Perspectives on high-energy resolution X-ray spectroscopy of supernova remnants

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EUROPEAN ASTRONOMICAL SOCIETY ANNUAL MEETING

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Introduction

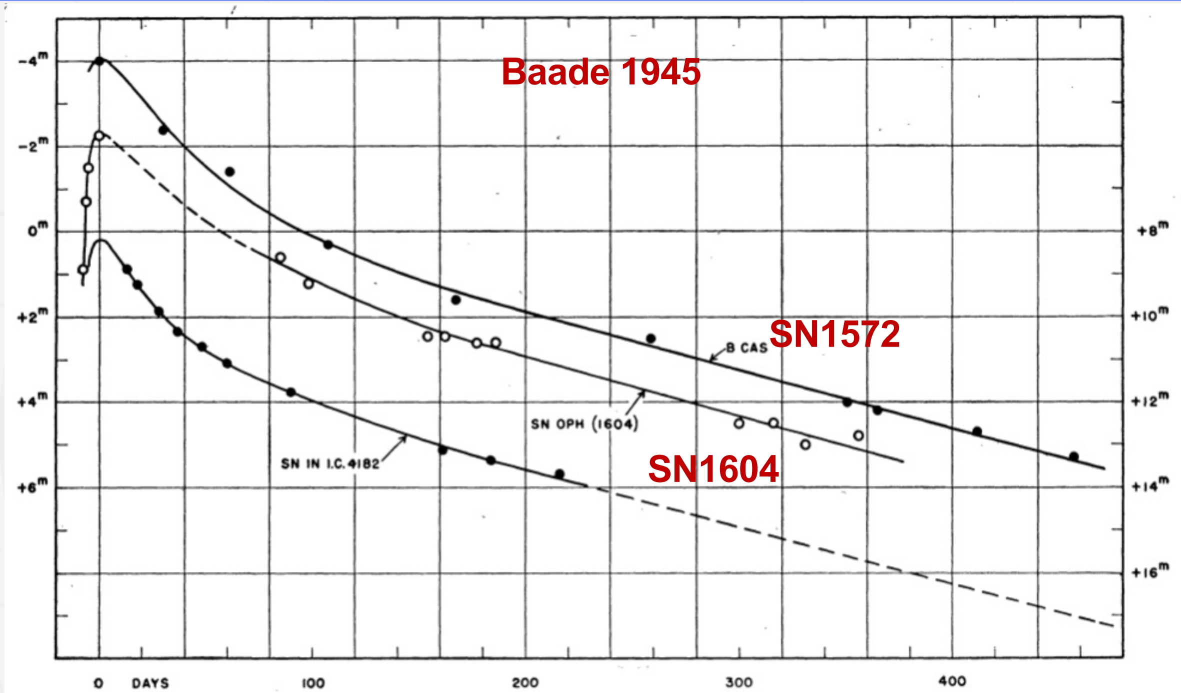
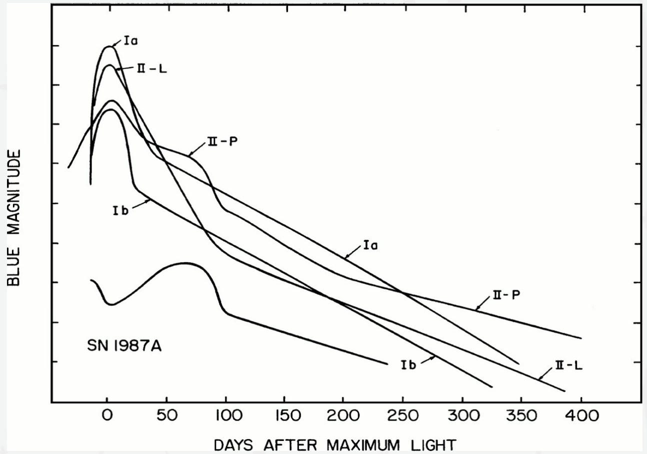


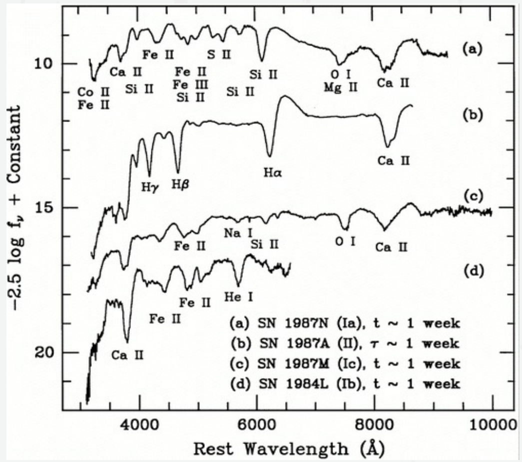
FIG. 1.—Visual light-curves of B Cas, SN Oph (1604), and SN in I.C. 4182. Magnitudes on the left refer to B Cas and SN Oph (1604); on the right, to SN in I.C. 4182. The extrapolated (*dotted*) part of the light-curve of SN in I.C. 4182 has been taken from the photographic light-curve, after an adjustment in zero point.

Schematic light curves for SN Ia, averaged Ib and Ic, II-L, II-P, and SN 1987A.



Fillipenko 1997, ARAA

Early-time optical spectra of supernovae for the four major types (Ia, II, Ib, Ic)



Historical light curve (Tycho Brahe 1573 in *De Stella Nova,* 1602 in *Progymnasmata)*

Supernova identification (Baade 1938)

Supernova type: Ia (Baade 1945)

"History of the SN1572 discovery" talk by Ralph Neuhaeuser

Classification in different categories of extragalactic supernovase

Type I: absence of hydrogen and helium

Thermonuclear explosion

Type Ia

- Presence of strong Si and iron peak elements
- Observed in elliptical and spiral galaxies
- Progenitor: white dwarf in a binary system
- Homogeneous subclass

Core collapse

Type Ib

- Strong He I emission
- Progenitor: interacting binary of moderate mass after H envelope lost
- Inhomogeneous subclass

Type Ic

- Absence of SI II and He I
- Progenitor: interacting binary of moderate mass after H and He envelope lost
- Inhomogeneous subclass

(e.g. Fillipenko 1997)

Type II: presence of hydrogen

Core collapse

- Observed in spiral galaxies, in or close to spiral arms and HII regions
- Progenitors: young massive stars
- Larger dispersion than type Ia

Type II-L

- Light curve: linear, similar to Type Ia

Type II-P

- Light curve: plateau, extended period of maximum brightness
- Progenitor : red supergiant
- Type II-P:

Type II-n

- Light curve: slightly decreasing
- Narrow emission lines
- Progenitor: with a very dense circumstellar wind

Type II-b

- Spectral characteristics evolving from Type II to Ib
- cIIb: compact progenitor, H envelope < 0.1 Msun
- eIIb: extended progenitor, H envelope > 0.1 Msun

Thermonuclear supernovae

Chandrasekhar mass white dwarf in a single degenerate binary system

- delayed detonation (deflagration to detonation transition) explosion mechanism.
- Multiple donors possible

In this explosion scenario carbon is ignited once the central density of the WD attains a critical value, but the star only explodes ~centuries after this 'simmering' phase of carbon burning.

Sub-Chandrasekhar mass white dwarf in a single degenerate binary system

- double detonation explosion mechanism
- Donors are hydrogen-poor, helium burning stars, or white dwarfs that contain a non-negligible fraction of helium in their outer layers, either helium or HeCO 'hybrid' WDs

A double white dwarf merger:

- Delayed detonation for Chandrasekar mass
- Double detonation for sub-Chandrasekar mass (more likely)

(Ruiter 2020)

Physics of supernovae

- Two main explosion mechanisms, but many different flavours and unknowns
- Various physical processes at work
- Large variety of systems and progenitors
- Range of circumstellar environments
- Various ISM environments

⇒ SNe have vast consequences in terms of metal enrichment, neutron star and black hole production, energy injection by shocks and turbulence in the ISM, with feedback effects on galactic scales eas 2022 Valencia

Supernovae remnants: at the crossroads of several physics

Understanding the physics of type Ia: *Talk by Carles Badenes*

- Nature of the binary system (single versus double degenerate)?
- Ignition of the burning?
- Burning front propagation (slow/fast deflagration, transition to detonation/double detonation)?

Understanding the physics of core-collapse SNe *Talk by Salvatore Orlando*

- Explosion mechanism (neutrino-driven versus MHD-driven)?
- Value of the mass cut between the residual compact object and the ejected envelope?
- The wide range of progenitors *Talk by Manami Sasaki*

Understanding the physics of particle acceleration and Galactic cosmic rays

- Particle acceleration: efficiency, obliquity
- Magnetic field amplification

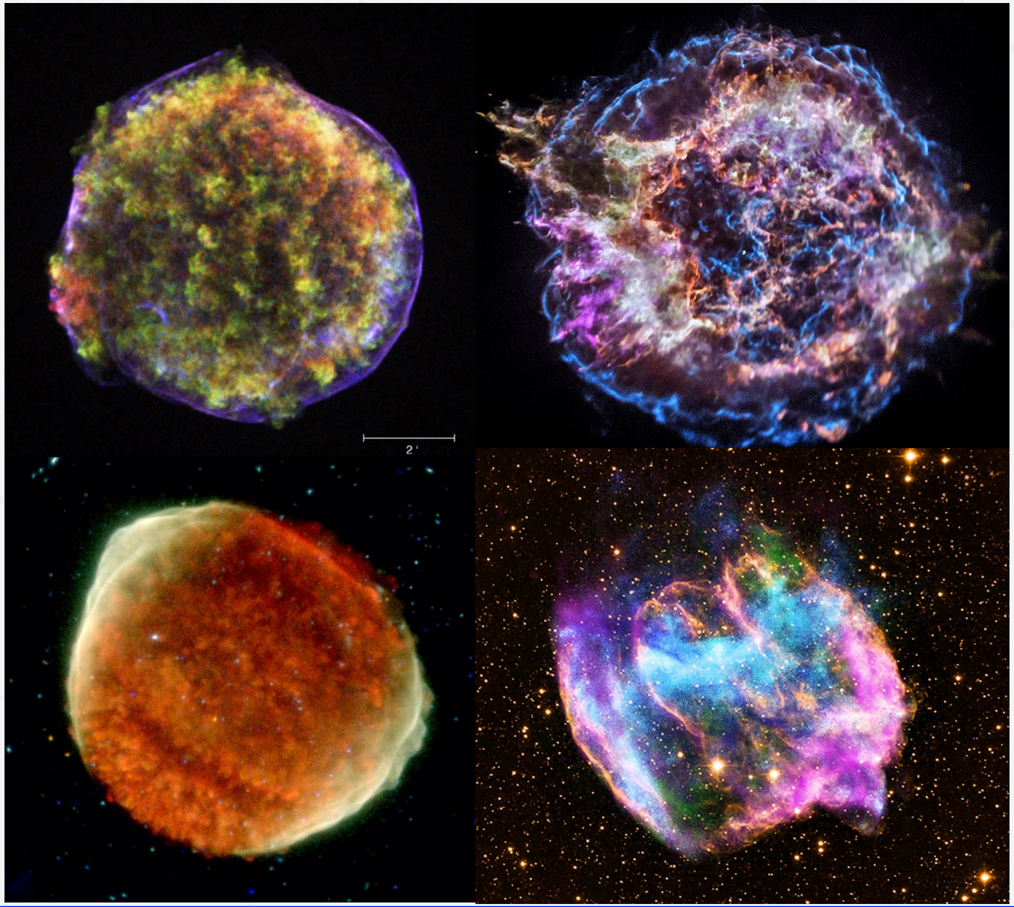
Talk by Jiro Shimoda, Vincenzo Sapienza, Pierre Cristofari, Roberta Zanin, Roberta Giuffrida, Marianne Lemoine-Goumard, Dimitri Prokhorov

Understanding plasma and shock physics

- Collision-less shock heating of electrons
- back-reaction of accelerated particle

Understanding the interaction with the ambient and ISM medium

- Nature and properties of the circumstellar medium?
- Evolution in dense environments/molecular clouds?
- Impact (heating, enrichment, turbulence, acceleration,…)



The role of X-ray spectroscopy

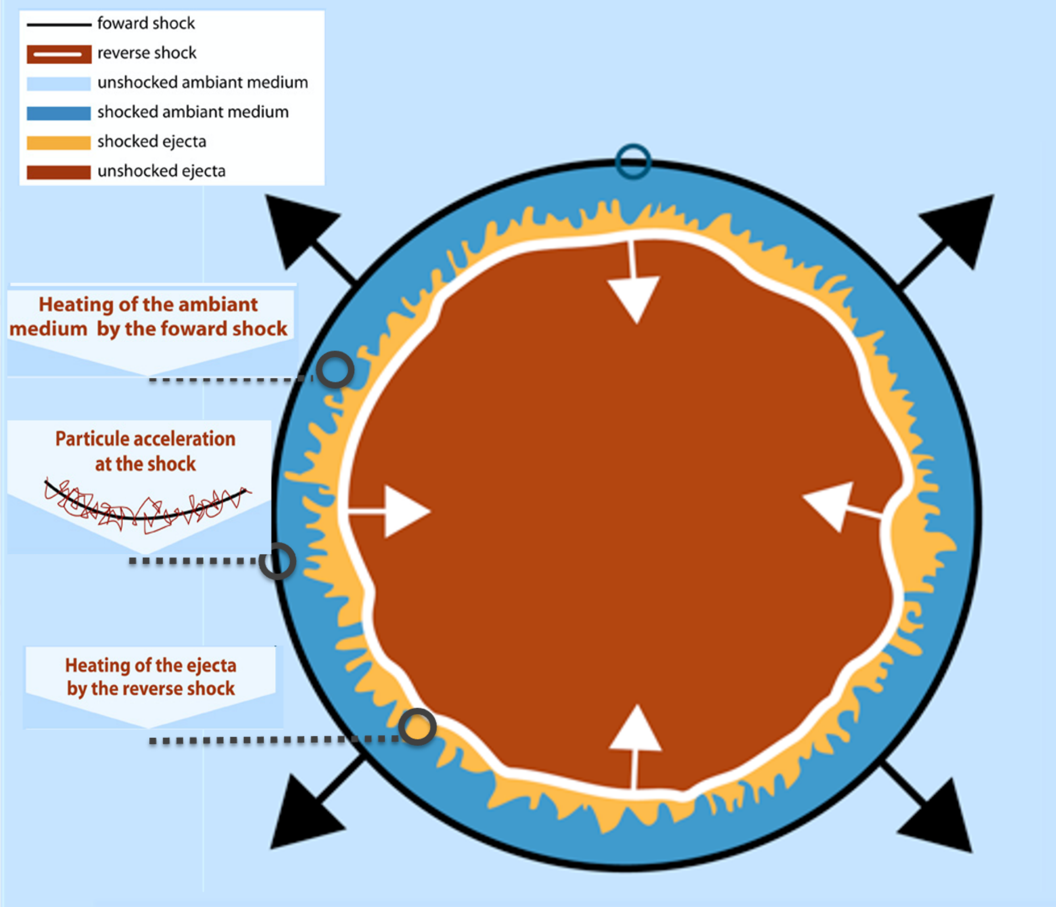
Plasma condition diagnostics through X-ray spectroscopy:

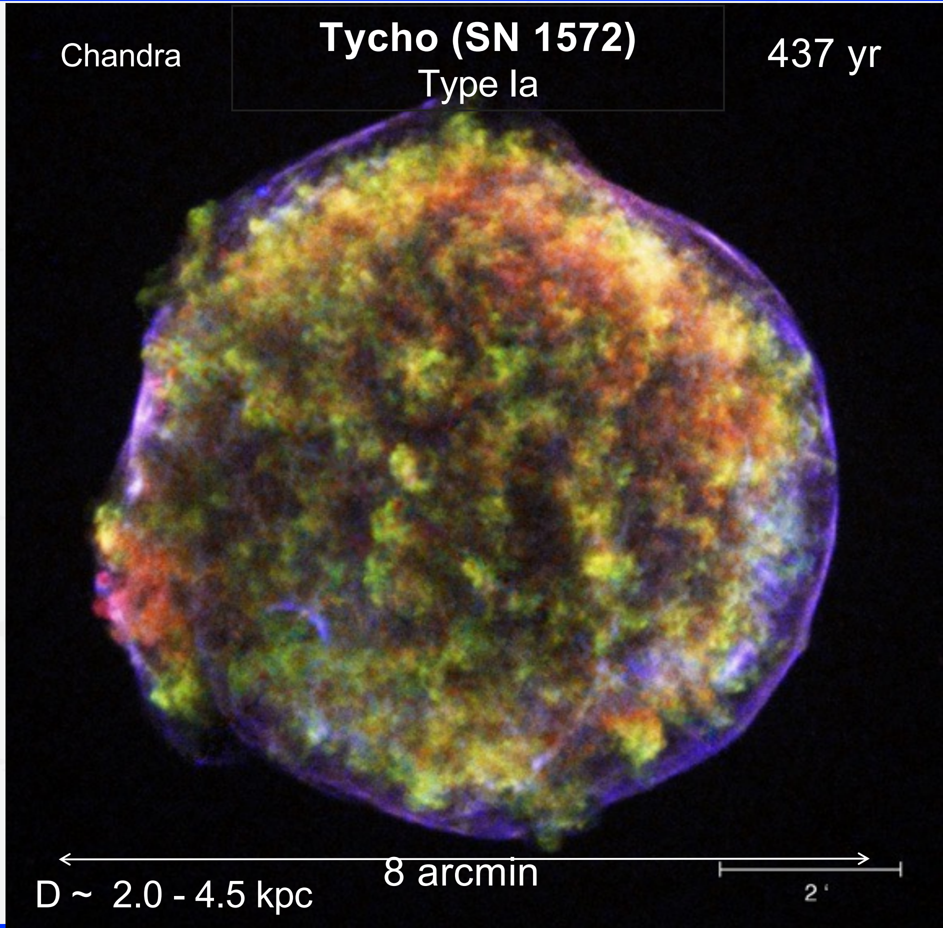
- Optically thin hot plasmas in SNRs: emitted photons leave "intact" the remnant, providing a direct insight into the plasma conditions
- Continuum emission: nature, brightness, shape (bremsstrahlung, recombination, two photons, synchrotron,..)
- Lines: brightness, energy, line ratios, line width, line shift

Contains a great deal of information on physical quantities

- Plasma characteristics: electronic temperature T_e, electronic density n_e, atomic element densities n_Z, element temperatures T_Z, ionisation states of elements $X_{Z,i}$, bulk velocity V
- Non-equilibrium state (ionisation/recombination): depends on the evolution of n_e and T_e since t_{shock}, time when the plasma was shocked => proxy~ $\int_{t_{shock}}^{t} n_e dt$
- Non-equilibrium equipartition between temperature (electron/ions): depends on Coulomb interaction between electrons and ions
- Collision-less heating of electrons at the shock: depends on plasma instabilities

Young supernova remnants

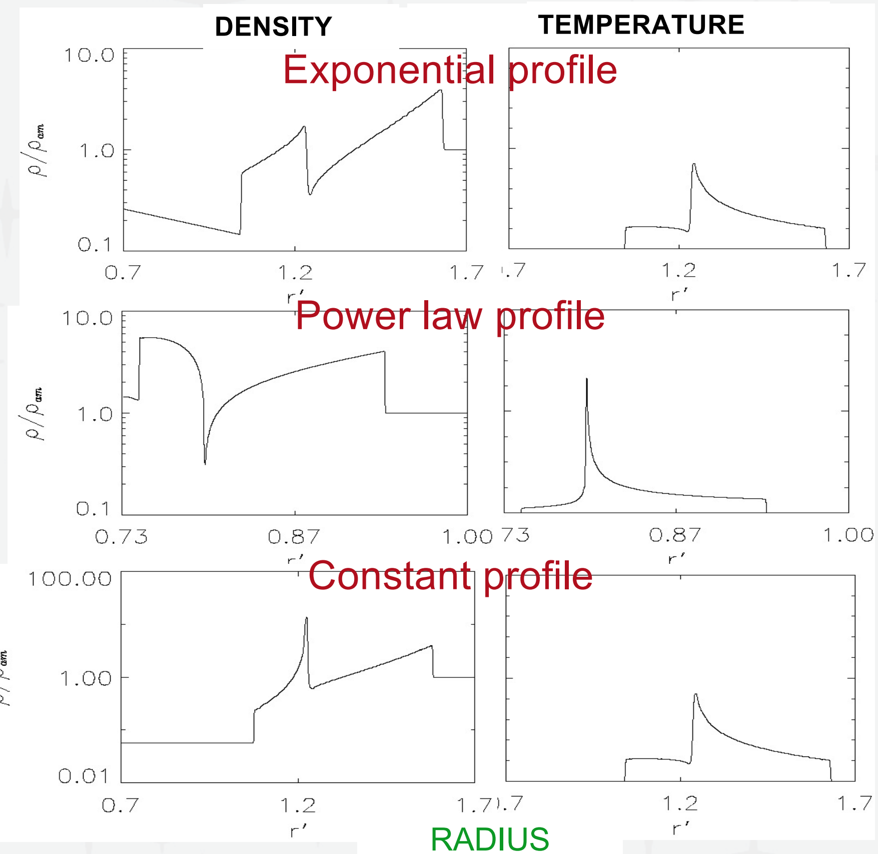




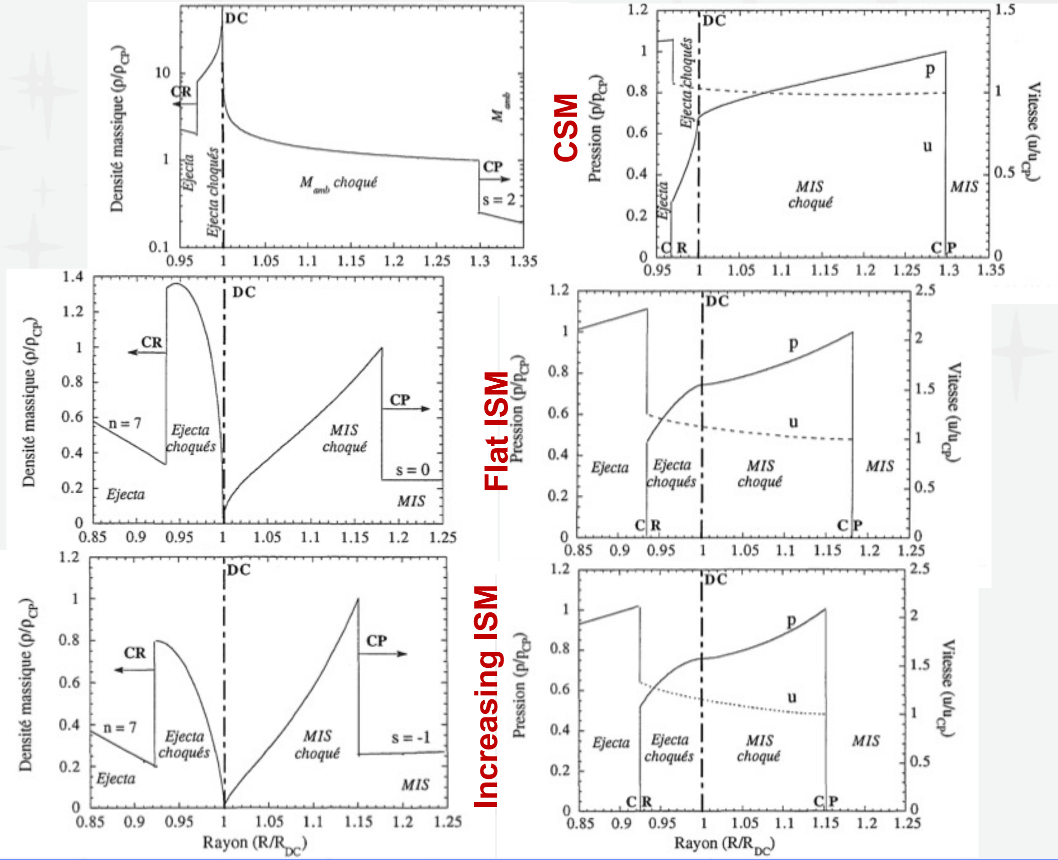
Structure of the interaction region

The structure of the interaction region depends on the initial density profiles of the ejecta and ambiant medium

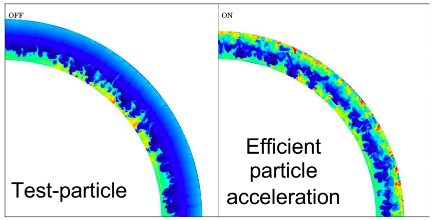
Dwarkadas and Chevalier 1998, ApJ 497, 807



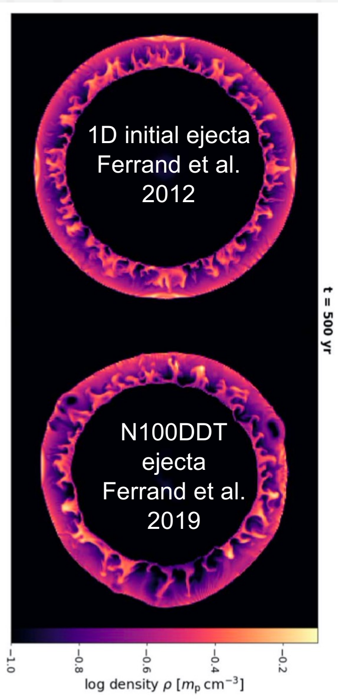
Power law profiles of different index (Chevalier 1982)



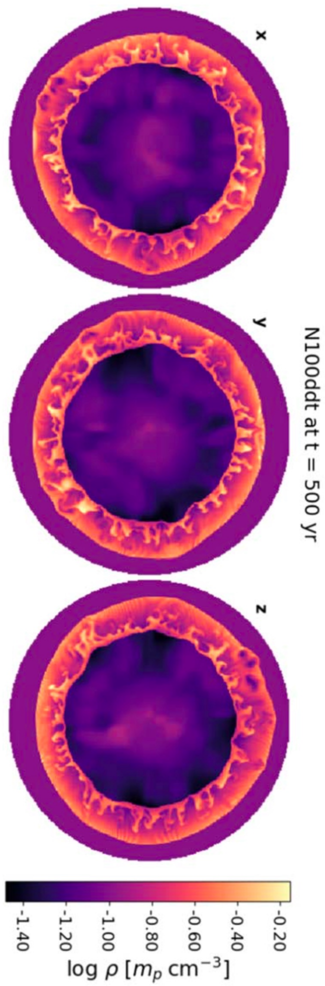
Density structure versus SNIa models



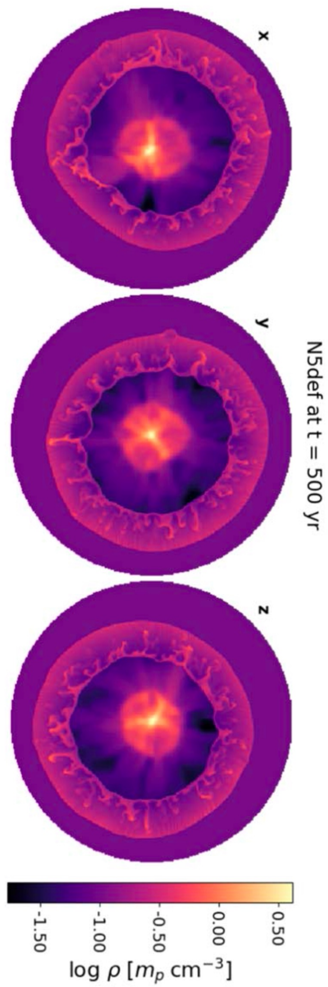
1D initial ejecta
Ferrand et al. 2012



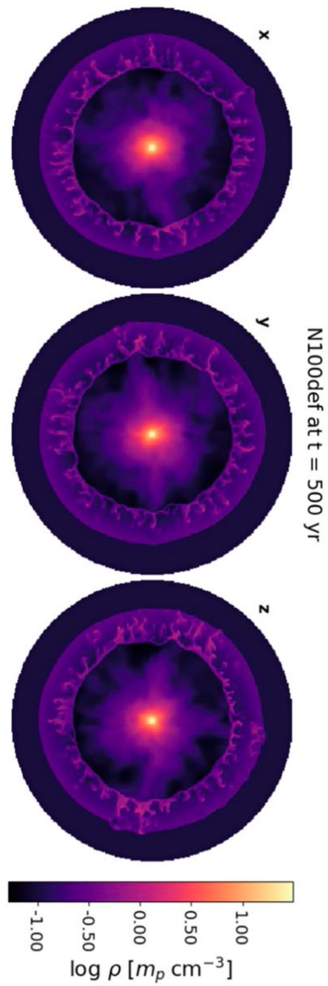
Delayed detonation
N100DDT
Ferrand et al. 2021



Pure deflagration
N5def
Ferrand et al. 2021



Pure deflagration
N100def
Ferrand et al. 2021



Delayed detonation
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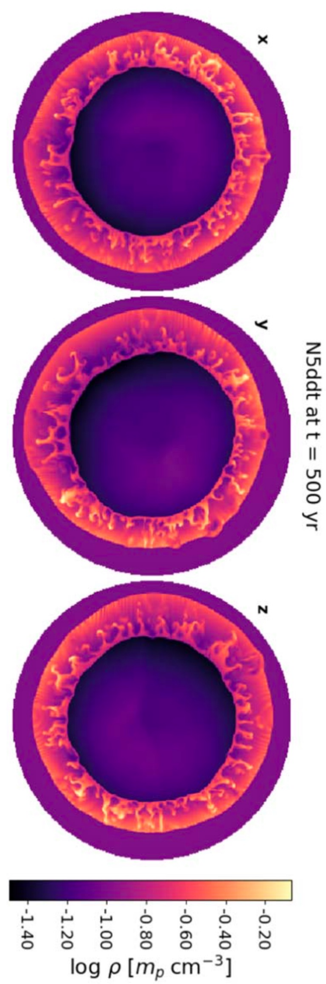
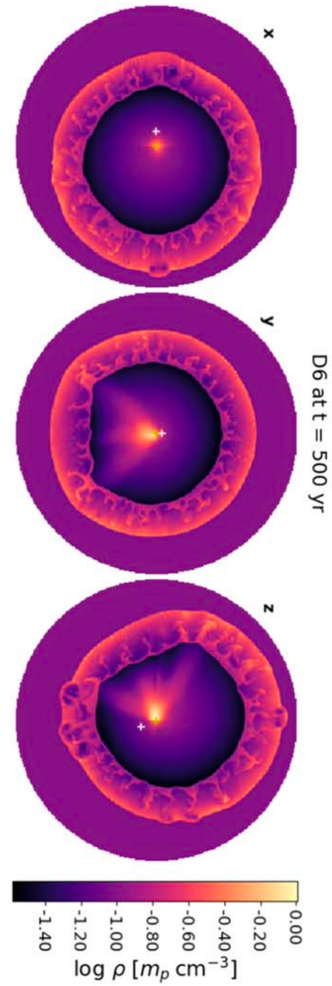
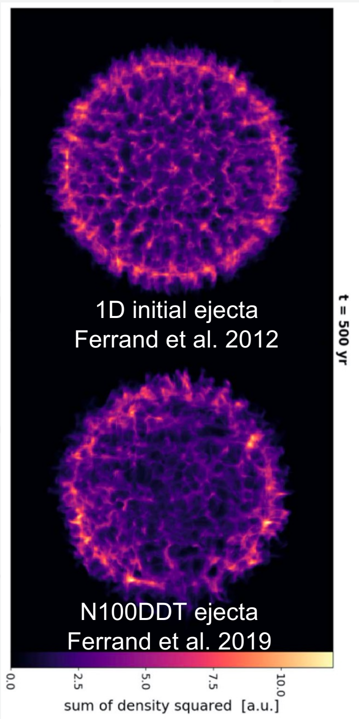
Ferrand et al. 2021



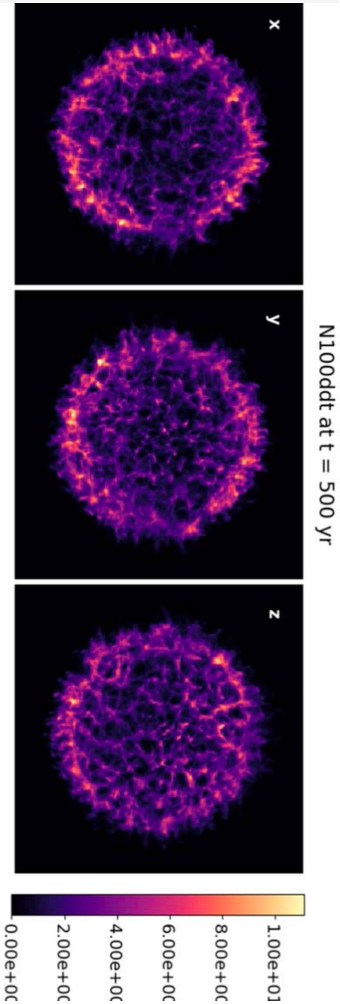
Double detonation
D6
Ferrand et al. 2022



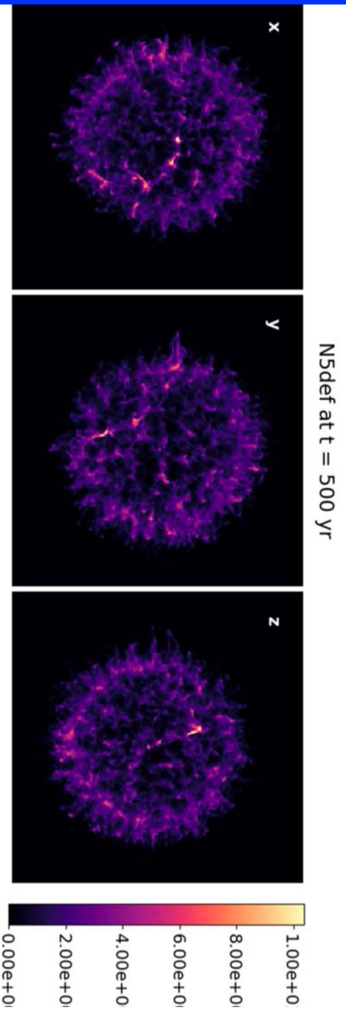
X-ray proxy structure versus SNIa models at 500 yrs



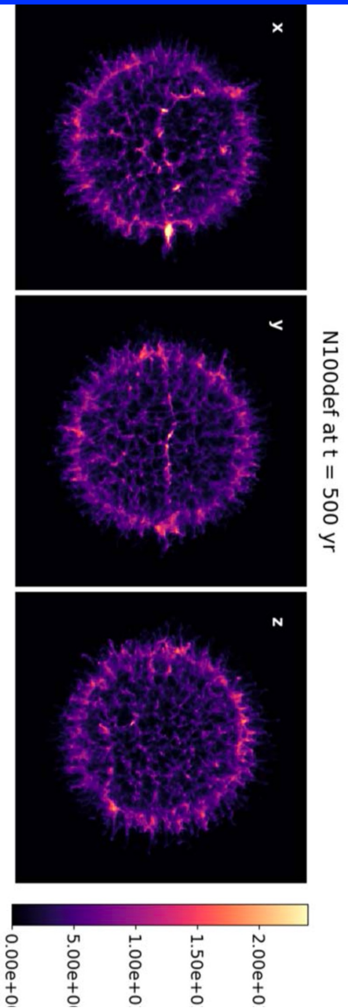
N100DDT
Ferrand et al. 2021



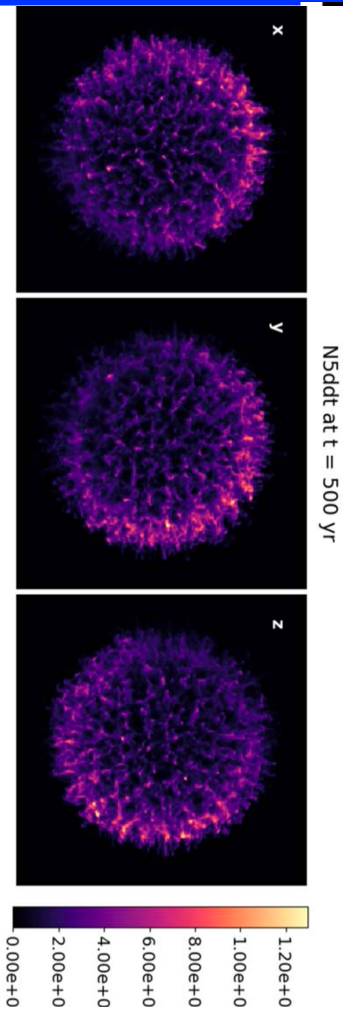
N5def
Ferrand et al. 2021



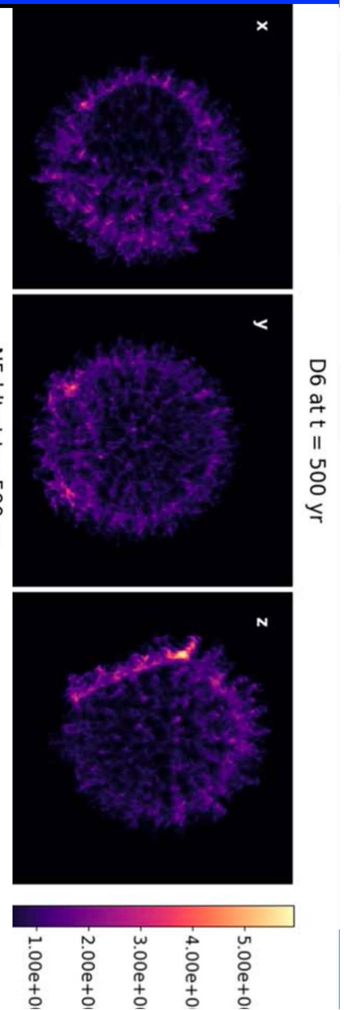
N100def
Ferrand et al. 2021



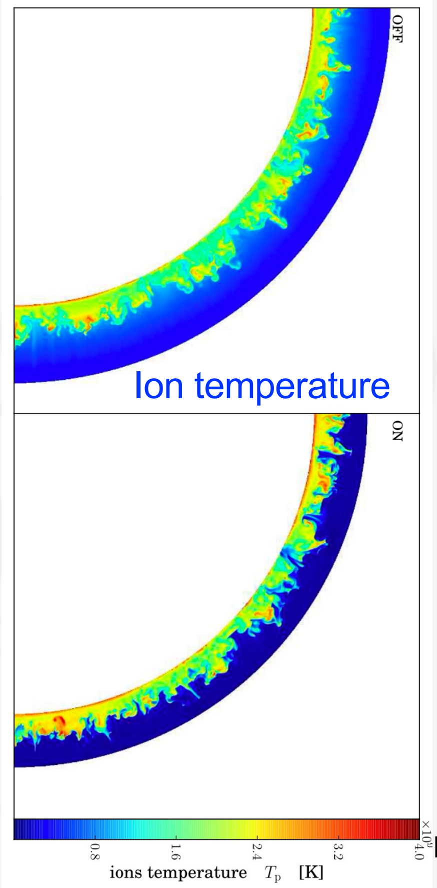
N5DDT
Ferrand et al. 2021



D6
Ferrand et al. 2022



Thermodynamical quantities: T_i, T_e, n_e, ionisation age

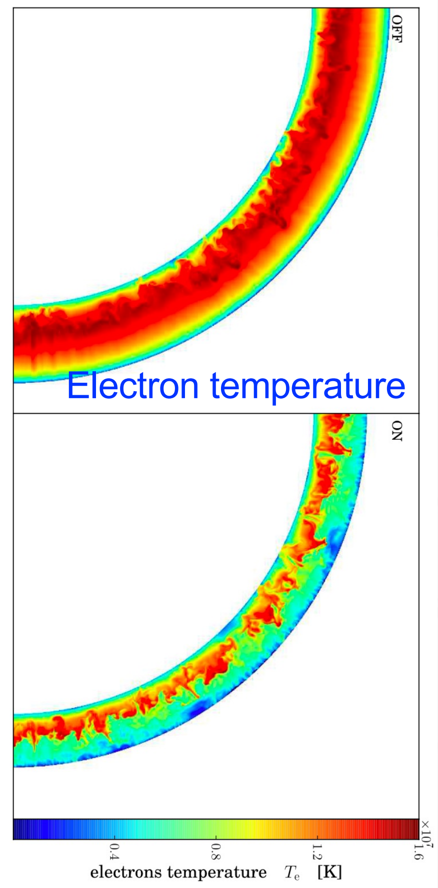


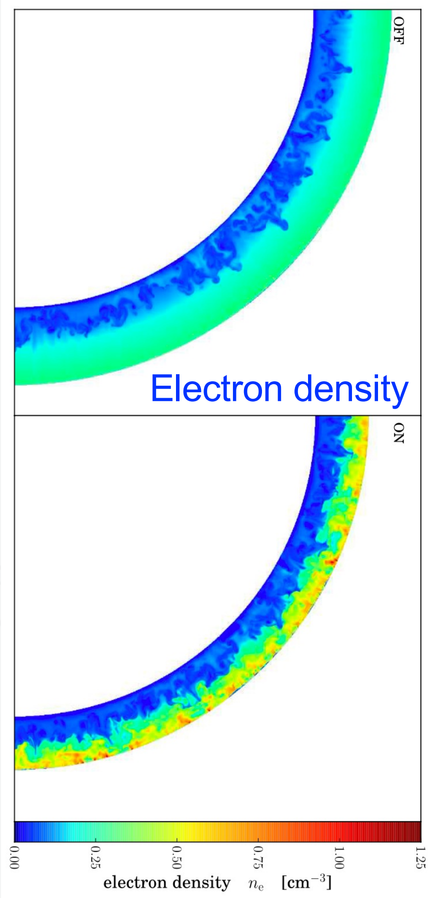
No (efficient) particle acceleration

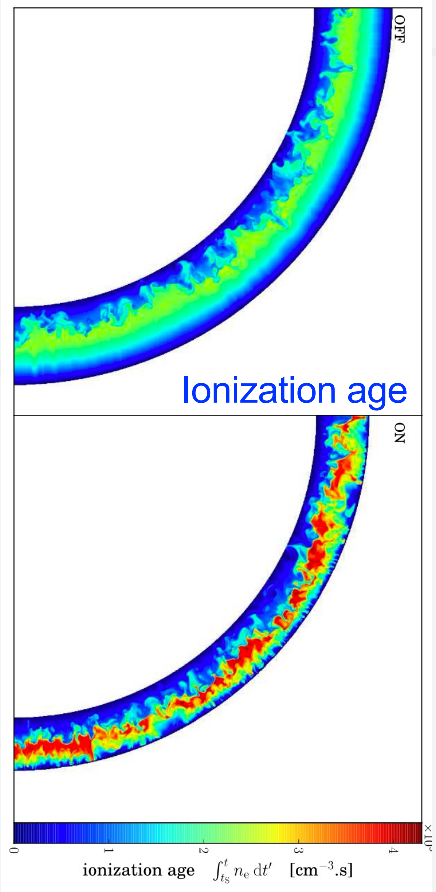
+ ejecta composition

Efficient particle acceleration at the forward shock

Ferrand et al. 2012

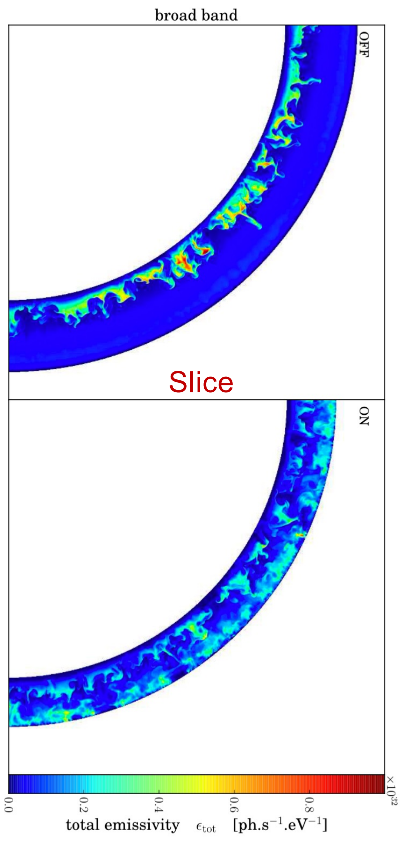


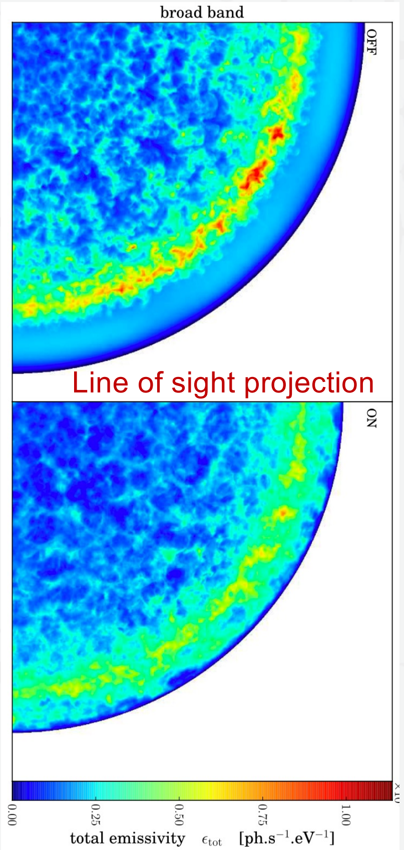




X-ray thermal emission

Broad band emissivity



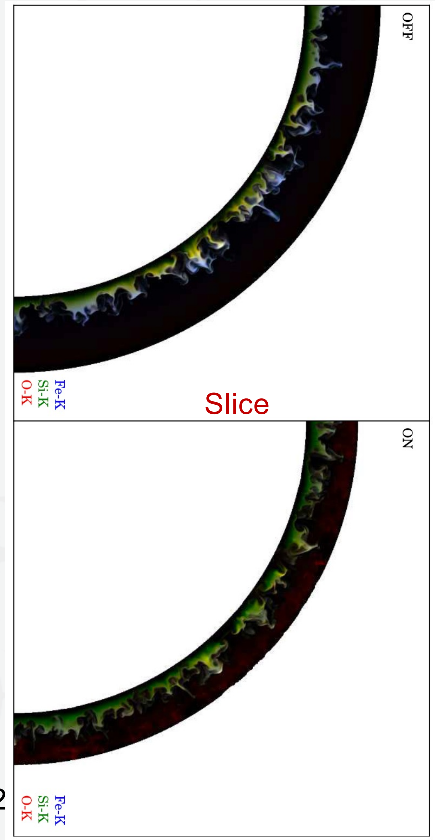


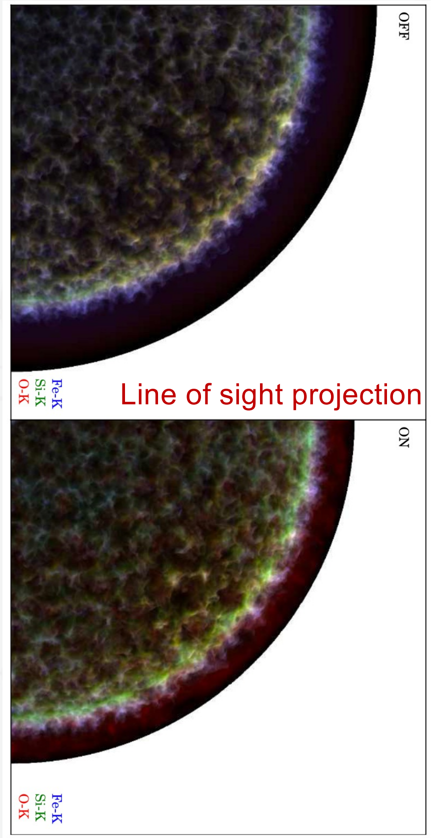
No (efficient) particle acceleration

Efficient particle acceleration at the forward shock

Ferrand et al. 2012

Composite maps O-K Si-K and Fe-K





X-ray spectrum: type Ia in a uniform ISM

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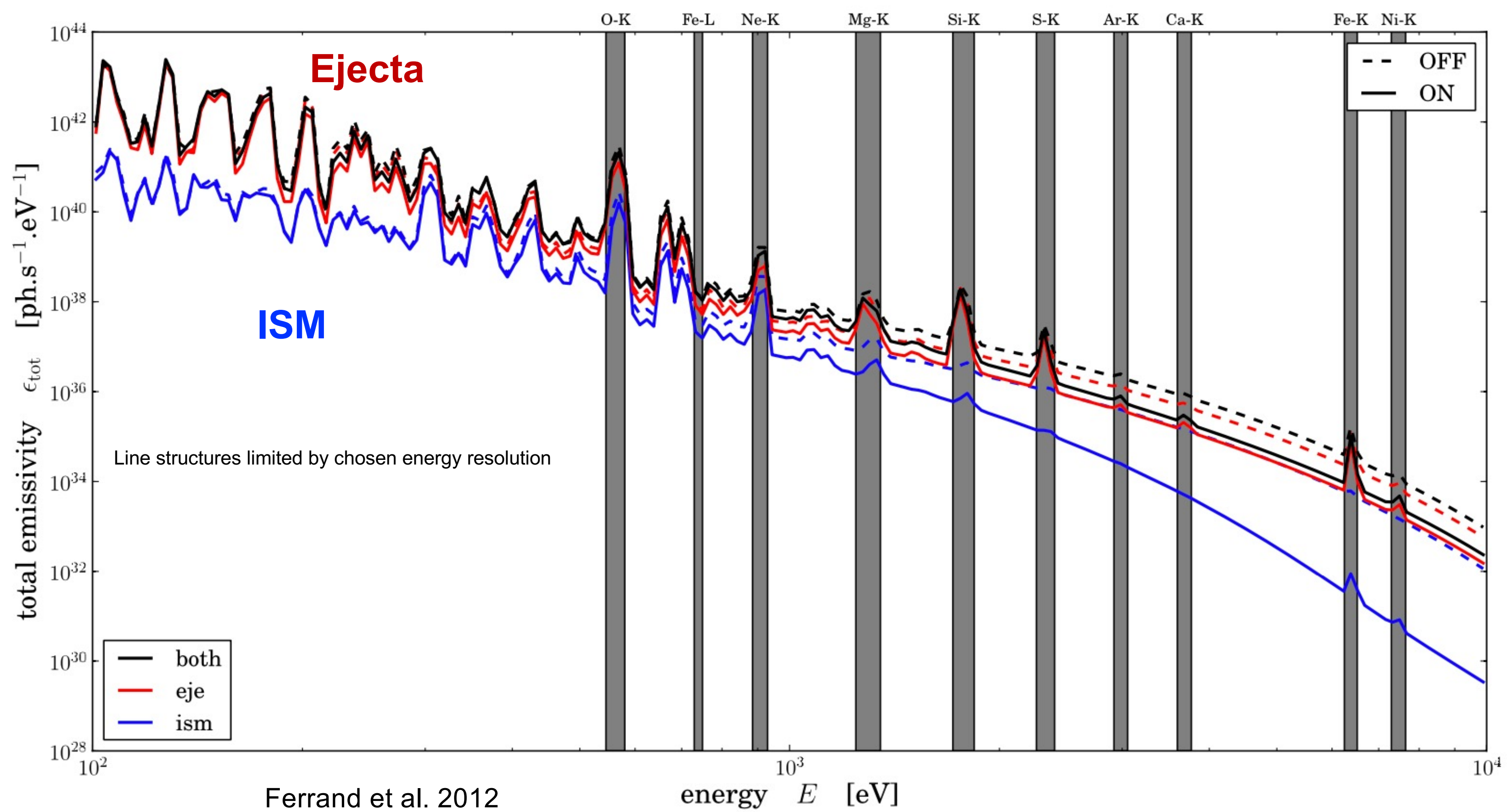
No (efficient) particle acceleration

———
Efficient particle acceleration at the forward shock

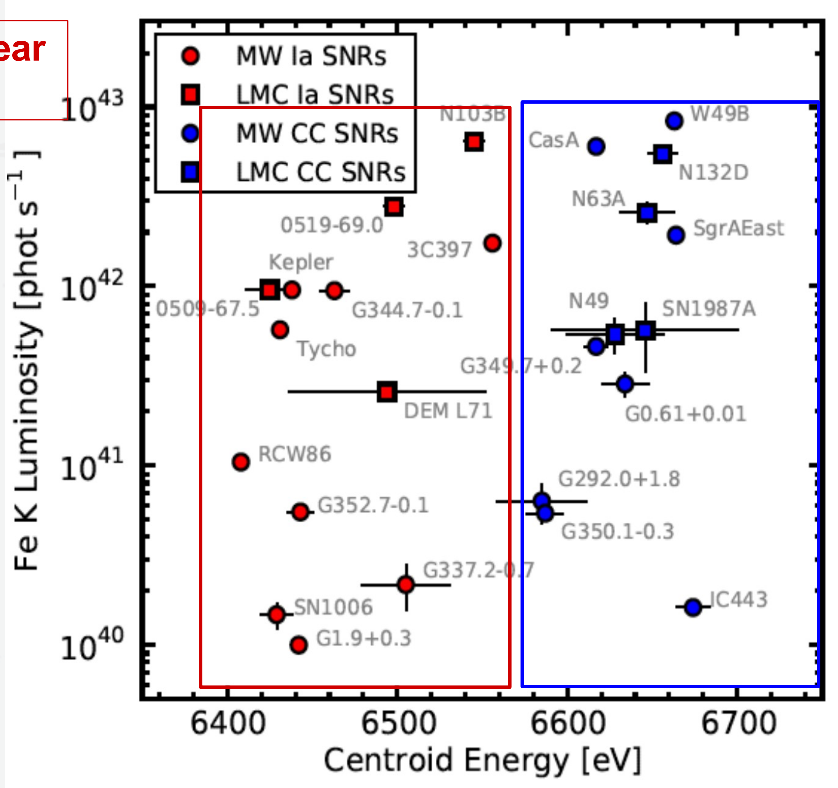


Ferrand et al. 2012

Fe K line energy / ionisation state constrain CS medium and SN types

Yamaguchi et al. ApJL 2014

Thermonuclear SNe



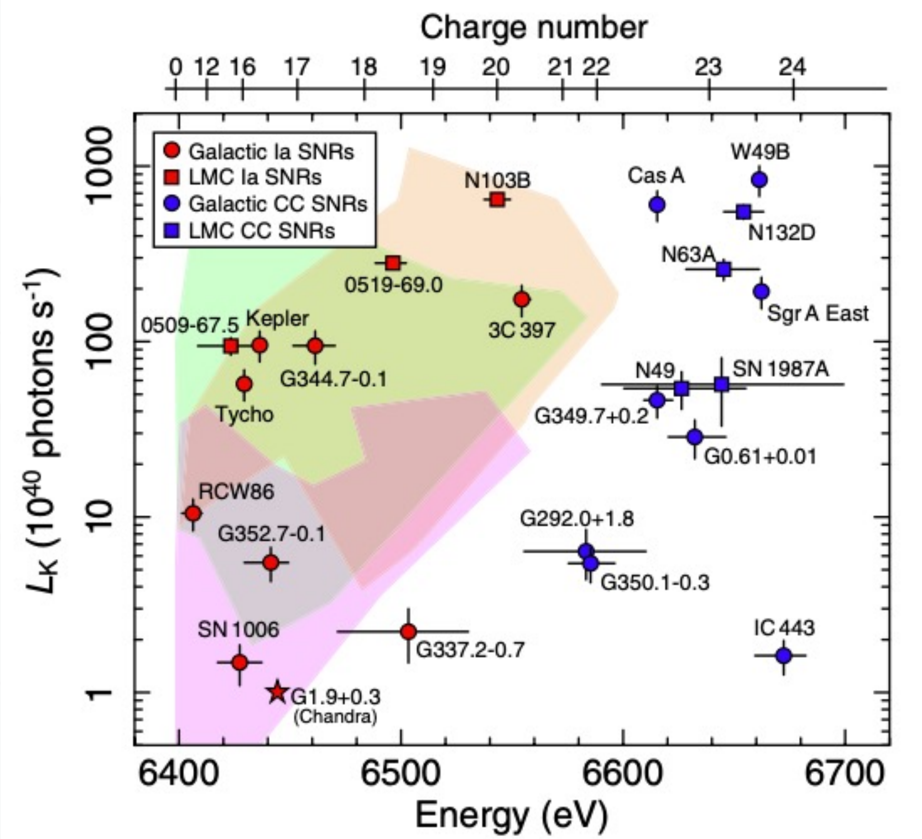
Core collapse SNe

Fe Kα centroids and luminosities measured in galactic and LMC SNRs

Discrimination between SN Ia and CC SNe based on Fe Kα centroids of their remnant

- arises from different ambient/circumstellar medium (stellar wind) densities in the medium around SN Ia /core collapse supernovae

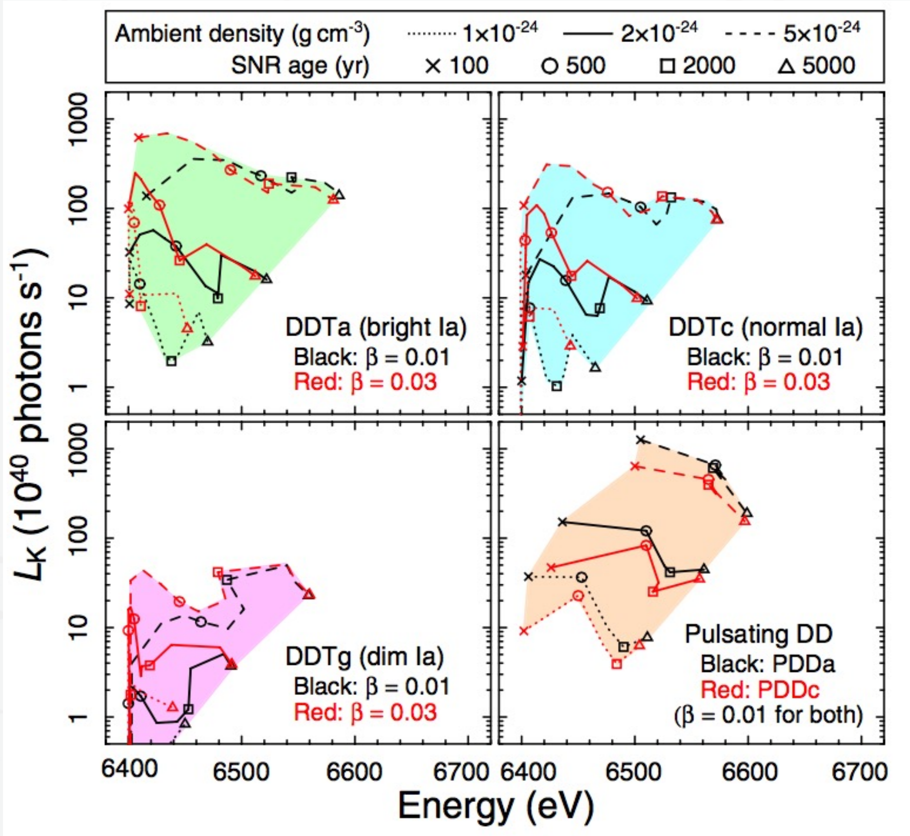
X-ray emission spectrum constrain SN types: Thermonuclear supernovae



Fe Kα luminosity versus centroid energy

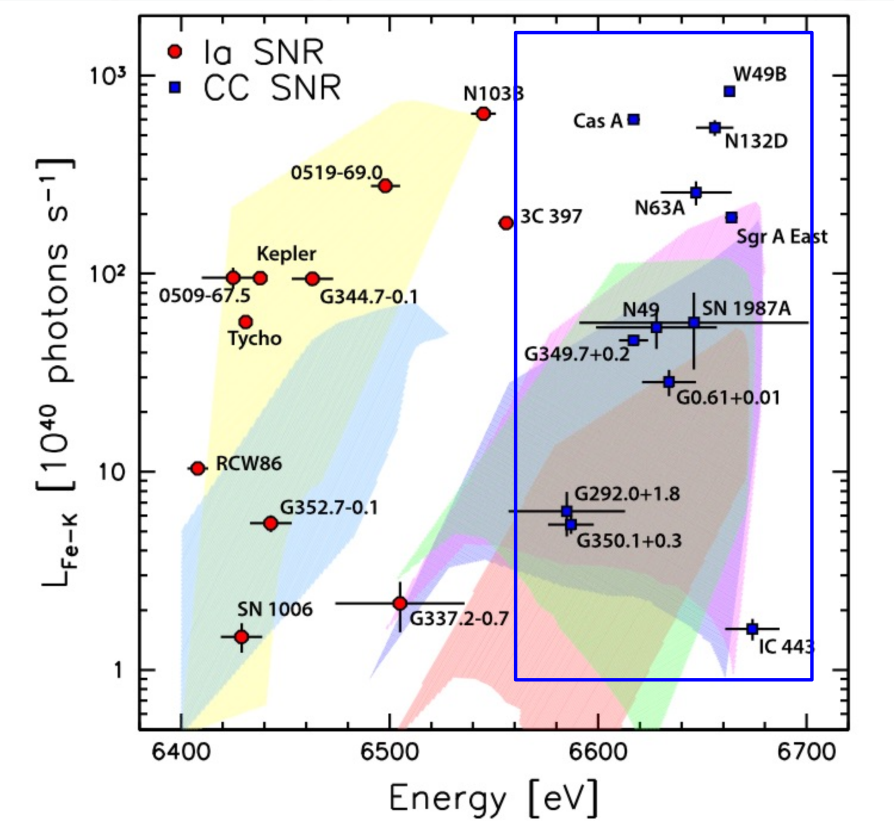
Yamaguchi et al. ApJL 2014

Models from Badenes et al. 2003, 2005, 2006



Predicted by theoretical Type Ia SNR models

X-ray emission spectrum constrain SN types: Core collapse supernovae



Fe Kα luminosity versus centroid energy

Ejecta Model	E_{SN} 10^{51} erg	M_{ej} ($M_\odot$)	n_{amb} [a] (cm^{-3})	v_{wind} [b] (km s^{-1})	$\dot{M}$ [b] 10^{-5} $M_\odot$ yr^{-1}	References
DDTa	1.27	1.38	0.1–3.0	⋯	⋯	Badenes et al. (2008)
DDTg	0.85	1.38	0.1–3.0	⋯	⋯	Badenes et al. (2008)
s12D	1.21	8.87	⋯	10–20	1–2	This work
s25D	1.21	12.2	⋯	10–20	1–2	This work
1987A	1.10	14.7	⋯	10–20	1–2	Saio et al. (1988)
1993J	2.00	2.92	⋯	10–20	1–2	Nozawa et al. (2010)

Predicted by theoretical CC SNR models with r^{-2} circumstellar wind
Patnaude et al., 2015 ApJ

Higher line centroids in CC SNRs => consequence of **the increased densities in the CSM** due to the slow-moving dense wind from massive progenitors.

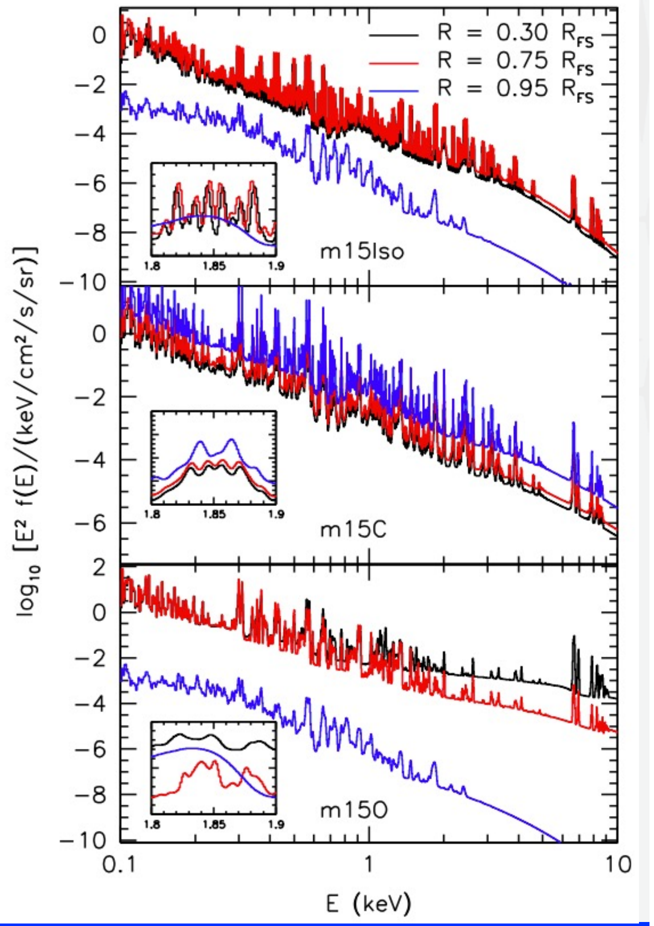
X-ray spectrum: history of mass loss and core collapse

Patnaude et al. 2017

- 1D model that only includes steady mass loss,
- 1D model with enhanced mass loss over a period of ~5000 yr prior to core collapse
- 1D model with extreme mass loss over a period of ~500 yr prior to core collapse.

Table 1
MESA Initial and Final Model Parameters

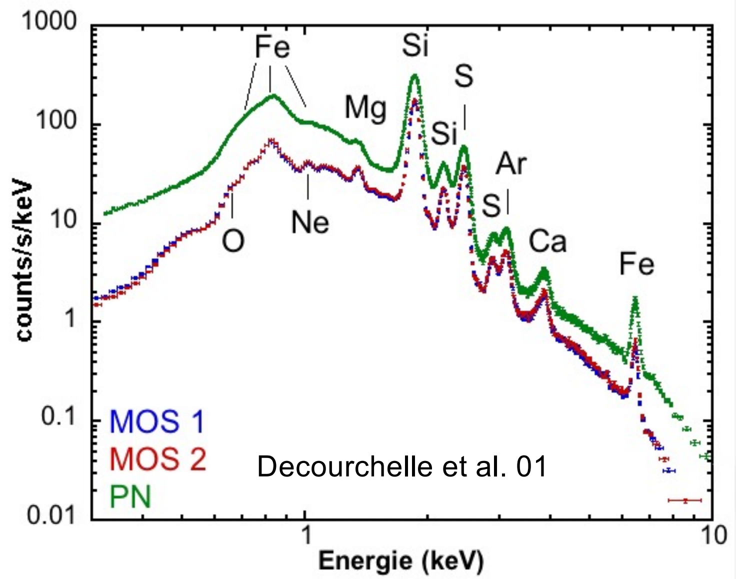
Model	M_{Final}	M_C	M_O ($M_\odot$)	M_{Si}	M_{Fe}	R ($\log_{10} R/R_\odot$)	$\dot{M}$[a] ($M_\odot$ yr^{-1})	$t_{mass\text{-}loss}$ (yr)
m15Iso	13.3	2.56	2.48	1.70	1.53	2.99	5×10^{-6}	11.1×10^{7}
m15C	10.0	2.56	2.49	1.68	1.51	3.03	2×10^{-4}	5000
m15O	5.7	2.56	2.46	1.69	1.53	2.93	0.1	50



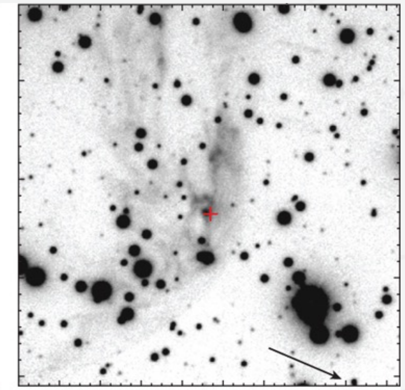
Tycho’s supernova remnant: overall spectra

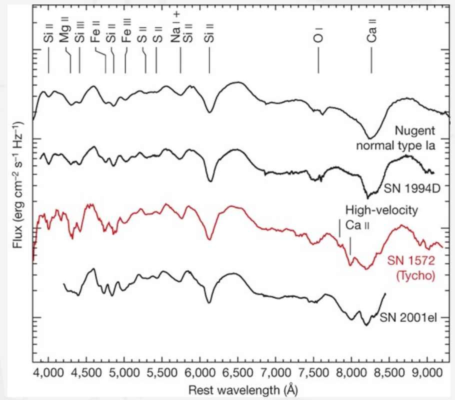
Overall X-ray spectrum constrains SN type and explosion mechanism

- delayed detonation favoured for Tycho (Badenes et al. 06)
- normal type Ia confirmed by optical light echo spectrum (Krause et al. 08)



Optical light echo image and spectrum of SN 1572 compared with spectra of normal extragalactic SNe Ia





Krause et al. 08

Talks on Tycho’s SNR by Bryan Williams, Leila Godinaud, Masamune Matsuda

Tycho's supernova remnant:
presence of rare elements

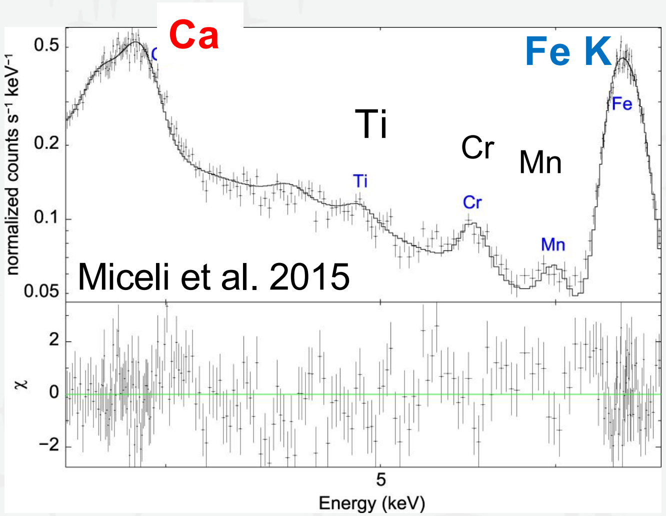
Elemental distribution in the ejecta

- **radial stratification** of the elements (Fe inside)
- **anisotropies** in the distribution of Fe-rich and Si-K/Ca-rich ejecta

Presence of rare elements: Ti, Cr and Mn

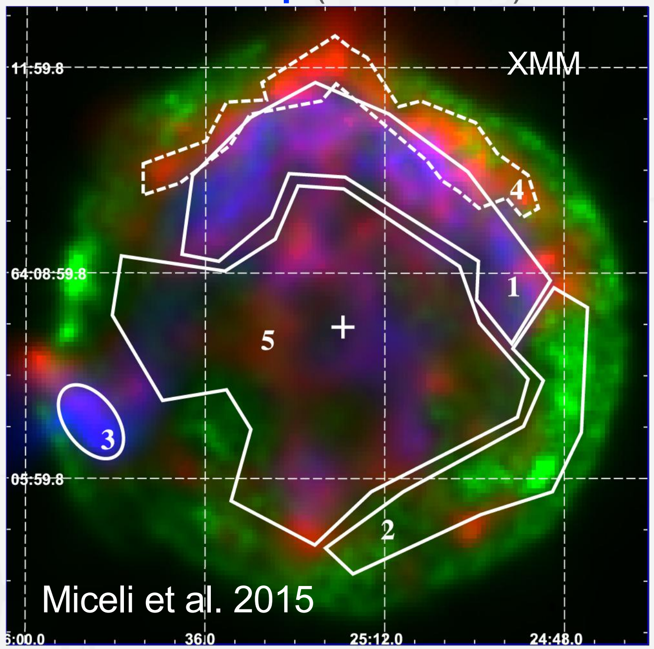
- Well **correlated to Fe K**
- Indications of Ti line emission (at >2 sigmas)

Fe-peak nuclei seem to be spatially co-located in the remnant, in agreement with the predictions of Type Ia SN models



Presence of rare elements Ti, Cr, Mn

Ca K EW map (3.6-4.05 keV)
Continuum (4.4-6.1 keV)
Fe K EW map (6.1-6.7 keV)



Equivalent width maps of Ca and Fe K lines

Tycho's supernova remnant: high-resolution spectra of bright knots

XMM-Newton RGS observations

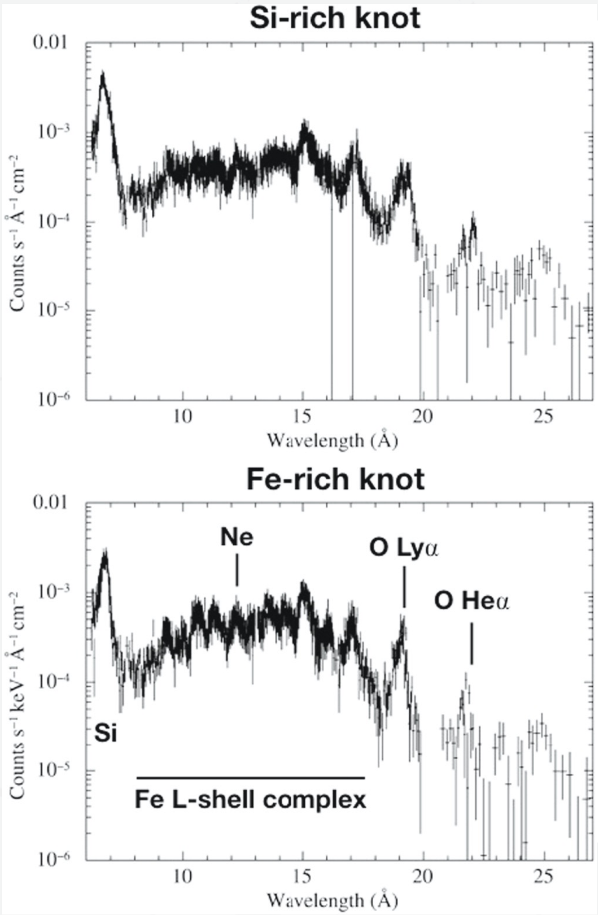
First clear detection of O lines

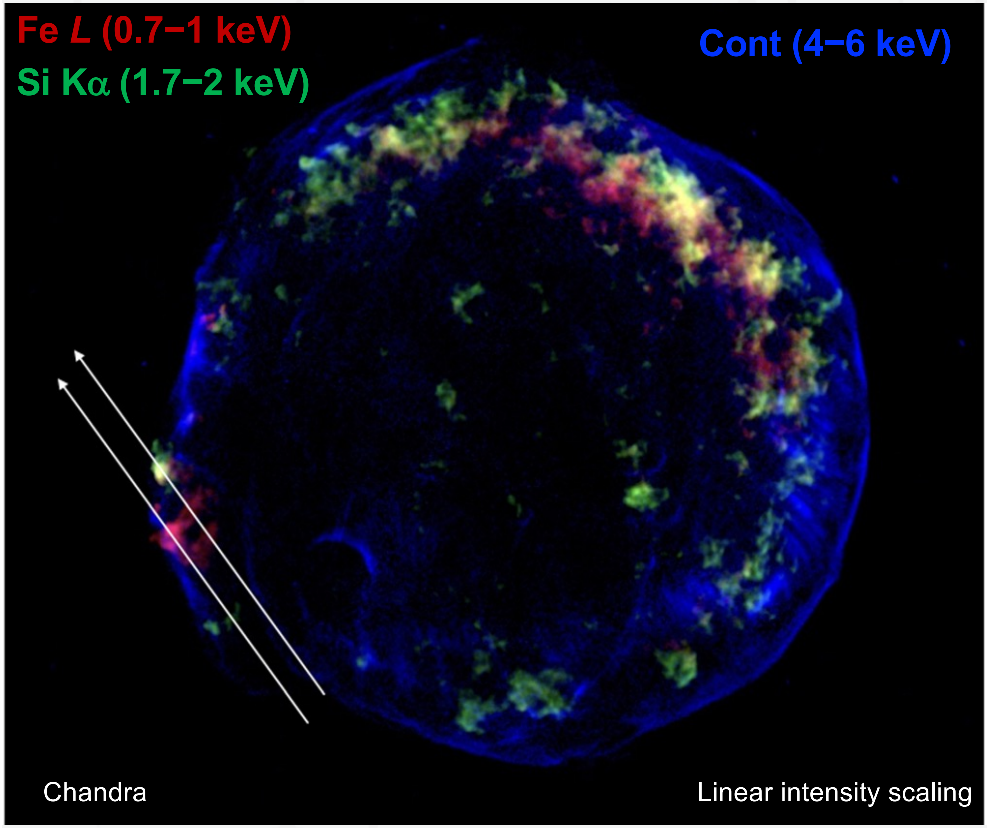
Line broadenings measurements

- O K ~ 3 eV => kT_O ~ 0.4 MeV
- Fe L ~ 4.5 eV => kT_{Fe} ~ 1.5 MeV

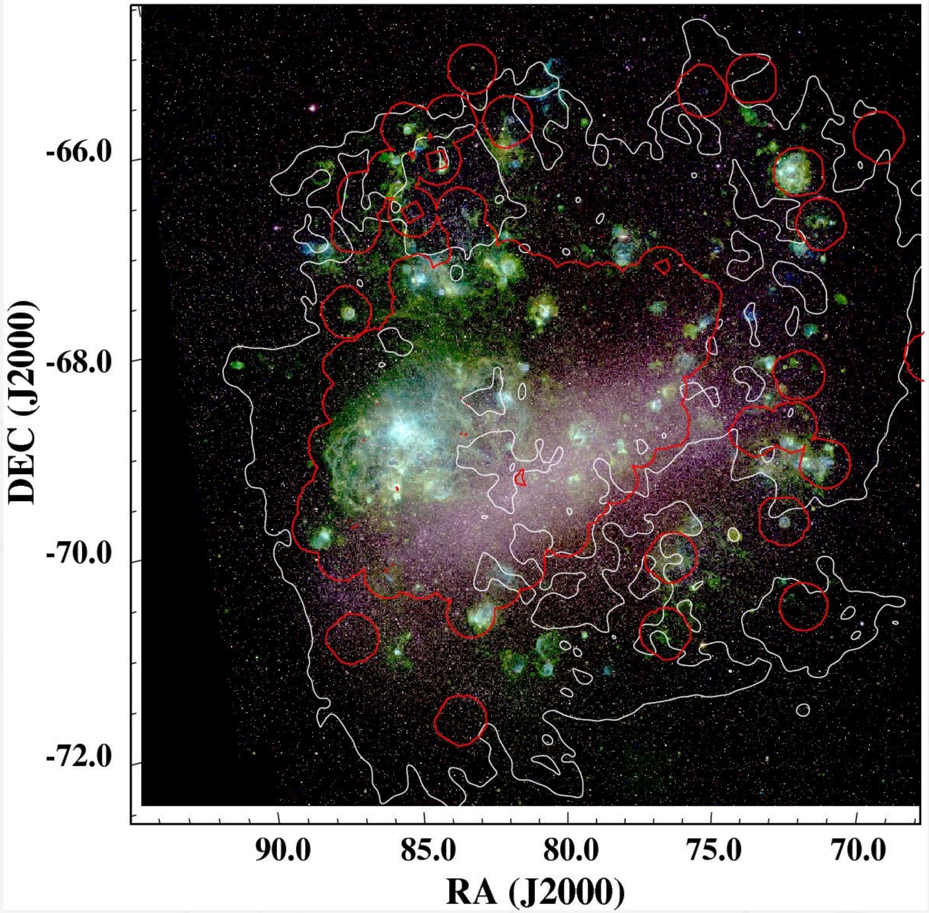
Thermal Doppler broadening for a RS velocity of 3500 km/s

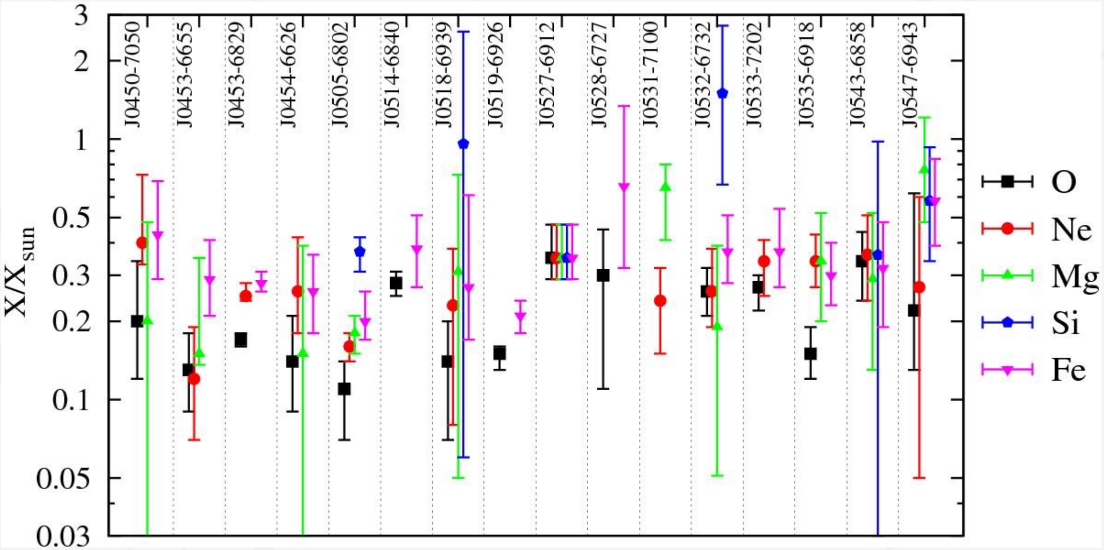
Williams et al. 2021





Population studies: SNRs in the LMC





First homogeneous catalogue of the X-ray spectral properties of SNRs (51) in the LMC (Maggi et al. 2016)

- Clues to progenitor types (13% exhibits Fe K lines, 39% supernova ejecta)
- ISM abundances (O, Ne, Mg, Si, Fe) ~ 0.2-0.5 solar
- Ratio of SN CC/SN Ia ~ 1.35 over last few 10^4 years

High-resolution spectra of small LMC SNRs

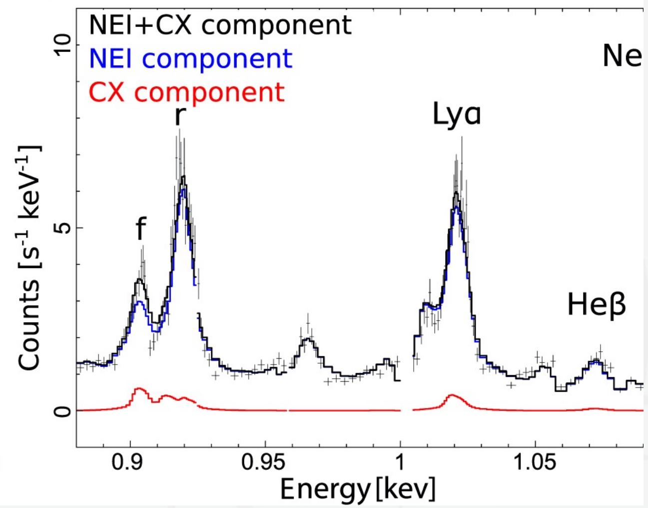
XMM-Newton RGS observations of N132D

Suzuki et al. 2020

- A dozen newly detected L-shell transitions of Si, S, Ar, Ca and Fe
- Abundance determination
- Thermal plasma: three components with different $T_{e,}$ NEI

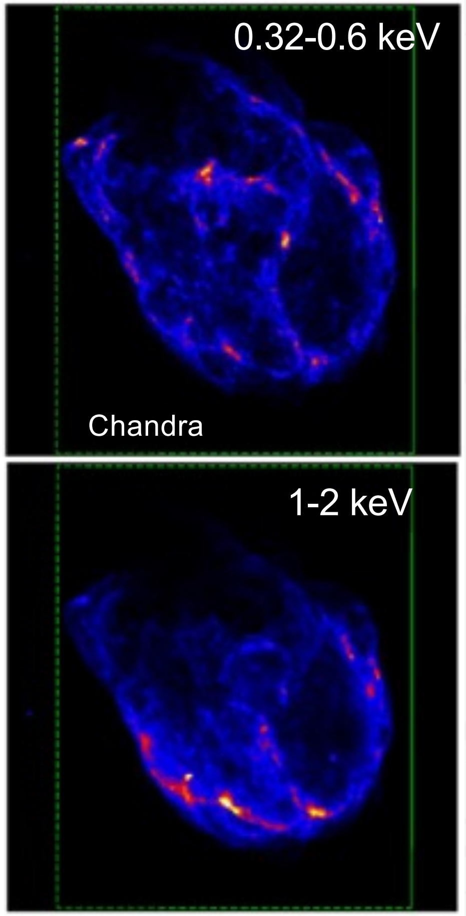
But unexpected forbidden-to-resonance line ratios of OVII and Ne IX: Resonance scattering ? Charge exchange ? Multi-temperature line of sight ?

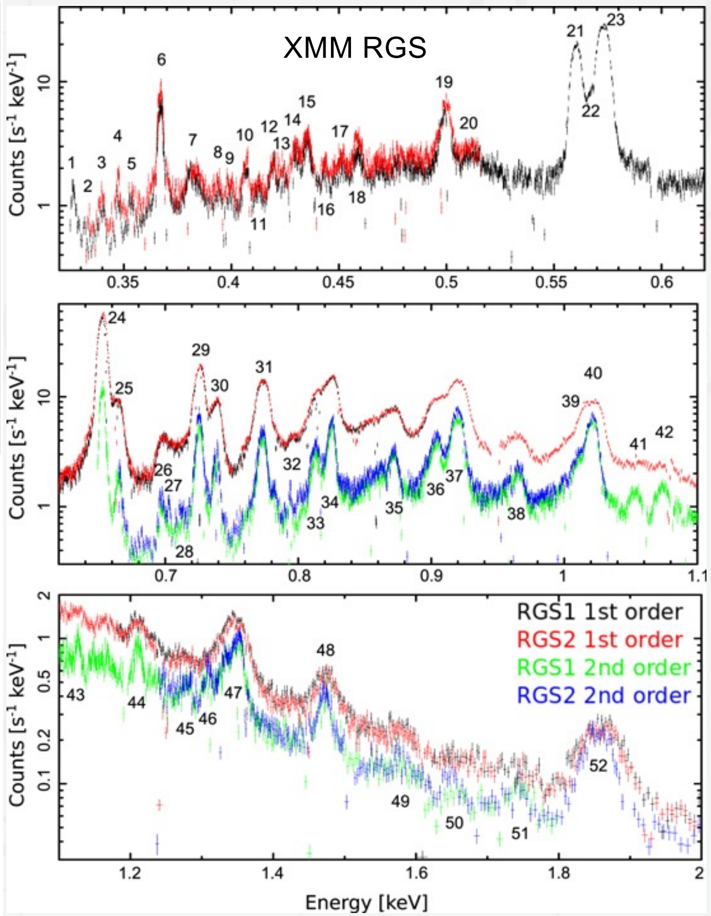
Limitation due to lack of spatial resolution



Also in others LMC SNRs:

- N23 (Broersen et al. 2011)
- N49 (Amano et al. 2020)
- J0453.6-6829 (Koshiba et al. 2022)



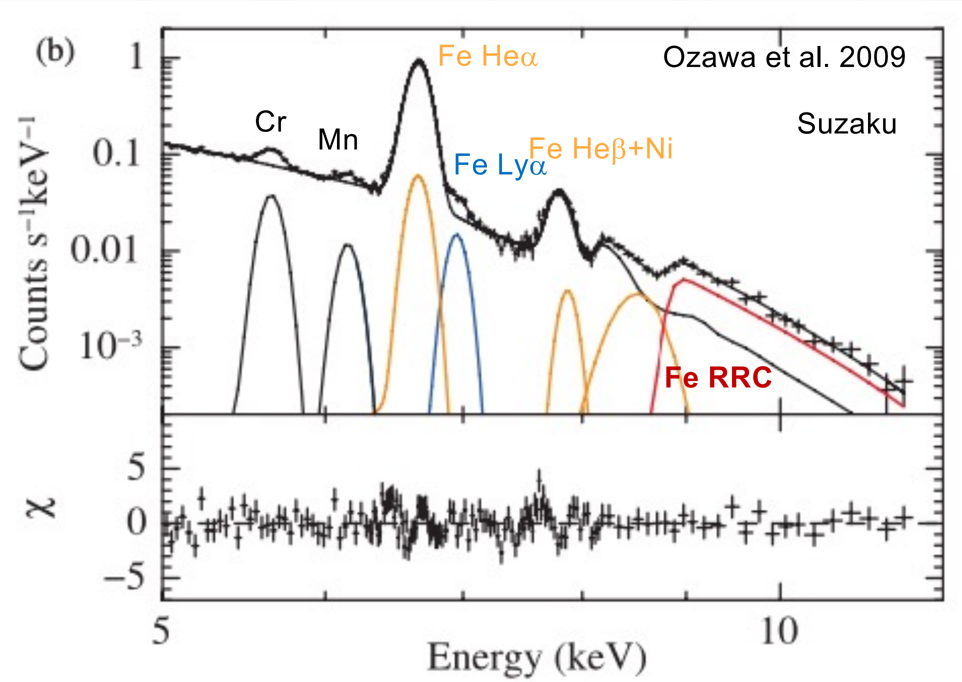


Overionized plasmas in Mixed morphology SNRs:
Adiabatic cooling in dense CSM ?
Interaction with clouds/thermal conduction ?

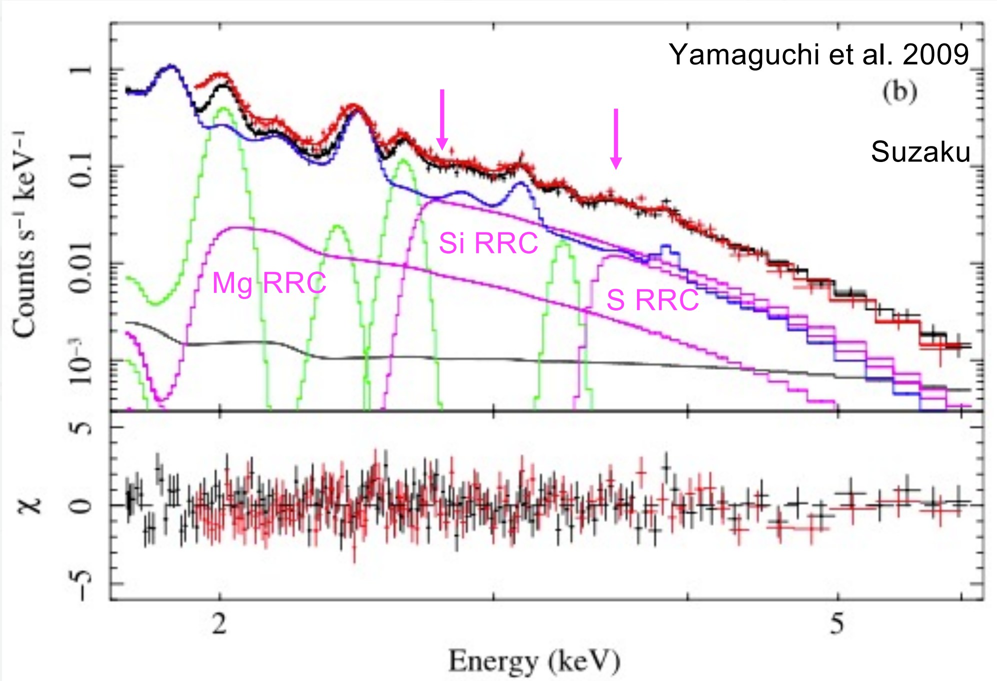
W49B, a hot and highly ionized plasma state

- Radiative recombination continuum of He-like Si, S, Fe at Edge
- Recombination lines of iron

(e.g., IC 443, W28, W44, N49:).

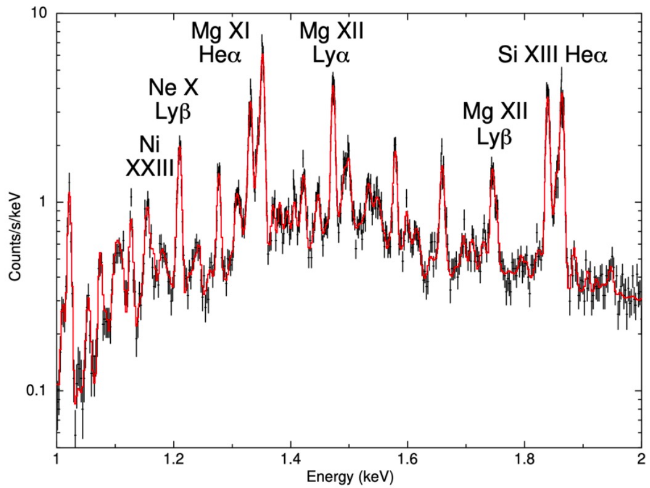


W49B



Near future: XRISM/resolve

- Understanding the progenitors of various kinds of SNRs
- Understanding the physics of collisionless shocks
- Understanding radiative processes of hot plasmas



Credit :
XRISM reference document

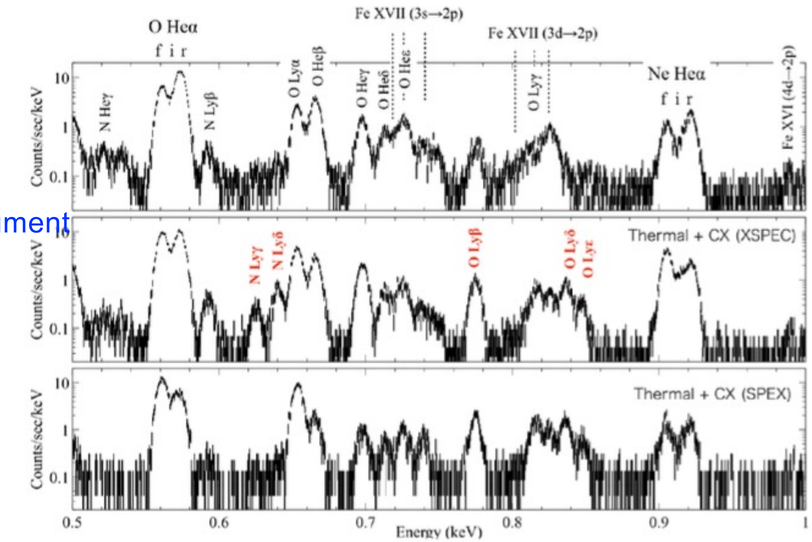


Fig. 22 *100ks simulation of western half of 3C397. Several lines via Ni and Fe L-shell emission are seen for example at 1.045,1.156 keV for Ni and 1.01 keV for Fe, respectively as well as peaks from K-shell transition of Si (1.84 keV) and Mg (1.33 keV).*

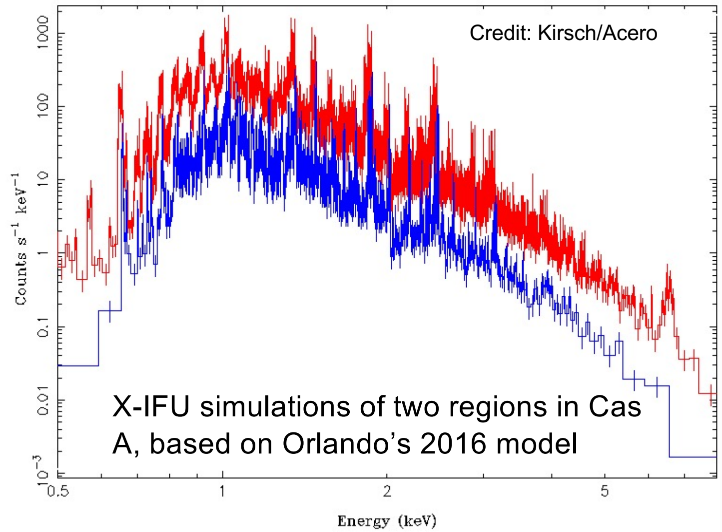
Fig. 23 *30-ks simulated Resolve spectra of a shell region of the Cygnus Loop. Top: Assumed model is a typical thermal plasma with electron temperature of 0.2 keV. Middle: Same as the top panel but added a charge-exchange model in XSPEC. Bottom: Same as the middle panel but simulated in SPEX with similar model parameters.*

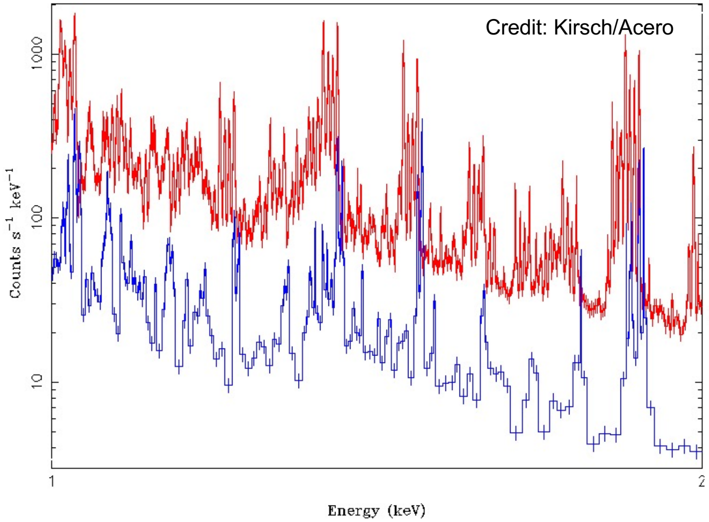
2030s future: ATHENA/X-IFU

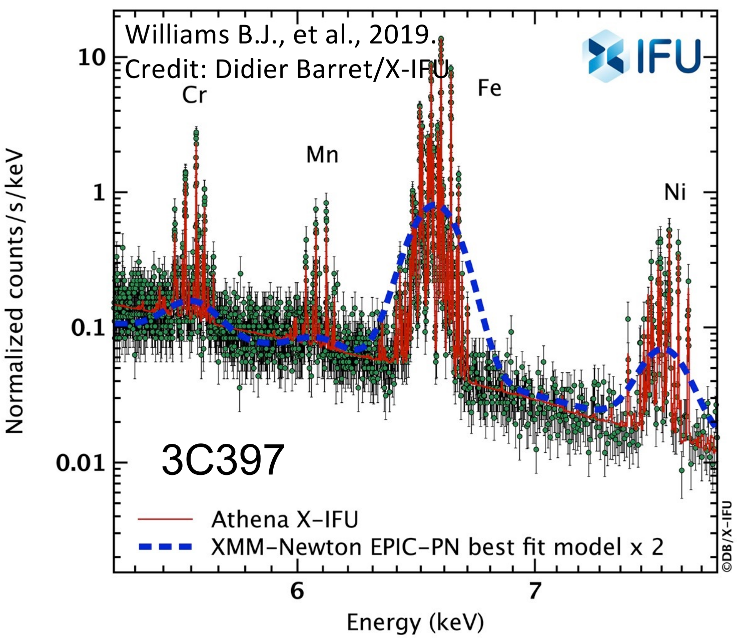
- physics of core collapse and thermonuclear explosions
- properties of the progenitors and CSM
- physics of collisionless shocks
- properties of particle acceleration at SNRs shocks (*talk by Jiro Shimoda)*
- interaction of SNR shocks with the interstellar medium

Athena X-IFU spectrum of the Fe group elements in 3C397 type Ia supernovae

The XMM-EPIC best fit model (scaled up by a factor of 2) is shown to illustrate the power of high-resolution spectroscopy.







- Understanding the physics of type Ia:
- Understanding the physics of core-collapse SNe
- Understanding the physics of particle acceleration and Galactic cosmic rays
- Understanding plasma and shock physics
- Understanding the interaction with the ambient and ISM medium

Very exciting future with high-resolution X-ray spectroscopy of supernova remnants

Thanks