TEPID: Time Evolving Photoionisation with Current and Future X-ray Telescopes

(an incomplete view from the side of ionized outflows in AGN)

Alfredo Luminari

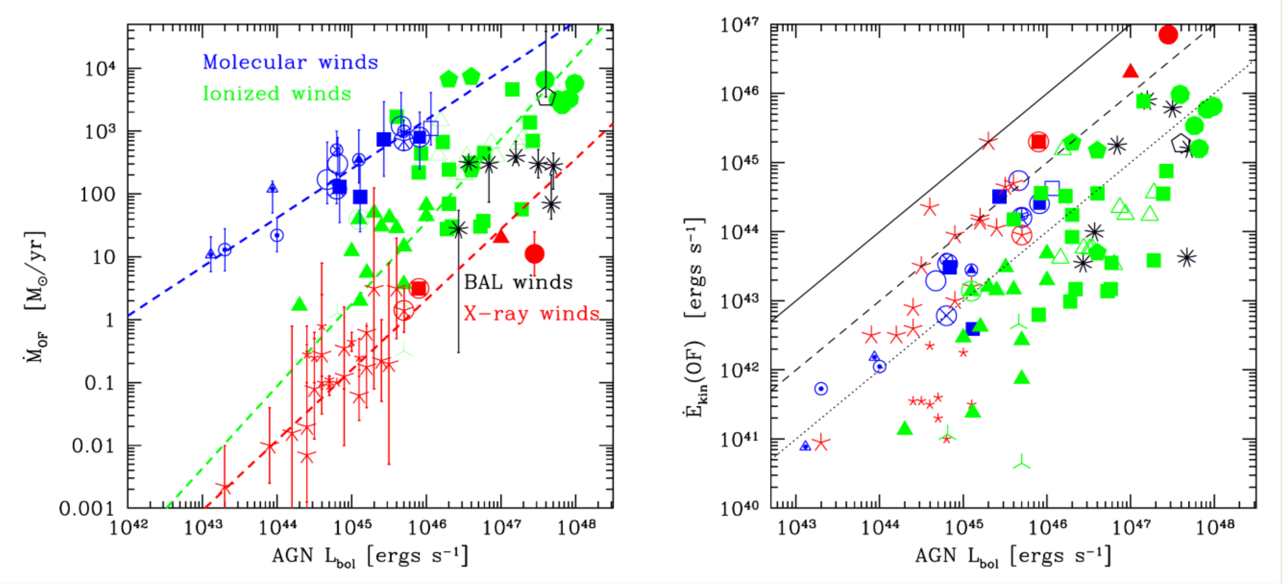
INAF – IAPS and Observatory of Rome (OAR)

+ *F.Nicastro, Y. Krongold, L. Piro, A. Thakur & many others*

i. Ionised gas in AGNs

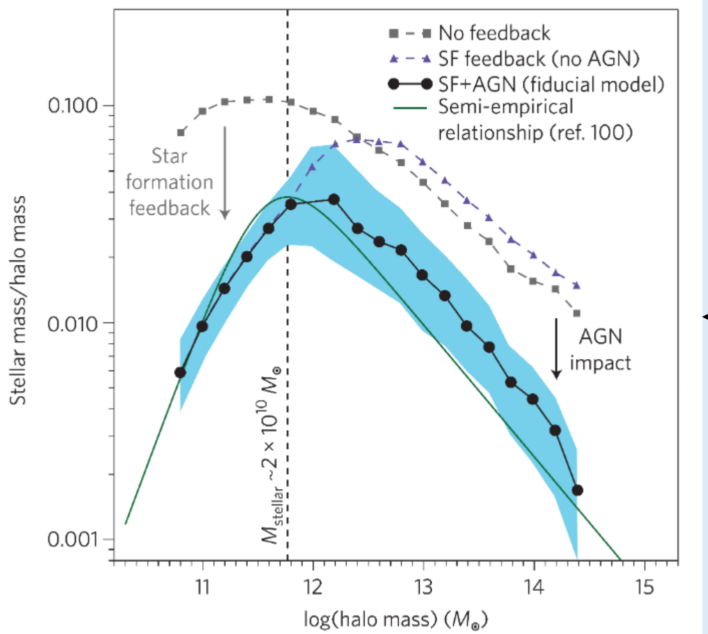
Outflows are ubiquitously observed in AGNs in all phases, from accretion-disc scales (X-rays) up to galaxy scales (optical, mm, radio).

Main hypothesis: outflow starts in the AGN nucleus as a mildly relativistic X-ray wind and then propagates to galaxy scales where it becomes visible in the optical to millimetric interval.



Fiore+17

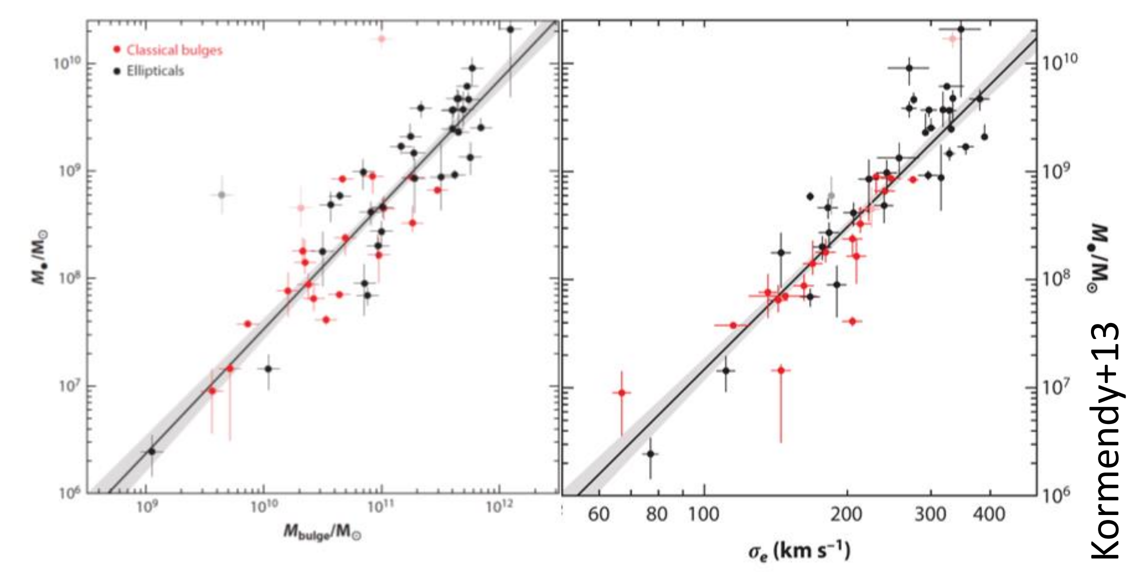
Main candidate for AGN feedback and coevolution with the host galaxy:



Harrison+17

Needed to reduce SFR in high-mass galaxies

Explains central black hole-host galaxy correlations

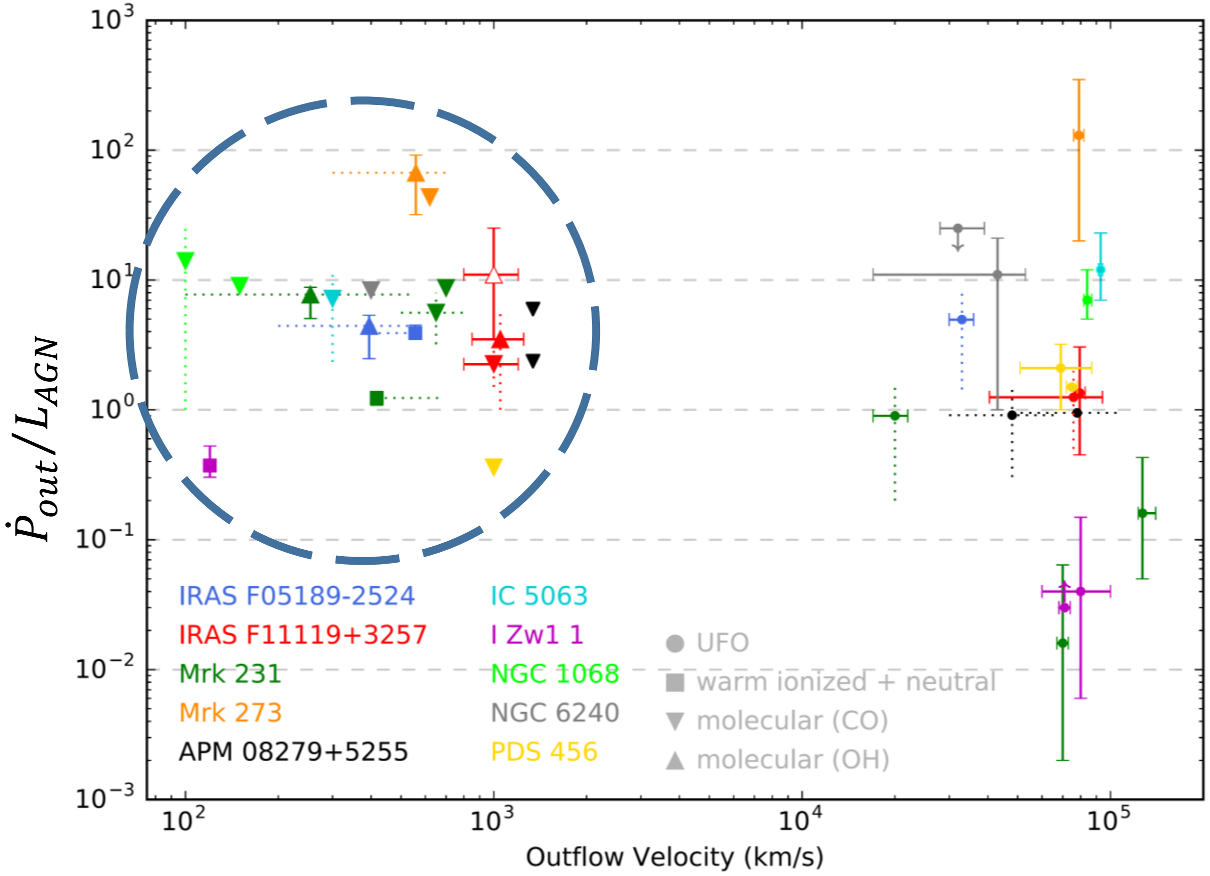


Kormendy+13

i. Ionised gas in AGNs

Energy of galactic and nuclear outflows:

Nuclear-scale outflows have been suggested as key players to drive galaxy-wide feedbacks. However…



Smith+19

Galactic outflows: relatively small errors

-> *Mostly spatial resolved observation from ground-based observatiories*

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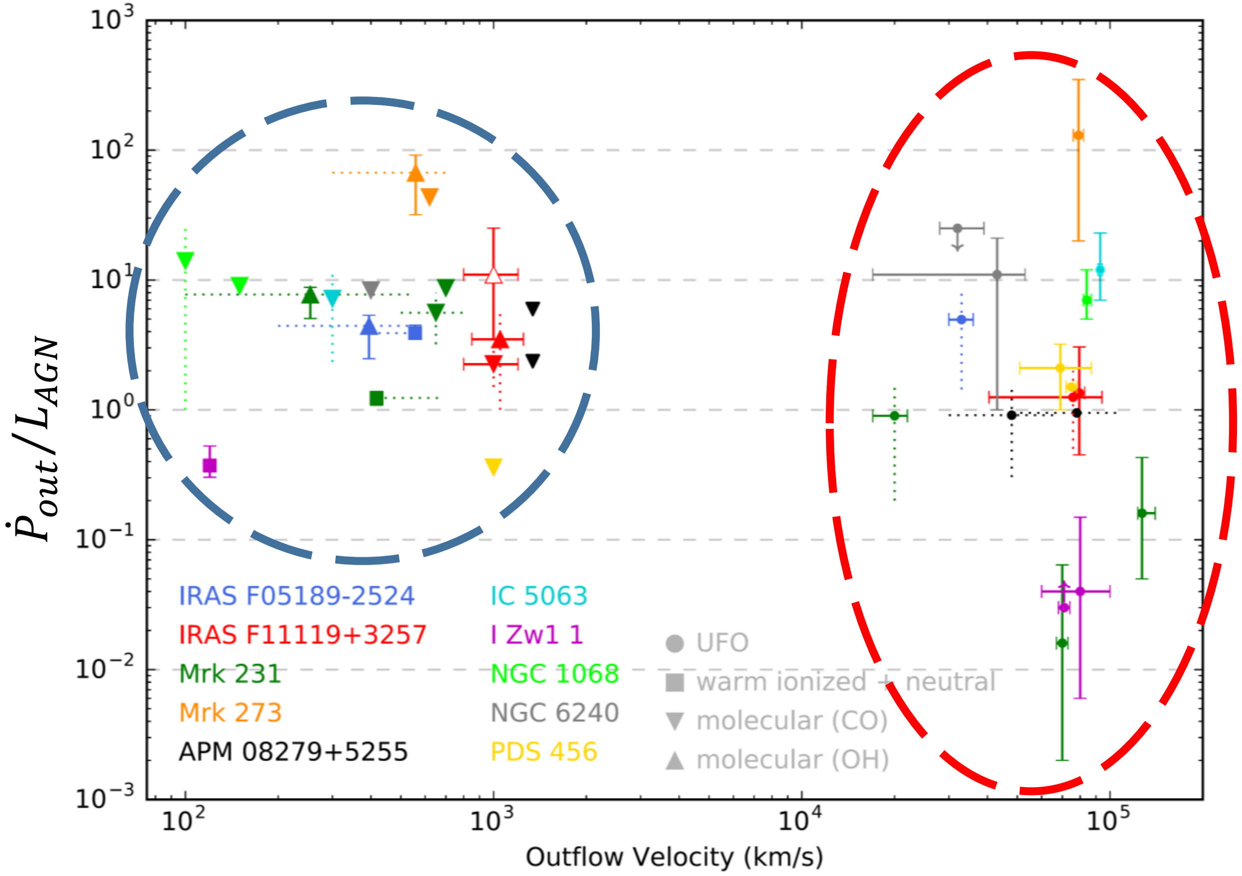

Smith+19

Galactic outflows: relatively small errors

Nuclear outflows (UV – X-ray): order-of-magnitude errors

-> *Unresolved sources: most of the information from absorption spectra.*

In photoionisation equilibrium, gas physics is encoded in only three main parameters:

U, v_{out}, N_H

ii. Photoionisation. Time-equilibrium regime

Constant ionisation source
→ Time-equilibrium photoionisation:

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

Rate of incident ionising photons

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

Gas density · distance

-> Temperature is a function of U

-> Ionic abundances are a function of U

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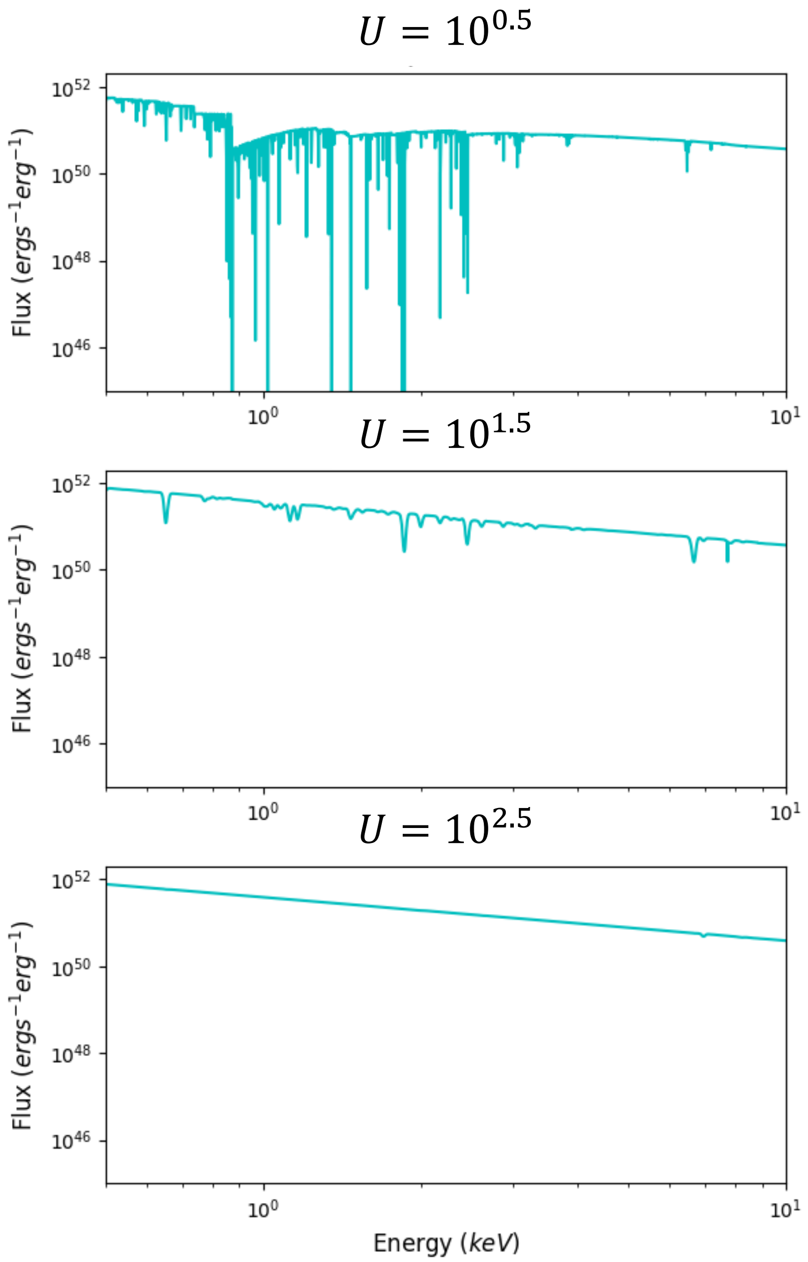
Spectra are a function of U

+ N_H regulates opacity
+ v_{out} regulates redshift



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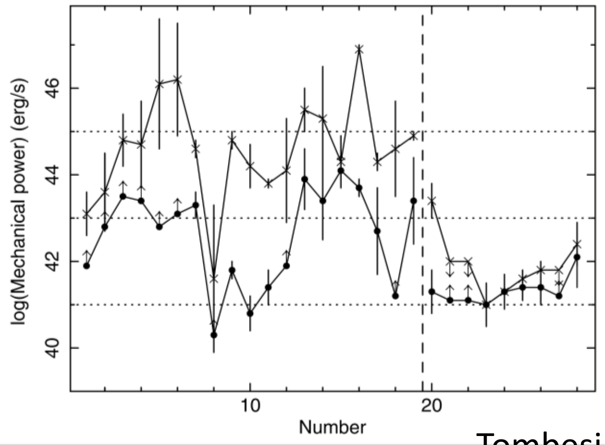
It is (almost) impossible to constrain gas density and radius from observed spectra. A number of key questions remain open:

i) What is the location and the energetic of such outflows?

$\dot{E}_{out}$ for a sample of Sy1 disk winds



Tombesi+12

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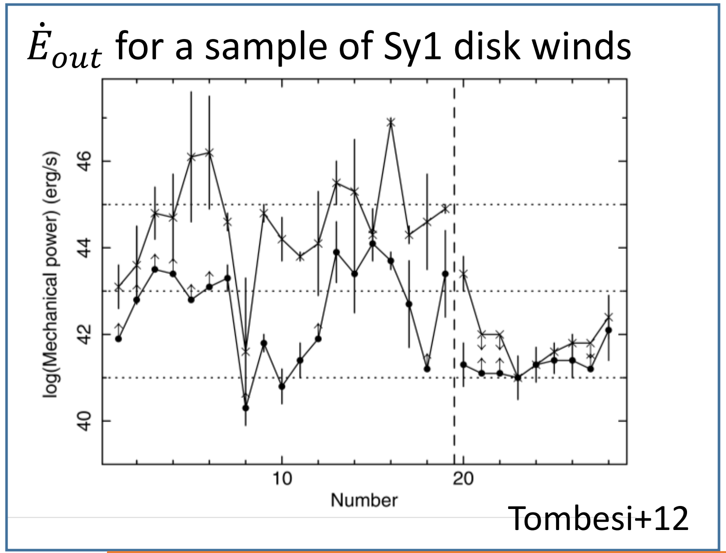
It is (almost) impossible to constrain gas density and radius from observed spectra. A number of key questions remain open:

i. *What is the location and the energetic of such outflows?*

ii. *Are multiphase winds co-spatial or they are the segmentation of a unique, continuous flow?*



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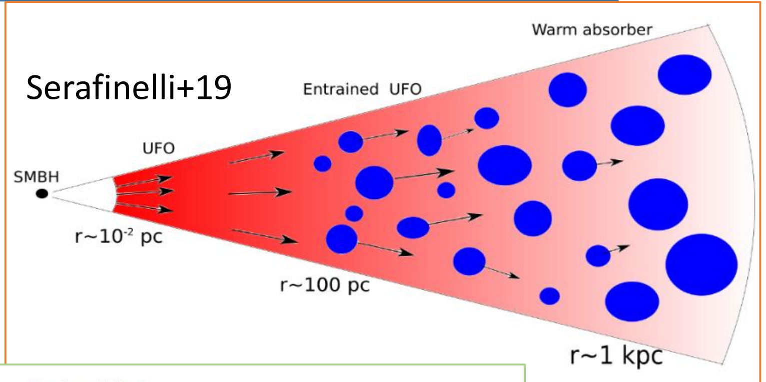
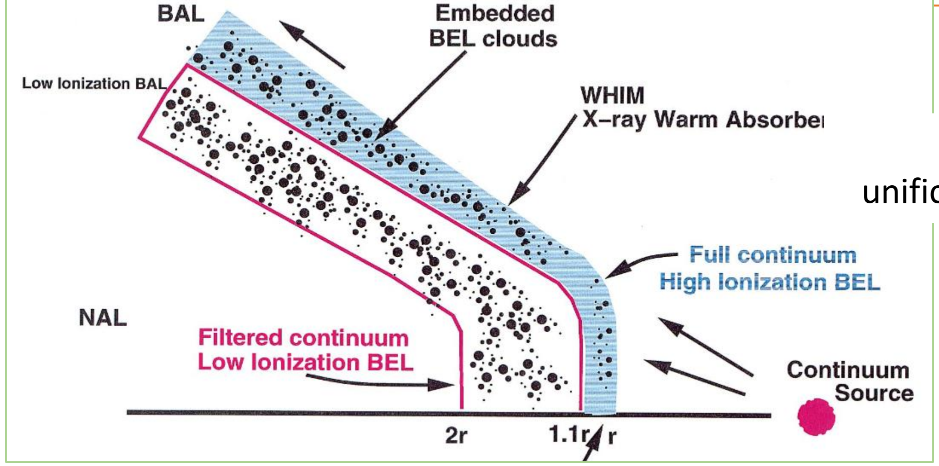


Serafinelli+19

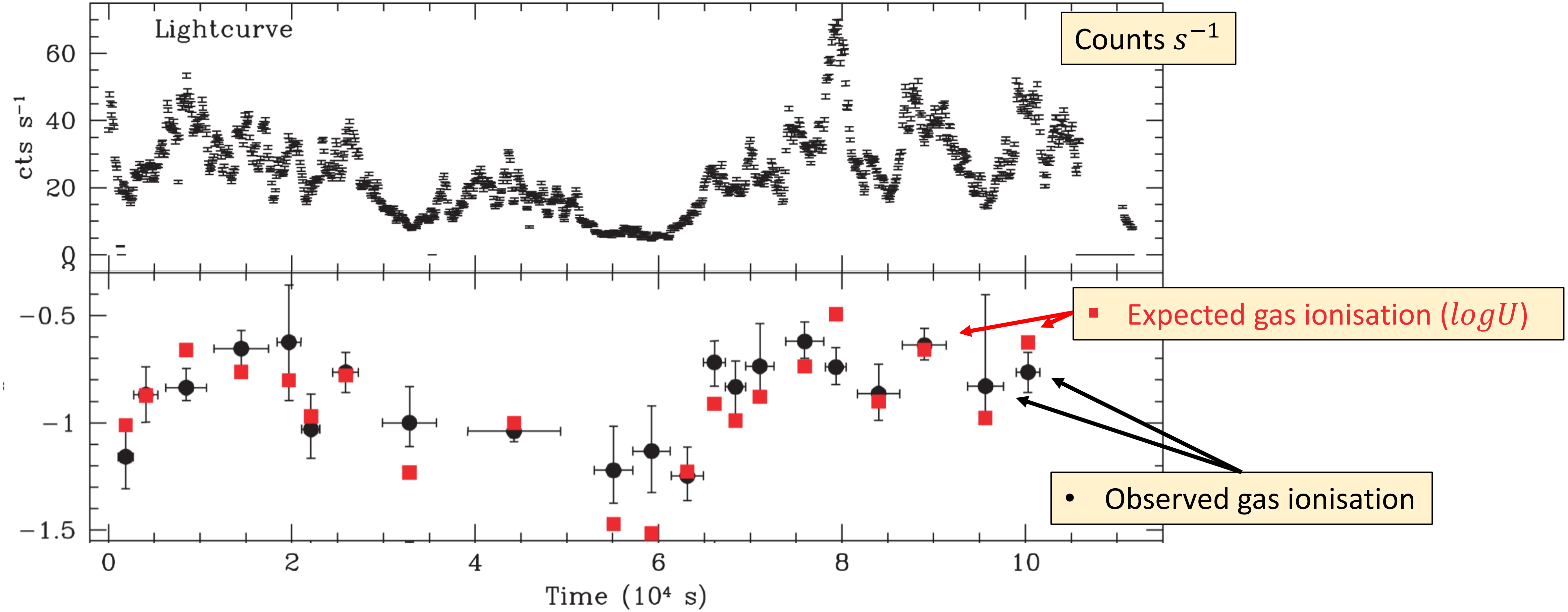


Elvis+00: AGN unification scheme

ii. Photoionisation. Time-evolving regime

Can we always assume the gas to be in **ionisation** equilibrium?

NGC4051 – Krongold, Nicastro+07



Counts s^{-1}

- Expected gas ionisation ($logU$)

- Observed gas ionisation

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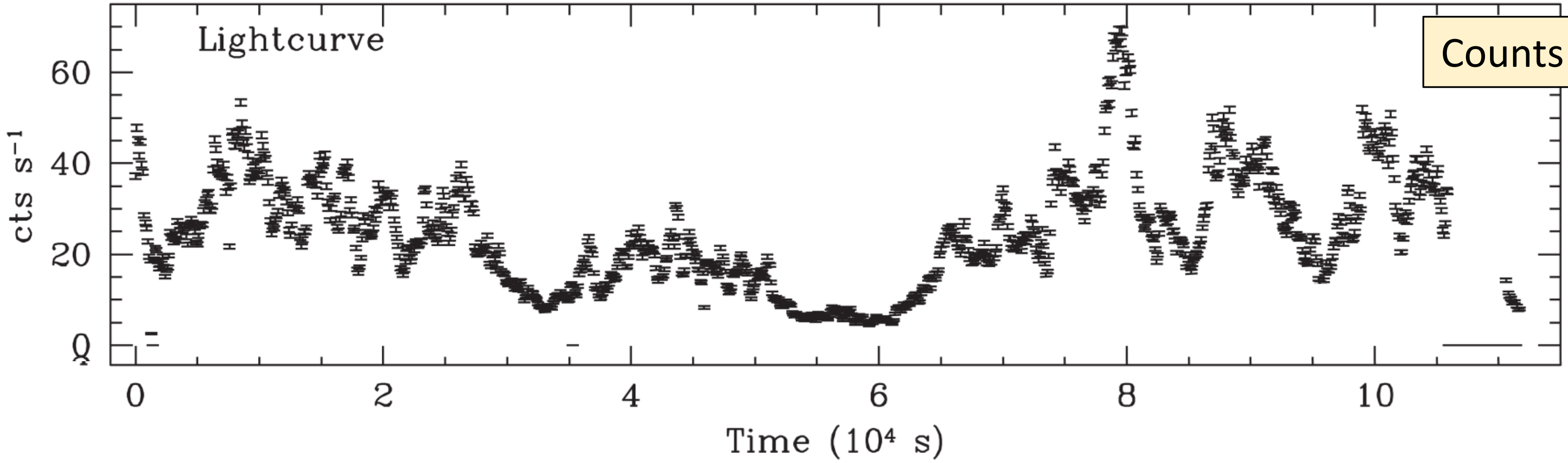


Counts s^{-1}

…no!

The equilibrium timescale is:

$$t_{eq} \approx 1 \Big/ \left(\alpha_{rec}^{X^i} \cdot n_e\right)\left(1 + \frac{\alpha_{rec}^{X^{i-1}}}{\alpha_{rec}^{X^i}} + \frac{n_{X^{i+1}}}{n_{X^i}}\right)$$

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!

ii. Time-evolving

Sets the energy transferred to the gas →

The driving parameters are:

1. the ionising flux $F_{ion} \propto \frac{Q_{ion}}{r^2}$
2. the gas density n_e

← *Sets the gas timescale: Ionisation rates and heating*

Ionic abundances

$$\frac{dn_{X^i}}{dt} = -\left[F_{X^i} + \alpha_{rec}^{X^i} n_e\right] n_{X^i} + F_{X^{i-1}} n_{X^{i-1}} + \alpha_{rec}^{X^{i+1}} n_e n_{X^{i+1}}$$

Charge conservation

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

Temperature

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

Radiative Transfer

$$F' = F_0 e^{-\tau} + \phi_{rrc}$$

Dependence on n_e breaks the distance-density degeneracy intrinsic in equilibrium photoionisation

Linearly depends on F_{ion}

Linearly depends on n_e

iii. TEPID

Constant Ionisation source
→ Time-equilibrium photoionisation:

Ionisation parameter sets the status of the gas:

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

- Temperature, ionic balance are functions of U
- “Universal” absorption and emission spectra

Variable ionisation source ($t_{var} < t_{eq}$):
→ 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)

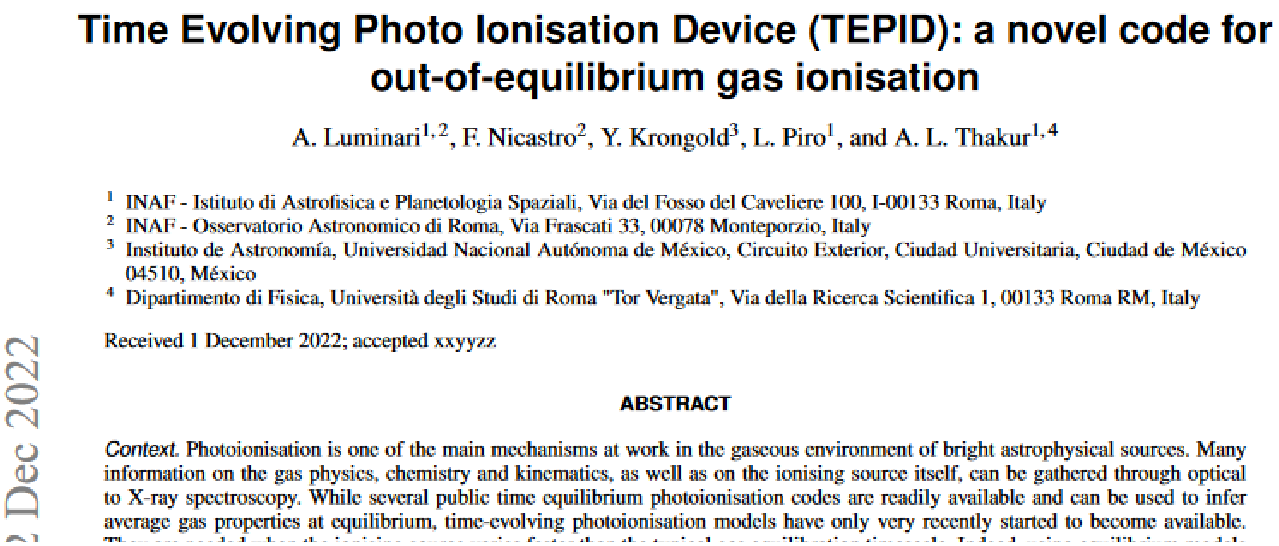
<u>No analytical solution known:</u>

→ *need to integrate over the entire lightcurve*

iii. TEPID

TEPID:
Time-Evolving PhotoIonisation Device

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



Time Evolving Photo Ionisation Device (TEPID): a novel code for out-of-equilibrium gas ionisation

A. Luminari[1,2], F. Nicastro[2], Y. Krongold[3], L. Piro[1], and A. L. Thakur[1,4]

[1] INAF - Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Caveliere 100, I-00133 Roma, Italy
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ABSTRACT

Context. Photoionisation is one of the main mechanisms at work in the gaseous environment of bright astrophysical sources. Many information on the gas physics, chemistry and kinematics, as well as on the ionising source itself, can be gathered through optical to X-ray spectroscopy. While several public time equilibrium photoionisation codes are readily available and can be used to infer average gas properties at equilibrium, time-evolving photoionisation models have only very recently started to become available.

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→ Time-evolving photoionisation:

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

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- dependence from initial conditions
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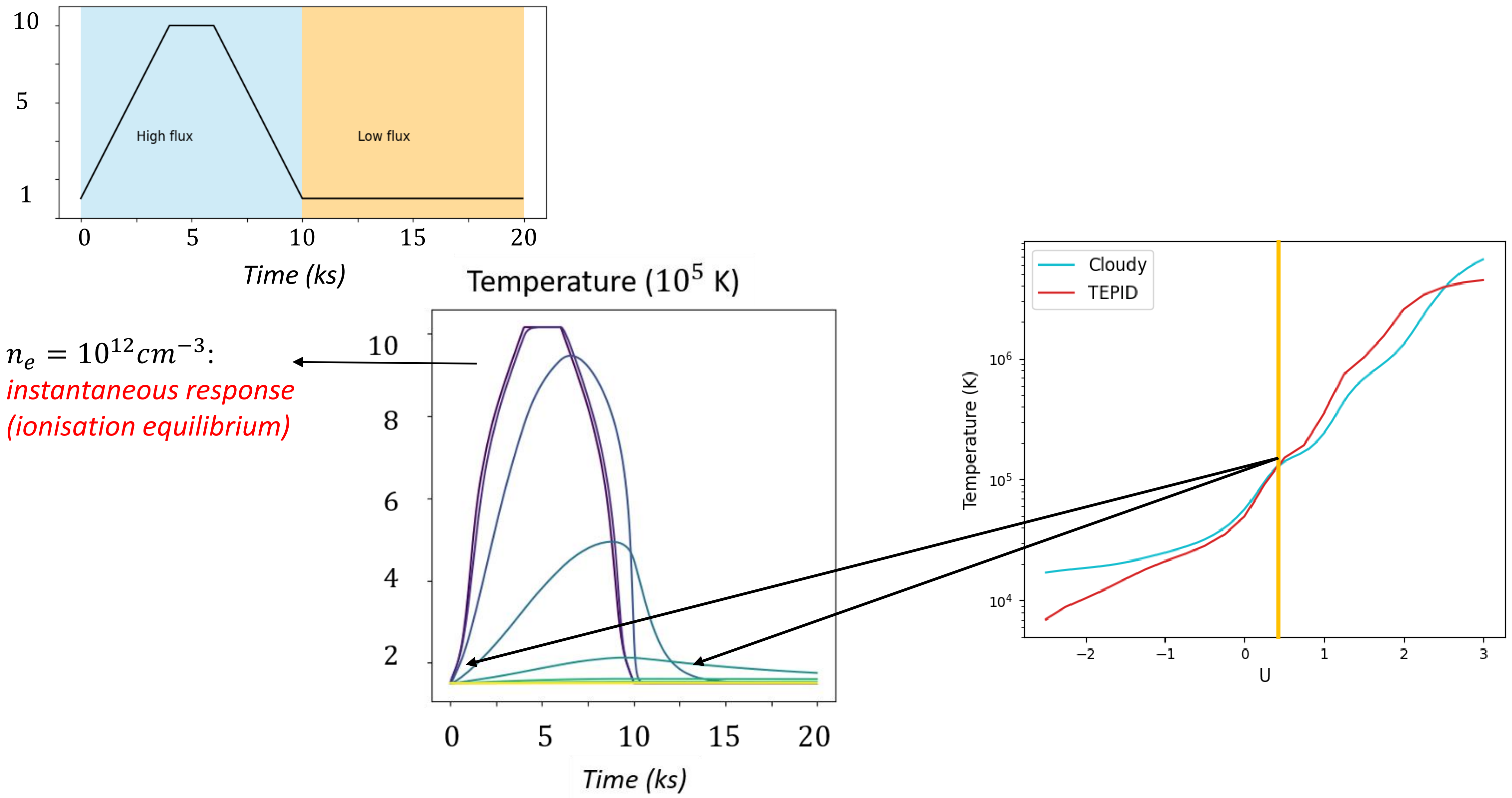
iii. TEPID

Evolution of a gas, initially at equilibrium with $\log(U) = 0.5$:



$n_e = 10^{12} cm^{-3}$:

instantaneous response (ionisation equilibrium)

iii. TEPID

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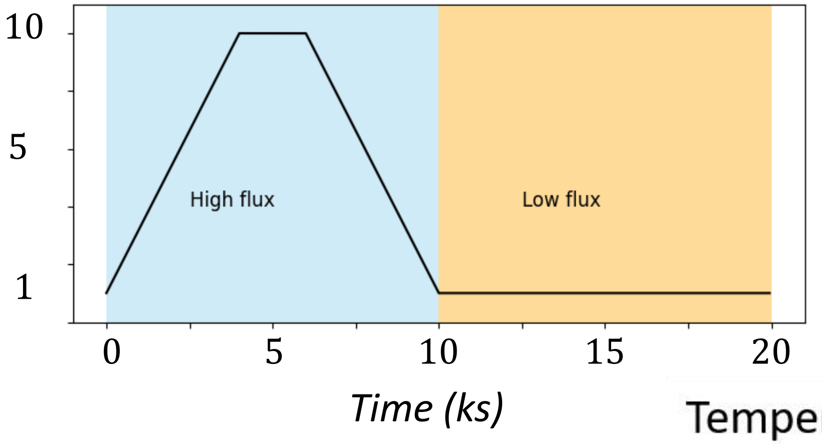

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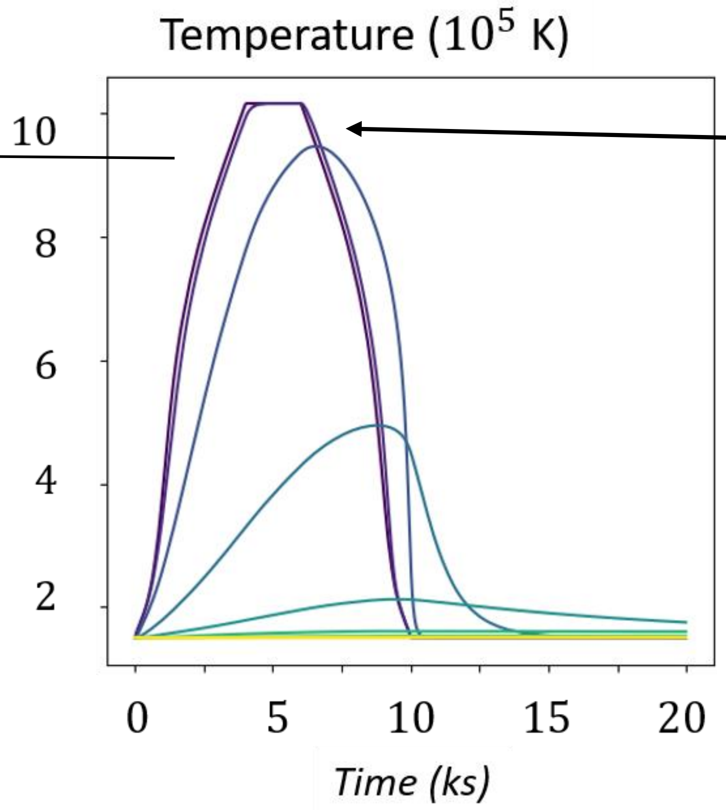

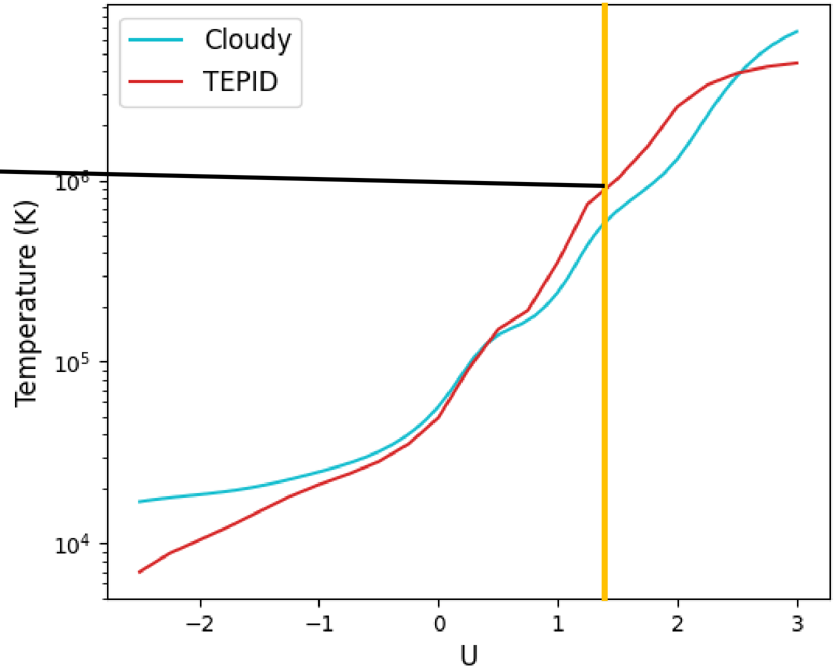

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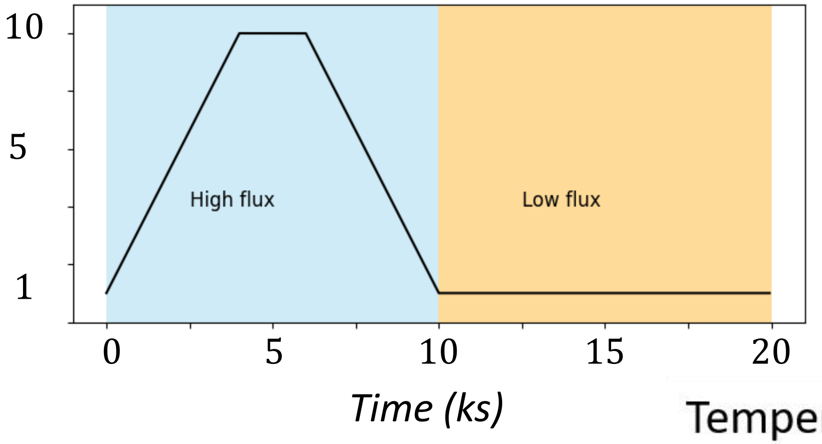

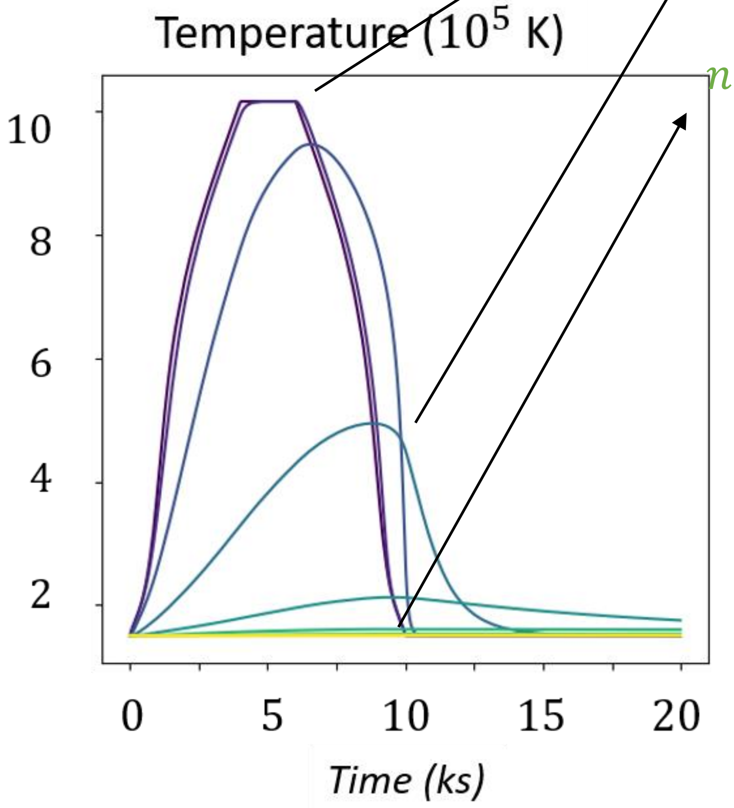

$n_e = 10^{12} cm^{-3}$: *instantaneous response (ionisation equilibrium)*

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

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

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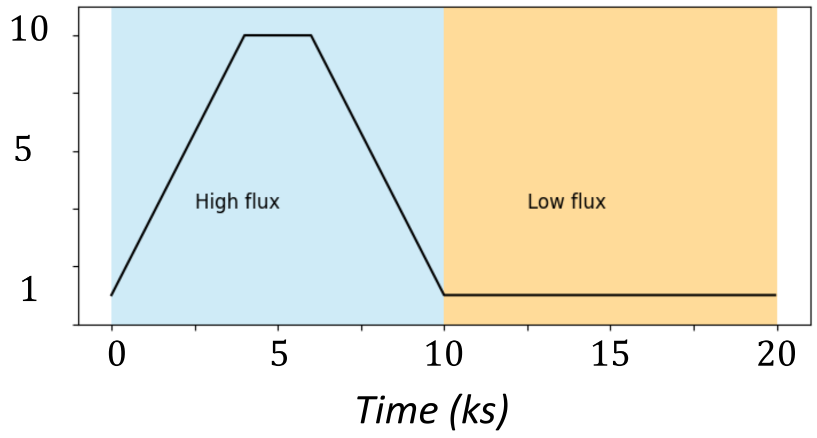

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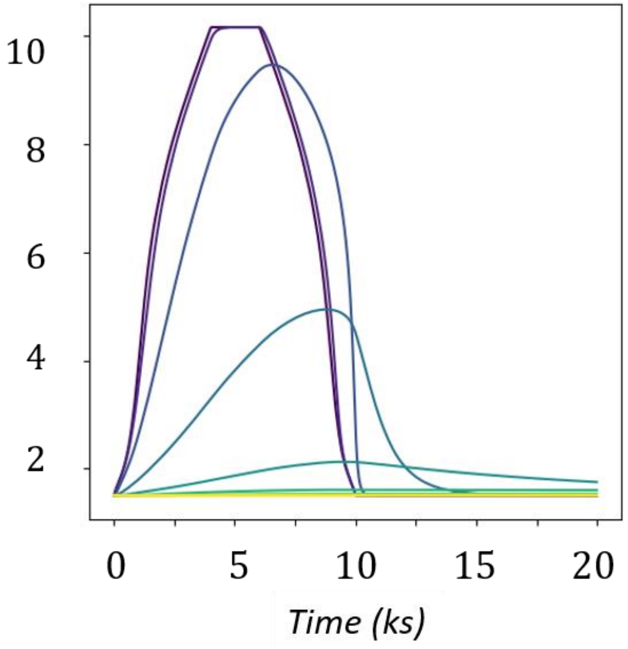
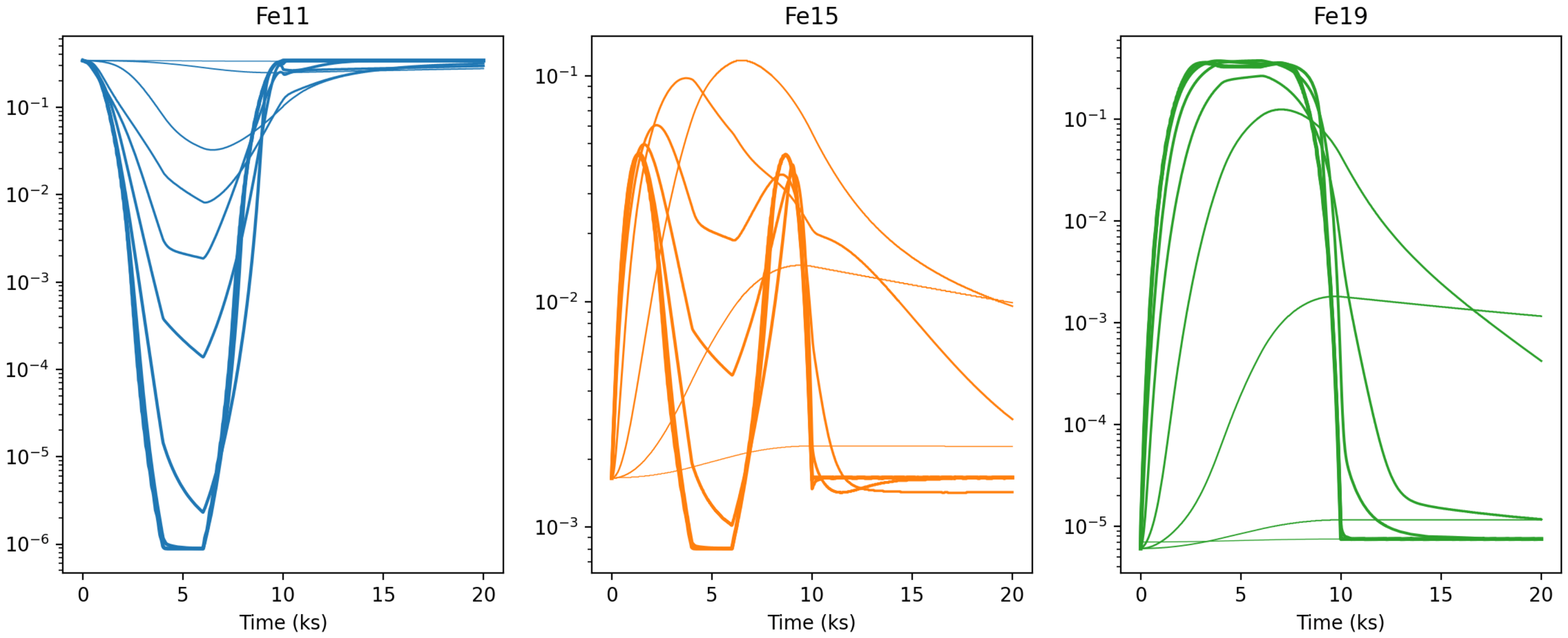
Temperature (10^5 K)



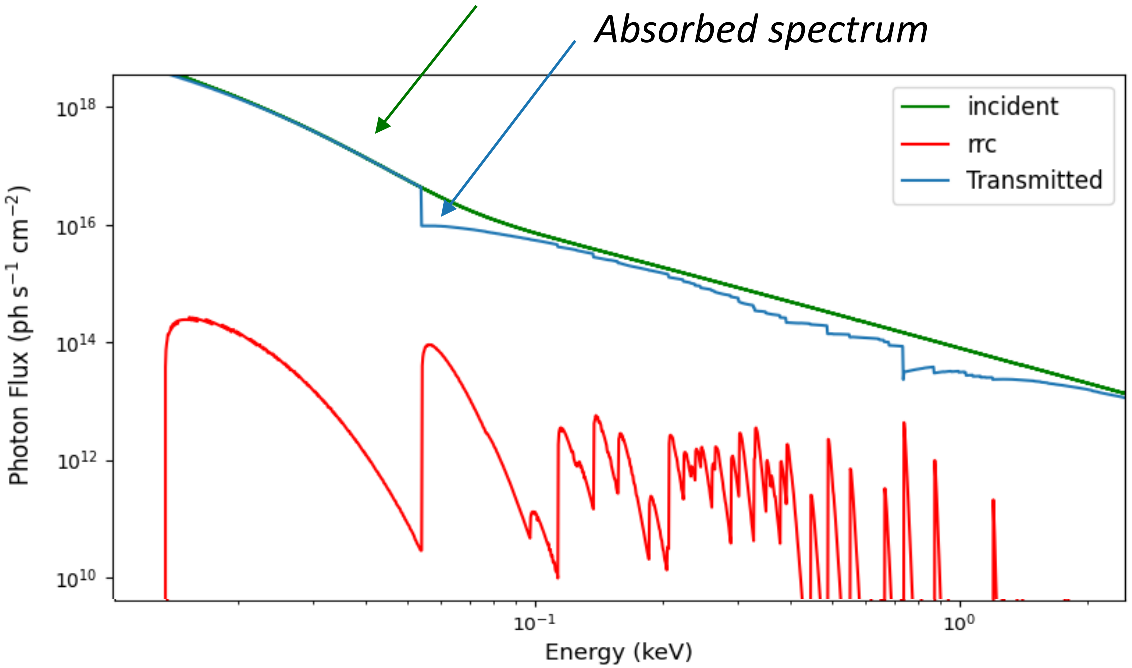
Iron ion abundances (ratio)



iii. Radiative transfer

The journey of the radiation through the gas column is due to the interplay between:

- gas absorption of the incident spectrum



Incident spectrum

Absorbed spectrum

iii. Radiative transfer

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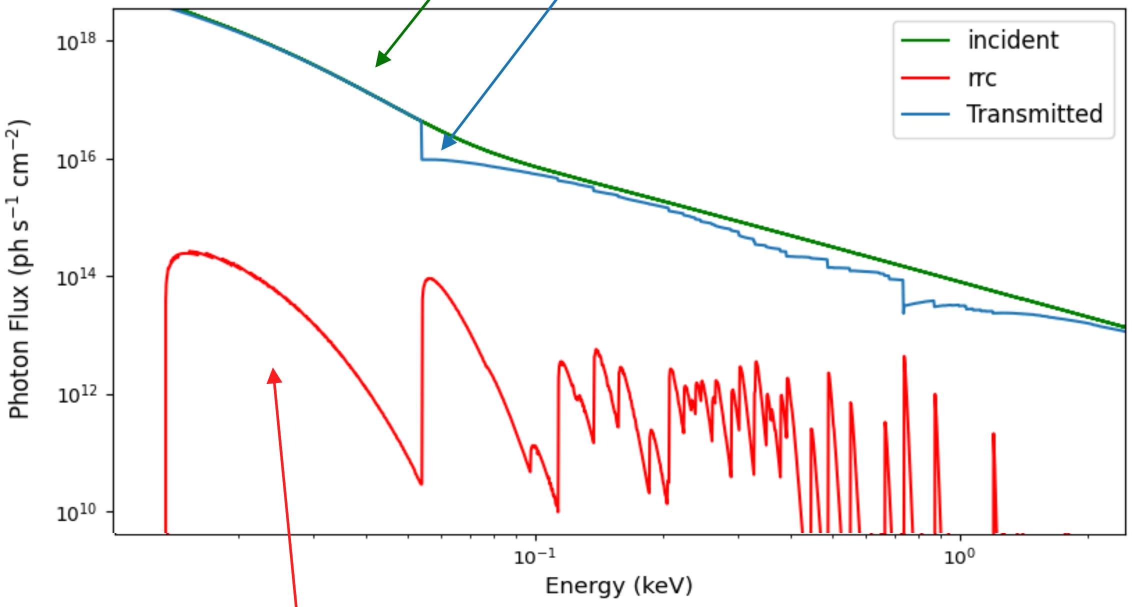
- gas absorption of the incident spectrum
- gas emission spectrum

Incident spectrum

Absorbed spectrum



Emission continuum spectrum

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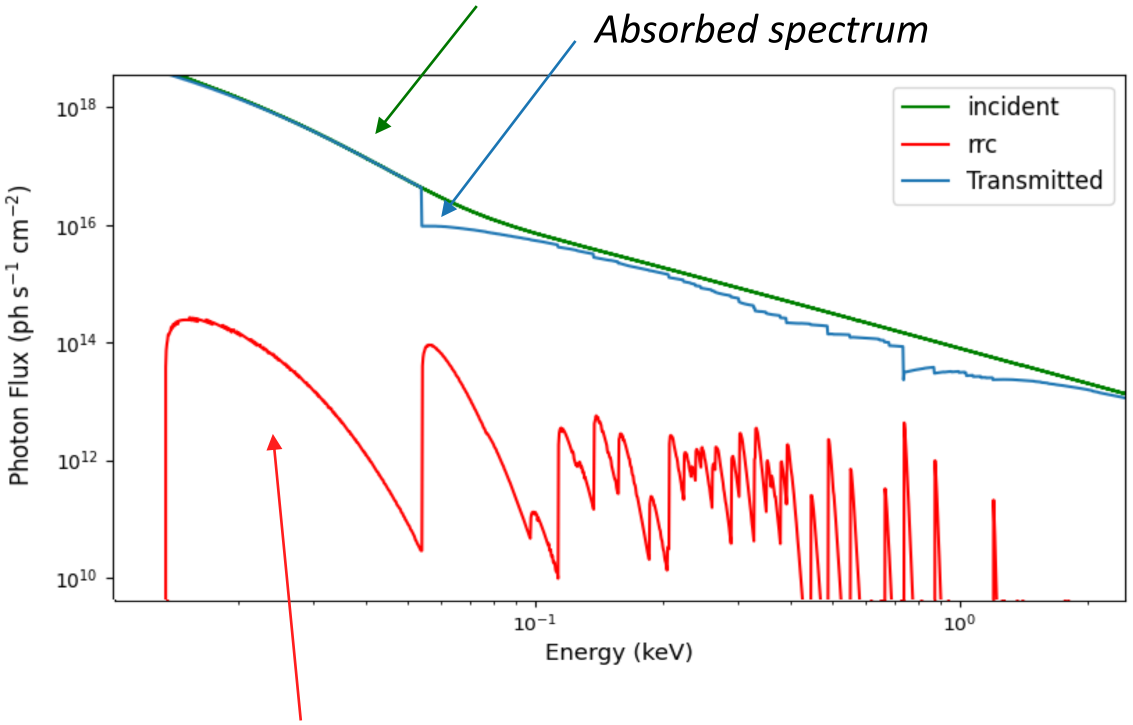
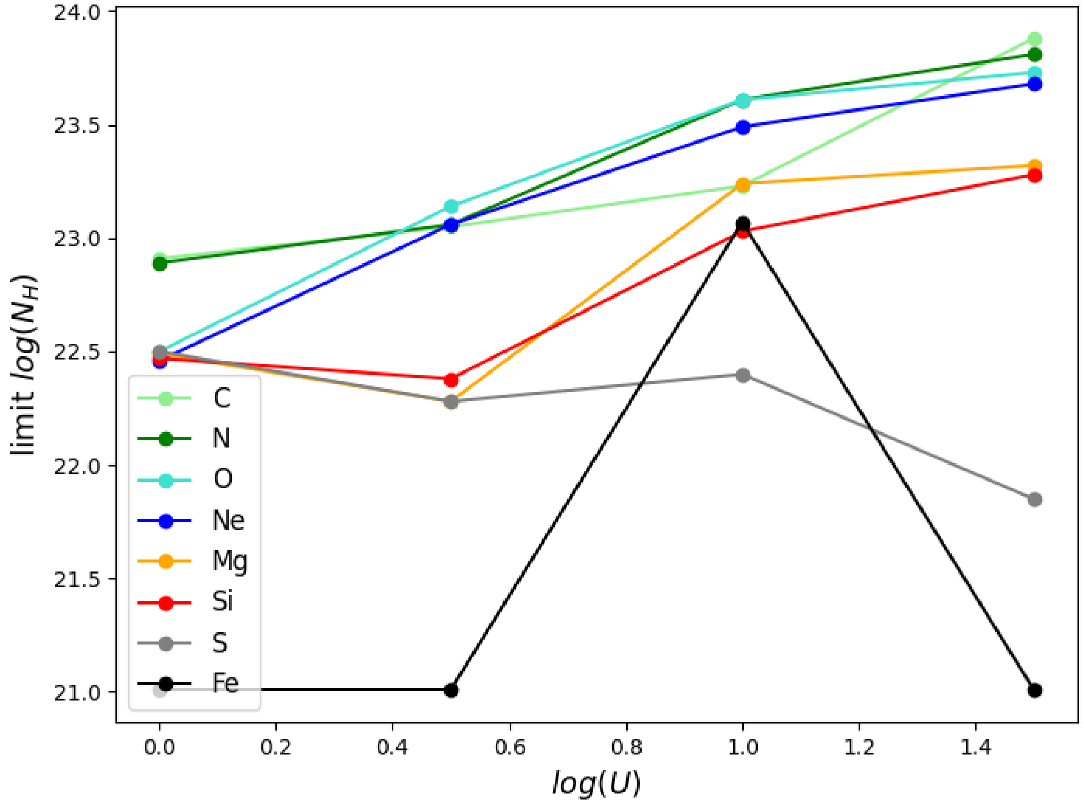
Incident spectrum

Absorbed spectrum



Emission continuum spectrum

Hydrogen-equivalent column density N_H up to which TEPID and Cloudy are in safe agreement :



(Agreement between XSTAR and Cloudy is way worse…)

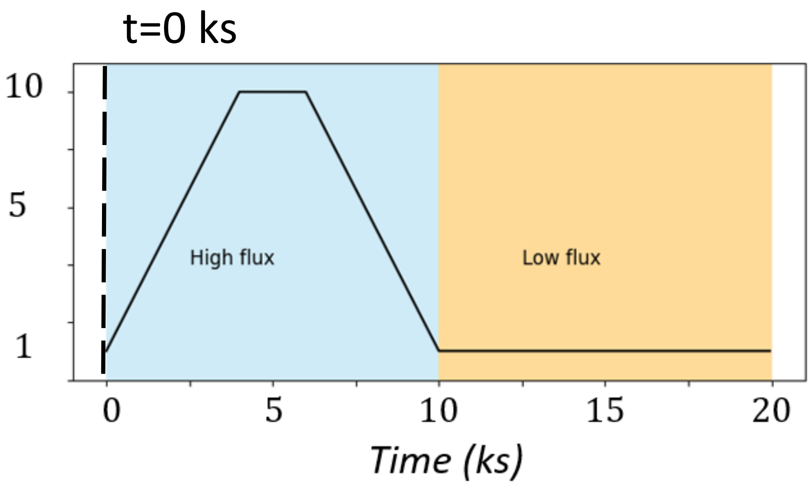
iv. Time-resolved spectra

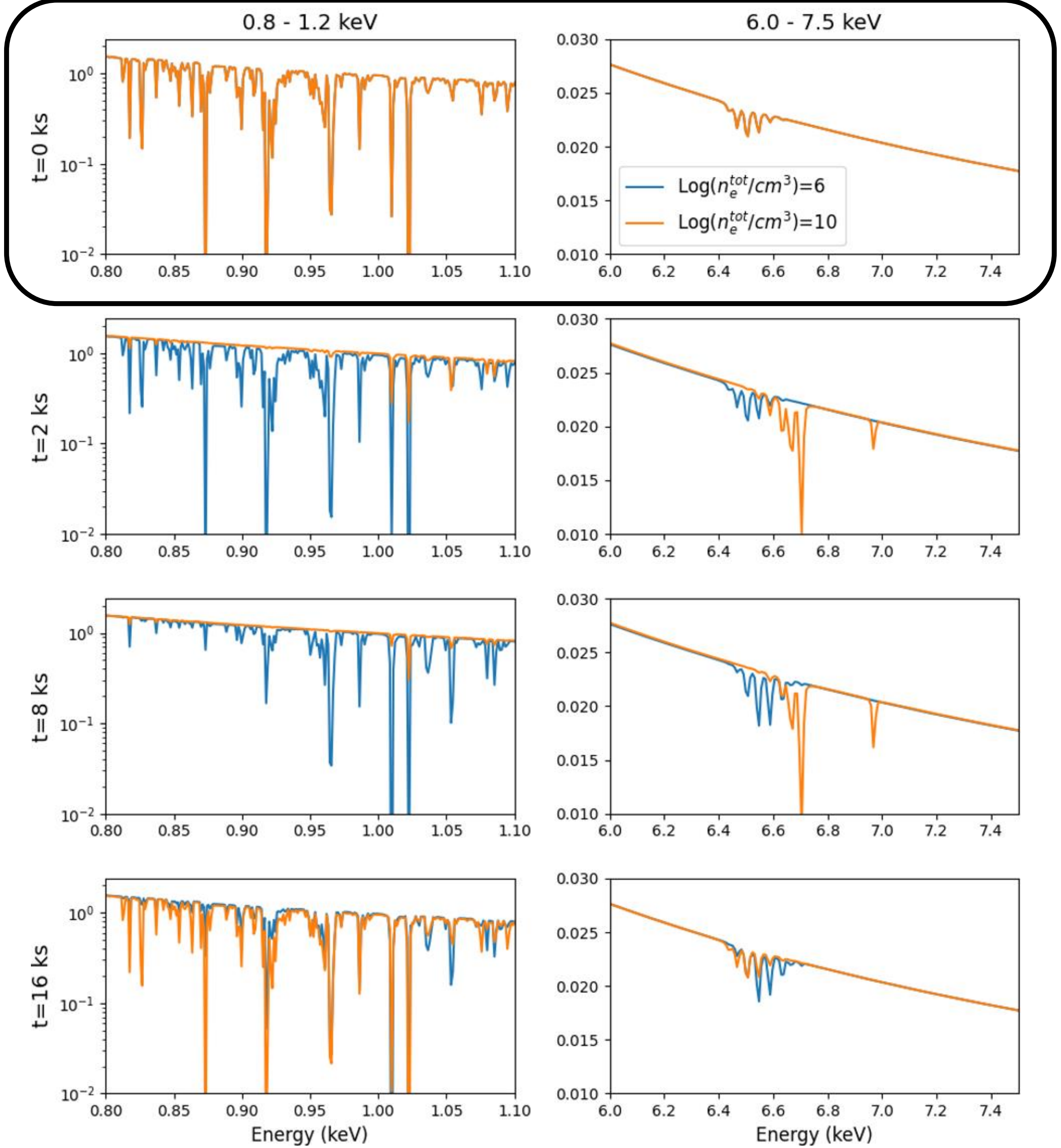
━ $\log(n_e/cm^3) = 6$

━ $\log(n_e/cm^3) = 10$

t=0 ks. Gas in equilibrium, $\log(U) = 1.5$

→ Spectra are identical by construction





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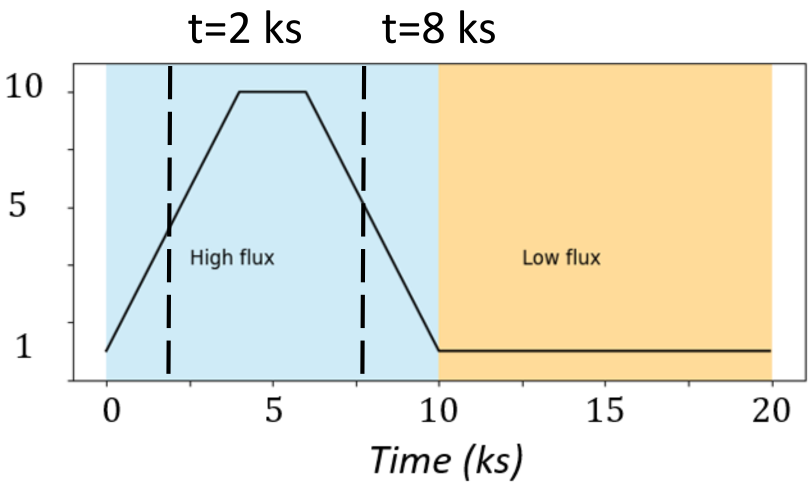
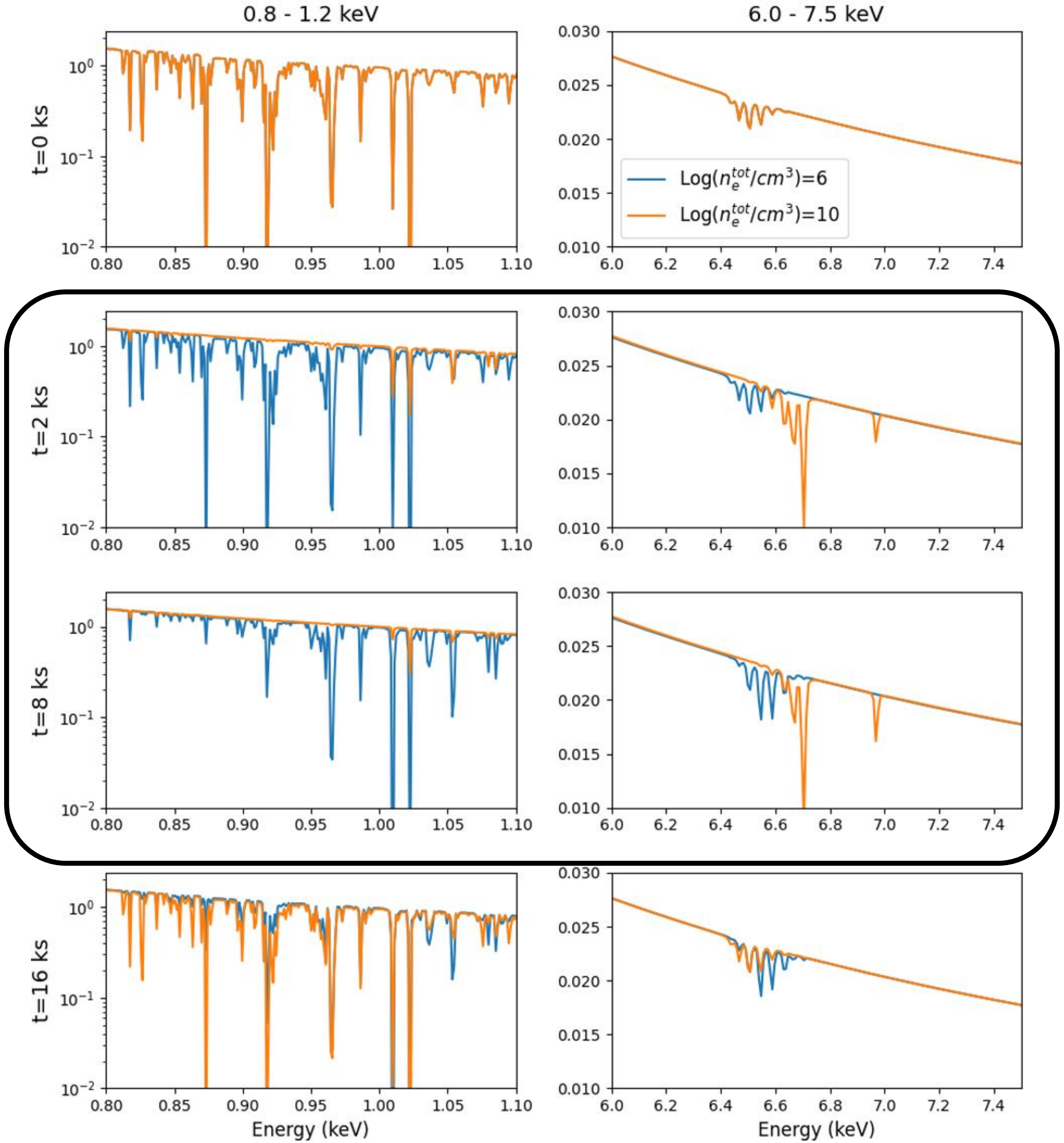
t=2,8 ks. Mid-time of the rise and decay phase (<u>same flux</u>):

- $n_e = 10^{10}$: gas in equilibrium → same opacity
- $n_e = 10^6$: gas is overionised → *lower opacity at t=8 ks!*





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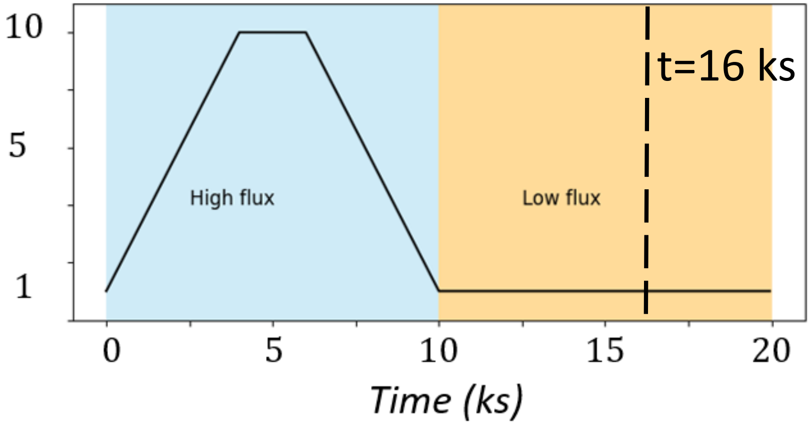
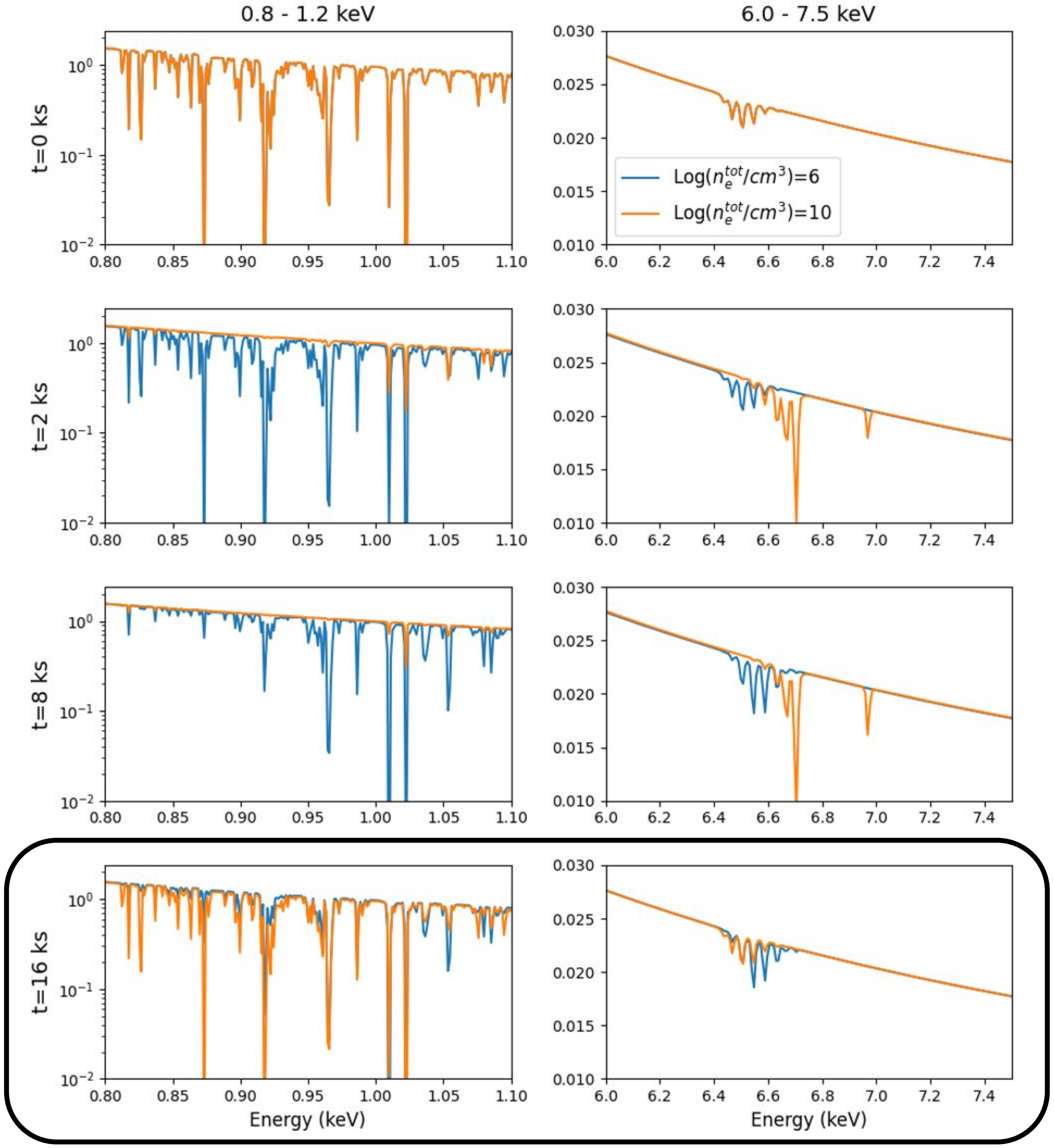
t=16 ks. Same flux as t=0.

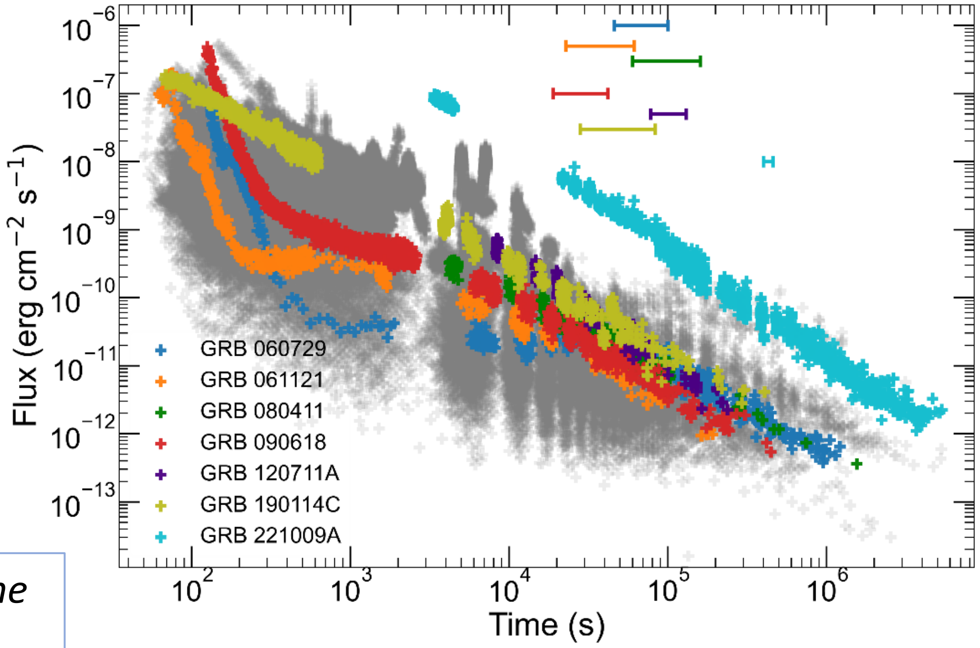
- $n_e = 10^{10}$: spectrum equal to T=0 ks
- $n_e = 10^{6}$: overionised spectrum





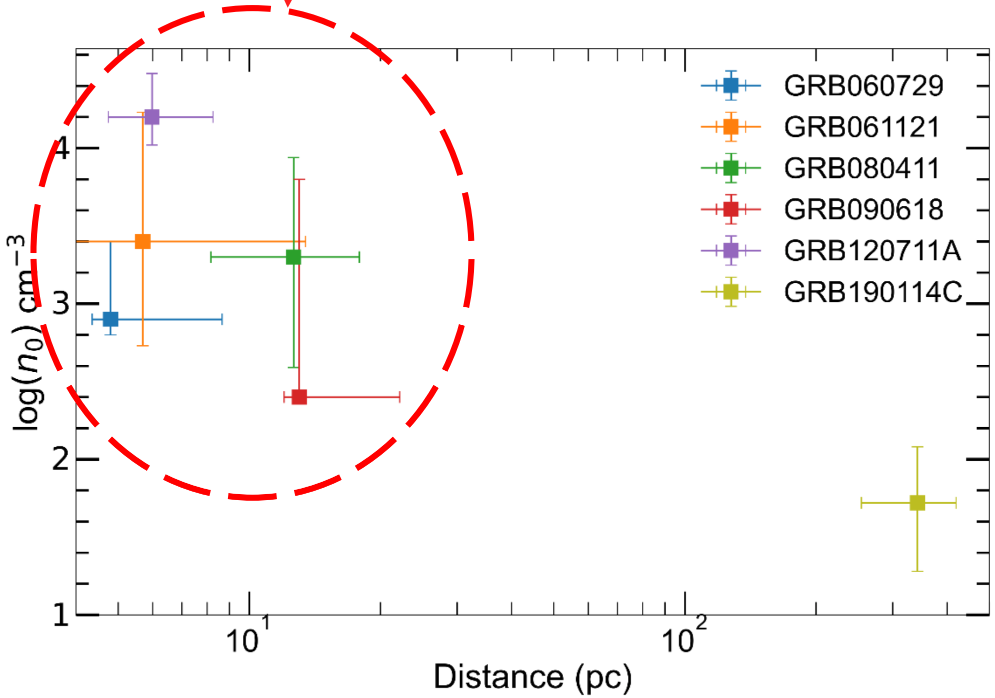
v. Work in progress:

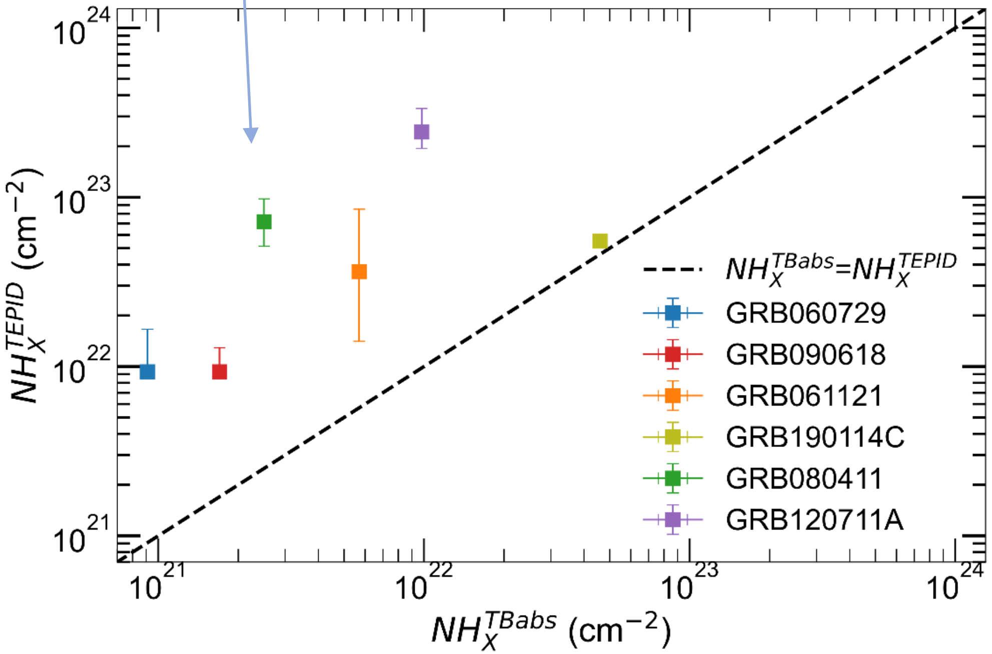
Fit of *XMM-Newton* spectra of high-flux GRB afterglows



TEPID reveals Star Forming Region-like overdensities around GRBs with ≈ 10 pc radii

A fit with a TBabs neutral screen underpredicts the N_H by up to a factor 10

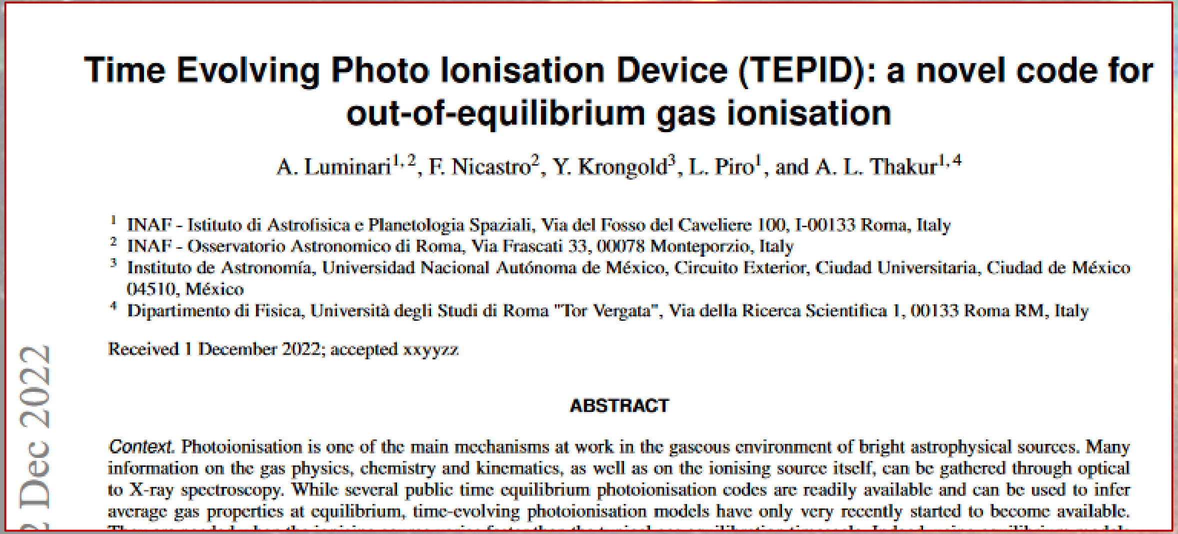




A. Thakur, L. Piro, A. Luminari, F. Nicastro et al,
to be submitted within this summer

Conclusions

- Equilibrium ionisation is a numerical approximation, which limits the constraining power of observed spectra
- Time-evolving ionisation offers a unique channel to constrain the gas number density and radial location
- TEPID is a novel code that follows temperature, ionisation of an out-of-equilibrium ionised gas
- TEPID can be used within Sherpa, XSPEC to fit time-resolved spectra



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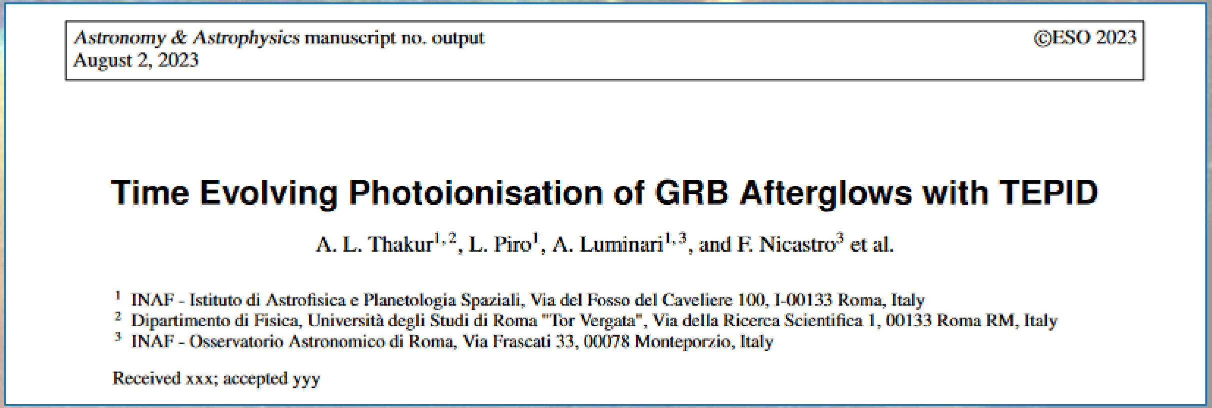
Luminari+23, A&A submitted



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Time Evolving Photoionisation of GRB Afterglows with TEPID

A. L. Thakur[1,2], L. Piro[1], A. Luminari[1,3], and F. Nicastro[3] et al.

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Received xxx; accepted yyy

Thakur+23, in prep.

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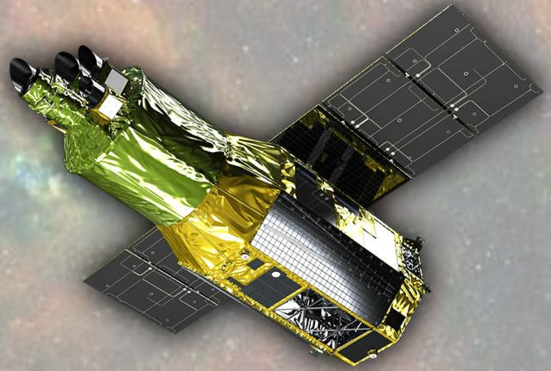
SRG/eROSITA

0.3-2.3 keV - RGB

Current steps

- Analysis of *XMM-Newton* (RGS, Epic) and *NuSTAR* observations of NGC4051
- *(soon)* Analysis of XRISM Performance Verification (PV) data of the powerful Quasar PDS456
- *(soon)* Application to XRISM AO through Japanese time (+ US, ESA times)

→ Talk to me for a time-evolving analysis of your favourite source



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