Friedrich-Alexander-Universität
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Supernova Remnants

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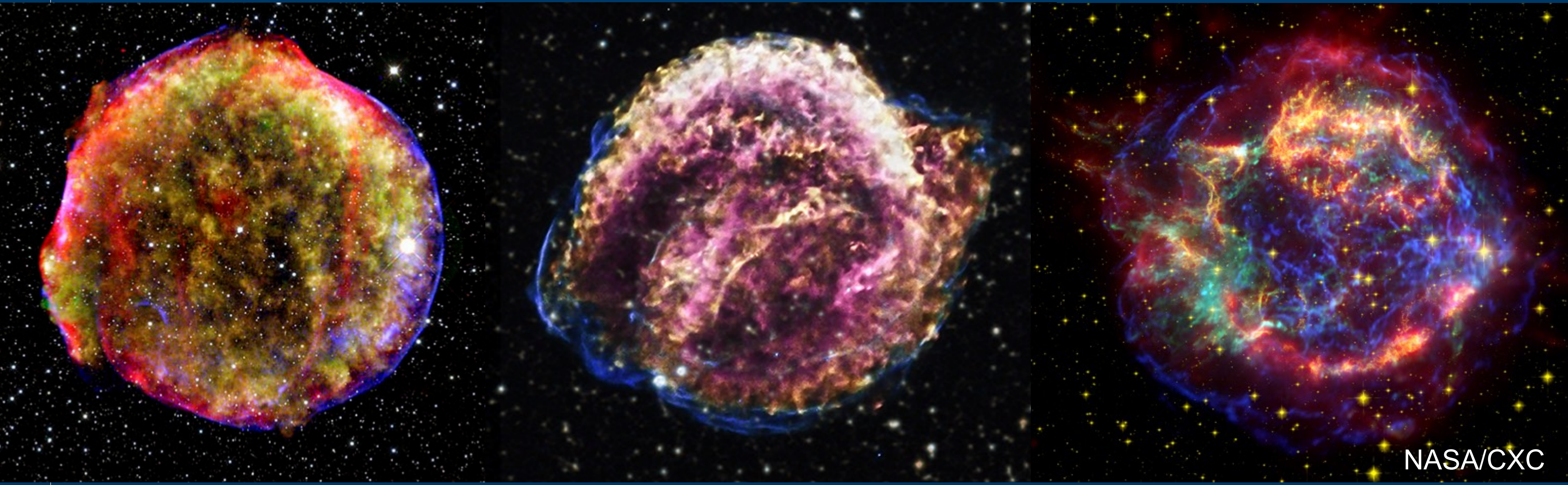
Supernova Remnants

Remains of a **supernova explosion**.

Strong shock waves expand into the surrounding medium and

- **ionize and heat** the interstellar medium,
- distribute the **heavy elements**, which were created in the progenitor star and in the explosion,
- **accelerate** cosmic rays,
- and form **new structures** in the interstellar medium.



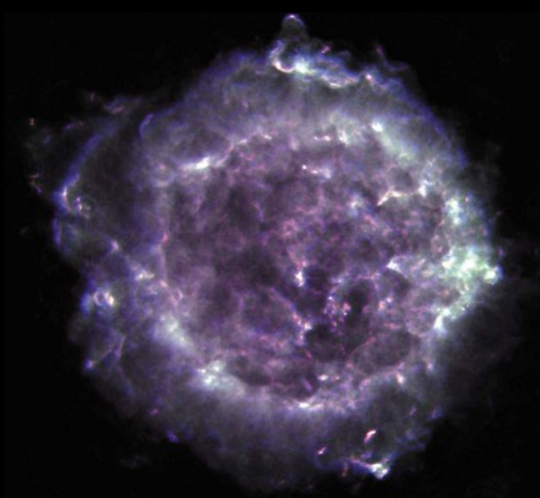
NASA/CXC

Supernova Remnants

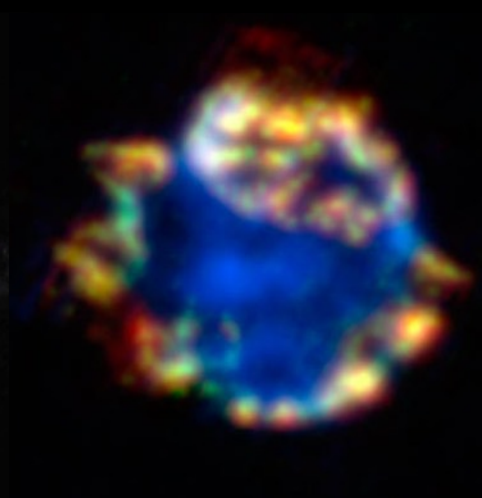
SNRs can be observed over the **entire electromagnetic spectrum** from

- **radio**: electron synchrotron emission,
- **infrared**: heated dust, cool ejecta,
- **optical**: Hα and forbidden (e.g. [SII]) line emission,
- **X-rays**: thermal emission of shocked hot gas, in some cases also non-thermal X-rays,
- **gamma-rays**: radioactive decay, Bremsstrahlung, inverse Compton, π^0-decay.

SNR Cas A



Radio (VLA, NRAO/AUI)



IR (Spitzer, NASA/JPL-Caltech/ J. Rho (Caltech-SSC)

Optical (HST, NASA/ESA/ Hubble Heritage, STScI/AURA)

X-rays (Chandra, NASA/CXC/MIT/ UMass Amherst/M.D.Stage et al.)

Interstellar Shocks

Shocks are **common** in galaxies and occur, e.g., in:

- stellar winds,
- supernovae,
- accreting compact objects, or
- expanding HII regions.

Interstellar medium can be regarded as a **fluid.**

Pressure-driven disturbance in a compressible medium propagates faster than the sound speed.

⇨ **Discontinuity**: shock wave.

Jump in fluid properties (density, velocity, pressure).

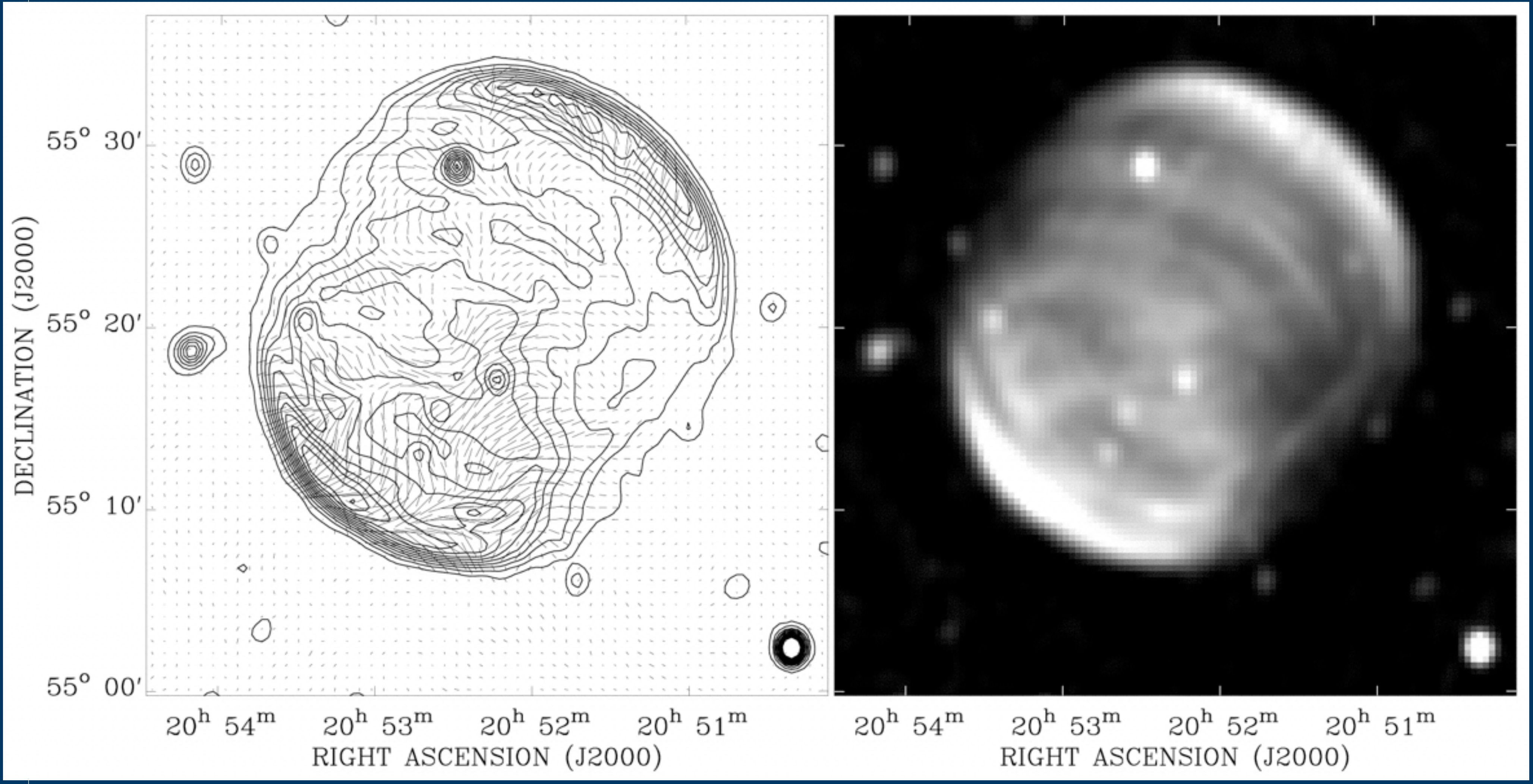
Kinetic energy of the shock is **converted into heat**.

ζ Oph (Spitzer IRAC/MIPS, Credit: NASA/JPL-Caltech)

Radio Synchrotron Emission

Continuum emission from **relativistic electrons** in SNR DA 530 at 1420 MHz.

Polarized intensity is shown by their length and direction of the E-field (left).

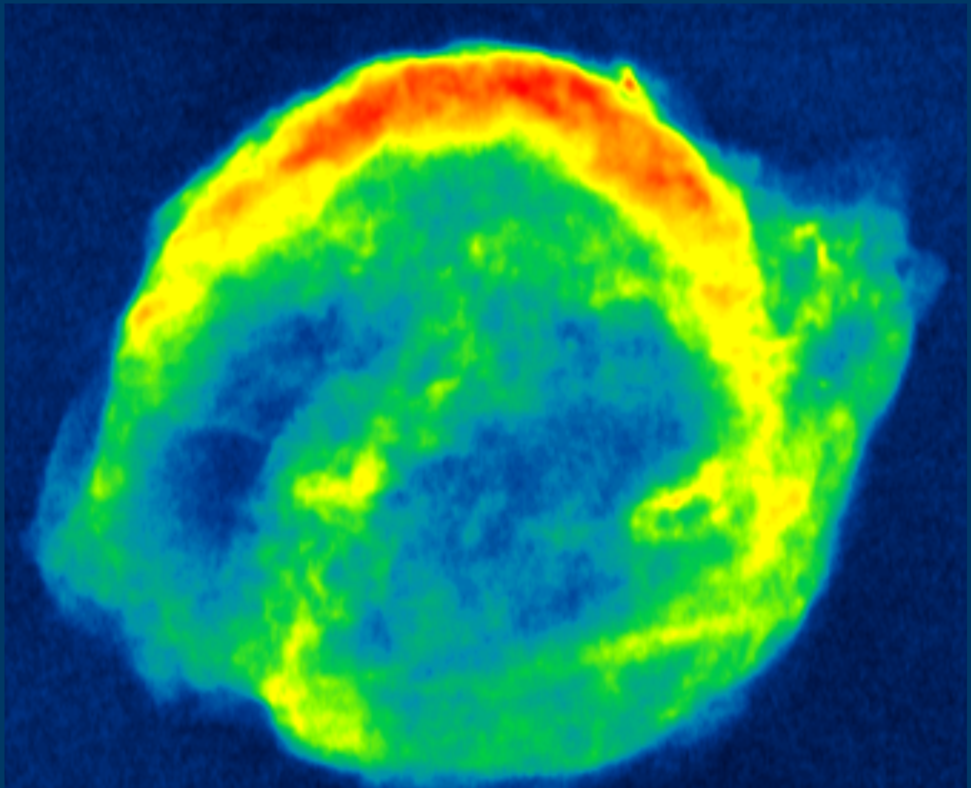


Landecker et al. (1999)

Radio and X-ray Emission

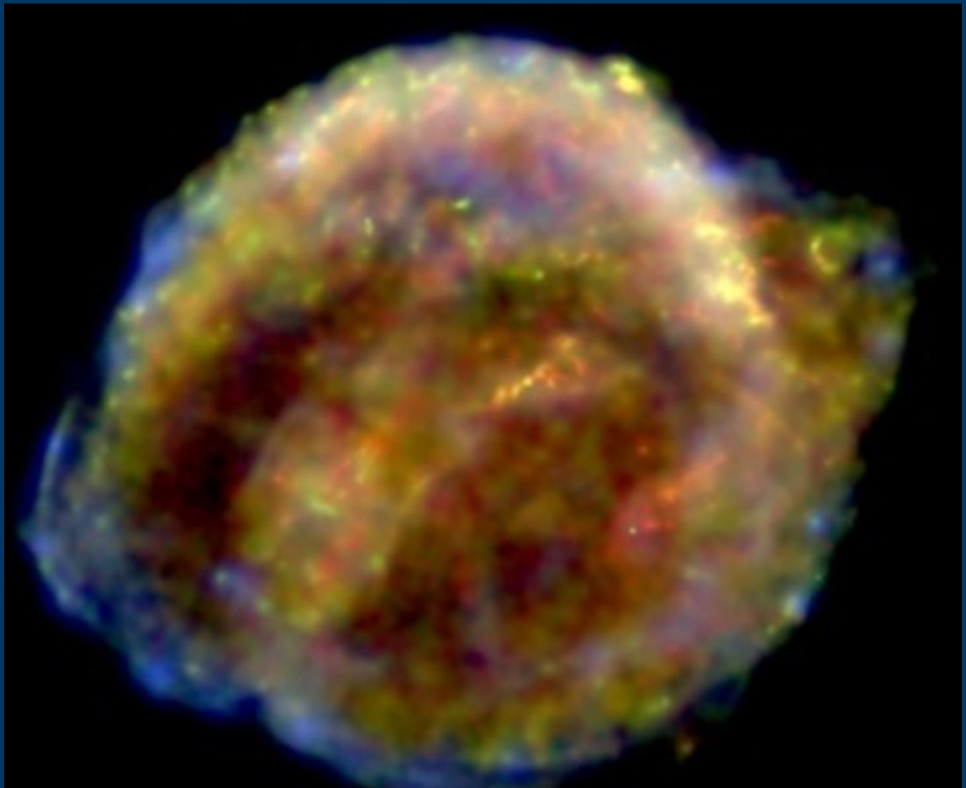
Kepler's SNR

Radio: Synchrotron from **electrons**



Radio (VLA)

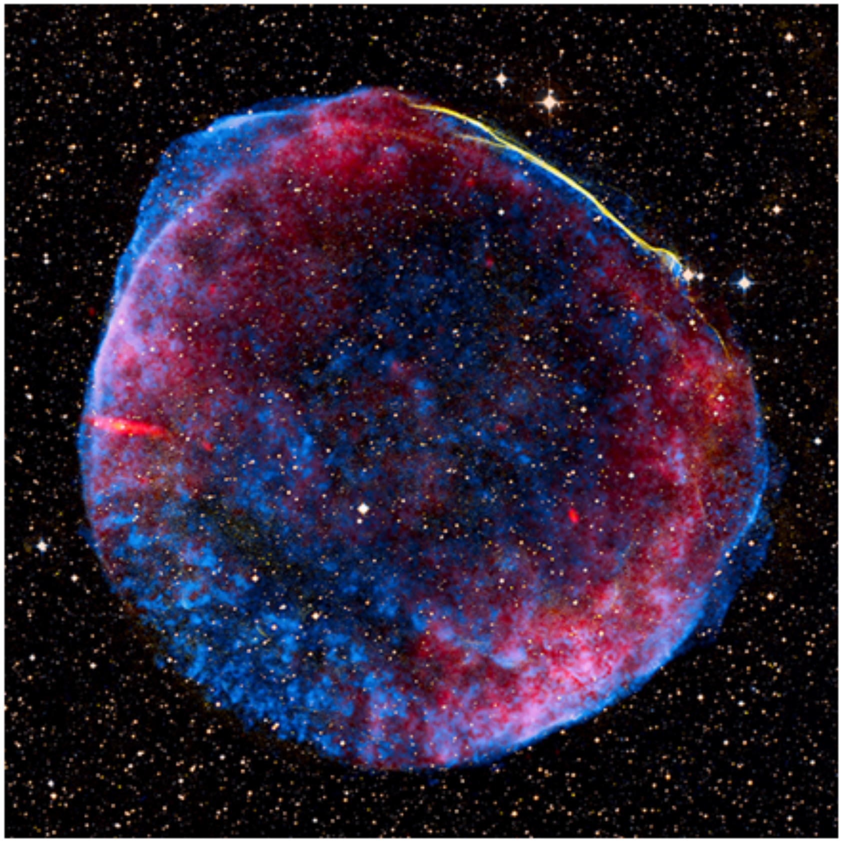
X-rays: Thermal Emission + Synchrotron



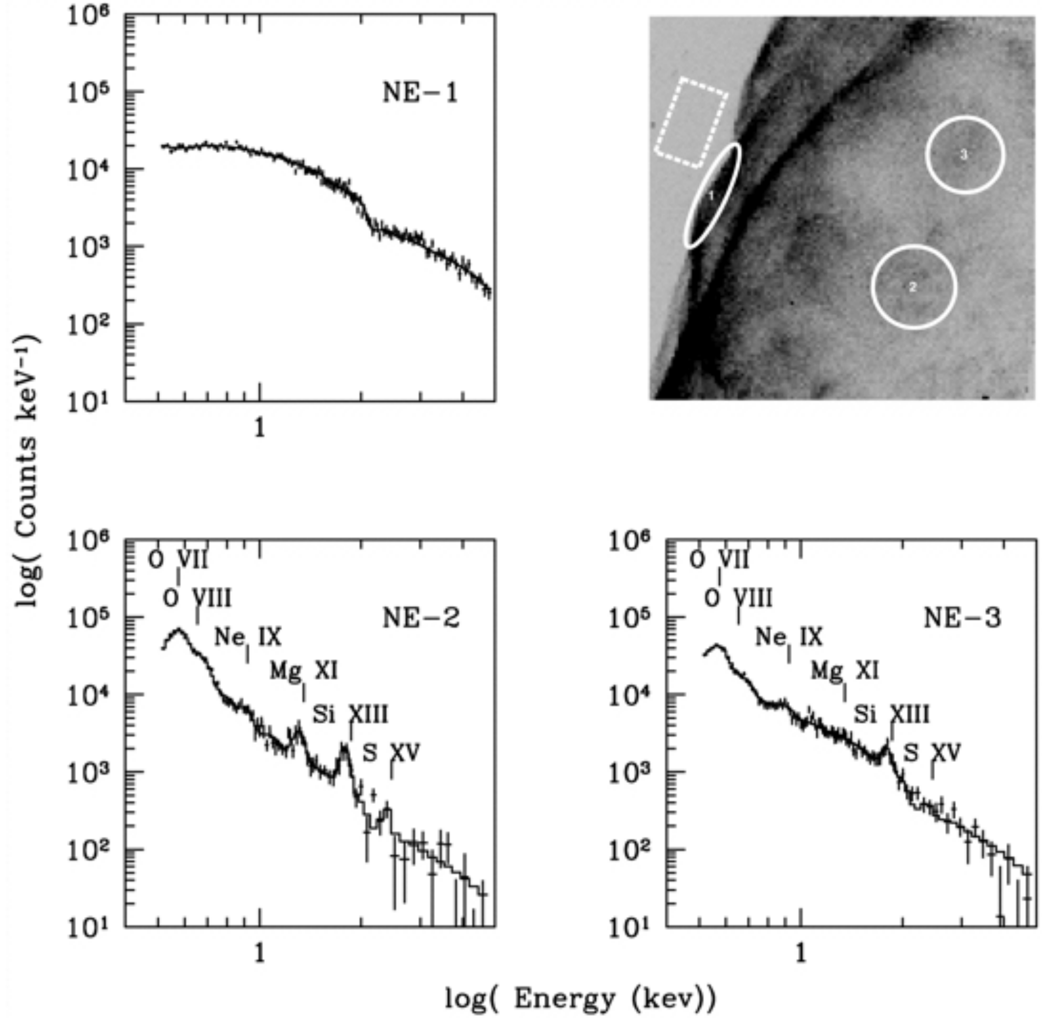
X-rays (Chandra)

Thermal and Non-thermal X-ray Emission

SN 1006



Red: radio (VLA/GBT). Yellow: optical (CTIO). Blue: X-ray (Chandra).

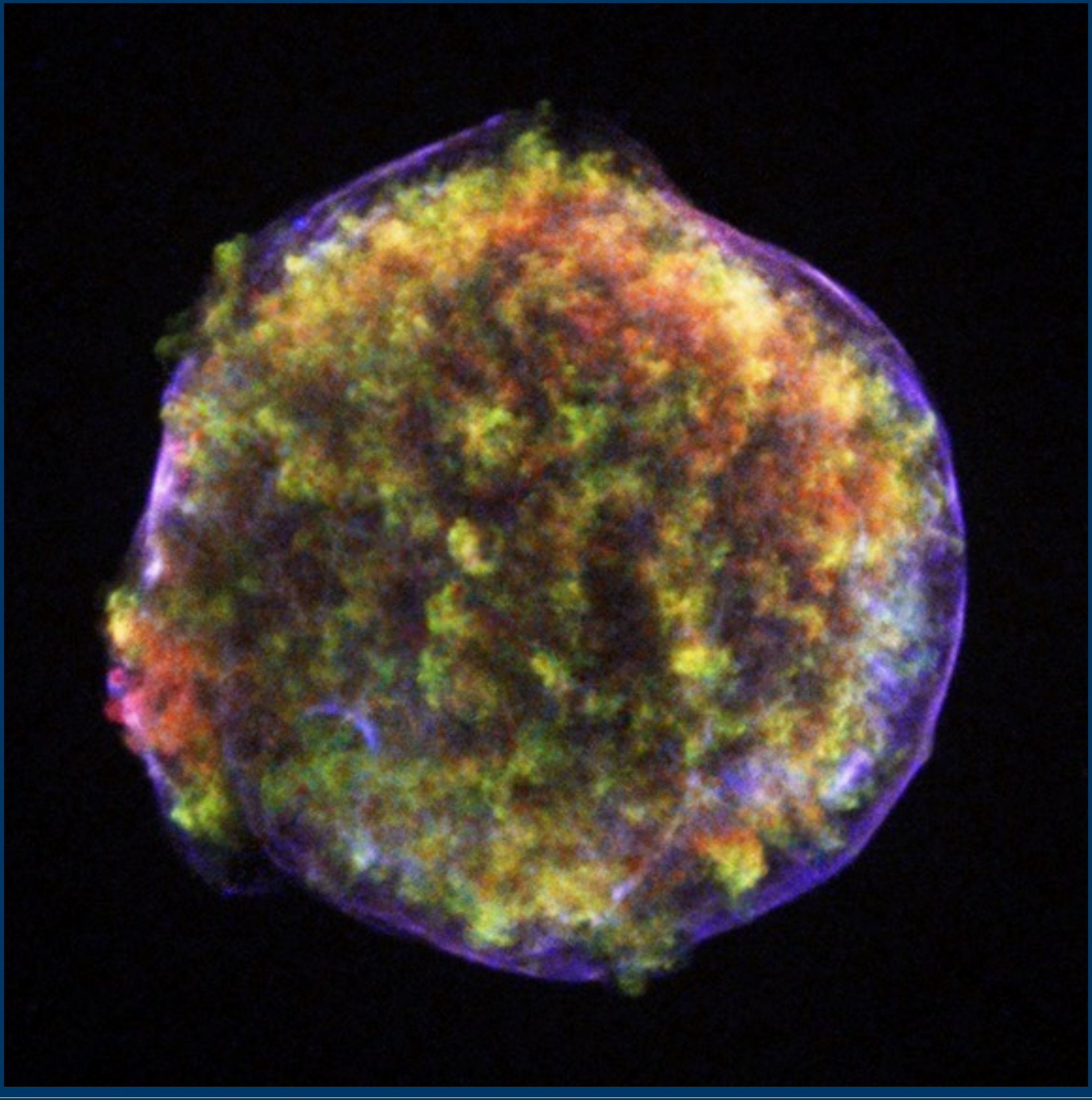


Long et al., 2003

X-ray: NASA/CXC/Rutgers/G.Cassam-Chenaï, J.Hughes et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS

Thermal and Non-thermal X-ray Emission

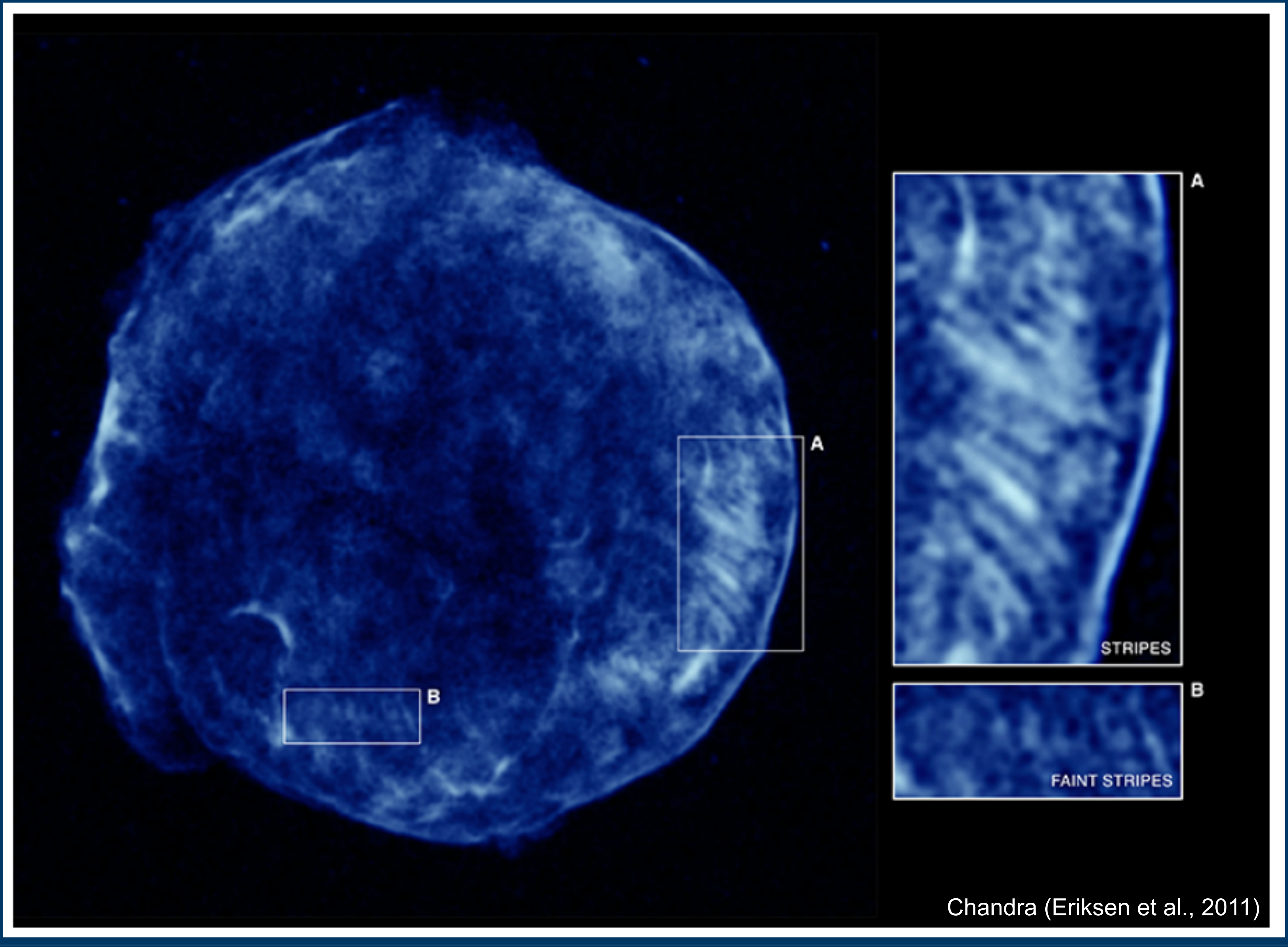
Tycho's SNR



NASA/CXC/Rutgers/J.Warren & J.Hughes et al.

Non-thermal X-ray Emission

Tycho's SNR

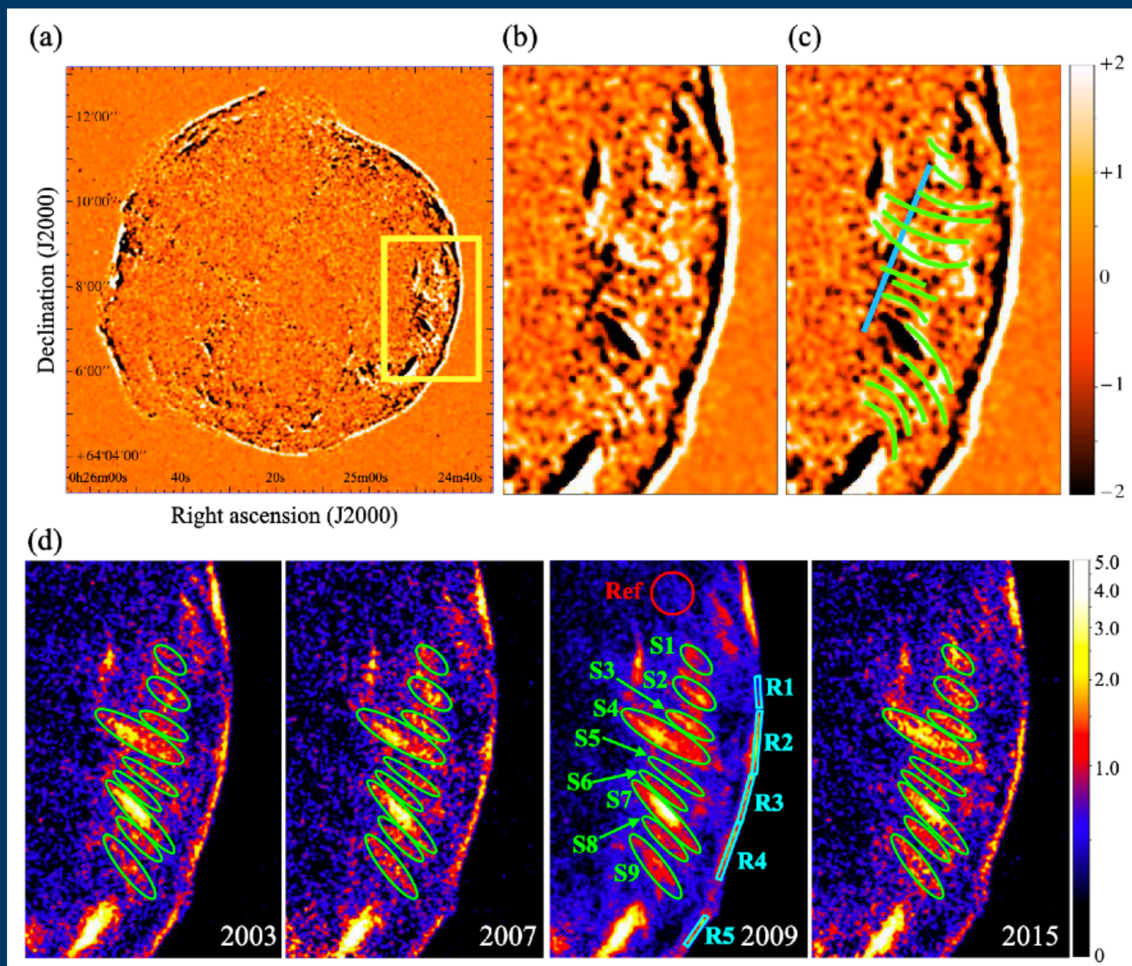


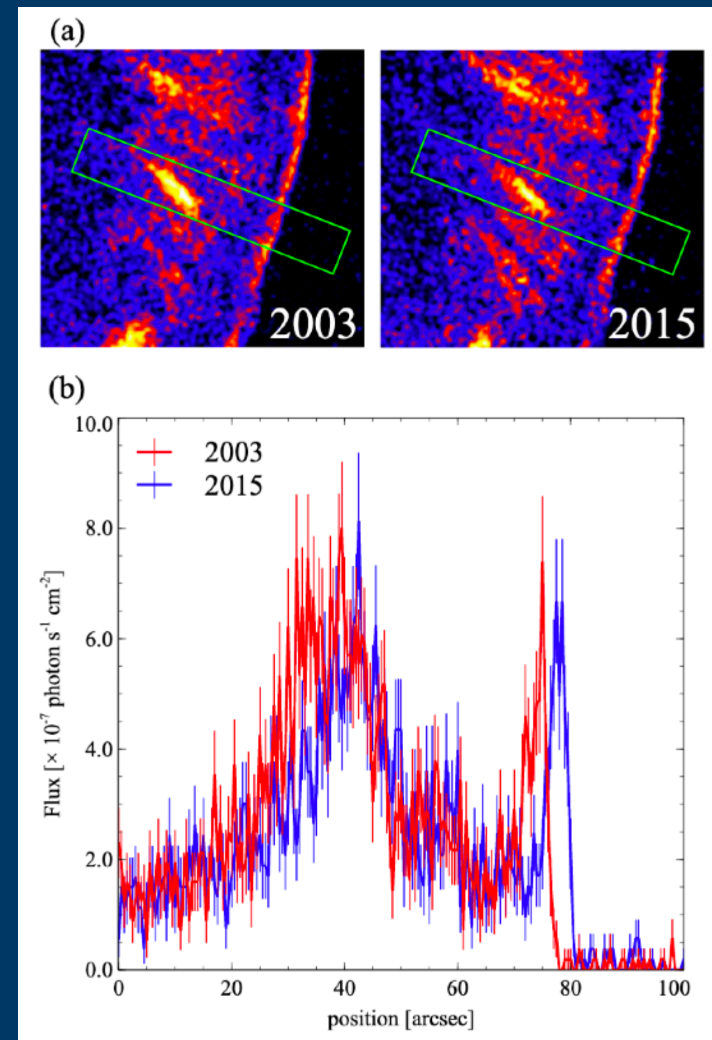
Tycho's SNR: Magnetic Stripes

Chandra data taken in 2003, 2007, 2009, and 2015.

Stripes in the southwestern region of the SNR, synchrotron X-rays in the region is time variable.

Enhanced magnetic fields in the blast wave region.



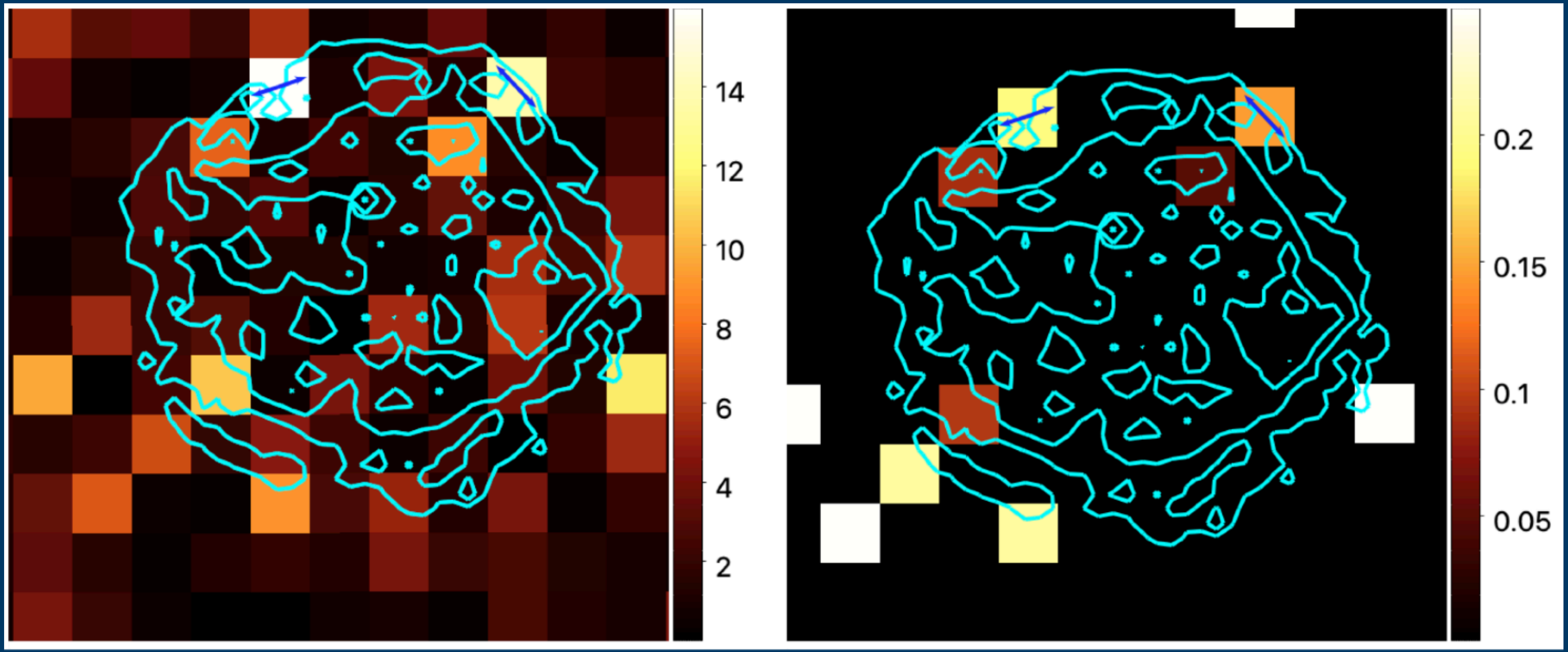


Matsuda et al. (2020)

Polarized Emission from Cas A

Detection of polarized emission with tangential polarization from Cas A in 3 - 6 keV band (Vink et al., 2022) with the Imaging X-ray Polarimetry Explorer (IXPE).

Polarization degree of 1.8 ± 0.3% for the total emission, 2.4% for synchrotron component only.

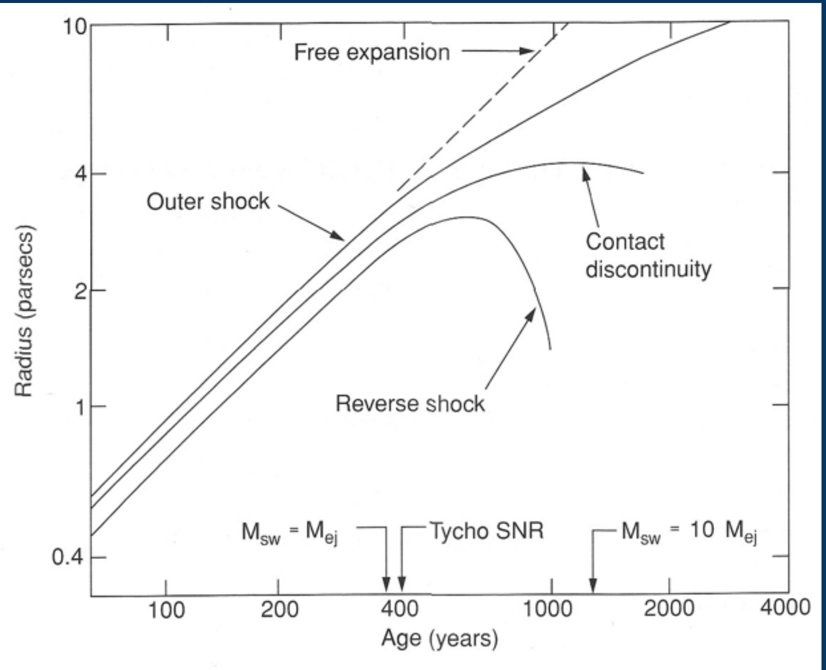


Map of χ^2 values for the polarization signal for the 3 - 6 keV band (left) and polarization degree map (right). Only pixels with confidence levels above 2σ are shown. For pixels with > 3σ confidence level the polarization angles are indicated with blue arrows.

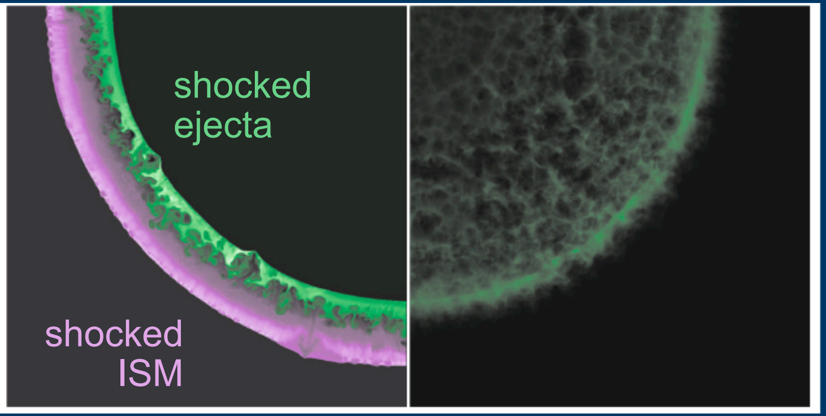
Supernova Remnant Evolution

1. **Free expansion** (a few 100 yrs):

   Constant expansion velocity and temperature.



Seward & Charles, 'Exploring the X-ray Universe'



Simulated density distribution (left) and ejecta emissivity for a 500 yr old SNR incl. particle acceleration (Ferrand et al., 2010)

Supernova Remnant Evolution

1. **Free expansion** (a few 100 yrs):

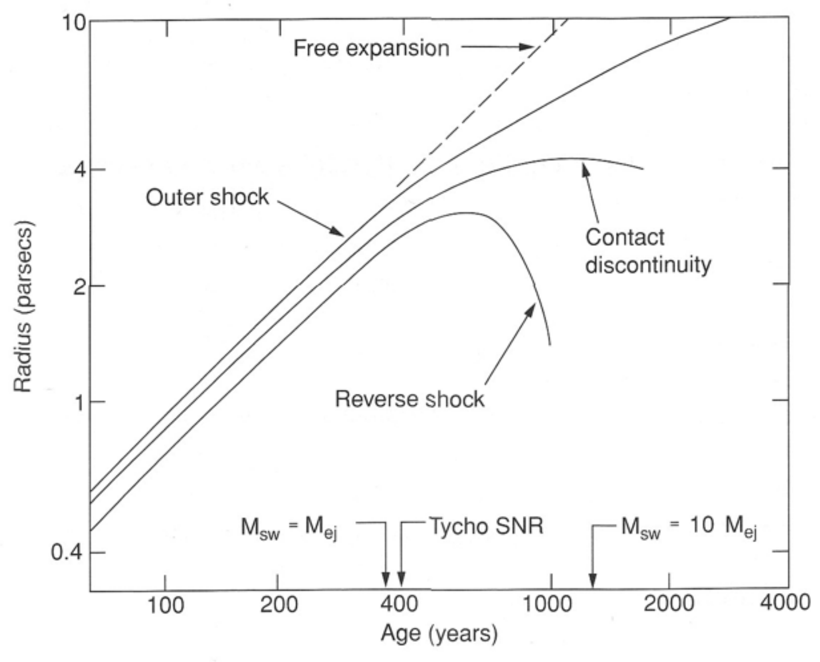
   Constant expansion velocity and temperature.

2. **Sedov or adiabatic phase** (1000 to 10 000 yrs):

   Interaction of the blast wave with the ISM causes deceleration.

   Reverse Shock runs into the ejecta.

   Ejecta mixes with shocked ISM.



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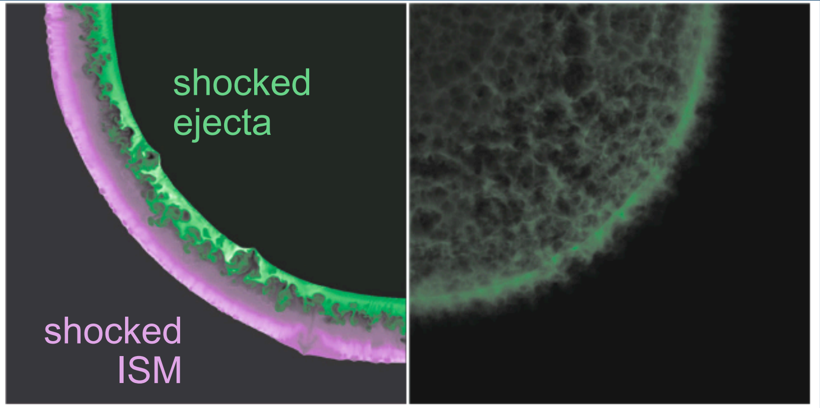

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Supernova Remnant Evolution

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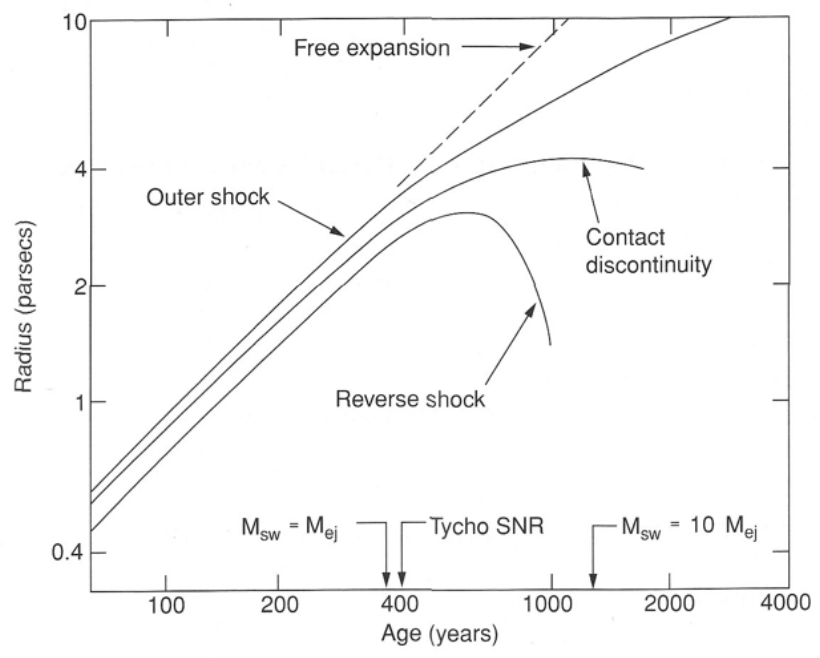
   Ejecta mixes with shocked ISM.

3. **Radiative phase** (10 000 to 100 000 yrs):

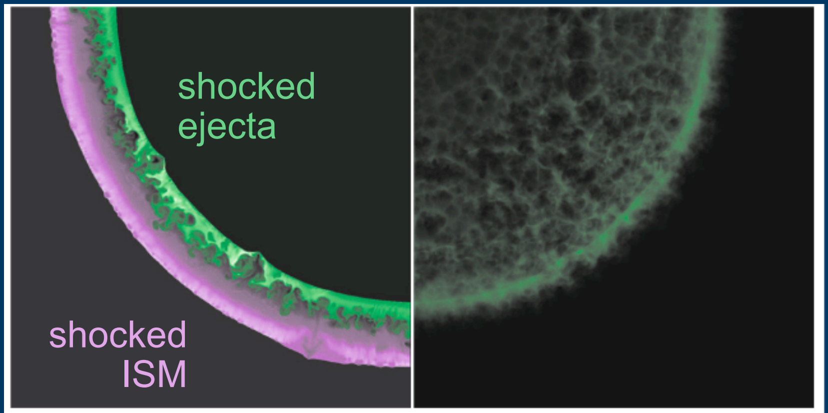
   SNR has cooled to < 10^6 K.

   Radiates energy efficiently, cooling becomes non-negligible.

   A thin shell is formed, which emits optical light.



Seward & Charles, 'Exploring the X-ray Universe'

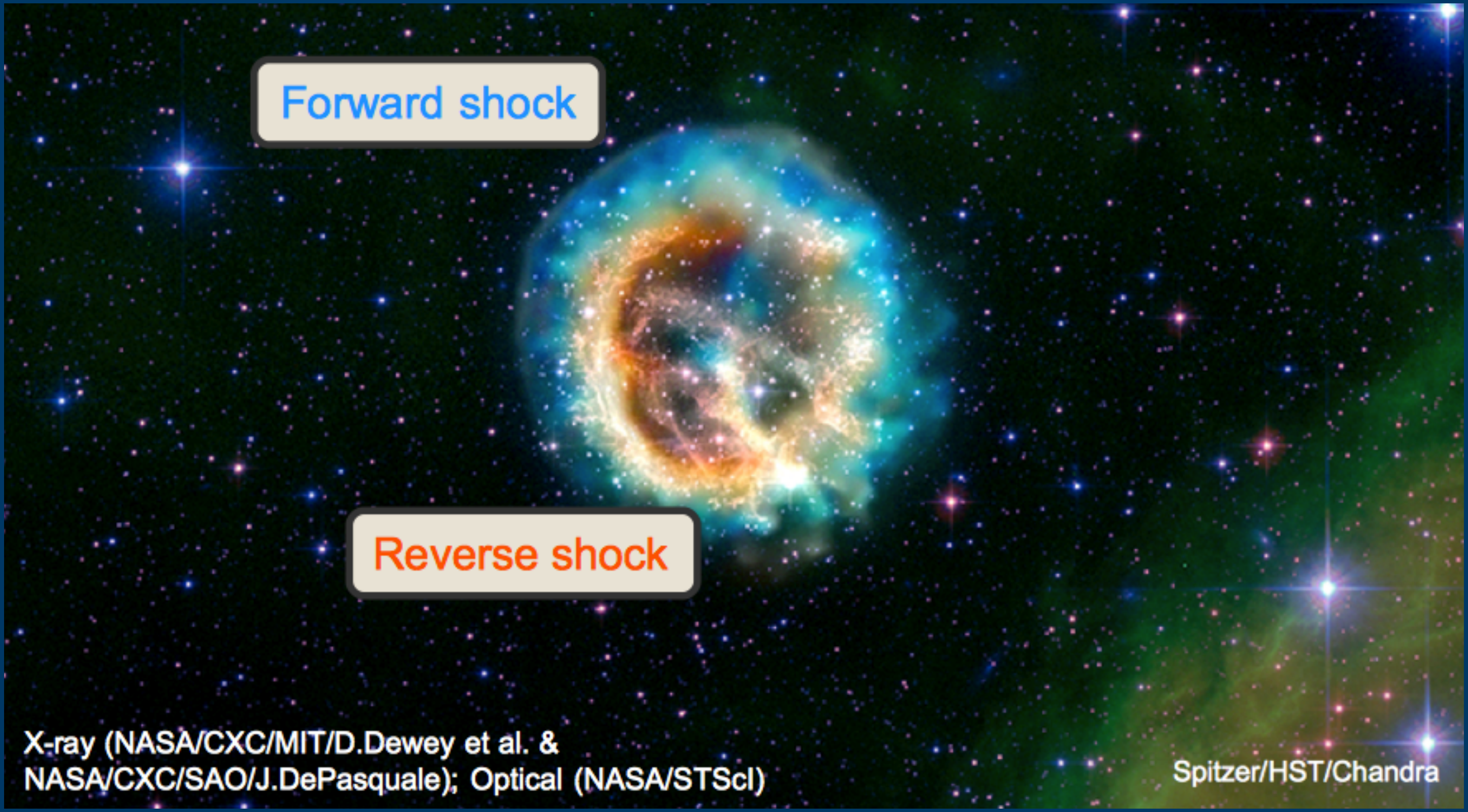


Simulated density distribution (left) and ejecta emissivity for a 500 yr old SNR incl. particle acceleration (Ferrand et al., 2010)

Shocked Plasma

SNR 1E0102.2-7219 in the Small Magellanic Cloud:

IR, optical, and X-ray emission

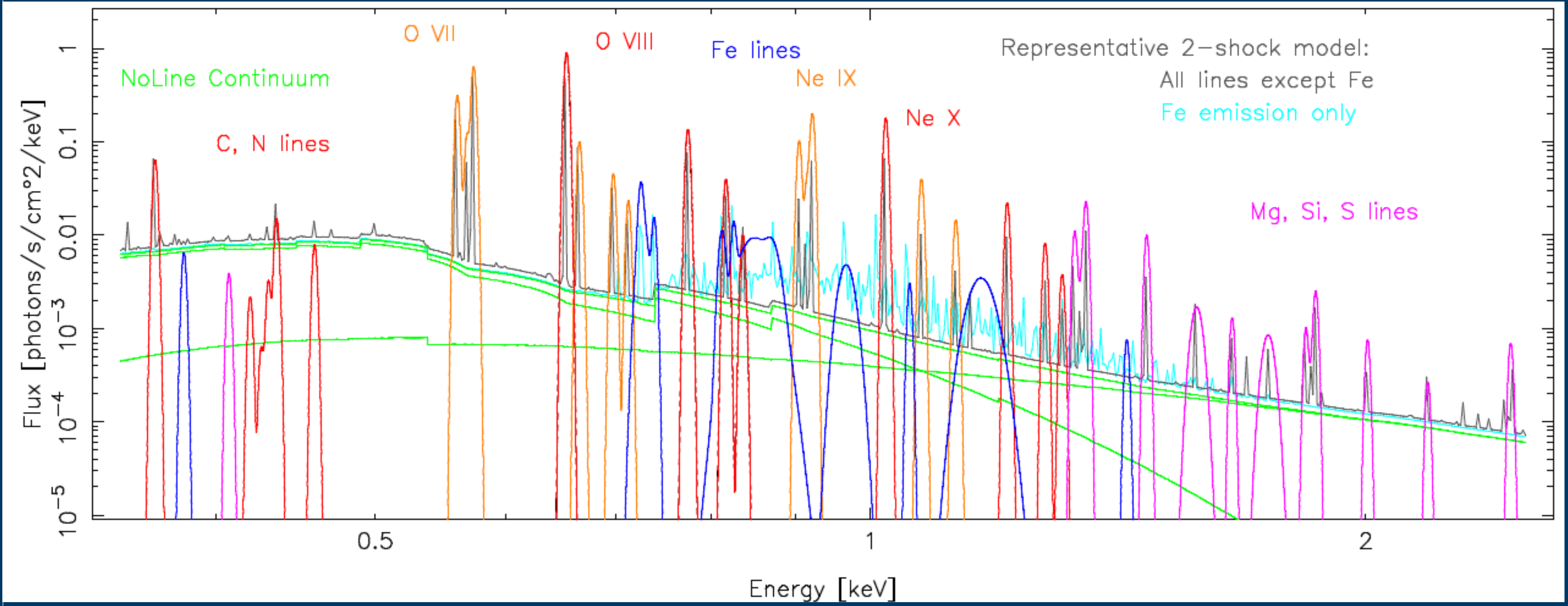


Thermal X-ray Spectrum

Lines of highly ionised elements (H- and He-like).

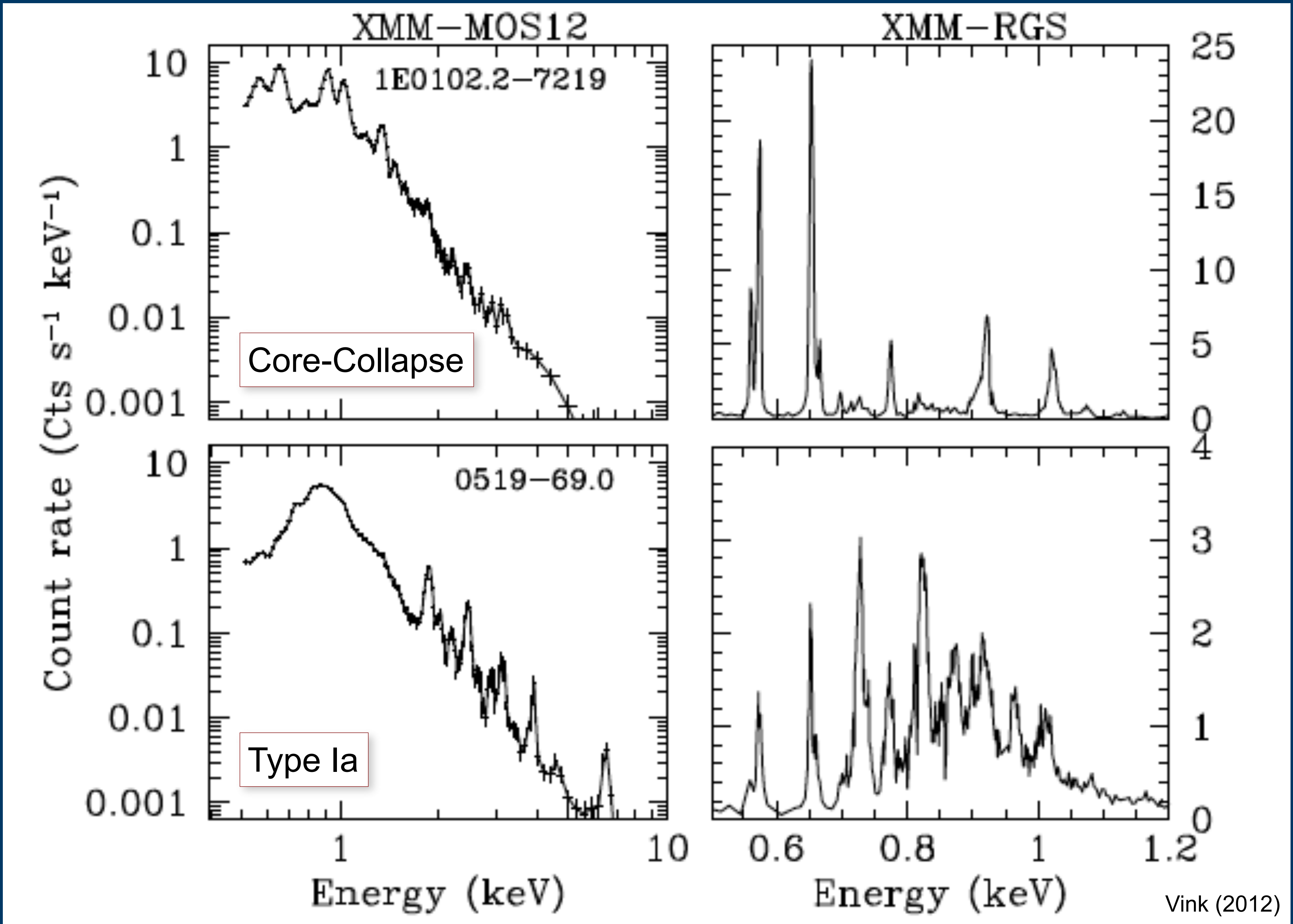
Continuum: Bremsstrahlung, radiative recombination continuum (RRC), and the 2s→1s two-photon continuum from hydrogenic and helium-like ions.

Spectral model for SNR E0102



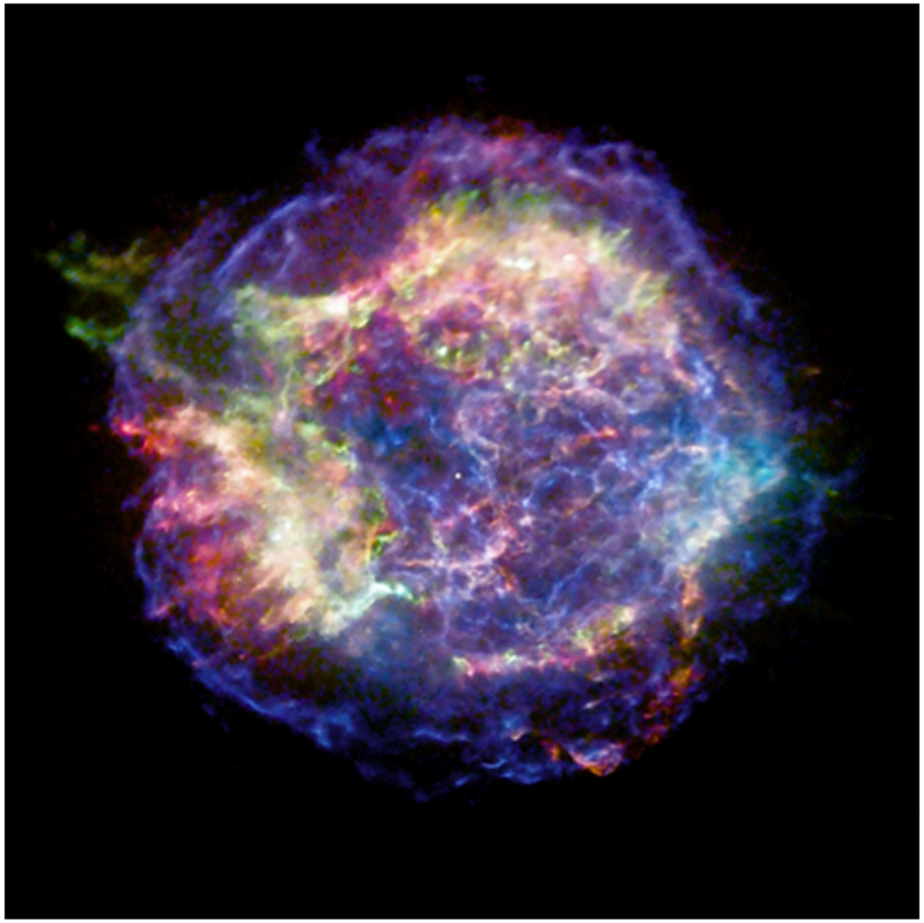
Plucinsky et al. (2008)

SN Types


XMM−MOS12
XMM−RGS
1E0102.2−7219
0519−69.0
Core-Collapse
Type Ia
Count rate (Cts s−1 keV−1)
10
1
0.1
0.01
0.001
0
5
10
15
20
25
0
1
2
3
4
1
10
0.6
0.8
1
1.2
Energy (keV)
Energy (keV)
Vink (2012)

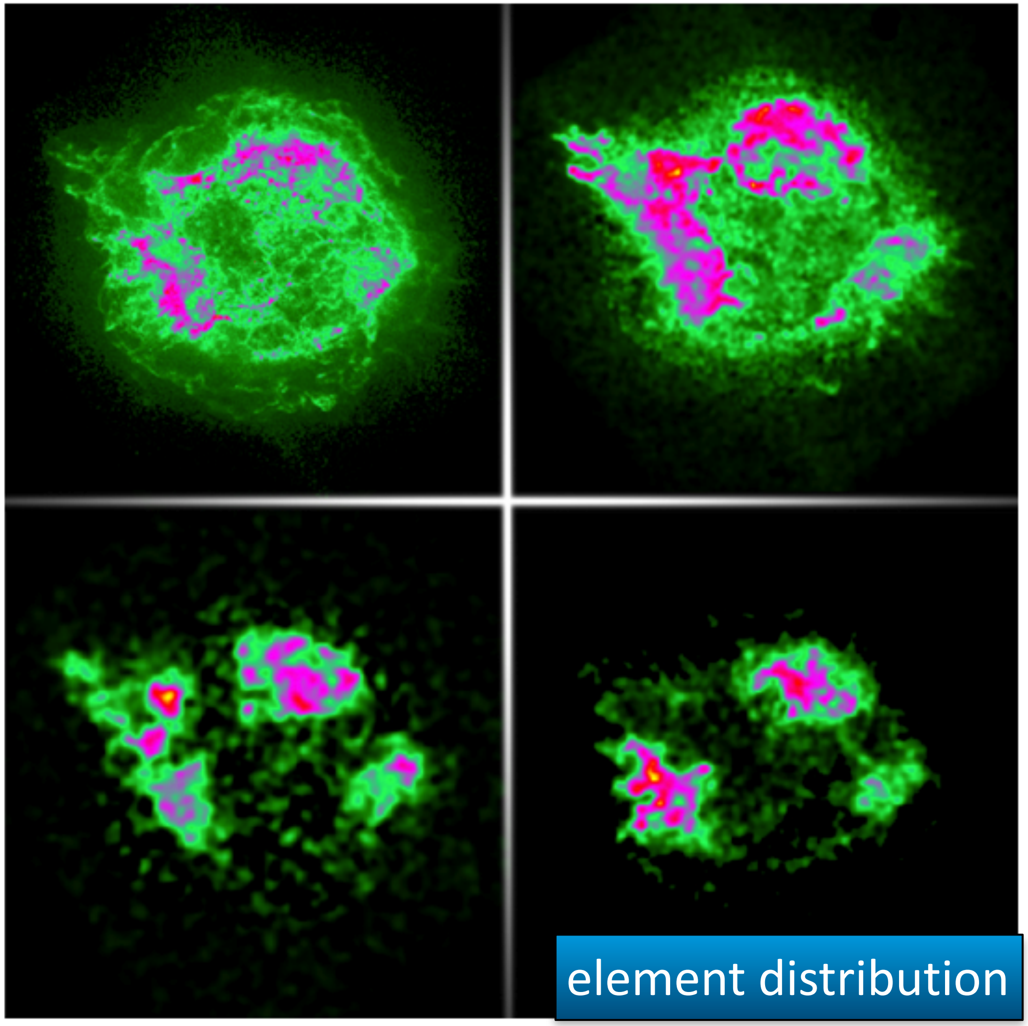
Hot Ejecta

Distribution of Elements in SNR Cas A



Chandra ACIS
(Red = 0.5-1.5 keV, Green = 1.5-3.0 keV, Blue = 4.0-6.0 keV)

NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.



Chandra ACIS
Upper right: silicon. Lower left: calcium. Lower right: iron.

NASA/GSFC/U.Hwang et al.

Hot Ejecta

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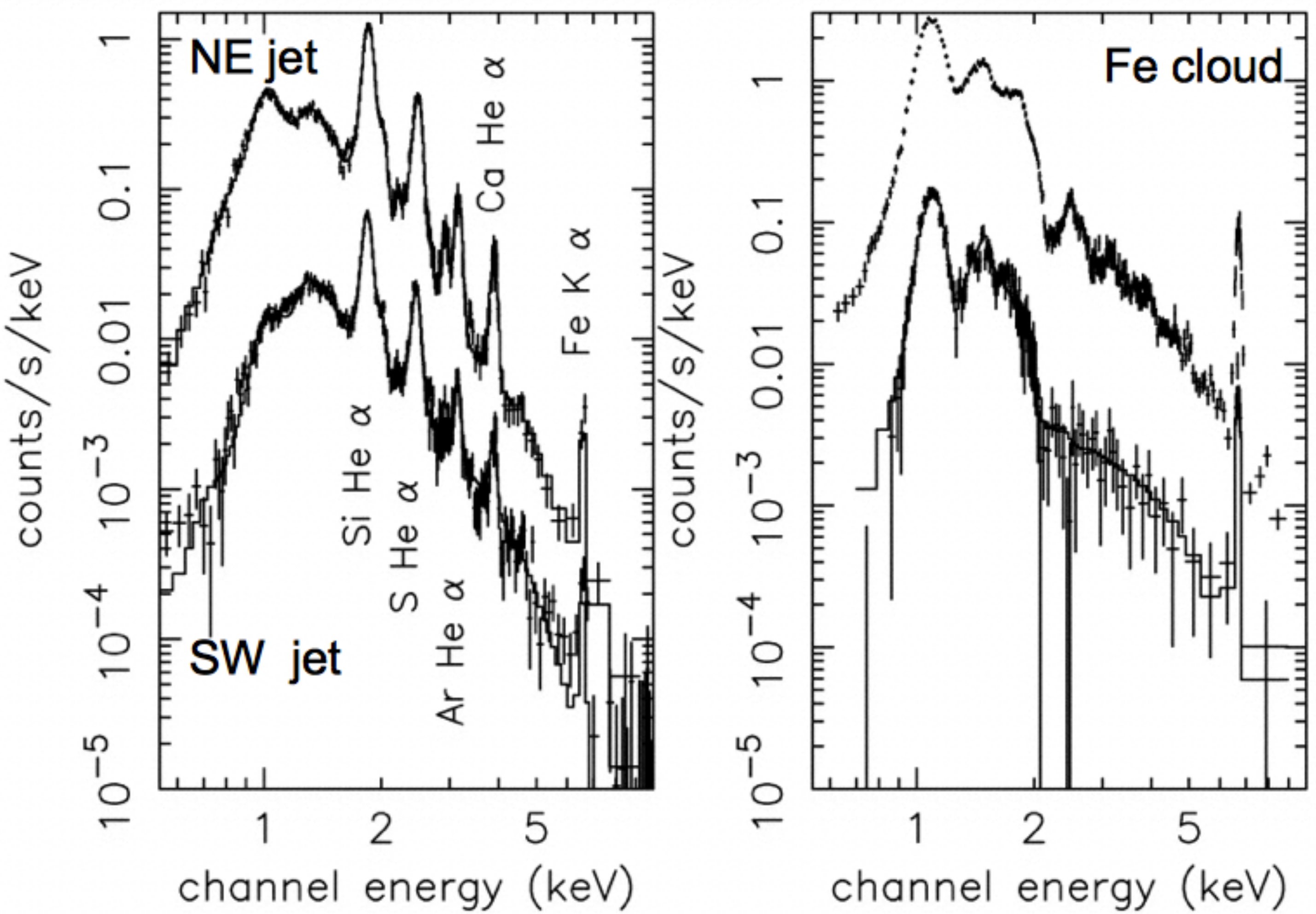

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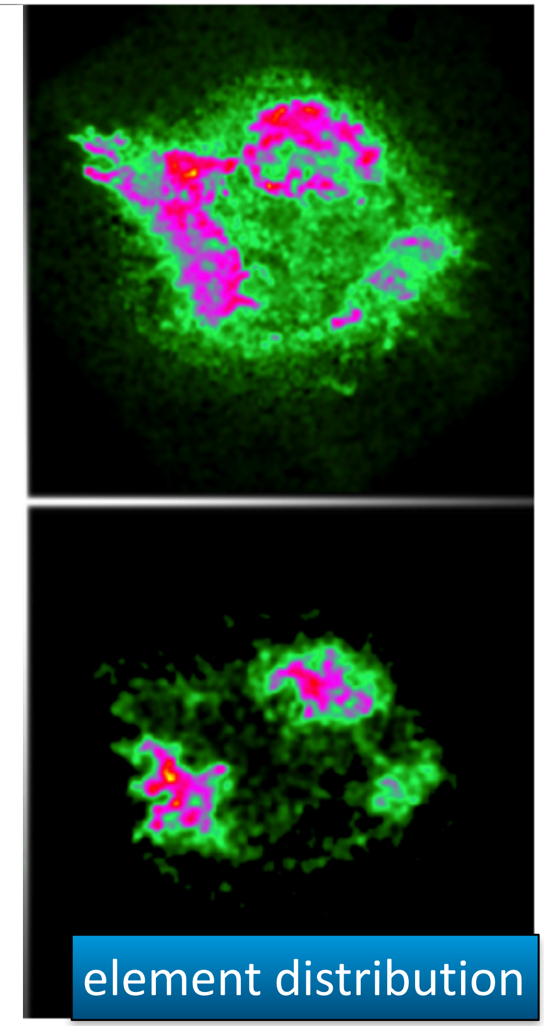

Chandra ACIS
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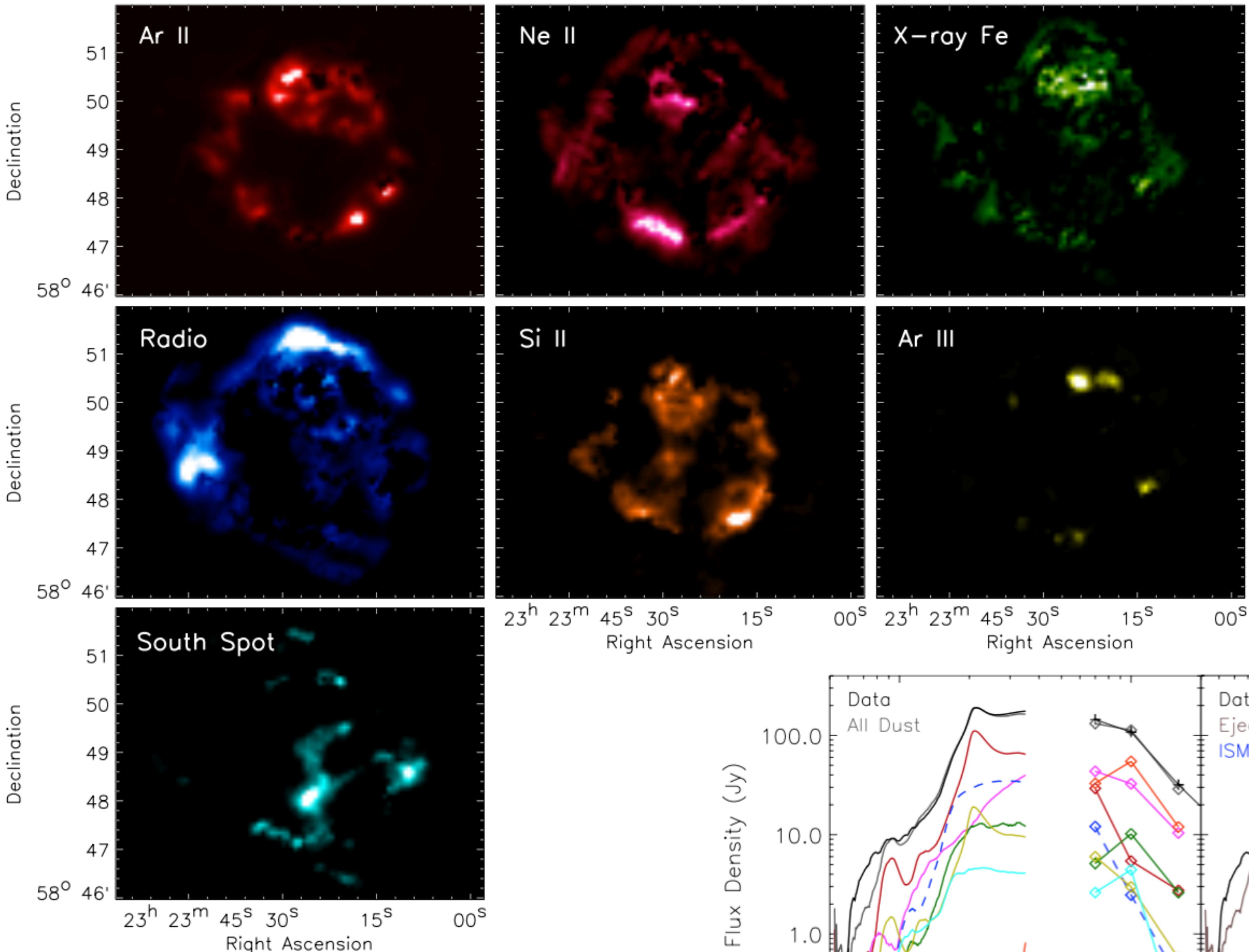
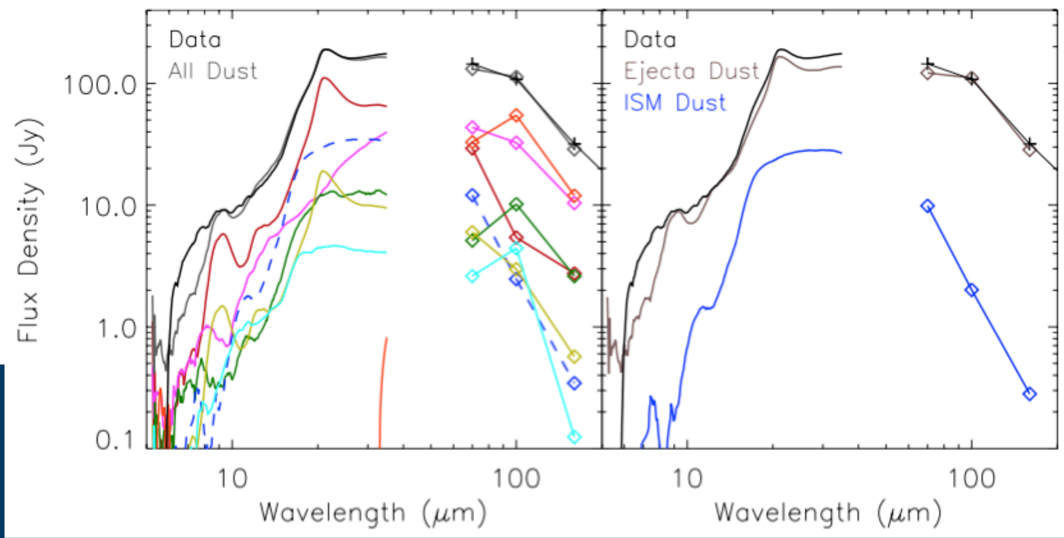
NASA/GSFC/U.Hwang et al.

Cold Ejecta

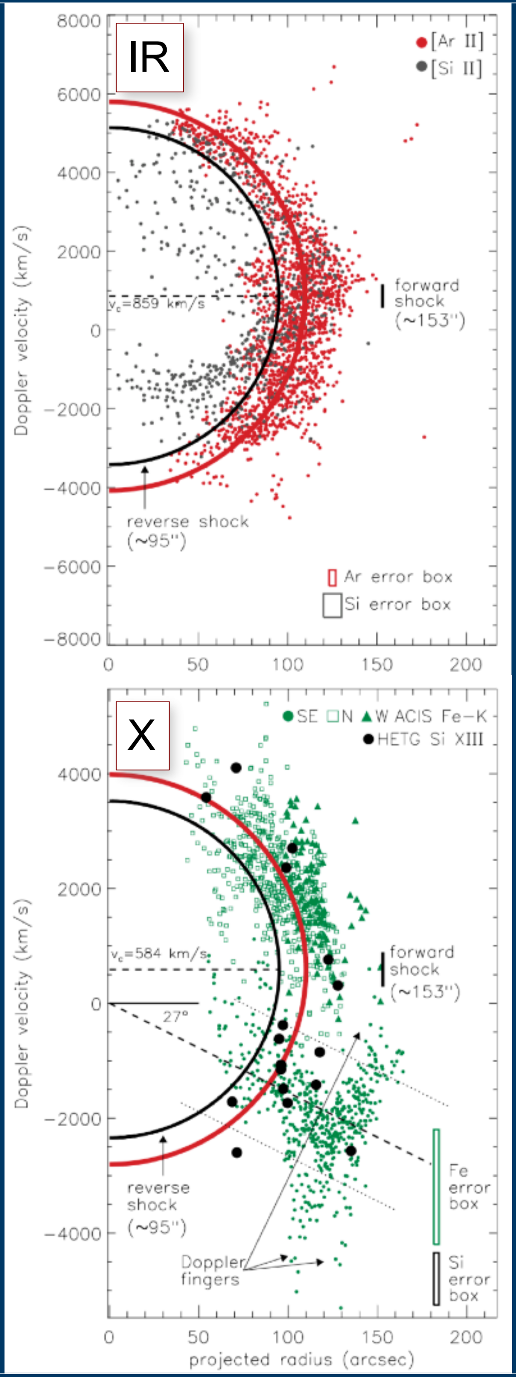


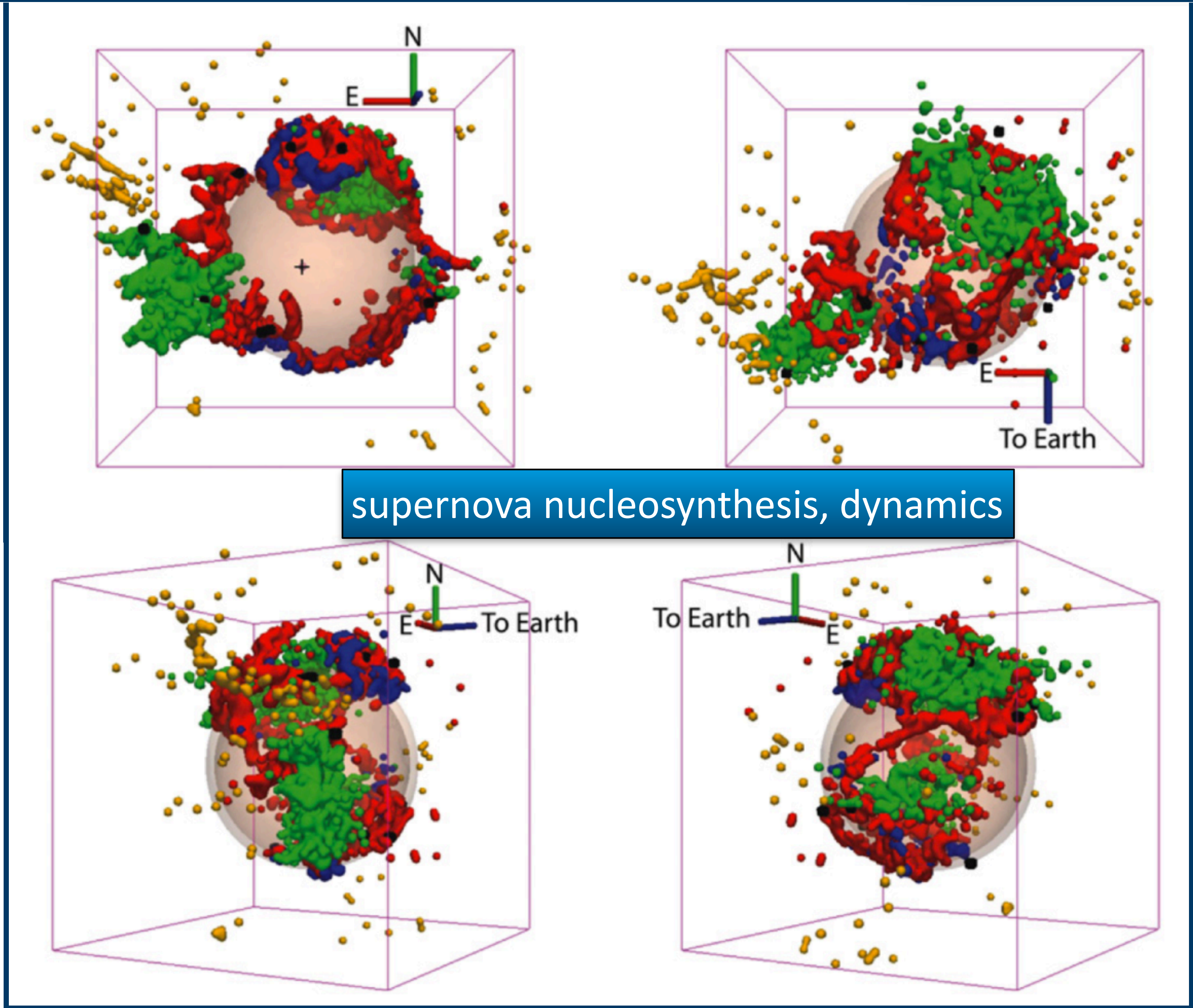


Arendt et al. (2014)

Infrared observation of Cas A

Distribution of Ejecta



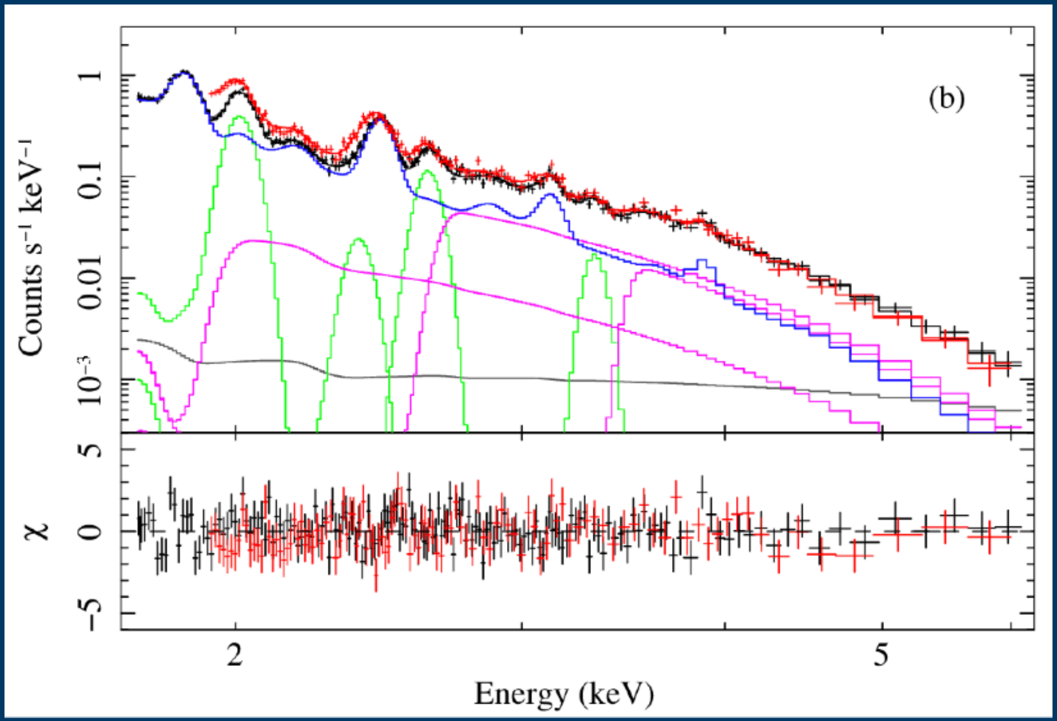


DeLaney et al. (2010)

Radiative Recombination

SNR IC 443

Chandra with radio and optical



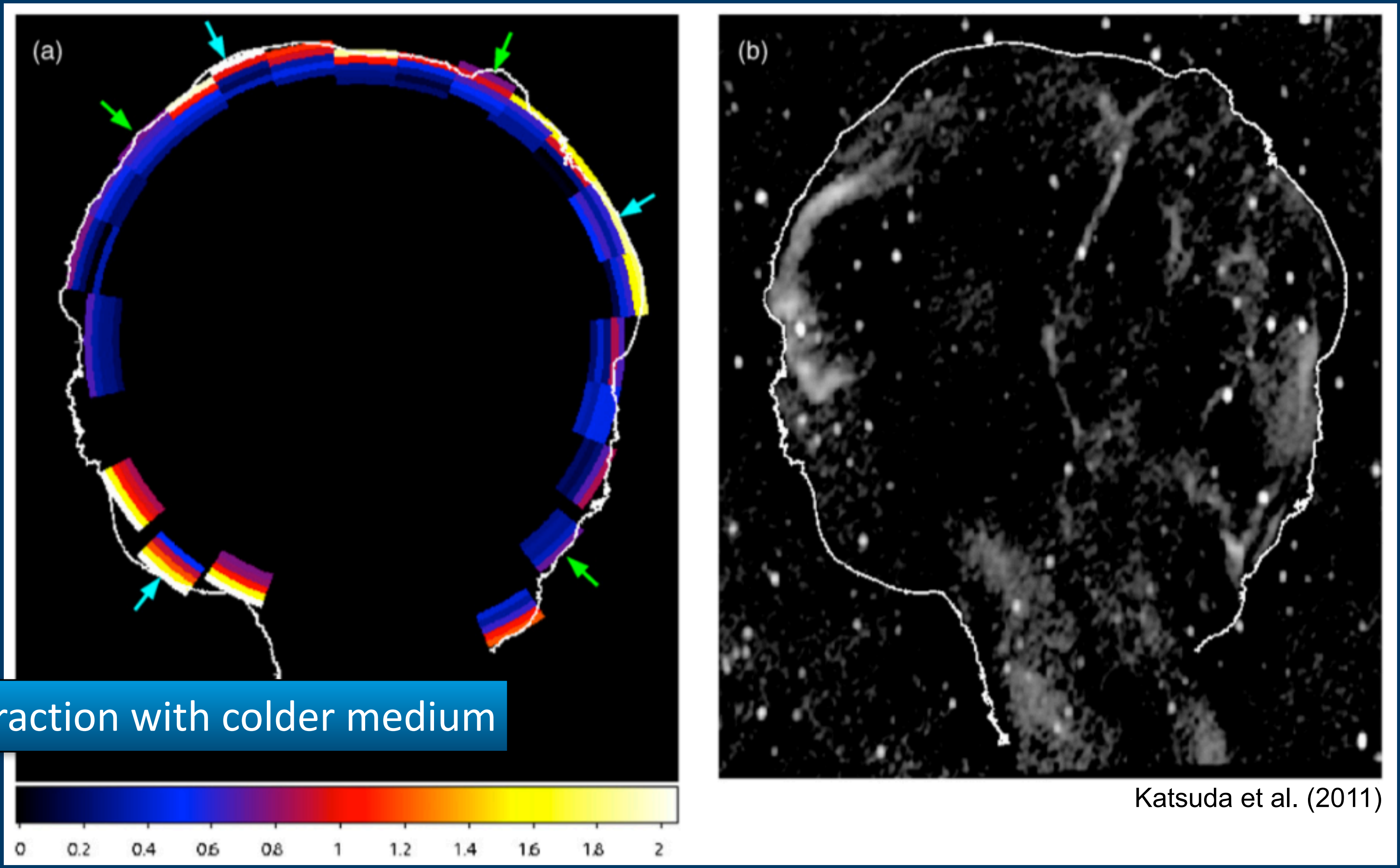
Suzaku spectrum
Magenta: radiative recombination continuum emission of H-like Mg, Si, and S

Yamaguchi et al. (2009)

Charge Exchange

Cygnus Loop SNR:

Excess emission near Fe L-complex at ~0.7 keV: charge exchange emission produced at sites where hot plasma interacts with (partially) neutral gas.



interaction with colder medium

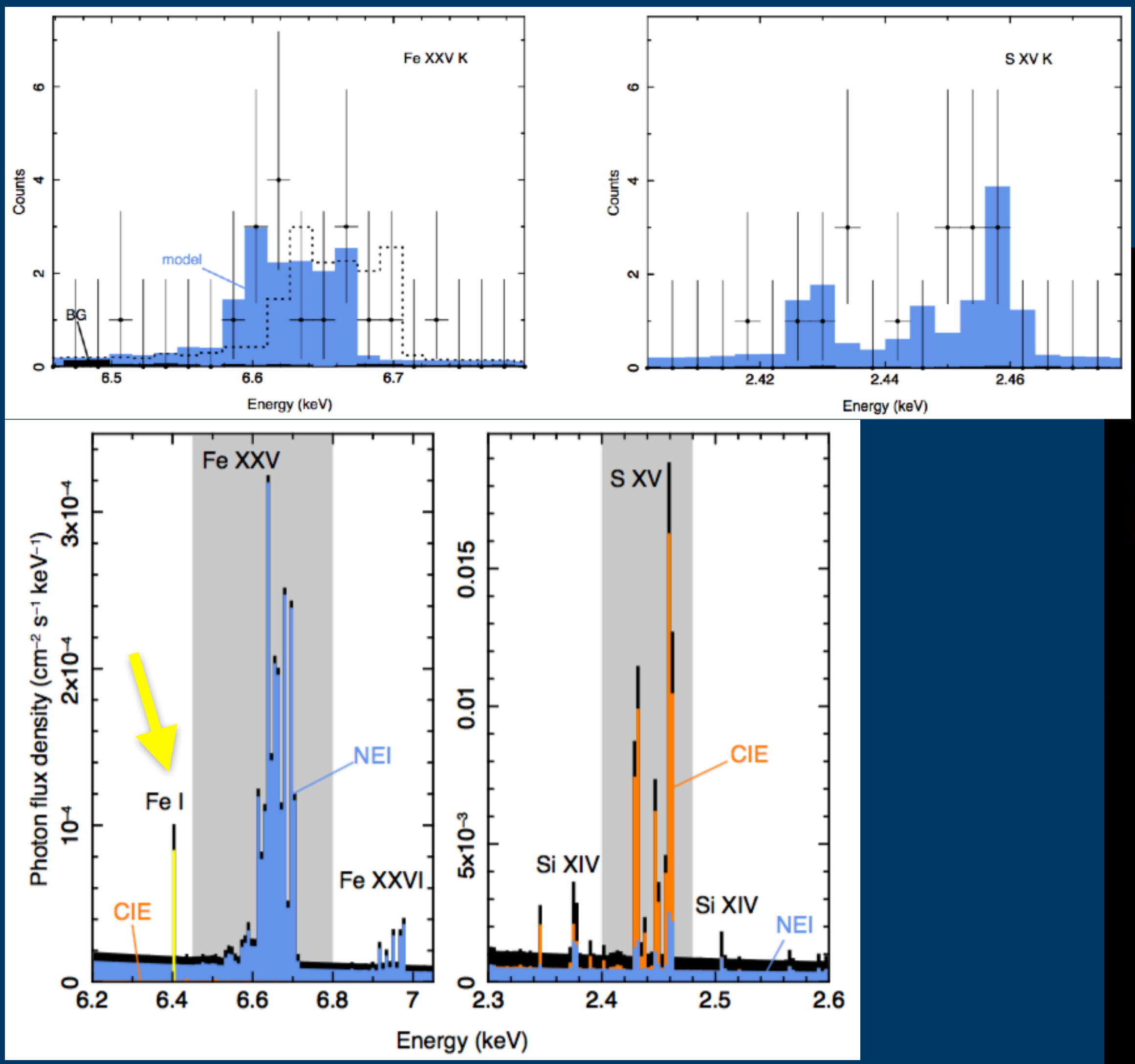
Line ratio map of the 0.7 keV line

Radio continuum image

X-ray Microcalorimeter Spectrum

Highly redshifted Fe lines (~800 km/s)

Neutral Fe I emission from interaction of cosmic rays with ambient medium? (Seen with NuSTAR, Bamba et al. 2018)

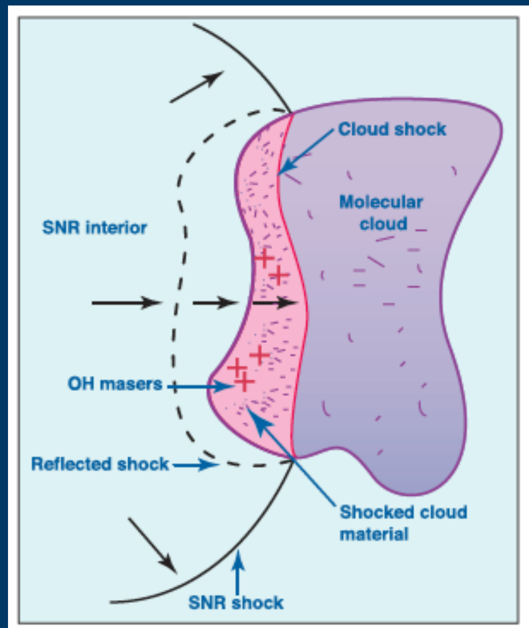


Hitomi Collaboration (2018)

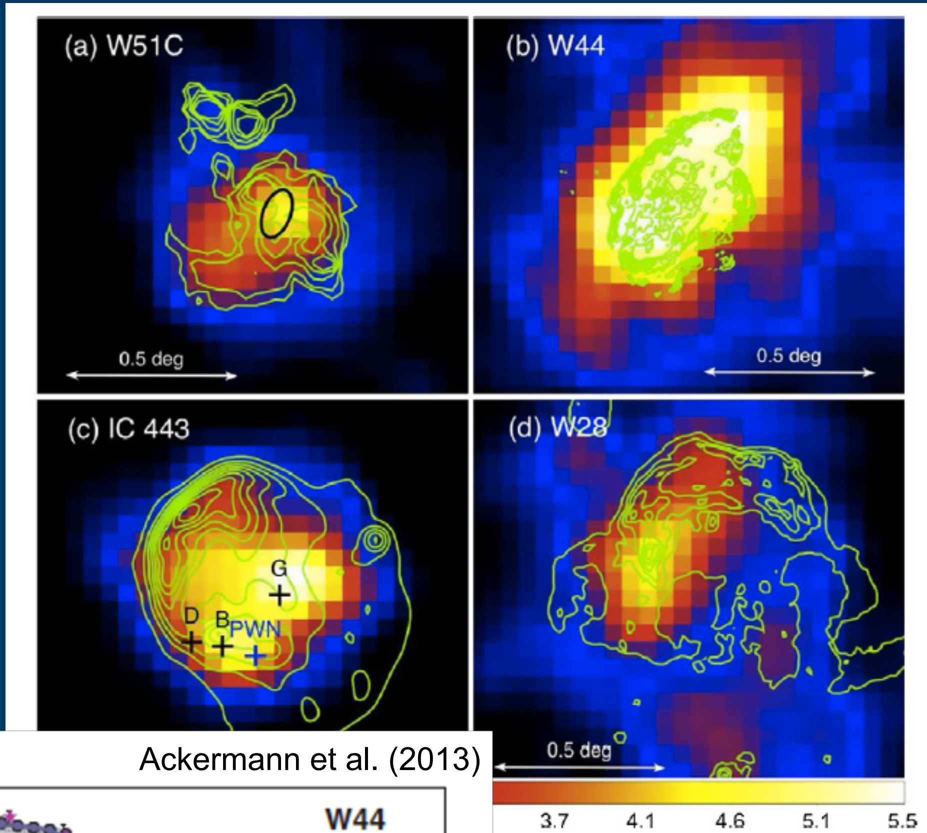
GeV to TeV Emission

SNRs interacting with molecular clouds:
p-p interactions followed by π^0 decay

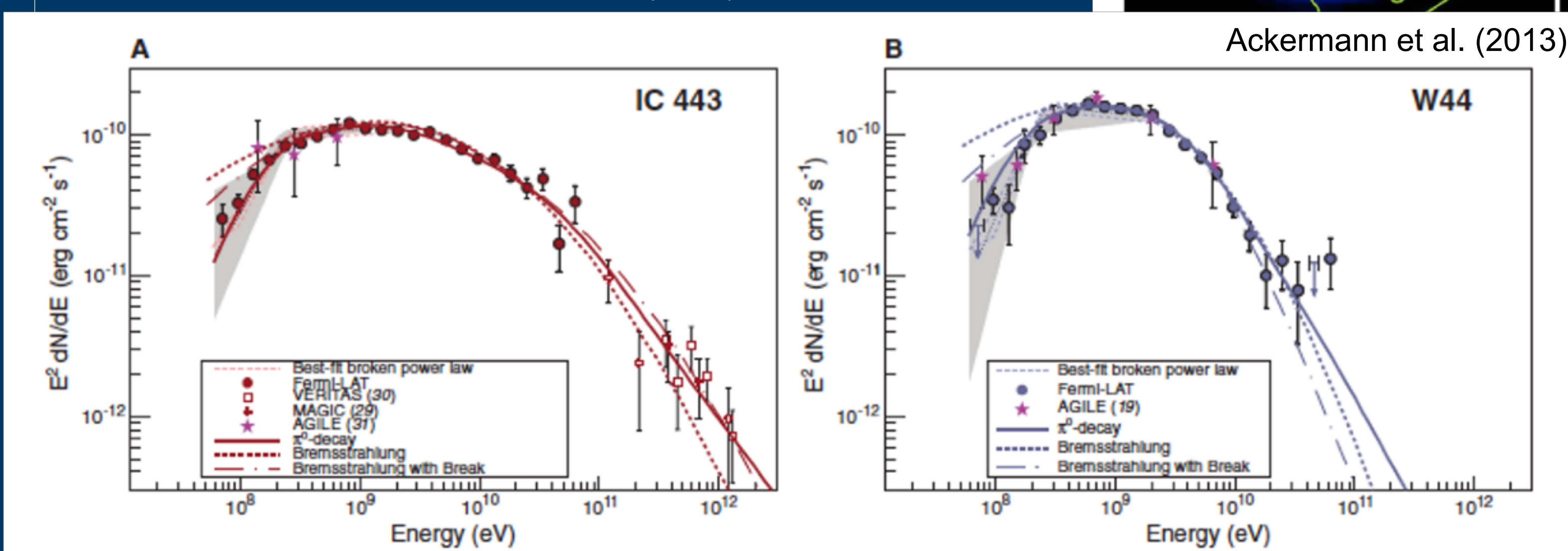
Fermi LAT 2 – 10 GeV count maps with VLA radio contours.
Ellipse: shocked CO clumps, crosses: OH masers.



Wardle & Yusef-Zadeh (2002)

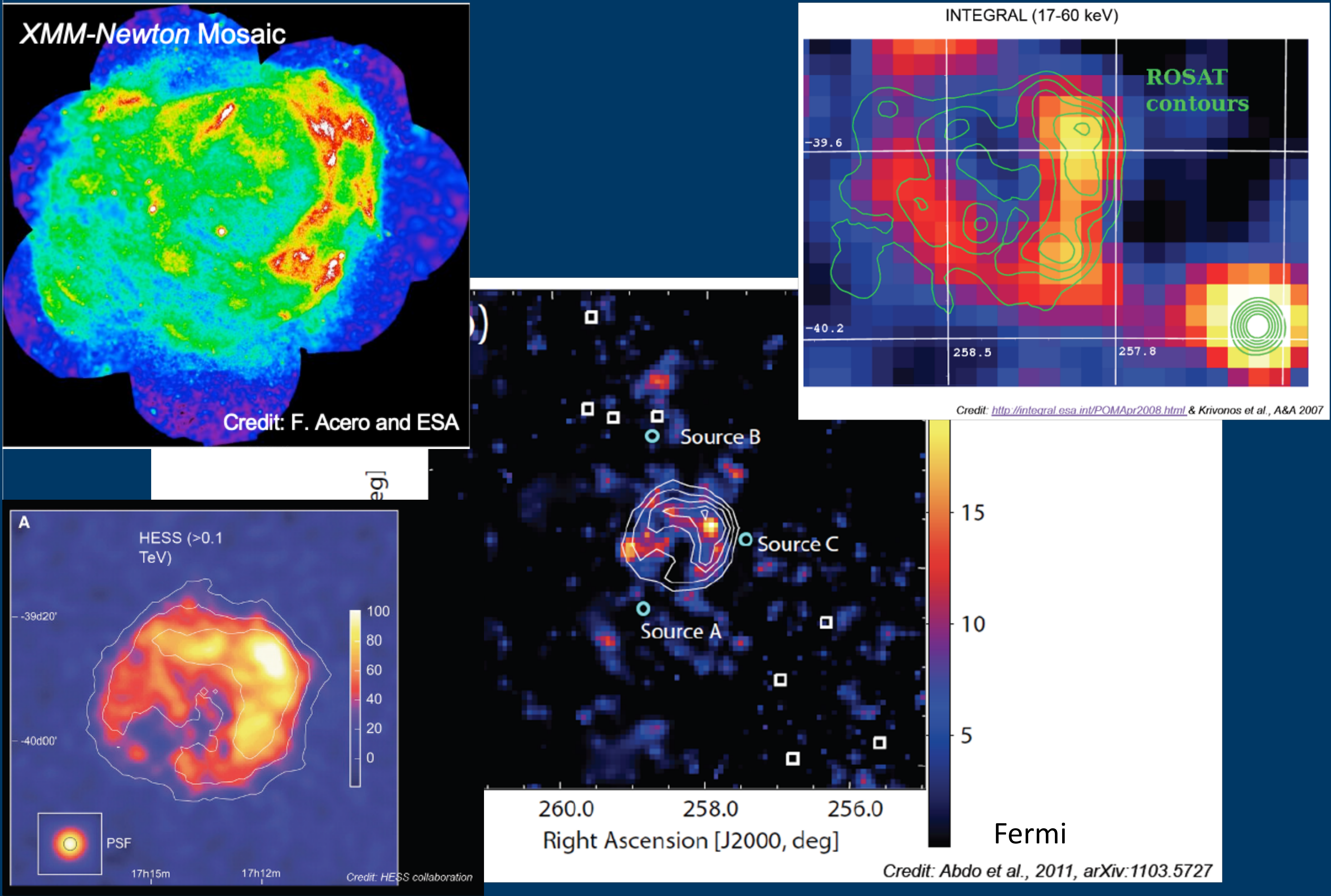


Thompson et al. (2011)

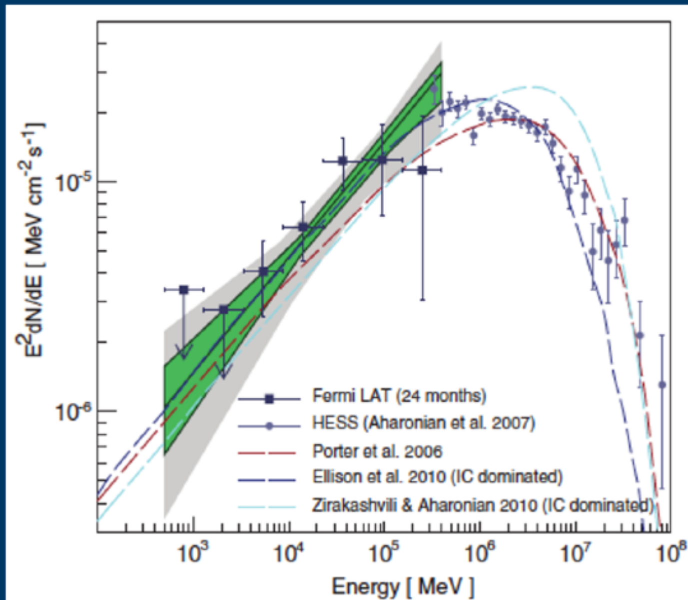


Ackermann et al. (2013)

RX J1713.7-3946



RX J1713.7-3946

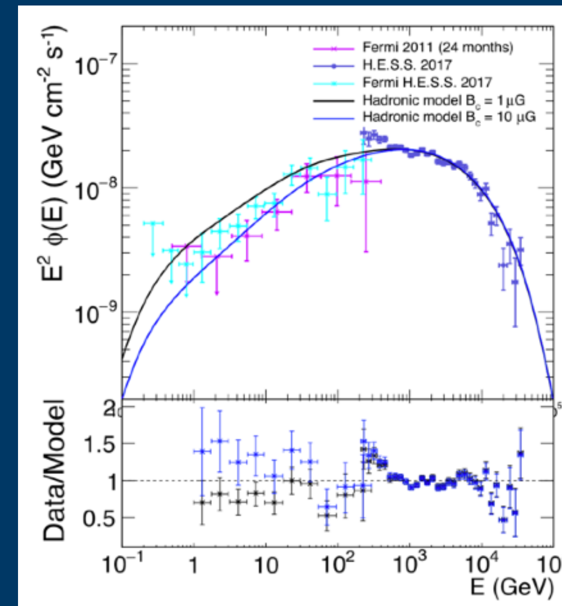


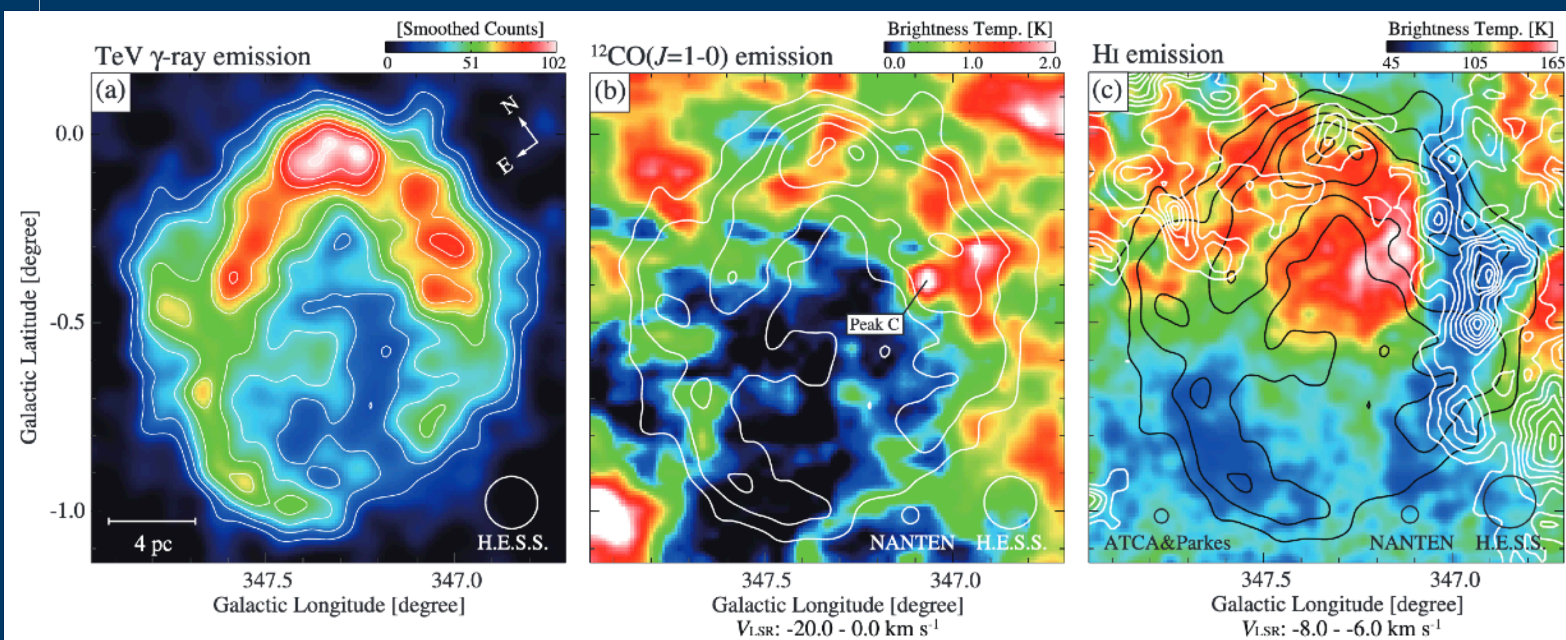
Leptonic Scenario

Abdo et al. (2011)

Hadronic Scenario

Celli et al. (2019)

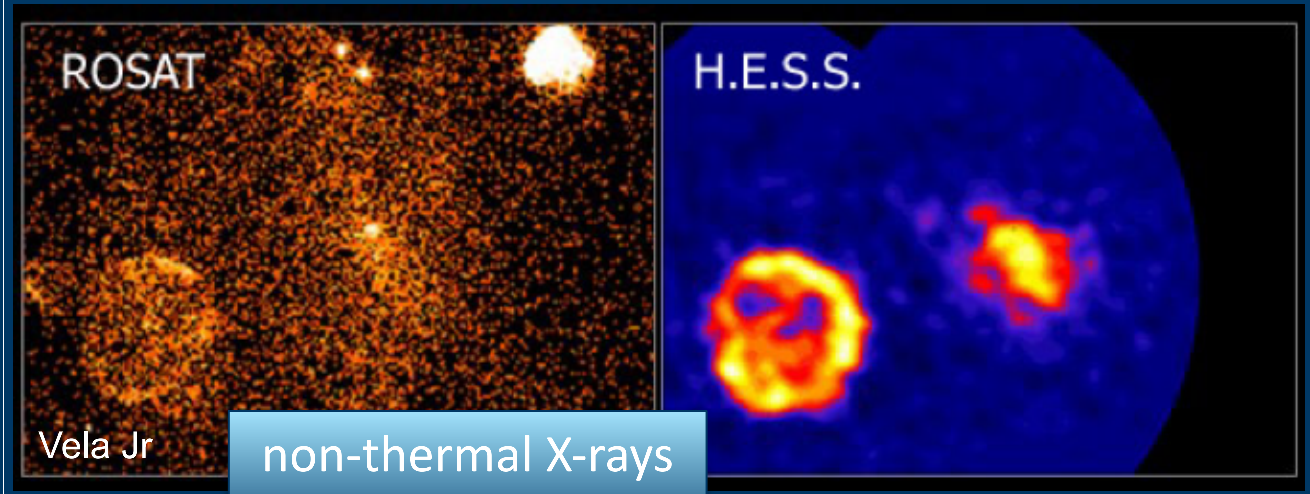




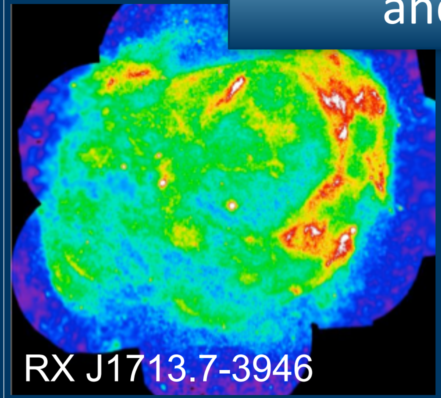
TeV emission and neutral ISM

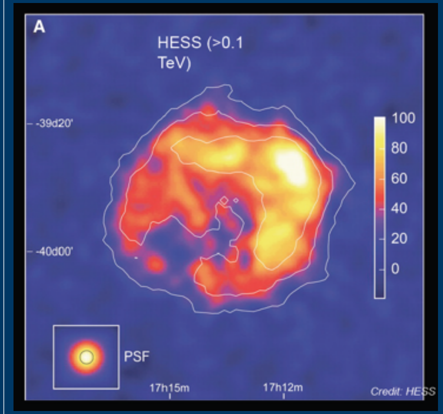
Fukui et al. (2012)

TeV Emission



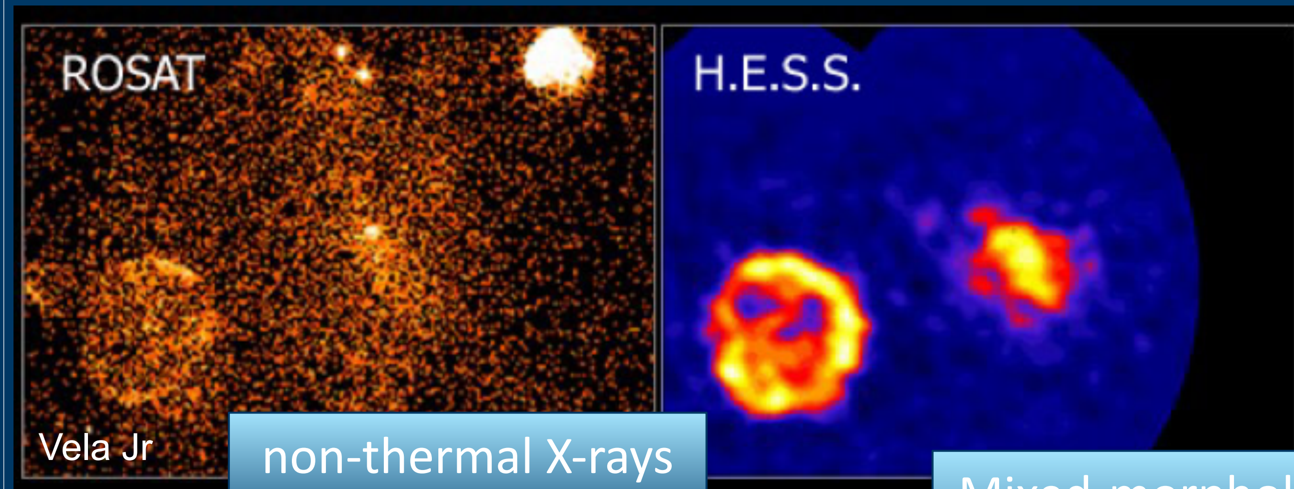
non-thermal X-rays and TeV





H.E.S.S. Collaboration

TeV Emission



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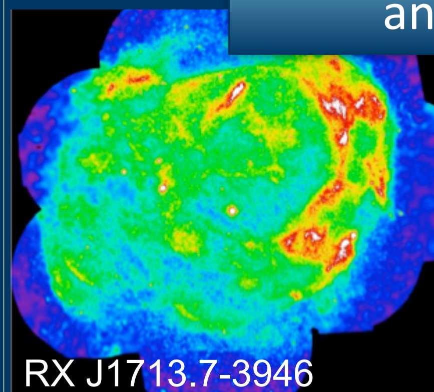
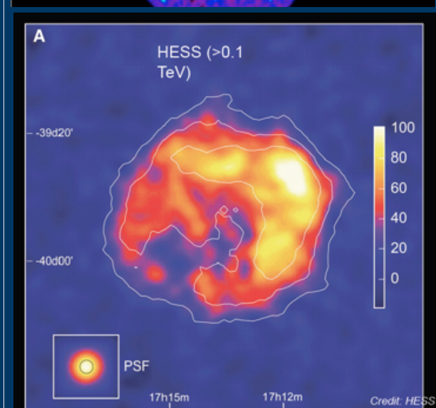
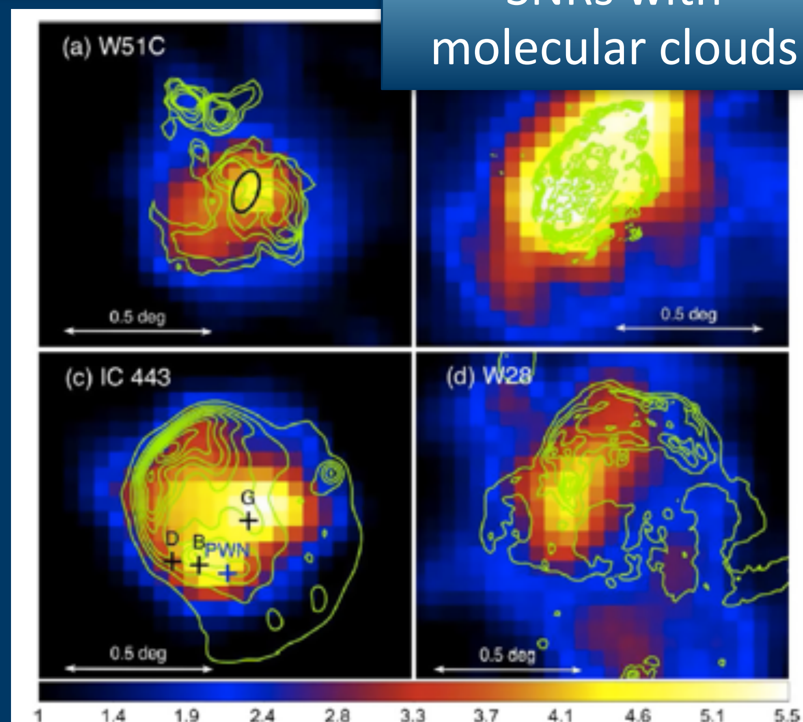




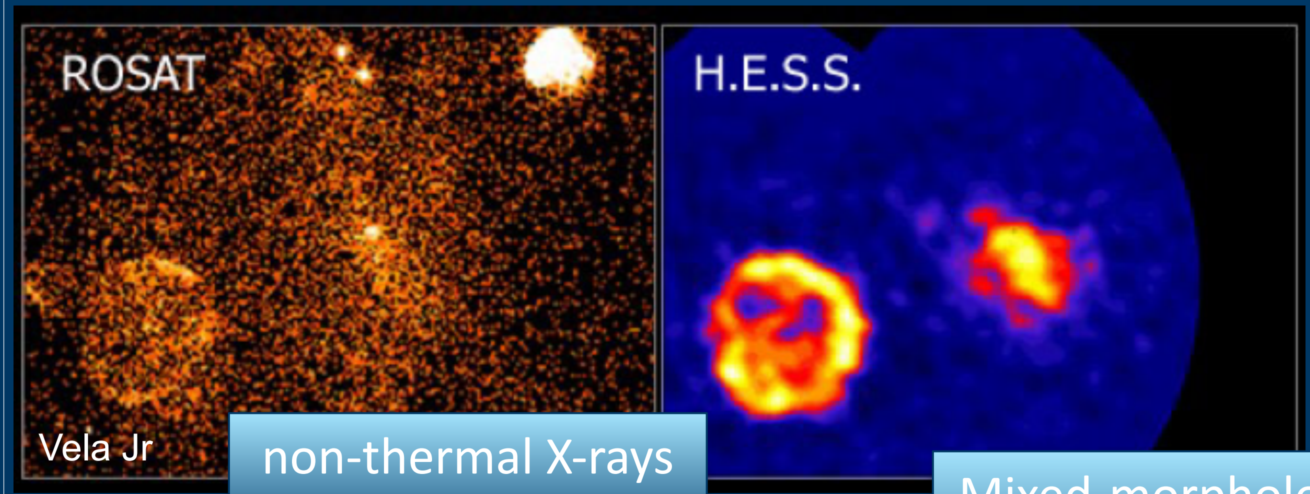
H.E.S.S. Collaboration

Mixed-morphology SNRs with molecular clouds

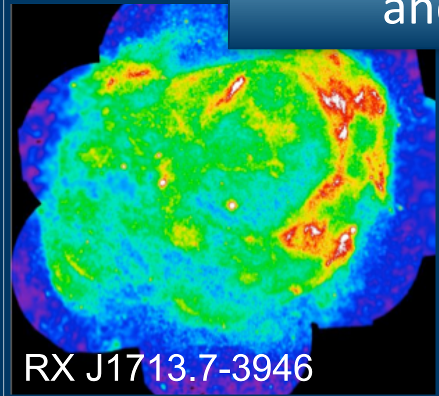


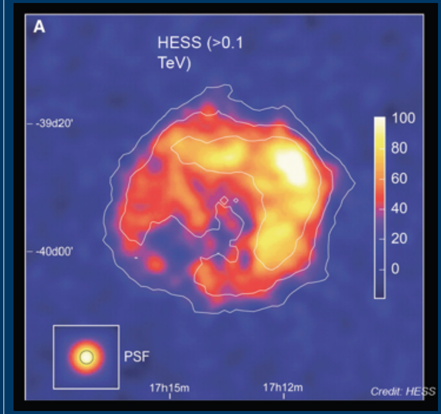
Fermi (Thompson et al., 2012)

TeV Emission



non-thermal X-rays and TeV





H.E.S.S. Collaboration

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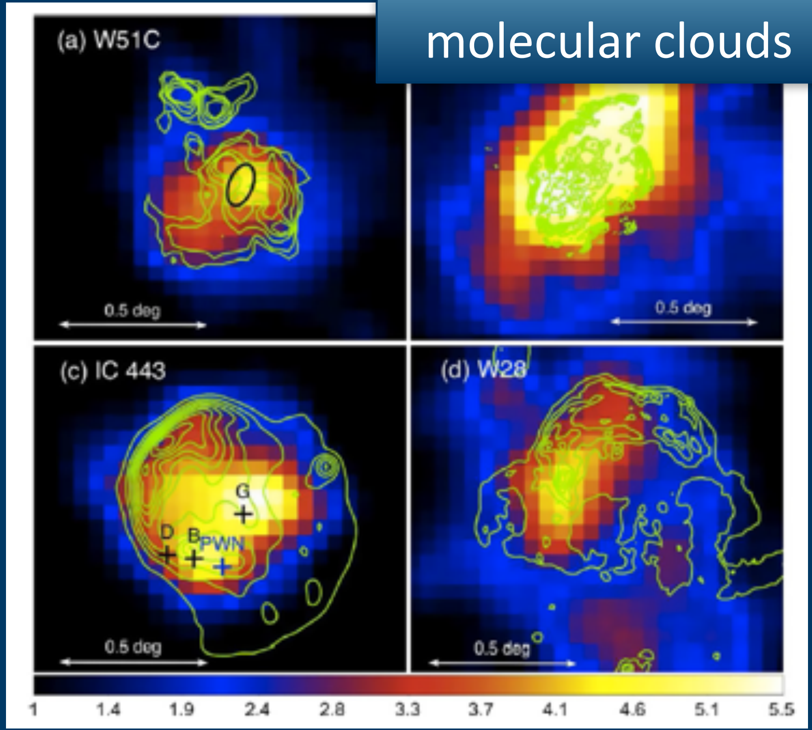
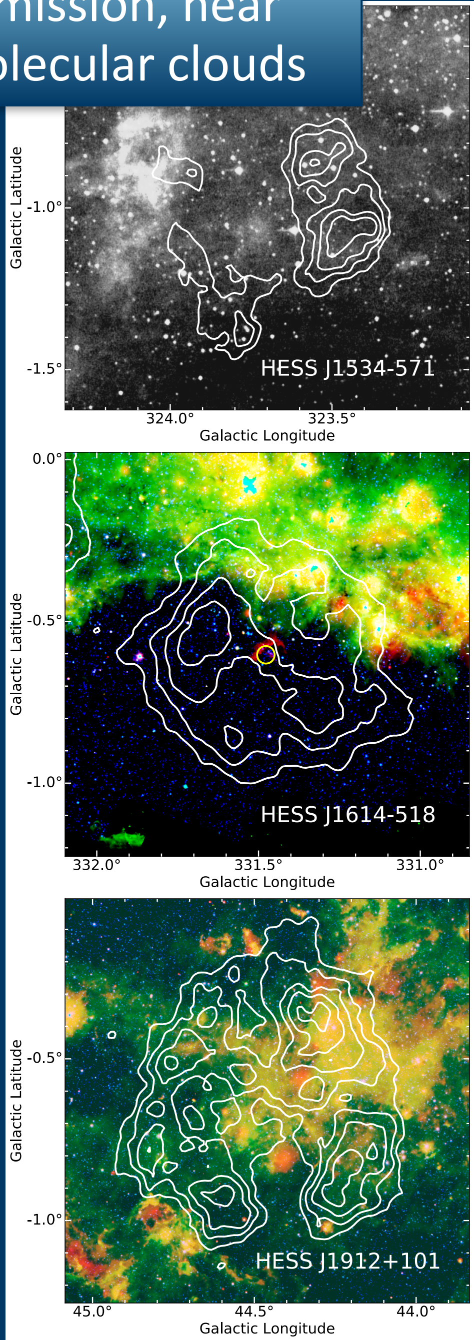


Fermi (Thompson et al., 2012)

No significant X-ray emission, near molecular clouds



H.E.S.S. Collaboration

TeV Emission

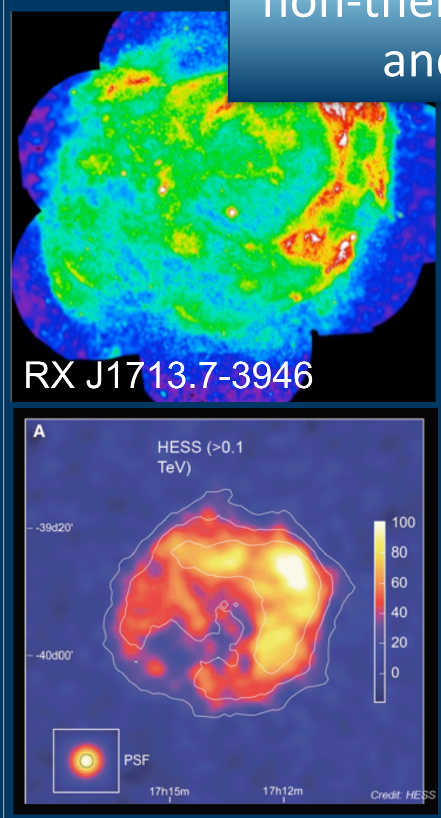
Leptonic scenario (Inverse Compton):

- Same particles responsible for synchrotron shell.
- Requires high shock velocities and downstream magnetic field of >10 μG.

Hadronic scenario (pp, π^0-decay):

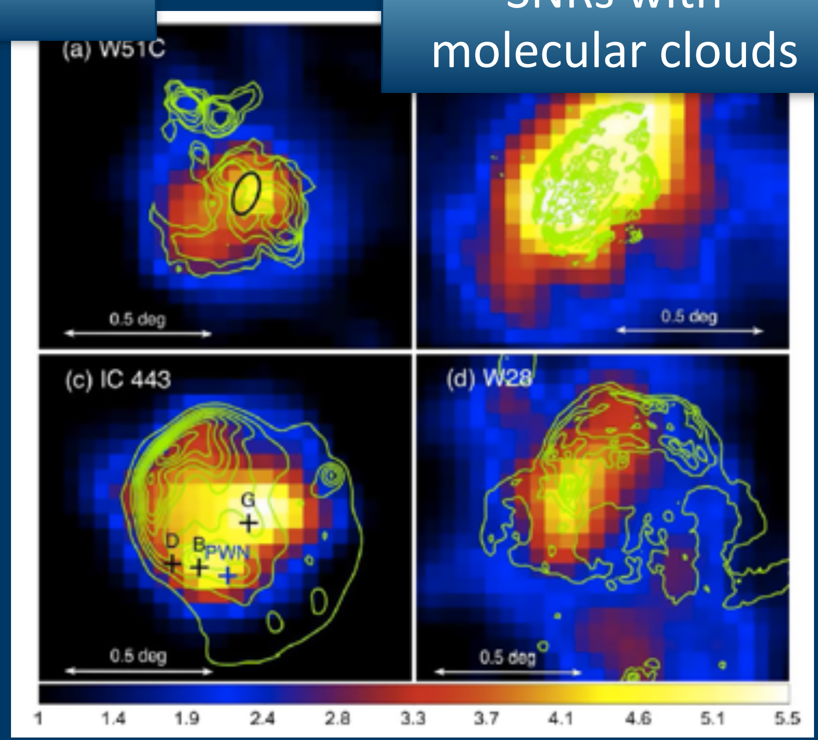
- Requires high densities (> 10 cm^{-3}) and high (amplified) magnetic field.

non-thermal X-rays and TeV



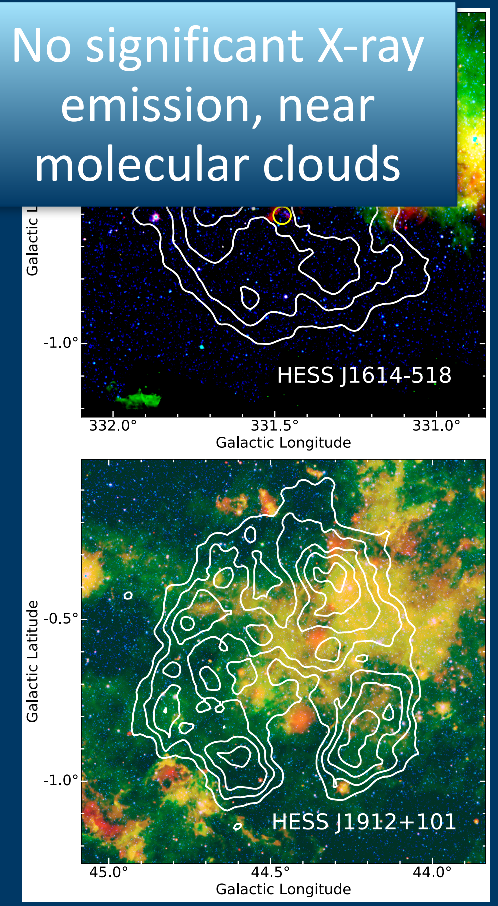
H.E.S.S. Collaboration

Mixed-morphology SNRs with molecular clouds



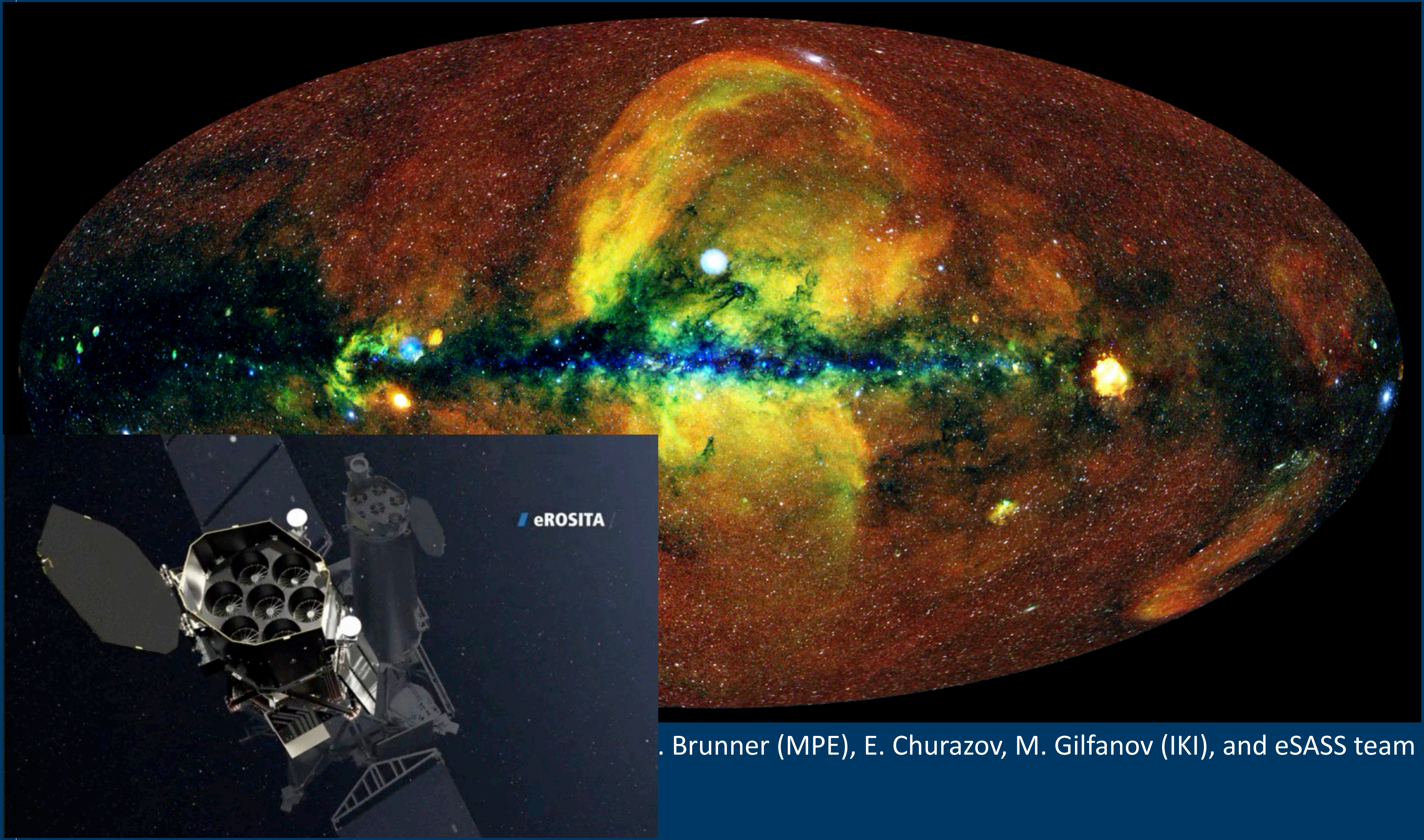
Fermi (Thompson et al., 2012)

No significant X-ray emission, near molecular clouds



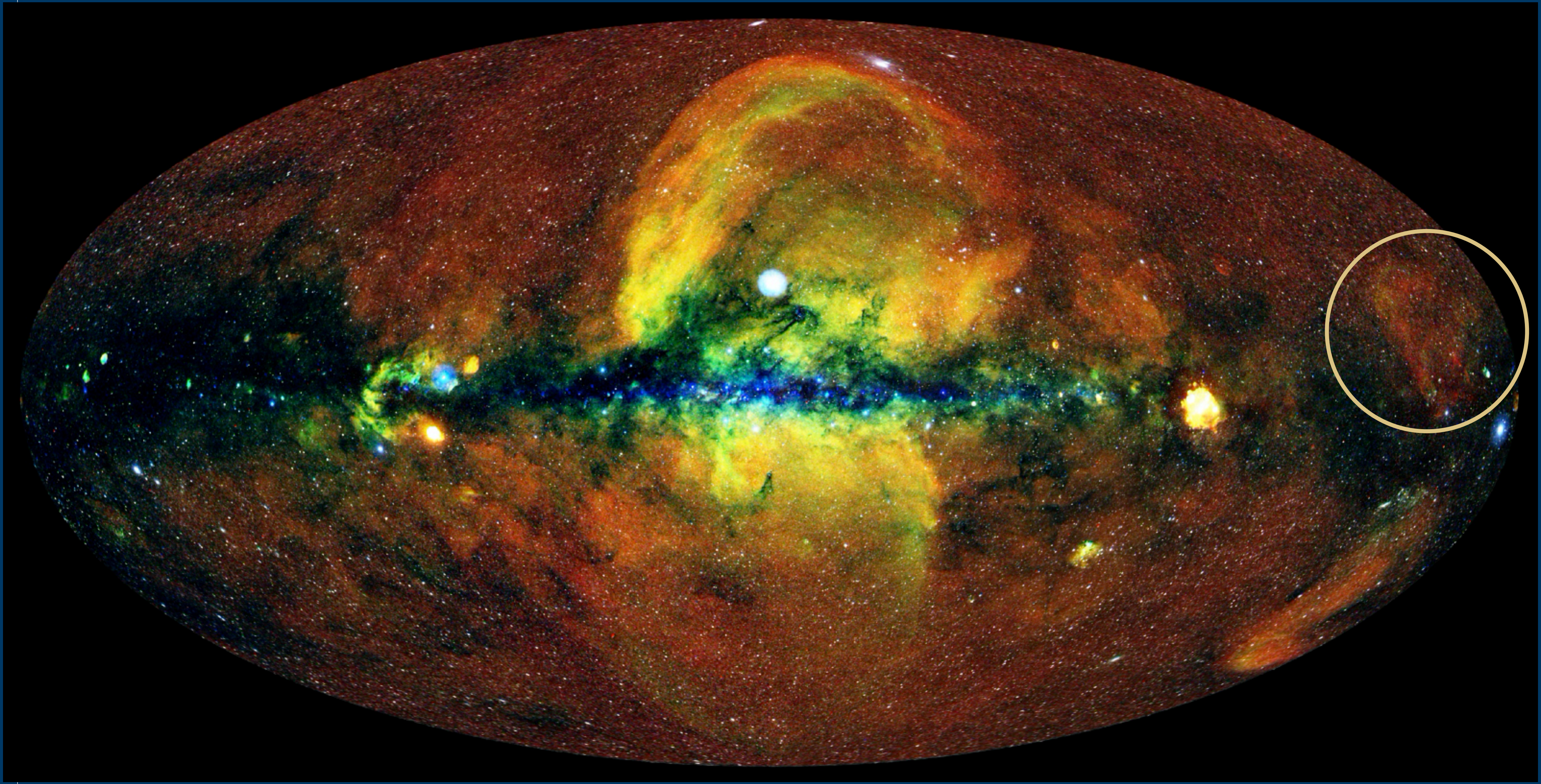
H.E.S.S. Collaboration

eROSITA All-Sky Survey



. Brunner (MPE), E. Churazov, M. Gilfanov (IKI), and eSASS team

Monogem Ring



J. Sanders, H. Brunner (MPE), E. Churazov, M. Gilfanov (IKI), and eSASS team

Monogem Ring

Old nearby SNR

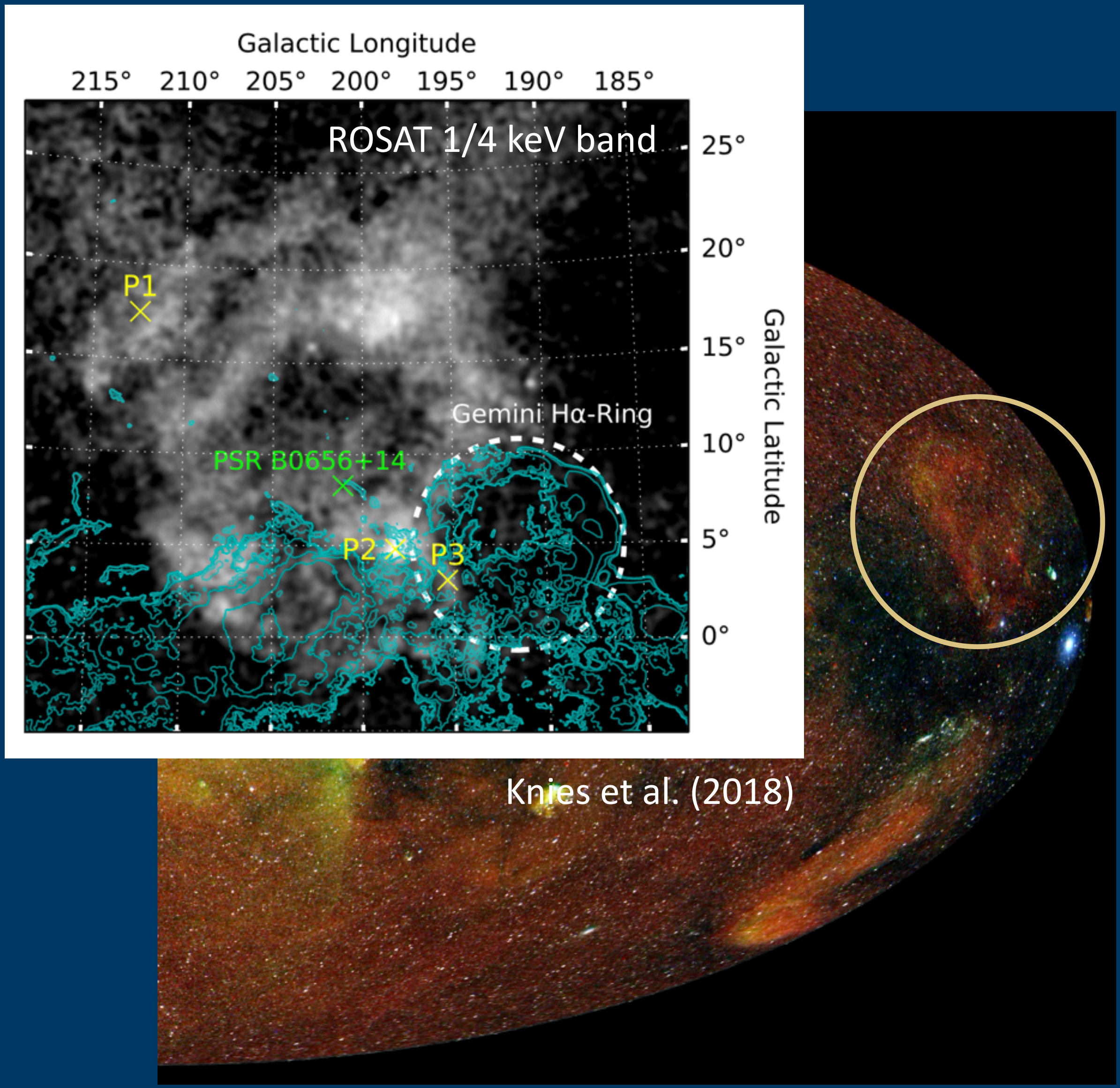
D=300pc, age about 70 kyr

Very large extent of 25°

Emission very soft < 1 keV

C IV emission in Far-UV

Difficult to study due to large extent



Knies et al. (2018)

J. Sanders, H. Brunner (MPE), E. Churazov, M. Gilfanov (IKI), and eSASS team

Monogem Ring

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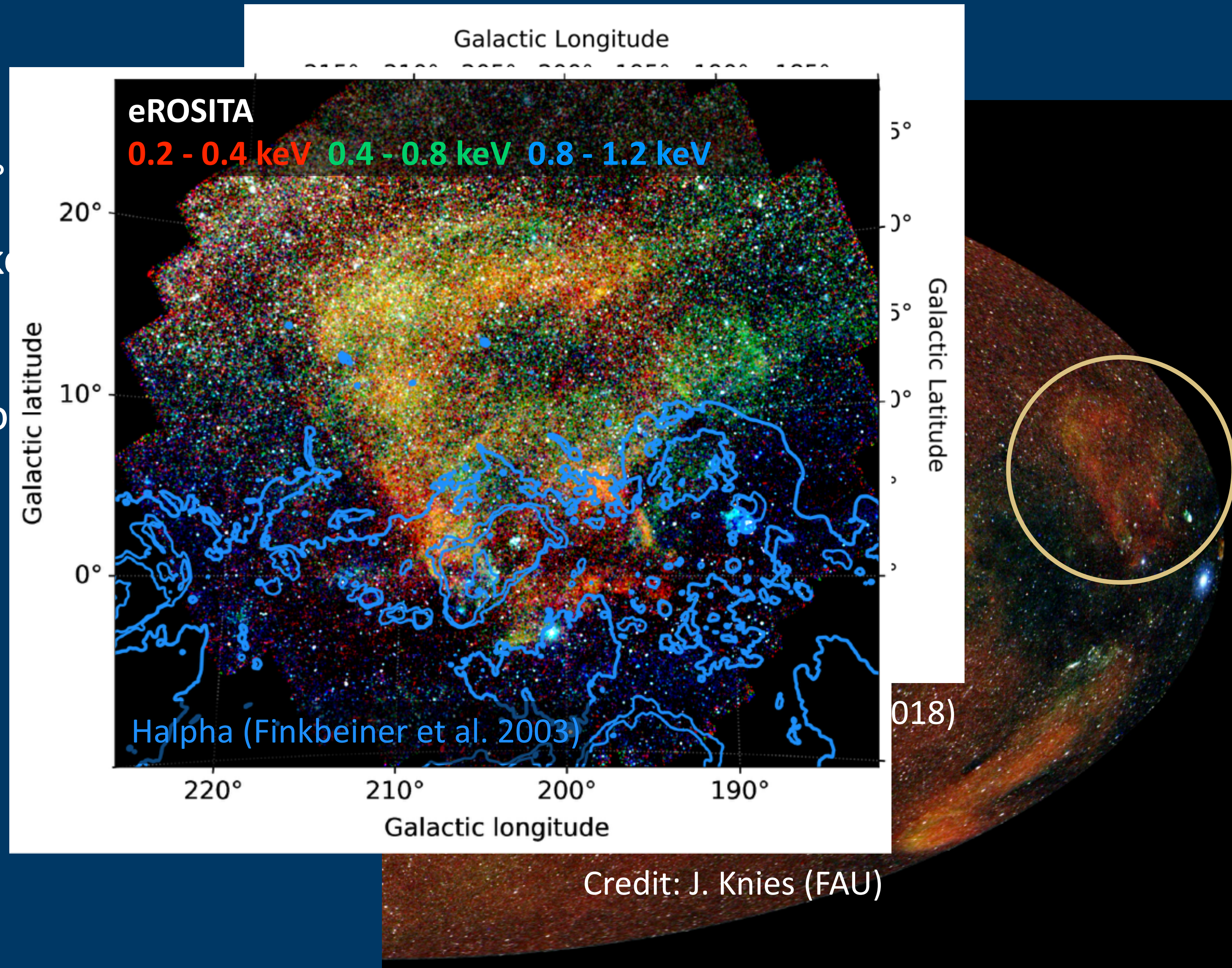

Credit: J. Knies (FAU)

Monogem Ring

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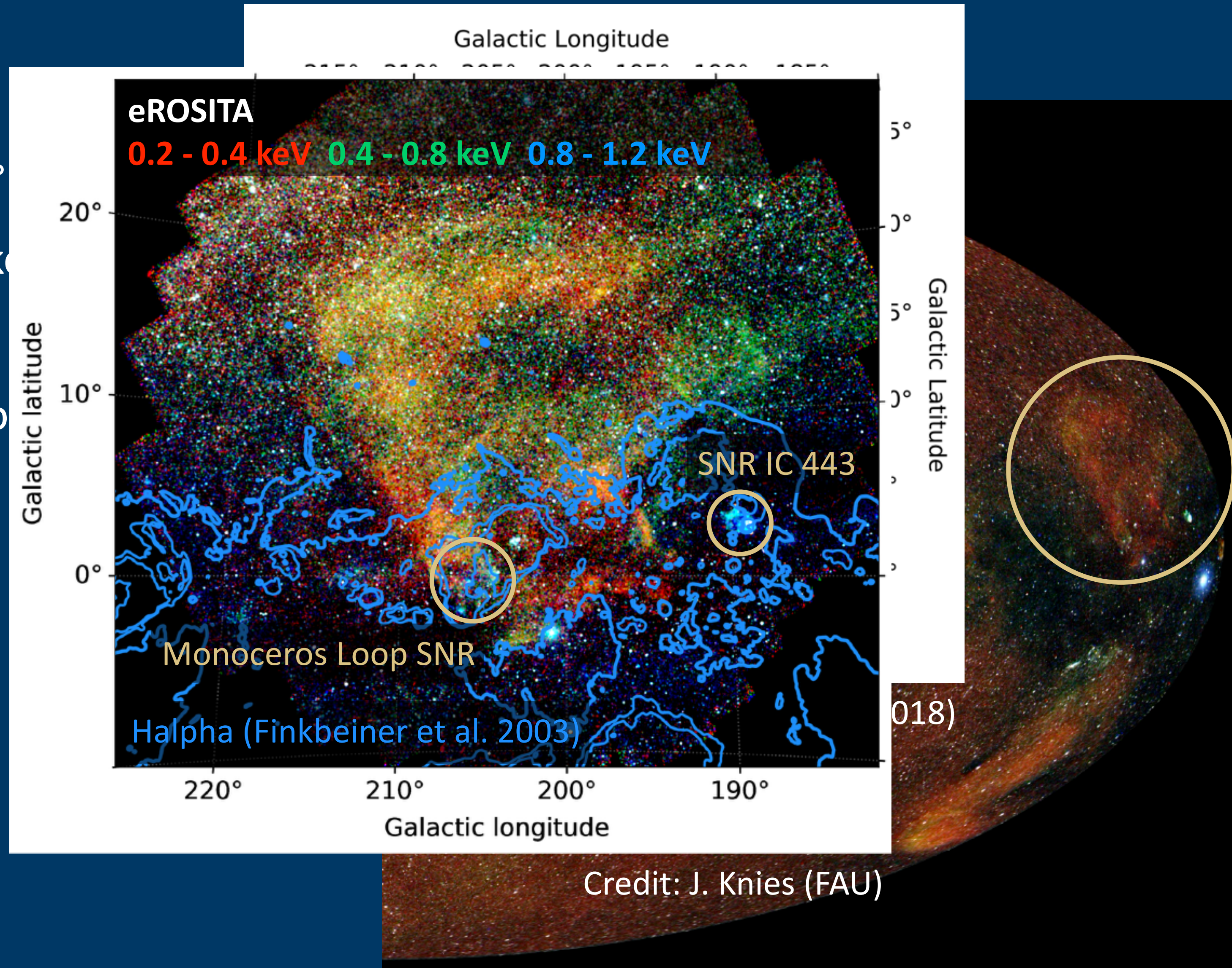
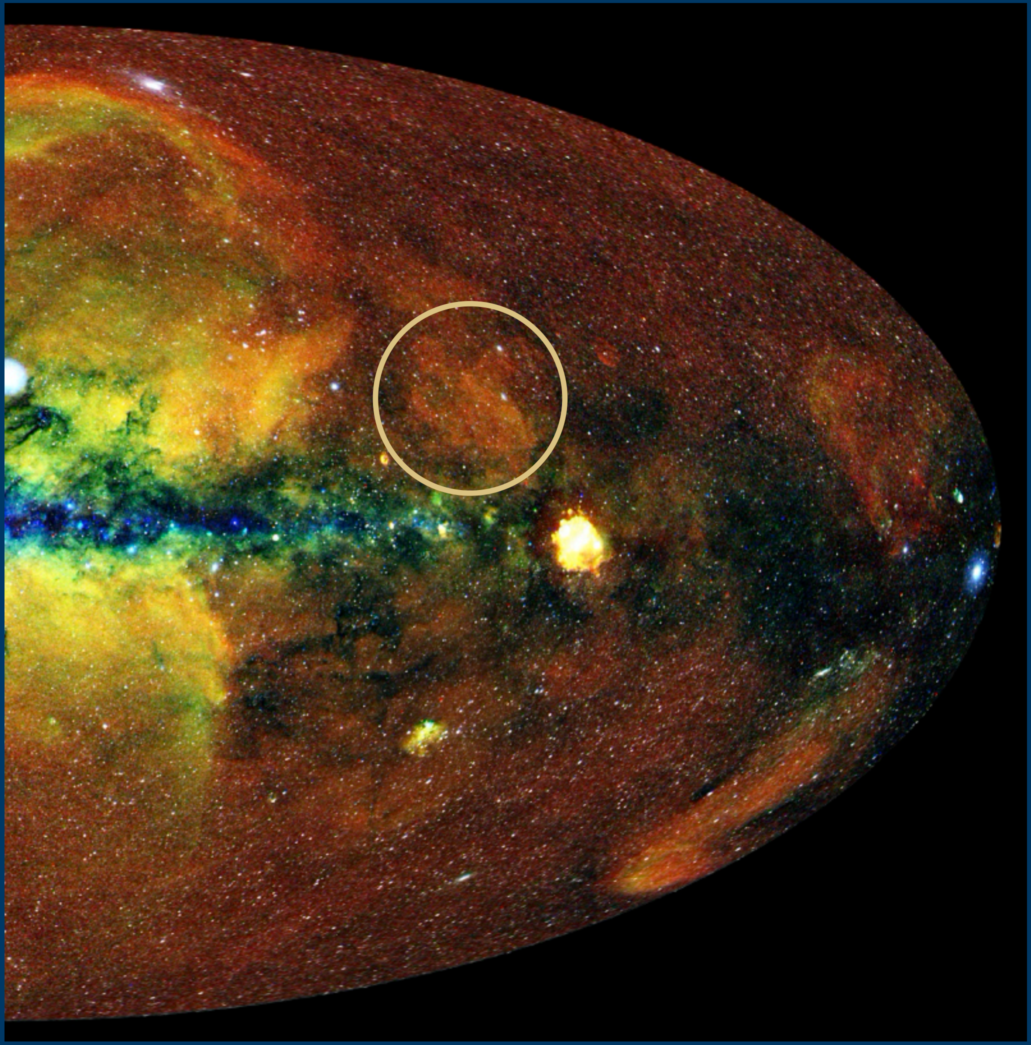


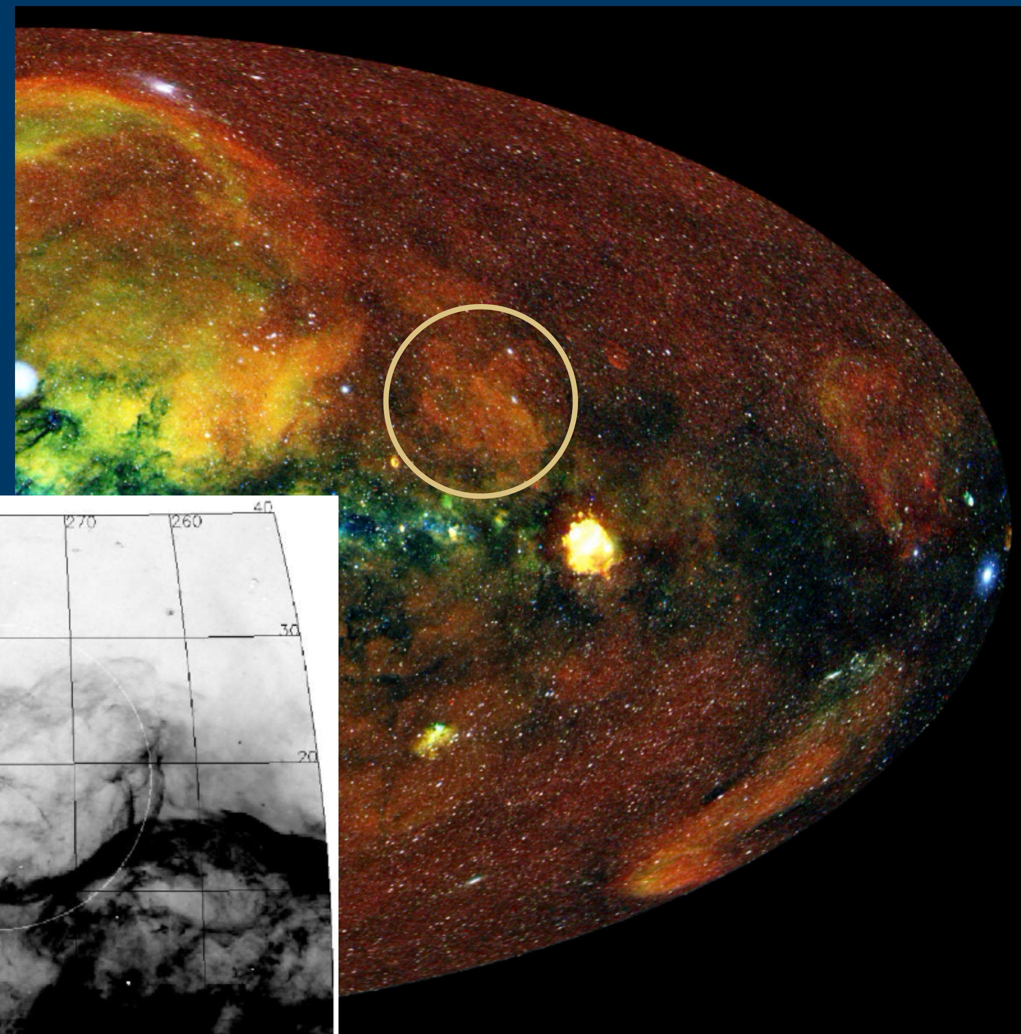
Antlia SNR



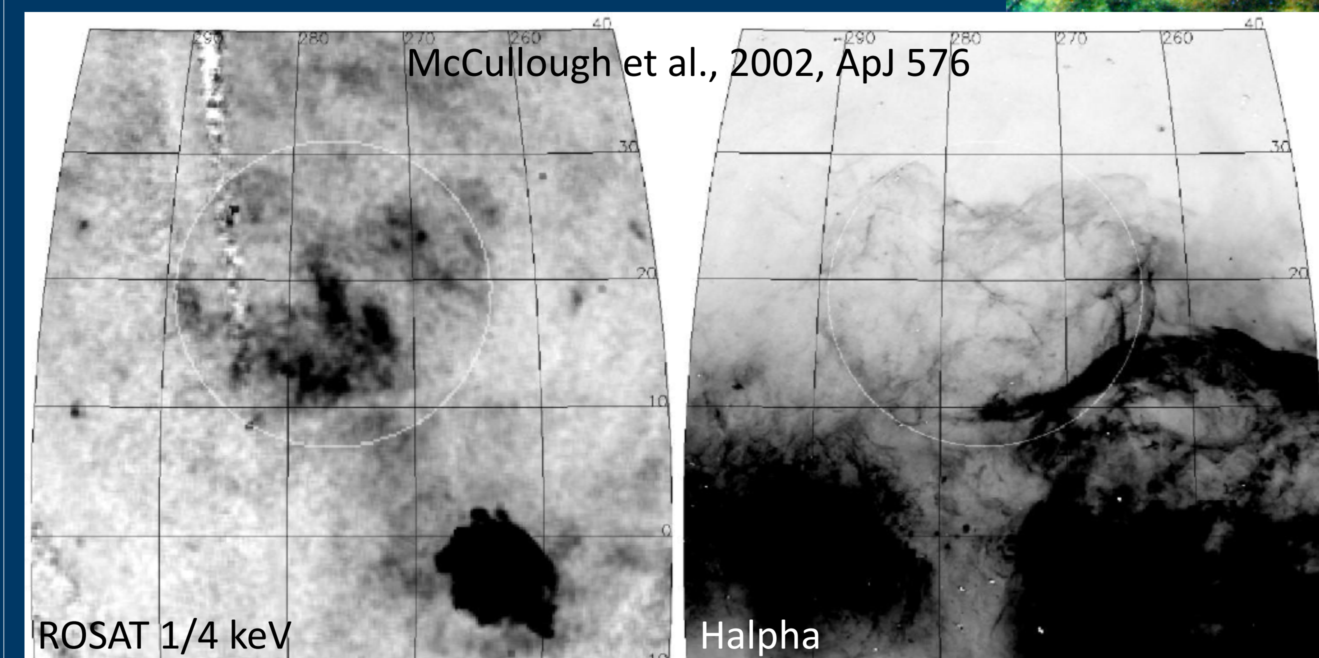
J. Sanders, H. Brunner (MPE), E. Churazov, M. Gilfanov (IKI), and eSASS team

Antlia SNR

- Nearby SNR candidate
- D < 240 pc, age > 1 Myr?
- Gamma-Ray emission at 1.8 MeV (^{26}Al)
- Very large extent of 25°
- Low absorption < 10^{21} cm^{-2}
- FUV filaments (Fesen et al., 2021)



razov, M. Gilfanov (IKI), and eSASS team



McCullough et al., 2002, ApJ 576

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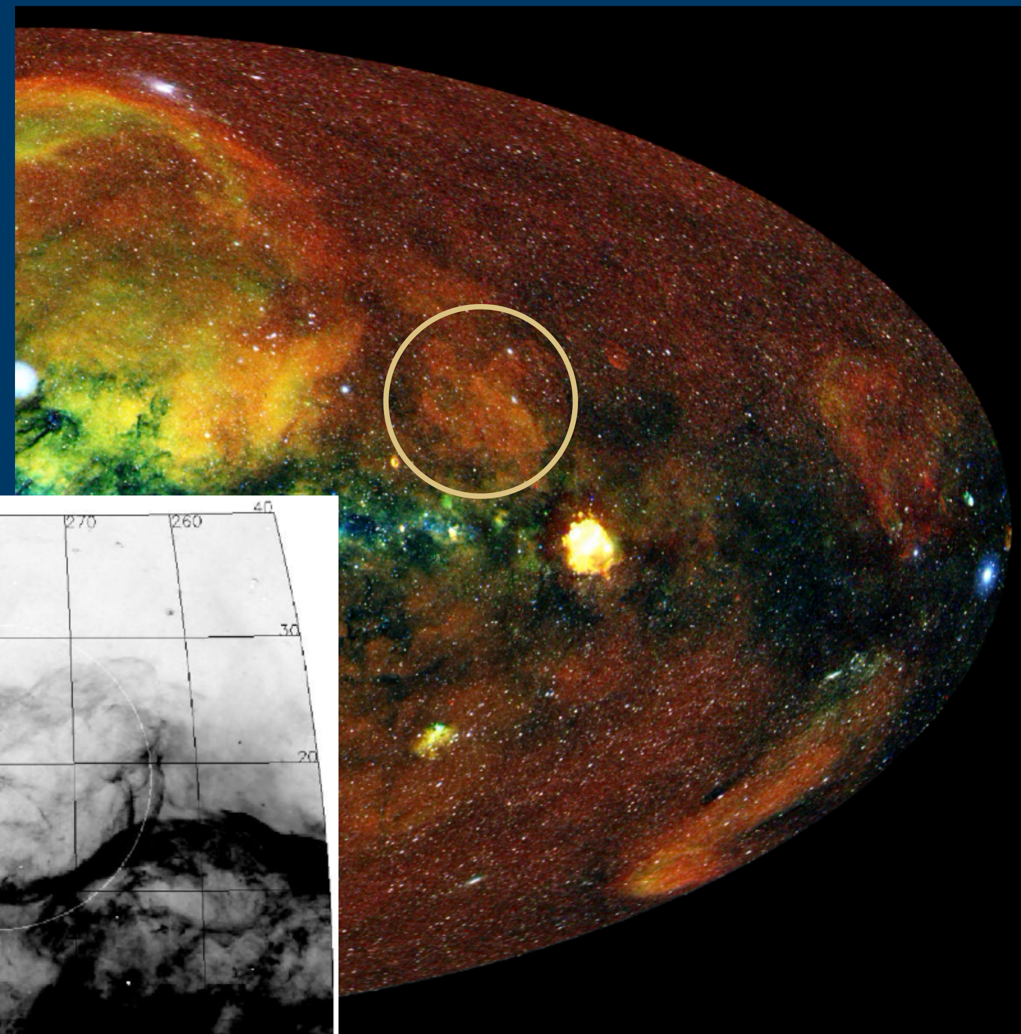

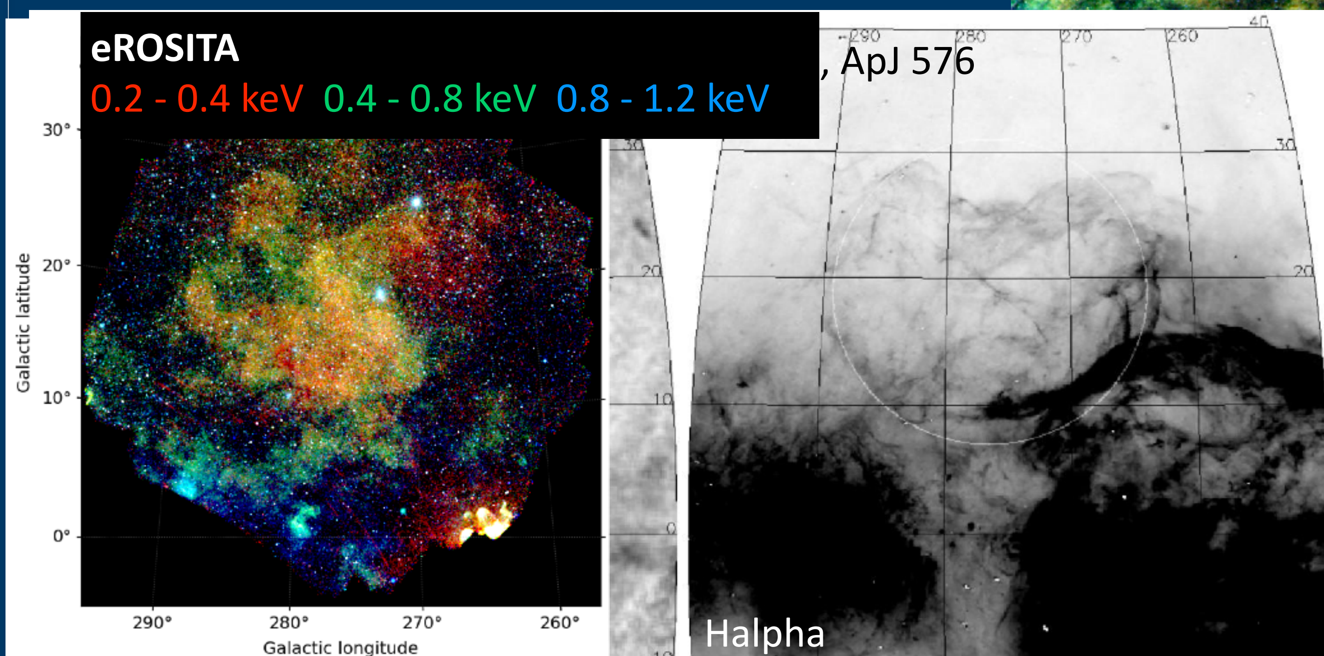

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Hoinga SNR

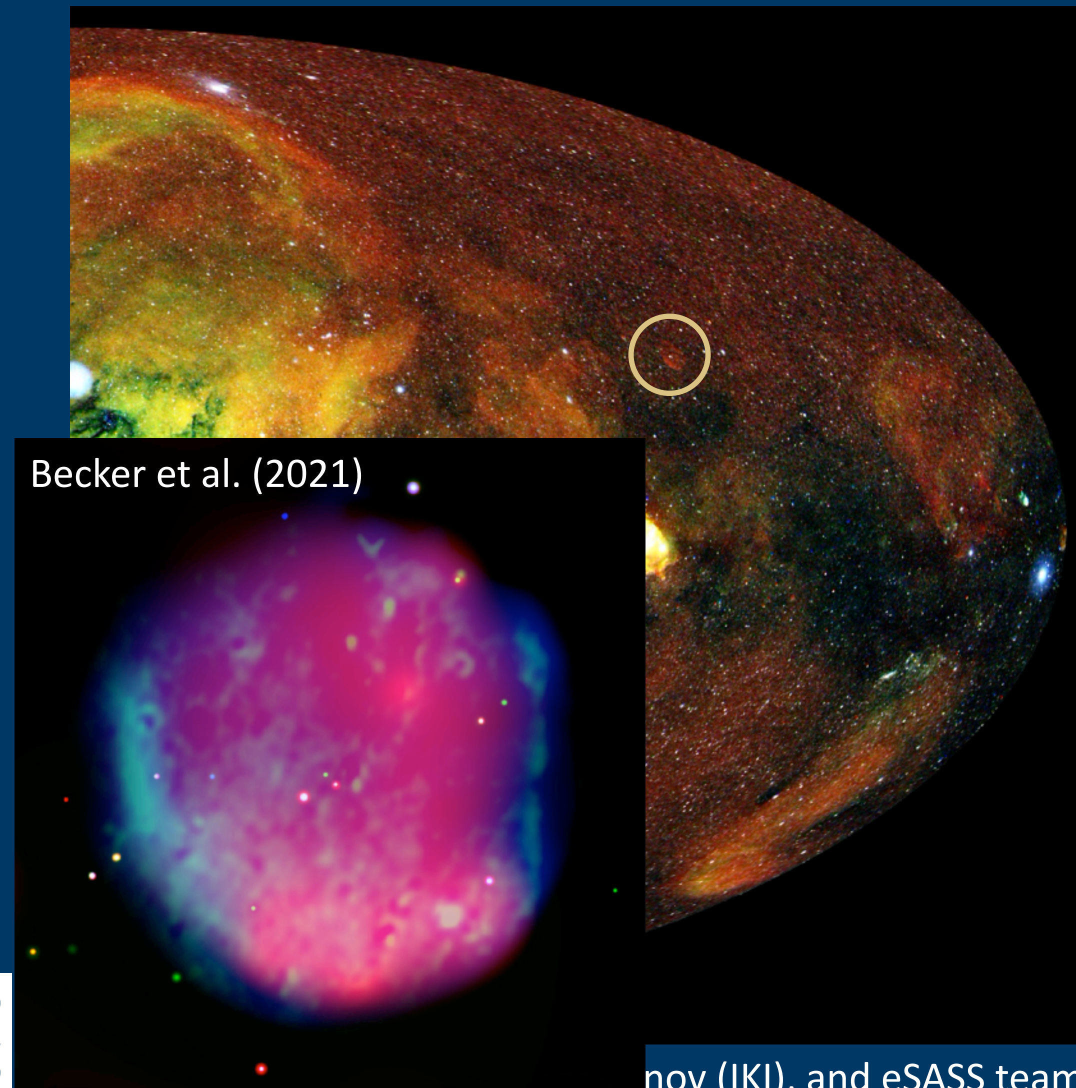
About 1200 SNRs are expected in the Milky Way, only 300 are known.

Newly detected SNR, confirmed in radio

Low absorption $N_H = 3.6 \times 10^{20}$ cm^{-2}

Low temperature kT = 0.11 keV

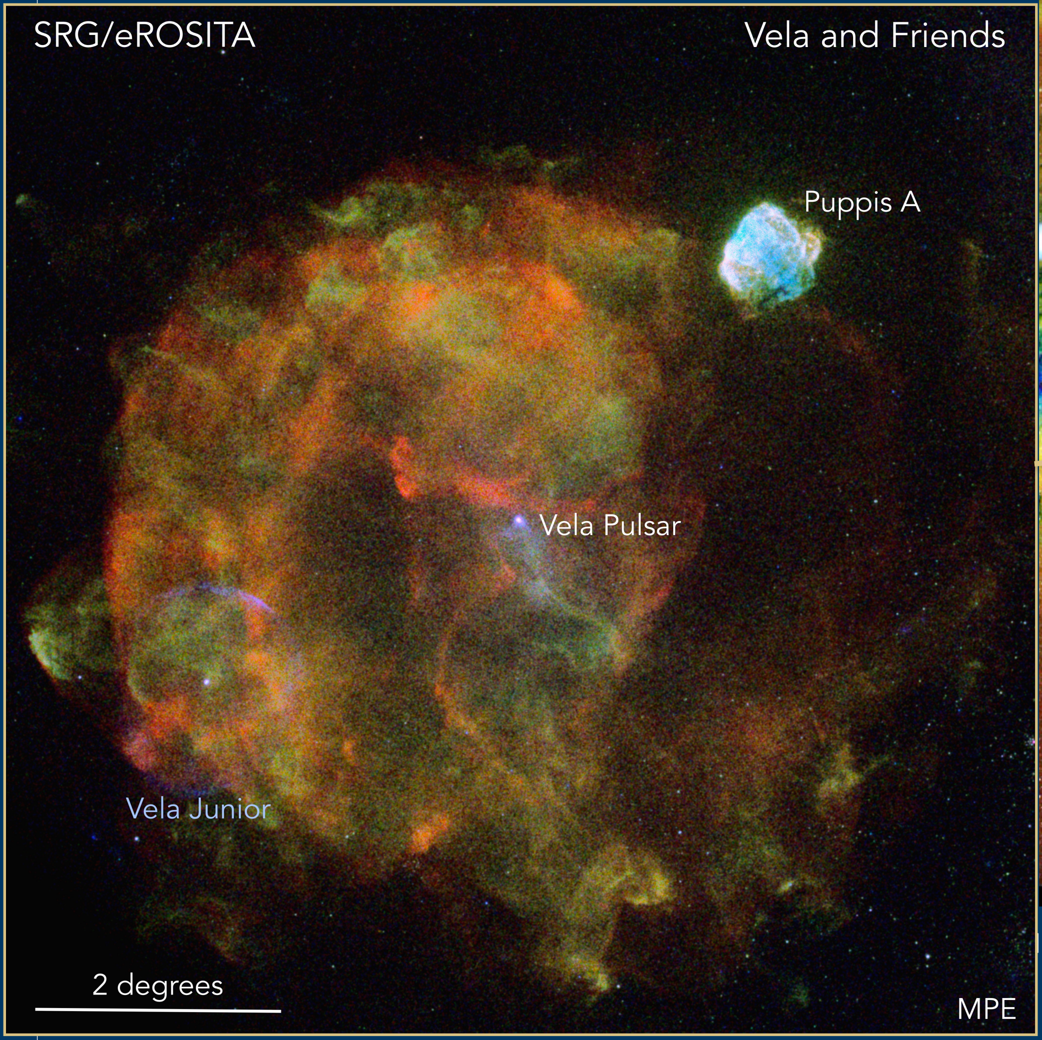
Middle-aged nearby (D ~500 pc) SNR

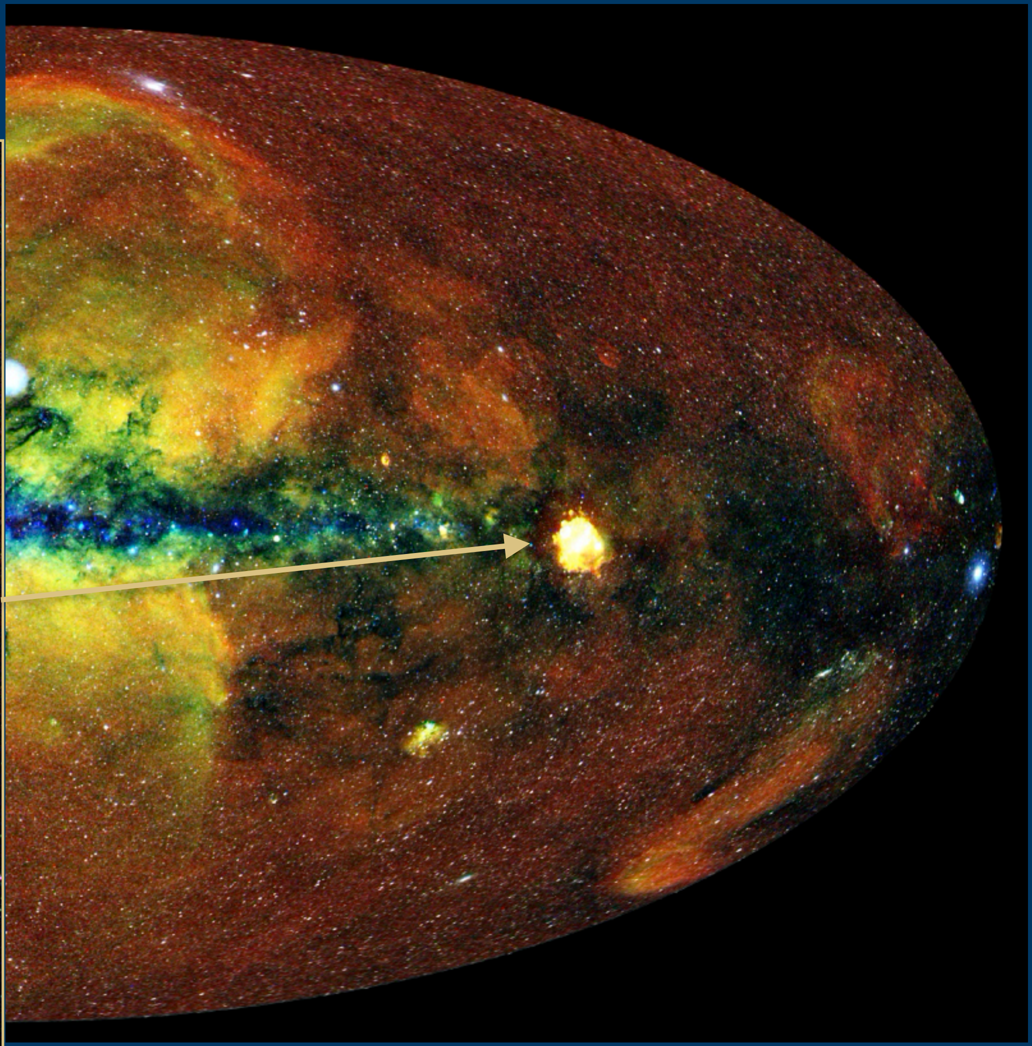


eROSITA/MPE (X-ray, magenta)
CHIPASS/SPASS/N. Hurley-Walker, ICRAR-Curtin (Radio, blue)

nov (IKI), and eSASS team

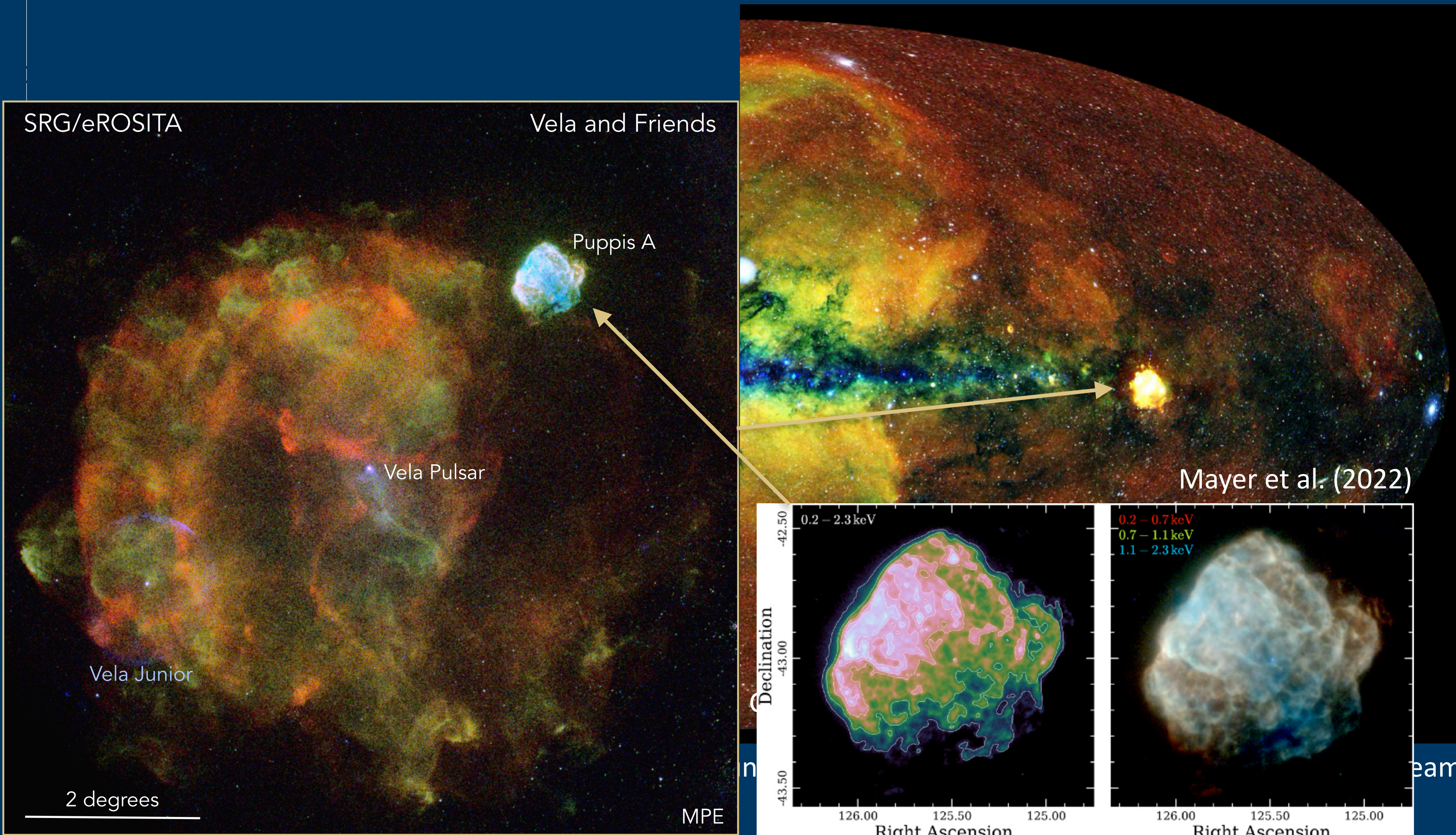
Vela and Friends





nner (MPE), E. Churazov, M. Gilfanov (IKI), and eSASS team

Puppis A SNR


SRG/eROSITA
Vela and Friends
Puppis A
Vela Pulsar
Vela Junior
2 degrees
MPE
Mayer et al. (2022)
0.2 – 2.3 keV
0.2 – 0.7 keV
0.7 – 1.1 keV
1.1 – 2.3 keV
Declination
-42.50
-43.00
-43.50
126.00
125.50
125.00
Right Ascension
126.00
125.50
125.00
Right Ascension

Summary

Supernova remnants **heat** and **create new structures** in the ISM.

Are responsible for the **chemical enrichment** of galaxies.

Supernova remnants allow studies of

- **supernova explosion** mechanisms and **nucleosynthesis**,
- formation and processing of **dust**,
- **interstellar shock waves**,
- the origin of the **hot interstellar plasma**,
- **interaction** of shocks with dense medium and the impact on **star formation**,
- **particle acceleration** and origin of **galactic cosmic rays**.

GeV and TeV obervations indicate inverse Compton as well as pion decay processes in and around SNR shocks.

Self-consistent modeling of the spectrum from radio to TeV helps us to understand both heating and acceleration processes in SNRs.