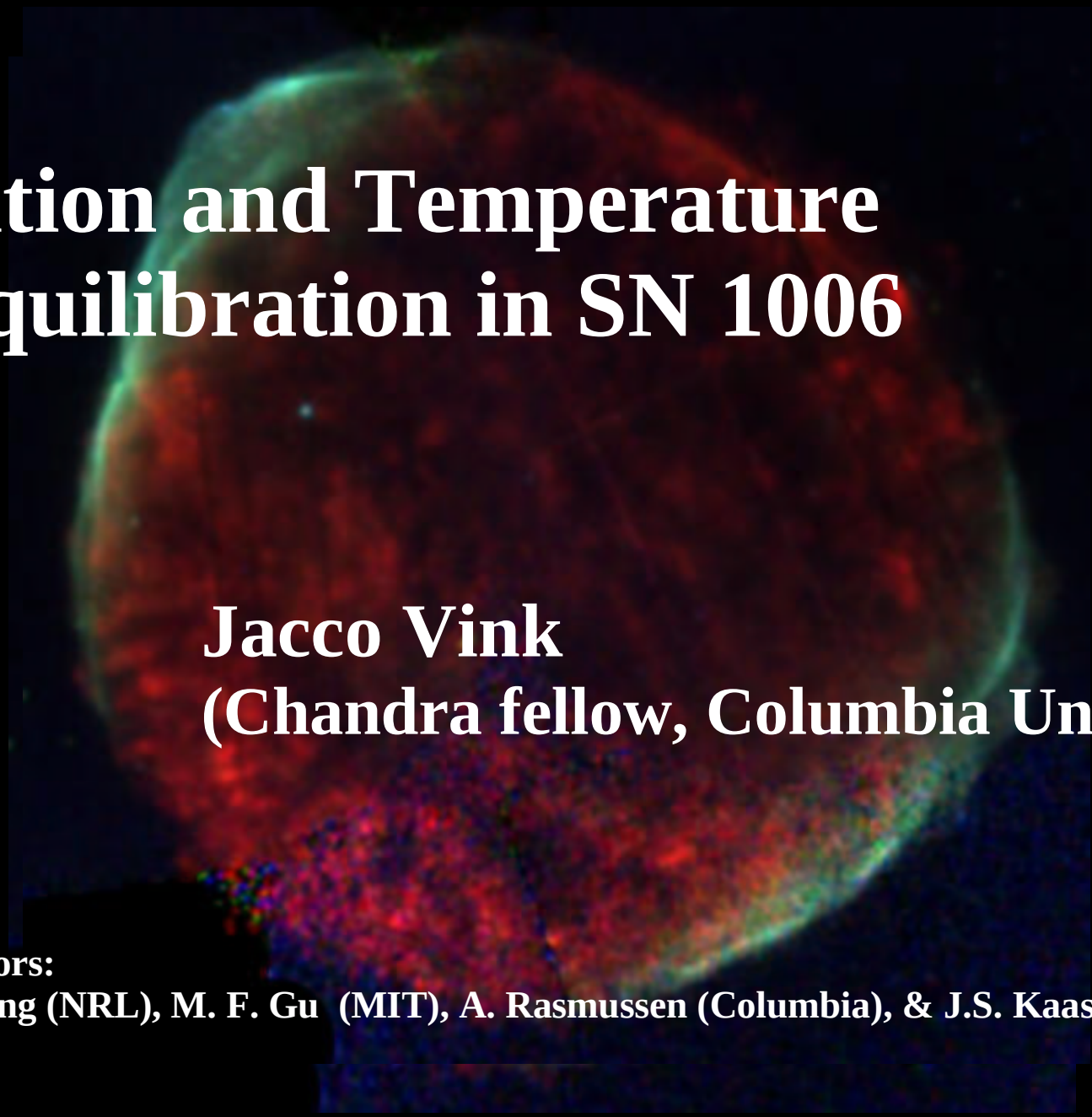

Ionization and Temperature non-equilibration in SN 1006

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Supernova remnant shocks

- The shocks are collisionless
  (particle free path > size of shocked region)
- shock heating process not well understood (plasma waves)
- sites of cosmic ray acceleration by 1st order Fermi acc.
- injection mechanism not well understood (plasma waves)
- cosmic rays influence shock structure
  (smooth shock structure, lower effective compression)
- initial electron temperature low/ ion temperature high

$$kT_i = 2(\gamma-1)(\gamma+1)^{-2}\, m_i\, v_s^2 = 3/16\, m_i\, v_s^2 \quad \text{(for } \gamma = 5/3\text{)}$$

$$\text{density compression ratio} = (\gamma+1)(\gamma-1)^{-1} = 4$$

- slow (Coulomb) or fast (plasma waves) temperature equilibration of ions and electrons?

Why SN1006?

- **young (~1000 yr) and low density (0.1 ions/cc)**
  ionization and equilibration scale with $n_e t$
  for SN 1006 ~ 3 10^9 $cm^{-3}s$
  cf Cas A $n_e t > 10^{11}$ $cm^{-3}s$
  ionization and temperature equilibrium $n_e t > 10^{12}$ $cm^{-3}s$
  We see post shock processes in " slow motion"

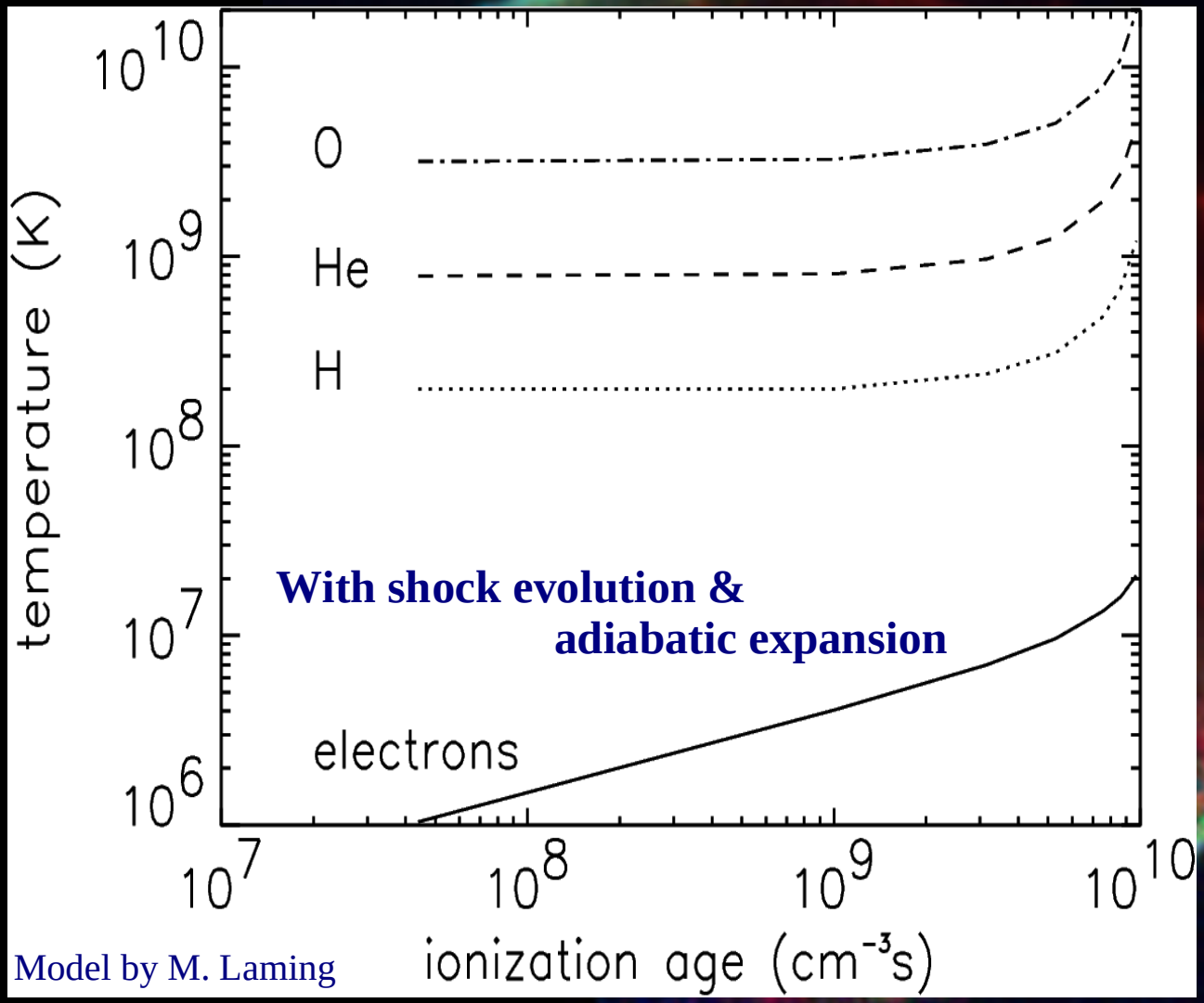
- **Optical/ UV spectroscopy indicates temperature non-equilibration**
  (Laming et al. 1996; Ghavamian et al 2002)
- **High Mach shock: >3000 km/s**
- **Interesting supernova remnant**

SN 1006 some background

SN 1006 aka G327.6+14.6 (NB high latitude!):

- **bright (<-6 mag) " guest star" in AD 1006 recorded in Middle East, Asia & Europe**
- **likely to be Type Ia (but lack of observed Fe)**
- **distance 2.1 kpc** *(Ghavamian et al. 2002, Winkler et al. 2002)*
- **30 arcmin diameter**
- **Absorption column: $N_H \sim 7 \times 10^{20}$ cm^{-2}**
- **First shell remnant for which X-ray synchrotron emission was established** *(Koyama et al. 1995)*

Post shock temperature equilibration



$n_e t \sim 3 \times 10^9$ cm^{-3}s,

$v_s \sim 3000$ km/s

(Ghavamian et al 2002)

$T_e \sim 10^7$ K,

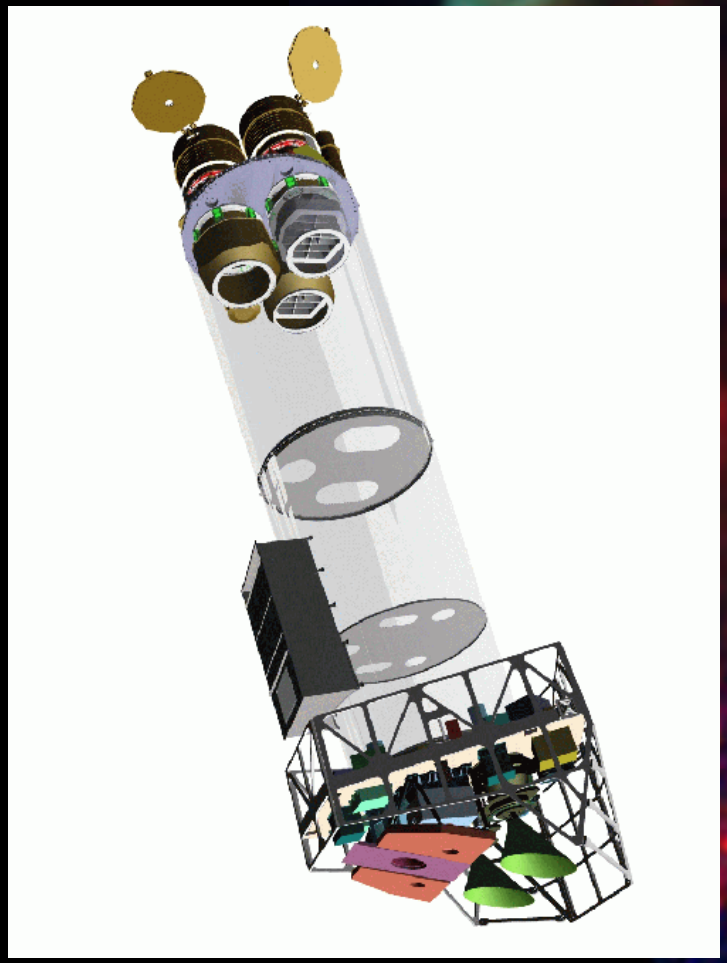
$T_{OVII} \sim 3 \times 10^9$ K

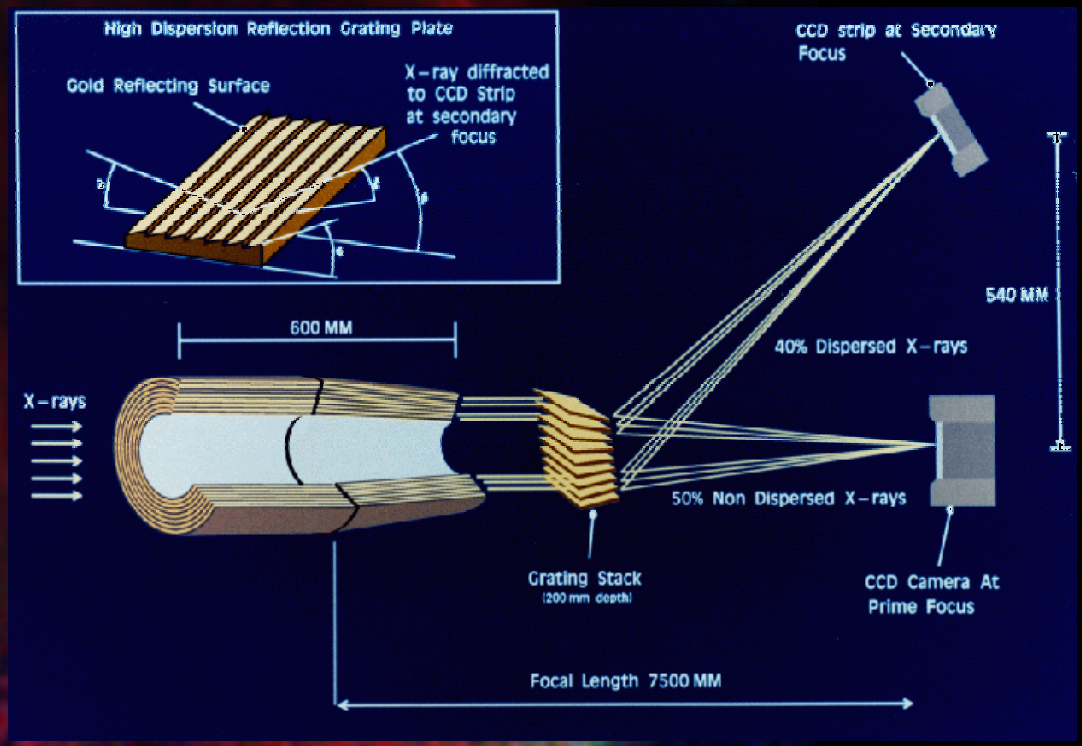
line dispersion

OVII @ 0.57 keV:

$\sigma_E \sim 2.5 \times 10^{-3}$ keV

XMM-Newton's Reflective Grating Spectrometer





Observational strategy with XMM-Newton

EPIC, Red = OVII

RGS target

Why this works:

$\Delta\lambda = 0.124(\Delta\varphi/1')$ Å

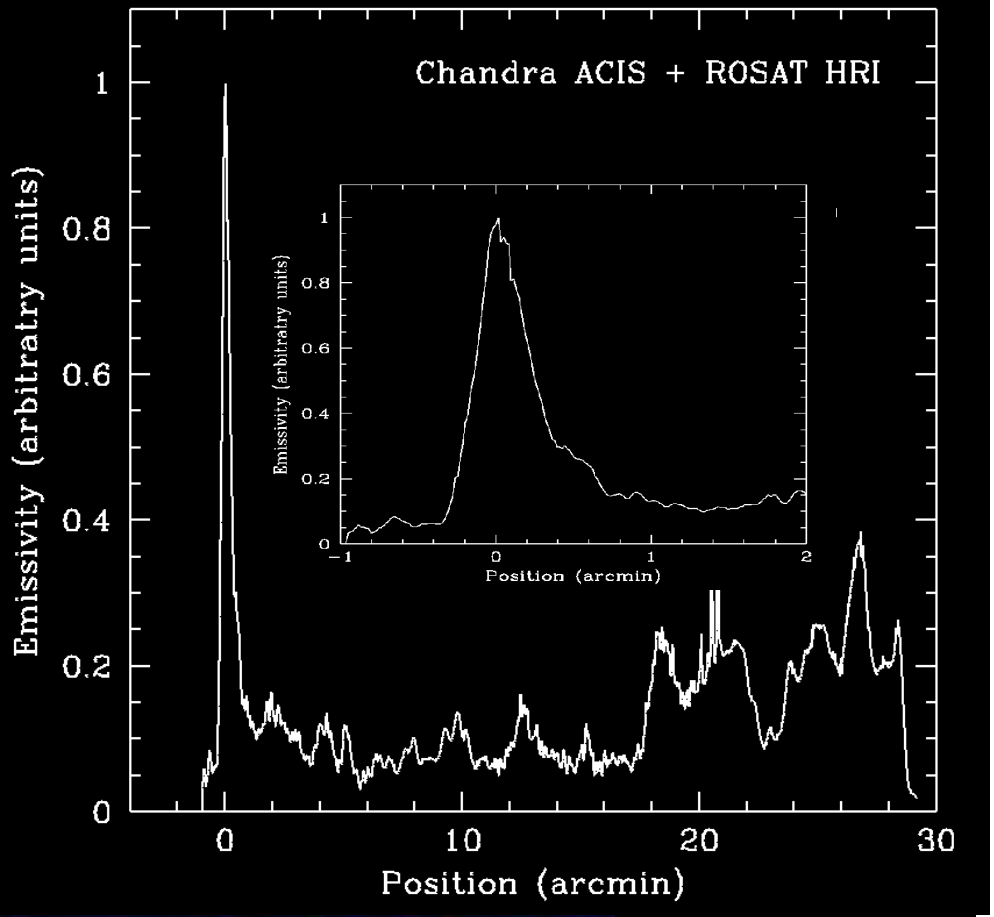
knot size ~ 1 arcmin

(0.4 arcmin FWHM)

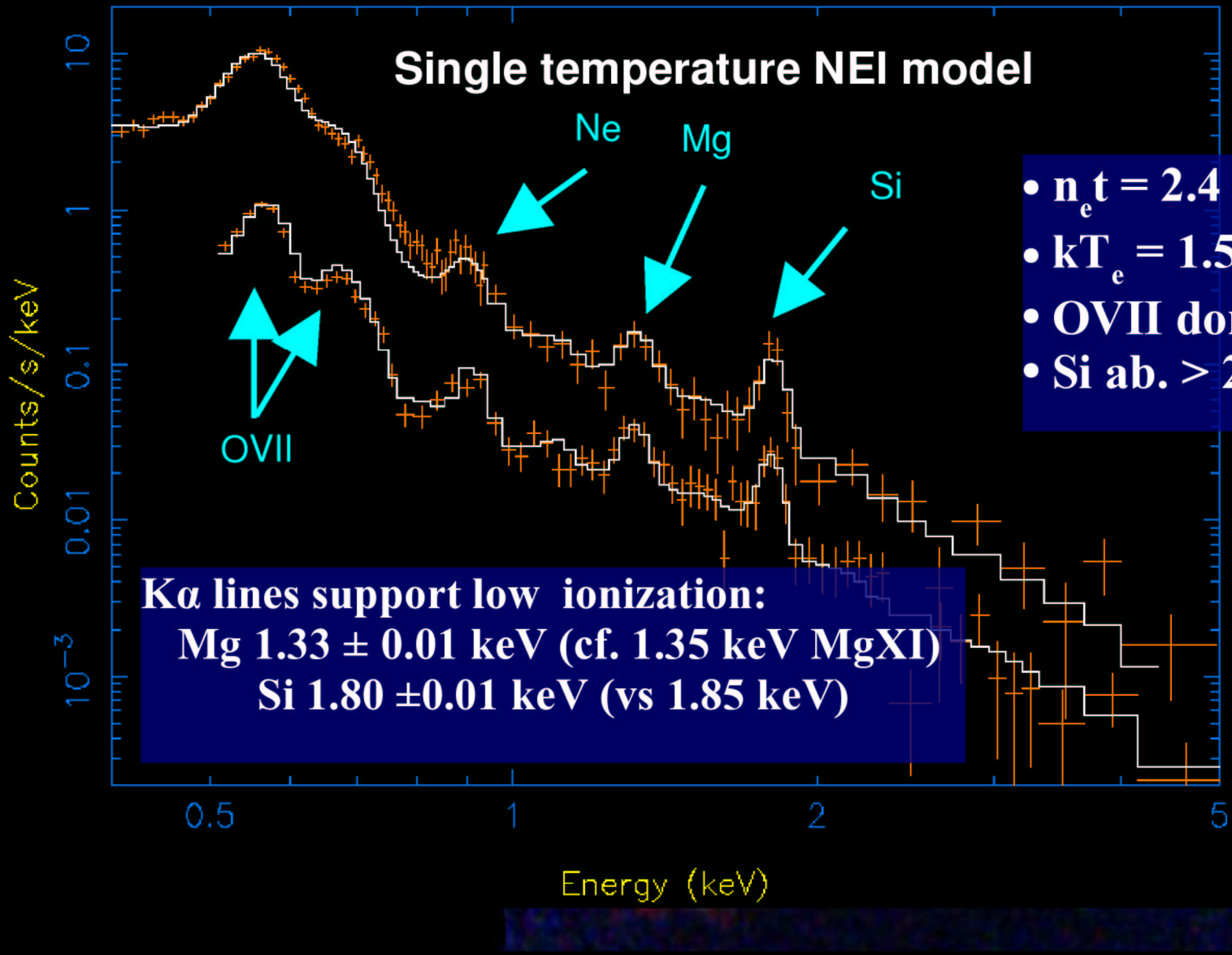
For OVII:

Resolution ~ 1/170

Disp. ~ 1/100 (FHWM)



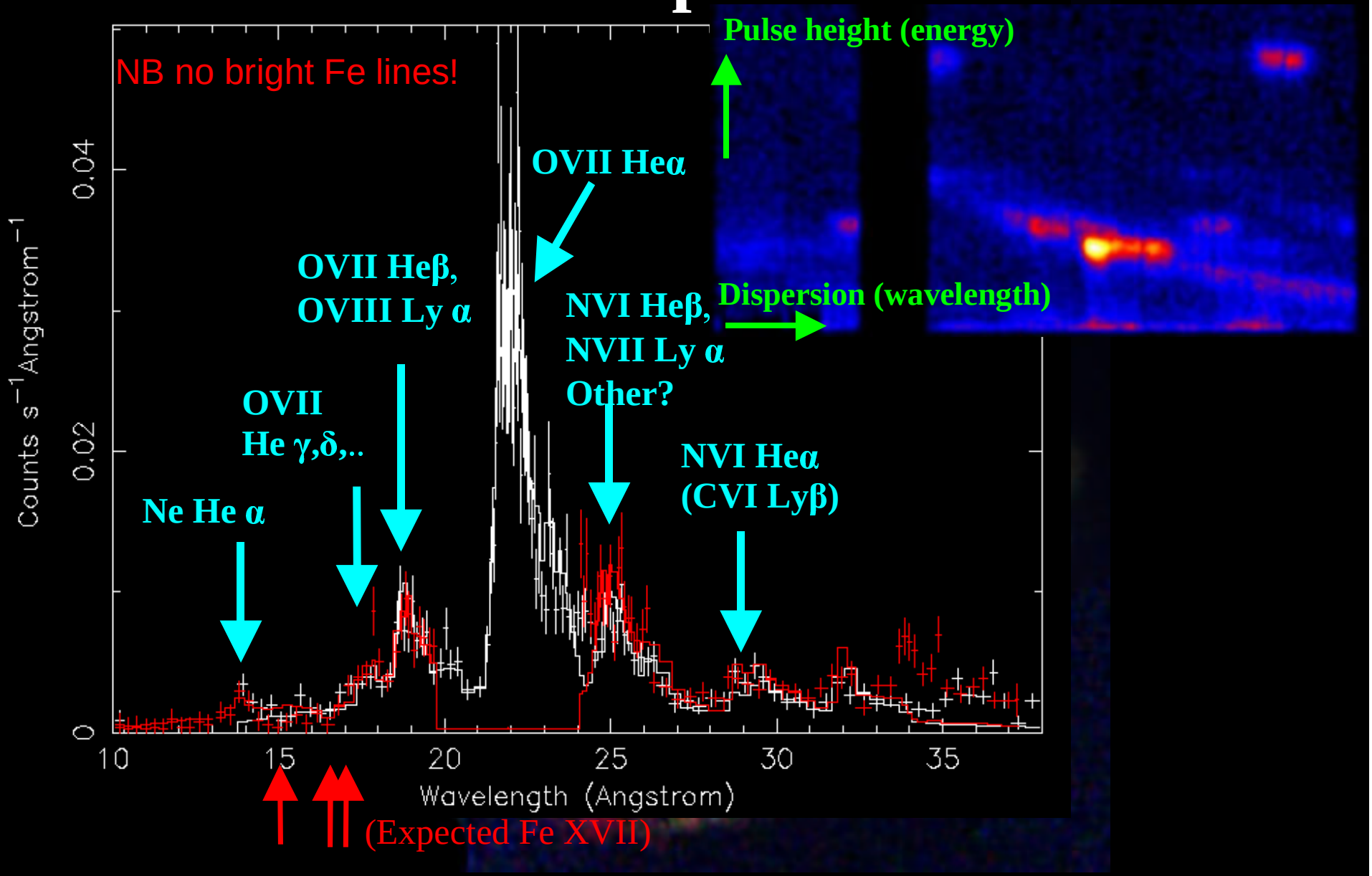
EPIC (CCD) spectra



- $n_e t = 2.4 \times 10^9$ cm^{-3}s
- $kT_e = 1.5 \pm 0.2$ keV
- OVII dominated
- Si ab. > 2 x solar

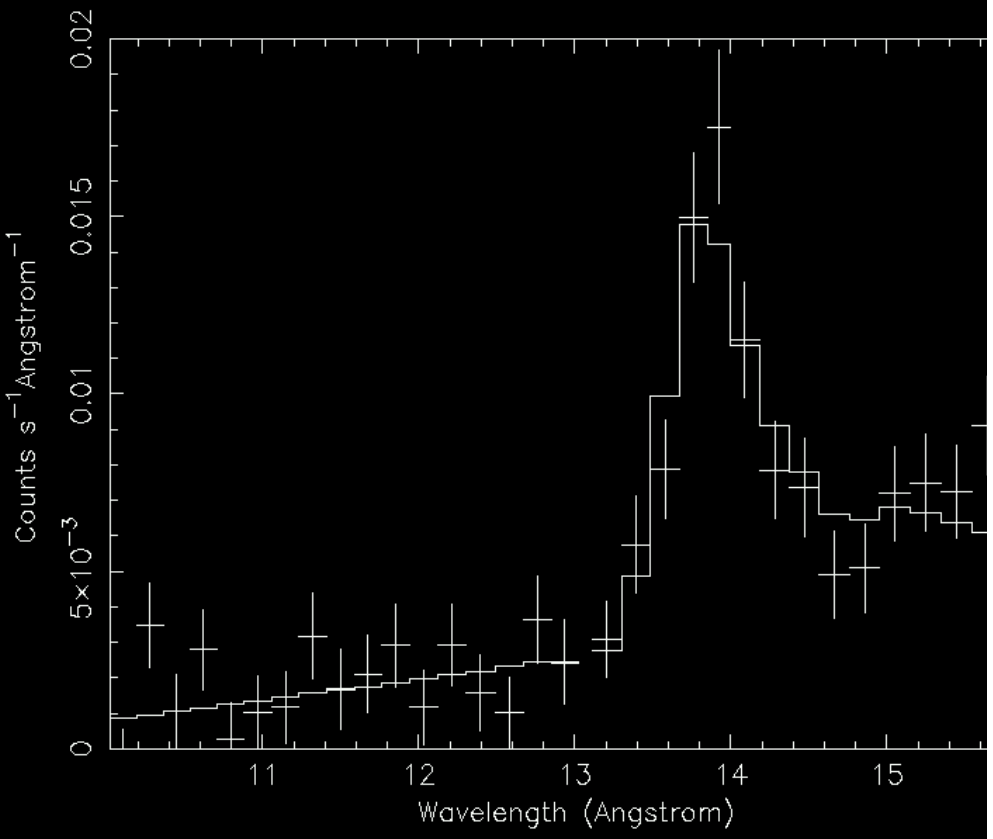
Kα lines support low ionization:
Mg 1.33 ± 0.01 keV (cf. 1.35 keV MgXI)
Si 1.80 ±0.01 keV (vs 1.85 keV)

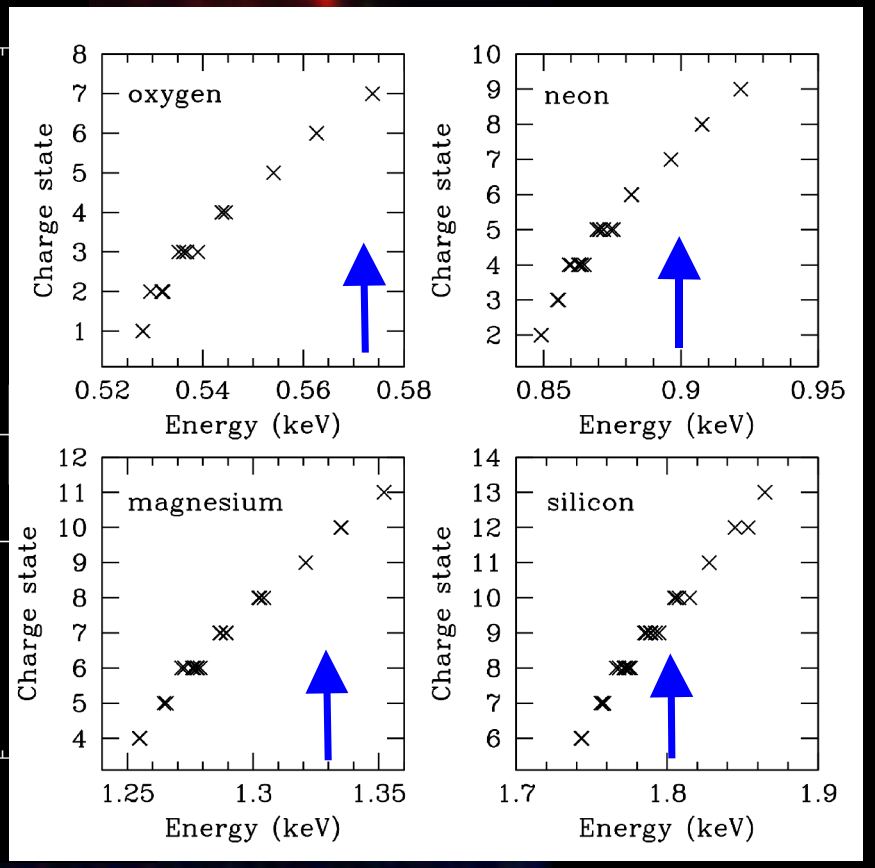
RGS Spectra


NB no bright Fe lines!
Pulse height (energy)
Dispersion (wavelength)
OVII Heα
OVII Heβ,
OVIII Ly α
NVI Heβ,
NVII Ly α
Other?
OVII
He γ,δ,..
NVI Heα
(CVI Lyβ)
Ne He α
(Expected Fe XVII)
Counts s^{-1}Angstrom^{-1}
0
0.02
0.04
10
15
20
25
30
35
Wavelength (Angstrom)

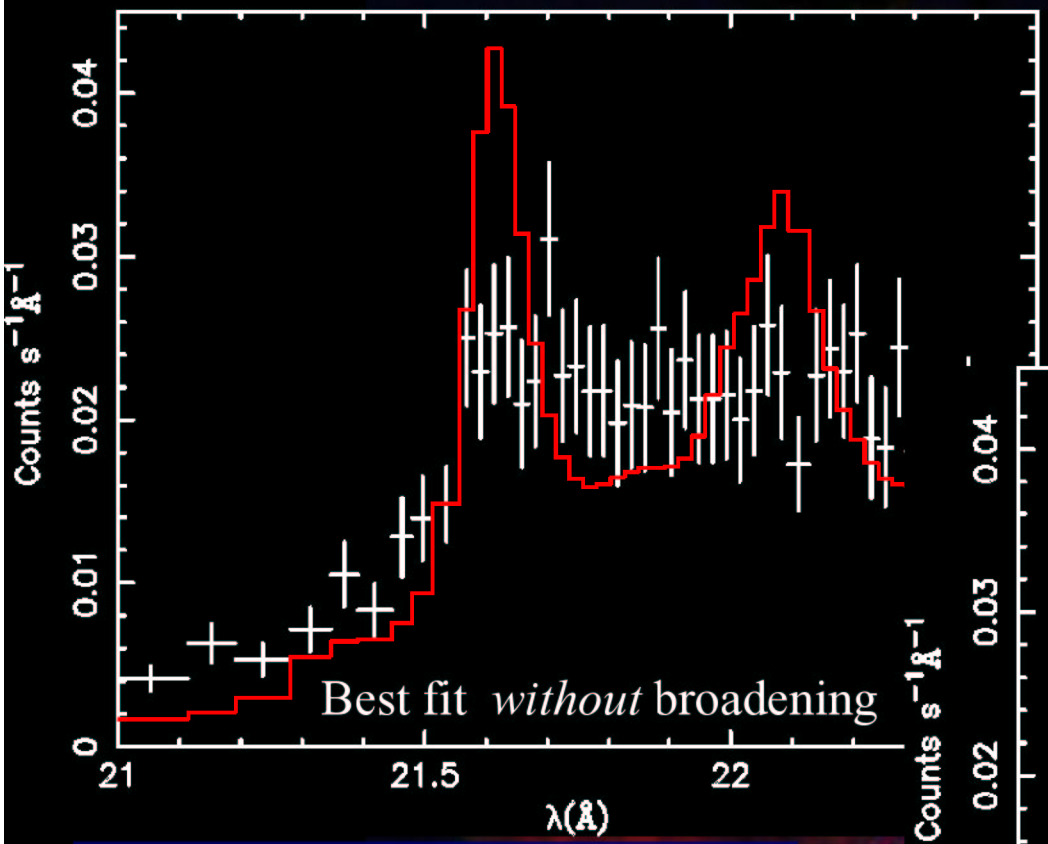
Low charge state of neon

Ne Kα (RGS 2 order 1)
measured centroid 13.78 +/- 0.06 Å
cf Ne IX w : 13.44 Å, z :13.70 Å

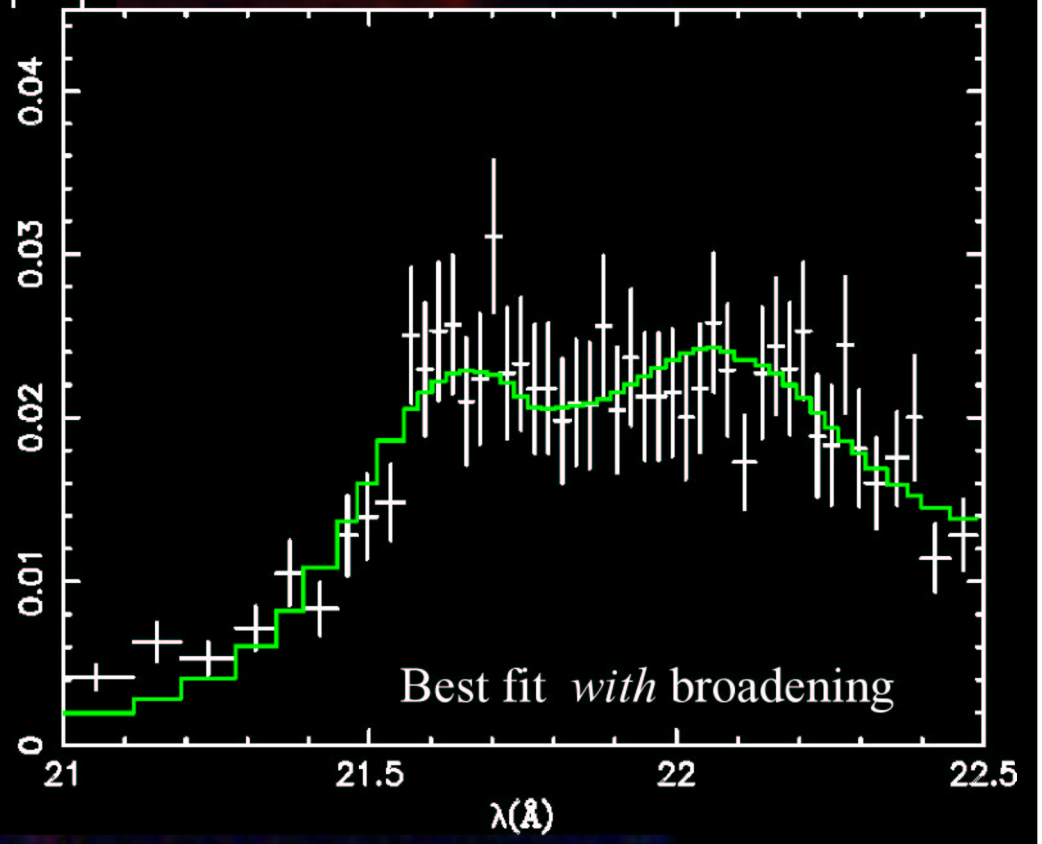




Measuring the OVII thermal broadening



No rapid equilibration of electron, proton and oxygen temperature!!



Results on line dispersion :

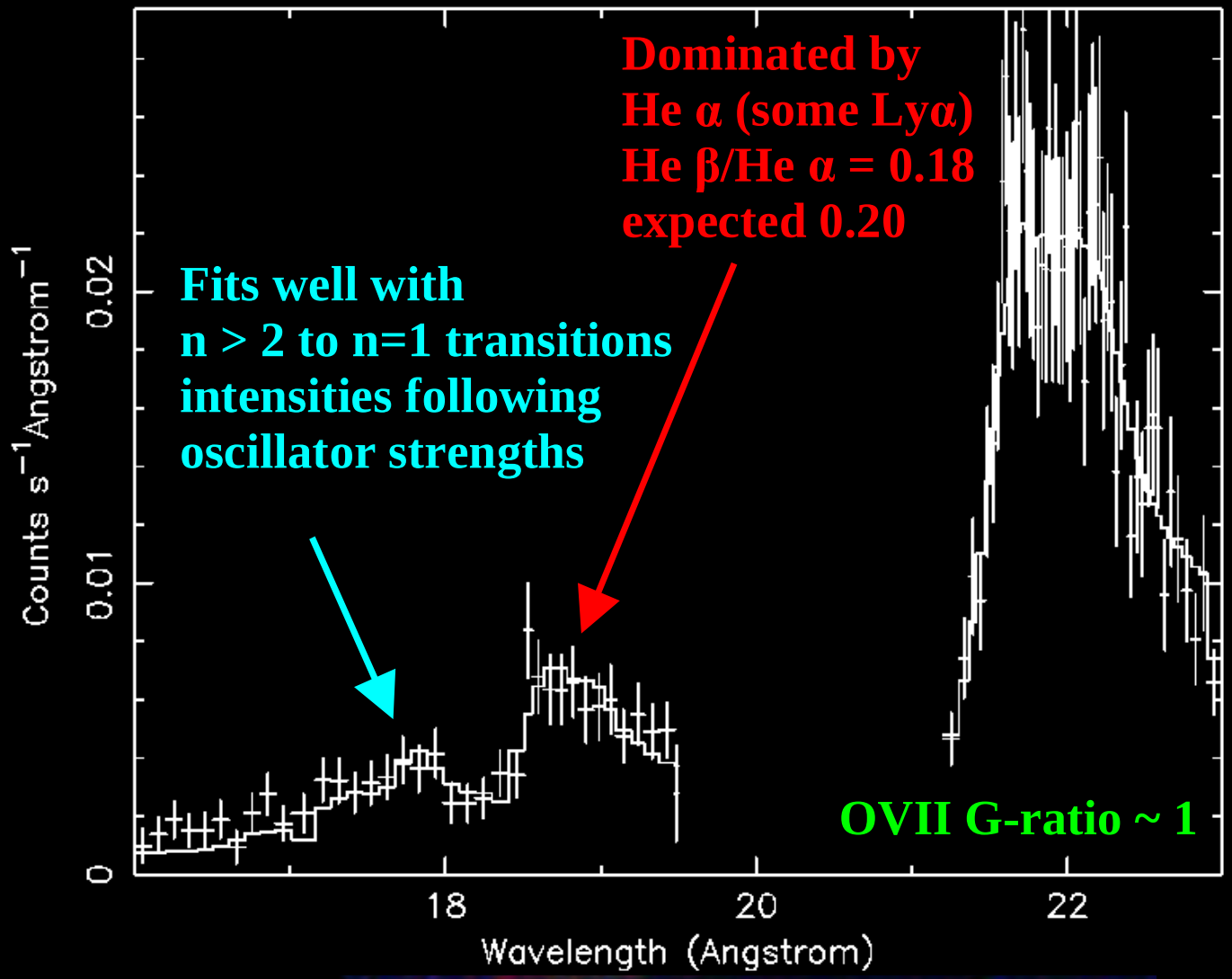
σ_E = 3.4±0.5 eV

kT_{OVII} = 528 ± 150 keV (6x10^9 K)

v_s ~ 4000 km/s

Statistical confidence : 6.5 – 9.8 σ

Some remarks



Conclusions

- **XMM's RGS allows high resolution spectrum of < 1 arcmin structures**
- **Slow (Coulomb) equilibration of electrons and ions in NW of SN 1006**
  i.e. $kT_e \sim 1.3$ ***keV and*** $kT_{OVII} \sim 500$ ***keV***
- **Is knot ejecta or swept up material?**
- **No evidence for Fe L emission**
- **Plasma in SN1006 shows extreme case of non-equilibrium ionization**

Results published in
Astrophysical Journal Letters (ApJ 587, L31)