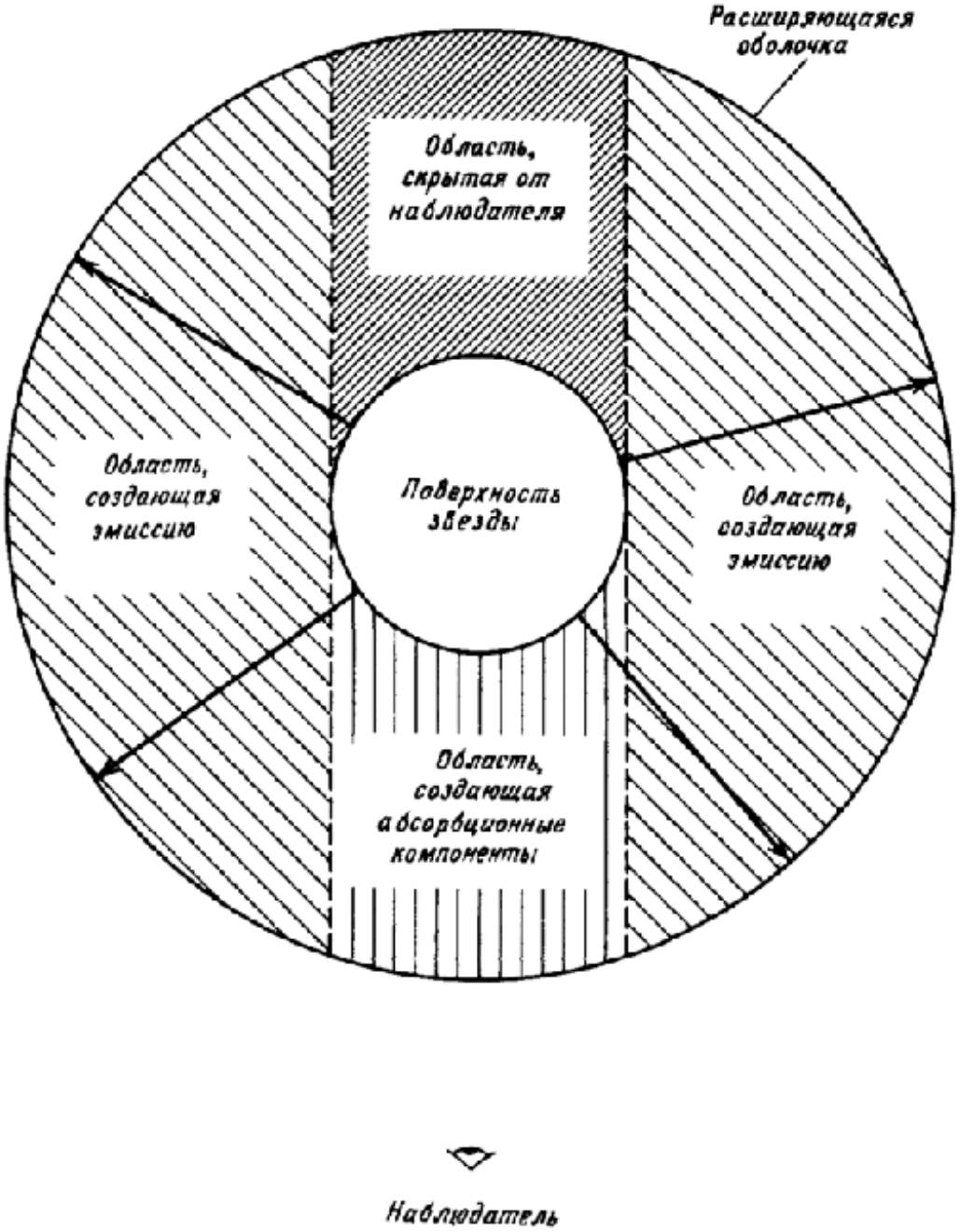
LEVELS

М. Поташов

вместе с С.И. Блинниковым, П.В. Баклановым, А.Д. Долговым


Расширяющаяся оболочка
Область, скрытая от наблюдателя
Область, создающая эмиссию
Поверхность звезды
Область, создающая эмиссию
Область, создающая абсорбционные компоненты
Наблюдатель

Rate equations

$$\frac{\partial n_{z,i}}{\partial t} + div(n_{z,i}\overrightarrow{v}) = \sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j})$$

Rate equations

$$\frac{\partial n_{z,i}}{\partial t} + div(n_{z,i}\vec{v}) = \sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j})$$

time-dependent

$$\frac{\mathrm{D}n_{z,i}}{\mathrm{D}t} + \frac{3n_{z,i}}{t} = \sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j})$$

Rate equations

$$\frac{\partial n_{z,i}}{\partial t} + div(n_{z,i}\vec{v}) = \sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j})$$

time-dependent

$$\frac{Dn_{z,i}}{Dt} + \frac{3n_{z,i}}{t} = \sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j})$$

Rate equations

$$\frac{\partial n_{z,i}}{\partial t} + div(n_{z,i}\vec{v}) = \sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j})$$

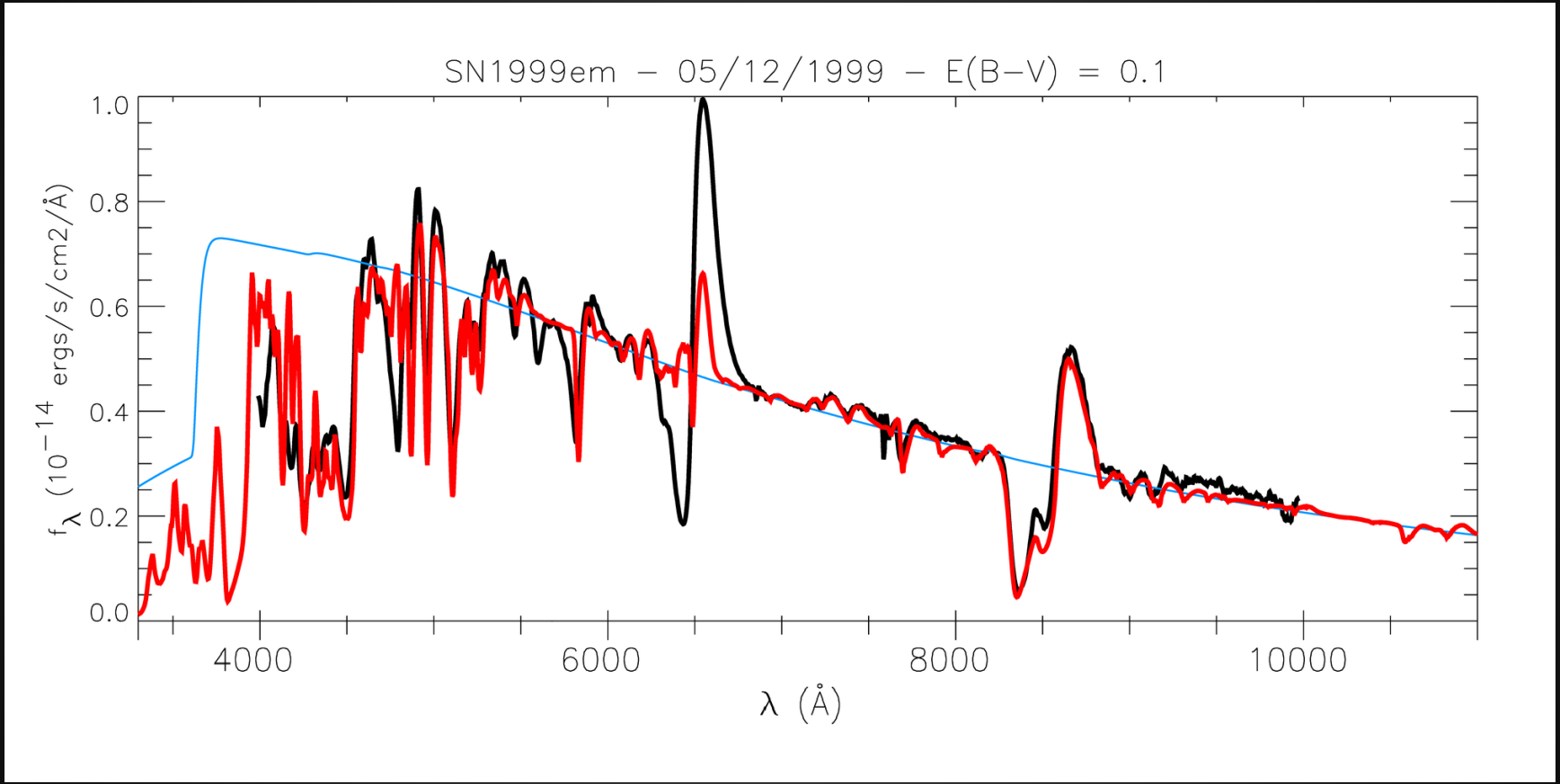
time-dependent

$$\frac{Dn_{z,i}}{Dt} + \frac{3n_{z,i}}{t} = \sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j})$$

steady-state approximation

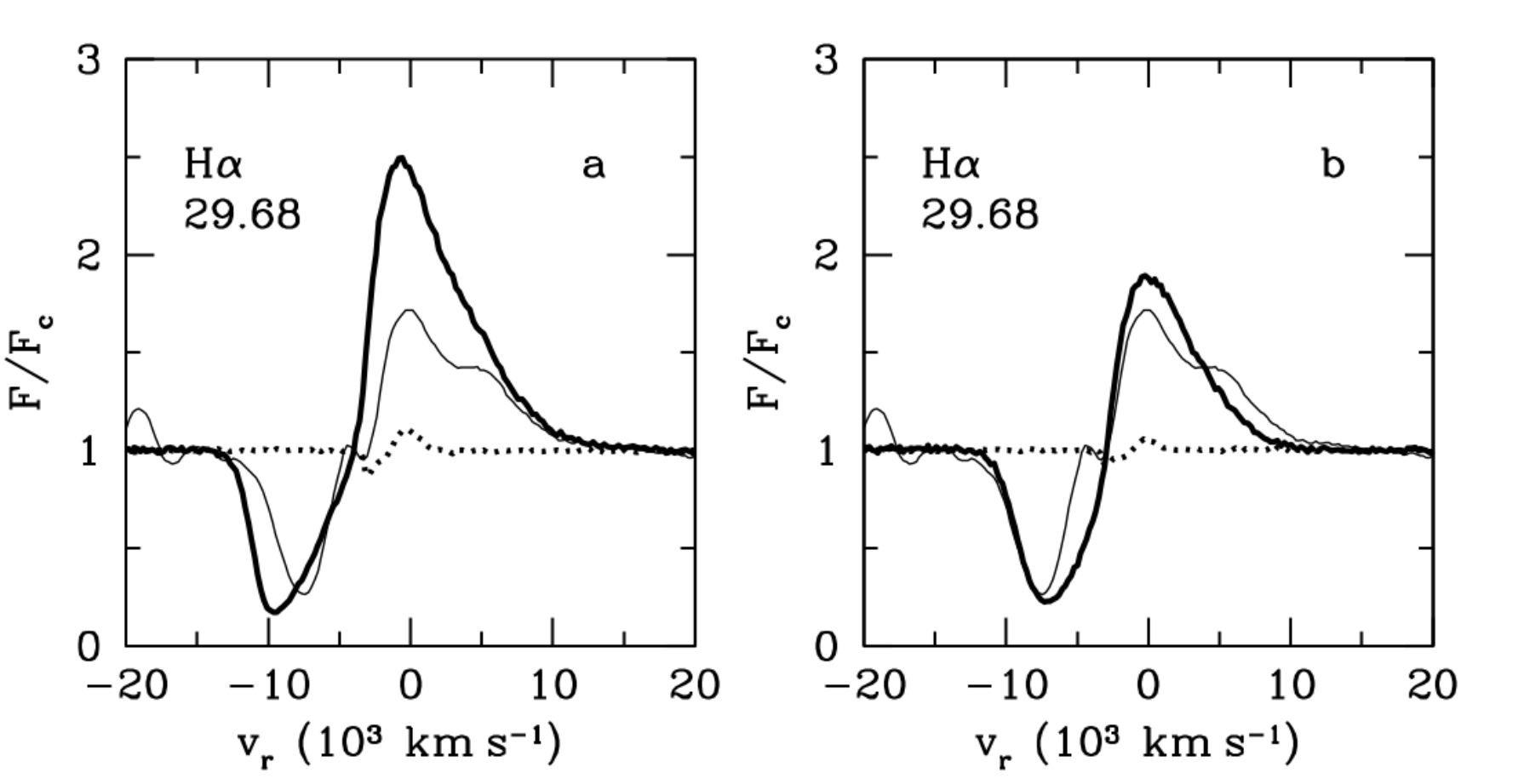
$$\sum_{j \neq i}(n_{z,j}P_{j,i} - n_{z,i}P_{i,j}) = 0$$

Weak line H-α, SN 1999em, 37 day



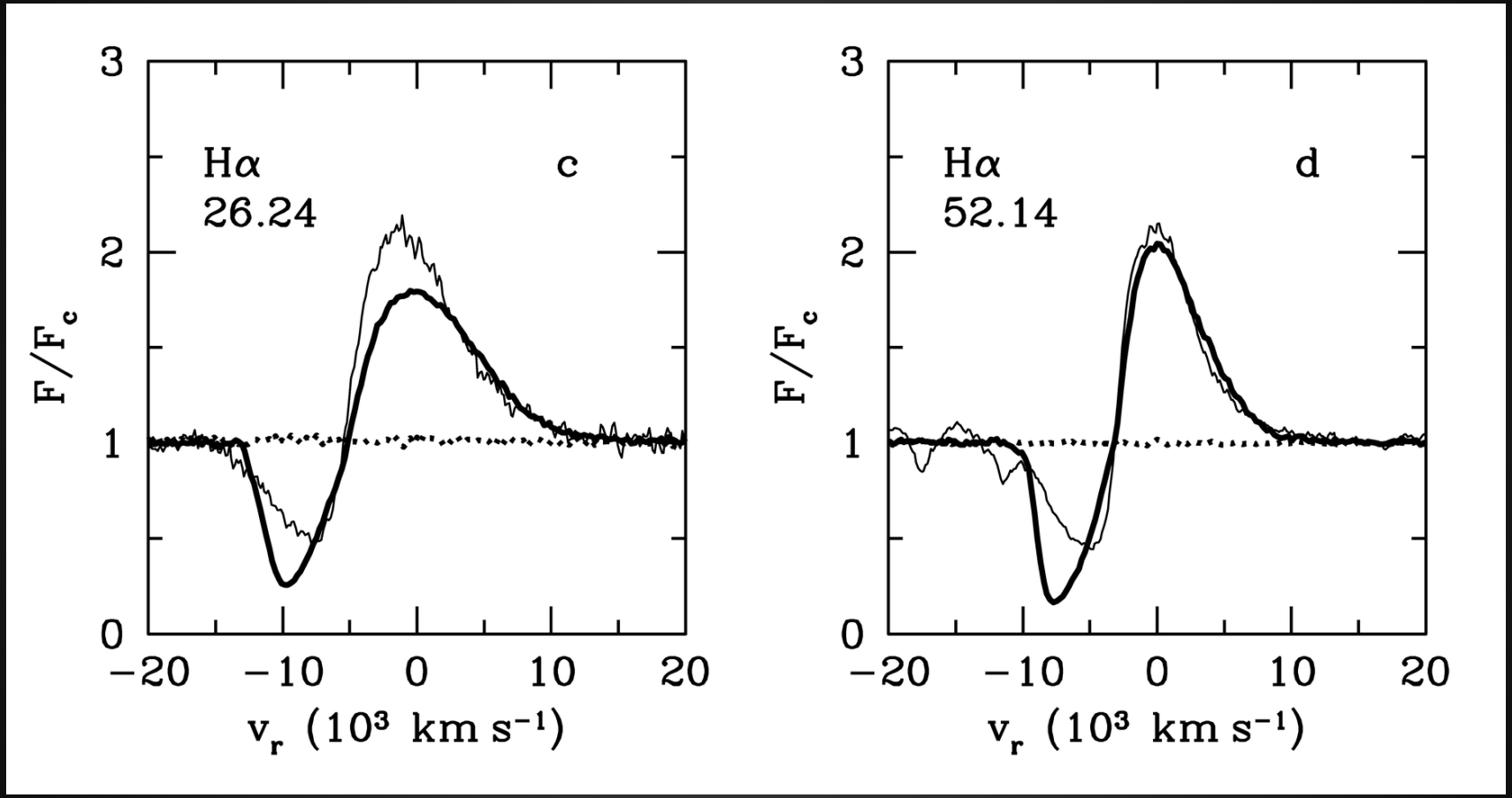
Dessart, L., Hillier, J. 2006, A&A 447, 691–707, CMFGEN

Time-dependent, SN 1987A, ~30 day



Utrobin, V., Chugai N. 2005, A&A 441, 271–281

Time-dependent, SN 1999em, 26 и 52 дни



Utrobin, V. P. 2007, A&A 461, 233–251

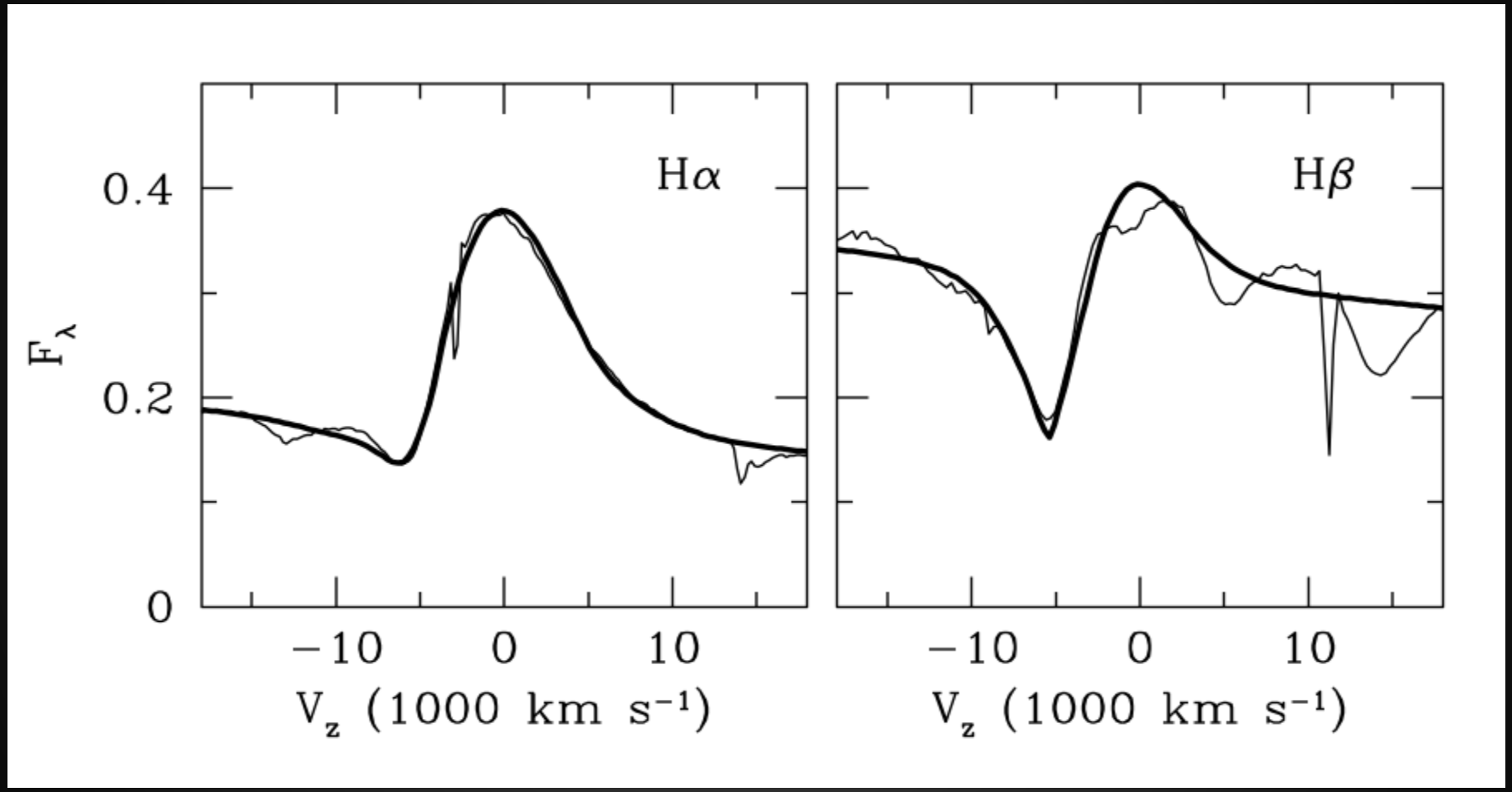
When the time dependence is important?

SN 1999em, 26 and 52 days

phase. Thus, it is possible to conclude that the hydrogen recombination in the atmosphere of SN 1999em during the whole plateau phase is essentially a time-dependent phenomenon.

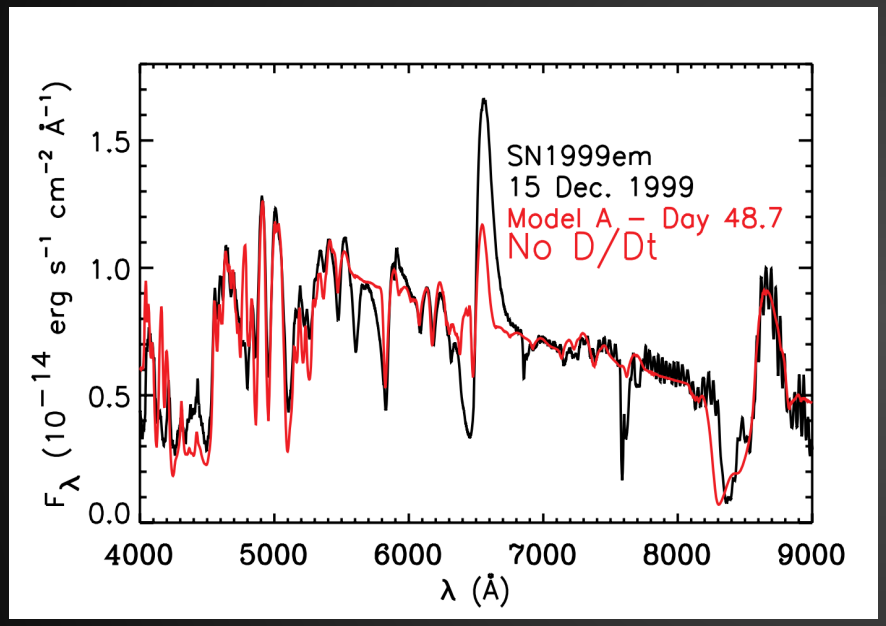
Utrobin, V. P. 2007, A&A 461, 233–251

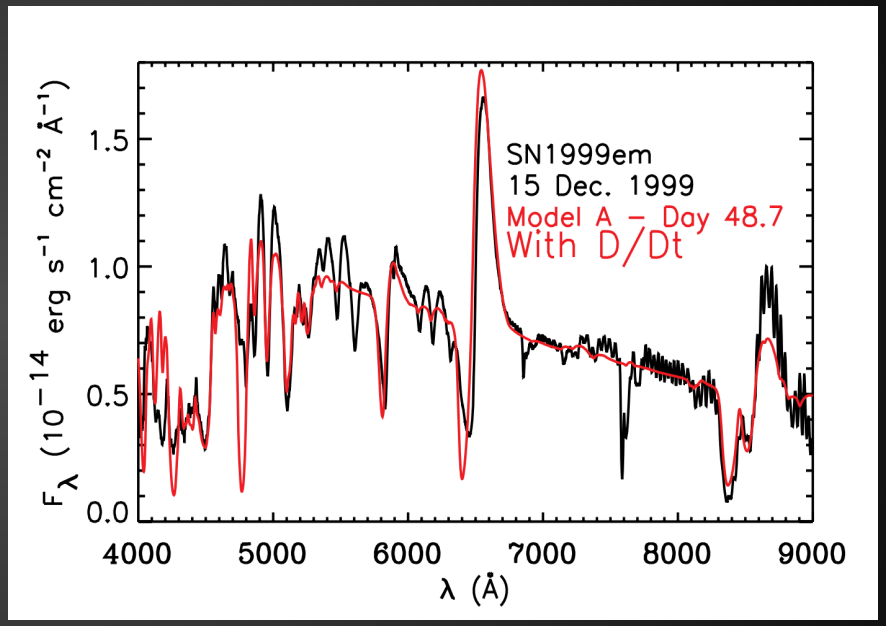
Time-dependent, SN 2008in, ~18 день



Utrobin, V., Chugai N. 2013, 2013arXiv1309.7814C

Time-dependent, SN 1999em, 48 day





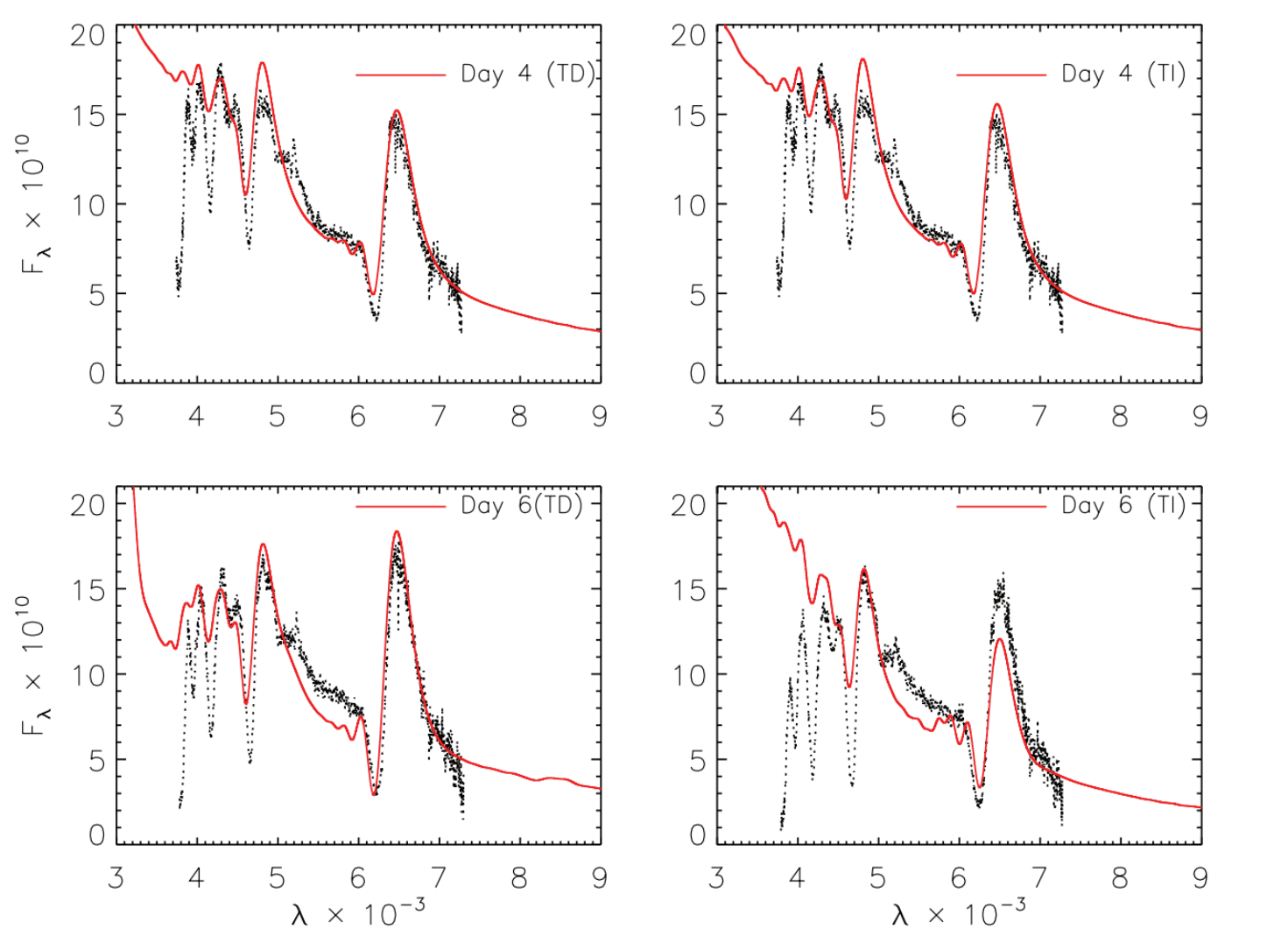
Dessart, L., Hillier, J. 2007, MNRAS 383, 57–74, CMFGEN

When the time dependence is important?

Time-dependent terms in the statistical- and radiative-equilibrium equations become important a few weeks after explosion (Utrobin & Chugai 2005; Dessart & Hillier 2007a,b).

Dessart, L. et al. 2008, ApJ 675, 644–669

Time-dependent, SN 1987A, 4 and 6 days



De, S., Baron, E. et al. 2010, MNRAS 401, 2081–2092, PHOENIX 1D

When the time dependence is important?

SN 1987A also supports the importance of time-dependent rate equations. Therefore, we conclude that time dependence is more important at early times than later times. The effect of multilevel atoms can be seen in Fig. 9 which clearly shows than even at later

De, S., Baron, E. et al. 2010, MNRAS 401, 2081–2092

Contradiction

Utrobin & Chugai Dessart & Hillier

Plateau phase

De & Baron

At early times

SE among l sublevels

2s, 2p ⇒ 2 - Super level

$$n_2 = n_{2s} + n_{2p}$$

$$n_{2s} = \frac{1}{4} n_2$$

$$n_{2p} = \frac{3}{4} n_2$$

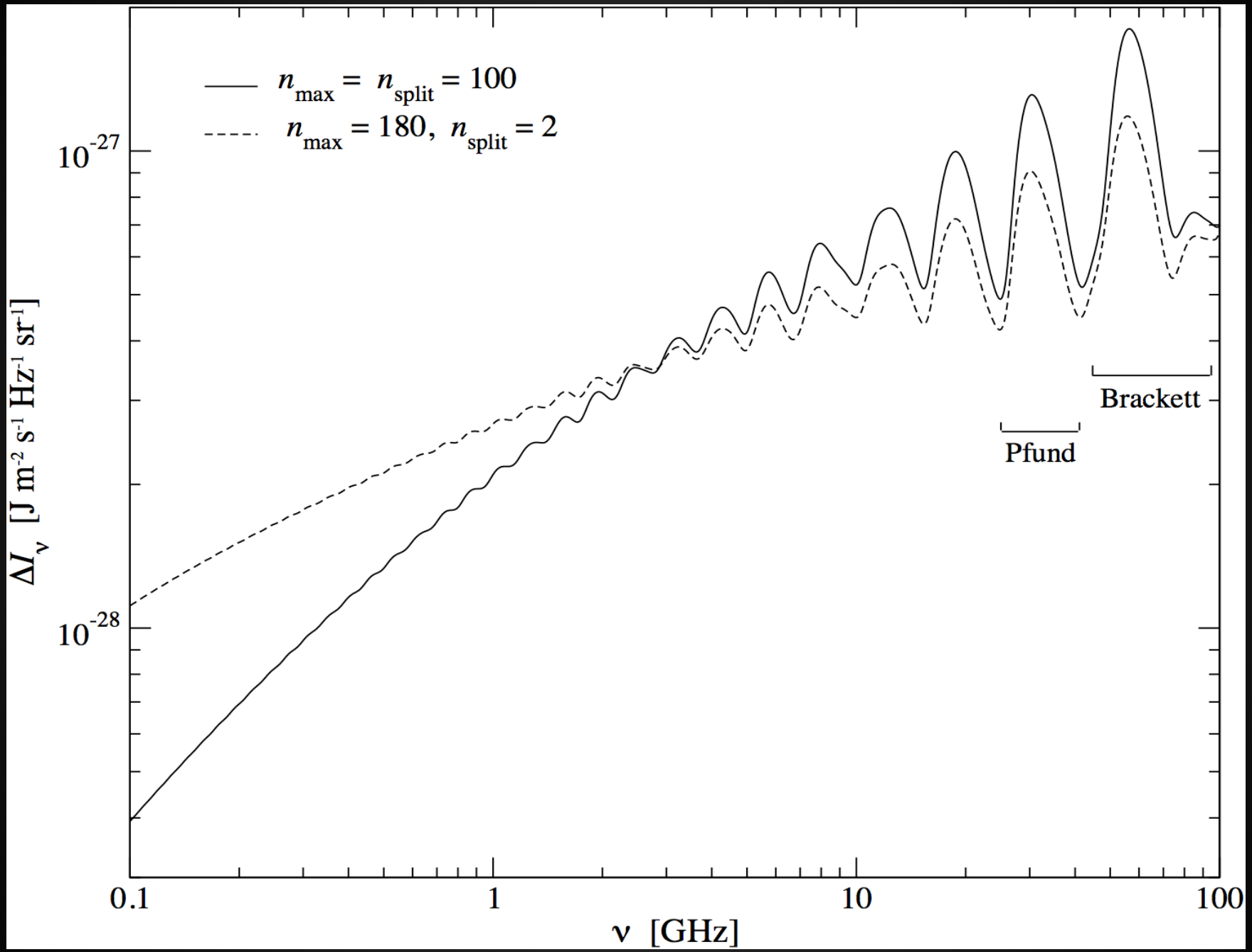
l - equilibrium

2s, 2p ⇒ **2** - Super level

$$n_2 = n_{2s} + n_{2p}$$

$$n_{2s} = \frac{1}{4} n_2$$

$$n_{2p} = \frac{3}{4} n_2$$


$n_{max} = n_{split} = 100$
$n_{max} = 180,\ n_{split} = 2$
10^{-27}
10^{-28}
ΔI_ν [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]
Pfund
Brackett
0.1
1
10
100
ν [GHz]

Importance of the
l-splitting

NO SE among
l sublevels

STELLA

STELLA

Hydrodynamics

Thermodynamics

Continuum

STELLA

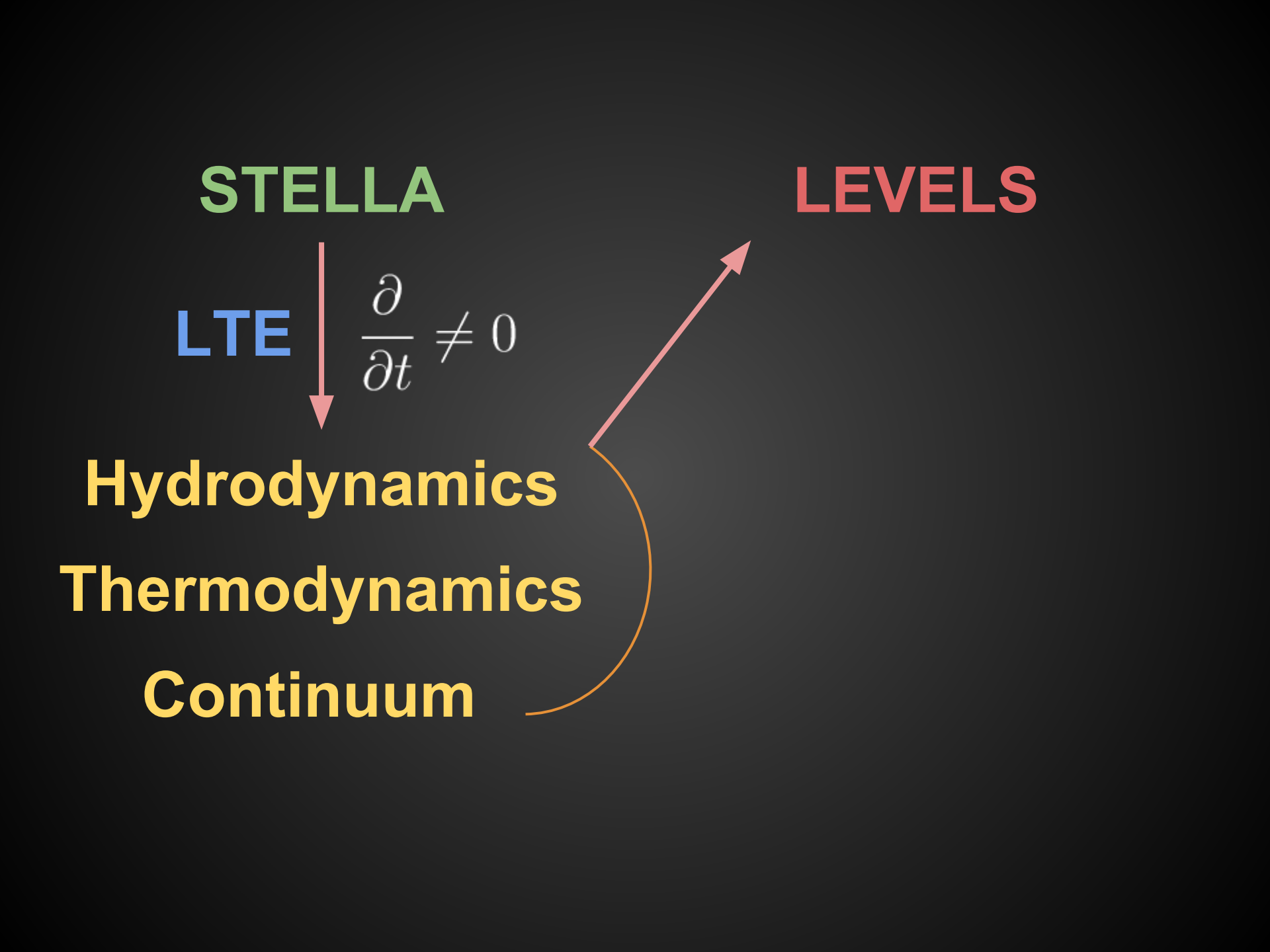
LTE

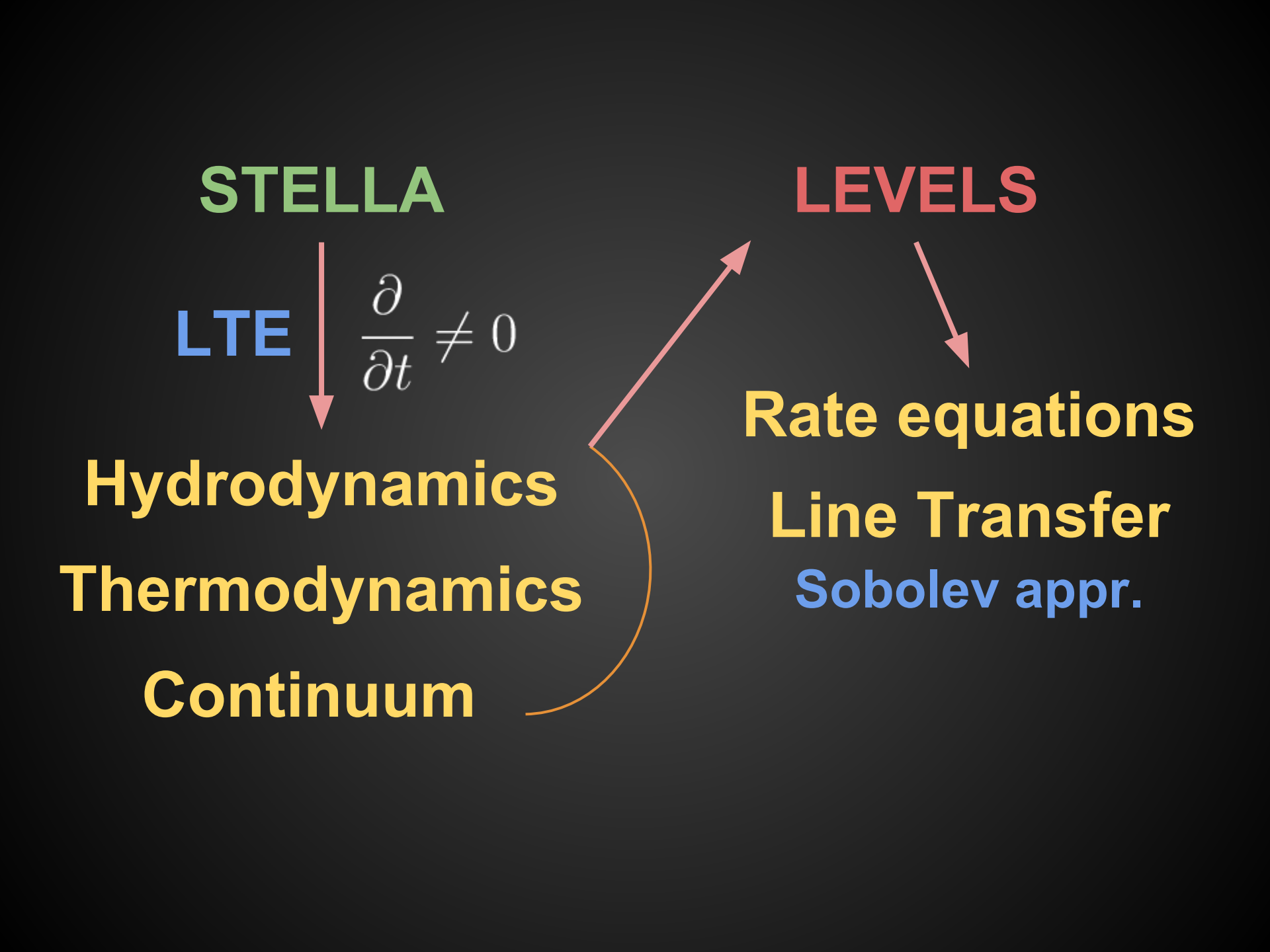
$$\frac{\partial}{\partial t} \neq 0$$

Hydrodynamics

Thermodynamics

Continuum


STELLA
LEVELS
LTE
$\frac{\partial}{\partial t} \neq 0$
Hydrodynamics
Thermodynamics
Continuum


STELLA
LEVELS
LTE
$\frac{\partial}{\partial t} \neq 0$
Hydrodynamics
Thermodynamics
Continuum
Rate equations
Line Transfer
Sobolev appr.

$$\frac{1}{c}\frac{DI_\nu}{Dt} + \mathbf{n}\cdot\nabla I_\nu - \frac{1}{c}\mathbf{n}\cdot\nabla\mathbf{u}\cdot\mathbf{n}\,\nu\frac{\partial I_\nu}{\partial\nu} - \frac{1}{c}\mathbf{n}\cdot\nabla\mathbf{u}\cdot(\ -\mathbf{nn})\cdot\nabla_{\mathbf{n}} I_\nu + \frac{3}{c}\mathbf{n}\cdot\nabla\mathbf{u}\cdot\mathbf{n}\,I_\nu = j_\nu - k_\nu I_\nu,$$

$$-\frac{1}{c}\mathbf{n}\cdot\nabla\mathbf{u}\cdot\mathbf{n}\,\nu\frac{\partial I_\nu}{\partial\nu} = j_\nu - k_\nu I_\nu.$$

$$\beta_{ul} = \frac{1 - \exp(-\tau_{lu})}{\tau_{lu}},$$

where

$$\tau_{lu} = \frac{\pi e^2}{m_e c} f_{lu} \lambda_{lu} t \left(N_l - \frac{g_l}{g_u} N_u \right)$$

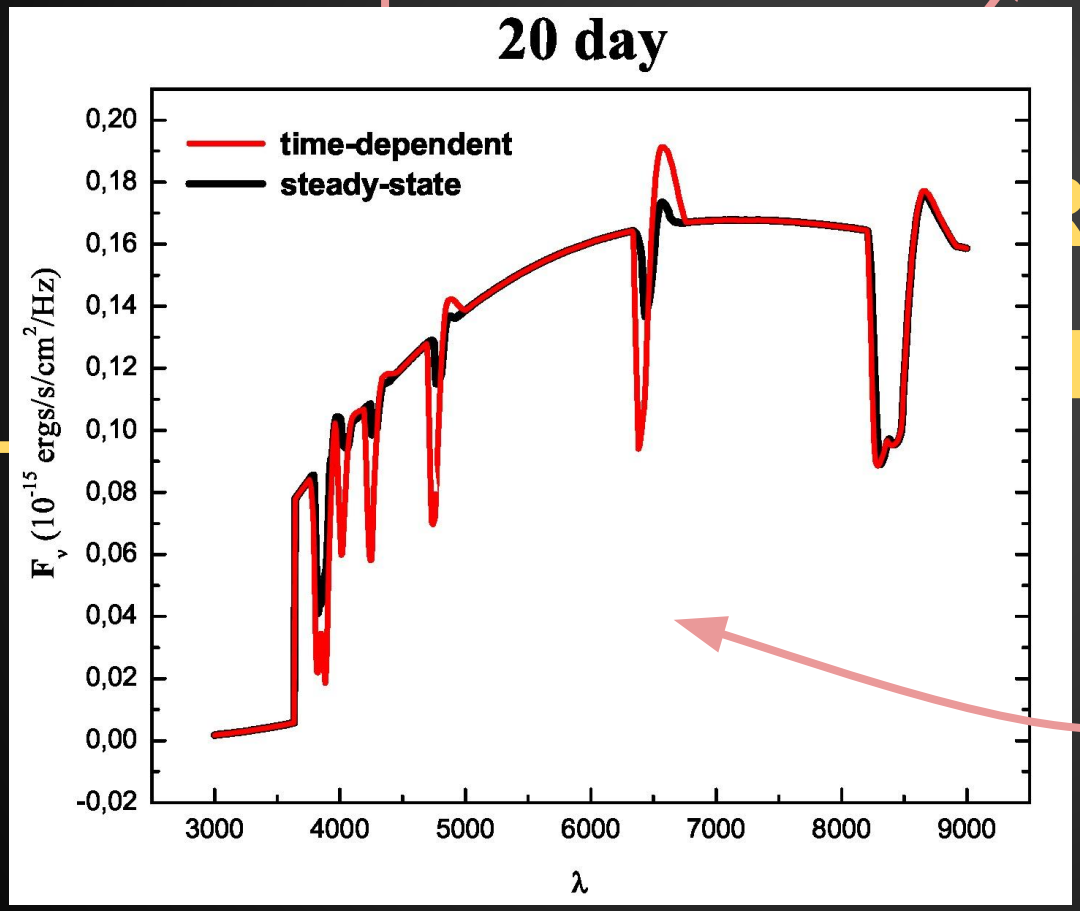
$$J_{lu} = (1 - \beta_{ul}) S_{lu} + \beta_{ul} J(\nu_{lu}),$$

where

$$S_{lu} = \frac{2h\nu_{lu}^3}{c^2} \left(\frac{g_u N_l}{g_l N_u} - 1 \right)^{-1}$$

STELLA

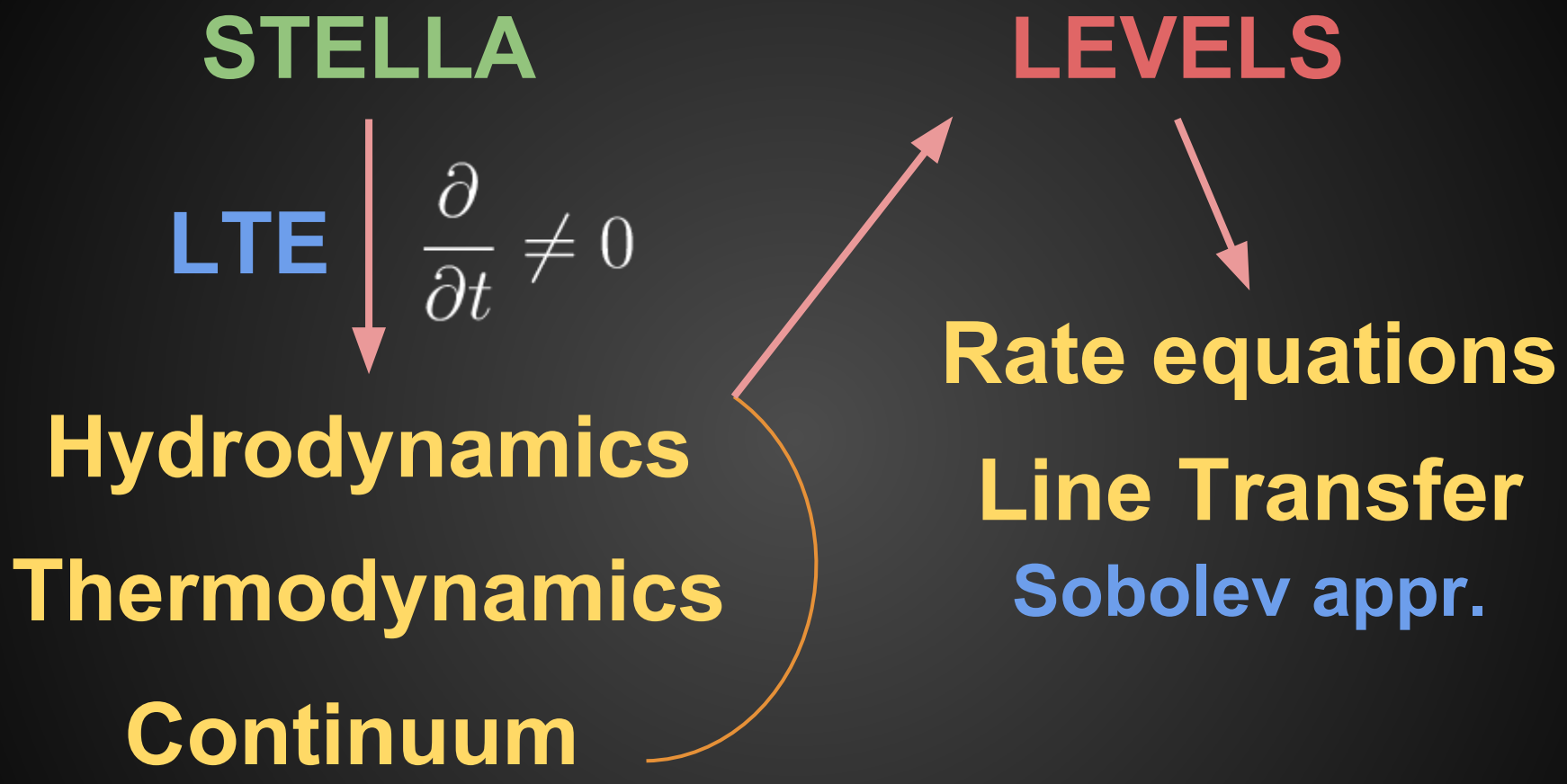
LEVELS



Rate equations

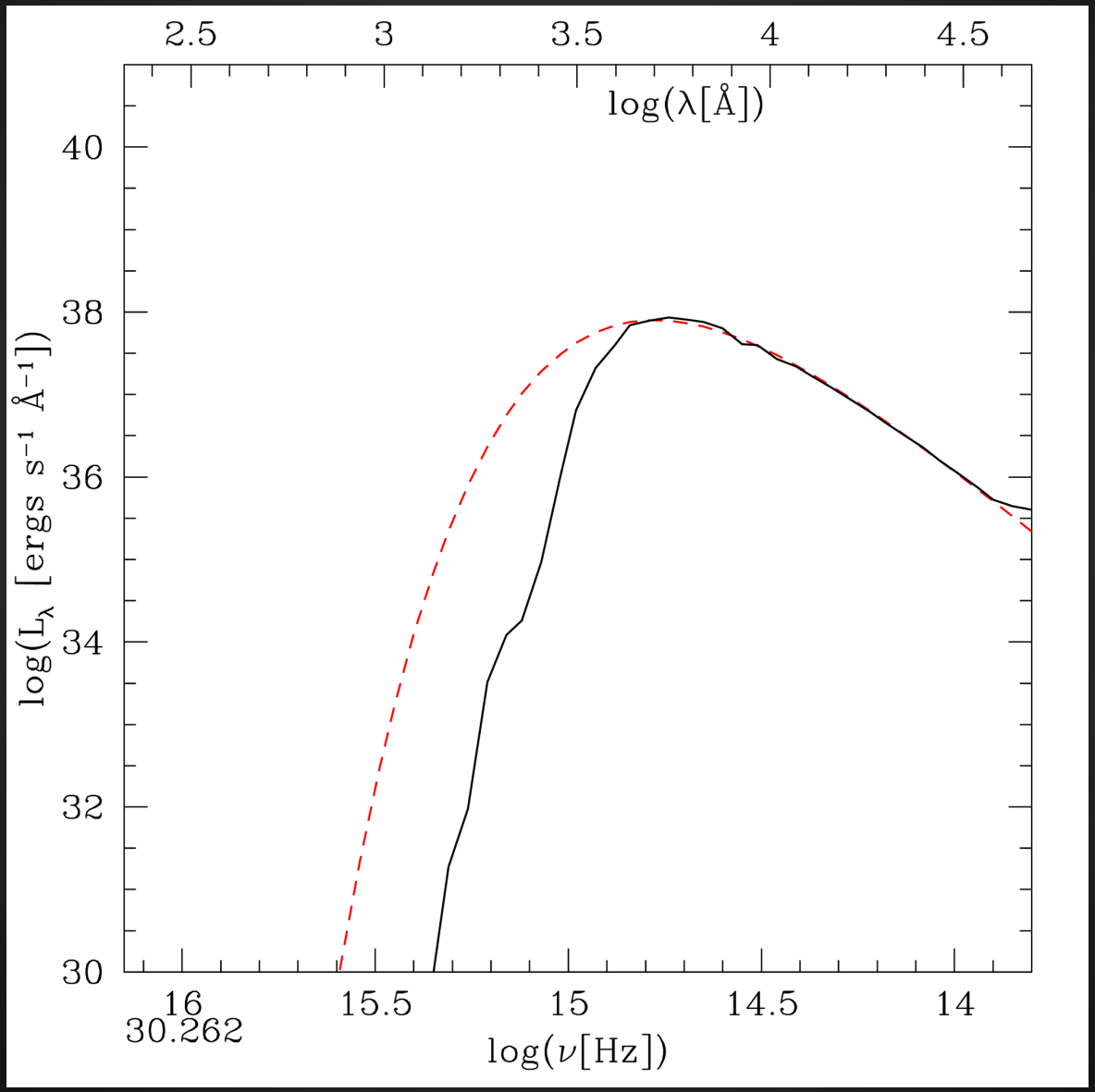
Line Transfer

Sobolev appr.

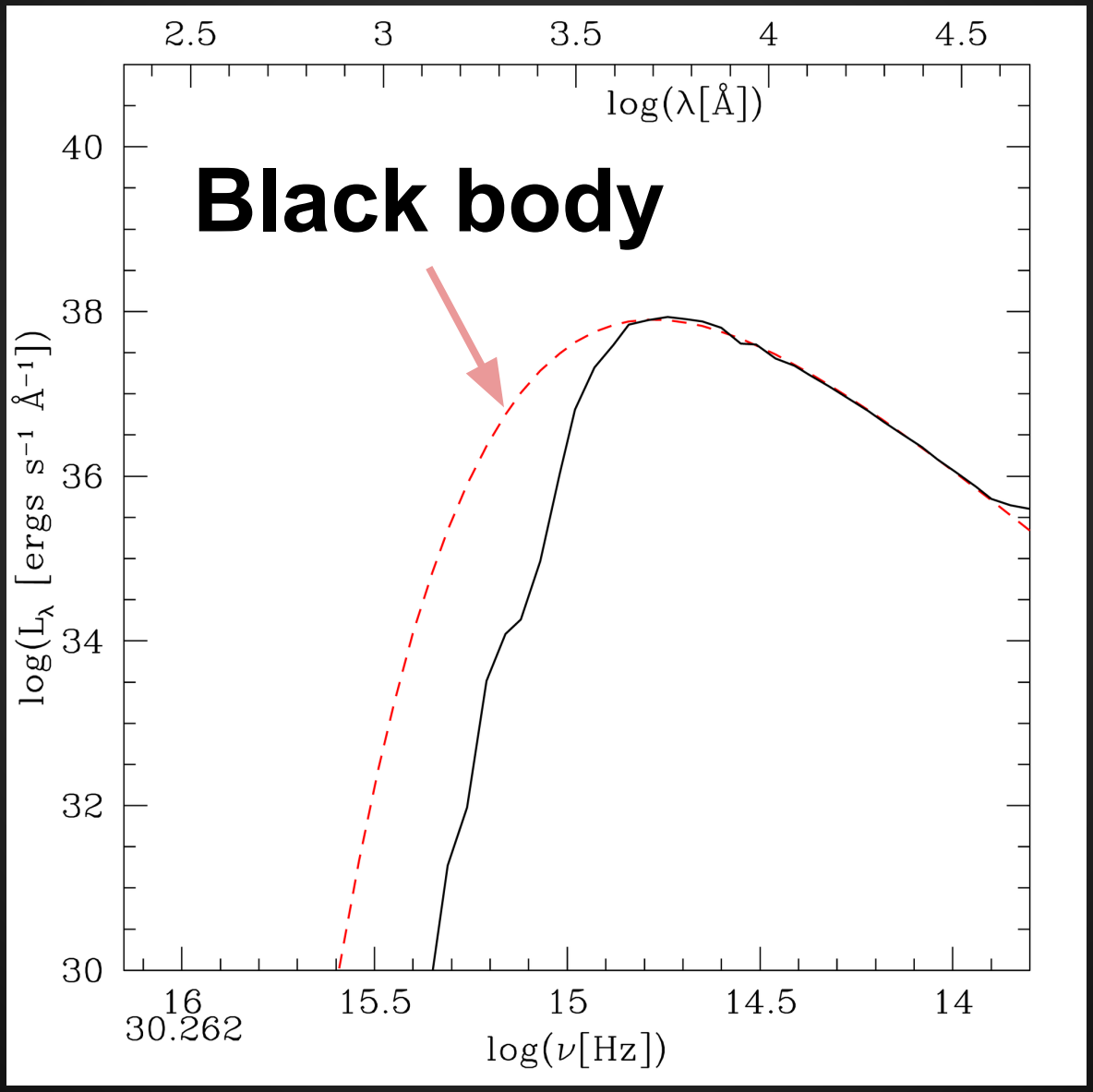


no self-consistent continuum!

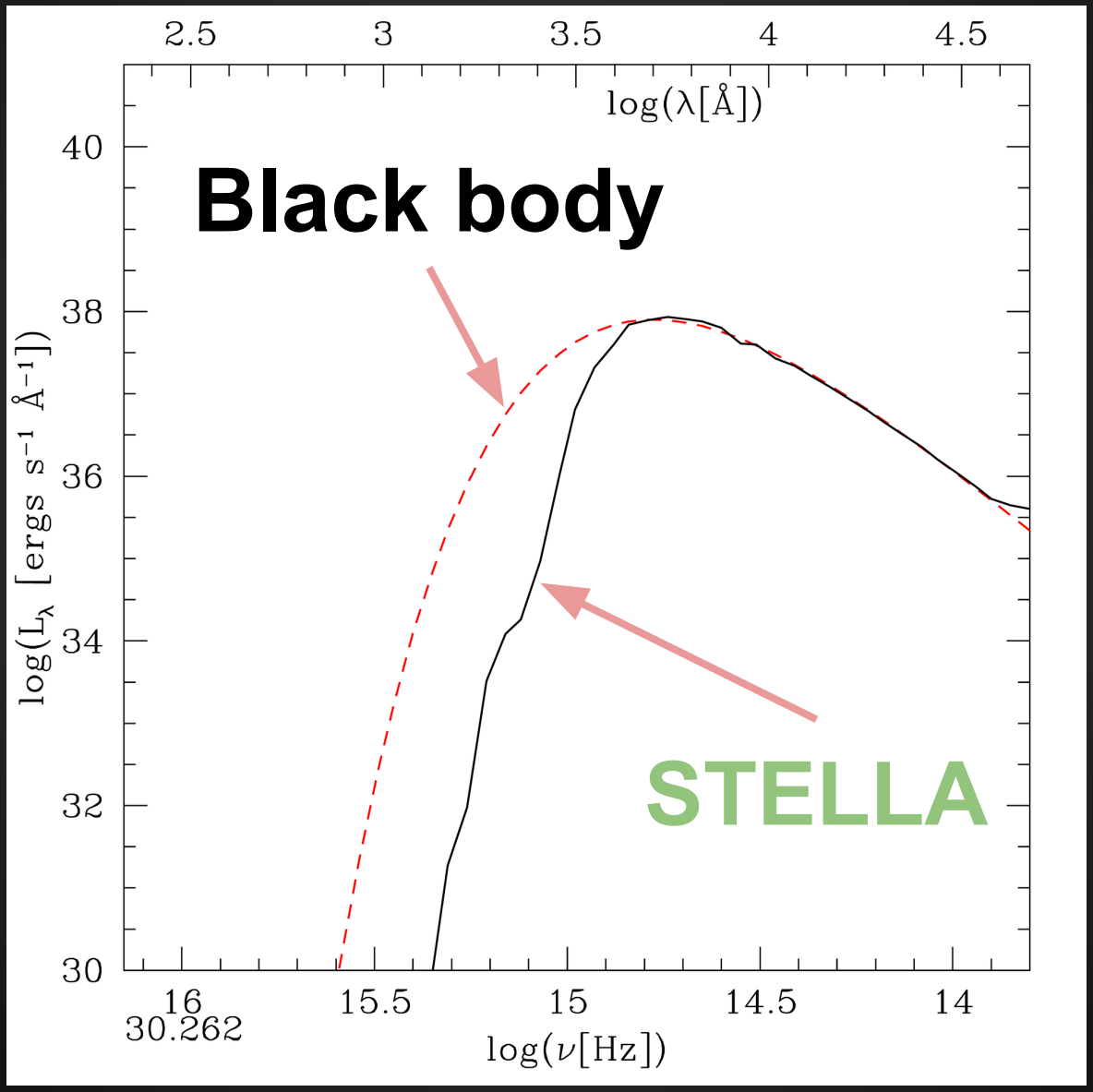
Continuum radiation



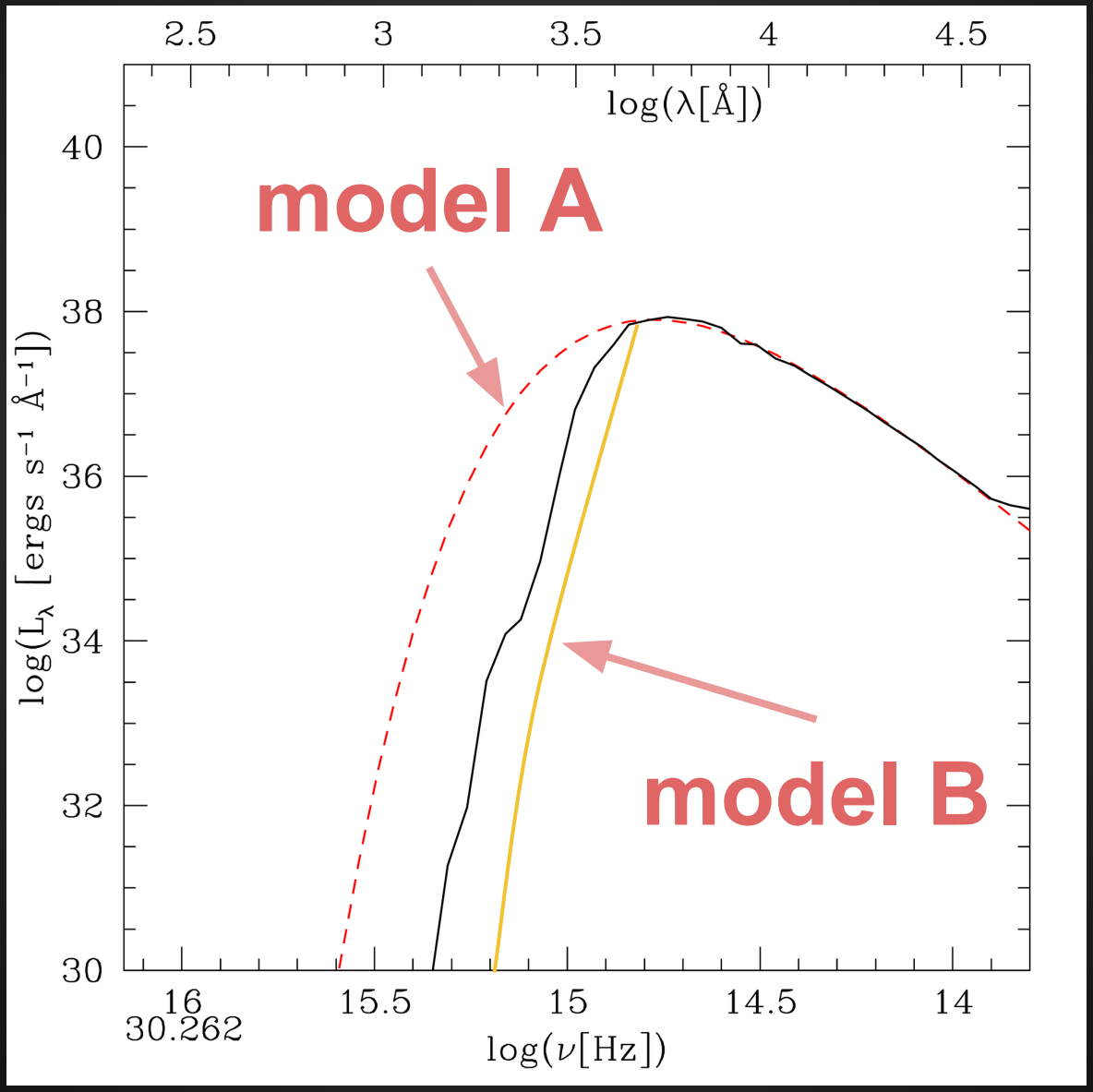
Continuum radiation



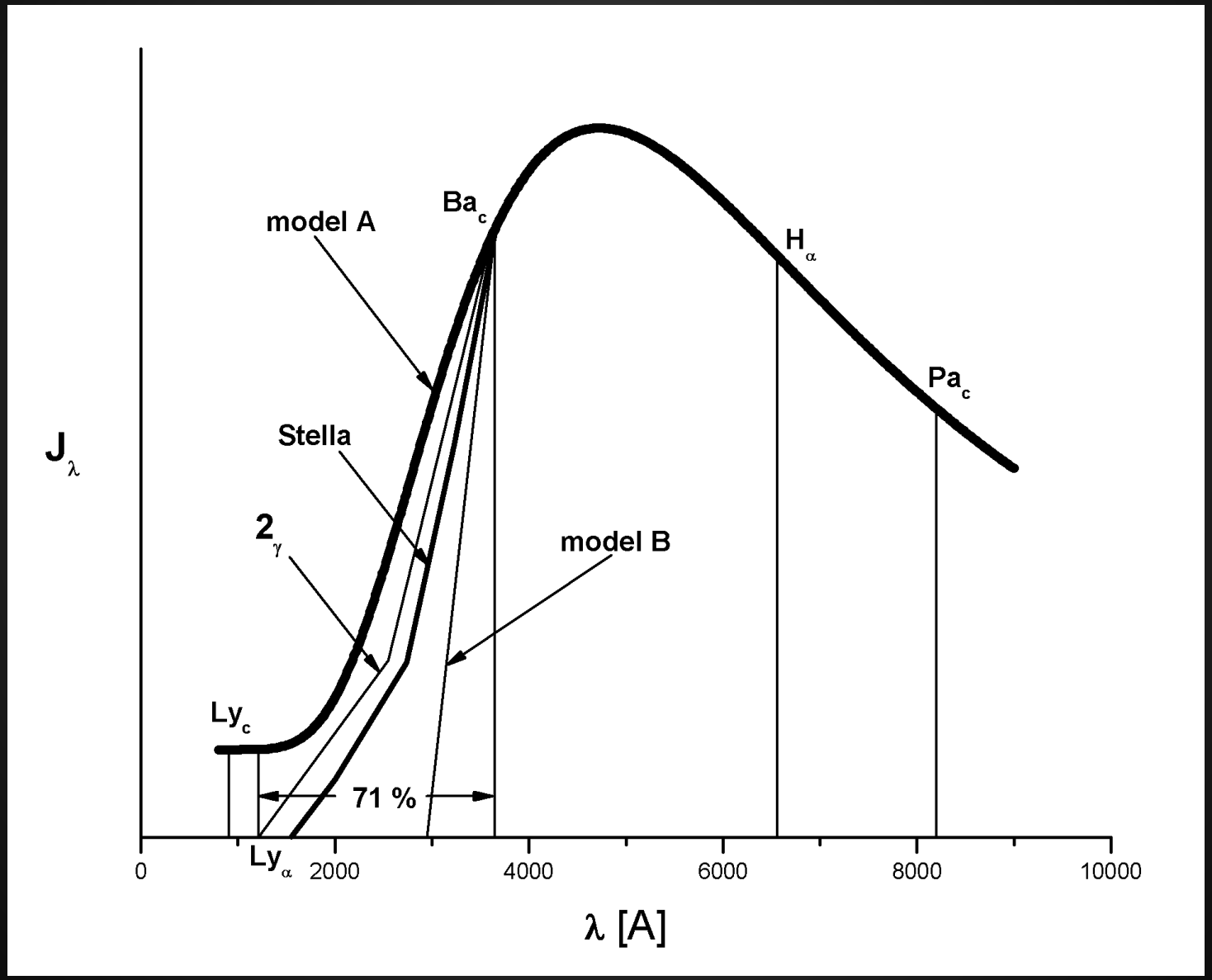
Continuum radiation



Continuum radiation



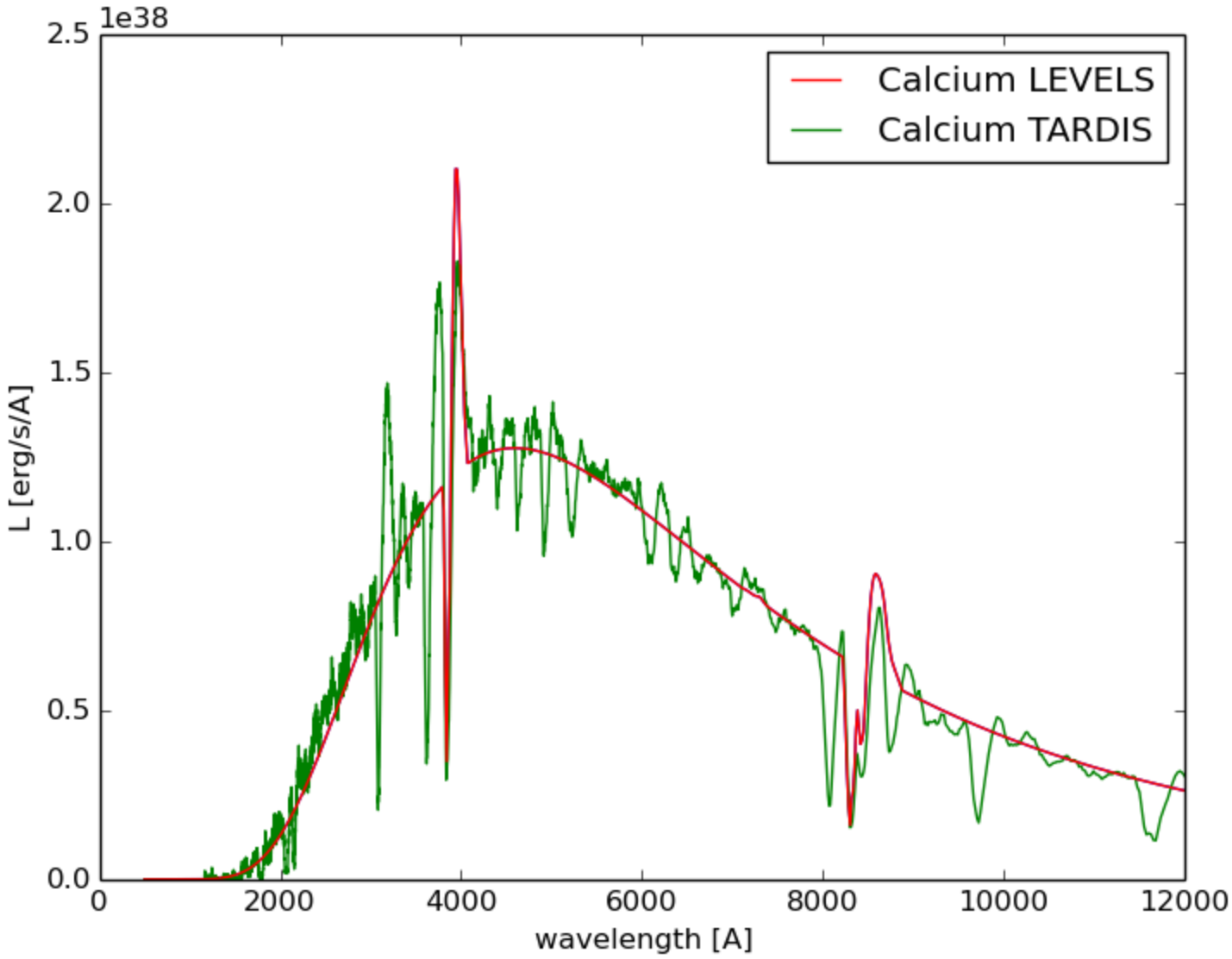
Continuum radiation

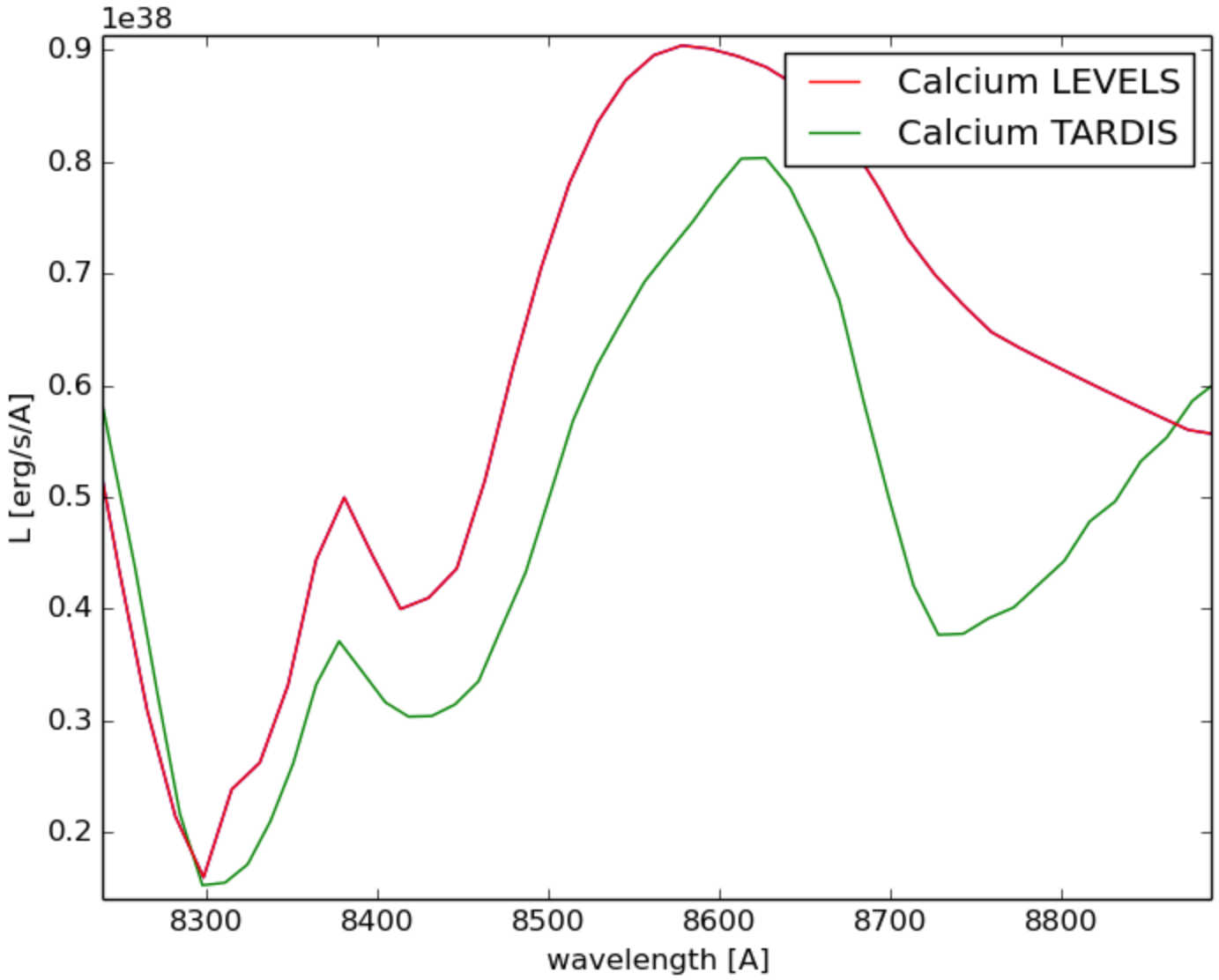


Continuum radiation

TARDIS

Kerzendorf, W. E. & Sim, S. A. A spectral synthesis code for rapid modelling of supernovae. Mon. Not. R. Astron. Soc. 440, 387–404 (2014).


1e38
2.5
2.0
1.5
1.0
0.5
0.0
L [erg/s/A]
0
2000
4000
6000
8000
10000
12000
wavelength [A]
Calcium LEVELS
Calcium TARDIS


1e38
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
L [erg/s/A]
8300
8400
8500
8600
8700
8800
wavelength [A]
Calcium LEVELS
Calcium TARDIS

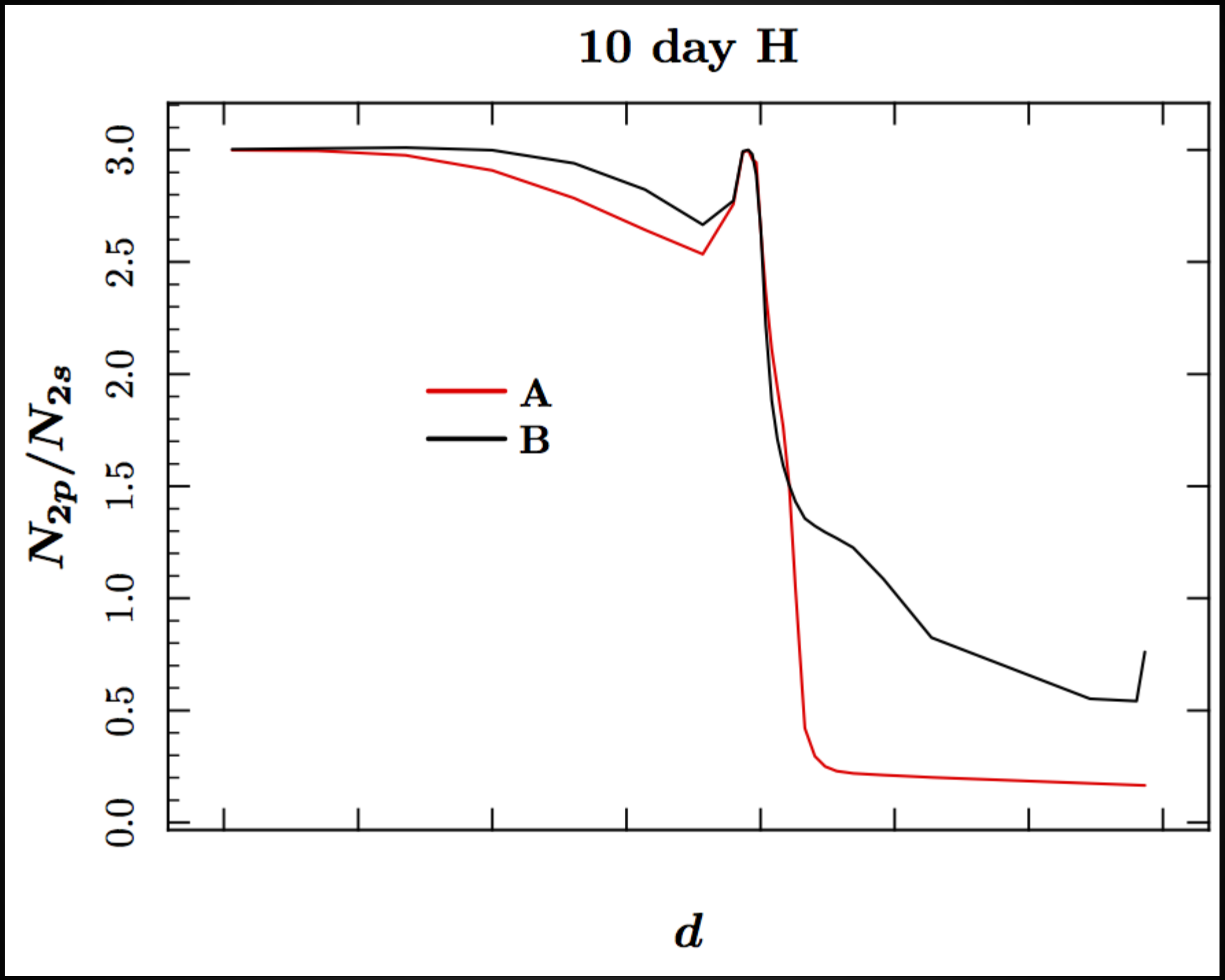
$$
\begin{aligned}
\left[\frac{\partial n_{\mathrm{z},\,i}}{\partial t}\right]^{to} &= \sum_{m<i}(n_{\mathrm{z},m}A_{im} + n_{\mathrm{z},i}B_{im}J_{mi} - n_{\mathrm{z},m}B_{mi}J_{mi}) \\
&- \sum_{k>i}(n_{\mathrm{z},k}A_{ki} + n_{\mathrm{z},k}B_{ki}J_{ik} - n_{\mathrm{z},i}B_{ik}J_{ik}) \\
&+ n_{\mathrm{z},i}n_{\mathrm{e}}\sum_{k\neq i}C_{ik} + n_{\mathrm{z},i}(B_{ic}J_{ic} + n_{\mathrm{e}}C_{ic}) \\
&- n_{\mathrm{e}}\sum_{k\neq i}n_{\mathrm{z},k}C_{ik} + n_{\mathrm{e}}n_{\mathrm{z}}^{+}(A_{ci} + B_{ci}J_{ci} + n_{\mathrm{e}}C_{ci})\ ,\ i = 2,3\ldots \quad (2)
\end{aligned}
$$

$$\bar{J} = \frac{1}{4\pi} \int d\Omega I^{\text{inc}} \frac{1 - e^{-\tau_L}}{\tau_L} + S_L(1 - P_S) + (S_C - S_L) \frac{1}{4\pi} \int d\Omega U\left(\frac{1}{\tau_L}, \beta\right)$$

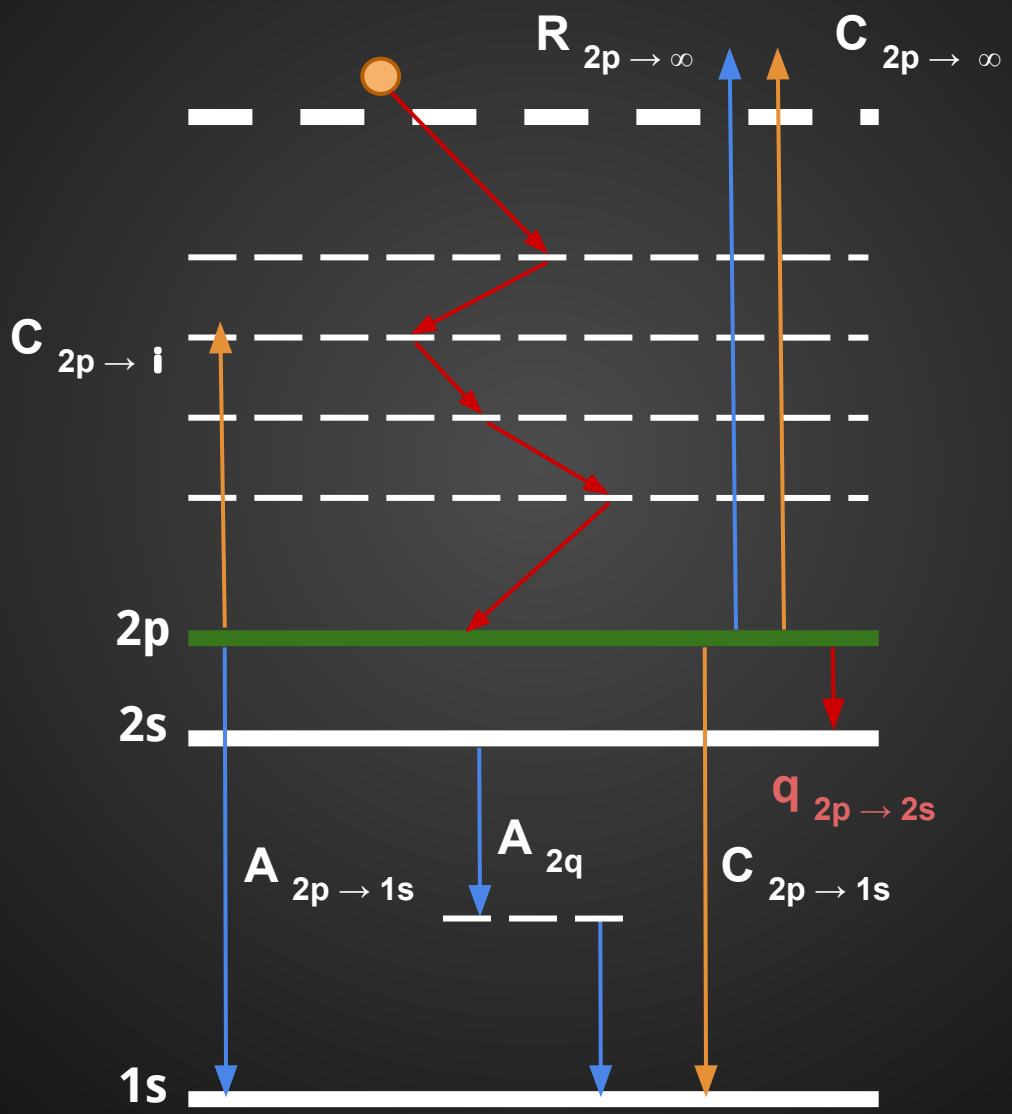
The Flexible Atomic Code (FAC)

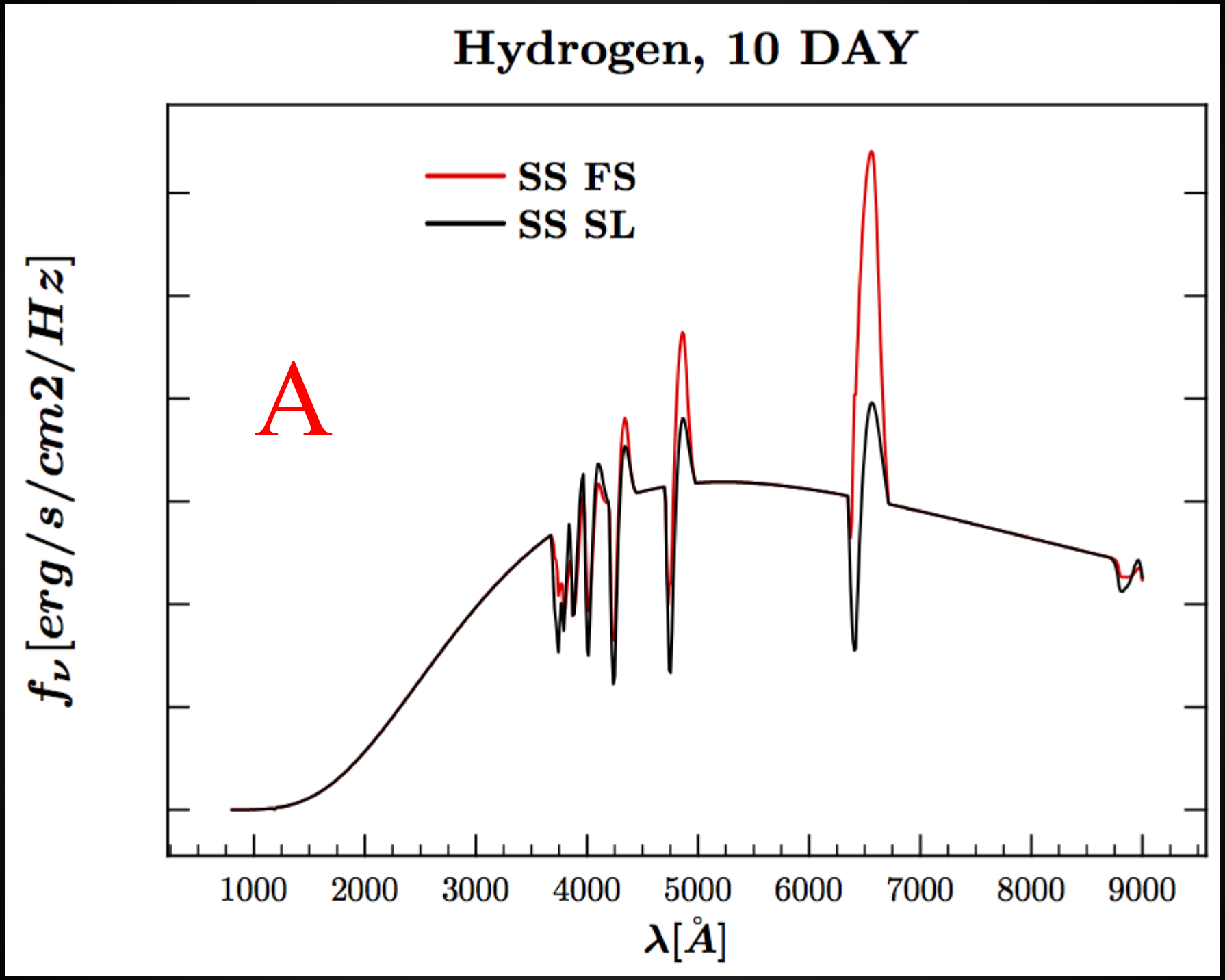
Ming Feng Gu

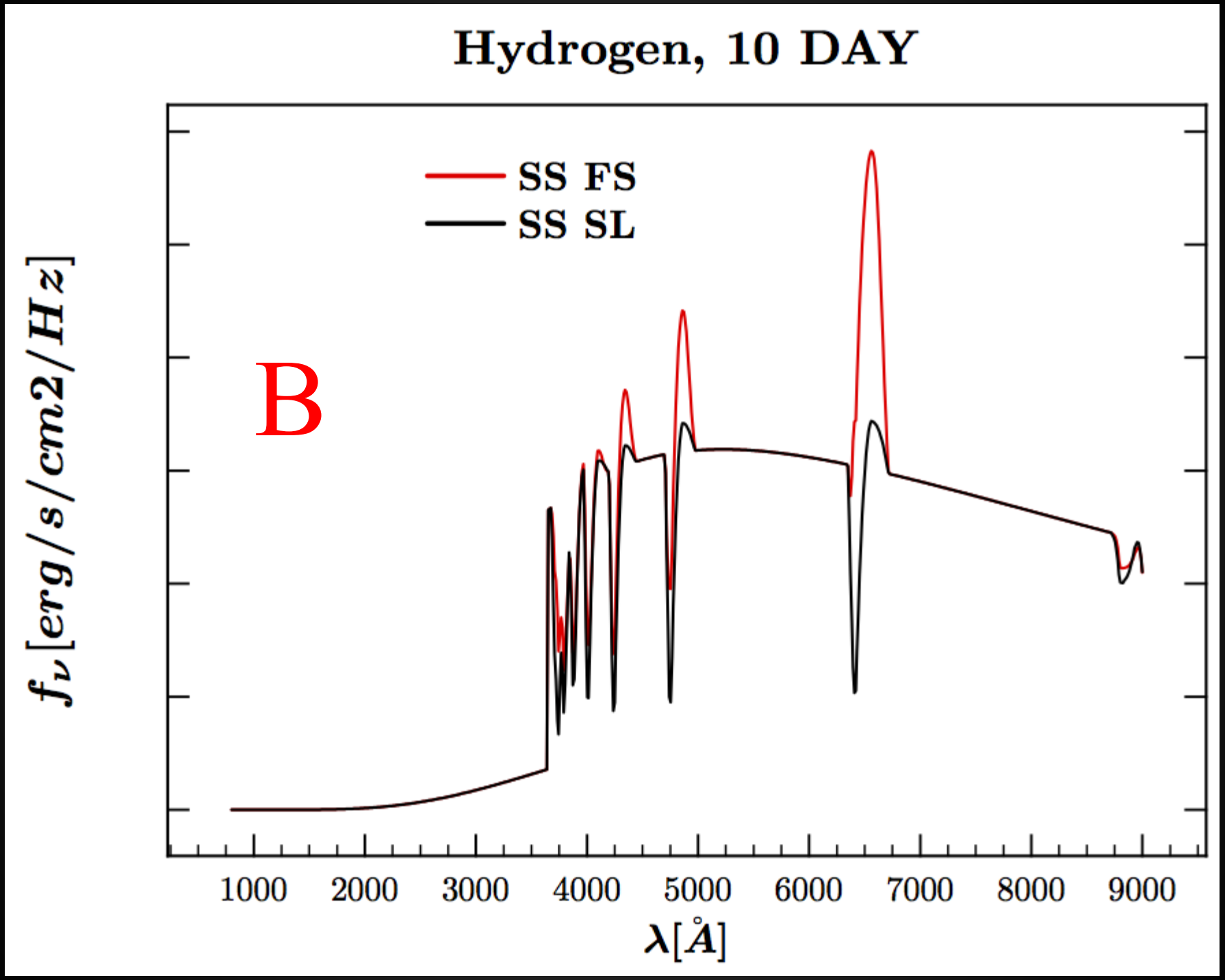
Hydrogen star
up to n = 10
100 level + continuum

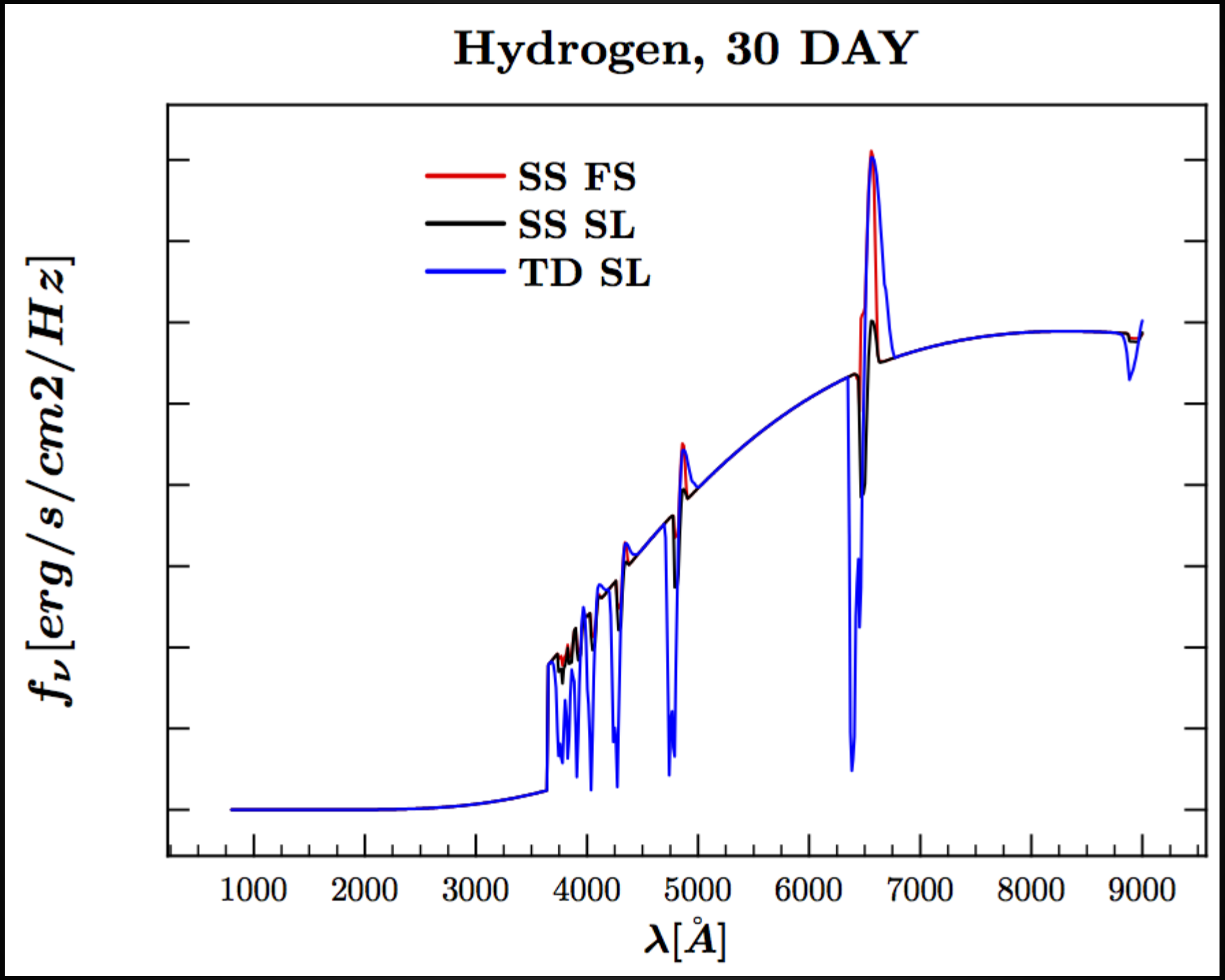

10 day H
N_{2p}/N_{2s}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
A
B
d

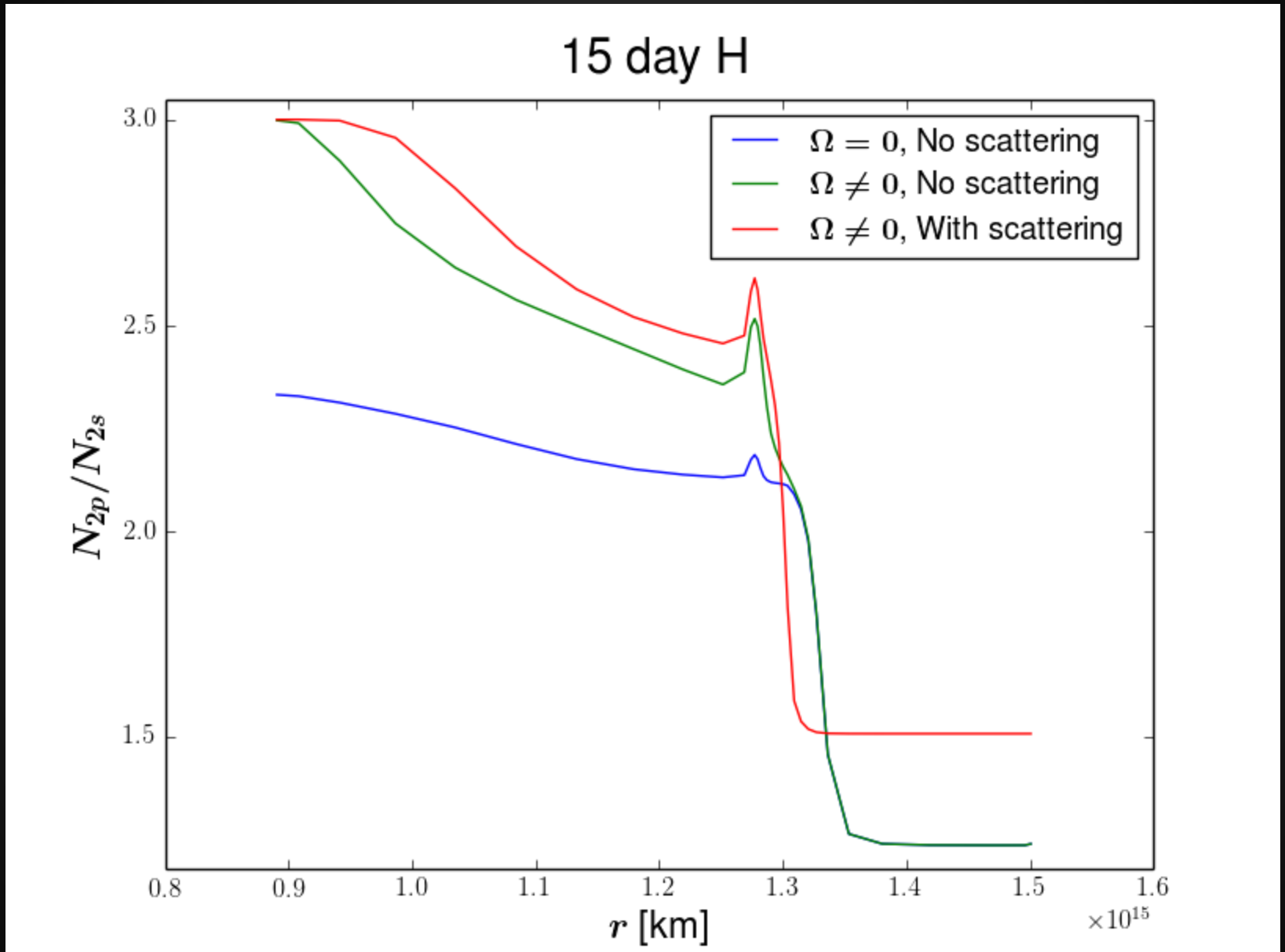
Hydrogen




Hydrogen, 10 DAY
SS FS
SS SL
A
$f_\nu [erg/s/cm2/Hz]$
1000
2000
3000
4000
5000
6000
7000
8000
9000
$\lambda[\AA]$


Hydrogen, 10 DAY
SS FS
SS SL
B
$f_\nu [erg/s/cm2/Hz]$
1000
2000
3000
4000
5000
6000
7000
8000
9000
$\lambda[\AA]$


Hydrogen, 30 DAY
SS FS
SS SL
TD SL
$f_\nu [erg/s/cm2/Hz]$
1000
2000
3000
4000
5000
6000
7000
8000
9000
$\lambda[\AA]$


15 day H
$\Omega = 0$, No scattering
$\Omega \neq 0$, No scattering
$\Omega \neq 0$, With scattering
N_{2p}/N_{2s}
3.0
2.5
2.0
1.5
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
r [km]
$\times 10^{15}$