Flare Loops

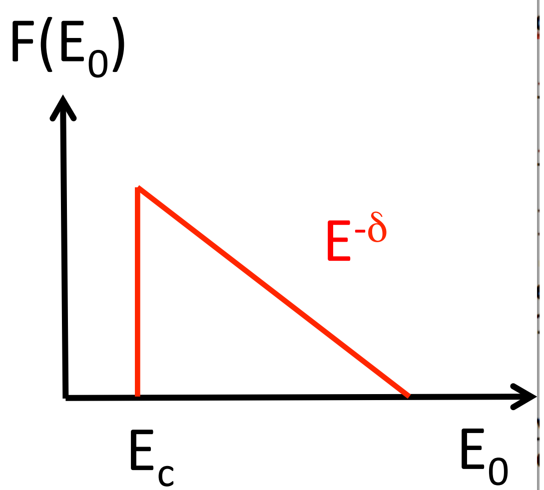
Emission lines & diagnostics

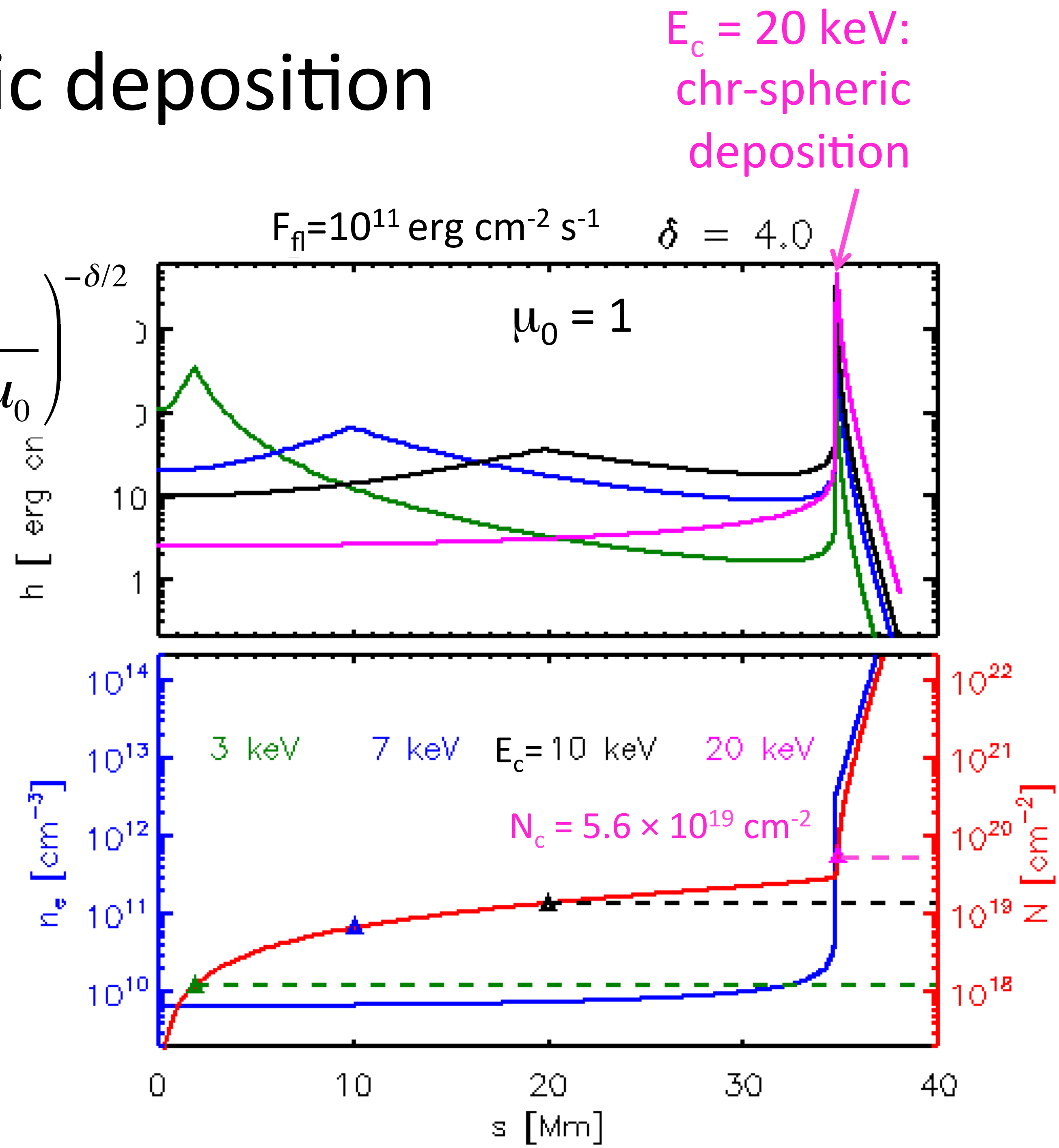
Lecture 11

Feb. 27, 2017

Chr-spheric deposition

$$h \sim F_{\mathrm{fl}}(t)\frac{n_e(s)}{\mu_0 N_c}\left(\frac{N}{N_c\mu_0}\right)^{-\delta/2}$$





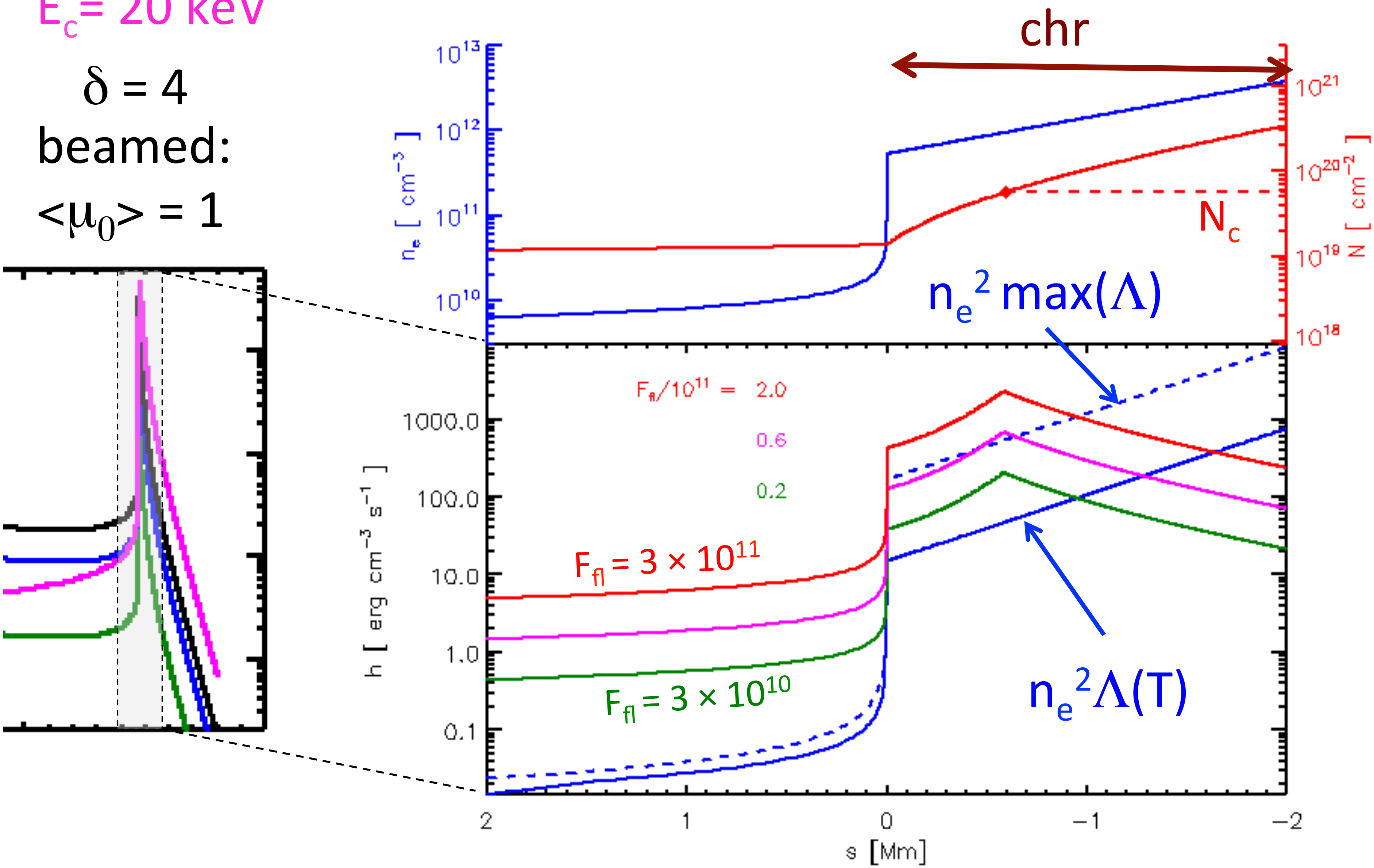
Chr-spheric deposition

E_c= 20 keV

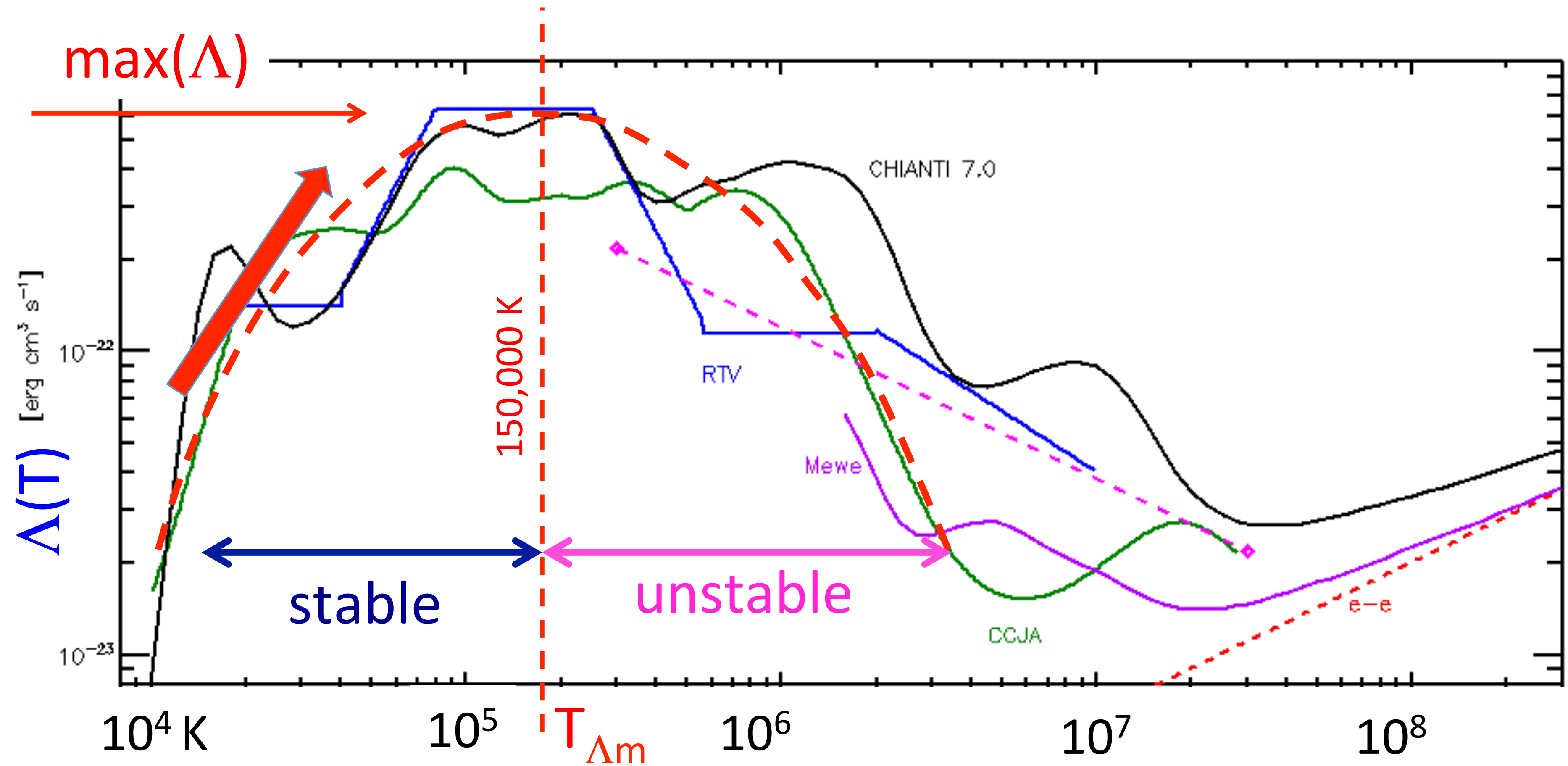
δ = 4

beamed:

$\langle\mu_0\rangle$ = 1



Radiative instability (@ constant n_e)



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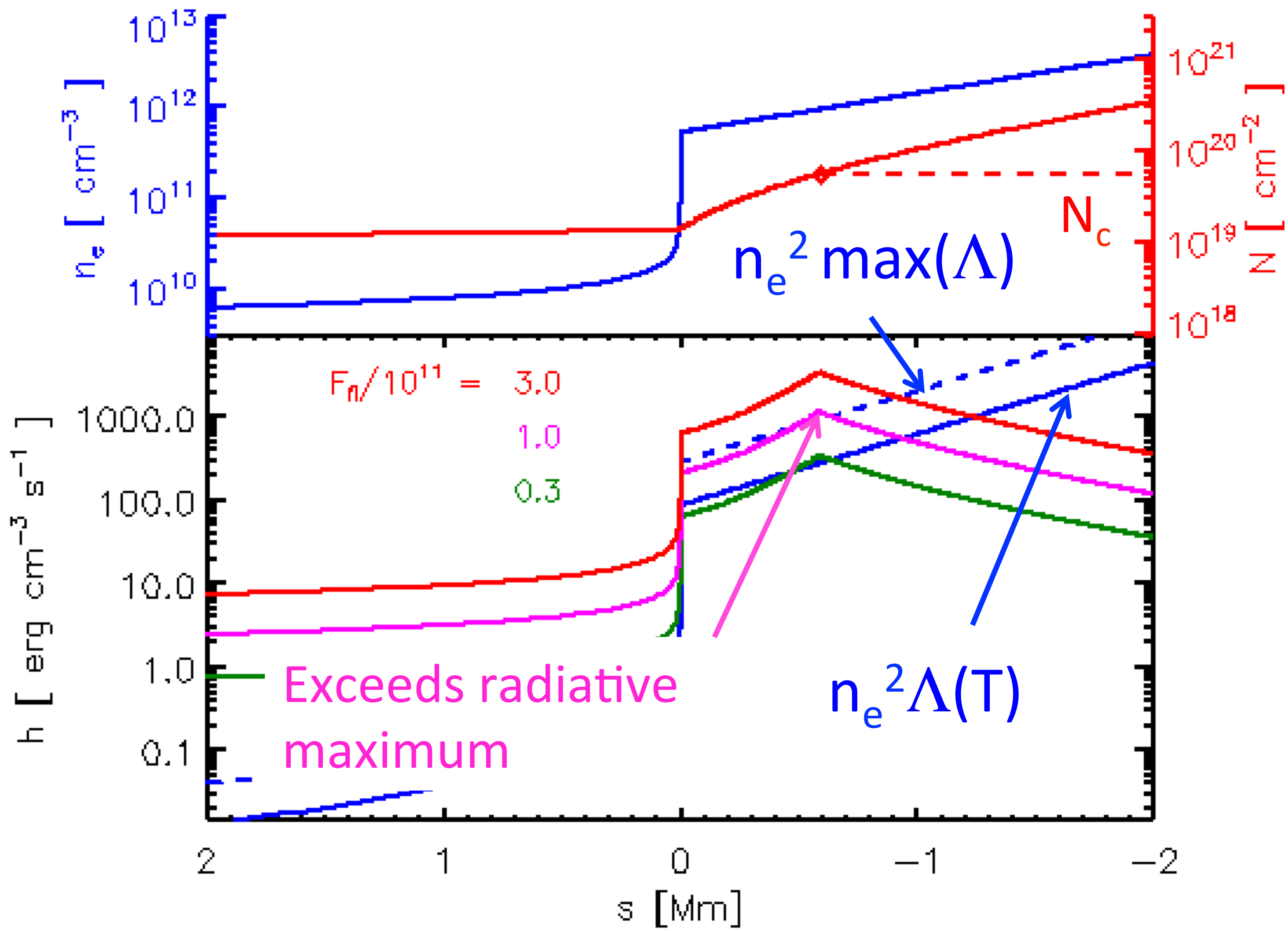
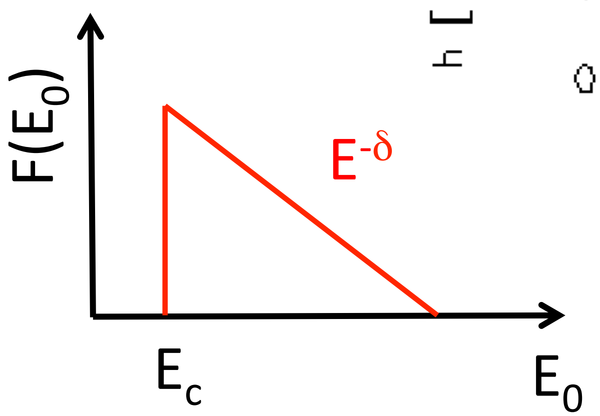
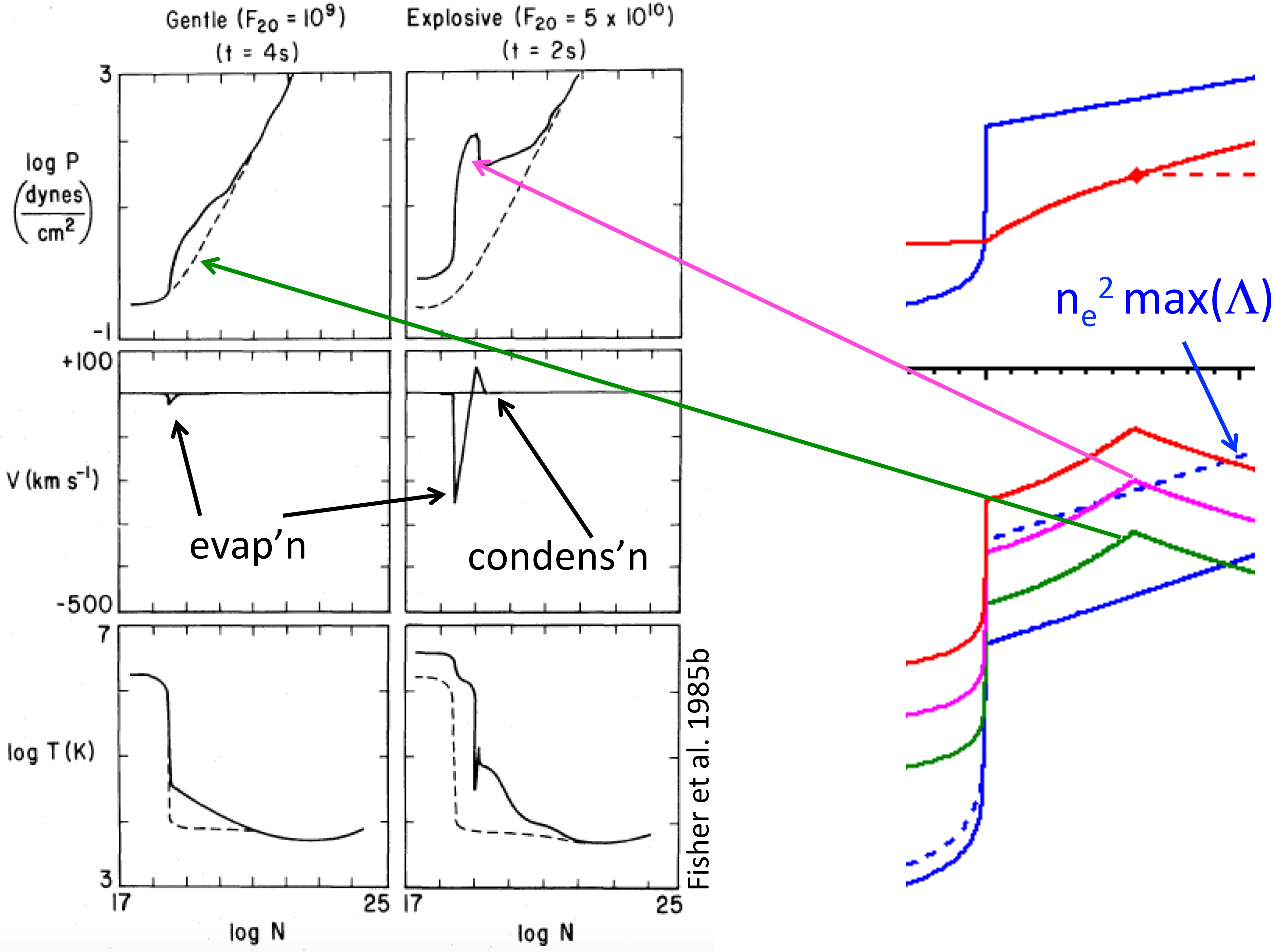
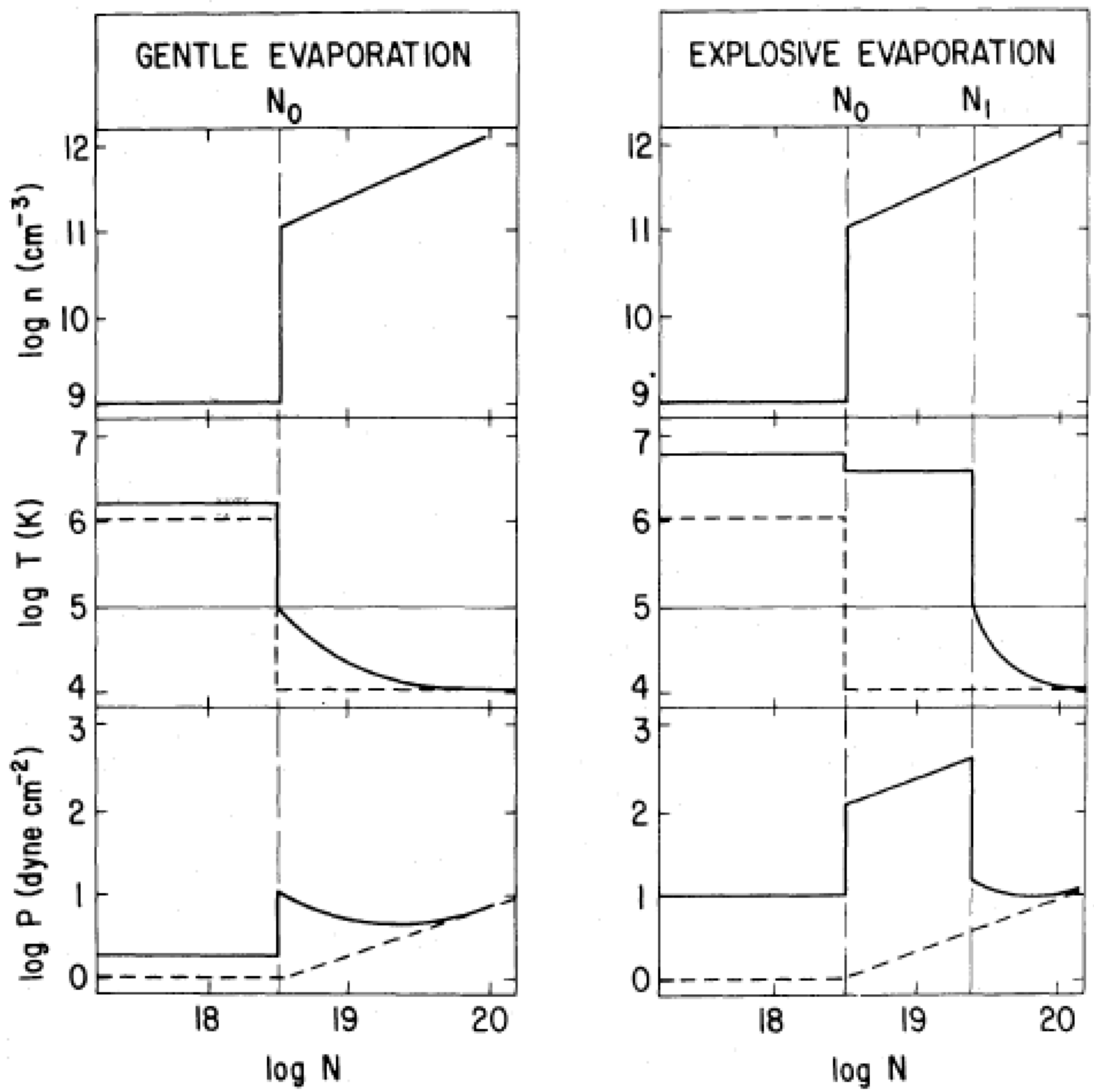






Gentle ($F_{20} = 10^9$)
(t = 4s)
Explosive ($F_{20} = 5 \times 10^{10}$)
(t = 2s)
log P (dynes/cm²)
3
-1
+100
-500
V (km s⁻¹)
evap'n
condens'n
7
3
log T (K)
17
25
log N
Fisher et al. 1985b
n_e^2 max(Λ)



Fisher et al. 1985b

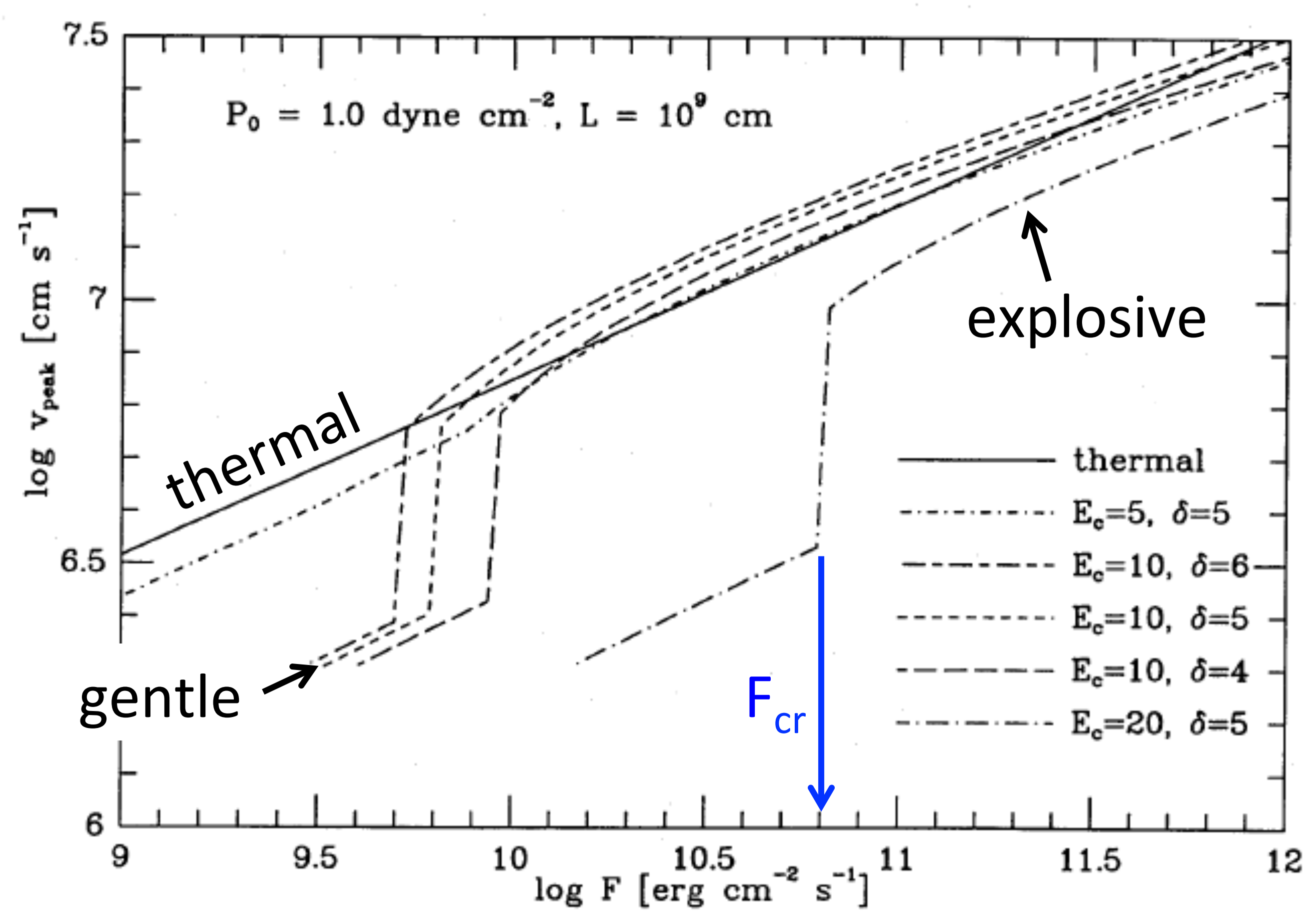
F_{cr}: local heating exceeds radiation

$F_{fl} < F_{cr}$: gentle evaporation

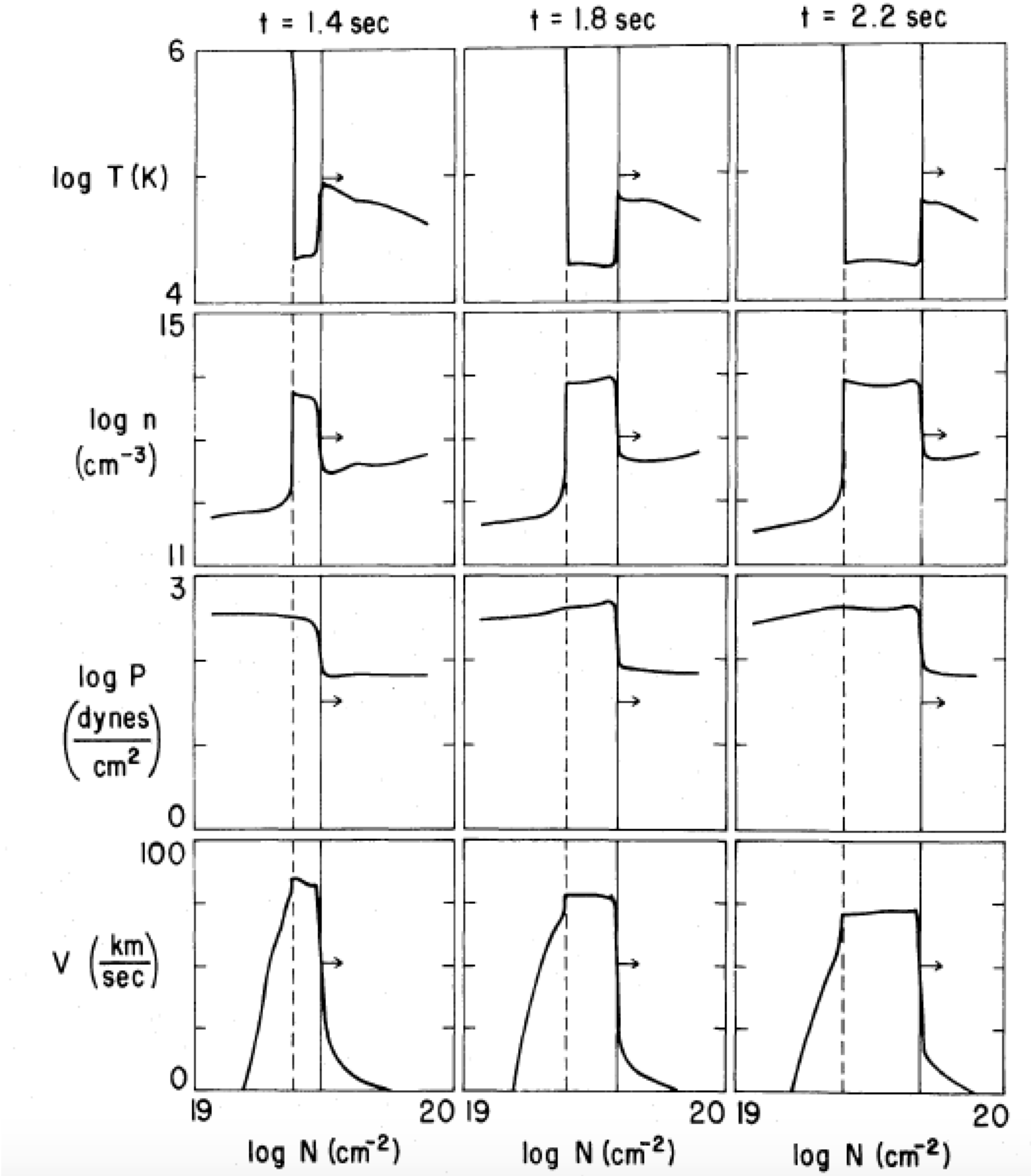
$F_{fl} > F_{cr}$: explosive evaporation

Fisher et al. 1985b

$$F_{cr} \approx \frac{N_* \max(\Lambda)}{2k_b T_{ch}} \left(p_{cor} + m_p g N_c \right) = 2 \times 10^{10} \, \mathrm{erg\,cm^{-2}s^{-1}} \left[p_{cor,cgs} + 0.64 \left(\frac{E_c}{10\,\mathrm{keV}} \right)^2 \right]$$



Fisher 1989

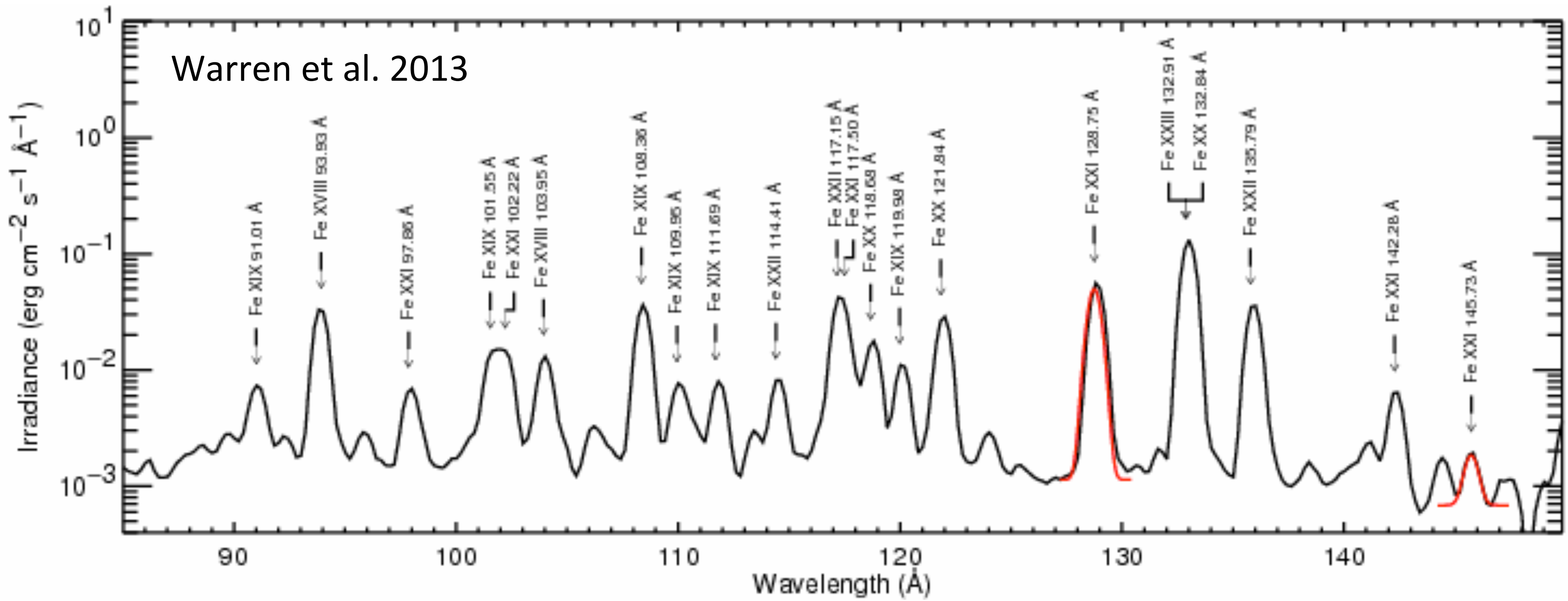


Fisher et al. 1985b

Observing the flare plasma

EVE data from X1.7 flare 2012-01-27

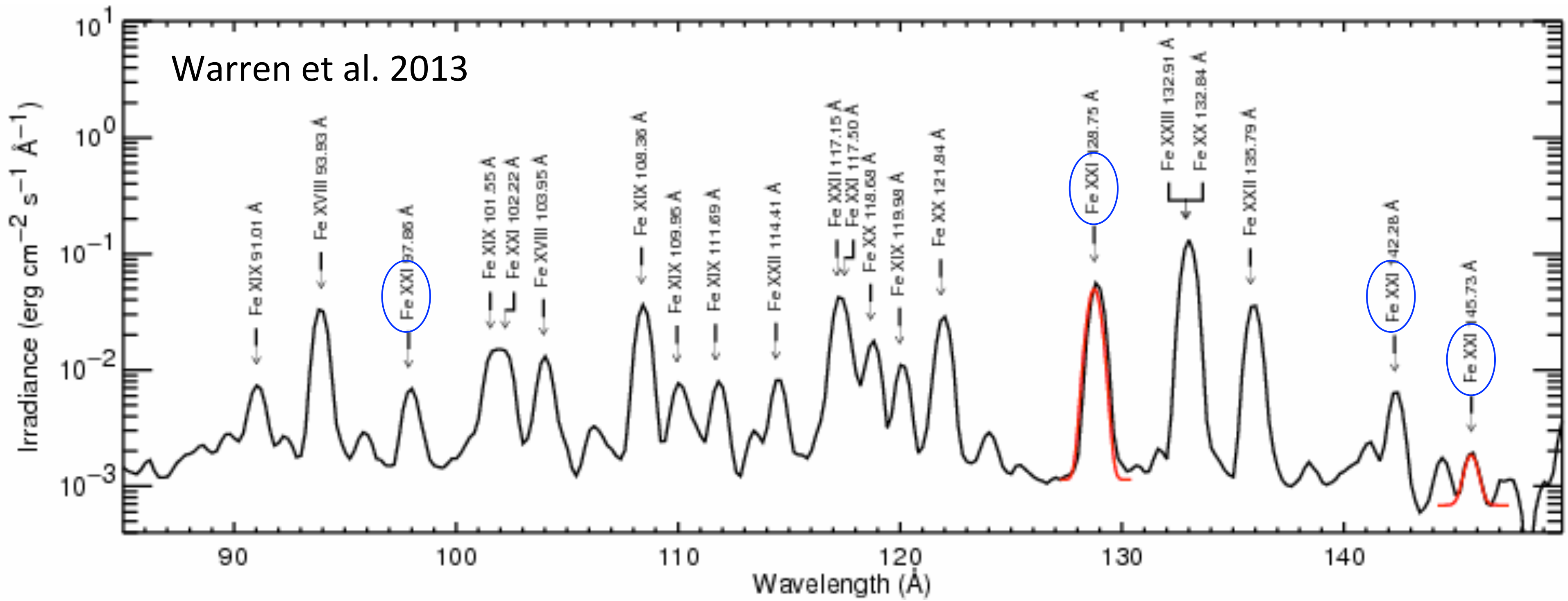
Emission spectrum: many highly ionized states of iron: Fe VIII – Fe XIII. Can tell us about n_e, T_e, and u in flare plasma – How?

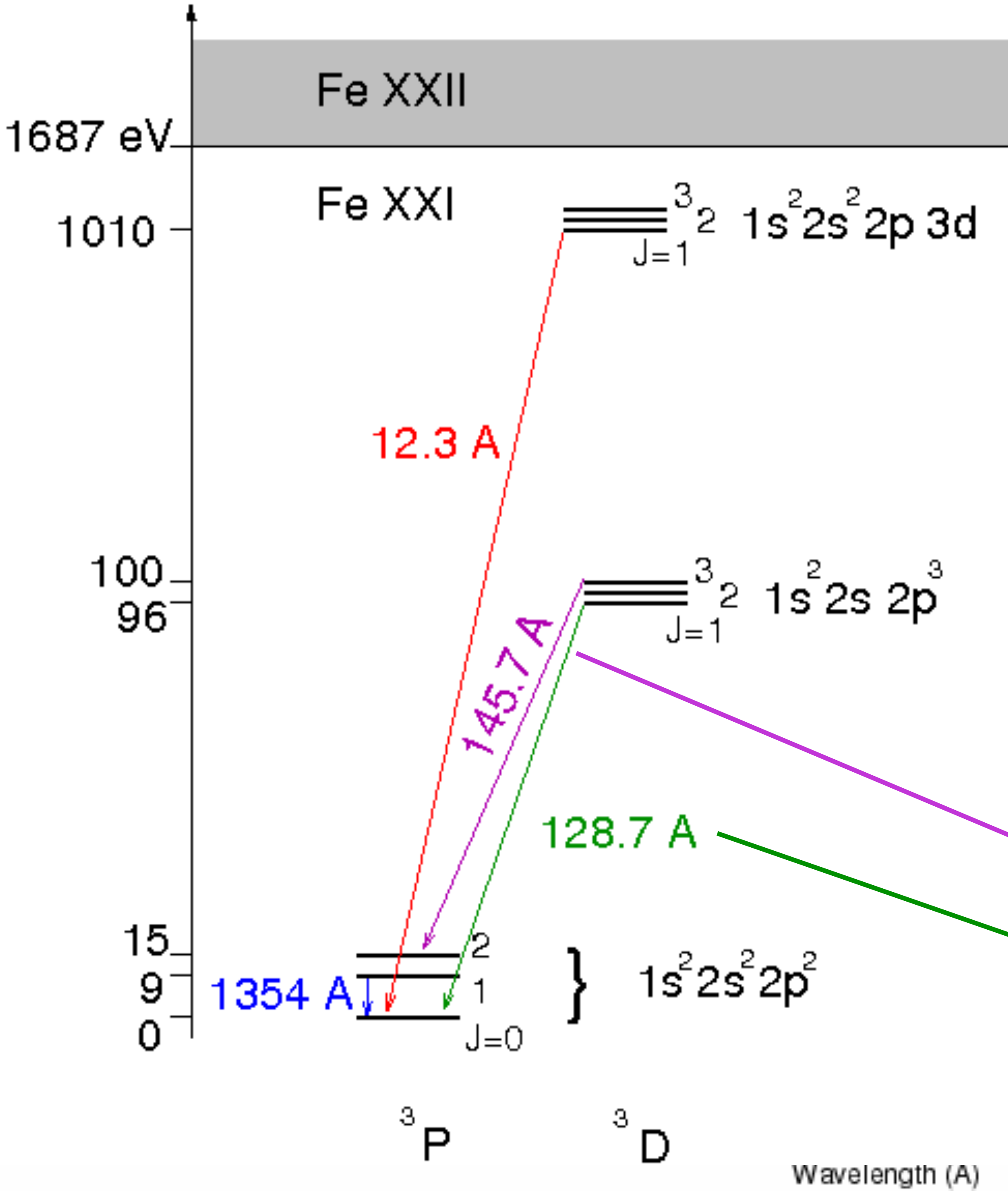


Observing the flare plasma

EVE data from
X1.7 flare
2012-01-27

e.g. **Fe XXI:** Fe ionized **20** times --- Z=26 nucleus w/ 6 electrons





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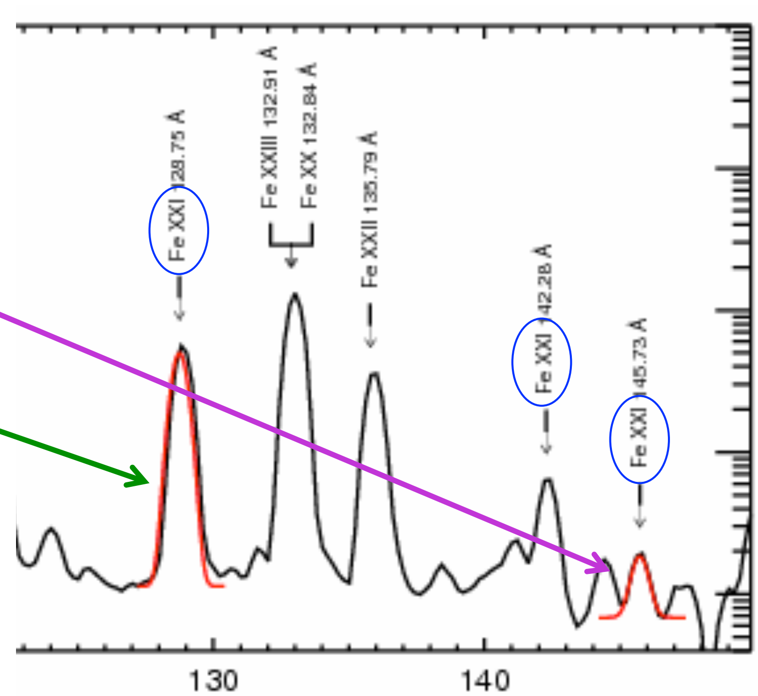
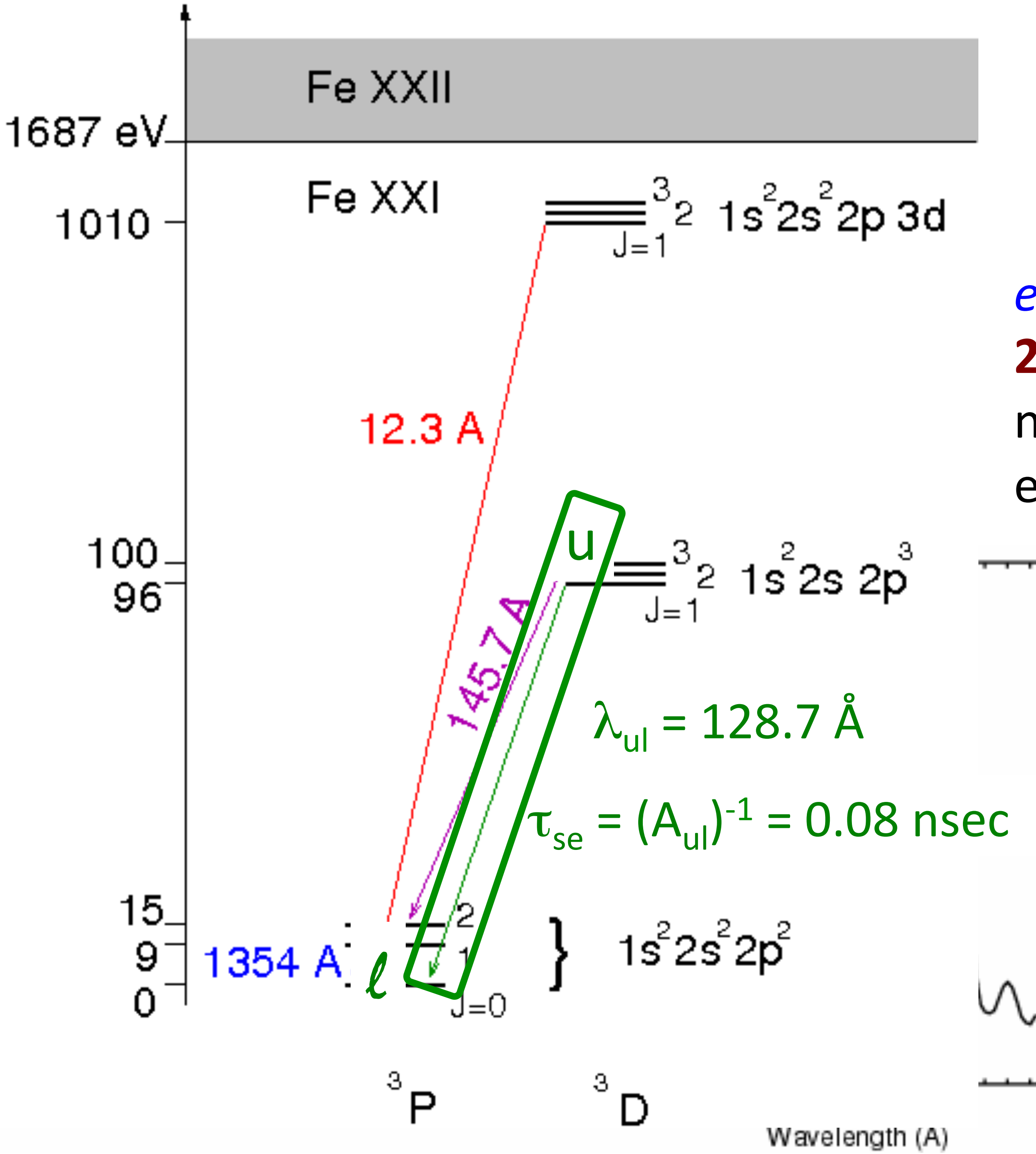
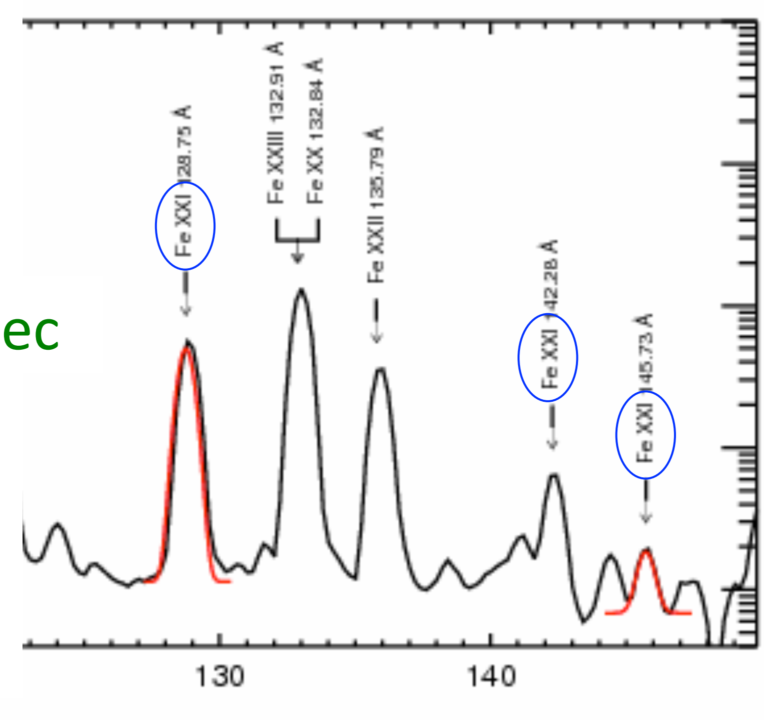




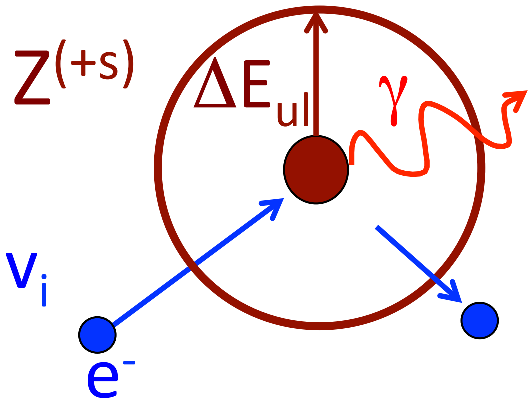
λ_{ul} = 128.7 Å

$\tau_{se} = (A_{ul})^{-1}$ = 0.08 nsec

e.g. **Fe XXI:** Fe ionized **20** times --- Z=26 nucleus w/ 6 electrons



Photons from collisional excitation



Assumption I: e^-s have **Maxwellian** dist'n w/ temp T_e

collision frequency

prob.

γ production rate per $Z^{(+s)}$

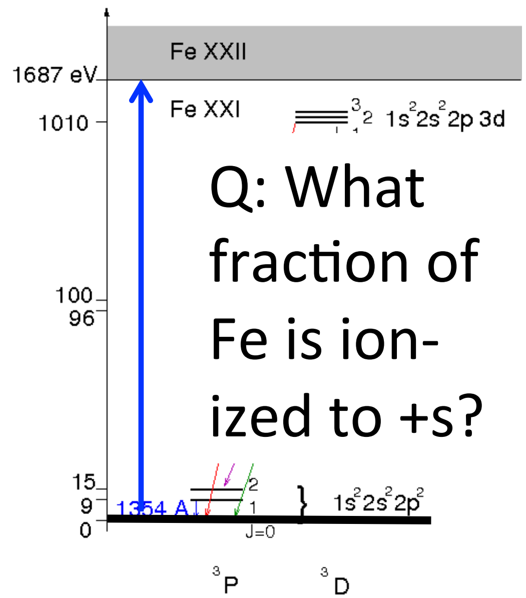
$$= \int \frac{e^{-m_e v_e^2/2k_b T_e}}{(2\pi k_b T_e / m_e)^{3/2}} n_e v_e \sigma_u(v_e) p_{ul} \; d^3 v_e$$

$$= n_e \int \frac{e^{-m_e v_e^2/2k_b T_e}}{(2\pi k_b T_e / m_e)^{3/2}} v_e \sigma_u(v_e) p_{ul} \, d^3 v_e$$

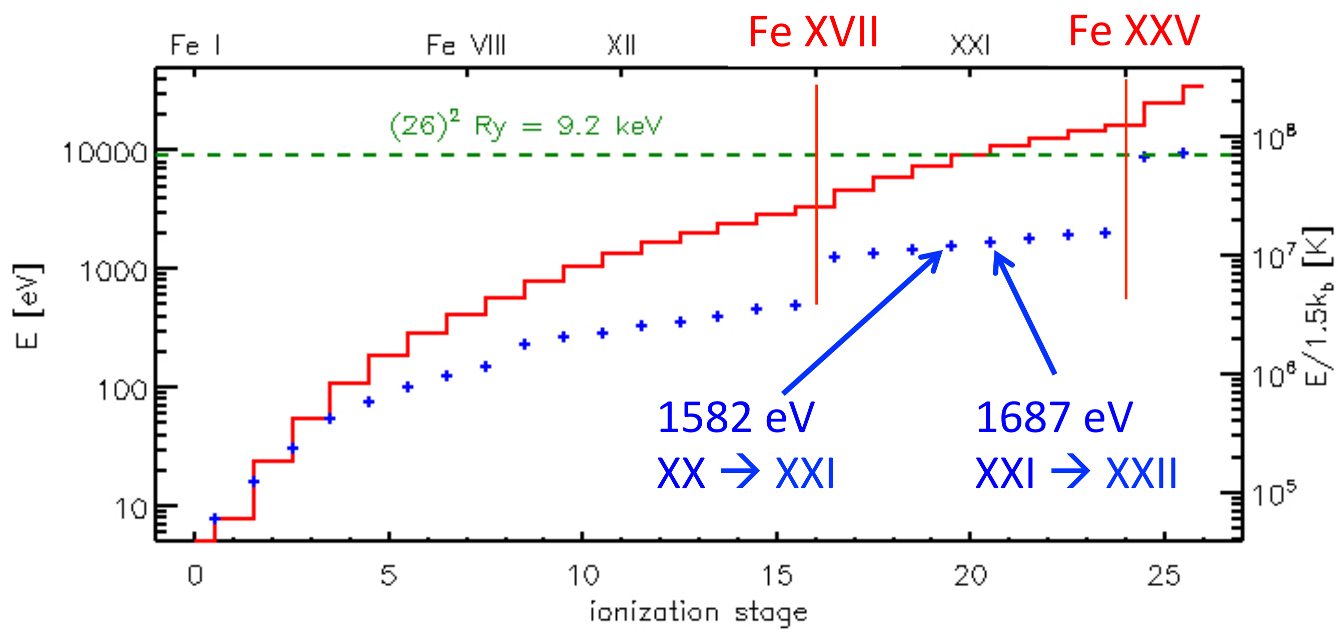
$C_{lu}(T_e)$ [$cm^3\ s^{-1}$]

From atomic physics data (i.e. CHIANTI)

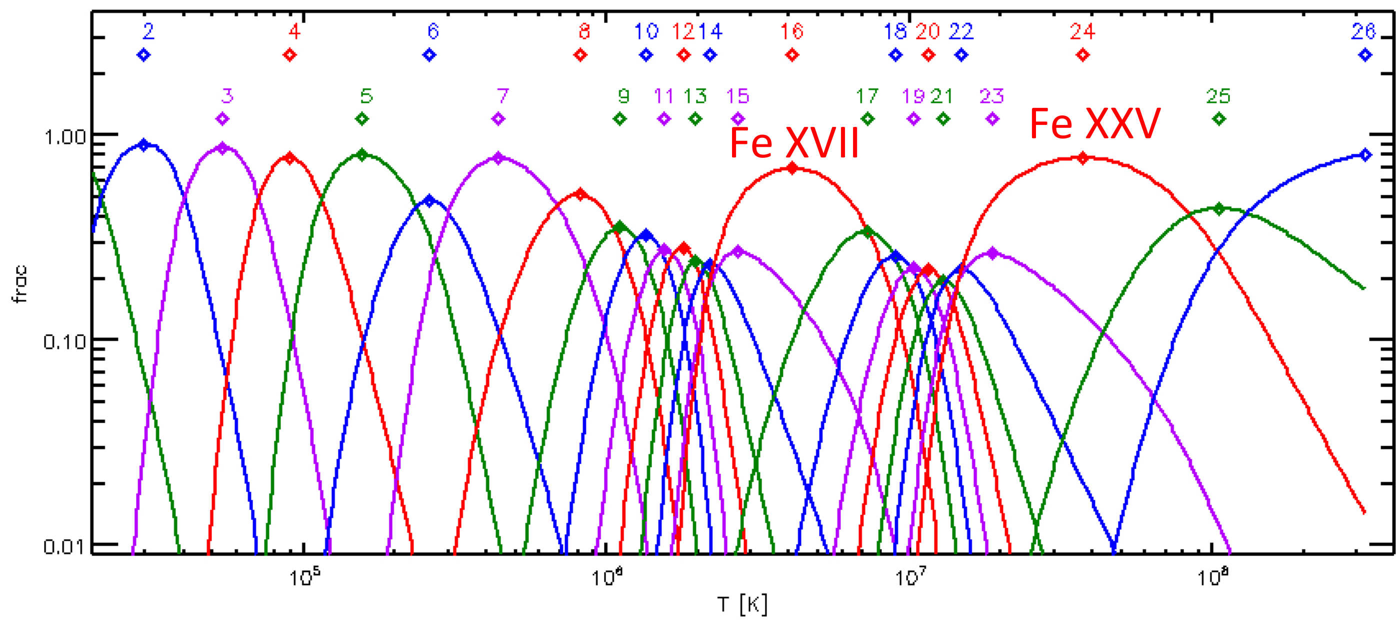
Ionization fraction



Q: What fraction of Fe is ionized to +s?



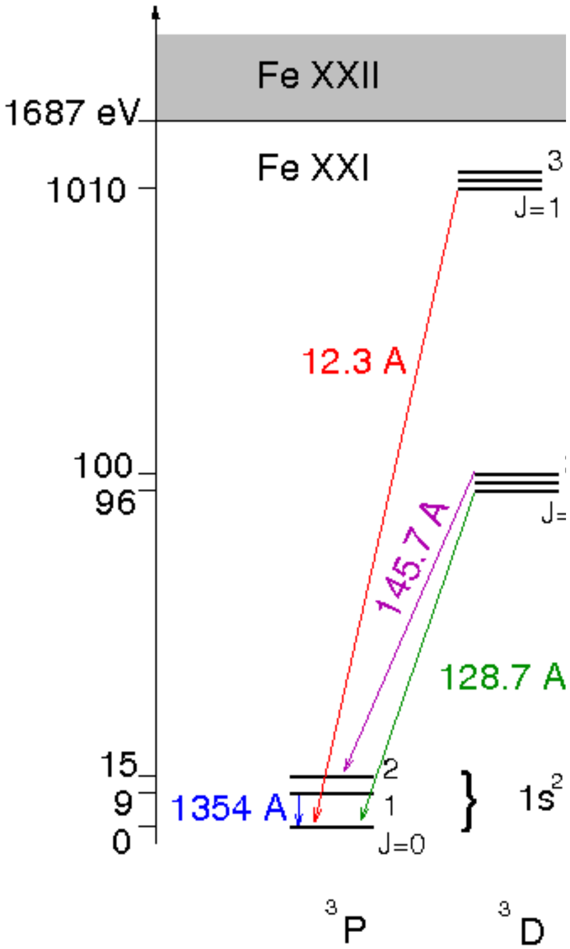
Fractions @ **statistical equilibrium** (Saha eq.)

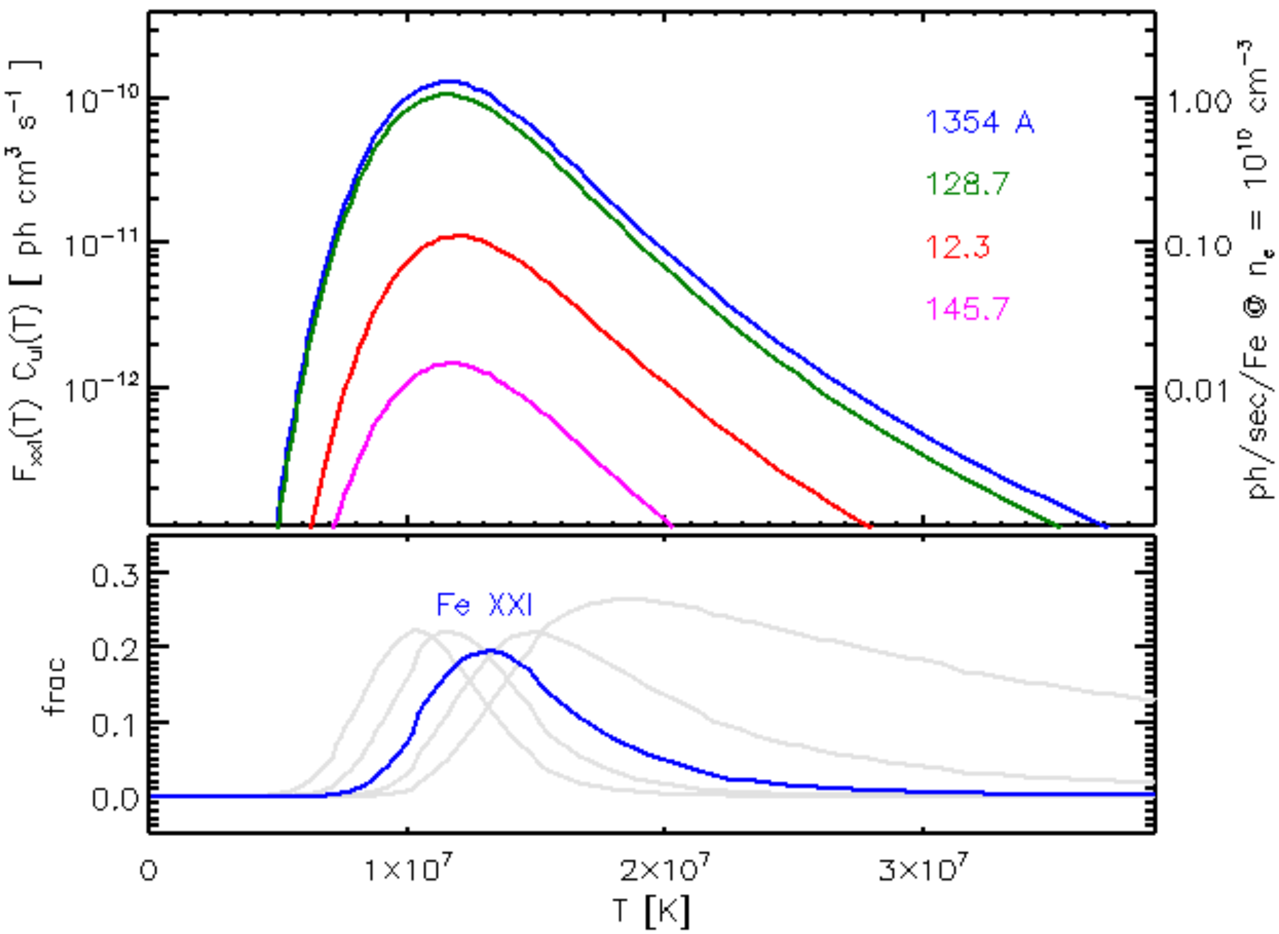


$n_{Z,s} = F_{Z,s}(T_e)\, n_Z$

γ production rate per Z nucleus $= n_e F_{Z,s}(T_e) C_{lu}(T_e)$

From CHIANTI

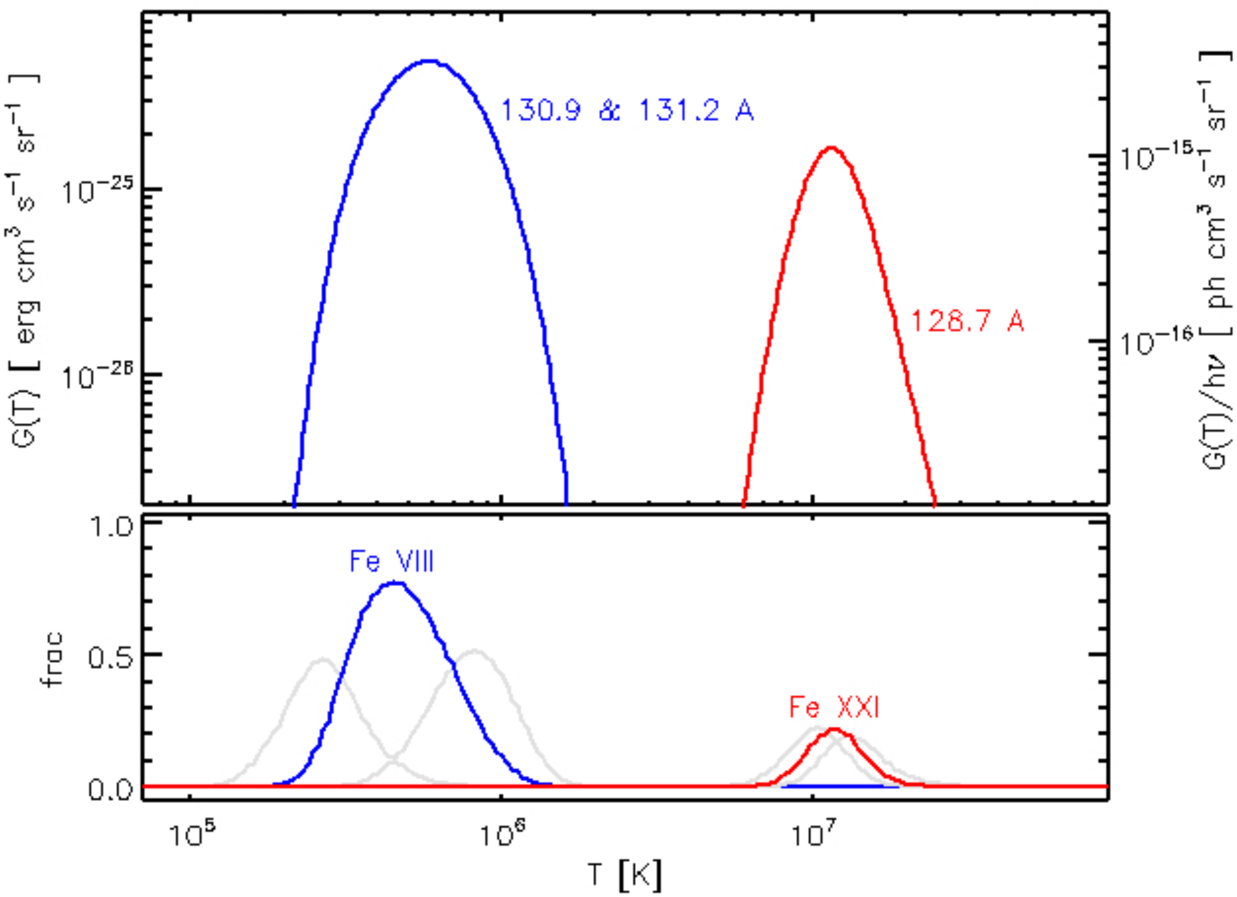




Volume density of element Z: $n_Z = n_H A_Z = n_e \frac{n_H}{n_e} A_Z$

Power per volume per solid angle over line λ :

$$\varepsilon_\lambda = \frac{hc/\lambda}{4\pi} n_e n_Z \, F_{Z,s}(T_e) C_{lu}(T_e) = n_e^2 \left[\frac{hc/\lambda}{4\pi} \frac{n_Z}{n_e} A_Z F_{Z,s}(T_e) C_{lu}(T_e) \right]$$



contribution function

$G_\lambda(T_e)$

[erg cm^3 s^{-1} sr^{-1}]

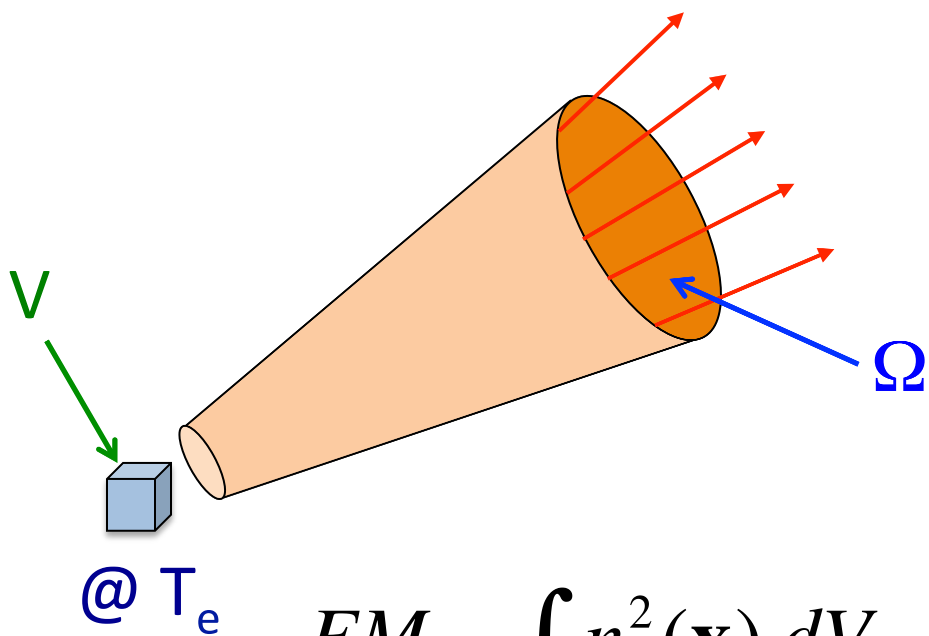
all atomic physics
CHIANTI

$$\varepsilon_\lambda = n_e^2 \, G_\lambda(T_e)$$

Volume V @ temperature T_e emits power

$$P_\lambda = \Omega \int_V \varepsilon_\lambda \, dV = \Omega G_\lambda(T_e) \int_V n_e^2(\mathbf{x}) \, dV$$

Emission measure – EM [cm^{-3}]

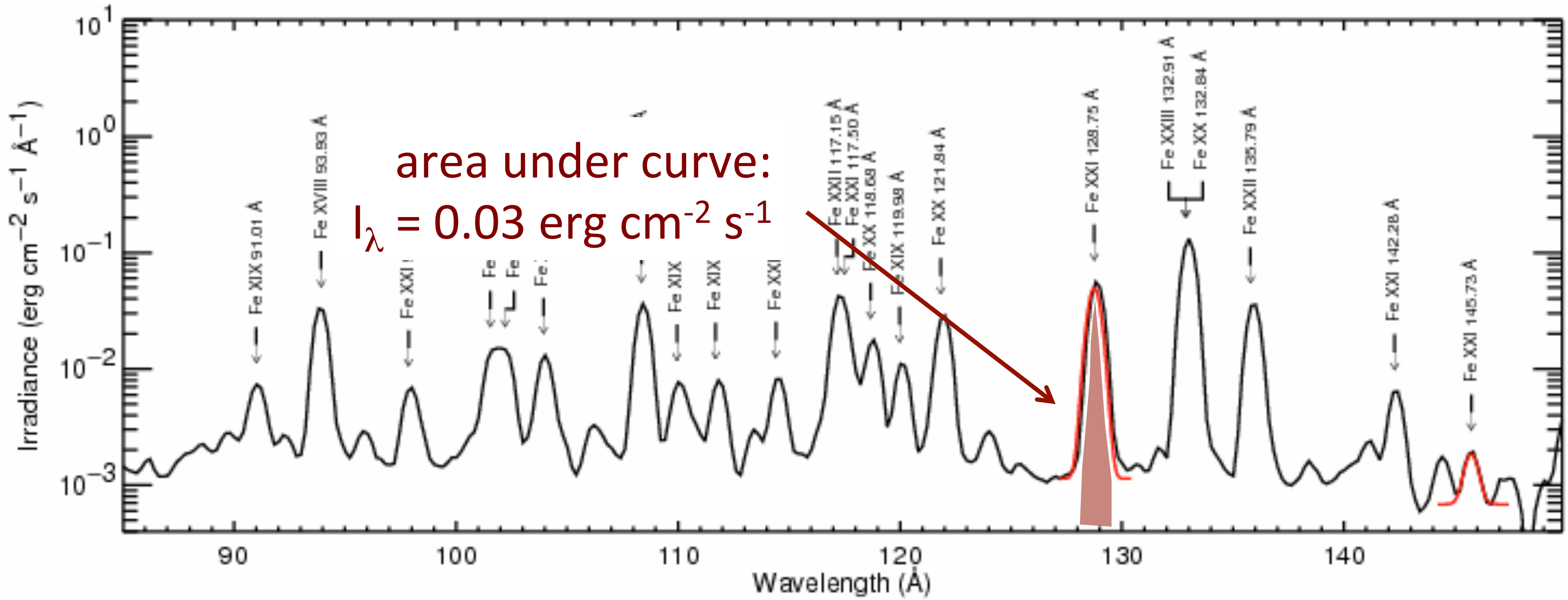


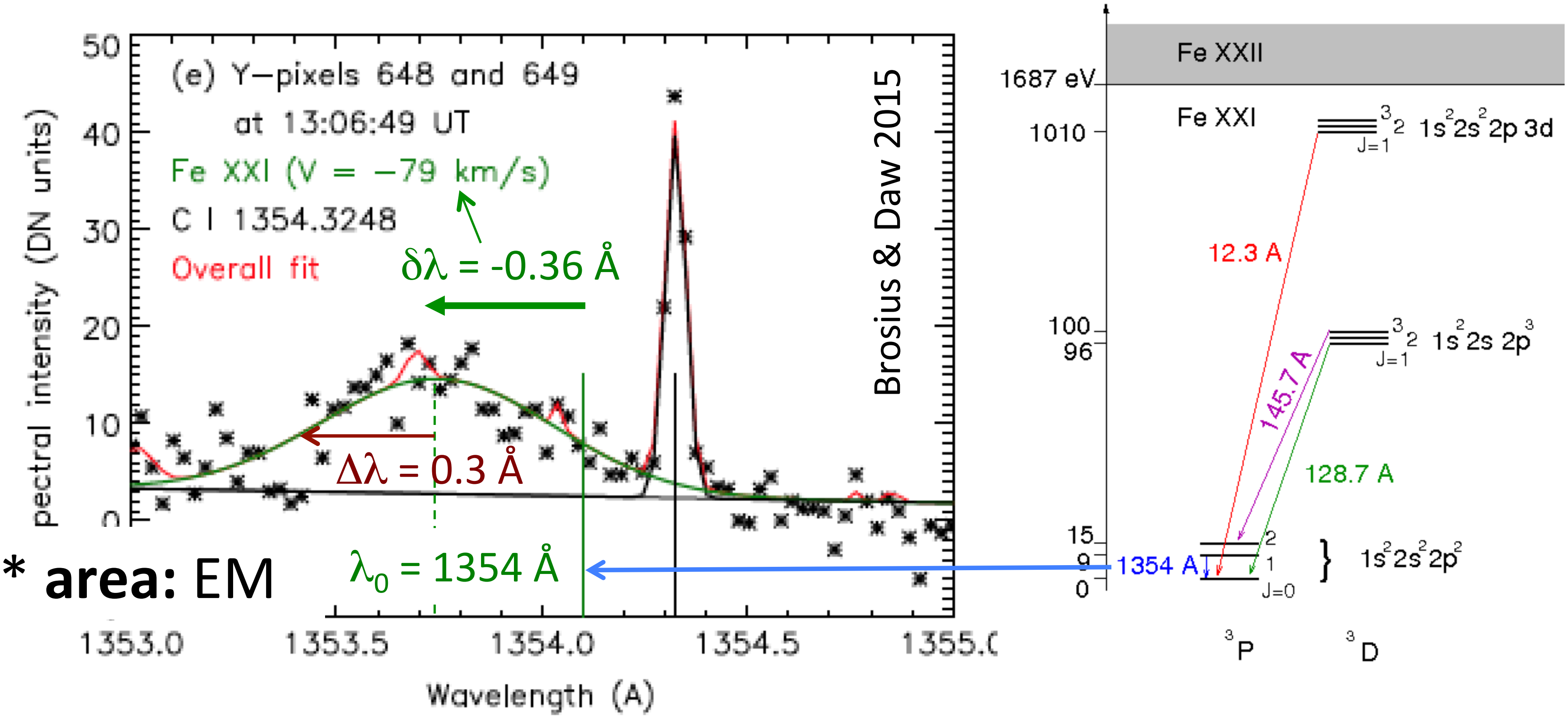
$$EM = \int_V n_e^2(\mathbf{x}) \, dV$$

Aperture A observing from a distance
d = 1 AU intercepts solid angle $\Omega = A/d^2$

$$P_\lambda = \frac{A}{d^2} G_\lambda(T_e) \int_V n_e^2(\mathbf{x})\, dV = A \left[\frac{G_\lambda(T_e)}{d^2} EM \right] = A\, I_\lambda$$

Integrated irradiance: I_λ [erg cm^{-2} s^{-1}]





* **area:** EM

* **centroid position** δλ = -0.36 Å:

→ mean velocity u = -79 km/s (blue shift) - evaporation

* **line width**

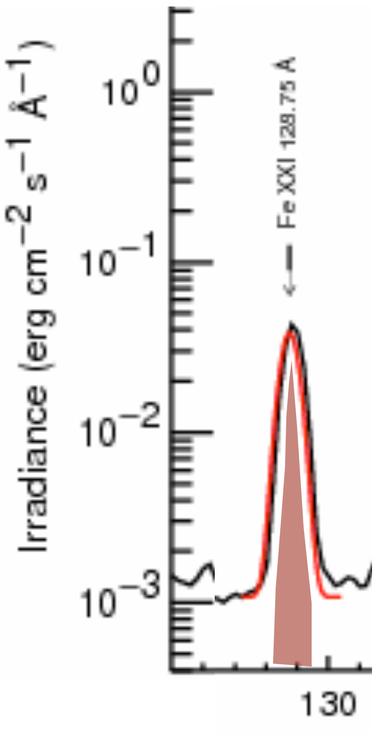
Δλ = 0.3 Å:

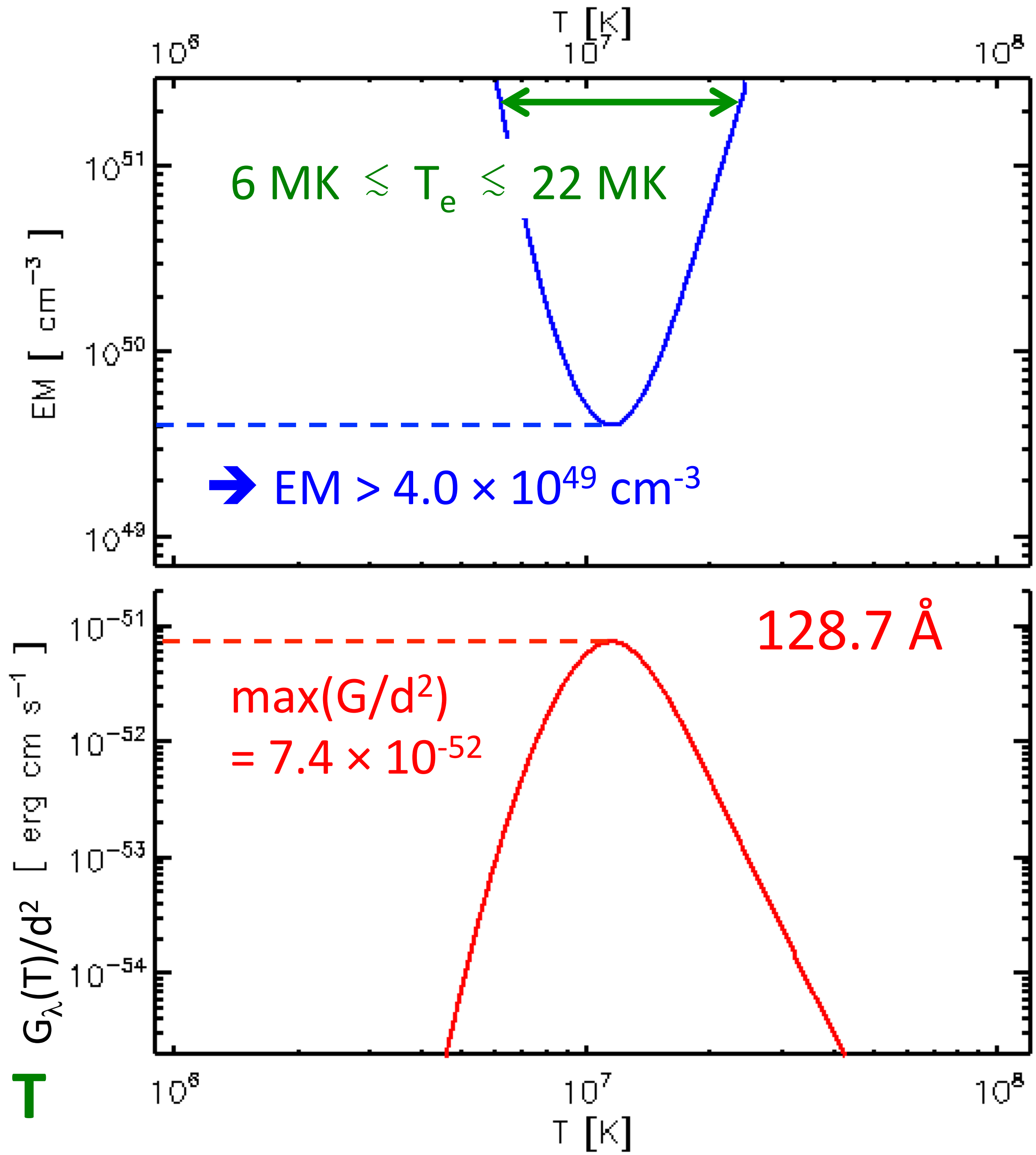
thermal motion $\Delta\lambda_{th} = \frac{1}{c}\sqrt{\frac{2\ln 2\, k_b T_i}{m_i}}\,\lambda_0 = 0.2\,A\sqrt{\frac{T_i}{10^7\,\mathrm{K}}}$

and turbulent motion $\Delta\lambda_{nt} = \frac{\langle u_t^2 \rangle^{1/2}}{c}\,\lambda_0$

$$I_\lambda = \frac{G_\lambda(T_e)}{d^2} EM$$

$= 0.03 \text{ erg cm}^{-2} \text{ s}^{-1}$





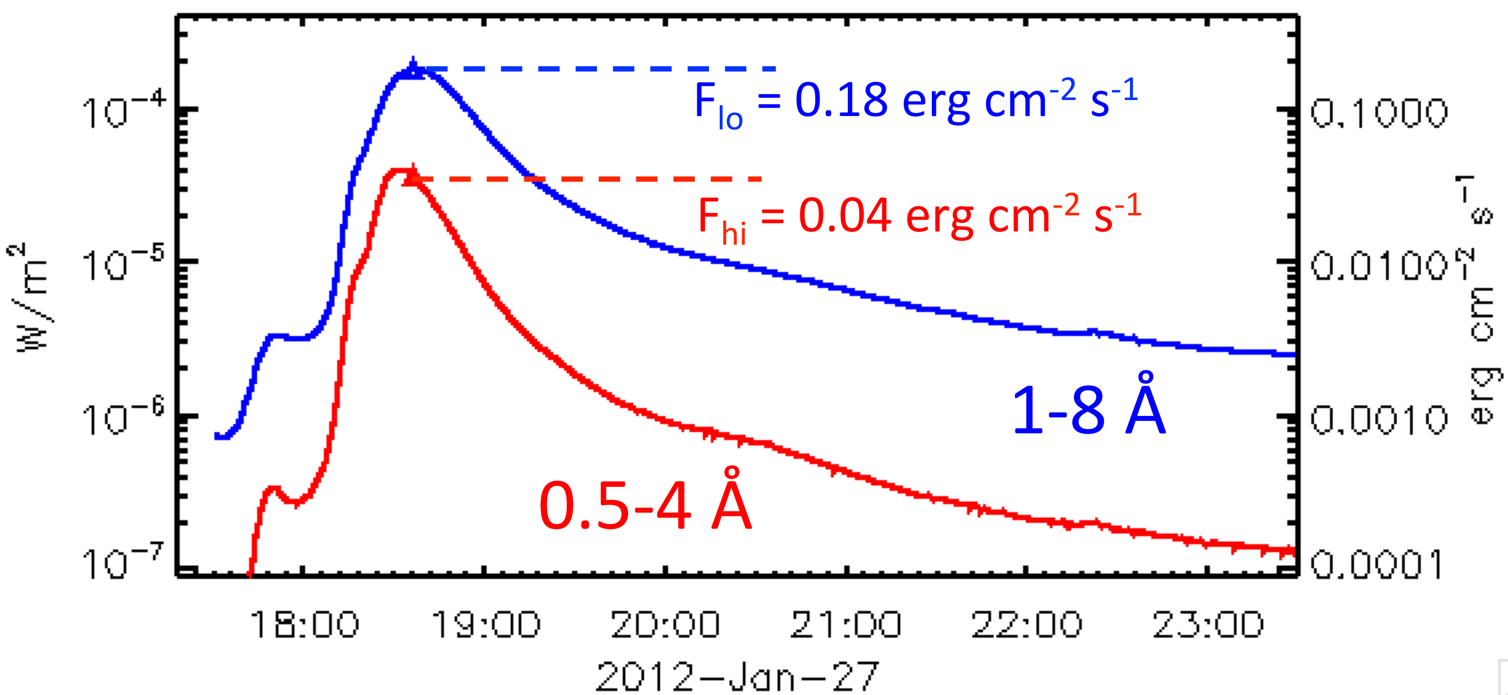
amplitude constrains EM & T

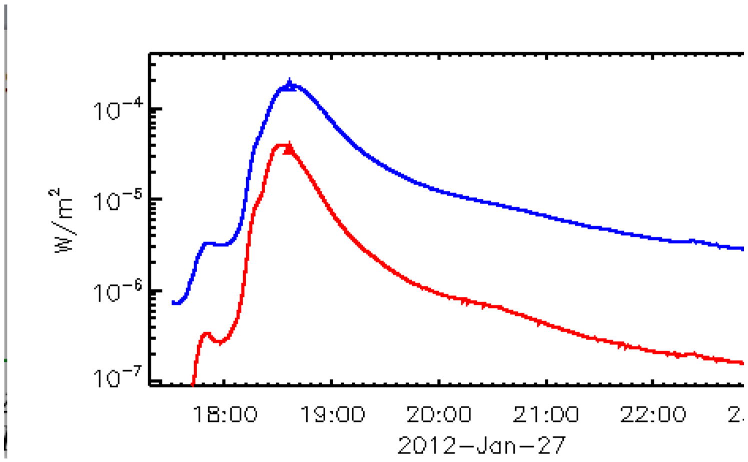
Compare to GOES: channel c has sensitivity $s_c(\lambda)$

$$F_c = \sum_\lambda s_c(\lambda) I_\lambda =$$

$$= EM \sum_\lambda s_c(\lambda) \frac{G_\lambda(T)}{d^2}$$

response $R_c(T)$

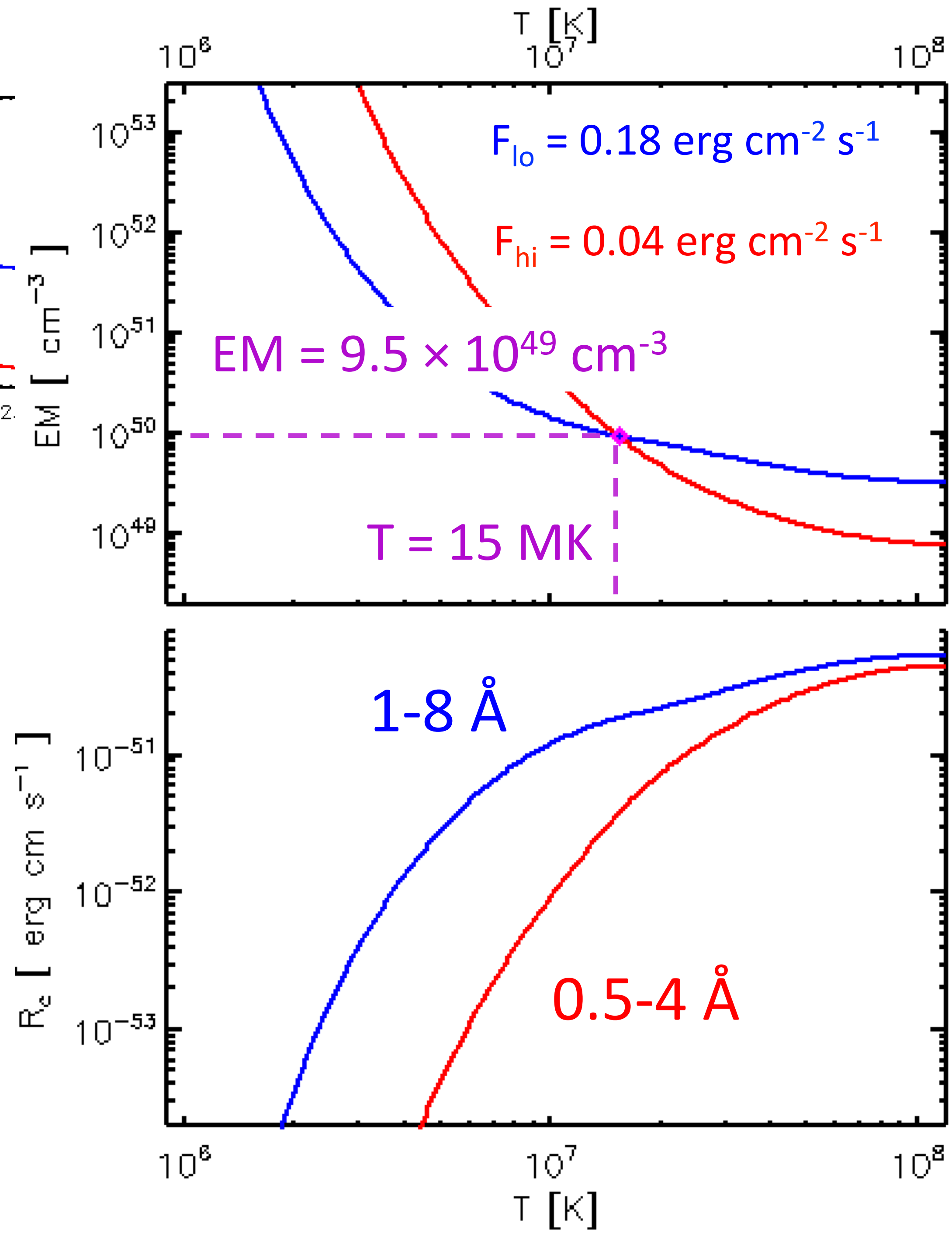


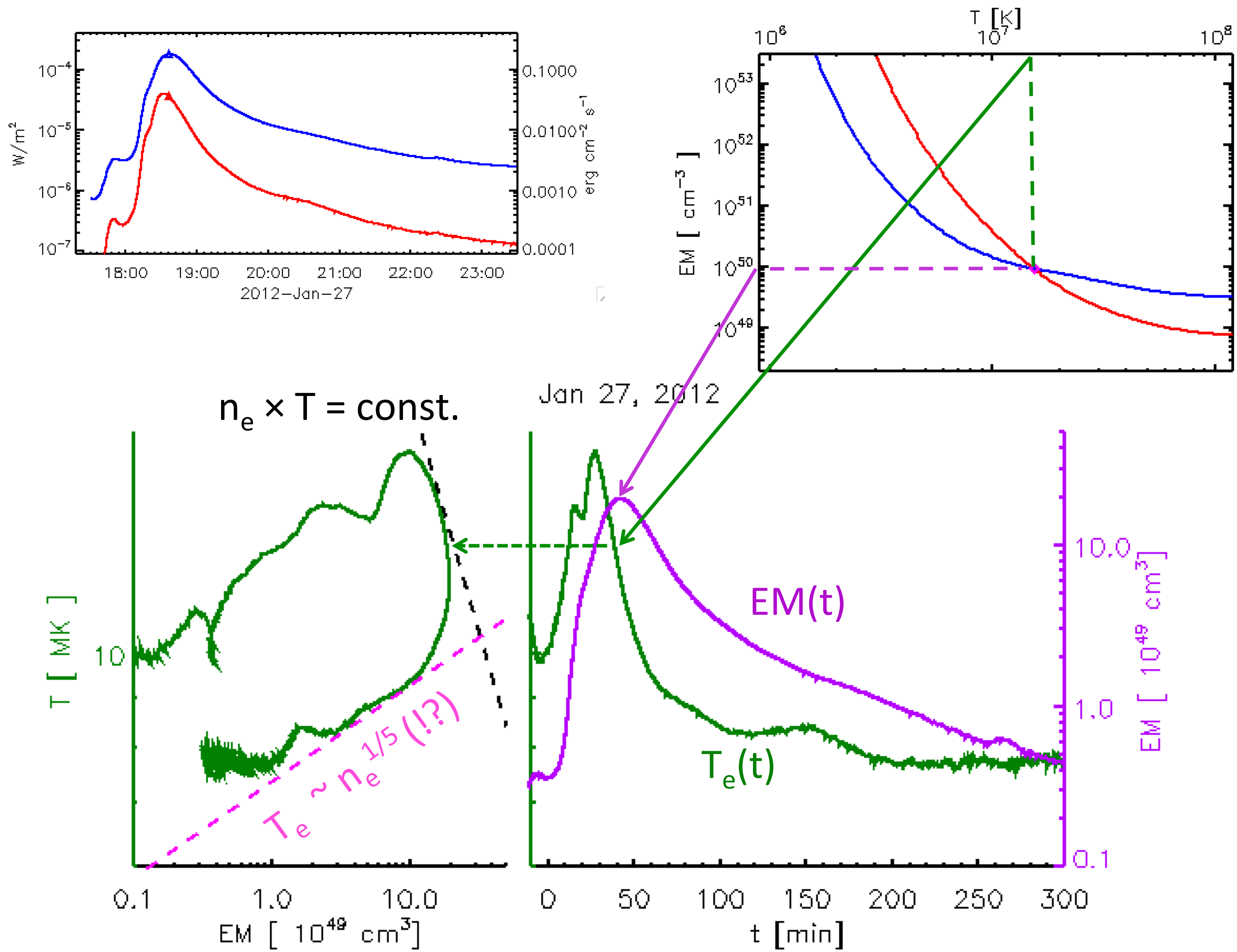


$$EM = \frac{F_c}{R_c(T)}$$

$$R_c(T) = \sum_{\lambda} s_c(\lambda) \frac{G_\lambda(T)}{d^2}$$

2 amplitudes fix EM & T





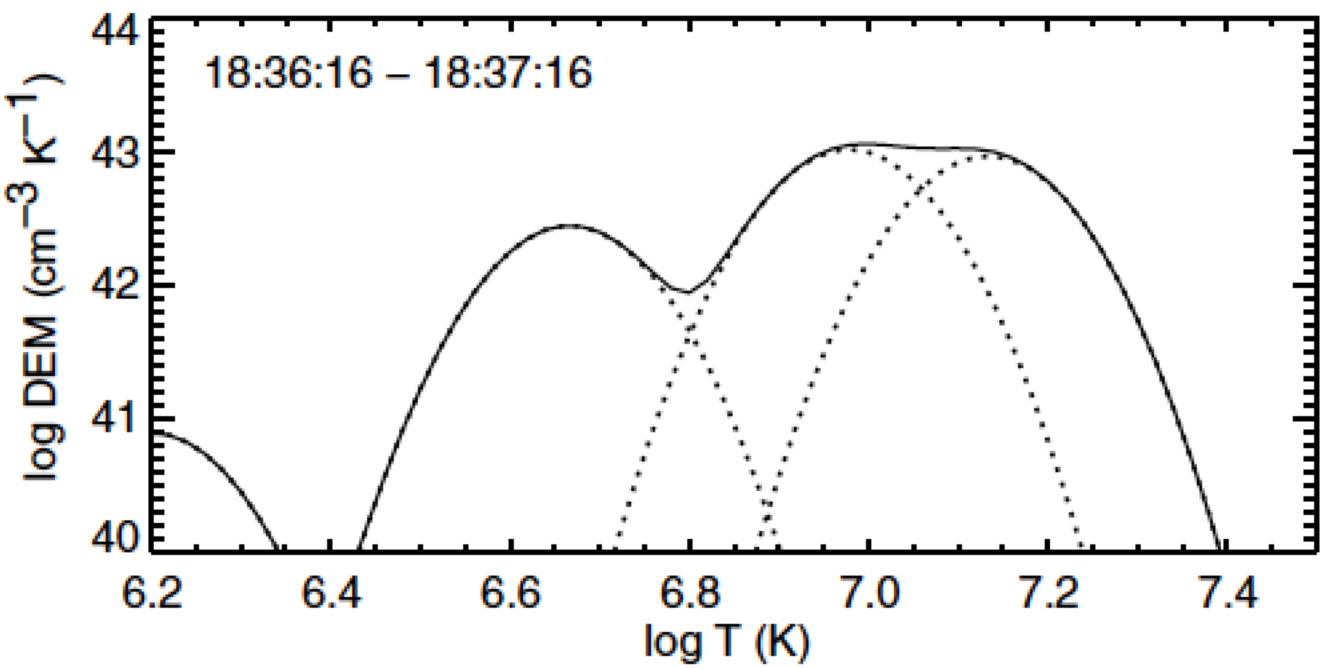
W/m^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.1000
0.0100
0.0010
0.0001
erg cm^{-2} s^{-1}
18:00 19:00 20:00 21:00 22:00 23:00
2012-Jan-27
T [K]
10^6 10^7 10^8
EM [cm^{-3}]
10^{53} 10^{52} 10^{51} 10^{50} 10^{49}
$n_e \times T$ = const.
Jan 27, 2012
T [MK]
10
$T_e \sim n_e^{1/5}$ (!?)
EM(t)
$T_e(t)$
10.0
1.0
0.1
EM [10^{49} cm^3]
0.1 1.0 10.0
EM [10^{49} cm^3]
0 50 100 150 200 250 300
t [min]

Plasma w/ temp. distribution

Volume differential emission measure – $DEM_V(T)$

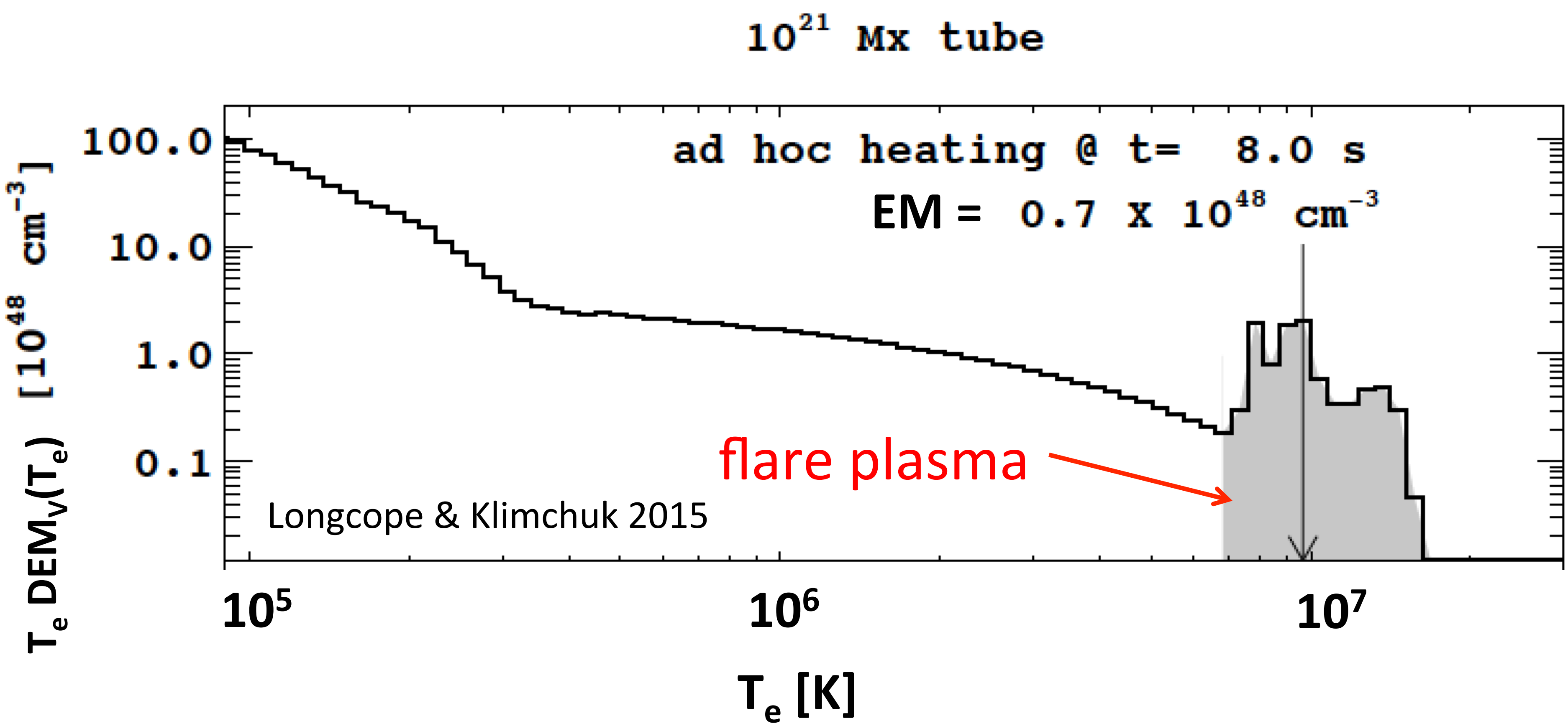
$$I_\lambda = \int_V \frac{G_\lambda\left[T(\mathbf{x})\right]}{d^2} n_e^2(\mathbf{x})\, dV = \int \frac{G_\lambda(T)}{d^2} \boxed{n_e^2 \frac{dV}{dT}} dT$$

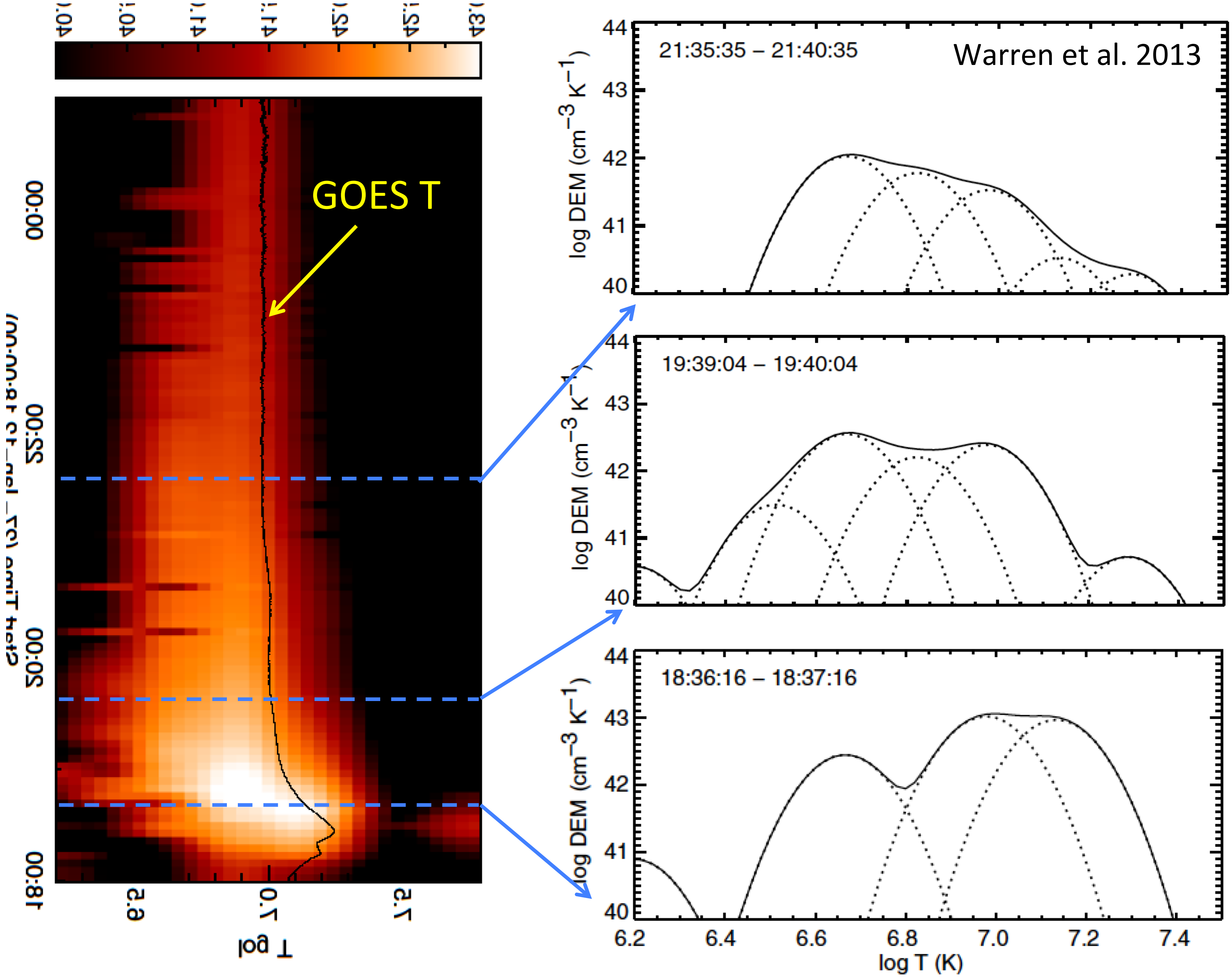
observe N ions ➔ N constraints on $DEM_V(T)$



Warren et al. 2013

$DEM_V(T_e)$ from 1d model of a single loop:





GOES T
Warren et al. 2013
21:35:35 – 21:40:35
19:39:04 – 19:40:04
18:36:16 – 18:37:16
log DEM (cm^{-3} K^{-1})
log T (K)

Filter-graph:

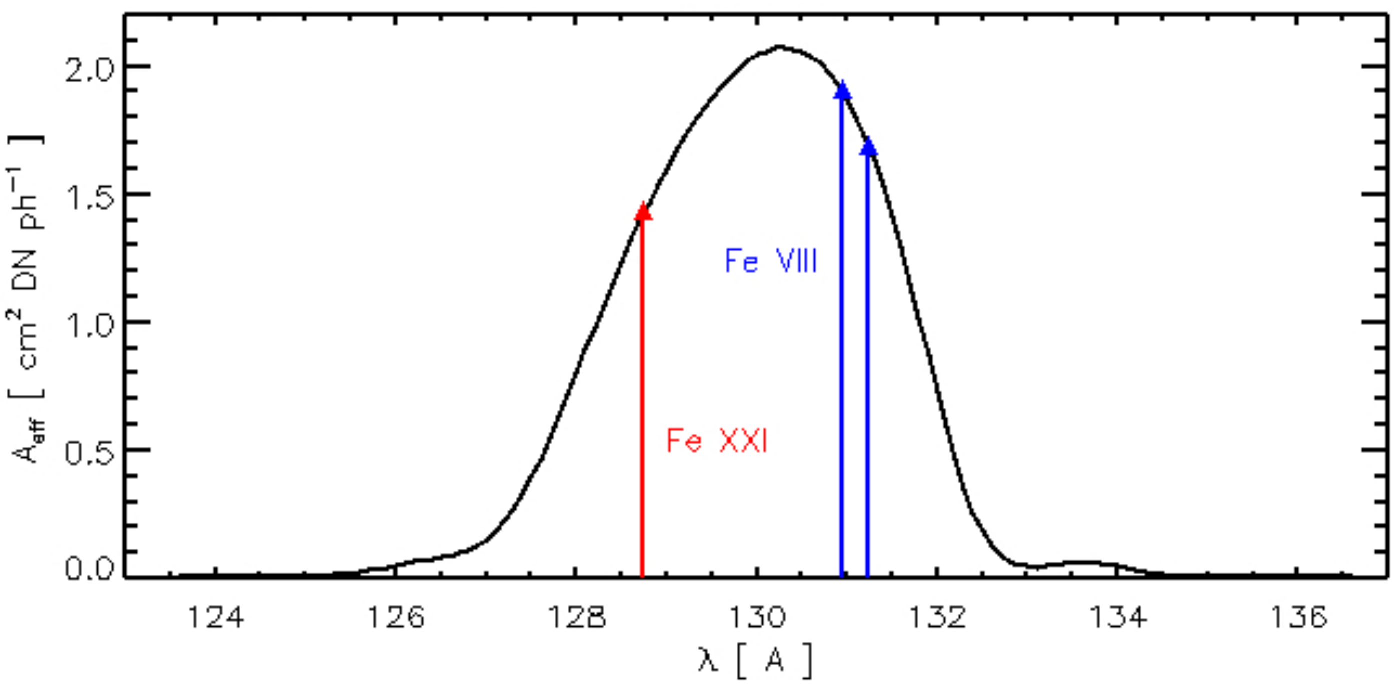
- Images over range of λ
- Effective area $A_{eff}(\lambda)$
- Response function

Photon flux: Φ_λ for Δt

➔ $N_\lambda = A_{eff}(\lambda)\ \Phi_\lambda\ \Delta t$

counts (a.k.a. DNs)

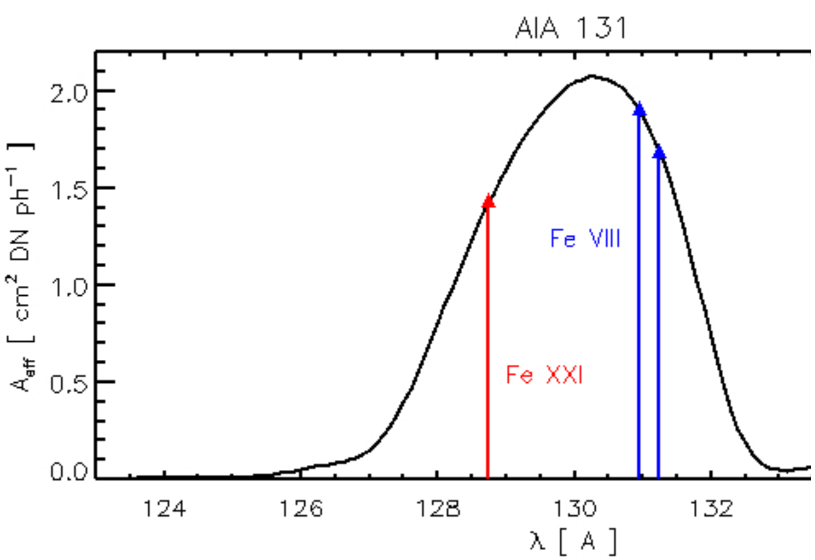
AIA 131 Å imager

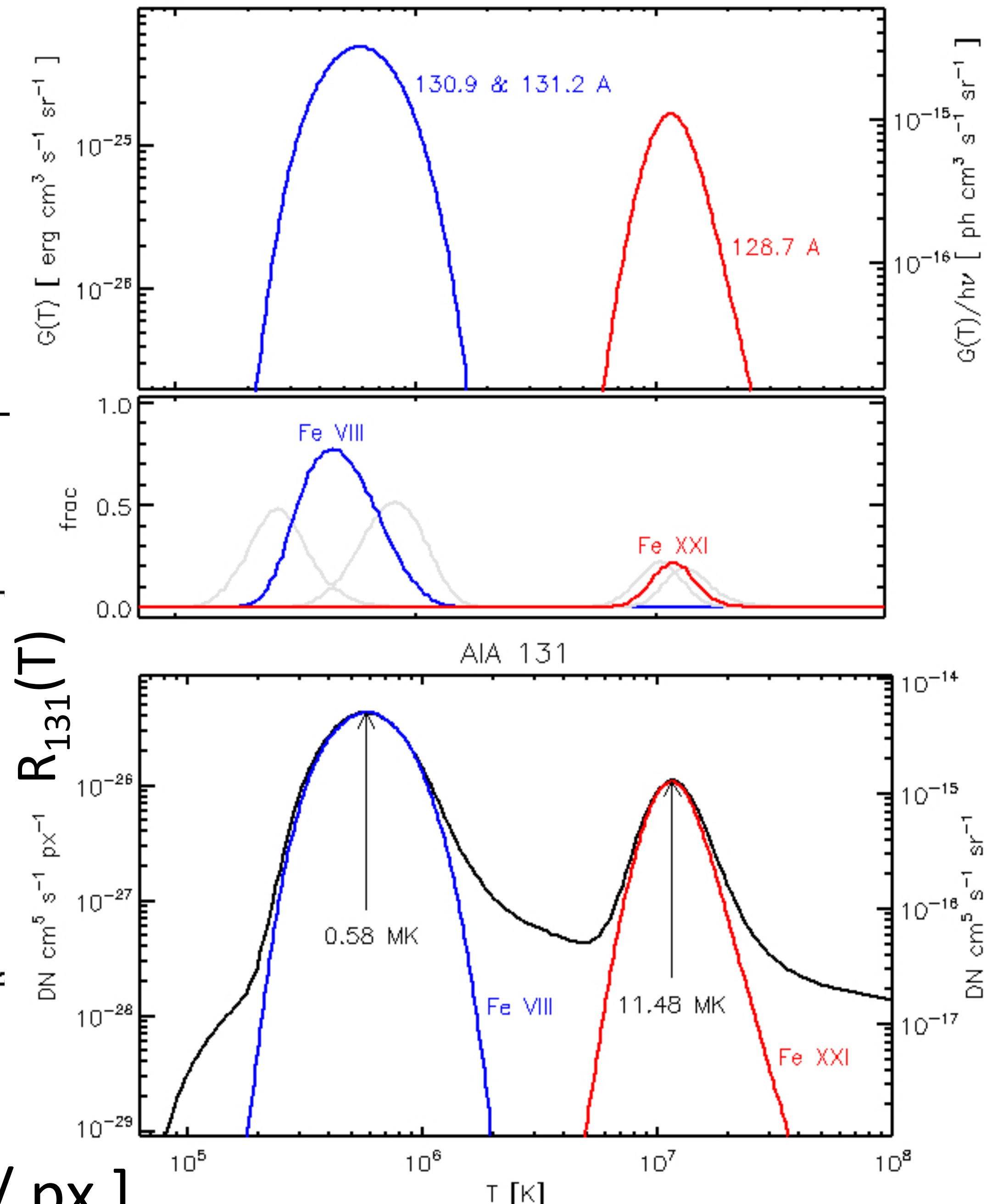


Filter-graph:

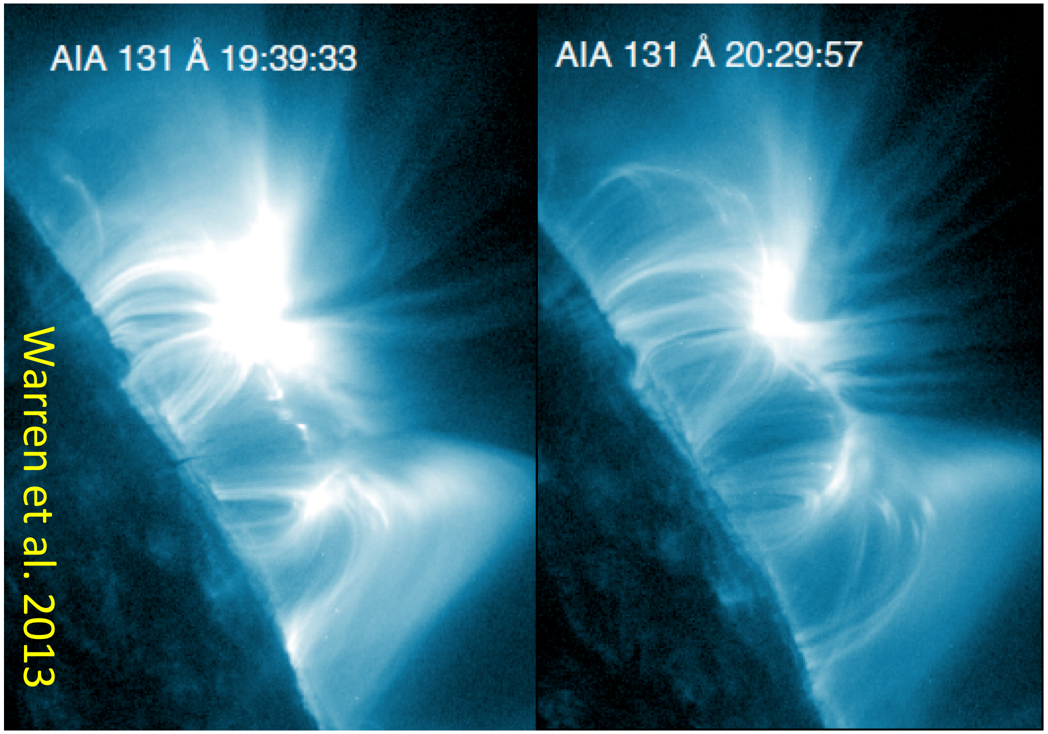
- Images over range of λ
- Response function

$$R(T) = \Omega_{\text{px}} \sum_{\lambda} A_{eff}(\lambda) \frac{G_{\lambda}(T)}{hc/\lambda}$$





Ω_{px} = solid angle imaged by one pixel [sr / px]



Pixel brightness
B [DN/s]

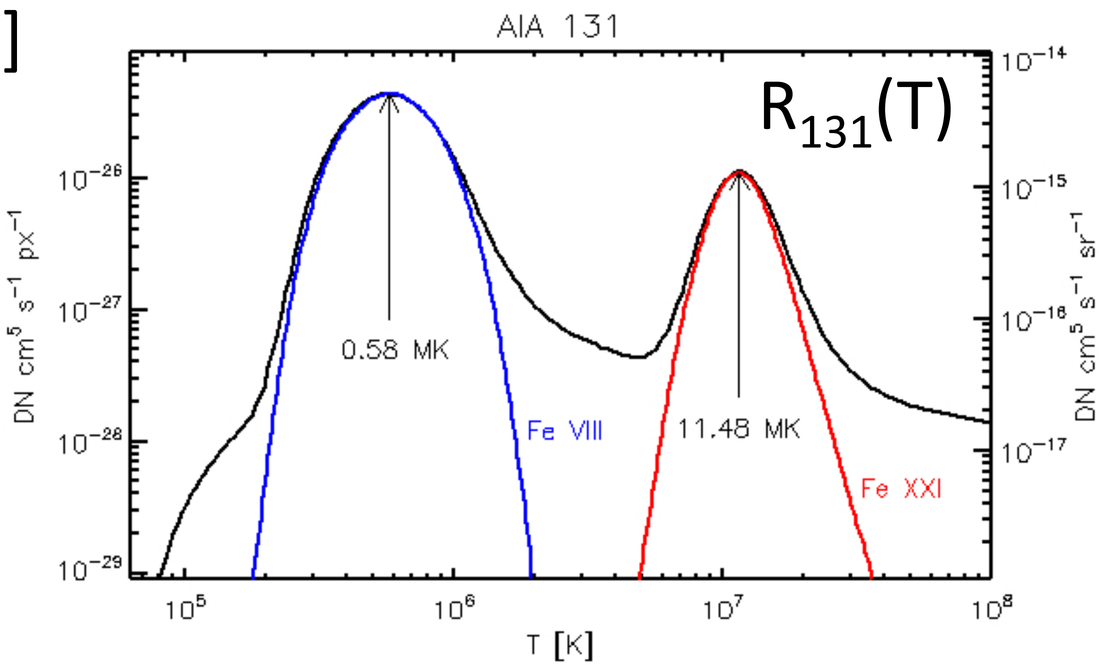
$$B = \int R(T)\, DEM_c(T)\, dT$$

Column DEM: [cm^{-5} K^{-1}]

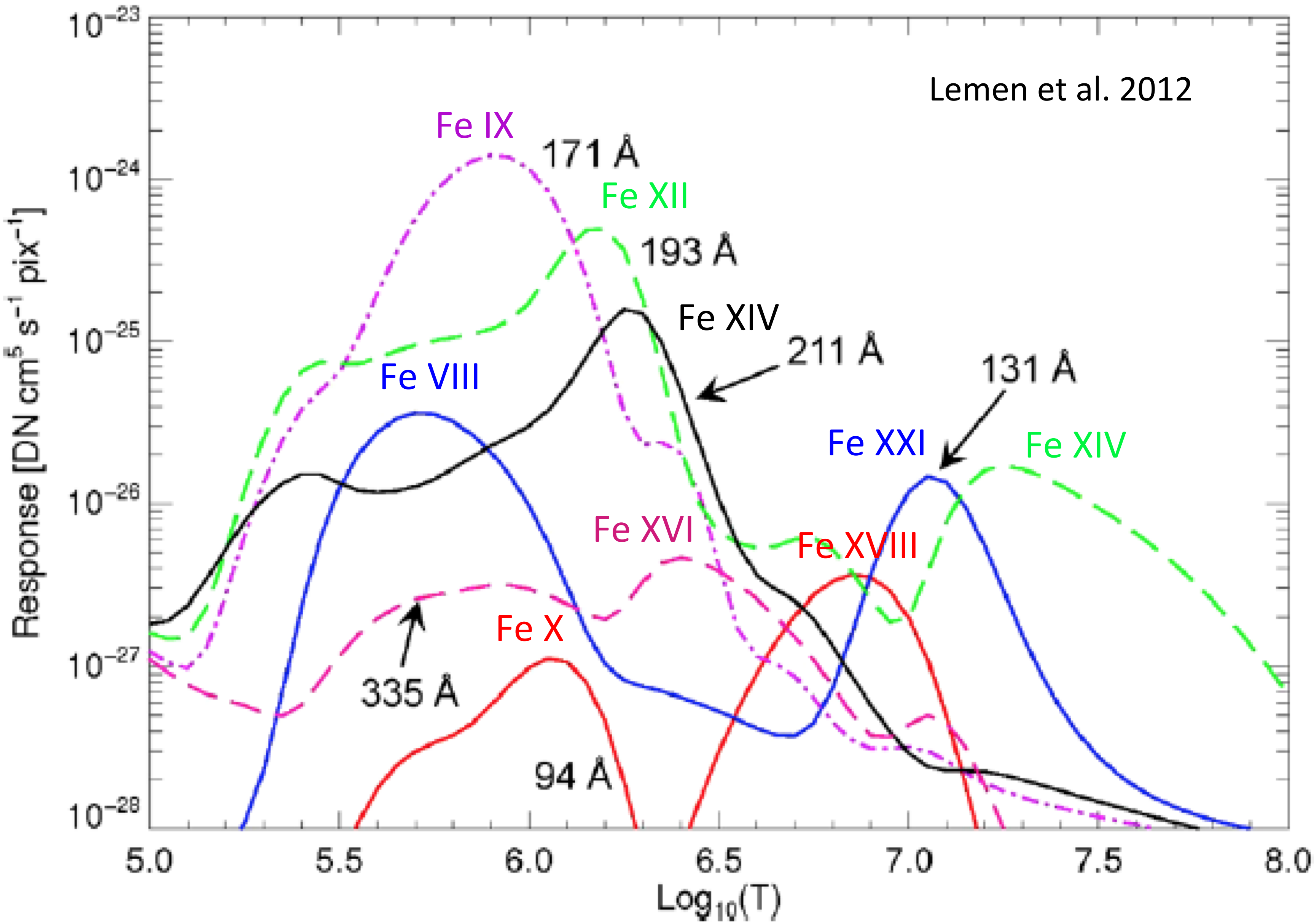
$$DEM_c = n_e^2 \frac{d\ell}{dT}$$

Volume DEM: [cm^{-3} K^{-1}]

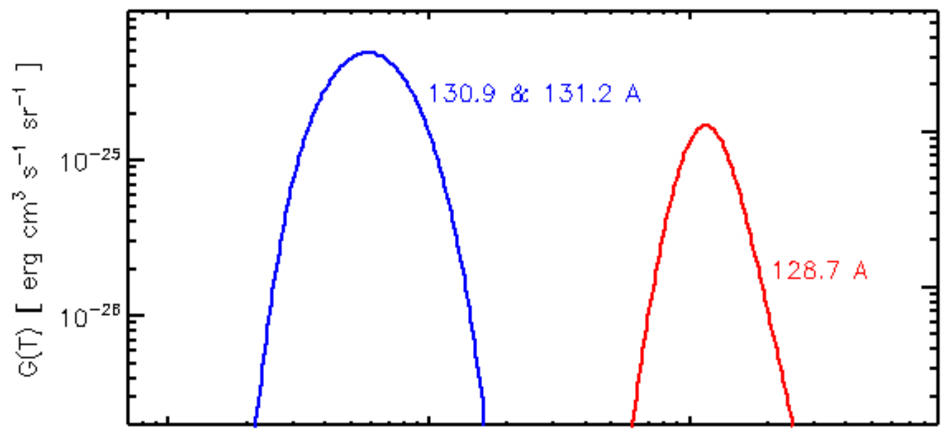
$$DEM_V = n_e^2 \frac{dV}{dT}$$



SDO/AIA – coronal Swiss Army knife



It's all in $G_\lambda(T)$



<u>What we assumed to derive it:</u>

- Optically thin radiation (no absorption)
- Collisional excitation by Maxwellian e^-s: T_e
- De-excitation only by spont's emission
- Known atomic physics: $\sigma(v)$ etc.
- Equilibrium ionization – fractions $F_{Z,s}(T_e)$ from Saha eq.
- Known abundances: A_Z

Summary

- Diagnose flare plasma using emission lines – mostly in EUV (but some UV)
- Typical line provides information about:
  - EM & T_e (combined) – integrated power
  - Bulk flow – centroid position
  - T_i & u_t (mixed) – line width
- Two lines (or bands) fix both EM & T_e
- Multiple lines to determine DEM(T_e)
- Filter-graph images characterized by R(T)