

Exploring Supernova Remnants with eROSITA in a Multiwavelength Universe

Werner Becker

Max-Planck-Institut für extraterrestrische Physik, Garching
Max-Planck-Institut für Radioastronomie, Bonn
Ludwig-Maximilians Universität, München

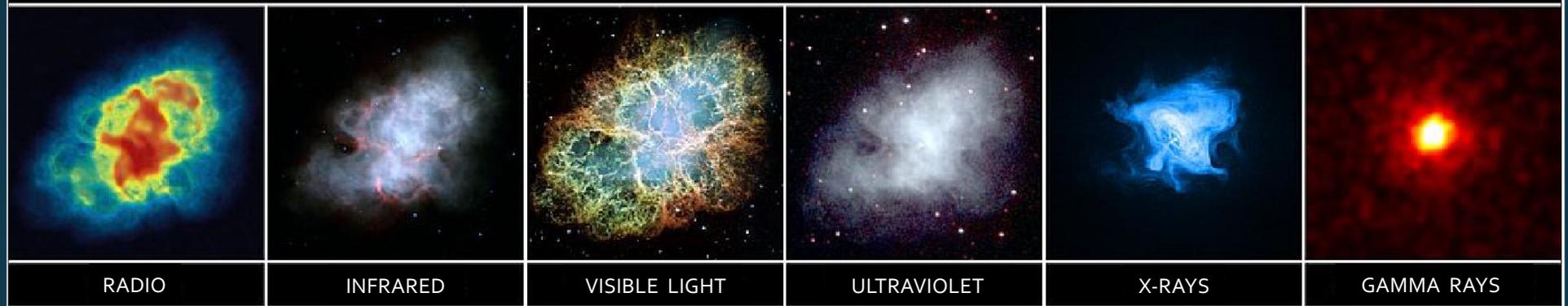


Outline:

- The eROSITA X-ray Observatory
 - Synergies with other observatories
 - Motivations, mission design & instrumentation, status
- Why are we studying X-ray emission from SNRs
- The missing SNR problem
- New SNRs in the eROSITA all-sky survey, e.g., Hoinga, G321.3-3.9
- Studying large nearby SNRs with eROSITA

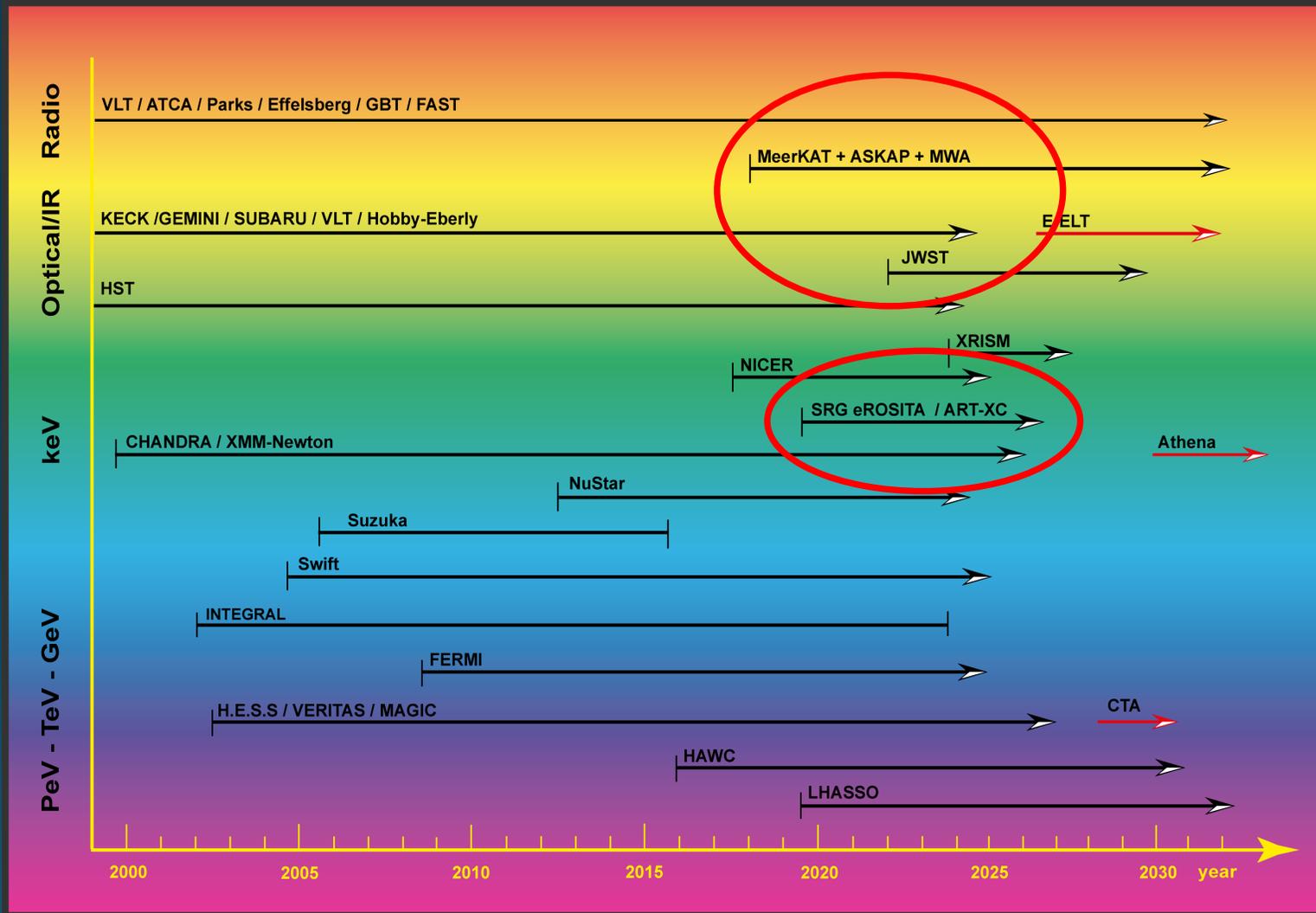
X-ray astronomy by default is multi-wavelength astronomy

For a complete understanding of SNR physics, observations at all wavebands are essential



SNR research, a truly multi-wavelength business

Current and Future Observatories



The Way to eROSITA

Spectrum-XG

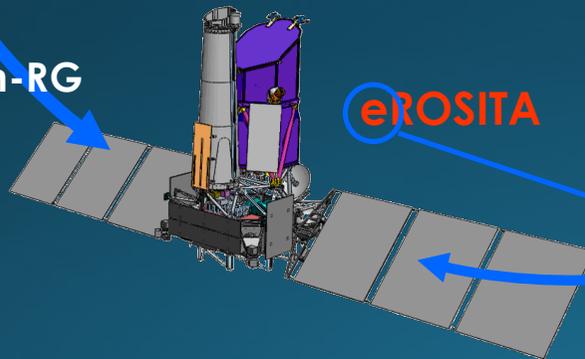
Jet-X, SODART, etc



Negotiations between Roskosmos and ESA
on a "new" Spectrum-XG mission (2005)

Agreement between Roskosmos and DLR (2007)

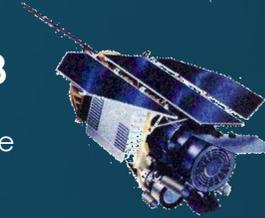
Spectrum-RG



extended **RO**entgen **S**urvey with an
Imaging **T**elescope **A**rray

ROSAT 1990-1998

First X-ray all-sky survey
with an imaging telescope



ABRIXAS 1999

To extend the all-sky survey
towards higher energies



ROSITA 2002

ABRIXAS science on the
International Space Station

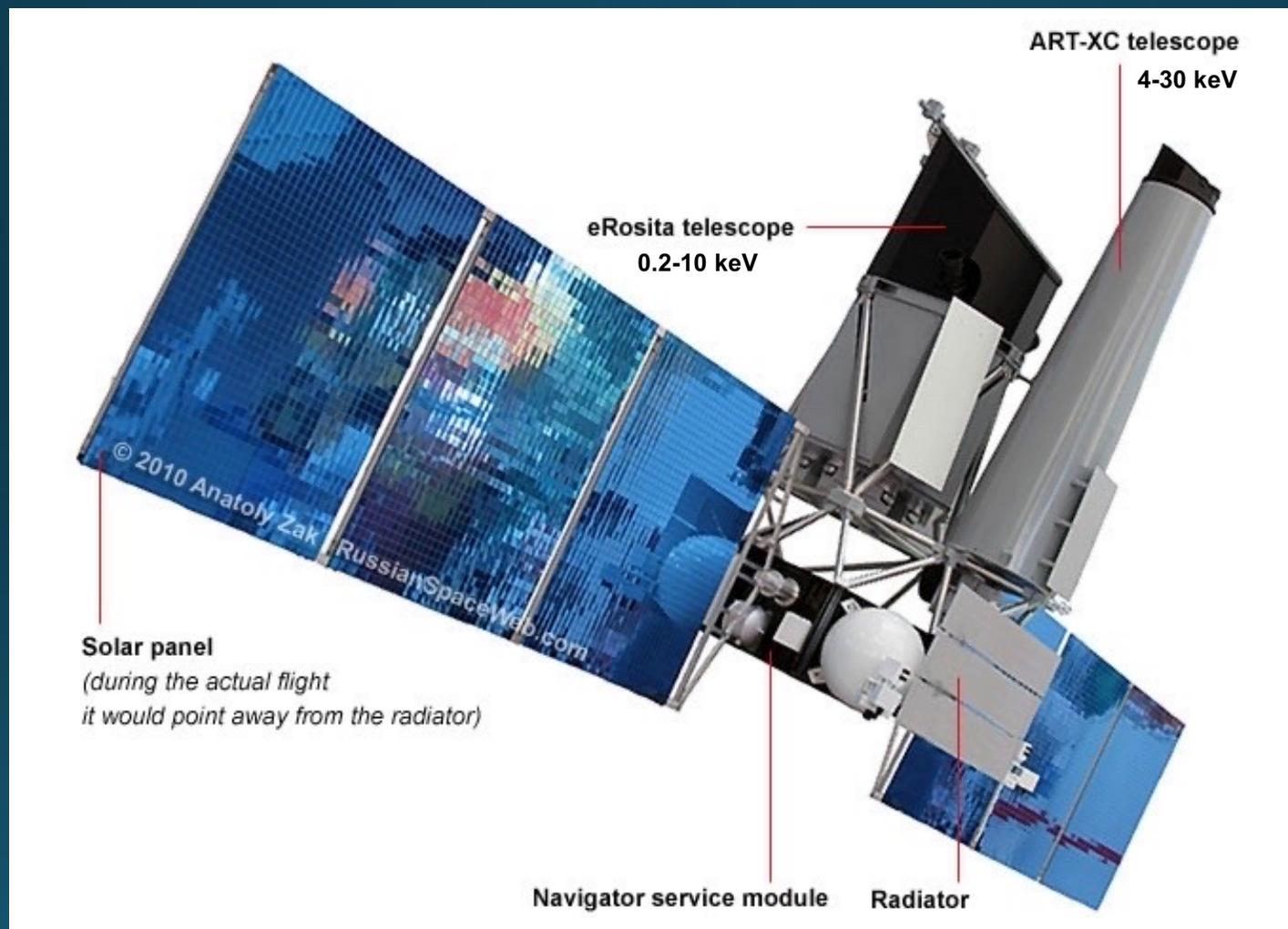


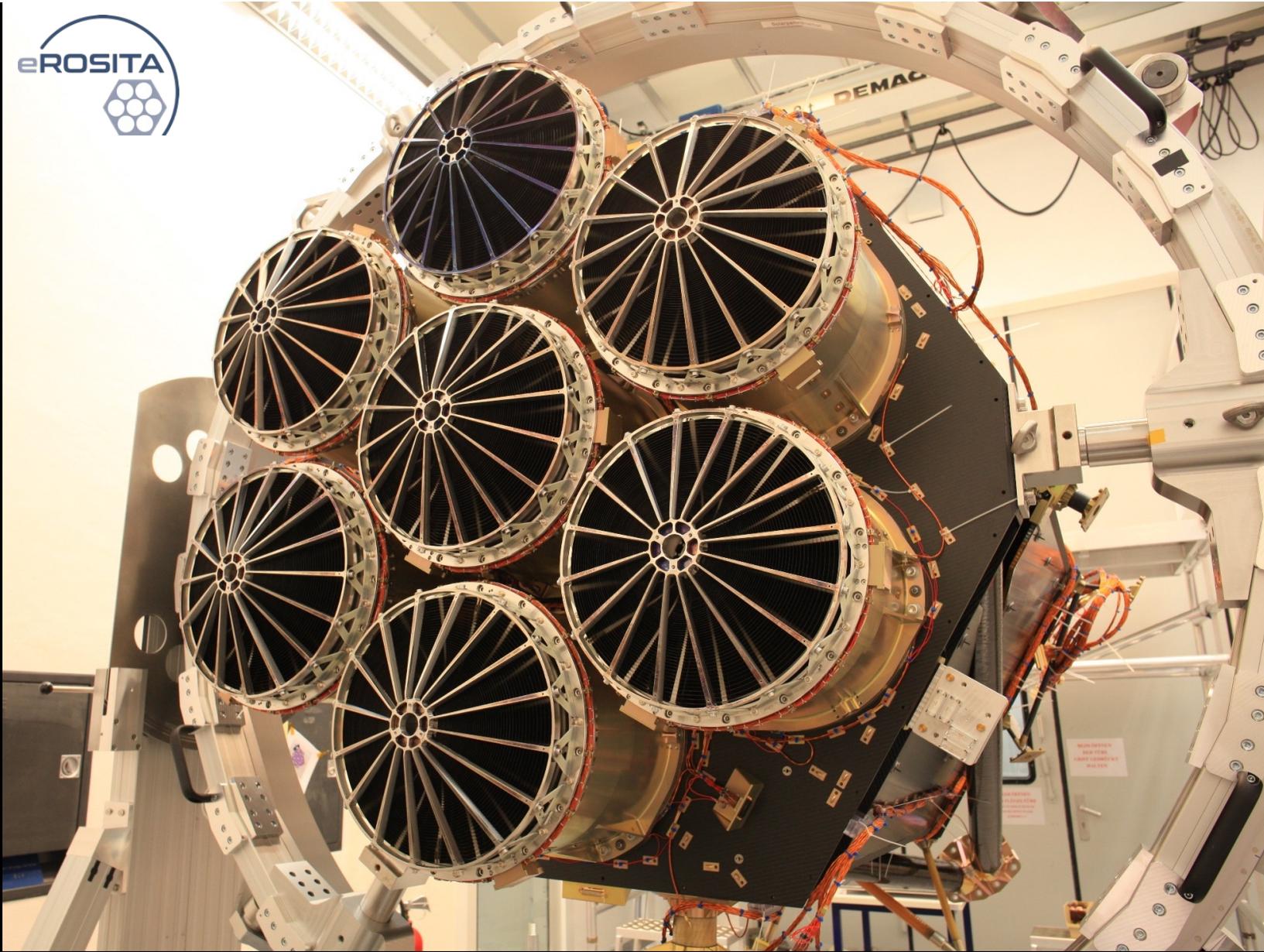
Dark Energy

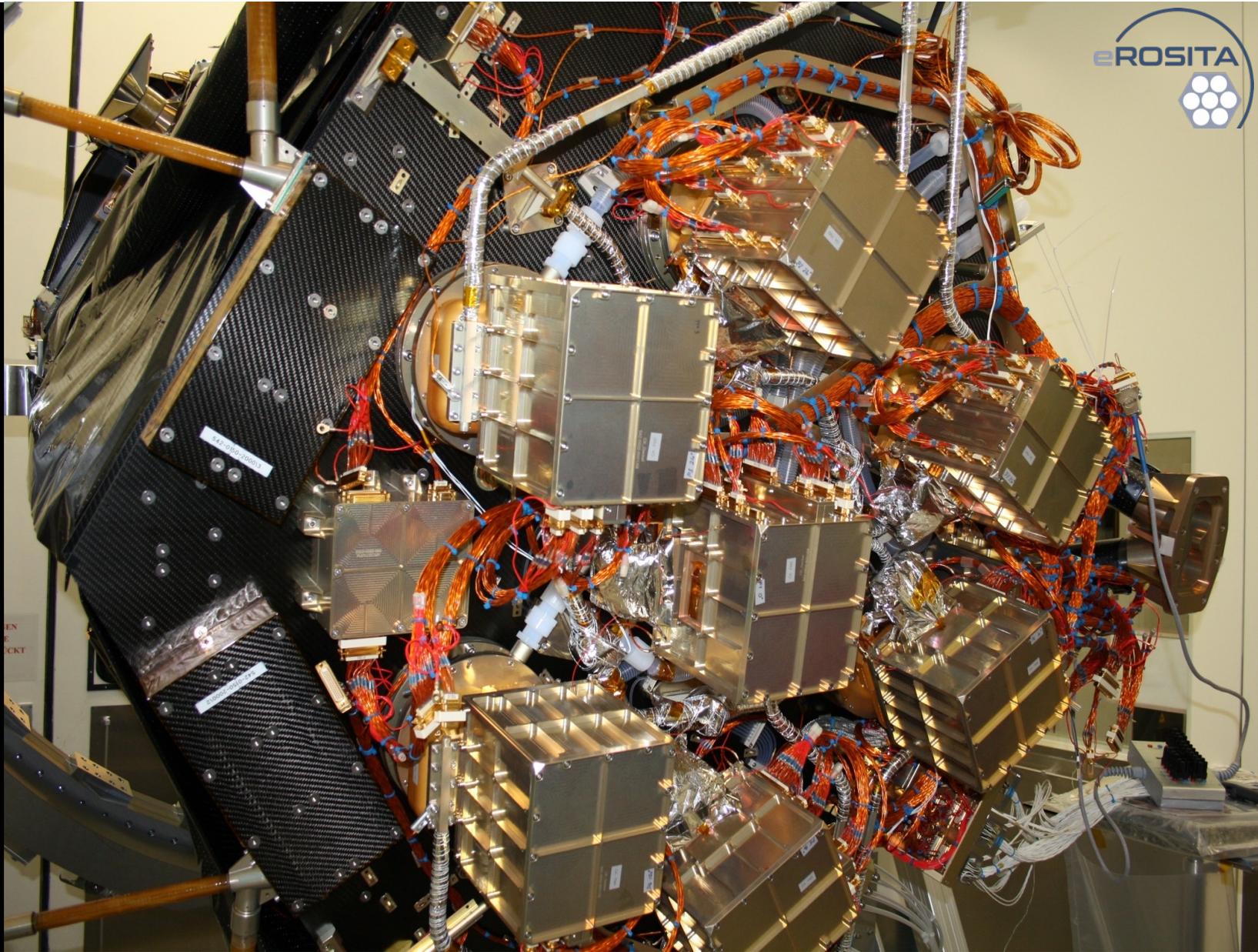
10^5 Clusters of Galaxies

eROSITA

eROSITA: Main instrument on Spectrum-Röntgen-Gamma







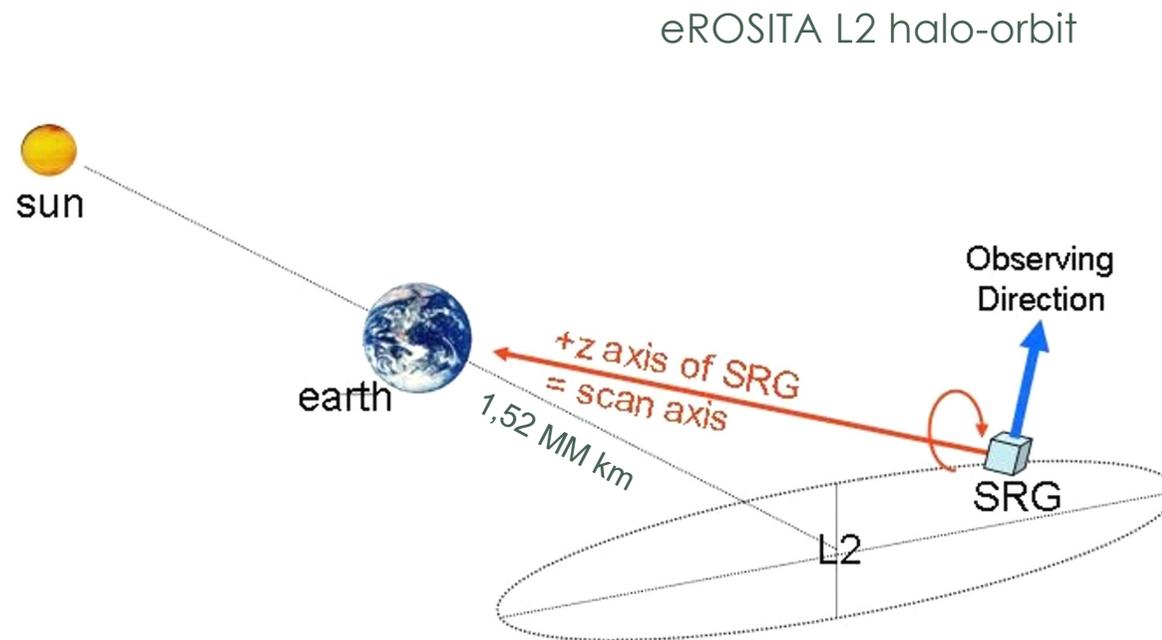


13th July 2019, 17:31

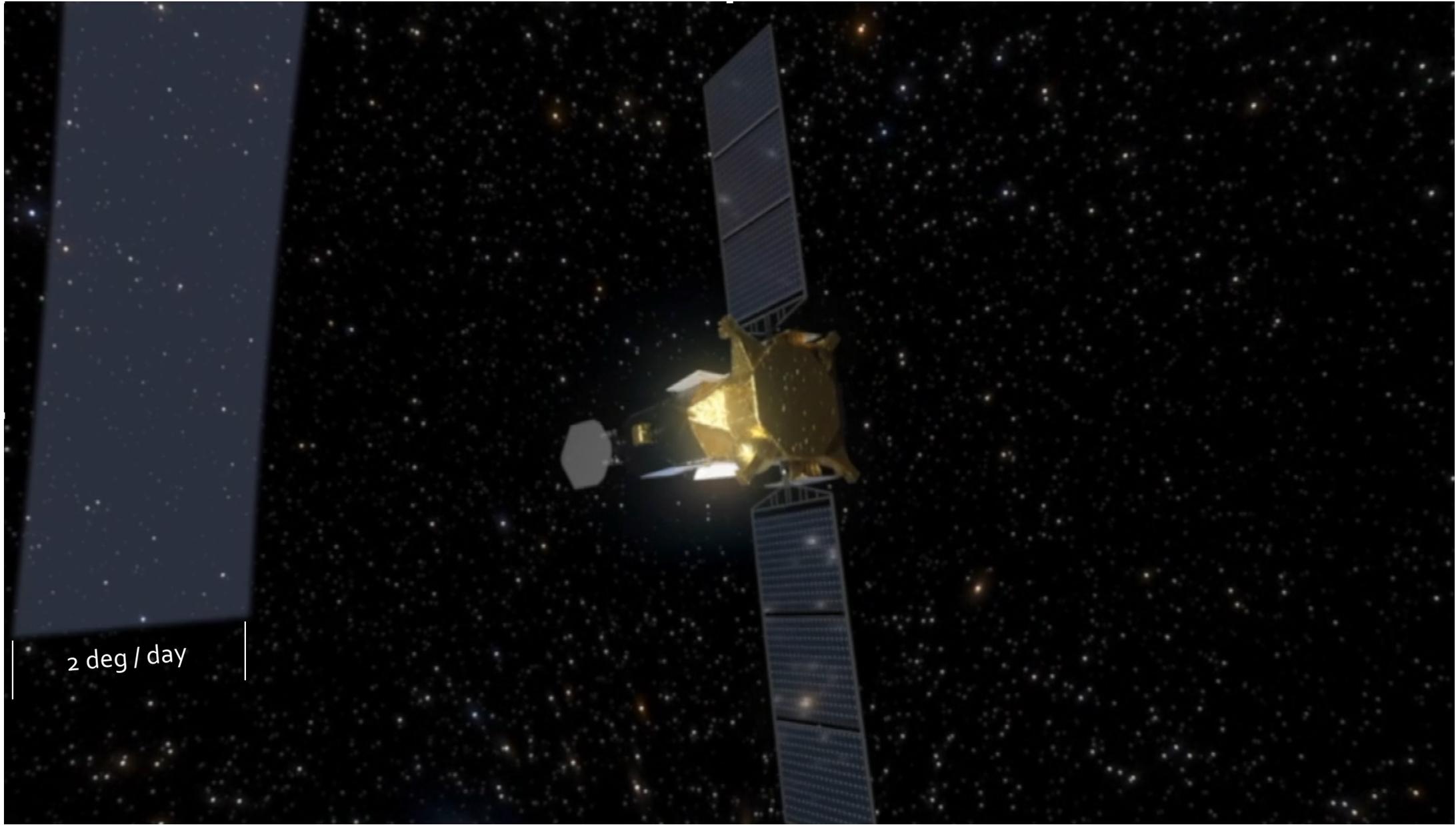


credit: Roscosmos

eROSITA: Mission geometry during the all-sky survey



SRG is continuously rotating around the z-axis, which always points to the Earth
Survey: ~ 4 hr/revolution, 6 scans per day, 2 deg/day $\rightarrow 360^\circ$ in 180 days



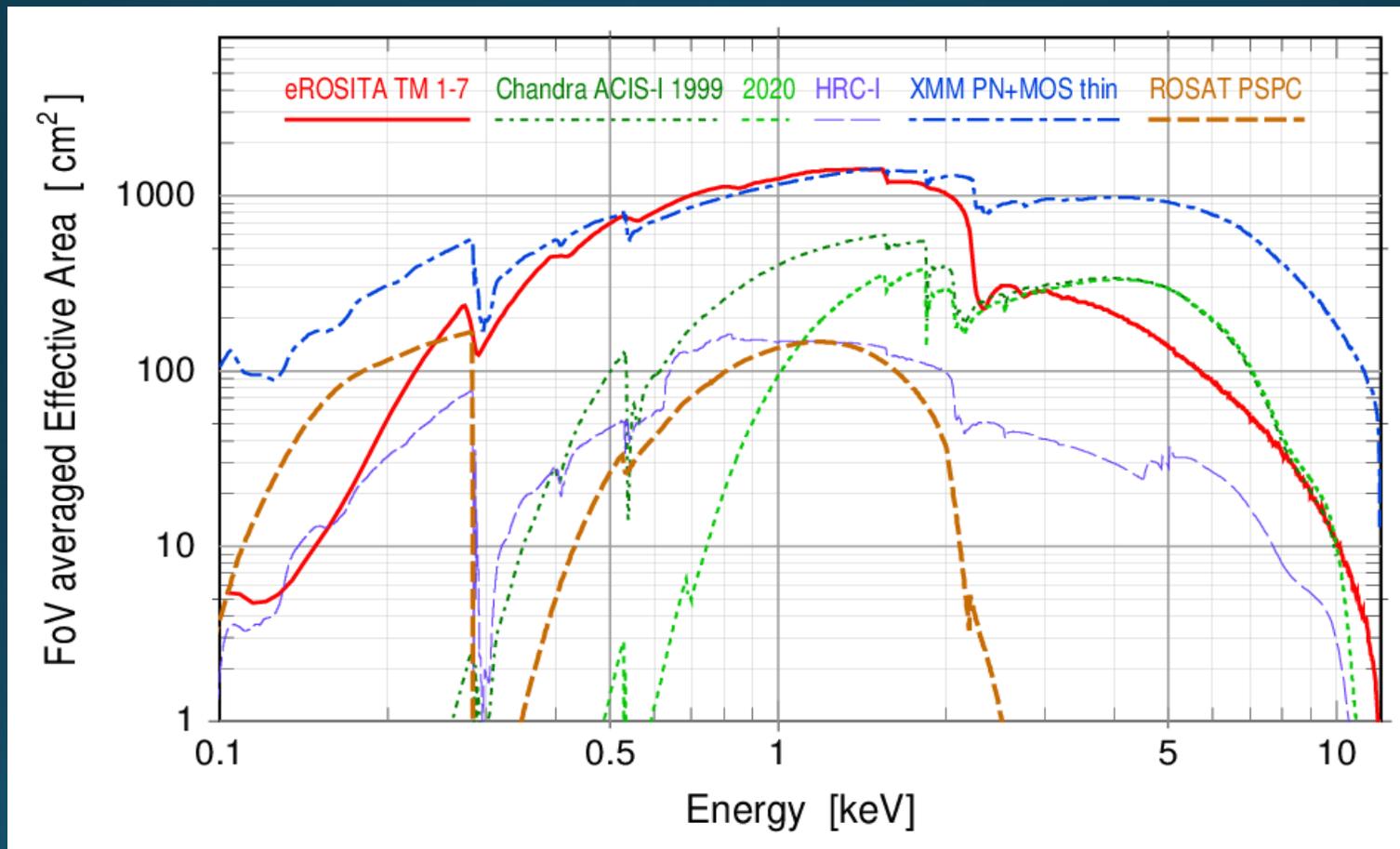
2 deg / day

Instrument specification & “planed” mission scenario

- Energy range ~ 0.2 - 10 keV
- FOV: 1 degree
- Temporal resolution ~ 50 ms
- Angular resolution ~ 26" in survey mode (15" in pointed mode)
- Energy resolution ~ 130 eV @ 6 keV / 80 eV @ 1.5 keV
- All-sky survey sensitivity ~ 6×10^{-14} erg cm⁻² s⁻¹ (about 4-5 x ROSAT by now)

- Launched in June 2019
- 3-month calibration & science verification phase
- eRASS1 started 15. Dec. 2019
- meanwhile, 4 1/3 all-sky surveys were completed -- **but in save mode since Feb 2022**

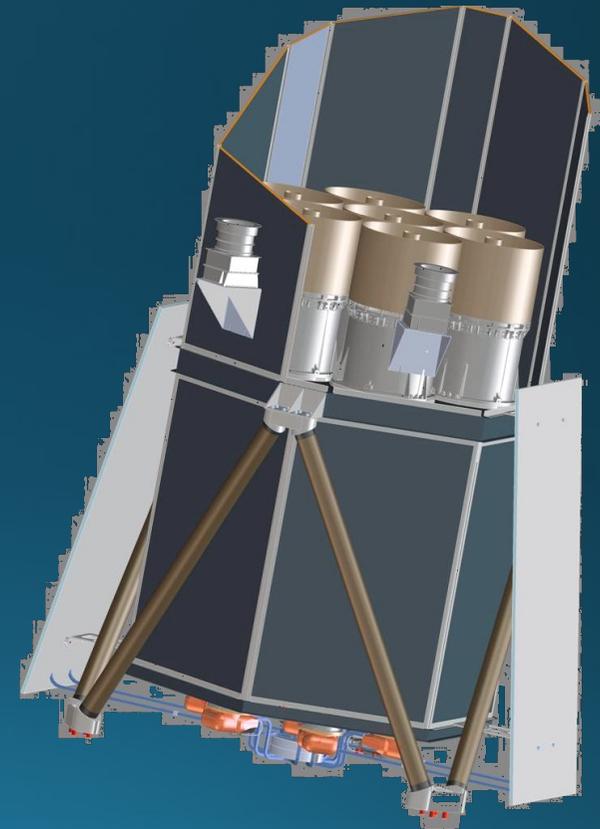
eROSITA's effective area $\sim 1300 \text{ cm}^2$ (FoV avg. @1keV)



Collecting power at 1 keV comparable with XMM-Newton

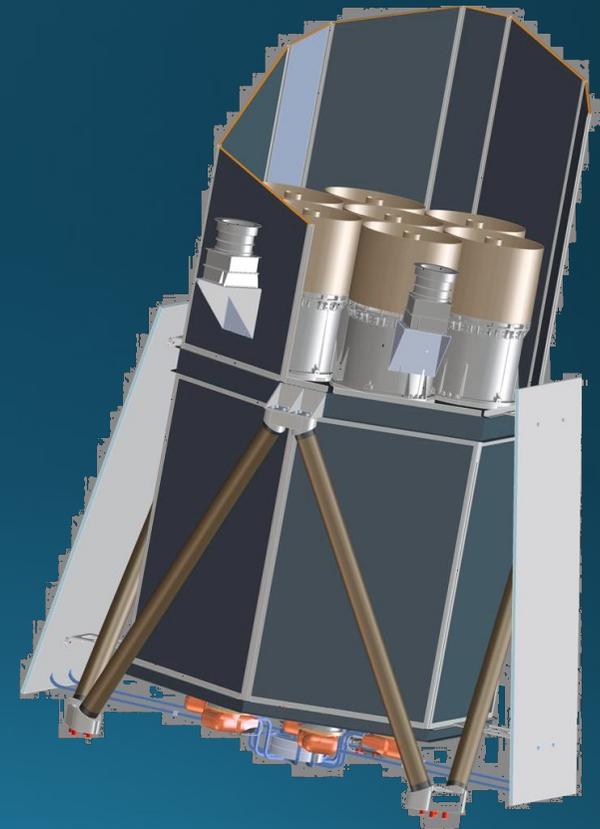
eROSITA: Science Goals

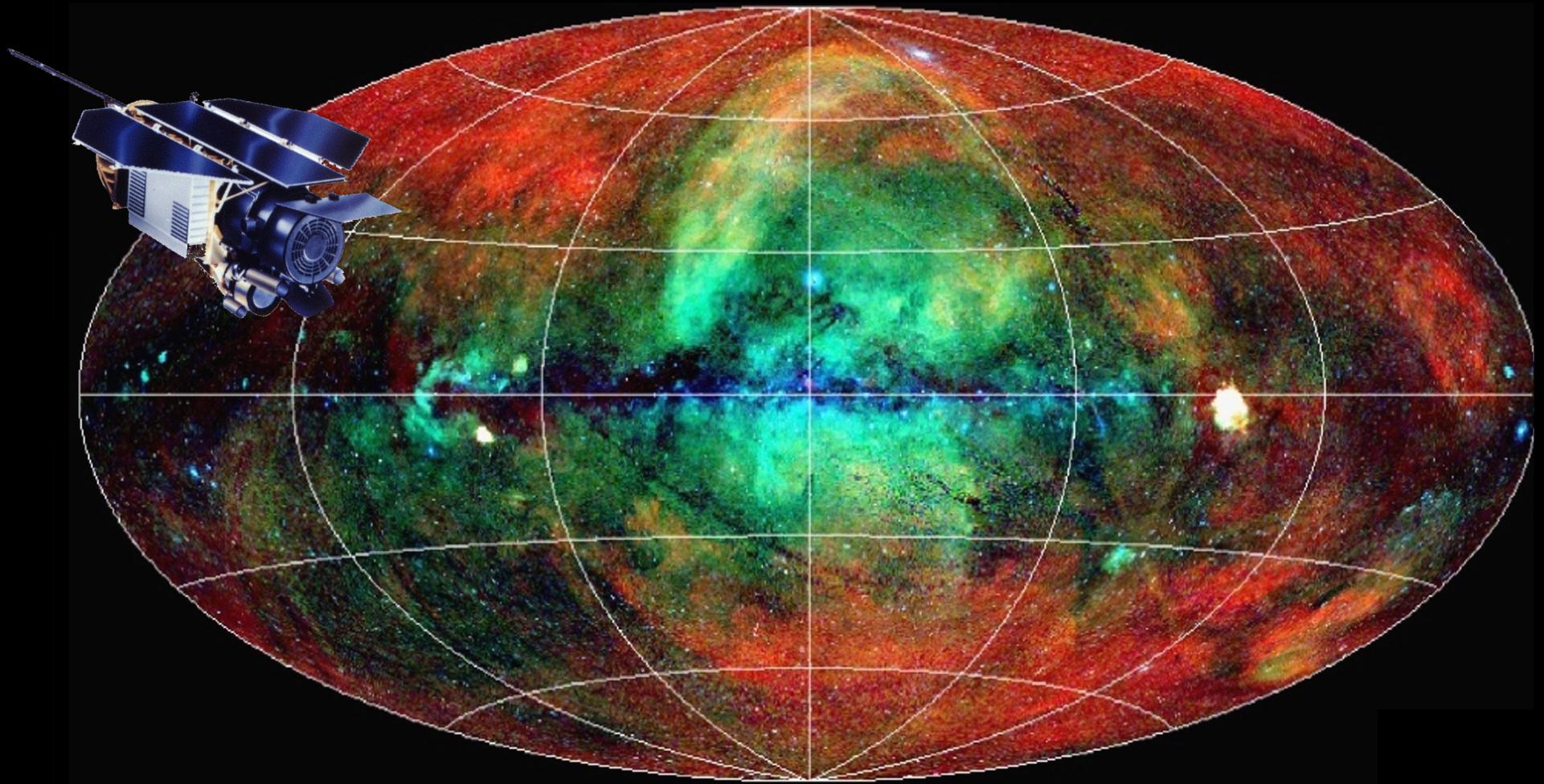
- ❖ Detection of 100.000 clusters of galaxies
→ exploring the nature of dark energy
 - ❖ Detection of ~3 Mill. AGN, many of them
hiding behind obscuring gas and dust clouds
 - ❖ + Relevance for lots of other galactic
scientific topics like SNRs, PSR, PWNe, stars, ...
- eROSITA, quasi-unlimited FOV in survey mode



eROSITA: Science Goals

- ❖ Detection of 100.000 clusters of galaxies
→ exploring the nature of dark energy
- ❖ Detection of ~3 Mill. AGN, many of them
hiding behind obscuring gas and dust clouds
- ❖ + Relevance for lots of other galactic
scientific topics like SNRs, PSR, PWNe, stars, ...
- eROSITA, quasi-unlimited FOV in survey mode
- best suited to study diffuse X-ray emission from
large and low surface brightness objects, e.g.,
faint and large supernova remnants





ROSAT All-Sky Survey 1990/91

SRG/eROSITA

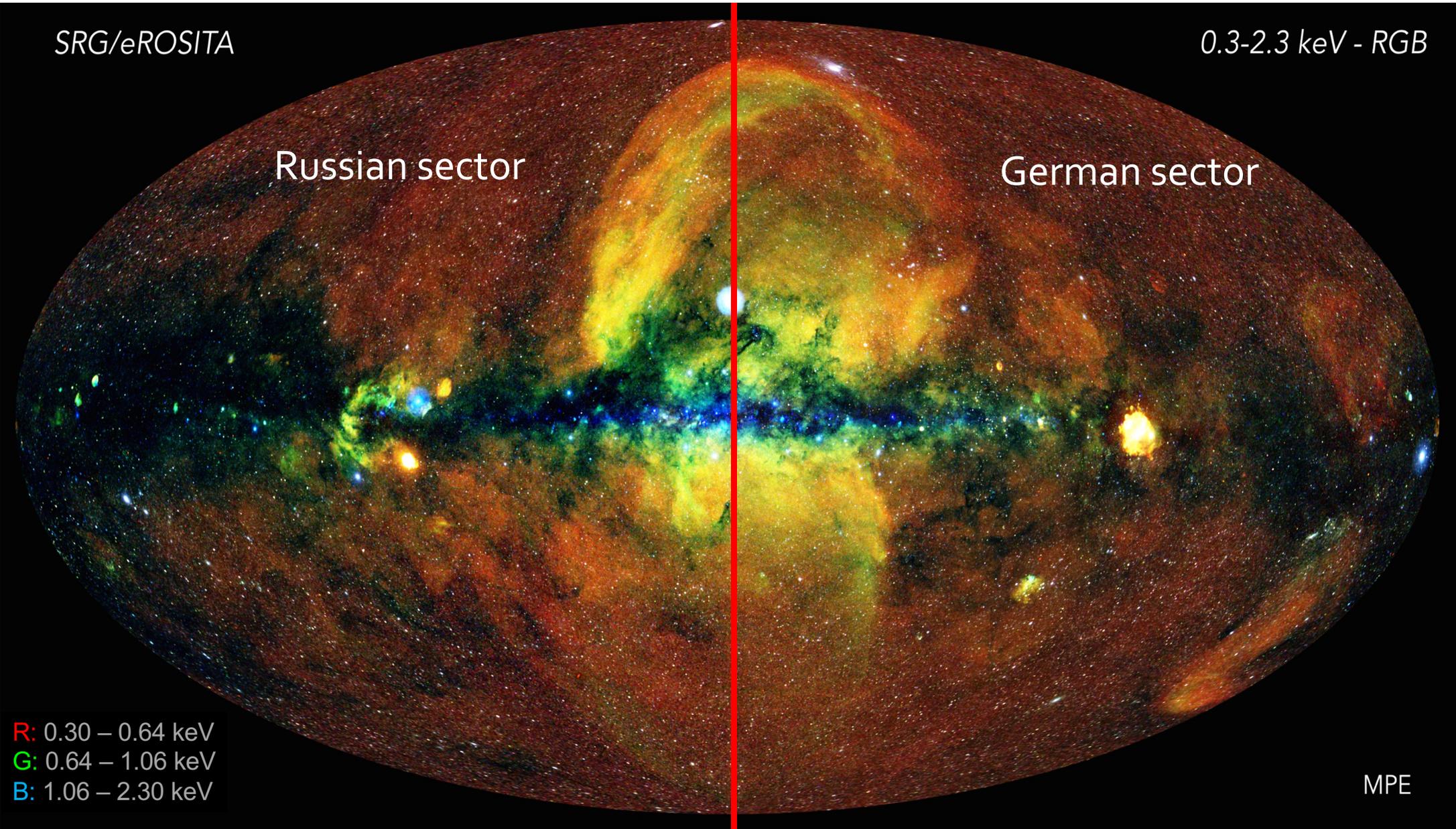
0.3-2.3 keV - RGB

Russian sector

German sector

R: 0.30 – 0.64 keV
G: 0.64 – 1.06 keV
B: 1.06 – 2.30 keV

MPE

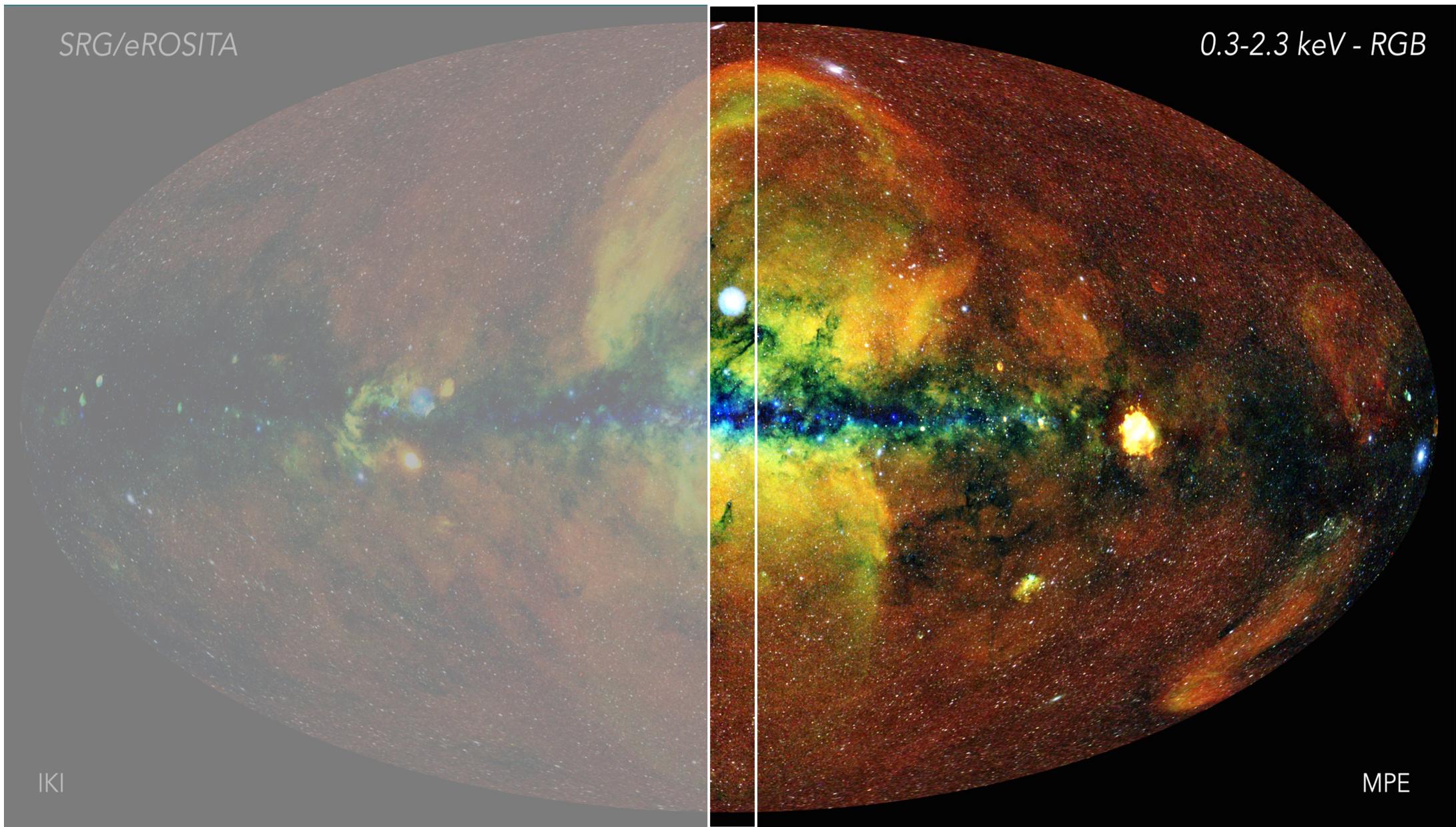


SRG/eROSITA

0.3-2.3 keV - RGB

IKI

MPE



eROSITA on Supernova Remnants

The end-state of stellar evolution depends only on the initial star mass!

- $M = 1 - 8 M_{\odot}$: The star will evolve to become a white dwarf which might explode in a Nuclear Carbon detonation SN
- $M > 8 - 30 M_{\odot}$: The star will undergo a core-collapse SN and forms a Neutron Star
- $M > 30 M_{\odot}$: The star will undergo a core-collapse SN and forms a Black Hole

SN rate in our Galaxy: ~2-3 SN per 100 yrs

SN → SNR:

The ejected matter of the SN mixes with the ISM and forms an expanding shock wave

If the SNR lifetime is ~60.000 – 100.000 yrs, 1200 – 2000 SNRs should be visible anytime.

→ Currently, only about ~300+ SNRs are known in our Galaxy.

What motivates us to study the diffuse X-ray emission from SNRs...

Open questions across different areas of physics:

→ Particle acceleration

What are the dominant mechanisms for cosmic ray acceleration at SNR shocks?

→ Shock physics

How does the shock structure change from young remnants to older, more diffuse systems?

→ Plasma processes

What is the role of charge exchange processes in shaping the X-ray spectra of SNRs?

→ Interaction with the ISM

How do SNRs interact with molecular clouds, stellar winds, or pre-existing cavities?

How do variations in ISM density and composition affect the observed X-ray properties?

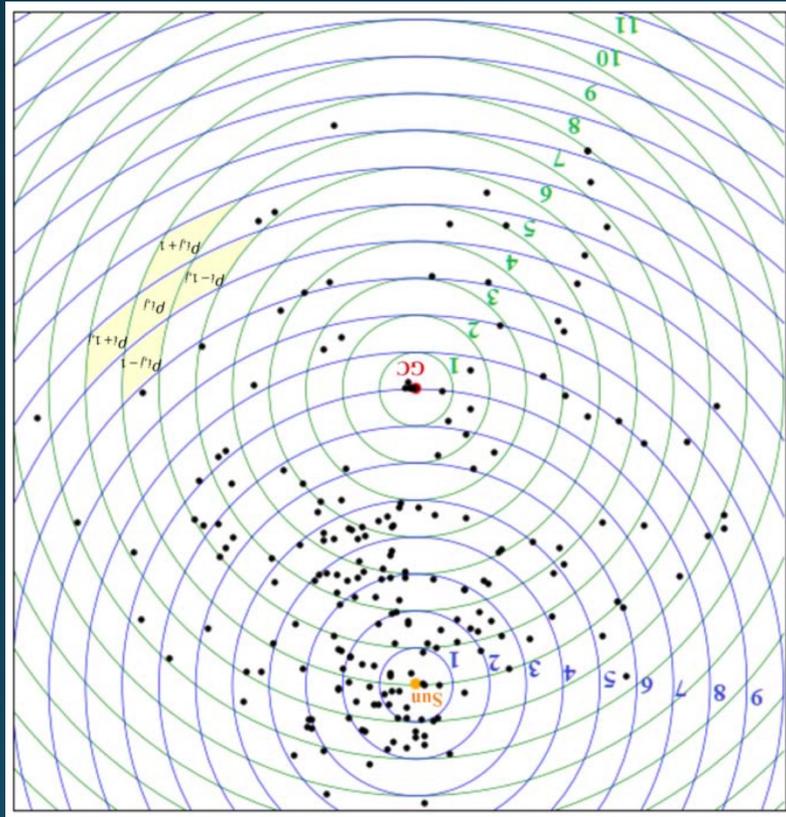
→ What is the SNR lifetime?

How does the X-ray emission correlate with radio, optical, and gamma-ray observations of SNRs?



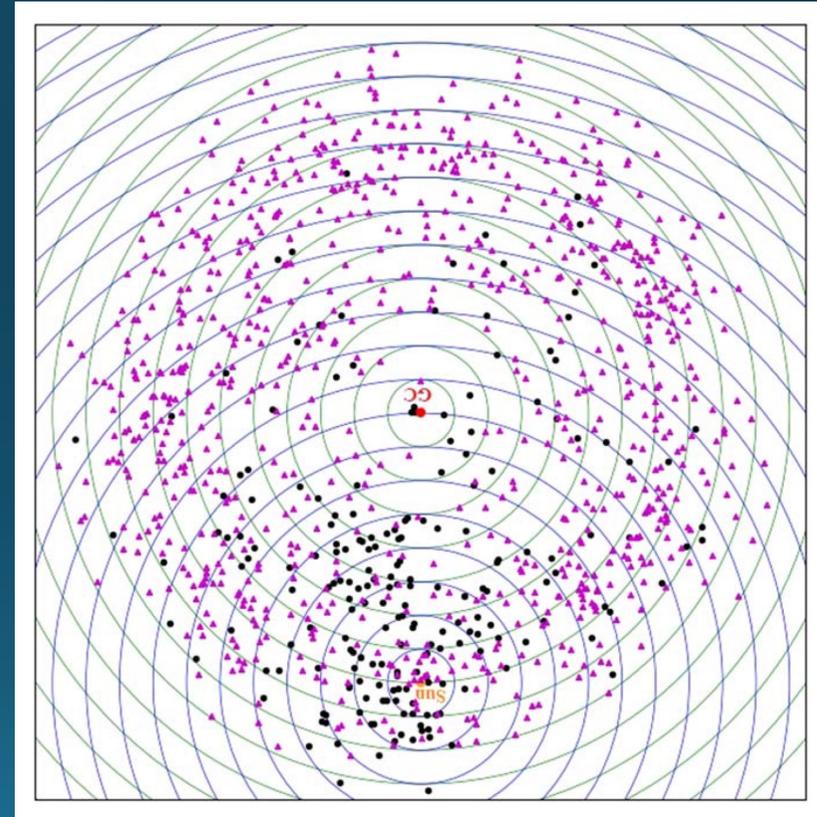
Massive discrepancy between the expected number of SNRs and the known ones

Observed distribution of 215 SNRs with known distance



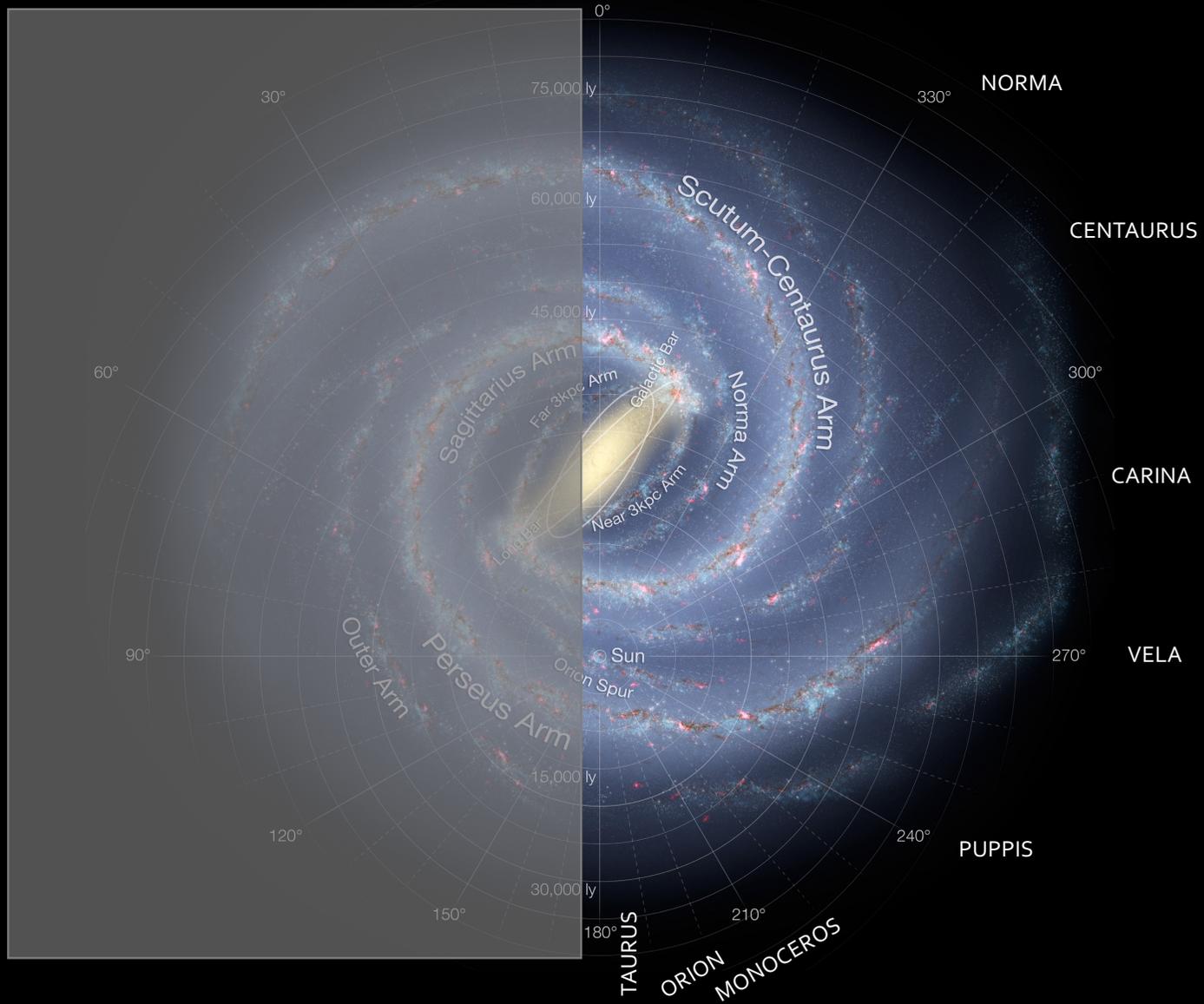
→ SNR density, on average 0.8 SNR/kpc²

Expected distribution of 1050 SNRs



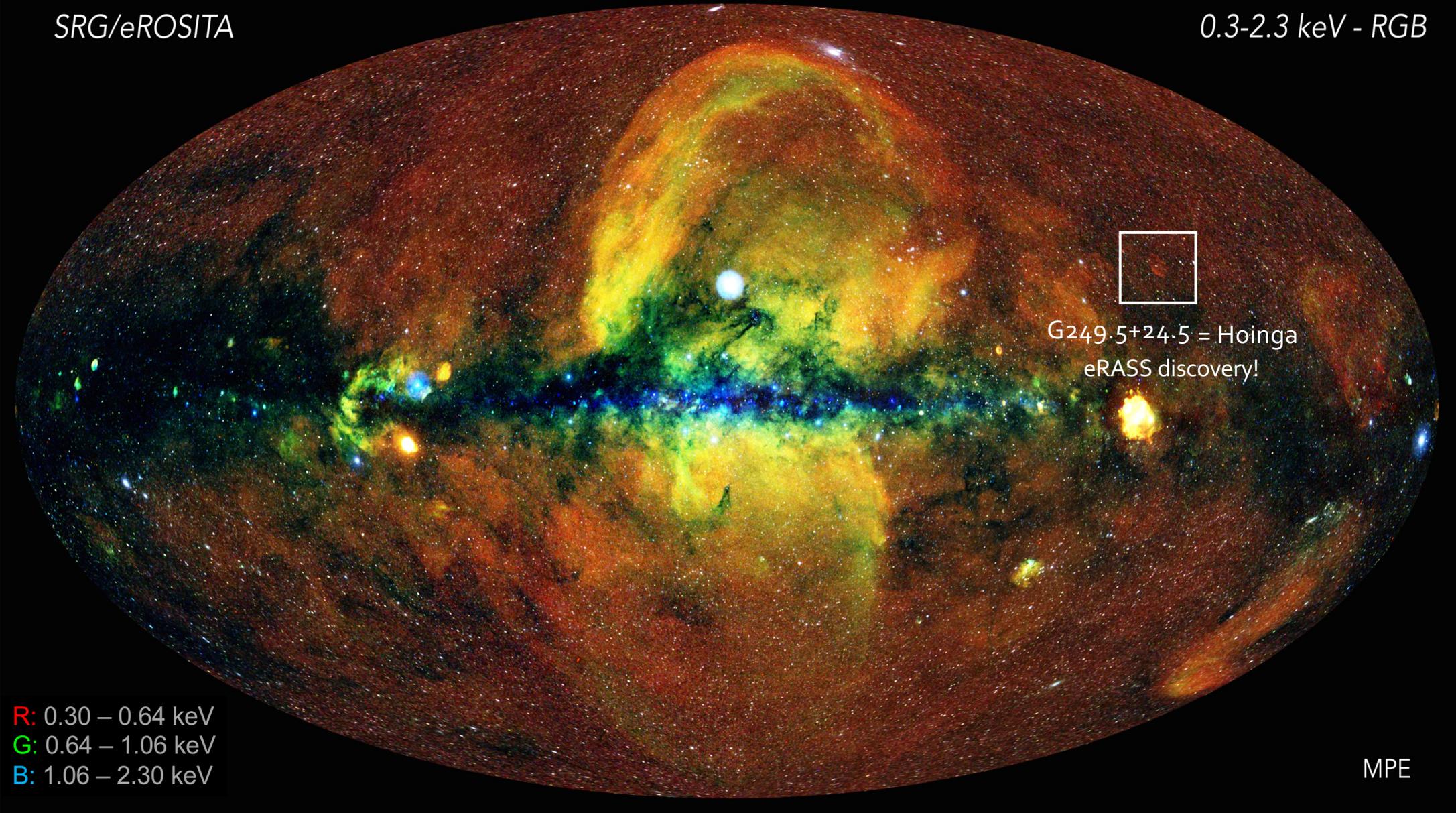
→ Expected SNR density: 3 - 5 SNRs/kpc²

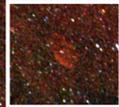
Galactic Longitude



SRG/eROSITA

0.3-2.3 keV - RGB

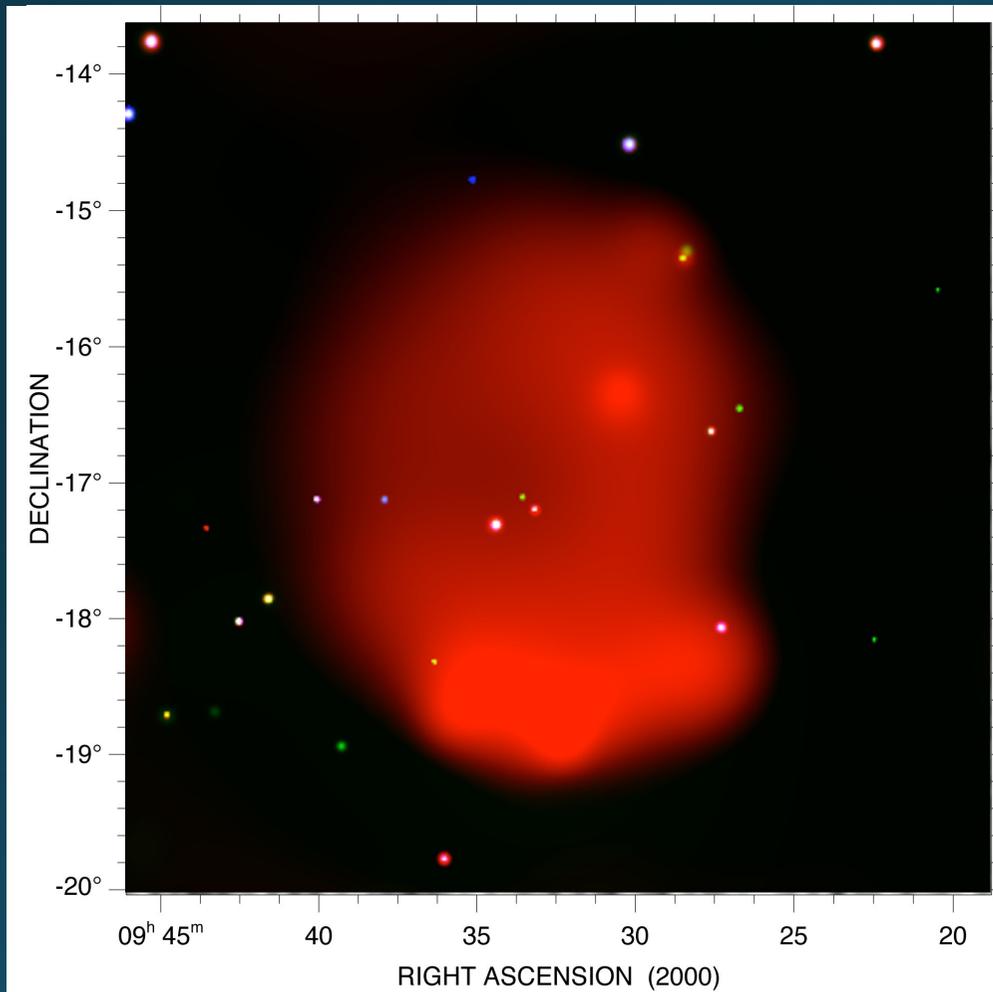



G249.5+24.5 = Hoinga
eRASS discovery!

R: 0.30 – 0.64 keV
G: 0.64 – 1.06 keV
B: 1.06 – 2.30 keV

MPE

Hoinga - The largest SNR ever discovered in X-rays



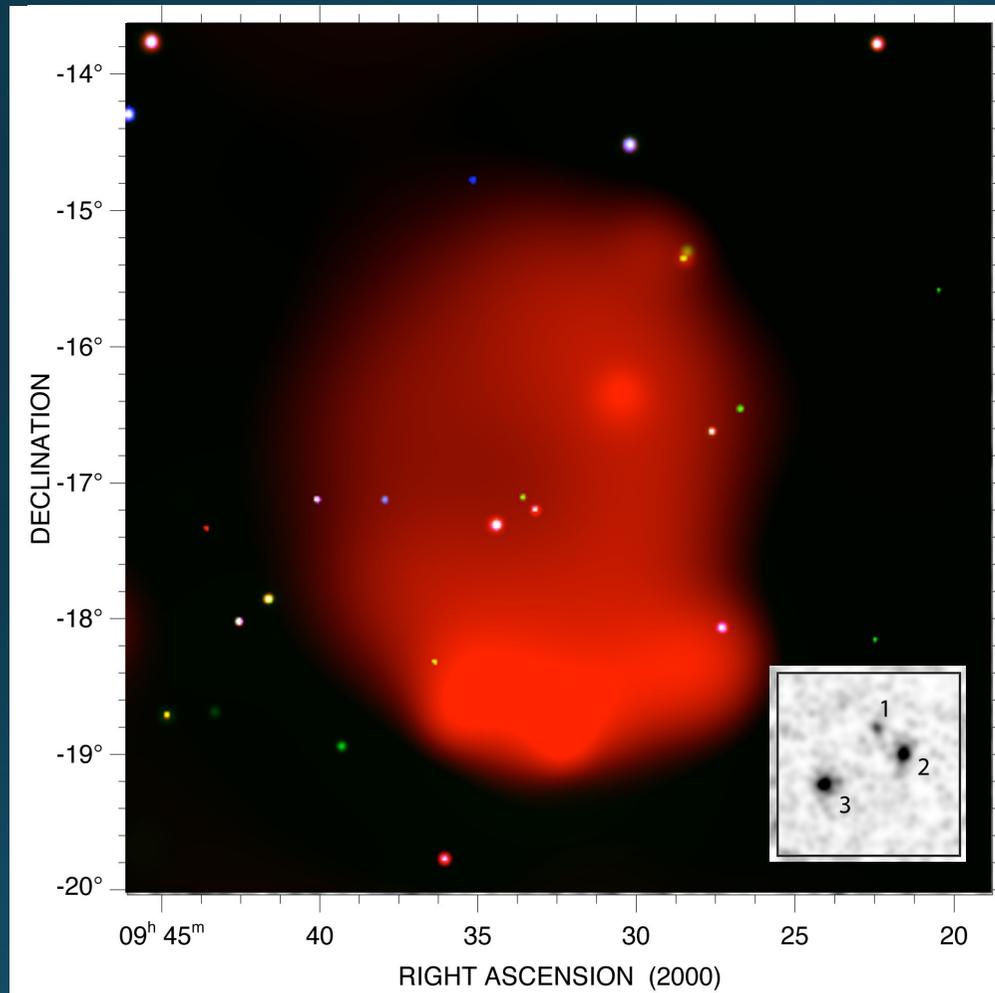
**An SNR at galactic latitude of +24.5°
was not expected and, indeed, hard to predict!**

- Source extent: 4.4 degrees diameter
- Hoinga shows a circularly shaped morphology with diffuse X-ray emission filling the entire remnant
- expanding into a relatively uniform dense region

← Image adaptively smoothed

Red: 0.2 - 0.7 keV
Green: 0.7 - 1.0 keV
Blue: 1.0 - 2.3 keV

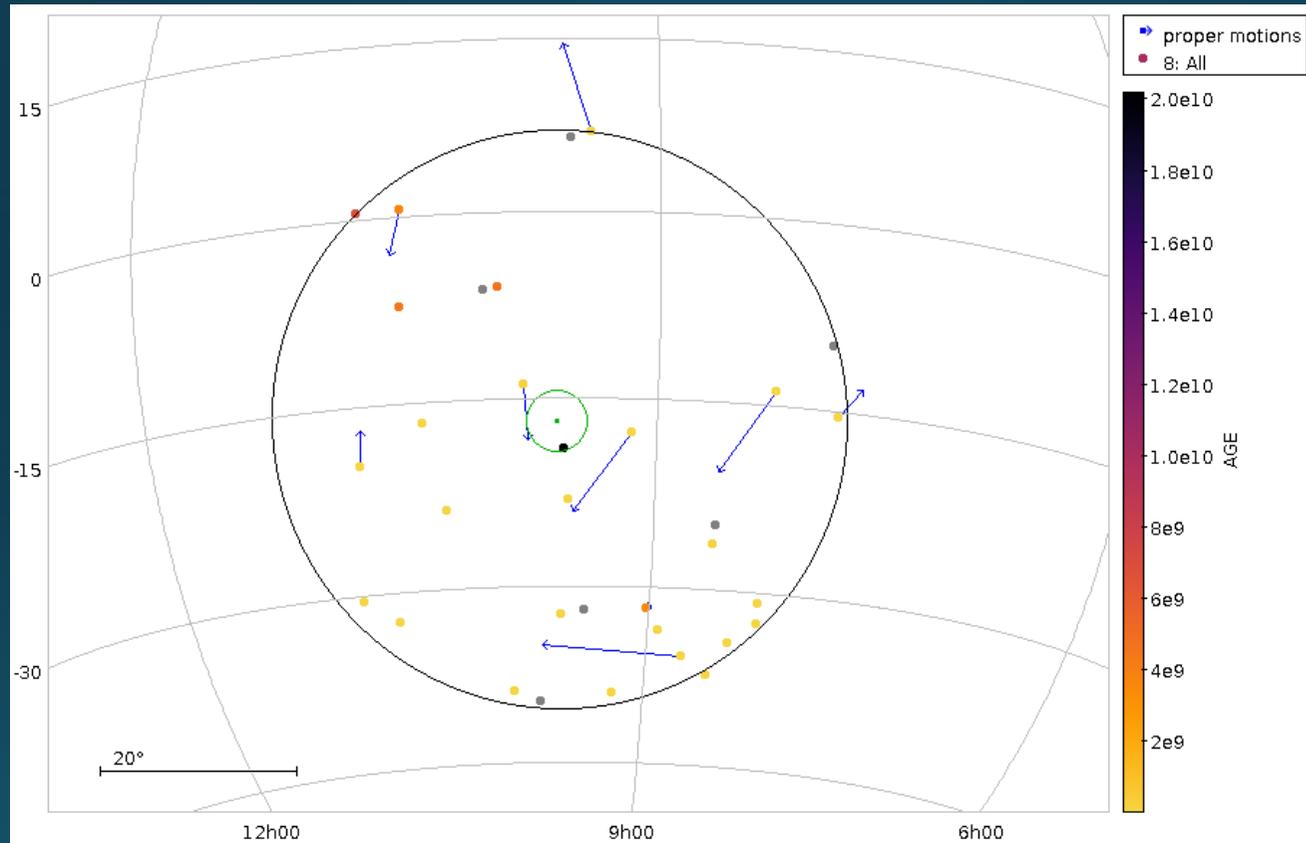
Hoinga - The largest SNR ever discovered in X-rays



- All central sources were identified to be of extragalactic origin
- All 11 sources detected within Hoinga are found to be either foreground or background sources unrelated to the remnant

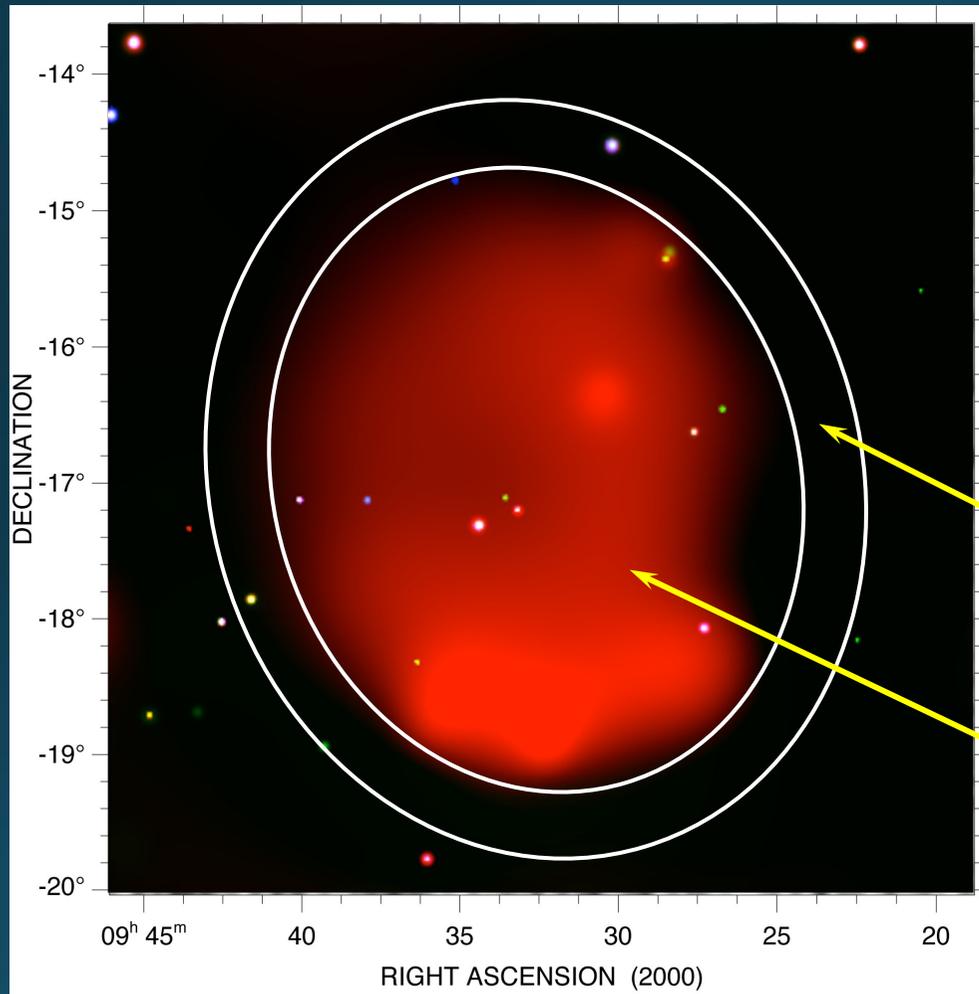
Hoinga – Radio Pulsar connection

Radio pulsars and their PM within 20°



→ None of the known radio pulsars seems to be associated with the remnant

Hoinga's X-ray emission properties:

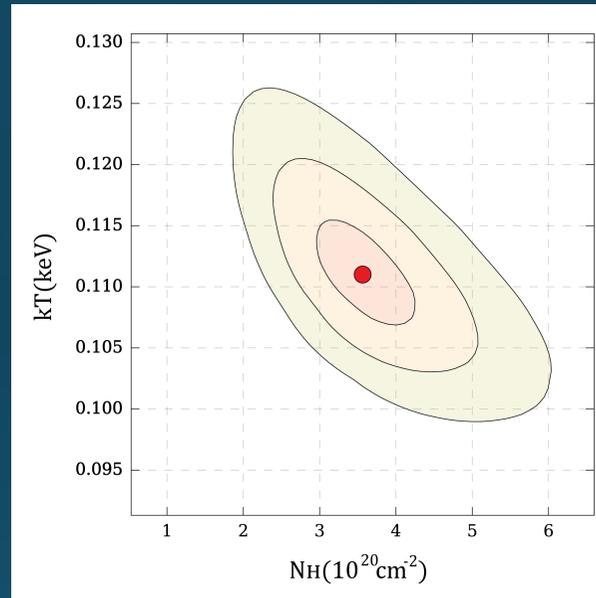
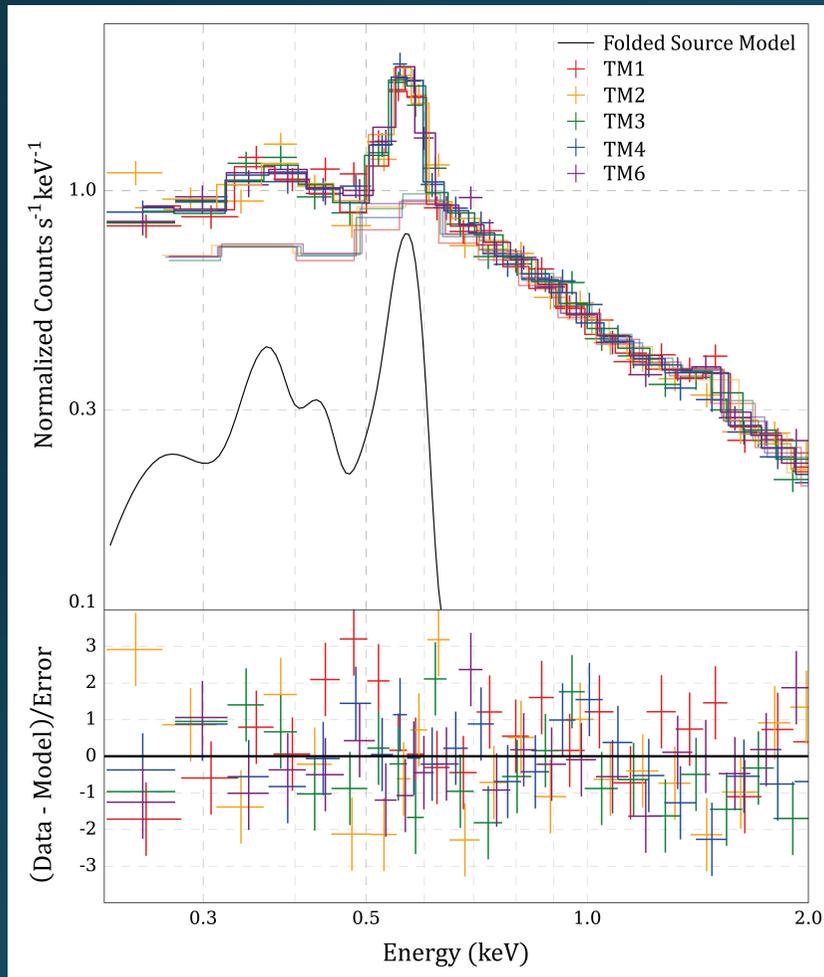


Spectral analysis: Data selection

Background region
(point source contribution was removed)

Source region
(point source contribution was removed)

Hoinga's X-ray emission properties:



APEC spectrum from collisionally-ionized diffuse gas:

→ Gas temperature $kT = 0.1^{+0.02} \text{ keV}$

→ Column density $N_H = 3.6^{+0.7} 10^{20} \text{ cm}^{-2}$

N_H through the Galaxy towards Hoinga is $6 \times 10^{20} \text{ cm}^{-2}$

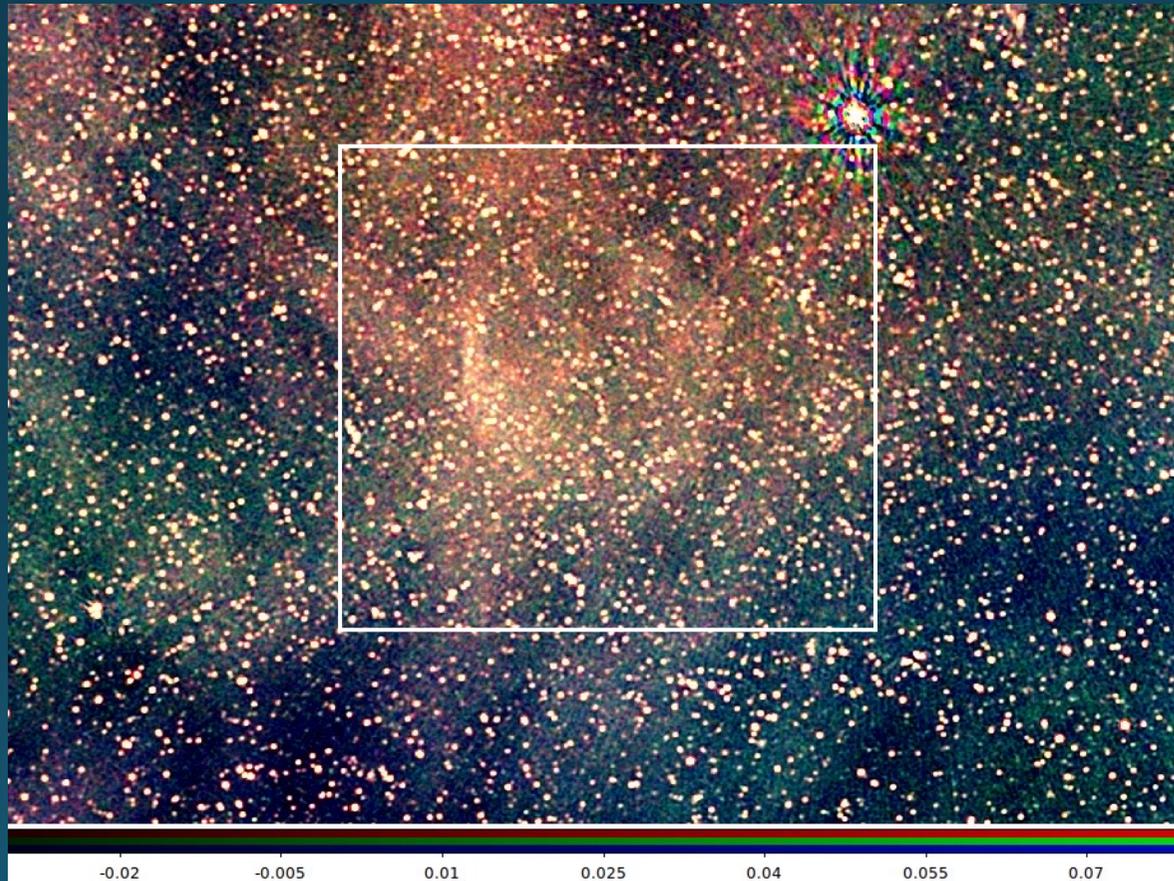
Hoinga – Does it have a radio counterpart?

We've studied radio data from the

- GaLactic and Extragalactic All-sky Murchison (GLEAM) Survey
(performed between 72 and 231 MHz, angular resolution 2 arcmin)
- All-sky 408-MHz "Haslam" survey performed with the Green Bank and Parkes Radio telescopes which, as of today, remains the lowest-frequency total-power measurement of the full sky (Haslam et al.1982)
- CHIPASS (Continuum map of the HI Parkes All-Sky Survey) at 1.4 GHz

Hoinga – Does it have a radio counterpart?

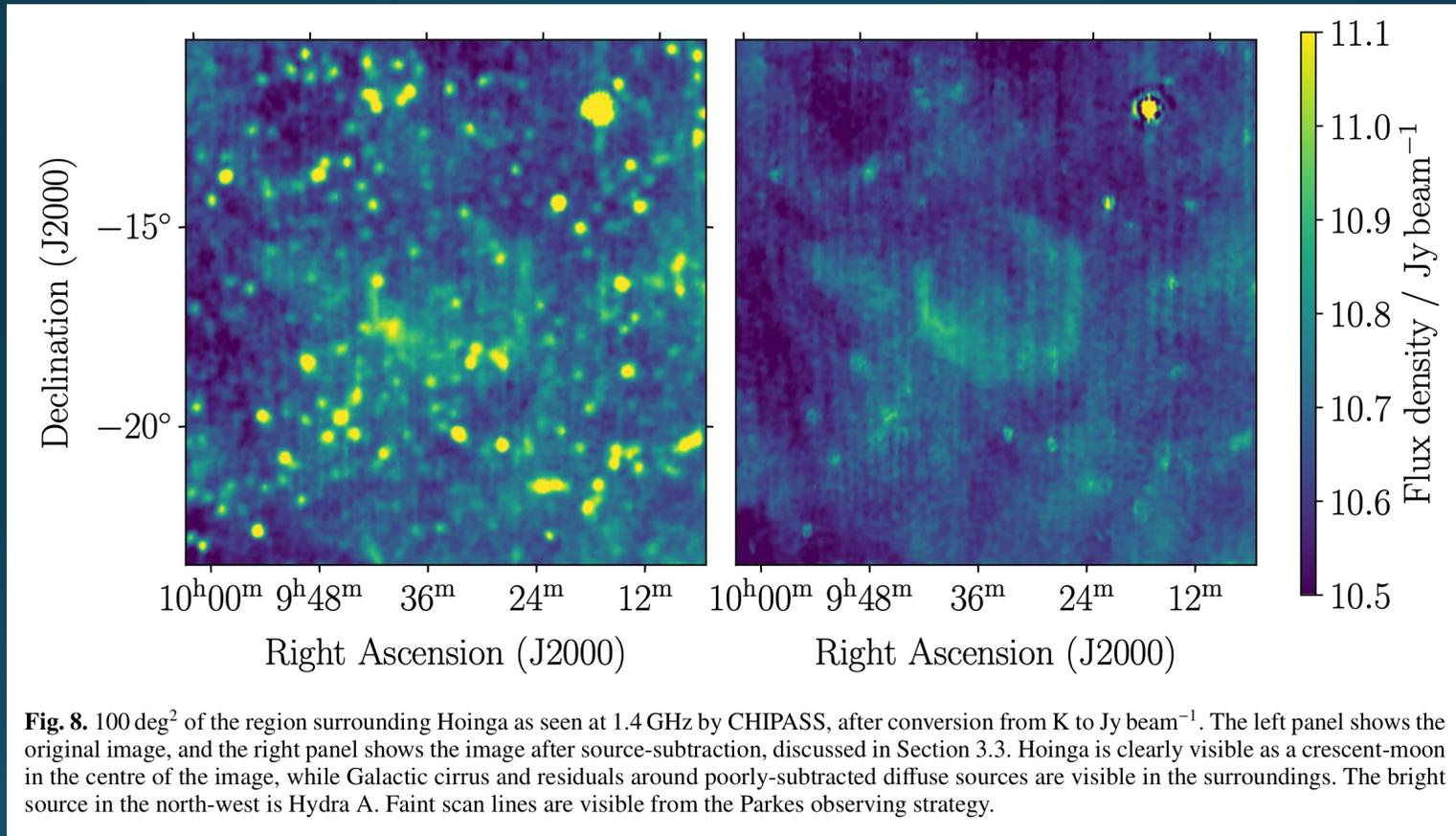
GLEAM Image from the MWA survey
(contaminated with hundreds of point sources)



Red: 72 -- 103 MHz
Green: 103 -- 134 MHz
Blue: 139 -- 170 MHz

Hoinga – Does it have a radio counterpart?

1.4 GHz image from the CHIPASS survey



Relatively low radio surface brightness and its location at high gal. latitude prevented a previous radio discovery

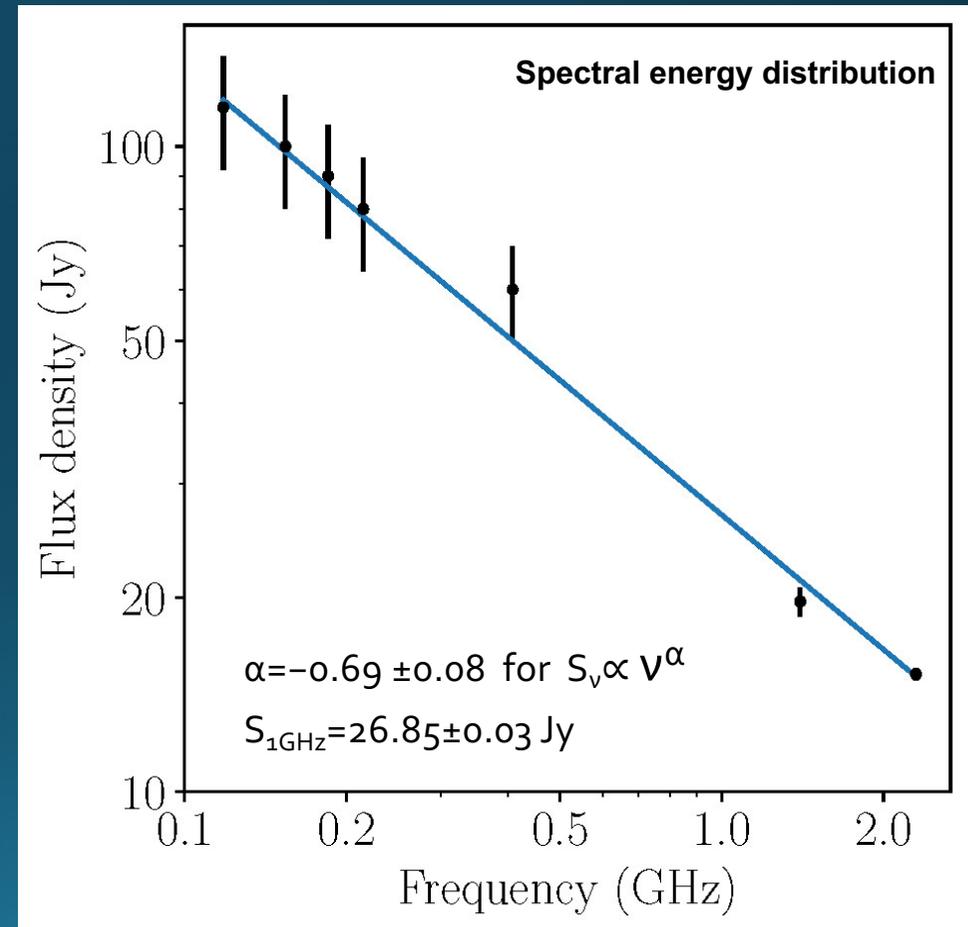
Hoinga – Radio emission properties

Radio spectrum

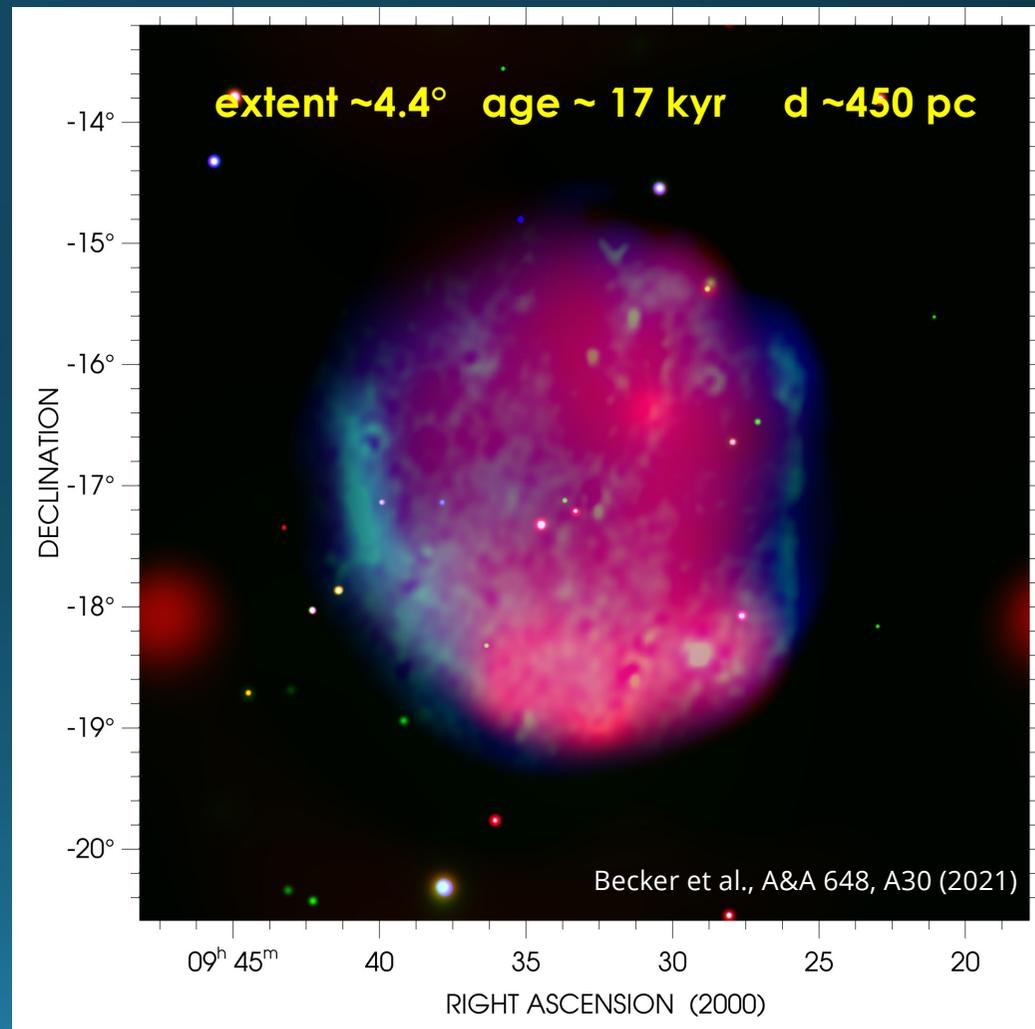
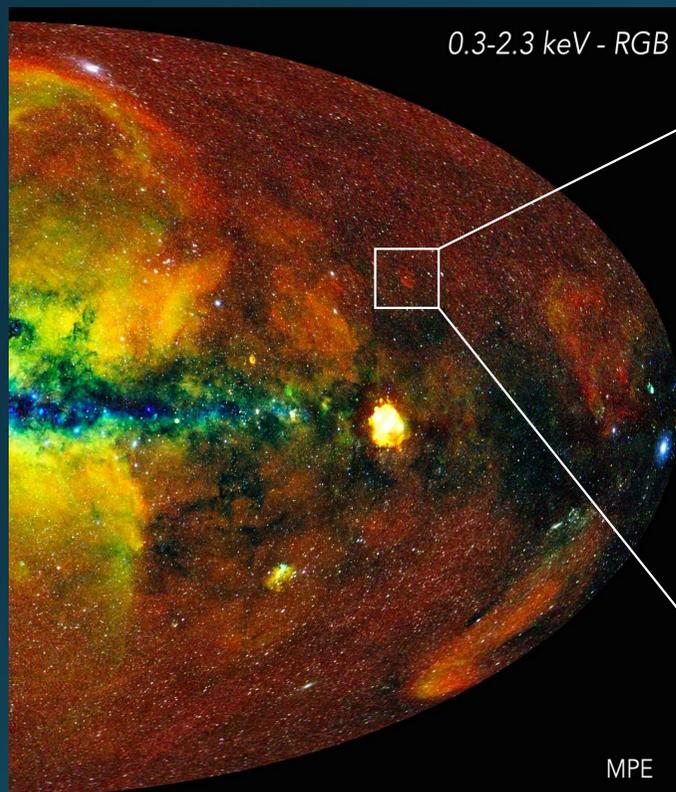
Table 3. Integrated flux densities of Hoinga measured from the radio data described in Section 3. Measurements were made on images where contaminating sources and background had been removed, using the software POLY_FLUX.

Survey	Frequency / MHz	Resolution / '	Flux density / Jy
GLEAM	118	7.8×6.6	115 ± 23
GLEAM	154	6.0×5.0	100 ± 20
GLEAM	185	5.0×4.2	90 ± 18
GLEAM	215	4.2×3.6	80 ± 16
Haslam	408	51	60 ± 10
CHIPASS	1400	14.4	19.7 ± 1.0
SPASS	2300	8.9	15.2 ± 0.3

→ indicates that non-thermal synchrotron emission dominates the radio spectrum, consistent with a shell-type SNR

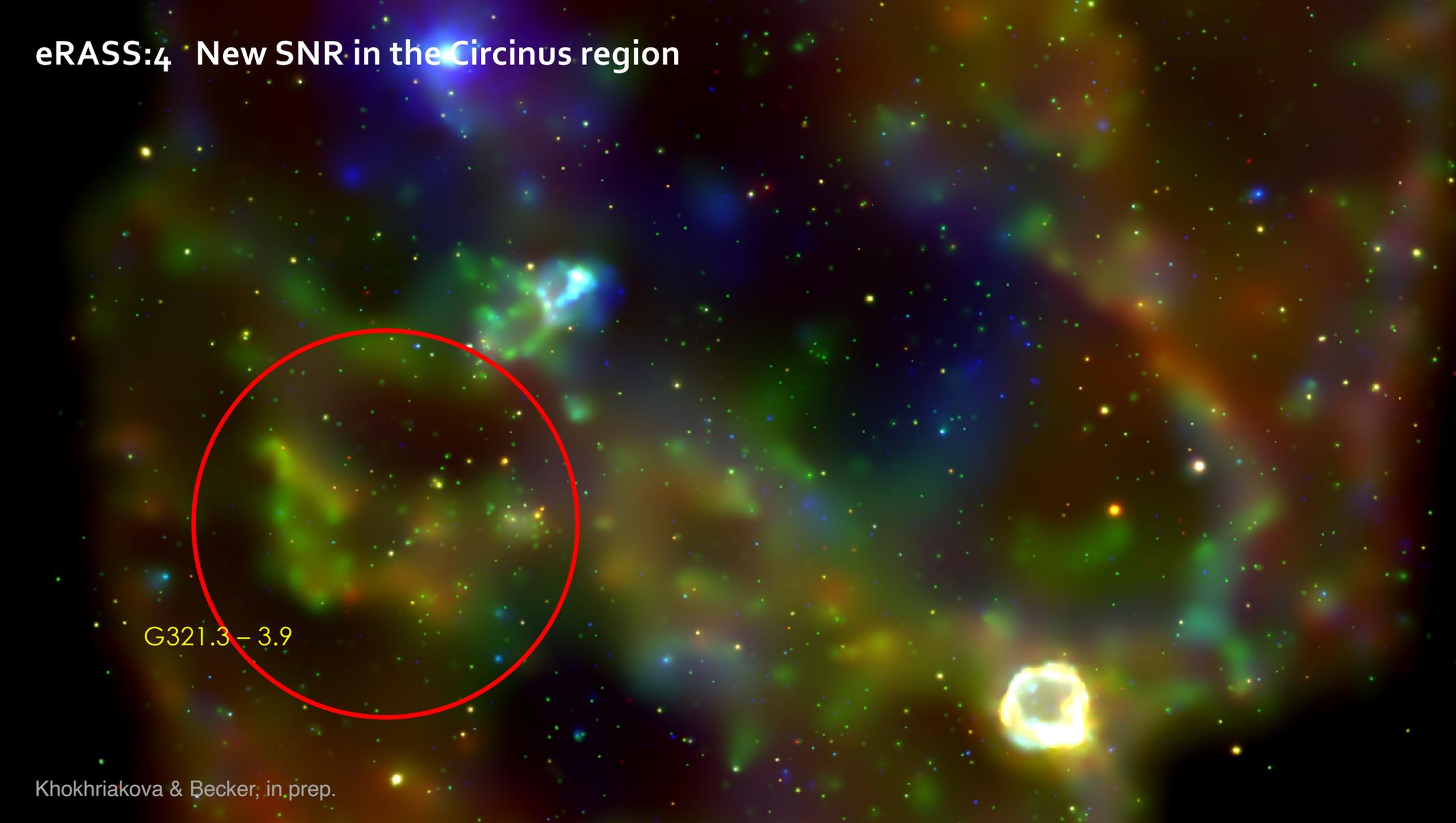


Hoinga – a middle-aged SNR located at about 450 pc

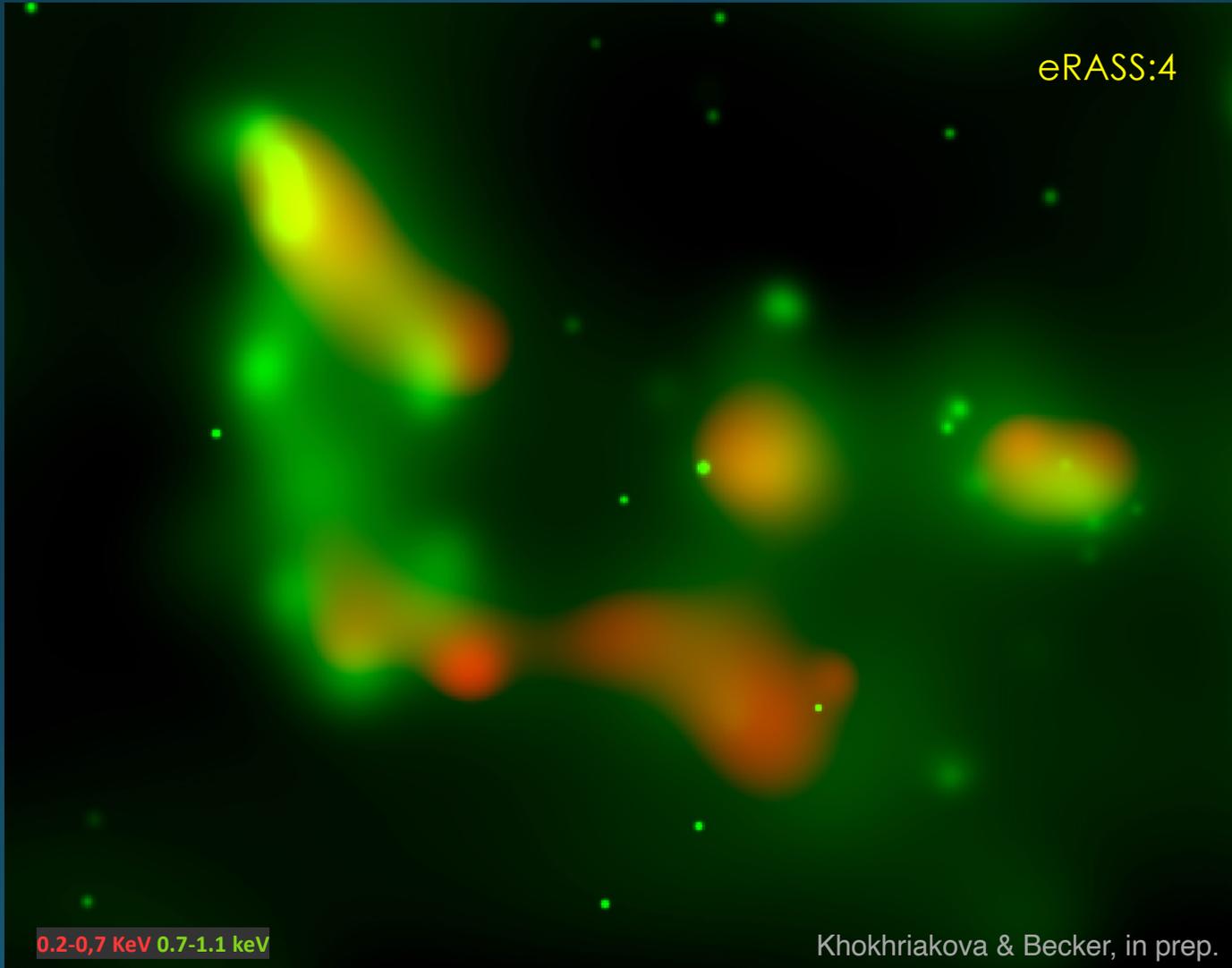


eRASS:4 New SNR in the Circinus region

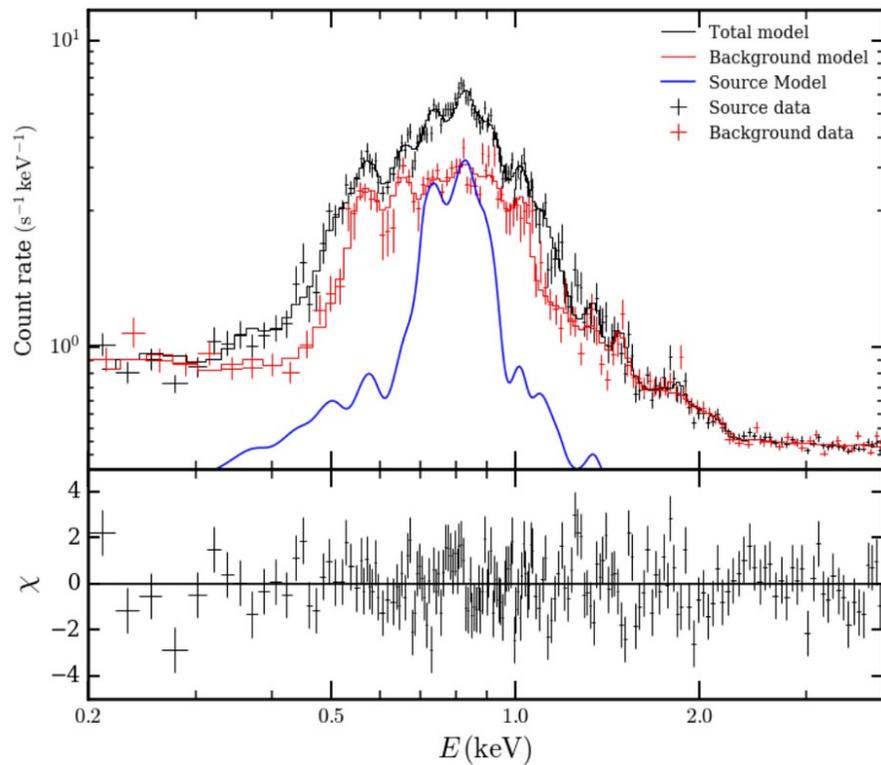
G321.3 - 3.9



G321.3 – 3.9



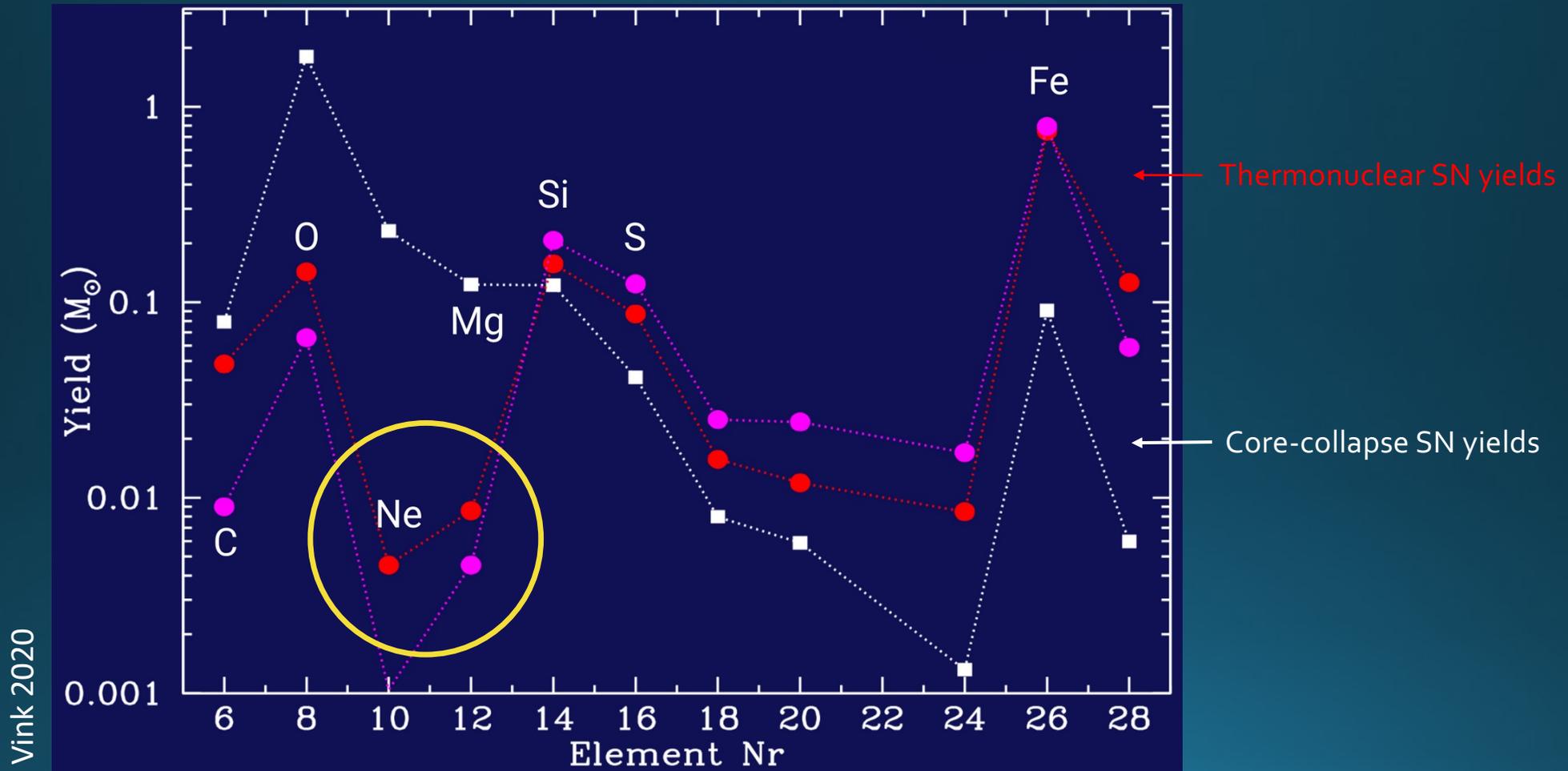
G321.3 – 3.9: eROSITA spectral analysis



TBabs*vpshock

Model	vpshock	vapec
N_H (10^{22} cm^{-2})	$0.15^{+0.04}_{-0.03}$	$0.11^{+0.02}_{-0.02}$
kT (keV)	$0.65^{+0.03}_{-0.03}$	$0.58^{+0.02}_{-0.02}$
O/ O_{\odot}	$0.17^{+0.08}_{-0.05}$	$0.18^{+0.15}_{-0.11}$
Ne/ Ne_{\odot}	< 0.05	$0.3^{+0.18}_{-0.12}$
Mg/ Mg_{\odot}	< 0.05	< 0.05
Si/ Si_{\odot}	$0.6^{+0.2}_{-0.2}$	$0.51^{+0.14}_{-0.23}$
Fe/ Fe_{\odot}	$0.5^{+0.2}_{-0.1}$	$0.30^{+0.07}_{-0.05}$
τ_u ($10^{10} \text{ cm}^{-3} \text{ s}$)	51^{+75}_{-26}	
Normalization	$0.018^{+0.007}_{-0.005}$	$0.023^{+0.005}_{-0.005}$
Statistics	1756/1597=1.10	1794/1602=1.12

G321.3 – 3.9: An SNR from a thermonuclear SN event



G321.3 – 3.9: Distance estimate from the X-ray spectral results

$$N_H \sim (0.9 - 1.9) \times 10^{21} \text{ cm}^{-2}$$

$$N_H [cm^{-2} / A_v] = 2.08 \pm 0.02 \times 10^{21} \text{ cm}^{-2} \quad (\text{Zhu et al 2017})$$

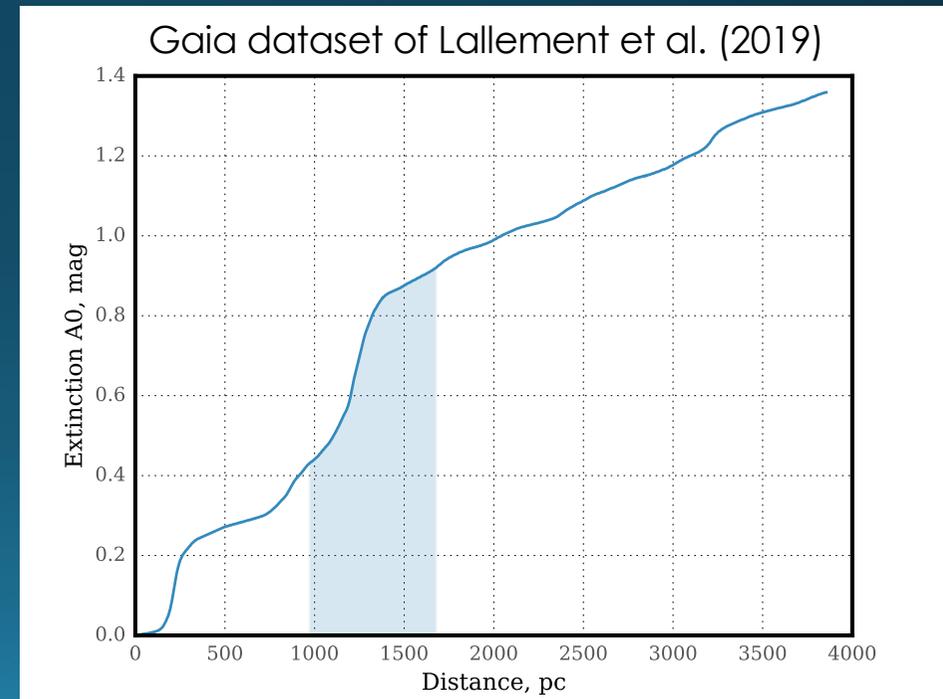
$$A_v \sim (0.4 - 0.9)$$

$$D \sim (1.0 - 1.7) \text{ kpc}$$

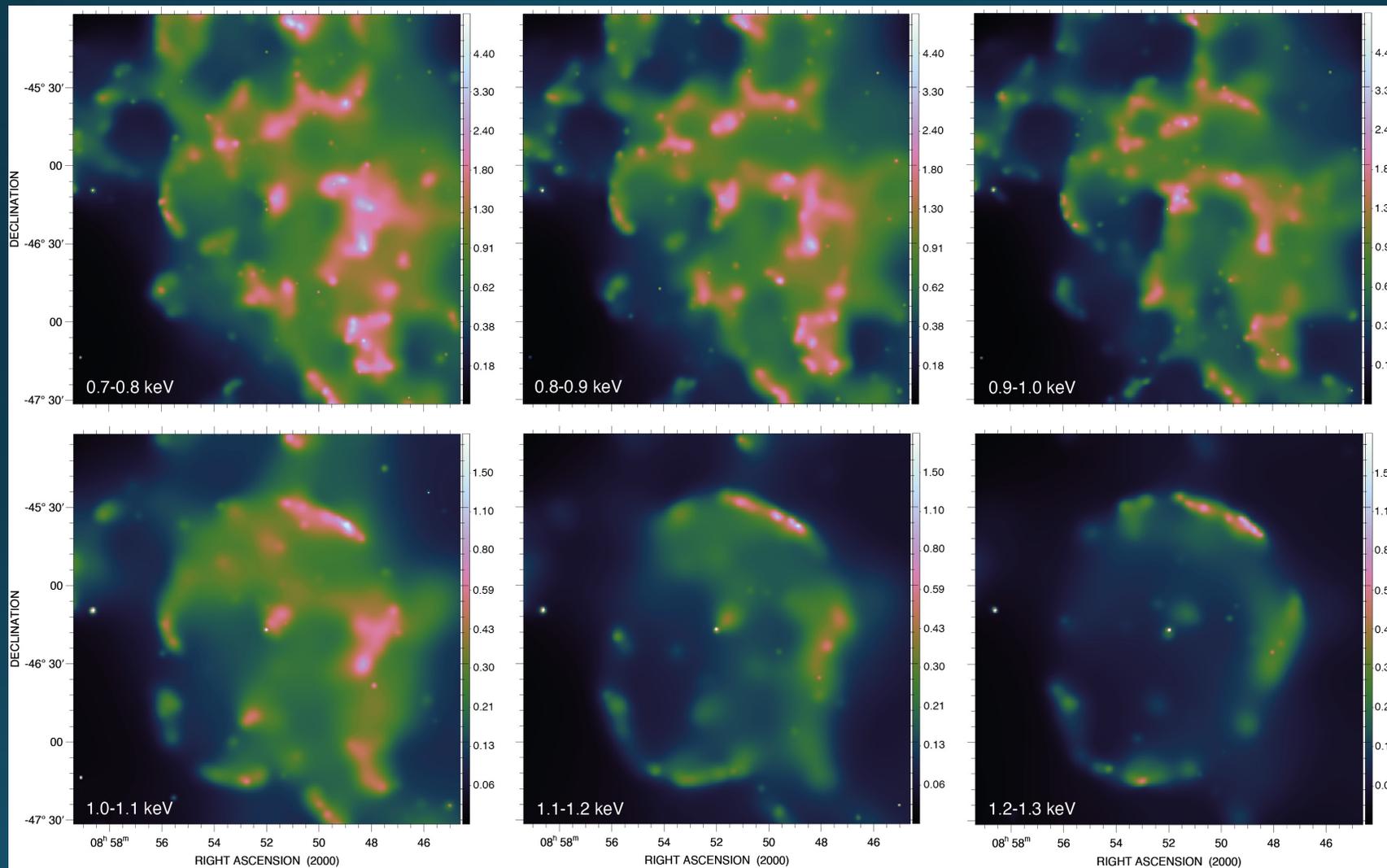
→ SNR radius: 14 - 25 pc

→ Density in the Galactic plane $1.11 \pm 0.15 \text{ cm}^{-3}$

→ SNR age: 14 – 70 kyrs (Leahy's SNR sim.)

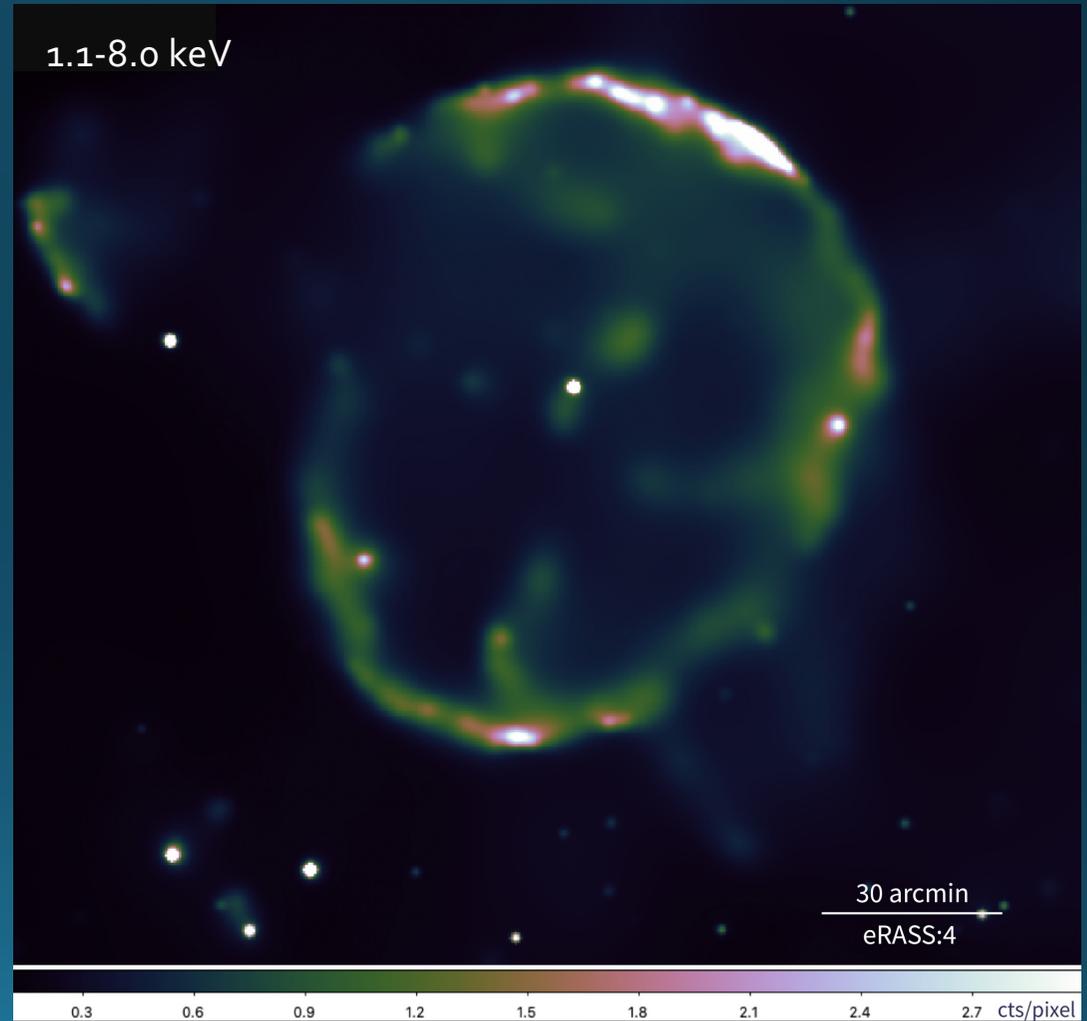


Vela & Friends: Vela Jr



Camilloni et al., 2024

Vela & Friends: Vela Jr geometrical centre and CCO PM

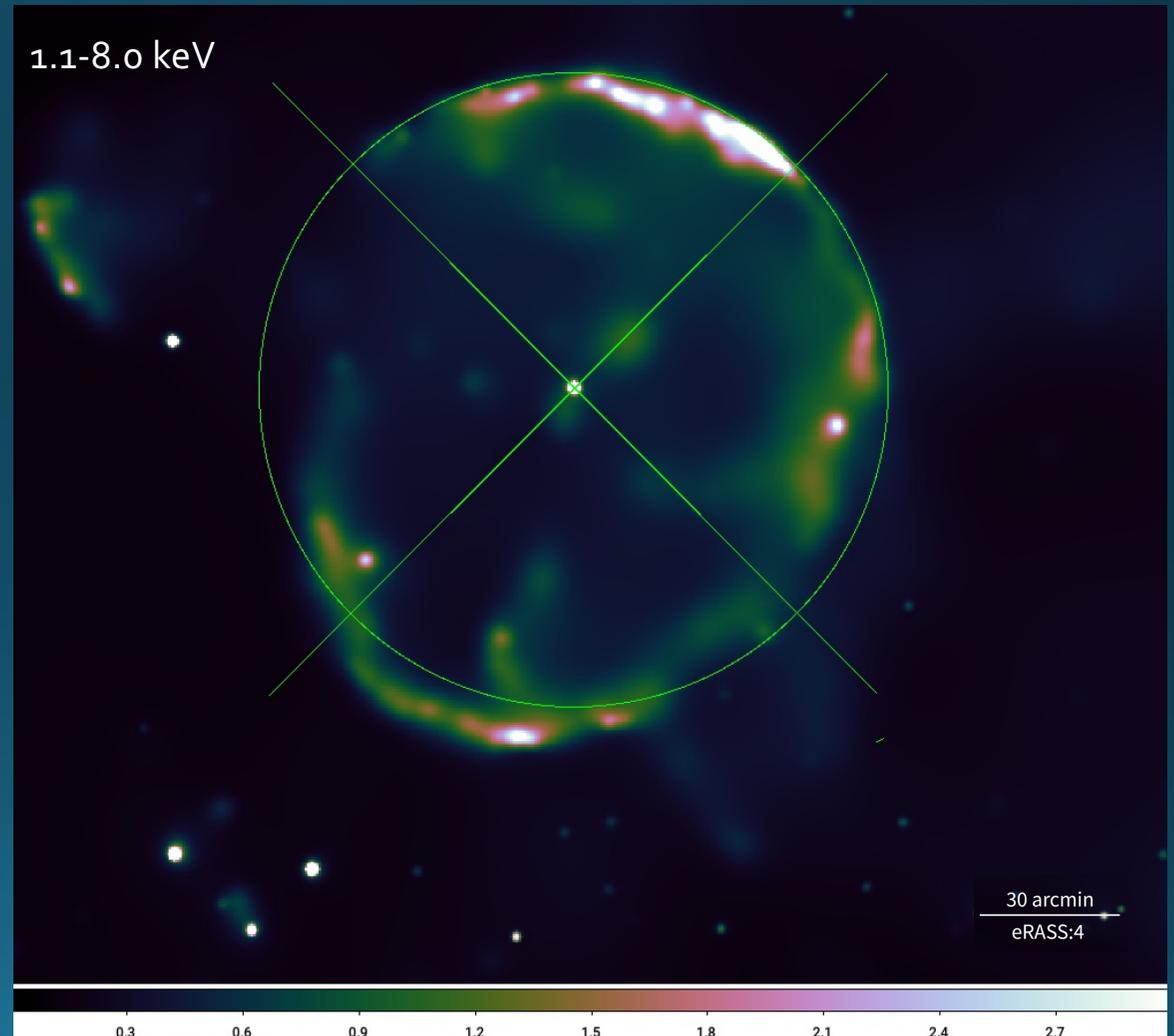


Vela & Friends: Vela Jr

The CCO position is in excellent agreement with the geometrical remnant centre –

obtained by fitting a circle to the northern part of the remnant

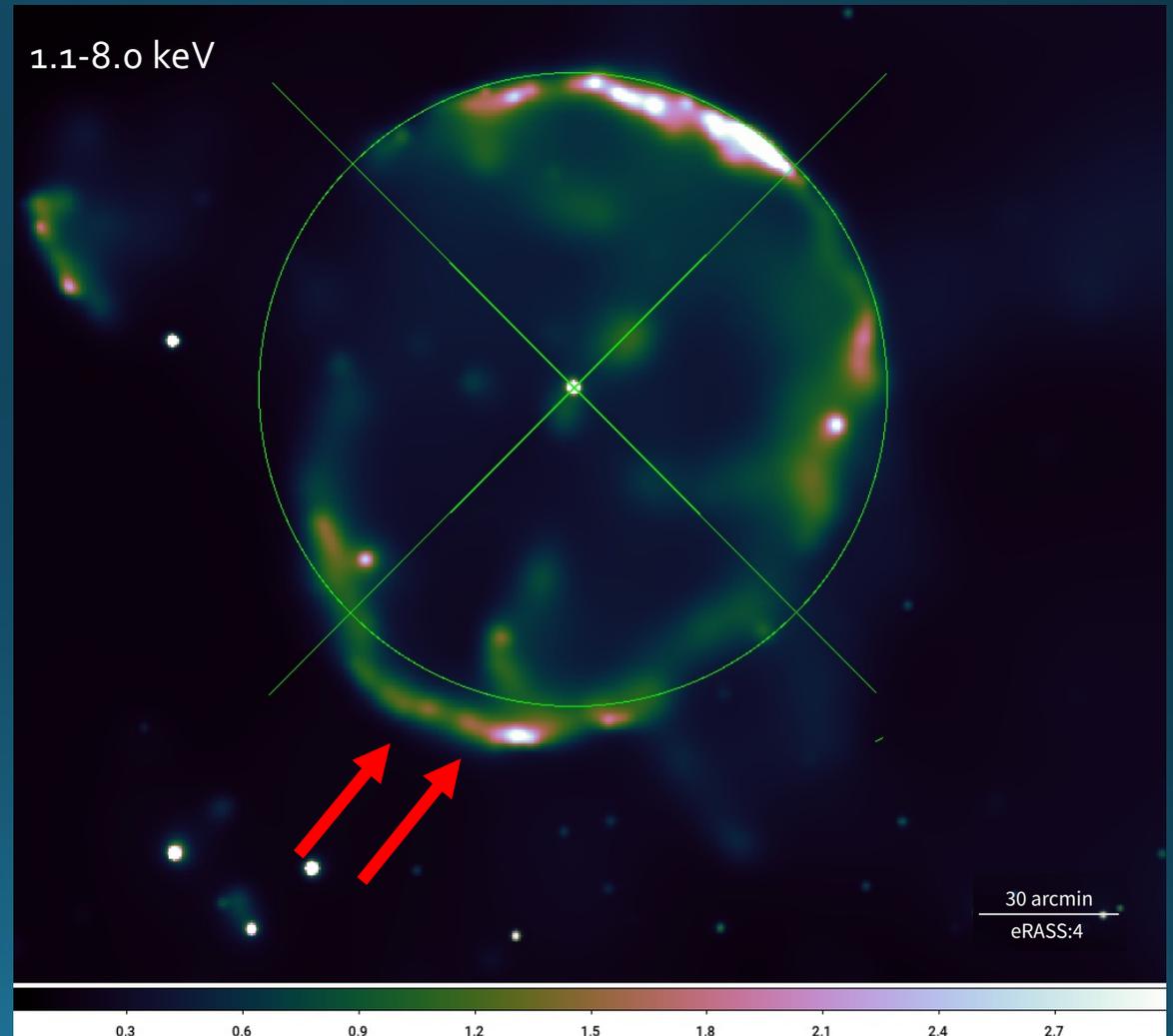
Circle radius: 1 degree



Vela & Friends: Vela Jr

But what's about the somewhat elongated remnant shape?

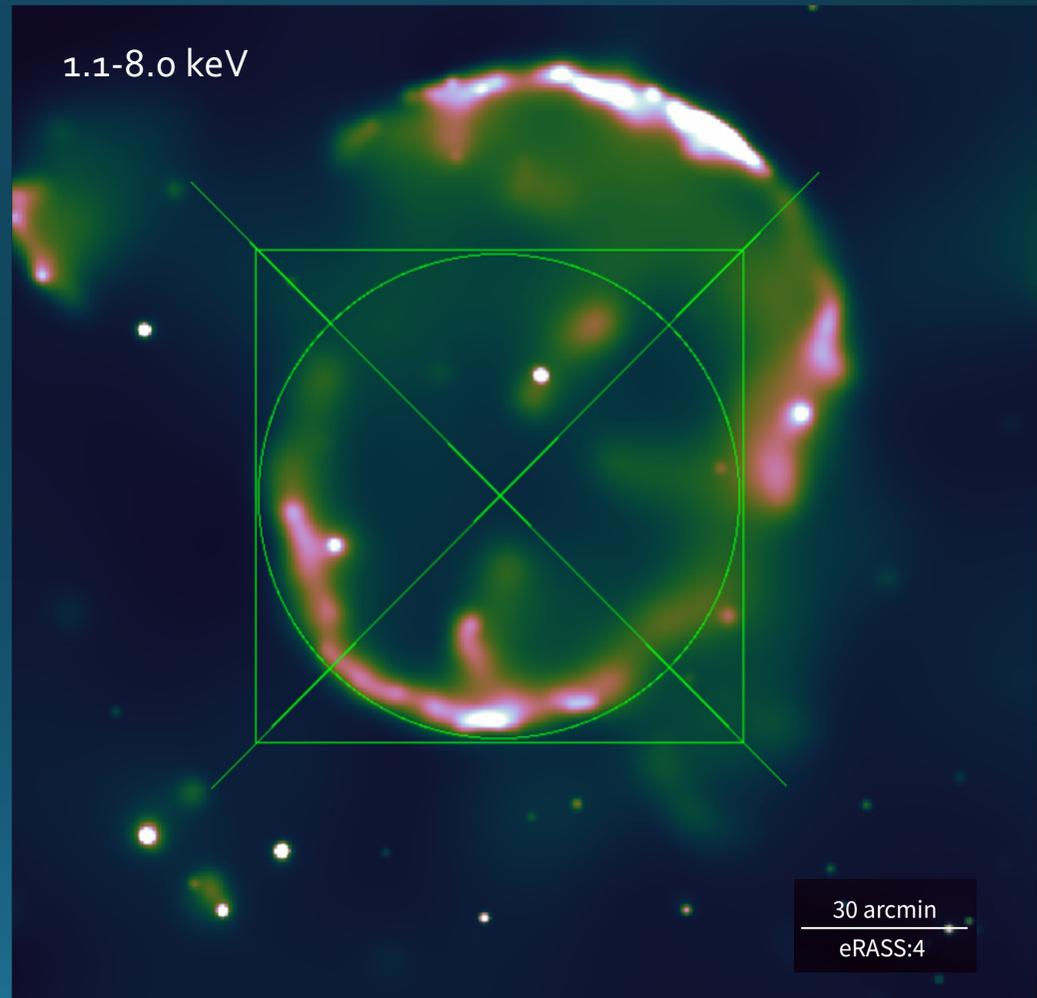
- A not perfectly circular SN explosion?
- Inhomogeneities in the surrounding ISM?



Vela & Friends: Vela Jr

The southern remnant part indeed fits
a second 44 arcmin radius circle!

Bi-annular structures in (at least some) SNRs
(see Manchester, A&A, 171, 205, 1987)

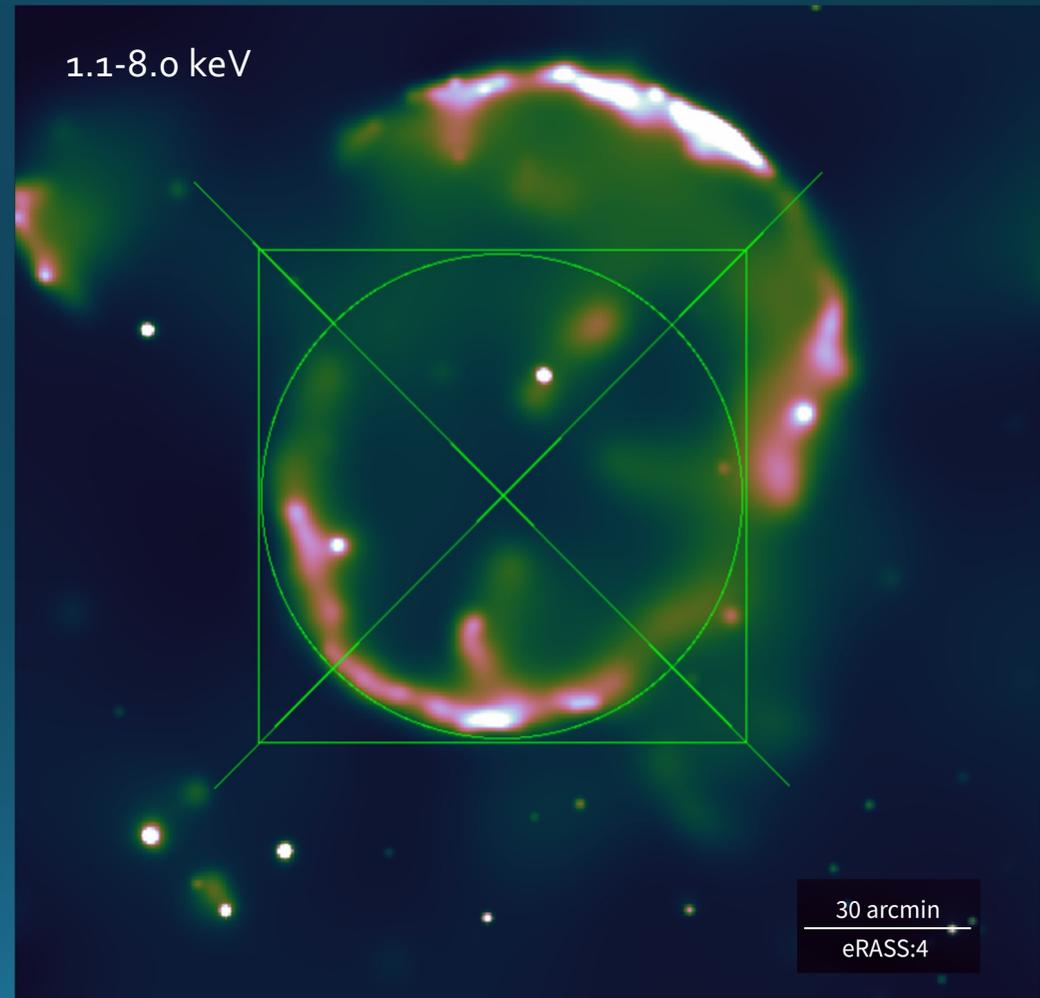


Vela & Friends: Vela Jr

The southern remnant part indeed fits a second 44 arcmin radius circle!

Alternative Hypothesis:

Could a second SN explosion have formed the southern shell?



Vela & Friends: Vela Jr

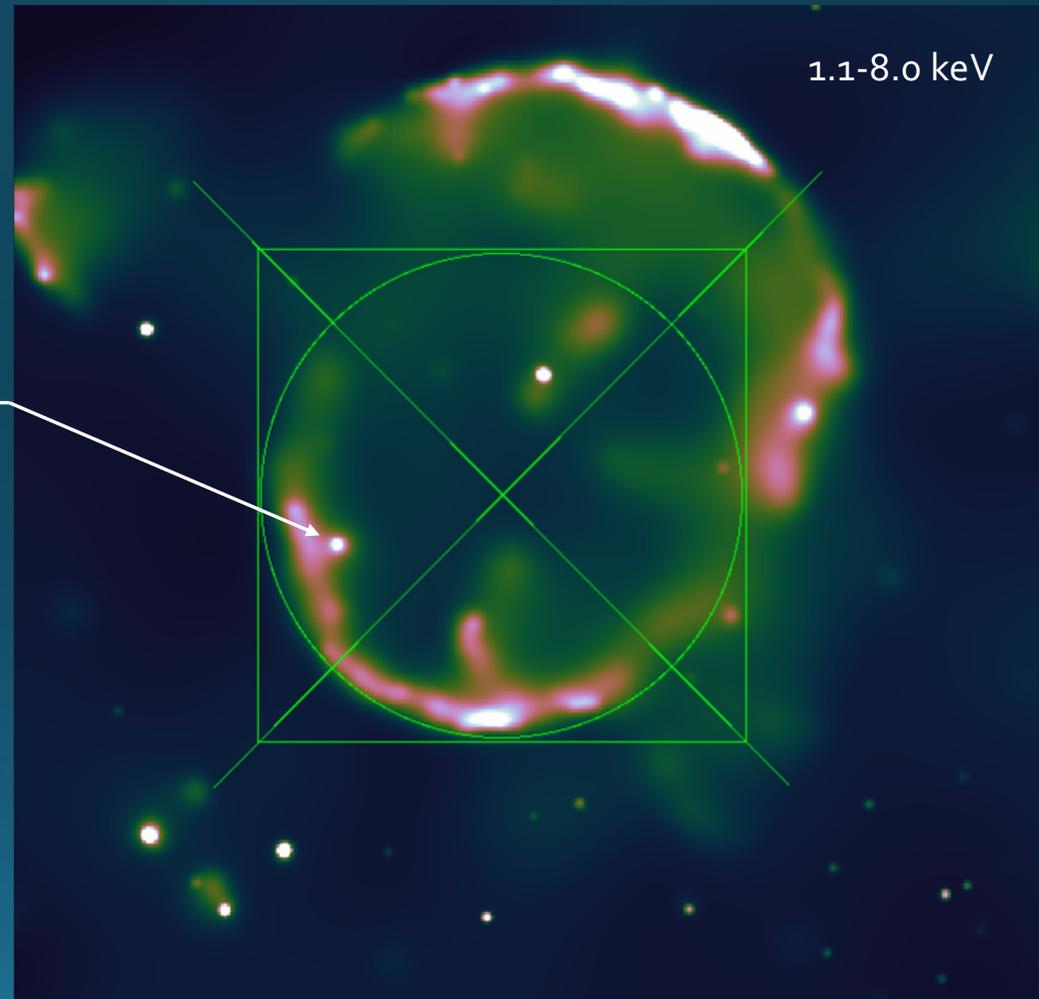
→ There is a 2nd compact object in the field!

PSR J0855-4644

$t \sim 1.4 \cdot 10^5$ yrs, $E_{\text{dot}} = 10^{36}$ erg/s, $P = 64$ ms

DM ($236.4 \text{ cm}^{-3} \text{ pc}$) suggests a distance of 5.6 kpc

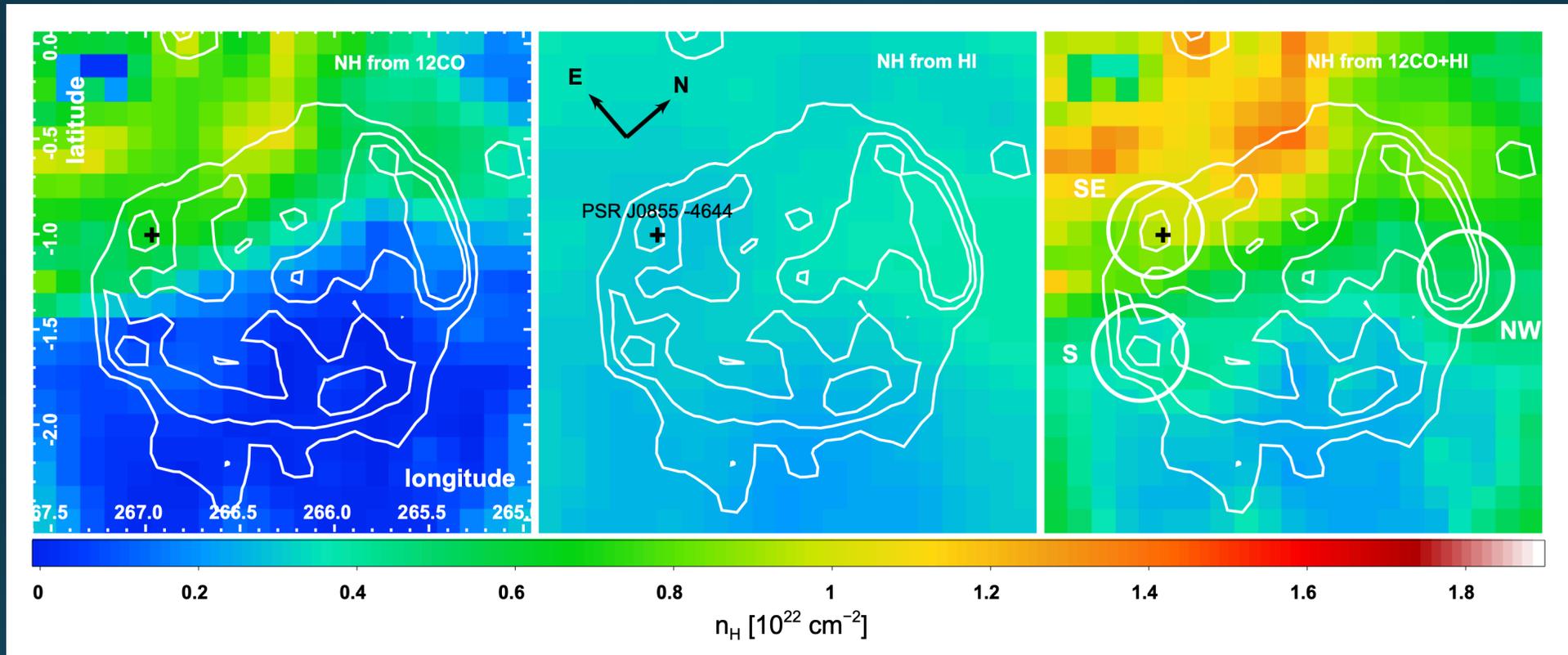
(cf. AFNT Pulsar database, Manchester et al., 2005)



Vela Jr: In front of or behind the Vela Molecular Ridge?

(see Acero, et al., 2013)

(Acero, et al., 2013)



Maps of the absorption column density, derived from the molecular gas (*left panel*), the atomic gas (*middle panel*), and the sum of the two previous components (*right panel*) when integrating over radial velocities from -10 to 15 km s^{-1} .

This specific velocity range provides an estimate of the absorption column for a source located just behind the Vela molecular ridge.

Vela Jr: In front of or behind the Vela Molecular Ridge? (see Acero, et al., 2013)

Distance estimate from a comparison of column densities:

Total column absorption through the Galaxy towards the pulsar:	$N_H = 1.65 \times 10^{22} \text{ cm}^{-2}$
Column absorption between the observer and the back of the VMR is:	$N_H = 0.97 \times 10^{22} \text{ cm}^{-2}$
Column absorption toward the SNR rim near the pulsar region:	$N_H = 0.88_{-0.06}^{+0.08} \times 10^{22} \text{ cm}^{-2}$
Column absorption toward the pulsar:	$N_H = 0.64_{-0.11}^{+0.34} \times 10^{22} \text{ cm}^{-2}$
Column absorption toward the CCO:	$N_H = 0.322_{-0.013}^{+0.014} \times 10^{22} \text{ cm}^{-2}$

→ Vela Jr is in front of the VMR, and the pulsar is closer to, or at the same distance as, Vela Jr.

→ Pulsar distance $d \leq 900 \text{ pc}$ (Acero, et al., 2013)

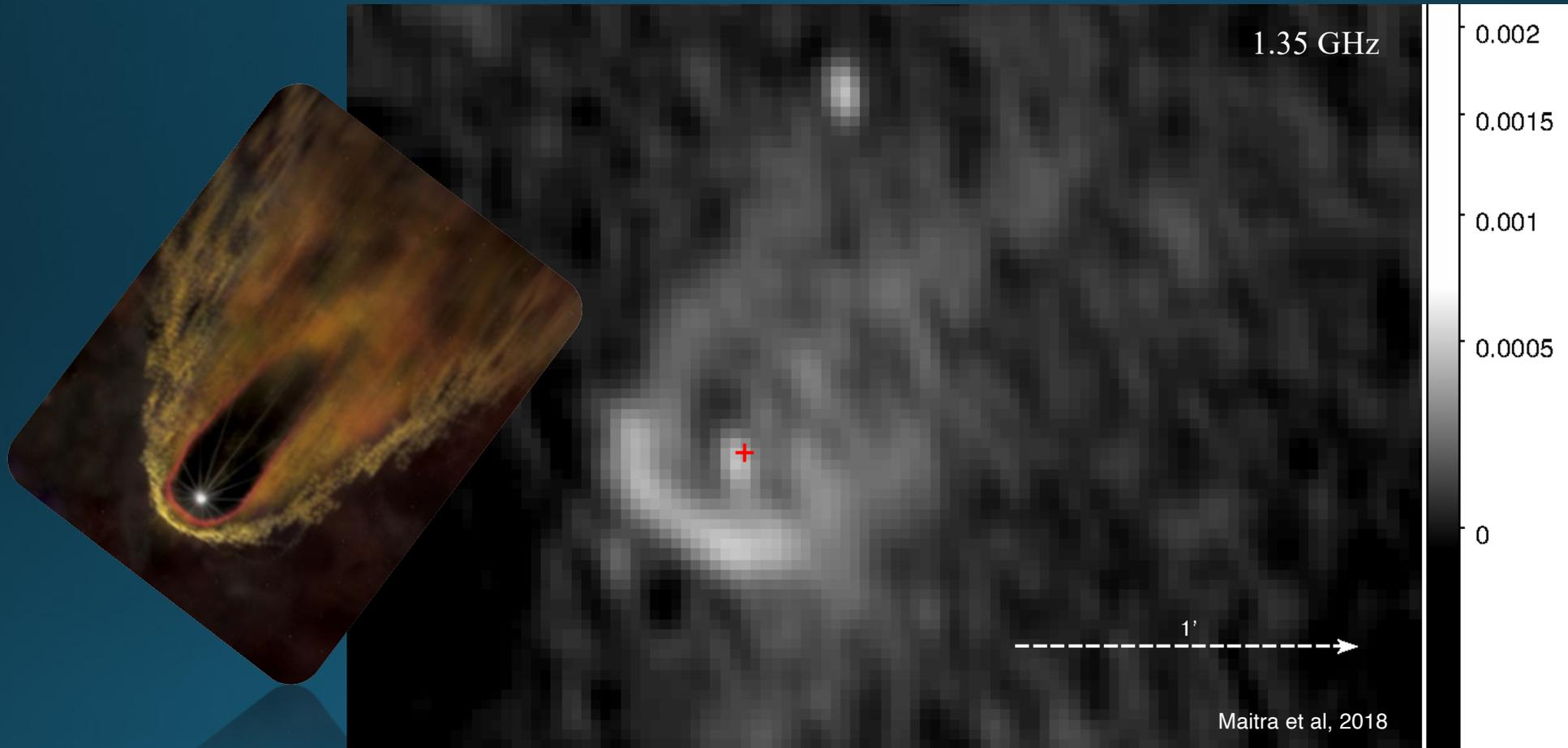
Ratio of neutral hydrogen (from X-ray spectral fits) to number of free electrons:

e.g. for PSR J1747–2958 and PSR 1757–24, which are located behind dense material: $N_H/\text{DM} = 85$ (40)

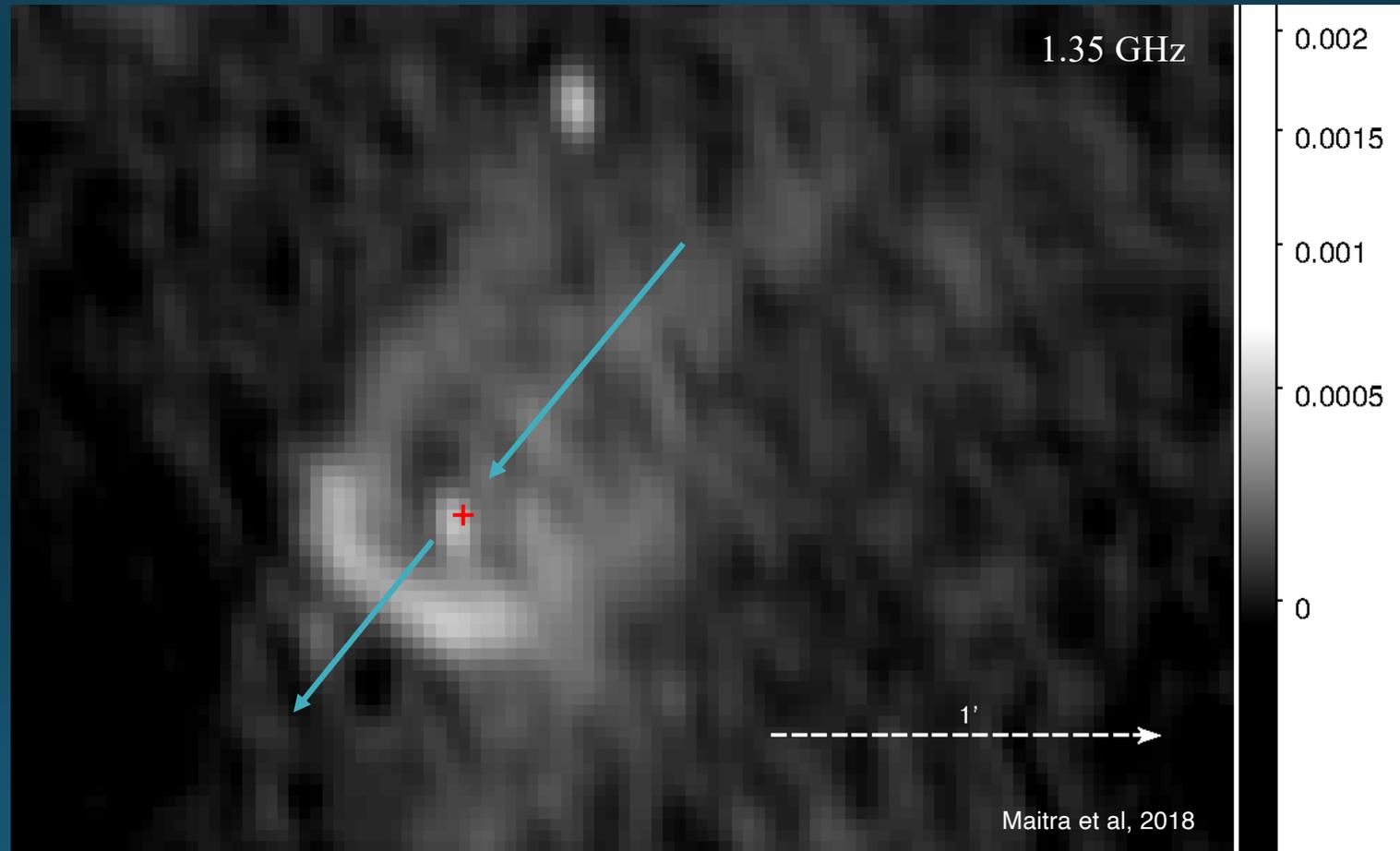
Typical values for other pulsars are of the order of 5 – 10

The value derived for PSR J0855–4644 is 8 ± 1.5 (Acero, et al., 2013)

PSR J0855-4644: radio bow-shock

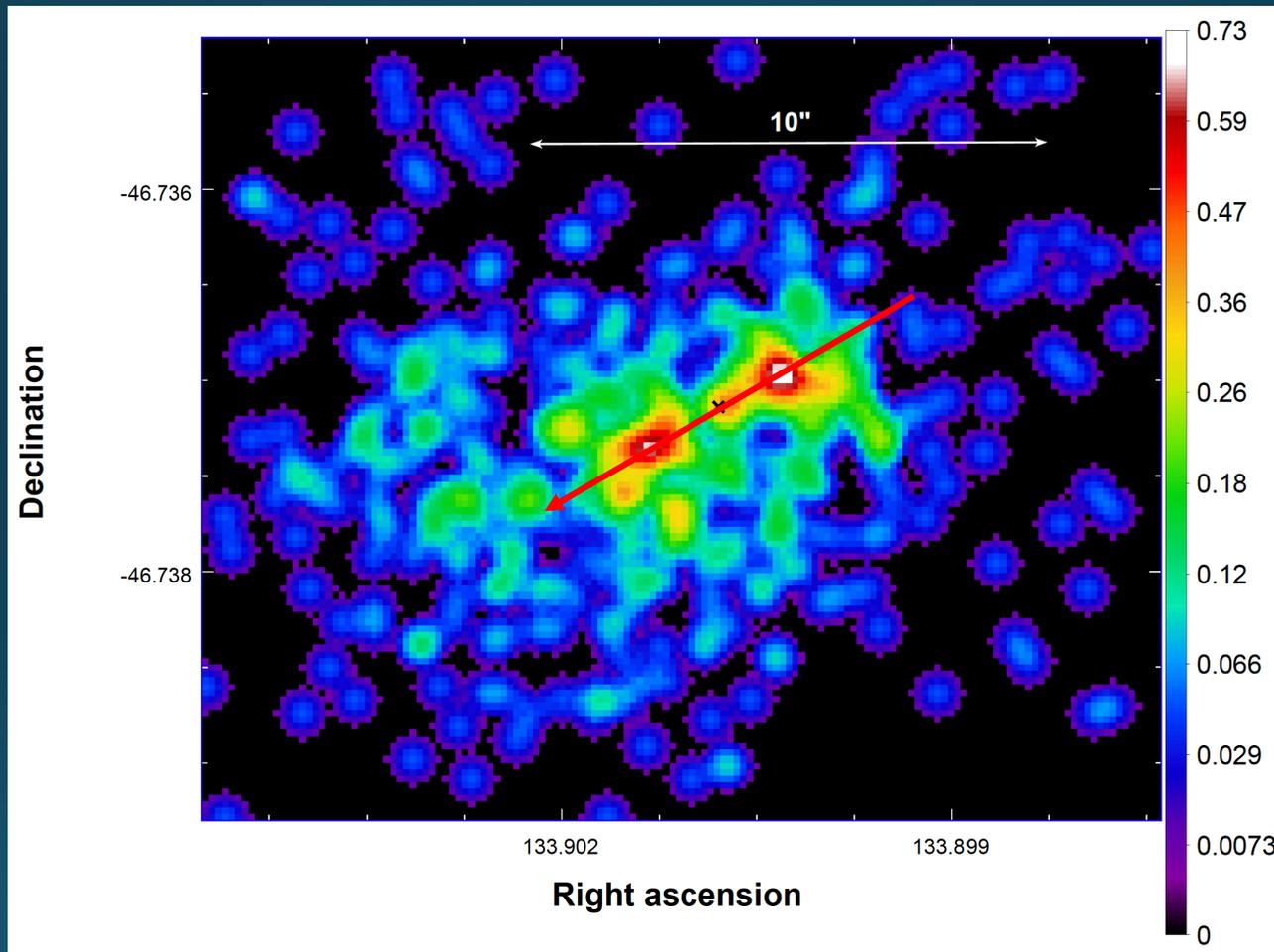


PSR J0855-4644: radio bow-shock



Velocity of the pulsar is estimated to be $V \sim 100$ km/s (Maitra et al, 2018)

PSR J0855-4644: X-ray bow-shock



Maitra et al 2017 : CXC pulsar wind

Vela & Friends: Vela Jr

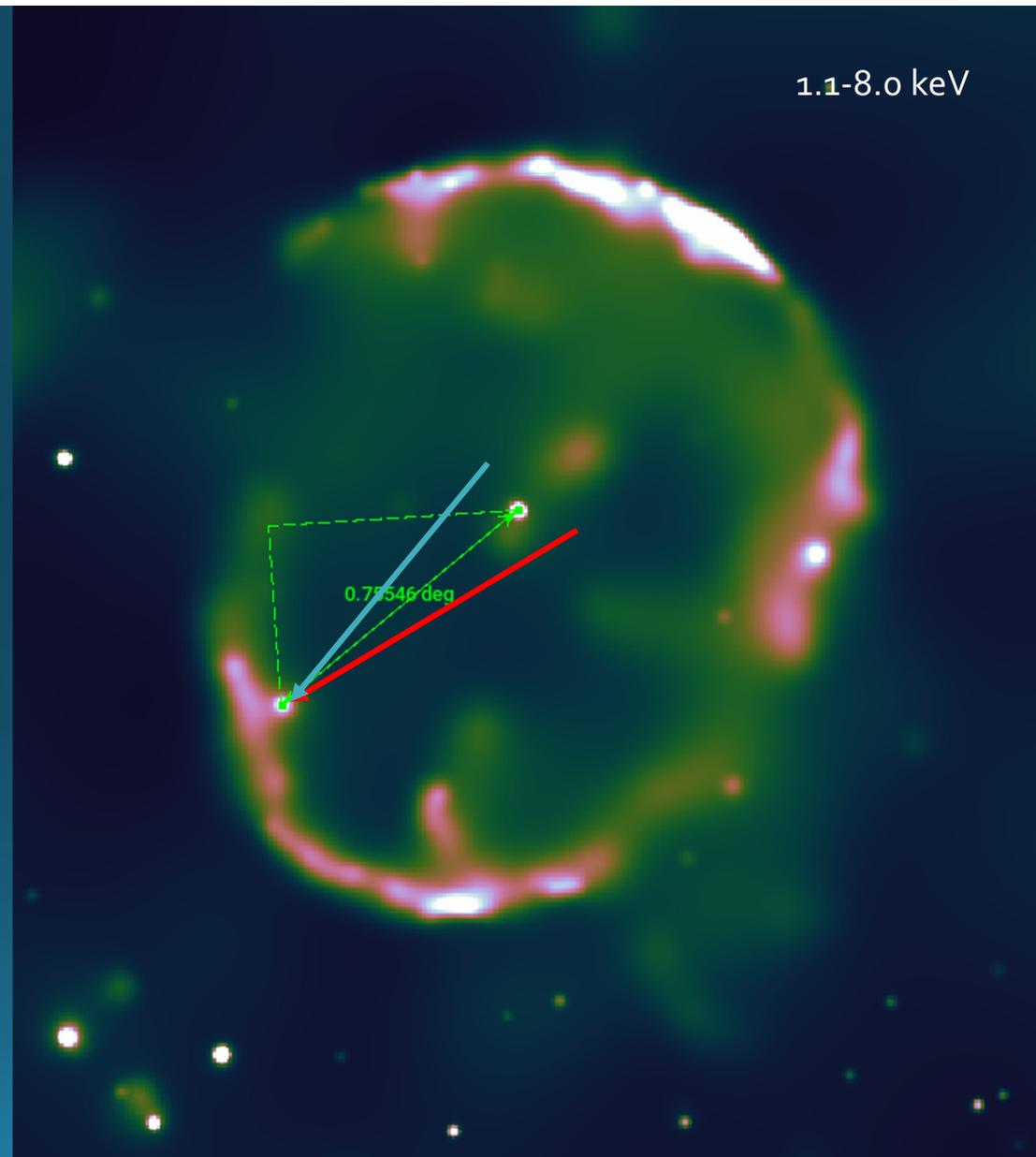
Distance between CCO and PSR Jo855-4644: ~ 0.74 deg

For Vela Jr at 1 kpc:

$V_{\text{PSR}} = 100$ km/s: It would require 1.26×10^5 yrs
to move from the position of
the CCO to its place in the shell

Would be in agreement with the pulsar's spin-down age
but probably not in agreement with the lifetime of the SNR

$V_{\text{PSR}} = 1000$ km/s: 12.600 yrs



Vela & Friends: Vela Jr

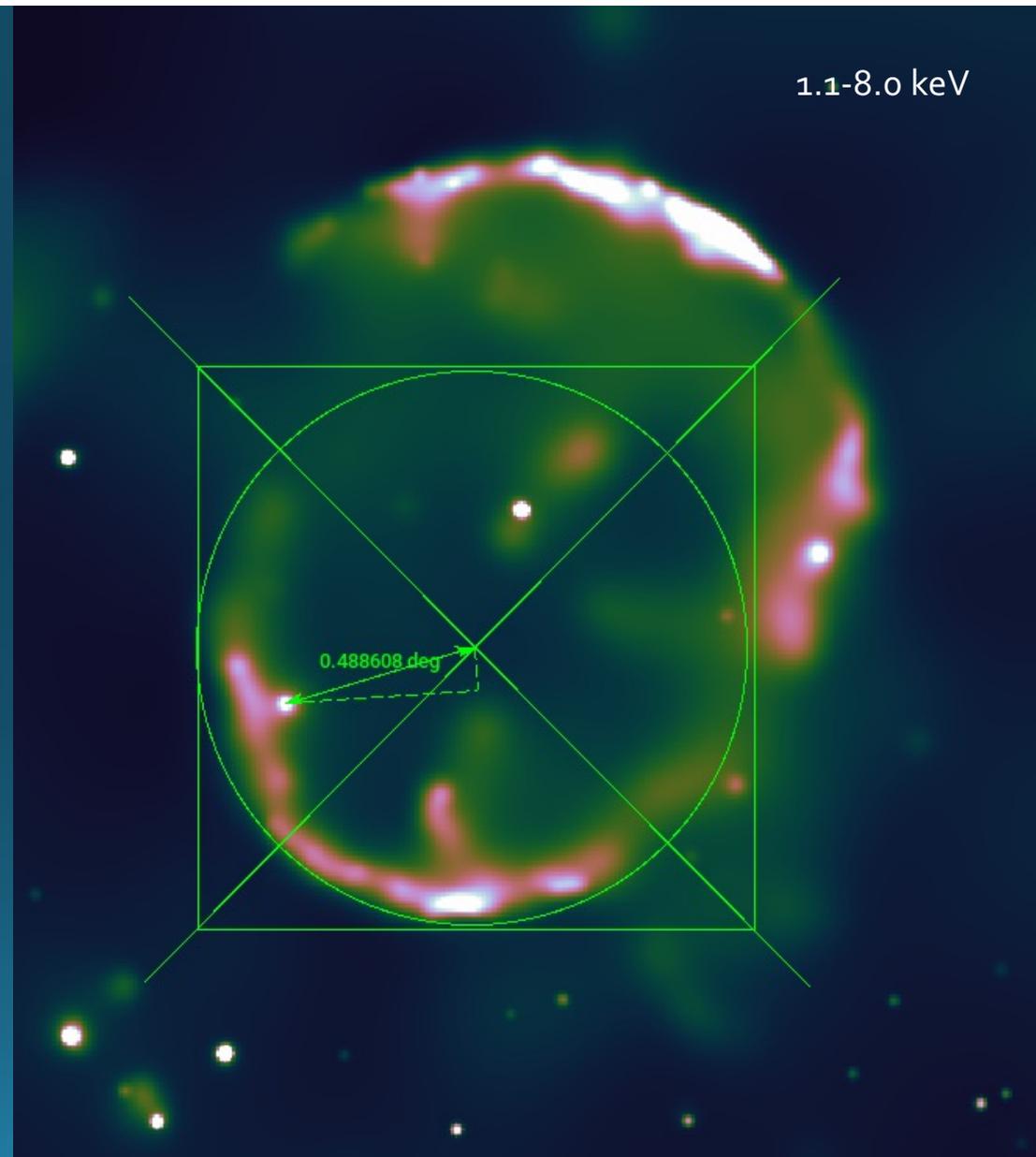
Distance between putative SN centre and PSR: ~ 0.5 deg

For distance of 1 kpc:

$V_{\text{PSR}} = 100$ km/s: It would require $\sim 85,000$ yrs
to move from a putative 2nd SN centre
to its position in the shell

$V_{\text{PSR}} = 1000$ km/s: ~ 8500 yrs

But the estimated PM directions don't really support this



Two Neutron Stars, Two Supernova Remnants?

Vela Jr, its CCO and PSR Jo855-4644

Conclusion:

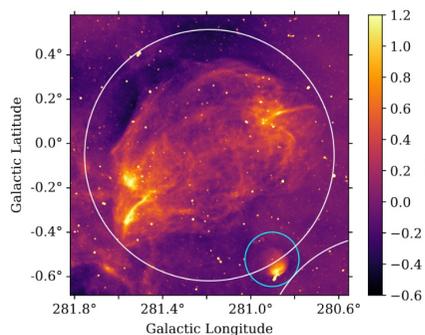
- PSR Jo855-4644 is at a distance comparable to Vela Jr
-
- We badly need a more accurate radio PM measurement
- to further constrain the PM direction and velocity of
- PSR Jo855-4644

Currently, the numbers are not fully consistent with the idea of having 2 SNRs here

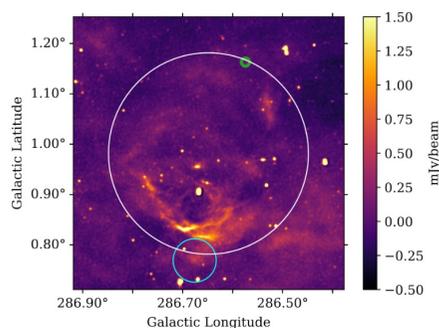
Maybe the ages are incorrect – a slim hope, I know, but stranger things have happened!

ASKAP & MeerKAT

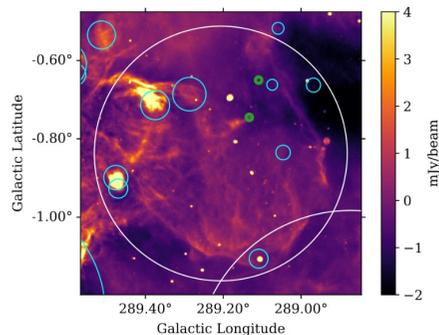




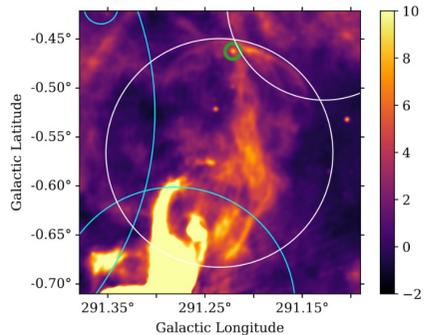
(a) G281.2-0.1



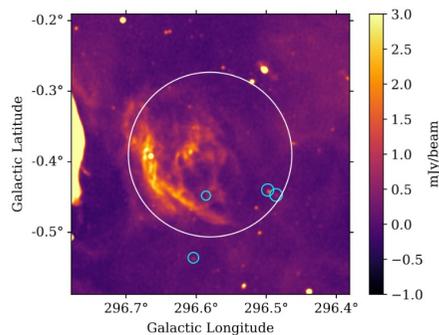
(b) G286.5+1.0



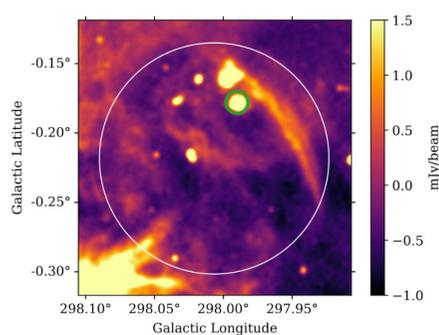
(c) G289.2-0.8



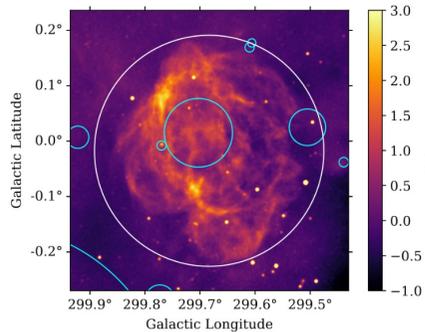
(d) G291.2-0.6



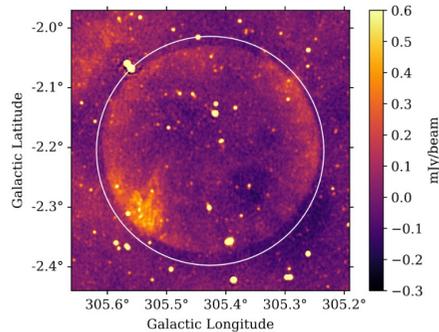
(e) G296.6-0.4



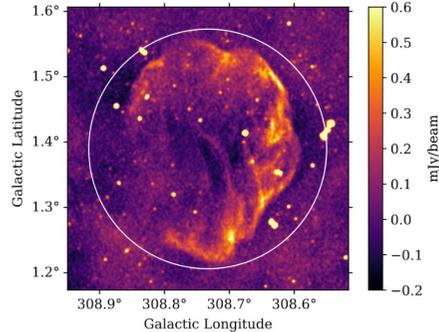
(f) G298.0-0.2



(g) G299.7-0.0



(h) G305.4-2.2



(i) G308.7+1.4

MeerKAT:

237 new Galactic SNR candidates in the SMGPS data (Anderson et al., 2025)

ASKAP:

~ 50 new Galactic SNRs & candidates (Ball et al., 2025)

eRASS:

~ 30 new Galactic SNRs & candidates (Becker, et al., 2026)

Is there a missing SNR problem?

There are several possible reasons for this „missing SNR problem“:

- SNRs may be too faint to be detected by current telescopes
- SNRs may be obscured by interstellar dust
- Some SNRs may have already dissipated into the ISM, making it difficult to distinguish them from other types of emission or leaving no trace of their past existence.
- The Core Collapse of very massive stars may not form an observable SN
- The lifetime of SNRs is overestimated.... e.g., a lifetime of 30.000 yrs → ~ 600 SNRs are expected to be seen

eROSITA + synergies from MeerKAT & ASKAP provide a promising window to explore known SNRs and to search for yet-undiscovered ones

Supernova Remnants Science with eROSITA and the new MeerKAT and ASCAP radio surveys

Exciting times !





TOPICS:

- Stars
- Compact Objects
- Supernova Remnants
- ISM and Galactic diffuse emission
- Population studies of galactic sources

Review talks by:

Christian Schneider, Yaël Nazé, Anna Watts, Marta Burgay, Robert Fesen, Anne Decourchelle, Steeve Body, Rainer Raupach, Mike Yeung, Martin Mayer, Elias Kyritsis, Basu-Zych

Galactic Frontiers 2026: Advancing X-Ray Astronomy in a Multiwavelength Universe

858. WE-Heraeus-Seminar

15 Jun - 18 Jun 2026



Where:

Physikzentrum Bad Honnef

Scientific organizers:

Prof. Dr. Werner Becker, MPI für extraterr. Physik, Garching *
Prof. Dr. Manami Sasaki, Dr. Karl Remeis-Sternwarte, Friedrich-Alexander-Universität, Erlangen-Nürnberg

The proposed WE-Heraeus seminar “Galactic Frontiers 2026” aims to bring together leading scientists and early-career researchers in the field of Galactic X-ray astronomy to explore recent advances enabled by the eROSITA X-ray telescope. eROSITA’s all-sky survey provides an unprecedented dataset for studying both diffuse and point-like X-ray sources