

X-raying the Stellar Graveyard

Mapping Supernova Remnants with eROSITA

Martin Mayer

Remeis Observatory Bamberg (ECAP/FAU Erlangen, Germany)

NewAthena Science Webinar – 13.11.2025

FAU



Outline

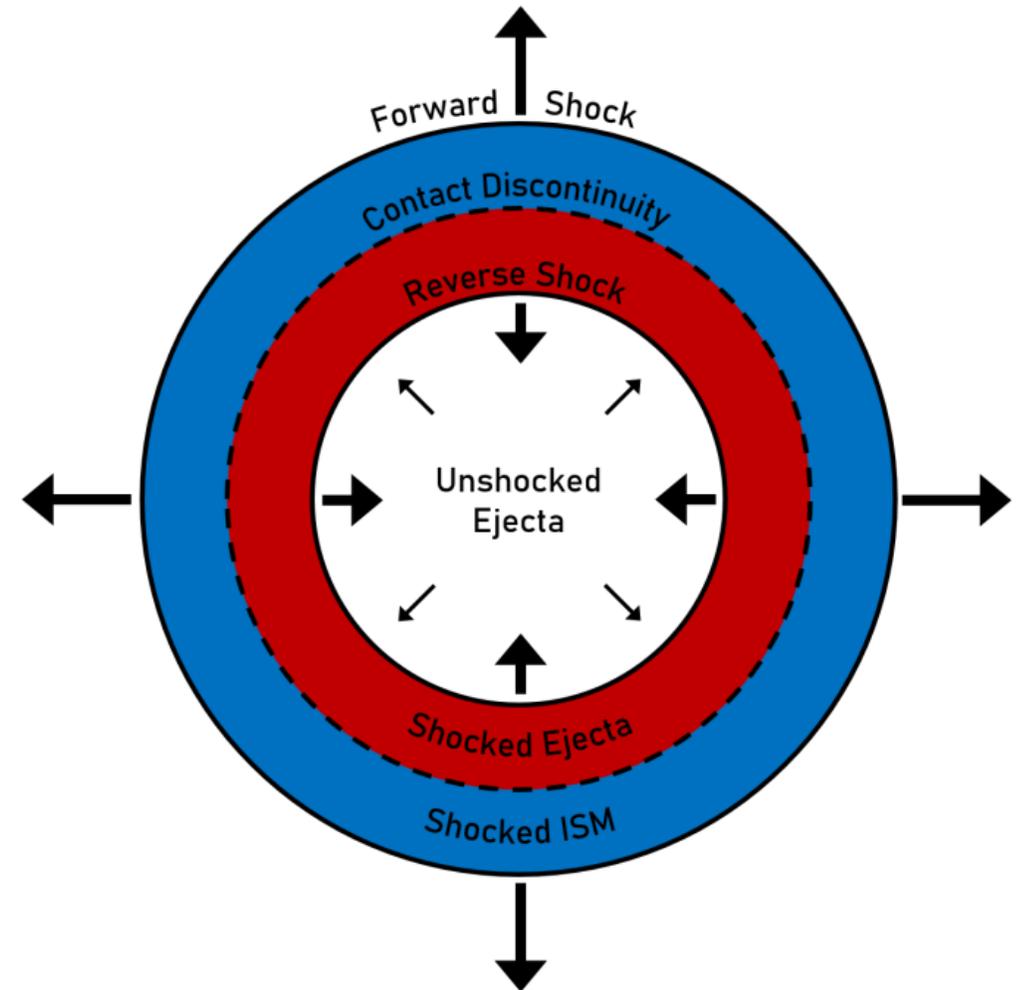
- Introduction
 - X-ray emission from supernova remnants
 - SRG/eROSITA and its all-sky survey
- The stellar graveyard with eROSITA
 - Serendipitous discoveries
 - Vela & Friends: Mapping extended objects with eROSITA
 - SNR populations in other galaxies
- The future with NewAthena

A vibrant, multi-colored nebula or galaxy core, featuring a mix of red, orange, yellow, green, blue, and purple hues. The central region is particularly bright and dense, with a prominent blue and purple structure. The background is dark, with scattered blue and green points of light.

Introduction

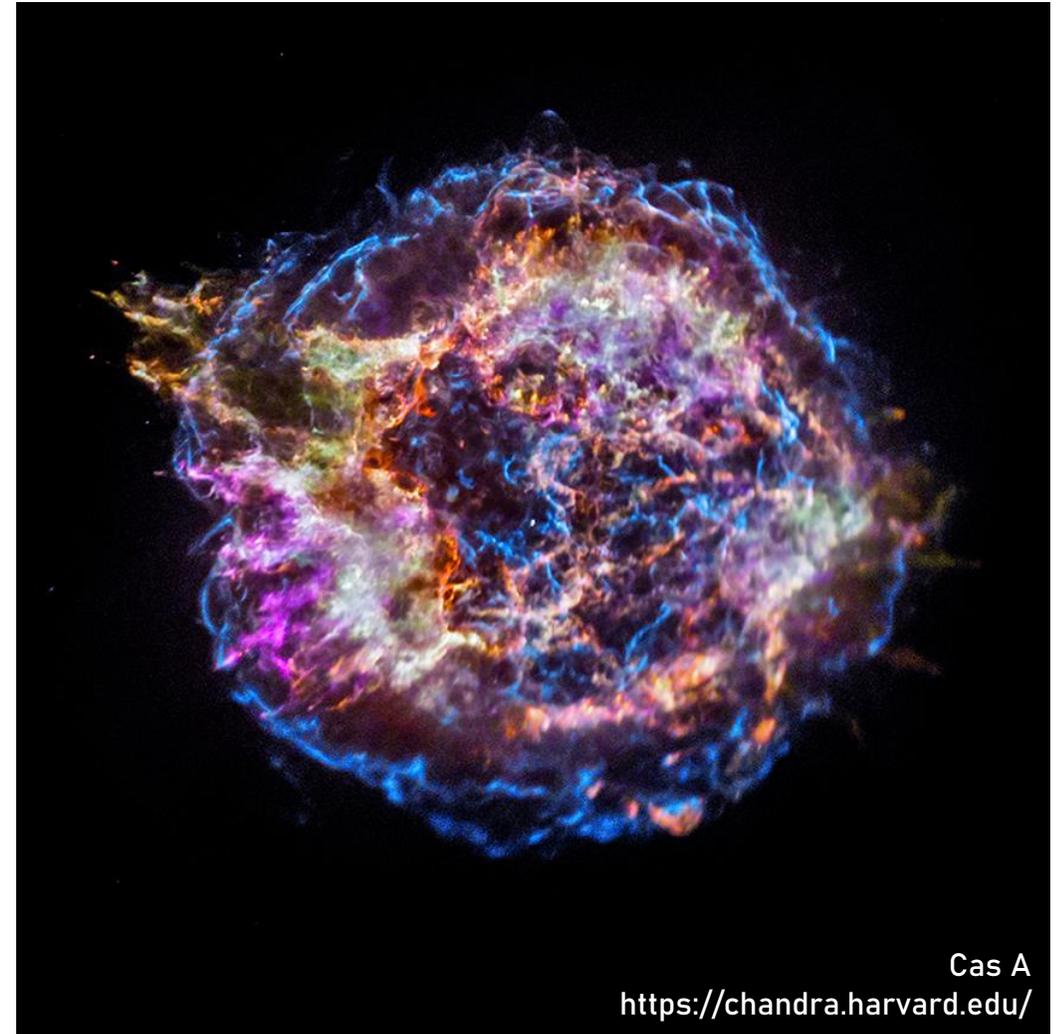
X-ray Emission of Supernova Remnants

- Supernova remnant (SNR) expanding into environment
 - Forward shock heats interstellar medium ($\sim 10^7$ K); Particle acceleration (GeV-TeV energies)
 - Reverse shock heats supernova ejecta



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 - Thermal bremsstrahlung + line emission (O, Si, Fe, ...)
 - Synchrotron radiation in magnetic field ($B \sim 10^{-5} - 10^{-4}$ G)



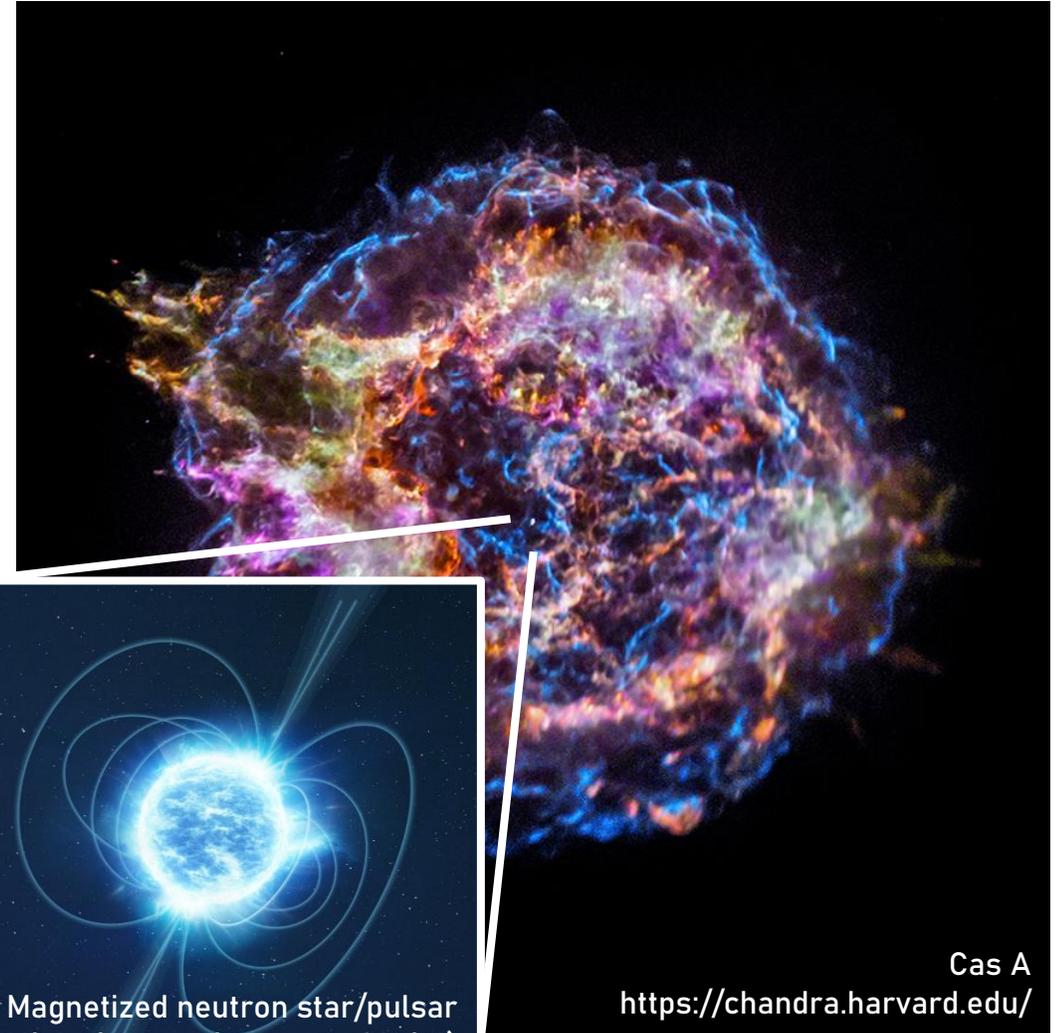
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- X-ray studies of SNRs:
 - Nucleosynthetic products of supernovae
 - Collisionless shock-heating of interstellar medium
 - Cosmic ray acceleration



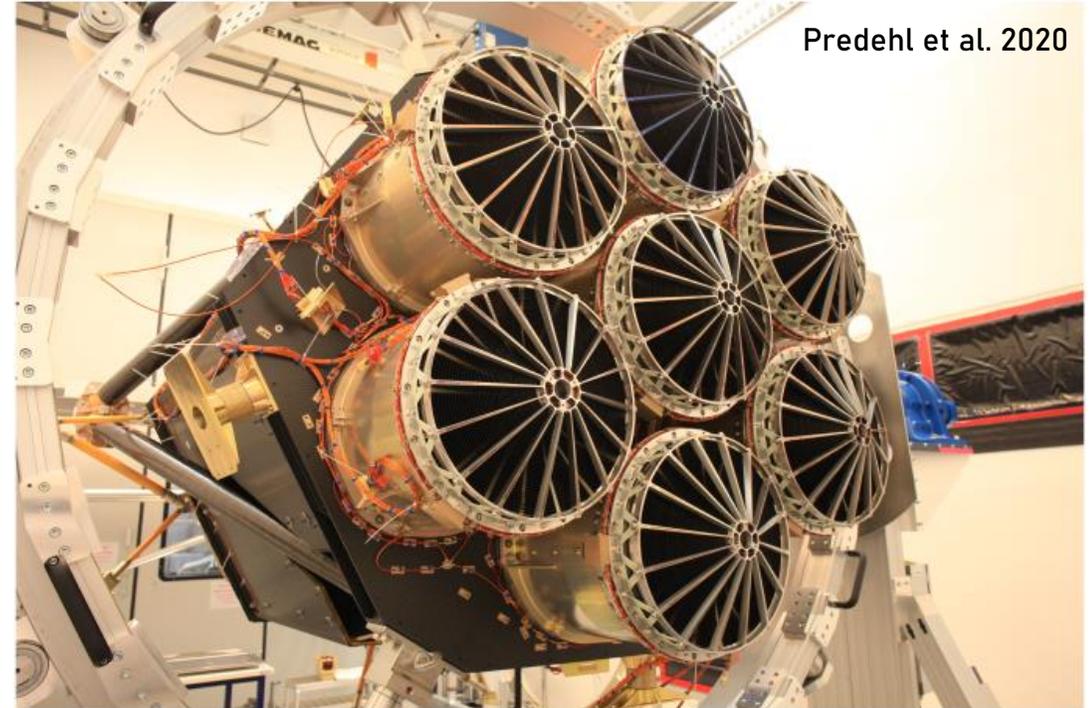
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The SRG/eROSITA telescope

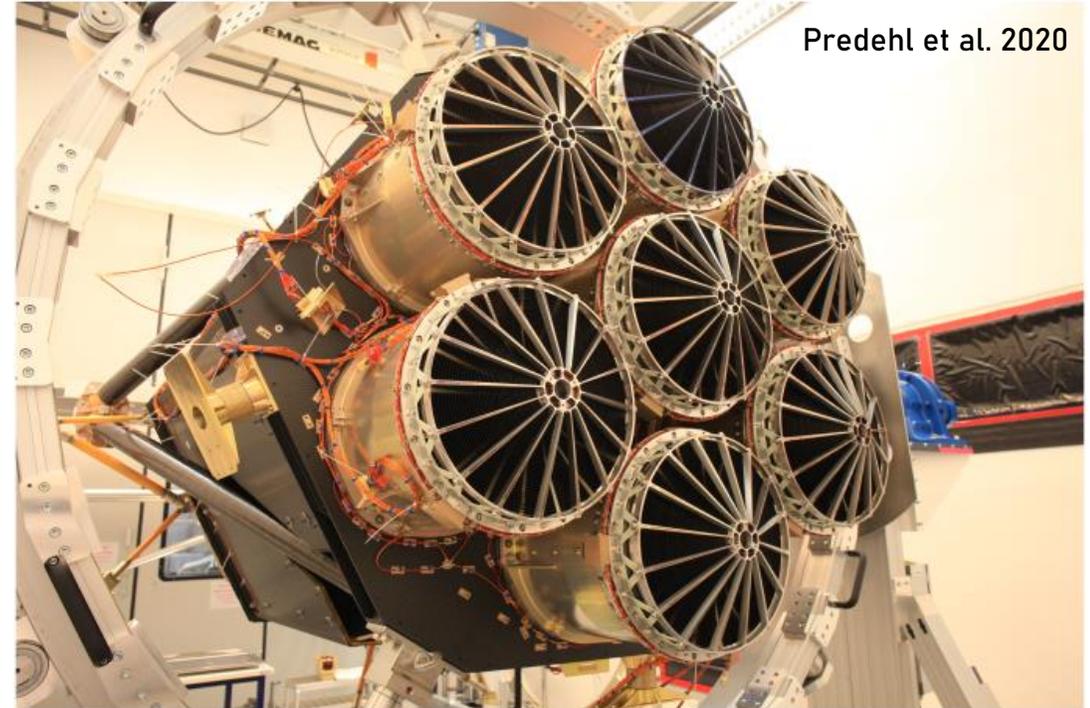
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 - Original mission goal: 4-year all-sky X-ray survey, ~ 25 times deeper than precursor ROSAT
 - 2.2 years achieved until mission interruption (Feb 2022)



Predehl et al. 2020

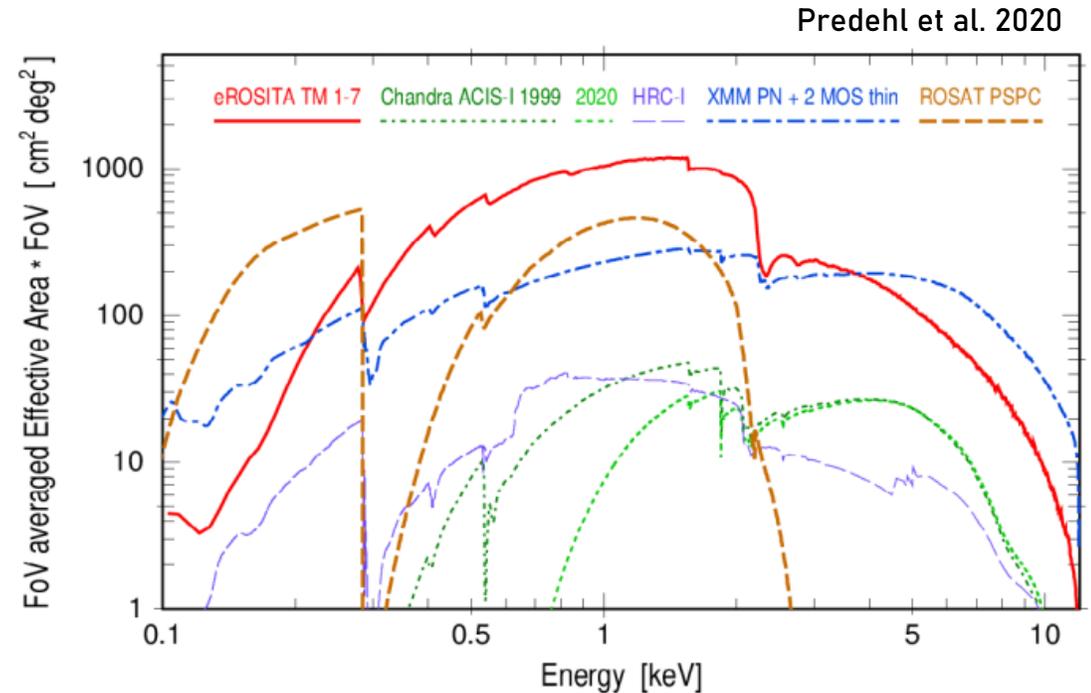
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 - Large combined effective area

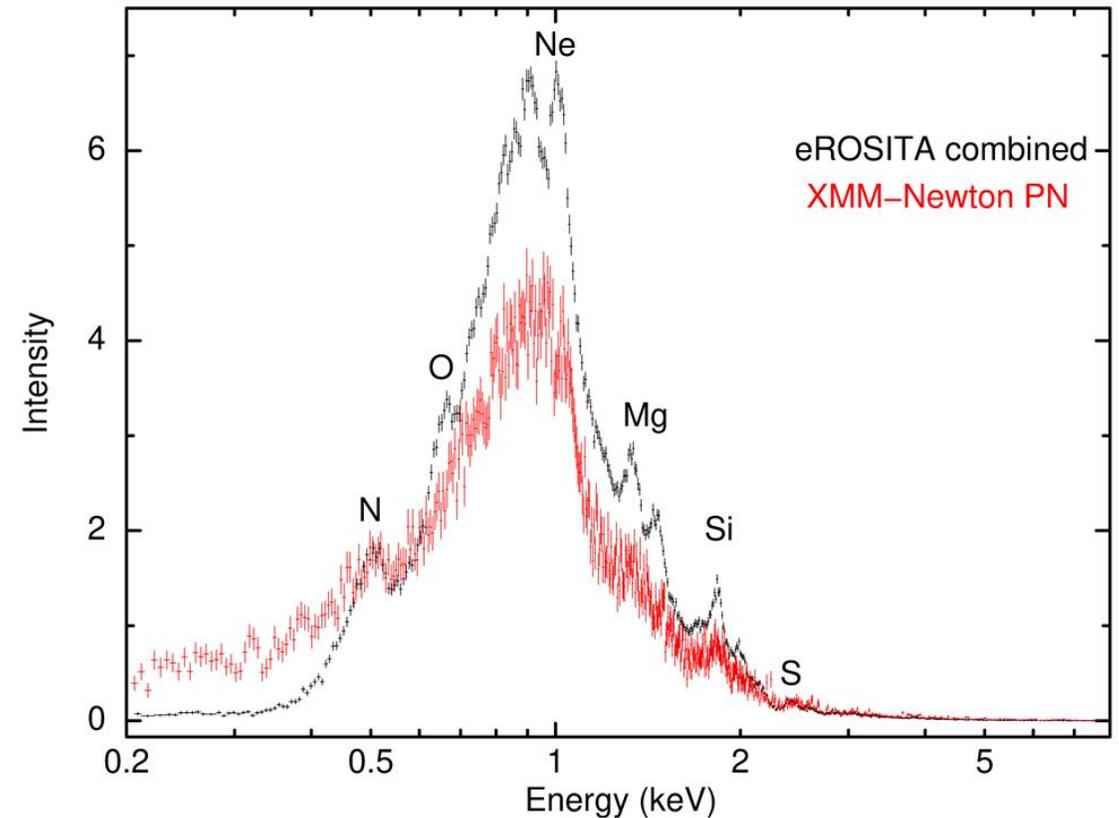


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 - Improved spectral resolution (cf. XMM EPIC-pn)

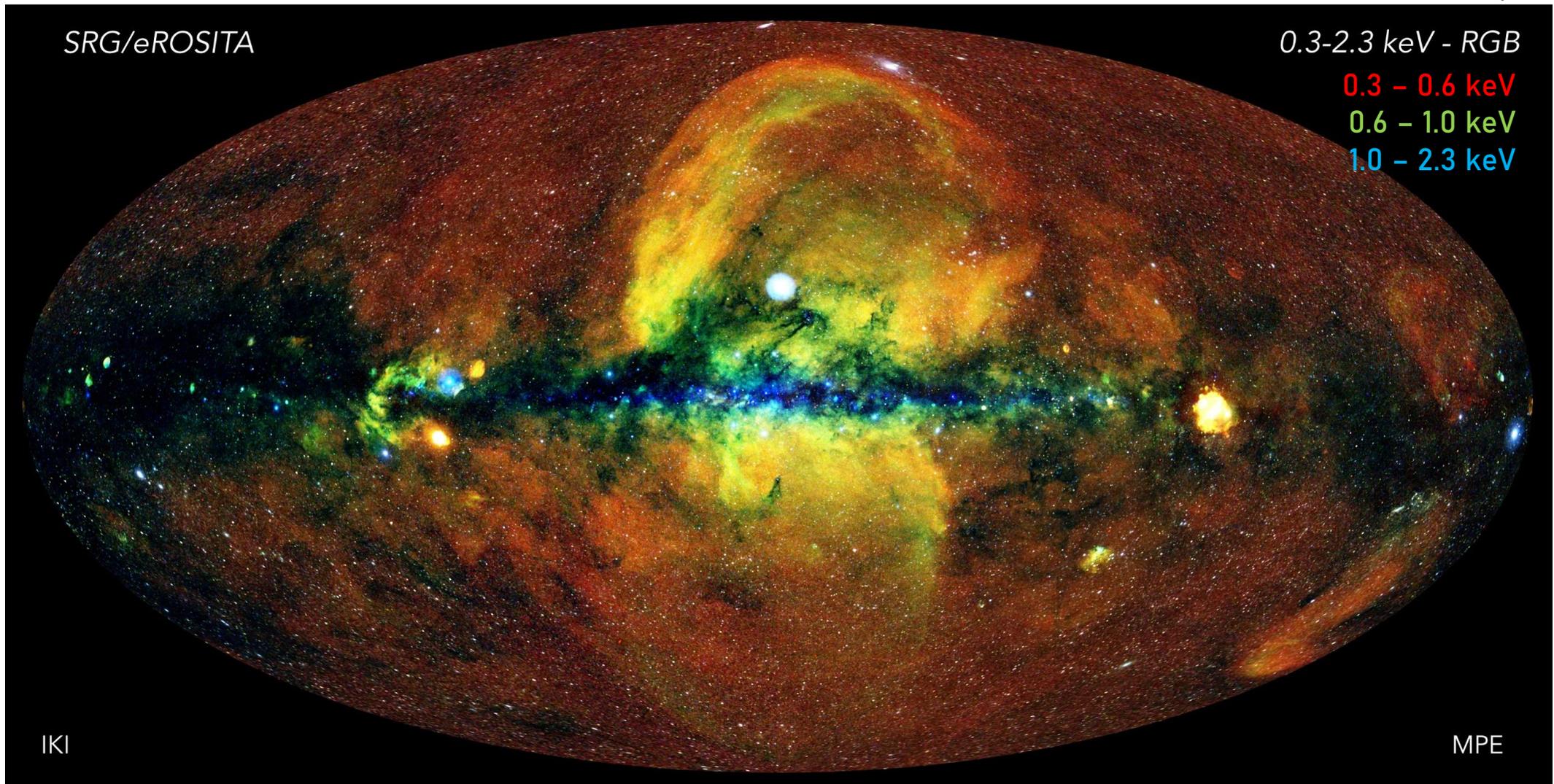
eROSITA first-light press release
C. Maitra, F. Haberl (MPE)

SN 1987A in the LMC



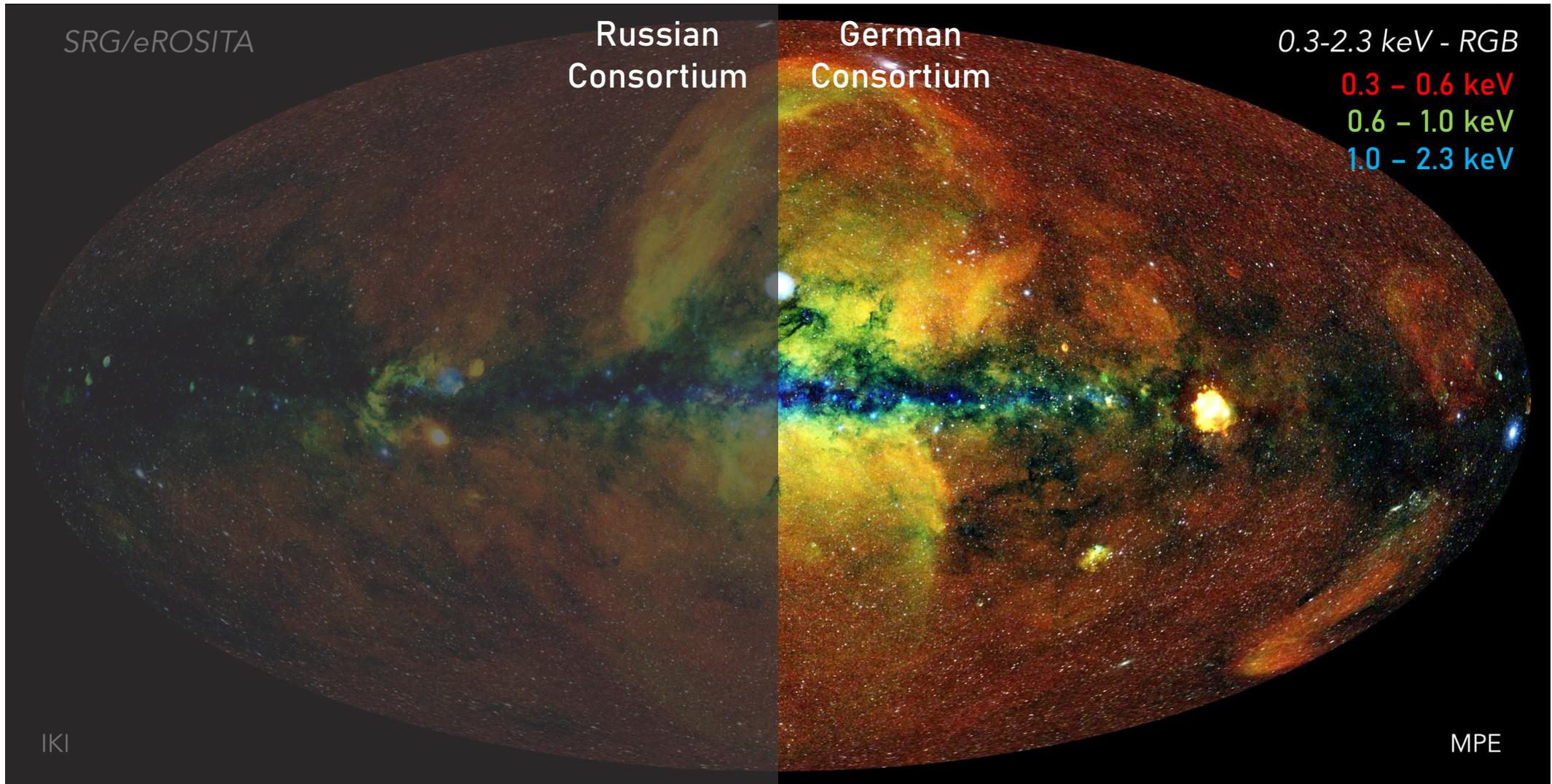
eROSITA All-Sky Survey (eRASS)

eRASS1 all-sky image
Credit: MPE/IKI

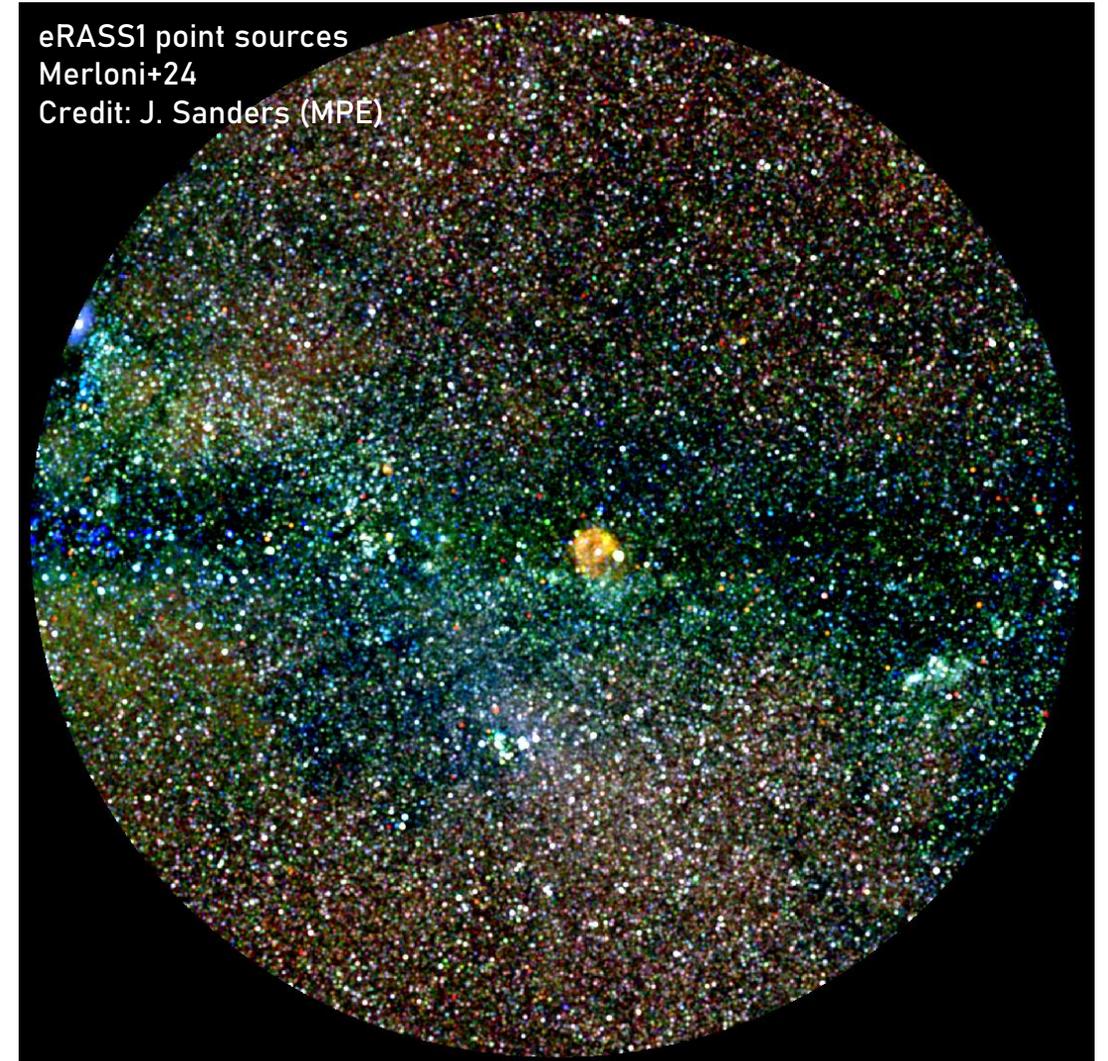
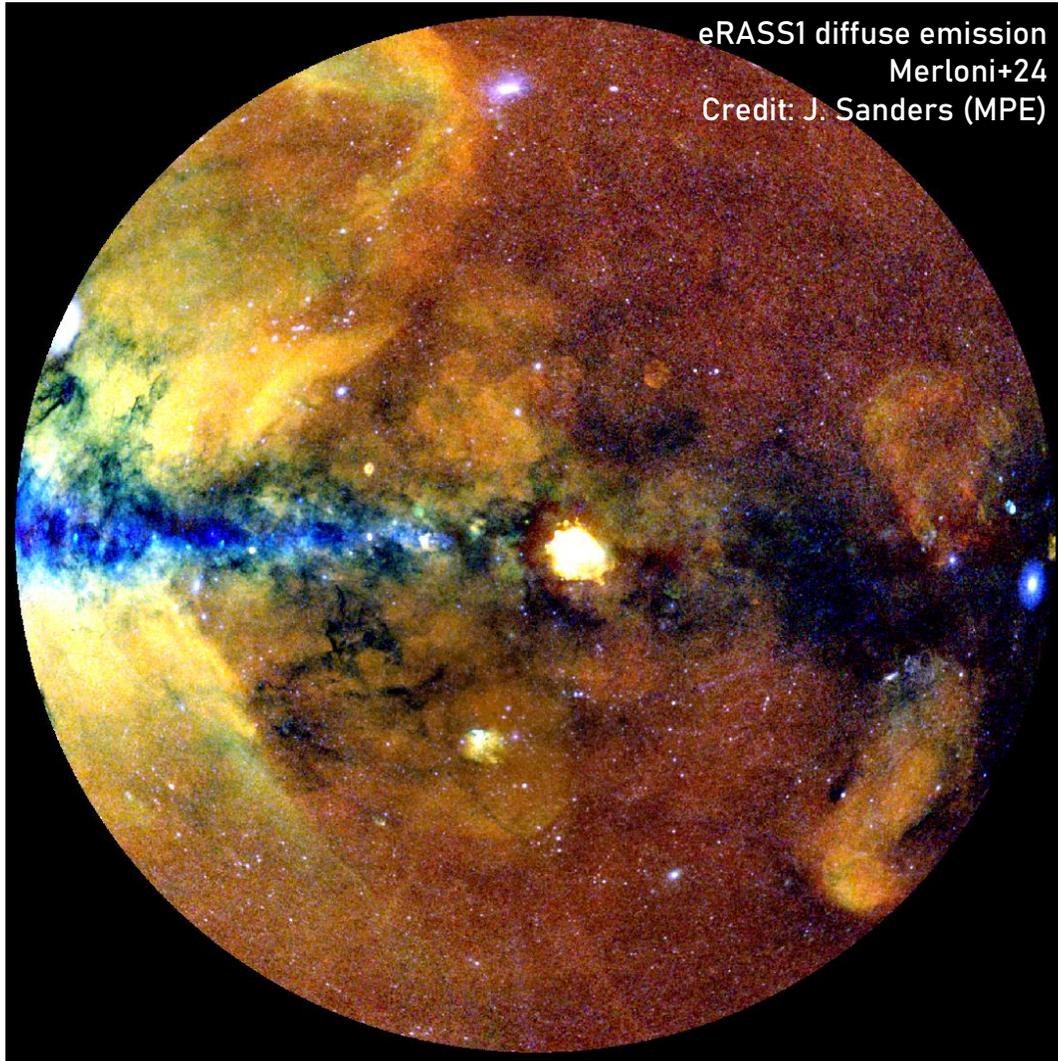


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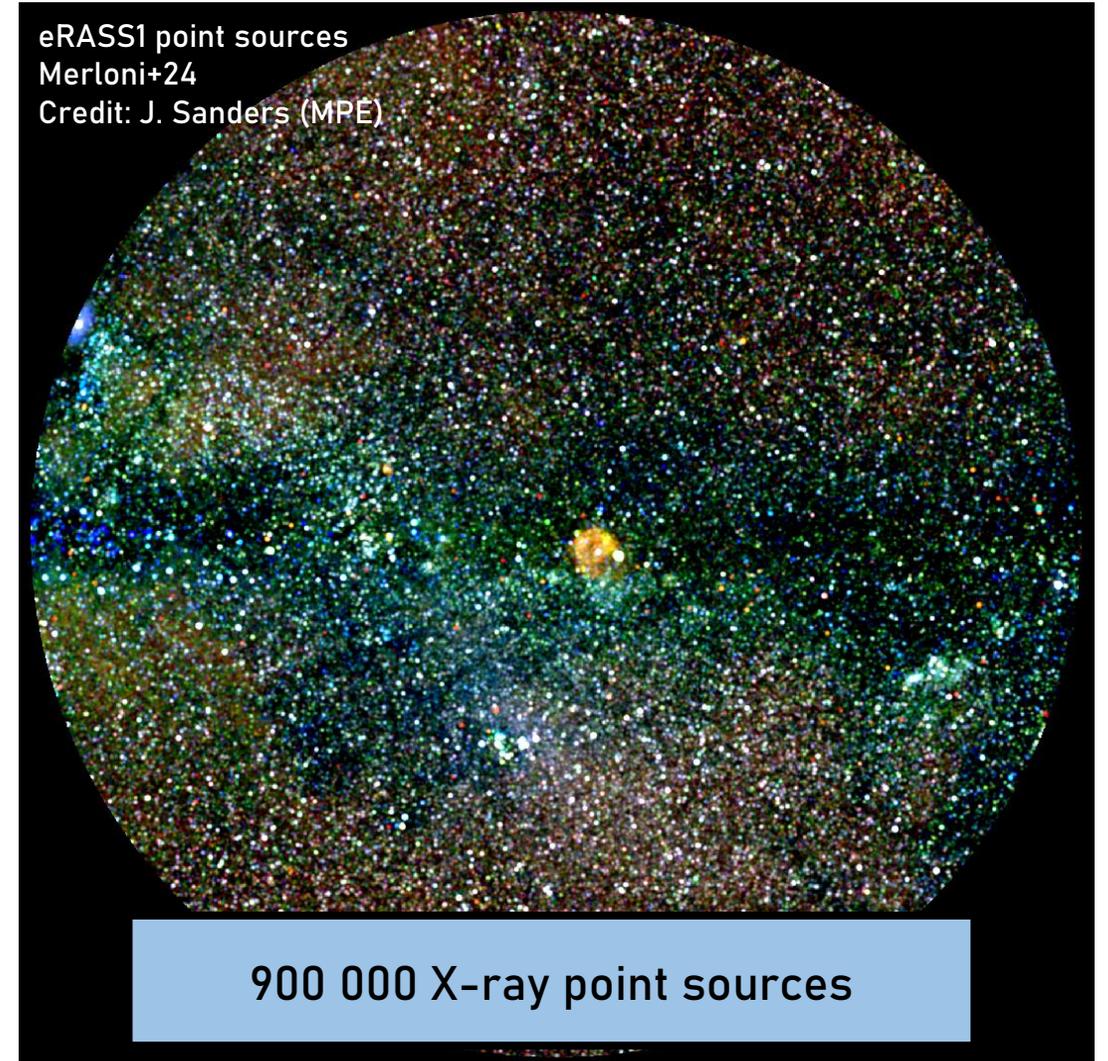
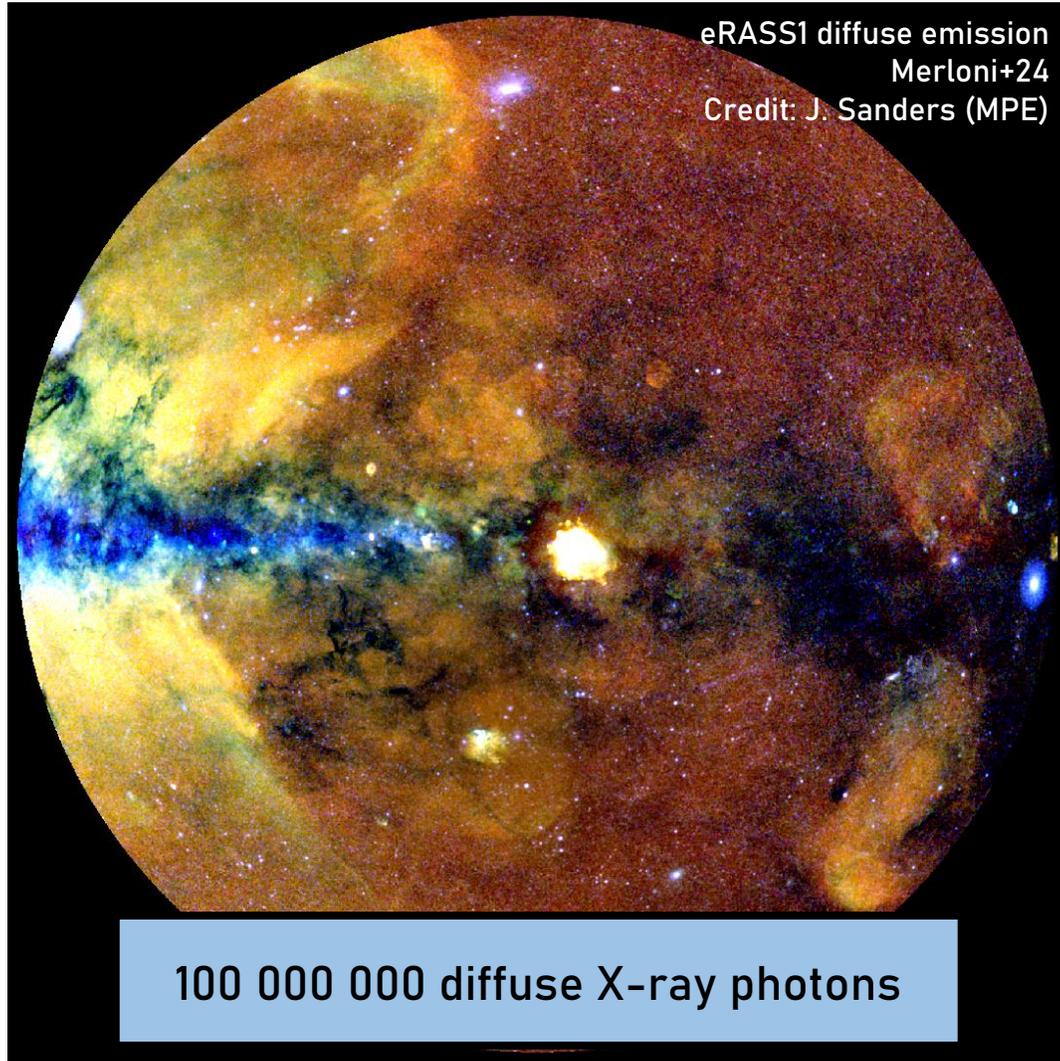
eRASS1 all-sky image
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eROSITA DR₁: The First All-Sky Survey (eRASS₁)



eROSITA DR₁: The First All-Sky Survey (eRASS₁)

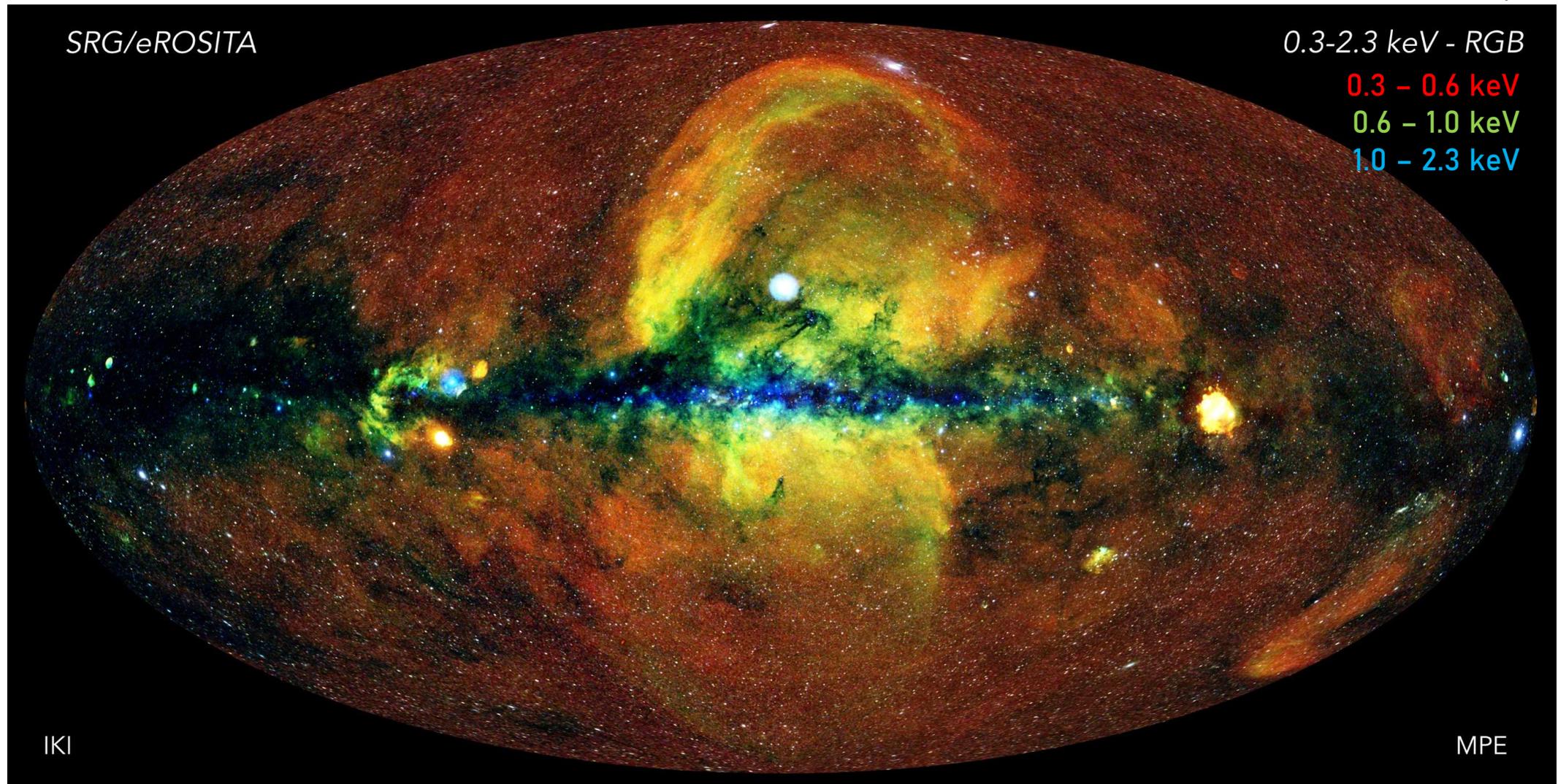




eROSITA Discoveries

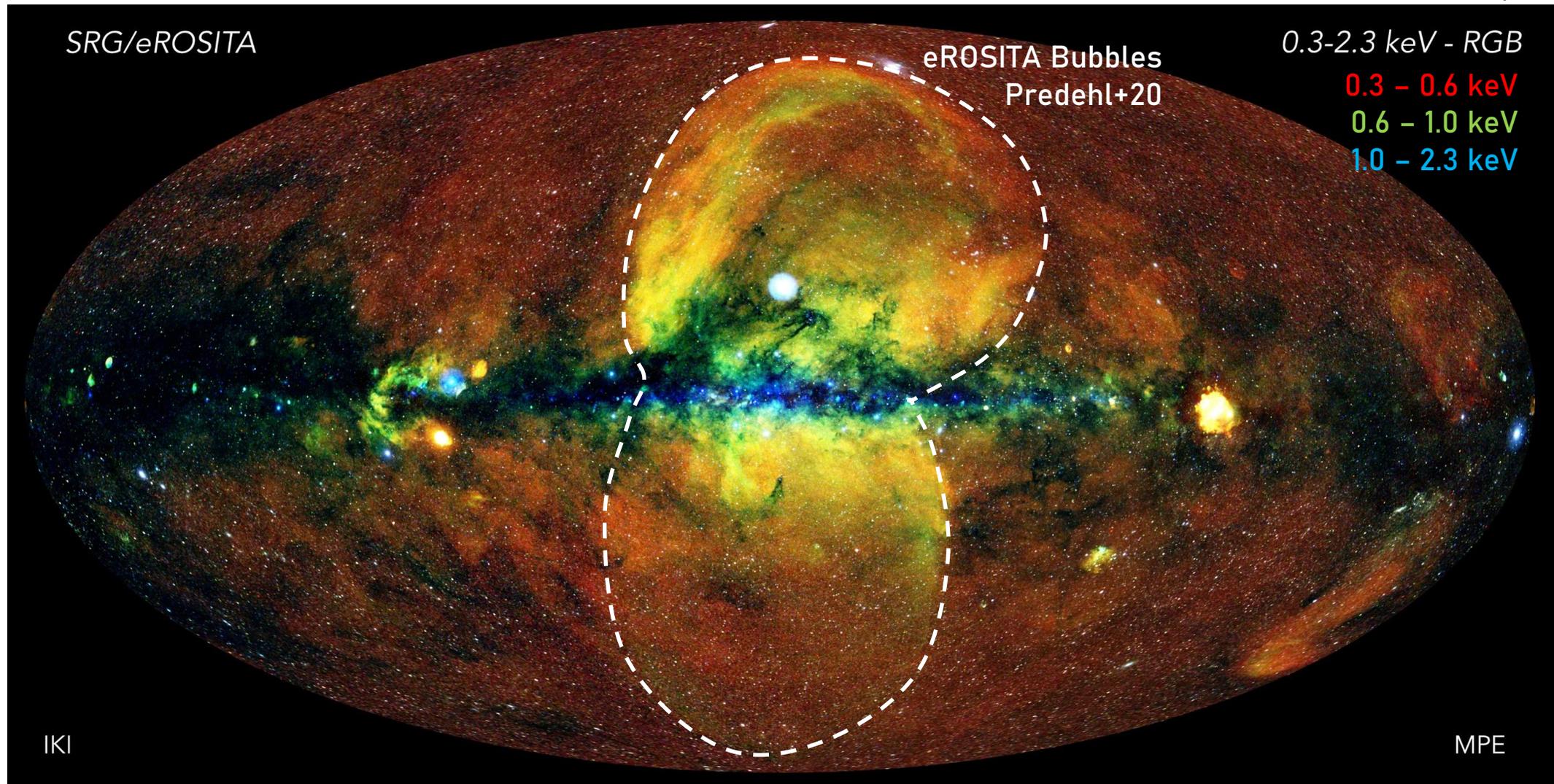
The eROSITA All-Sky Map

eRASS1 all-sky image
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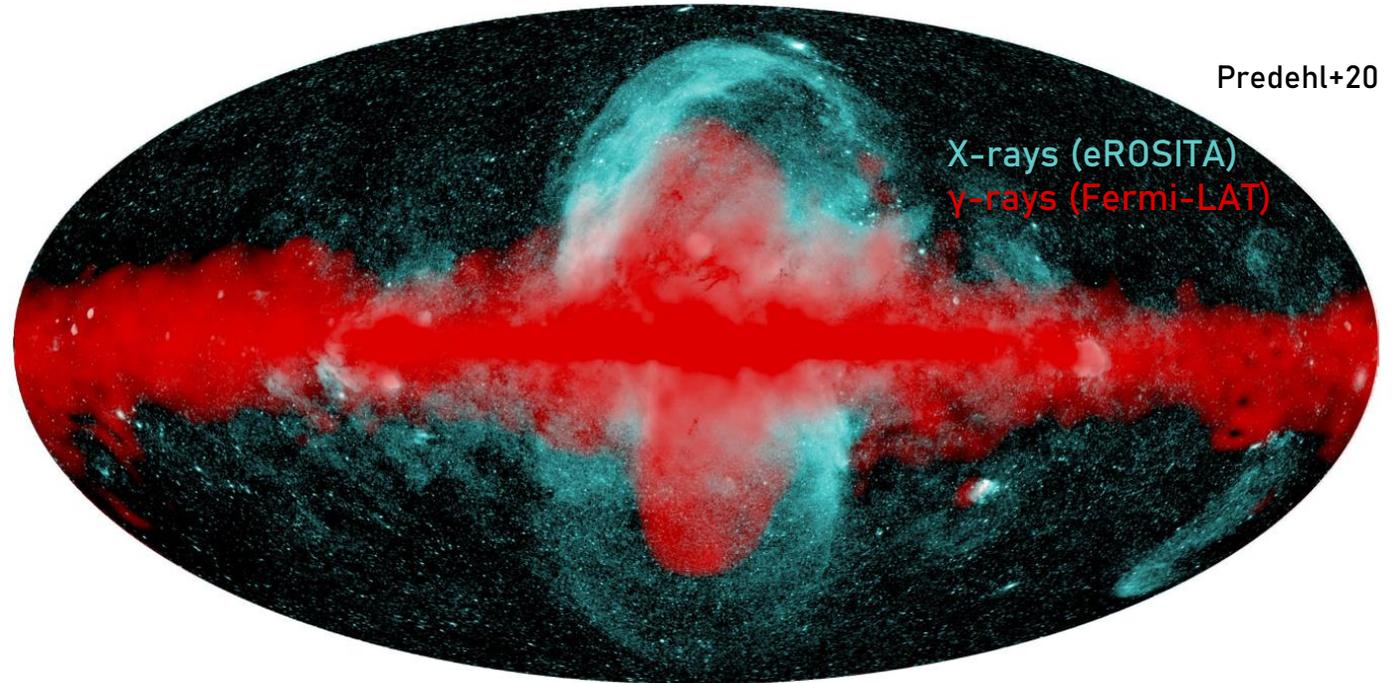
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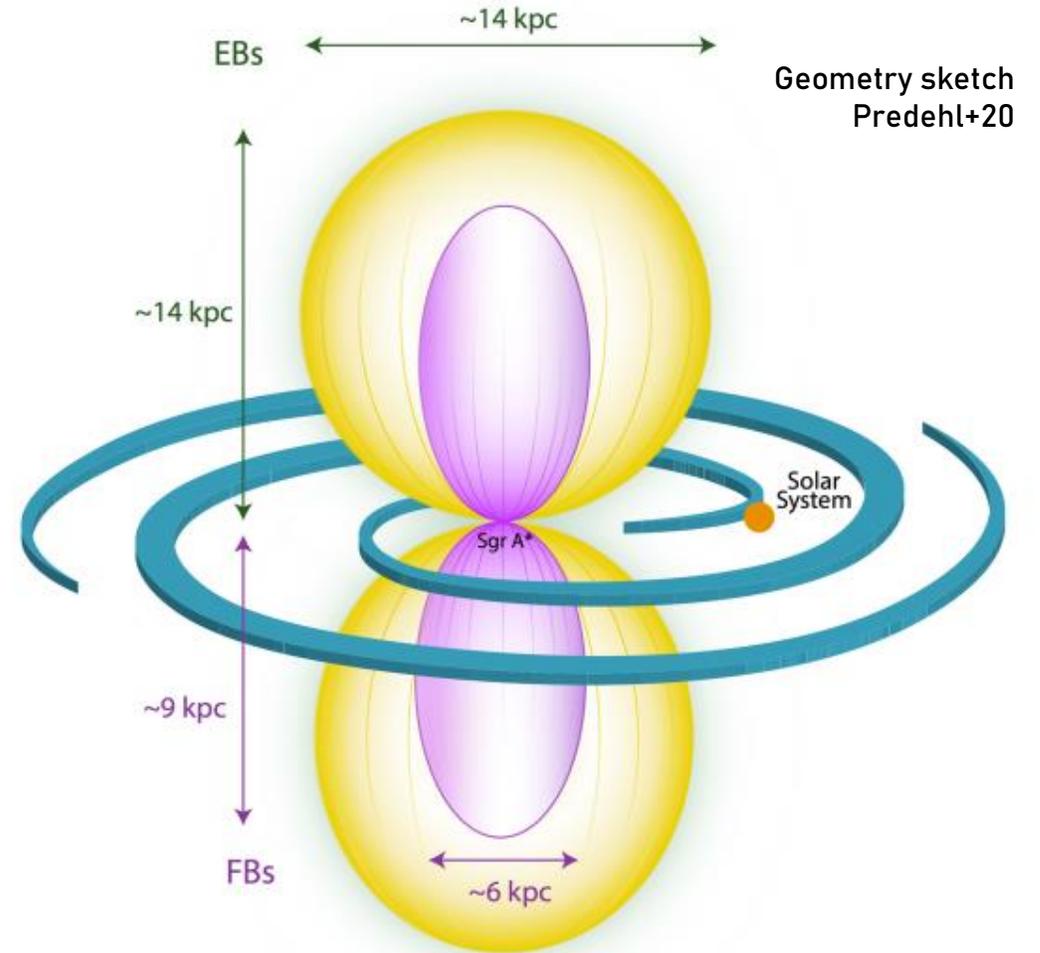
eROSITA & Fermi Bubbles

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- Origin: Nuclear starburst or supermassive black hole outburst? (Predehl+20)

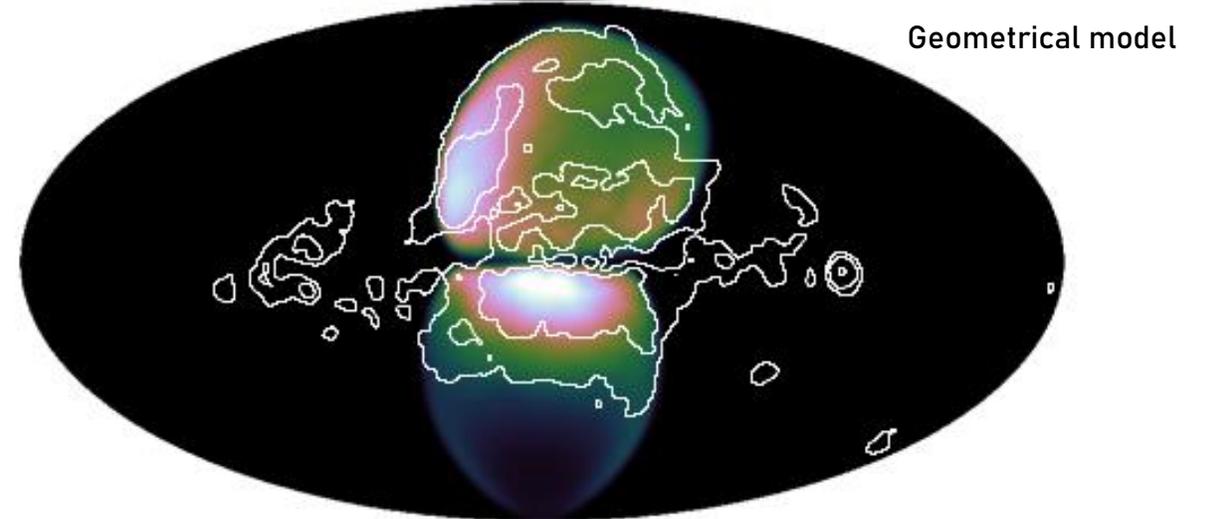
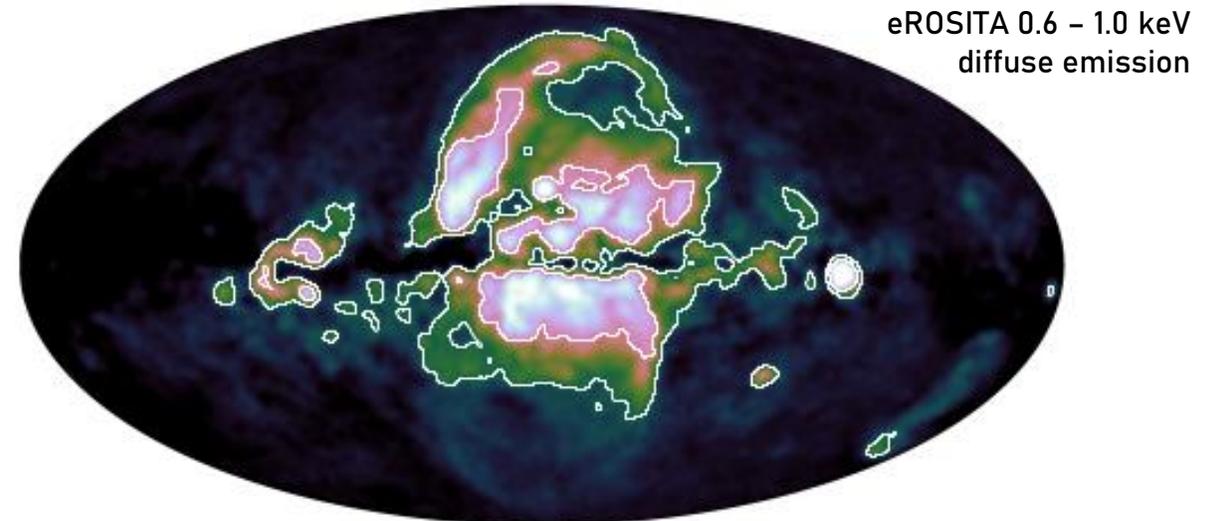


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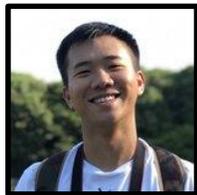


M. Yeung,
M. Mayer,
et al., in prep.

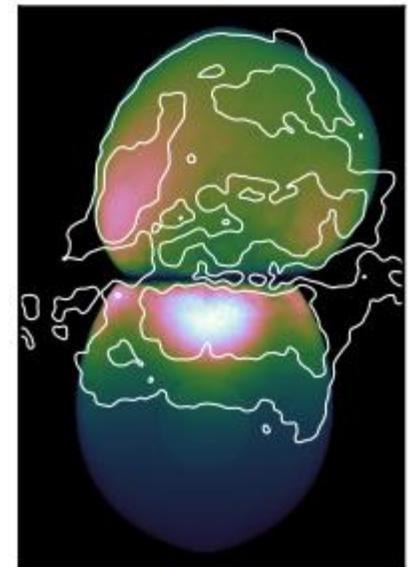
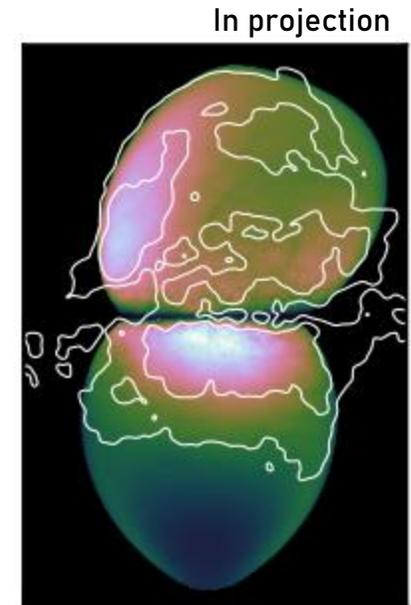
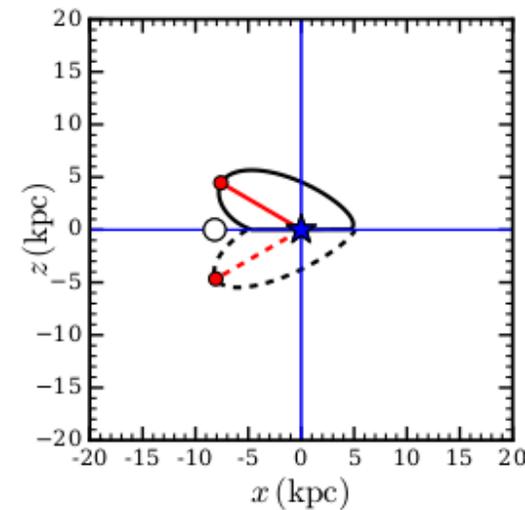
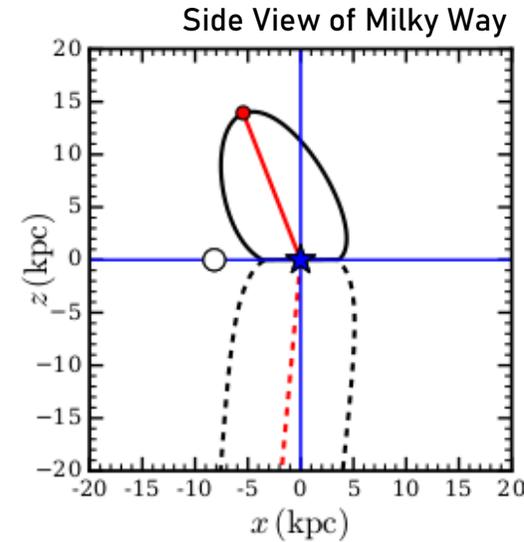


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- Morphology reproducible with giant blast wave from Galactic center
- Vertical extent of emission hard to constrain

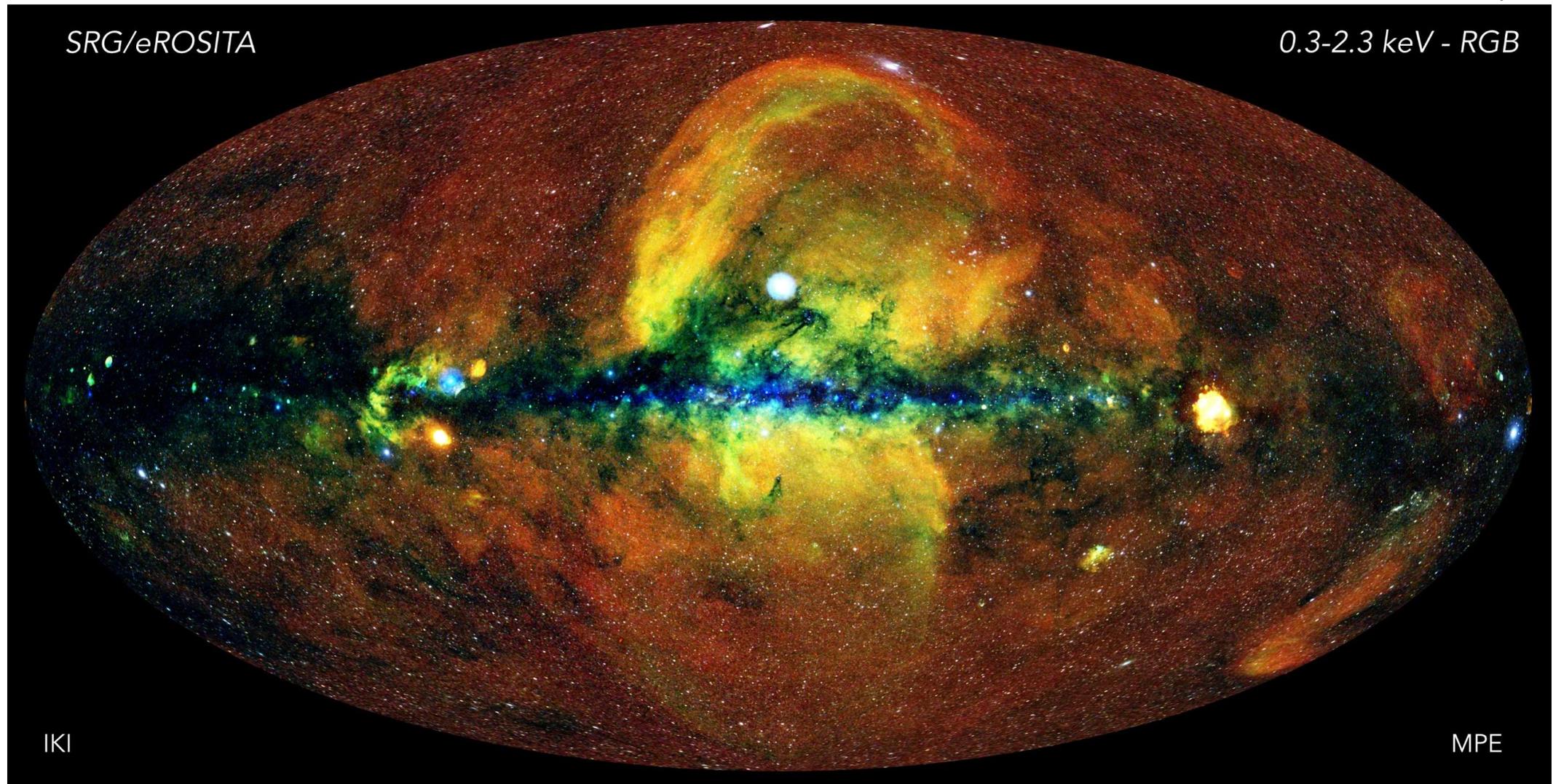


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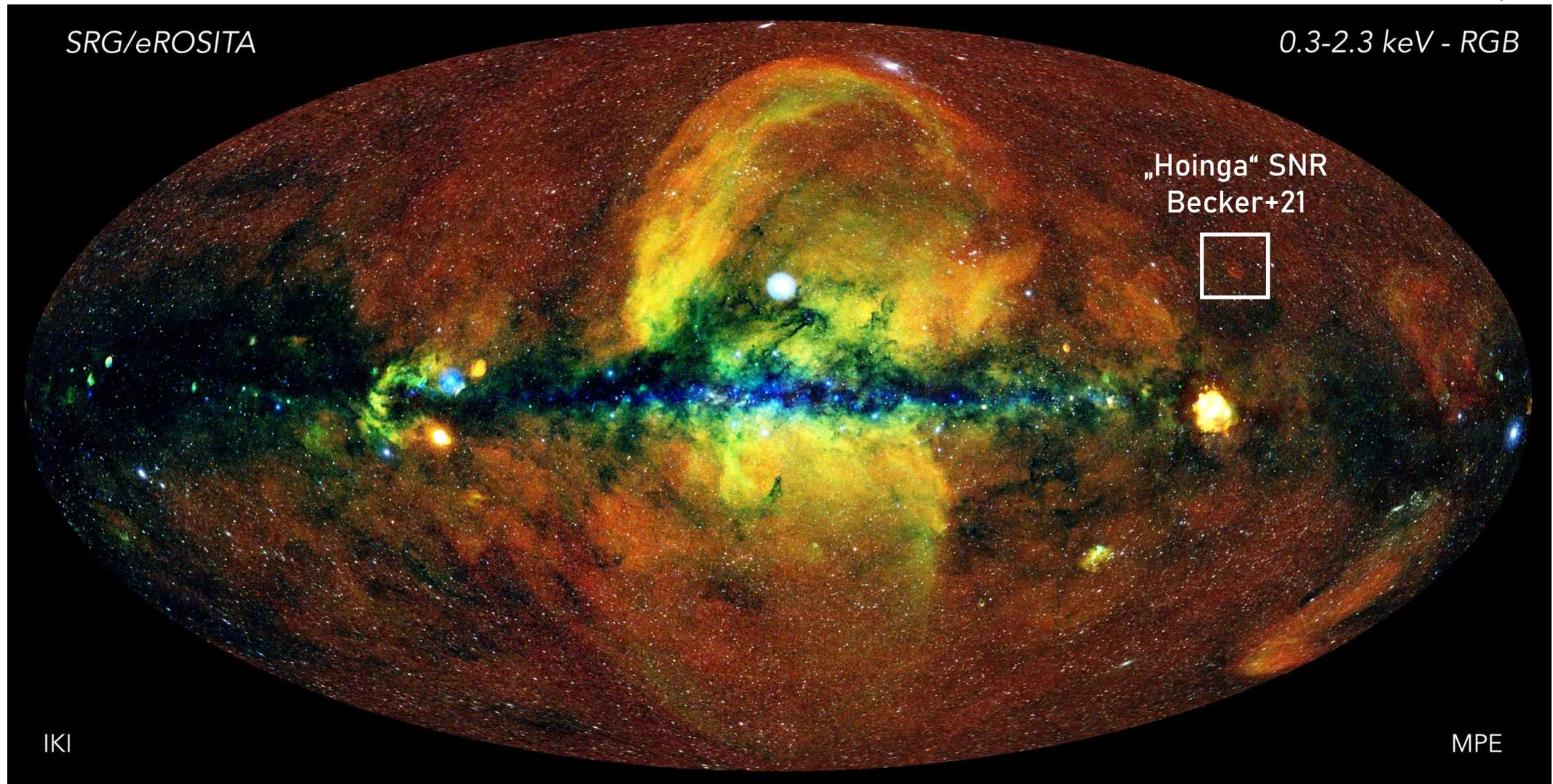
The eROSITA All-Sky Map

eRASS1 all-sky image
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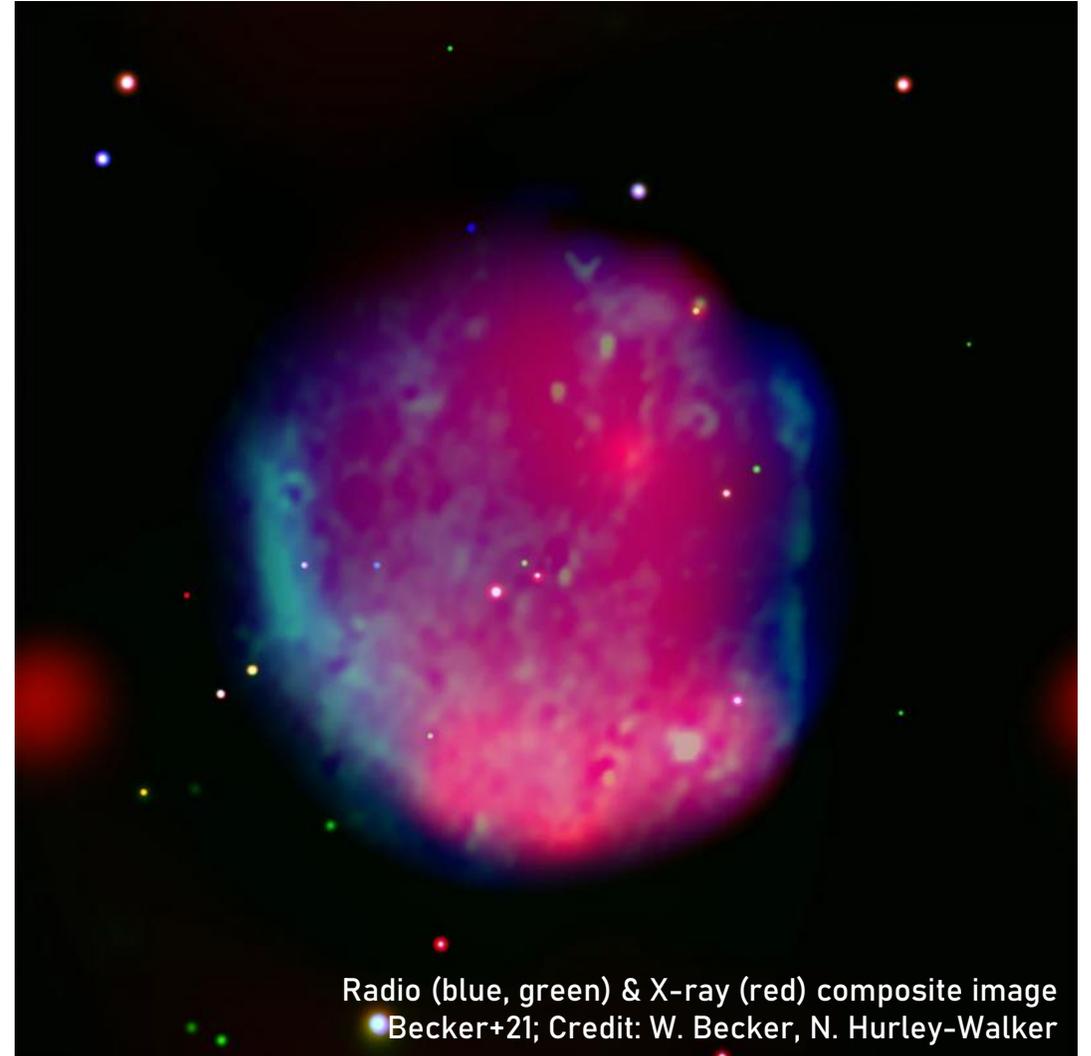
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The „Hoinga“ SNR (G249.5+24.5)

- High-latitude & extended SNR ($\sim 4.5^\circ$)
 - Soft thermal X-ray emission ($T \sim 1.3 \times 10^6$ K) filling nonthermal radio shell (Becker+21)
 - Likely old ($> 10^4$ yr) and nearby (~ 500 pc)

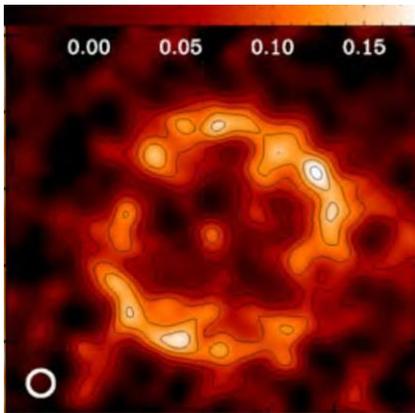


Radio (blue, green) & X-ray (red) composite image
Becker+21; Credit: W. Becker, N. Hurley-Walker

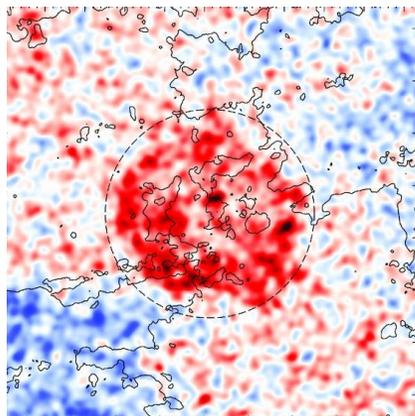
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- Further discoveries indicate population of SNRs outside Galactic plane

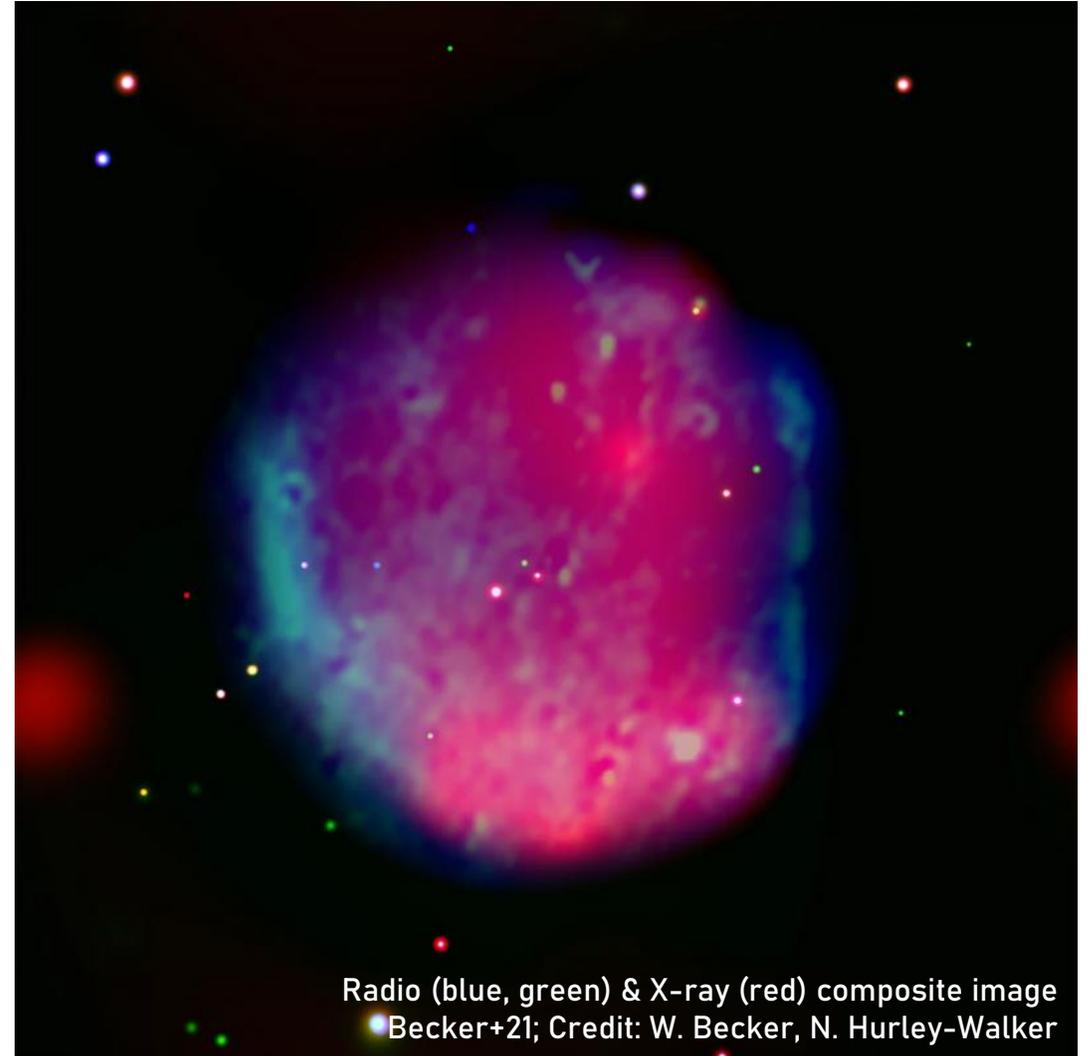
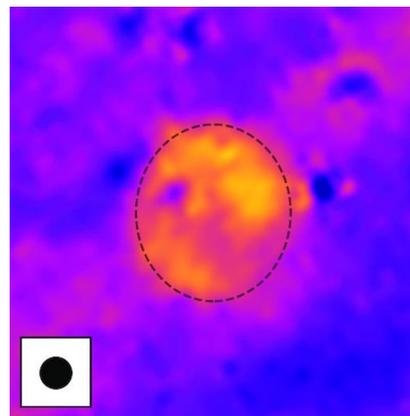
J0624-6948 (Filipovic+21)



G116.6-26.1 (Churazov+21)



G17.8+16.7 (Araya+22)

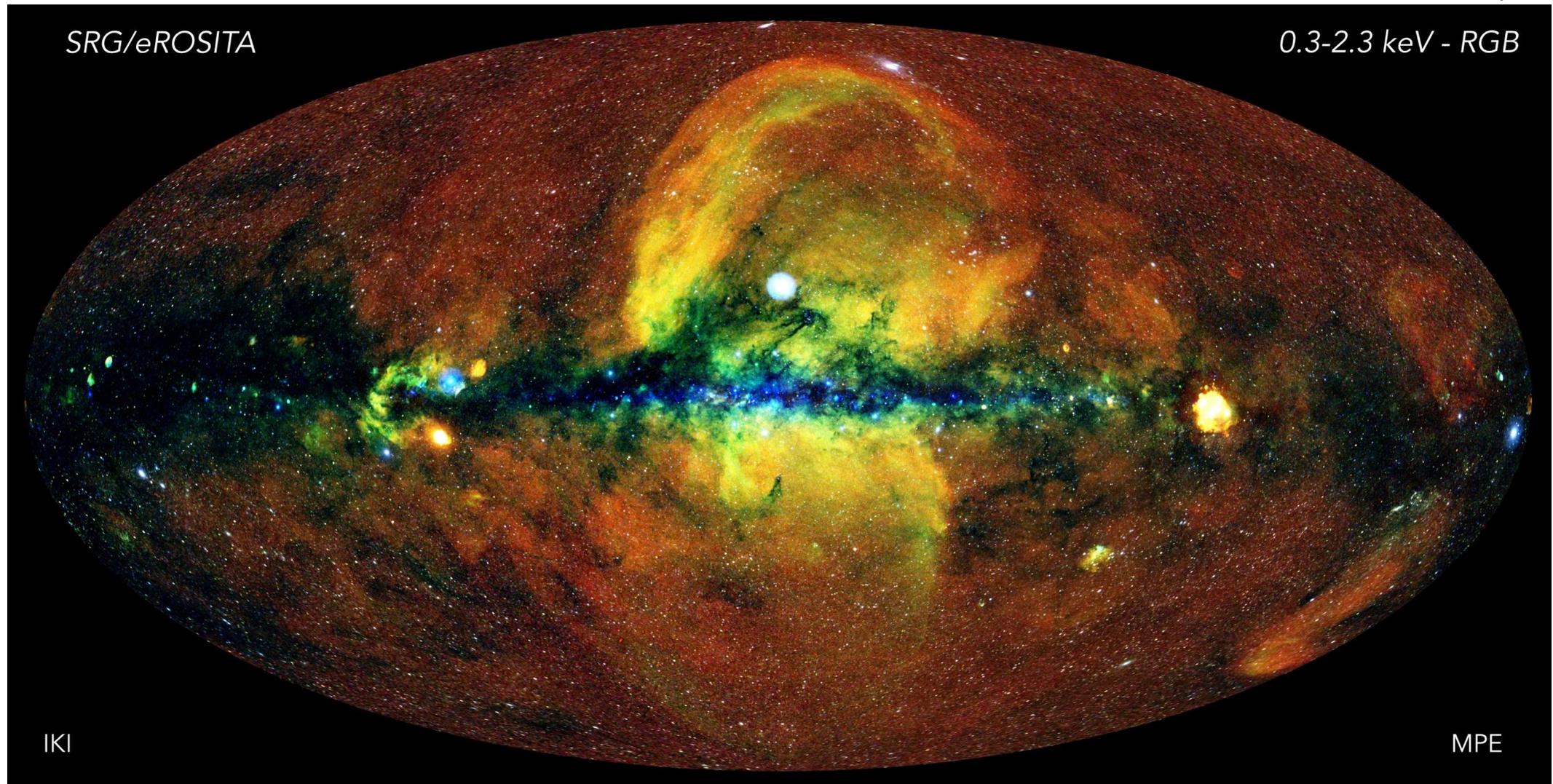




*Vela & Friends:
Extended SNRs with eROSITA*

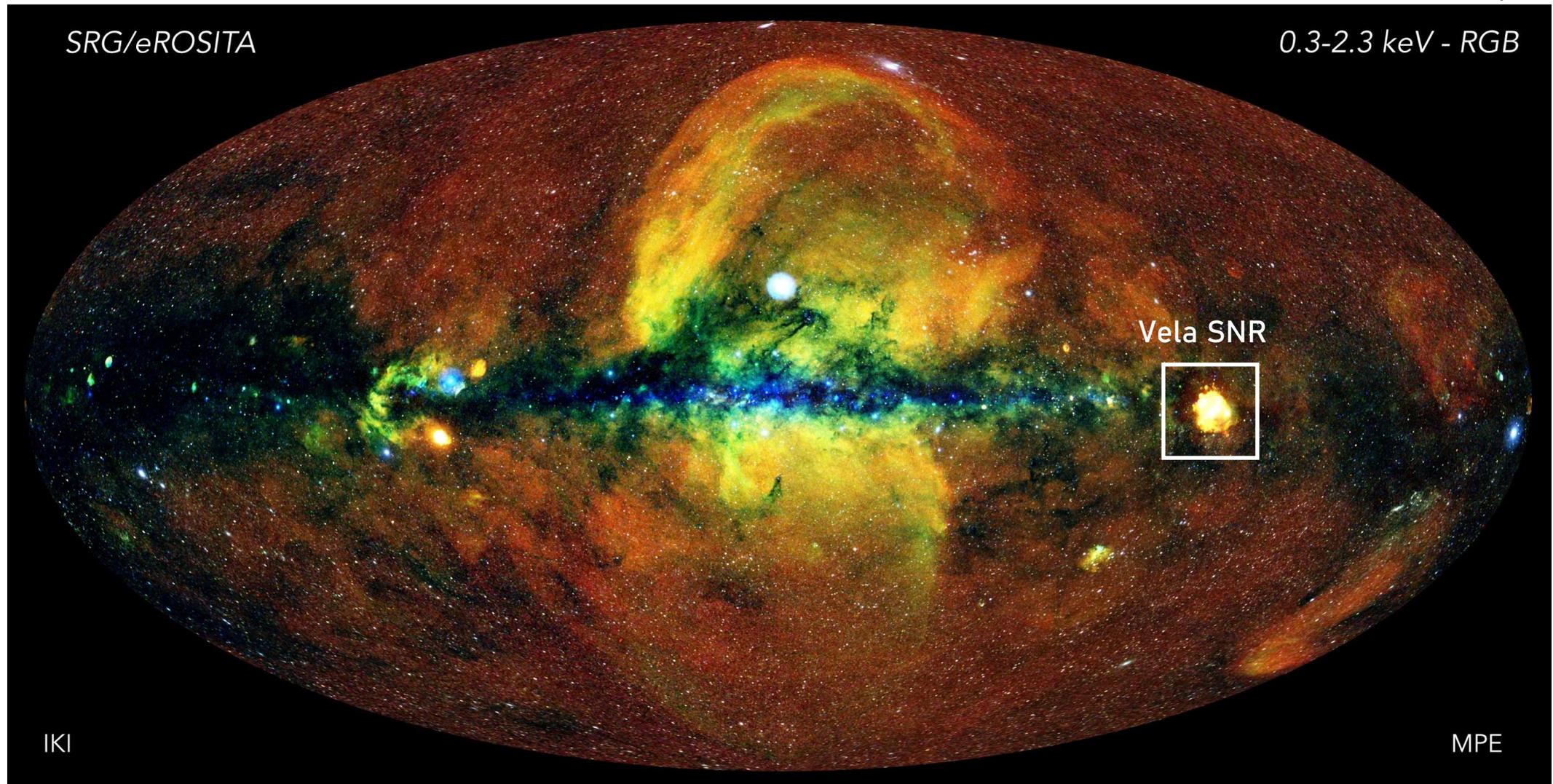
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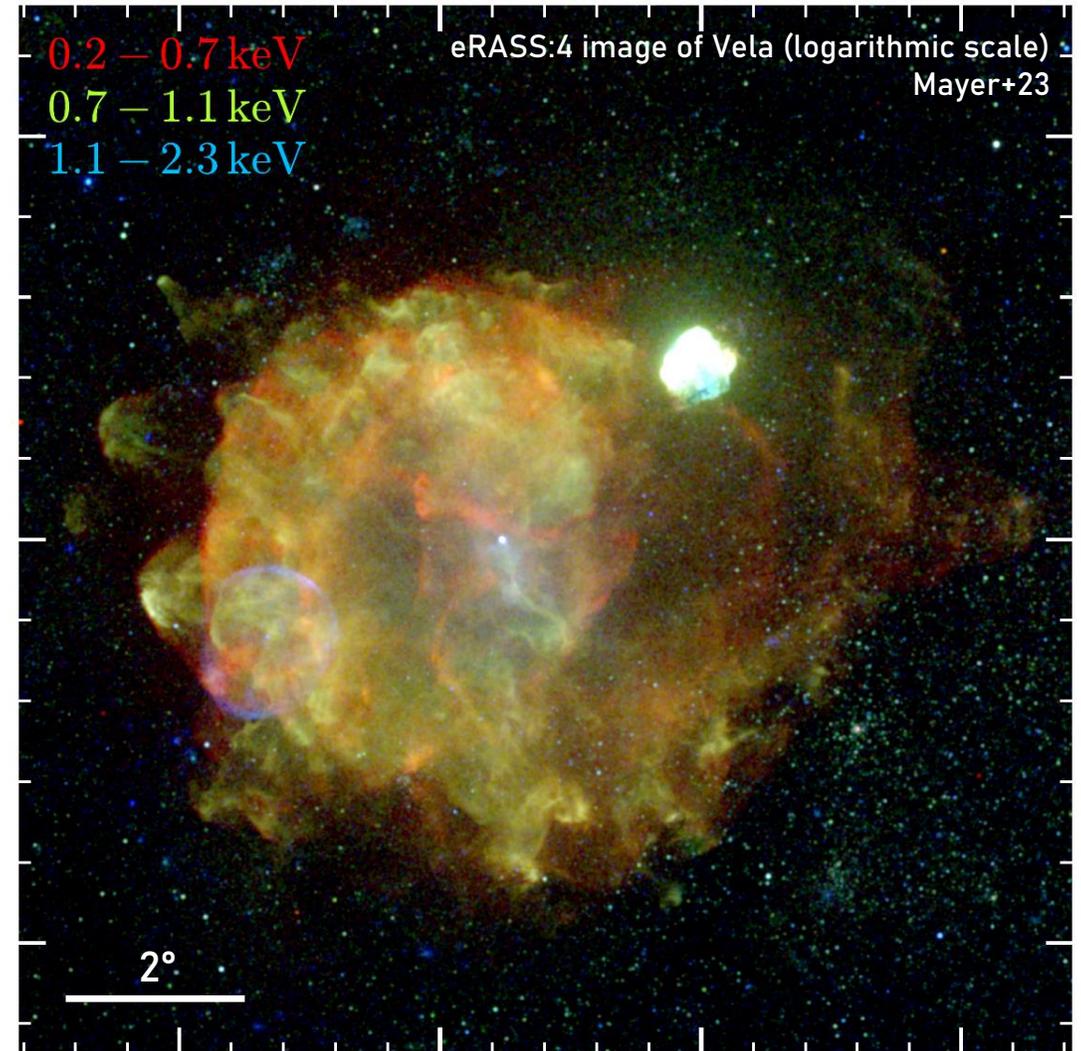
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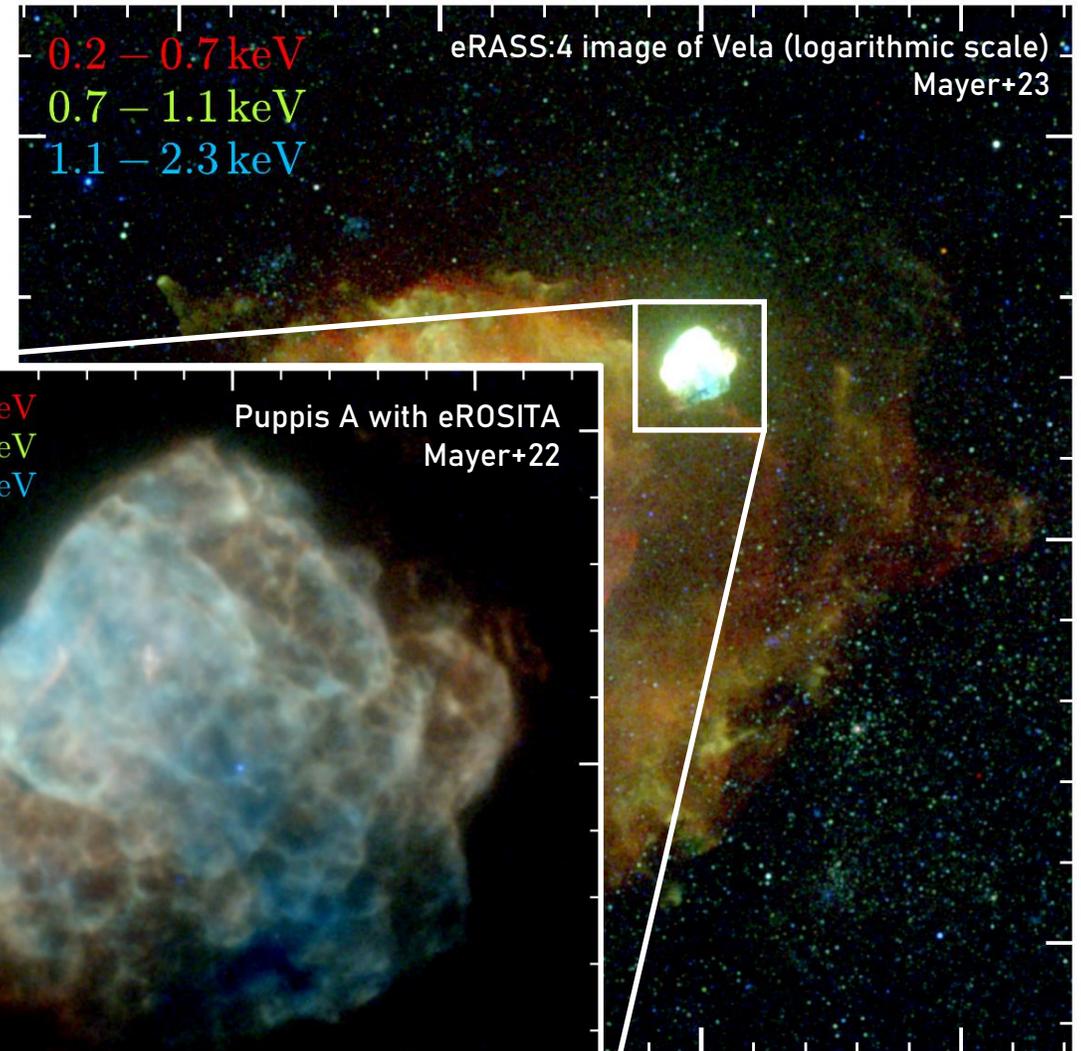
Vela and Friends

- Vela: Very extended ($\sim 8^\circ$) core-collapse SNR
 - Central energetic pulsar B0833+45
 - Nearby (~ 290 pc; Dodson+03)
 - Age $\sim 11 - 30$ kyr (Aschenbach+95, Lyne+96, Espinoza+17)



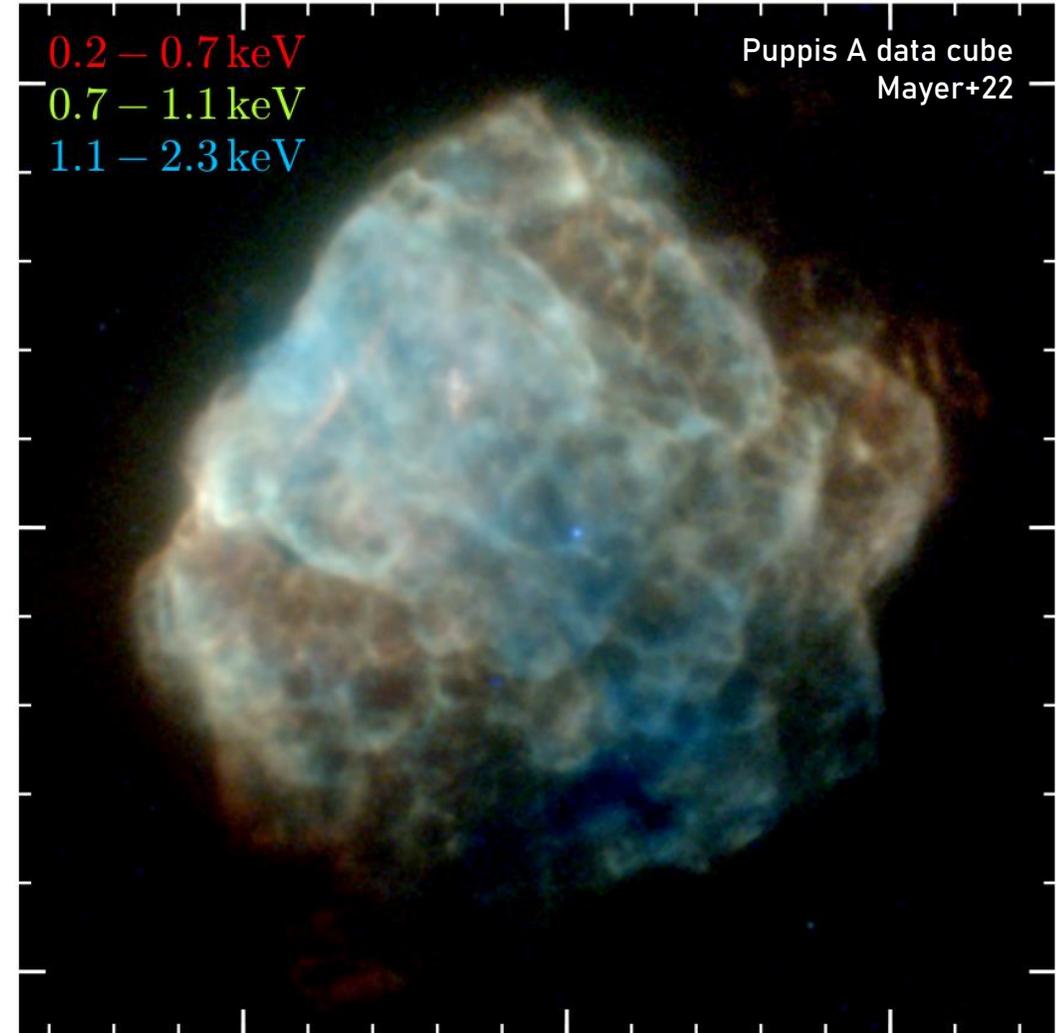
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- Superimposed SNR: Puppis A
 - 4000 yr old (Mayer+20, Winkler+88)
 - Core-collapse SNR
 - Central neutron star (Petre+96)
 - X-ray-bright due to interaction with dense ISM (Hwang+05)



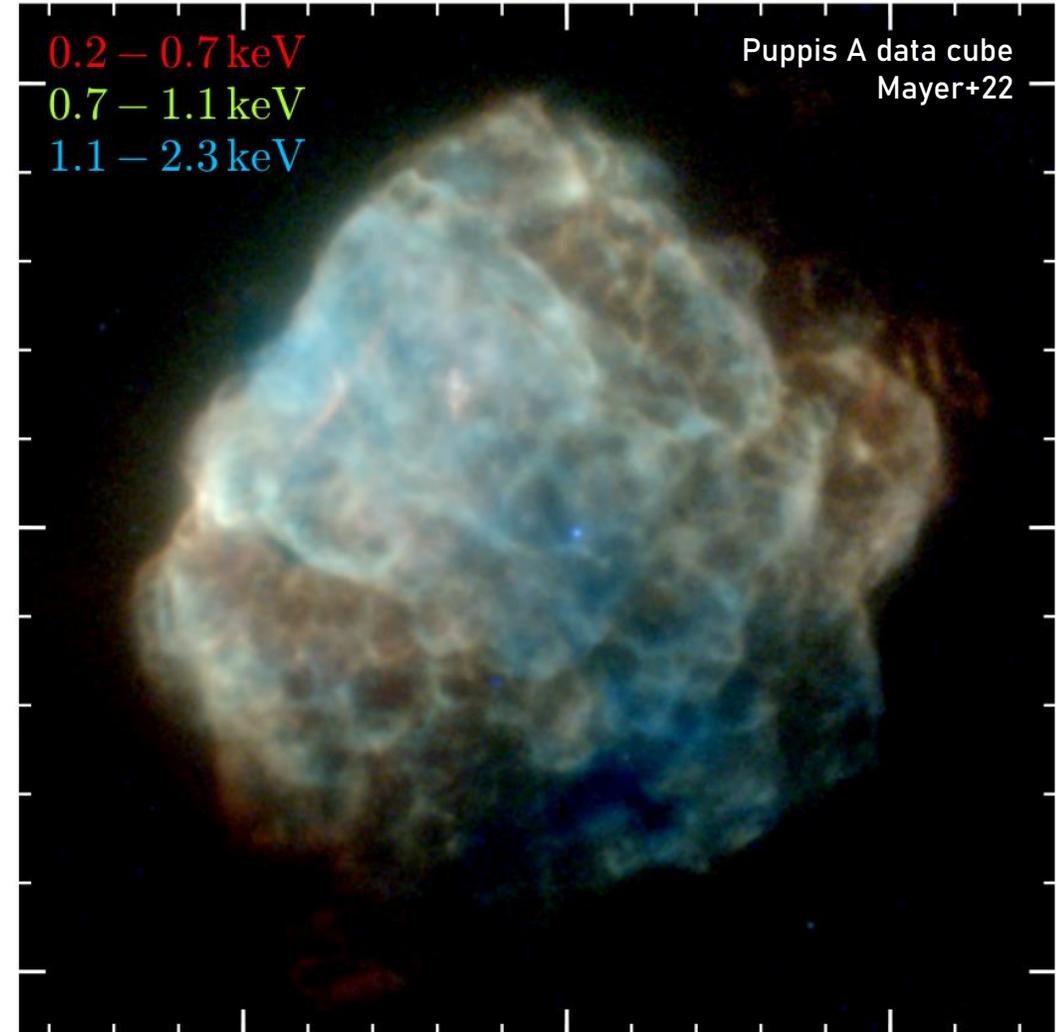
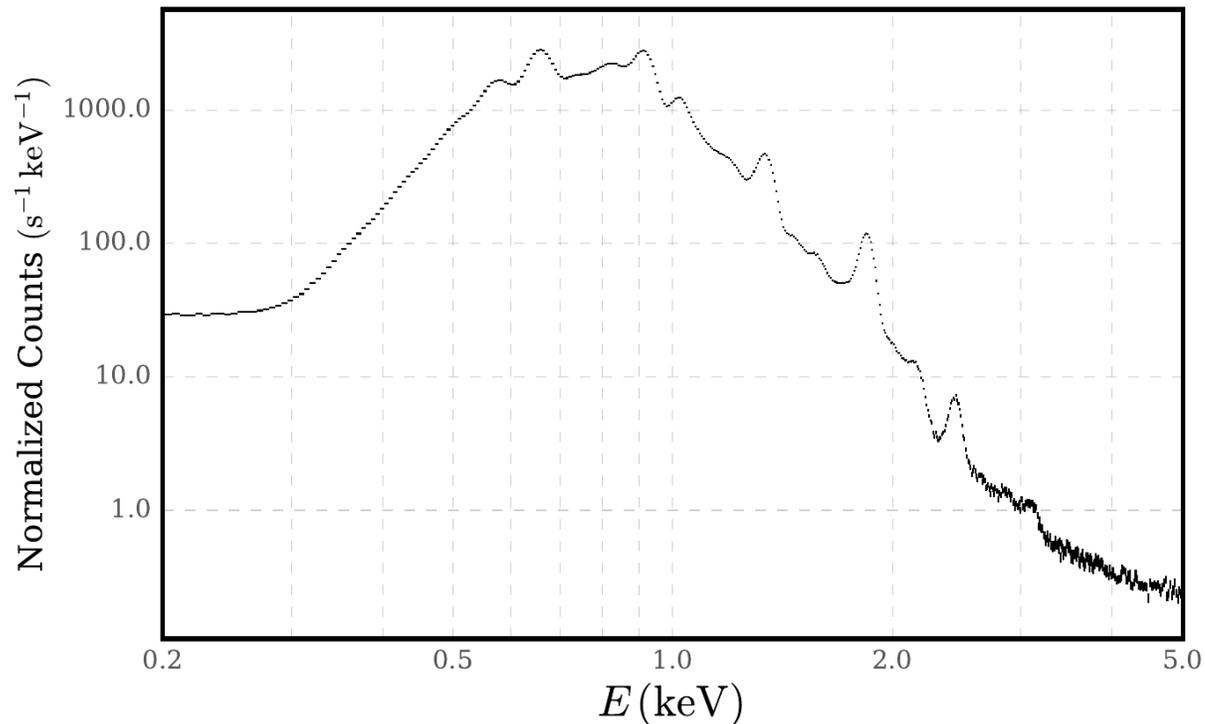
An „IFU“ View of Puppis A

- eROSITA data: 30 ks observation of Puppis A during calibration & PV phase
 - X-ray datacube reveals spectromorphological changes



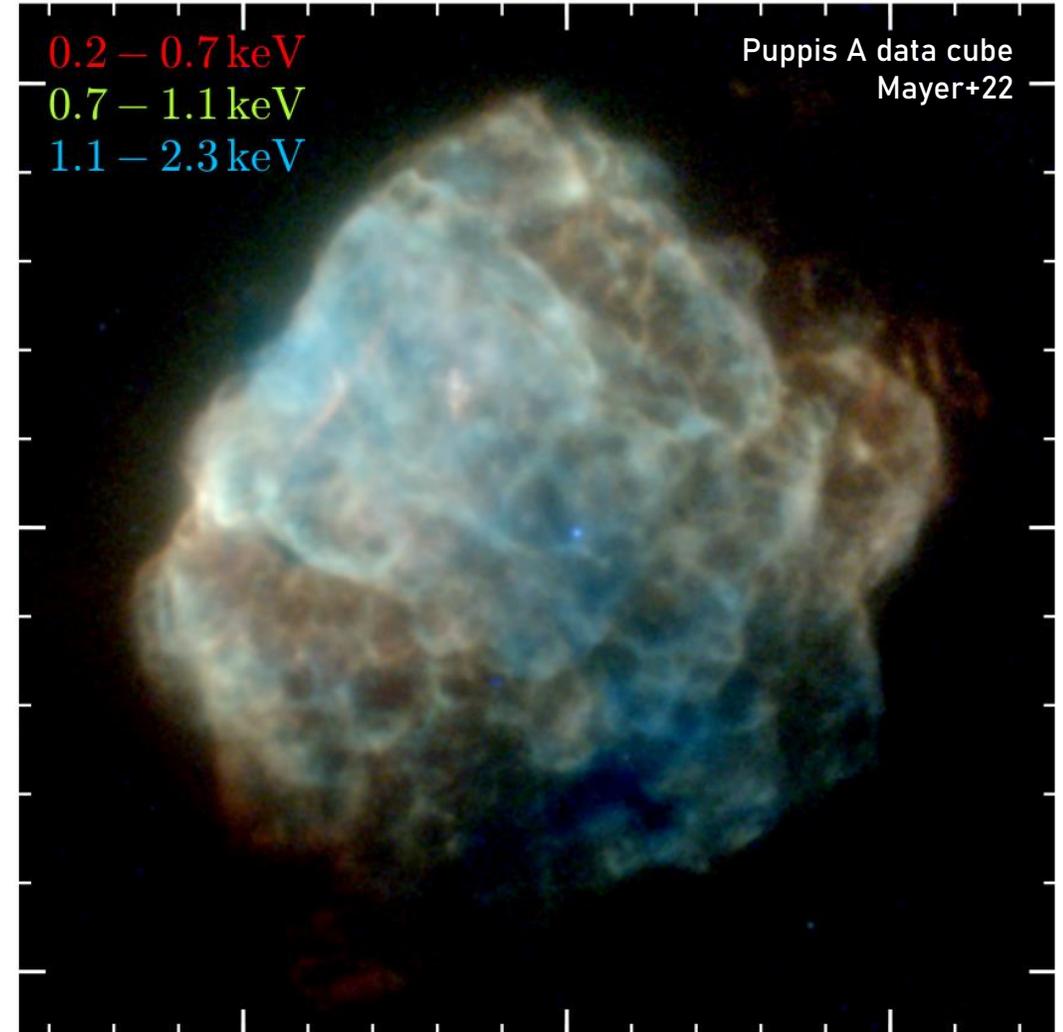
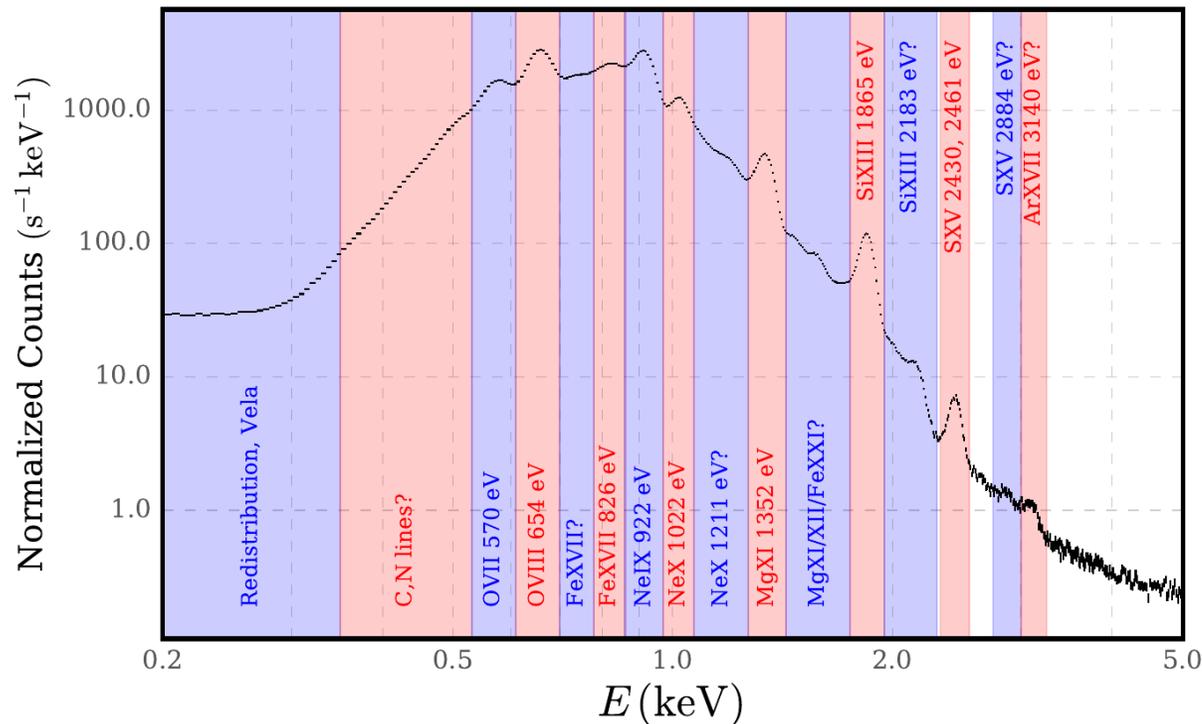
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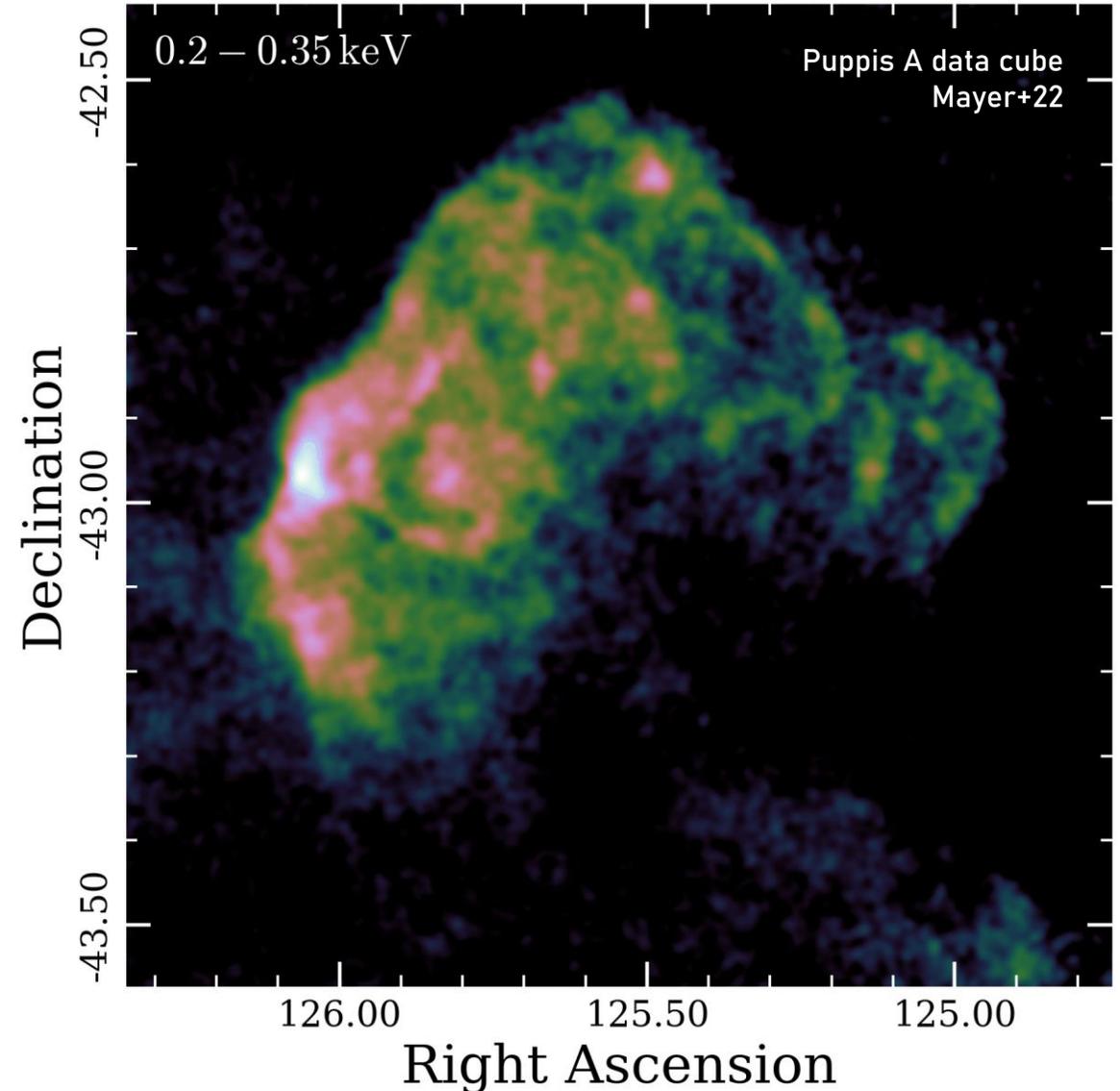
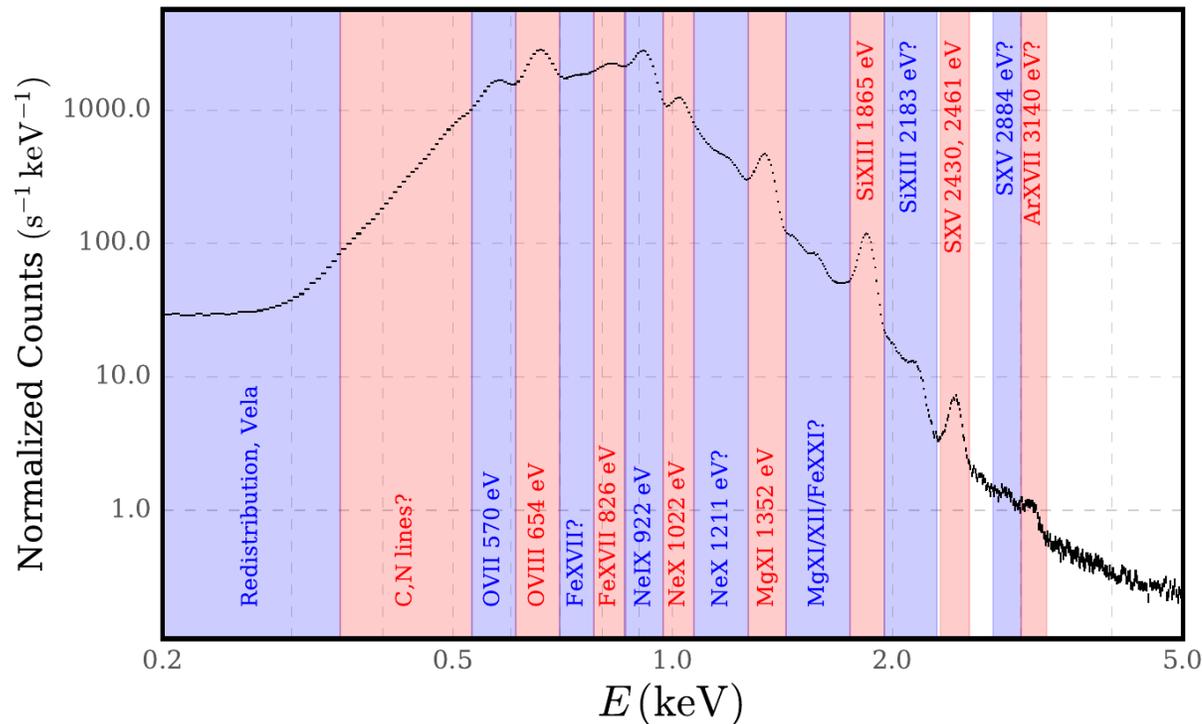
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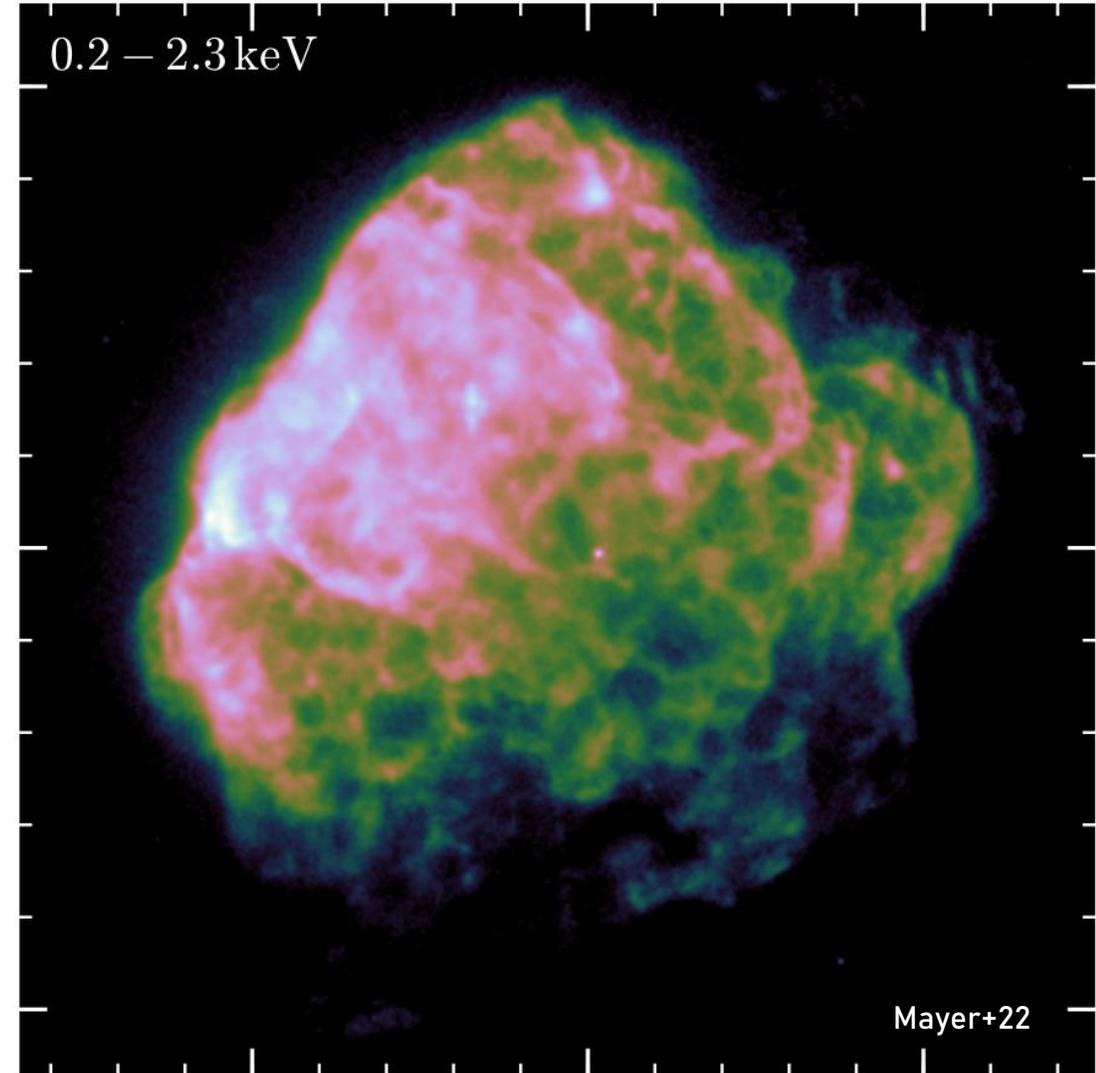


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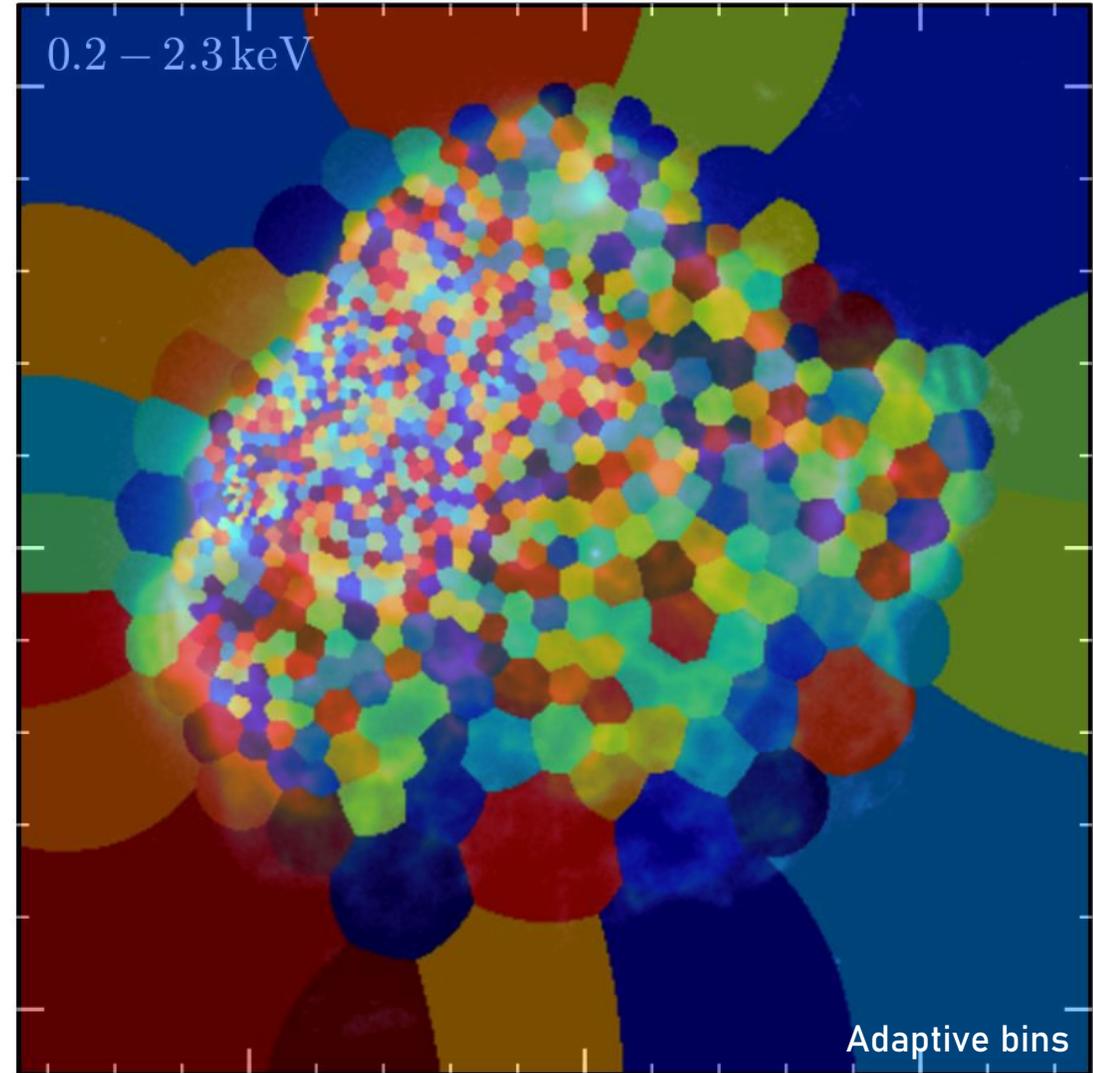


Spatially resolved spectroscopy



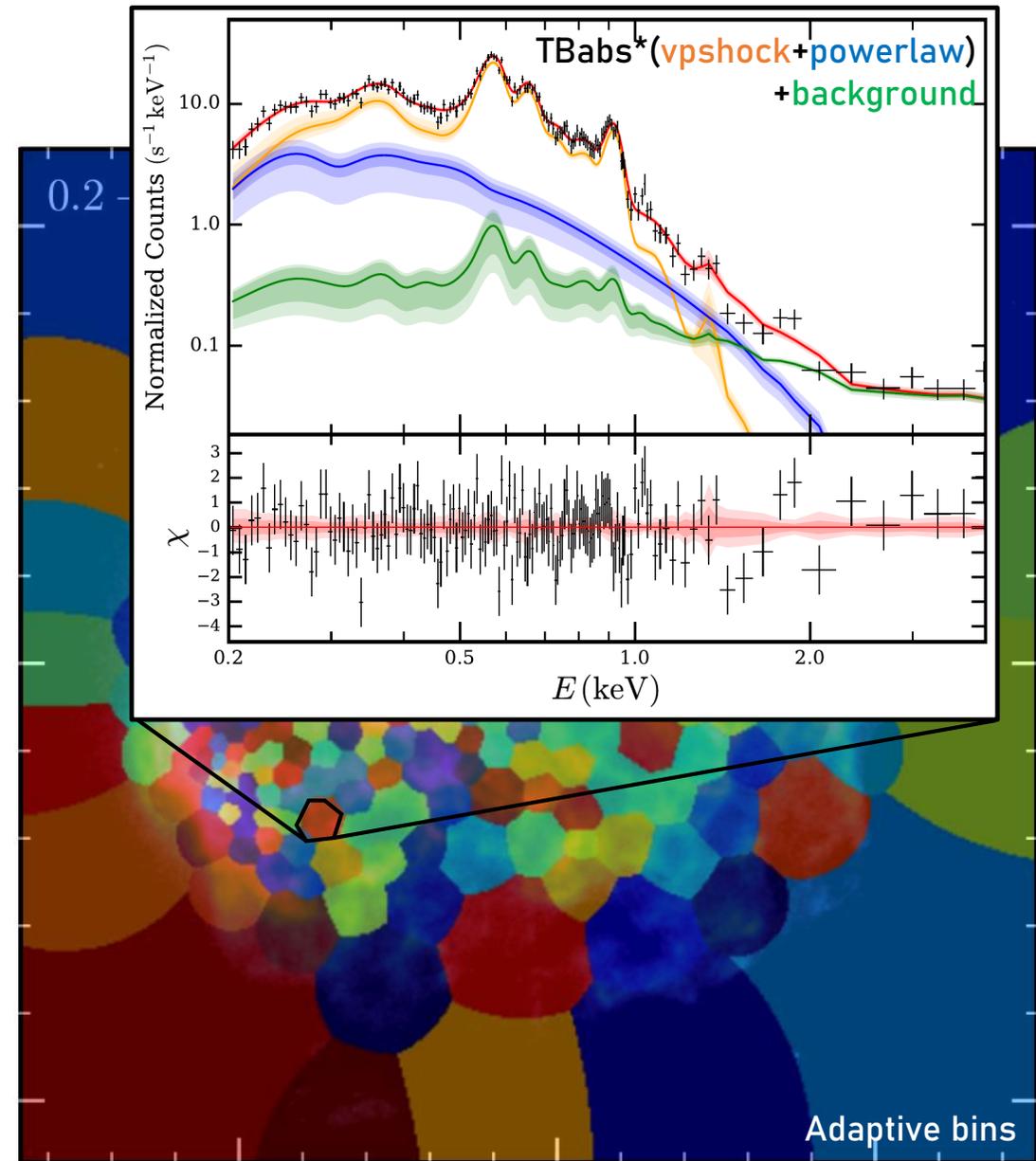
Spatially resolved spectroscopy

- Adaptive Voronoi binning (Cappellari+03)
- Extract spectra from regions binned to equal S/N



Spatially resolved spectroscopy

- Adaptive Voronoi binning (Cappellari+03)
 - Extract spectra from regions binned to equal S/N
 - Characterize spectral components via spectral modelling
 - Foreground absorption
 - Hot gas phase (density, temperature, abundances)
 - Non-equilibrium ionization (NEI)
 - (Synchrotron emission)



Puppis A – Shock History

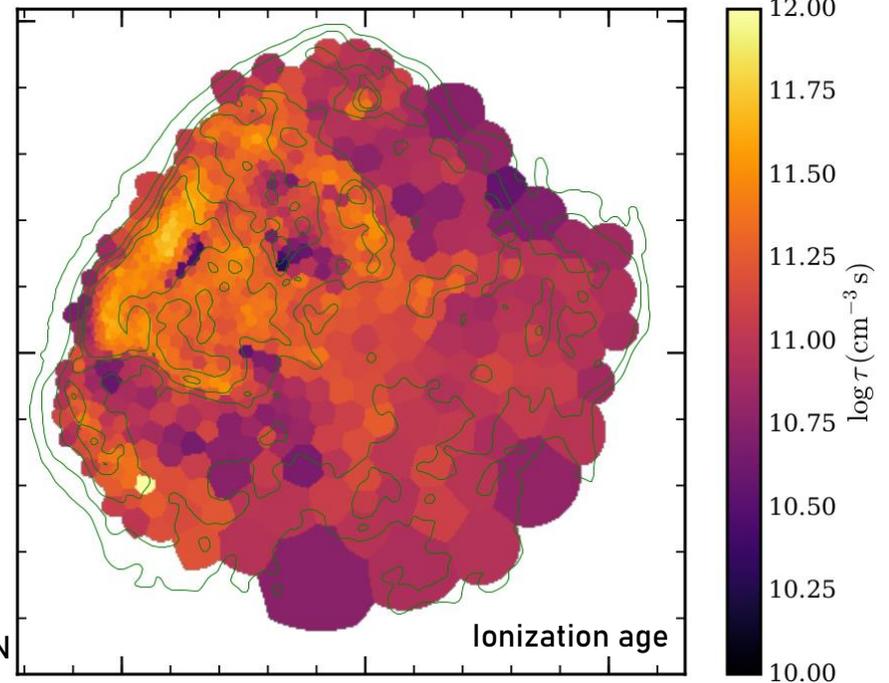
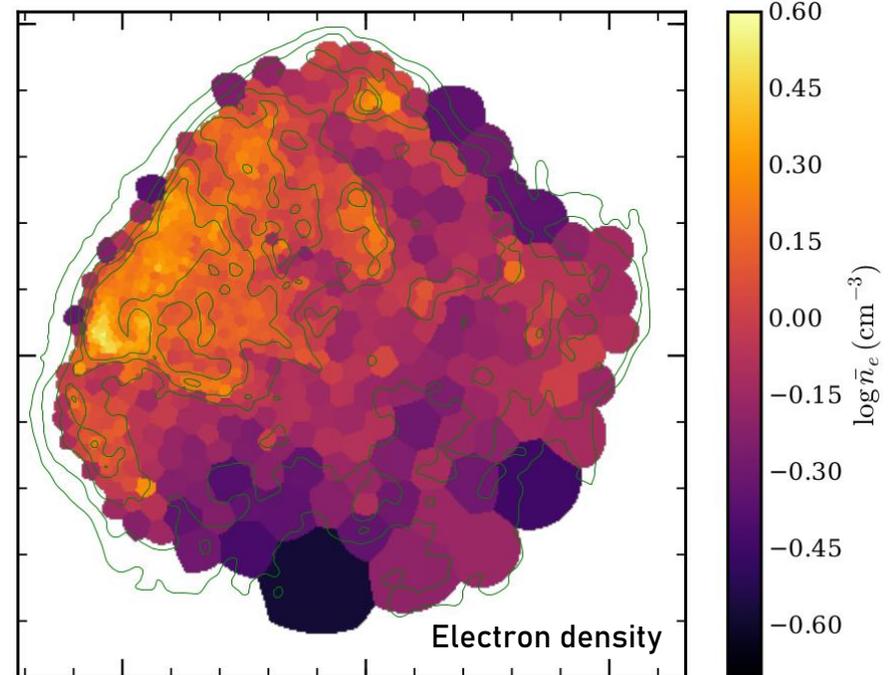
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$$EM = \frac{10^{-14}}{4\pi d^2} \int n_e n_H dV,$$

Assume

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$$\tau_s = n_e t_s$$



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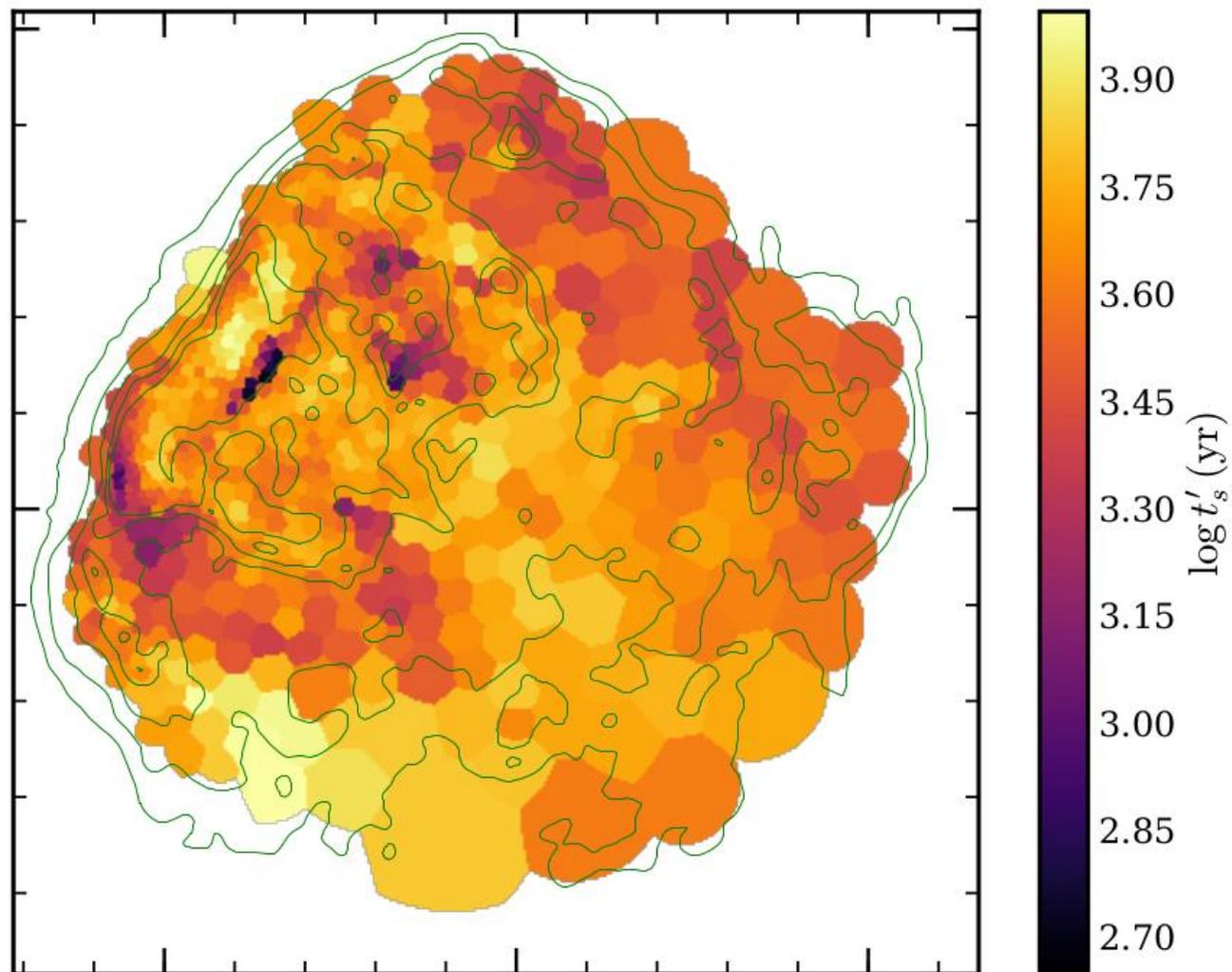
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Mayer+22



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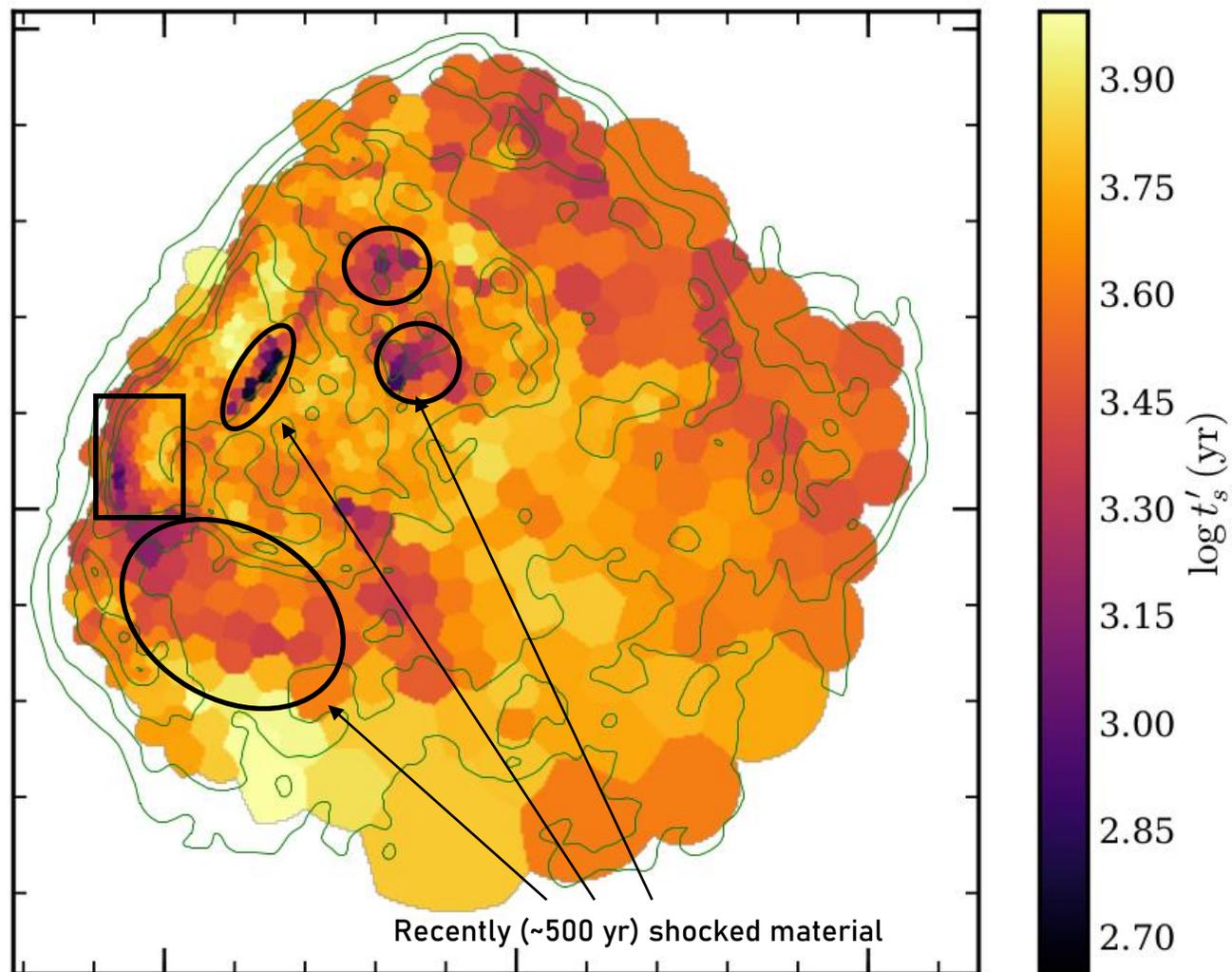
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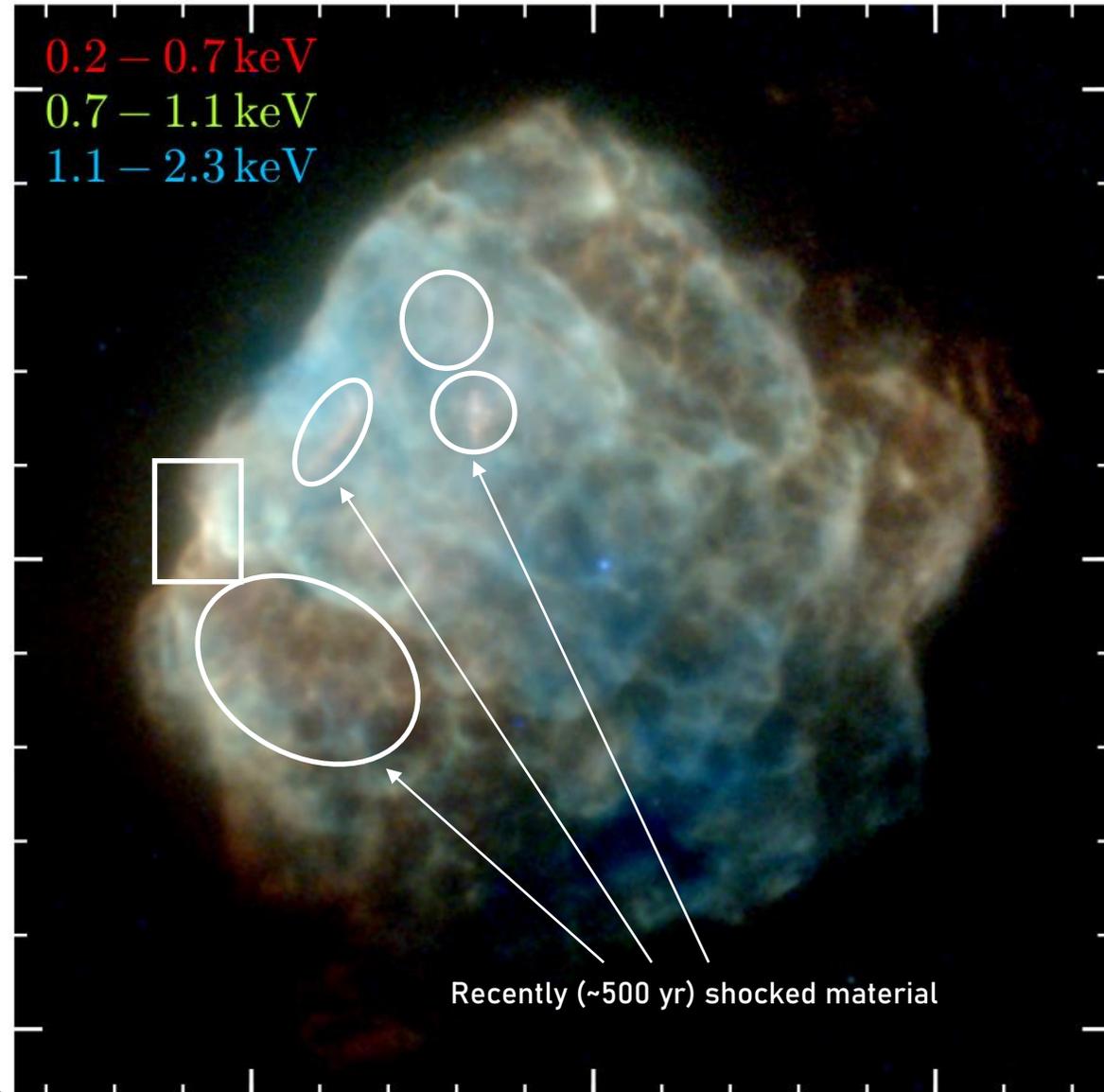
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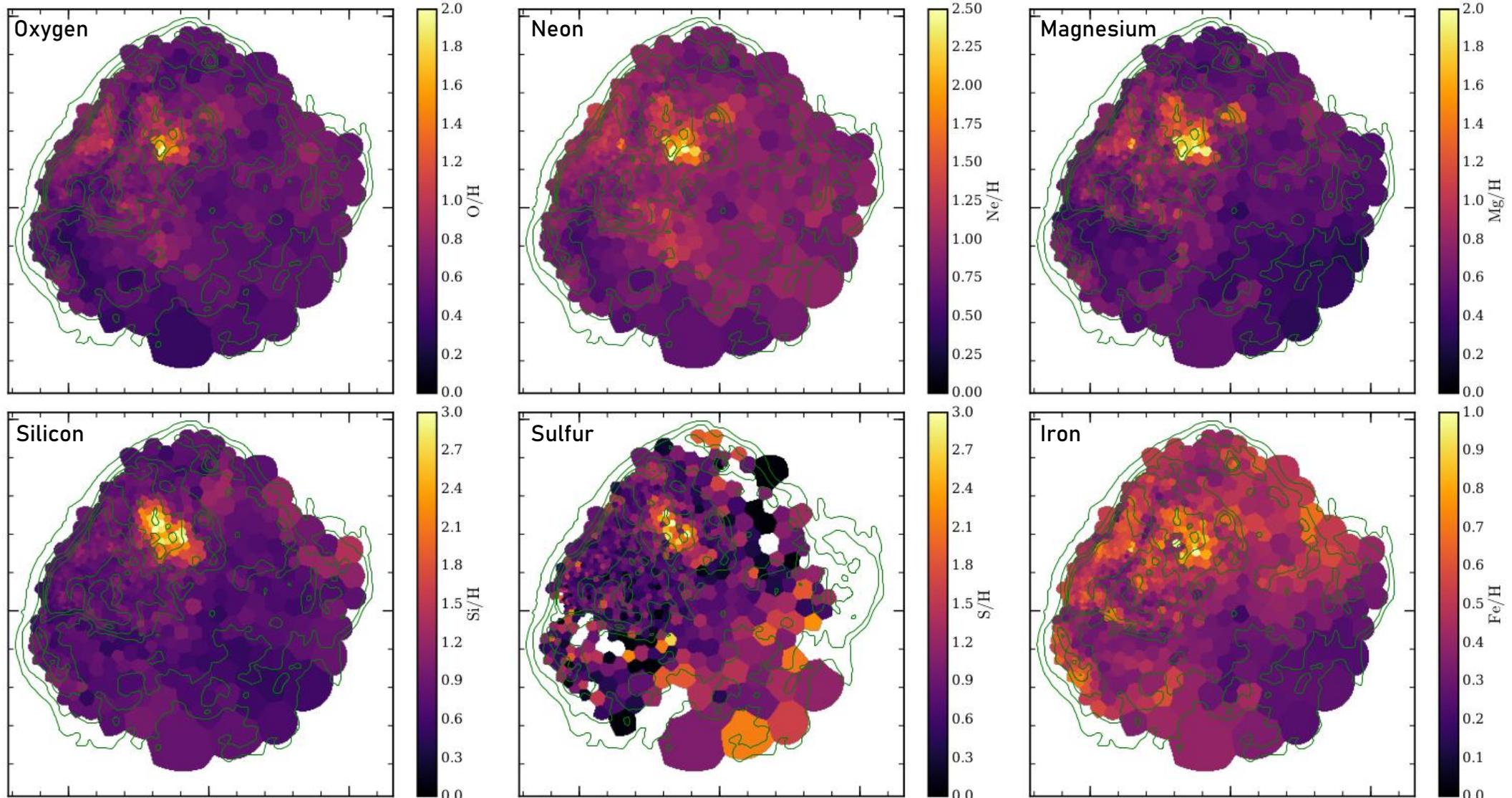
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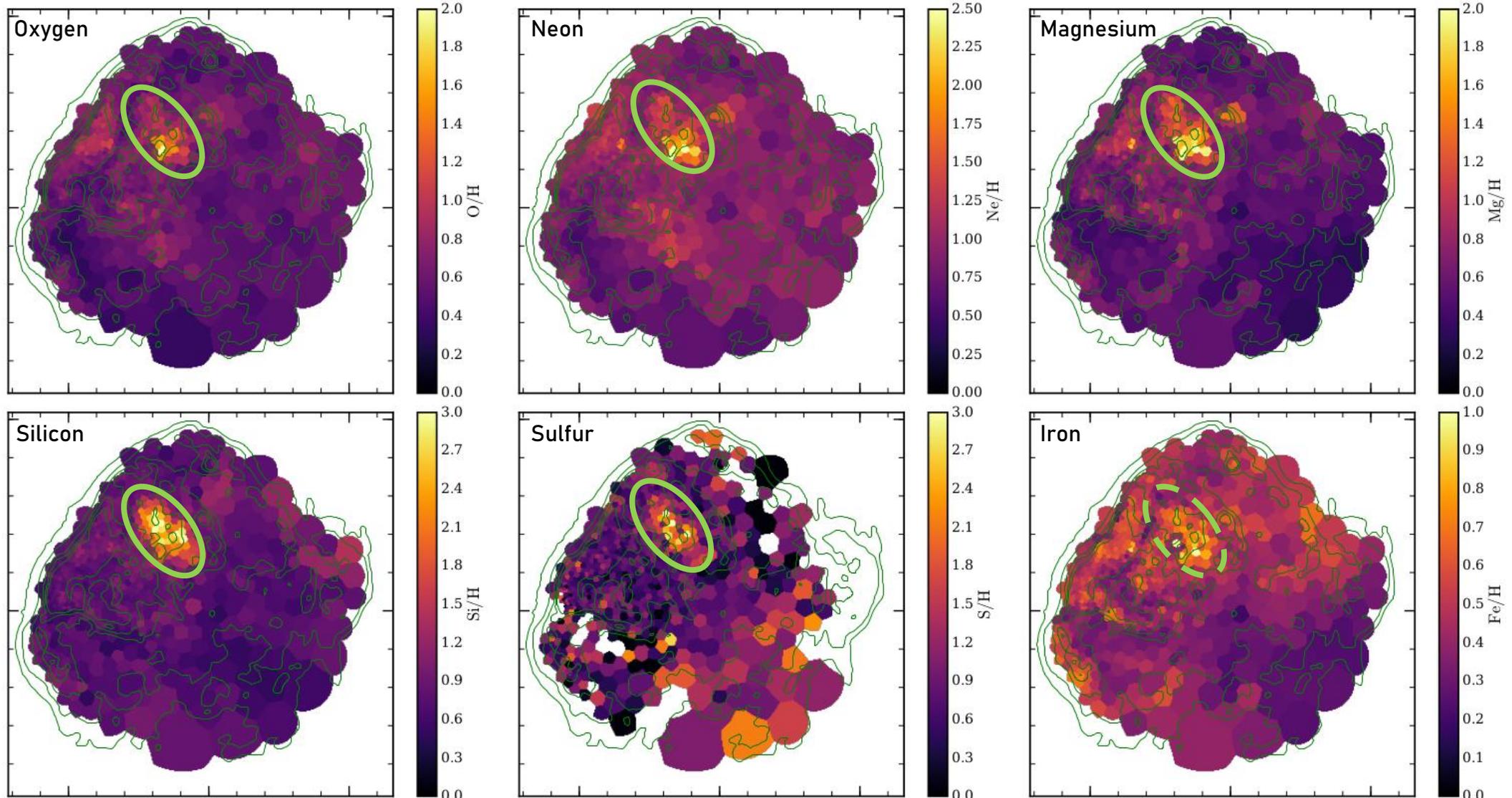


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Puppis A – Ejecta



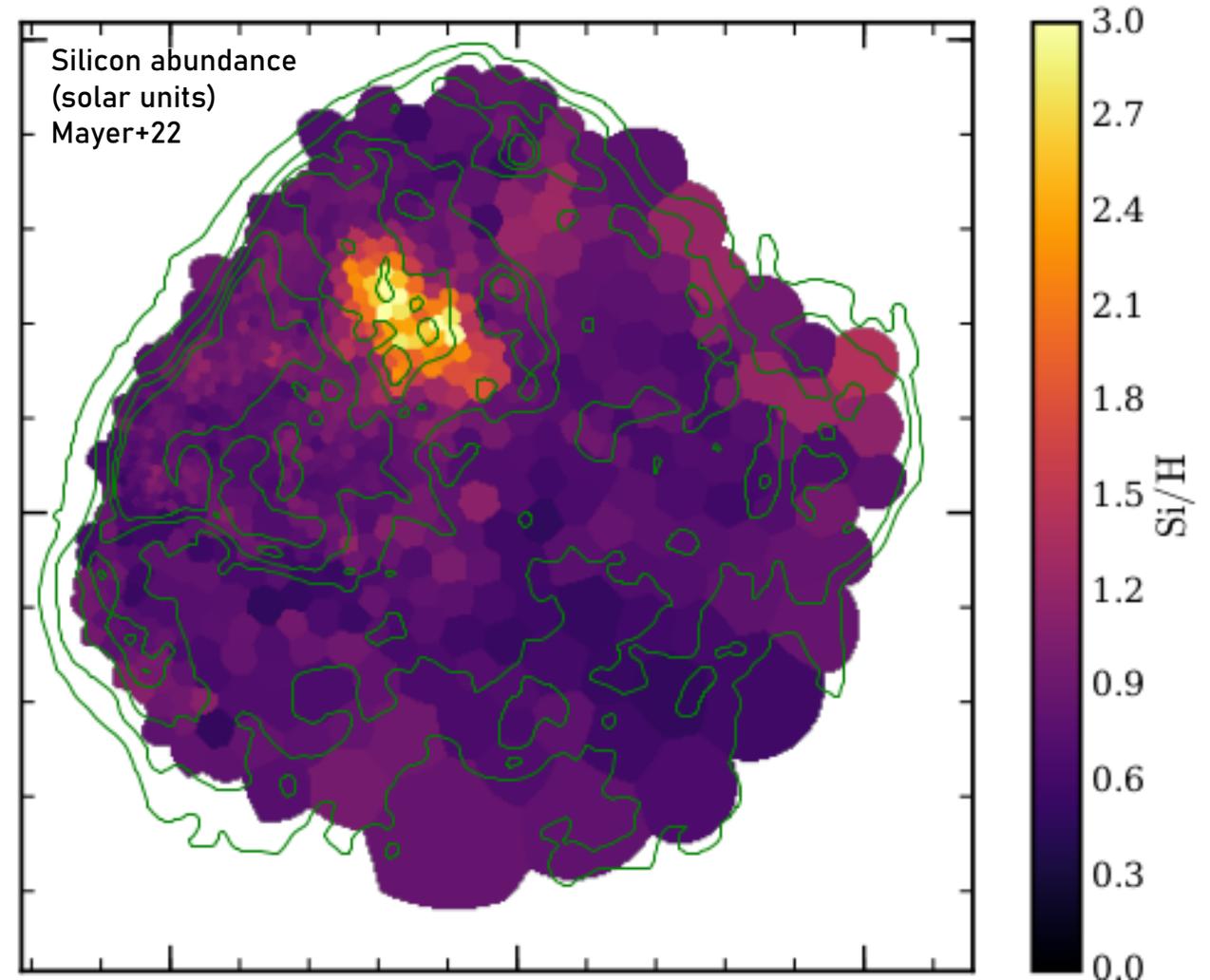
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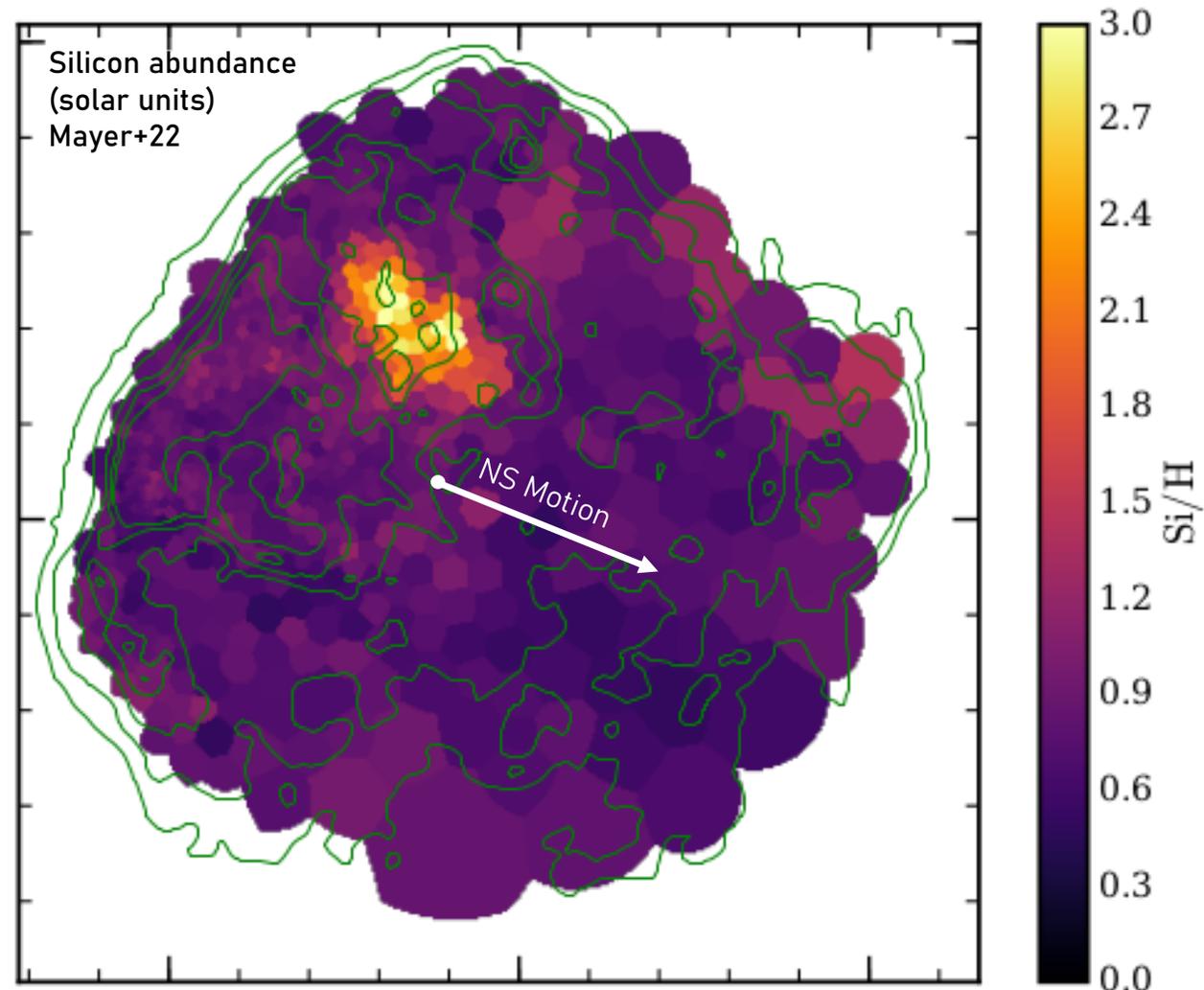
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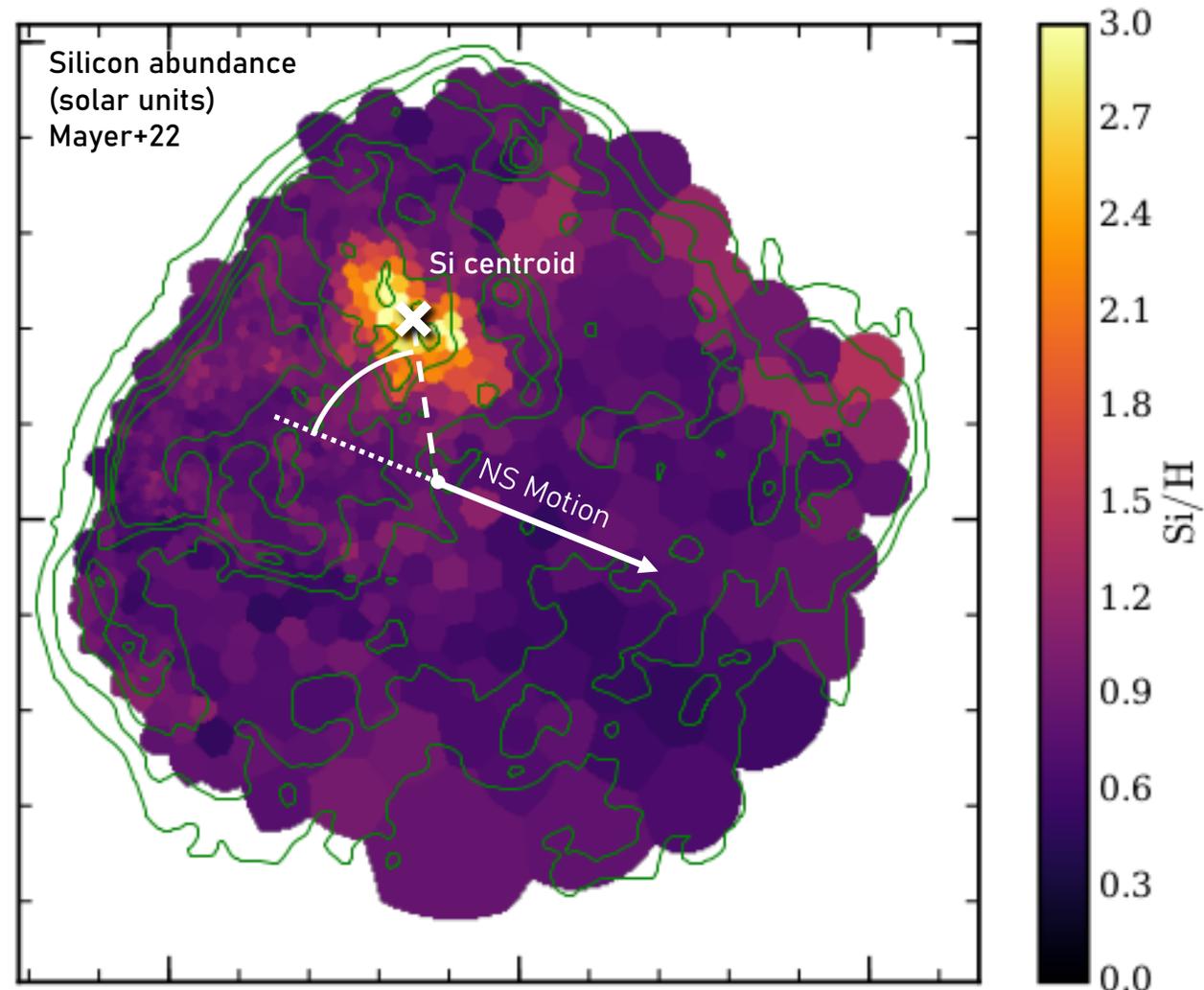
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- Rapid neutron star motion (~ 500 km/s; Mayer+20)
 - Hydrodynamic kick: Recoil from heavy ejecta elements (Wongwathanarat+2013)



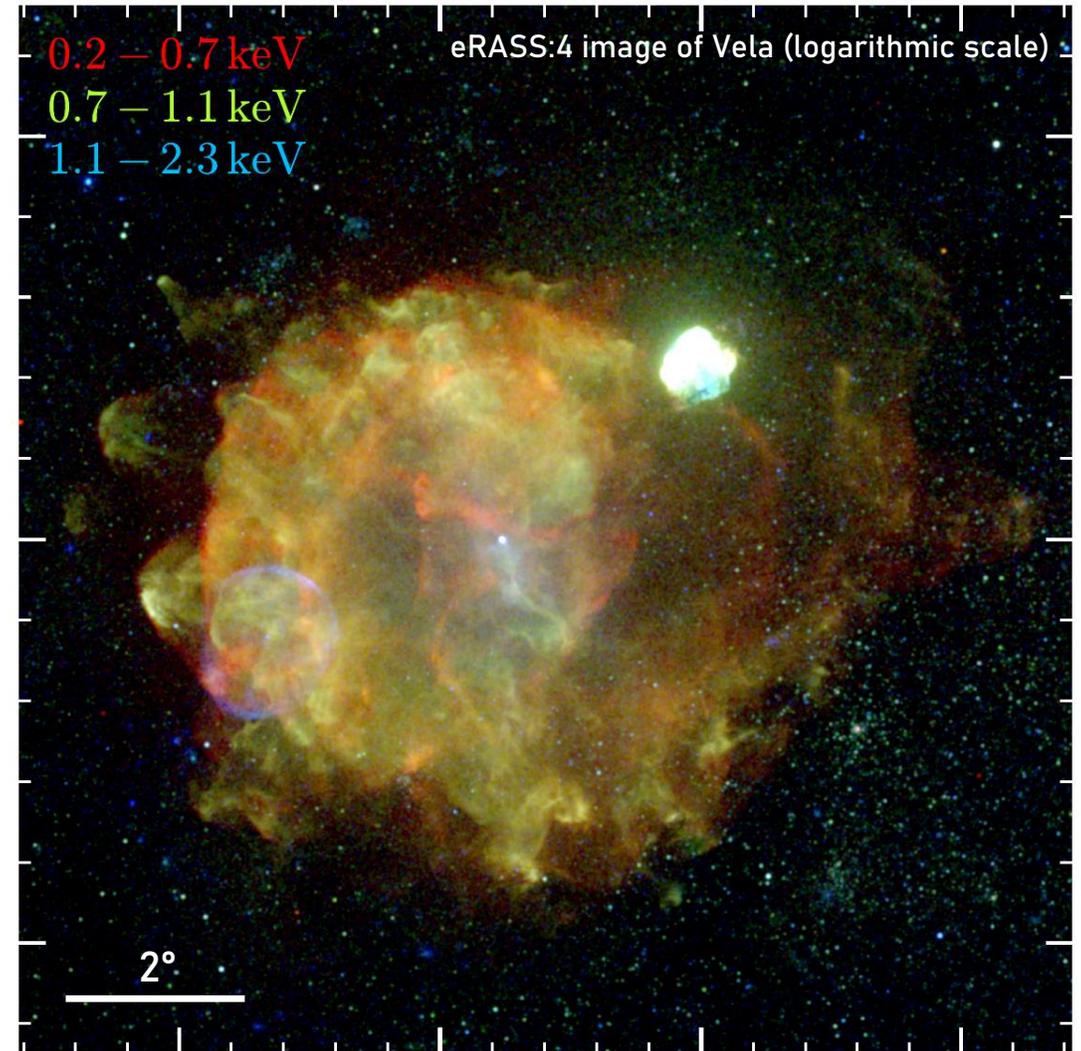
Puppis A – Ejecta and Hydrodynamics

- Abundance maps reveal clump of silicon-rich ejecta material
- Rapid neutron star motion (~ 500 km/s; Mayer+20)
 - Hydrodynamic kick: Recoil from heavy ejecta elements (Wongwathanarat+2013)
- Apparent disagreement between silicon ejecta and recoil $\sim 55^\circ$



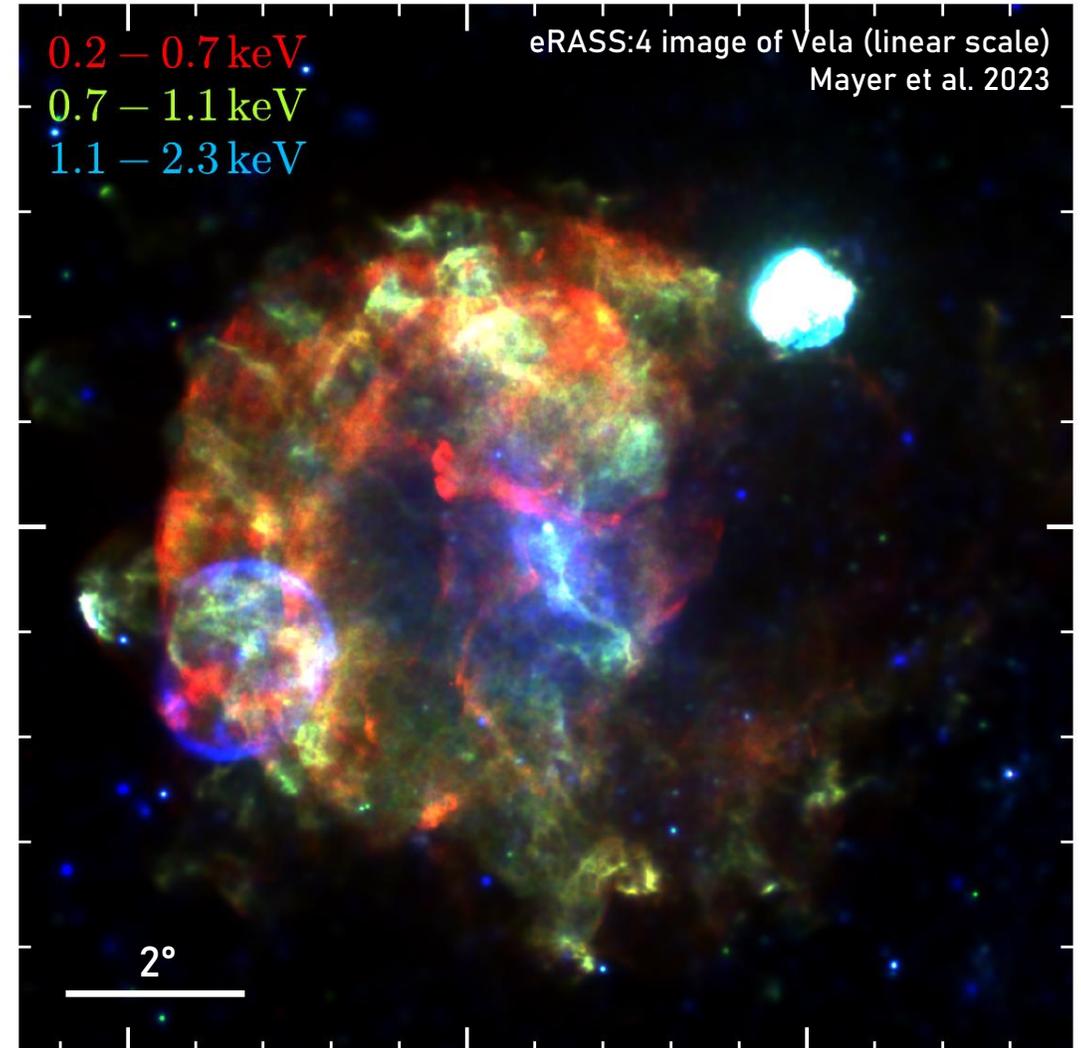
Vela and Friends

- Vela: Very extended ($\sim 8^\circ$) core-collapse SNR
 - Central energetic pulsar B0833+45
 - Nearby (~ 290 pc; Dodson+03)
 - Age $\sim 11 - 30$ kyr (Aschenbach+95, Lyne+96, Espinoza+17)



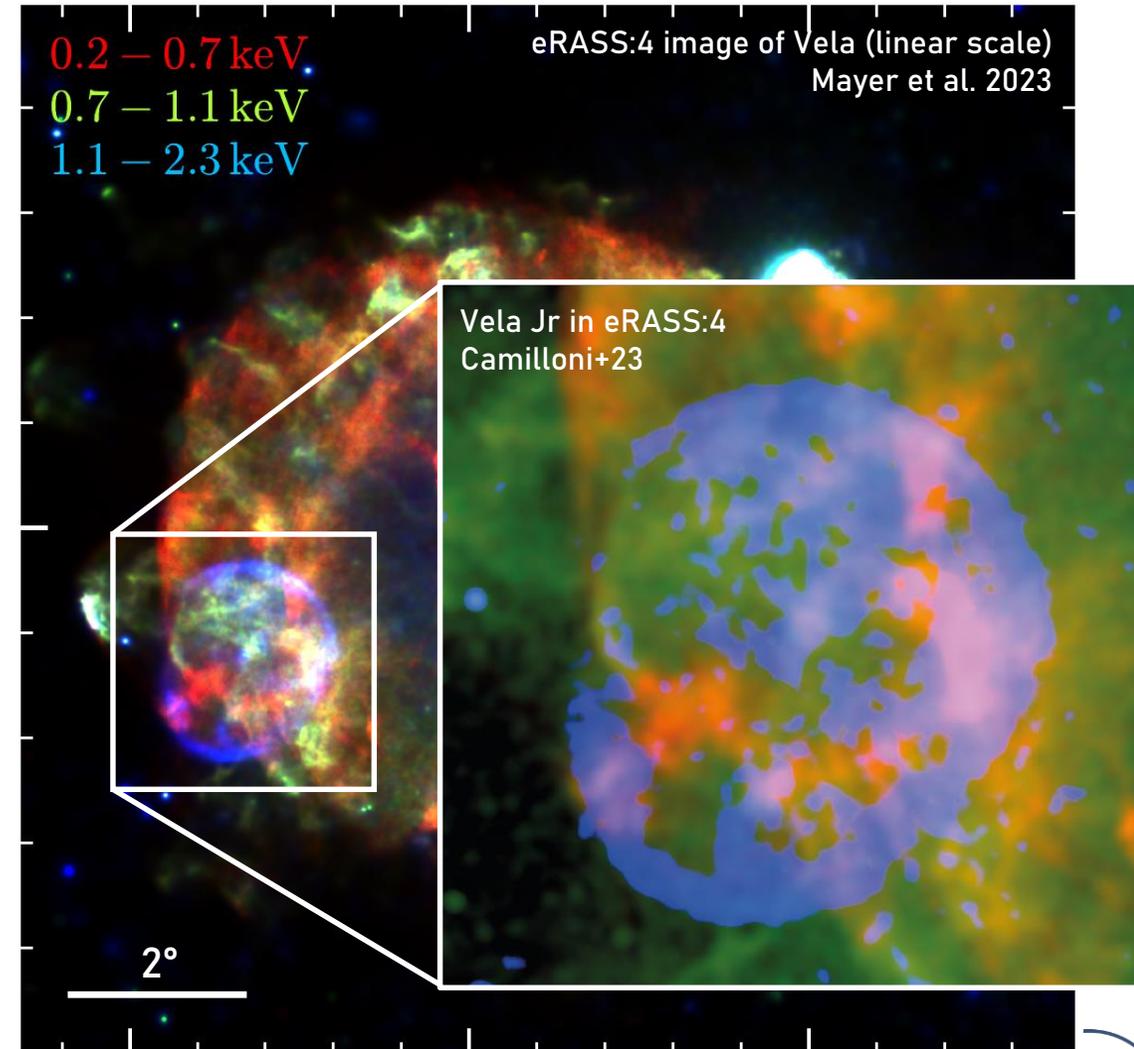
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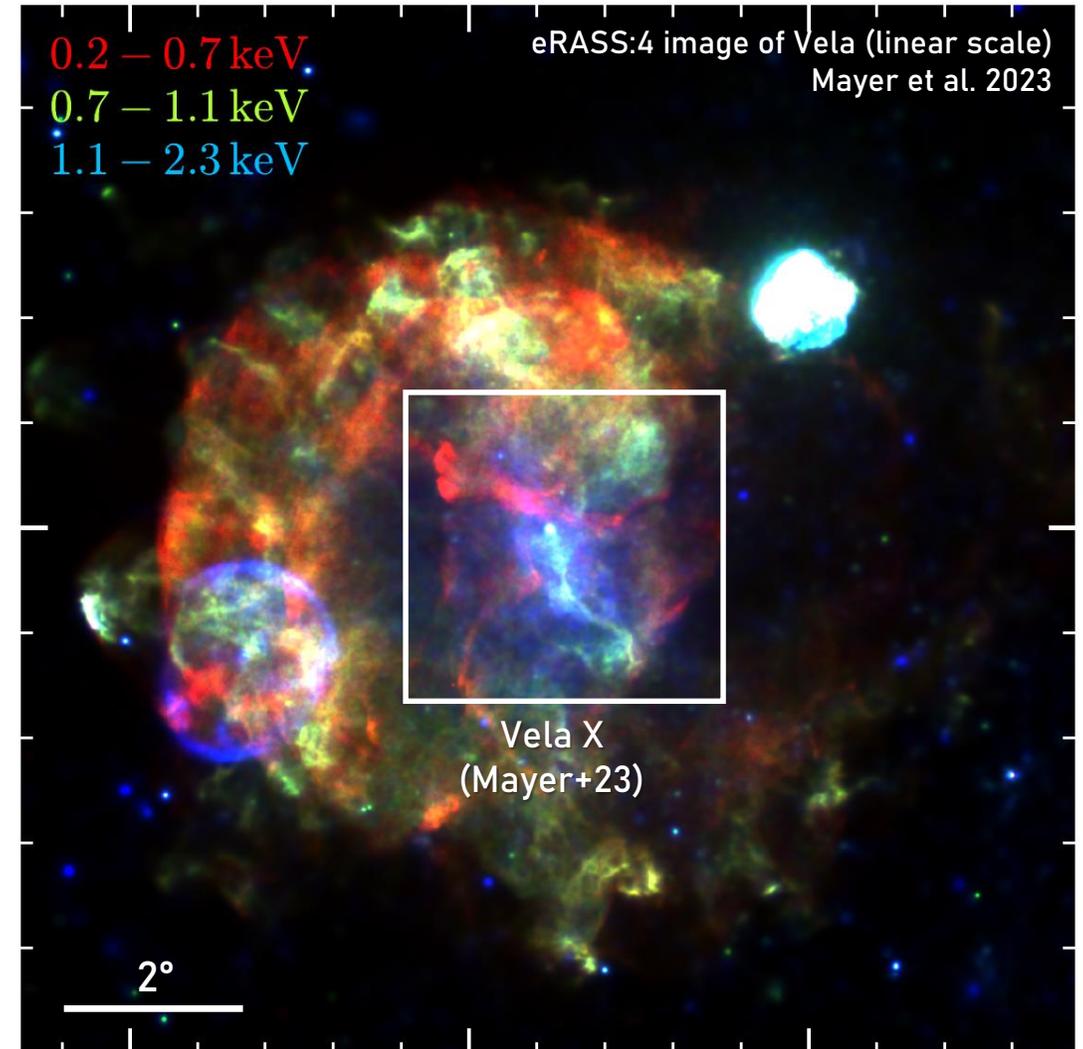
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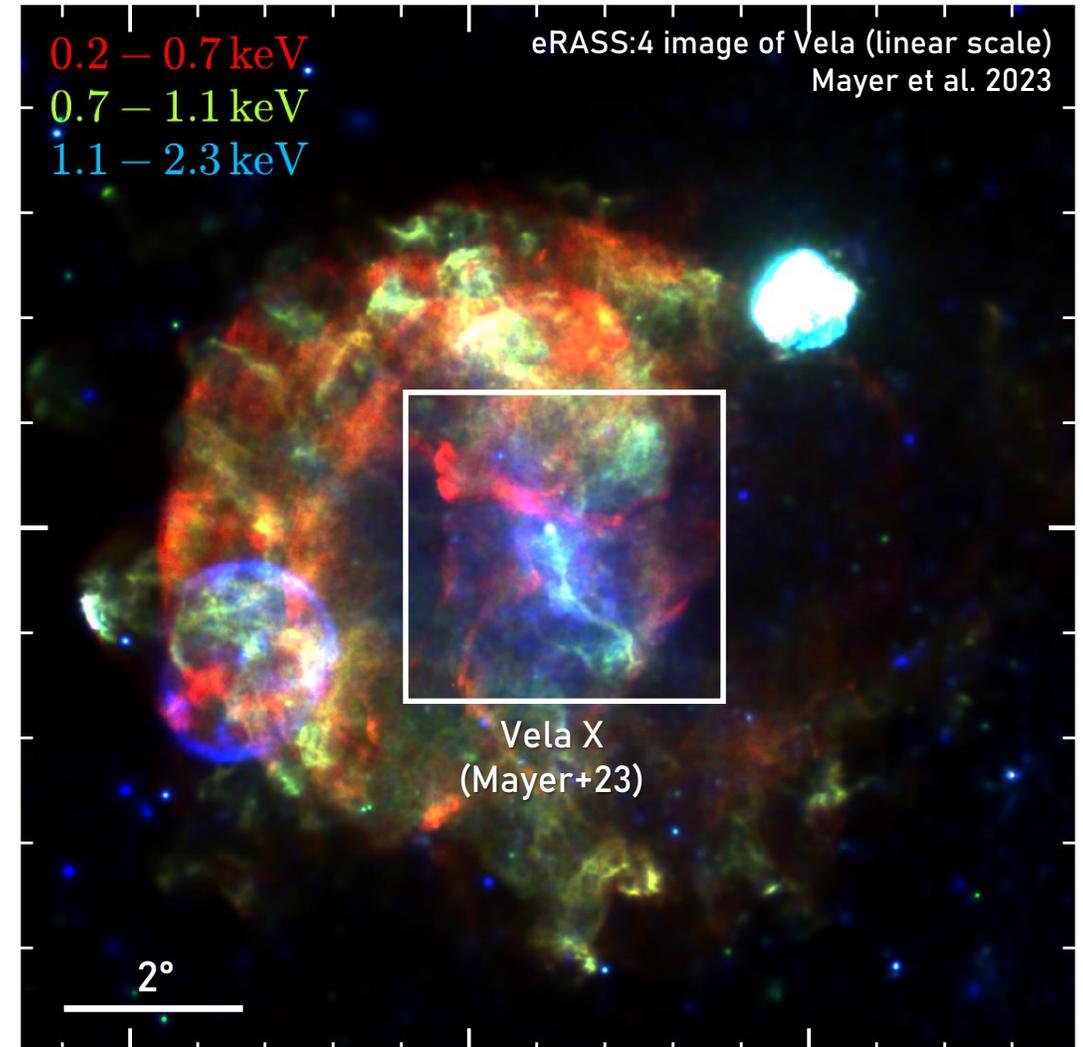
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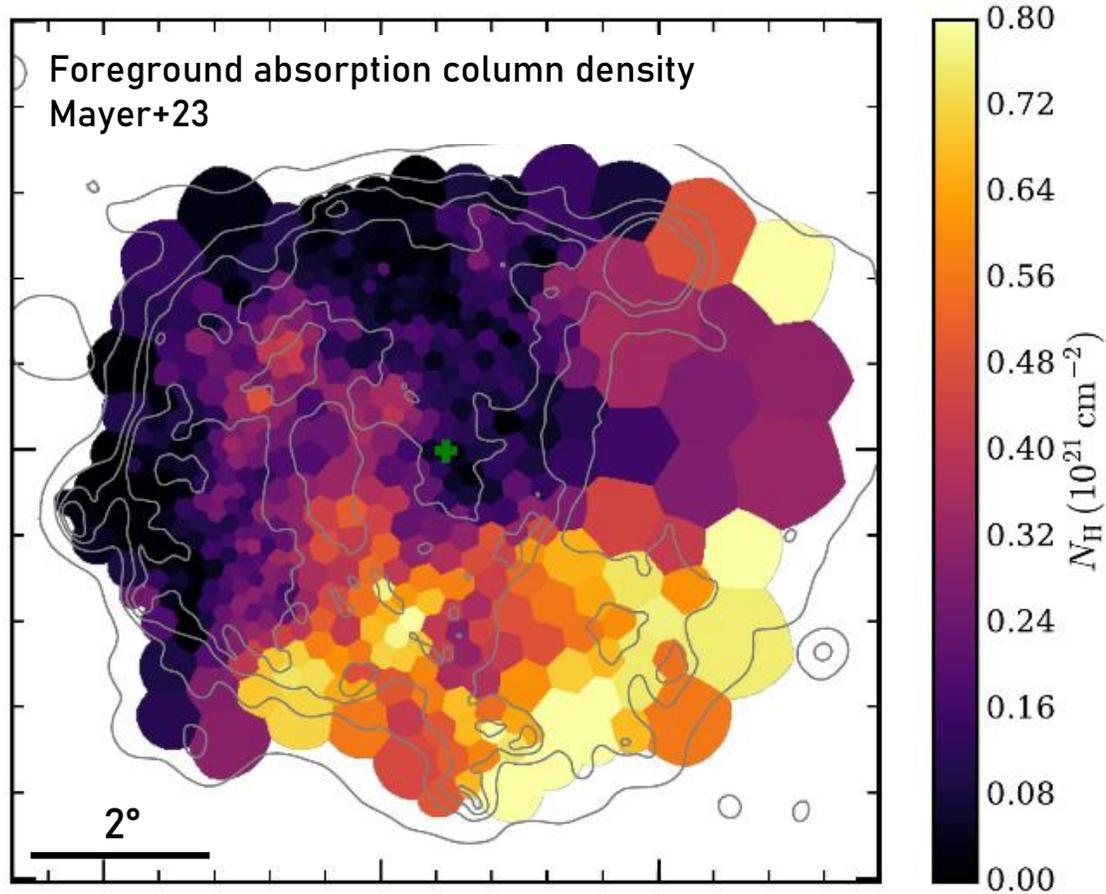


Vela and Friends

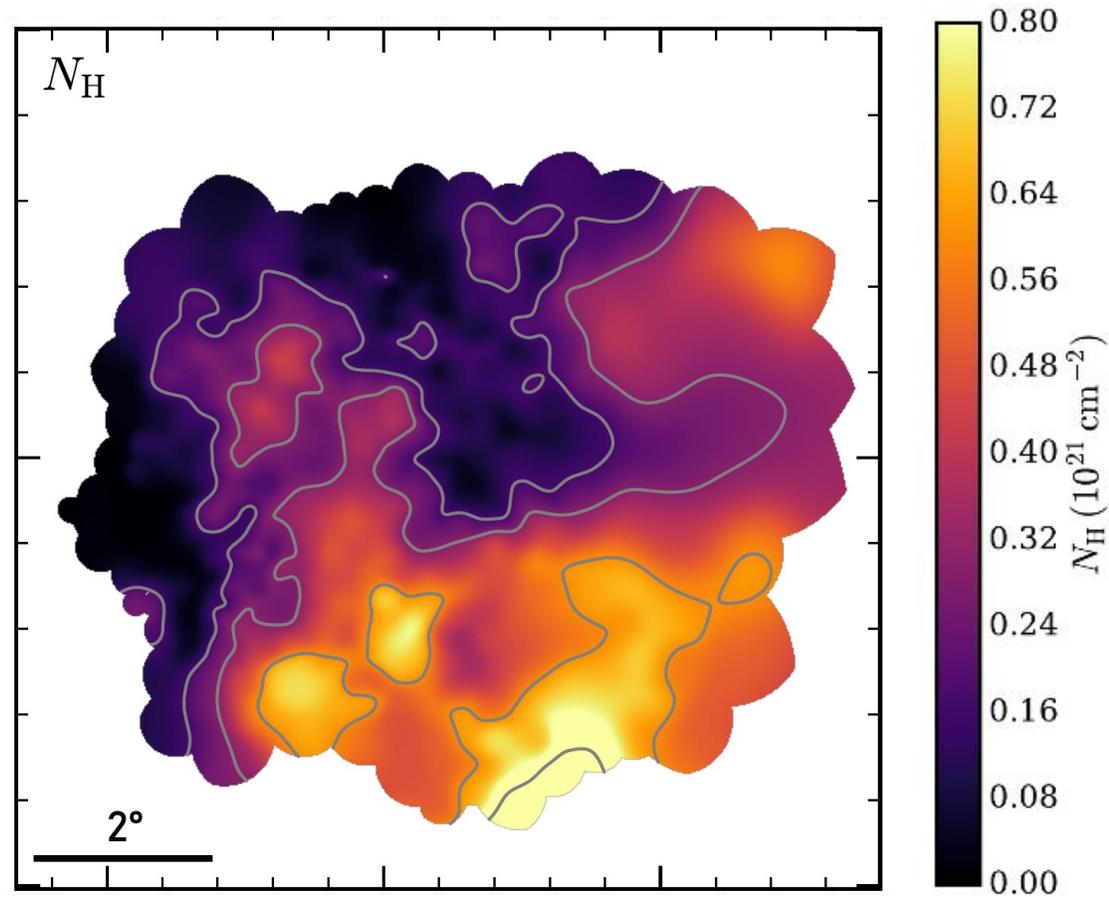
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- Vela X: Pulsar wind nebula of central pulsar
- eROSITA allows for disentangling thermal & nonthermal X-rays on large scales



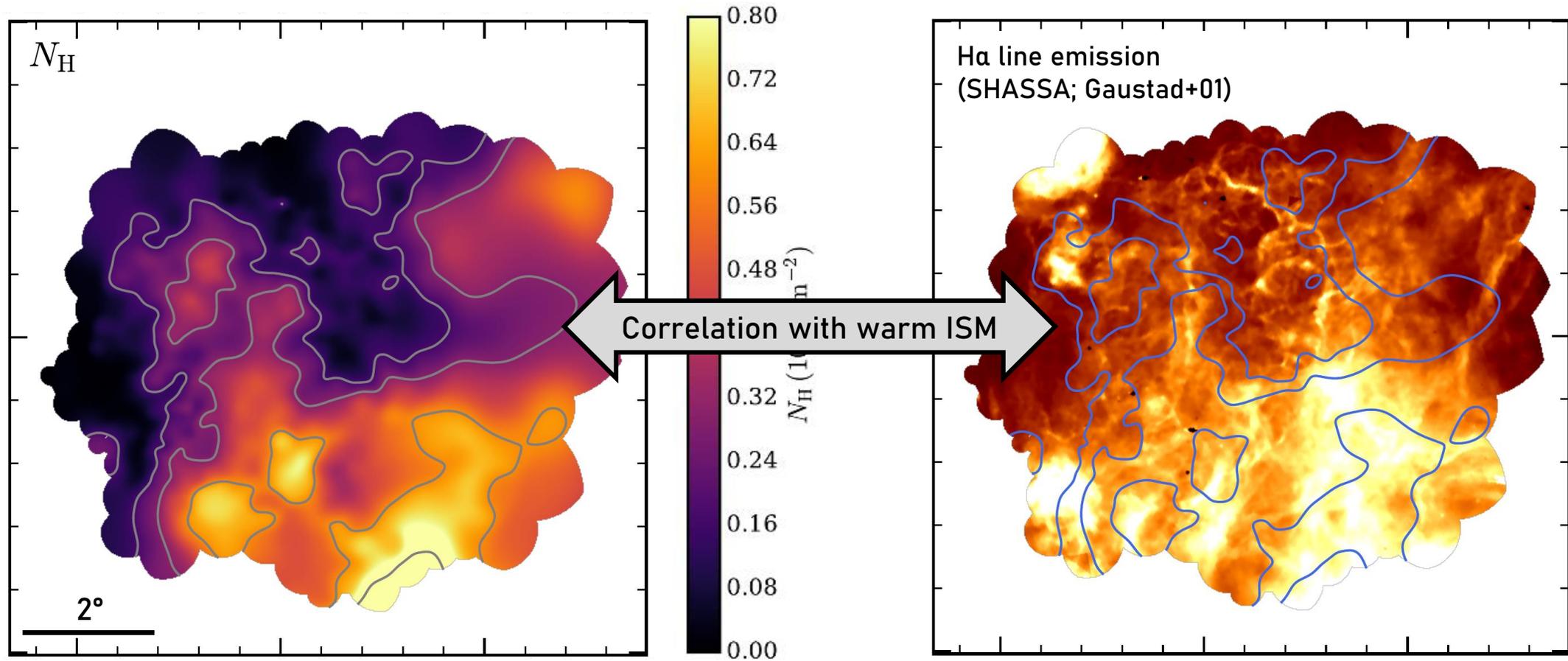
Vela SNR – Intervening ISM



Vela SNR – Intervening ISM

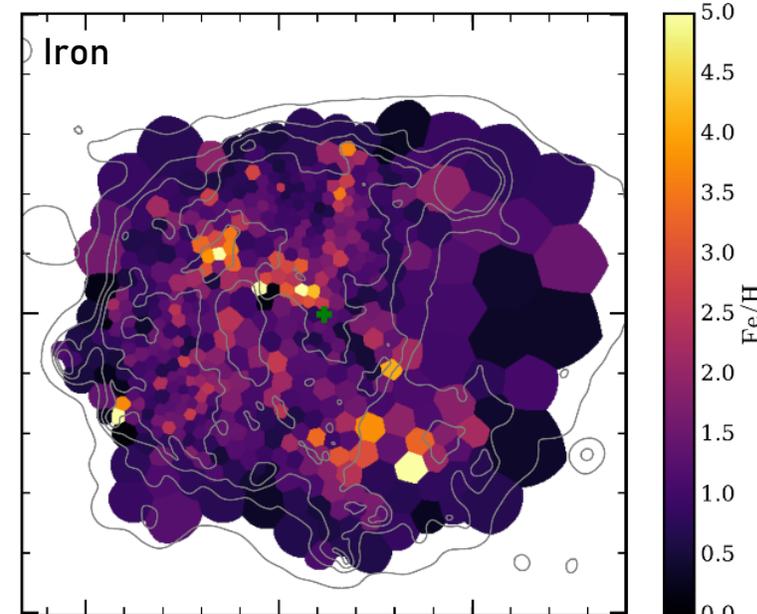
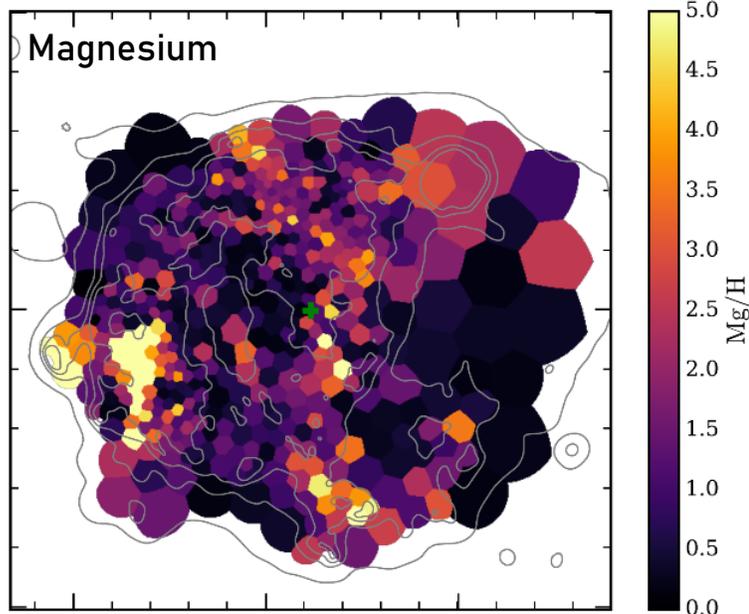
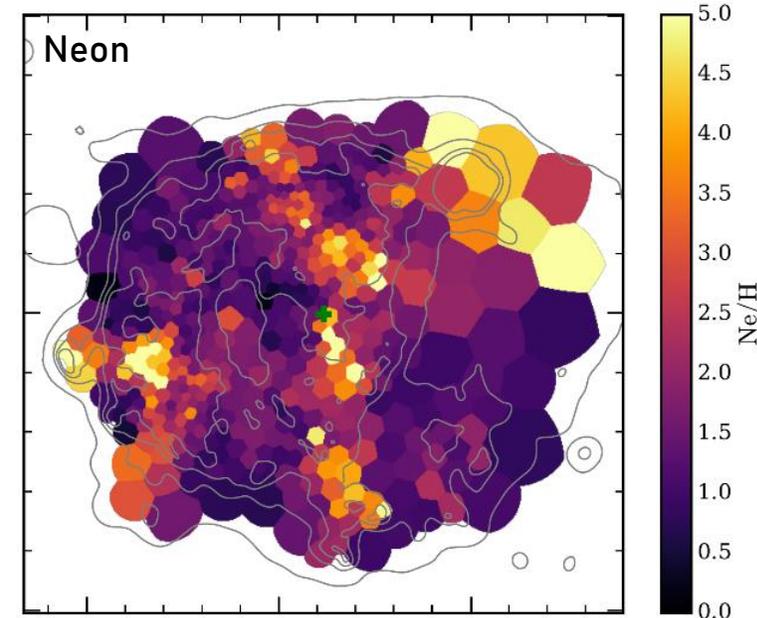
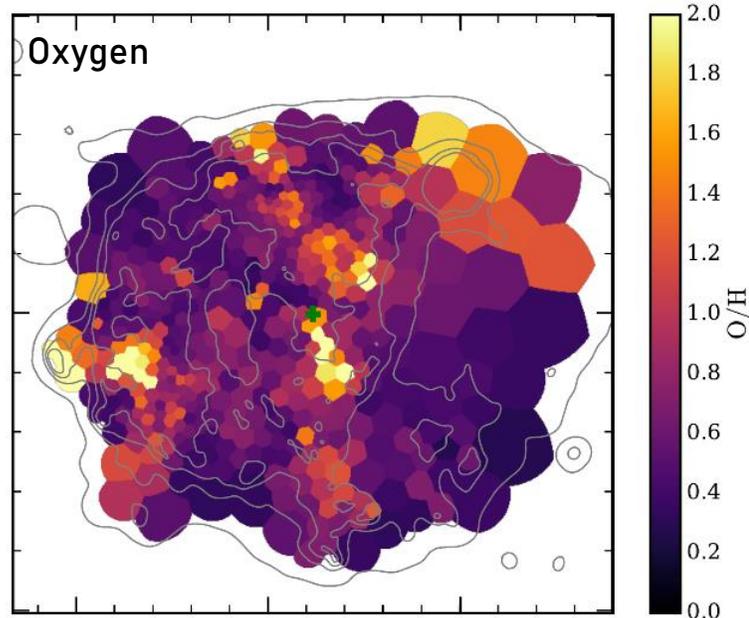


Vela SNR – Intervening ISM



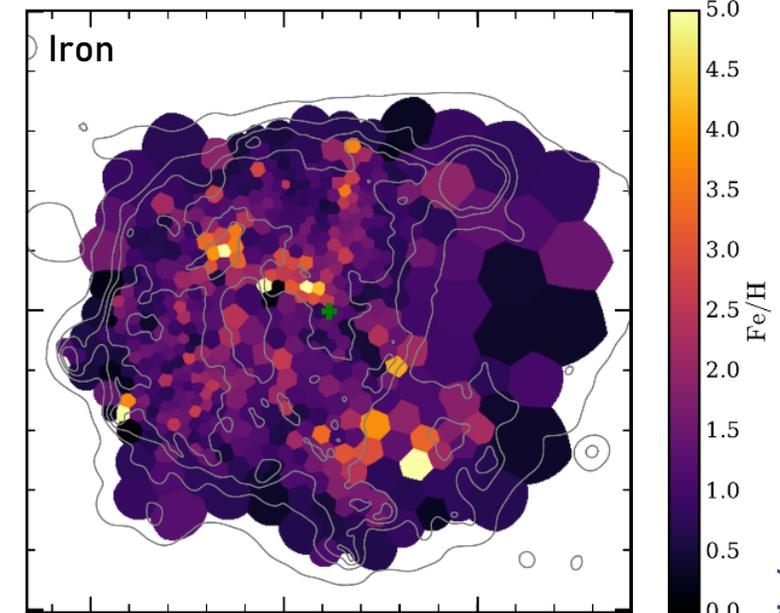
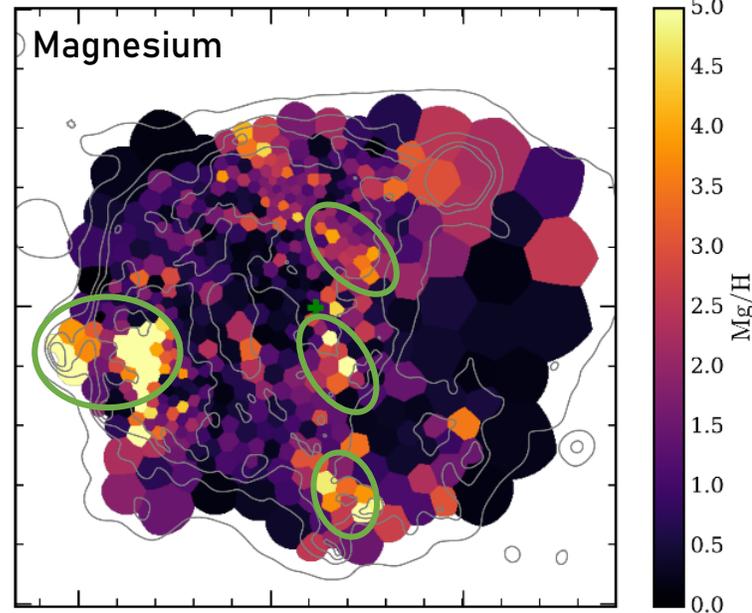
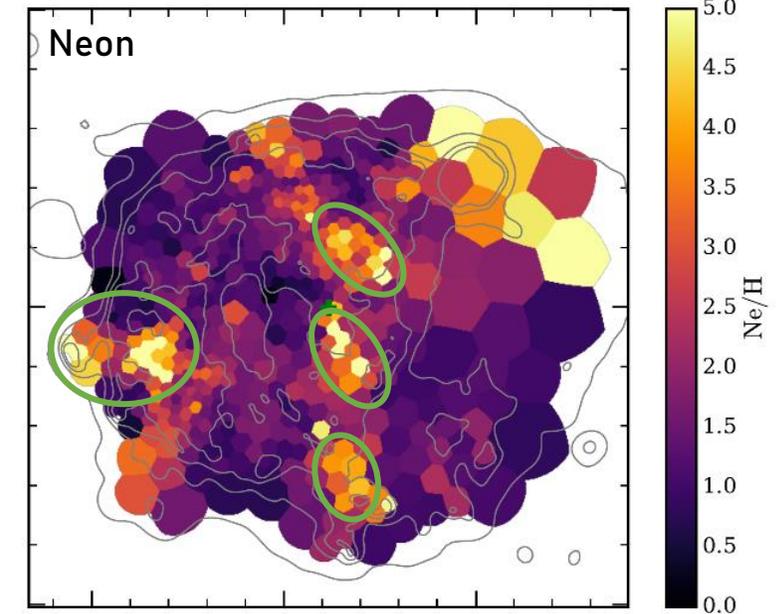
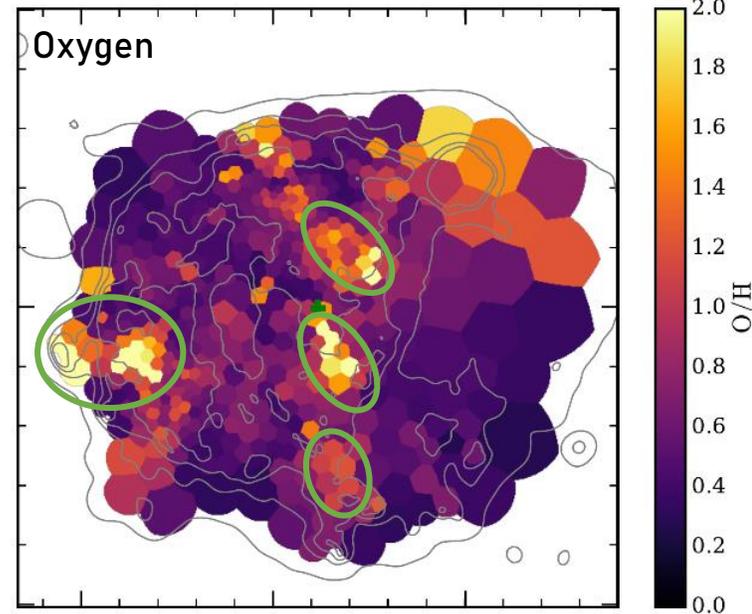
Vela SNR – Ejecta

Mayer+23



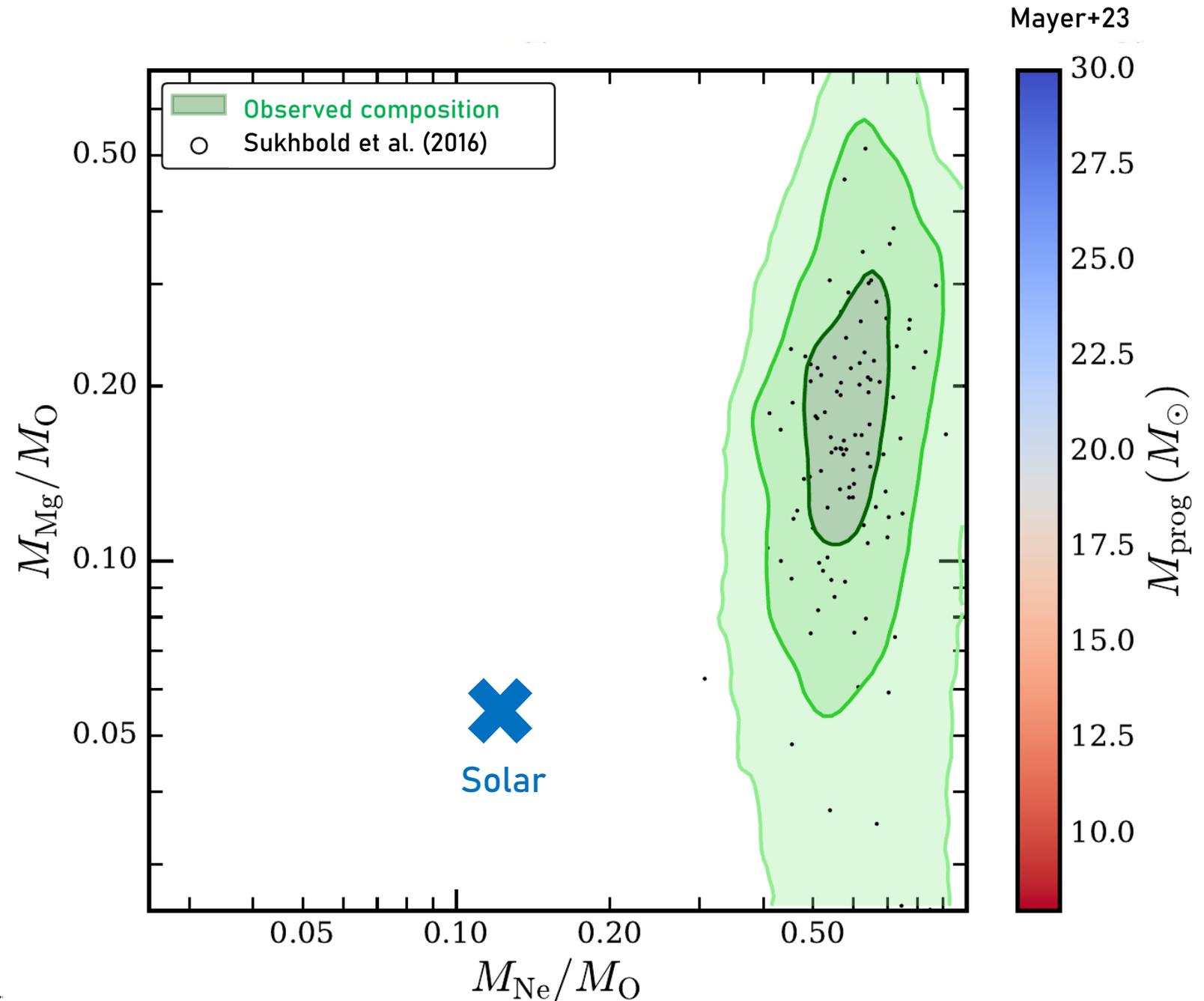
Vela SNR – Ejecta

- Correlated abundance peaks of oxygen, neon, magnesium
- Iron distribution independent from lighter elements



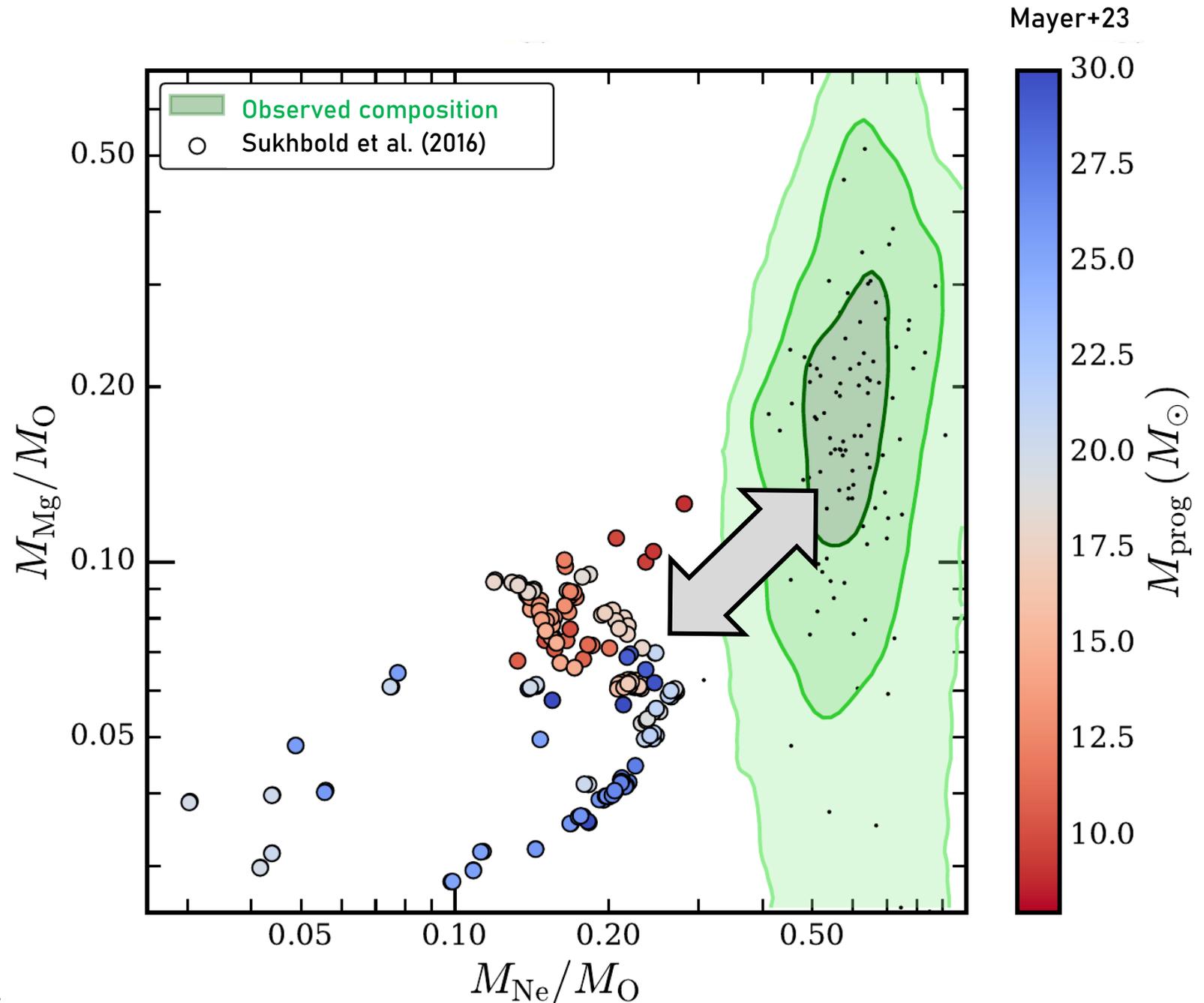
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 - General pattern: Ne/O, Mg/O supersolar



Vela SNR – Ejecta

- Correlated abundance peaks of oxygen, neon, magnesium
 - Iron distribution independent from lighter elements
 - General pattern: Ne/O, Mg/O supersolar
 - Not reproduced in nucleosynthesis models (e.g. Sukhbold+16)



Mayer+23

30.0

27.5

25.0

22.5

20.0

17.5

15.0

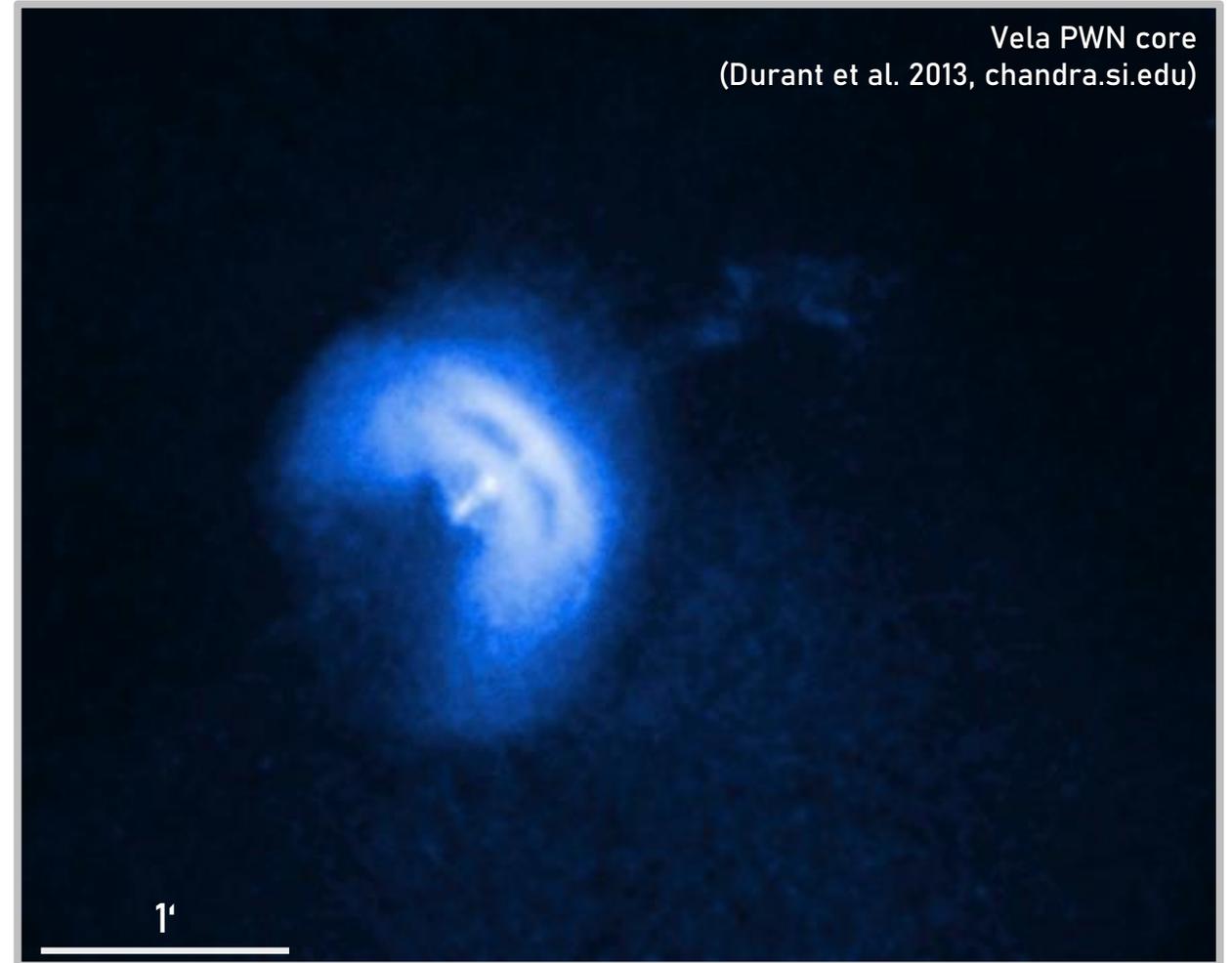
12.5

10.0

$M_{\text{prog}} (M_{\odot})$

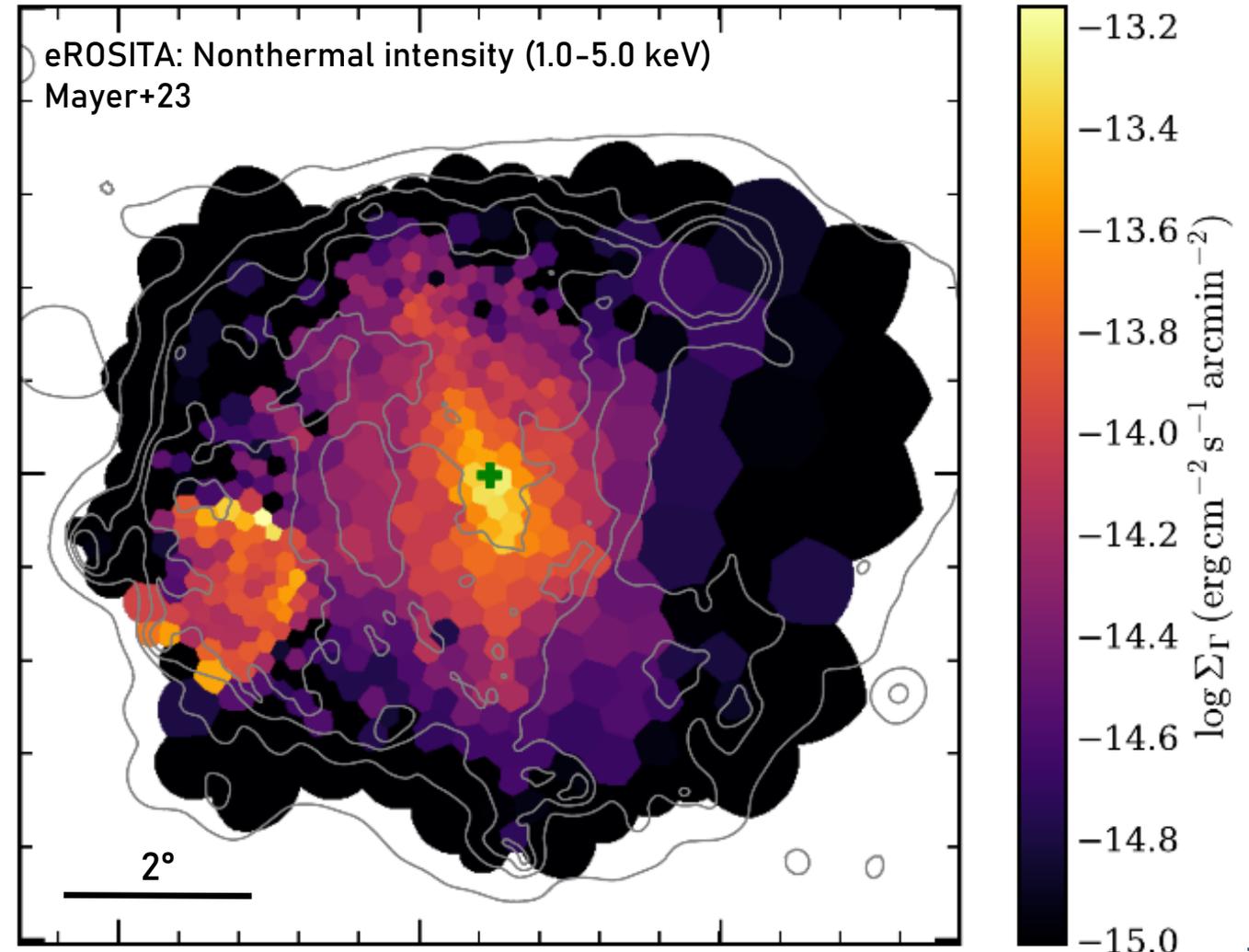
X-ray Synchrotron Emission from Vela X

- Vela X in X-rays (prior to eROSITA): Compact PWN core with „jet“ and equatorial torus (e.g., Helfand+2001)



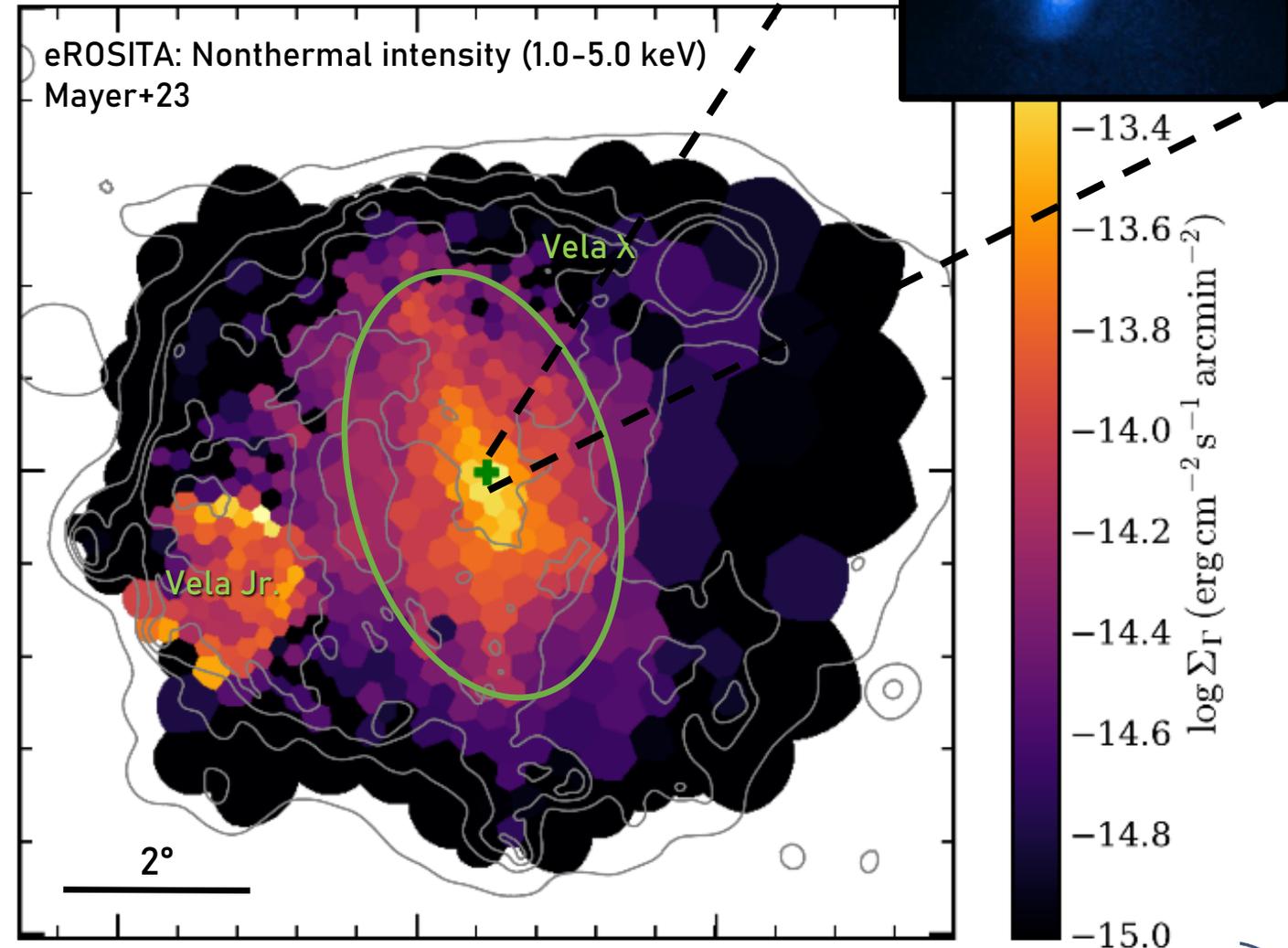
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X-ray Synchrotron Emission from Vela X

- Vela X in X-rays (prior to eROSITA): Compact PWN core with „jet“ and equatorial torus (e.g., Helfand+2001)
- eROSITA reveals extended X-ray PWN (~ 15 pc)
- Diffusion of multi-TeV electrons in ambient magnetic field

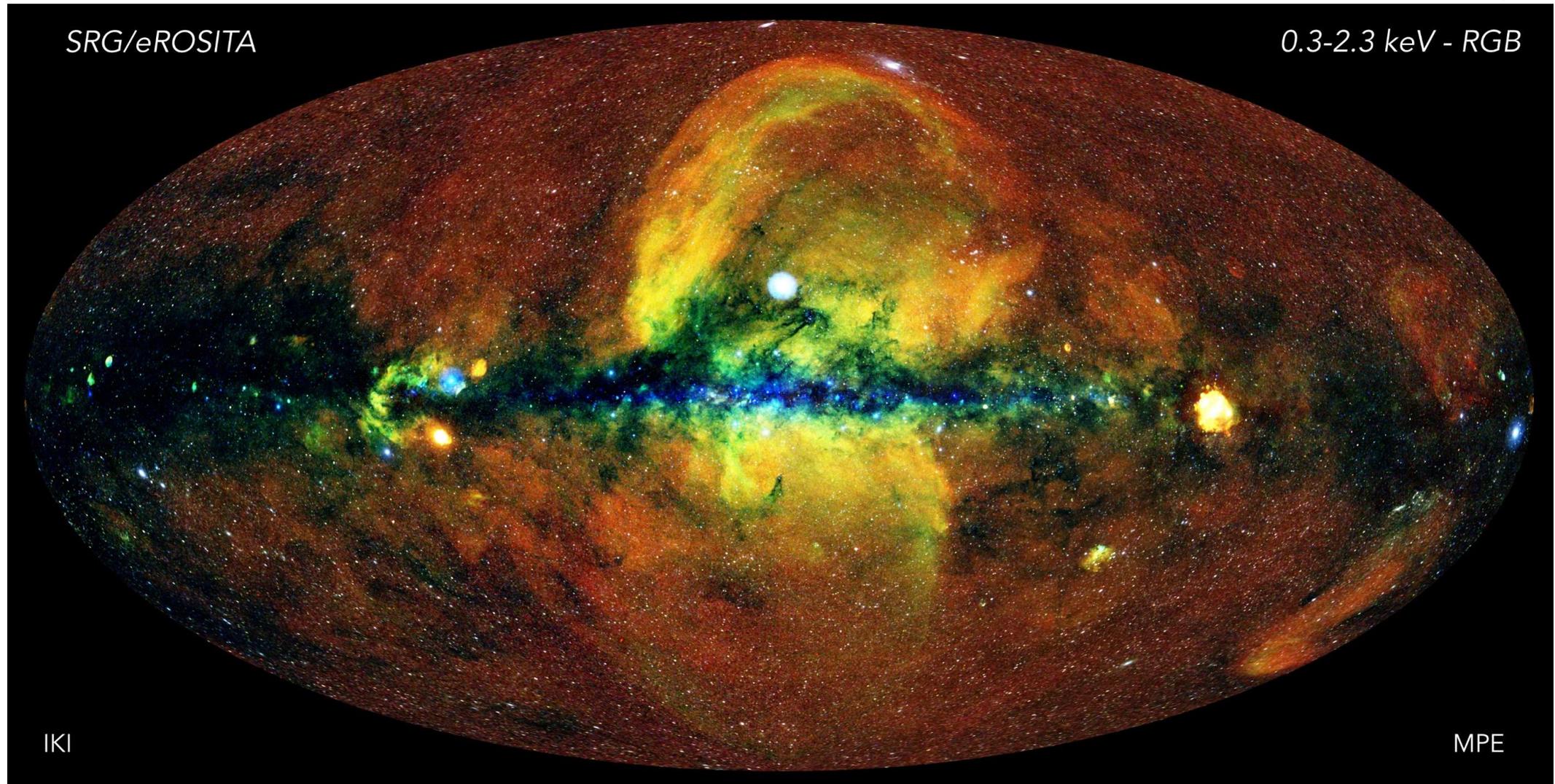




SNR Populations with eROSITA

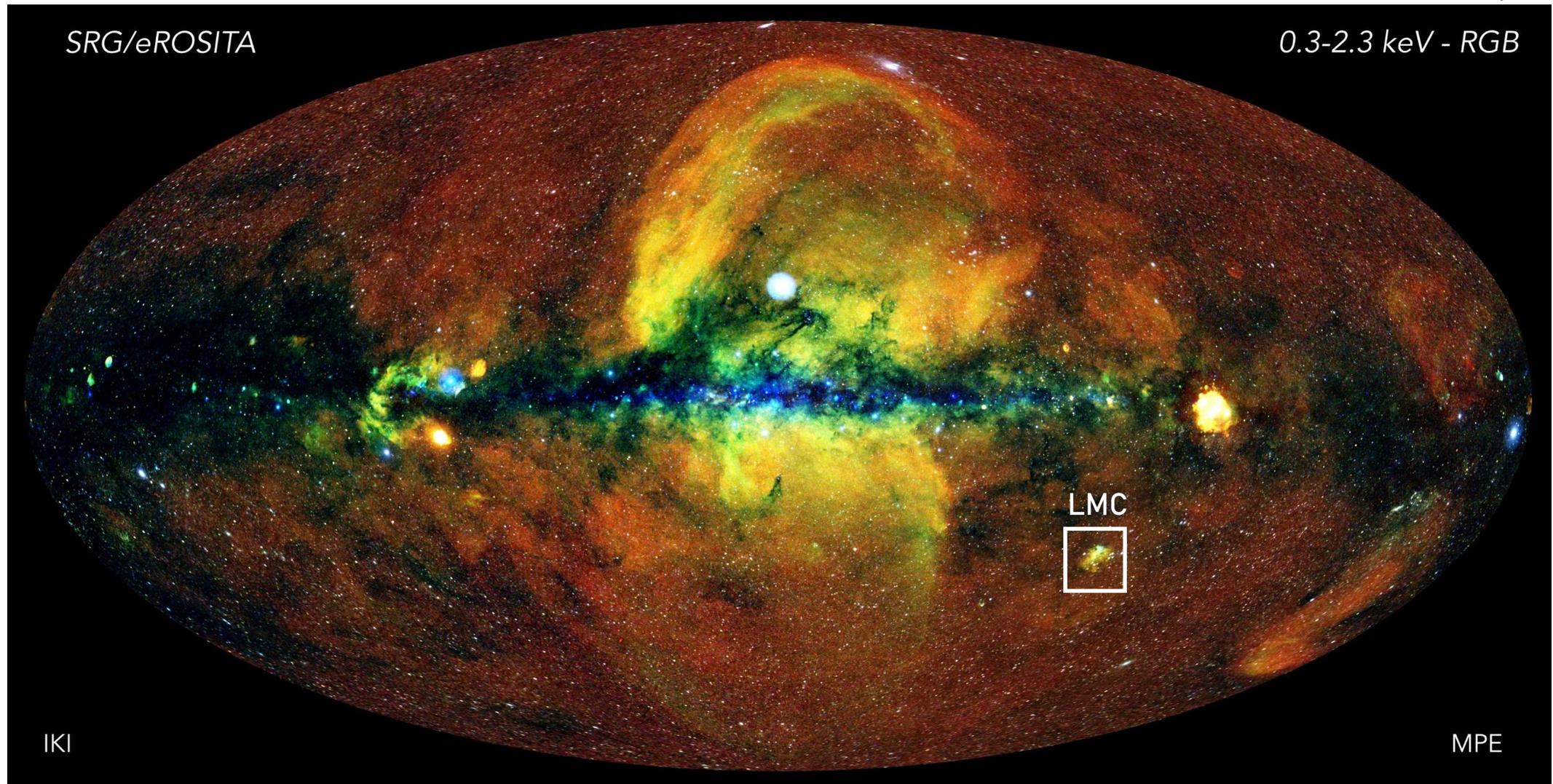
The eROSITA All-Sky Map

eRASS1 all-sky image
Credit: MPE/IKI



The eROSITA All-Sky Map

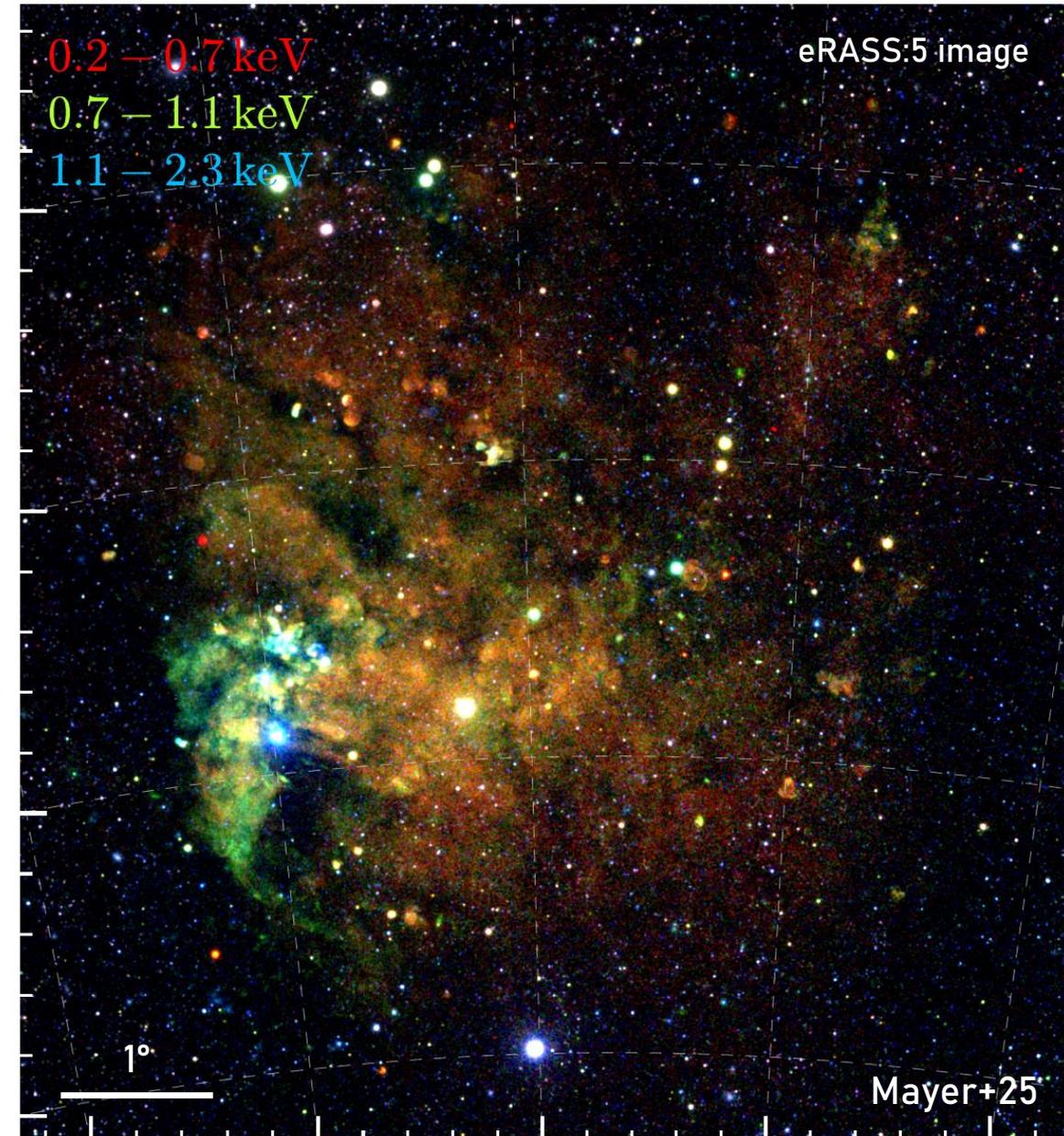
eRASS1 all-sky image
Credit: MPE/IKI



SNR population in the LMC

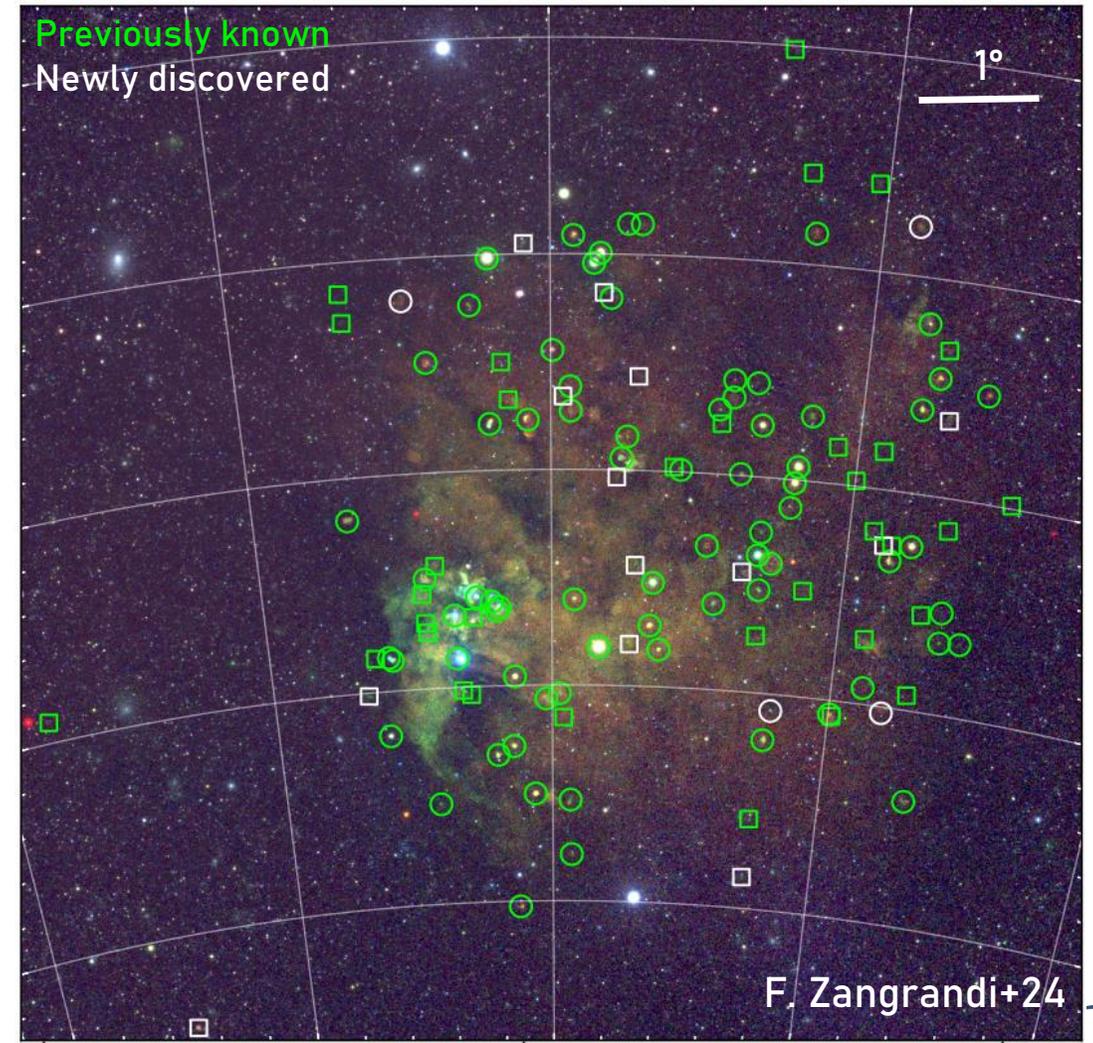
- Large Magellanic Cloud (LMC)
 - Nearby (~ 50 kpc) Milky Way satellite
 - Face-on & low foreground absorption ($< 10^{21}$ cm $^{-2}$)
 - Close to eROSITA survey pole
 - eROSITA all-sky survey (eRASS:5) provides most sensitive X-ray view of LMC

- Full coverage of star-forming galaxy for unbiased study of SNR population



SNR population in the LMC

- Systematic SNR study in LMC finds 77 X-ray bright SNRs and 13 new candidates (Zangrandi+24)

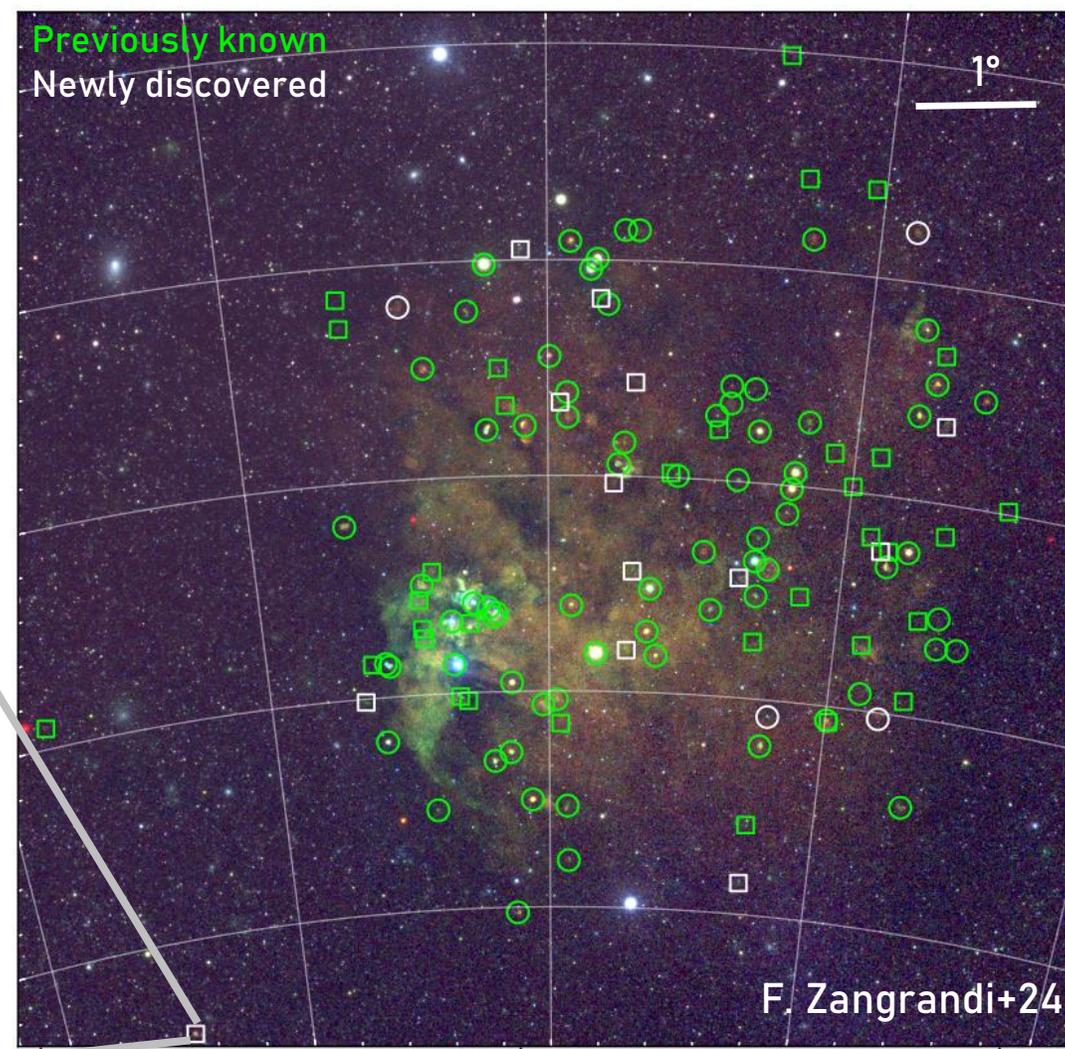
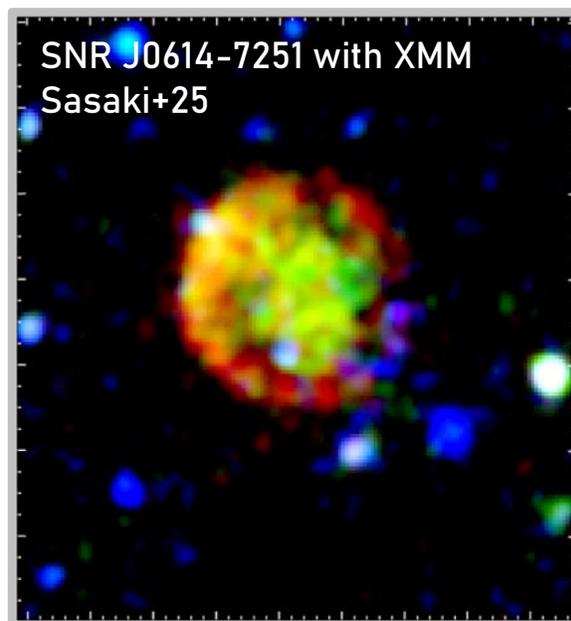


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➤ 2 SNRs in far outskirts of LMC disk; Ejected during tidal interactions? (Sasaki+25)



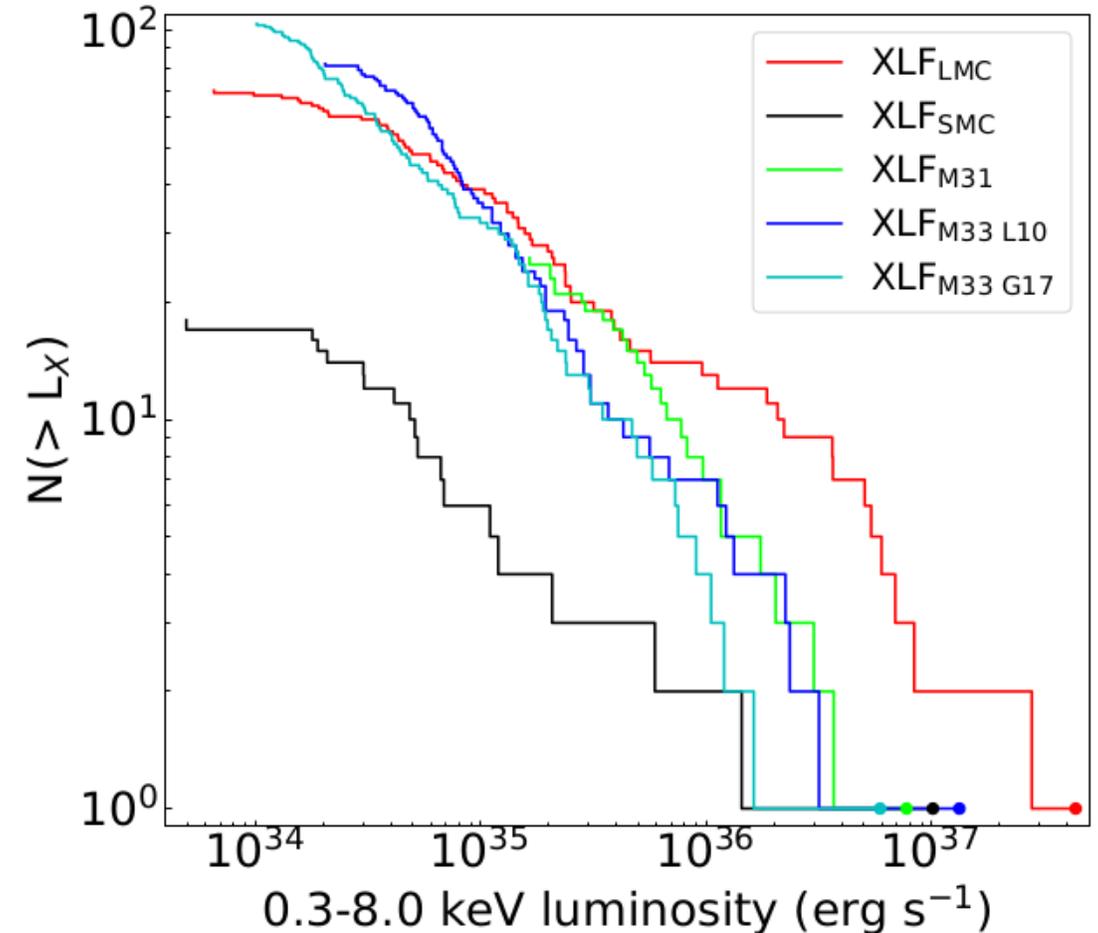
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F. Zangrandi+, submitted

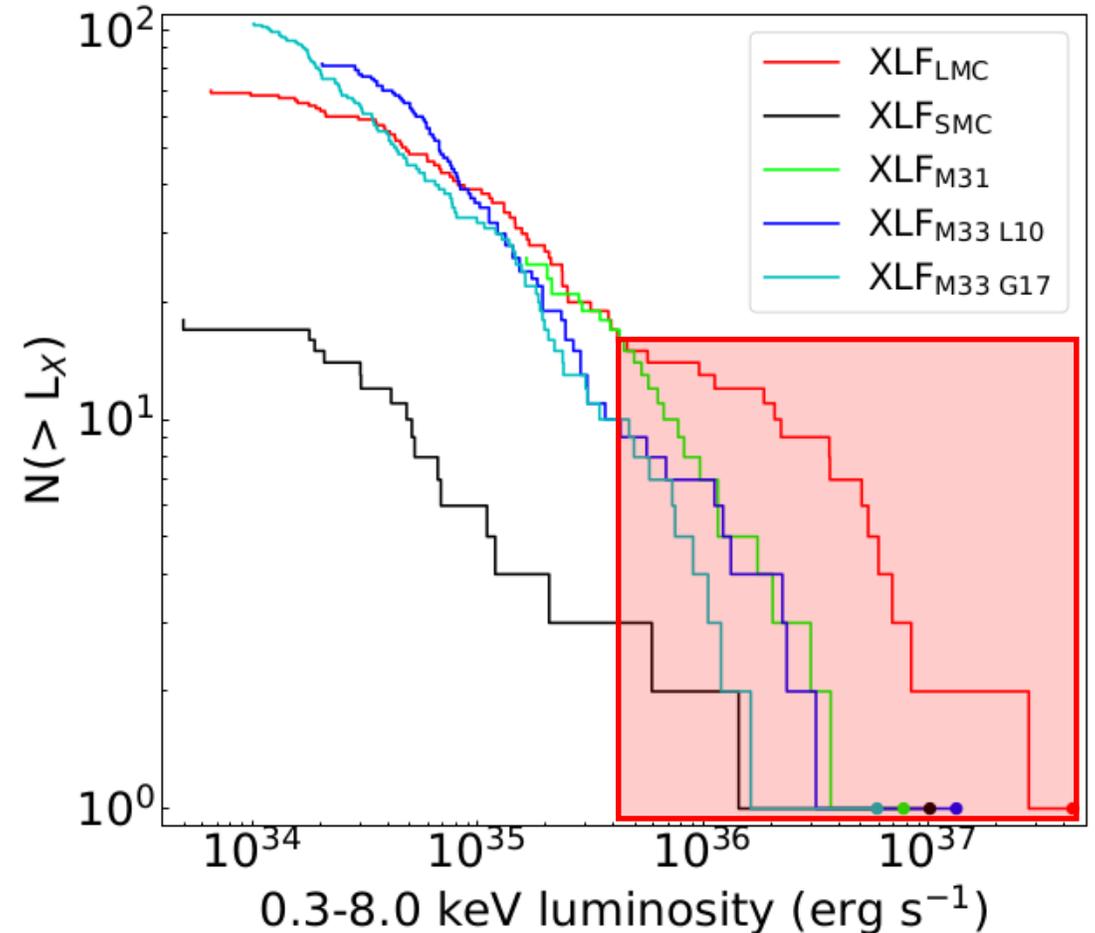


SNR population in the LMC

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 - 2 SNRs in far outskirts of LMC disk; Ejected during tidal interactions? (Sasaki+25)
- Luminosity function reveals tail of X-ray bright SNRs (Zangrandi+, submitted)
 - Flatter slope due to active star formation?



F. Zangrandi+, submitted



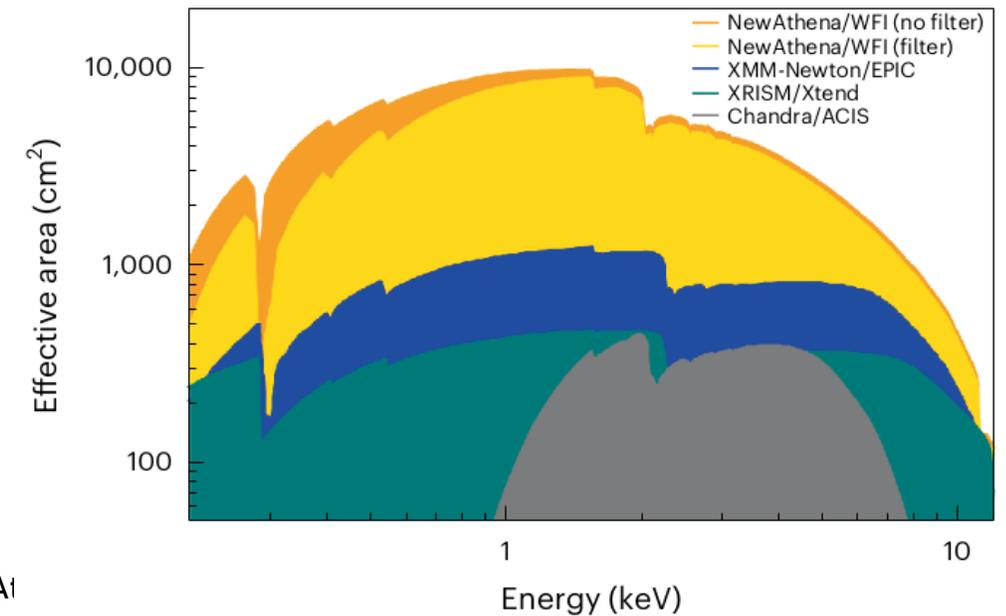
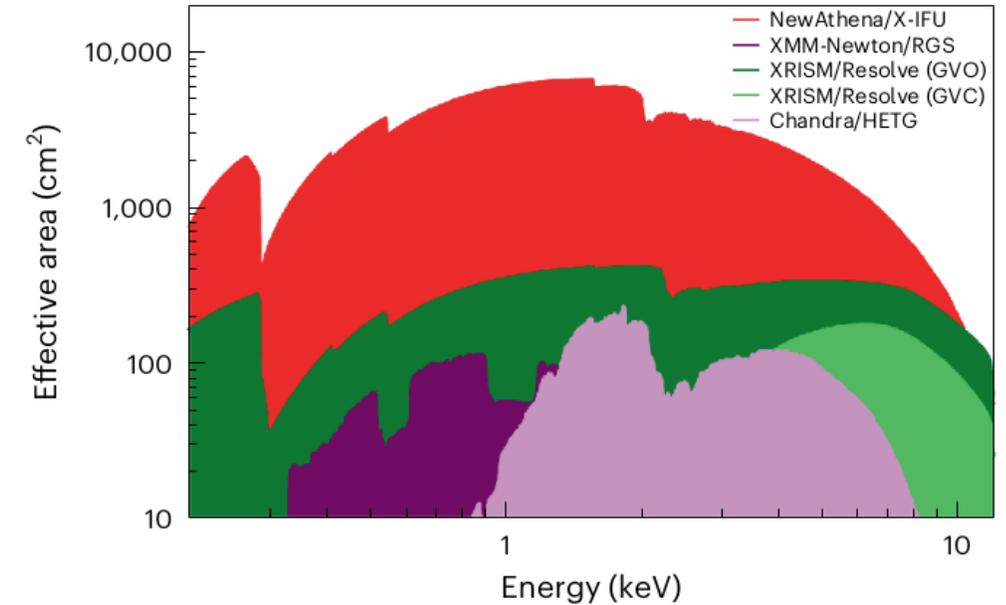


The Stellar Graveyard with NewAthena

SNR Science with NewAthena

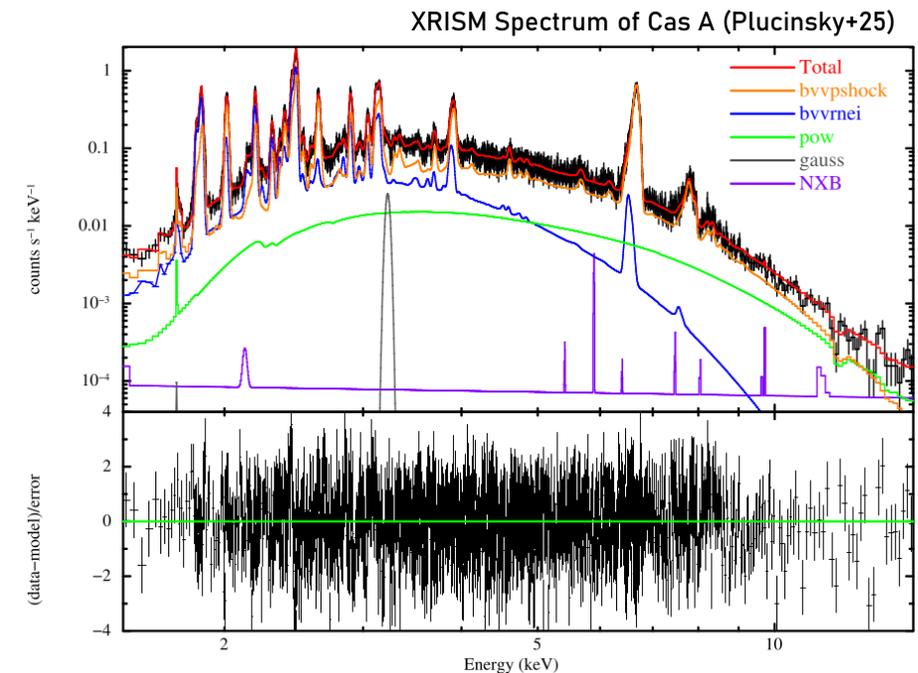
- Vast improvements in imaging sensitivity (WFI) & spectral resolution (X-IFU)

NewAthena WFI and X-IFU effective areas
Cruise+25



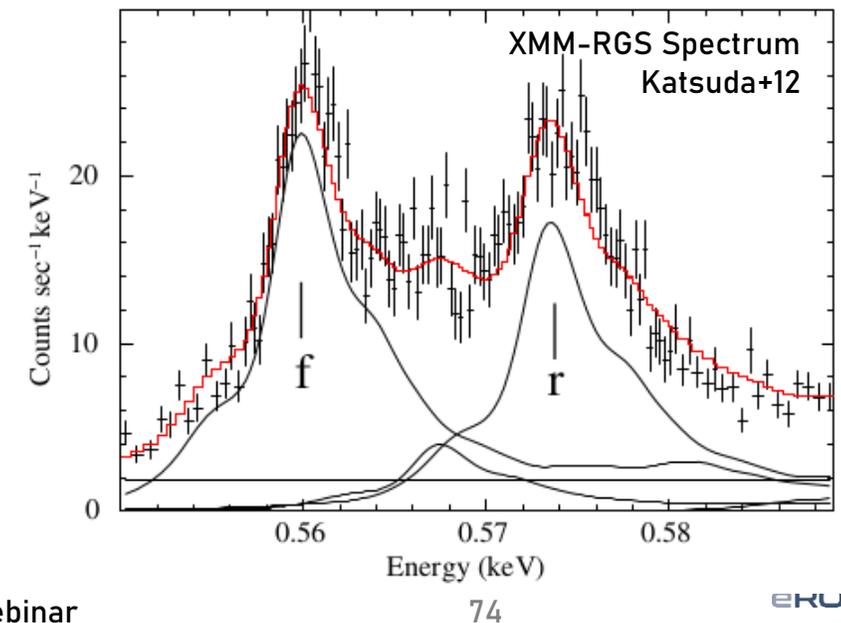
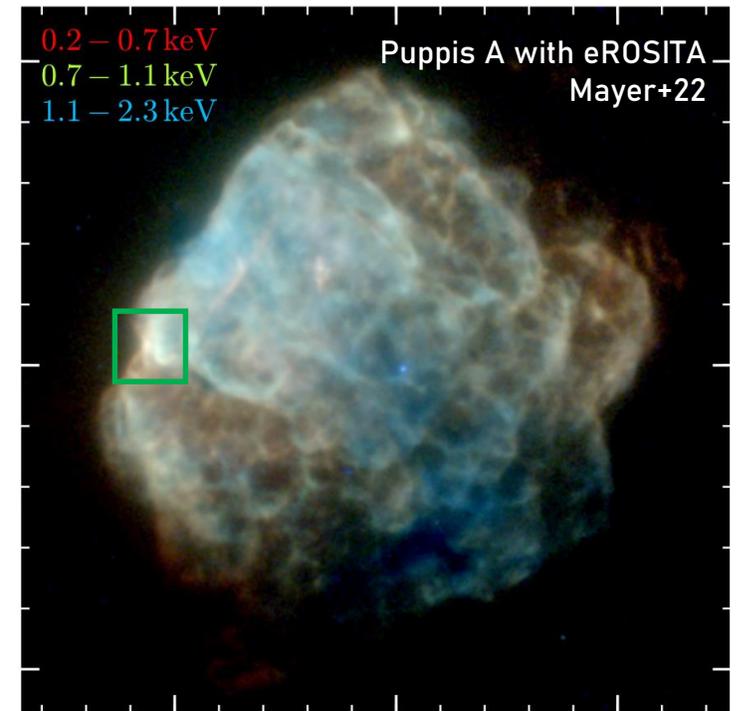
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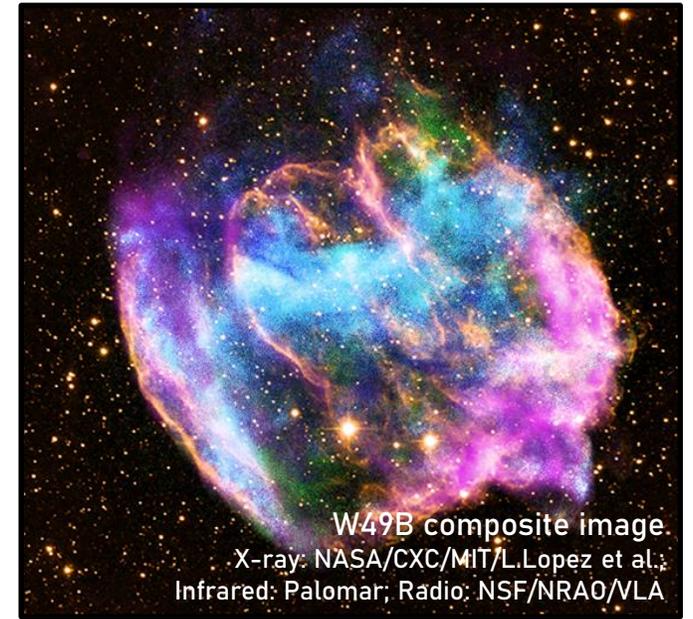


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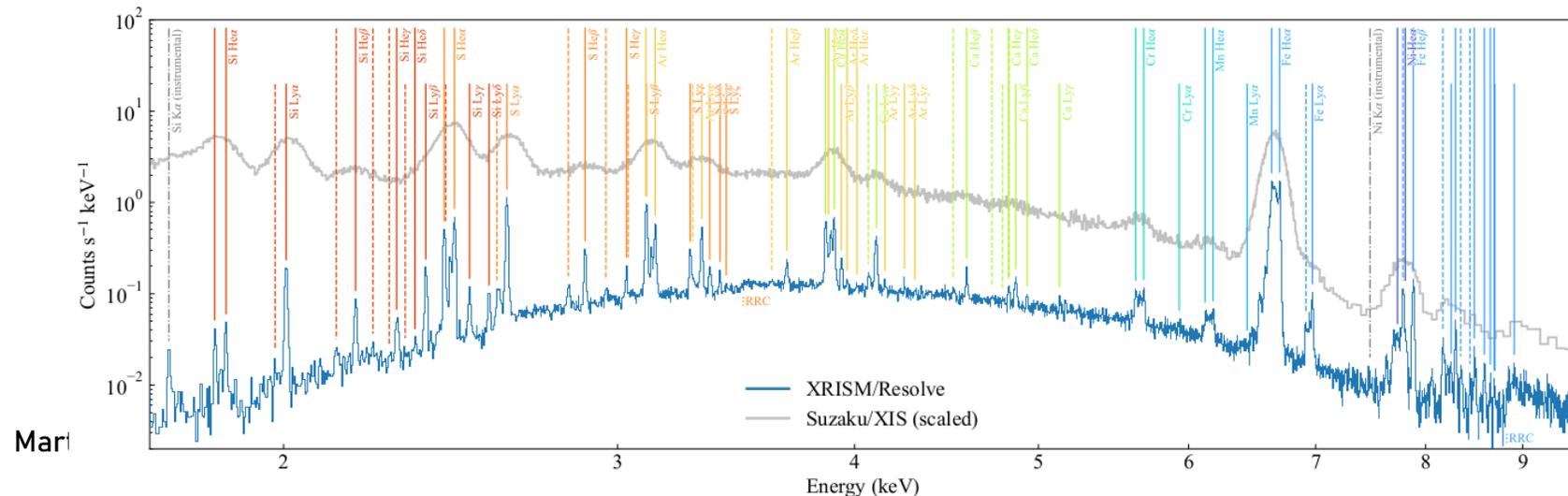
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- Reliable ejecta composition; rare elements (X-IFU)



XRISM Spectrum of SNR W49B
Audard+25

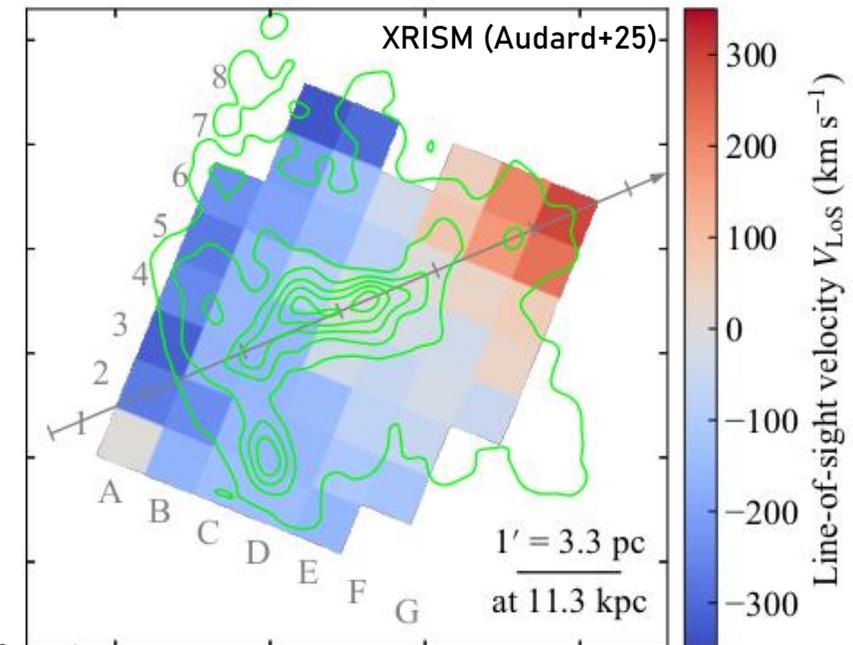
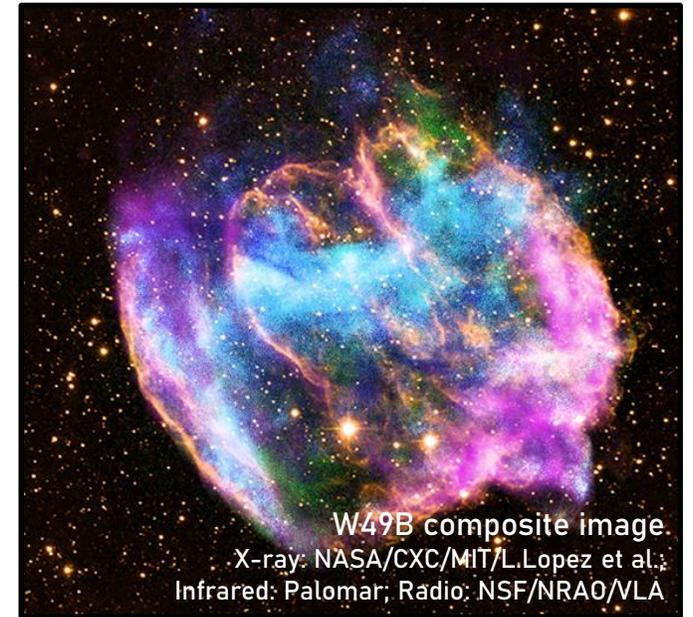


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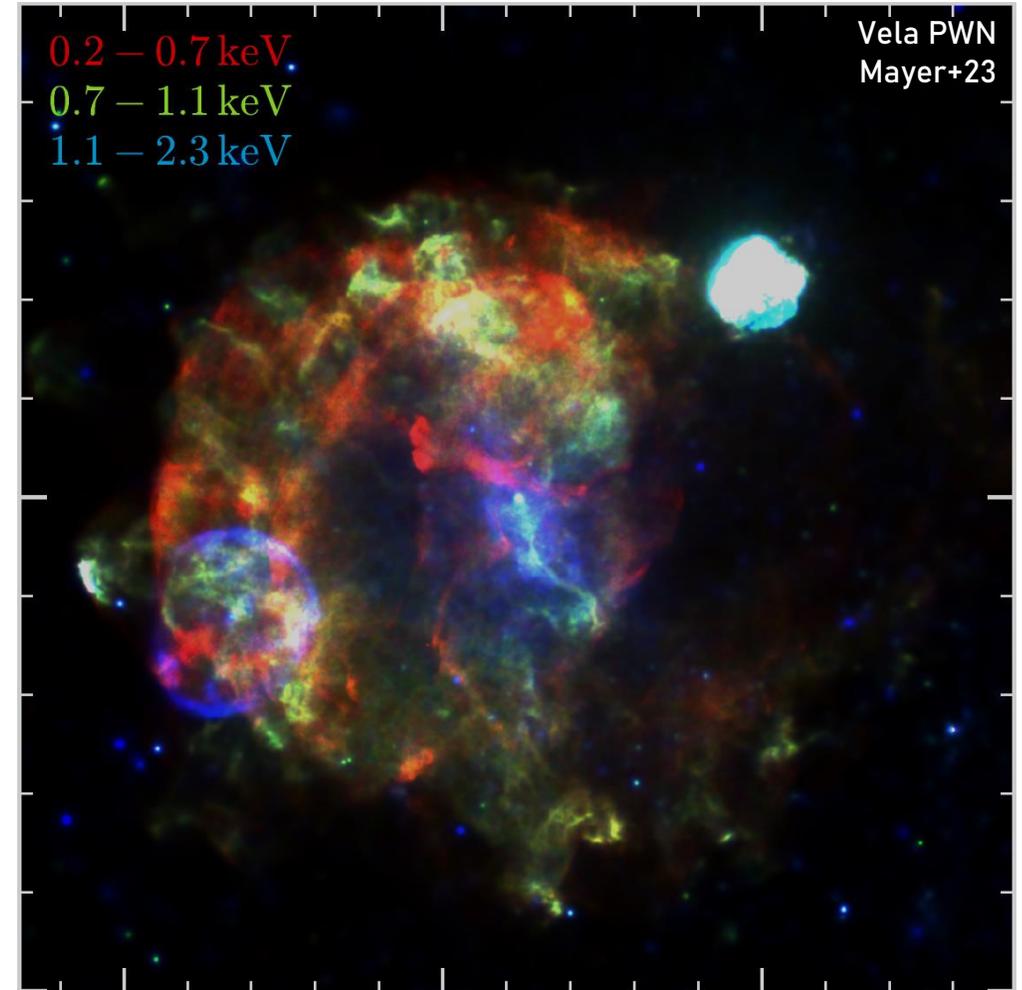
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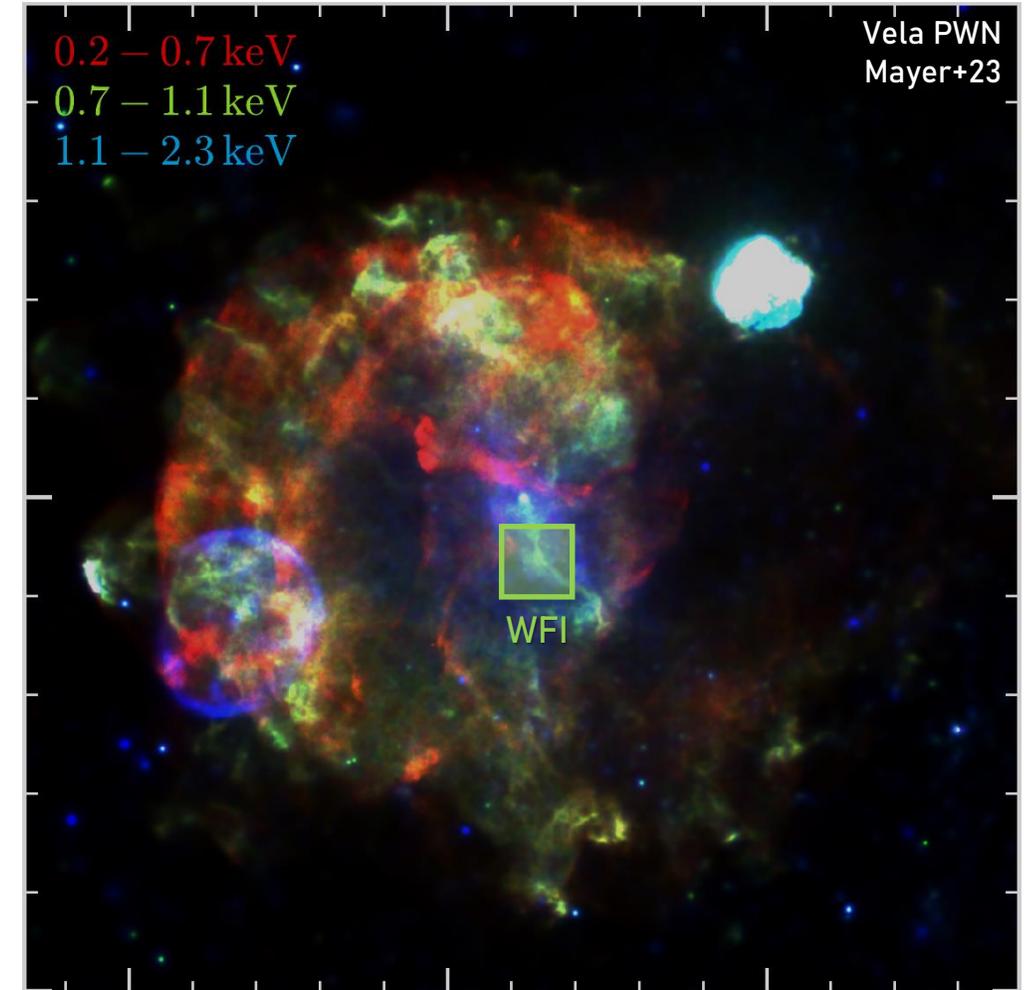
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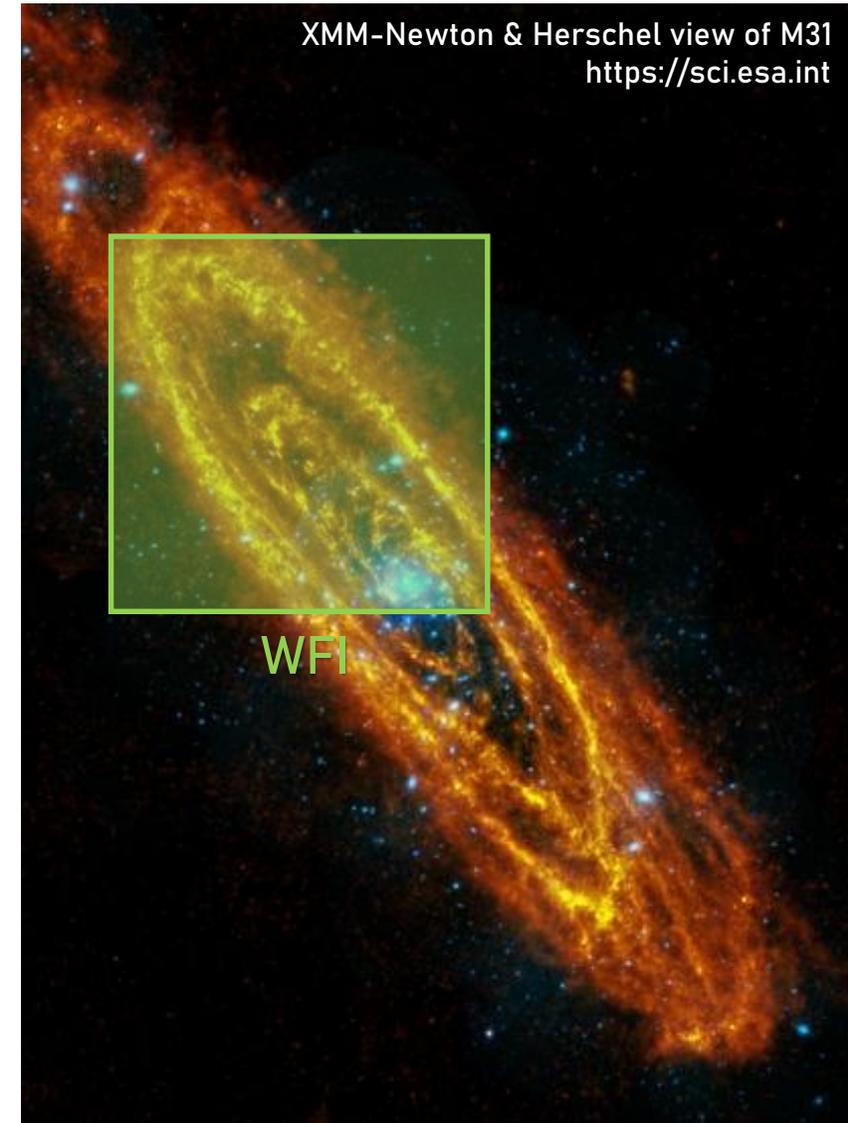
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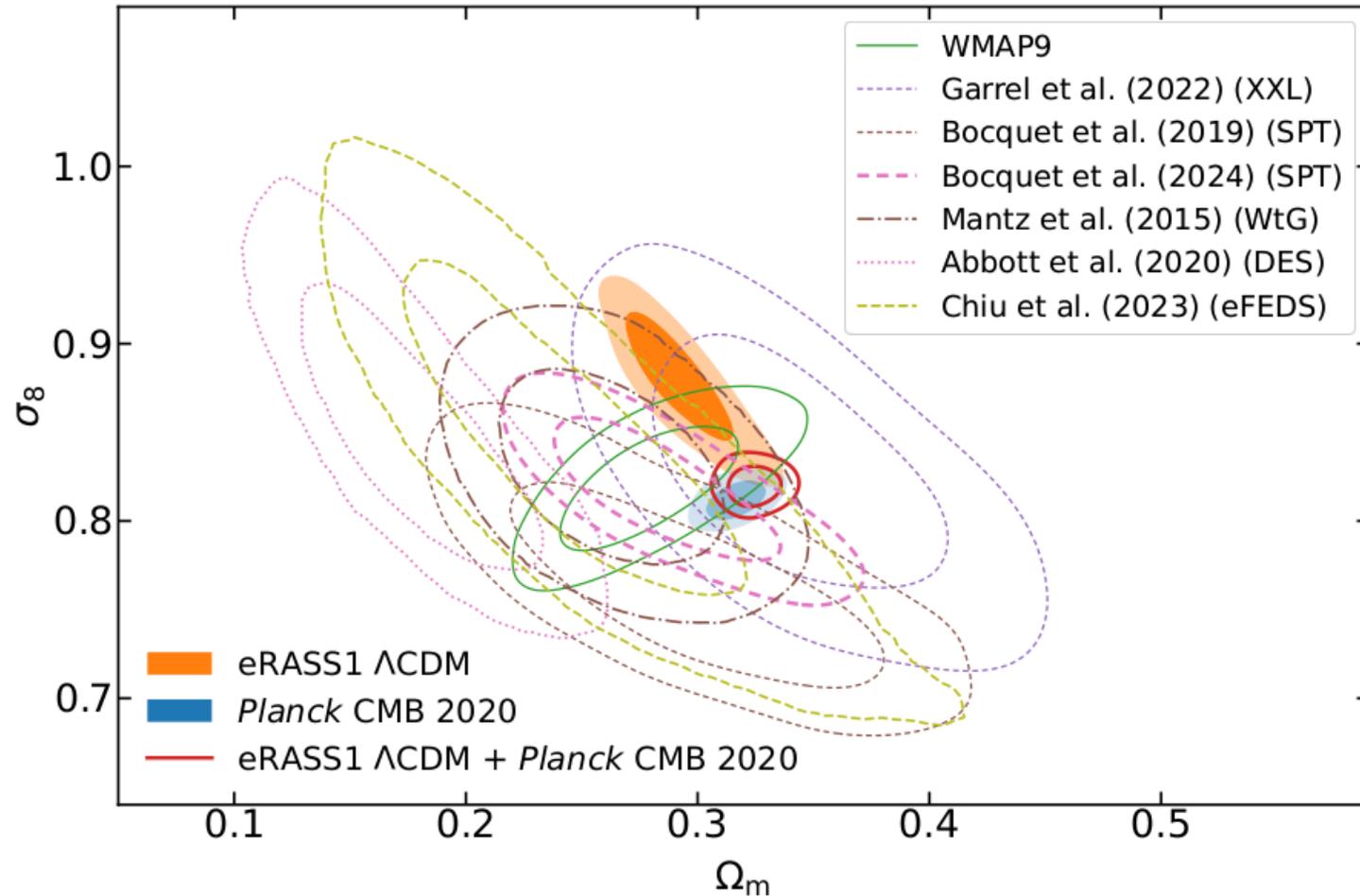
Summary

- **Using eROSITA All-Sky Survey data to study „stellar graveyard“**
 - Discoveries across the sky: Hoinga SNR, eROSITA Bubbles
 - Detailed study of extended SNRs: Puppis A, Vela
 - Systematic population studies of SNRs in galaxies
- **eROSITA DR1 data are public!**
- **The future: Microphysics, kinematics & populations of SNRs with NewAthena**

Extra Slides eROSITA

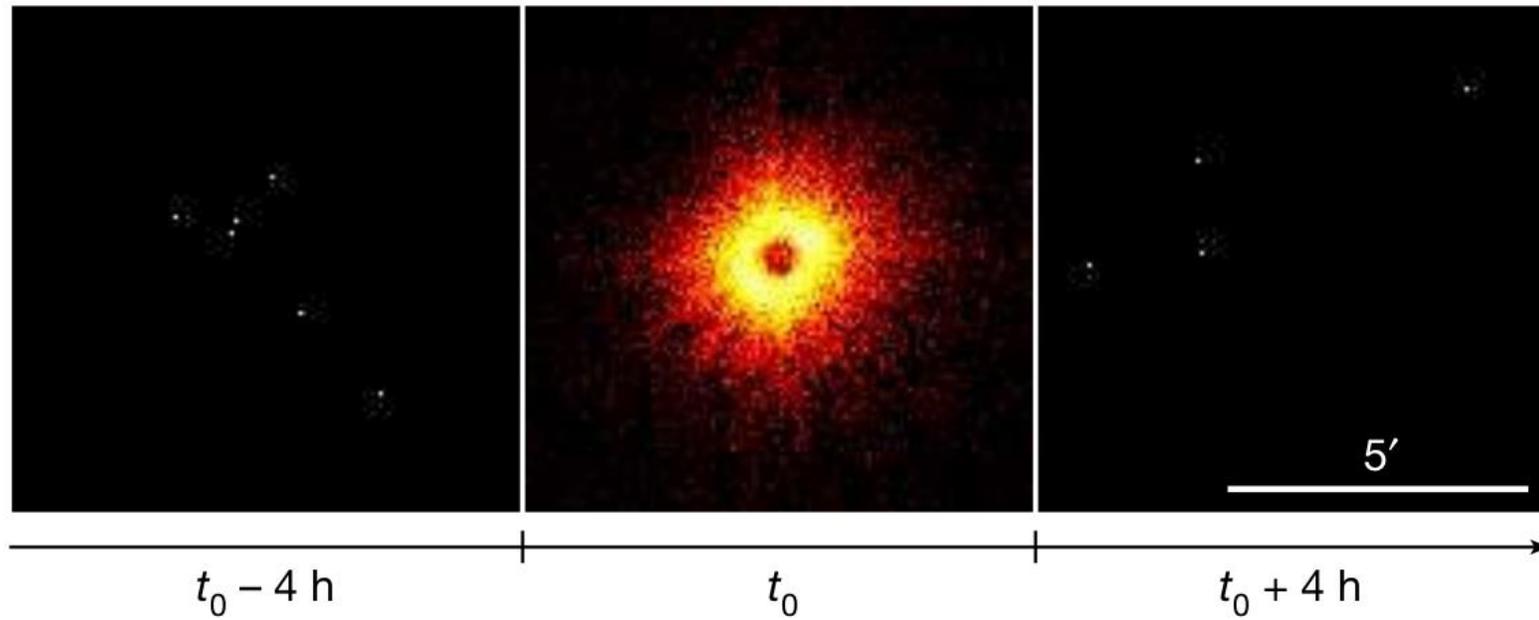
eROSITA DR₁: The Target Science

eRASS1 Cosmology constraints from galaxy cluster counts
Ghirardini+24



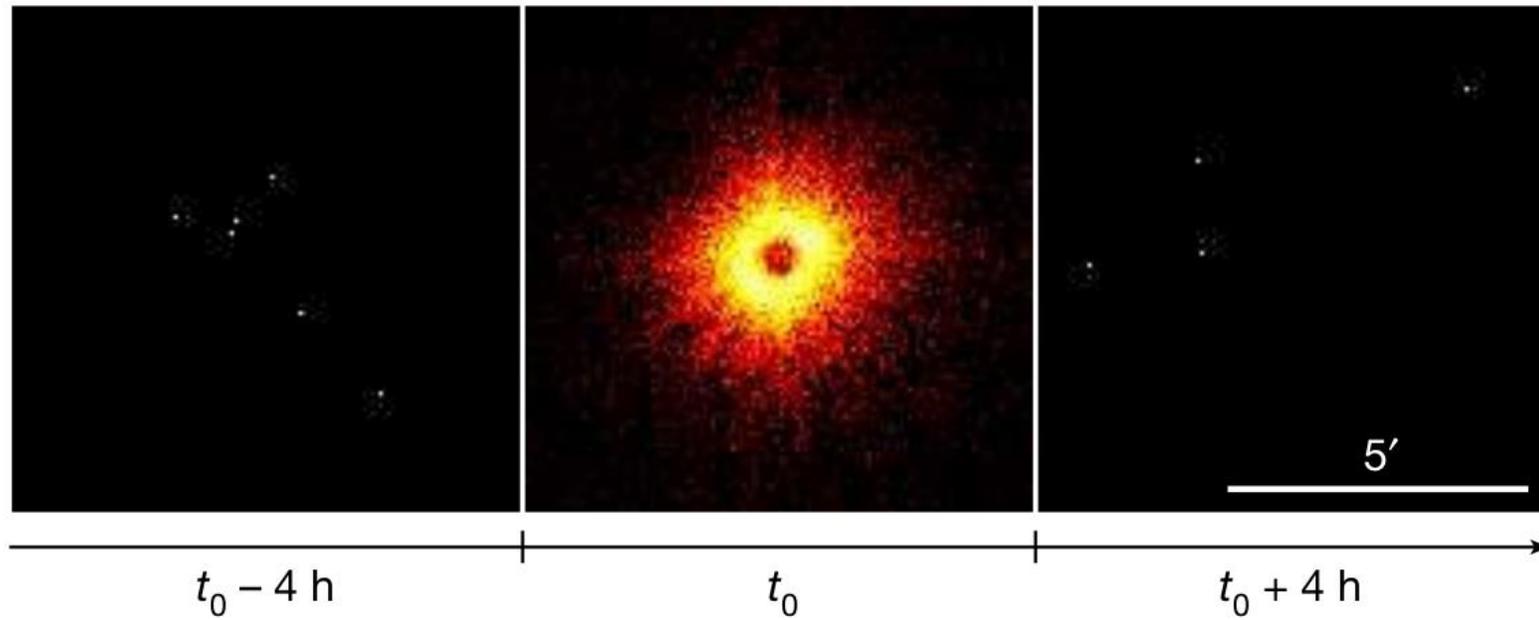
YZ Reticuli – The Nova Fireball

X-ray timeseries of YZ Reticuli
König+22

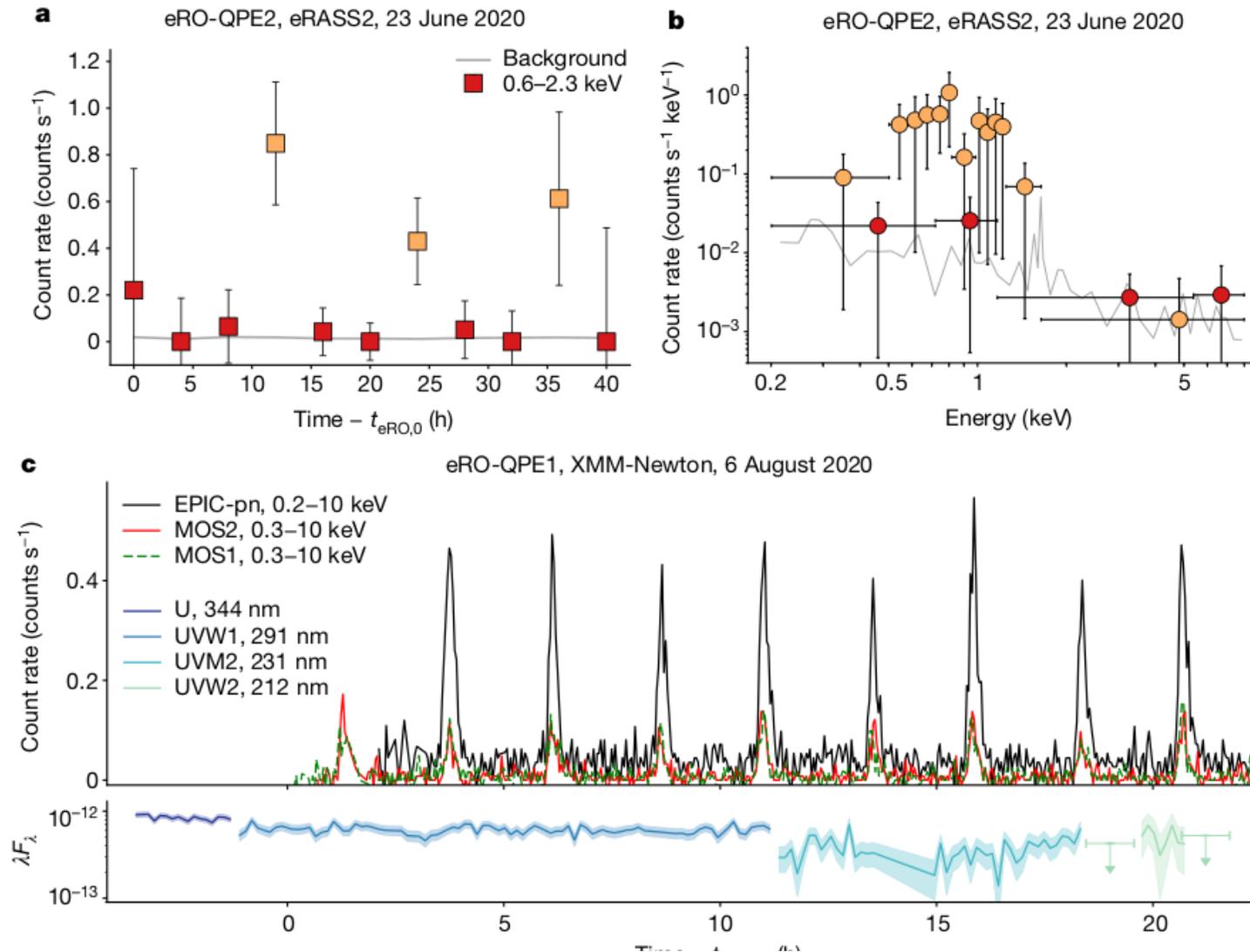


YZ Reticuli – The Nova Fireball

X-ray timeseries of YZ Reticuli
König+22



Quasi-Periodic Eruptions

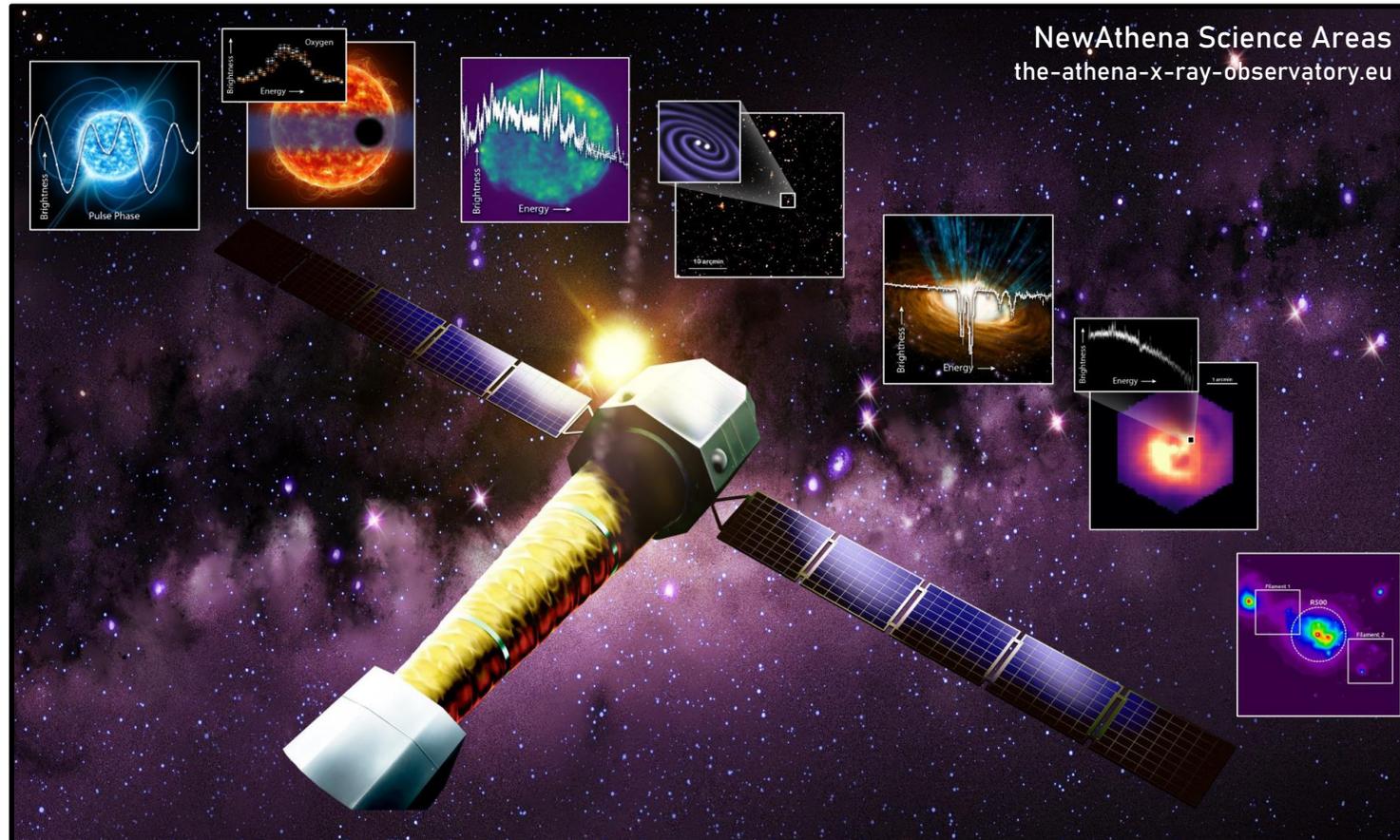


eROSITA lightcurve & spectrum;
Followup X-ray lightcurve
Arcodia+20

Extra Slides Pulsars

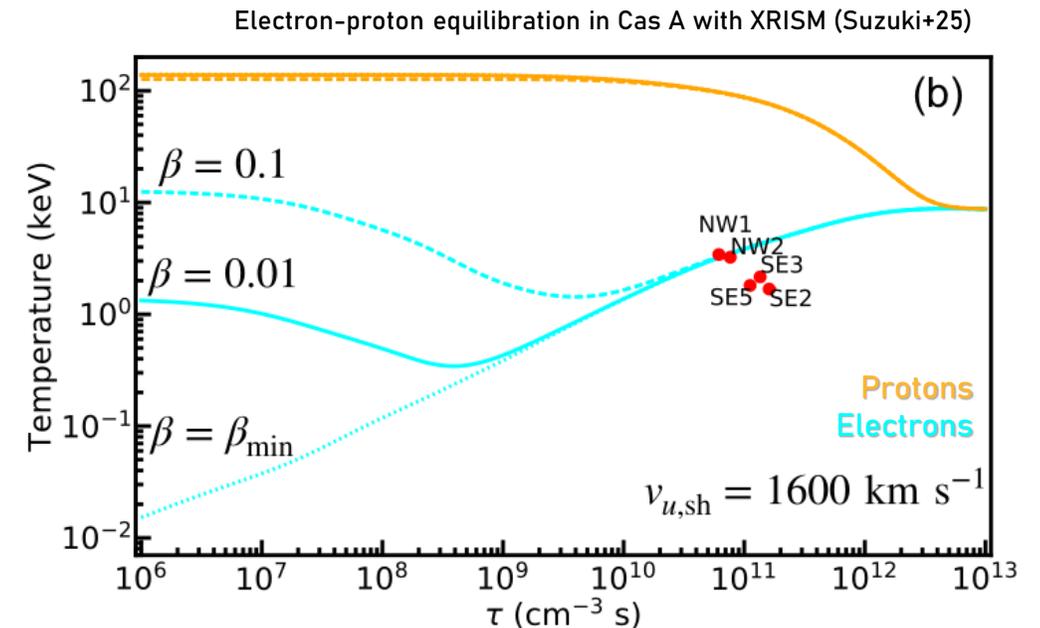
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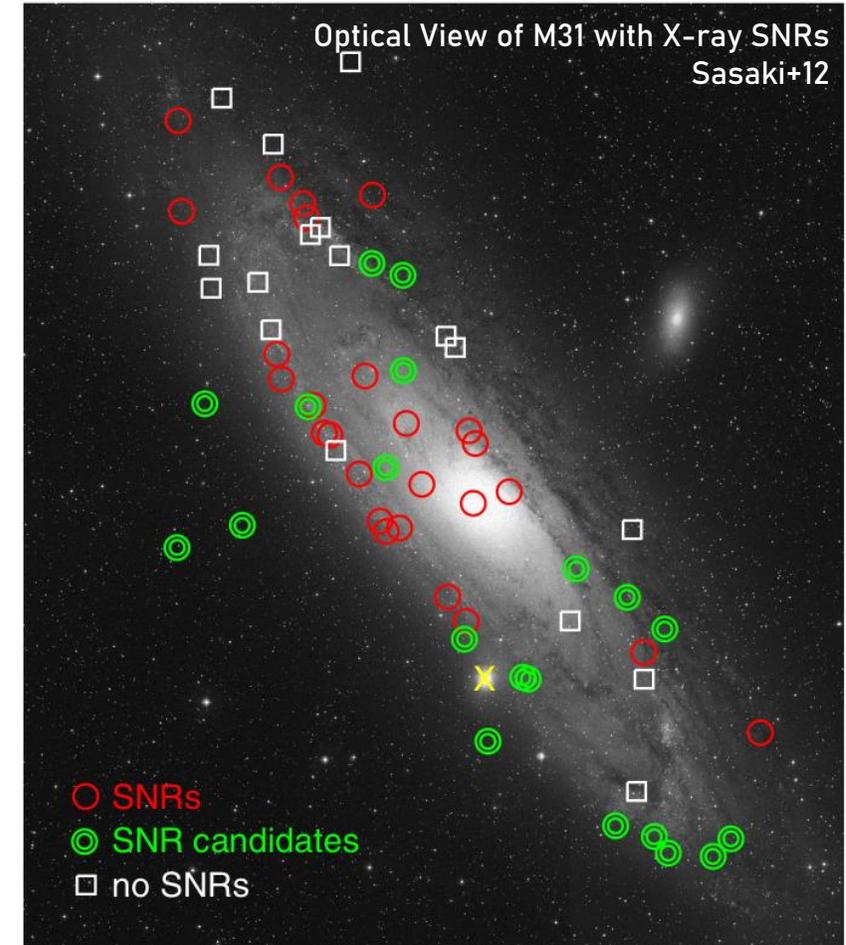
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- Large-scale nonthermal emission (WFI)

➤ Sensitive SNR population studies in local-group galaxies (WFI)



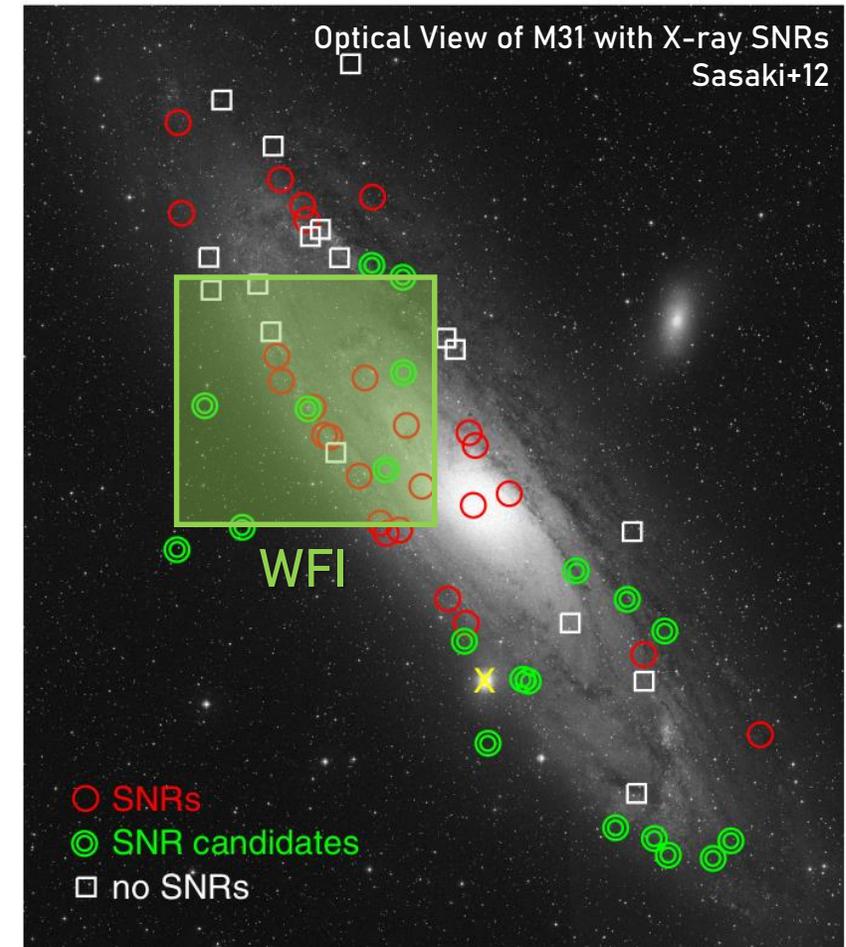
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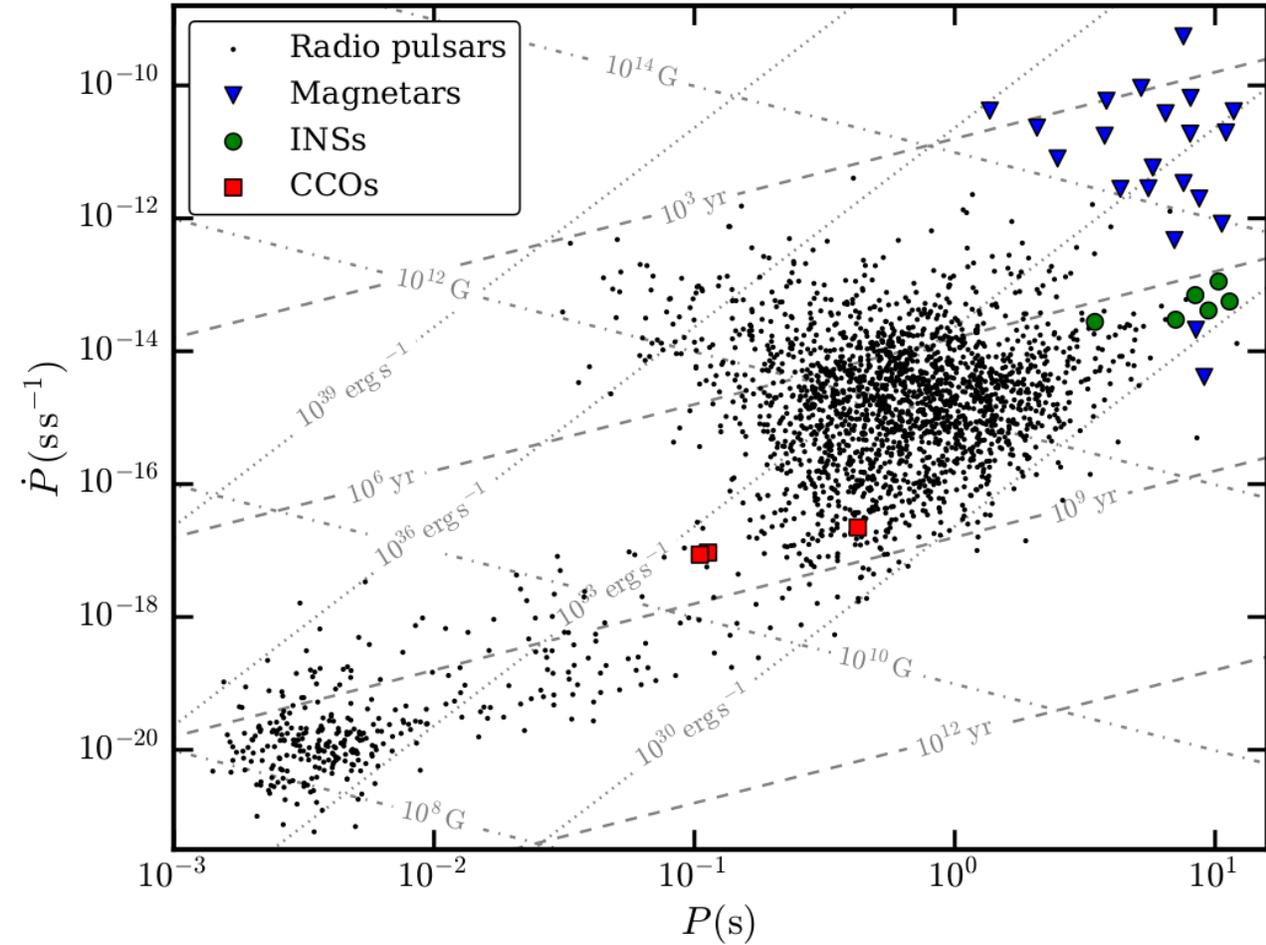
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Extra Slides Pulsars

Introduction: Neutron Stars & Pulsars

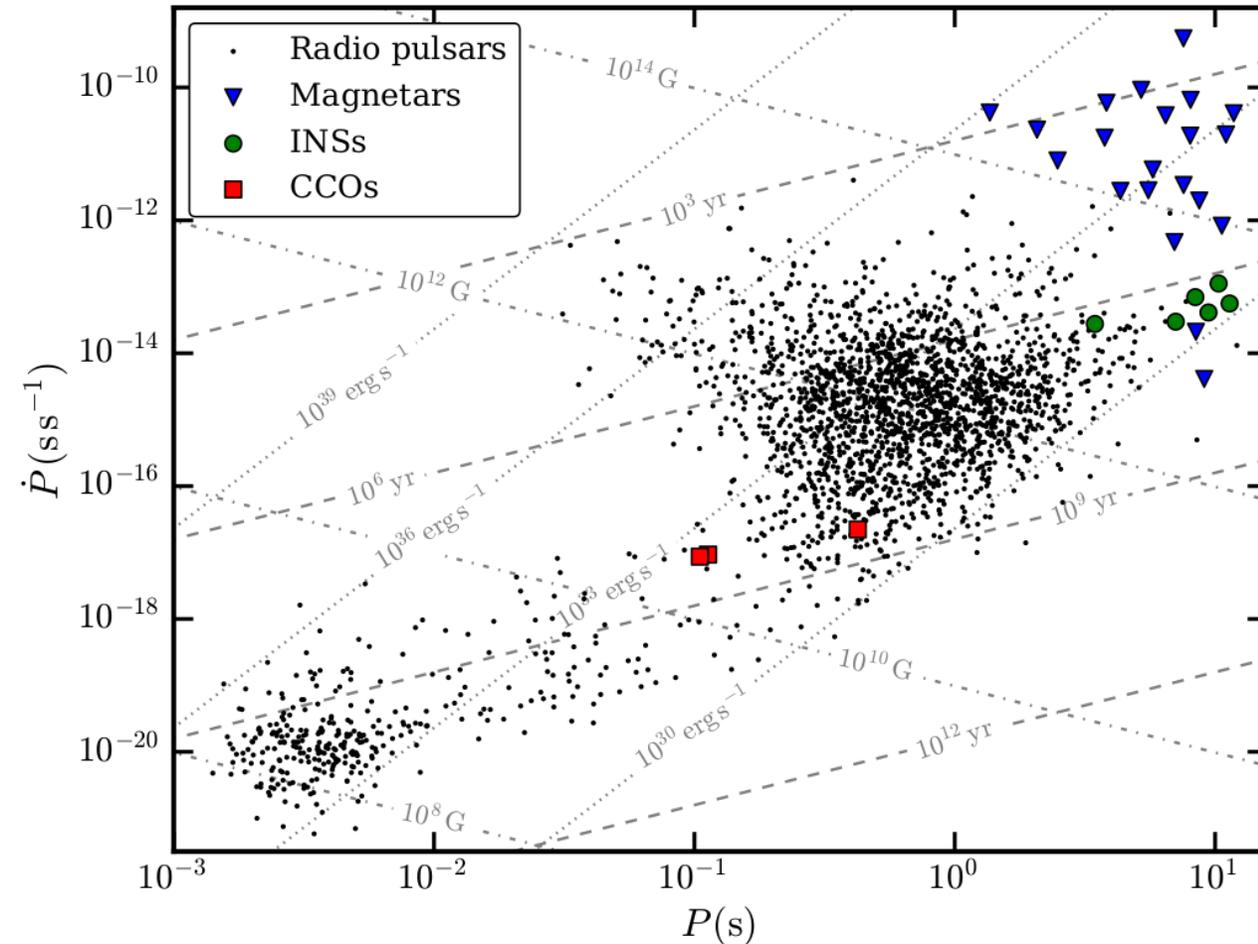
Zoo of non-accreting neutron stars
(Credit: ATNF pulsar database, Manchester et al. 2005)



Introduction: Neutron Stars & Pulsars

- Rotation-powered pulsars: Energy for emission supplied by spin-down
 - Young energetic pulsars (e.g. Crab, Vela)
 - Millisecond („recycled“) pulsars: Small periods due to accretion-induced spin-up in binaries
- Nonthermal magnetospheric emission from accelerated electrons at radio, X-ray & gamma-ray energies

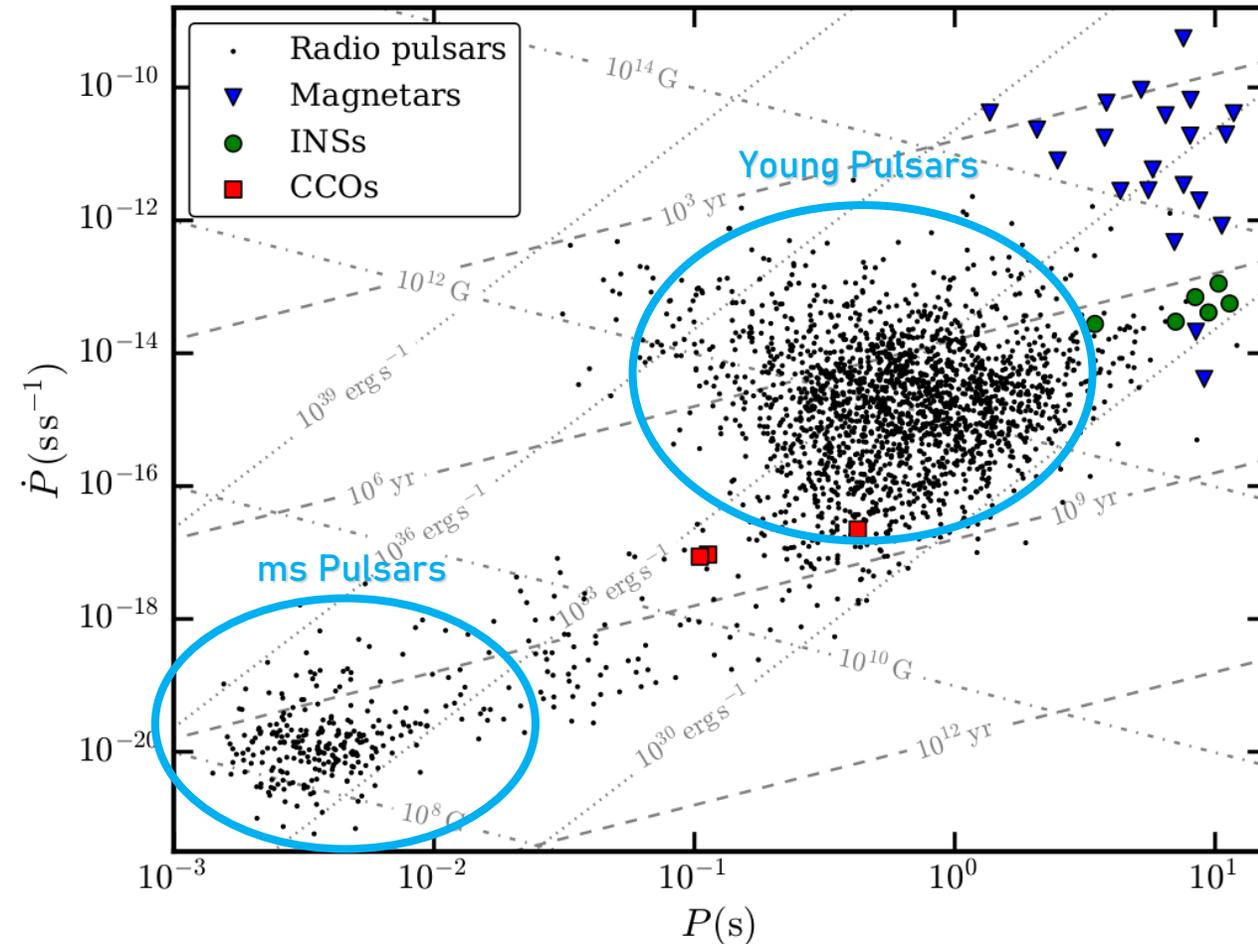
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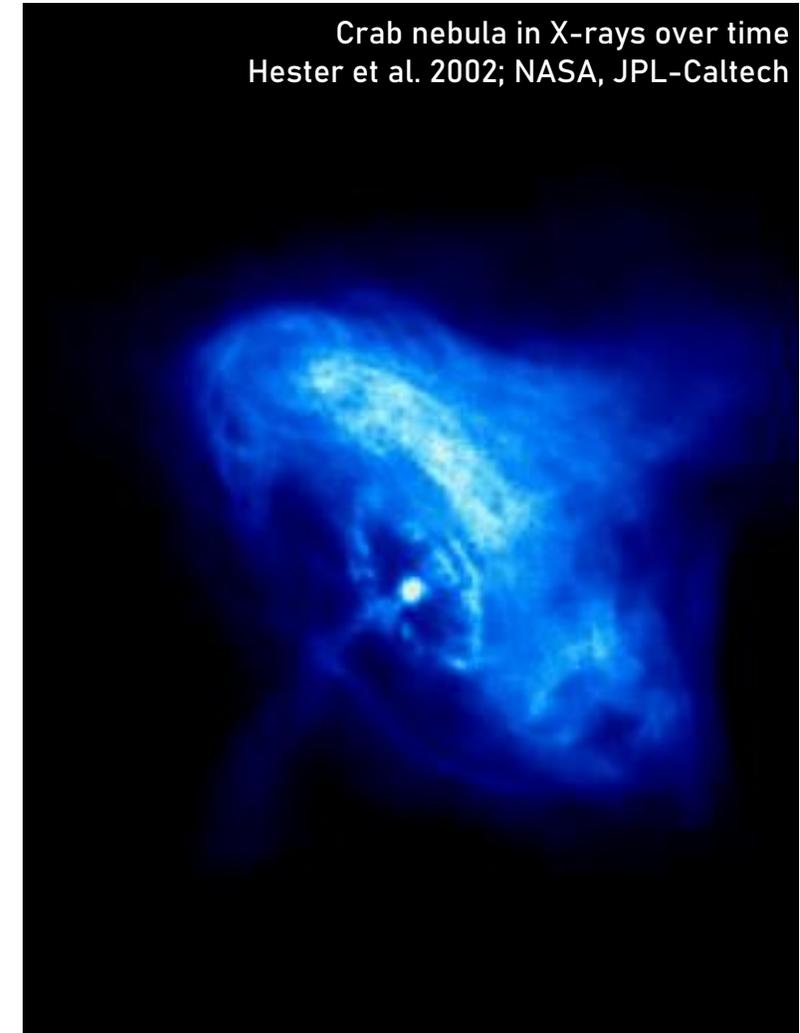
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Zoo of non-accreting neutron stars
(Credit: ATNF pulsar database, Manchester et al. 2005)



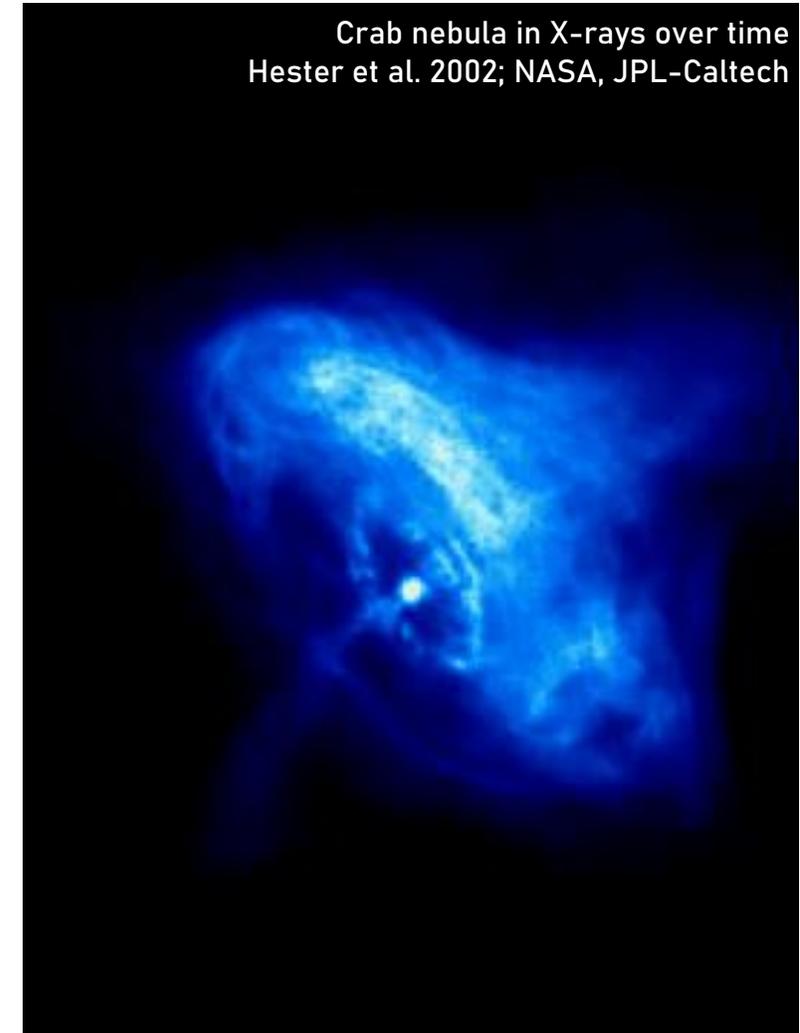
Introduction: Pulsar Wind Nebulae

- PWN: Nebula of electrons (& positrons) accelerated in young pulsar magnetosphere
 - GeV to TeV (PeV?) energies
- Typical magnetic field $\sim 10^{-5} - 10^{-4}$ G
 - Synchrotron emission from radio to X-rays
- Ambient radiation field
 - Inverse Compton scattering powers gamma-rays



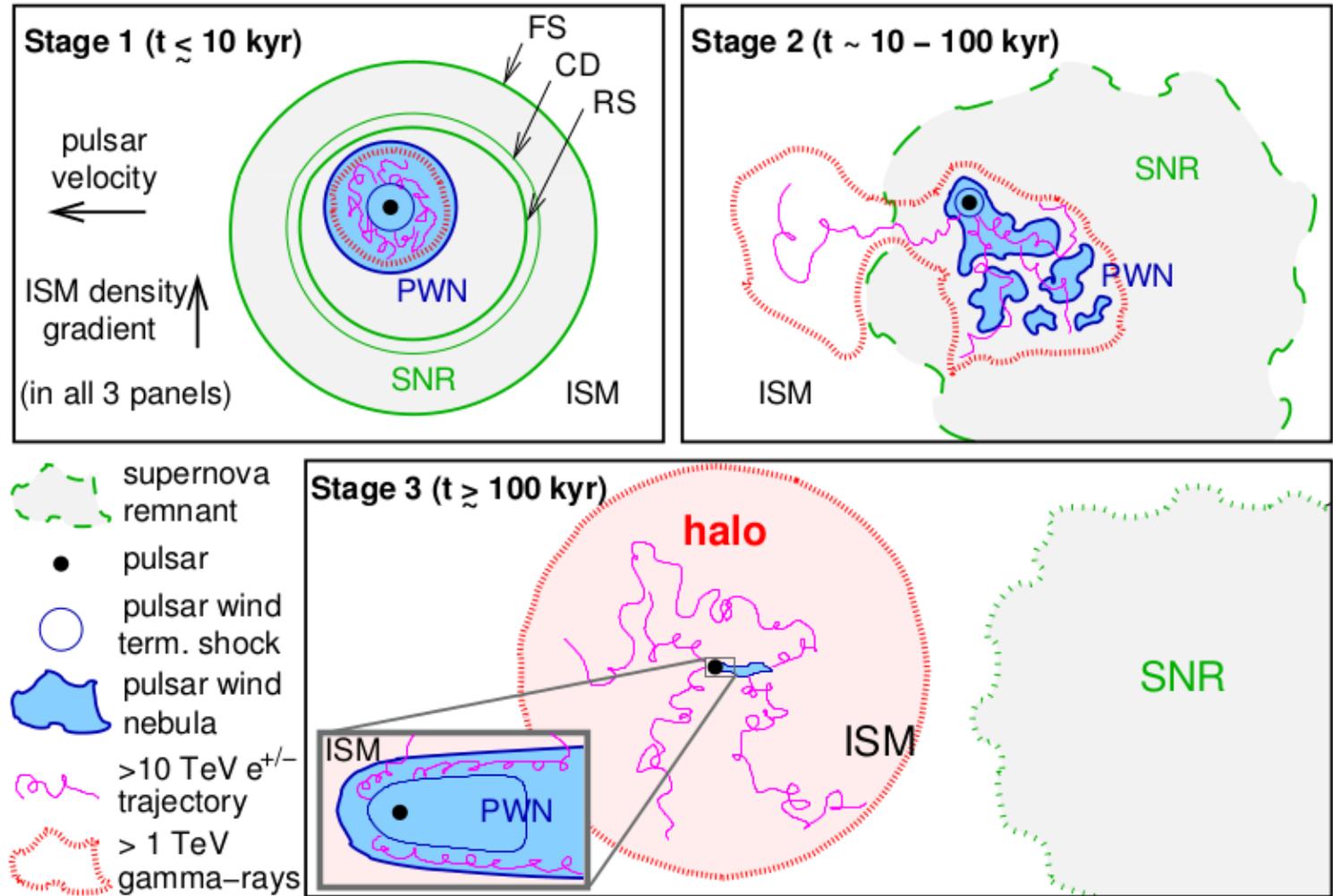
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- X-ray studies of PWNe:
 - TeV-electron population & distribution
 - Magnetic field strength & morphology



Vela X & PWN Evolution

Giacinti et al. (2020)



Vela X & PWN Evolution

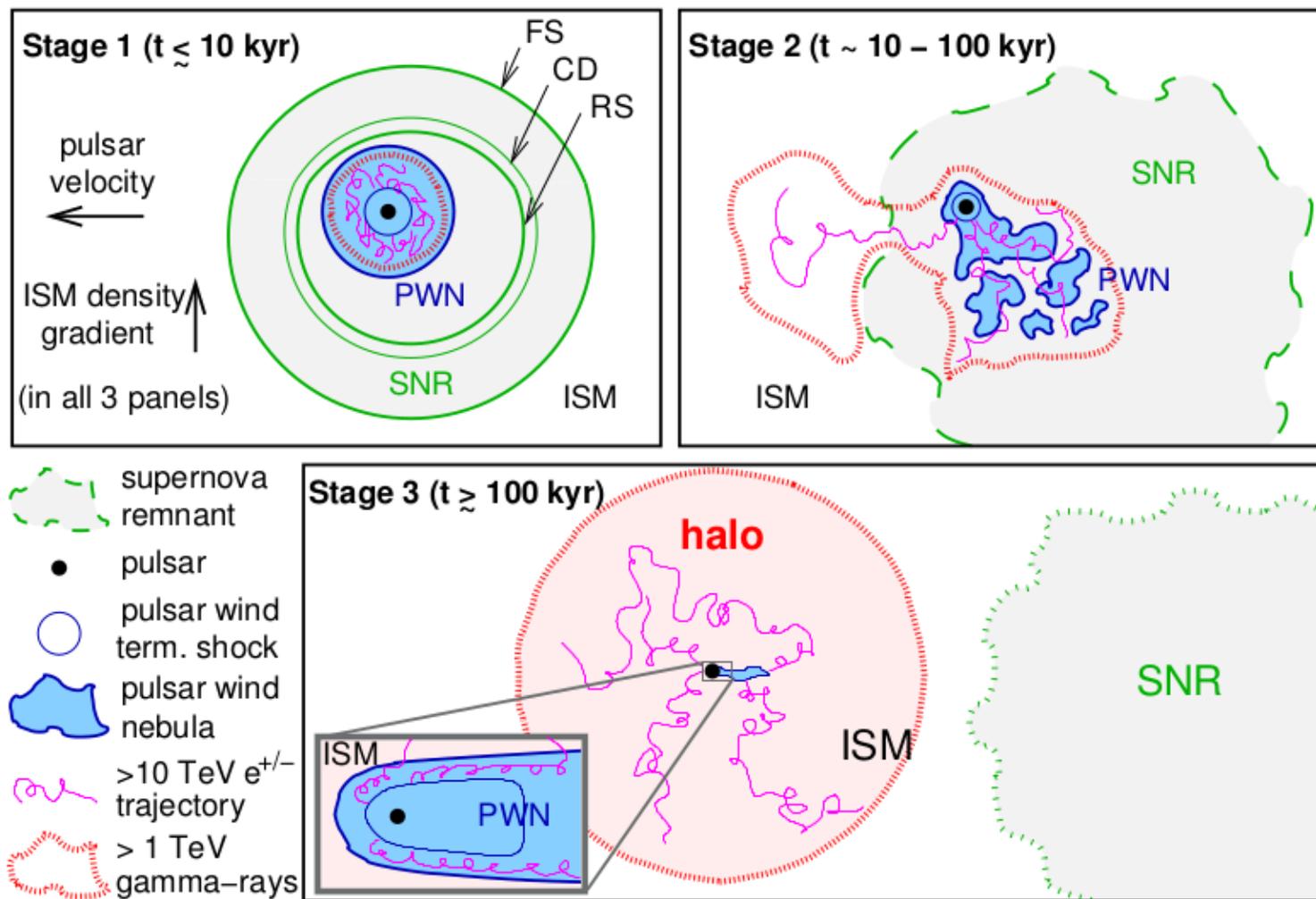
Giacinti et al. (2020)

- Cocoon as relic PWN?
(Slane+18)

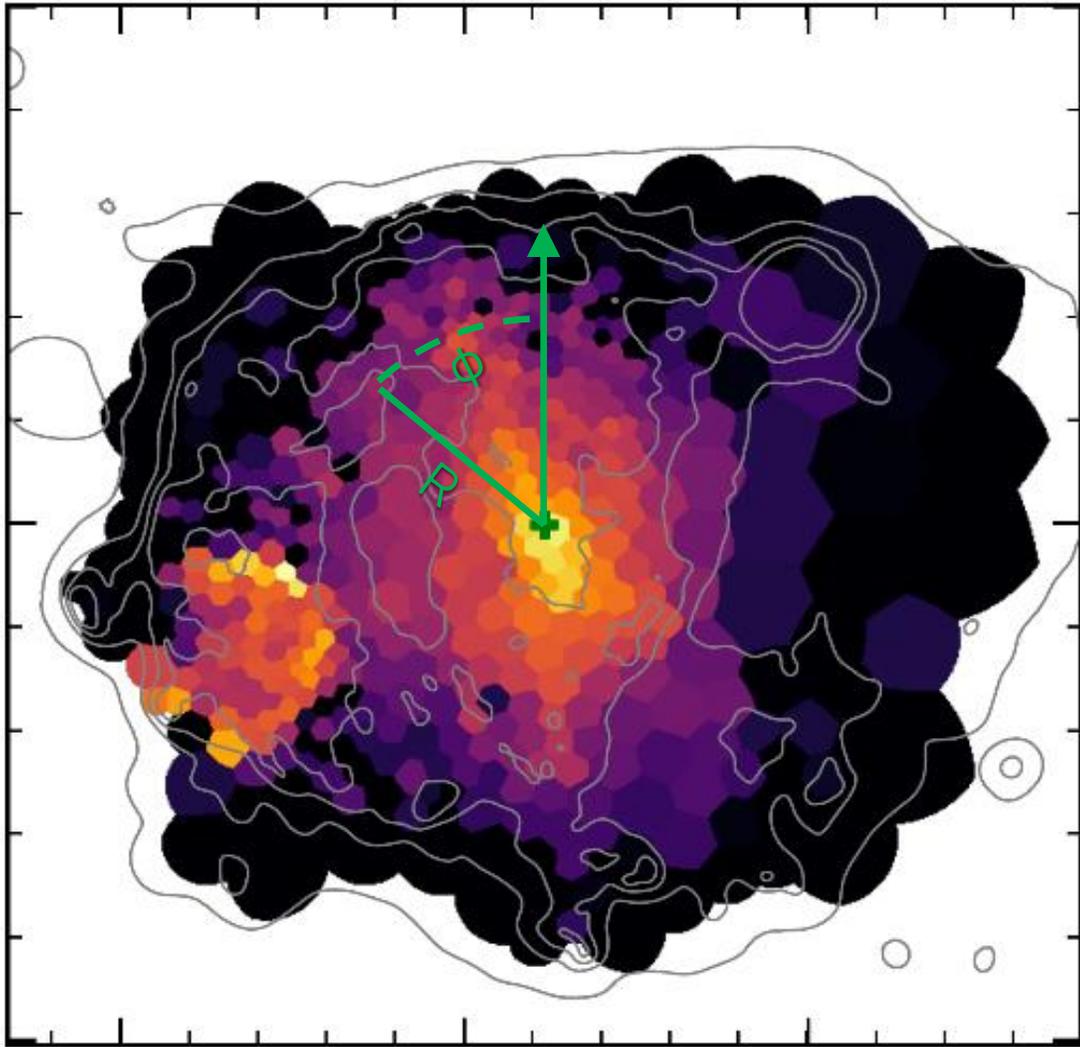
- Extended emission through diffusing electrons?

- Radiative losses soften and limit extent of emission:

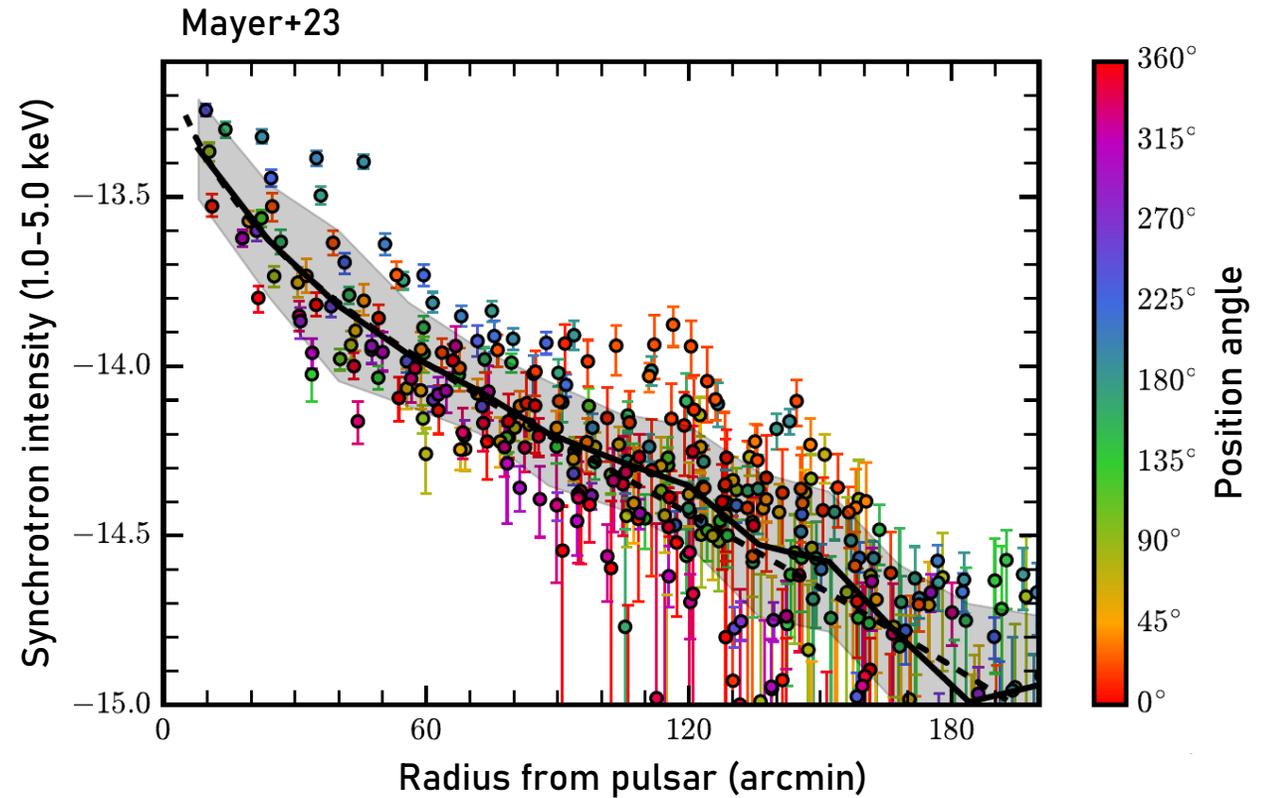
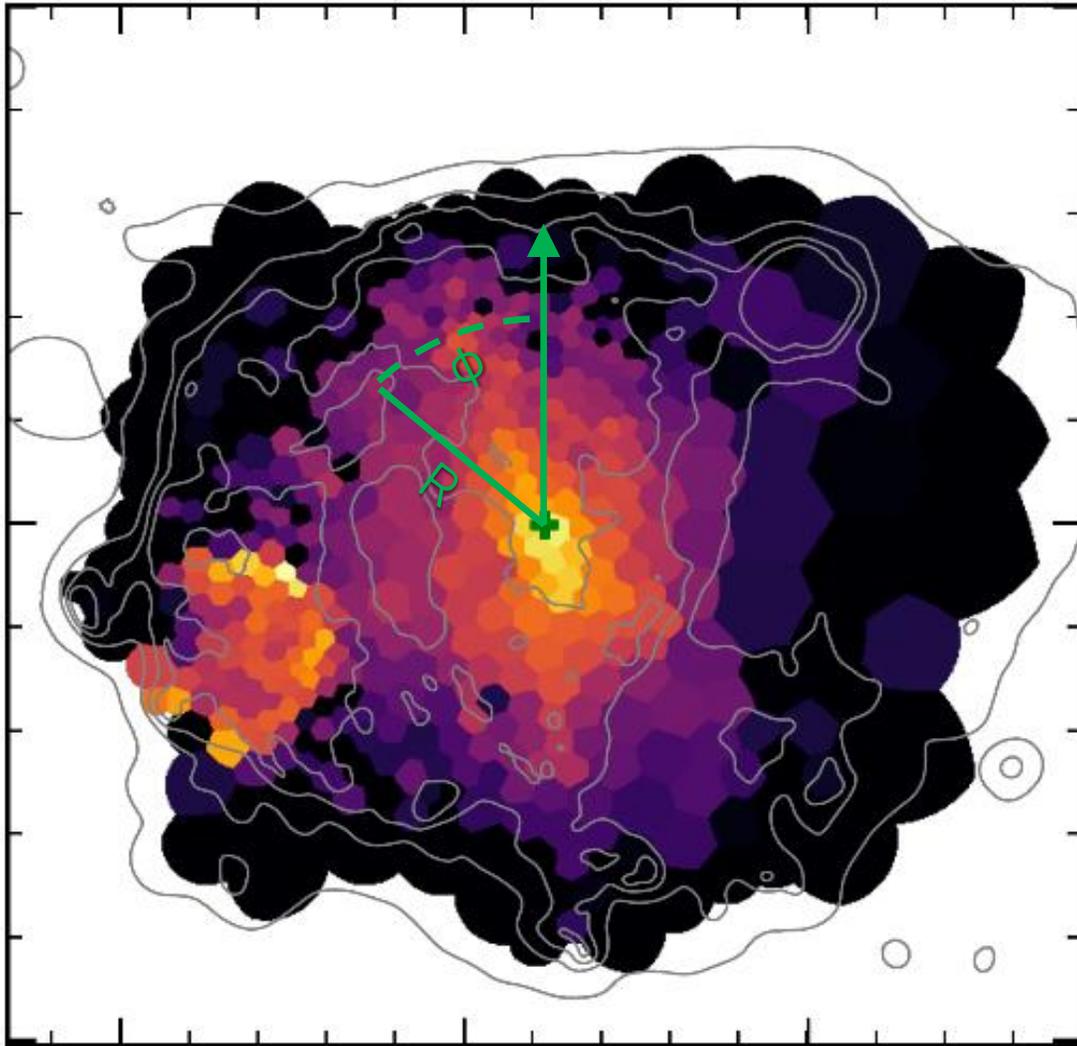
$$dE/dt \propto - (U_B + U_\gamma) E^2$$



Particle Diffusion in Vela X

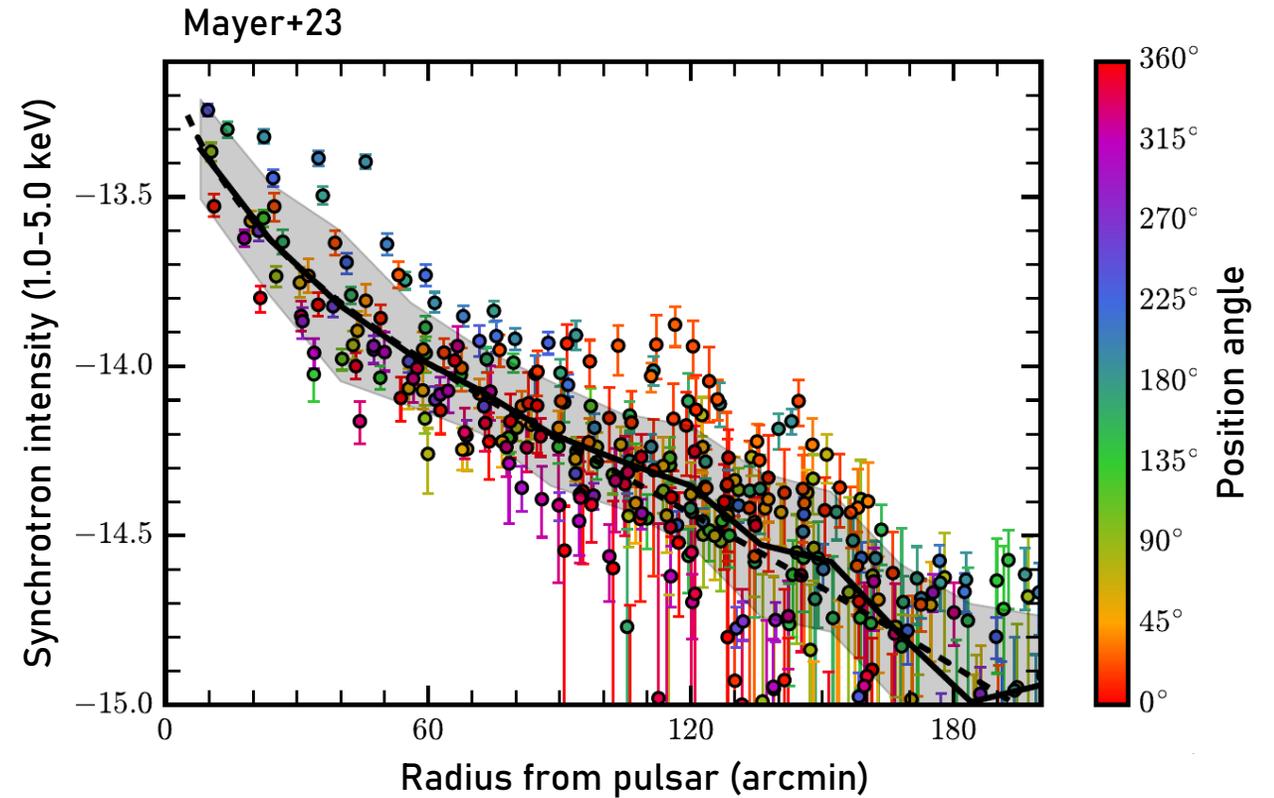


Particle Diffusion in Vela X



Particle Diffusion in Vela X

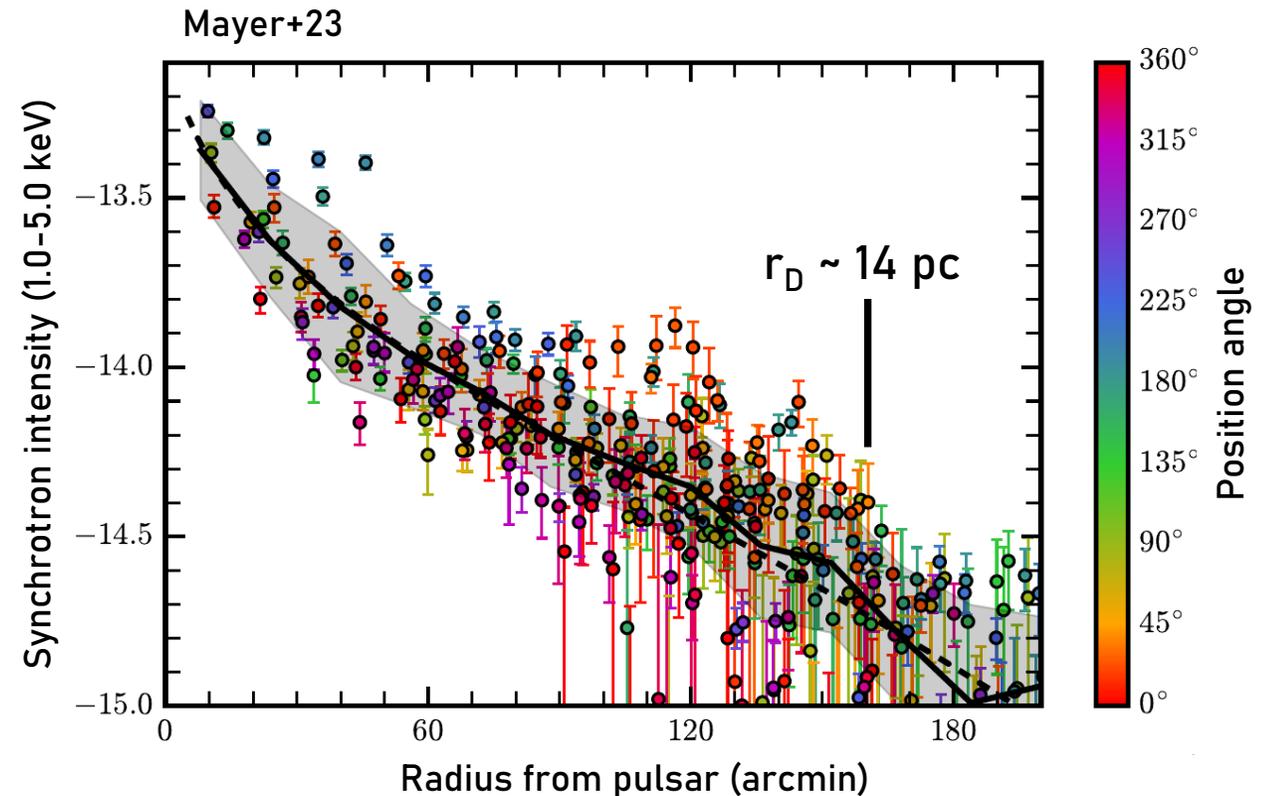
- Synchrotron emission from relativistic electrons diffusing through ambient medium



Particle Diffusion in Vela X

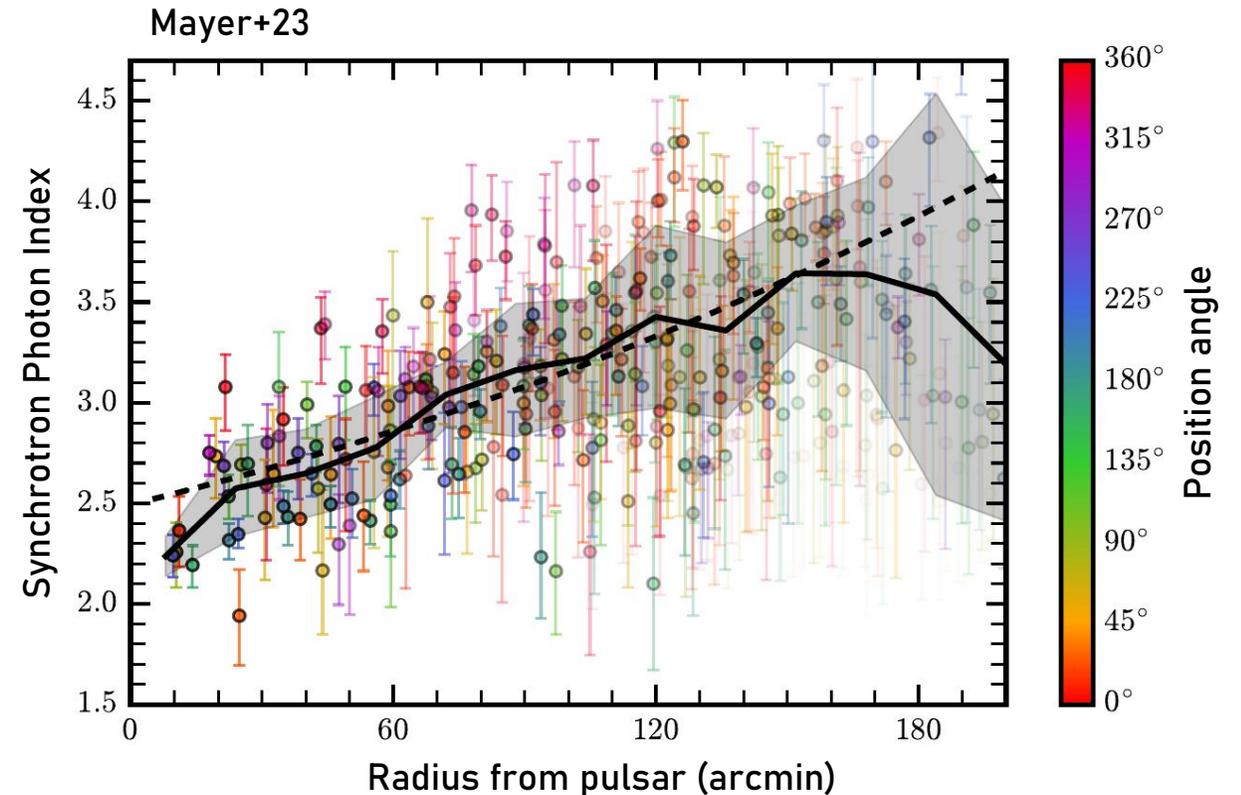
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- Characteristic physical extent (Abeysekara+17) limited by energy loss

$$r_D = (4D\tau)^{1/2}$$



Particle Diffusion in Vela X

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Particle Diffusion in Vela X

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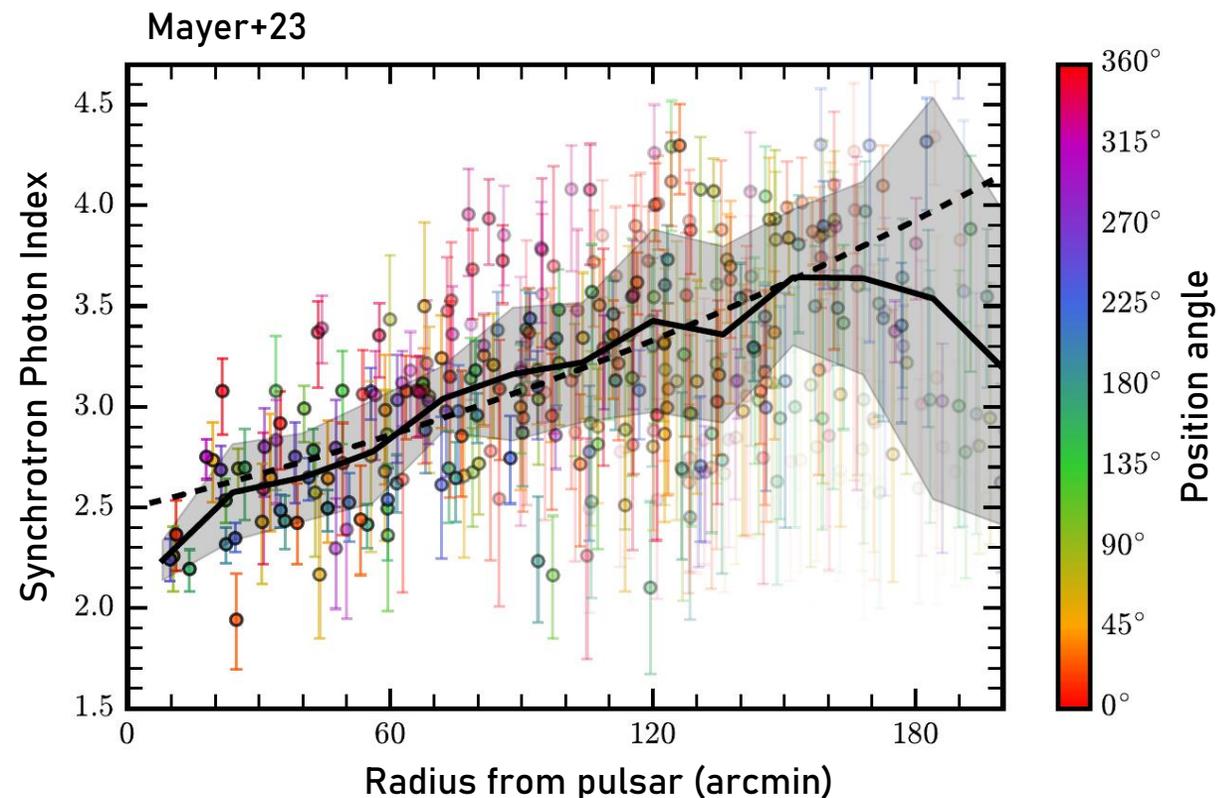
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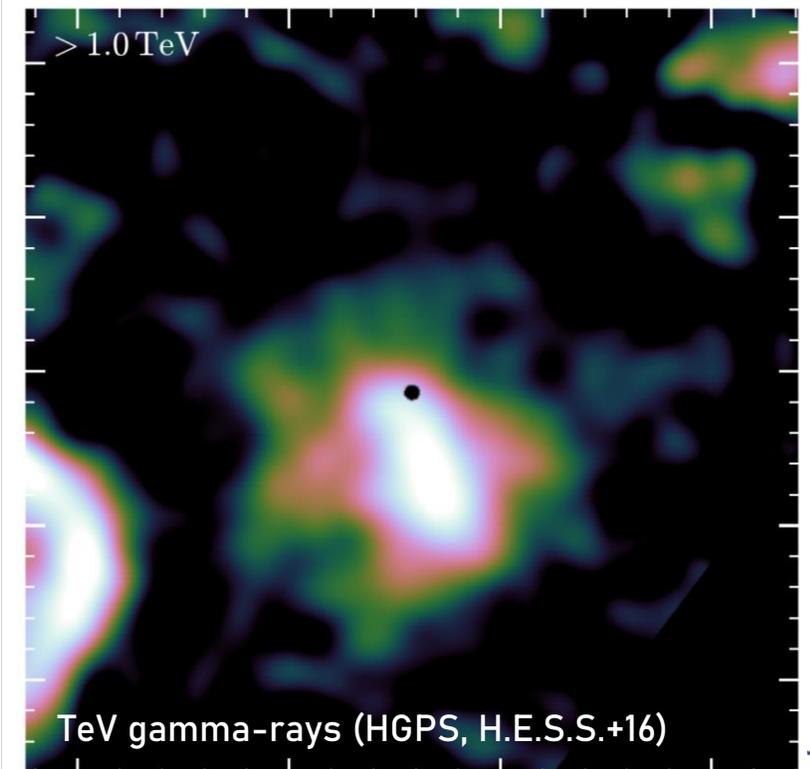
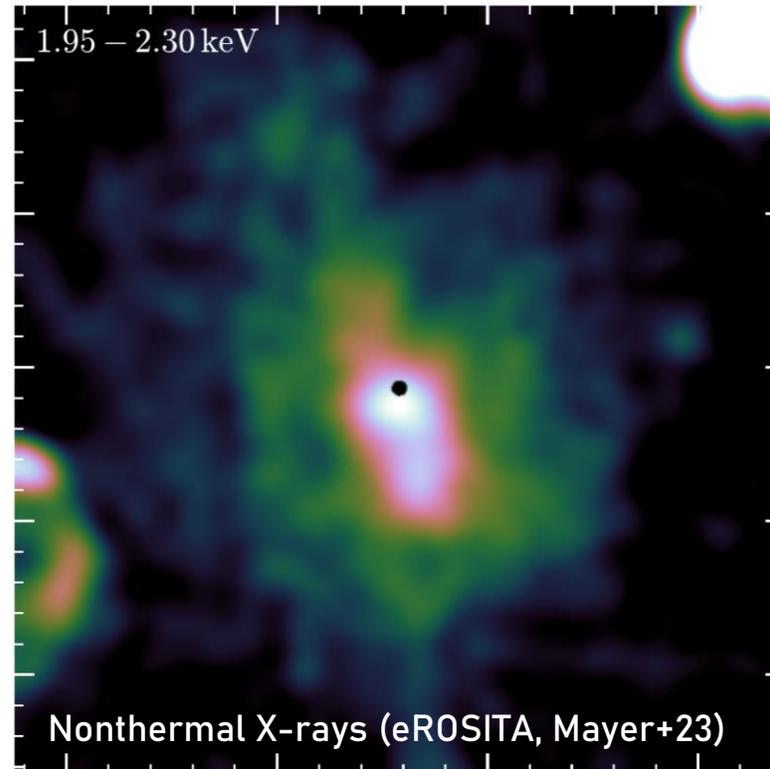
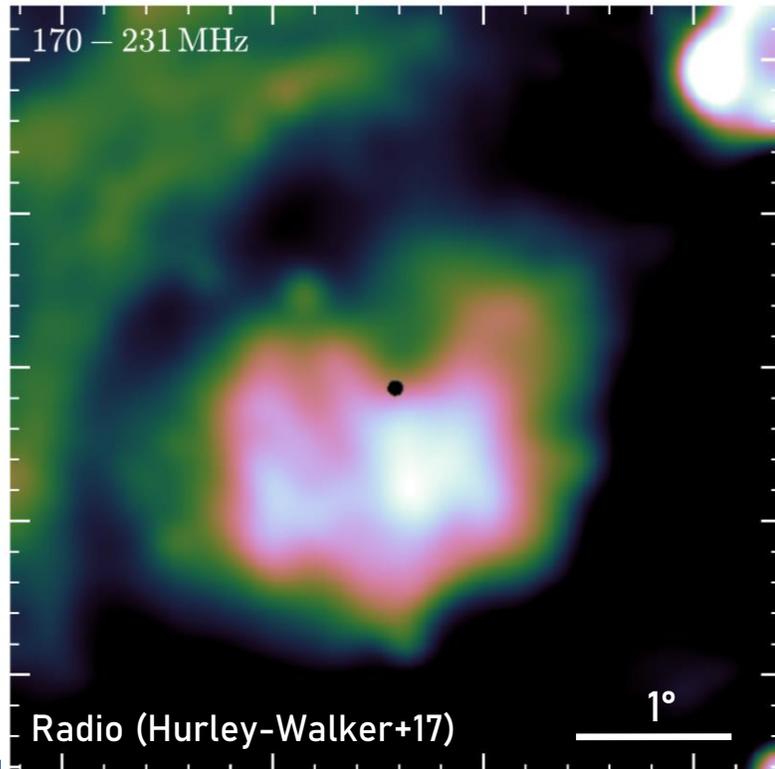
- For typical ISM B-field ($\sim 3 \mu\text{G}$):

$$D = 3.6_{-0.5}^{+0.6} \times 10^{27} \text{ cm}^2 \text{ s}^{-1}$$



Multiwavelength View of Vela X

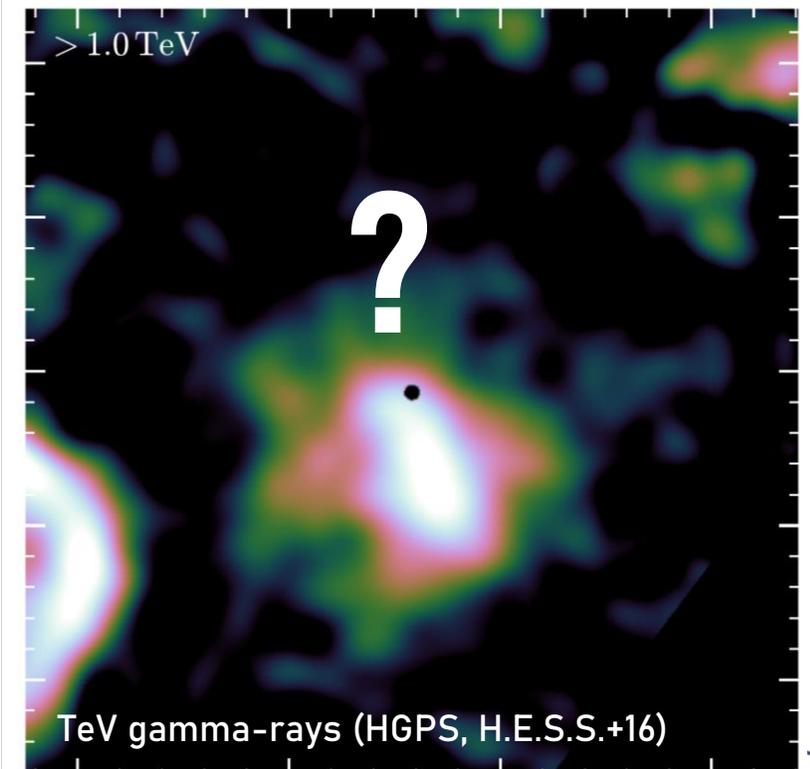
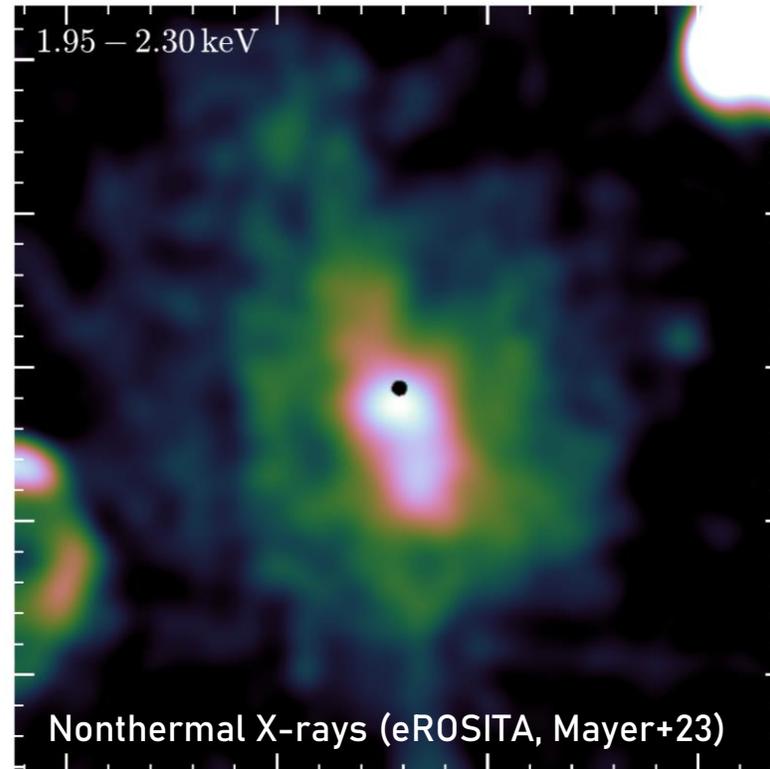
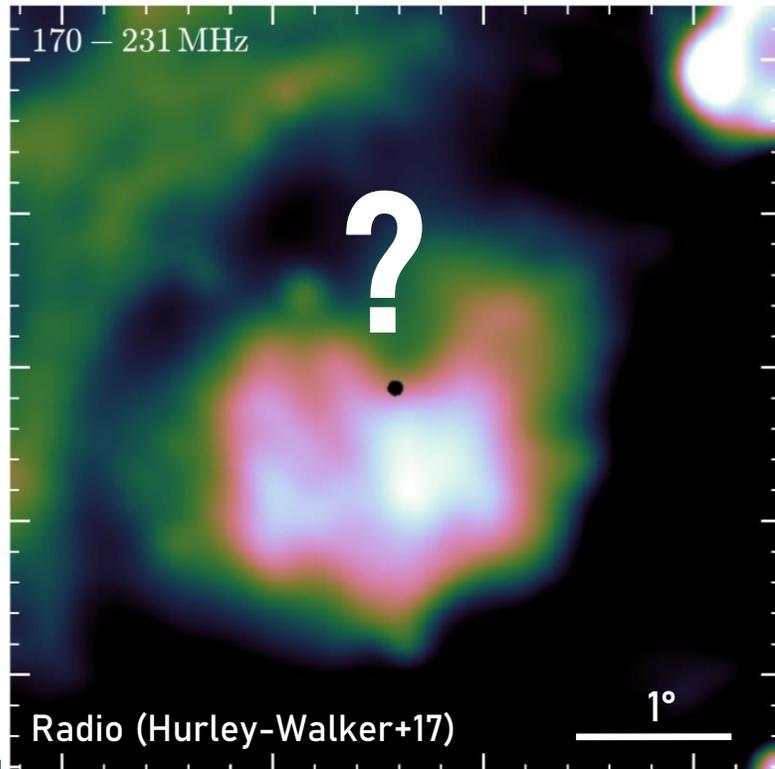
X-ray synchrotron emission originates from multi-TeV electron population



Multiwavelength View of Vela X

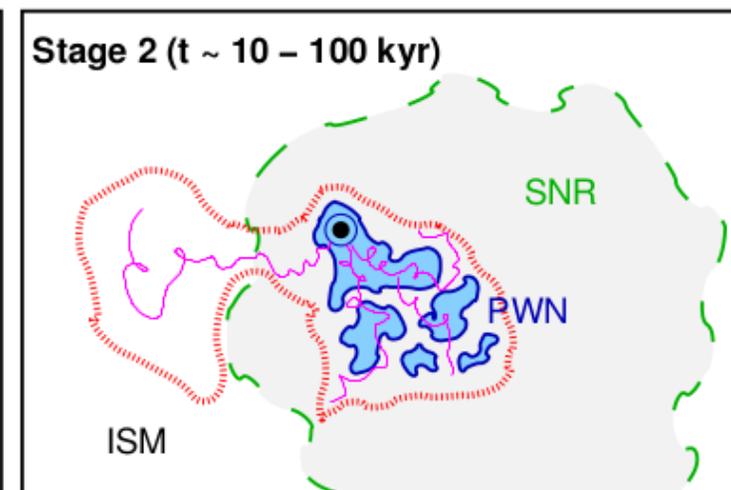
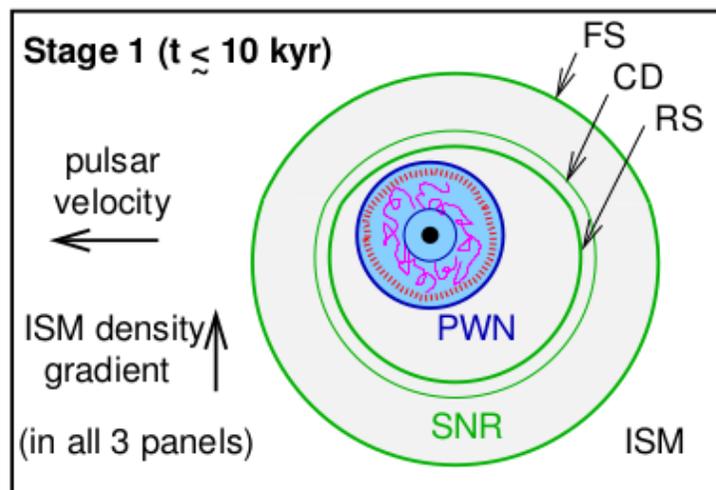
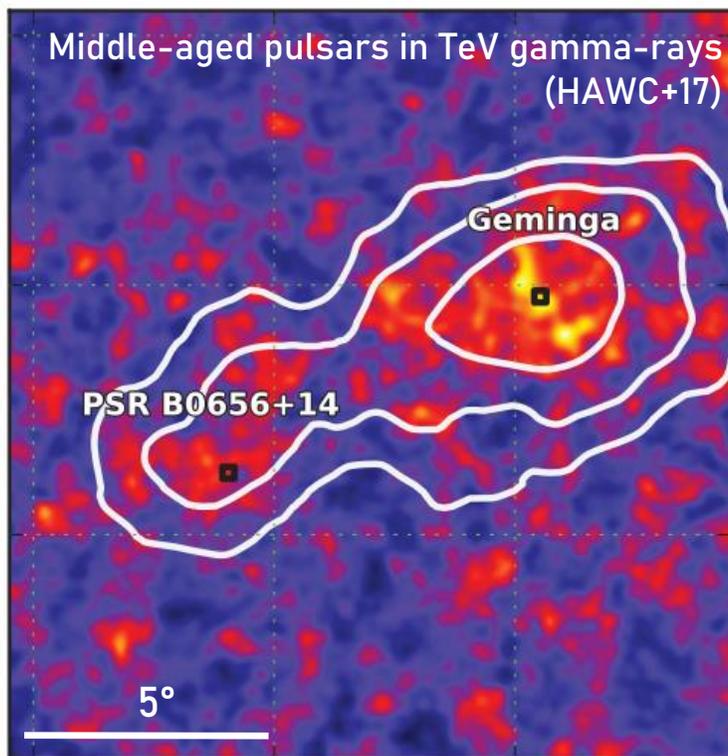
X-ray synchrotron emission originates from multi-TeV electron population

➤ No apparent counterpart in the north in TeV & radio bands

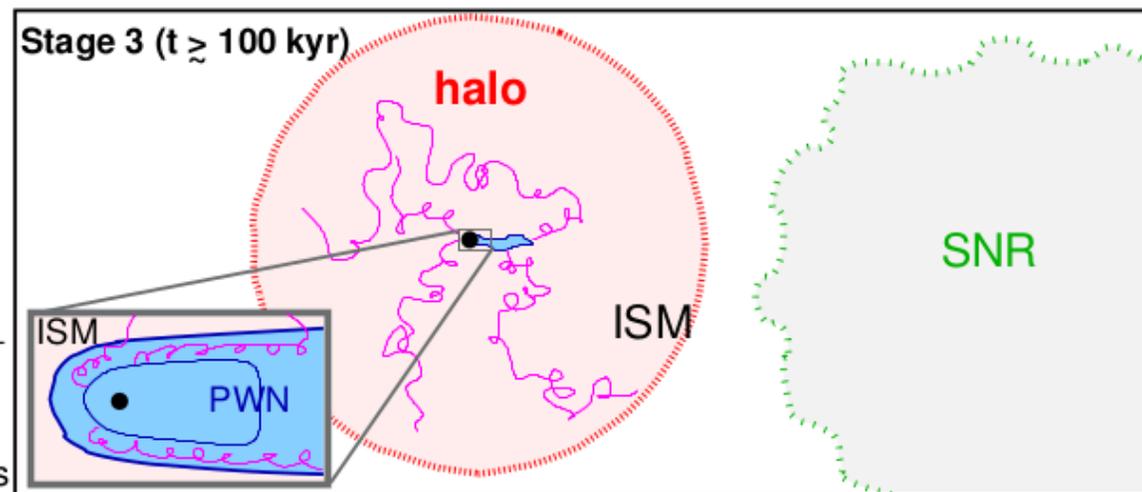


Pulsar Halos in X-rays?

Giacinti et al. (2020)

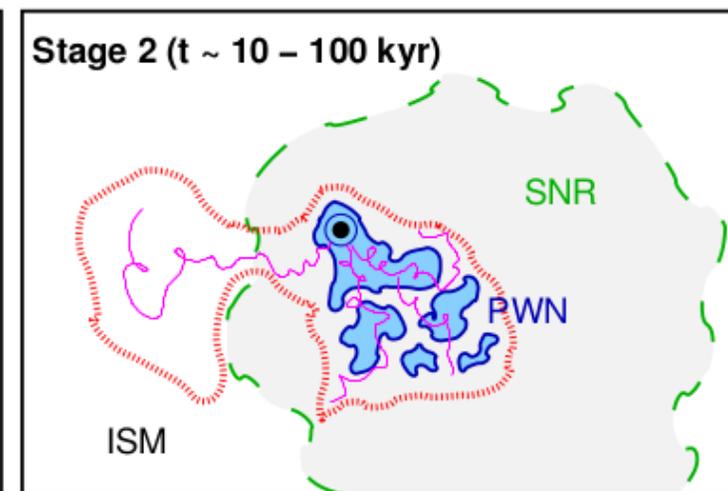
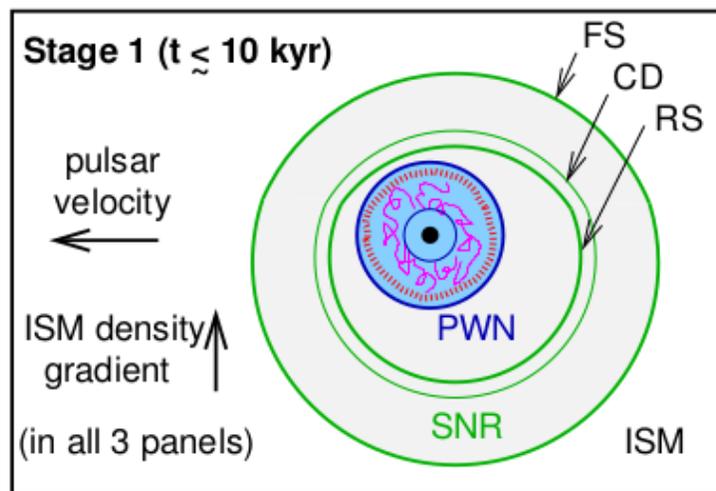
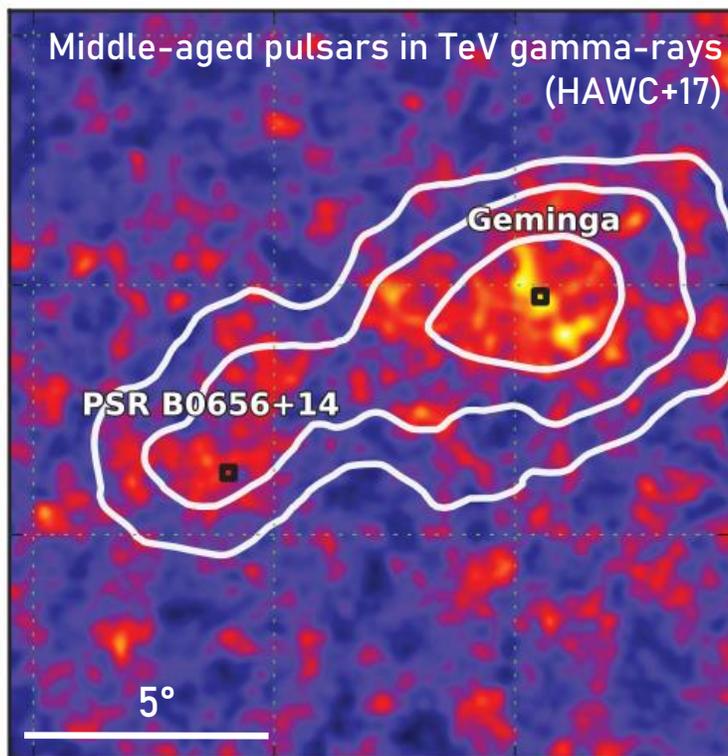


- supernova remnant
- pulsar
- pulsar wind term. shock
- pulsar wind nebula
- >10 TeV e^{\pm} trajectory
- > 1 TeV gamma-rays

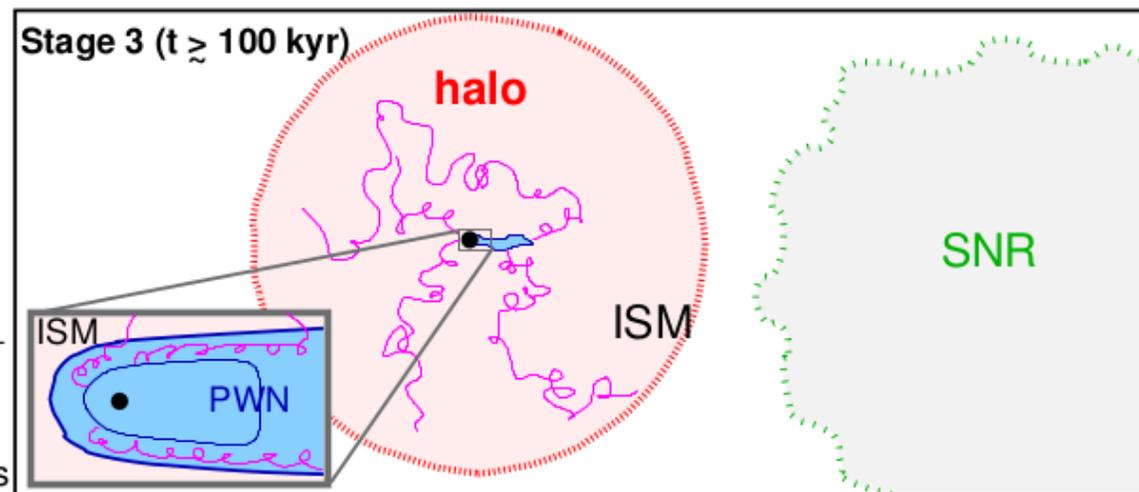


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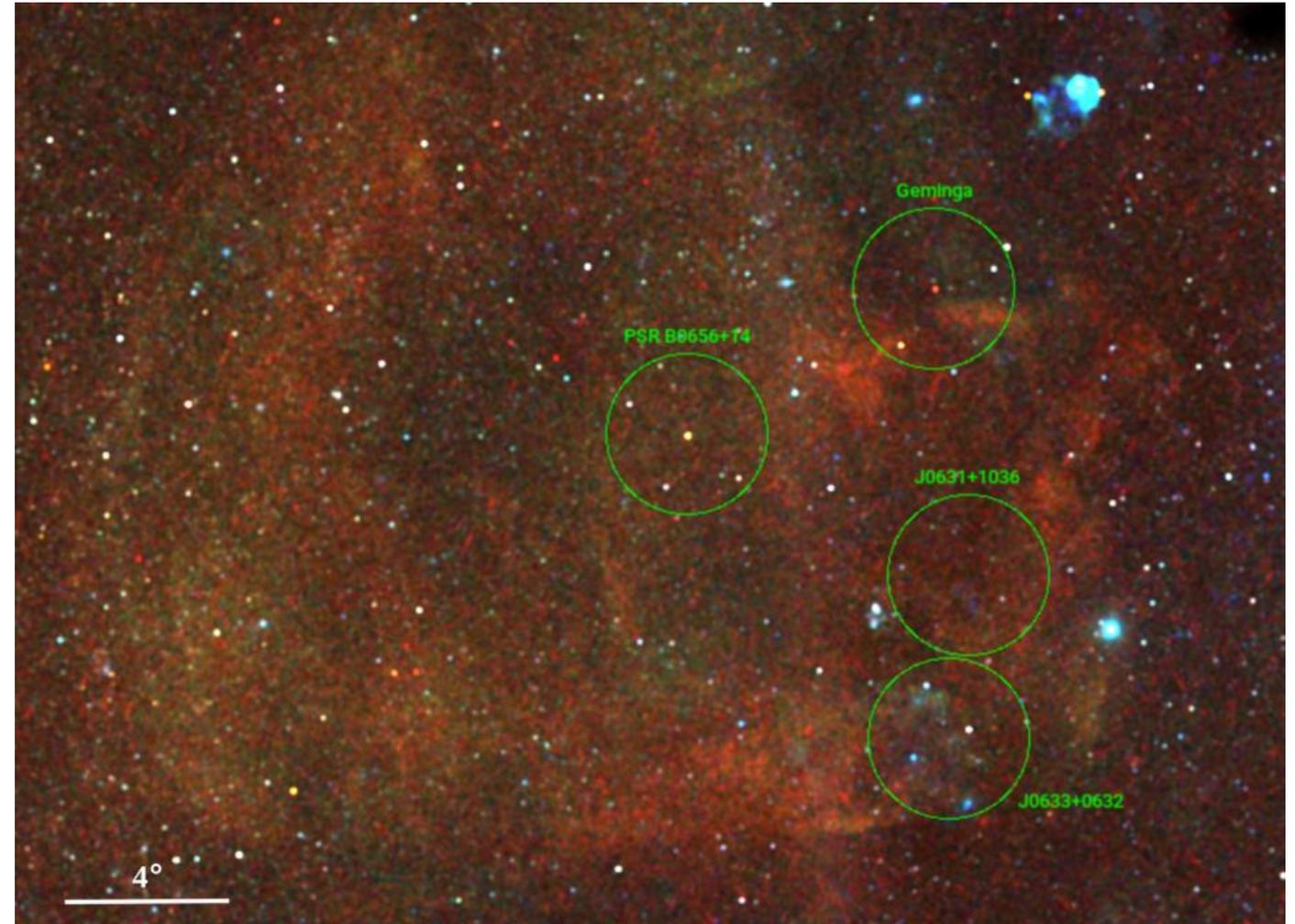


➤ ISM B-field should produce detectable synchrotron emission (Li+2023)

Pulsar Halos in X-rays?

- Systematic study of (candidates for) pulsar halos with eROSITA (Khokhriakova+24)

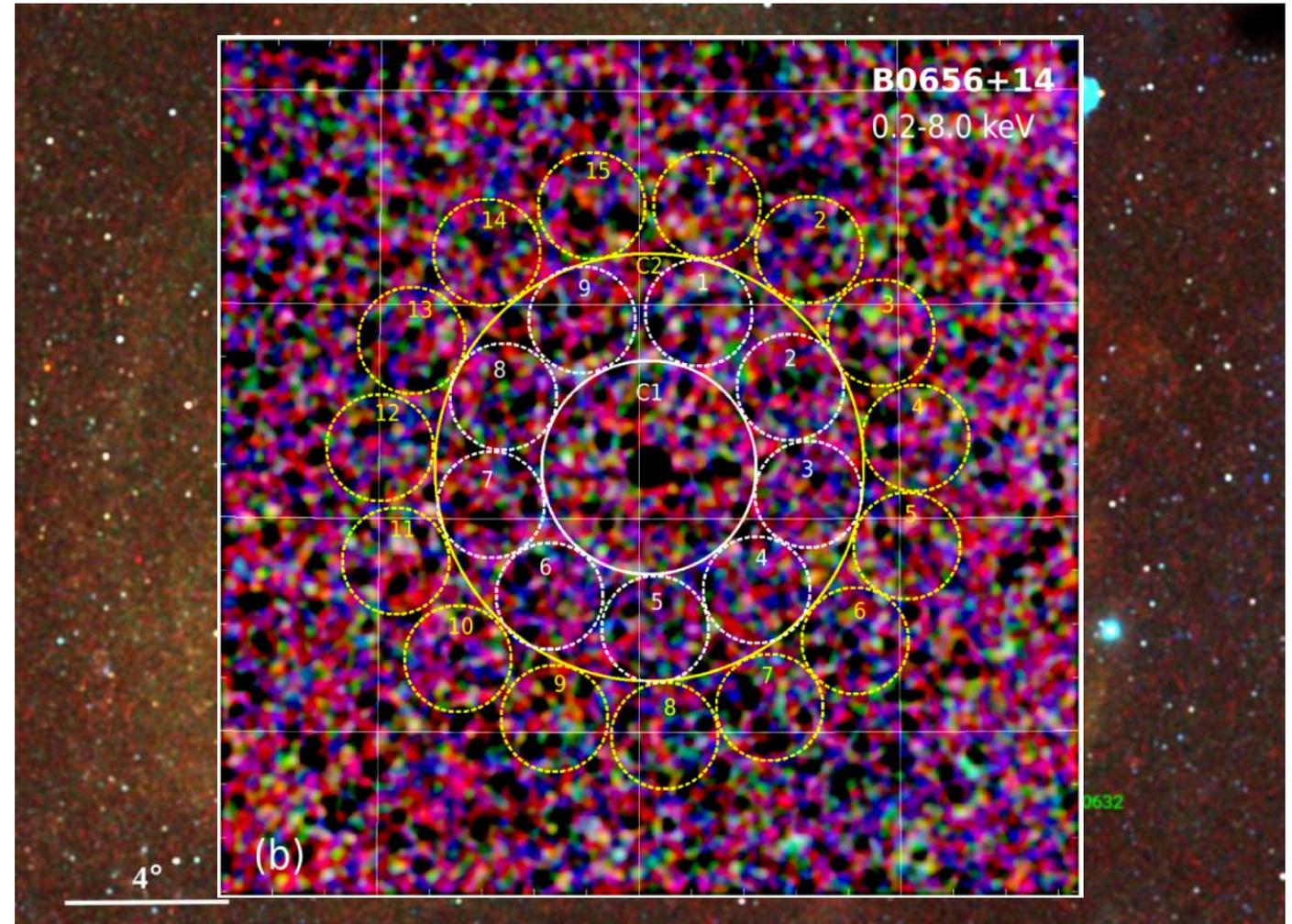
Middle-aged pulsars with eROSITA
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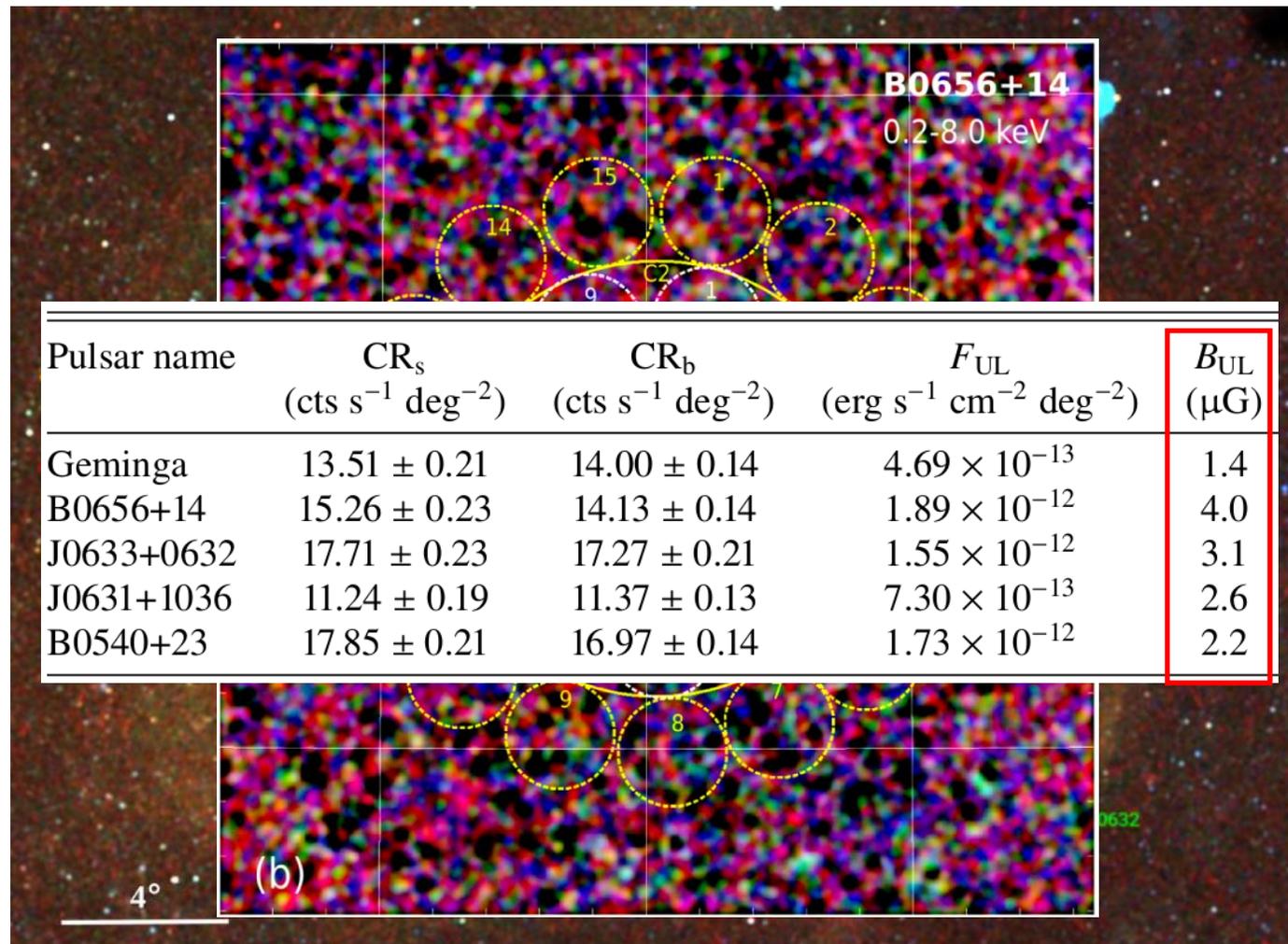
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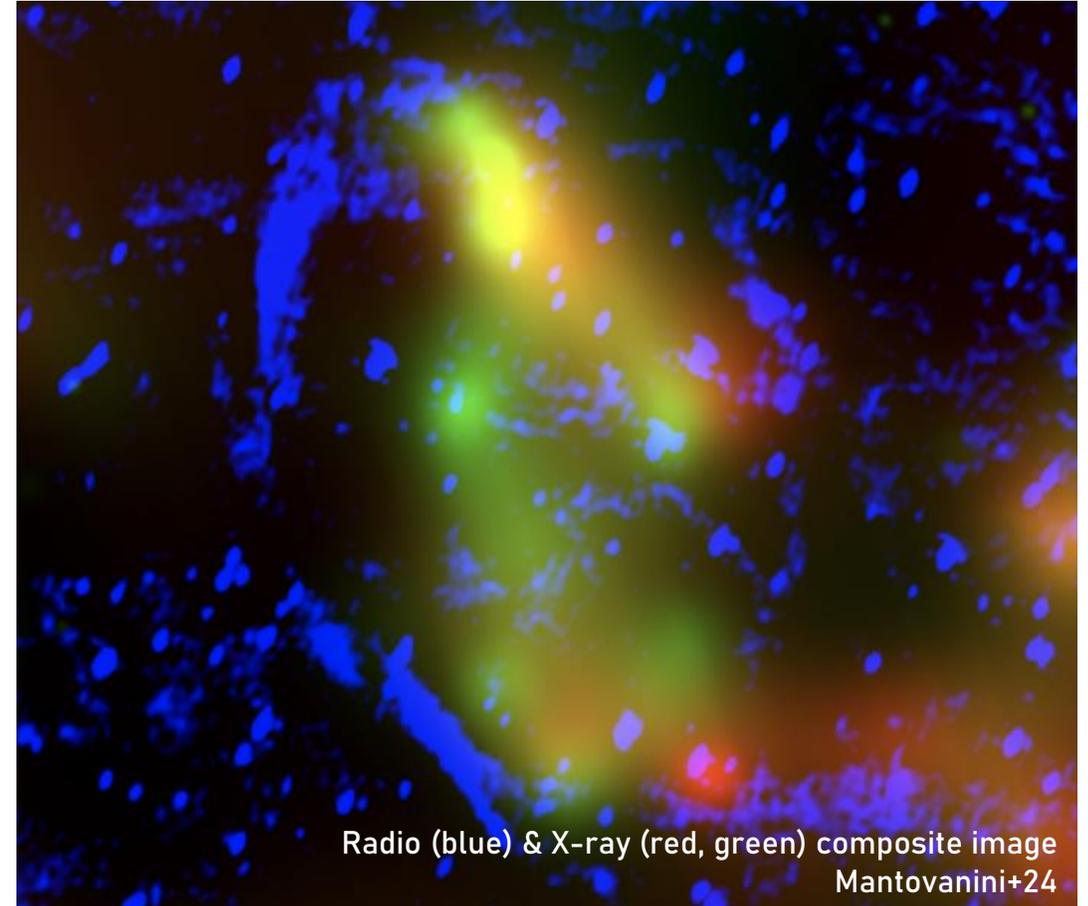
- Systematic study of (candidates for) pulsar halos with eROSITA (Khokhriakova+24)
- No significant detections
 - $B < 1.4 \mu\text{G}$ (Geminga); multiple pulsars below typical ISM values
 - Consistent with XMM-Newton (Liu+19, H.E.S.S.+23)



Extra Slides Populations

G321.3-3.9 – An Elongated, Iron-Rich SNR

- 1.5 deg, elongated SNR, with X-ray emission filling radio shell
- Brightness around 1.0 keV implies iron-rich ejecta, i.e. Type Ia supernova?
- Strong asymmetry (due to environment or explosion) implies core-collapse supernova?



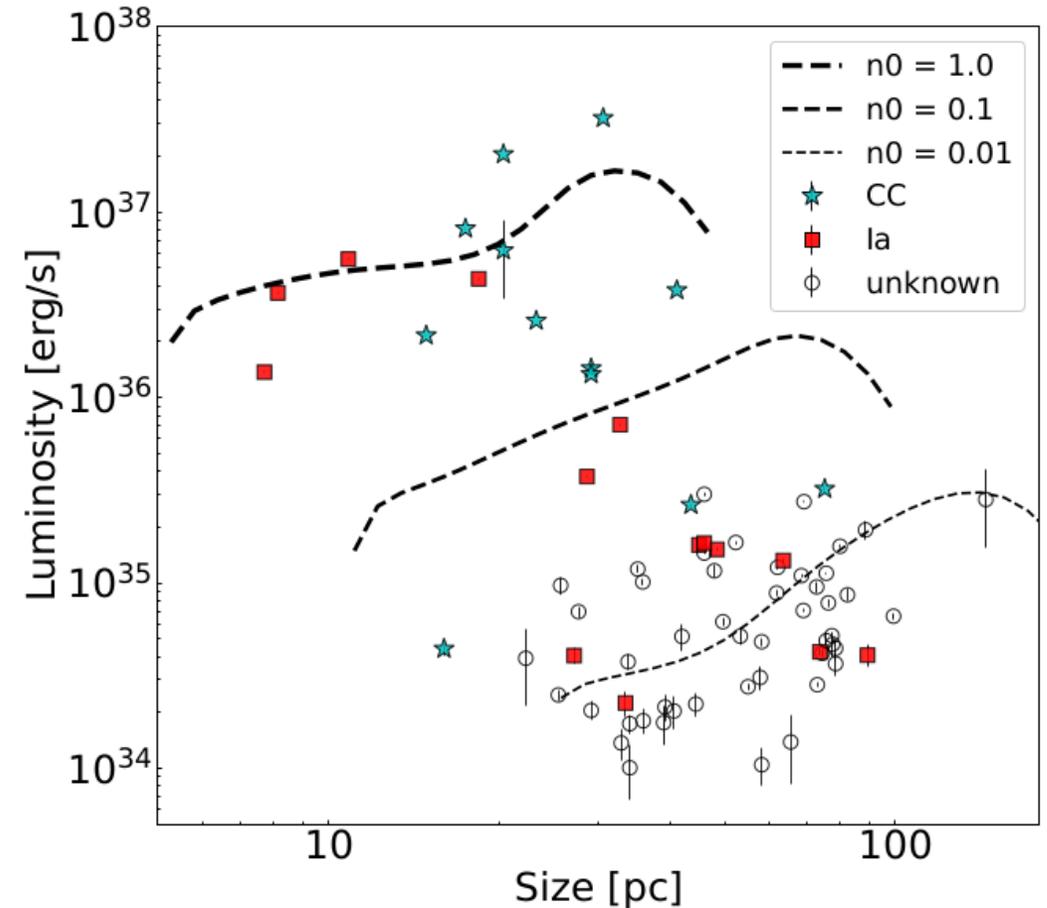
Radio (blue) & X-ray (red, green) composite image
Mantovanini+24

SNR population in the LMC

- Systematic SNR study in LMC finds 77 X-ray bright SNRs and 13 new candidates (Zangrandi+24)
 - 2 SNRs in far outskirts of LMC disk; Ejected during tidal interactions? (Sasaki+25)
- Anticorrelation of SNR size and X-ray luminosity
 - Different density regimes probed by SNR evolution



F. Zangrandi+, submitted



Diffuse X-rays from the LMC

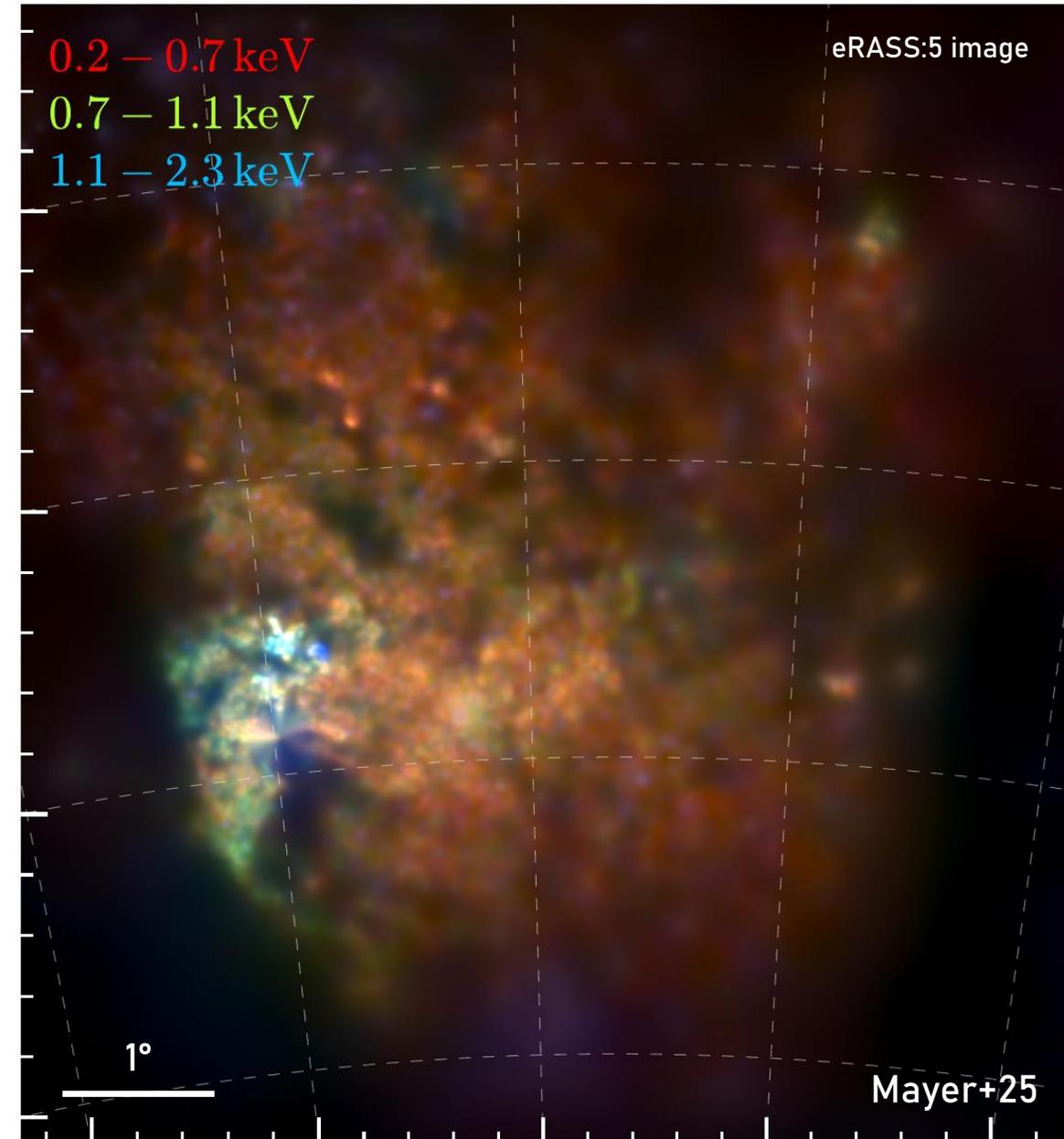
- Large Magellanic Cloud (LMC)
 - Nearby (~ 50 kpc) Milky Way satellite
 - Face-on & low foreground absorption ($< 10^{21}$ cm $^{-2}$)
 - Close to eROSITA survey pole
 - eROSITA all-sky survey (eRASS:5) provides most sensitive X-ray view of LMC

- Supernovae and stellar winds produce hot ISM phase

Diffuse X-rays from the LMC

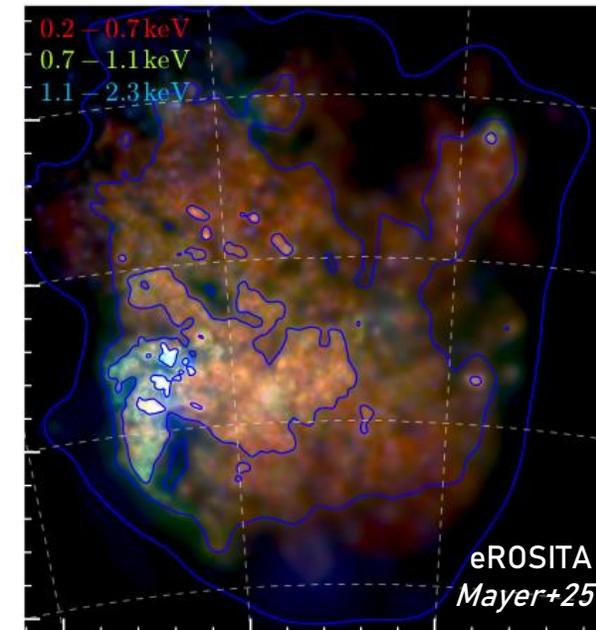
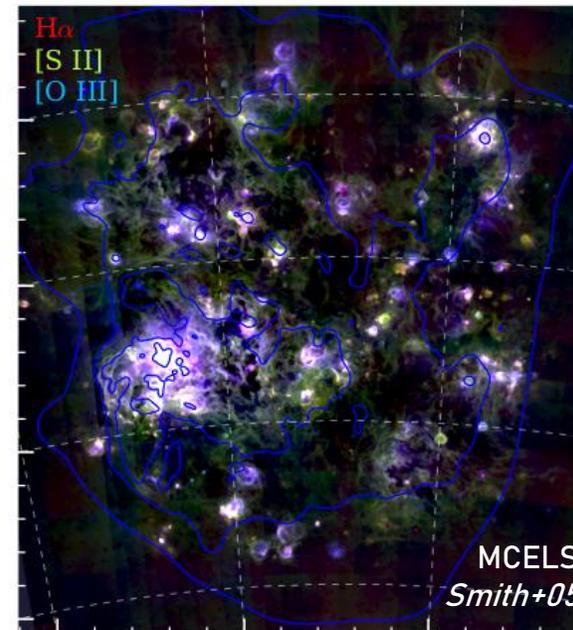
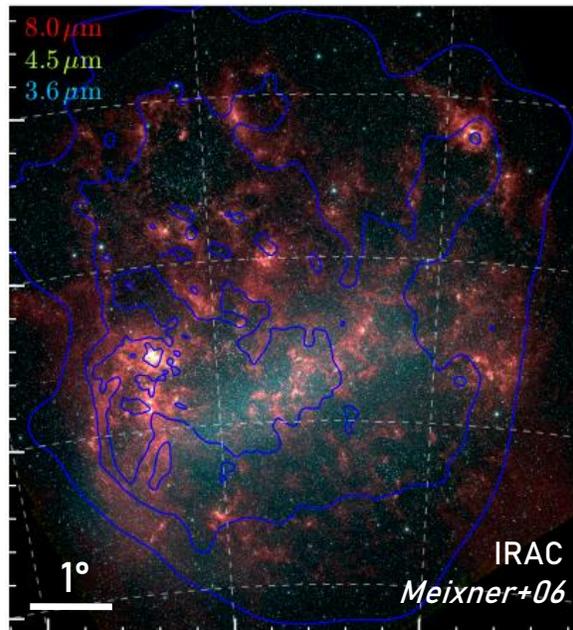
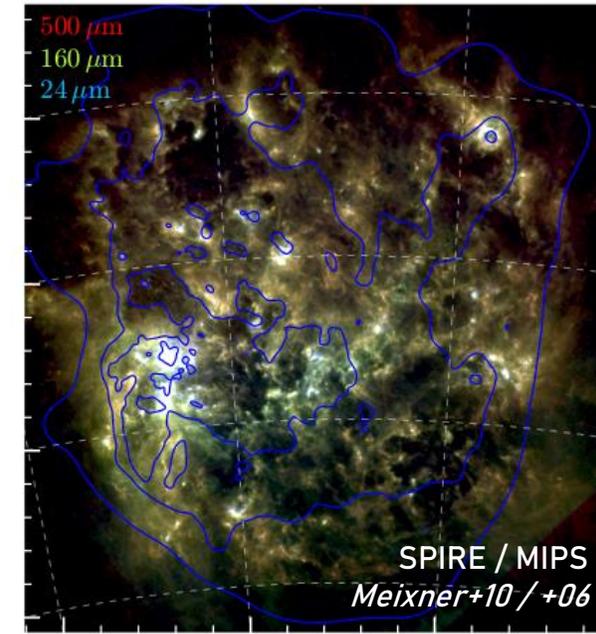
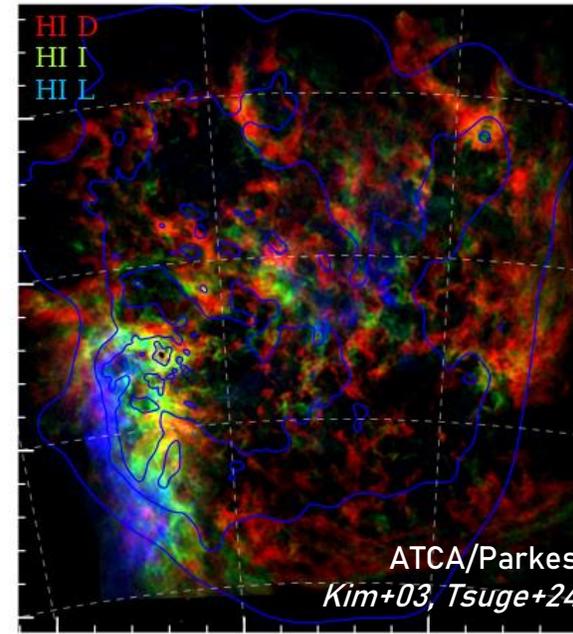
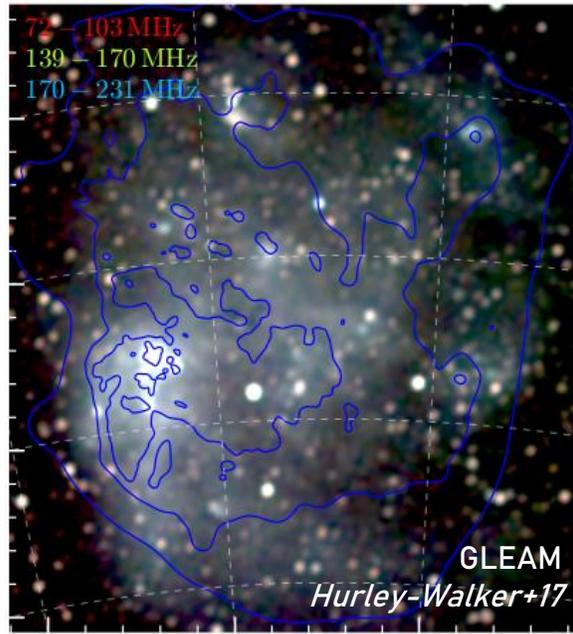
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Multiwavelength View of the LMC

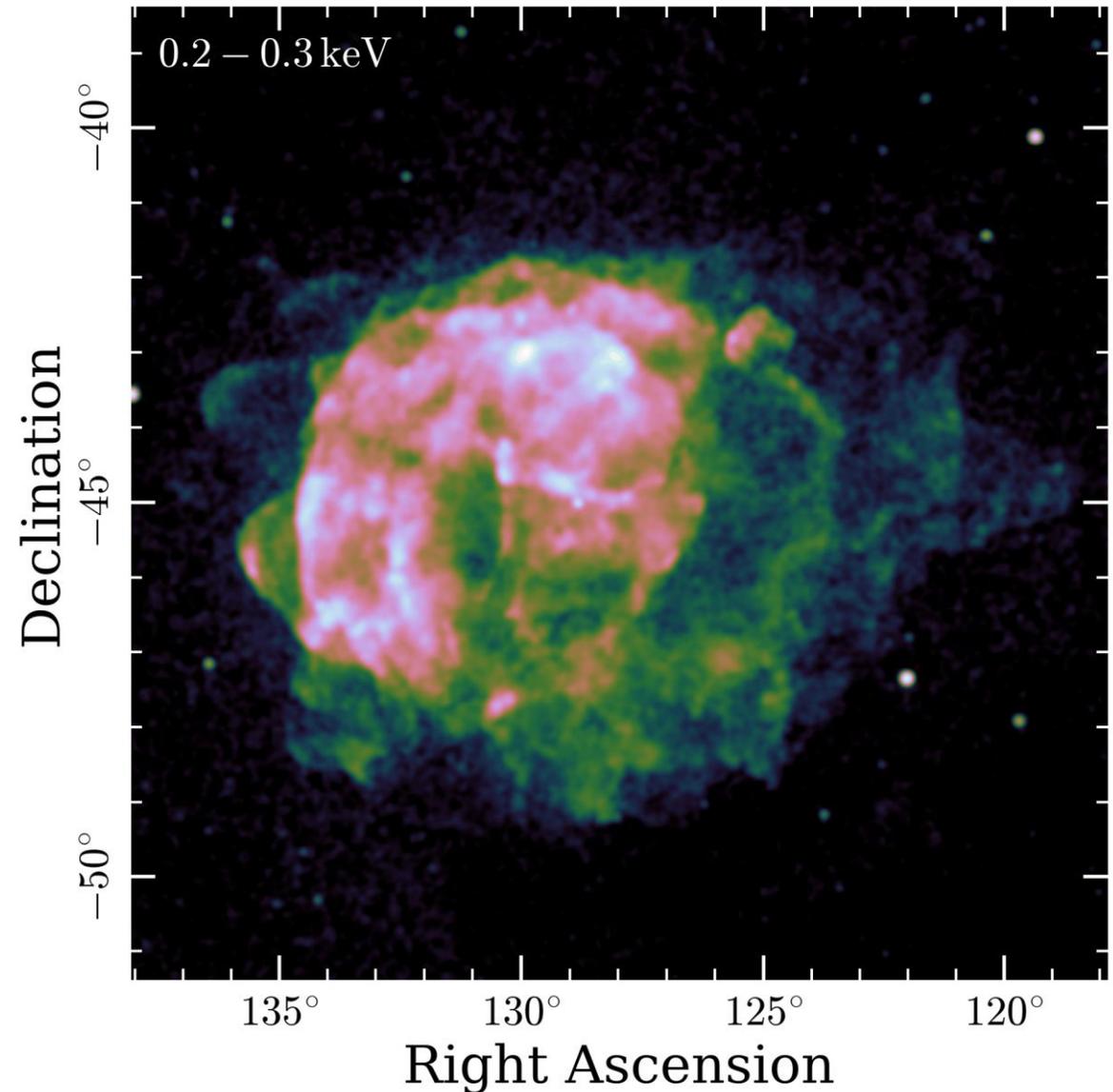
- Radio: Cosmic rays
- HI: Cold gas
- Far/Mid infrared: Cold/warm dust
- Near infrared: Stellar mass
- Optical lines: HII regions & SNRs
- X-rays: Diffuse, hot plasma



Extra Slides Vela

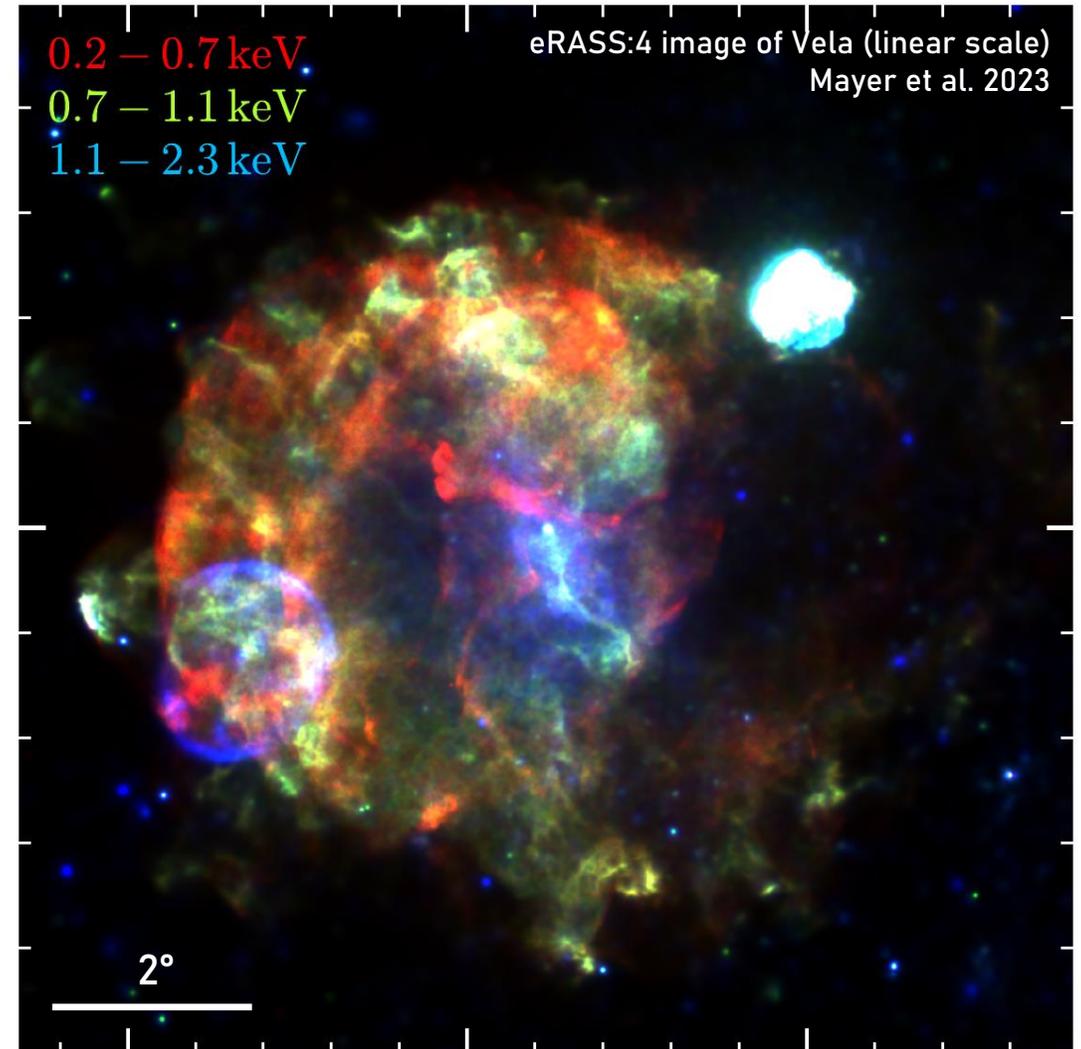
Imaging & Morphology

- Complex energy-dependent morphology with multiple components
 - **Soft band:** Diffuse shell & thick tangential filaments
 - **Medium band:** Thin radial fingers & clumps
 - **Hard band:** Nonthermal emission from Vela X & Vela Jr.



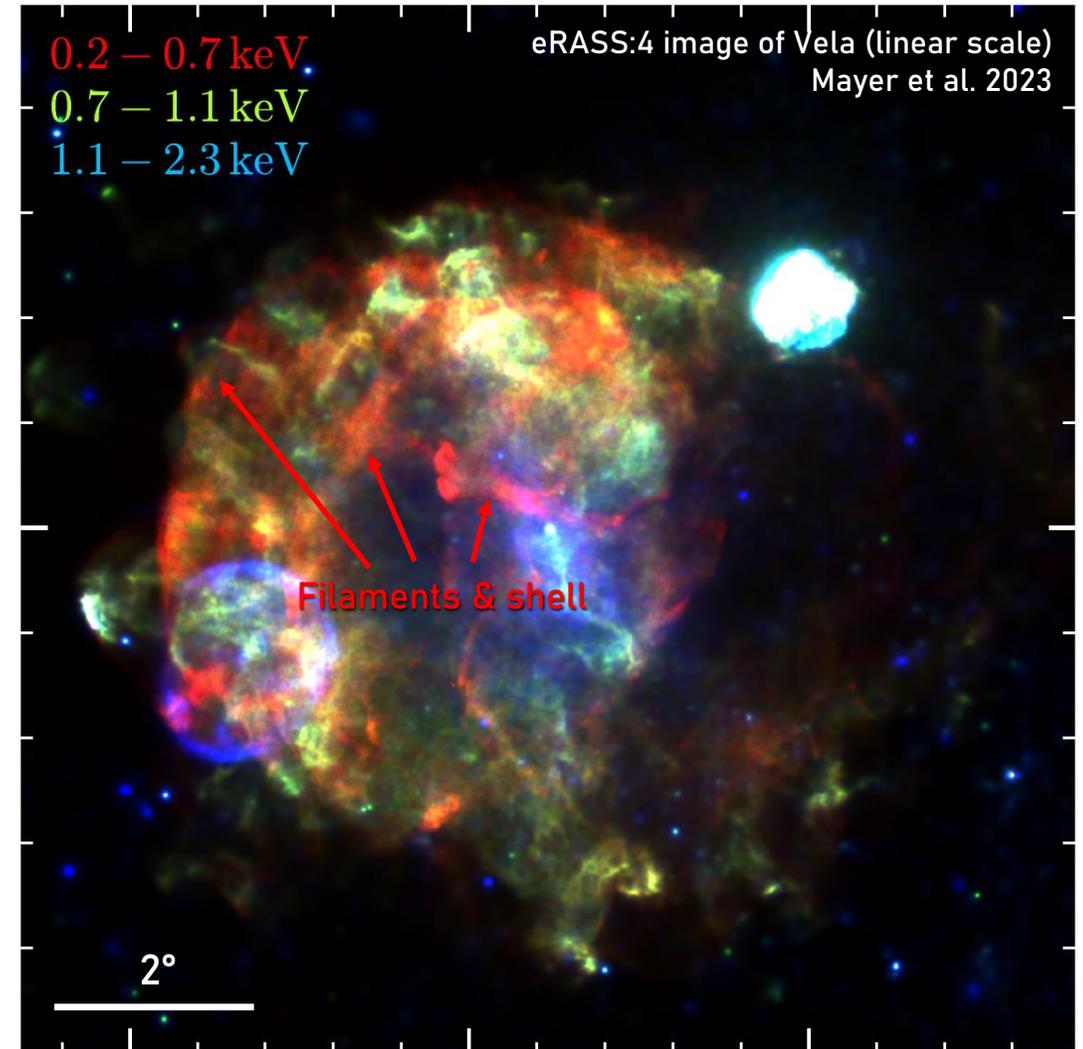
Vela SNR Morphology

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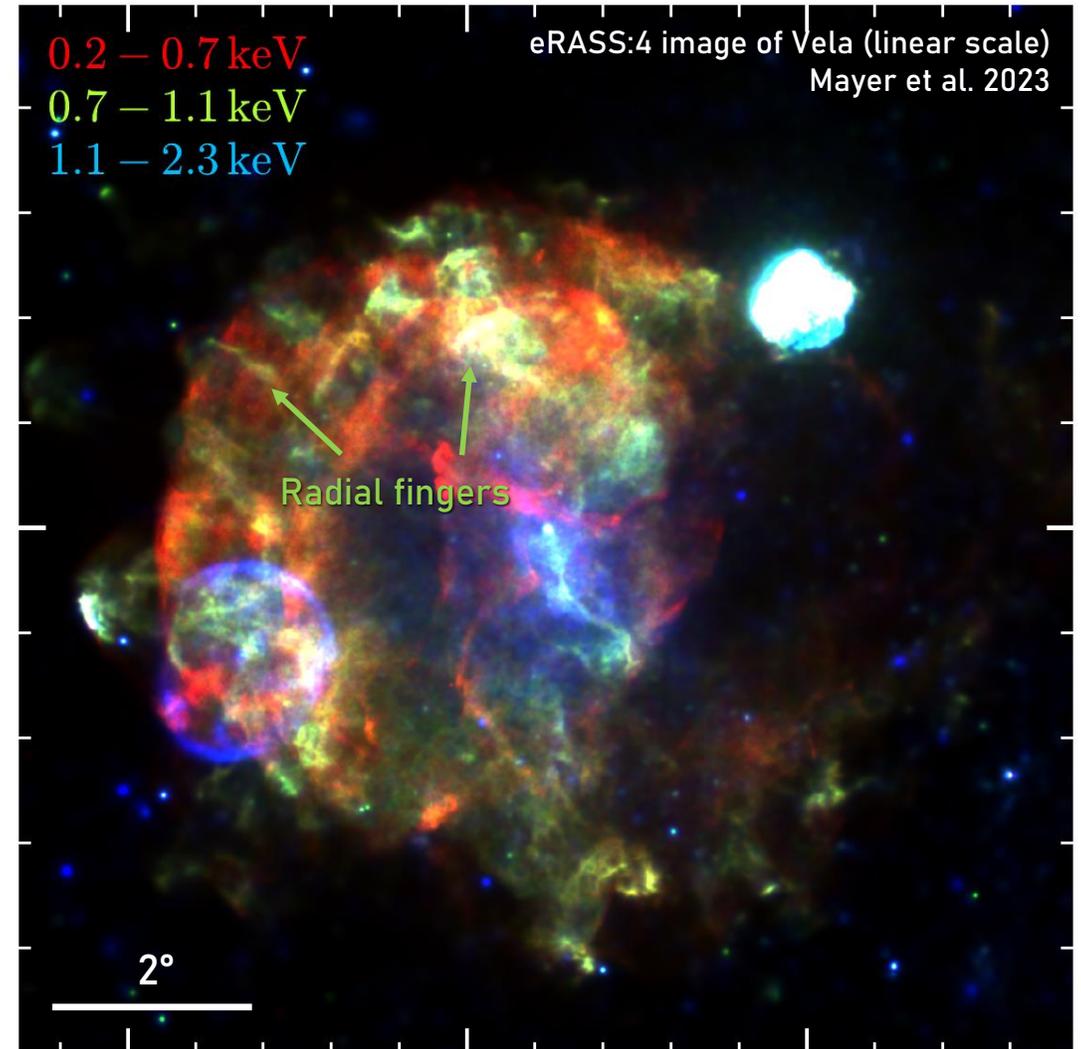
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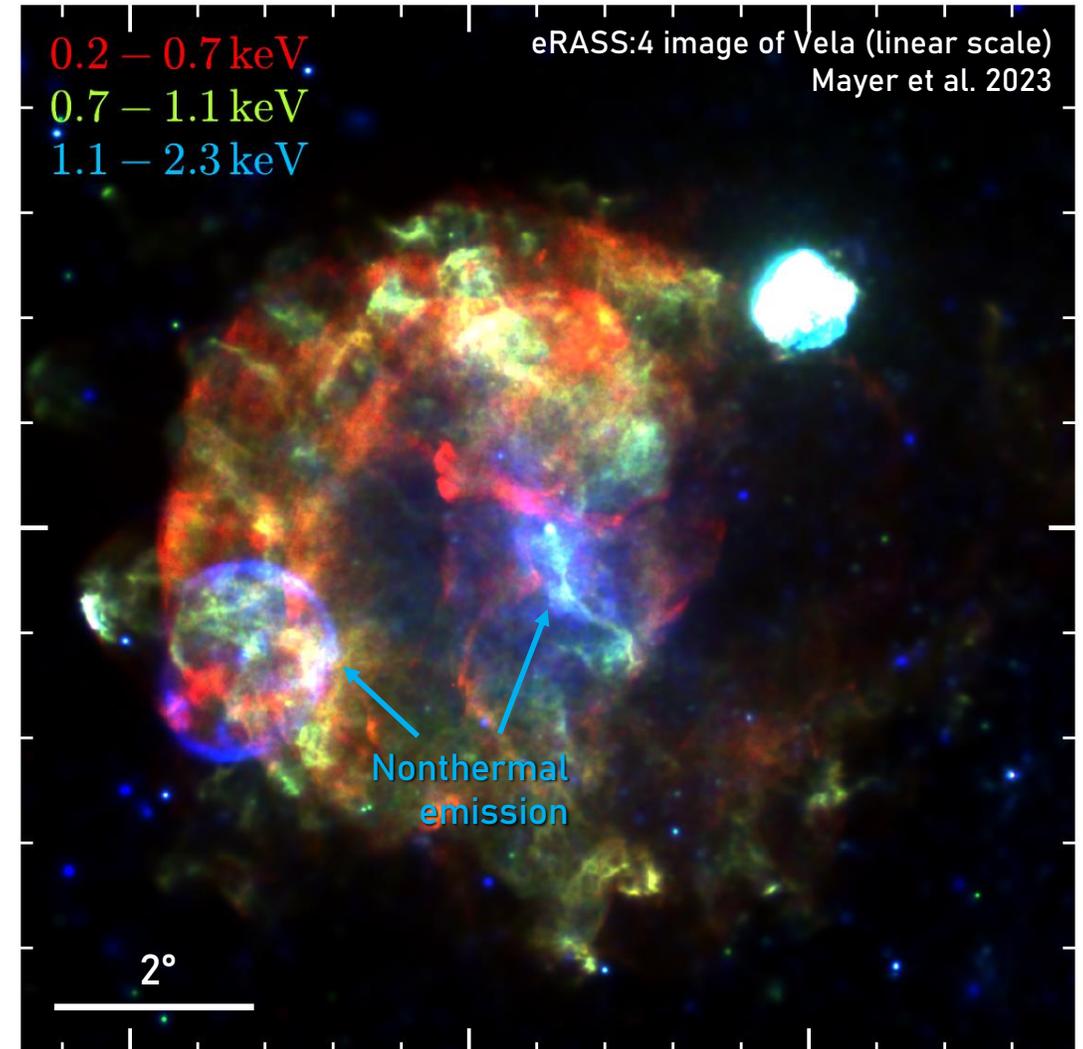
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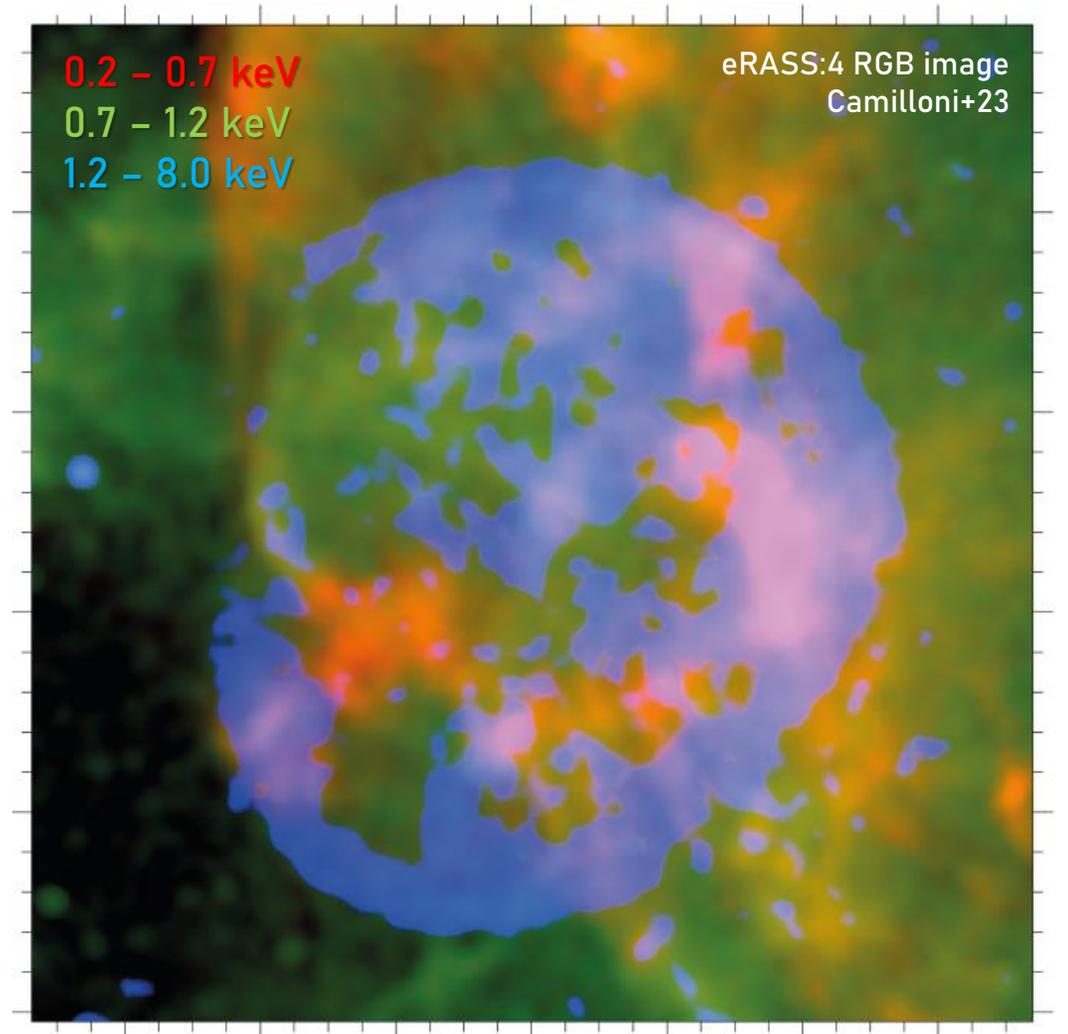


Vela SNR Morphology

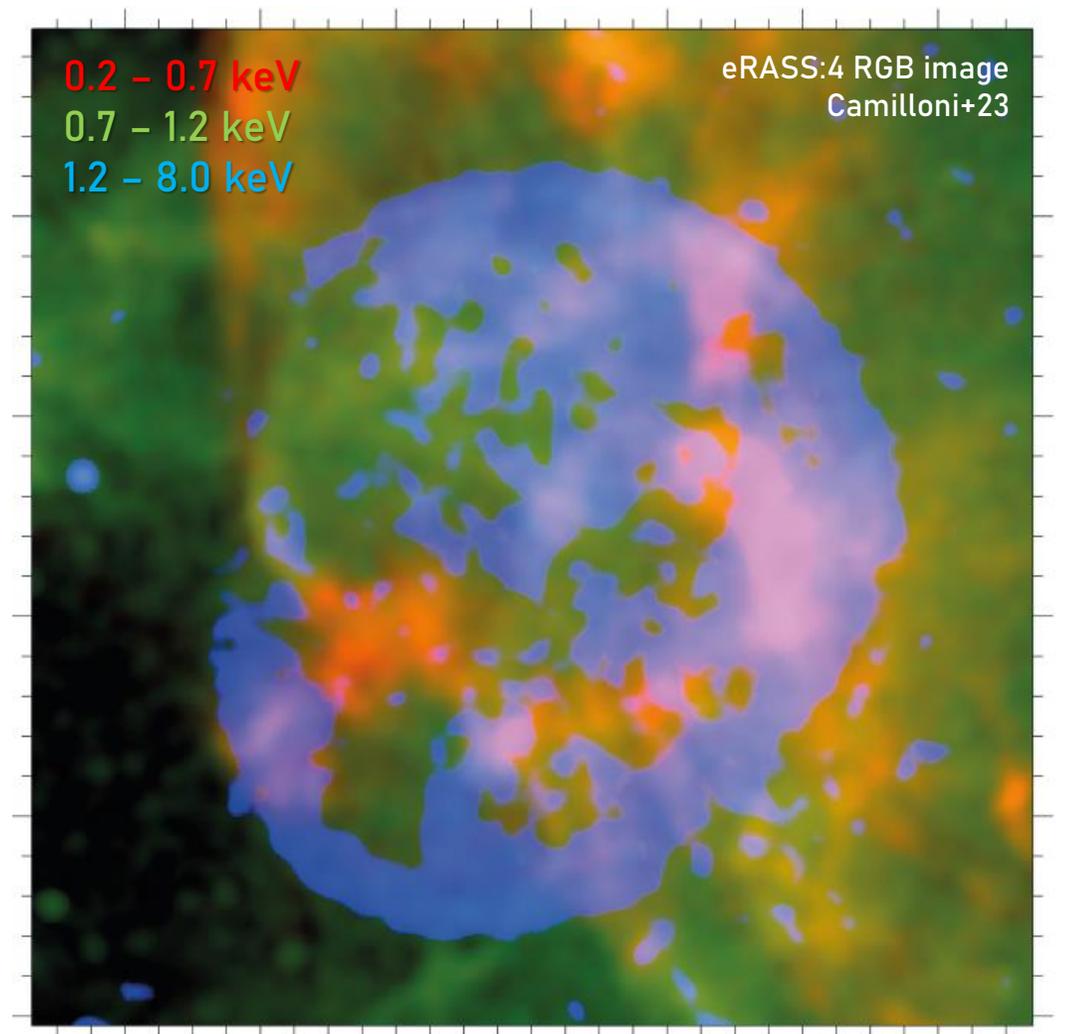
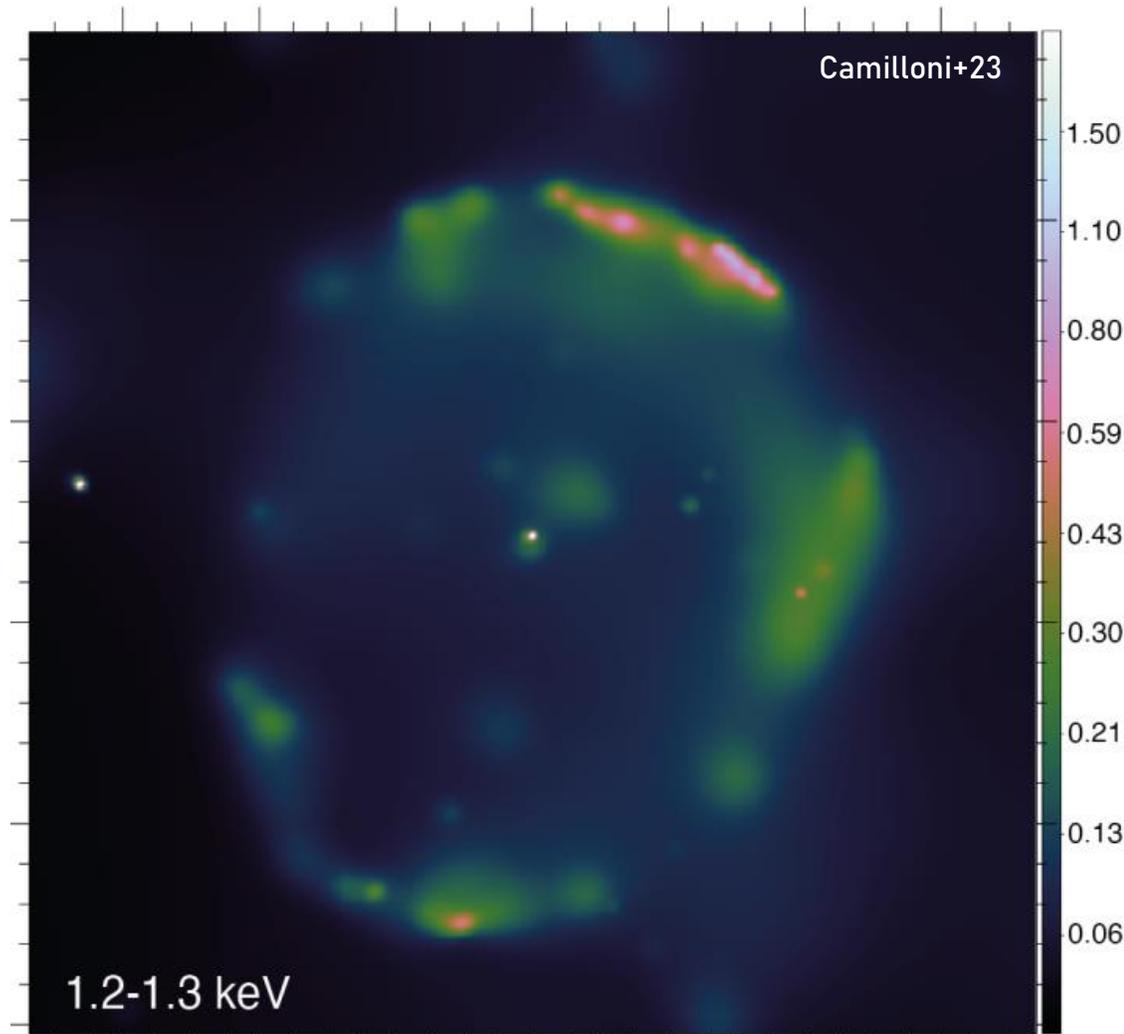
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Vela Jr – a Pure Synchrotron Shell?

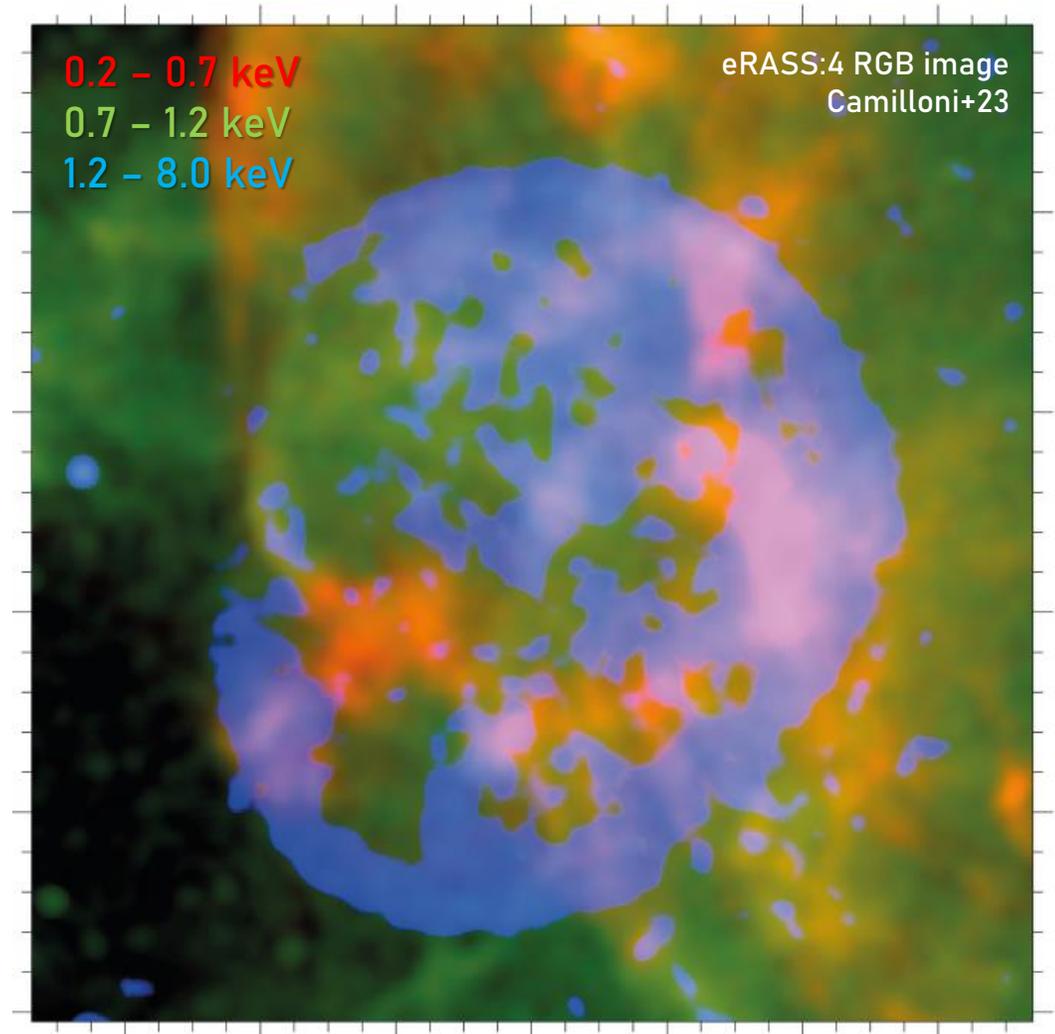


Vela Jr – a Pure Synchrotron Shell?



Vela Jr – a Pure Synchrotron Shell?

- X-ray synchrotron emission fills shell
- No hint of associated thermal emission (but morphological separation challenging)



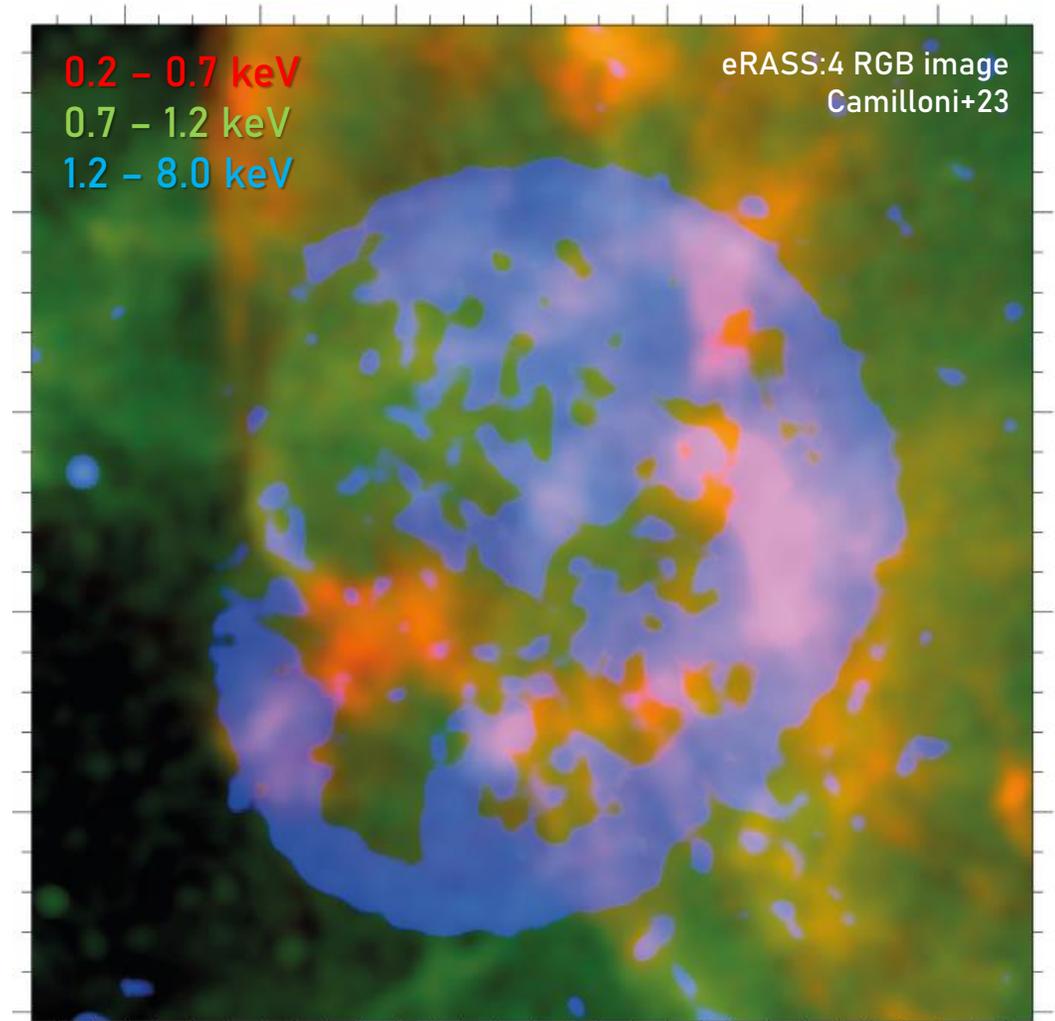
Vela Jr – a Pure Synchrotron Shell?

- X-ray synchrotron emission fills shell
- No hint of associated thermal emission (but morphological separation challenging)
- Fits with loss-limited acceleration model (Zirakashvili & Aharonian07):

Region	N_H (10 ²² cm ⁻²)	$V_f \eta_B^{-1/2}$ (km s ⁻¹)
1	0.36 ^{+0.02} _{-0.02}	2330 ⁺¹⁶⁰ ₋₁₃₀
2	0.23 ^{+0.01} _{-0.01}	2460 ⁺²¹⁰ ₋₁₈₀
3	0.56 ^{+0.02} _{-0.02}	2380 ⁺¹³⁰ ₋₁₁₀
4	0.63 ^{+0.02} _{-0.01}	1900 ⁺⁷⁰ ₋₇₀
5	1.03 ^{+0.04} _{-0.04}	1020 ⁺⁵⁰ ₋₅₀
6	0.77 ^{+0.07} _{-0.06}	1110 ⁺¹⁰⁰ ₋₉₀
7	0.33 ^{+0.02} _{-0.02}	3400 ⁺⁵⁰⁰ ₋₄₀₀

Camilloni+23, Allen+15

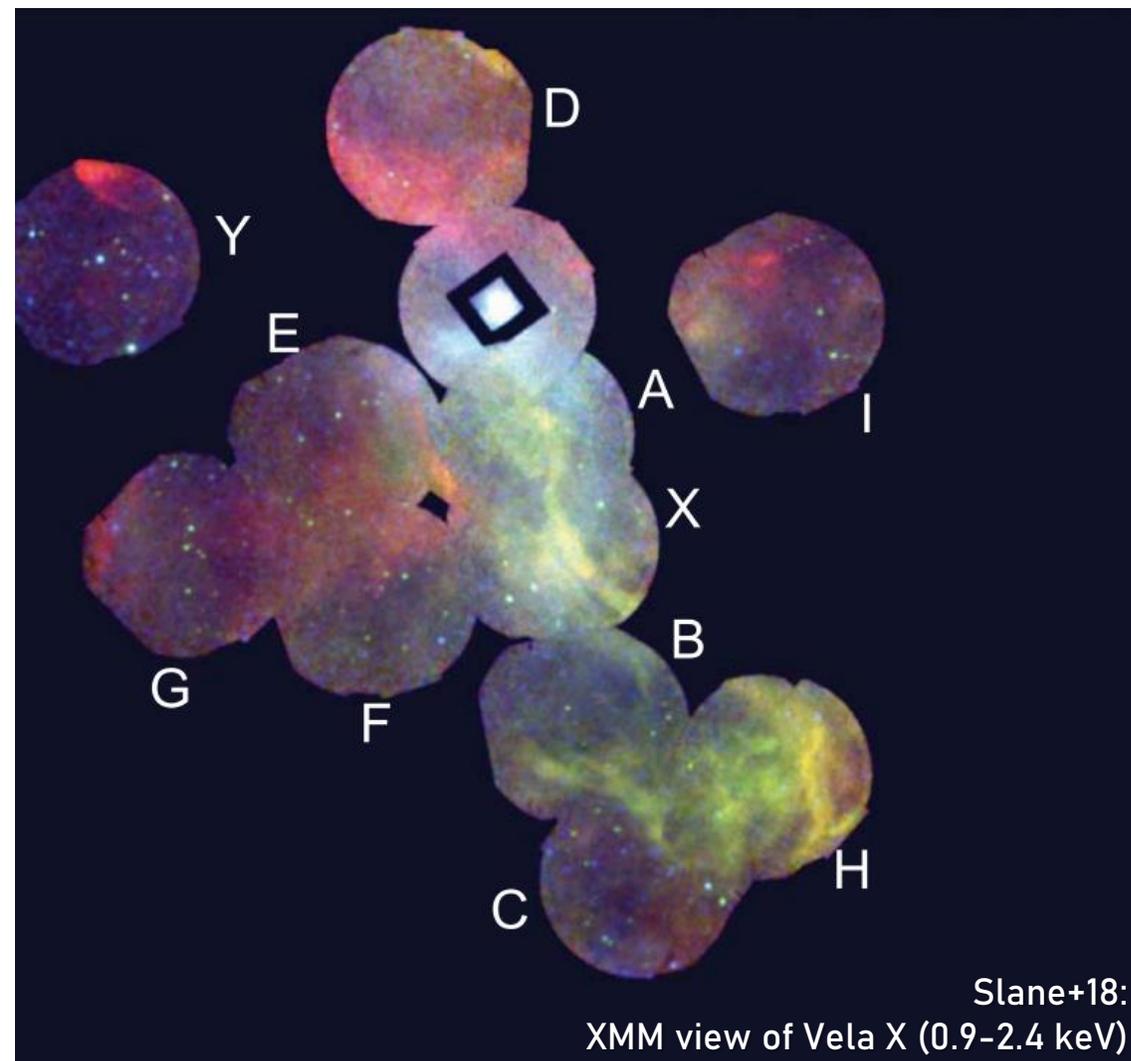
$$D \approx \frac{2140 \text{ km s}^{-1}}{420 \text{ mas yr}^{-1}} \eta_B^{1/2} \approx 1100 \eta_B^{1/2} \text{ pc.}$$



Results: Nonthermal Emission

- Vela X, prior to eROSITA:
 - Compact PWN core with „jet“ and equatorial torus (e.g., Helfand+2001)
 - X-ray synchrotron emission in „Cocoon“ visible with ROSAT & XMM (e.g. Markwardt+1995, Slane+2018)

➤ Now: observe much larger size of pulsar's diffuse X-ray nebula, with radial extent of $2^\circ - 3^\circ$

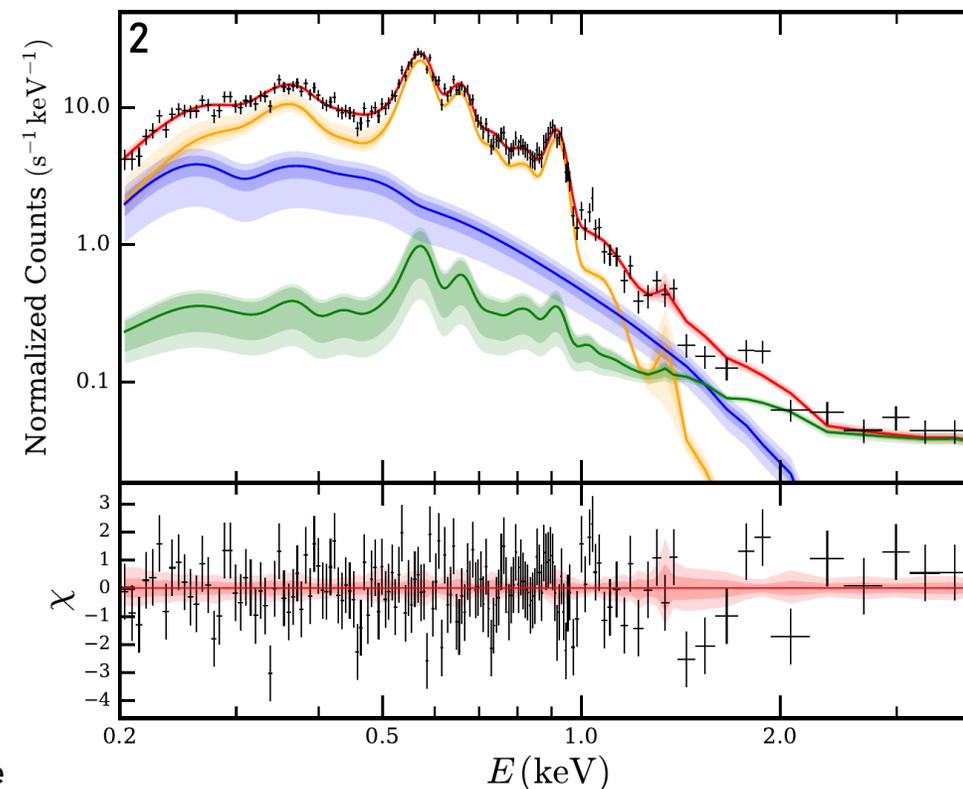
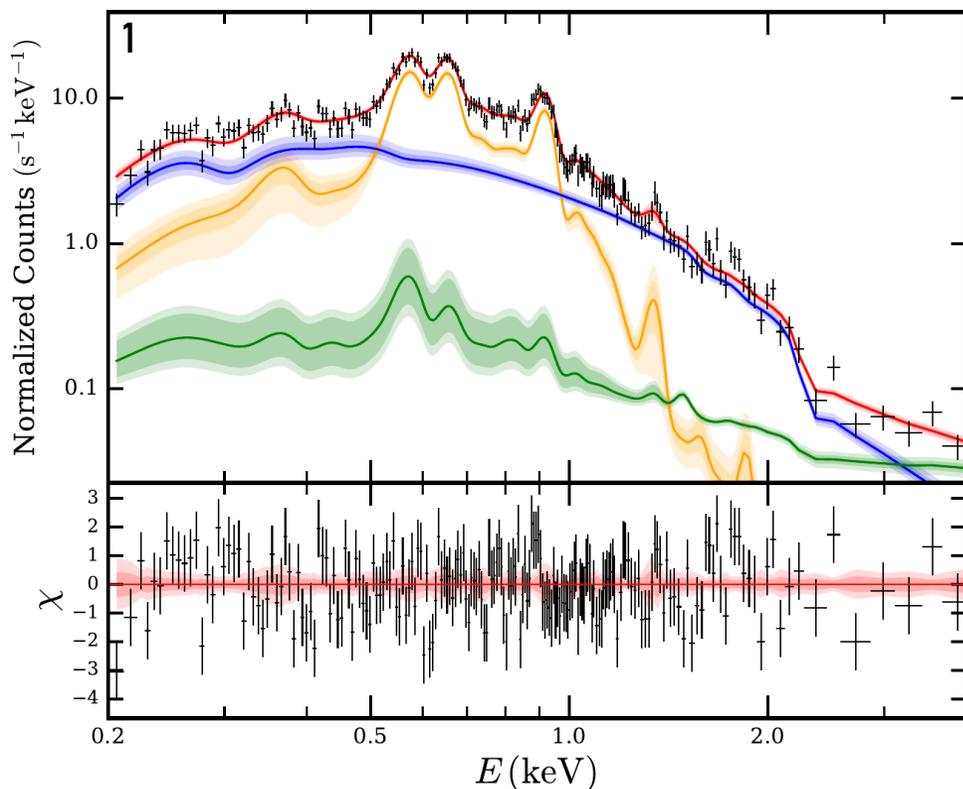
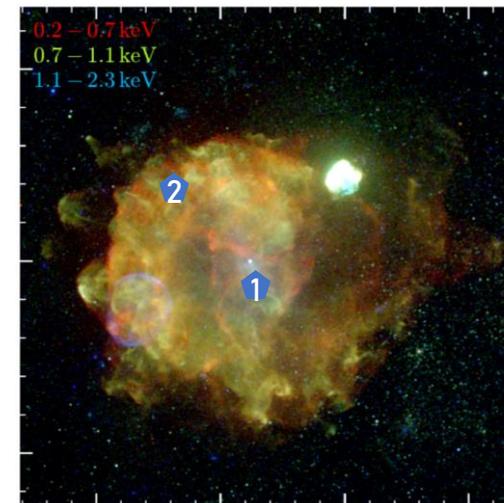


Spectral model

Absorbed plasma in NEI + nonthermal component

TBabs*(vps shock+powerlaw) + background

- Photon index in region 2 too steep ($\Gamma = 4$)
- Hard to constrain kT , τ individually



yer@fau.de

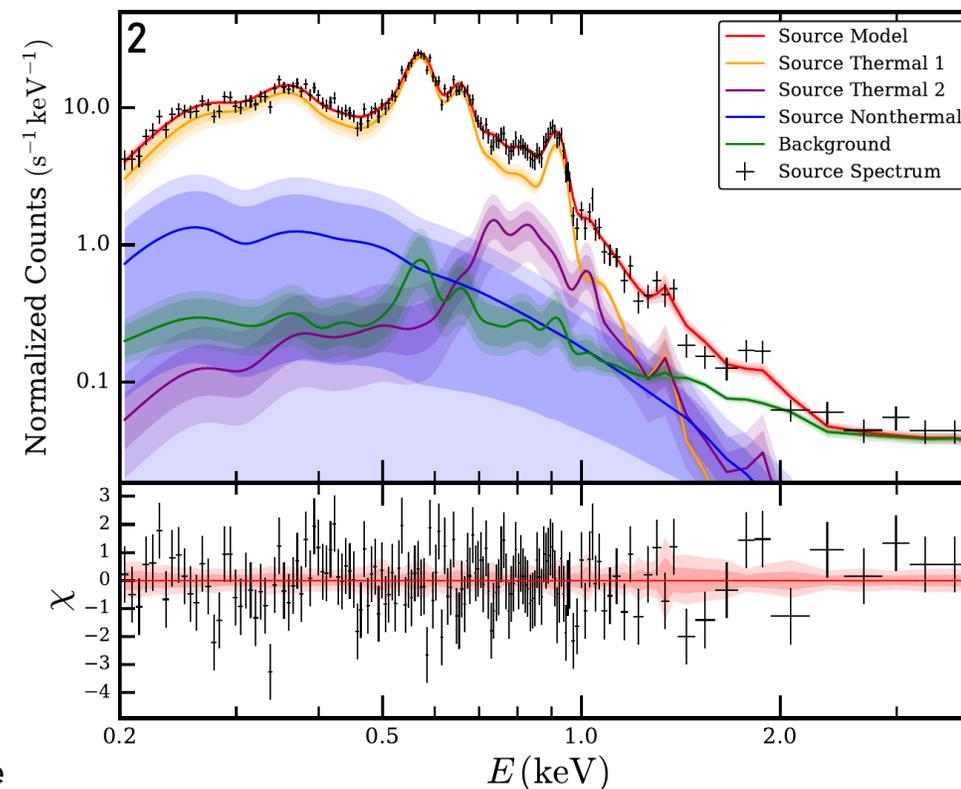
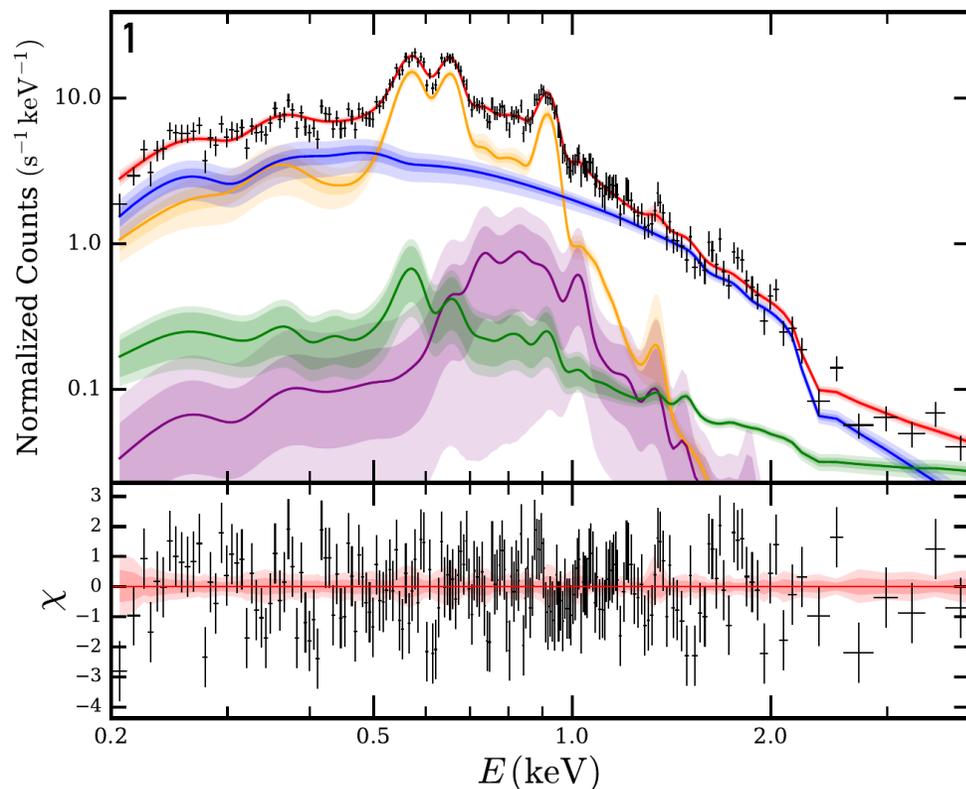
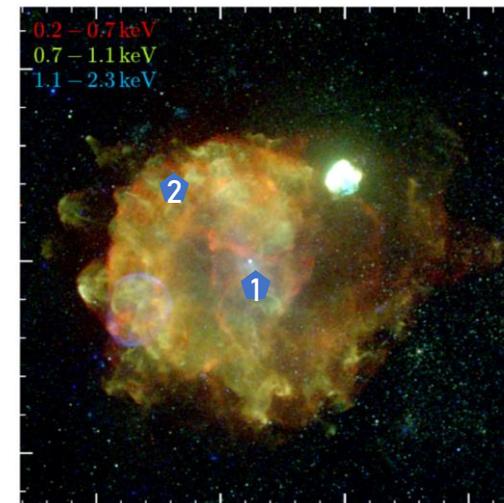
Spectral model

Two absorber plasmas + nonthermal component

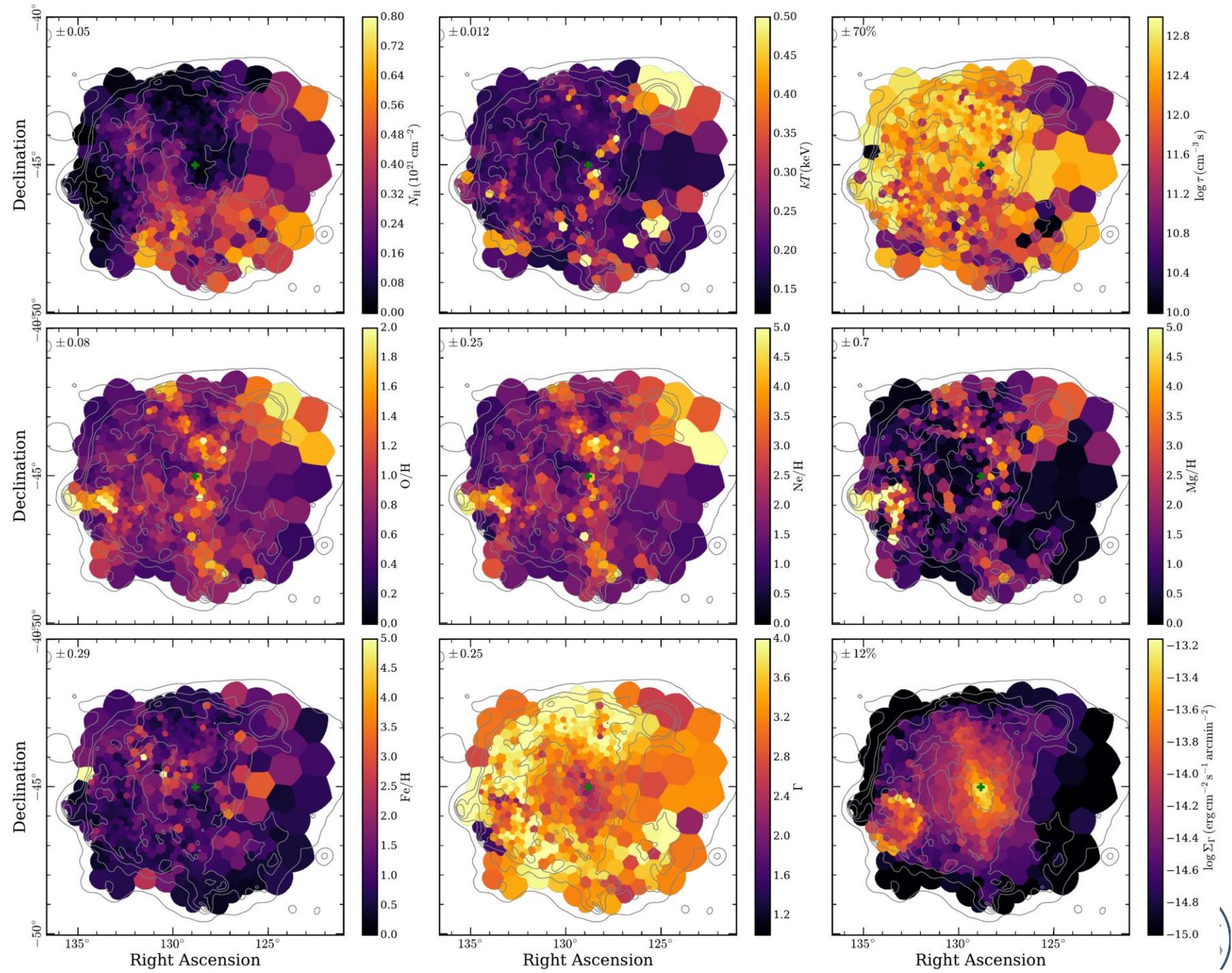
TBabs*(vapec+vapec+powerlaw) + background

➤ Mean plasma temperature more well-defined

•

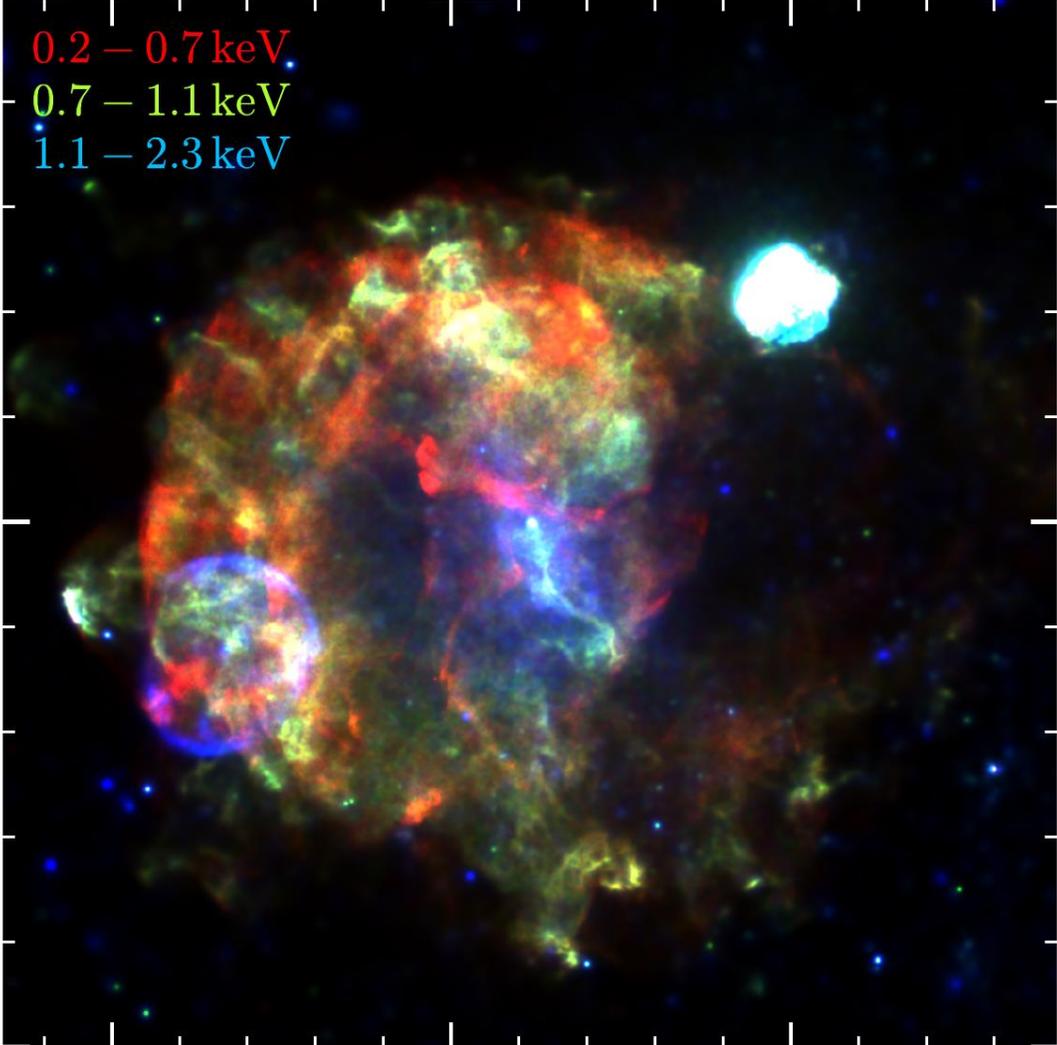


Fits with NEI Plasma



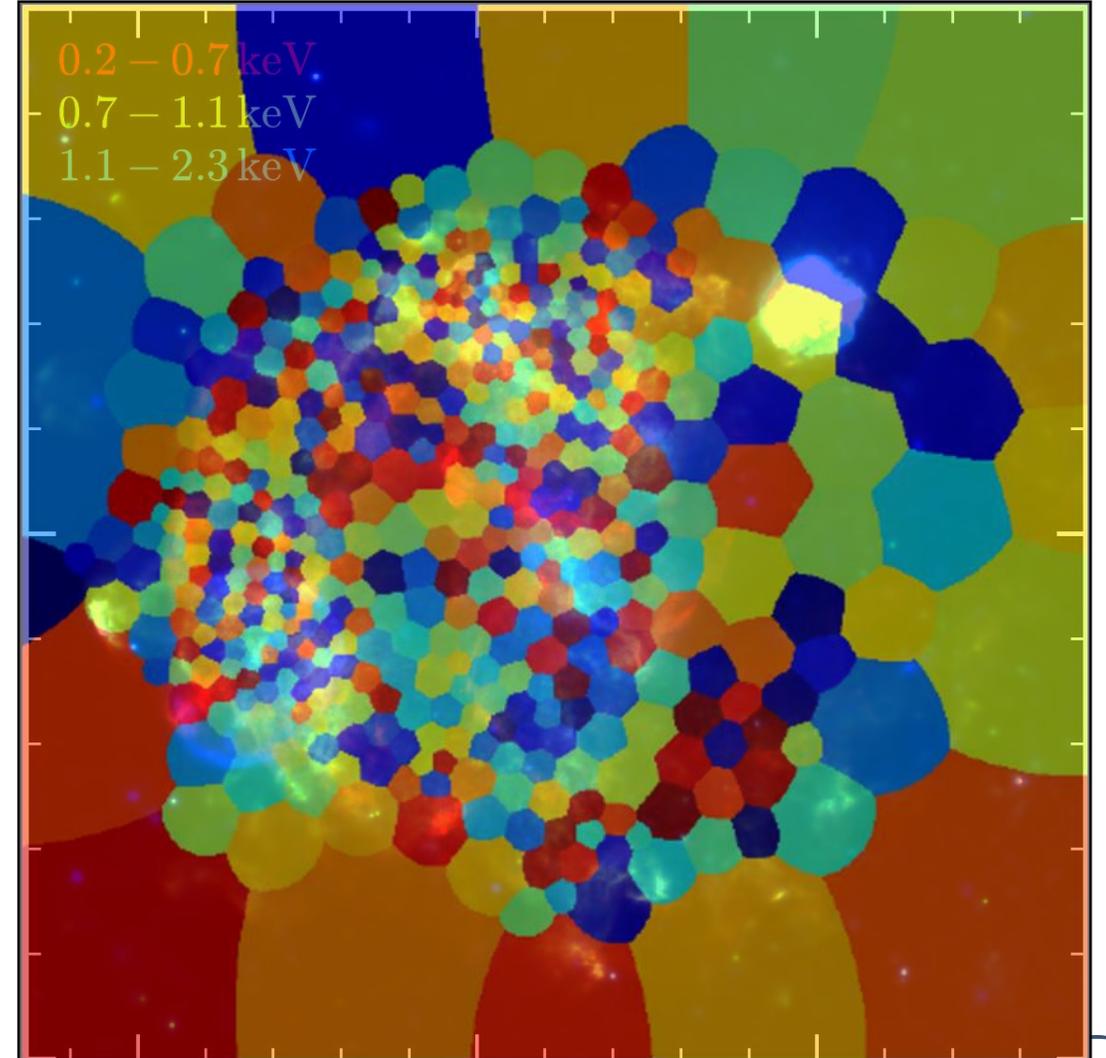
13.11.2025

Spatially resolved spectroscopy



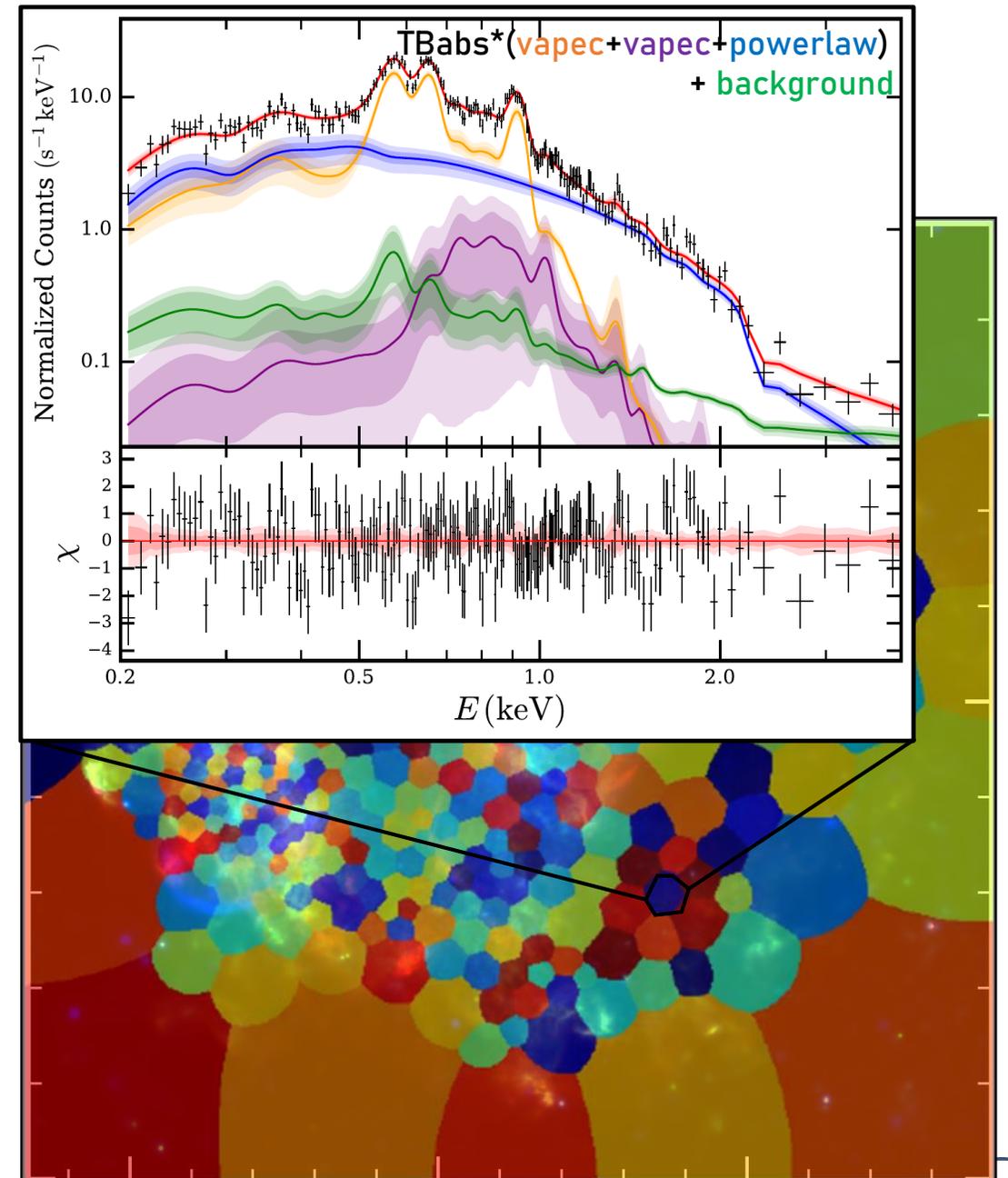
Spatially resolved spectroscopy

- Adaptive Voronoi binning (Cappellari+03)
- Around 500 spectra with uniform statistics ($\sim 10^4$ X-ray photons)

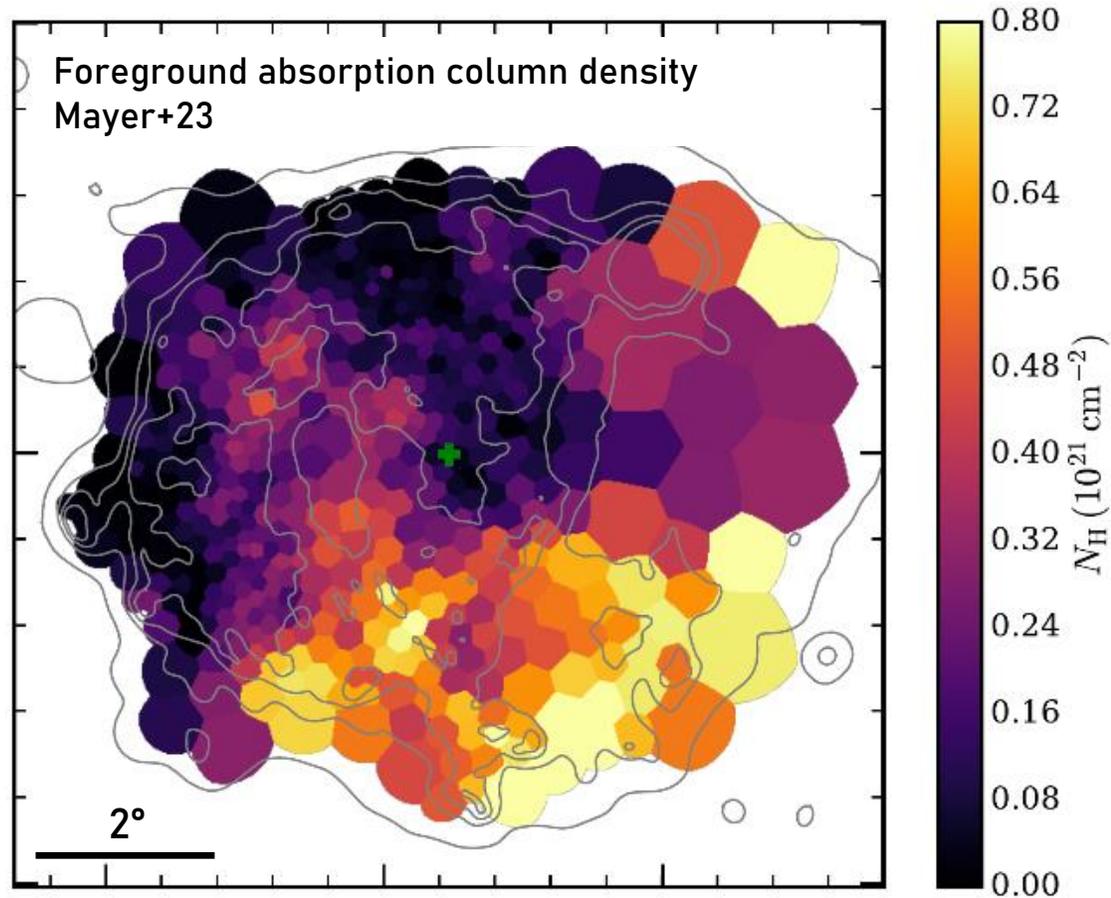


Spatially resolved spectroscopy

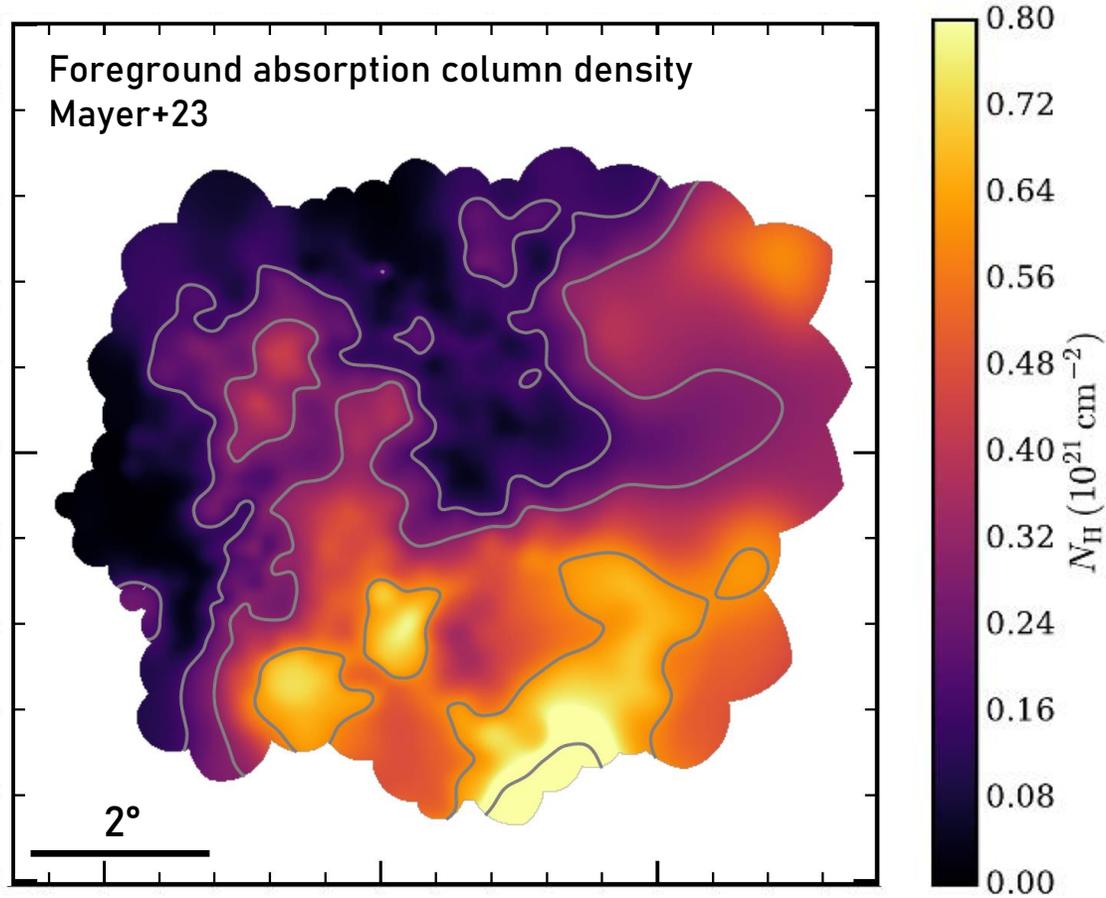
- Adaptive Voronoi binning (Cappellari+03)
- Around 500 spectra with uniform statistics ($\sim 10^4$ X-ray photons)
- Characterize thermal & nonthermal components via spectral modelling



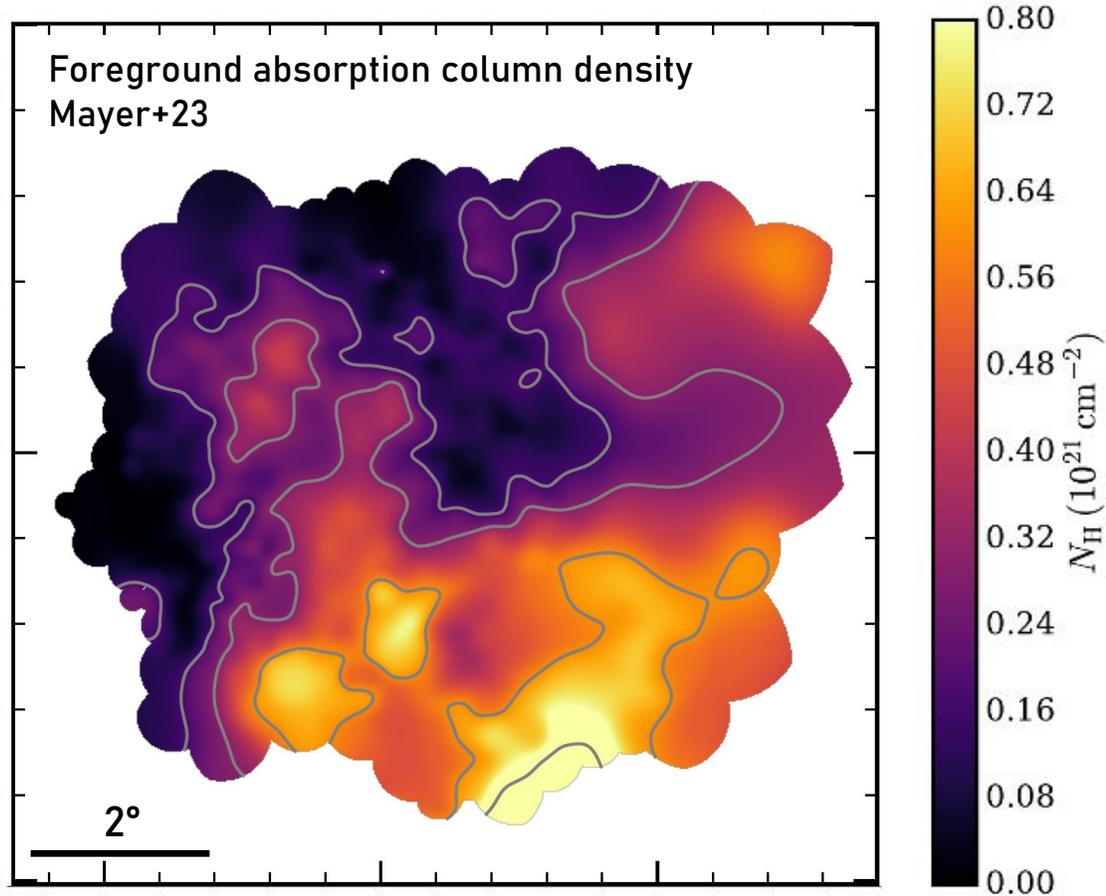
Vela SNR – Intervening ISM



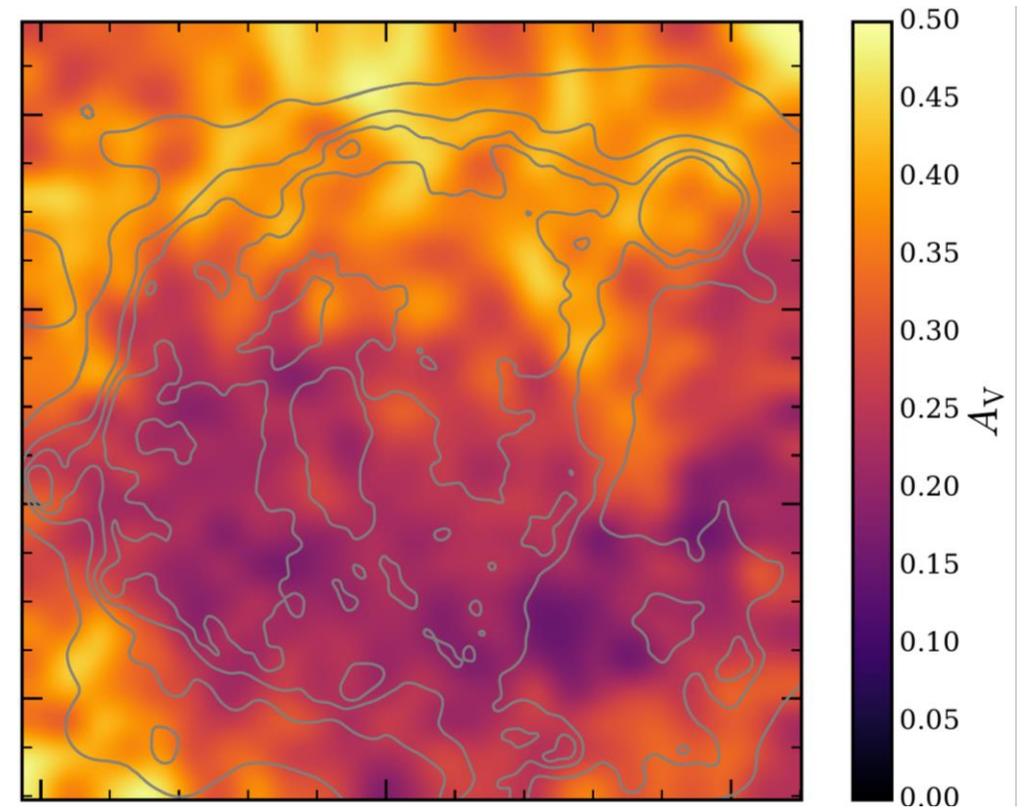
Vela SNR – Intervening ISM



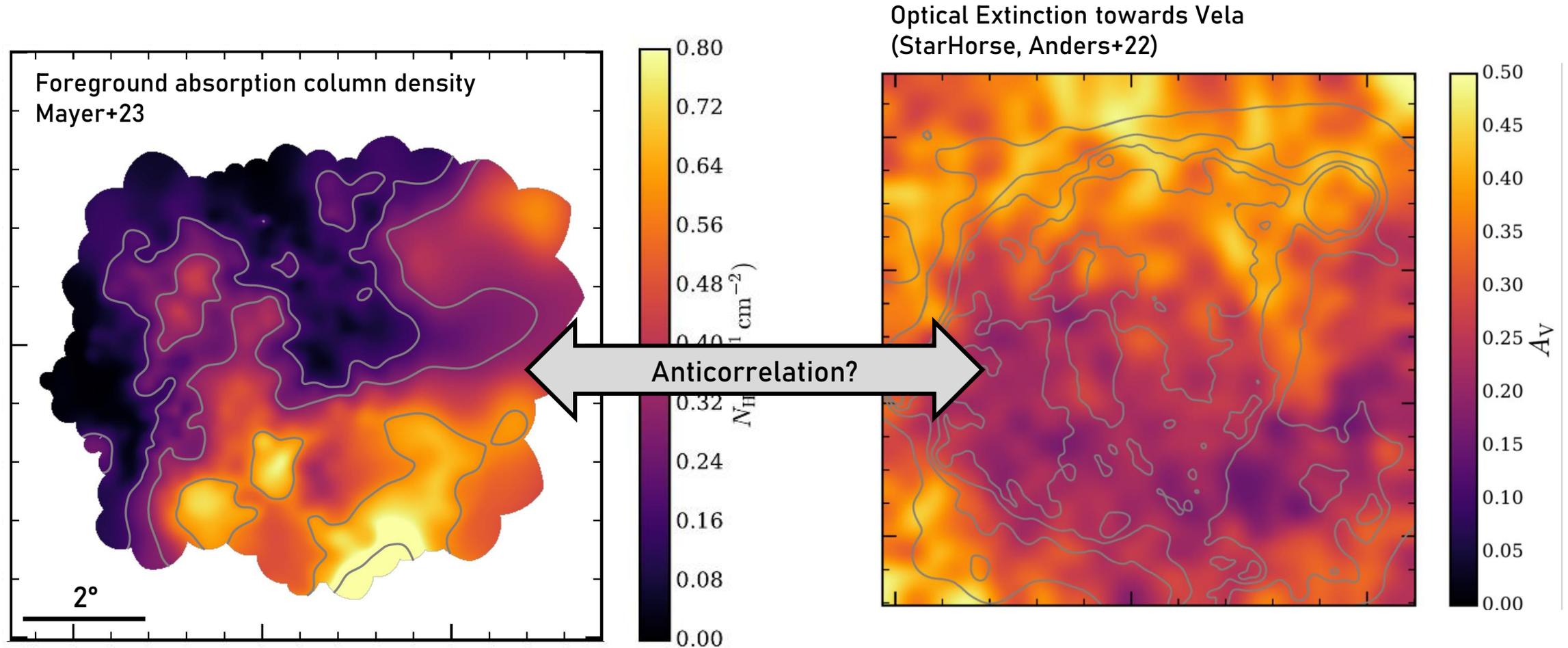
Vela SNR – Intervening ISM



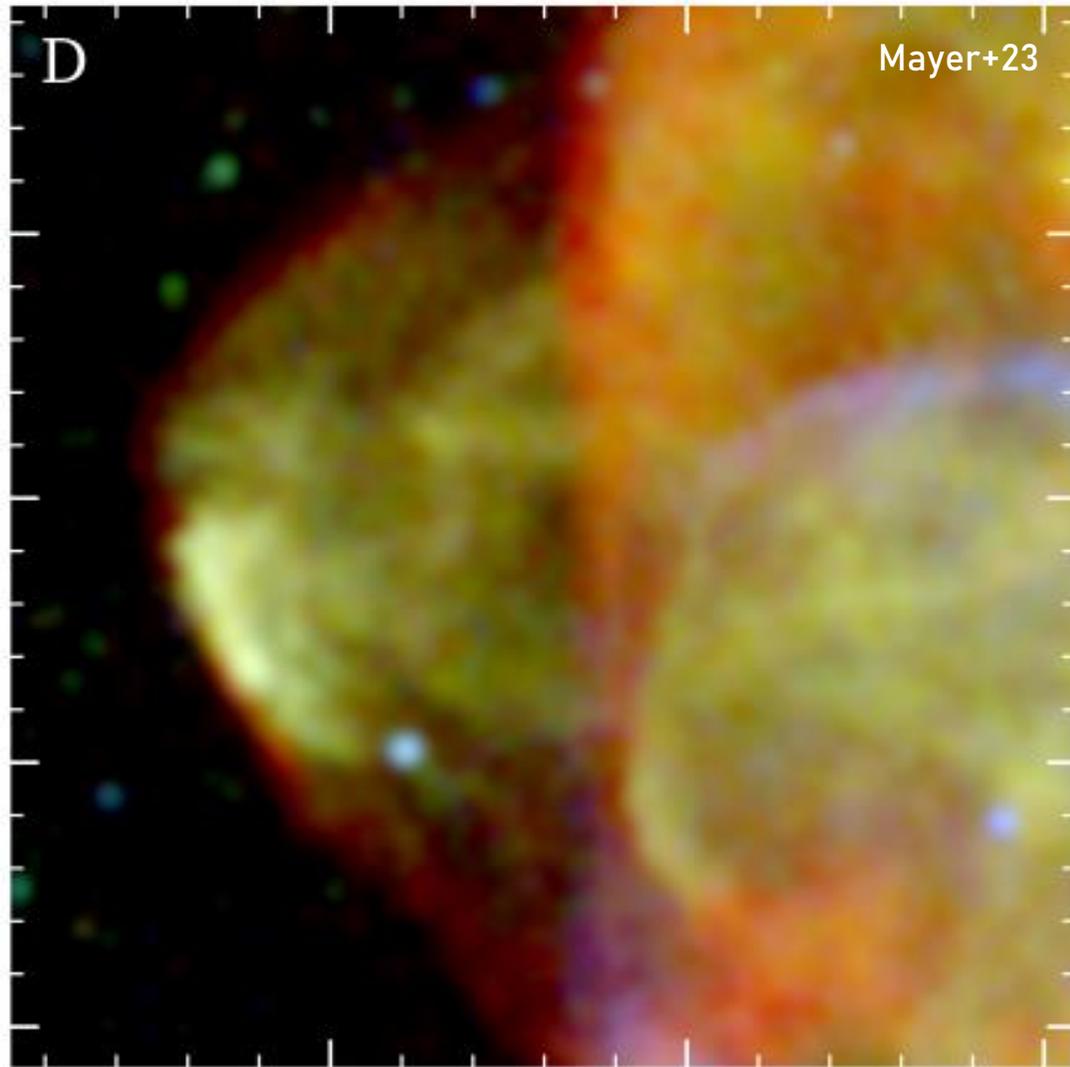
Optical Extinction towards Vela
(StarHorse, Anders+22)



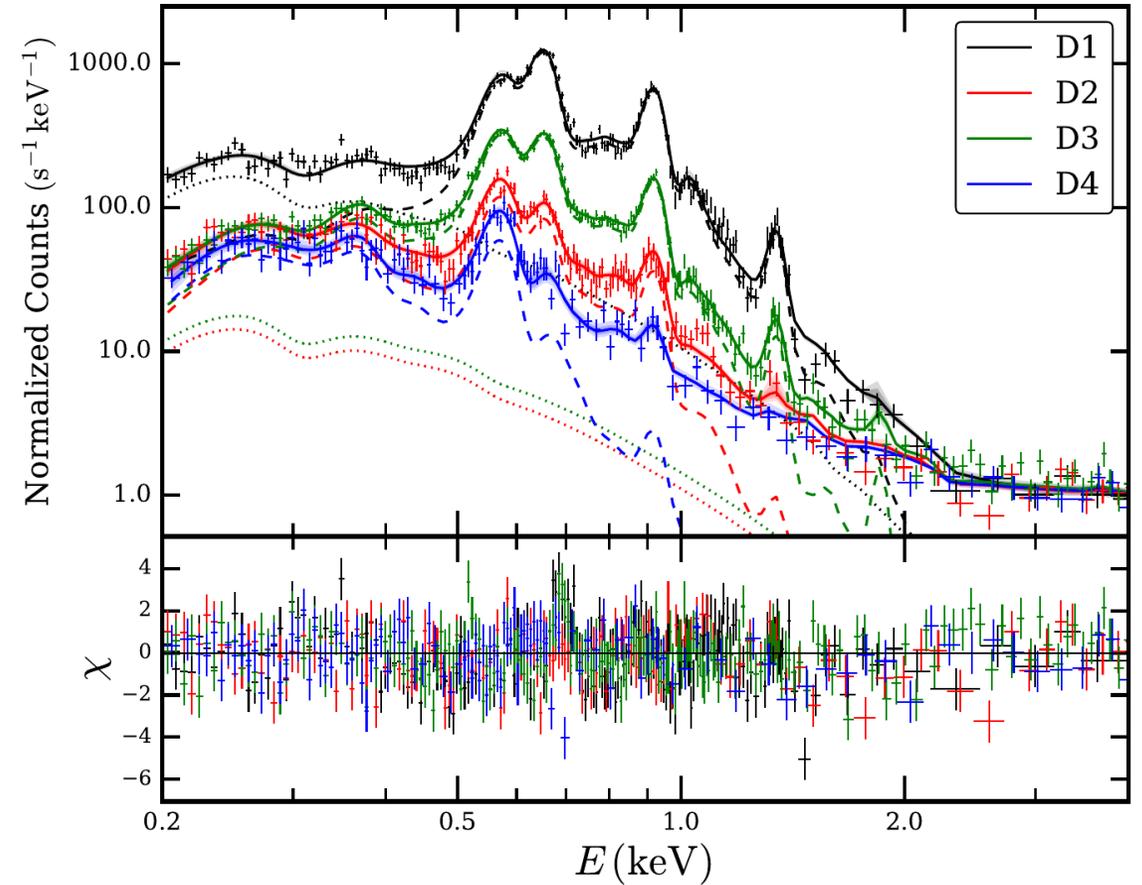
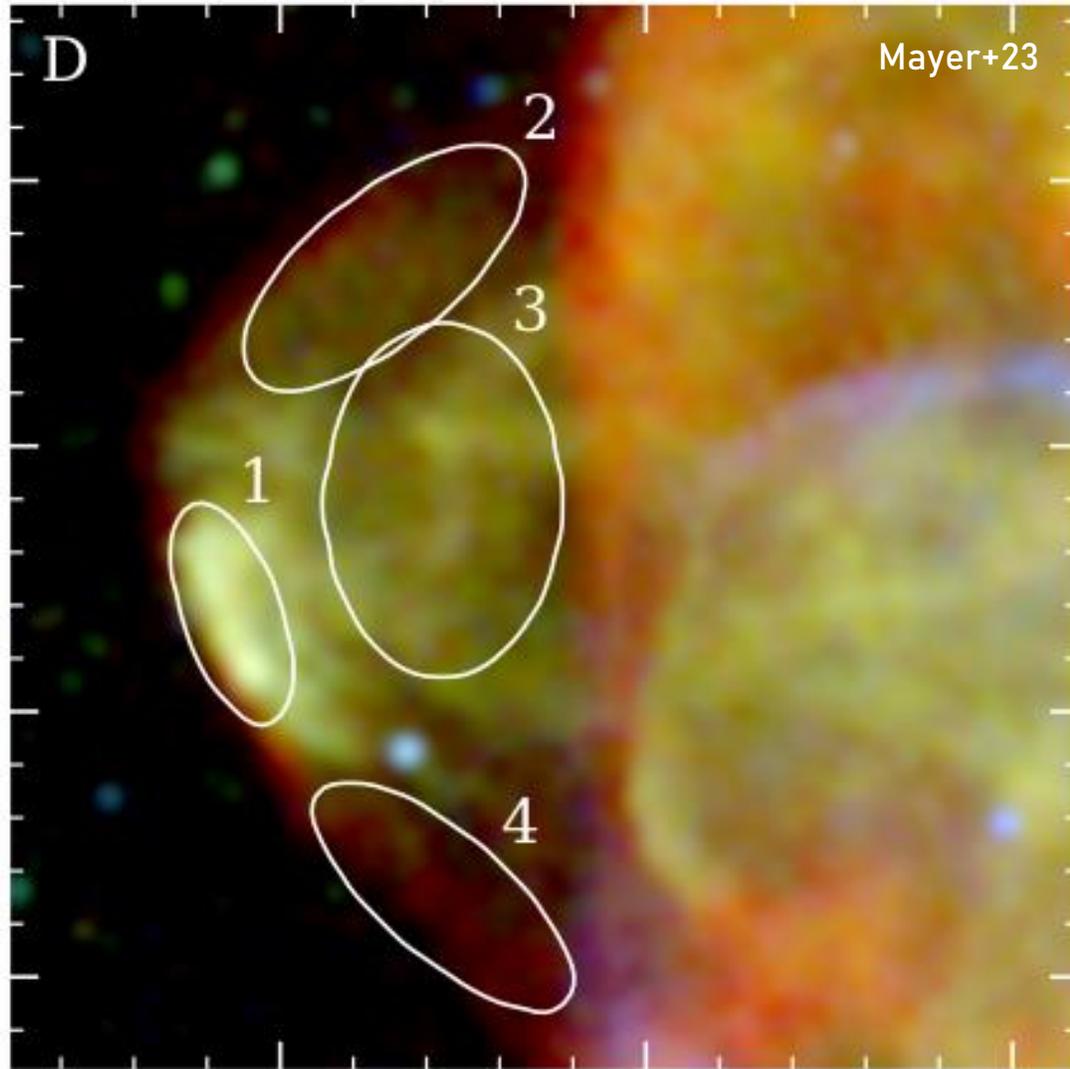
Vela SNR – Intervening ISM



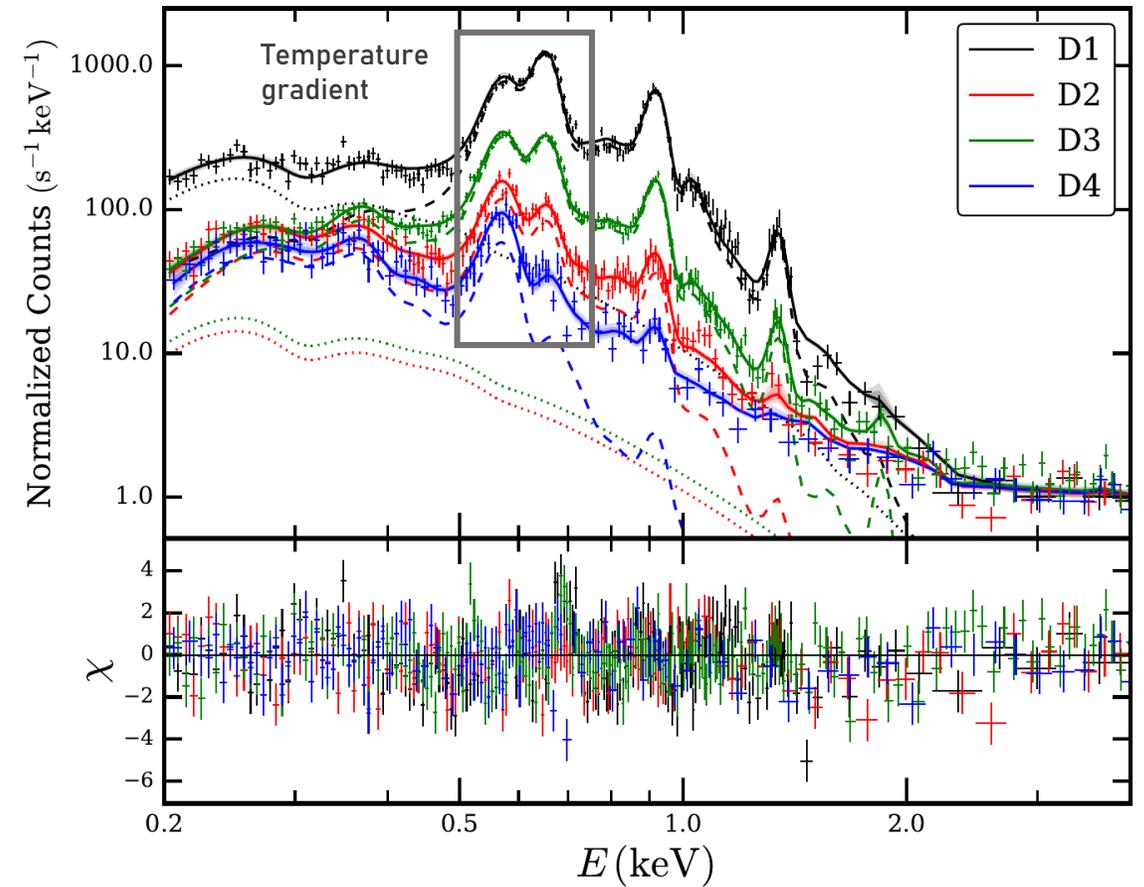
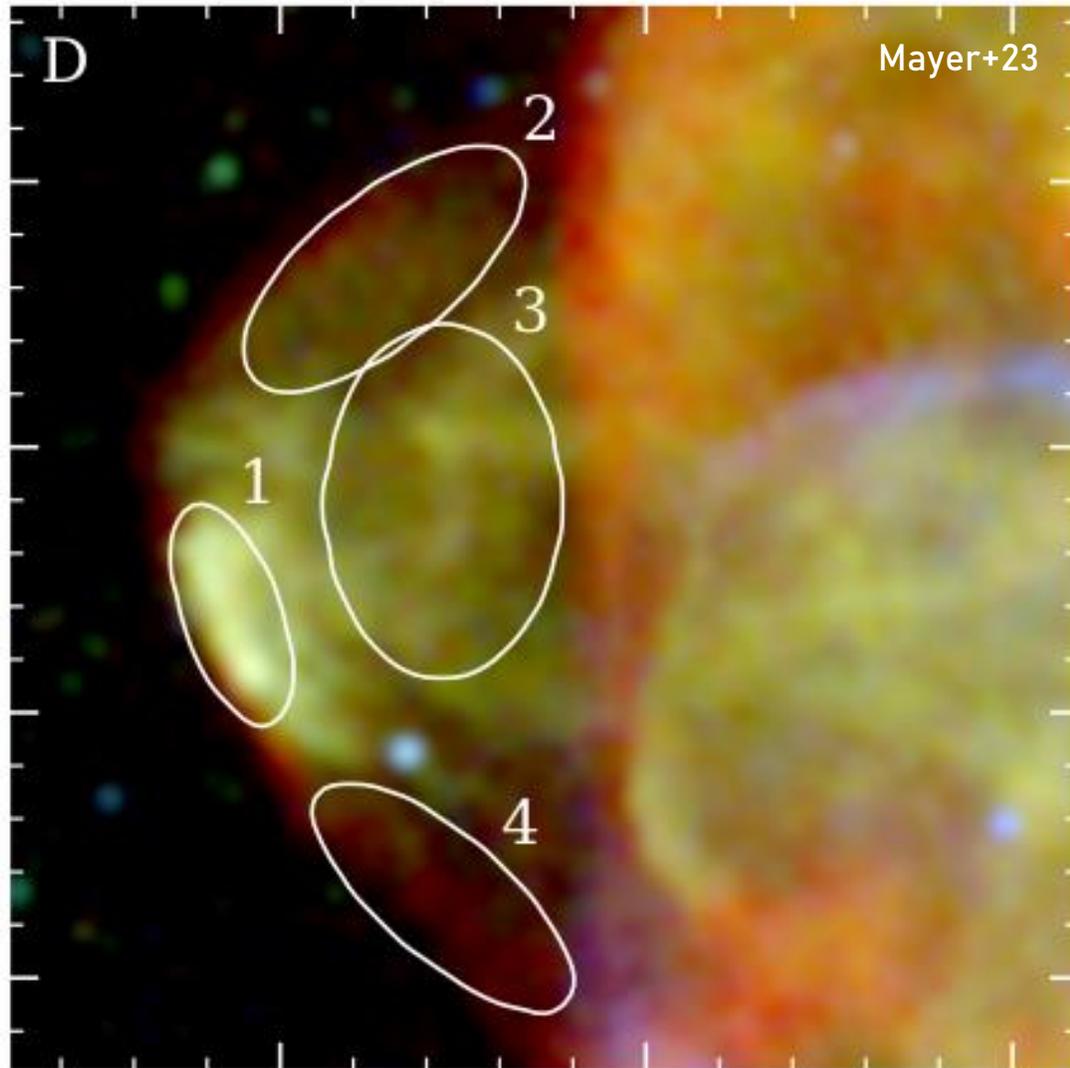
Vela SNR – Ejecta in Shrapnel



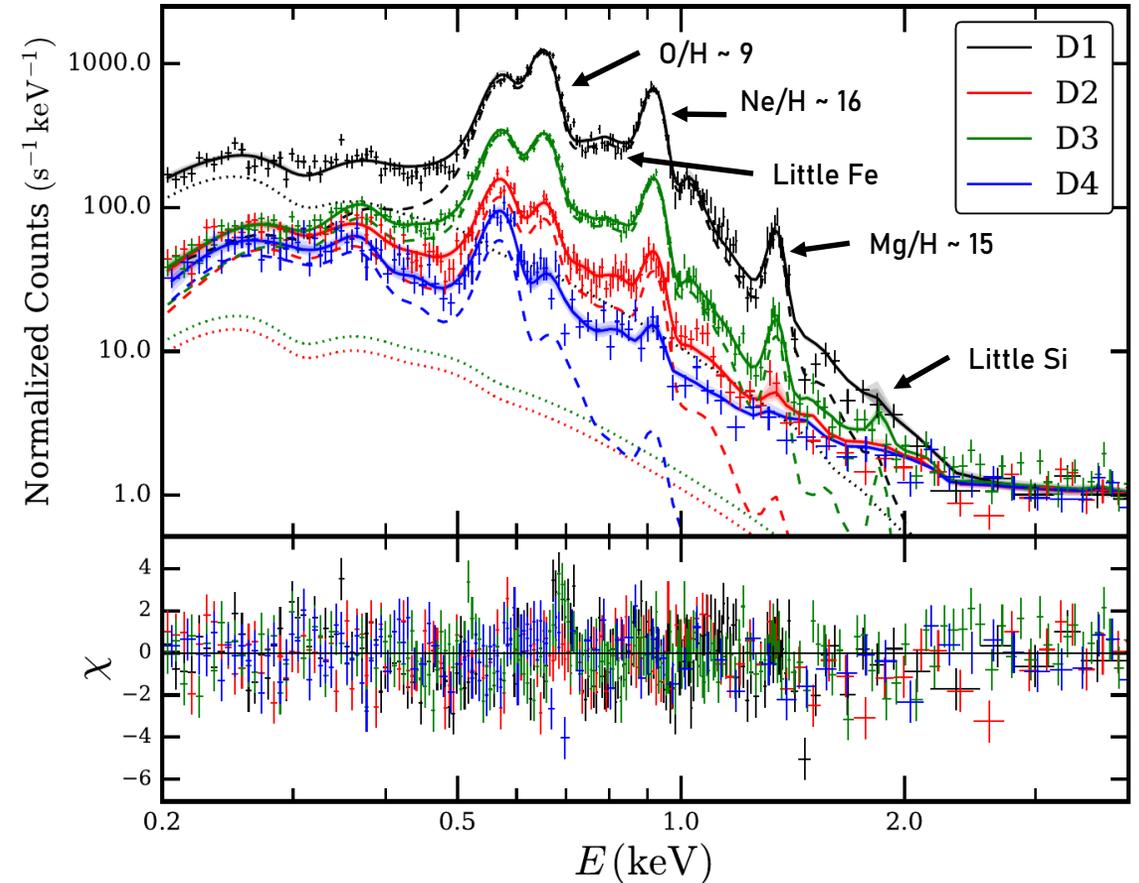
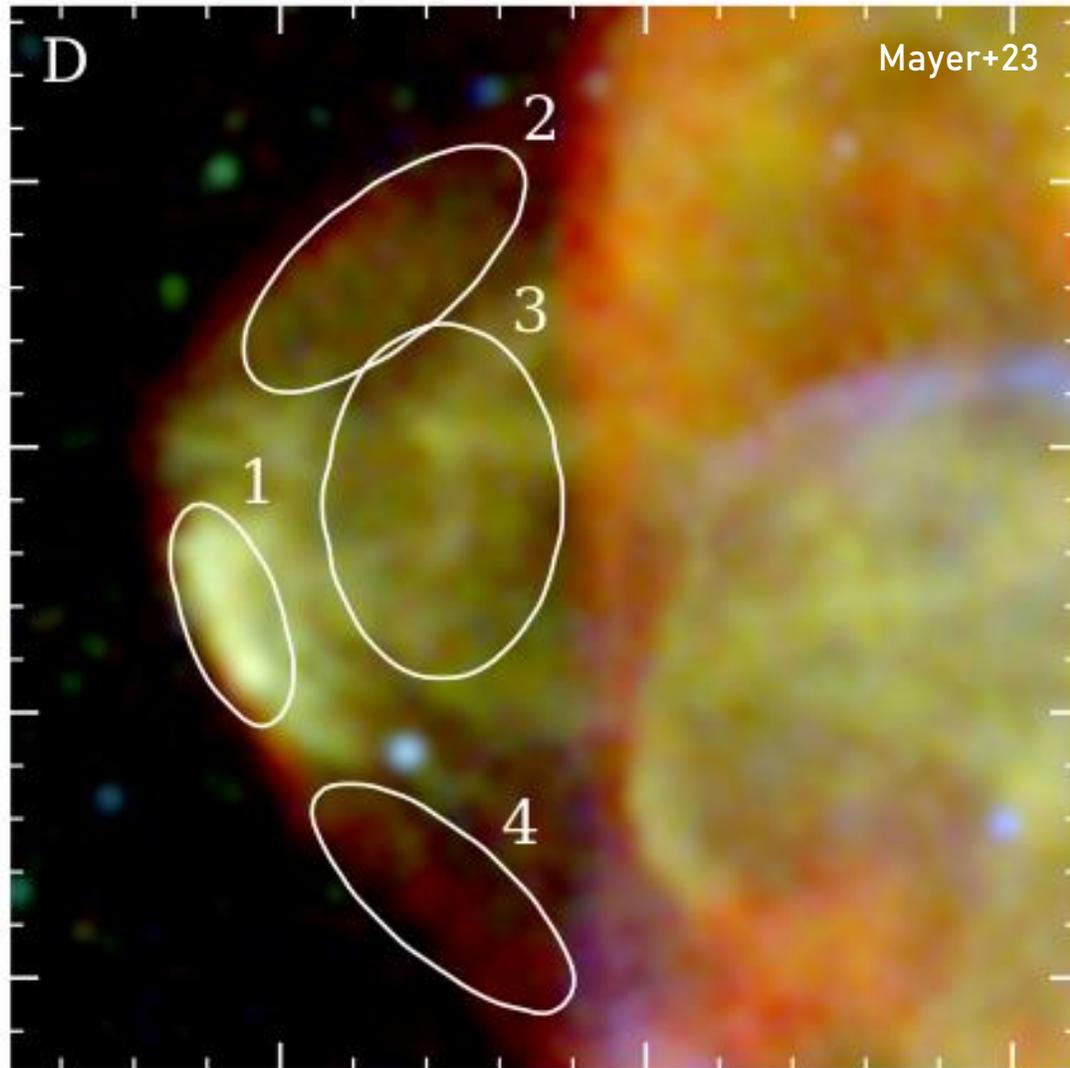
Vela SNR – Ejecta in Shrapnel



Vela SNR – Ejecta in Shrapnel

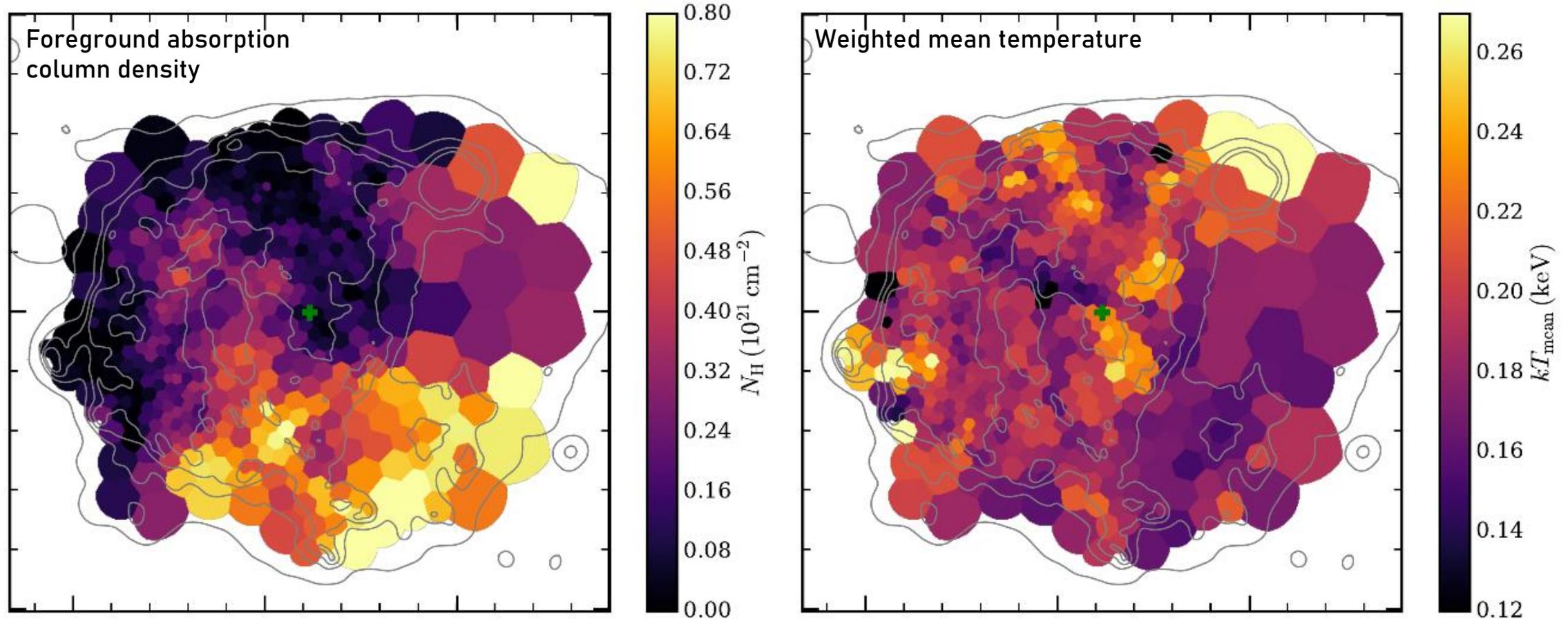


Vela SNR – Ejecta in Shrapnel

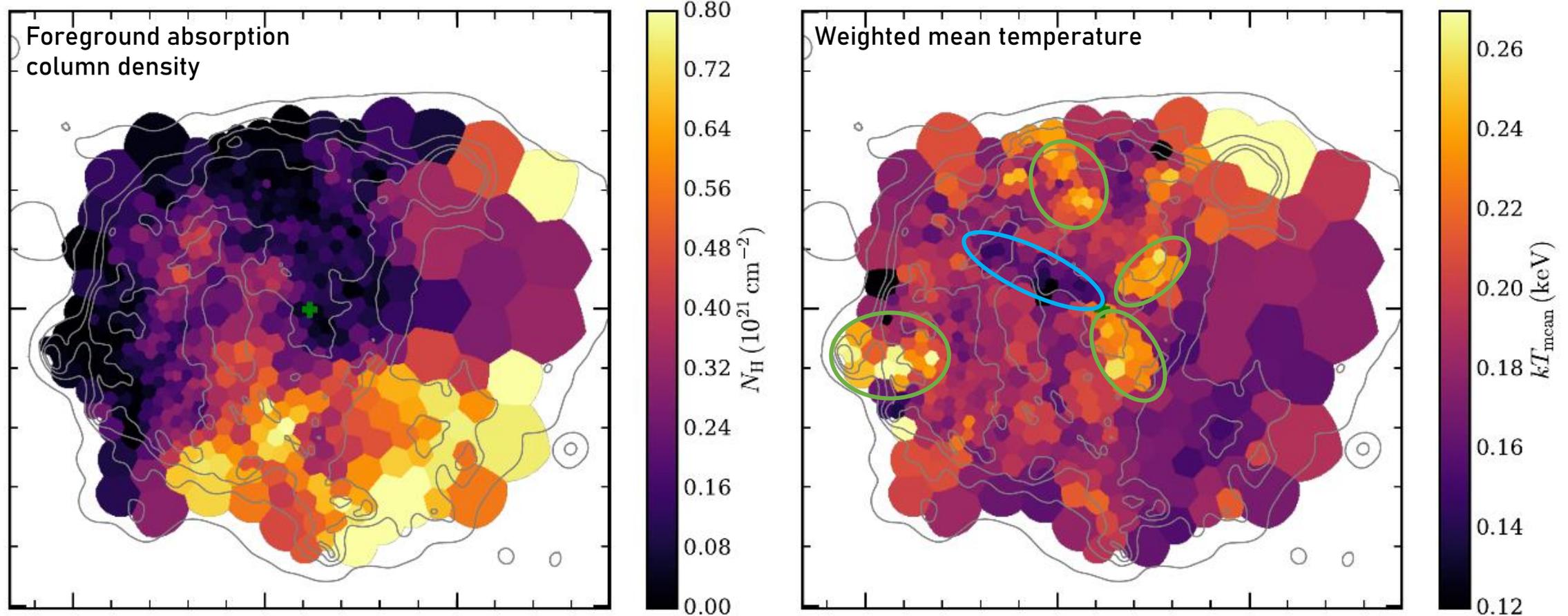


➤ Hot & pure light-element ejecta at the apex;
cooler shocked ISM along the sides

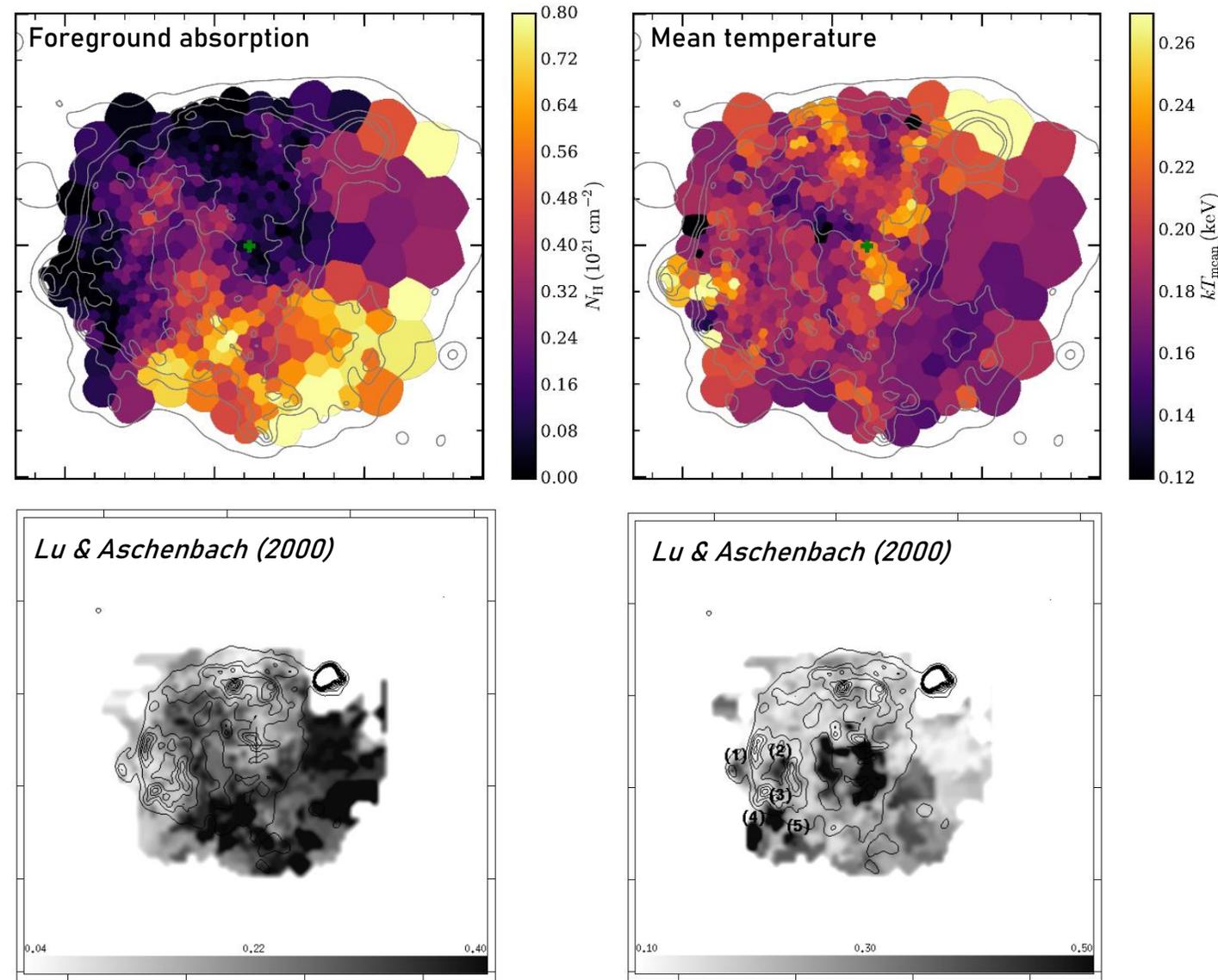
Results: Absorption & Plasma Temperature



Results: Absorption & Plasma Temperature



Comparison with ROSAT (Lu & Aschenbach, 2000)



Results: Ejecta

Results: Ejecta

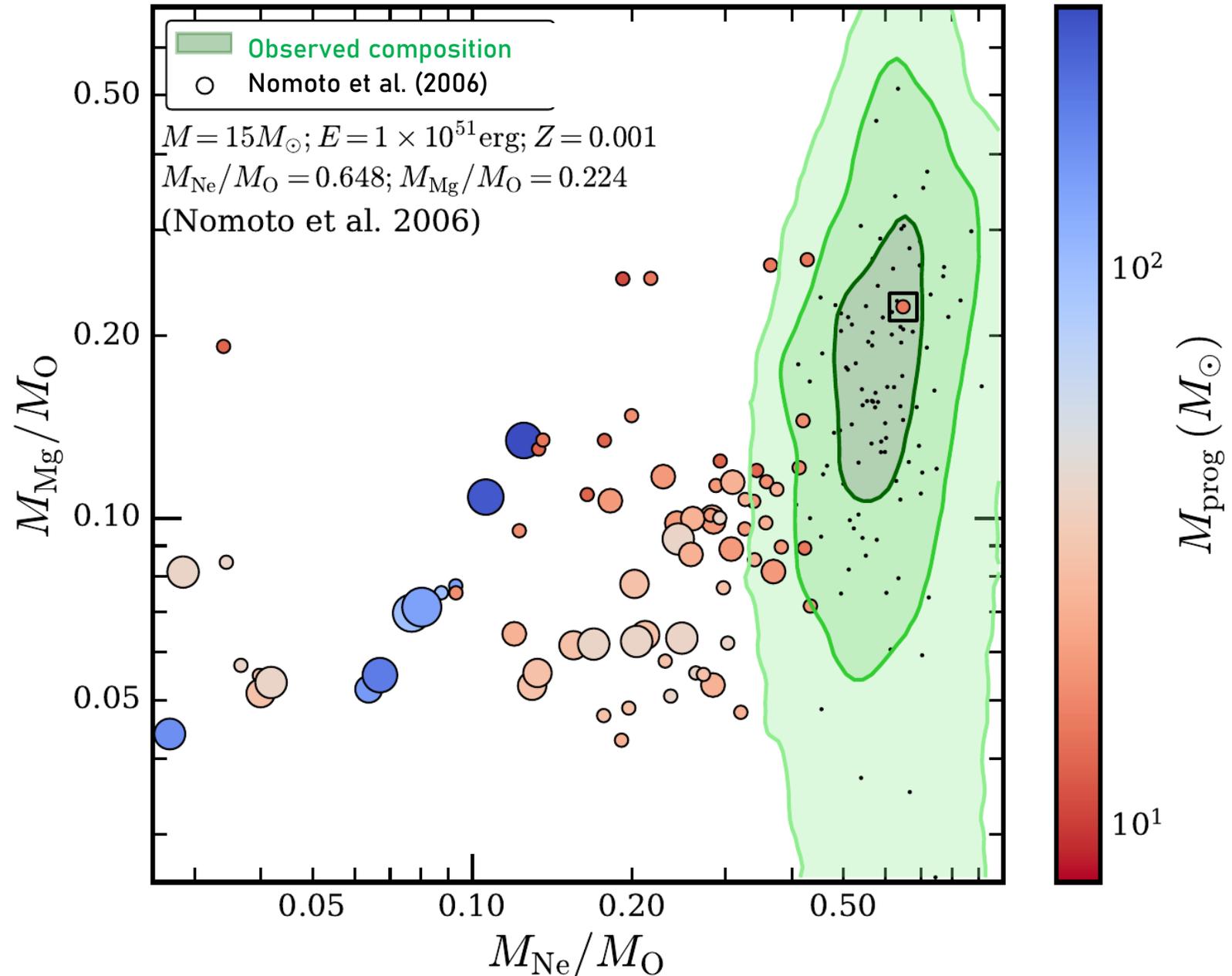
- Correlated abundance peaks of oxygen, neon, magnesium

Results: Ejecta

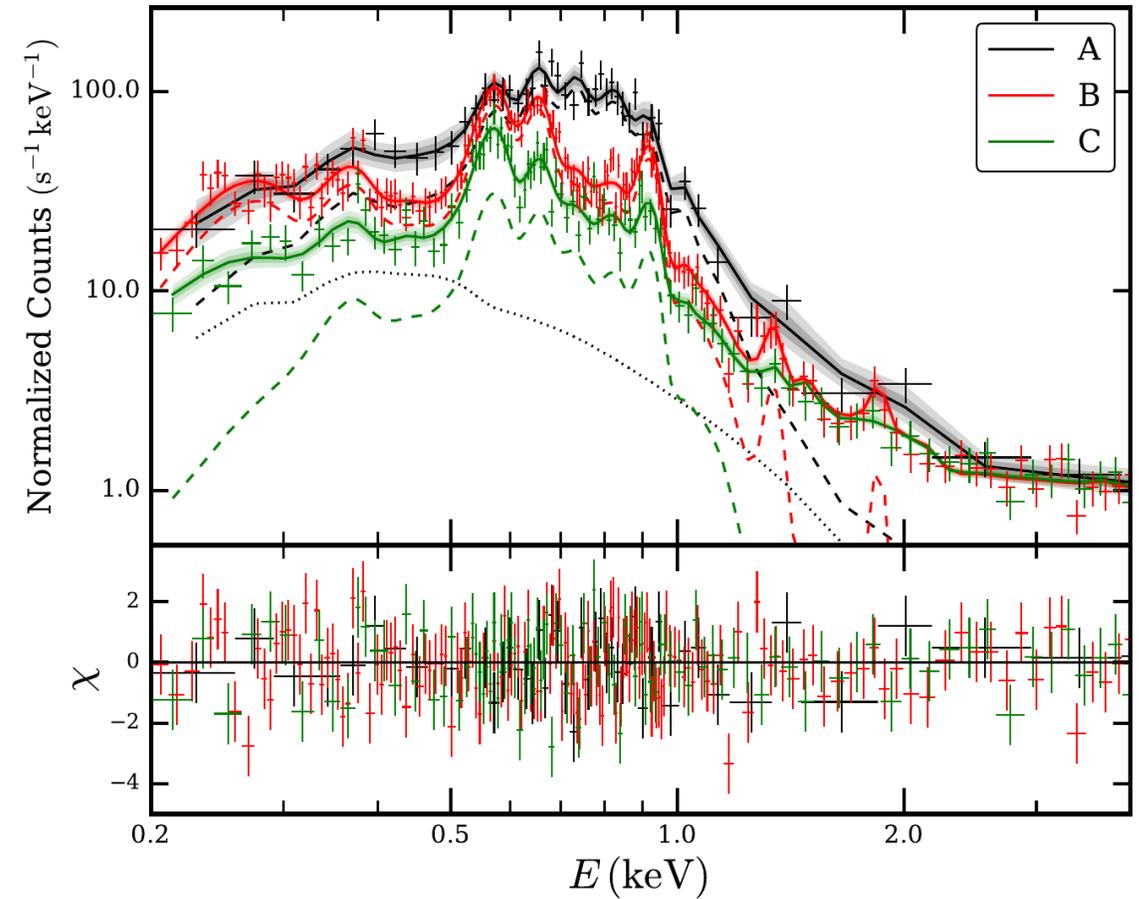
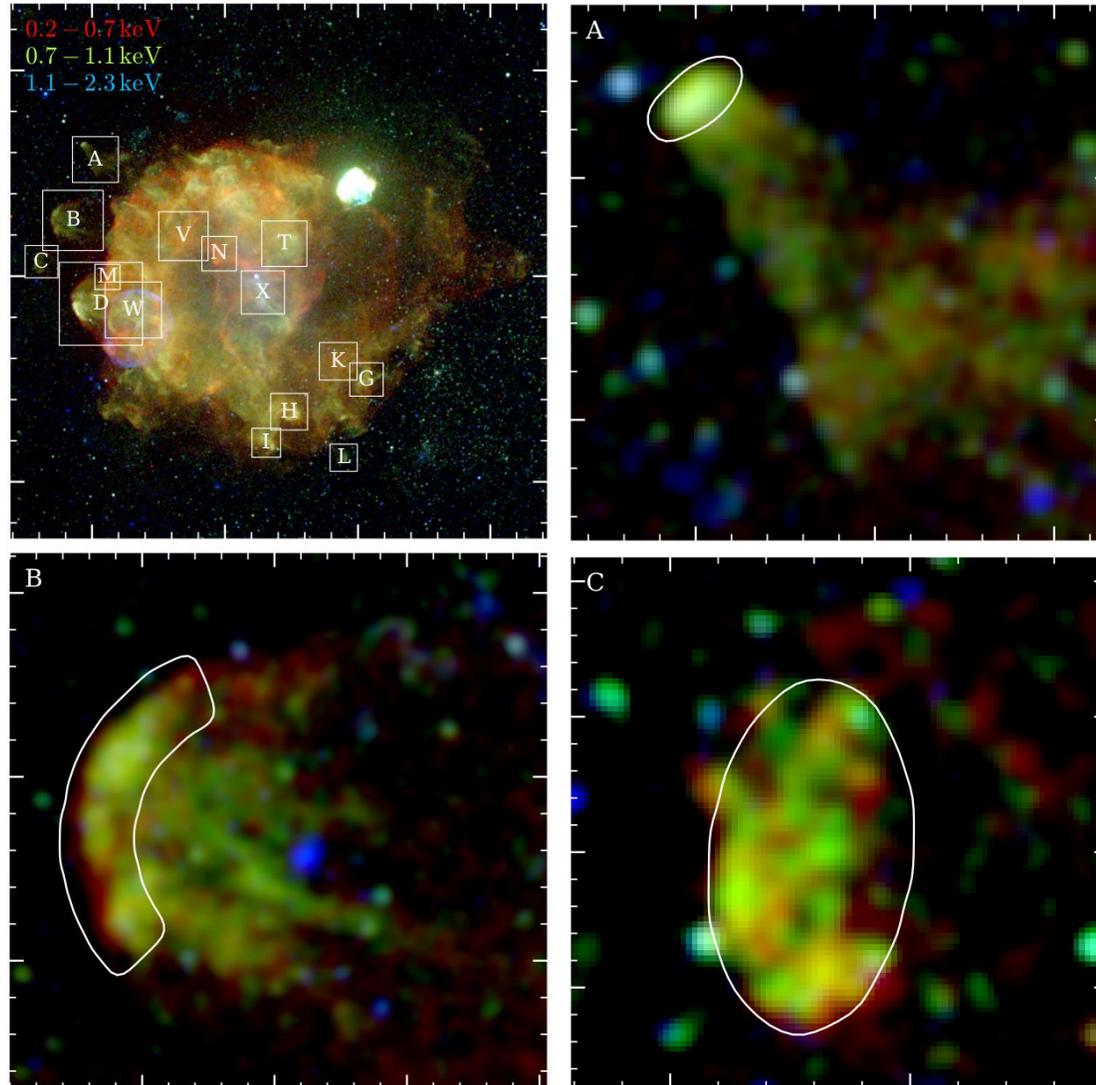
- Correlated abundance peaks of oxygen, neon, magnesium
 - Iron distribution independent from lighter elements

Results: Ejecta

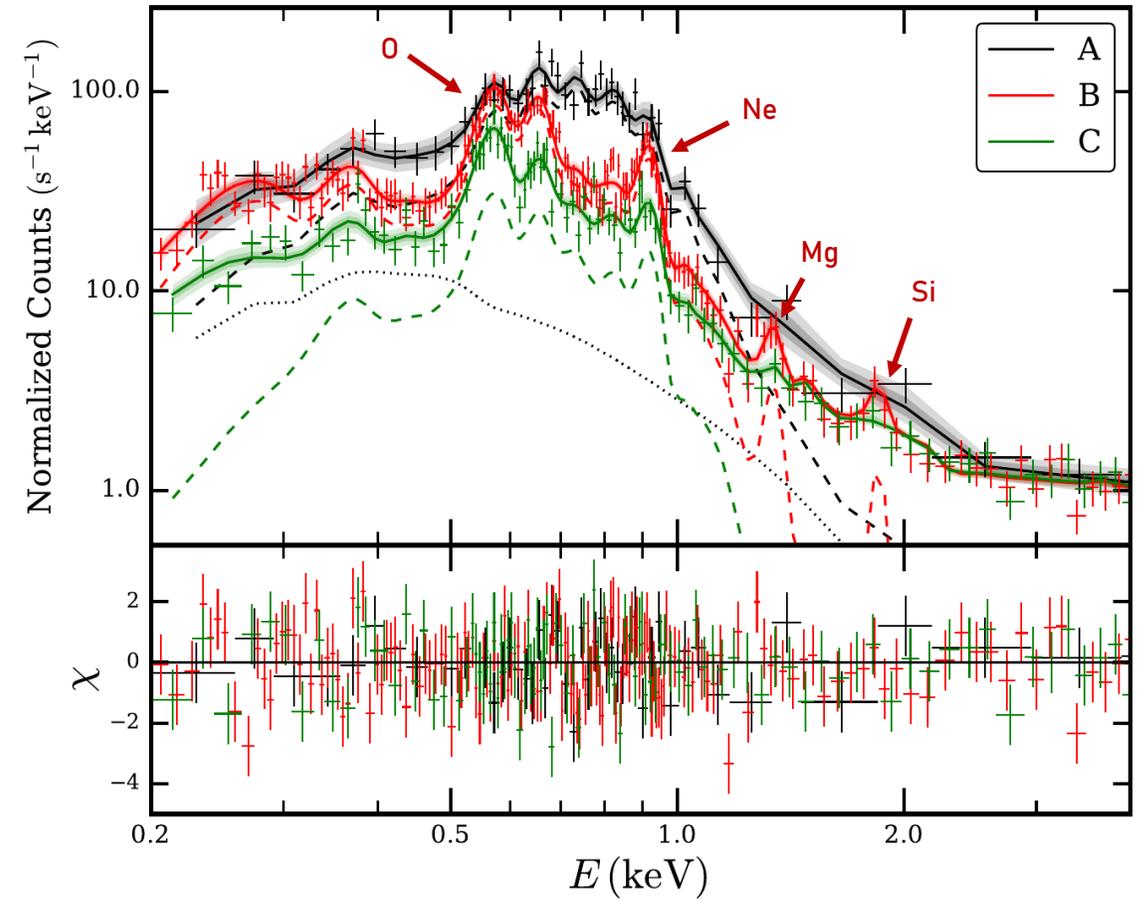
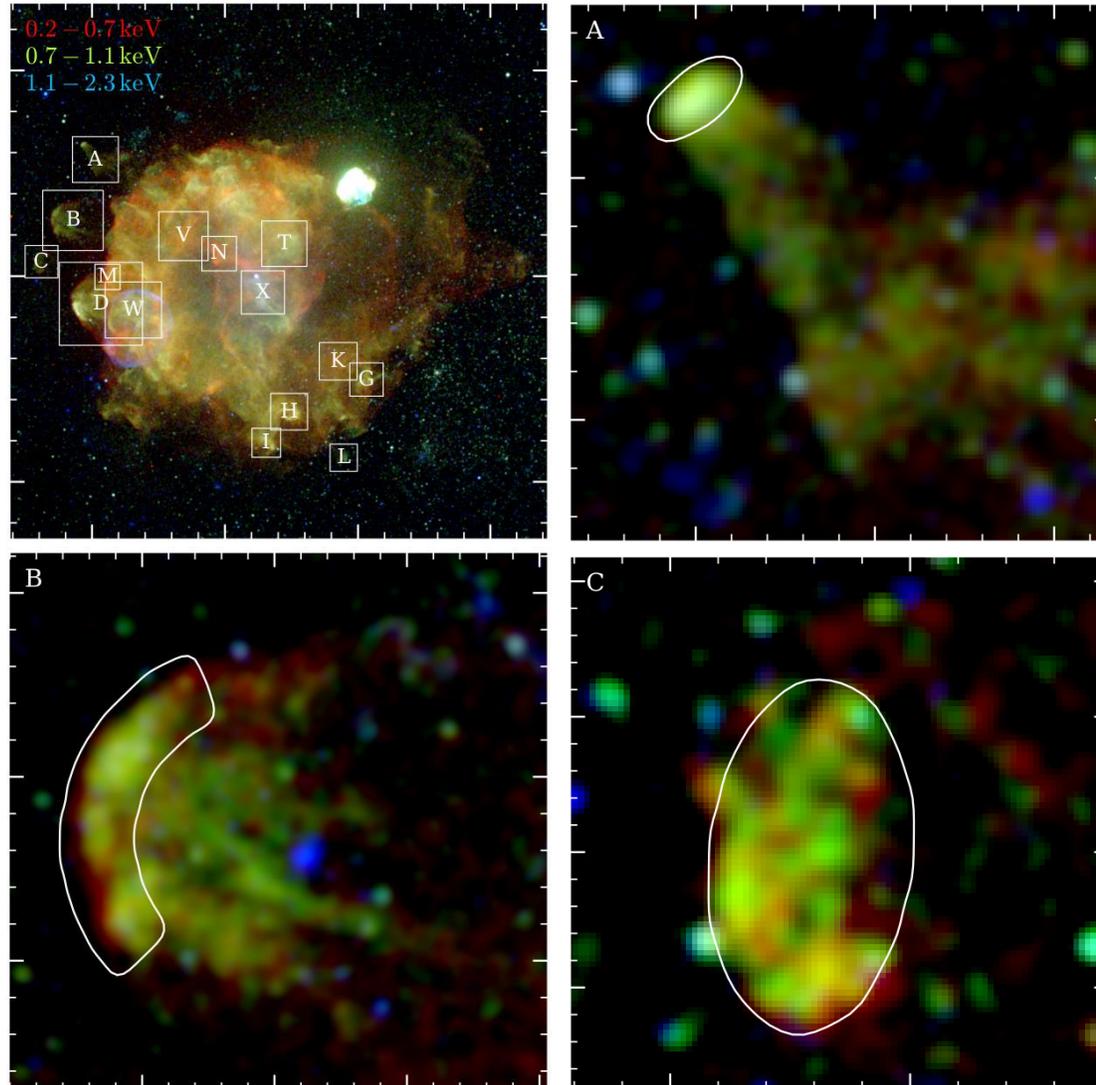
- Correlated abundance peaks of oxygen, neon, magnesium
 - Iron distribution independent from lighter elements
 - General pattern: Ne/O, Mg/O supersolar
 - Reproducible in low-metallicity model? (Nomoto+06)



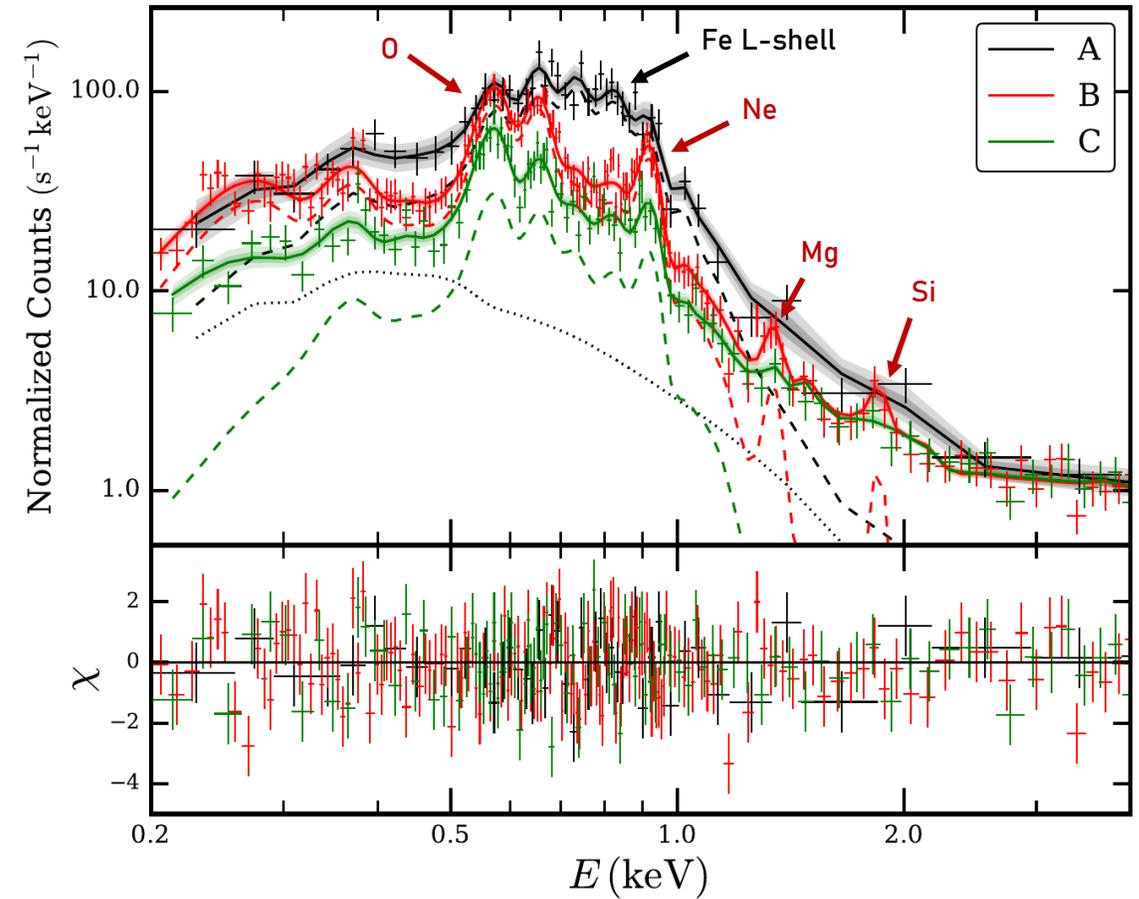
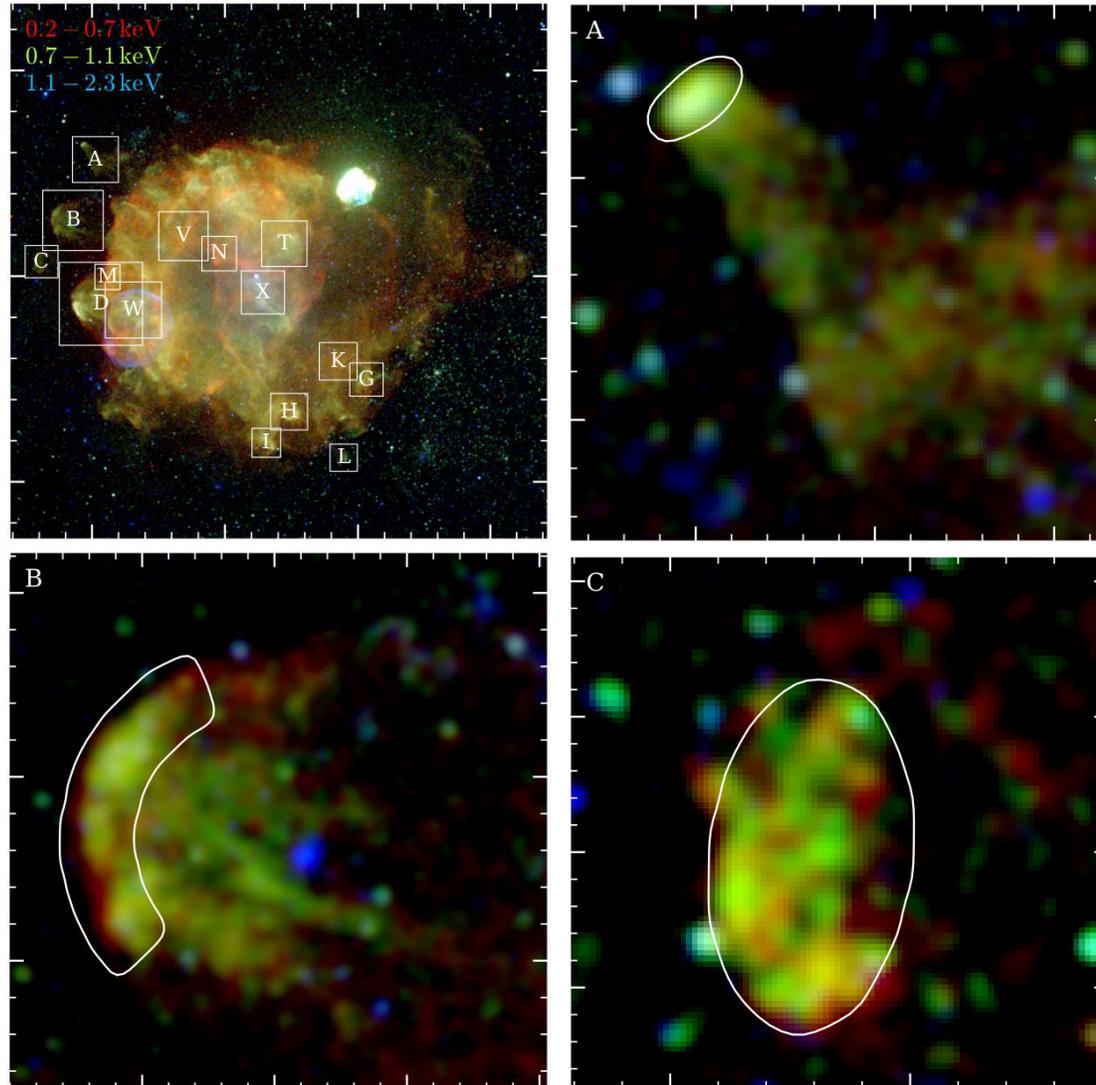
Results: Shrapnel A, B, C



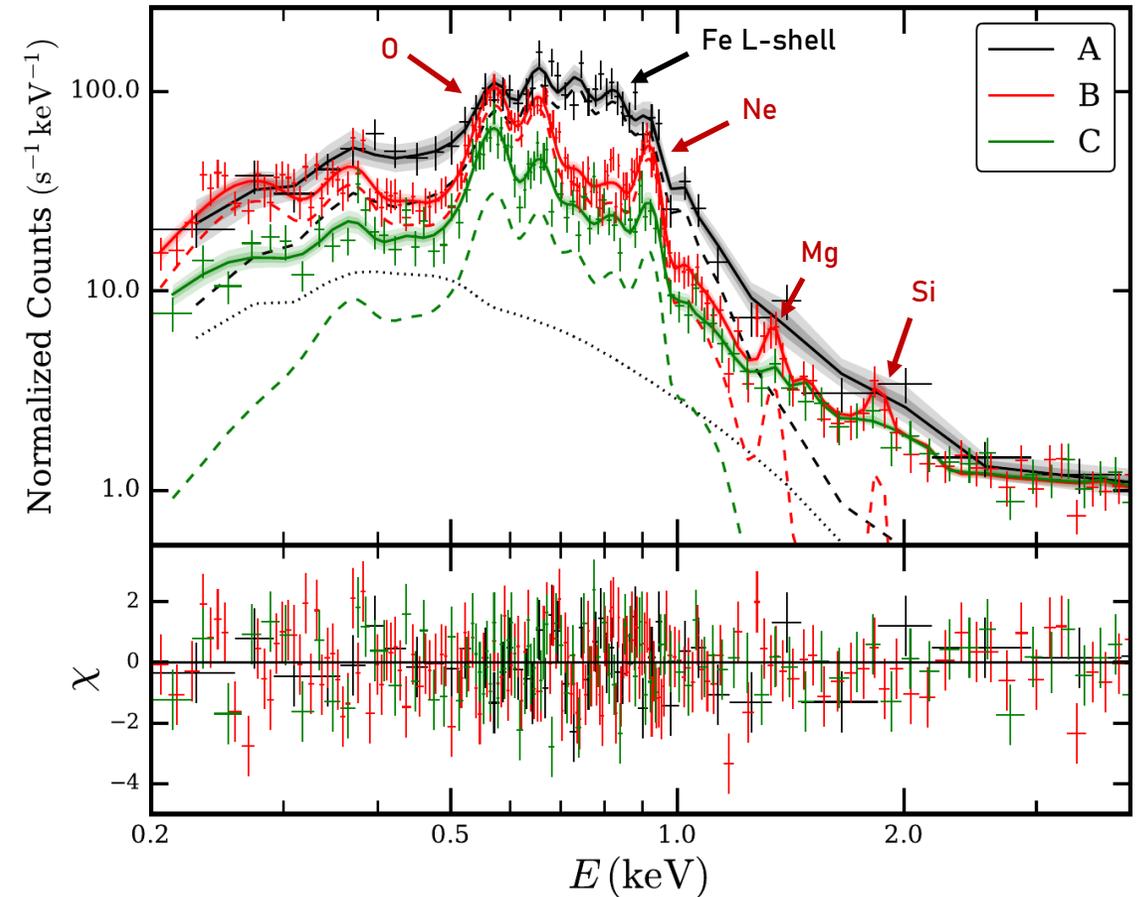
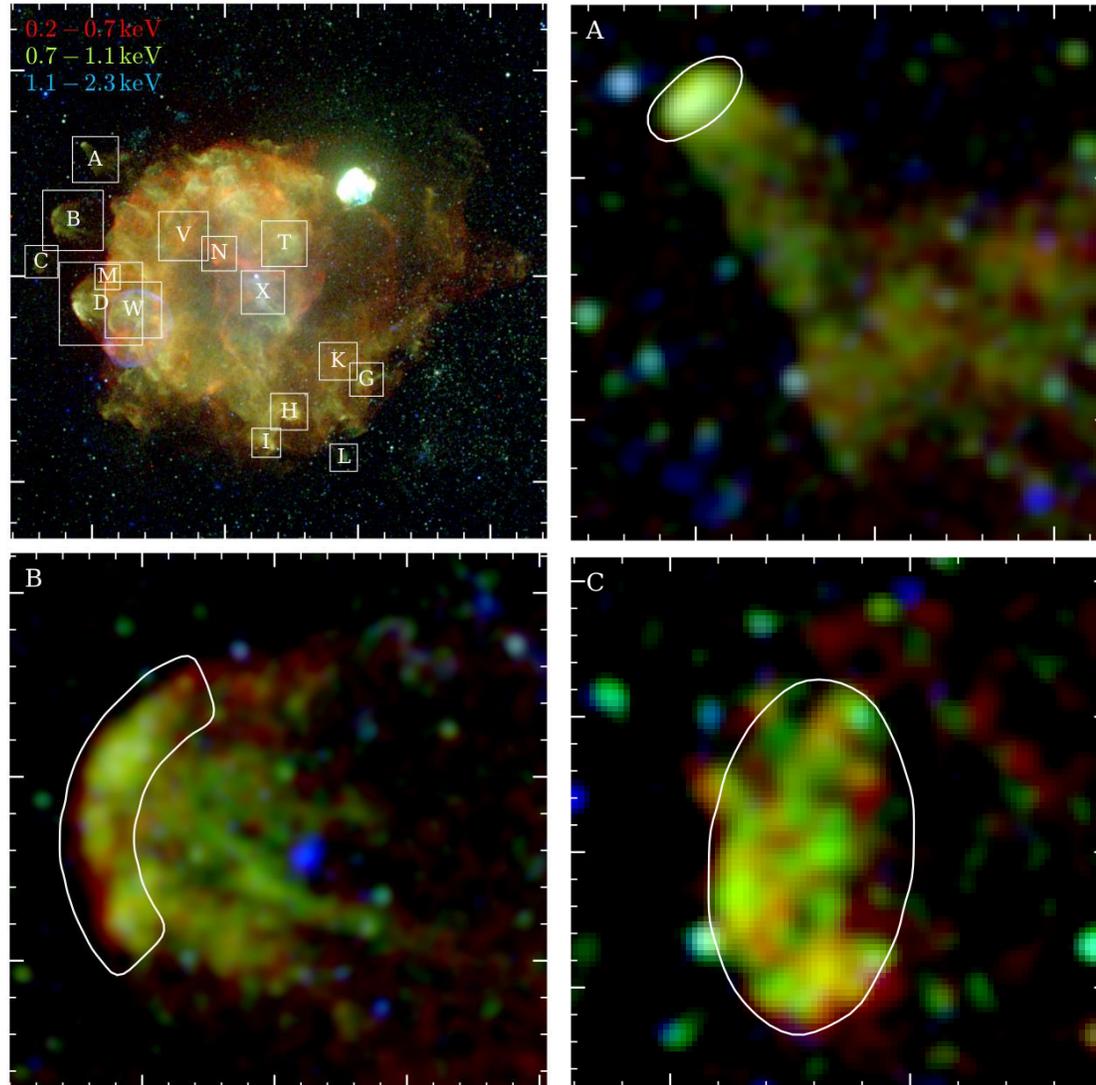
Results: Shrapnel A, B, C



Results: Shrapnels A, B, C

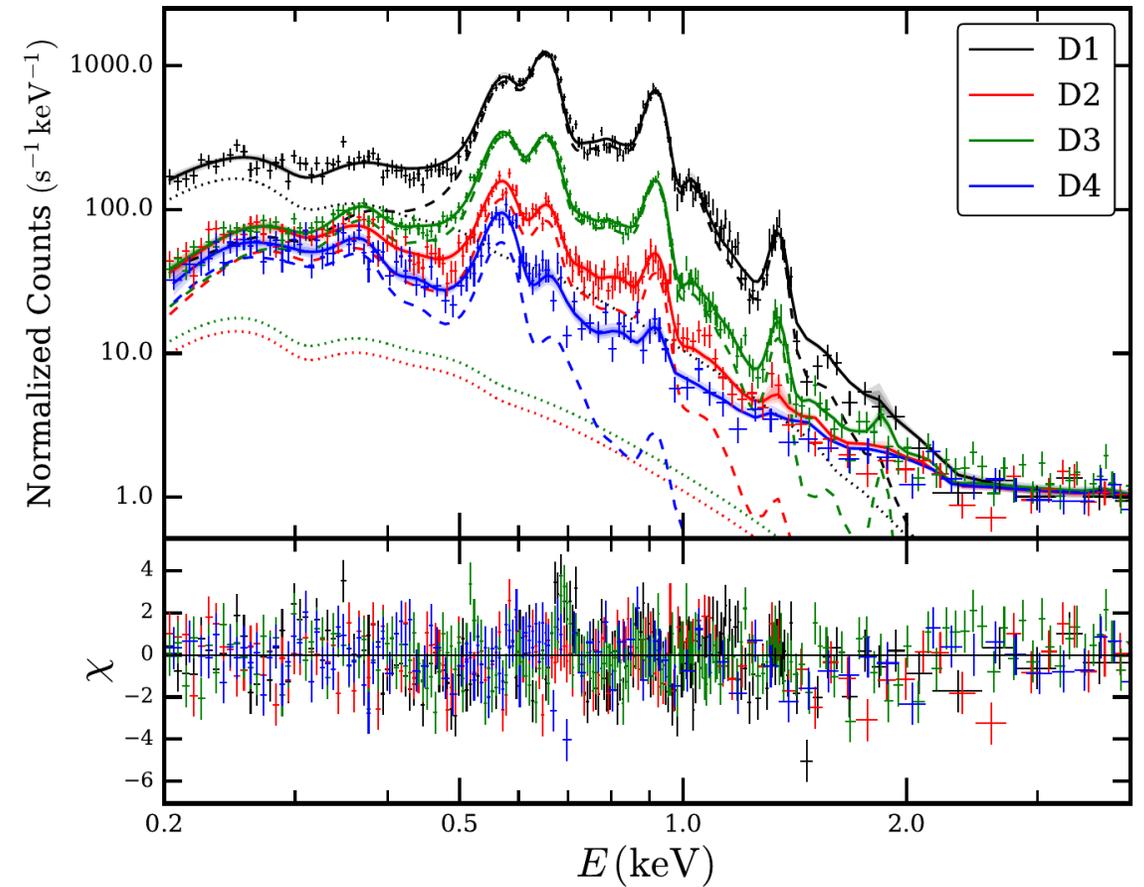
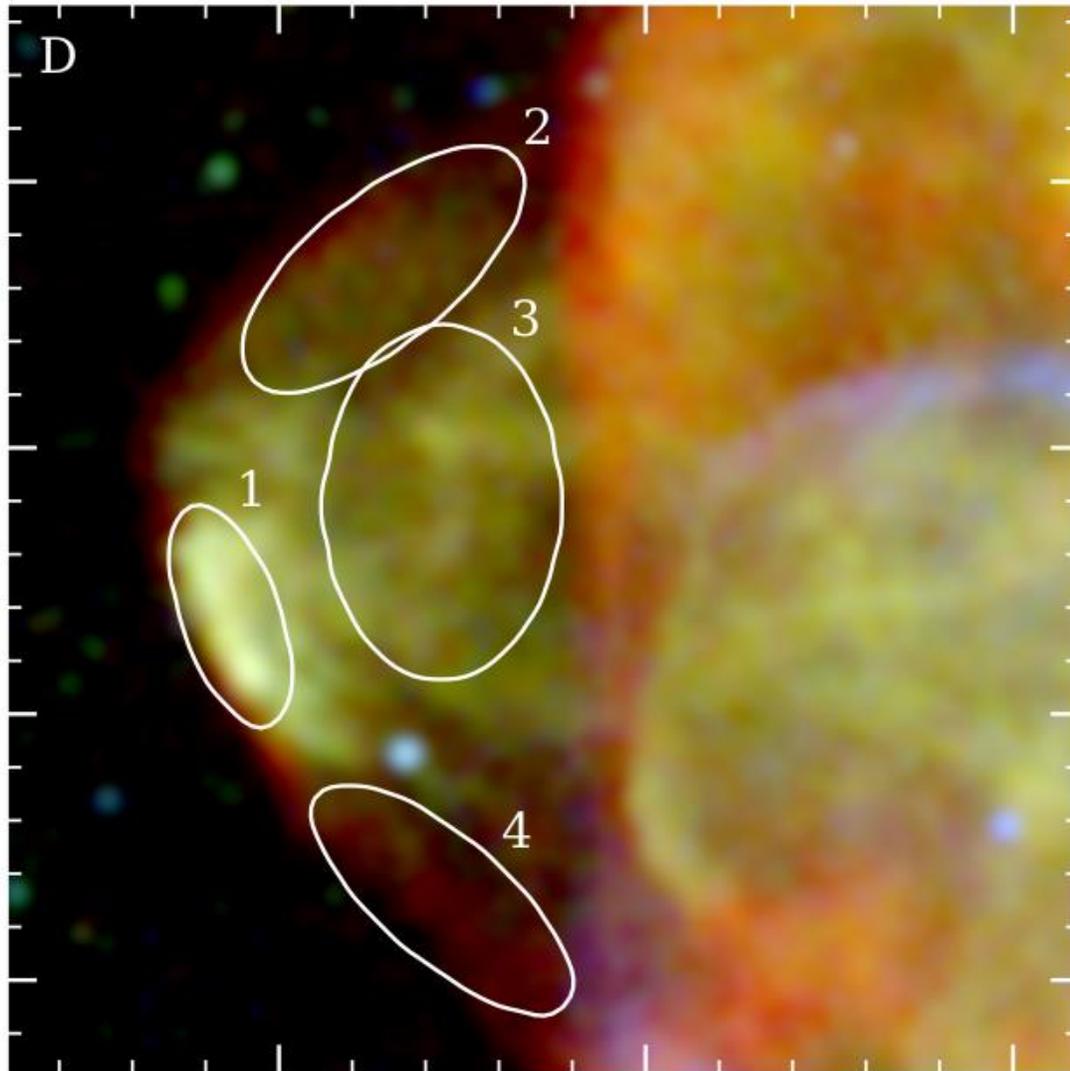


Results: Shrapnels A, B, C

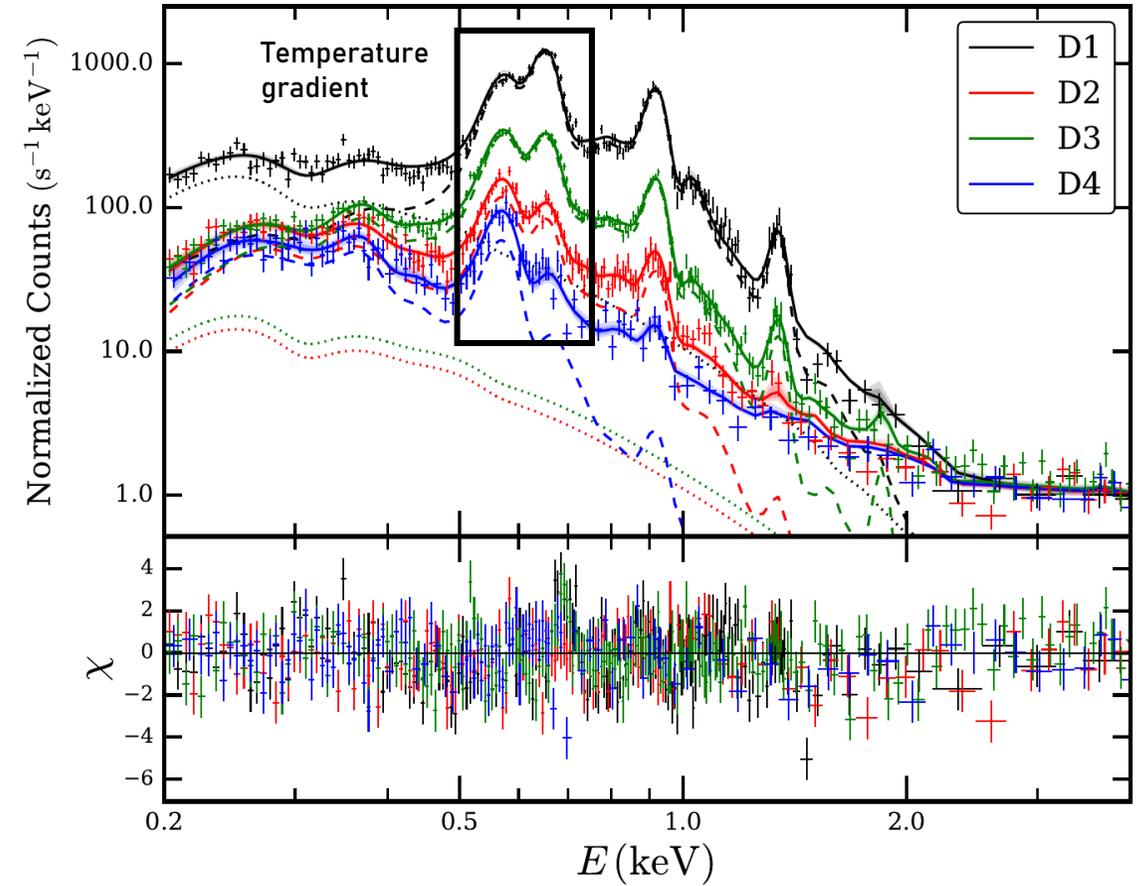
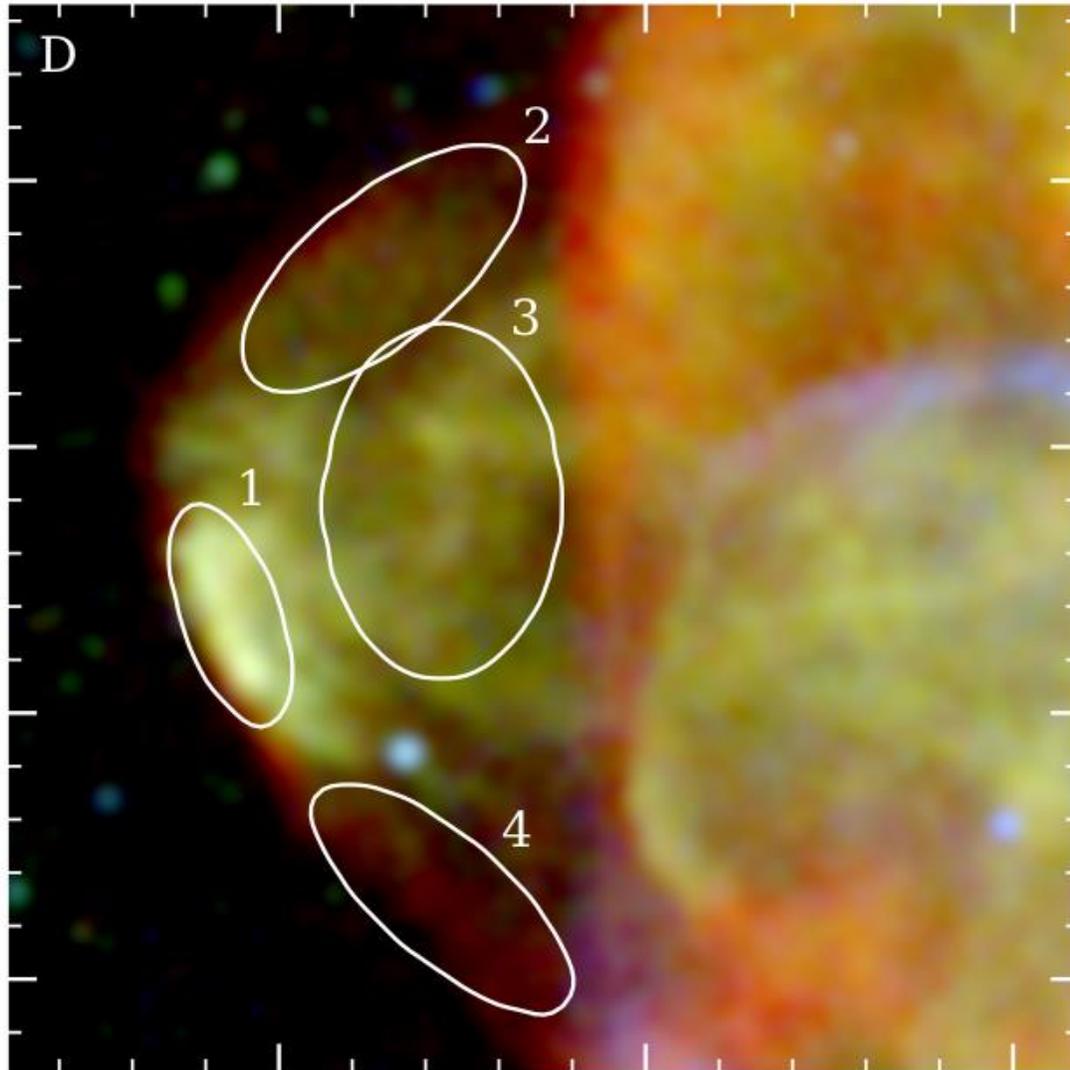


➤ Iron ejecta present in silicon-rich (*Katsuda+06*), fast shrapnel A?

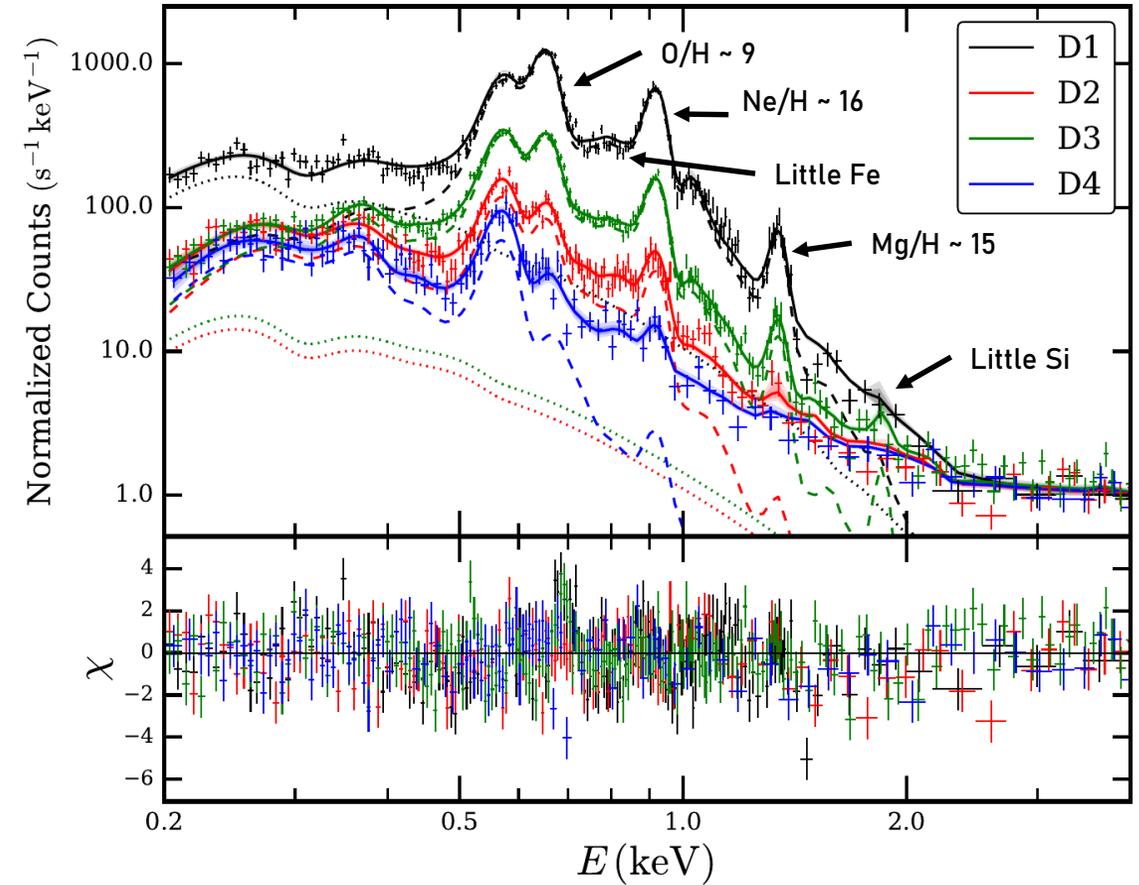
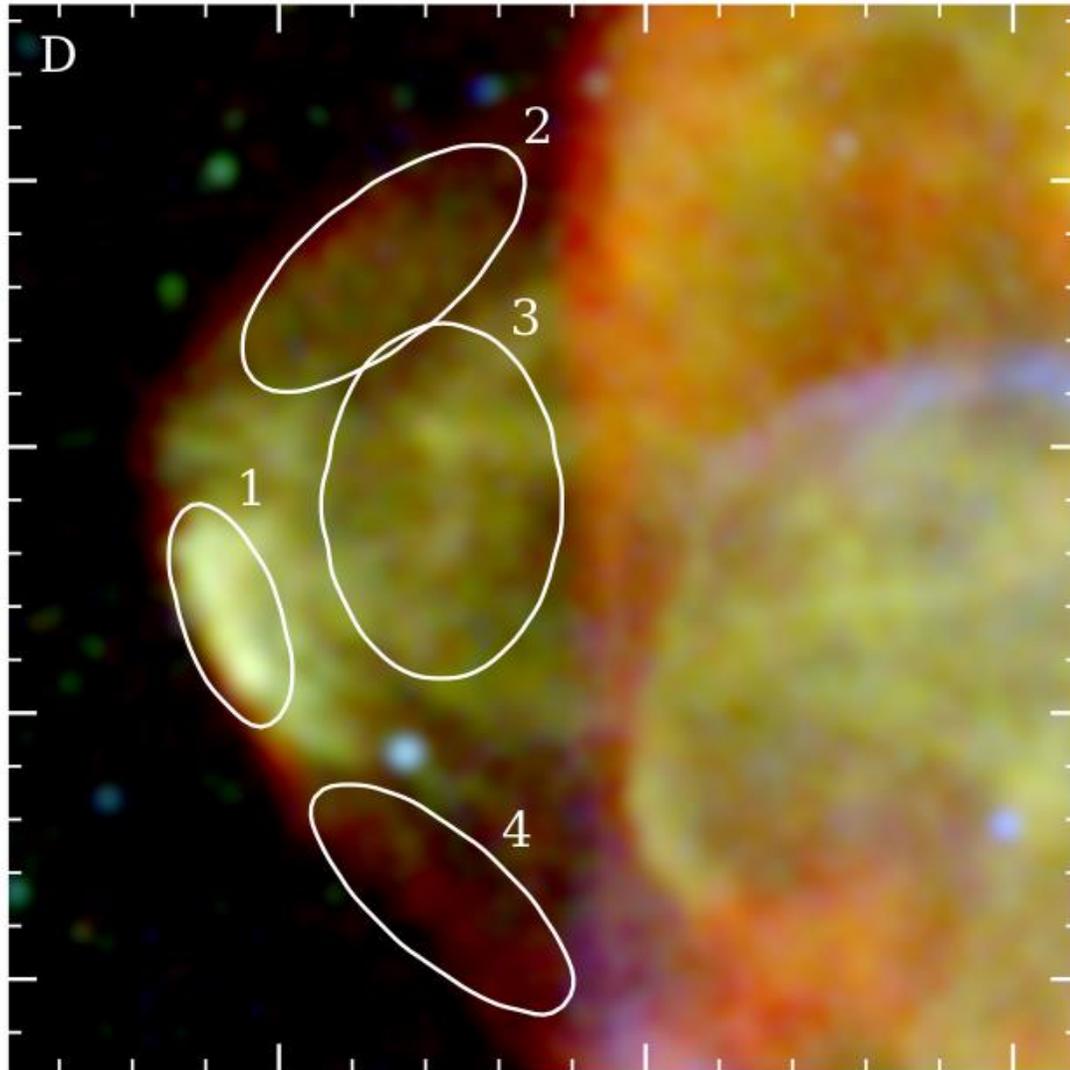
Results: Ejecta in Shrapnel D



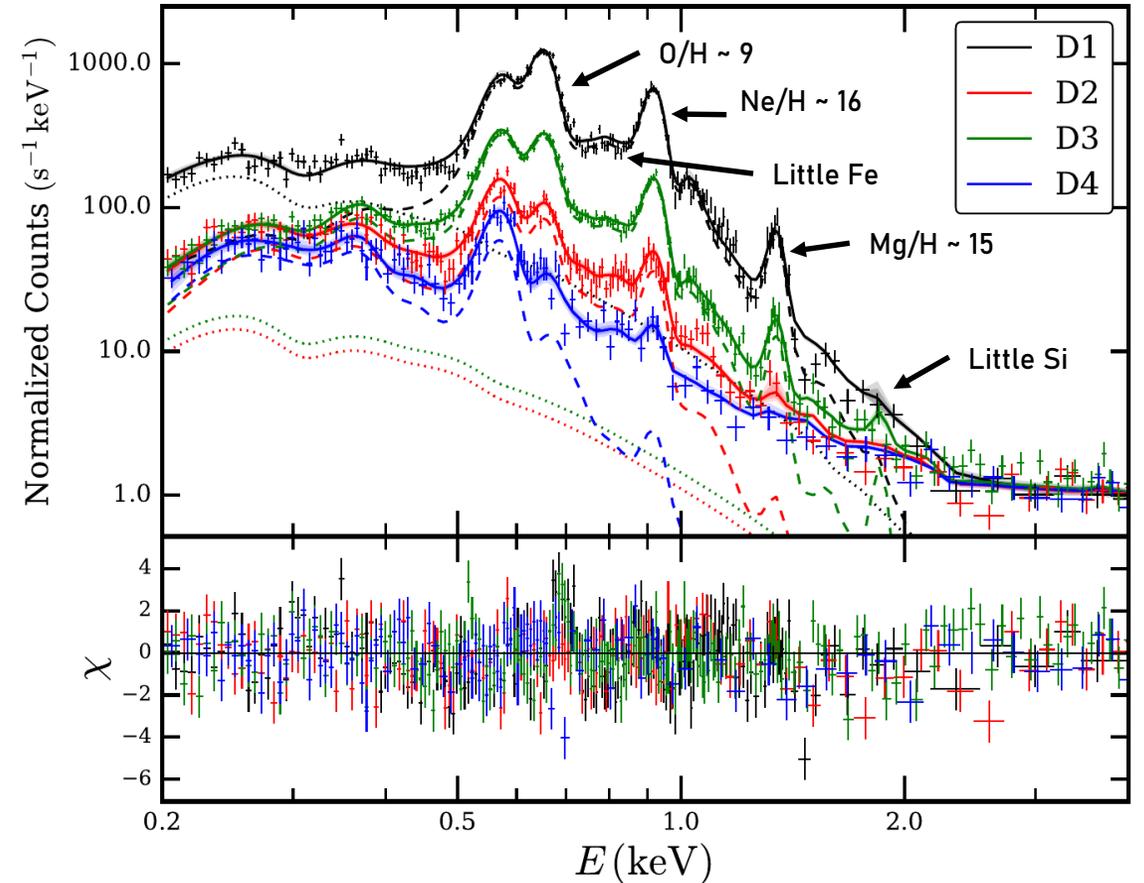
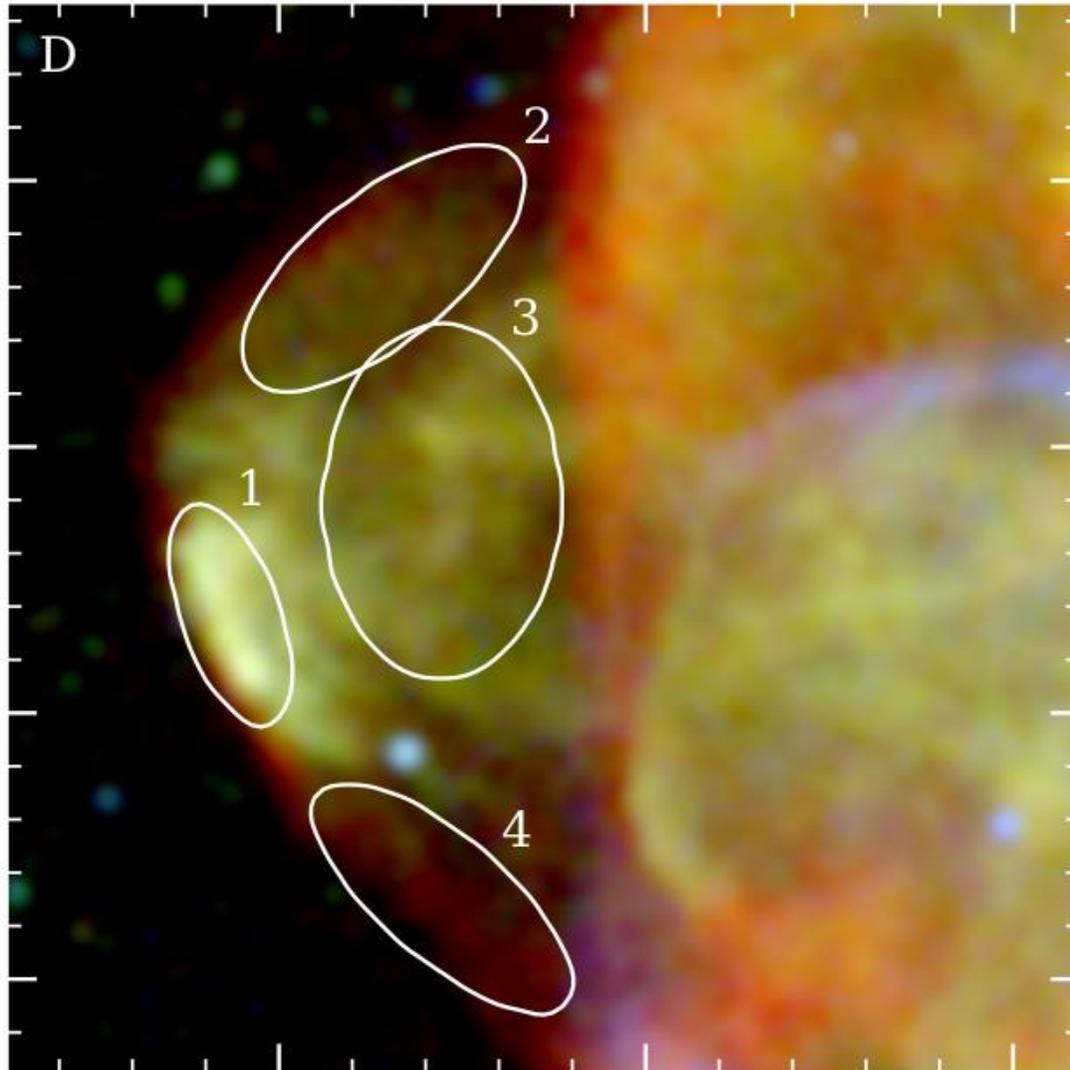
Results: Ejecta in Shrapnel D



Results: Ejecta in Shrapnel D

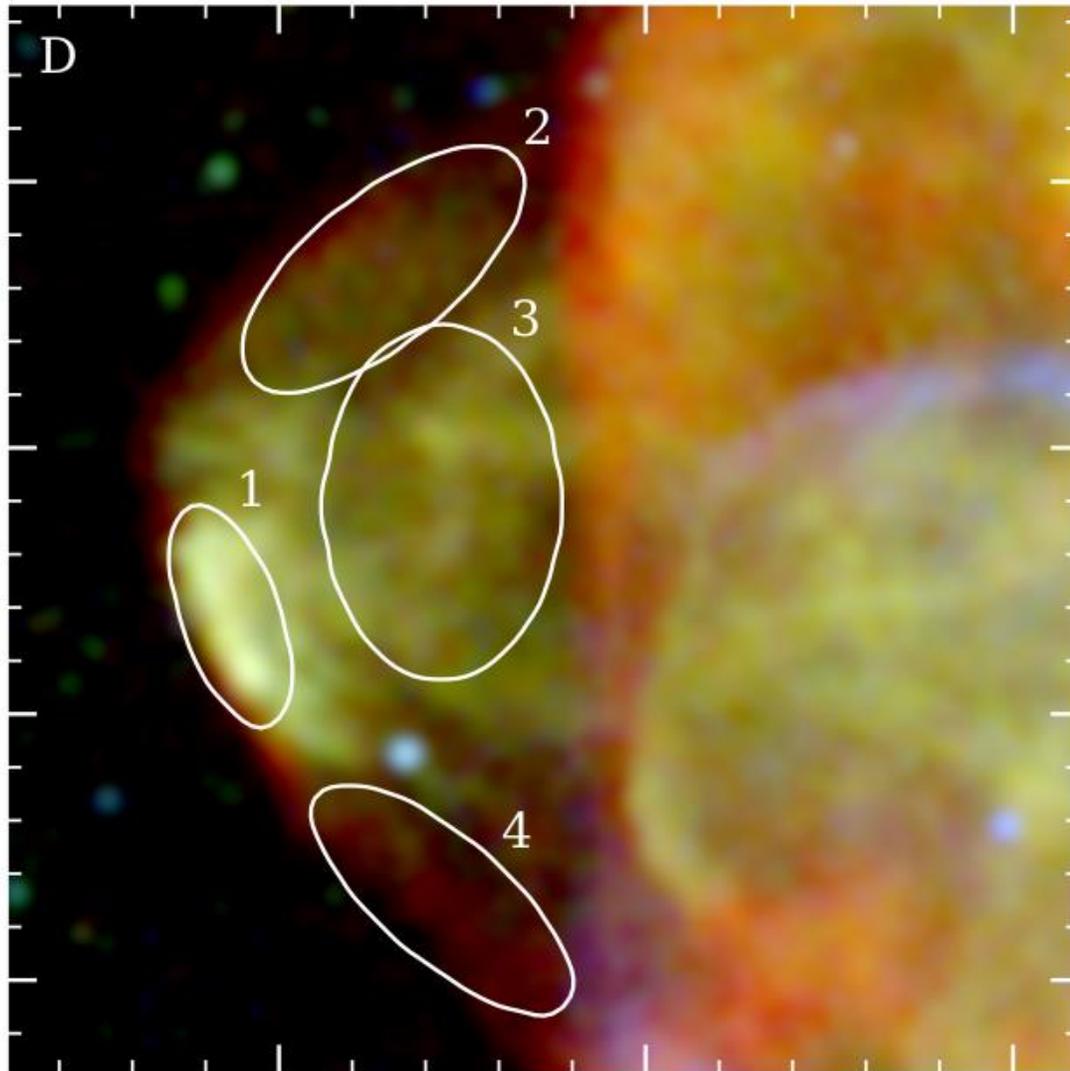


Results: Ejecta in Shrapnel D

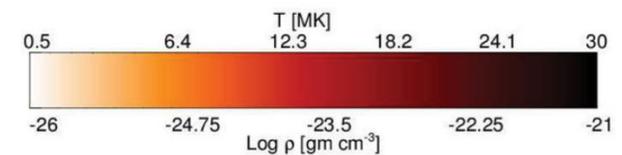
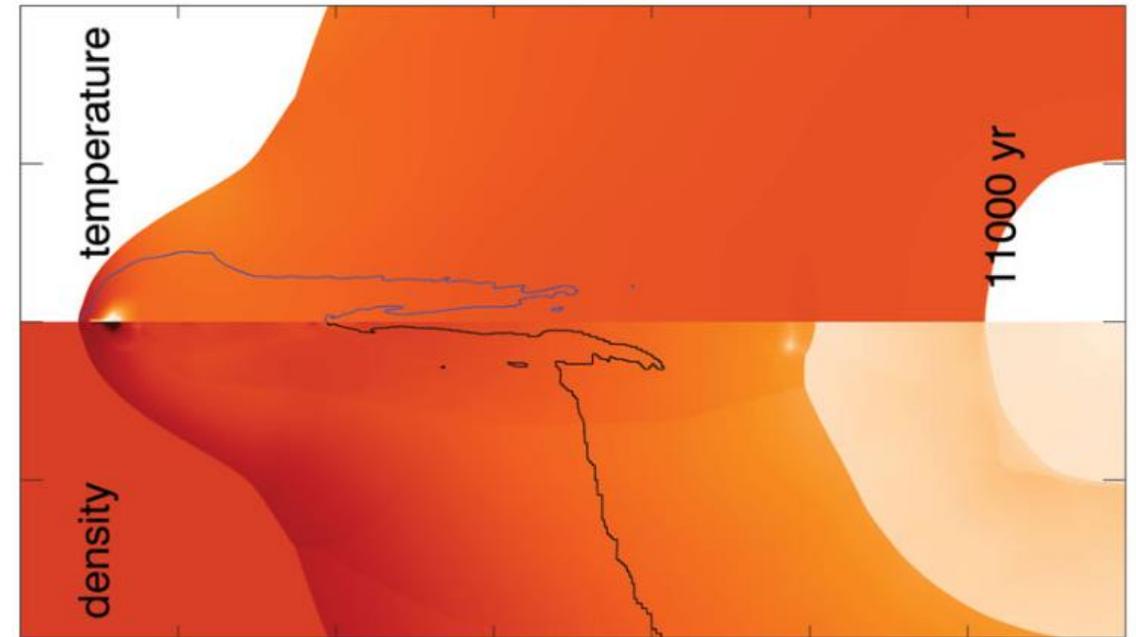


➤ Hot light-element ejecta at the apex; cooler shocked ISM along the sides

Shrapnel D: Simulations (Miceli et al. 2013)

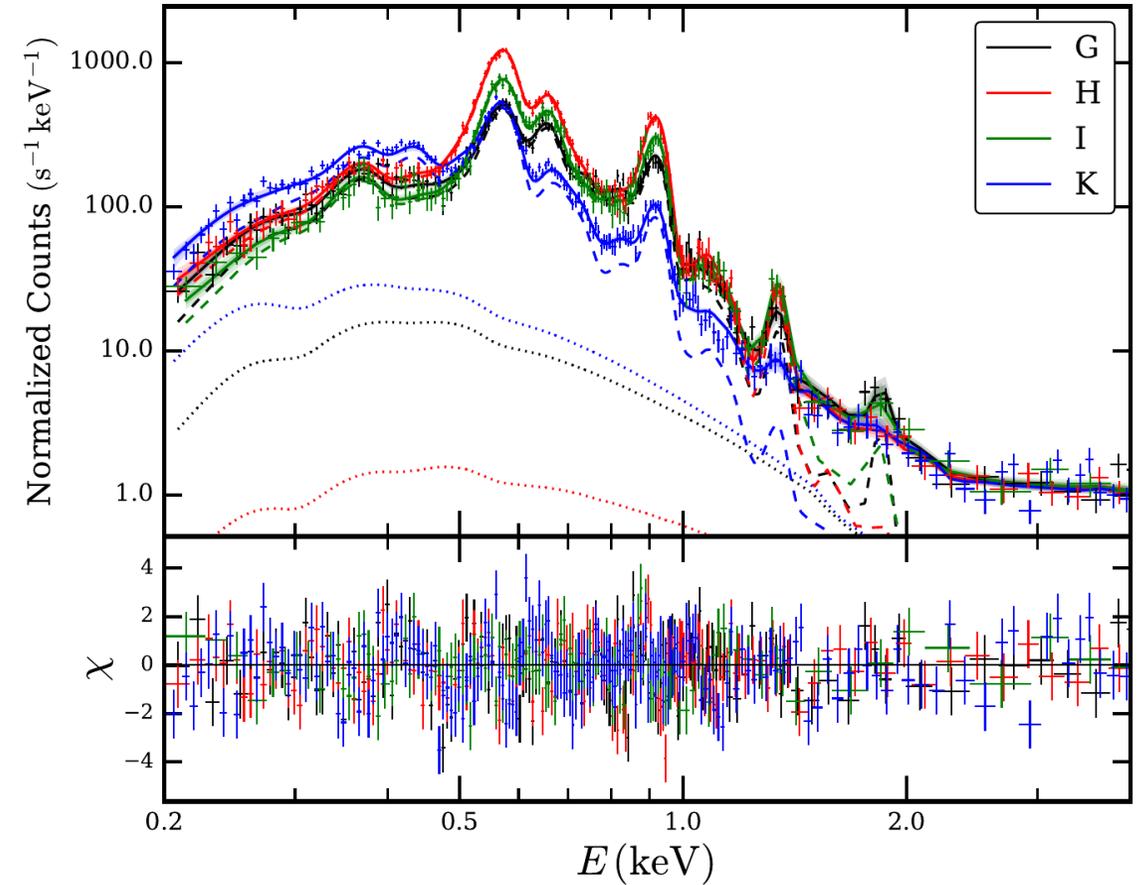
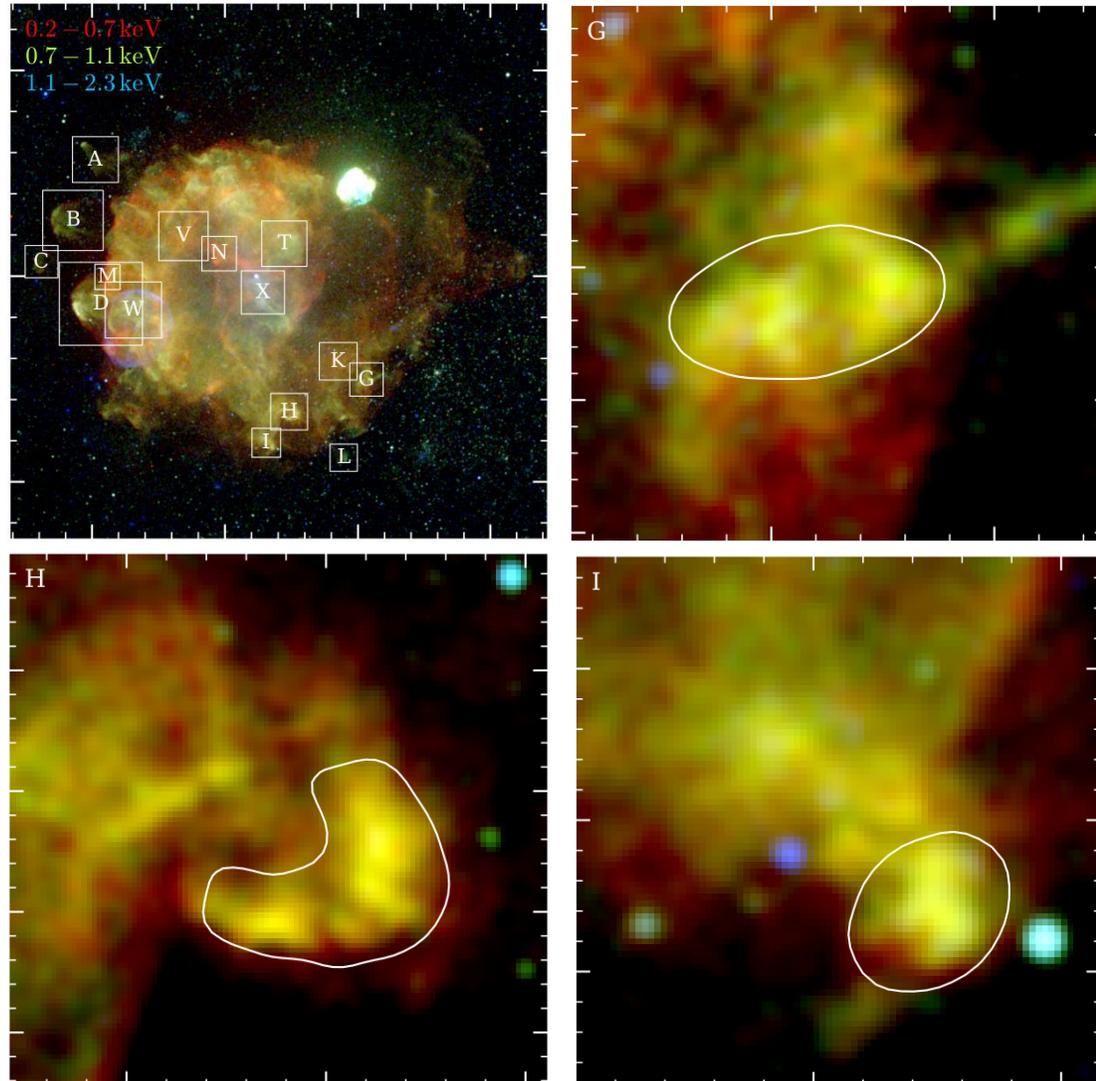


Miceli+13: Simulation of an ejecta clump protruding into the unshocked ISM

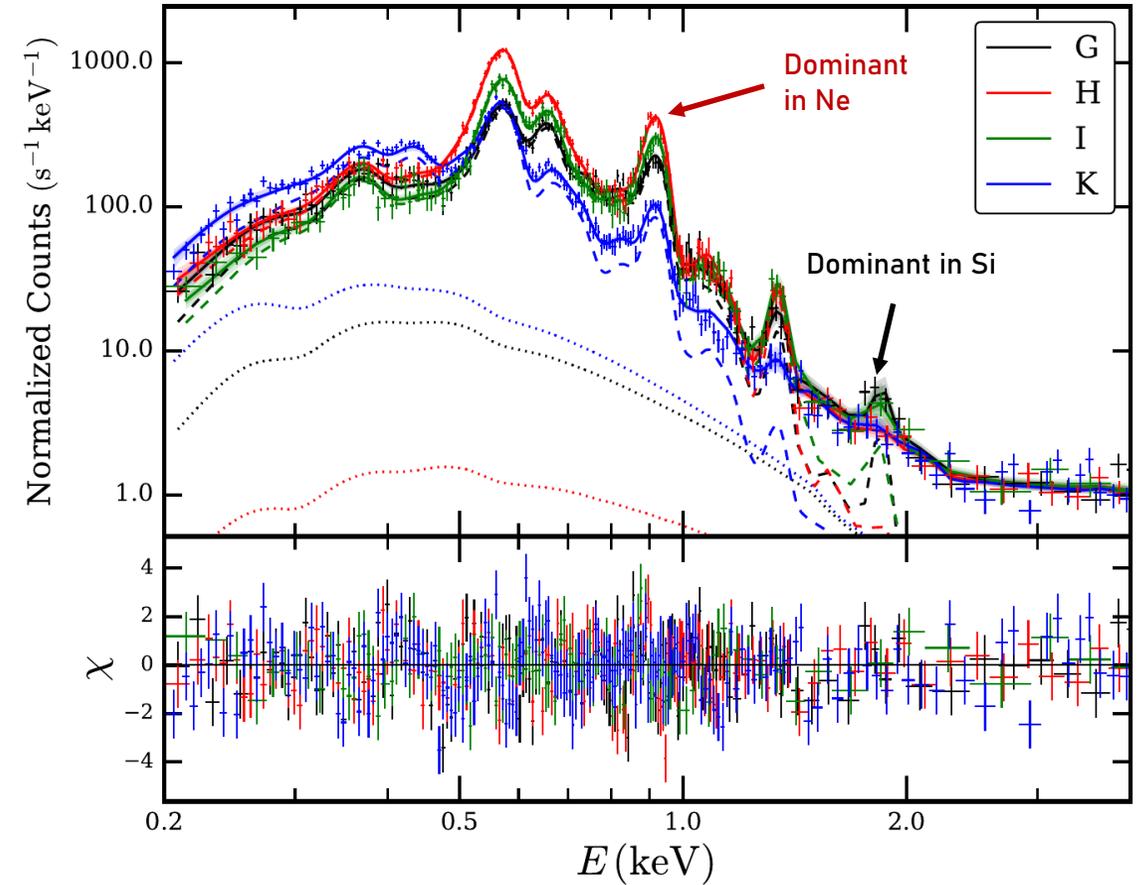
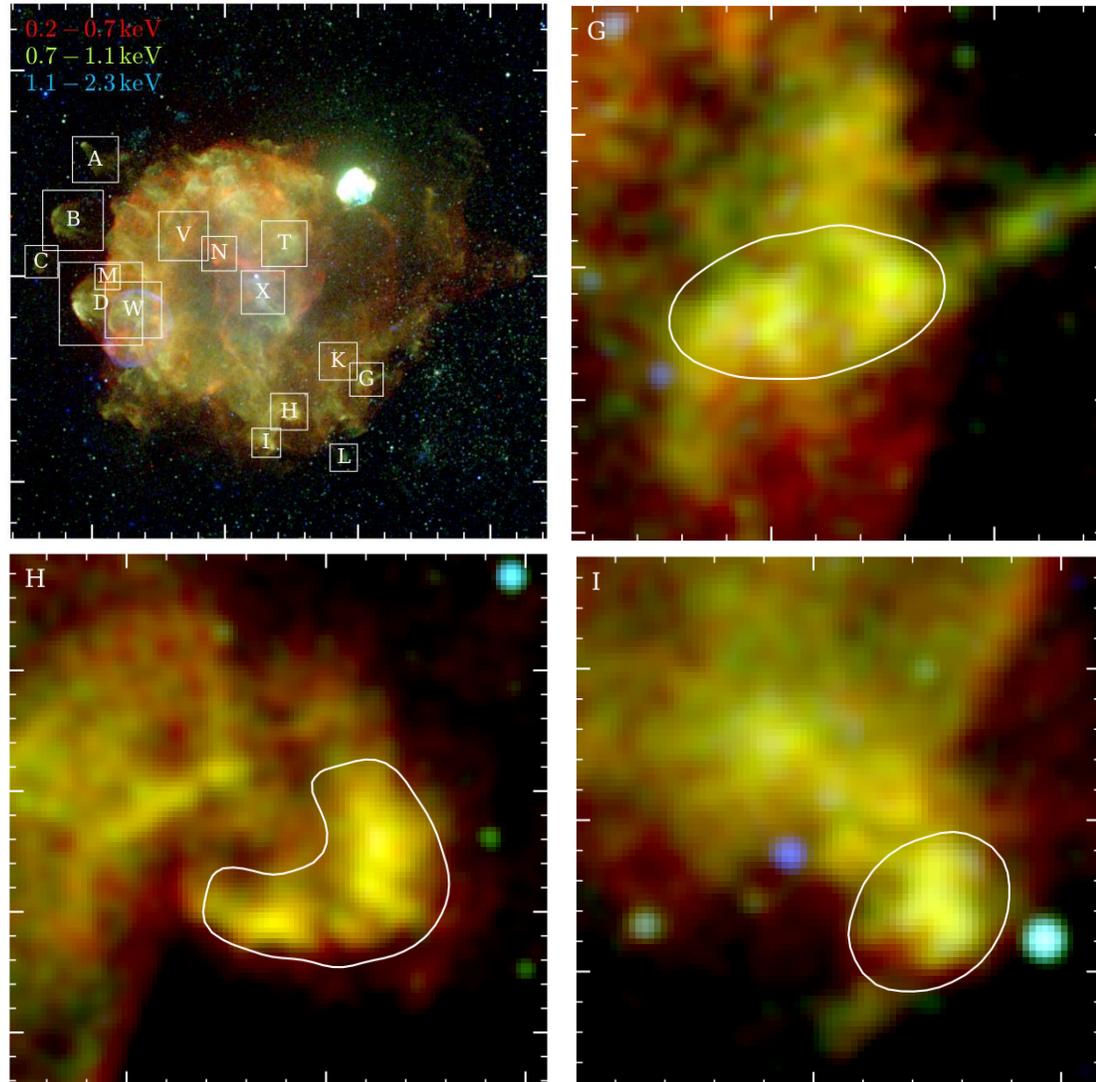


➤ Unexpected temperature structure?

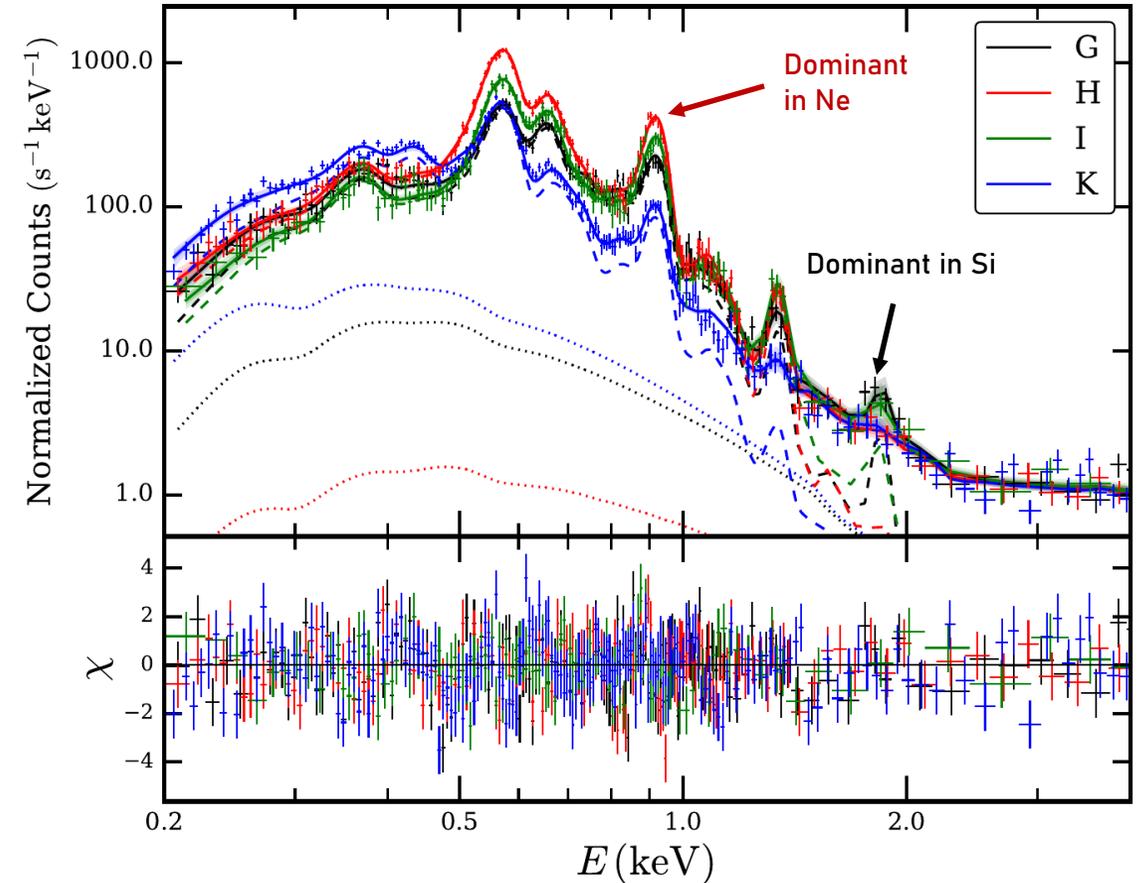
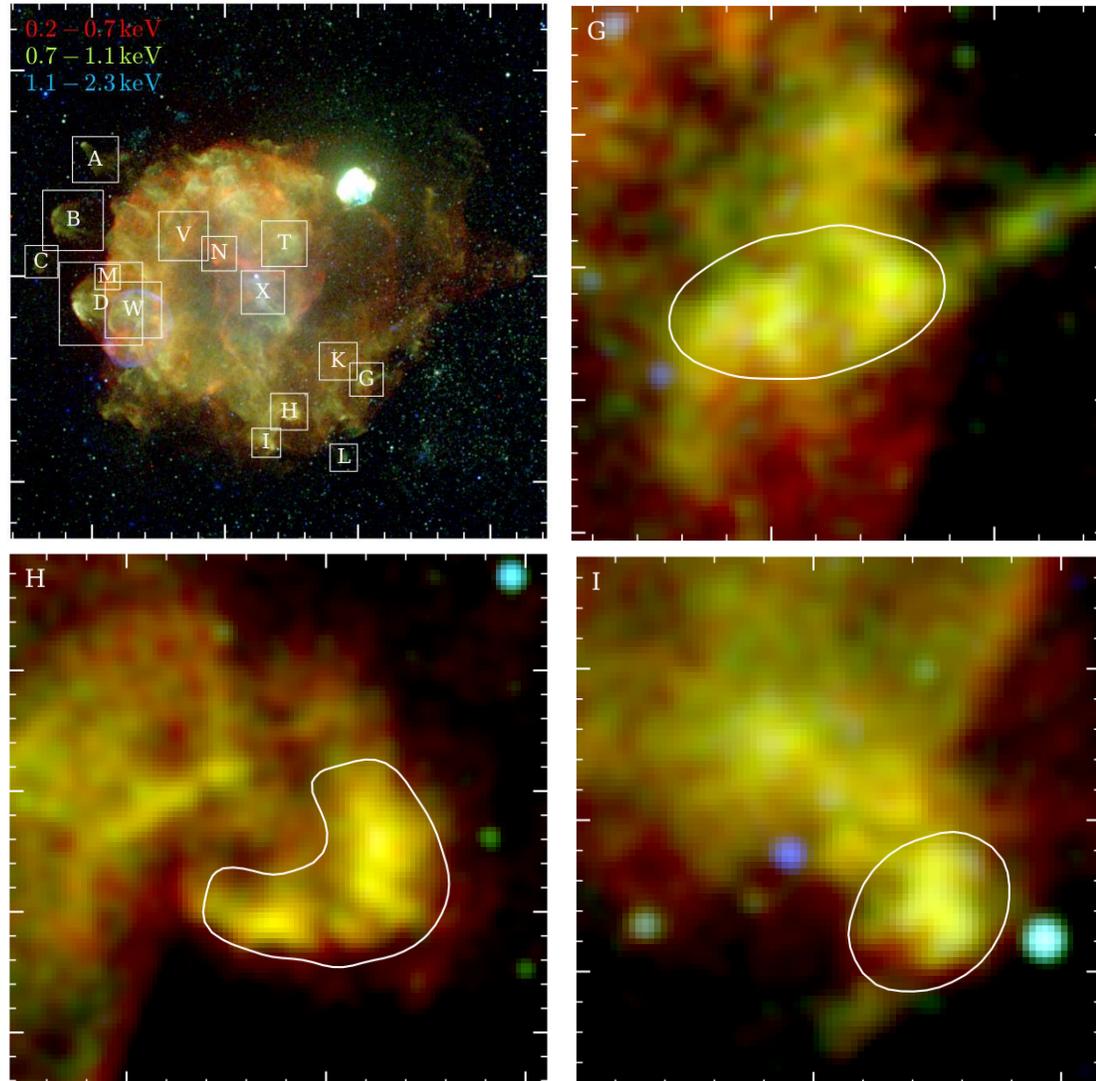
More Ejecta Clumps



More Ejecta Clumps

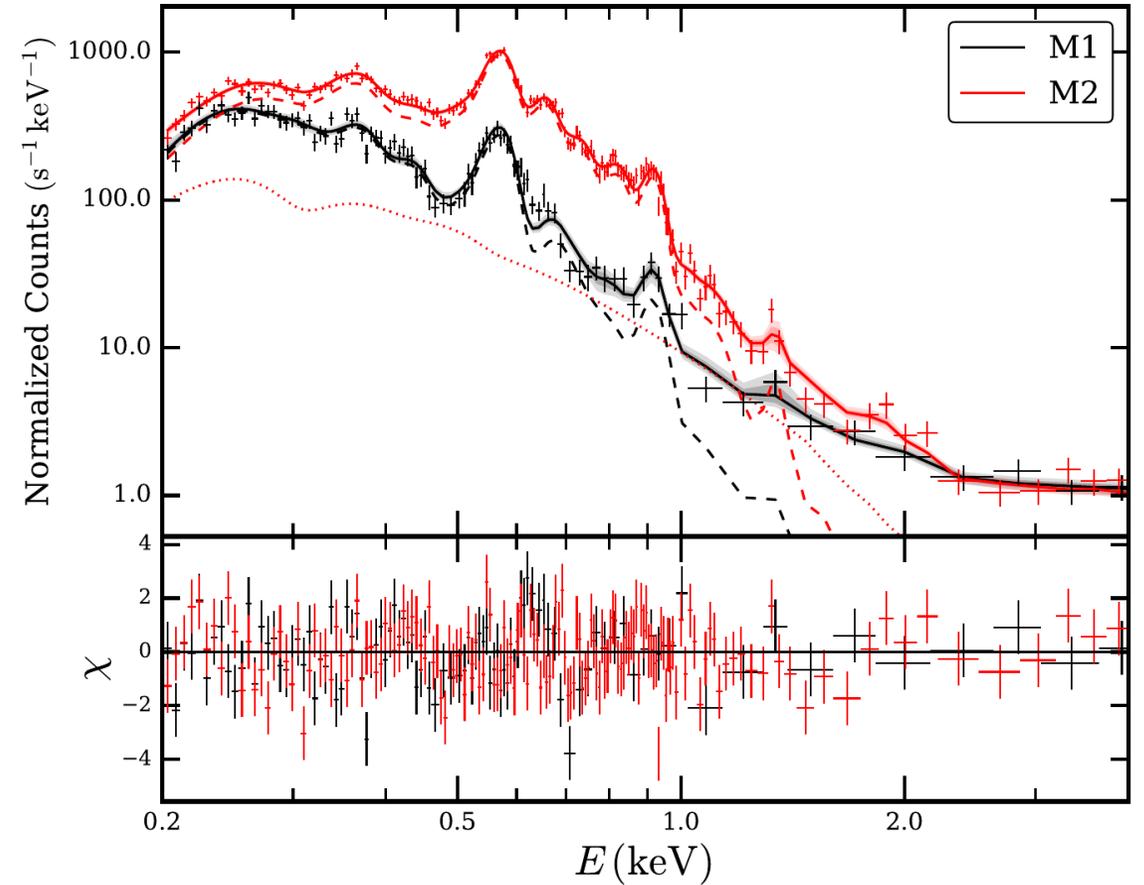
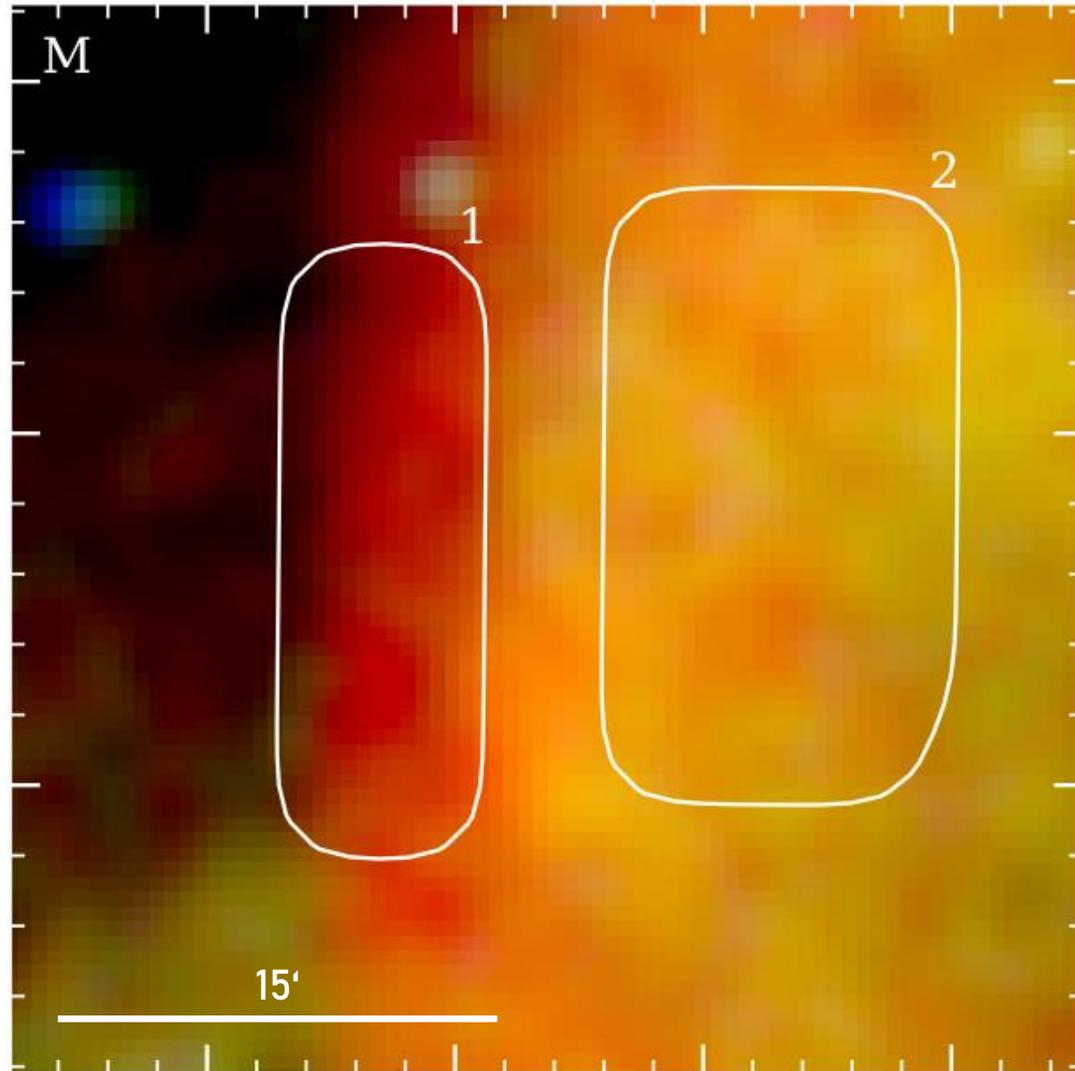


More Ejecta Clumps

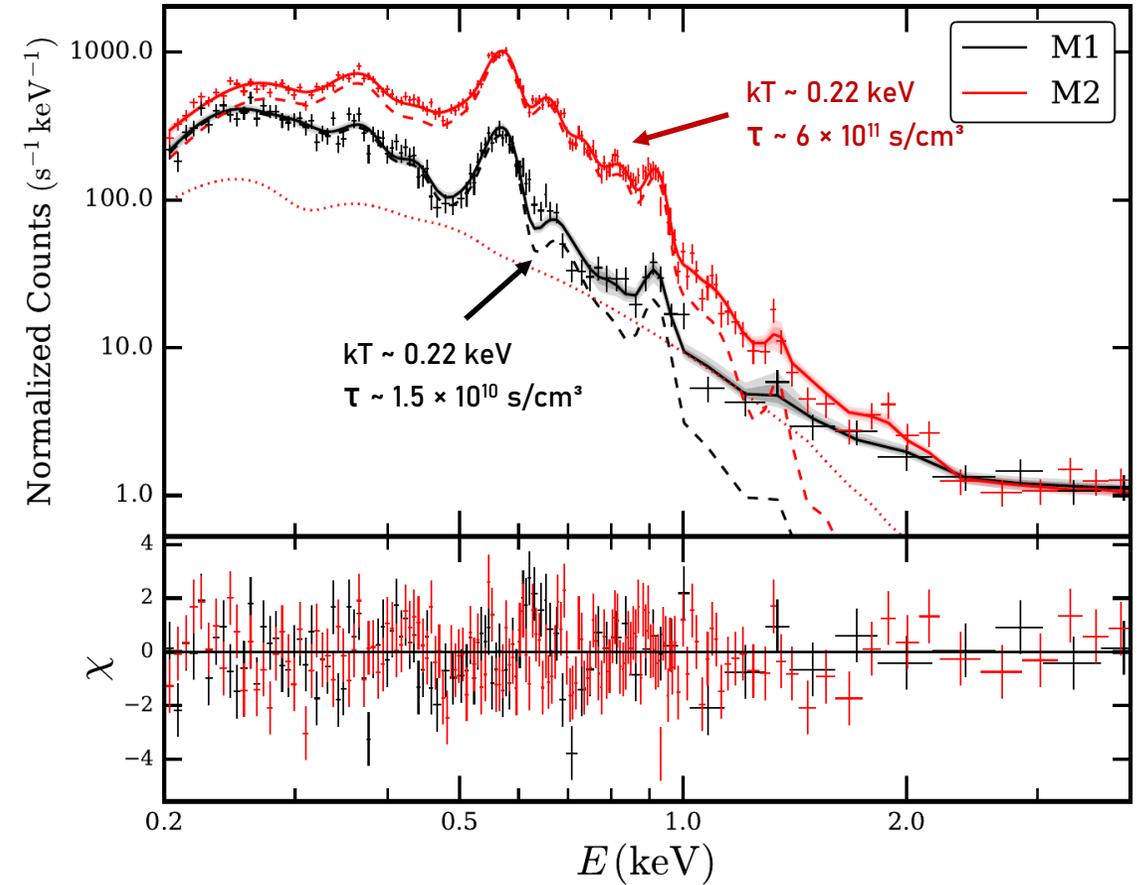
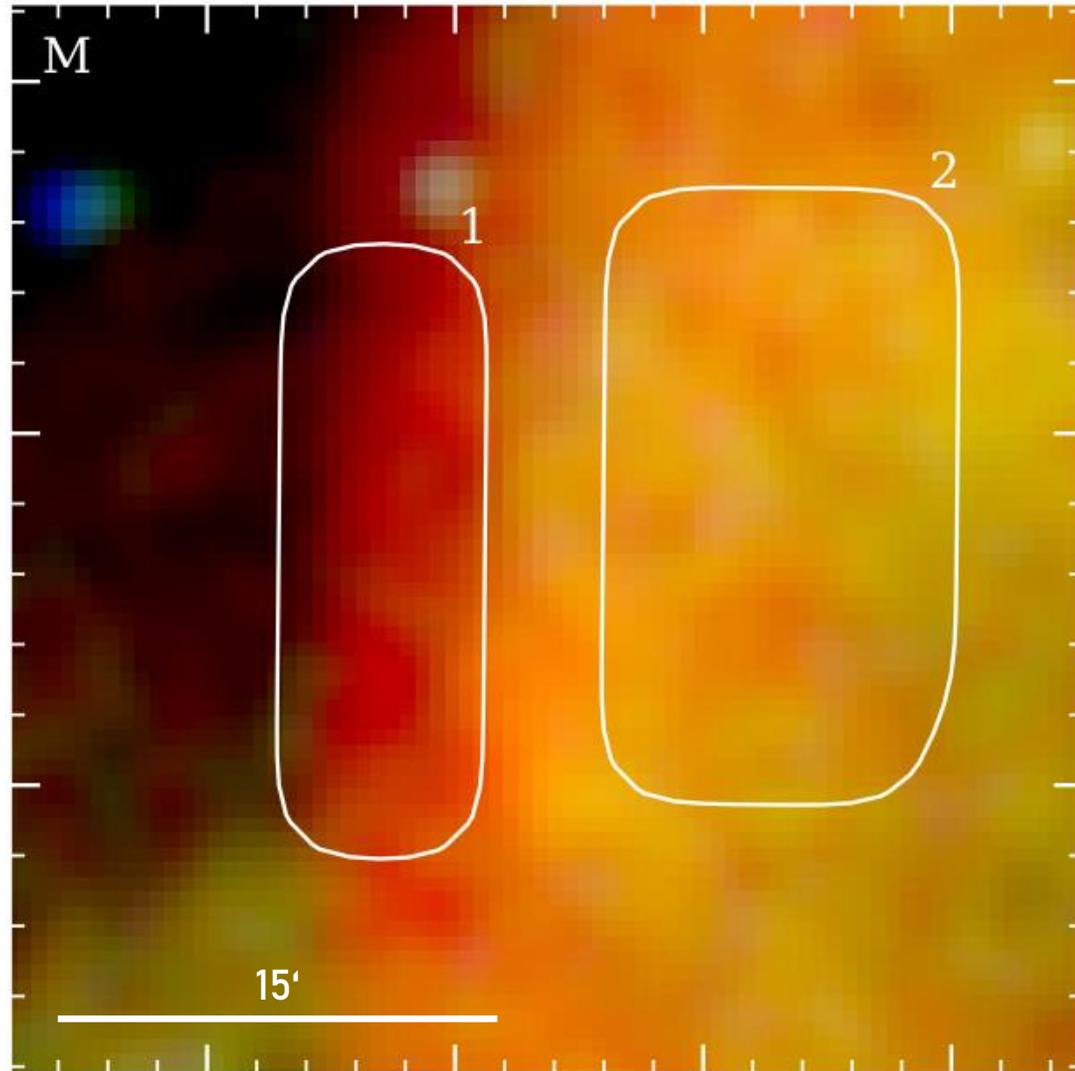


➤ Silicon abundance varies between individual clumps

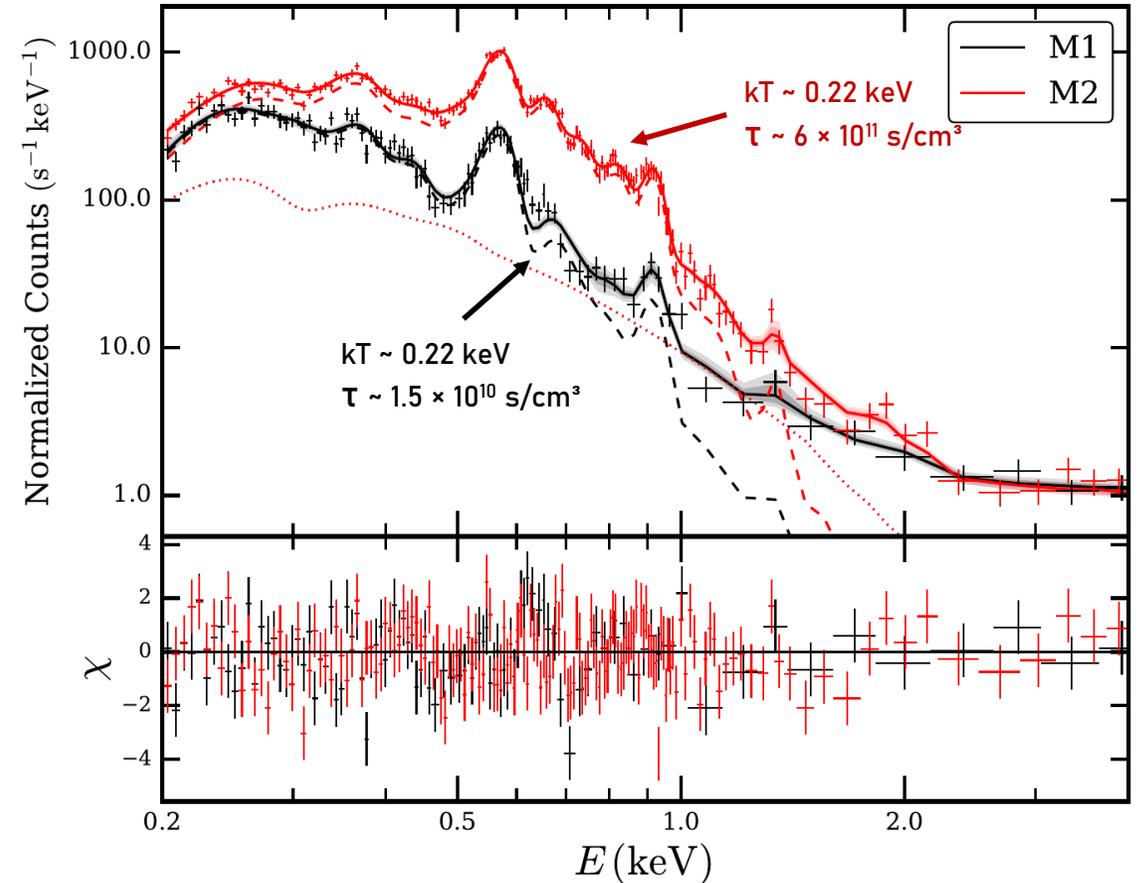
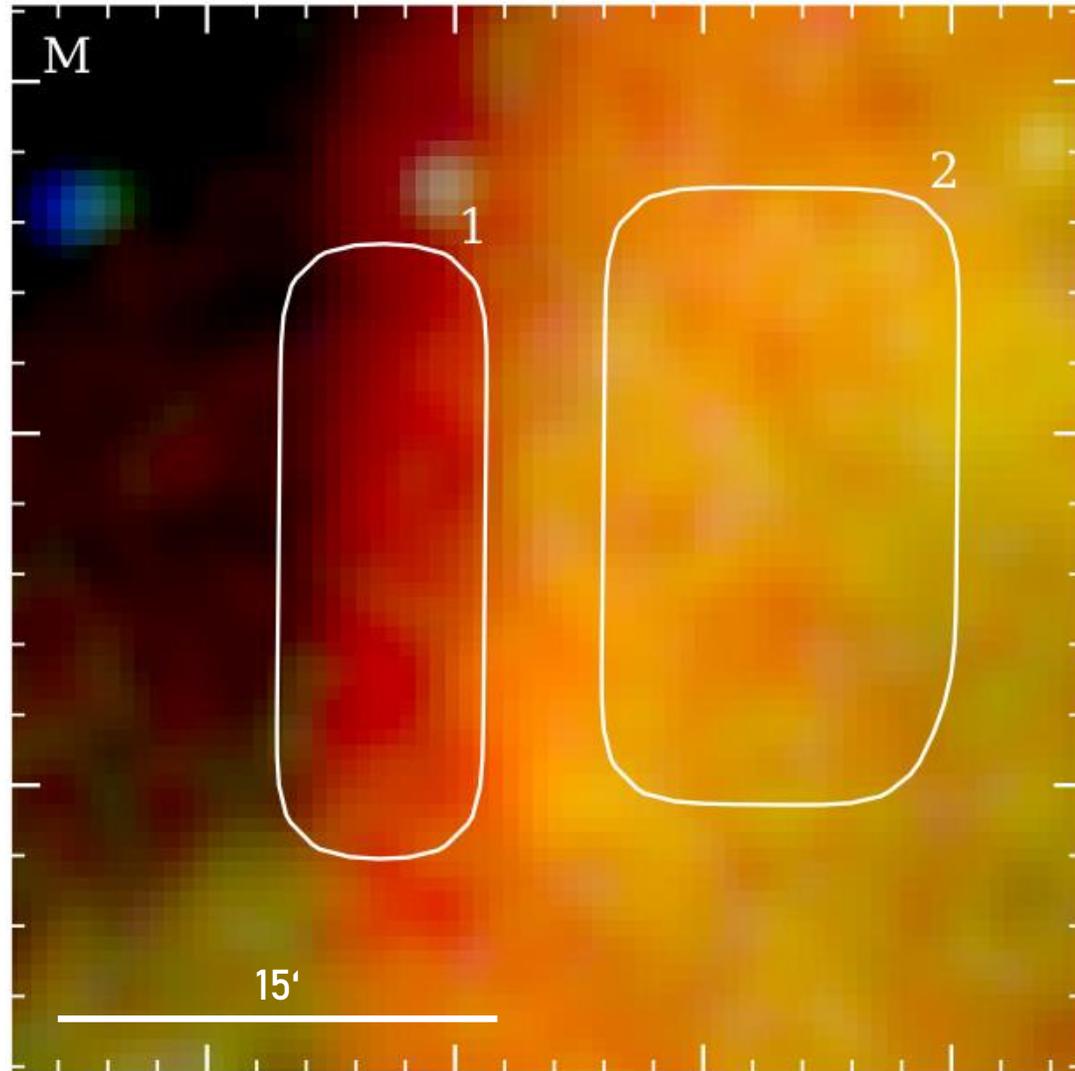
Spectrum at the shock front



Spectrum at the shock front

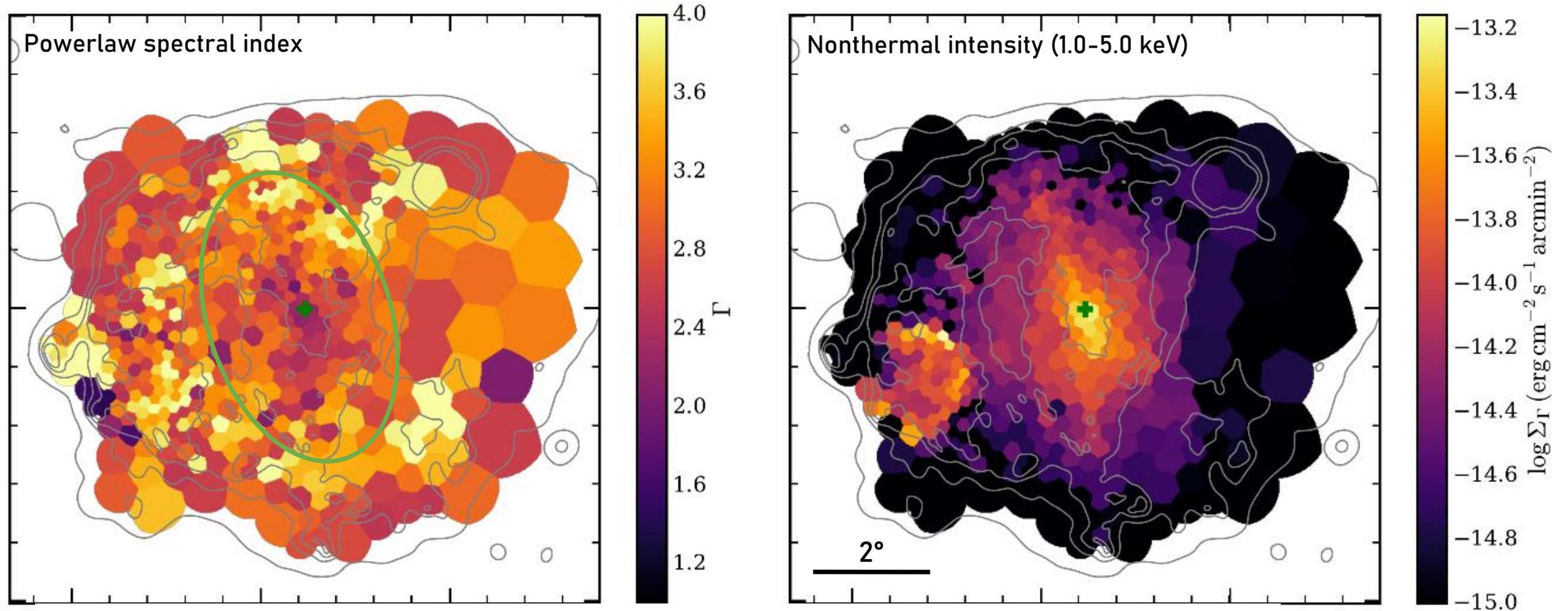


Spectrum at the shock front

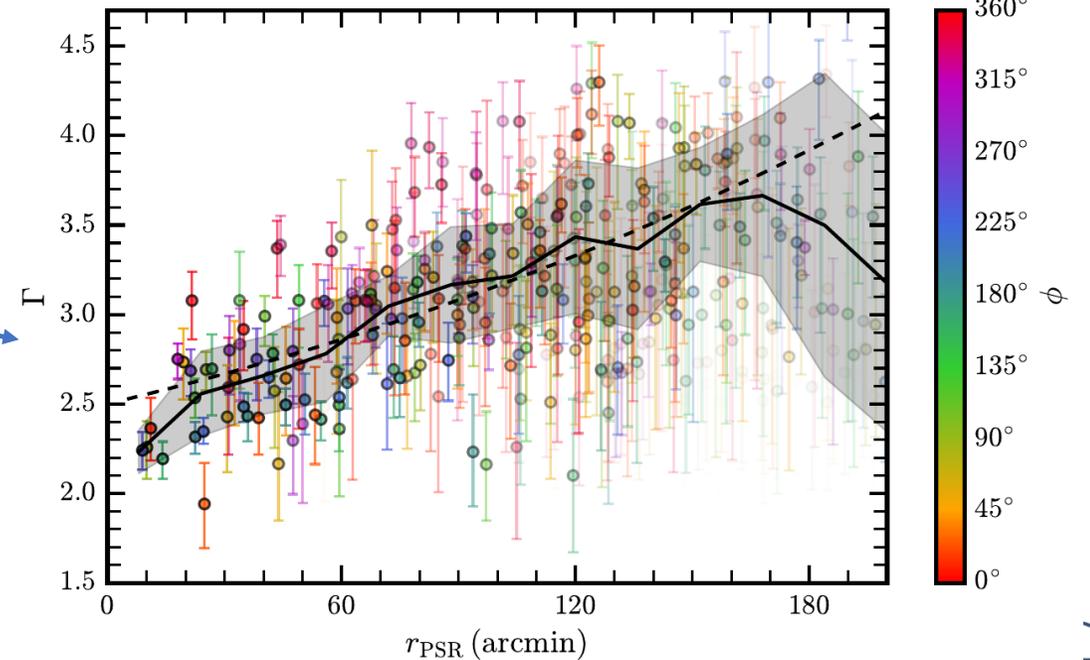
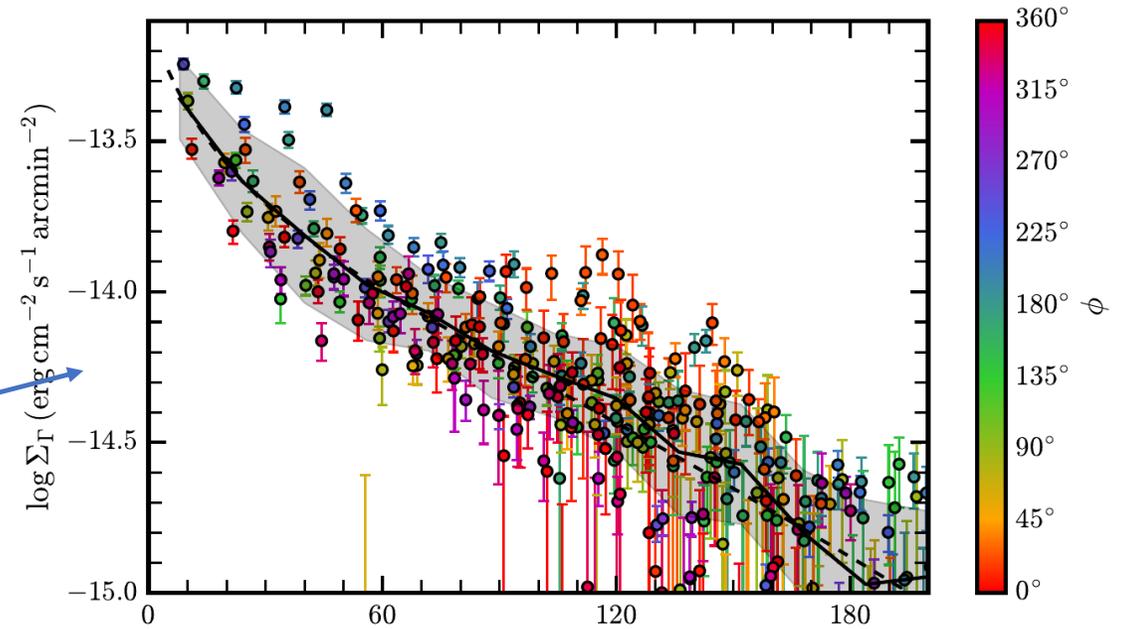
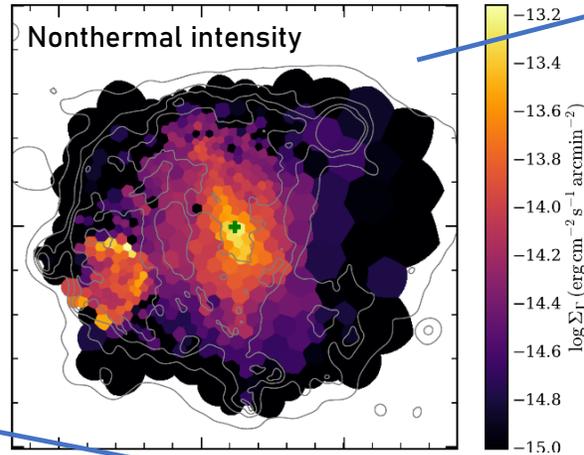
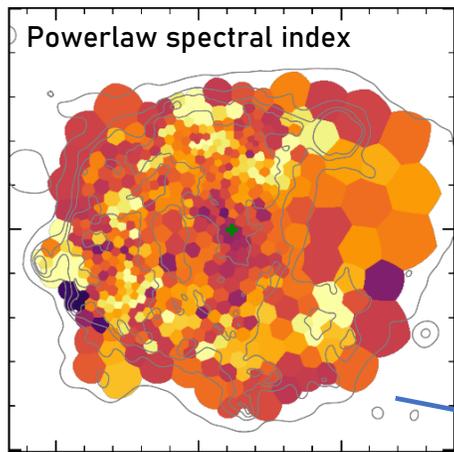


➤ Spectral differences mostly due to different shock ages!

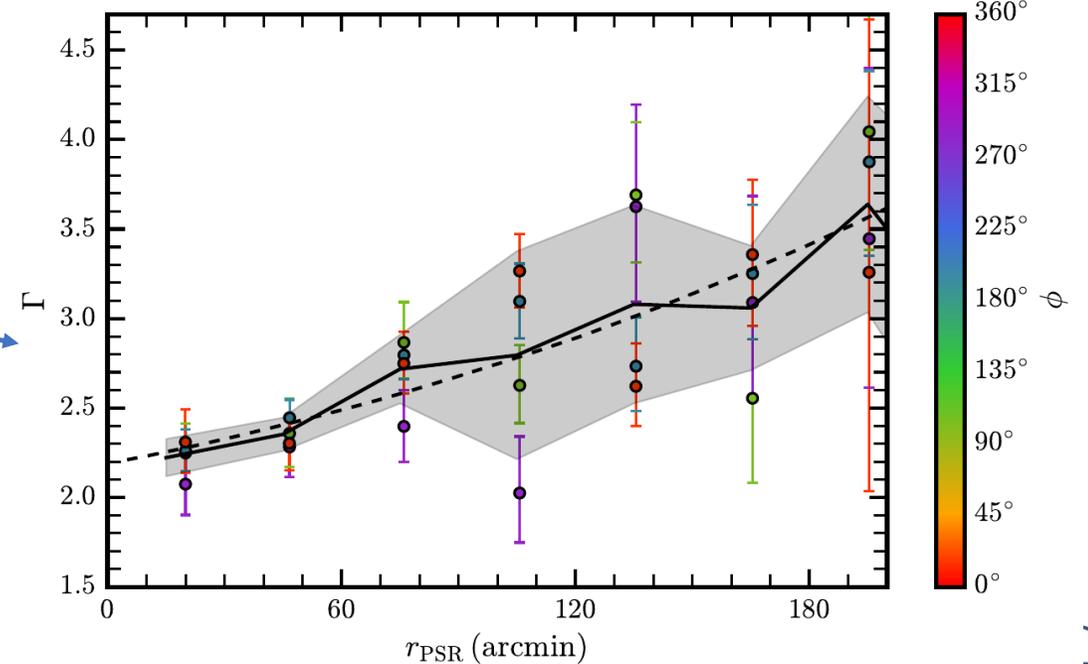
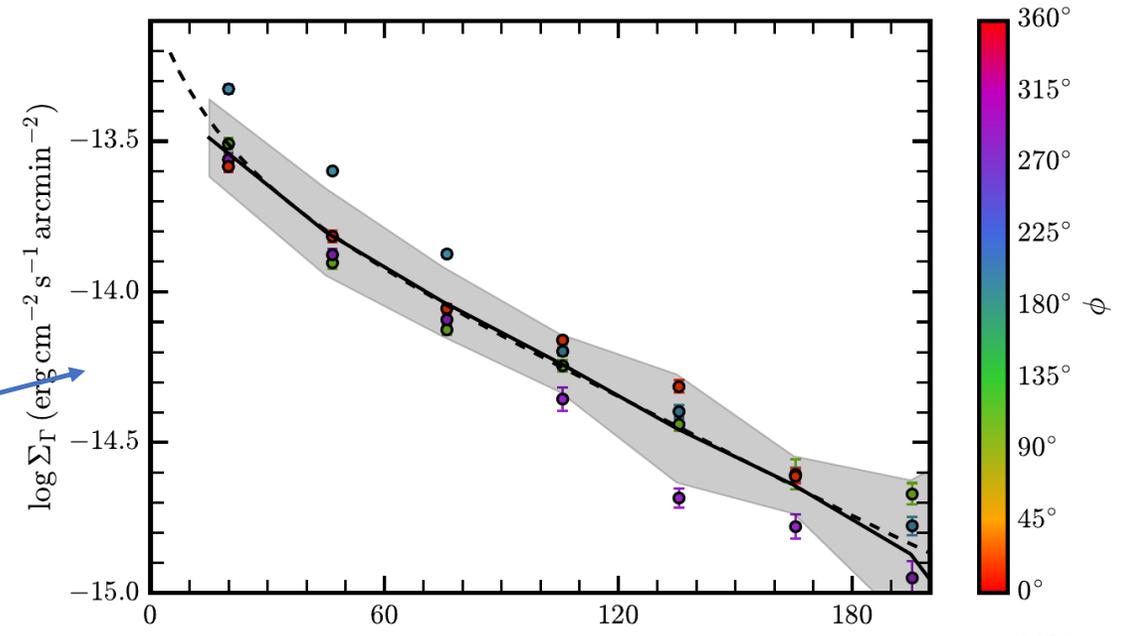
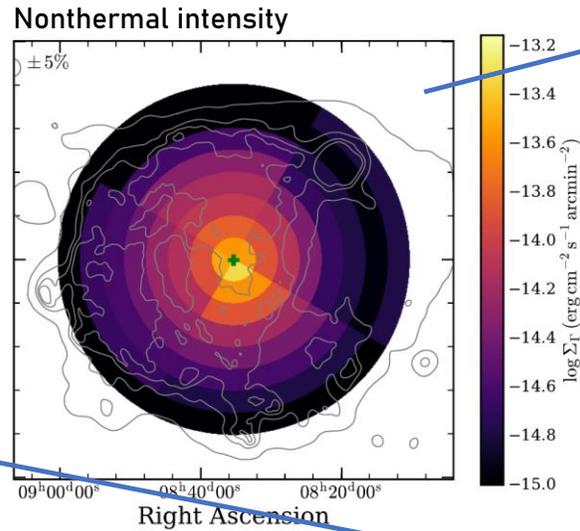
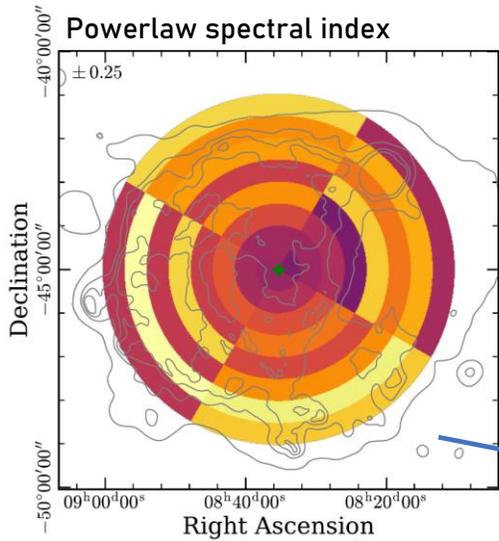
Nonthermal Photon Index & Surface Brightness



Nonthermal Emission in radial projection



Nonthermal Emission in radial projection II



Bayesian Evidence in Favor of Nonthermal Emission

