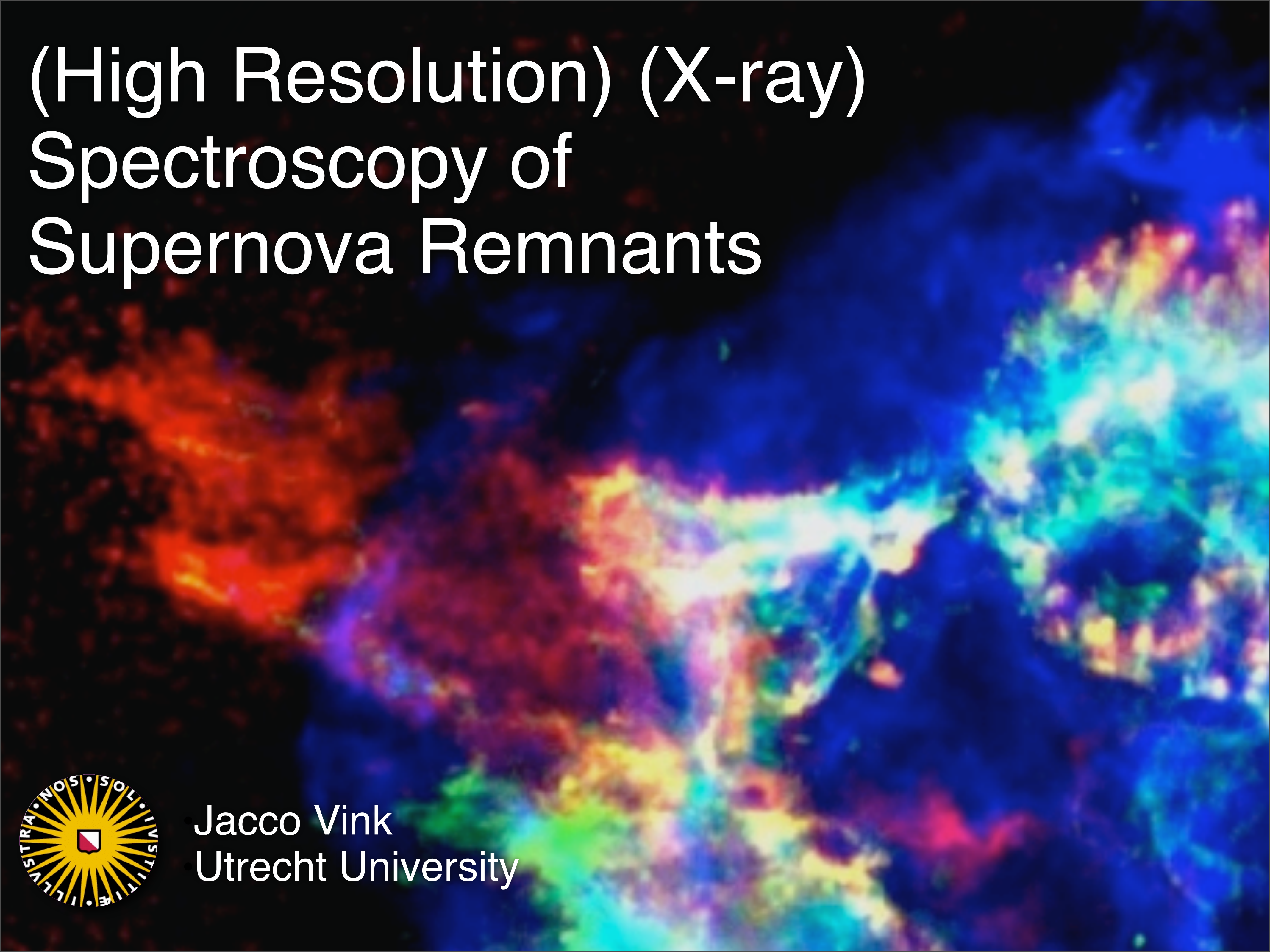
(High Resolution) (X-ray) Spectroscopy of Supernova Remnants



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X-ray Spectropy of SNRs

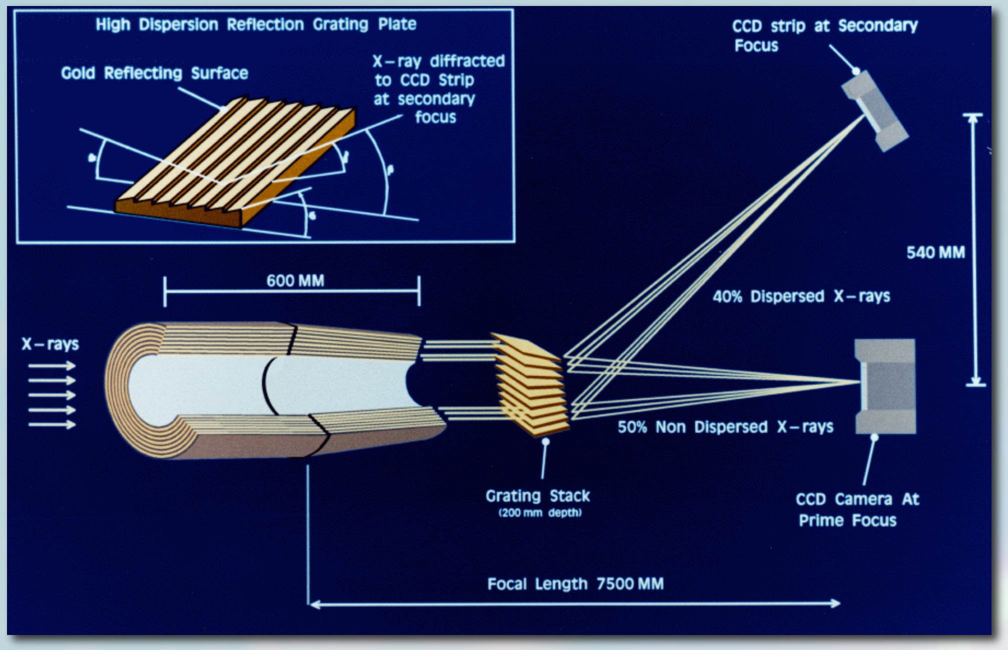
- Goals:
  - Study of fresh nucleosynthesis products (probe the progenitor star and its explosion)
  - Study the kinematics of the plasmas

    →explosion properties, CSM interaction
  - Study shock physics:
    - collisionless shock heating
    - shock may accelerate cosmic rays: back reaction on shock

- Challenges:
  - SNRs are extended sources
  - Current instruments (Chandra gratings/XMM RGS) are dispersive w.o. slit: spectra are blurred

- Future:
  - Non-dispersive spectrometers: Astro-H, IXO

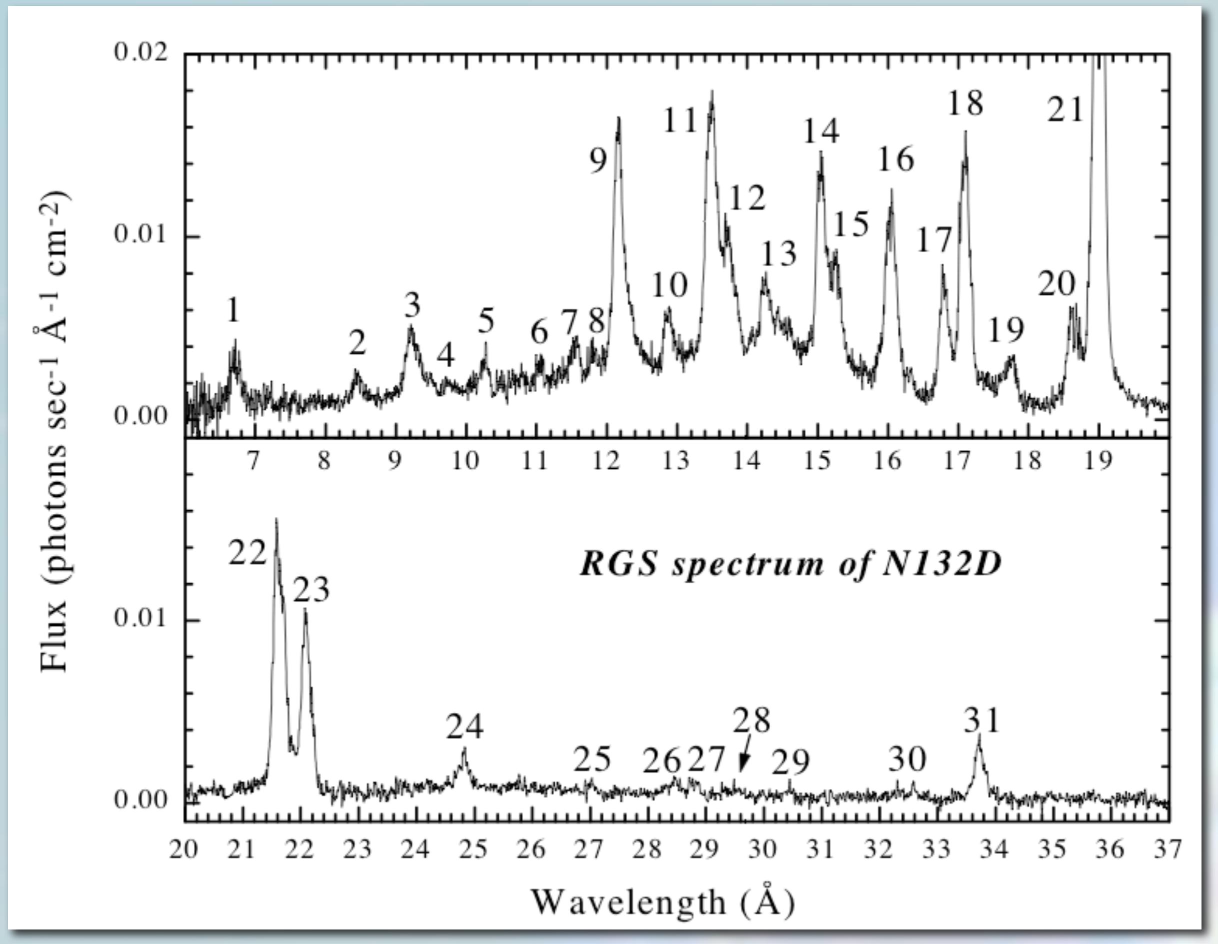
XMM vs Chandra gratings



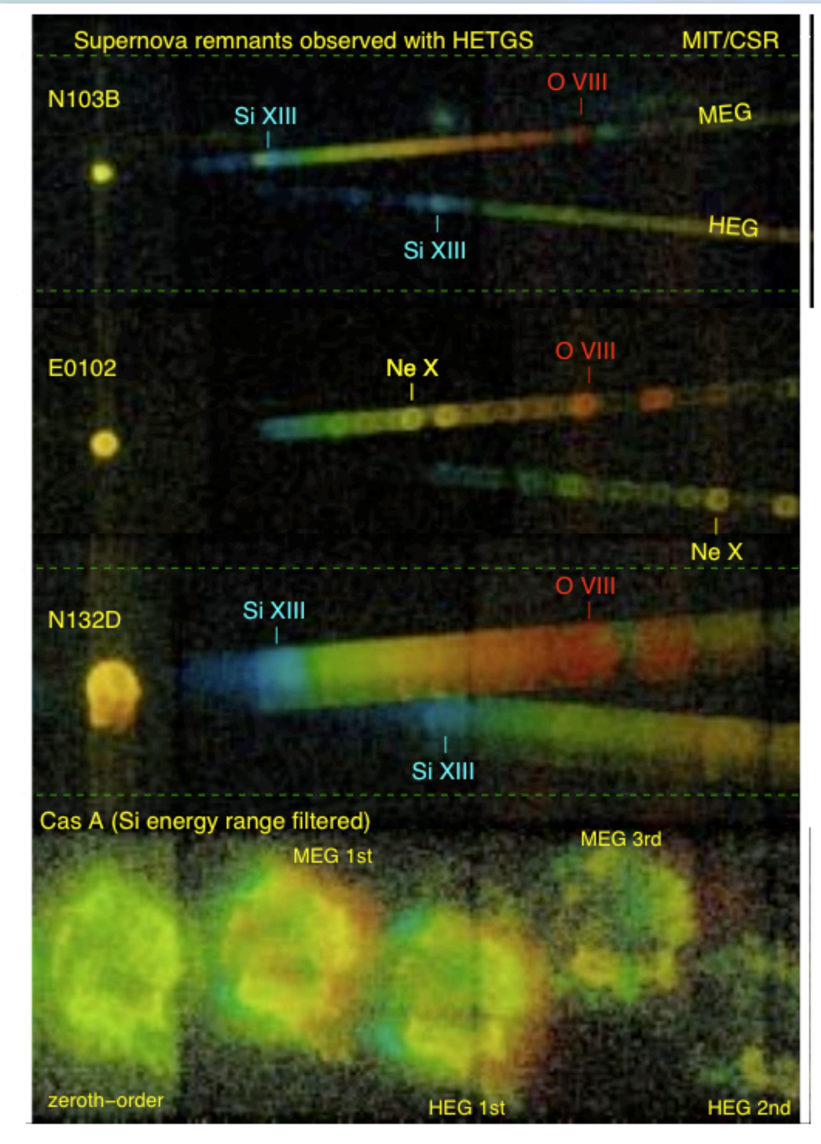
- Reflective gratings
- Large dispersion angle (2.3º)
- Image squeezed → less spectral blurring
- 1 arcmin →Δλ ≈ 0.1 Å
- Works well for **total** spectra of small SNRs (except cross disp.)

- Transmission gratings (L/M/HE)
- Small dispersion angle (fits on ACIS-S)
- Substantial blurring (particularly bad for Fe-L)
- For Fe-L poor spectra one uses **images** in single lines

Some RGS and ME/HETG spectra



Behar+ 01

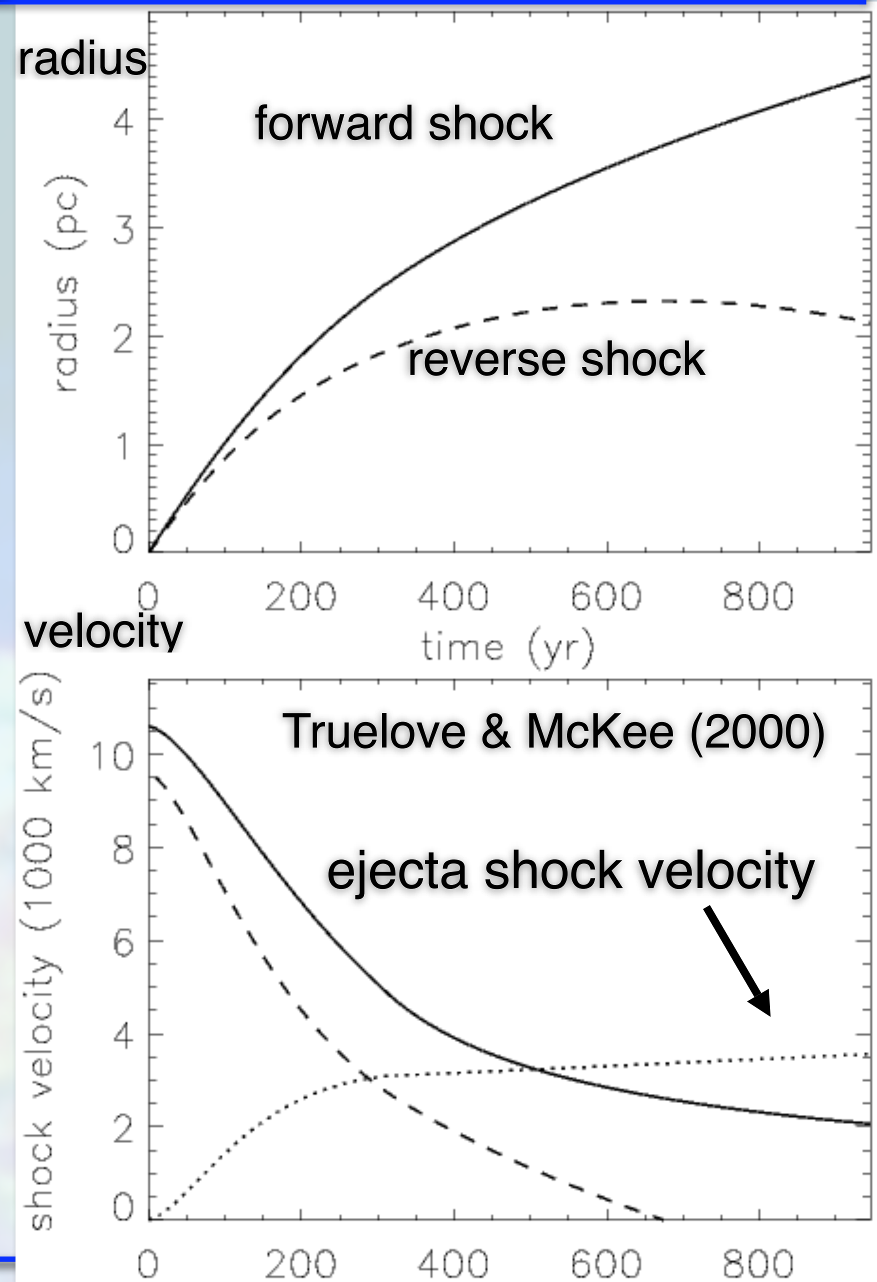


Dewey+ 02

Plasma heating in SNRs

Heating by two shocks:
1. forward shocks heating ISM/CSM
2. reverse shock heating ejecta

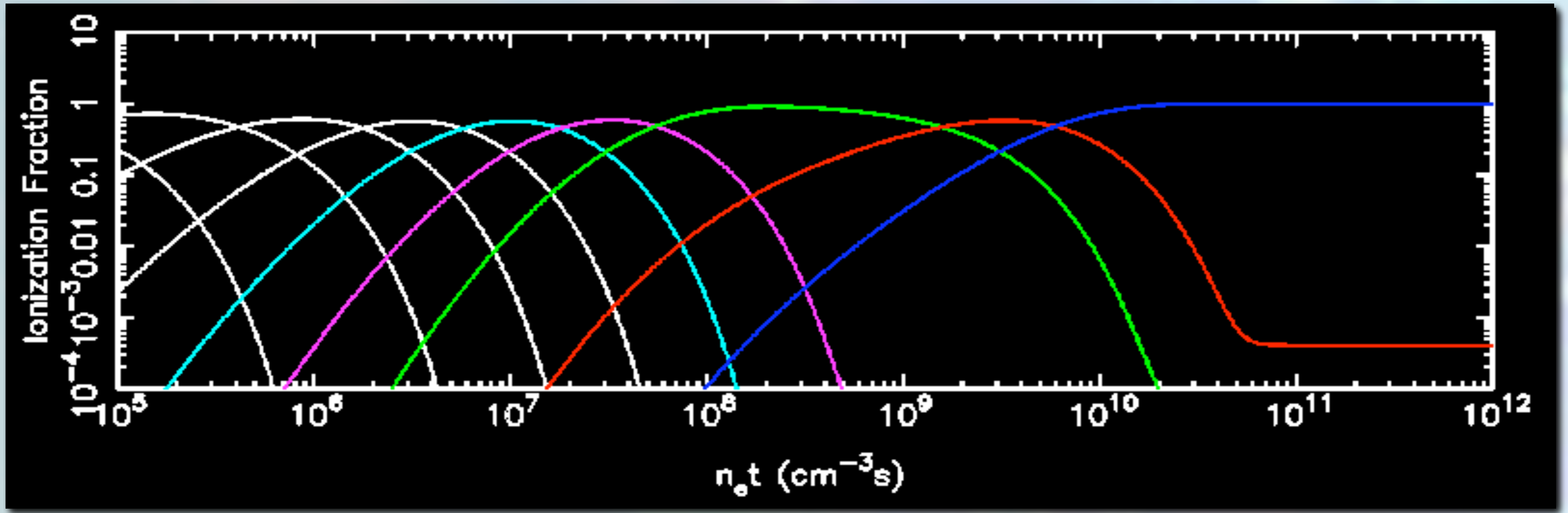
ISM/CSM very tenuous (~1 cm^{-3})
→ atomic collisions too slow to heat the shocked gas
→ heating occurs through plasma waves (collisionless)



Time Dependent Ionization

- SNR plasma's are tenuous -> collisions are rare
- SNRs are young -> number of collisions limited
- Ionization is out of equilibrium-> Non-Equilibrium Ionization (NEI)
- Example: For Fe^{+25} you need ~25 collisions: hard in SNRs!!

$$N_{coll} \propto \int dt\ n_{\mathrm{e}}\sigma_i(T)\sqrt{kT} \propto\sim n_{\mathrm{e}}t$$



Shock heating

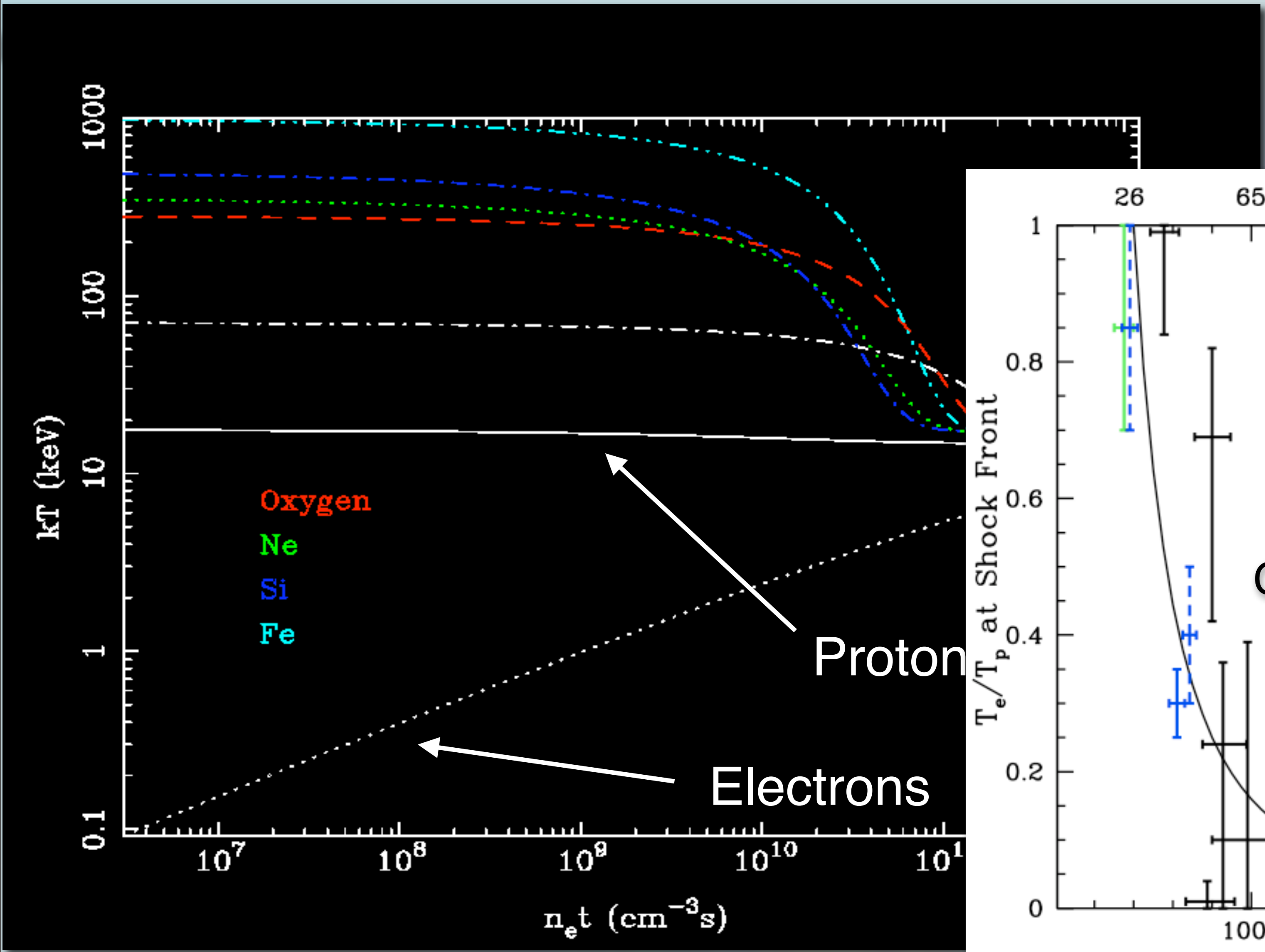
- Expected temperature follows from flux conservation laws: mass, momentum (pressure), energy
- Relations express thermodynamics: microscopic processes not important, nor shock structure or width
- For High Mach Number shocks the temperature is (γ=5/3):

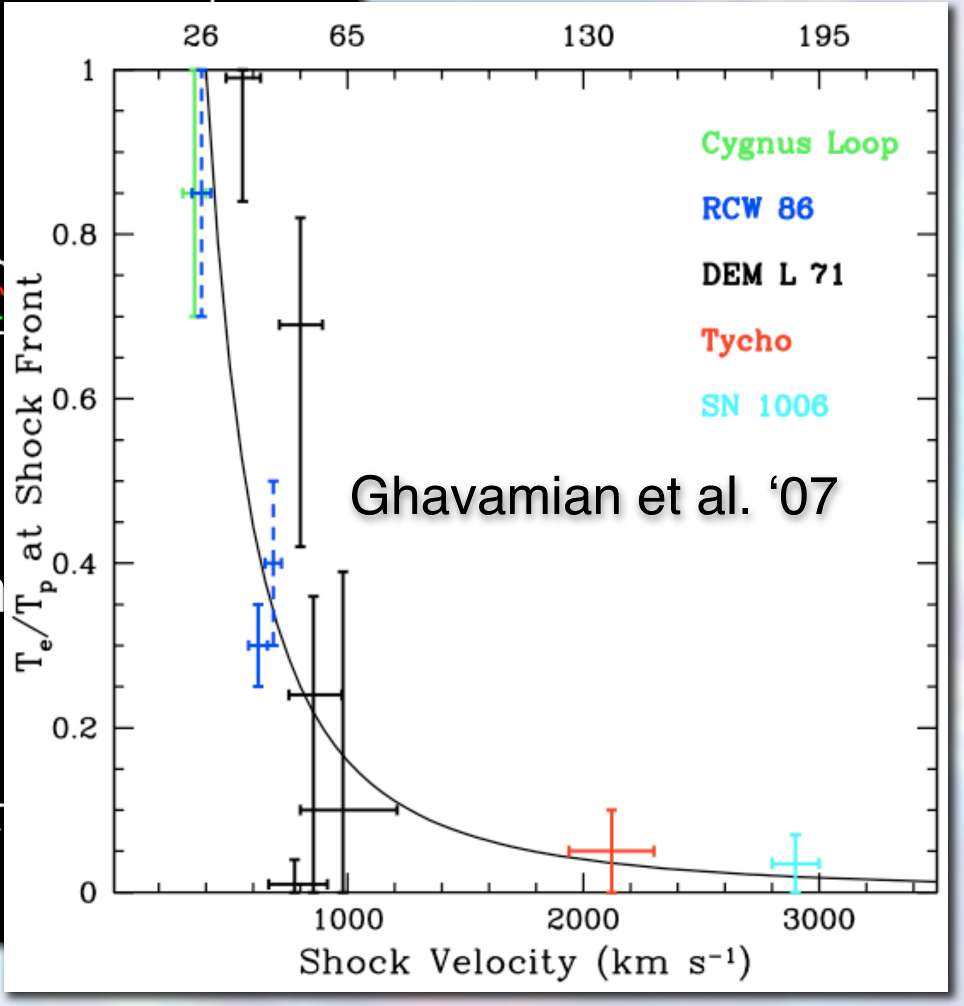
$$kT = 2\frac{\gamma - 1}{(\gamma + 1)^2}\mu m_{\rm p} V_s^2 = \frac{3}{16}\mu m_{\rm p} V_s^2$$

NB:

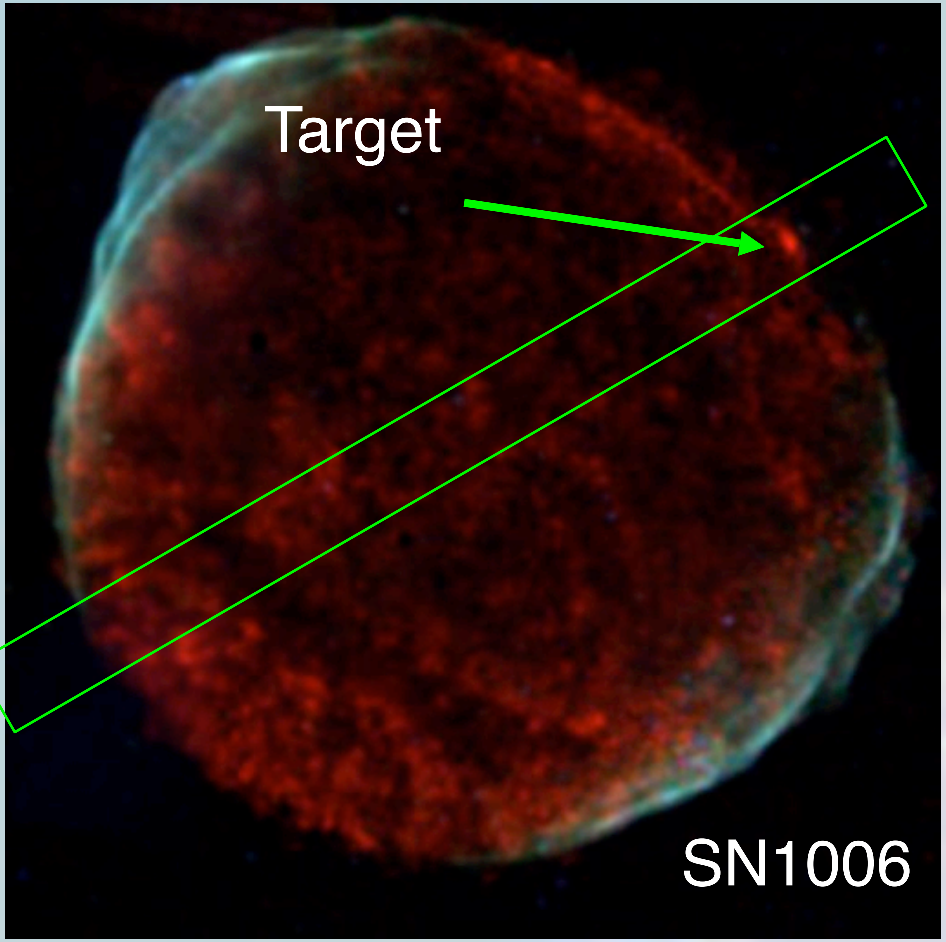
- Different particles can have different temperatures
- Equation does not take into account pressure/energy in other components (cosmic-rays, magnetic fields), nor energy losses

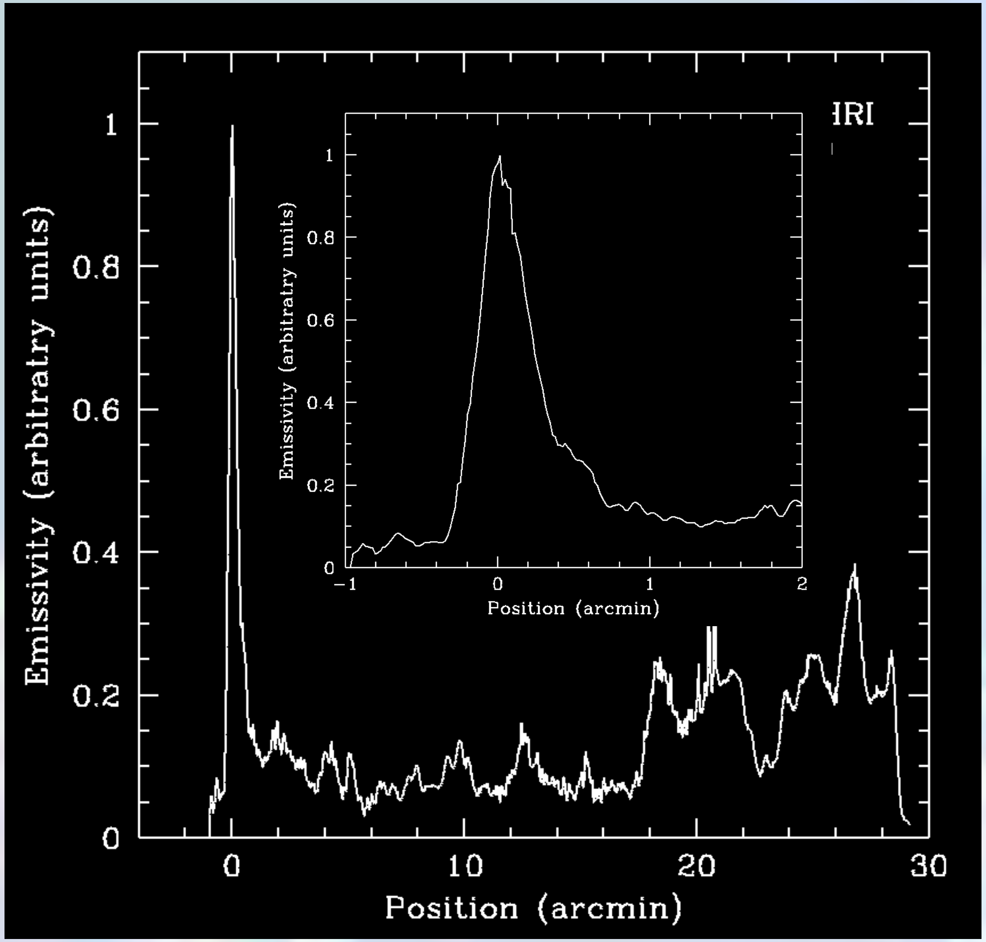
Temperature Non-equilibration





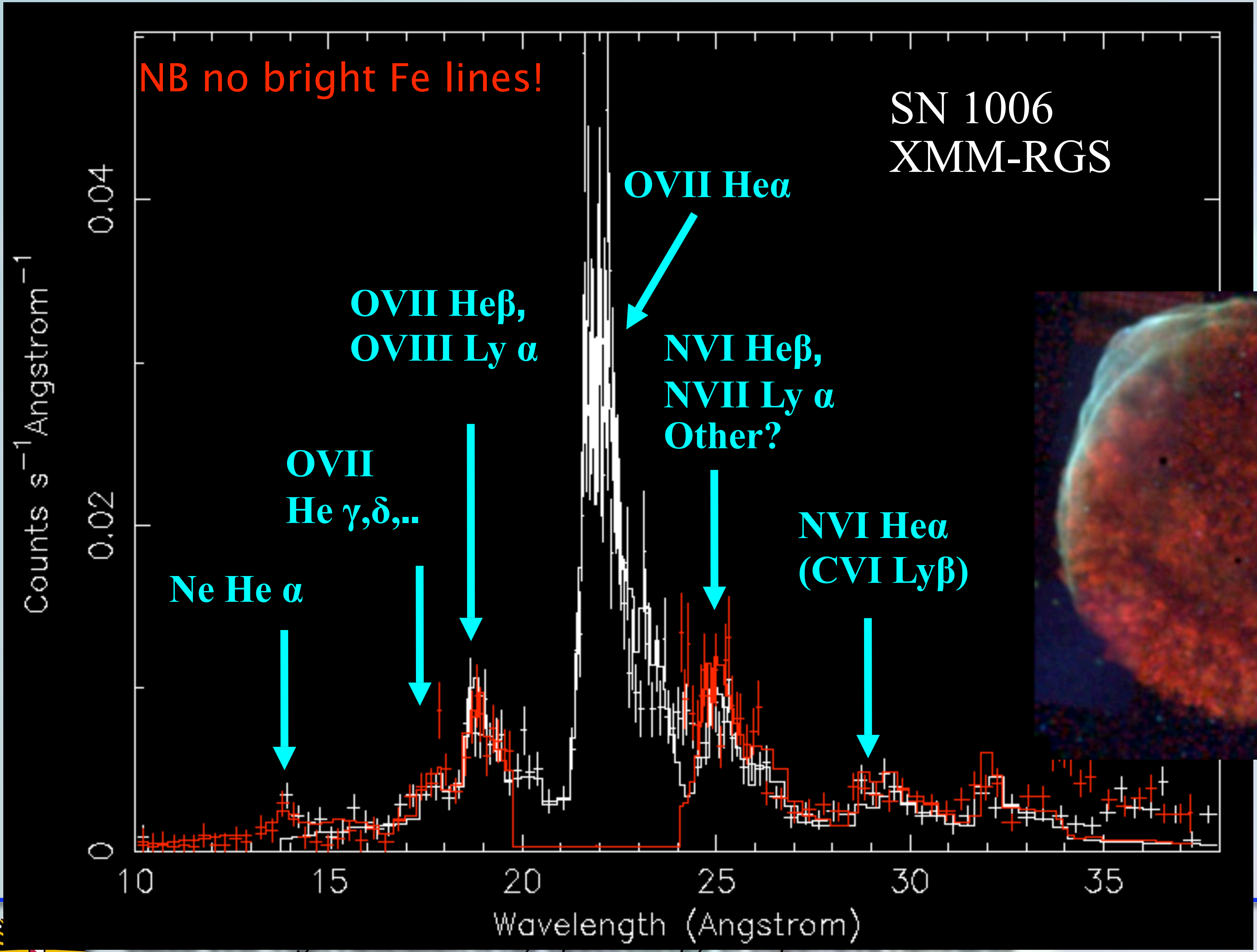
A bright knot in SN1006

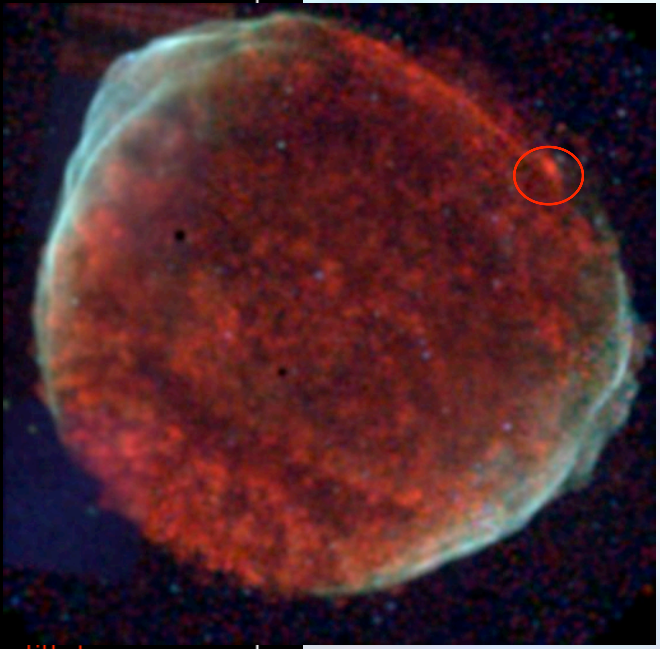




Knot size ~ 1 arcmin (0.4 arcmin FWHM)
Spectral resolution for bright lines
e.g OVII (~22Å): ~ 1/170

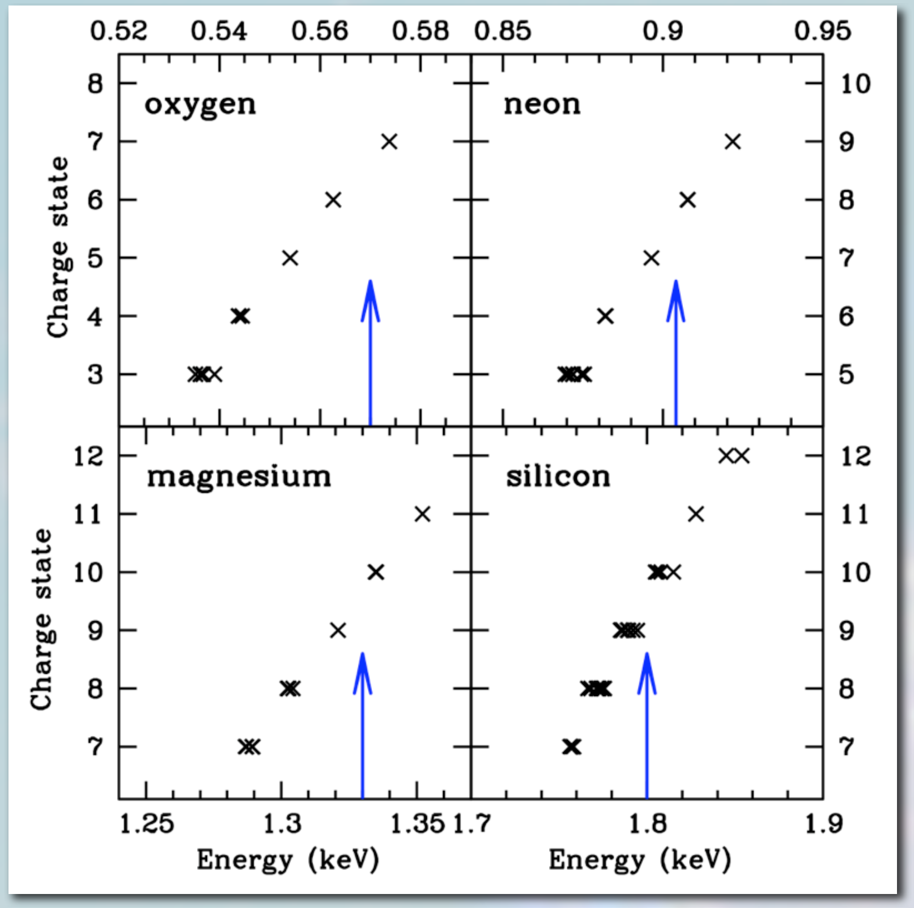
RGS spectrum of SN1006

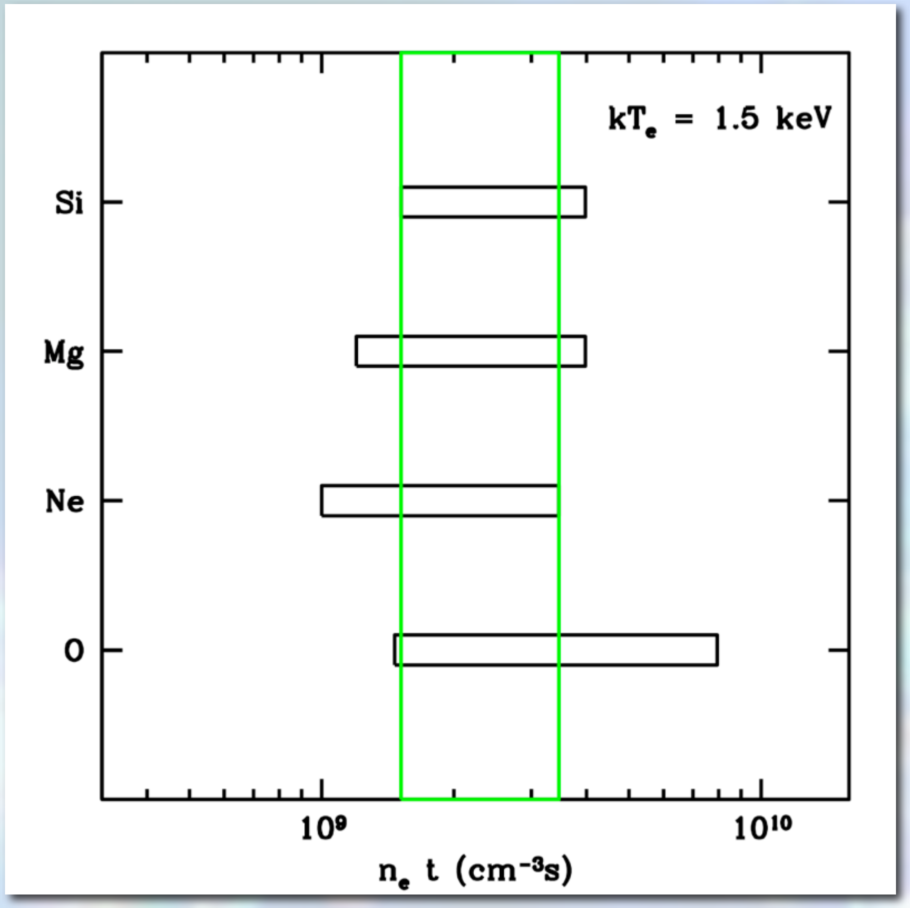




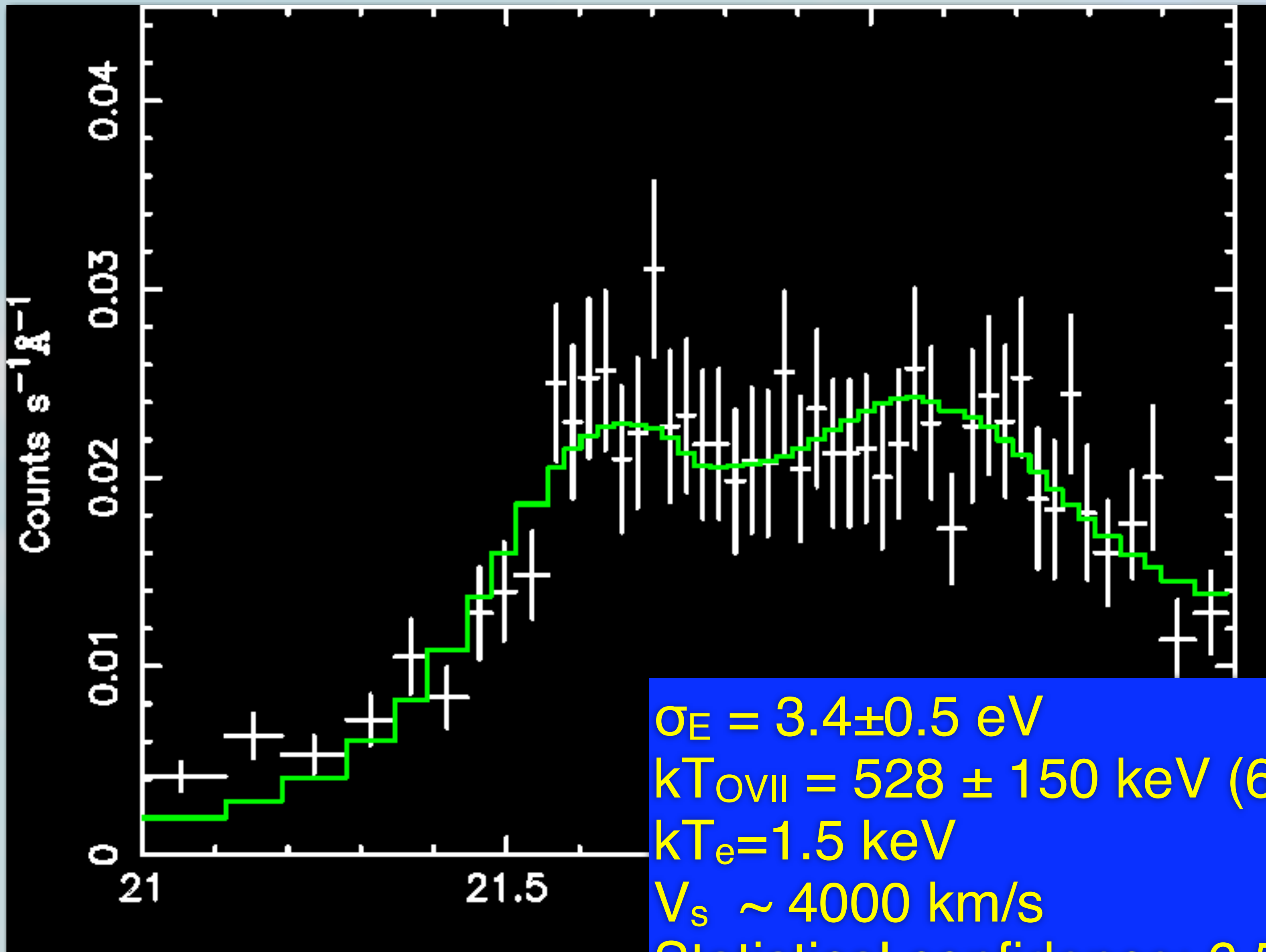
Vink+ 03

Constraining $n_e t$ SN1006 knot



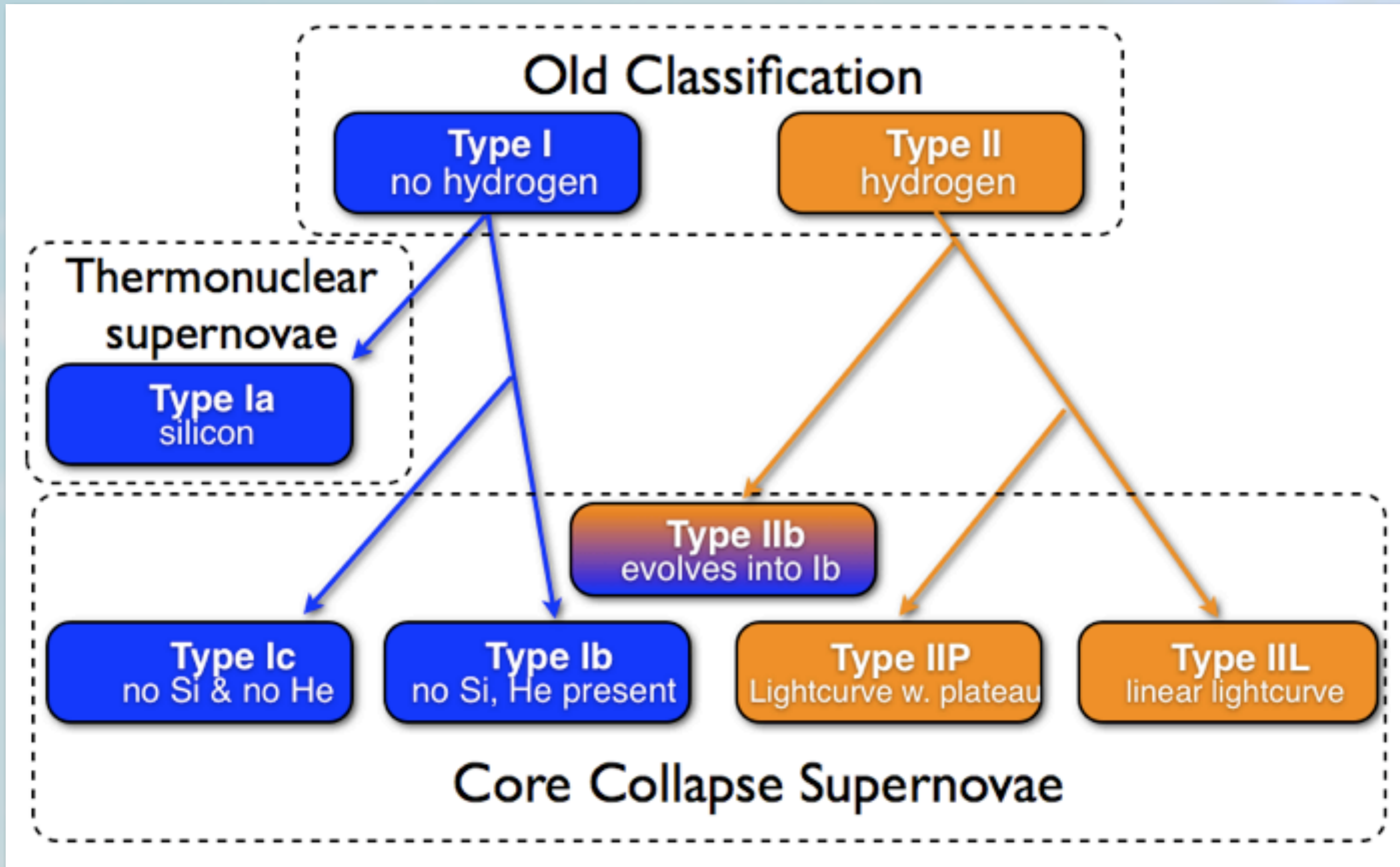


The OVII Thermal Broadening

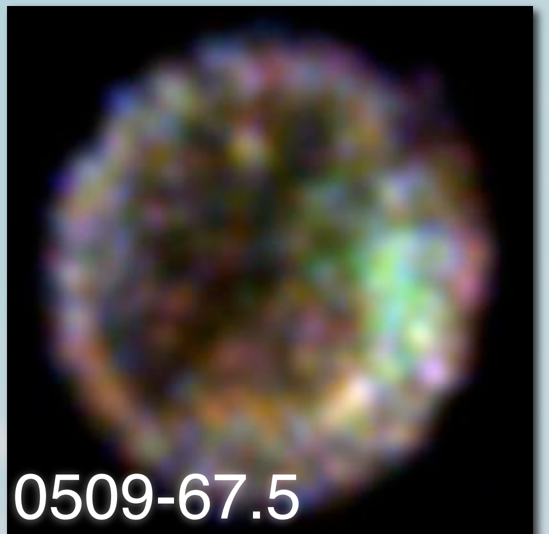


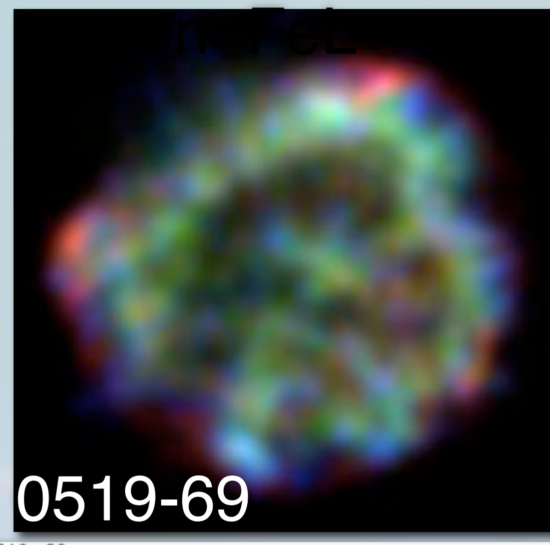
σ_E = 3.4±0.5 eV
kT_{OVII} = 528 ± 150 keV (6x10^9 K)
kT_e=1.5 keV
V_s ~ 4000 km/s
Statistical confidence: 6.5–9.8 σ

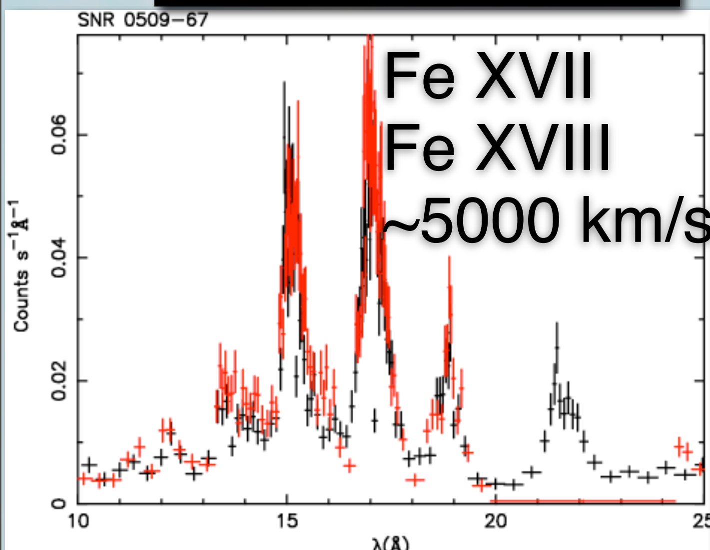
Supernova Types

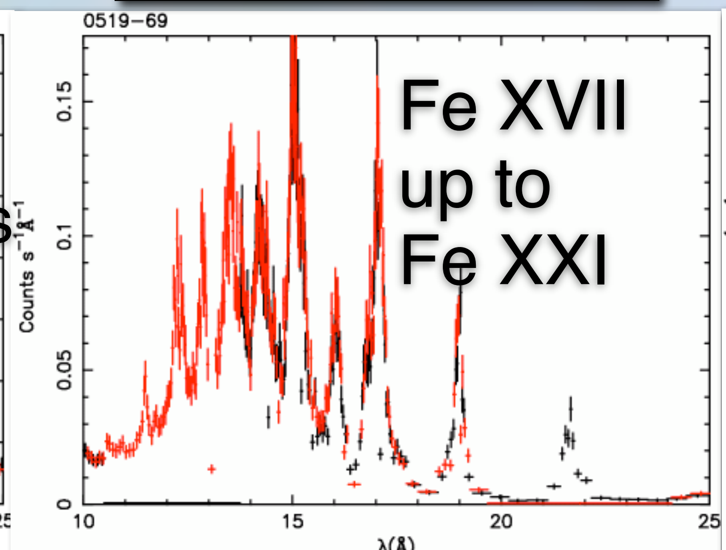


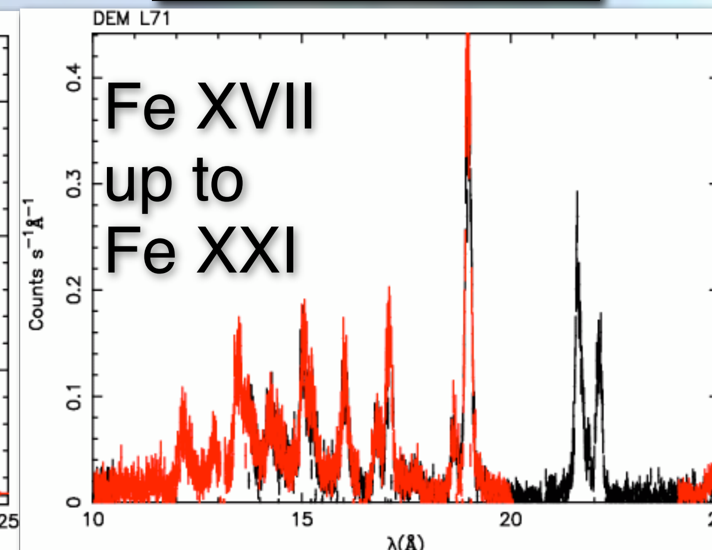
LMC/Ia SNRs: an age sequence









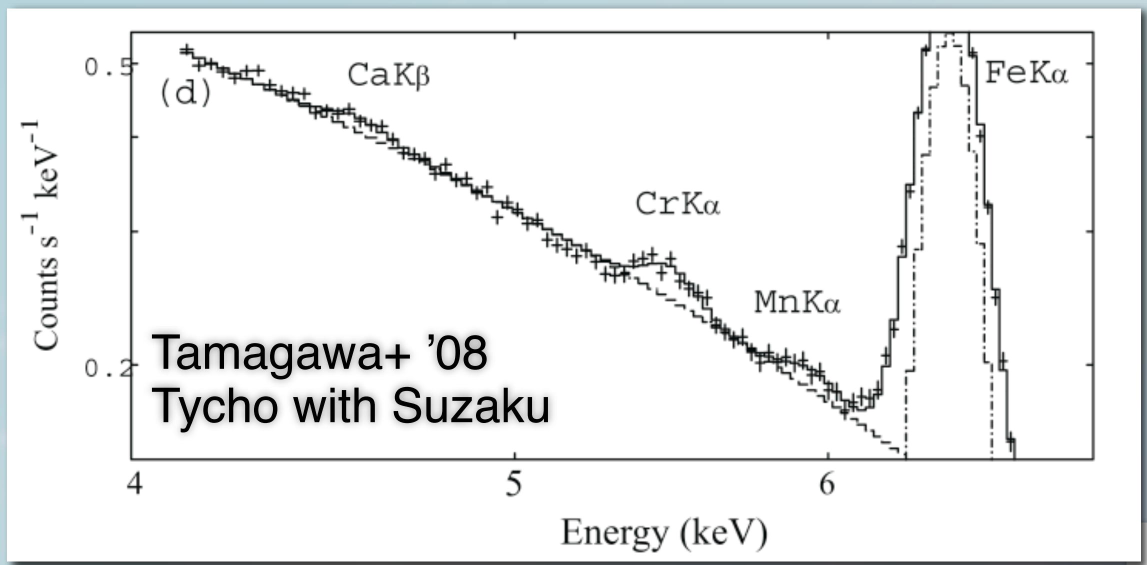


Warren et al. 2004
Kosenko, et al. 2008 (see Talk)

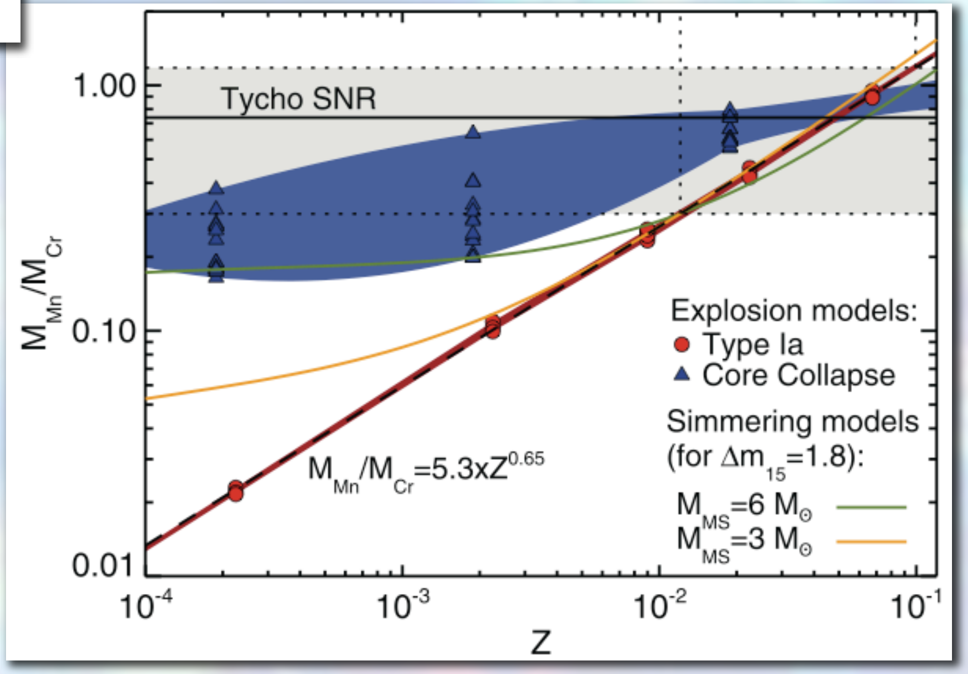
Kosenko, et al. in prep.

Rakowski et al. 2003
van der Heyden et al. 2003

Not HiRes, but interesting anyway

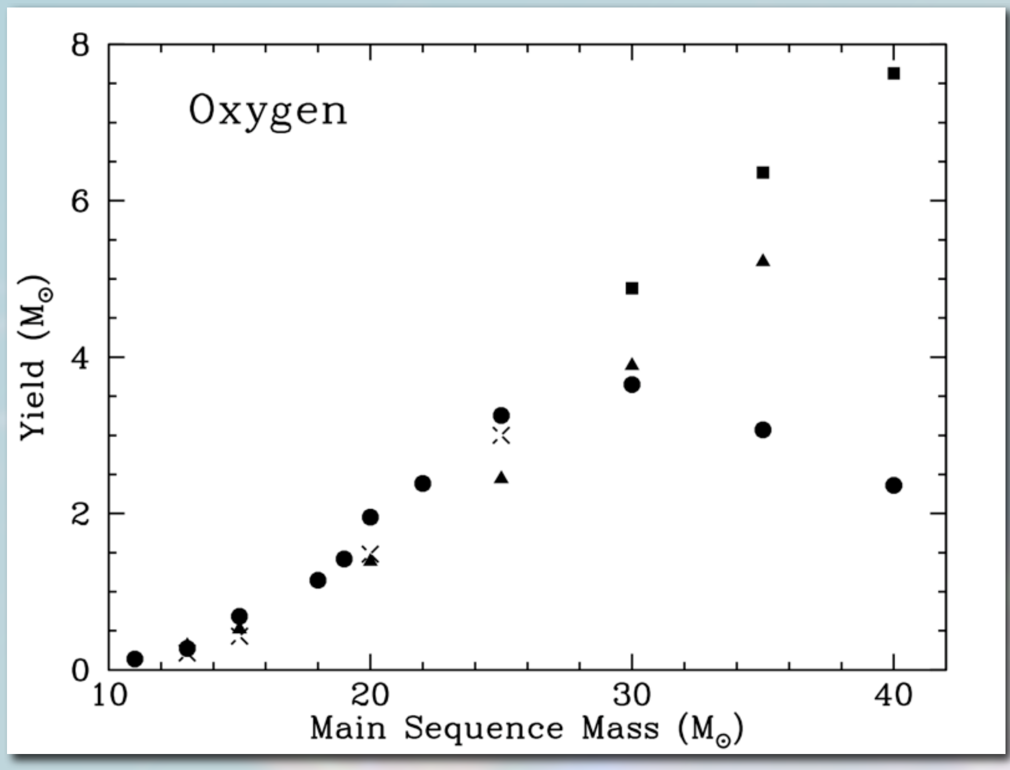


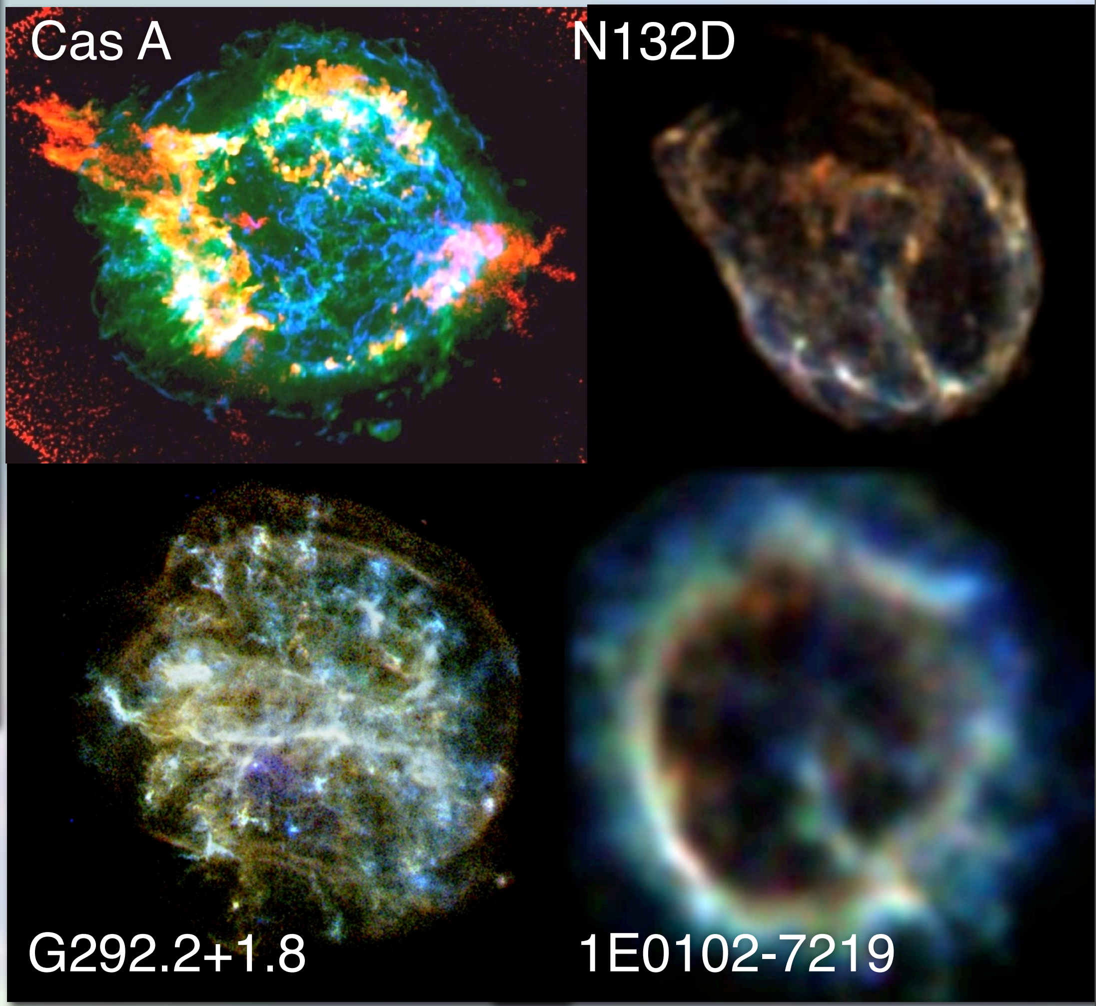
- Several SNRs show evidence for Mn and Cr line emission
- Mn/Cr ratio can constrain the progenitor metallicity (Badenes+ 08)



Badenes+ '08

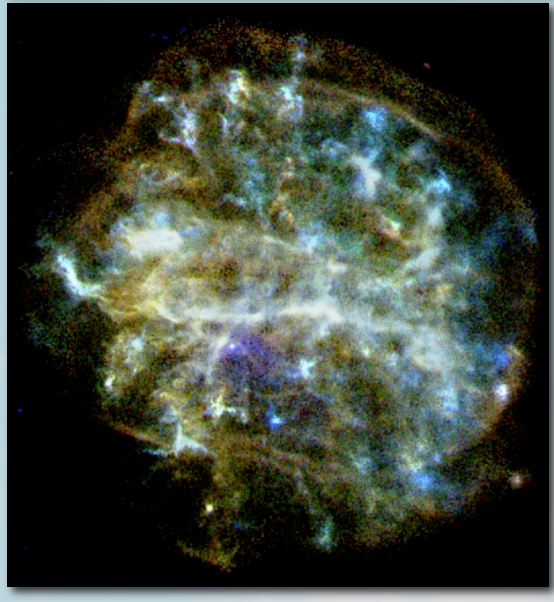
Oxygen-rich SNRs

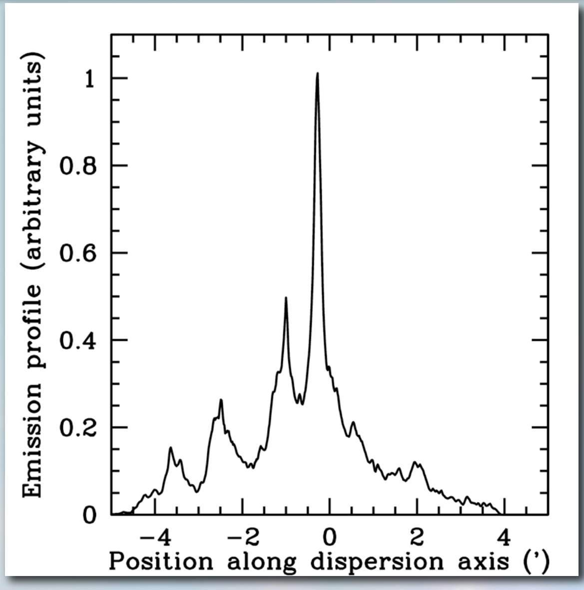


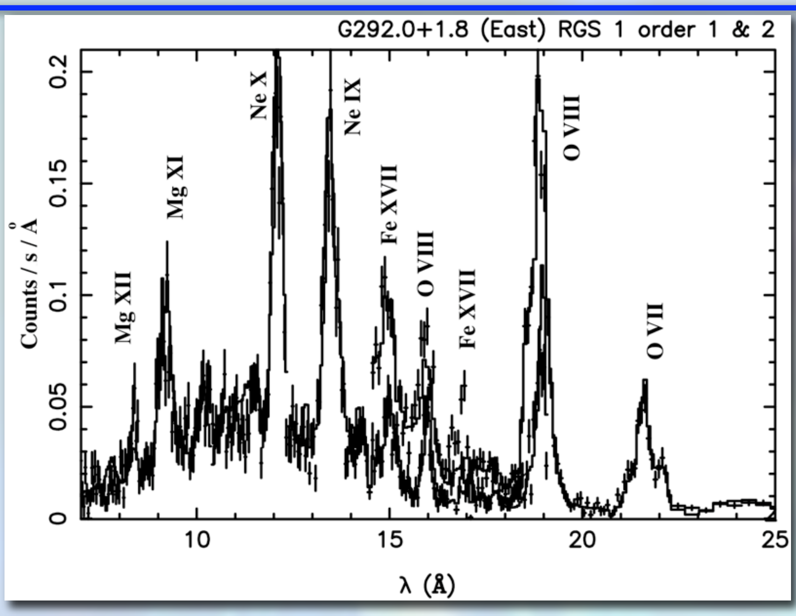


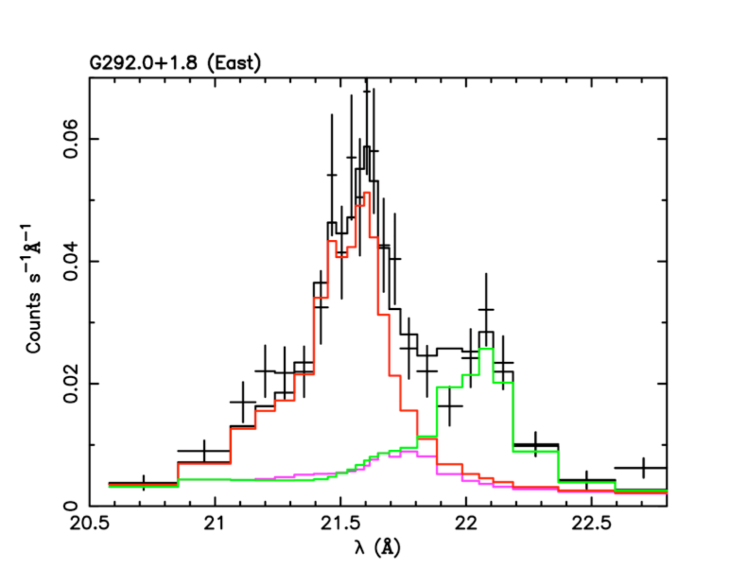
- M_O correlates with MS mass
- Several O-rich SNRs known
- For several, but not all, show evidence for neutron stars (BHs?)

G292.2+1.8





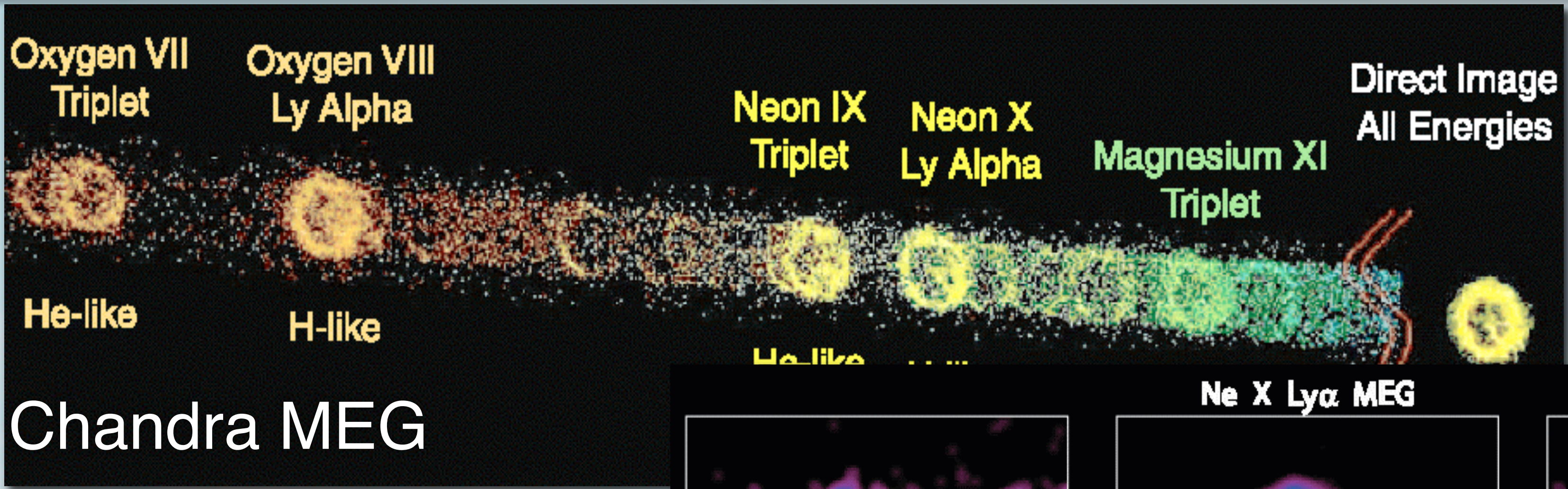




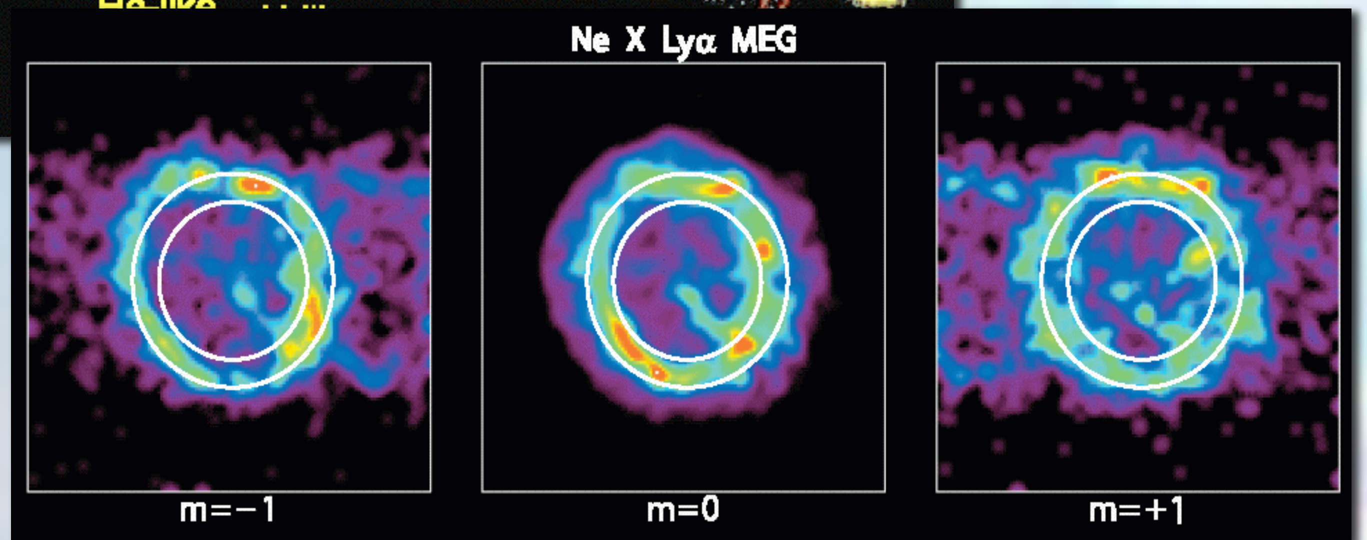
- O VII emission easily missed in CCD spectra
- Presence of cooler (0.3 keV) component
- Needs still further analysis (kinematics)
- G-ratio=0.46-0.91
  (SPEX: kT=0.3-05keV)

Vink+ '04

Spectroscopy of 1E0101.2-7219

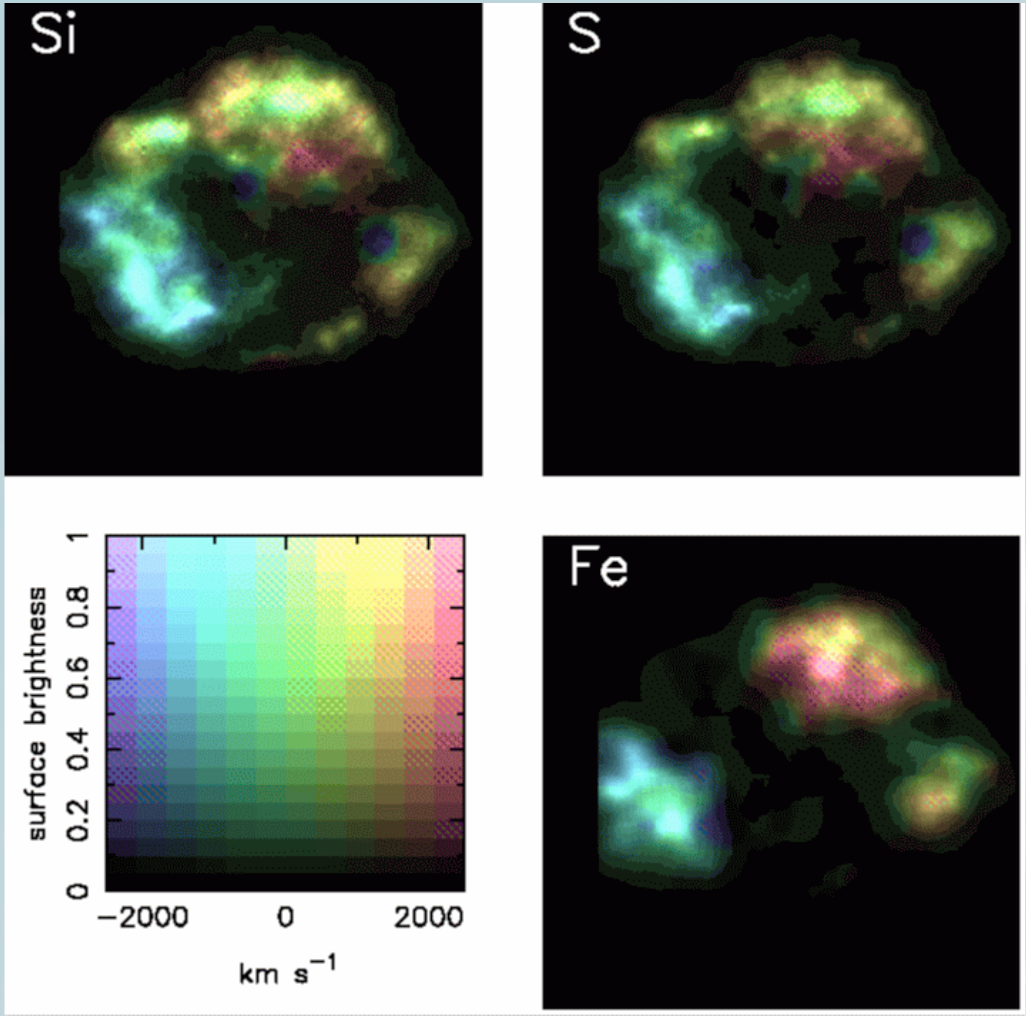


Flanagan et al. '04



- SMC remnant
- Oxygen rich (6 M_{sun}): i.e. massive progenitor (~35 M_{sun})
- Difference +/- orders (wavelengths are mirrored, images not)
  → aspherical doppler shifts
- Expanding **donut** rather than sphere?

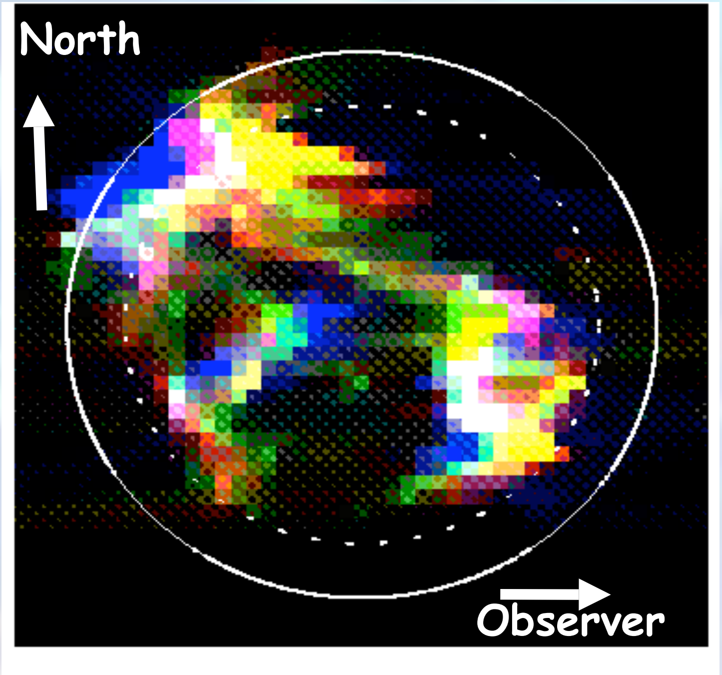
Kinematics of Cas A



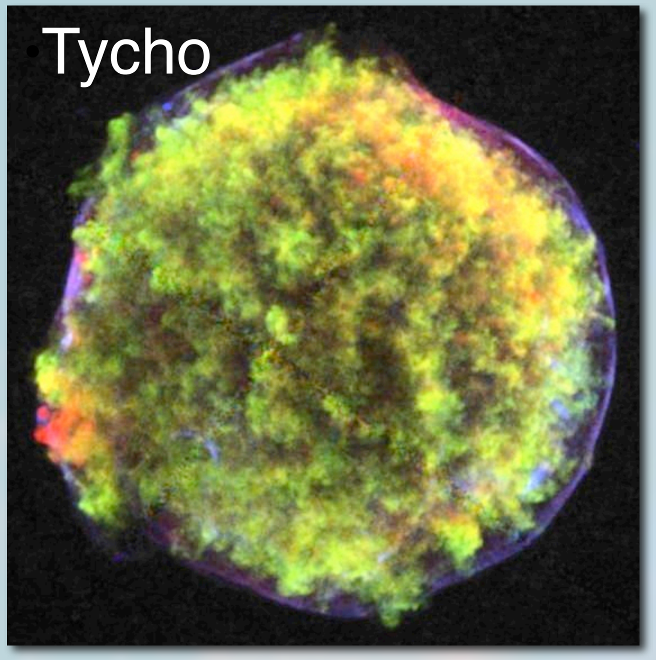
- XMM Doppler maps
- Asymmetric velocity profile: **donut shape**
- Velocities up to 2600 km/s
- Fe (deep layer) has overturned Si (both spatially and in Doppler space)

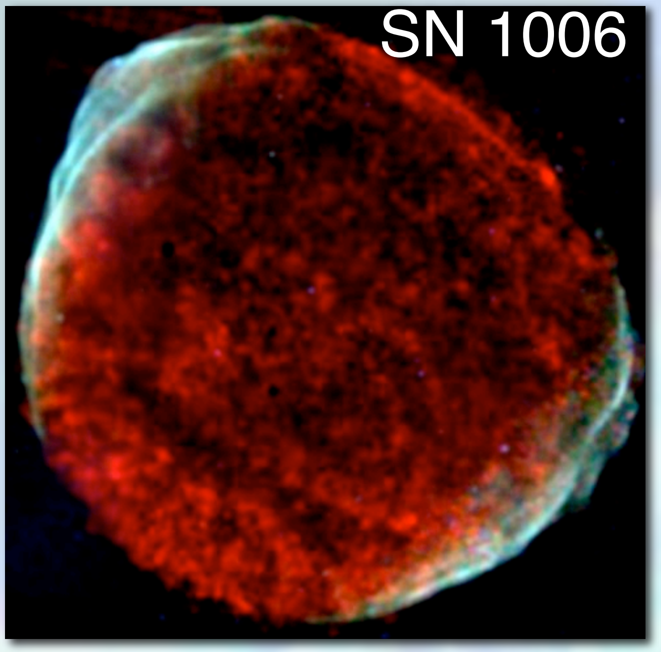
Willingale+ 02
C.f. Markert+ '83

Reconstructed "side view"



X-ray synchrotron emission





- All historical shell SNRs emit X-ray synchrotron emission (1st detected SN1006, Koyama+ '95)
- Implies electron cosmic ray energies ~ 10-100 TeV
- Requires fast shocks, efficient acceleration
- Emission regions often narrow (few arcsec)
- Implied magnetic fields > 30 μG (more than shocked ISM)

Effects of Cosmic Rays

- Efficient cosmic ray acceleration has two potential effects:
  - the equation of state change (relativistic particles $\gamma=4/3$)
  - cosmic rays may escape -> energy is lost

- Compression ratio going $\gamma=5/3$ to $\gamma=4/3$

$$\chi = \frac{\gamma+1}{\gamma-1} = 4 \rightarrow \chi = 7$$

- We have to intoduce two additional parameters, relating to the fraction and escape of cosmic rays:

$$w \equiv \frac{P_{CR}}{P_{CR}+P_{thermal}}, \quad \epsilon \equiv \frac{F_{CR}}{\frac{1}{2}\rho_0 V_S^3}$$

Effect CRs on Temperature

- Recall the equation for normal high Mach number shocks:

$$kT = 2\frac{\gamma - 1}{(\gamma+1)^2}\mu m_{\rm p} V_s^2 = \frac{3}{16}\mu m_{\rm p} V_s^2$$

- Including cosmic rays this becomes:

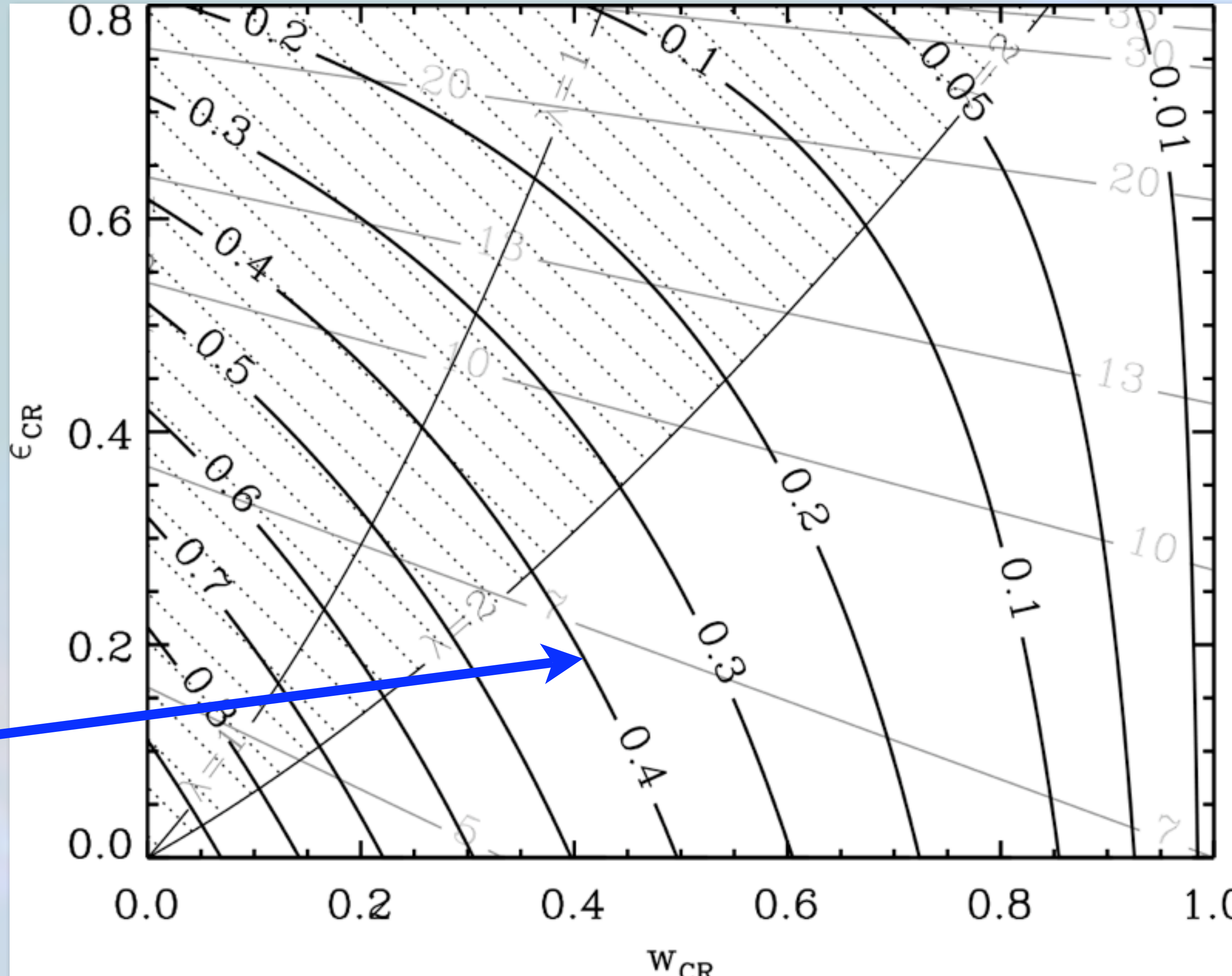
$$kT = (1-w)\frac{1}{\chi}\Big(1 - \frac{1}{\chi}\Big)\mu m_{\rm p} V_s^2$$

- NB X depends on w-ϵ (e.g. Helder+ 09 submitted)

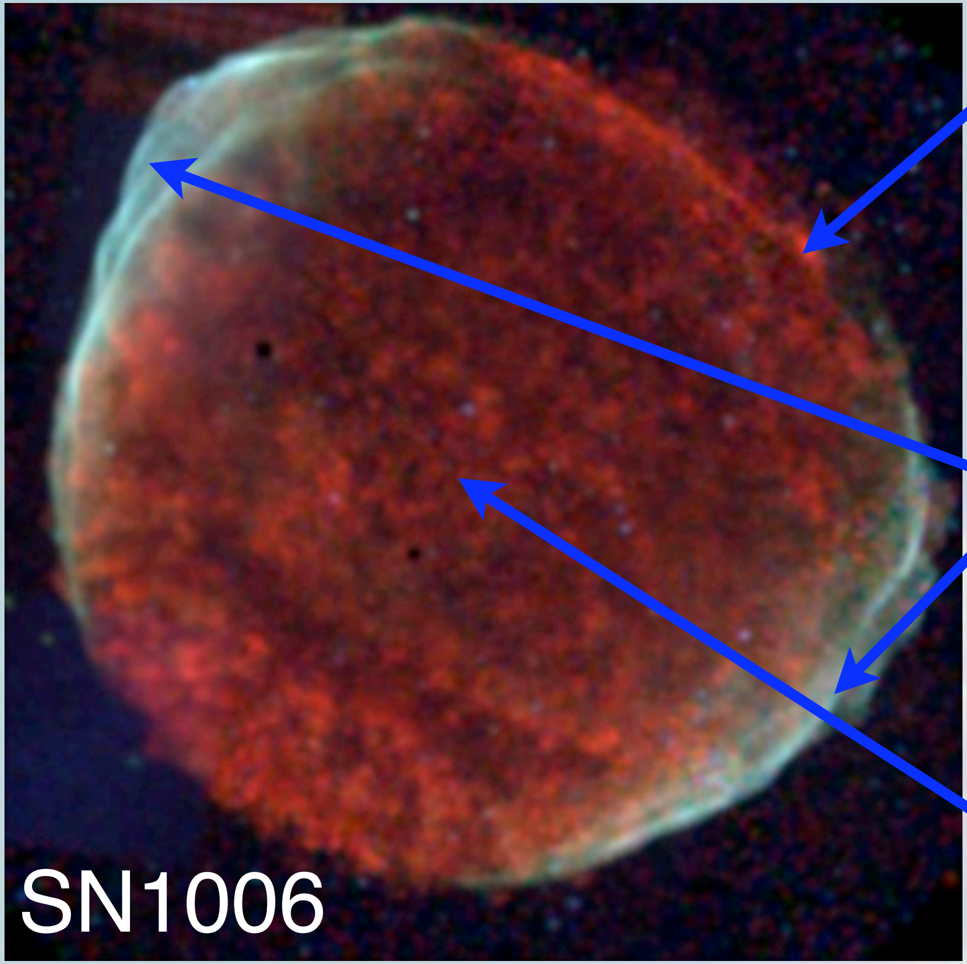
kT decrease in w-ϵ plane

Light gray: compression ratio

Correction factor on kT wrt to no cosmic rays



A project for Astro-H/IXO



Line shape dominated by thermal broadening

Dominated by thermal broadening?
But presence of cosmic rays:
lower ion temperatures?

Dominated by bulk velocities
2 peaks: separation ΔV~9000 km/s
(ΔE= 17 eV for OVII Heα)

Summary

- High Resolution X-ray spectroscopy offers many possibilities:
  - More accurate abundance determination also of less abundant elements
  - Accurate kinematics → explosion properties, assymetries
  - Measurement of ion temperatures at rims
  - Measuring back reaction cosmic ray acceleration on plasma

- High resolution spectroscopy currently challenging:
  - Object angular size blurs spectral information
  - Use is limited to small angular size (LMC SNRs) or using “knots” in bigger objects
  - Some successes (SMC/LMC SNRs, SN1006, Cas A)
    → talks by Dan Dewey, Frank Haberl
  - Need calorimeters for extended objects like SNRs
  - Full potential has to await Astro-H, IXO