supernova remnants and particle acceleration

fermi summer school – may 2014

daniel castro - mit

outline

part I: SNRs

why should you care about SNRs?

what do we know about SNRs in general?

- executive summary
- types
- structure and evolution
- emission
- x-ray observations
- balmer dominated shocks

i. why should you care about SNRs?

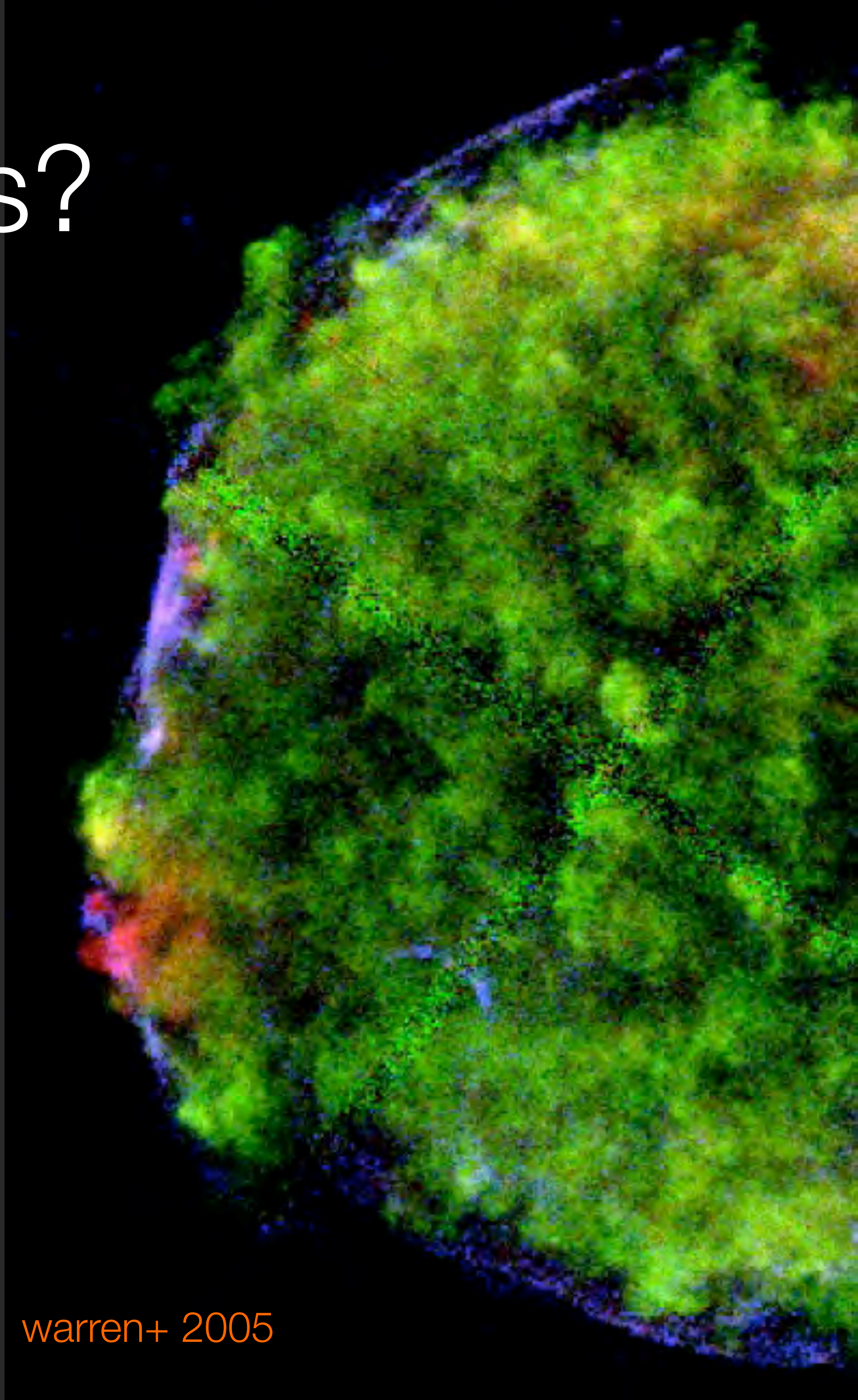
i. why should you care about SNRs?

- supernovae
- pulsars + pwn
- feedback
  - shocks
  - chemistry
  - crs
- SN – GRB
- dust production

lopez+ 2013

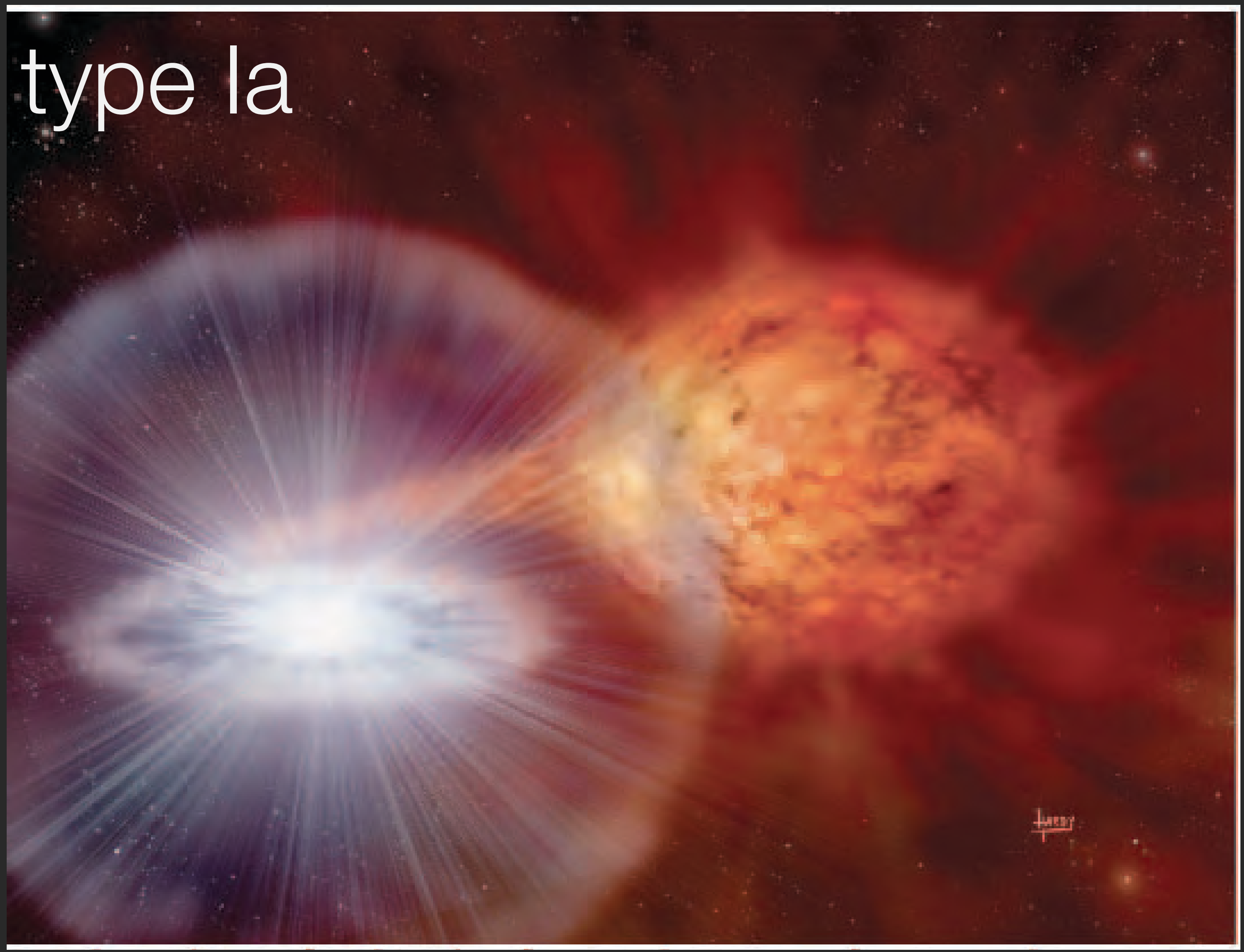
ii. what are snrs?

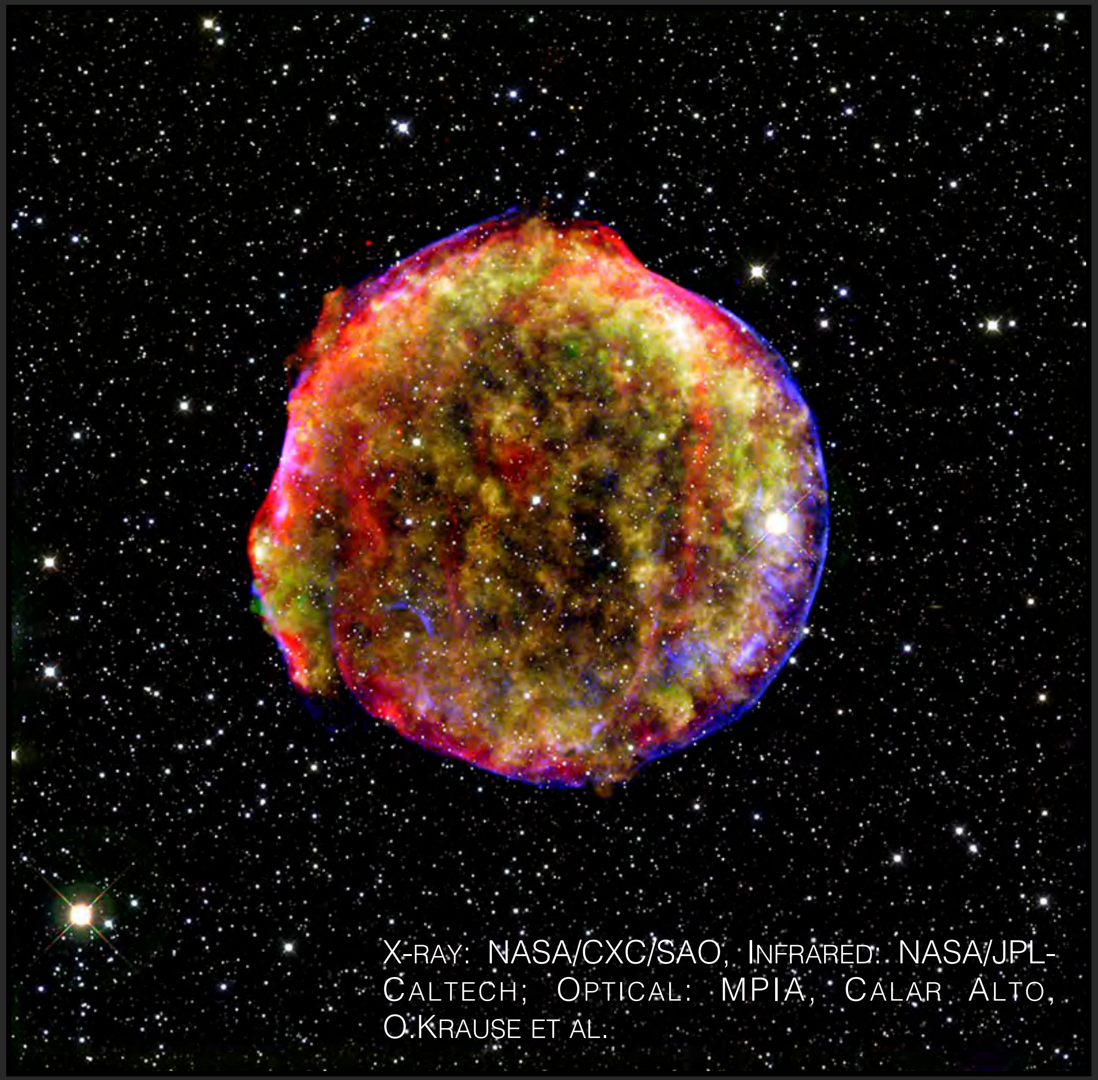
- explosive end of a star
- two types:
  - core-collapse
  - thermonuclear
- material ejected with ~10^{51} erg kinetic energy
- shock wave forms & sweeps up ISM/CSM



warren+ 2005

ii. types

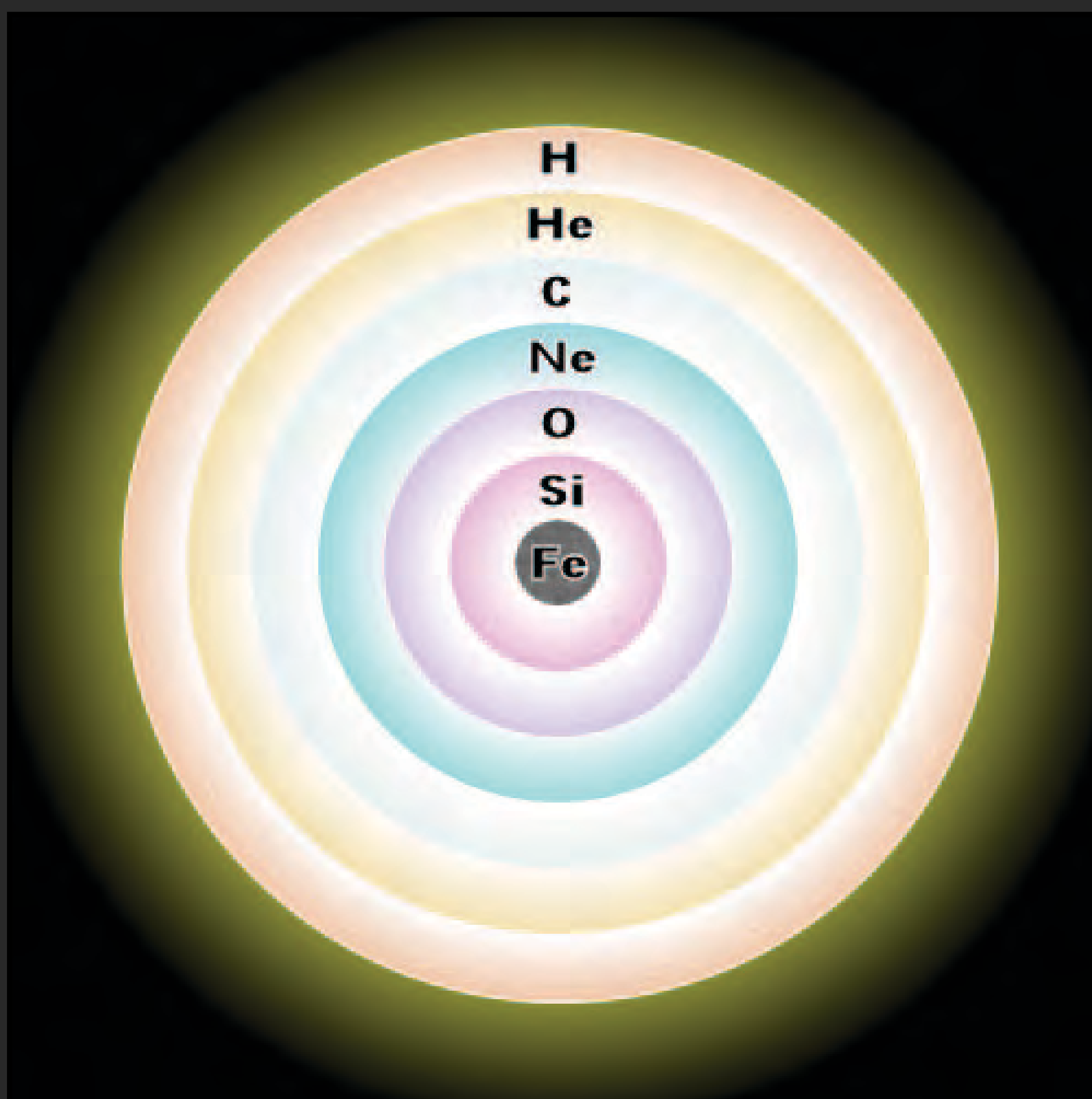


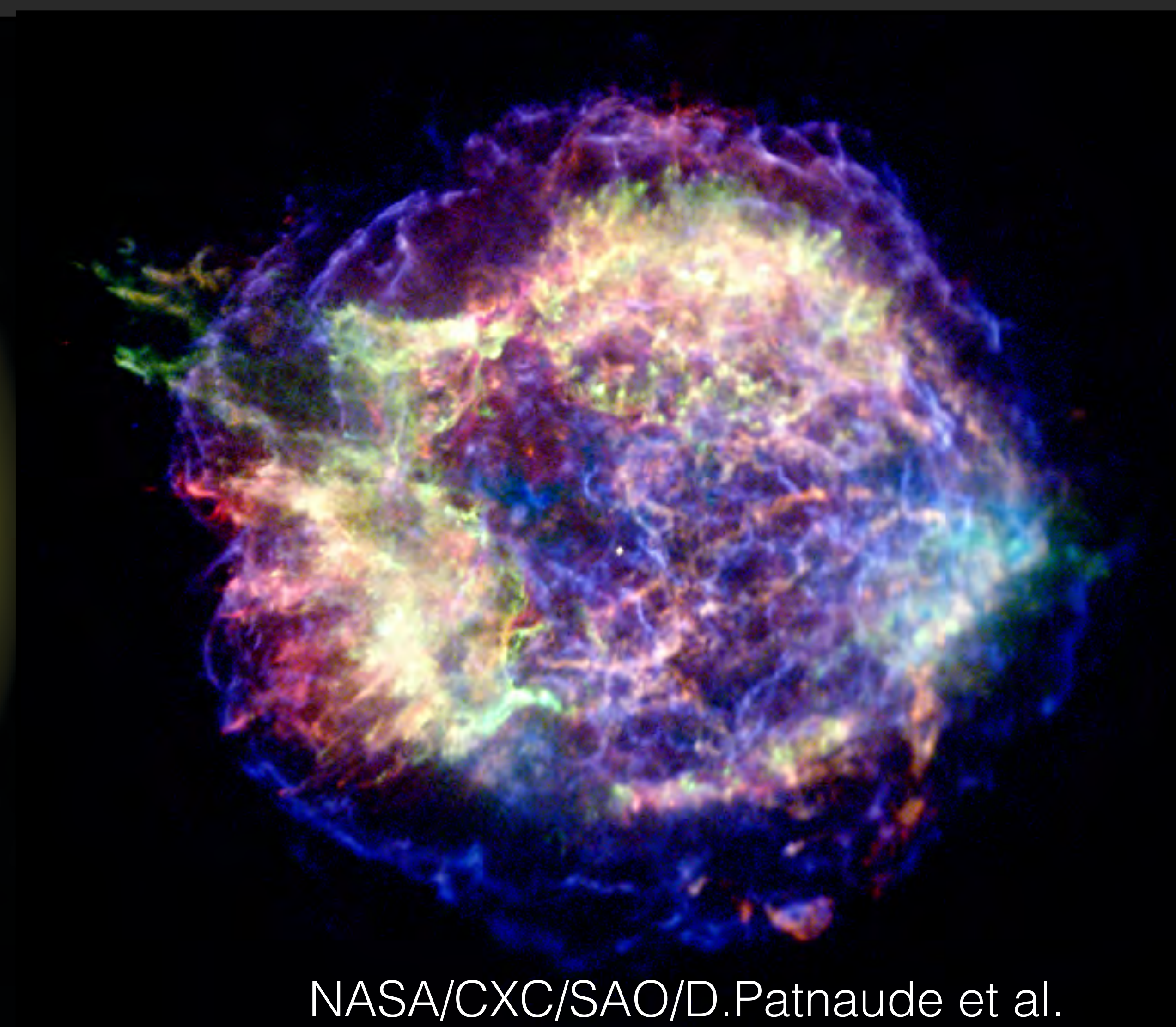


- ejecta mass ~ 1.4 solar masses
- expands into approx uniform ISM

ii. types

core-collapse

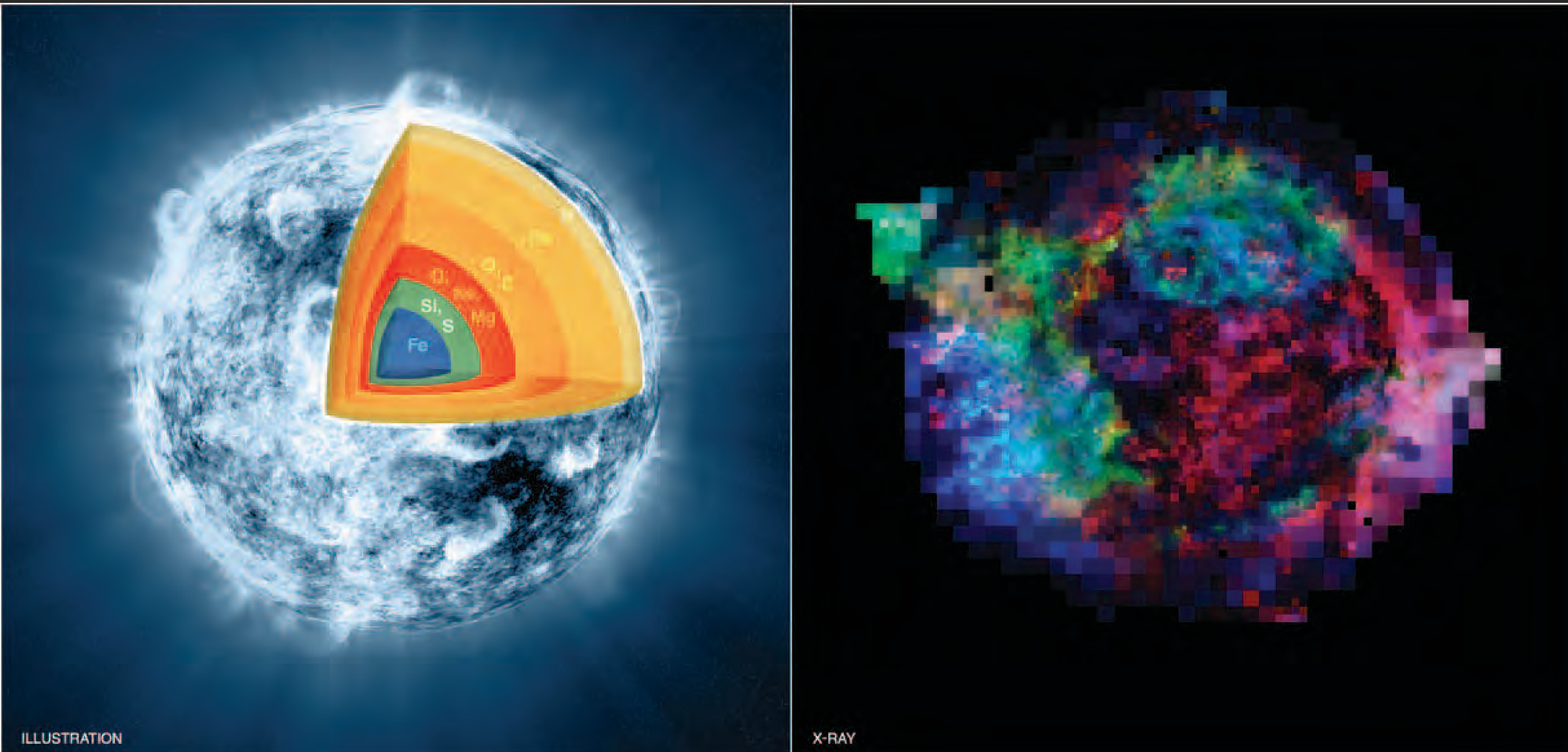




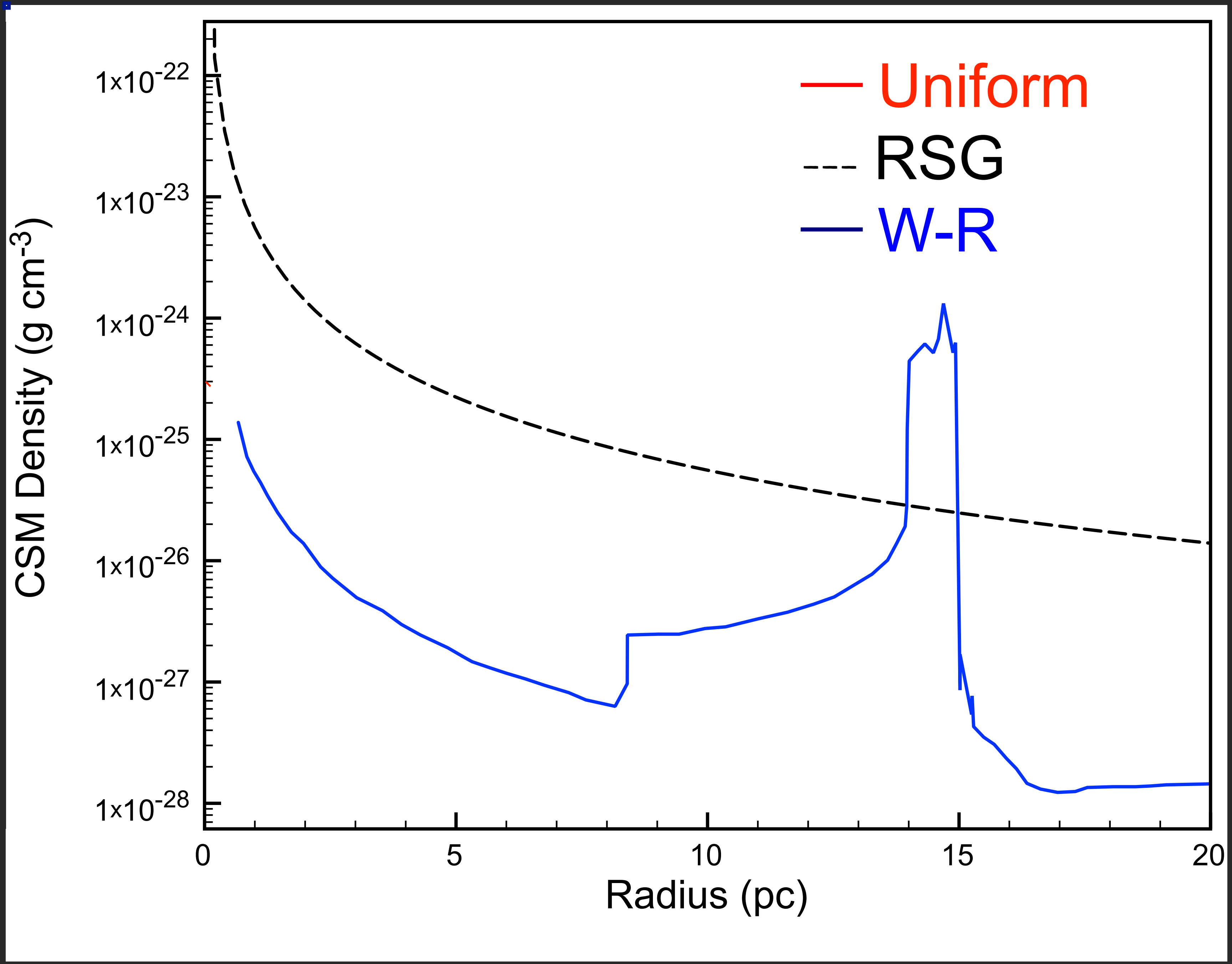
NASA/CXC/SAO/D.Patnaude et al.

- progenitor mass > 8 solar masses
- expands into modified CSM

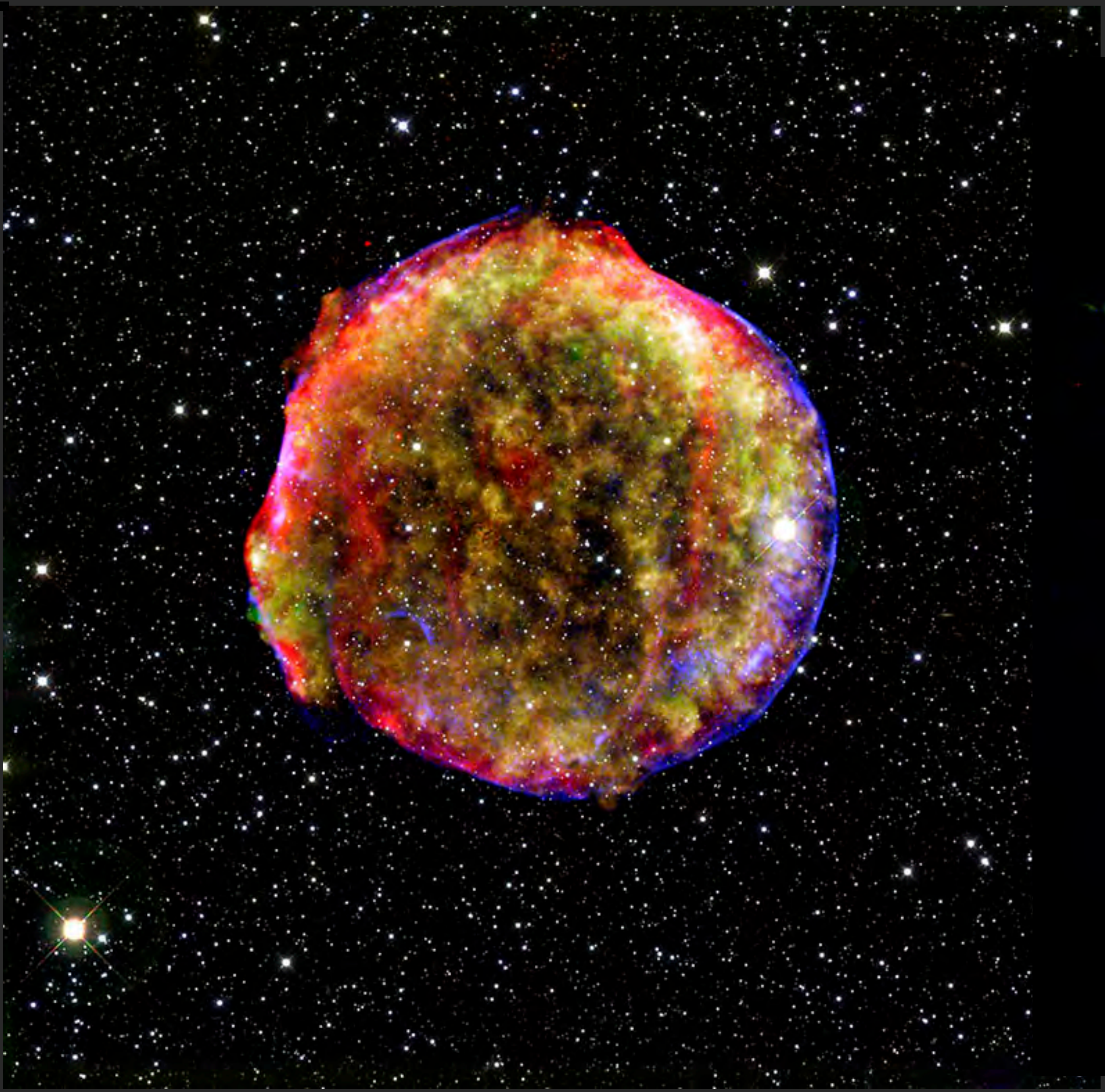
ii. types

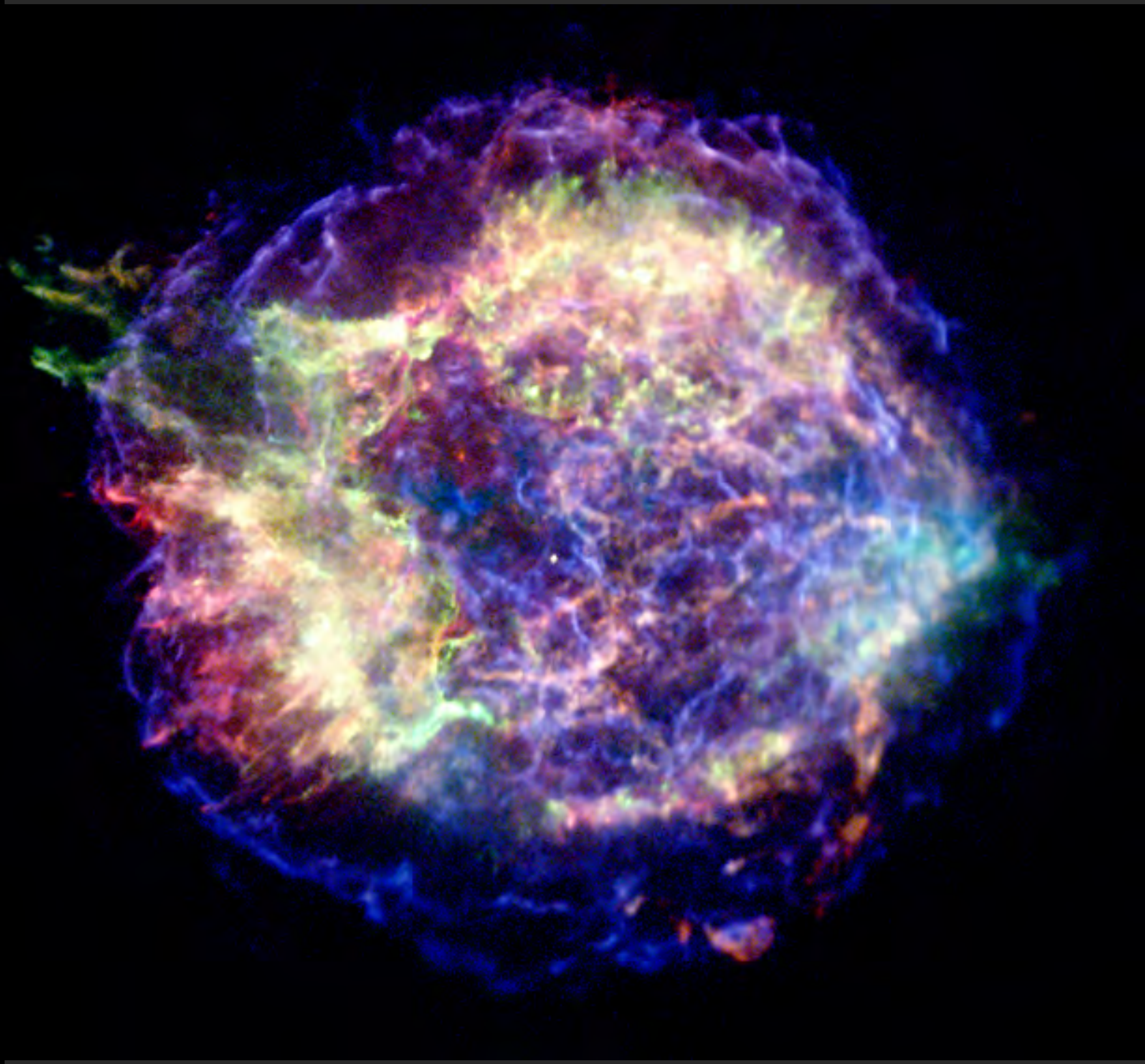


ii. types (surrounding media)

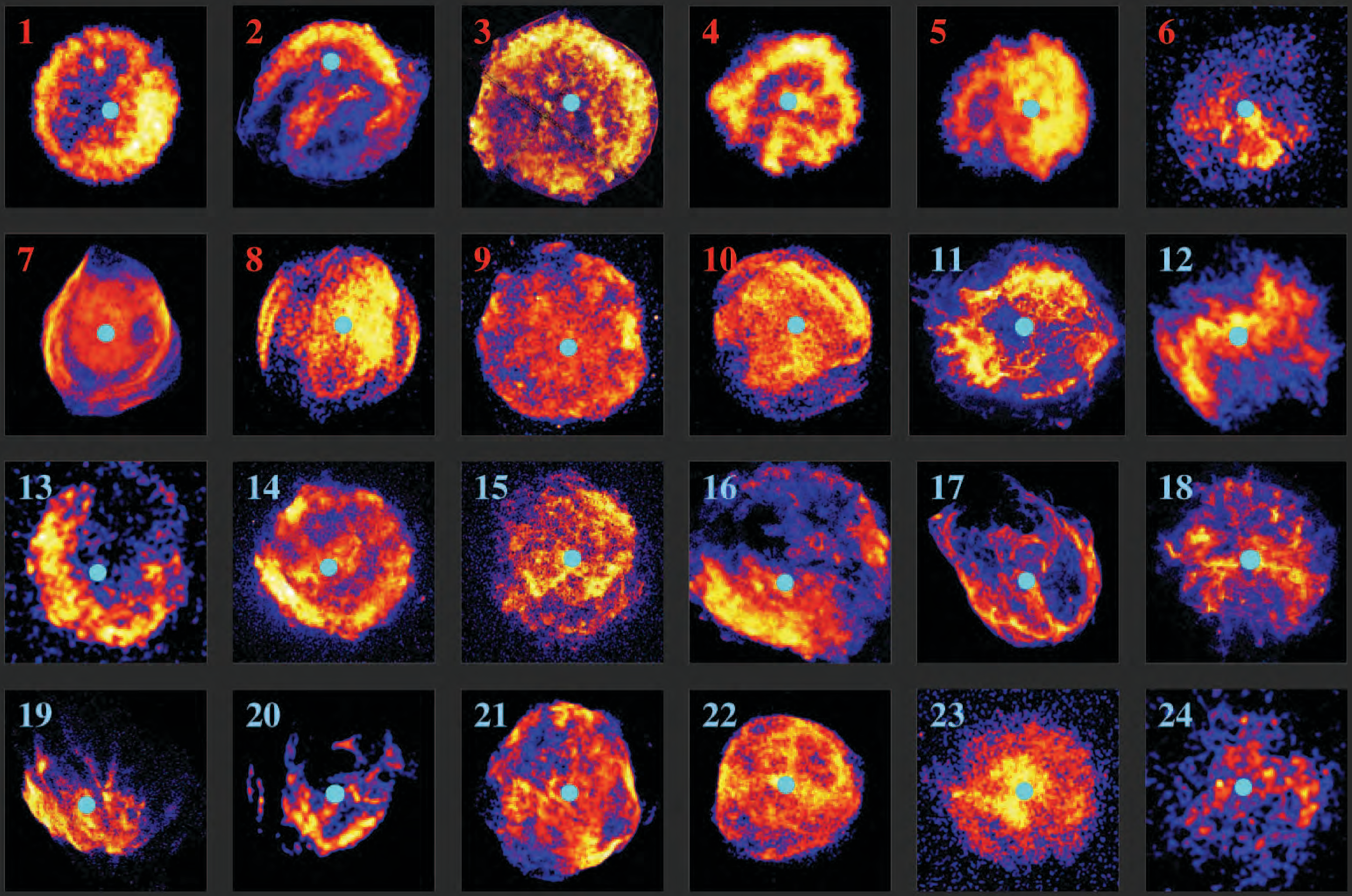


ii. determining type



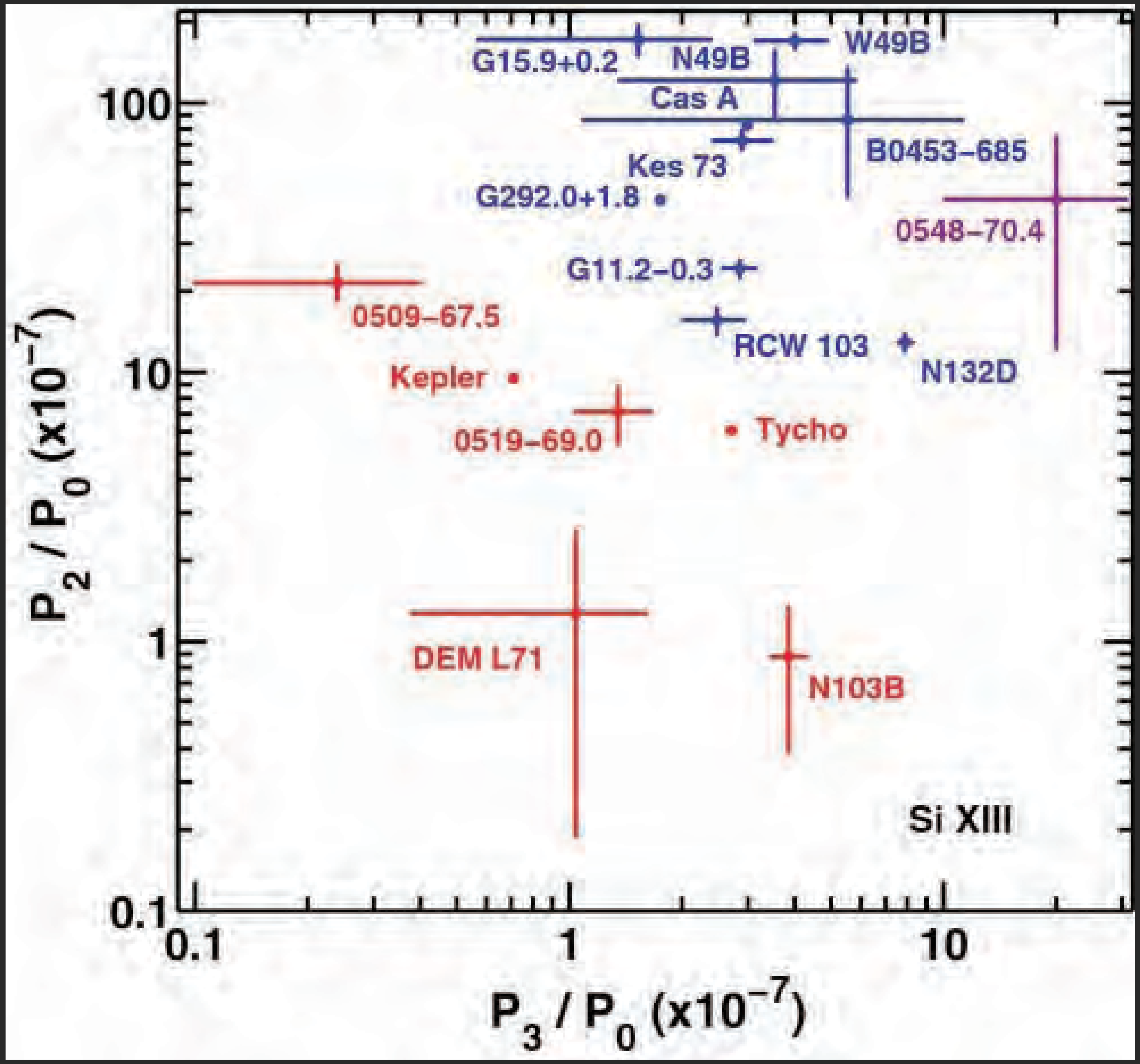


ii. morphology & type



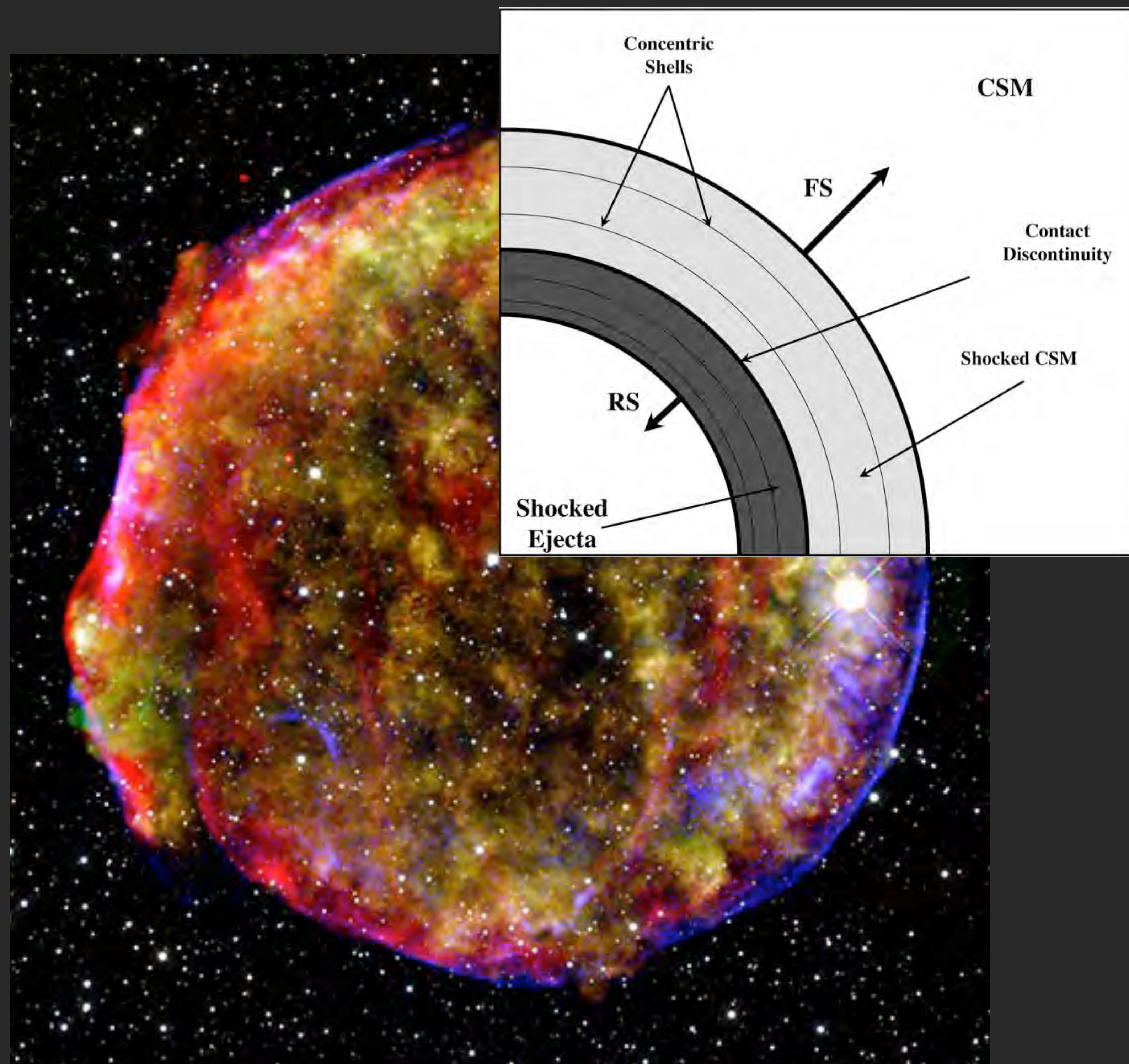
ii. morphology & type

ellipticity / elongation



mirror asymmetry

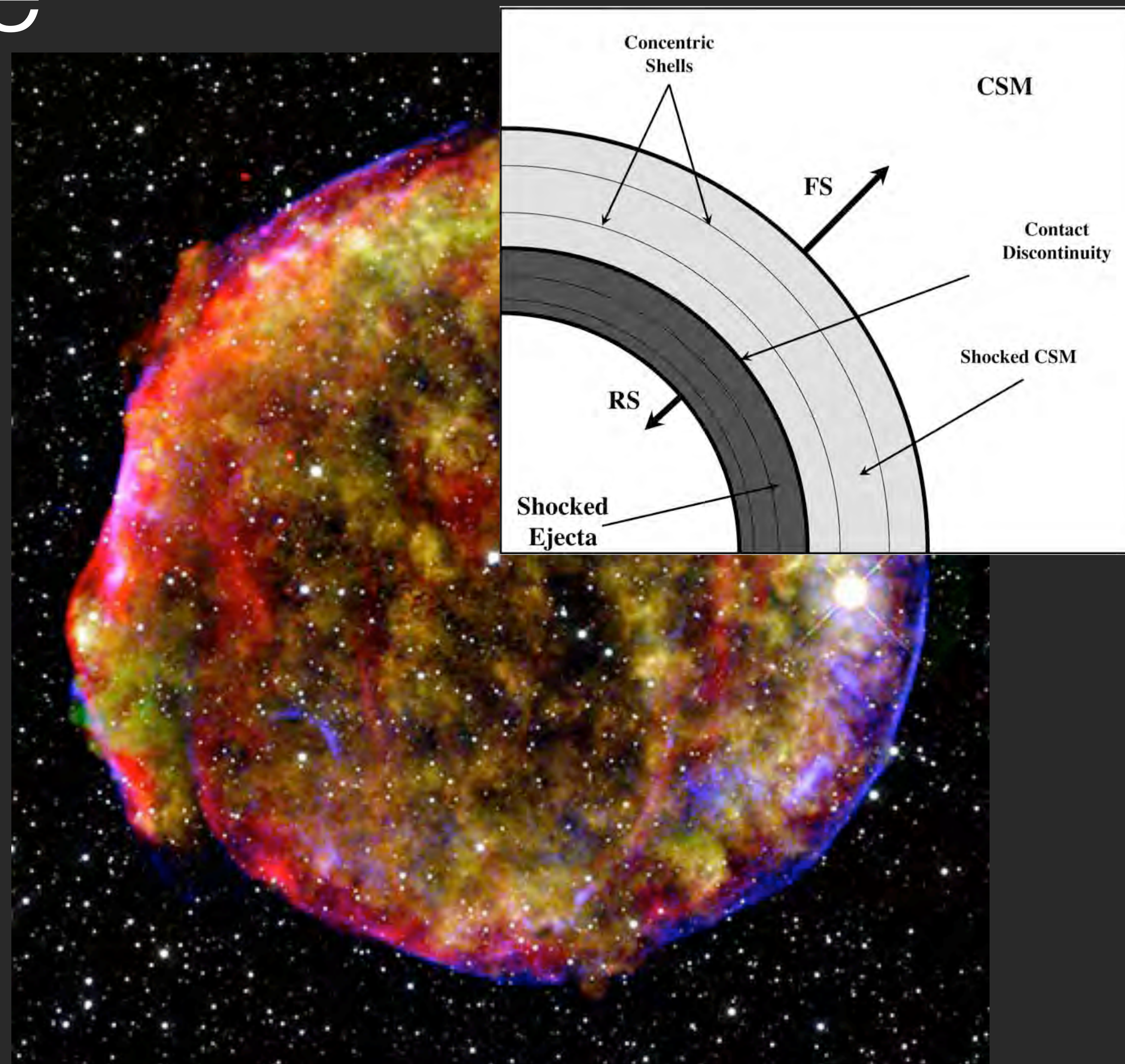
ii. structure



x-ray: nasa/cxc/sao, infrared: nasa/jpl-caltech; optical: mpia, calar alto, o.krause et al.

ii. structure

- free expansion: dynamics and emission dominated by ejecta, R ∝ t
- adiabatic/sedov-taylor: swept up material dominates, R ∝ $t^{2/5}$
- radiative/snow-plow, radiative losses become significant



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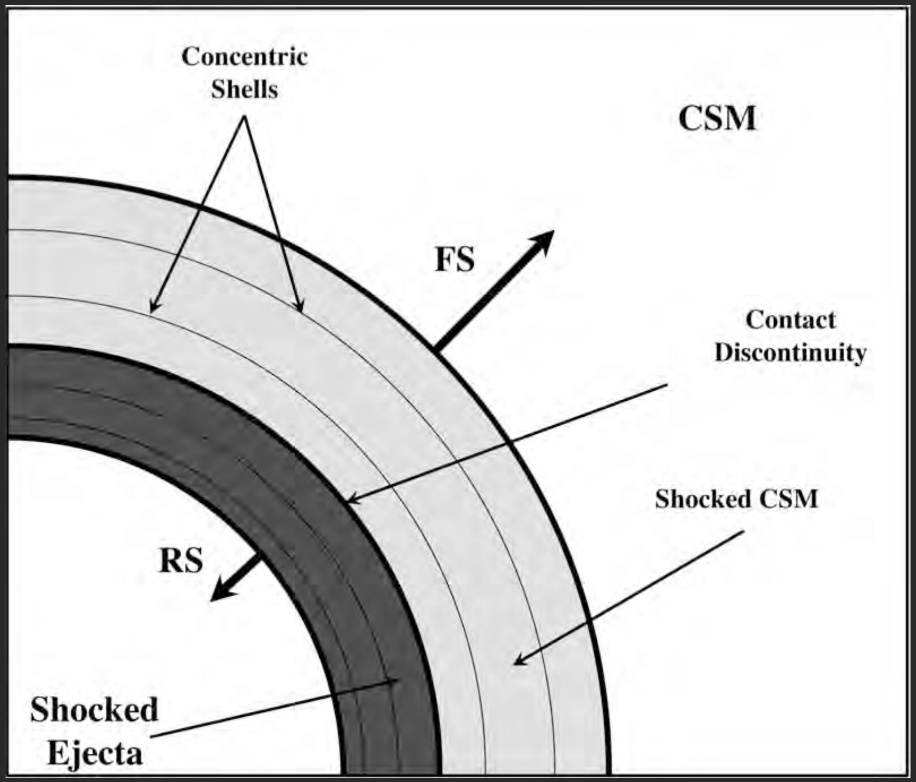

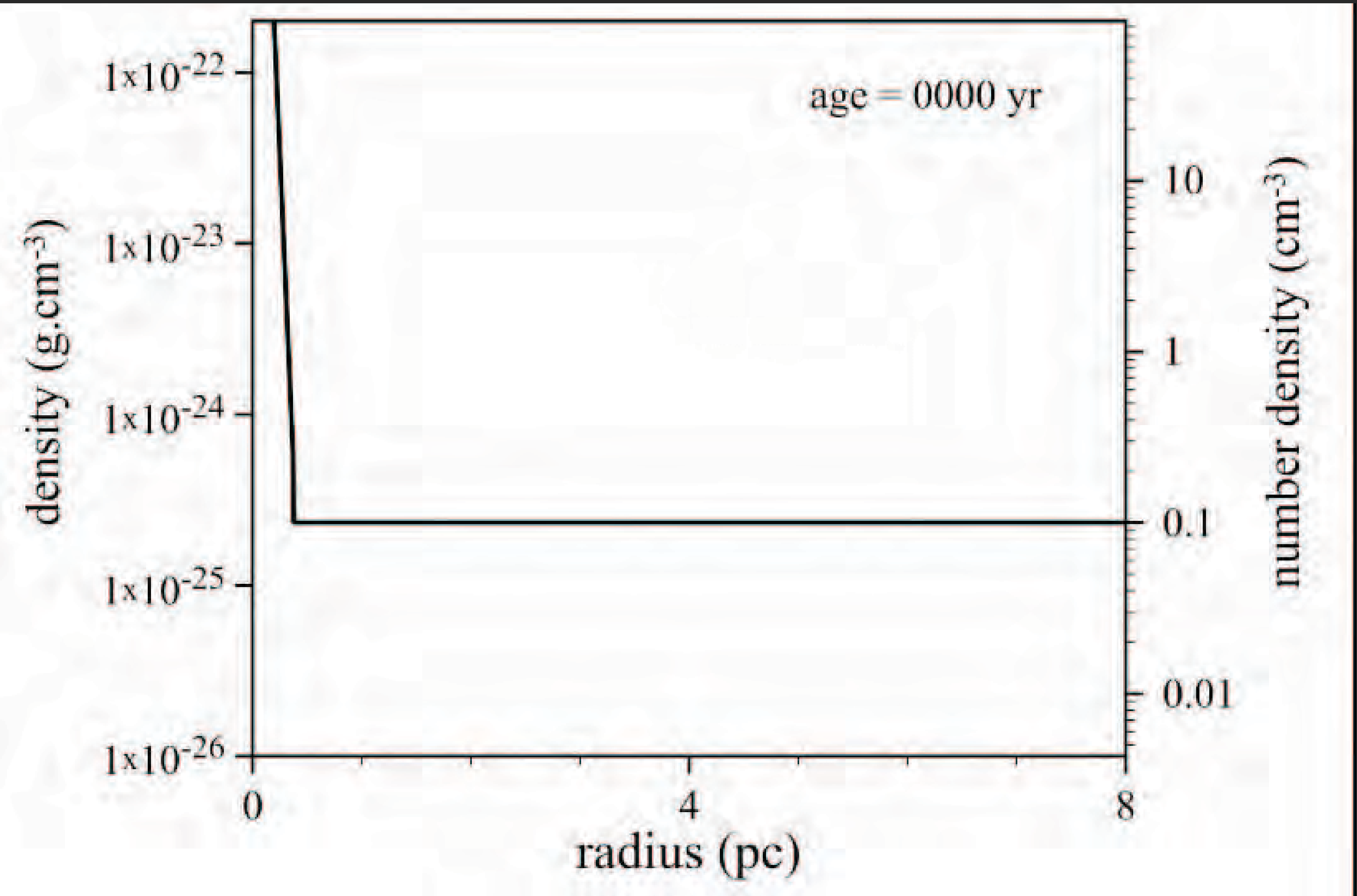

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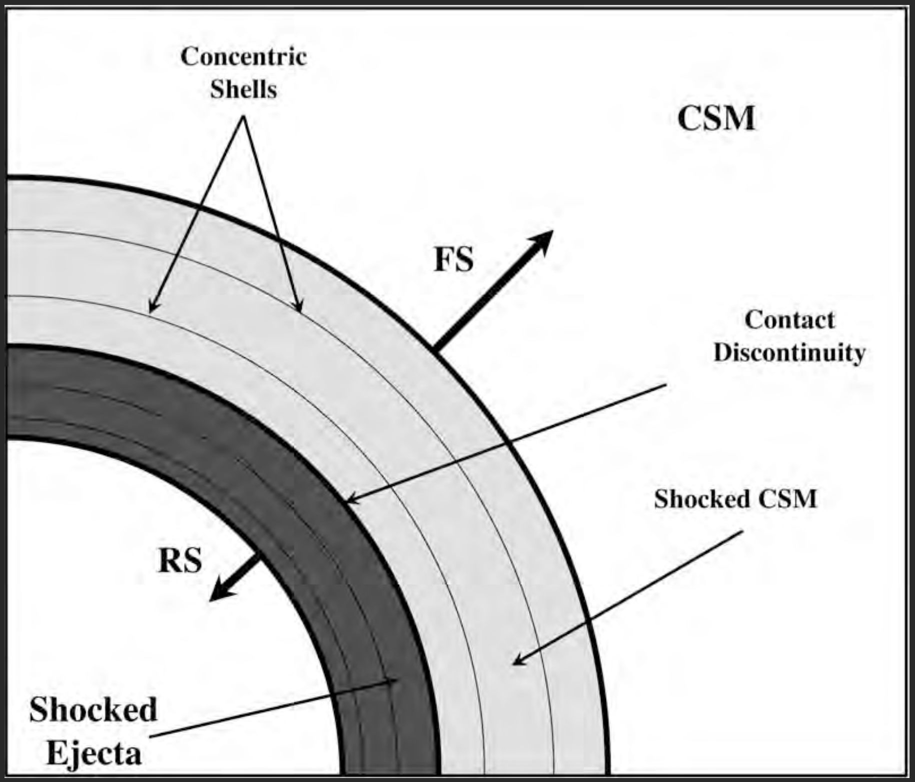
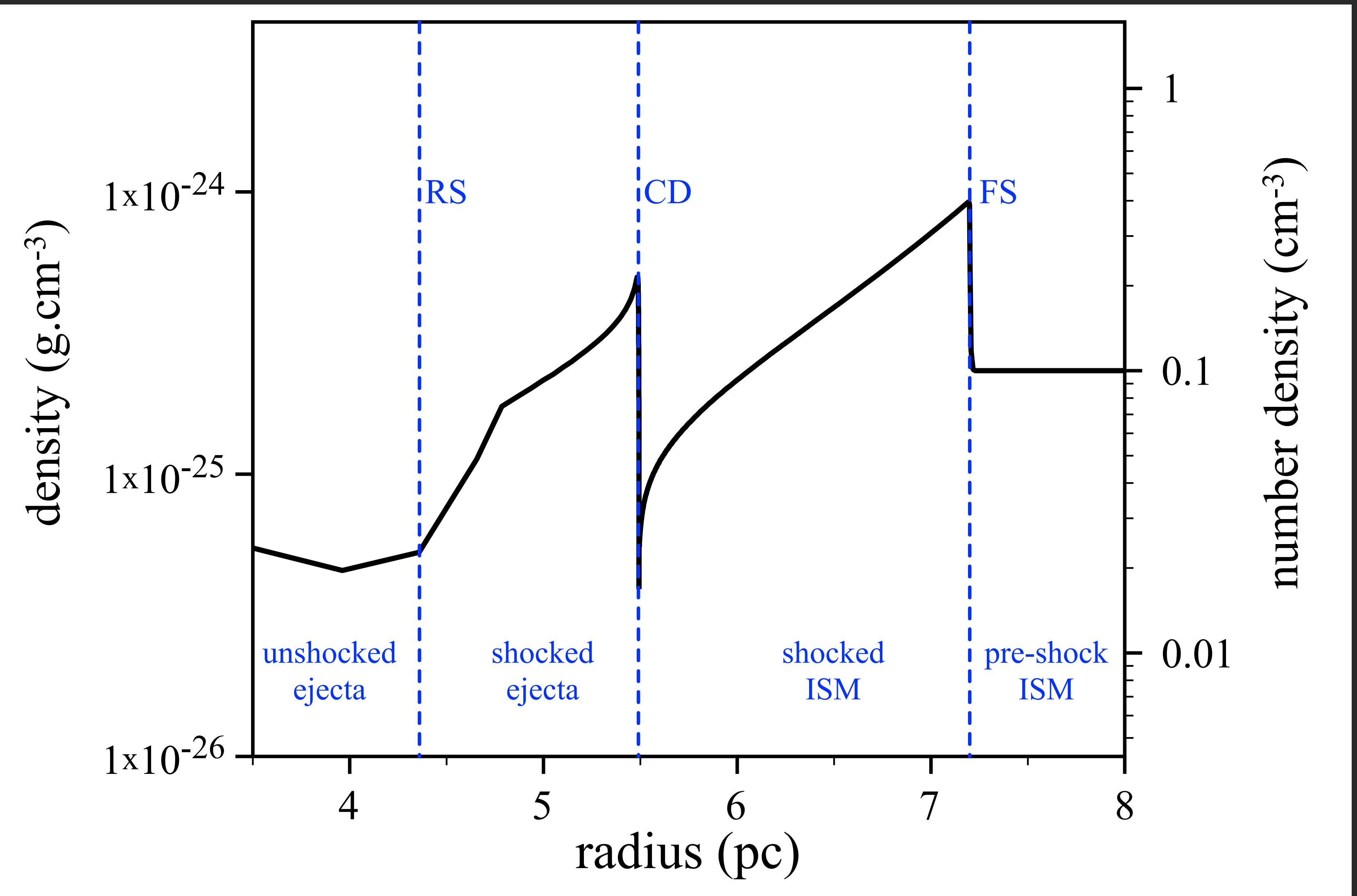
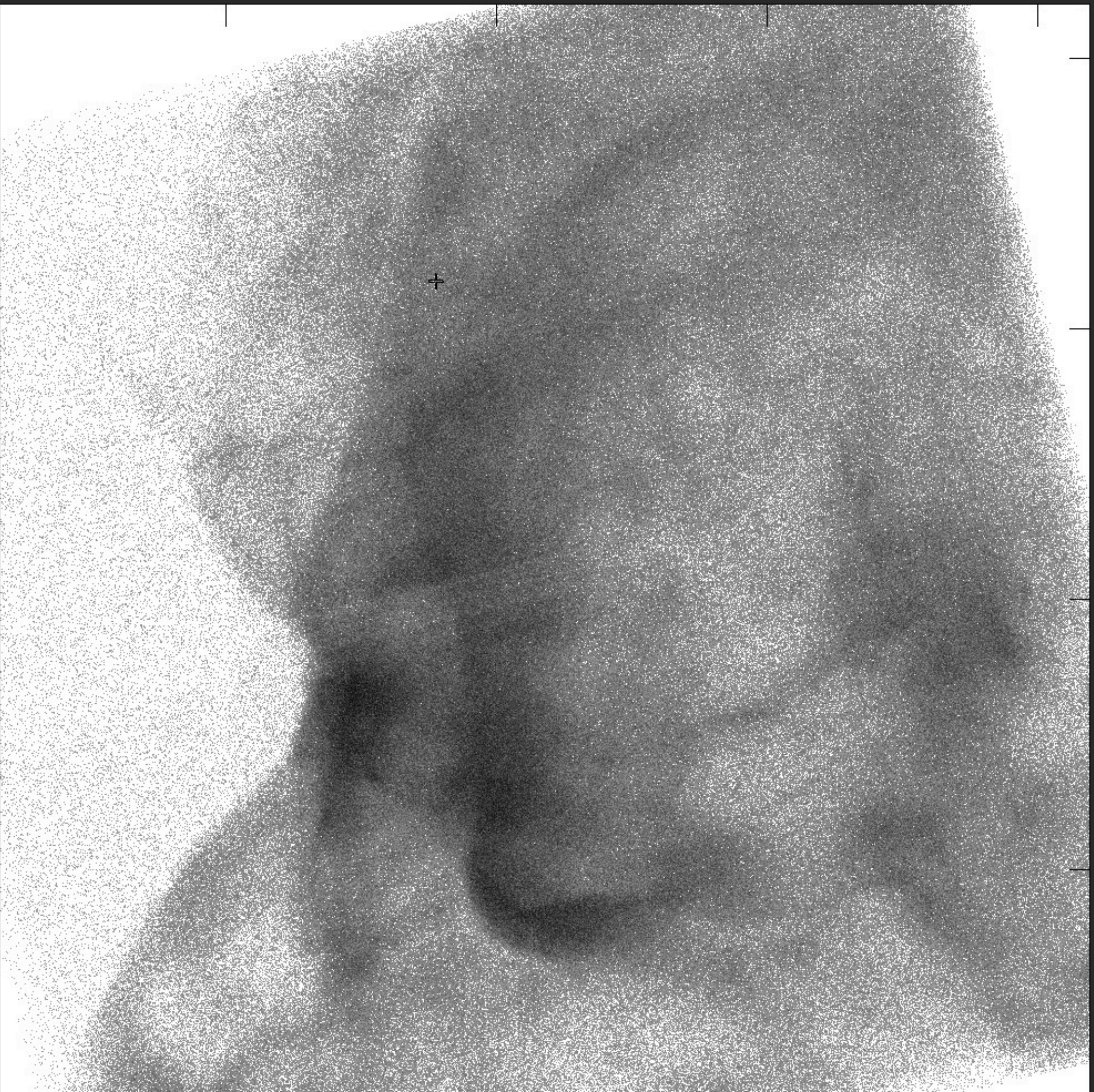




ii. structure (caveats)



why should you care?

- puppis A is interacting with a dense cloud at BEK (hwang+ 2005)
- detected with Fermi-LAT (hewitt+ 2012)
- katsuda+ (2012) found enhanced f/r ratios in xmm-newton RGS x-ray spectra of BEK

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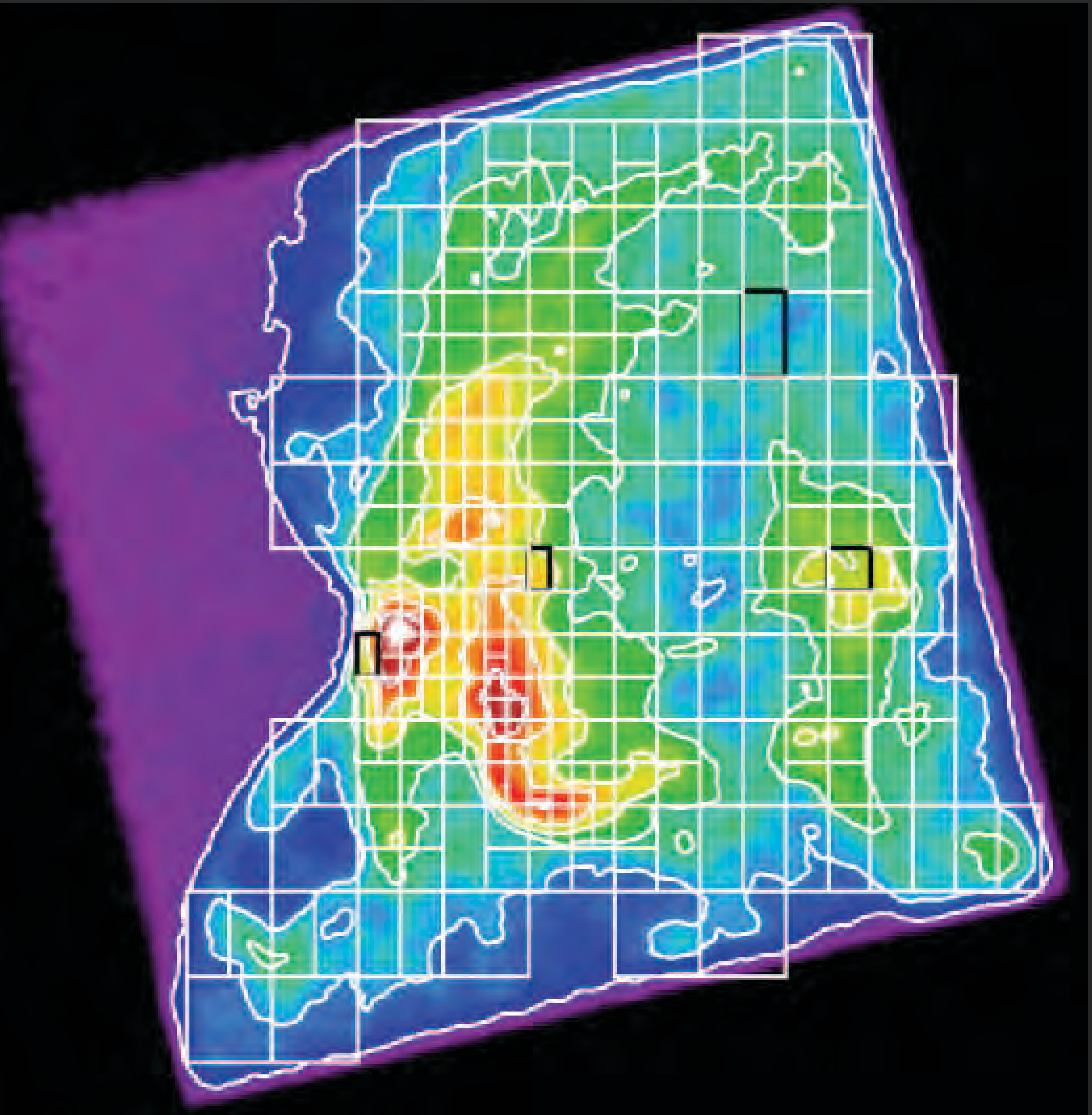

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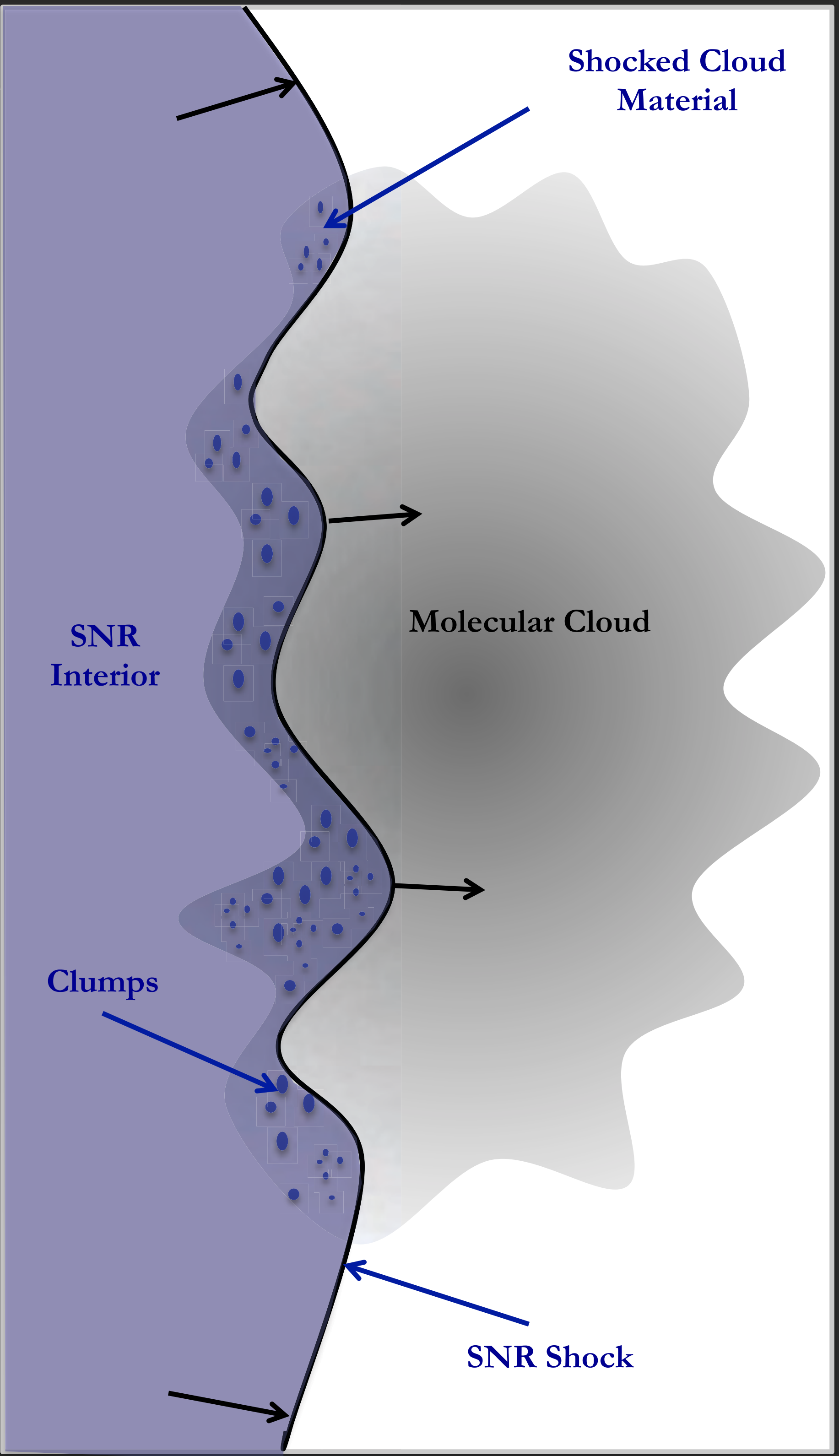

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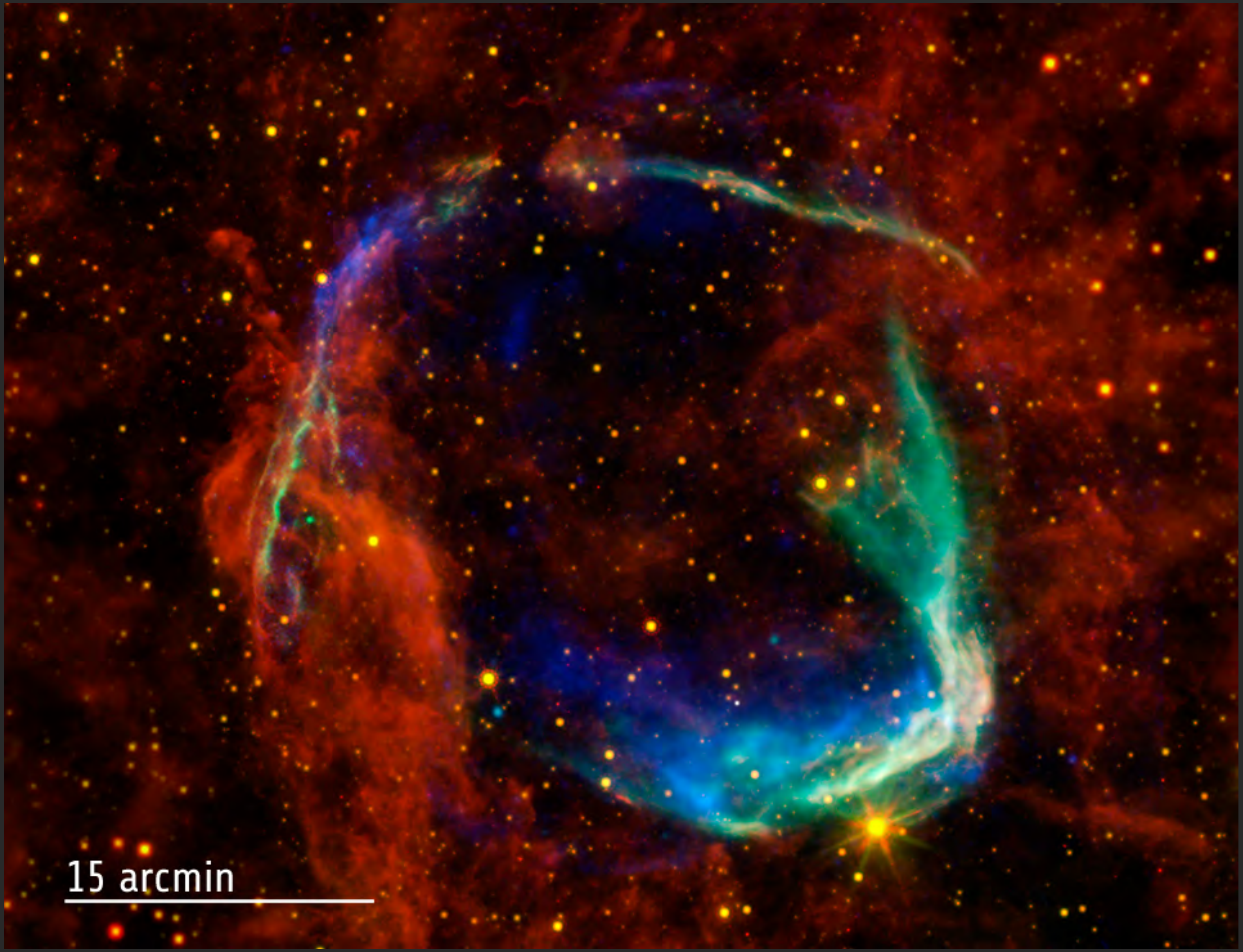
ii. x-rays: rcw 86

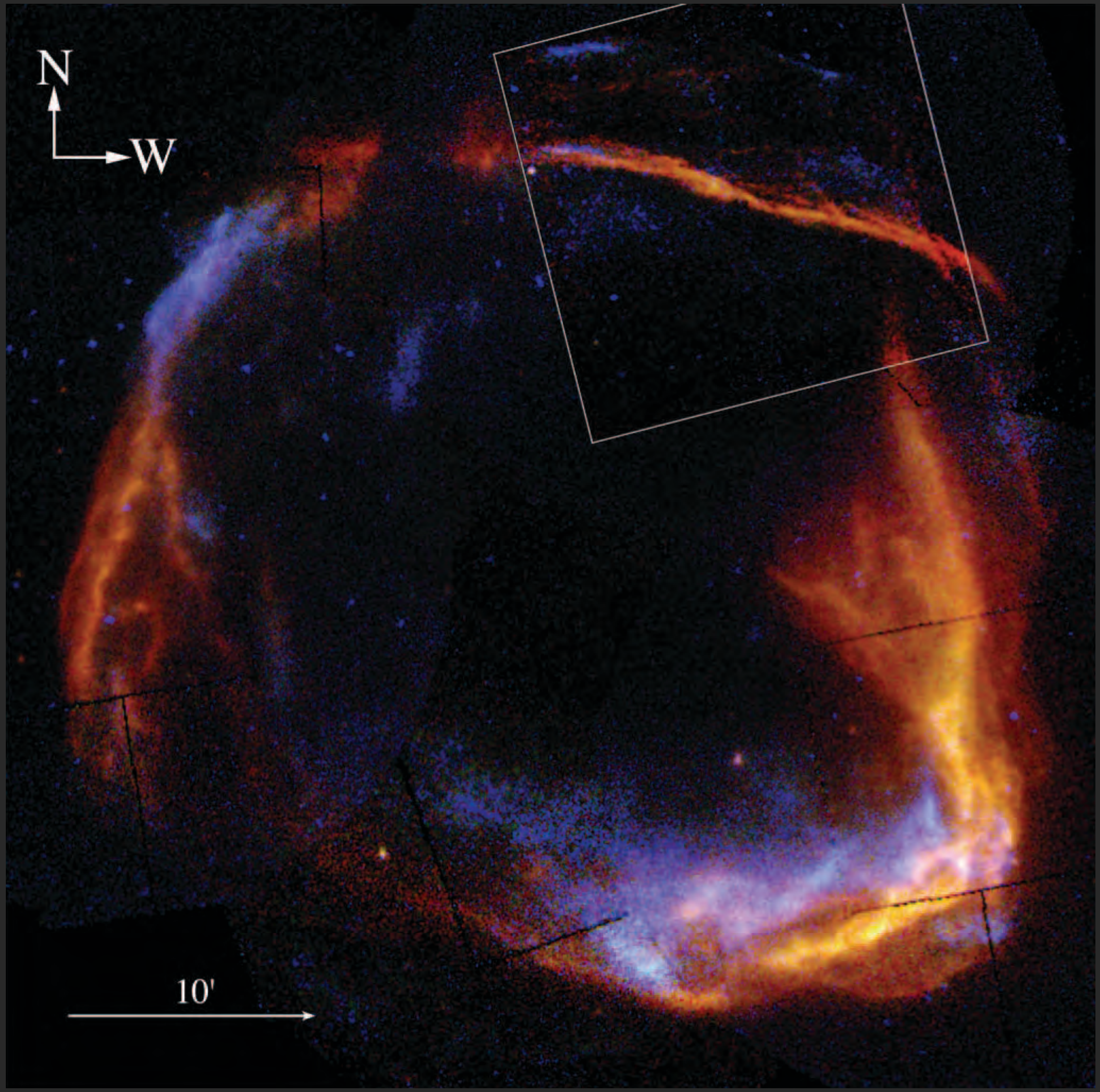


red: spitzer 24 microns
(wise 22 microns)

chandra and xmm
green:0.5-1.95 keV
blue: 1.95-6.8 keV

x-ray: nasa/cxc/sao & esa; infared: nasa/jpl-caltech/b. williams (ncsu)

ii. x-rays: rcw 86

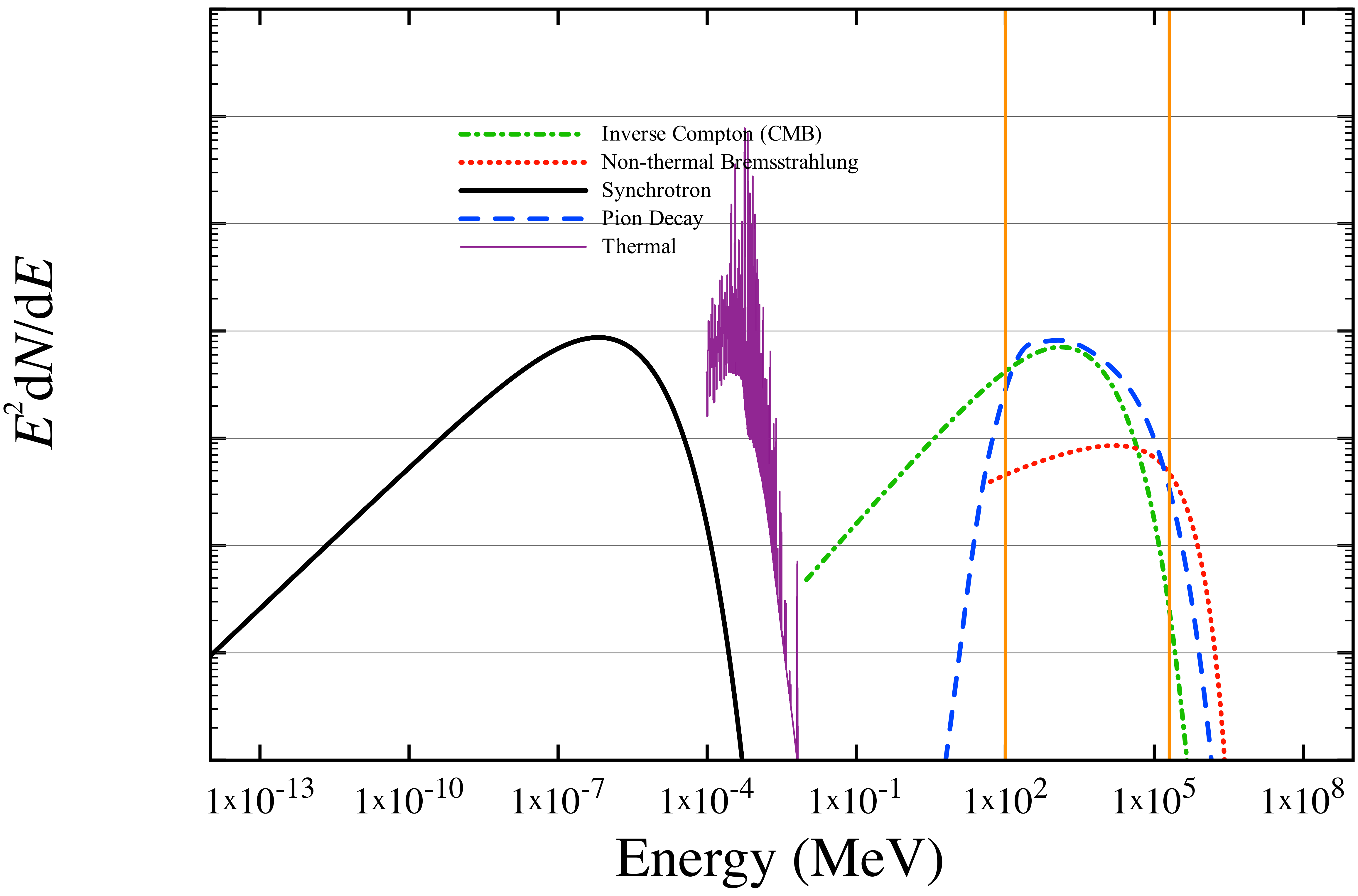


chandra and xmm

red: 0.5 - 1 keV
green: 1.5 - 2 keV
blue: 2 - 8 keV

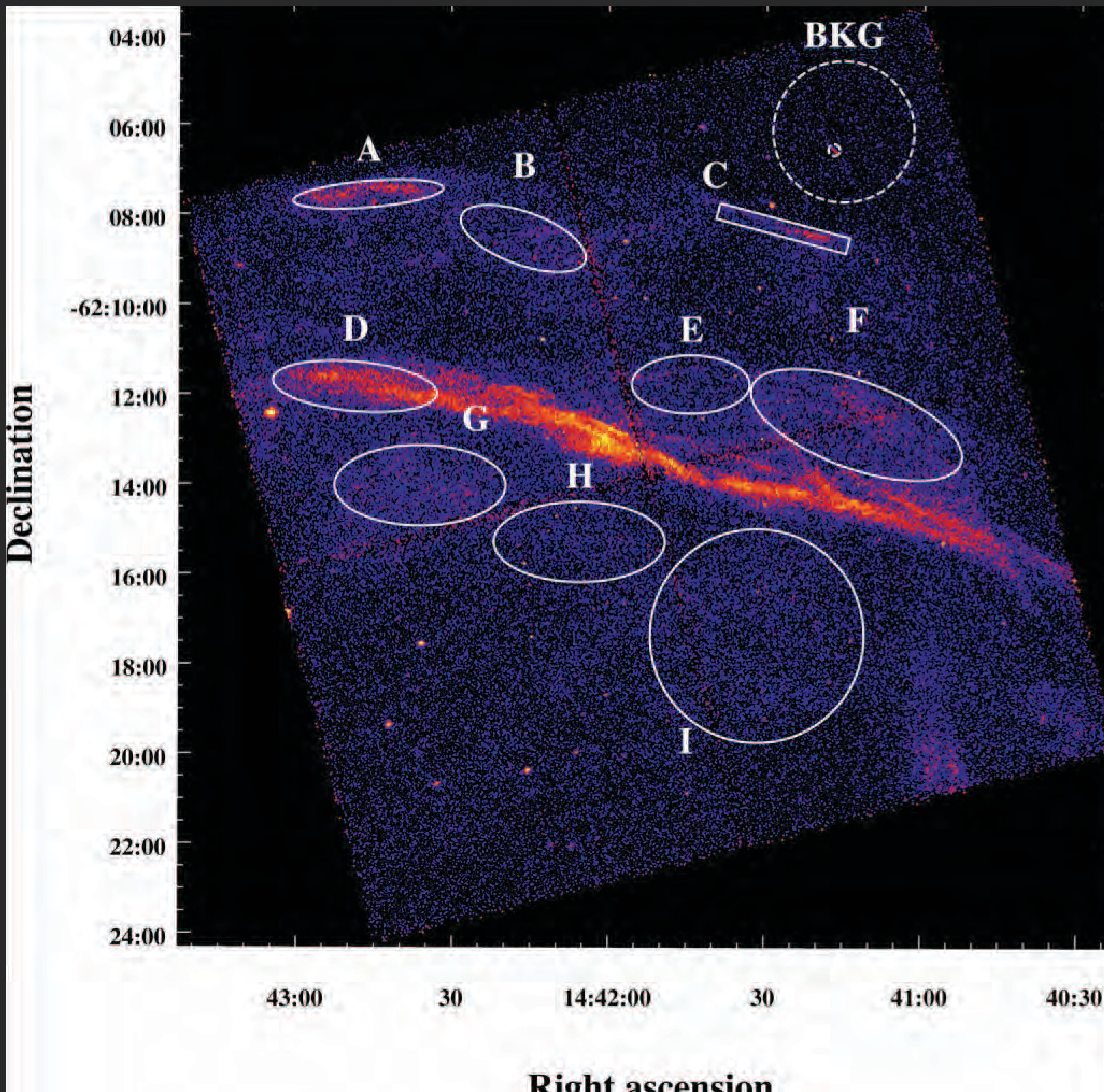
ii. x-rays: rcw 86

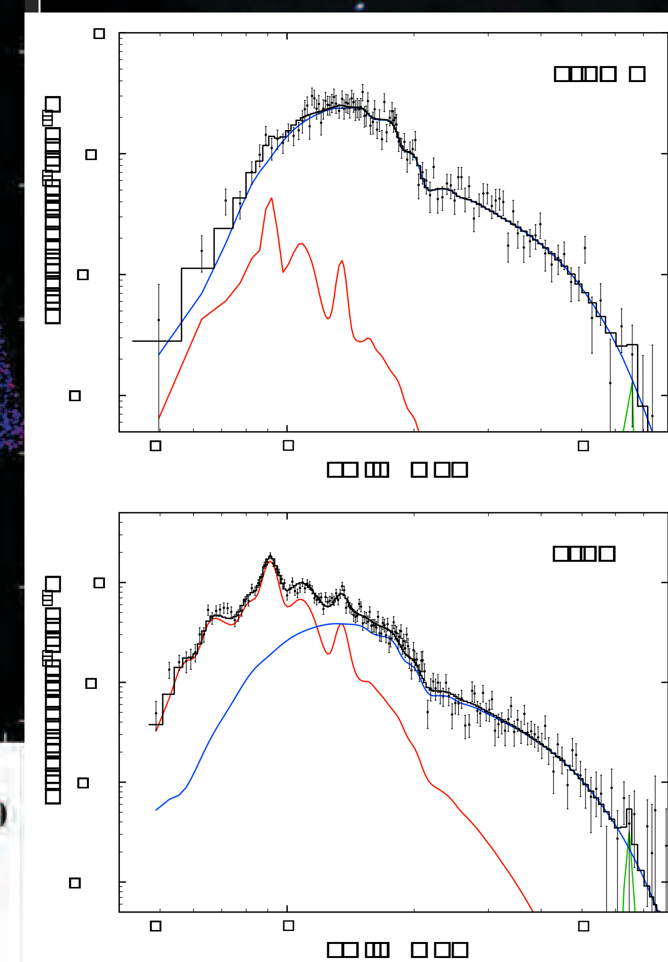
ii. emission



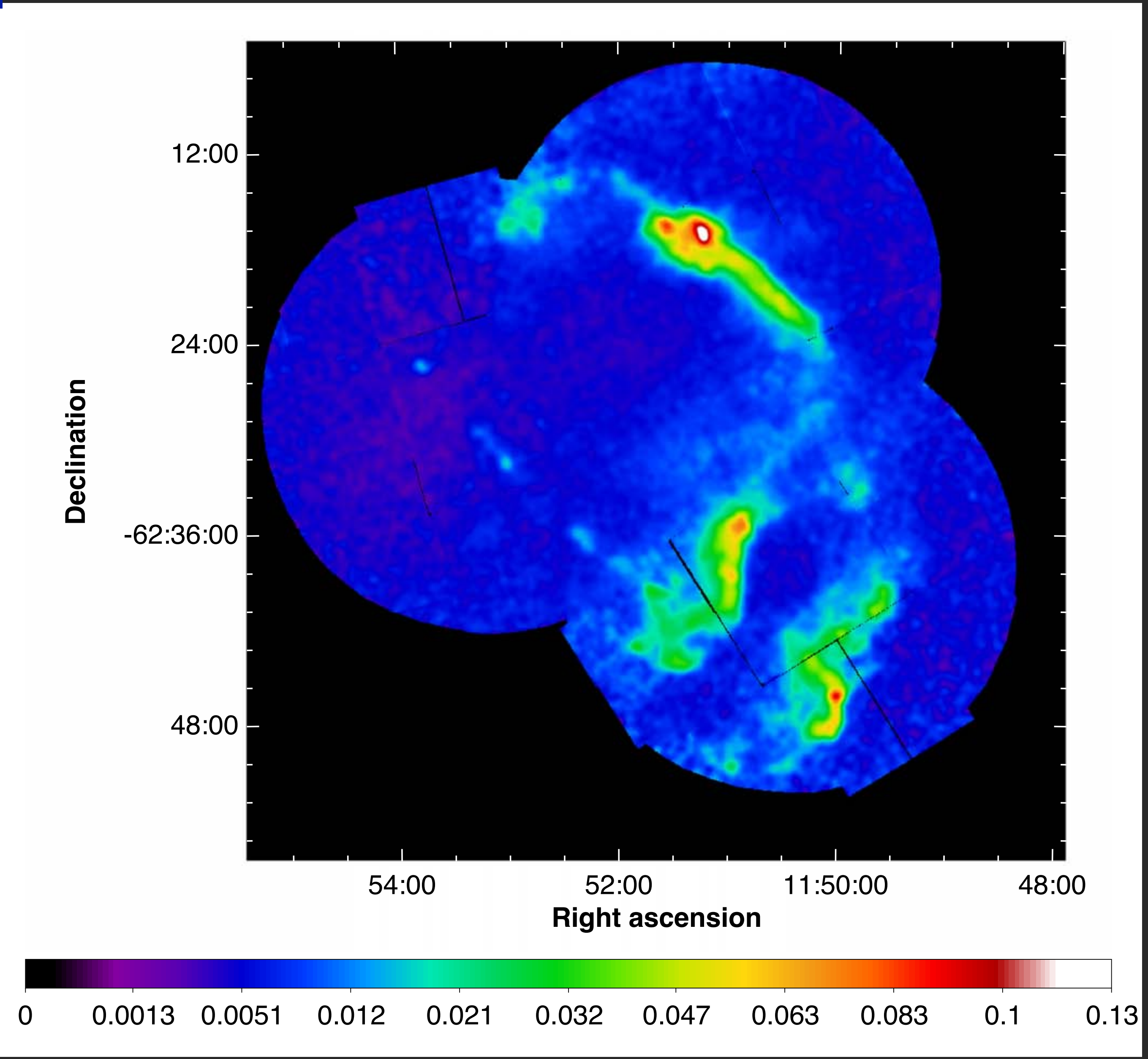
Inverse Compton (CMB)
Non-thermal Bremsstrahlung
Synchrotron
Pion Decay
Thermal
E^2dN/dE
1x10^{-13}
1x10^{-10}
1x10^{-7}
1x10^{-4}
1x10^{-1}
1x10^{2}
1x10^{5}
1x10^{8}
Energy (MeV)

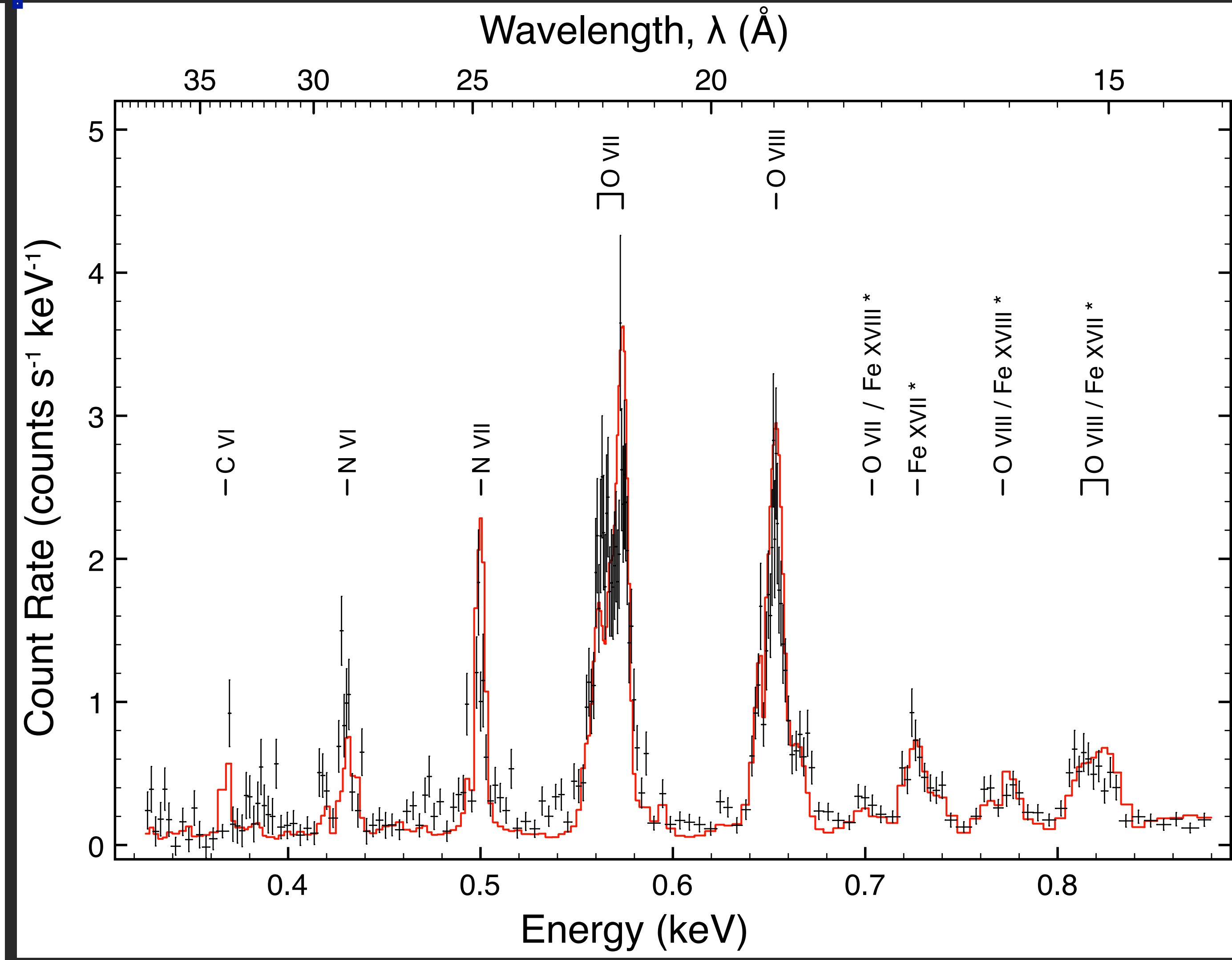
ii. x-rays: rcw 86





ii. thermal x-rays



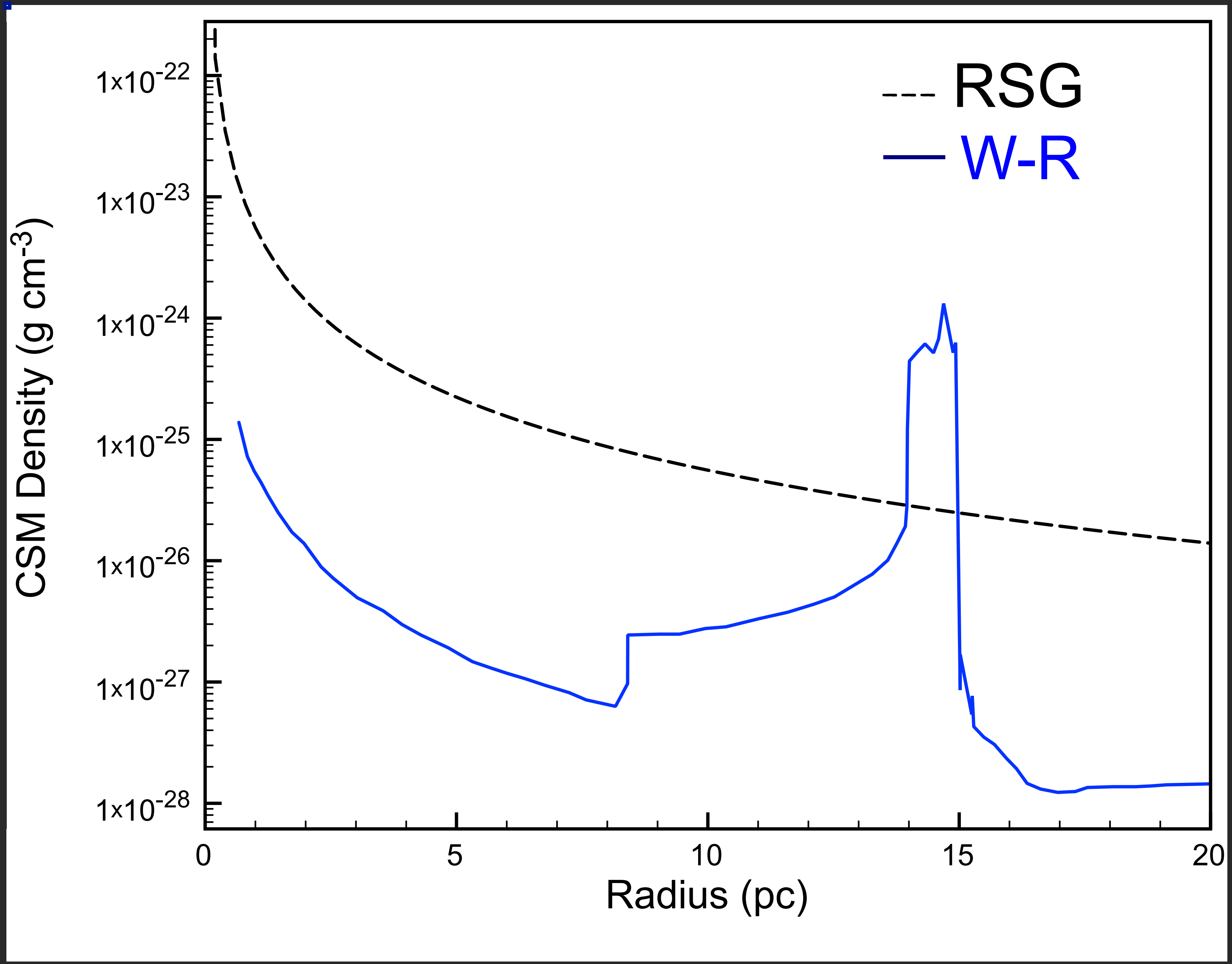


abundances

N = 1.85

O = 0.6

ii. thermal x-rays + progenitor?



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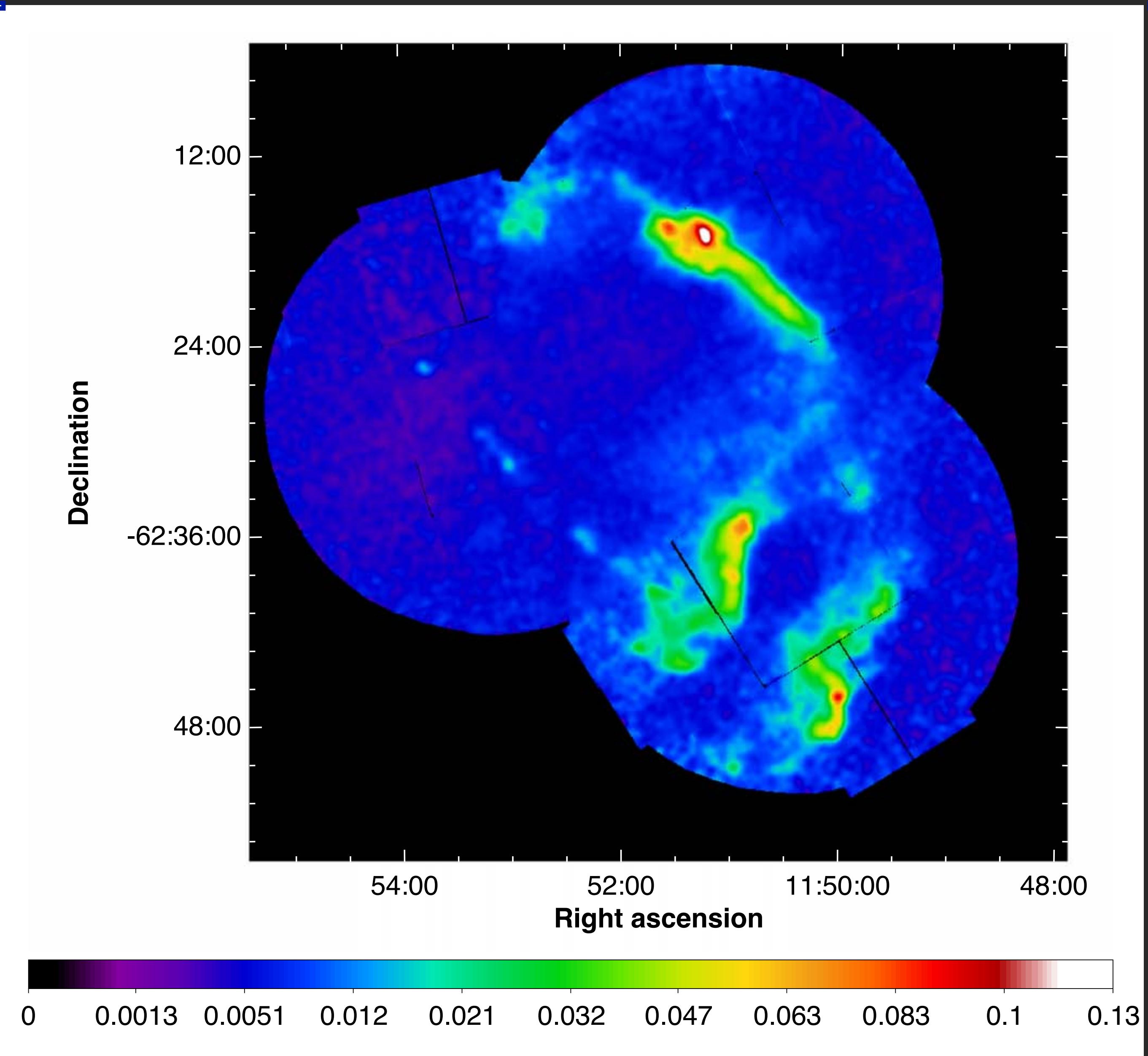
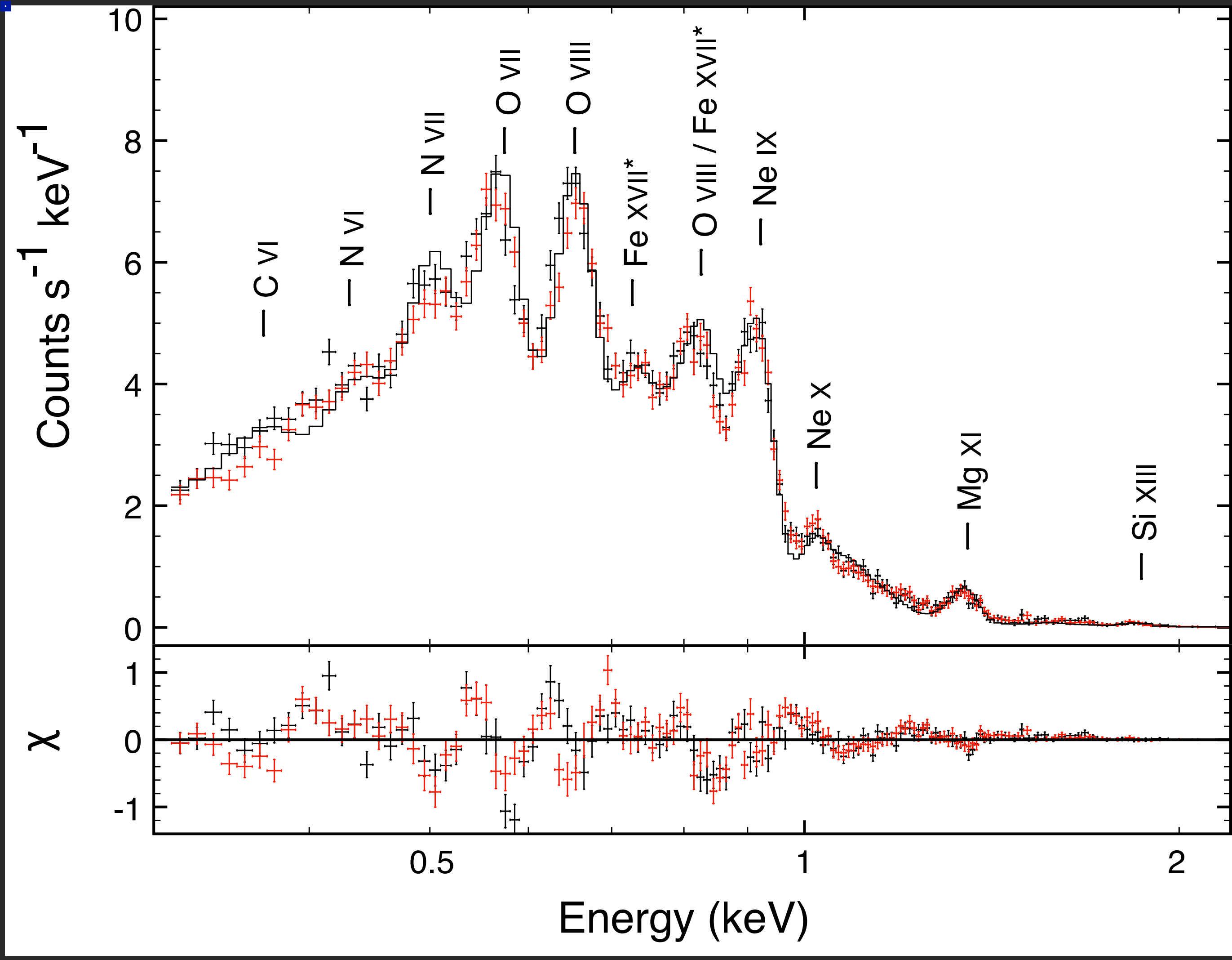




castro et al. (2011)

ii. thermal x-rays - sedov

- sedov expansion

$$R_S = \left[\frac{\alpha(\gamma)Et^2}{\rho_0}\right]^{1/5}$$

- Rankine-Hugoniot jump conditions

$$kT_S = \frac{2(\gamma-1)}{(\gamma+1)^2}\mu m_{\mathrm{H}} v_S^2$$

- $EM = n_e n_{\mathrm{H}} V$ $\longrightarrow$

$$EM = \frac{(\gamma+1)}{(\gamma-1)}\left(\frac{n_e}{n_H}\right) n_0^2 \frac{4}{3}\pi R_S^3$$

ii. thermal x-rays - sedov

$$n_0 = 40.64 \left(\frac{EM}{10^{60}\,\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{R_S}{1\,\mathrm{pc}} \right)^{-3/2} \mathrm{cm}^{-3}\,,$$

$$t = 423.9 \left(\frac{kT_S}{1\,\mathrm{keV}} \right)^{-1/2} \left(\frac{R_S}{1\,\mathrm{pc}} \right) \mathrm{yr}\,,$$

$$E_0 = 0.075 \left(\frac{EM}{10^{60}\,\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{kT_S}{1\,\mathrm{keV}} \right) \left(\frac{R_S}{1\,\mathrm{pc}} \right)^{3/2} \times 10^{51}\mathrm{ergs}\,.$$

ii. balmer-dominated shocks

what are balmer-dominated shocks? why are they important to SNR science?

ii. balmer-dominated shocks

impact excitation of neutral hydrogen

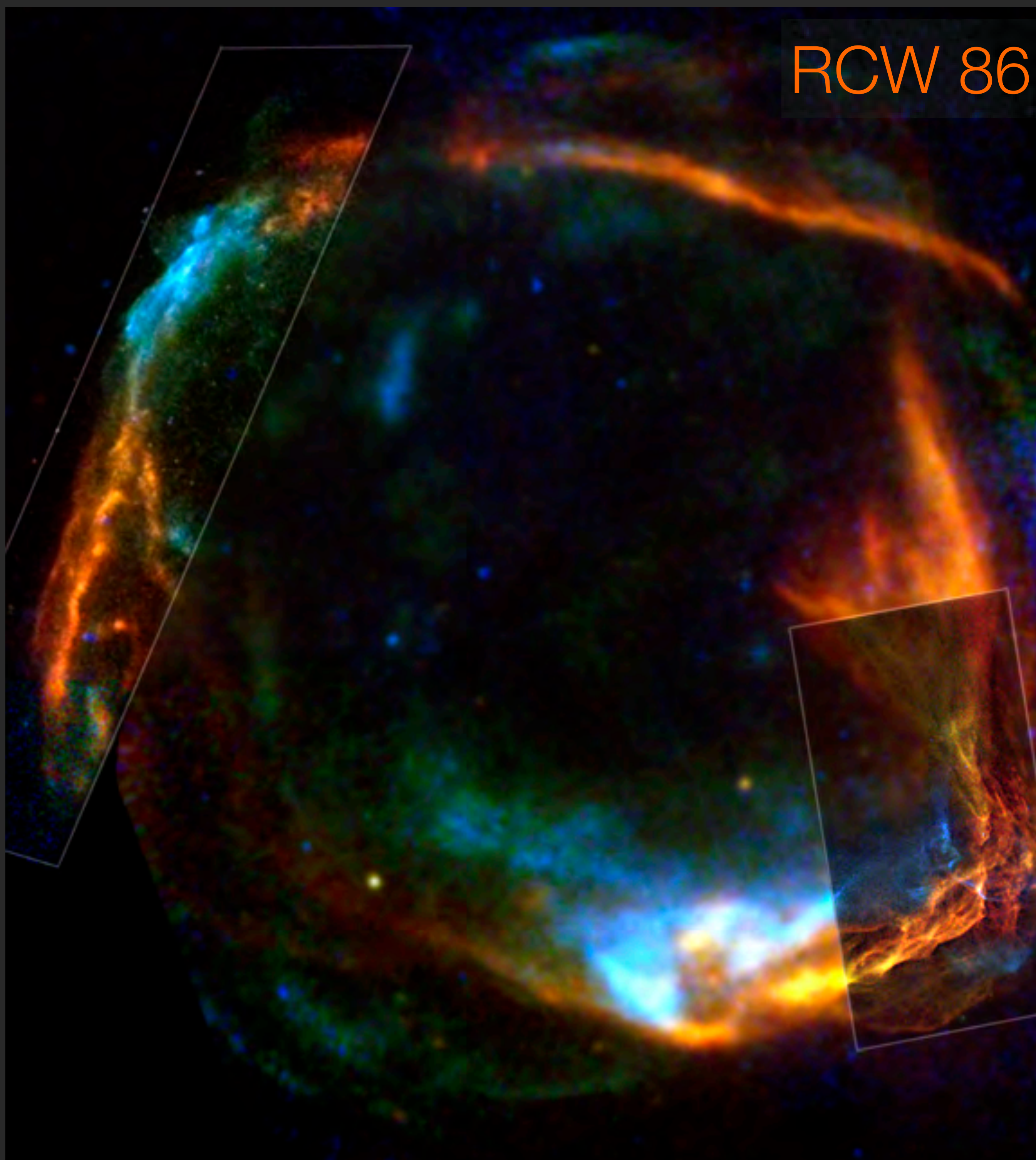
two components: narrow and broad

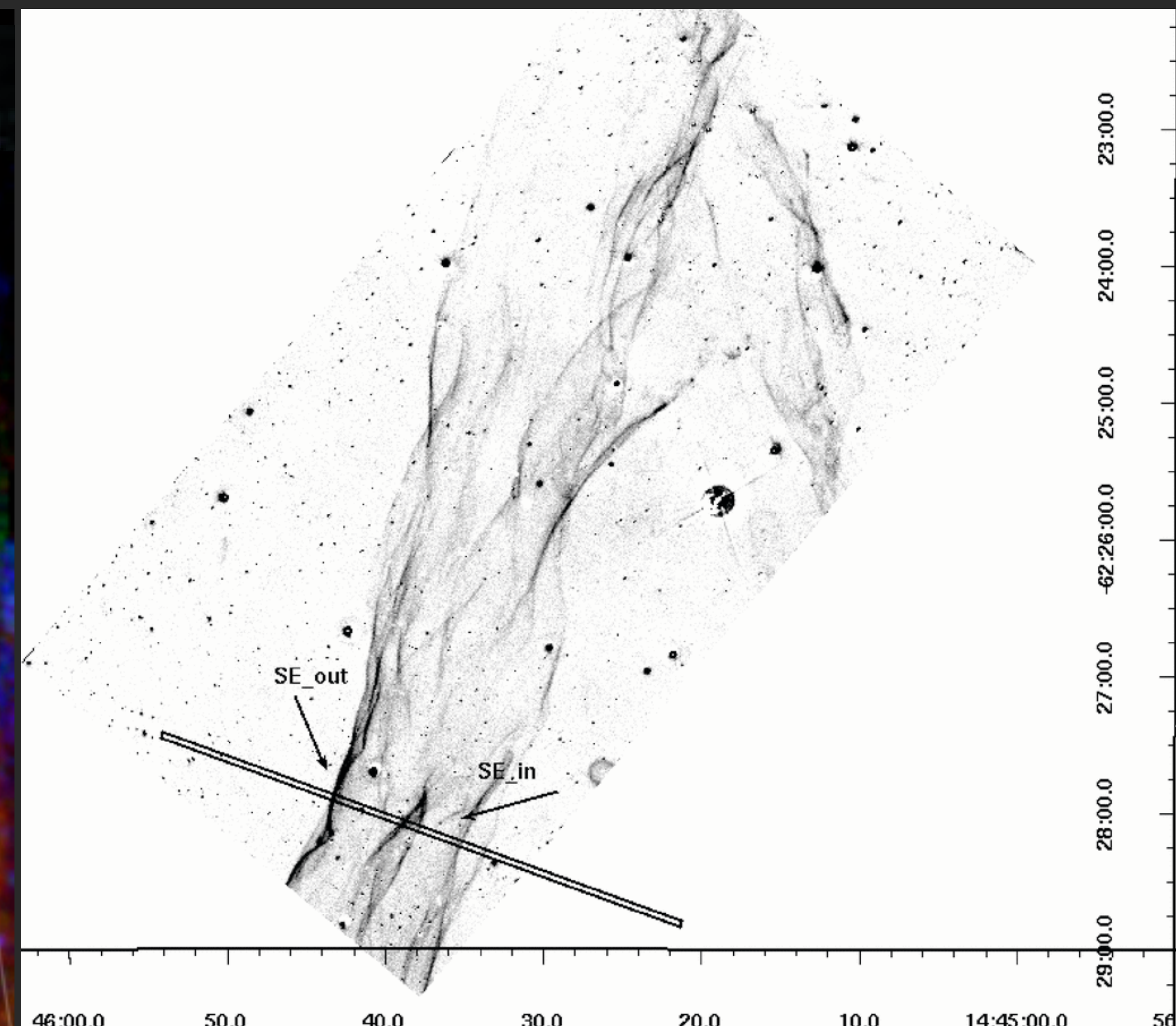
narrow – cold pre-shock gas

broad – thermal broadening of shocked protons

weak presence of forbidden lines

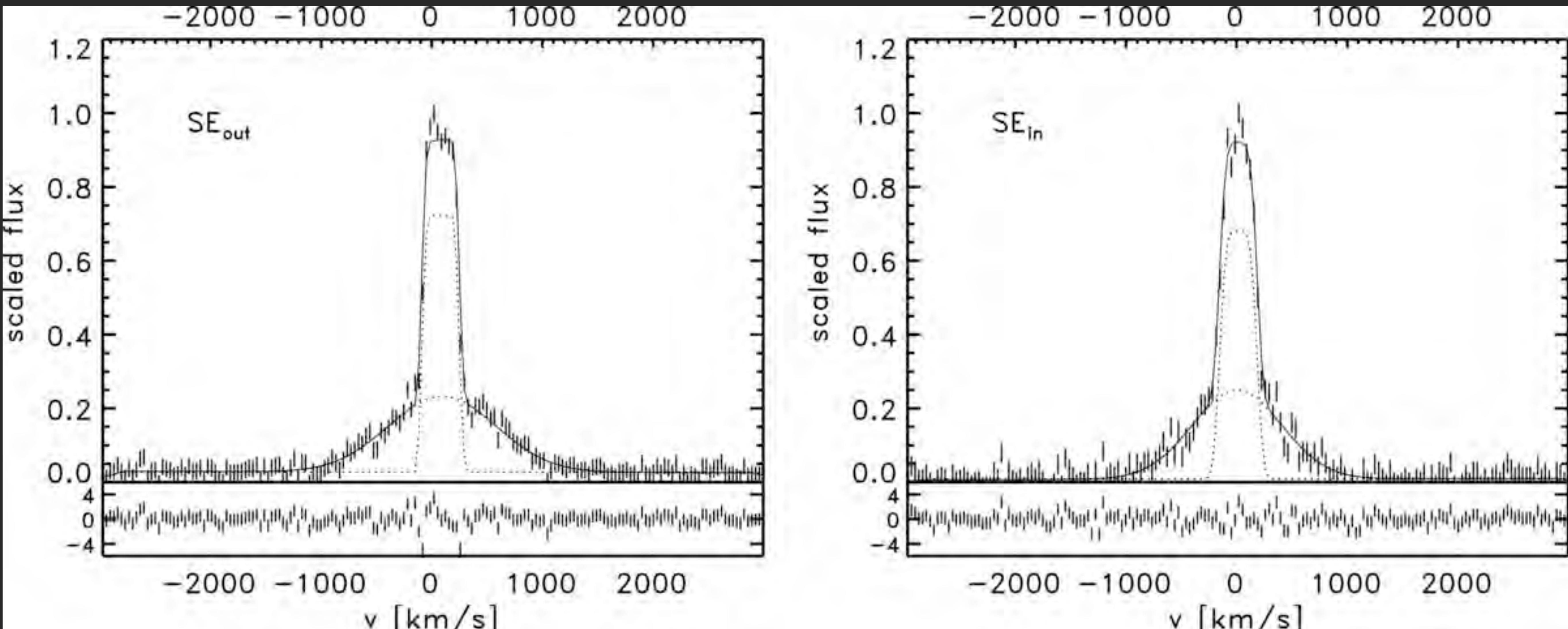
ii. balmer-dominated shocks





helder, vink & bassa (2011)

ii. balmer-dominated shocks



helder, vink & bassa (2011)

end of part I

up to now...

part I: SNRs

why should you care about SNRs?
what do we know about SNRs in general?
- executive summary
- types
- structure and evolution
- emission
- x-ray observations
- balmer dominated shocks

part II: particle acceleration

outline

why should you care about SNRs-CRs?

what evidence is there that SNRs accelerate cosmic rays?

how has the fermi-lat contributed?

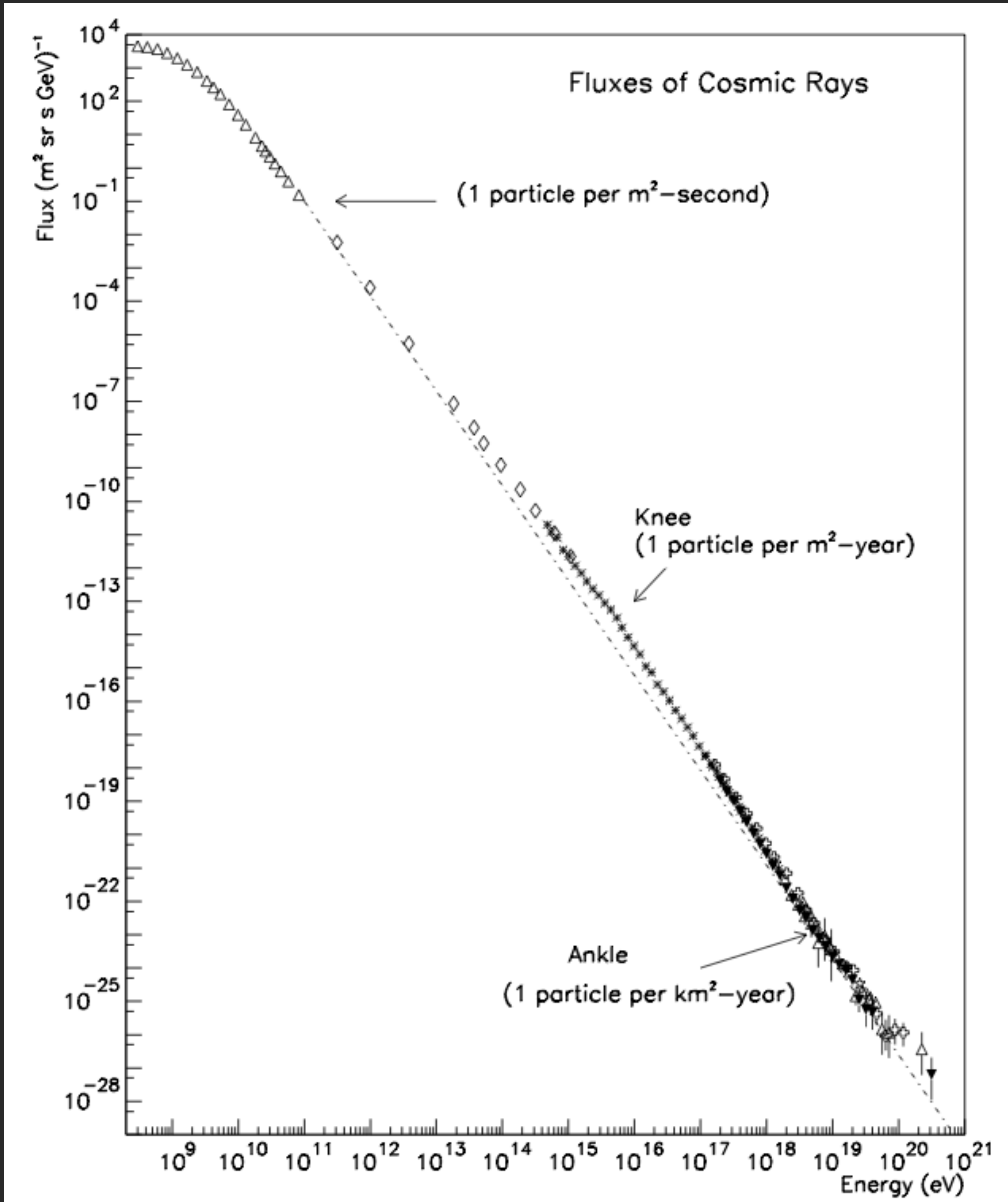
what are the open questions?

i. why?

why should we care about the connection between SNRs and cosmic rays?

i. why?

- origin
- γ-ray background
- particle acceleration
- SNR evolution



i. why?

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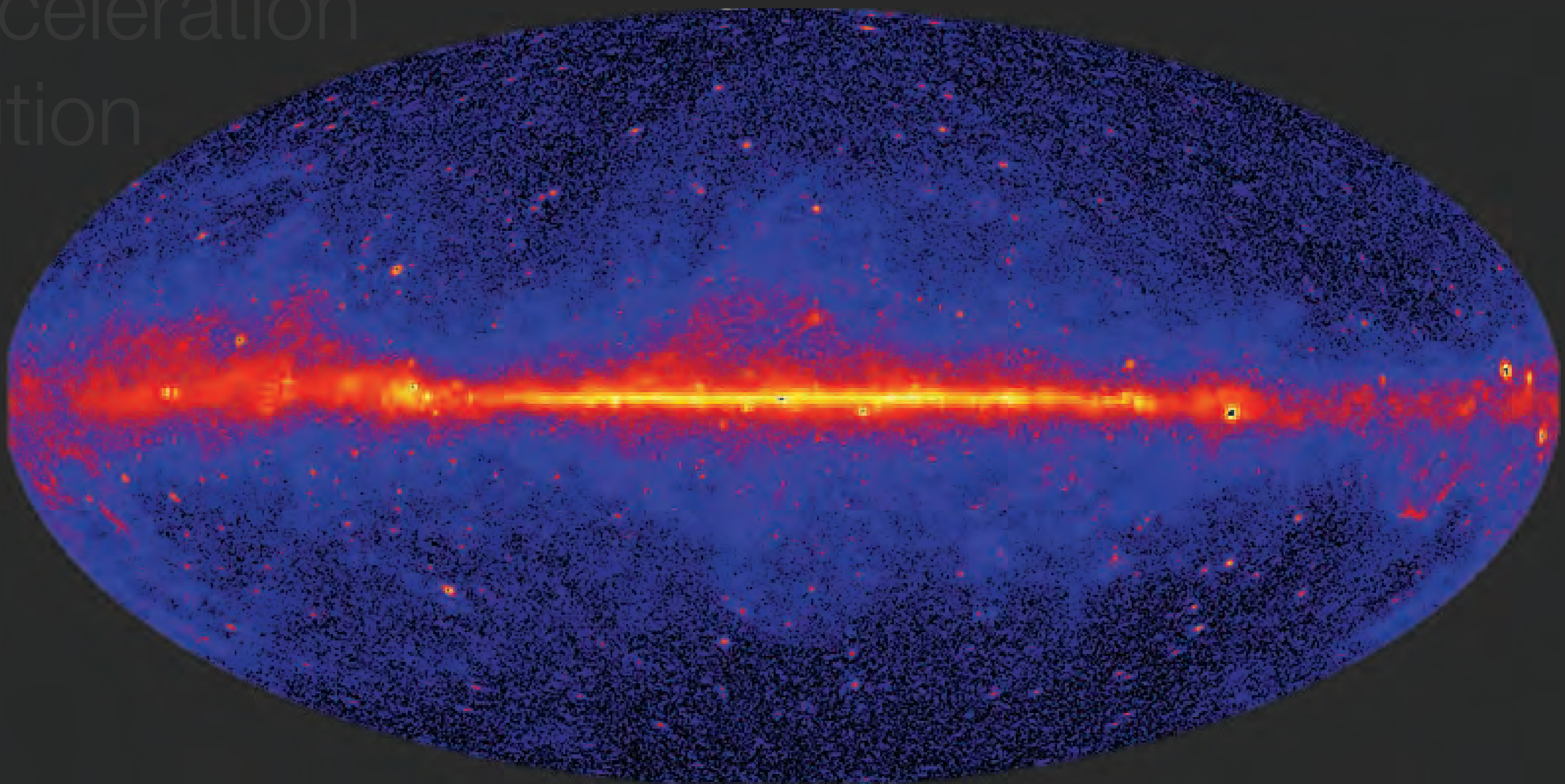
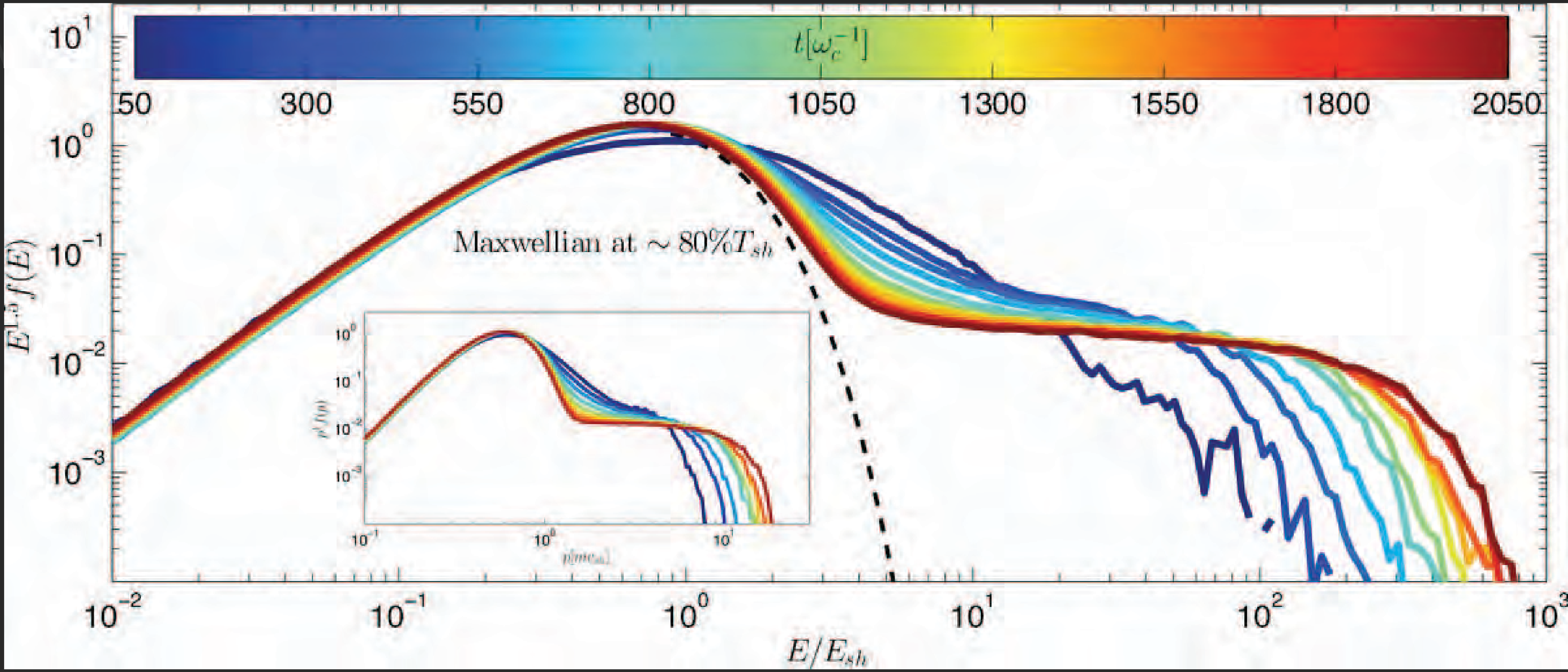


i. why?

- origin
- γ-ray background
- particle acceleration
- SNR ev

caprioli & spitkovsky 2014



i. why?

- origin
- γ-ray background
- particle acceleration
- SNR evolution

ii. evidence

what evidence is there that SNRs accelerate cosmic rays?

ii. evidence

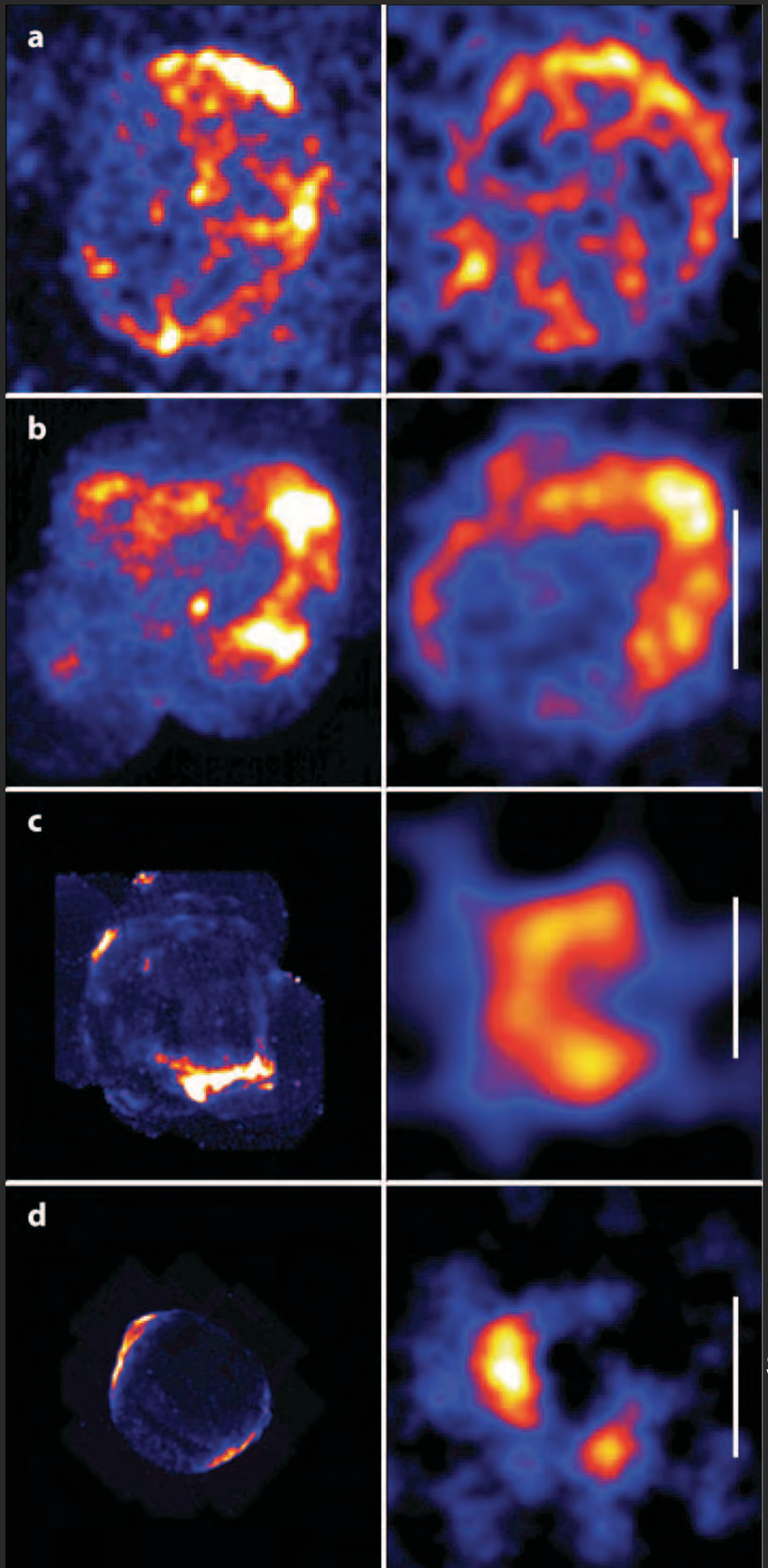
- non-thermal X-rays
- γ-ray emission
- dynamical properties
- structure

koyama+ 1995

ii. evidence

- non-thermal X-rays
- γ-ray emission
- dynamical properties
- structure

keV TeV



vela jr.

rx j1713.7-3936

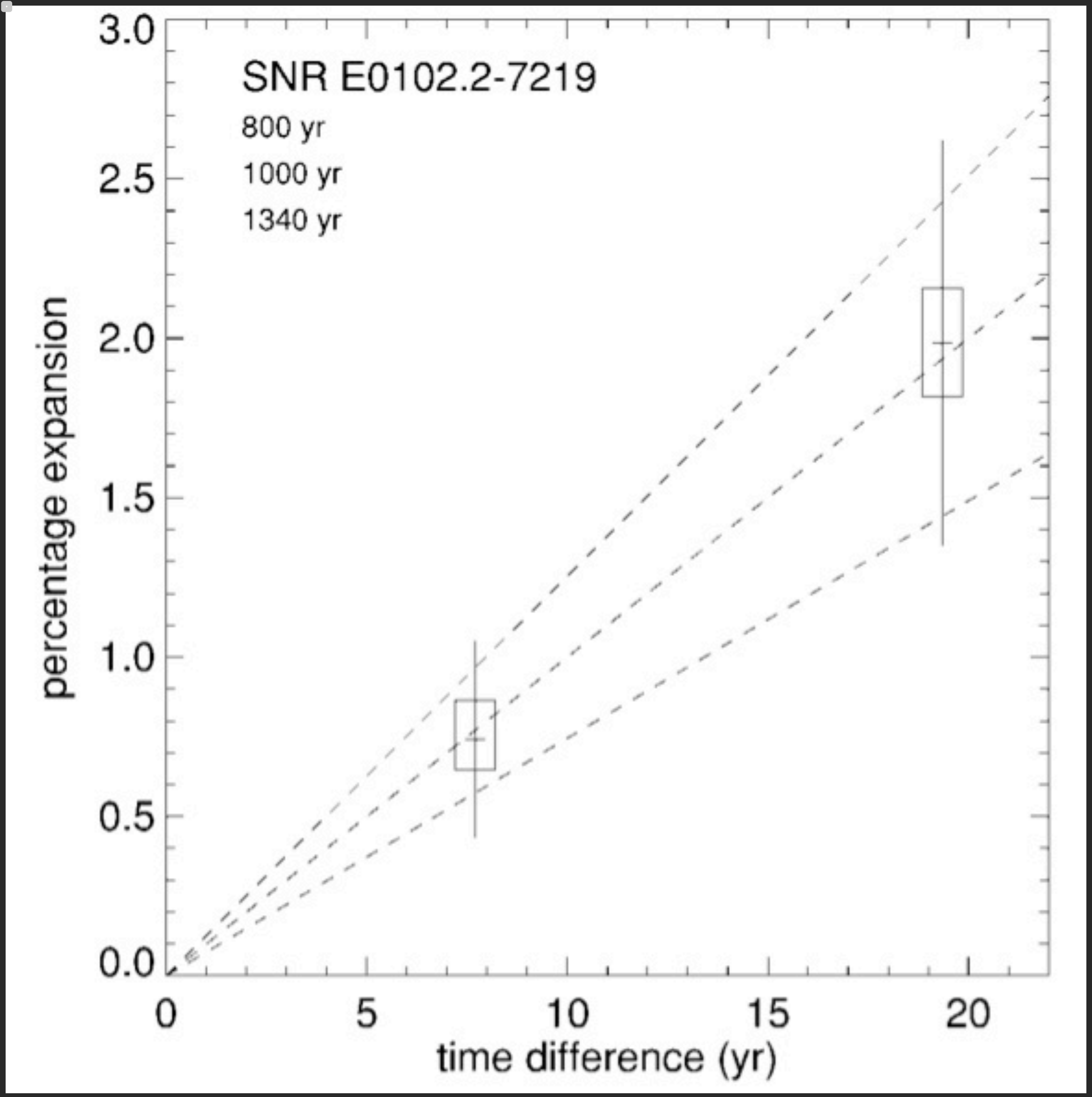
rcw 86

sn 1006

hinton & hofmann 2009
uchiyama+ 2002
aschenbach 1998
vink+ 2006
aharonian+ 2006, 2007,2008
naumann-godo+ 2006

ii. evidence

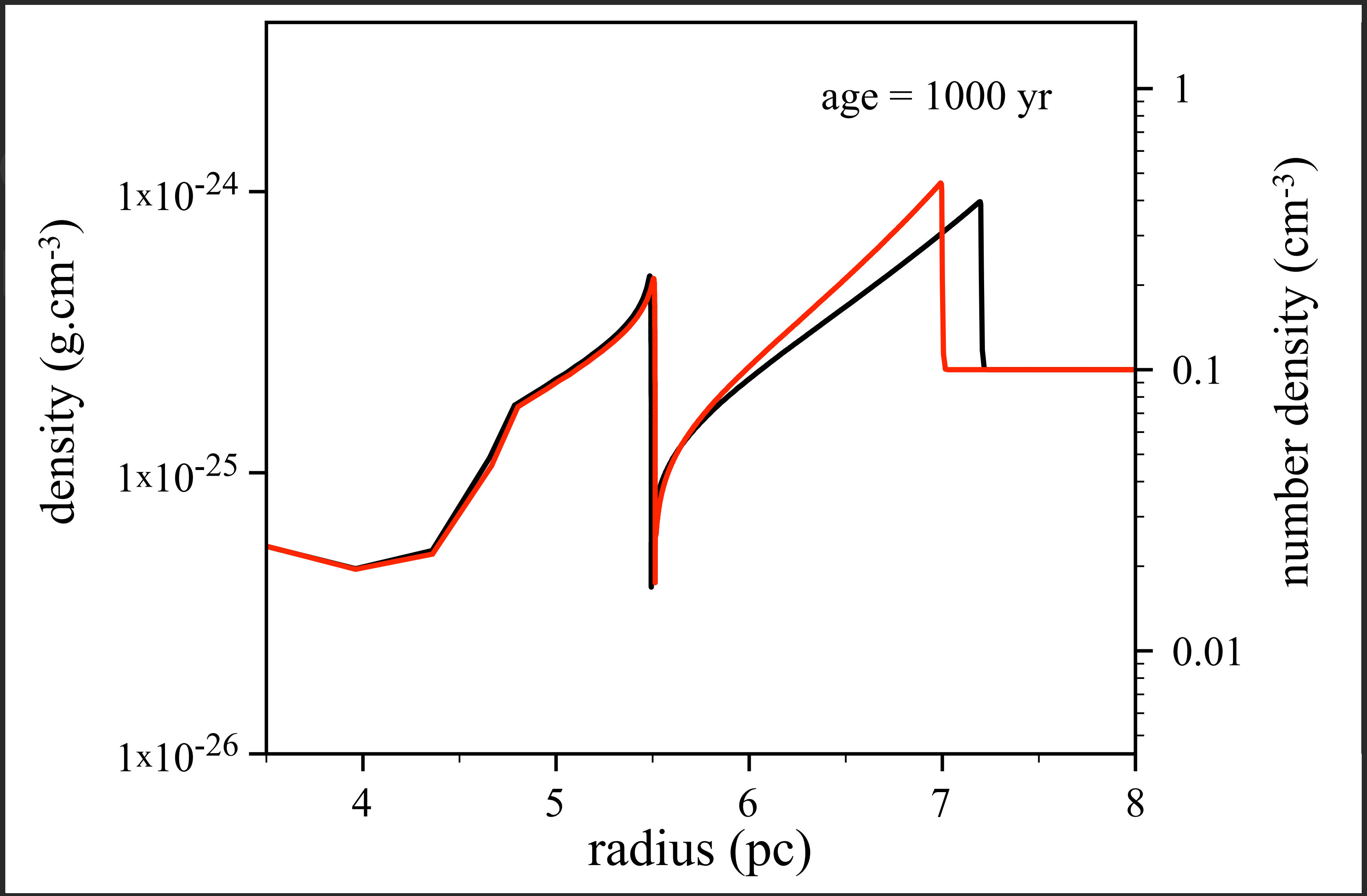
- non-thermal X-rays
- γ-ray emission
- **dynamical properties**
- structure



hughes+ 2000

ii. evidence

- non-thermal
- γ-ray emissi
- dynamical p
- structure



ii. evidence

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- γ-ray emission
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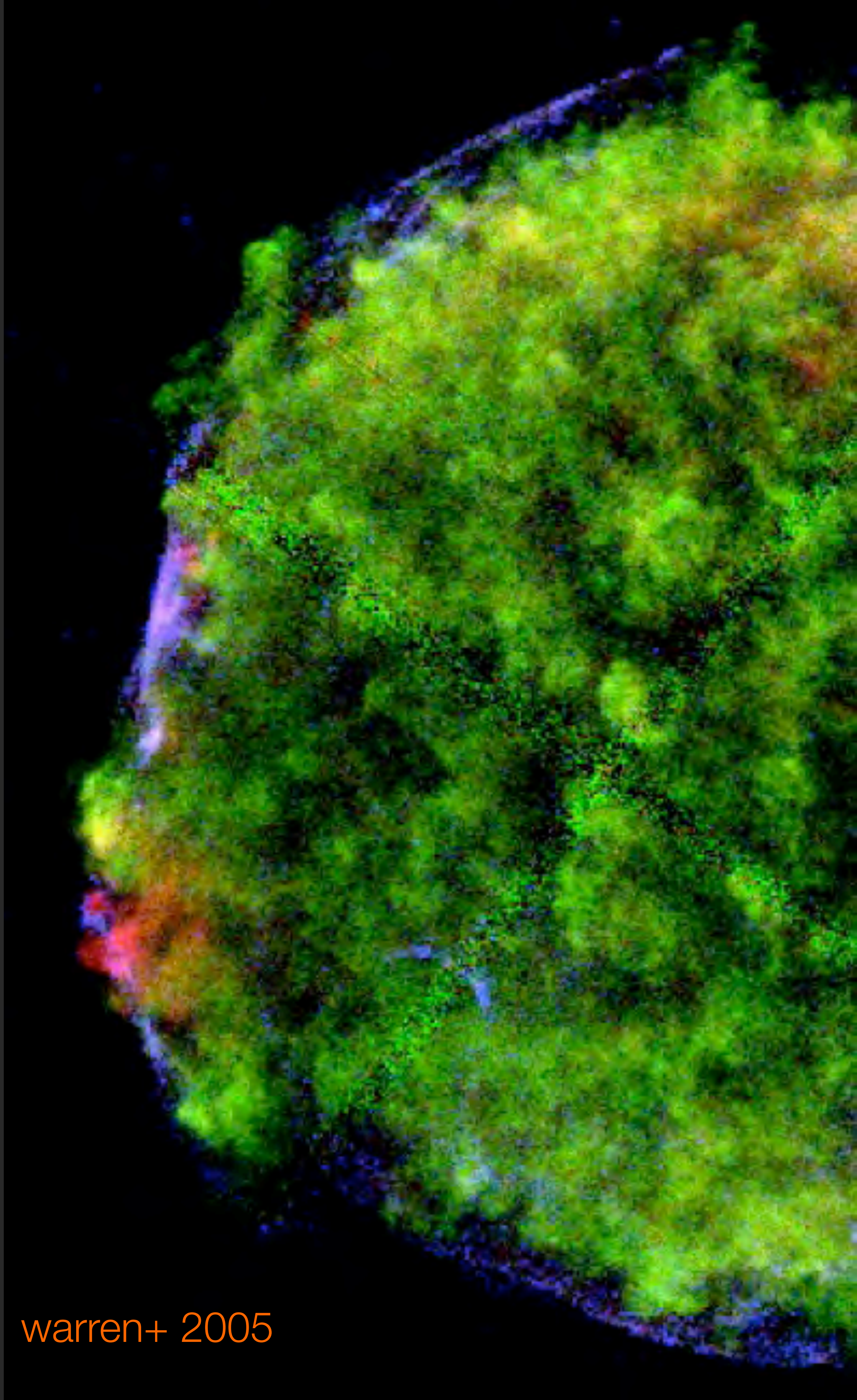

warren+ 2005

ii. evidence

- non-thermal X-rays
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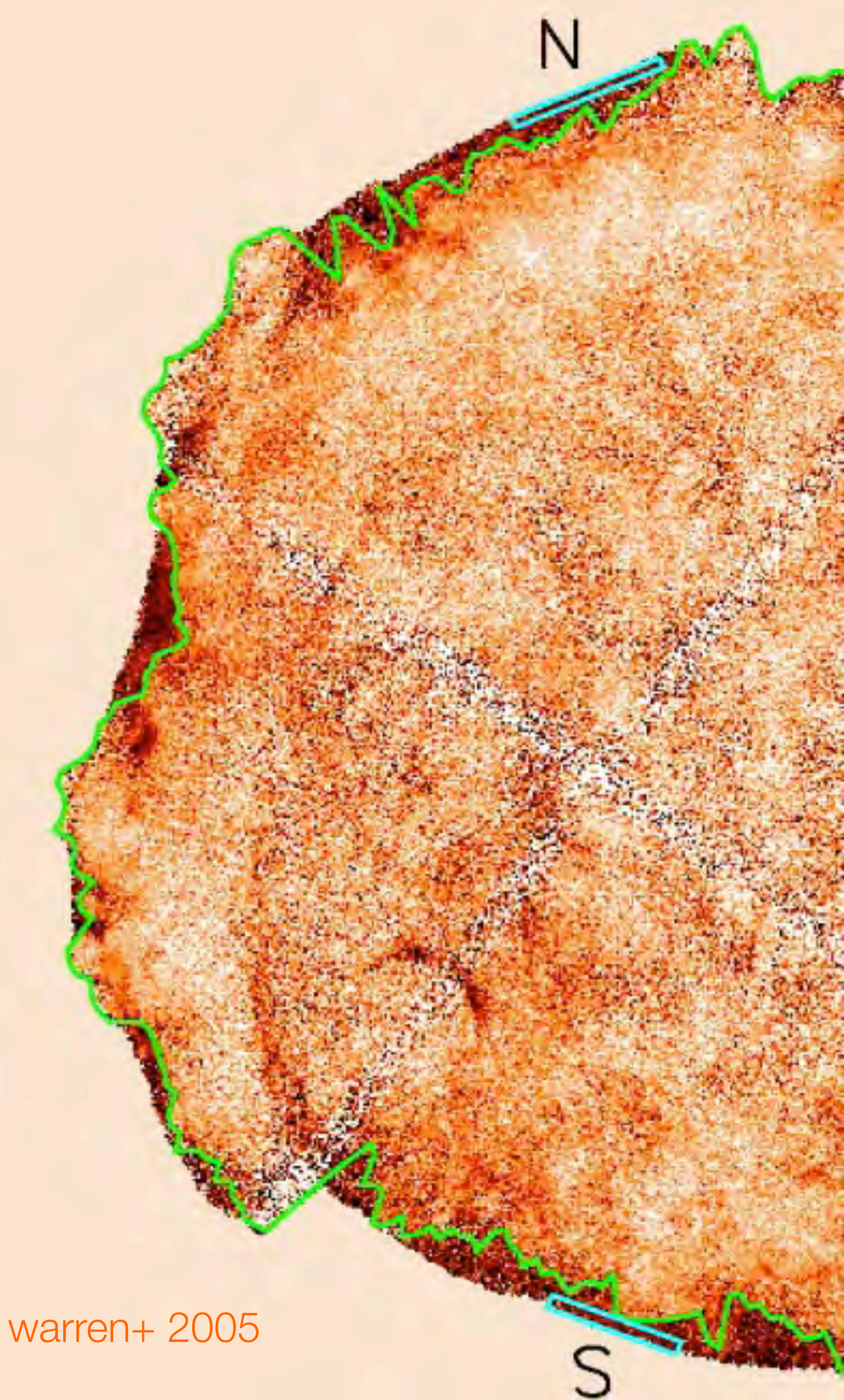
- structure

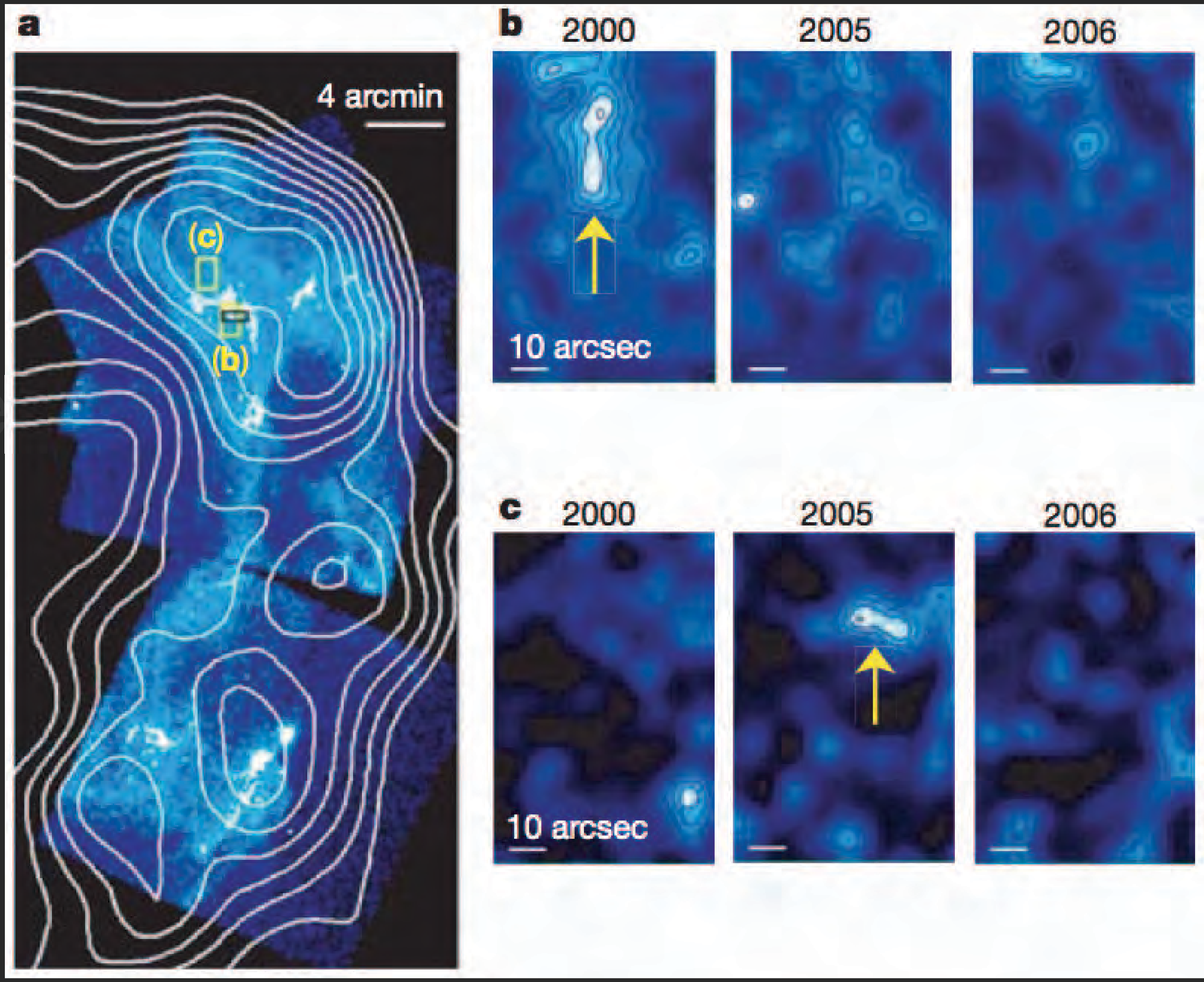


warren+ 2005

ii. evidence

- non-thermal X-rays
- ?-ray emission
- dynamical properties
- structure
- **non-thermal X-rays**

$$t_{\rm sync} \sim 1.5 \left(\frac{B}{\rm mG}\right)^{-1.5} \left(\frac{\epsilon}{\rm keV}\right)^{-0.5} \ {\rm year}$$



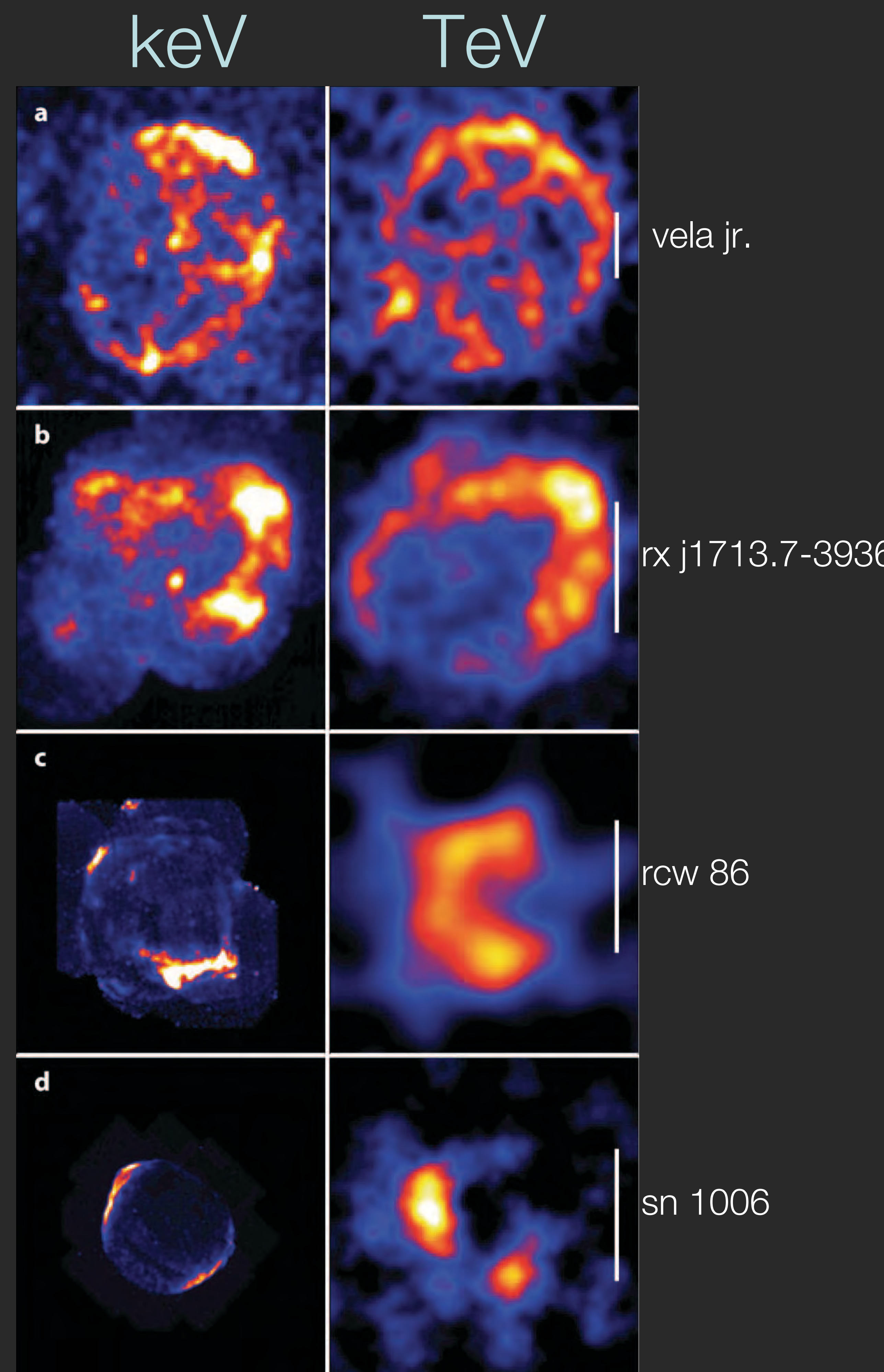
uchiyama+ 2007

iii. fermi-lat

how has the fermi-lat contributed?

ii. evidence

- non-thermal X-rays
- γ-ray emission
- dynamical properties
- structure



hinton & hofmann 2009
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naumann-godo+ 2006

iii. fermi-lat

- many snrs (>25)
- most are snr-mc
- structure

LAT SNR catalog
(sometime in the next few months)

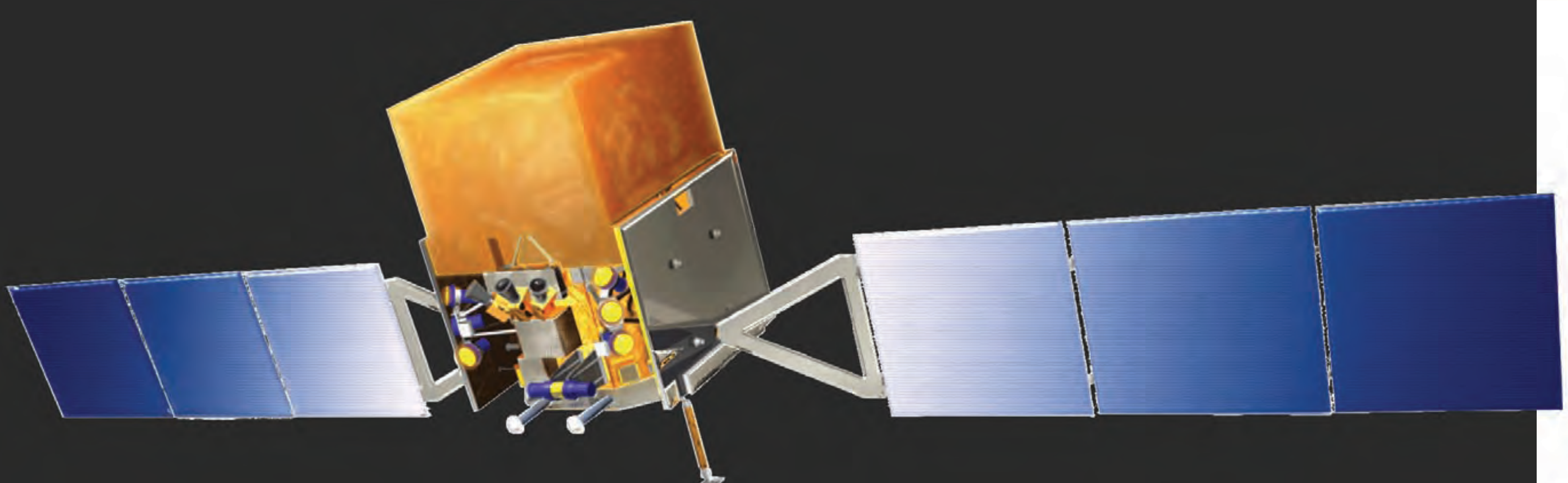

Table 1: *Fermi*-LAT SNRs

Name	Reference
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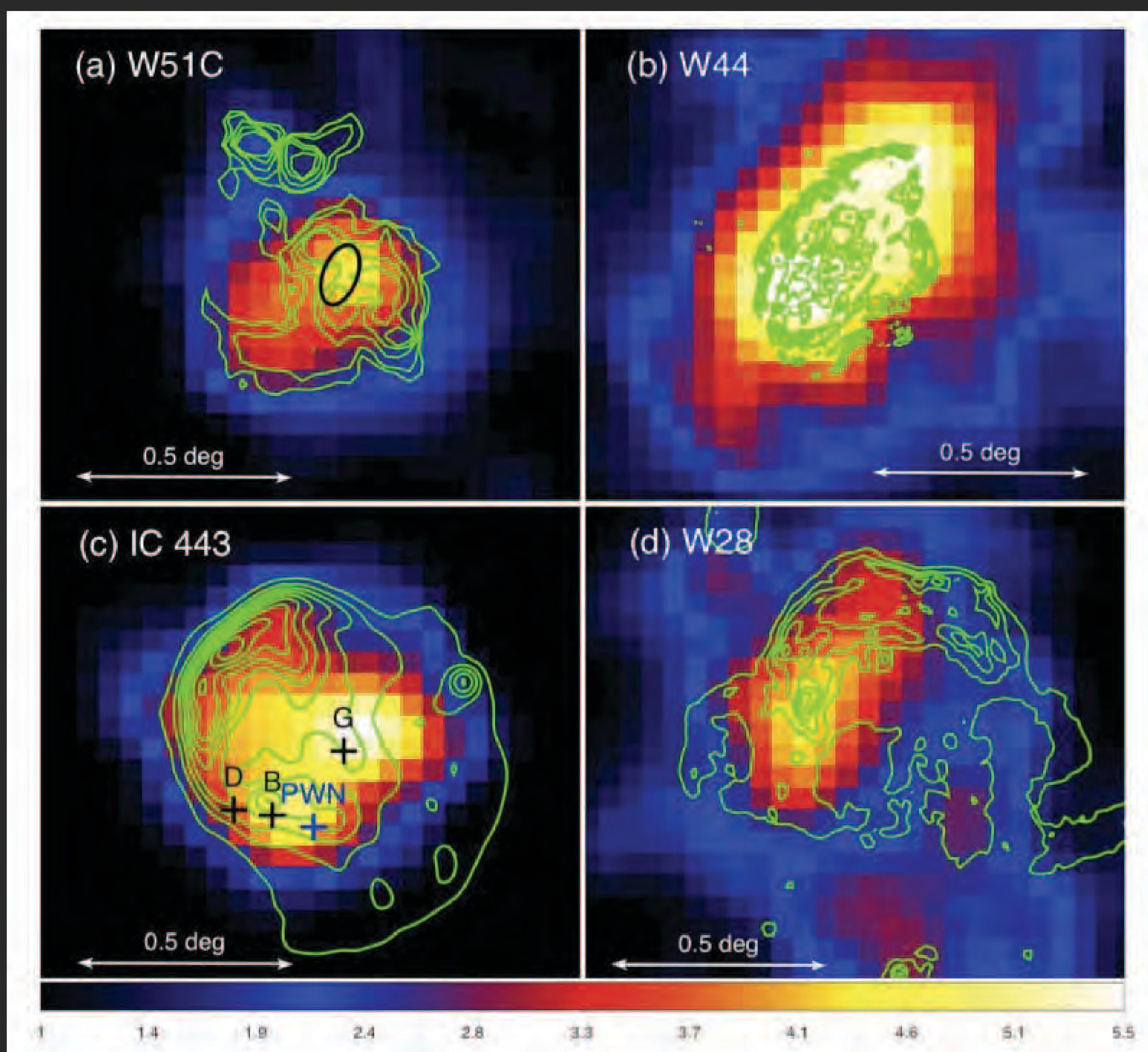
W30	Castro & Slane (2010)
W41	Castro et al. (2013c)
3C 391	Castro & Slane (2010)
W44	Abdo et al. (2010c)
W49b	Abdo et al. (2009)
W51C	Abdo et al. (2009)
Cygnus Loop	Katagiri et al. (2011)
γ-Cygni SNR	Lande et al. (2012)
HB 21	Reichardt et al. (2012)
CTB 109	Castro et al. (2012)
Cas A	Abdo et al. (2010b)
Tycho	Giordano et al. (2012)
S147	Katsuta et al. (2012)
IC443	Abdo et al. (2010d)
Puppis A	Hewitt et al. (2012)
Vela Jr.	Tanaka et al. (2011)
Kes 17	Wu et al. (2011)
CTB 33	Castro et al. (2013c)
Kes 41	Castro et al. (2013a)
RX J1713	Abdo et al. (2011)
CTB 37A	Castro & Slane (2010)
G349.7-0.5	Castro & Slane (2010)
MSH 17-39	Castro et al. (2013c)

Blue indicates likely interaction with a molecular cloud (Jiang et al., 2010)

iii. fermi-lat

- many snrs (>25)
- most are snr-mc
- structure



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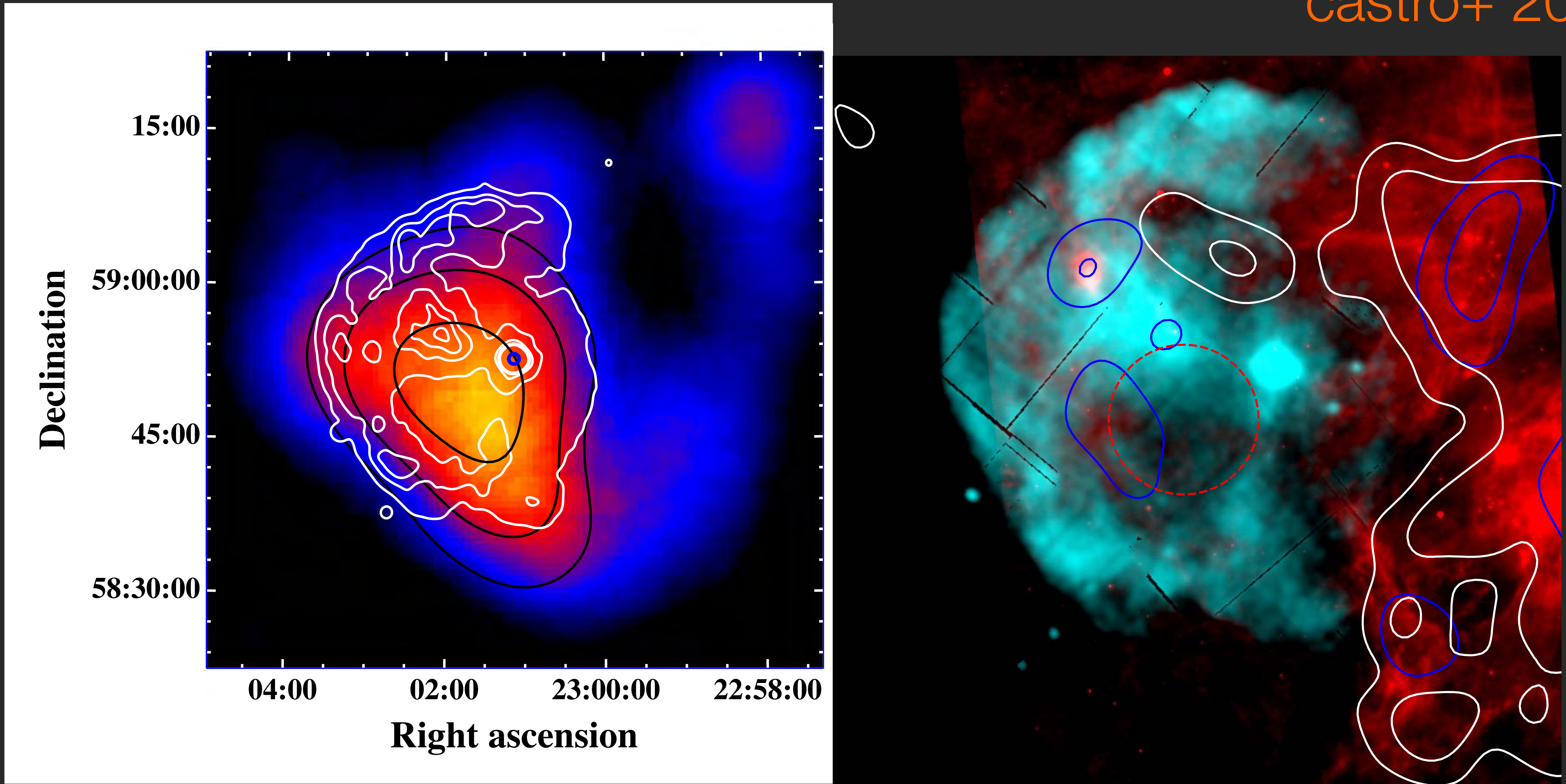
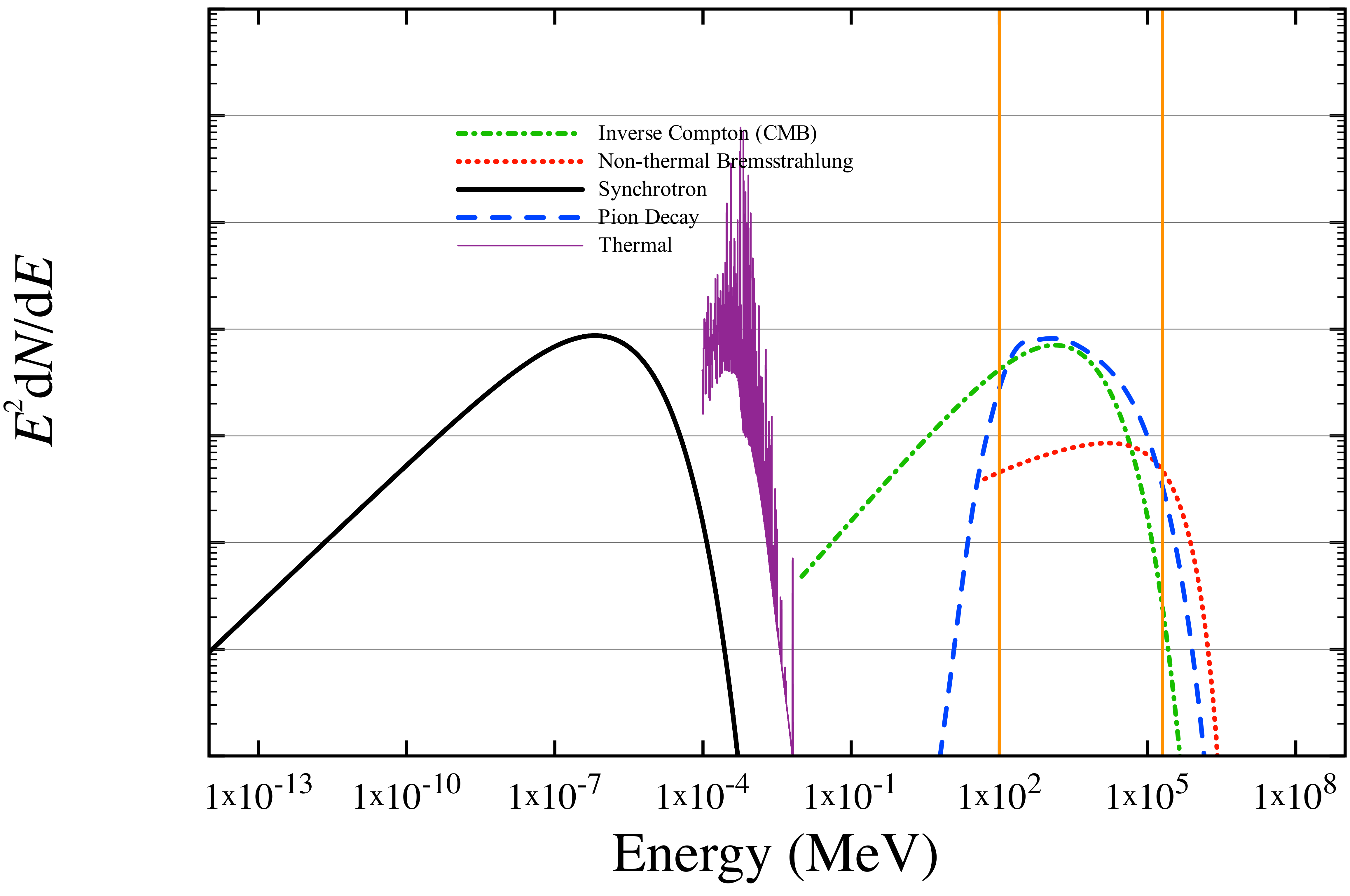
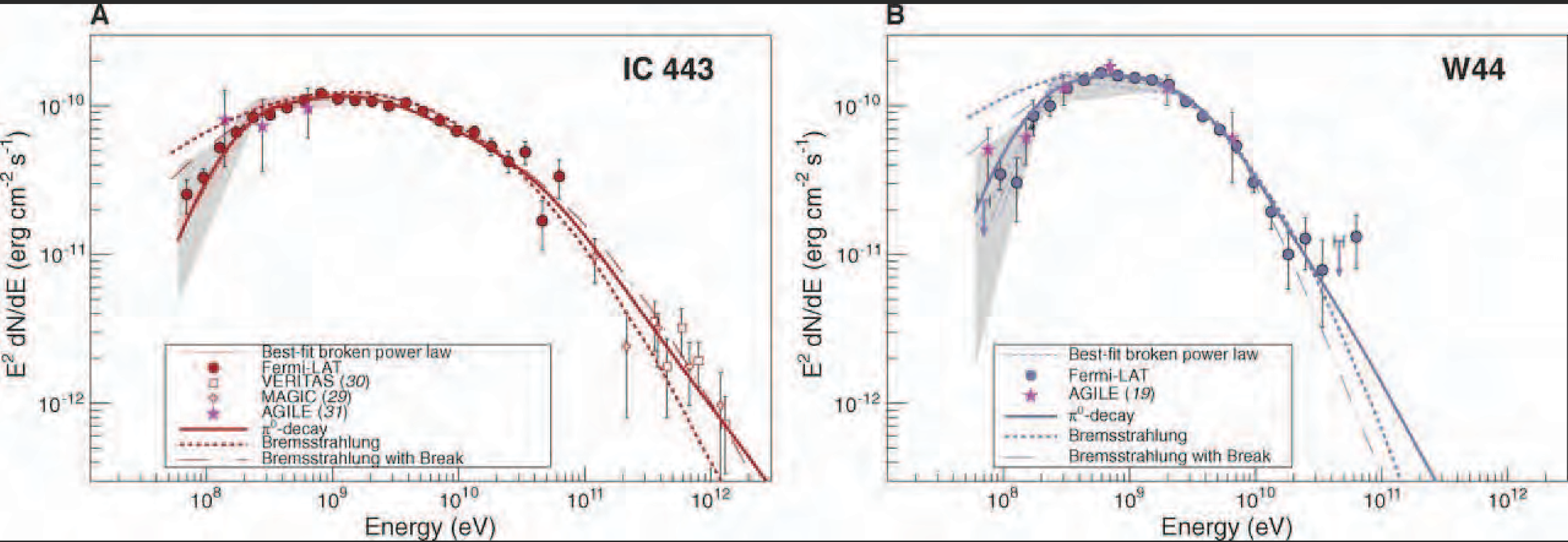
castro+ 2012



iii. fermi-lat



iii. fermi-lat



ackermann et al. 2013 (Funk, Tanaka, Uchiyama)

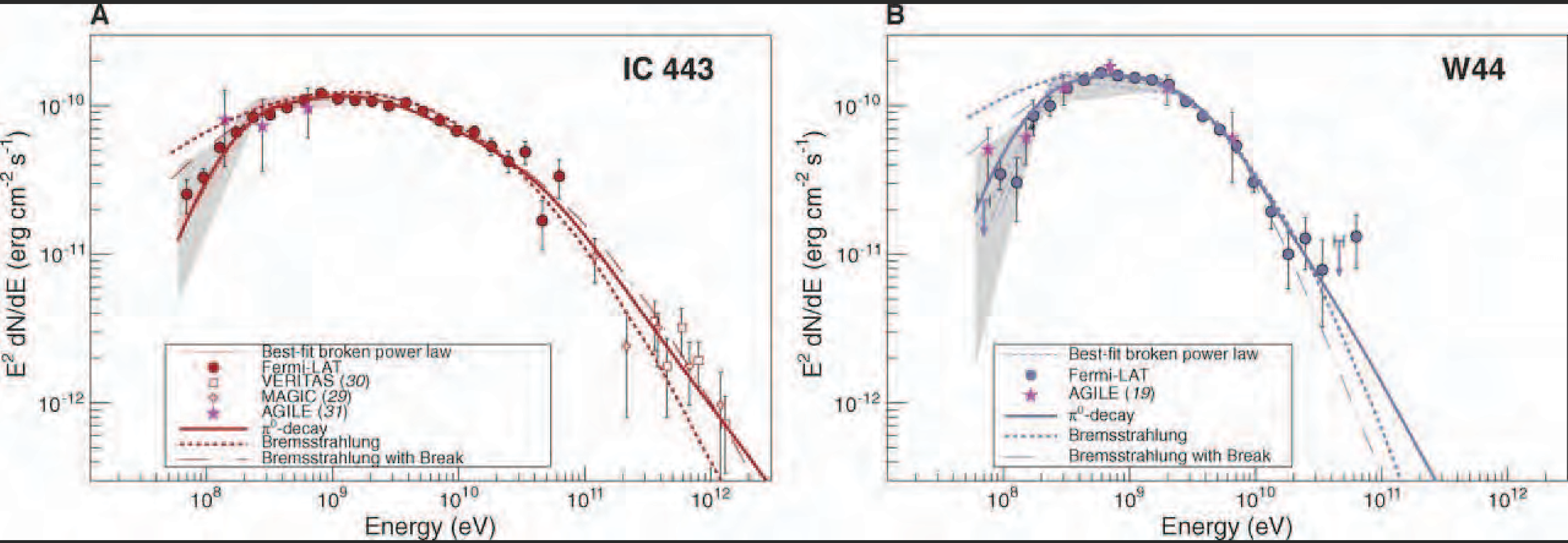
iv. open questions

what are the open questions being addressed today?

iv. hadronic or leptonic

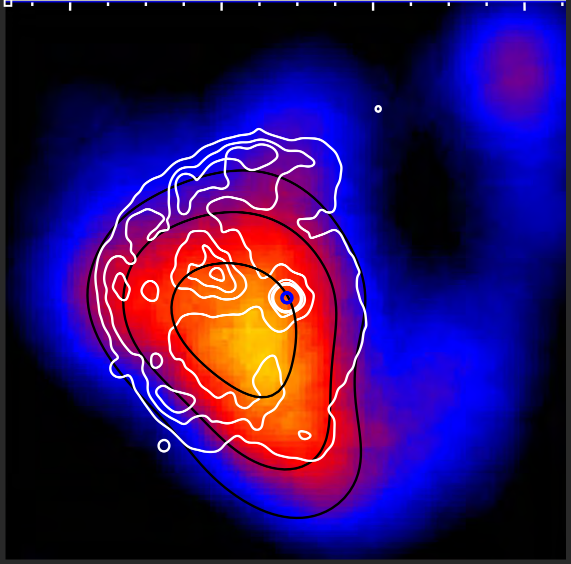
what mechanism produces the γ-ray emission from SNRs?

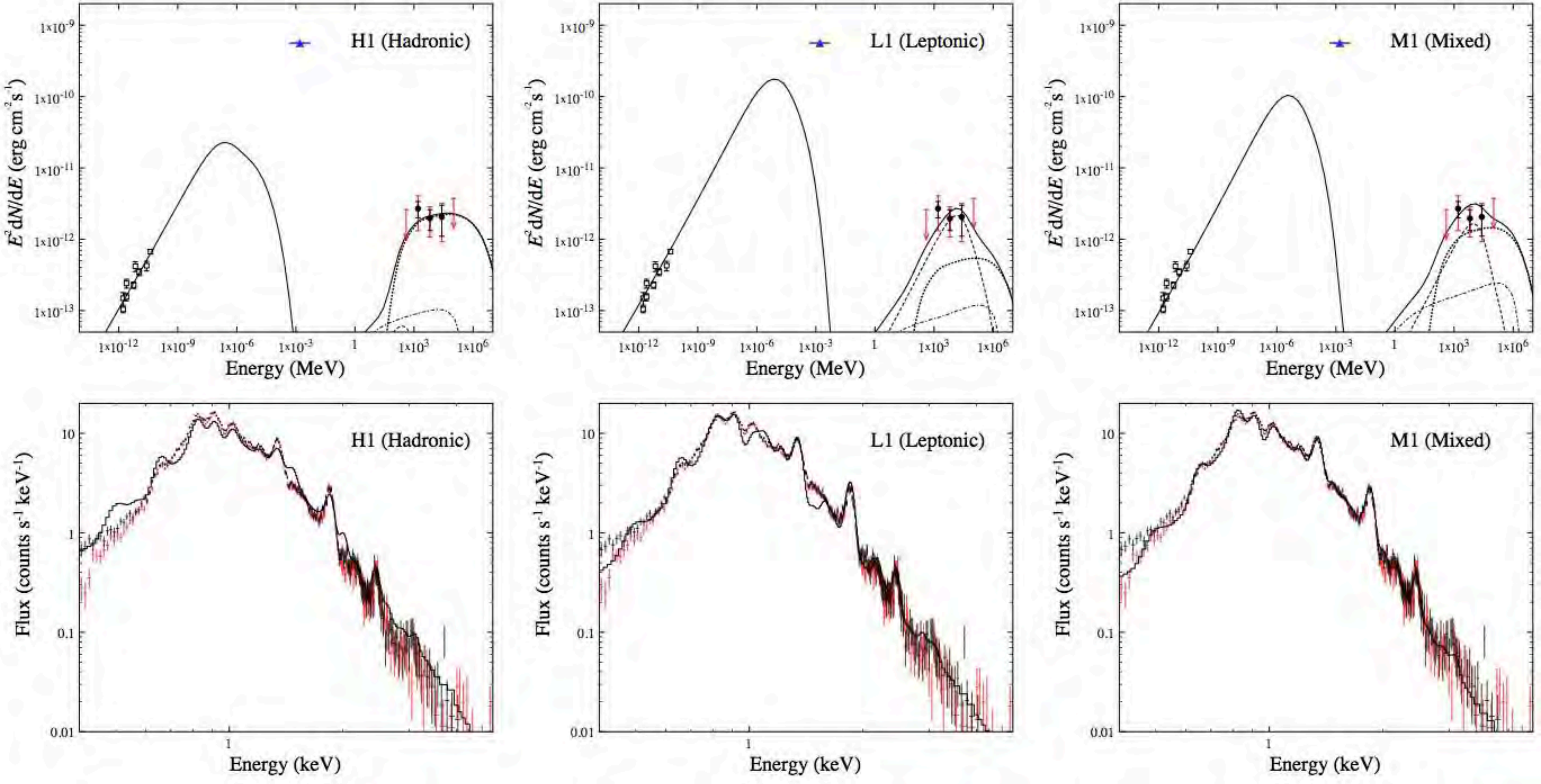
iv. hadronic or leptonic



ackermann et al. 2013 (Funk, Tanaka, Uchiyama)

iv. hadronic or leptonic





iv. magnetic field amplification

how does the magnetic field get amplified by particle acceleration and escape in SNRs?

iv. magnetic field amplification

how

.resonant cosmic ray streaming instability e.g. zirakashvili 2000
.bell's non-resonant instability bell 2004
.non-resonant long-wavelength instability bykov & toptygin 2005
.others…

iv. magnetic field amplification

evidence

.rapid variability of nonthermal X-ray emission from bright filaments in SNRs

.sharp X-ray edges

iv. magnetic field amplification

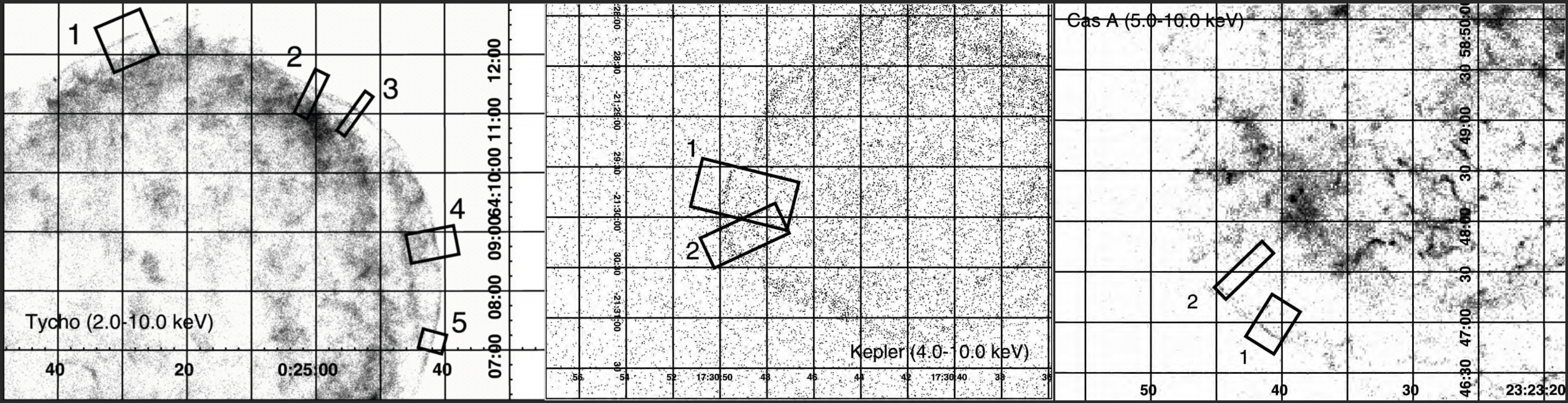
evidence

.rapid variability of nonthermal X-ray emission from bright filaments in SNRs

.sharp x-ray edges

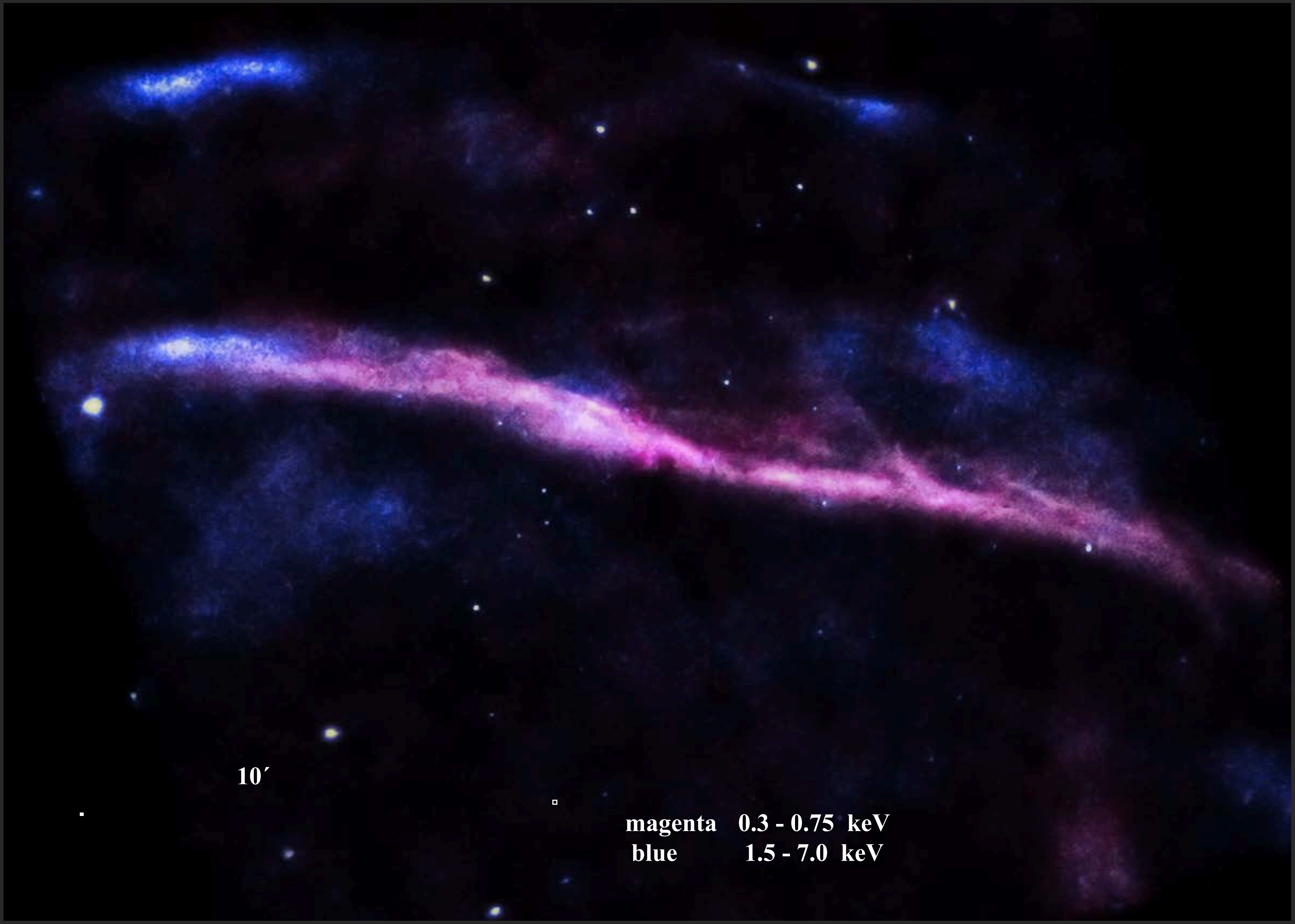
iv. magnetic field amplification

.sharp x-ray edges



bamba et al. 2005

iv. magnetic field amplification

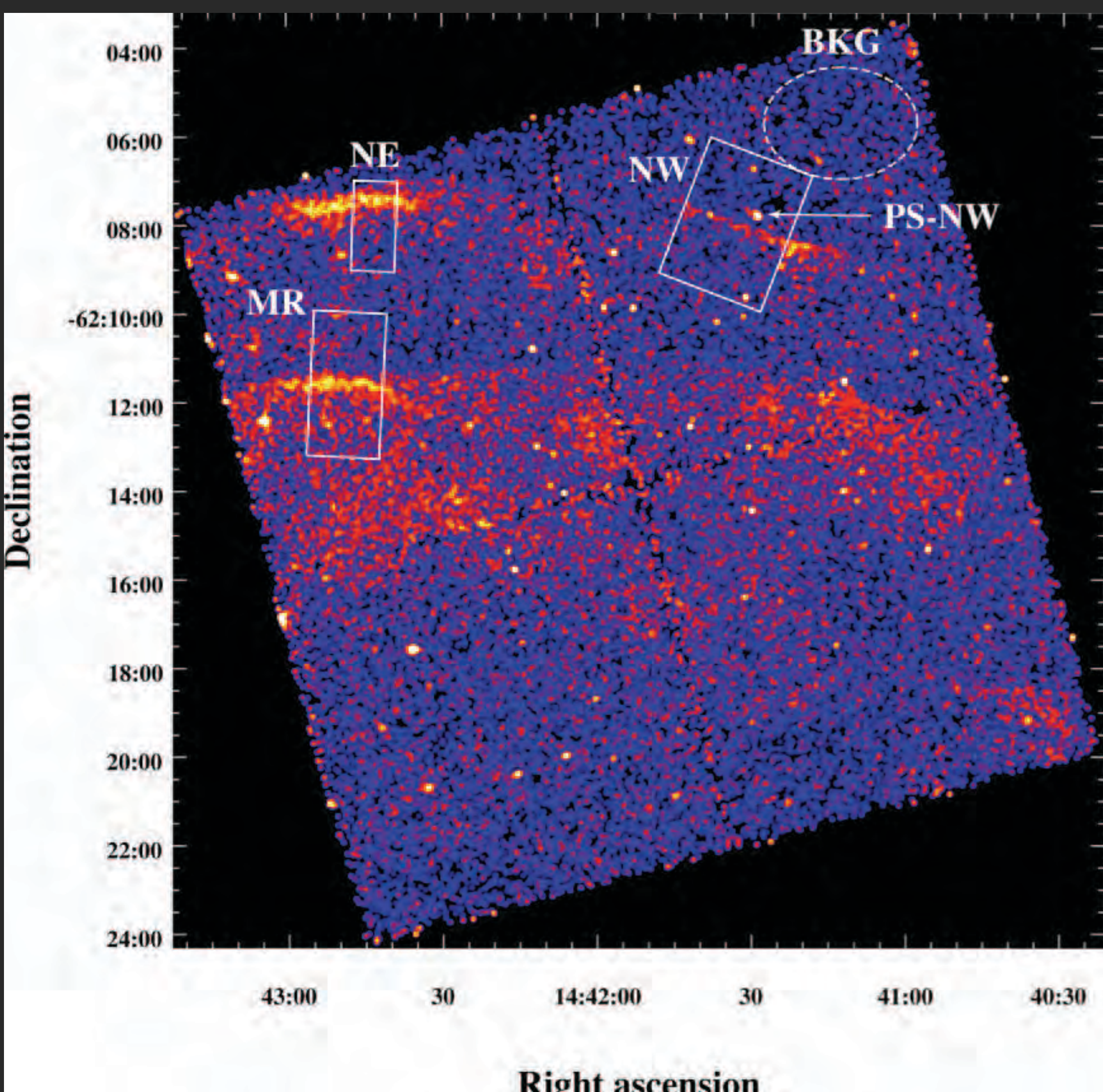


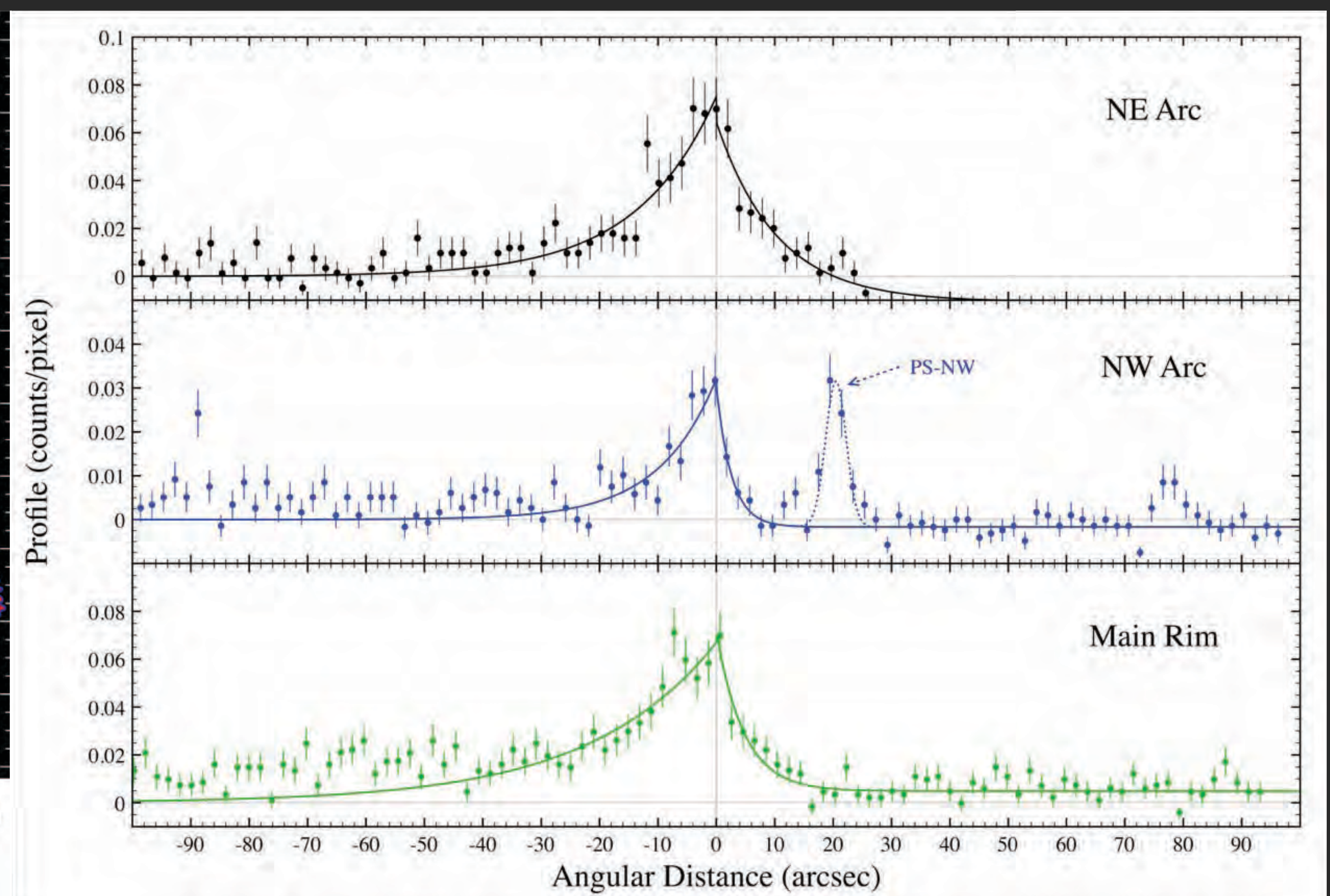
iv. magnetic field amplification

from Bamba+ 2003

$$f(x) = \begin{cases} A \exp\left(-\left|\frac{x_0 - x}{l_{\rm up}}\right|\right) & x > x_0 \\ A \exp\left(-\left|\frac{x_0 - x}{l_{\rm down}}\right|\right) & x < x_0 \end{cases}$$

Castro+ 2013





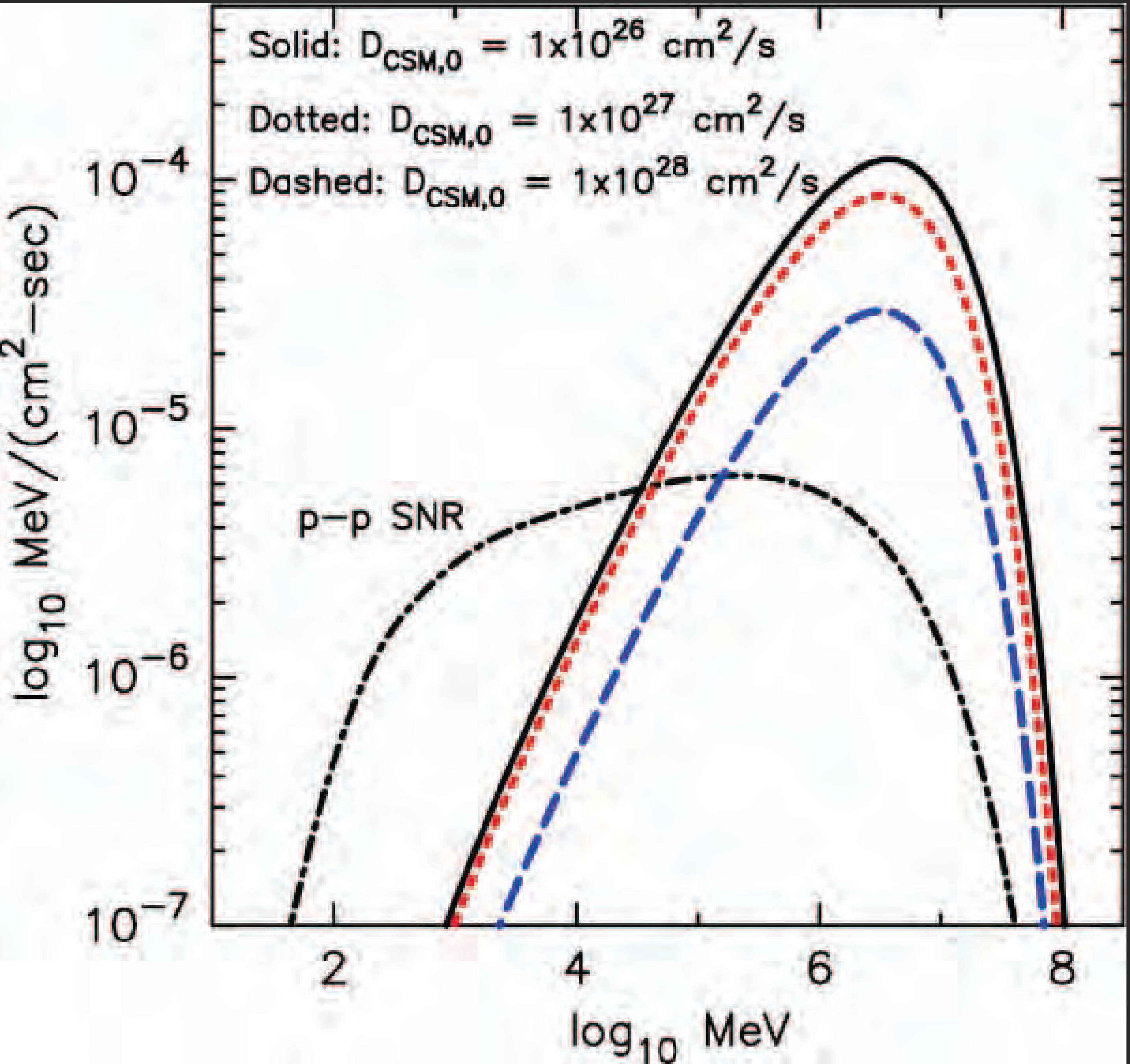
iv. escape and diffusion

what is the spectrum of accelerated particles which escape the SNR shock?

how do these particles diffuse through the ISM and CSM?

can we observe signatures of escape in γ-ray emission near SNRs?

iv. escape and diffusion

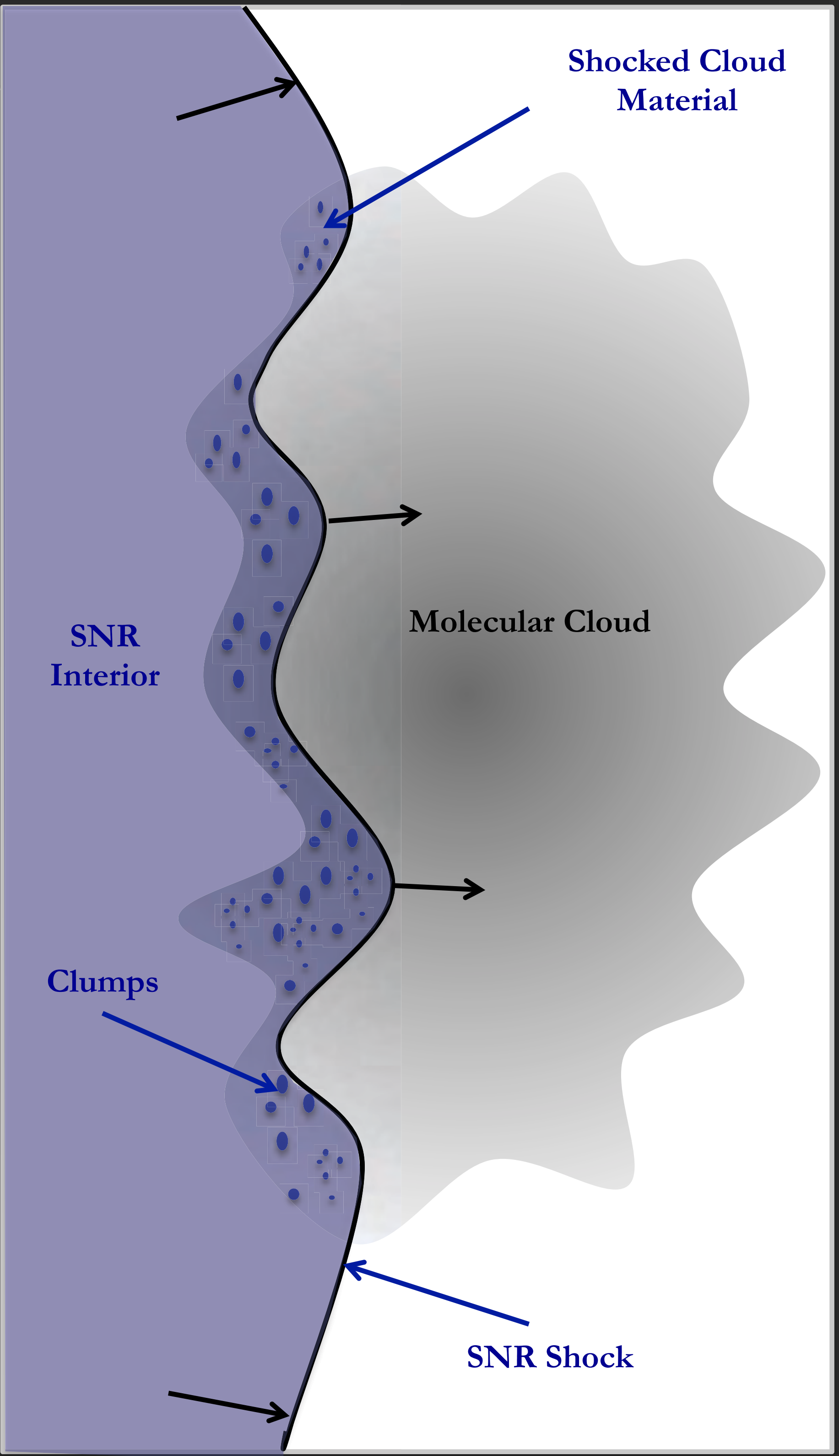


ellison & bykov+ 2011

iv. molecular clouds

what happens when SNR shocks interact with dense clouds of material?

iv. molecular clouds



- castro & slane (2010,2013):
  - w30 + ctb 37a + g349.7-0.5 + 3c391
  - w41 + ctb 33 + msh 17-39
  - x-ray density << -ray density

see also:

- uchiyama+ 2010 – reacceleration
- inoue+ 2010 – diffusion
- schuppan+ 2012 – ionization

end of part II