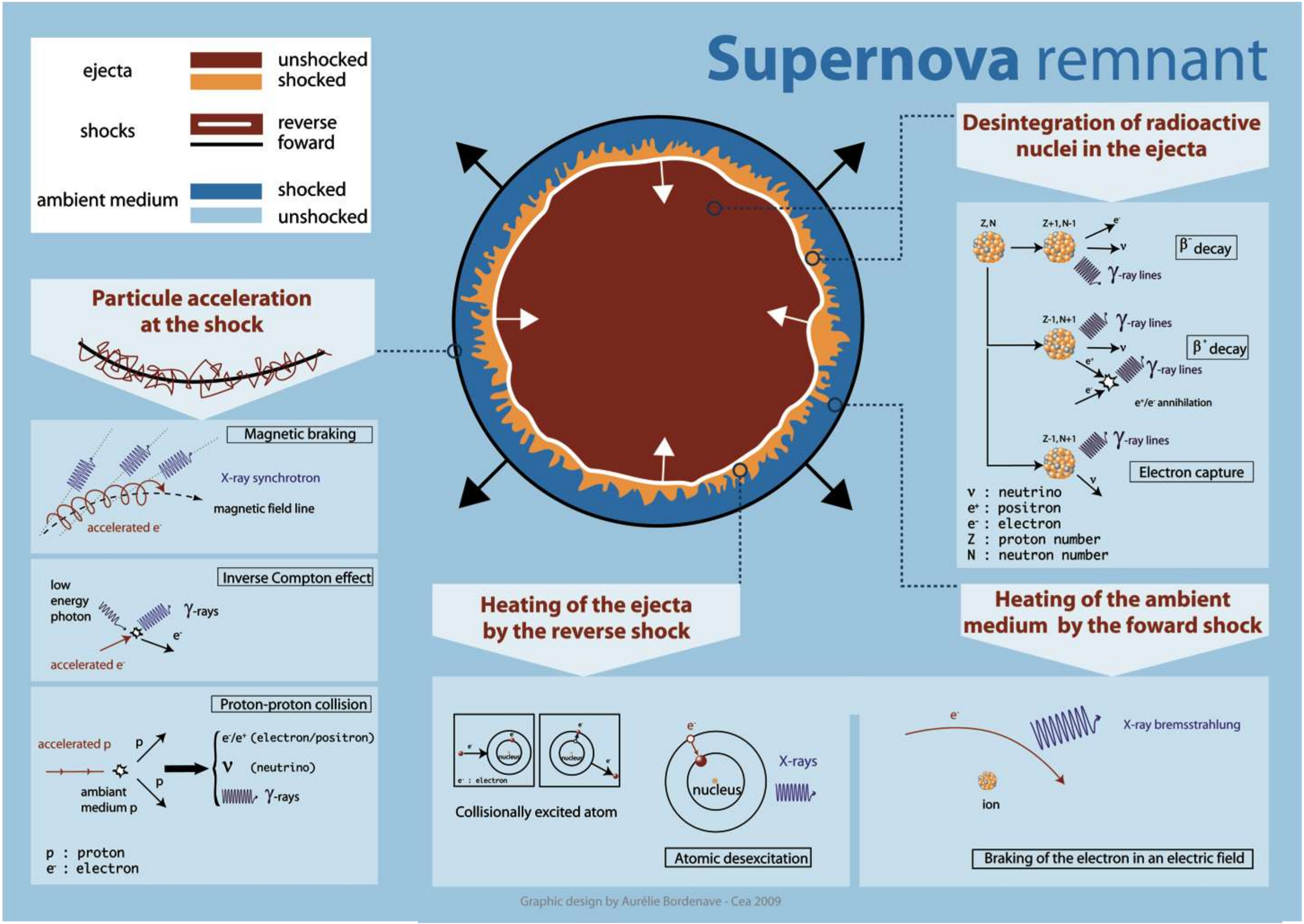
Supernova remnants and their progenitors

- Impact of the winds: Can **dense winds** help accelerating Cosmic-Rays up to 3 PeV?
- Nucleosynthesis: What is the **yield** of supernovae?
- Explosion: What is its **geometry**?

Let us see what we can learn from SNR observations

High energy emission of young supernova remnants



Young SNRs: Hydrodynamics

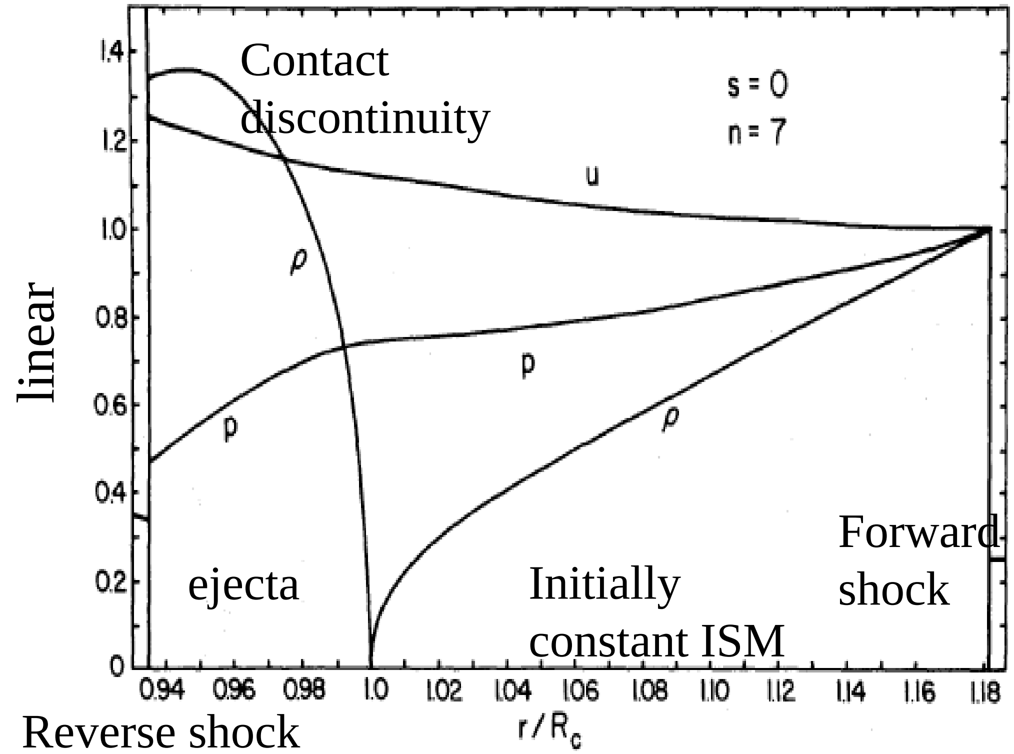
Early phases of SNRs

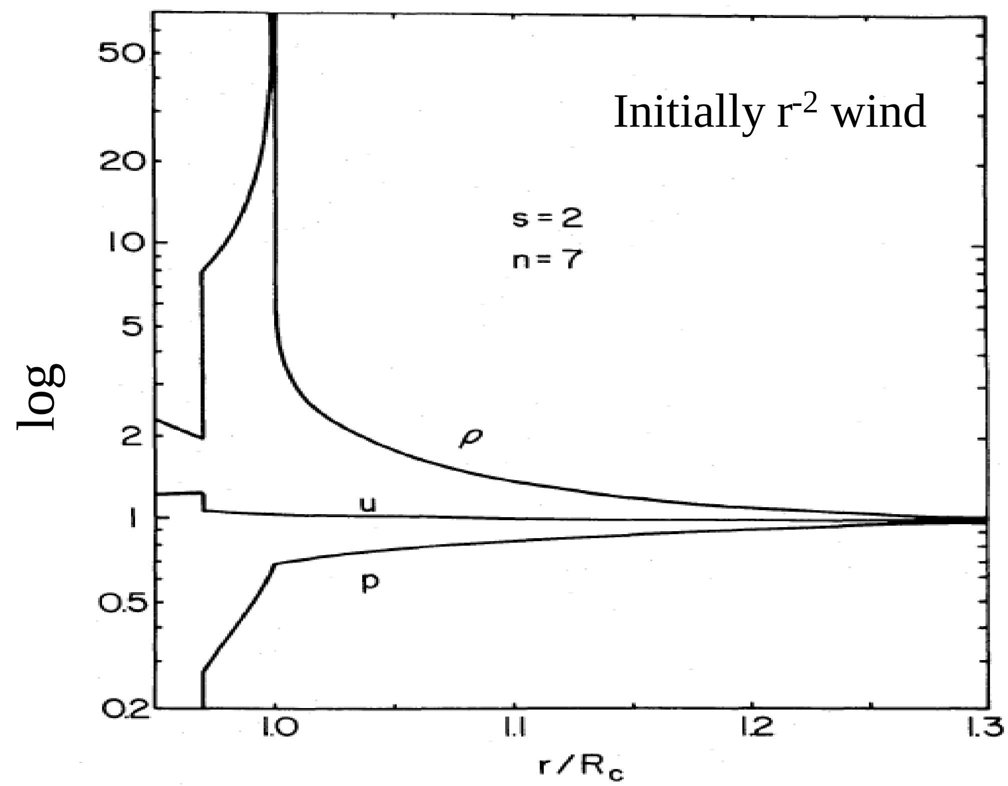
Outer ejecta density profile is power-law

Self-similar solution if ambient density profile is constant or power-law (Chevalier 1982, ApJ 258, 790)

Flat profile results in low density at contact discontinuity ➔ slow ionization, faint emission

Wind profile results in **high density** at contact discontinuity ➔ **fast ionisation, bright emission, cooling**



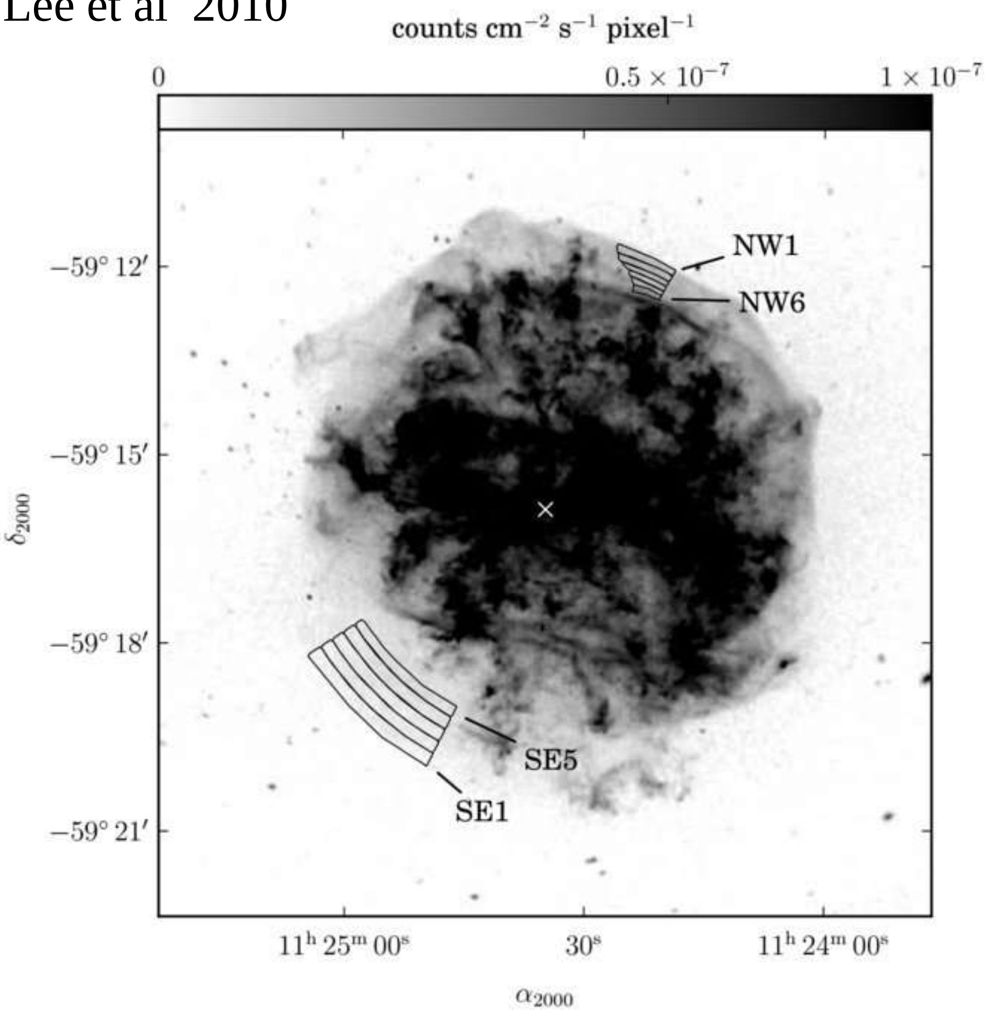


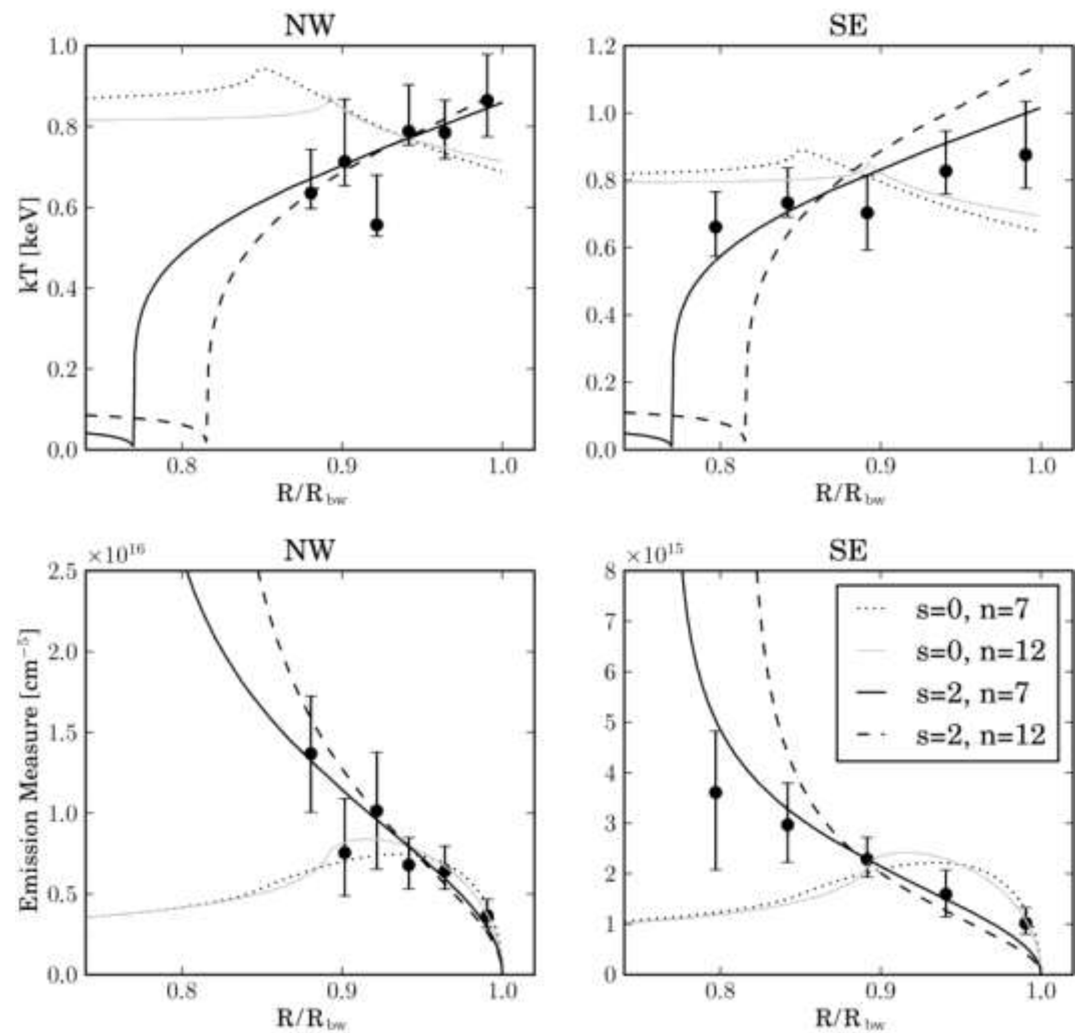
Thermal emission from the shocked ambient medium

G292.0+1.8

- Thermal emission is detected in SE. Ambient density ≈ 0.2 cm^{-3}.
- Shock speed ≈ 2500 km/s. Synchrotron rim emission not detected
- Radial profiles consistent with expansion in wind $\rho \propto r^{-2}$

Lee et al 2010





Thermal emission from the ejecta

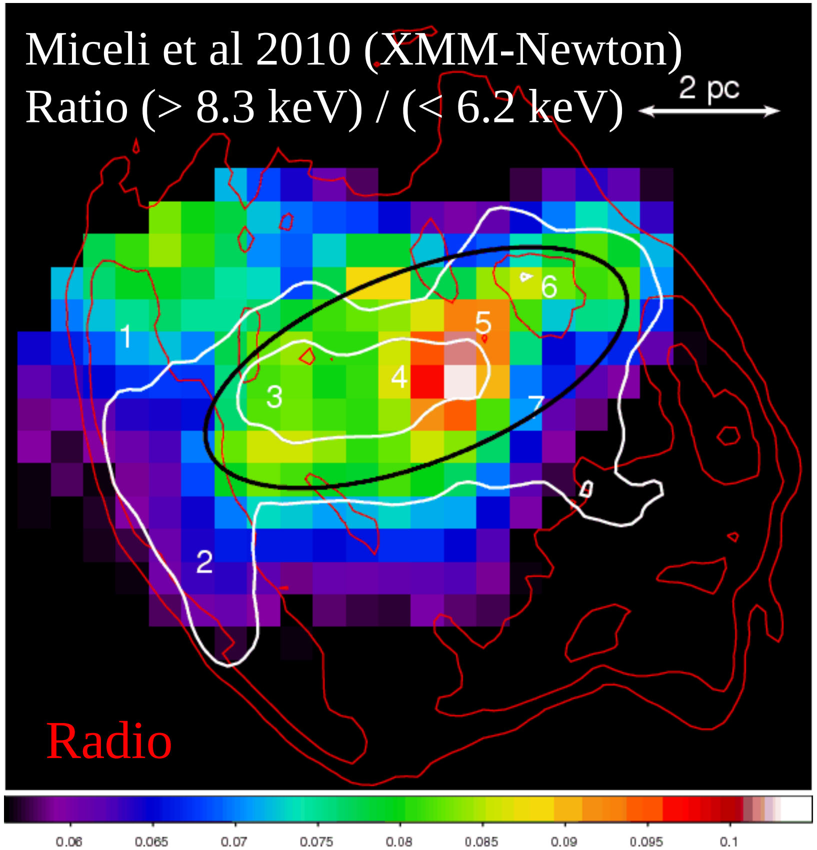
Suzaku has found many other examples of overionised plasma, sometimes on Si.

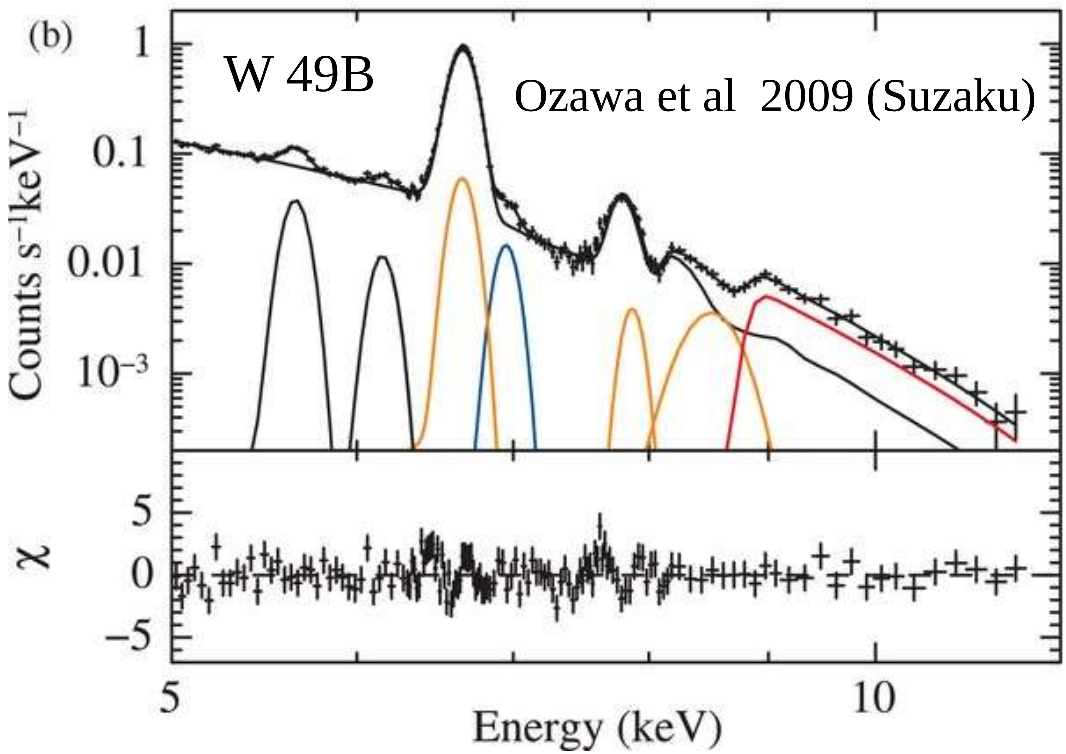
Many are older SNRs not currently in wind.

Implies **early evolution in dense RSG wind**.

Associated X-ray excess in the center.

- **Recombination** continuum of Fe
- Implies **overionisation** of Fe
- Due to higher density in the past for wind profile (ρ α r^{-2})





Blast wave image

Chandra image

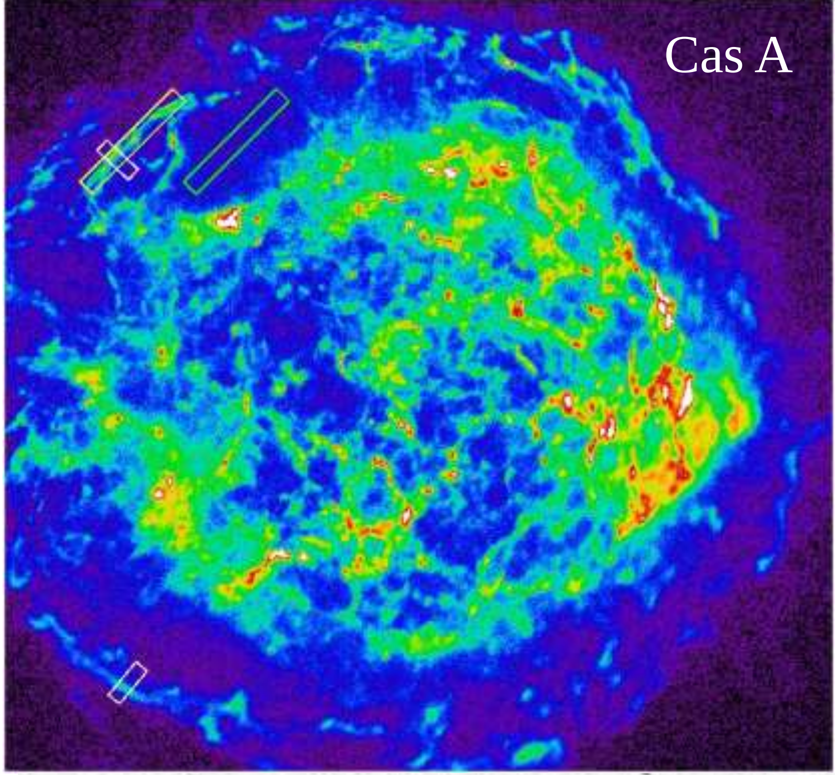
X-ray continuum (4 – 6 keV)

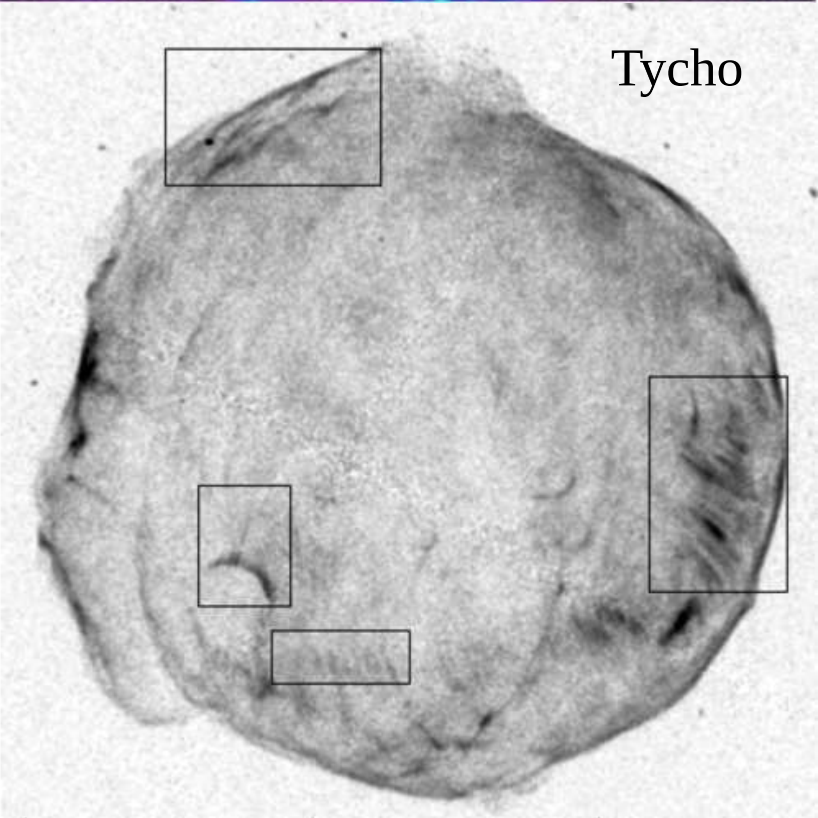
Filaments dominated by synchrotron emission from electrons accelerated at the blast wave

Thin due to strong cooling

Blast wave much **less regular in wind** (Cas A) than in more uniform gas (Tycho)

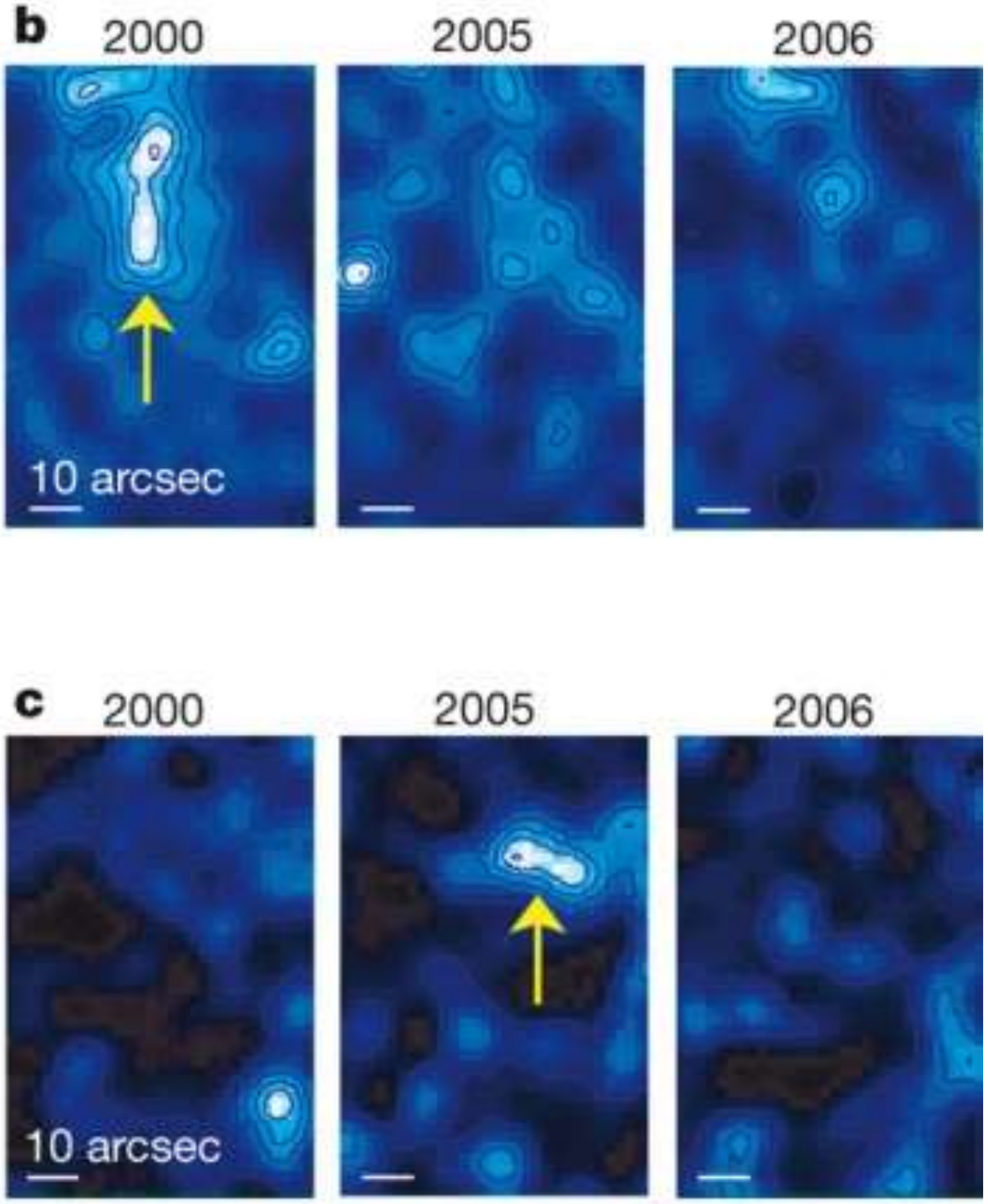
Probably reflects pre-existing density structures in wind





Fast variability

- RX J1713.7-3946
- Found when looking for expansion
- Small bright features (not really filaments) come and go over a few years
- Significance somewhat difficult to assess (number of trials) but probably real
- Implies locally mG magnetic field if interpreted as acceleration and cooling
- Also seen in Cas A, possibly related to wind density structure



Uchiyama et al 2007, Nature 449, 576

Maximum energy of accelerated particles

Electrons are a few % of cosmic rays but reveal a lot on the mechanism of diffusive shock acceleration; accelerated like protons, except for the radiative losses

Acceleration time $t_{acc} \propto \frac{E}{B_{turb}\, v_{sh}^2}$

Cooling time (electrons) $t_{cool} \propto \frac{1}{E\, B^2}$

Maximum energy of electrons ($B \approx B_{turb}$) $E_{max}^e \propto v_{sh}\, B^{-1/2}$

Maximum synchrotron frequency (electrons) $\nu_{max} \propto B\, E_{max}^2 \propto v_{sh}^2$

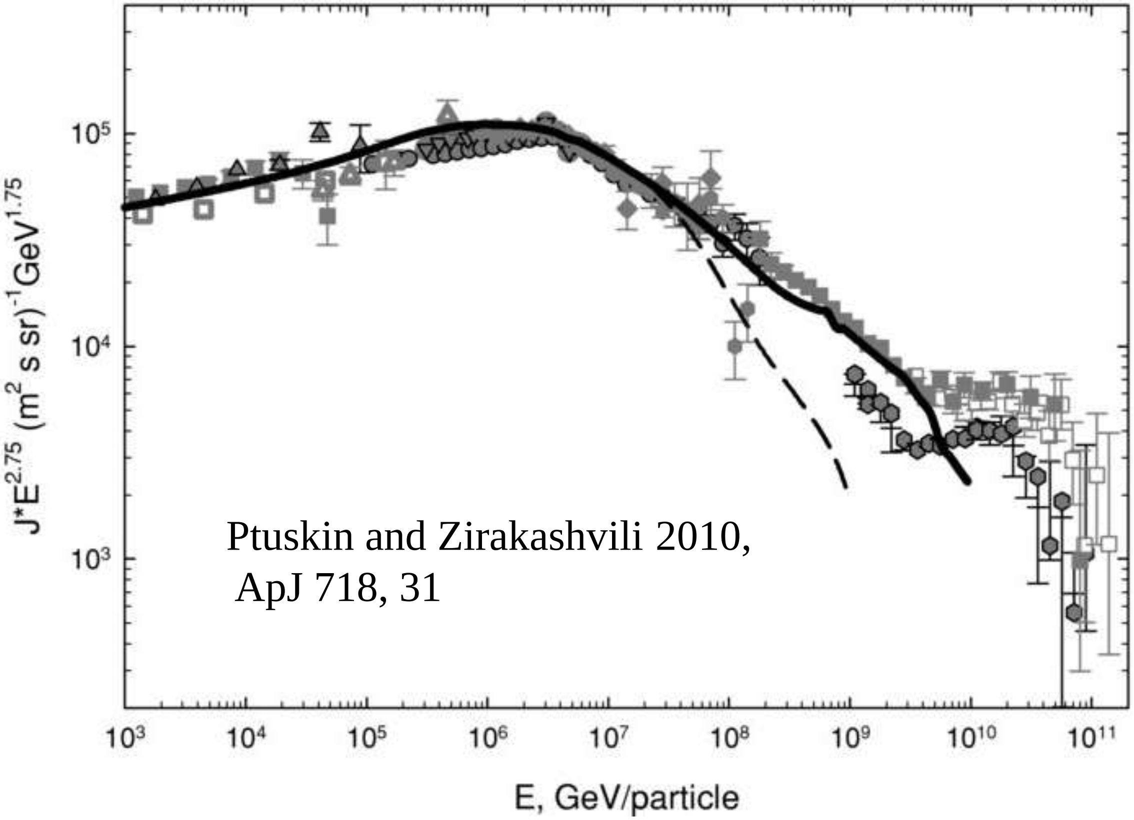
Magnetic turbulence amplified by cosmic-rays themselves; magnetic energy density possibly proportional to ram pressure $B_{turb}^2 \propto \rho\, v_{sh}^2$

Maximum energy of protons then $\boldsymbol{E_{max}^p \propto \sqrt{\rho}\ v_{sh}^3\, t}$ favors dense winds

Integrated cosmic-ray spectrum

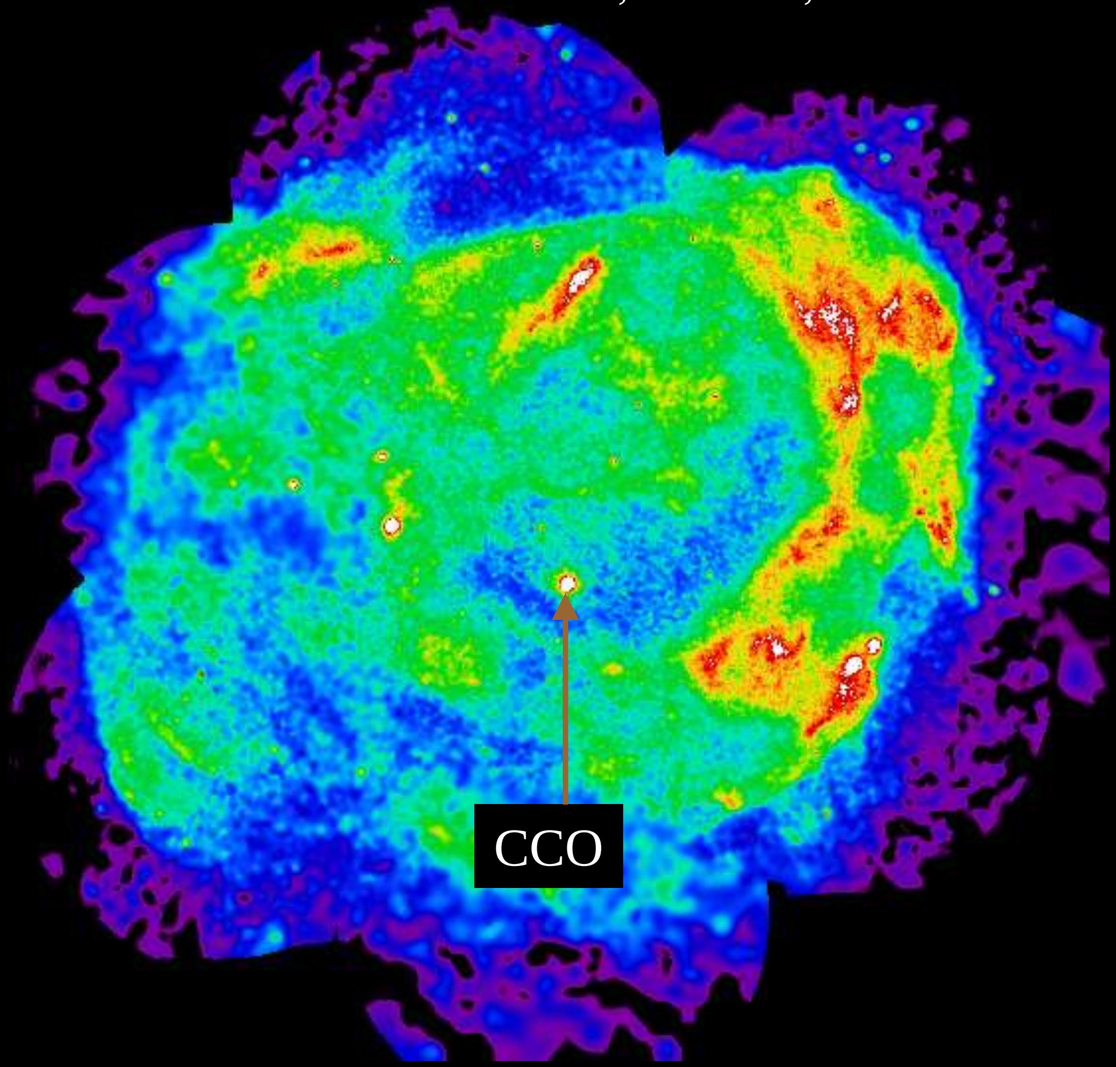
- ✓ Integrate all CRs accelerated during SNR evolution
- ✓ Varying V_{sh} implying varying B field)
- ✓ Sum over all types of SNRs including SN IIb going through dense wind
- ✓ Account for usual Galactic escape ($p^{-0.54}$)

- ✓ Reproduces quite well the observed CR spectrum around the “knee” at 3 10^{15} eV
- ✓ Can extend up to the “ankle” at 3 10^{18} eV
- ✓ Still several free parameters



RX J1713.7-3946 : Interaction with denser gas

XMM-Newton: Acero et al. 2009, A&A 505, 157



Large nearby remnant (1° diameter, **10 pc radius** at 1 kpc)

No obvious thermal emission implies early evolution in tenuous (fast) wind

Indications of current interaction with denser gas ➔ wind shell ?

Similar indications of early tenuous wind + shell in **older SNRs** in which shock encountered shell some time ago; Cygnus Loop ➔ **15 pc radius**

Shells impact a lot X-ray emission

Small wind bubbles for O star; probably progenitors just massive enough to end in SNe

Ejecta in young supernova remnants

Young supernova remnants : emission

Lines of elements from **O to Fe**

Mostly **optically thin**

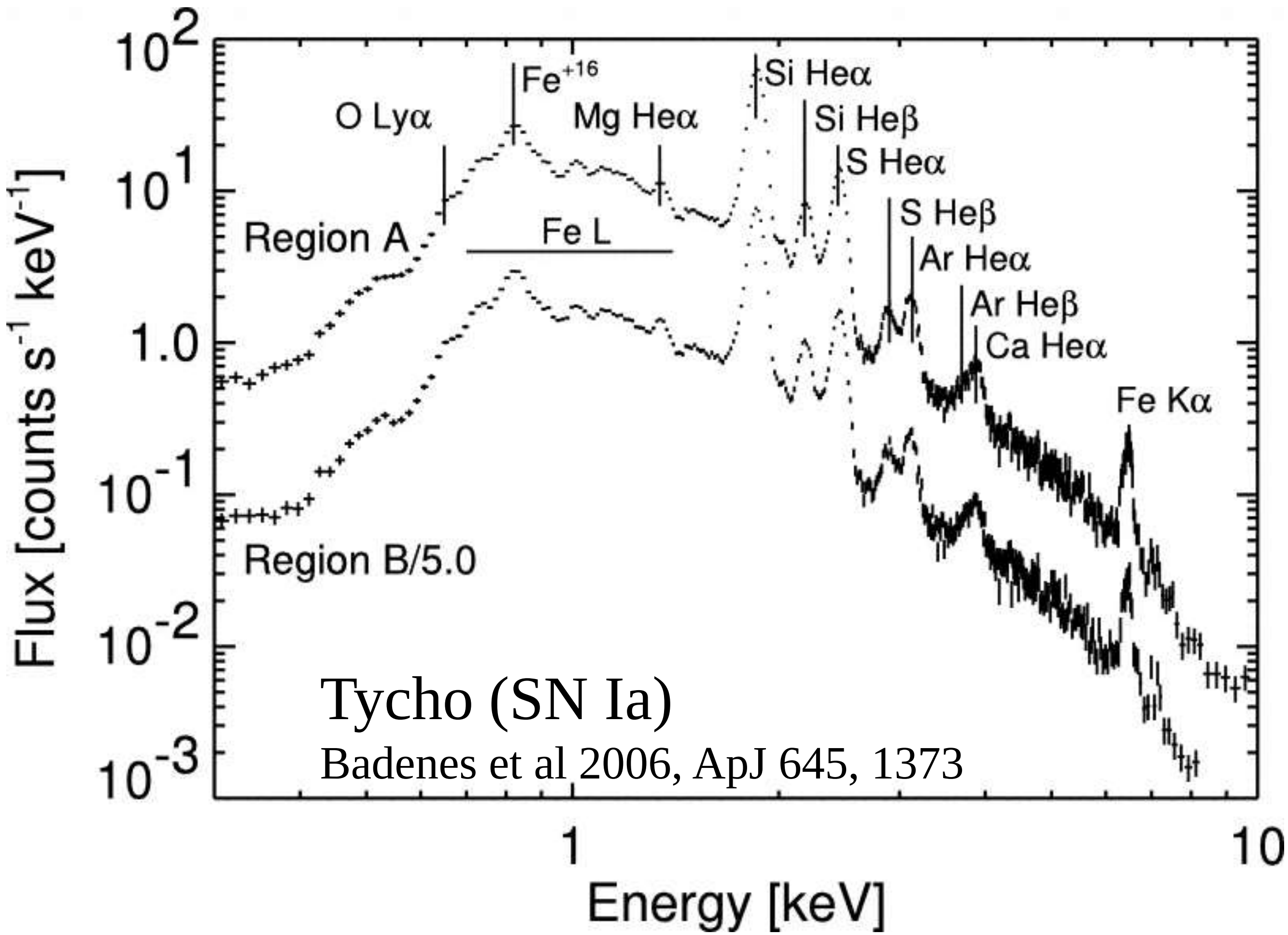
Trace **hot ejecta** in young SNRs

Observables are line **strengths and energies**

Can be **resolved** (size several arcmin in Galaxy)

Depend on **temperature and ionisation state**

Continuum can have several origins (synchrotron)



Tycho (SN Ia)

Badenes et al 2006, ApJ 645, 1373

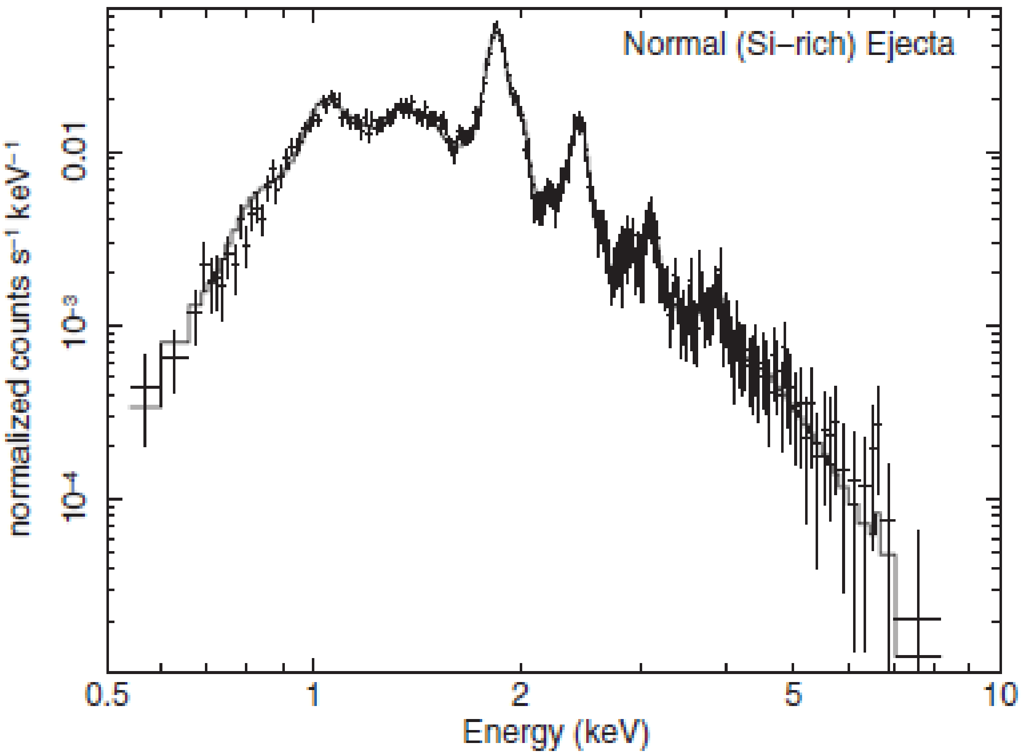
Enough to tell CC from Ia, but **difficult** to obtain **model-independent** mass estimates

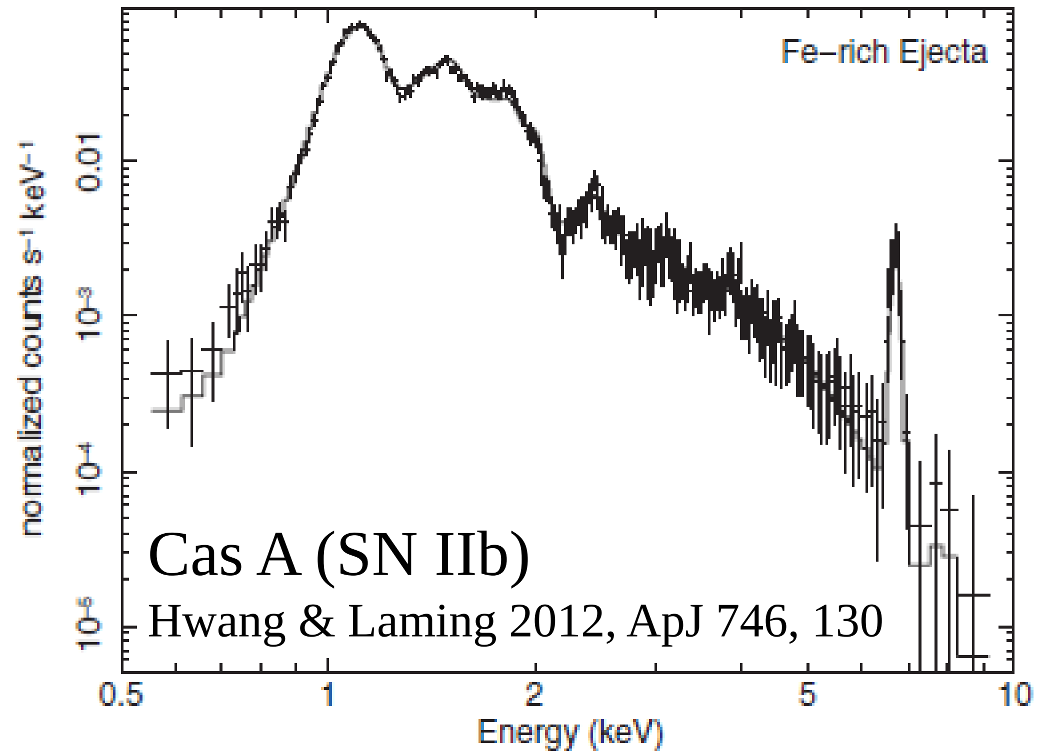
Dependent on **ejecta mixing** (where do the electrons come from?), line of sight

Can be used to test precise ejecta combinations (from nucleosynthesis models)

In Tycho, does not agree with direct estimate of ambient density

Young supernova remnants : emission





Very deep Chandra exposure, spectra analyzed at scale of 2.5''

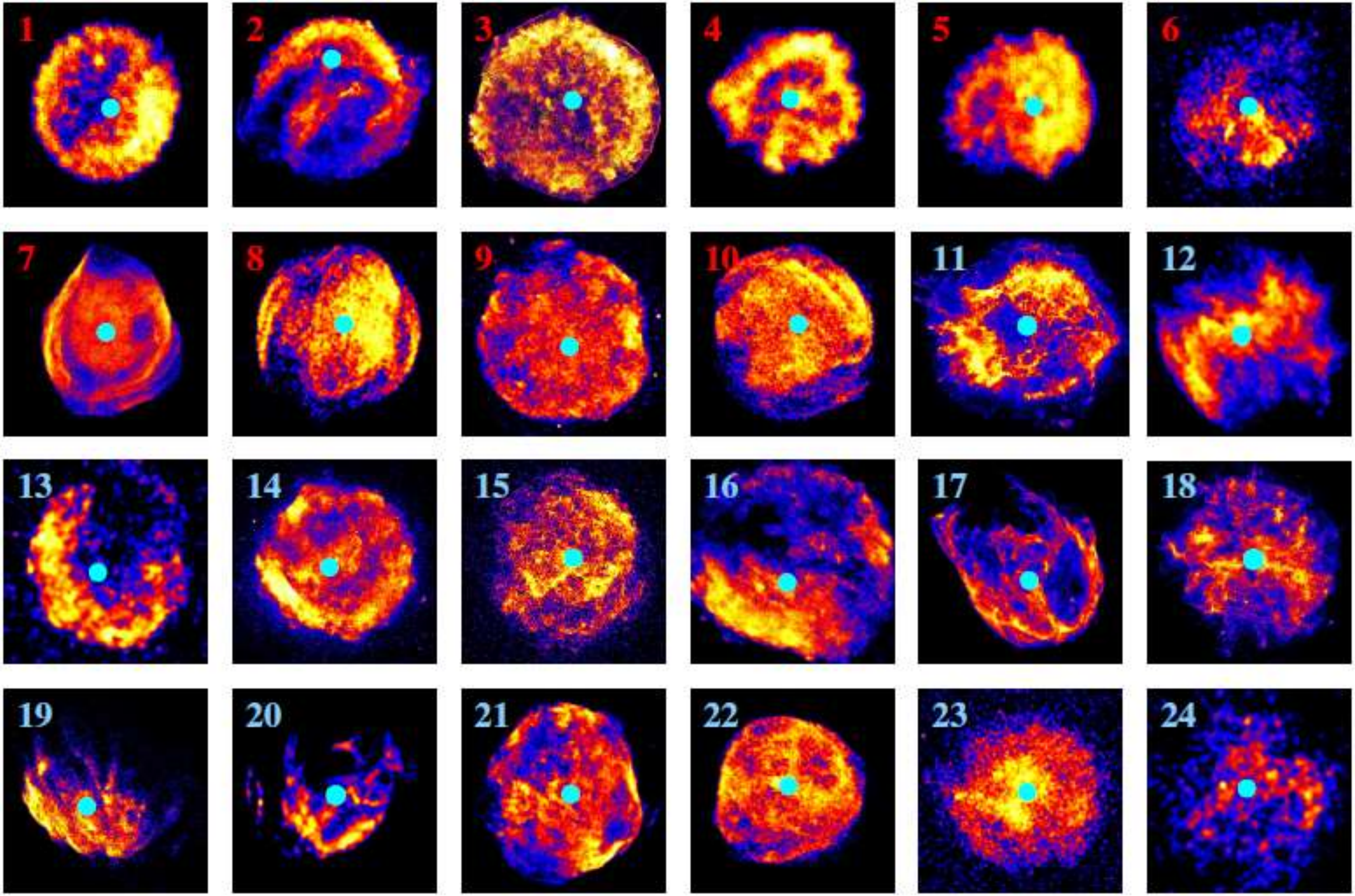
Model CSM contribution, use state-of-the-art emission models

Assume ejecta dominated by (ionised) oxygen, except a few pure Fe knots

Ionisation stage not really as expected, result still model-dependent

Require 2 to 3 Mo of ejecta, including 0.1 – 0.15 Mo of Fe, 0.04 – 0.05 Mo of Si

Young supernova remnants : CC vs SN Ia

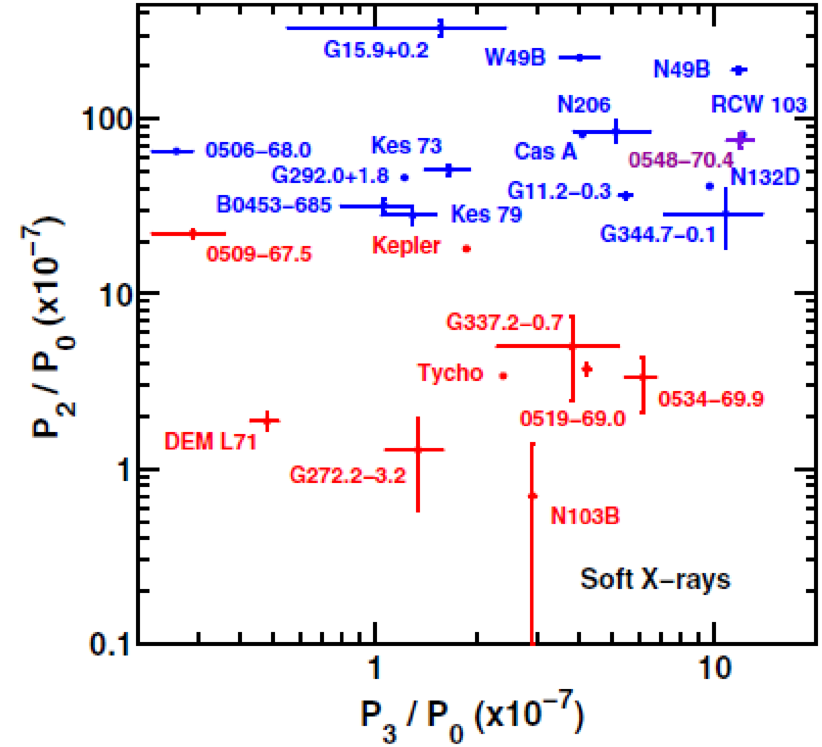


Young supernova remnants : CC vs SN Ia

Lopez et al 2011, ApJ 732, 114

Geometry of the X-ray emission (or of Si line only)

SN Ia have a much lower quadrupole component, more regular overall

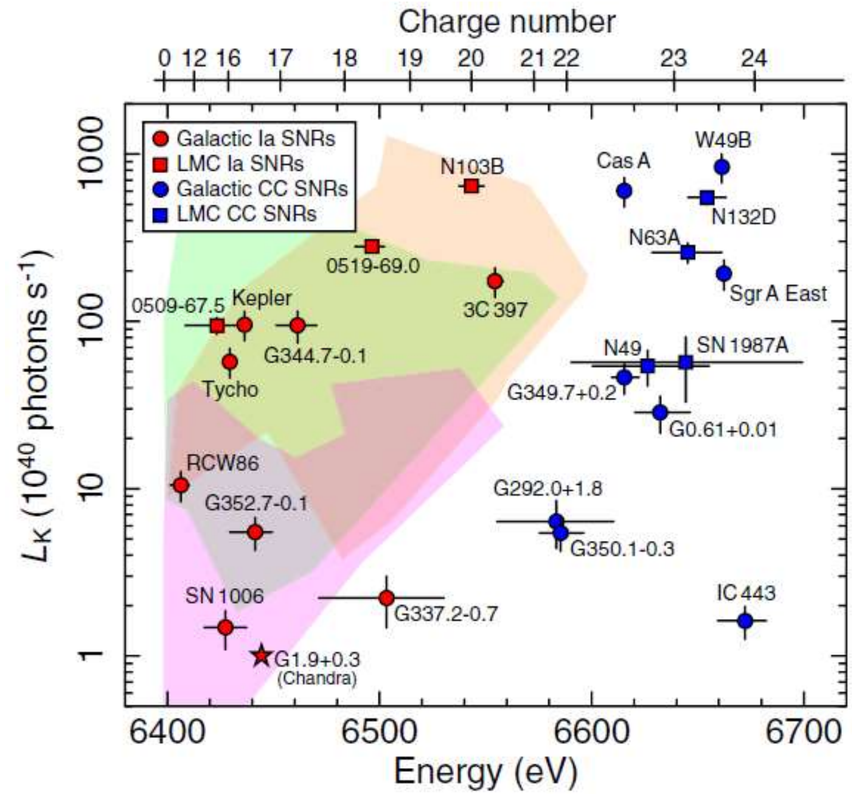


Yamaguchi et al 2014, ApJ 785, L27

Centroid of the Fe K emission

Fe in CC SNe is more ionised

More ambient gas around (not clear this is actually related to ejecta)



Young supernova remnants : CC vs SN Ia

Borkowski et al 2006, ApJ 652, 1259

RGB Chandra images

R: 0.3 – 0.7; G: 0.7 – 3; B: 3 – 7 keV

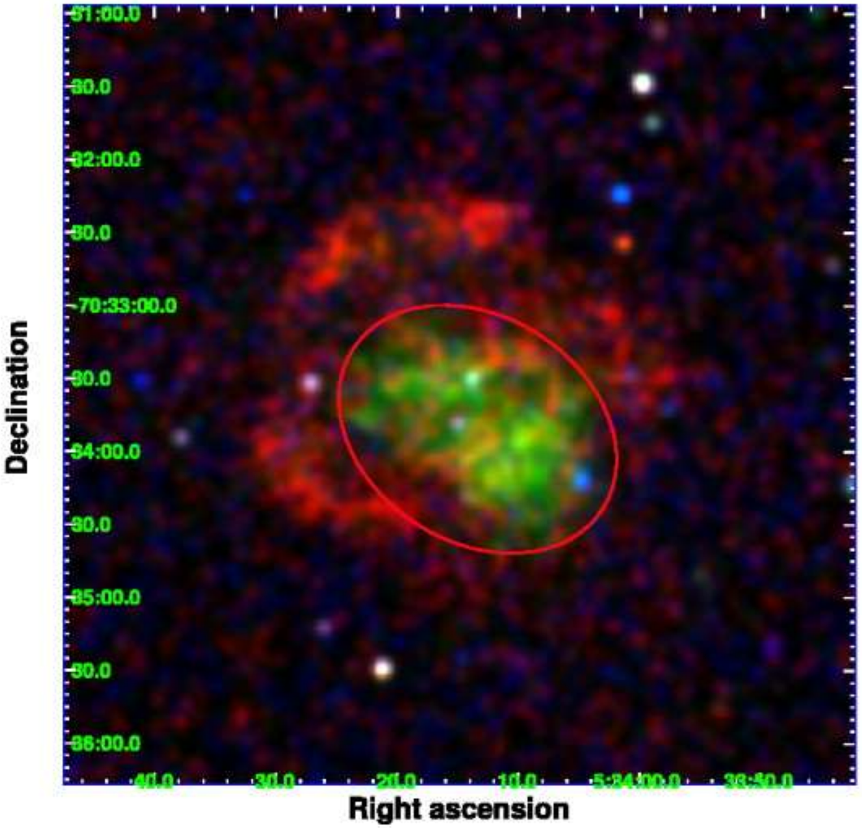
Center appears green

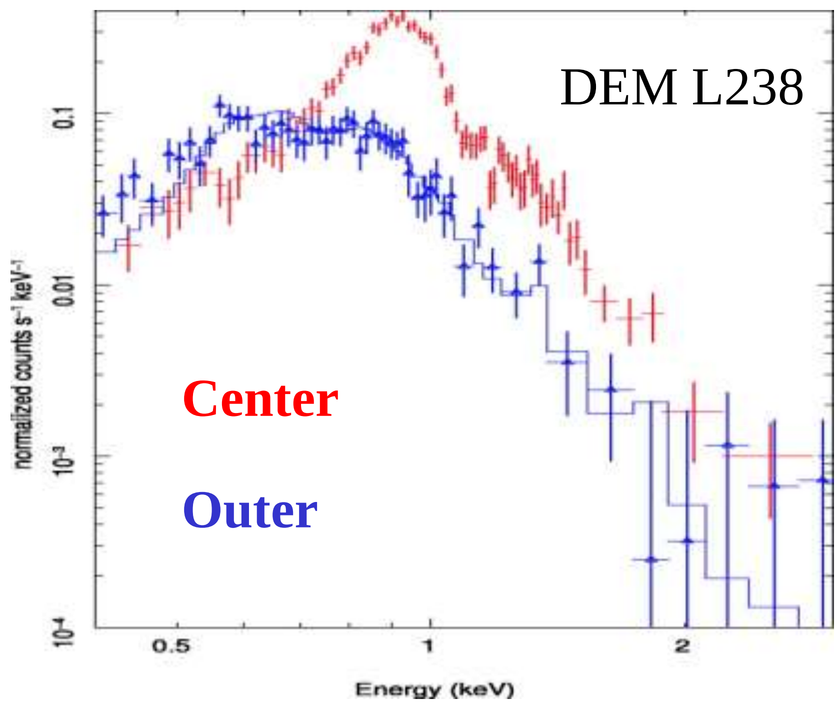
Spectrum shows **Fe L peak**, large Fe **overabundance** hints at SN Ia

Two oldish LMC SNRs, and more in Maggi et al 2014, A&A 561, A76

Ambient medium implies low density

But central Fe at collisional equilibrium, implies **higher density in the past**, possibly due to circumstellar material as in center-filled SNRs, but now in SN Ia





Young supernova remnants : absorption

Trace **cold** (unshocked) ejecta

SN 1006 illuminated by very blue star

Hamilton et al 1997, ApJ 482, 838

Electron density low enough that shocked Si II actually dominates

Not much detected on blue side, implies entirely shocked (larger density)

Very precise but only one light of sight

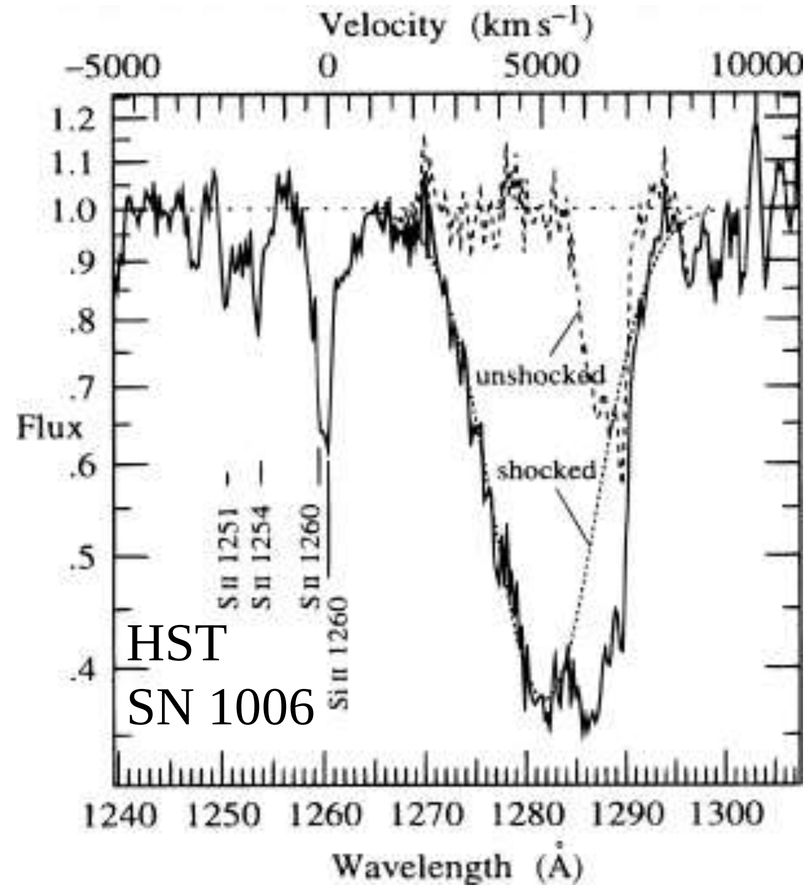
No sign of Fe II absorption

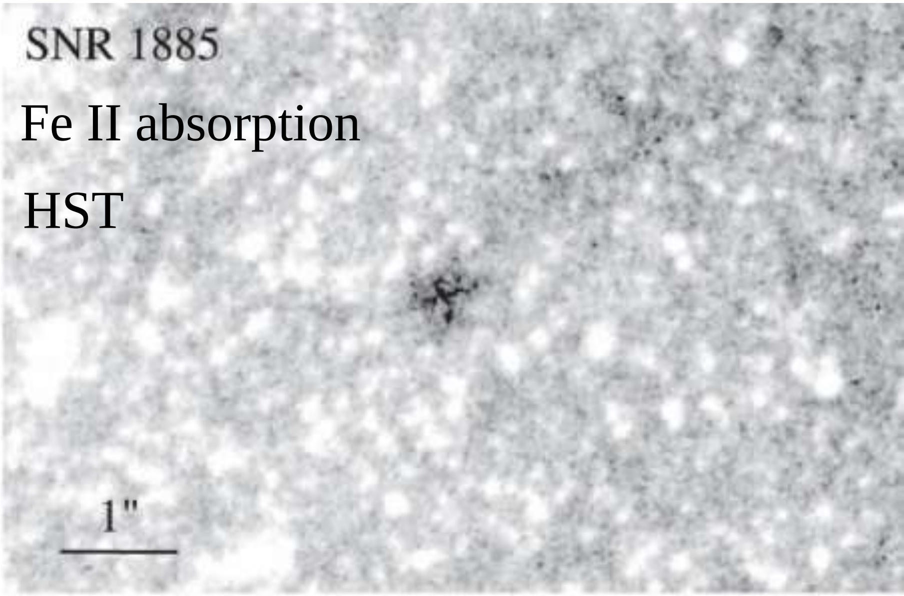
SN 1885 absorbs M31 bulge

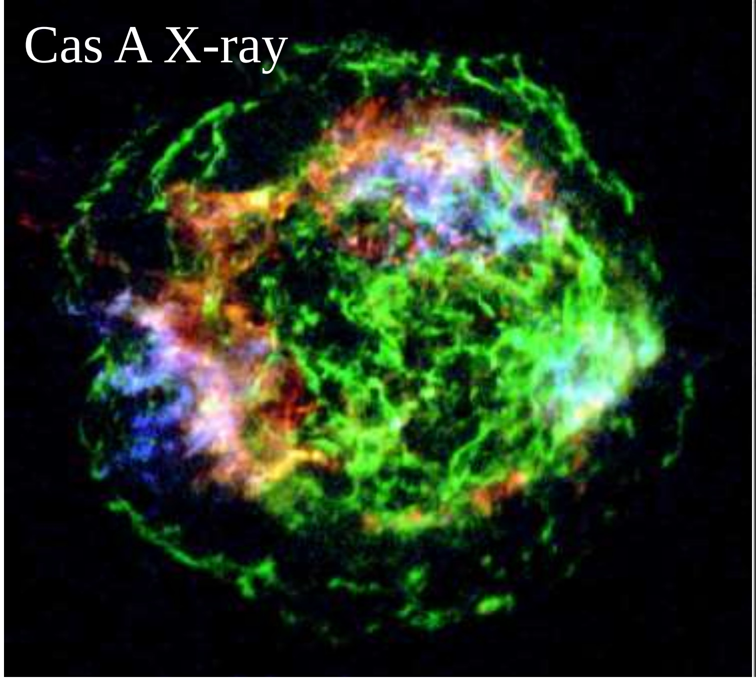
Very obvious in Ca II

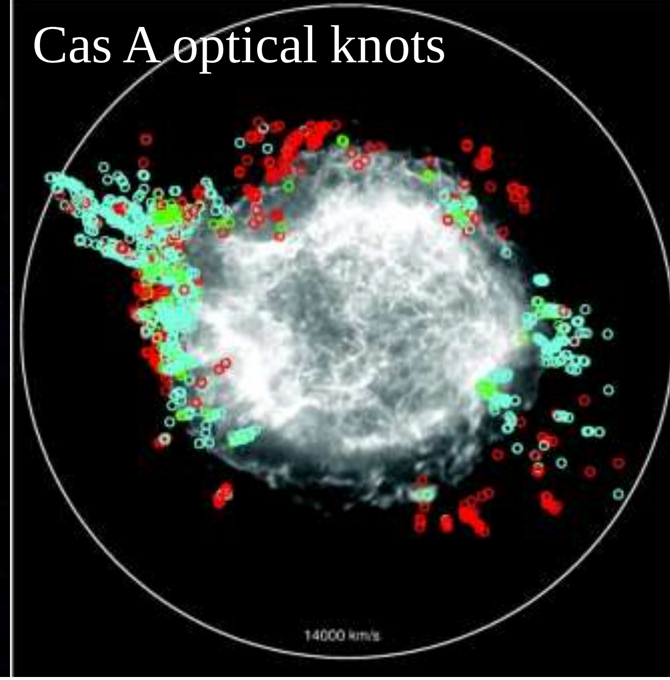
Fesen et al 2015, ApJ 804, 140

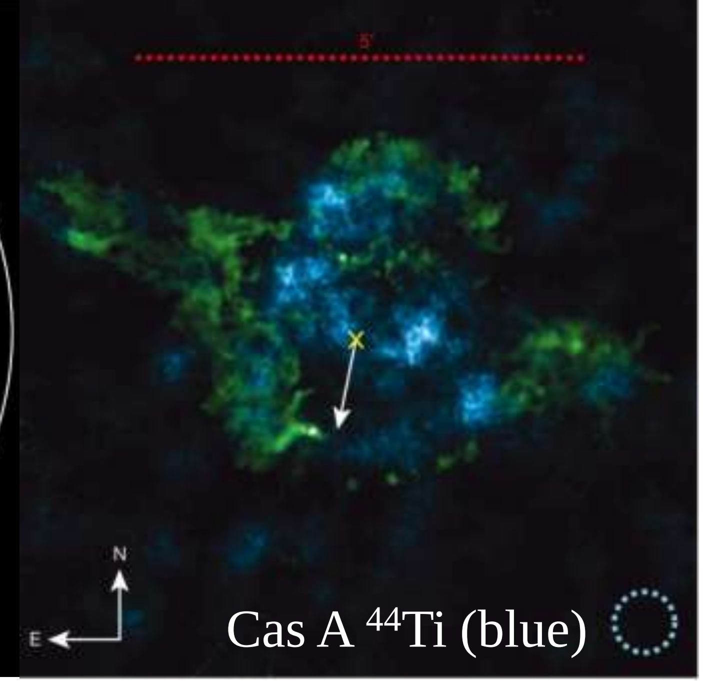
Weak detection of Fe II (bulge not so blue)











Young supernova remnants : geometry

Hwang et al 2004, ApJ 615, L117. X-ray RGB image. R: Si K; G: continuum; B: Fe K

Fesen et al 2006, ApJ 645, 283. R: [N II]; G: [O II]; C: [S II]

Fast moving optical knots, due to strong cooling of initially very dense shocked ejecta, very fast Si « jet » (seen here in [S II]) up to 14 000 km/s

Grefenstette et al 2014, Nature 339, 506. NuSTAR obs of ^{44}Ti in Cas A. As asymmetric as Fe, Si but not at the same place

Supernova remnants and their progenitors

- Dense (RSG) winds show at the center of SNRs, and can provide **seeds for CR acceleration to PeV**
- Shells can affect strongly SNR emission, and **perturb population studies**
- Obvious difference between spectra of SNe Ia and CC SNe, but **hard to measure masses precisely.** High spectral resolution will help
- Particularly **complex geometry in CC SNe**, but even SNe Ia show large scale asymmetries