INTRODUCTION TO RADIATIVE-HYDRODYNAMIC MODELING

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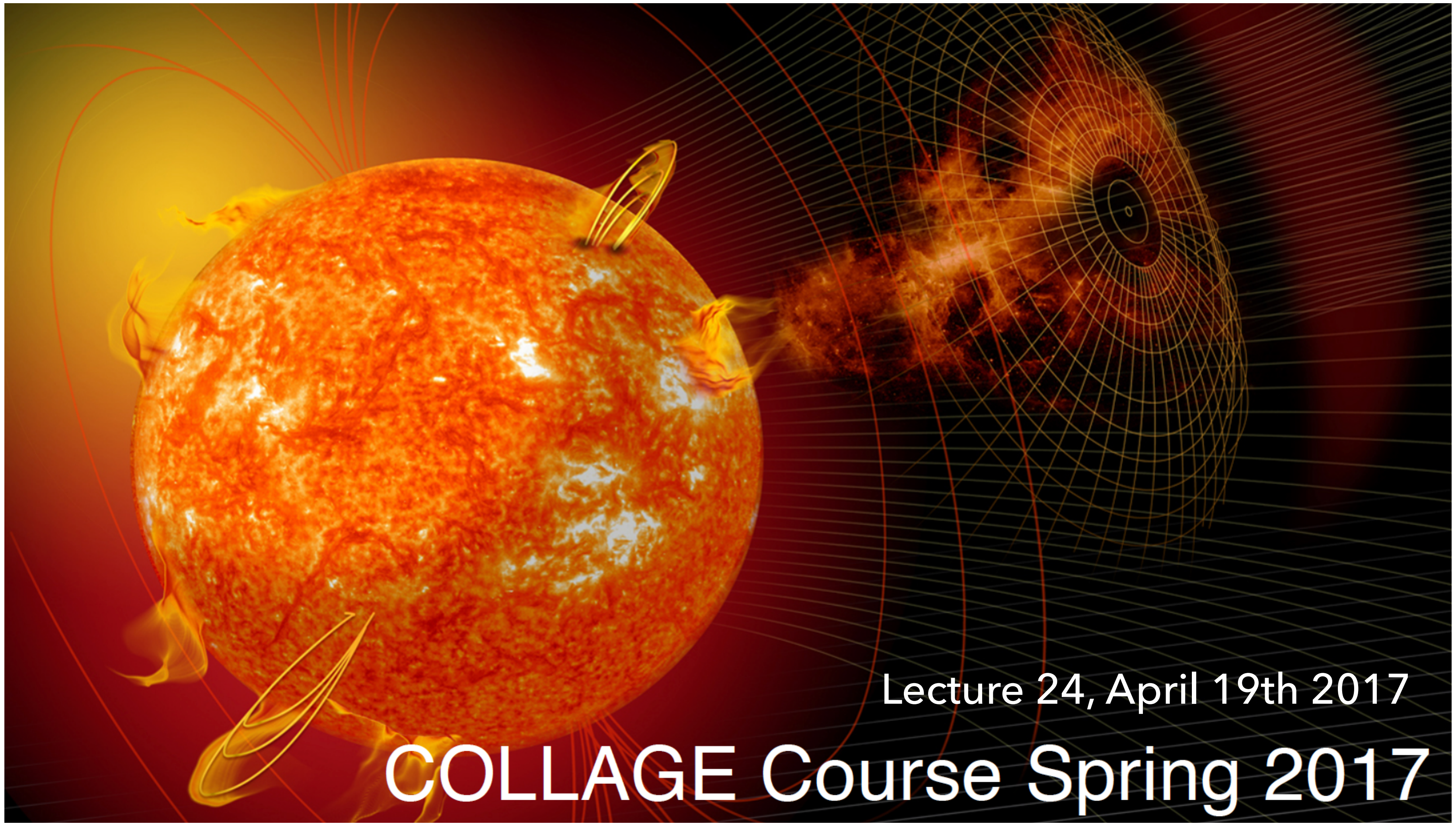
With Contributions from Joel Allred (NASA/GSFC) and Mats Carlsson (Univ. of Oslo)



RADIATIVE-HYDRODYNAMIC (RHD) MODELING

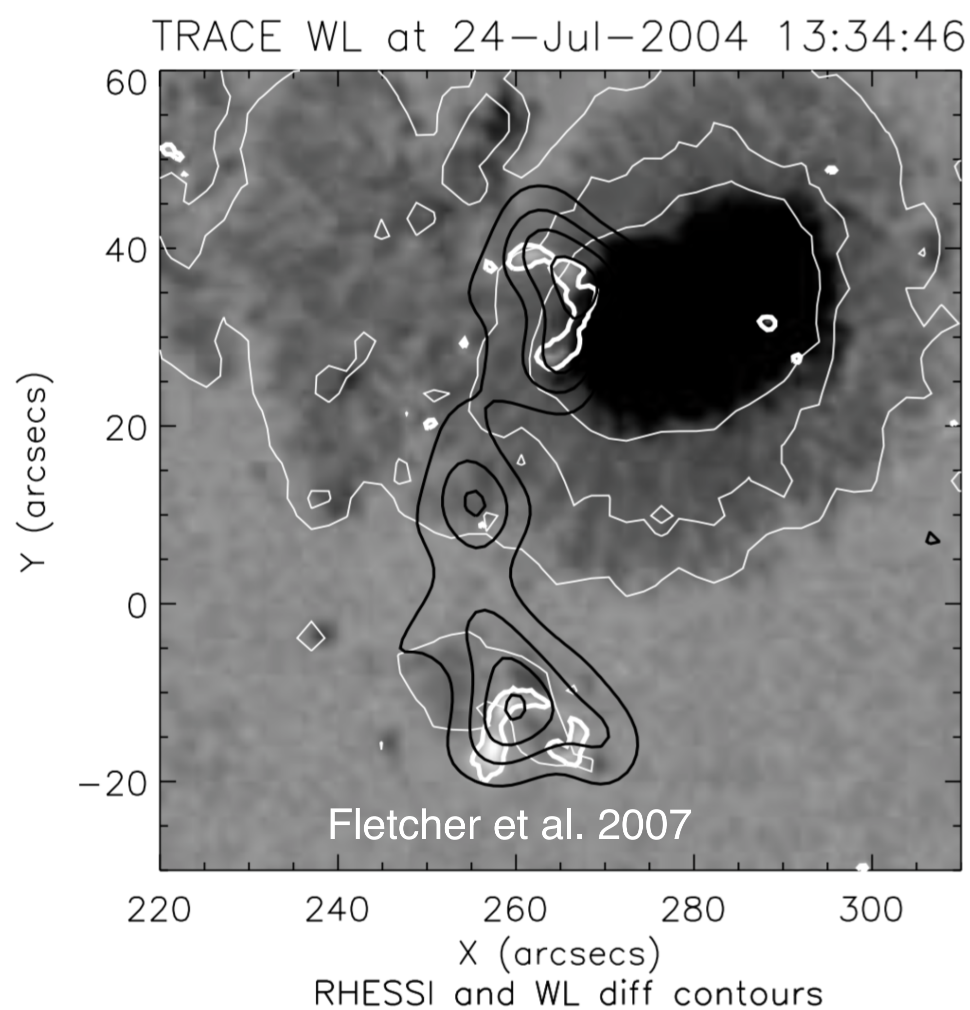
- Suggested reading (on Prof Longcope's website):
  - Allred et al. 2015 *ApJ*
  - Carlsson 1998

RADIATIVE-HYDRODYNAMIC (RHD) MODELING

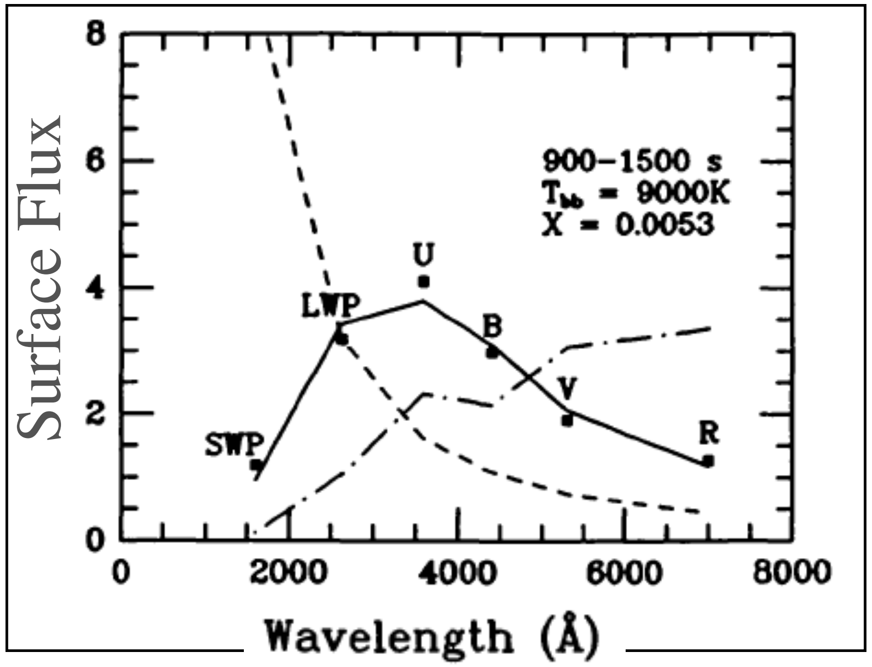
- Goals for today's lecture:
  - Motivate modeling the chromosphere
  - Introduce the essentials of radiative-hydrodynamics
  - On Monday: will do an IDL-based lab with RADYN (Carlsson & Stein 1997 ApJ) model output
    - analyze the physics of chromospheric evaporation and condensation resulting from electron beam heating

OBSERVATIONAL MOTIVATION FOR MODELING THE RADIATIVE TRANSFER

- White-light continuum radiation
  - chromospheric? photospheric? A combination?
- T ~ 9000 - 10,000 K blackbody(-like) in optical and NUV



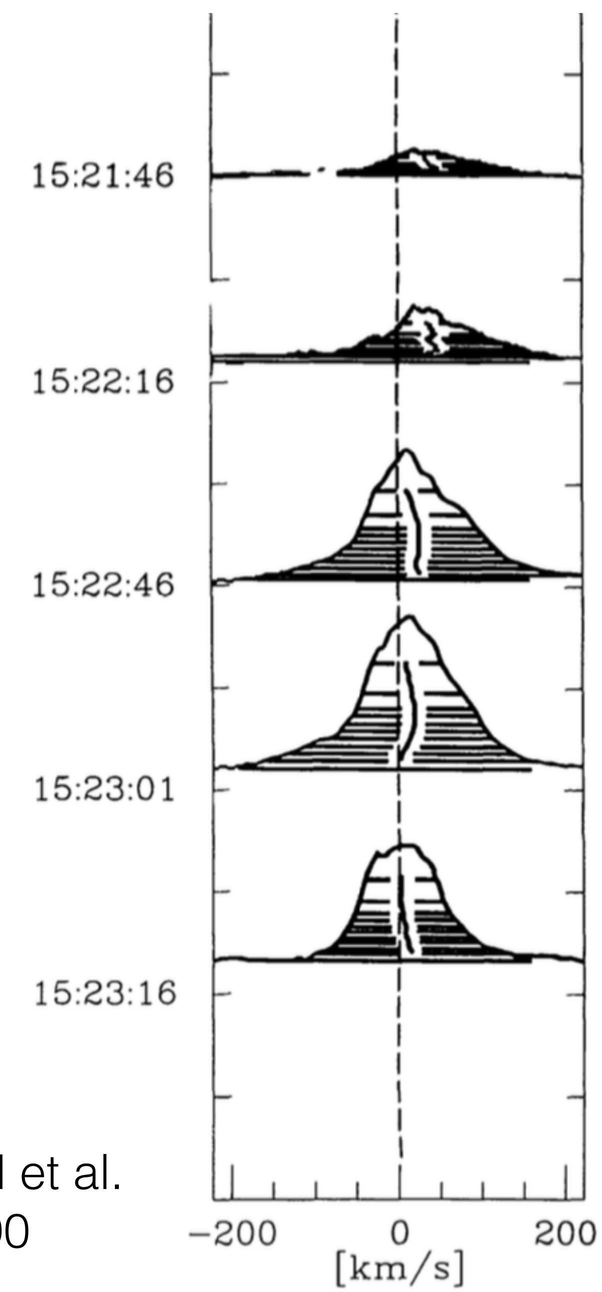
Fletcher et al. 2007



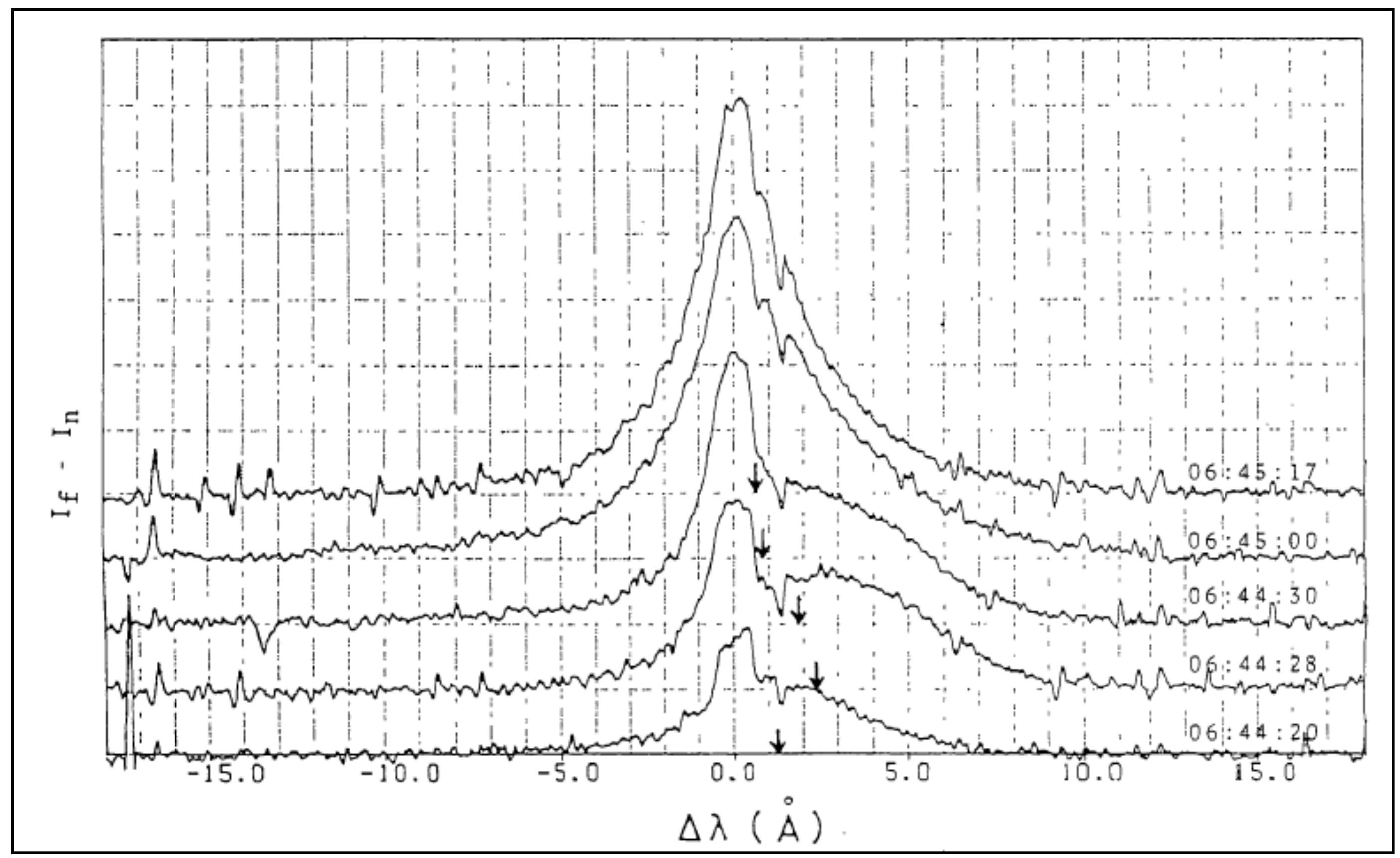
Hawley & Fisher (1992)

OBSERVATIONAL MOTIVATION FOR MODELING THE DYNAMICS

- Redshifts in Hα in solar flares: signatures of chromospheric condensation (heated, downflowing compressions)



Canfield et al. 1990



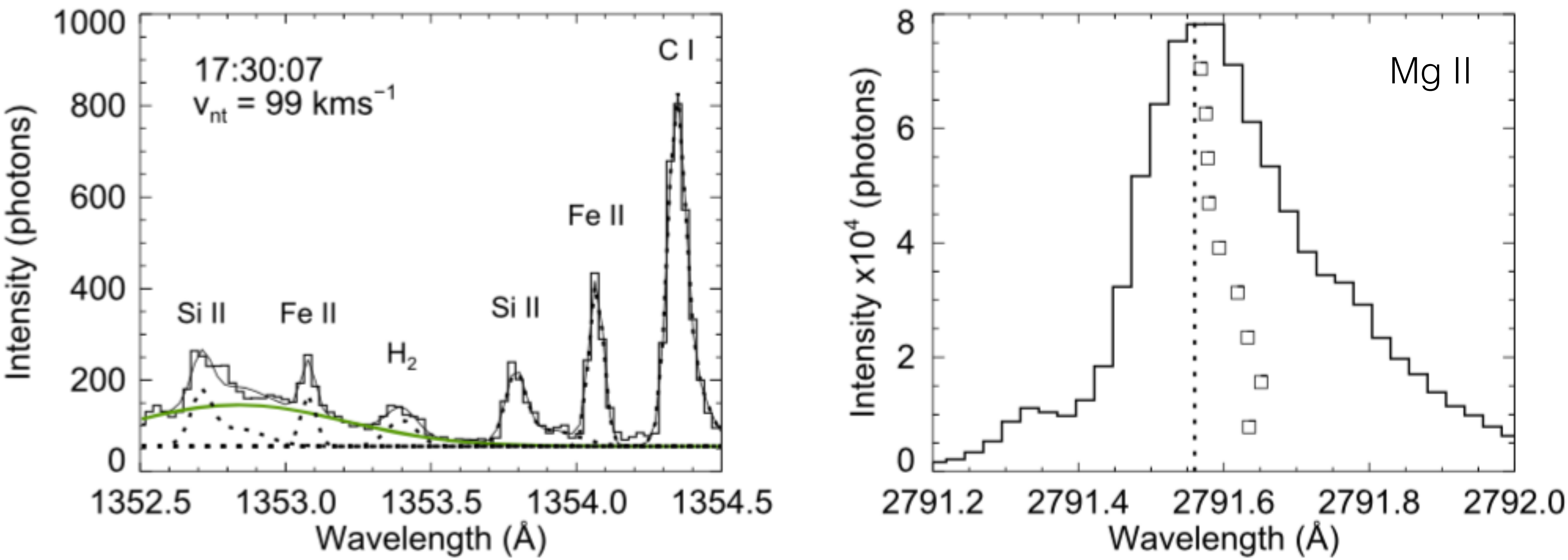
Ichimoto & Kurokawa 1984:
40-140 km/s redshifts in Hα

...Sometimes blueshifts observed too

OBSERVATIONAL MOTIVATION FOR MODELING THE DYNAMICS

- Redshifts in Mg II (and other singly ionized chromospheric lines from *IRIS* data) in solar flares

Graham & Cauzzi 2015



Evaporation flows

Condensation flows

- In hard X-ray phase: Can we understand these processes with electron beam heating?

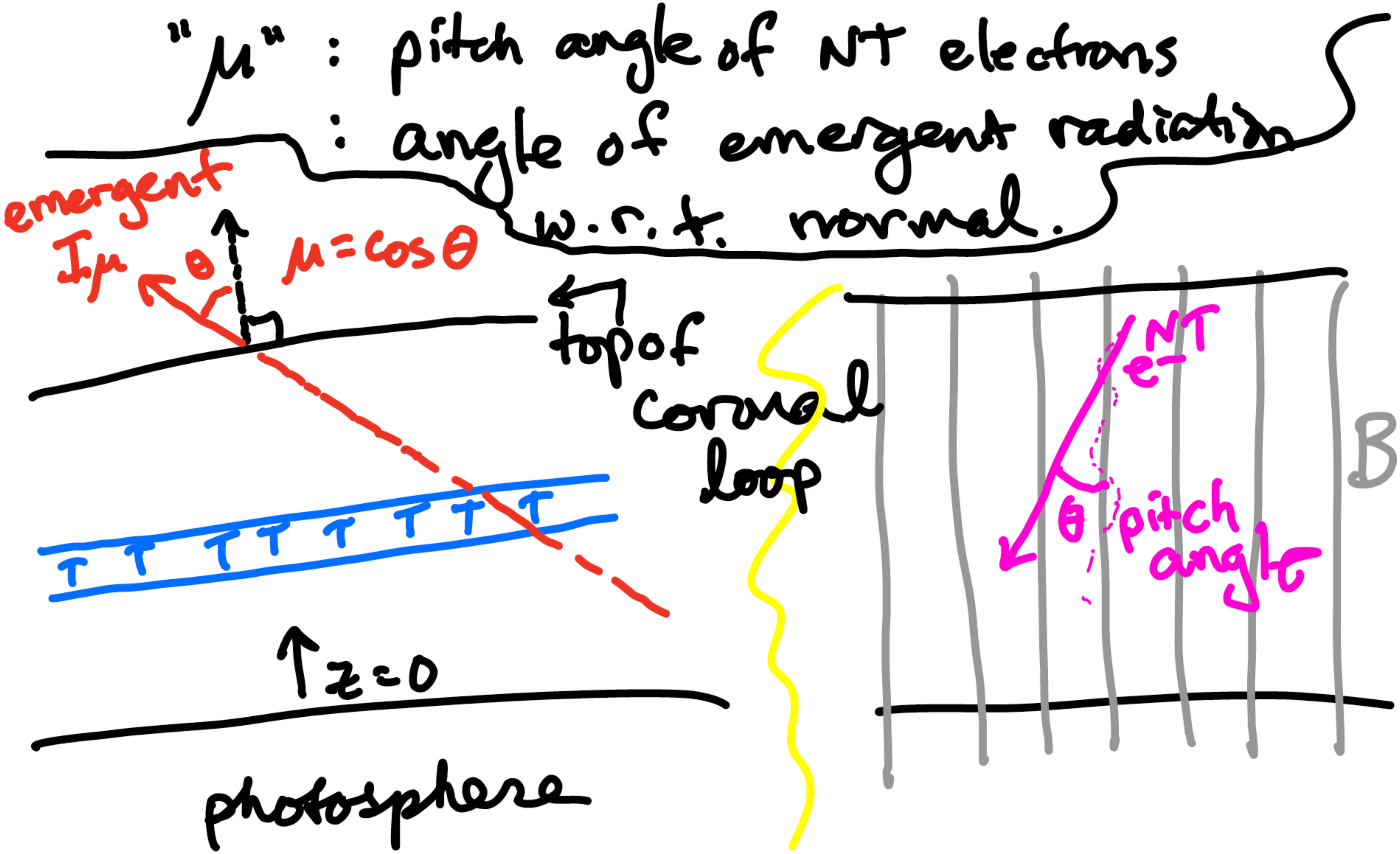
INGREDIENTS FOR RADIATIVE-HYDRODYNAMIC FLARE MODELING

- 1D model atmosphere with photosphere, chromosphere, transition region, and corona.
- Solve the radiative-transfer, rate, and charge conservation equations simultaneously with the equations of mass, momentum, and energy conservation.
- Flare heating prescription from solving the Fokker-Planck equation, as appropriate for partially ionized chromosphere.

1D PLANE-PARALLEL MODELING

- All motion confined to vertical (z-direction), so what are we assuming?
  - The magnetic pressure is much greater than the gas pressure
  - The center of a strong magnetic flux tube

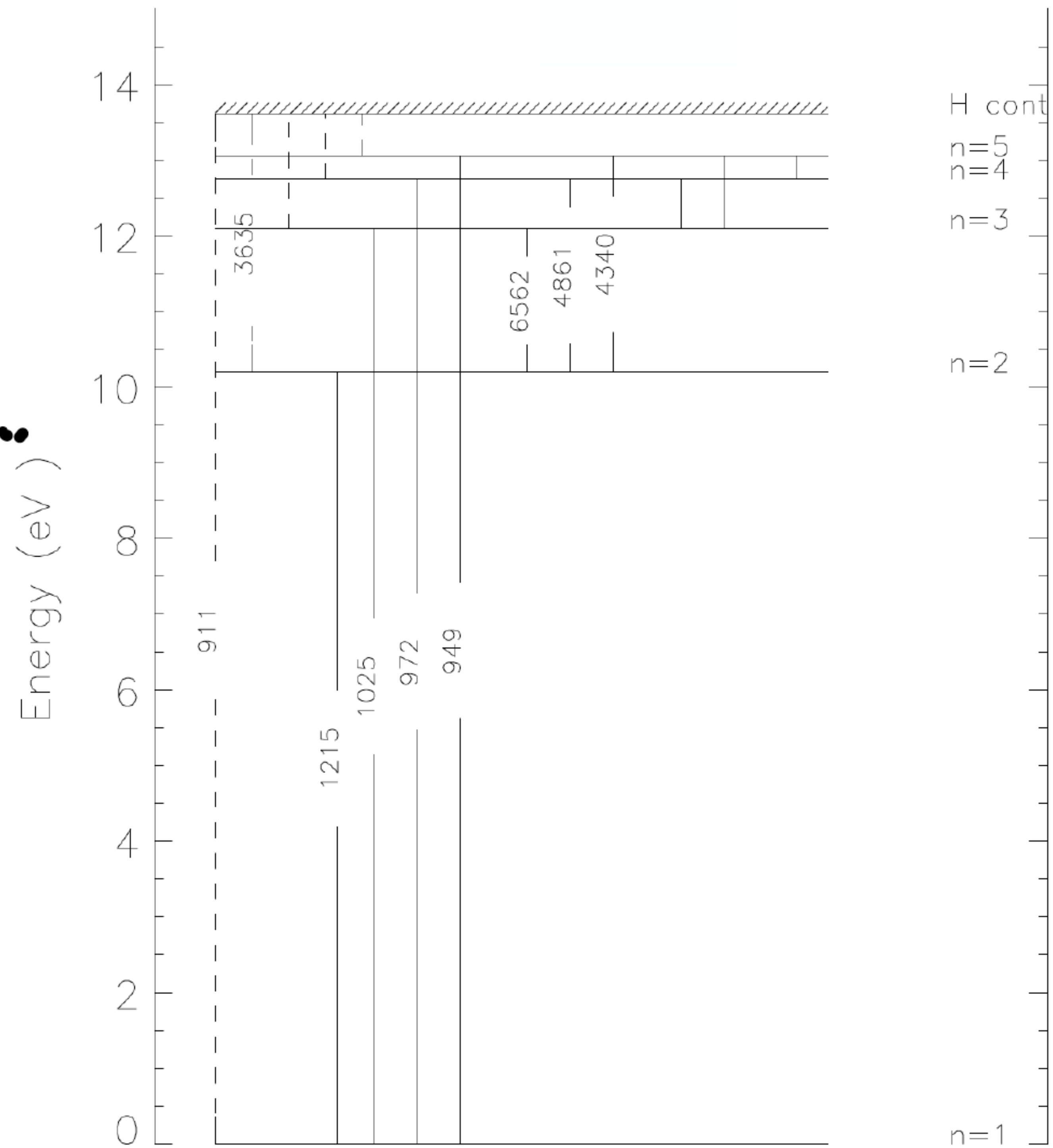
TERMINOLOGY: 1D PLANE-PARALLEL MODELING



***For this lecture z=0 is at top of atmosphere; for lab z=0 is at photosphere

TERMINOLOGY: THE HYDROGEN ATOM

Lyman, Balmer, Paschen.....



Hγ

e^-

Balmer continuum photon

n=2

TERMINOLOGY: LTE VS. NON-LTE

- LTE: local thermodynamic equilibrium
  - level populations determined by temperature (collisions)
  - When collisional rates are high (density is high), can make use of Saha-Boltzmann
  - The ratio of emissivity to opacity is the Planck function
- non-LTE:
  - level populations affected by the radiation field (which can originate from somewhere else in the atmosphere)
  - scattering of radiation changes levels from their Saha-Boltzmann values

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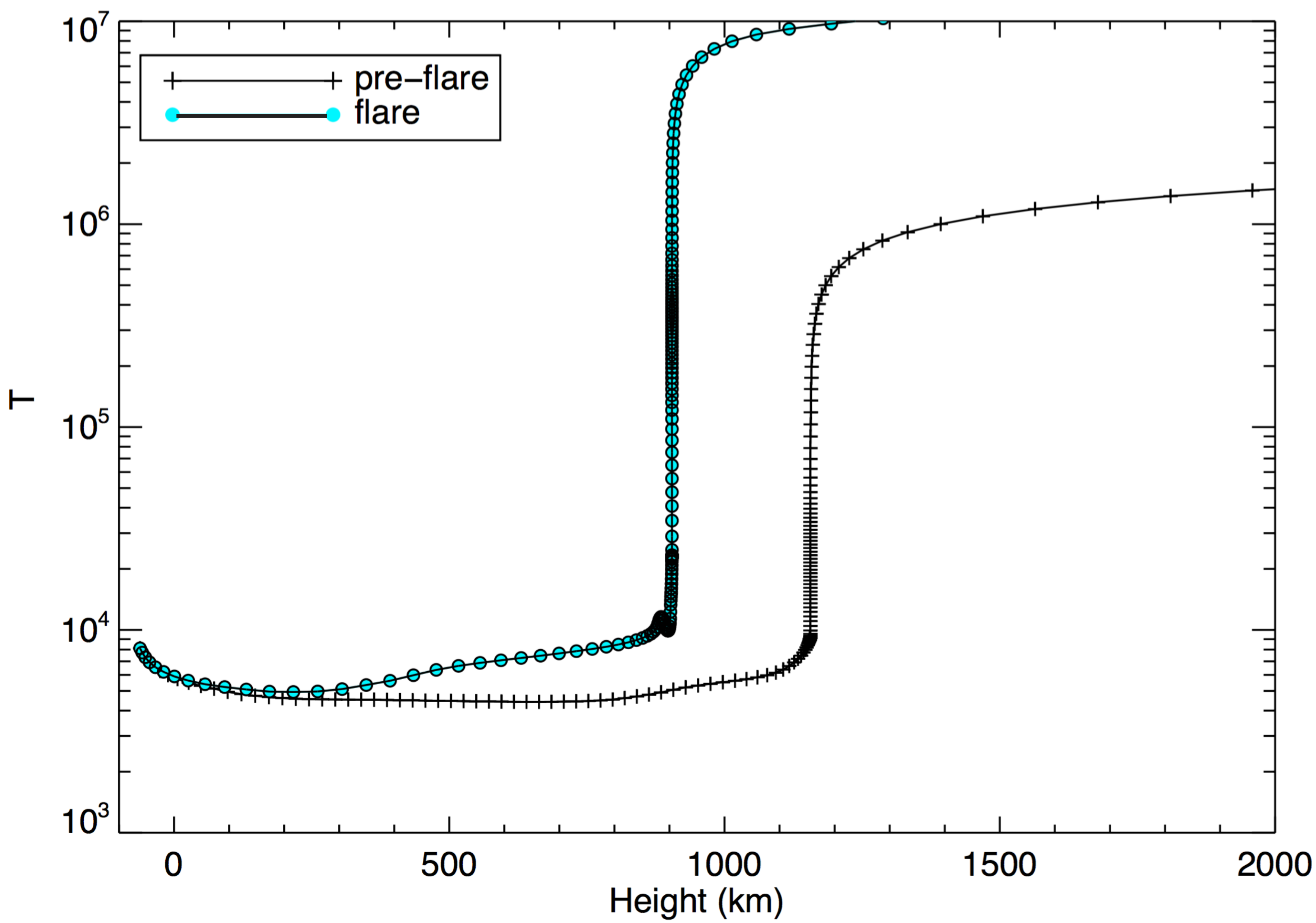
INITIAL MODEL ATMOSPHERE (1D)

- Adaptive grid (Dorfi & Drury 1987) to resolve transition region and steep pressure gradients / shocks during flare.



EQUATIONS OF RHD

(0) Charge conservation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial z} = 0, \tag{1}$$

mass

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho v^2}{\partial z} + \frac{\partial (p + q_{\mathrm{v}})}{\partial z} + \rho g - A_{\mathrm{beam}} = 0, \tag{2}$$

momentum

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho v e}{\partial z} + (p + q_{\mathrm{v}}) \frac{\partial v}{\partial z} + \frac{\partial \left(F_{\mathrm{c}} + F_{\mathrm{r}}\right)}{\partial z} - Q_{\mathrm{cor}} - Q_{\mathrm{beam}} - Q_{\mathrm{rc}} = 0, \tag{3}$$

energy

$$\frac{\partial n_i}{\partial t} + \frac{\partial n_i v}{\partial z} - \left(\sum_{j \neq i}^{N'} n_j P_{ji} - n_i \sum_{j \neq i}^{N'} P_{ij} \right) = 0, \tag{4}$$

rate of level population

$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \underbrace{\eta_{\nu\mu}}_{\text{emissivity}} - \underbrace{\chi_{\nu\mu}}_{\text{opacity}} I_{\nu\mu} \tag{5}$$

radiate transfer.

EQUATIONS OF RHD

"beam" = nonthermal electron distribution

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial z} = 0, \tag{1}$$

$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho v^2}{\partial z} + \frac{\partial (p + q_v)}{\partial z} + \rho g - A_{\text{beam}} = 0, \tag{2}$$

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho v e}{\partial z} + (p + q_v)\frac{\partial v}{\partial z} + \frac{\partial (F_c + F_r)}{\partial z} - Q_{\text{cor}} - Q_{\text{beam}} - Q_{\text{rc}} = 0, \tag{3}$$

erg/s/cm^3

e = internal energy density (thermal + excitation/ ionization)

$$\frac{\partial n_i}{\partial t} + \frac{\partial n_i v}{\partial z} - \left(\sum_{j \neq i}^{N'} n_j P_{ji} - n_i \sum_{j \neq i}^{N'} P_{ij} \right) = 0, \tag{4}$$

$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \eta_{\nu\mu} - \chi_{\nu\mu} I_{\nu\mu} \tag{5}$$

* Q_{rc} = energy deposition rate from return current.

EQUATIONS OF RHD

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial z} = 0, \tag{1}$$

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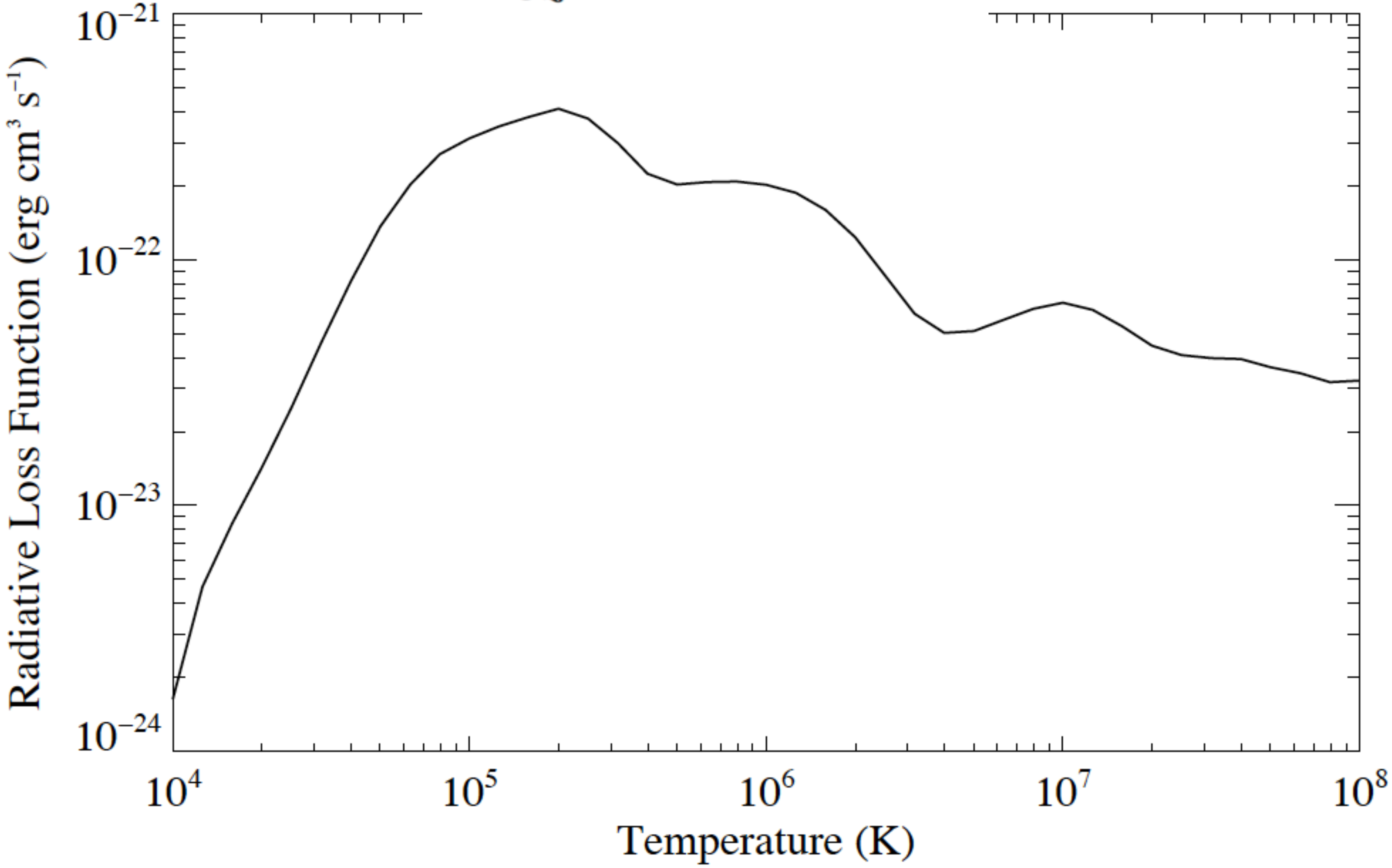
$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \eta_{\nu\mu} - \chi_{\nu\mu} I_{\nu\mu} \tag{5}$$

integrate over $\mu, \nu \rightarrow F_r$

Solve for $I_{\nu,\mu}(\tau_\nu)$ ....

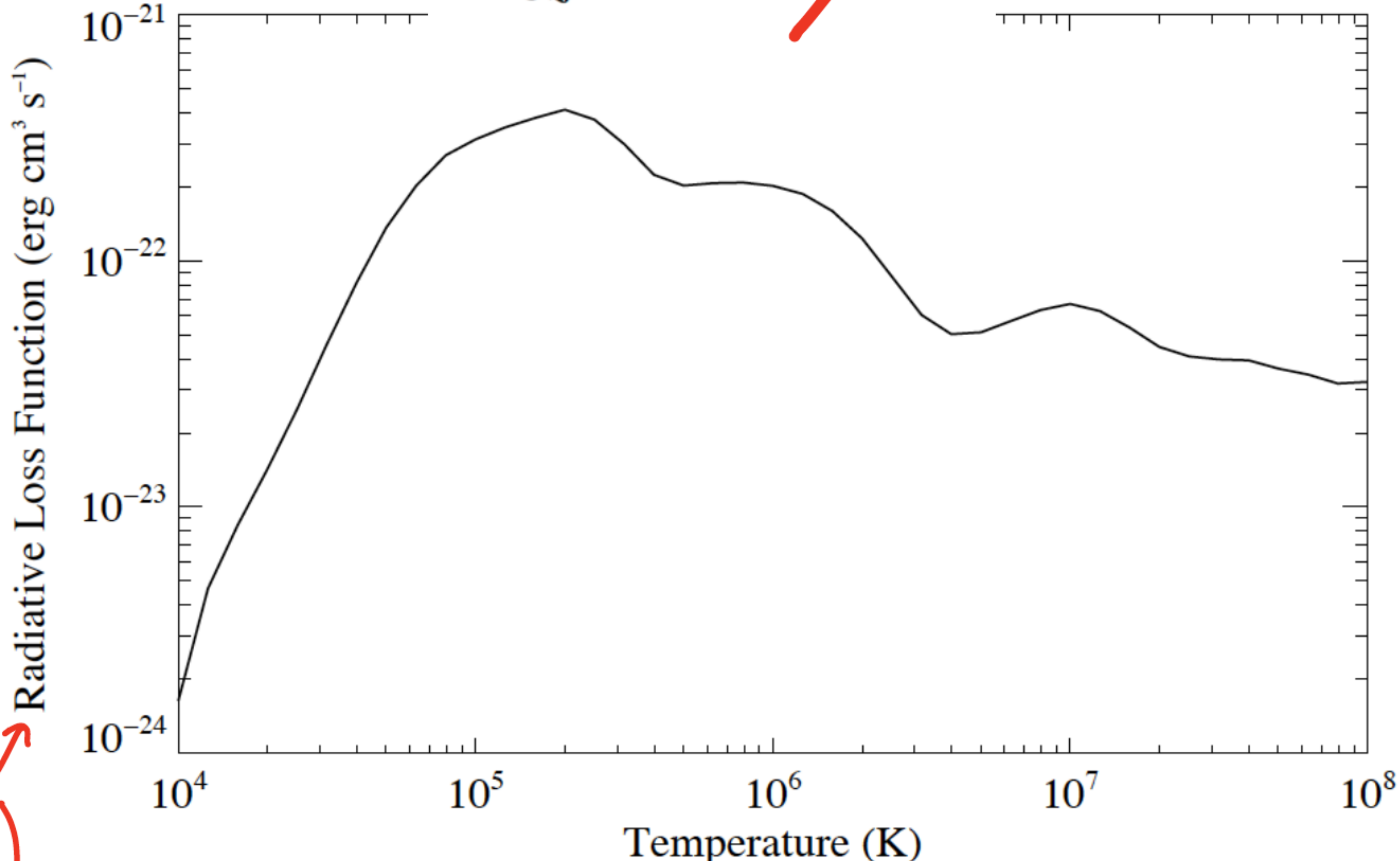
OPTICALLY THIN RADIATIVE LOSS FUNCTION

$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \eta_{\nu\mu} - \chi_{\nu\mu} I_{\nu\mu}$$



OPTICALLY THIN RADIATIVE LOSS FUNCTION

$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \eta_{\nu\mu} - \cancelto{0}{\chi_{\nu\mu} I_{\nu\mu}}$$



$\Lambda(T_e)$

See Prof. Longcope's lectures 9, 11

EQUATIONS OF RHD

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$$\frac{\partial \rho v}{\partial t} + \frac{\partial \rho v^2}{\partial z} + \frac{\partial (p + q_{\mathrm{v}})}{\partial z} + \rho g - A_{\mathrm{beam}} = 0, \tag{2}$$

$$\frac{\partial \rho e}{\partial t} + \frac{\partial \rho v e}{\partial z} + (p + q_{\mathrm{v}})\frac{\partial v}{\partial z} + \frac{\partial \left(F_{\mathrm{c}} + F_{\mathrm{r}}\right)}{\partial z} - Q_{\mathrm{cor}} - Q_{\mathrm{beam}} - Q_{\mathrm{rc}} = 0, \tag{3}$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial n_i v}{\partial z} - \left(\sum_{j \neq i}^{N'} n_j P_{ji} - n_i \sum_{j \neq i}^{N'} P_{ij}\right) = 0, \tag{4}$$

$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \eta_{\nu\mu} - \chi_{\nu\mu} I_{\nu\mu} \tag{5}$$

integrate over $\mu, \nu \to F_r$

Solve for $I_{\nu,\mu}$ (χ_ν)....

certain elements/ions treated "in detail"
→ non-LTE and optically thick, non-equilibrium ionization/excitation

EQUATION OF RADIATIVE TRANSFER AND PLANE-PARALLEL GEOMETRY

$$I_{\nu\mu}(\tau_\nu) = \begin{cases} \frac{1}{\mu}\int_{\tau_\nu}^{\infty} S_\nu(t) e^{-(t-\tau_\nu)/\mu} dt & \text{if } \mu > 0 \\ \frac{1}{-\mu}\int_0^{\tau_\nu} S_\nu(t) e^{-(\tau_\nu - t)/(-\mu)} dt & \text{if } \mu < 0 \end{cases}$$

$I_{\mu,\nu}(\tau_\nu=0)$ = emergent intensity

$$= \frac{1}{\mu}\int_0^{\infty} S_\nu(t) e^{-t/\mu} dt$$

For optically thick frequencies.

* NOT $G_x(T_x)$ from Lecture 11

THE CONTRIBUTION FUNCTION*

Emergent Intensity $= I_{\nu,\mu}(\tau_\nu = 0)$

$$= \int_0^\infty \frac{1}{\mu} S_\nu(\tau_\nu)\, e^{-\tau_\nu/\mu}\, d\tau$$

$$S_\nu \equiv \frac{\eta_\nu}{\chi_\nu} \;;\quad \tau_\nu = \int \chi_\nu\, dz$$

$$\Rightarrow \quad I_{\nu,\mu}(z=0) = \int_{z=0}^{\infty} \underbrace{\frac{1}{\mu} \eta_\nu\, e^{-\int \chi_\nu dz}}_{\text{The contribution function to the emergent intensity.}} dz$$

$C_I(z)$ tells you where the emergent intensity is formed. [erg / s / cm^2 / Å / s.r. / cm]

THE CONTRIBUTION FUNCTION

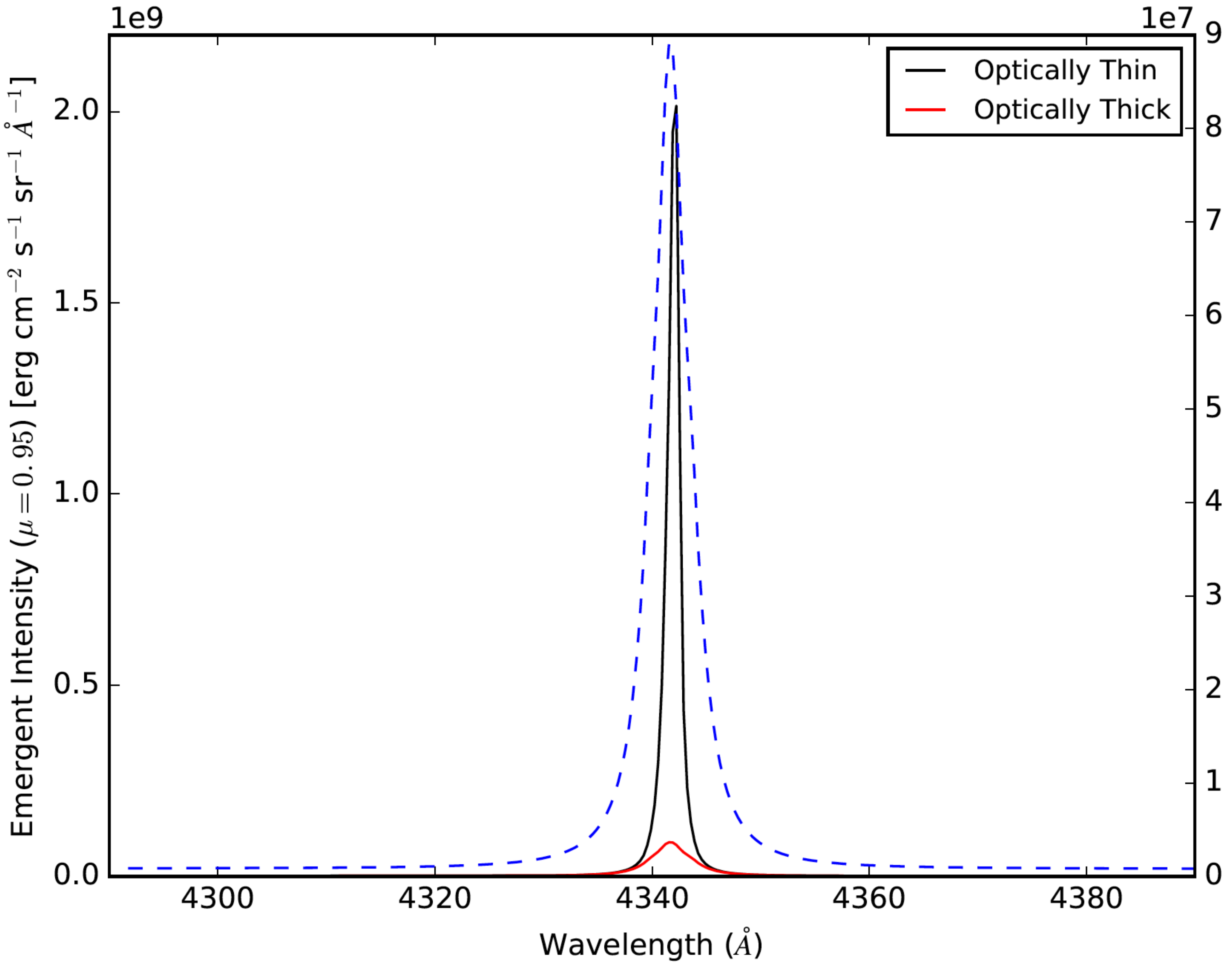
- Integrating the contribution function over height gives emergent intensity
- Integrating (via Gaussian quadrature sum) the emergent intensity over μ gives the *emergent* radiative flux:

$$F_\nu = 2\pi \sum_\mu I_{\nu,\mu} \mu w_\mu$$
$$w_\mu = [0.118, 0.239, 0.284, 0.239, 0.118]$$
$$\mu = [0.0469, 0.231, 0.5, 0.769, 0.953]$$

THE CONTRIBUTION FUNCTION: WHY DO WE CARE?

- Compare emergent flux from a flare atmosphere to observations.
- Use contribution function to determine the atmospheric parameters.

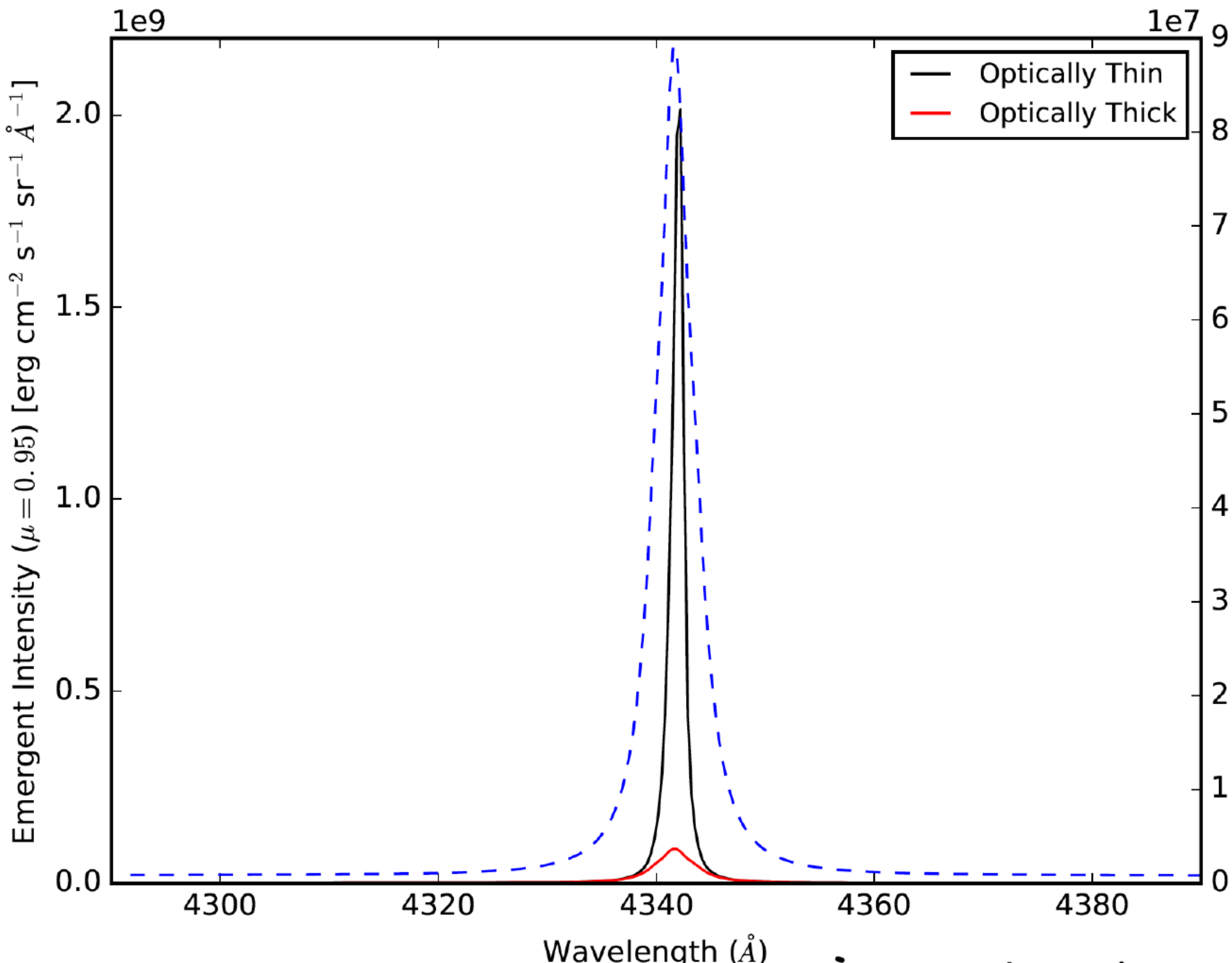
OPTICALLY THICK VS. OPTICALLY THIN



OPTICALLY THICK VS. OPTICALLY THIN

$$\tau_\nu(z) = \int_0^z \chi_\nu(z)\, dz$$

$z=0$ is the top of atmosphere



The exponential attenuation of radiation in deep layers results in much less emergent intensity.

OPTICALLY THICK VS. OPTICALLY THIN

$$\frac{\partial\rho}{\partial t} + \frac{\partial\rho v}{\partial z} = 0, \tag{1}$$

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Q: What happens in the energy equation if one assumes that all losses are optically thin?

OPTICALLY THICK VS. OPTICALLY THIN

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$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \eta_{\nu\mu} - \chi_{\nu\mu} I_{\nu\mu} \tag{5}$$

Q: What happens in the energy equation if one assumes that all losses are optically thin?

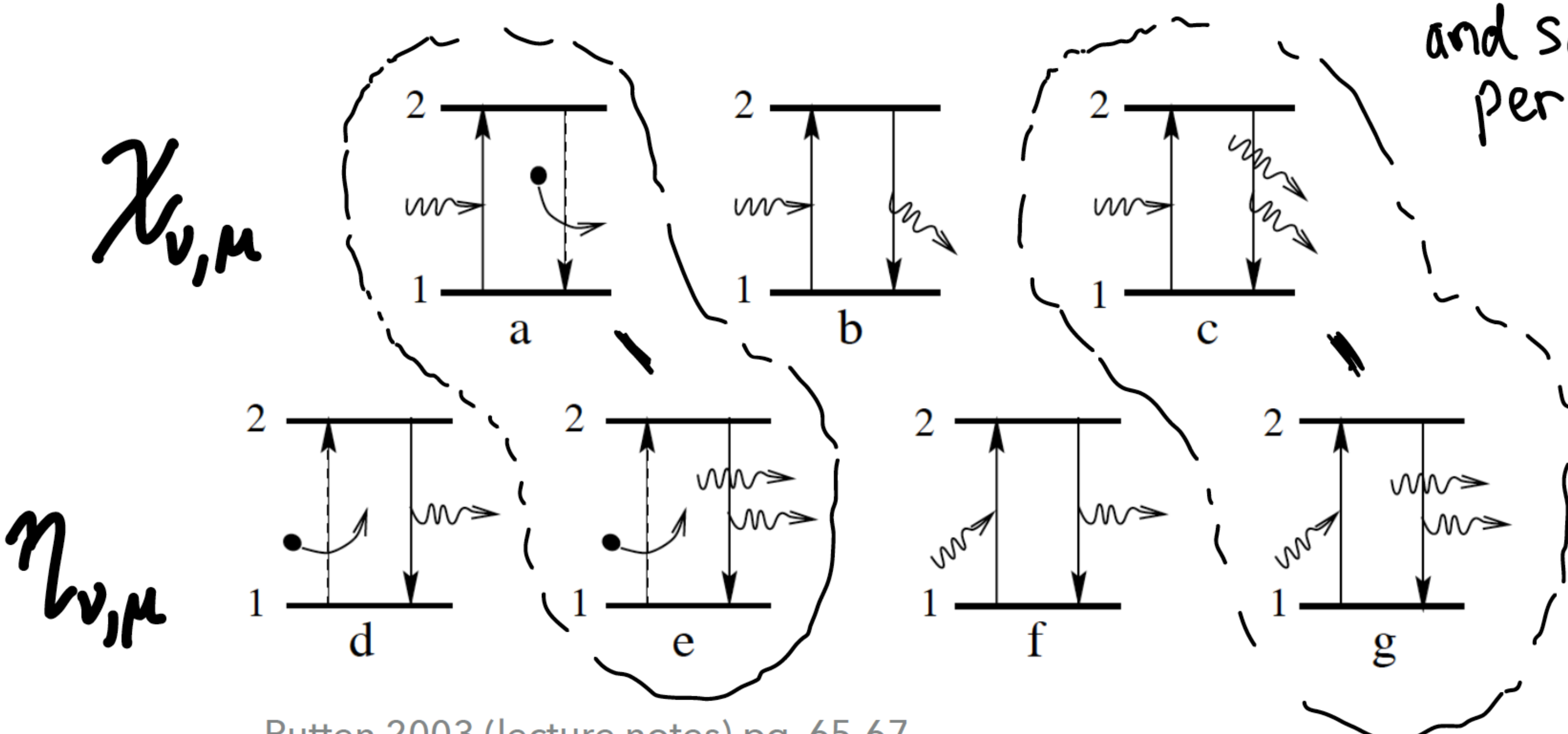
The radiative flux divergence would be too large → too much cooling.

OPTICALLY THICK RADIATIVE TRANSFER: OPACITY SOURCES

$$\mu \frac{\partial I_{\nu\mu}}{\partial z} = \eta_{\nu\mu} - \chi_{\nu\mu} I_{\nu\mu}$$

$[\chi] = cm^{-1}$

= # of absorptions and scatterings per cm.



Rutten 2003 (lecture notes) pg. 65-67

OPTICALLY THICK RADIATIVE TRANSFER: OPACITY SOURCES

- free-free
- bound-bound
- bound-free

state i computed from the usual Saha–Boltzmann formulae [equation (5-14)] using the *actual* ion density. Then summing over all levels and processes we have the *non-LTE opacity*

$$\chi_\nu = \sum_i \sum_{j>i} [n_i - (g_i/g_j)n_j]\alpha_{ij}(\nu) + \sum_i (n_i - n_i^* e^{-h\nu/kT})\alpha_{i\kappa}(\nu) + \sum_\kappa n_e n_\kappa \alpha_{\kappa\kappa}(\nu, T)(1 - e^{-h\nu/kT}) + n_e \sigma_e \quad (7\text{-}1)$$

where the four terms represent, respectively, the contributions of bound–bound, bound–free, and free–free absorptions, and of electron scattering (other scattering terms—e.g., Rayleigh scattering—may also be added). To calculate the *spontaneous thermal emission* (non-LTE) we use the rates derived in equations (5-55) and (5-62) to write

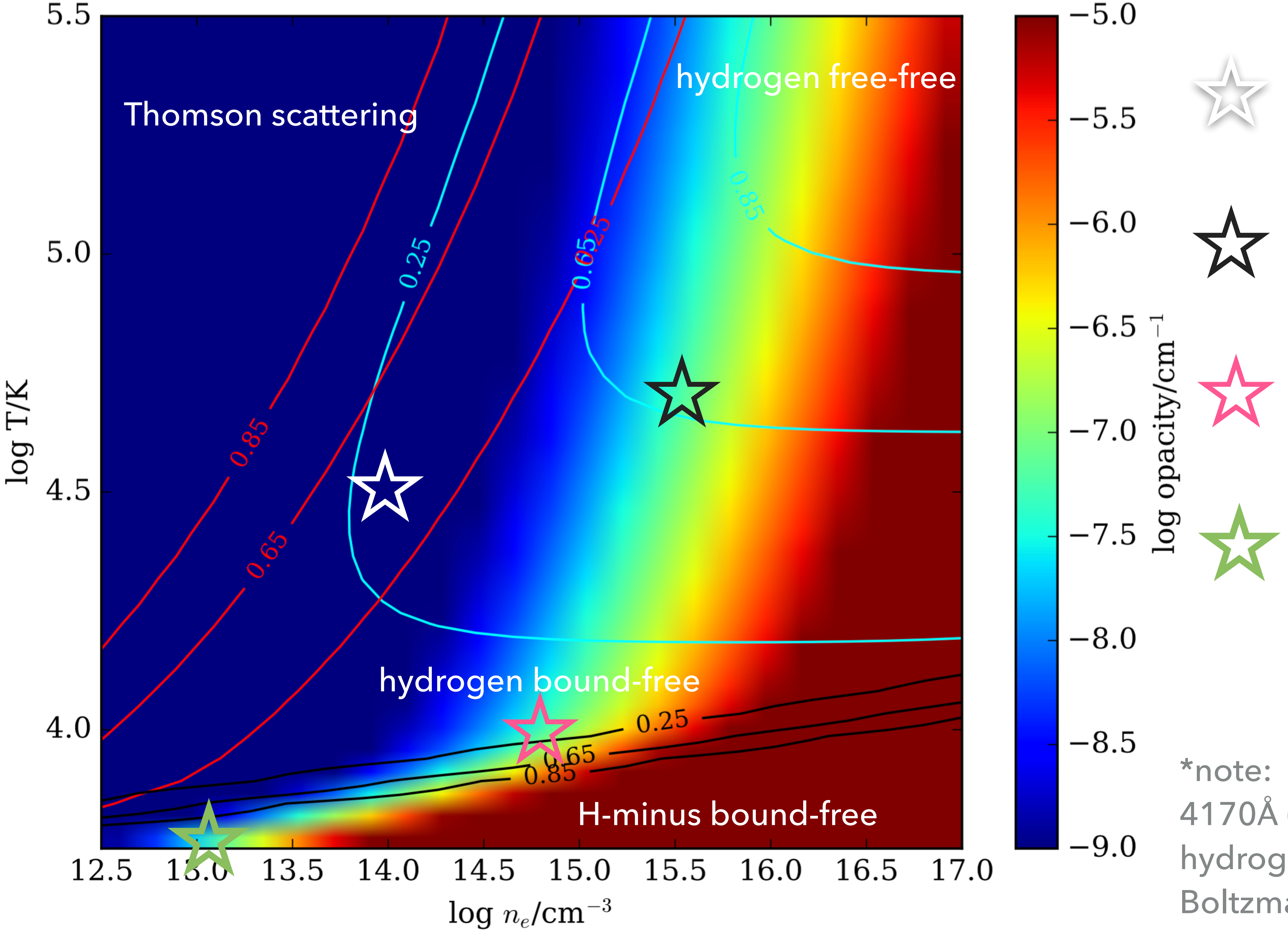
$$\eta_\nu = (2h\nu^3/c^2)\left[\sum_i \sum_{j>i} n_j (g_i/g_j)\alpha_{ij}(\nu) + \sum_i n_i^* \alpha_{i\kappa}(\nu) e^{-h\nu/kT} + \sum_\kappa n_e n_\kappa \alpha_{\kappa\kappa}(\nu, T) e^{-h\nu/kT}\right] \quad (7\text{-}2)$$

Mihalas 1978 (*Stellar Atmospheres*, 2nd Ed.)

*alpha is the respective cross section in cm^2 (see Rutten 2003 lecture notes)

OPTICALLY THICK RADIATIVE TRANSFER: CONTINUUM OPACITY

choices: photosphere of O star, outer atmosphere of O star, photosphere of Vega, photosphere of the Sun



*note: this diagram for 4170Å (blue) photons, pure hydrogen with Saha-Boltzmann

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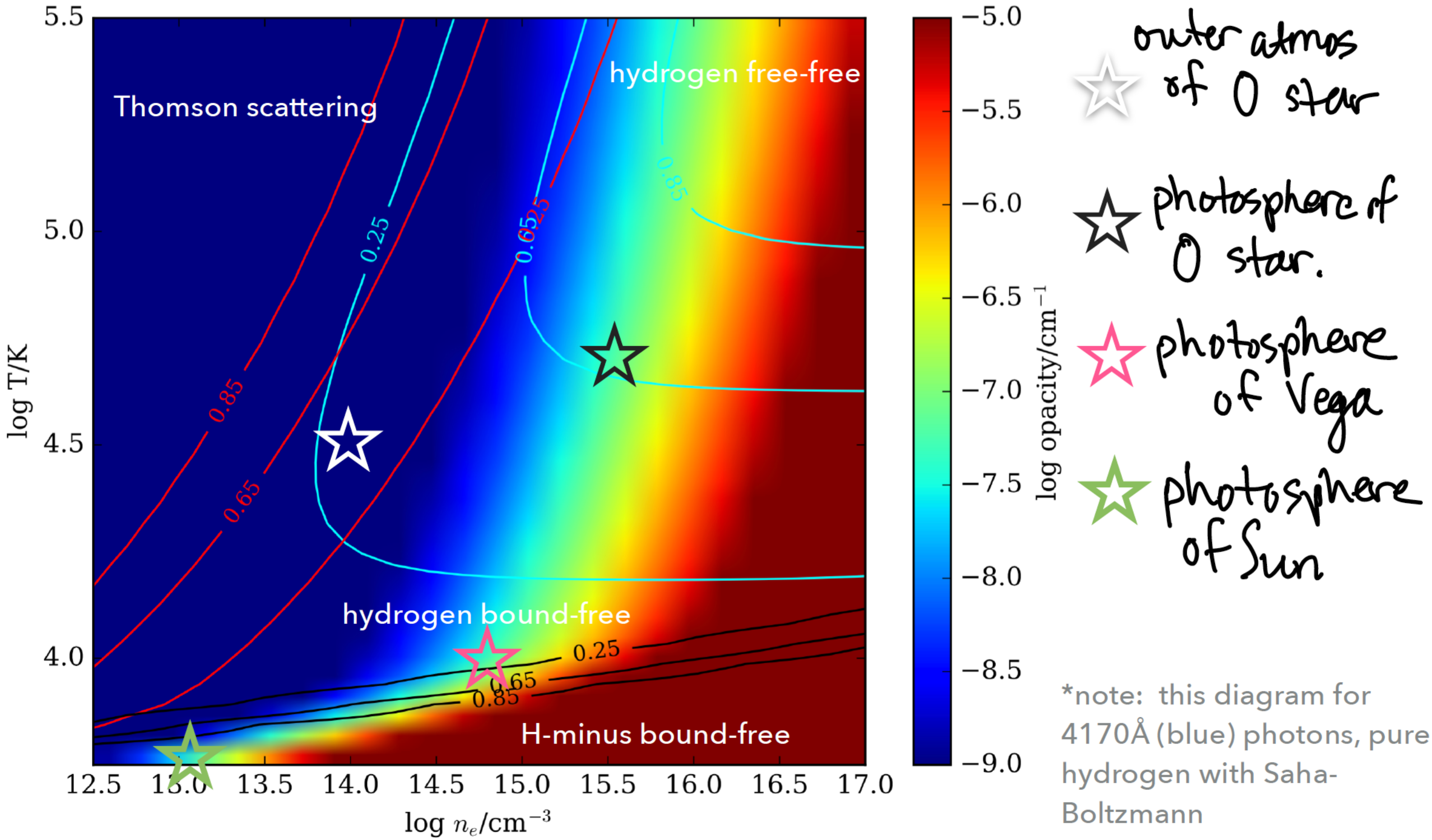

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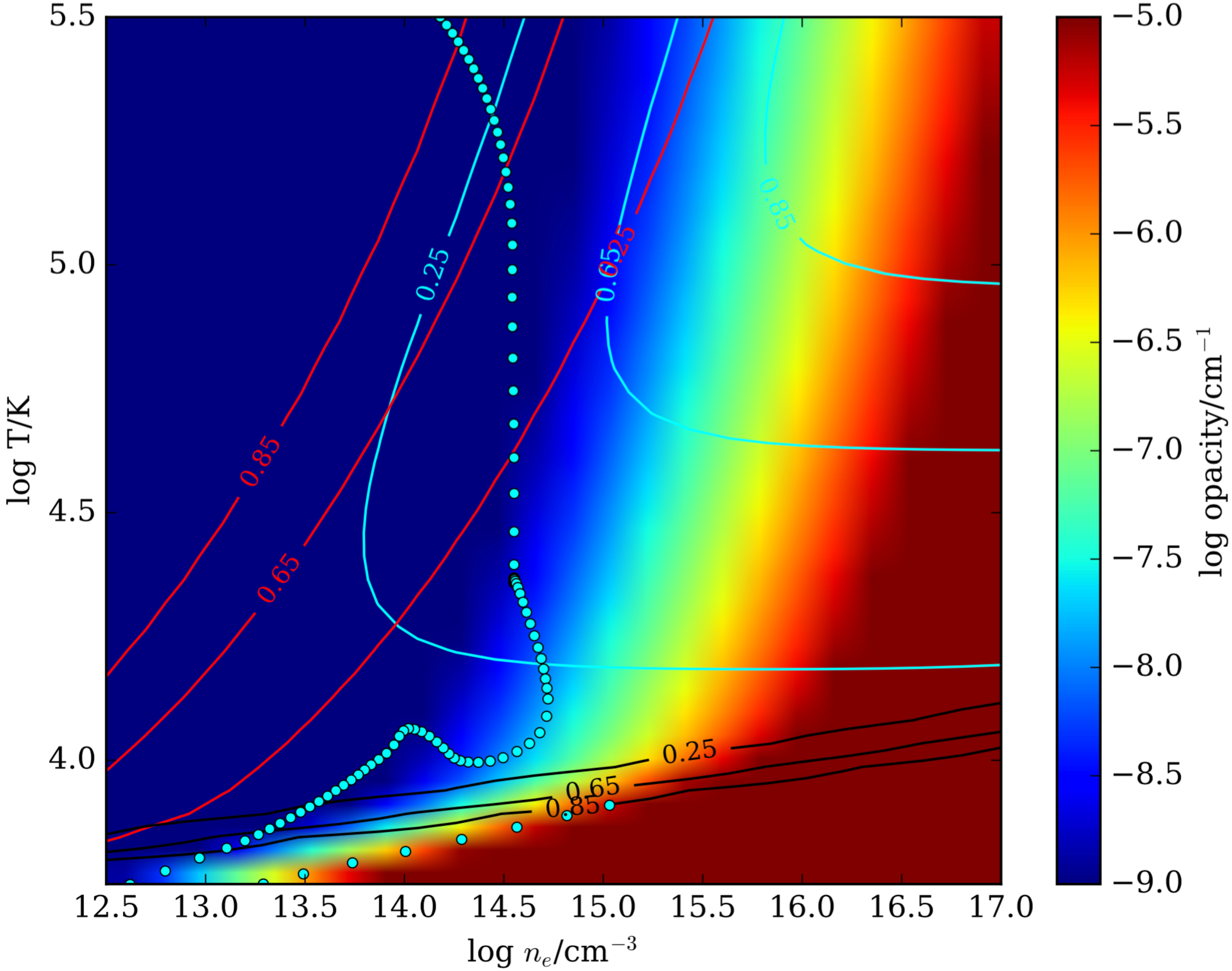
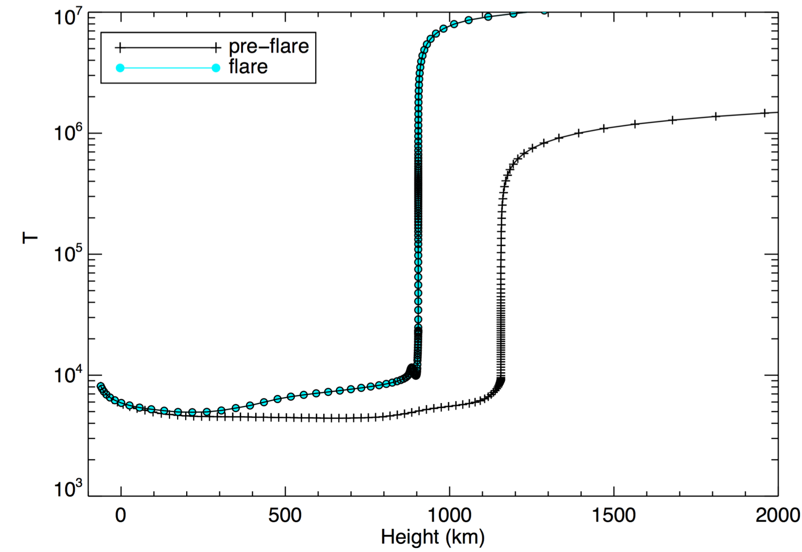
OPTICALLY THICK RADIATIVE TRANSFER: CONTINUUM OPACITY

- For a flare atmosphere (open circles):

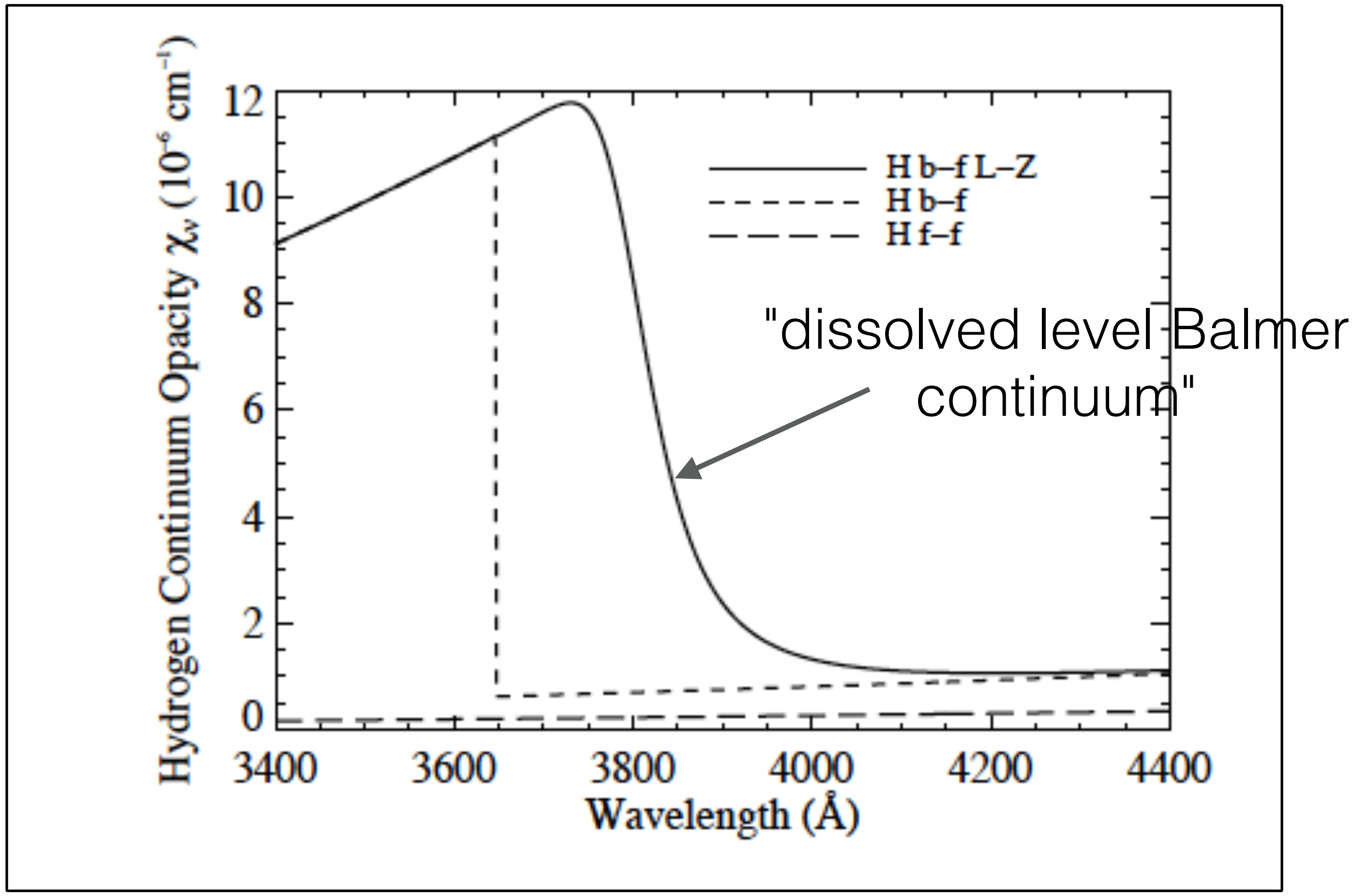




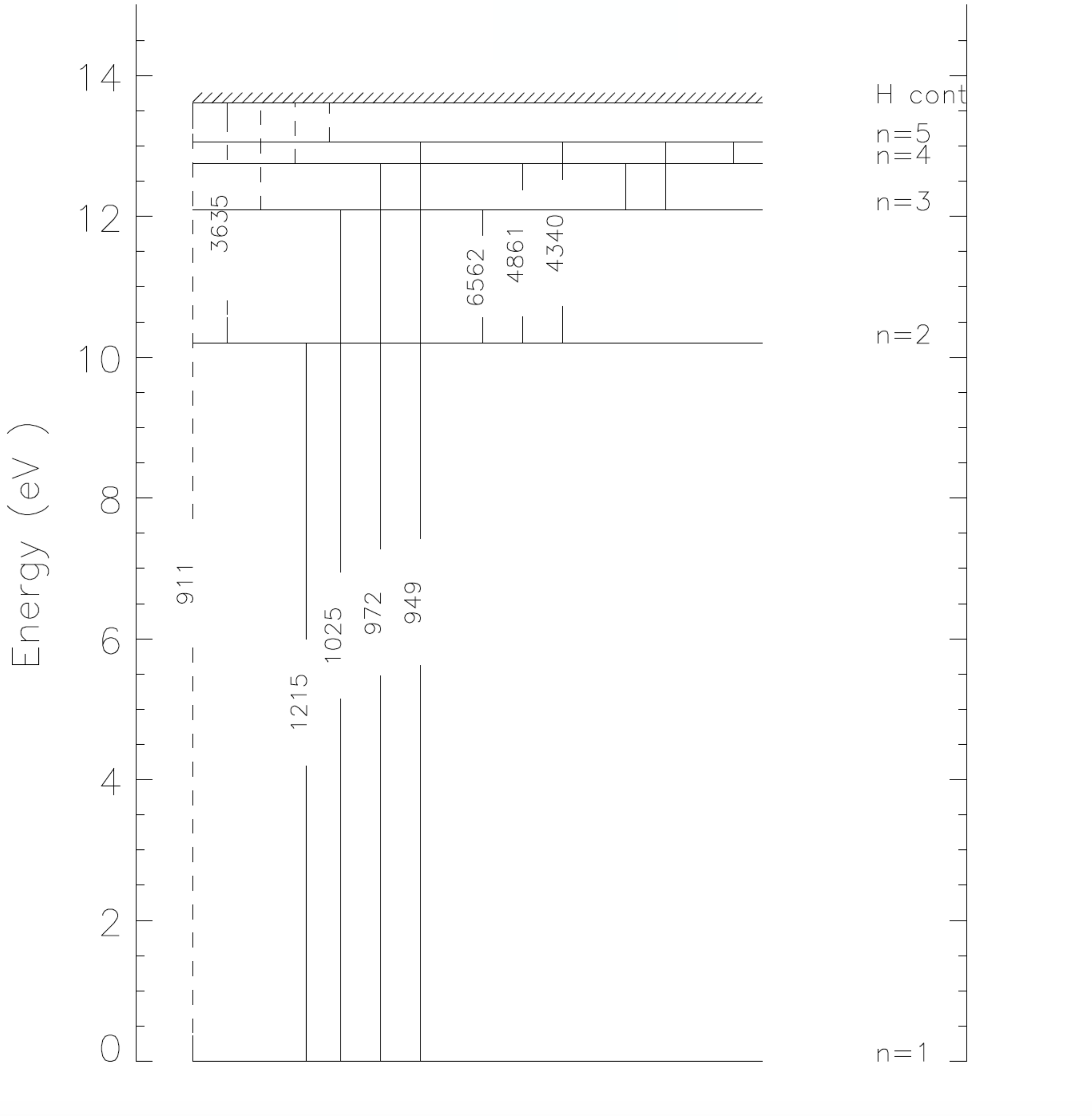
- A flare atmosphere has many sources of opacity

OPTICALLY THICK RADIATIVE TRANSFER: CONTINUUM OPACITY

- "dissolved level continuum" opacity (see Tremblay & Bergeron 2009, *ApJ*) for hydrogen



Kowalski et al. 2015 SoPh



OPTICALLY THICK RADIATIVE TRANSFER: EMISSIVITY

- erg / s / cm^3 / s.r. / Angstrom
- bound-free for hydrogen (LTE):

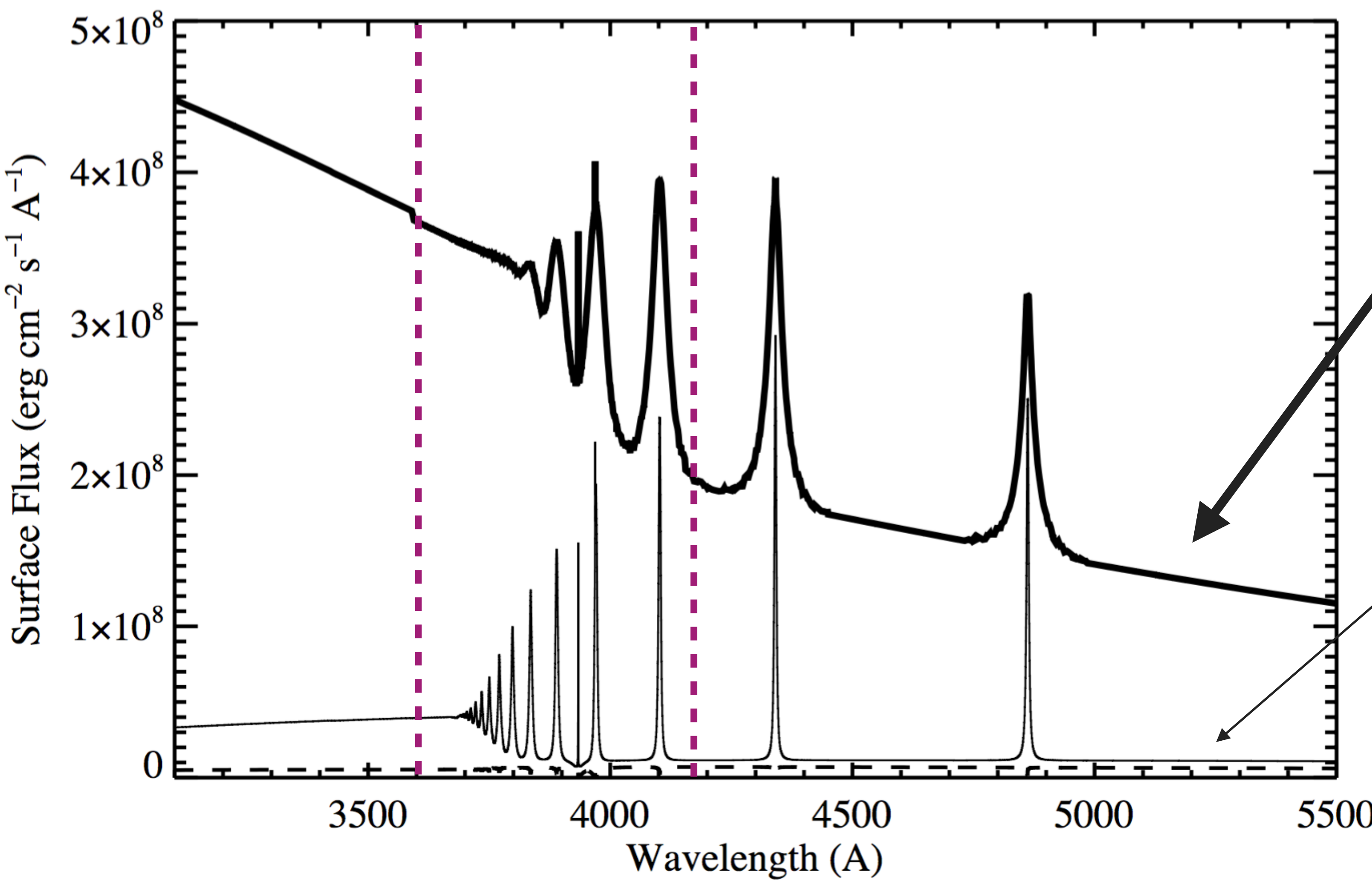
$$\eta_\lambda = \frac{6.48\times 10^{-14}}{4\pi\lambda^2}\frac{n_e n_p}{T^{3/2} n^3} e^{\frac{1.58\times 10^5}{n^2 T} - \frac{1.44\times 10^8}{\lambda T}}$$

$$\eta_\lambda \propto \frac{1}{\lambda^2} e^{\frac{-hc}{\lambda k T}}$$

(for a given principal quantum number *n* and temperature *T*)

CONTINUUM FORMED AT T=10,000 K OVER LOW OR HIGH OPTICAL DEPTH?

- Photospheric-like or chromospheric-like?
- Measure the Balmer jump ratio = F_{3600} / F_{4170}
- Measure a blue-to-red continuum ratio = F_{4170} / F_{6000}



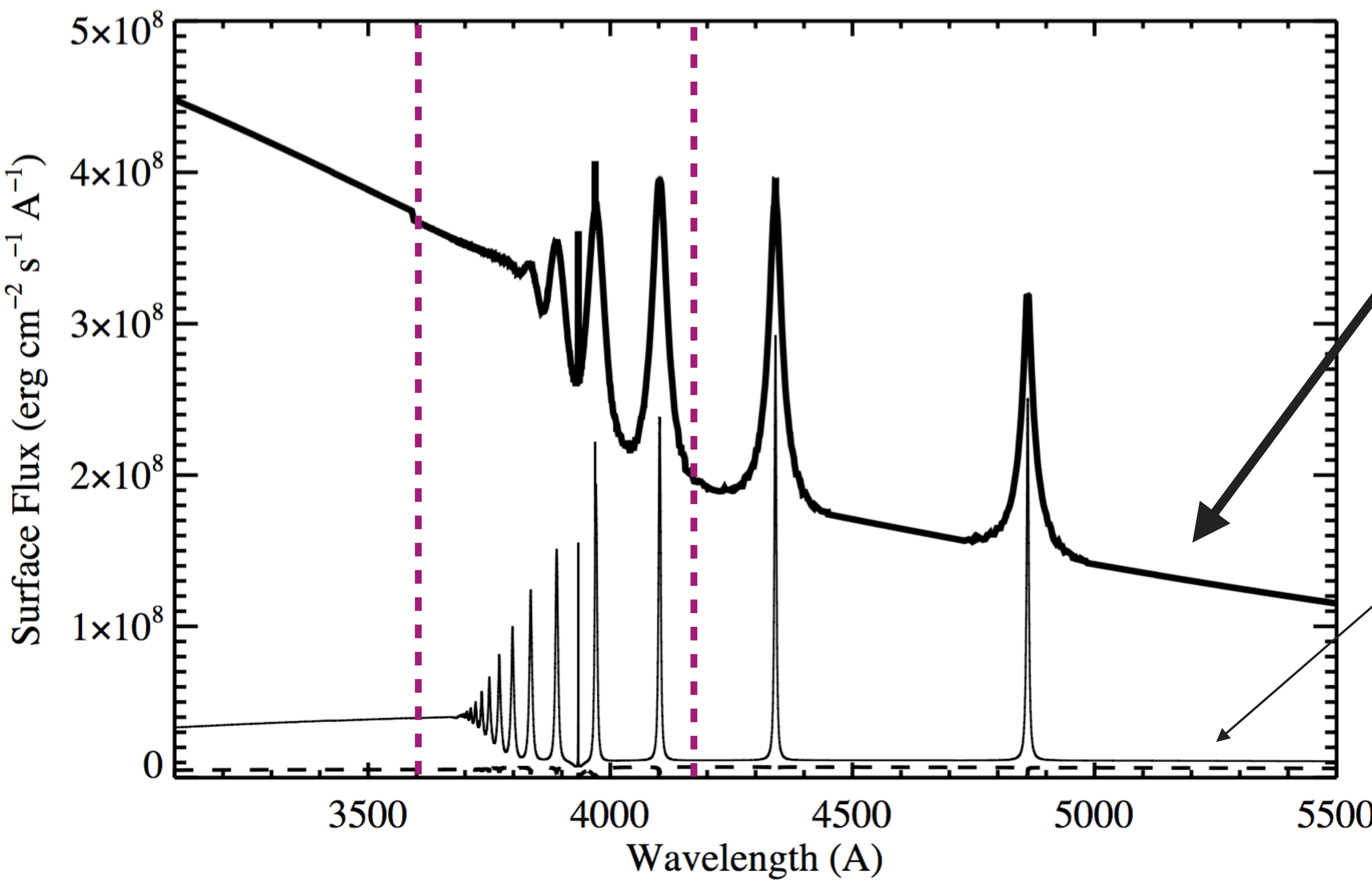
For hydrogen recombination radiation over high optical depth and T~10,000 K, Balmer jump ratio is ~2 or lower

For hydrogen recombination radiation over low optical depth and T~10,000 K, Balmer jump ratio is close to 9-10

CONTINUUM FORMED AT T=10,000 K OVER LOW OR HIGH OPTICAL DEPTH?

- Photospheric-like or chromospheric-like?
- Measure the Balmer jump ratio = F_{3600} / F_{4170}
- Measure a blue-to-red continuum ratio = F_{4170} / F_{6000}

$\gtrsim 2$ or $\lesssim 1$



For hydrogen recombination radiation over high optical depth and T~10,000 K, Balmer jump ratio is ~2 or lower

For hydrogen recombination radiation over low optical depth and T~10,000 K, Balmer jump ratio is close to 9-10

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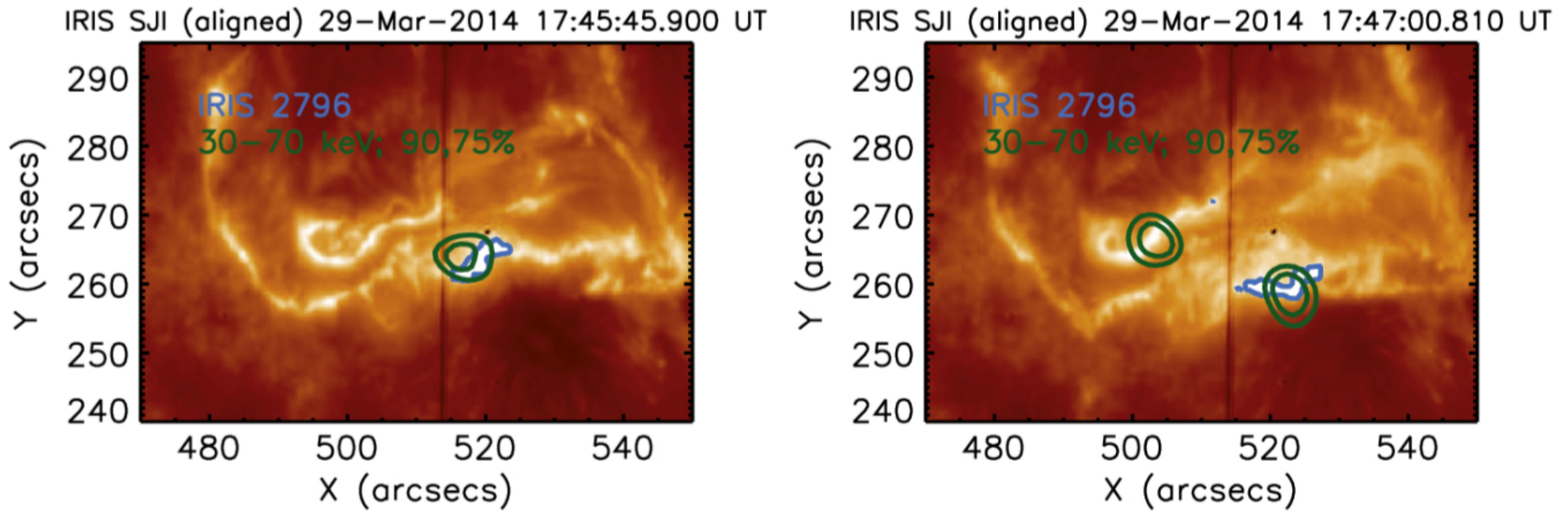
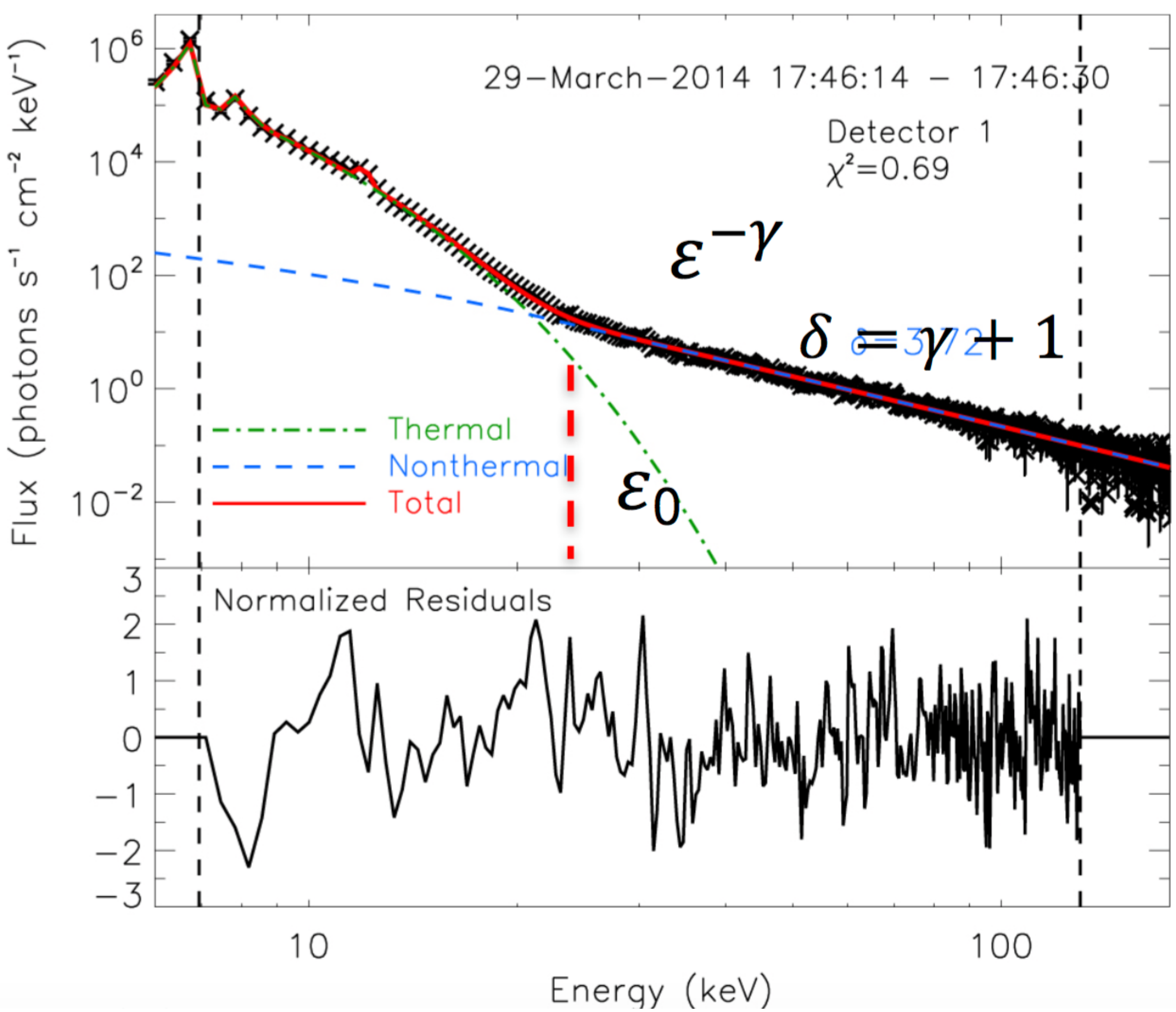
FLARE HEATING PRESCRIPTION IN RHD CODES

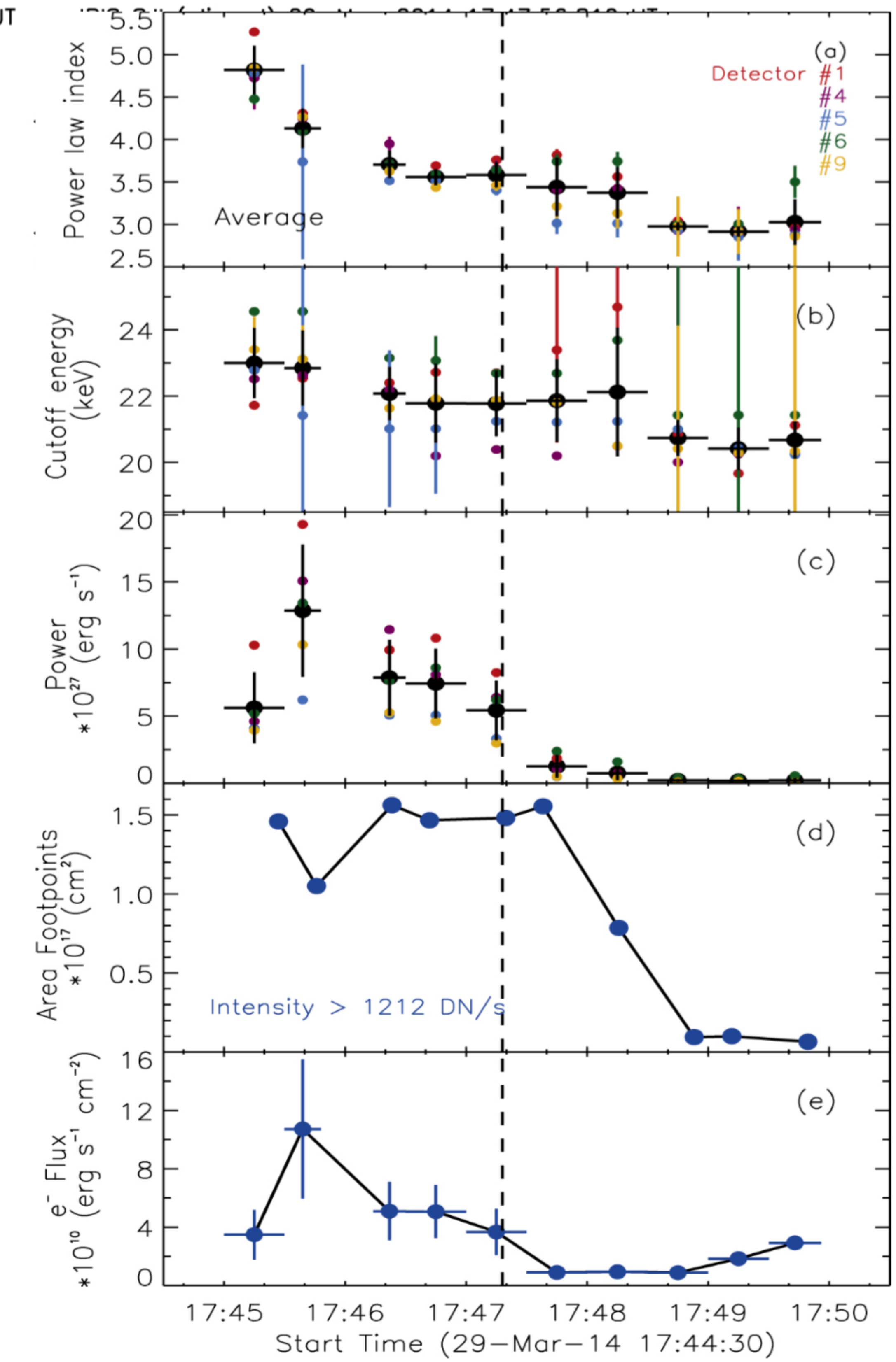
- Bright redshifts, bright white-light (optical) co-spatial and co-temporal with hard X-ray emission: nonthermal electron distributions
- See Prof. Chen's previous lecture on modeling hard X-ray emission to infer power-law index (δ), low energy cutoff (keV), and power in nonthermal electrons (erg / s).
- In every flare loop, one must specify a nonthermal energy flux (erg / s / cm^2) injected at the top of the loop: e.g., F11, 3.5F11, ... F13?
- See Prof. Longcope's lecture on stochastic and shock acceleration mechanisms; radiative-hydro models do not model reconnection and initial particle acceleration/injection.

DYNAMICS WITH NT PARTICLES

From Prof. Qiu's lecture #3



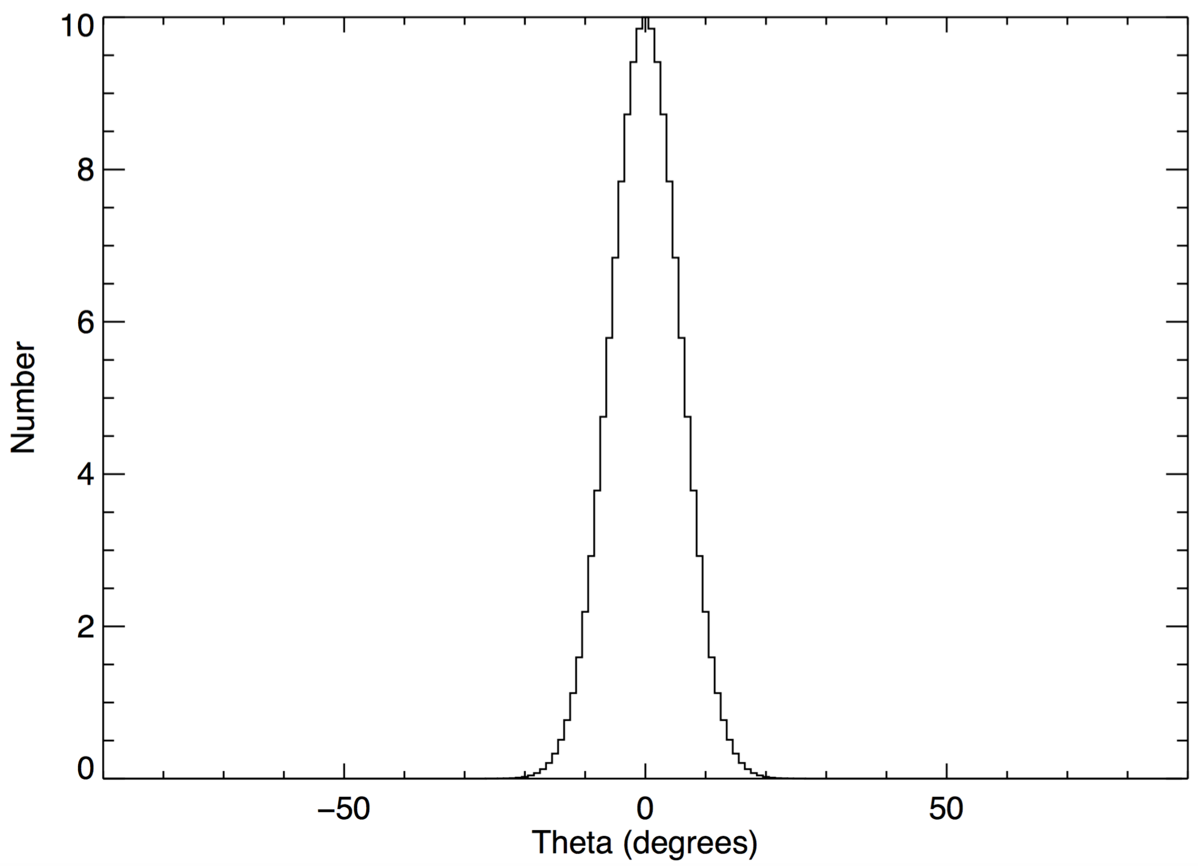




See also Kleint et al. 2016, Kowalski et al. 2017

INPUT PARAMETERS TO RADYN

```
*mass of beam particle, charge of particle, kfan (3=isotropic in forward
 hemi, 2=gaussian in forward hemi), sigma_mu^2 of forward gaussian
511d3  -1.0    2 0.1
* Example ftab.dat
*npts
          9
*      Time (s)       delta       Ec (keV)    Flux (erg/s/cm^2)
*---------------------------------------------------------
0.00     4.00     25.00    1e11
0.10     4.00     25.00    1e11
1.00     4.00     25.00    1e11
5.00     4.00     25.00    1e11
10.0     4.00     25.00    1e11
10.01    4.00     25.00    1e-20
20.1     4.00     25.00    1e-20
50.0     4.00     25.00    1e-20
60.0     4.00     25.00    1e-20
```



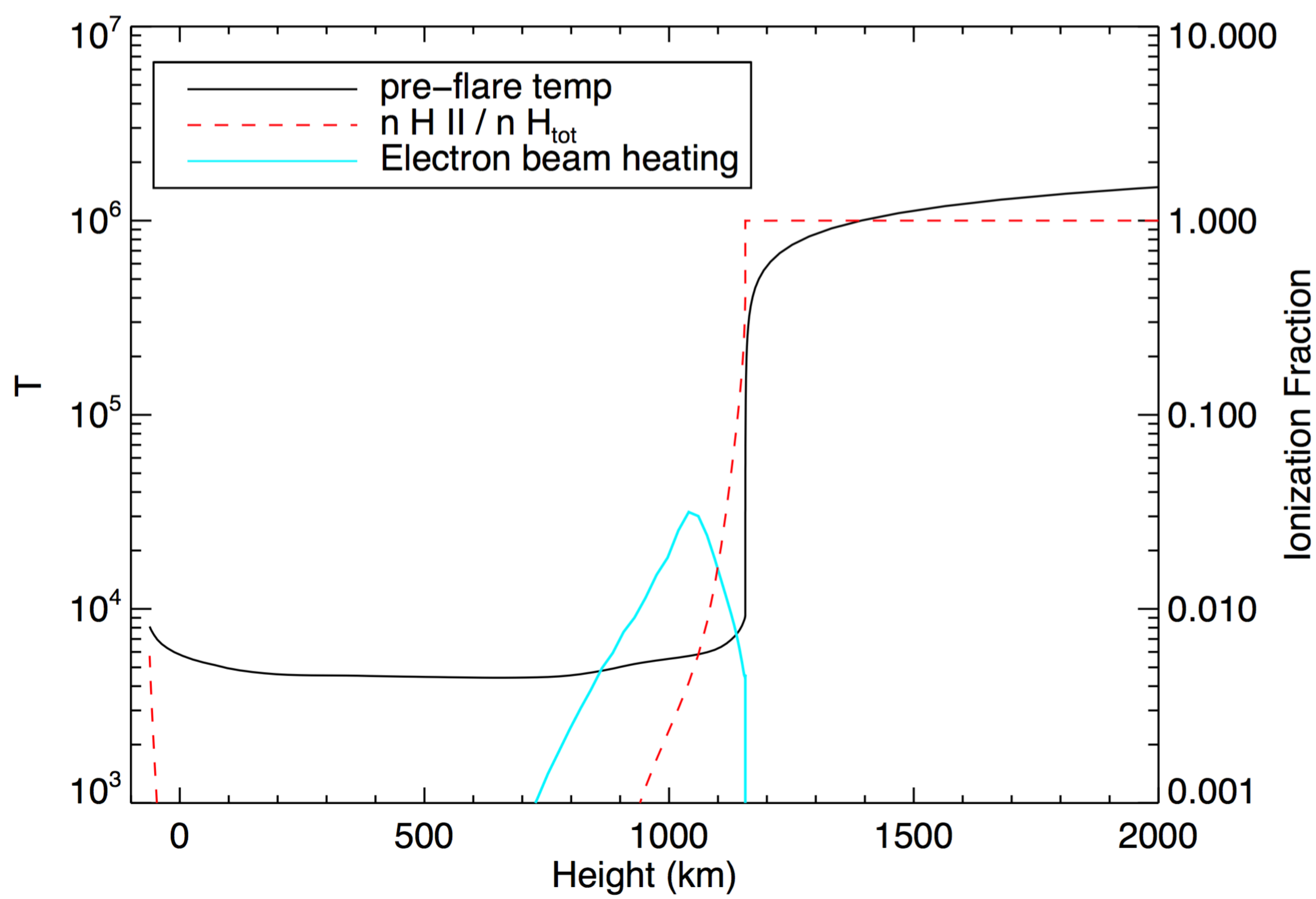
Quite highly collimated / "beamed"

THE FOKKER-PLANCK EQUATION

- additional reading:
  - McTiernan & Petrosian 1990, Allred et al. 2015
  - https://hesperia.gsfc.nasa.gov/hessi/flarecode/efluxdoc.pdf
  - f(**x**, **p**, t) → f(z, E, mu), units of [number/cm^3/keV/steradian]
    - time-independent solution to the Fokker-Planck equation where *d*f(z,E,mu)/*d*t = 0
    - re-solved when the atmosphere has changed state

PARTIALLY IONIZED CHROMOSPHERE

- Energy loss rate due to elastic Coulomb collisions with ambient electrons and electrons bound to atoms.

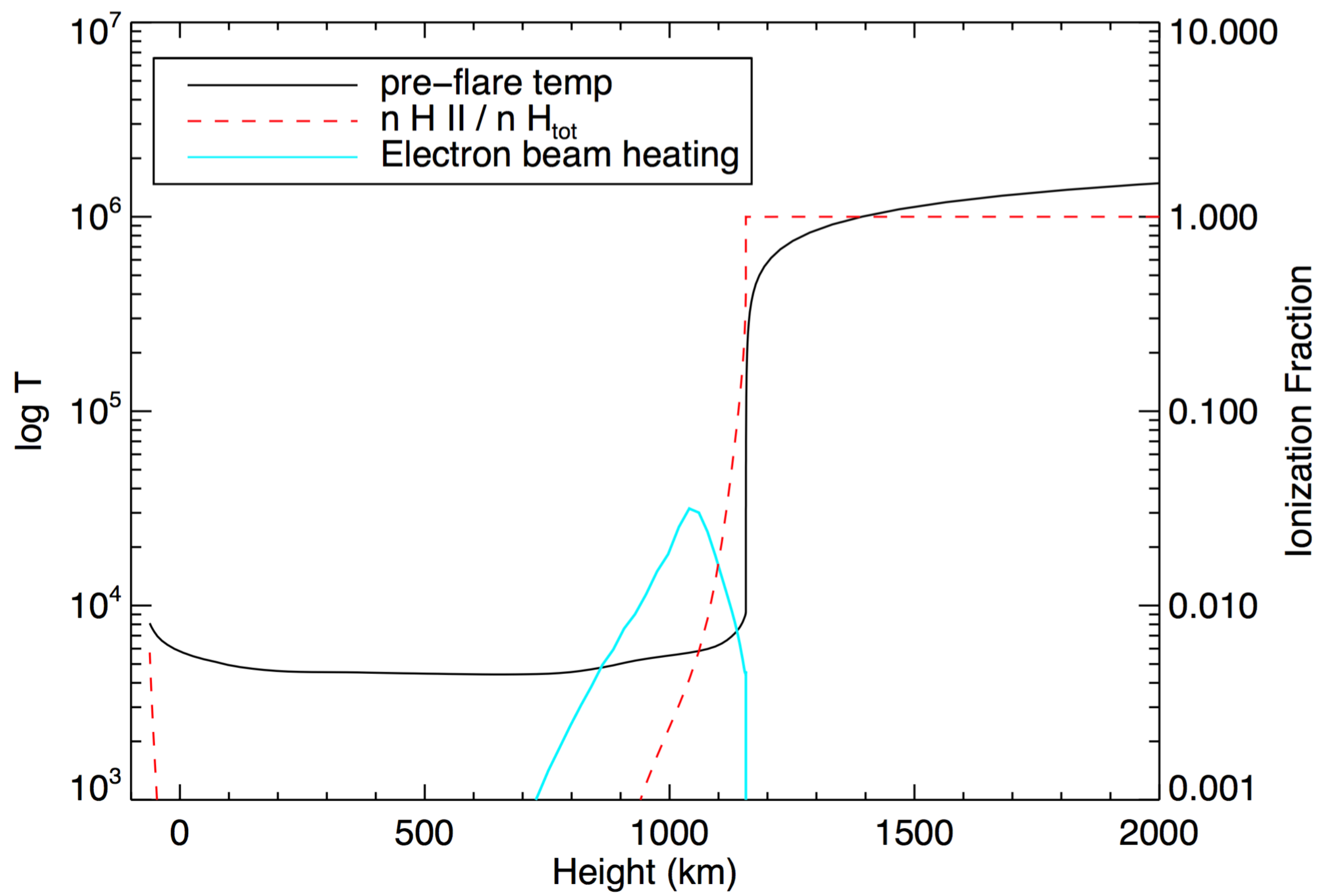


- A ratio of about three (Hawley & Fisher 1994, Mott & Massey 1965)

*Electron beam heating [erg/s/cm^3, left axis] here is at t=0s for E_c=25 keV, 5F11, δ=4.2

CALCULATING BEAM ENERGY DEPOSITION RATES

$$Q_{beam} = \frac{\mathrm{d}}{\mathrm{d}z}\left(\int_{\mu}\int_{E}\mu v E f \,\mathrm{d}E \mathrm{d}\mu\right)$$

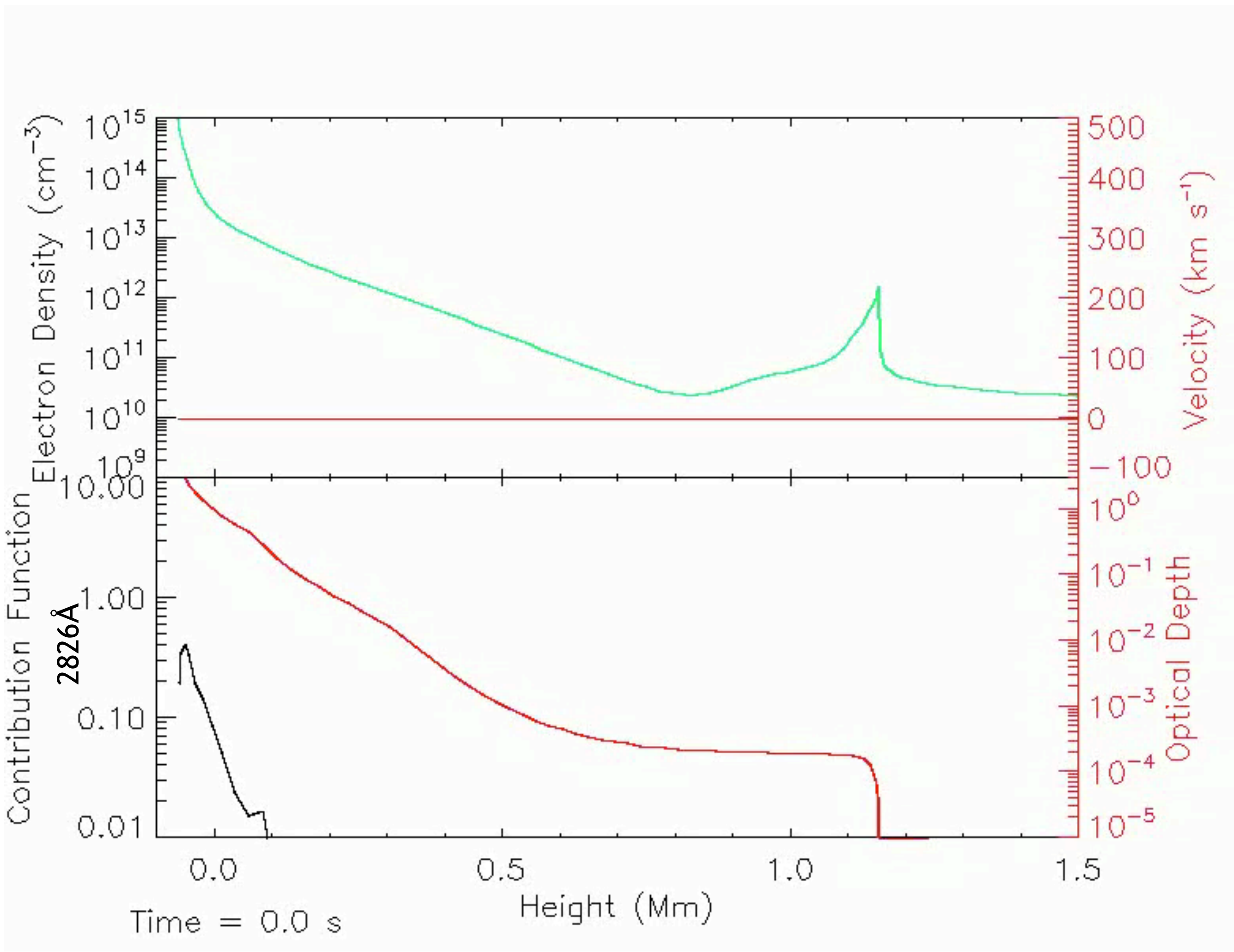


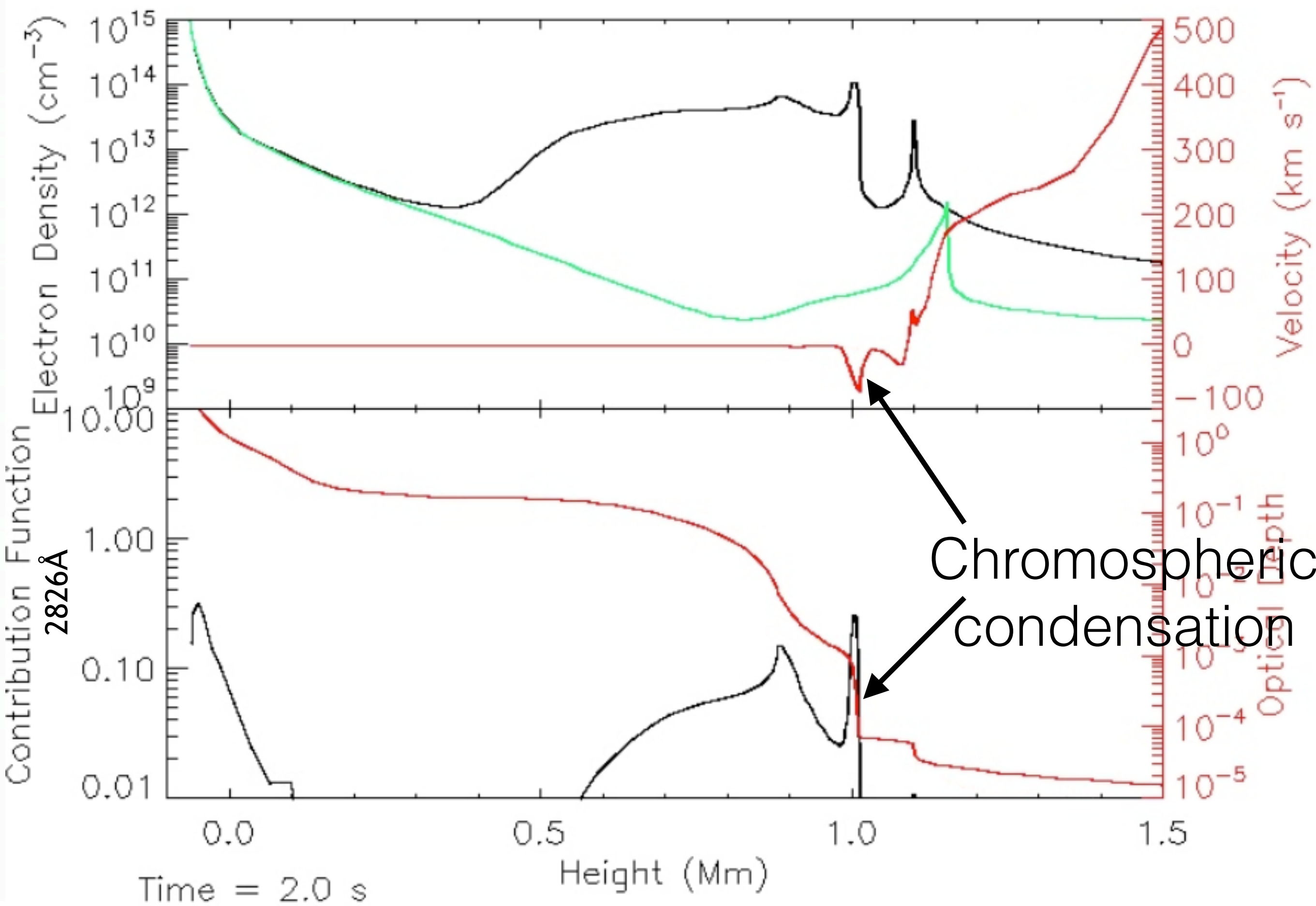
TERMS CAN BE TURNED ON OR OFF IN NUMERICAL F-P SOLVER

The F-P solver in RADYN written by Joel Allred (NASA/GSFC)

```
!
! bfield: (nz) Magnetic field strength (Gauss) at each z.
!
! thermE: (nz) Energy (eV) at which a particle is considered thermalized.
!         Particles with energies below this will not contribute to the
!         number flux.
!
! res: (nmu, nE, nz) If icntl(9).eq.1, then output the normalized residual
!                    after the solver has been run. Otherwise, not used.
!
! tol: When the average change between iterations is below tol, the
!      solver is assumed to have converged. Typical value is 1e-3.
!
! theta: Must be between 0 to 1. Relative weight of the new solution. This
!        can be used to damp changes in the iterative solver.
!           phi(n+1) = phi(n) * (1-theta) + new_phi * theta.
!        Small values will slow changes and can be used to damp
!        oscillations produced by the non-linear return current terms.
!        If no oscillations occur, then large values will speed up
!        convergence.
!        A typical value is 0.5, but this can be lowered if the return
!        current causes oscillations in the solution.
!
! icntl: (10) Parameters which control how the code is run.
!
!   Setting the following switches to zero turns off the corresponding terms:
!    icntl(1): Energy loss from collisions.
!    icntl(2): Pitch angle diffusion from collisions.
!    icntl(3): Energy loss and scattering due to synchrotron emission.
!    icntl(4): Pitch angle scattering due to magnetic mirroring.
!    icntl(5): Energy loss and scattering due to return currents.
!
!    icntl(6): Top of loop boundary condition
!            = 0: Inject flux given in ftop for positive mu. Negative mu
!                 is allowed to vary according to the solver. This is
!                 effectively an OPEN boundary for negative mu.
!
!            = 1: Inject flux given in ftop for positive mu, and reflect
!                 back downward the flux for negative mu. This is a
!                 REFLECTING condition. Recommended for typical flare
!                 situations.
!
```

MOVIE OF ATMOSPHERIC EVOLUTION AND CONTRIBUTION FUNCTION





Simulation from Kowalski et al. 2017

SUMMARY

- For modeling radiation from the chromosphere, need to include optical depth (absorption, scattering).
- Many sources of opacity.
- Modeling continuum opacity and emergent intensity provides an important and powerful diagnostic of the optical depth at T~10,000 K in flares.
- On Monday: will do an IDL-based lab with RADYN model output.
  - analyze the physics of chromospheric evaporation and condensation that result from electron beam heating.
  - Will look at a contribution function!