

Calculations of supernova spectra, taking into account  
time-dependent NLTE processes for multiply charged ions  
in the Sobolev approximation.

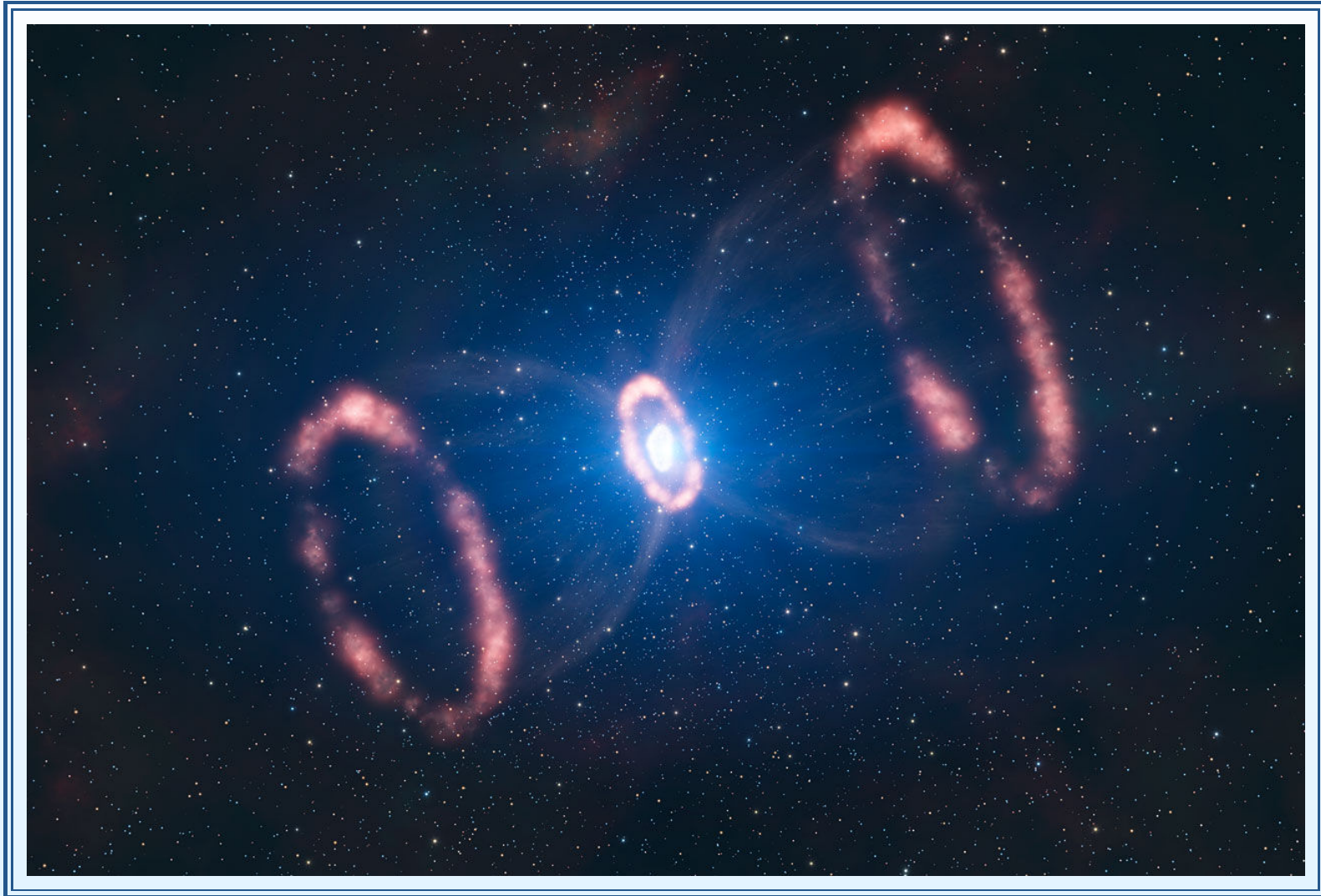
M.Sh.Potashov

S.I.Blinnikov, P.V.Baklanov, A.A.Andronova

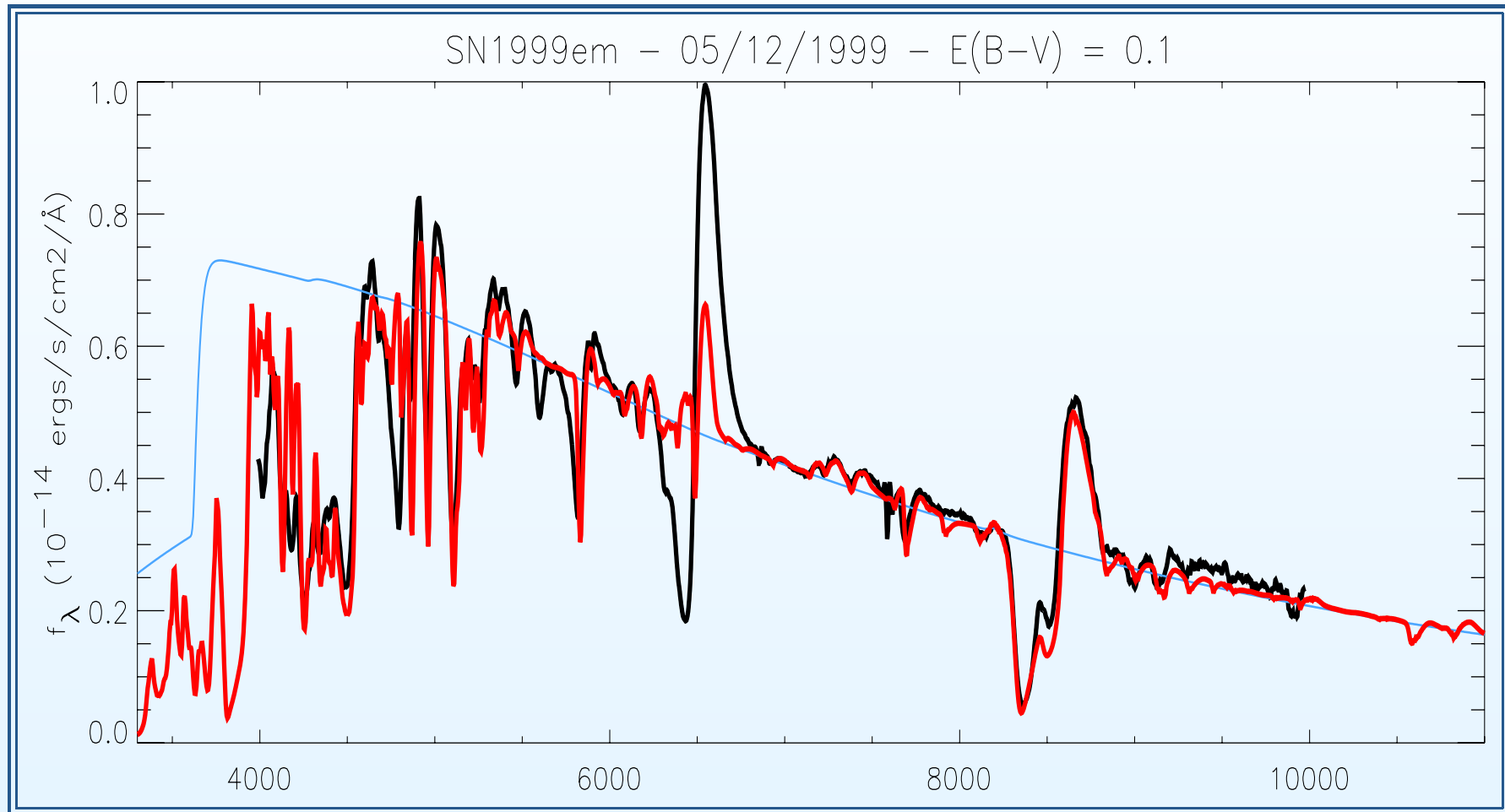
marat.potashov@gmail.com

ITEP

# SN 1987A

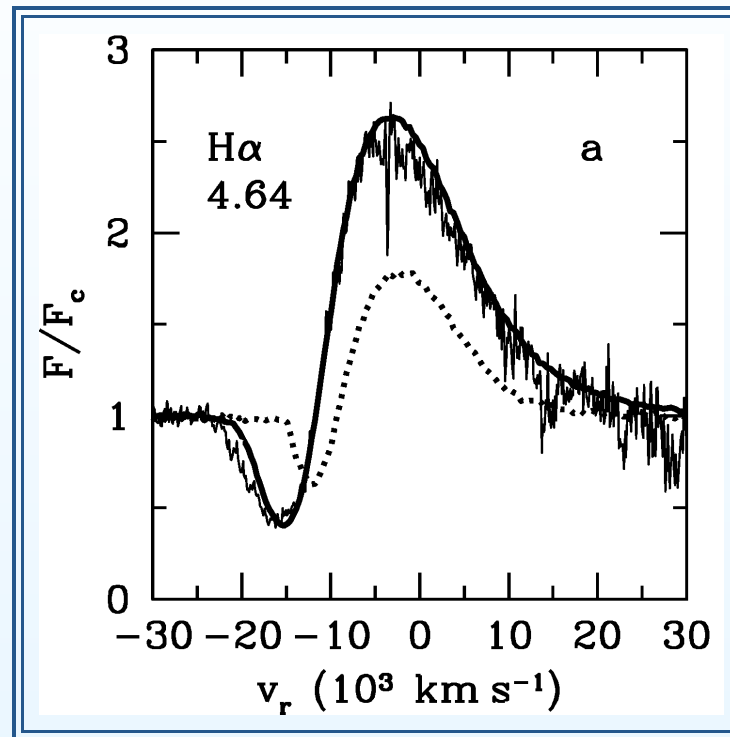


# $H\alpha$ line is weak, SN1999em, day 37



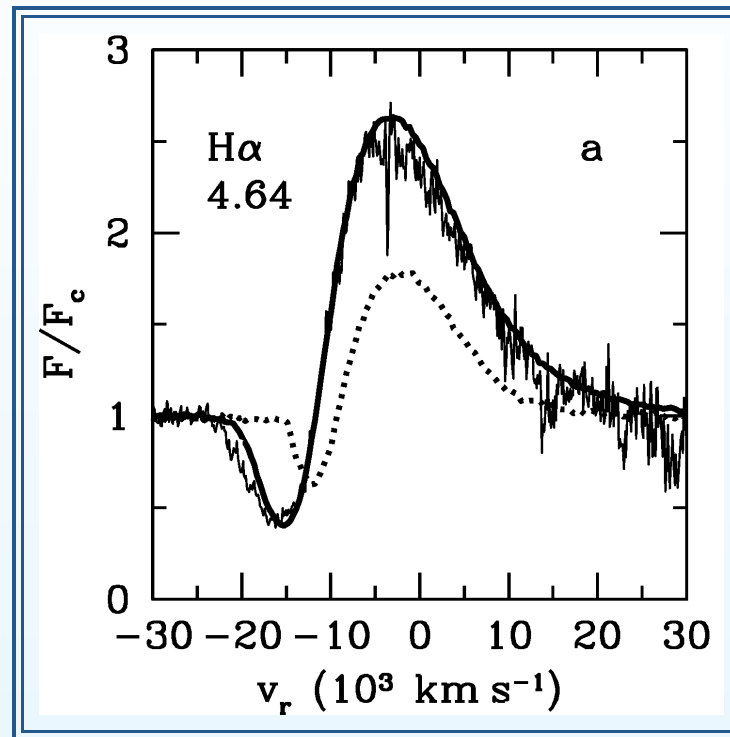
**Dessart, L., Hillier, J. 2005, CMFGEN**

# Time dependent effects



- **Utrobin, V. U., Chugai, N. 2002 - 2005**  
A time-dependent hydrogen ionization in the atmosphere of SN 1987A.

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A time-dependent hydrogen ionization in the atmosphere of SN 1987A.
- **Zeldovich, Ya. B., Kurt, V. G., and Sunyaev, R. A. 1968**  
Importance of the ionization freeze-out effect in cosmology.

# Spectra calculation

- Advantages and disadvantages of the radiations-hydrodynamic **STELLA** code
  - + **CMFGEN** - hydrodynamic is **NOT** included
  - + Utrobin, Chugai - **grey atmosphere**
  - – **LTE**

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- Transfer equations in **Sobolev** approximation and taking into account **multiplet coupling**

# Initial conditions

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- **Second path:** Number densities from first path

# Rate equations

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

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- $\frac{Dn_{z,i}}{Dt} = -\frac{3n_{z,i}}{t} + \sum_{j < i} (n_{z,j} A_{ij} + n_{z,i} B_{ij} J_{ji} - n_{z,j} B_{ji} J_{ji})$   
 $- \sum_{j > i} (n_{z,j} A_{ji} + n_{z,j} B_{ji} J_{ij} - n_{z,i} B_{ij} J_{ij})$   
 $+ n_e \sum_{j \neq i} n_{z,j} C_{ji} - n_e n_{z,i} \sum_{j \neq i} C_{ij}$   
 $- n_{z,i} (B_{z,ic} + n_e C_{z,ic}) + n_e n_{z^+} (B_{z,ci} + n_e C_{z,ci})$   
 $+ \frac{n_{z,i}}{n_z} \sum_{j=1}^n n_{z^-,j} (B_{z^-,jc} + n_e C_{z^-,jc})$   
 $- n_{z,i} \sum_{j=1}^n n_e (B_{z^-,cj} + n_e C_{z^-,cj}), \quad i = 1, 2, \dots$

# Rate equations

- $$\frac{\partial n_{z,i}}{\partial t} = -\text{div}(n_{z,i} \vec{v}) + \sum_{j \neq i} (n_{z,j} P_{j,i} - n_{z,i} P_{i,j})$$
- $$\begin{aligned} \frac{Dn_{z,i}}{Dt} = & -\frac{3n_{z,i}}{t} + \sum_{j < i} (n_{z,j} A_{ij} + n_{z,i} B_{ij} J_{ji} - n_{z,j} B_{ji} J_{ji}) \\ & - \sum_{j > i} (n_{z,j} A_{ji} + n_{z,j} B_{ji} J_{ij} - n_{z,i} B_{ij} J_{ij}) \\ & + n_e \sum_{j \neq i} n_{z,j} C_{ji} - n_e n_{z,i} \sum_{j \neq i} C_{ij} \\ & - n_{z,i} (B_{z,ic} + n_e C_{z,ic}) + n_e n_{z^+} (B_{z,ci} + n_e C_{z,ci}) \\ & + \frac{n_{z,i}}{n_z} \sum_{j=1}^n n_{z^-,j} (B_{z^-,jc} + n_e C_{z^-,jc}) \\ & - n_{z,i} \sum_{j=1}^n n_e (B_{z^-,cj} + n_e C_{z^-,cj}), \quad i = 1, 2, \dots \end{aligned}$$
- $$\frac{Dn_e}{Dt} = n_{z,i} (B_{z,ic} + n_e C_{z,ic}) - n_e n_{z^+} (B_{z,ci} + n_e C_{z,ci})$$

# Rate equations

## Two photon decay

$$\frac{Dn_{H,1}}{Dt} = \frac{Dn_{H,1}}{Dt} + A_{2q}$$
$$\frac{Dn_{H,2}}{Dt} = \frac{Dn_{H,2}}{Dt} - A_{2q}$$

## System closure

$$\frac{Dn_{z,p}}{Dt} = -\frac{3n_{z,p}}{t} - \sum_{j \neq p} \frac{Dn_{z,j}}{Dt}$$

# Line transfer

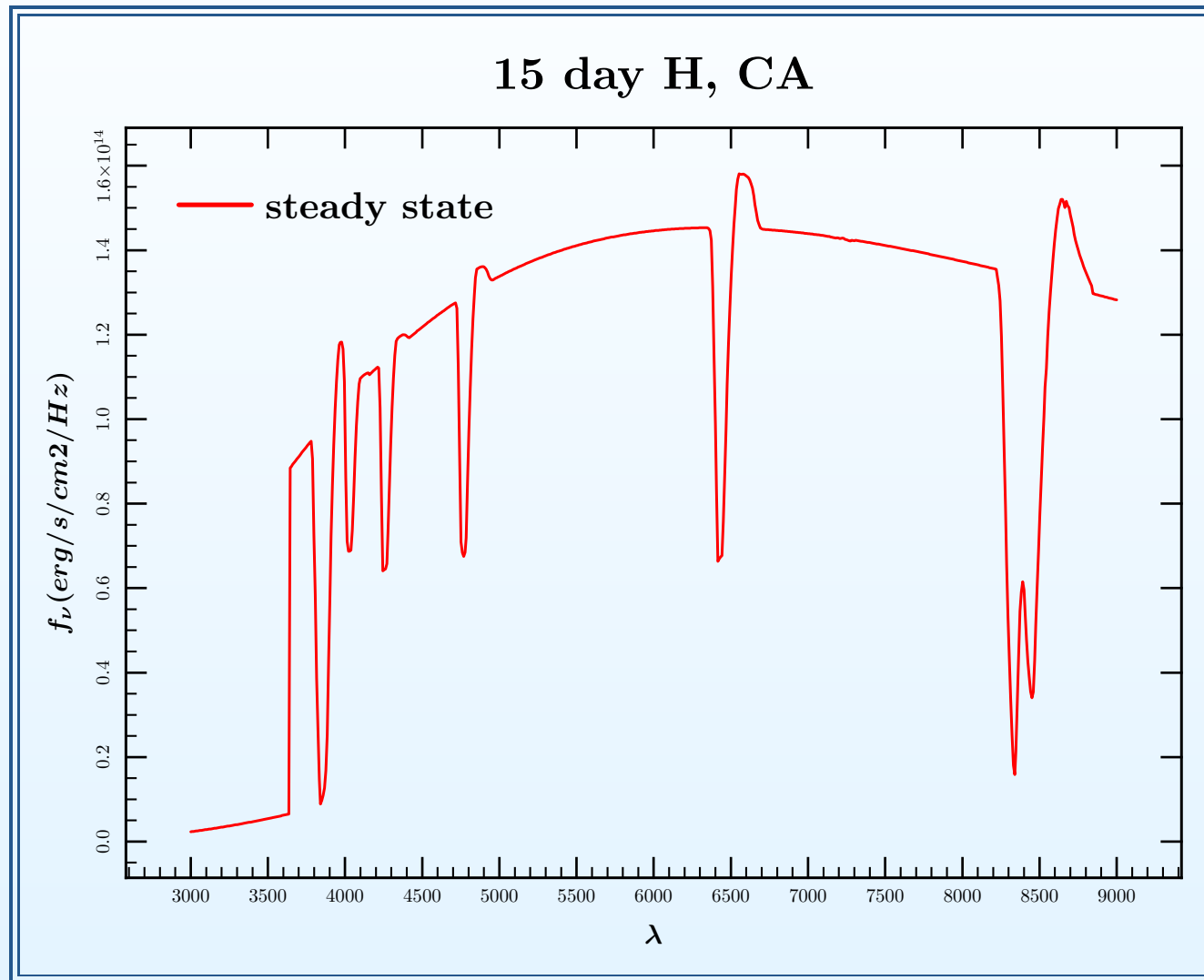
- $J_{lu} = (1 - \beta_{lu})S_{lu} + \beta_{lu}I^* \cdot W$



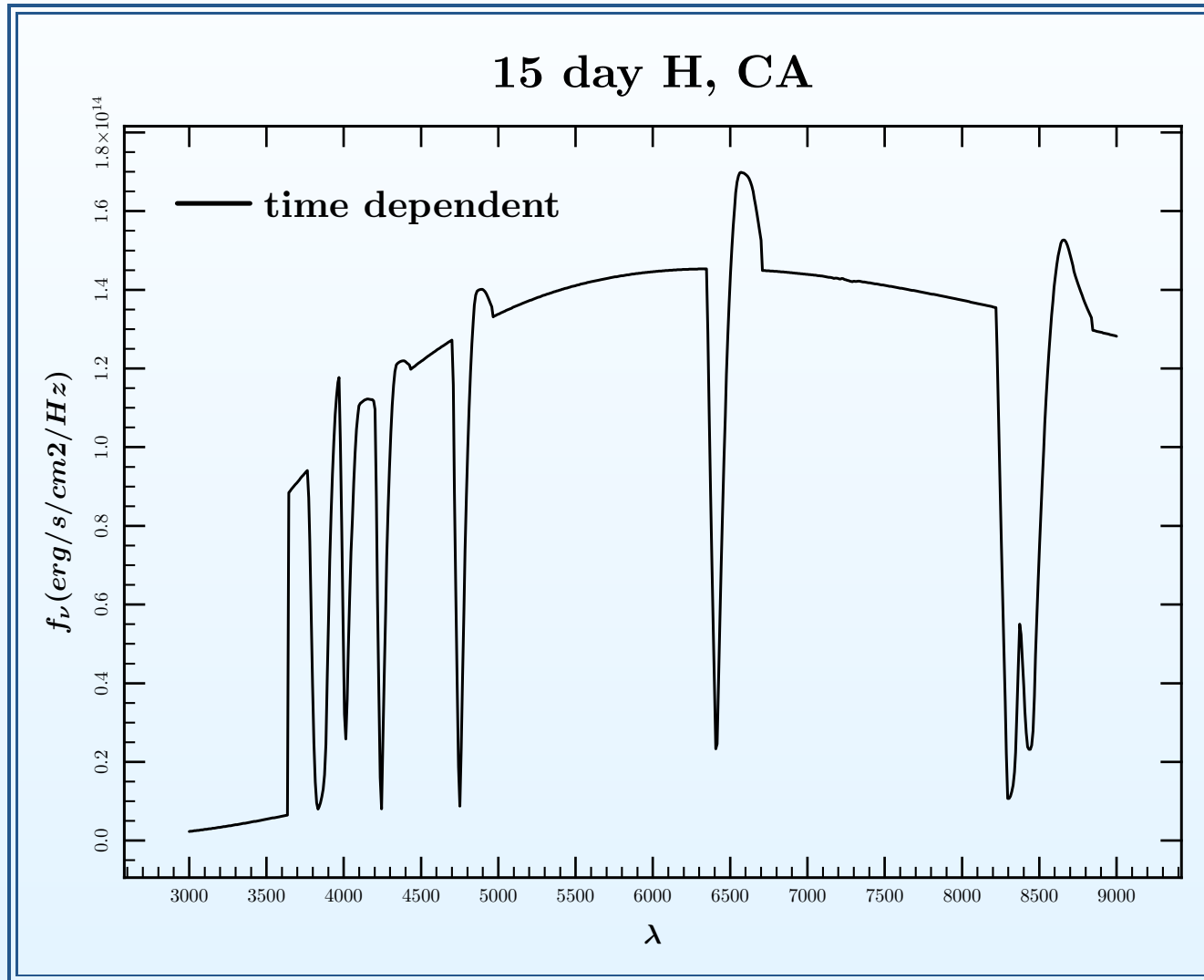
# Line transfer

- $J_{lu} = (1 - \beta_{lu})S_{lu} + \beta_{lu}I^* \cdot W$
- $\beta_{ul} = \frac{1 - \exp(-\tau_{lu})}{\tau_{lu}}$   
 $\tau_{lu} = \frac{c^3}{8\pi \nu_{lu}^3} \frac{g_l}{g_u} A_{ul} t \left( n_l - \frac{g_l}{g_u} n_u \right)$   
 $S_{lu} = \frac{2h\nu_{lu}^3}{c^2} \left( \frac{g_u n_l}{g_l n_u} - 1 \right)^{-1}$

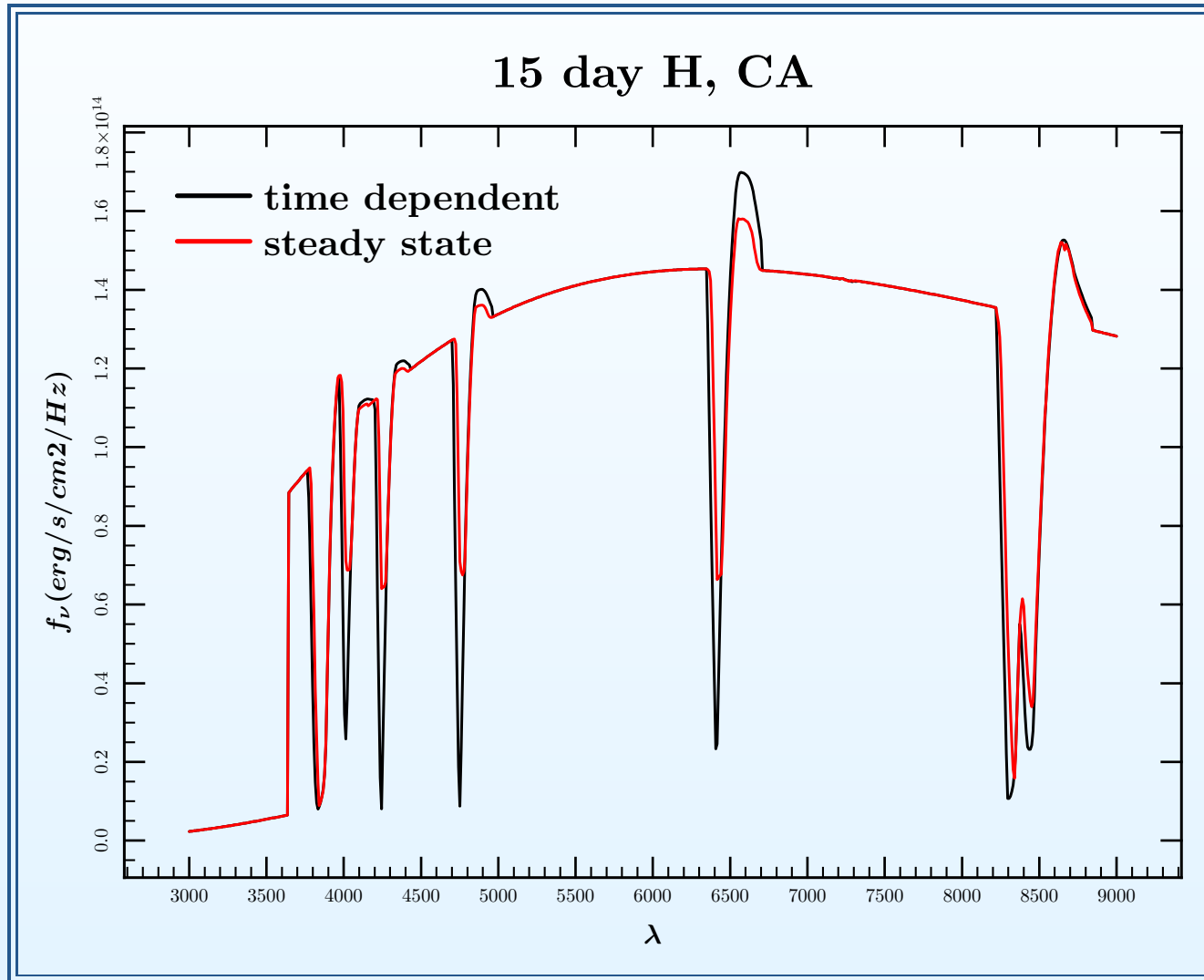
# Steady state at 15 Day



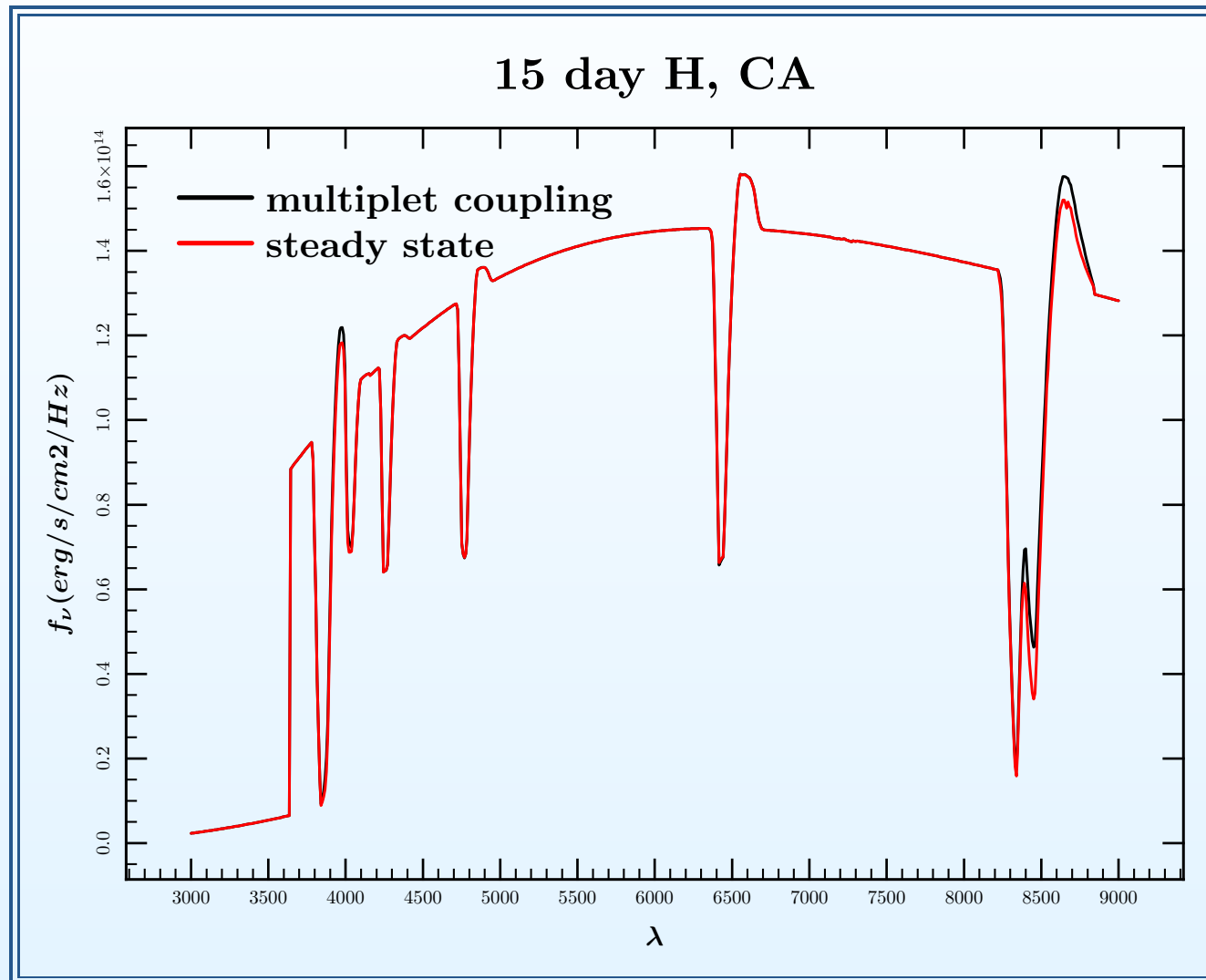
# Time dependent at 15 Day



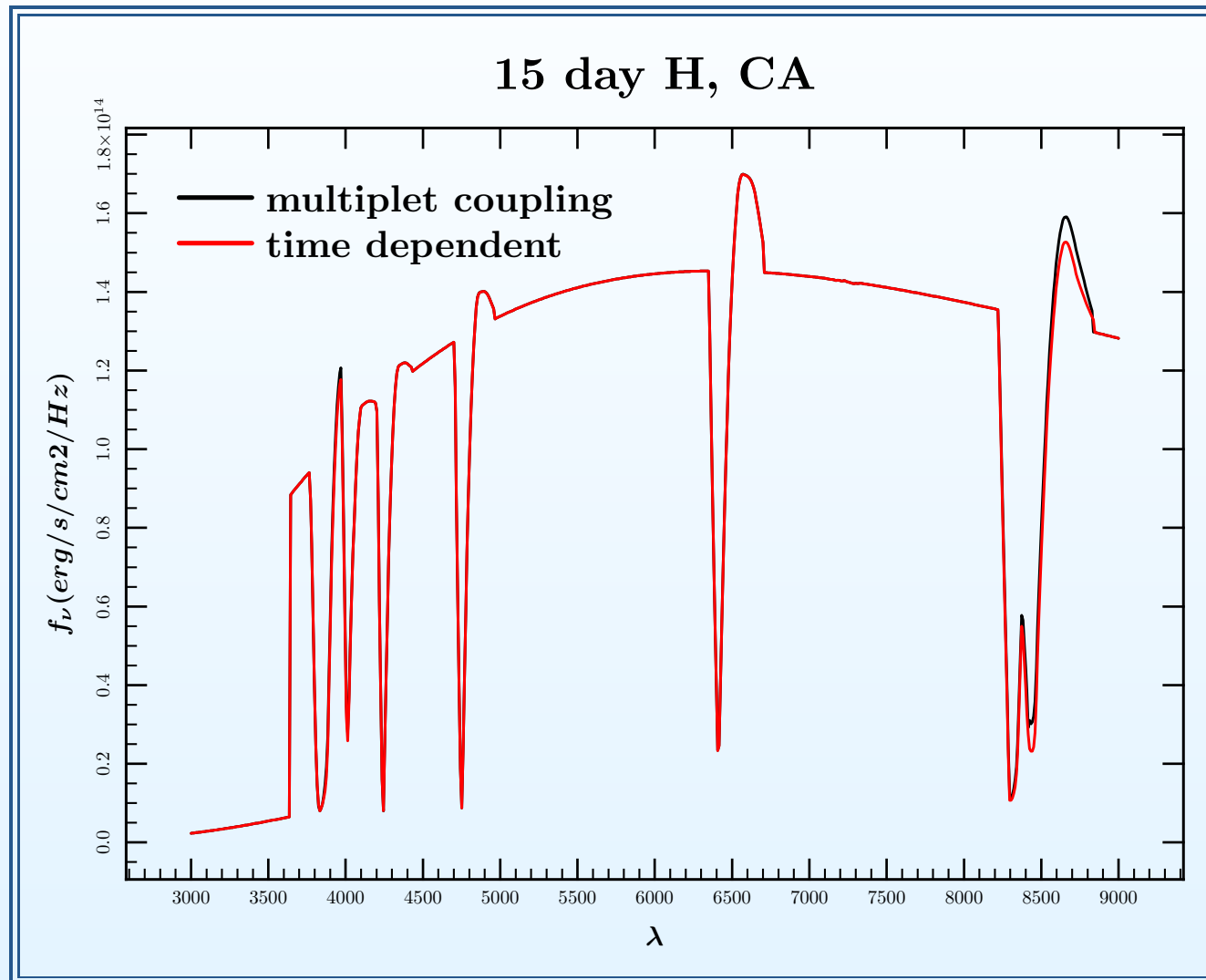
# Steady state, time dependent at 15 Day



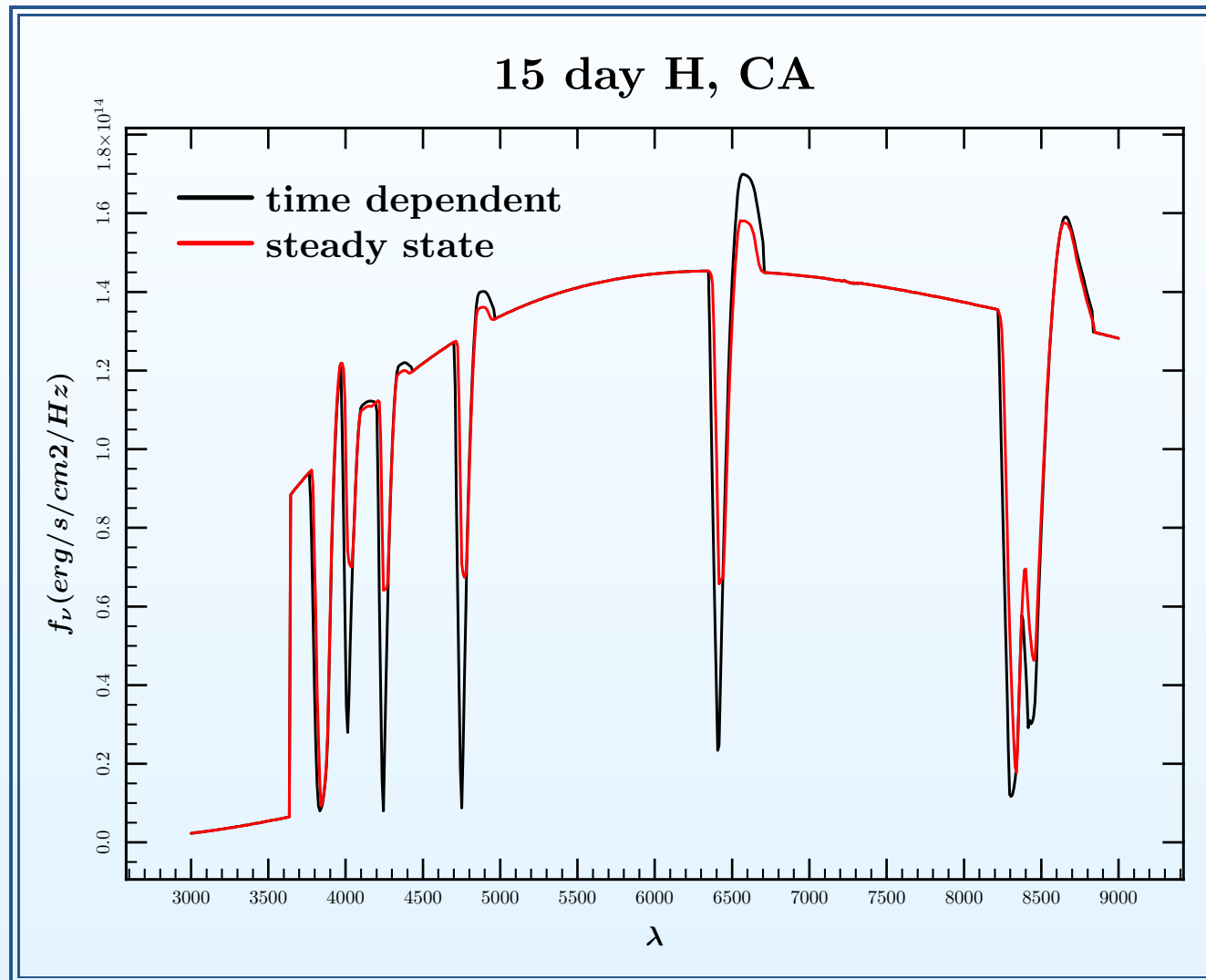
# Steady state, multiplet coupling at 15 Day



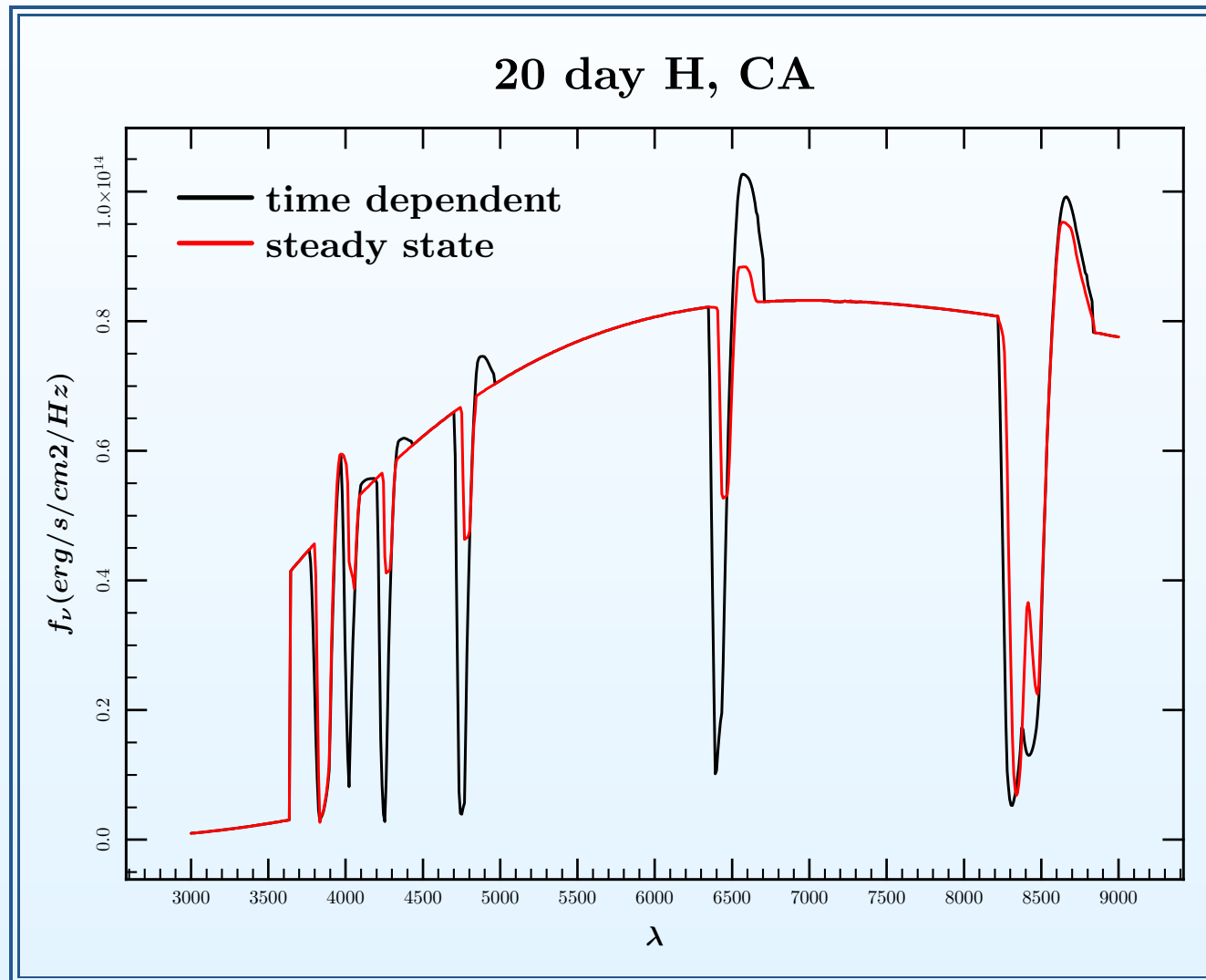
# Time dependent, multiplet coupling at 15 Day



# All, multiplet coupling at 15 Day

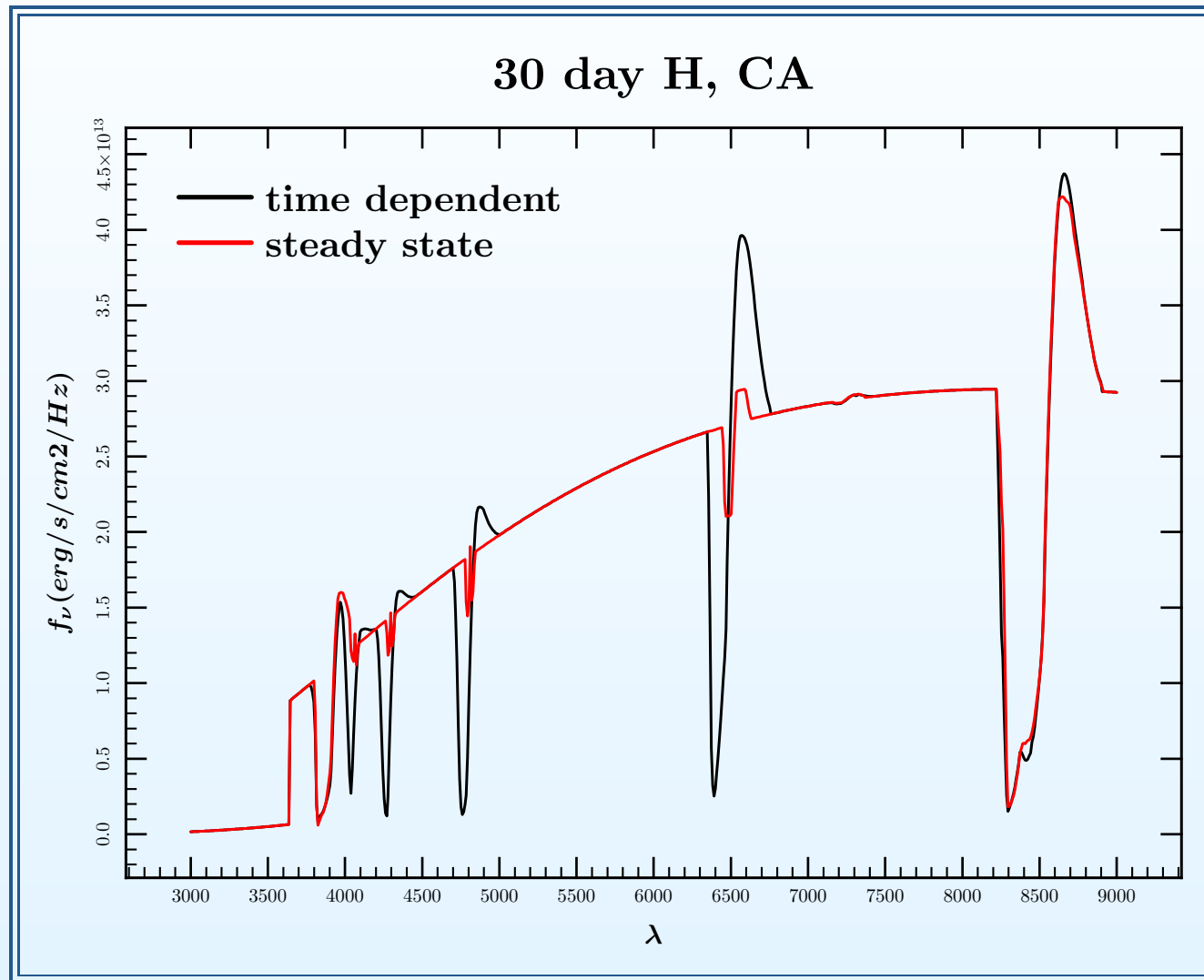


# 20 Day

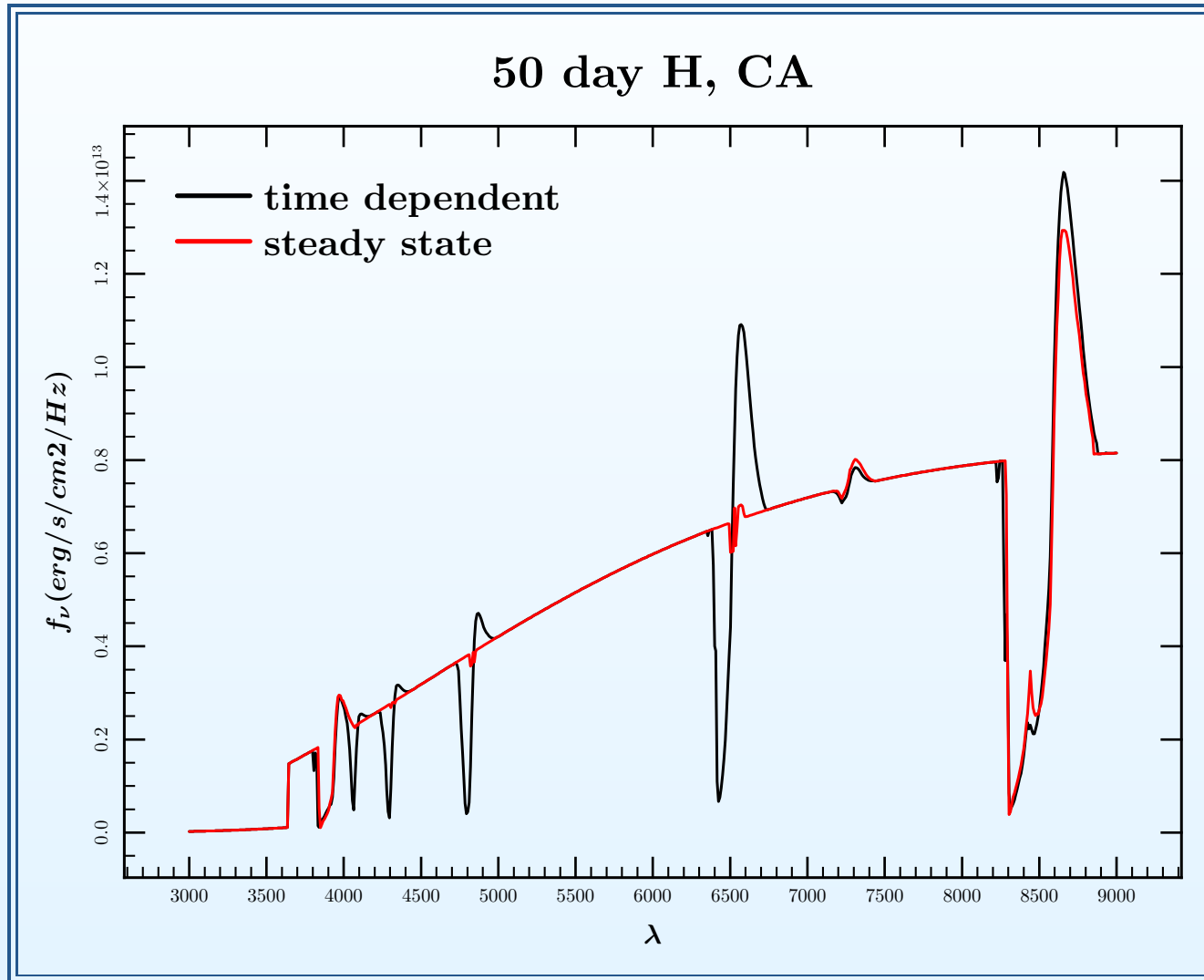




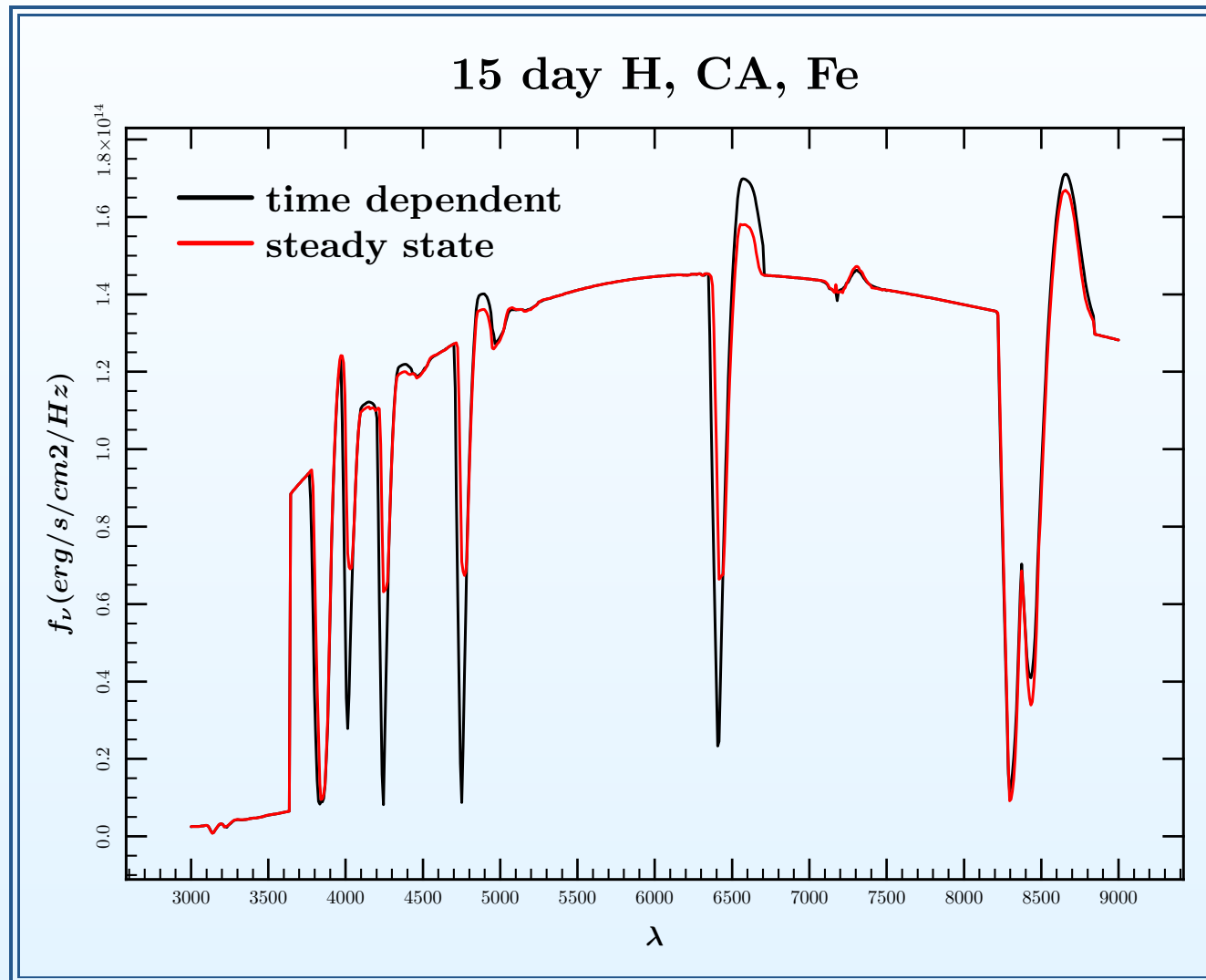
# 30 Day



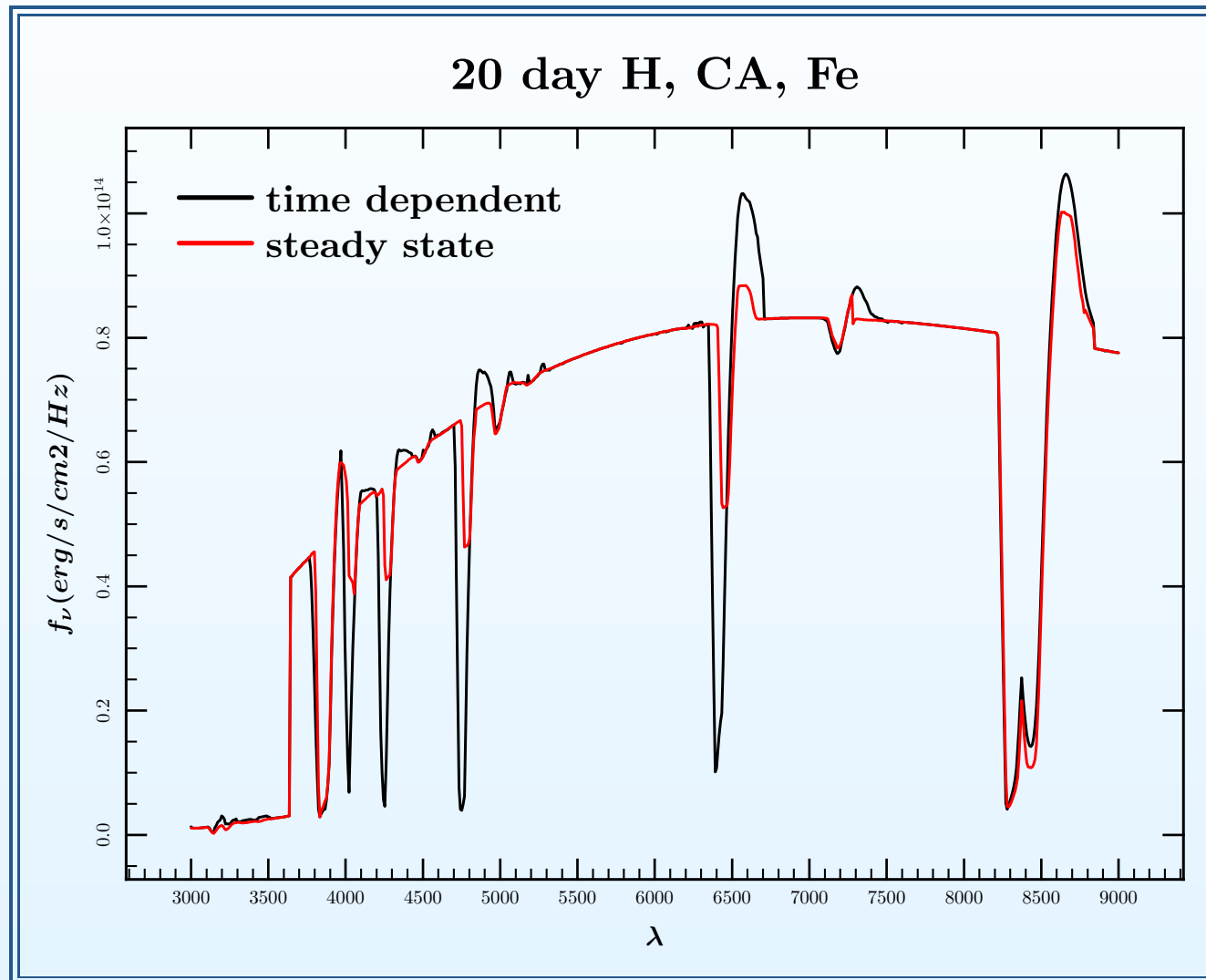
# 50 Day



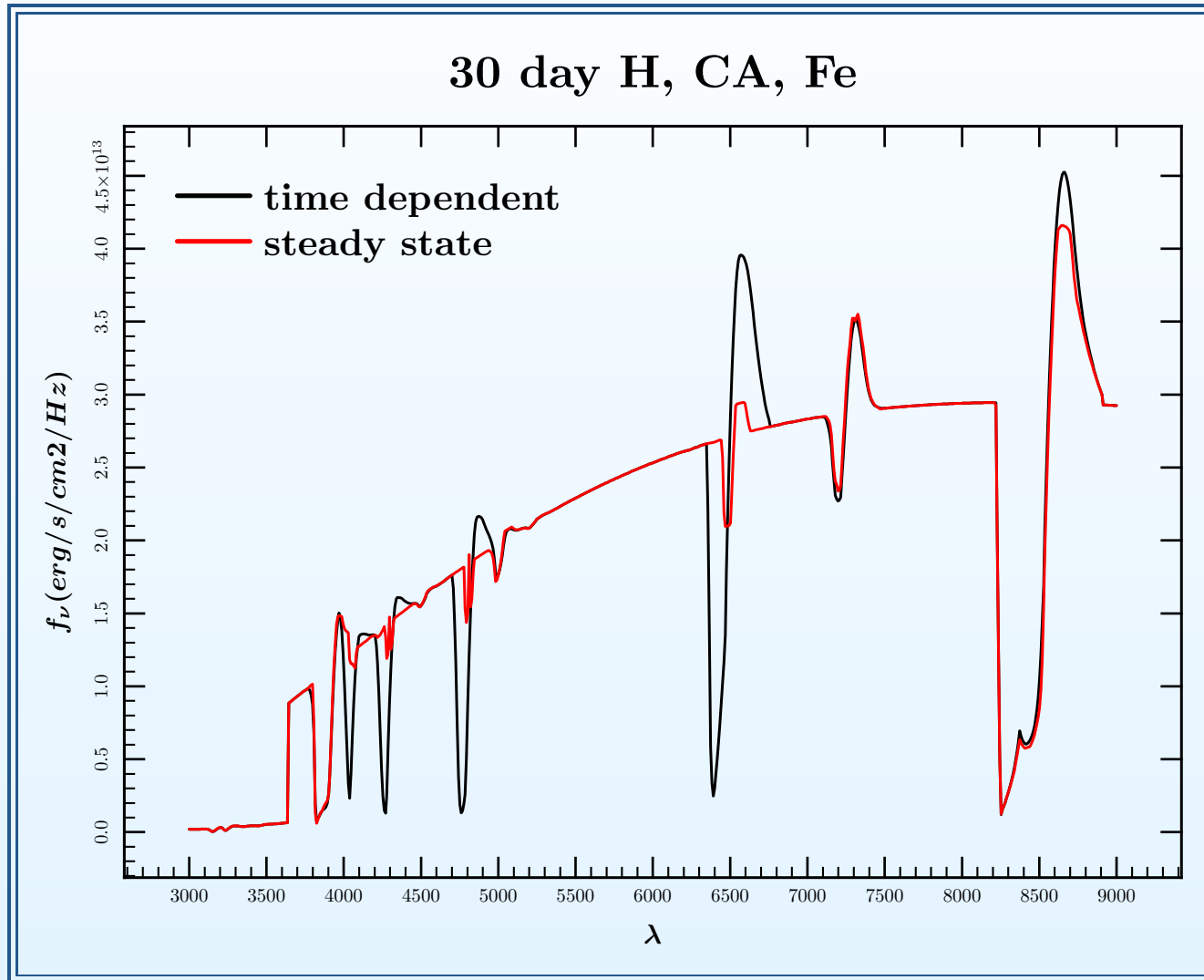
# 15 Day



# 20 Day



# 30 Day



# 50 Day

