Non-trivial effects of time-dependent level populations in SNe II atmospheres

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Blinnikov S. I.
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September 9, 2013, SCOPES

Main idea

STELLA

Main idea

STELLA

↓

Hydrodynamics

Thermodynamics

Continuum

Main idea

STELLA

LTE

Hydrodynamics

Thermodynamics

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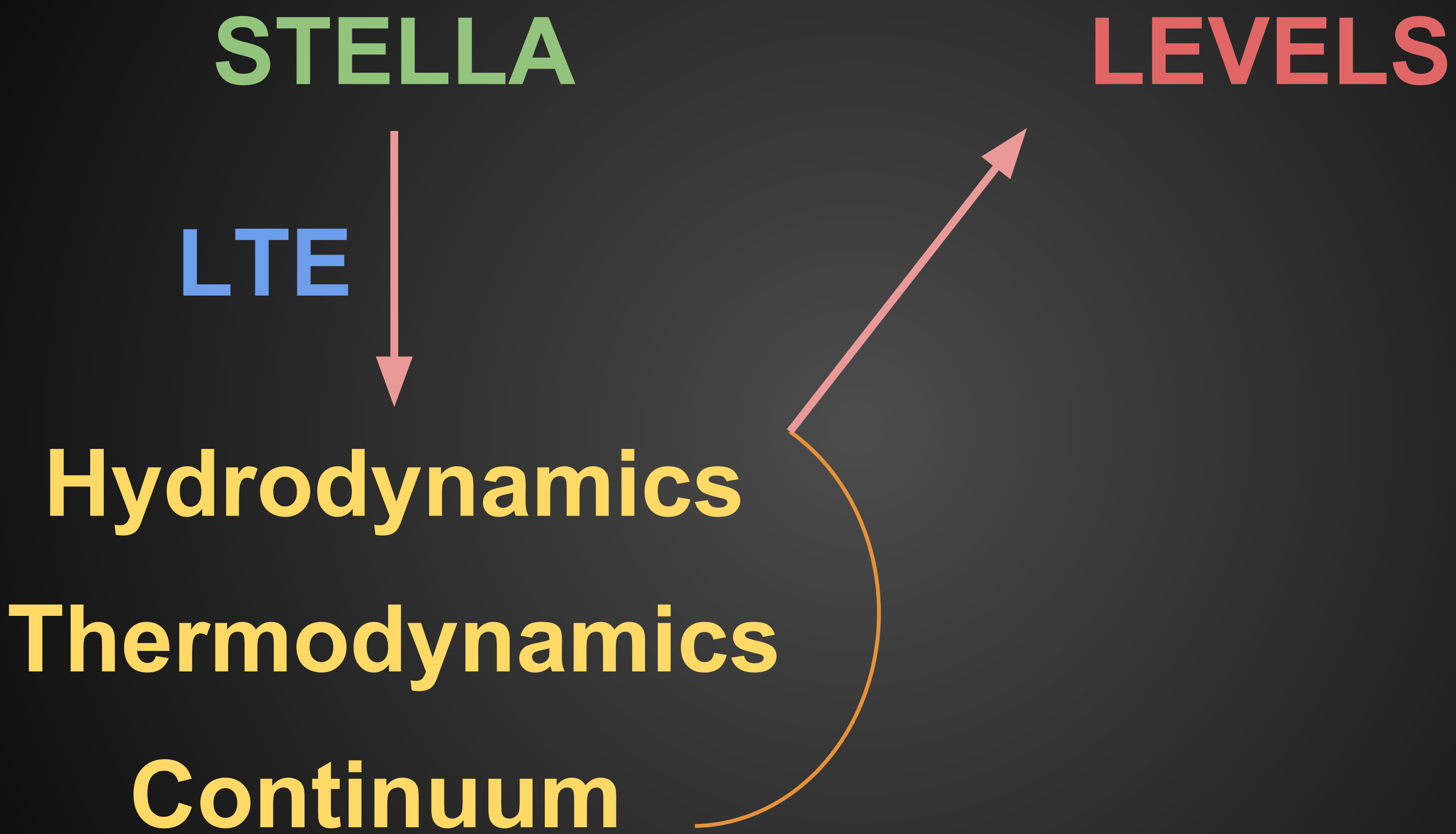
Main idea


STELLA
LEVELS
LTE
Hydrodynamics
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Main idea

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LEVELS

Rate equations

Line Transfer

Sobolev appr.

Main idea

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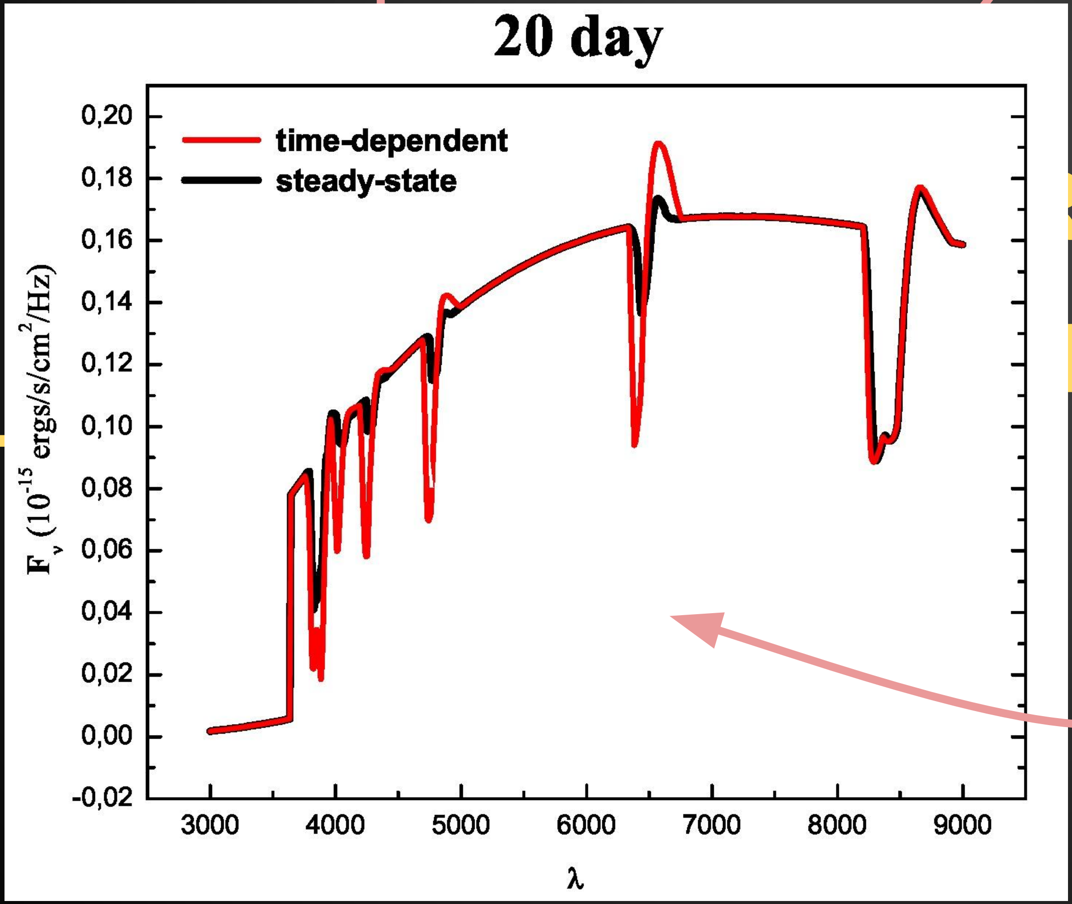

Main idea

STELLA

LTE

Hydrodynamics

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LEVELS

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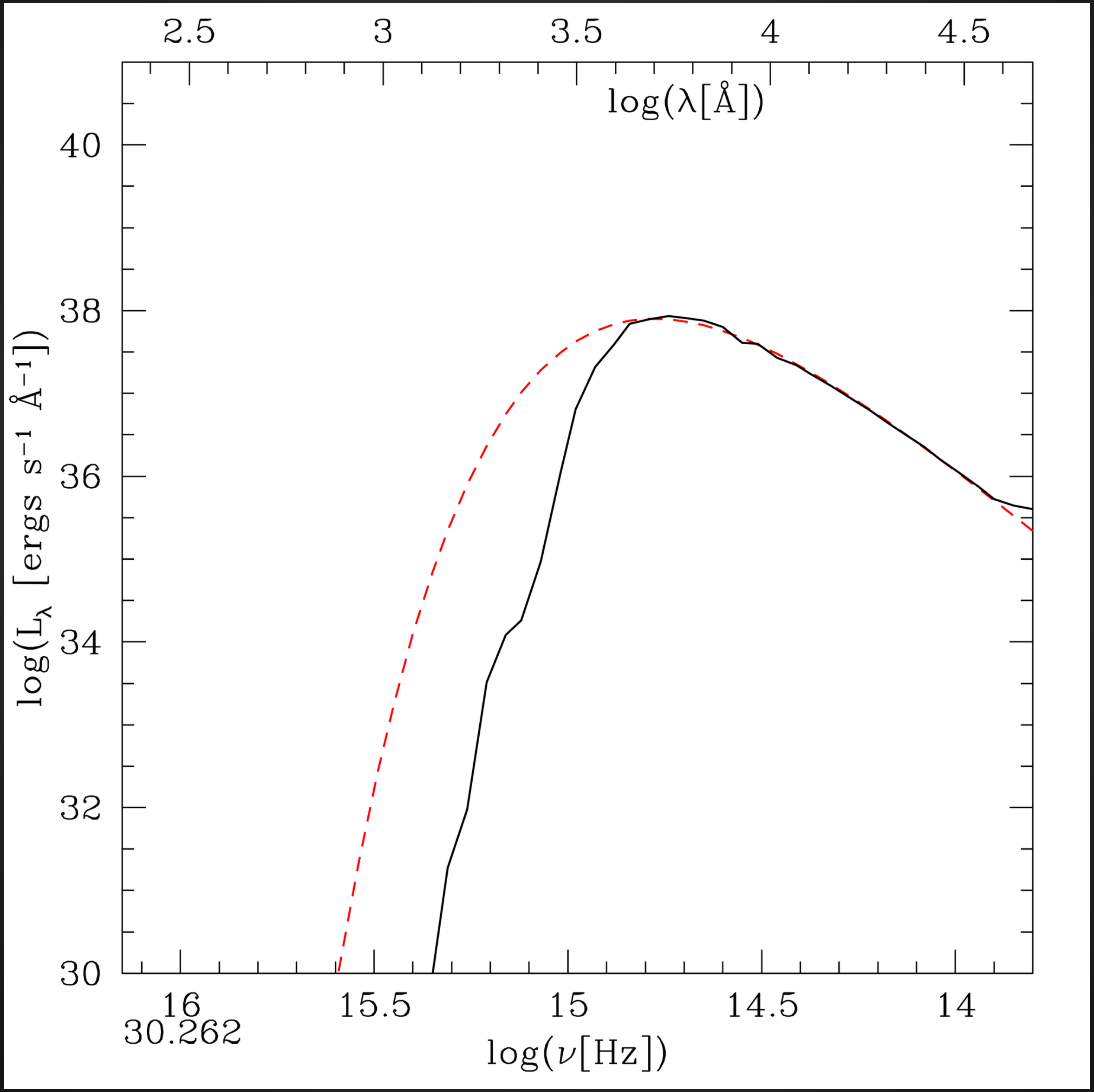
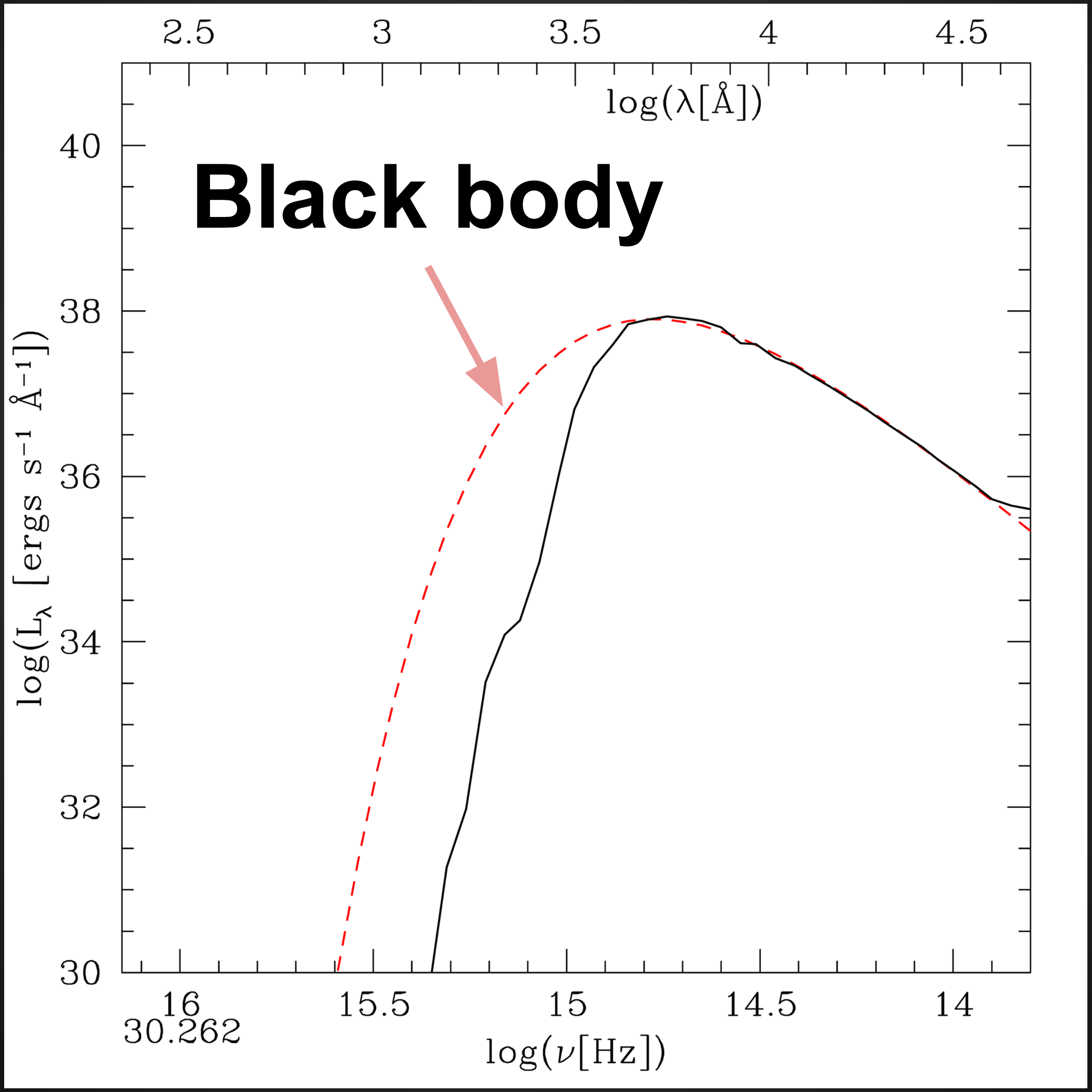
no self-consistent continuum!

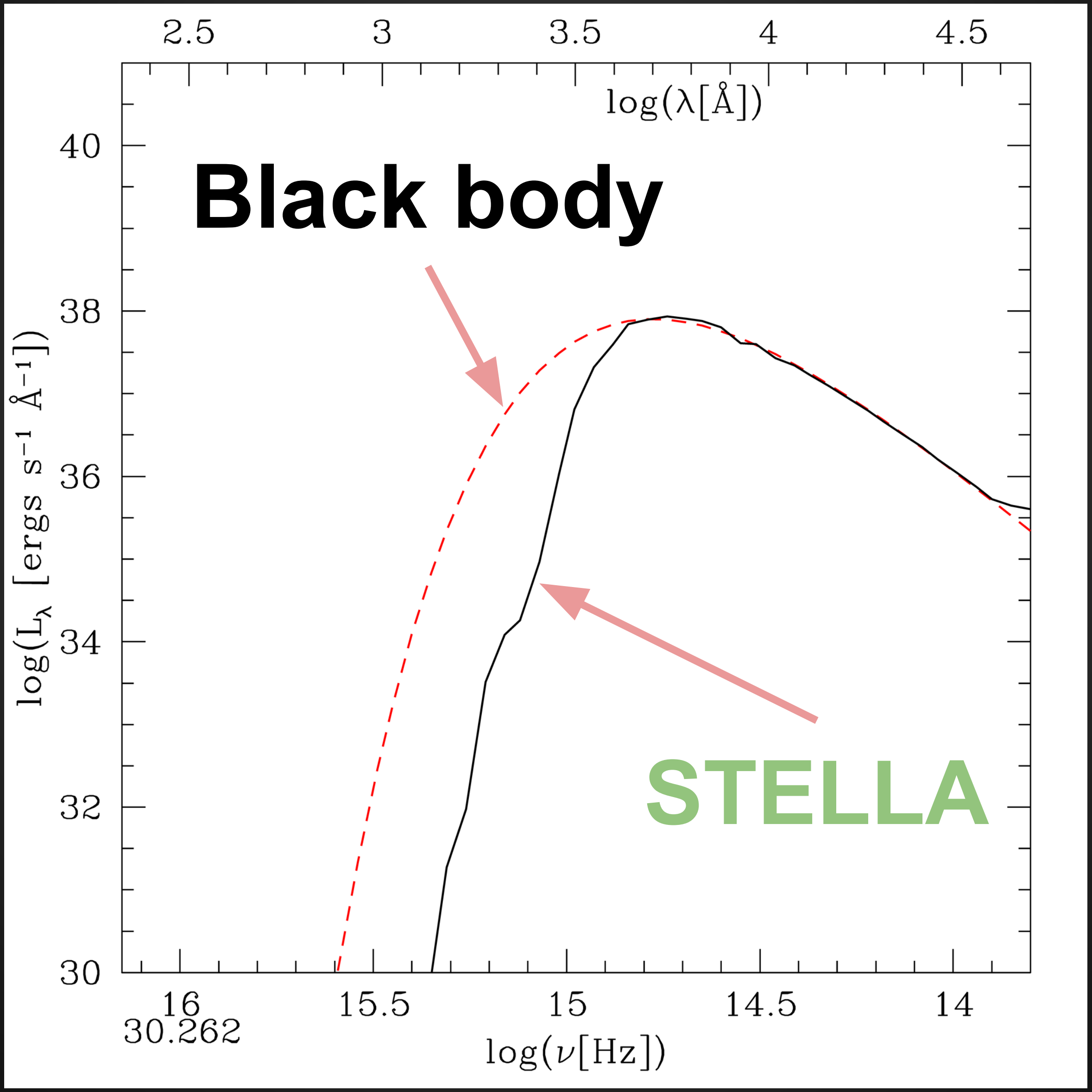
Continuum radiation



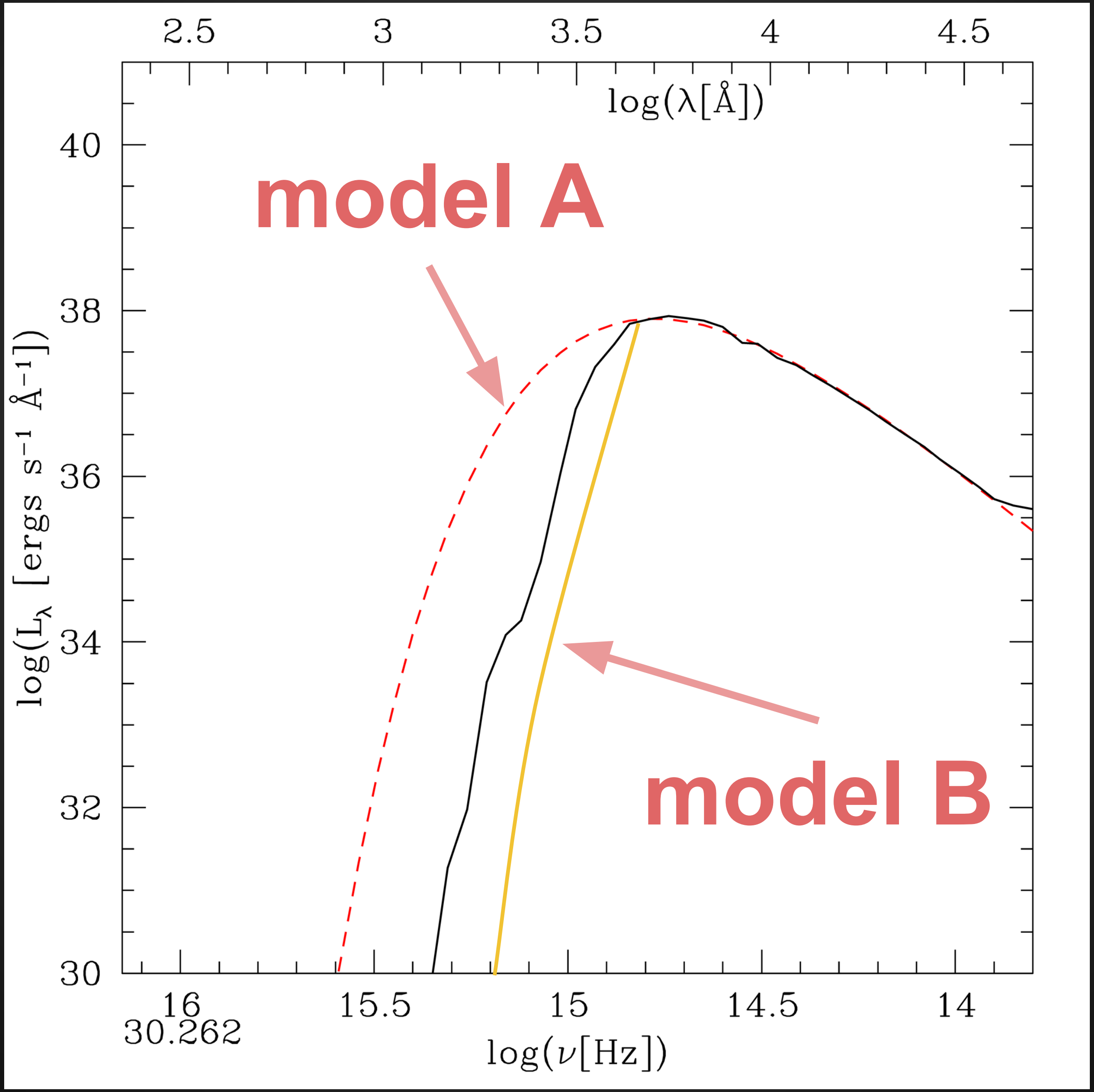
Continuum radiation



Continuum radiation



Continuum radiation



Rate equations

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

Rate equations

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time-dependent

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

Rate equations

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Rate equations

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time-dependent

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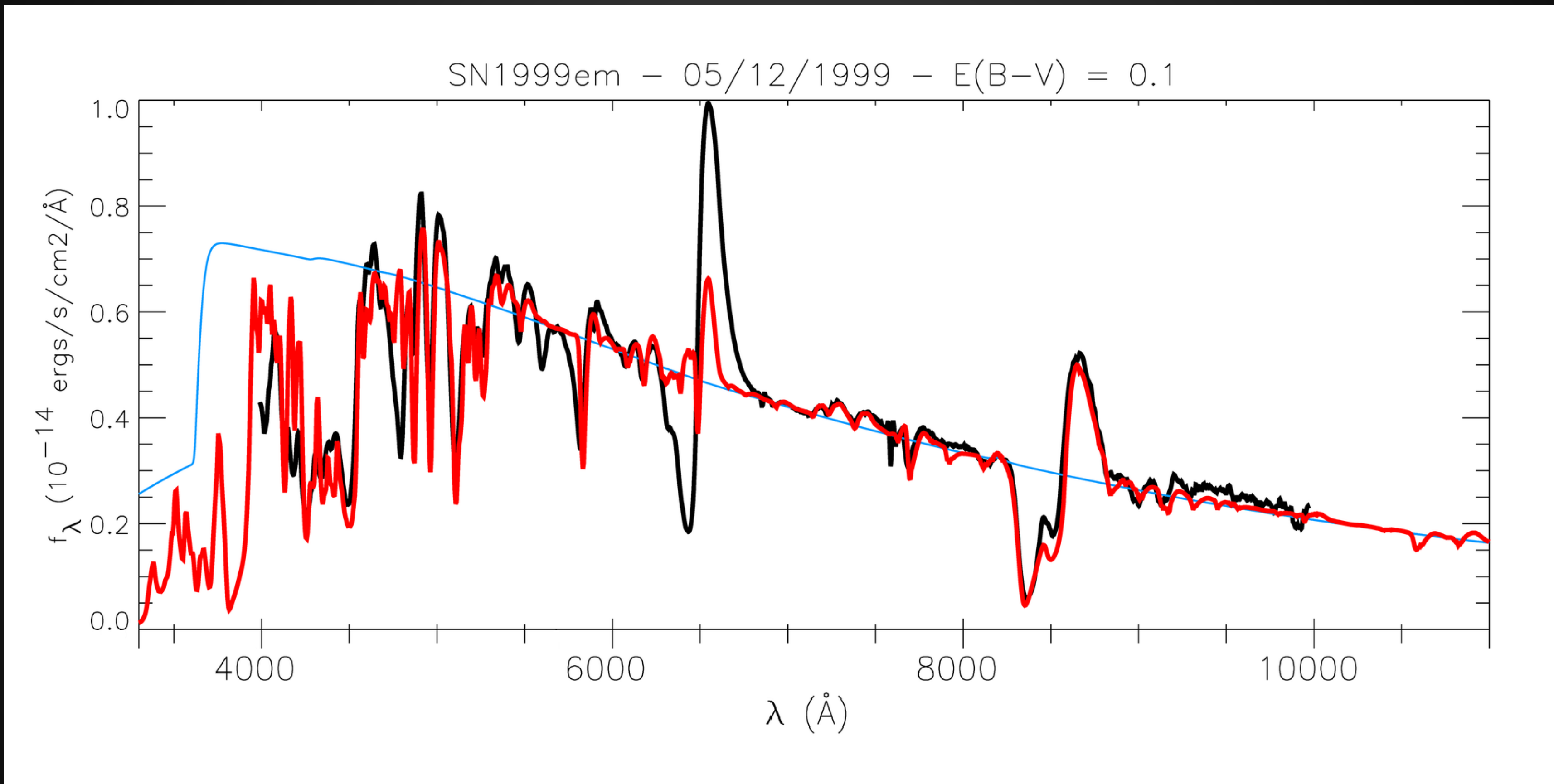
steady-state approximation

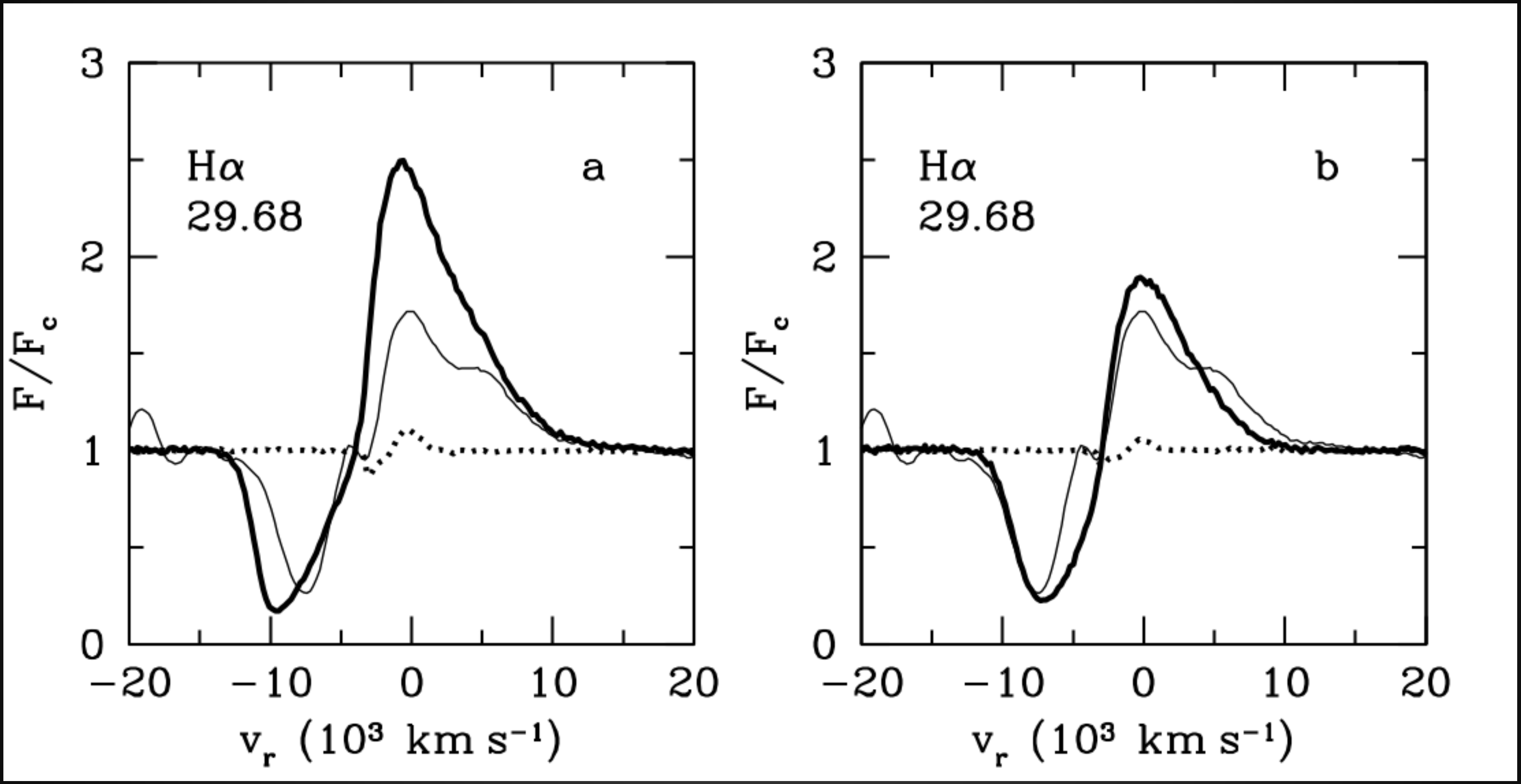
$$\sum_{j \neq i} (n_{z,j} P_{j,i} - n_{z,i} P_{i,j}) = 0$$

Weak line H-α, SN 1999em, 37 day



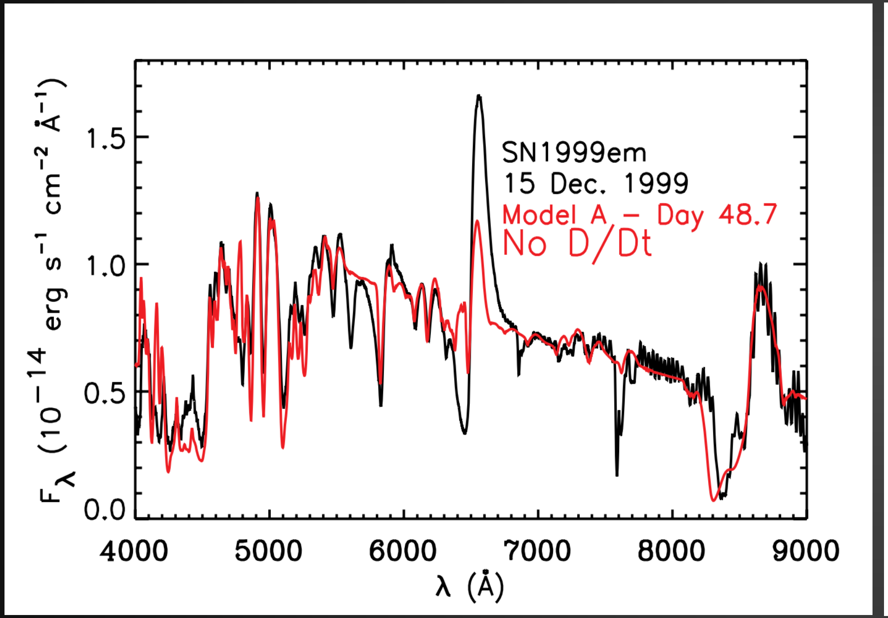
Dessart, L., Hillier, J. 2006, A&A 447, 691–707, CMFGEN

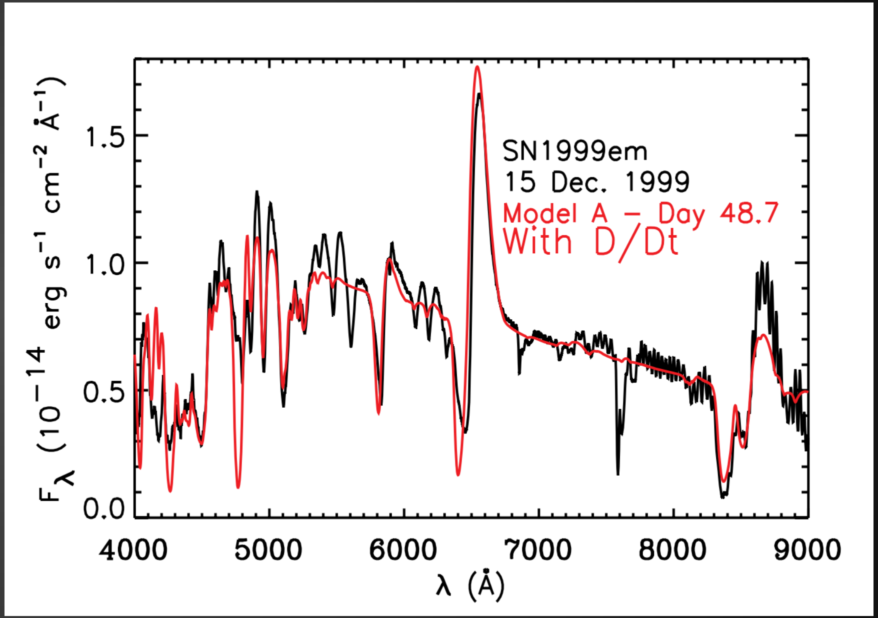
Time-dependent, SN 1987A, ~30 day



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

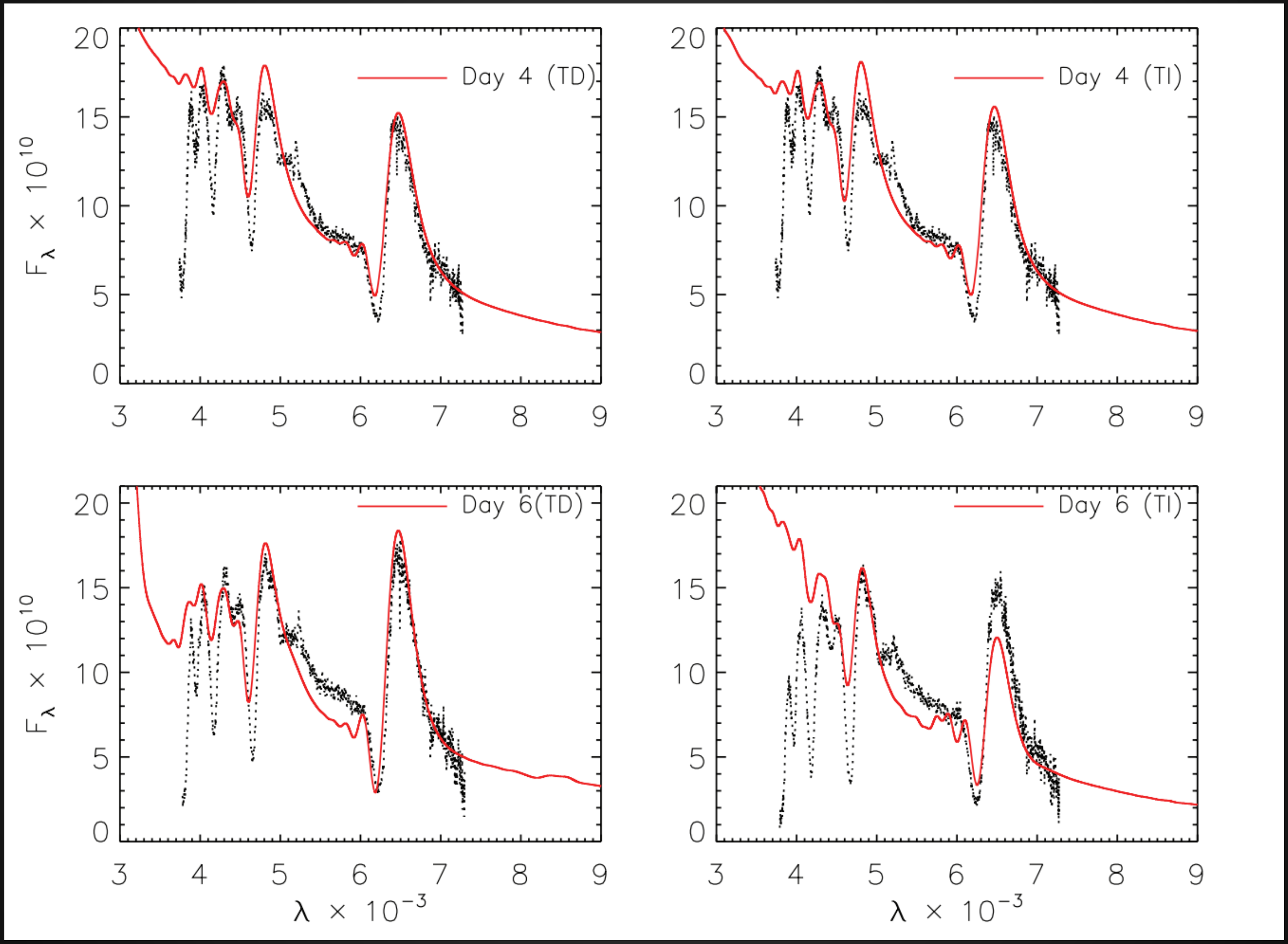
Time-dependent, SN 1999em, 48 day





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

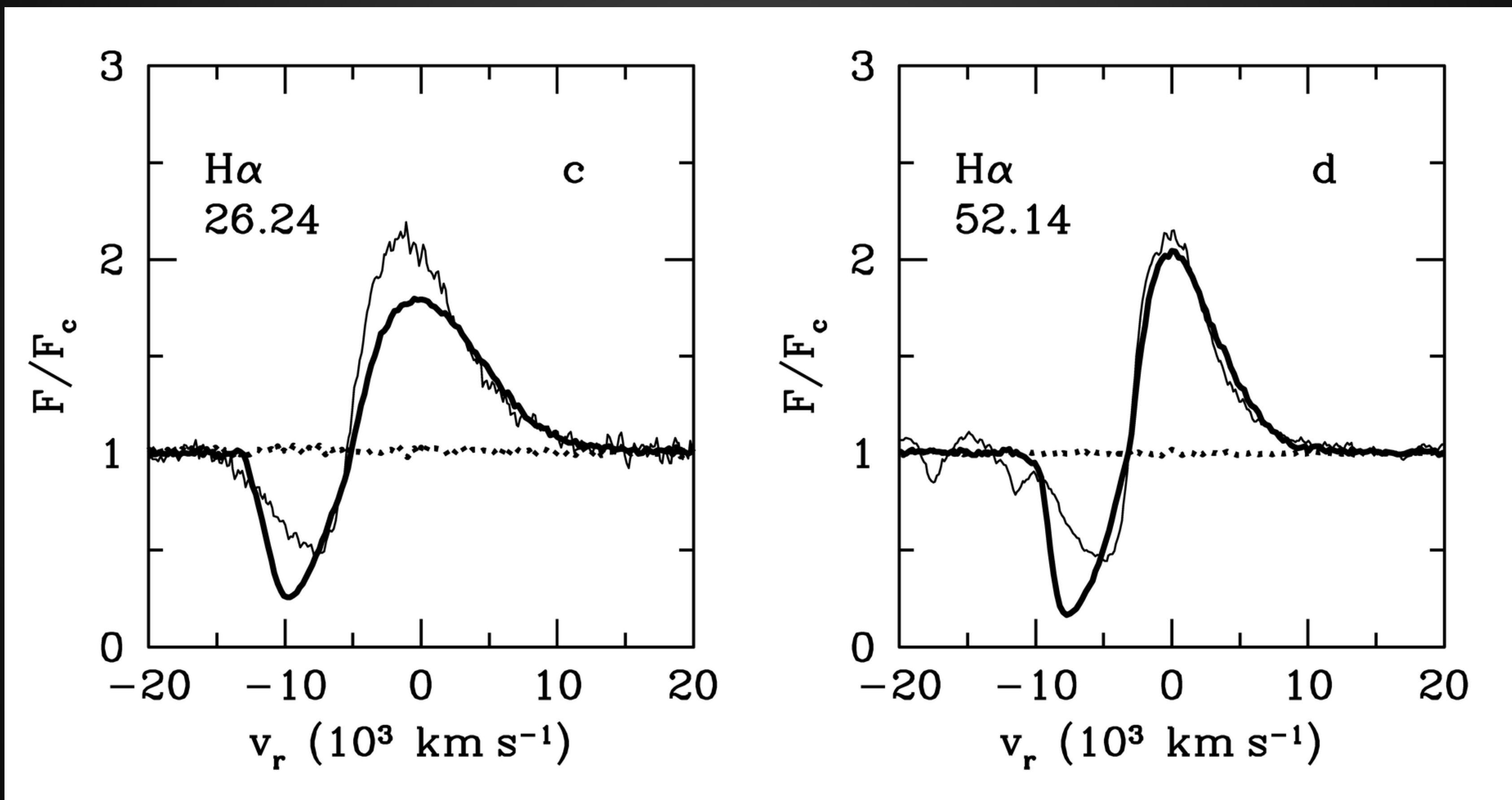
Time-dependent, SN 1987A, 4 and 6 days



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

When the time dependence is important?

SN 1999em, 26 and 52 days



Utrobin, V. P. 2007, A&A 461, 233–251

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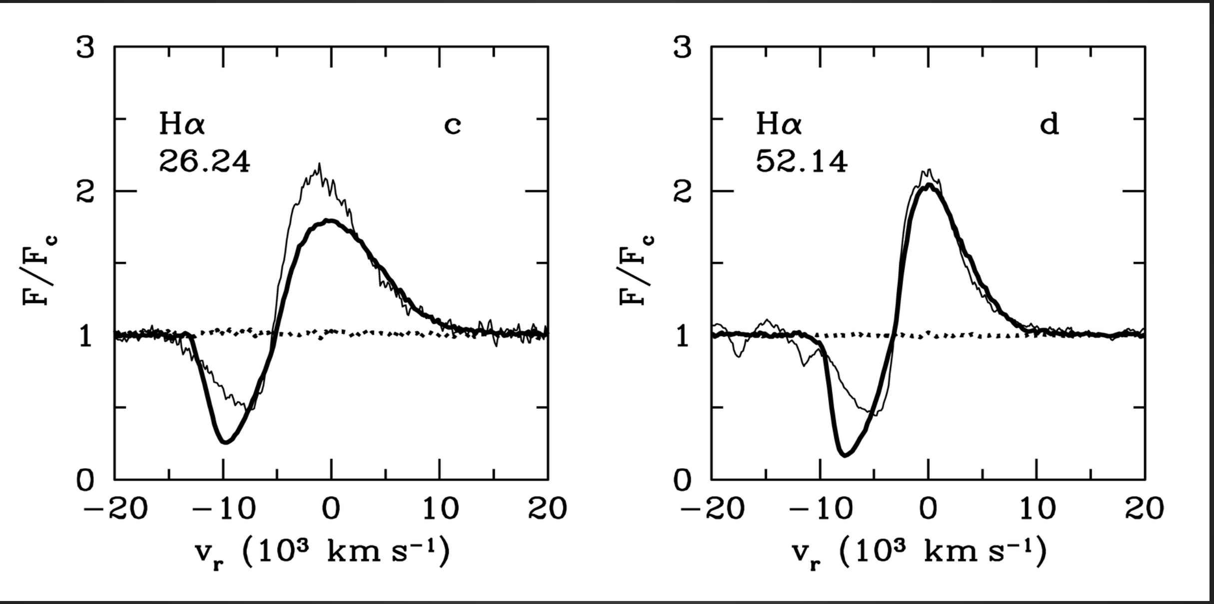
SN 1999em, 26 and 52 days



Utrobin, V. P. 2007, A&A 461, 233–251

All the time

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

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

Few weeks after explosion

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

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

At early times

Contradiction

Utrobin & Chugai

All the time

Dessart & Hillier

Few weeks after explosion

De & Baron

At early times

Contradiction

↓

Break the problem into pieces

Contradiction

Break the problem into pieces

Importance of the 2 photon decay

Contradiction

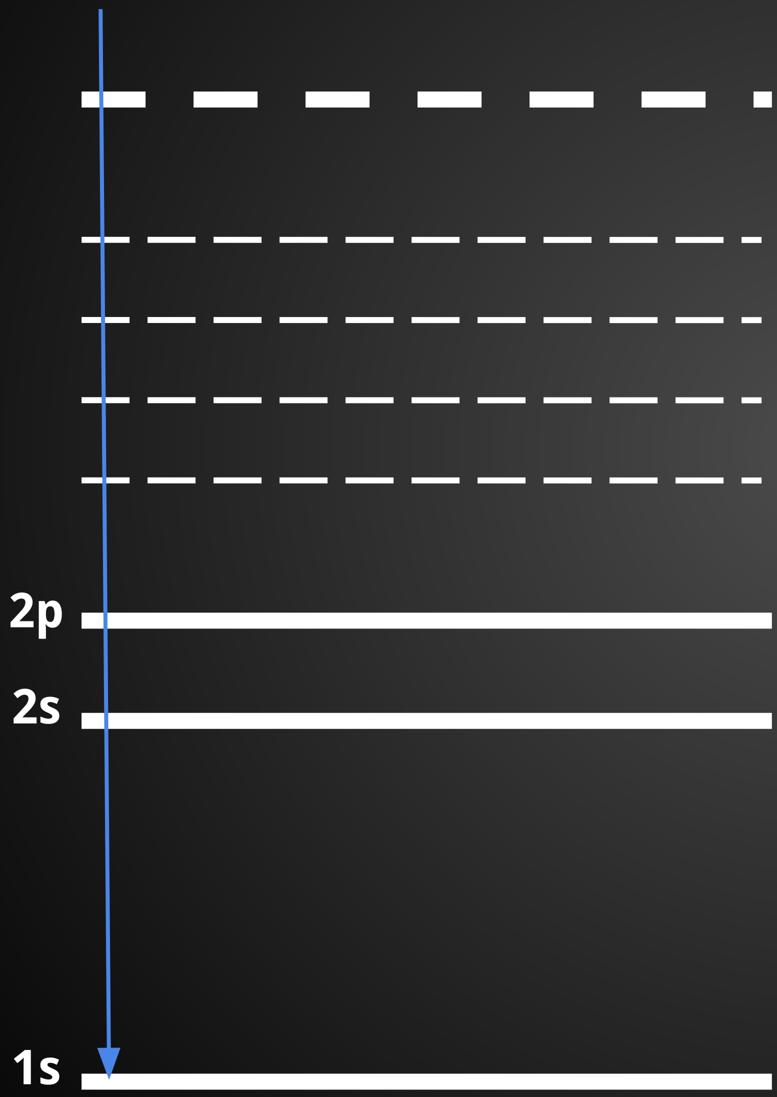
Break the problem into pieces

Importance of the 2 photon decay

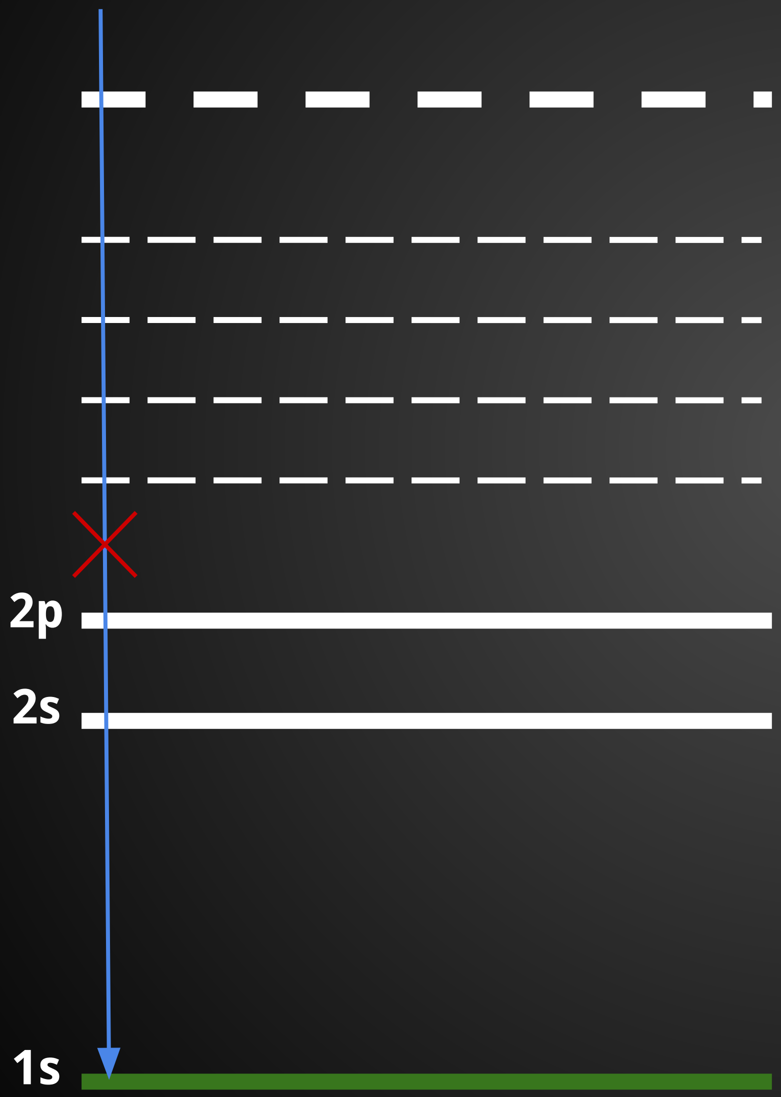
Importance of the l-splitting

NO SE among l sublevels

Where the two-photon process is important?

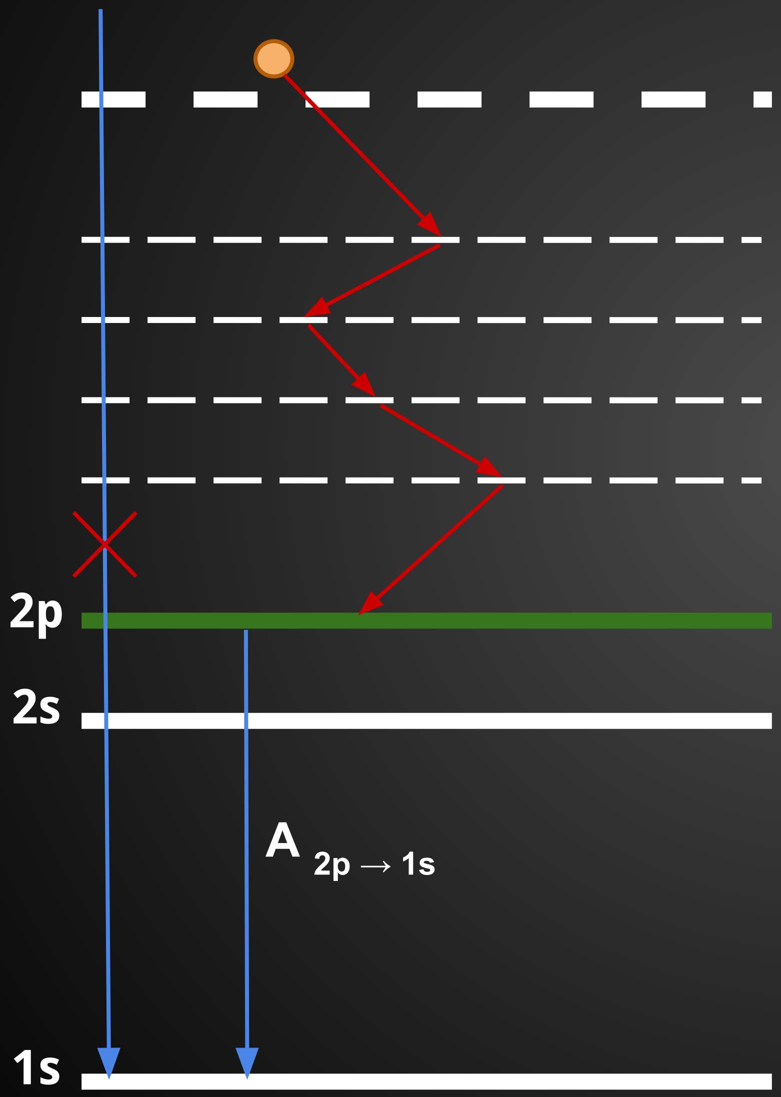


Hydrogen



Direct recombination to the ground state of hydrogen is neglected

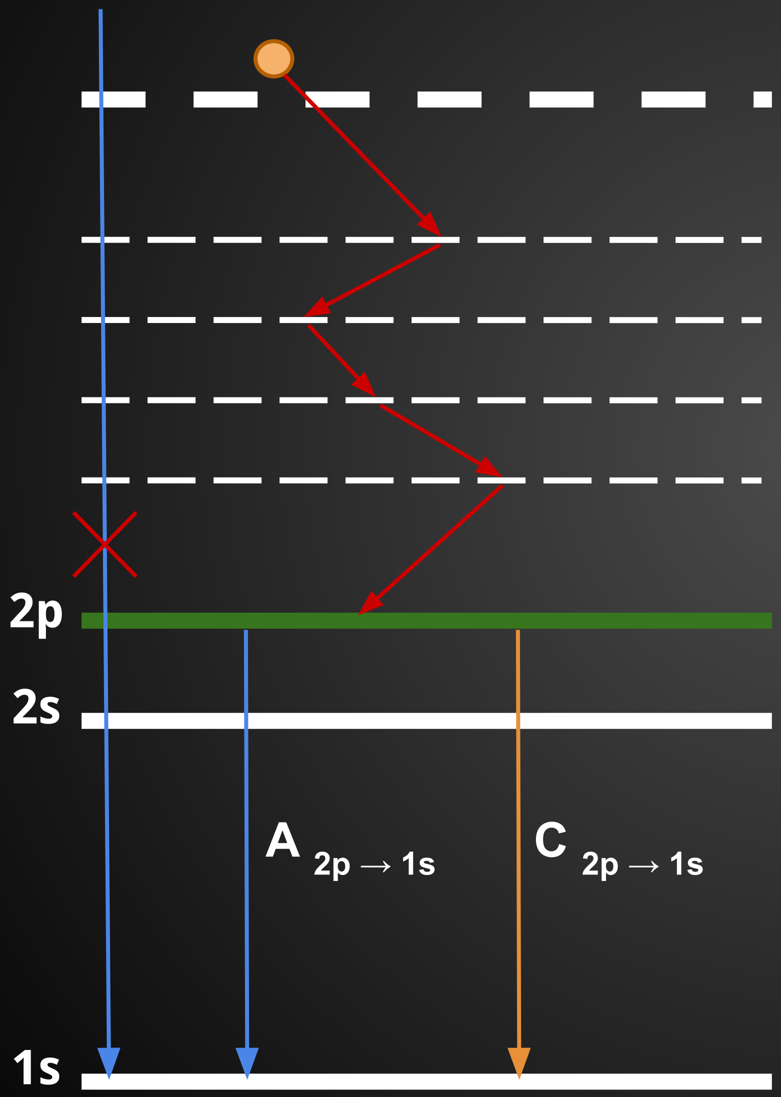
Hydrogen



Direct recombination to the ground state of hydrogen is neglected

Emission **2p → 1s**

Hydrogen



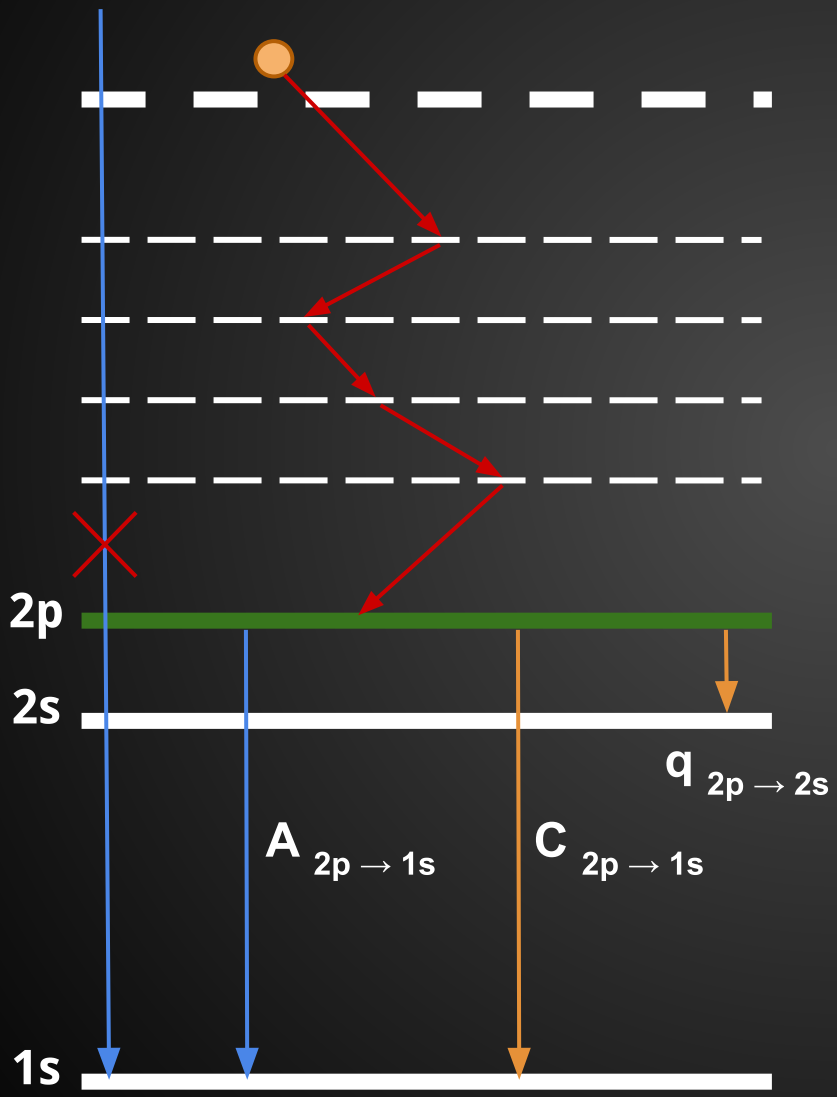
Direct recombination to the ground state of hydrogen is neglected

Emission 2p → 1s

Collisional deexcitation

2p → 1s

Hydrogen



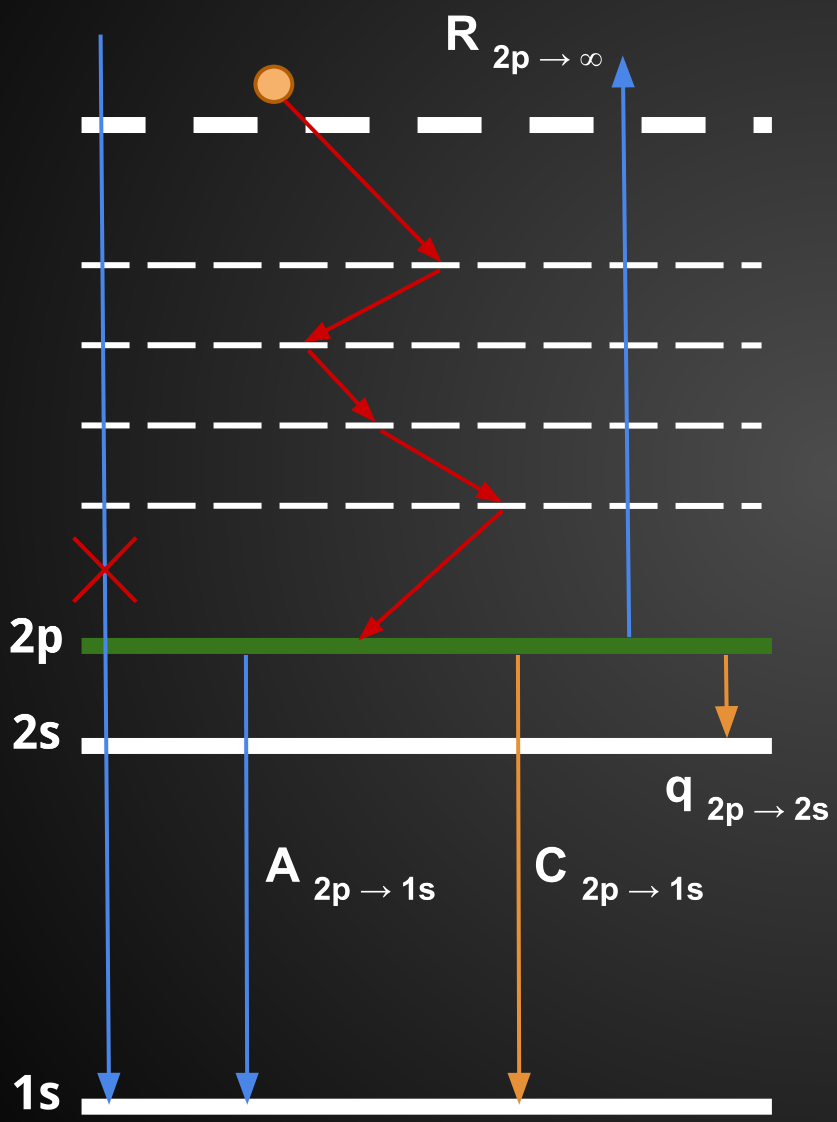
Direct recombination to the ground state of hydrogen is neglected

Emission 2p → 1s

Collisional deexcitation
2p → 1s

Collisional excitation
2p → 2s

Hydrogen



Direct recombination to the ground state of hydrogen is neglected

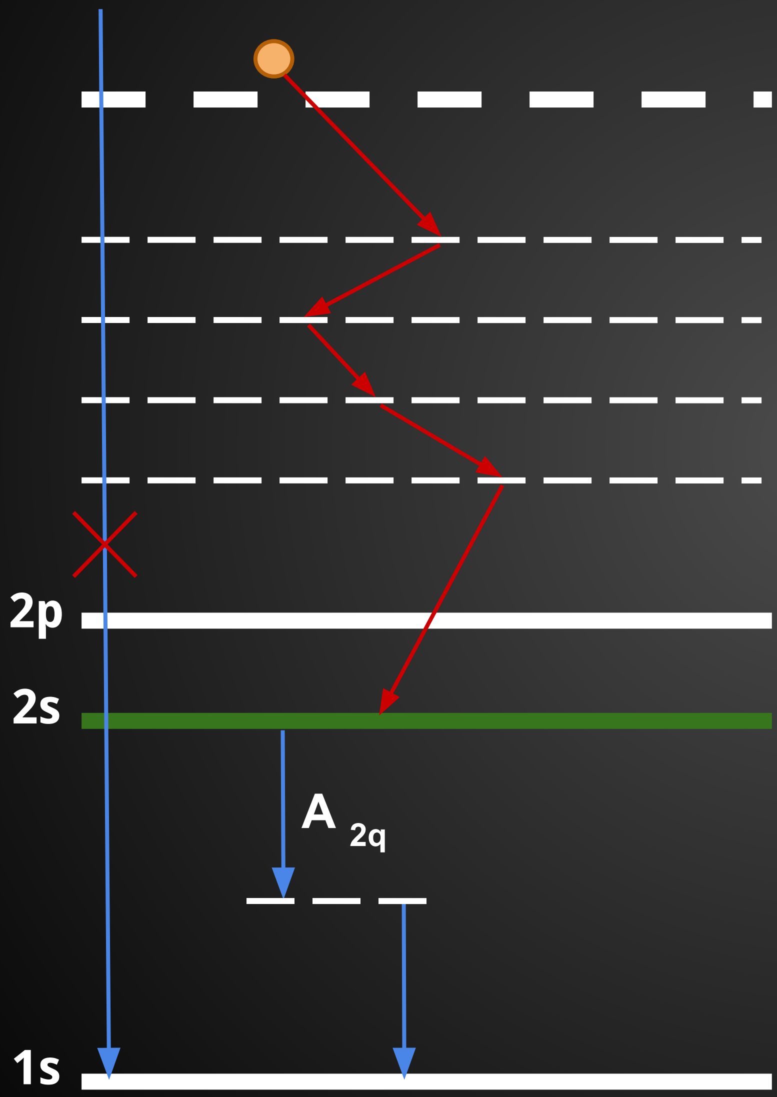
Emission $2p \to 1s$

Collisional deexcitation $2p \to 1s$

Collisional excitation $2p \to 2s$

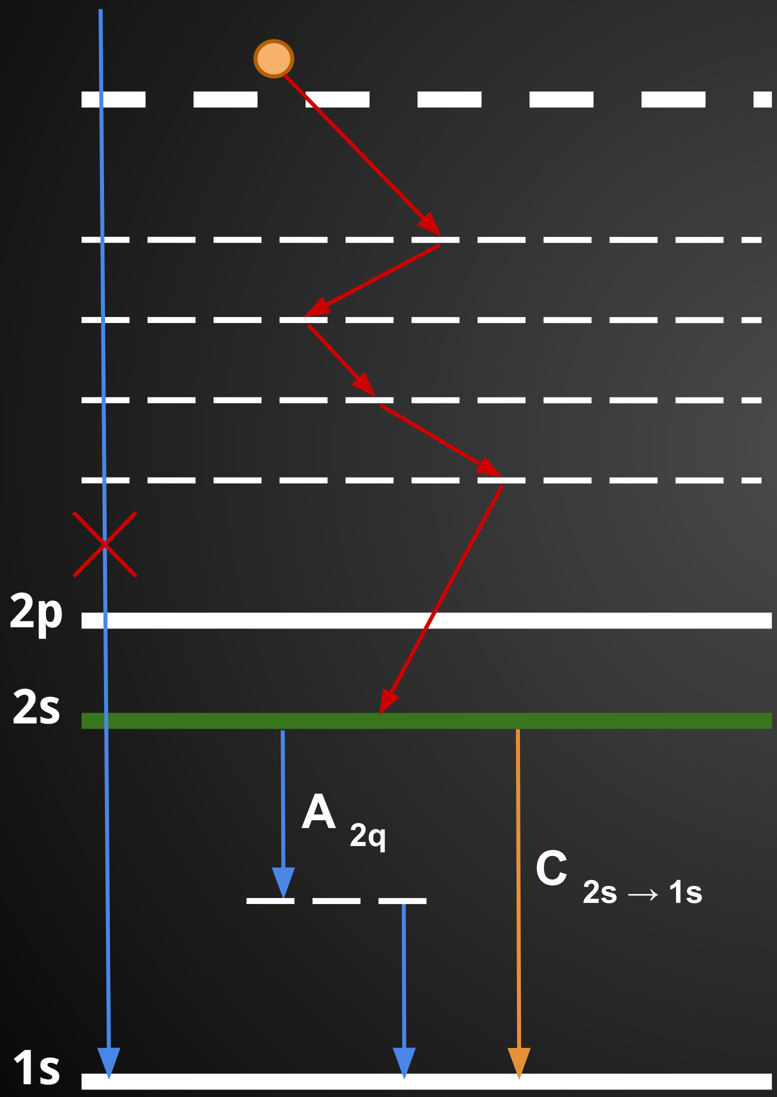
Photoionization $2p \to \infty$

Hydrogen



Two photon decay **2q**

Hydrogen

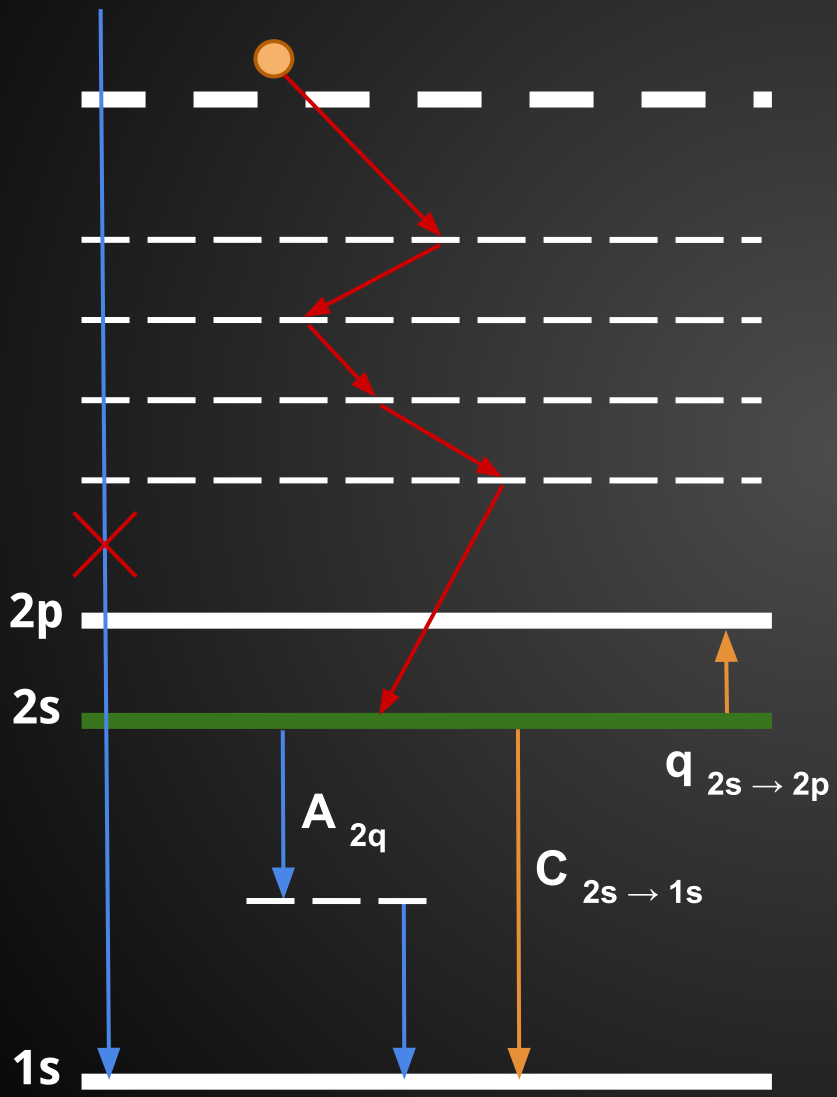


Two photon decay **2q**

Collisional deexcitation

2s → 1s

Hydrogen



Two photon decay 2q

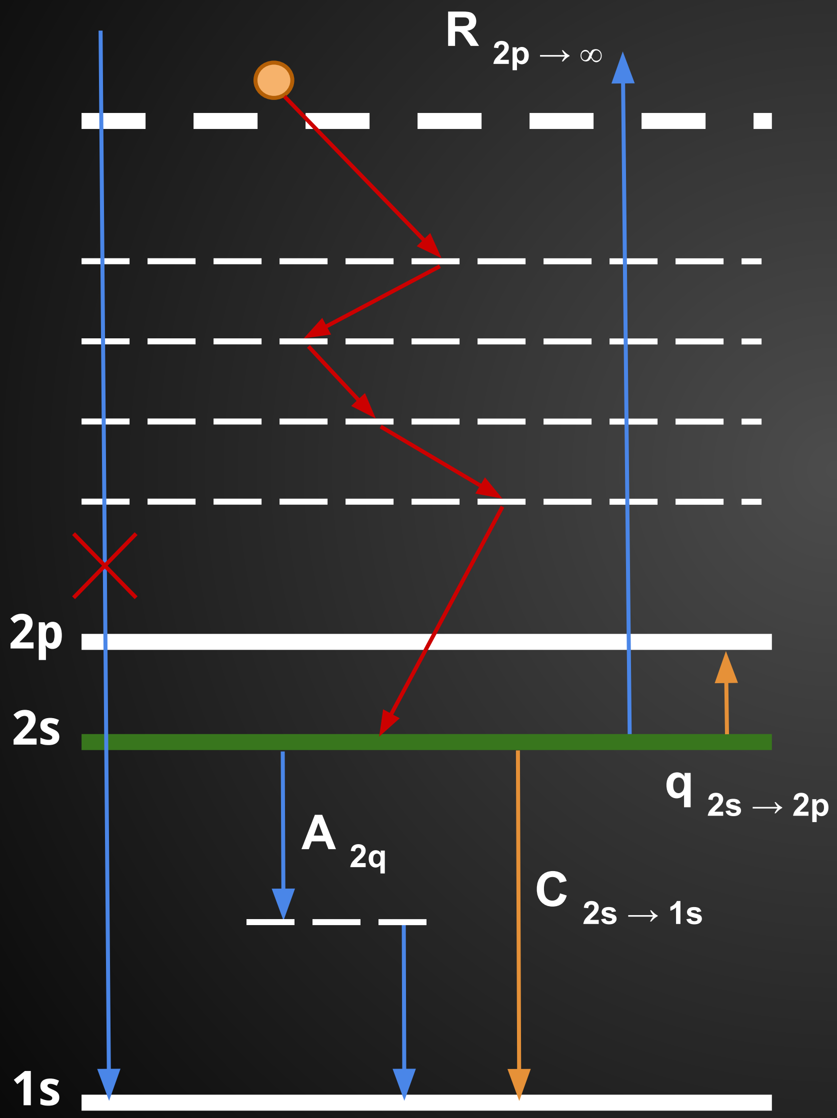
Collisional deexcitation

$2s \longrightarrow 1s$

Collisional excitation

$2s \longrightarrow 2p$

Hydrogen



Two photon decay **2q**

Collisional deexcitation

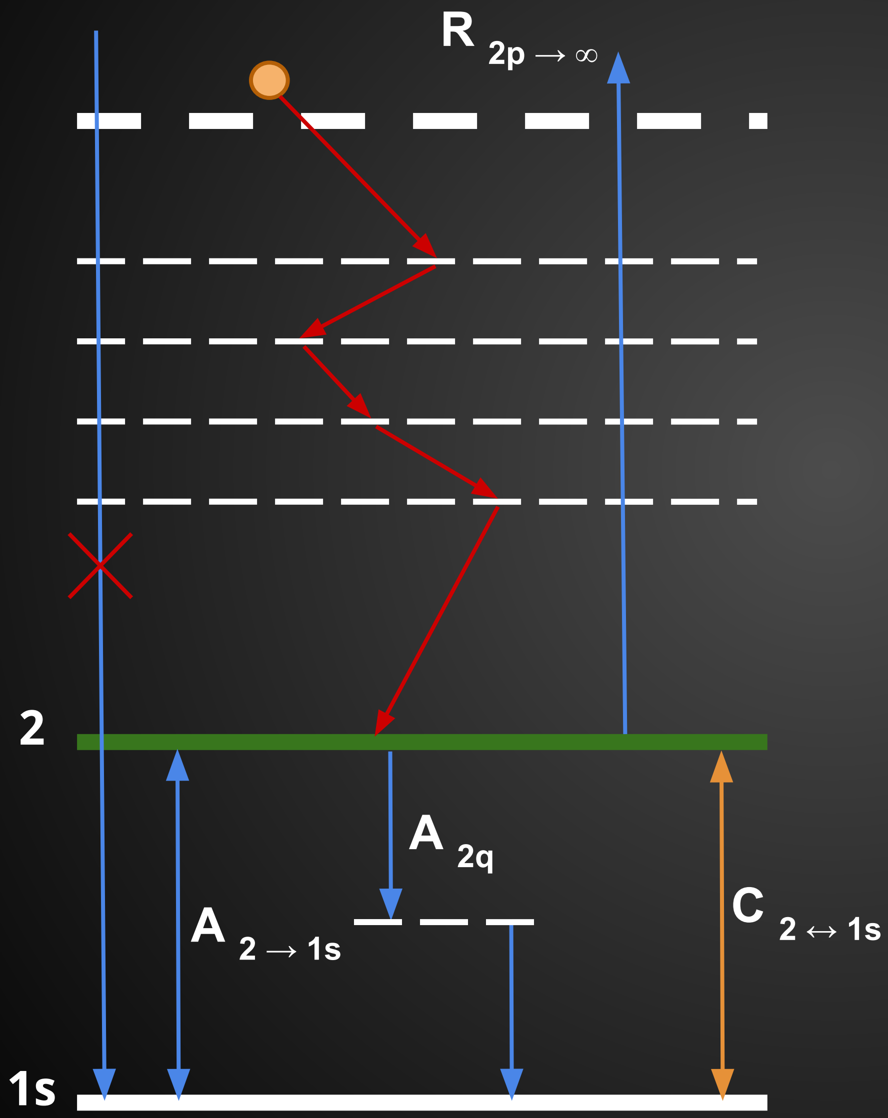
2s → 1s

Collisional excitation

2s → 2p

Photoionization **2s → ∞**

Hydrogen



2s, 2p - LTE ⇒

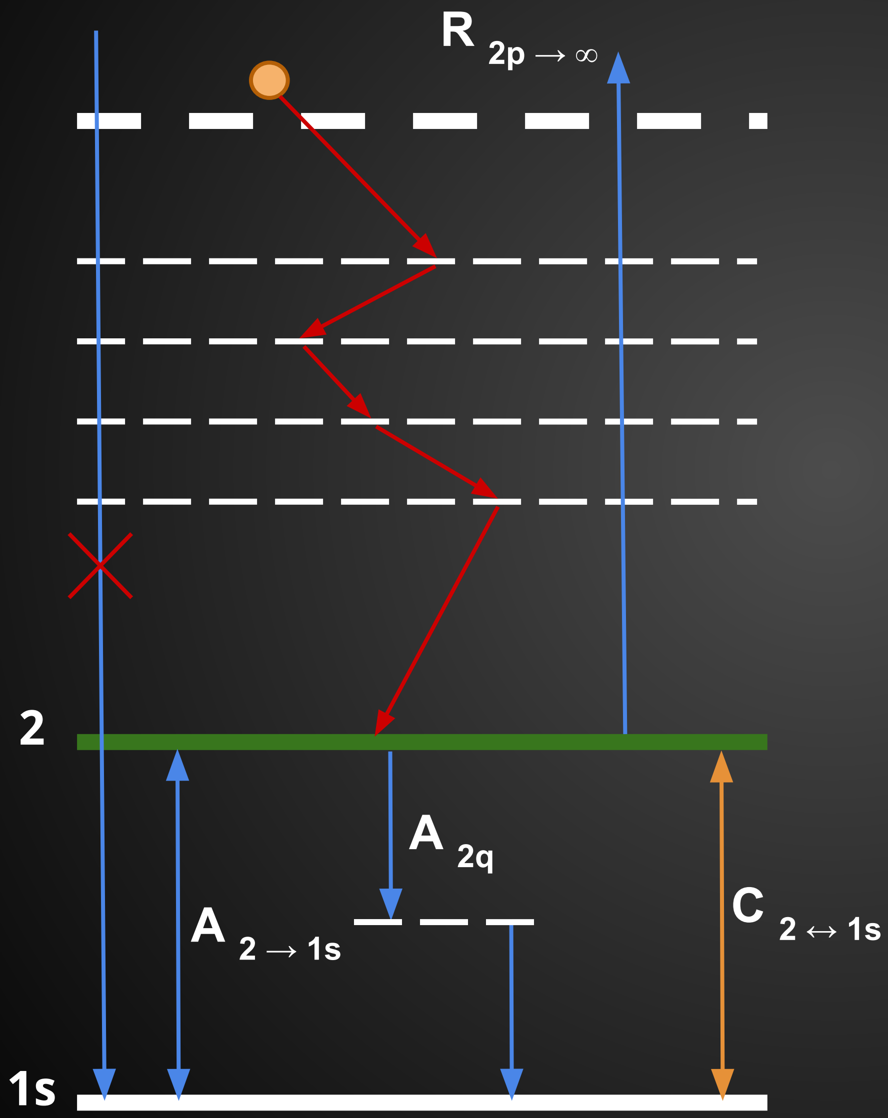
2 - Super level

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

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

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

Hydrogen



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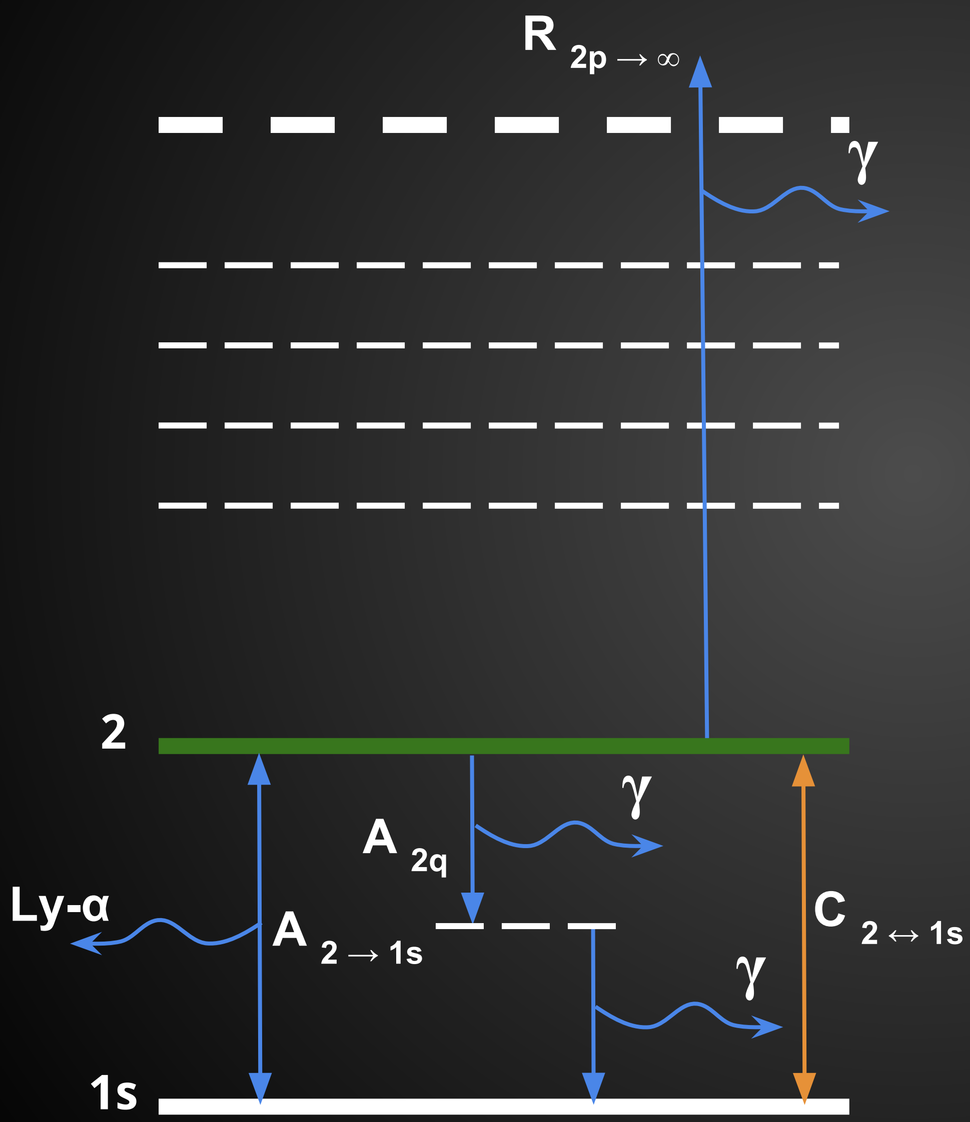
SE among l sublevels: 2s and 2p

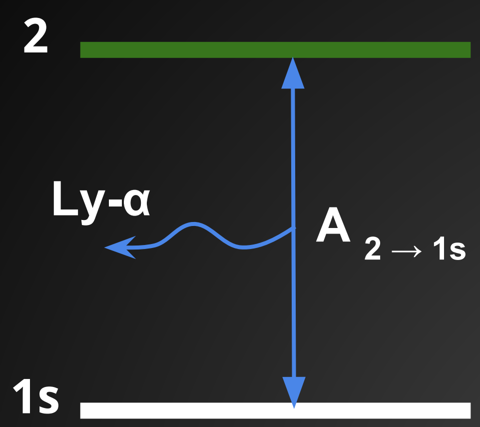
Hydrogen



Effectively 3 states: 1s, *n*=2, e-+p

Zeldovich et al. 1968, Peebles 1968

Sobolev approximation in Ly-α

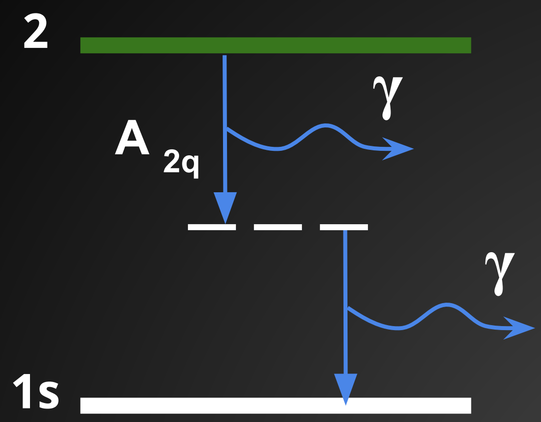


$$P_{\rm esc} = \beta \sim 1/\tau_S$$

$$P_{\rm esc} \times A_{2p\rightarrow 1s} \sim \frac{8\pi}{c^3} {\nu_{\rm Ly\alpha}}^3 \frac{g_{1s}}{g_{2p}} \frac{1}{n_{1s} t}$$

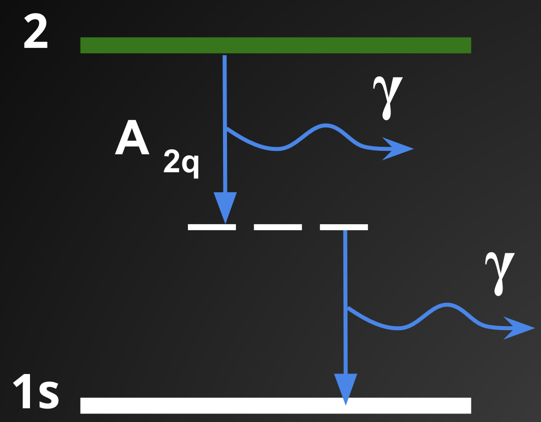
$$\sim 10^{-3} - 10^{3}\ {\rm s}^{-1}$$

Greater in the outer layers



$$A_{2s \to 1s} \sim 8.225\ \mathrm{s}^{-1}$$

The same in all layers



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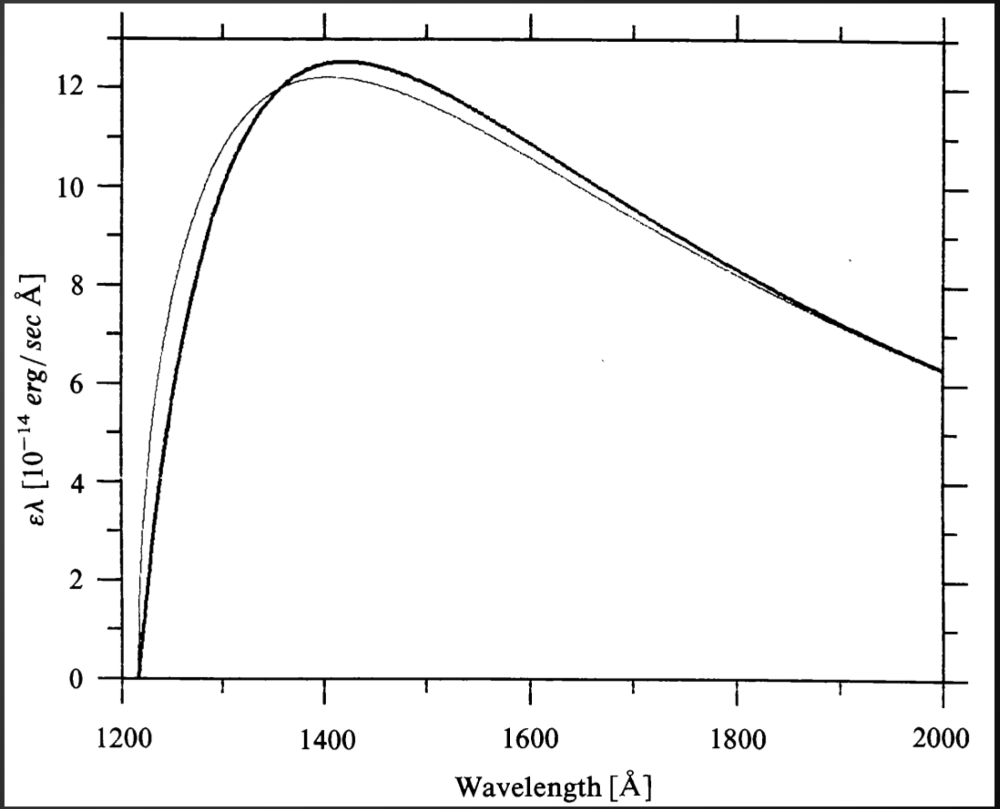
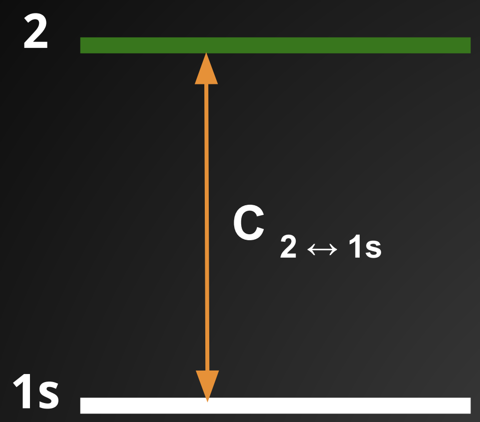


71%

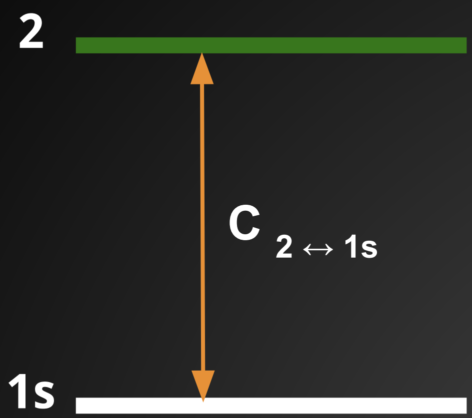
for frequencies higher than Balmer jump 3646 Å

Nussbaumer, H. and Schmutz, W. 1984, A&A 138, 495–496



$$n_e n_2 \, C_{2\to 1} =$$

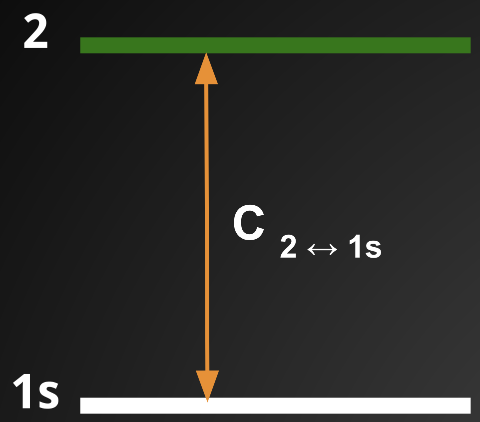
$$= n_e n_2 \, C_{1\to 2} \left(\frac{n_1}{n_2}\right)^{*}$$



$$n_e n_2 \, C_{2\to 1} =$$

$$= n_e n_2 \, C_{1\to 2} \left(\frac{n_1}{n_2}\right)^*$$

$$n_e n_1 \, C_{1\to 2}$$



$$n_e n_2 \, C_{2\rightarrow 1} =$$

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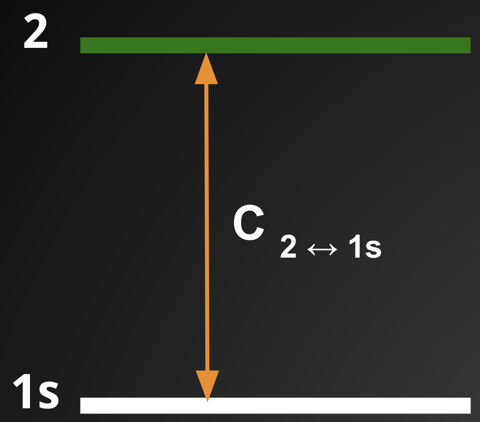
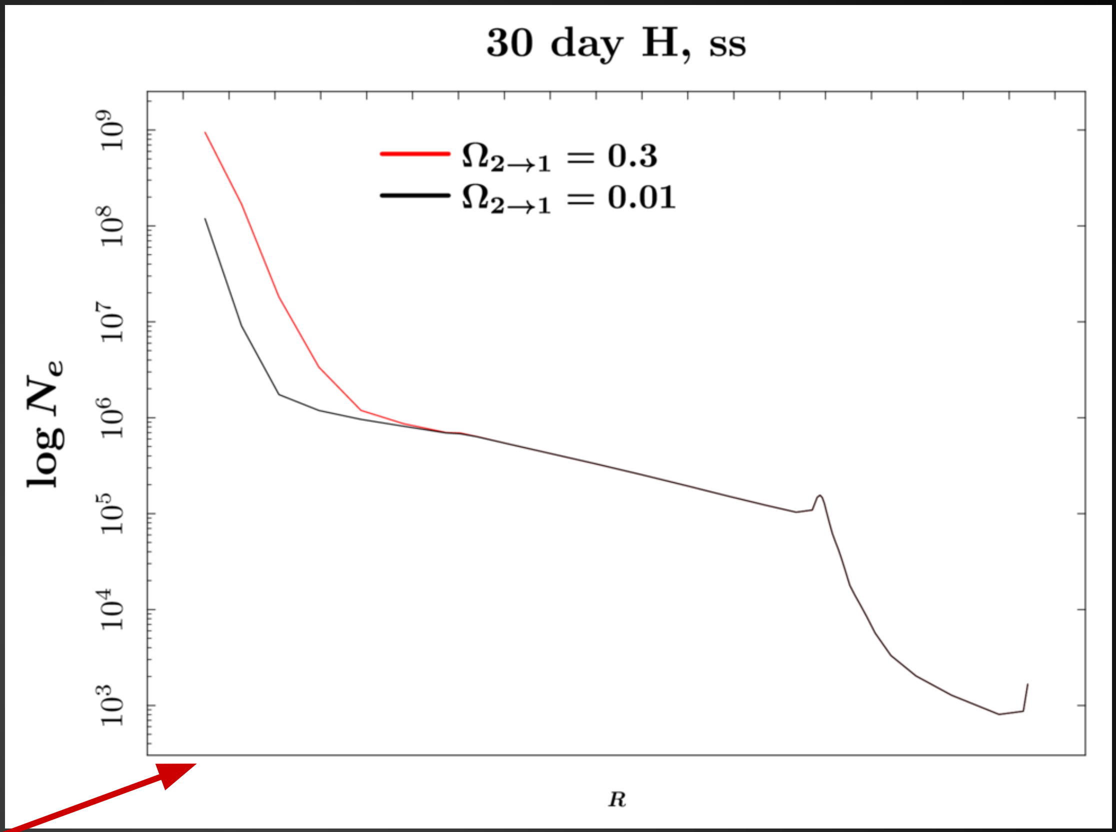
$$n_e n_1 \, C_{1\rightarrow 2}$$

$$n_e \, C_{1\rightarrow 2} \left(\left(\frac{n_1}{n_2} \right)^* - \frac{n_1}{n_2} \right)$$



$$\sim 10^3 - 0\ \mathrm{s}^{-1}$$

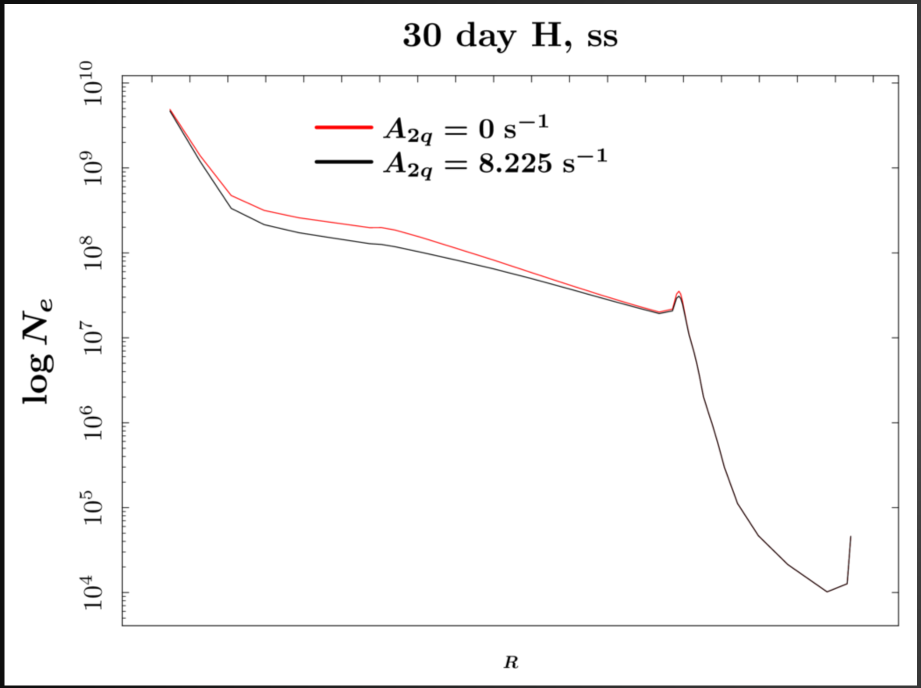


Photosphere

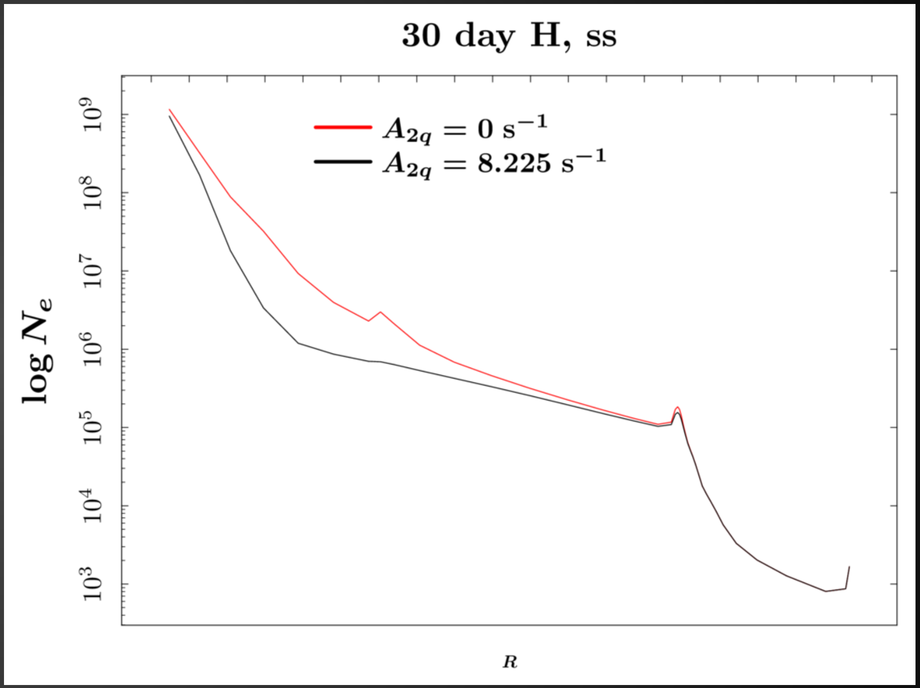
Greater in the near-photospheric layers

Hydrogen star, 2 level + continuum

30 day



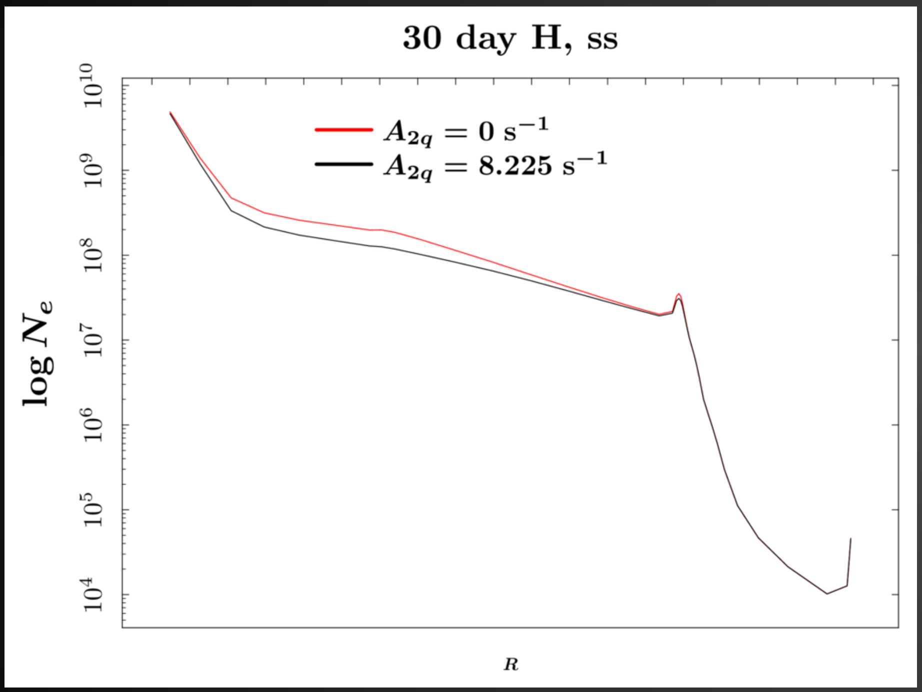
Model A

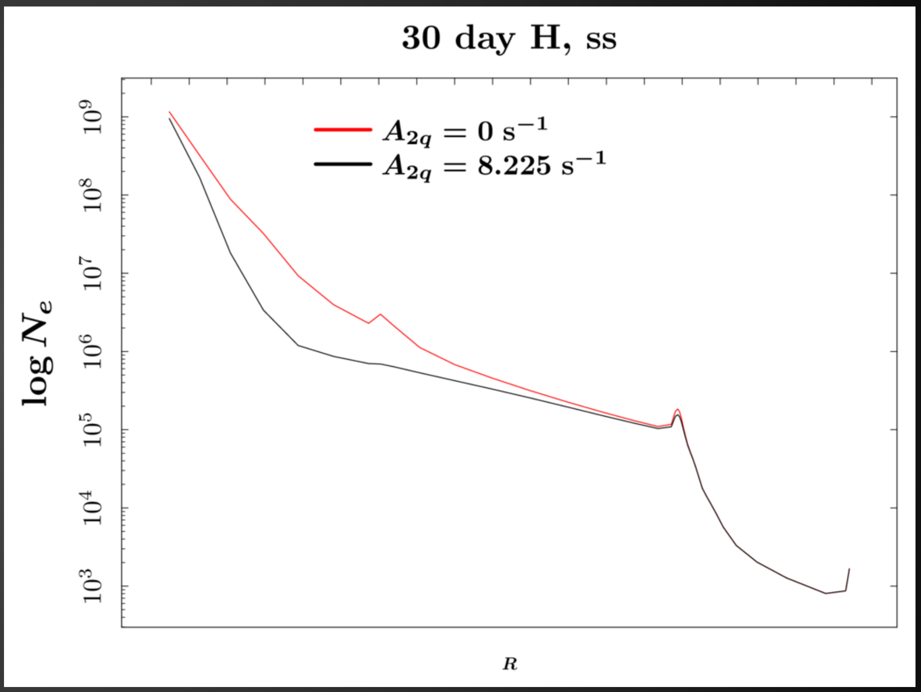


Model B

Hydrogen star, 2 level + continuum

30 day





Model A

Model B

Important in the middle layers

Where the two-photon process is important?

the changes due to the 2γ process. For model A, at low optical depths ($\tau_{\rm std} \sim 10^{-4}$) turning on the 2γ process produces about a 20 per cent change in the free electron density, but for $\tau_{\rm std} \gtrsim 10^{-3}$ no significant change is seen. For model B, there is a significant

De, S., Baron, E. et al. 2010, MNRAS 407, 658–668

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4-level

1s, 2s, $2p_{1/2}$, $2p_{3/2}$

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De, S., Baron, E. et al. 2010, MNRAS 407, 658–668

4-level

1s, 2s, $2p_{1/2}$, $2p_{3/2}$

Important in the outer layers for pure hydrogen models

The Flexible Atomic Code (FAC)

Ming Feng Gu

↓

Hydrogen star, 81 level + continuum

If there is no collision process the effect disappears!

Further steps
(instead of conclusions)

- The time dependence effect is not fully understood
- We need to reject Sobolev approximation in Lyα decays
- We need to include b-b and b-f collisions
- Metal-rich models