Designing and implementing a physically realistic photoionization model

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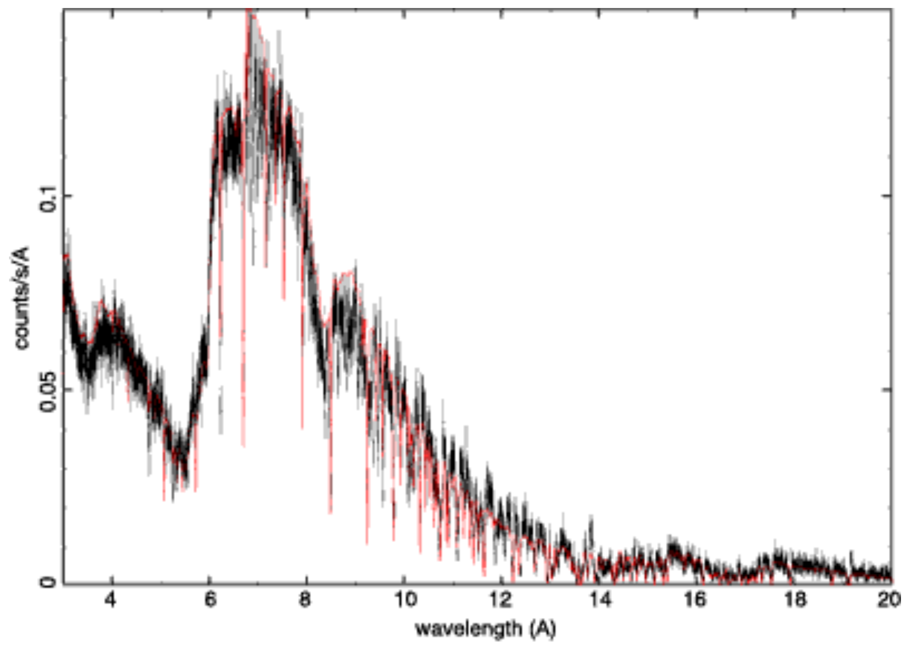
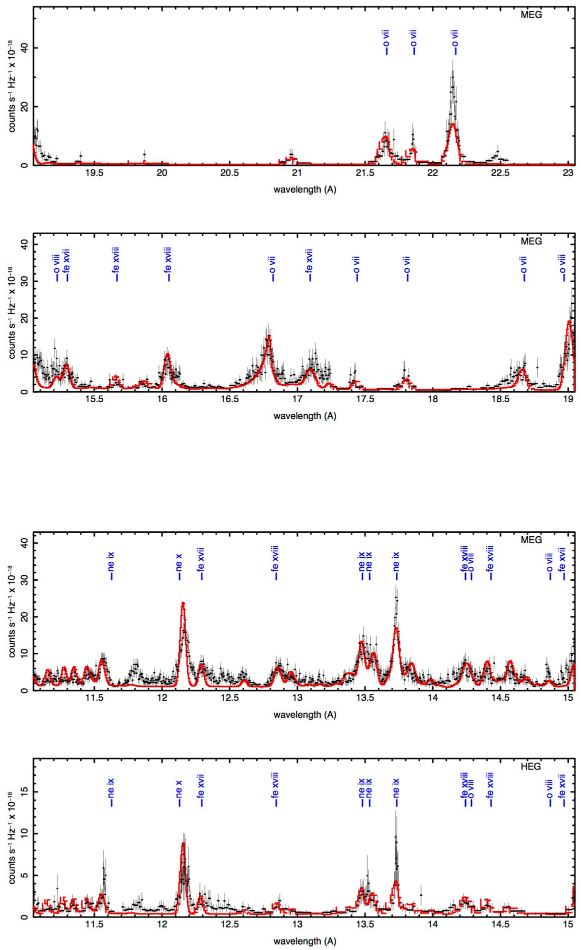
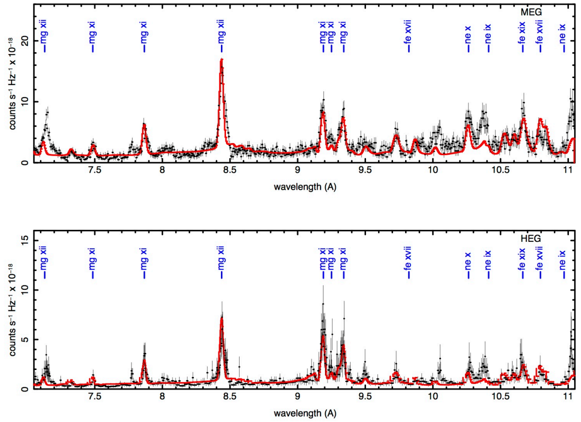
Photoionization is (likely) important whenever gas reprocesses X-rays from a compact source

NGC 3783





NGC 1068



photoionization modeling is simple…

- We solve equations of statistical and thermal equilibrium for level populations n_j and electron kinetic temperature T.
- R_{ji} contains rates for:
  - Photoionization
  - Recombination (radiative, dielectronic, 3 body)
  - Electron impact ionization and excitation
  - Radiative decay
  - Auger decay

$$\frac{dn_i}{dt} = \Sigma_j \left(n_j R_{ji}(T,F,n..) - n_i R_{ij}(T,F,n...)\right)$$

Rate out Rate in

$$\frac{d}{dt}\left(\frac{3}{2}nkT\right) = H(T,F,n..) - C(T,F,n..)$$

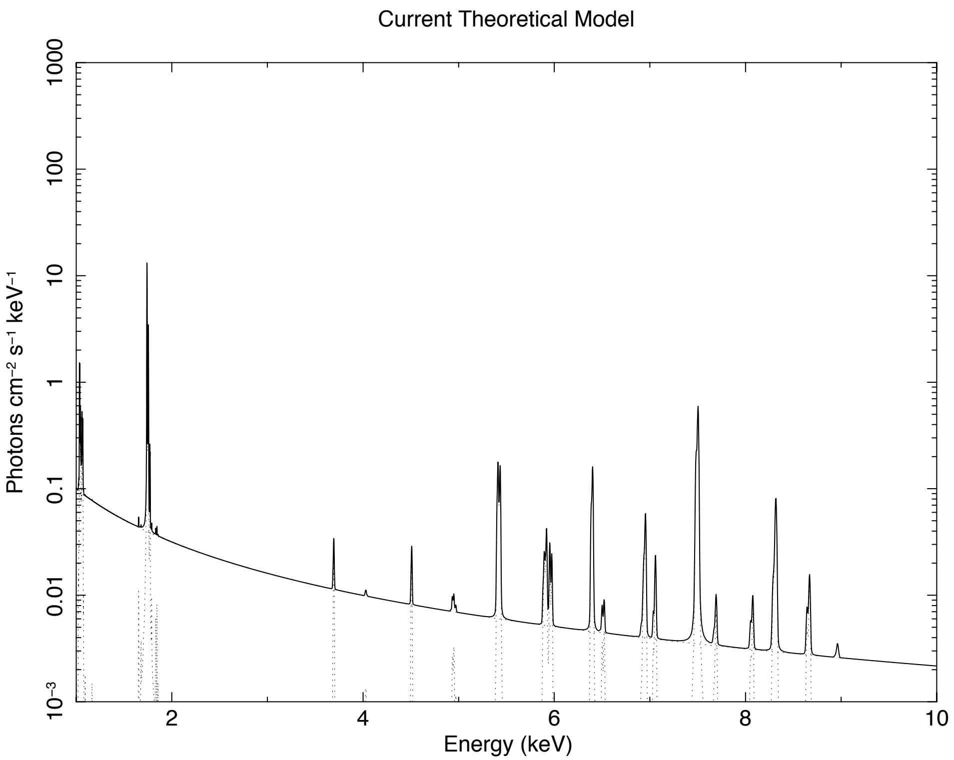
Heating rate Cooling rate

- Both temperature and ionization balance depend on the 'ionization parameter':

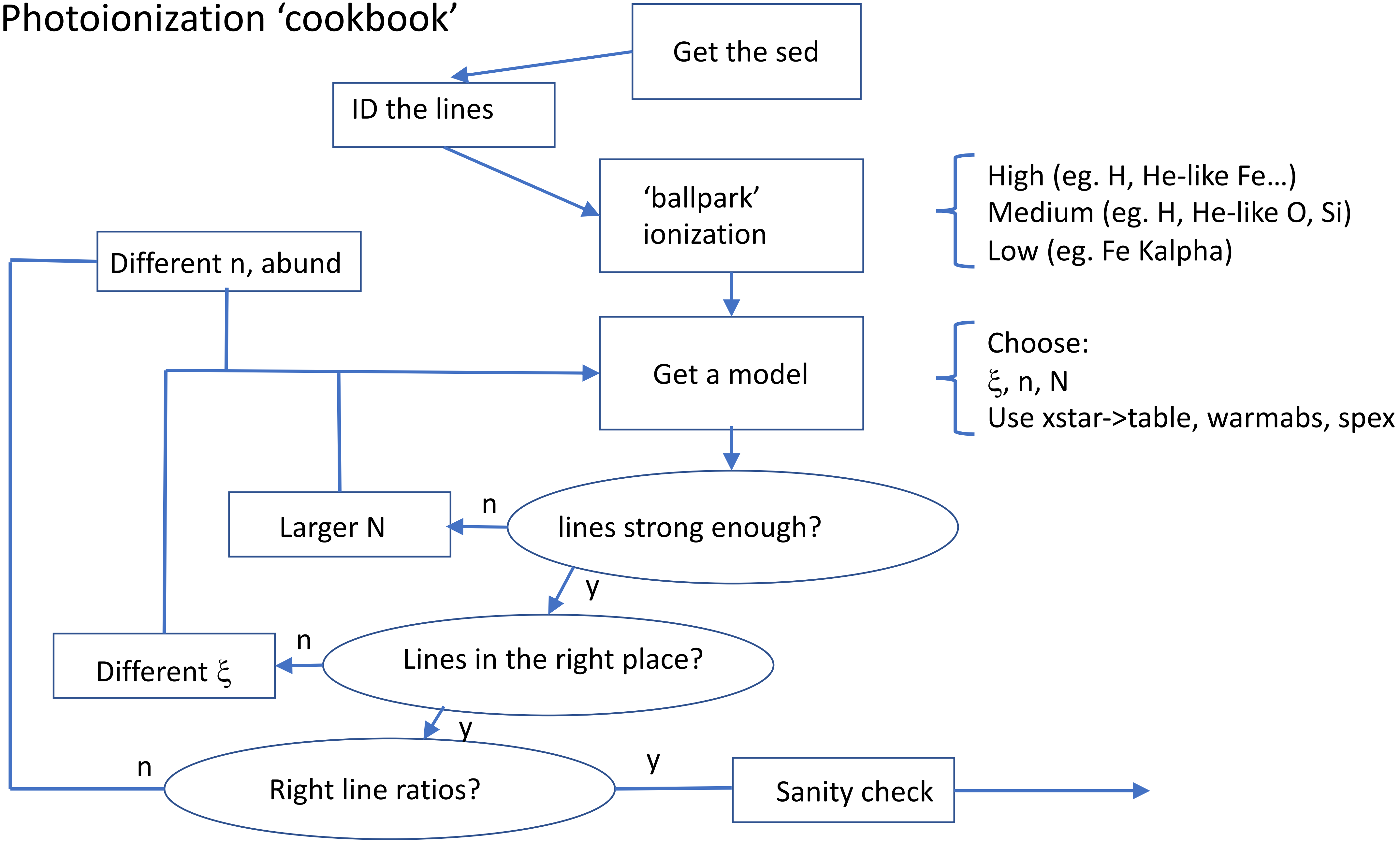
$$\frac{\text{radiation flux}}{\text{gas density}} \equiv \frac{F}{n} \equiv \frac{\xi}{4\pi}$$

New Xstar Features

- New atomic data: R-matrix calculations of K shell processes in odd-Z elements + iron peak (F, Na, P, K, Cl, Sc, Ti, V, Cr, Mn, Co, Cu, Zn)
- Treatment of continuum lowering and cascades for densities up to 10^{22} cm^{-3}.
- (Some) Python tools for parsing output



Photoionization ‘cookbook’



Sanity check:things that might not make physical sense

- Ionization parameter: do ξ, n, N make sense? (eg. $N<\mathrm{sqrt}(Ln/\xi)$?)
- Emission measure: what is $\mathrm{norm}/(n^{1/2}L^{3/2}/\xi^{3/2})$?
- Abundances?
- Explore v_{turb} vs. N space
- Temperature from rrcs?
- Multiple components?
- Look outside your energy band..
- Look at *count space spectra*
- Variability?

Model Resolution vs. instrument resolution

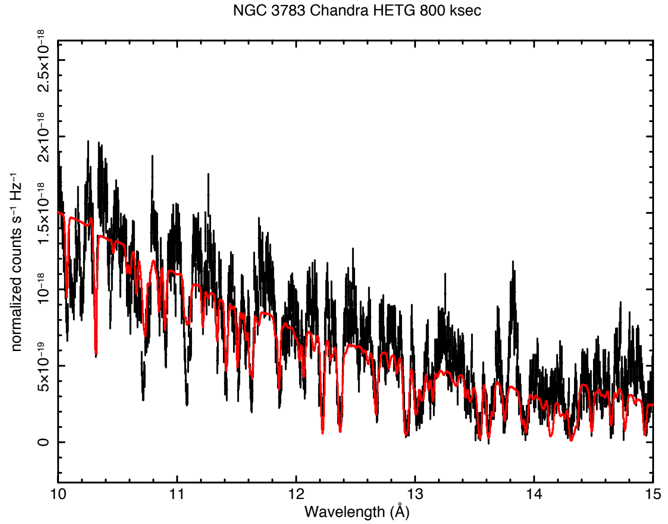
- Line width:

$$\frac{\Delta\varepsilon}{\varepsilon} = \sqrt{\frac{2kT}{Mc^2}} = 4.3 \times 10^{-5}(T_4/A)^{1/2}$$ Thermal Doppler

$$= \frac{2\varepsilon\alpha}{mc^2}\frac{g_l}{g_u}f_{lu} = 4 \times 10^{-7}Z^2$$ Natural

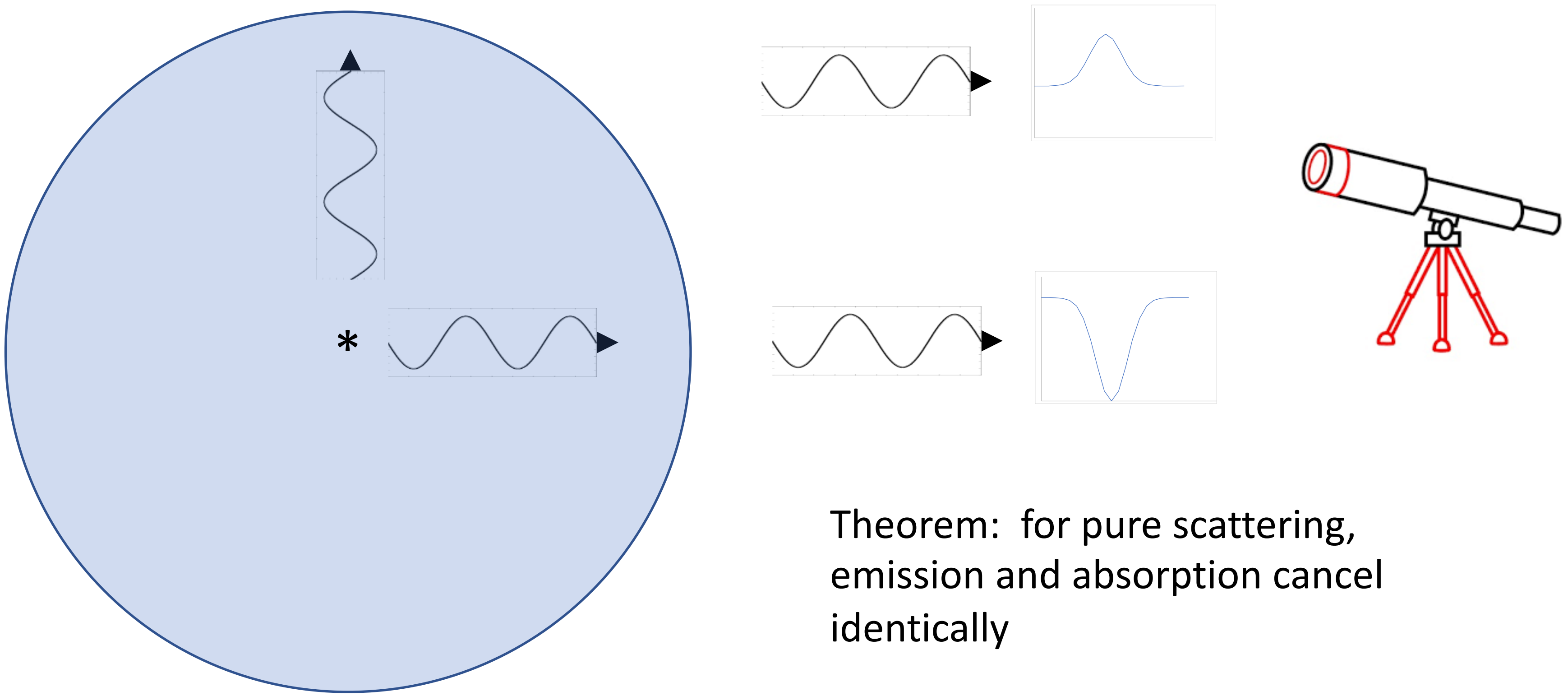
$$= \frac{v_{Turb}}{c} = 3.3 \times 10^{-6}v_{kms}$$ Turbulent

- Instrument resolution is >1.e-3!
- Xstar tries to be careful
  - Calculate absorption on very fine temporary grid
  - Map to main grid to match
  - Is this correct? How well is 0 calibrated?



Xstar calculates the emission and absorption by gas exposed to an external radiation source

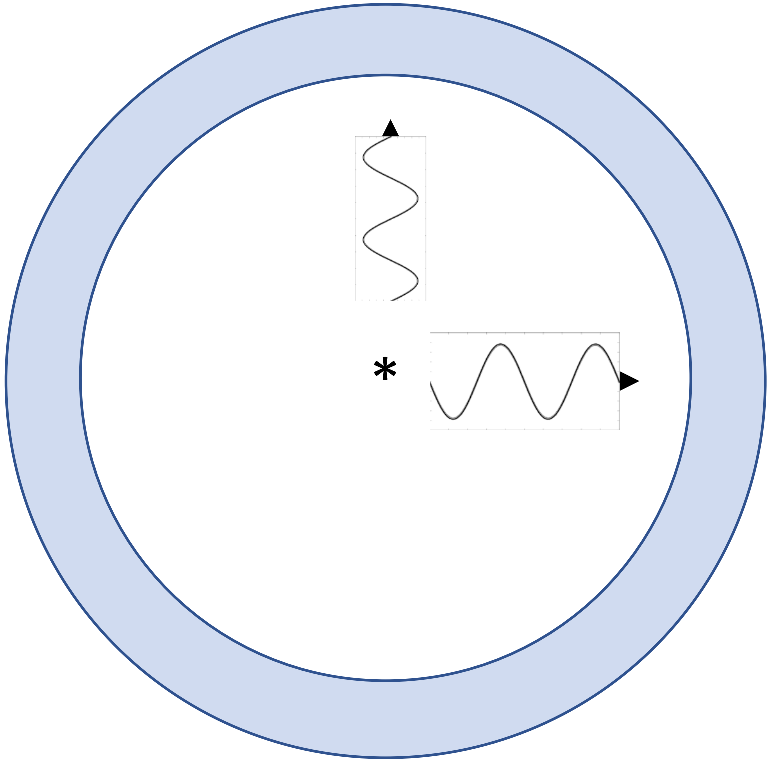
- The problem is idealized:
  - A point source of radiation at the center of a spherical gas cloud

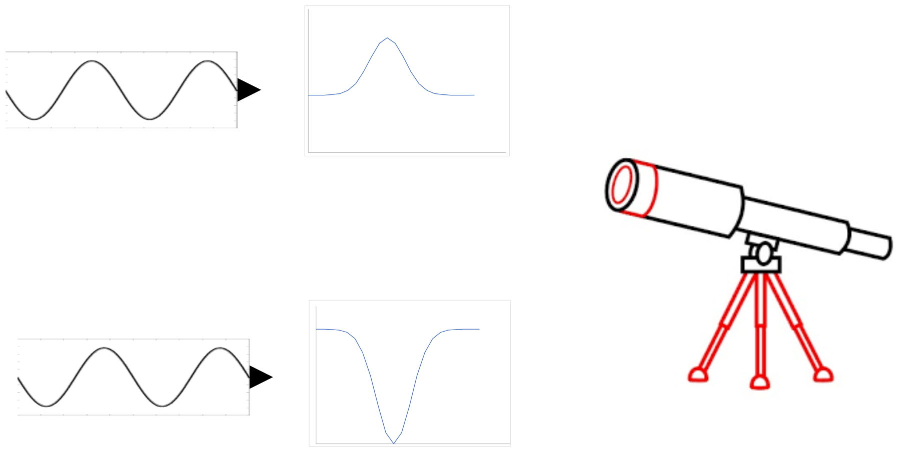


Theorem: for pure scattering, emission and absorption cancel identically

This can be modified to treat other cases:

- A thin shell:

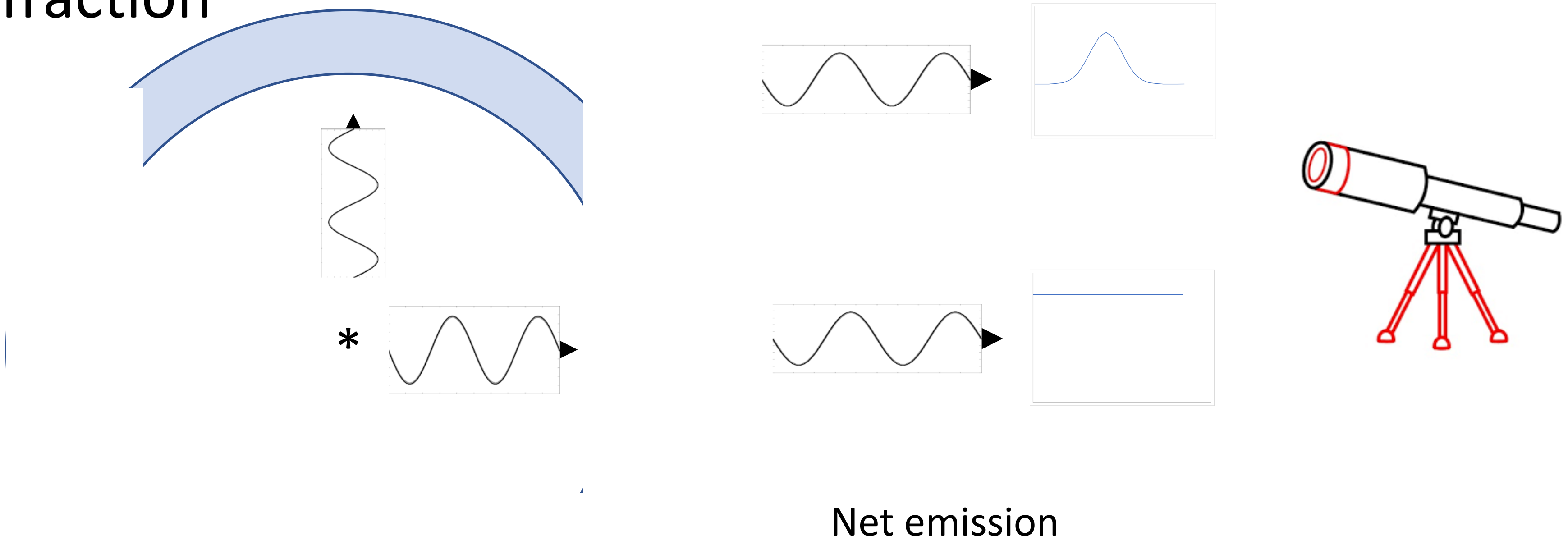




Theorem: for pure scattering, emission and absorption cancel identically

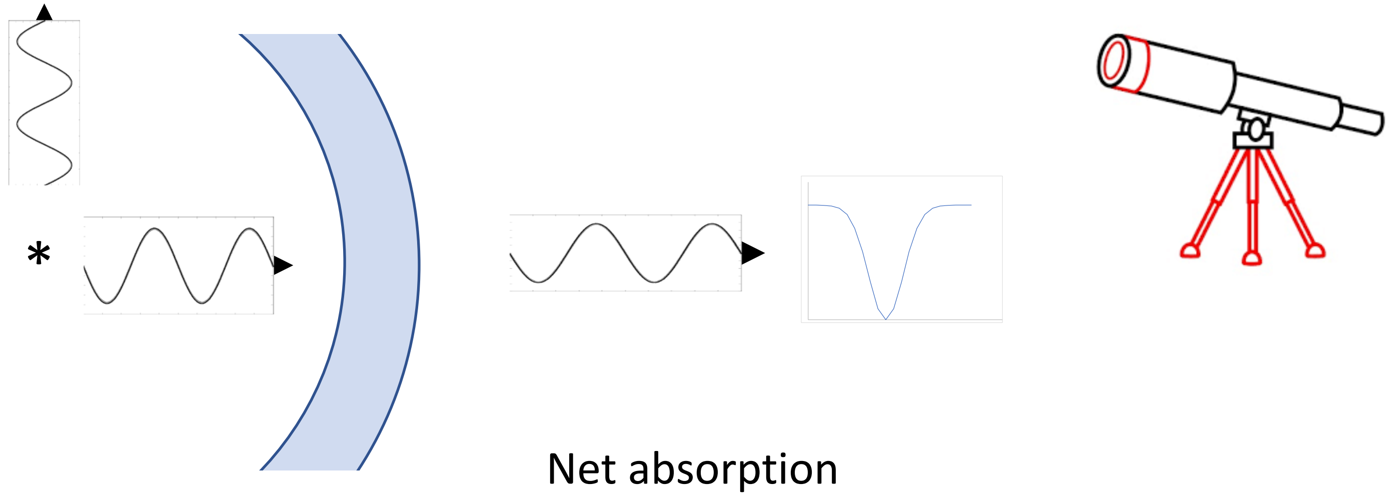
This can be modified to treat other cases:

- A sector of a shell:
- Viewed in reflection
- Define covering fraction
- $F_\varepsilon \sim C$



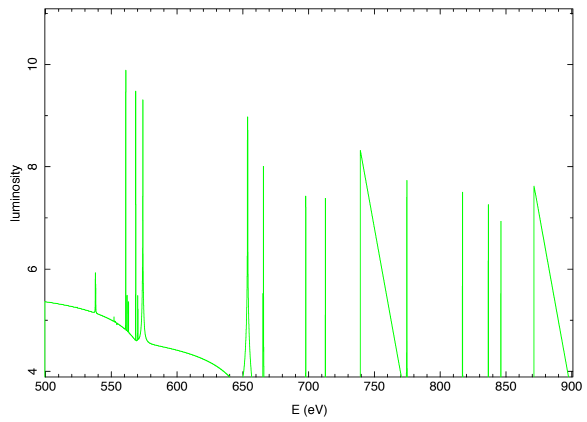
This can be modified to treat other cases:

- A sector of a shell:
- Viewed in transmission



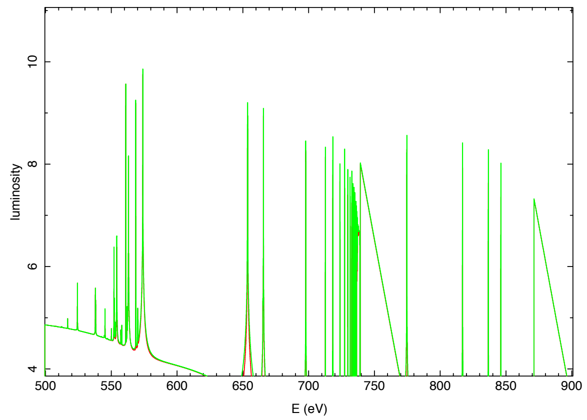
Xstar attempts to take care of this using the covering fraction parameter

C=1, corresponds to traditional assumption: scattering is ignored



Pure oxygen, logξ=1

C<1, scattering is included



Makes a significant difference, eg. for w line!

Free-free and Compton heating-cooling sample the entire SED

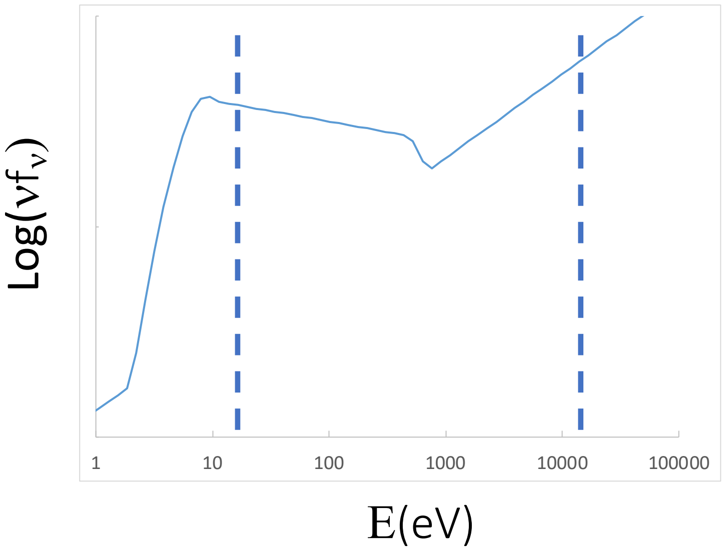
$$H_{ff} = 2.09 \times 10^{-38} Z^2 g_{ff} T_4^{-1/2} n^3 \xi \int_0^\infty f_\varepsilon \varepsilon^{-3} d\varepsilon$$

$$H_{Compton} = 1.04 \times 10^{-31} n^2 \xi \int_0^\infty f_\varepsilon (\varepsilon - 4kT) d\varepsilon$$

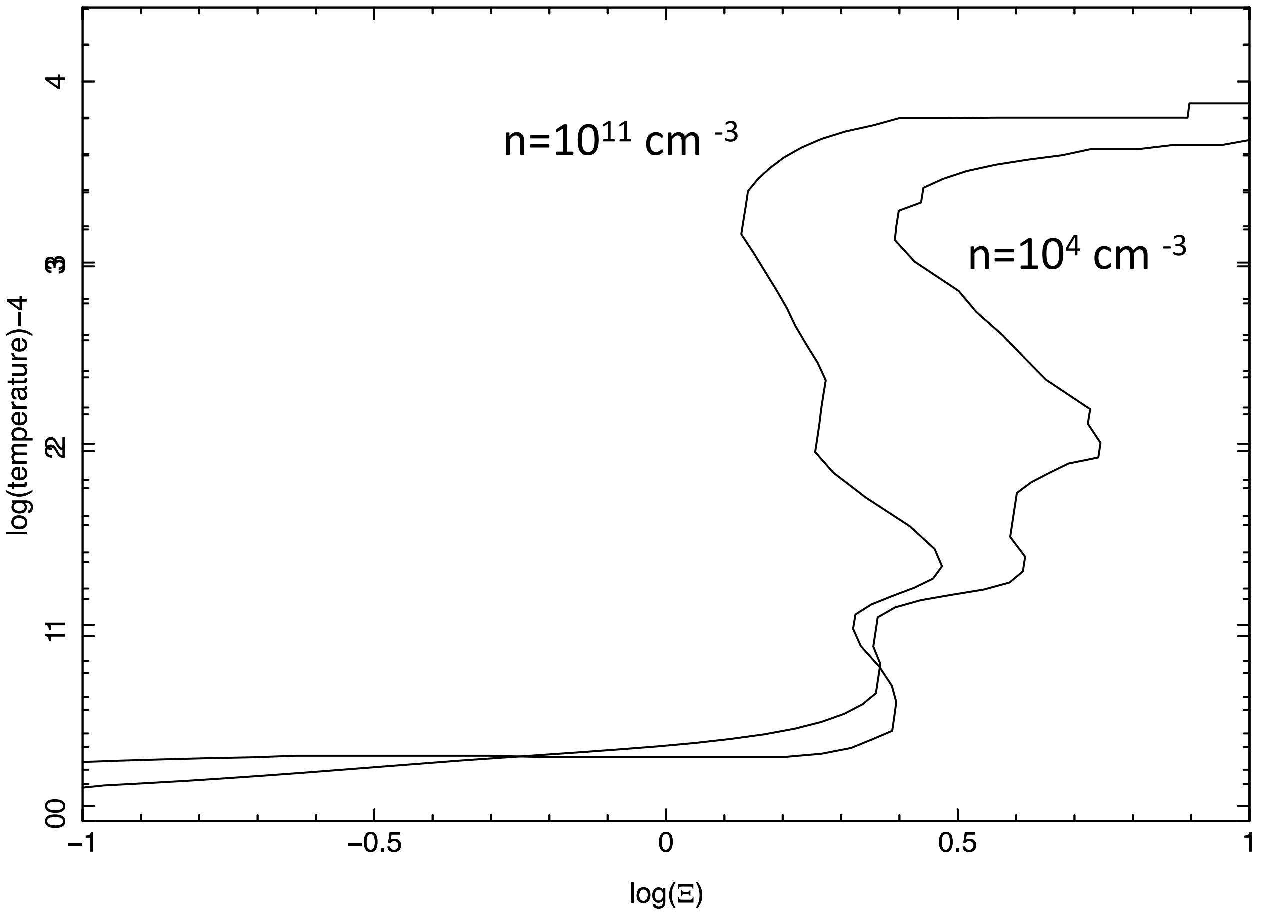
Free-free heating Can be important above density $n>10^{10}$ cm $^{-3}$ depending on SED and temperature

Compare with:

$$H_{PI} = 7.96 \times 10^{-20} \xi n^2 \int_{\varepsilon_{Th}}^\infty \sigma_{\mathrm{PI,MB}}(\varepsilon) f_\varepsilon d\varepsilon$$



This is yet another thing that can affect thermal stability curves



+see poster by Anna O.

Summary

- We make simple assumptions:
  - Time independent
  - Prescribed density or pressure
  - Simple (spherical or plane parallel) geometry
  - Simple dynamics (turbulence or radial flow)
- But the science goals are more complex:
  - Geometry
  - Dynamics
  - Abundances
  - Exotic physics: GR, NT particles
- Need to be careful to avoid inconsistencies