Heating/cooling of IGM due to Lyman-α Photons during Cosmic Dawn

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with

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Advanced 21-cm Cosmology workshop

20th December, 2023

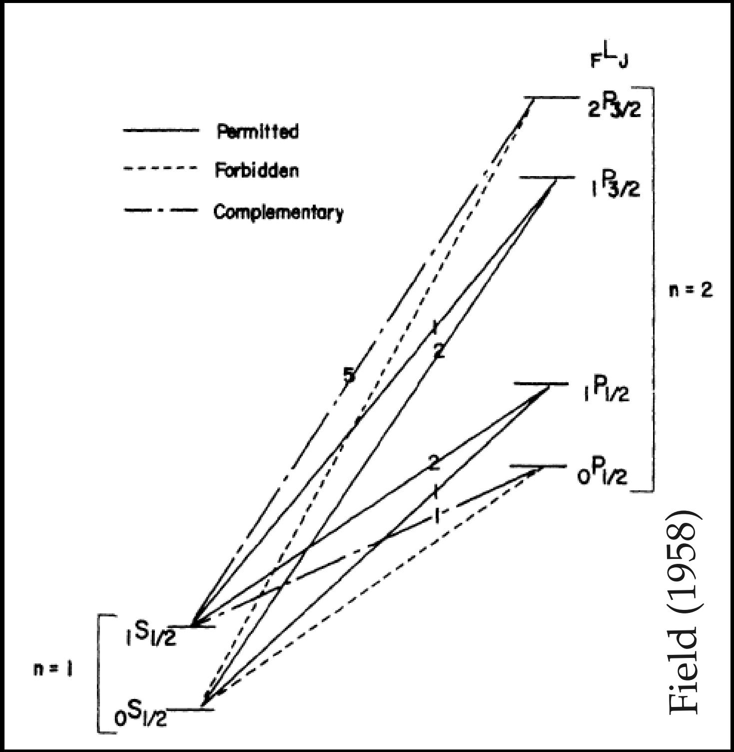
Outline

- The 21-cm Signal and Lyman-α photons cosmic dawn
- Injected and Continuum Lyman-α photons
- Shape of Lyman-α photons profiles and quasi-static solution
- Energy exchange between Lyman-α photons and HI atoms
- Coupled evolution of temperature and Lyman-α profile with time

Lyman-α Photons and 21-cm Signal from Cosmic Dawn

$$\Delta T_B \simeq 27\ \mathrm{mK}\ x_{\mathrm{HI}}(1+\delta)\left(1-\frac{T_{\mathrm{CMB}}}{T_S}\right)\left(1+\frac{1}{H}\frac{\mathrm{d}v_p}{\mathrm{d}s}\right)^{-1}\left(\frac{1+z}{10}\right)^{\frac{1}{2}}\left(\frac{0.14}{\Omega_m h^2}\right)^{\frac{1}{2}}\left(\frac{\Omega_b h^2}{0.022}\right)$$

- Photons with frequencies between Lyman-α and Lyman-limit escape the source halo and free stream into the medium
- When they redshifts into one of the Lyman series lines, they are absorbed by the HI atoms in the IGM.
- They undergo multiple scatterings before being redshifted out of the resonance width. These scatterings couple the spin temperature T_S to T_K :



Field (1958)

$$T_{\mathrm{S}} = \frac{T_{\mathrm{CMB}} + y_c T_{\mathrm{K}} + y_\alpha T_\alpha}{1 + y_c + y_\alpha}$$

$$y_\alpha \simeq 5.9 \times 10^{11} \frac{n_\alpha}{T_K^{3/2}}$$

Pritchard and Loeb (2012)

Time evolution of Lyman-α photons intensity profile

- Diffusion equation with Fokker-Planck approximation:

$$\frac{\partial J(x,t)}{\partial t} = \frac{1}{2}\frac{\partial}{\partial x}\left[\phi(x)\frac{\partial J}{\partial x}\right] + \gamma\frac{\partial J}{\partial x} + \eta\frac{\partial}{\partial x}[\phi J] + C(t)$$

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diffusion term redshift recoil source function

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diffusion term

redshift

recoil

source function

$$x = \frac{\nu - \nu_\alpha}{\Delta\nu_D}$$

$$\Delta\nu_D = \nu_\alpha\frac{v_T}{c} = \sqrt{\frac{2k_B T_K}{m_p c^2}}\nu_\alpha$$

$$\eta = \frac{h_p \nu_\alpha}{c\sqrt{2k_B T_K m_p}}$$

$$\phi(x,a) = \frac{a}{\pi^{3/2}}\int_{-\infty}^{\infty}\frac{\exp(-y^2)}{a^2 + (x-y)^2}\mathrm{d}y$$

$$\gamma = \frac{1}{\tau_{\mathrm{GP}}} = \frac{m_e \nu_\alpha}{\pi e^2 f_\alpha}\frac{H(z)}{n_{\mathrm{HI}}}$$

$$a = \frac{A_\alpha}{4\pi\Delta\nu_D}$$

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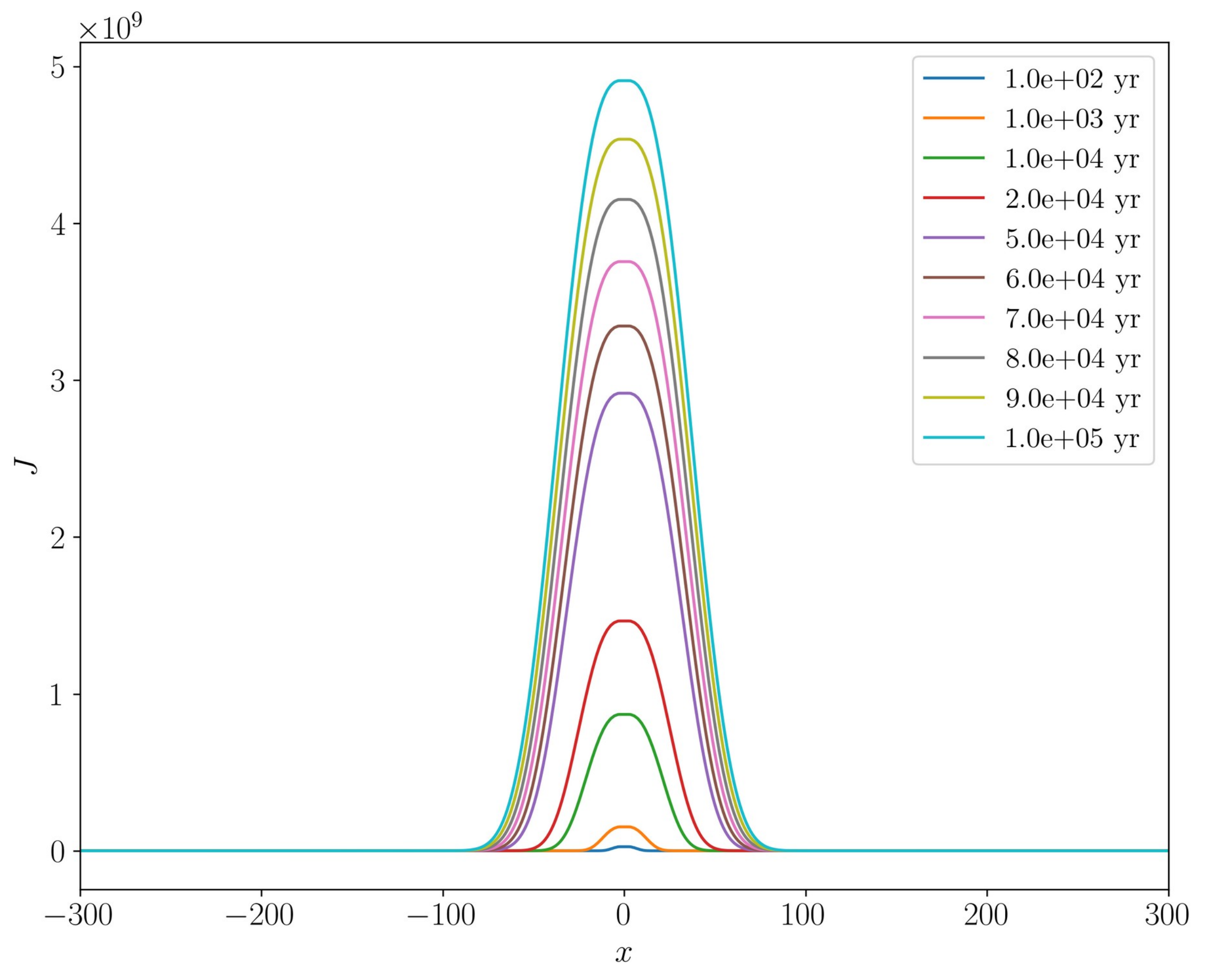
diffusion term redshift recoil source function

- **Continuum photons**:
  - Photons which have redshifted into the Lyman-α line
- **Injected photons**:
  - Photons which are injected at the Lyman-α line centre due to de-excitation of HI atoms

Injected Photons profile shape



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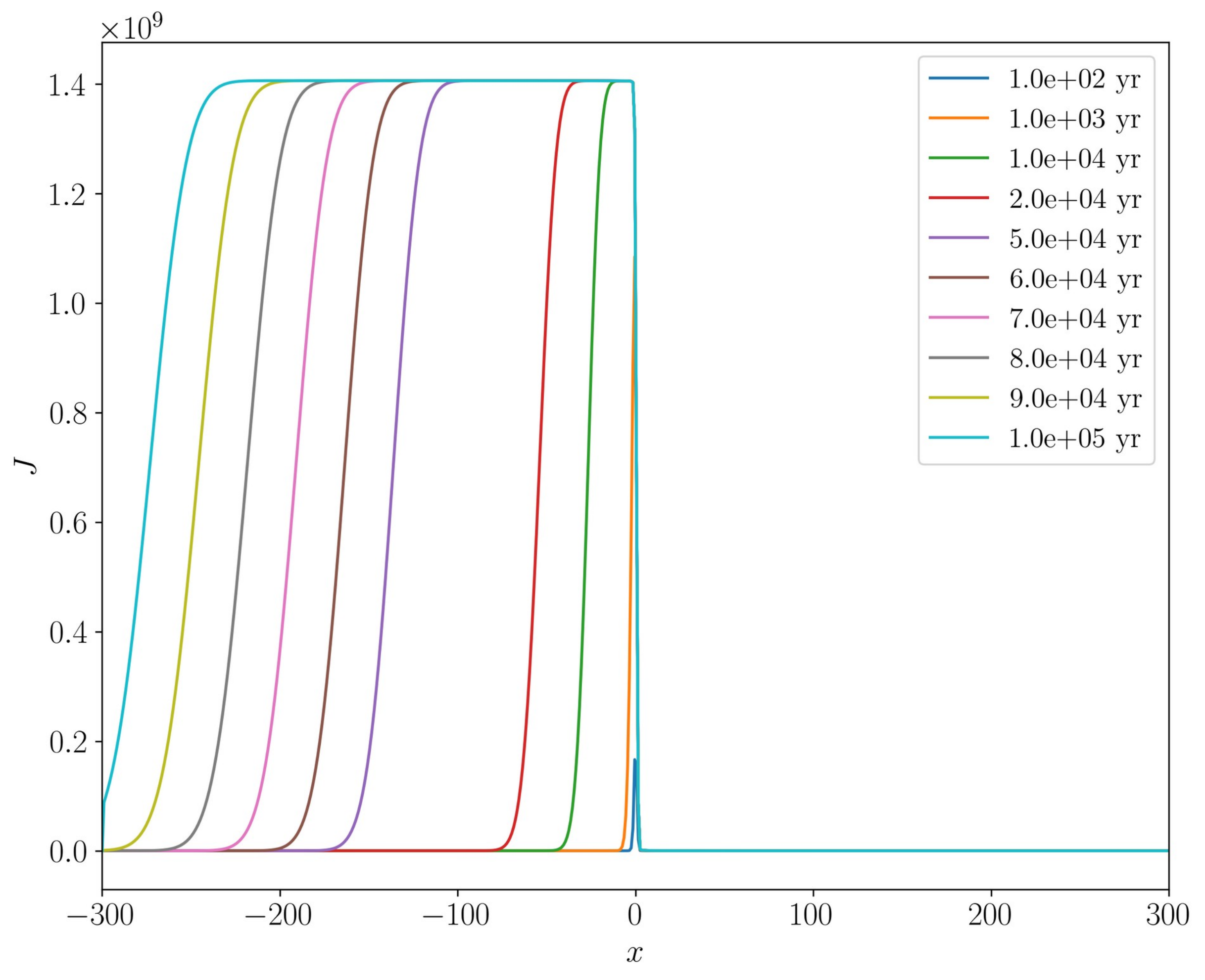

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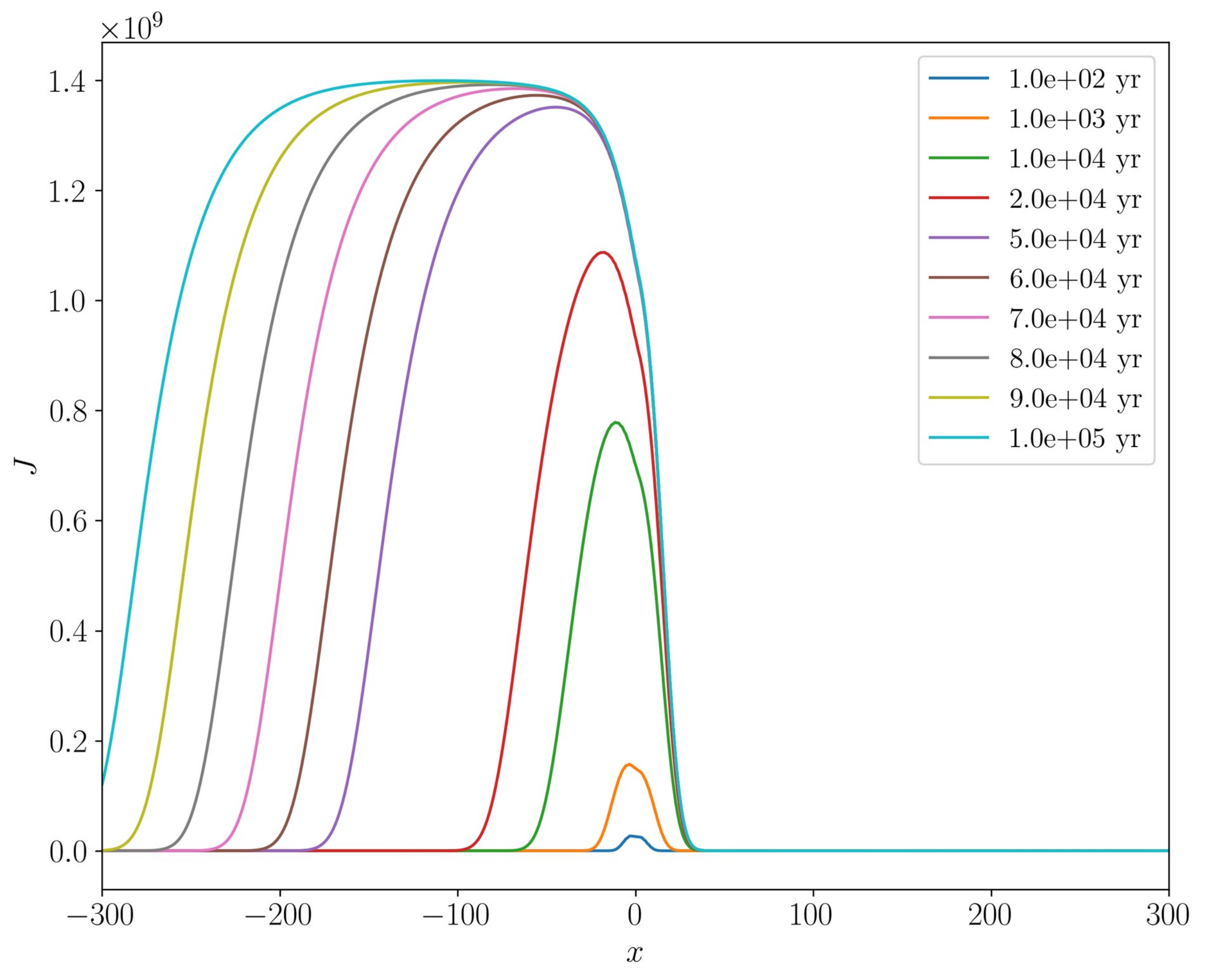

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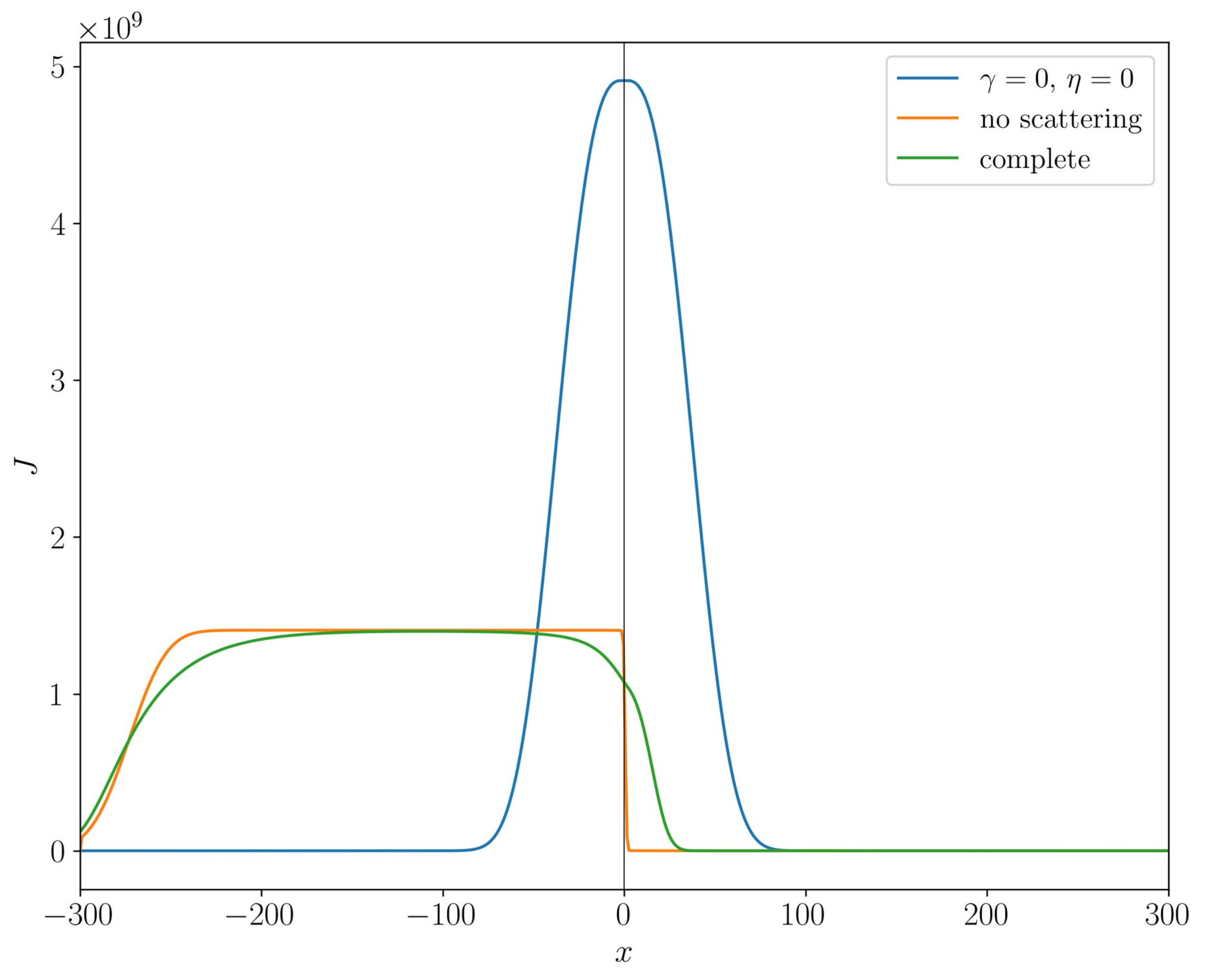
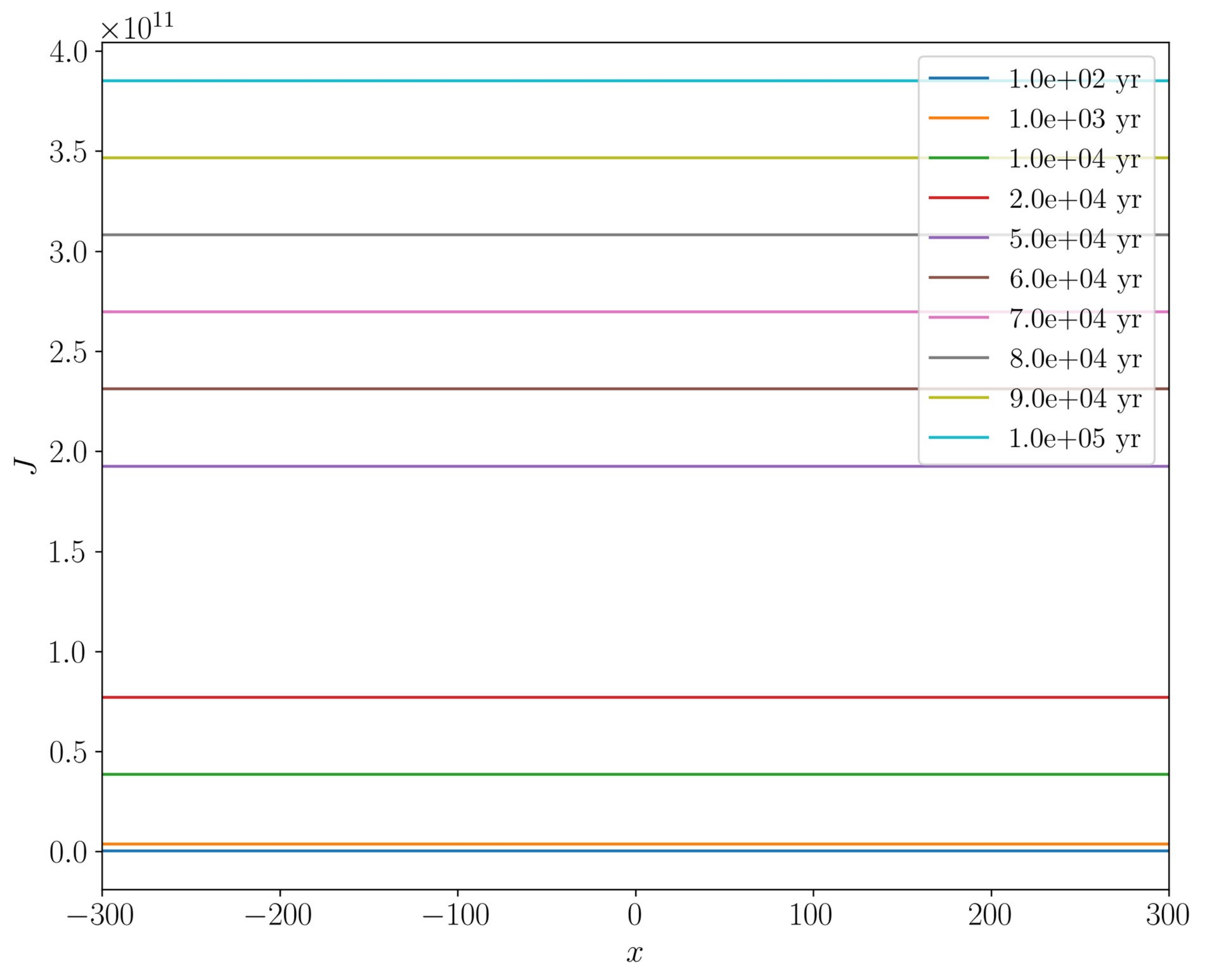


Continuum Photons profile shape



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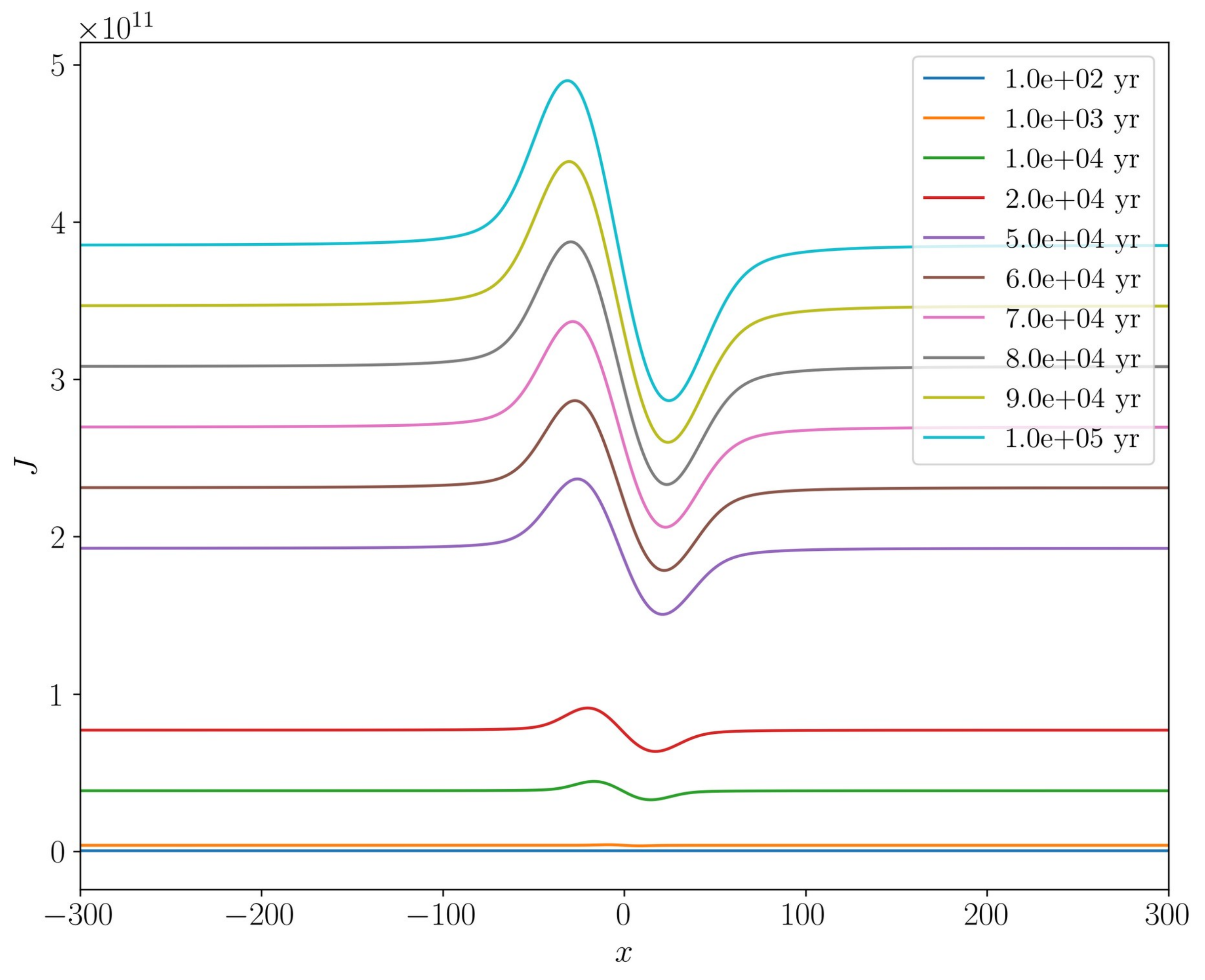

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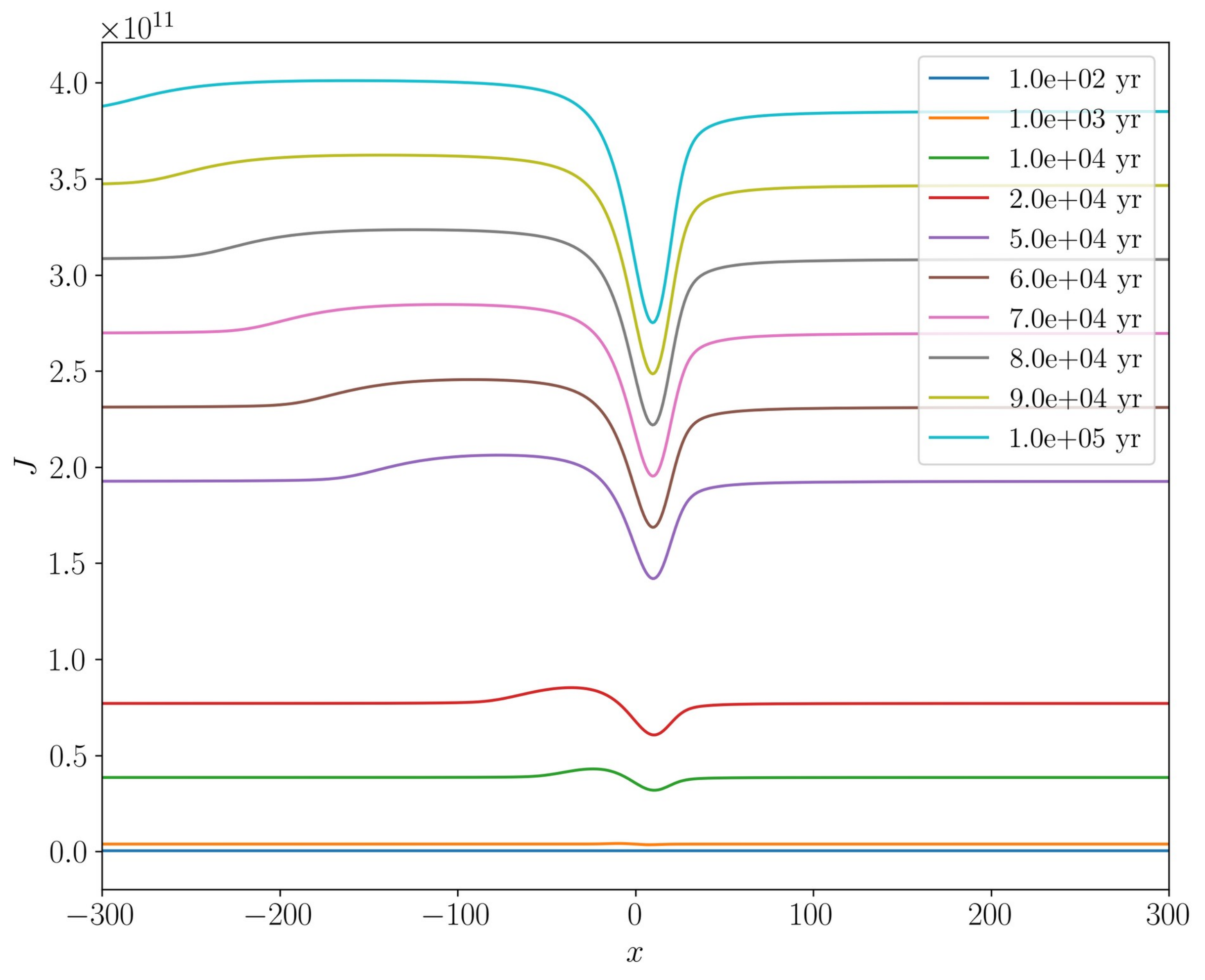

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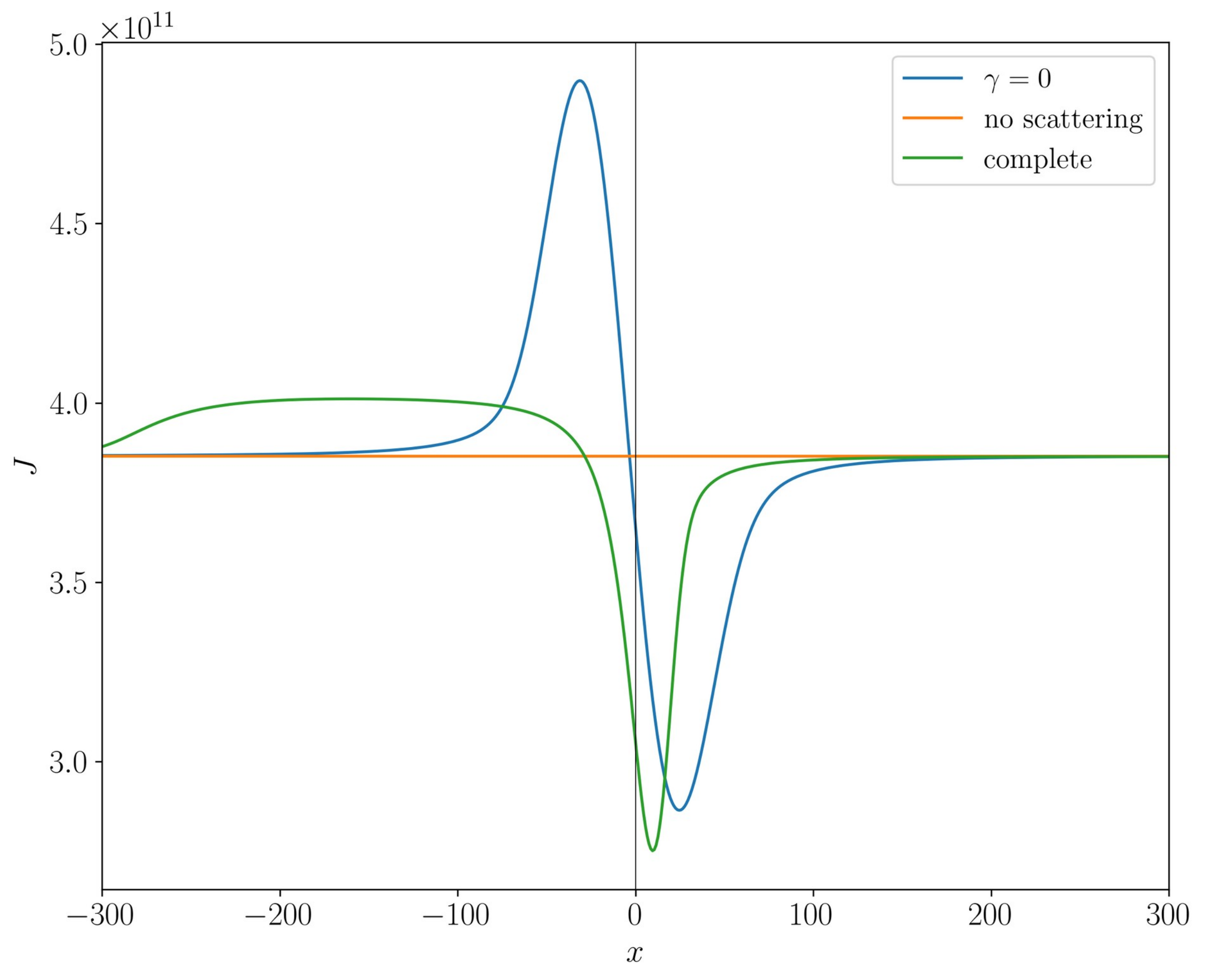

Energy exchange between Lyman-α Photons and HI atoms

- During the repeated scattering process, the Lyman-α photons also exchange energy with the medium.
    - Compton and inverse-compton scattering between Lyman-α photons and HI atoms
    - Wouthuysen-Field effect in which the energy exchange occurs owing to the change in the level populations of hyperfine states

$$\dot{Q} = \int \frac{(h\nu_\alpha)^2}{m_p c^2}\sigma_0\phi\left(J + \frac{kT_k}{\Delta\nu_D h}J'\right)\mathrm{d}x + \int \frac{(h\nu_{21})^2}{2kT_s}\sigma_0\phi\left(J + \frac{kT_s}{\Delta\nu_D h}J'\right)\mathrm{d}x$$

- **Continuum photons** usually heat up the medium
- **Injected photons** usually cool the medium

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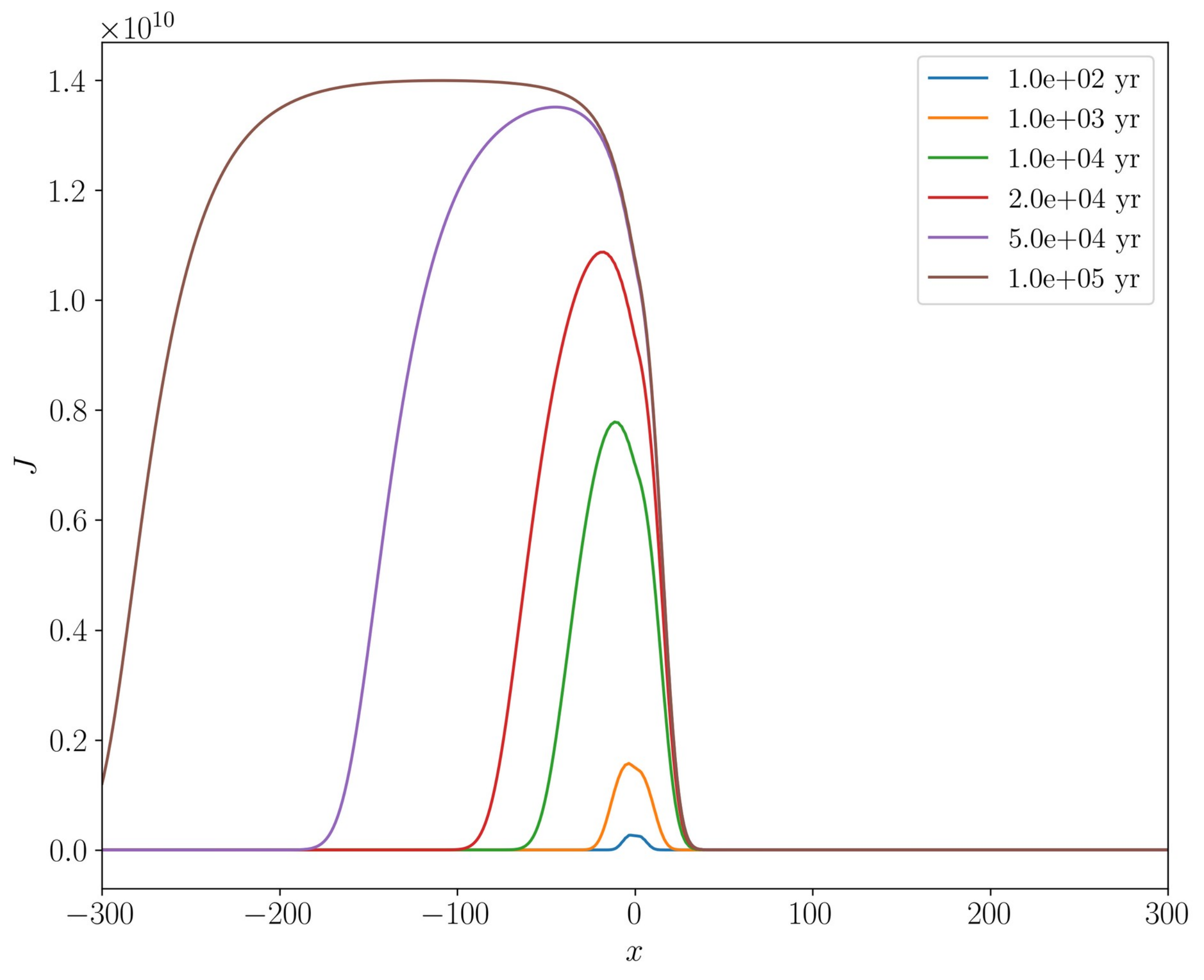
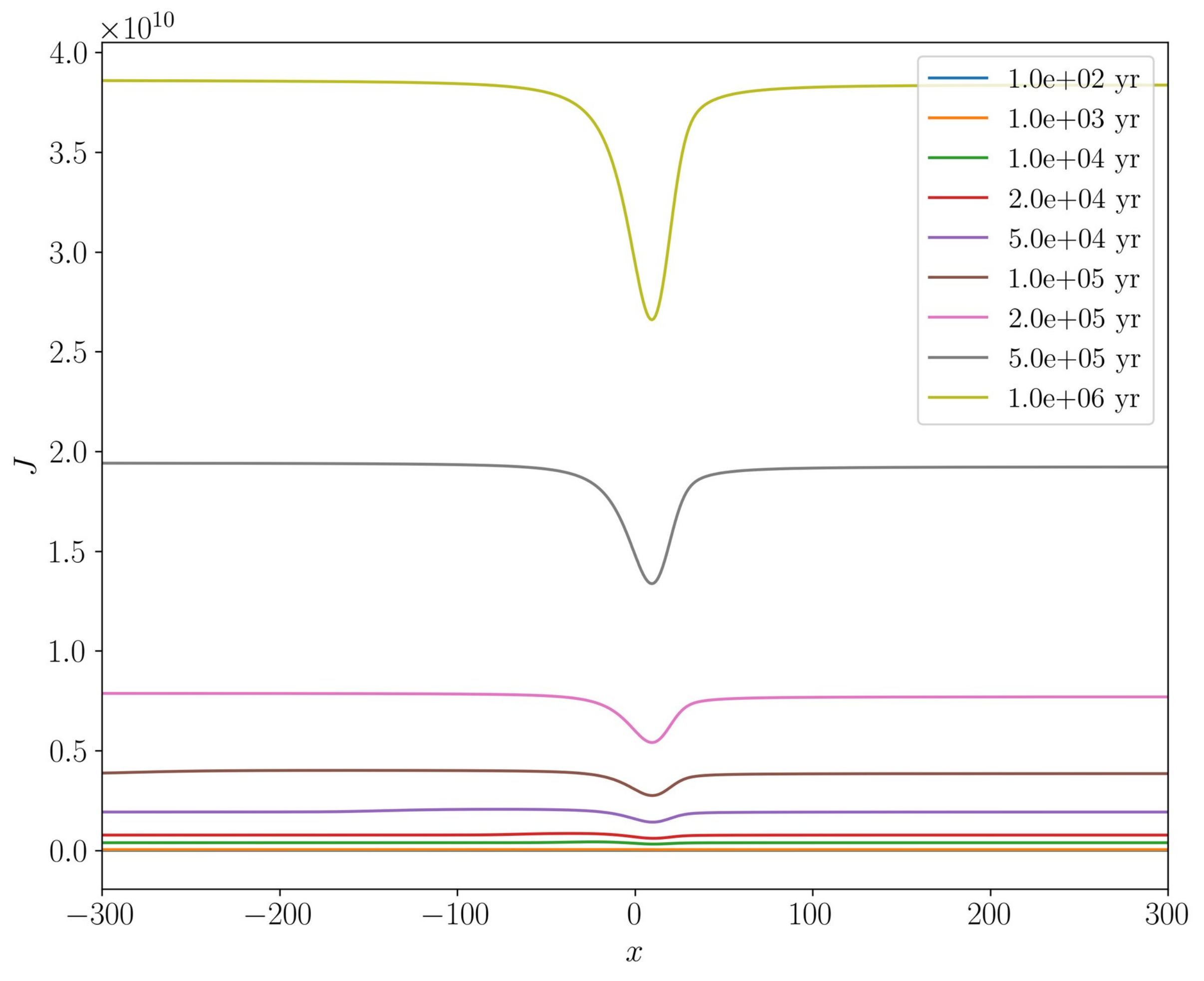
- **Continuum photons** usually heat up the medium
- **Injected photons** usually cool the medium
- **Caveat**: Quasi-static equilibrium of the Lyman-α profile is assumed

Why do Injected Photons Cool?



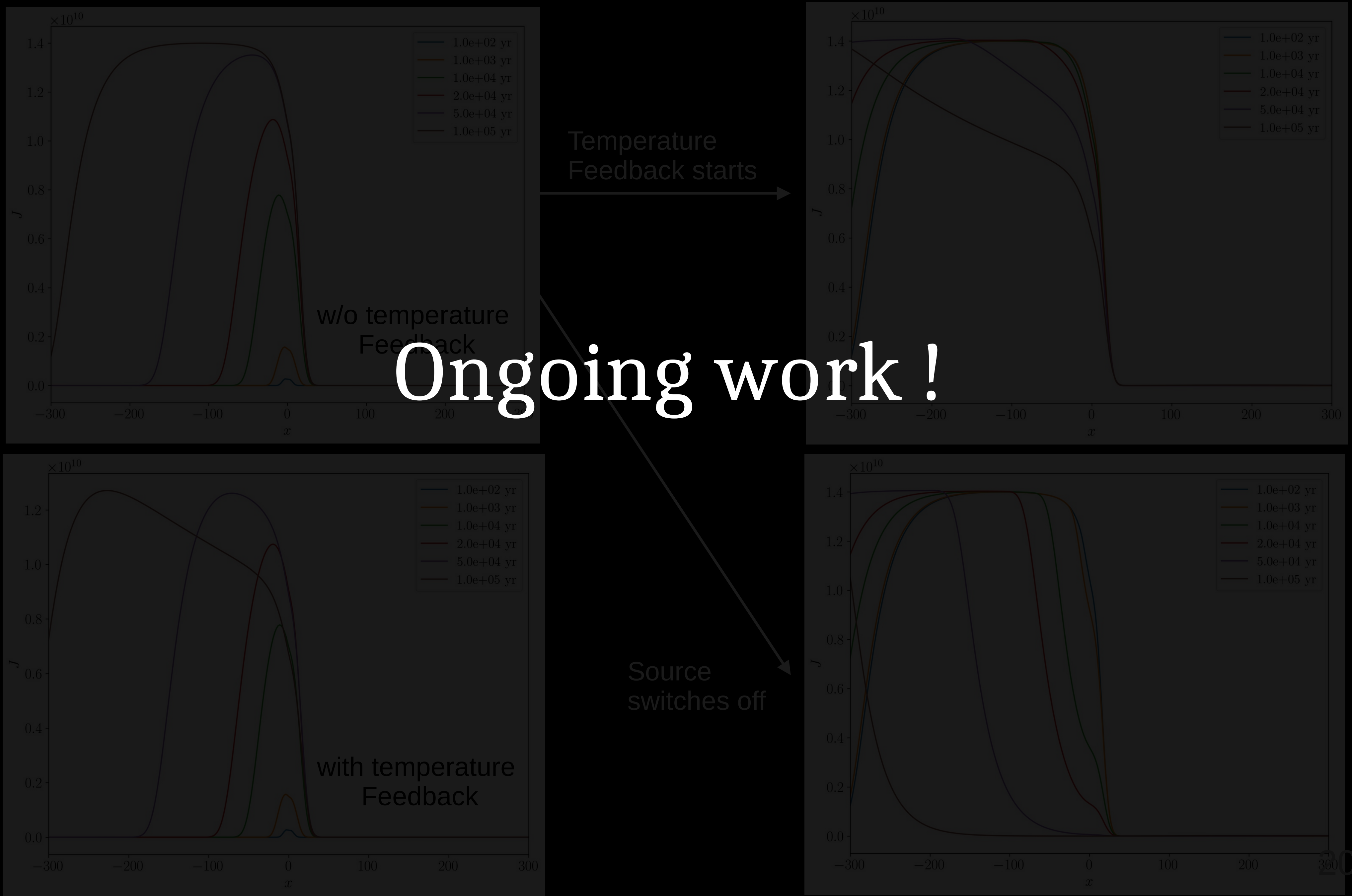
- Photons injected with Voigt profile at the Lyman-α line center.
- Due to redshifting, more redward photons than blueward photons
- More red -> blue scattering
- More cooling

Why do Continuum Photons Heat?



- Photons redshifting into the Lyman-α line.
- More new blueward photons due to redshift
- More blue -> red scattering
- More heating

Fiducial Injected Ly-α profile evolution for z = 20 and T_K = 10 K



w/o temperature Feedback

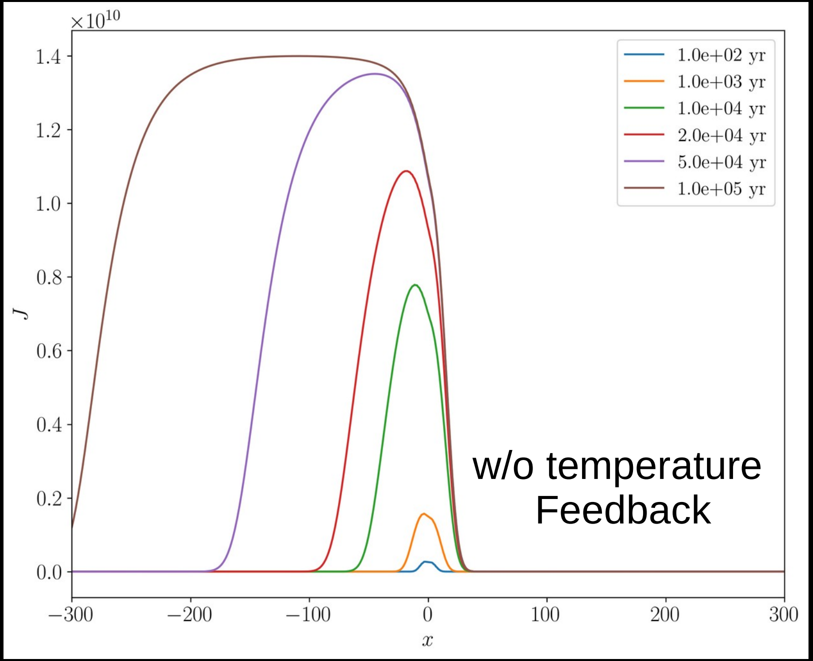
Temperature Feedback starts

with temperature Feedback

Source switches off

Ongoing work !

Fiducial Injected Ly-α profile evolution for $z = 20$ and $T_K = 10$ K



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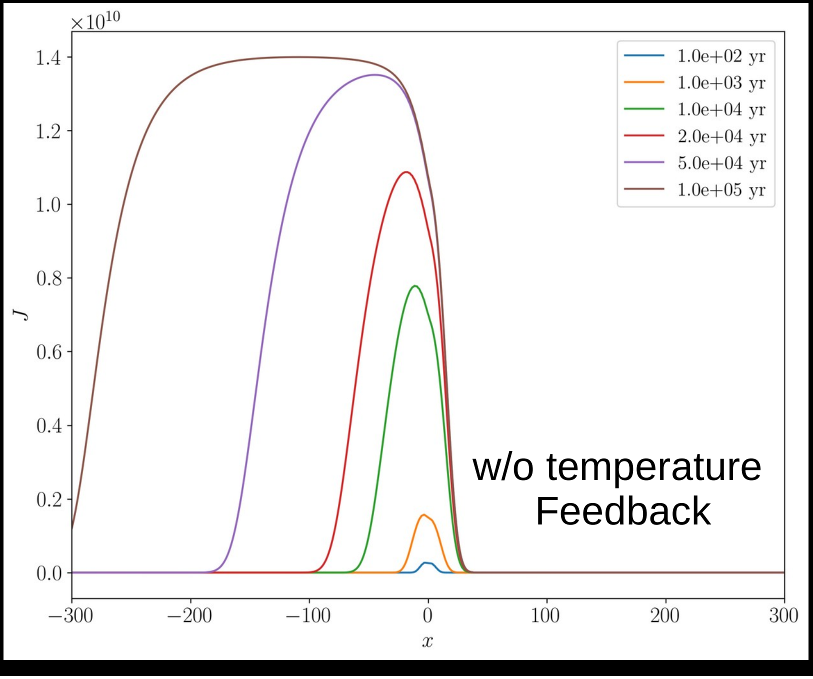

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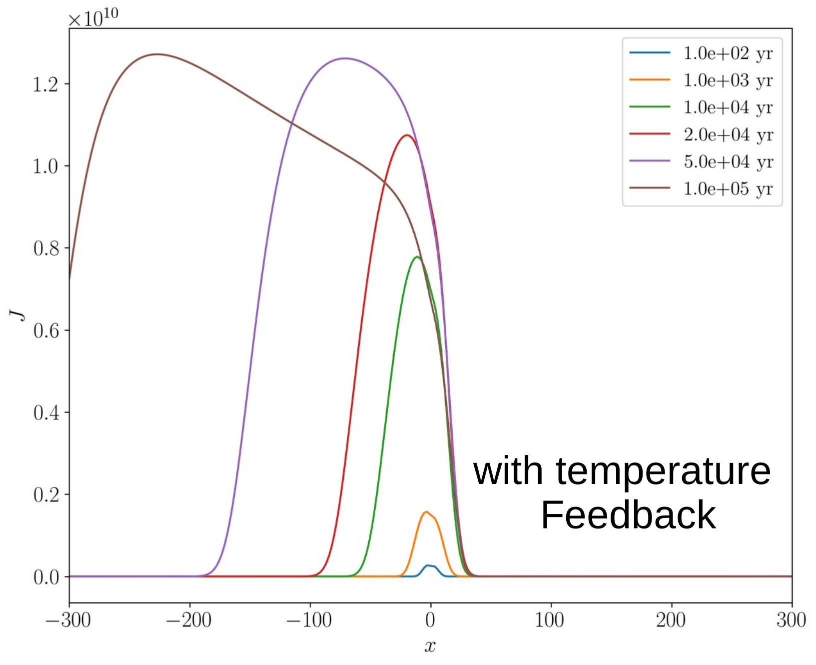

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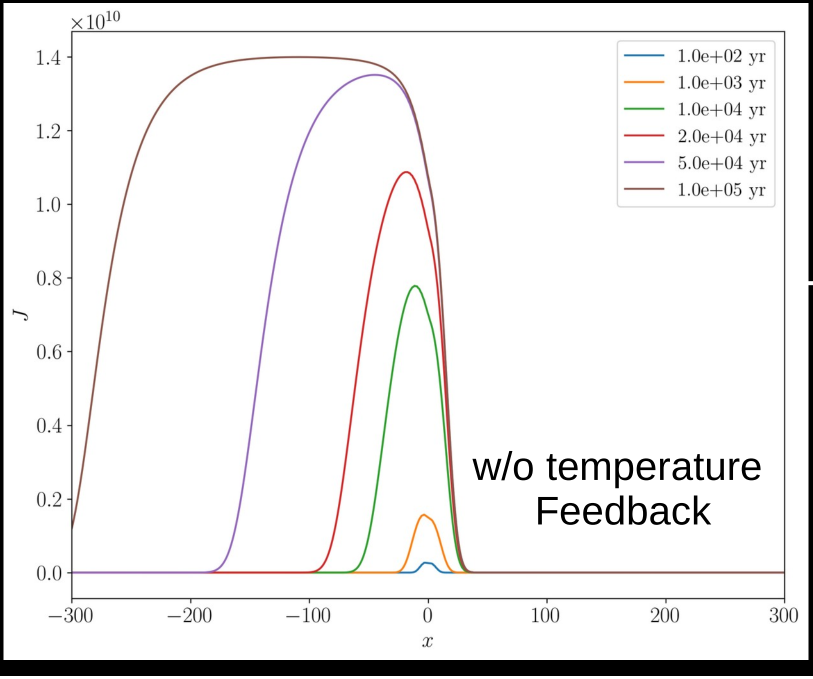

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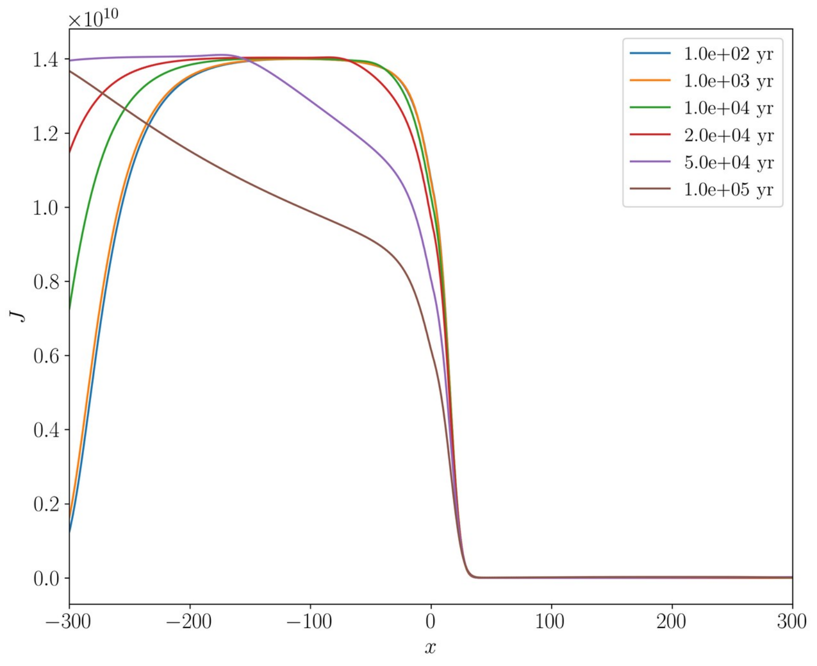

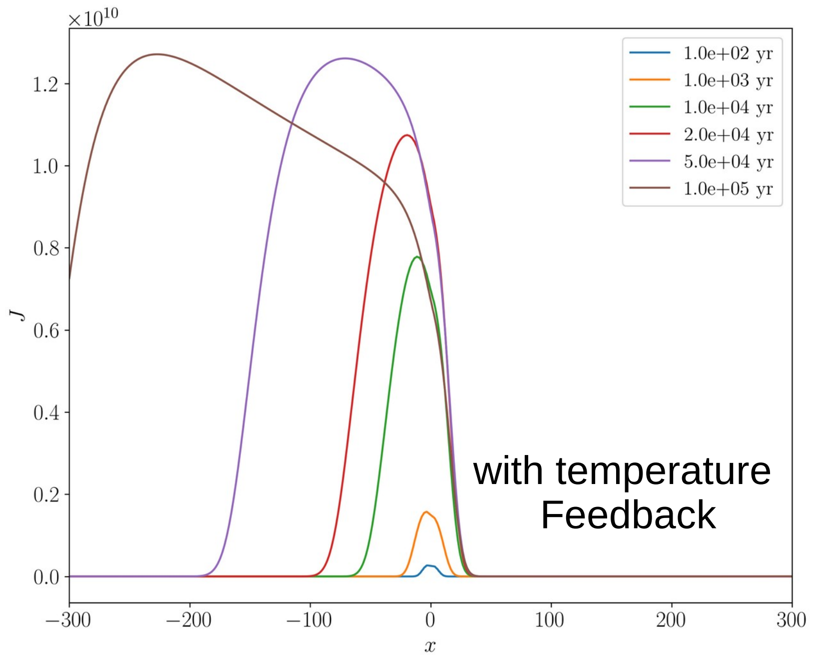

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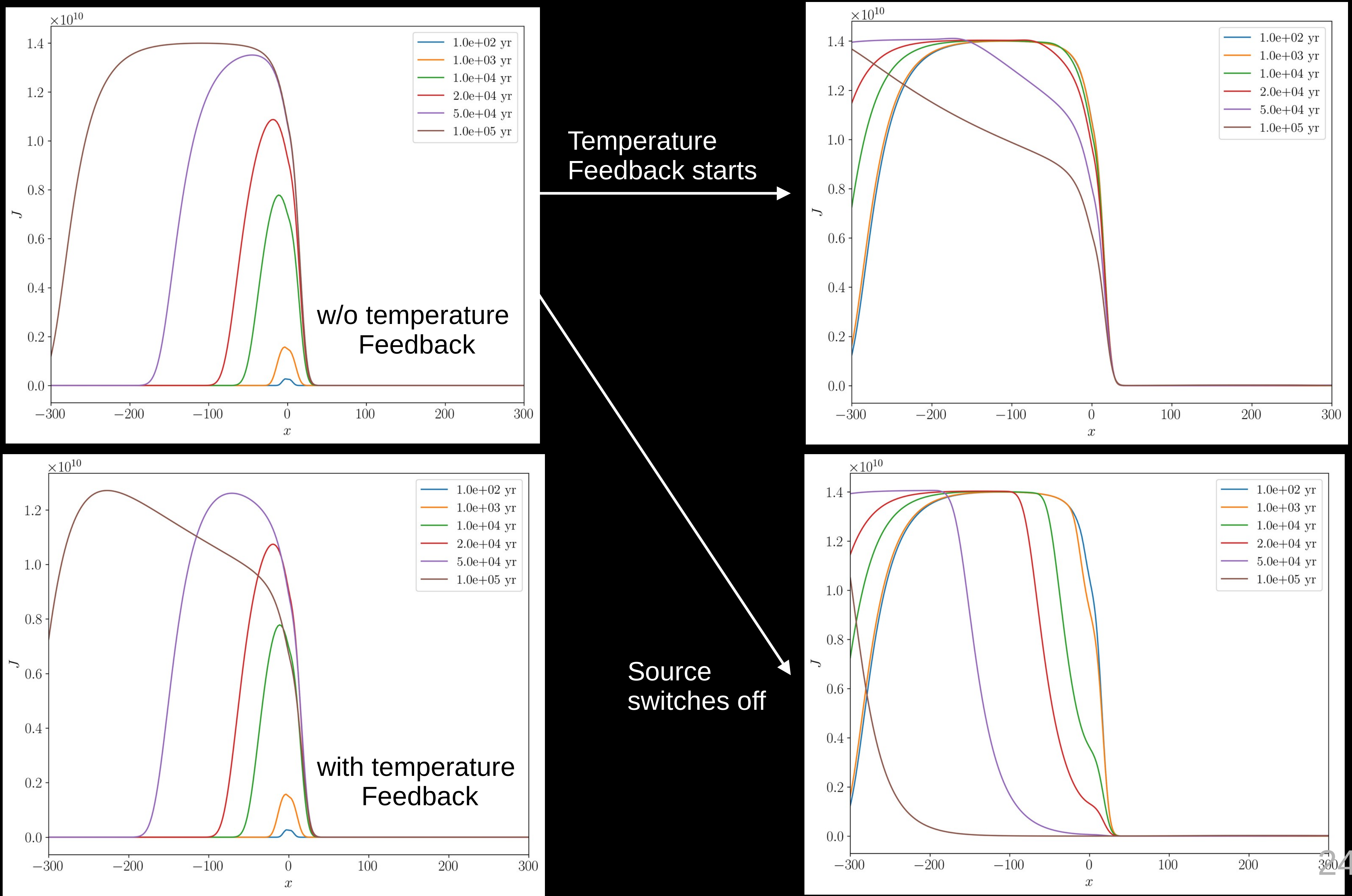

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Source switches off

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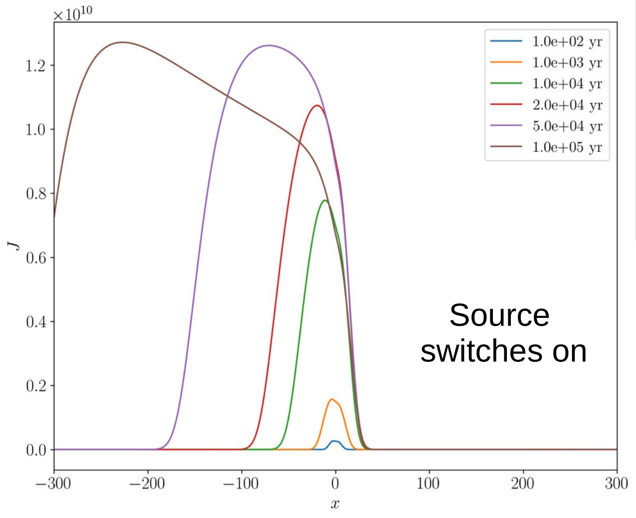

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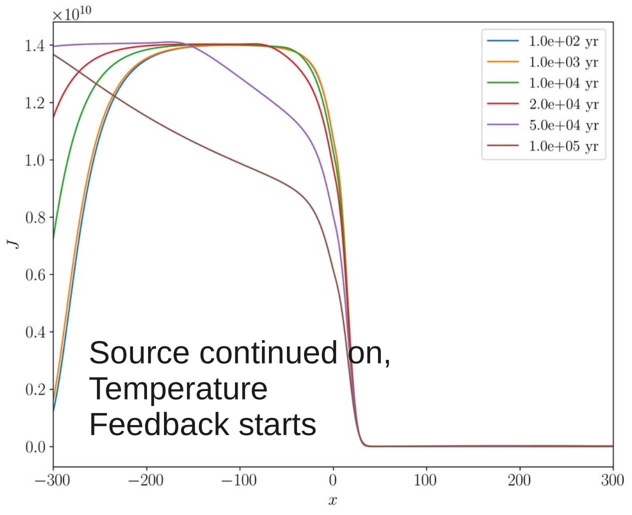

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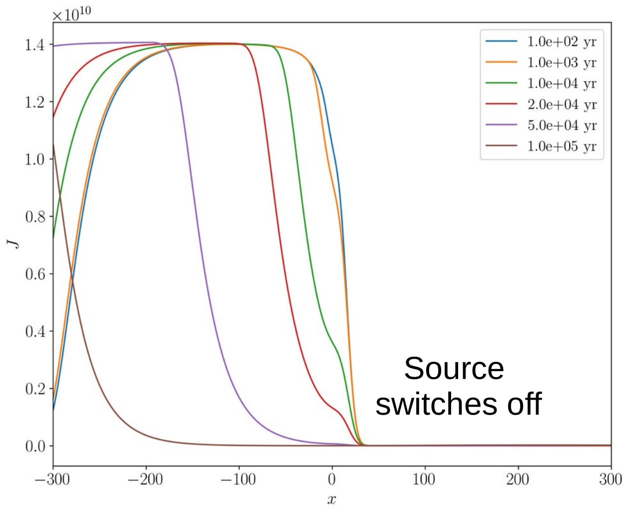
Temperature
Feedback starts



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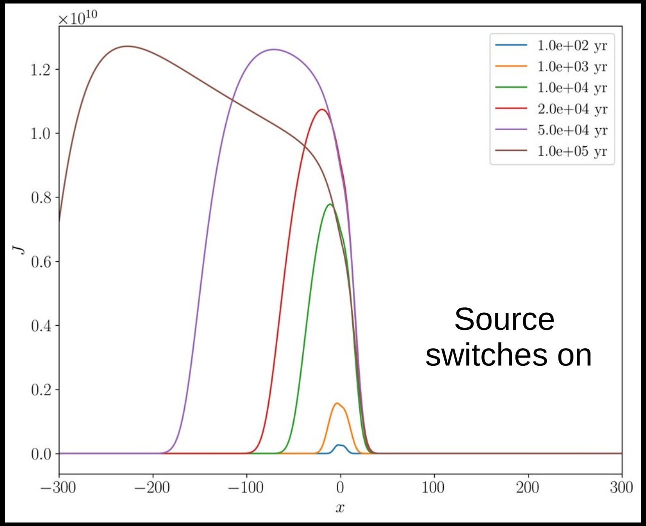

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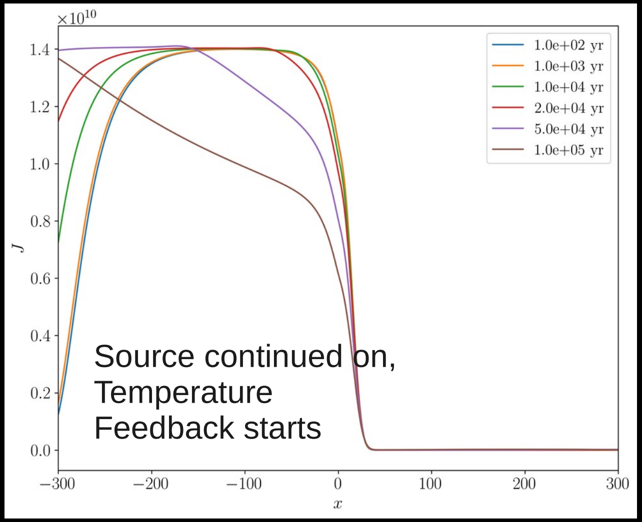

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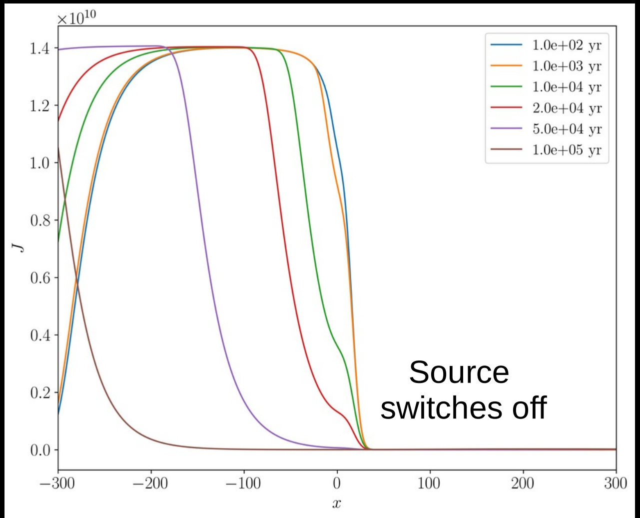

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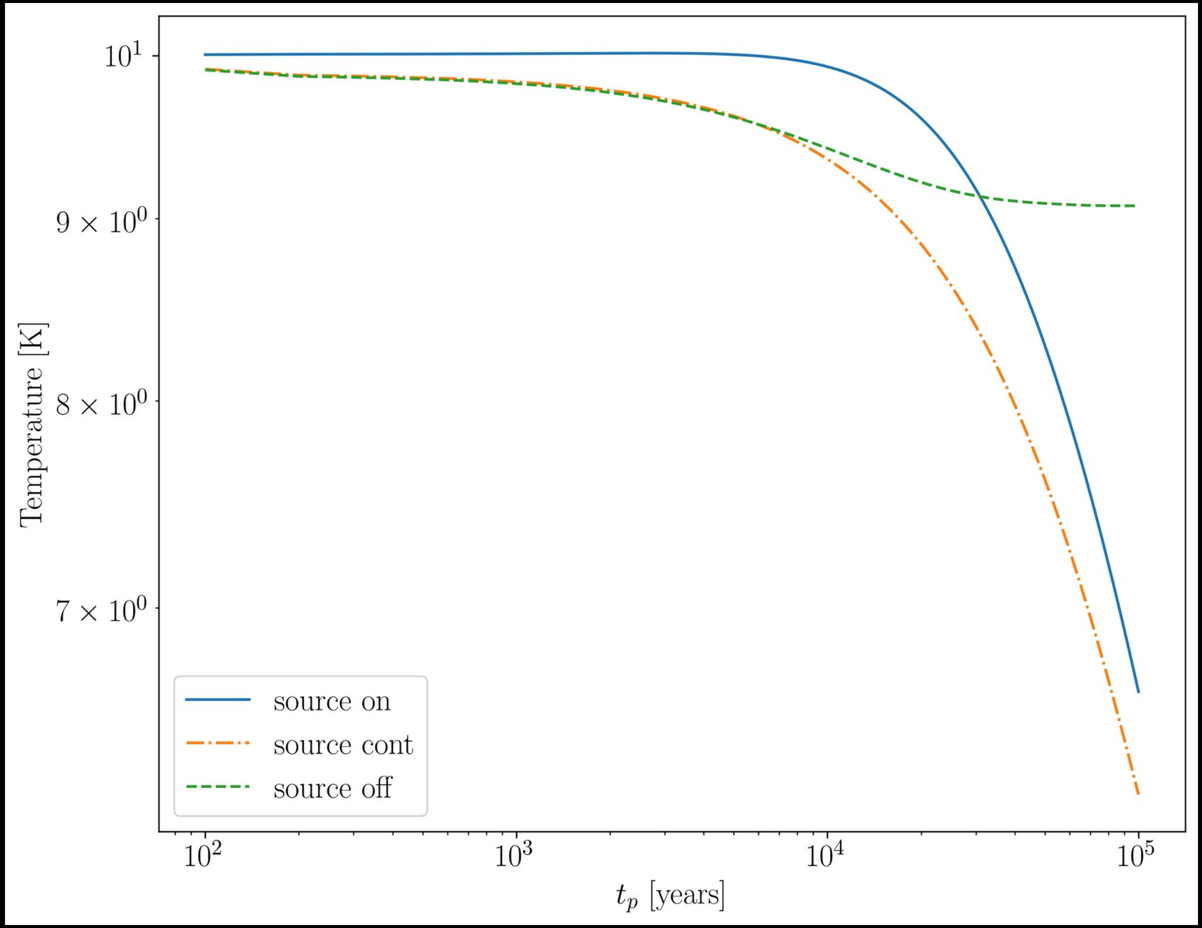
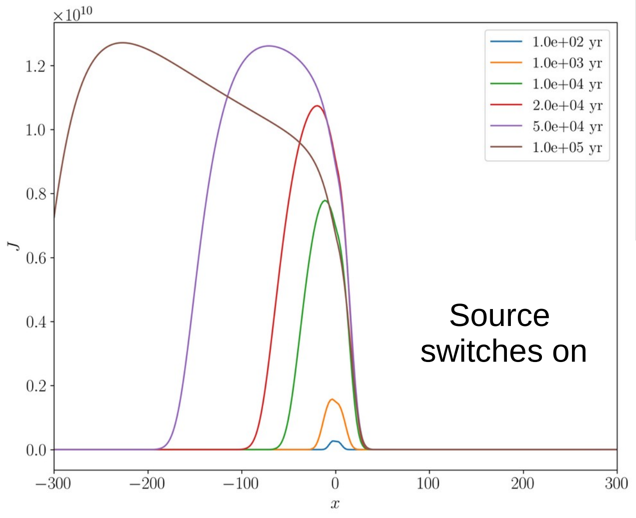


Fiducial Injected Ly-α profile evolution for z = 20 and T_K = 10 K



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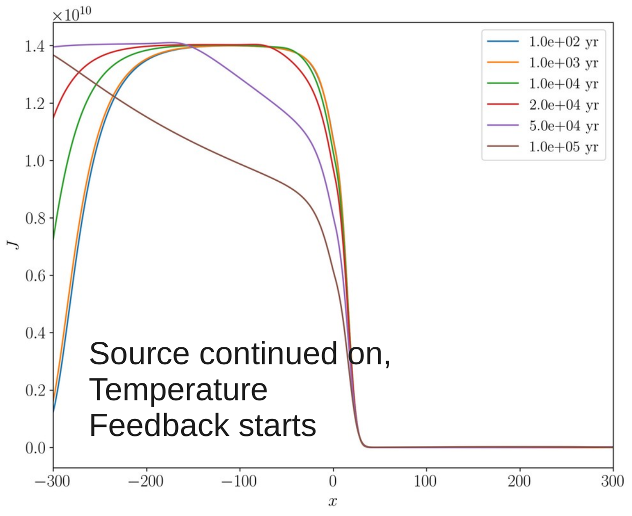

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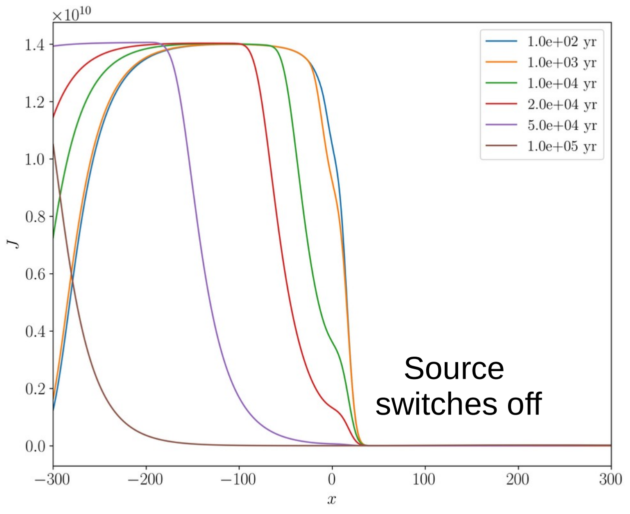

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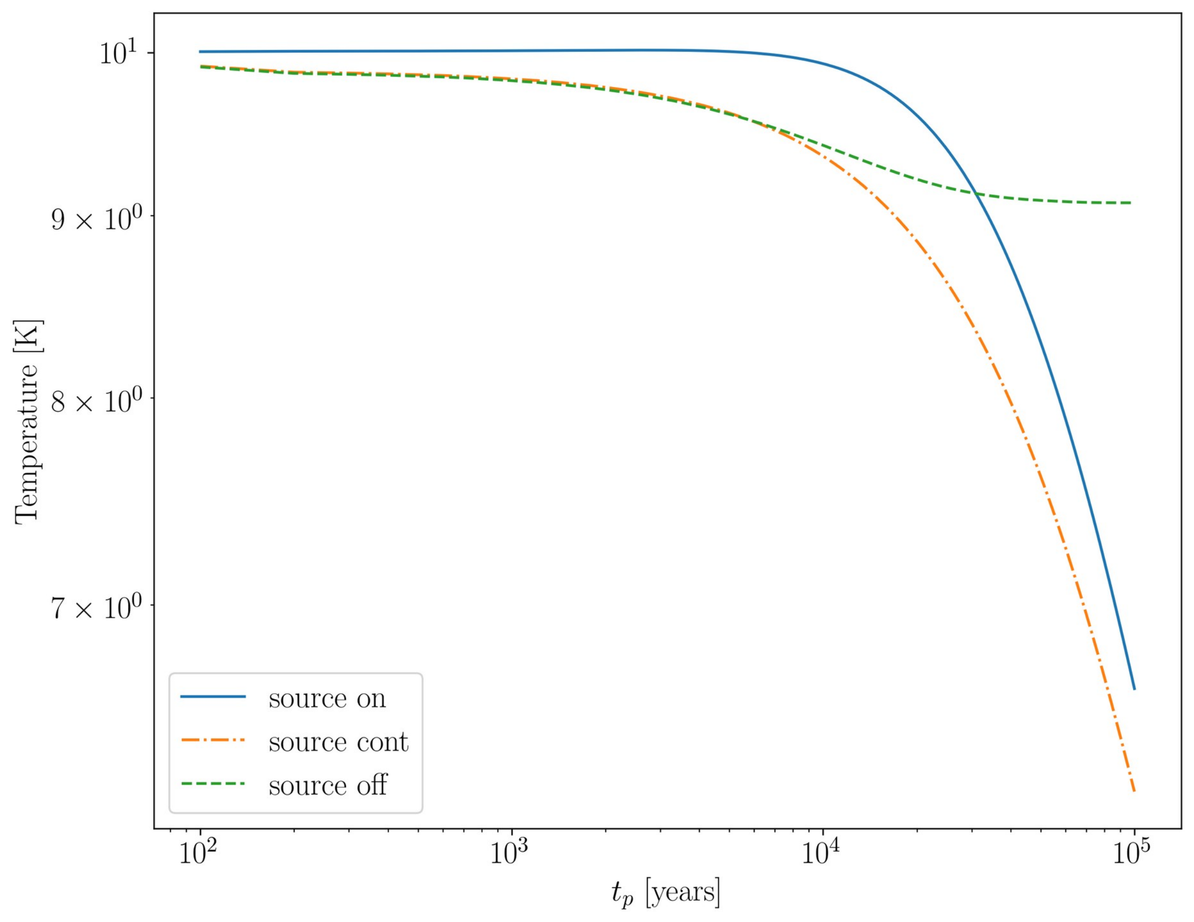
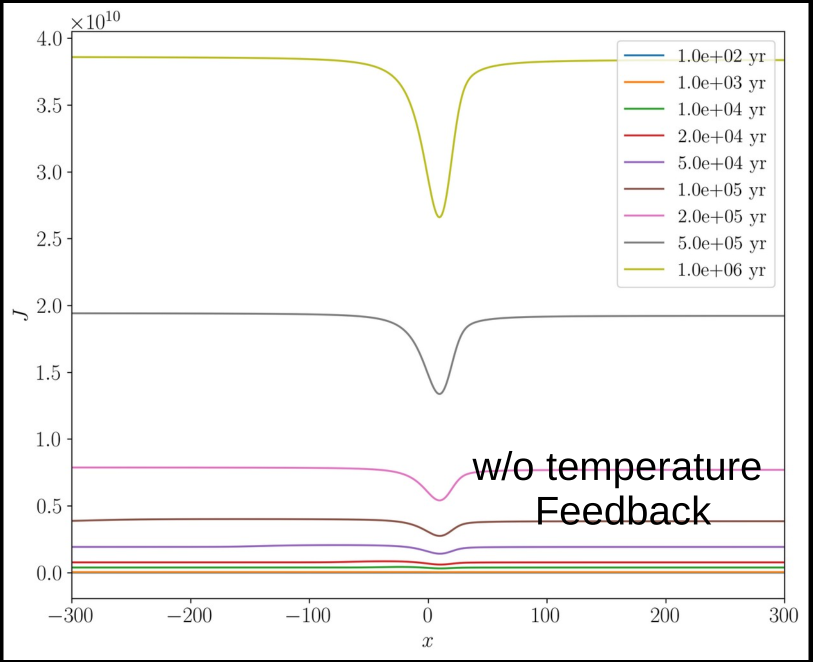


- Temperature feedback, source switching on, switching off delay/prevent quasi-static solution
- Injected photons cause overall less cooling than previously computed in literature.

Fiducial Continuum Ly-α profile evolution for $z = 20$ and $T_K = 10$ K



w/o temperature Feedback

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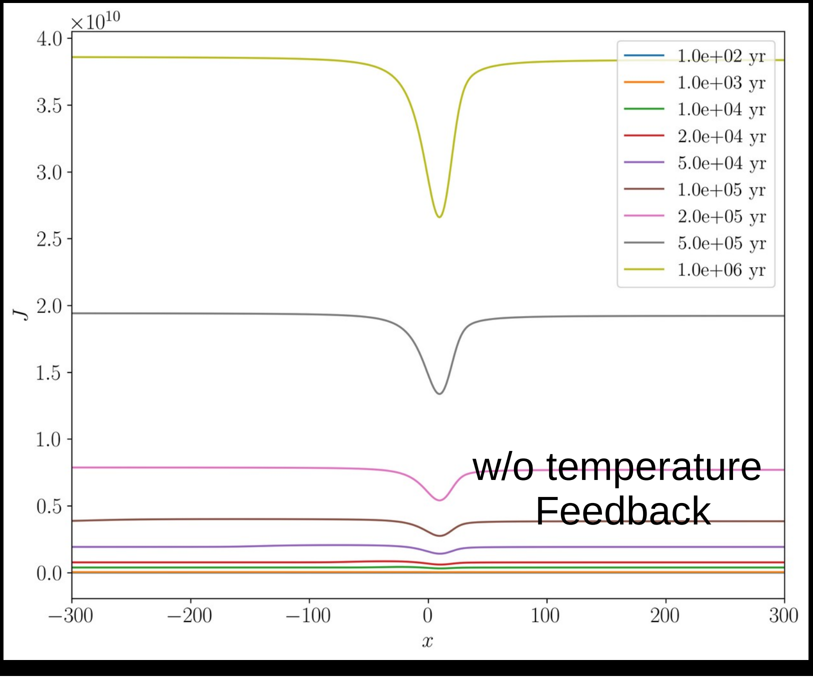

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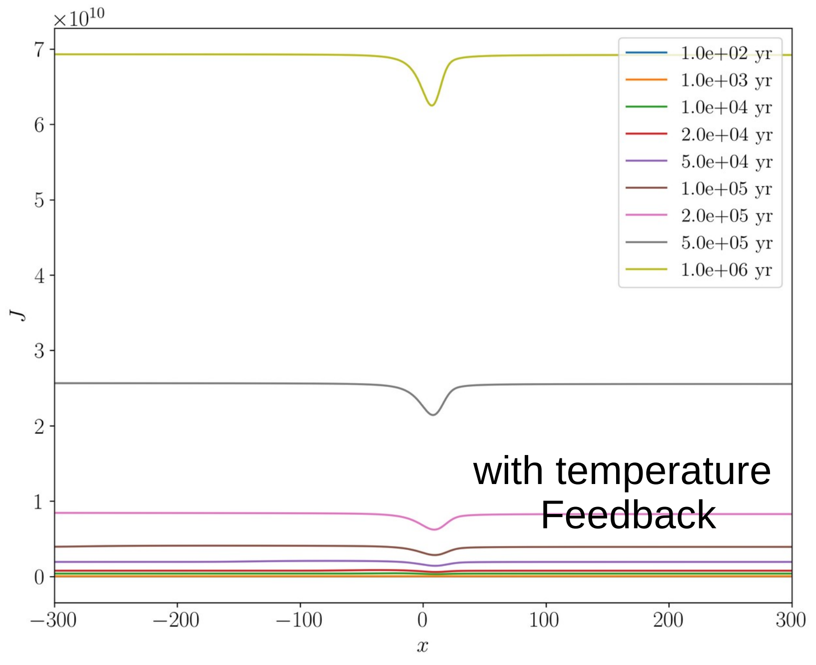

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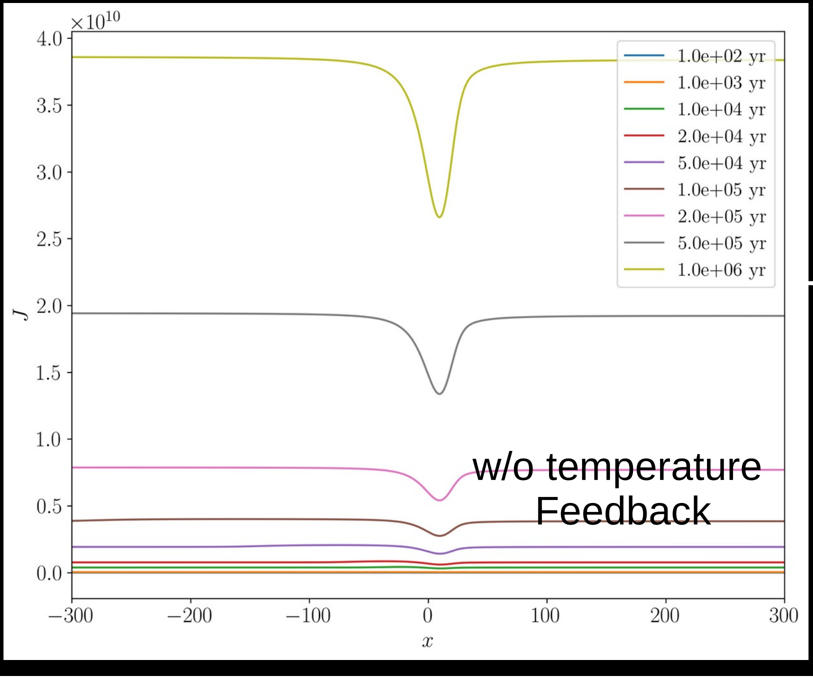
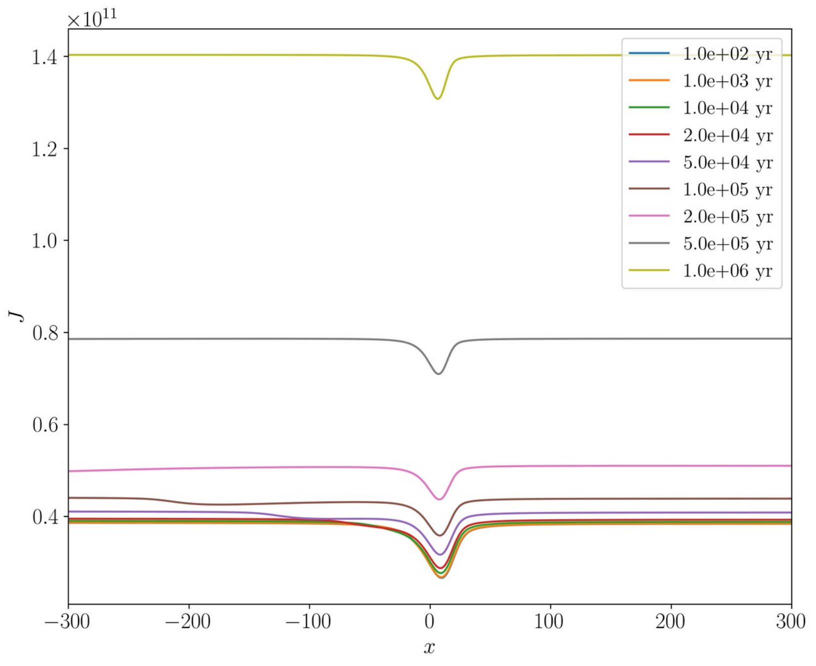
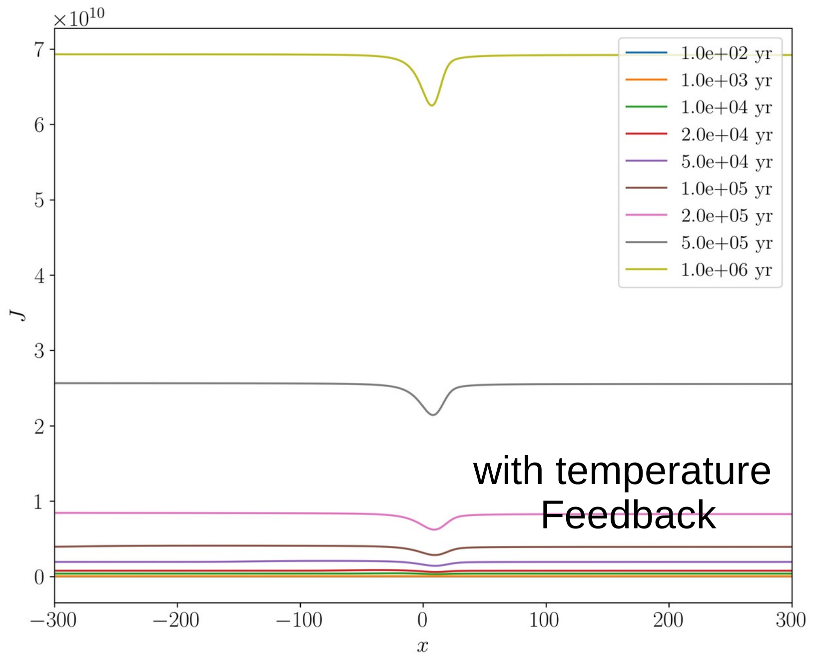


w/o temperature Feedback

Temperature Feedback starts





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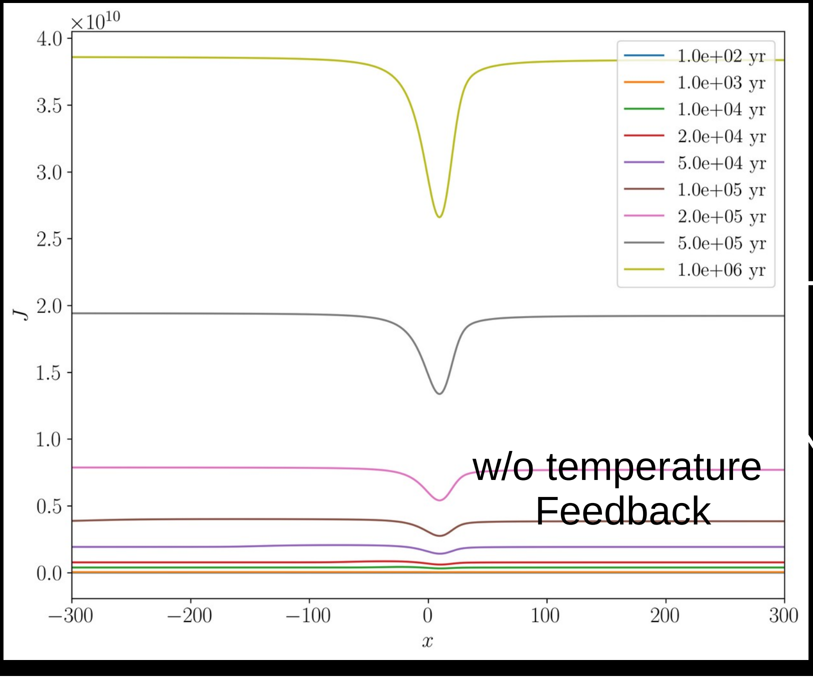

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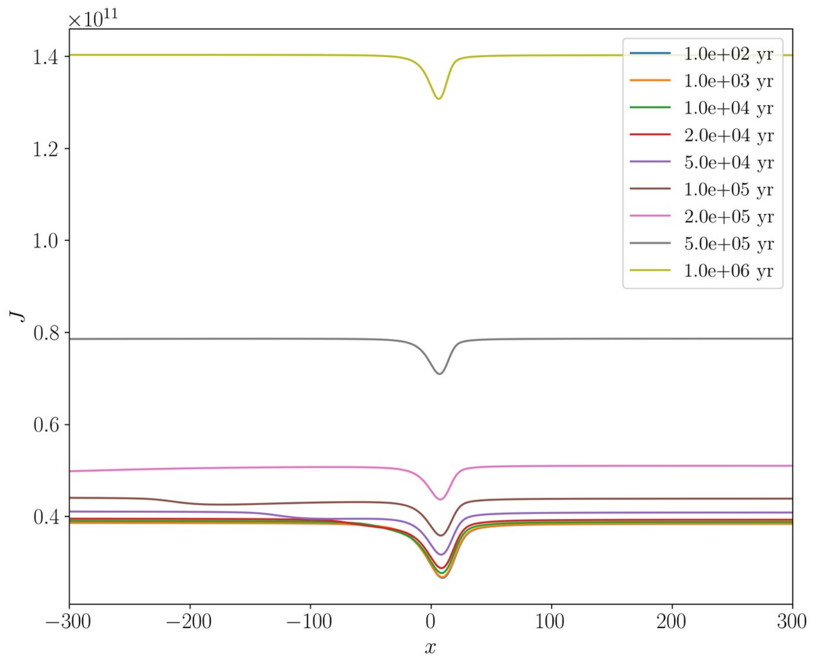

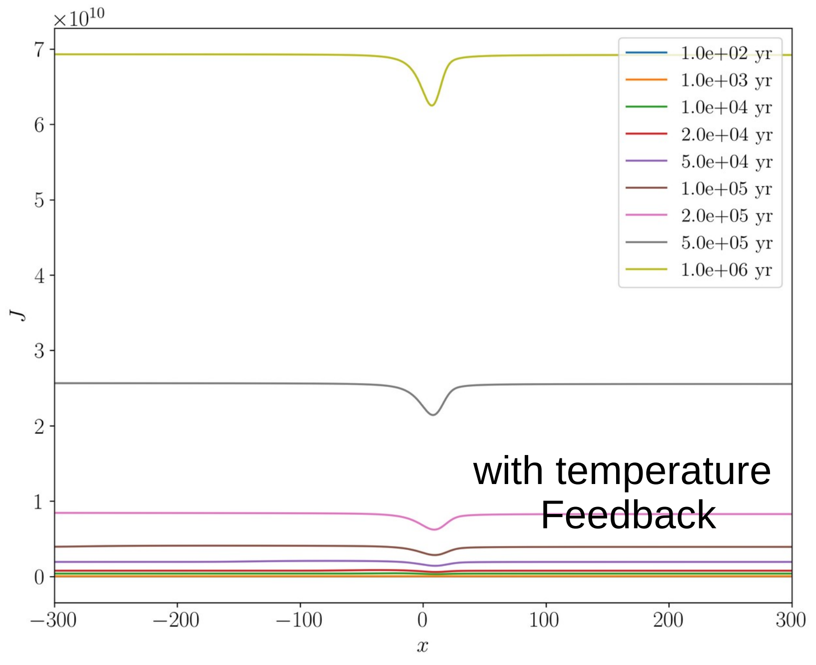

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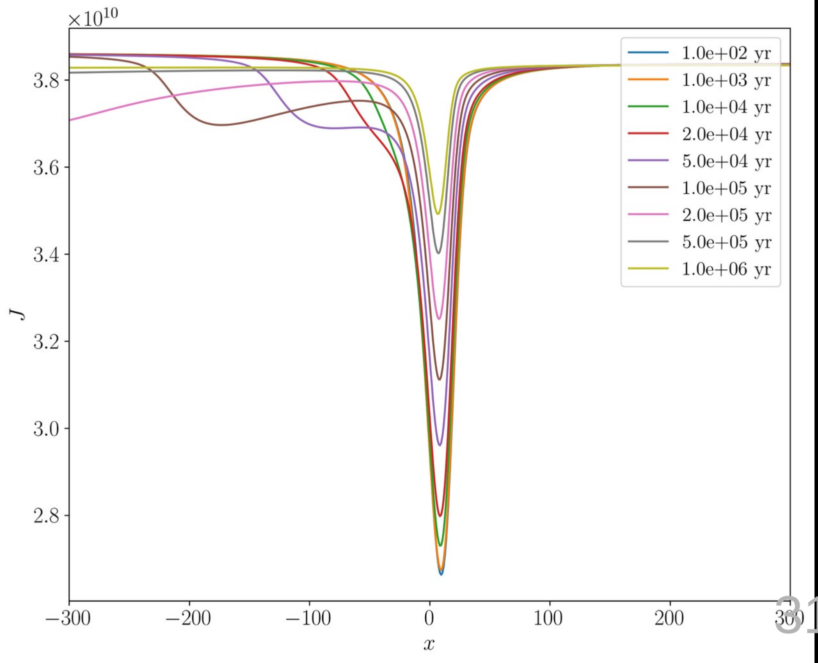
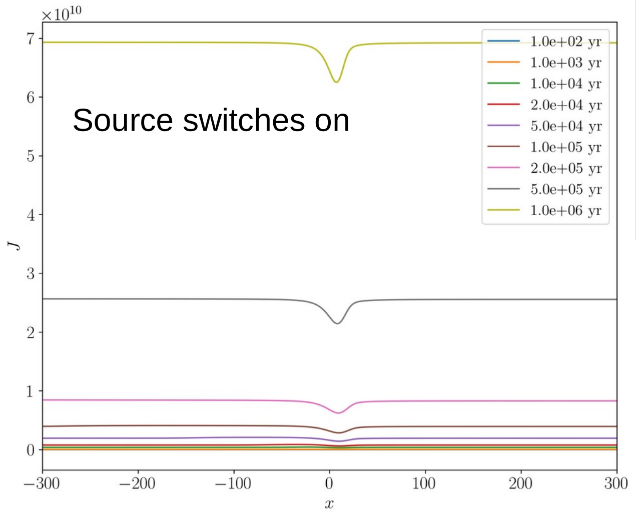


Fiducial Continuum Ly-α profile evolution for z = 20 and T_K = 10 K



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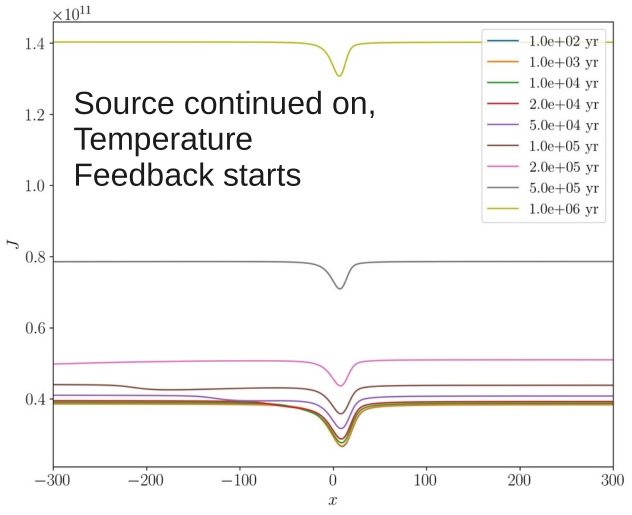

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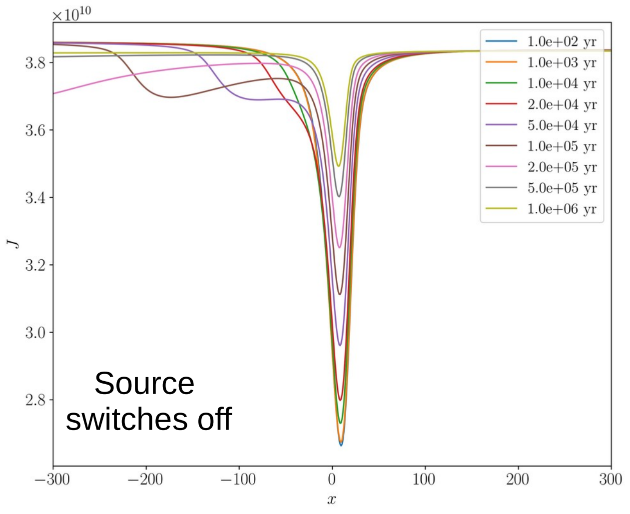
Temperature
Feedback starts



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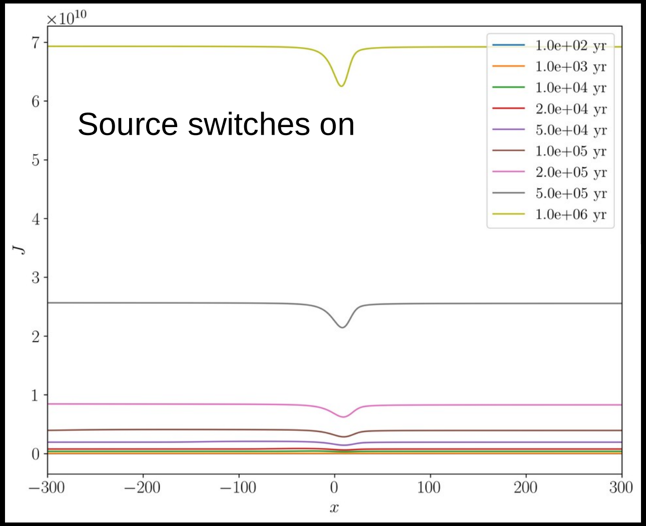

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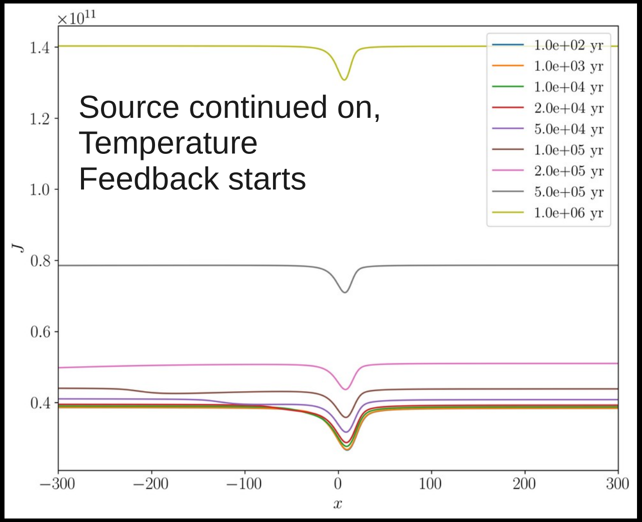

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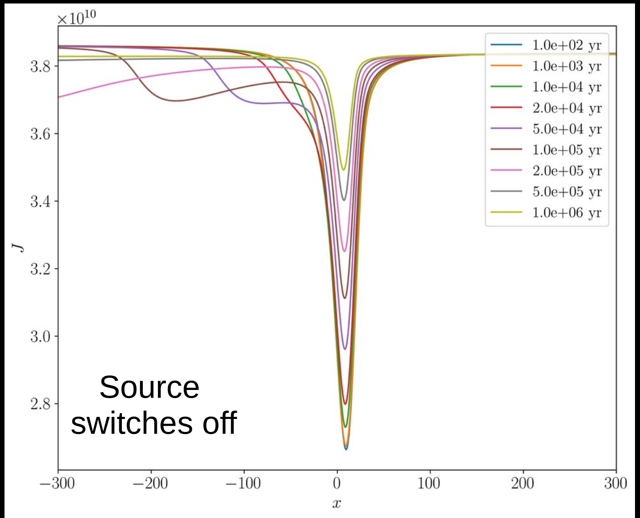

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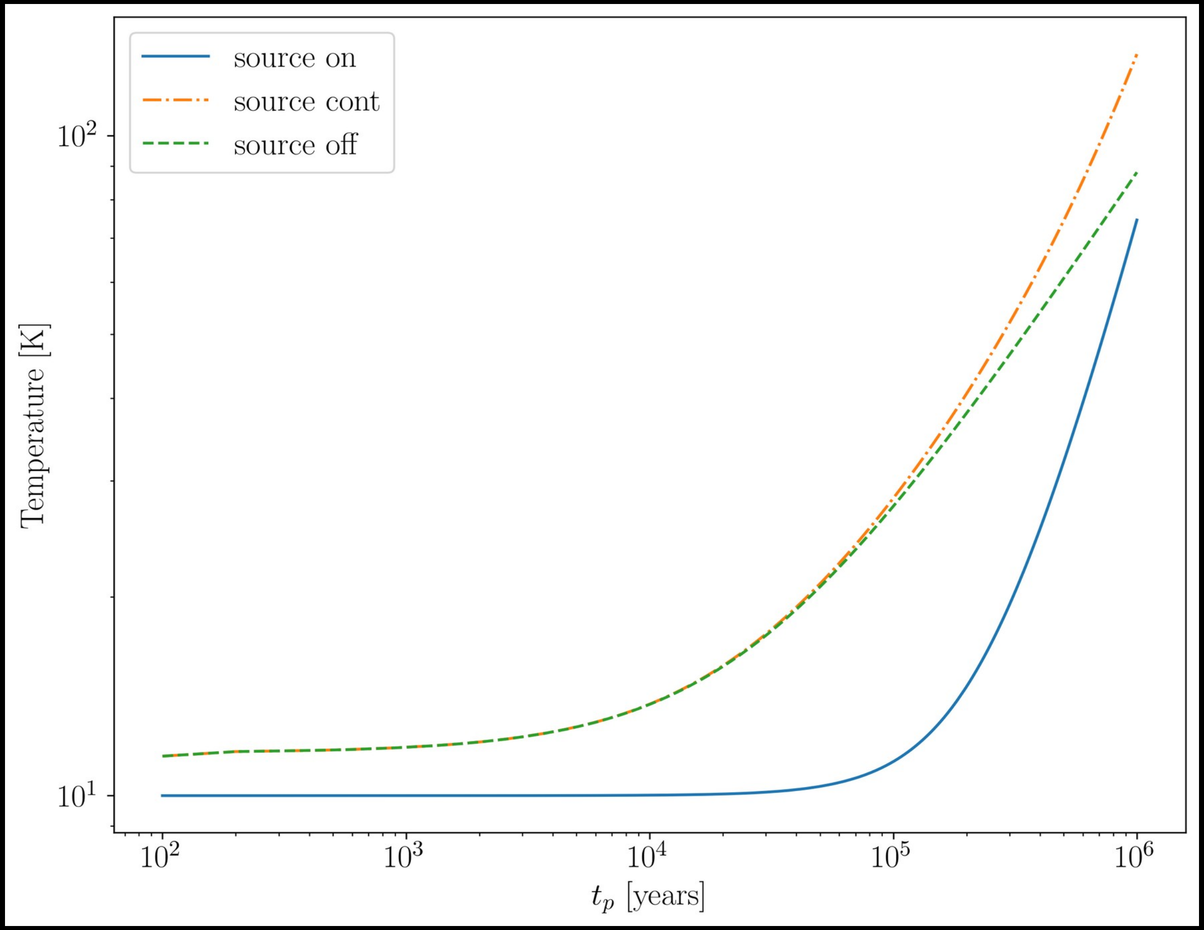
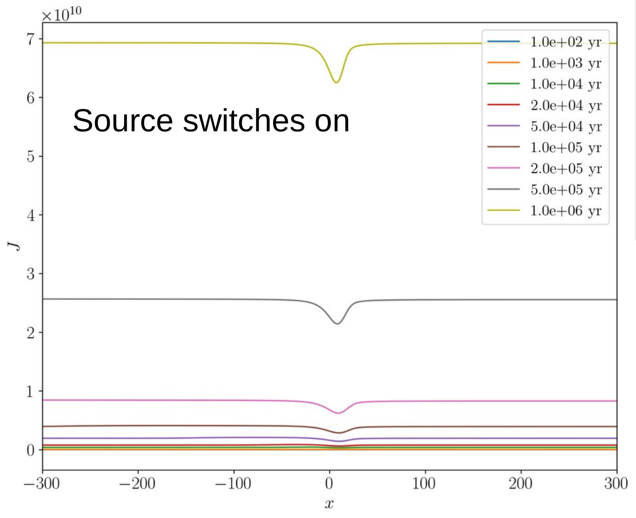
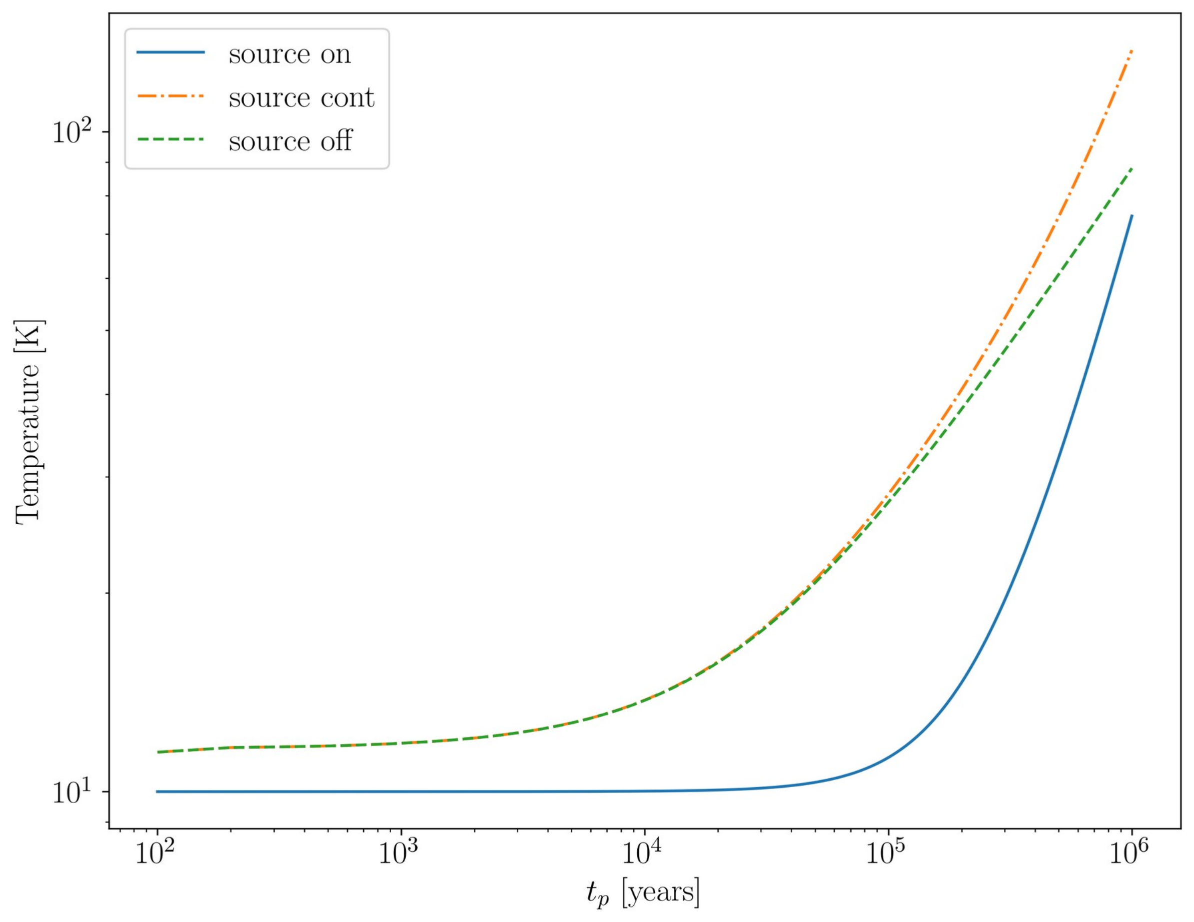
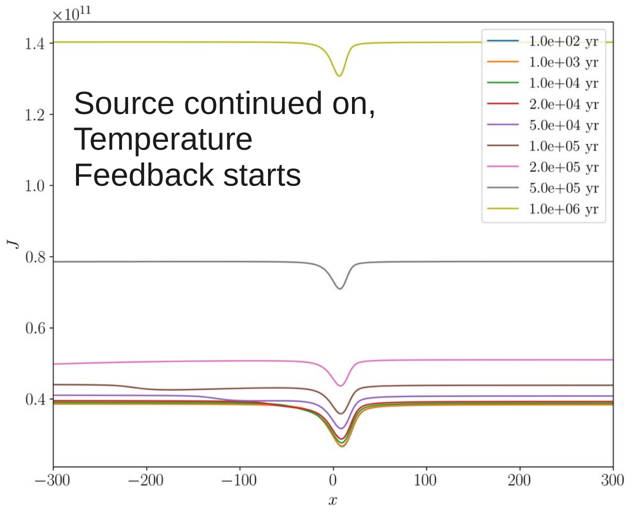




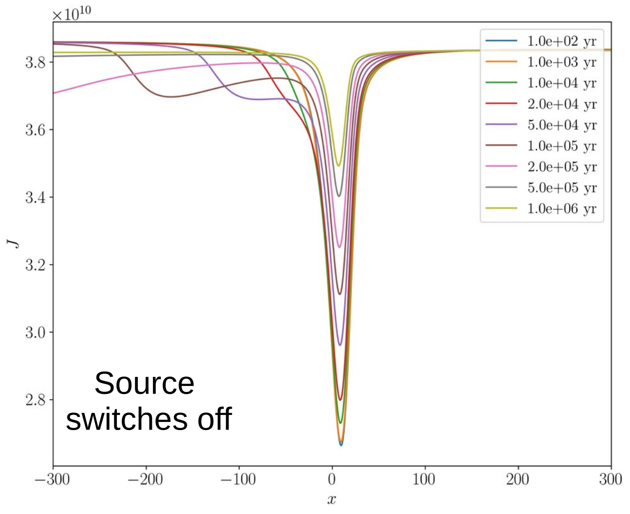
Source switches on

Fiducial Continuum Ly-α profile evolution for $z = 20$ and $T_K = 10$ K





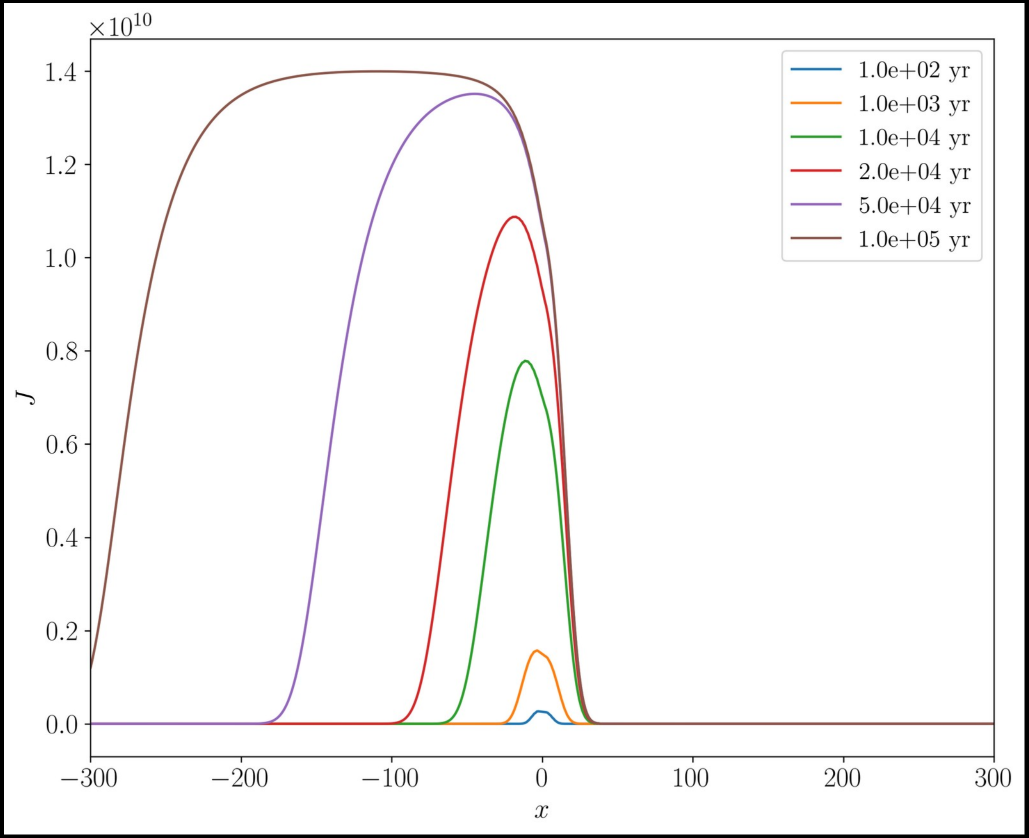
Source continued on, Temperature Feedback starts

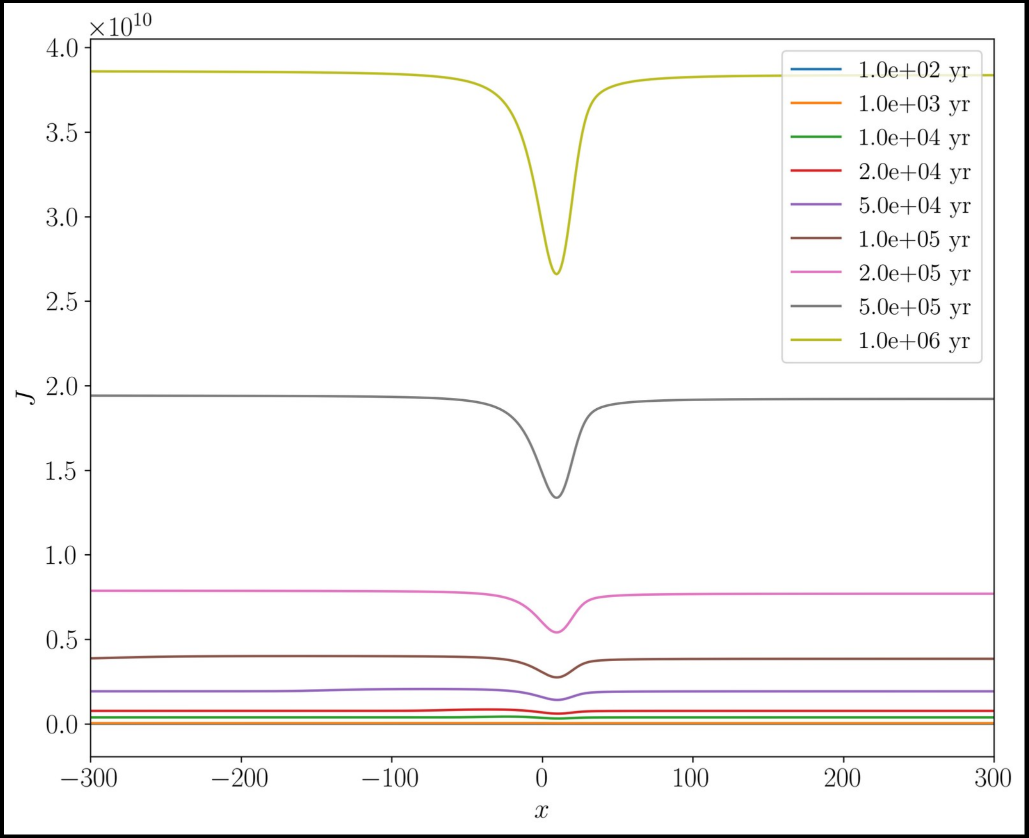


Source switches off

- Temperature feedback, source switching on, switching off delay/prevent quasi-static solution
- Continuum photons cause overall less heating than previously computed in literature.

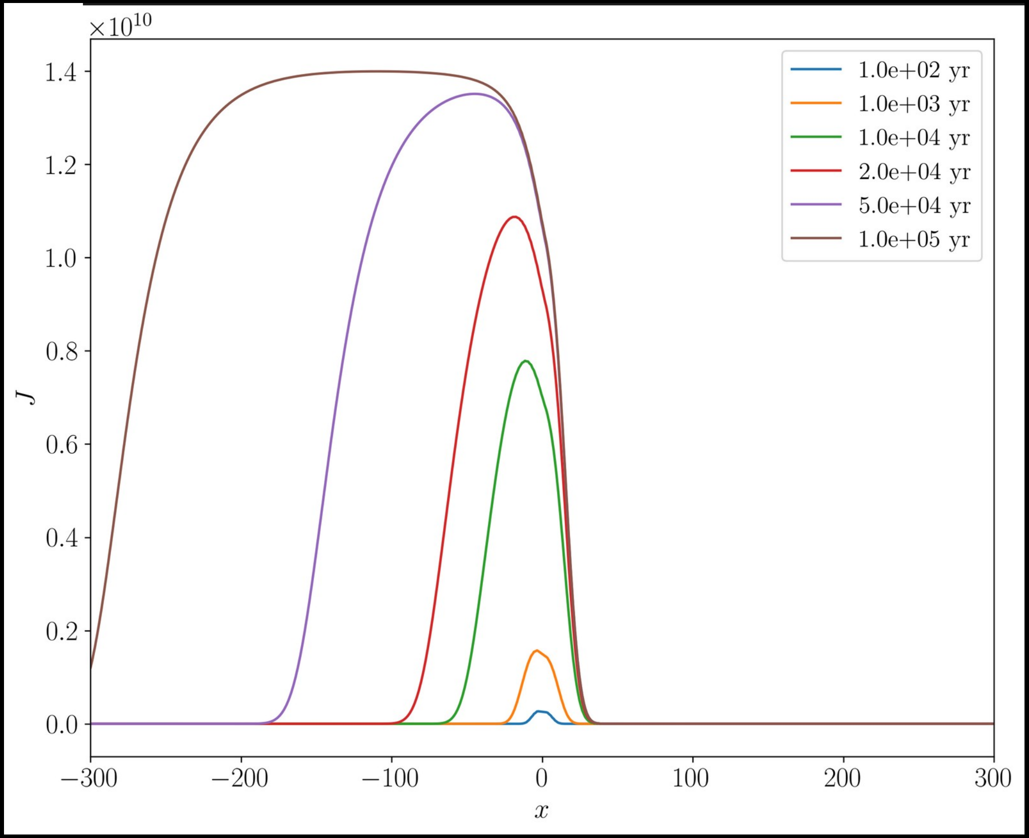
When does Lyman-α photons profile reach quasi-static state?

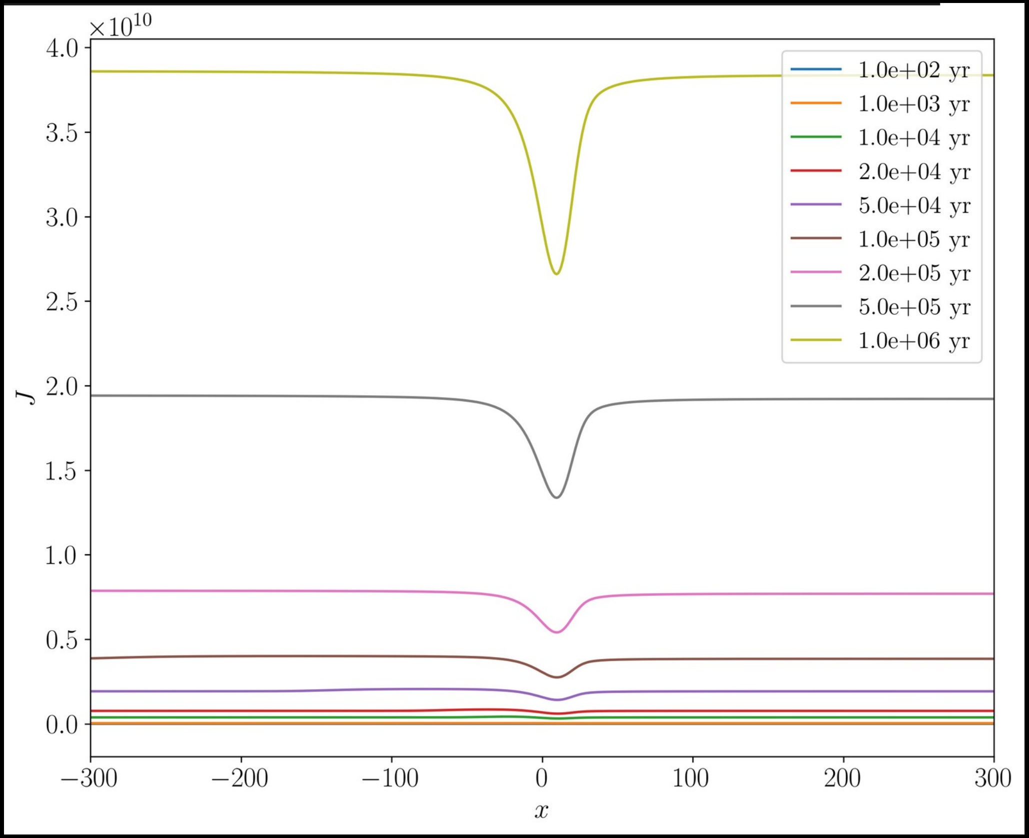




- Fiducial continuum Lyman-α photons profile evolution for $z = 20$ and $T_K = 10$ K

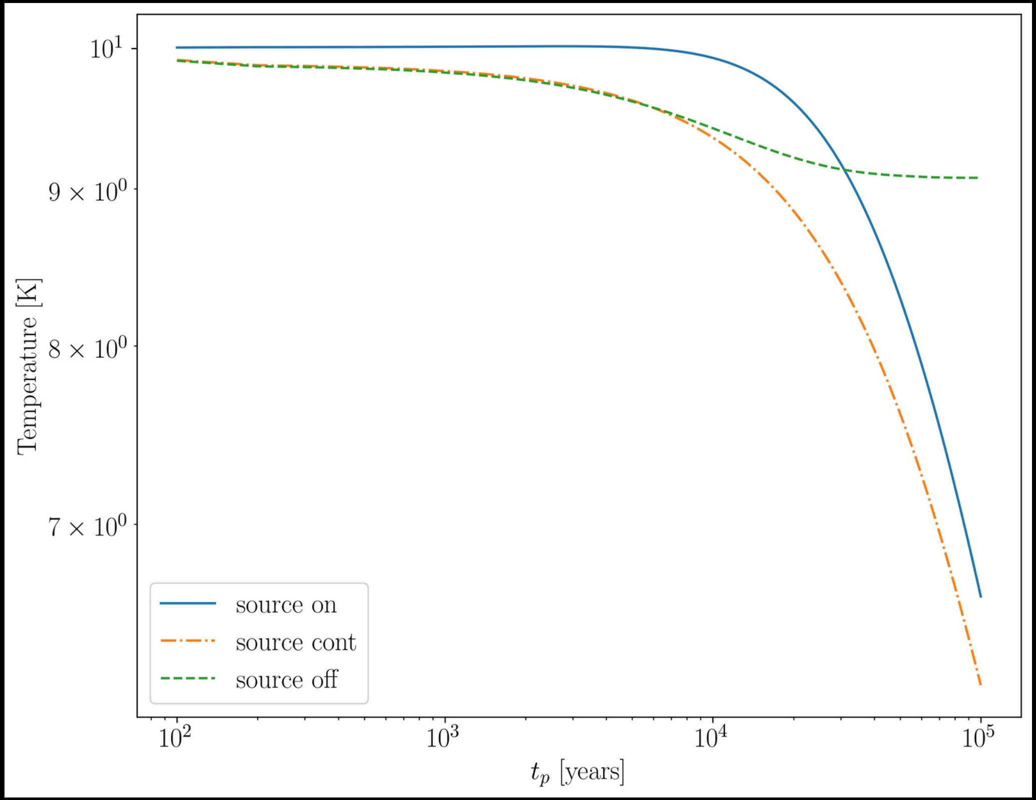
What is the lifetime of the Lyman-α photons Sources?

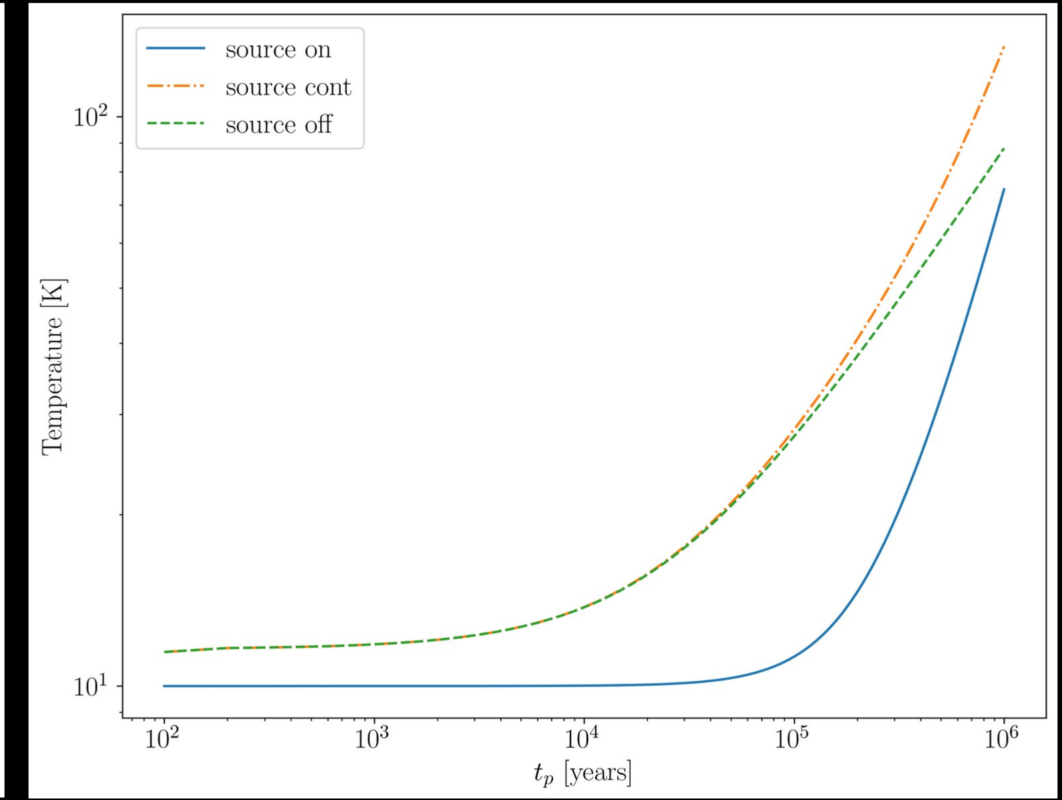




- Fiducial continuum Lyman-α photons profile evolution for $z = 20$ and $T_K = 10$ K
- Life span of Pop III stars ~ 0.1-10 Myr

How do the source and temperature feedback affect temperature evolution?





- Fiducial continuum Lyman-α photons profile evolution for $z = 20$ and $T_K = 10$ K
- Life span of Pop III stars ~ 0.1-10 Myr
- Continuum photons cause overall less heating than previously computed in literature. Injected photons cause less cooling.

Summary

- Lyman-α continuum photons heat up and injected photons cool the IGM during cosmic dawn – for quasi-static solution.
- Temperature feedback, source switching on and off delay or prevent quasi-static solution.
- The time scale to reach quasi-static solution is of the same order of magnitude as the source lifetime of PopIII stars during CD.

➢ Due to all these effect continuum photons cause overall less heating than previously computed in literature. Injected photons cause overall less cooling.

➢ **Future Work**: Combine effects of continuum and injected photons.

Thank you!