GRBV

Trieste, Sept. 2022

Time Evolving Photoionisation Device (TEPID)

a new code for time evolving photoionisation and spectral fitting

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In collaboration with:
F.Nicastro, L. Piro, A. Thakur (INAF) , *Y. Krongold* (UNAM) +
many others!

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Time Evolving Photoionisation Device

Outline

- *i. GRBs as time-evolving ionisation sources*
- *ii. Time-evolving photoionization with TEPID:*
  - *i. Outline of the code*
  - *ii. Initial conditions*
  - *iii. Time-evolving integration*
  - *iv. UV and X-ray absorption spectra*
- *iii. Conclusions*

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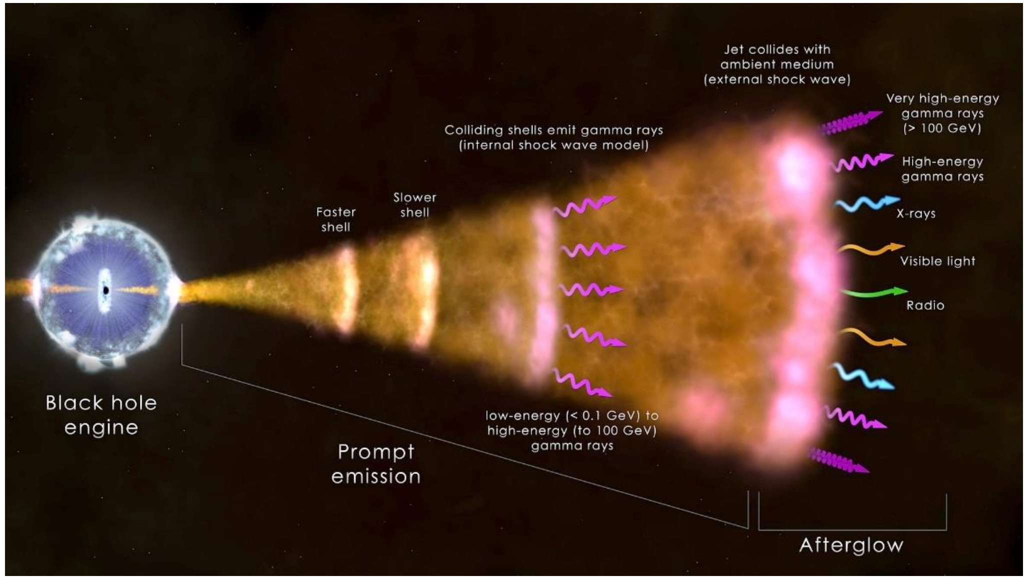
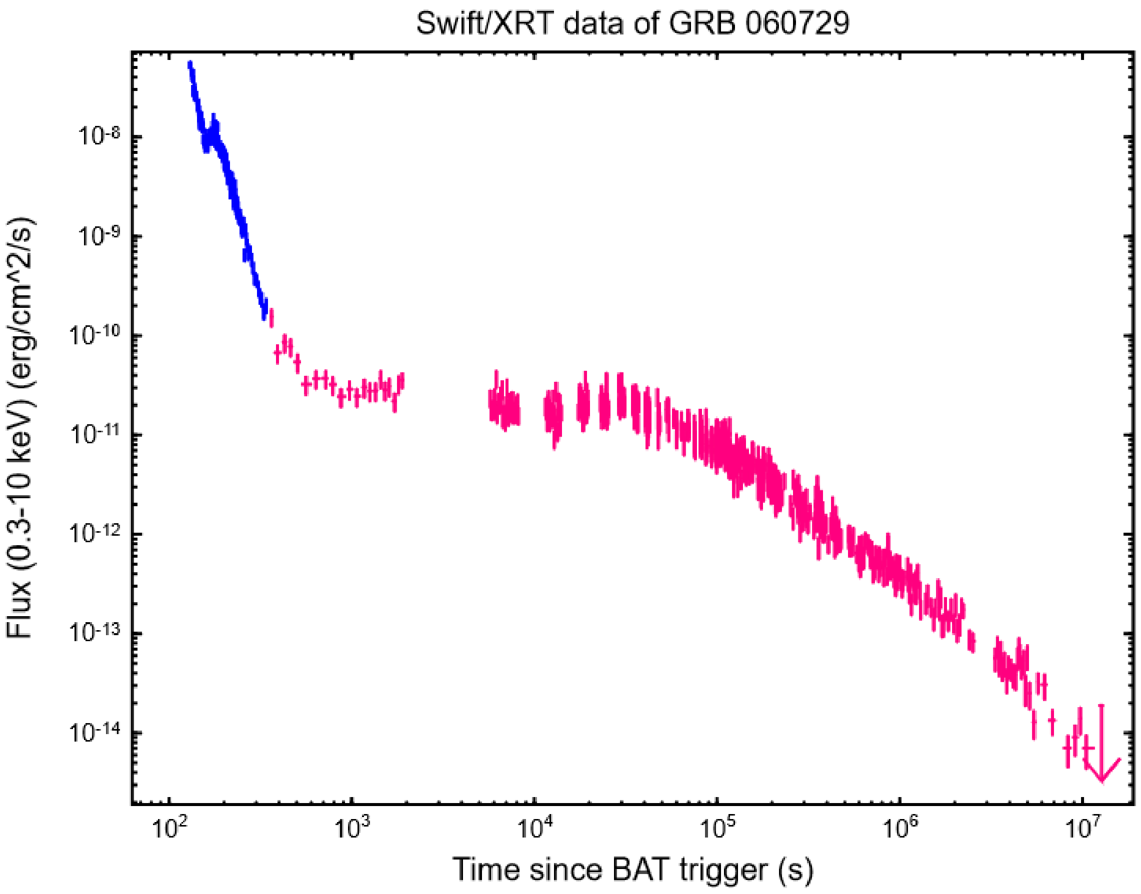
i. GRBs as time-evolving sources

GRB are intrinsically transient,
non-equilibrium sources:





Piro+02, D’Elia+09 , Krongold+13, Heintz+18

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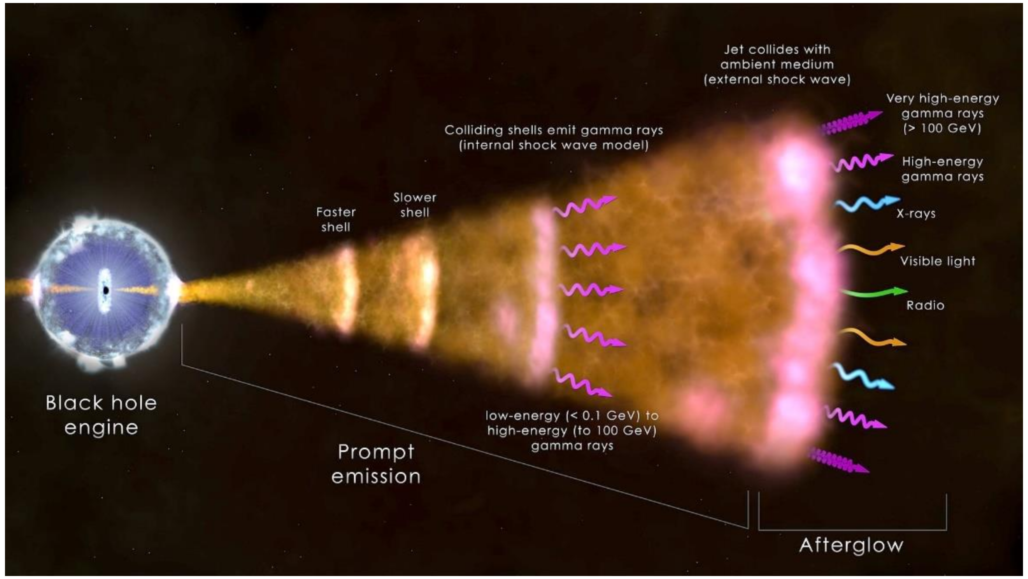

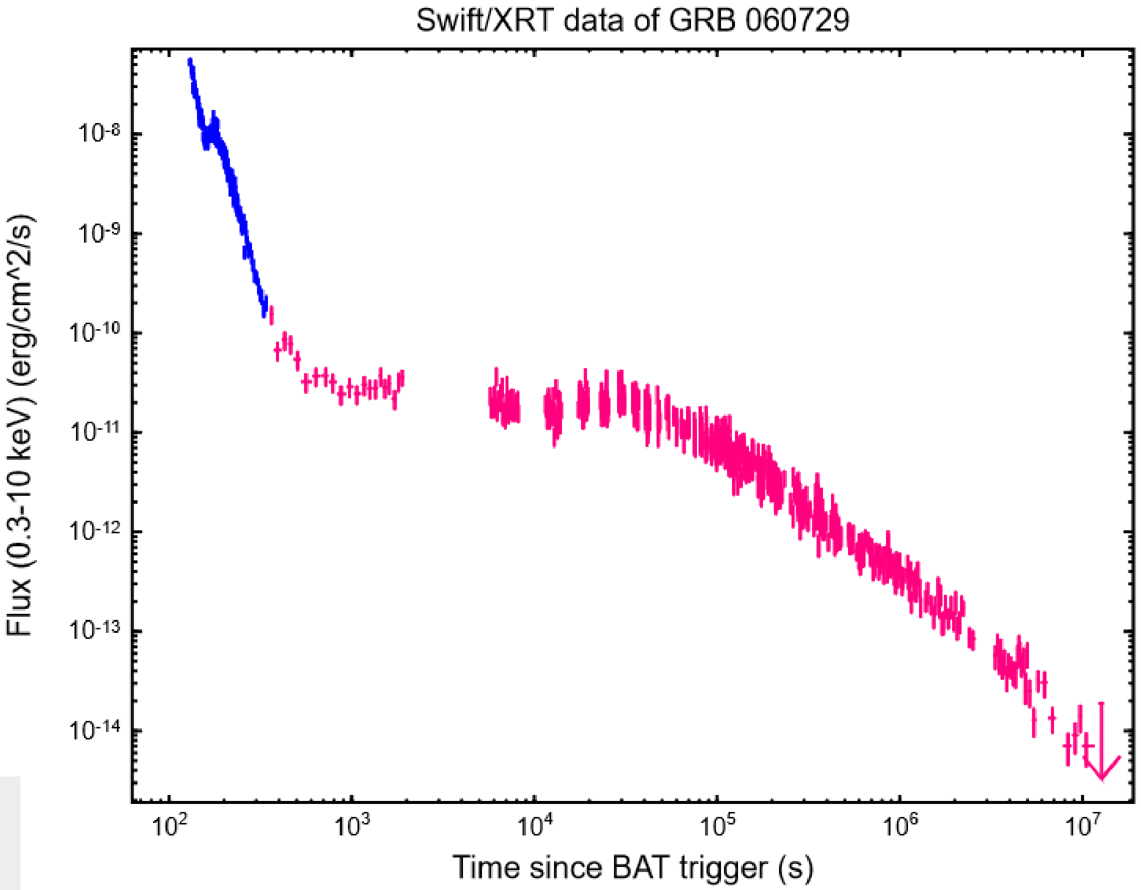

GRB are ideal probes to illuminate surrounding environment and shed light on <u>density, metallicity, volume</u> of Star Forming Regions and host galaxies… but:

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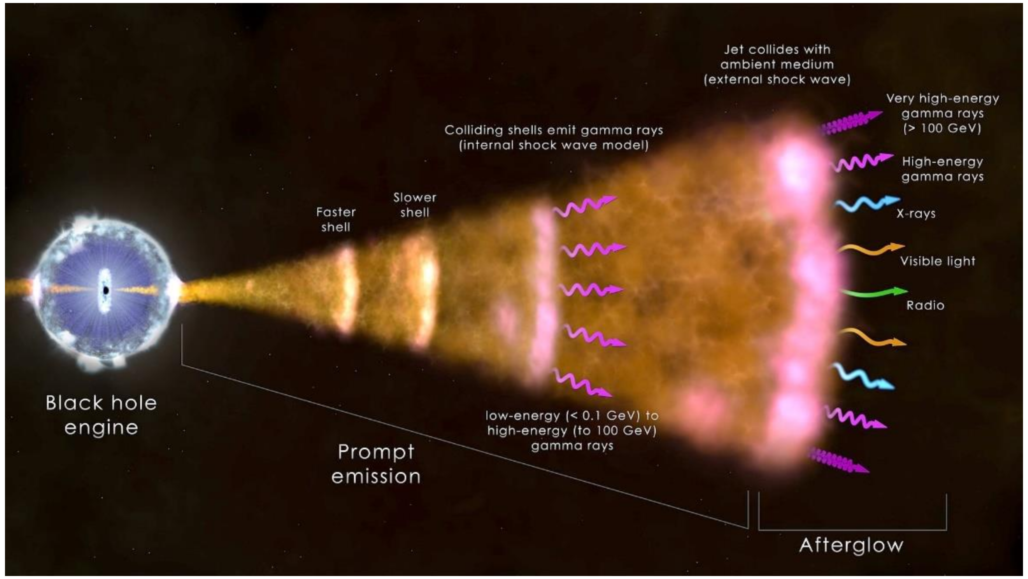

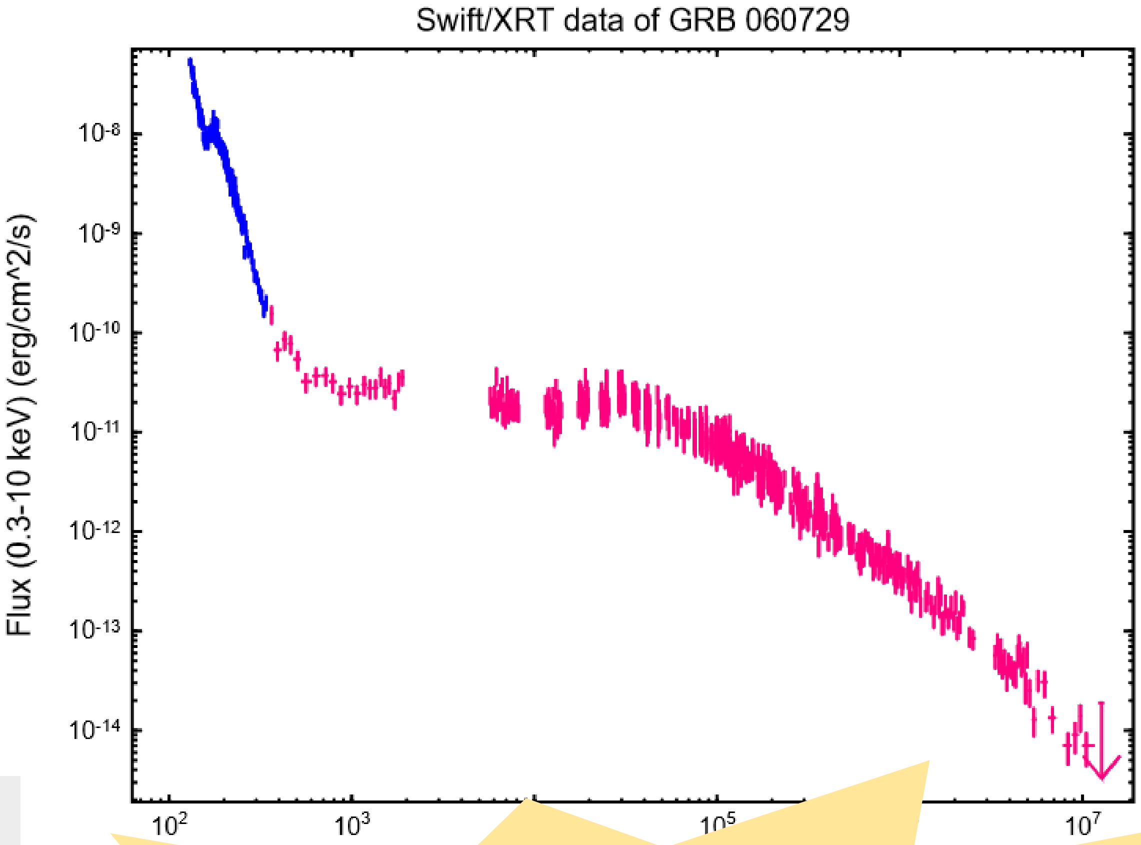

GRB are ideal probes to illuminate surrounding environment and shed light on <u>density, metallicity, volume</u> of Star Forming Regions and host galaxies… but:

Illuminated ambient gas is out of photoionisation equilibrium:
Need for time-evolving modelling!

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i. GRBs as time-evolving sources

Constant ionisation source
→ Time-equilibrium photoionisation:

- Gas physical status is solely dictated by the ionisation parameter:

Ionising flux

$$U \propto \frac{Q_{ion}}{nr^2}$$

Gas density · distance

- Temperature is a function of U
- Ionic abundances are given by the balance between recombination and photoionisation:

$$n_{X^i} \propto \frac{\alpha_{rec}}{F_{X^i}}$$

Plenty of dedicated codes:
Cloudy, XSTAR, SPEX….

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Transient ionisation source
→ Time-evolving photoionisation:

Gas ionisation, temperature and density change in time following the ionising flux:

- non-linear behaviour
- dependence from initial conditions
- gas response delayed with respect to the lightcurve
- time-evolving radiative transfer

→ *need to integrate over the full prompt+afterglow lightcurve*

Piro+02, D'Elia+09 , Krongold+13, Heintz+18

i. GRBs as time-evolving sources

Transient ionisation source
→ Time-evolving photoionisation:

TEPID:
Time-Evolving PhotoIonisation Device

Non-equilibrium gas ionisation and transmitted spectrum from optical to X-ray

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ii. TEPID

Time Evolving PhotoIonisation Device (TEPID)

An optical to X-ray code to follow the time evolving gas ionisation (based on Nicastro+99, Krongold+13):

Ionic abundances

$$\frac{dn_{X^i}}{dt} = -\left[F_{X^i} + C_{X^i}\, n_e + \alpha_{rec}\, n_e \; + I^{AU}_{X^{i-2}}\right] n_{X^i}$$
$$+\left[F_{X^{i-1}} + C_{X^{i-1}}\, n_e\right] n_{X^{i-1}} + \alpha_{rec}\, n_e n_{X^{i+1}} + I^{AU}_{X^i} n_{X^{i-2}}$$

n_e: electron number density $n_e \approx 1.2\, n_H$

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Destruction:
recombination to $i-1$ and
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Destruction:
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Creation:
recombination from $i+1$ and
photoionisation from $i-1$ (Auger $i-2$)

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Temperature

Γ : heating (photoionisation)

$$\frac{dT}{dt} = \sum_{X,i}[\Gamma - \Lambda] + \Theta$$

Λ : cooling (gas emission)

Θ : Compton

Summed over the gas elements

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Charge conservation

$$n_e = n_{HII} + n_{HeI} + 2n_{HeII} + \; \ldots$$

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Gas absorption:

$$F_{trans} = F_0 \cdot \frac{1-e^{-\tau}}{\tau}$$

ii. TEPID

The driving parameters are:

1. the ionising flux F_{ion}
2. the gas density n_e

Sets the energy transferred to the gas

Sets the gas timescale: Ionisation rates and heating

Ionic abundances

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Temperature

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Summed over the gas elements

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ii. TEPID

The driving parameters are:

1. the ionising flux F_{ion}
2. the gas density n_e

Linearly depends on F_{ion}

Linearly depends on n_e

Ionic abundances

$$\frac{dn_{X^i}}{dt} = -\left[F_{X^i} + C_{X^i}\, n_e + \alpha_{rec}\, n_e + I^{AU}_{X^{i-2}}\right] n_{X^i} + \left[F_{X^{i-1}} + C_{X^{i-1}}\, n_e\right] n_{X^{i-1}} + \alpha_{rec}\, n_e n_{X^{i+1}} + I^{AU}_{X^i}\, n_{X^{i-2}}$$

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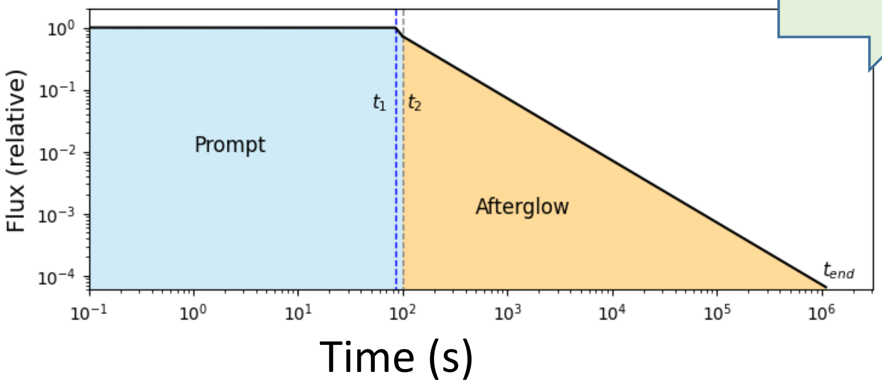
ii. TEPID. Code outline

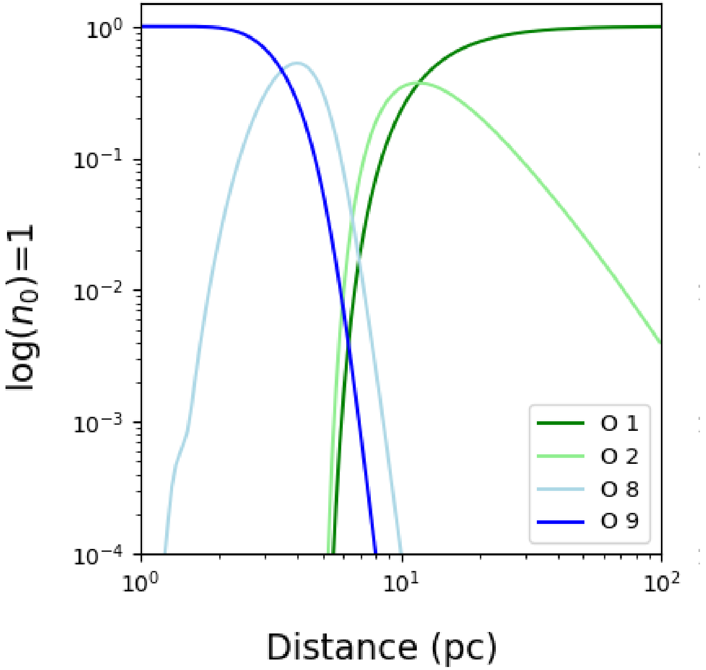
Work flow of TEPID:

1. Input quantities:

i. Lightcurve
ii. Gas density
iii. Initial ionic abundances

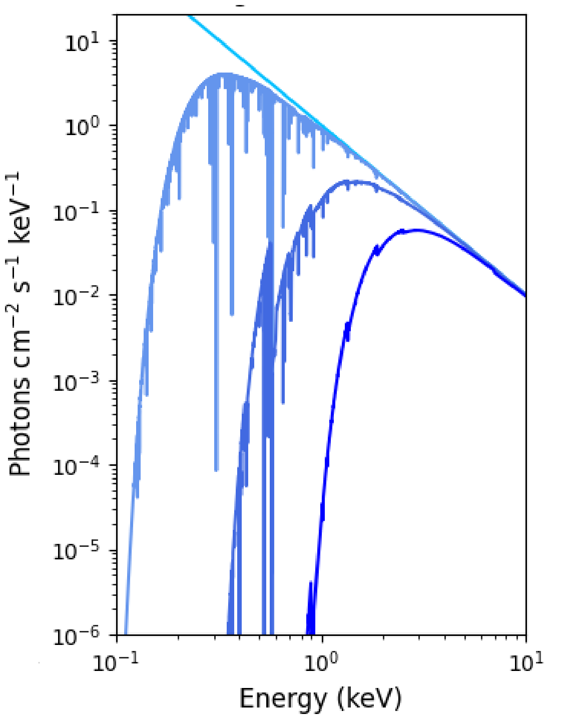


2. Time evolving computation:



Temporal evolution of the ionisation and temperature of the surrounding ISM

3. Absorption spectrum:



Time-resolved optical to X-ray spectra as a function of the ISM density and distance

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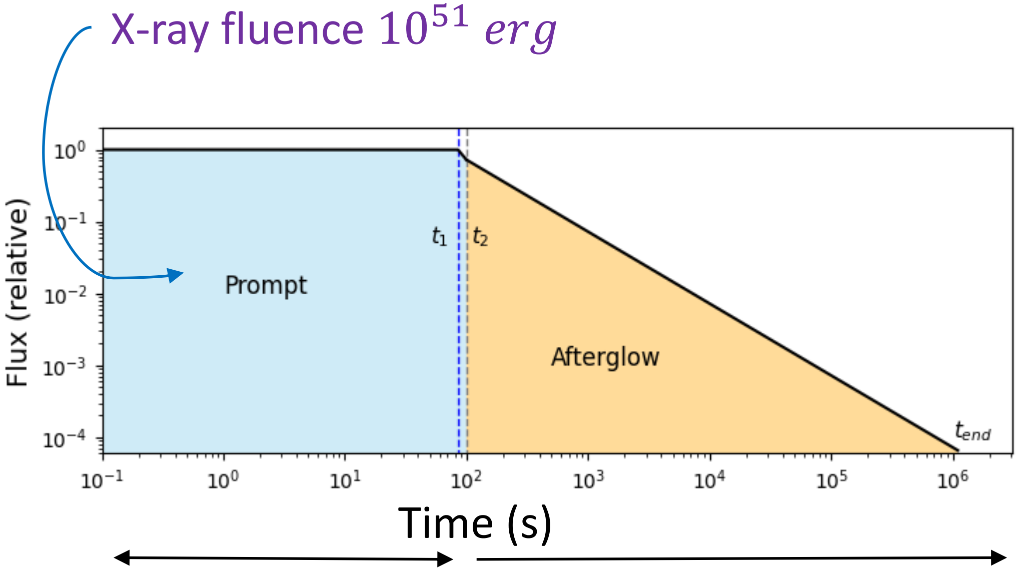
ii. TEPID

1. Input quantities:

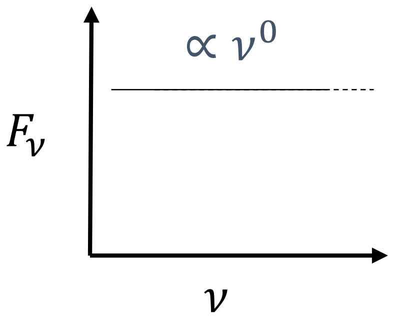
We focus on the circumbust environment of a long GRB

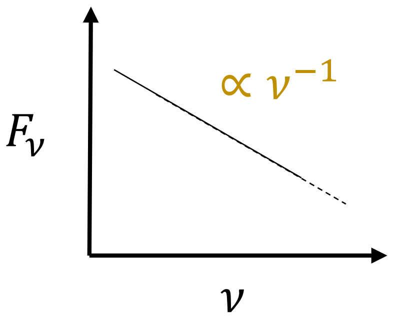
X-ray fluence $10^{51}\ erg$



100 seconds

10^6 seconds





- Typical long GRB lightcurve
- Gas density: $n_e = 10^1 - 10^4\ cm^{-3}$, as expected in Star Forming Regions around long GRBs
- Inner gas radius: 1 pc to encompass the forward shock
- The gas is assumed to be initially neutral

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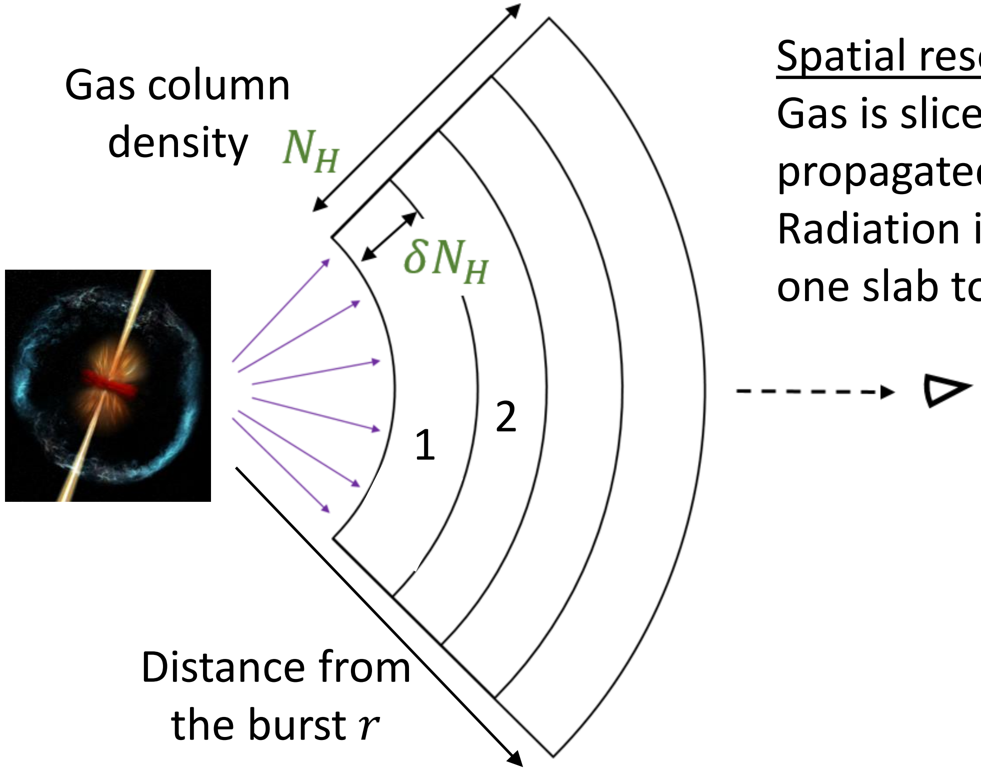
2. Time evolving computation

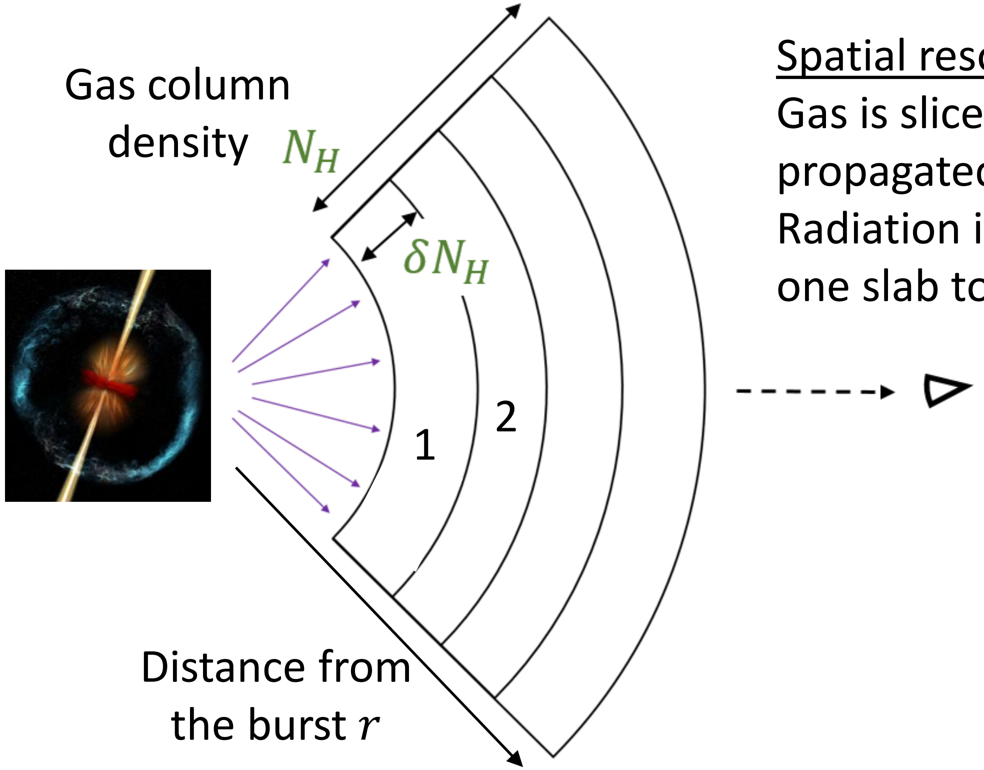


<u>Spatial resolution:</u>

Gas is sliced in optically-thin slabs. Simulation is propagated from the innermost to the outermost. Radiation is absorbed and geometrically diluted from one slab to the other:

$$F_2 = F_1 \cdot \frac{1 - e^{-\tau}}{\tau} \cdot \left(\frac{r_2}{r_1}\right)^2$$

ii. TEPID 2. Time evolving computation



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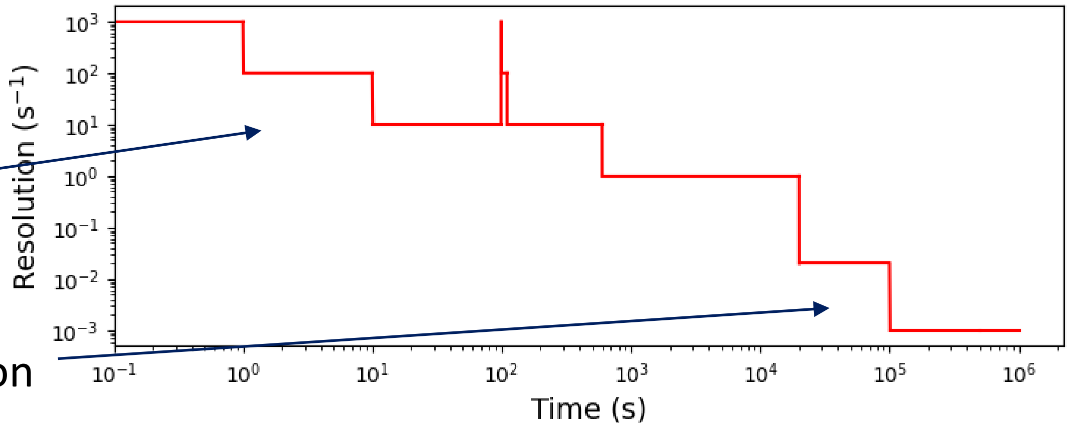
<u>Temporal resolution:</u>
computed by the code through an adaptive approach



Higher luminosity, higher photoionisation: finer resolution

Low luminosity: coarser resolution

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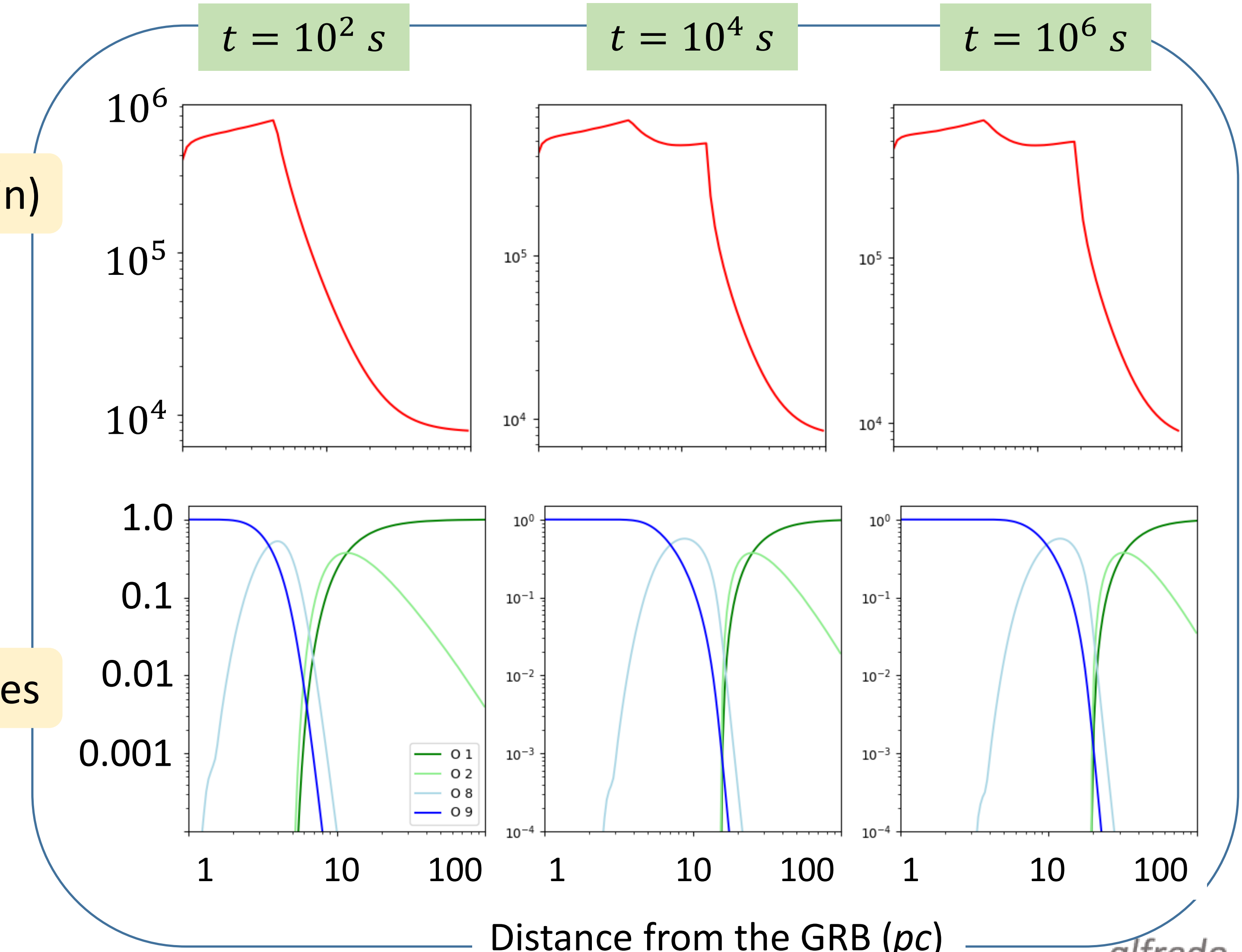
ii. TEPID

2. Time evolving computation

$n_e = 10^1\ cm^{-3}$



Temperature (Kelvin)

Oxygen ionic abundances

Distance from the GRB (*pc*)

O 9 (fully stripped)
O 8
O 2
O 1 (neutral)

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ii. TEPID

2. Time evolving computation

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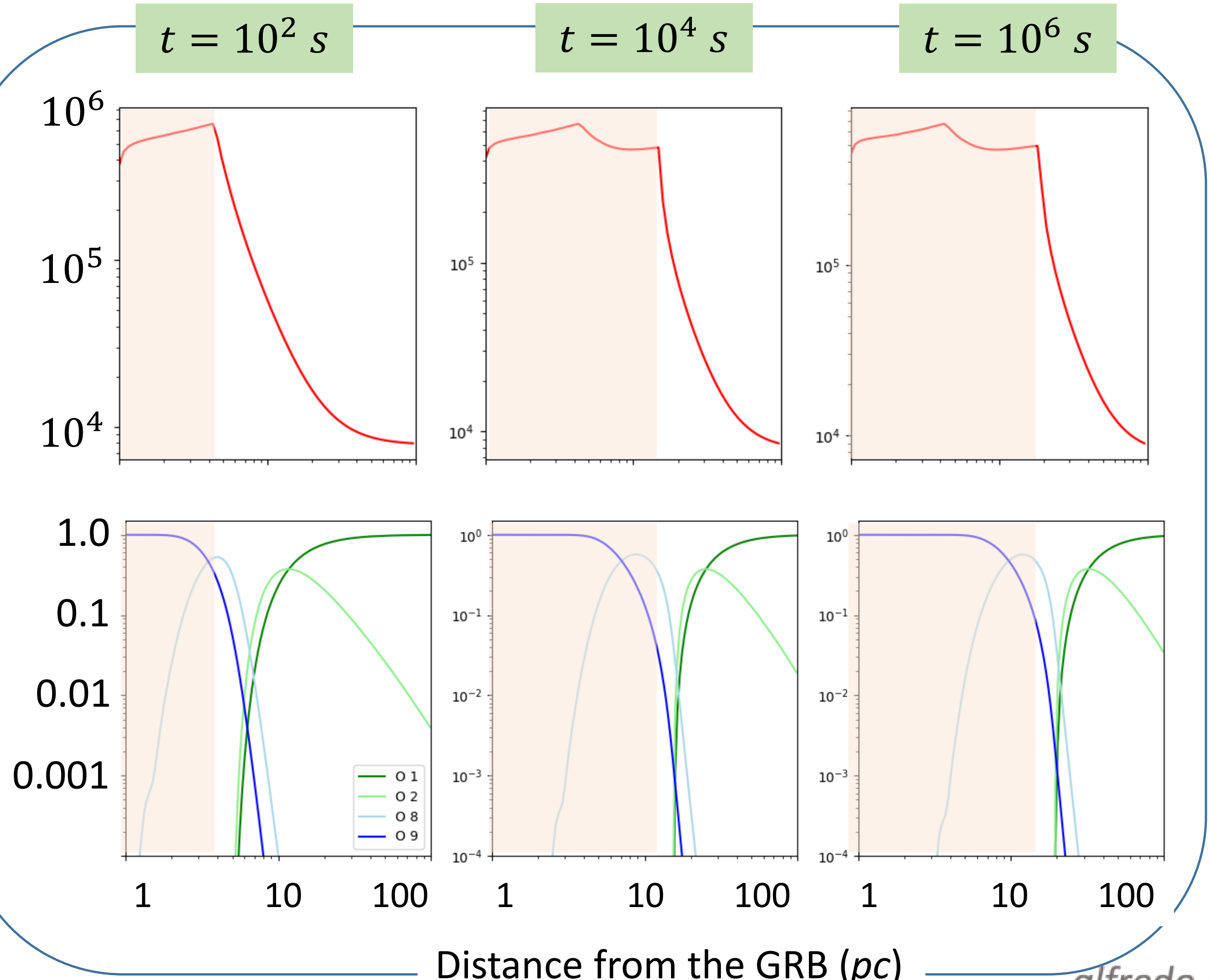
Increasing time from the burst:
temperature and ionisation front moves outwards

Temperature (Kelvin)

Oxygen ionic abundances



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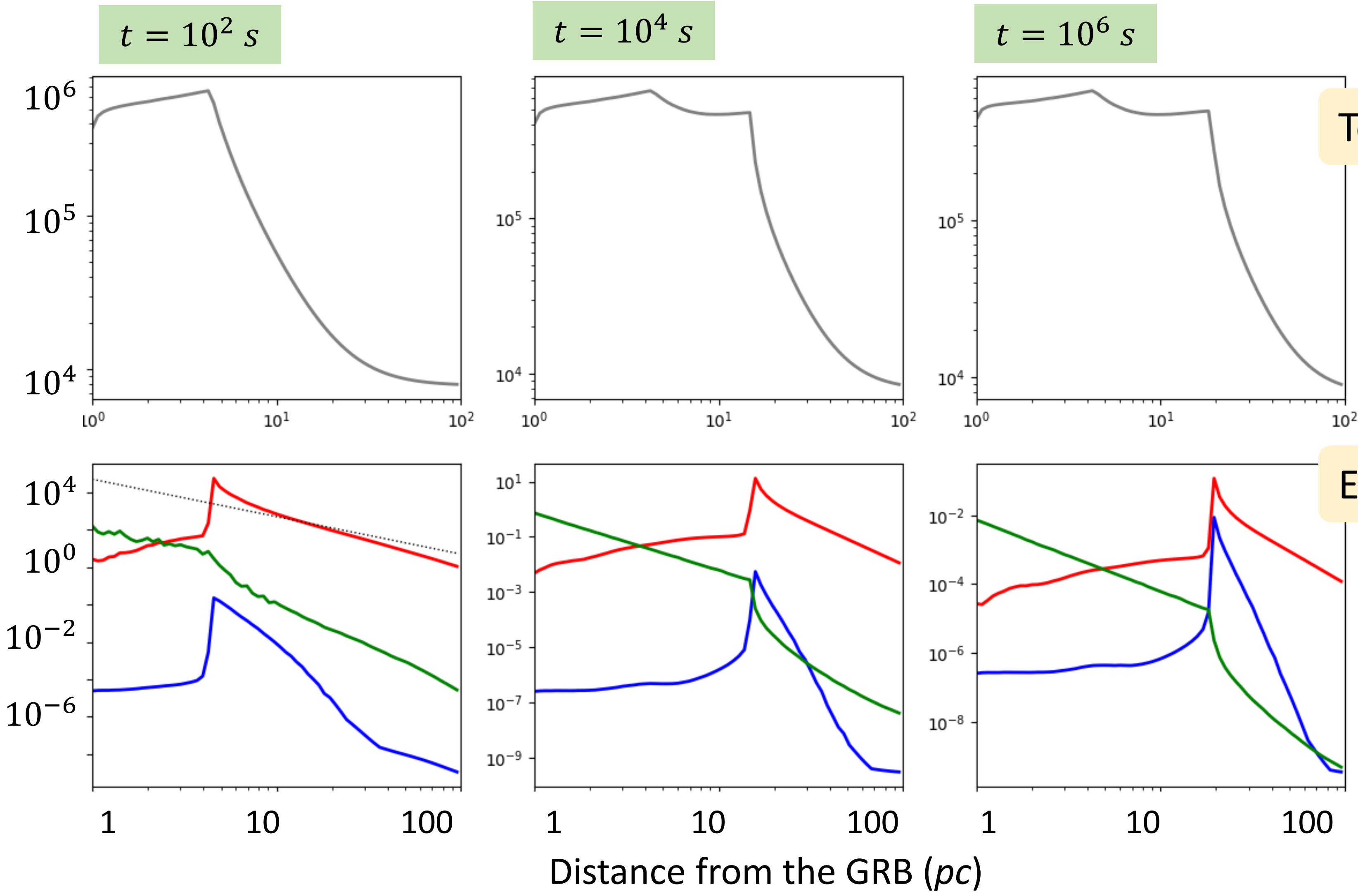

Temperature (Kelvin)

Energy Balance (Kelvin/second)

Heating photonionisation+Auger

Cooling gas emission (incl. lines)

Compton photon-electron interaction

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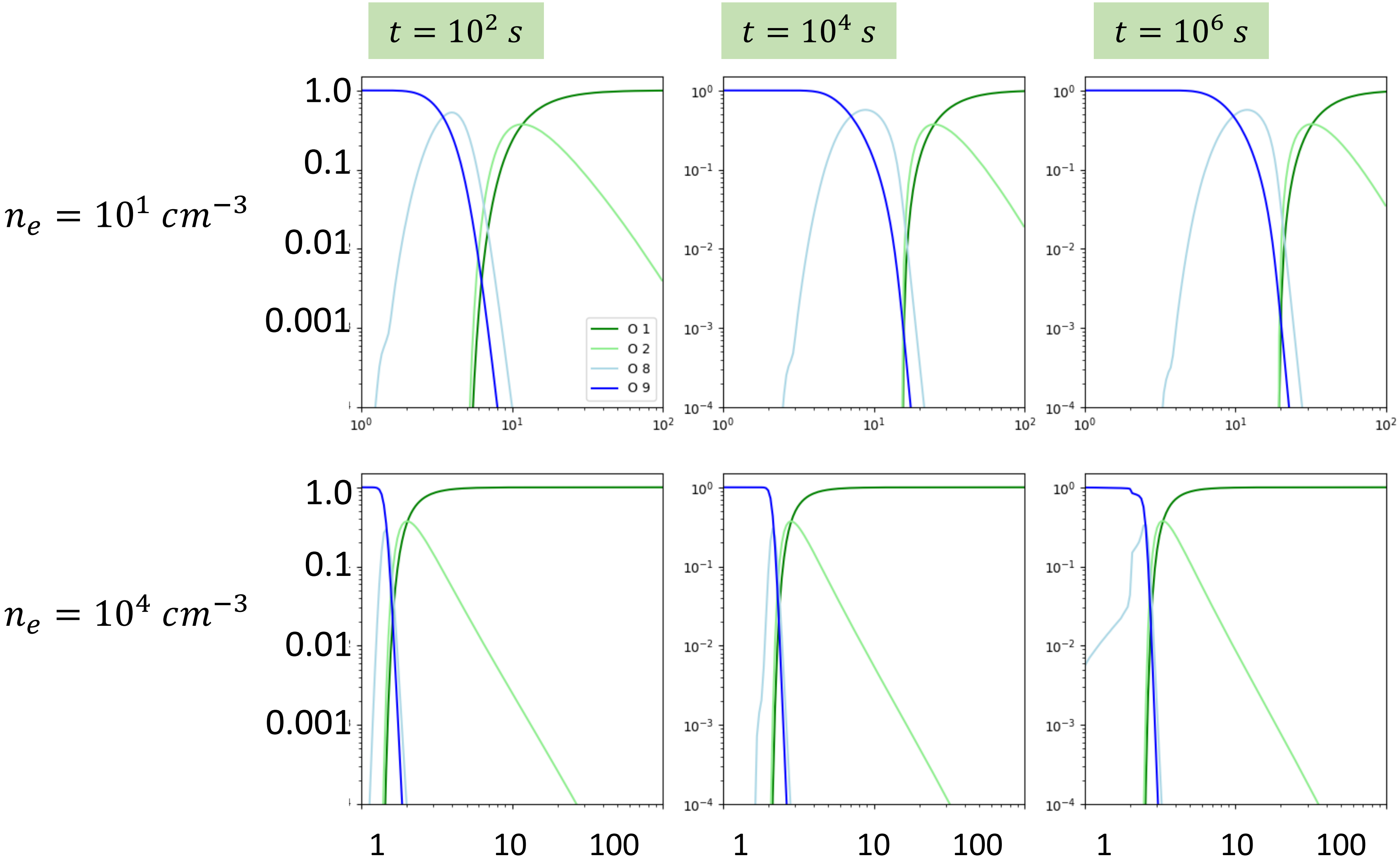

$t = 10^2\ s$ $t = 10^4\ s$ $t = 10^6\ s$

$n_e = 10^1\ cm^{-3}$

$n_e = 10^4\ cm^{-3}$

Oxygen

Increasing gas density

ii. TEPID

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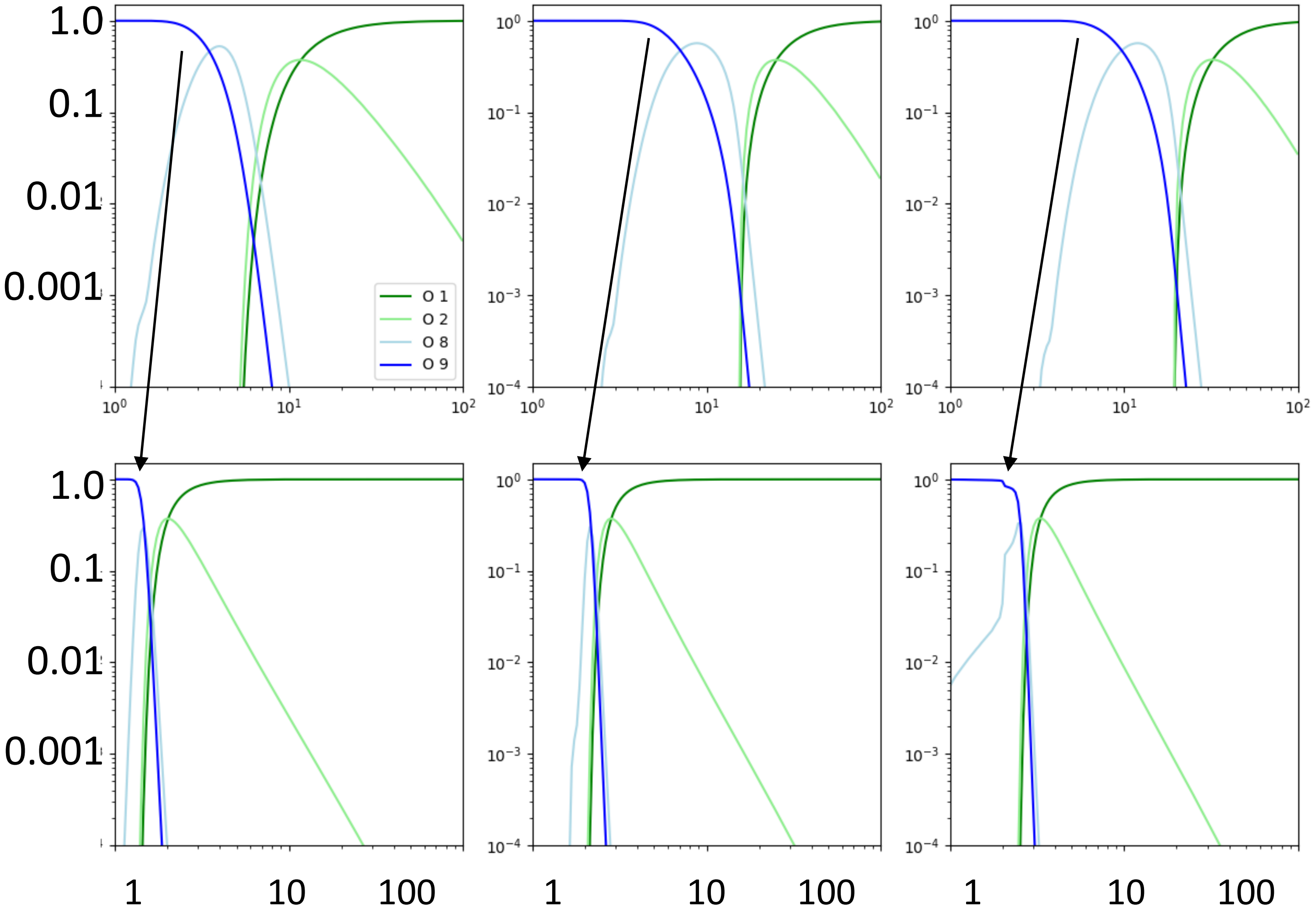

Oxygen

Increasing gas density

ionisation front moves inwards

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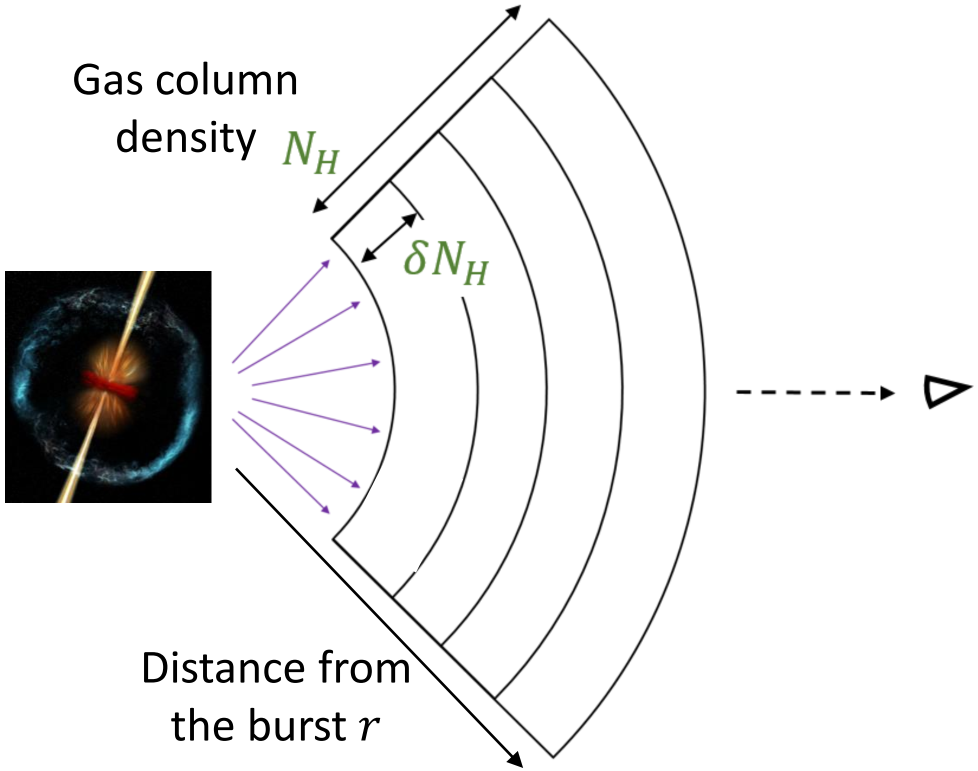
3. Absorption spectra

The gas column is $N_H = \delta r \cdot n$:

$$\rightarrow \delta r = N_H / n$$



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ii. TEPID

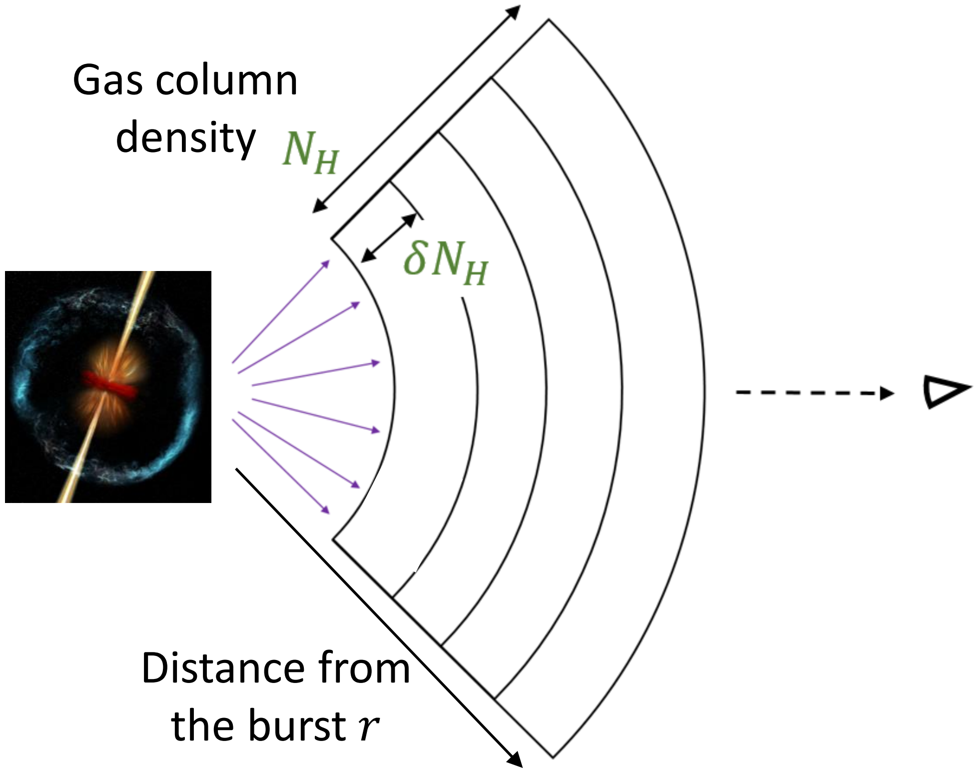
3. Absorption spectra

The gas column is $N_H = \delta r \cdot n$:

$\rightarrow \delta r = N_H / n$

for given N_H, denser gas is closer to the GRB

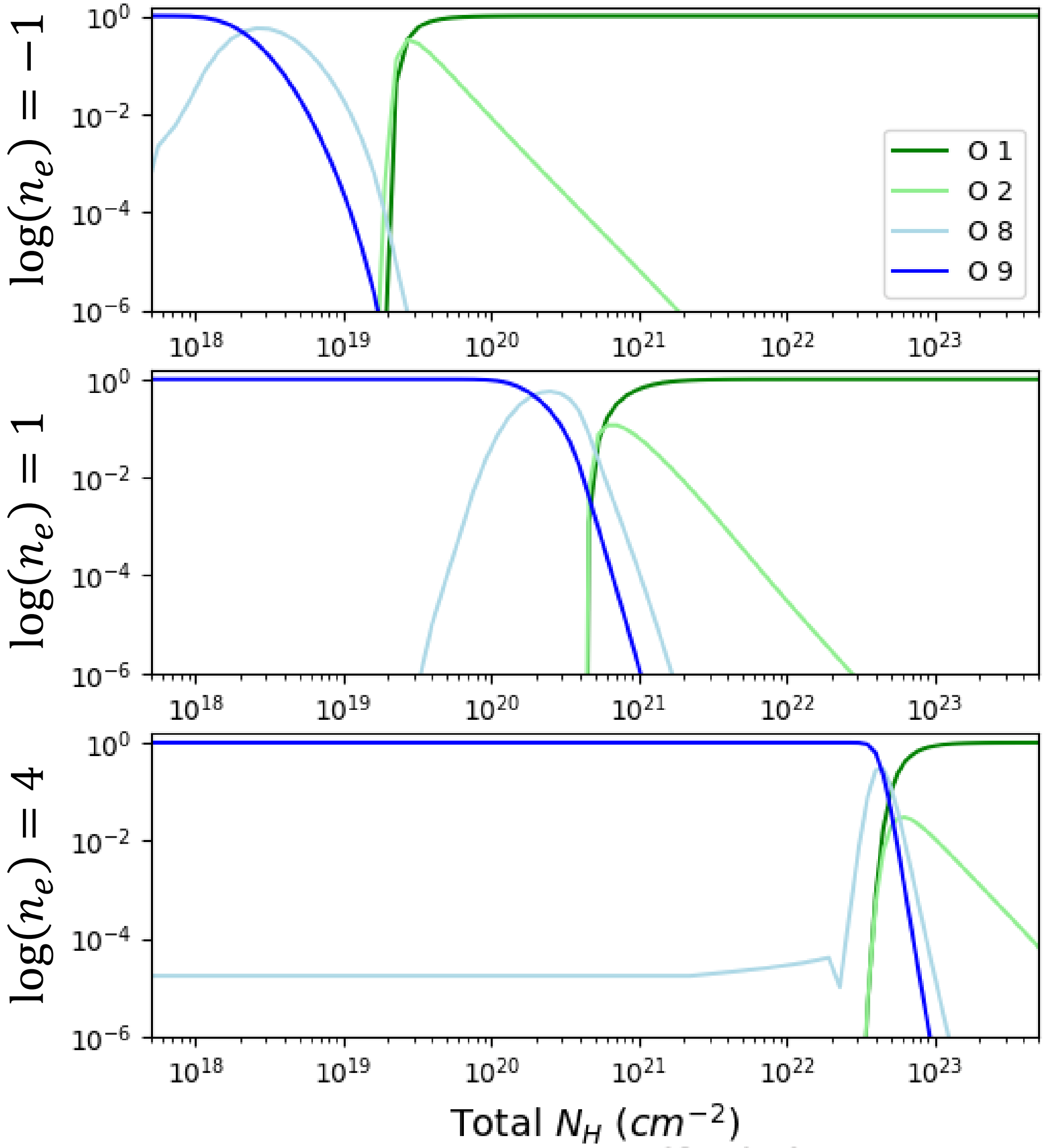
→ more ionised



Gas column density N_H

δN_H

Distance from the burst r



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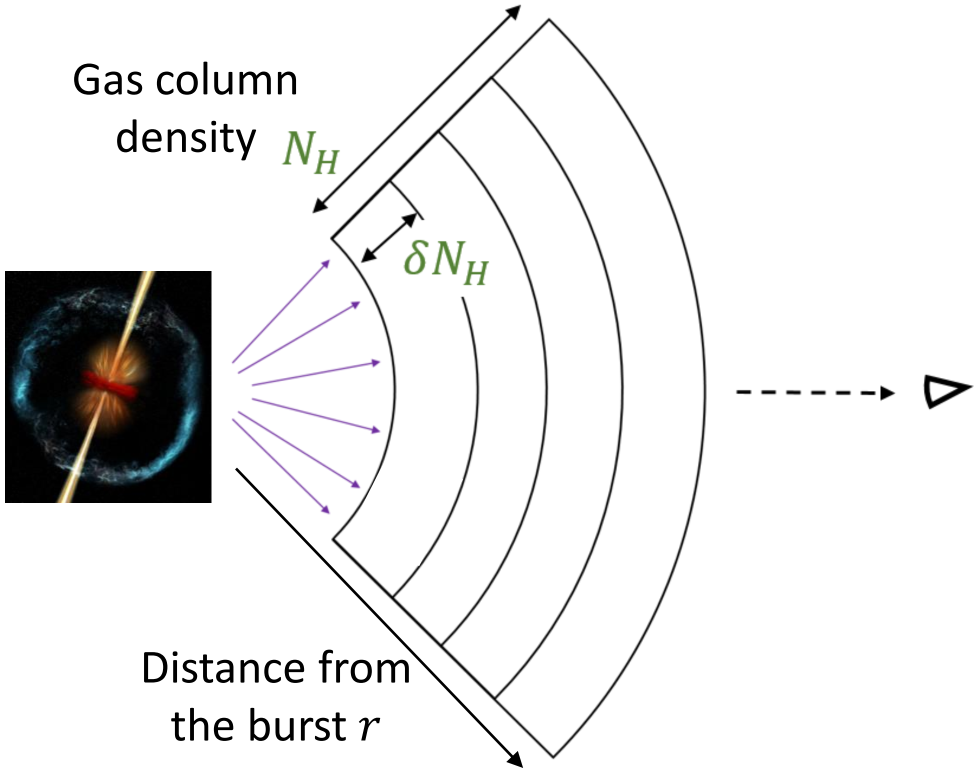

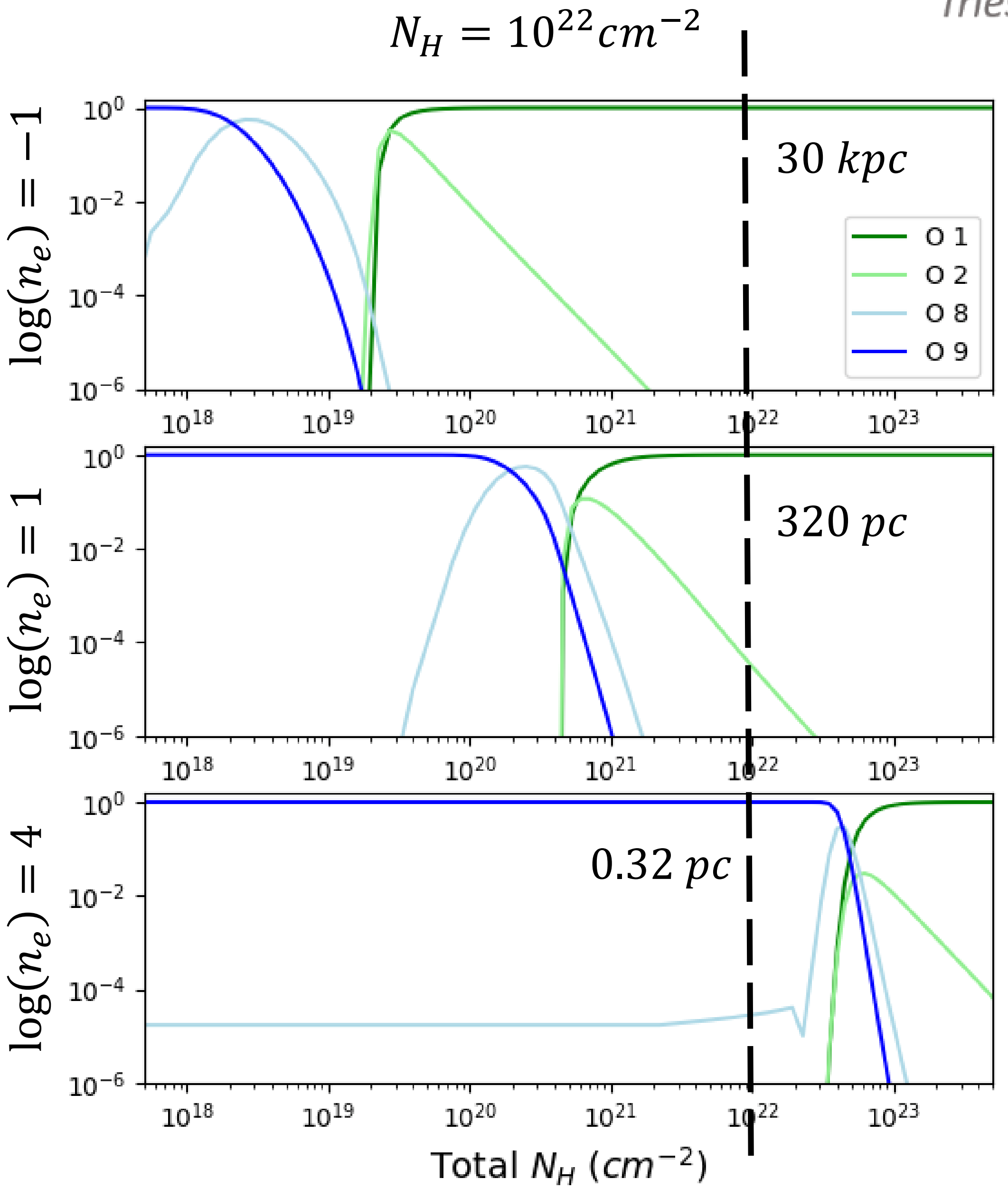

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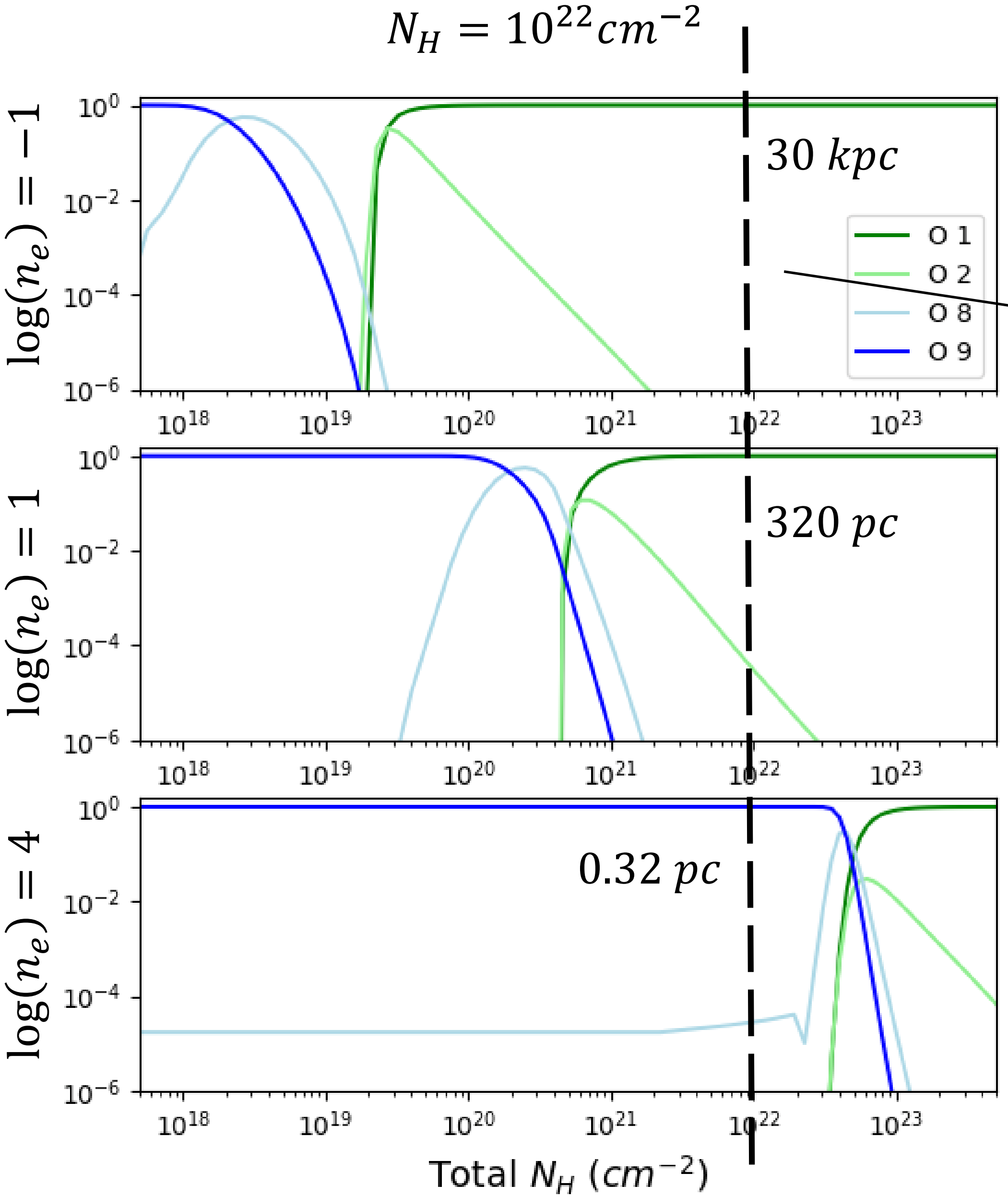
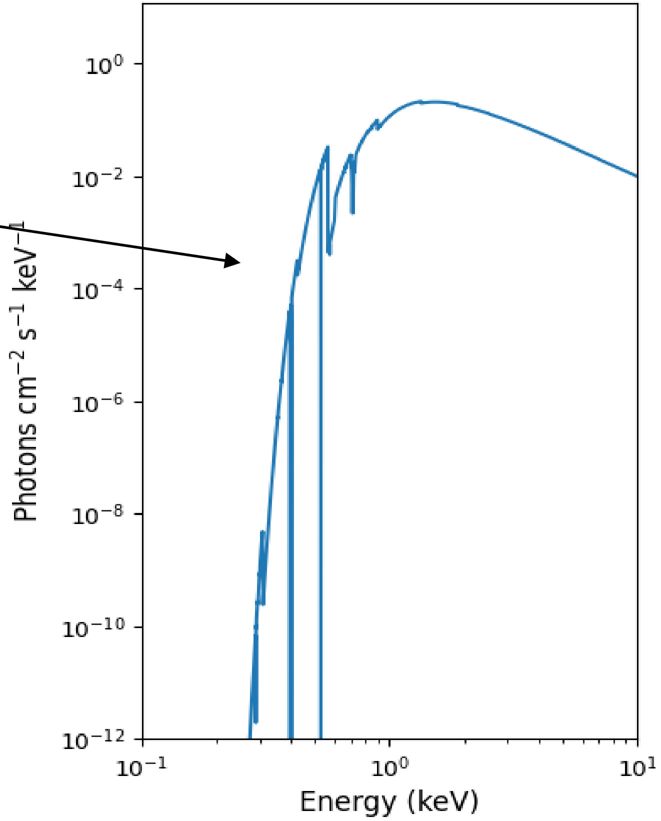
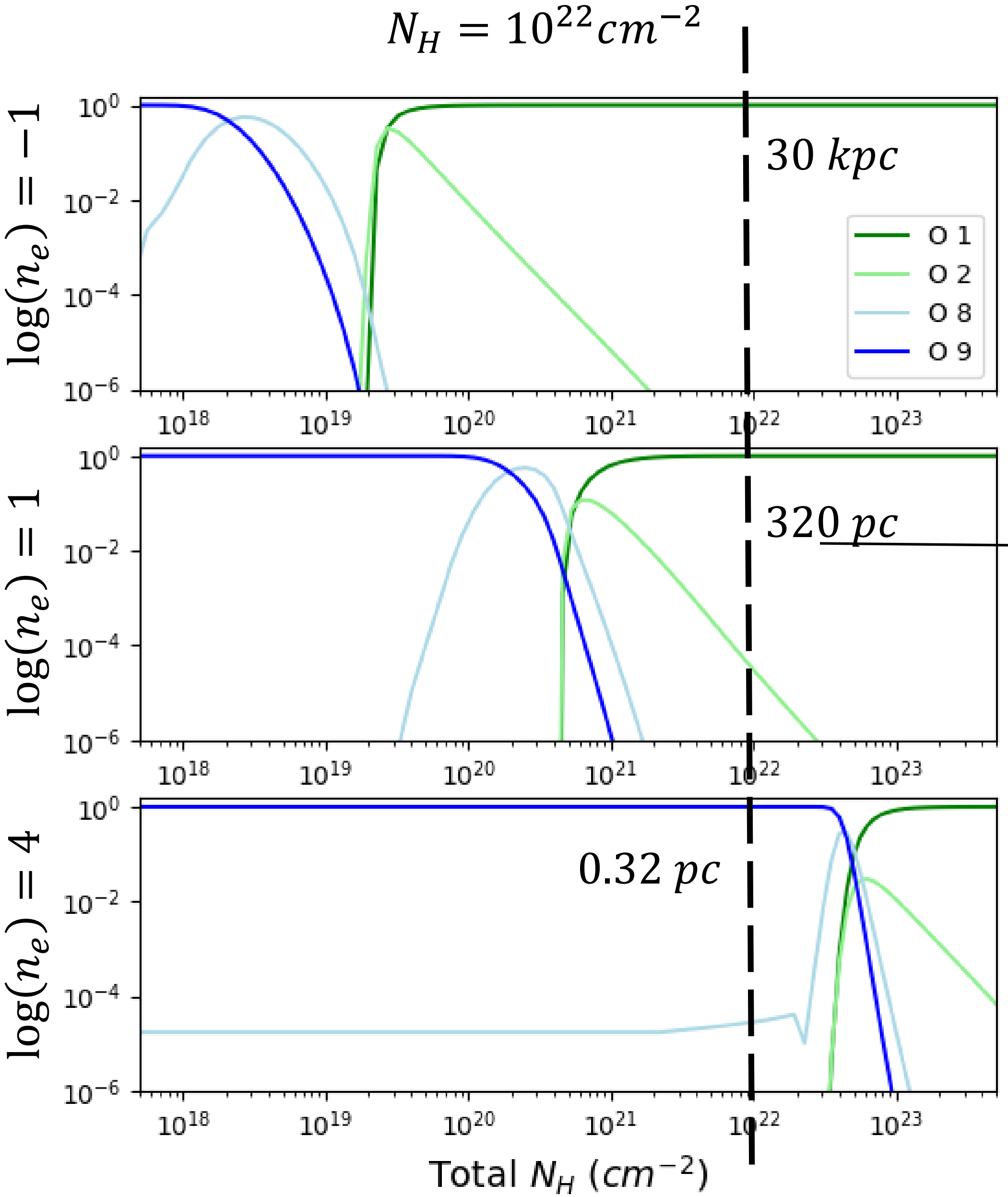
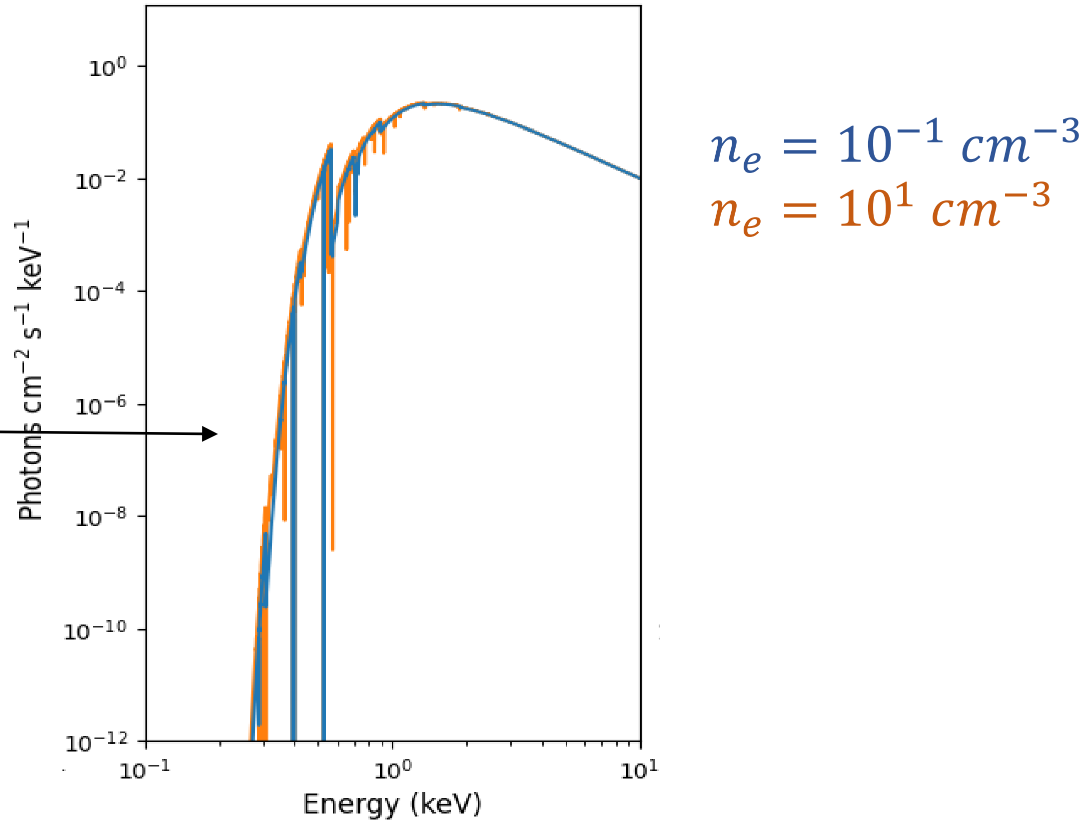




$n_e = 10^{-1}\ cm^{-3}$

3. Absorption spectra





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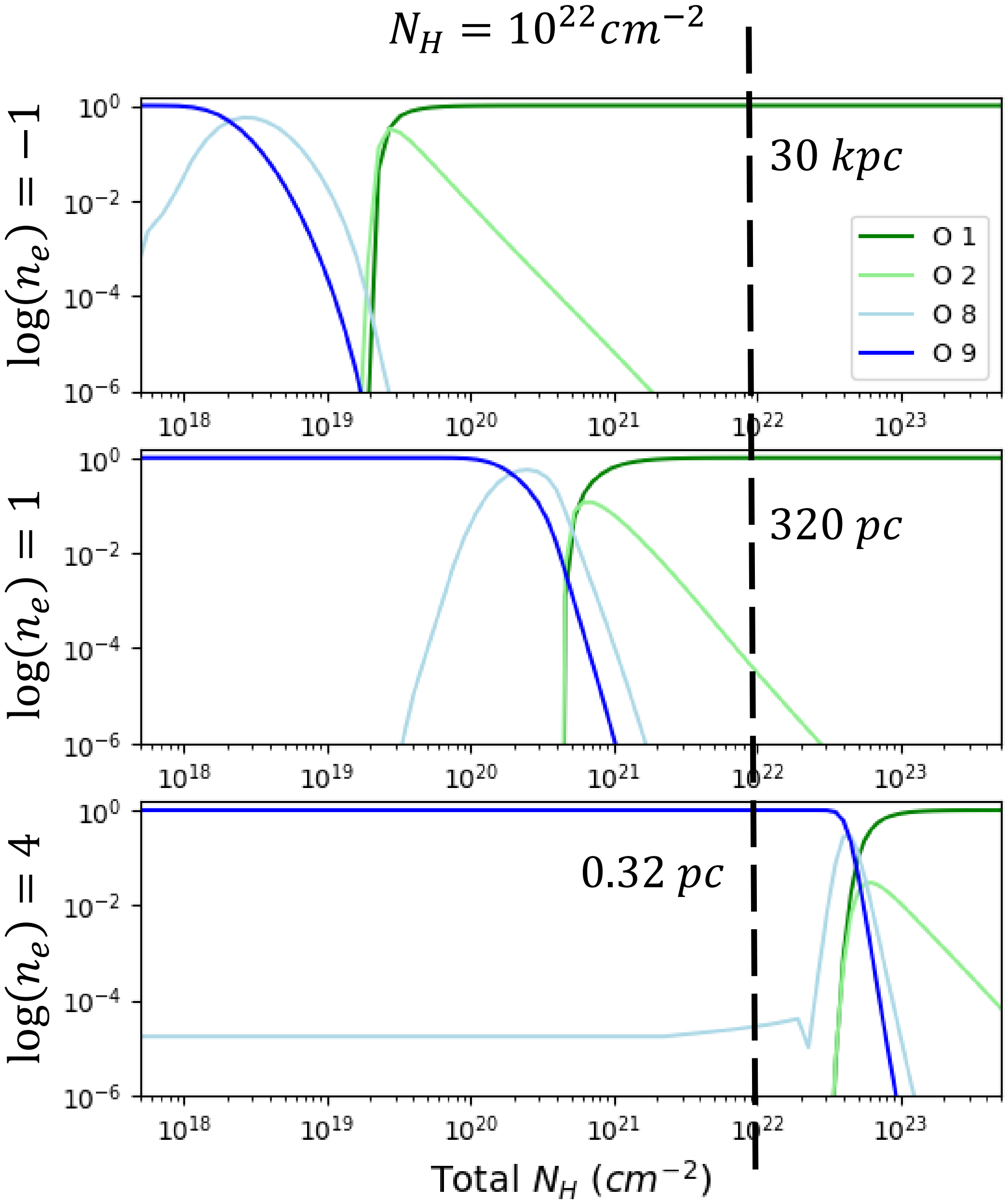

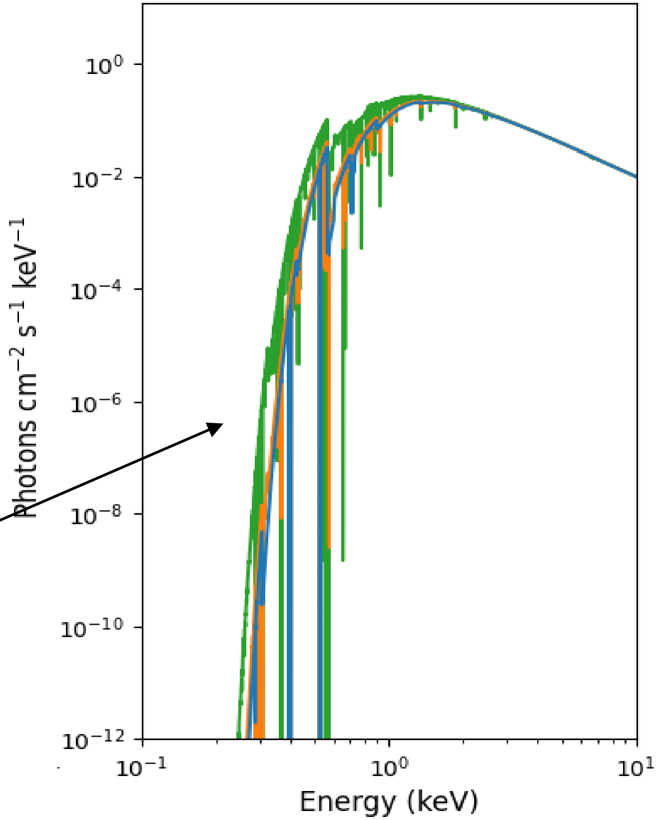

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$n_e = 10^{2}\ cm^{-3}$

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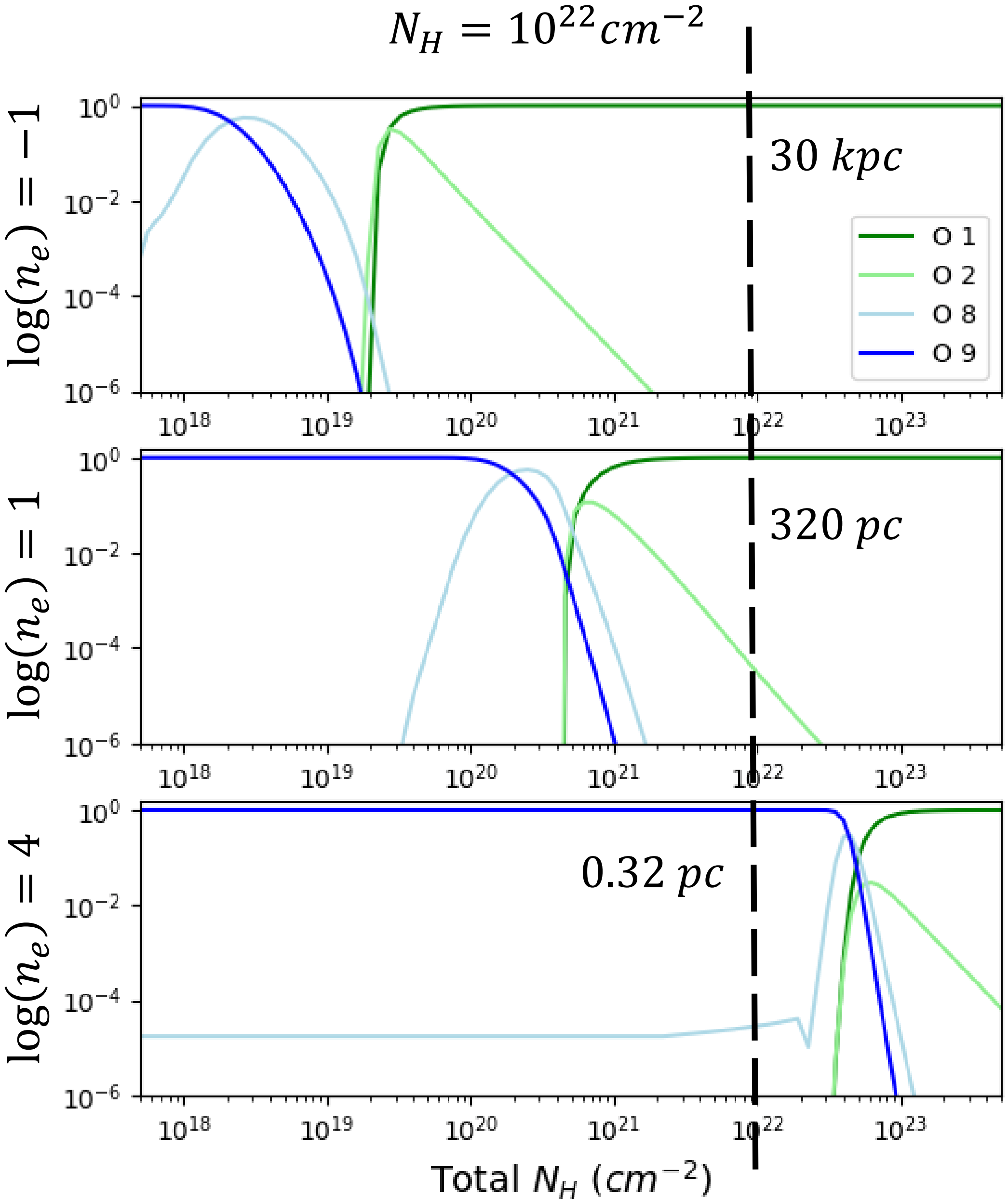

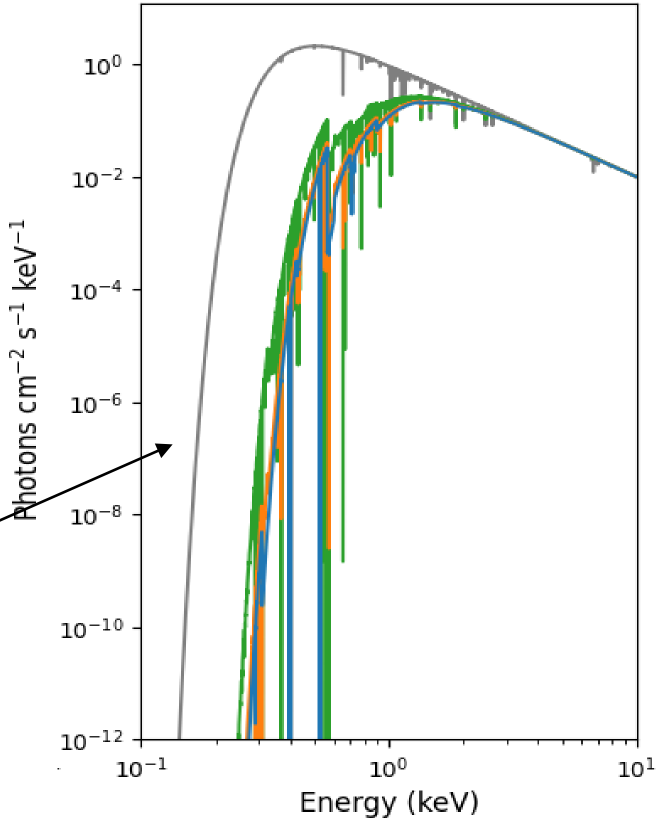

$n_e = 10^{-1}\ cm^{-3}$

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$n_e = 10^{2}\ cm^{-3}$

$n_e = 10^{3}\ cm^{-3}$

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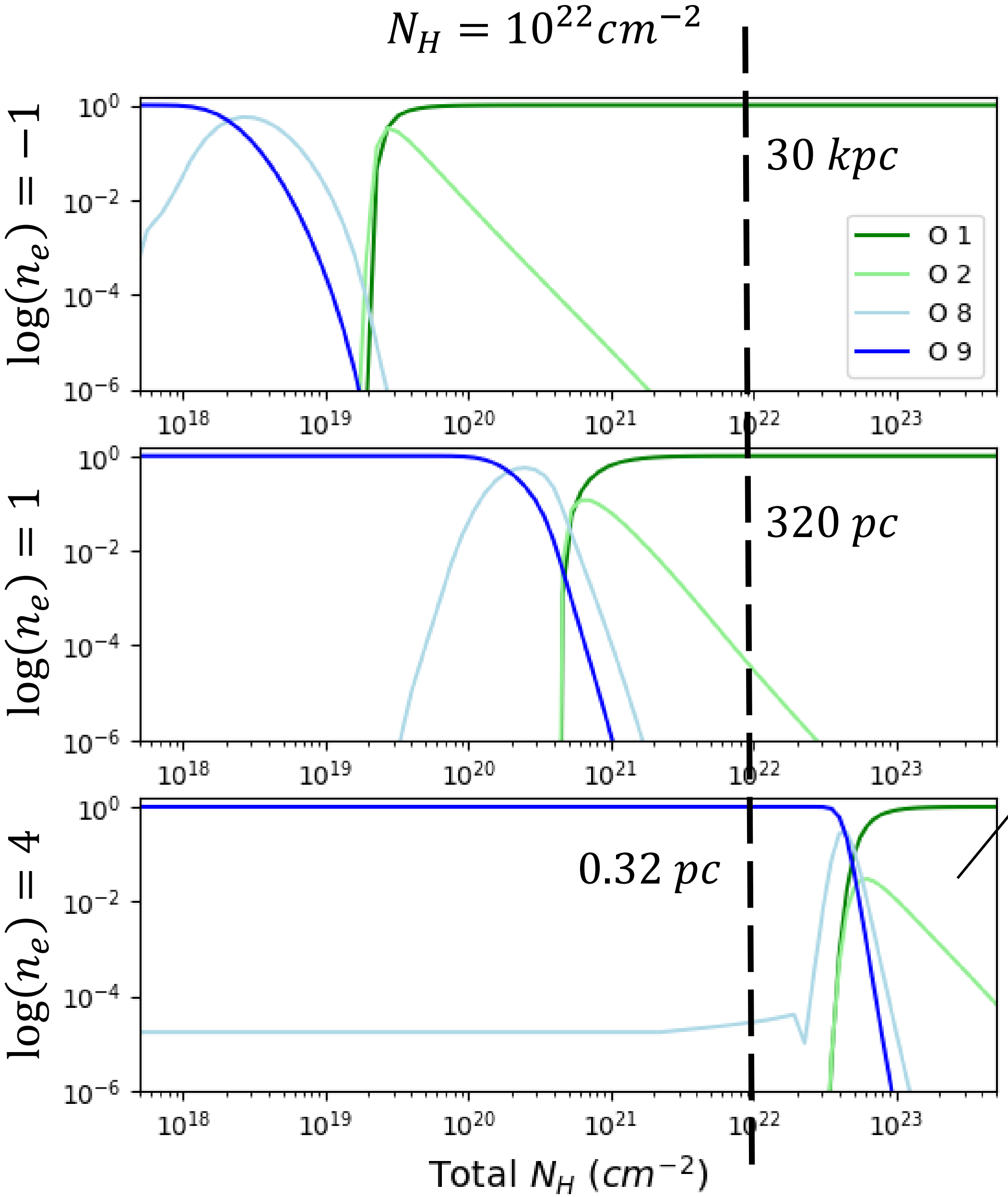
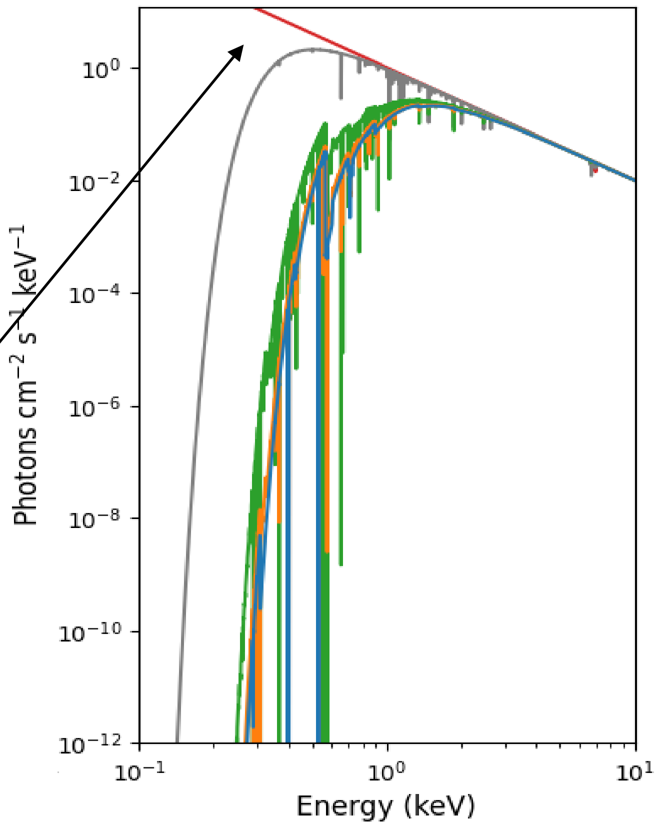
3. Absorption spectra





$n_e = 10^{-1}\ cm^{-3}$

$n_e = 10^{1}\ cm^{-3}$

$n_e = 10^{2}\ cm^{-3}$

$n_e = 10^{3}\ cm^{-3}$

$n_e = 10^{4}\ cm^{-3}$

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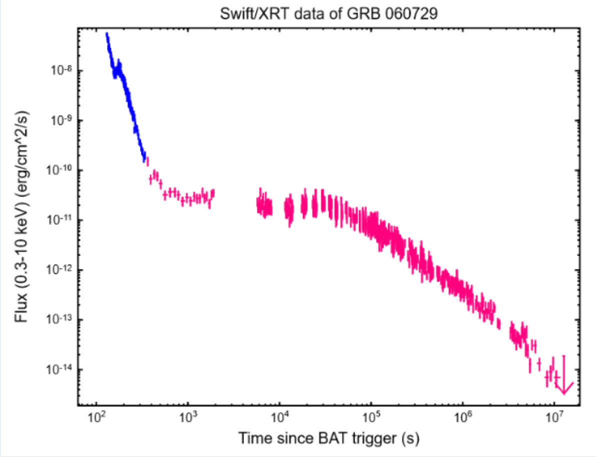
Conclusions

GRBs are powerful light houses

they probe density, metallicity, volume of their surroundings

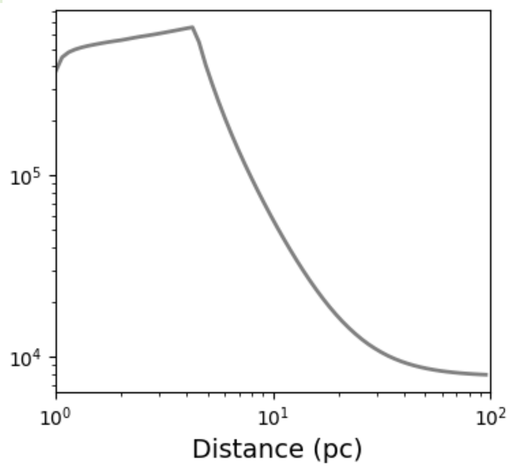
There are extremely variable:

→ need for time-evolving photoionisation models!

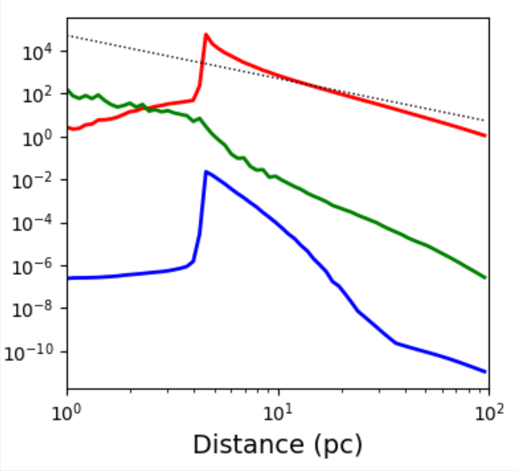


TEPID - Time-Evolving PhotoIonisation Device

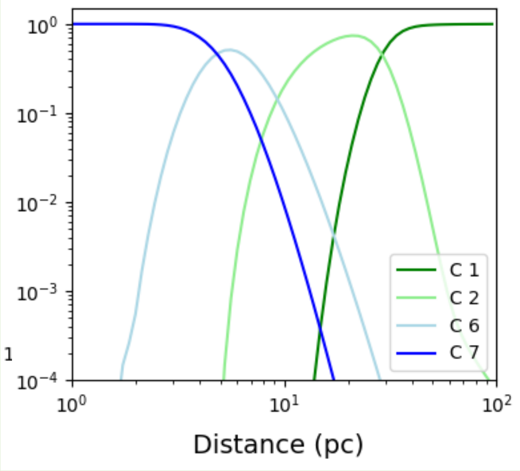
Follows non-equilibrium, time-dependent gas ionisation:



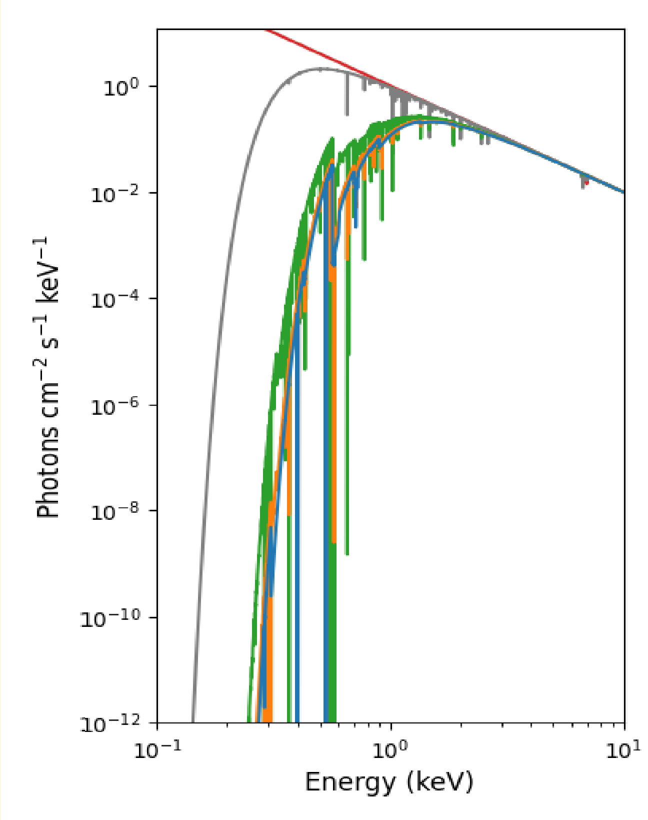
Temperature



Energy balance



Ionic abundances

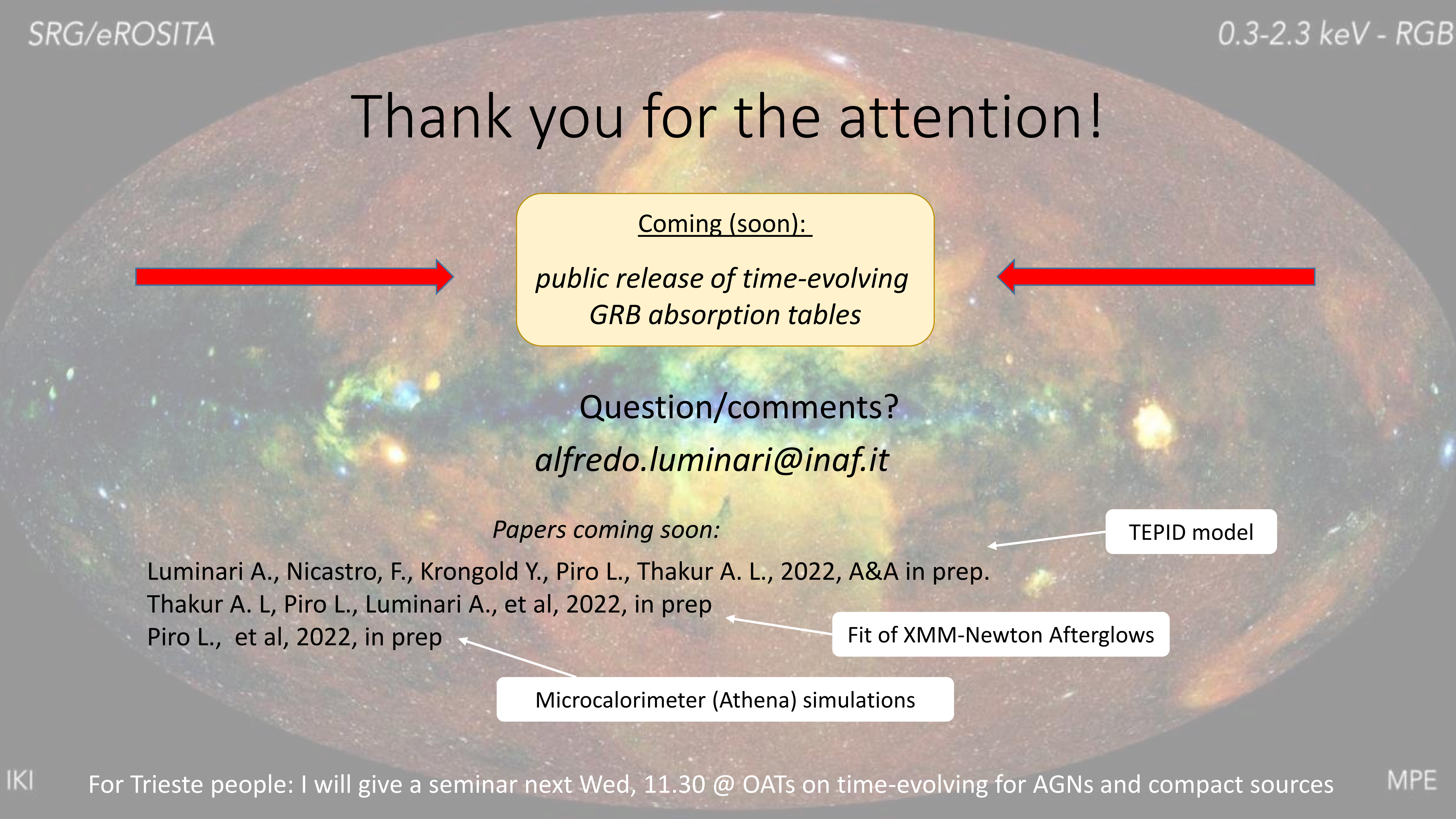


X-ray absorption spectra

Compute time-resolved spectra for a set of input parameters (n, N_H, r) and compare with afterglow observations

See following talk by A. Thakur!

Thank you for the attention!



Coming (soon):

public release of time-evolving GRB absorption tables

Question/comments?

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Papers coming soon:

Luminari A., Nicastro, F., Krongold Y., Piro L., Thakur A. L., 2022, A&A in prep.
Thakur A. L, Piro L., Luminari A., et al, 2022, in prep
Piro L., et al, 2022, in prep

TEPID model

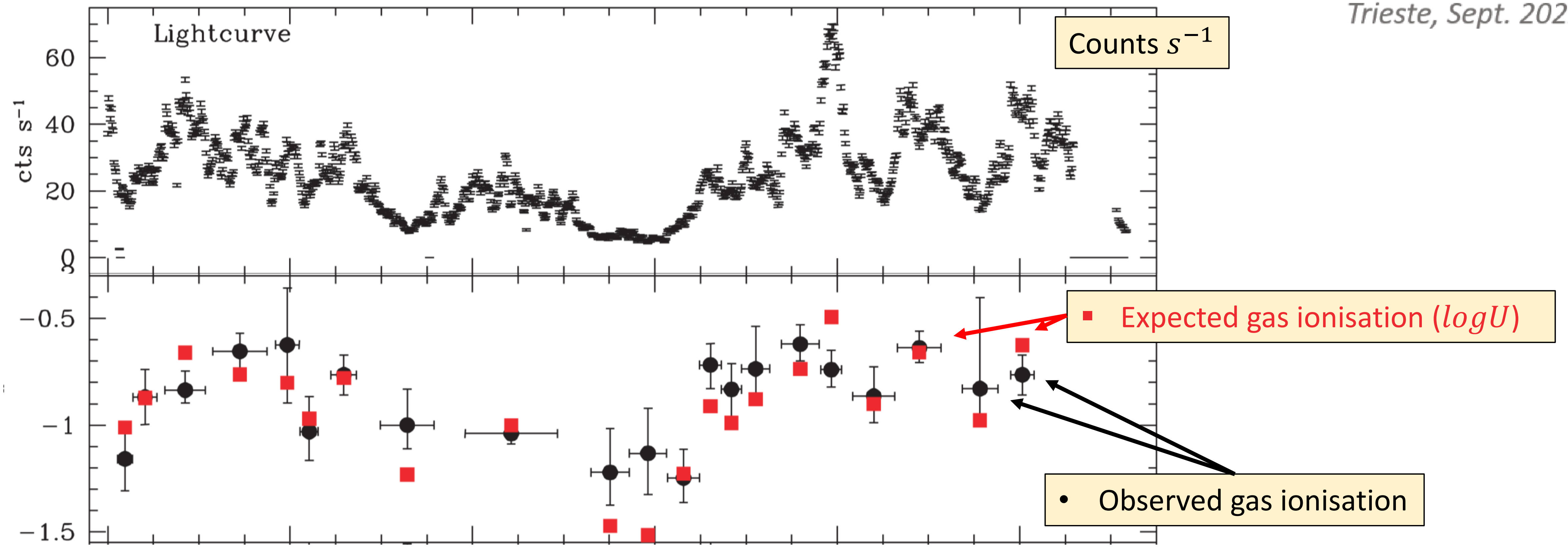
Fit of XMM-Newton Afterglows

Microcalorimeter (Athena) simulations

For Trieste people: I will give a seminar next Wed, 11.30 @ OATs on time-evolving for AGNs and compact sources

Back up slides

AGN NGC4051 – Krongold, Nicastro+07



Counts s^{-1}

🟥 Expected gas ionisation ($logU$)

● Observed gas ionisation

The equilibrium timescale is: $t_{eq} \approx 1 \Big/ \left[\left(\alpha_{rec}(n_{Xi}) \cdot n_e\right) \left(1 + \frac{\alpha_{rec}(n_{Xi-1})}{\alpha_{rec}(n_{Xi})} + \frac{n_{Xi+1}}{n_{Xi}}\right) \right]$ Nicastro+99

Low density: longer t_{eq} , equilibrium not granted

High density: smaller t_{eq} , closer to the equilibrium limit

→ time-evolving ionisation breaks the density degeneracy!

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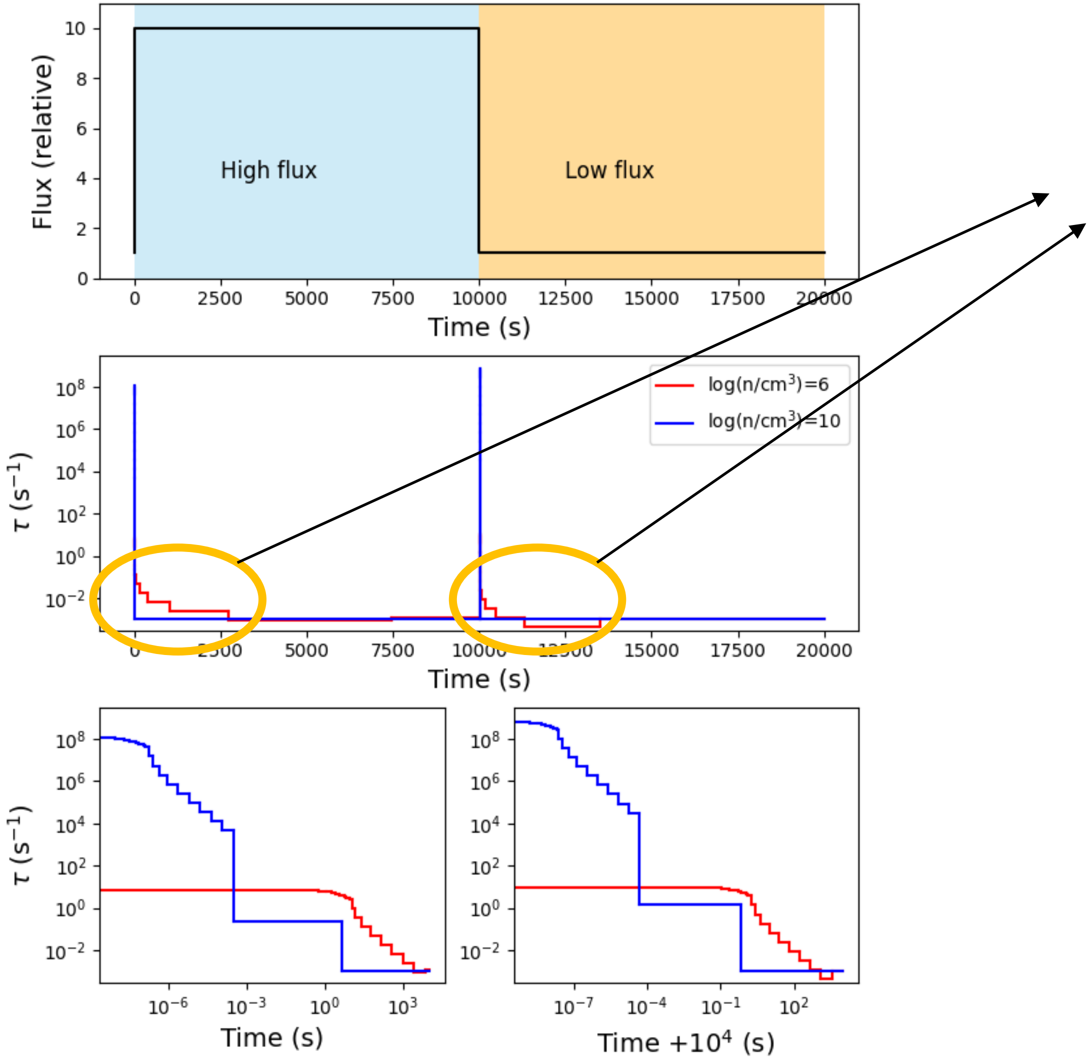
Adaptive time binning



2-step time binning:

1. Decay interval given by t_{eq} :

   Lower density → slower gas reaction → slower decay

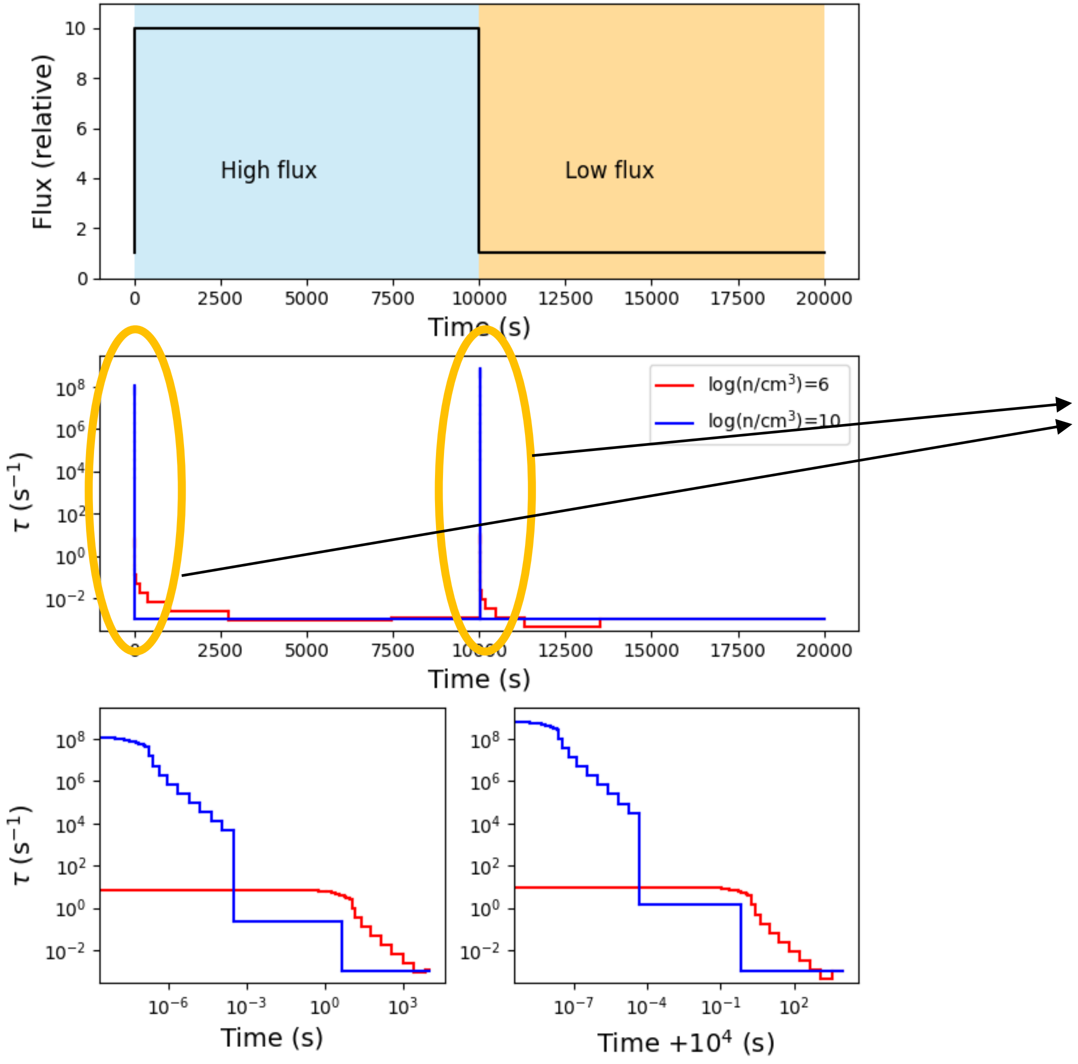
   Higher density → faster gas reaction → faster decay

2. Resolution $\omega \propto 1/t_{err}$ (error on numerical integration)

   Lower density → slower gas reaction → lower ω

   Higher density → faster gas reaction → higher ω

Adaptive time binning



2-step time binning:

1. Decay interval given by t_{eq} :
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2. Resolution $\omega \propto 1/t_{err}$ (error on numerical integration)
   Lower density → slower gas reaction → lower ω
   Higher density → faster gas reaction → higher ω

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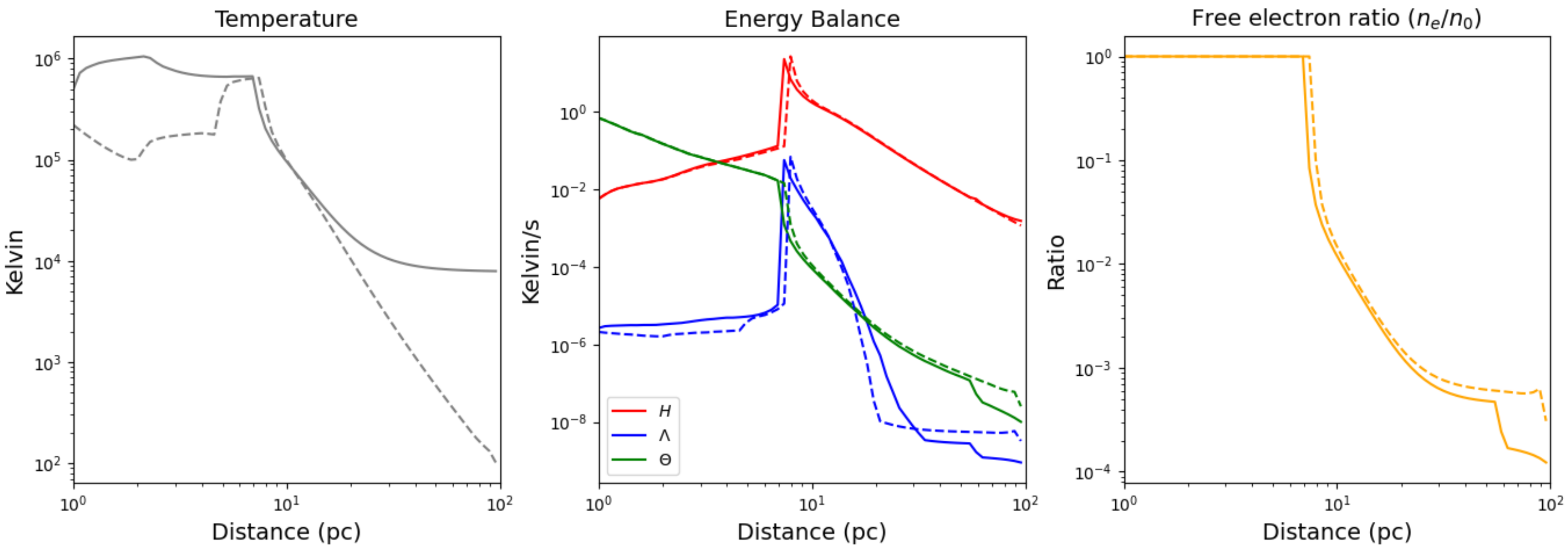
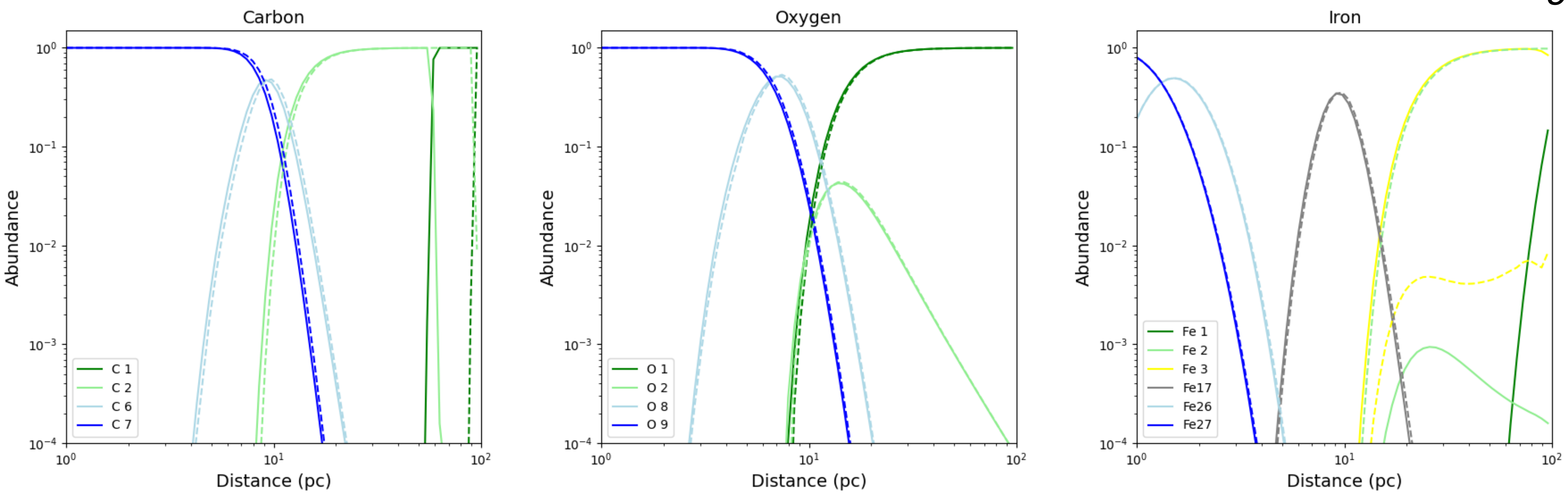
Wolf Rayet-like preionisation





——— Initially neutral medium

- - - Wolf-Rayet preionisation

No differences on the resulting ions and spectra:
GRB radiative output washes out initial conditions

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