Supernova Spectra and SYNAPPS

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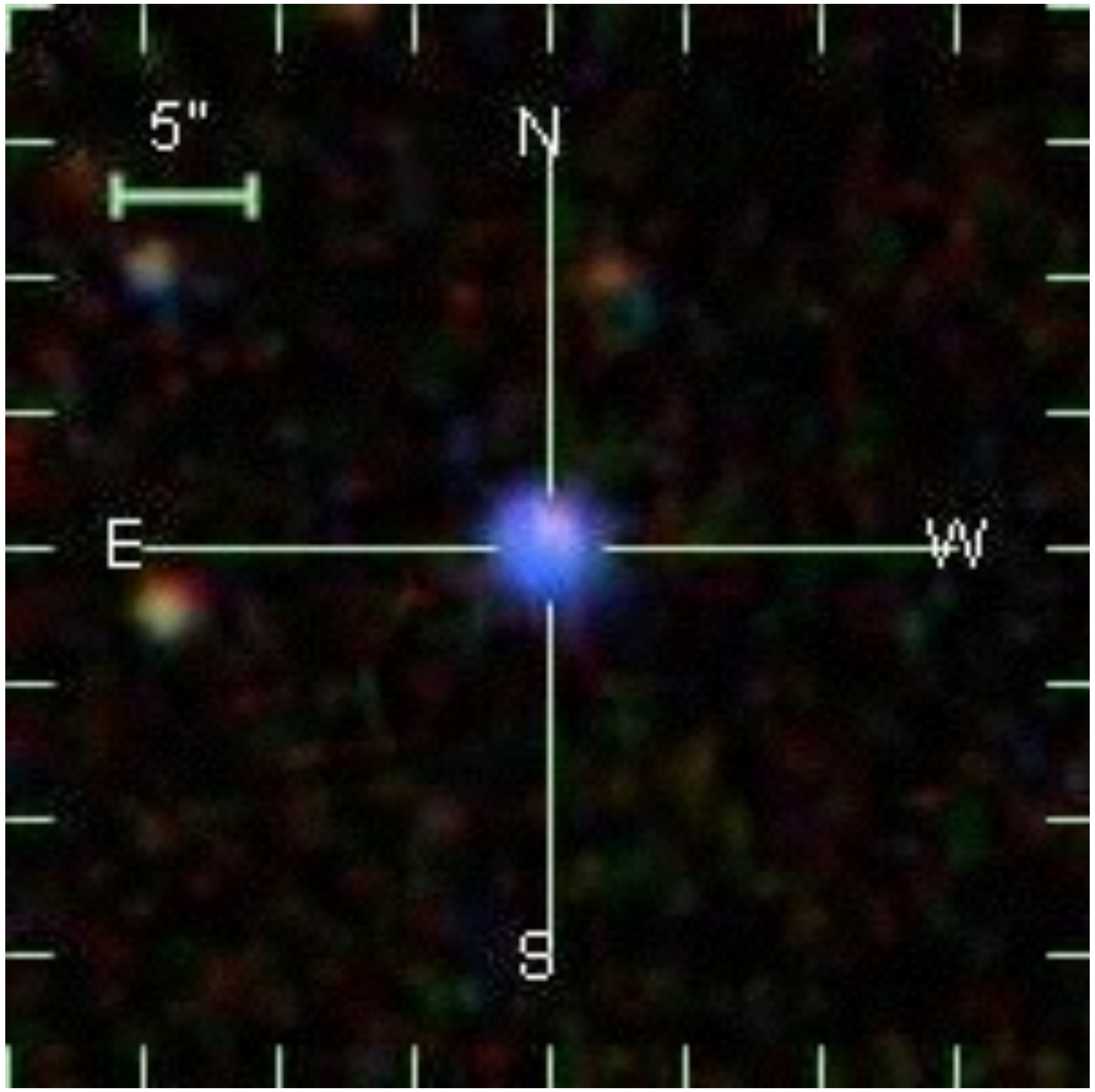
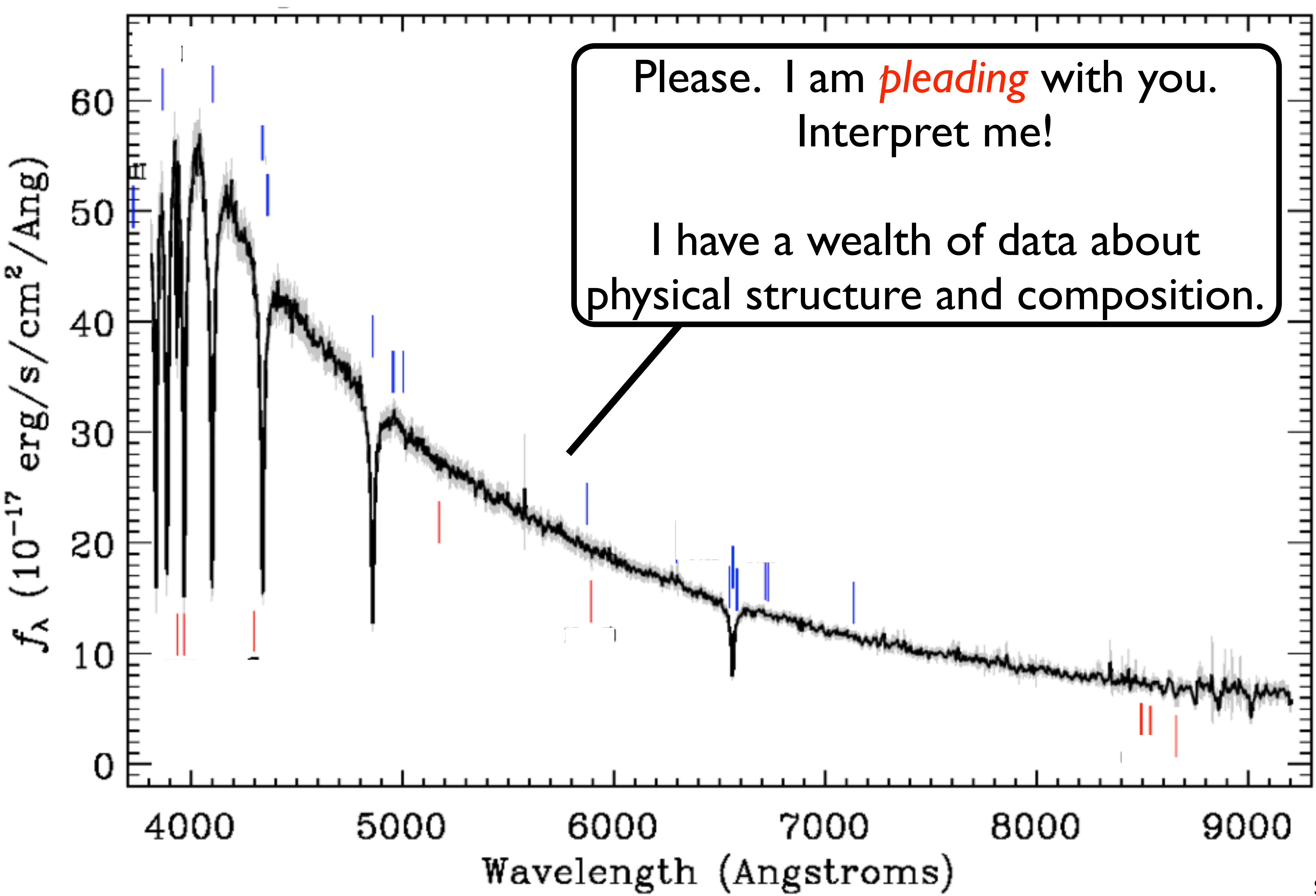
...modeling stellar interiors yields only two numbers connected to the real world: a star's "radius" and luminosity. Even then the theoretician's numbers must be converted to *observable* quantities using models of stellar atmospheres. In contrast, the *spectrum* of a star contains a wealth of data about its physical structure and composition, just *pleading* for interpretation...

D. Mihalas, 2002, in *Stellar Atmosphere Modeling*,
(Hubeny, Mihalas & Werner, eds.), p. 677.

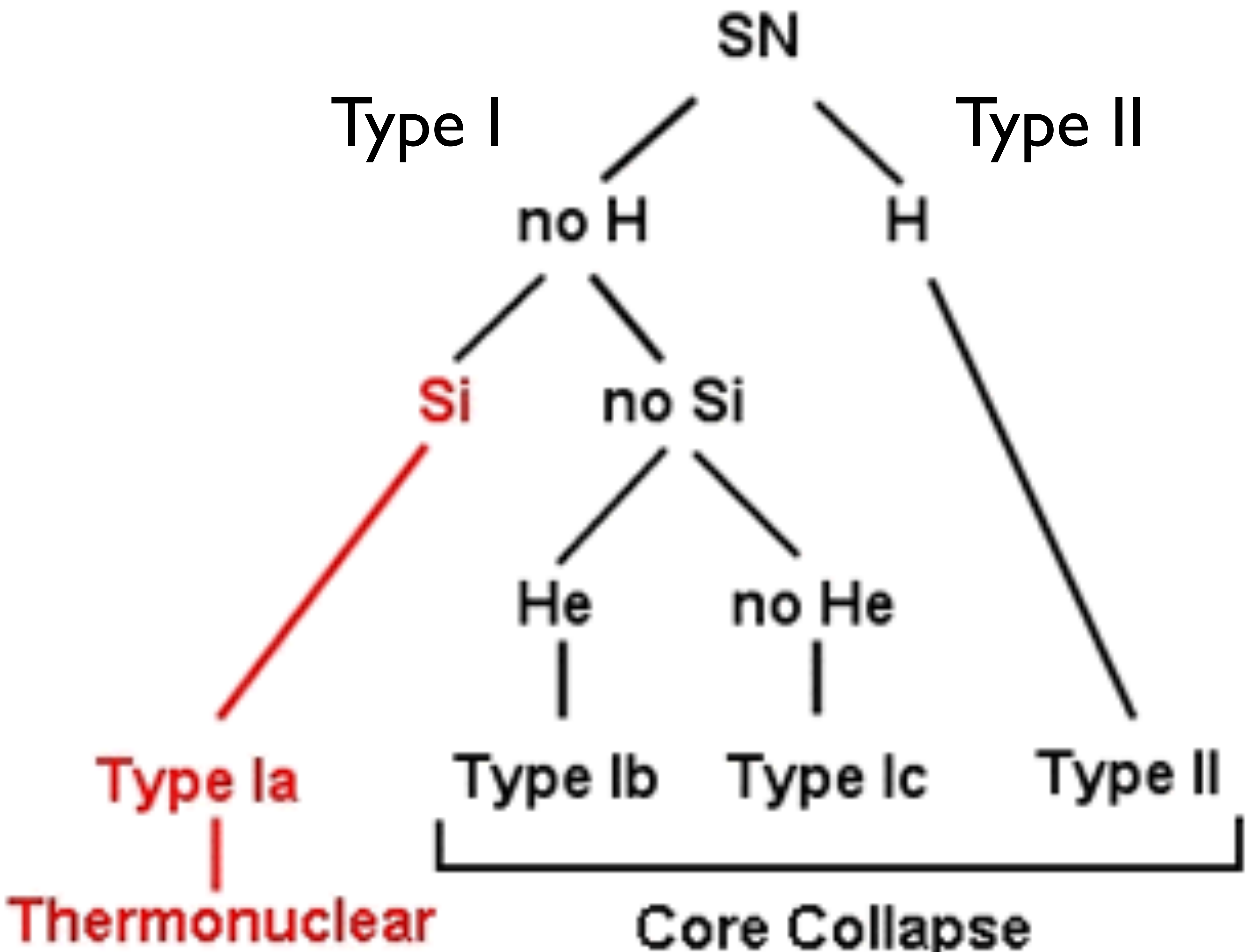


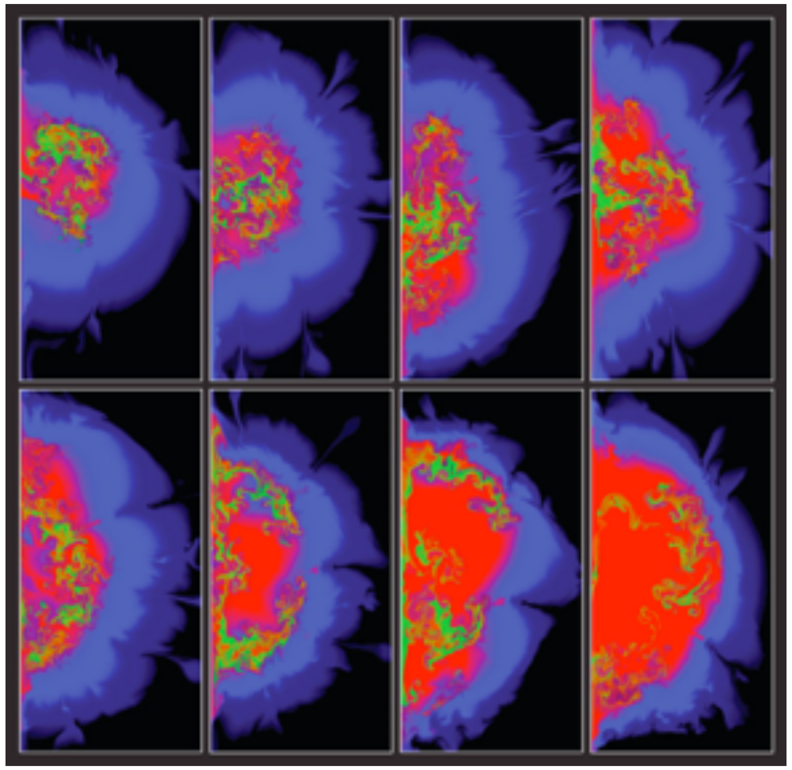
SDSS DR8
http://www.sdss3.org/dr8/

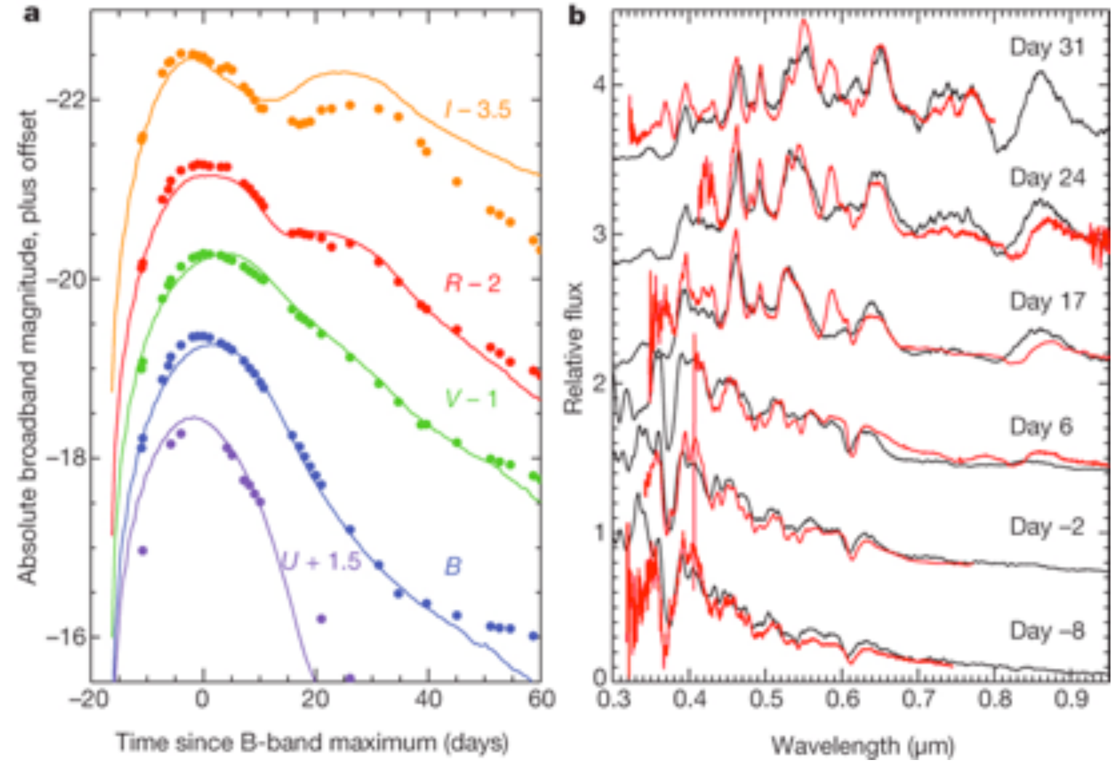


SDSS DR8
http://www.sdss3.org/dr8/

Spectrum = Classification





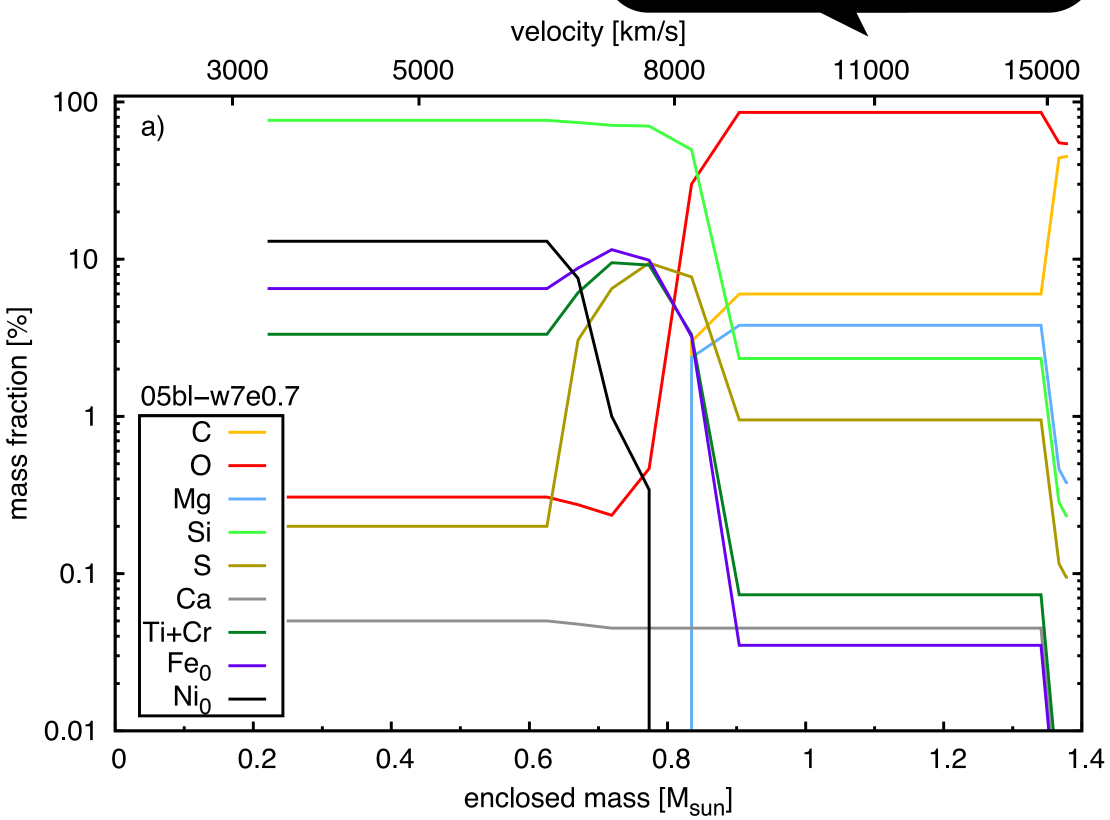


(Kasen et al. 2008, Nature, 460, 869)

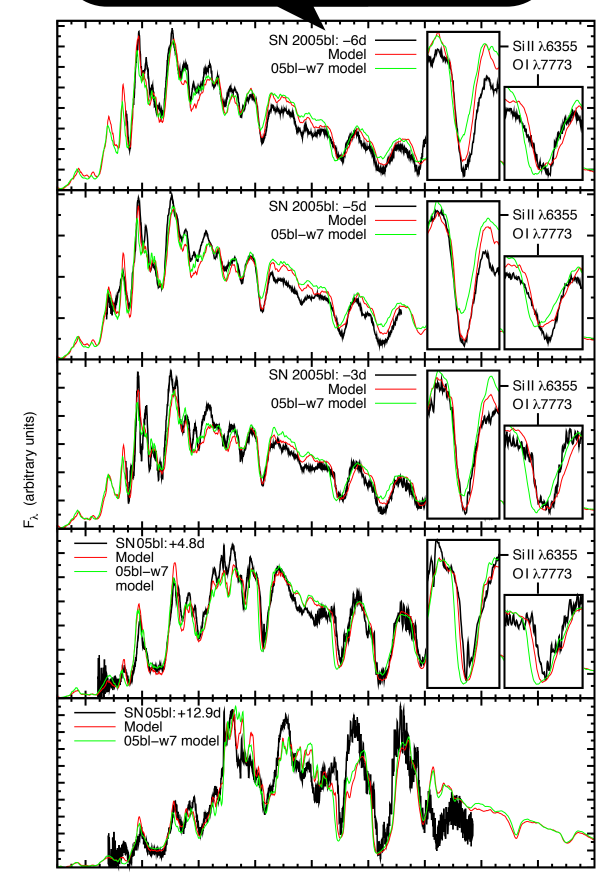
Simulated Stellar Death

Model SN Atmosphere

Comparison to



Hachinger et al. 2009, MNRAS, 399, 1238



abundances by mass
energy deposition
kinetic energy

ionization
level populations
electron density
radiation field

spectra
light curves
etc.

Radiative Transfer Equation

$$\frac{1}{c}\frac{\partial}{\partial t}I(\vec{r},\hat{n},\nu;t) + \hat{n}\cdot\nabla \underbrace{I(\vec{r},\hat{n},\nu;t)}_{\text{Specific Intensity}} = \underbrace{\eta(\vec{r},\hat{n},\nu;t)}_{\text{Emissivity}} - \underbrace{\chi(\vec{r},\hat{n},\nu;t)}_{\text{Extinction}}I(\vec{r},\hat{n},\nu;t)$$

Radiative Transfer Equation

$$\mu \frac{\partial}{\partial z} I(z, \hat{n}, \nu) = \eta(z, \hat{n}, \nu) - \chi(z, \hat{n}, \nu) I(z, \hat{n}, \nu)$$

Time-Independent Planar Form

$$\mu \frac{\partial I}{\partial \tau} = I - S$$

$$\tau(z, \nu) = \int dz' \; \chi(z', \nu)$$

$$S(z, \nu) = \frac{\eta(z, \nu)}{\chi(z, \nu)}$$

Optical Depth

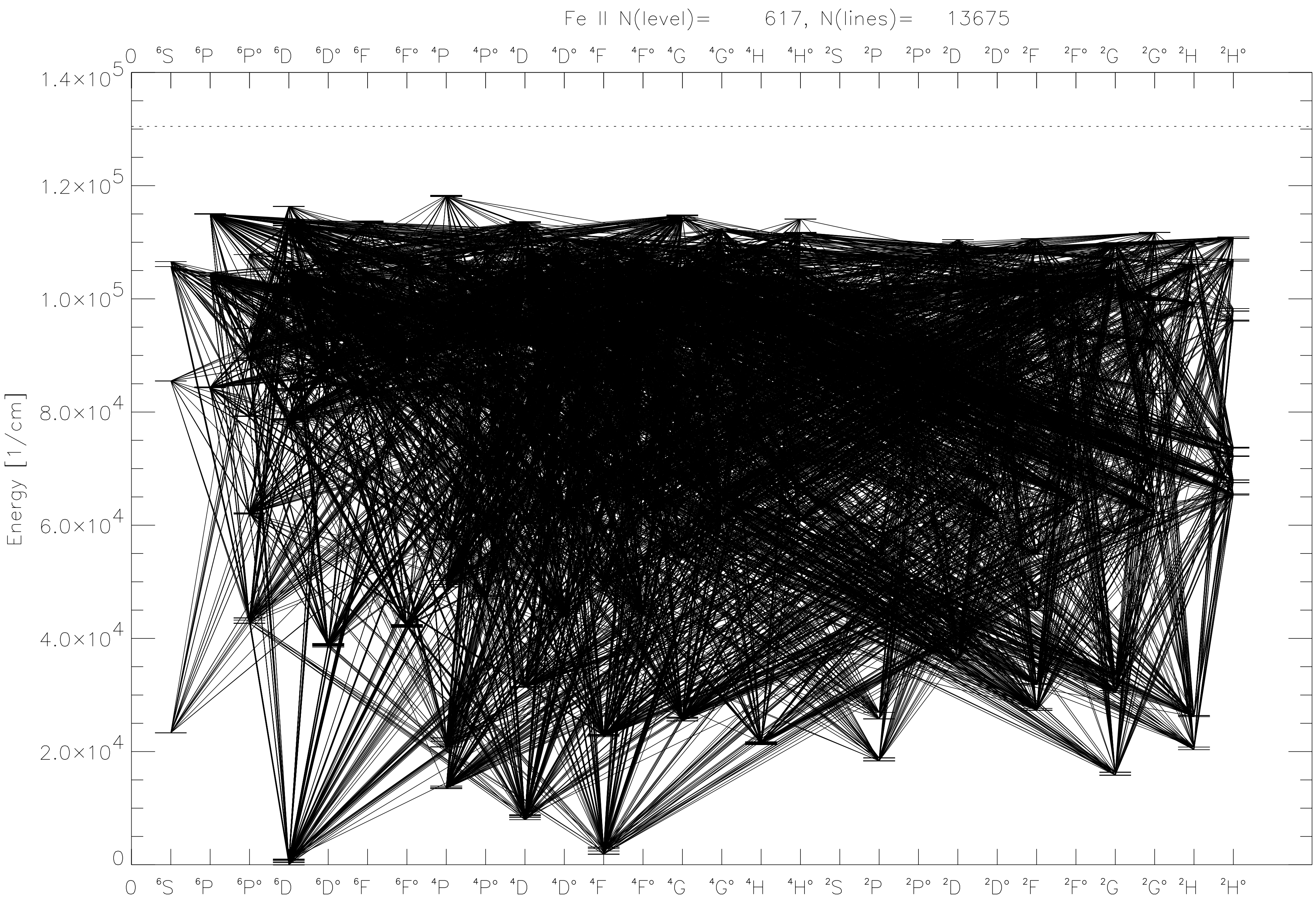
Source Function

Stellar Atmospheres (Mihalas 1978)
Fundamentals of Stellar Astrophysics (Collins 1989, also web)
Radiative Transfer in Stellar Atmospheres (Rutten, web)

Solution of RTE

- Photon trajectories natural in "lab" frame; emissivity/opacity in "comoving."
- Given BCs, opacity, emissivity: explicit formal solution.
- BUT: Need to know the radiation field to know level populations & thermo to get opacity and emissivity, to get the radiation field... etc.
- Also: Solution involves space, angle, wavelength points, direct inversion does not scale. Need a faster way.
- Direct ("lambda") iteration saturates to the wrong answer in general. Can use instead approximate, but easy to invert solutions, corrected iteratively (ALI). (Hubeny 2003 ASPC, 288, 17 & refs therein).
- Atomic physics...

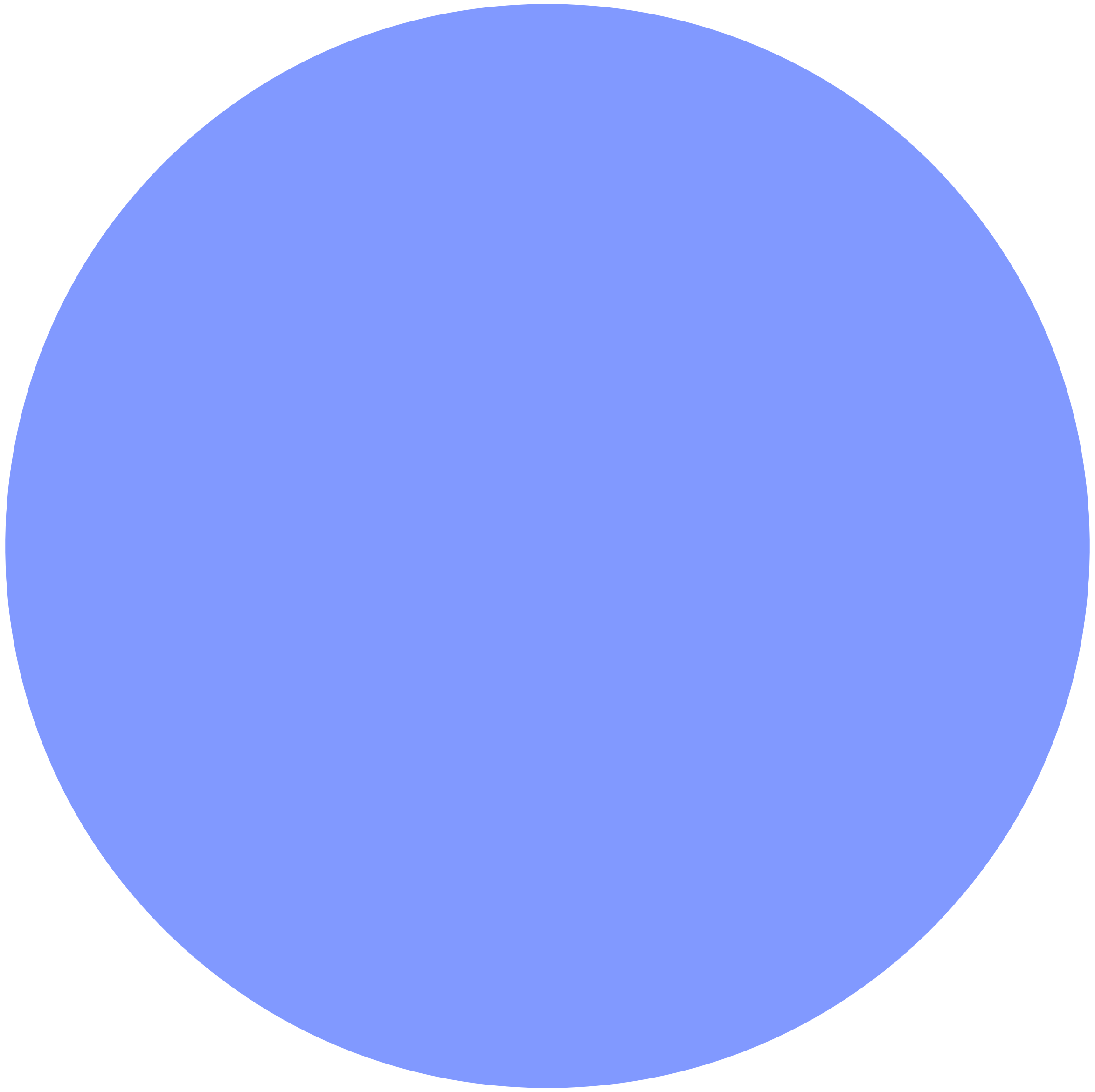
Ionization, Excitation, Lines

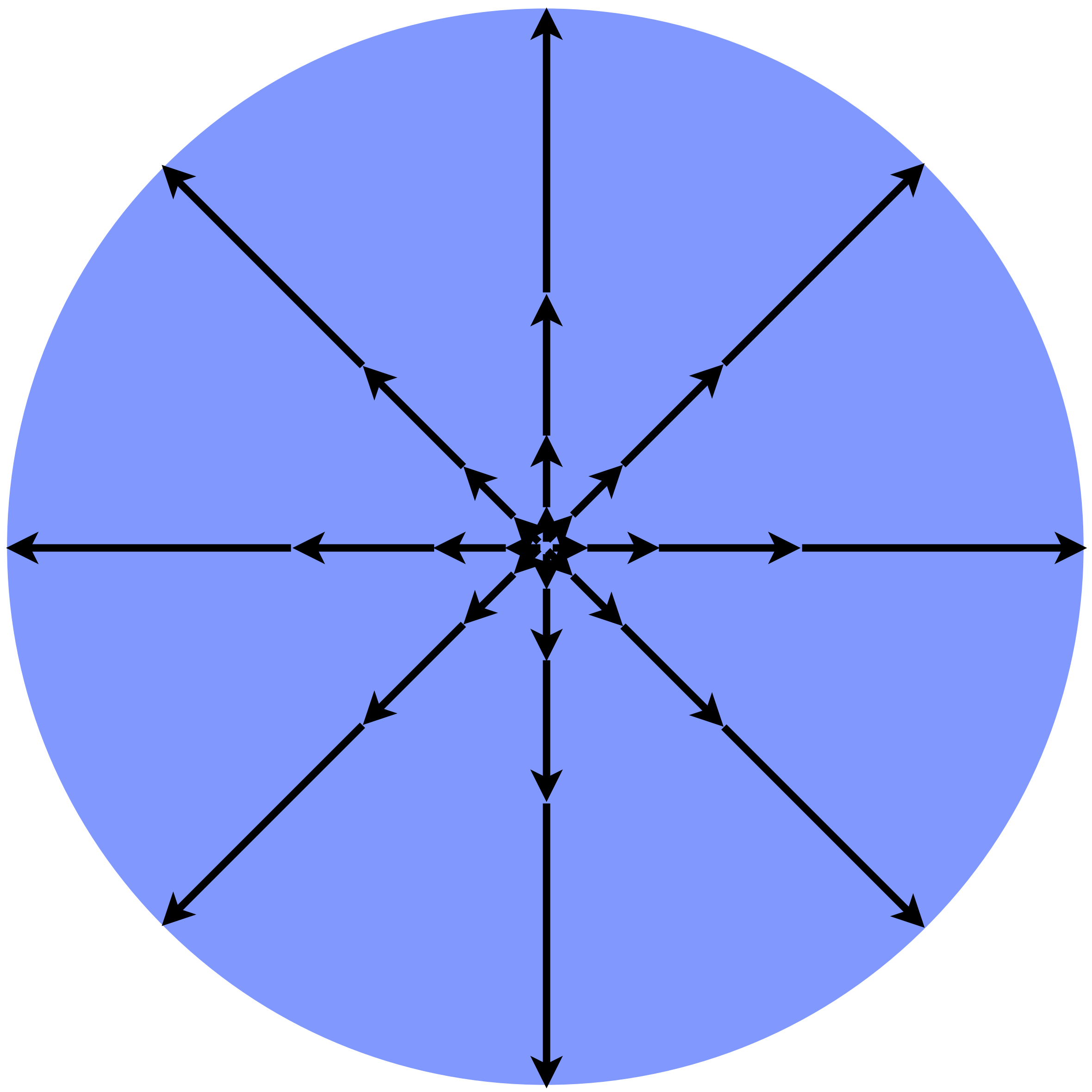


FeII Grotrian Diagram
617 levels – 13675 bound-bound transitions - 1.2 million total

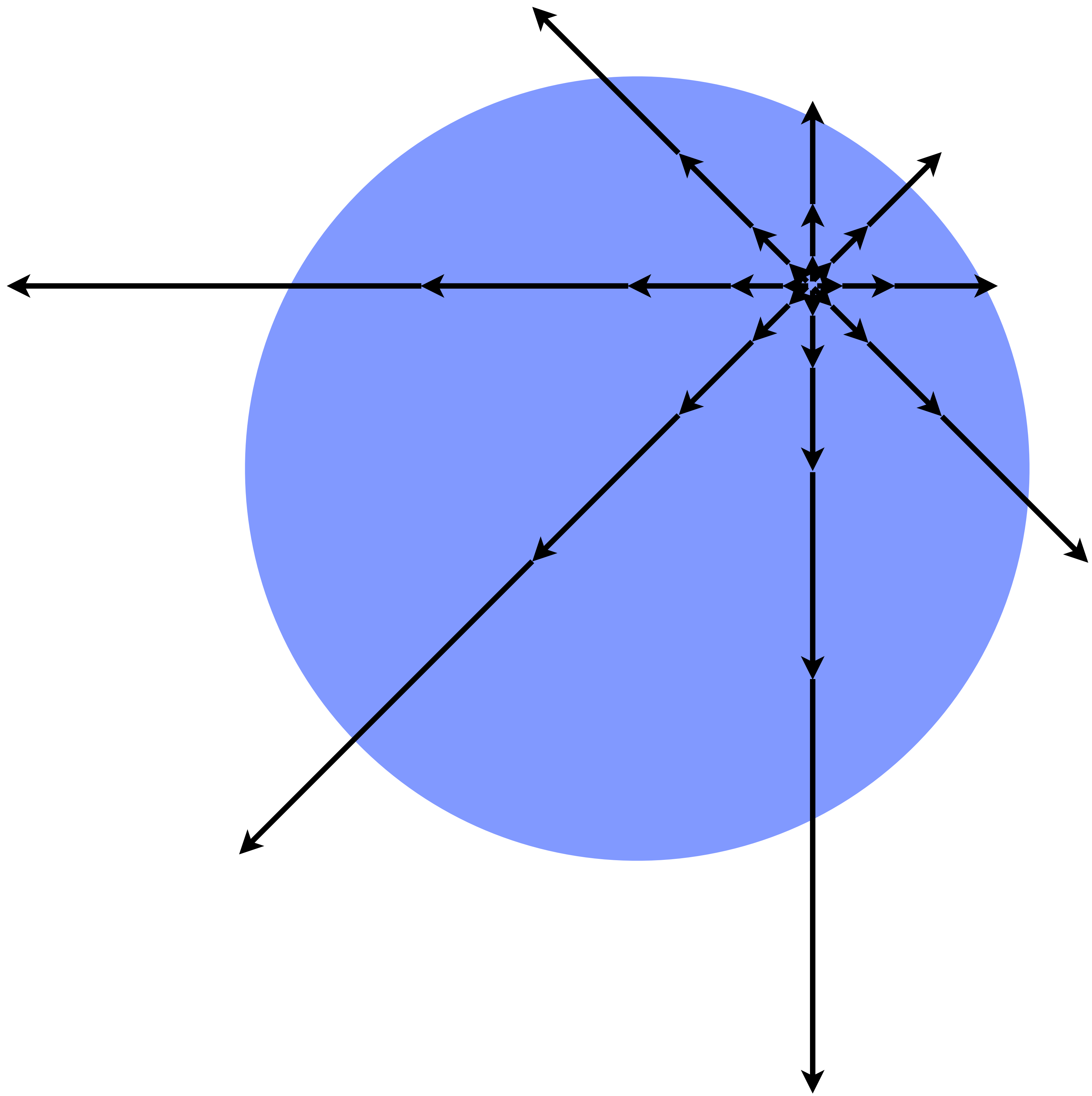
Simple Supernova Spectrum

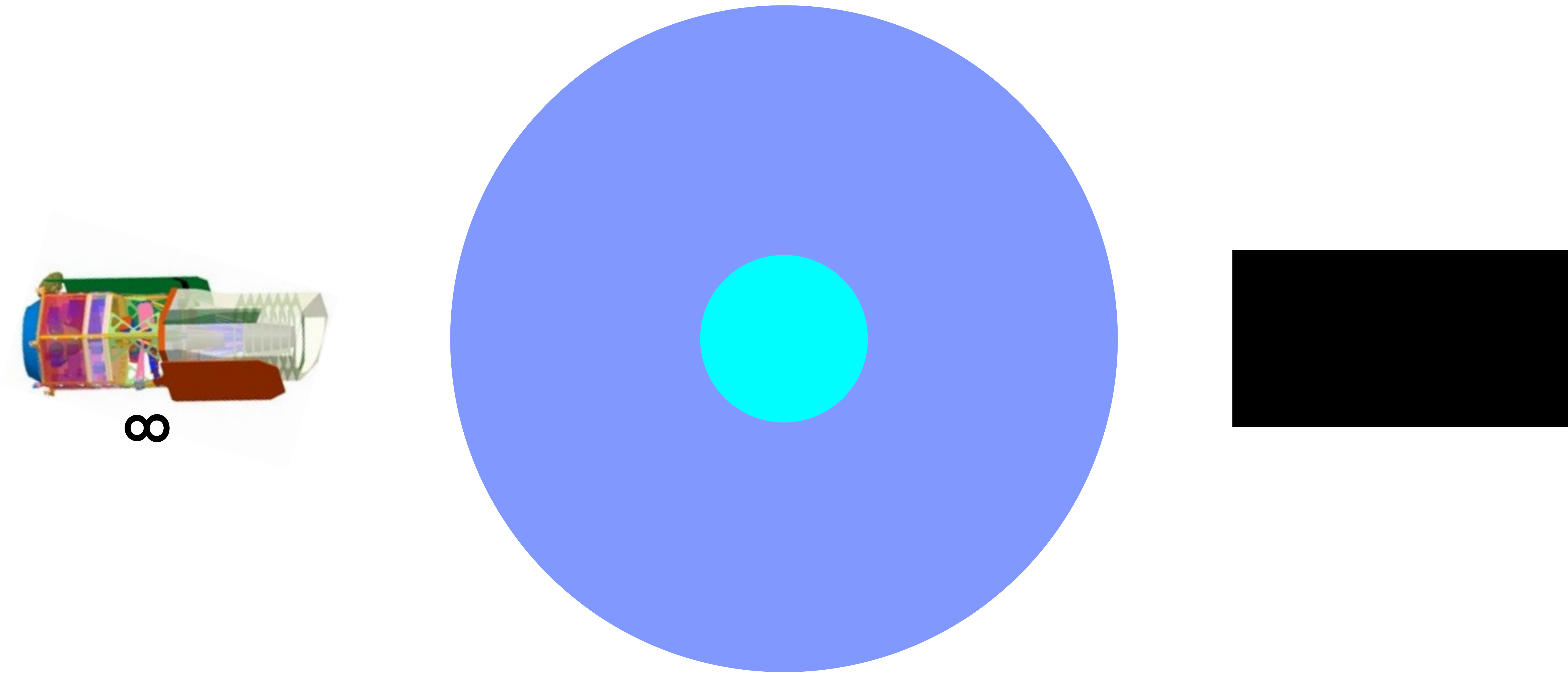
- Set of basic assumptions: Symmetry, opacity, source function.
- First order in v/c.
- Assume thermodynamic equilibrium for level populations.
- Basis for a number of existing codes.

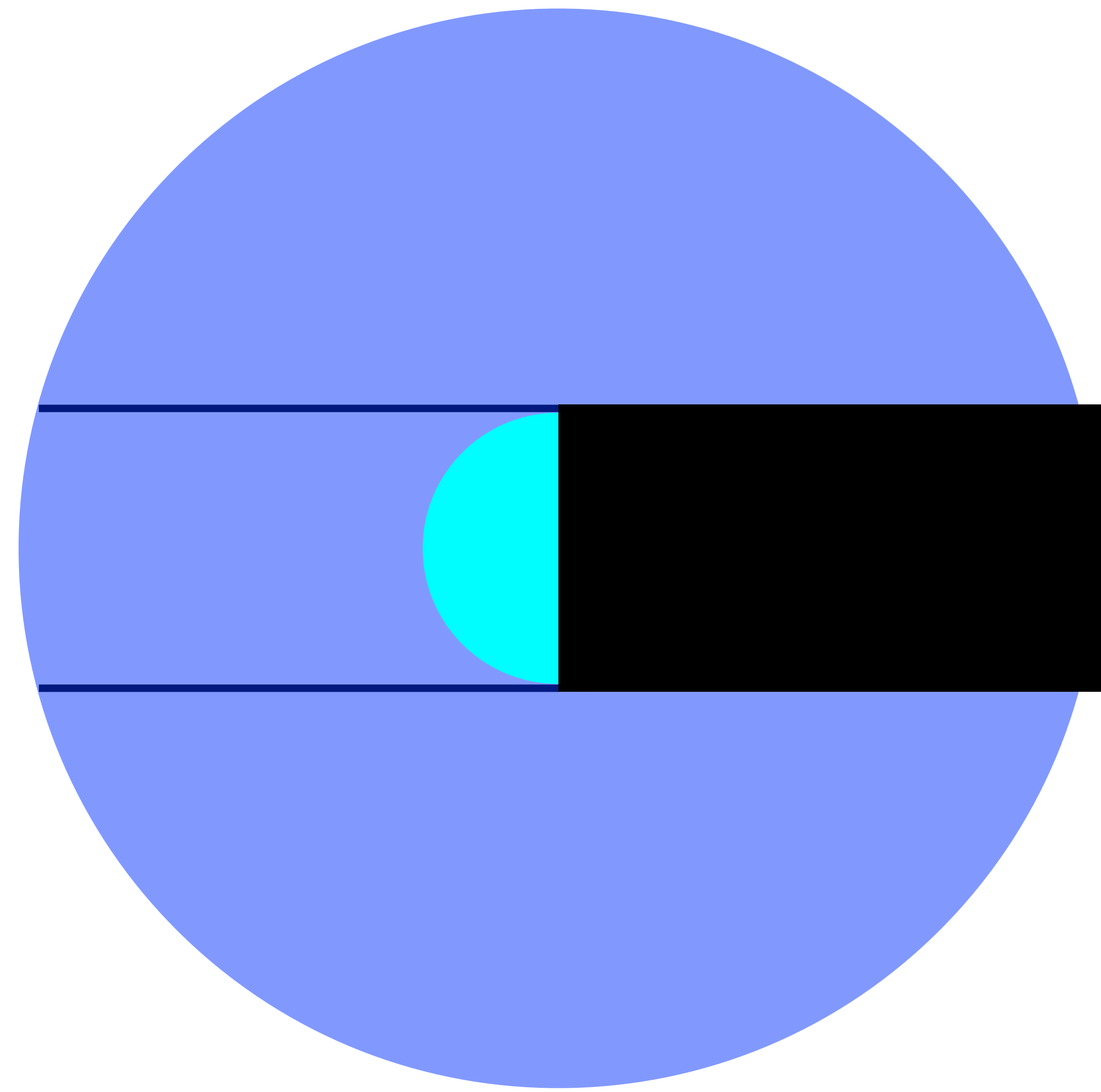


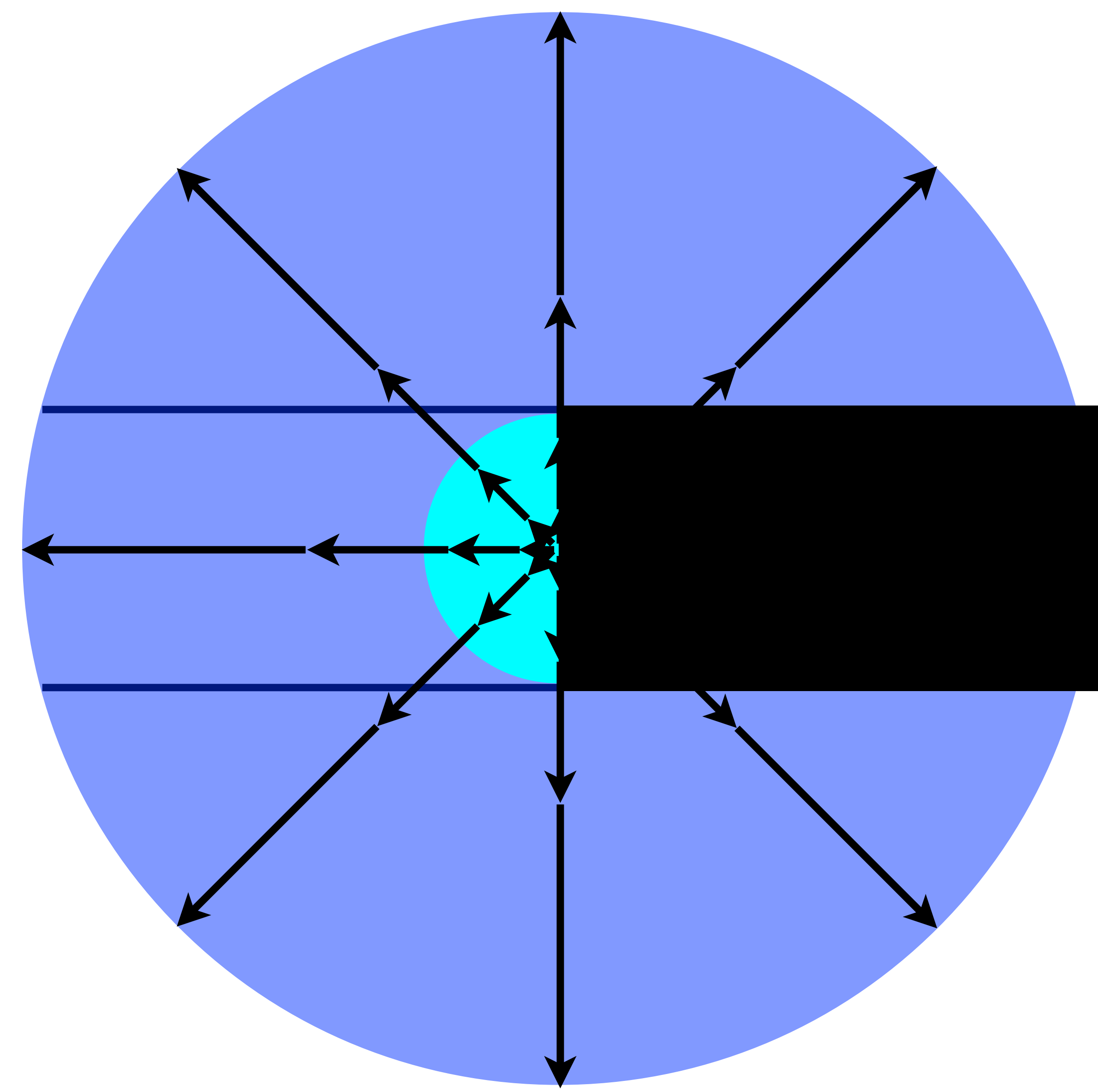


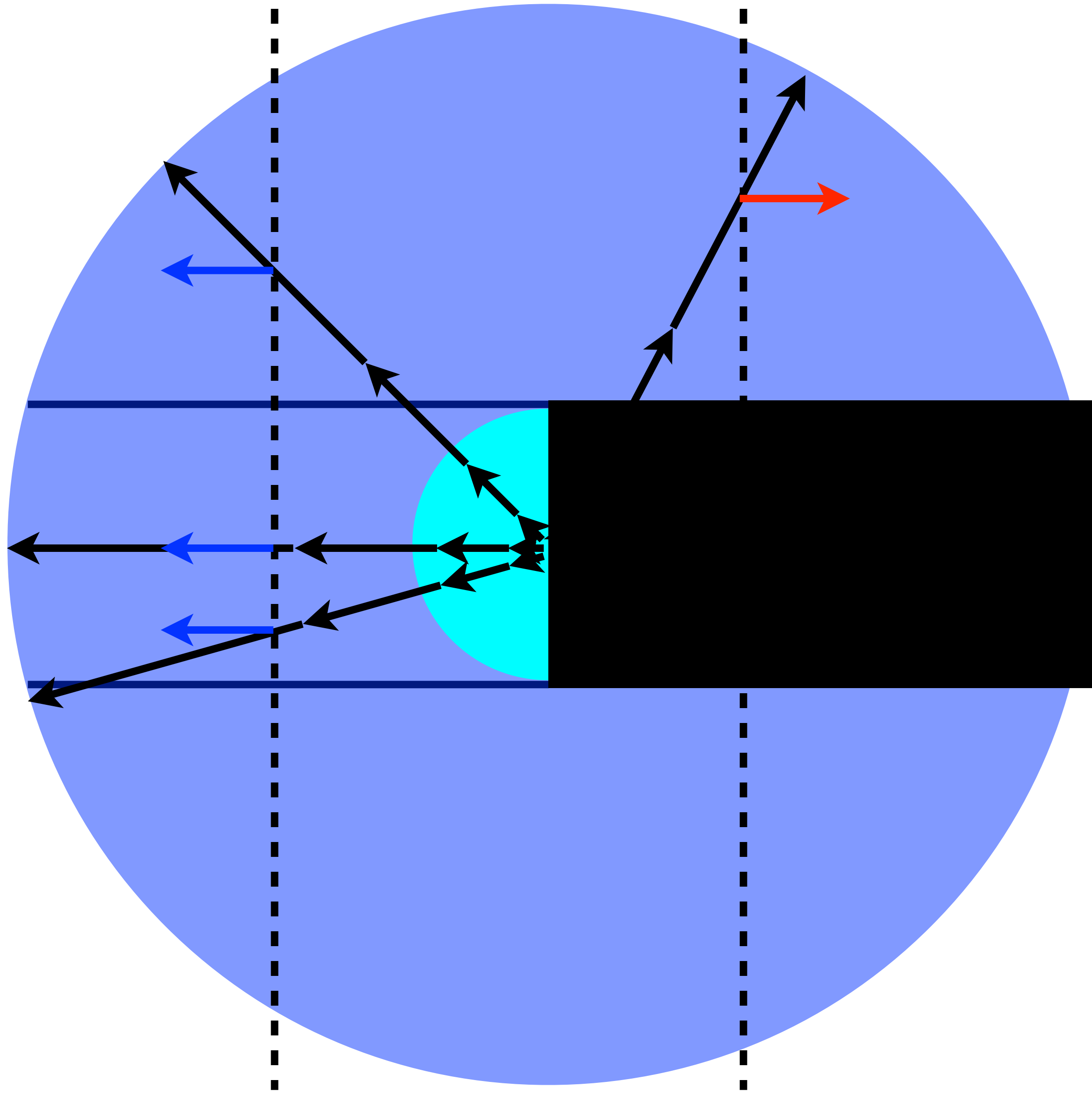
$$r(t_{exp}) = r_0 + v\ t_{exp} \approx v\ t_{exp}$$

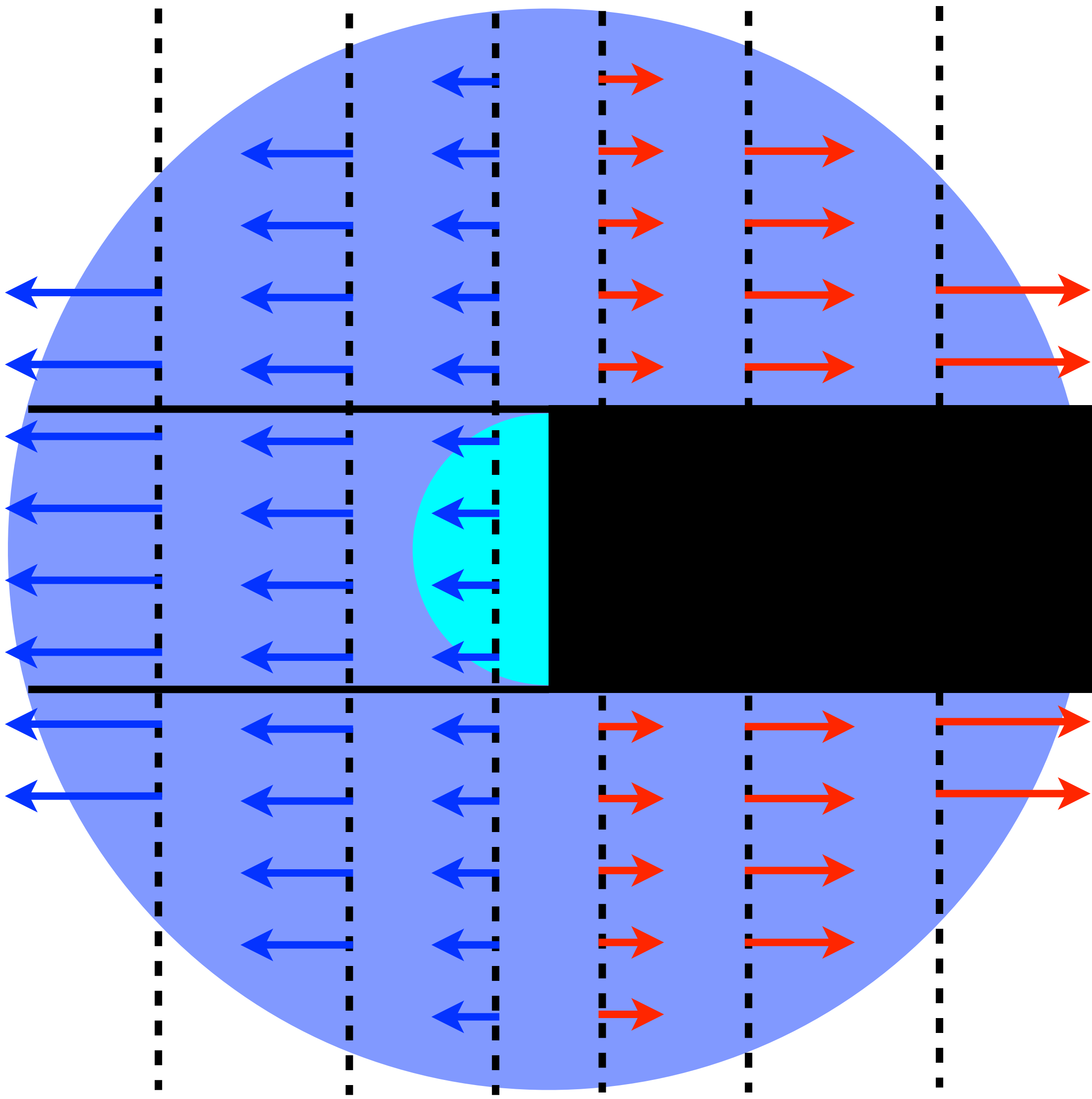








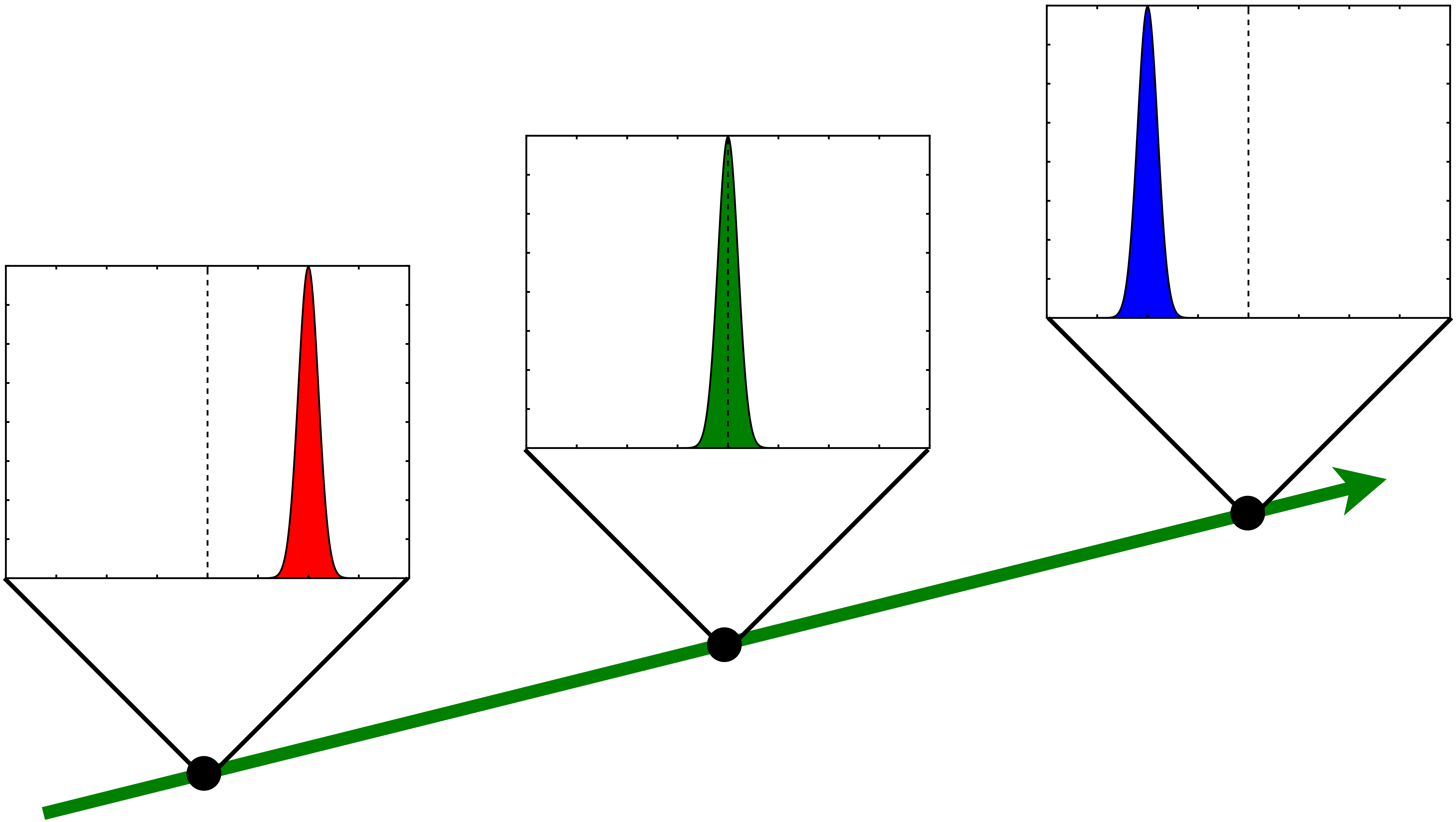




$$
\begin{aligned}
&\gamma(1+\beta\mu)\,\frac{\partial I_\nu}{\partial t}+\gamma(\mu+\beta)\,\frac{\partial I_\nu}{\partial r}+\frac{\partial}{\partial\mu}\Bigg\{\gamma(1-\mu^2)\\
&\times\left[\frac{1+\beta\mu}{r}-\gamma^2(\mu+\beta)\,\frac{\partial\beta}{\partial r}-\gamma^2(1+\beta\mu)\,\frac{\partial\beta}{\partial t}\right]I_\nu\Bigg\}\\
&-\frac{\partial}{\partial\nu}\left\{\gamma\nu\left[\frac{\beta(1-\mu^2)}{r}+\gamma^2\mu(\mu+\beta)\,\frac{\partial\beta}{\partial r}+\gamma^2\mu(1+\beta\mu)\,\frac{\partial\beta}{\partial t}\right]I_\nu\right\}\\
&\qquad+\gamma\Bigg\{\frac{2\mu+\beta(3-\mu^2)}{r}+\gamma^2(1+\mu^2+2\beta\mu)\,\frac{\partial\beta}{\partial r}\\
&\qquad\qquad\qquad\qquad+\gamma^2[2\mu+\beta(1+\mu^2)]\,\frac{\partial\beta}{\partial t}\Bigg\}I_\nu\\
&\qquad\qquad\qquad\qquad=\eta_\nu-\chi_\nu I_\nu\,.
\end{aligned}
$$

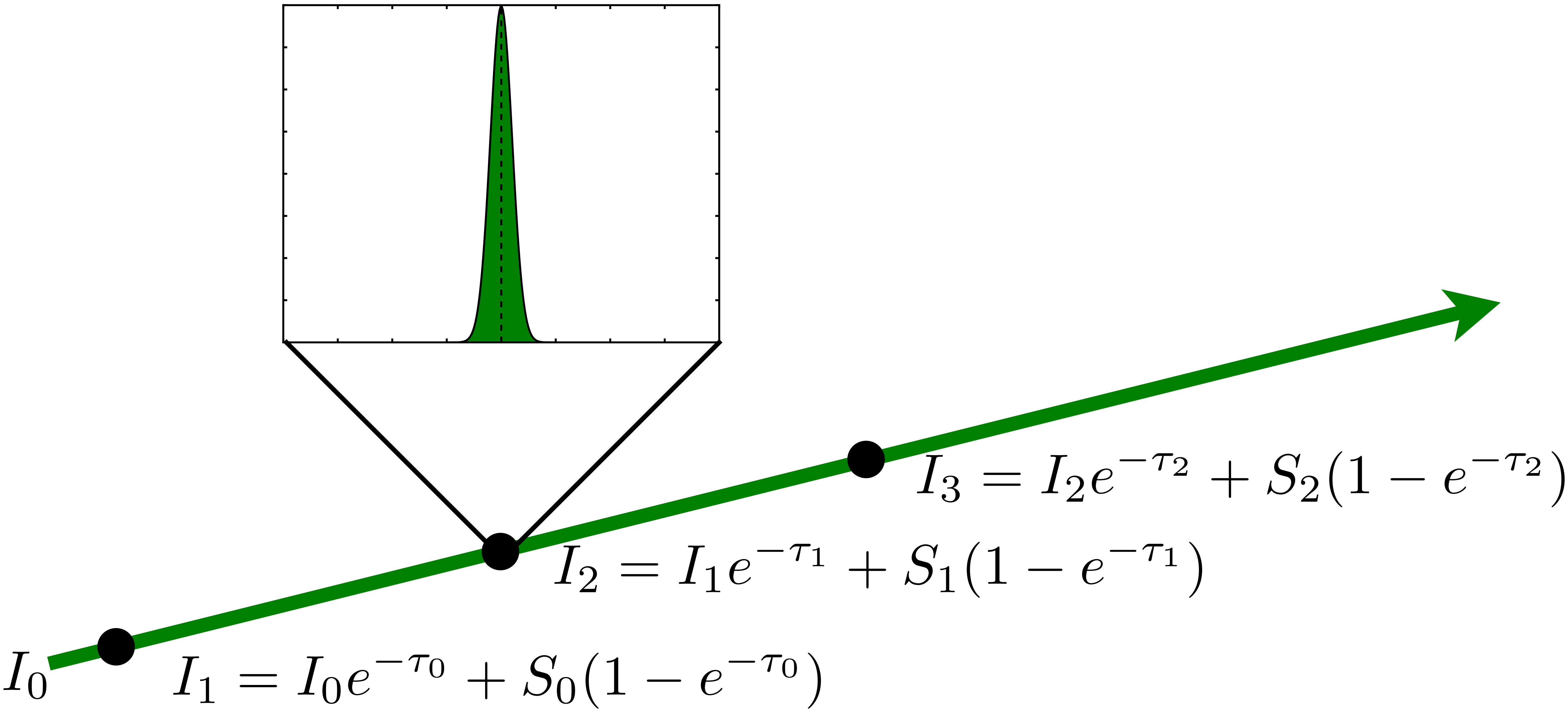
from Hauschildt, Baron & Allard, 1997, ApJ, 483, 390

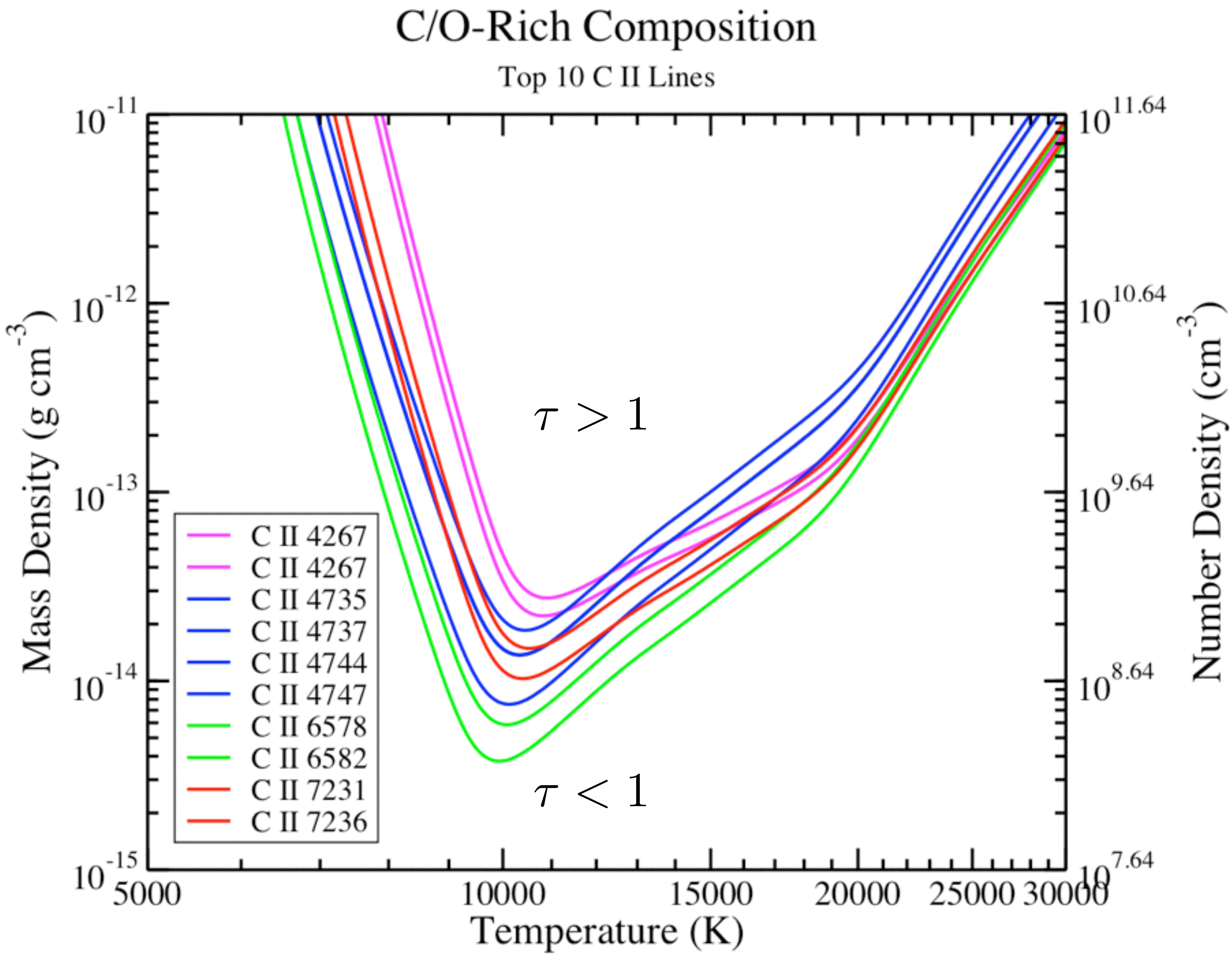
Sobolev Technique



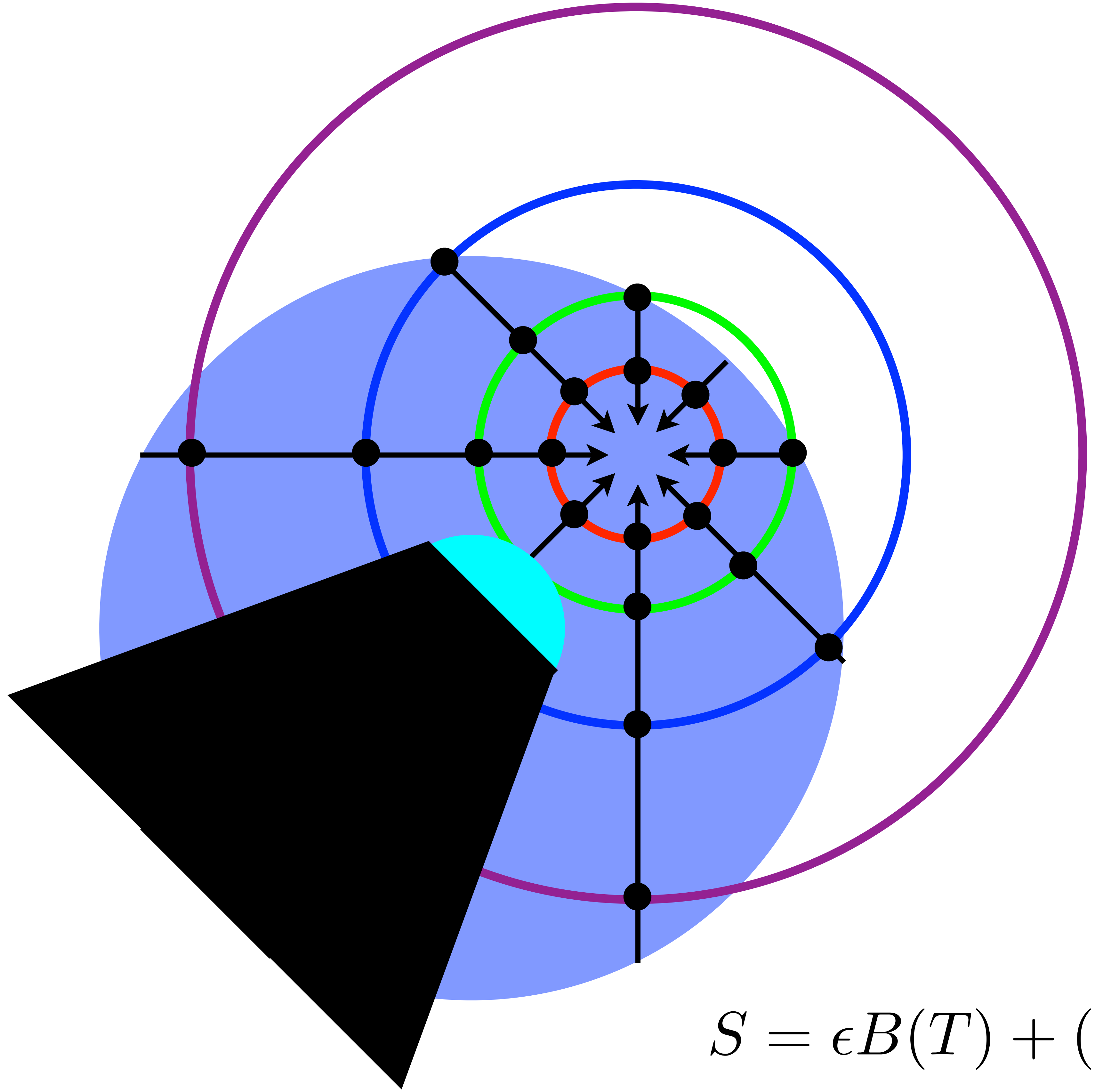
See Also: Jeffery & Branch 1990, Jerusalem Winter School Proceedings
Rybicki & Hummer 1978, ApJ, 219,654
(and references therein)

$$I_{out} = I_{in}e^{-\tau} + S(1 - e^{-\tau})$$



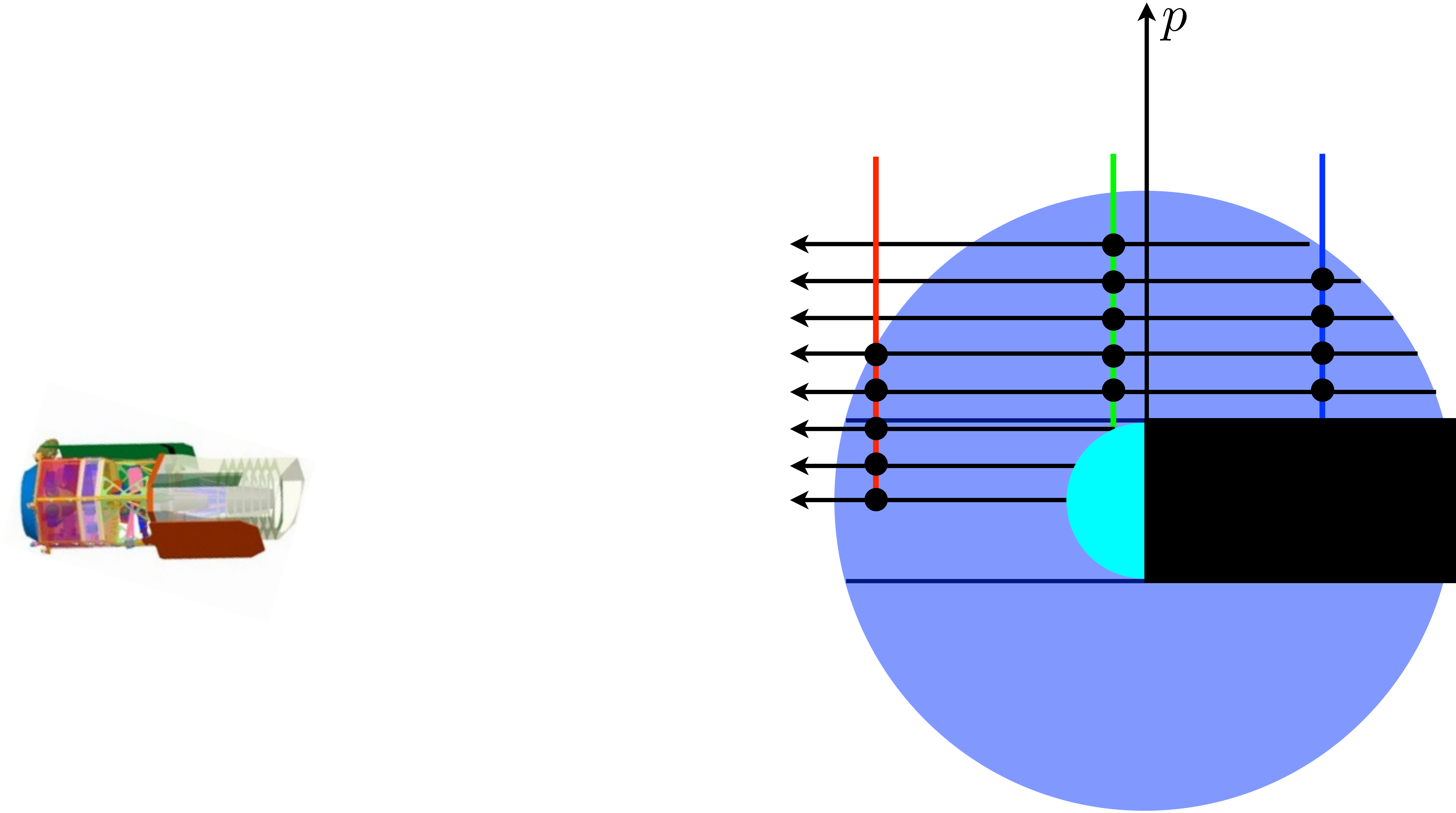


C/O-Rich Composition
Top 10 C II Lines
Mass Density (g cm^{-3})
Number Density (cm^{-3})
Temperature (K)
$\tau > 1$
$\tau < 1$
C II 4267
C II 4267
C II 4735
C II 4737
C II 4744
C II 4747
C II 6578
C II 6582
C II 7231
C II 7236
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$10^{11.64}$
$10^{10.64}$
$10^{9.64}$
$10^{8.64}$
$10^{7.64}$
5000
10000
15000
20000
25000
30000

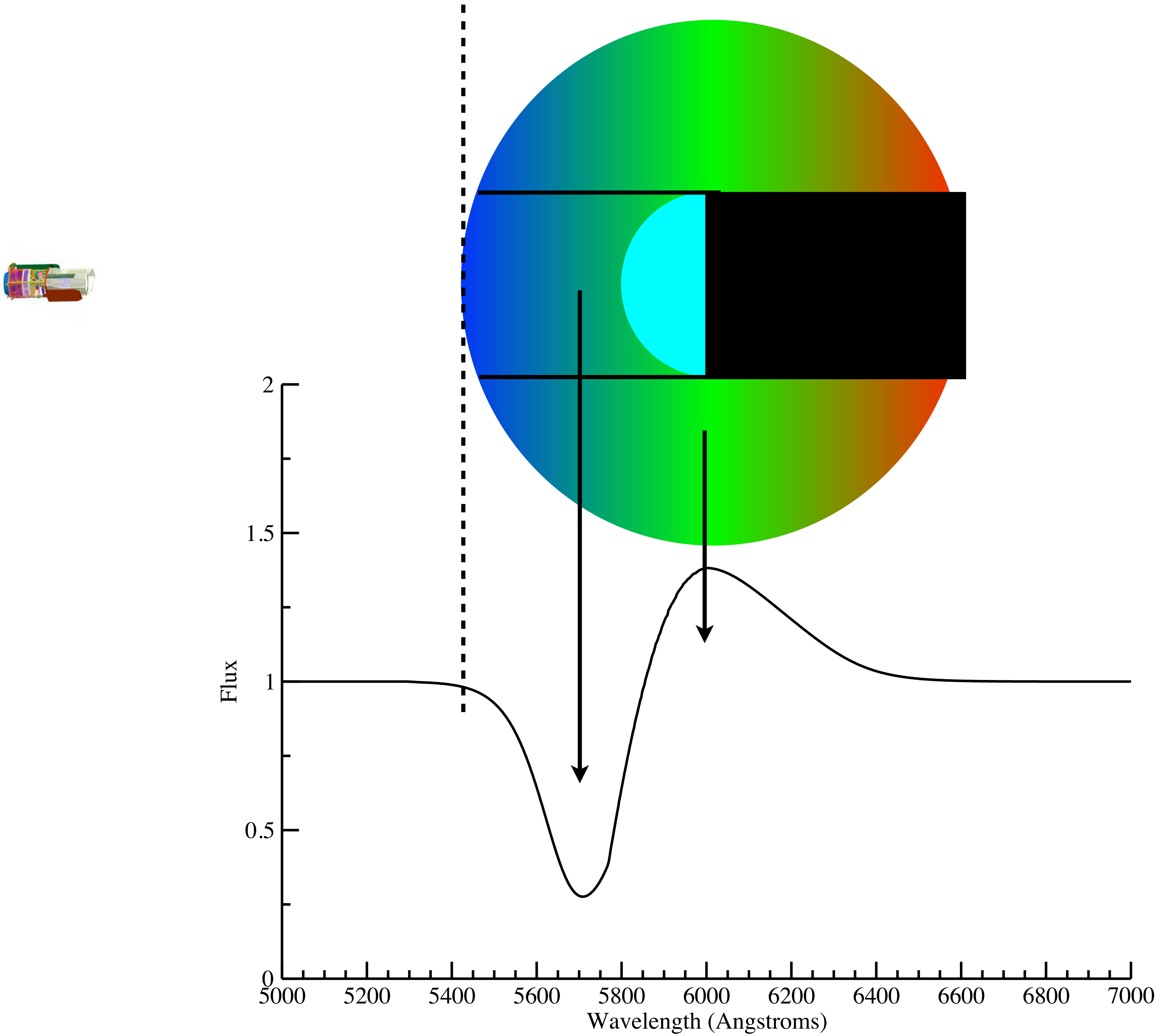


$$S = \epsilon B(T) + (1 - \epsilon) J$$

$$J(v, \lambda) = \frac{1}{4\pi} \int d\Omega \; I(v, \hat{n}, \lambda)$$

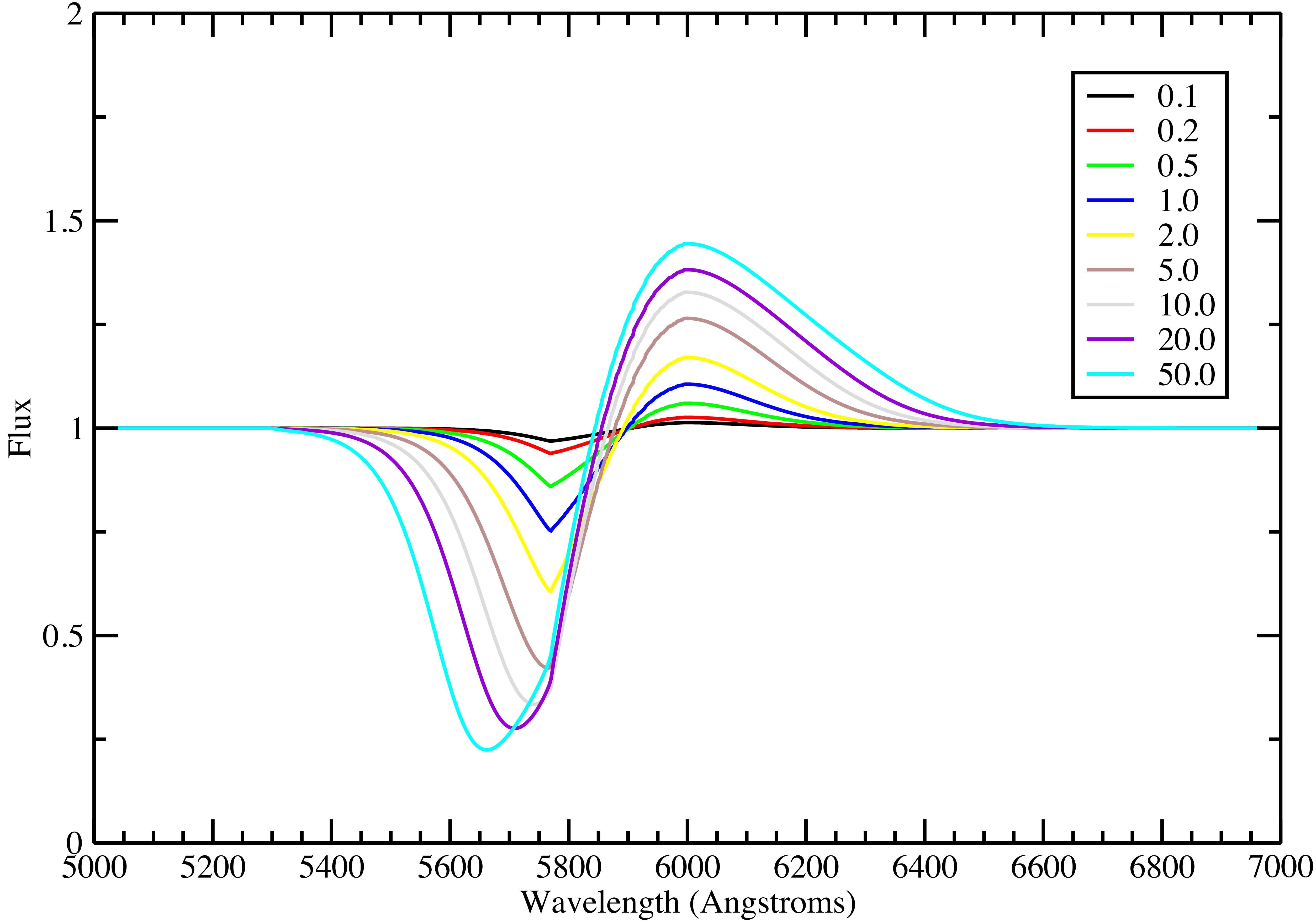


$$F(\lambda) \propto \int_0^{p_{max}} p \; dp \; I(p)$$

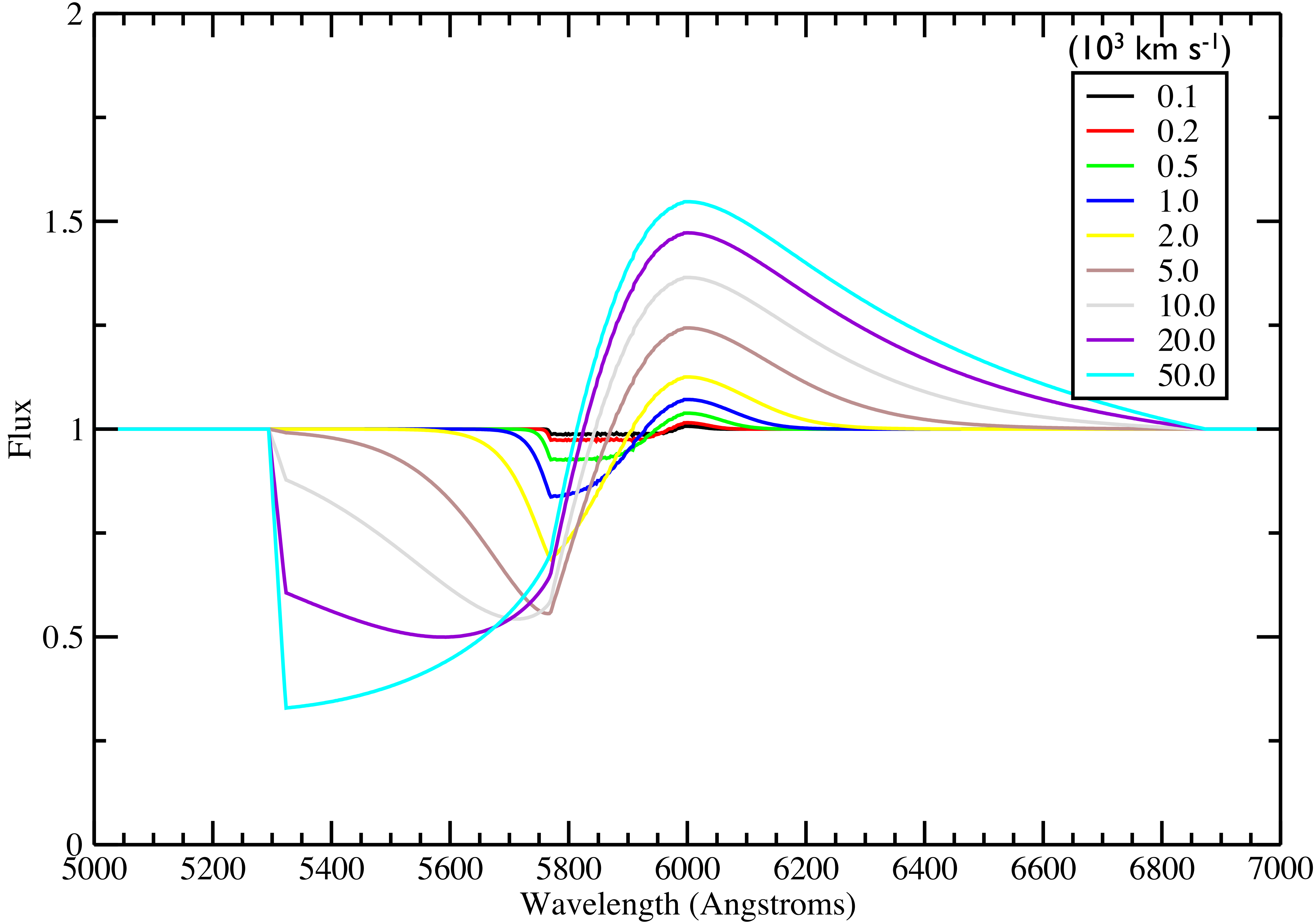


2
1.5
1
0.5
0
Flux
5000
5200
5400
5600
5800
6000
6200
6400
6600
6800
7000
Wavelength (Angstroms)

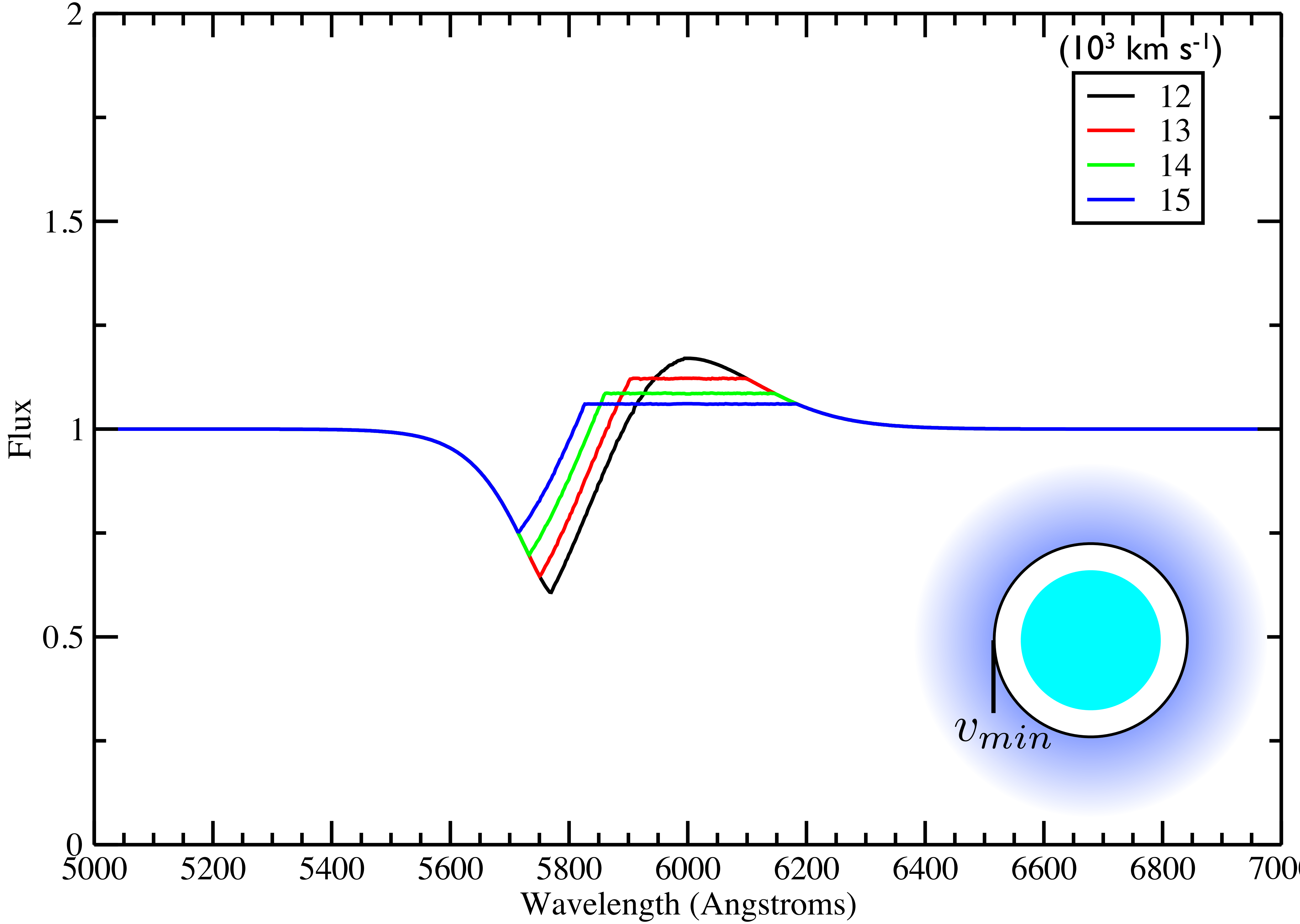
$$\tau(v) = \tau(v_{ref}) \exp\left(\frac{v_{ref} - v}{v_e}\right)$$



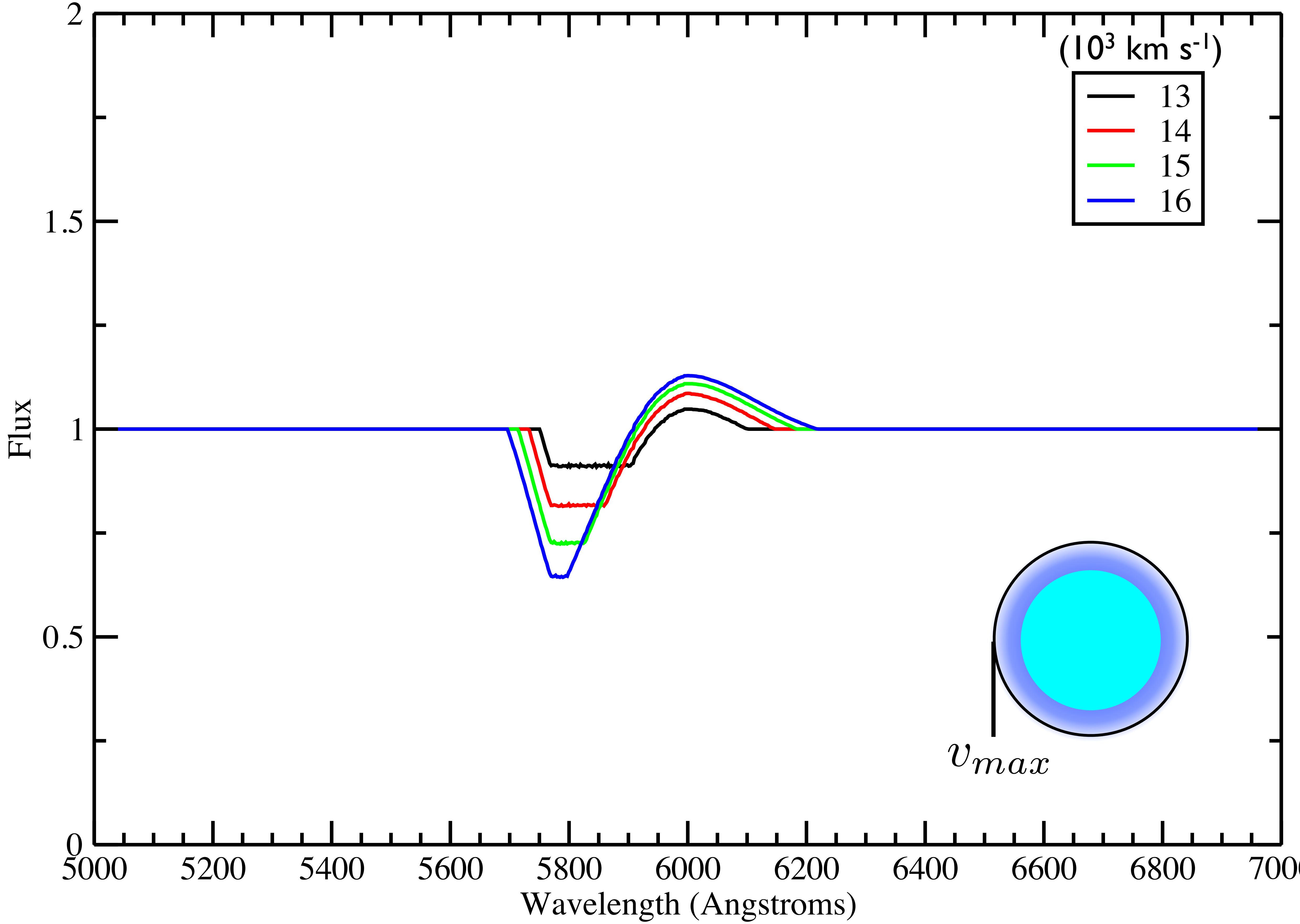
$$\tau(v) = \tau(v_{ref}) \exp\left(\frac{v_{ref} - v}{v_e}\right)$$

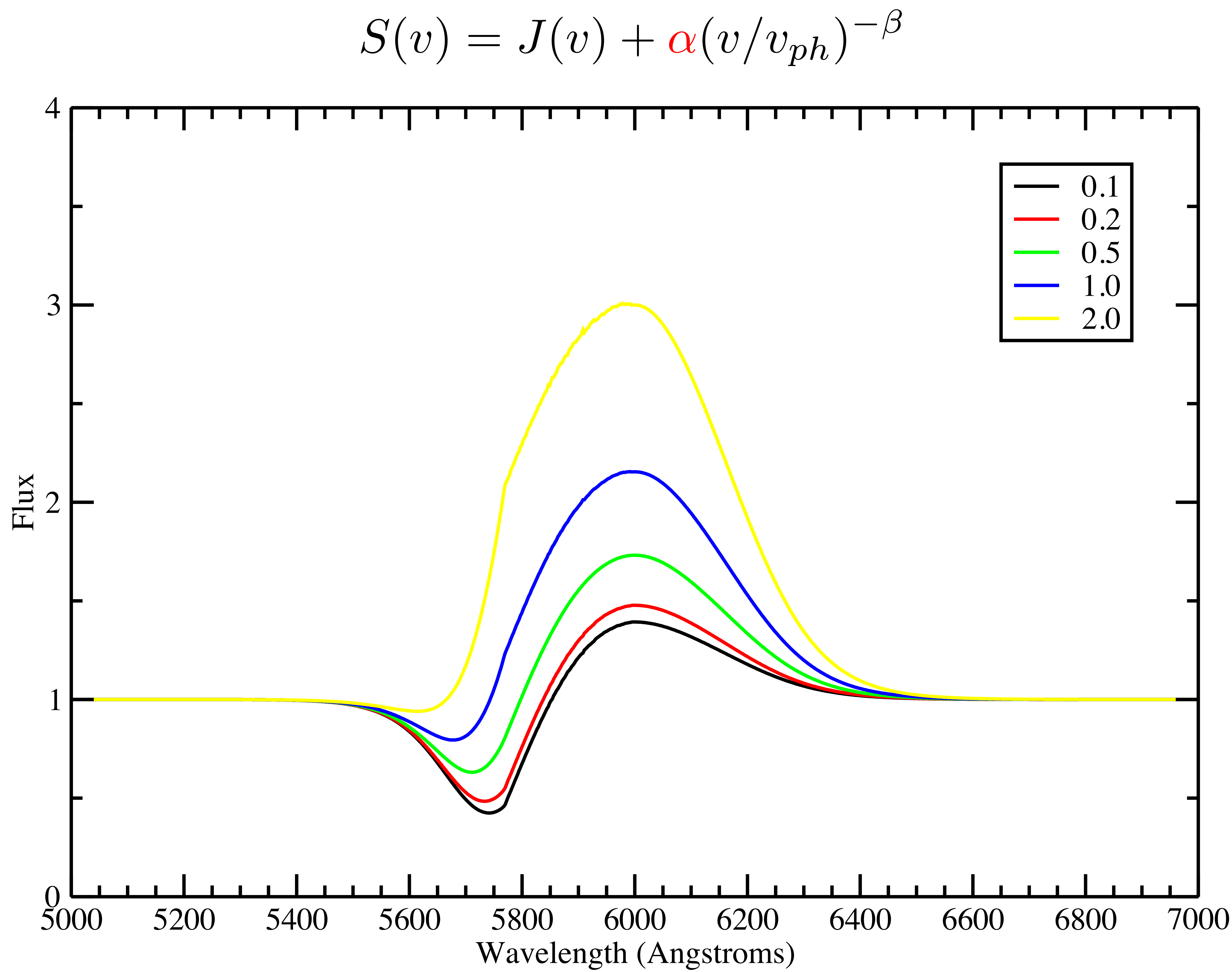


$$\tau(v) = \tau(v_{ref}) \exp\left(\frac{v_{ref} - v}{v_e}\right), (v > v_{min})$$

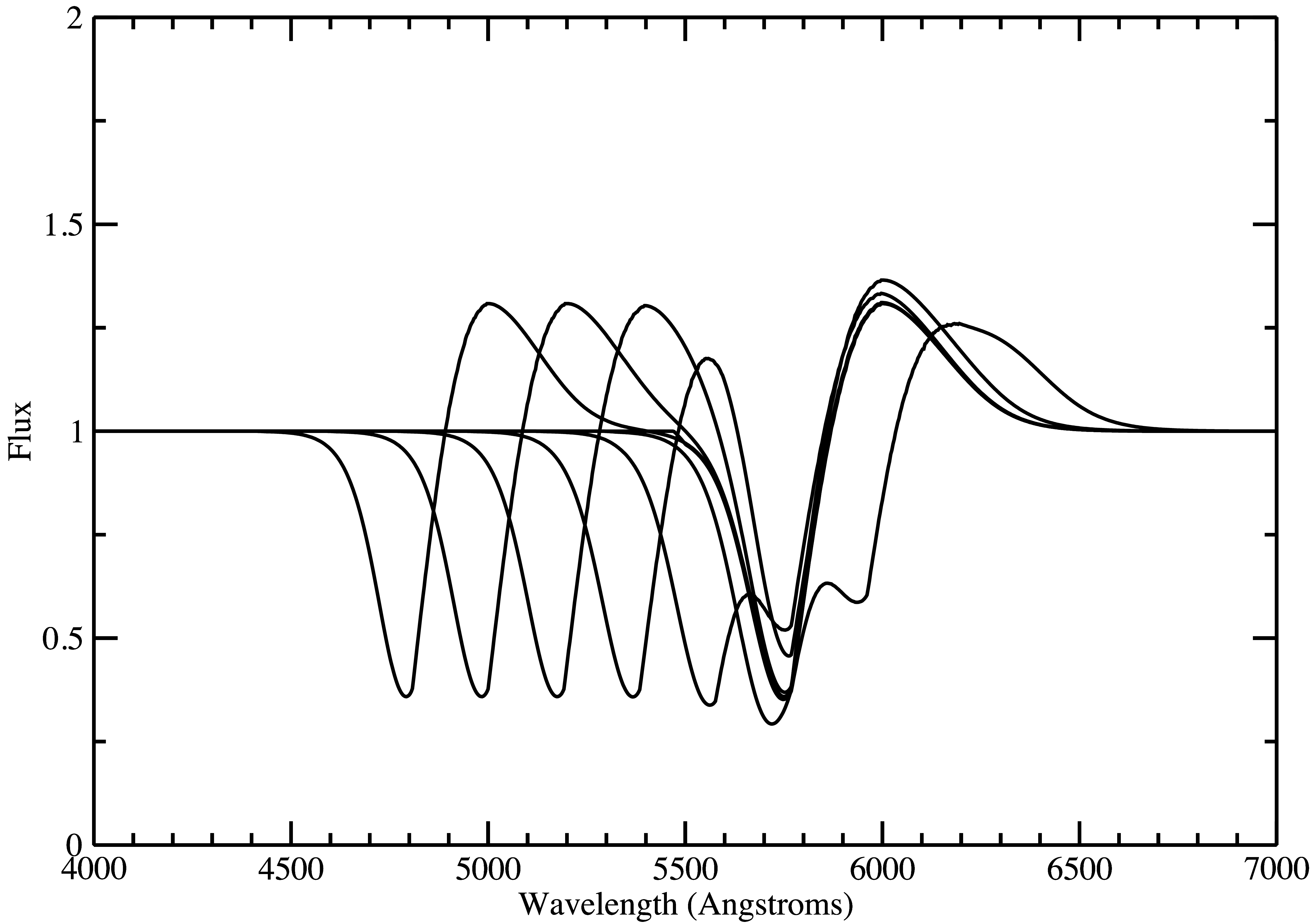


$$\tau(v) = \tau(v_{ref}) \exp\left(\frac{v_{ref} - v}{v_e}\right), (v < v_{max})$$



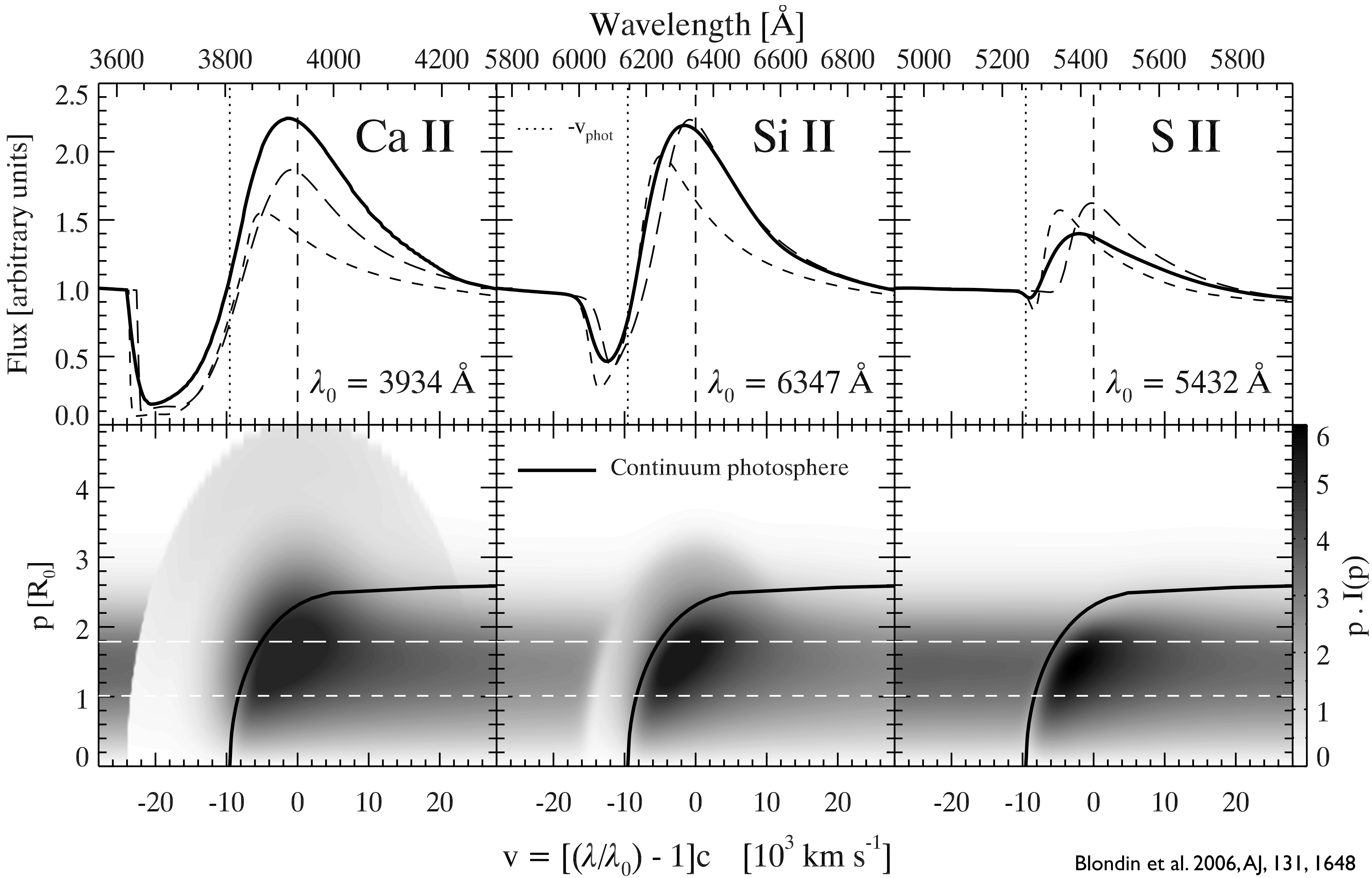


$S(v) = J(v) + \alpha(v/v_{ph})^{-\beta}$
0.1
0.2
0.5
1.0
2.0
Flux
Wavelength (Angstroms)
0
1
2
3
4
5000
5200
5400
5600
5800
6000
6200
6400
6600
6800
7000



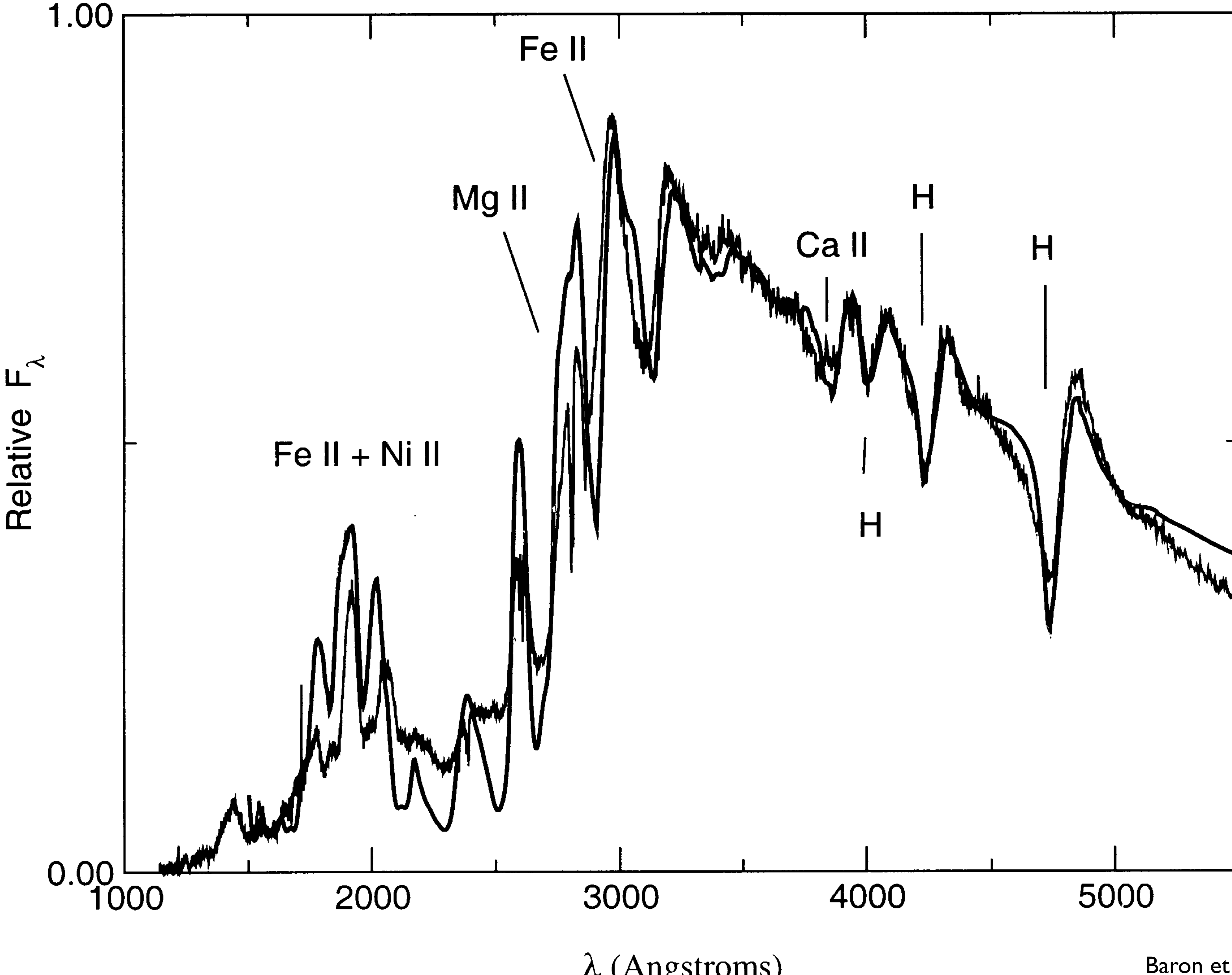
2
1.5
1
0.5
0
Flux
4000
4500
5000
5500
6000
6500
7000
Wavelength (Angstroms)

Real Picture More Fuzzy



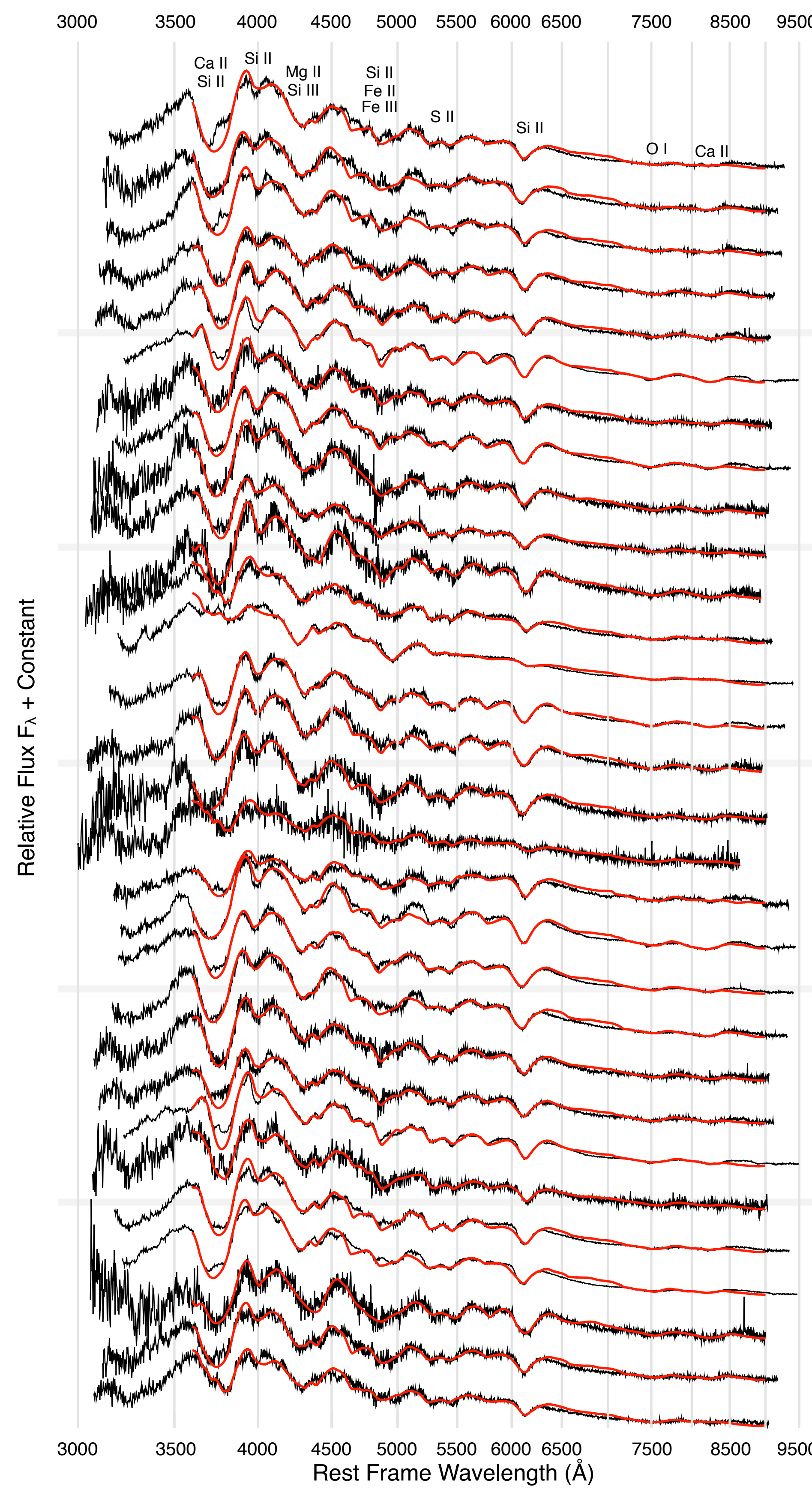
Blondin et al. 2006, AJ, 131, 1648

Type II Supernova



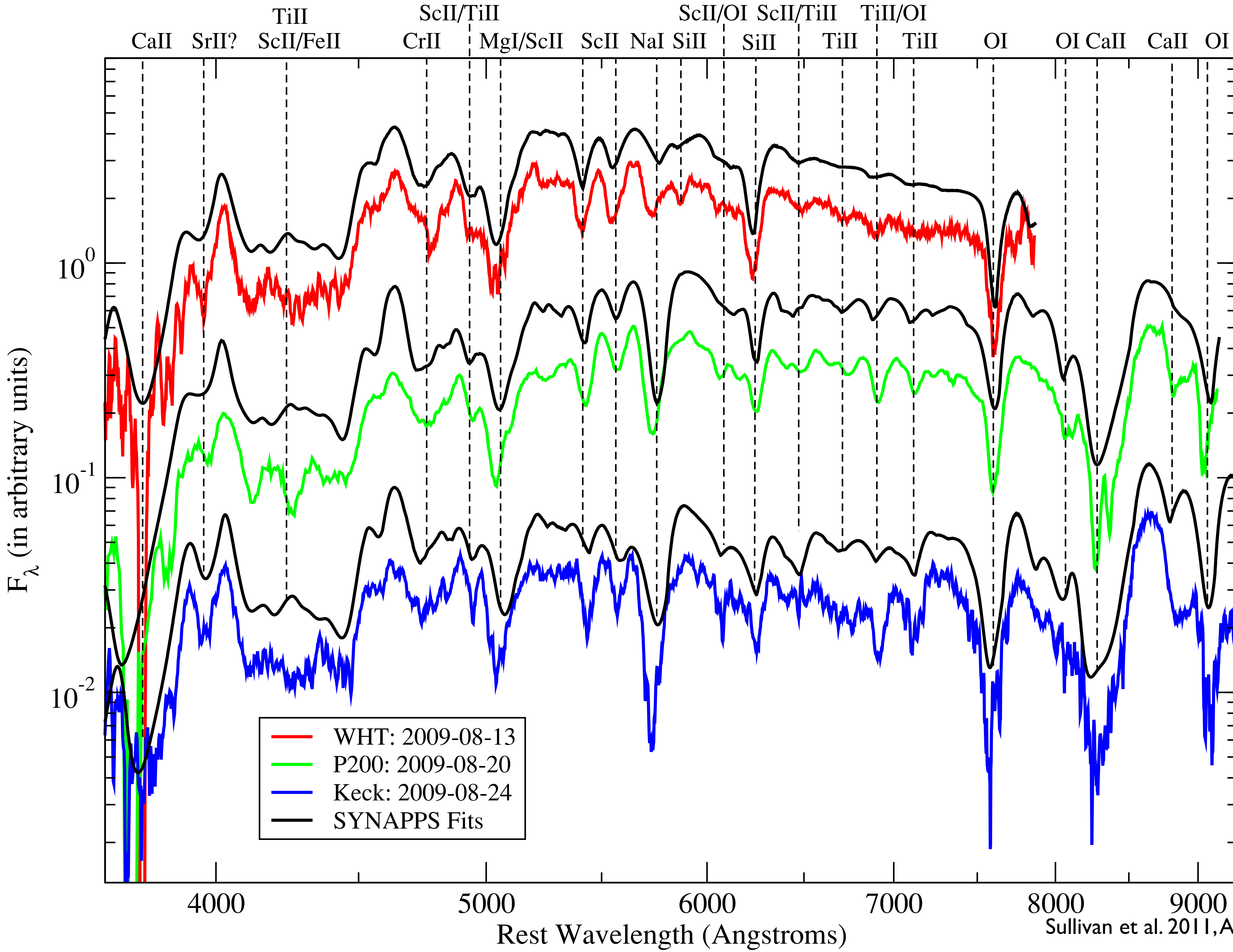
Baron et al 2000, ApJ, 545, 444

Type Ia Supernovae



Thomas, Nugent, & Meza, 2011, PASP, 123, 237

...and Weird Stuff

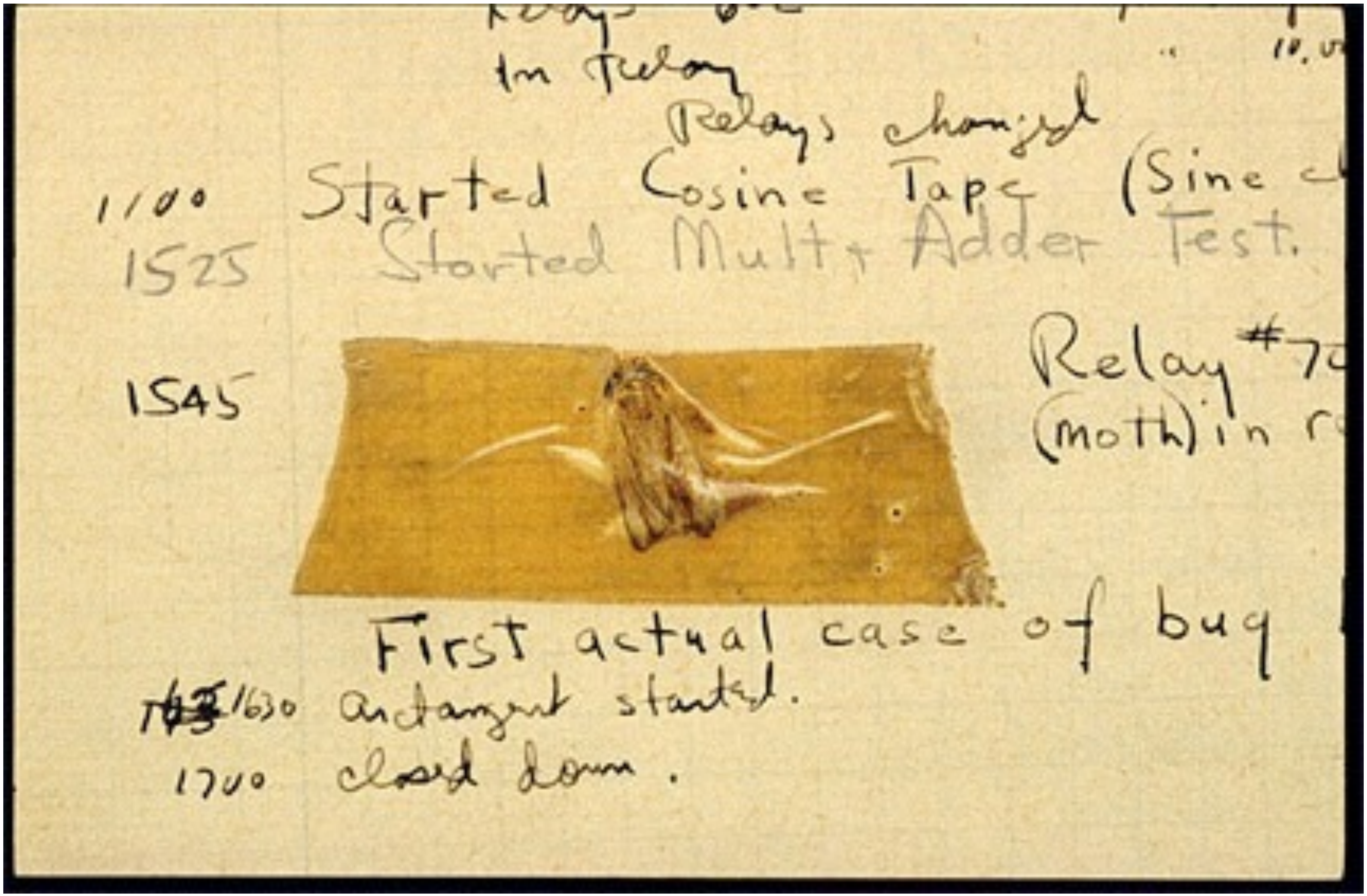


Sullivan et al. 2011, ApJ, 732, 118

Some Codes

- PHOENIX
  - Hauschildt, Baron, & Allard, 1997, ApJ, 483, 390
  - Jack, Hauschildt, & Baron, 2009, A&A, 502, 1043
  - Hauschildt & Baron, 2010, A&A, 509, 36
- CMFGEN
  - Hillier & Lanz, 2001, ASPC, 247, 343
  - Dessart & Hillier, 2005, ASPC, 332, 415
- RAGE
  - Gittings et al. 2008, CS&D, 1, 015005
- SEDONA
  - Kasen, Thomas, & Nugent, 2006, ApJ, 651, 366
- SAMURAI
  - Tanaka, et al. 2008, AIPC, 1016, 249
  - Tanaka, et al. 2009, AIPC, 1111, 413
- Mazzali & Lucy Code
  - Mazzali & Lucy 1993, A&A, 279, 447
- SN Monte Carlo in general:
  - Lucy 1999, A&A, 344, 282; 345, 211
  - Lucy 2002, A&A, 384, 725
  - Lucy 2003, A&A, 409, 737
  - Lucy 2005, A&A, 429, 19
- SYNOW/SYN++ and SYNAPPS
  - Branch, Baron, & Jeffery, 2003, LNP, 598, 47
  - Thomas, Nugent, & Meza, 2011, PASP, 123, 237
  - https://c3.lbl.gov/es
- TARDIS
  - Kerzendorf & Sim, 2014, MNRAS, 440, 337
  - http://tardis.readthedocs.org/en/latest

Codes



National Museum of American History
http://americanhistory.si.edu/collections/object.cfm?key=35&objkey=30

SYN++, SYNAPPS

- Open source! Actively maintained!
- Spherical symmetry.
- Sharply defined, BB-continuum emitting photosphere.
- Line transfer under Sobolev approximation.
- Optical depth parameterized spatially and in wavelength.
- Pure resonance scattering source function.

SYN++

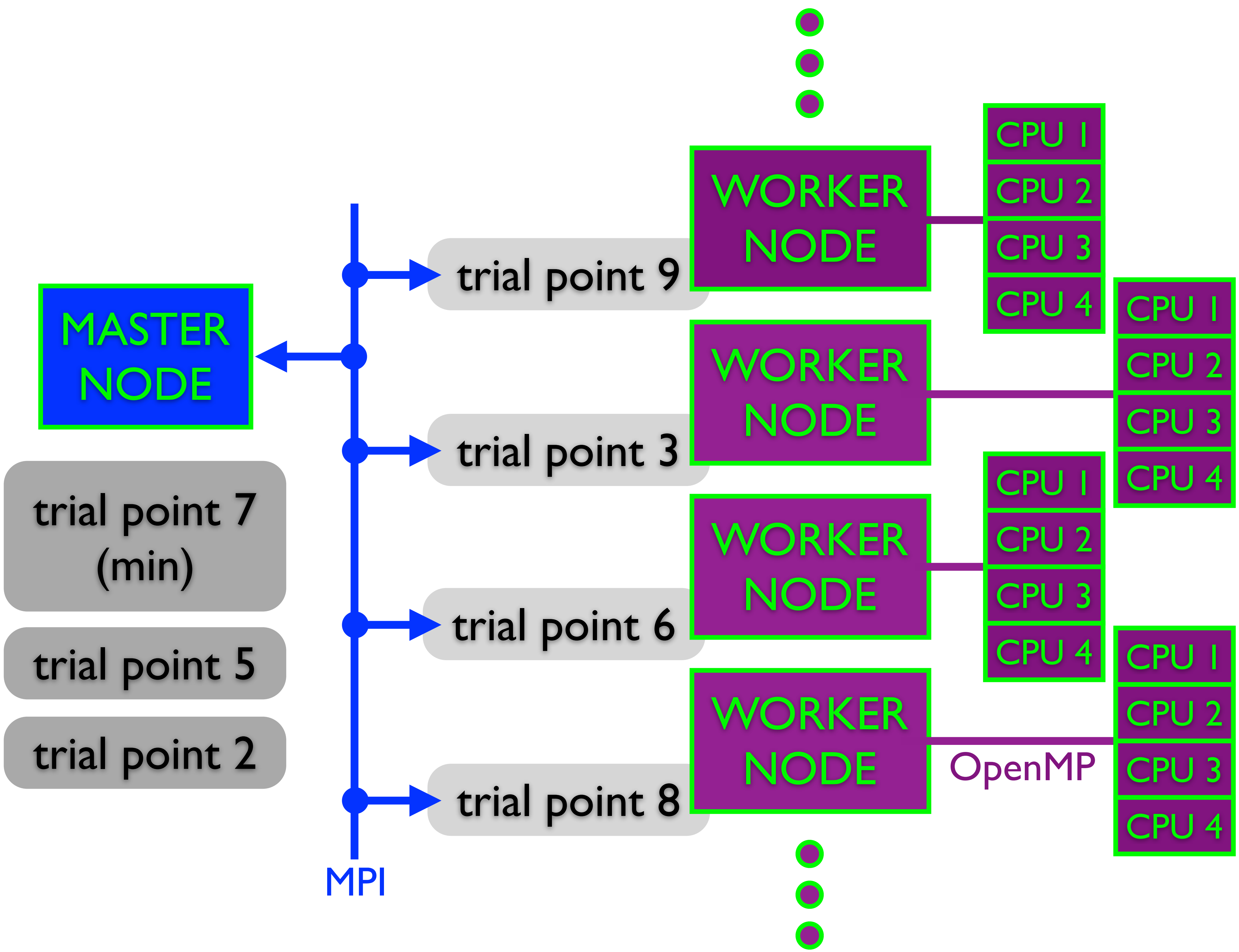
- SYN++ is a stand-alone “single shot” executable that creates a parameterized synthetic spectrum.
- OpenMP loop-level parallelism in computation of the source function.
- Can be used interactively to “fit” observations, identify lines (what’s there, what’s not), estimate ejection velocities, etc., explicitly including line blending.

```yaml
---
output :
    min_wl       : 2500.0          # min. wavelength in AA
    max_wl       : 10000.0         # max. wavelength in AA
    wl_step      : 5.0             # wavelength spacing in AA
grid :
    bin_width    : 0.3             # opacity bin size in kkm/s
    v_size       : 100             # size of line-forming region grid
    v_outer_max  : 30.0            # fastest ejecta velocity in kkm/s
opacity :
    line_dir     : /usr/local/share/es/lines      # path to atomic line data
    ref_file     : /usr/local/share/es/refs.dat   # path to ref. line data
    form         : exp             # parameterization (only exp for now)
    v_ref        : 10.0            # reference velocity for parameterization
    log_tau_min  : -2.0            # opacity threshold
source :
    mu_size      : 10              # number of angles for source integration
spectrum :
    p_size       : 60              # number of phot. impact parameters for spectrum
    flatten      : No              # divide out continuum or not
setups :
    -   a0       :  1.0            # constant term
        a1       :  0.0            # linear warp term
        a2       :  0.0            # quadratic warp term
        v_phot   :   8.0           # velocity at photosphere (kkm/s)
        v_outer  :  30.0           # outer velocity of line forming region (kkm/s)
        t_phot   :  12.0           # blackbody photosphere temperature (kK)
        ions     :  [ 1601, 2201, 2401, 2601 ]  # ions (100*Z+I, I=0 is neutral)
        active   :  [  Yes,  Yes,  Yes,  Yes ]  # actually use the ion or not
        log_tau  :  [  0.1,  1.0,  1.0,  1.0 ]  # ref. line opacity at v_ref
        v_min    :  [ 10.0, 10.0, 10.0, 10.0 ]  # lower cutoff (kkm/s)
        v_max    :  [ 30.0, 30.0, 30.0, 30.0 ]  # upper cutoff (kkm/s)
        aux      :  [  1.0, 10.0, 10.0, 10.0 ]  # e-folding for exp form
        temp     :  [ 10.0, 10.0, 10.0, 10.0 ]  # Boltzmann exc. temp. (kK)
```

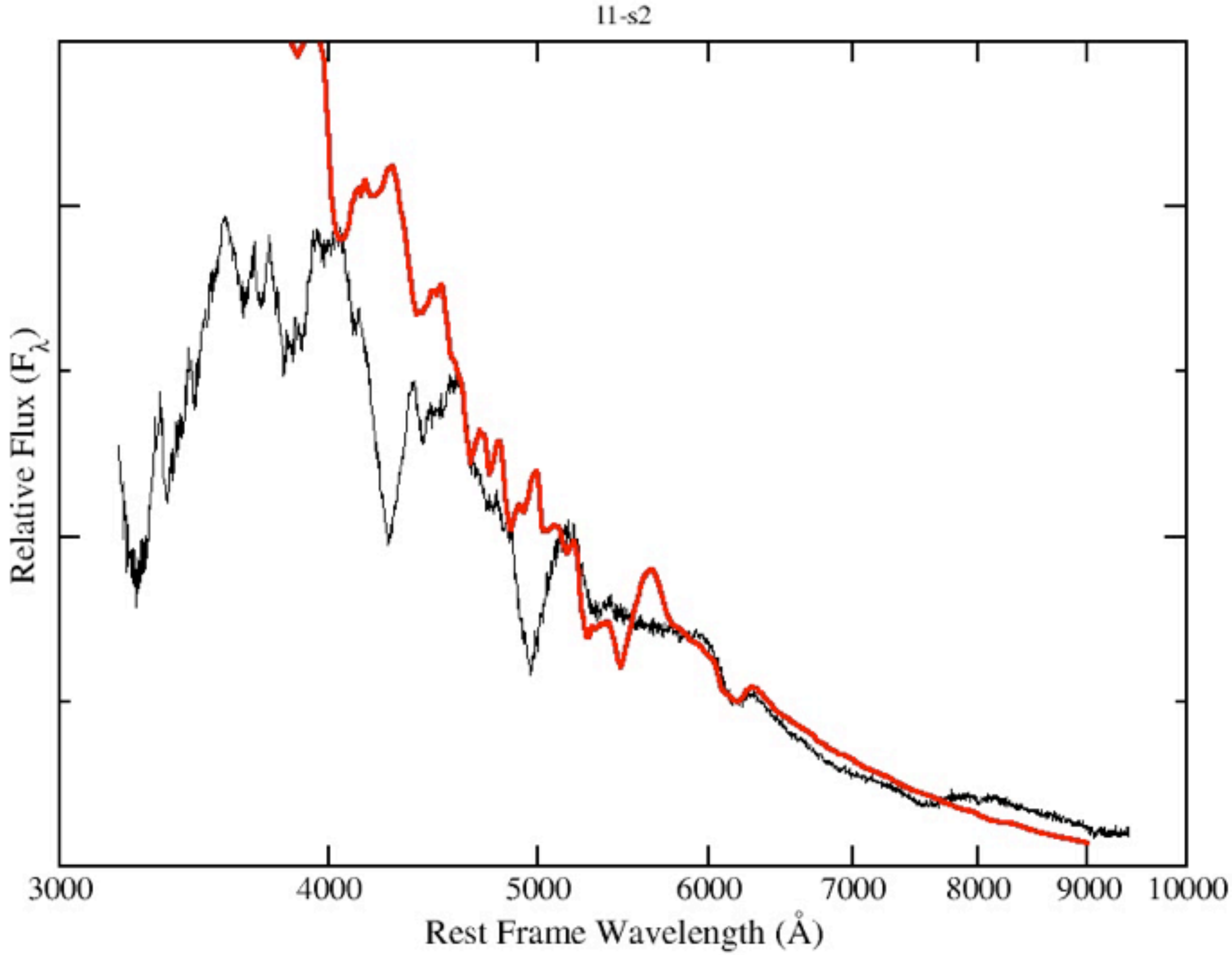
SYNAPPS

- Fitting spectra is tedious, so we automated it by wrapping SYN++ API calls in a multidimensional, parallel optimizer, APPSPACK:
  - Kolda, 2005, SIAM J. Optim., 16, 563
  - Gray & Kolda, 2005, ACM Trans. Math. Software, 32, 485
  - Griffin & Kolda, 2006, SAND2006-4621
  - http://software.sandia.gov/appspack/version5.0/index.html
- Hybrid Parallelism:
  - MPI for master-worker architecture.
  - OpenMP for synthetic spectrum.

SYNAPPS Architecture



SYN++, SYNAPPS



- http://c3.lbl.gov/es/
- http://github.com/rcthomas/es

- Next up, thesis of D. Goldstein….