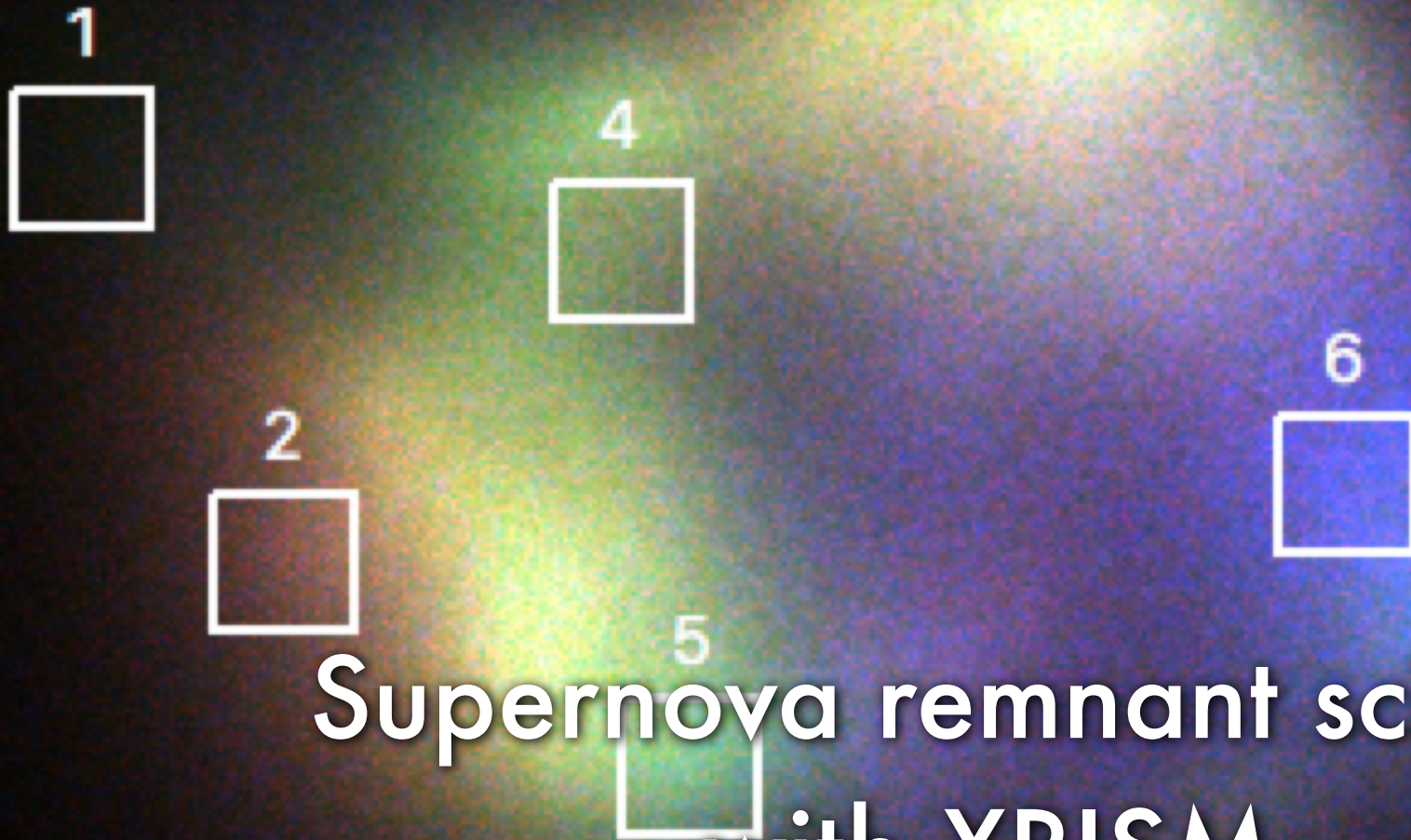




Supernova remnant science with XRISM

Jacco Vink

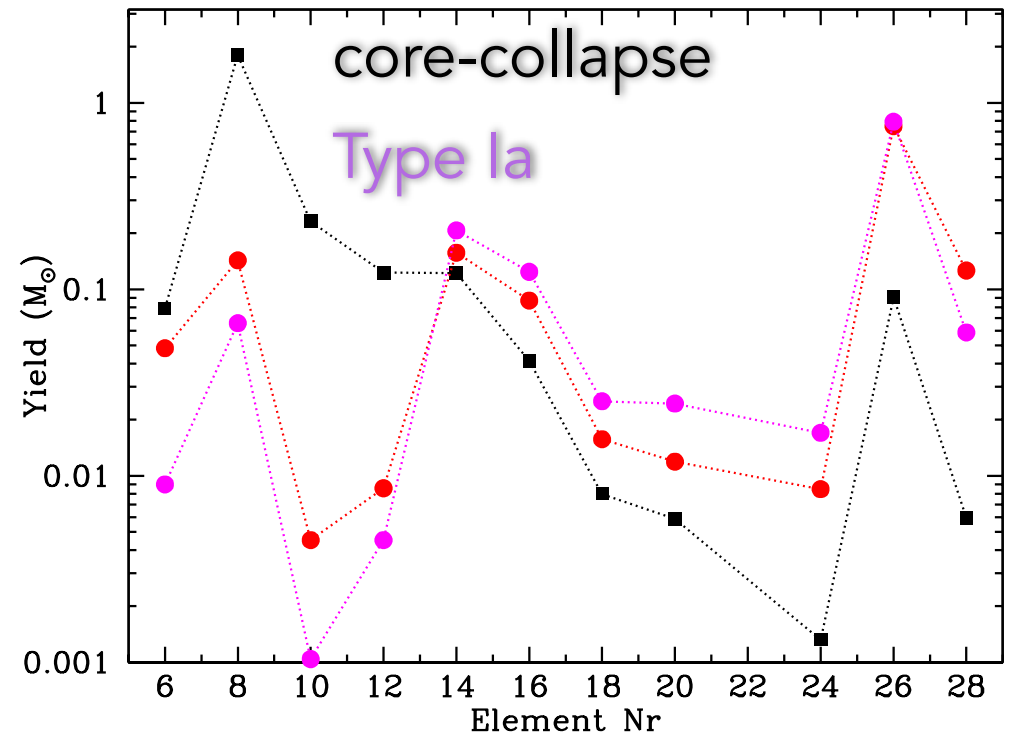
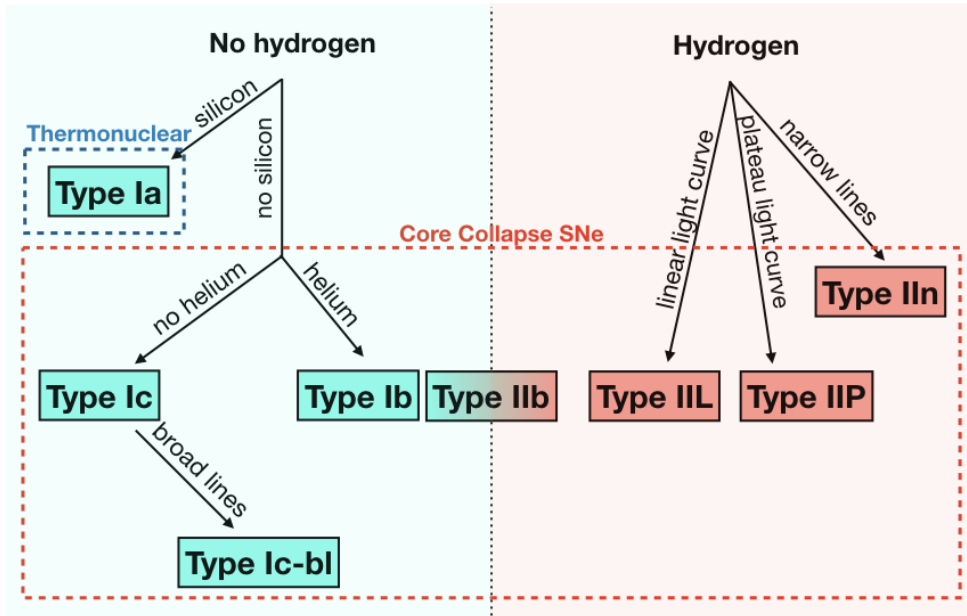
University of Amsterdam

XRISM science

- XRISM-Resolve: first time calorimeter are used from space
- Allows for high-spectral-resolution imaging
 - Currently at 1' level -> better with newAthena
 - Spectral resolution 5eV @ 6 keV: $R \sim 1200$
 - *Bummer*: gate-valve not open (yet?) -> spectroscopy above ~ 1.8 keV
- Until now:
 - CCD spectroscopy (150 eV @ 6 keV: $R \sim 40$)
 - Excellent imaging: 0.5" CXO/ACIS
 - *Slitless grating spectrometers*: $R \sim 1000$ as well!
 - But: does not work (or difficult) for extended sources!!!
 - Resolution better at lower energies -> XRISM wins @6 keV
 - Gratings have low eff. area
- Largest impact calorimeters: extended sources!
 - supernova remnants
 - clusters of galaxies
 - diffuse ISM -> but too soft with gate-valve closed

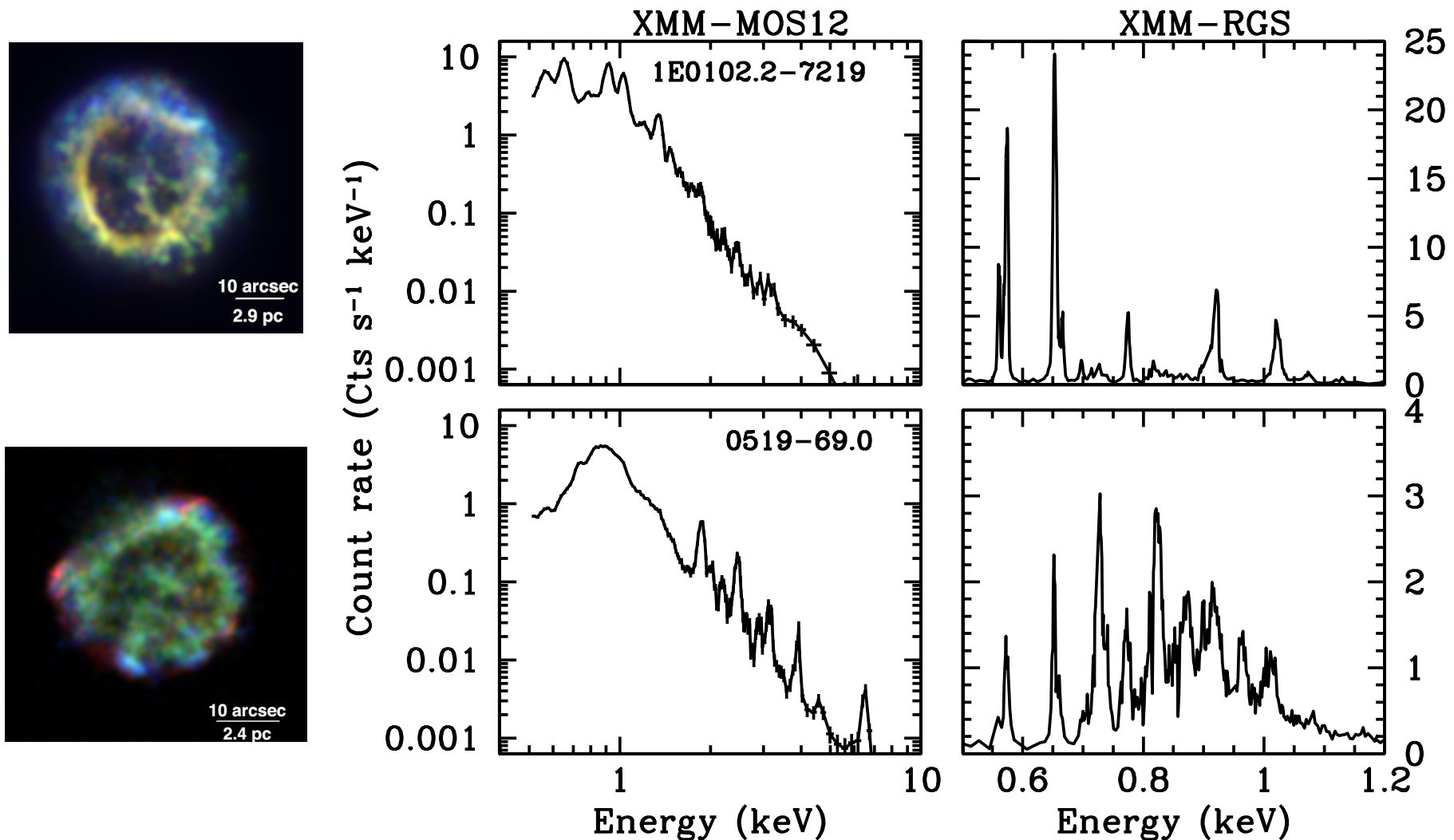
Supernovae

Supernova Classification



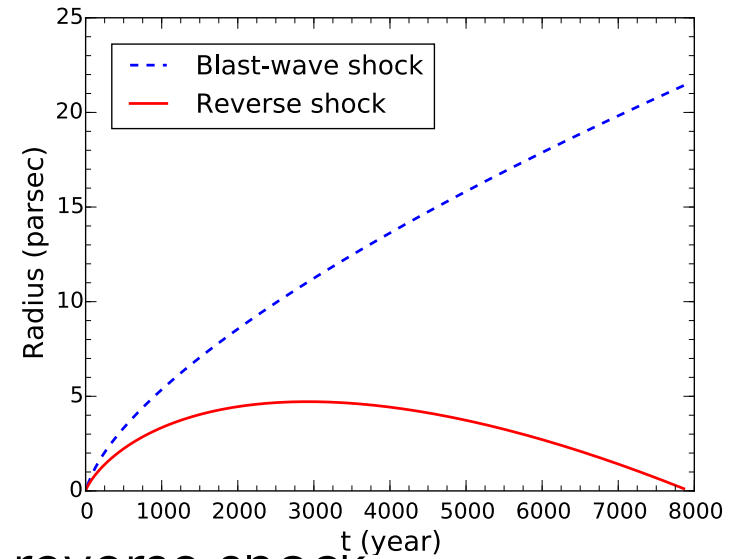
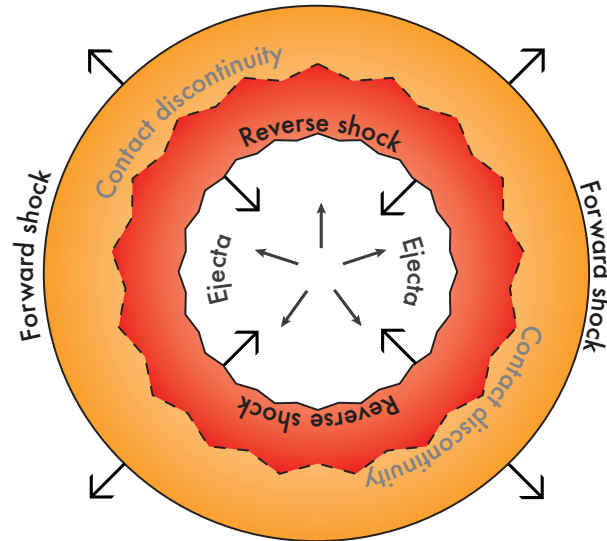
- Two basic types:
 - core collapse supernovae:
 - massive stars, leave neutron star, oxygen-rich
 - thermonuclear/Type Ia supernovae:
 - % white dwarf in binary, ~0.7 Msun of iron, total disruption

Grating spectra



- LMC/SMC remnants: size small ($\sim 1'$) not much spectral degradation

supernova remnant shocks



- Two (or more) shocks: forward- (blastwave) and reverse shock
 - FS: shocks ISM/CSM
 - RS: shocks supernova material
- Shocks velocities: $\sim 10,000$ km/s down to ~ 30 km/s ($t \sim 2 \times 10^4$ yr?)
- For $\sim 10 - 30$ km/s : approach sound speed ISM turbulence speeds
- Post-shock temperature ($\mu = 0.6$ average particle mass cosmic plasma):

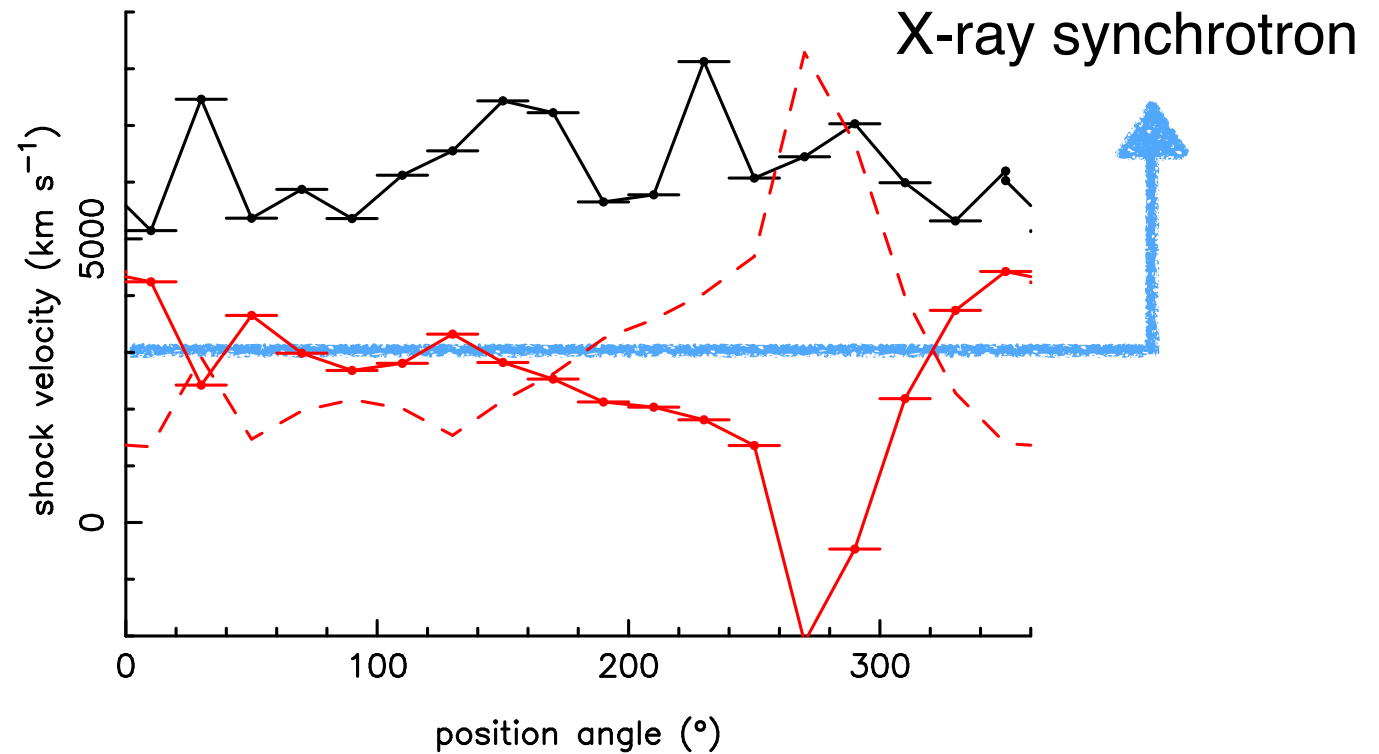
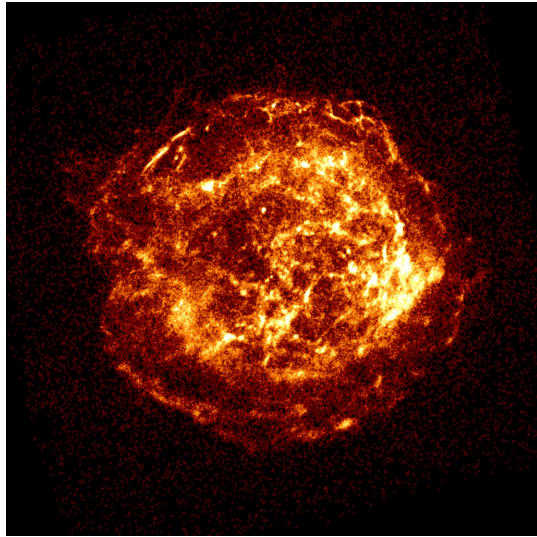
$$\langle kT \rangle = \frac{3}{16} \mu m_p V_s^2 = 29 \left(\frac{\mu}{0.6} \right) \left(\frac{V_s}{5000 \text{ km/s}} \right)^2$$

- But: electron temperatures may be lower and metal temperatures may be hotter!!

Thermal X-ray emission from SNRs

- Nonthermal emission: young SNRs with very fast shocks ($V_s > 3000$ km/s)
- For XRISM: thermal emission more interesting:
 - Plasma optically thin (perhaps not in some lines!)
 - We see through entire SNR, front and back
 - SNRs: may expect “pure metal” plasmas (no hydrogen!)
 - Plasma is “young” and not in equilibrium:
 - non-equilibrium ionization (NEI): ionization low for kT_e
 - likely also non-equilibrium between electron, proton, metal temperatures
 - some older SNRs: reverse NEI: ionization too high for kT_e

Forward and reverse shock velocities



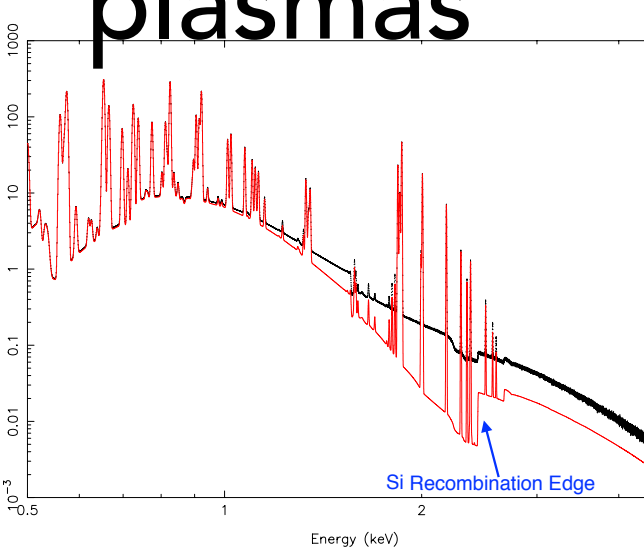
- Reverse shock velocity: $V_s = \frac{dR}{dt} - \frac{R}{t}$
- $\frac{dR}{dt}$ = shock displacement in observer frame
- $\frac{R}{t}$ free expansion velocity

Emission from hot optical thin plasma

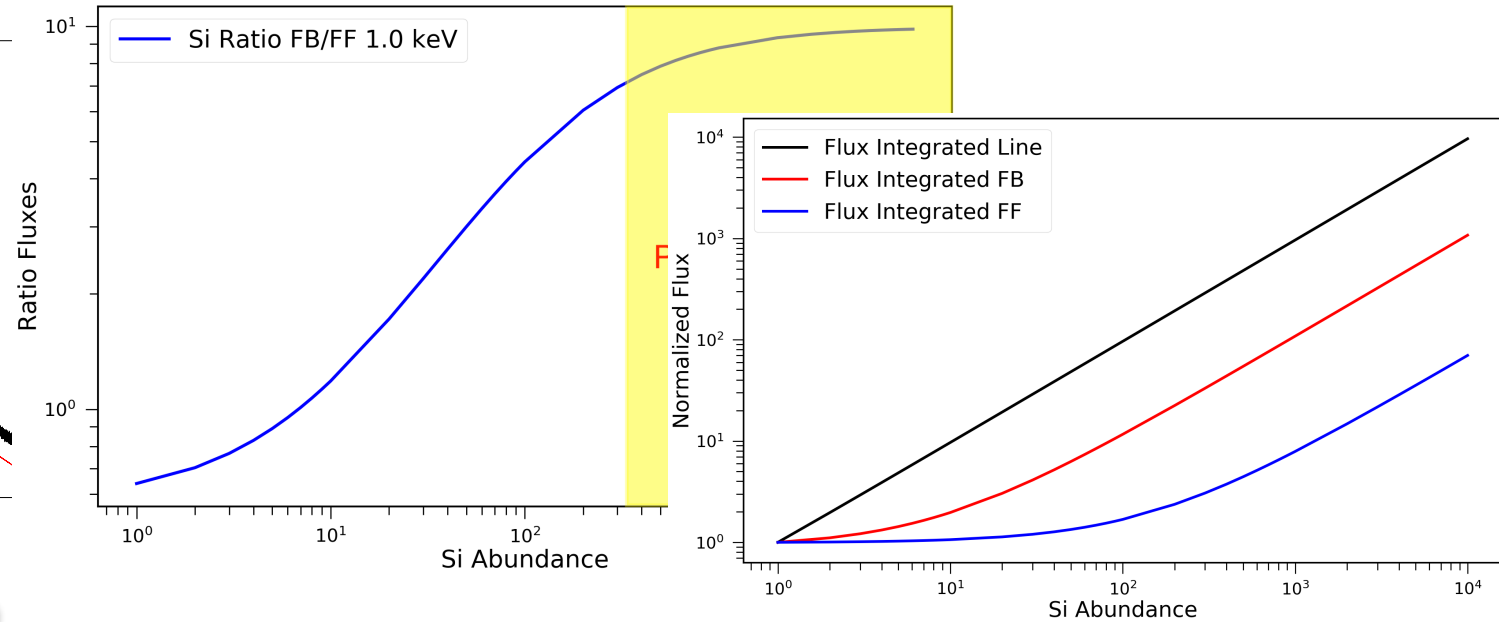
- Radiation processes:

- thermal bremsstrahlung $\epsilon_{\text{ff}} \propto n_e \sum_i n_i Z_i^2 T_e^{-1/2} \exp(-h\nu/kT_e)$
 - free-bound emission -> can dominated for pure metal plasma!
 - shape similar to brems: but starts at edge energy!
 - two-photon continuum -> important for pure metal plasma!
 - line emission: depends on T_e , ionization balance, composition
- All emission depends on electron temperature, not on ion temperatures!
 - All emission proportional to $\sum_i n_e n_i V$
 - standard: replace by *emission measure* $n_e n_H V$ (assumes that hydrogen/He dominates bremsstrahlung!)

Free-bound emission in pure metal plasmas



Greco, JV+ '19



- In hydrogen-dominated spectrum: line emission goes up with increasing abundances
 - above certain abundances (Si ~ 100 xsolar): also continuum goes up
 - i.e. line equivalent width stays constant above $[\text{Si}] \sim 100$
- Pure metals:
 - bremsstrahlung/FB and line emission come from same species
 - free-bound becomes dominant above abundances of ~ 100
 - Be careful deriving densities and masses from emission measure!

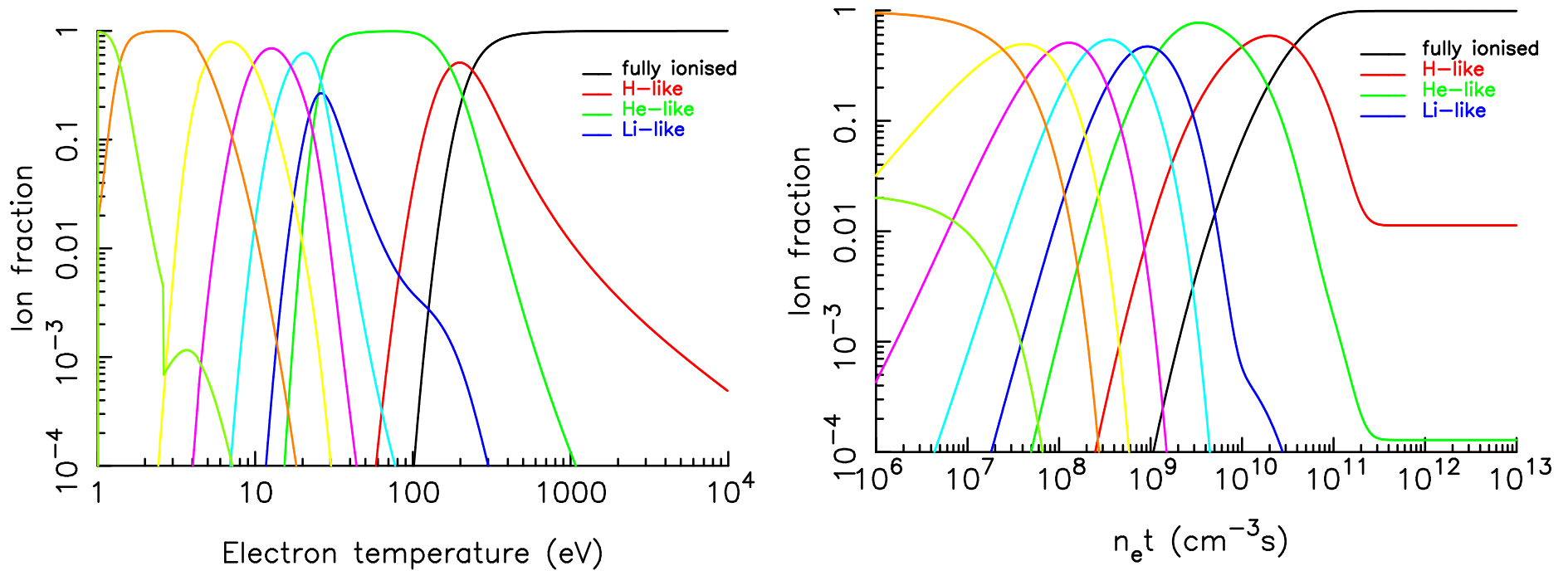
NEI

- The rate change for given ion i (species), z (charge):

$$\frac{dn_{i,z}}{dt} = n_e \left\{ \alpha_{i,z+1}(T_e)n_{i,z+1} + S_{i,z-1}(T_e)n_{i,z-1} - [\alpha_{i,z}(T_e) + S_{i,z}(T_e)n_{i,z}] \right\},$$

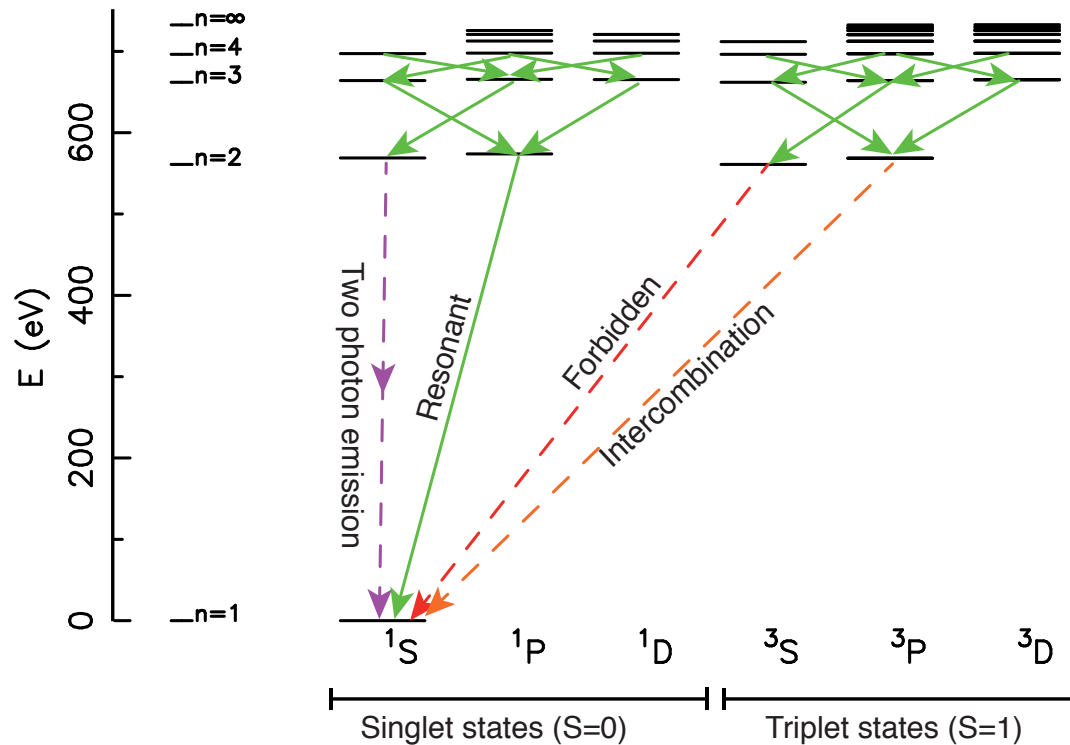
- $\alpha_{i,z+1}$ recombination rate from ion $z+1$
- $S_{i,z-1}$ ionization from $z-1$,
- Driven by electron collisions: $dn_{i,z}/dt \propto n_e$
- Equilibrium: $dn_{i,z}/dt = 0$ (ionizations/recombinations in balance): collisional ionization equilibrium (CIE)
- In SNRs: not enough collisions (10^{-26} for iron!) for equilibrium!
- The plasma is hotter, ionization lags behind!
- In some cases: overionization $\rightarrow$ electrons have cooled but ionization has not followed!
- Relevant parameter: $\tau = n_e t$ (ionization age, or parameter)

NEI



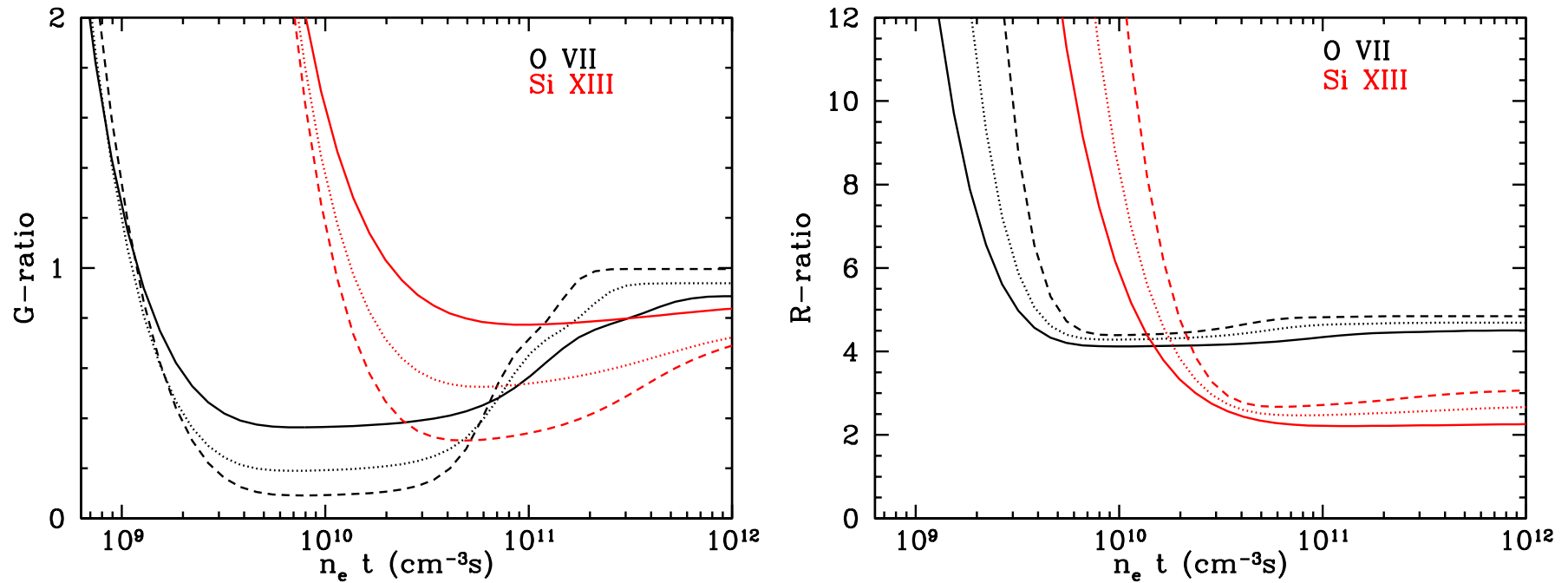
- NEI: to relevant parameters T_e and $n_e t$
 - More difficult to fit accurately!
 - Clusters/stars: only T_e
 - Line emission: T_e and $n_e t$; continuum: T_e (but not always reliable in case of nonthermal emission)
- Typical values: $n_e t \approx 2 \times 10^9$ cm $^{-3}$ s (SN1006) to 10^{12} cm $^{-3}$ s (N132D)
- In all sources (SNRs, clusters..): multiple T_e , $n_e t$ along line of sight!

He-triplets: G and R-ratios



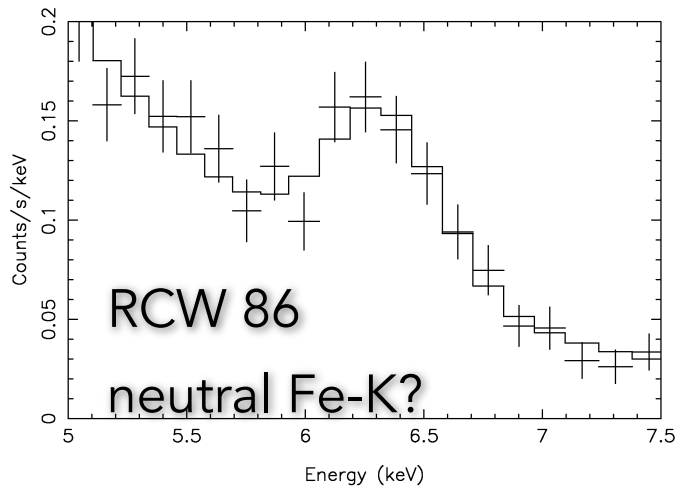
- High resolution spectroscopy with XRISM: resolve line complexes $\rightarrow$ He-like ions $\rightarrow$ triplets
- Sensitive to both T_e and $n_e t$ $\rightarrow$ break degeneracies
- Forbidden line: driven by inner shell ionization, or recombination

He-triplets: G and R-ratios

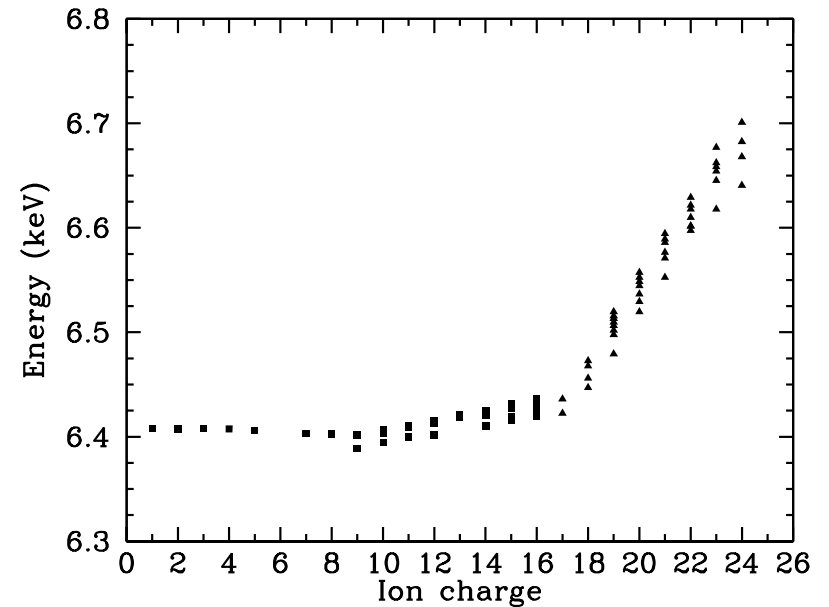


- $G=(f+i)/r$, $R=f/i$
 - issue: sometimes Li-like line contamination
- G ratio: high for severely underionized or over-ionized
- R high for underionized

Fe-K line diagnostics

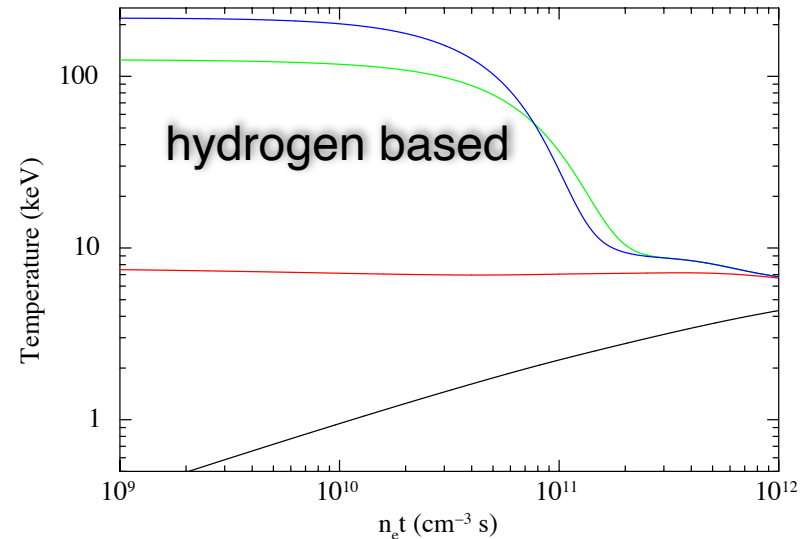
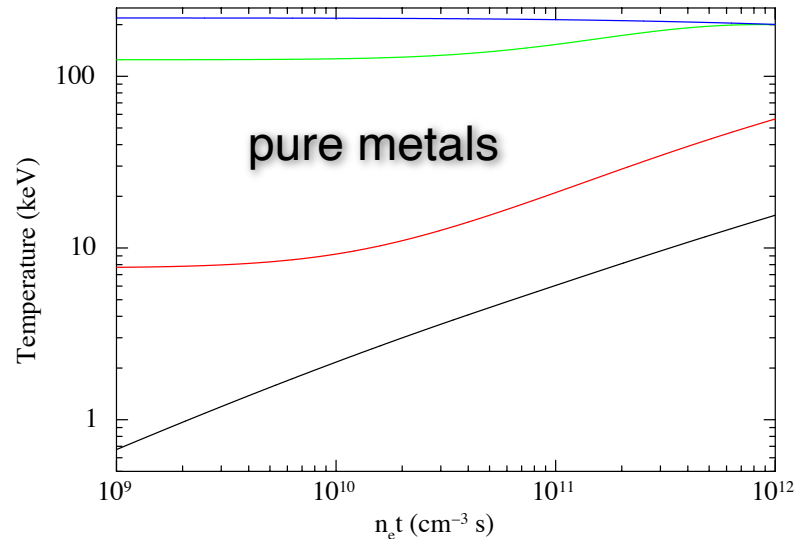


Vink+ '97



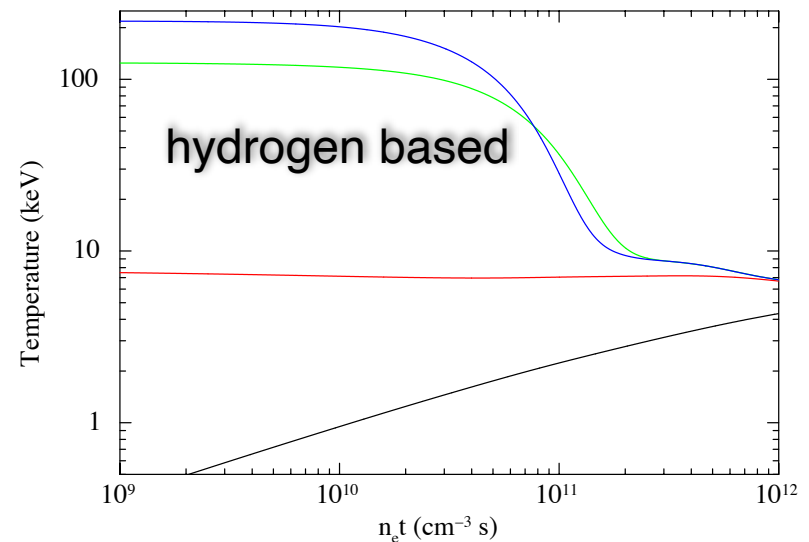
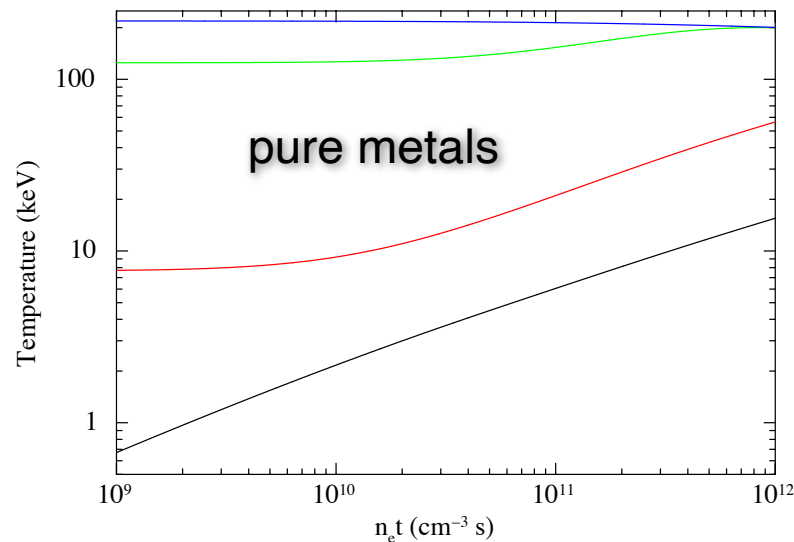
- Gate-valve closed: iron K diagnostics more important
- Fe-K lines: from neutral ($K\alpha$, FeI) to Fe XXV
 - Neutral Fe: 6.4 keV, fluorescence (inner shell ionization)
 - So far: centroiding
 - XRISM: getting better charge states
- In addition: getting Fe XXVI (H-like) and Ni K lines
 - With CCDs difficult to see, at edge of sensitivity
 - blending of Fe and Ni lines
 - Fe-K line ratios: evidence for nonthermal electron distributions?
 - Type Ia SNRs: Fe/Ni ratio informs us on pre-supernova conditions

What about ion temperatures?



- SNR shocks: collisionless -> may heat up electrons and ions differently!
- Extreme case: $kT_i = \frac{3}{16} m_i V_s^2$
 - i.e. iron 54x hotter than protons, electrons 1840x cooler than protons!!
- Postshock: Coulomb energy exchange
 - depends on mass ratio and charge Z
 - equilibrium scales with $n_e t \approx 10^{12} \text{ cm}^{-3} \text{ s}$ (same as NEI!)

What about ion temperatures?

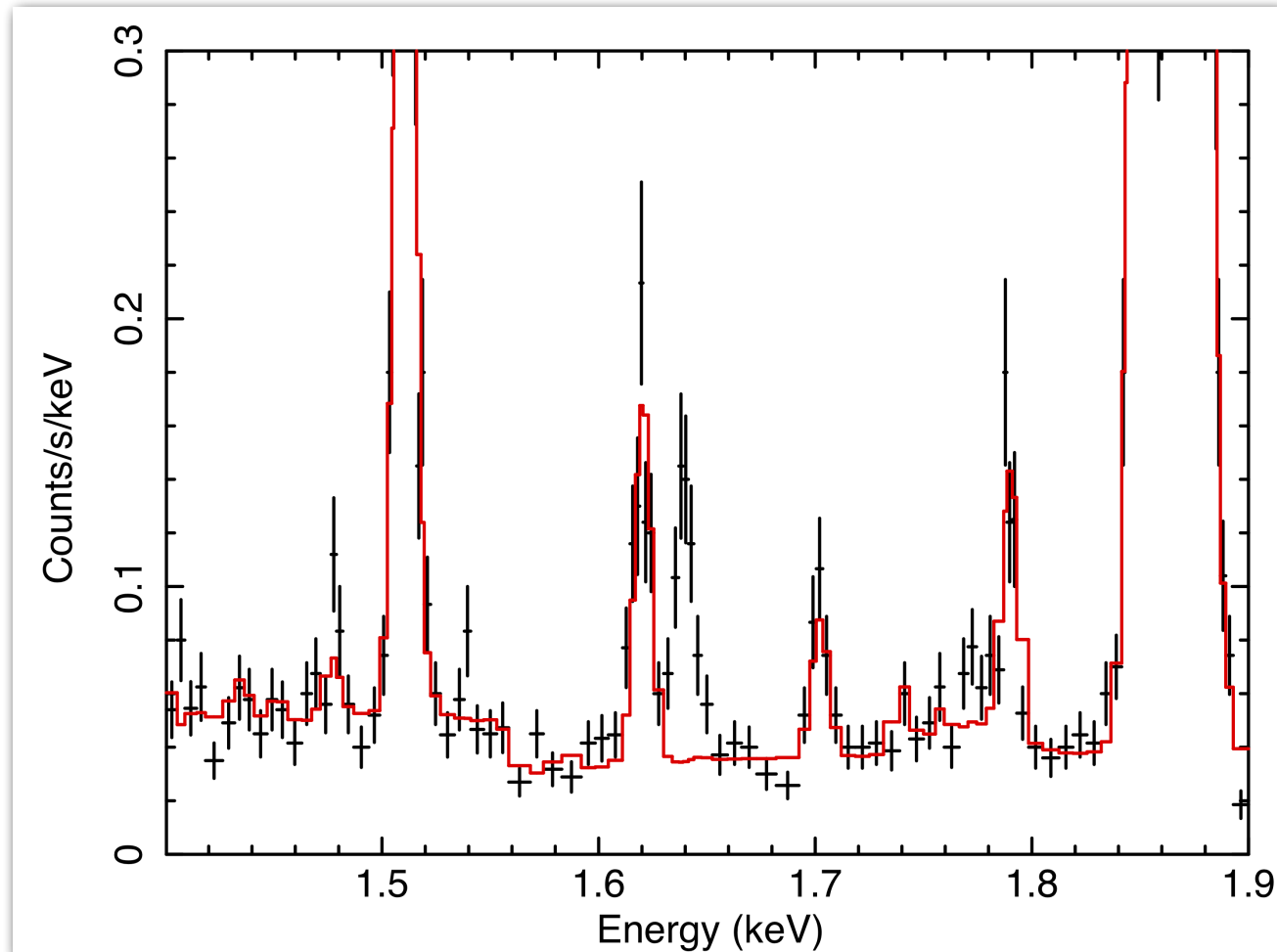


- Ion temperature: little influence on line excitations/ionizations
- Measuring ion temperature: thermal Doppler broadening
- Equation: $kT_i = m_i \sigma_v^2$
- So measure line width $\rightarrow$ get ion temperature
- But:
 - Also plasma velocity gradients cause lines to broaden
 - Solution: measure close to edge
 - Issue with Resolve: difficult to isolate emission from edge

What to expect from XRISM-Resolve?

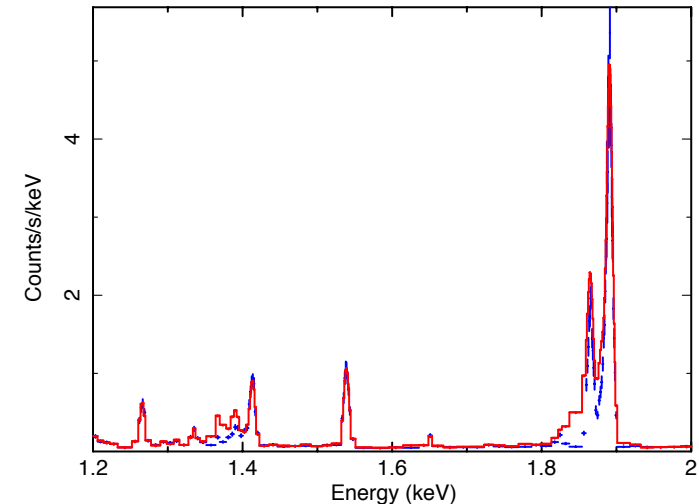
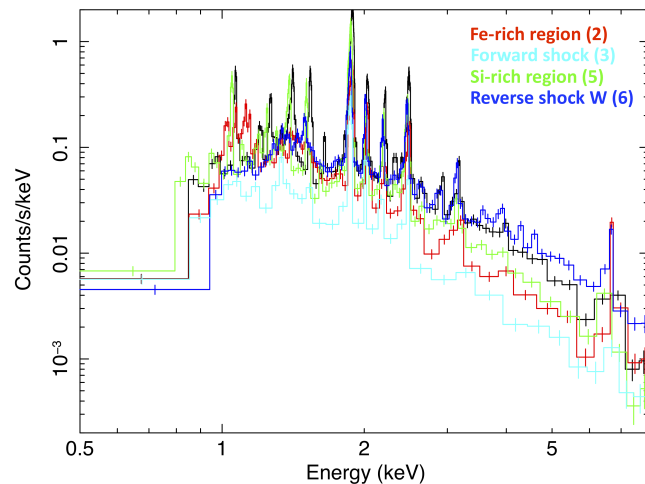
- From line blends to individual lines
 - Measure triplets -> better constraints on $n_e t$, kT_e
 - Detect weak lines: due to resolution even weak lines stand out!
 - Higher n transitions
 - Common: abundances even elements (O,Ne,Mg, Si,S,...)
 - Lines from rare elements: Na, Al, P, Cl, K,Ti, Cr, Mn,Ni
 - some (Cr,Mn,Ni) have been detected but barely
 - Odd elements: sensitive to pre-supernova abundances, details of explosive nucleosynthesis elements
 - Currently: gate-valve will hamper detecting some of these lines

Al-K



- Simulation for 100 ks, gatevalve open
- Al-K line at 1.65 keV

Cas A: signature of dust grain emission



- Cas A most important young (350yr) core-collapse SNR
- Infrared studies (e.g. De Looze+ 17): a lot (most?) Si contained in dust
- Nevertheless: bright Si-K lines (brightest lines!)
- How much Si in grains? And do they emit X-rays?
- Answer: yes
 - Dust sputtering: refreshing of Si ions $\rightarrow$ low ionization Si
 - Electron/grain collisions: Si-K fluorescence lines from dust
 - Critical: dust destruction time
 - $t < 30$ yr: most grains destroyed $\rightarrow$ no difference
 - $t > 30$ yr: most Si in dust $\rightarrow$ expect signatures

Summary

Or: the things I am looking forward to!

- Detecting for the first time *odd-Z elements*, and pinpointing in which ejecta layers they reside (young SNRs)
- Routine measurements of Cr, Mn, Ni abundances (Fe group)
- *Ion* temperature measurements
 - Special case: reverse shock heating; RS velocity cannot be easily measured with proper motions
- Direct evidence for pure metal plasmas: free-bound emission
- Better plasma velocity diagnostics -> can help disentangle different plasma elements along LoS
- Evidence for silicon in dust grains
- Better diagnostics of plasma elements, i.e. disentangling plasma blends