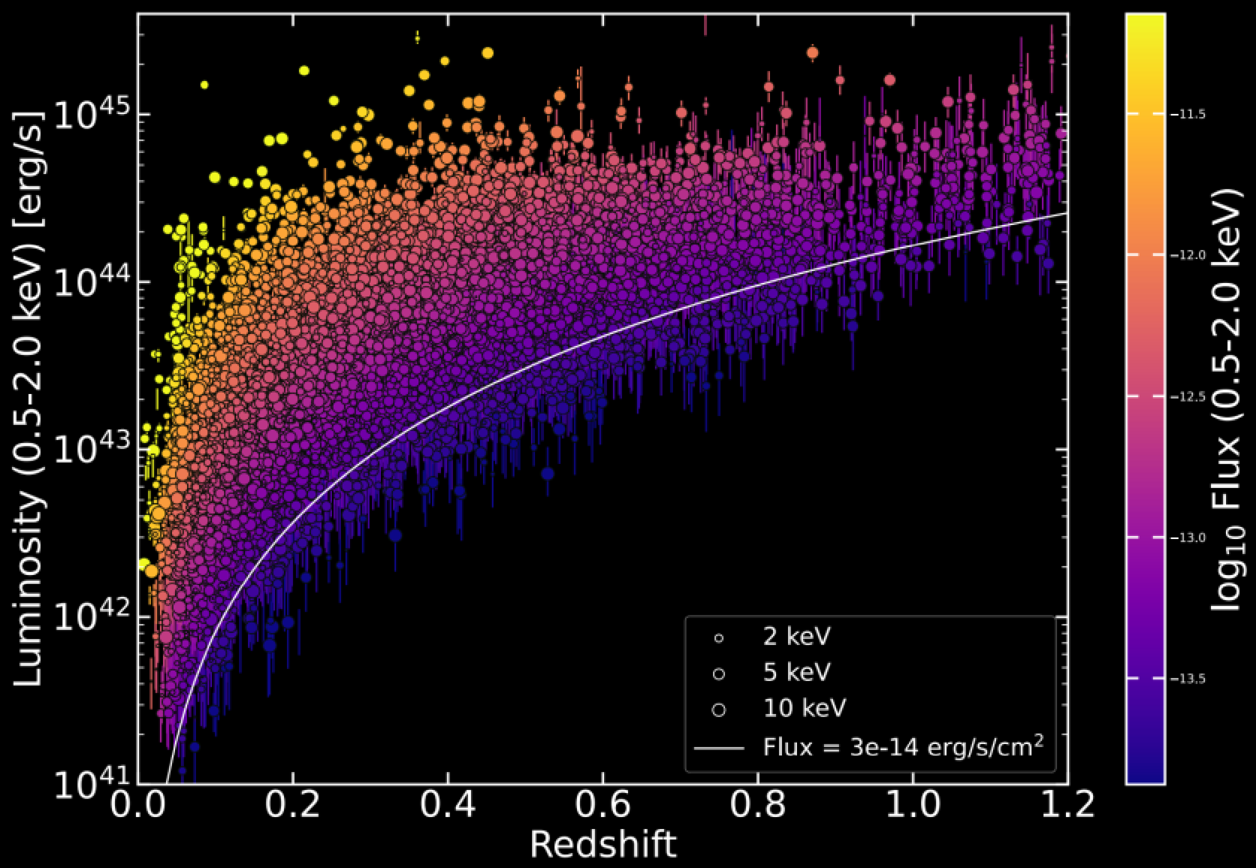
- 5,263 clusters
- Total Effective Area: 12,791 deg^2
- 95% purity

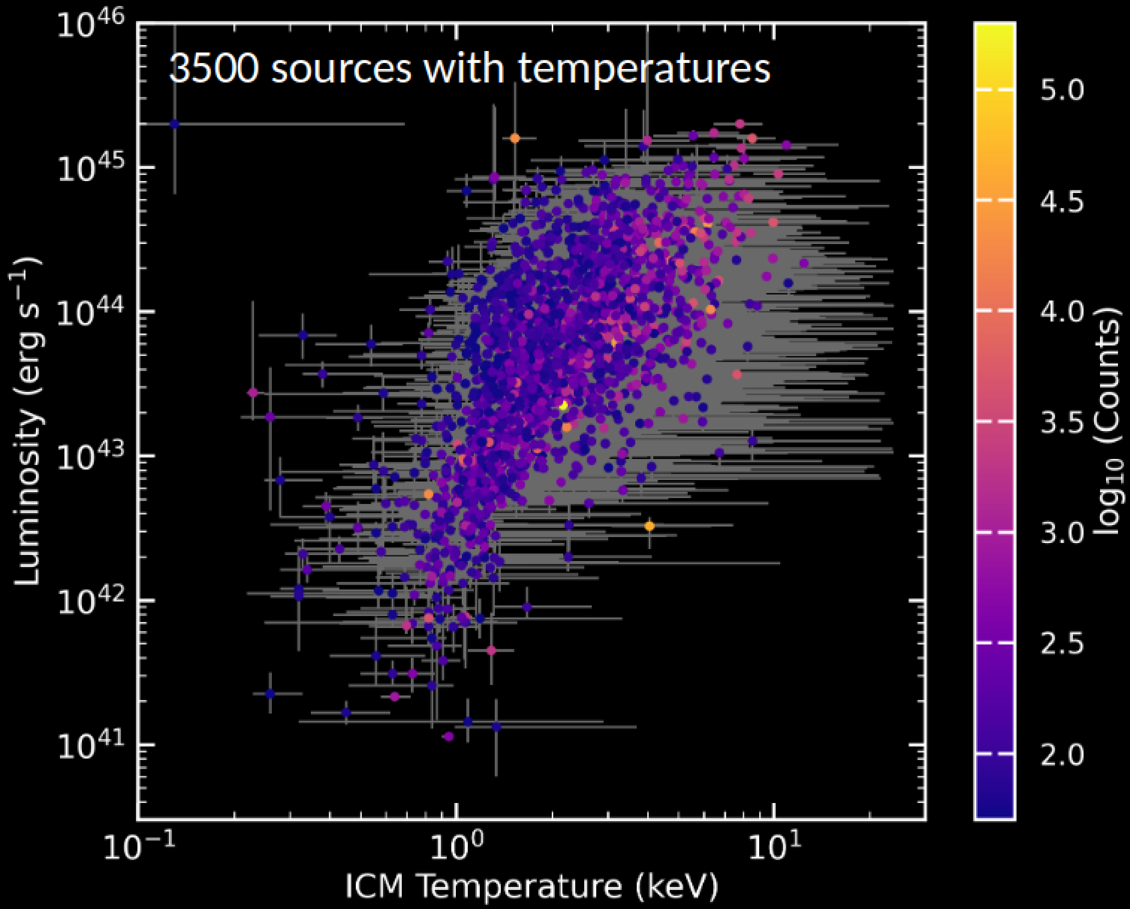


Bulbul et al. in prep.

eRASS1 cluster sample

Clusters are confirmed in optical waveband using Legacy DR9-10 surveys
Self-consistent fitting of cluster X-ray profiles with MBProj2D to obtain luminosity and temperature

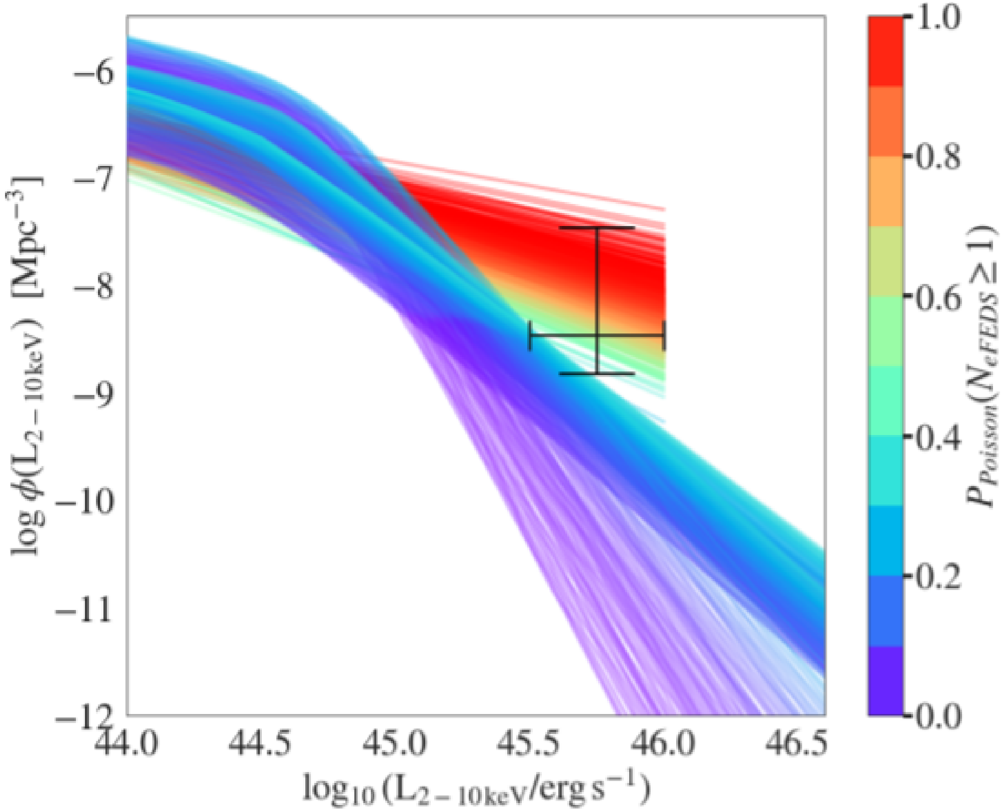


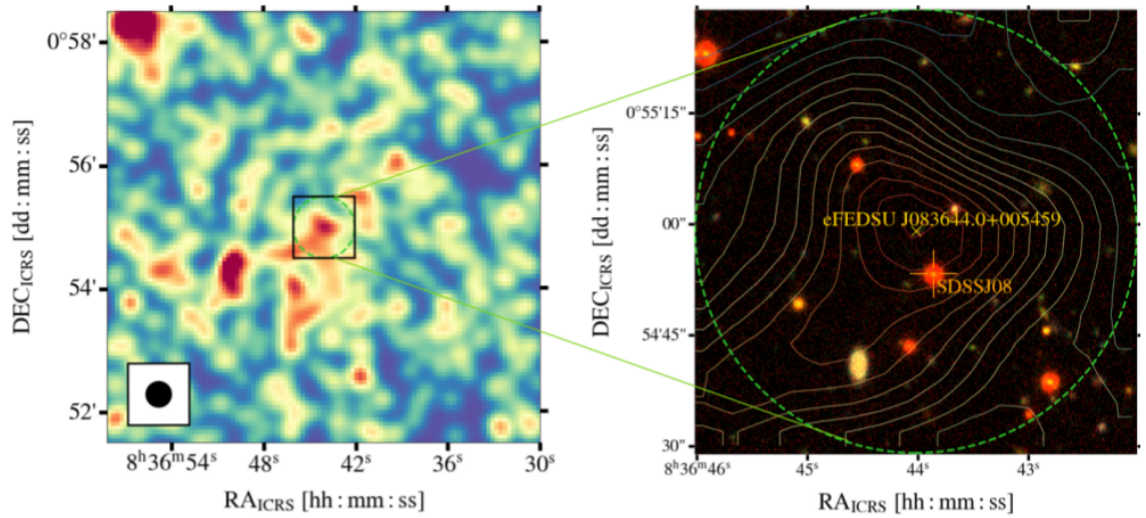


A. Liu, J. Sanders X. Zhang, M. Kluge, E. Bulbul (MPE)

Bulbul et al. in prep

High z AGN





eFEDS: 1 source w/$z = 5.81$

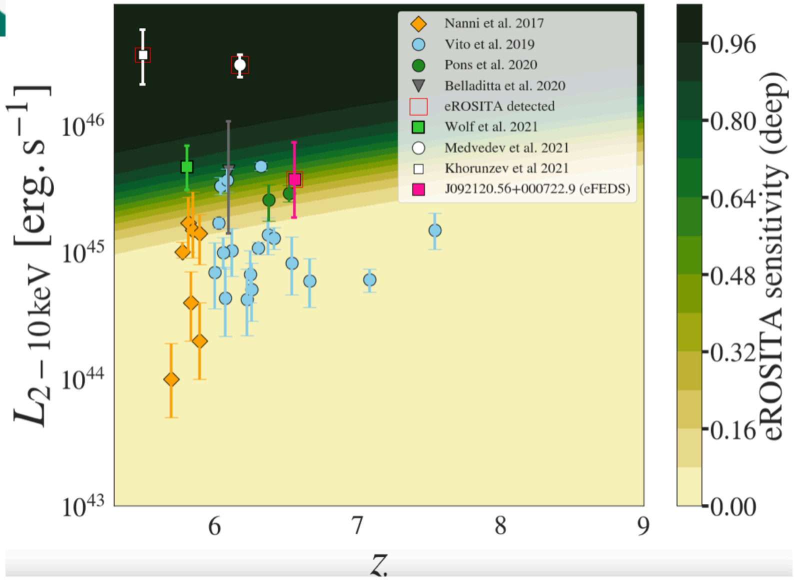
SDSS J083643.85+005453.3

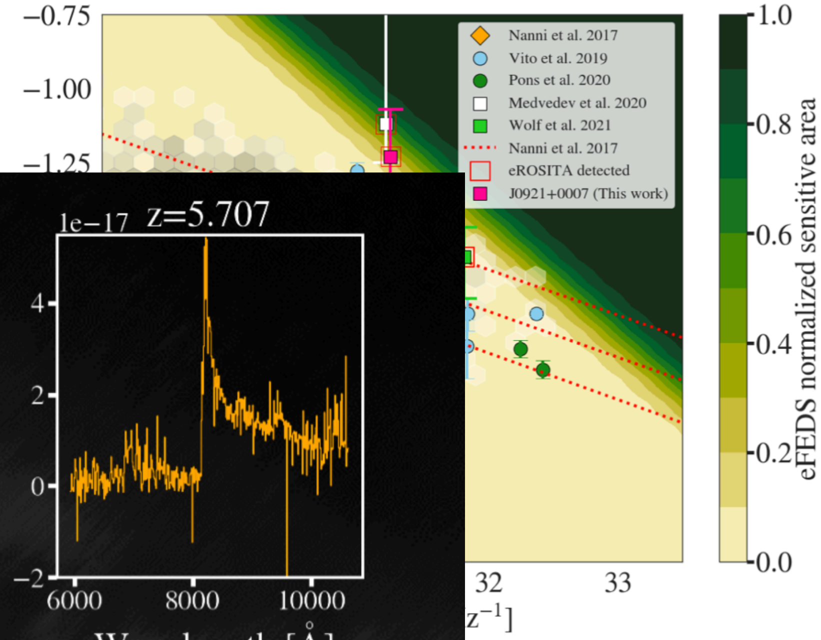
Already constrained models for black hole evolution

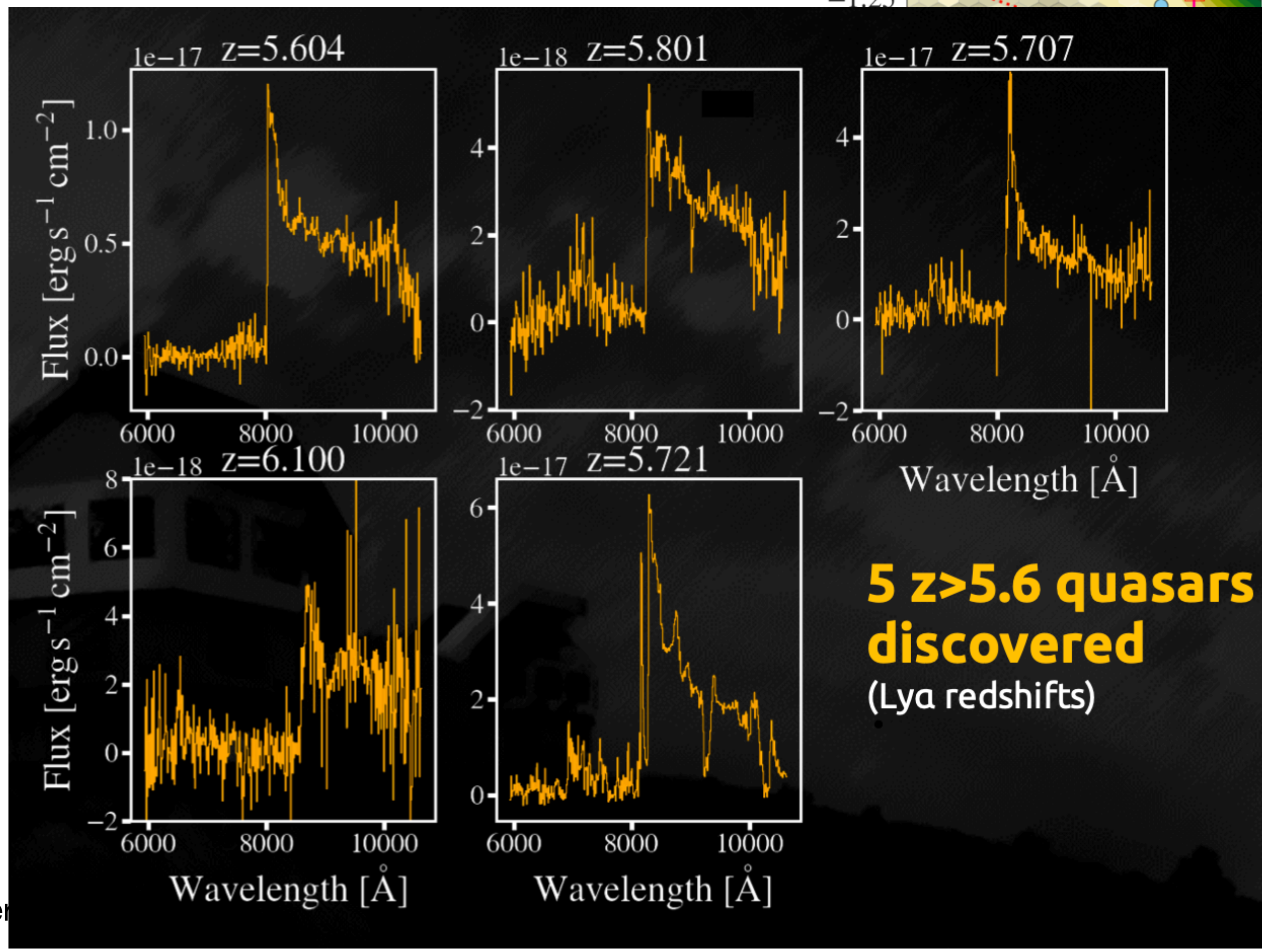
Wolff et al. (2021, 647, A5)

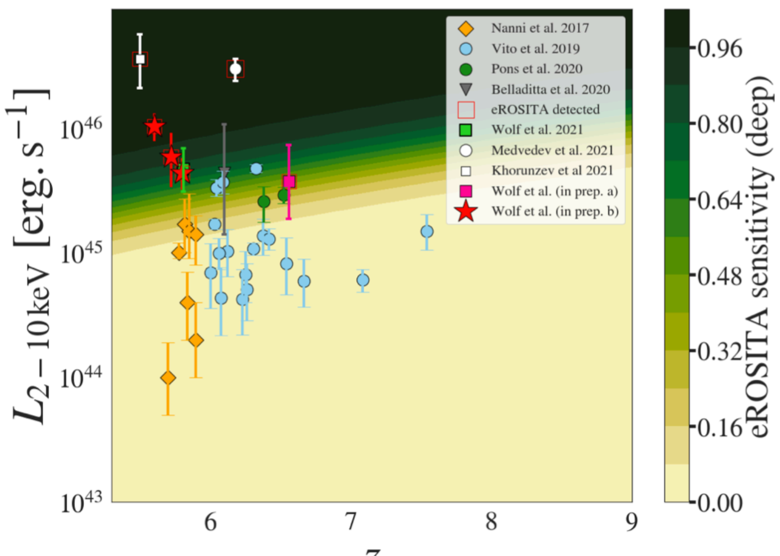
Uncovering the X-ray luminous z>5.5 quasar population

Wolf et al 2022a A&A special Issue
Wolf et al 2022b
Wolf et al, in prep









e luminosity function.

M. 022

Summary

eROSITA is already revolutionizing our knowledge of the x-ray sky

- 4.4 surveys done
- In safe mode since March 2022 due to Russian attack on Ukraine

  if data taking will resume is unclear

- Scientific areas:
  - galaxy clusters
  - evolution of Black Holes
  - Black Hole and Neutron Star Binaries in our Galaxy
  - Supernova remnants
  - variable sources
  - stars

  Release of first eRASS in next few months