Diagnostic Power in the *“Low-Resolution”* Spectroscopy of Non-Equilibrium Plasmas

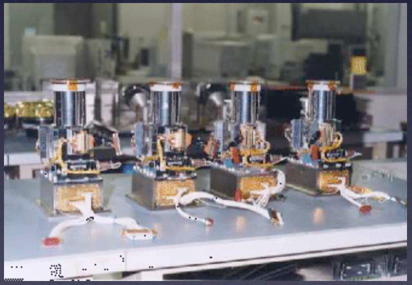
Hiroya Yamaguchi (NASA/GSFC, UMD)

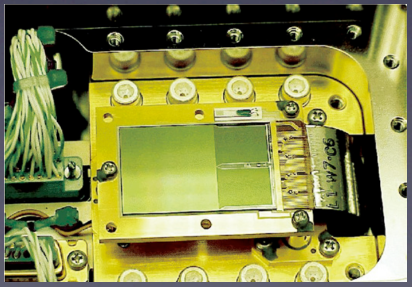
Apologies:

- I have little experience of “high-resolution spectroscopy” (i.e., grating).
- I hate to show lots of “fake data” of future missions (i.e., calorimeter).

So I’m going to ...,

present real data from the X-ray CCD *Suzaku*/XIS with ~~low~~ moderate energy resolution ($E/\Delta E \sim 40$).

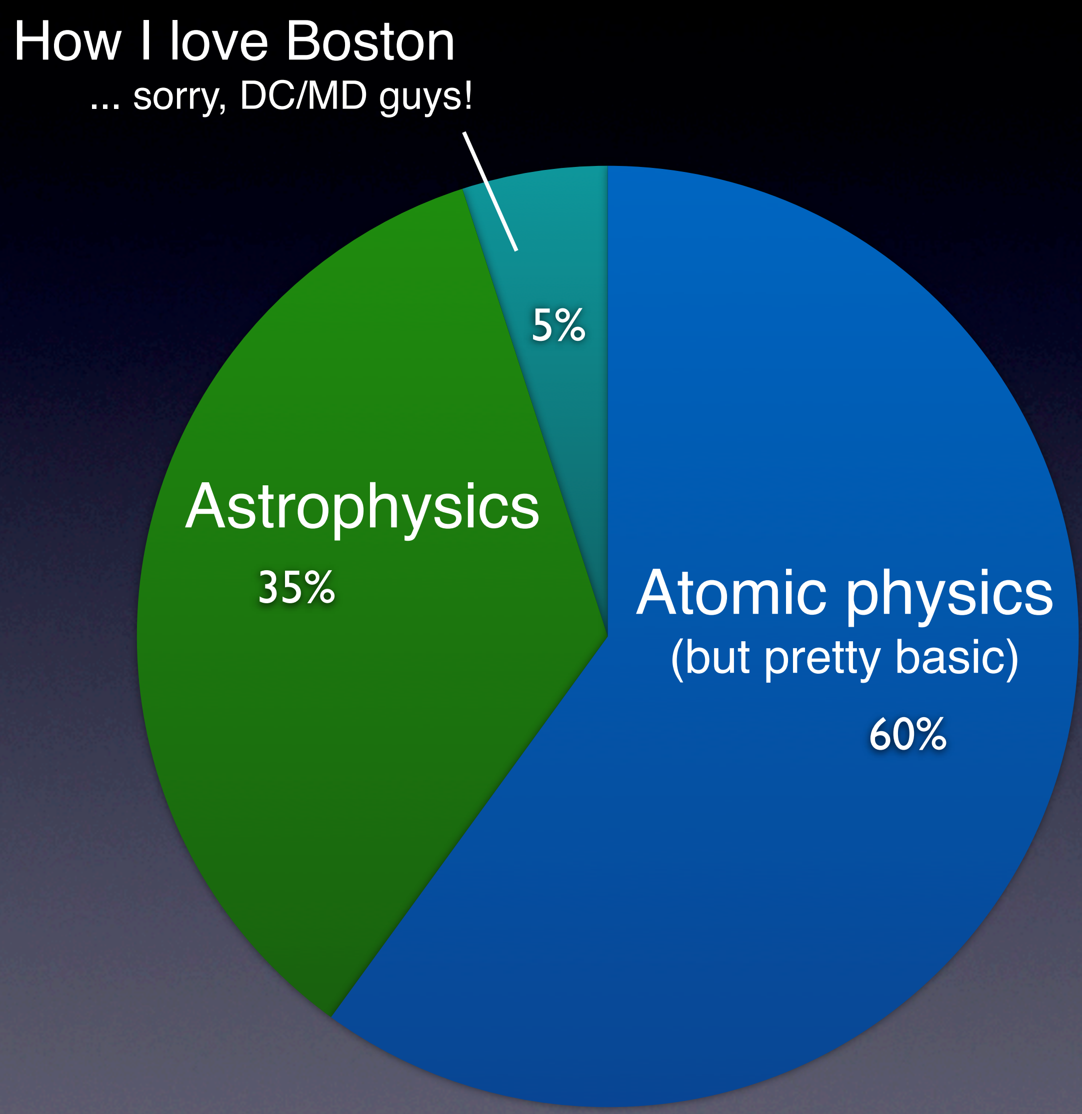




In order to convince you that:

- There are a number of powerful diagnostics even in the moderate-energy spectroscopy.
- Knowledge of physics behind radiation processes helps get an unexpected, exciting results.

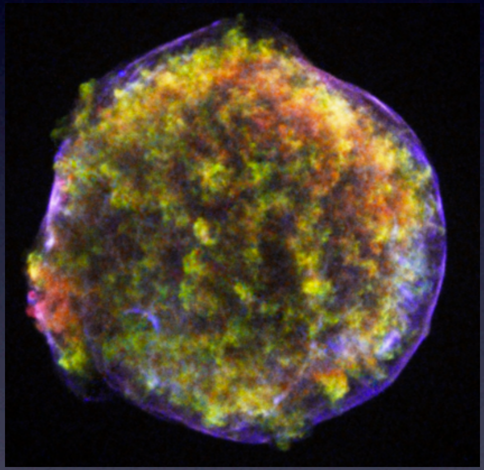
Today's Talk


How I love Boston
... sorry, DC/MD guys!
5%
Astrophysics
35%
Atomic physics
(but pretty basic)
60%

Scientific Motivation

Supernova Remnants (SNRs, especially of Type Ia):
to solve progenitor's evolution and explosion mechanism.

Cliche: "X-ray observation of SNRs is best suitable for studying SNe."
... Is it true?



In principle, TRUE:
SNRs allow us to directly measure chemical composition and distribution.

~~In practice, NOT TRUE:
Plasma is in non-equilibrium ionization (NEI), making the abundance measurement very difficult.~~

Thanks to the NEI,

- We can understand supernova physics in detail.
- We can discover new interesting phenomena.

CIE? NEI? ("Textbook"-ish explanation)

Definition:

$$Fe^{z+} \rightleftharpoons Fe^{(z+1)+} + e^{-}$$

CIE: Ionization rate = Recombination rate (for all ions)
NEI: Ionization rate ≠ Recombination rate (for any ion)

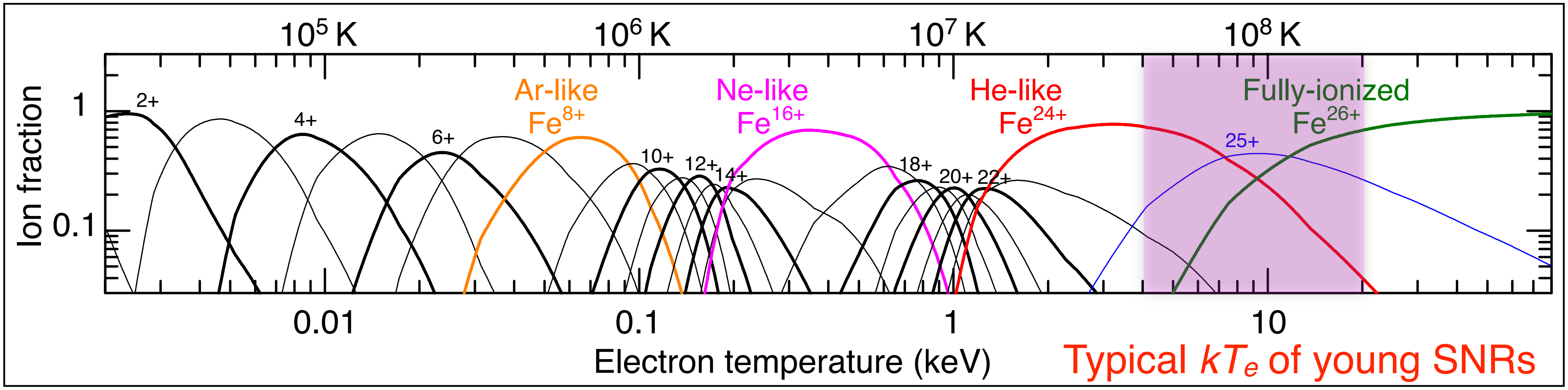
Convention among plasma physicists:

CIE: Electron temperature = Ionization temperature
NEI: Electron temperature ≠ Ionization temperature

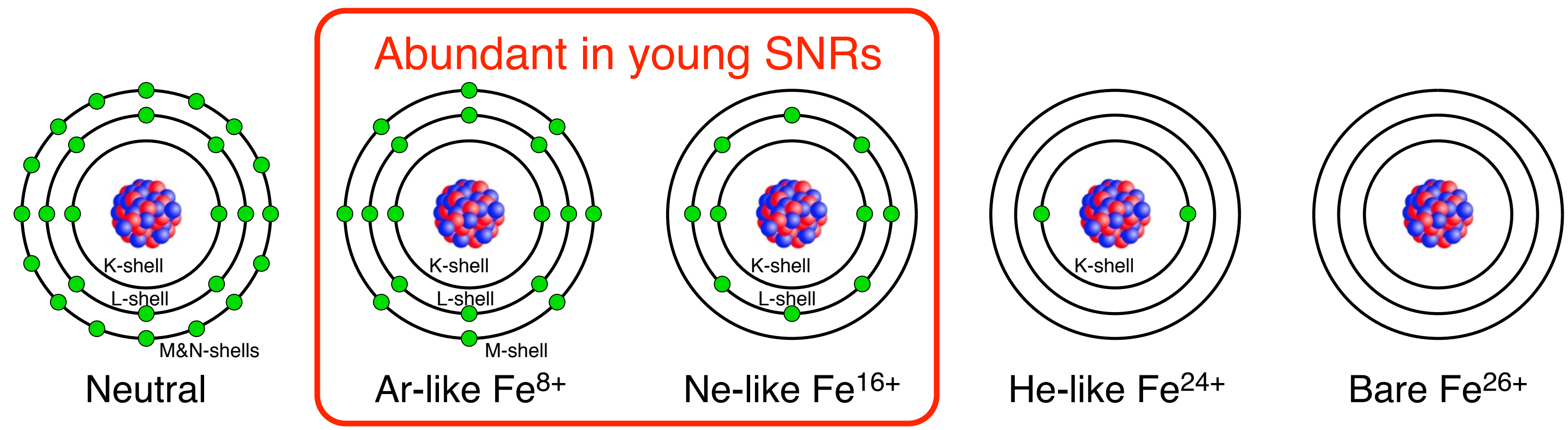
What's the major difference between CIE and NEI
<u>in terms of atomic processes and resulting spectral features</u>?

CIE? NEI? (Atomic-physics point of view)

Ionization & recombination rates depend on electron temperature.
➔ Ion fraction in a CIE plasma is uniquely determined by kT_e.



Potential Energy .... M shell .... L shell .... K shell



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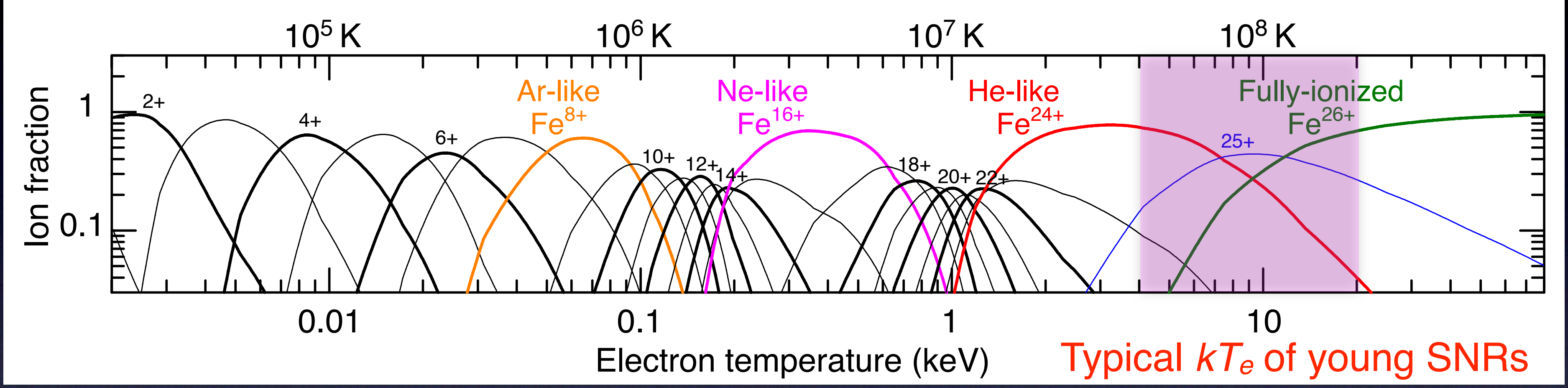
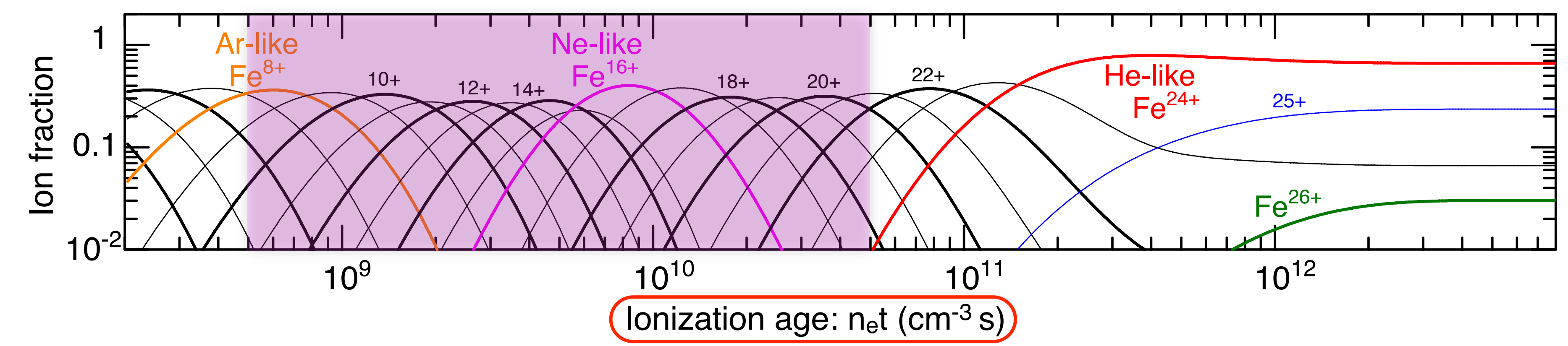




Ionization speed depends on the electron density
To reach CIE, $n_e t \sim 10^{12}$ cm^{-3} s ➔ 3×10^4 $(n_e / 1$ cm$^{-3})^{-1}$ yr

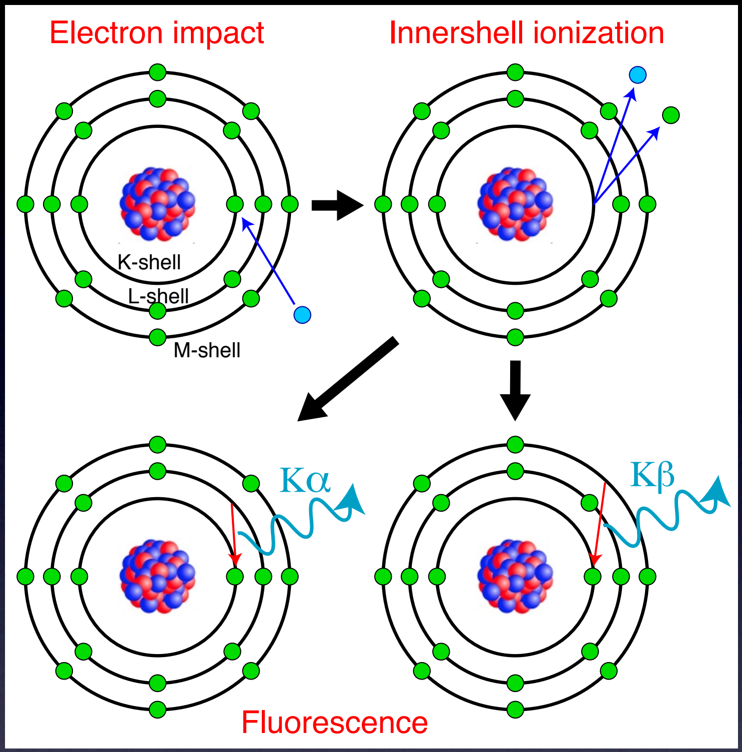
Characteristic Atomic Processes in NEI

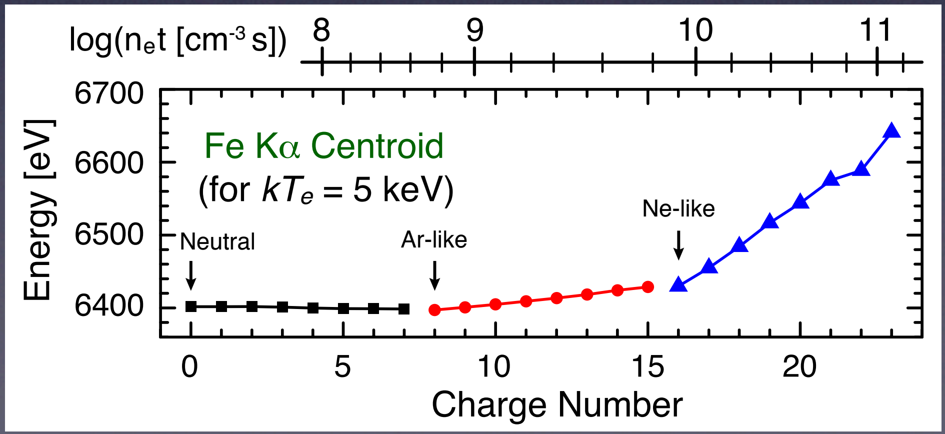
In an NEI plasma, (i) hot free electrons with the energy higher than the K-shell potential, and (ii) low-ionized ions with a lot of L-shell and M-shell electrons co-exist.

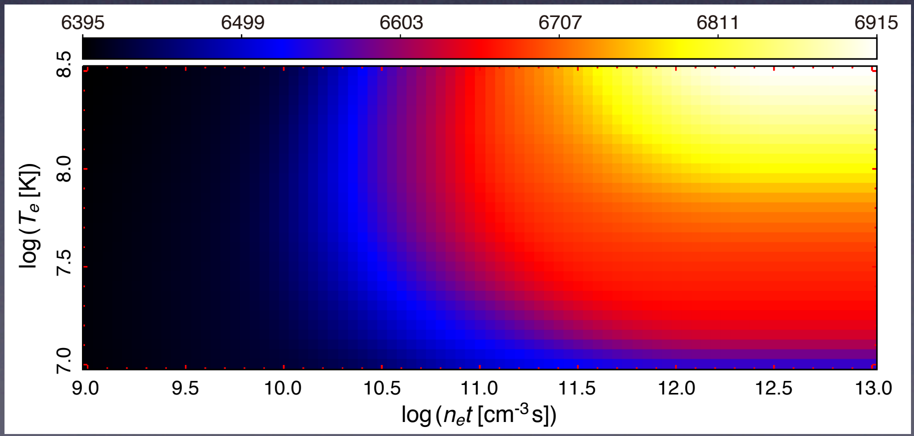
➔ Innershell processes take place.

Fluorescence emission offers key to diagnosing the plasma condition. (e.g., Kaastra+1993; Palmeri+2003)

e.g., centroid energy which depends on the charge number (hence $n_e t$).

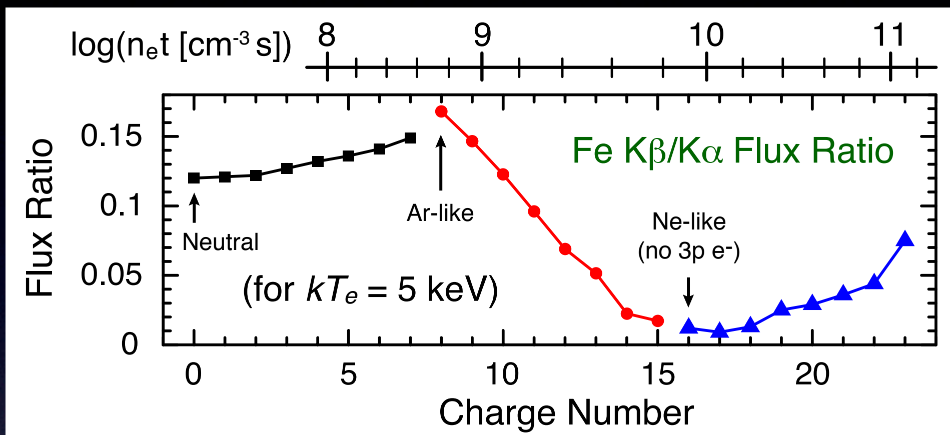


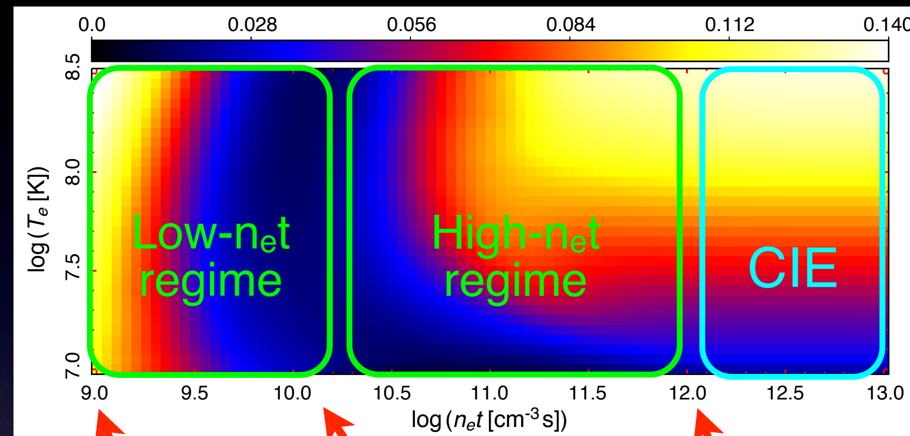


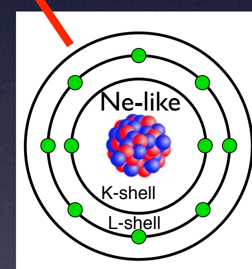


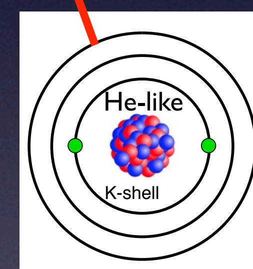
Characteristic Atomic Processes in NEI

Kβ/Kα flux ratio would be even more interesting (see also Adam's poster).









Low-ionization regime:

- Drops with ionization.
  (Fe atoms lose 3*p* electrons.)
- Doesn't depend on temperature.
  (ionization dominant)

High-ionization regime:

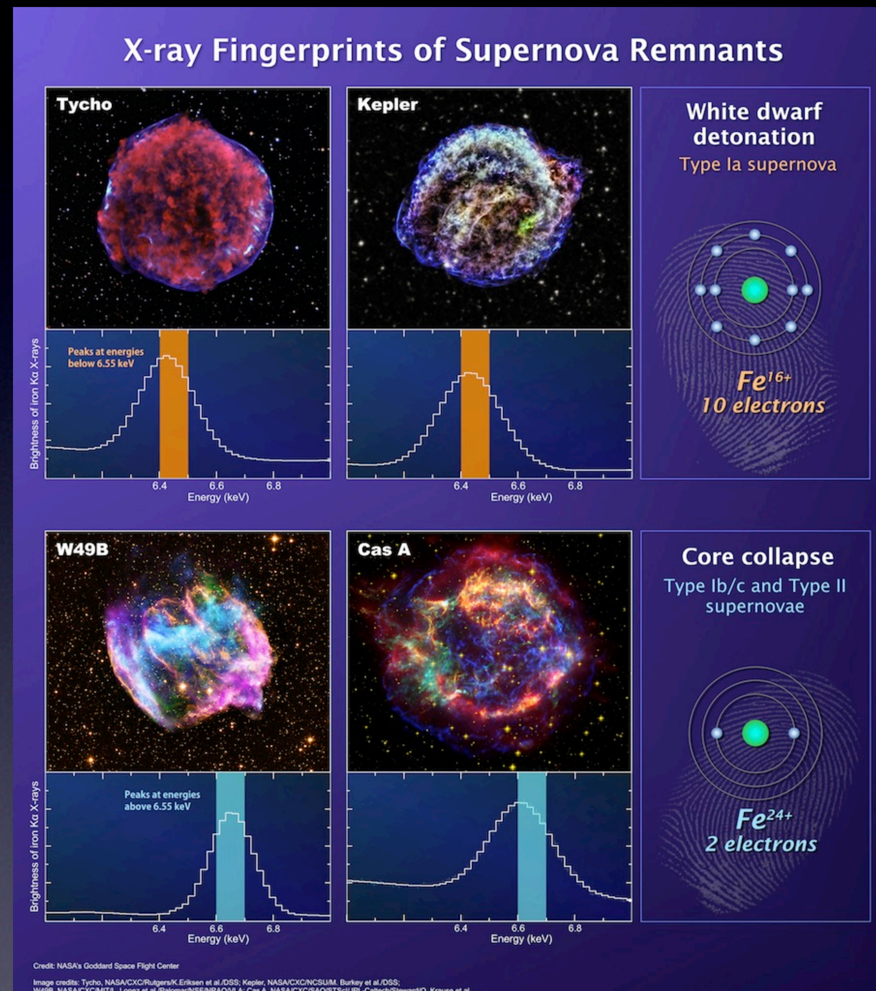
- Goes up with ionization.
  (Fe atoms lose 2*p* electrons too.)
- Strongly depends on temperature.
  (excitation dominant)

Innershell processes offer important diagnostics for NEI plasma.

$E/\Delta E > 100$ is not necessary for the simple diagnostics (centroid, ratio)

Fe Kα Emission Diagnostics on SNRs

Centroid energies discriminate the SNR progenitor type.



Yamaguchi+2014a, ApJL, 785, L27

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Density effect:

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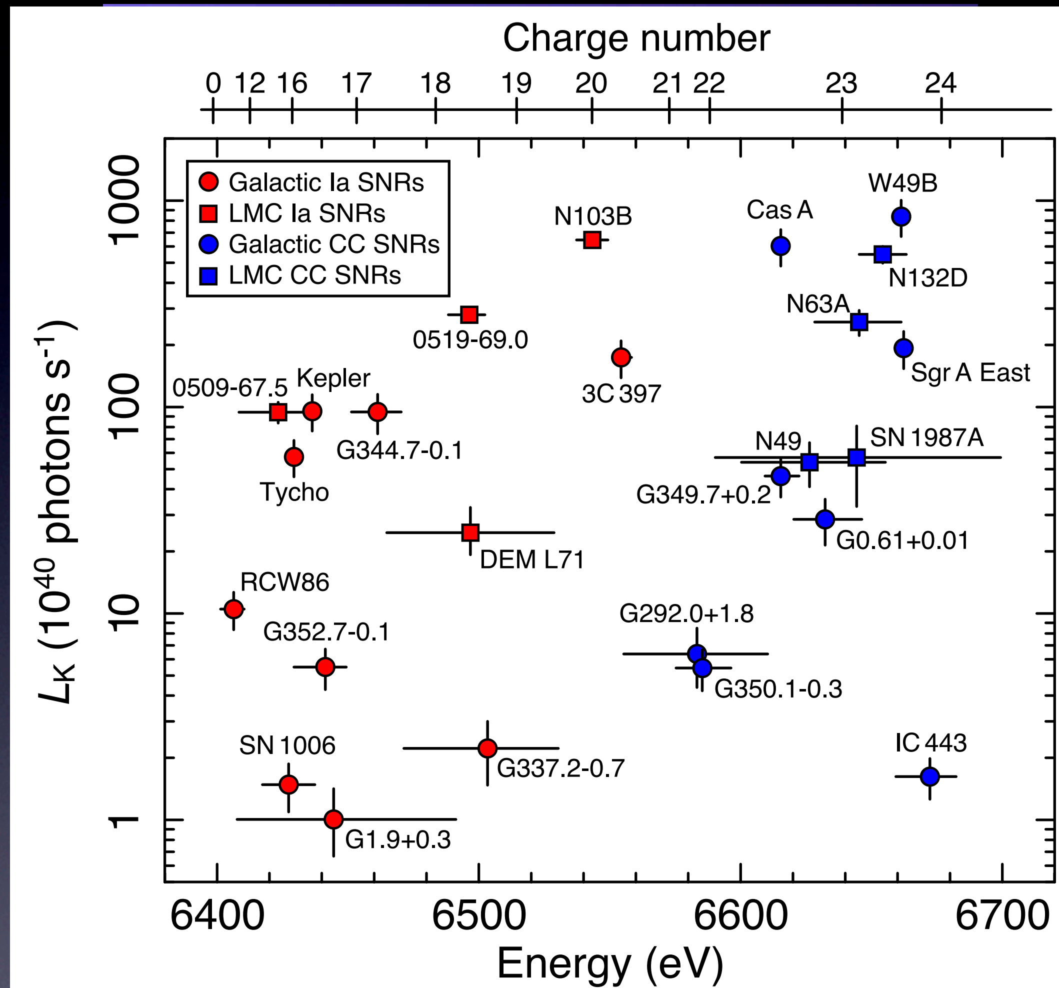
- Luminosity ∝ $n_e N_{Fe}$



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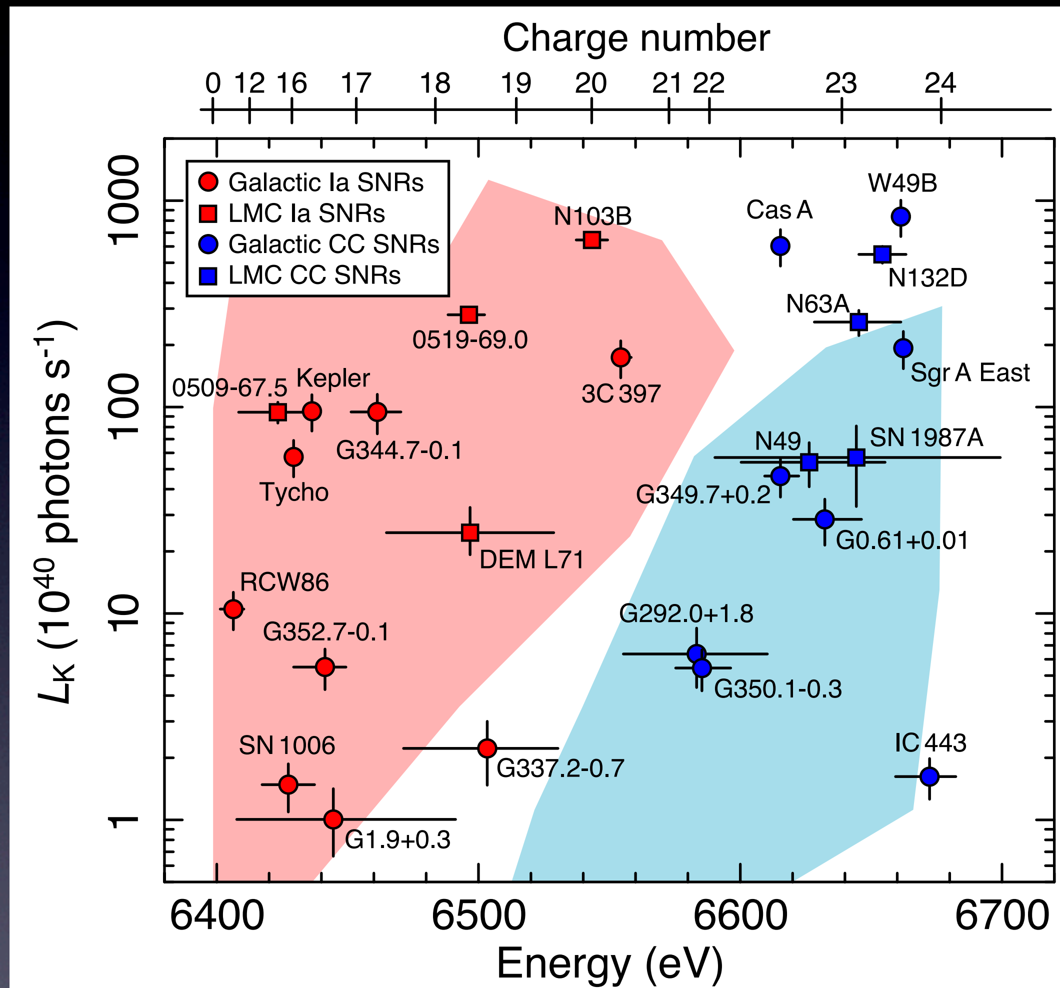
Comparison with hydro models:

- Type Ia = uniform ambient
- CC = dense CSM

Ionization state (Fe-K centroid) constrains SNR's environment.



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(Patnaude+2015; Follow-up studies for CC models)

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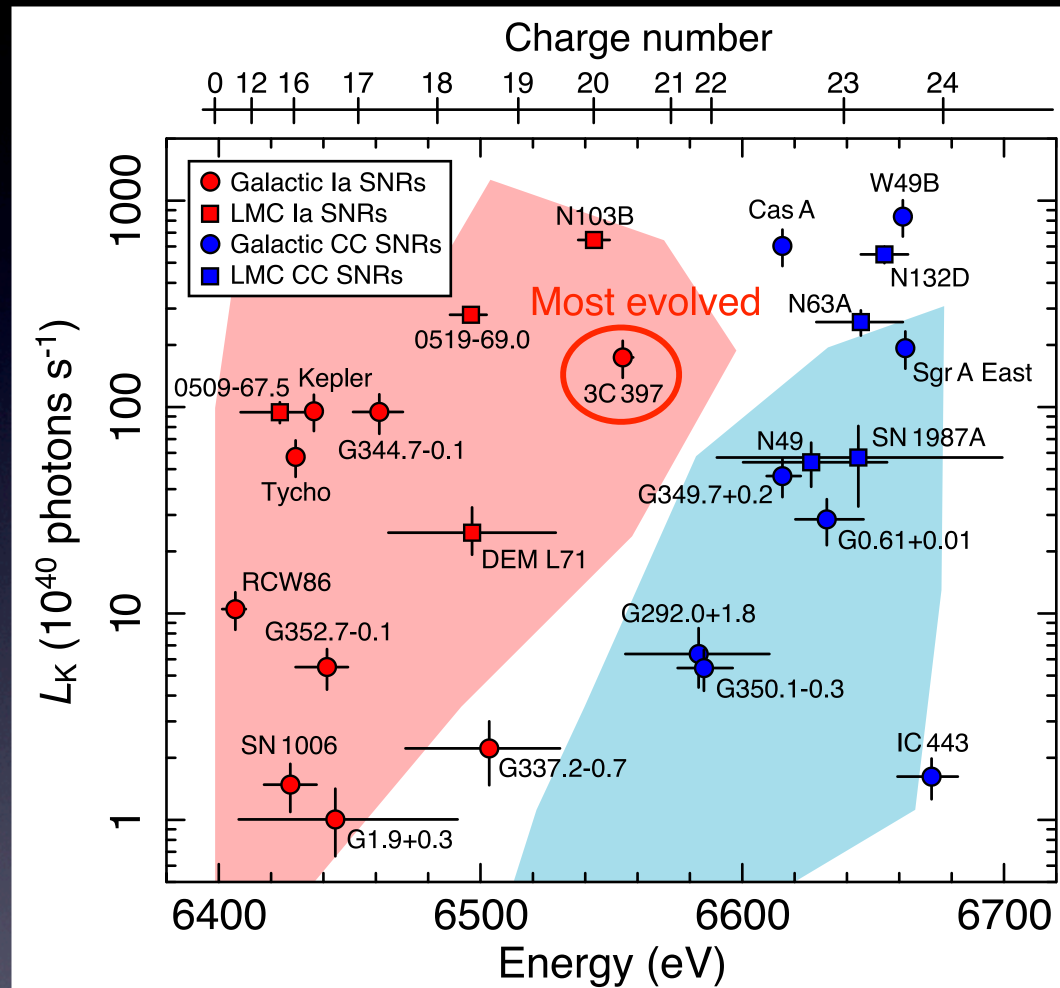
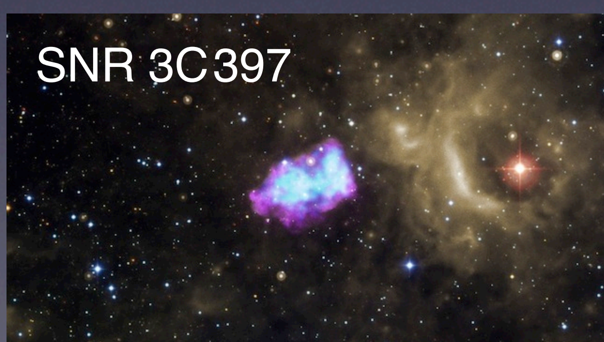


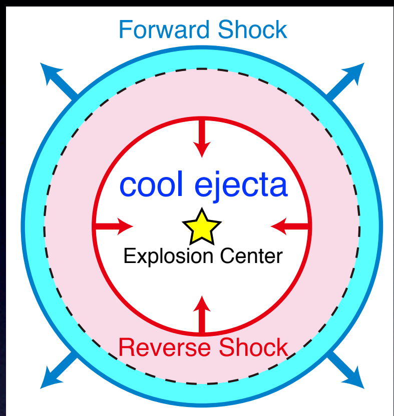


Yamaguchi+2014a, ApJL, 785, L27

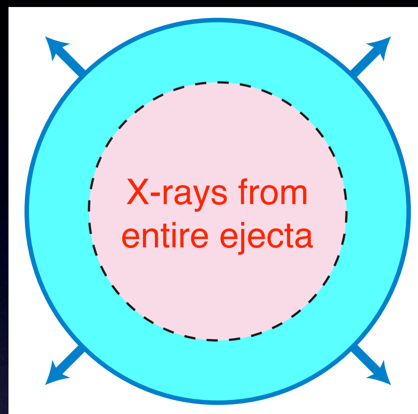
(Patnaude+2015; Follow-up studies for CC models)

SNR 3C 397

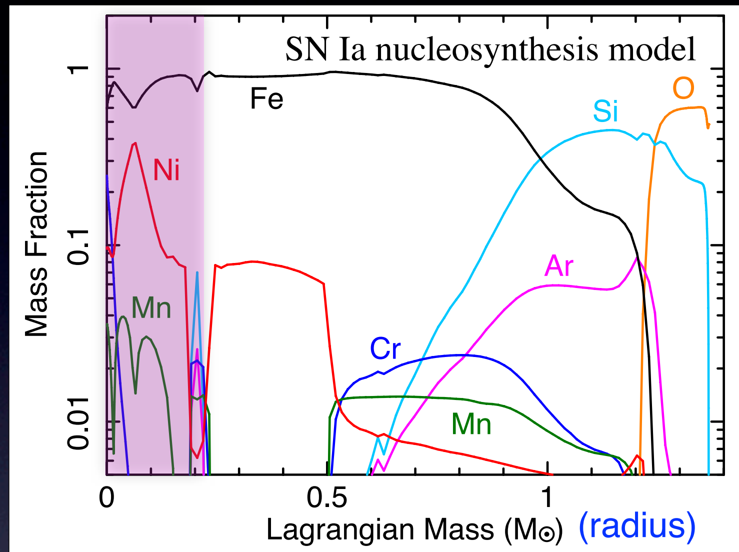
The Fe Kα diagnostic suggests 3C 397 is the most evolved Type Ia SNR.



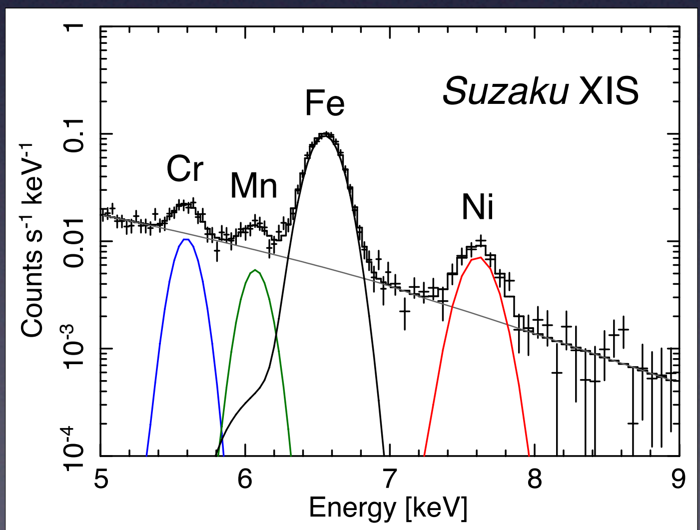
Young SNR



Evolved SNR



Electron capture reactions ($p + e^- \rightarrow n + \nu_e$) increase abundances of *n*-rich elements.



Yamaguchi+2015, ApJL, 801, L31

Allows us to investigate if electron captures indeed take place in the Type Ia SN core.

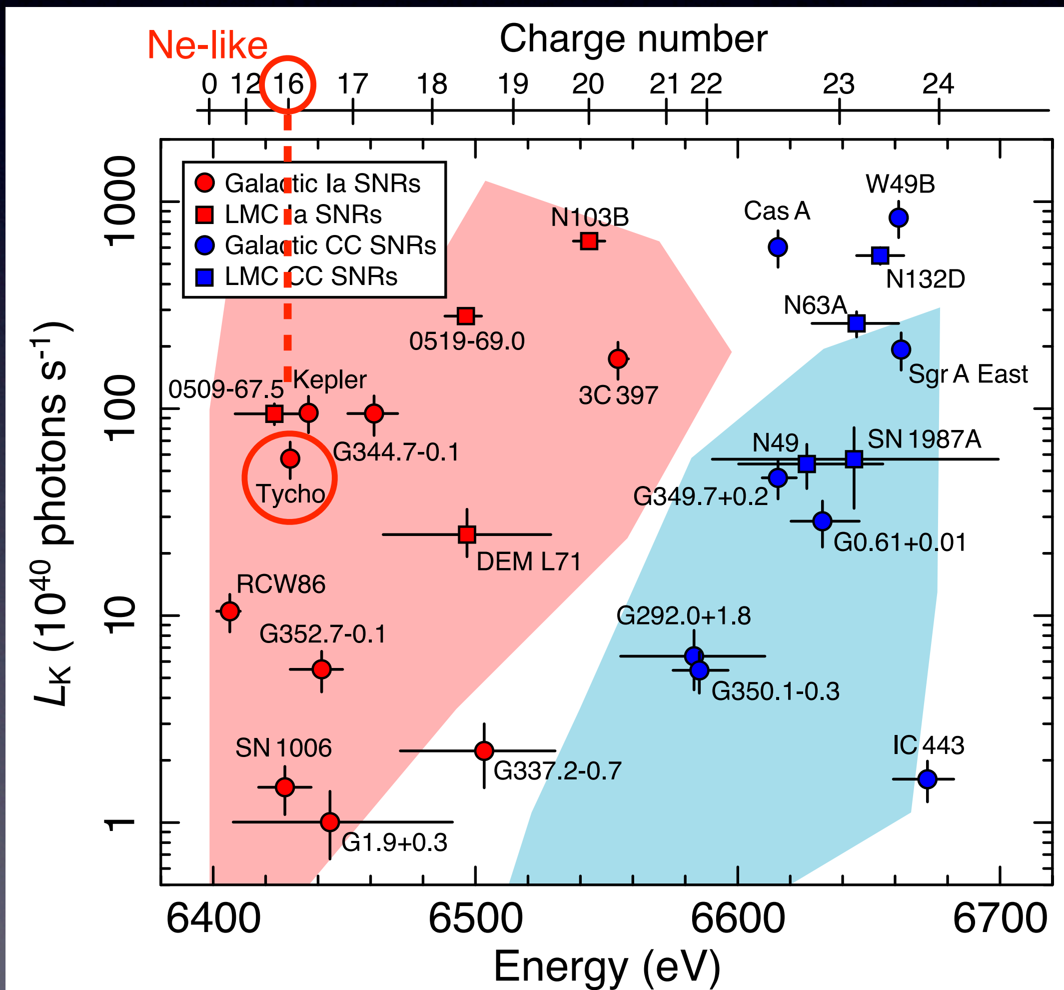
Detected strong emission from Mn and Ni, also due to fluorescence; New AtomDB!

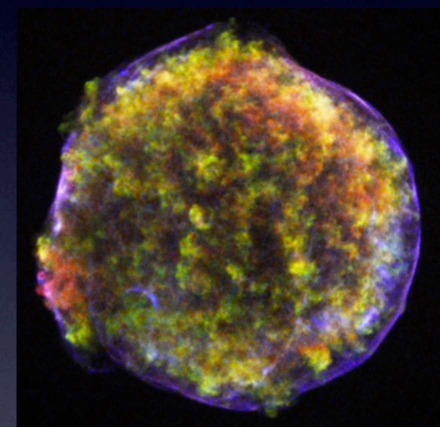
Tycho's SNR

Conclusions:

- Identified physical condition and location of immediate postshock plasma
- (Actually,) this was robust evidence for collisionless electron heating

Yamaguchi+2014b, ApJ, 780, 136





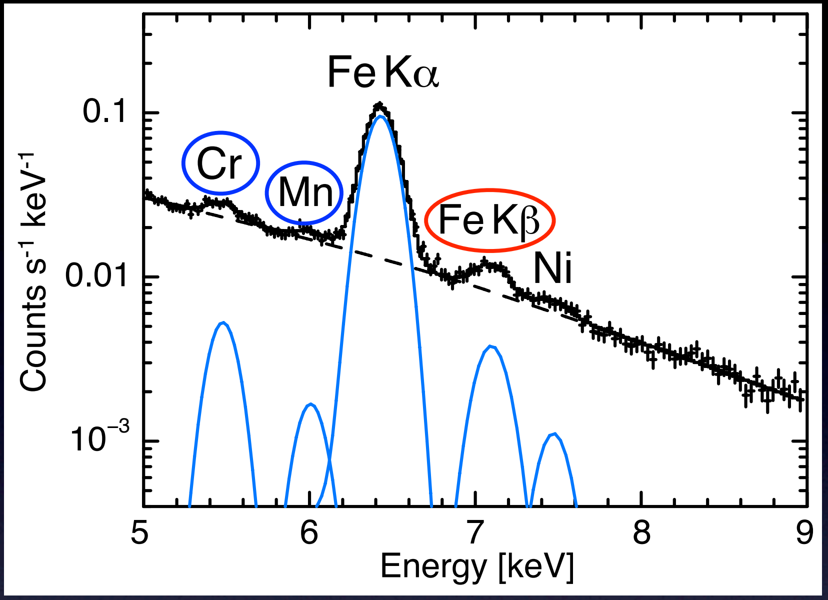
Tycho Brahe
(1546–1601)

Anomalously Strong Fe Kβ Emission

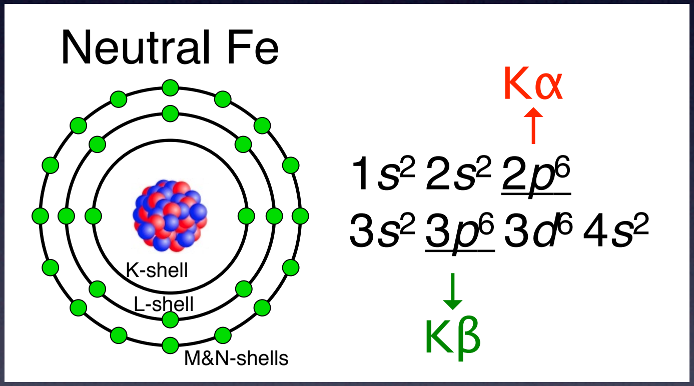
An early Suzaku observation achieved the first detection of Cr and Mn from a Type Ia SNR (Tamagawa+2009).

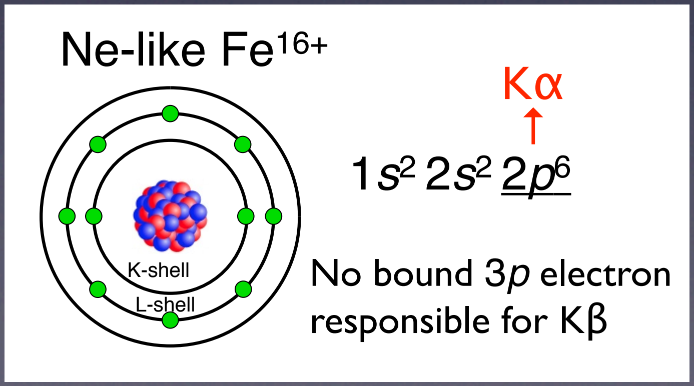
➔ Weak-line search became popular.

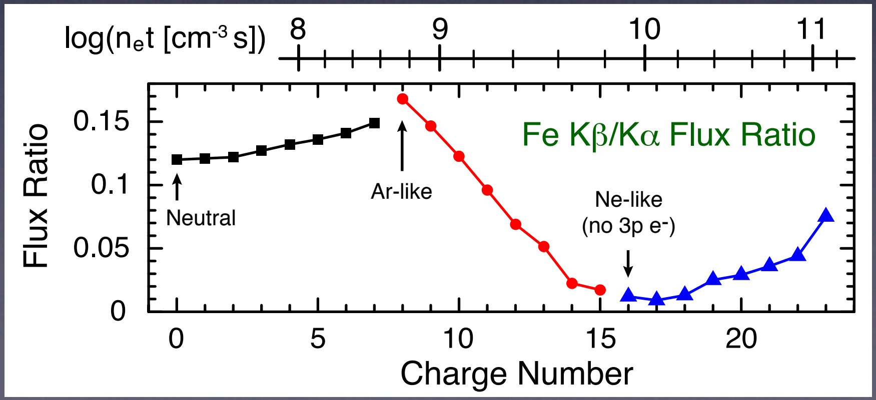
Detection of Fe Kβ is more surprising.



Kα centroid = 6435 (± 1) eV
Kβ centroid = 7104 (± 10) eV
Kβ/Kα flux ratio = 5.5 (± 0.5) %







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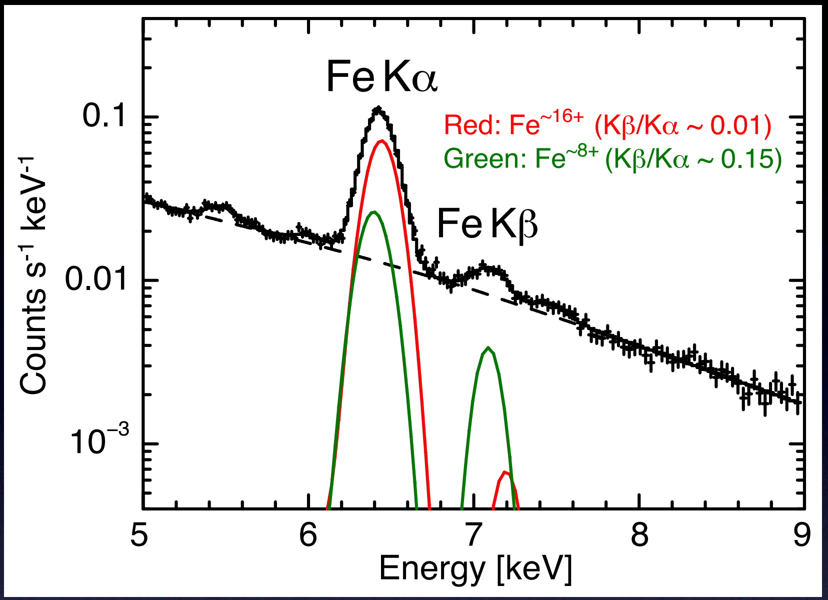
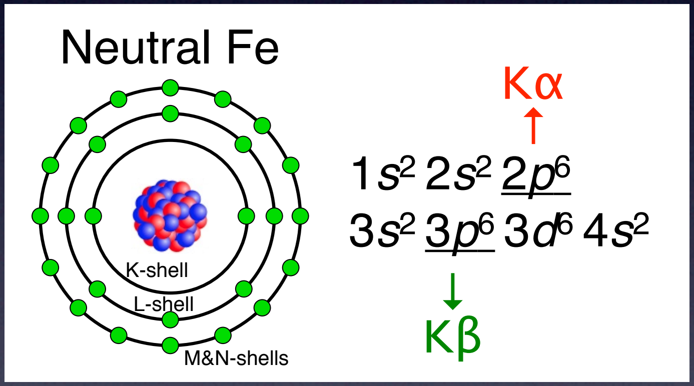
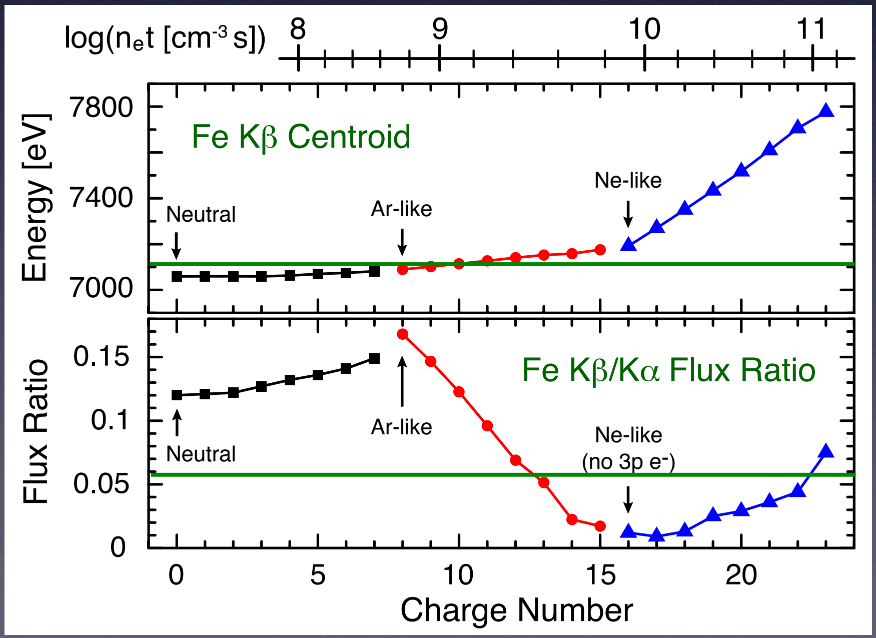
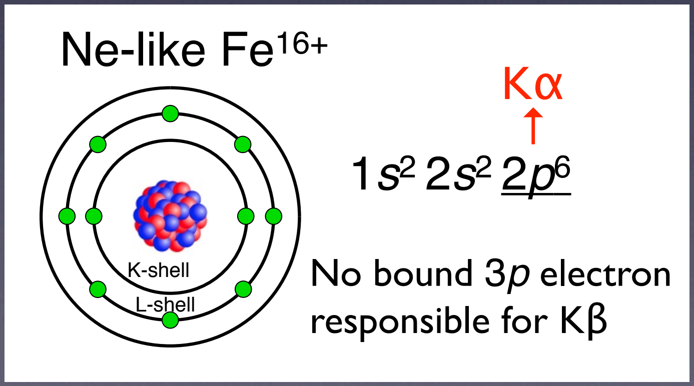


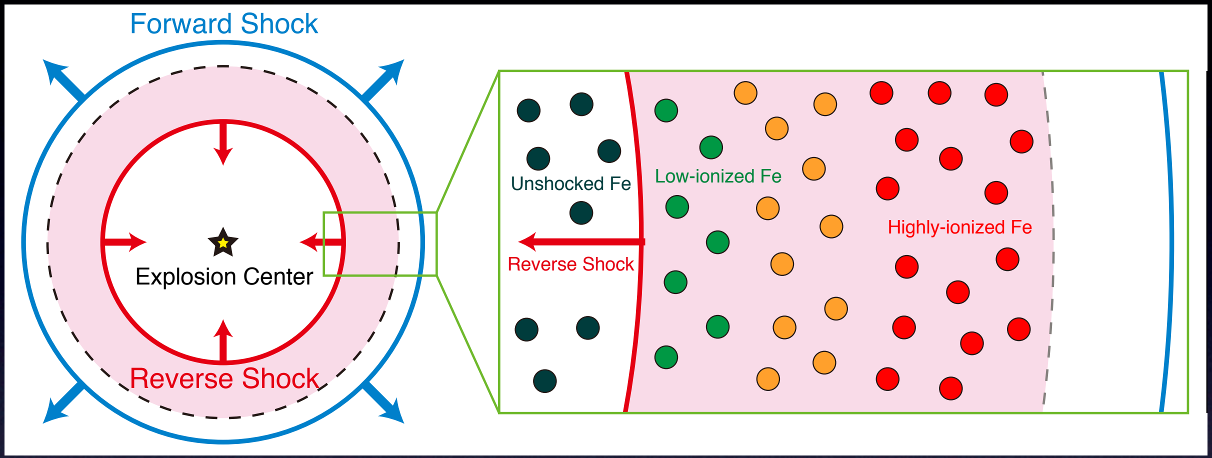


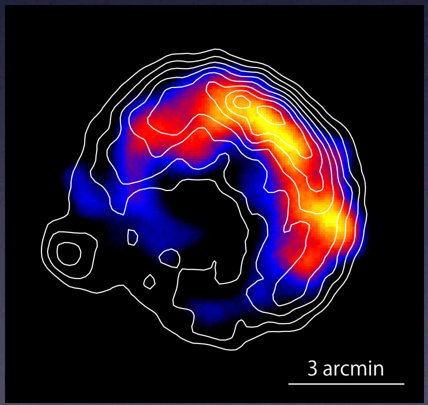




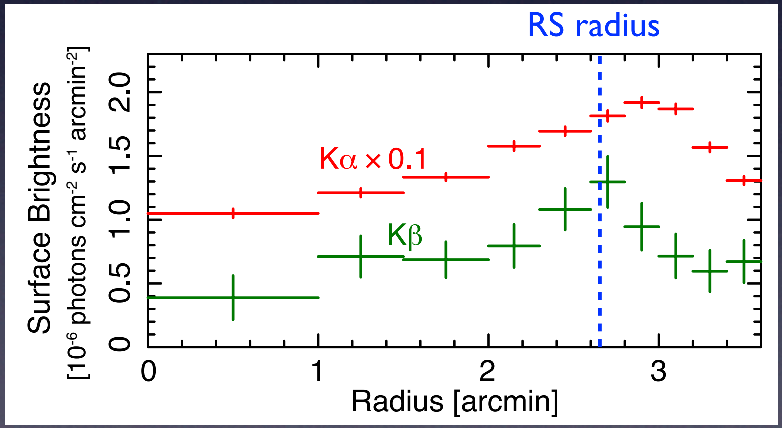
Origin of the Strong Kβ Emission

Low-ionized plasma at the immediate post-reverse-shock region.





Contour: Kα, Color map: Kβ



- Fe Kβ emission reveals the location of the reverse shock front.
- Furthermore, it actually indicates efficient electron heating at the RS.

Evidence for Collisionless Electron Heating

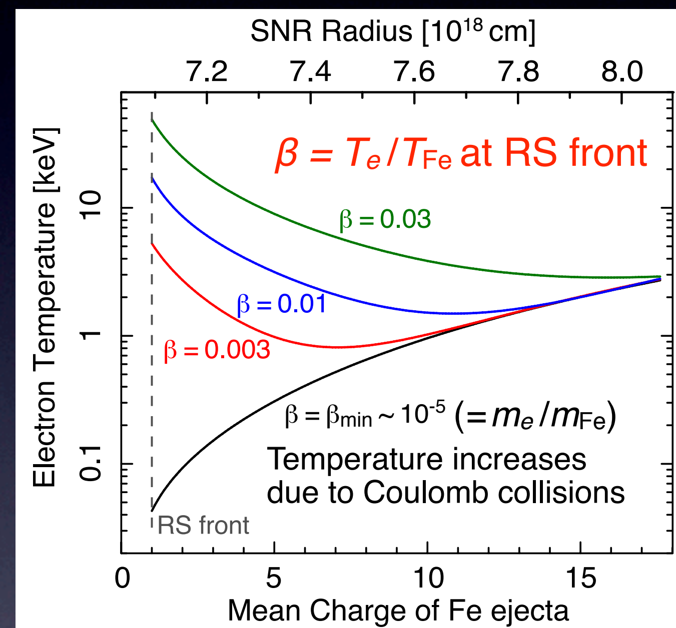
Strong K-shell emission from very low ionized ejecta is NOT easy to produce, because these Fe ions <u>must coexist with free electrons energetic enough to ionize K-shell electrons</u>.

Relationship between shock velocity (V_s) and downstream temperature (T_i):

$$kT_i = (3/16)\, m_i V_s^2$$

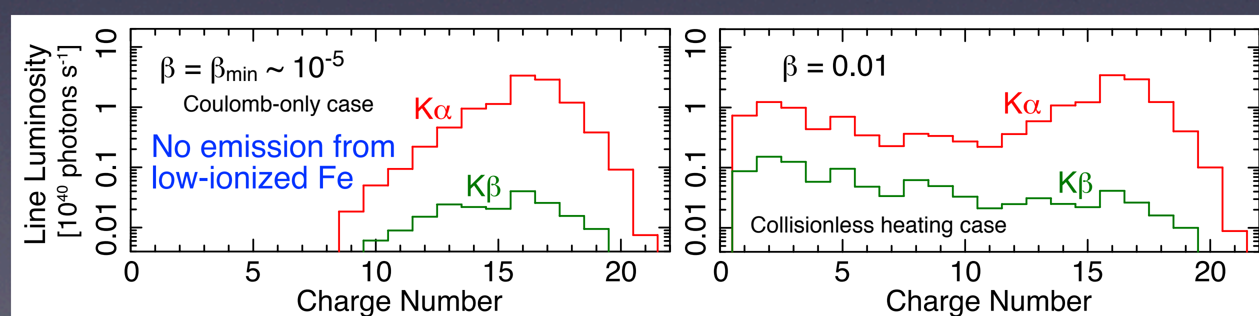
Tycho: V_s = 5000 km/s ➔ $kT_e \approx 0.03$ keV

Comparison with hydrodynamical simulations indicates instantaneous electron heating to a temperature ~1000 times higher.



Efficient collisionless heating at the SNR RS!

See Yamaguchi+2014b, ApJ, 780, 136 for details.



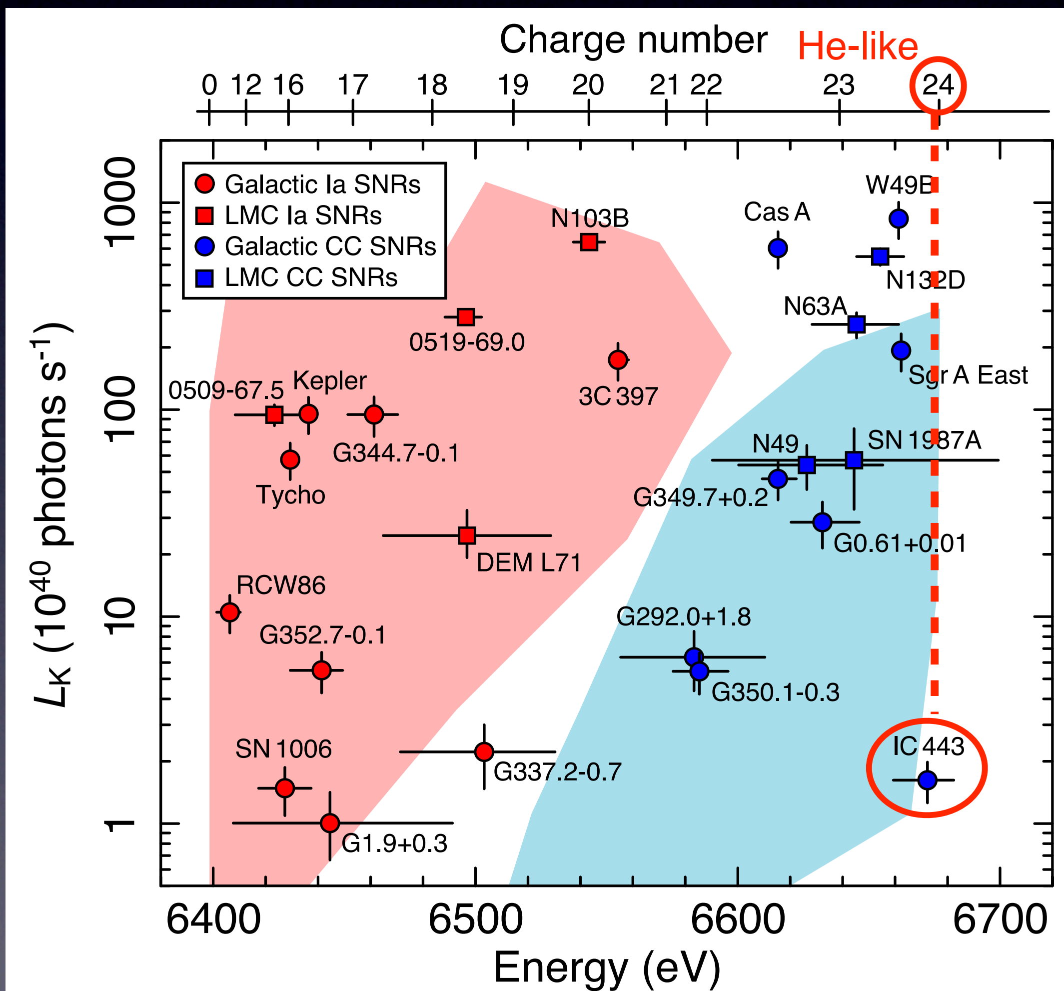
Predicted line luminosity for each charge number

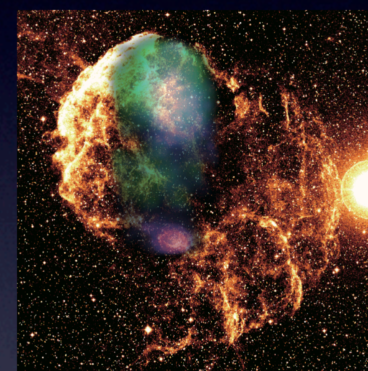
IC 443

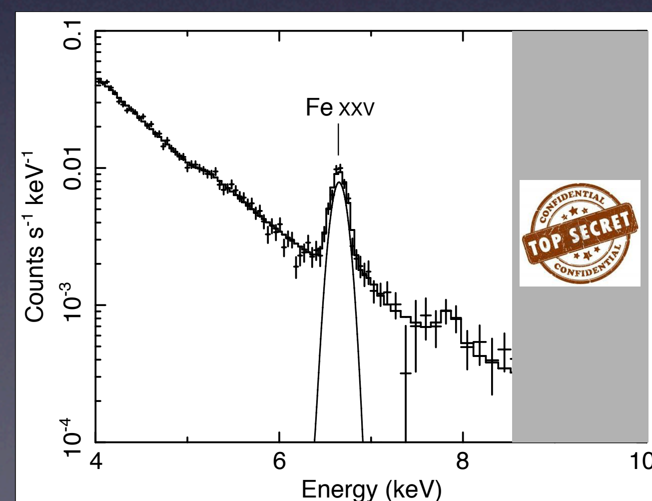
Conclusions:

- Detected a signature of “recombining plasma” (opposite of typical NEI)
- Initiated many discoveries of such SNRs

Yamaguchi+2009, ApJL, 705, L6
Ohnishi+2014, ApJ, 784, 74

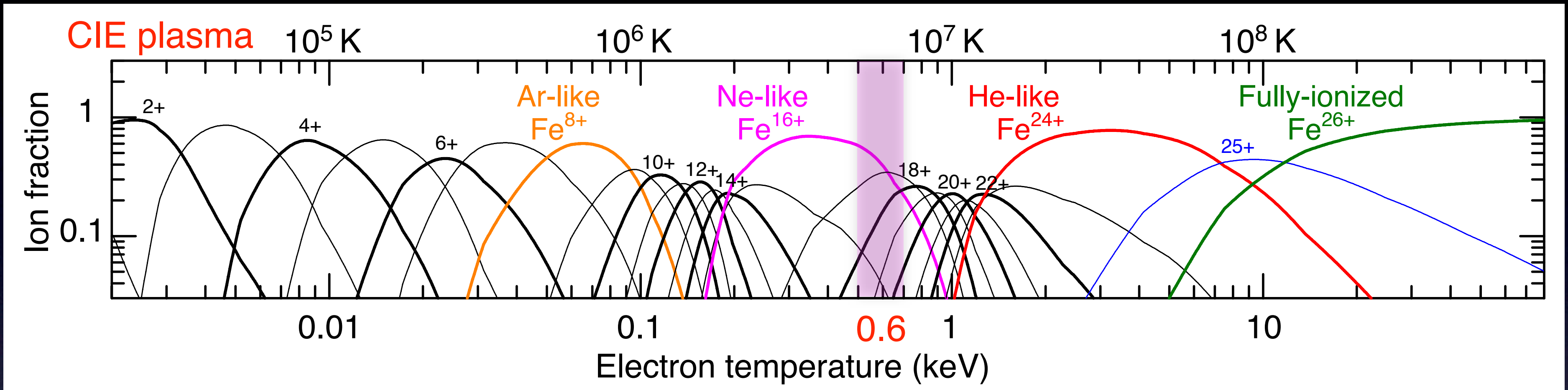






Why Surprising?

IC 443 is an evolved SNR with a low electron temperature (~0.6 keV)



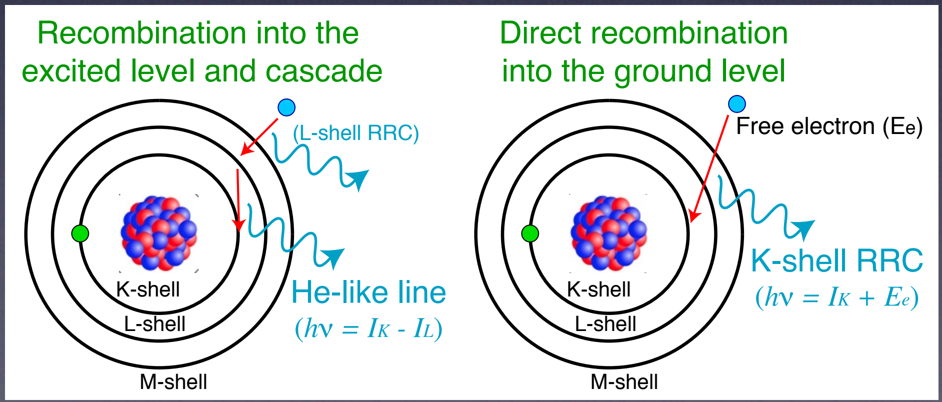
Anyway, K-shell electrons cannot be excited by a sub-keV free electron.

Emission originates from H-like ions?

➔ Direct recombination into ground level should also be observed.

X-ray energy: $h\nu = I_K + E_e$

Spectrum $\propto \exp\left(-\frac{h\nu - I_K}{kT_e}\right)$



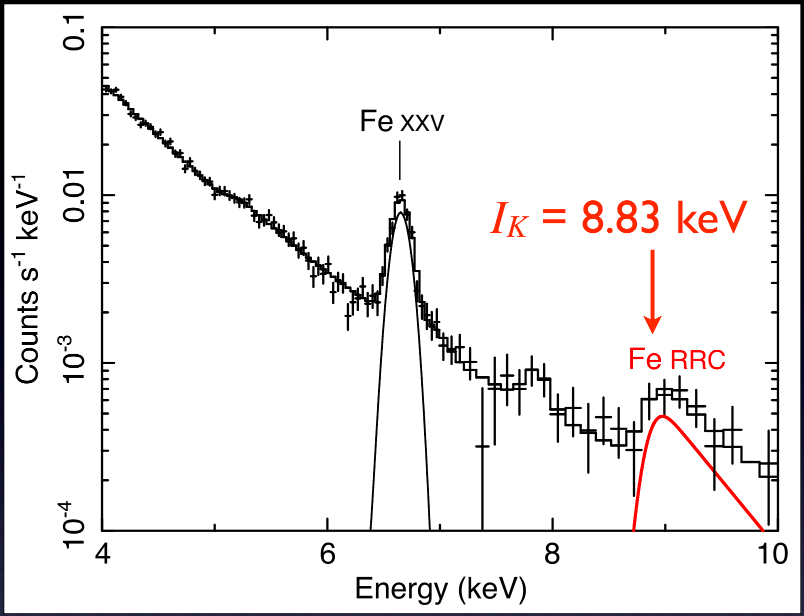
Another Type of NEI (Recombining)

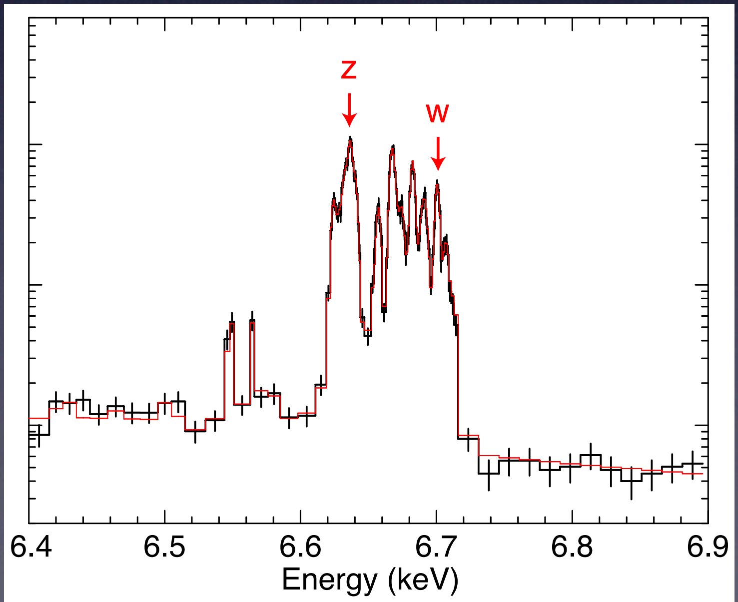
Radiative recombination continuum (RRC) was detected, confirming the H-like-ion origin of the Fe XXV line.

cf. CIE: Fe XXV mainly from He-like ions.

Interpretation: the plasma was much hotter in the past and cooled rapidly.

$kT_{e(\text{past})}$ must be >10 keV, not ~2 keV.





Another kind of "co-existence":

(i) Low-energy electrons that can barely excite L-shell electrons.

(ii) Highly-charged ions with a K-shell vacancy.

ASTRO-H should confirm enhanced forbidden emission (high G-ratio).

Conclusions and Prospects

- SNRs are indeed best suitable for studying supernova physics, <u>owing to the NEI</u> (innershell process, recombination, etc.).
- SNRs offer a good “laboratory” for fundamental atomic physics.
- There are a number of simple, but powerful diagnostics (e.g., centroid, Kβ/Kα ratio, RRC/line) where the grating/calorimeter resolution ($E/\Delta E \sim 1000$) is not necessarily required.
- There MUST be still new diagnostics in future high-resolution spectral data, not only famous ones, like G-ratio, R-ratio, etc.
- Don’t rely on (only) performance of hardware and software.
    - Understand the physics behind radiation processes.
    - “Press-‘fit’ analysis” might overlook a key spectral feature.
- Ambitious for ground experiments of innershell processes.