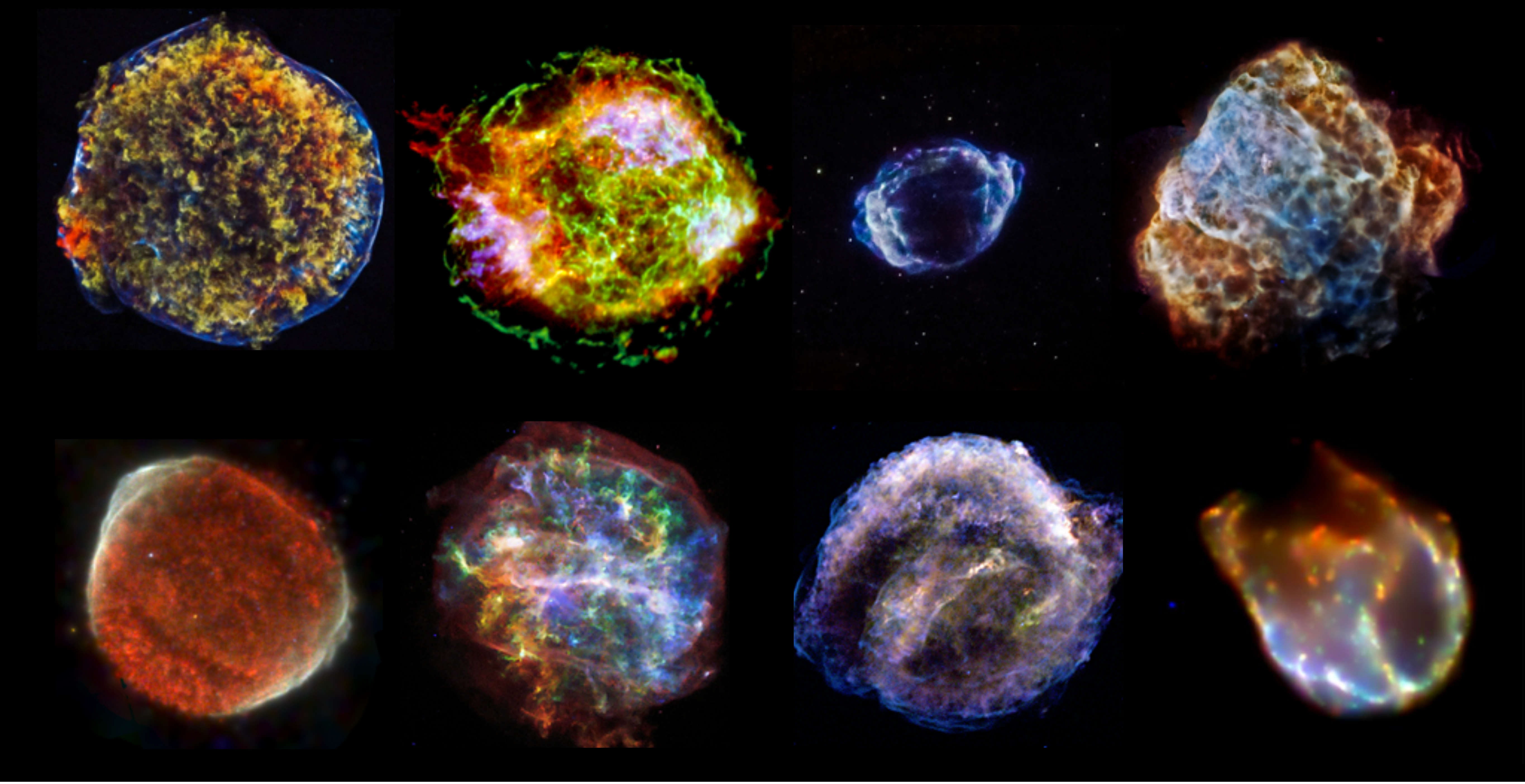
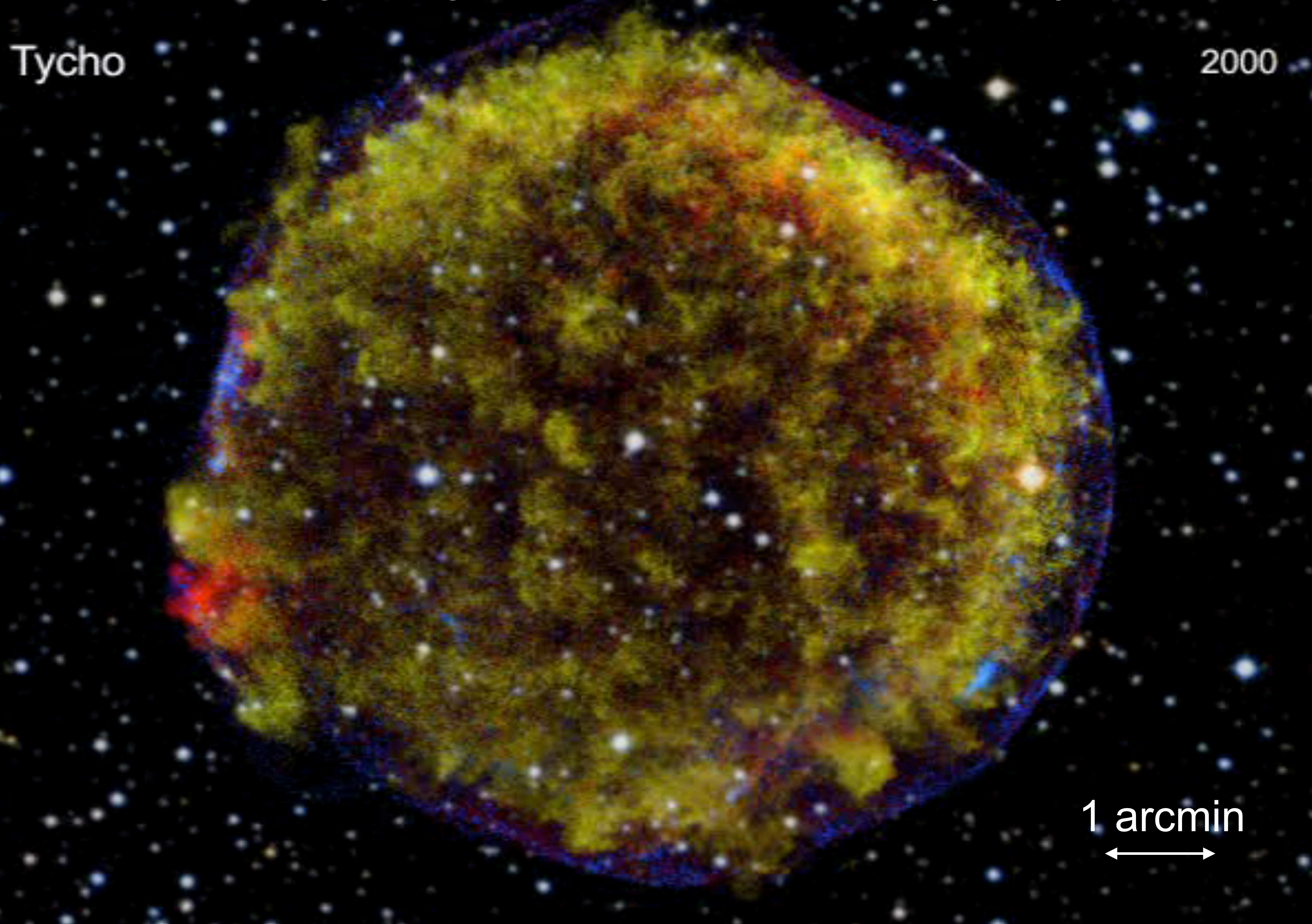


Supernova Remnants in X-rays

F. Acero, AIM/CEA-Saclay

www.github.com/facero/OHP-2016-material

Why study supernova remnants (SNRs)



Outline

launch binder

Click me

- Supernova though history, SN type and classification
- Supernova remnants
- Structure and time evolution of a SNR
- Thermal X-ray emission processes in SNR
- What can we learn from thermal X-rays
- Particle acceleration theory
- Evidence for accelerated particles
- X/gamma connection

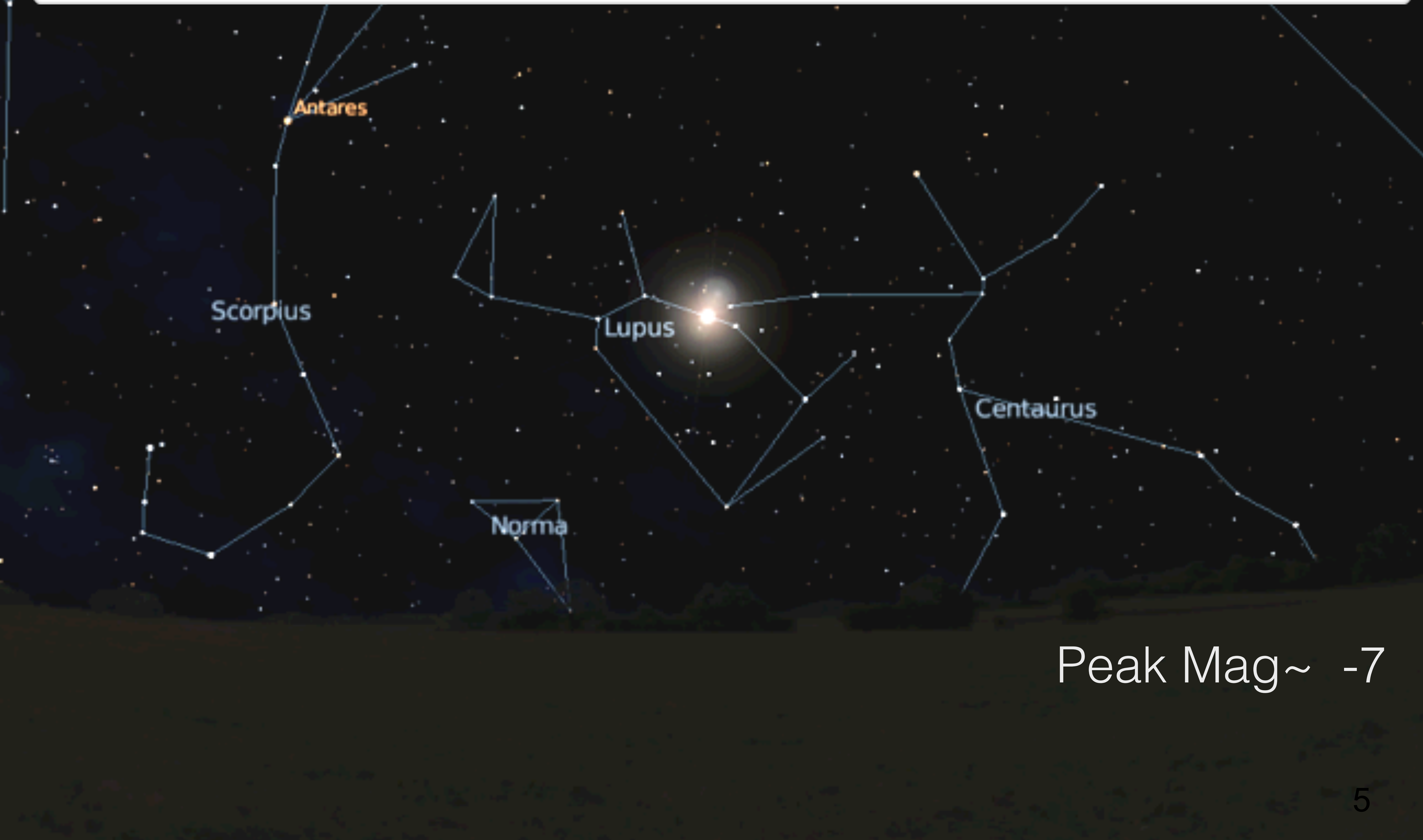
Reviews:
Reynolds+08
Vink+12

Supernova through history, SN type and classification

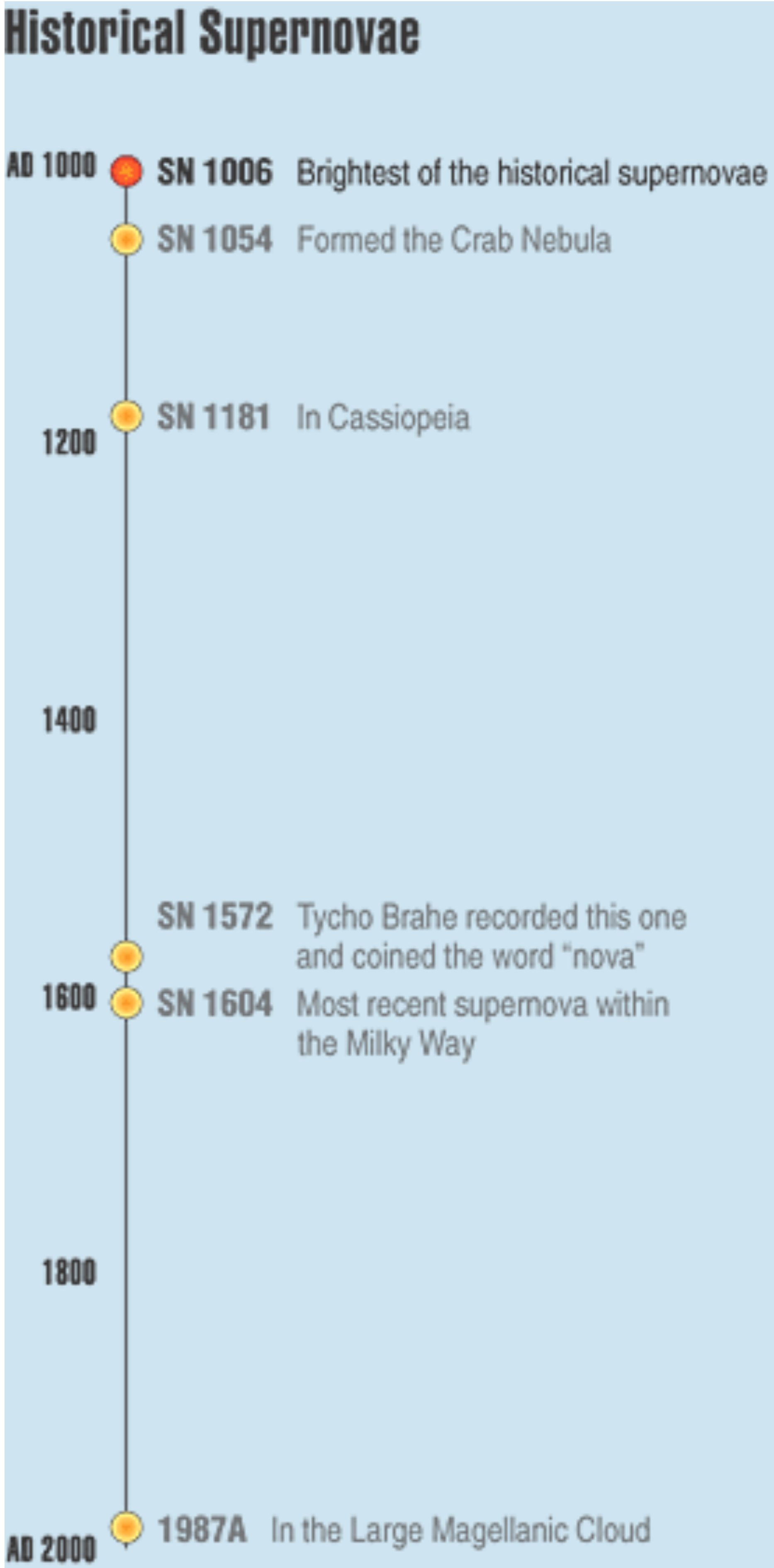
Tycho & SN 1572

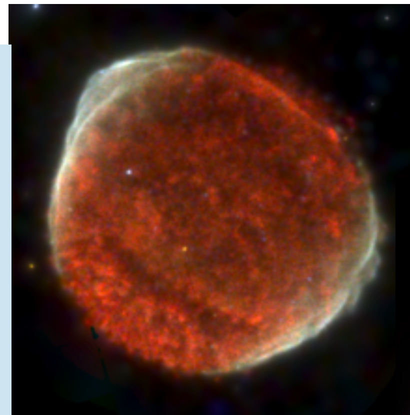
Ali ibn Ridwan (Egypt) in April 1006

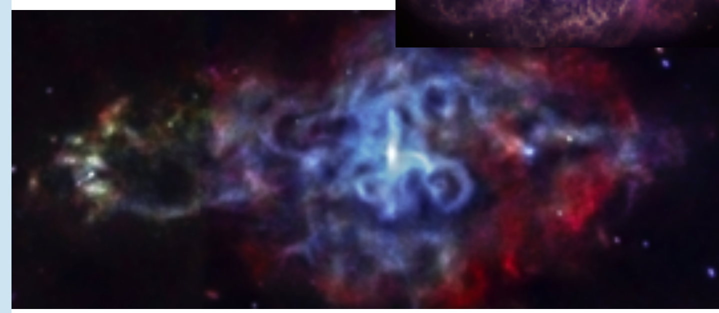
The sky was shining because of its light. The intensity of its light was a little more than a quarter of that of moonlight. It remained where it was and it moved daily with its zodiacal sign until the sun was in sextile with it in Virgo, when it disappeared at once.

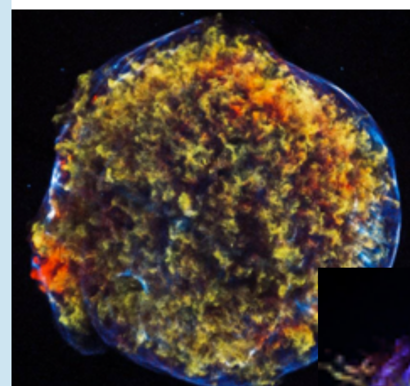


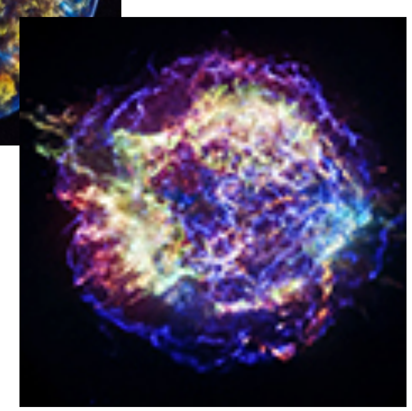
Peak Mag~ -7

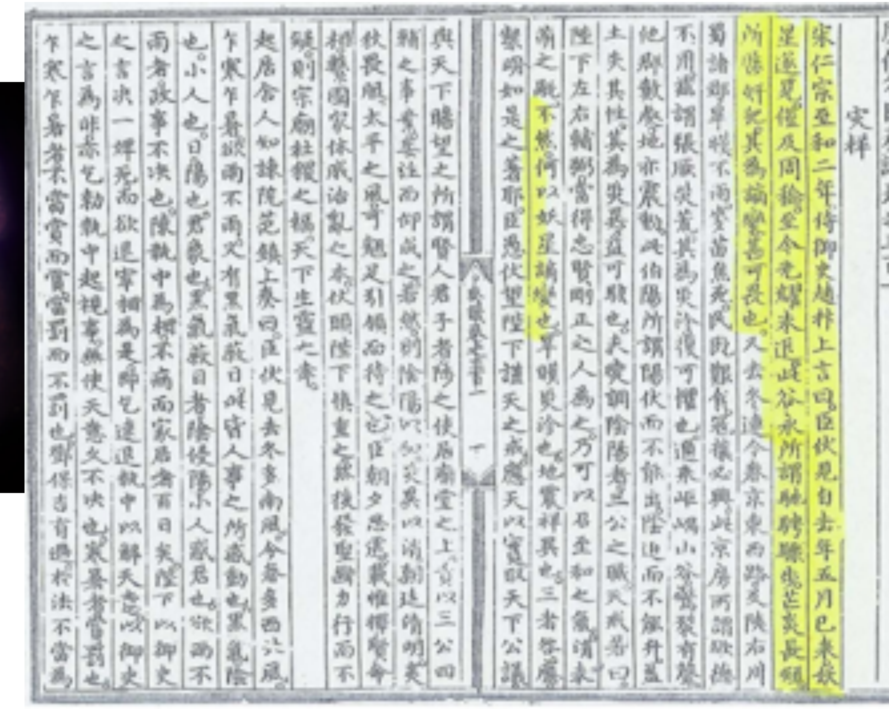










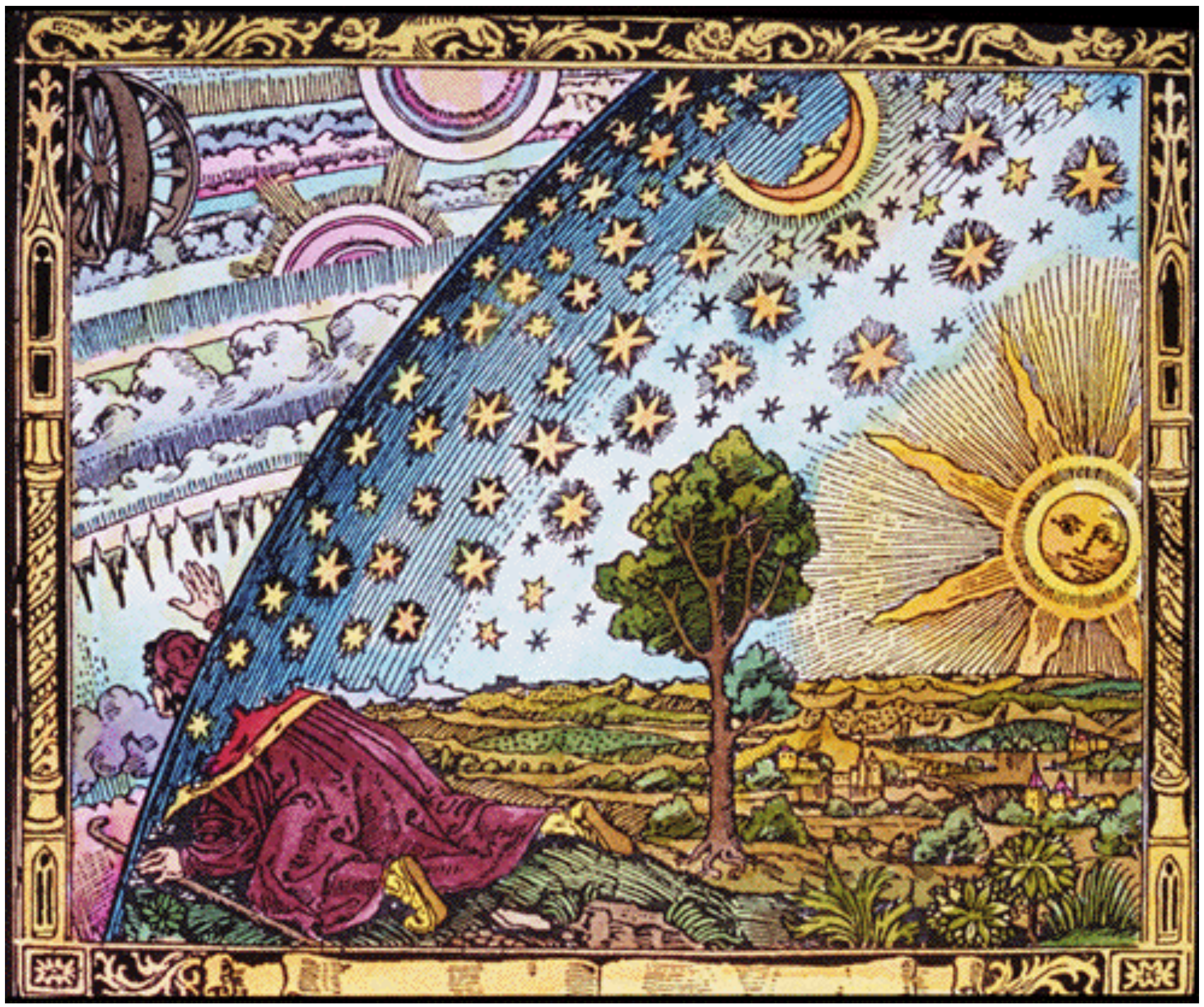


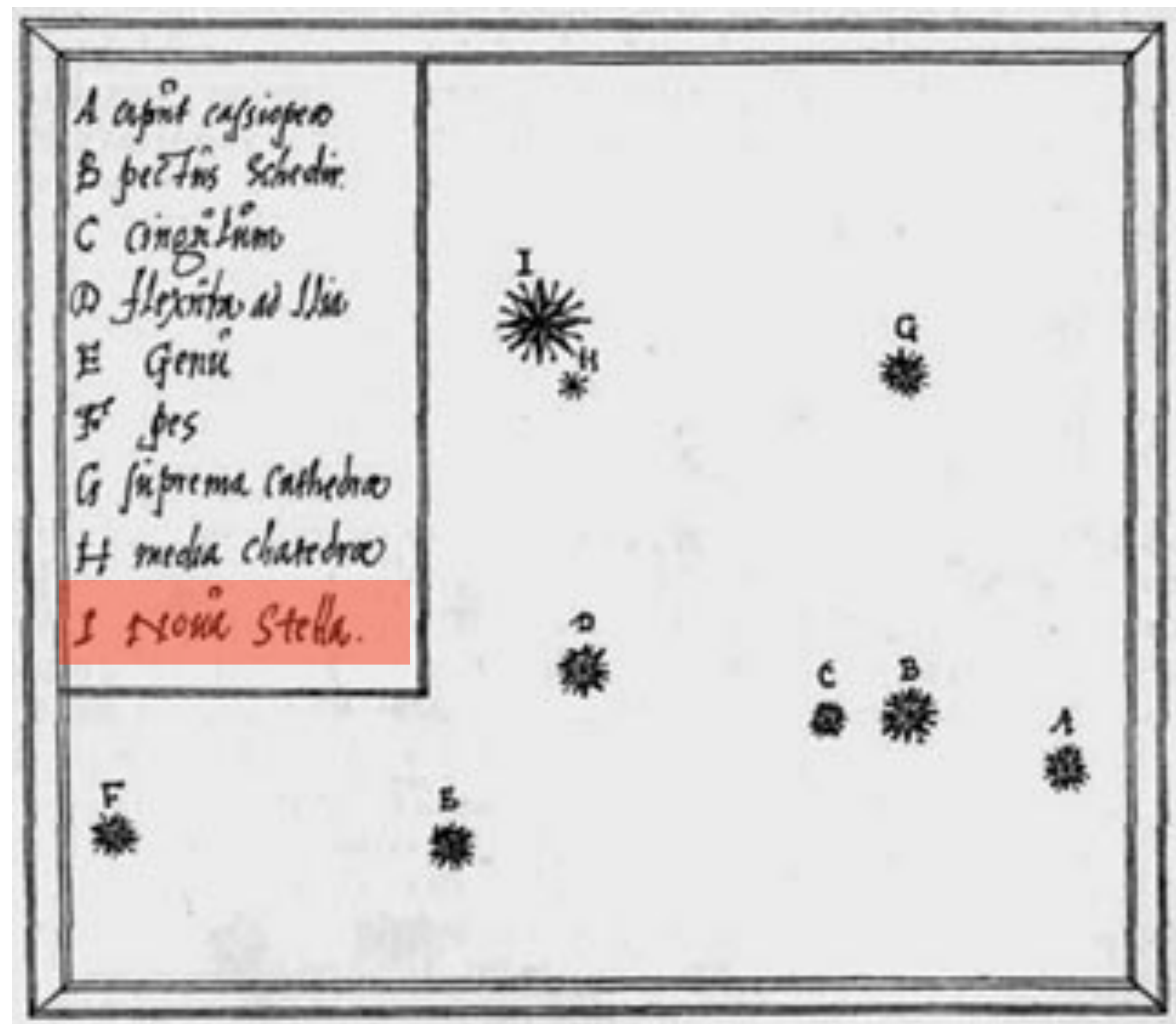
Chinese records from SN1054

No Galactic visible SN in the last 400 yrs !

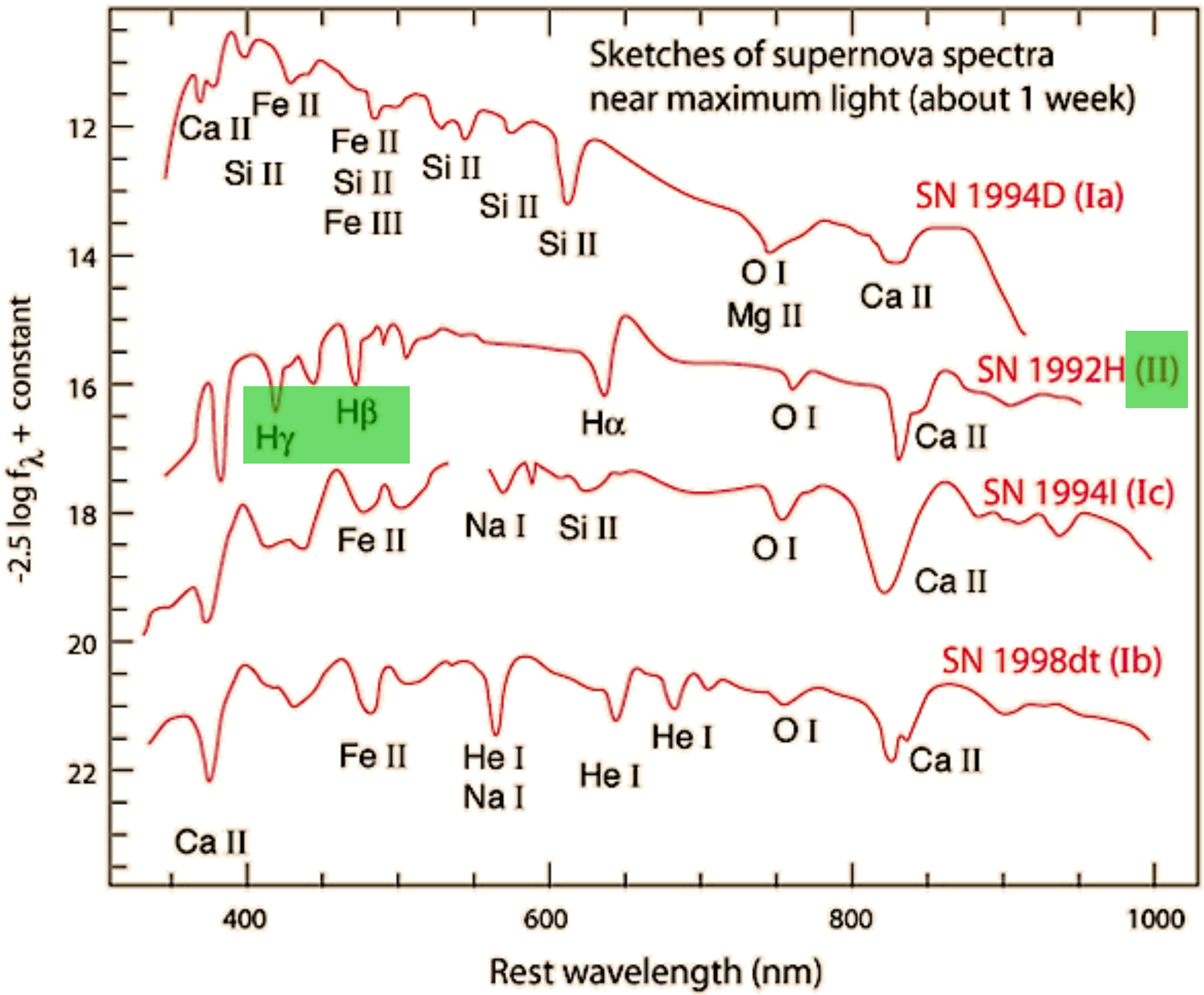
Historic impact

Supernova played an important role in breaking the idea of immutable heavens



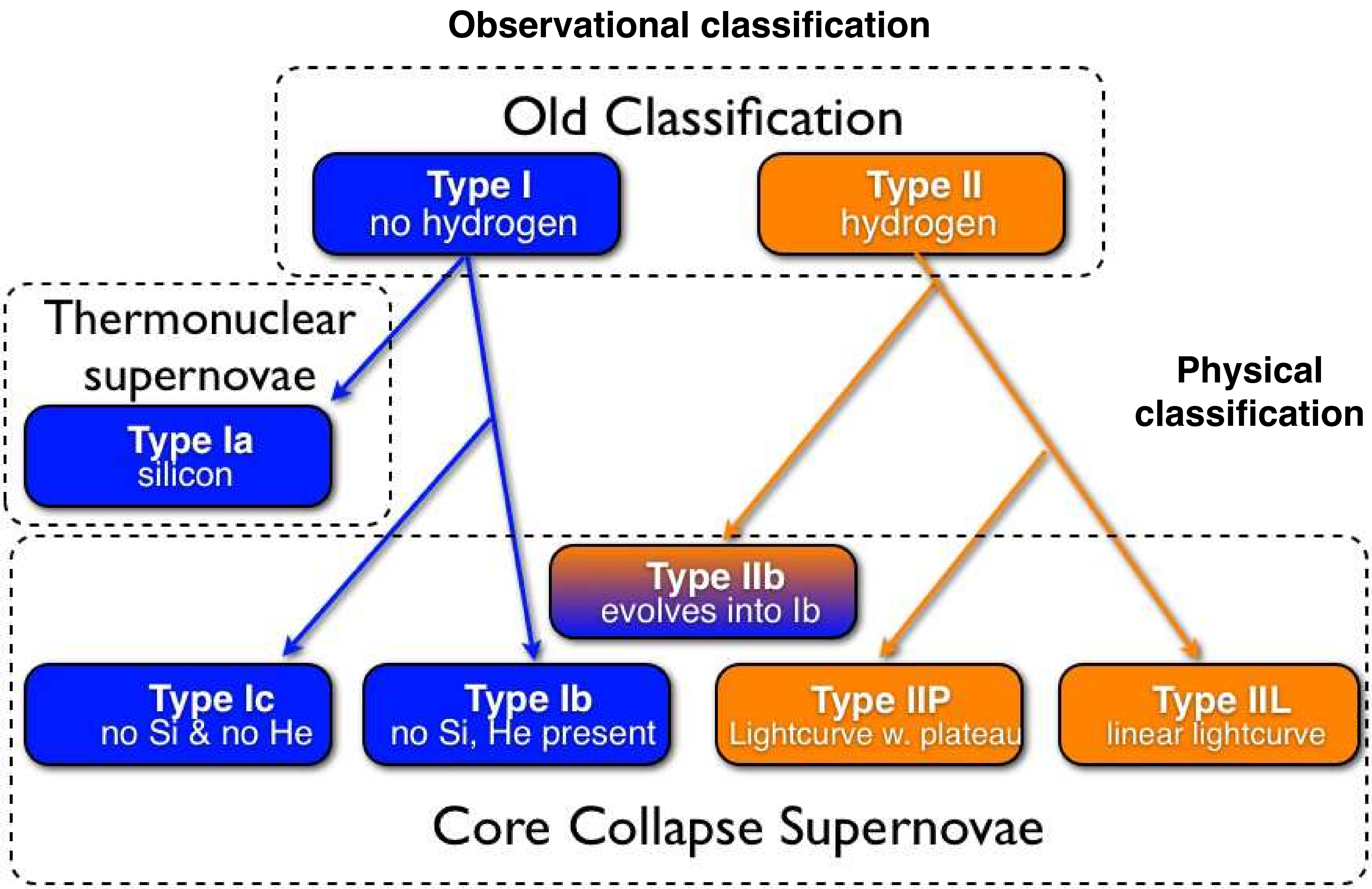


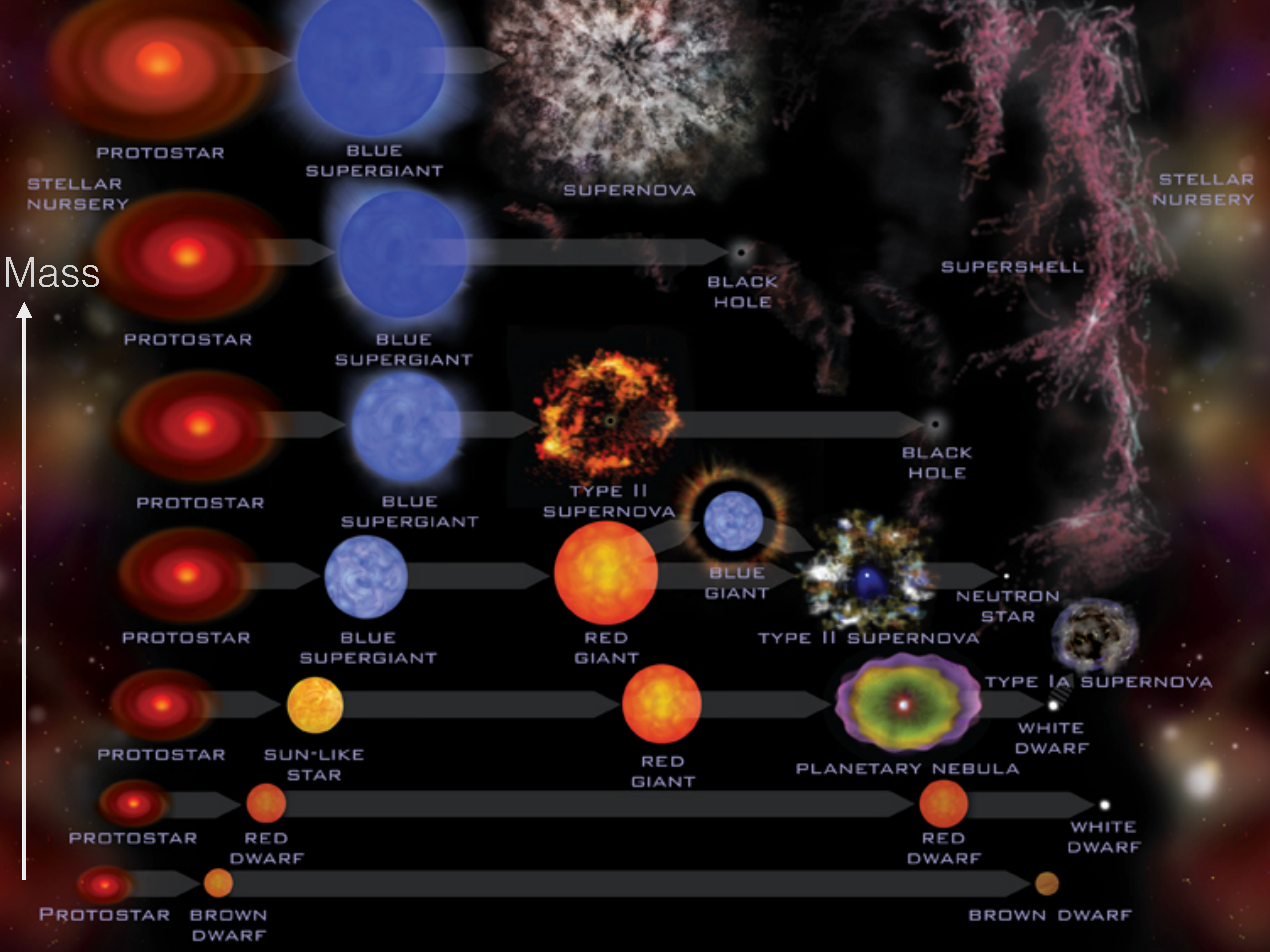
Supernovae classification



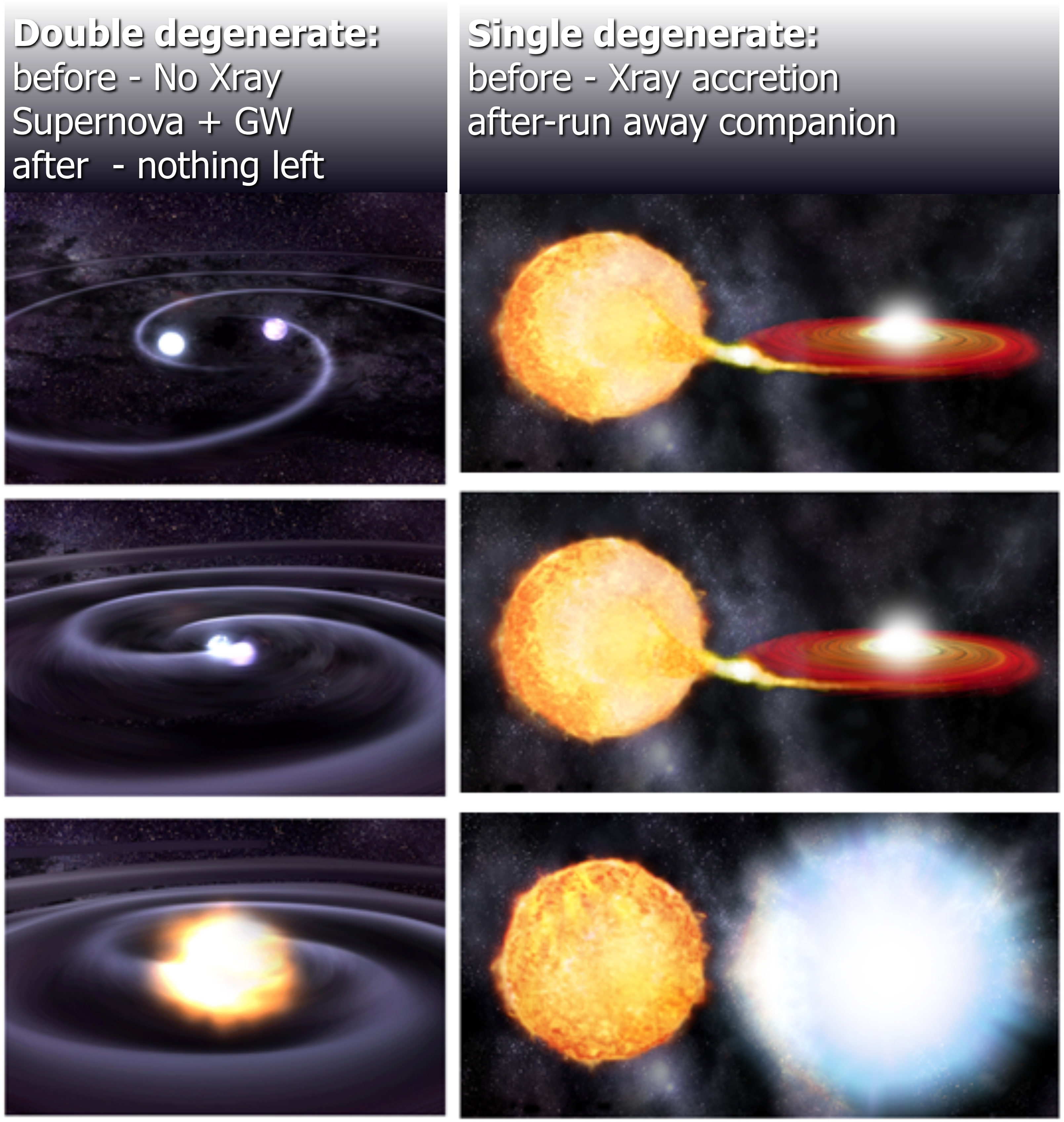
Sketches of spectra from Carroll & Ostlie, data attributed to Thomas Matheson of National Optical Astronomy Observatory.

Supernovae classification




Mass
STELLAR NURSERY
PROTOSTAR
BLUE SUPERGIANT
SUPERNOVA
STELLAR NURSERY
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

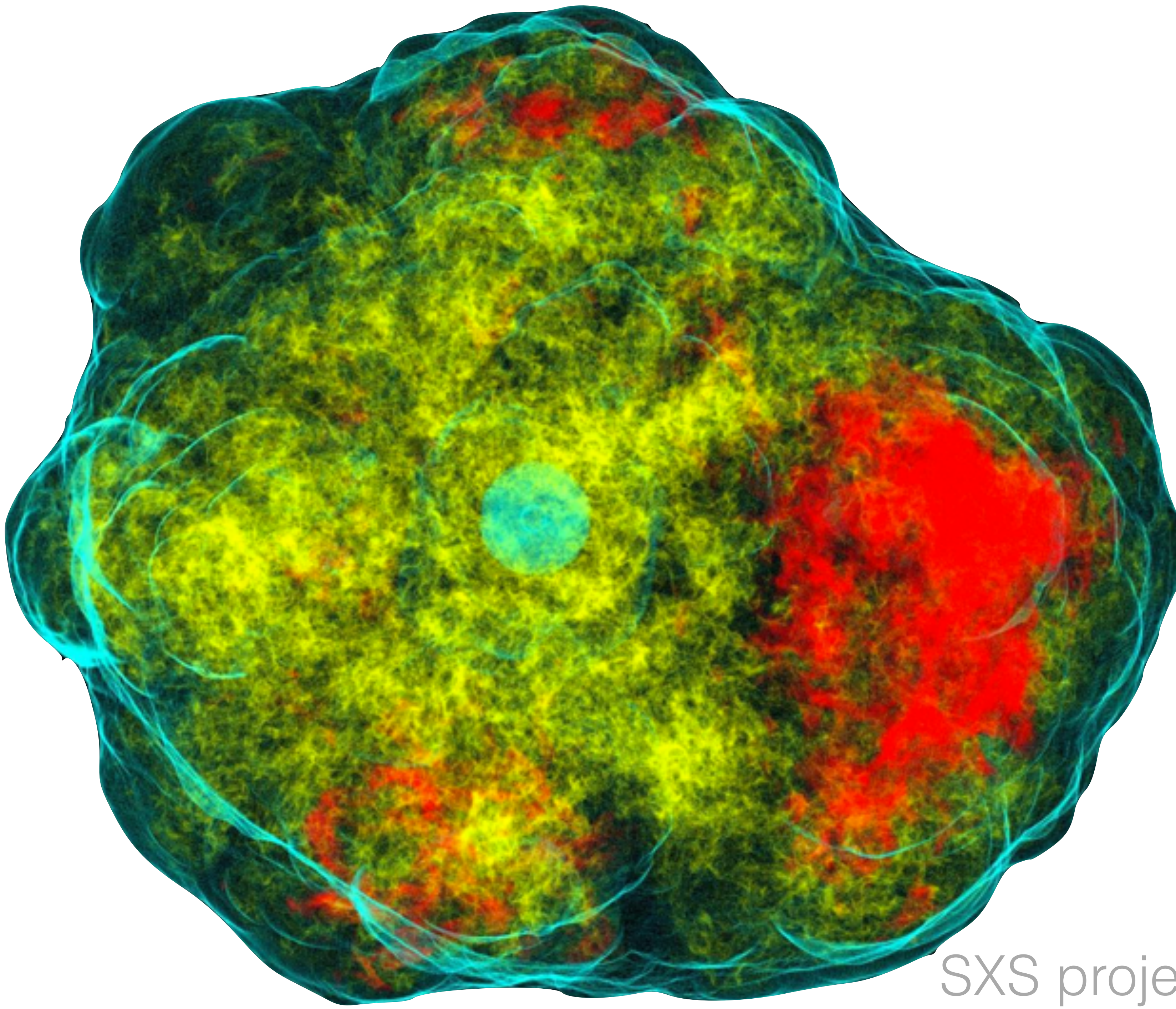
How do type Ia supernova explode ?



Thermonuclear reaction

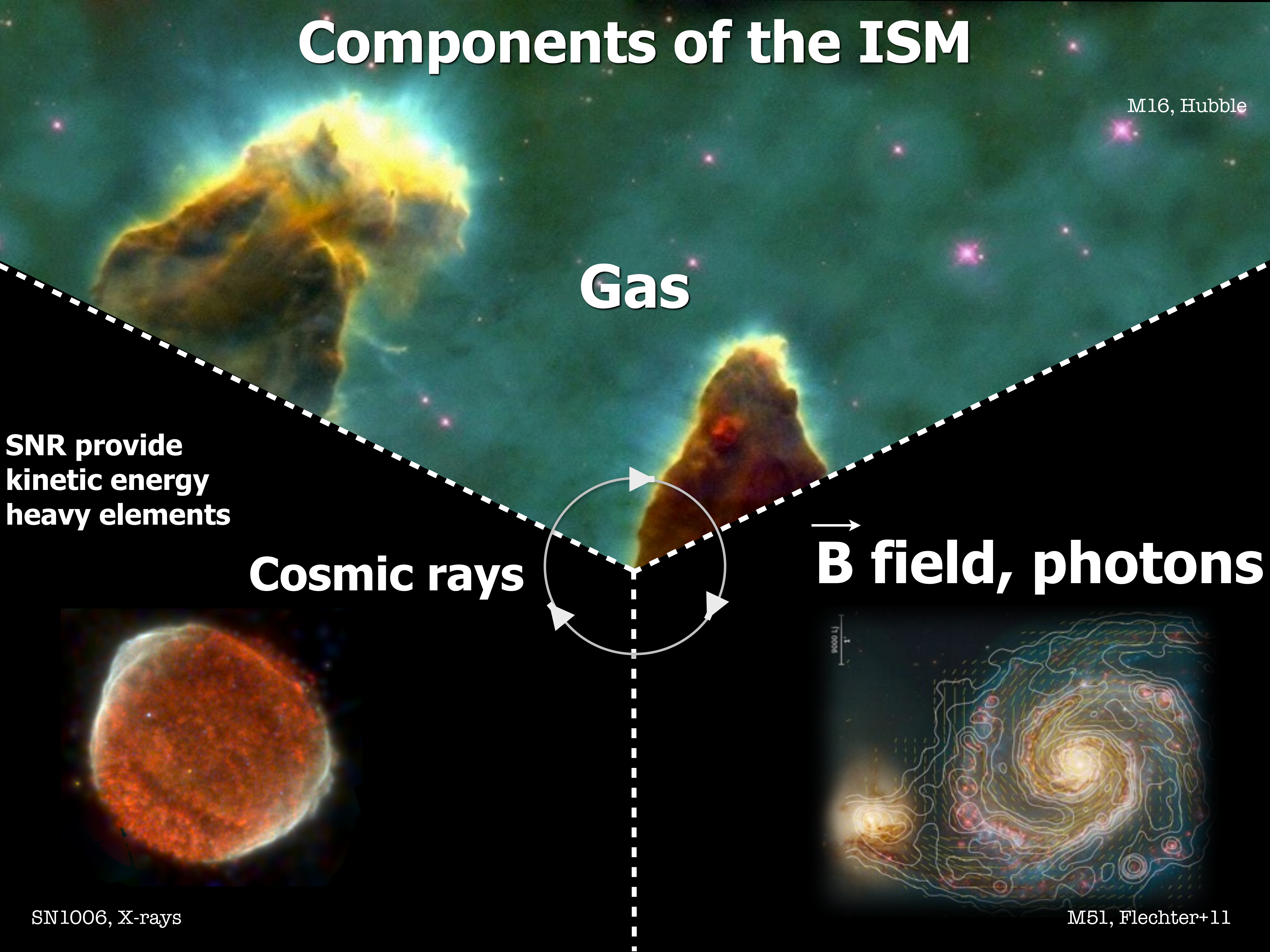
How do CC supernova explode ?

- **SN simulation almost explode but not yet**
- **Important role of neutrinos and asymmetric sloshing instabilities**

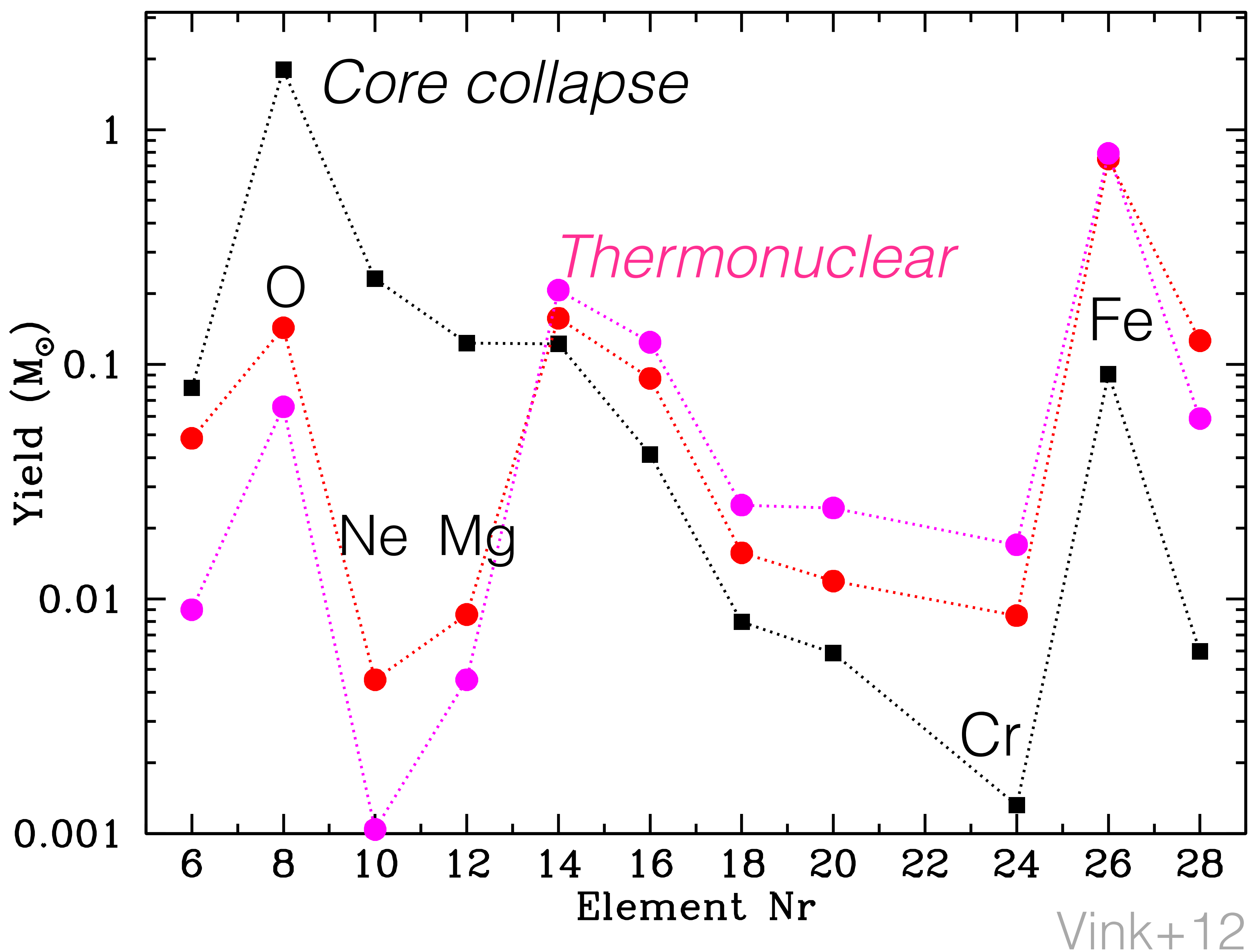


SXS project

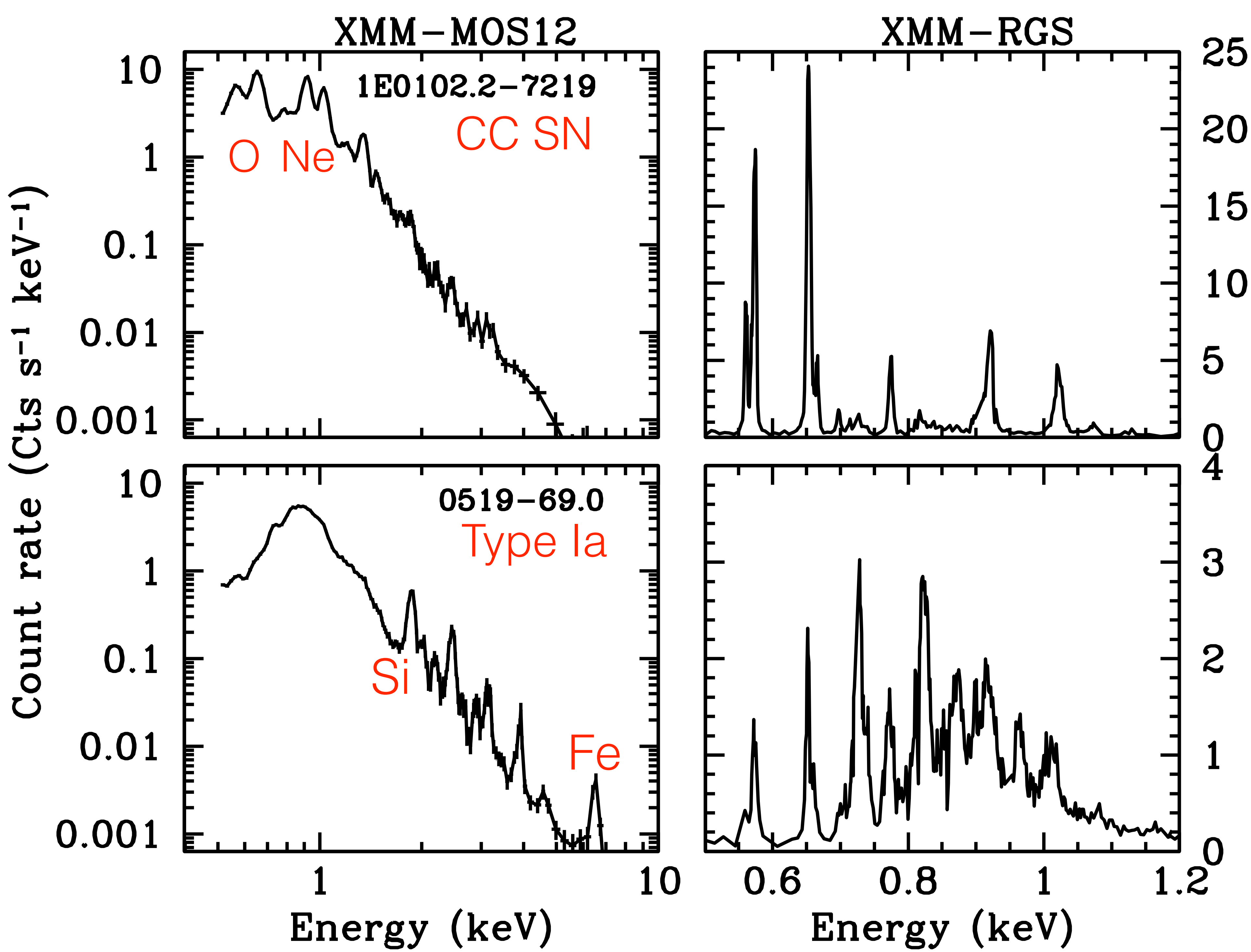
Supernova remnants


Components of the ISM
M16, Hubble
Gas
SNR provide
kinetic energy
heavy elements
Cosmic rays
$\vec{B}$ field, photons
SN1006, X-rays
M51, Flechter+11

Nucleosynthesis: SN yield



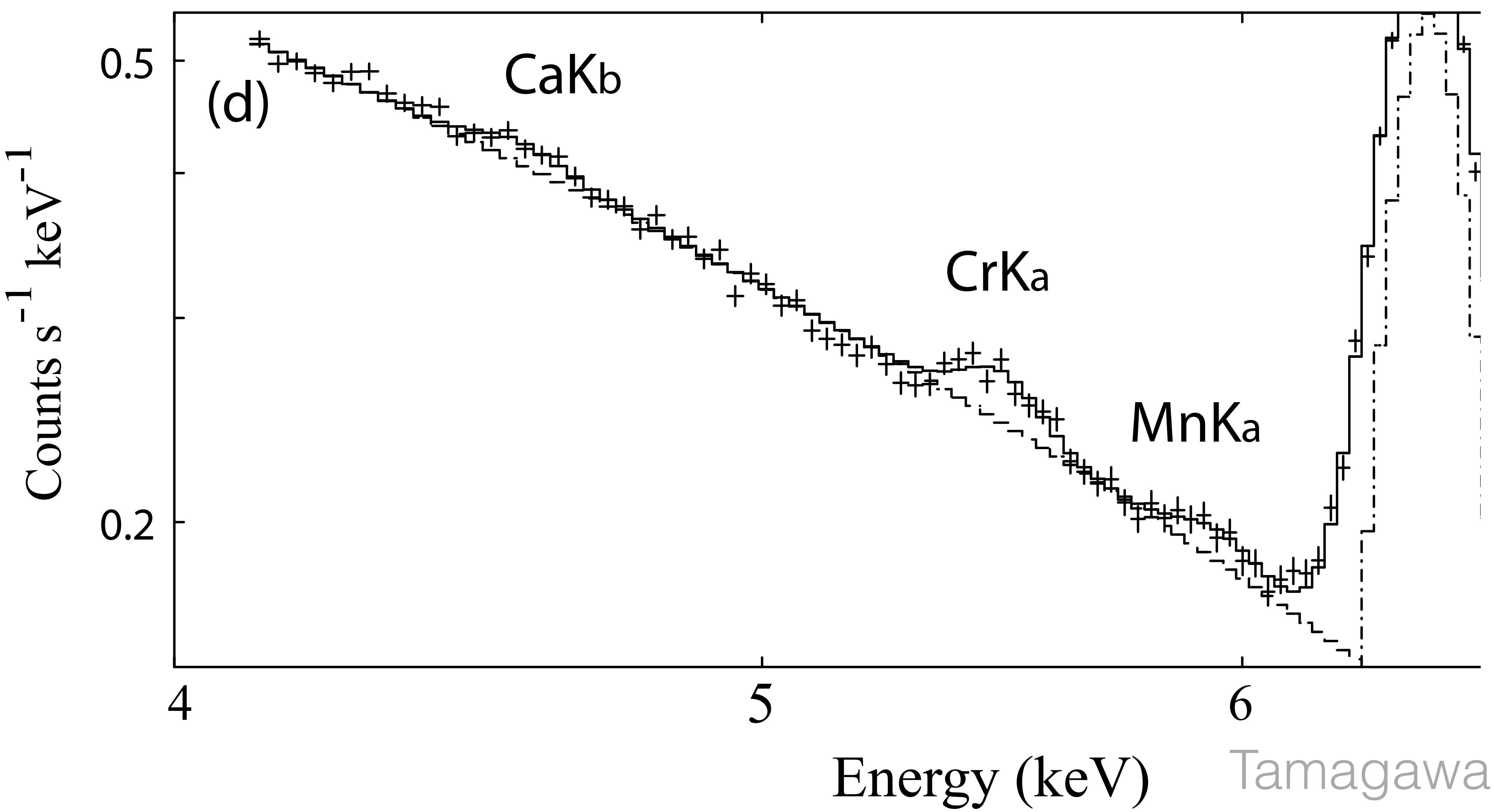
Nucleosynthesis in CC/Type Ia



Vink+12

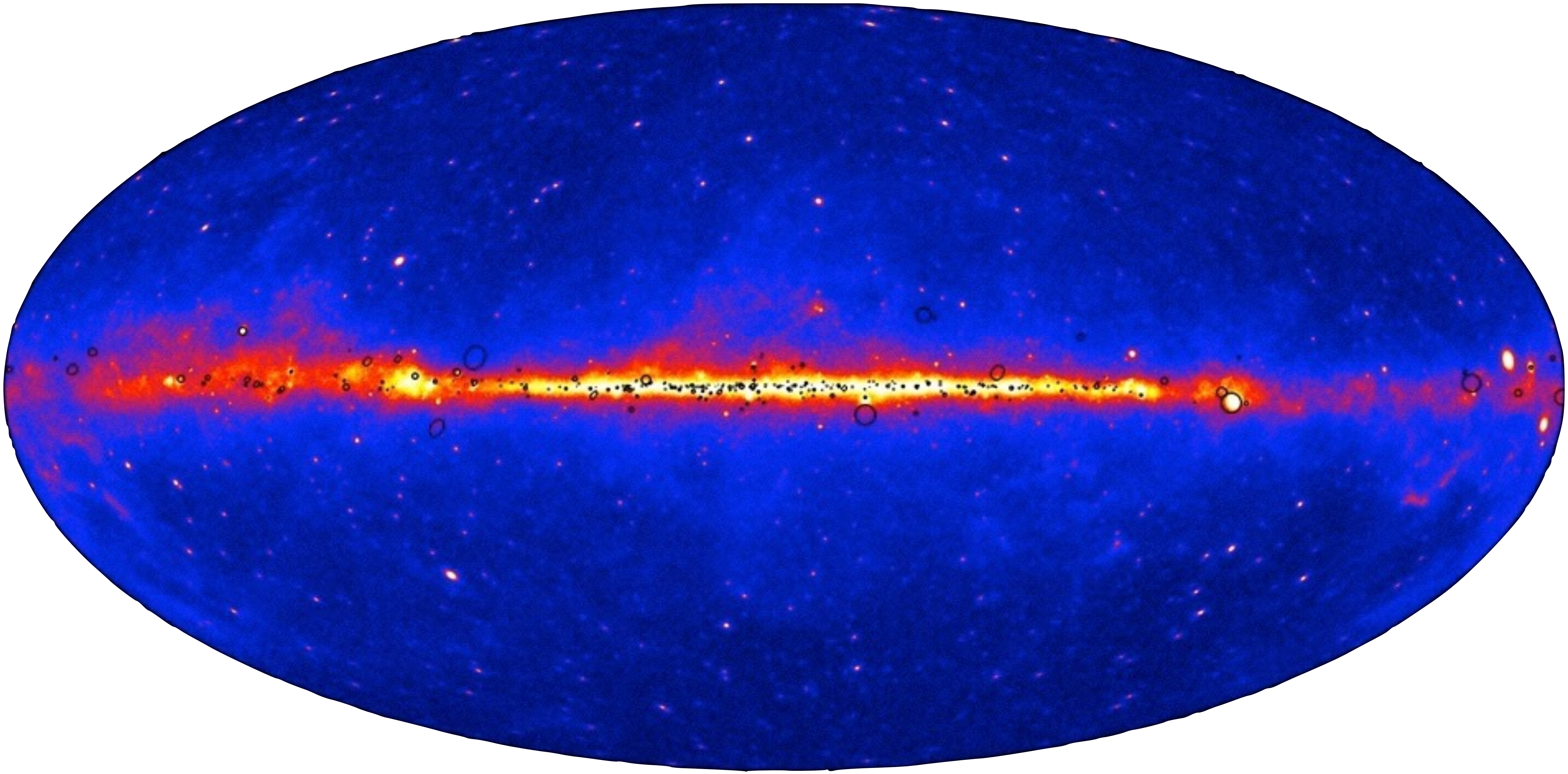
Emission lines

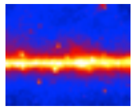
- **Faint emission from heavy elements in Tycho SNR (type Ia)**

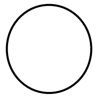


Tamagawa+09

SNRs in our Galaxy




Fermi-LAT γ-ray counts maps, E > 1 GeV


~300 known SNRs from radio Green's (2009) SNR Catalog

SNRs catalogs

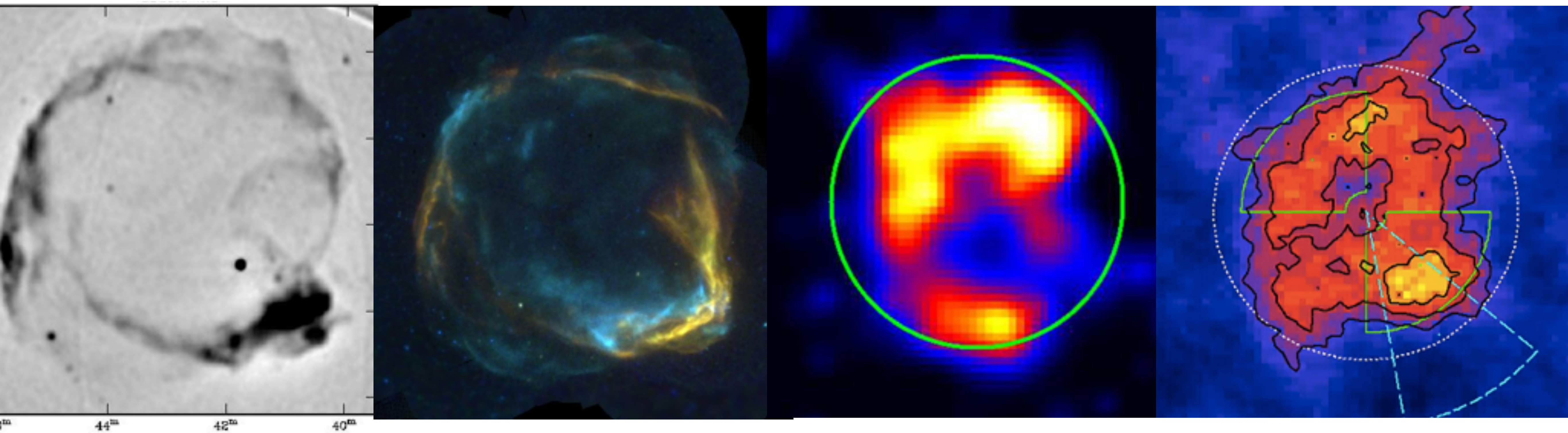
- **79% are shell type (<20% have a nice complete nice ring)**
- **12% composite**
- **5% plerions (pwn)**

http://www.physics.umanitoba.ca/snr/SNRcat/

https://www.mrao.cam.ac.uk/surveys/snrs/snrs.data.html

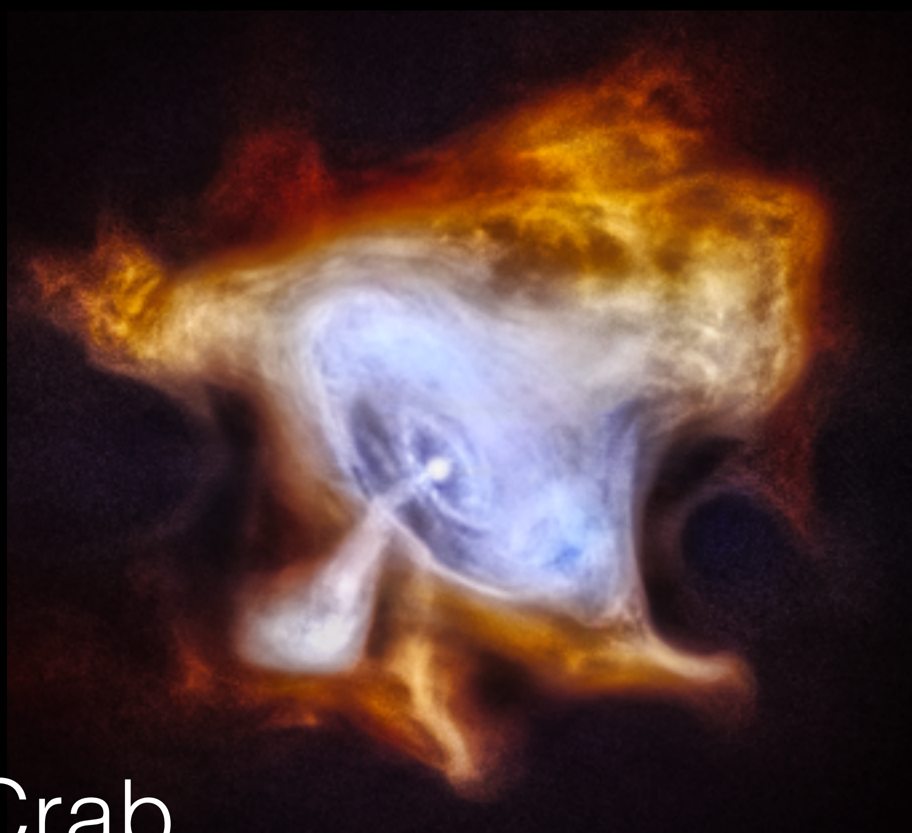
SNRs - Shell types

Radio | Thermal X / Synch X | GeV | TeV



- **Radio, optical, X-ray, gamma-ray come from a shell.**
- **Shell is expanding.**
- **Power source is inertia left from initial supernova.**

SNRs - Plerions

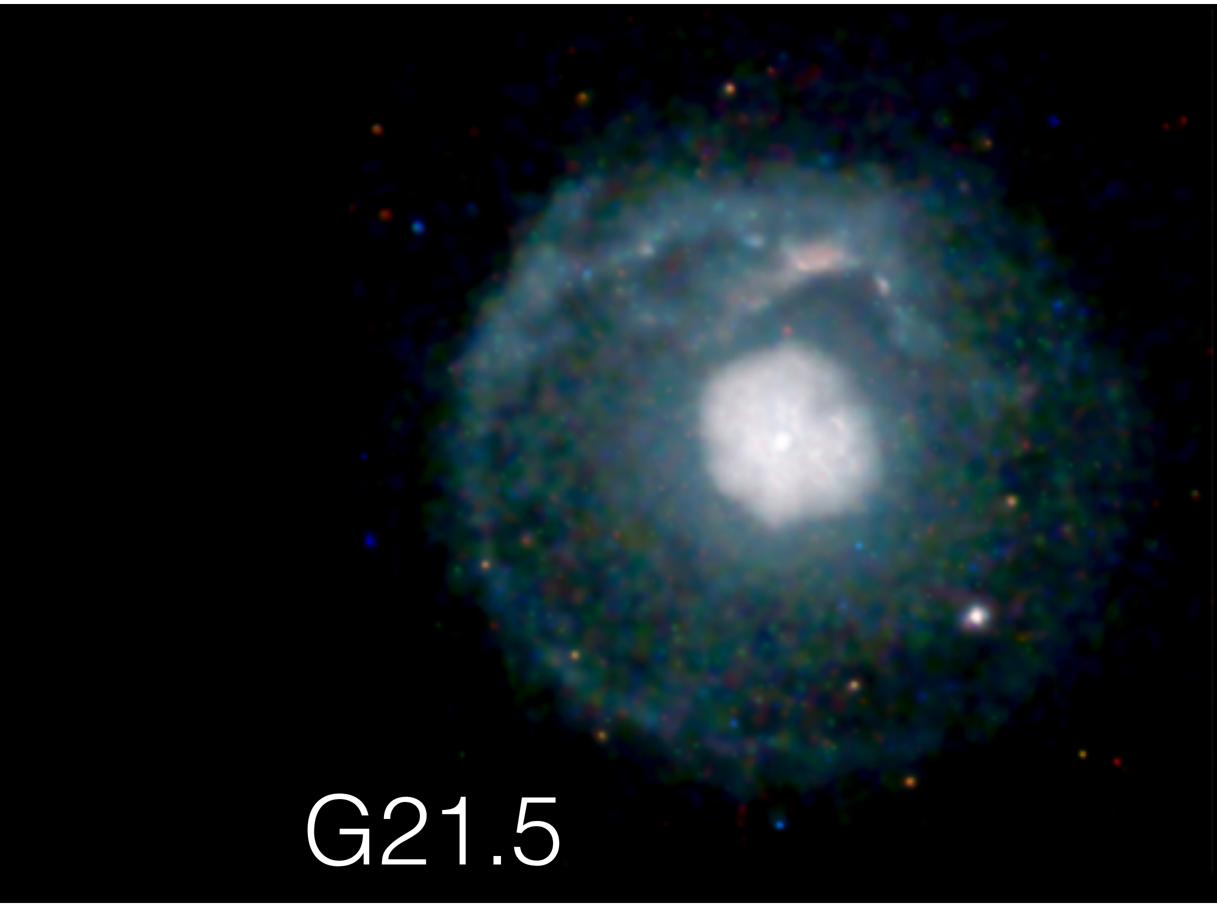


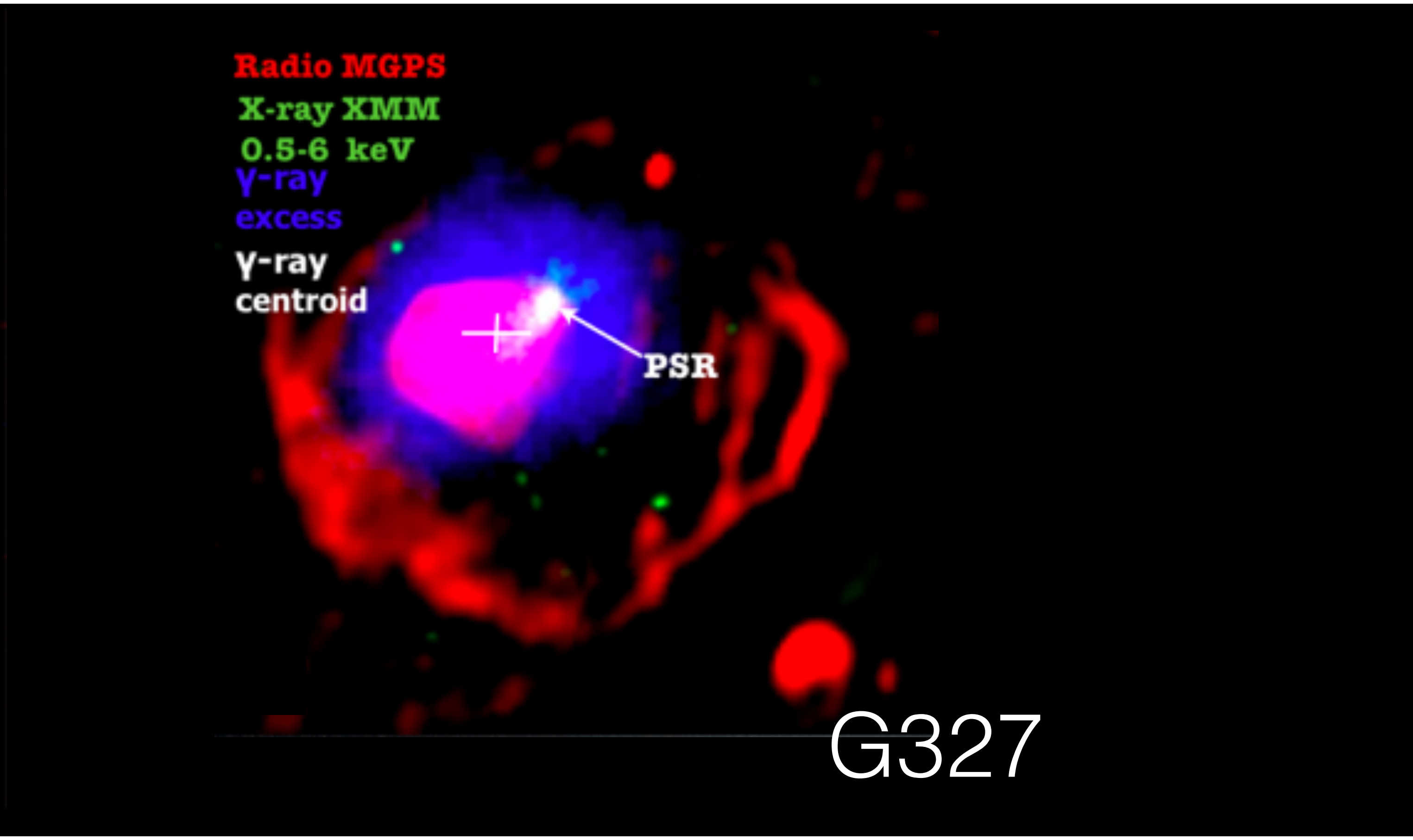
Crab

3C58

- Center filled or pulsar wind nebulae
- Radio, optical, X-ray, gamma-ray come from filled centre region
- X-rays are non- thermal
- Powered by relativistic wind from pulsar at center of nebula

SNRs - Composite



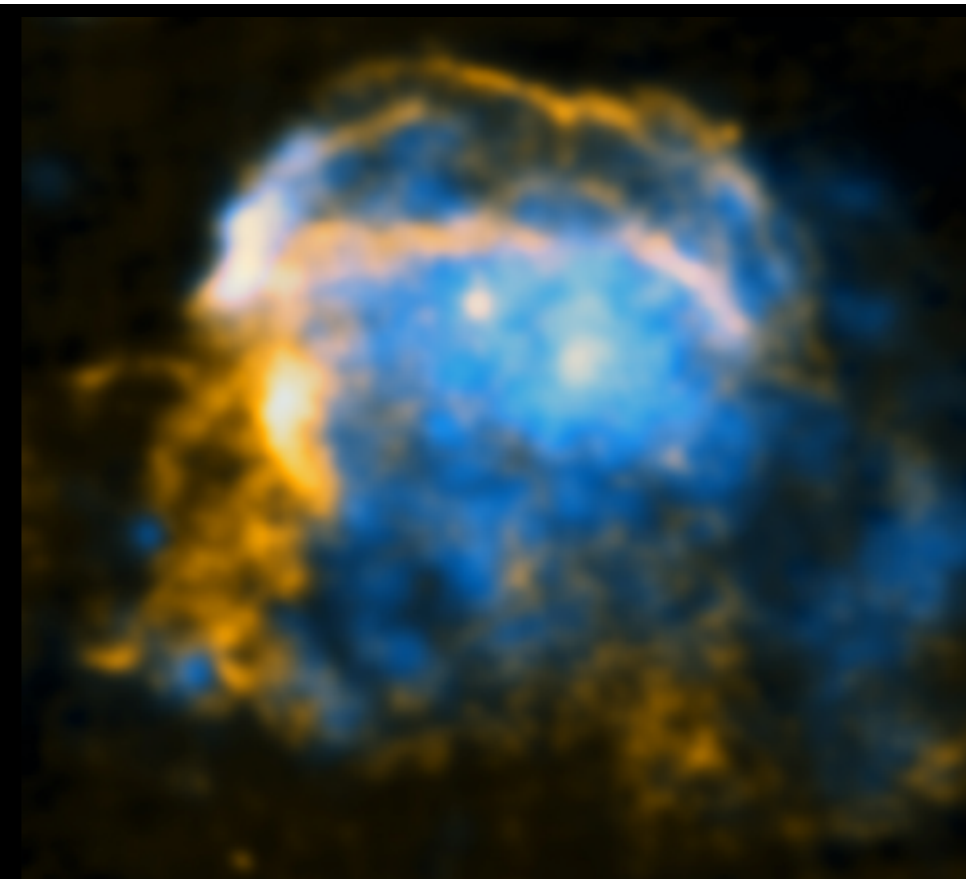


- Center filled + shell
- Radio, optical, X-ray, gamma-ray come from centre+shell region
- X-rays are thermal and/or non-thermal
- Powered by PWN + supernova inertia

SNRs - Mixed morphology

Optical
X-rays

W44



Radio
X-rays

W28

- Center filled with thermal X-rays + SNR shell
- « Fossil » hot X-ray interior
- Slow exterior (radiative). Compressed electrons (radio shell)
- Usually old SNRs (~10 kyr) evolving in dense ISM (OH maser)

SNR phases

Supernova explosion

ejecta $V_{shock} \sim 10^4$ km/s

Ejecta dominated

ejecta mass > swept up mass

Sedov

swept-up mass > eject mass

Snow-plow or Radiative

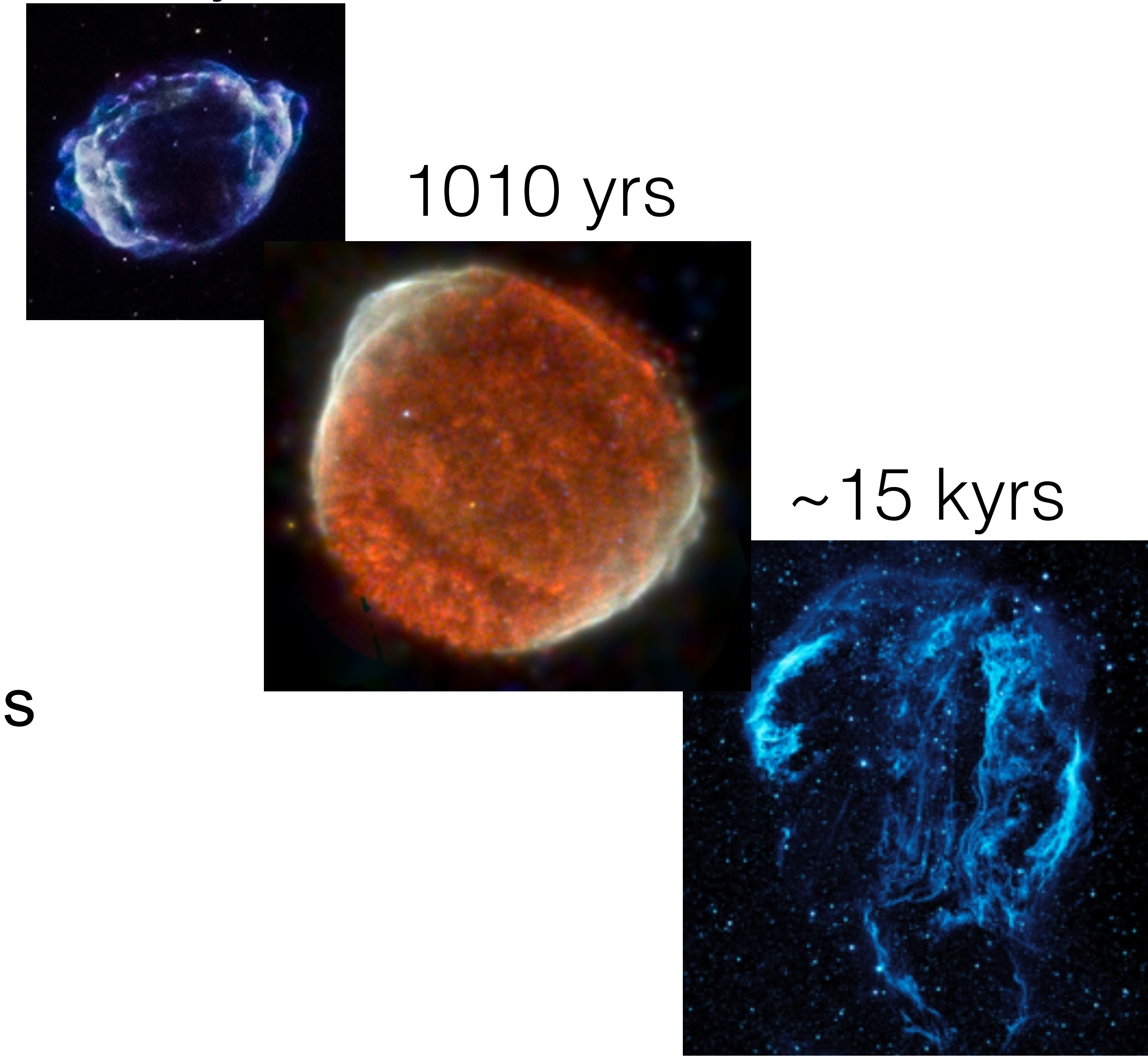
shock front cools, interior also cools

Merging with ISM

150 yrs

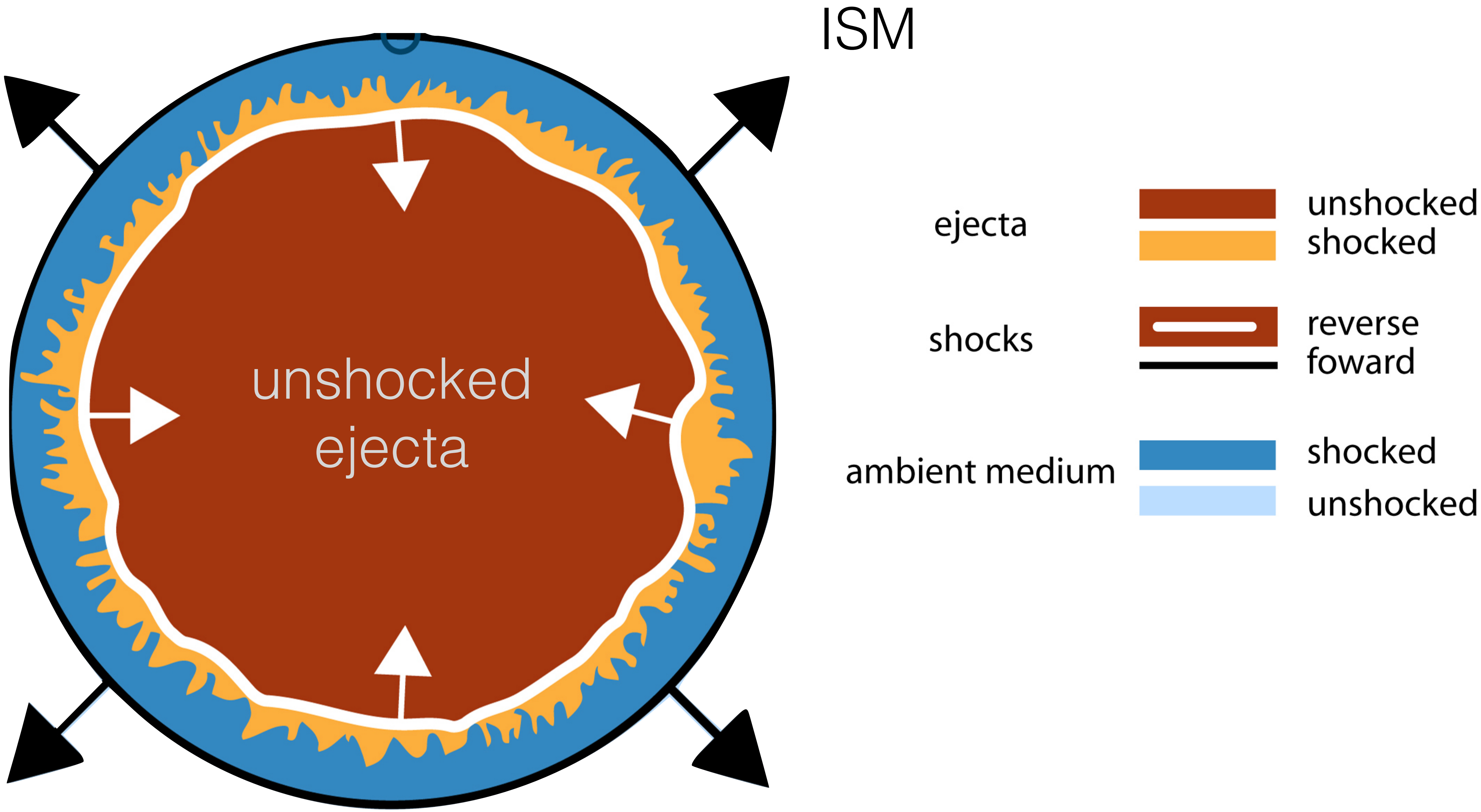
1010 yrs

~15 kyrs



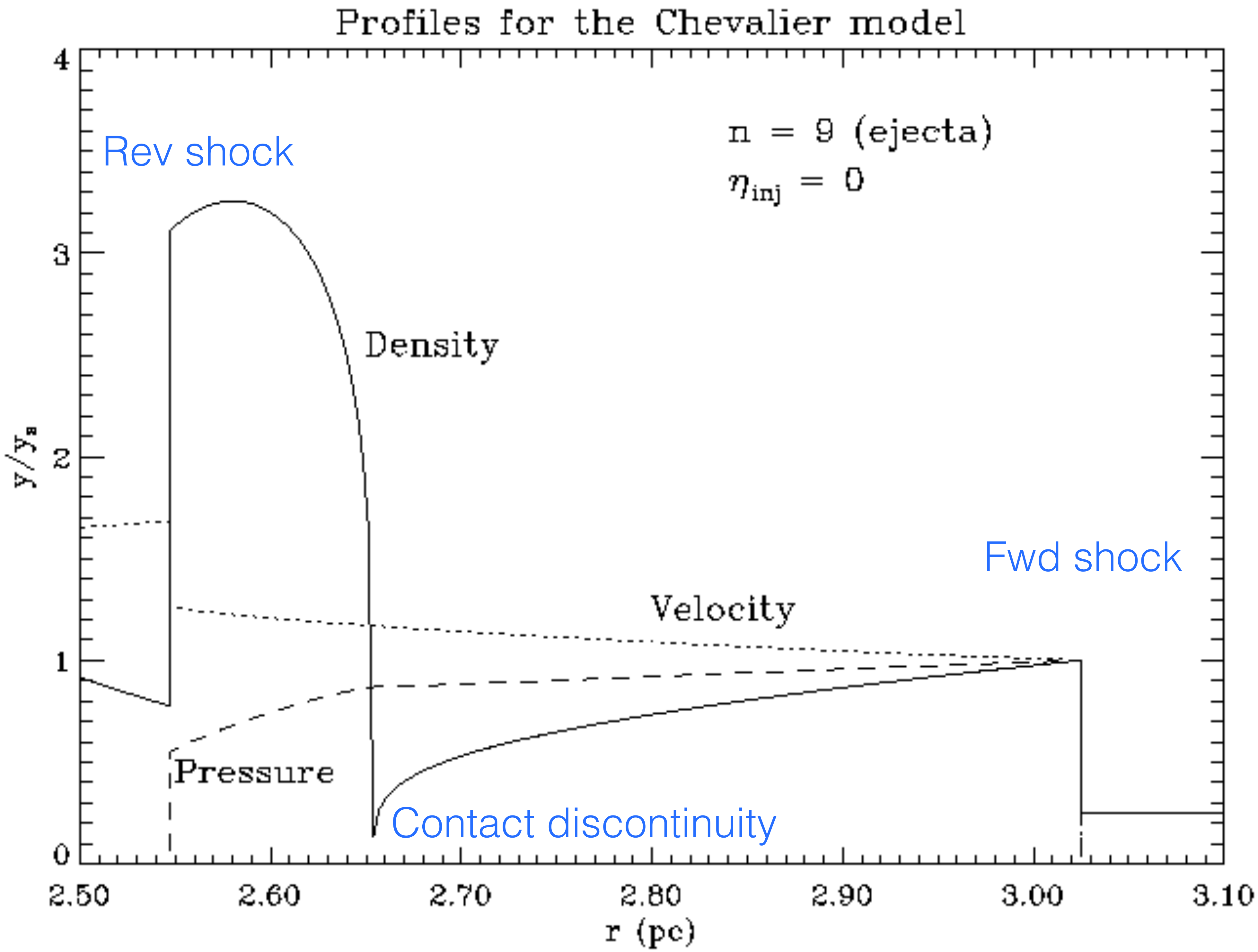
Caveat: Age is not always the best indicator of the SNR phase

SNR structure



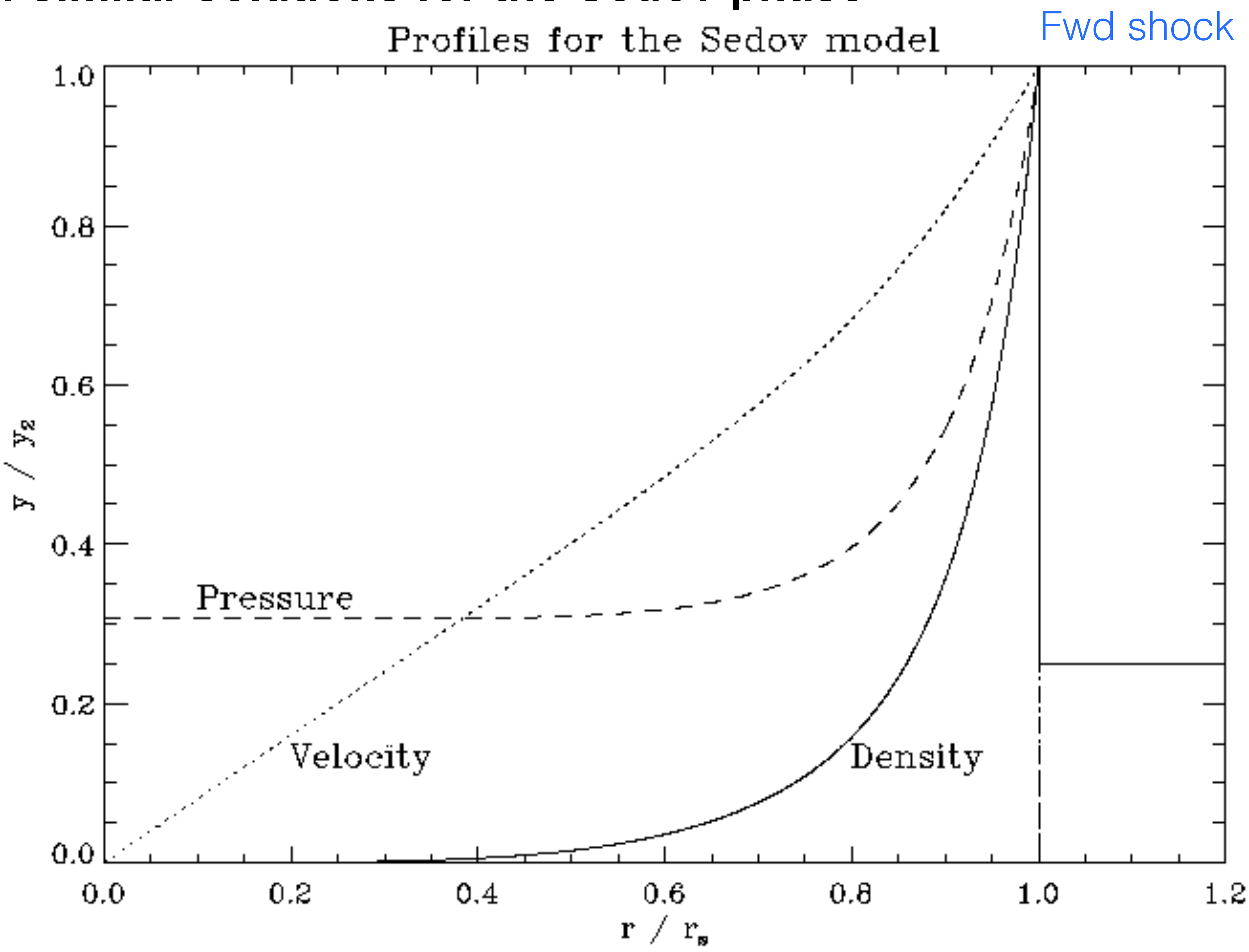
SNR hydrodynamics

- **Self similar solutions for the ejecta dominated phase**

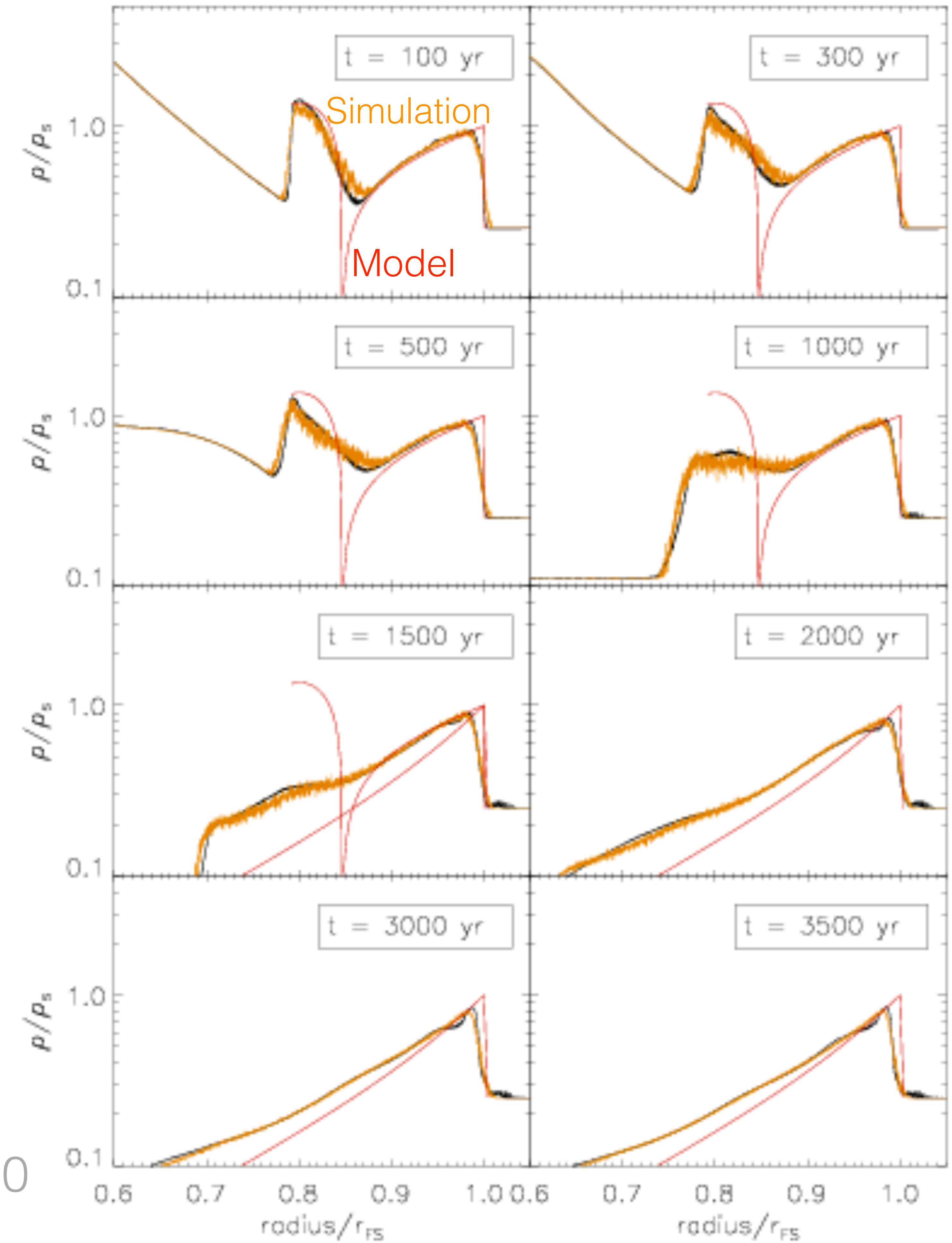


SNR hydrodynamics

- **Self similar solutions for the Sedov phase**



Structural time evolution



Fraschetti+10

Self similar solutions

- **Analytical model to describe $R_{shock}(t)$ and $V_{shock}(t)$**

$$R_s \propto t^{\beta}$$

$$\beta = (n-3)/(n-s) \quad \text{Ejecta phase}$$

$$\beta = 2/(5-s) \quad \text{Sedov phase}$$

where n (ejecta profile),s (ambient density profile) => $\rho(r) \propto r^{-n,s}$

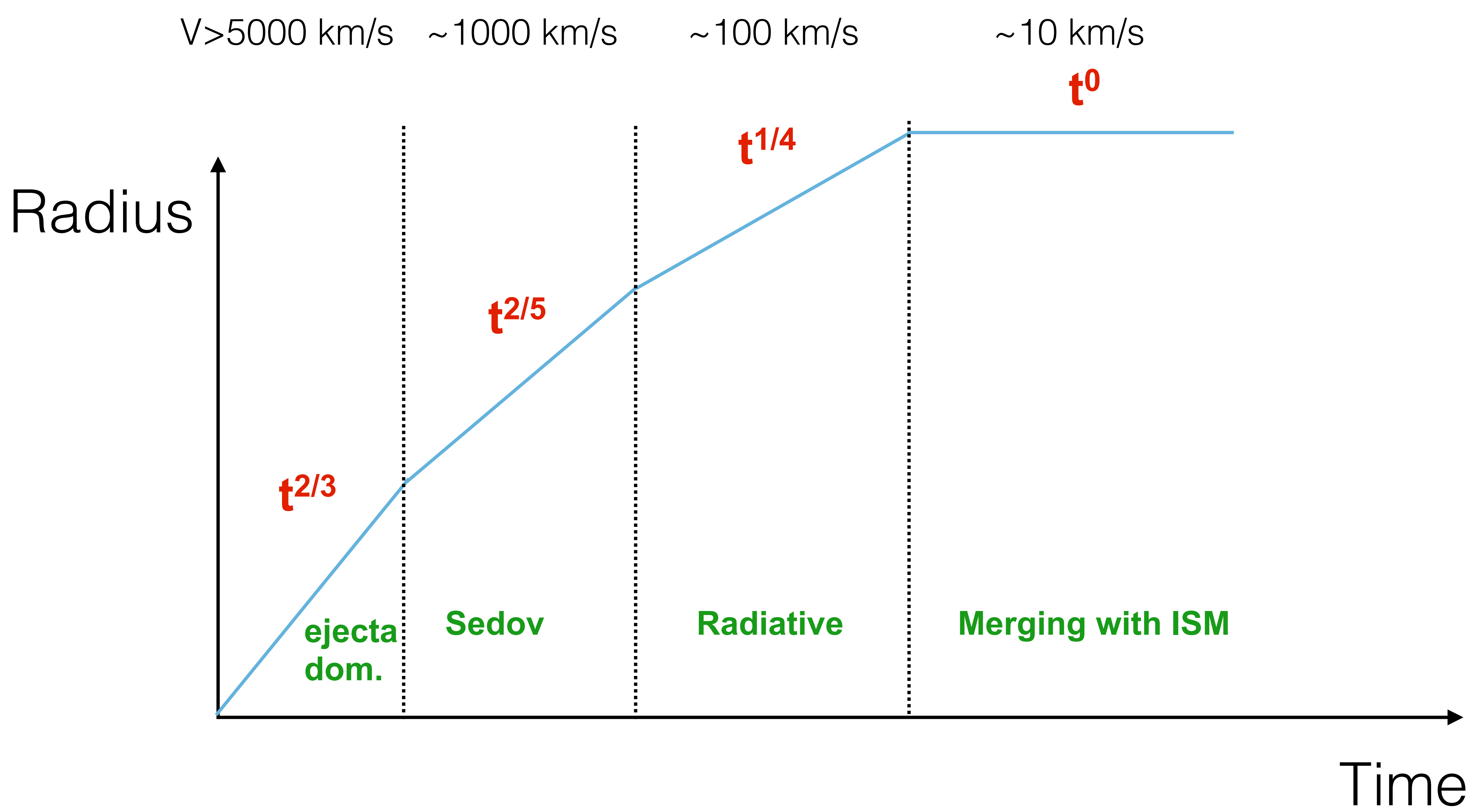
- **s = 0 — homogenous ambient medium (e.g. Type Ia SNR)**
  – **β = 0.66 => 0.4 (for n=9)**

- **s = 2 — SNR evolving in a wind density profile (CC supernova)**
  – **β = 0.86 => 0.66 (for n=9)**

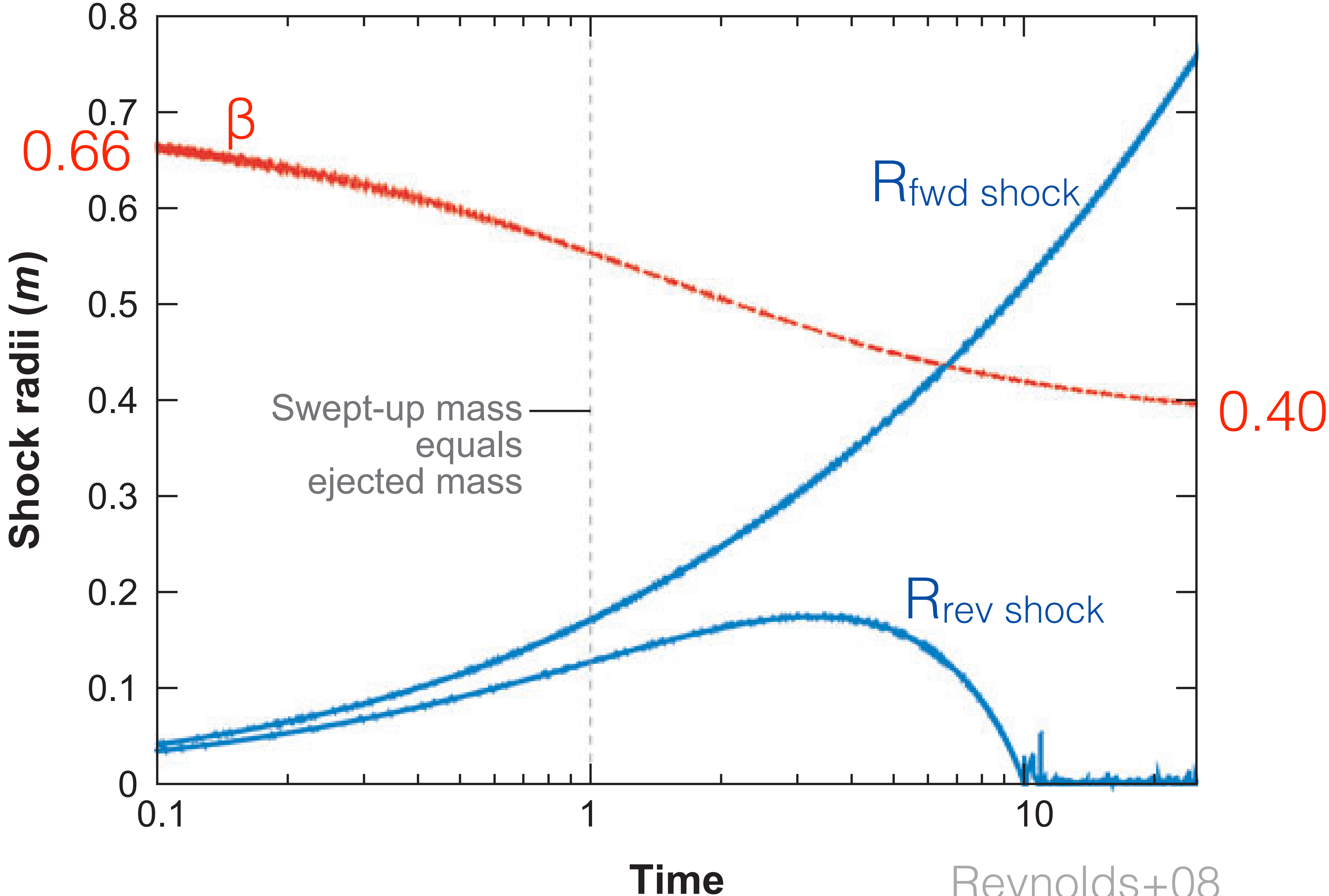
- **Observations: in Galaxy M81, CC SN1993J β=0.85 => n=8.5**

Marcaide+09

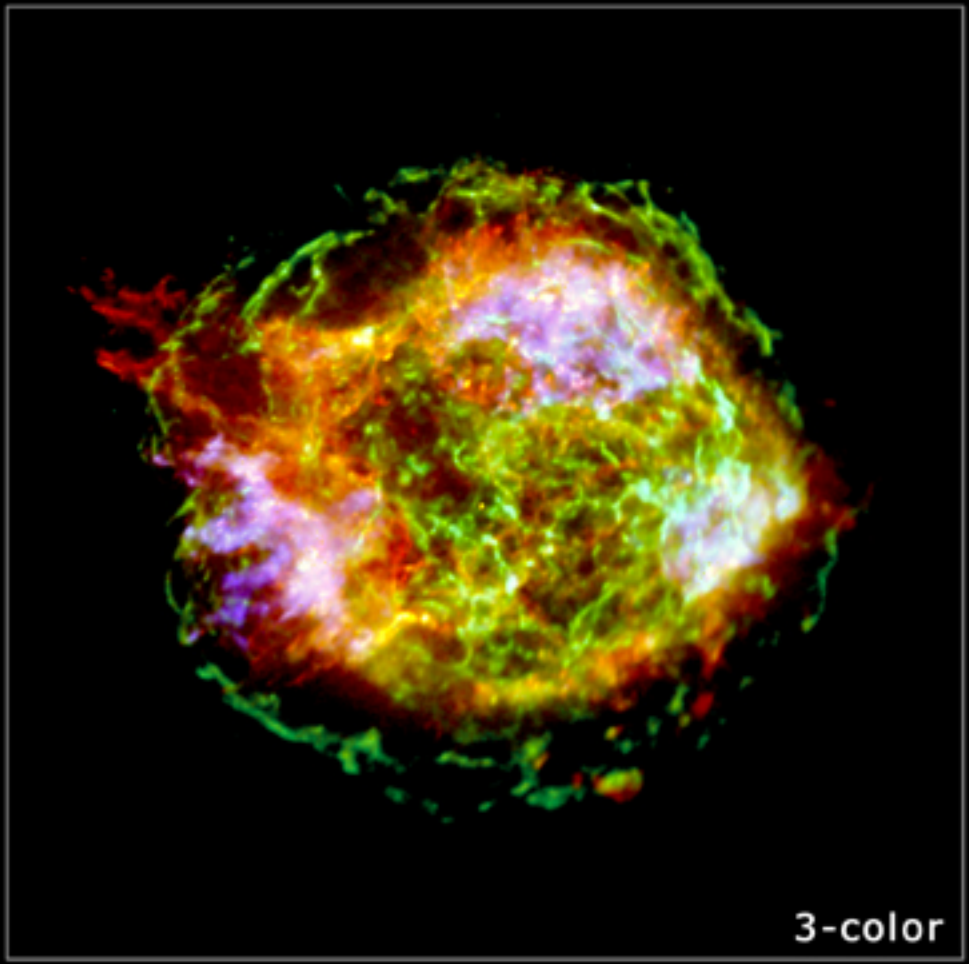
Time evolution

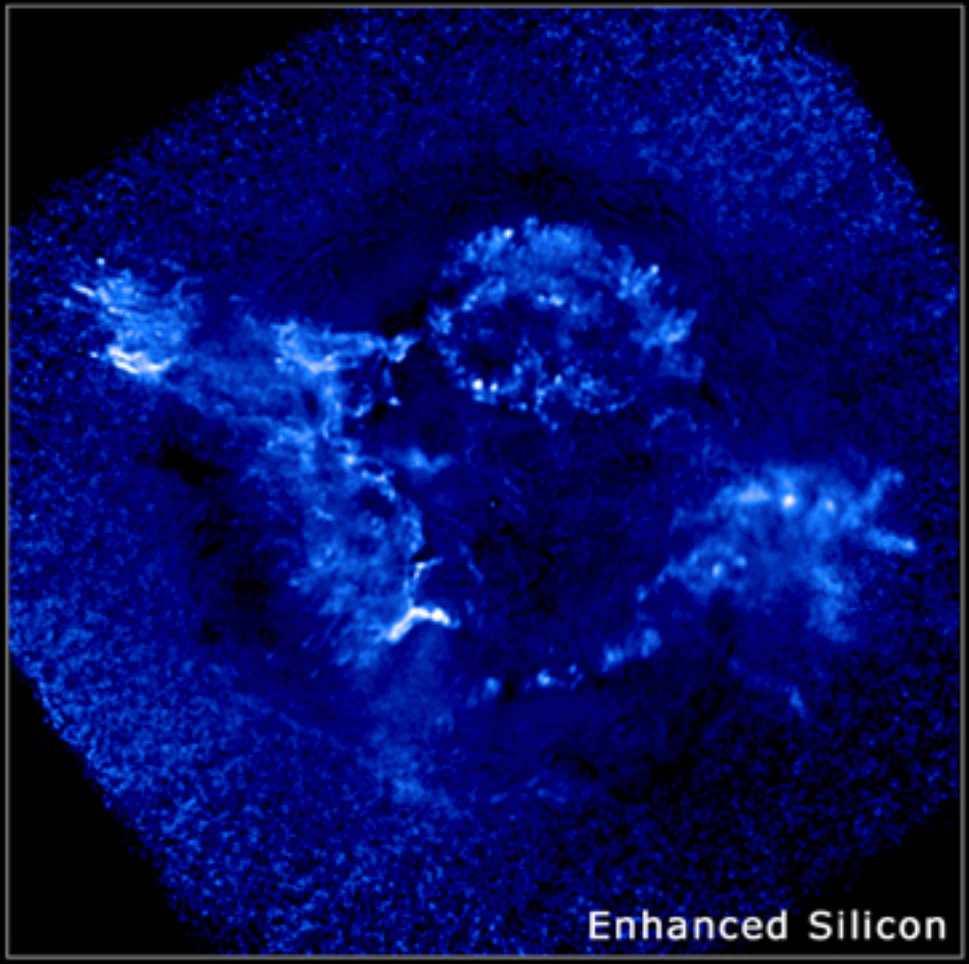


Self similar solutions vs Hydro simulation

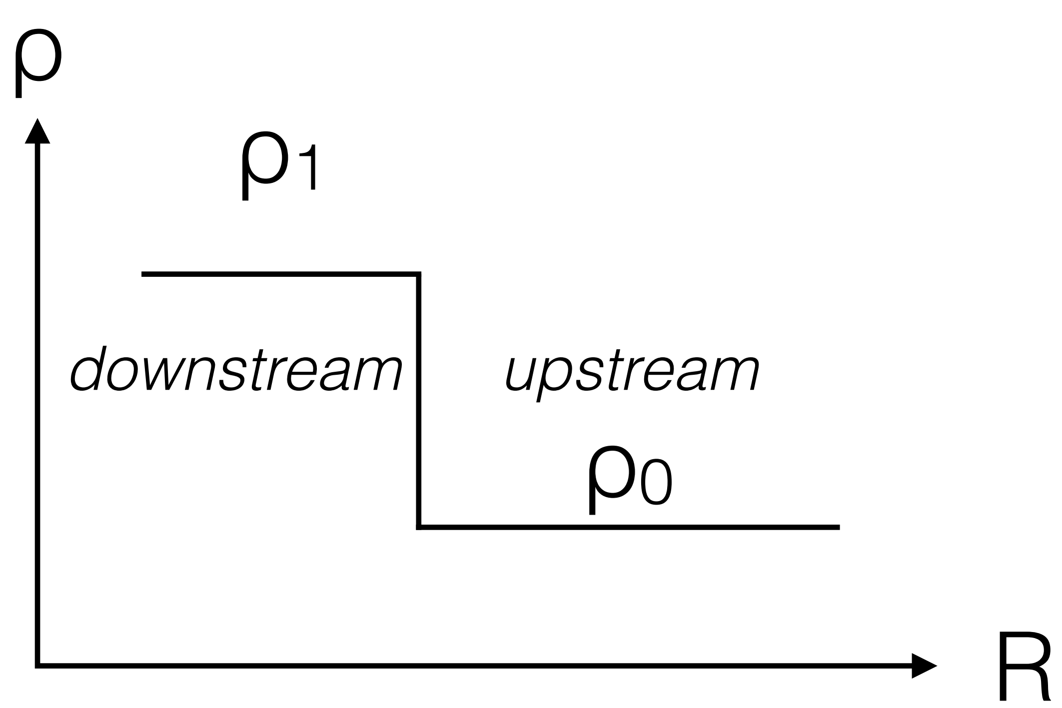


What can we learn from thermal X-rays





Shock hydrodynamics



Conservation of

Mass

$$\rho u = constant$$

Momentum

$$P + \rho u^2 = constant$$

Energy

$$\frac{u^2}{2} + \frac{5P}{2\rho} = constant$$

Shock hydrodynamics

For strong shocks:

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0 \qquad \rho_1 = 4\rho_0$$

$$u_1 = \frac{\gamma-1}{\gamma+1}u_0 \xrightarrow{\gamma = 5/3} u_1 = \frac{1}{4}u_0$$

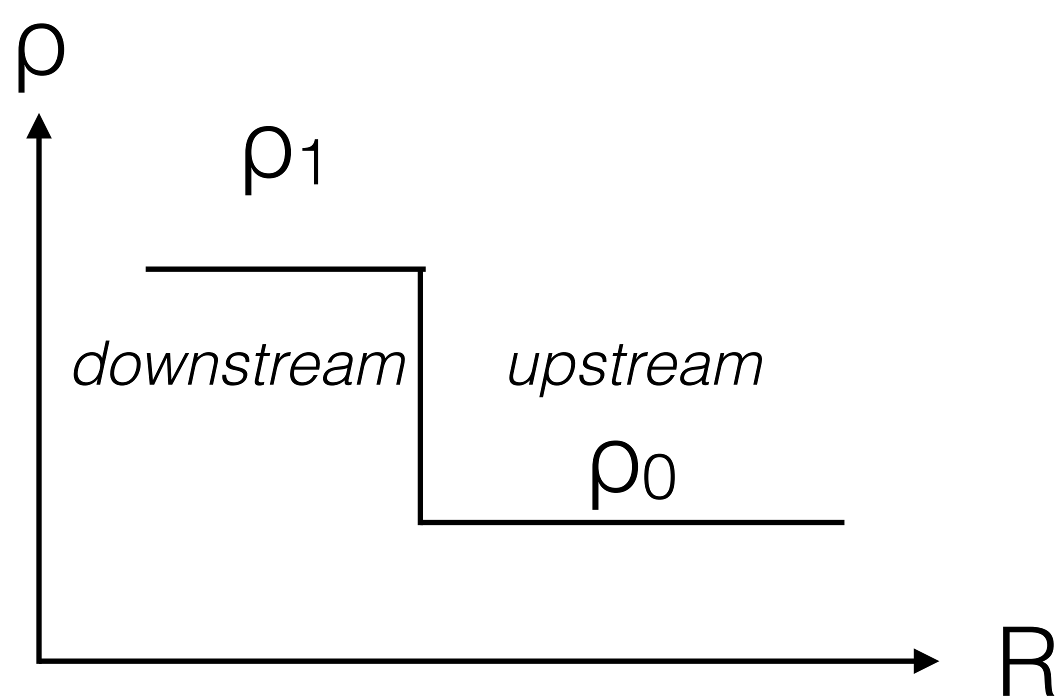
$$P_1 = \frac{2\rho_0 u_0^2}{\gamma+1} \qquad P_1 = \frac{3}{4}\rho_0 u_0^2$$

$$\downarrow$$

$$kT_s = \frac{3}{16}\mu m_H \times V_s^2$$

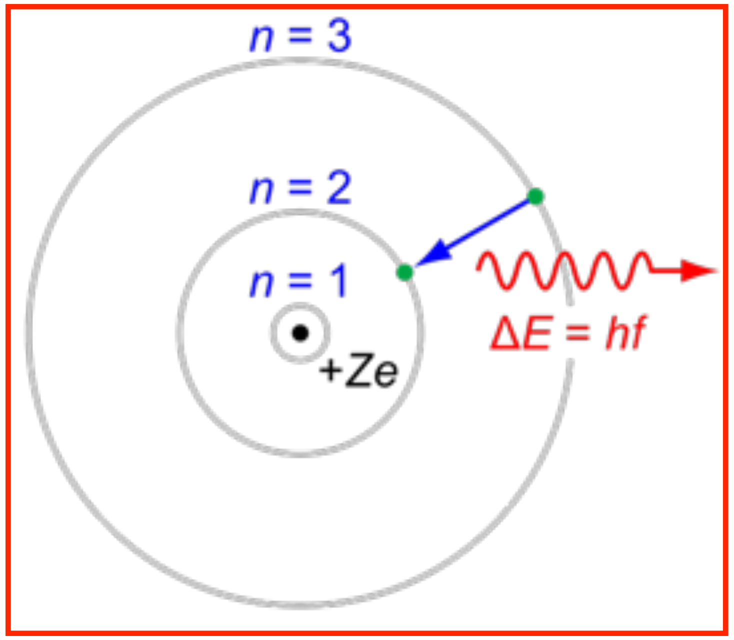
T ~ 10^7 K for V_S=1000 km/s

$$kT_i \propto m_i V_s^2$$

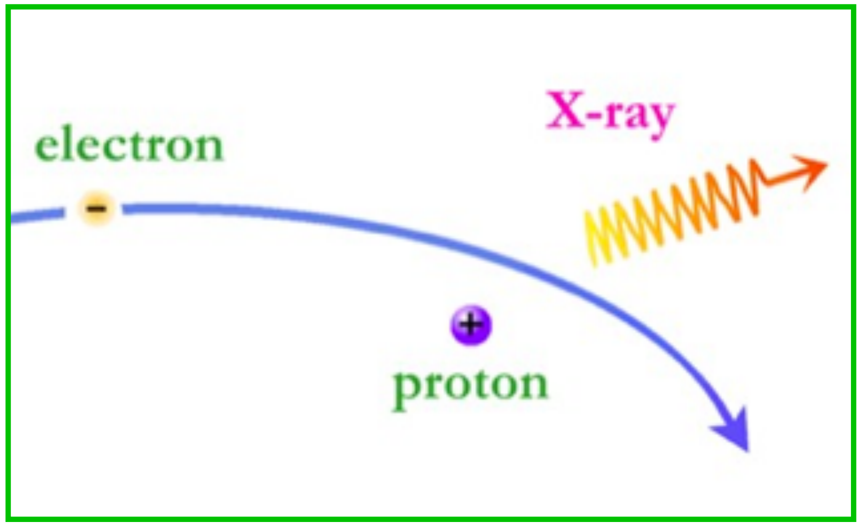


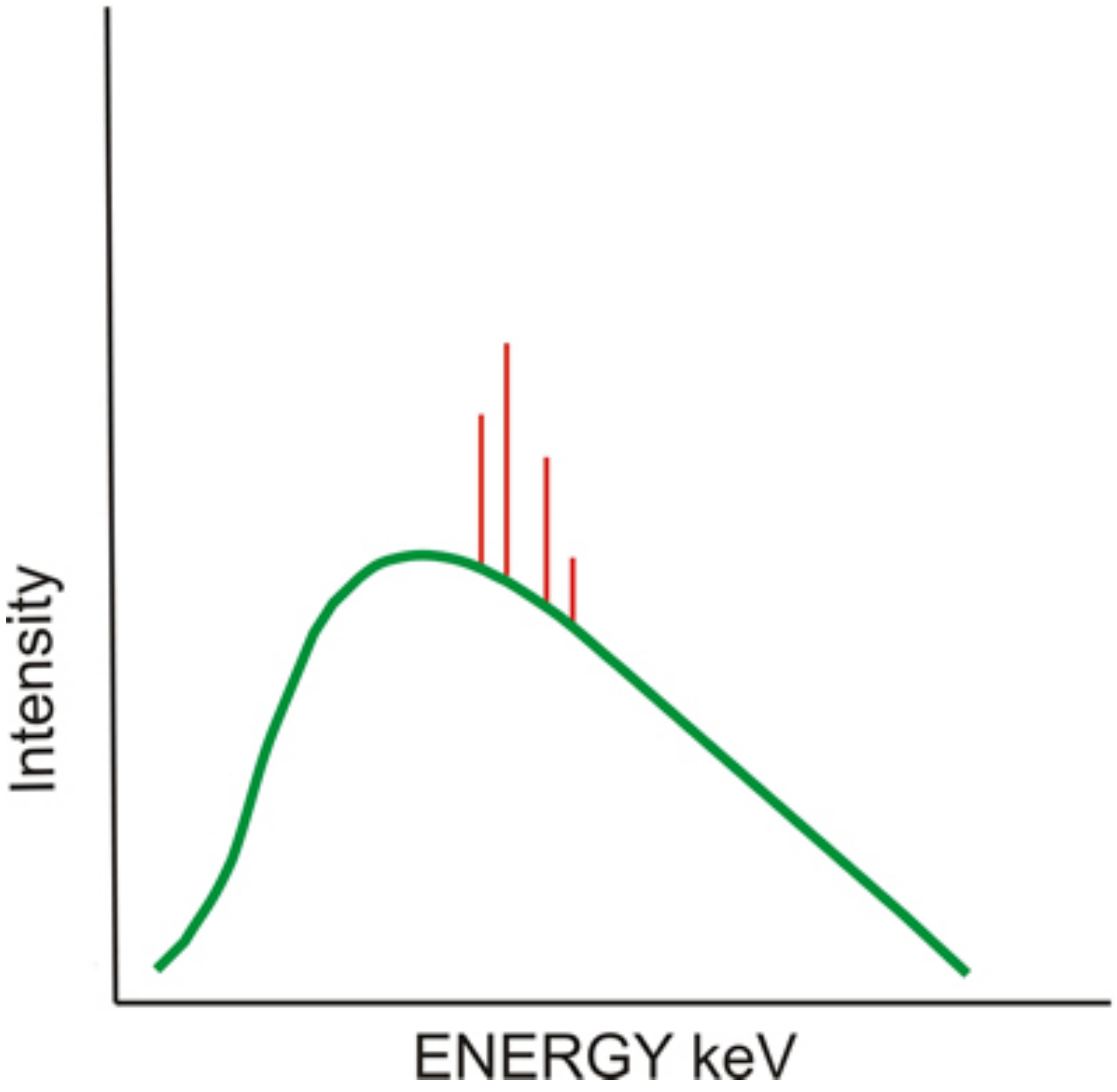
Thermal X-ray emission

Line emission



Bremsstrahlung



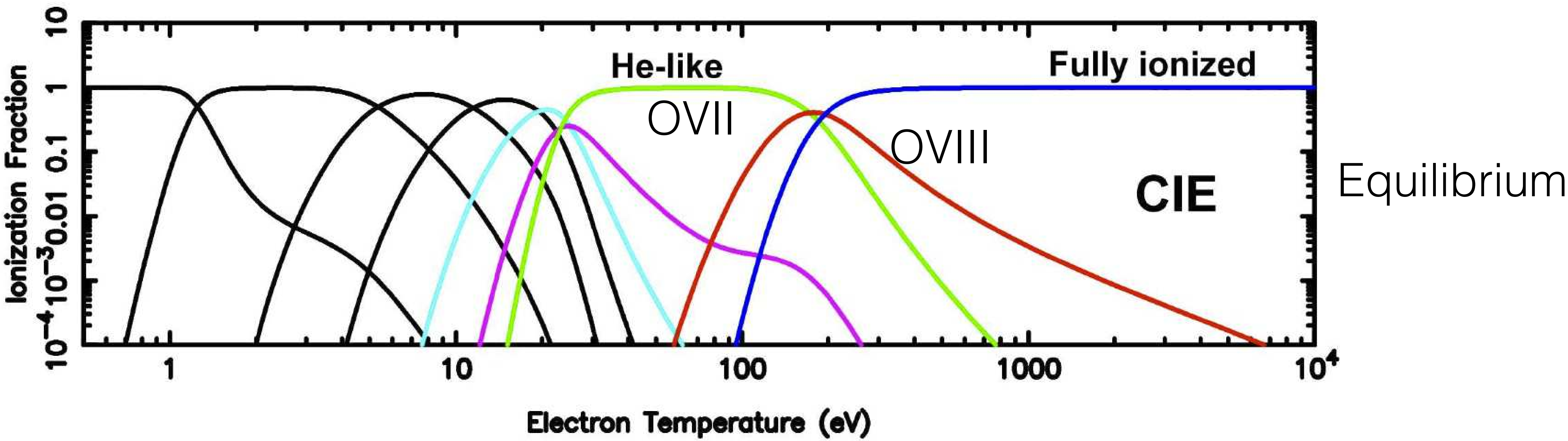


Also:

radiative-recombination continua observed in over-ionized plasma.

Non-equilibration ionization (NEI)

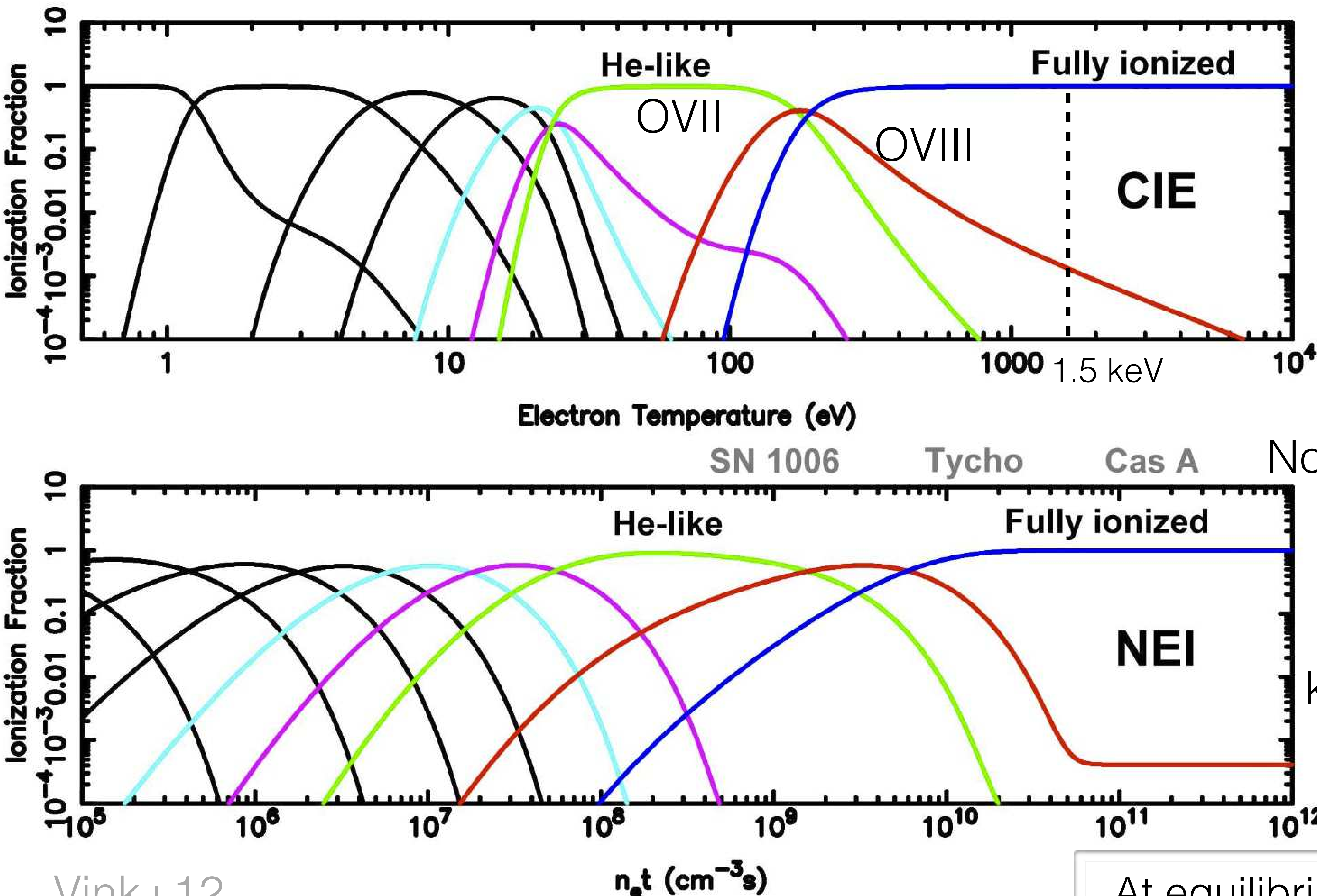
Ionization fraction for Oxygen



Non-equilibration ionization (NEI)

launch binder

NEI creates a delay in ionization state



Equilibrium

Non-equilibrium

Fixed
kT_e=1.5 keV

Vink+12

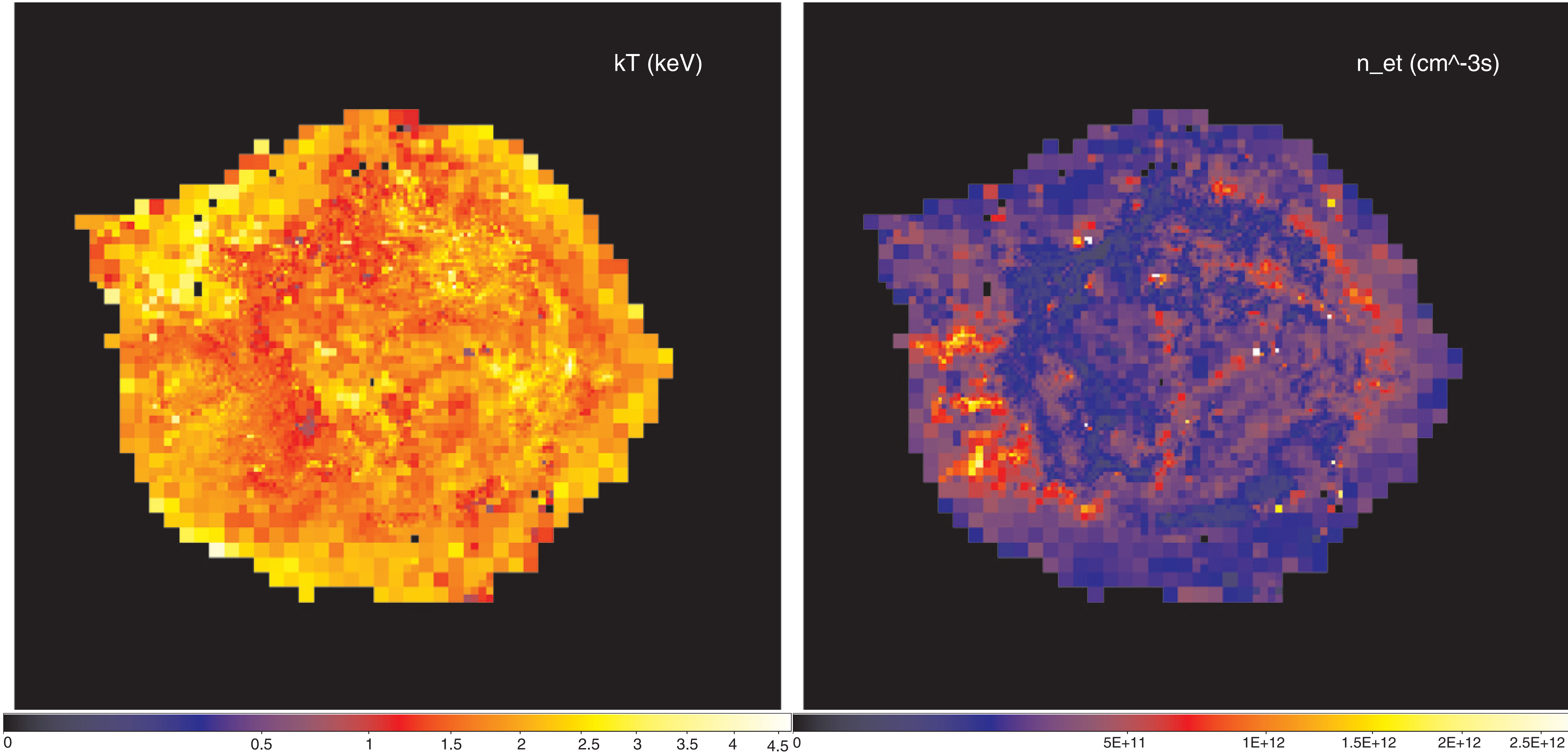
At equilibrium for
$n_e t > 10^{12}$ cm^{-3} s

What can we learn

- From continuum shape: temperature (mostly kT_e)
  - ~ shock speed (but depends on T equilibration)
- From continuum normalization: Emission measure: $\int n_e n_H dV$
  - Density of emoting plasma => ISM density
- From line ratio: ionization state ($n_e t$ parameter)
  - age since shock if n_e known
- From line over continuum ratio: element abundance
  - Disentangle ejecta from shocked ISM ; Nucleosynthesis

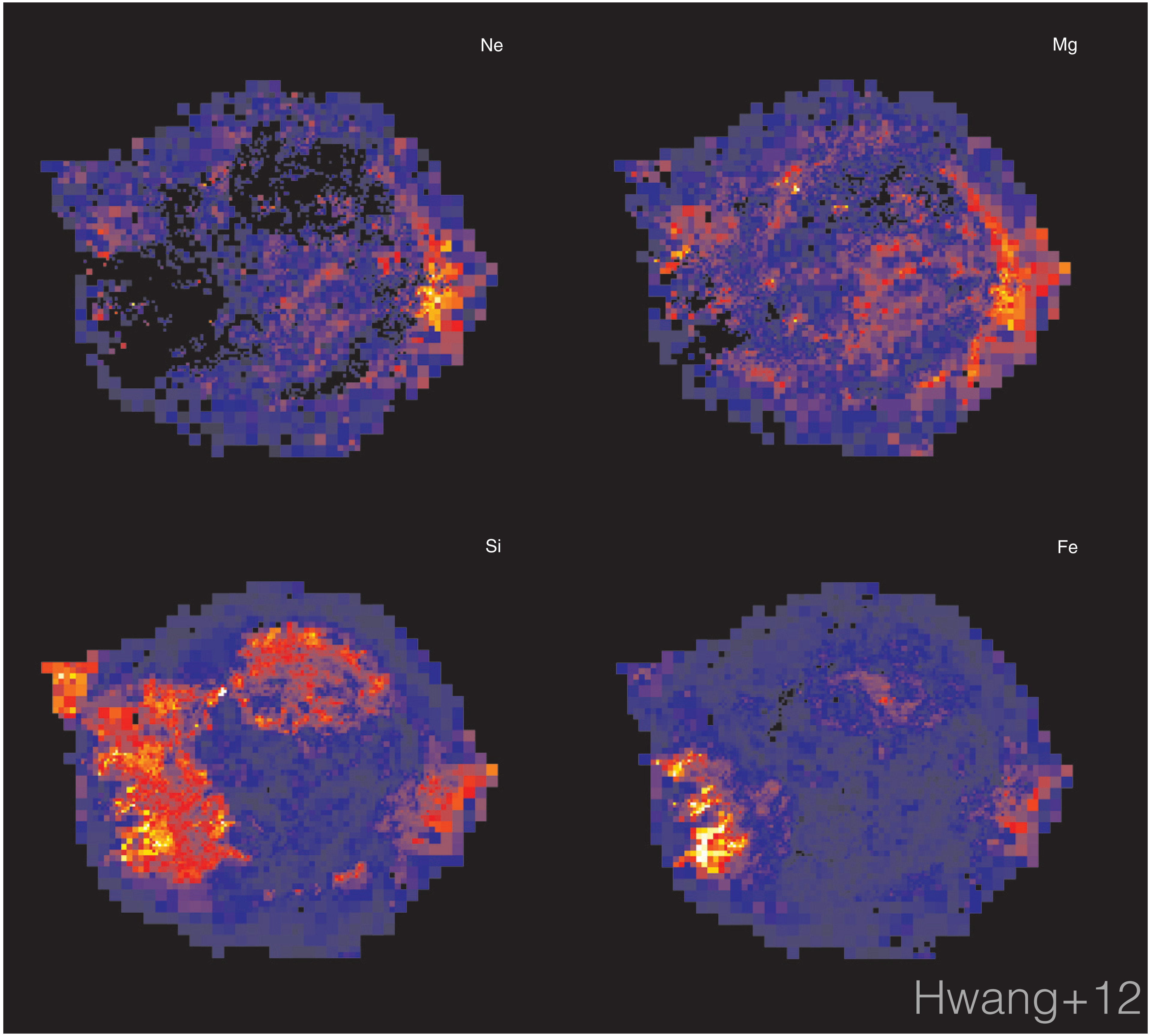
Spatially resolved spectroscopy

CasA SNR

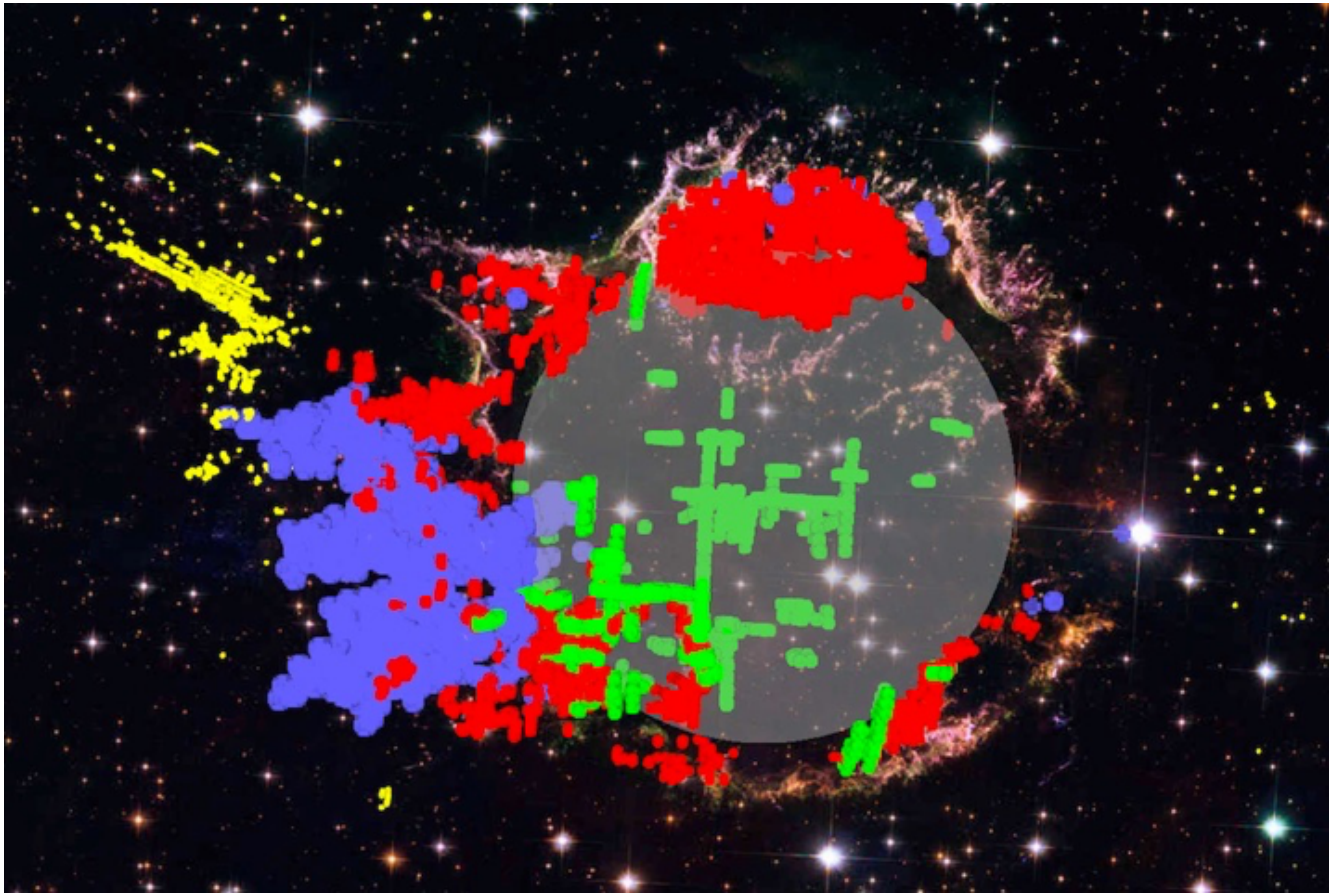


Hwang+12

Nucleosynthesis in CasA

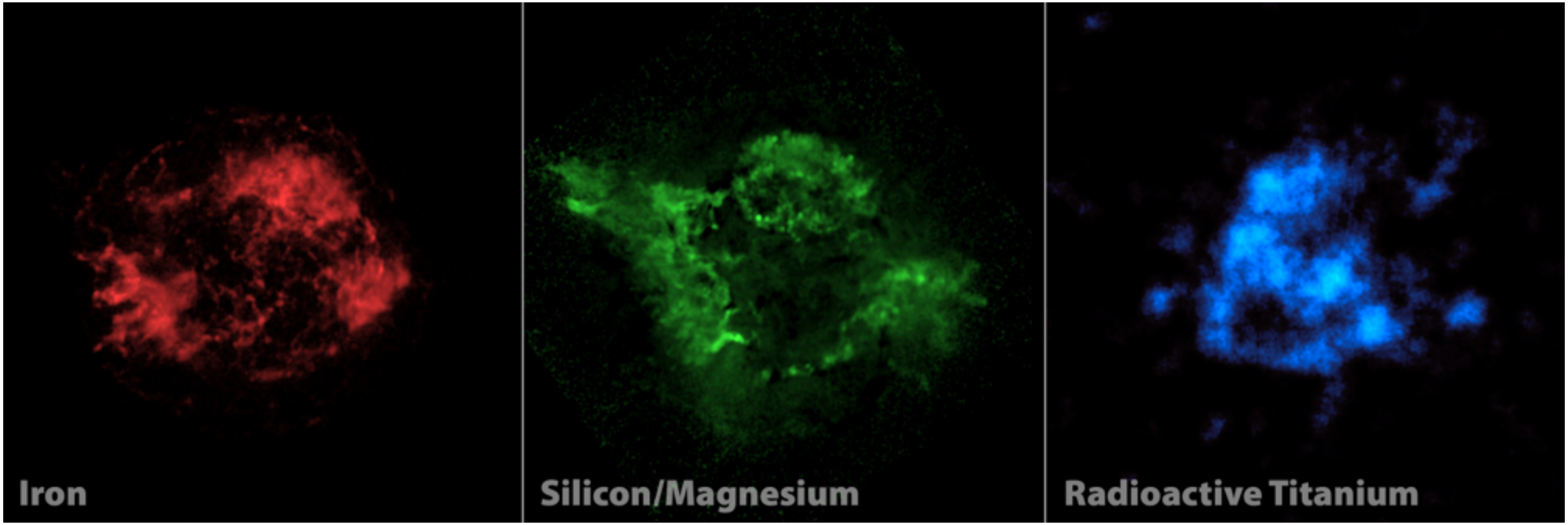


3D mapping of ejecta in CasA

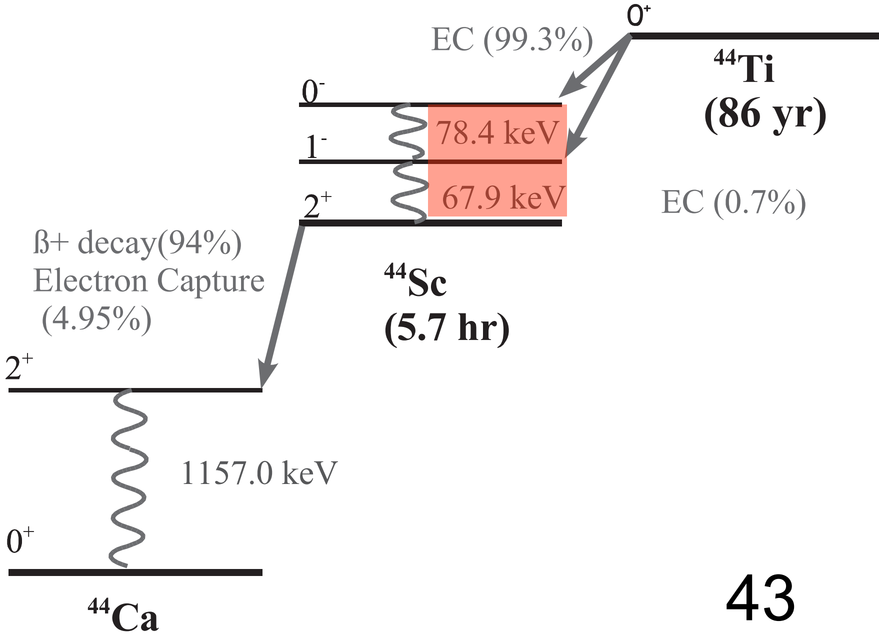


- https://www.cfa.harvard.edu/~dmilisav/casa-webapp/model.html

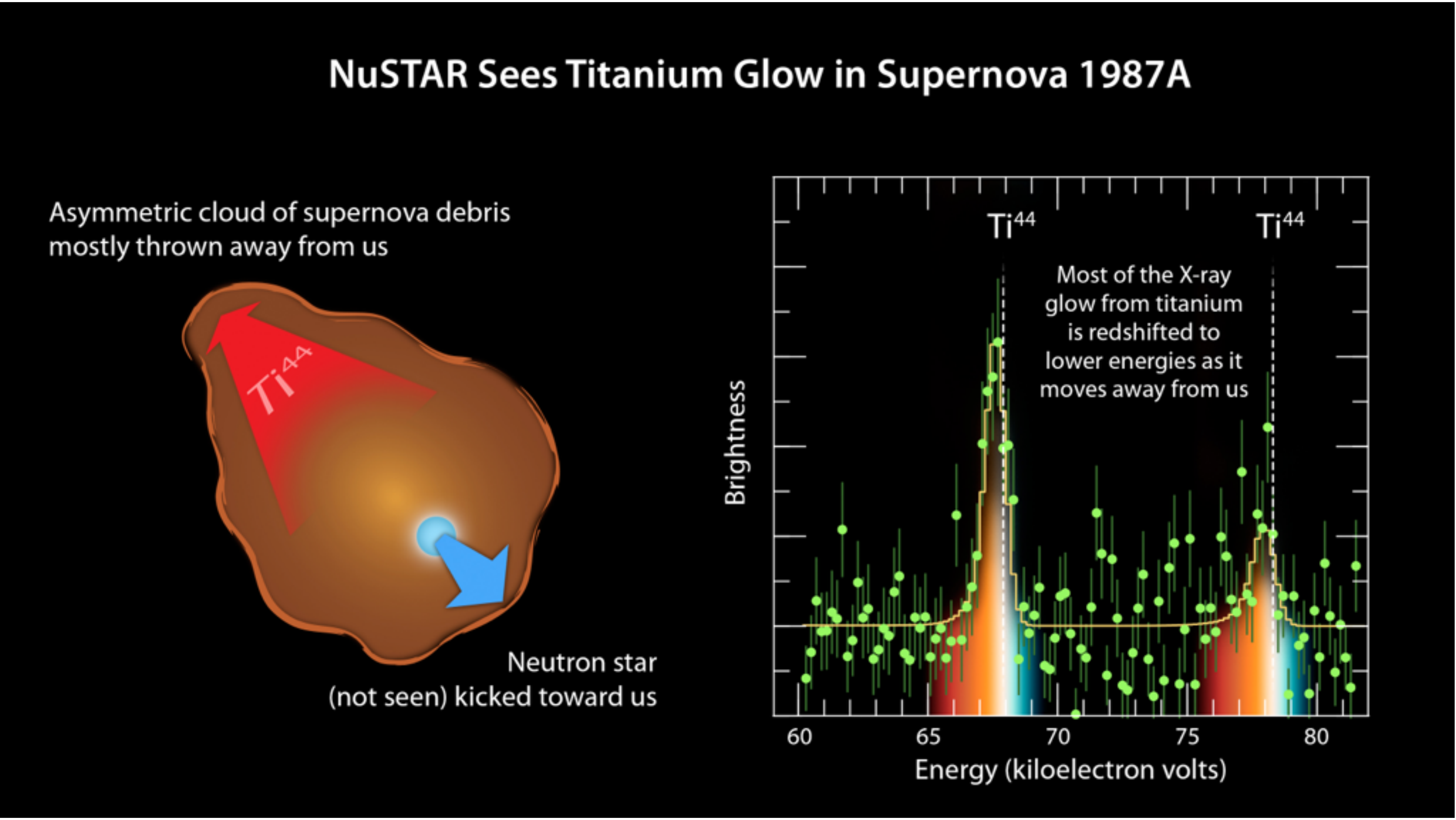
Explosion mechanism & nucleosynthesis



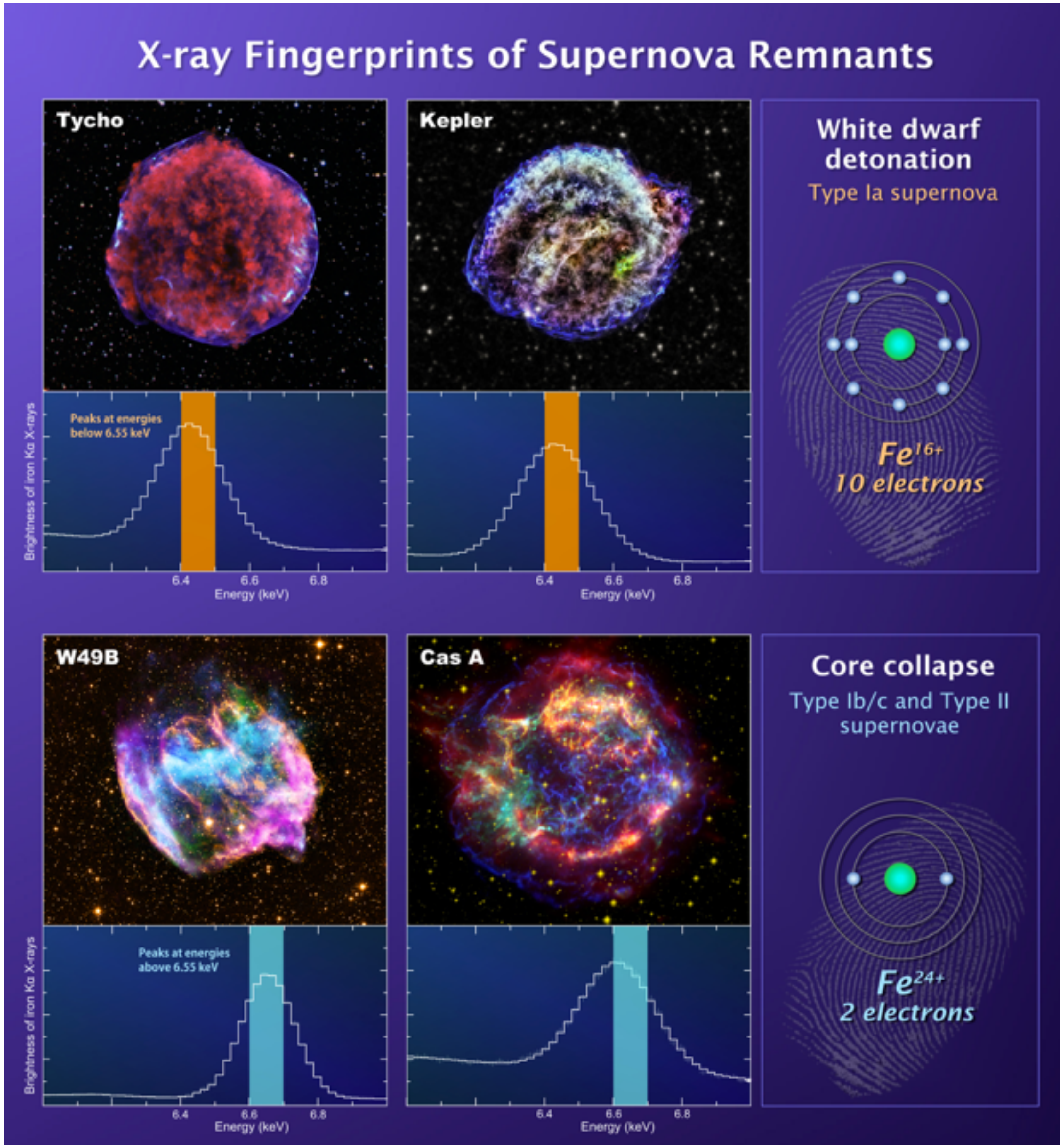
Chandra Chandra NuSTAR



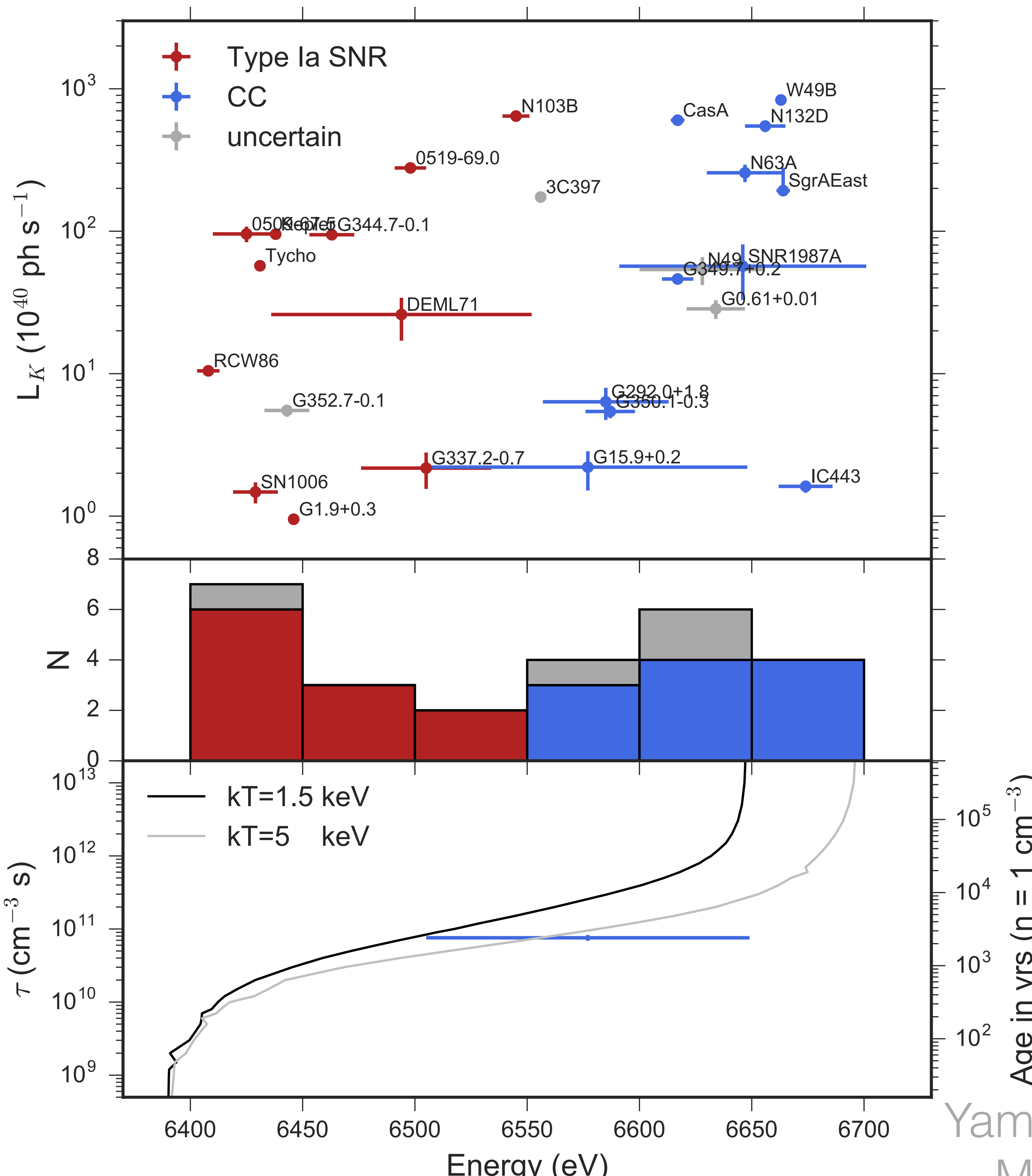
Explosion mechanism



Fe line reveals the nature & past history of SNRs



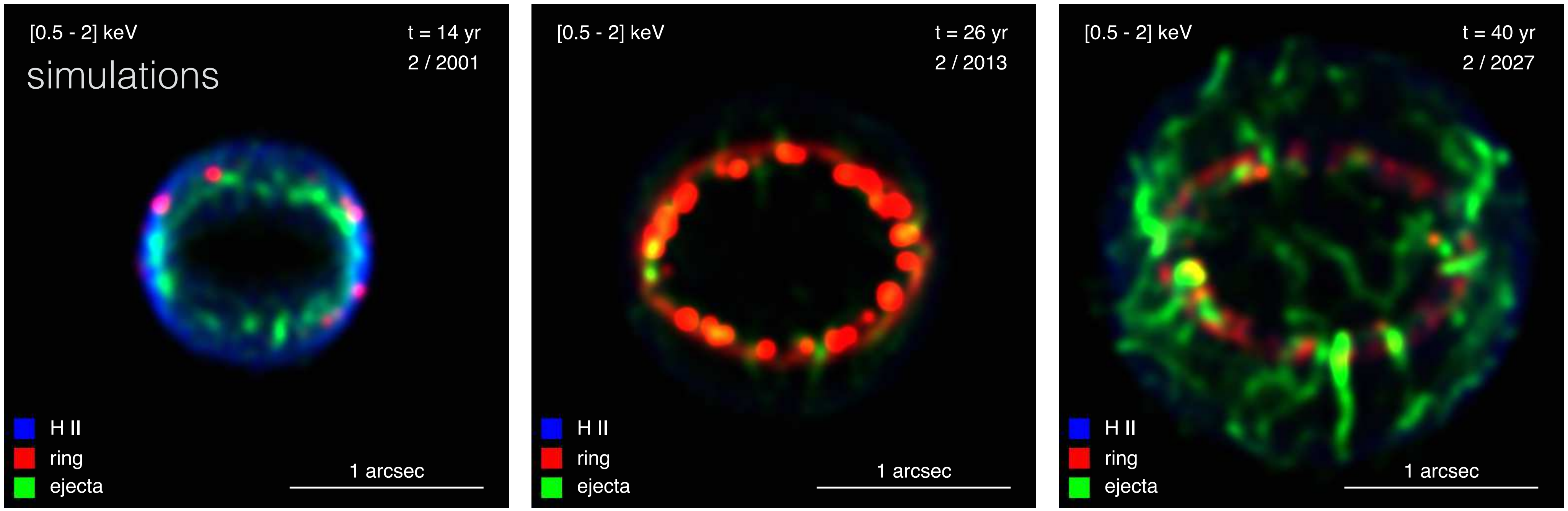
Fe line reveals the nature & past history of SNRs



$$\tau = \int n_e dt$$

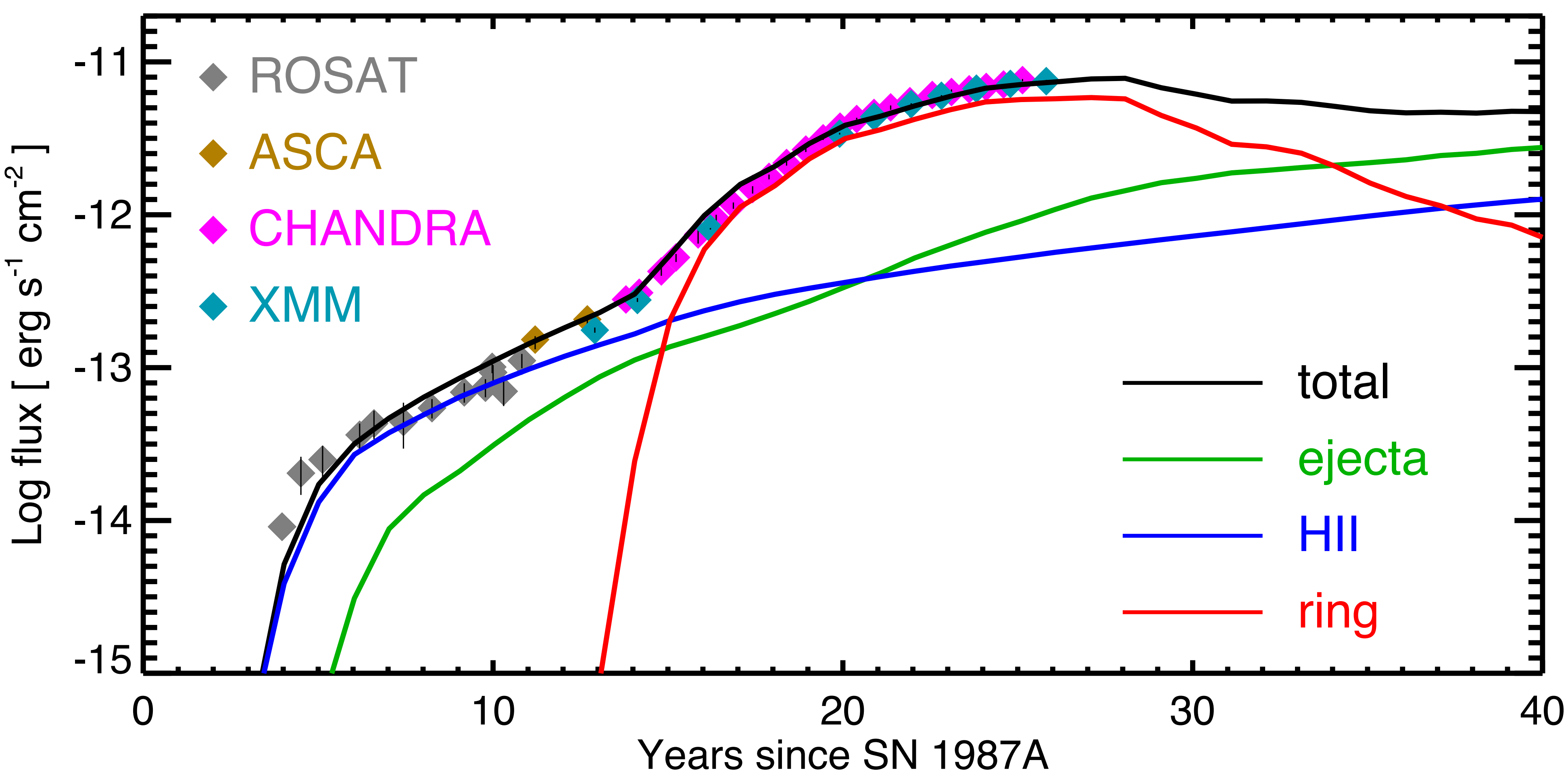
Yamaguchi+14
Maggi+16

« the ring of fire » in SN1987a



(b) [0.5, 2.0] keV

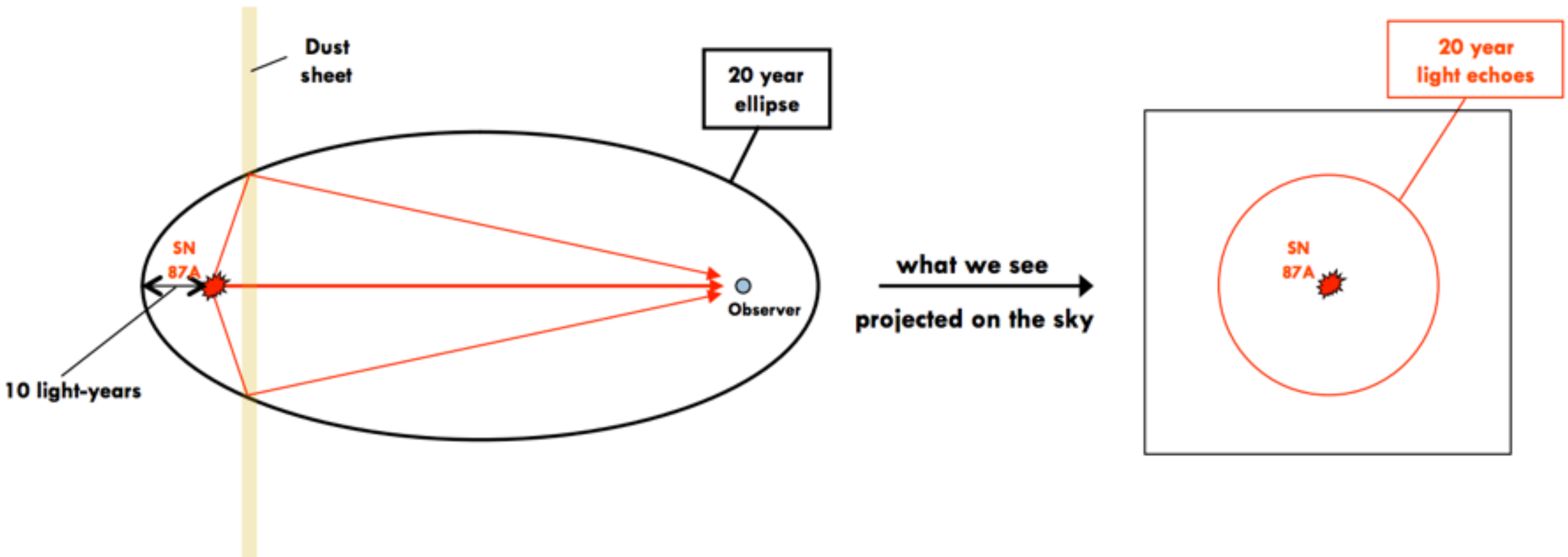
Orlando+15



Measuring light echo from past SN

Movie

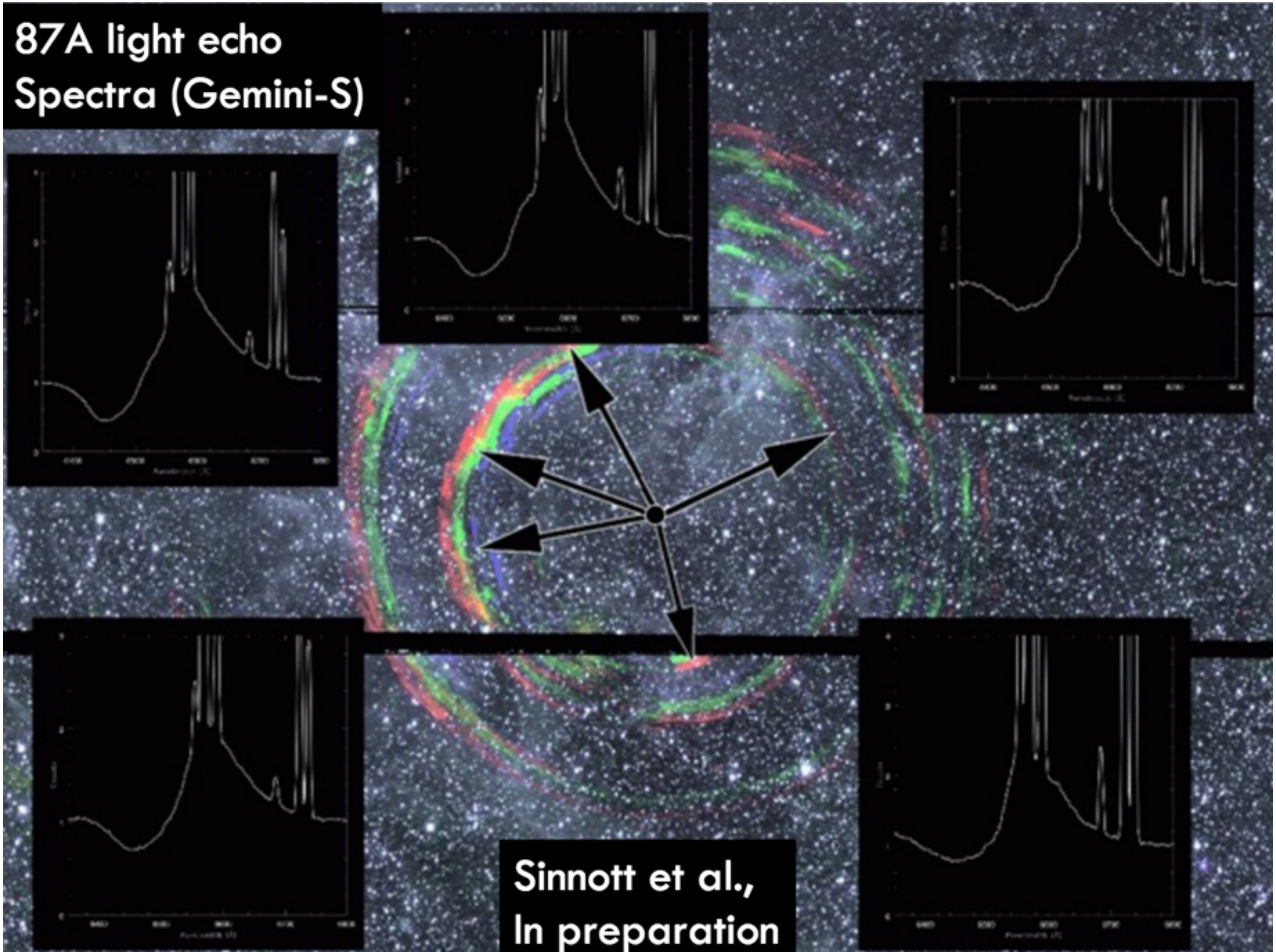
Ellipsoids trace out surfaces of constant arrival time



Extra path: 2 x 10 light years ⇨ Light echo after 20 years

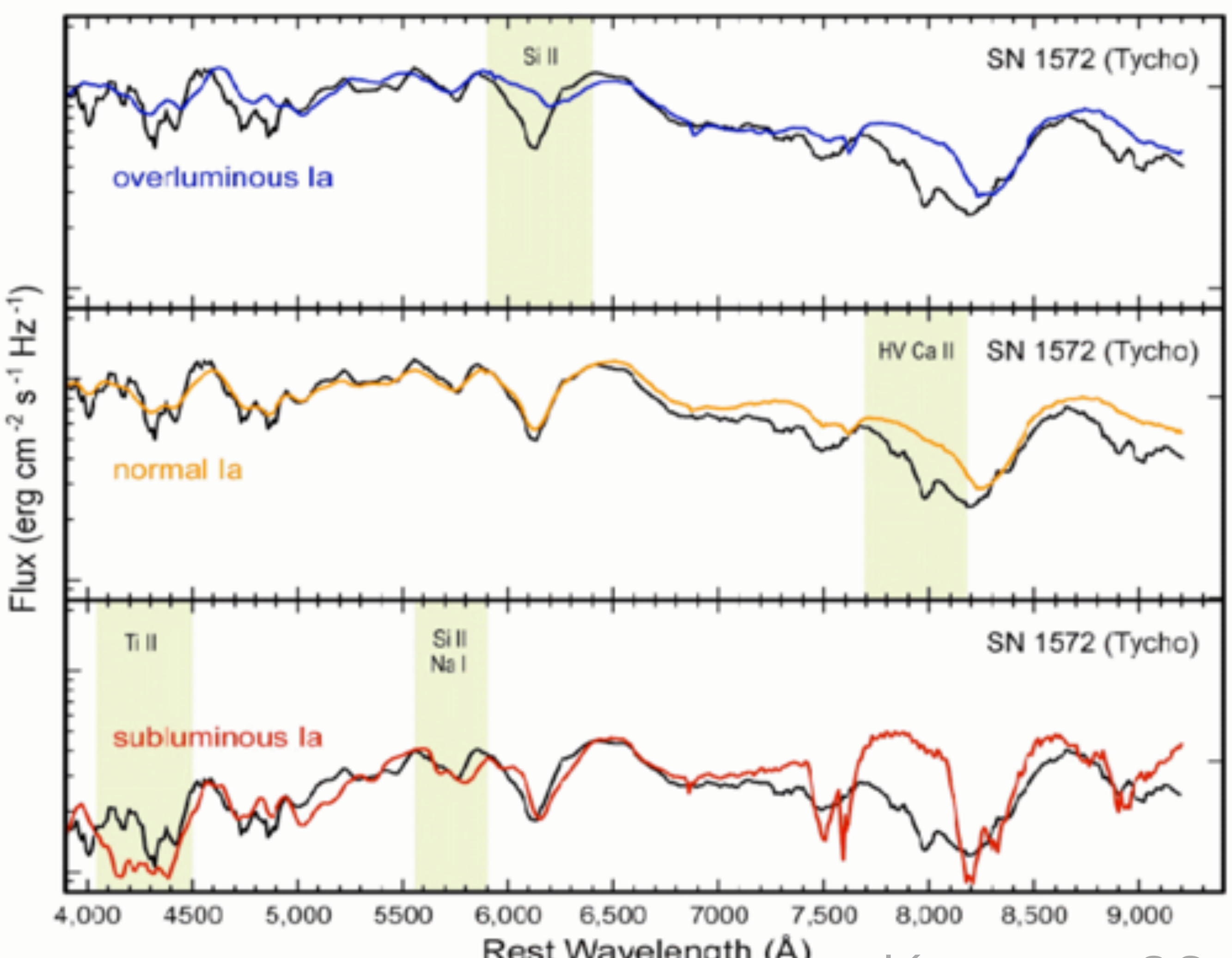
From Armin Rest:
http://cxc.harvard.edu/cdo/snr09/pres/Rest_Armin.pdf

Light echoes from 87a



Tycho & SN 1572

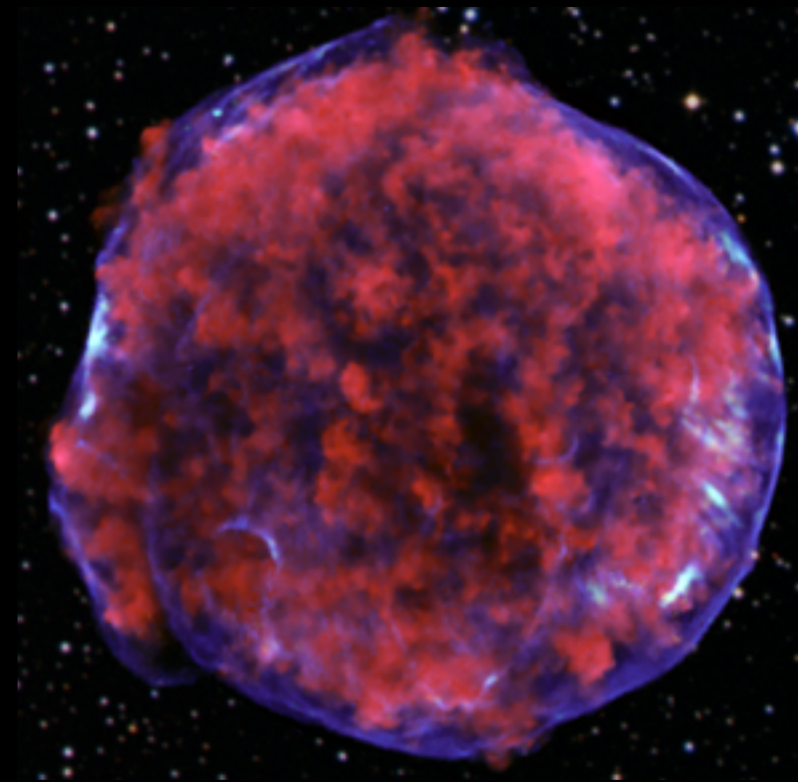
Don't worry Tycho, we've got you covered !

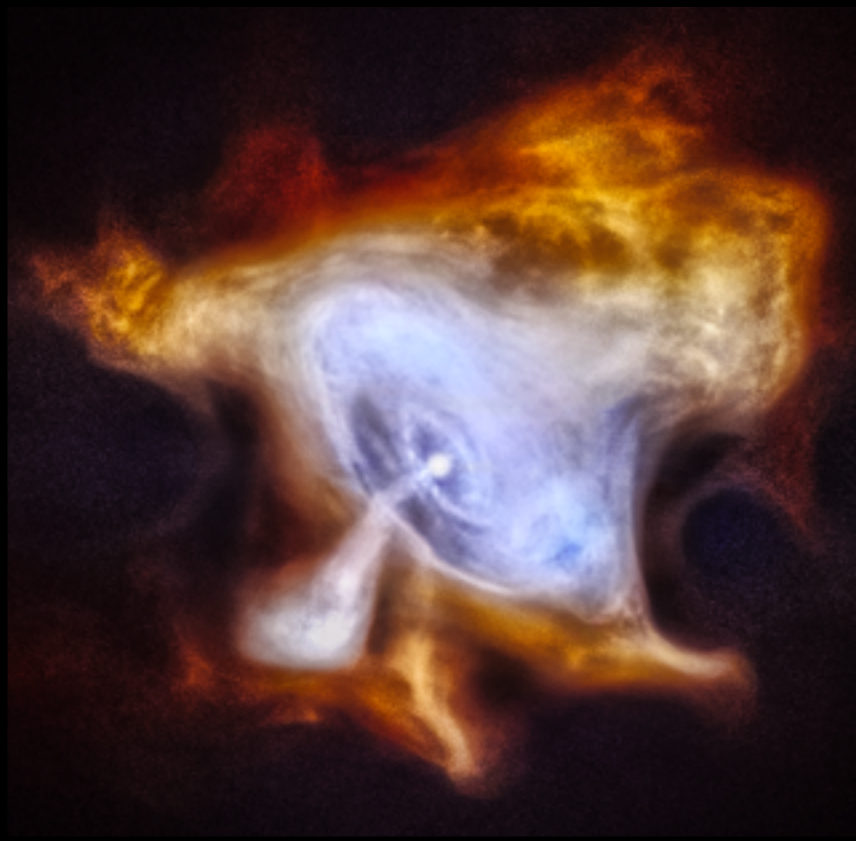


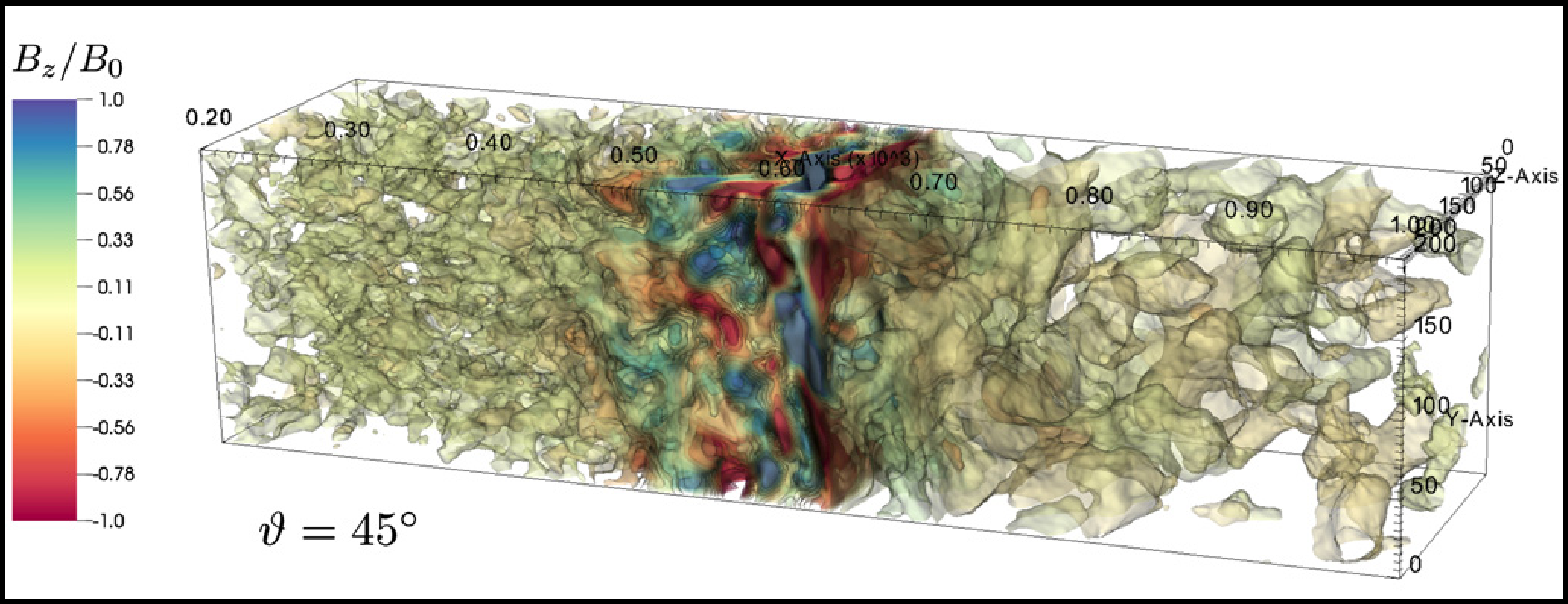
Krause+08

Tycho & SN 1572

Particle acceleration at SNR shocks

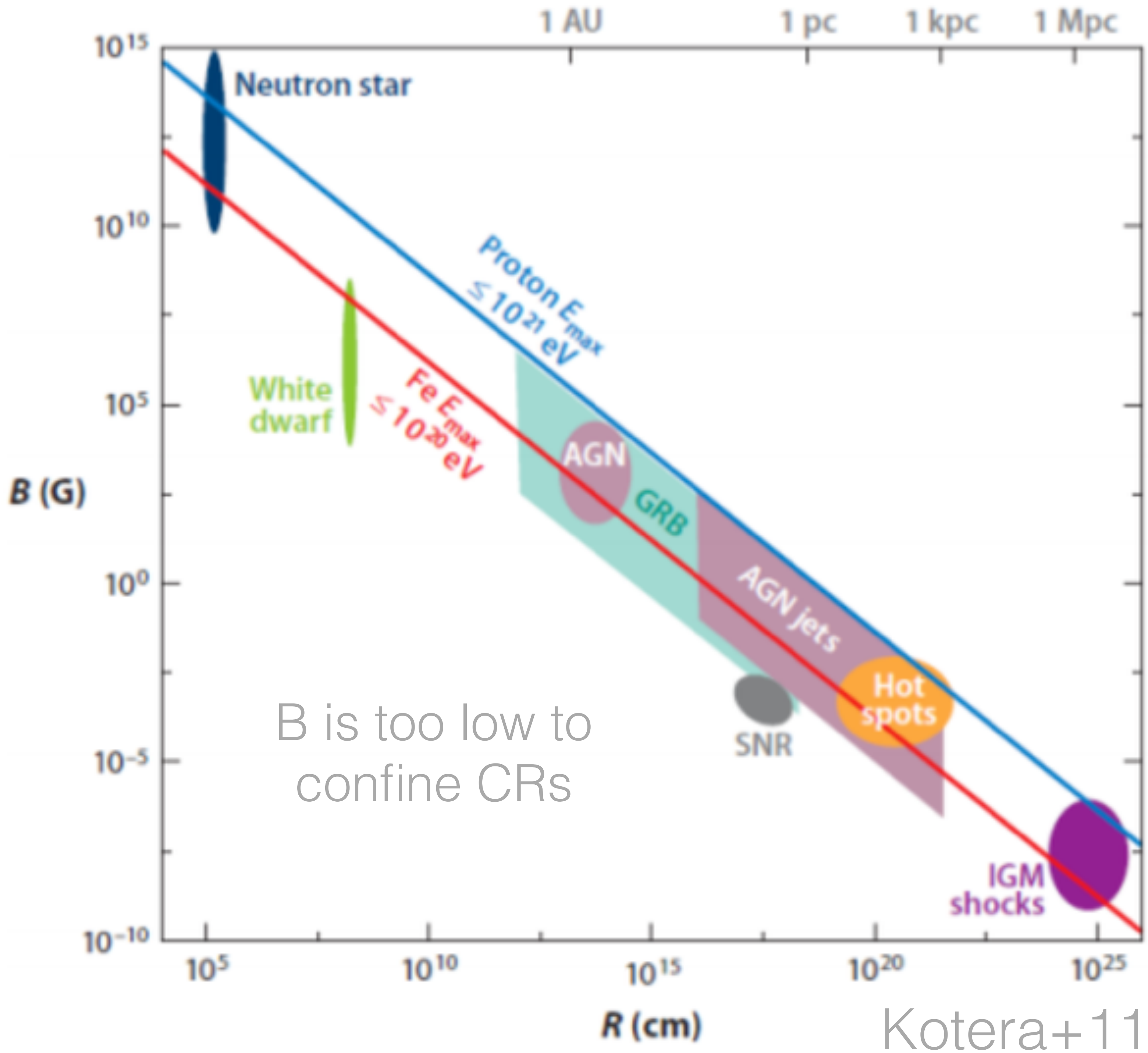






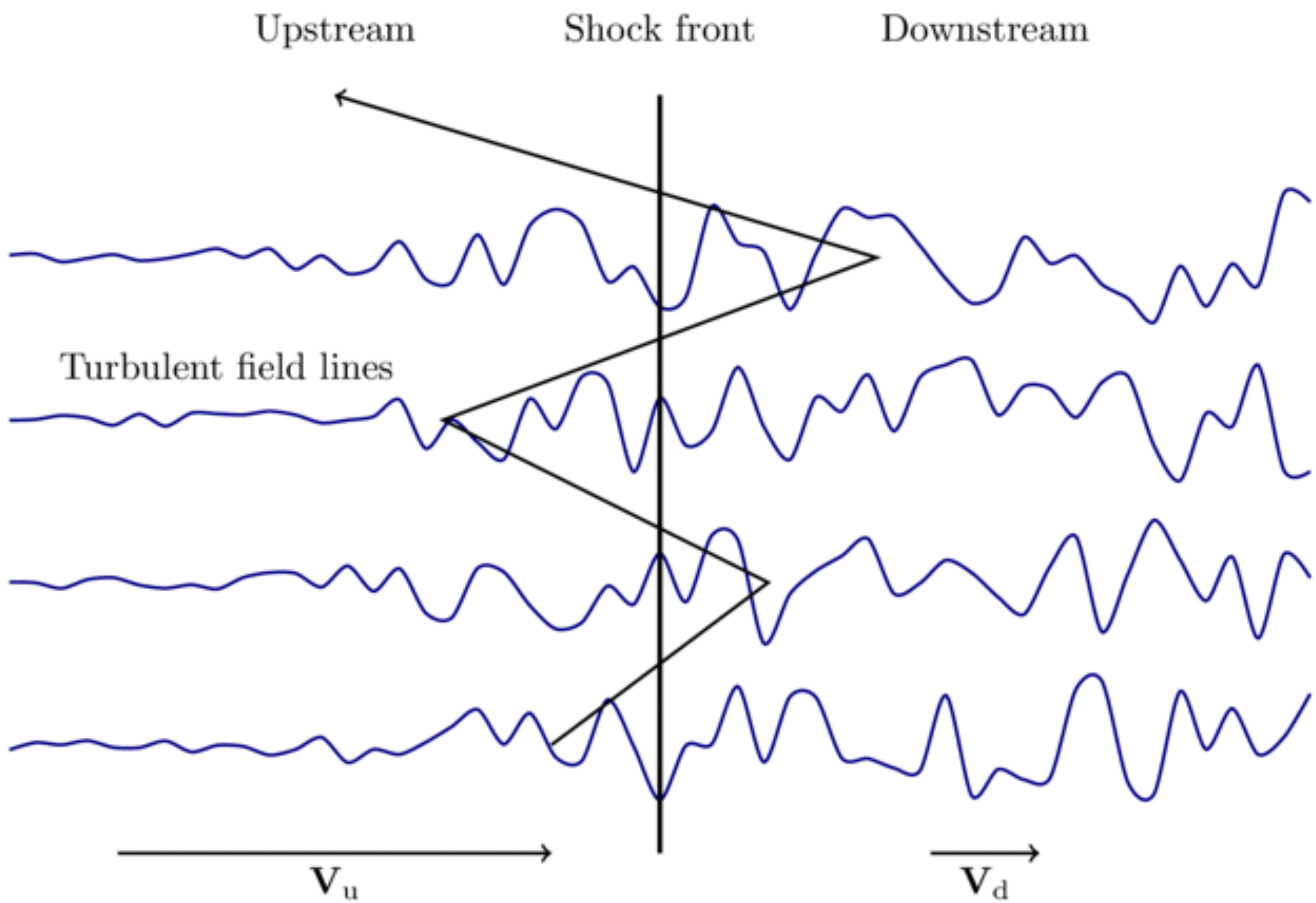
Where can we accelerate Cosmic Rays

- **Need to be able to confine high-energy particles.**
  - **Hillas plot: Radius vs B-field**



Kotera+11

Shock acceleration



$V_{down}=1/4V_{up}$

- **Acceleration by Fermi 1st order acceleration aka diffusive shock acceleration (DSA)**
- **Particles repeatedly scatter back/forth across shock and get a kick at each crossing :** $\frac{\Delta E}{E} \sim \frac{\Delta V_{\rm sh}}{c} = \frac{4}{3}\frac{r-1}{r}\frac{V_{\rm sh}}{c}$ **and** $E^{-\frac{r+2}{r-1}}$

Shock acceleration

- **At each crossing:**

$$\frac{\Delta E}{E} \sim \frac{\Delta V_{\rm sh}}{c} = \frac{4}{3}\frac{r-1}{r}\frac{V_{\rm sh}}{c}$$

- **At each step, particles can be advected downstream or scatter upstream. Naturally produces a powerless distribution:**

$$E^{-\frac{r+2}{r-1}}$$

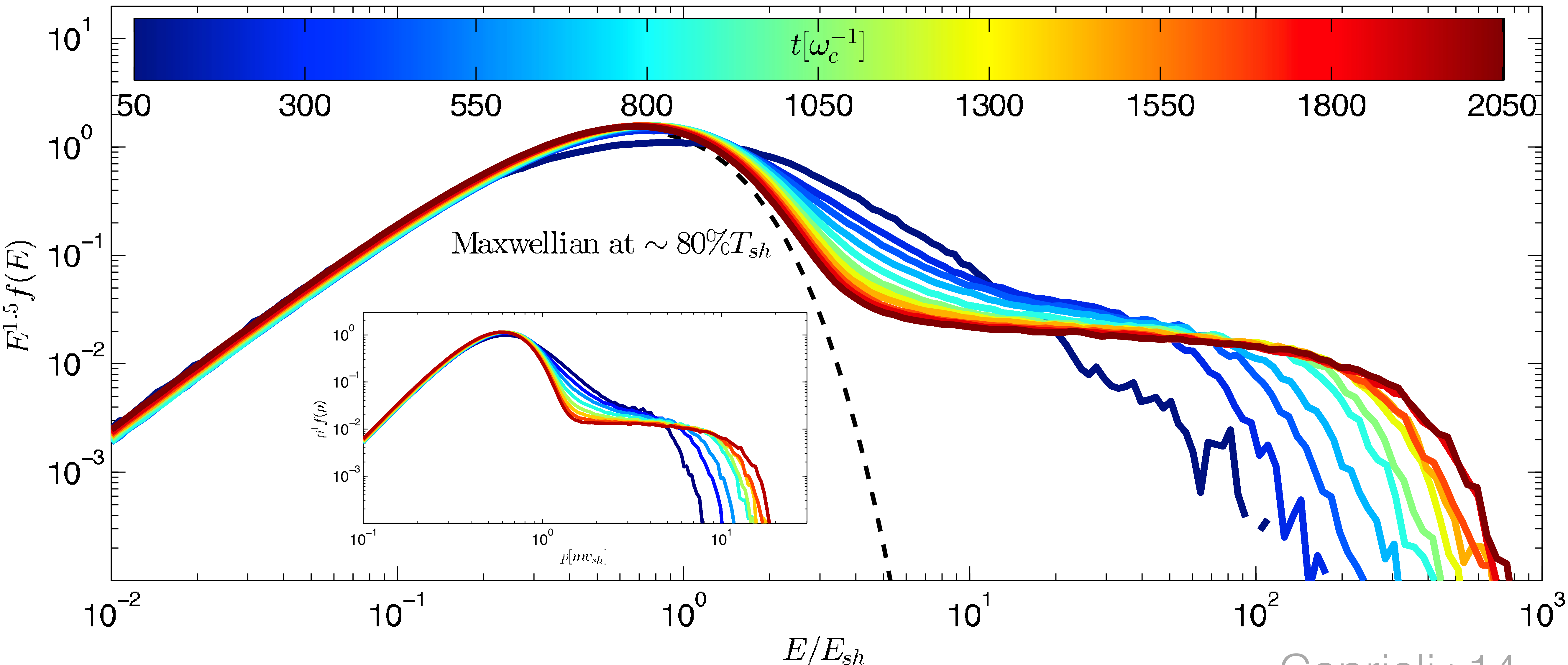
- **To reach high energy, need to confine particle**

$$E_{\rm max} = Z \cdot 10^{14}\,{\rm eV}\left(\frac{B}{10\,\mu{\rm G}}\right)\left(\frac{R_{\rm sh}}{3\,{\rm pc}}\right)\left(\frac{u_{\rm sh}}{3000\,{\rm km\,s^{-1}}}\right)$$

- **Open questions: how to get started ?**
  - **Injection**
  - **Create turbulence to scatter particles**

Acceleration at shock

Particle in cell simulations

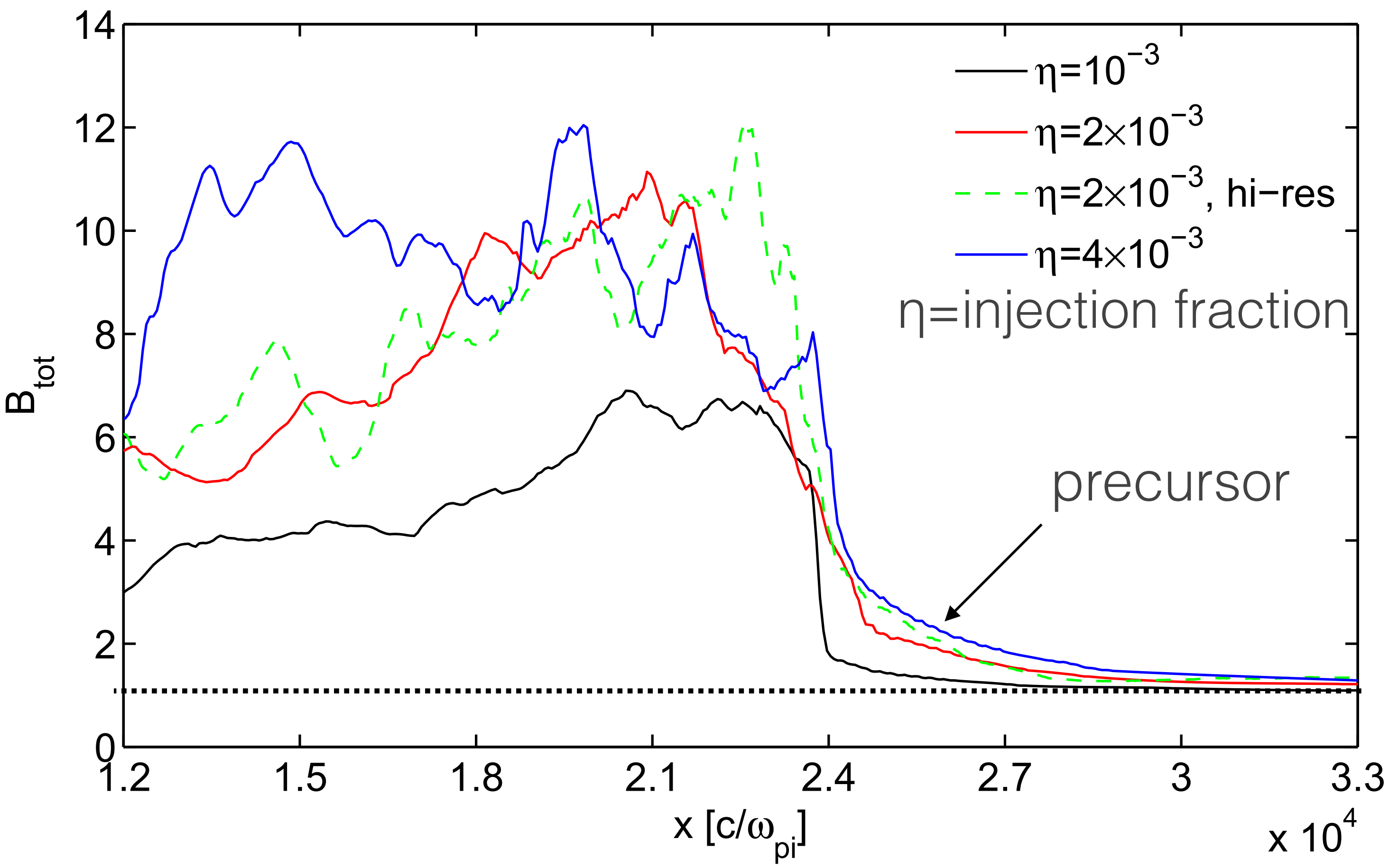


Caprioli+14

Movie

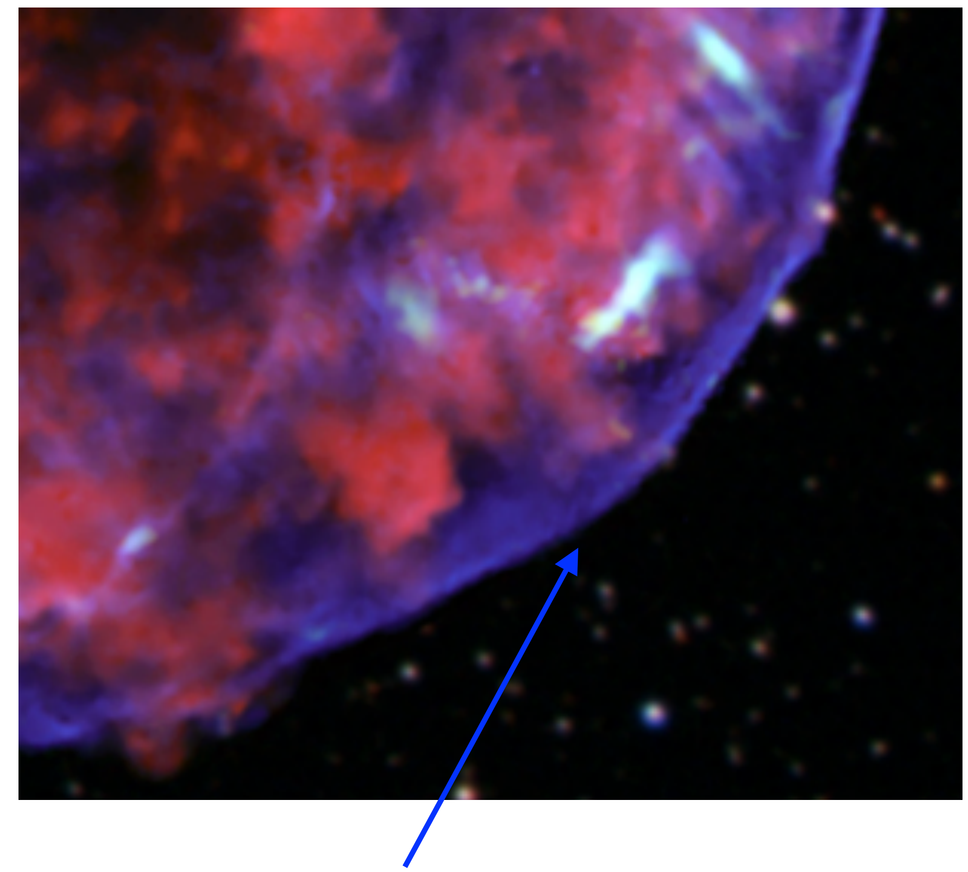
Magnetic field amplification

PIC simulation + MHD



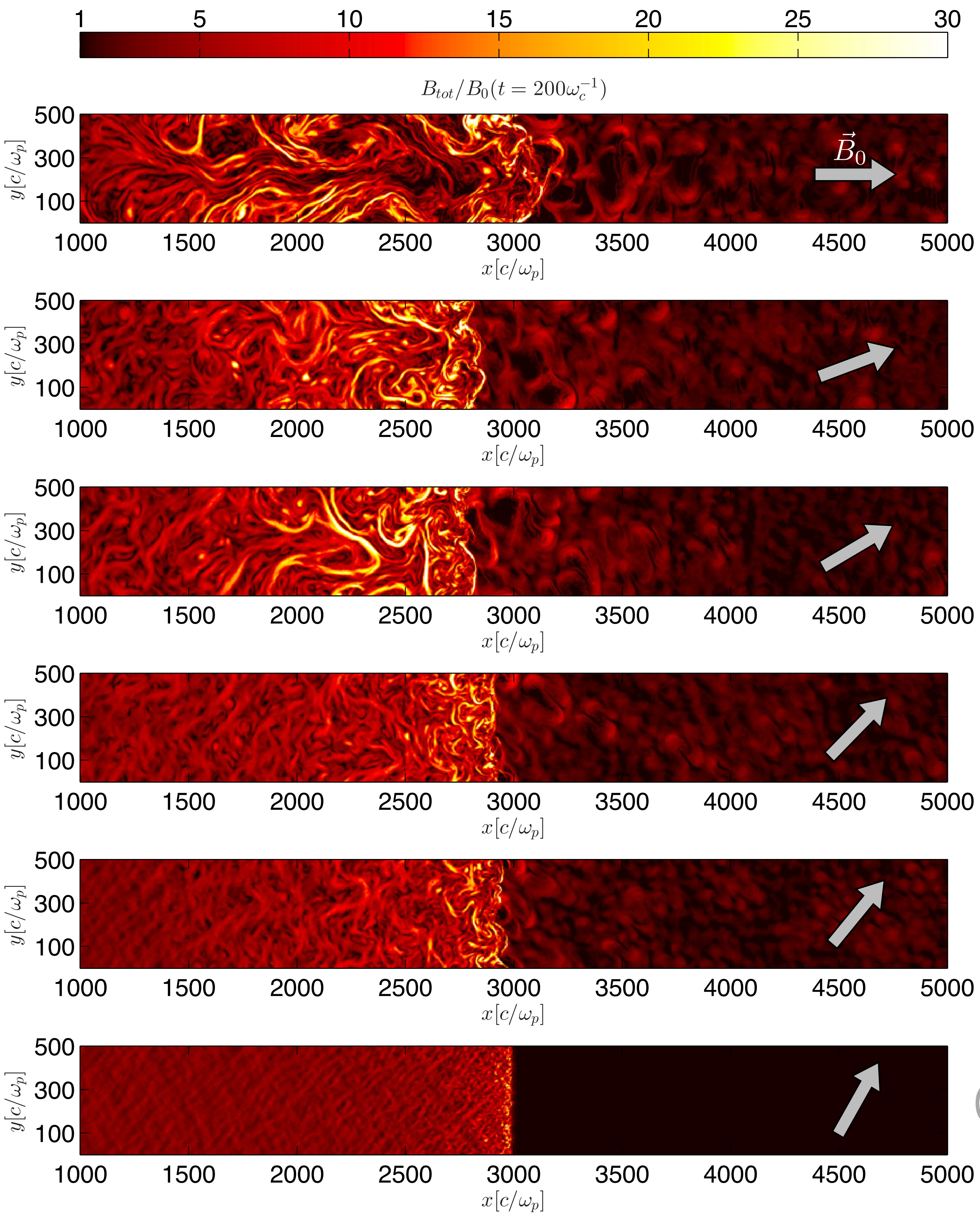
Bai+15

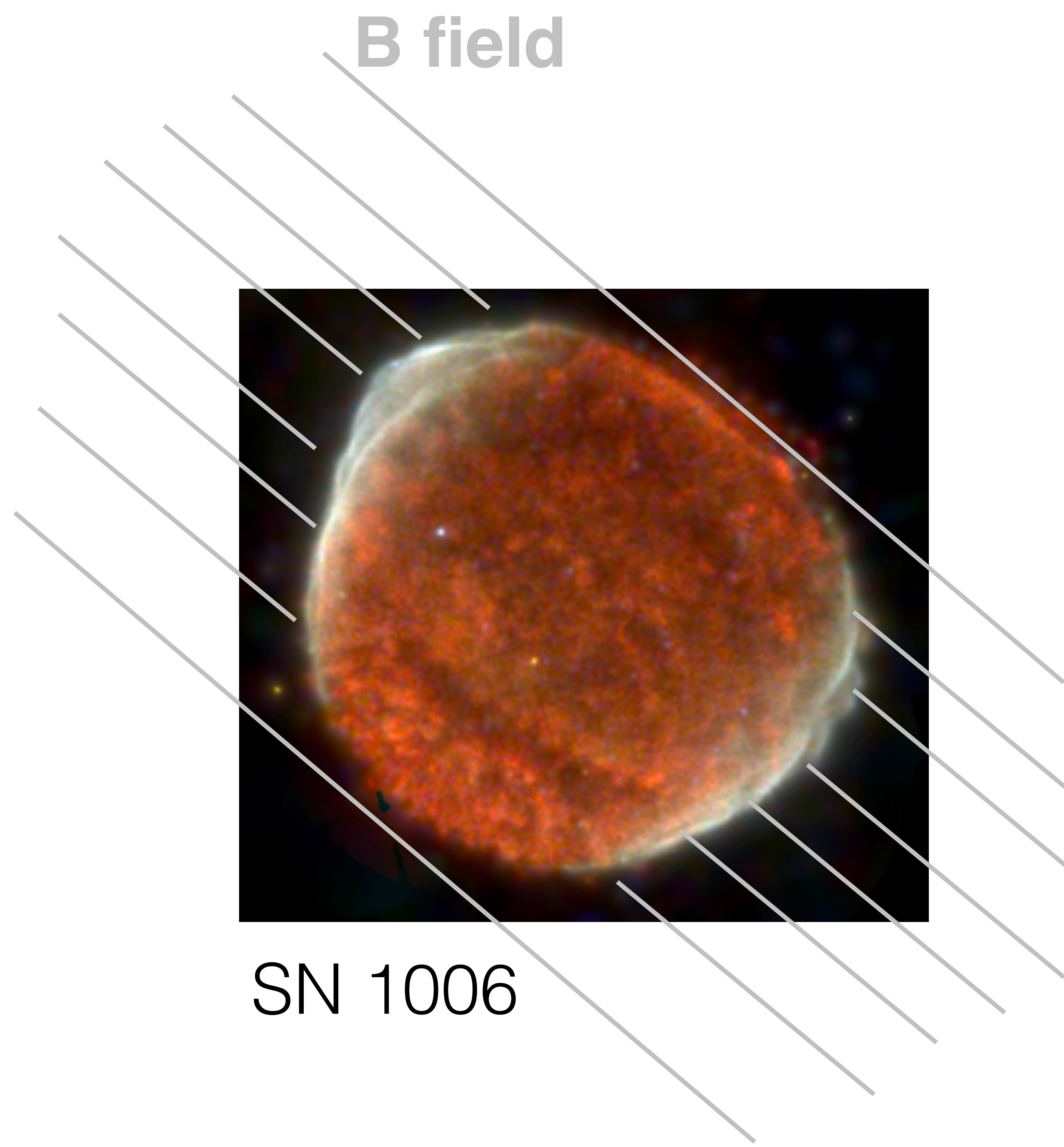
Tycho SNR



Very thin synchrotron filaments

Acceleration efficiency - Injection

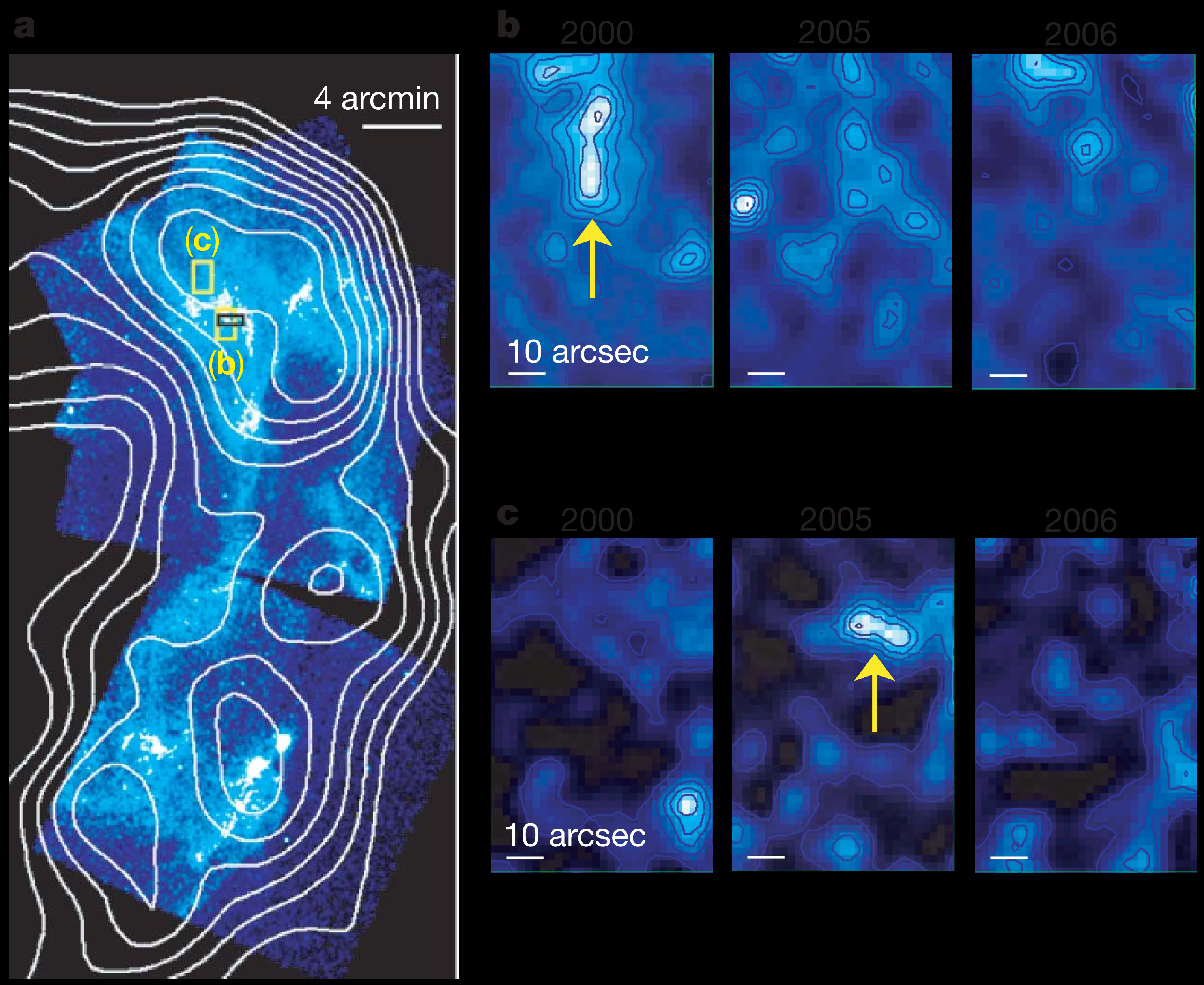




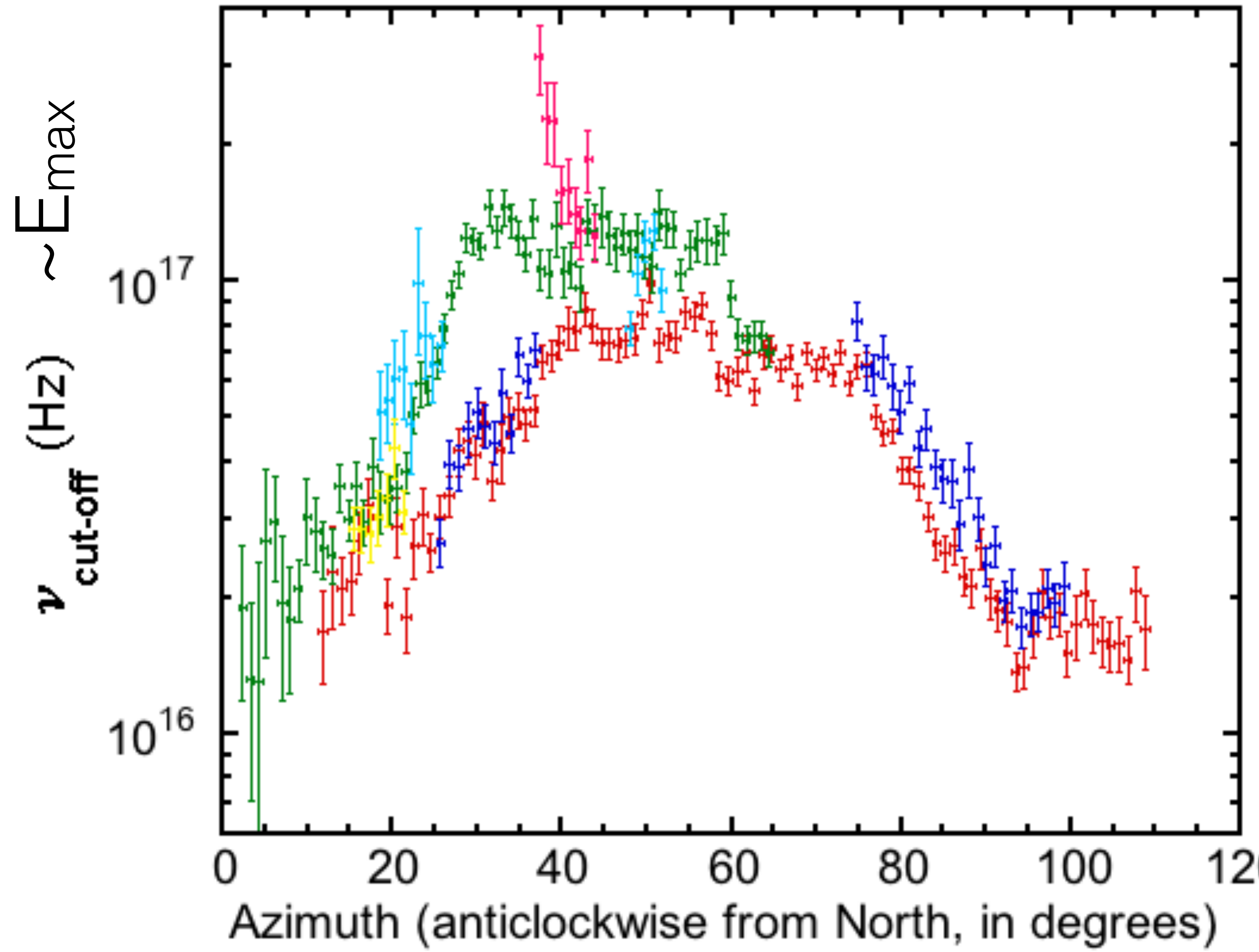
SN 1006

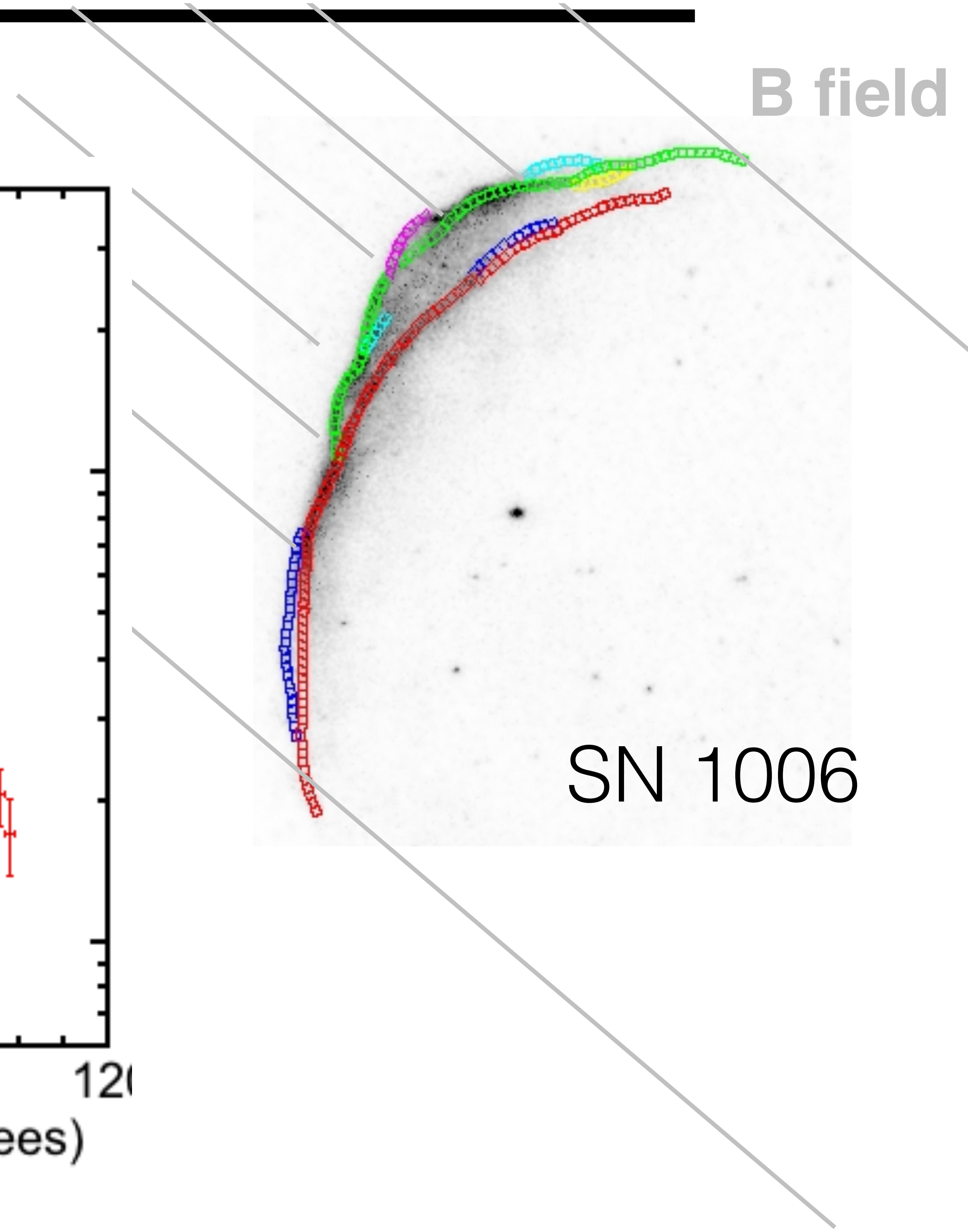
Caprioli+14a

What can we learn from non-thermal Xrays (synchrotron)

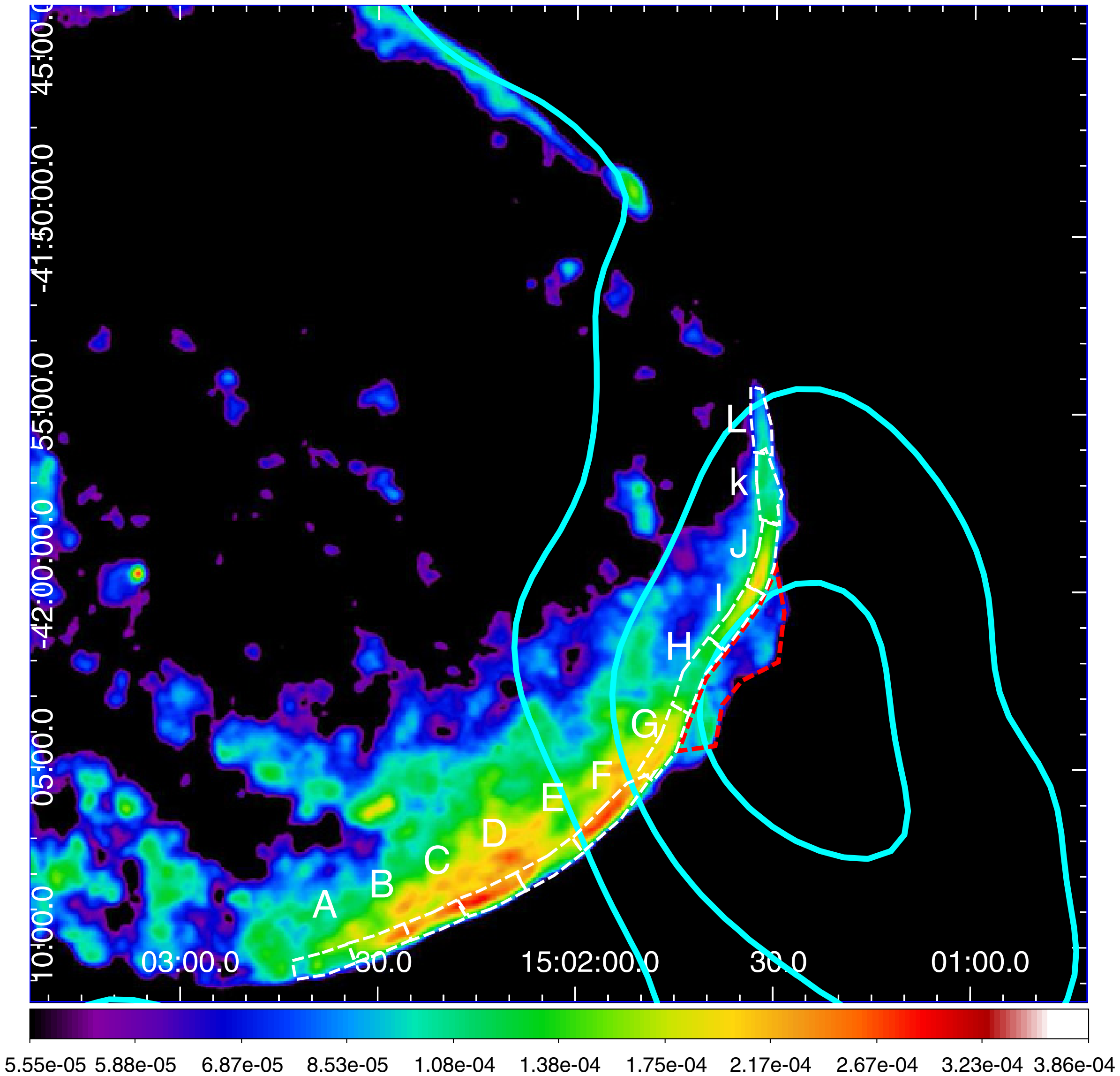


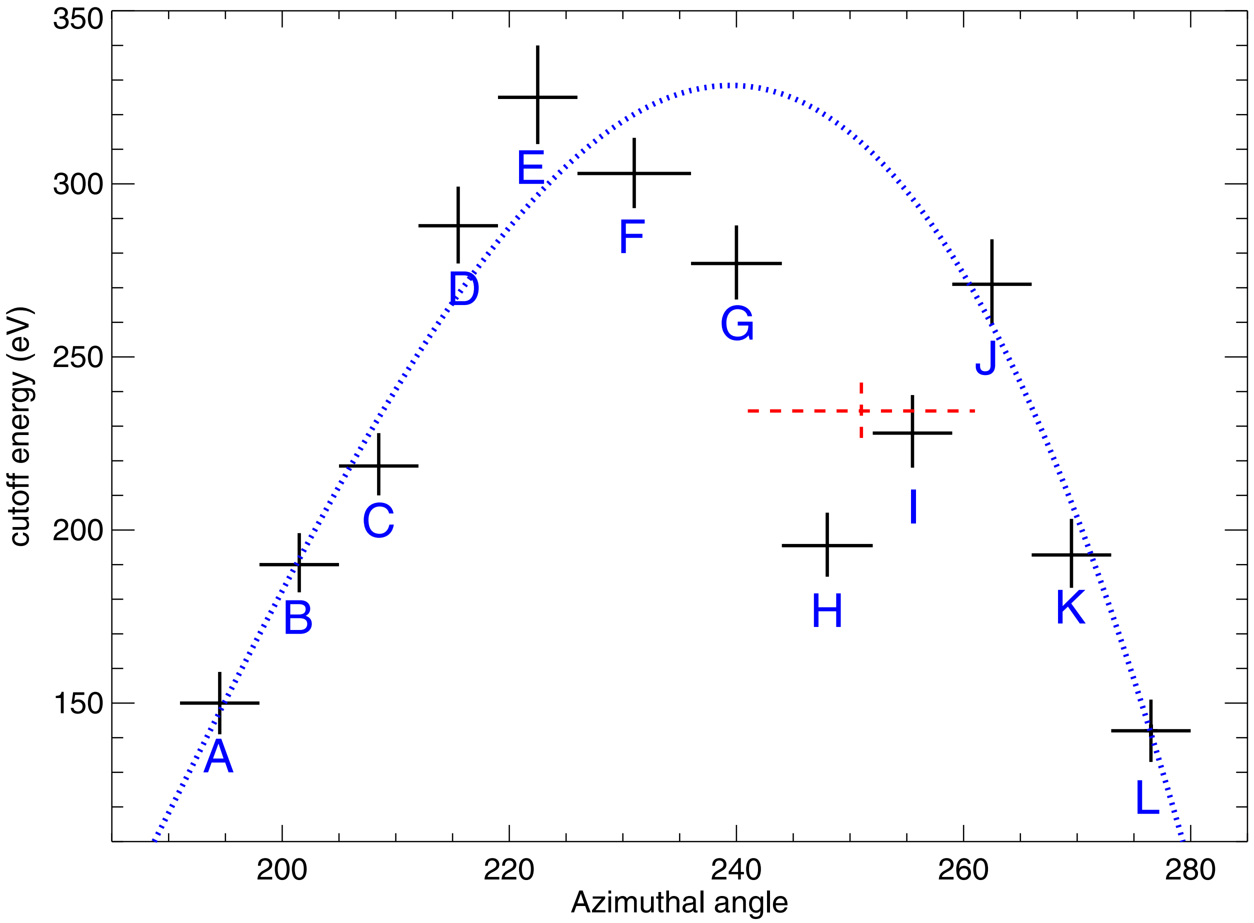
Acceleration efficiency: E_{max} vs B field





Acceleration efficiency: E_{max} vs V_{shock}





Miceli+Acero+14

- **Interaction with a small cloud**
- **Cutoff frequency decreases at interaction point**
- **Consistent with v_{cut} α V_{sh}^2 α 1/ρ in cooling-limited regime**

X-ray thin synchrotron filaments

Thin filaments due to synchrotron loss limited:

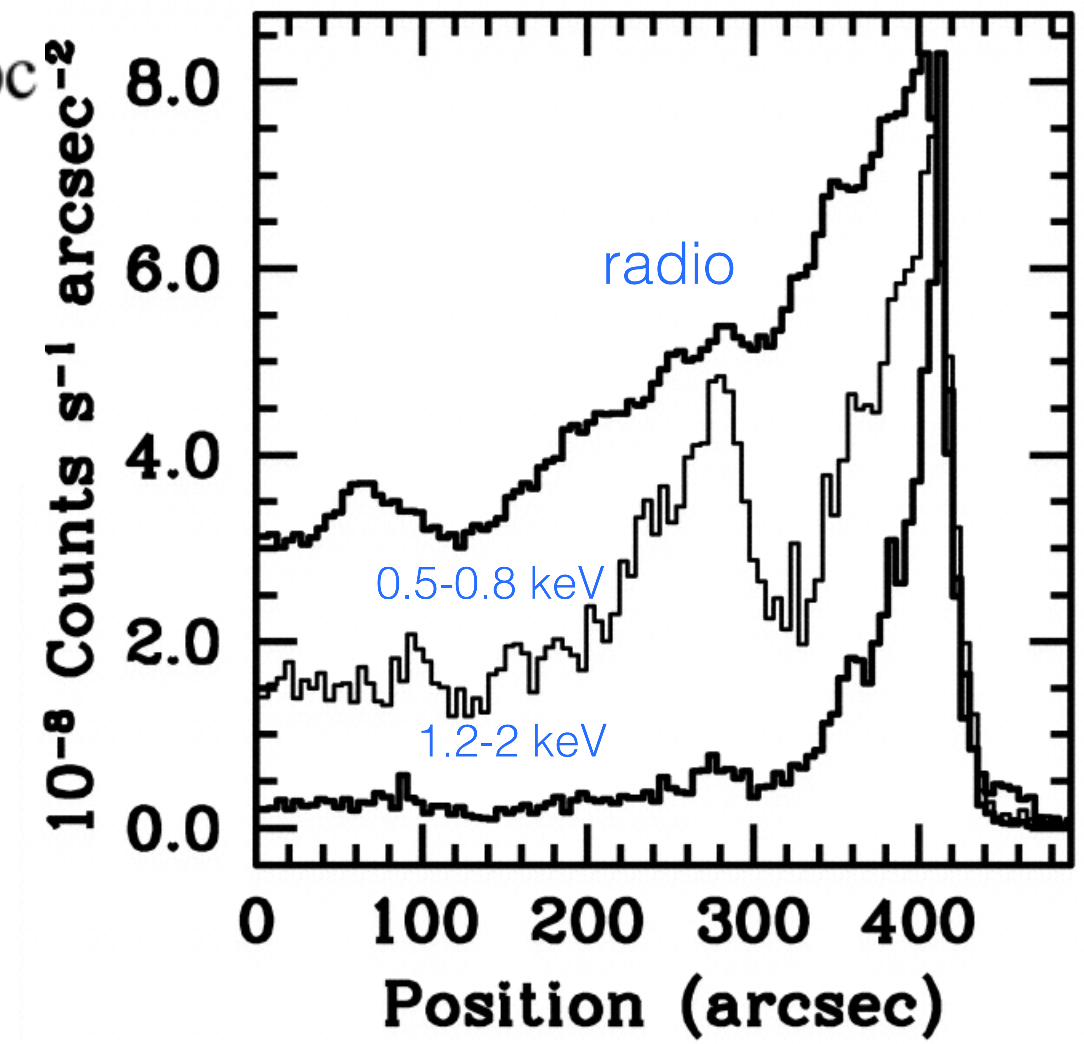
- Advection (Vink+03; Bamba+03) depends on the shock speed and the compression ratio
- Diffusion (Berezhko+03, Yamazaki+04) assuming Bohm limit

$$t_{\rm cool} = (57\,{\rm yrs}) \times B_{100}^{-3/2}\,E_{\rm ph,keV}^{-1/2}$$

$$l_{\rm adv} = t_{\rm cool} V_{\rm sh} / r = 1.8 \times 10^{-3}\, B_{\rm mG}^{-3/2}\, \nu_{\rm keV}^{-1/2}\, V_{1000} / r \quad {\rm pc}$$

$$l_{\rm dif} = \sqrt{\kappa_{\rm d} t_{\rm cool}} = 1.2 \times 10^{-3} B_{\rm mG}^{-3/2}\,{\rm pc}$$

$$l_{\rm adv} / l_{\rm dif} = 1.5\, \nu_{\rm keV}^{-1/2}\, V_{1000} / r$$



Filaments limited by B-field damping behind the shock

X-ray thin synchrotron filaments

- **Width of filaments can provide info about B-field**

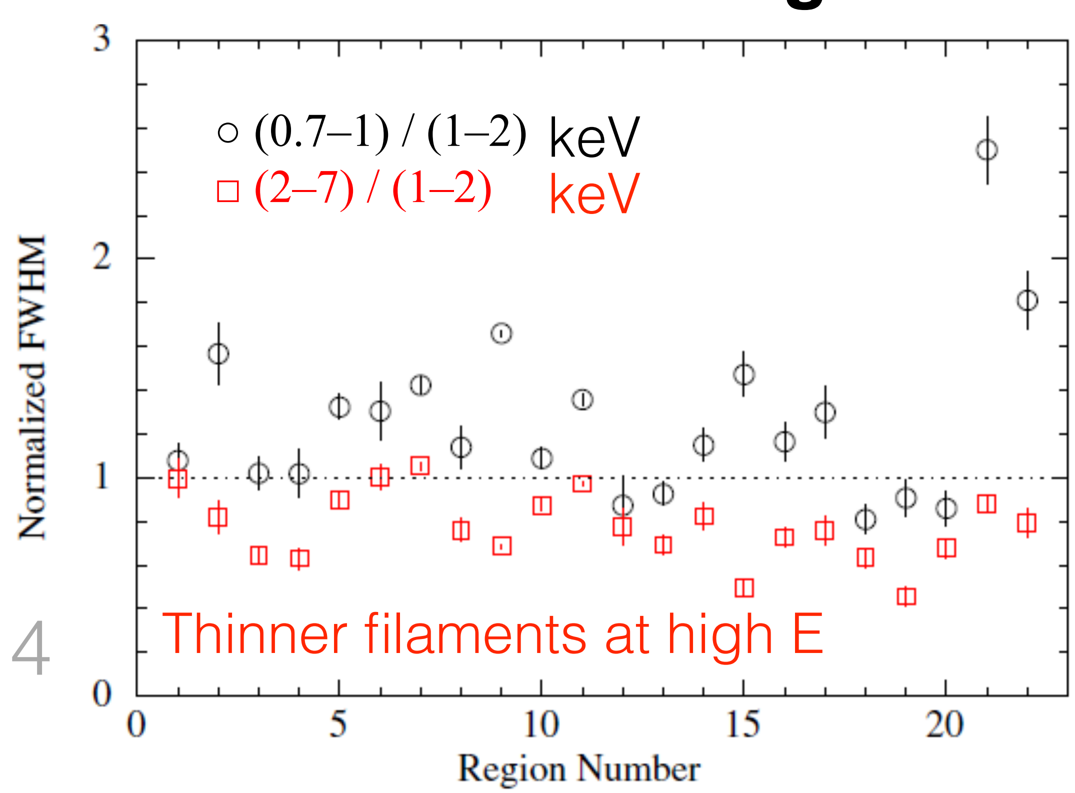
SNR name	$\tau_{\rm syn}^{\rm max}/t_{\rm SNR}$ $(\times 4\bar{P}/r)$	$B_{\rm adv}$ (μG)	$B_{\rm diff}$ (μG)
Cas A	<2.6%	210	230
Kepler	<2.8%	170	180
Tycho	<2.1%	200	230
SN 1006	<5.9%	57	90
G347.3−0.5	<3.3%	61	77

Parizot+06

Strong B-field amplification

- **Energy dependence of width disentangle loss/damping limited**

Ressler+14



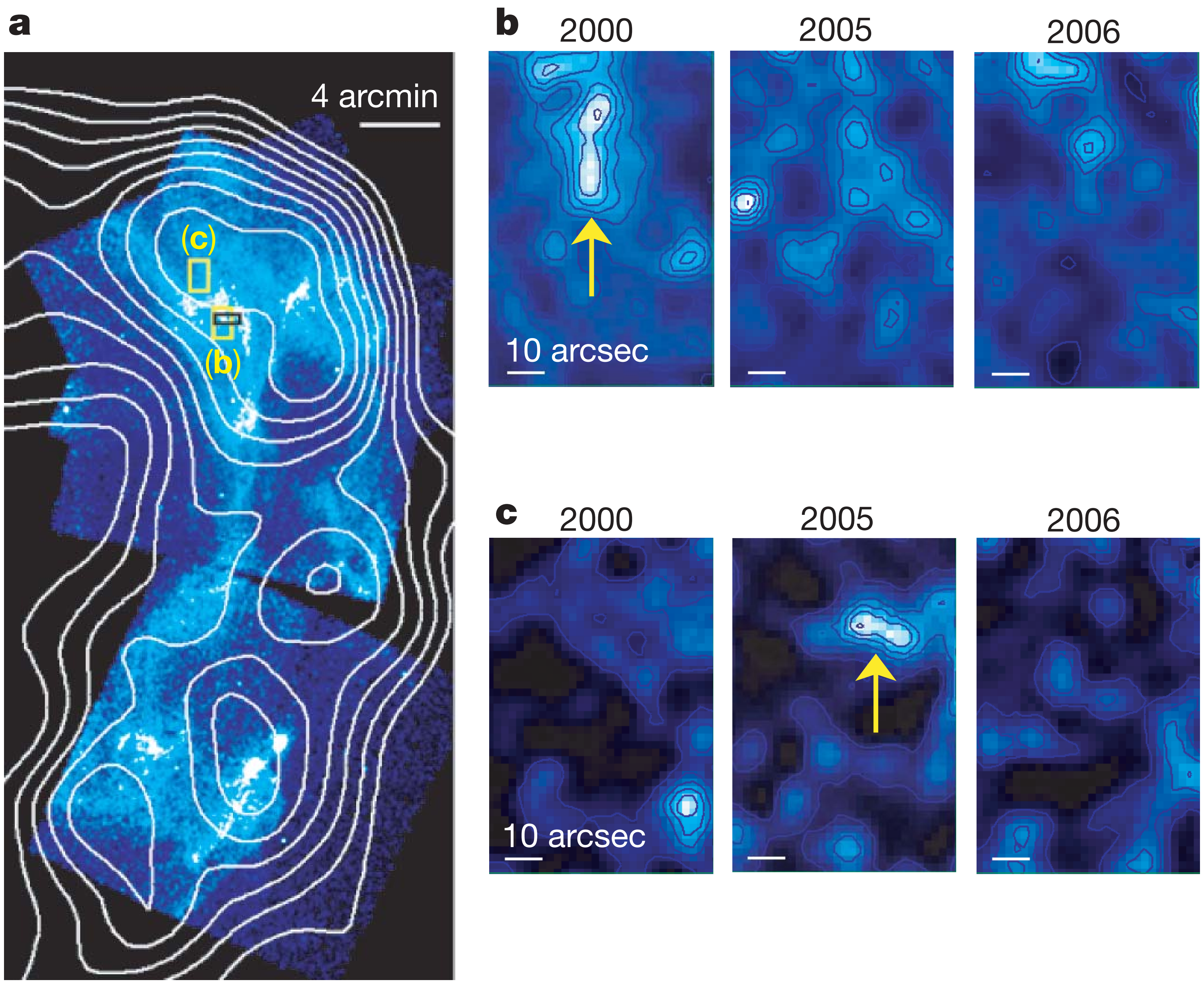
In SN1006:

filaments are thinner at high E rules out B-field damping

Diffusion : $D \propto E^{\mu}$

with μ > 1 (not Kolmogorov)

Turbulent B-field



Uchiyama+07

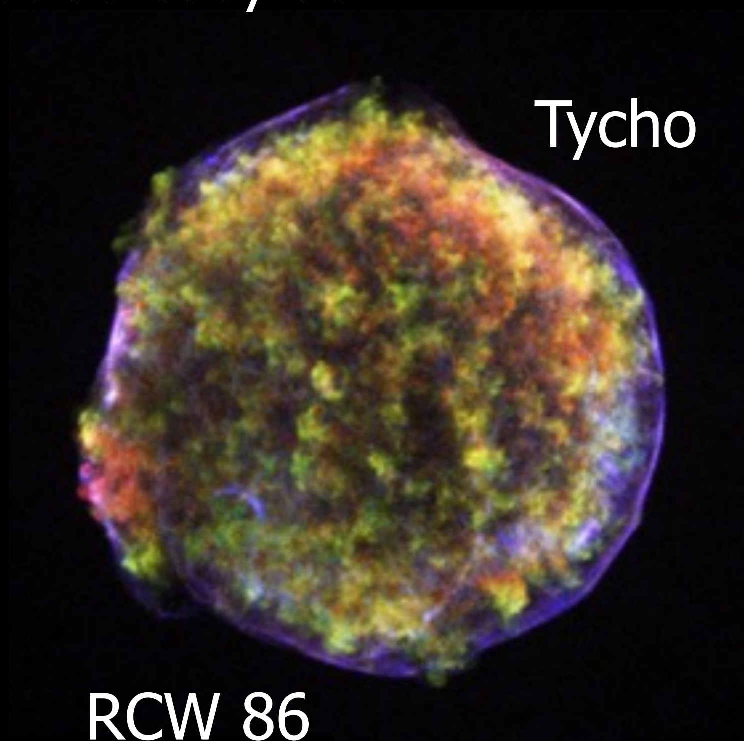
Disappearance is due to :

- High B and cooling time~yr
=> B ~ 1 mG

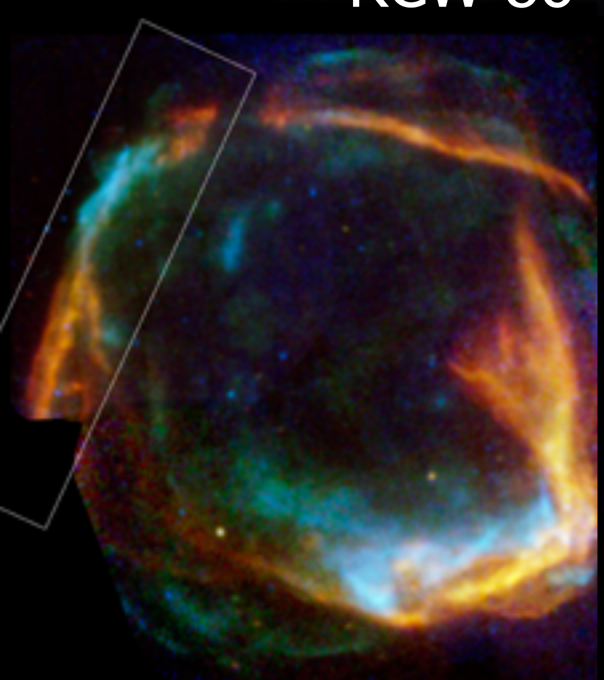
- Turbulent B-field

How to constrain V_{sh}, ambient medium: Filament proper motion

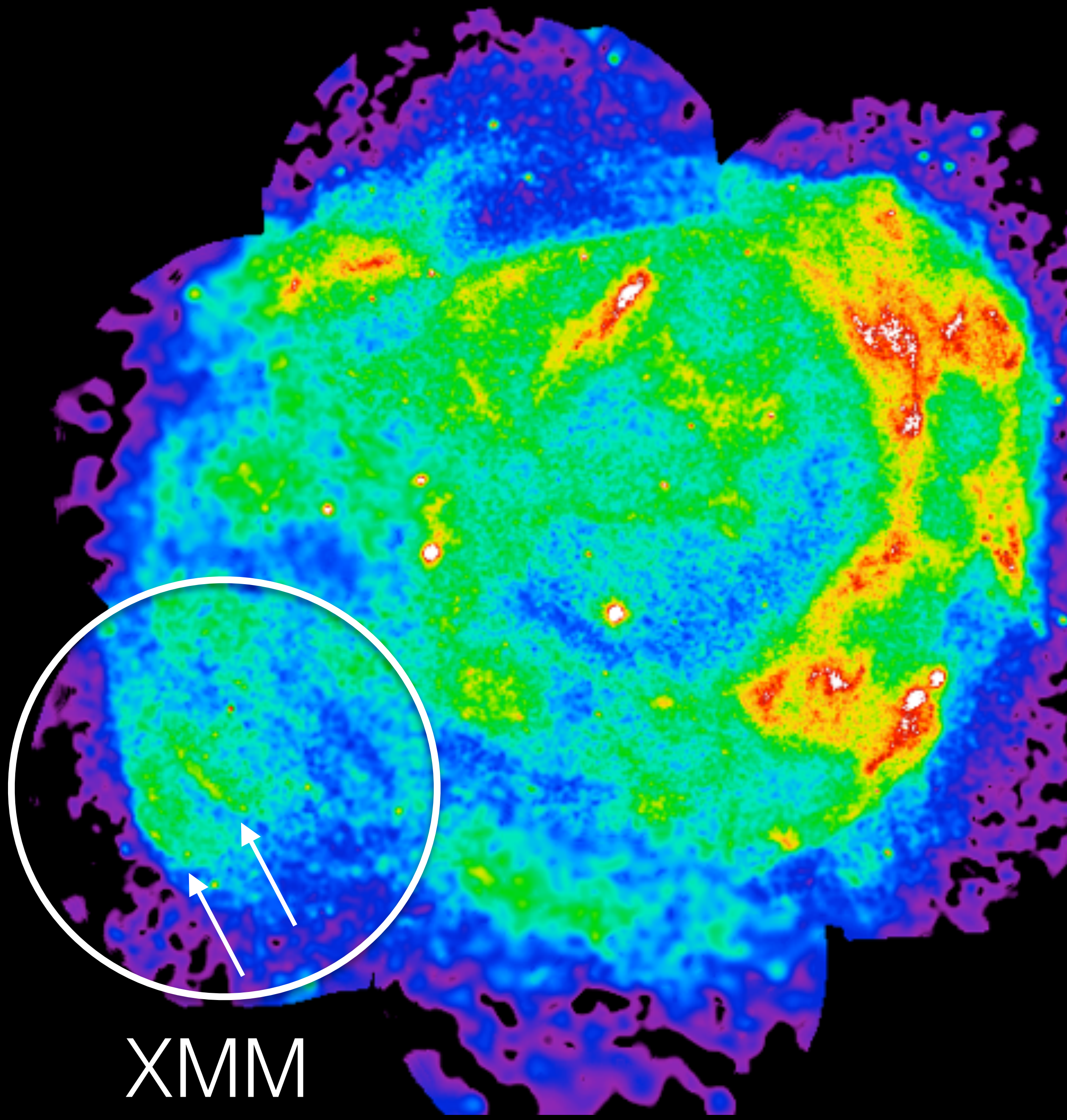
Filament structures in RXJ … ?
Not as easy as in:



RCW 86



SN 1006



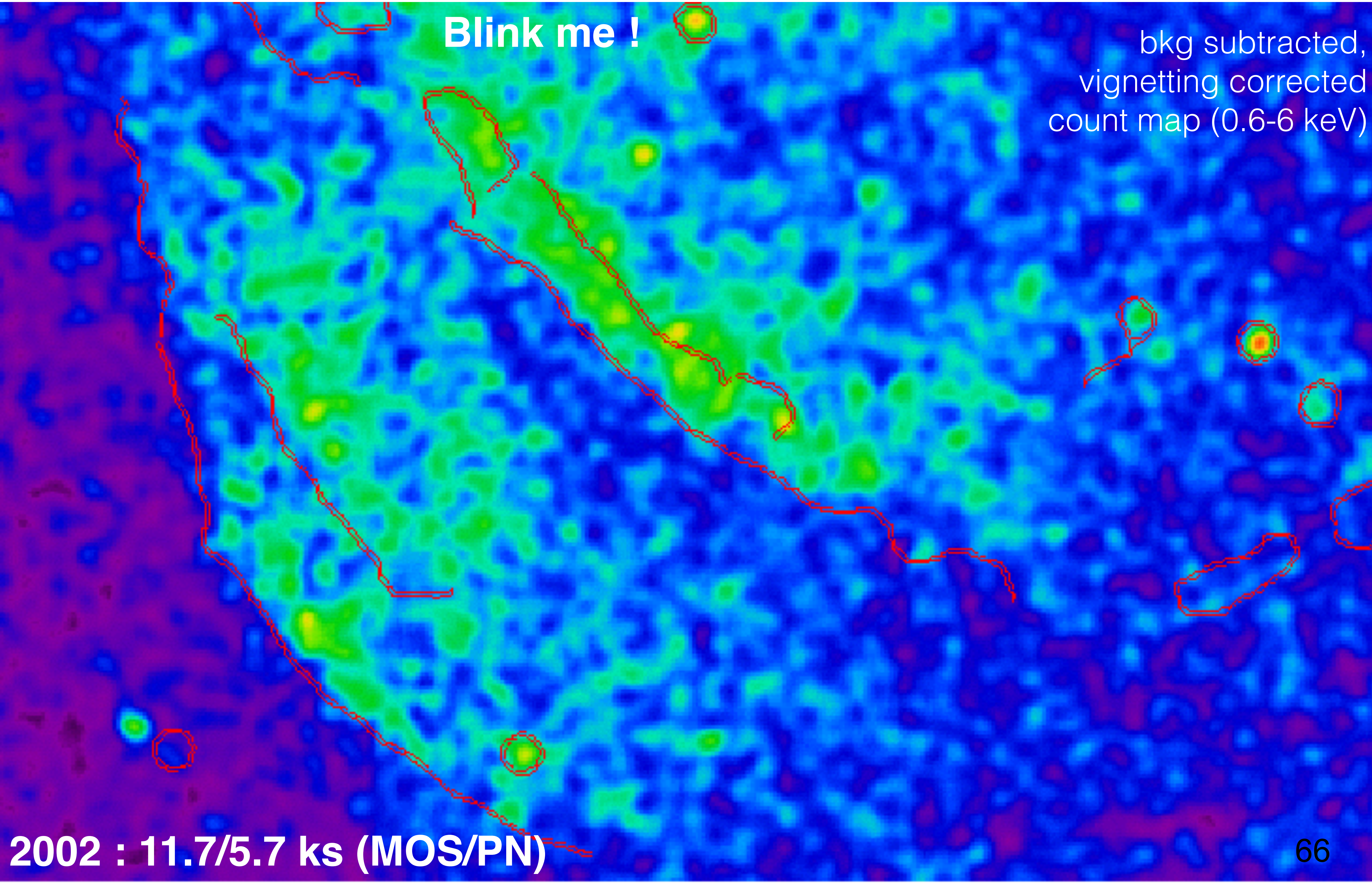
XMM

2002: 11 ks

2015: 64 ks

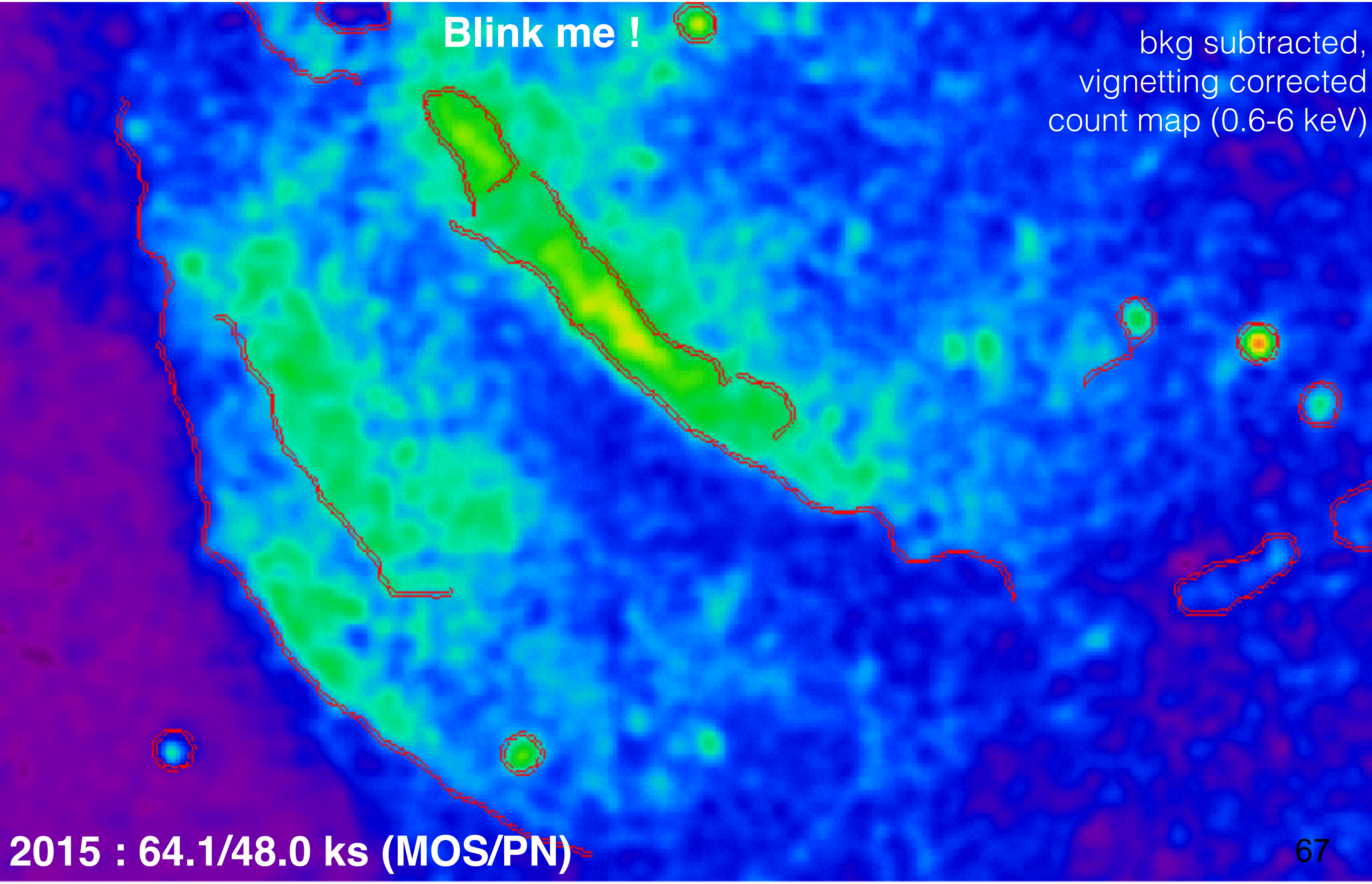
2002 image
2015 edges

X-ray proper motion in the SE

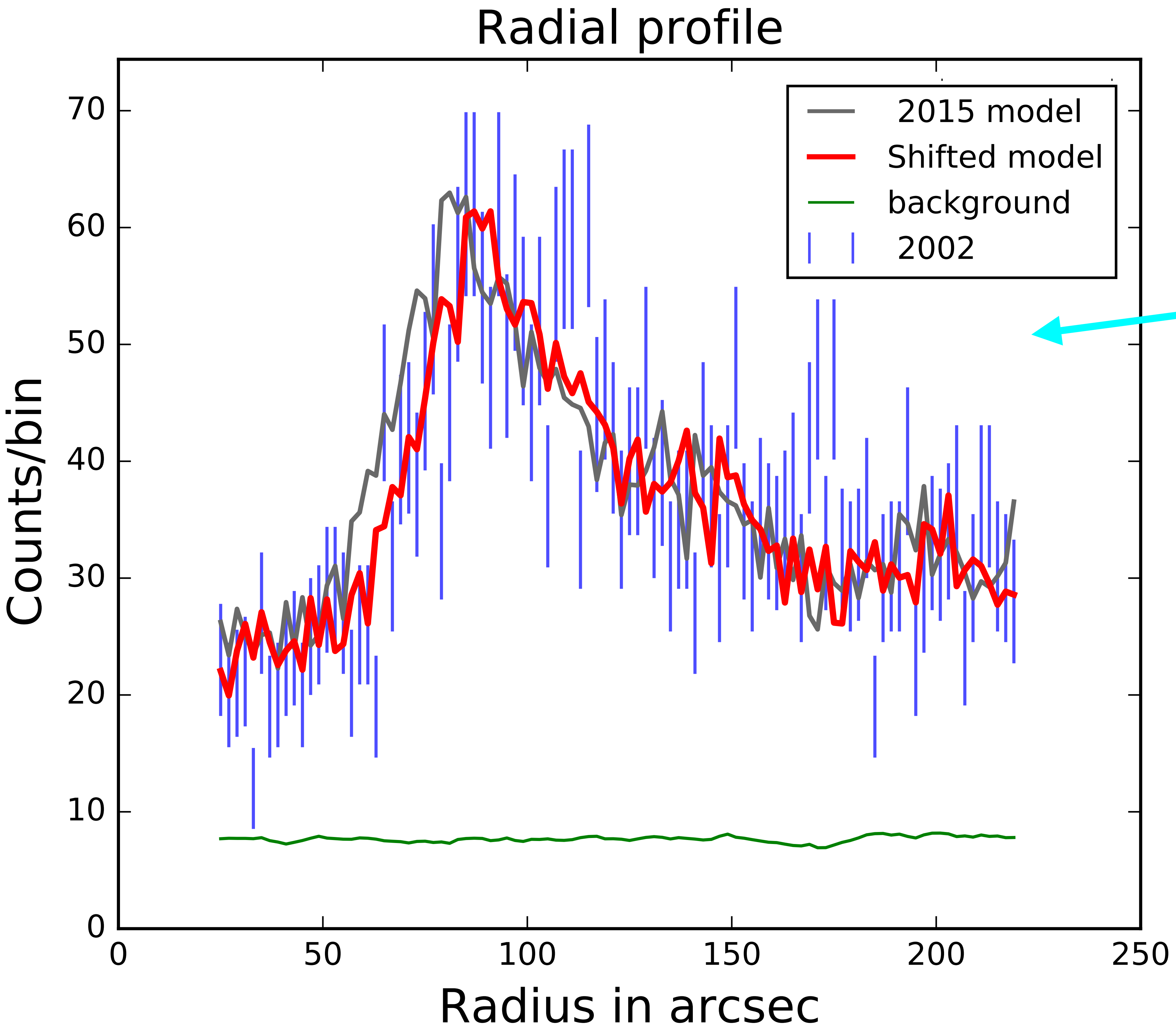


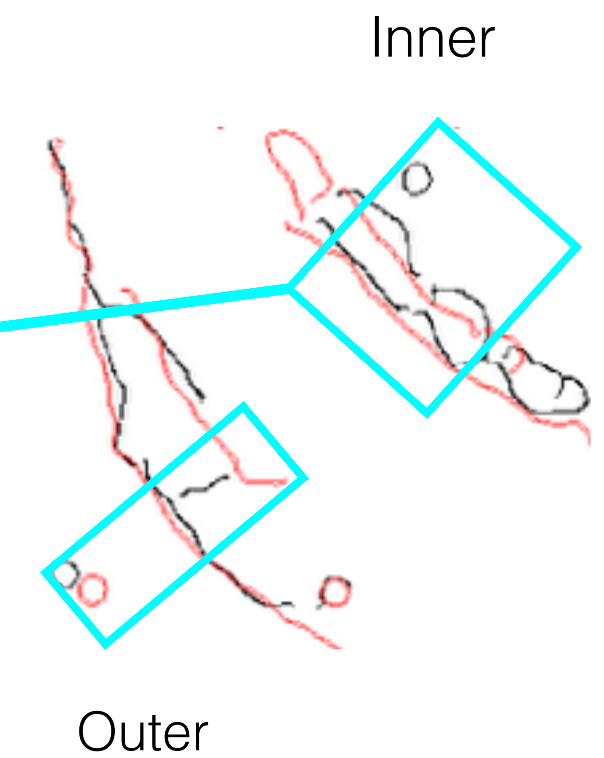
2015 image
2015 edges

X-ray proper motion in the SE

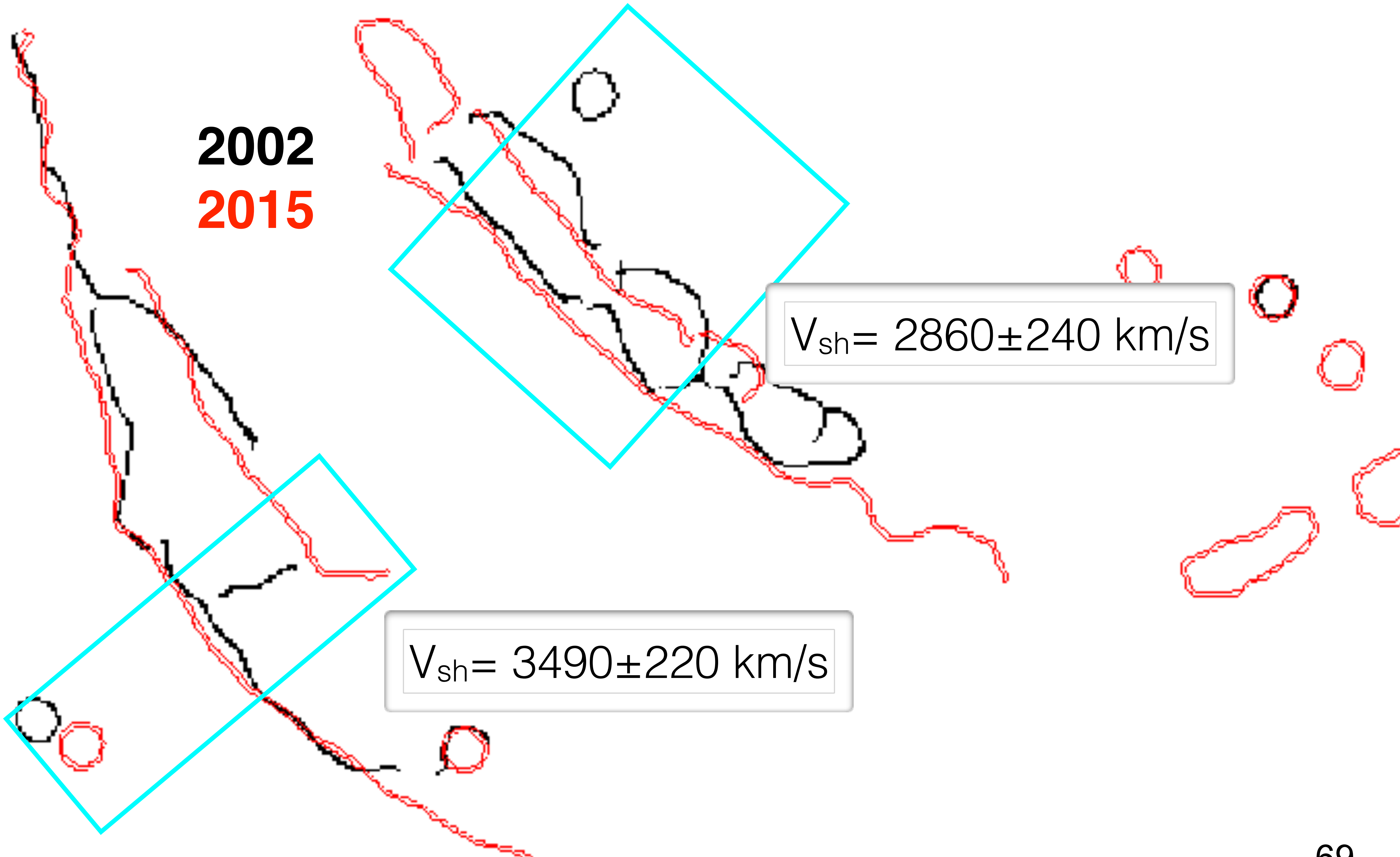


Results


Radial profile
Counts/bin
Radius in arcsec
0
10
20
30
40
50
60
70
0
50
100
150
200
250
2015 model
Shifted model
background
2002


Inner
Outer

Results



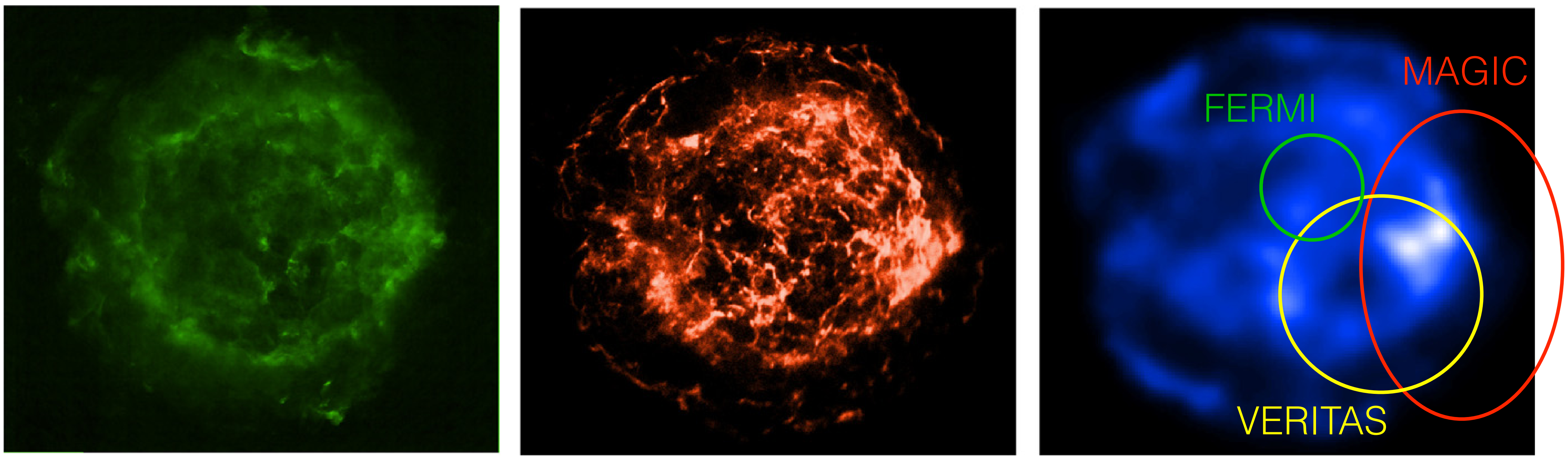
SNR age

- **Simple evolution solution:**
  - $R_{shock} \sim t^{m}$ and $V_{shock} \sim m * t^{m-1}$
    where m is the expansion parameter
    $T_{snr} = m*R/V = m * \underbrace{\theta/\dot{\theta}}_{\text{observable parameter}}$
- **In a stellar wind (as in CC supernova):**
  - $\underset{\text{ejecta phase}}{0.86} < m < \underset{\text{Sedov phase}}{0.66}$
  - 2330 yrs < T_{snr} < 1810 yrs
  - not associated with SN393
- **Age estimate independent of the distance !**

Hard X-rays with Nustar

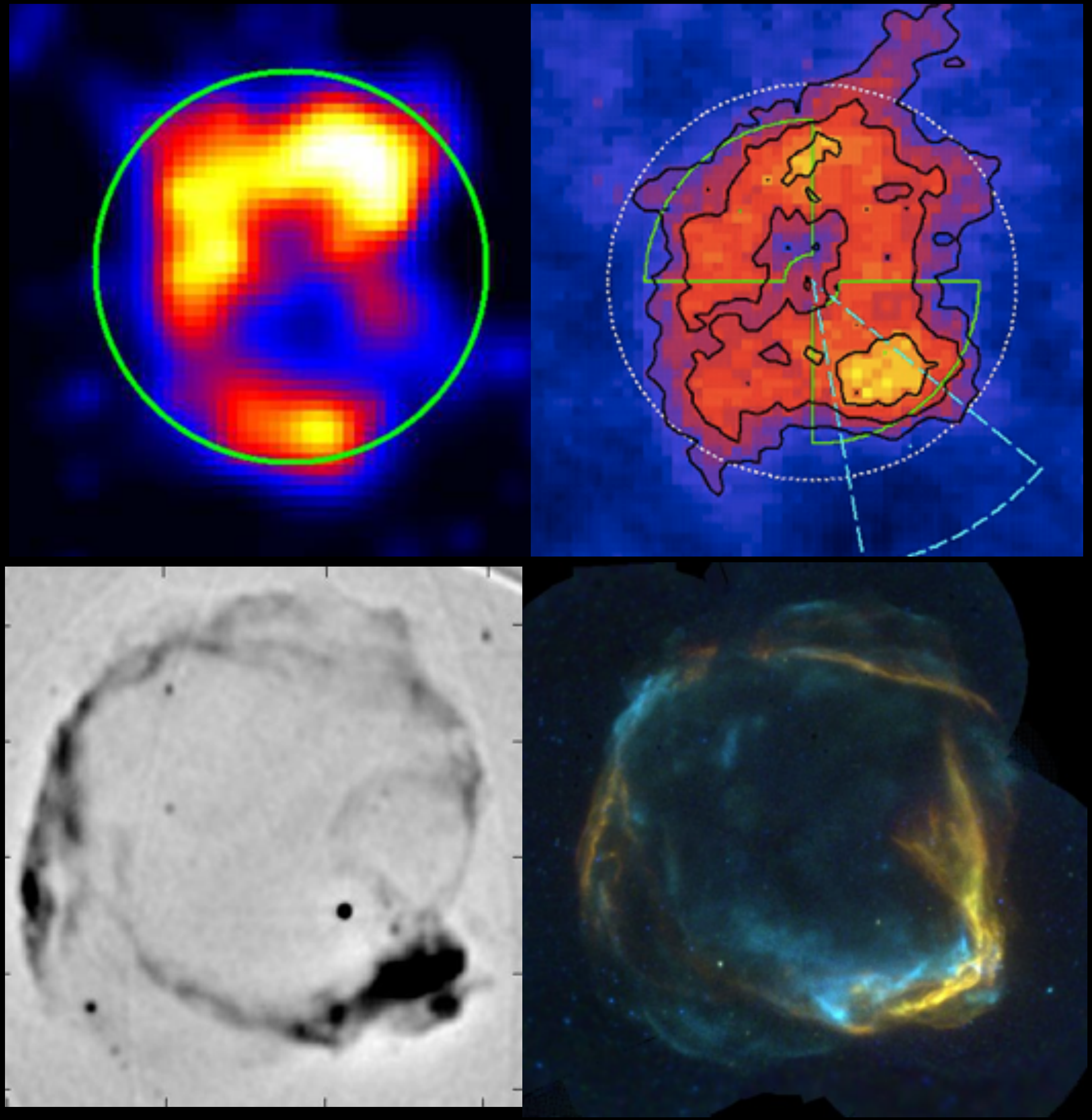
- **Non-thermal X-rays up to hard X-rays**
- **Locating the highest energy electrons**

Radio—VLA 4-6 keV — Chandra 10-15 keV — NuSTAR



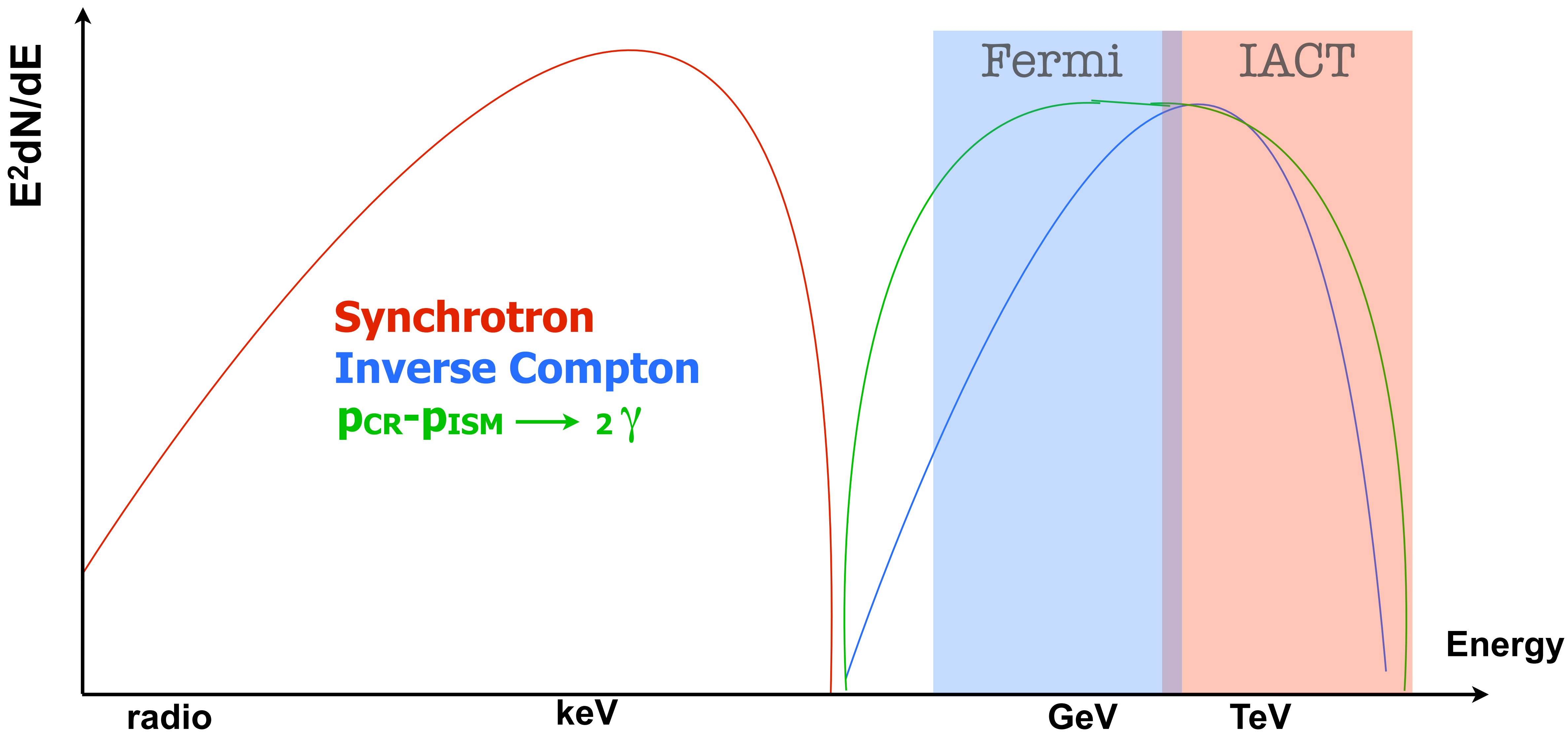
Grefenstette+15

The X/gamma-ray connection



Multi-wavelength emission from SNRs

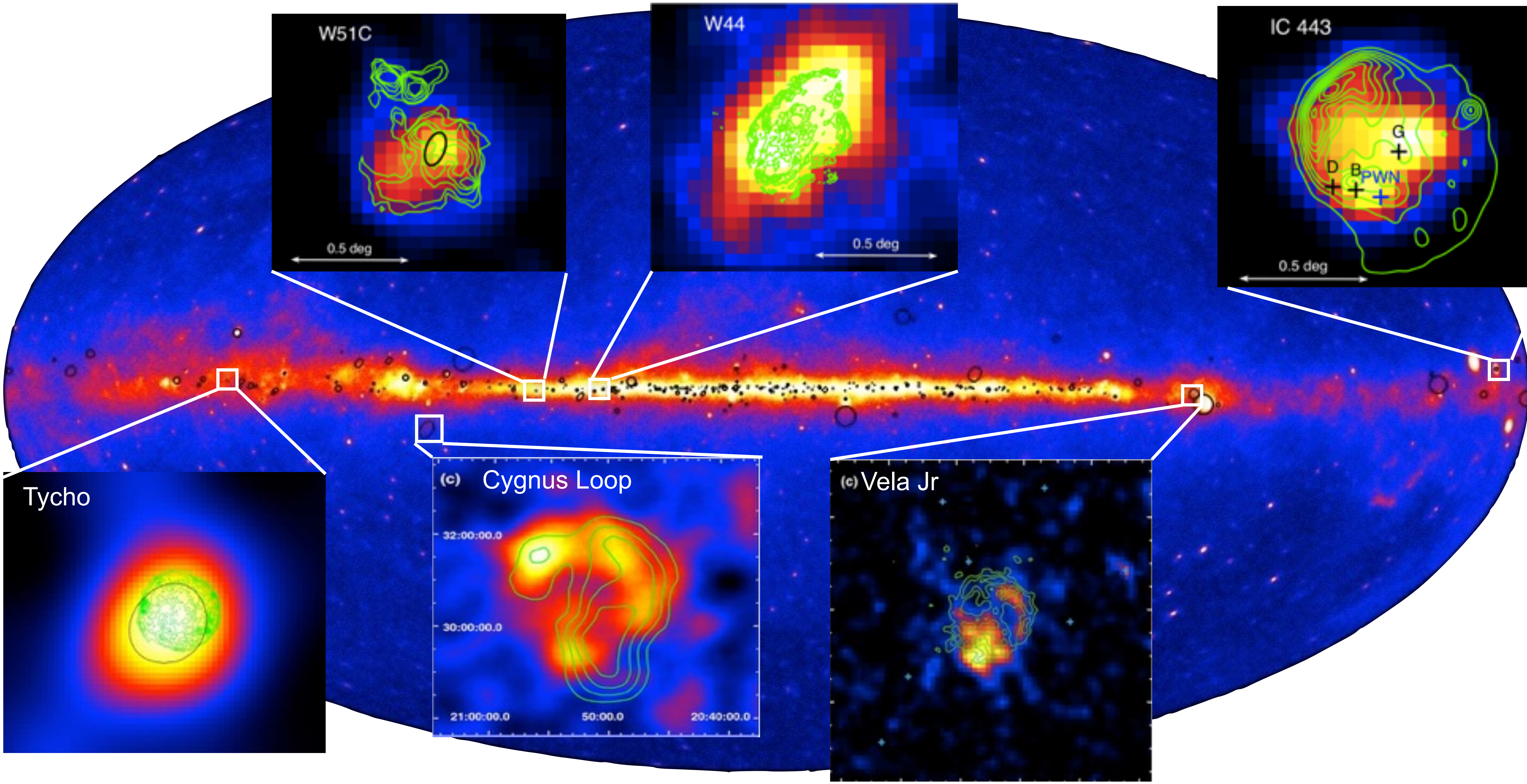
launch binder



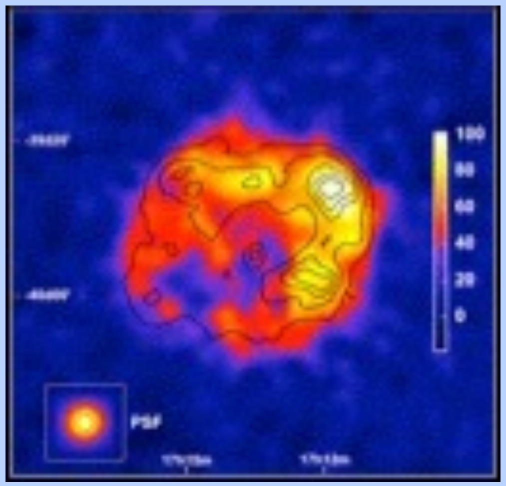
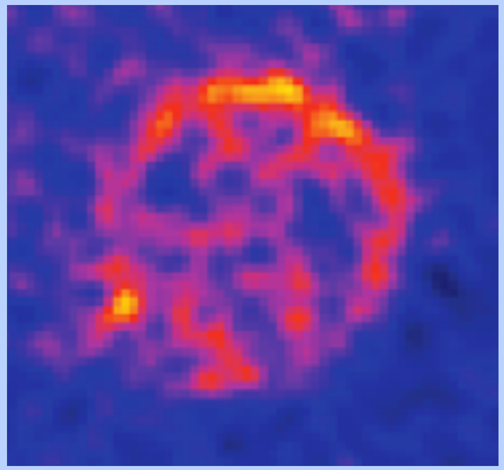
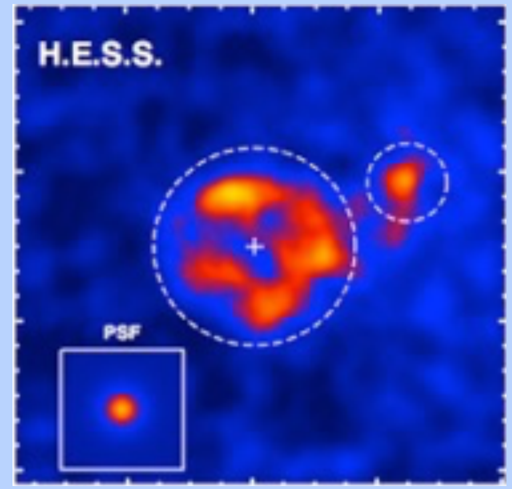
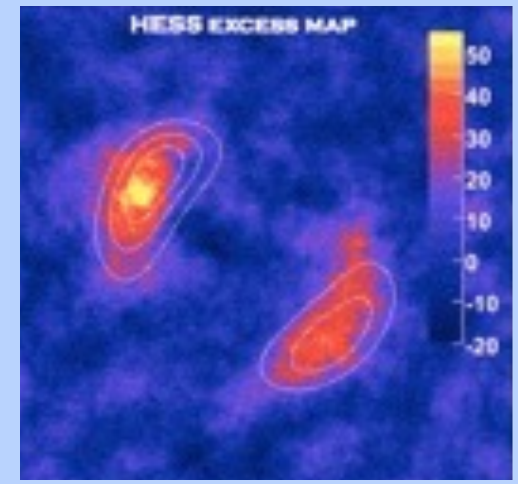
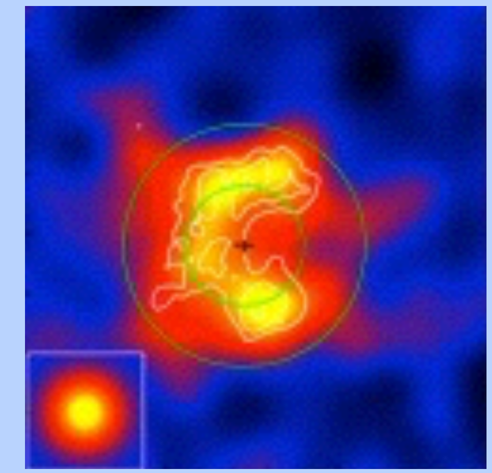
- **Test the SNR CR acceleration paradigm through SNR's particle radiation:**

- Nature of the γ-ray emission, E_{max}, Energetic SNR ⟶ CRs

SNRs as seen by Fermi-LAT

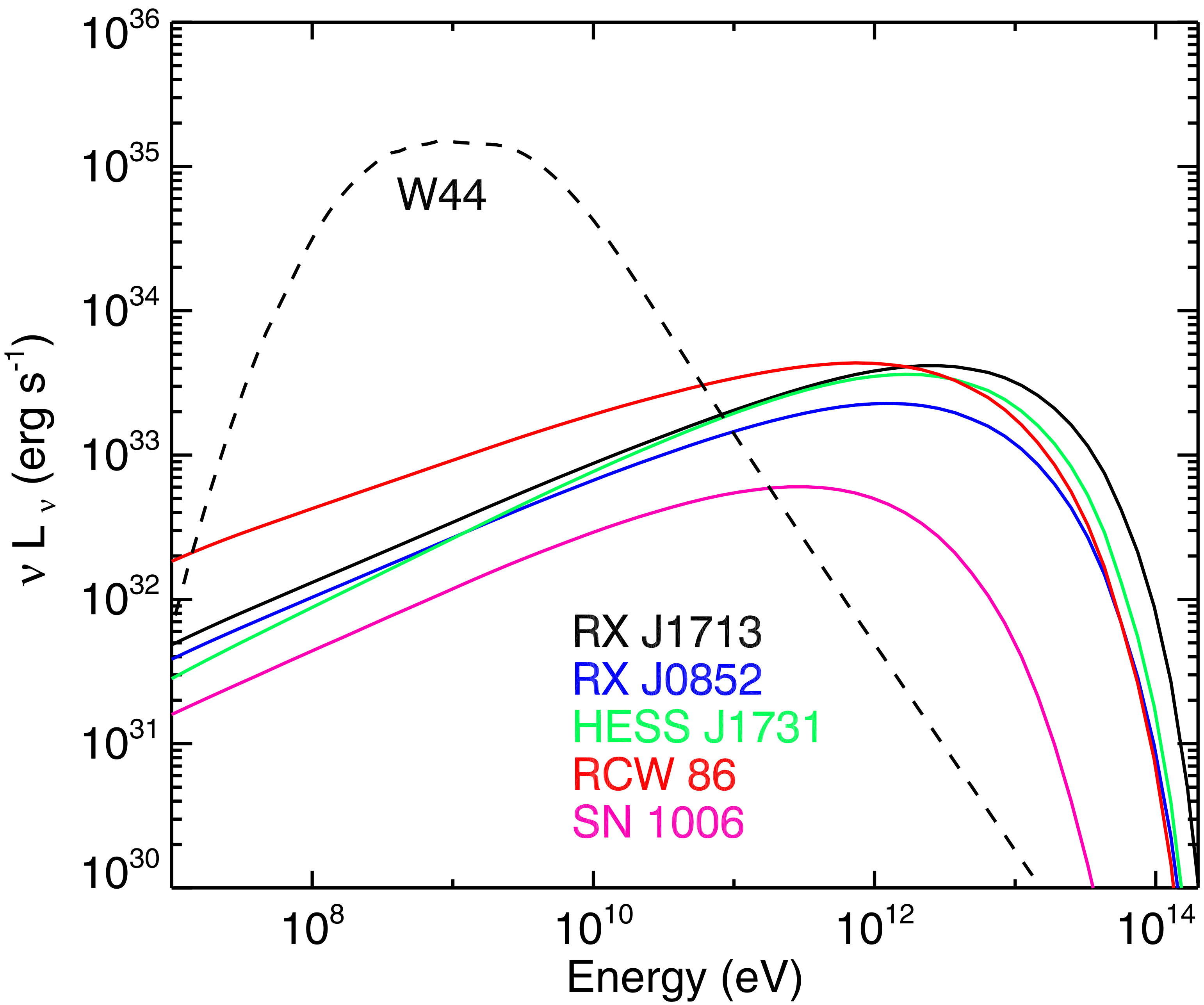


TeV SNRs: young and shell types

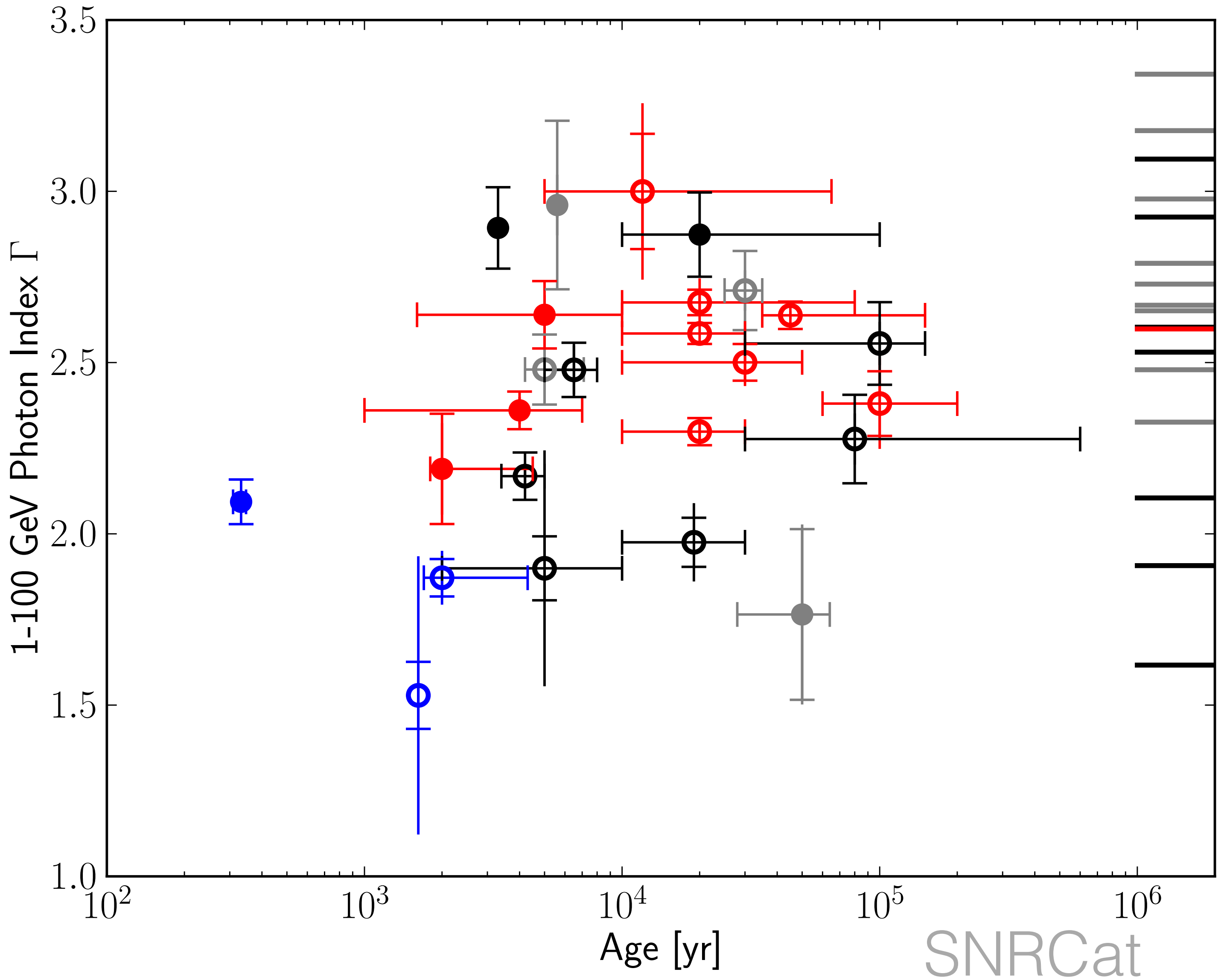
	RX J1713	VelaJr	HESS J1731	SN 1006	RCW 86
TeV images					
Density	<0.02 cm^{-3}	<0.03 cm^{-3}	***<0.02 cm^{-3}***	***0.05 cm^{-3}***	10^{-2} - 1 cm^{-3}
Age	1.6 kyrs	2-4 kyrs	**2-4 kyrs**	1.008 kyrs	1.8 kyrs
Distance	1 kpc	**<0.8 kpc**	**>3.2 kpc**	2.2 kpc	2.5 kpc
GeV spectral index	1.5 ± 0.1	1.85 ± 0.06	<1.5	<1.7	1.42±0.1

GeV/TeV populations

- **Middle-aged interacting GeV bright SNRs**
- **Young TeV bright shell SNRs**



Age - GeV index



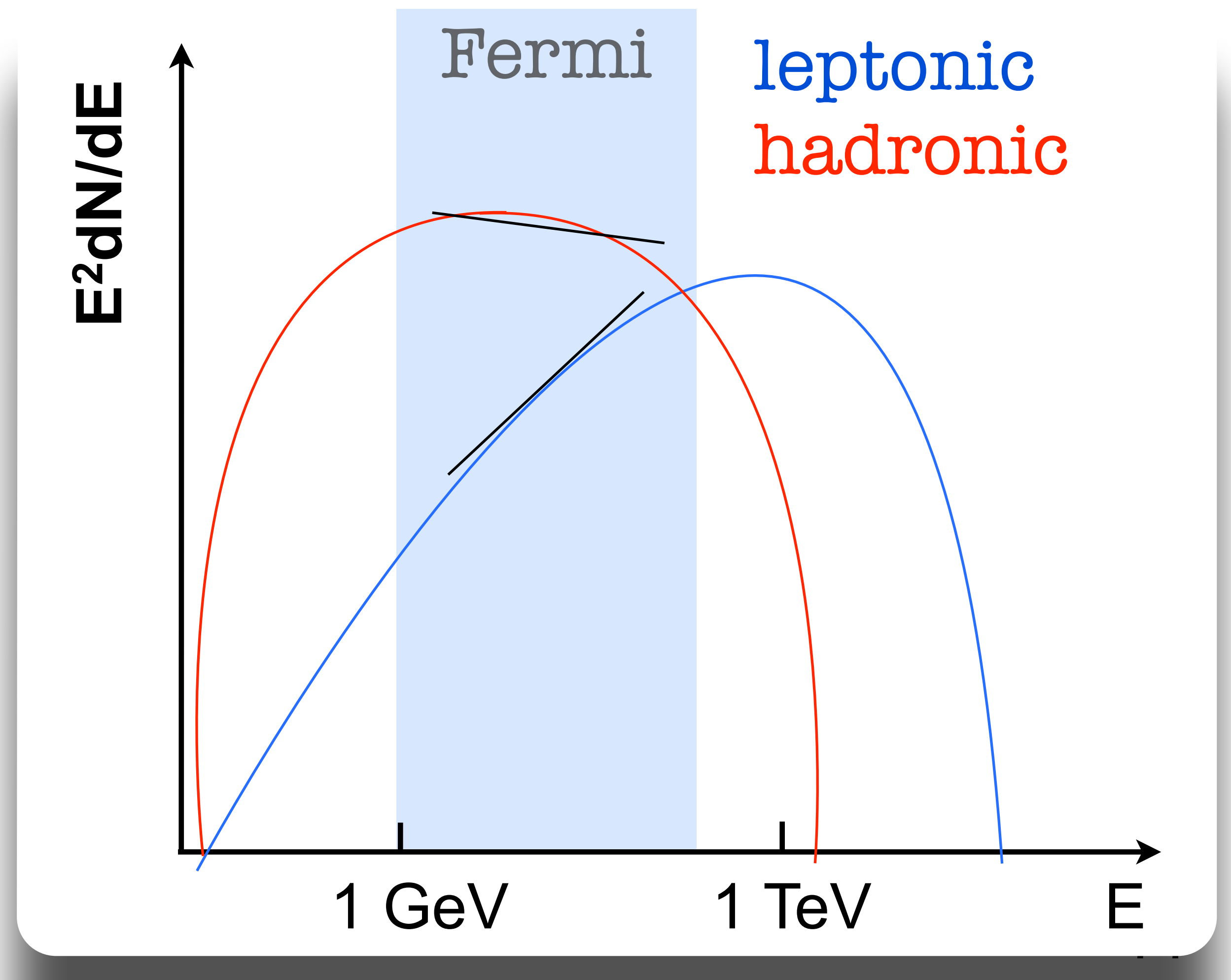
SNRCat
Acero+16

Older SNRs appear to have softer indices than young SNRs. This could be due to:

-E_{break} evolution (related to V_{shock})

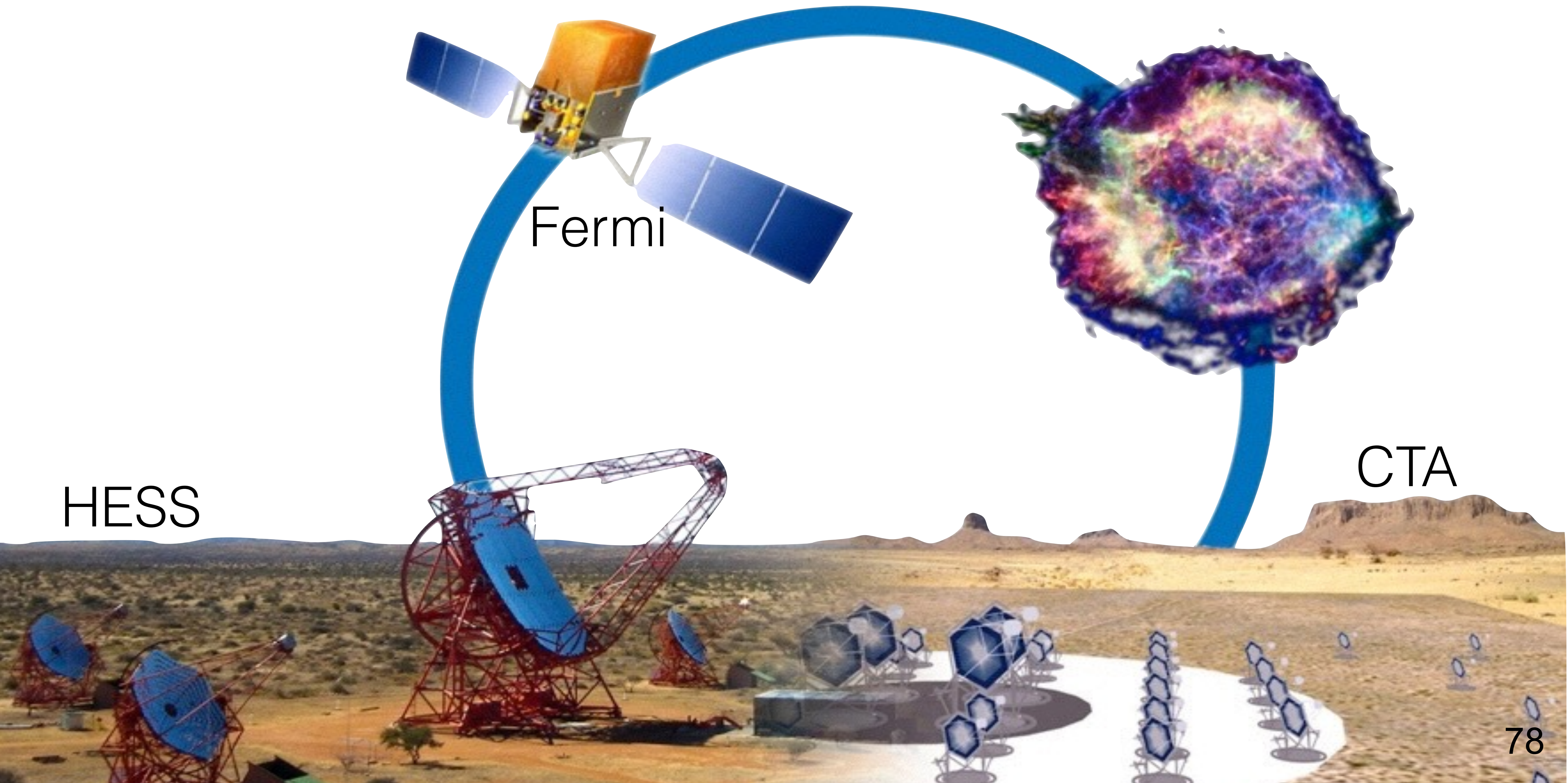
-Change of dominant emission mechanism

-Different zones properties



Futur high energy synergies

- Large field high energy survey instrument (Fermi + future CTA) will need X-rays to find counterpart.
- XMM + Chandra (+eRositta) will continue to be key instruments



Conclusions