Time-Evolving Photo-Ionization Device for Compact Sources

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Time Evolving Photo-Ionization Device (TEPID)

from theoretical modelling to spectral fitting

Outline

i. *Ionised Outflows: open questions*
ii. *Time-evolving photoionization with TEPID:*
    i. *Code setup*
    ii. *Time-evolving computation*
    iii. *X-ray absorption spectra*
iii. *Conclusions*

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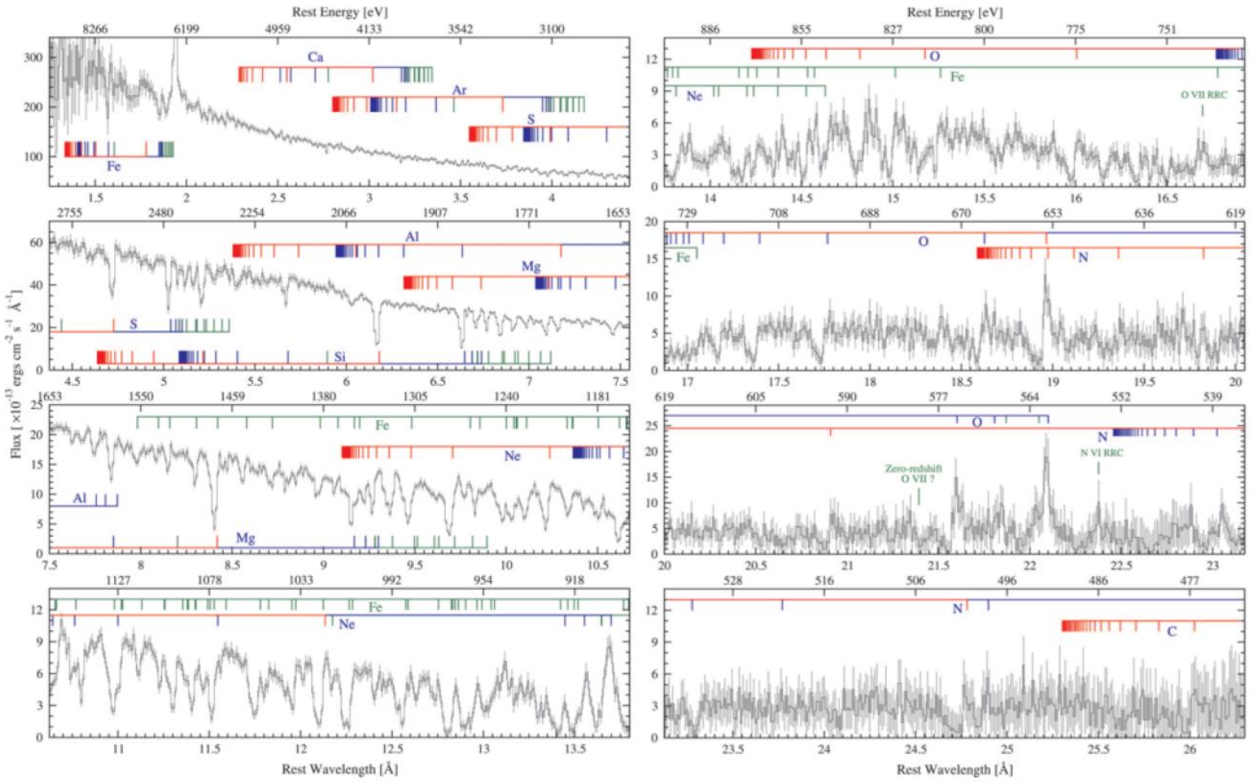
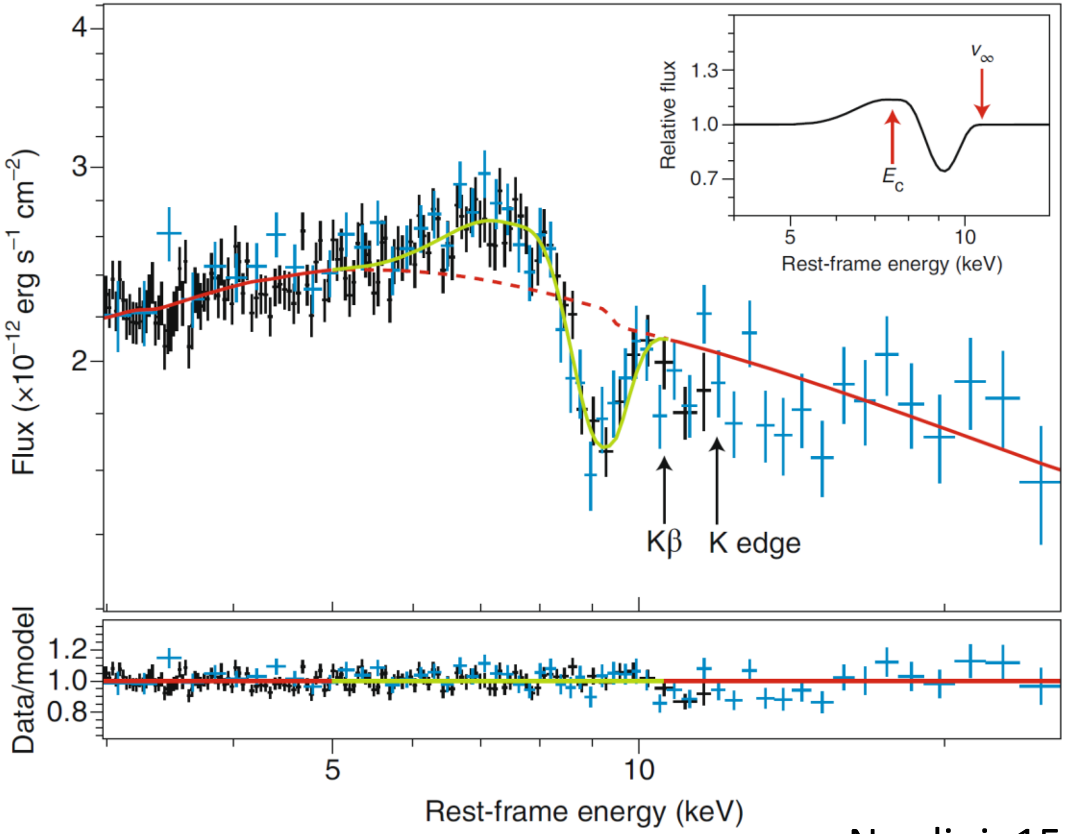
i. Ionised Outflows. AGNs

NGC 3783: a 900 ks *Chandra* grating spectrum.
Wealth of absorption features at 600 km/s

PDS456: a P-Cygni profile in the hard X-ray band.
$$\log(\xi) = 5.5, N_H = 7 \cdot 10^{23}\ cm^{-2}, v_{out} = 0.25\ c$$



Kaspi+02



Nardini+15

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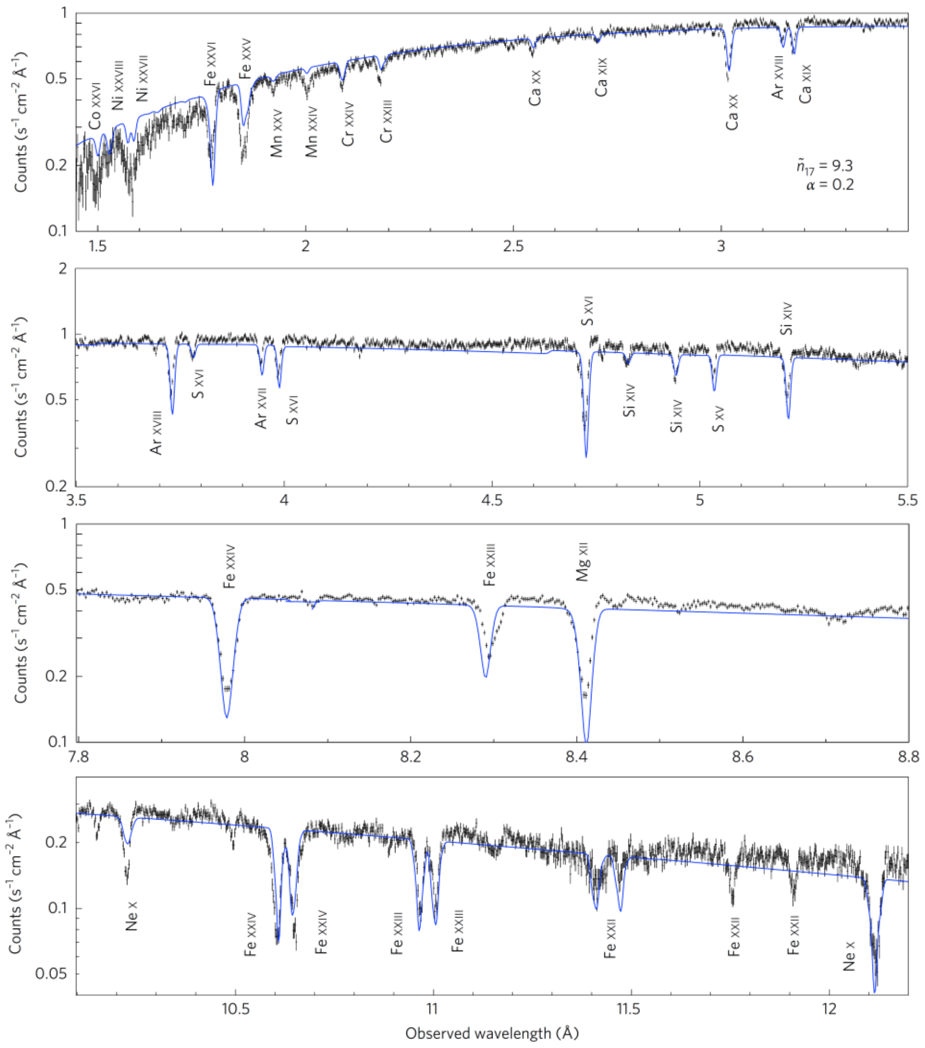
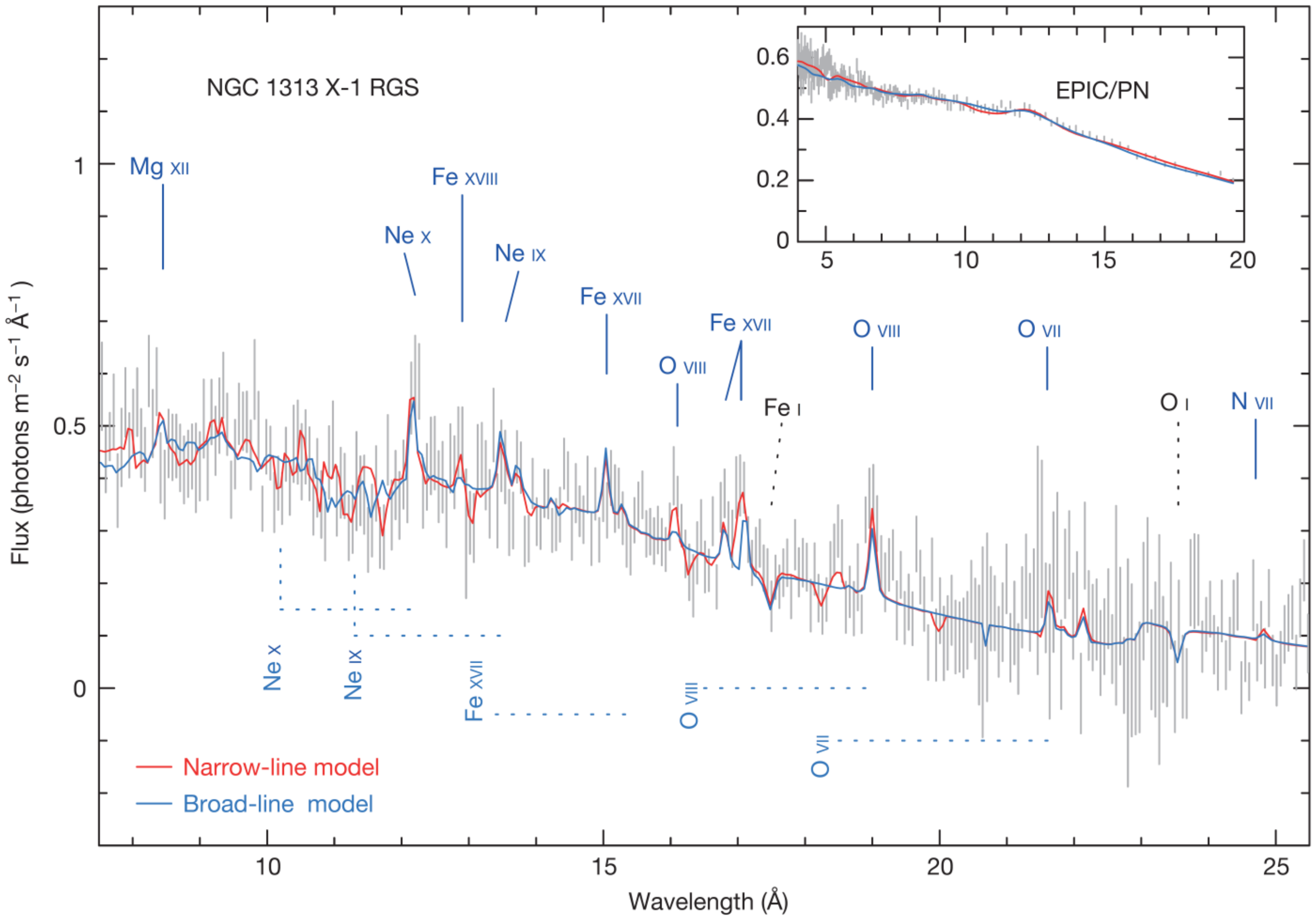
i. Ionised Outflows. Compact sources



XRB GRO J1655 - Fukumura+17

ULX NGC1313-X1 – Pinto+16 +20



$$\log(\xi) = 3.5, v_{out} = 0.25\ c, N_H = 10^{24} cm^{-2}$$

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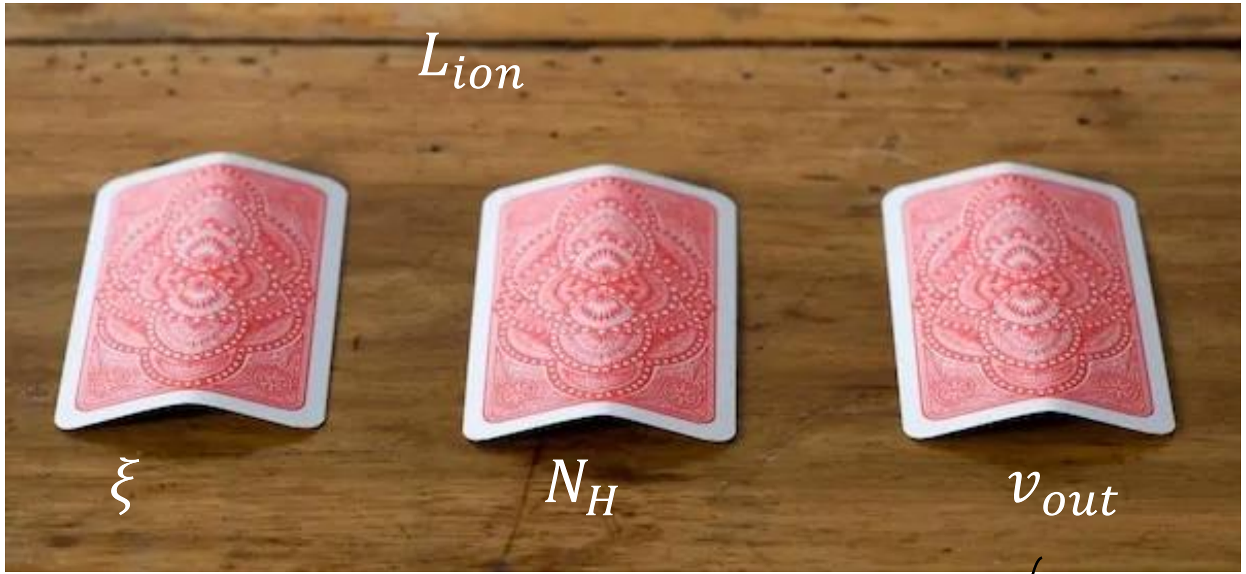
i. Ionised Outflows. Open questions

Main observables:



$+, -, \dfrac{\xi}{v_{out}}, N_H^{\xi}, \ldots$

....abracadabra...

Obtain $r, n, \dot{M}_{out}, \dot{E}_{out}, \ldots$

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i. Ionised Outflows. Open questions

Still after >20 years of X-ray spectroscopy, several questions remain open:

1. Location
2. Density
3. Energetic

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i. Ionised Outflows. Open questions

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1. Location
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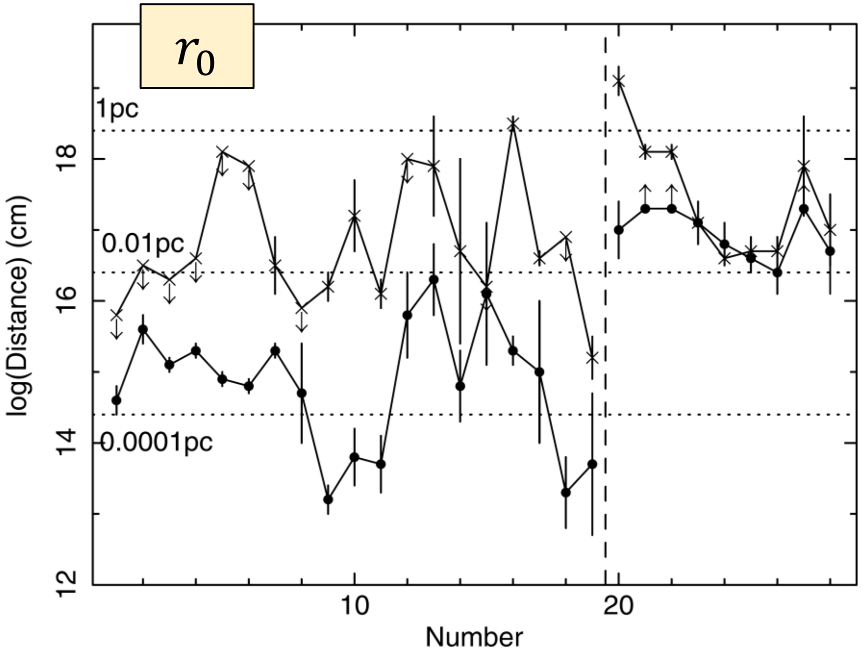
<u>Lower and upper limits</u>
estimated through <u>indirect arguments</u> and <u>assumptions</u>
(e.g. $r_{min} = \frac{2\,G\,M_{BH}}{v^2}$, $r_{max} = \frac{L}{\xi N_H}$)



+ covering factor C_f is basically unconstrained….

Sample of local Sy1 galaxies from Tombesi+12

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i. Ionised Outflows. Open questions

Still after >20 years of X-ray spectroscopy,
several questions remain open:

1. Location
2. **Density**
3. Energetic

<u>Degenerate parameter when ionisation is at equilibrium</u>

Status and appearance of the gas is uniquely determined by the ionisation parameter $\xi = \frac{L_{ion}}{nr^2}$

<u>But…</u>
→ degeneration is broken out of ionisation equilibrium!

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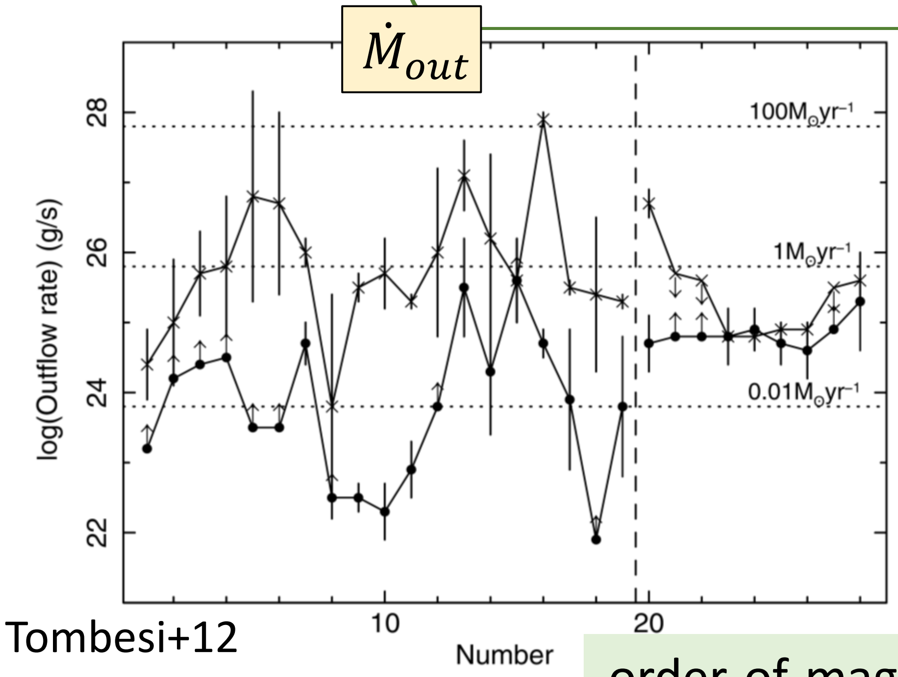
i. Ionised Outflows. Open questions

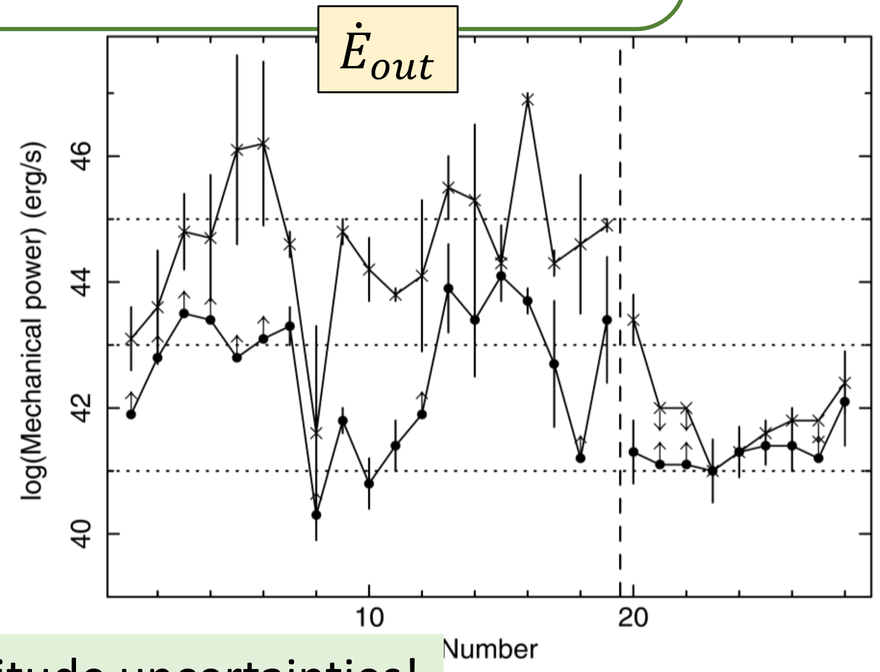
Still after >20 years of X-ray spectroscopy,
several questions remain open:

1. Location
2. Density
3. Energetic

Mass rate: $\dot{M}_{out} \propto C_f \int_{r_0}^{r_1} n(r)v(r)r\,dr \propto r_0 C_f N_H v_{out}$

Energy rate: $\dot{E}_{out} = \frac{1}{2}\dot{M}_{out} v_{out}^2$





Tombesi+12

order-of-magnitude uncertainties!

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ii. Time-evolving photoionization with TEPID

Constant Ionisation source
→ Time-equilibrium photoionisation:

Density and distance are degenerate!

Ionisation parameter dictates the physical status of the gas:

Ionising flux

$$\xi \propto \frac{F_{ion}}{nr^2}$$

Gas density·distance

i) Temperature is a function of ξ
ii) 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….

→ measure ξ through the ratio of different absorption lines
→ measure N_H from line depth
→ measure v_{out} from line blueshift

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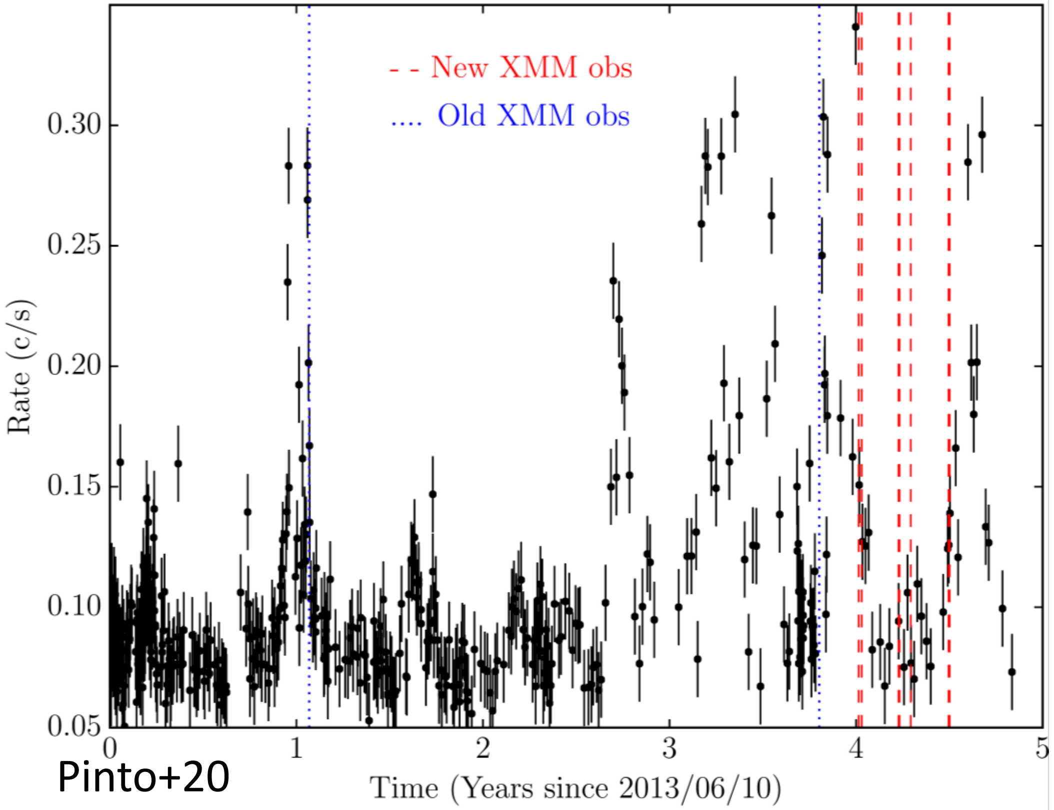
ii. Time-evolving photoionization with TEPID

…can we do better?

Yes! Let's exploit time variability!

Variable ionisation source ($t_{var} < t_{eq}$):
→ Time-evolving photoionisation:



Pinto+20

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 source lightcurve*

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ii. Time-evolving photoionization with TEPID

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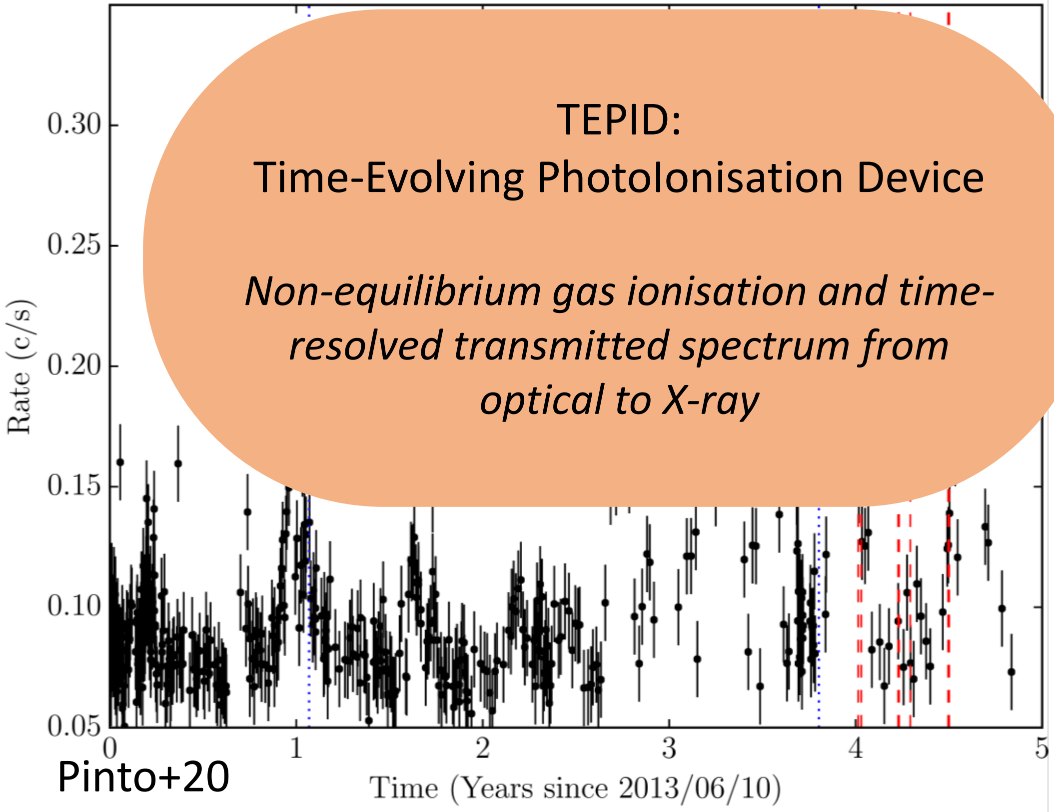
Variable ionisation source ($t_{var} < t_{eq}$):
→ Time-evolving photoionisation:

TEPID:
Time-Evolving PhotoIonisation Device

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



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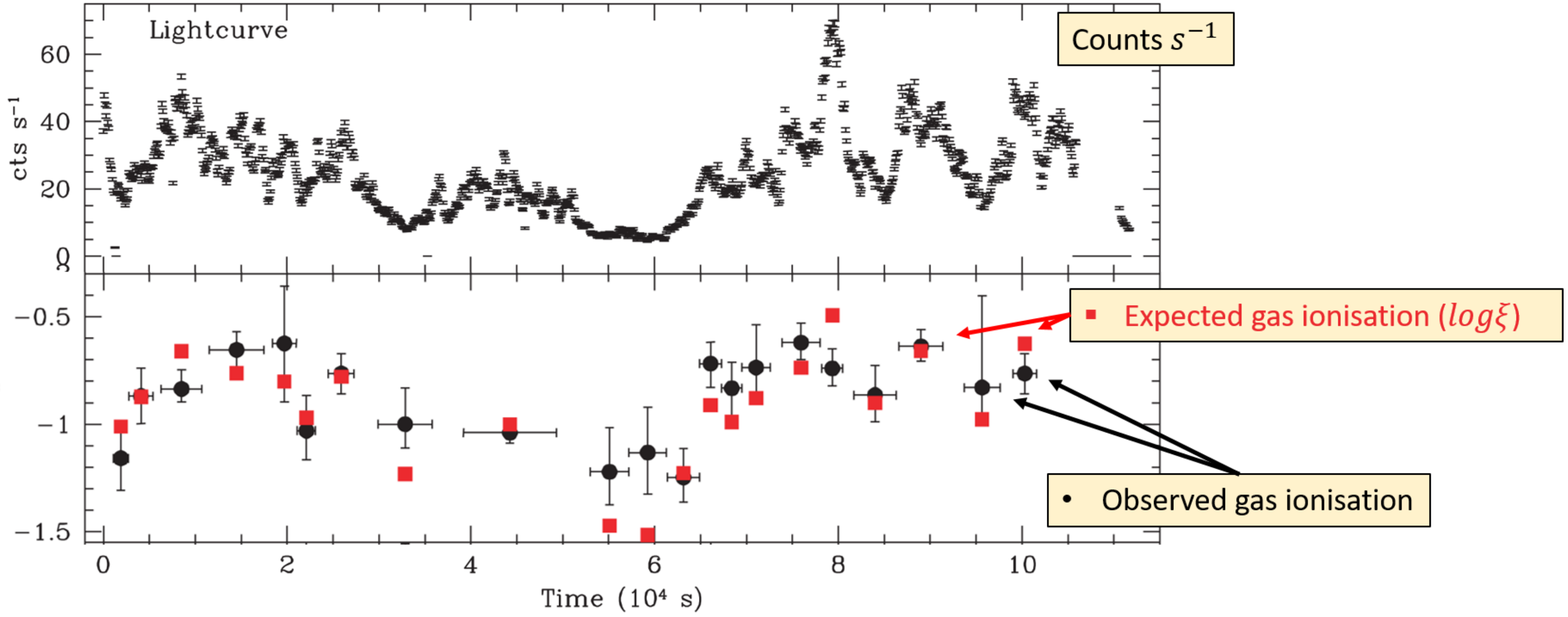
ii. Time-evolving photoionization with TEPID

NGC4051 – Krongold, Nicastro+07



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

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

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

→ time-evolving ionisation breaks the density degeneracy!

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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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<u>Destruction:</u>
recombination to $i-1$ and
photoionisation to $i+1$ (Auger $i+2$)

<u>Creation:</u>
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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Summed over the gas elements

Charge conservation

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

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ii. TEPID

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Summed over the gas elements

Charge conservation

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

Gas absorption:

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

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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

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

Temperature

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

Summed over the gas elements

Charge conservation

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

Gas absorption:

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

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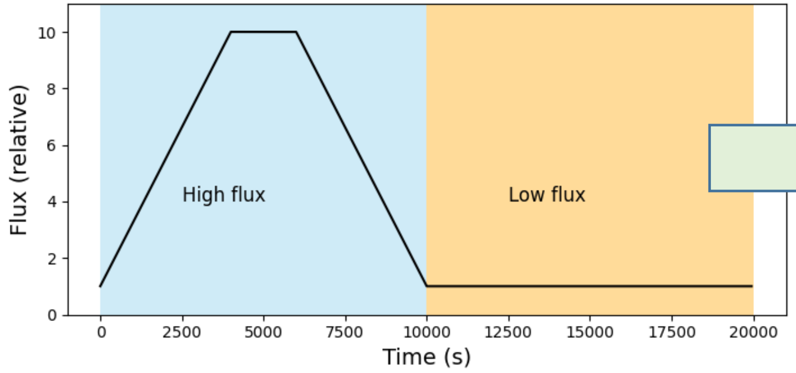
ii. TEPID. Code outline

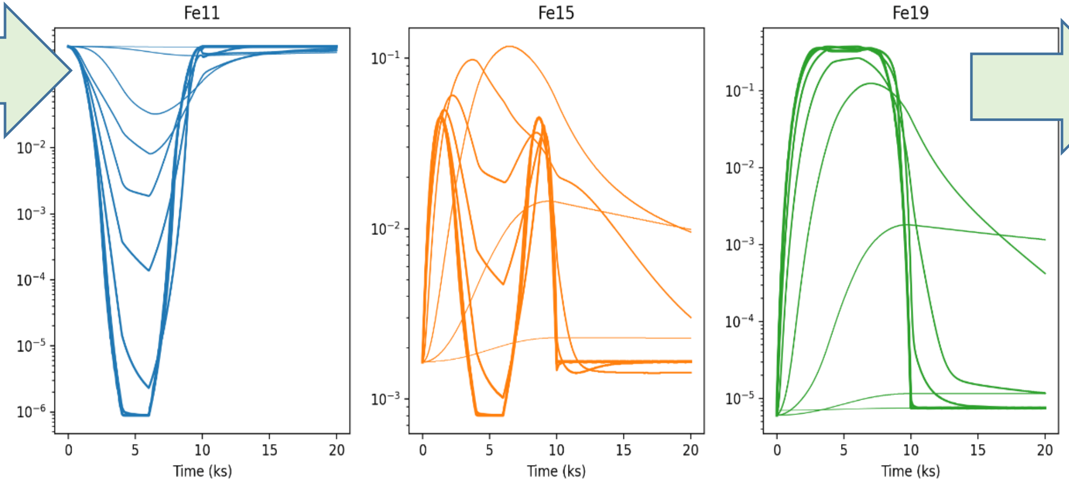
Work flow of TEPID:

1. Code setup:



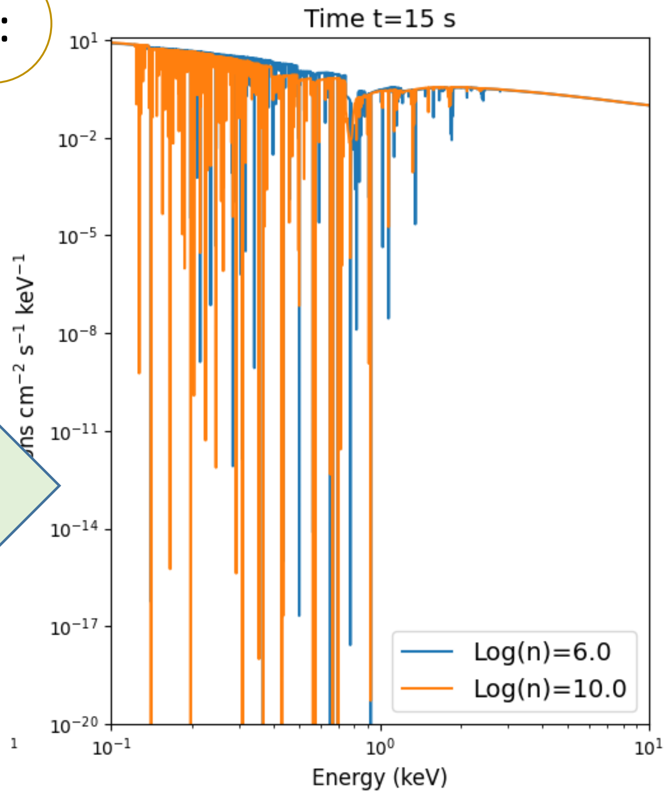
i. Lightcurve
ii. Gas density
iii. Initial $\log(\xi)$

2. Time evolving computation:



Temporal evolution of the gas ionisation and temperature

3. Absorption spectrum:



Time-resolved X-ray spectra as a function of the gas density, using PHASE (Krongold+03)

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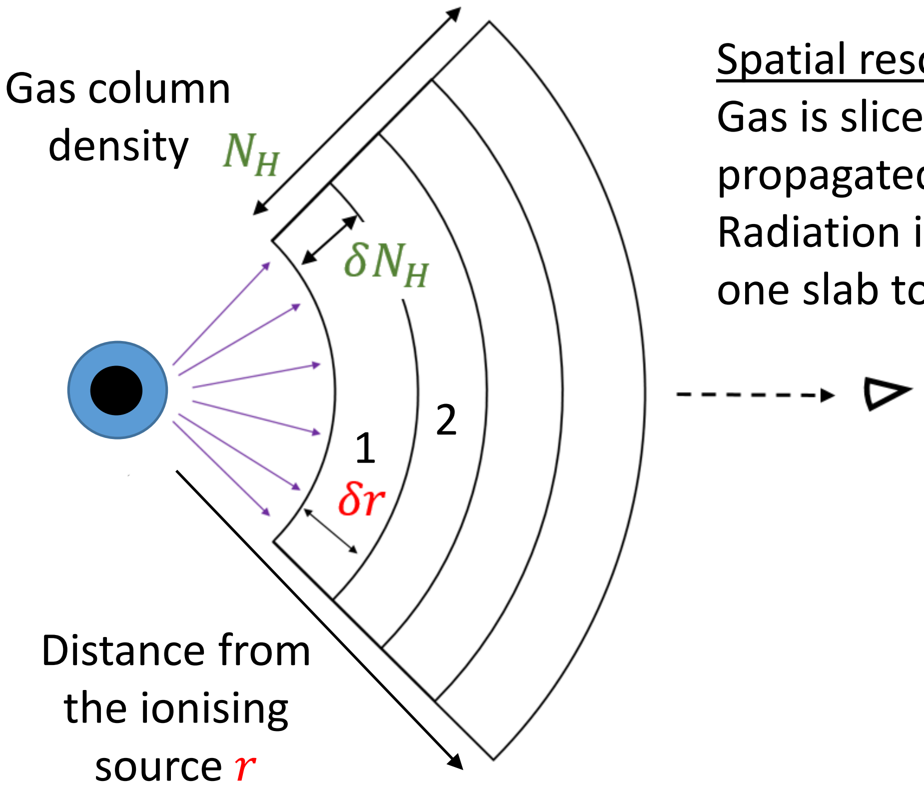
ii. TEPID

1. Code setup



Spatial resolution:

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:

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

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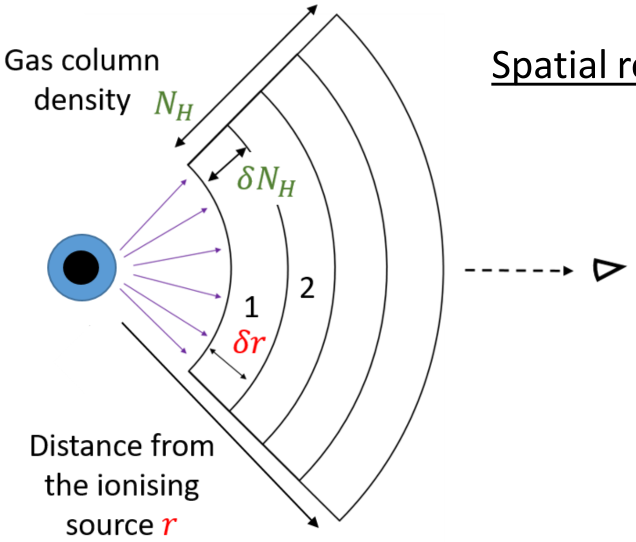
ii. TEPID

1. Code setup

Spatial resolution

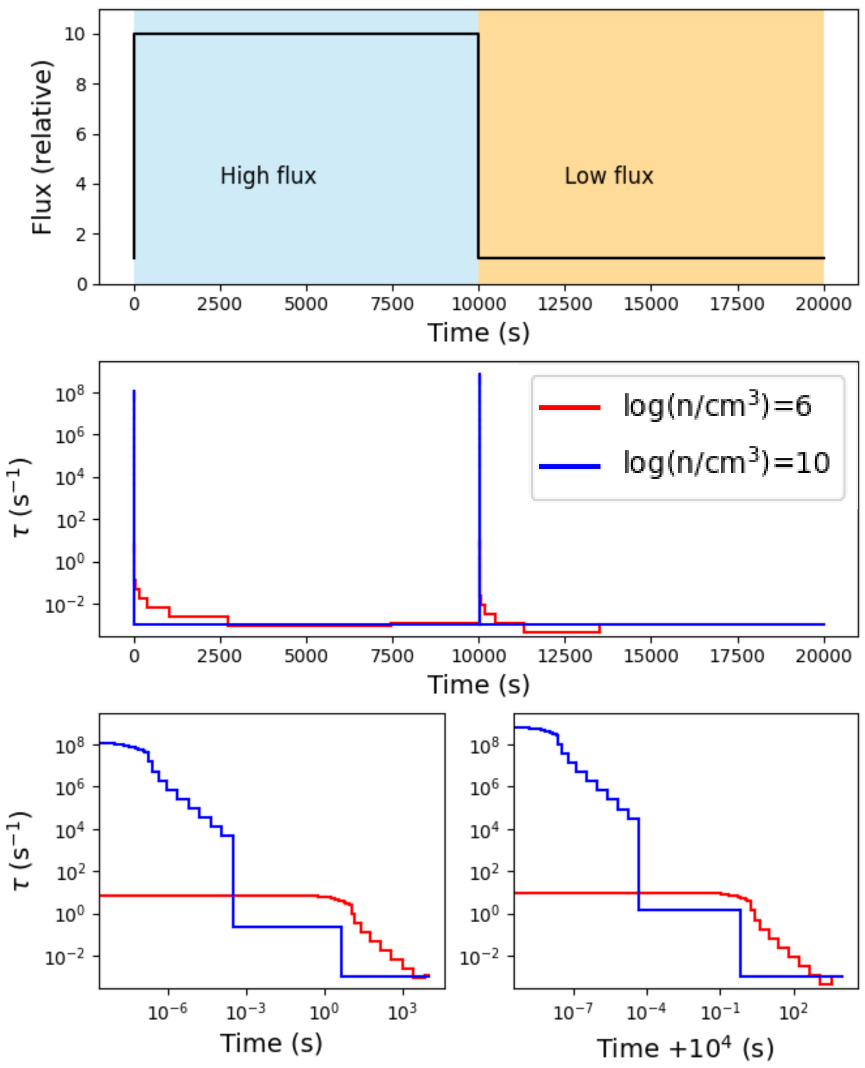


Temporal resolution

computed by the code through an *adaptive approach* as a function of:

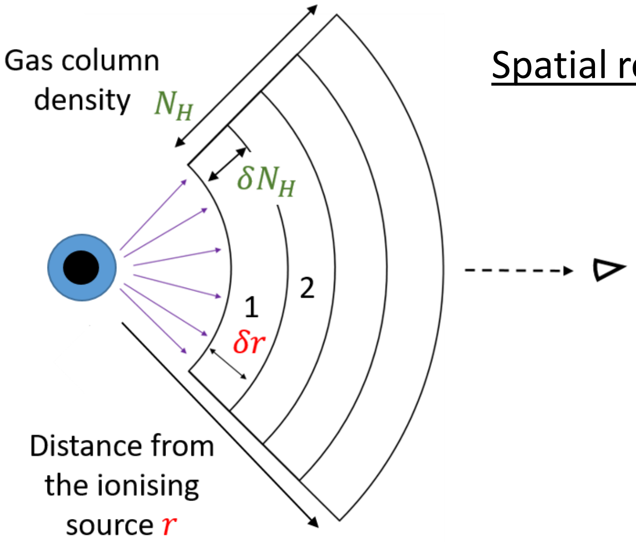
i) Lightcurve

ii) n_e



ii. TEPID

1. Code setup



Spatial resolution

Temporal resolution

computed by the code through an *adaptive approach* as a function of:

i) Lightcurve

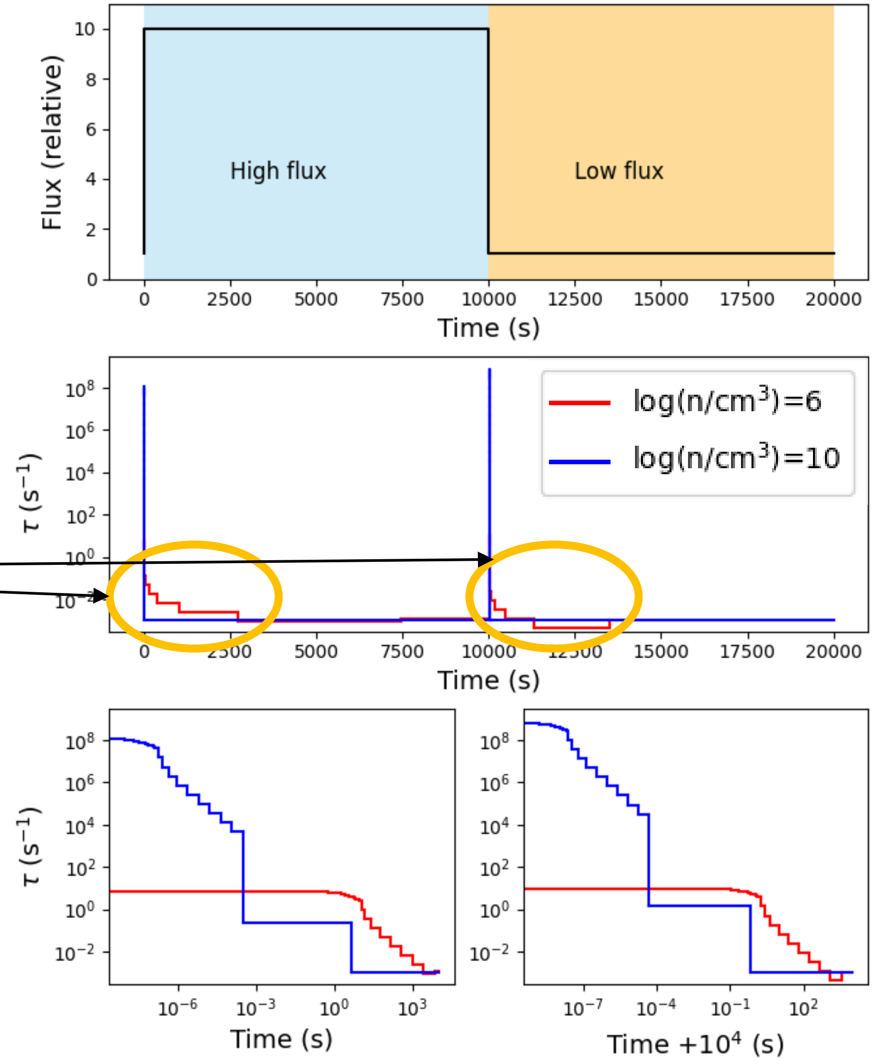
ii) n_e

2-step time binning:

1. Decay interval given by $\mathrm{t_{eq}}$:

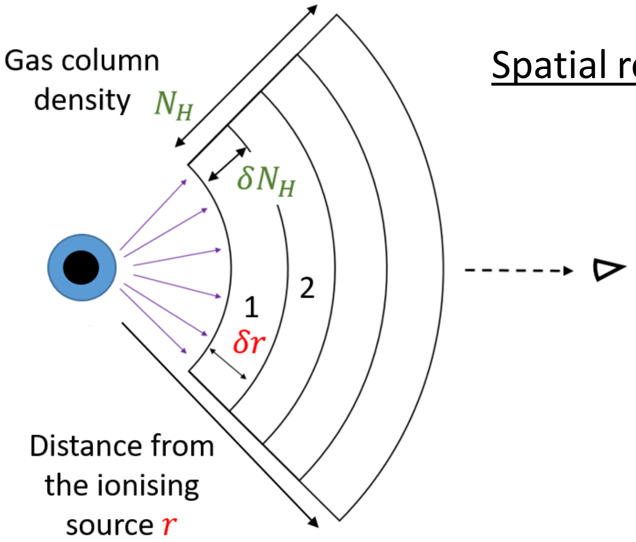
   Lower density → slower gas reaction → slower decay

   Higher density → faster gas reaction → faster decay



ii. TEPID

1. Code setup



<u>Spatial resolution</u>

<u>Temporal resolution</u>

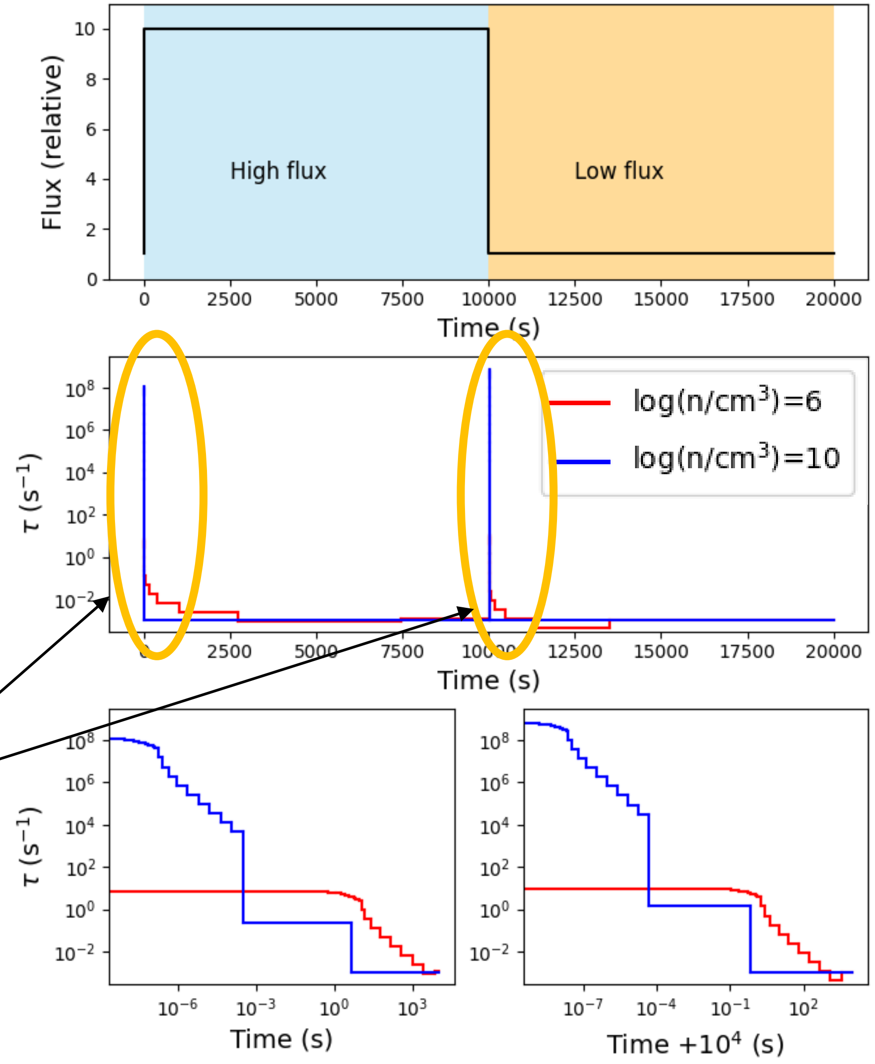
computed by the code through an *adaptive approach* as a function of:

i) Lightcurve

ii) n_e

2-step time binning:

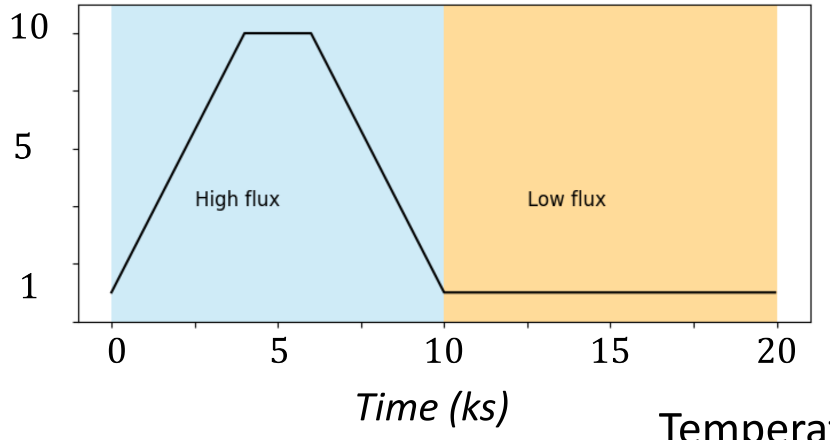
1. Decay interval given by $\mathrm{t_{eq}}$:
   - Lower density → slower gas reaction → slower decay
   - Higher density → faster gas reaction → faster decay
2. Resolution $\omega \propto 1/\mathrm{t_{err}}$ (error on numerical integration)
   - Lower density → slower gas reaction → lower ω
   - Higher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



ii. TEPID

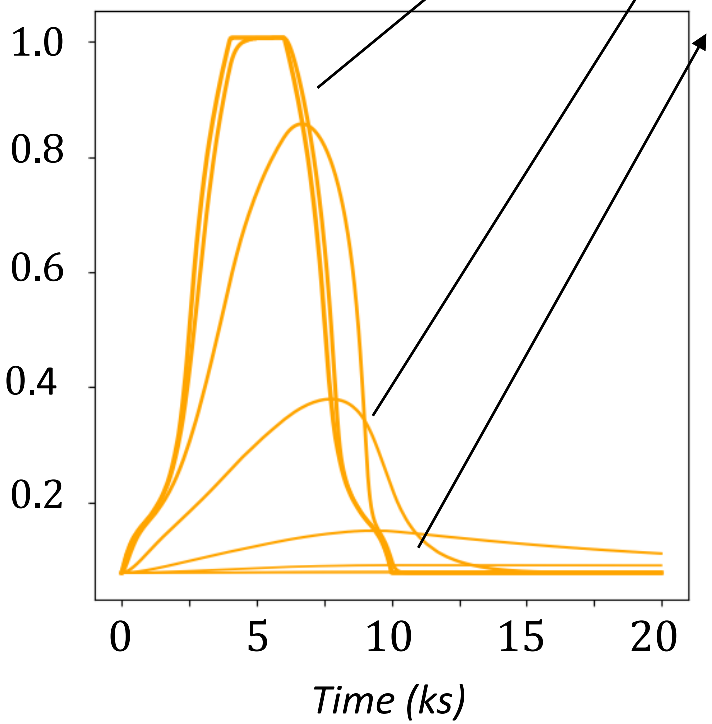
2. Time evolving computation:

Lightcurve:



We assume gas to be in photoionisation equilibrium at $t = 0$ with $\log(\xi) = 2$

Temperature (10^6 K)



$n_e = 10^{12} cm^{-3}$: *instantaneous response (ionisation equilibrium)*

$n_e = 10^{8} cm^{-3}$: *damped and delayed response*

$n_e = 10^{4} cm^{-3}$: *always out of equilibrium (no gas response)*

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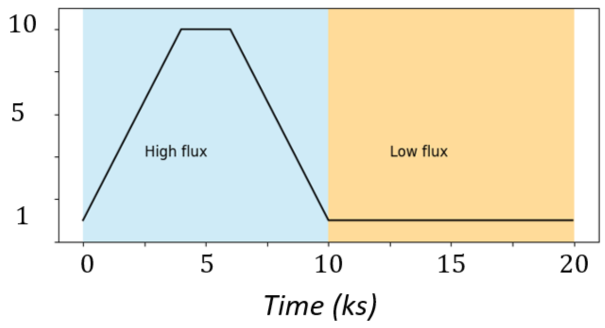
ii. TEPID

2. Time evolving computation:



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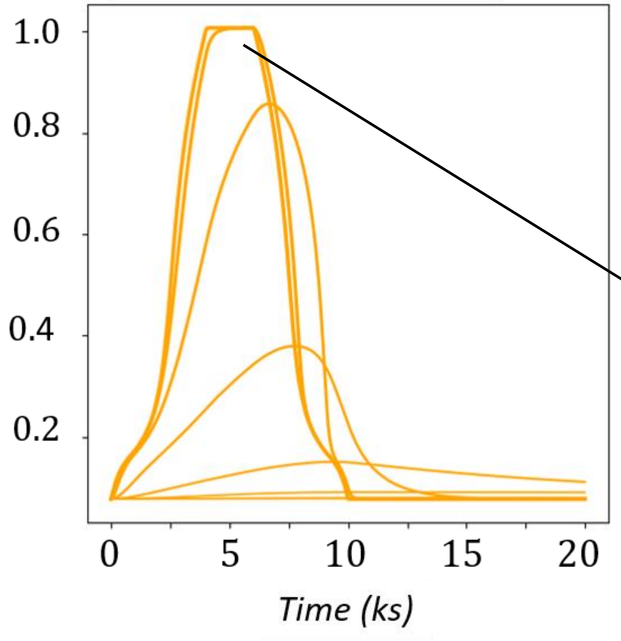
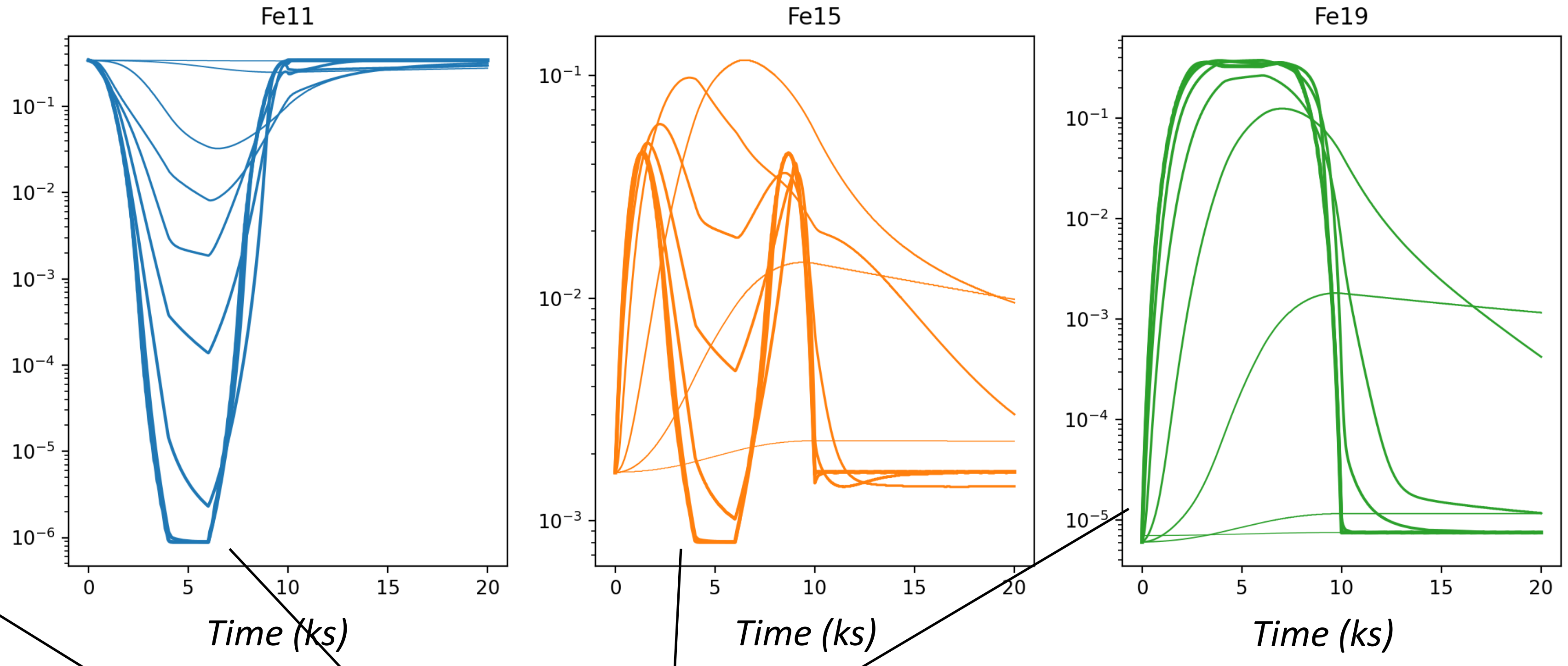


Iron ionic abundances (ratio)



$n_e = 10^{12} cm^{-3}$: temperature and ionic abundances adjust instantaneously to the lightcurve

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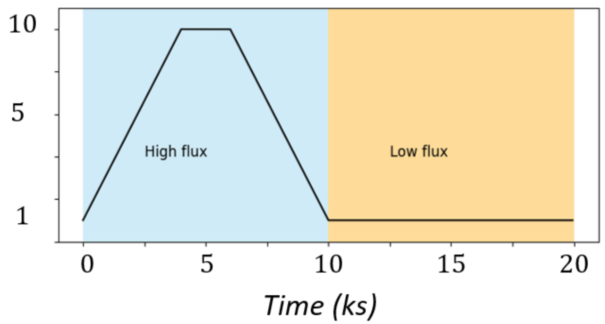
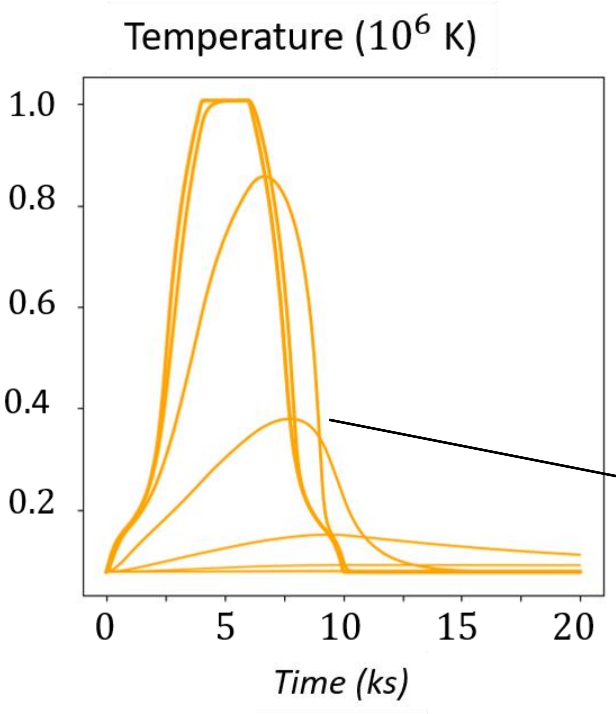
ii. TEPID

2. Time evolving computation:





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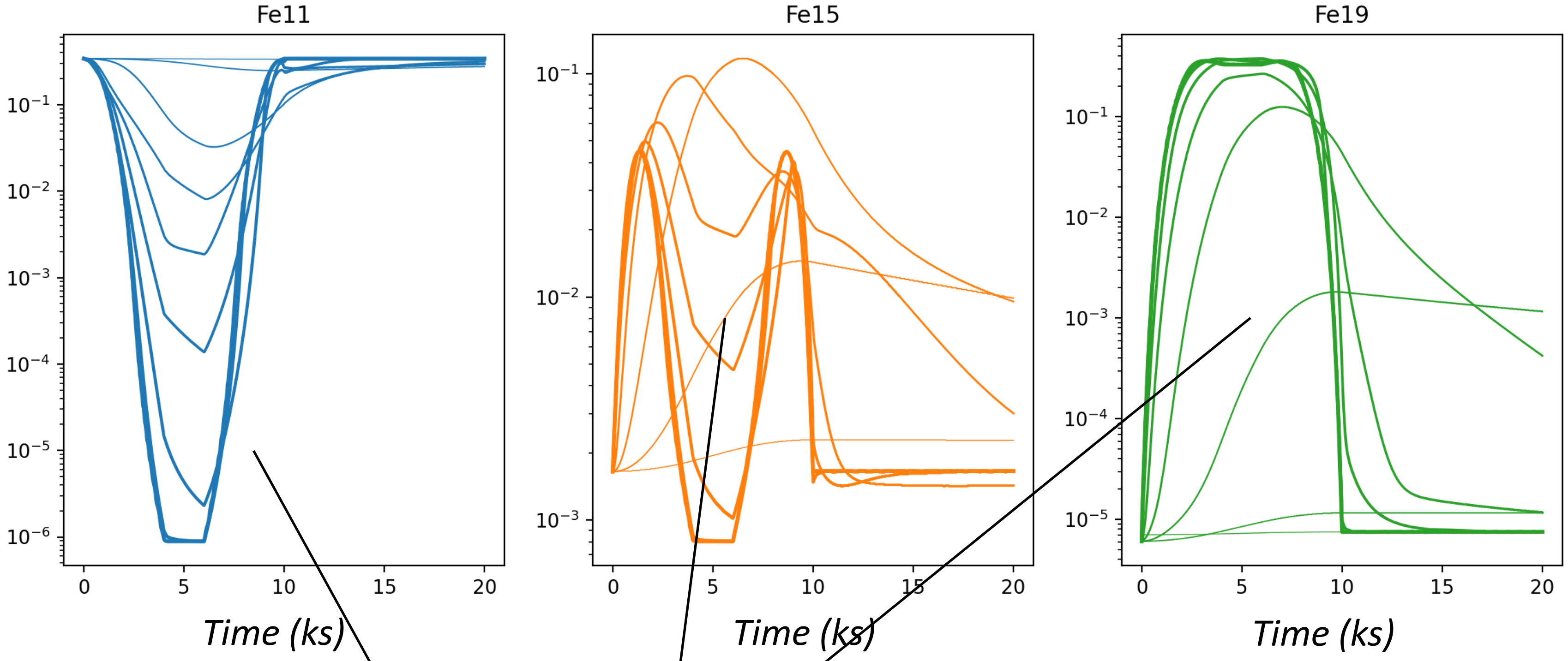

$n_e = 10^6 - 10^{10} cm^{-3}$: gas response to the lightcurve is ***damped*** and ***delayed***

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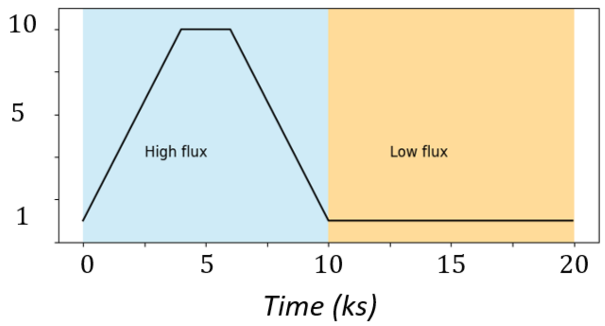
ii. TEPID

2. Time evolving computation:



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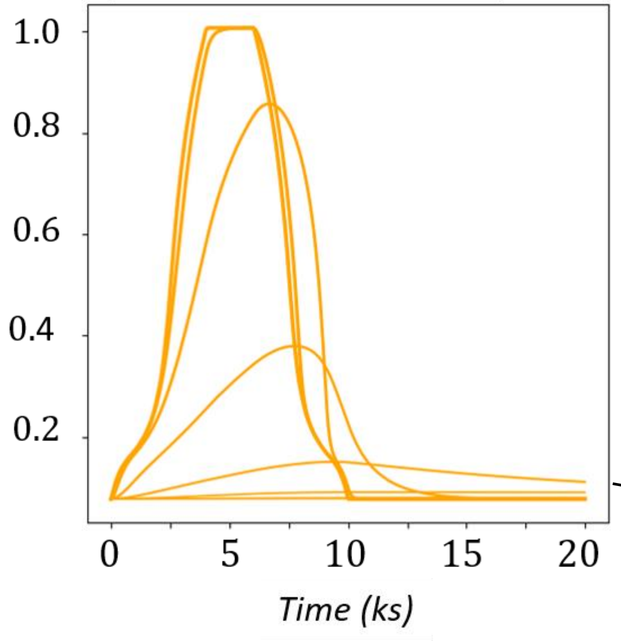

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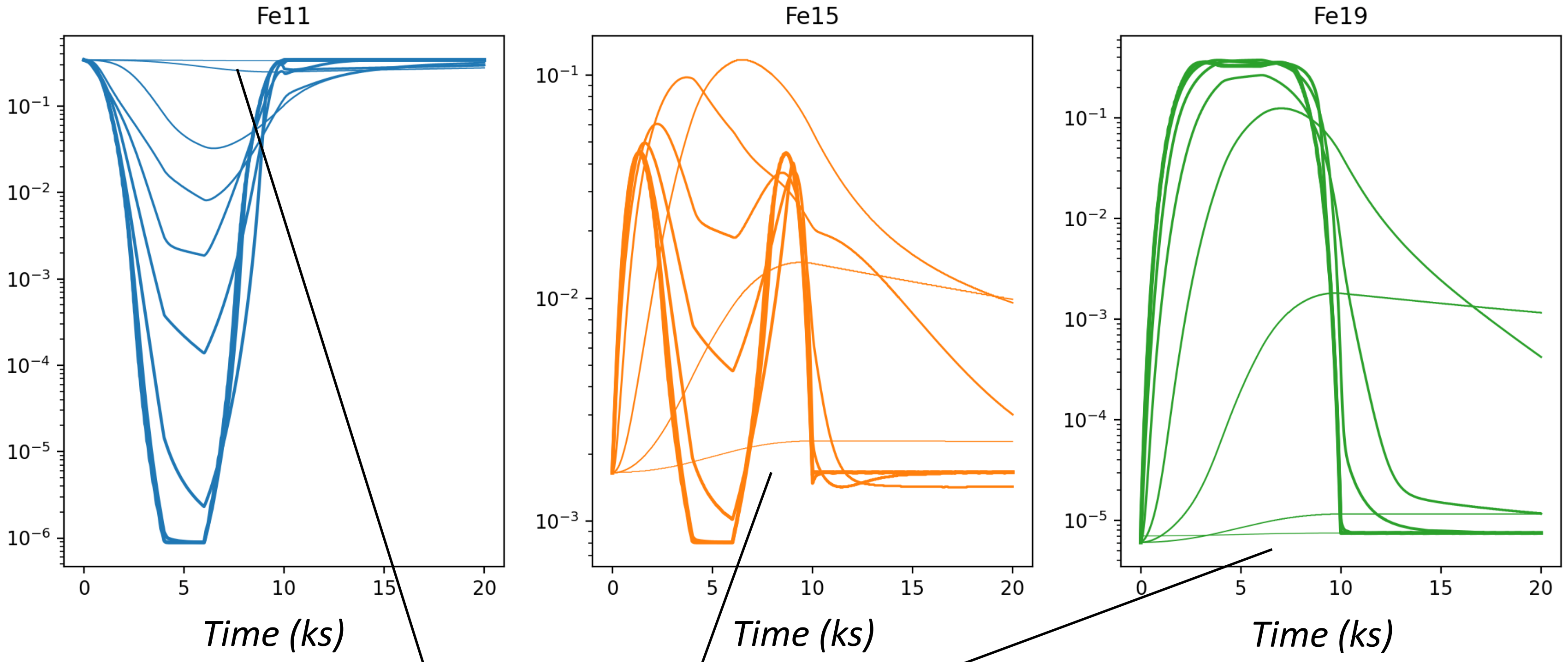

$n_e = 10^4\ cm^{-3}$: gas is insensitive to flux variations

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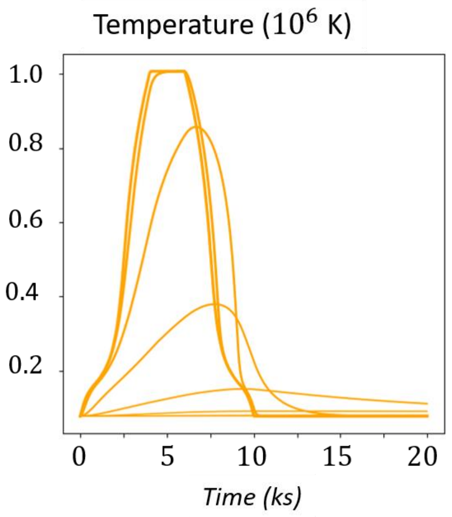
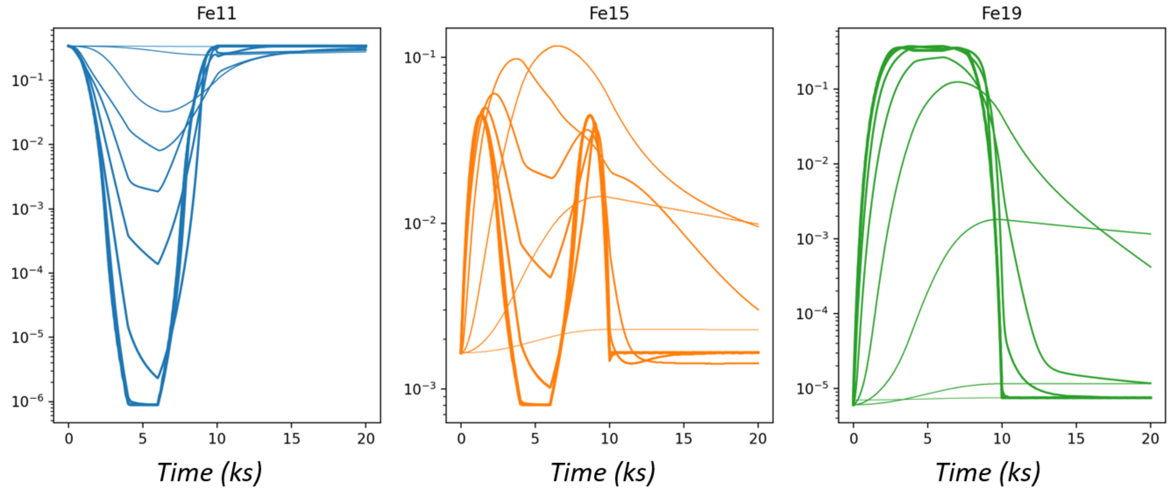
ii. TEPID

2. Time evolving computation:



Iron ionic abundances (ratio)



$n_e = 10^{12} cm^{-3}$: *instantaneous response (ionisation equilibrium)*
$n_e = 10^{8} cm^{-3}$: *damped and delayed response*
$n_e = 10^{4} cm^{-3}$: *always out of equilibrium (no gas response)*

Why this?

For decreasing n_e the gas response is:

i. <u>Damped</u>: both photoionisation and recombination rates linearly depends on n_e
ii. <u>Delayed</u>: recombination decreases faster than photoionisation → gas is over ionised with respect to ionisation equilibrium

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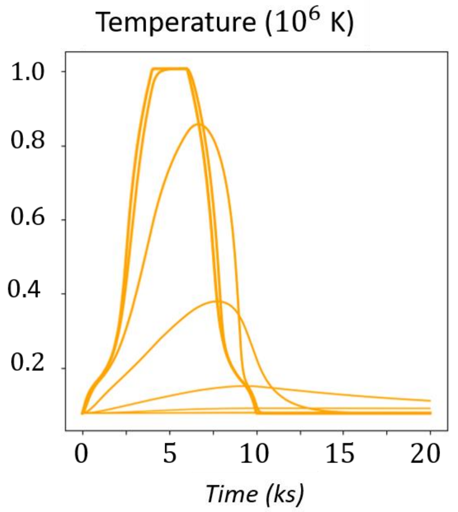
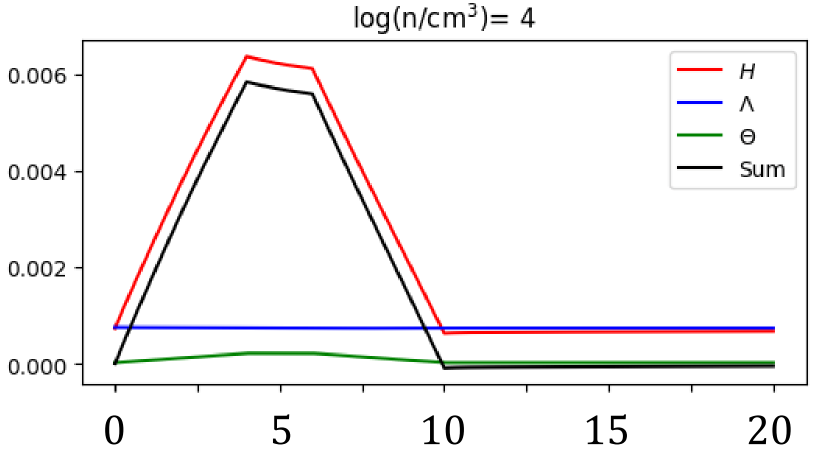
ii. TEPID

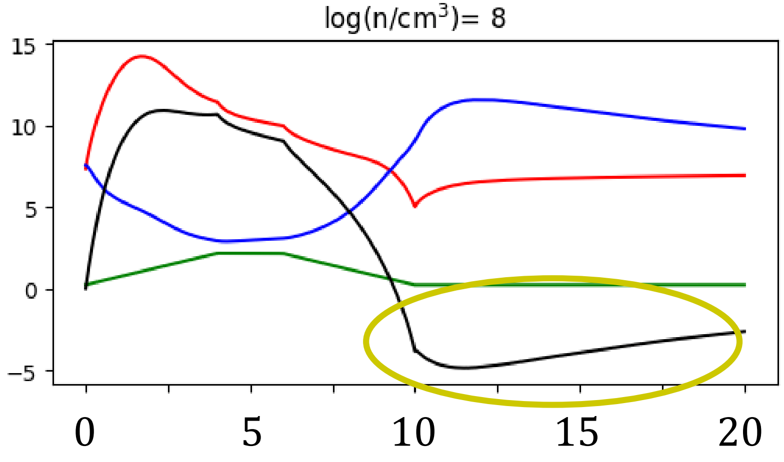
2. Time evolving computation:

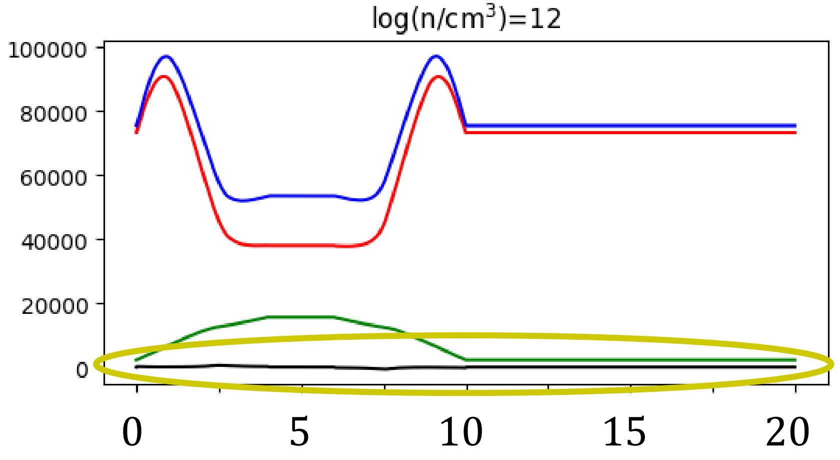


Heating *photonionisation+Auger*
Cooling *gas emission (incl. lines)*
Compton *photon-electron interaction*
Sum *total temperature derivative* $= \frac{dT}{dt}$

Energy Balance (Kelvin/second):







- H passively follows the lightcurve
- constant Λ, Θ

$\frac{dT}{dt} < 0$: gas is over ionised

$\frac{dT}{dt} = 0$: gas self-adjusts to get instantaneously in equilibrium

ii. TEPID

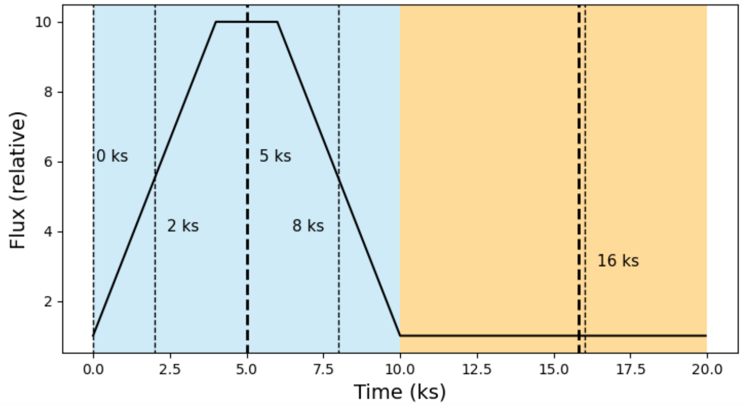
3. X-ray spectra:

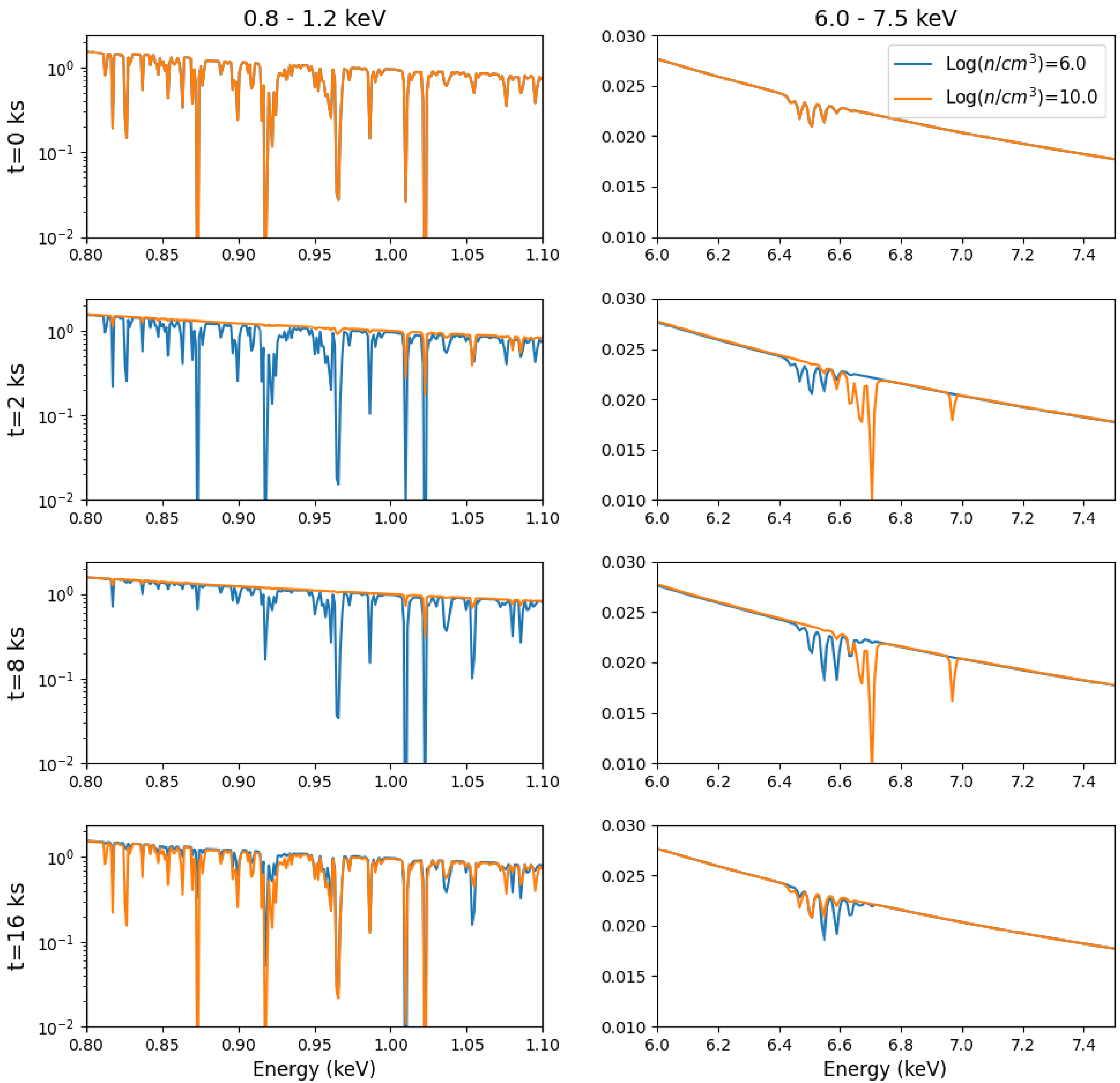
$\log(n_e/cm^3) = 6$

$\log(n_e/cm^3) = 10$

T=0 ks. Gas in equilibrium, $\log(\xi) = 4$

→ Spectra are identical by construction





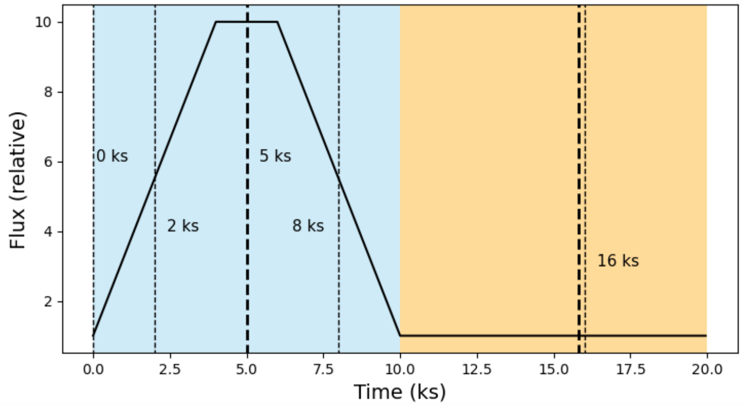
ii. TEPID

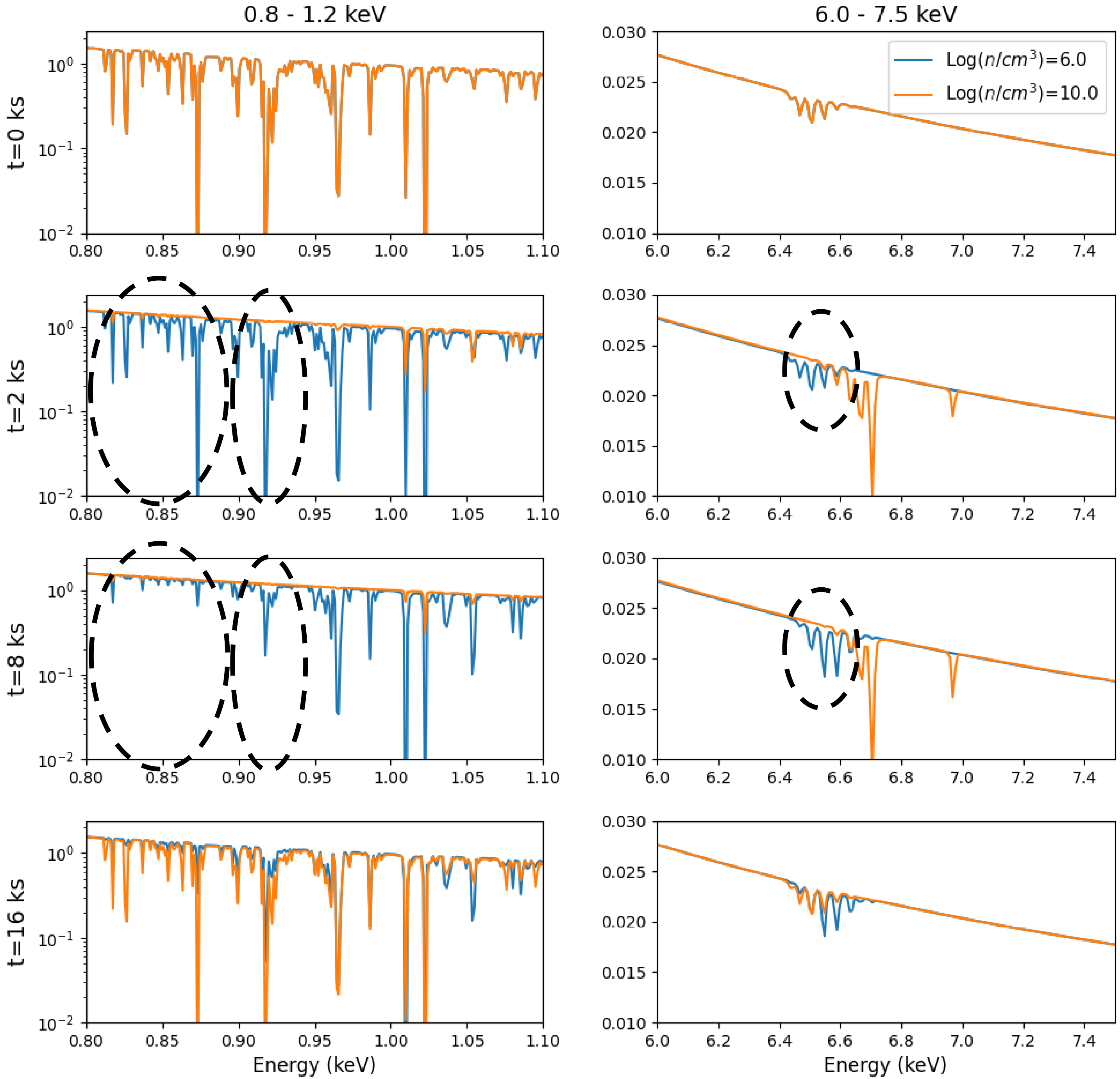
3. X-ray spectra:

— $\log(n_e/cm^3) = 6$
— $\log(n_e/cm^3) = 10$

T=0 ks. Gas in equilibrium, $\log(U) = 1.5$
→ Spectra are identical by construction

T=2,8 ks. Mid-time of the rise and decay phase
→ $\log(n_e/cm^3) = 10$: spectra are identical since flux is the same
→ $\log(n_e/cm^3) = 6$: gas is overionised, opacity lowers for increasing time





ii. TEPID

3. X-ray spectra:

$\log(n_e/cm^3) = 6$

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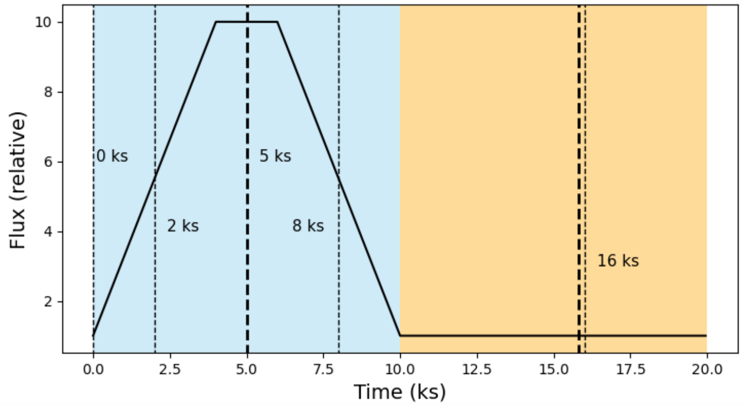
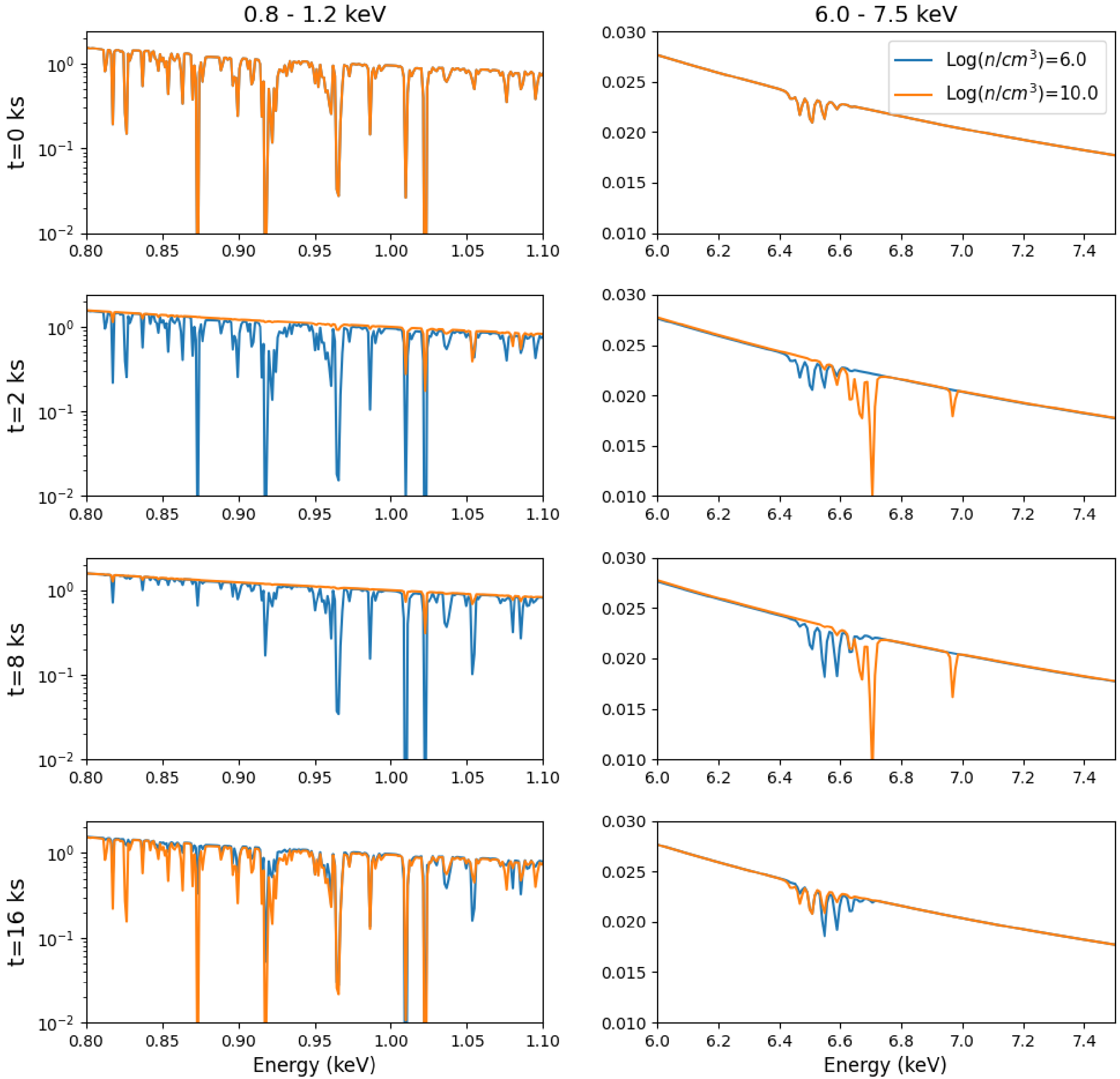
T=2,8 ks. Mid-time of the rise and decay phase
→ $\log(n_e/cm^3) = 10$: spectra are identical since flux is the same
→ $\log(n_e/cm^3) = 6$: gas is overionised, opacity lowers for increasing time

T=16 ks. Same flux as t=0.
→ $\log(n_e/cm^3) = 10$: spectrum equal to t=0
→ $\log(n_e/cm^3) = 6$: overionised spectrum

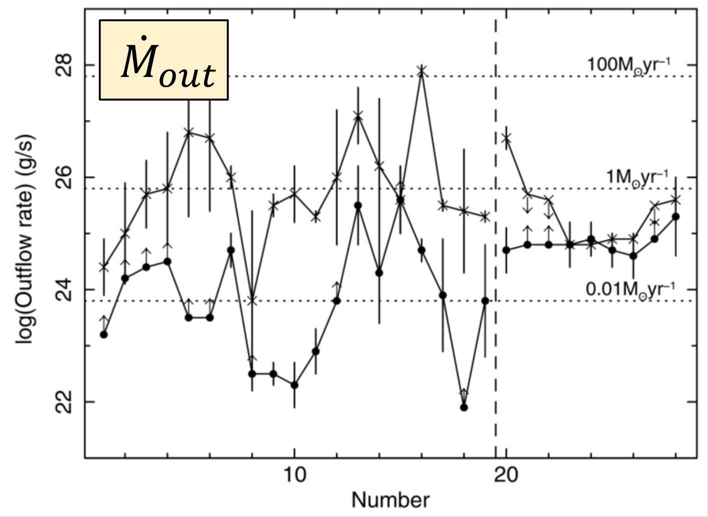


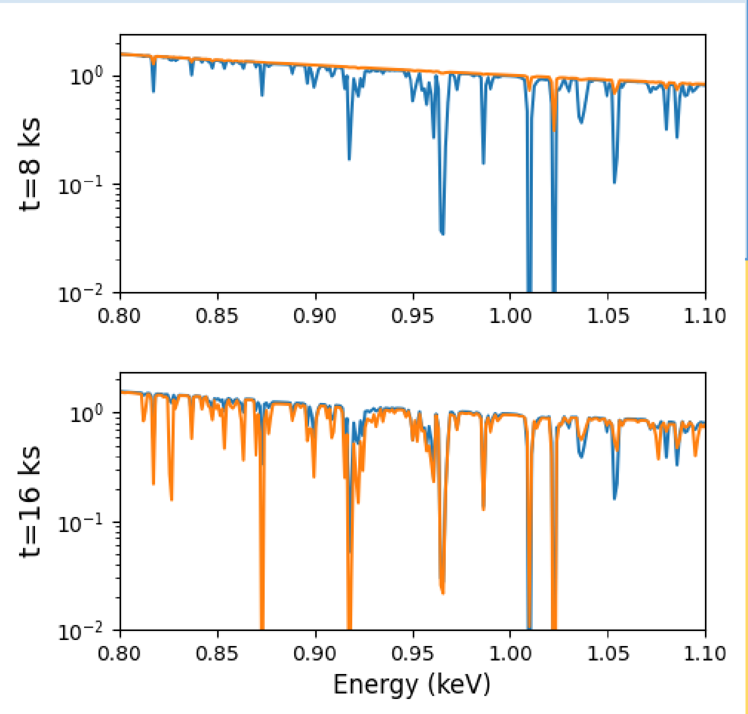


Conclusions

Time-equilibrium ionisation only allows for a basic description of the intervening gas (ξ, N_H, v_out)

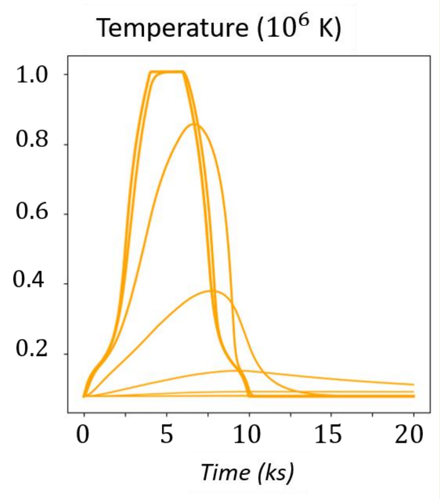
Time-evolving photionisation also constrains r, n! compute self-consistently the mass and energy flux

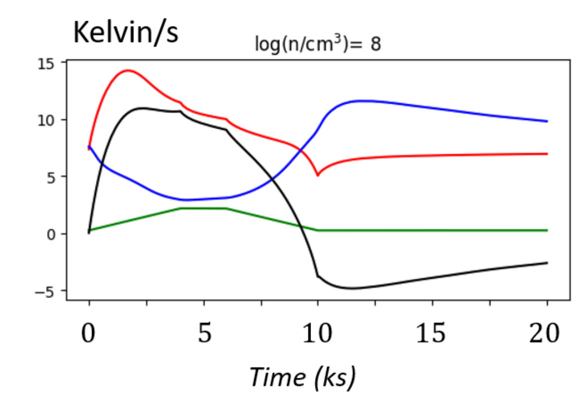


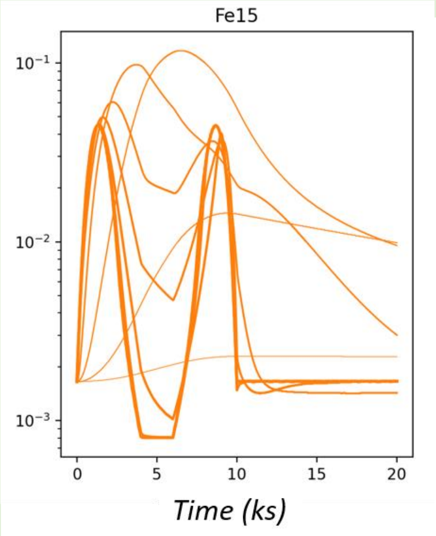


TEPID - Time-Evolving PhotoIonisation Device

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, U) and compare with observations

Thank you for the attention!

Question/comments?

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TEPID model

TEPID application to GRBs

Absorption/emission relativistic effects

PHASE

Time evolving ionisation