

# Supernova Remnants in X-rays

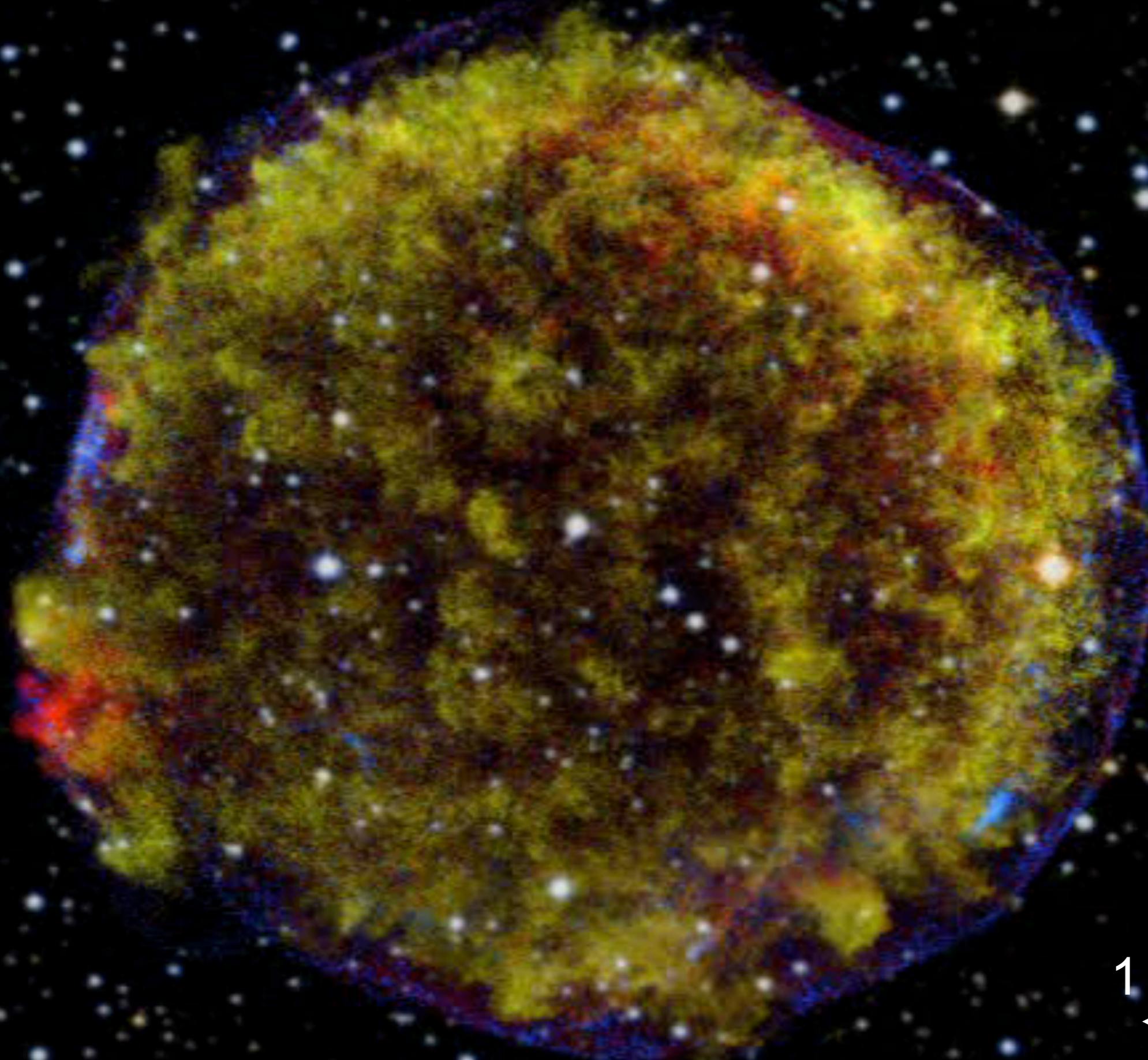
F. Acero, AIM/CEA-Saclay

[www.github.com/facero/OHP-2016-material](https://www.github.com/facero/OHP-2016-material)

# Why study supernova remnants (SNRs)

Tycho

2000



1 arcmin  
↔

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

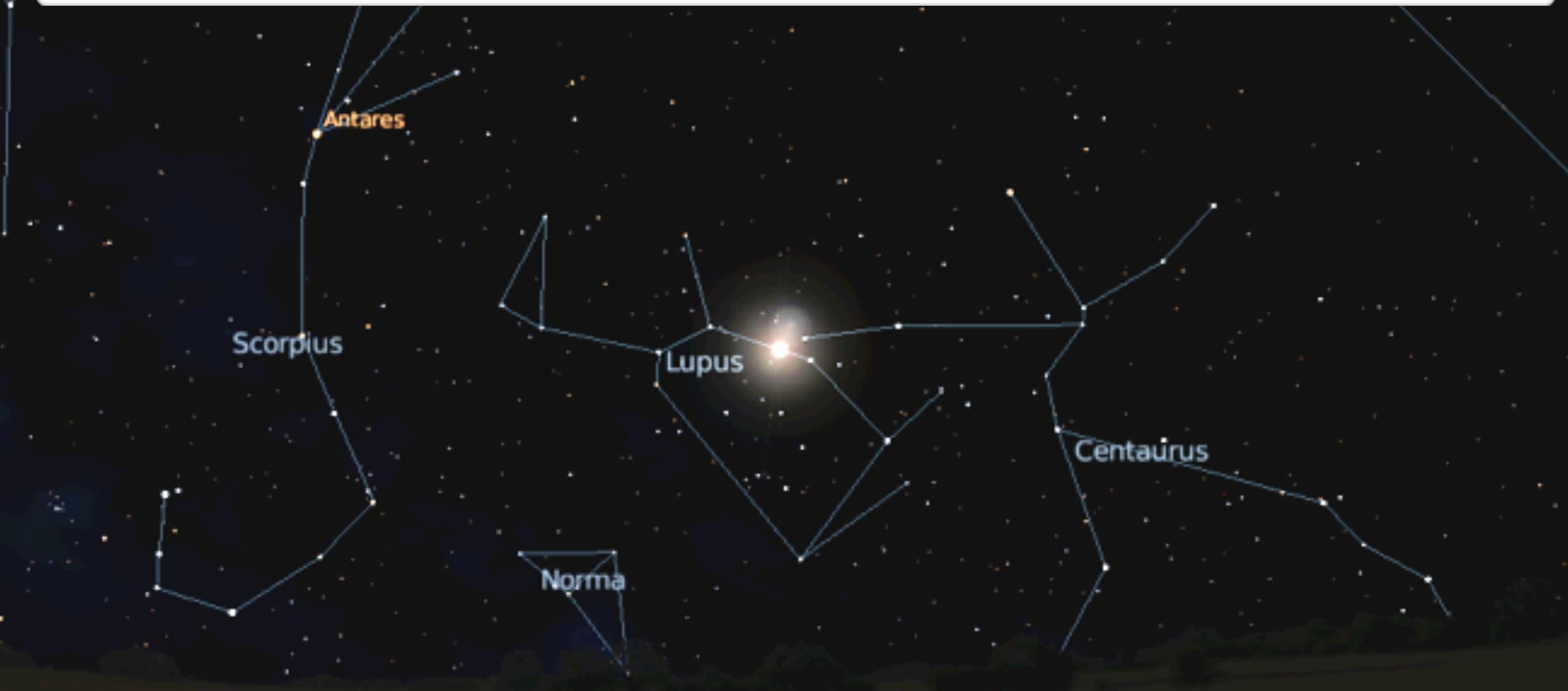
Reviews:  
[Reynolds+08](#)  
[Vink+12](#)

# Supernova through history, SN type and classification



## **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.

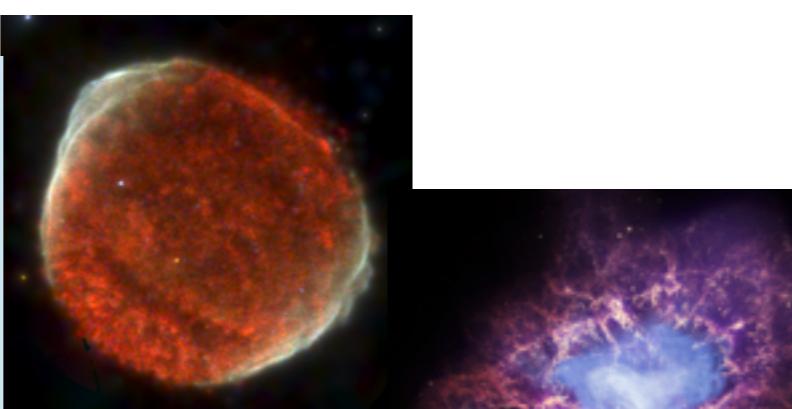


Peak Mag~ -7



# Historical Supernovae

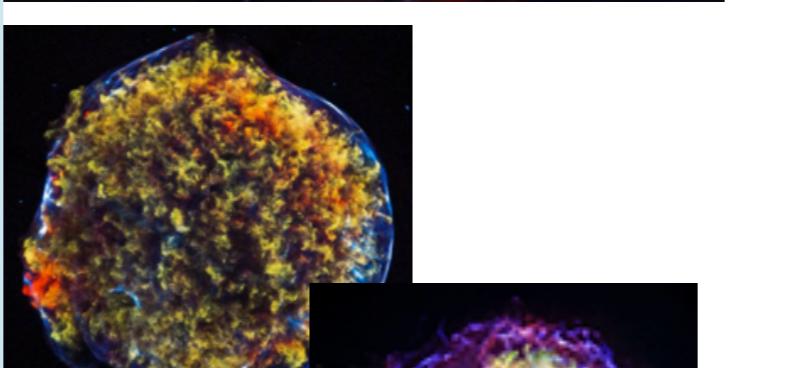
AD 1000 SN 1006 Brightest of the historical supernovae



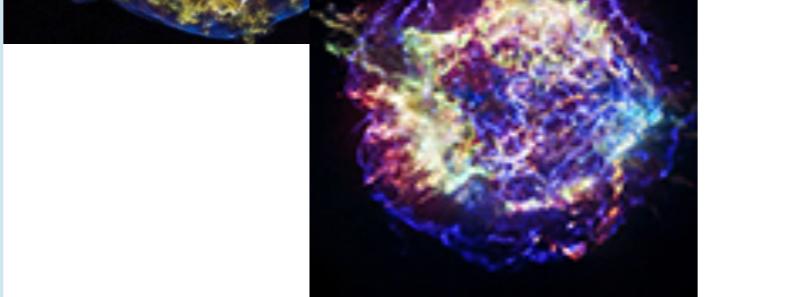
SN 1054 Formed the Crab Nebula



1200 SN 1181 In Cassiopeia



SN 1572 Tycho Brahe recorded this one and coined the word "nova"



1600 SN 1604 Most recent supernova within the Milky Way



AD 2000 1987A In the Large Magellanic Cloud

No Galactic visible SN in the last 400 yrs !

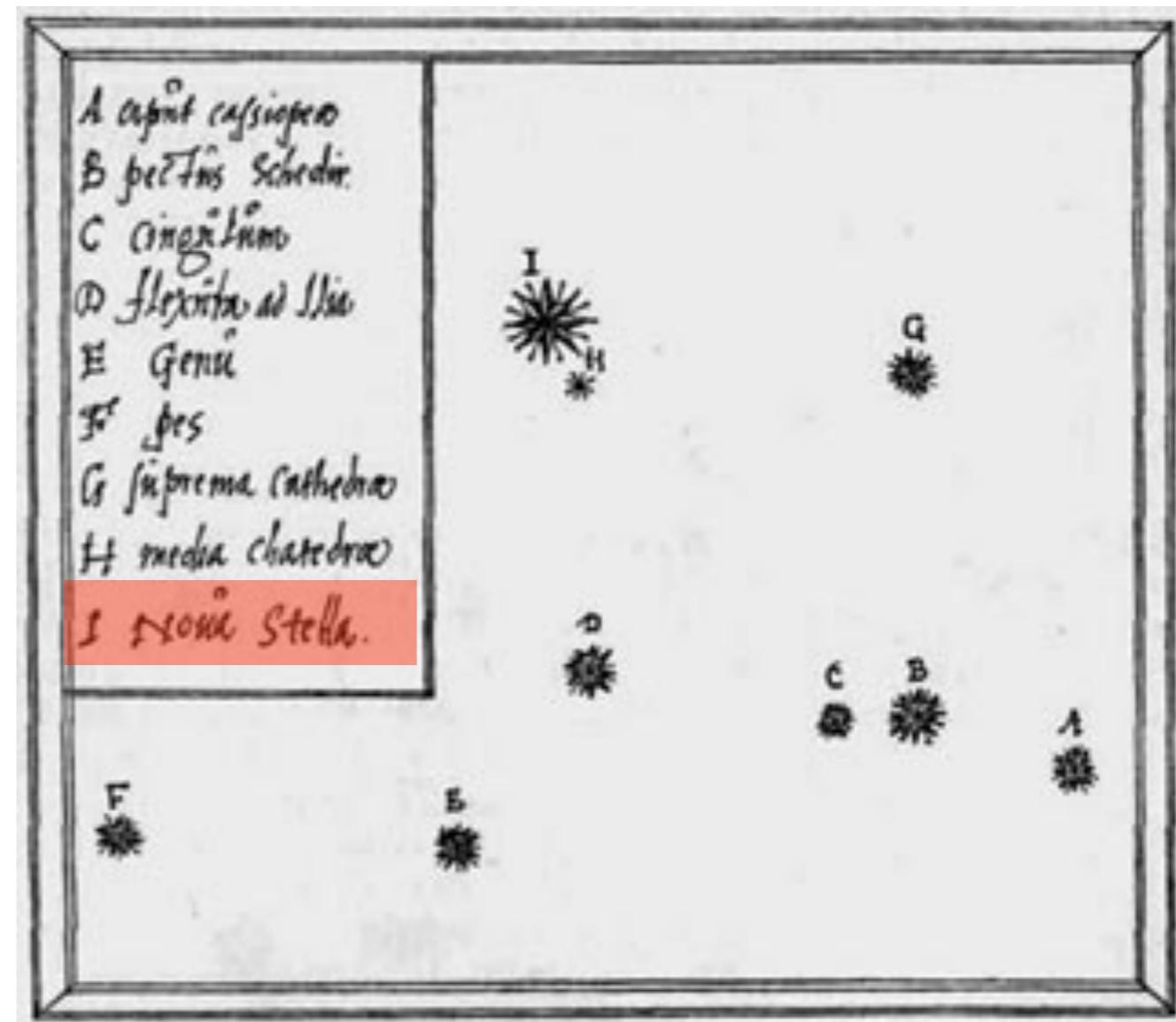
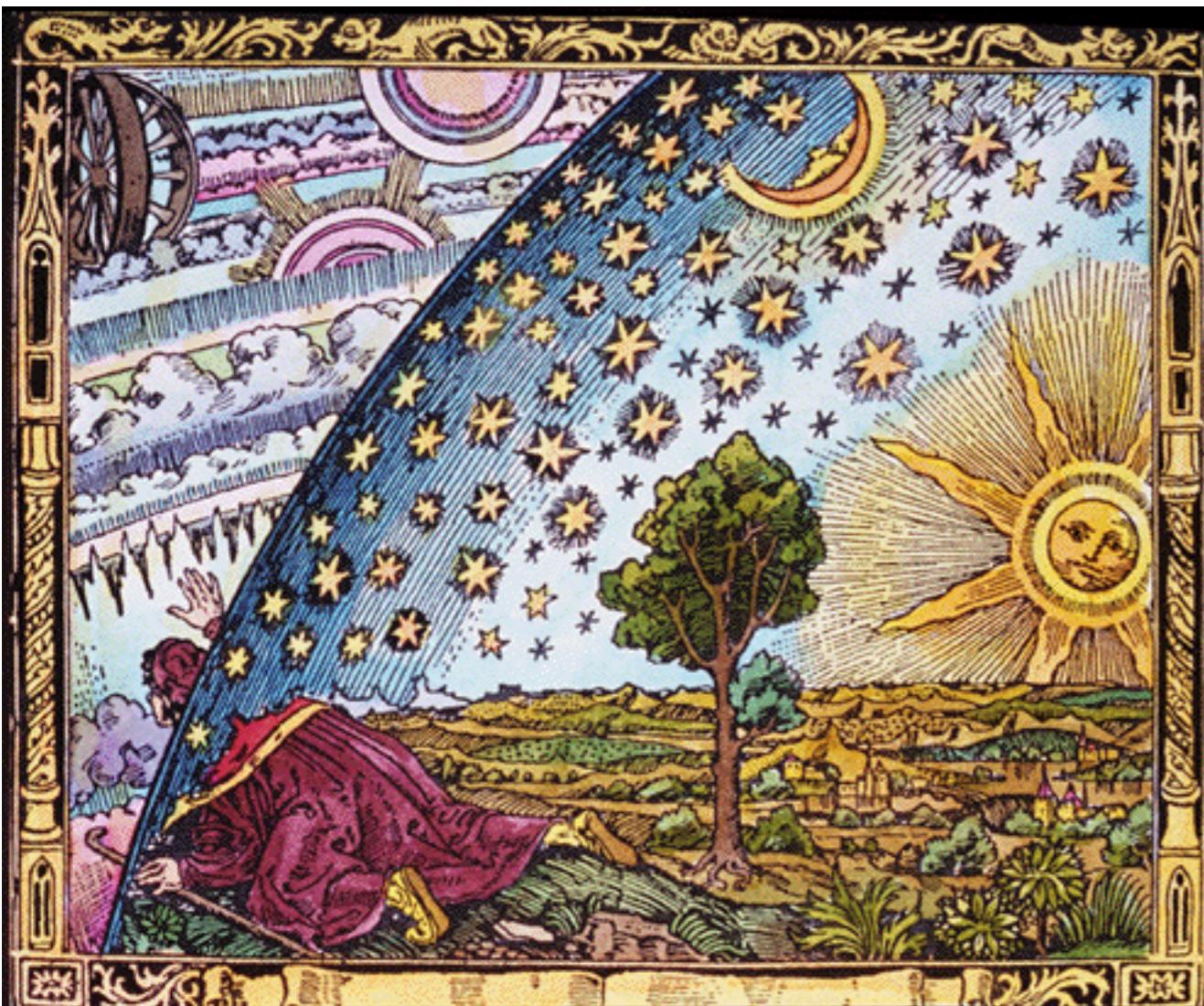
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來疾  
星遂更健及同輪至今光輝未退此谷永所謂耽耽驟處炎長頸  
所勝好犯其為病害當可畏也人去冬遠今春京東西路及陝右川  
蜀諸郡草木不雨室苗魚死民既艱食甚稼必與此京房所謂跋  
土失其性其為災甚益可賅也夫疫調陰陽者三公之職天威若曰  
陛下左右輔弼當得忠賢明正之人為之方可以居安知之氣消未  
萌之說不然何以妖星謂變也草昧更滌也地震祥異也三者皆屬  
禦明如是之著耶臣愚伏望陛下謹天之戒應天以寬服天下公攝  
與天下瞻望之所謂賢人君子者陽之後居廟堂之上貢以三公四  
輔之事務委任而仰成之若然則陰陽以和安矣以消弭此清明矣  
秋長颶太平之風竚翹足引領而待之臣朝夕愚陋敢惟擇賢命  
相整國家休戚治亂之本伏願陛下慎重之蘇後發聖斷力行而不  
疑則宗廟社稷之福天下生靈之幸  
起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風  
乍寒乍暑愆雨不雨又有黑氣蔽日晦皆人事之所感動也黑氣陰  
也小人也日傷也君象也黑氣蔽日者陰侵陽小人惑君也欲雨不  
雨者政事不決也陳執中為相不病而家居禽百日矣陛下以御史  
之言決一憲元而欲退宰相為是師乞速退執中以解天憲以御史  
之言為昨亦乞勅執中起視事無使天意久不决也家晏者當罰也  
乍寒乍暑者不當震而震到而不到也皆保吉有過於法不當為

Chinese records from SN1054

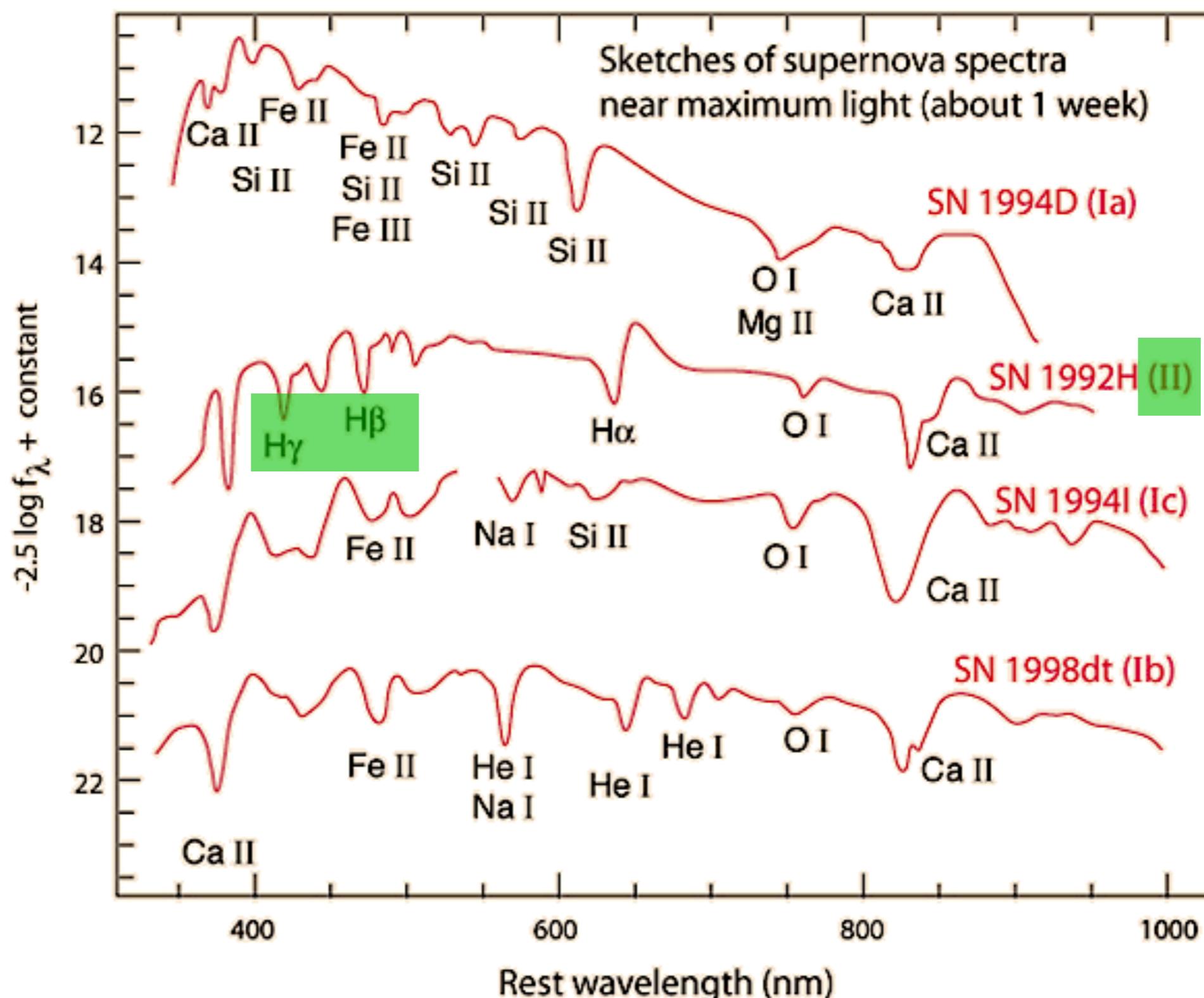
# Historic impact

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

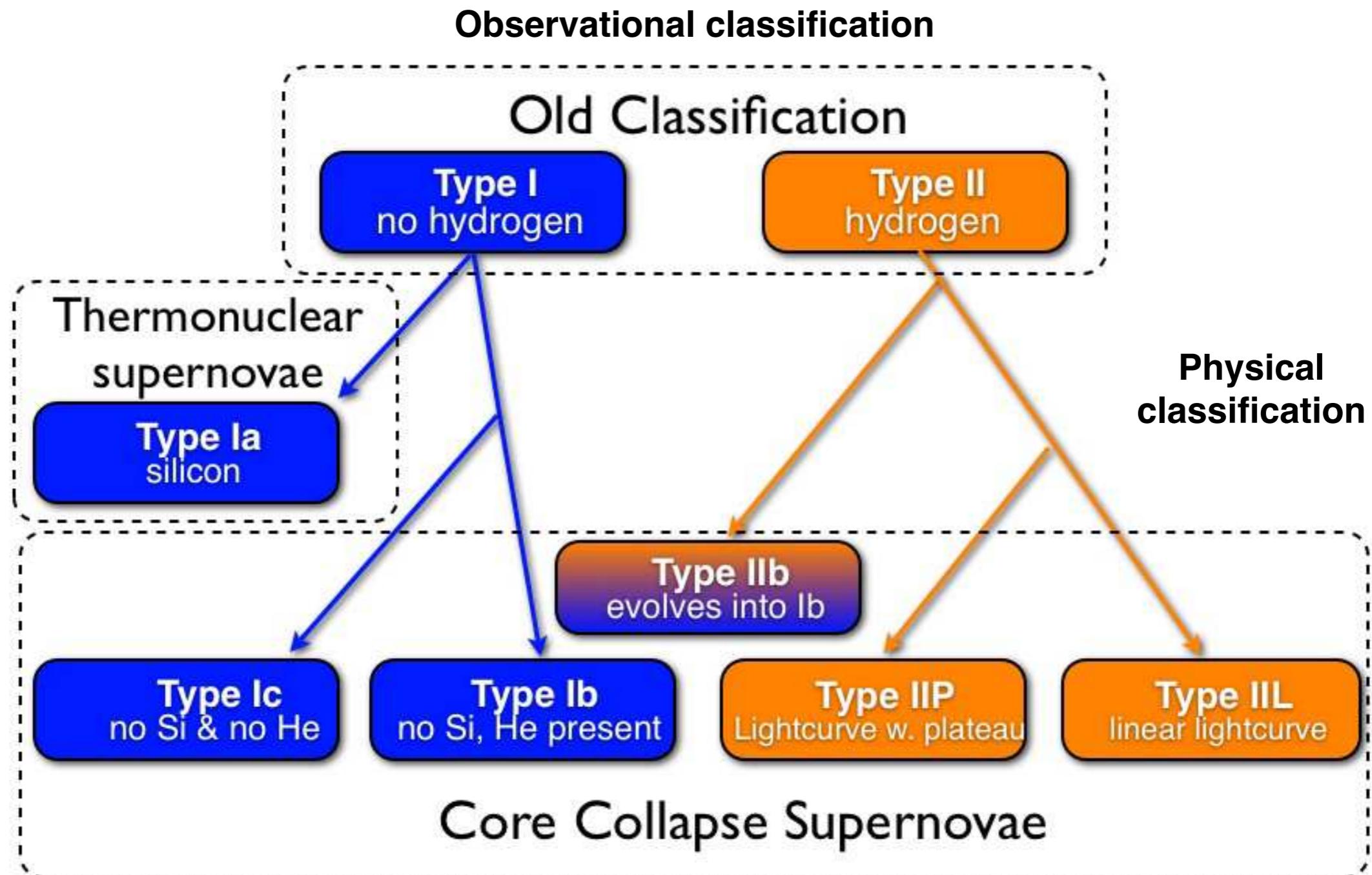


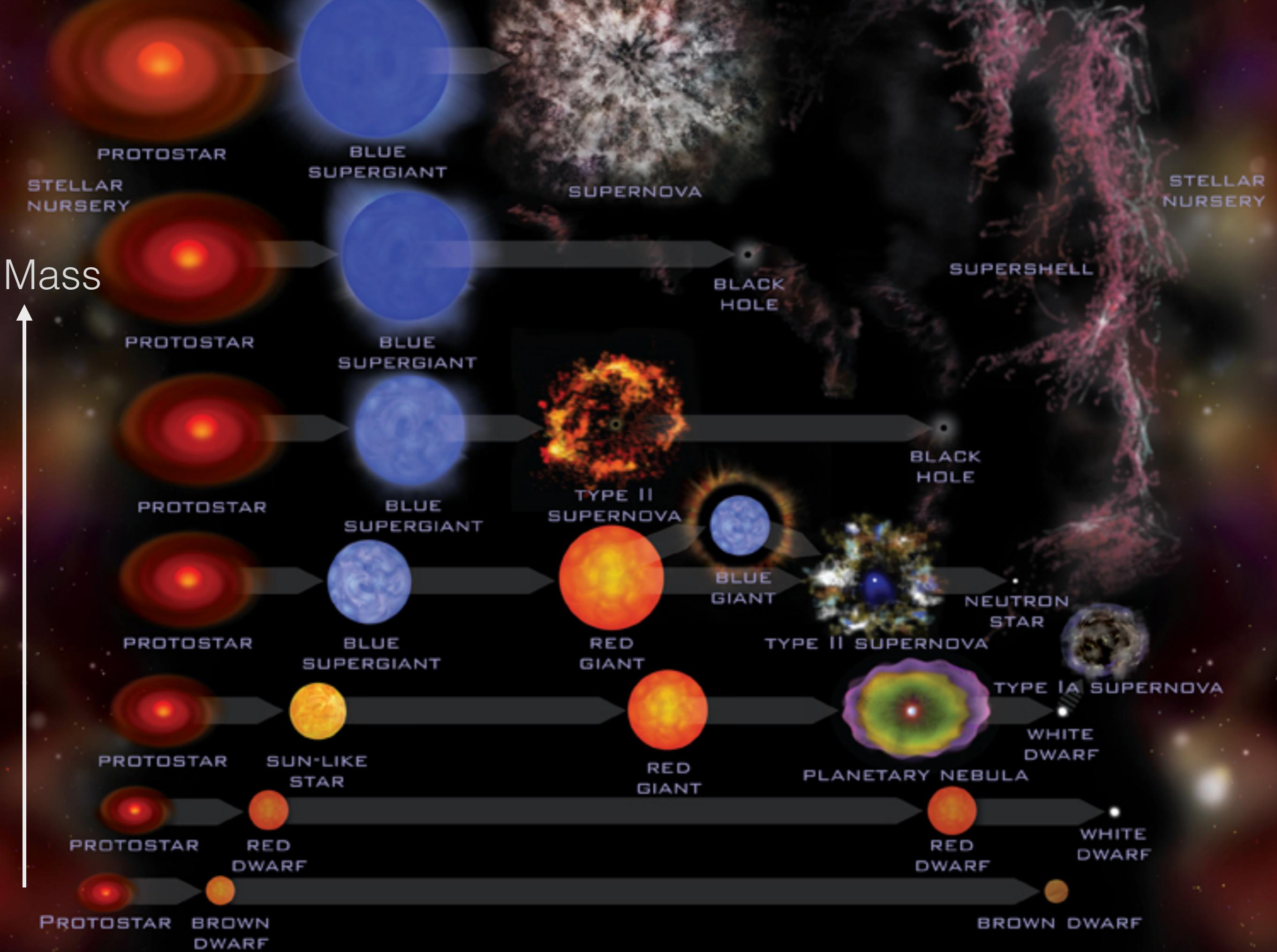
# Supernovae classification



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

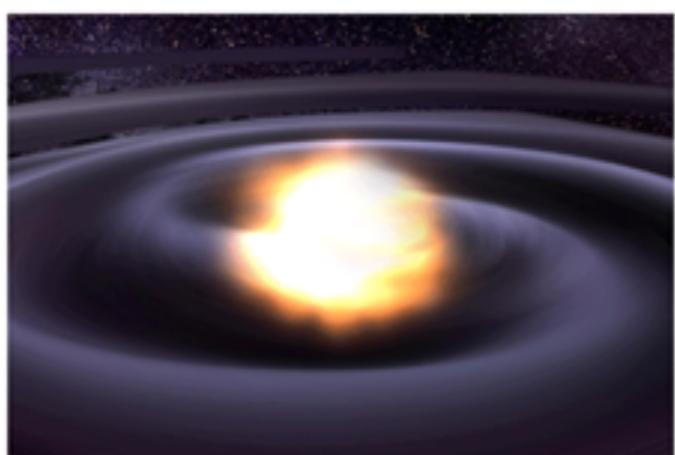
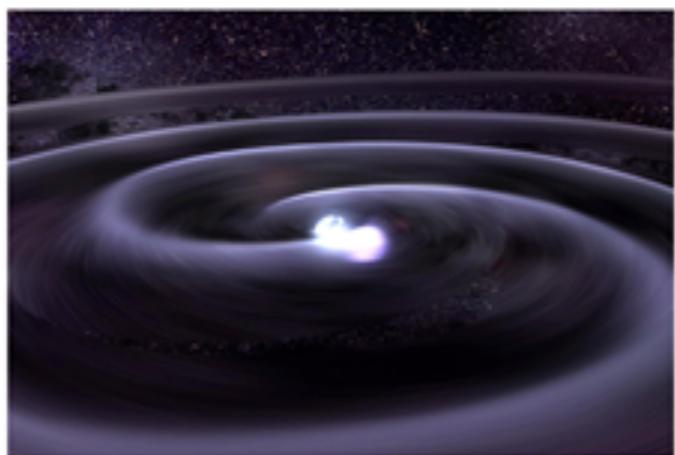
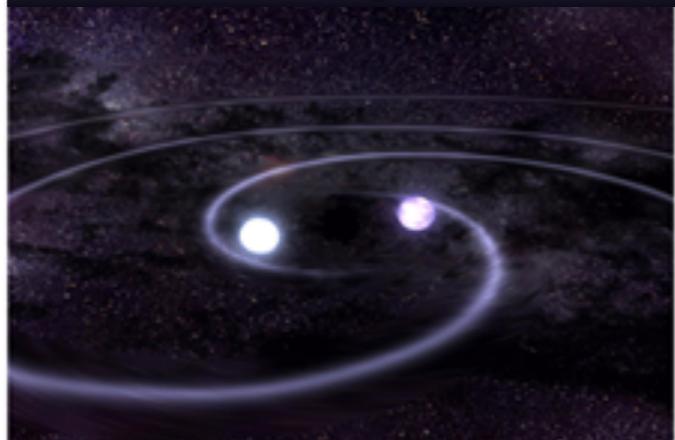
# Supernovae classification



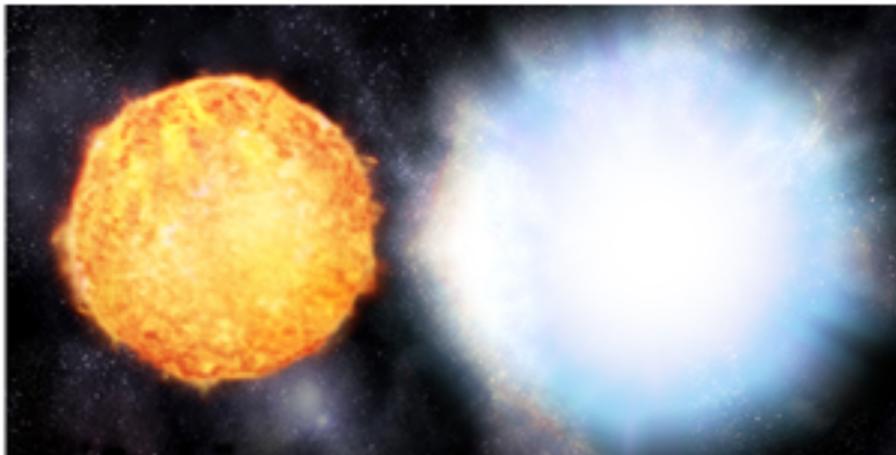
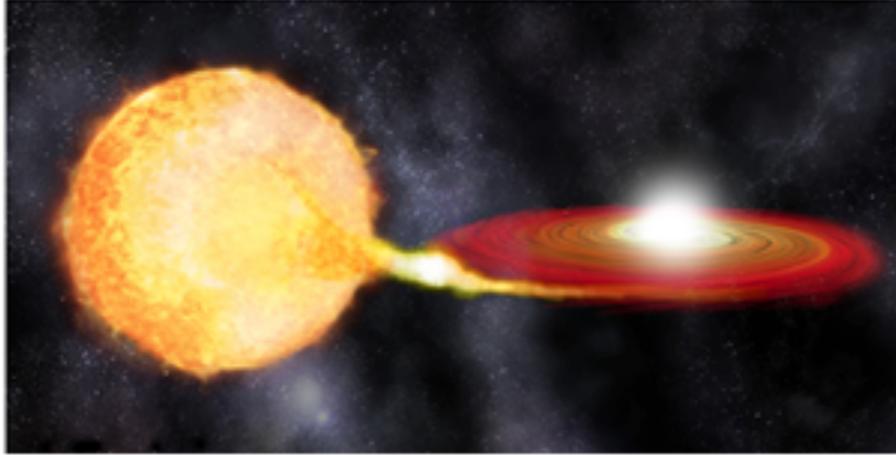
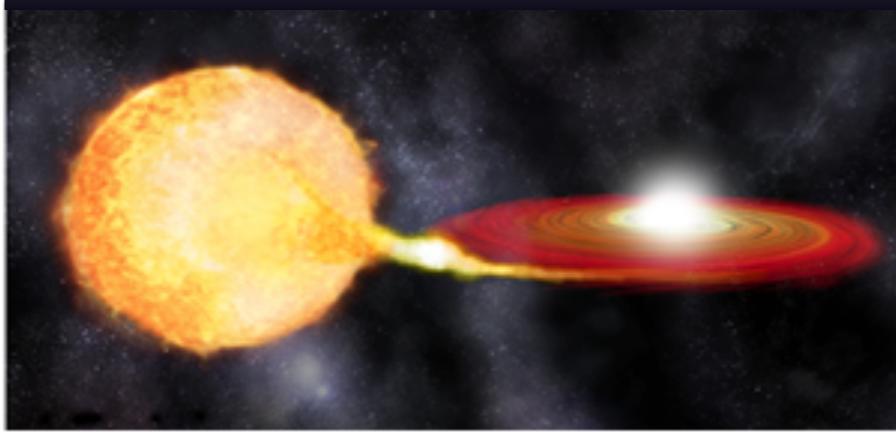


# How do type Ia supernova explode ?

**Double degenerate:**  
before - No Xray  
Supernova + GW  
after - nothing left

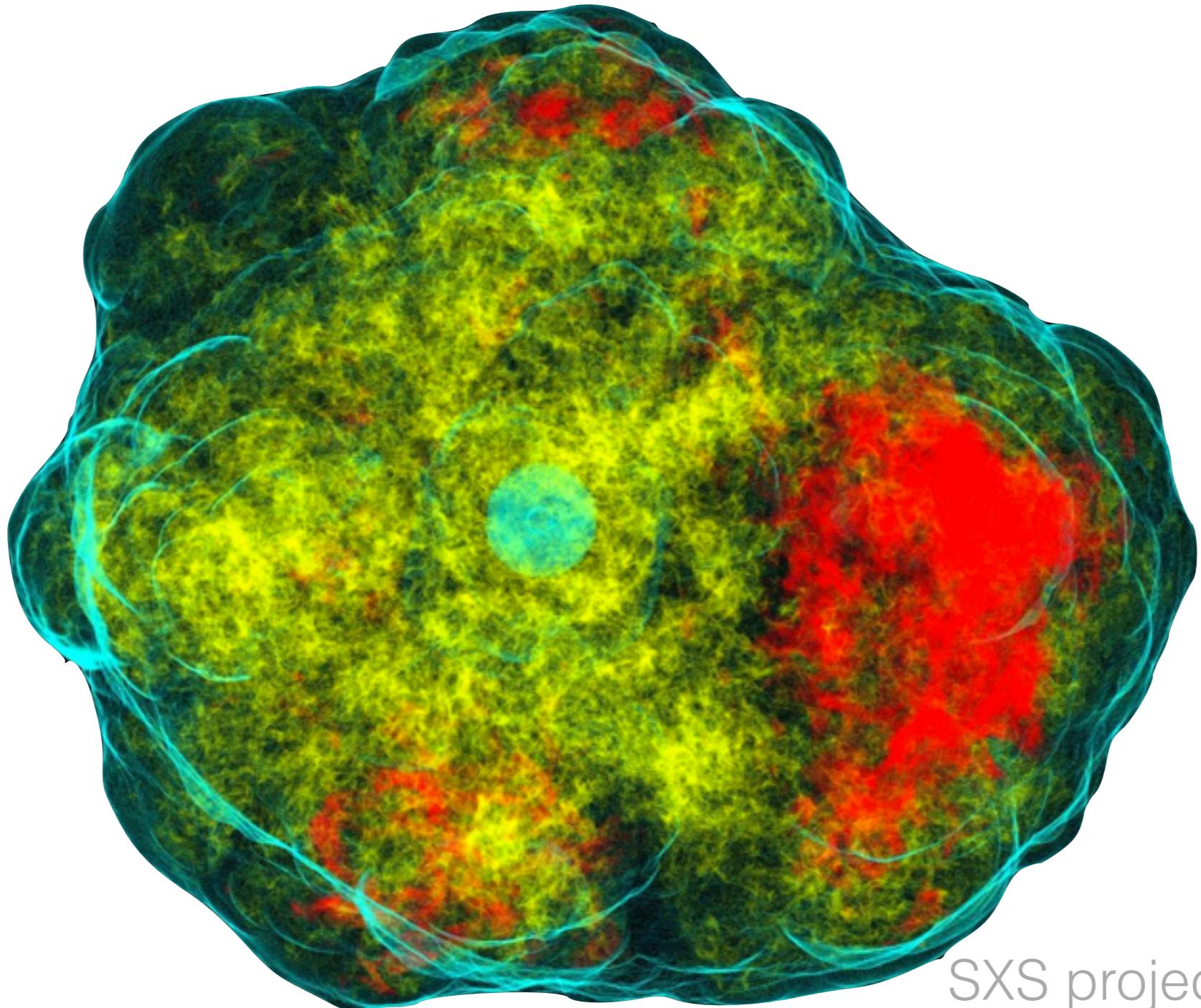


**Single degenerate:**  
before - Xray accretion  
after-run away companion



Thermonuclear  
reaction

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



## Supernova remnants



# Components of the ISM

M16, Hubble

Gas

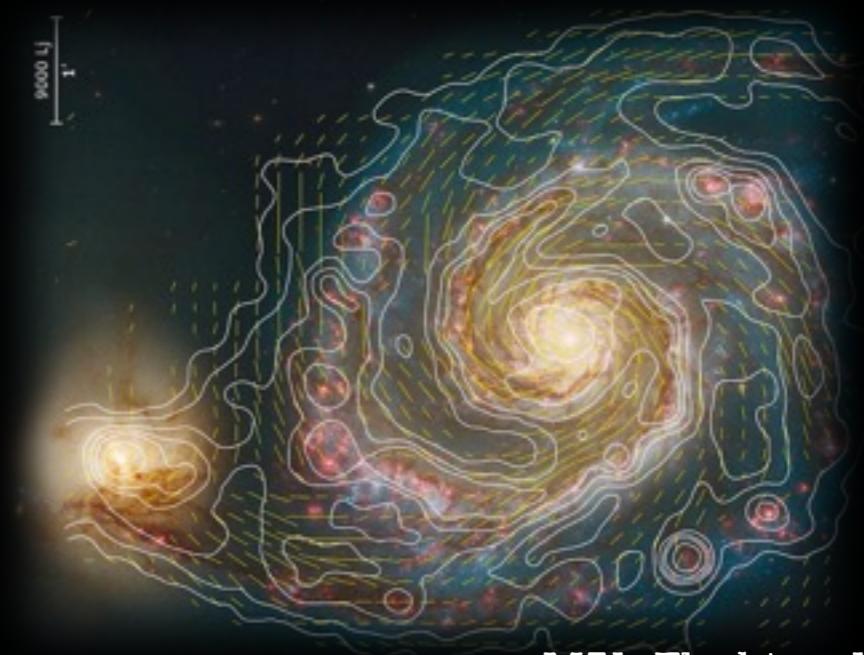
SNR provide  
kinetic energy  
heavy elements

Cosmic rays

B field, photons



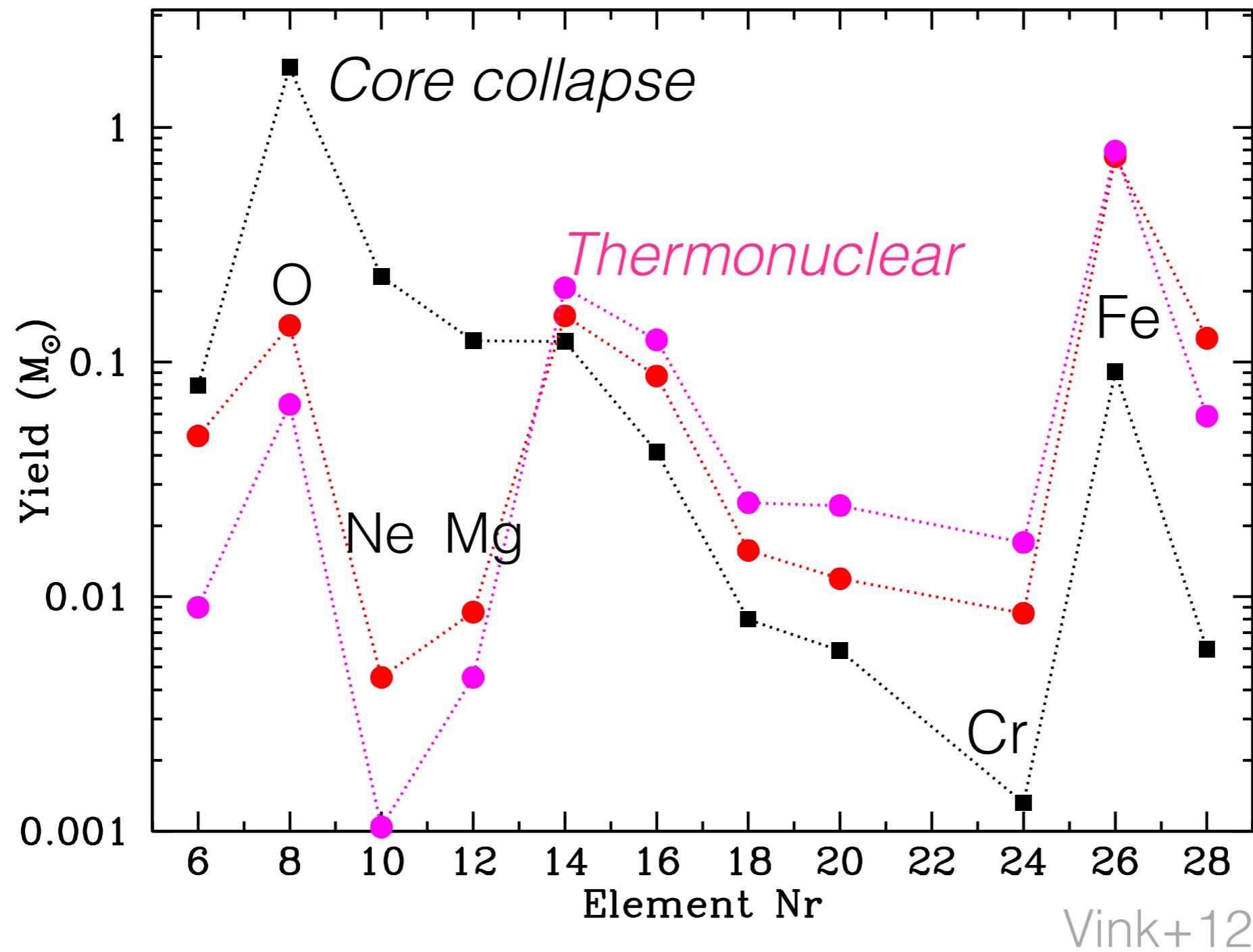
SN1006, X-rays



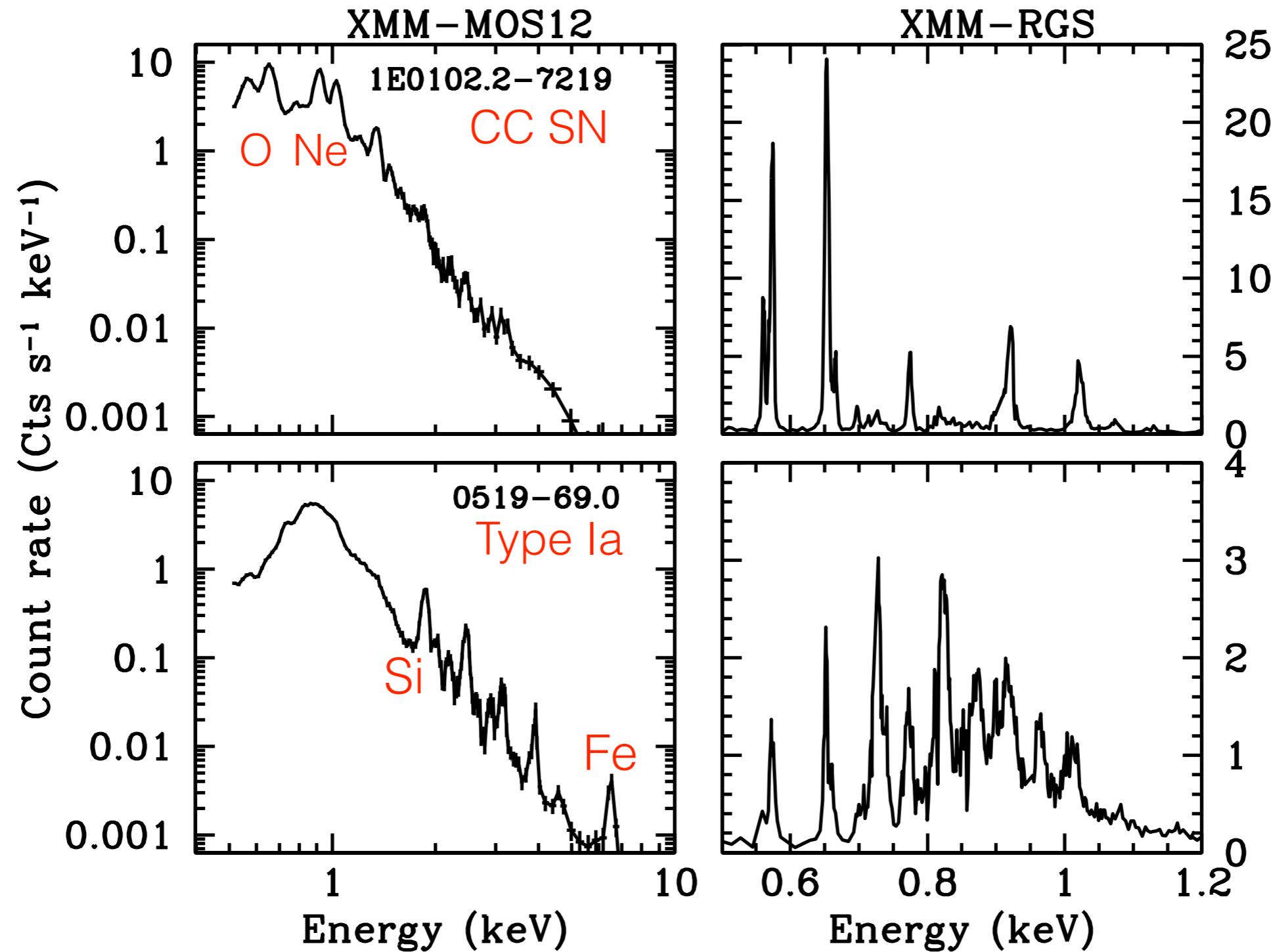
M51, Flechter+11

# Nucleosynthesis: SN yield

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# Nucleosynthesis in CC/Type Ia

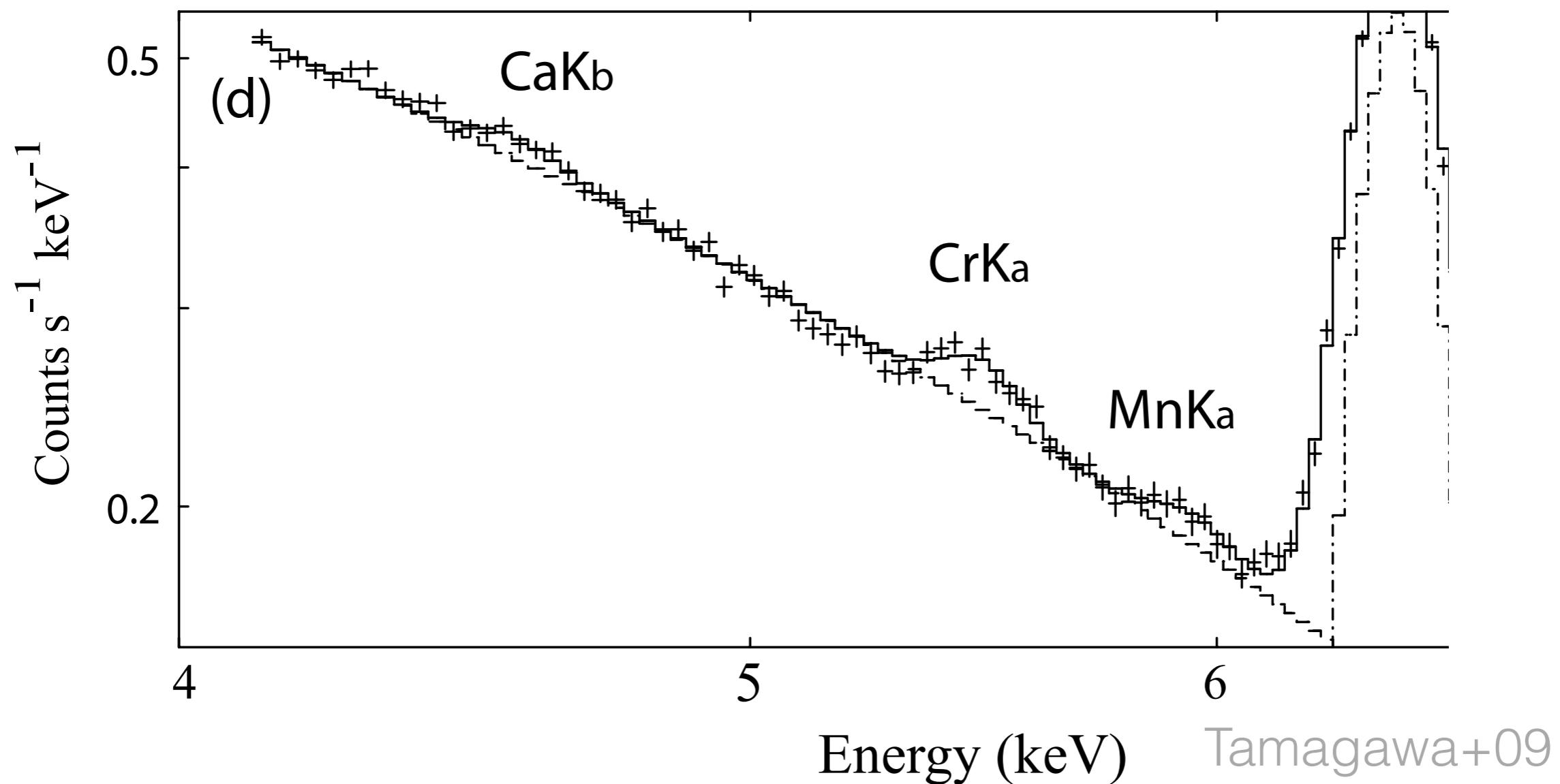


Vink+12

## Emission lines

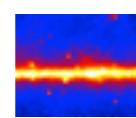
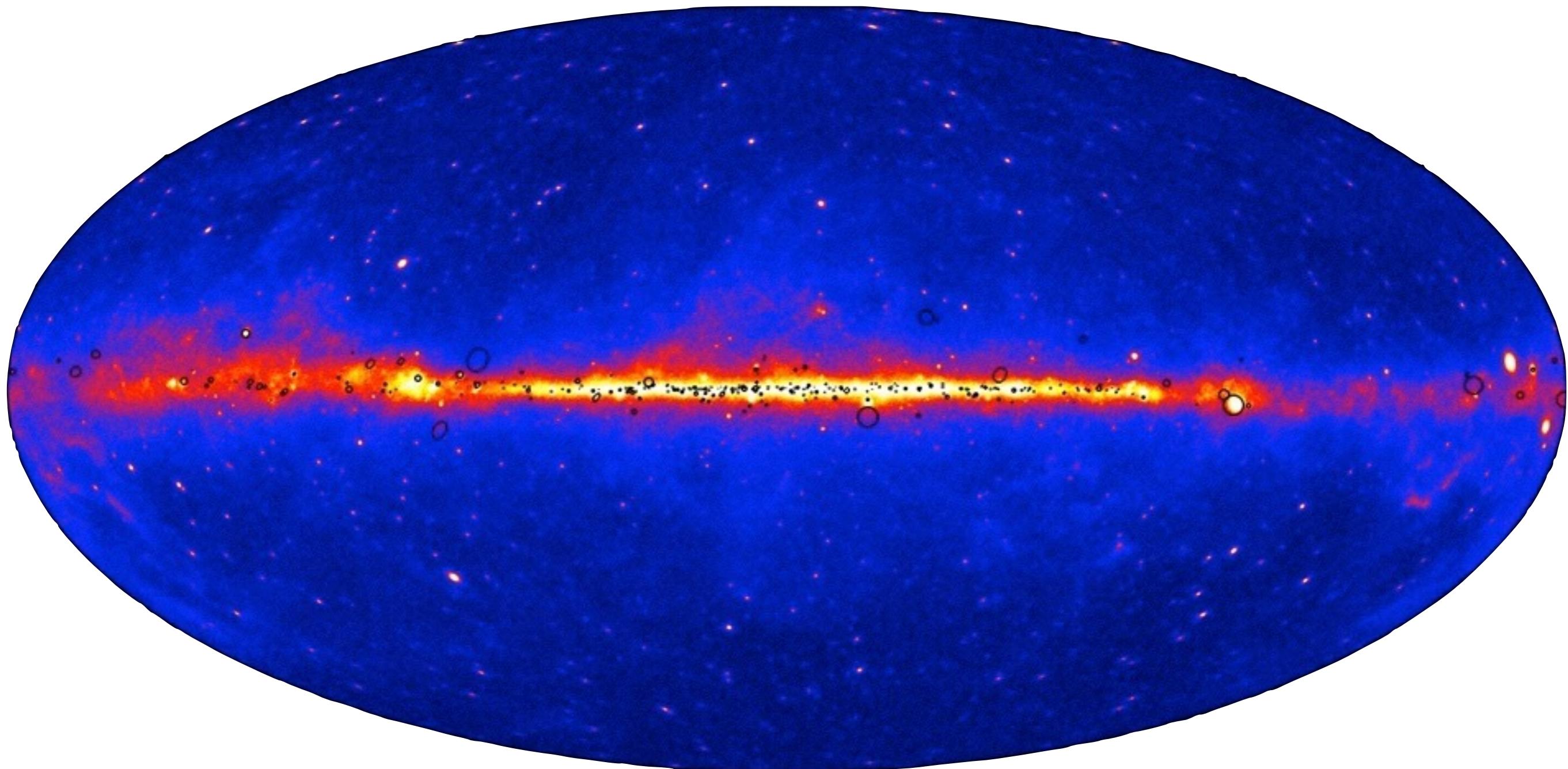
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- Faint emission from heavy elements in Tycho SNR (type Ia)

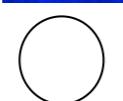


# SNRs in our Galaxy

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Fermi-LAT  $\gamma$ -ray counts maps,  $E > 1$  GeV



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

## SNRs catalogs

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- **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

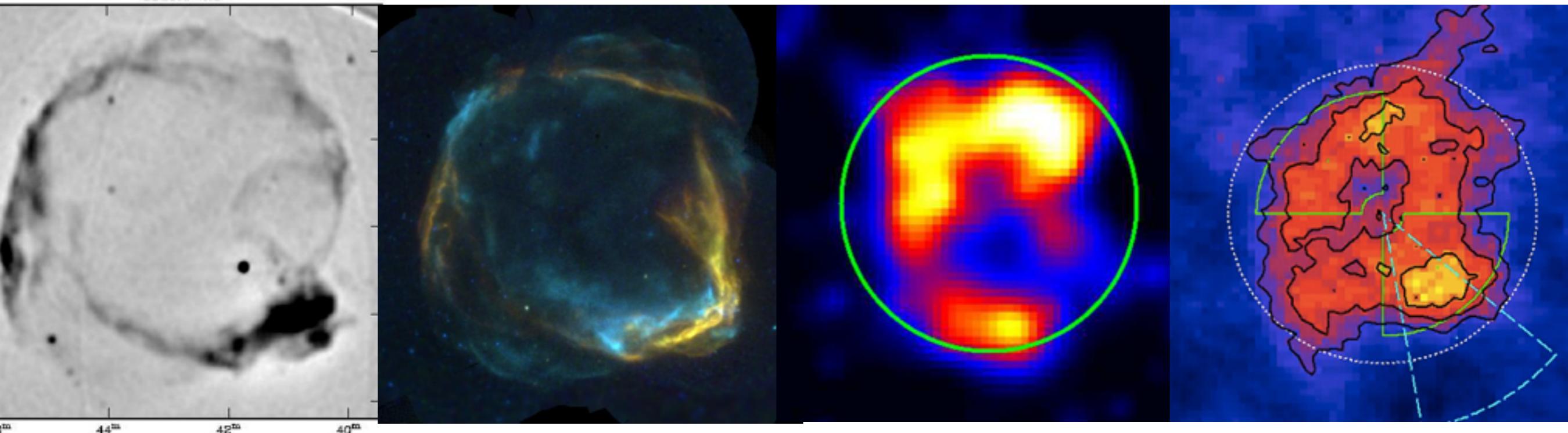
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Radio

Thermal X  
Synch X

GeV

TeV



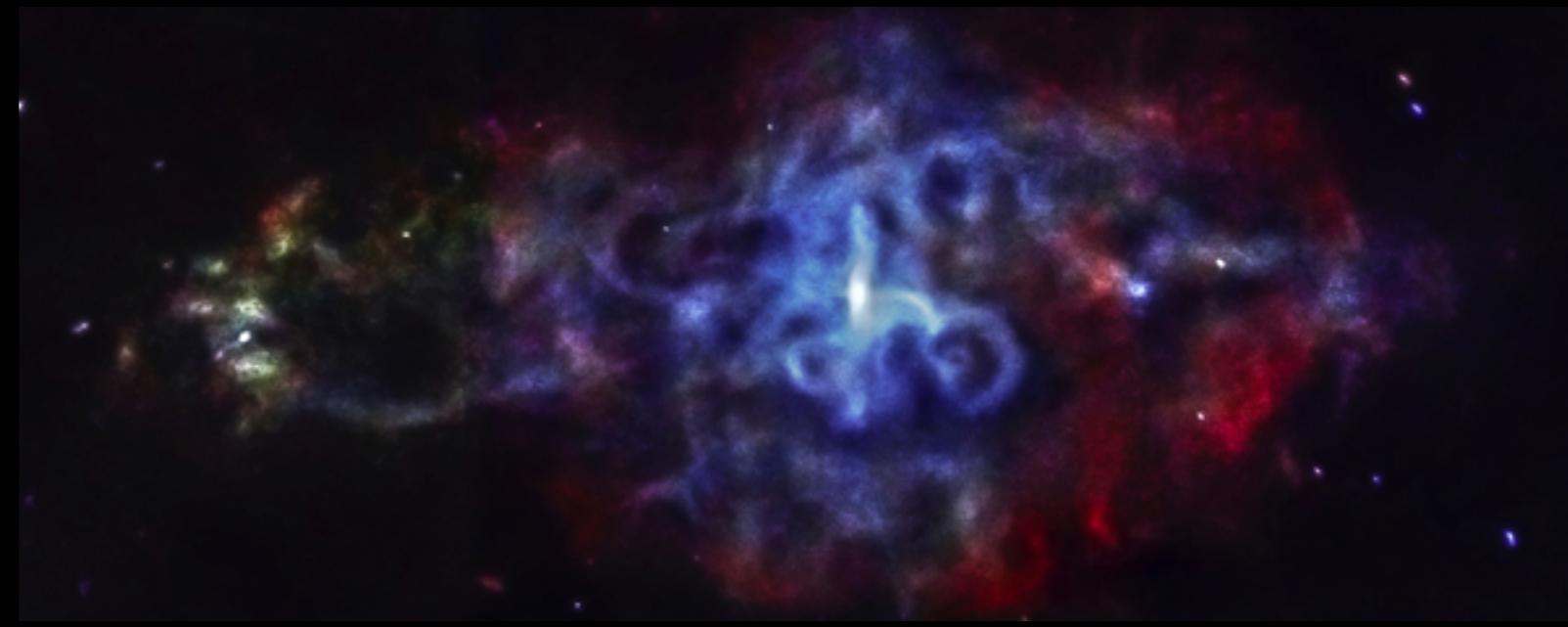
- Radio, optical, X-ray, gamma-ray come from a shell.
- Shell is expanding.
- Power source is inertia left from initial supernova.

## SNRs - Plerions

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Crab

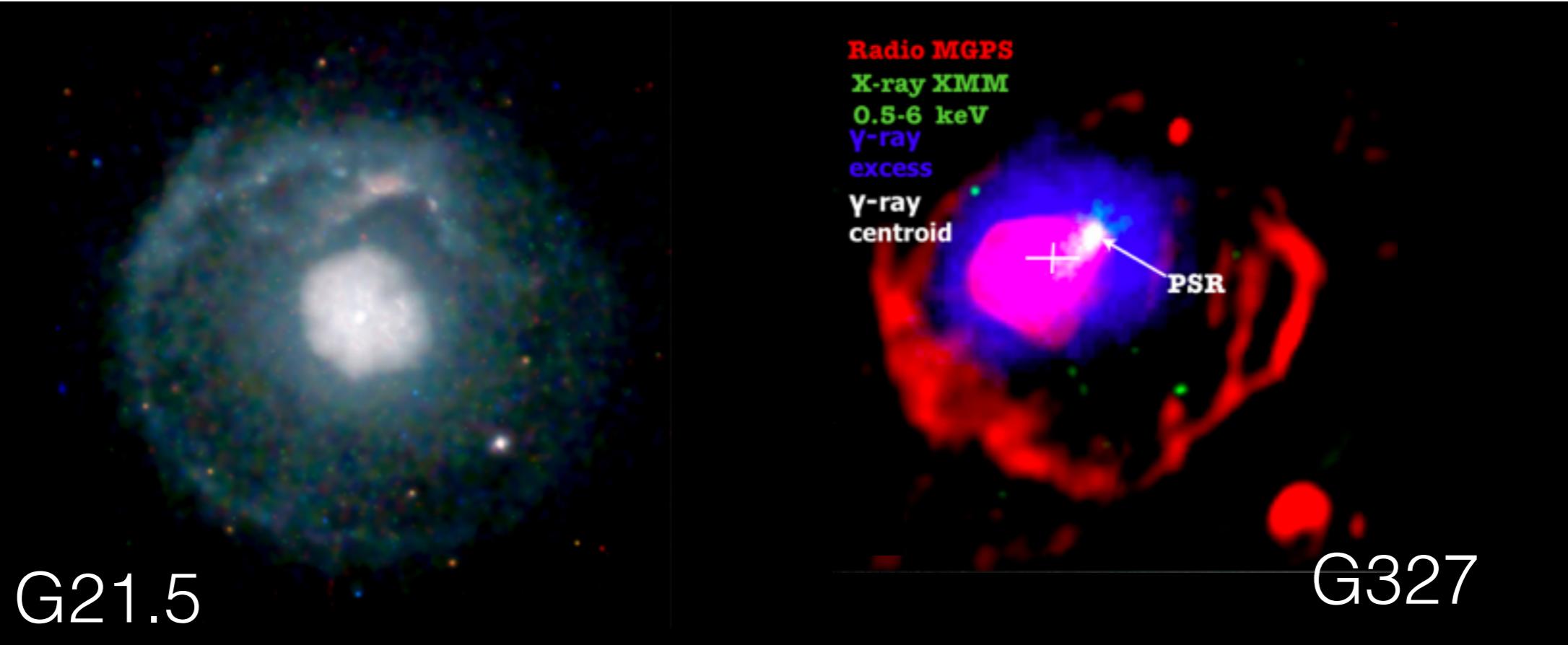


3C58

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

## SNRs - Composite

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

## SNRs - Mixed morphology

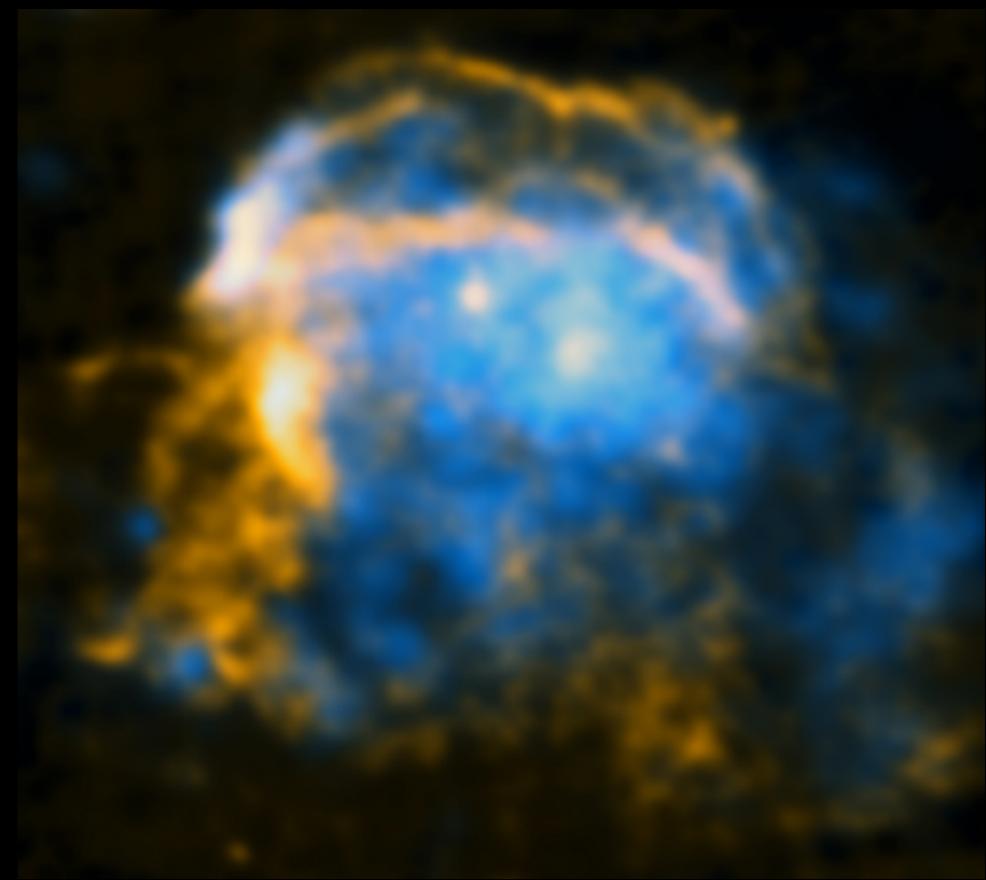
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Optical  
X-rays



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

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### Supernova explosion

ejecta  $V_{\text{shock}} \sim 10^4$  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

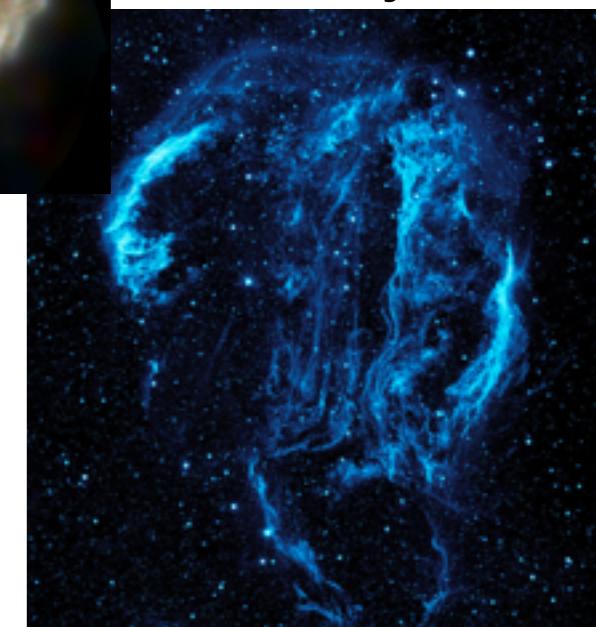
150 yrs



1010 yrs



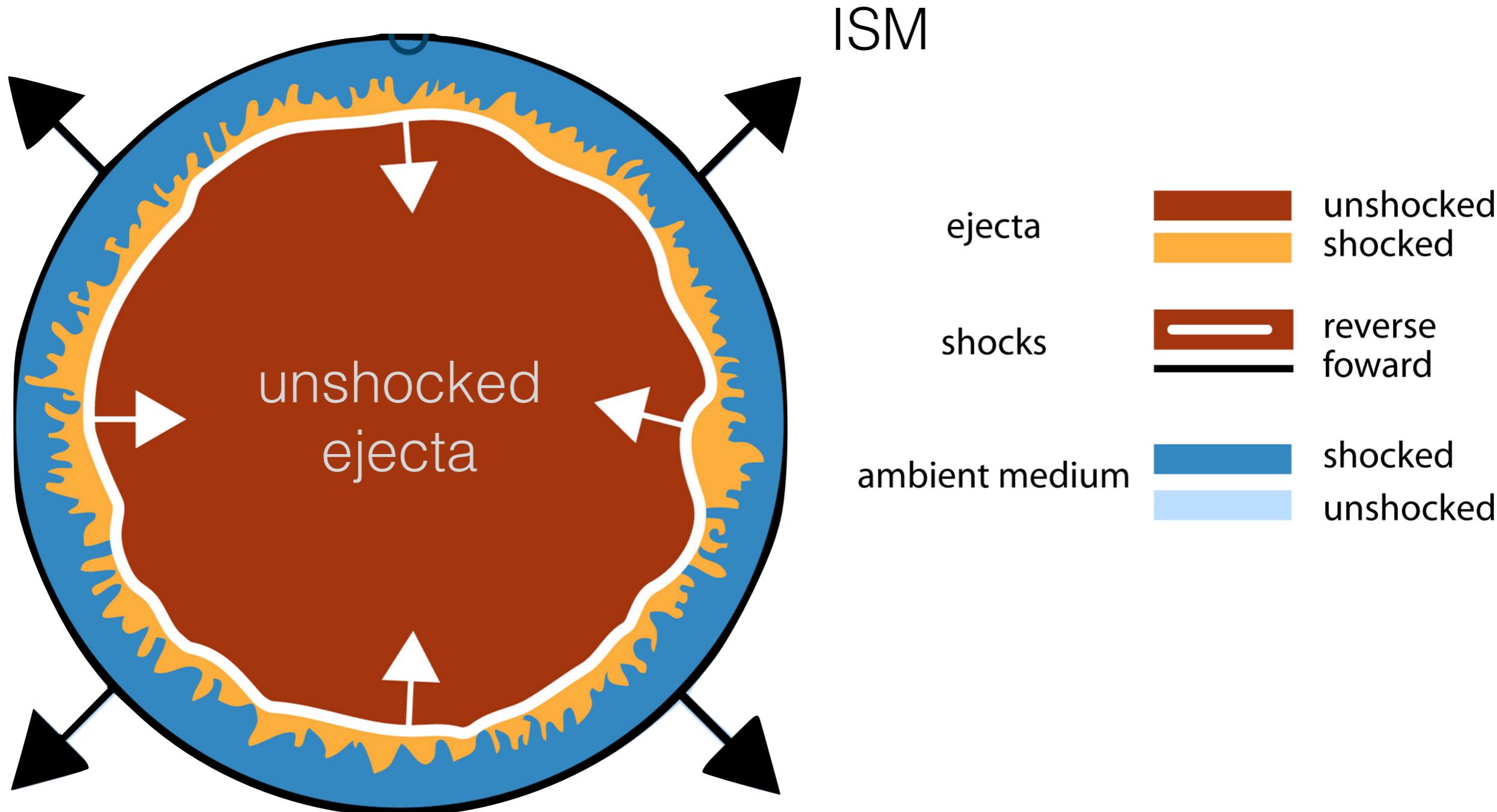
~15 kyrs



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

# SNR structure

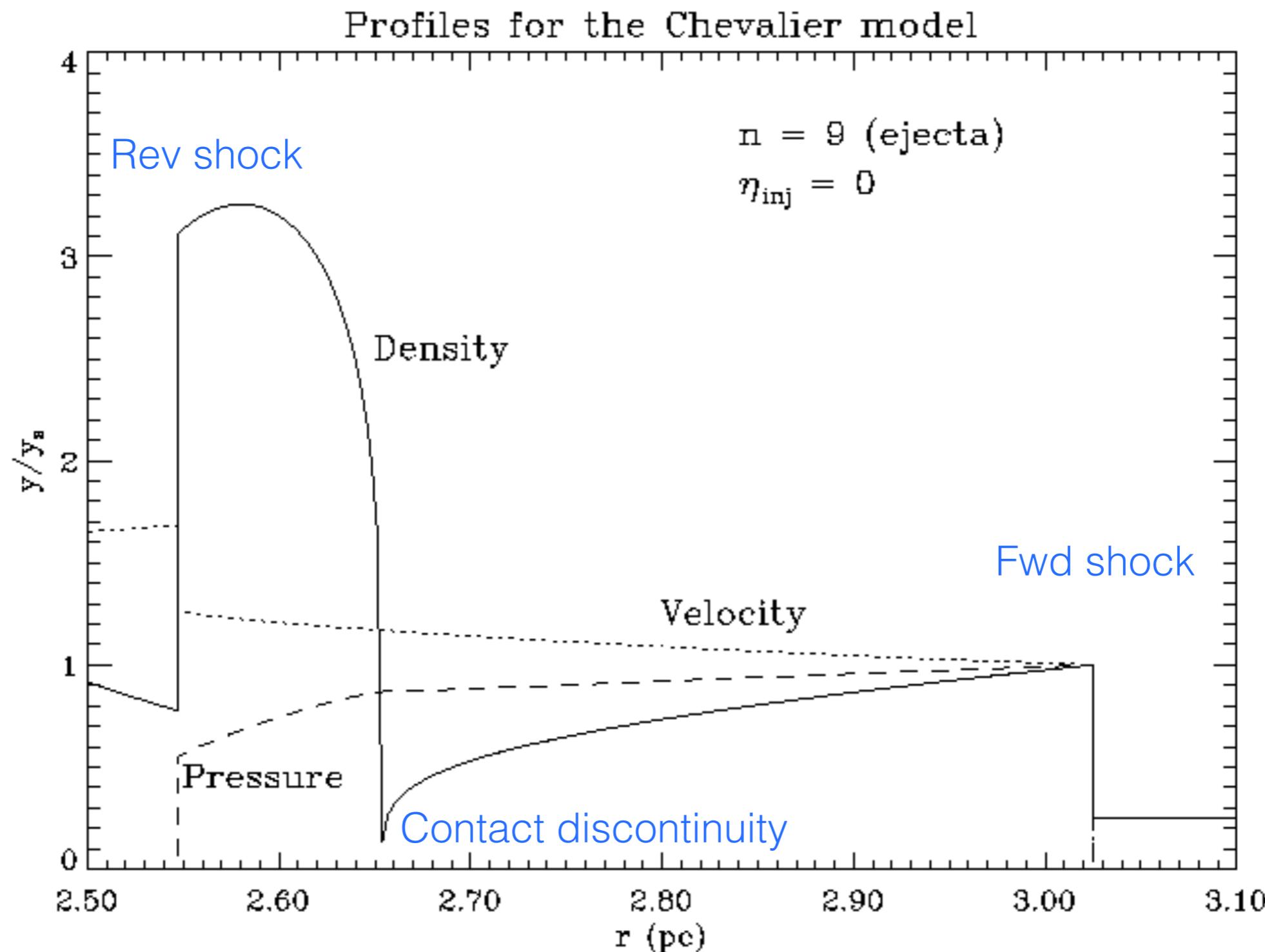
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# SNR hydrodynamics

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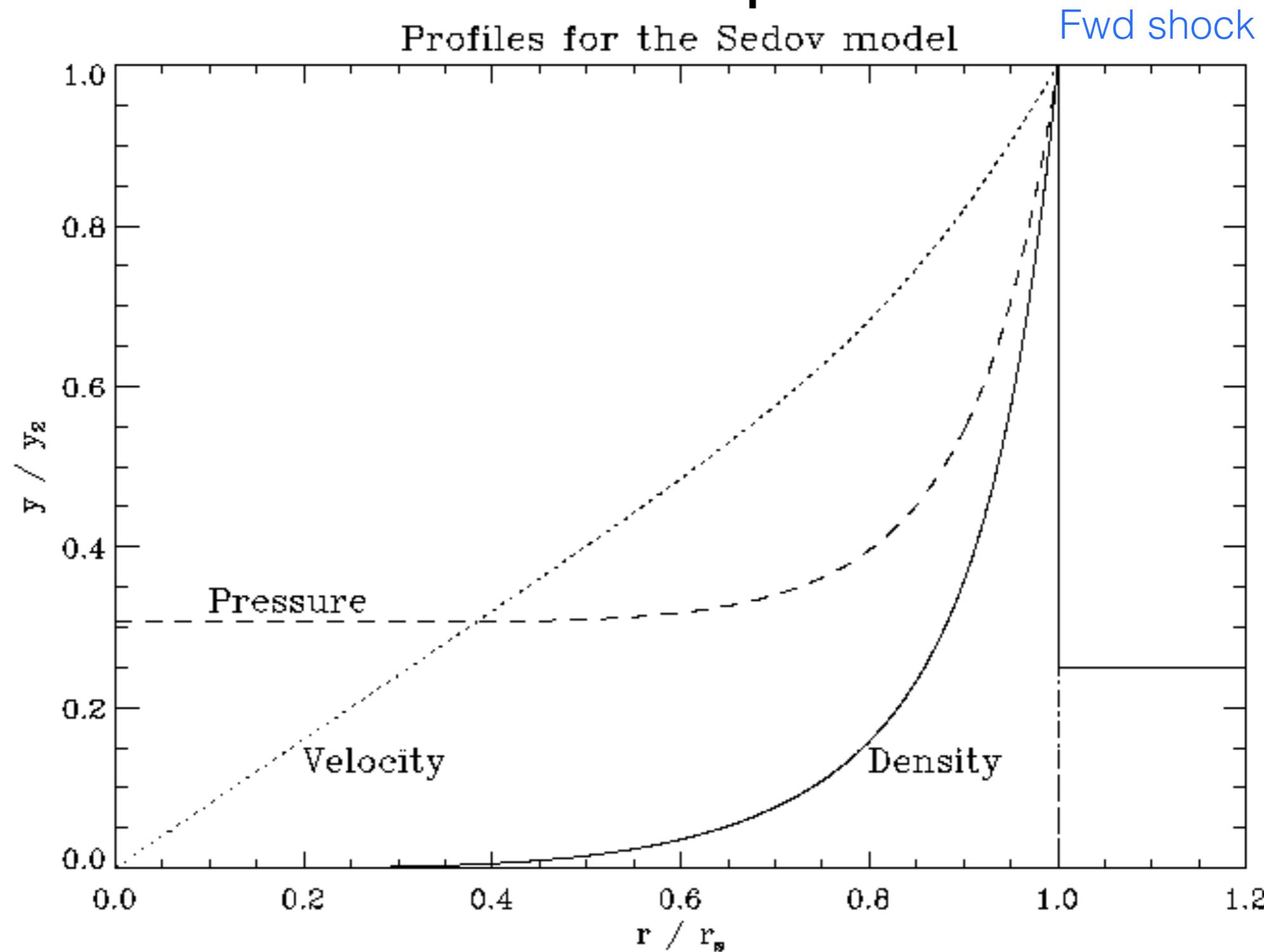
- Self similar solutions for the ejecta dominated phase



# SNR hydrodynamics

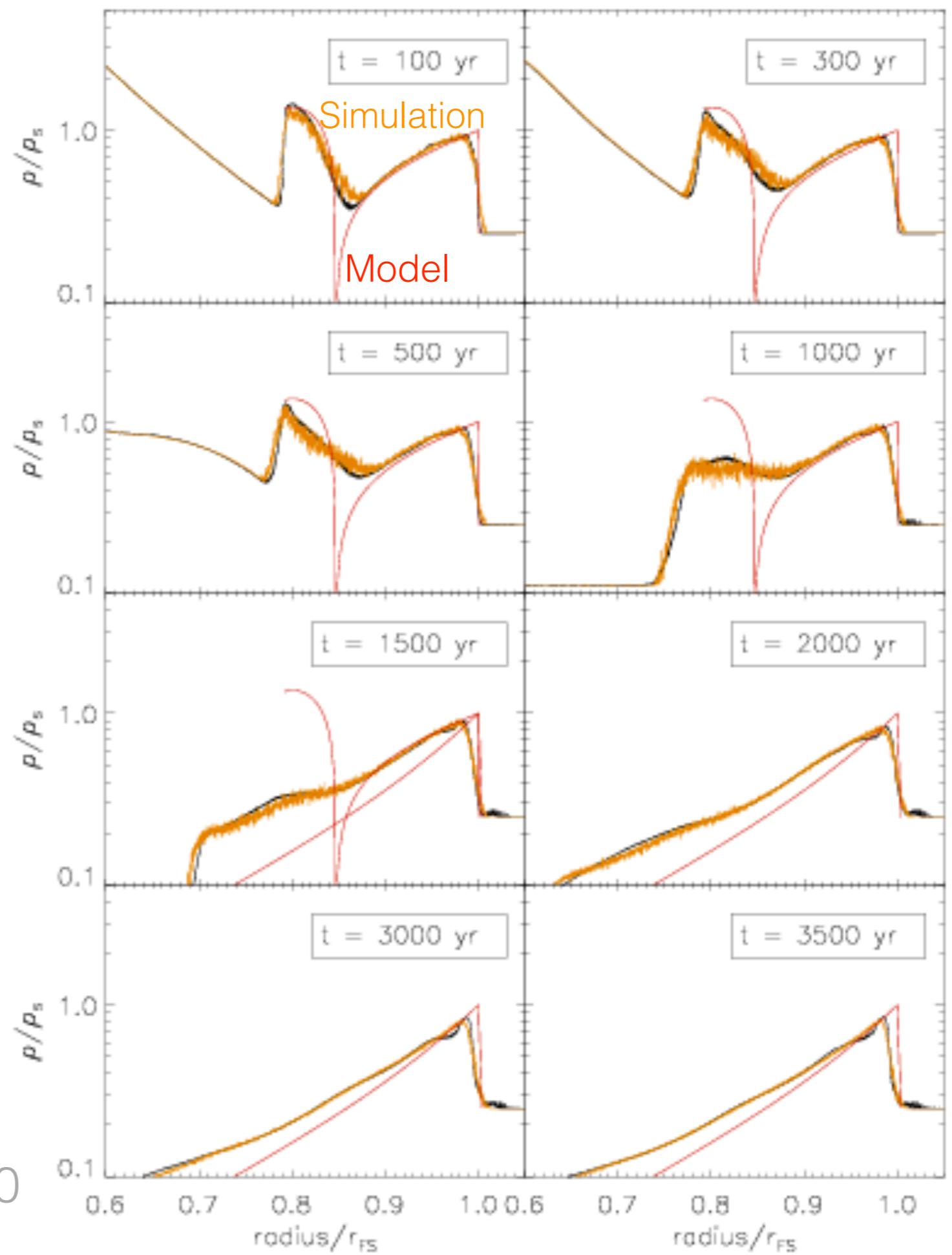
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- Self similar solutions for the Sedov phase



# Structural time evolution

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## Self similar solutions

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

$$R_S \propto t^\beta$$
$$\beta = (n - 3)/(n - s) \quad \text{Ejecta phase}$$
$$\beta = 2/(5 - s) \quad \text{Sedov phase}$$

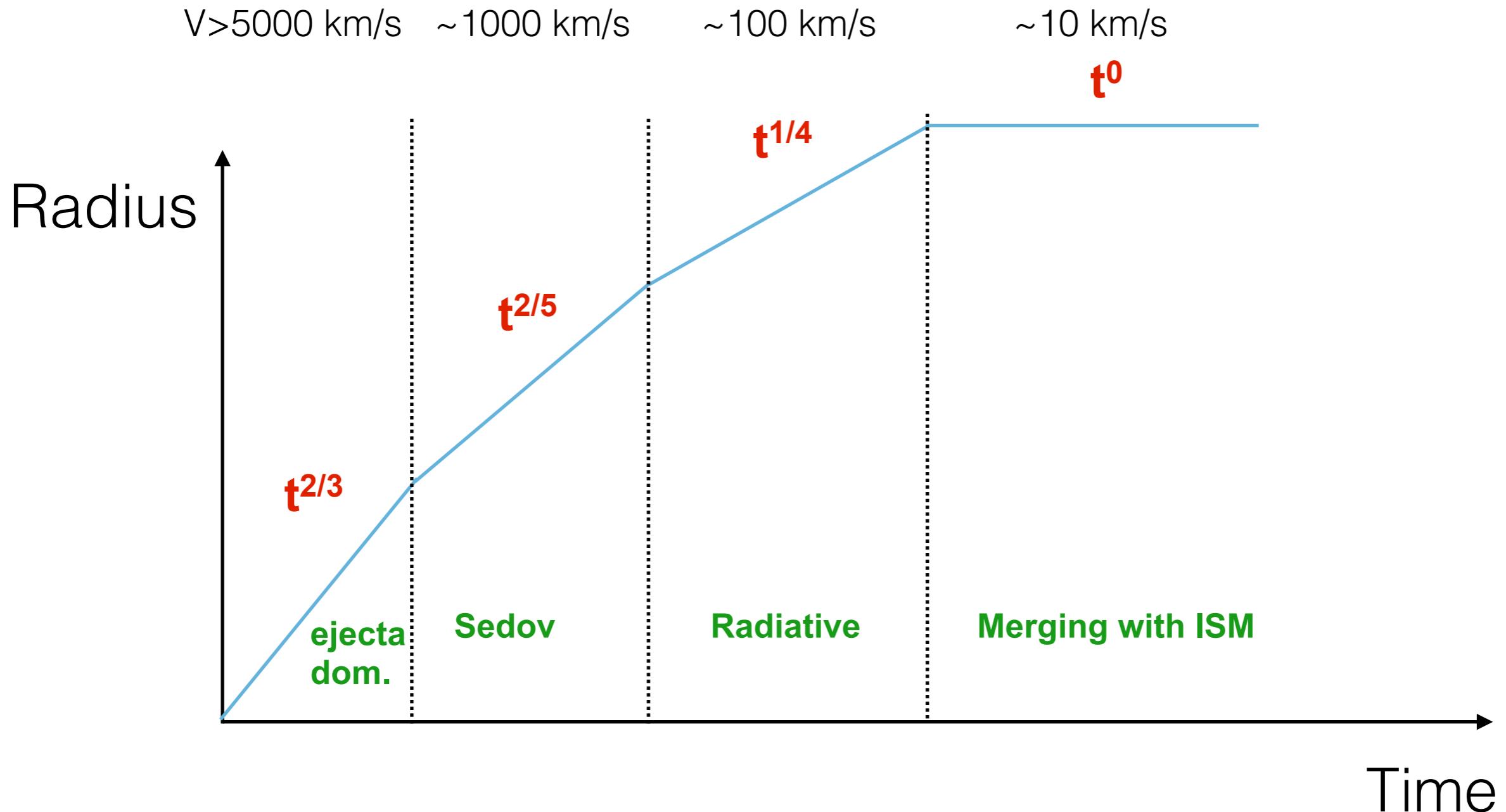
where n (ejecta profile), s (ambient density profile)  $\Rightarrow \rho(r) \propto r^{-n,s}$

- **s = 0 — homogenous ambient medium (e.g. Type Ia SNR)**
  - $\beta = 0.66 \Rightarrow 0.4$  (for n=9)
- **s = 2 — SNR evolving in a wind density profile (CC supernova)**
  - $\beta = 0.86 \Rightarrow 0.66$  (for n=9)
- **Observations: in Galaxy M81, CC SN1993J  $\beta=0.85 \Rightarrow n=8.5$**

Marcaide+09

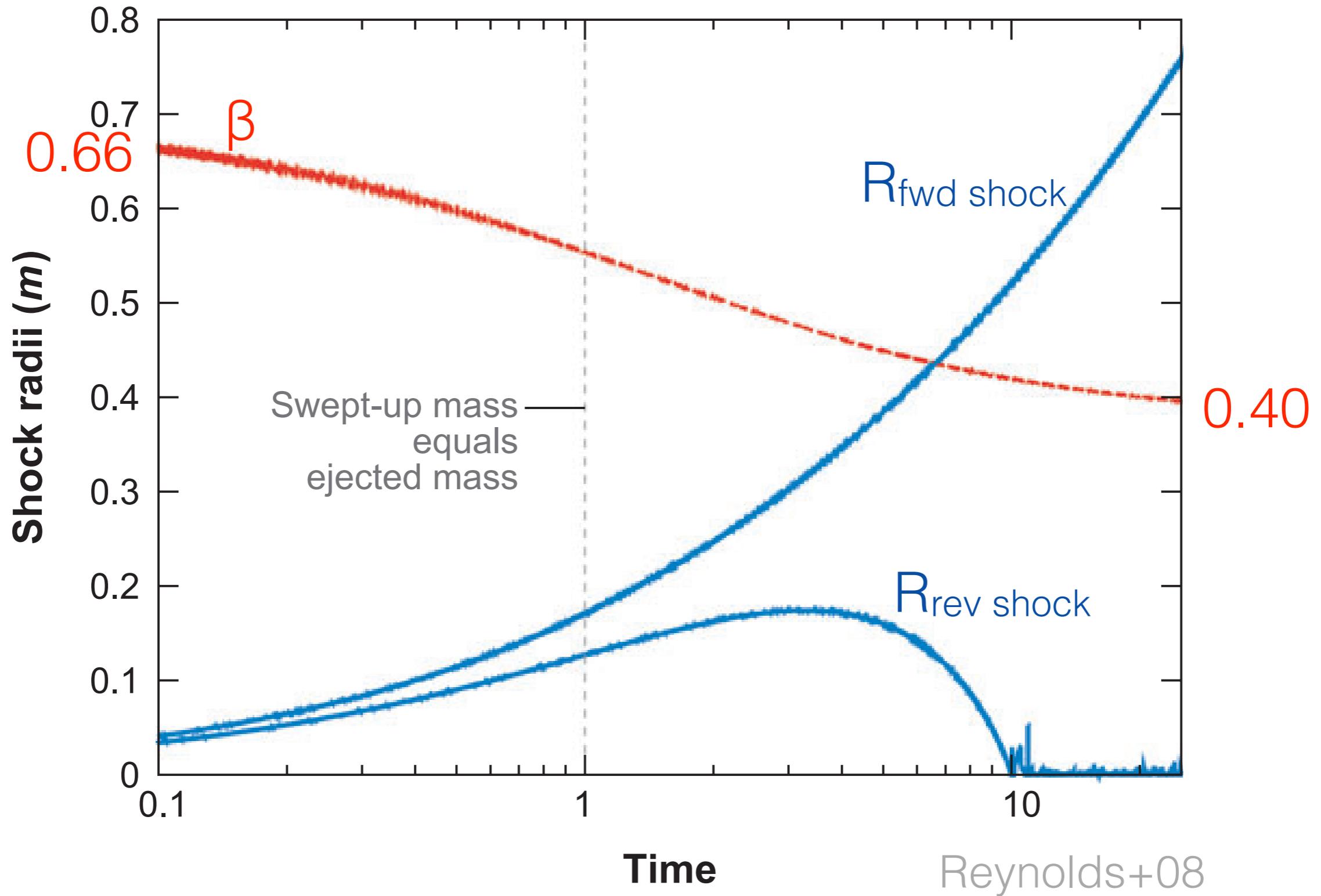
# Time evolution

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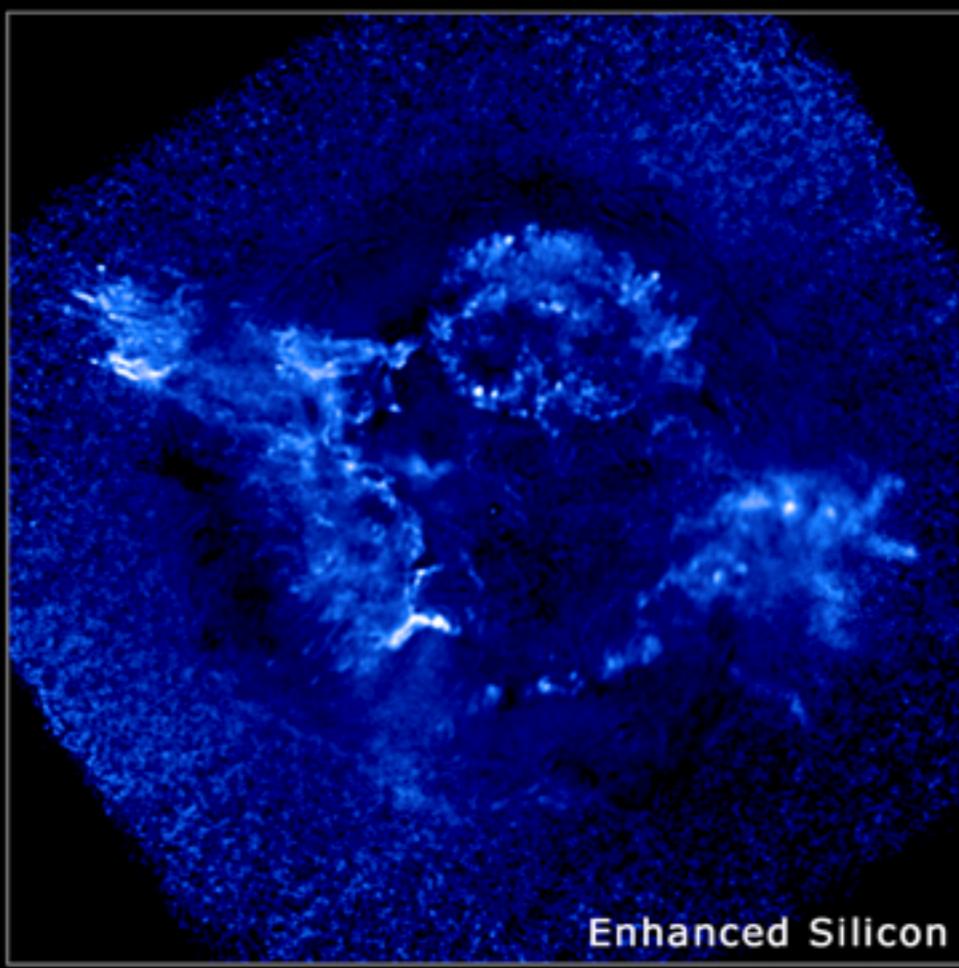
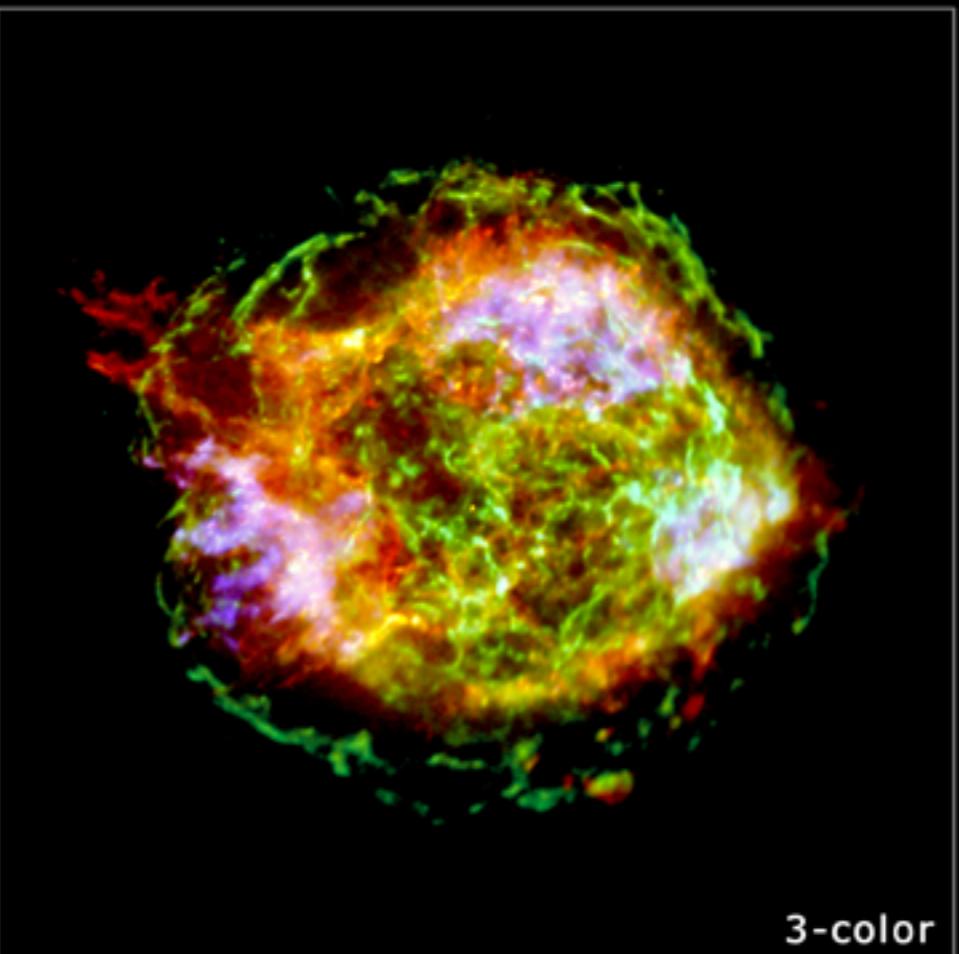


# Self similar solutions vs Hydro simulation

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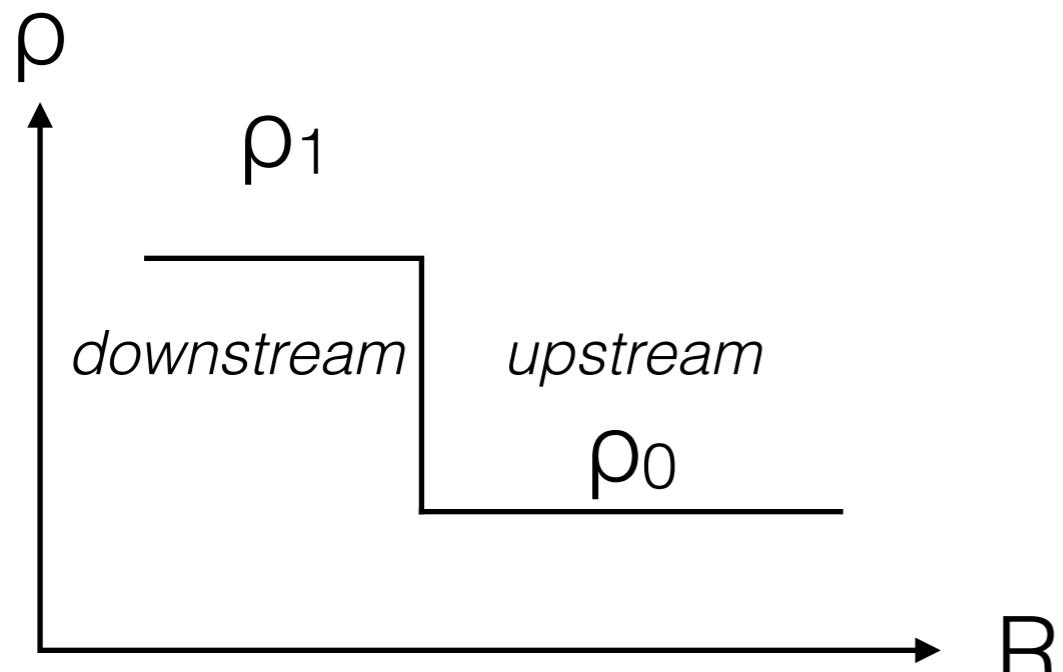


# What can we learn from thermal X-rays



# Shock hydrodynamics

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Conservation of

Mass

$$\rho u = \text{constant}$$

Momentum

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

Energy

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

# Shock hydrodynamics

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For strong shocks:

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

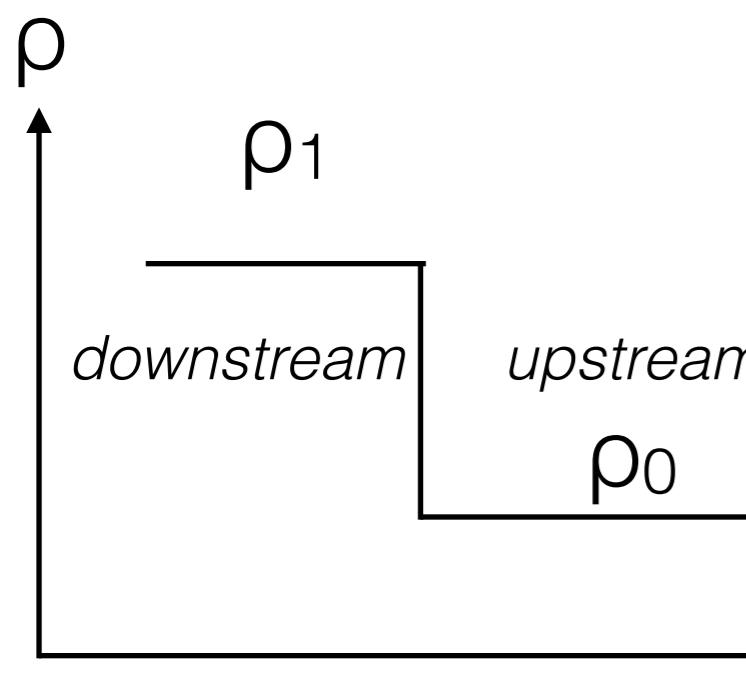
$$u_1 = \frac{\gamma - 1}{\gamma + 1} u_0$$

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

$$\rho_1 = 4\rho_0$$

$$u_1 = \frac{1}{4} u_0$$

$$P_1 = \frac{3}{4} \rho_0 u_0^2$$



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

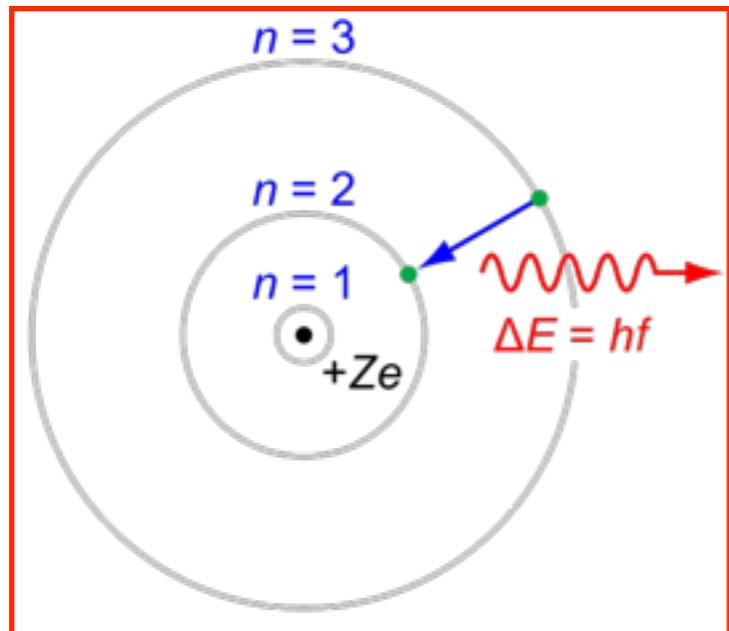
$T \sim 10^7$  K for  $V_s = 1000$  km/s

$$kT_i \propto m_i V_s^2$$

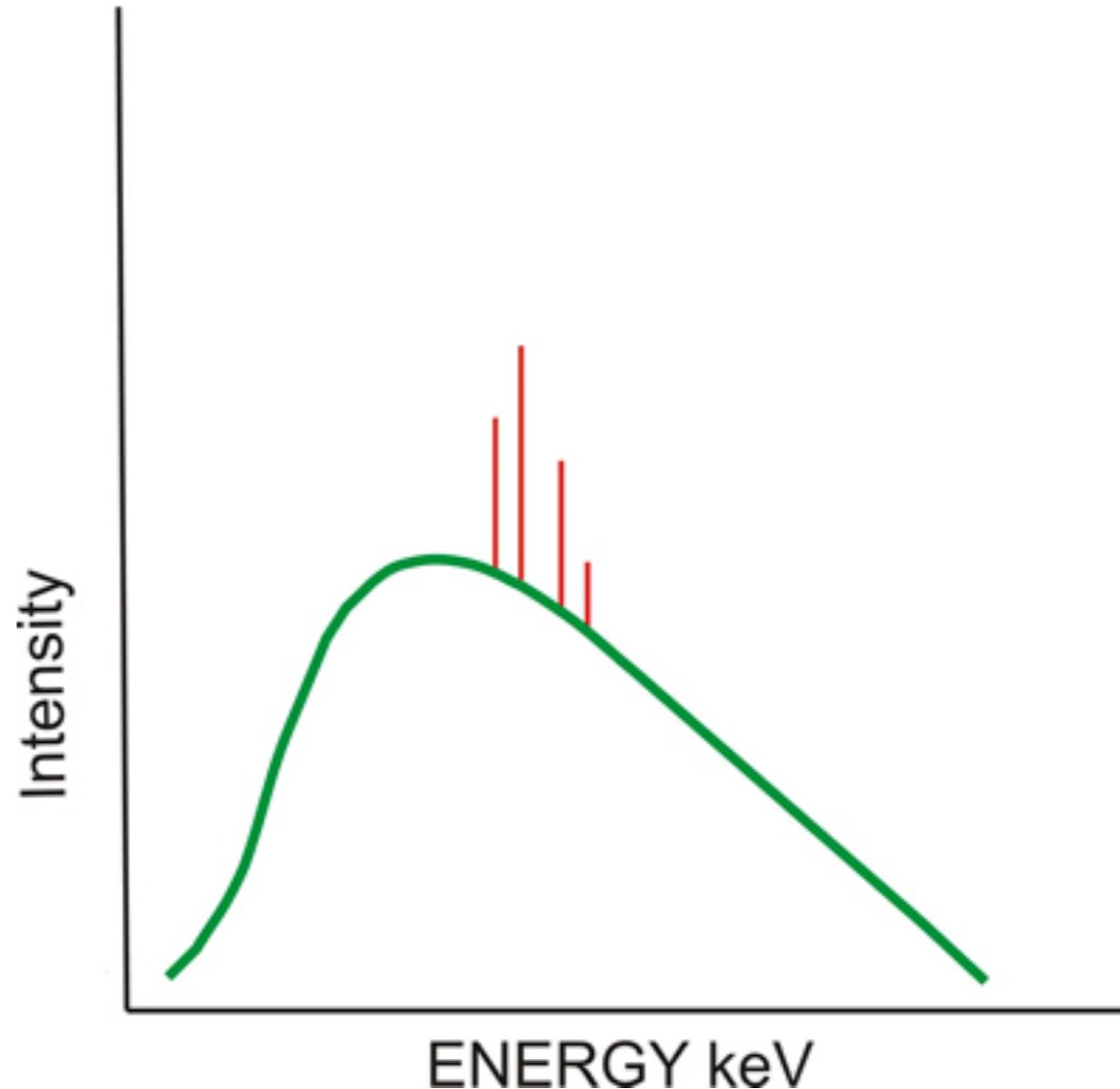
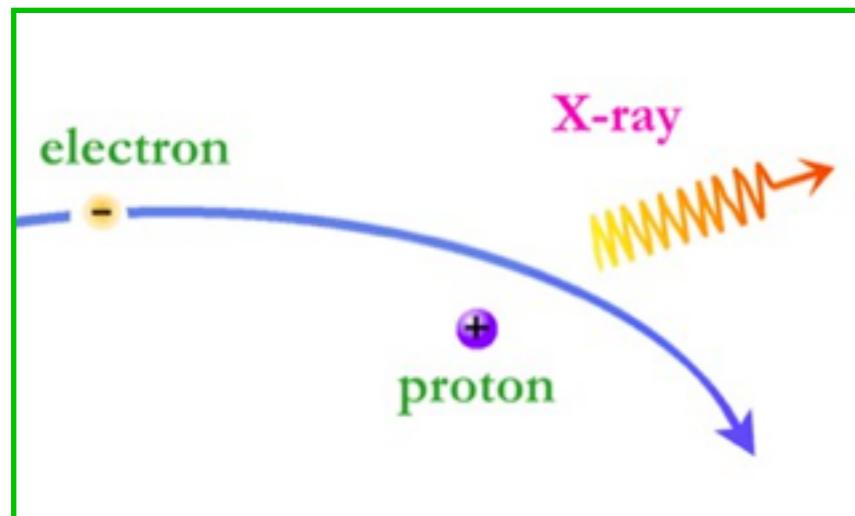
# Thermal X-ray emission

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## Line emission



## Bremsstrahlung

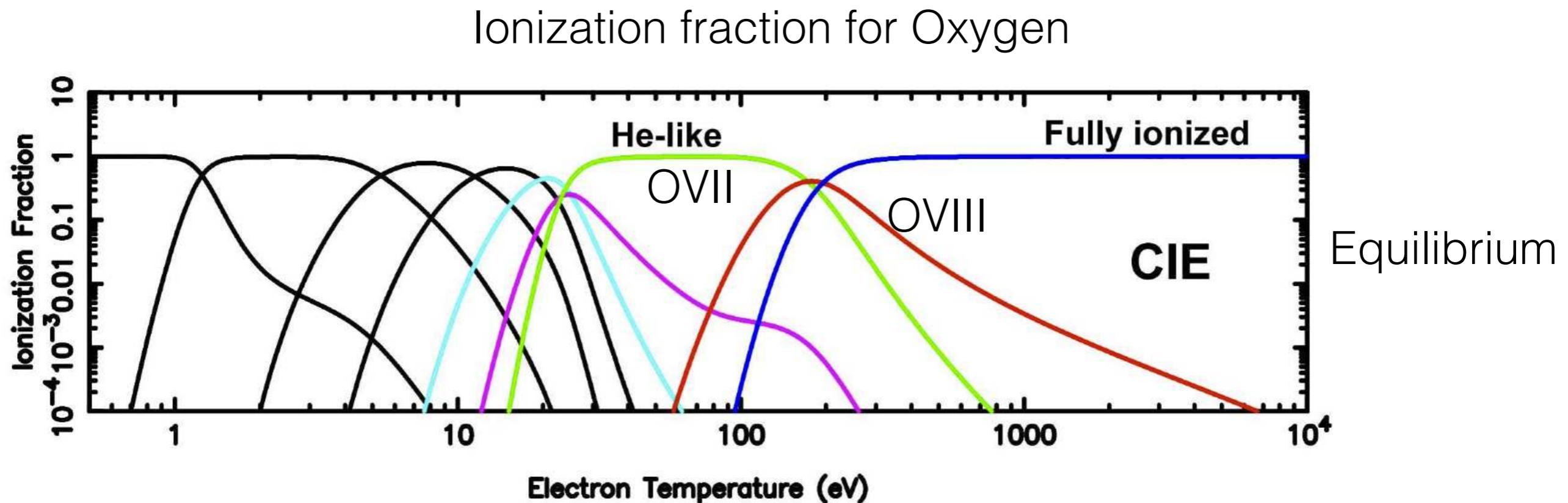


Also:

radiative-recombination continua observed in over-ionized plasma.

# Non-equilibration ionization (NEI)

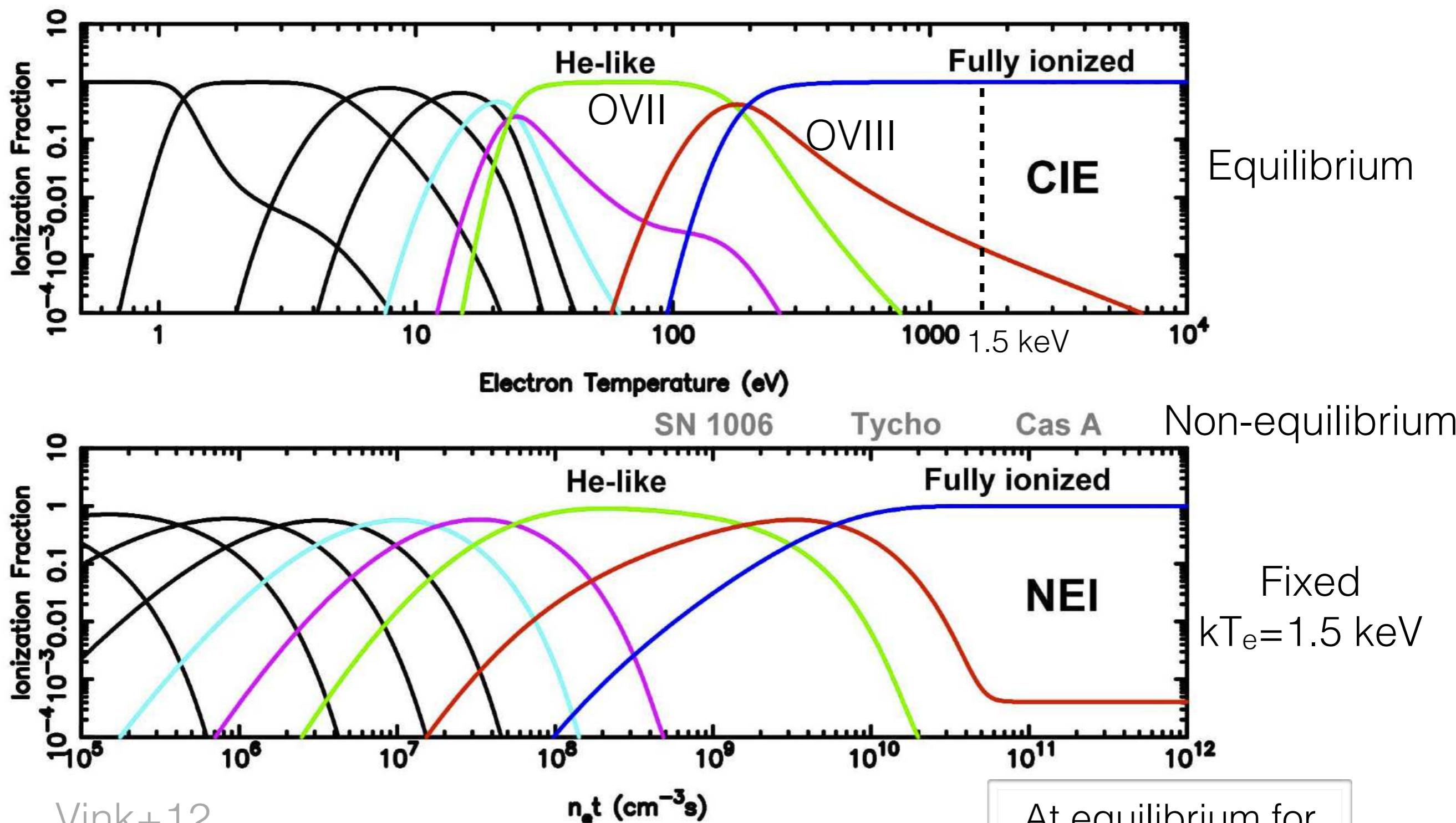
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# Non-equilibration ionization (NEI)

launch binder

NEI creates a delay in ionization state



Vink+12

At equilibrium for  
n<sub>e</sub>t > 10<sup>12</sup> cm<sup>-3</sup> s

## What can we learn

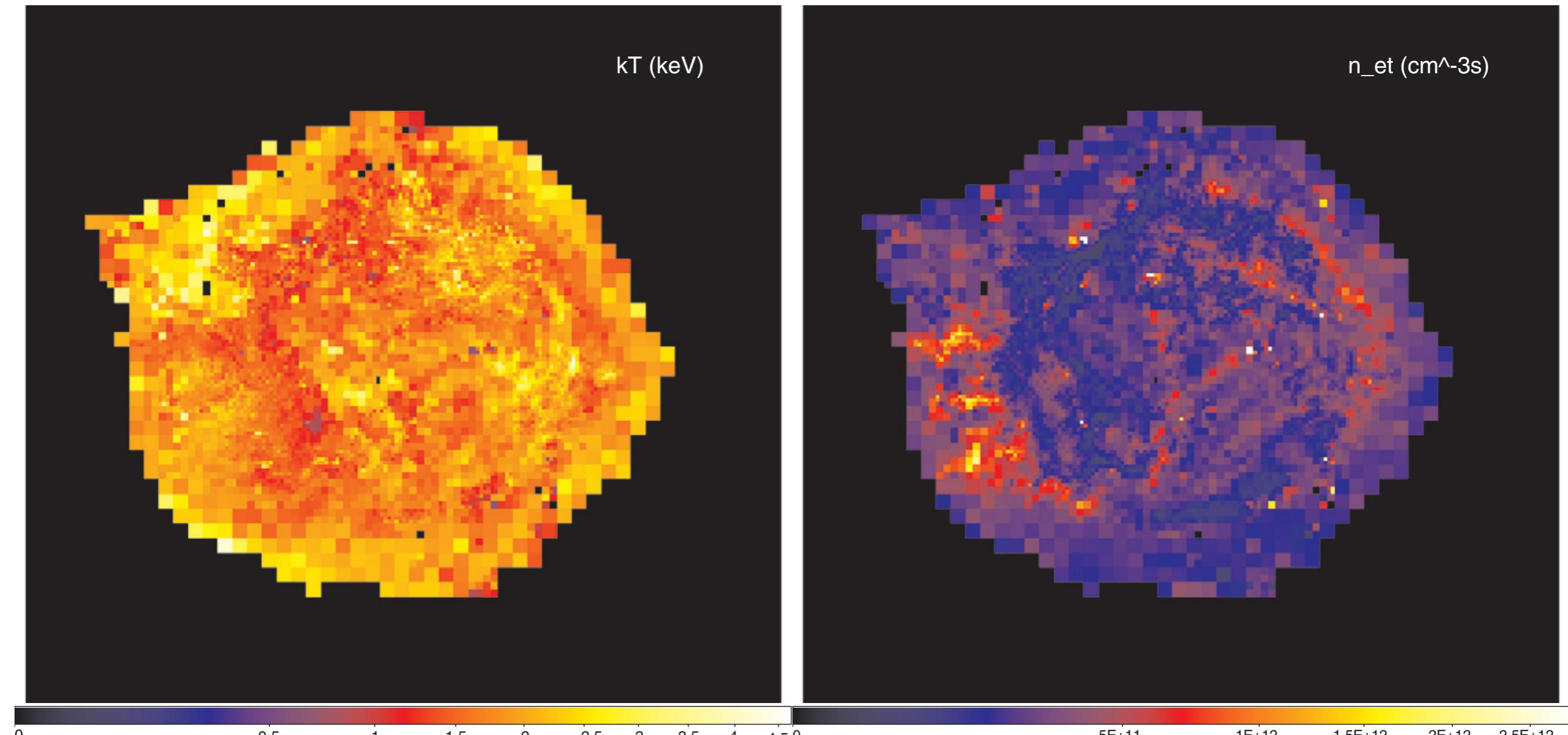
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- From continuum shape: temperature (mostly  $kT_e$ )
  - ~ shock speed (but depends on T equilibration)
- From continuum normalization: Emission measure:  $\int n_e n_H dV$ 
  - Density of emoting plasma => ISM density
- From line ratio: ionization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

# Spatially resolved spectroscopy

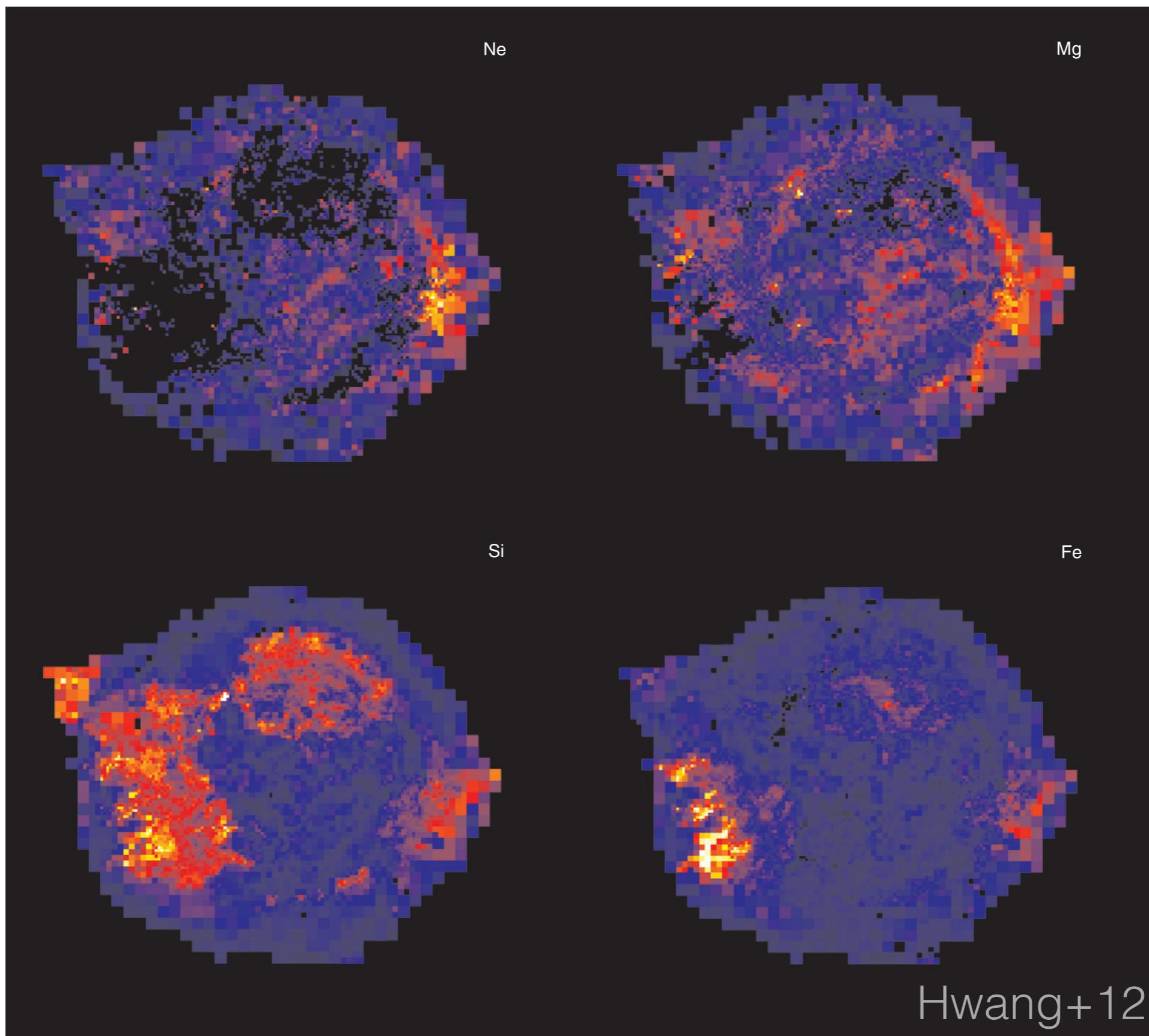
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CasA SNR



Hwang+12

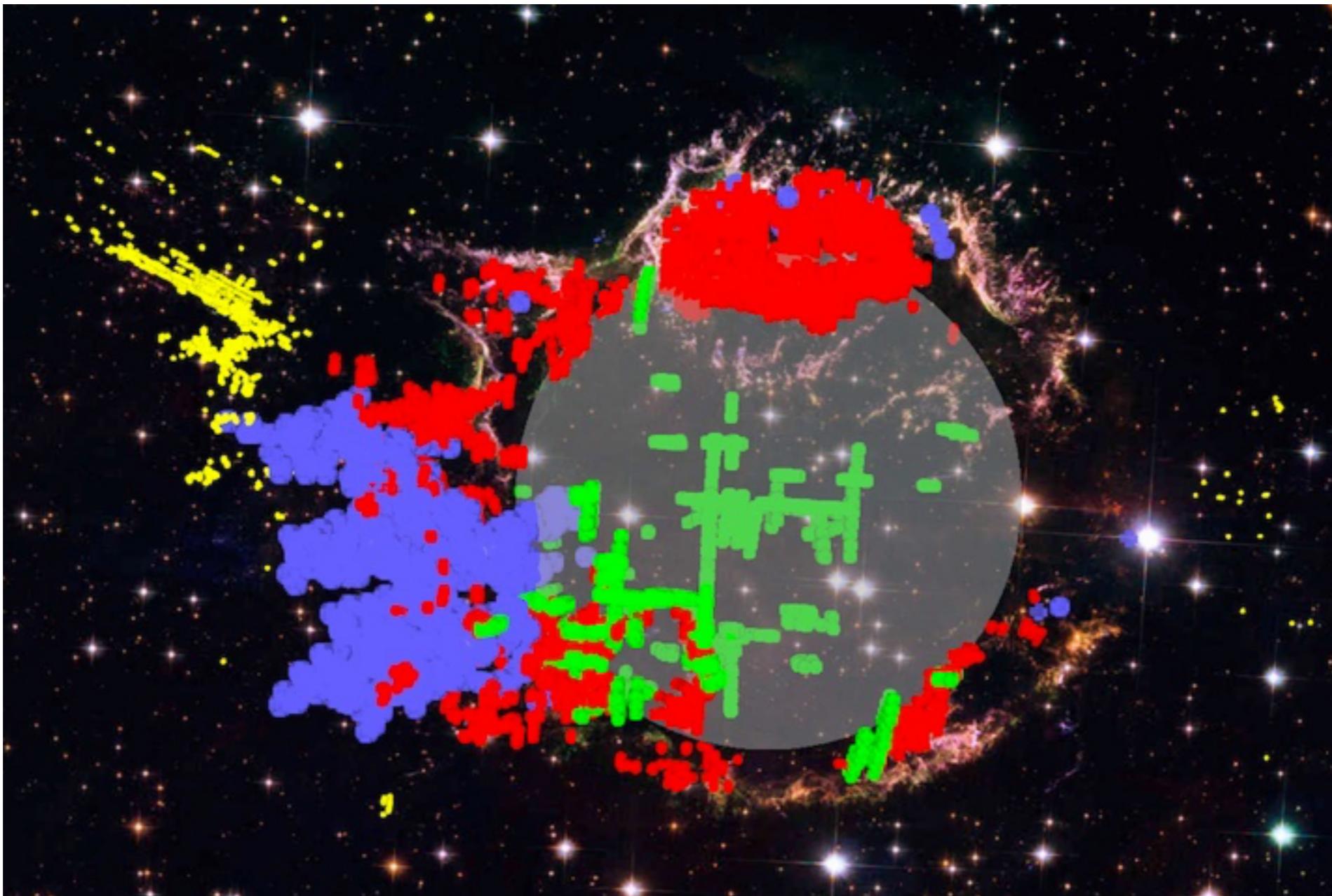
# Nucleosynthesis in CasA



Hwang+12

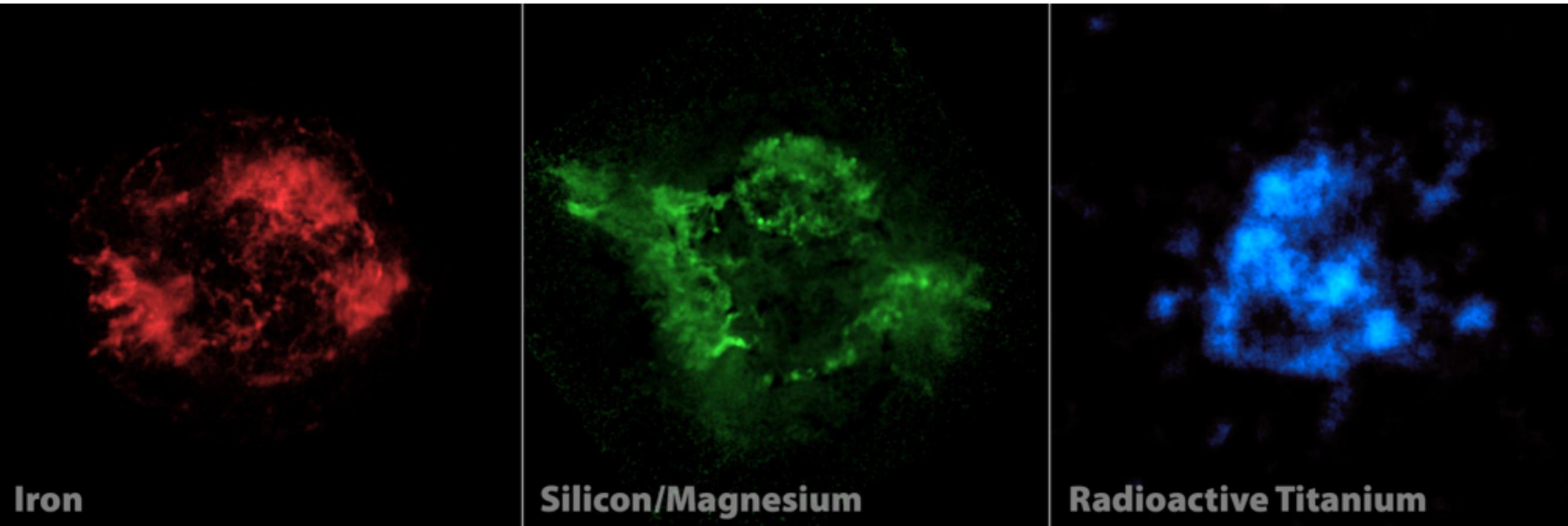
# 3D mapping of ejecta in CasA

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

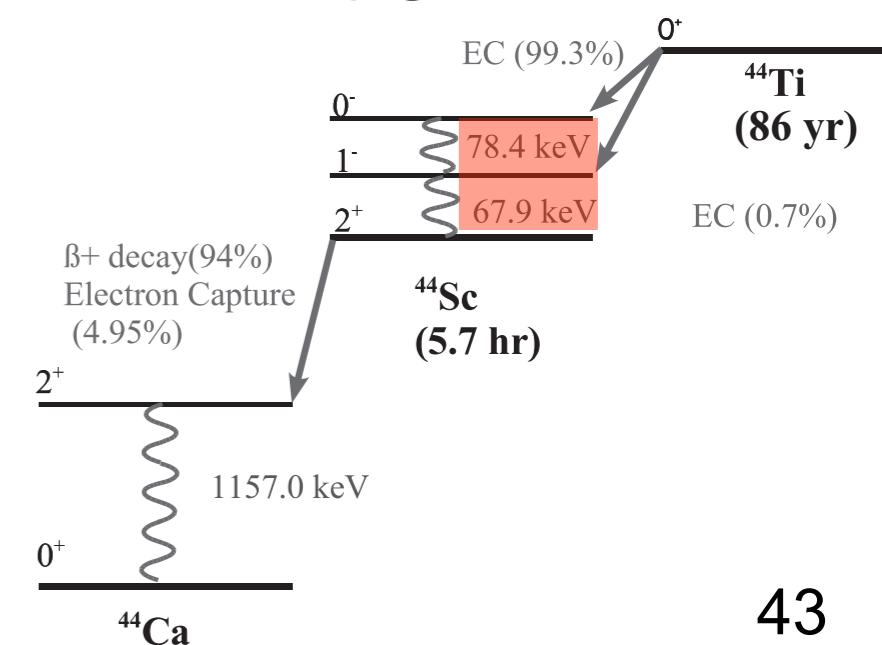
# Explosion mechanism & nucleosynthesis



Chandra

Chandra

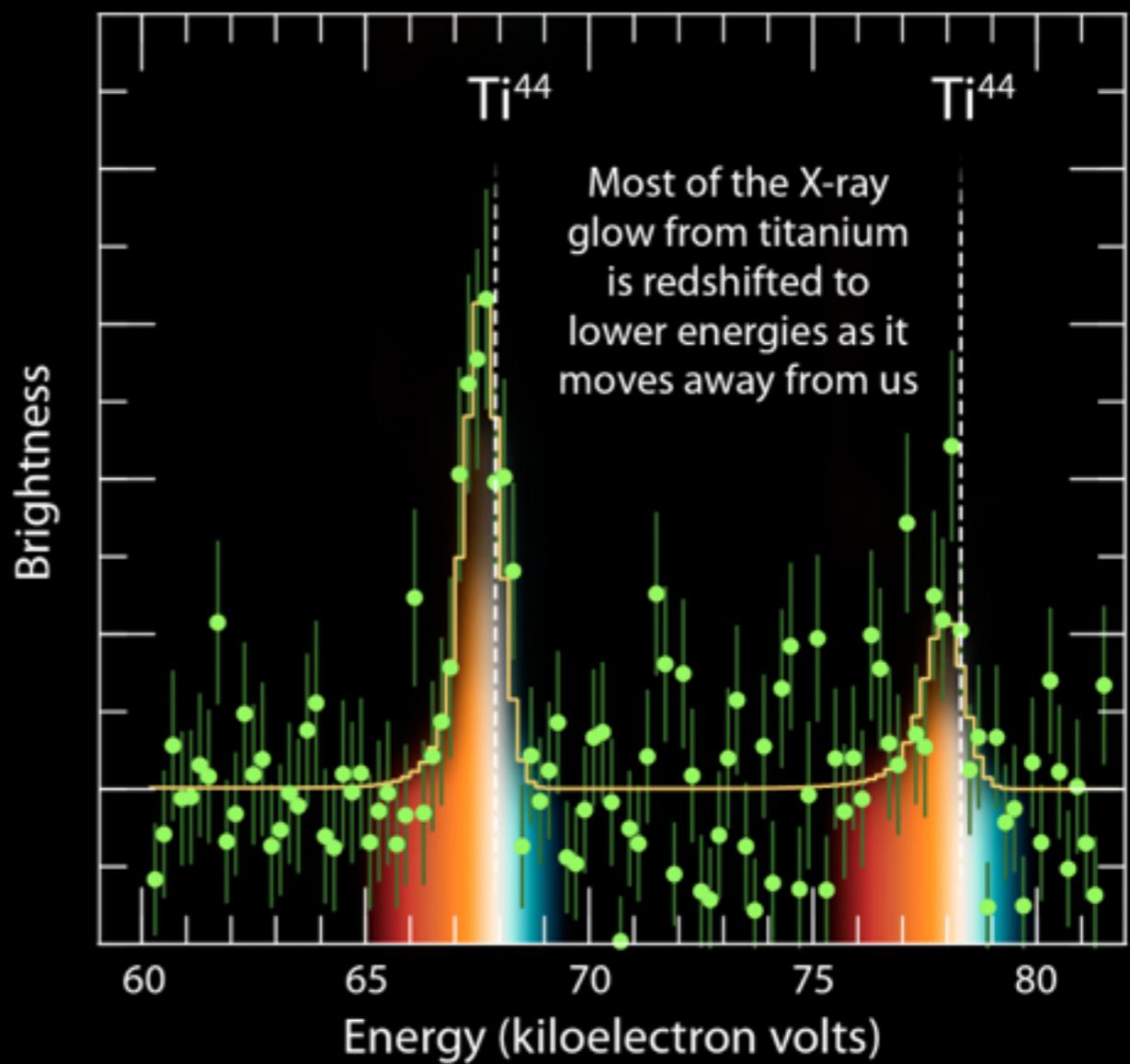
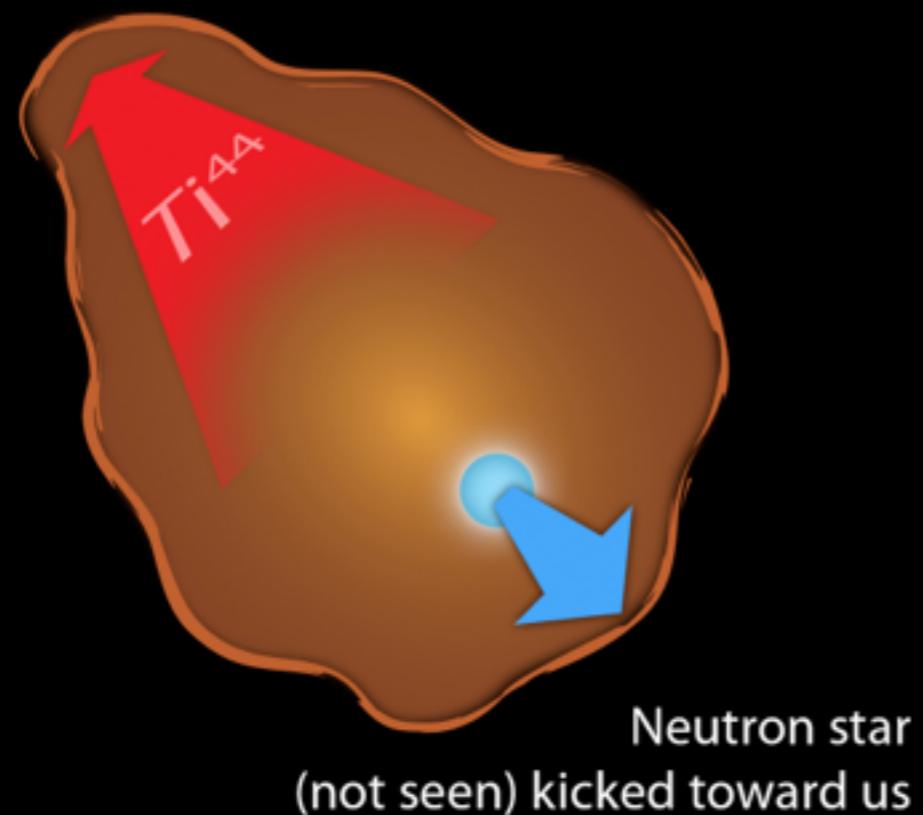
NuSTAR



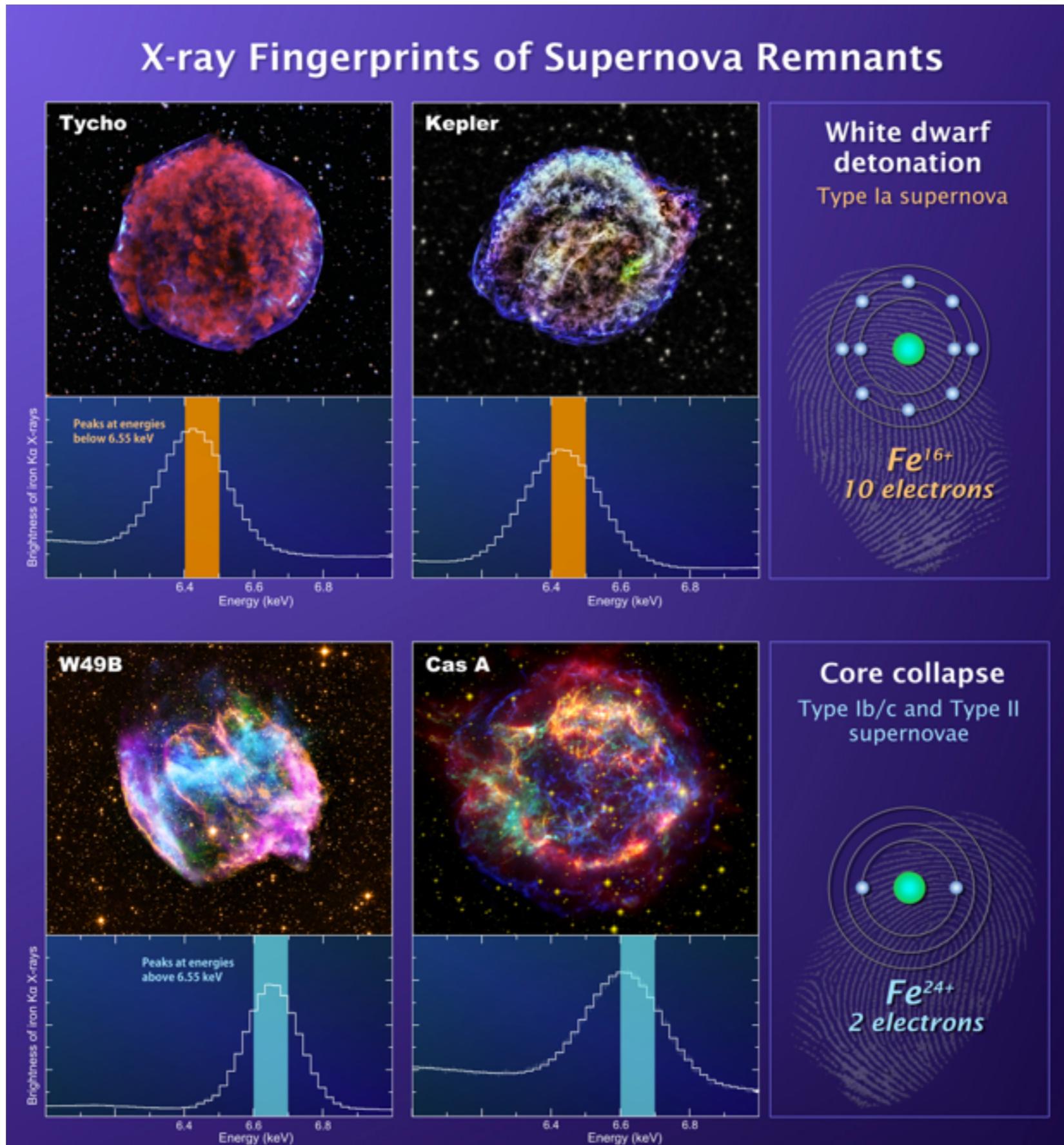
# Explosion mechanism

## NuSTAR Sees Titanium Glow in Supernova 1987A

Asymmetric cloud of supernova debris  
mostly thrown away from us

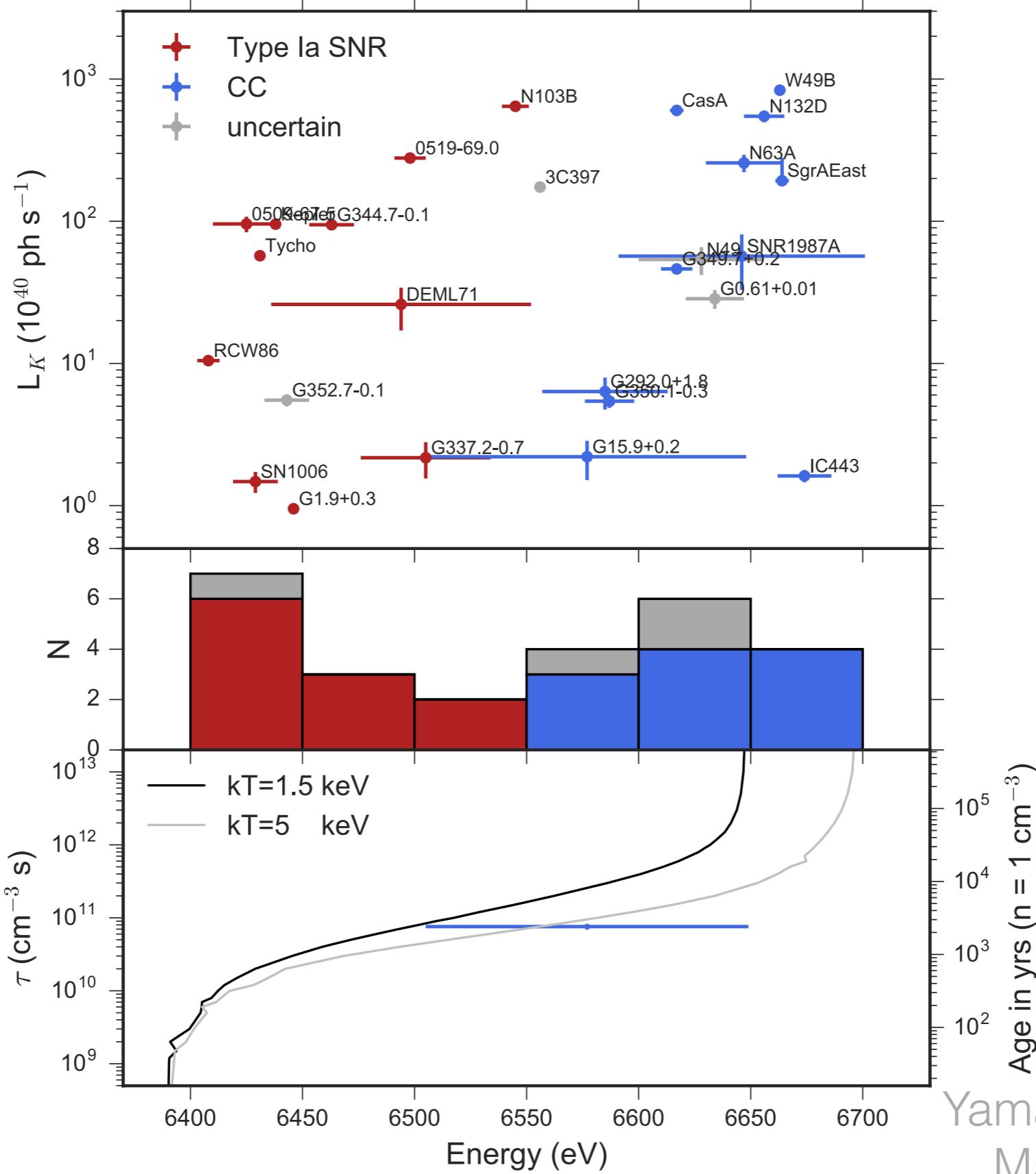


# Fe line reveals the nature & past history of SNRs



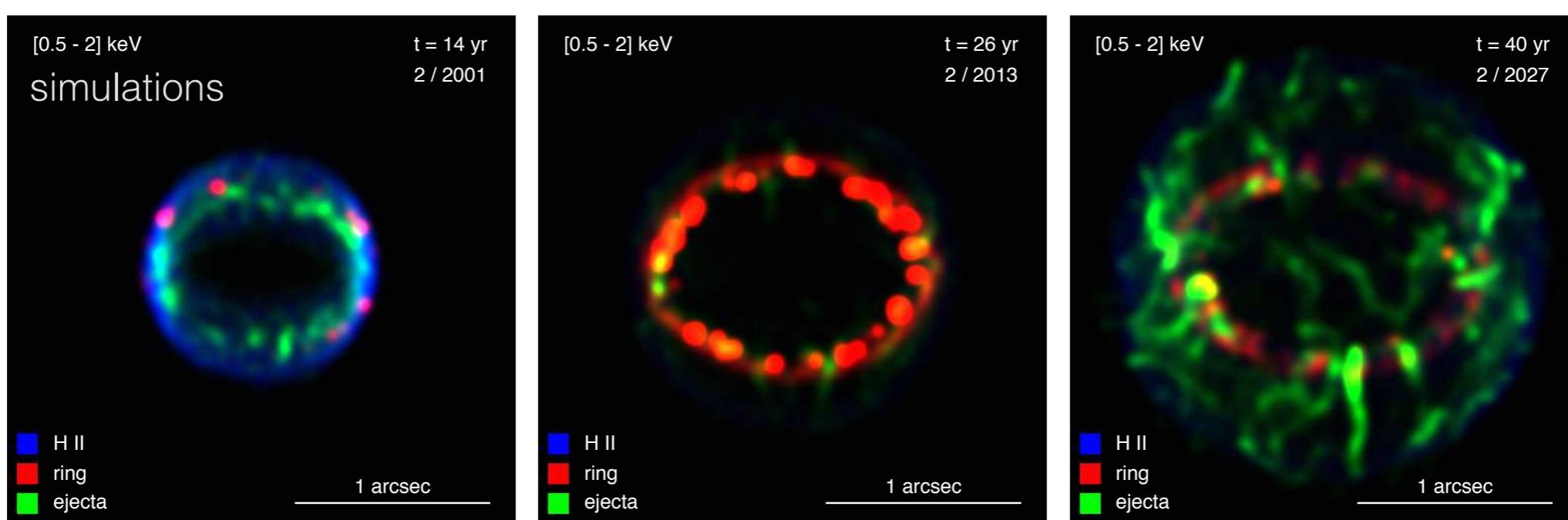
# Fe line reveals the nature & past history of SNRs

$$\tau = \int n_e dt$$



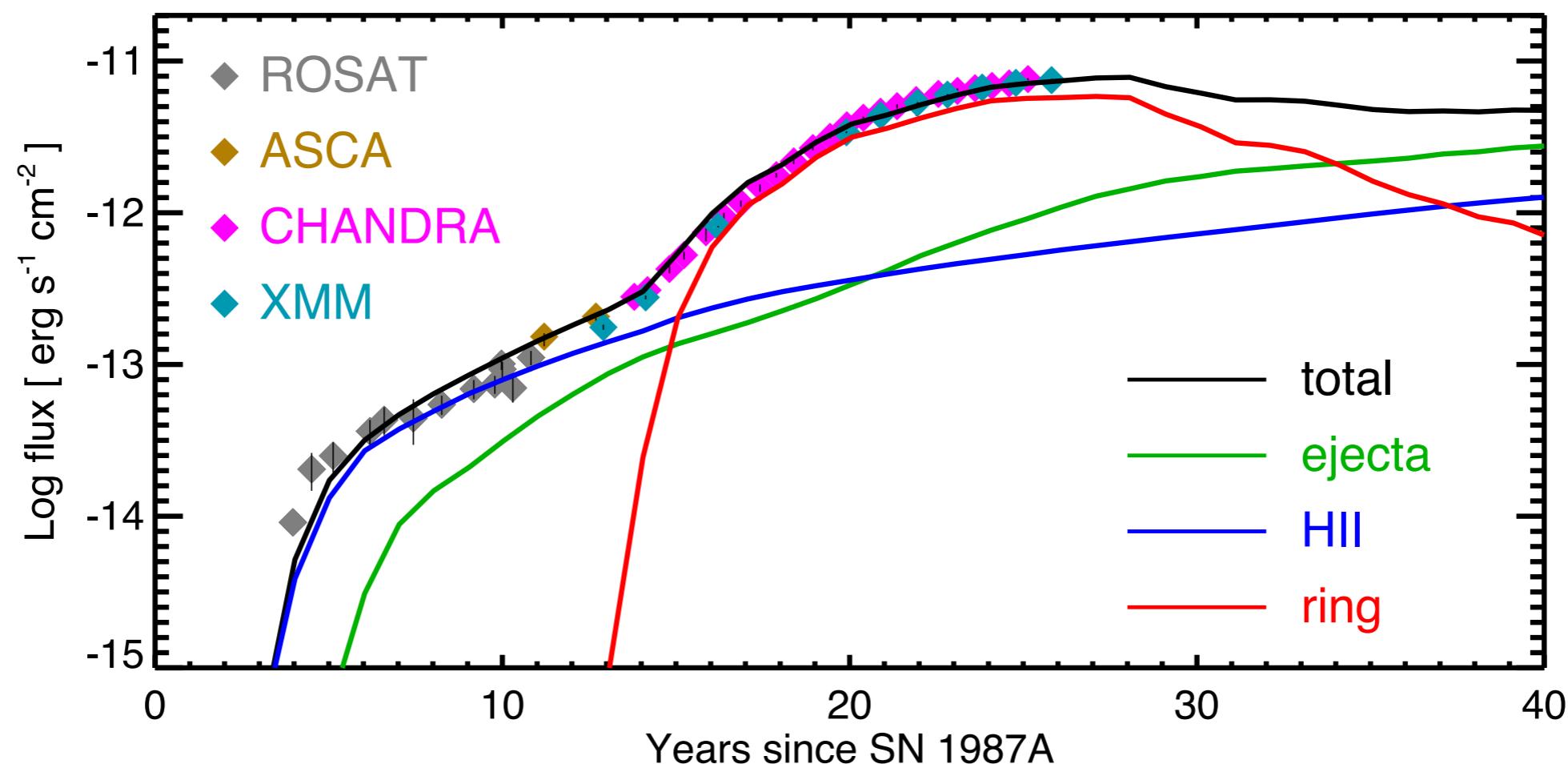
Yamaguchi+14  
Maggi+16

# « the ring of fire » in SN1987a

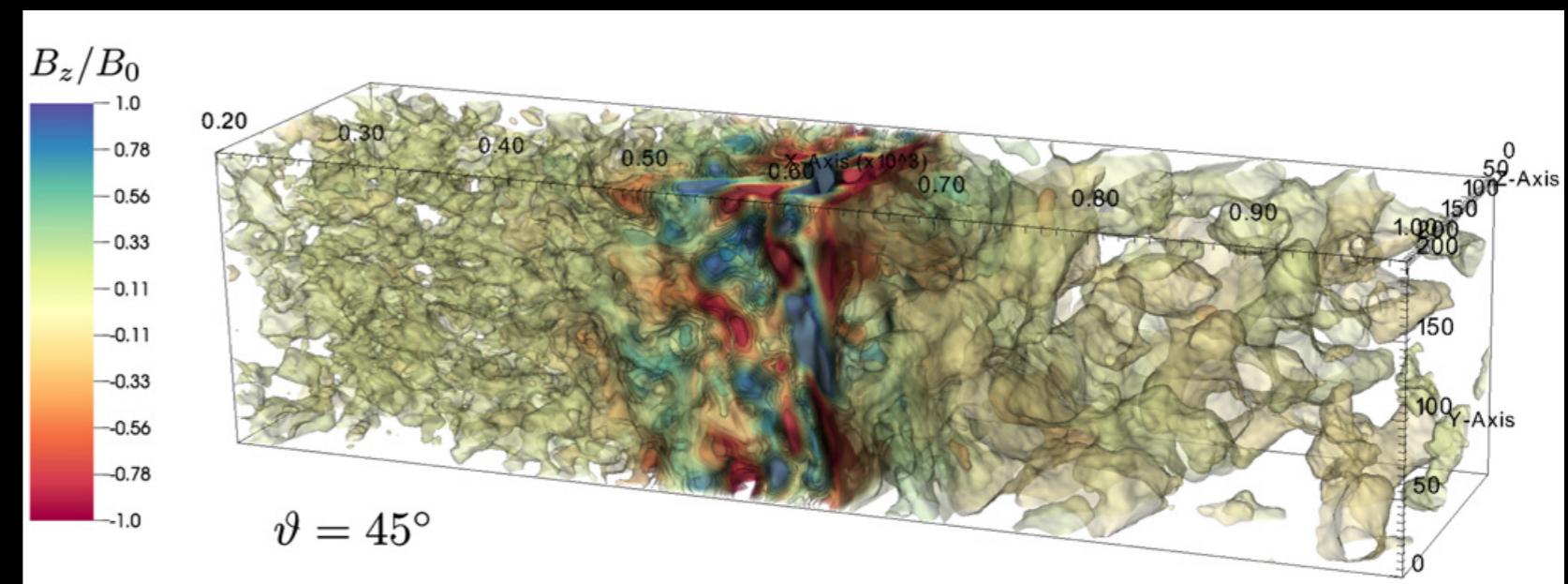
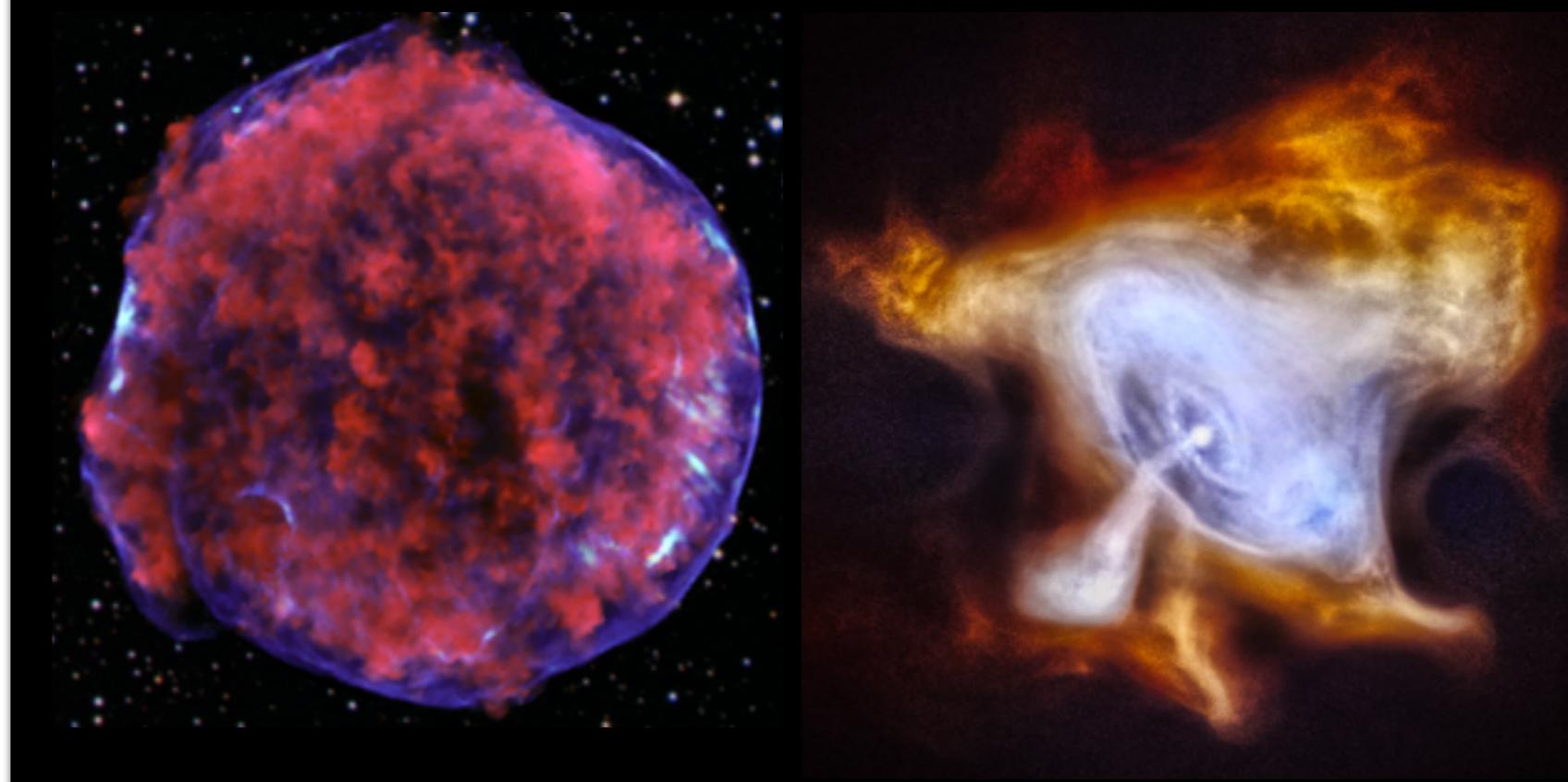


(b) [0.5, 2.0] keV

Orlando+15



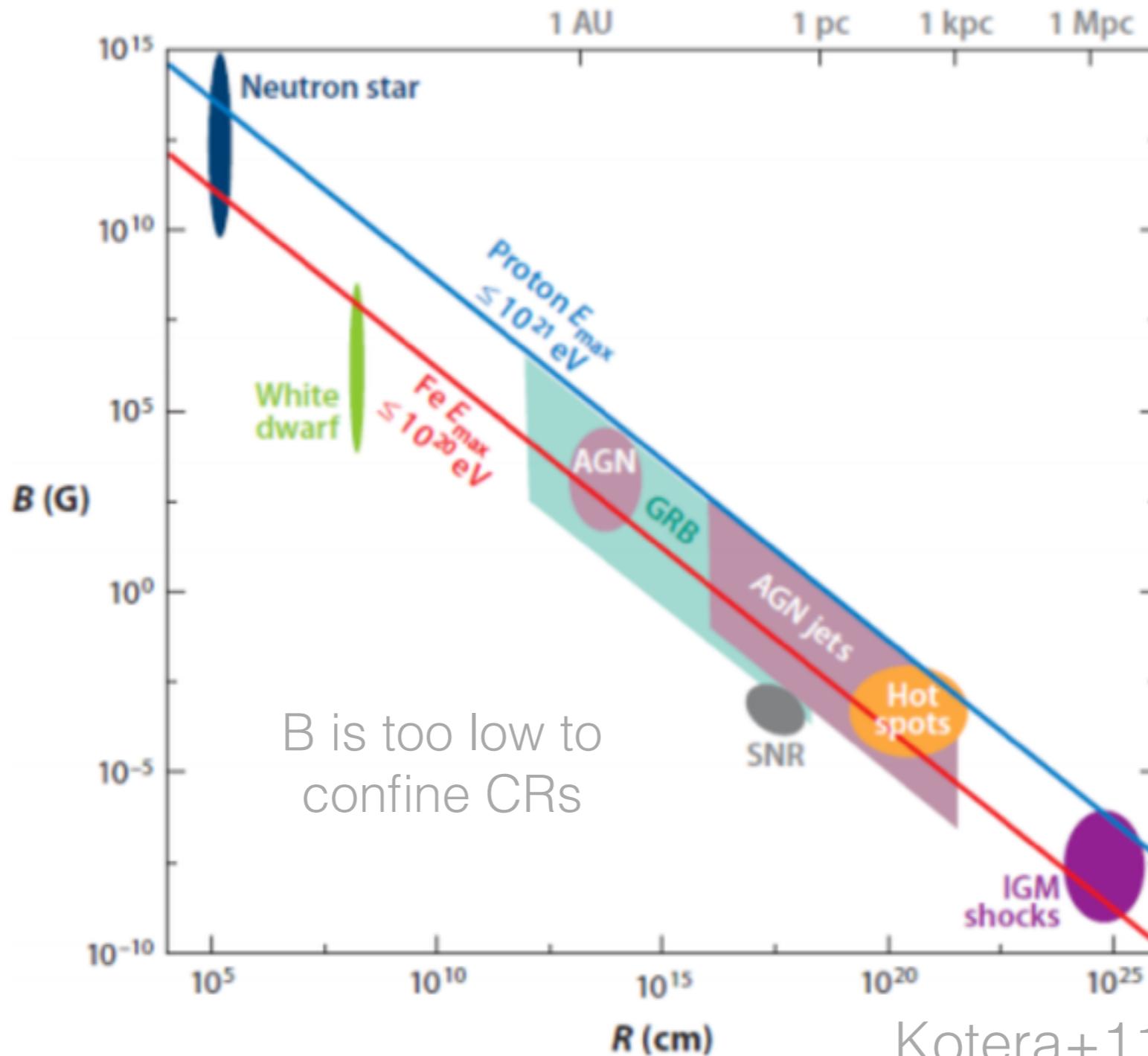
# Particle acceleration at SNR shocks



# Where can we accelerate Cosmic Rays

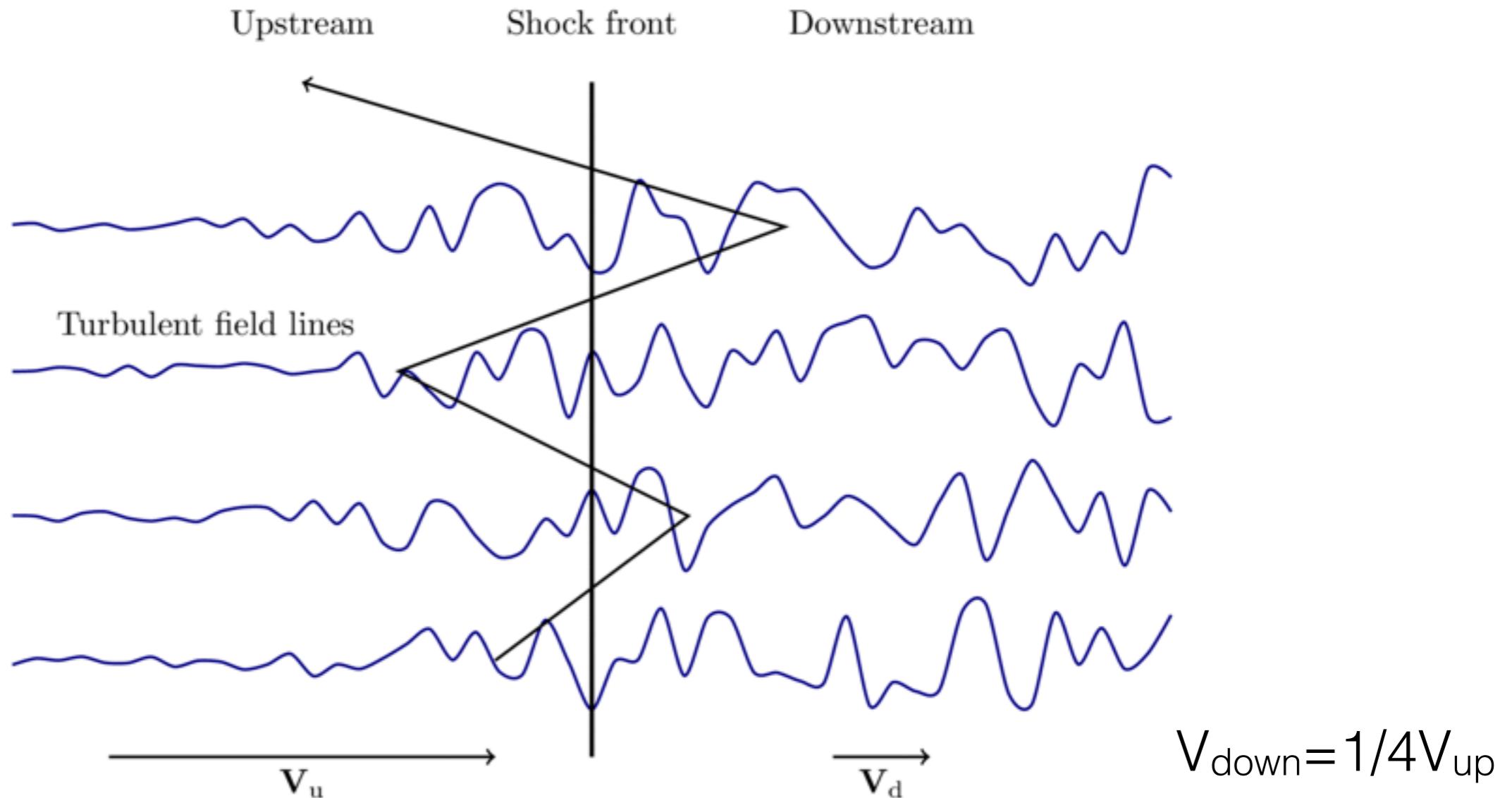
---

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



Kotera+11

# Shock acceleration



- 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 : 
$$\frac{\Delta E}{E} \sim \frac{\Delta V_{\text{sh}}}{c} = \frac{4}{3} \frac{r-1}{r} \frac{V_{\text{sh}}}{c}$$
 and  $E^{-\frac{r+2}{r-1}}$

# Shock acceleration

---

- At each crossing:

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

- 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

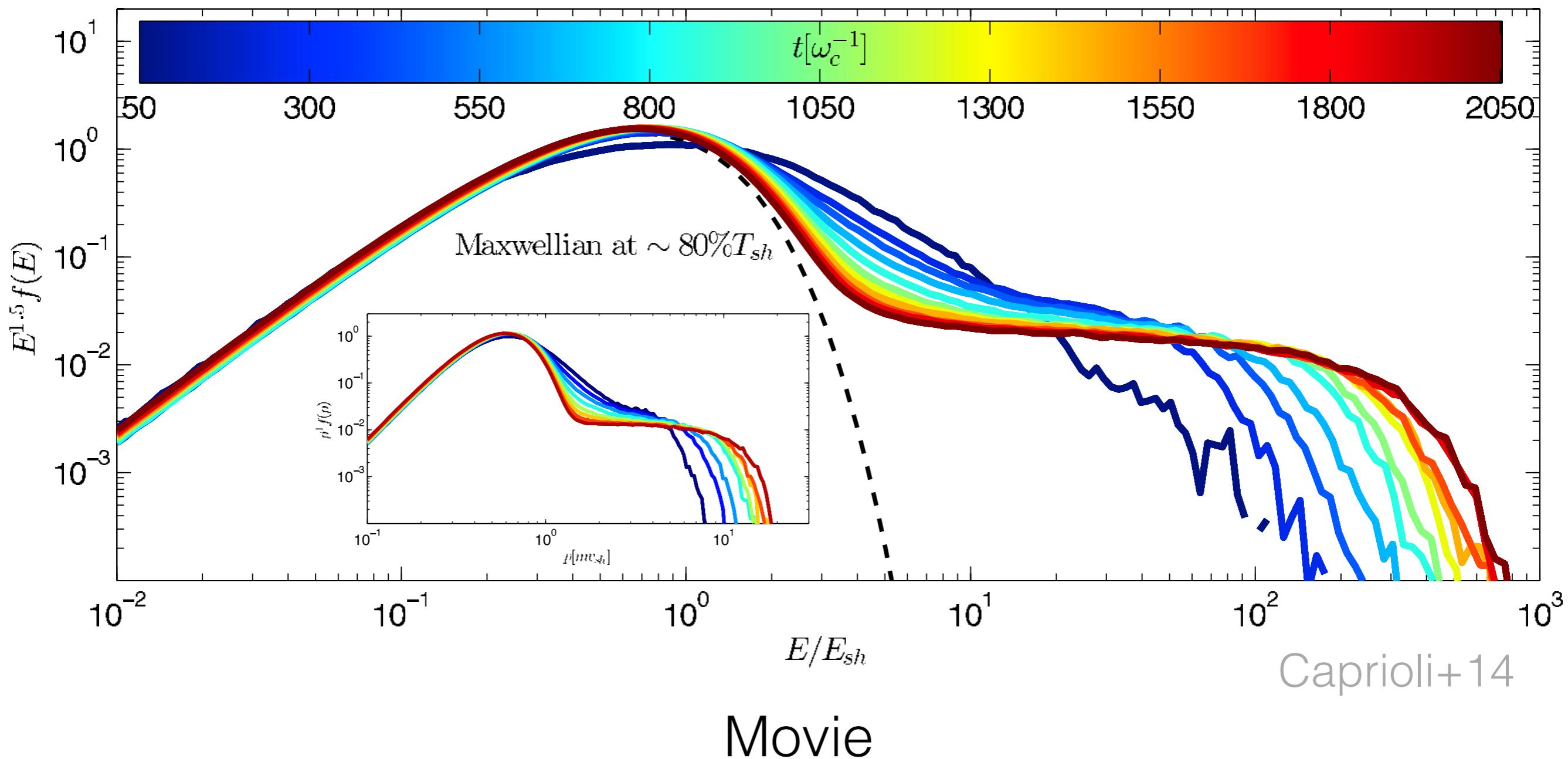
$$E_{\text{max}} = Z \cdot 10^{14} \text{ eV} \left( \frac{B}{10 \mu\text{G}} \right) \left( \frac{R_{\text{sh}}}{3 \text{ pc}} \right) \left( \frac{u_{\text{sh}}}{3000 \text{ km s}^{-1}} \right)$$

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

# Acceleration at shock

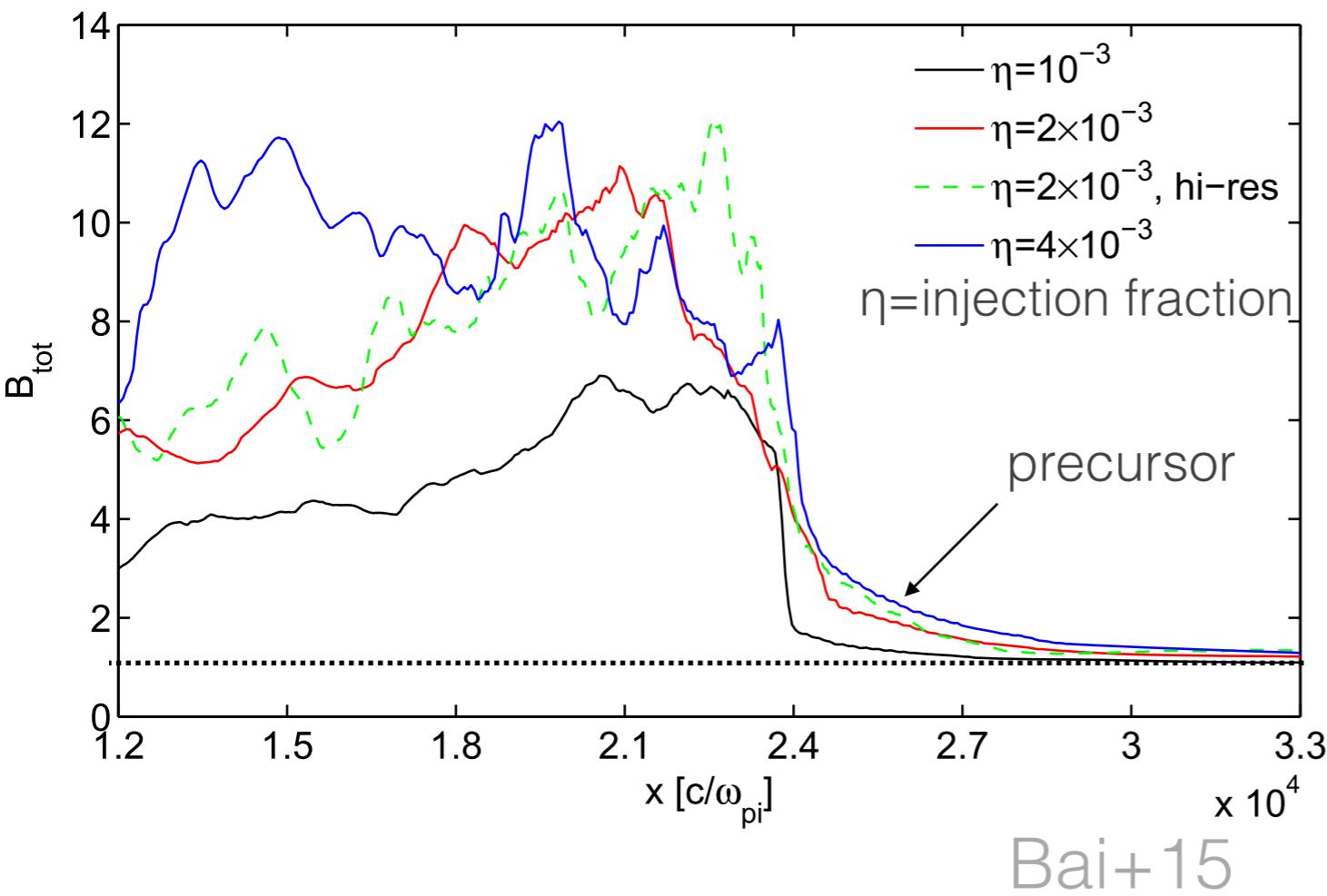
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Particle in cell simulations

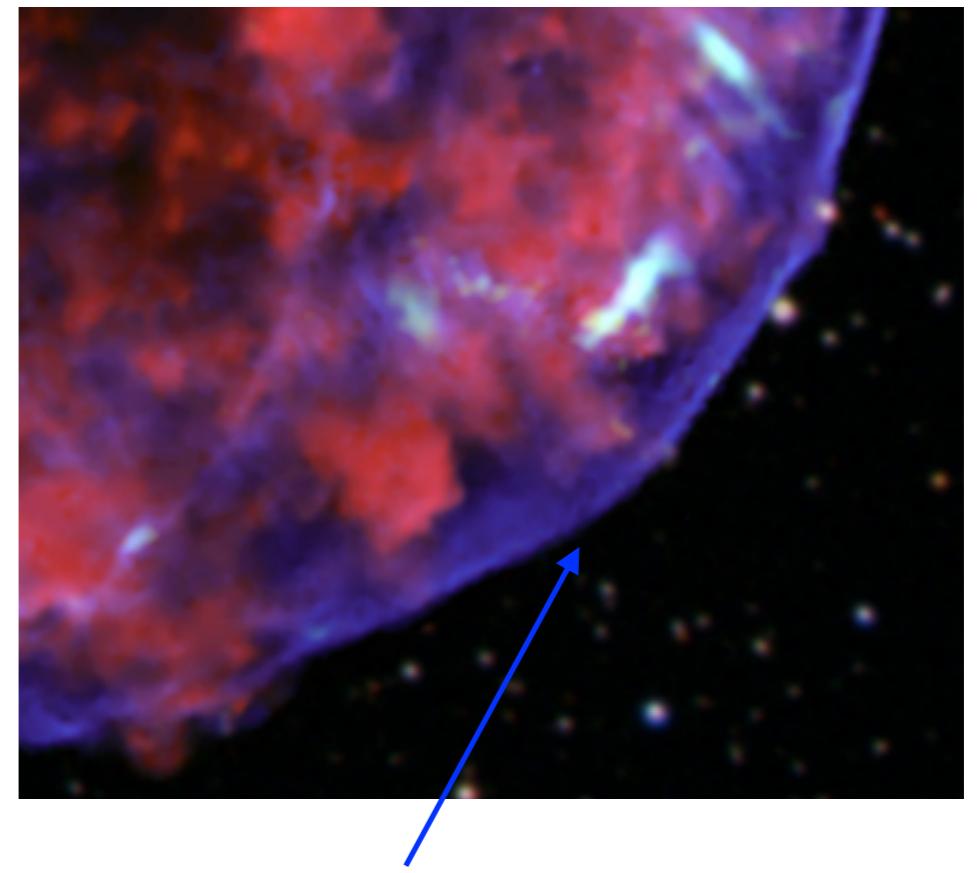


# Magnetic field amplification

PIC simulation + MHD

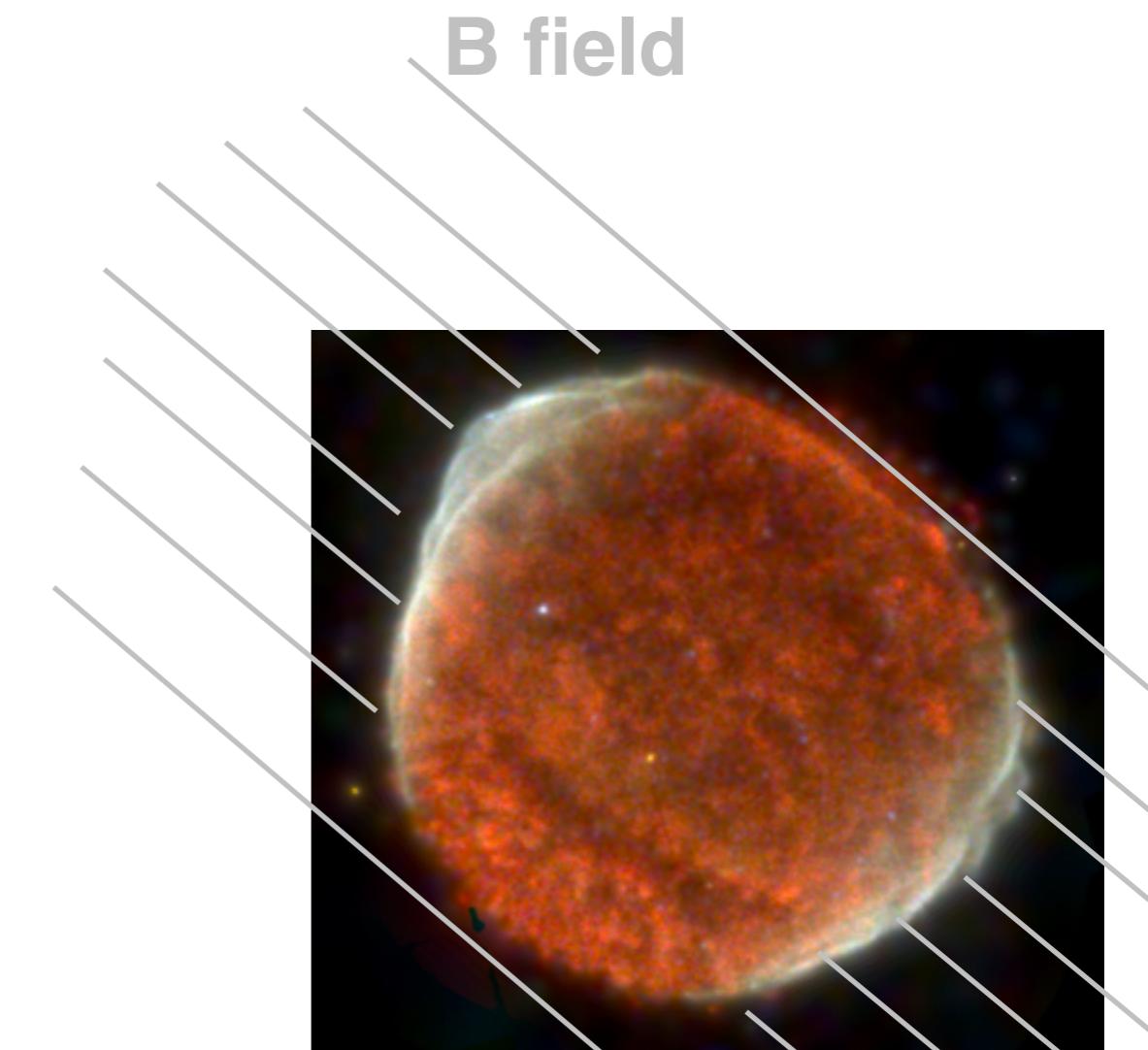
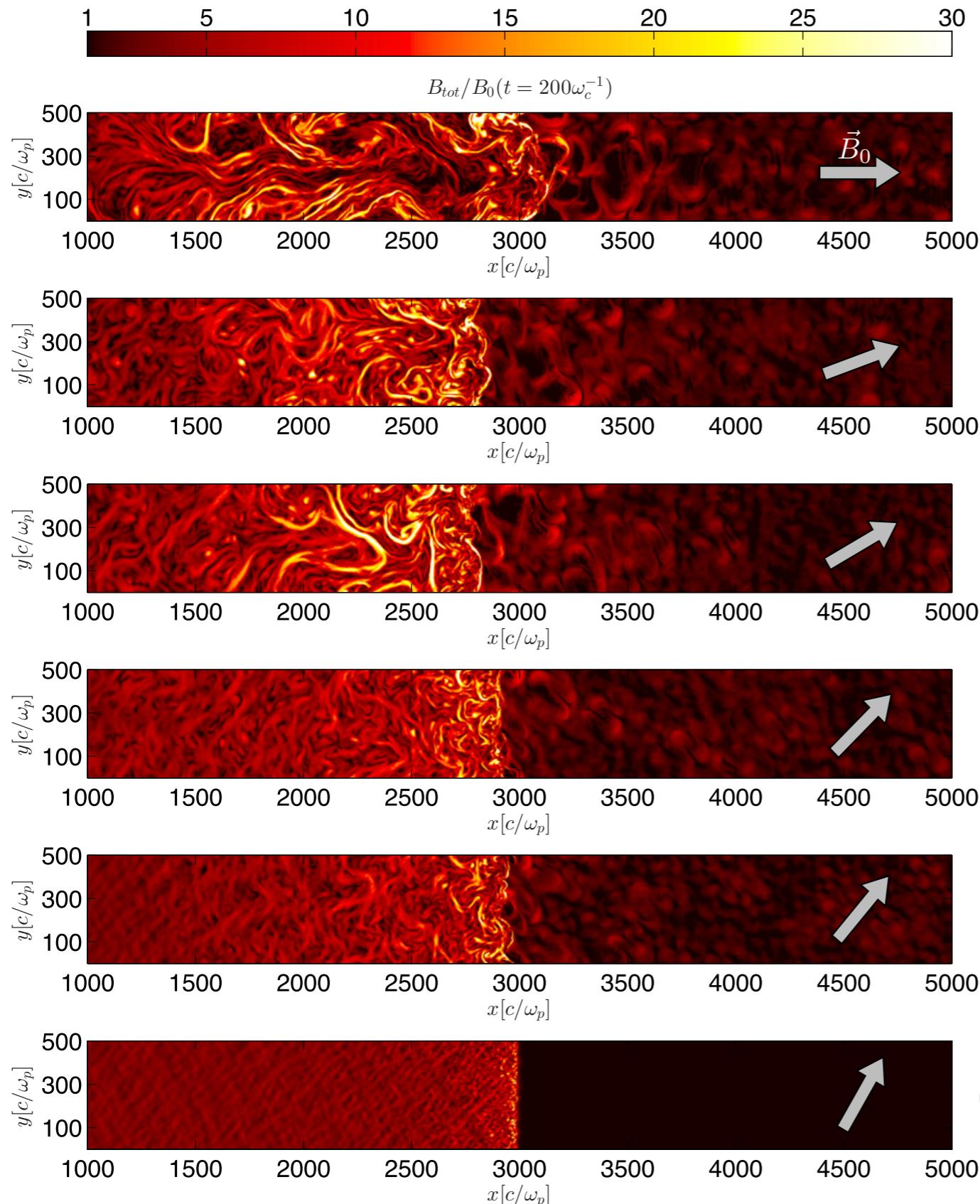


Tycho SNR



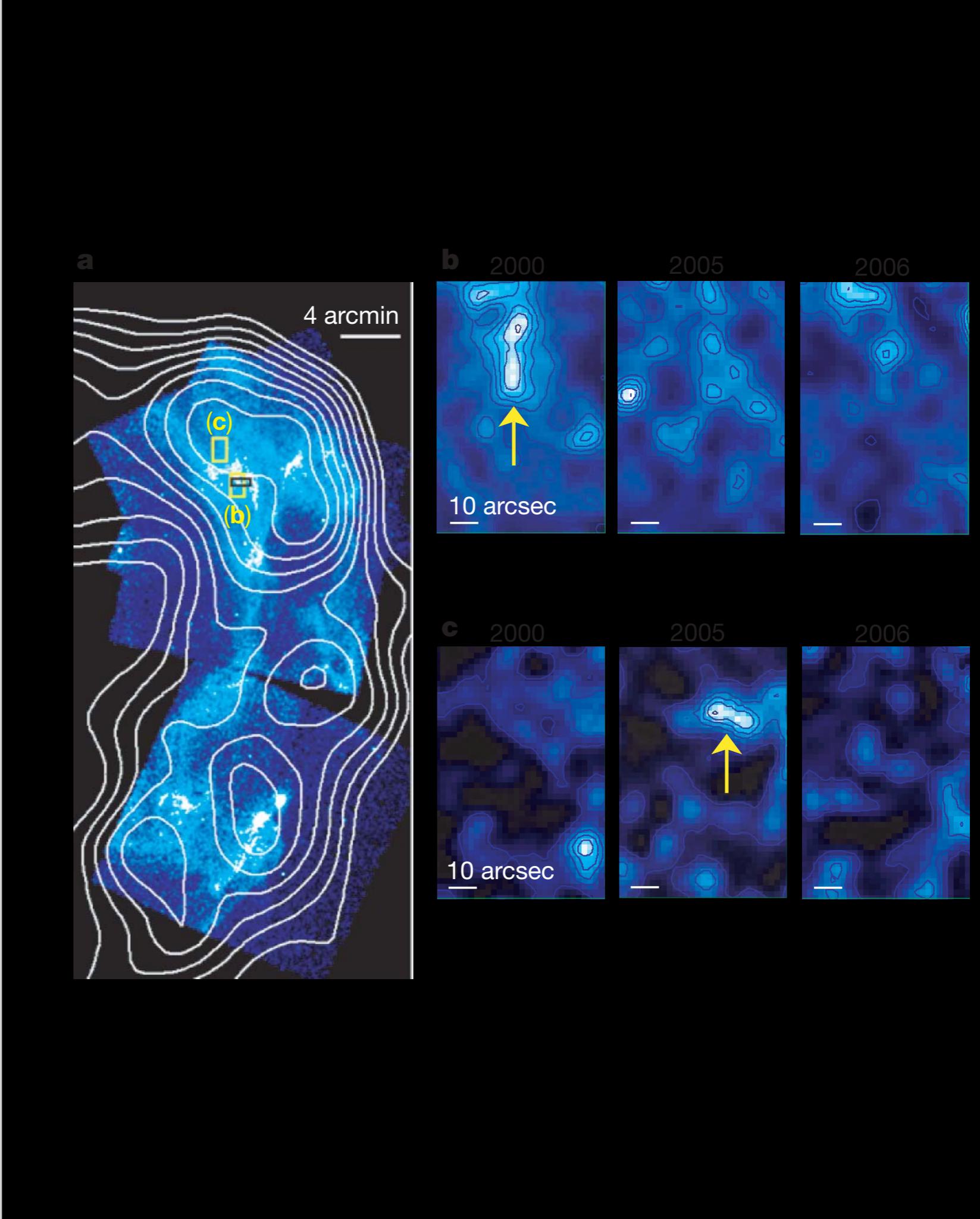
Very thin synchrotron filaments

# Acceleration efficiency - Injection

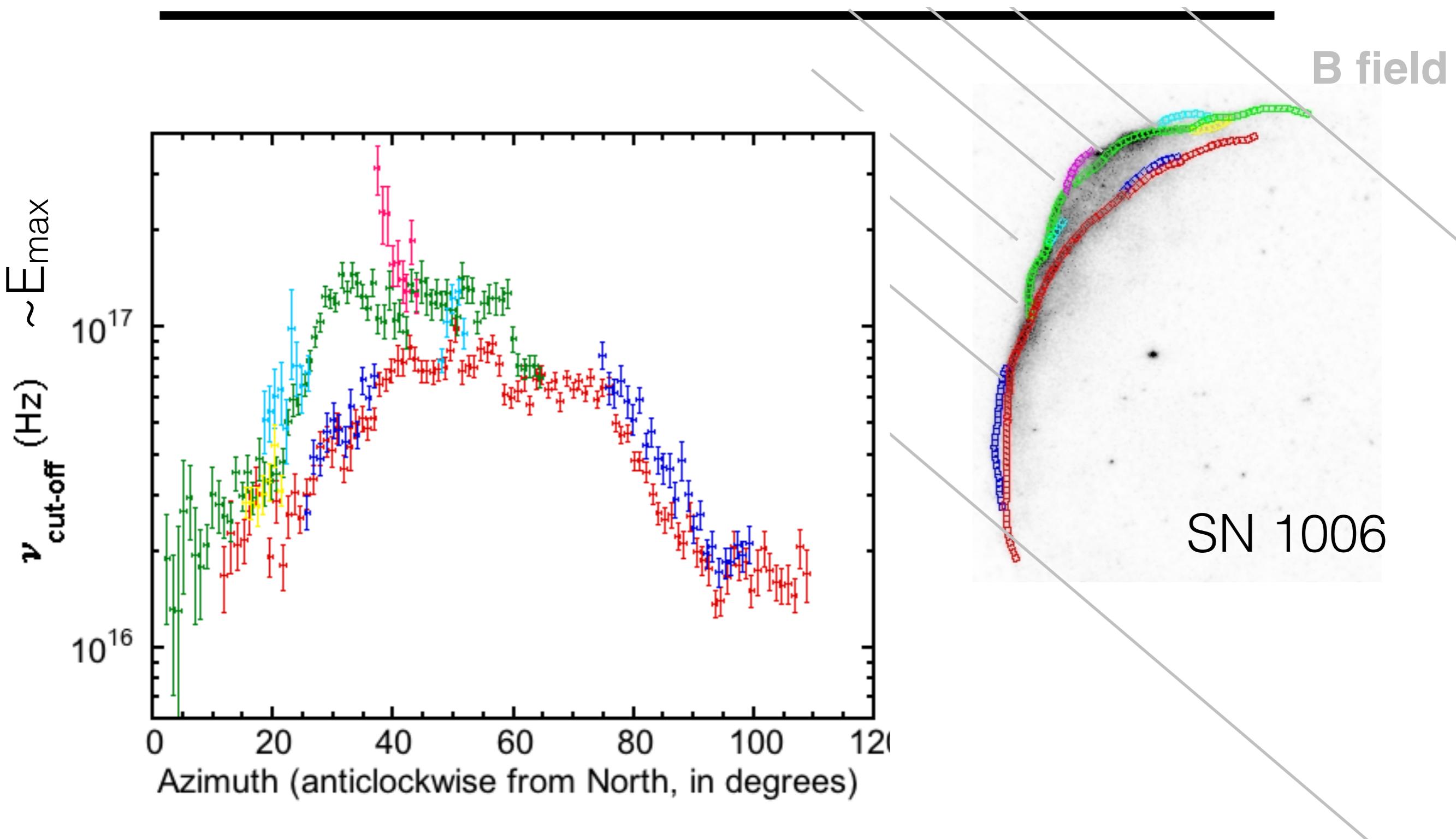


Caprioli+14a

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

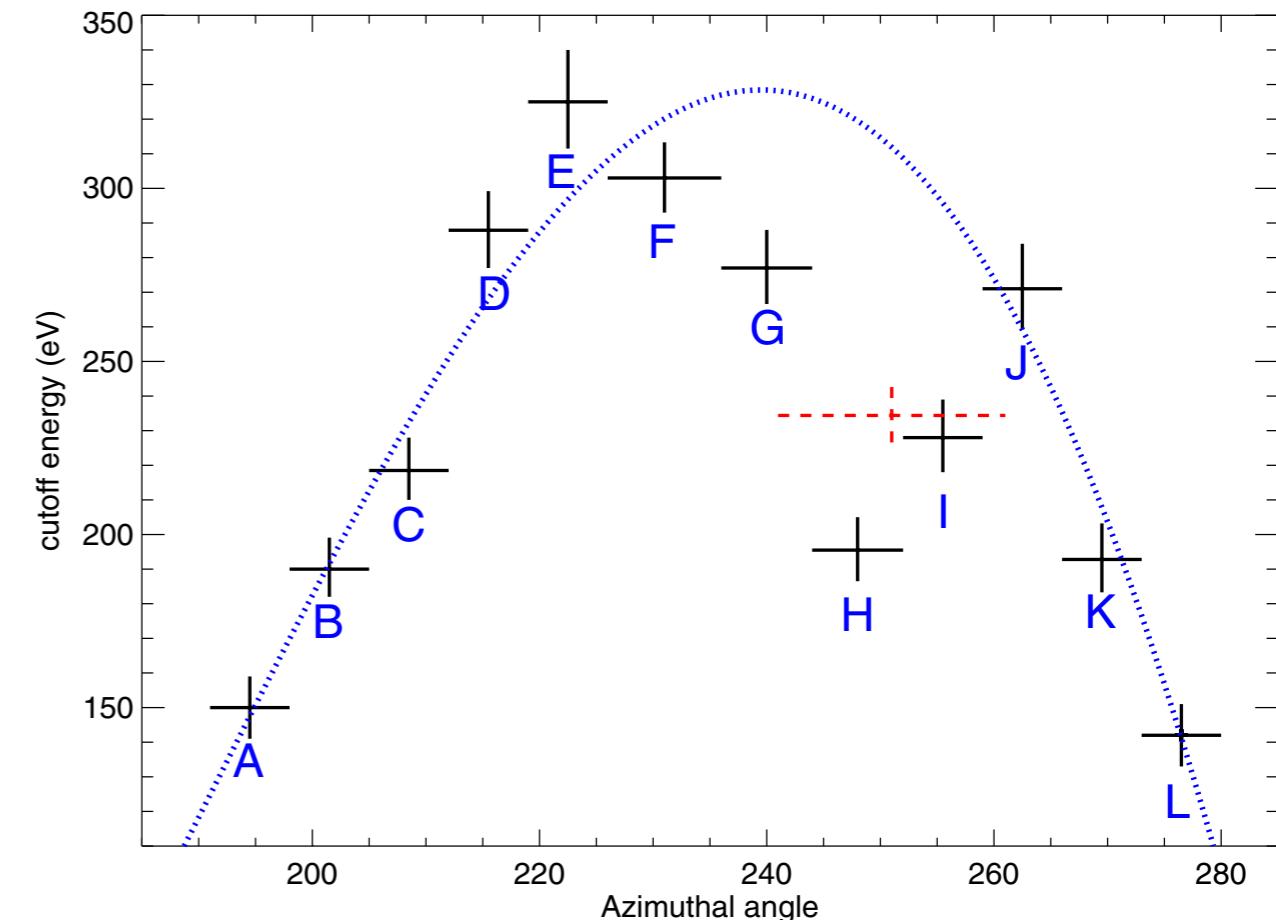
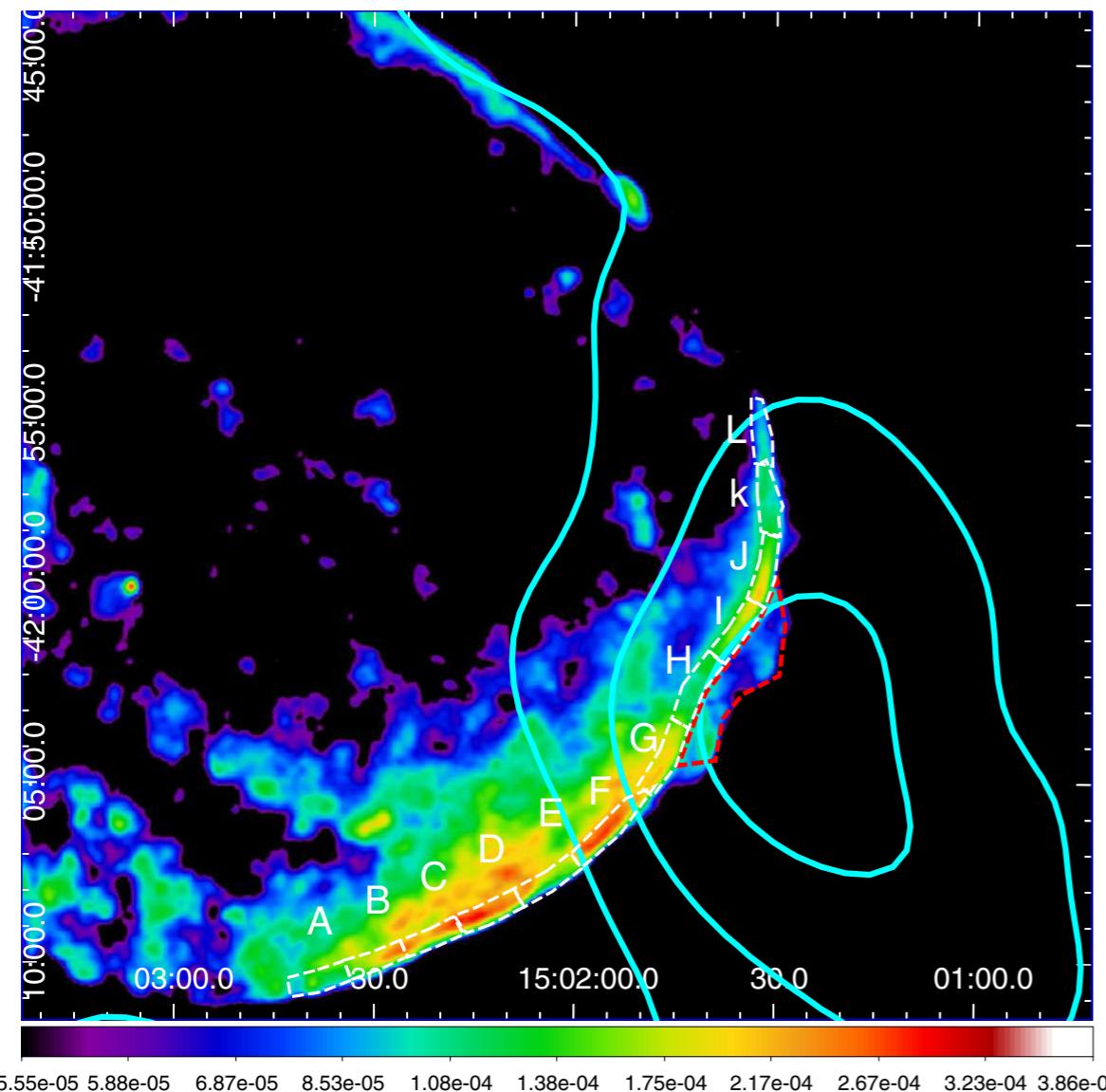


# Acceleration efficiency: $E_{\max}$ vs B field



# Acceleration efficiency: $E_{\max}$ vs $V_{\text{shock}}$

---



- Interaction with a small cloud
- Cutoff frequency decreases at interaction point
- Consistent with  $v_{\text{cut}} \propto V_{\text{sh}}^2 \propto 1/\rho$  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

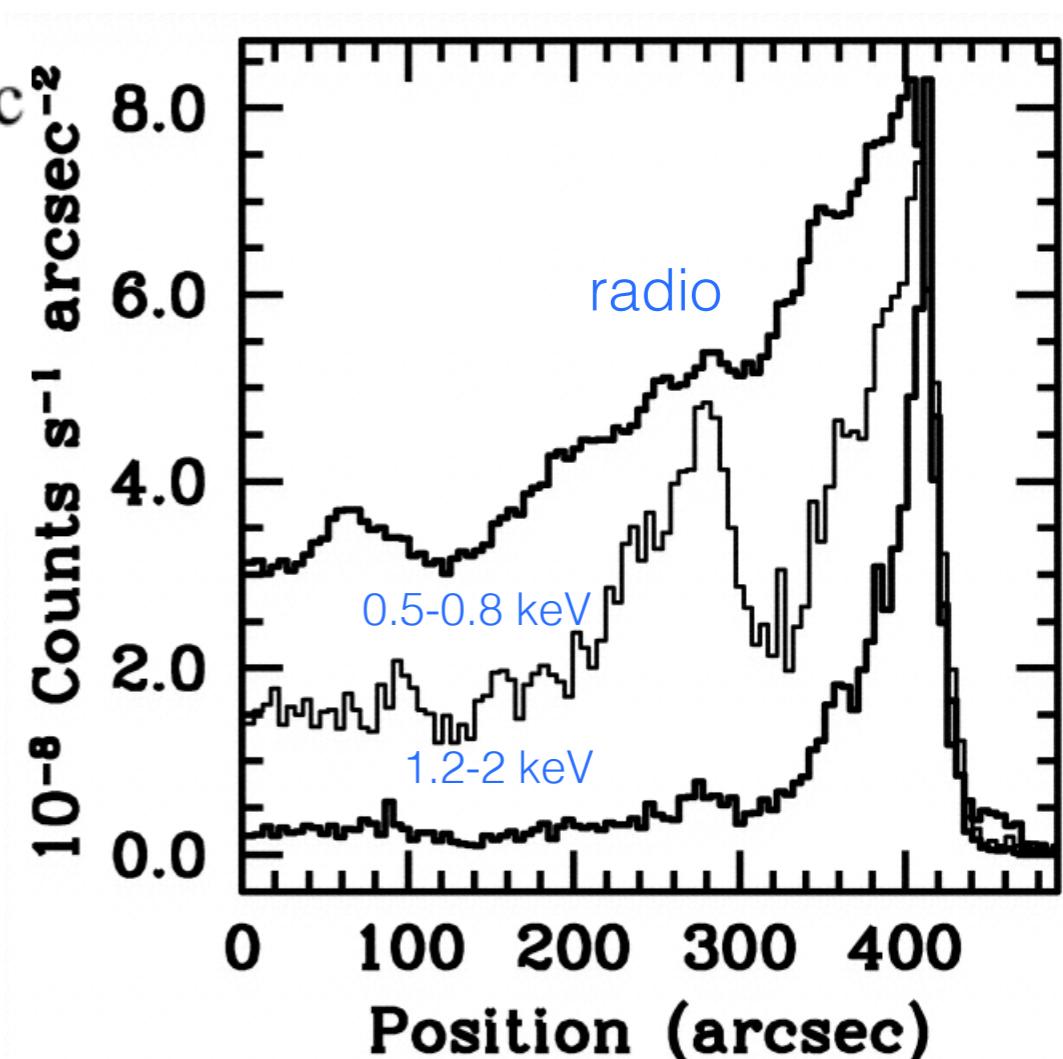
$$t_{\text{cool}} = (57 \text{ yrs}) \times B_{100}^{-3/2} E_{\text{ph,keV}}^{-1/2}$$

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

$$l_{\text{dif}} = \sqrt{K_d t_{\text{cool}}} = 1.2 \times 10^{-3} B_{\text{mG}}^{-3/2} \text{ pc}$$

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

Filaments limited by B-field damping  
behind the shock



# X-ray thin synchrotron filaments

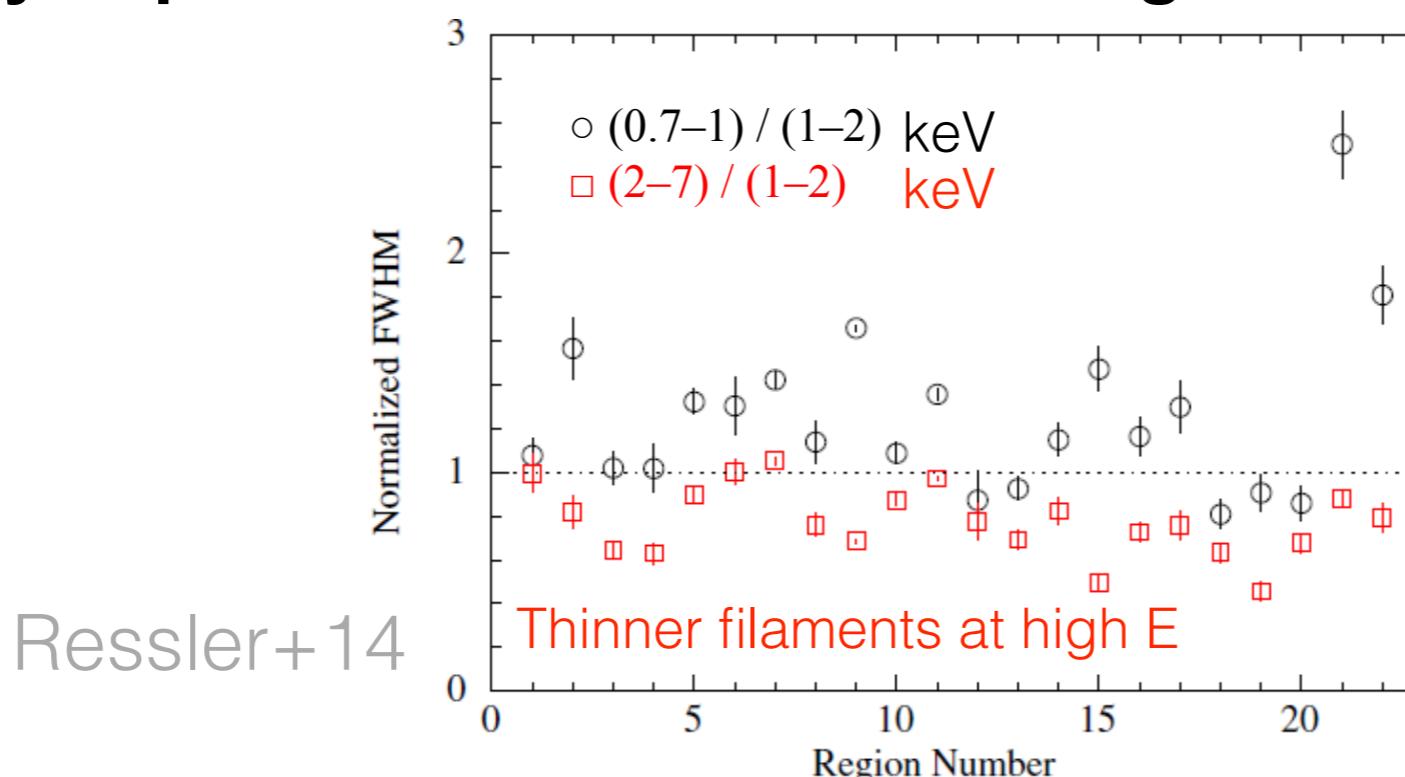
- Width of filaments can provide info about B-field

SNR name	$\tau_{\text{syn}}^{\max} / t_{\text{SNR}}$ ( $\times 4\bar{P}/r$ )	$B_{\text{adv}}$ ( $\mu\text{G}$ )	$B_{\text{diff}}$ ( $\mu\text{G}$ )
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

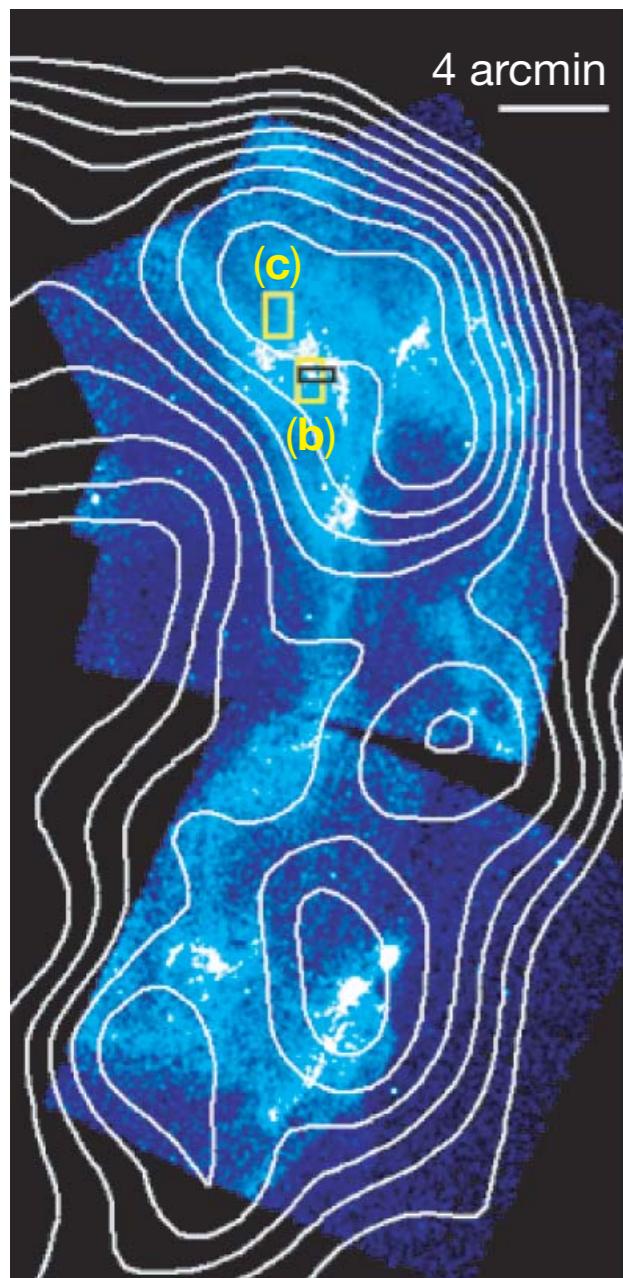
- Energy dependence of width disentangle loss/damping limited



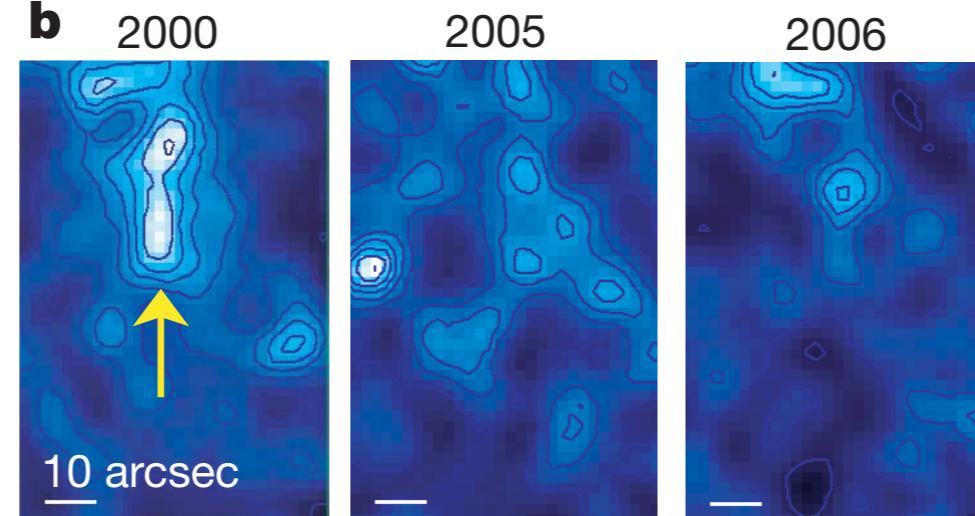
In SN1006:  
filaments are thinner at high E  
rules out B-field damping  
Diffusion :  $D \propto E^\mu$   
with  $\mu > 1$  (not Kolmogorov)

# Turbulent B-field

a



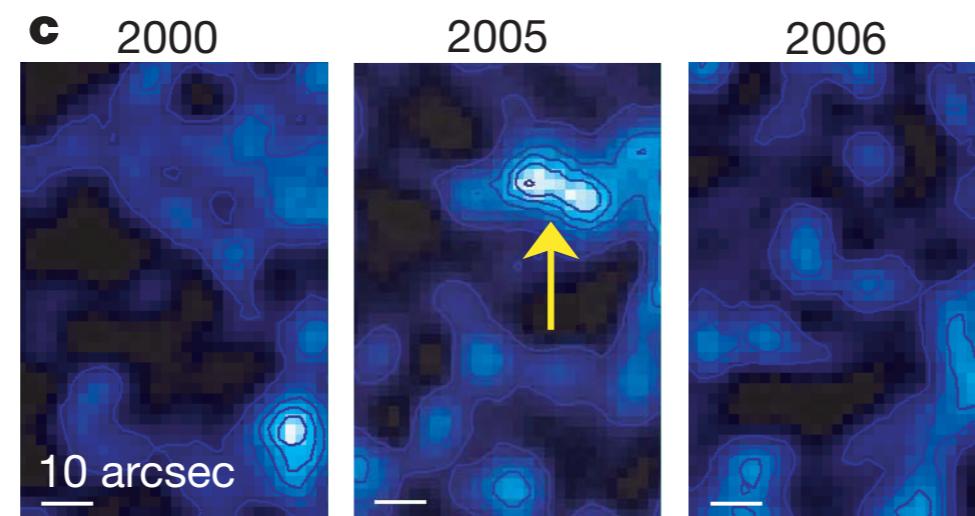
b



Disappearance is due to :

- High B and cooling time~yr  
 $\Rightarrow B \sim 1 \text{ mG}$
- Turbulent B-field

c

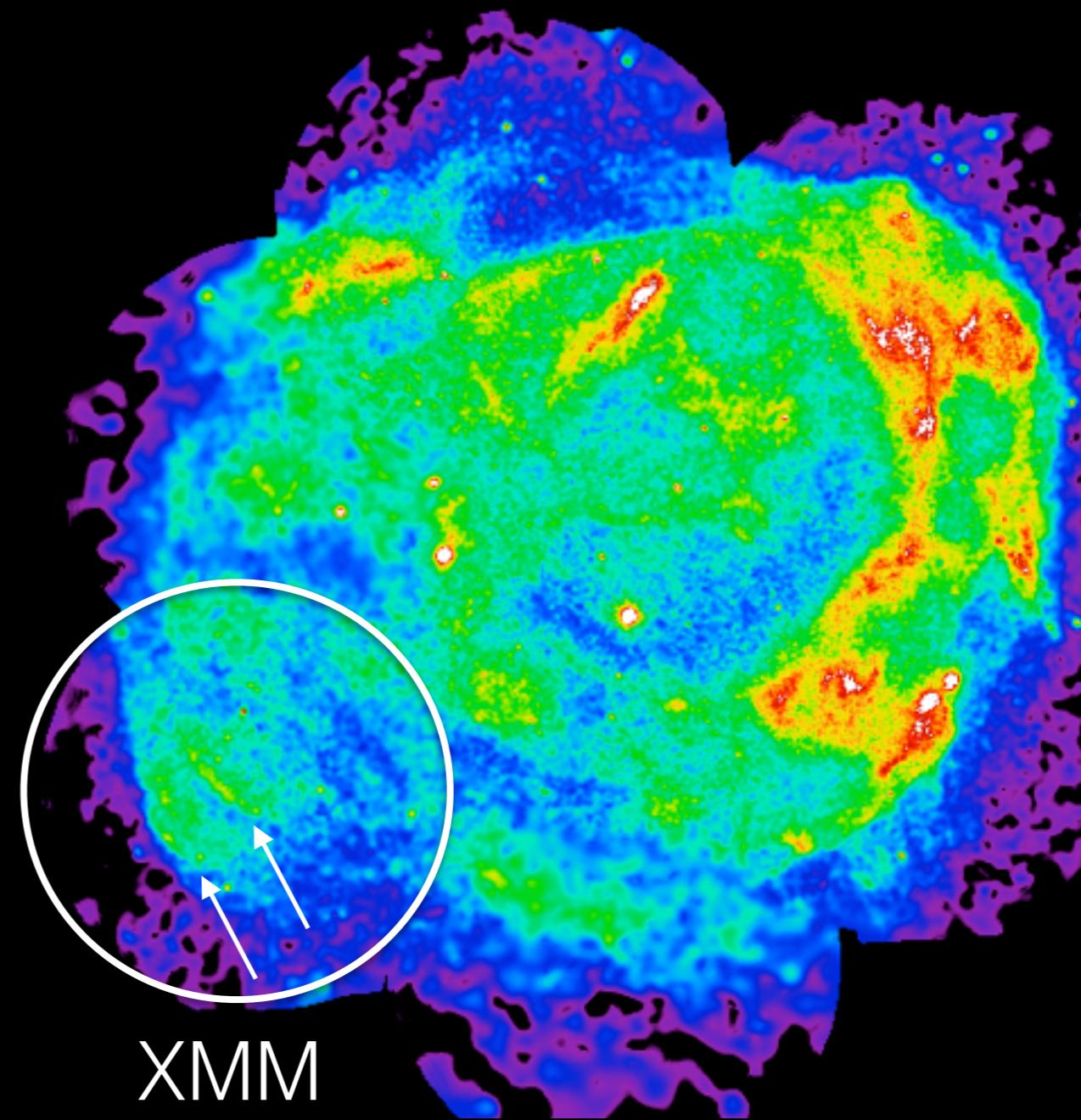
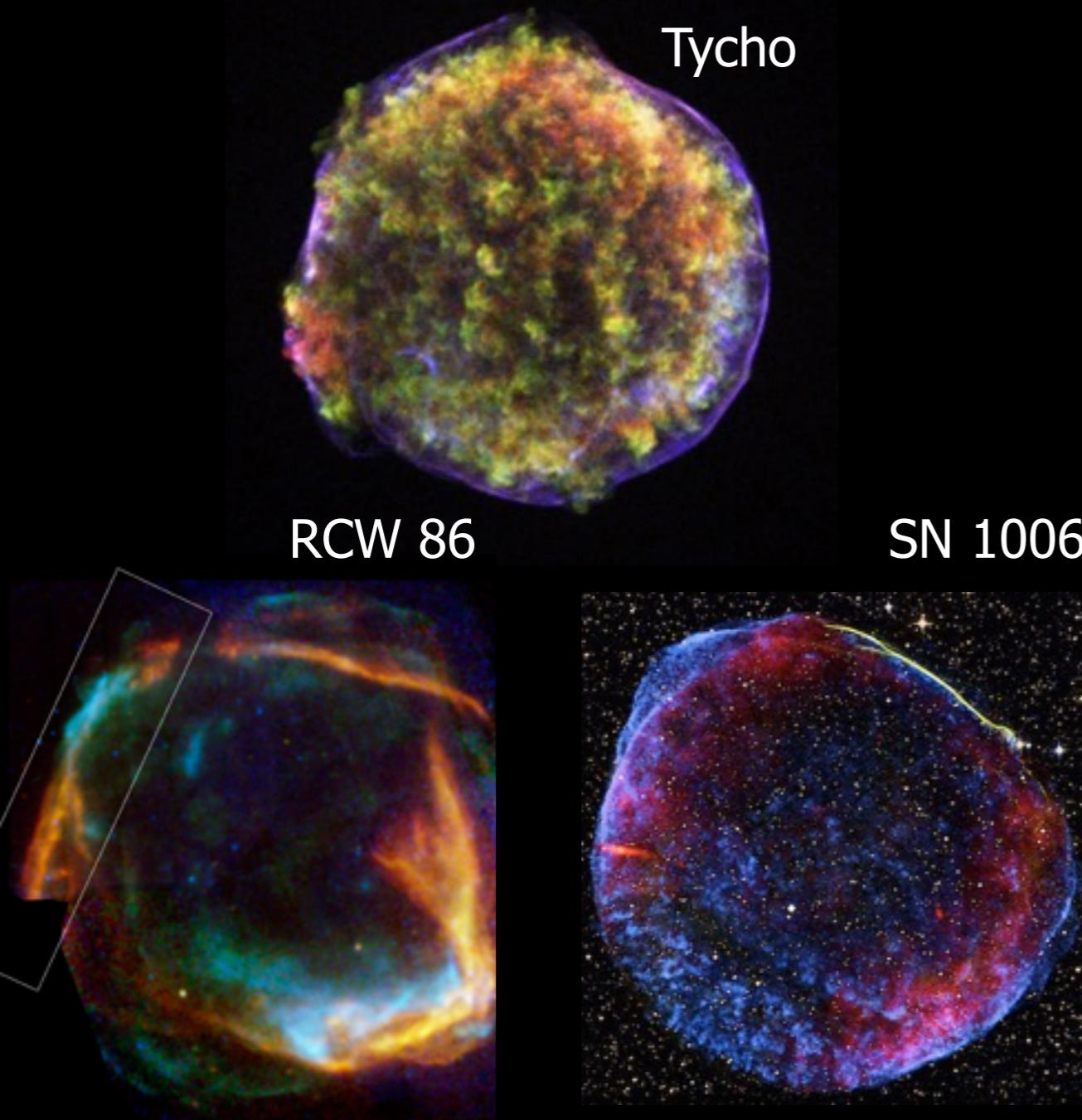


Uchiyama+07

# How to constrain $V_{\text{sh}}$ , ambient medium: Filament proper motion

Filament structures in RXJ ... ?

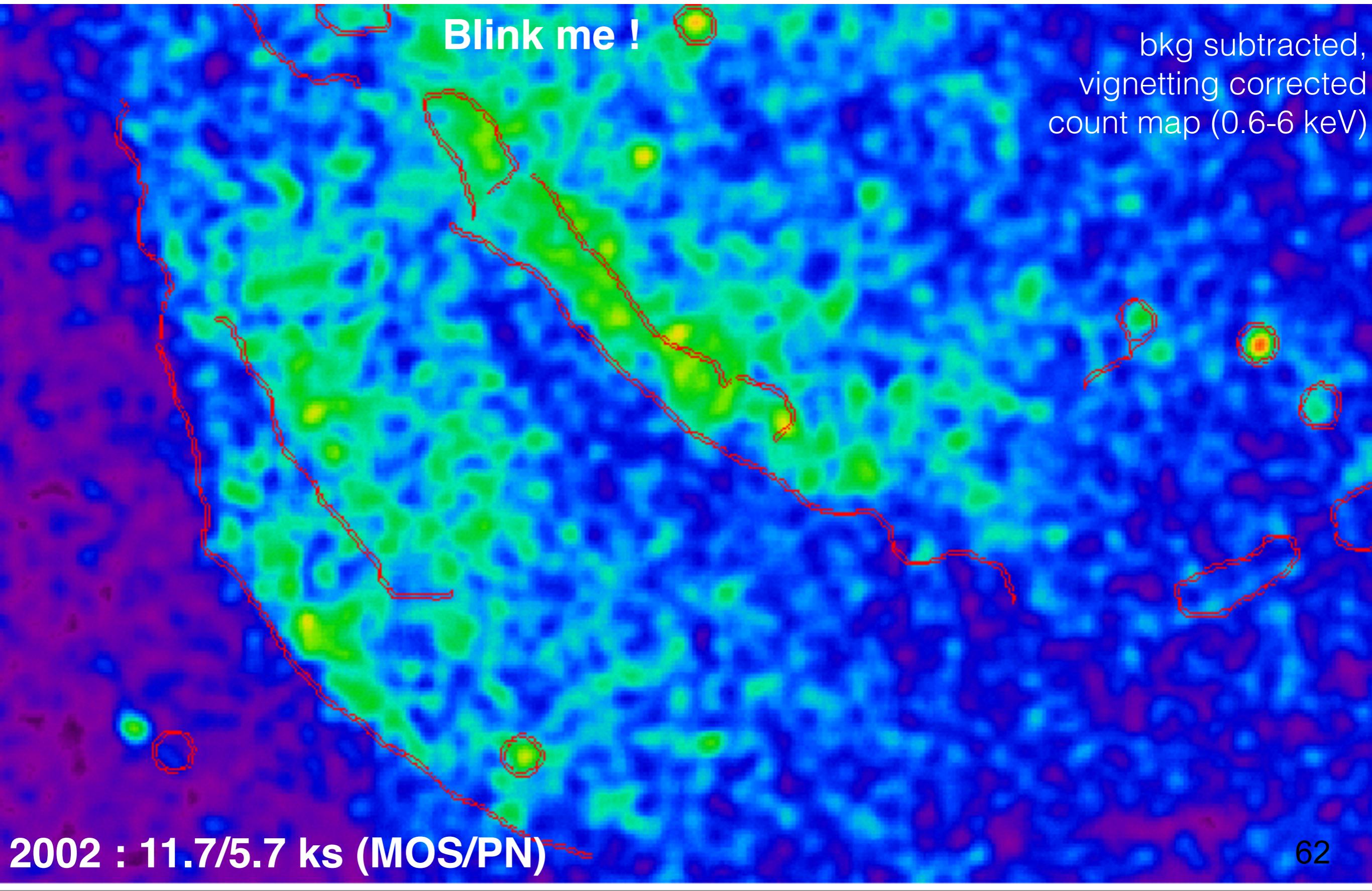
Not as easy as in:



XMM  
2002: 11 ks  
2015: 64 ks

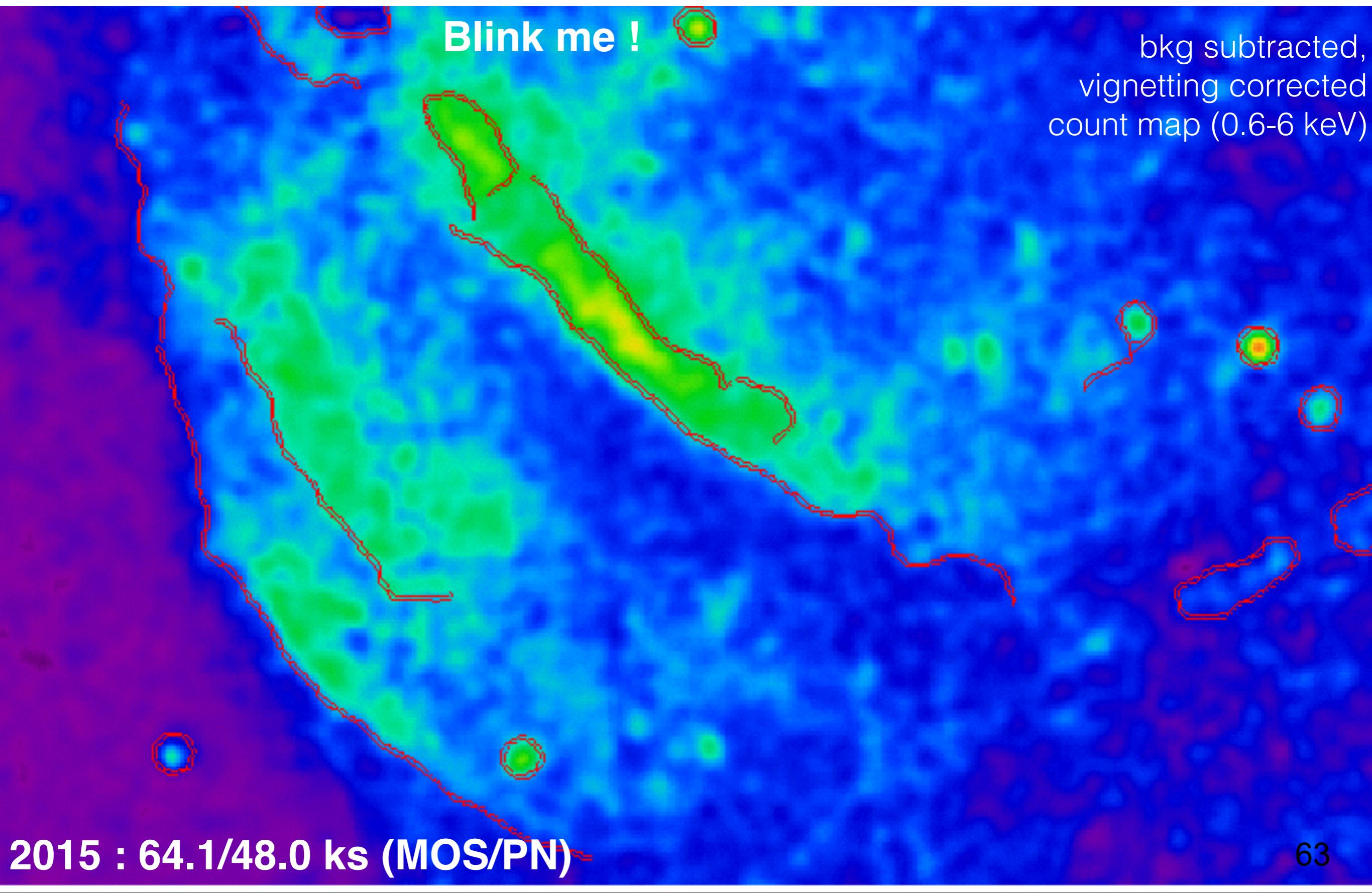
2002 image  
2015 edges

## X-ray proper motion in the SE



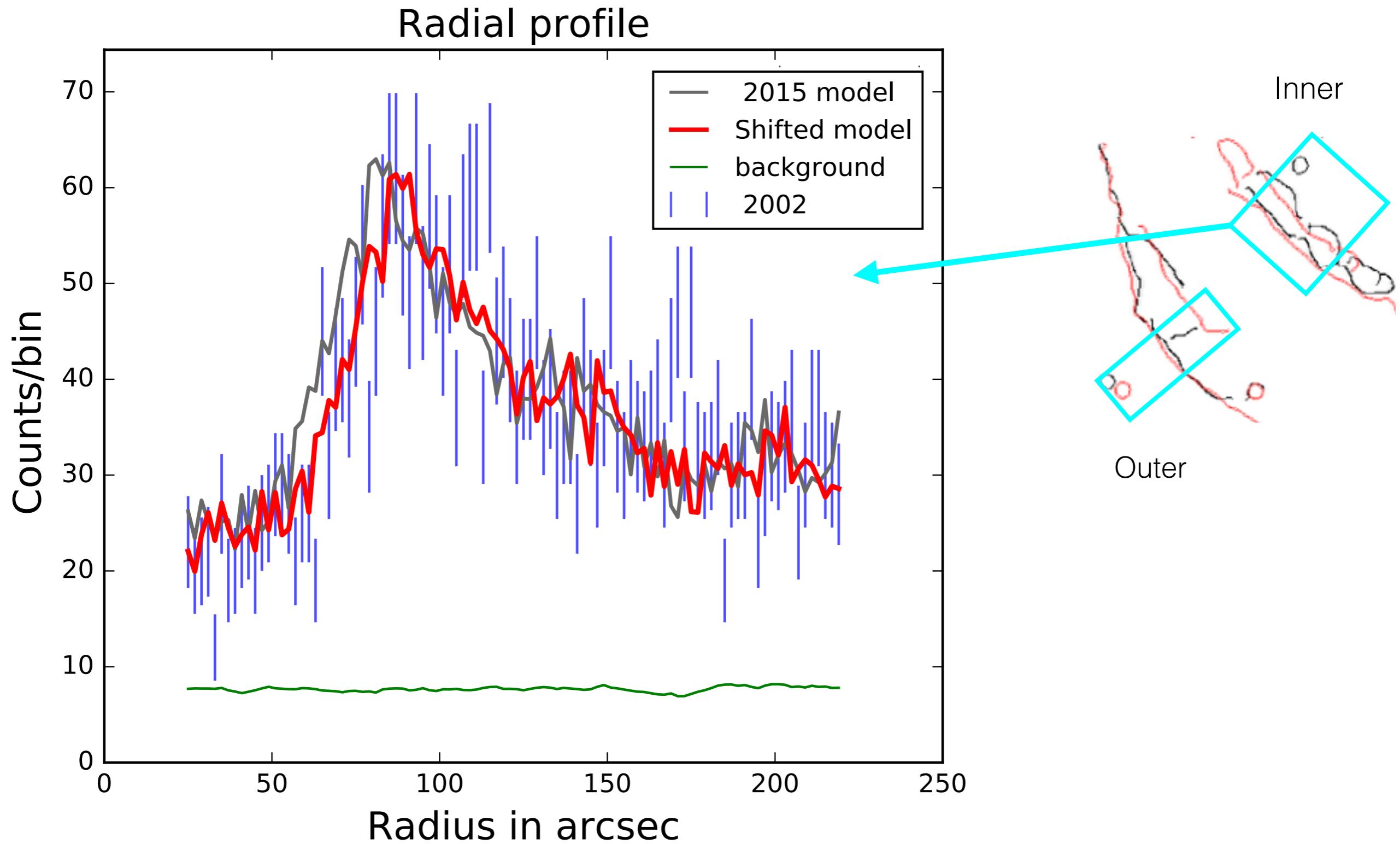
2015 image  
2015 edges

## X-ray proper motion in the SE



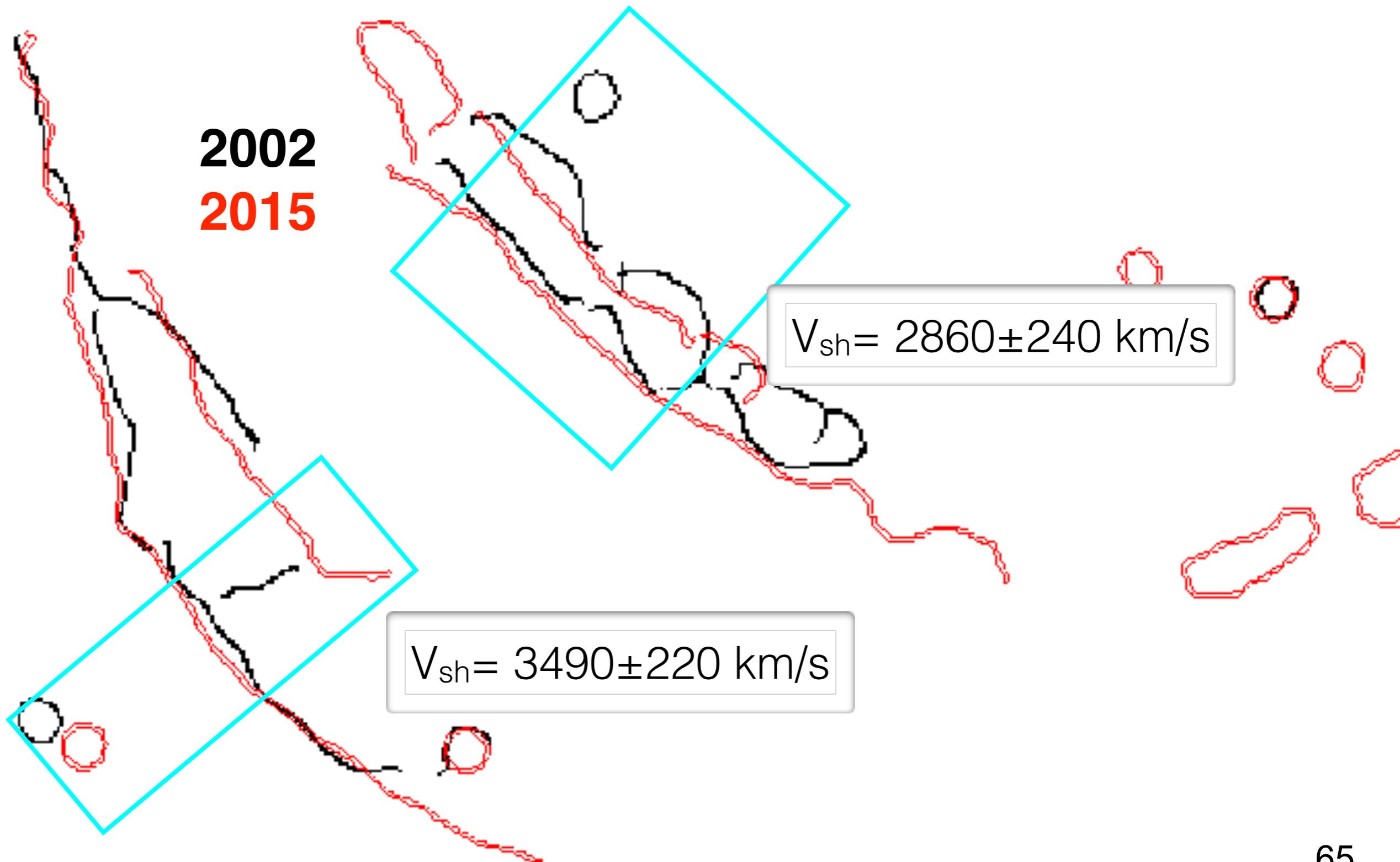
# Results

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# Results

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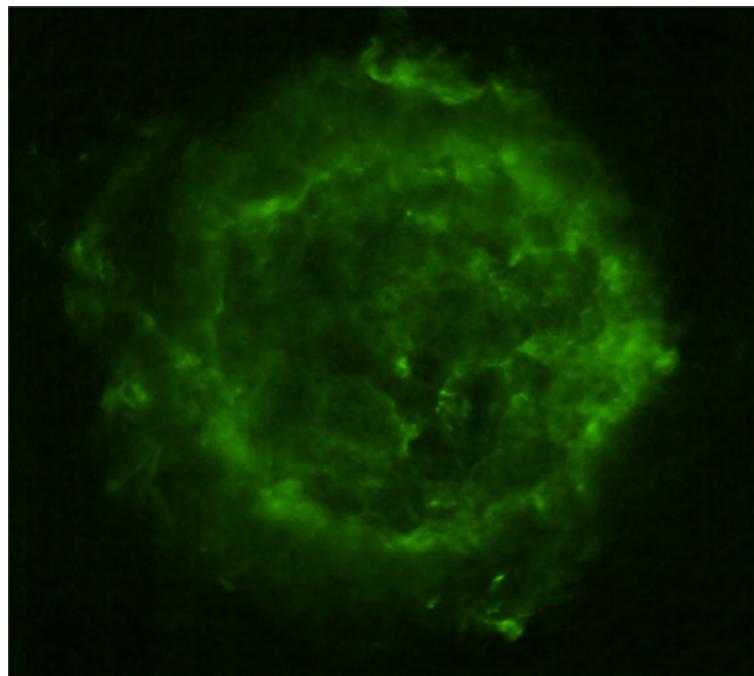
# SNR age

# Hard X-rays with NuStar

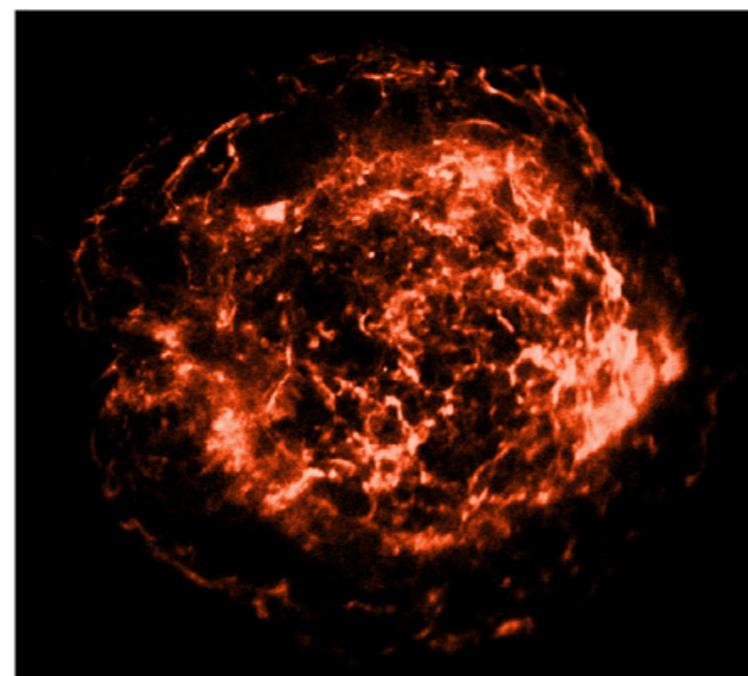
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- Non-thermal X-rays up to hard X-rays
- Locating the highest energy electrons

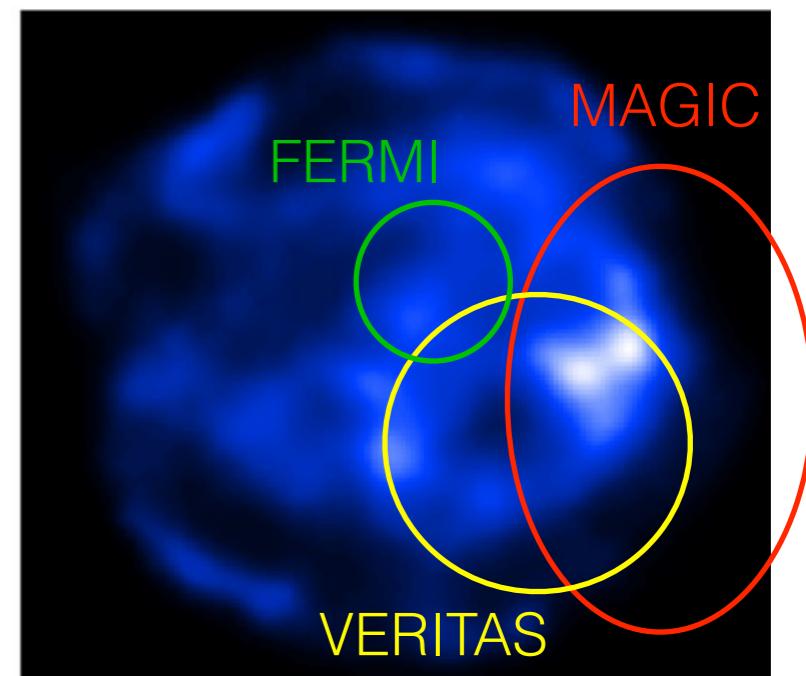
Radio—VLA



4-6 keV — Chandra

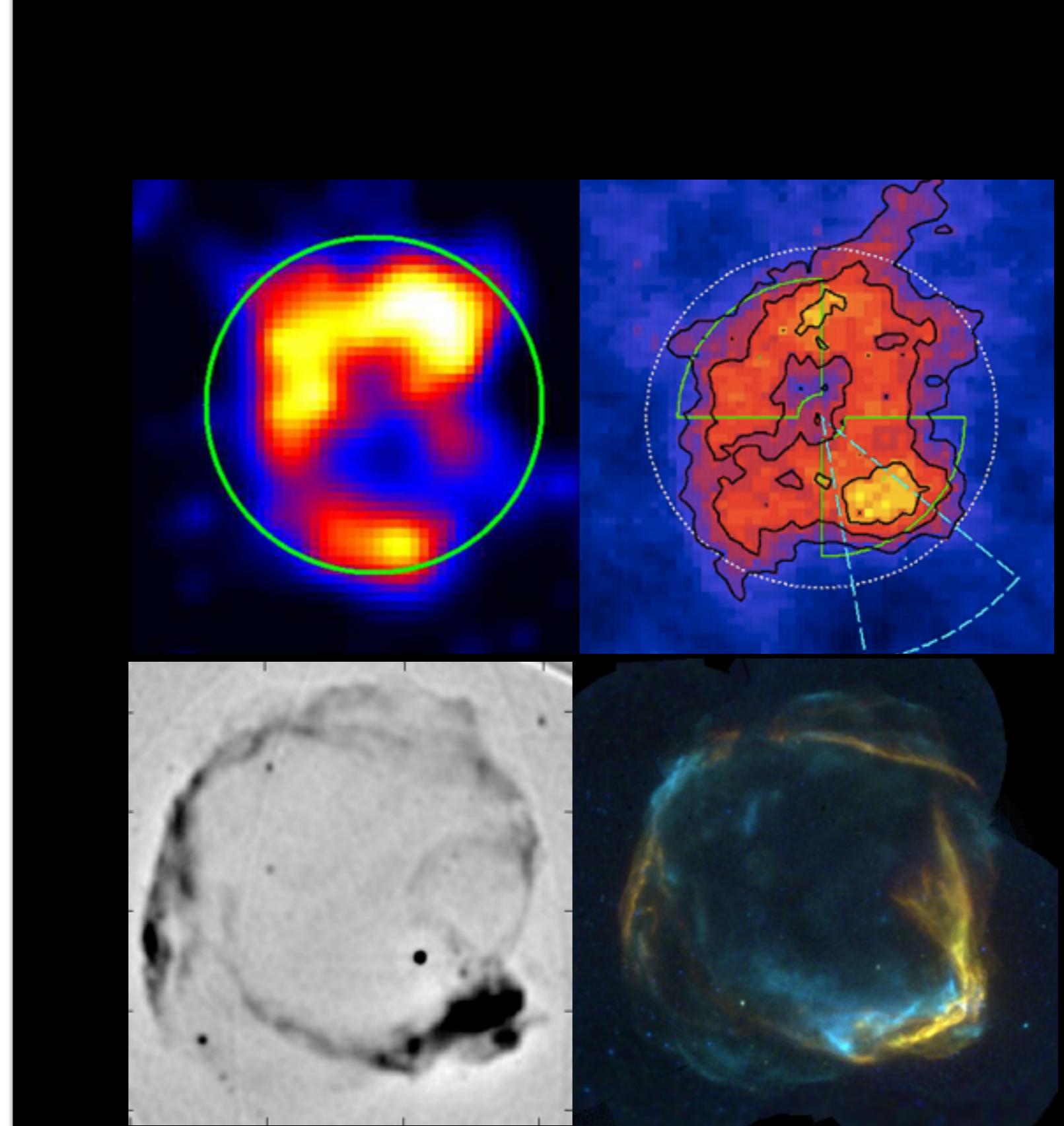


10-15 keV — NuSTAR



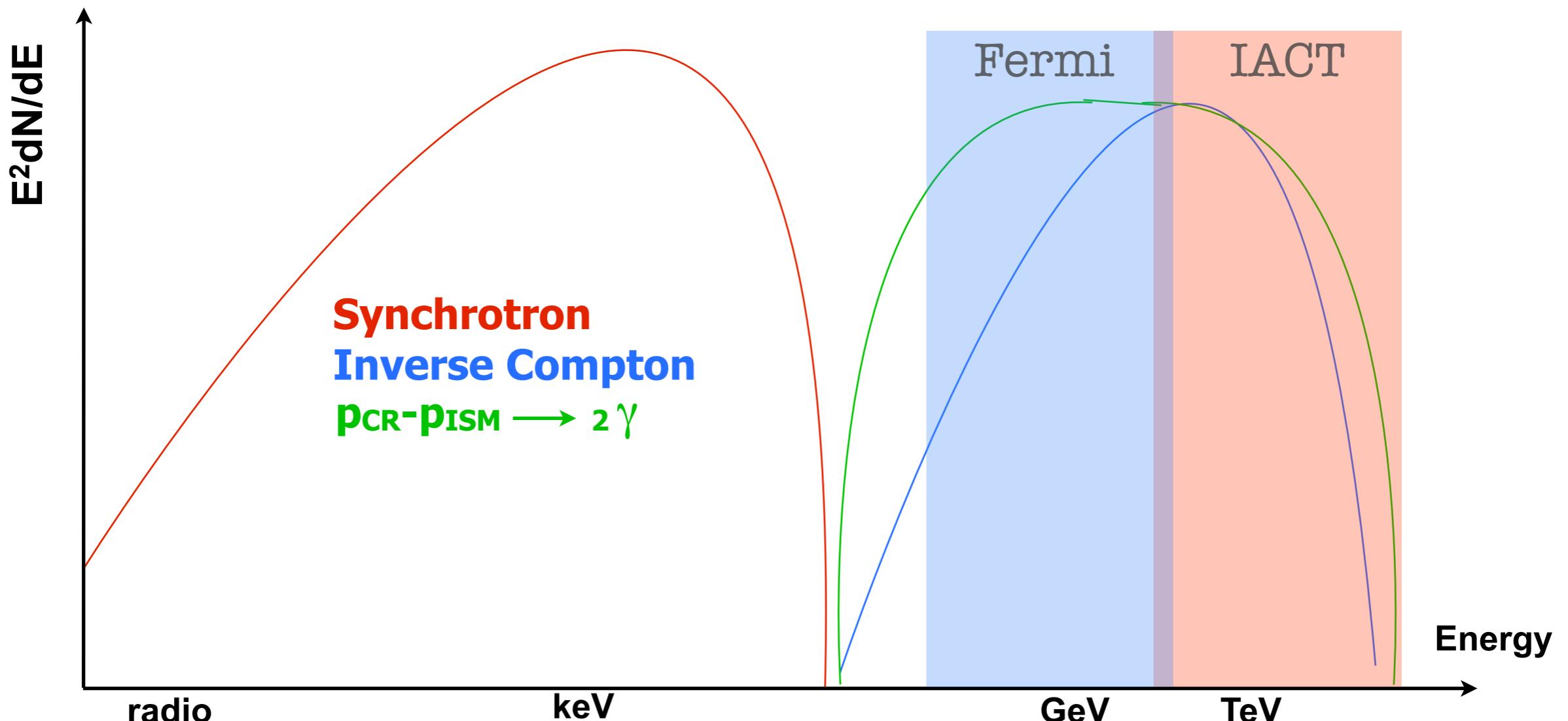
Grefenstette+15

## The X/gamma-ray connection



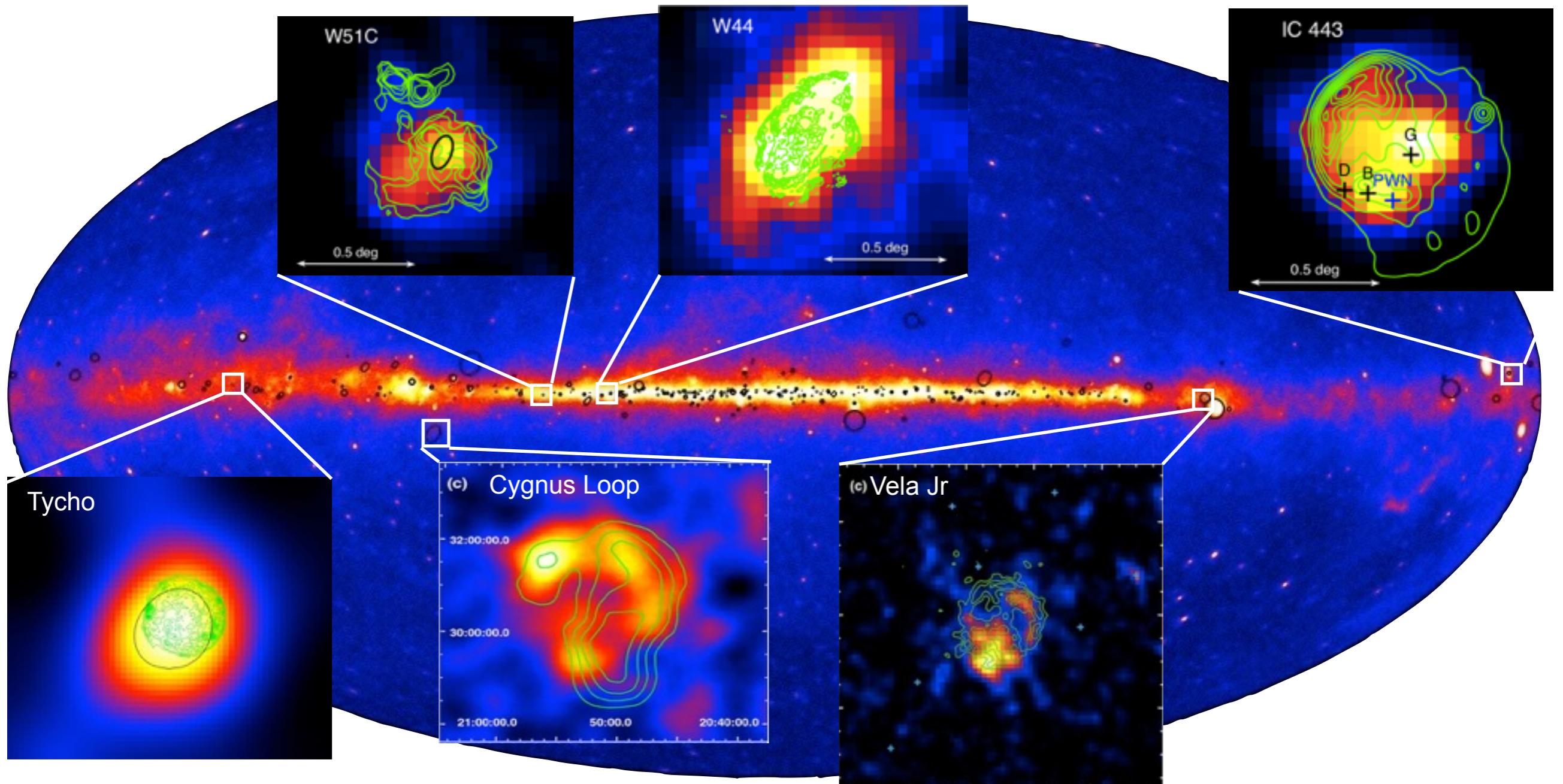
# Multi-wavelength emission from SNRs

launch binder



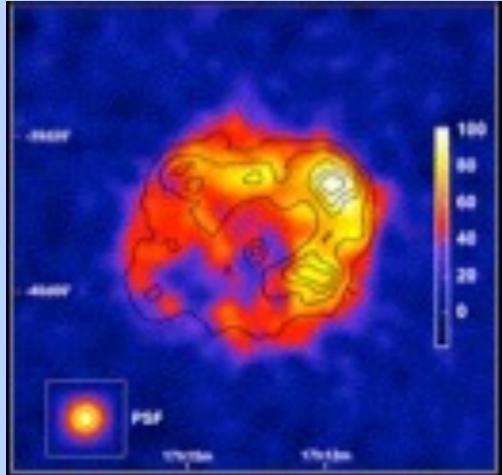
- Test the SNR CR acceleration paradigm through SNR's particle radiation:
  - Nature of the  $\gamma$ -ray emission,  $E_{max}$ , Energetic SNR  $\longrightarrow$  CRs

# SNRs as seen by Fermi-LAT

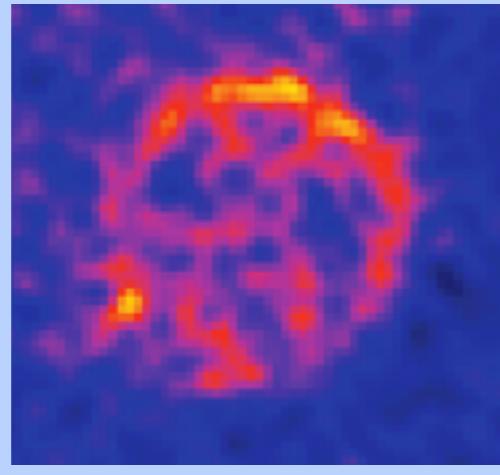


# TeV SNRs: young and shell types

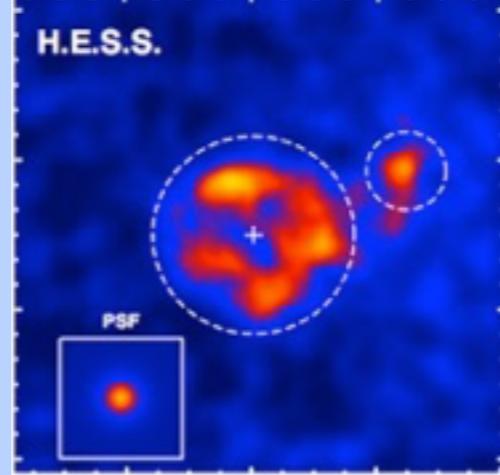
RX J1713



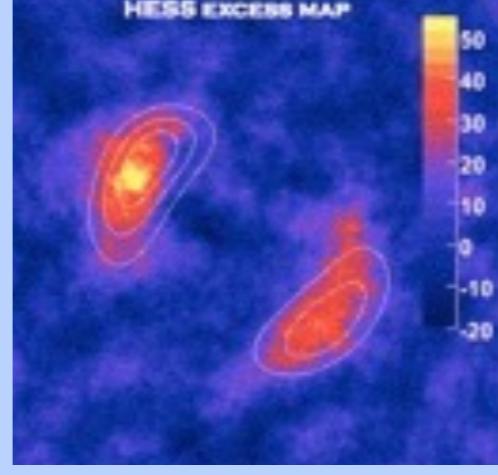
VelaJr



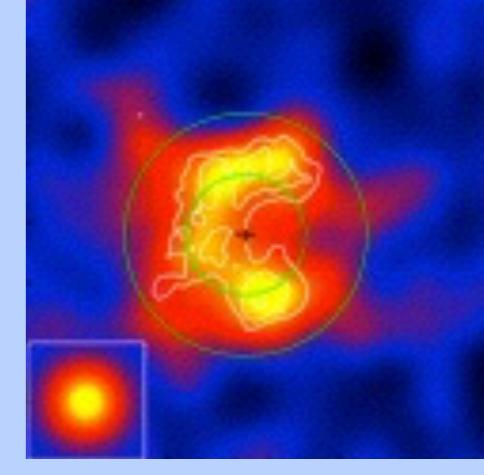
HESS J1731



SN 1006



RCW 86



TeV images

## Density

$<0.02 \text{ cm}^{-3}$

$<0.03 \text{ cm}^{-3}$

**$<0.02 \text{ cm}^{-3}$**

**$0.05 \text{ cm}^{-3}$**

$10^{-2} - 1 \text{ cm}^{-3}$

## Age

1.6 kyrs

2-4 kyrs

**2-4 kyrs**

1.008 kyrs

1.8 kyrs

## Distance

1 kpc

**$<0.8 \text{ kpc}$**

**$>3.2 \text{ kpc}$**

2.2 kpc

2.5 kpc

## GeV spectral index

$1.5 \pm 0.1$

$1.85 \pm 0.06$

$<1.5$

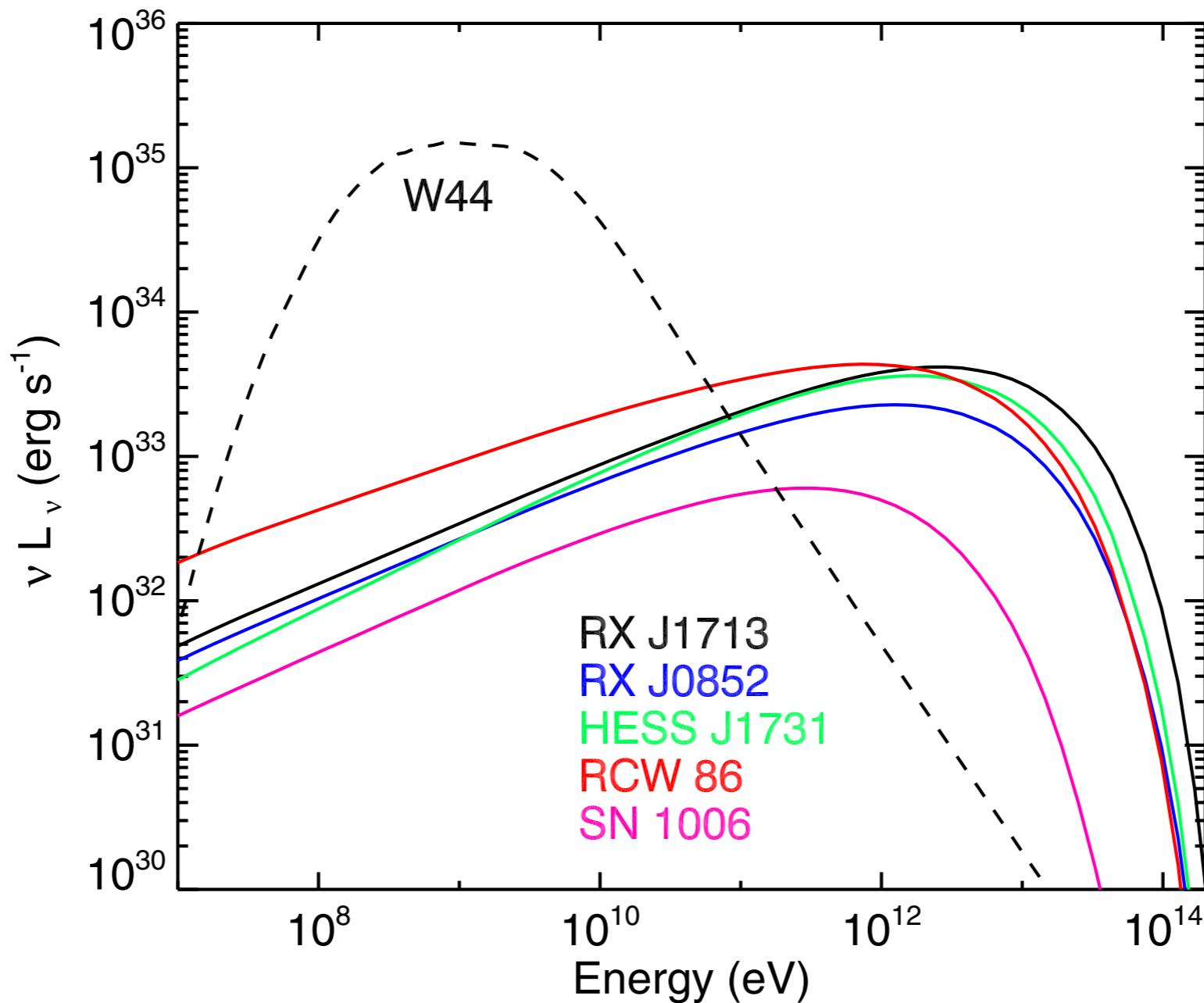
$<1.7$

$1.42 \pm 0.1$

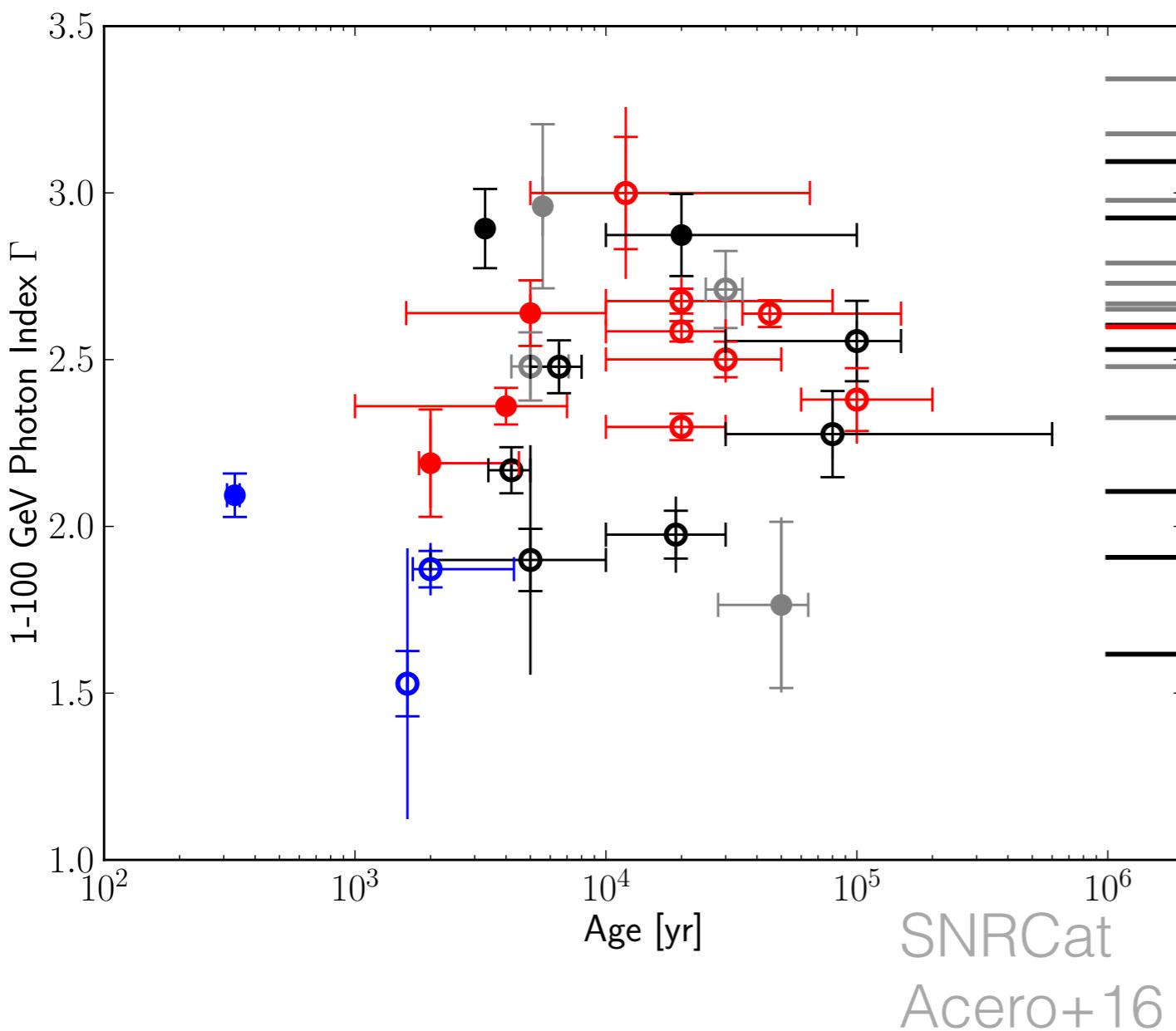
# GeV/TeV populations

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



# Age - GeV index



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

- $E_{\text{break}}$  evolution (related to  $V_{\text{shock}}$ )
- Change of dominant emission mechanism
- Different zones properties

