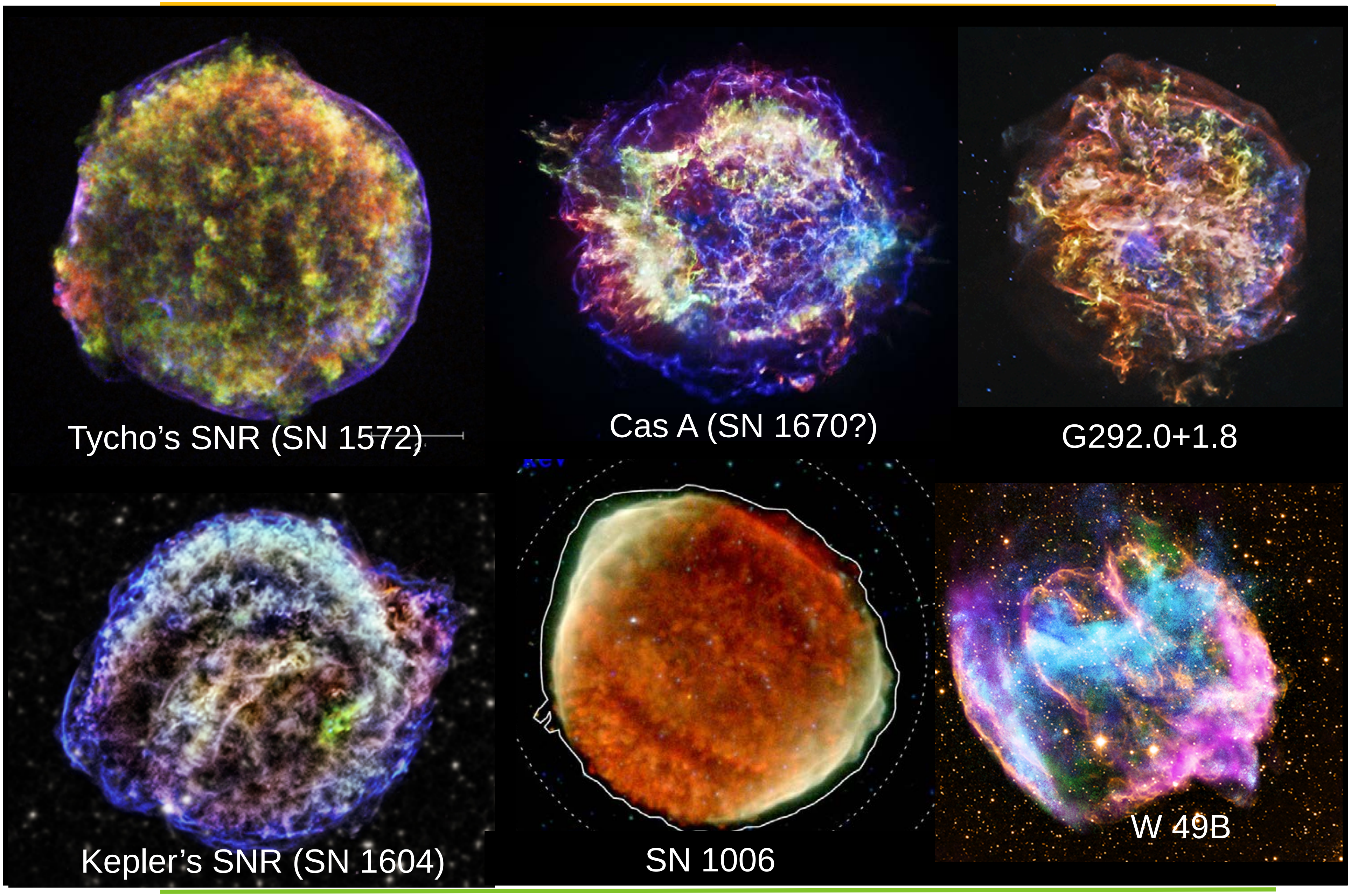
Supernova remnants dynamics

Anne DECOURCHELLE

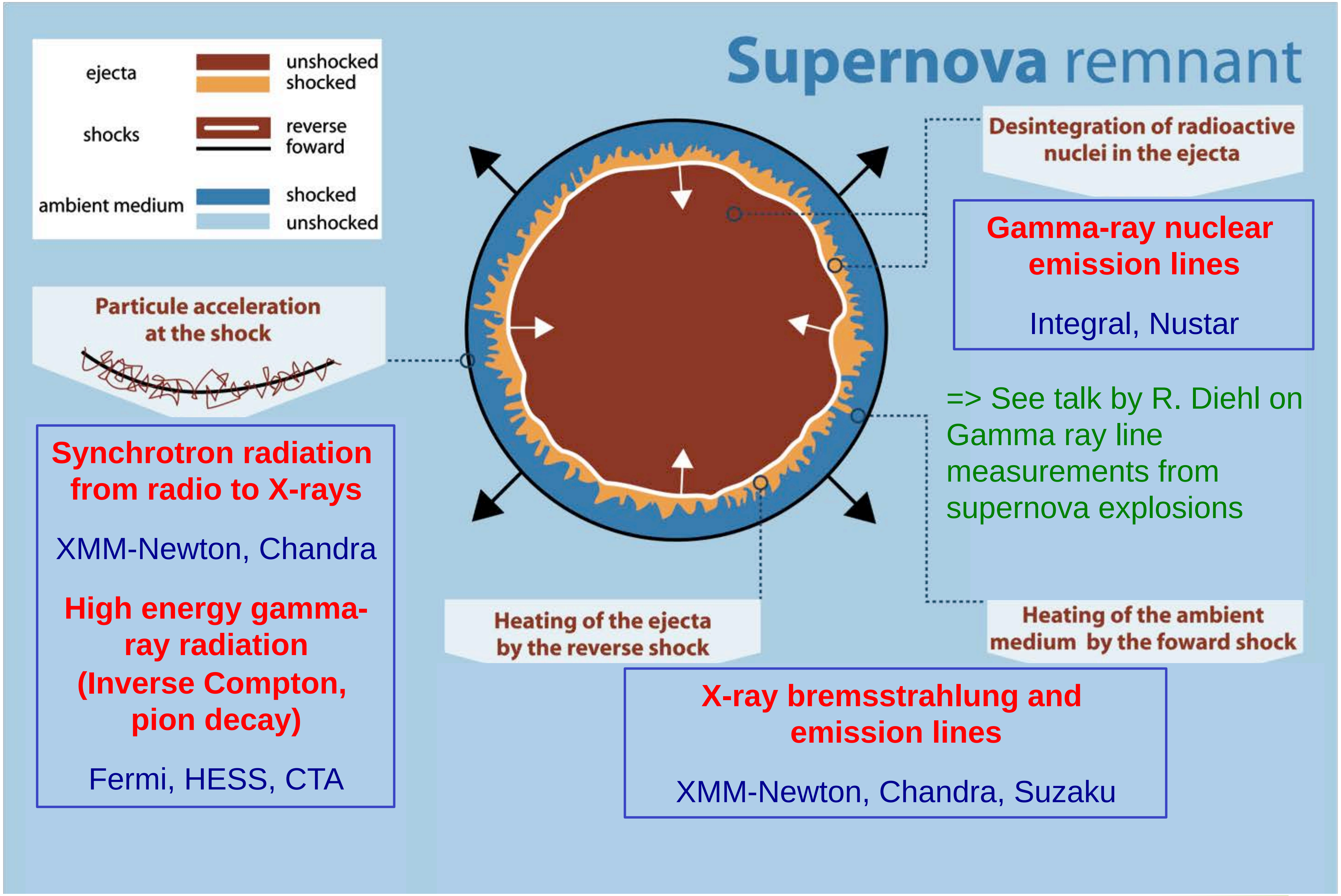
UMR AIM /Department of Astrophysics, CEA Saclay

- Hydrodynamics of young supernova remnants
- Morphological and spectral properties of a sample of SNRs
- A close-up view of Cas A and Tycho
- A new X-ray mission for spatially-resolved high-resolution spectroscopy : Athena

Young supernova remnants



High energy: a key domain for observing Supernova Remnants



Synchrotron radiation from radio to X-rays

XMM-Newton, Chandra

High energy gamma-ray radiation (Inverse Compton, pion decay)

Fermi, HESS, CTA

Gamma-ray nuclear emission lines

Integral, Nustar

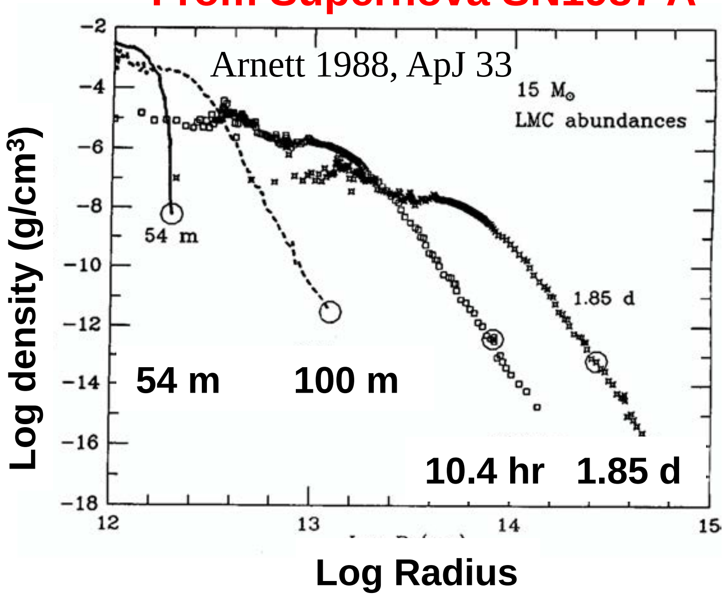
=> See talk by R. Diehl on Gamma ray line measurements from supernova explosions

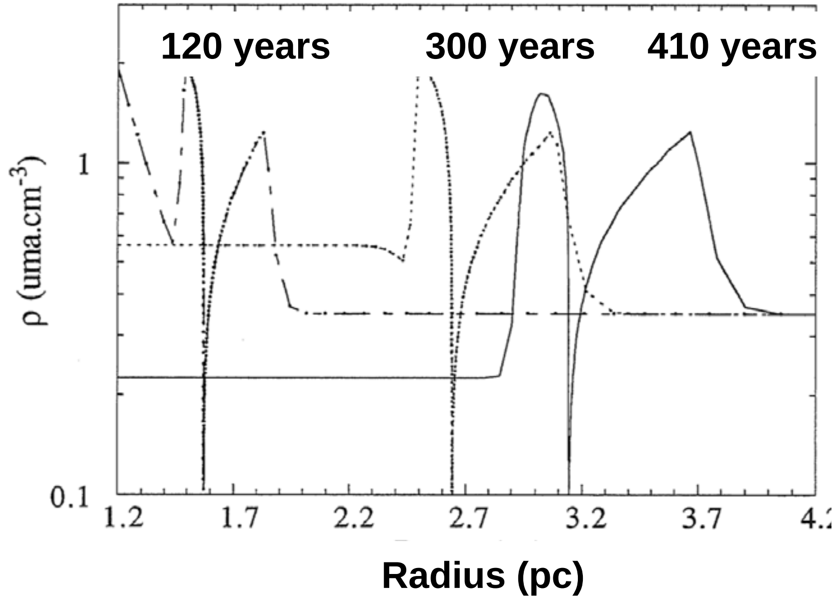
X-ray bremsstrahlung and emission lines

XMM-Newton, Chandra, Suzaku

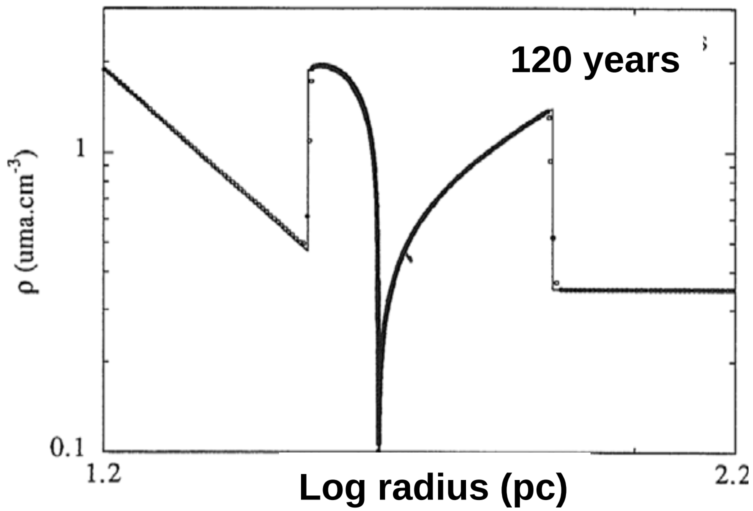
Hydrodynamics of supernova remnants: from SNe to SNR

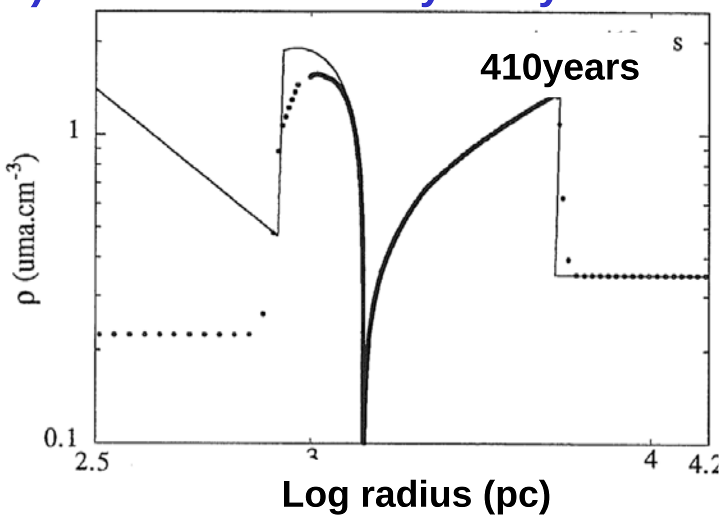
From Supernova SN1987 A **to** **young supernova remnants**

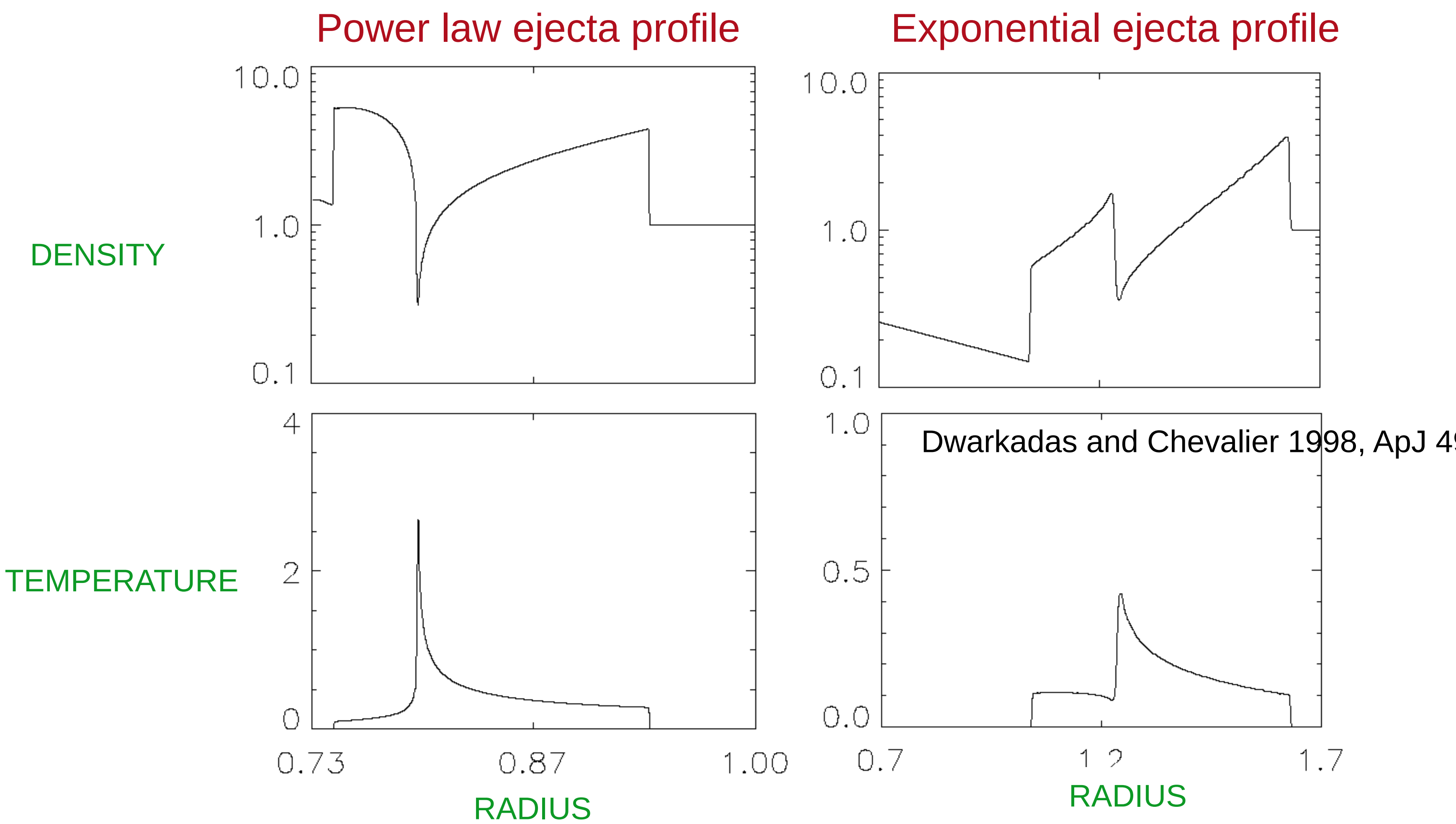




From self-similar solutions (Chevalier et al. 1982) **to numerical hydrodynamics**







Dwarkadas and Chevalier 1998, ApJ 497

The hydrodynamical profile of the interaction region depend on the initial ejecta density profile and on the ambient medium

See talk by M. Gabler, The infancy of SNRs: evolving a supernova into its remnant in 3D

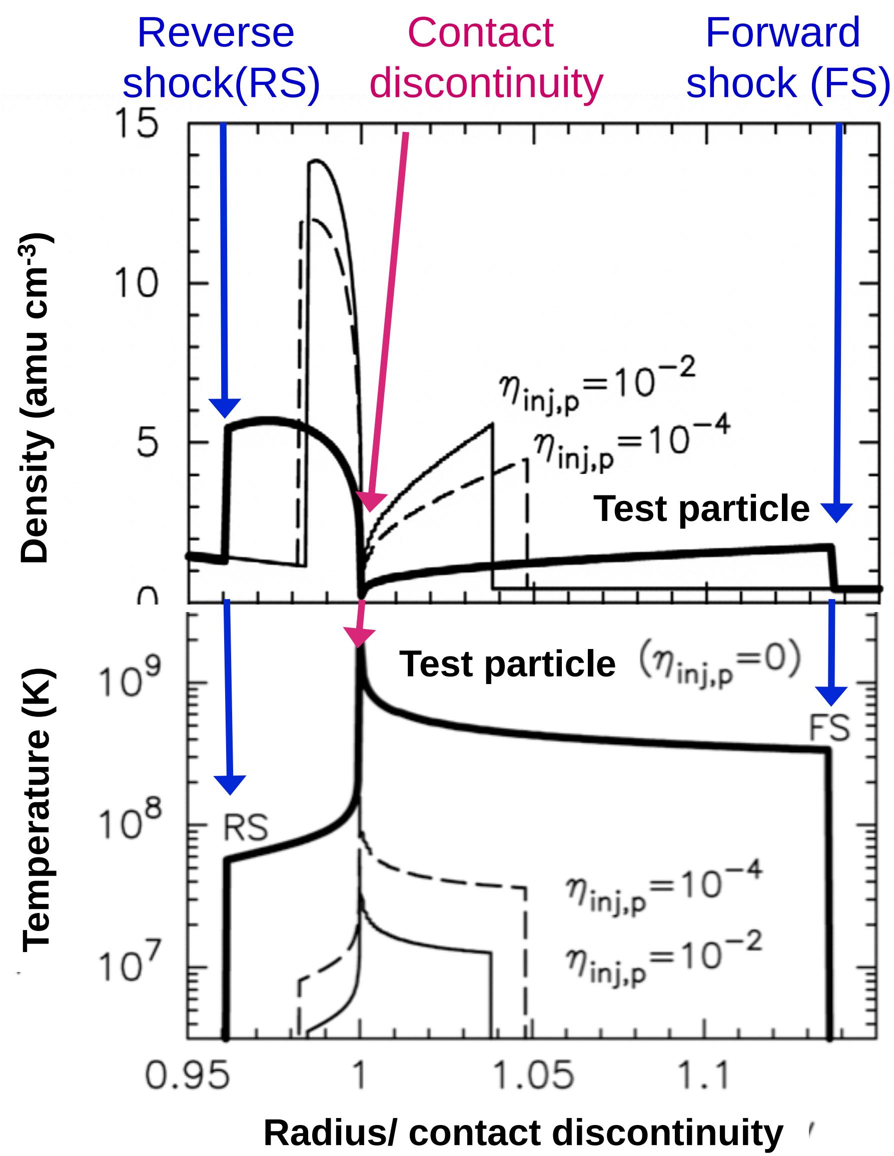
Hydrodynamics of SNRs: back-reaction of particle acceleration

Model:

- self-similar solutions with a prescribed back-reaction (Chevalier 1983)
- coupled to a model of particle acceleration (Berezhko & Ellison 1999)

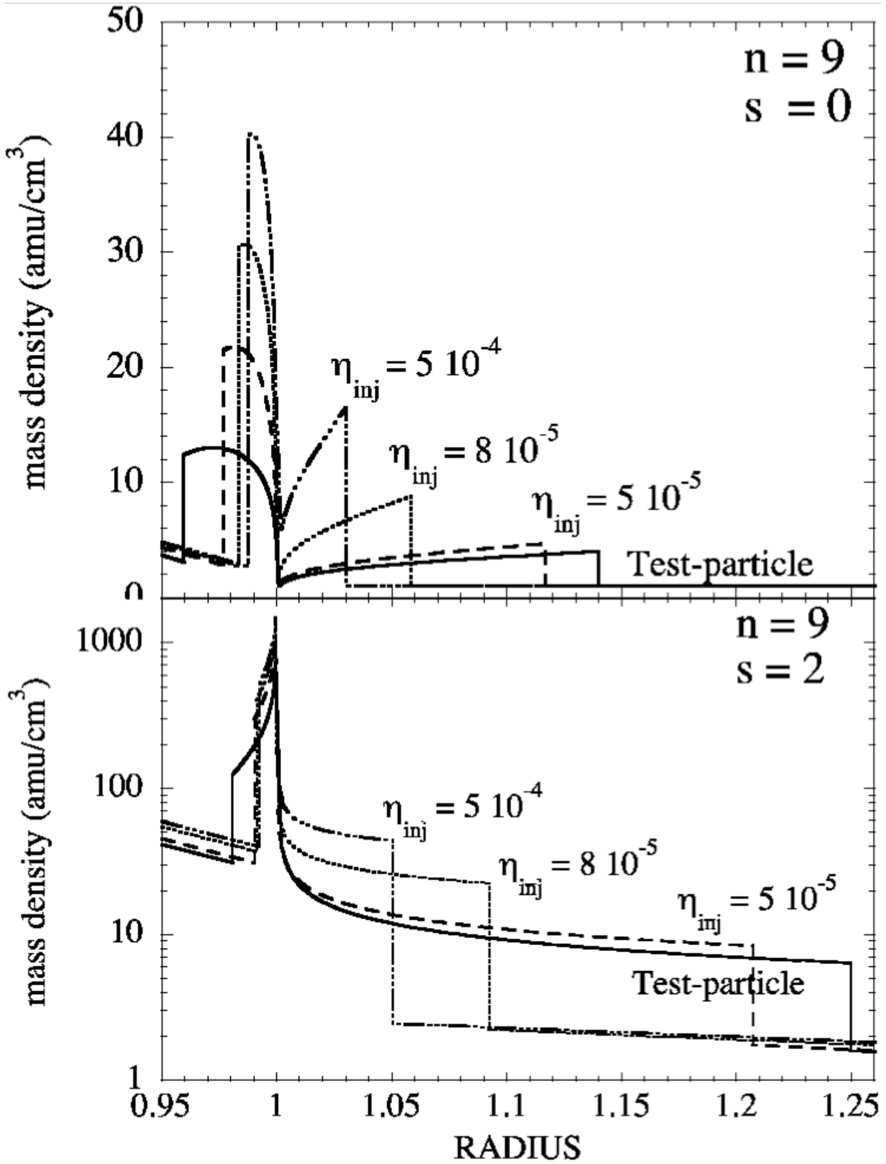
If efficient ion diffusive shock acceleration:

- larger compression ratio (> 4 at the shock)
- lower post-shock temperature than for test-particle case **=> R. X**
- Shrinking of the post-shock region **=> R. X**

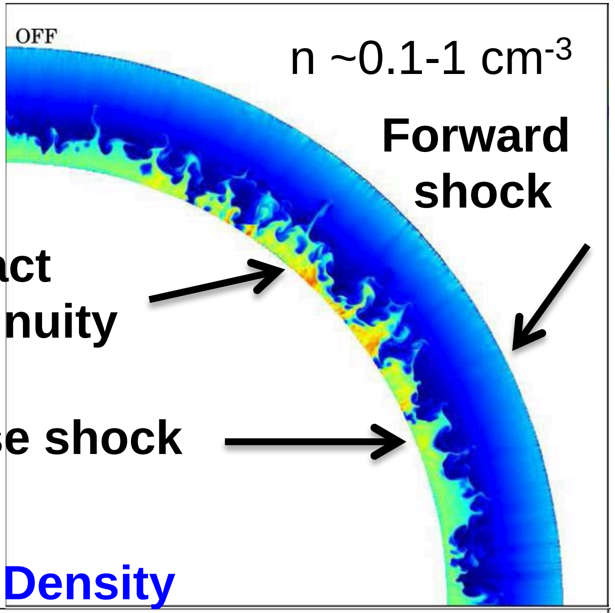


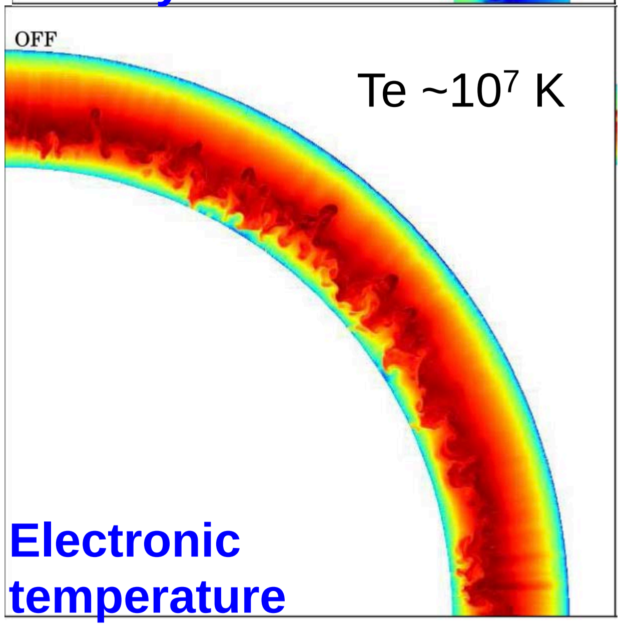
Decourchelle, Ballet, Ellison (2000)

Evolution of young SNRs : effect of stellar wind

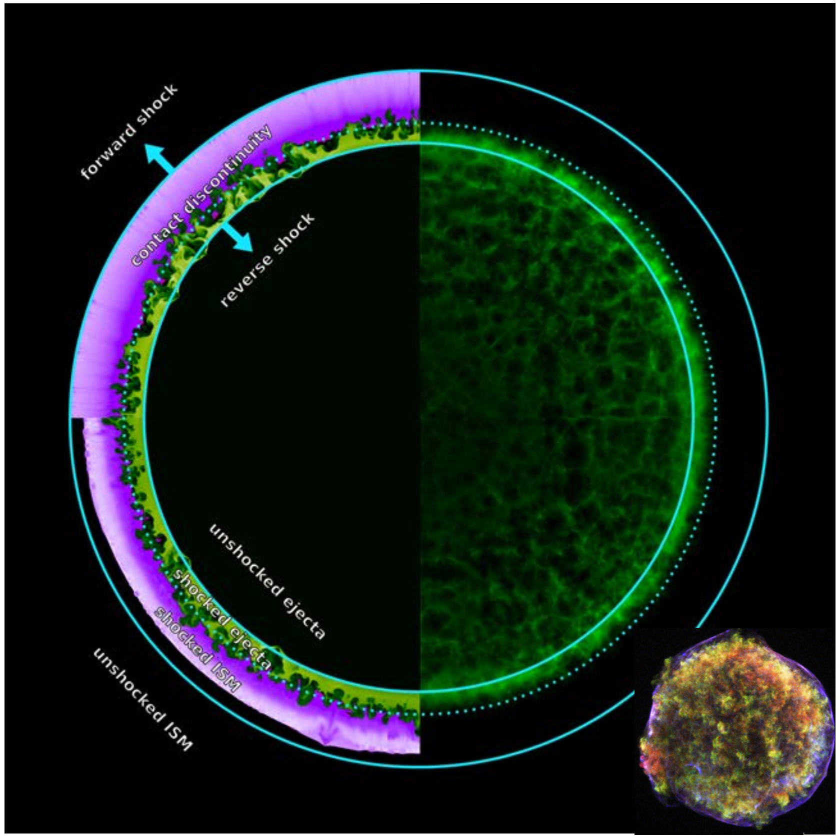


3D simulations of SNRs: back-reaction of particle acceleration





3D simulations(1/8 of sphere) with coupling of a non linear particle acceleration model (Blasi 2002)



Ferrand et al. 2010

3D maps of the thermal emission

Ferrand et al., 2012

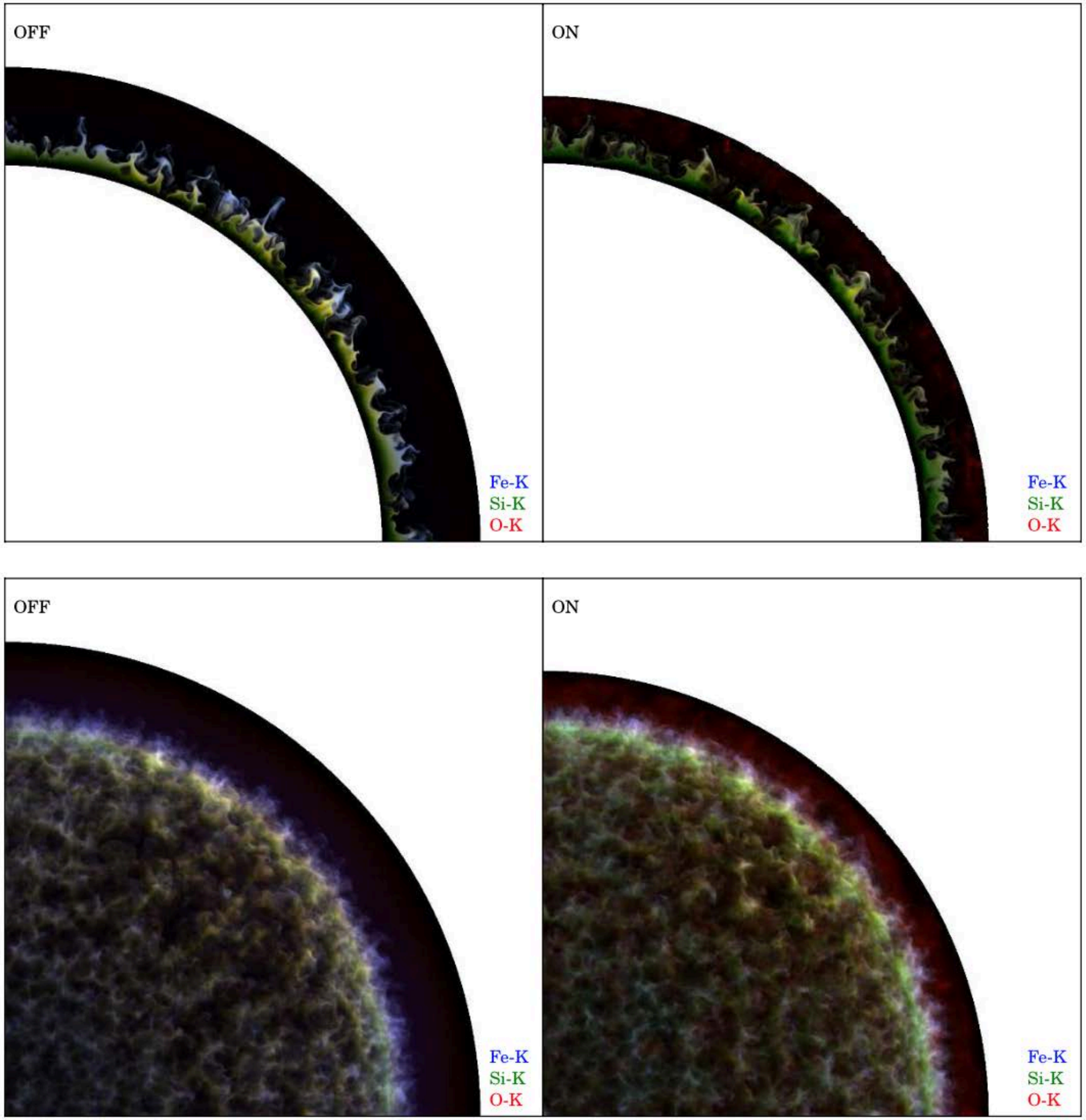
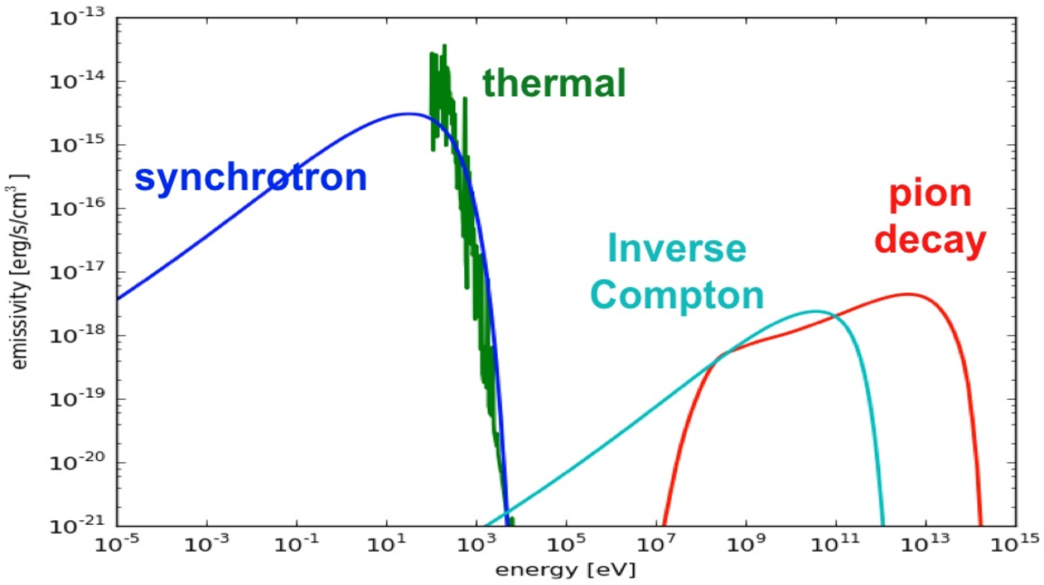


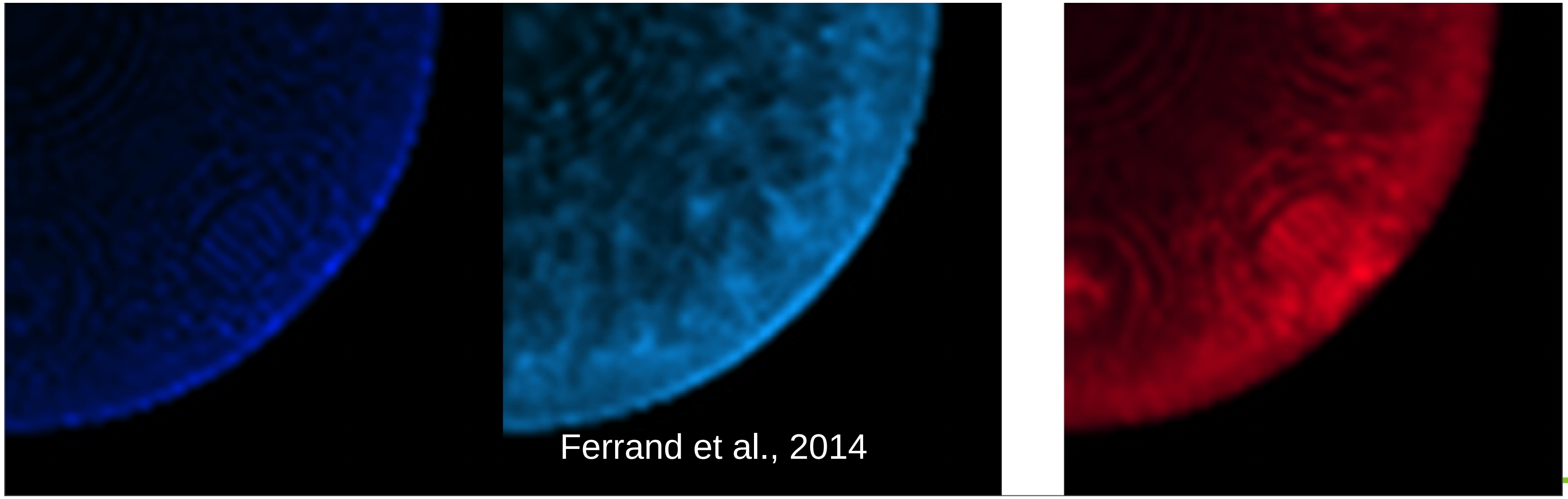
Figure 12. RGB rendering of three line emissions. For each pixel, the value of the red/green/blue channel is assigned from the emissivity of, respectively, the O–K band/Si–K band/Fe–K band, as displayed in Figures 8–10 (linearly normalized to 256 levels). Regions of pure blue, for instance, are dominated by Fe–K line emission. Regions of yellow = red + green are made out of a blend of O–K and Si–K line emission. Top: slices in the $z = 0$ plane; bottom: projected maps along the z-axis. Cases without ("OFF," on the left) and with ("ON," on the right) back-reaction of particles are compared.

3D maps of the non-thermal emission



See talks by:

- S. Orlando "Bridging the gap between SNe and their remnants through multi-D hydrodynamic modeling"
- S. Katsuda "Detections of Thermal X-Ray Emission and Proper Motions in RX J1713.7-3946"

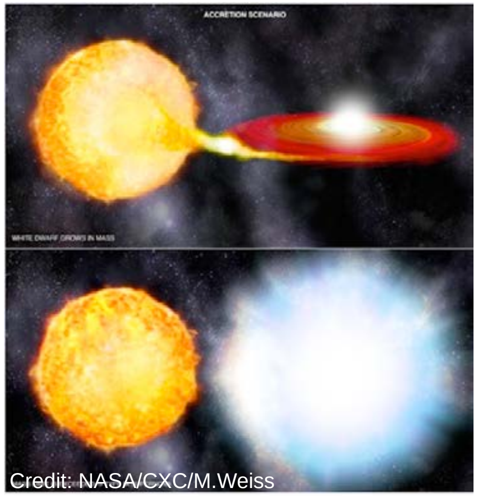


The physics of supernovae: thermonuclear supernovae SN Ia

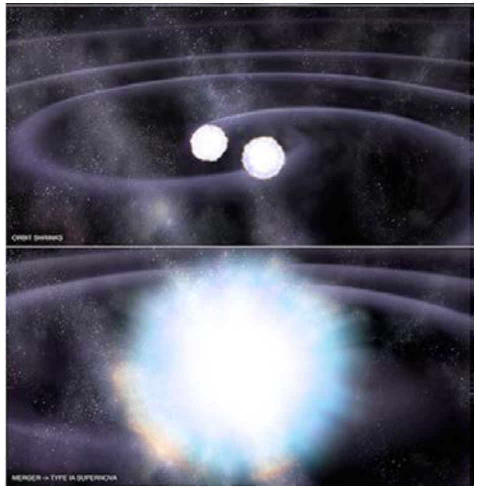
Open questions

- **Nature of the companion in the binary system:**
  - normal star (single degenerate)?
  - white dwarf (double degenerate)?
- **Ignition of the burning and burning front propagation ?**

Single degenerate (1 WD)



Double degenerate (2 WDs)



Quantity of synthesized elements depends of SN type and physics of the explosion

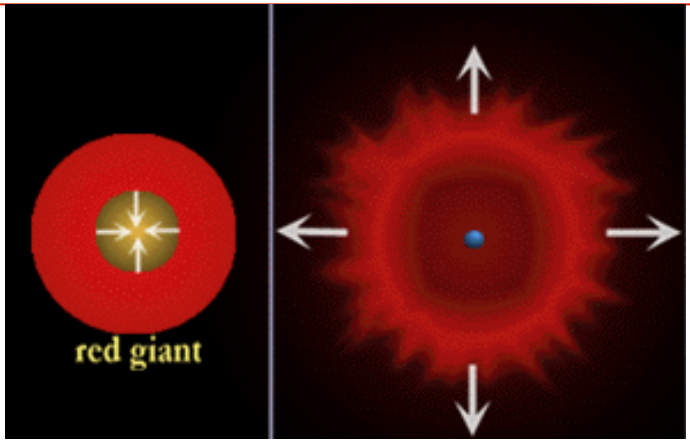
In SN Ia, ratio between **intermediate elements and iron** constrains :

- accretion rate from the companion star
- physics of propagating flame fronts (slow / fast deflagration, transition to detonation)

The physics of supernovae: core collapse supernovae

Open questions

- **Value of the mass-cut to form the compact object?**
- **Explosion mechanism ?**



Quantity of synthesized elements depends on:

- **progenitor for element lighter than Si** (essentially produced during hydrostatic evolution and spread away in the explosion)
- **explosion energy** and **amount of matter accreting** onto the core before the explosion **for intermediate elements** enhanced through explosive oxygen burning.
- **details of the explosion and mass-cut** between the residual compact object and the ejected envelope **for iron-group nuclei**

Objectives of observing young ejecta dominated SNRs

- How much **heavy elements** are synthesized, how they are mixed and dispersed in the ISM ?
- How stars explode ? What are their progenitor ? What is the **explosion mechanism ?**

SNRs : direct measurements of the **composition** and **spatial distribution of synthesized elements** in the ejected material accessible through X-ray observations (all K-shell lines from C to Zn)

=> provide constraints to **supernova models**, **stellar population at play** and **chemical enrichment**

- N, (C and F) mainly produced by Asymptotic Giant Branch stars
- Oxygen to Si related to massive progenitor of core collapse supernovae

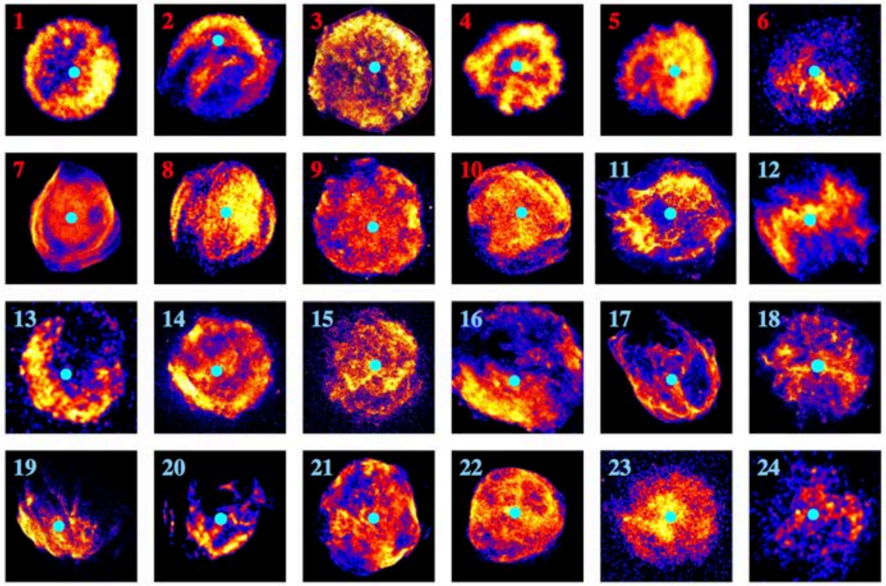
For either type of explosion

- Intermediate elements (Si to Ca)
- Fe production
- Asymmetries/mixing of layers

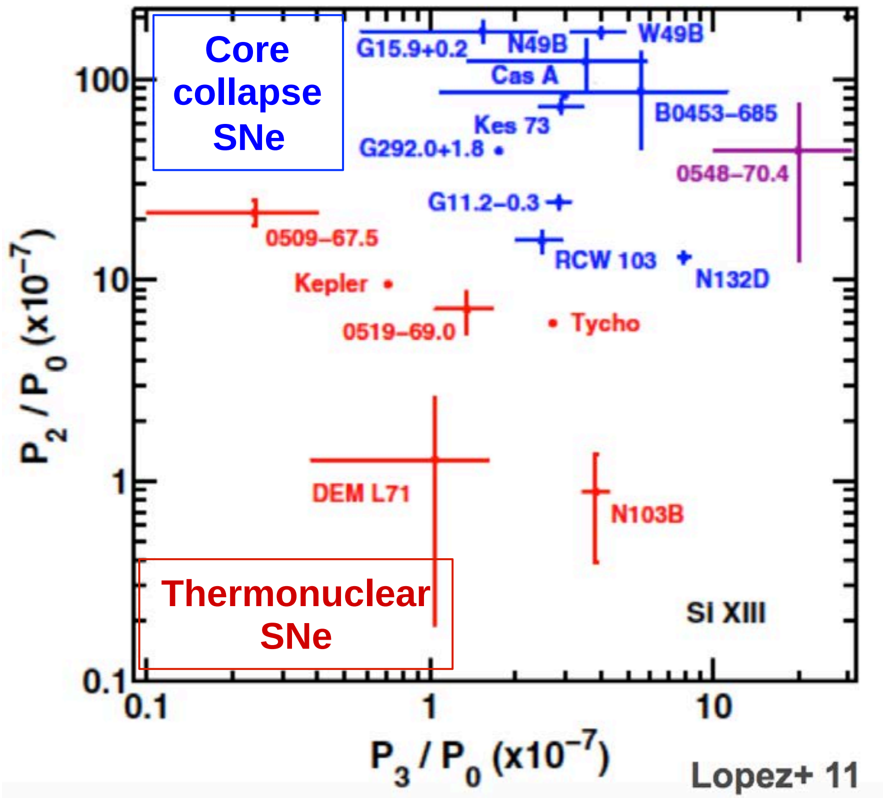
are closely related to the explosion mechanism

Sampling SNRs X-ray morphology characterizes SN types

Lopez et al. ApJ 2011



0.5-2.1 keV emission for 24 SNRs in the Milky Way and LMC.



Power ratios : quadrupole ratio vs. the octupole ratio of the Si K line maps

SN Ia more symmetrical than core collapse SNe

⇒ Level of asymmetry related to explosion mechanism

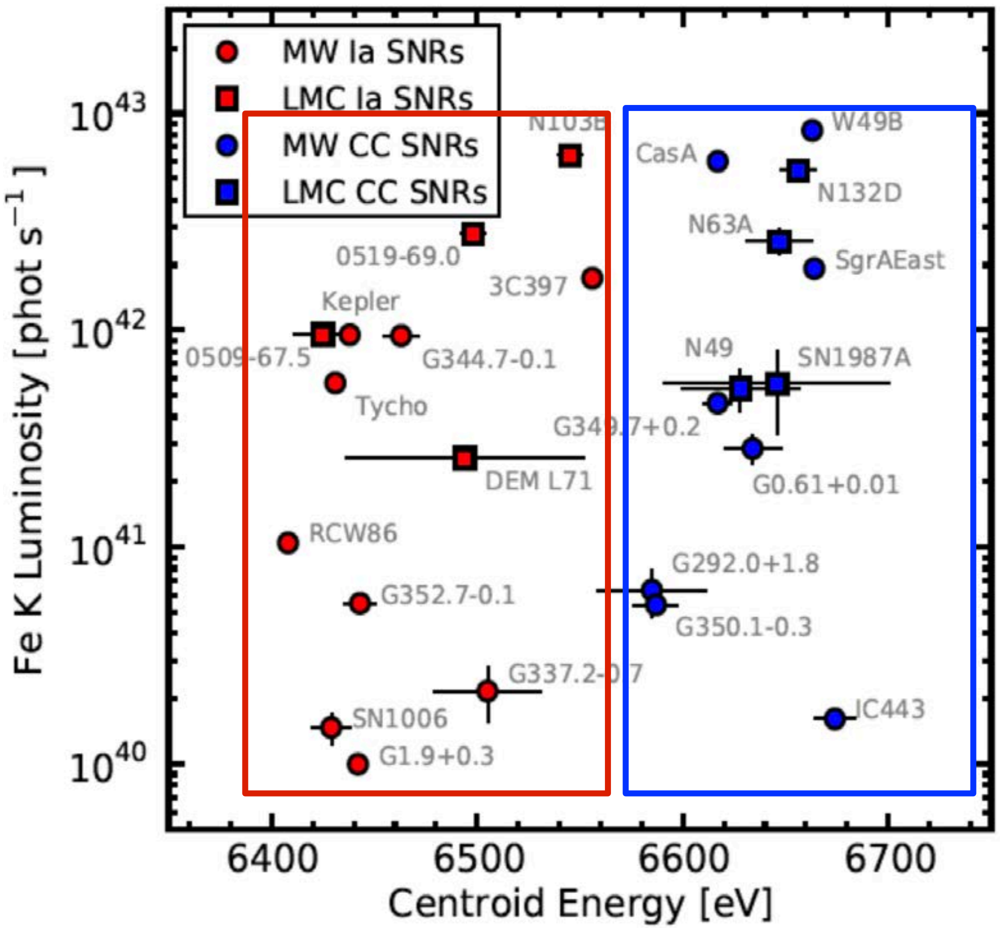
Line energy / ionisation state constrain CS medium and SN types

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

- arises from different ambient densities in the medium around SN Ia /SN CC (mass loss) -

Thermonuclear SNe

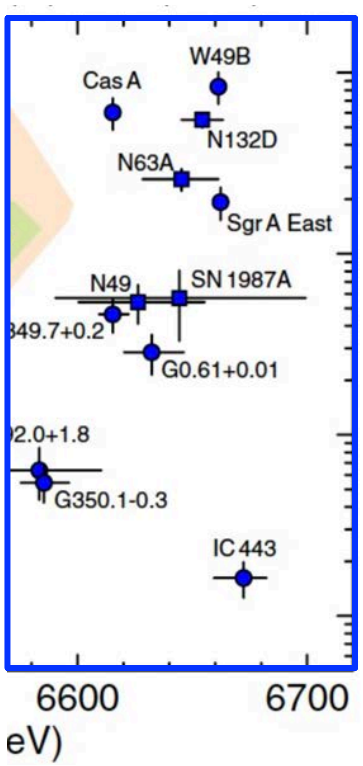
Yamaguchi et al.
ApJL 2014



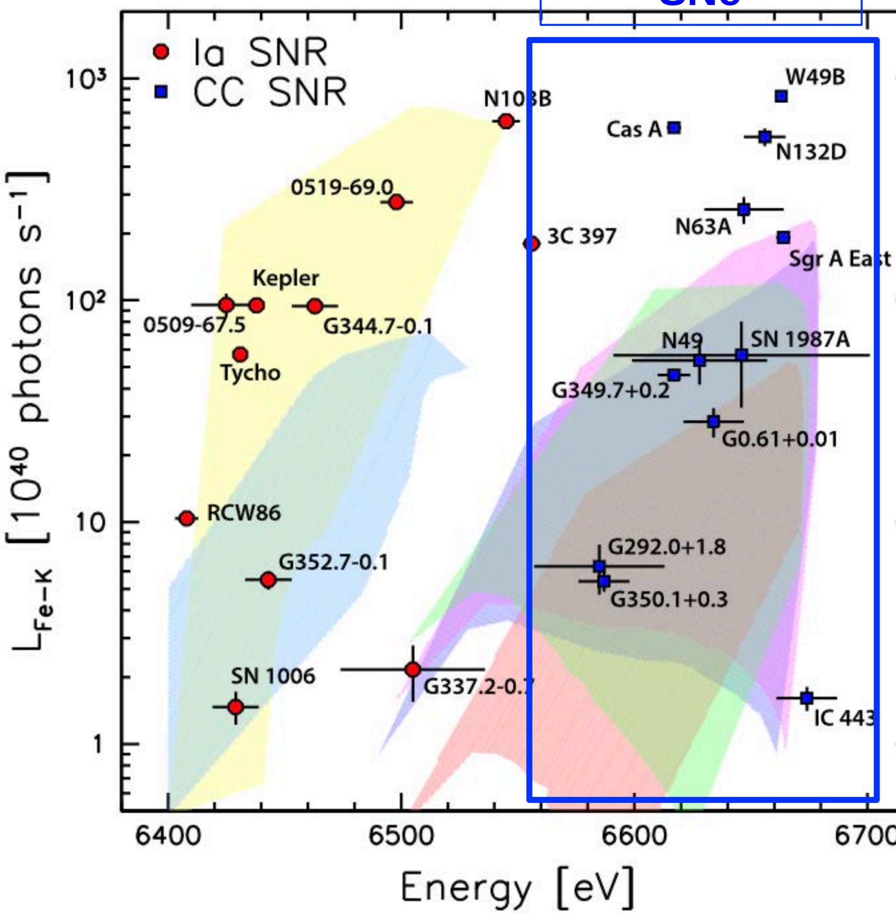
Core collapse SNe

Fe Kα centroids and luminosities measured in galactic and LMC SNRs

X-ray emission spectrum constrain SN types



Observed Fe Kα centroids and luminosities

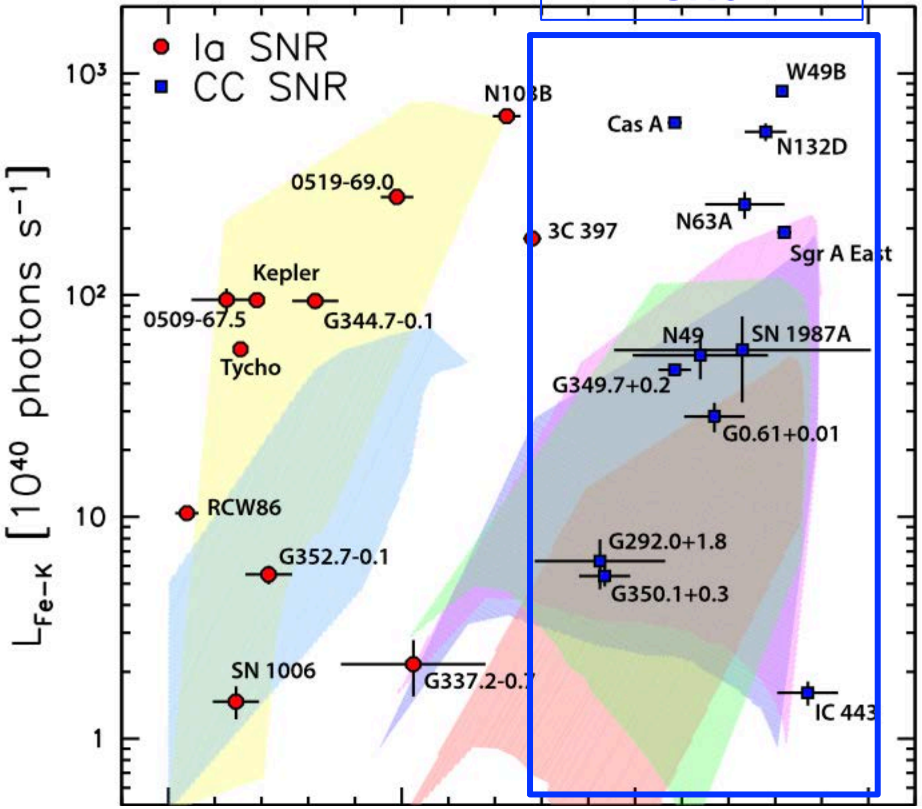


Predicted by theoretical Type CC SNR models
Patnaude et al., 2015 ApJ

X-ray emission spectrum constrain SN types

Core collapse SNe

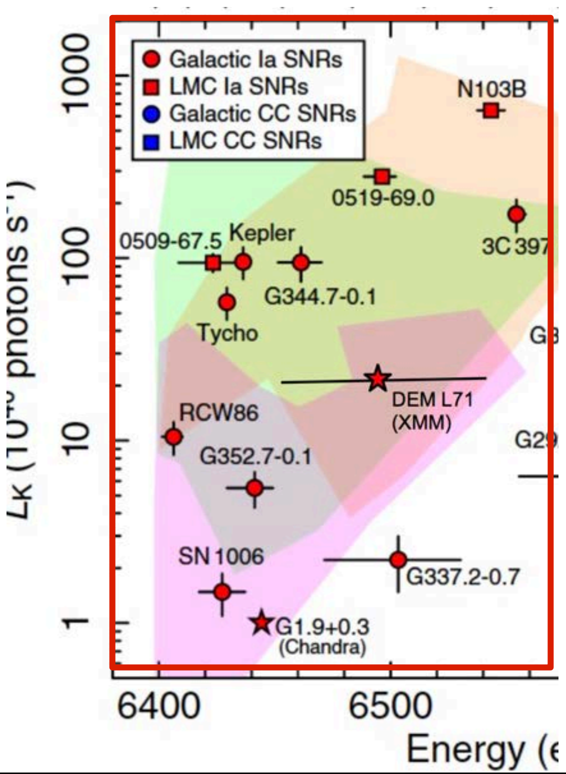
Predicted by theoretical Type CC SNR models
Patnaude et al., 2015 ApJ



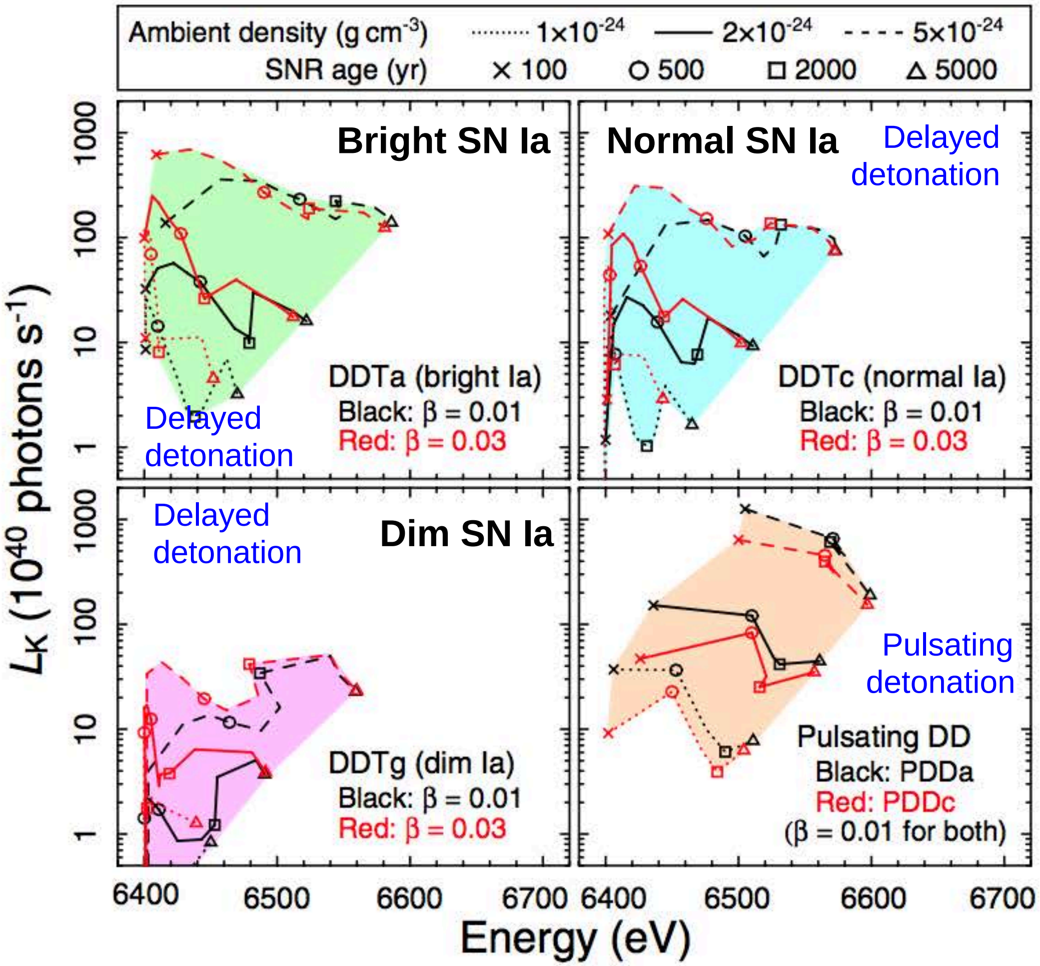
Ejecta Model		E_{SN} 10^{51} erg	M_{ej} ($M_\odot$)	n_{amb} [a] (cm^{-3})	v_{wind} [b] (km s^{-1})	$\dot{M}$ [b] 10^{-5} $M_\odot$ yr^{-1}	References
DDTa	(yellow)	1.27	1.38	0.1–3.0	...	...	Badenes et al. (2008)
DDTg	(cyan)	0.85	1.38	0.1–3.0	...	...	Badenes et al. (2008)
s12D	(pink)	1.21	8.87	...	10–20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

X-ray emission spectrum constrains explosion mechanism

Thermonuclear SNe



Fe Kα centroids and luminosities

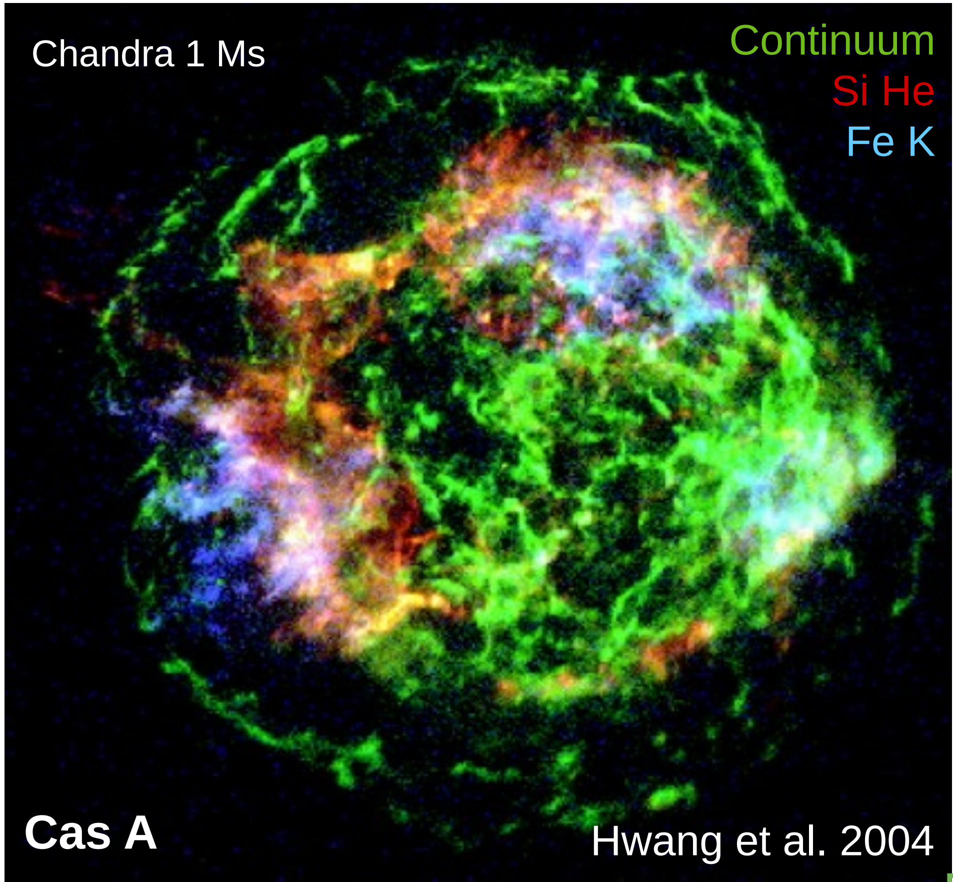


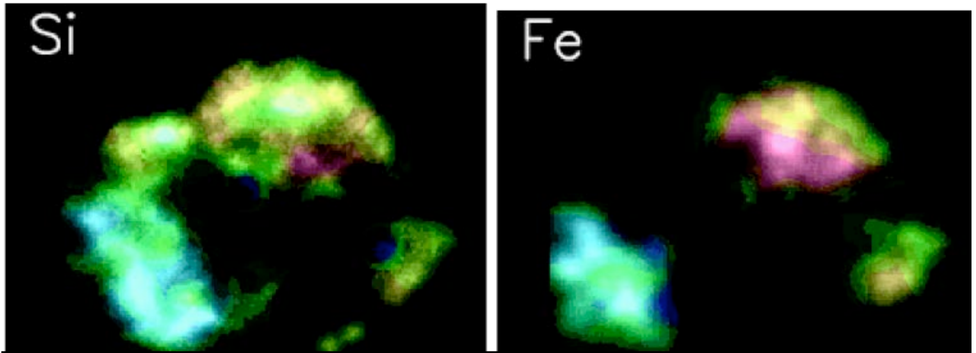
Predicted by theoretical Type Ia SNR models

Yamaguchi et al.
ApJL 2014

Courtesy of
Carles Badenes

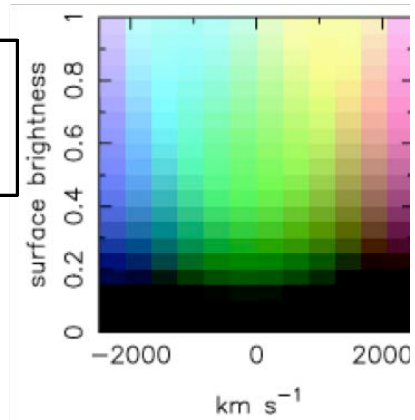
Non-uniform distribution of elements and bulk motions in CC SNe





86 ks XMM-Newton observation of Cas A
(Willingale et al. 01)

Si-K, S-K and Fe-K Doppler shift maps
20” x 20“ images



Spatial distribution of elements

Highly non-uniform distribution of elements => spatial inversion of a significant portion of the SN core

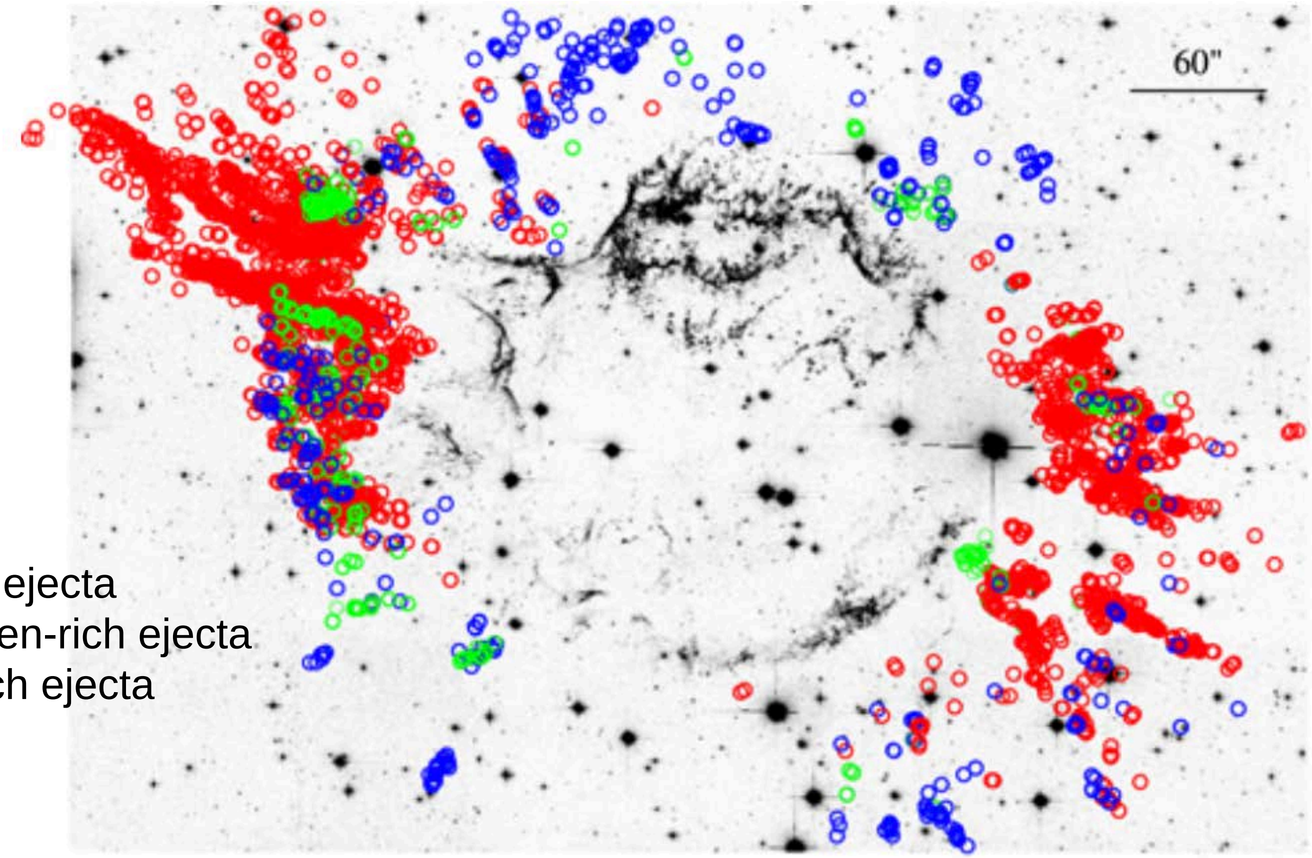
Bulk motion of the ejecta through Doppler shift measurements

=> deep insight in the expansion of the ejecta and explosion mechanism through asymmetries and inversion of the nucleosynthesis products

Non-uniform distribution of elements in CC SNe

HST observations of Cas A high-velocity, S-rich debris in the NE jet and SW counterjet regions

(Fesen & Milisavljevic 2016)



Red: Si-rich ejecta
Blue: Nitrogen-rich ejecta
Green: O-rich ejecta

Hubble Space Telescope WFC3/IR images of the Cassiopeia A supernova remnant that survey its high-velocity, S-rich debris in the NE jet and SW counterjet regions through [S III] $\lambda\lambda$9069, 9531 and [S II] $\lambda\lambda$10,287–10,370 line emissions. We identify nearly 3400 sulfur emitting knots concentrated in ~120° wide opposing streams, almost triple the number previously known.

Non-uniform distribution of elements and bulk motions in CC SNe

HST observations of Cas A high-velocity, S-rich debris in the NE jet and SW counterjet regions

(Fesen & Milisavljevic 2016)

- Sulfur-rich have transverse velocities approaching **~15,000 km s−1, some 8000 km s−1**

=> these jets could contain ~**10% or more of the overall expected 10^{51} erg supernova explosion kinetic energy.**

- The NE jet and SW counterjet streams of ejecta are **chemically and kinematically unlike any other observed areas of Cas A**.

⇒ Formation around the time of core collapse by **an explosive, jet-like mechanism that accelerated interior material from the Si–S–Ar–Ca-rich regions** near the progenitor's core up through and out **past the He- and O-rich outer layers** with velocities that greatly exceeded that of the expanding photosphere.

Consistent with :

- the dynamical scenario (Burrows 2005) that the NE and SW jet/counterjet is associated with **a proto neutron star wind that emerged after the neutrino-driven supernova explosion and pushed into the expanding, turbulently mixed supernova debris**.
- the notion that a **continuum of high-velocity, bipolar expansions** may exist in core-collapse supernovae.

Non-uniform distribution of elements and bulk motions in CC SNe

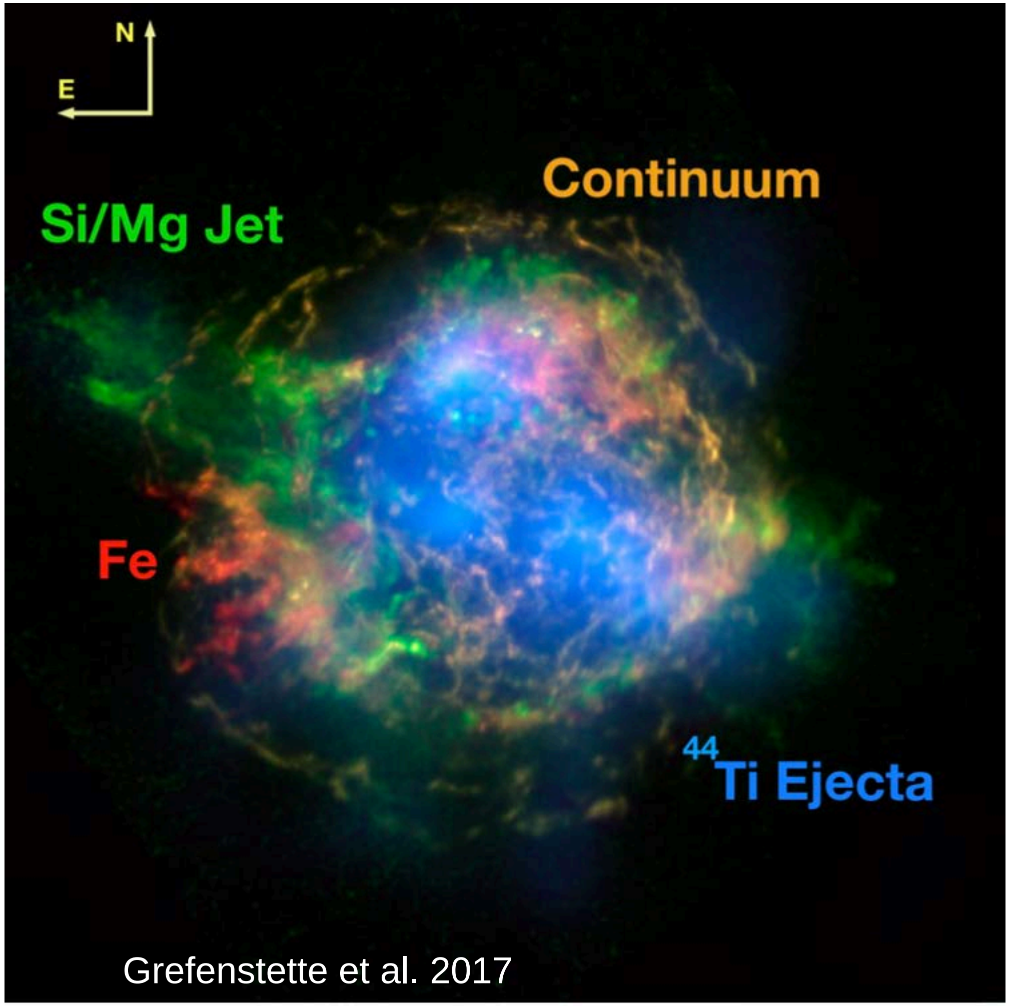
⇒ See talks by :

- ***B. Grefenstette,***
"Bringing the High Energy Sky into Focus: NuSTAR's View of Supernova Remnants"

- ***T. Ikeda***
"Discovery of Titanium-K Lines in the Northeastern Jet of Cas A"

- ***H.-T. Janka***
*"*3D Supernova Explosion Models for the Production and Distribution of 44Ti and 56Ni in Cassiopeia A"

^{44}Ti observed by Nustar in Cas A



M(^{44}Ti) ~1.54 10^{-4} M_{sun}

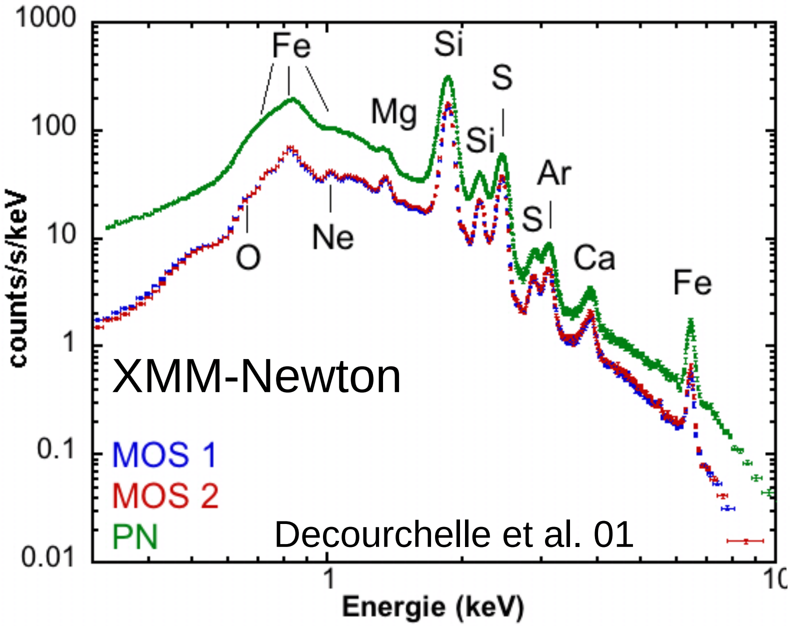
Line emission and abundances: SN type and explosion mechanism

X-ray spectra constrain SN type and explosion mechanism through line emission and heavy element abundances

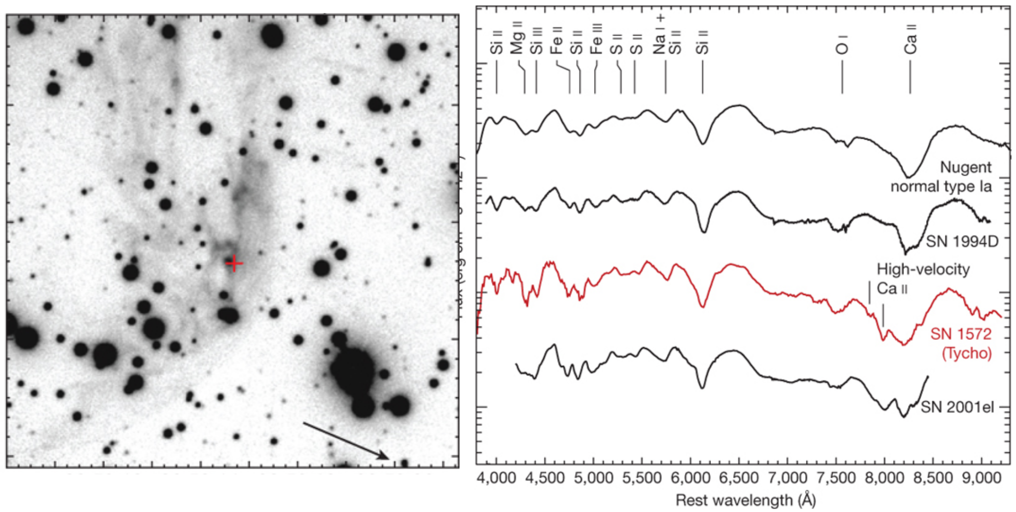
Exemple : Tycho'SNR

- delayed detonation model explains the X-ray spectrum (Badenes et al. 06)
- normal type Ia confirmed by optical light echo spectrum (Krause et al. 08)

X-ray spectrum

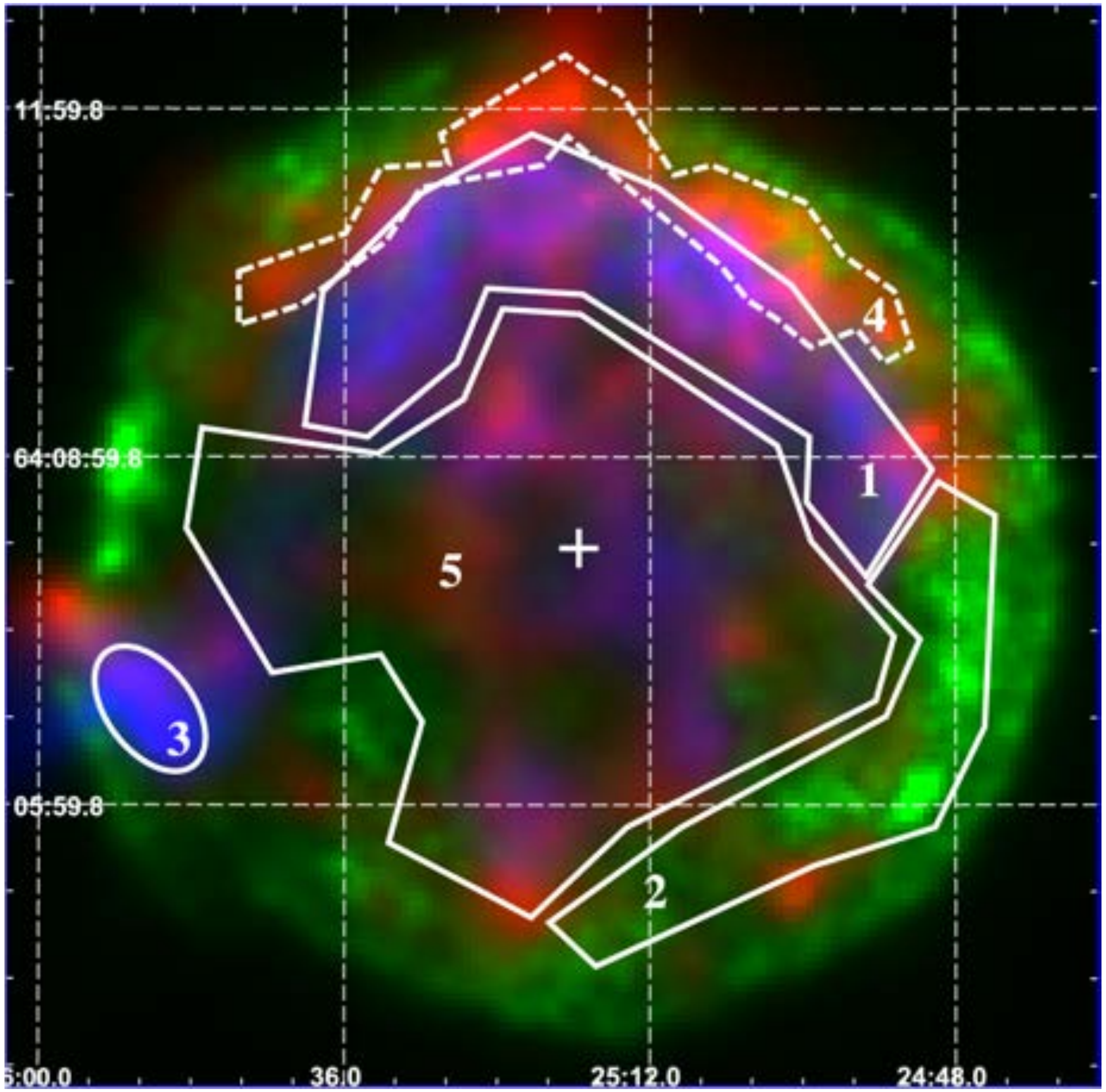


Optical light echo image and spectrum
compared with spectra of normal extragalactic SNe Ia
Krause et al. 08, Nature

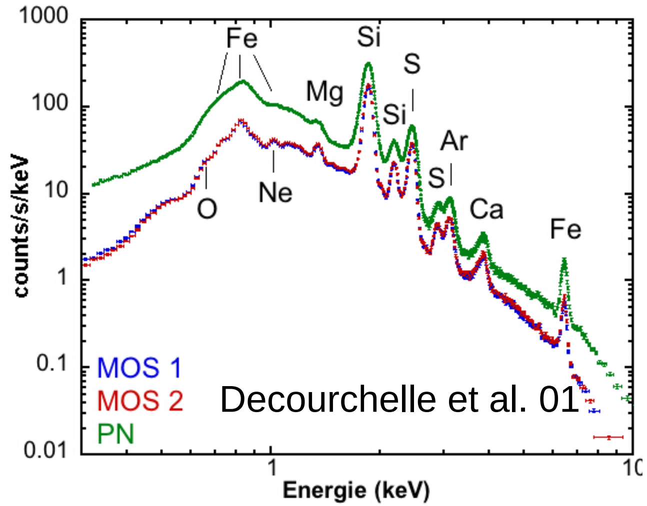


Tycho's SNR: equivalent width maps of Ca and Fe K lines

Miceli et al. 2015



Equivalent width maps of Ca and Fe K lines

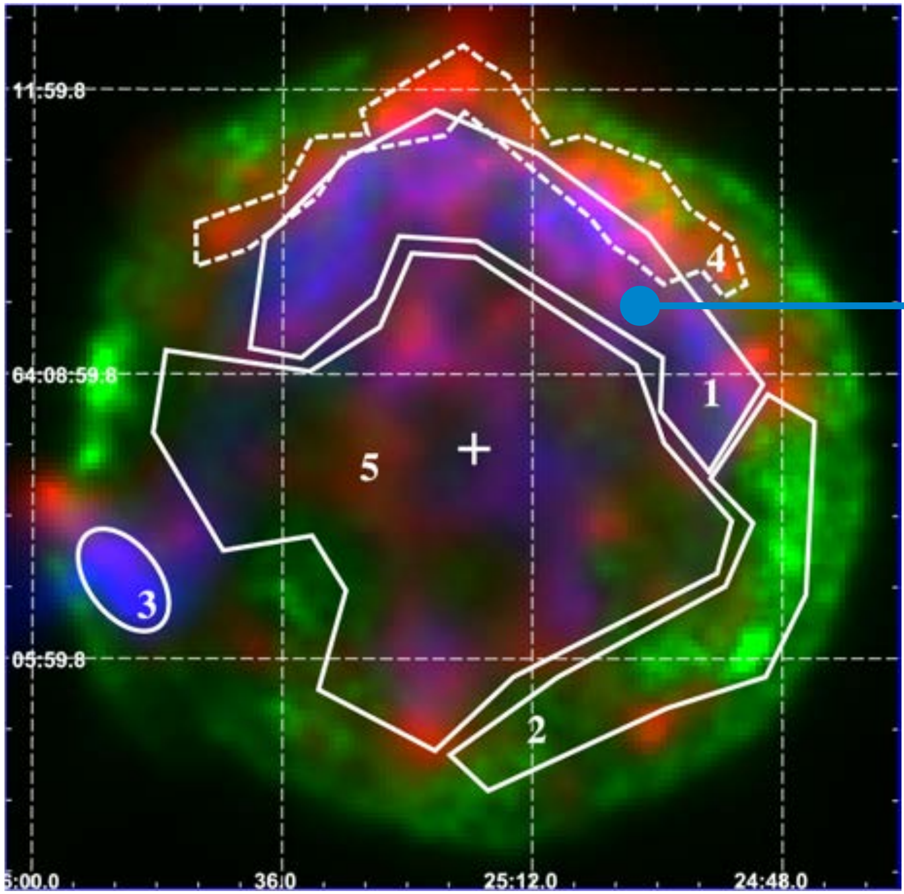


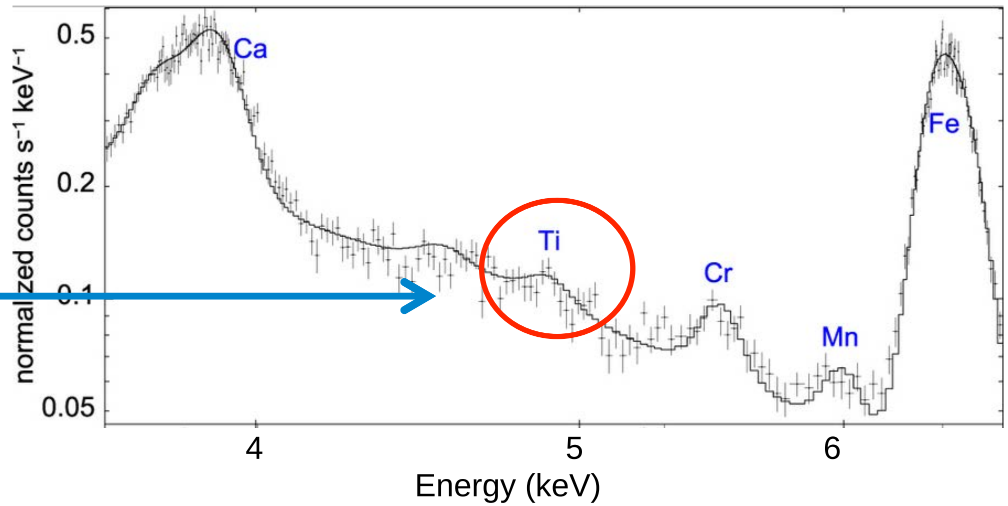
- **radial stratification** of the ejecta composition with **Ca** and Si localized in an outer shell with respect to **Fe**.
- **anisotropies** in the distributions of Fe-rich and Ca-rich ejecta

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

Detection of rare elements in Tycho's SNR: Ti, Cr, Mn

Miceli et al. 2015



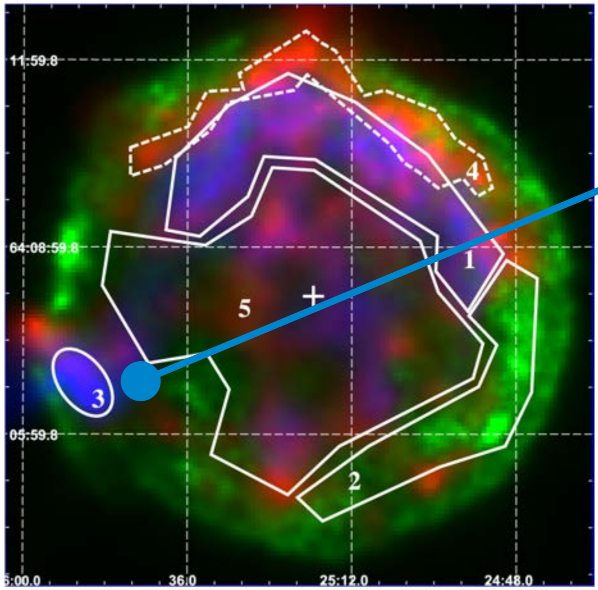


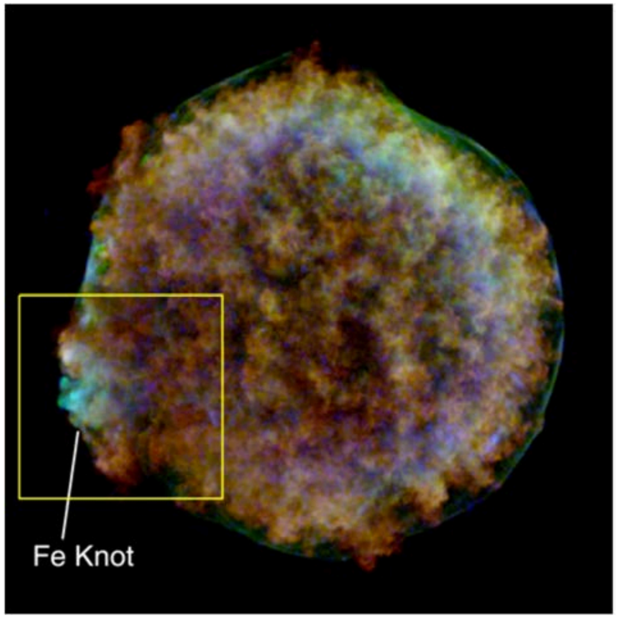
- Regions with high Fe EW **show indications of Ti line emission** (at >2 sigmas)

- The Fe K EW is correlated with the Cr EW

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

Detection of rare elements in Tycho's SNR: Ti, Cr, Mn





However, outer iron knot with surprisingly no emission from Cr, Mn, or Ni (Suzaku).

Within the framework of the canonical delayed-detonation models for SN Ia :

- $M_{Cr} / M_{Fe} < 0.023$
- $M_{Mn} / M_{Fe} < 0.012$
- $M_{ni} / M_{Fe} < 0.029$

$\Rightarrow$ **peak temperature of (5.3–5.7) 10^9 K and neutron excess of less than 2 10^{-3}.**

Yamaguchi et al. 2017, ApJ

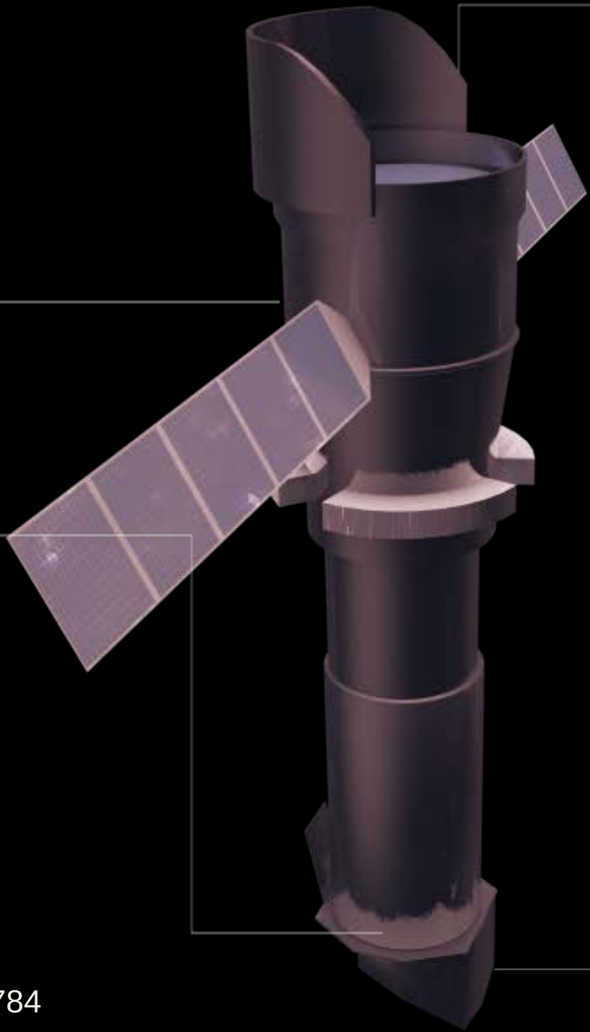
$\Rightarrow$ **rule out the deep, dense core of a Chandrasekhar-mass white dwarf as the origin of the Fe knot**

$\Rightarrow$ **favor either incomplete Si burning or an *α*-rich freeze-out regime, probably close to the boundary.**

The Athena Observatory (2028)

Willingale et al, 2013
arXiv1308.6785

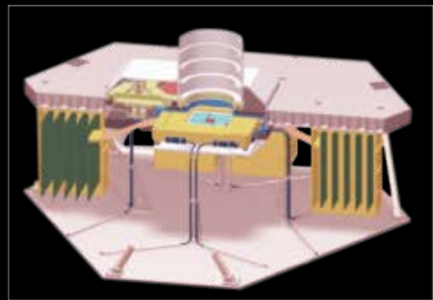
L2 orbit Ariane 6
5 year mission



Silicon Pore Optics:
$2\ m^2$ at 1 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: $3\ 10^{-17}$ erg $cm^{-2}\ s^{-1}$

X-ray Integral Field Unit:
ΔE: 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mK

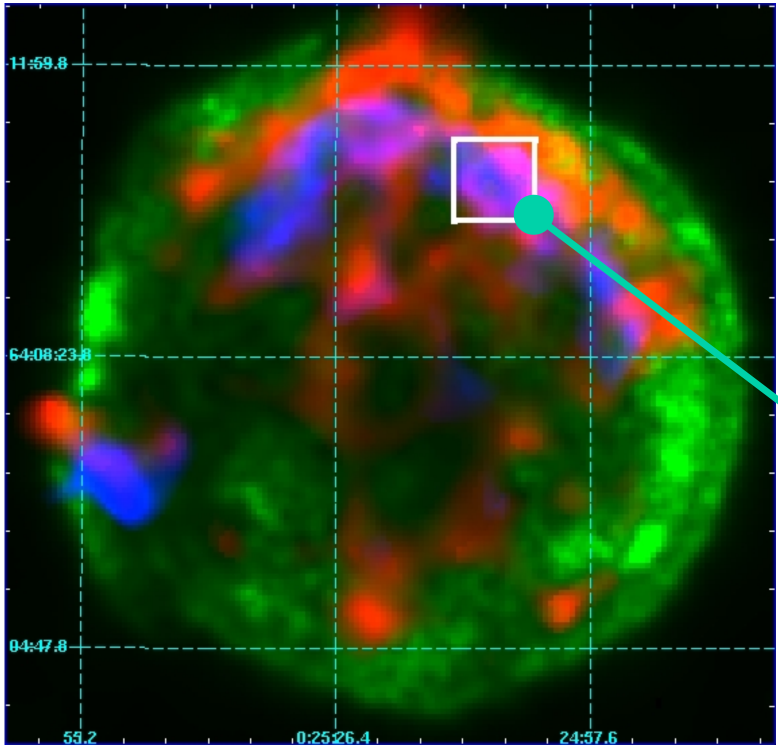
Barret et al., 2013 arXiv:1308.6784

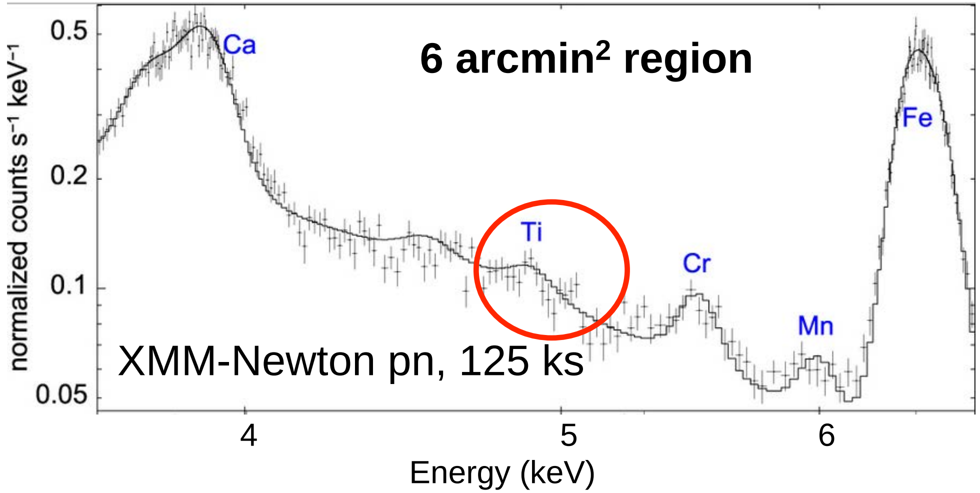


Wide Field Imager:
ΔE: 125 eV
Field of View: 40 arcmin
High countrate capability

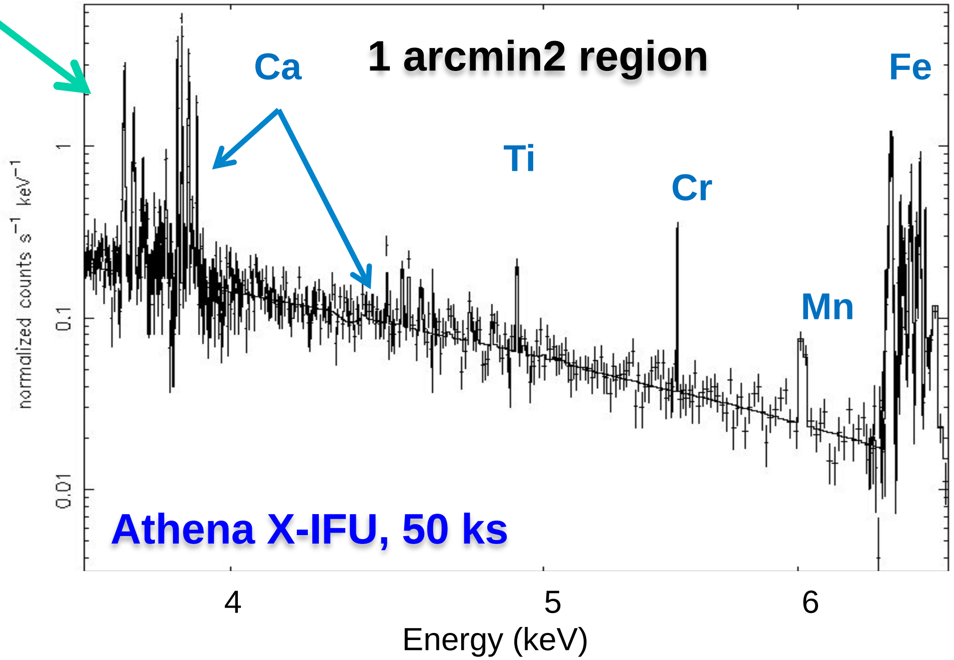
Rau et al. 2013 arXiv1307.1709

Athena detection of rare elements: Ti, Cr, Mn





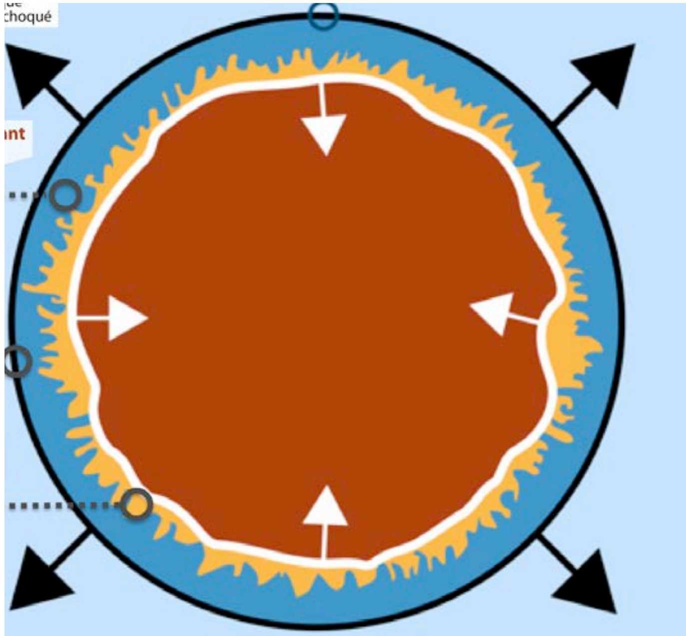
Miceli et al. 2015



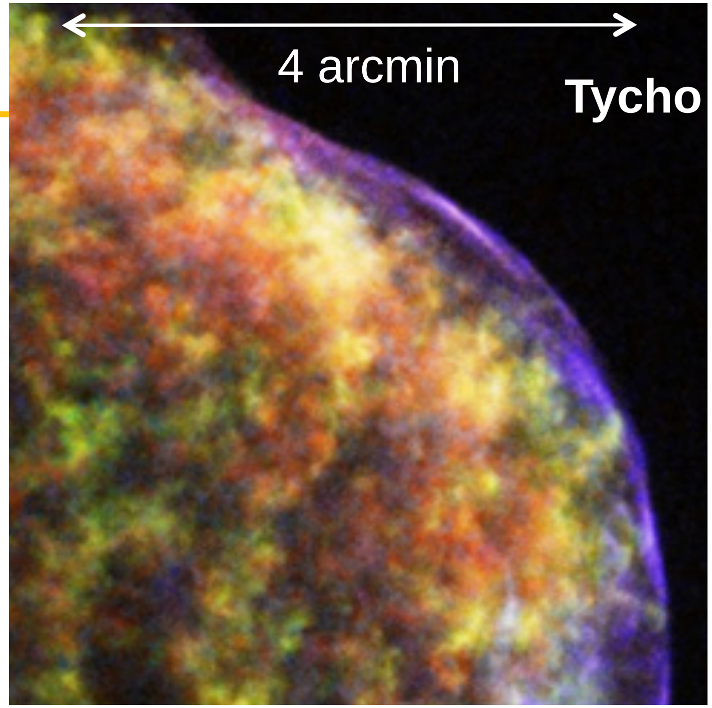
Continuum (4.4-6.1 keV)
Ca EW map (3.6-4.05 keV))
Fe K EW map (6.1-6.7 keV)

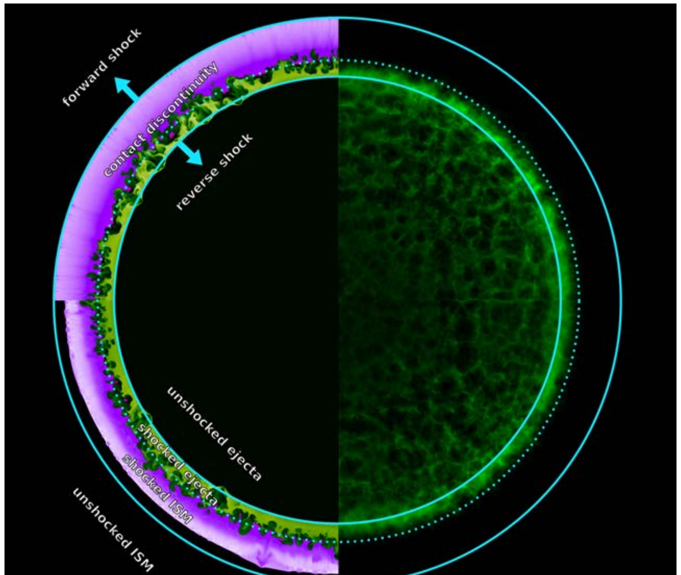
Miceli et al. 2015

A Tycho-like SNR 3D simulation



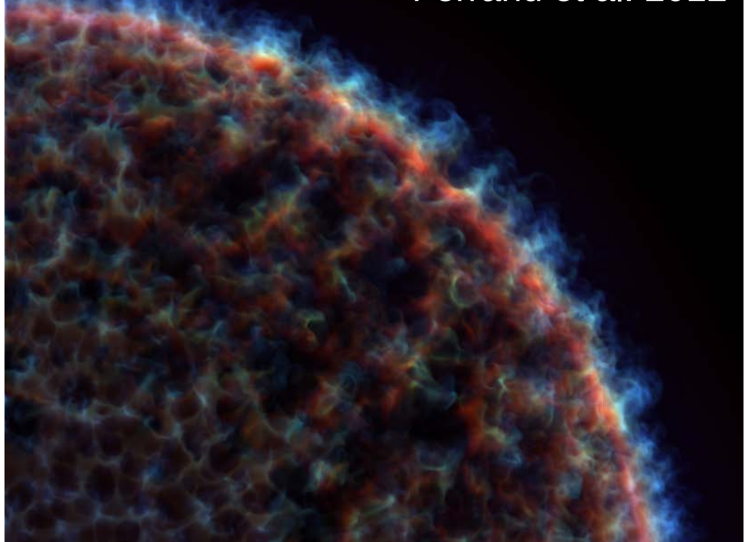
3D Simulations: thermal X-ray emission





Ferrand et al. 2010

- Hydrodynamics
- Back-reaction of accelerated particles
- Non equilibrium Te/Ti
- Non-equilibrium ionisation
- X-ray emission



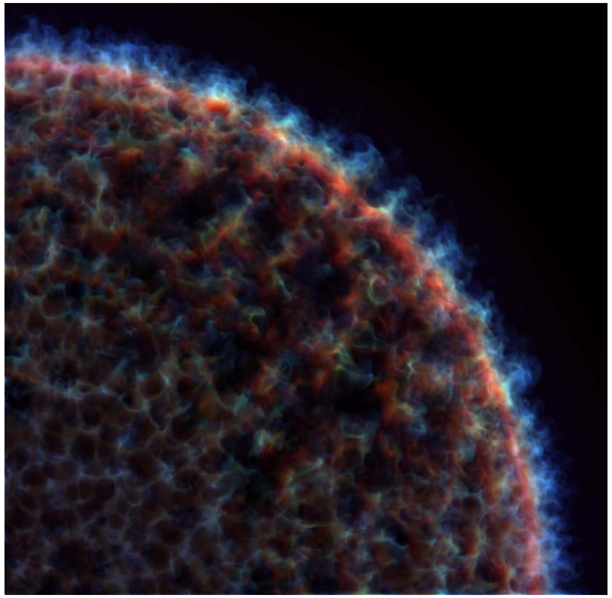
Ferrand et al. 2012

3-color image of the X-ray emission: green(O K) red (Si K) blue (Fe K line)

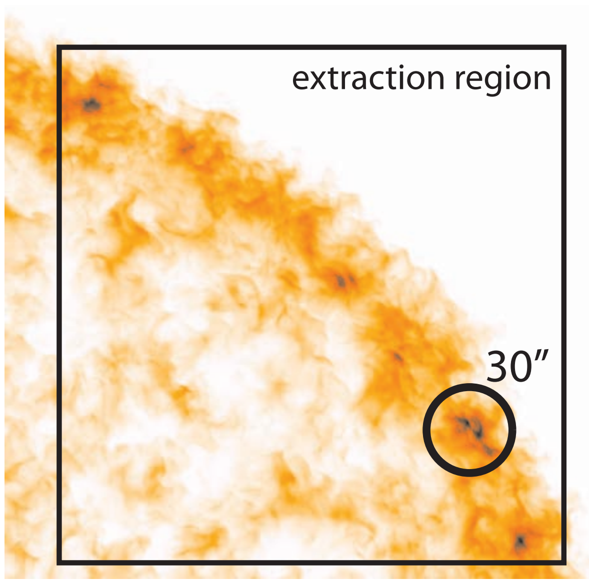
Athena expectation using a Tycho-like 3D SNR simulation

Key issue: Understanding the physics of core collapse and type Ia supernova remnants, quantifying the level of asymmetry in the explosion mechanism, the production of heavy elements, and their impact on the galactic environment.

Means: First detailed 3D mapping of the hot ejected material in the line of sight (velocity, temperature, ionization state and composition) to determine the full geometry and properties of the different layers of shocked ejecta.

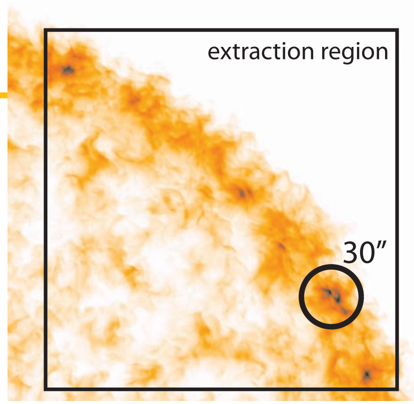


Simulation of a Tycho-like remnant (Ferrand et al. 2012)



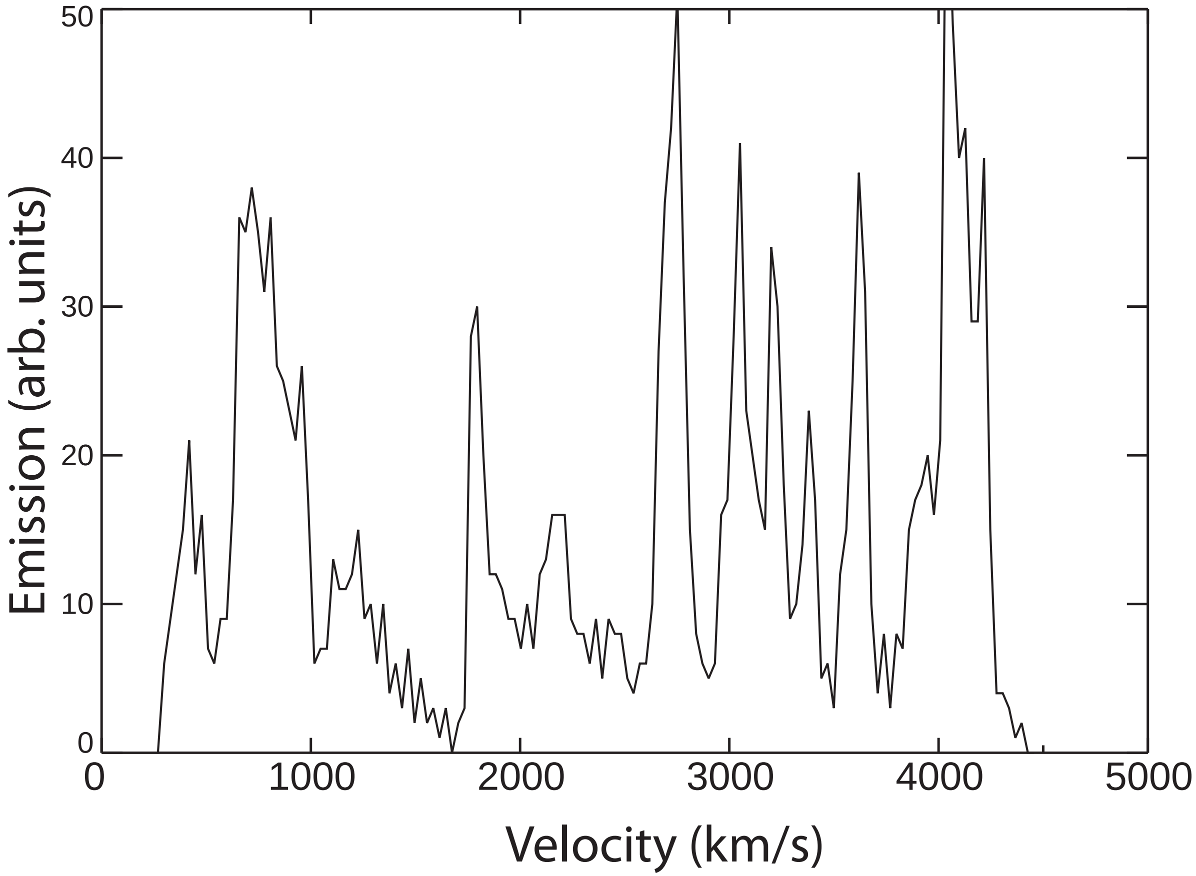
The Silicon K-shell emission: one particular ‘knot’

Velocity structure

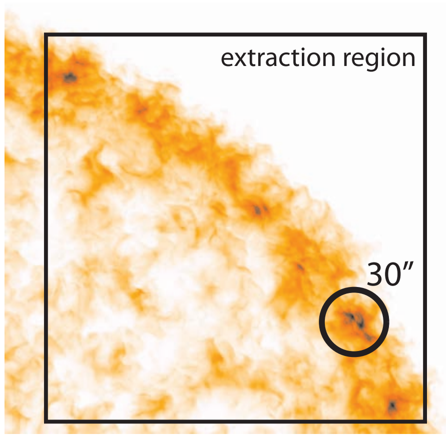


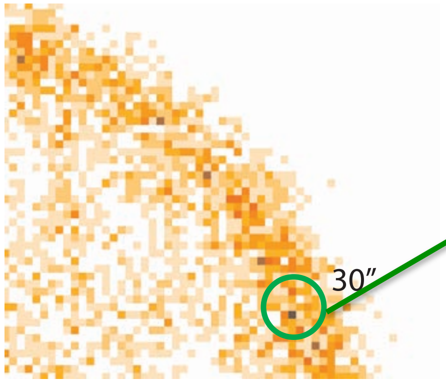
Each observed region includes a range of velocities that depend upon the global shock structure as well as local instabilities and initial stratification of the supernova material

Measuring this as a function of position, along with the elemental abundances, temperatures, and ionization states will reveal the underlying explosion mechanism, the initial conditions in the progenitor, as well as structure in the circumstellar and interstellar media.

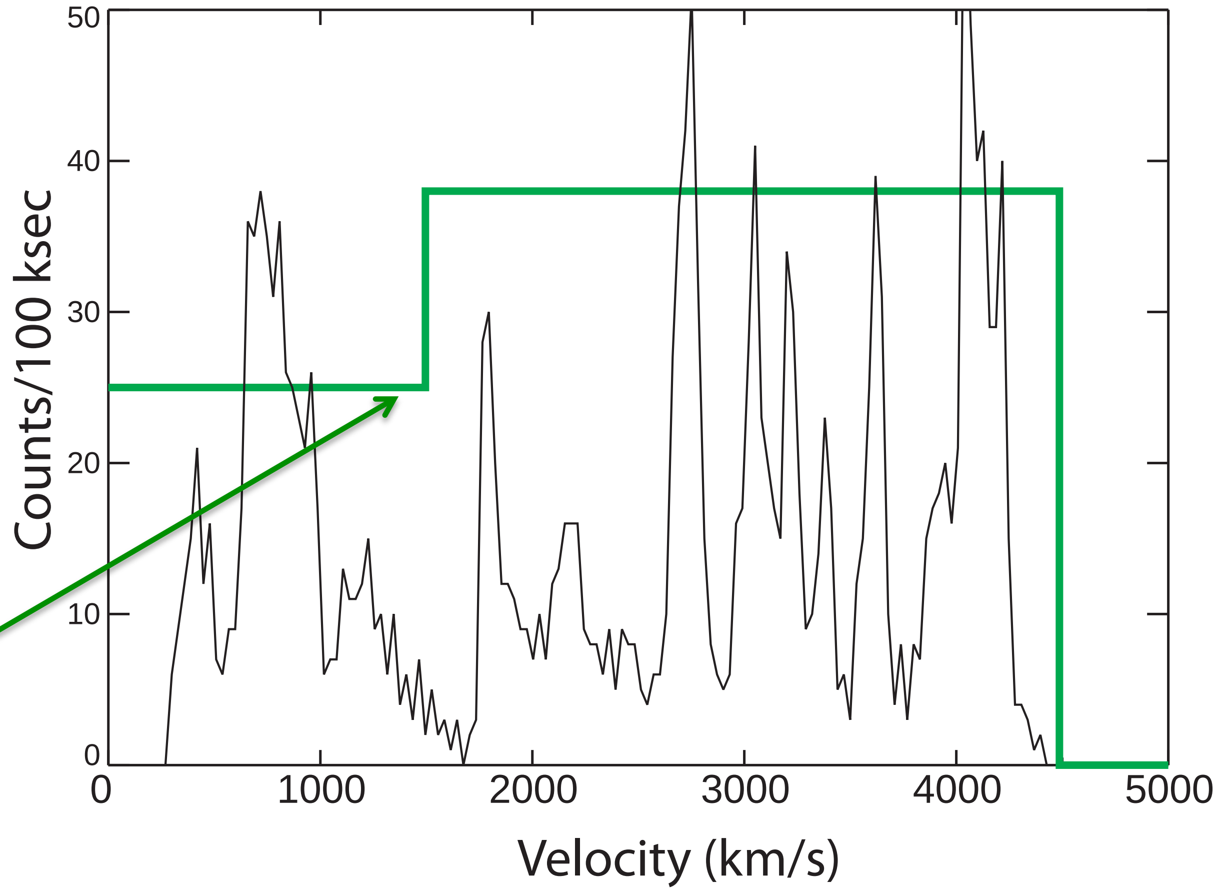


XMM & Velocity structure

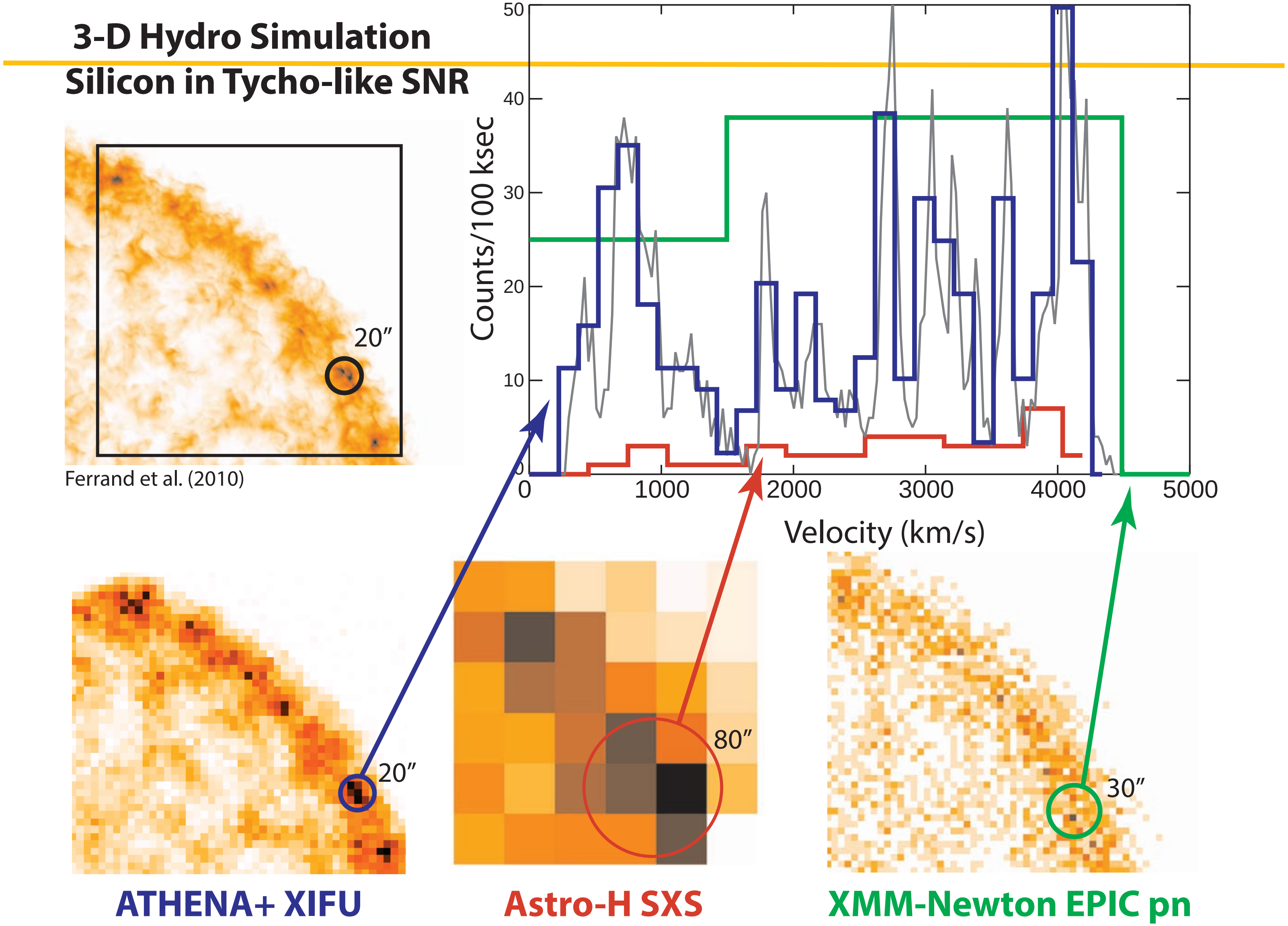




XMM-Newton EPIC pn



XMM-Newton does not have the energy resolution to reveal useful information about the velocity structure, although the PSF is enough to show the knot.



Athena will resolve the velocity structure on the scale of the fluctuations in the SNR. This result is for Silicon only, but each observation will get similar data for all the abundant elements from carbon (Z=6) through iron (Z=26).

Conclusion

Observations of SNRs have provided a number of information on the nucleosynthesis yields, plasma conditions and on the level of asymmetries
=> Constraints on the SN type, explosion mechanism and progenitor

To go further, spatially-resolved high-resolution spectroscopy is required.

Athena will be the first observatory to provide spatially-resolved spectroscopy with high spectral (2.5 eV) and spatial resolution (5arcsec)

Combine a high energy resolution over a large bandpass, a large effective area and a good spatial resolution

⇒ to perform spectroscopic diagnostics (temperature, ionization, abundances) at the relevant spatial scale, including rare elements lines

⇒ **to yield bulk and turbulent velocities**

Through detailed 3D mapping, we can learn consistently on the progenitor, SN type, and explosion mechanism through yields including rare elements, ionisation states, velocities and level of asymmetries.