Theory and observations of photoionised gas (around supermassive black hole)

Alfredo Luminari

INAF – IAPS and Observatory of Rome (OAR)

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

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

Theory and observations of photoionised gas

Outline

i. *Astrophyiscal Ionised Gas: state of the art and open questions*
ii. *Time-equilibrium photoionisation (the analytic paradise)*
iii. *Time-evolving photoionization (the analytic nightmare)*
    i. *What is being currently done (spoiler: brute force)*
    ii. *Gas behaviour out-of-equilibrium*
    iii. *Can we do (statistically) better?*
iv. *Conclusions*

Foreword

Before coming here, I was ready for my usual, theoretical-astrophysicist presentation on photoionisation….

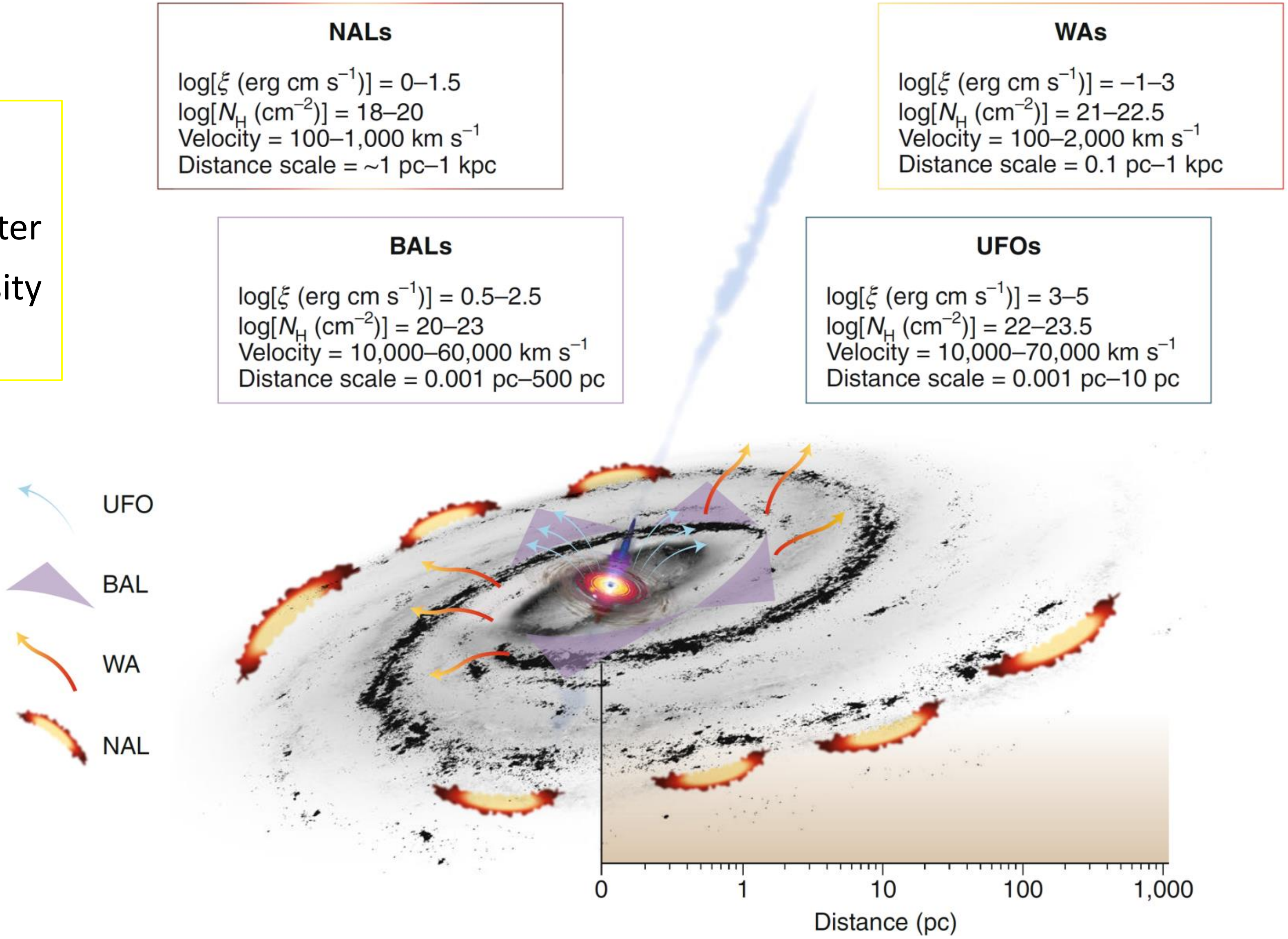
… but then my collaborator told me:

So I will do my best to build upon the many interesting presentations of these days and propose something new

i. State of the art. AGNs

Main observables:

- ξ: ionisation parameter
- N_H: gas column density
- v_{out}: gas velocity



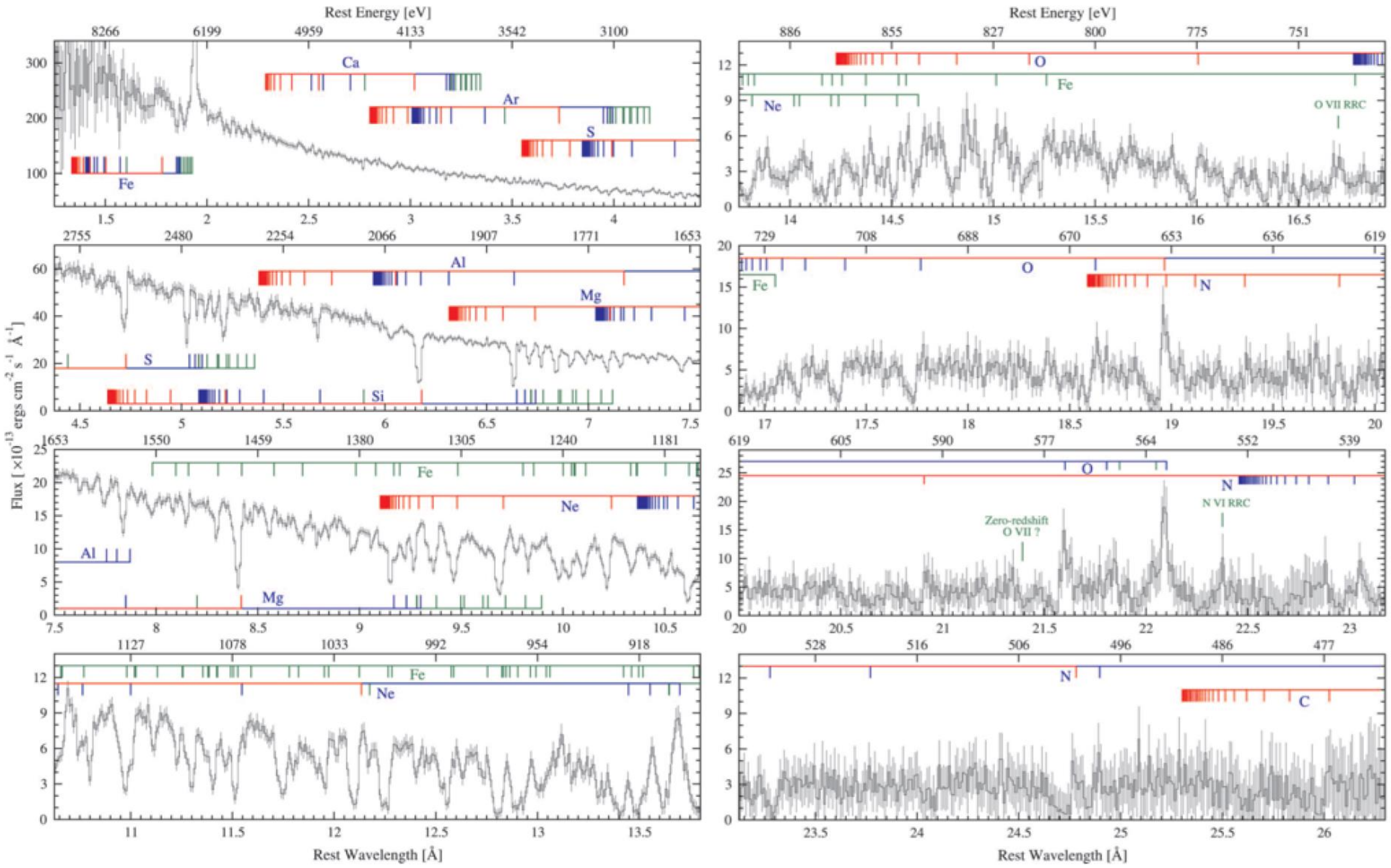
Laha+20

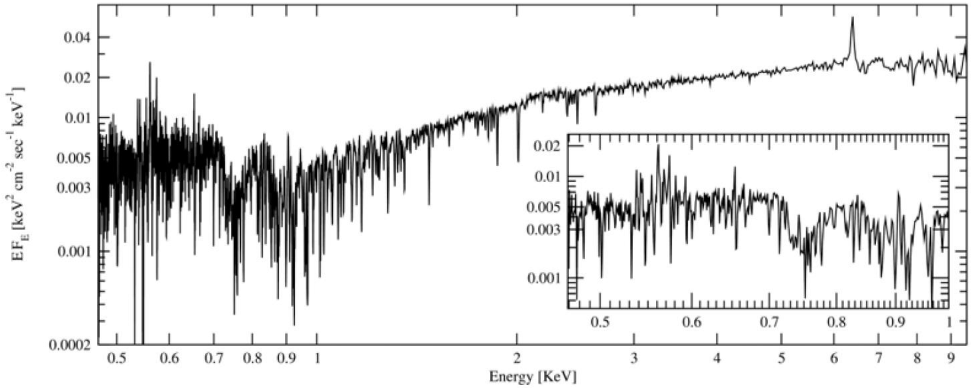
i. State of the art. AGNs

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

WAs

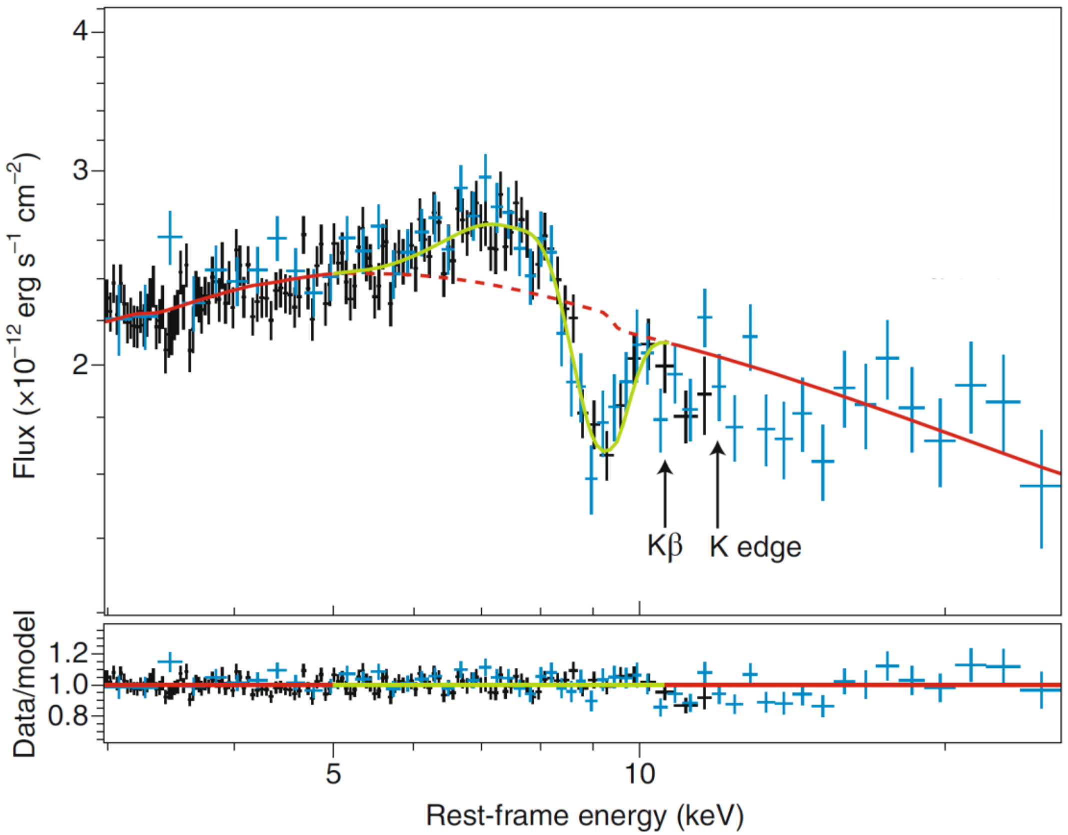
log[ξ (erg cm s^{-1})] = −1–3
log[N_H (cm^{-2})] = 21–22.5
Velocity = 100–2,000 km s^{-1}
Distance scale = 0.1 pc–1 kpc



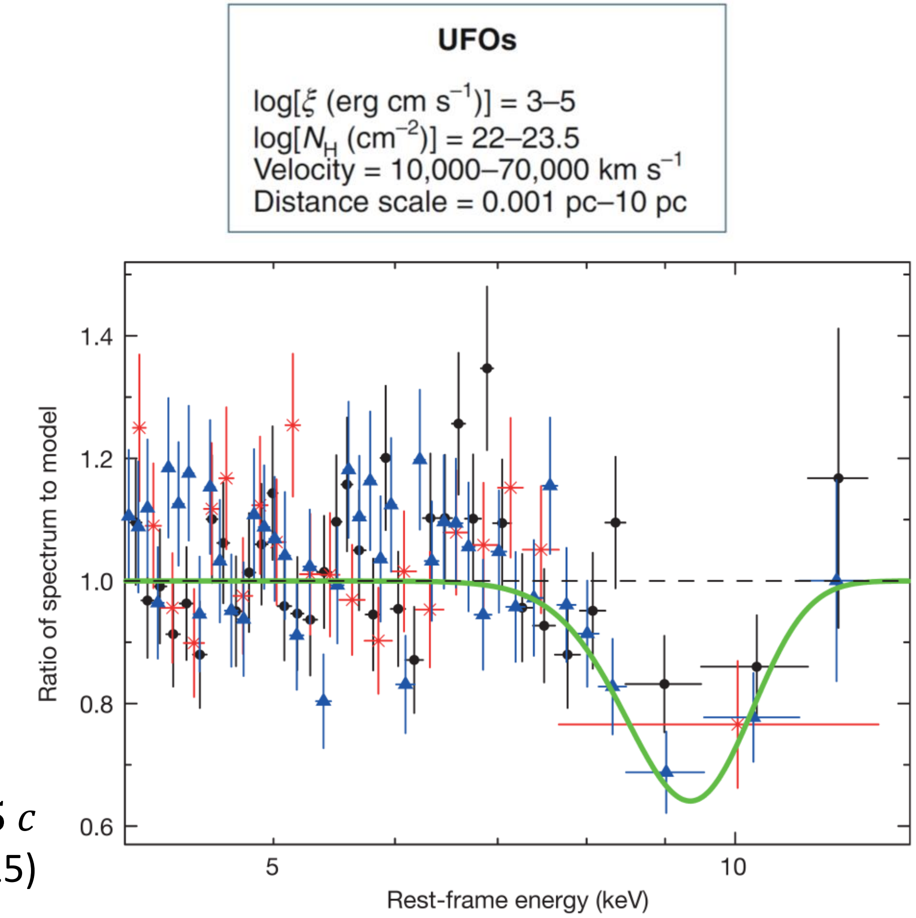


Kaspi+02

i. State of the art. AGNs



PDS456: $v_{out} = 0.2\ c$
(Nardini+15)

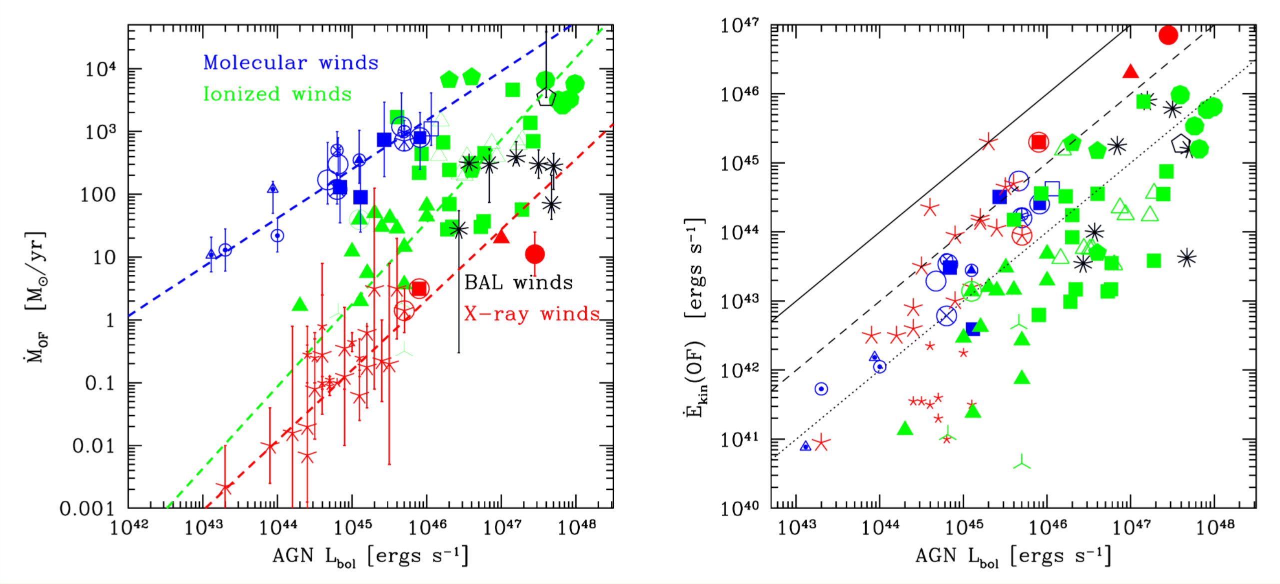


IRAS F11119+3257: $v_{out} = 0.25\ c$
(Tombesi+15)

i. Open questions

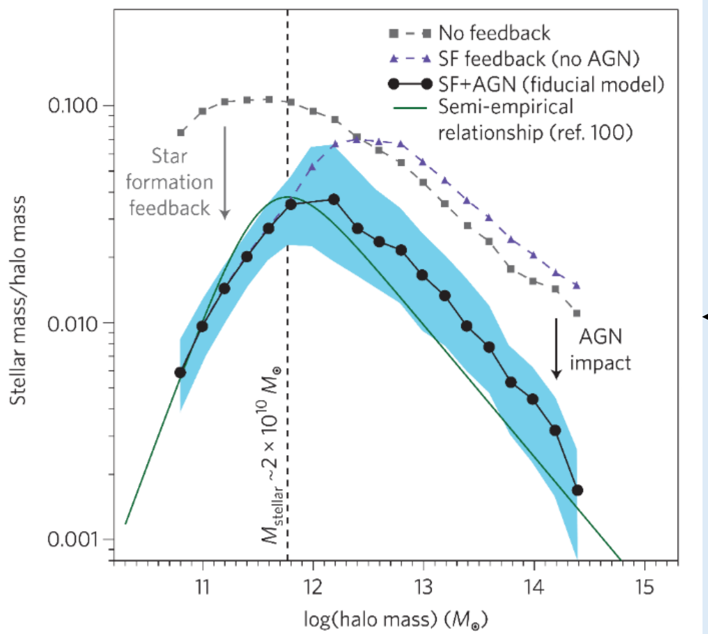
Outflows are ubiquitously observed in AGNs in all phases, from accretion-disc scales (X-rays) up to galaxy scales (optical, mm, radio).

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

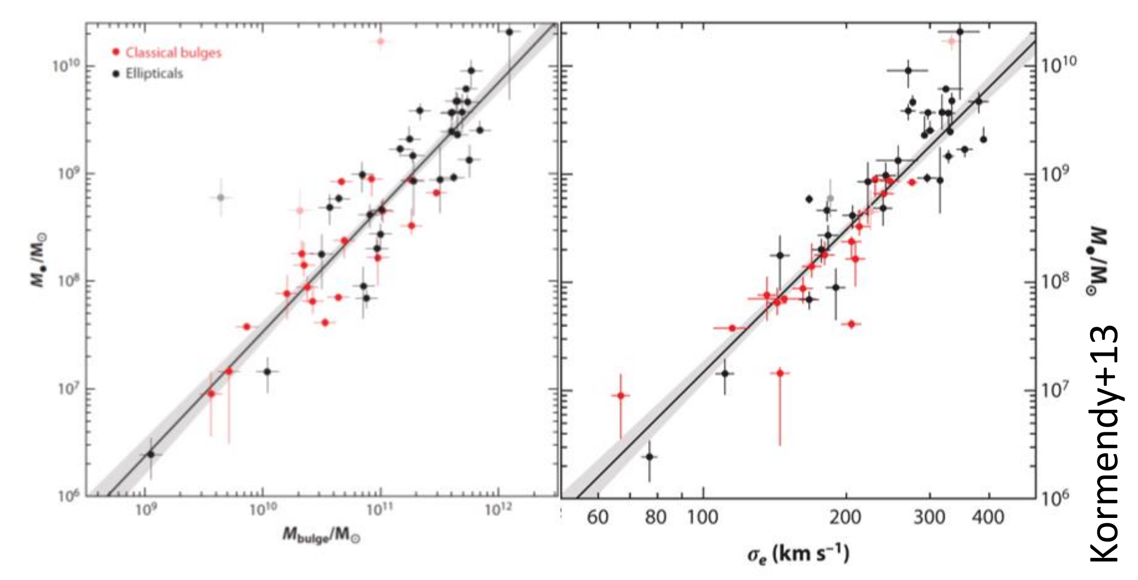
Main candidate for AGN feedback and coevolution with the host galaxy:



Harrison+17

Needed to reduce SFR in high-mass galaxies

Explains central black hole-host galaxy correlations

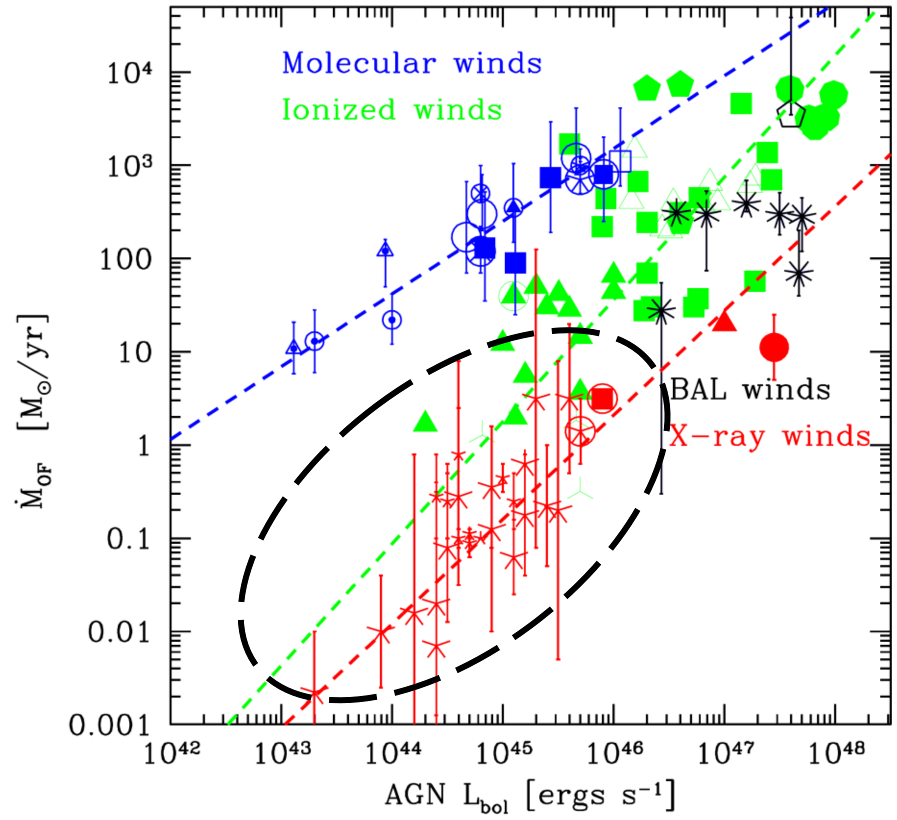


Kormendy+13

i. Open questions

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

1. Location
2. Density
3. Energetic



Fiore+17

i. Open questions

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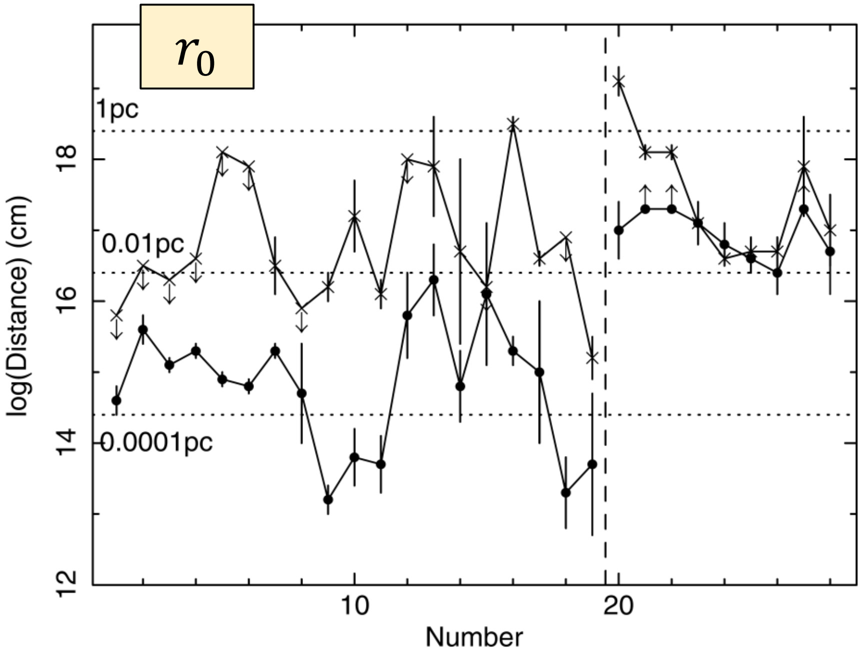
1. Location
2. Density
3. Energetic

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



Sample of local Sy1 galaxies
from Tombesi+12

i. Ionised Outflows. Open questions

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

<u>But…</u>

→ degeneration is broken out of ionisation equilibrium!

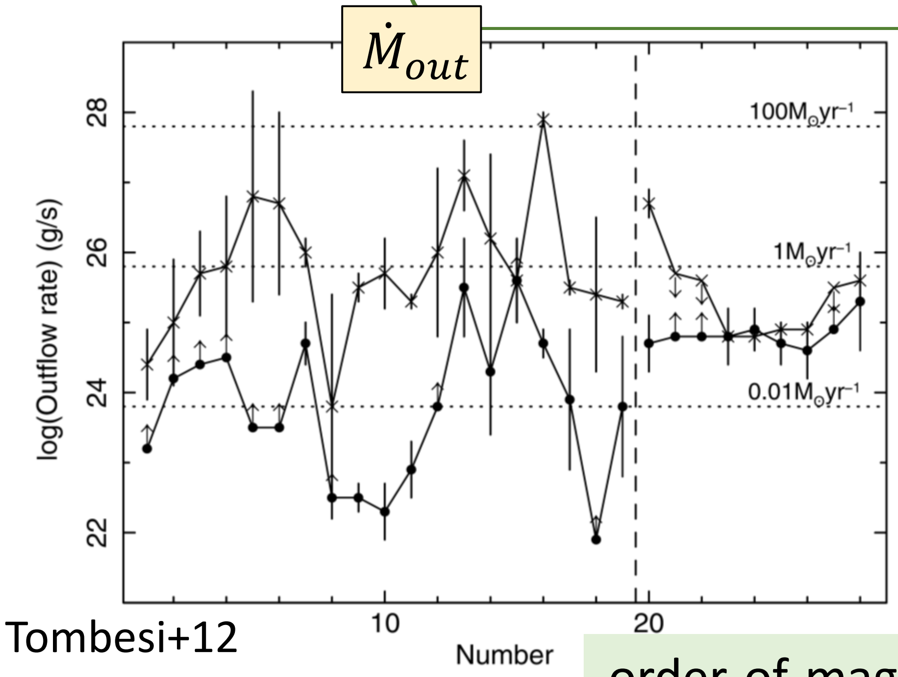
i. Ionised Outflows. Open questions

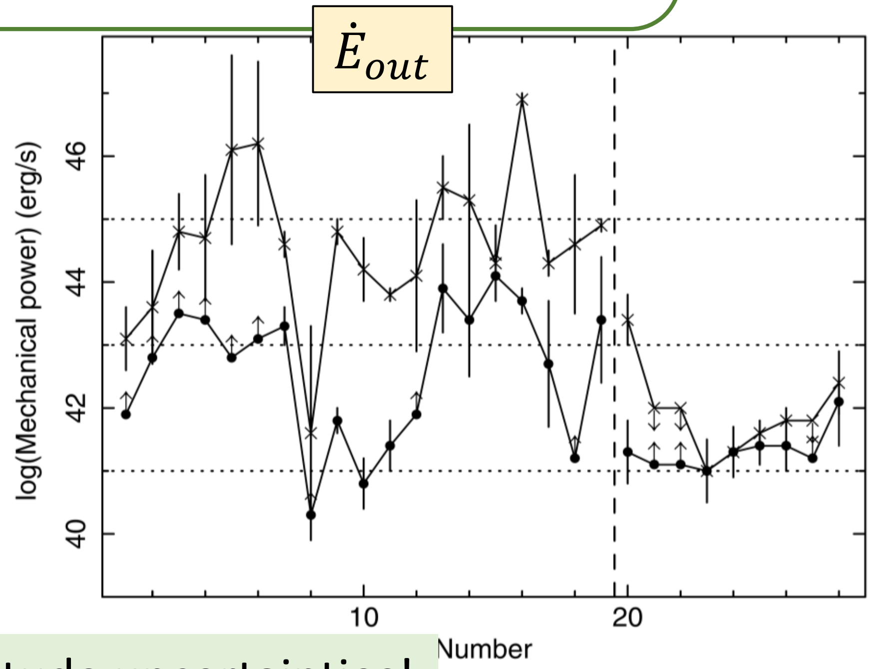
Still after >20 years of X-ray spectroscopy,
several questions remain open:

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





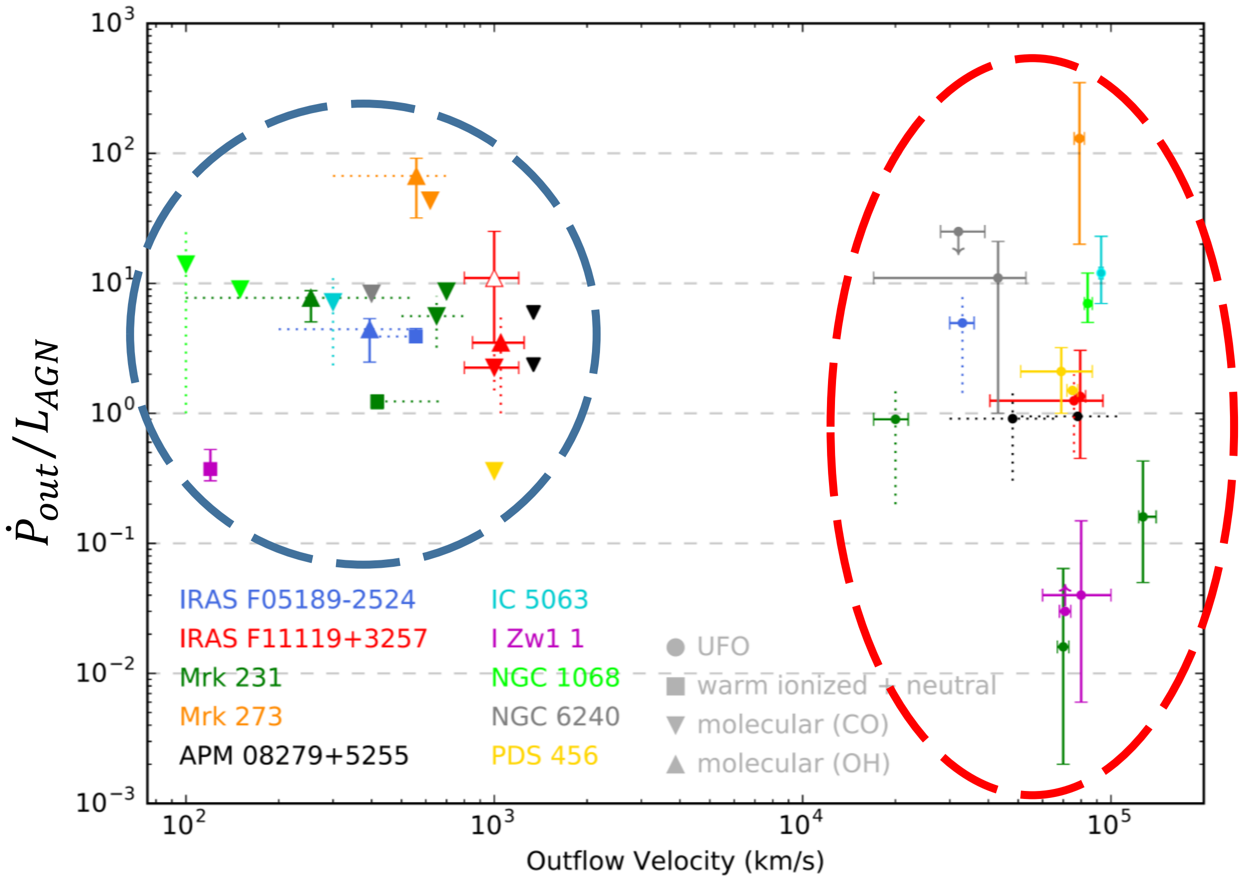
Tombesi+12

order-of-magnitude uncertainties!

i. Ionised Outflows. Open questions

Energy of galactic and nuclear outflows:

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



Smith+19

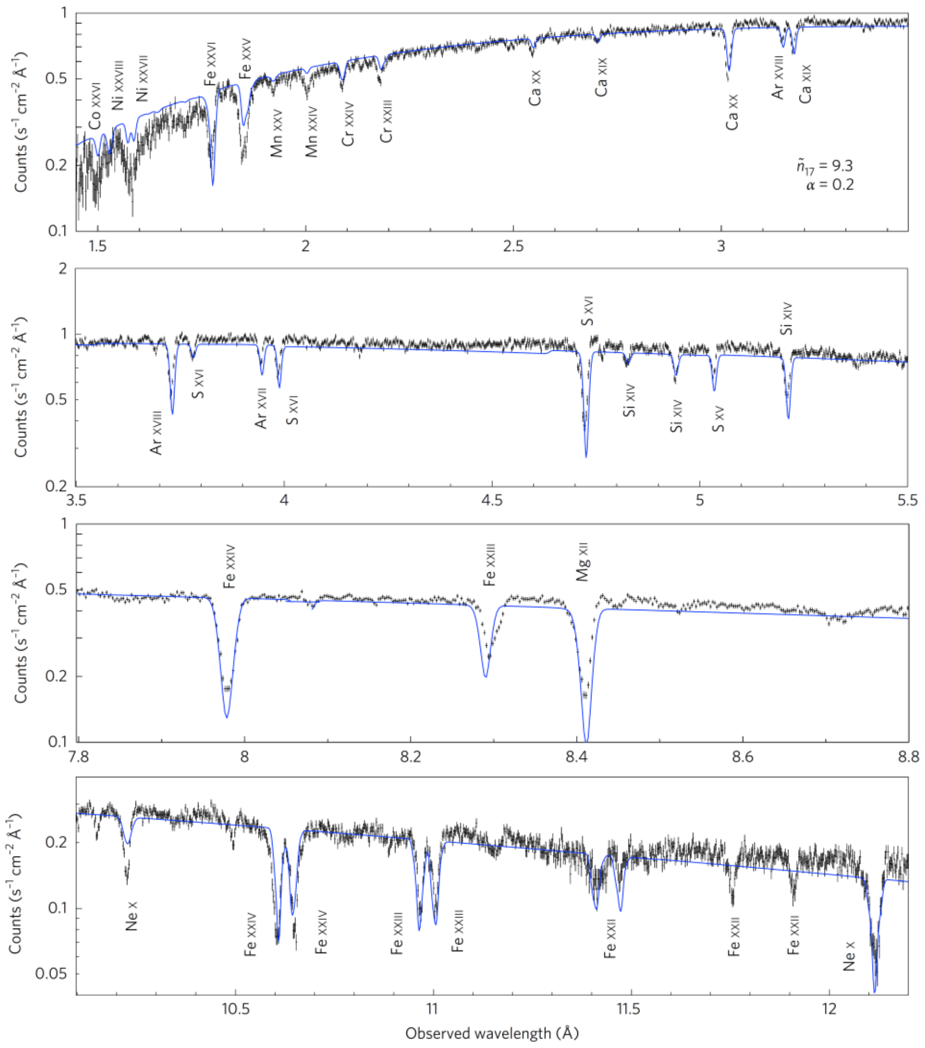
Galactic outflows: relatively small errors

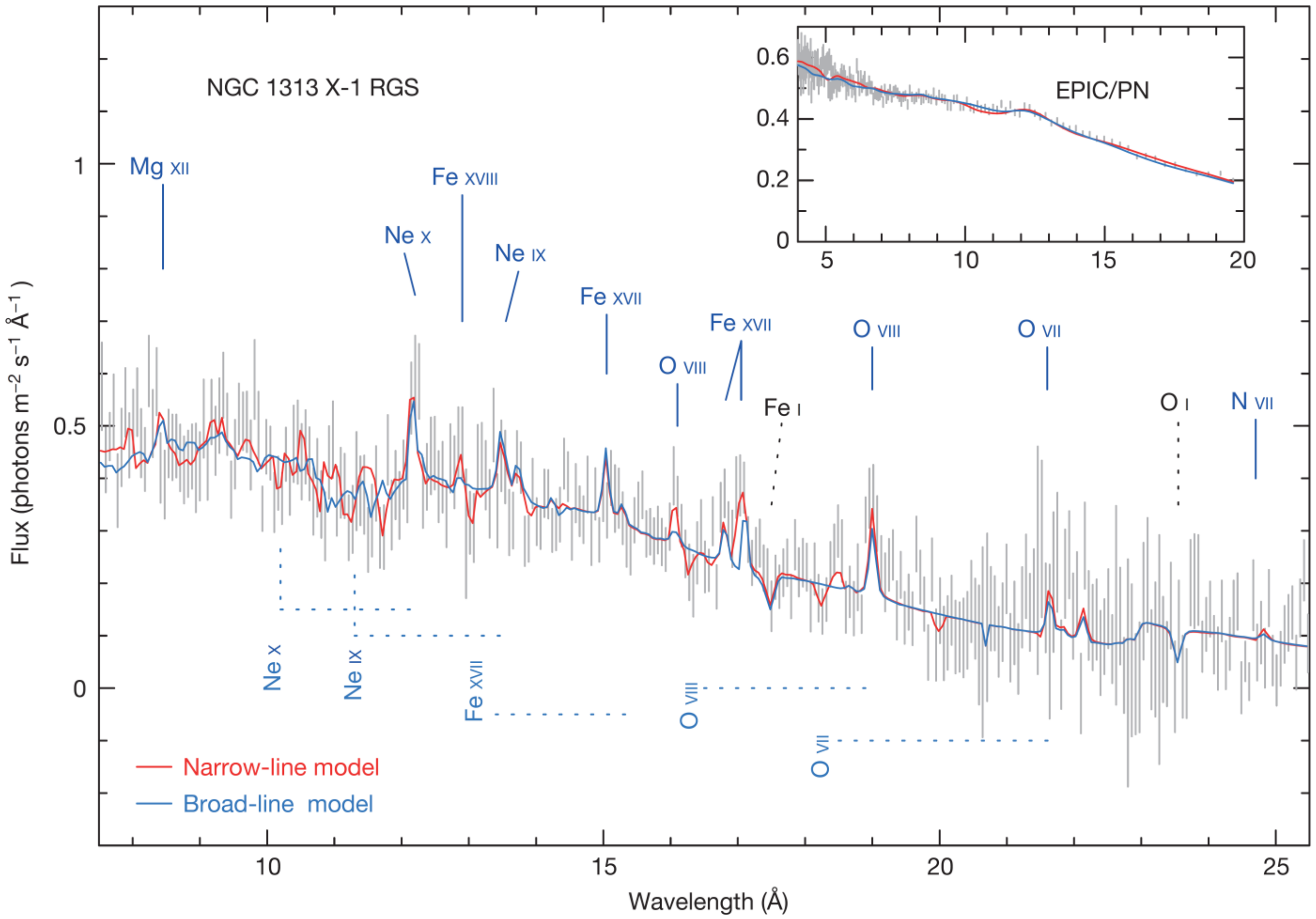
Nuclear outflows (UV – X-ray): order-of-magnitude errors

Cannot meaningfully compare the two scales!

i. State of the art. Compact accreting sources

ULX NGC1313-X1 – Pinto+16



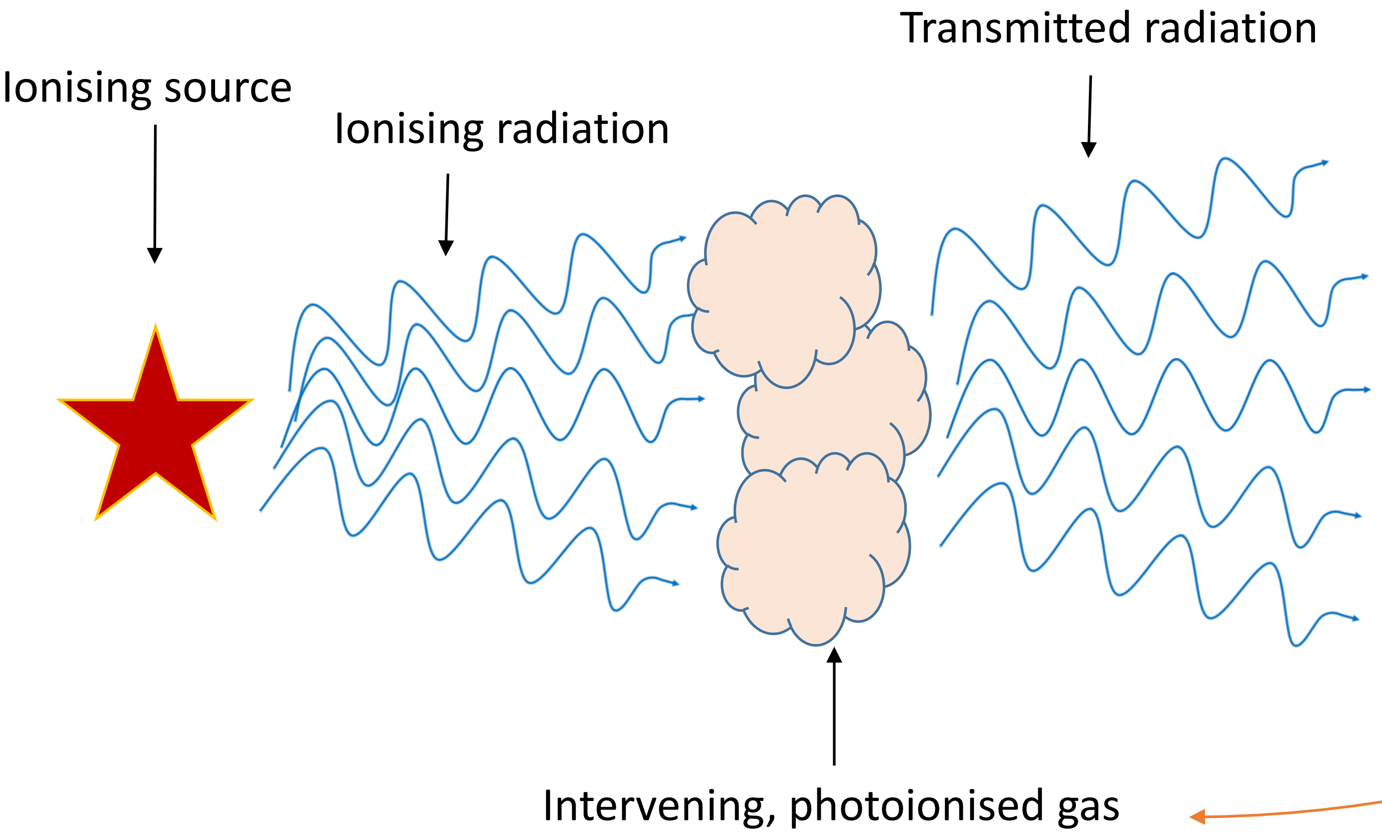


XRB GRO J1655 - Fukumura+17

$$v_{out} = 0.25\ c, N_H = 10^{24} cm^{-2}, \log(\xi) = 3.5\ erg\ cm\ s^{-1}$$

i. Photoionisation. The physical problem

Photoionisation is (in principle) a simple problem:



Question is:
What is the physical status of the gas and the spectrum of the transmitted radiation?

i. Photoionisation. The physical problem

Gas physical status is regulated by its interaction with the radiation field.

Ionic abundances

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

n_e: electron number density $\approx 1.2\ n$

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<u>Creation:</u>
recombination from $i + 1$ and photoionisation from $i - 1$

<u>Destruction:</u>
Photoionisation (rate F_{X^i}) to upper level ($i + 1$) and recombination (rate $\alpha_{rec}^{i} n_e$) to lower level ($i - 1$)

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Temperature

Γ : heating (photoionisation)

$$\frac{dT}{dt} = \sum_{X,i}[\Gamma - \Lambda] + \Theta = \sum_{X,i}\left[\Gamma(n_{X^i}) - \Lambda(T, n_e, n_{X^i})\right] + \Theta(T)$$

Θ : Compton

Λ : cooling (gas emission)

Summed over the gas elements

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Summed over the gas elements

Charge conservation

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

i. Photoionisation.

The driving parameters are:

Sets the energy transferred to the gas

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

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

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

Linearly depends on F_{ion}

Linearly depends on n_e

Ionic abundances

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

Temperature

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i. Photoionisation. Time-equilibrium regime

In the equilibrium, steady-state regime a (quasi) analytic solution exists:

$$\frac{dn_{X^i}}{dt} = -\left[F_{X^i} + \alpha_{rec}^{X^i} n_e\right] n_{X^i} + F_{X^{i-1}}\, n_{X^{i-1}} + \alpha_{rec}^{X^{i+1}}\, n_e n_{X^{i+1}} = 0$$

$$\frac{dT}{dt} = \sum_{X,i}[\Gamma - \Lambda] + \Theta = 0$$

For fixed T , the ion abundance is set by the ratio between photoionisation (source term) divided by recombination (sink term):

$$n_{X^i} = A \left| \frac{F_{X^{i-1}}}{n_e\, \alpha_{rec}^{i}} \right|_T$$

(A = normalisation constant)

Then, you iterate for different values of T (updating n_{X^i} at each step) until you obtain energy balance (i.e. heating equals cooling):

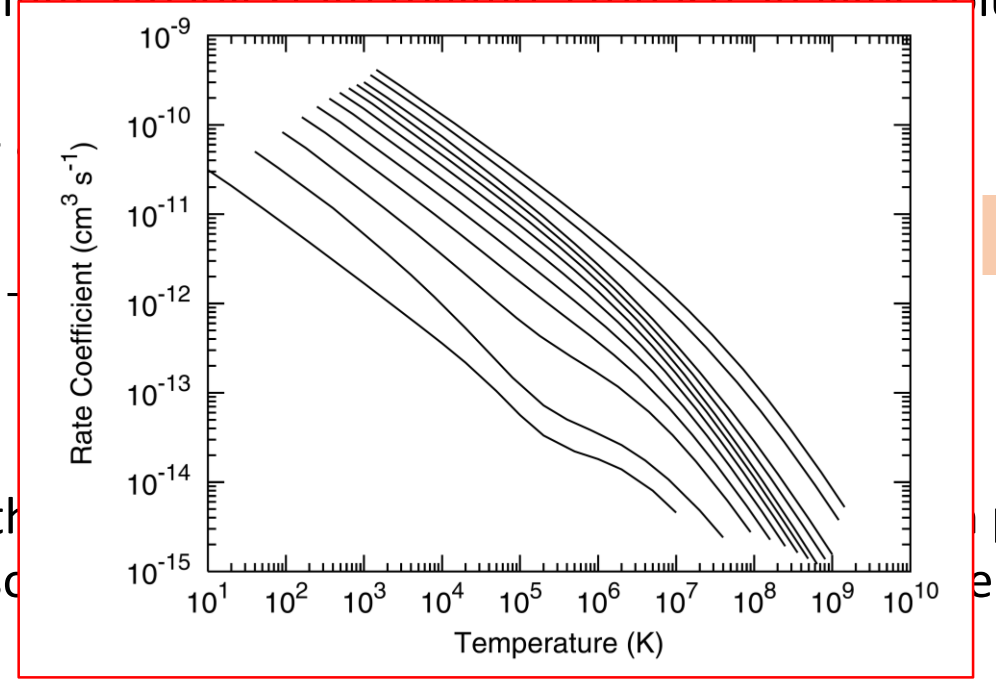
$$\frac{dT}{dt} = \sum_{X,i}[\Gamma - \Lambda] + \Theta = \sum_{X,i}\left[\Gamma(n_{X^i}) - \Lambda(T, n_e, n_{X^i})\right] + \Theta(T) = 0$$

i. Photoionisation. Time-equilibrium regime

In the equilibrium, steady-state regime a (quasi) analytic solution exists:

$$\frac{dn_i}{dt} = -[F_i + \ldots$$

$$\frac{dT}{dt} = \sum_{X,i}[\Gamma - \ldots$$



α^i_{rec} for Magnesium ions

For fixed T , th … photoionisation

(sc … erm):

$$n_{X^i} = A\,\frac{F_{X^{i-1}}}{n_e\,\alpha^i_{rec}}$$

$F_{X^{i-1}}$ is the photoionisation rate. $F \propto \frac{Q_{ion}}{r^2} \cdot \sigma$, where:

- σ is the ion cross section
- $\frac{Q_{ion}}{r^2}$ the flux of ionising photons at the gas position

$\alpha^i_{rec}(T)$ is the recombination rate. Function of the given ion and of the temperature

i. Photoionisation. Time-equilibrium regime

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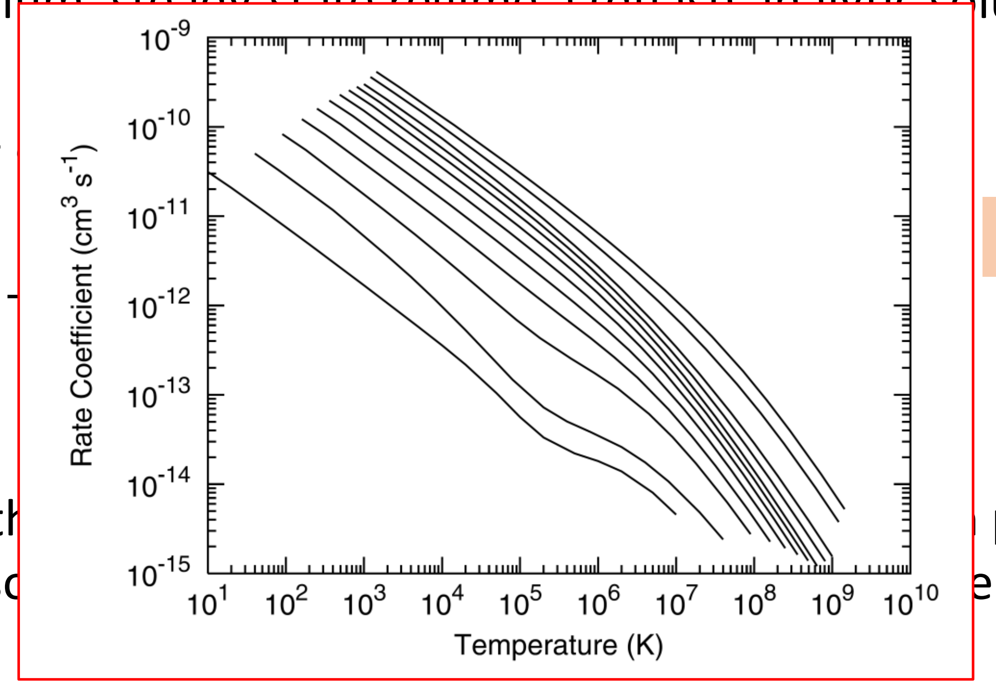

α^i_{rec} for Magnesium ions

For fixed T , th... photoionisation

(sc... erm):

$$n_{X^i} = A\,\frac{F_{X^{i-1}}}{n_e\,\alpha^i_{rec}} \propto \frac{Q_{ion}\sigma}{r^2}\cdot\frac{1}{n_e\alpha^i_{rec}} = U\,\frac{\sigma}{\alpha^i_{rec}}$$

$U = \frac{Q_{ion}}{r^2 n}$ is the ionisation parameter:
<u>proxy for the overall wind ionisation</u>

i. 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

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

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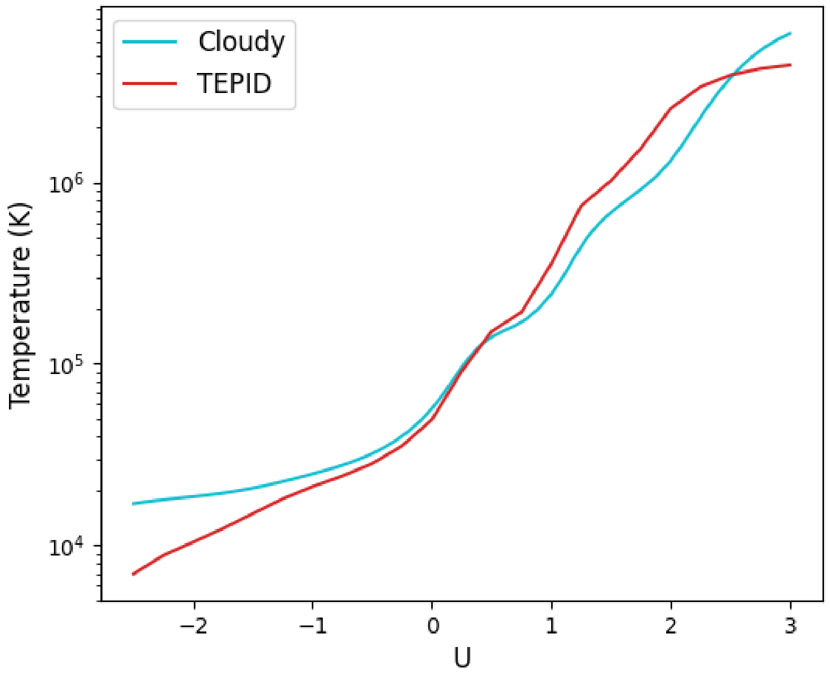

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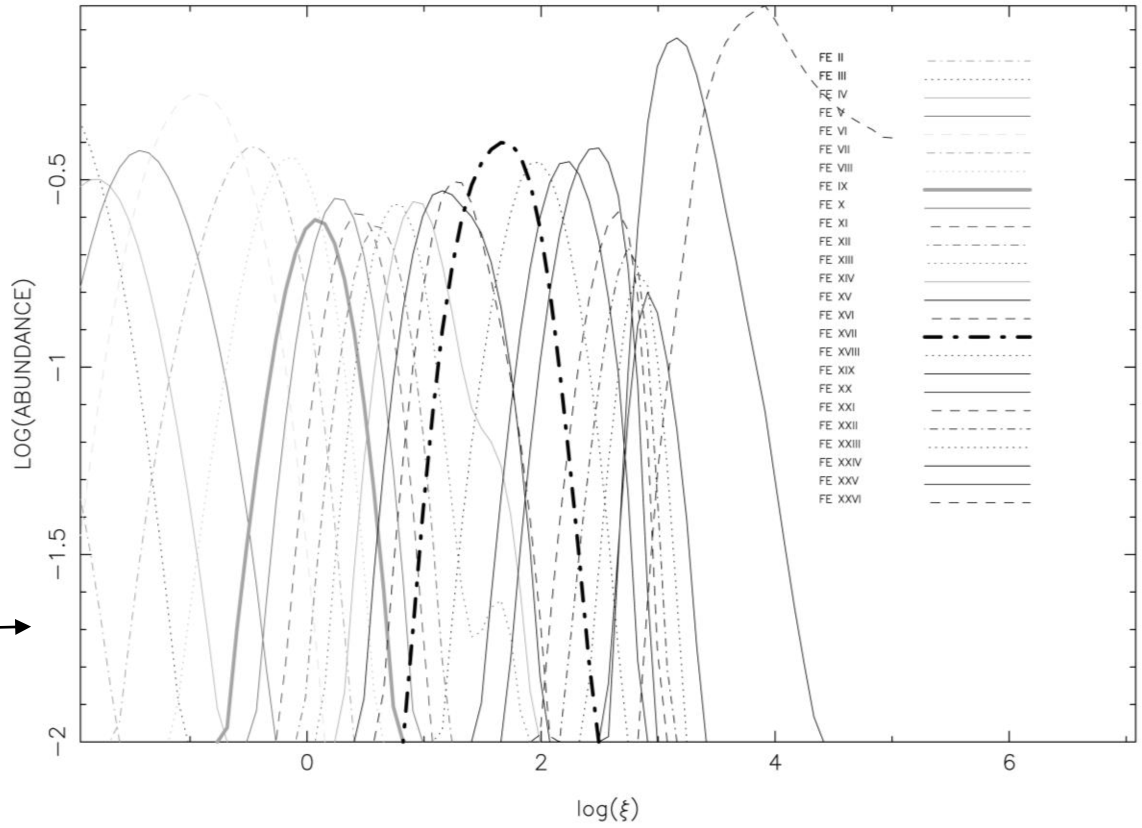

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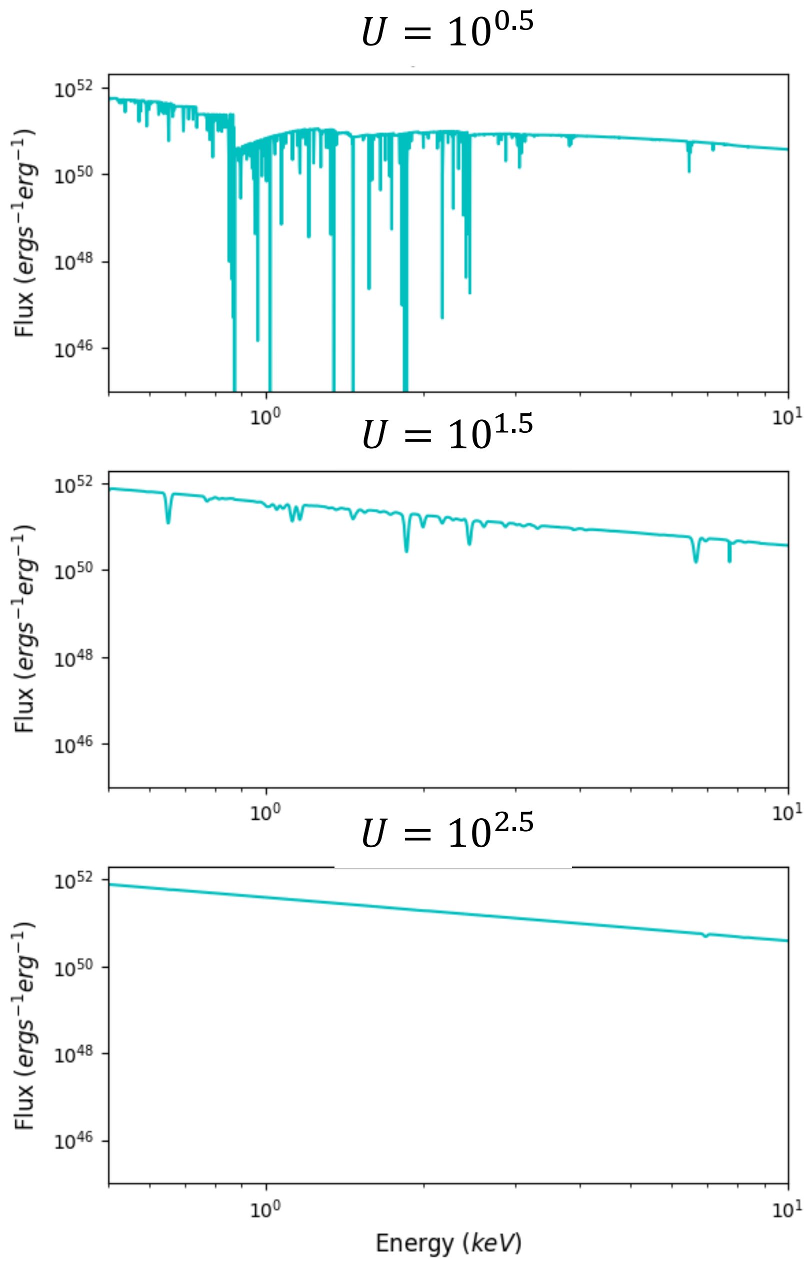
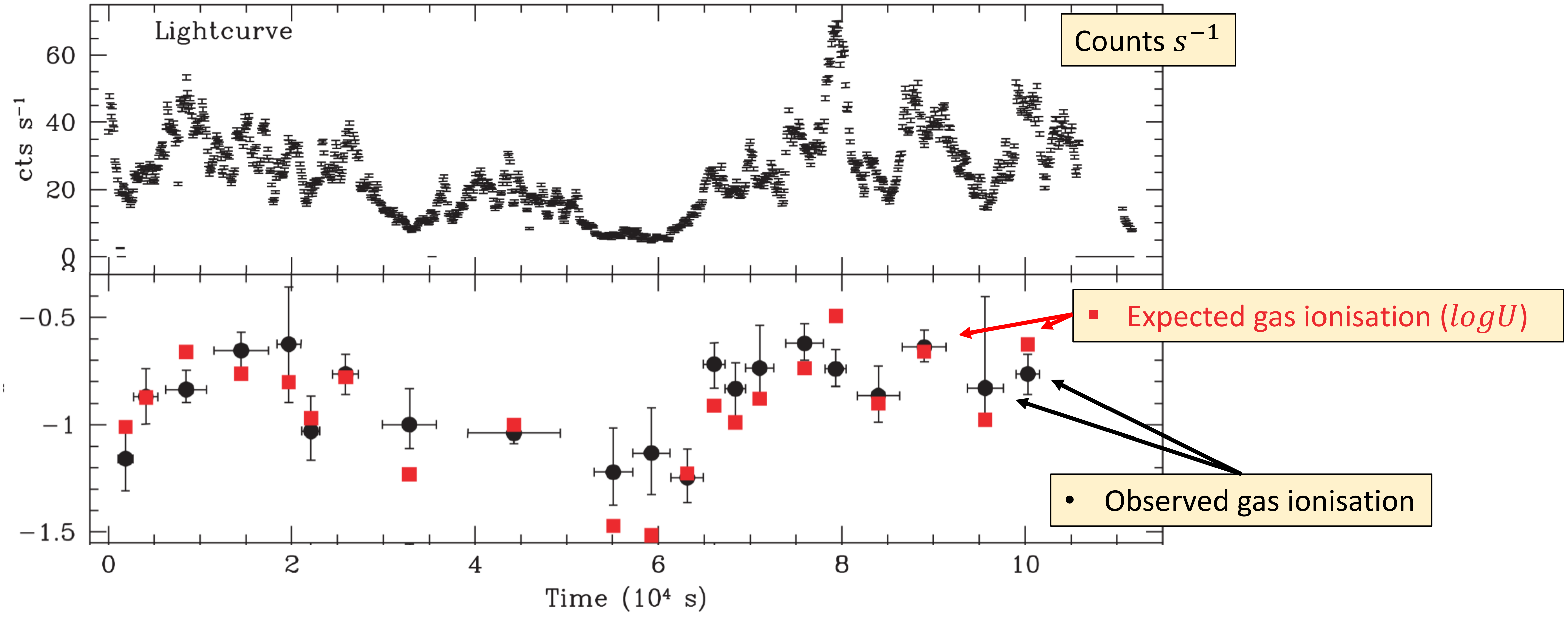


Plenty of dedicated codes:
Cloudy, XSTAR, SPEX….

iii. Time-evolving regime

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

NGC4051 – Krongold, Nicastro+07



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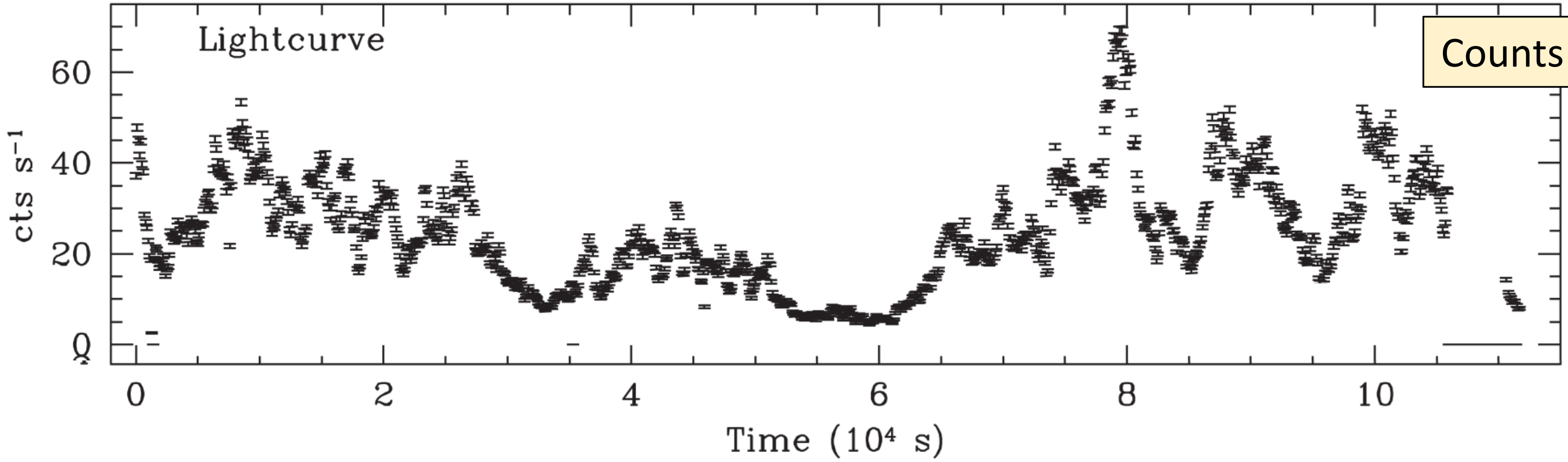

Counts s^{-1}

…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!*

iii. Time-evolving regime

Constant Ionisation source
→ Time-equilibrium photoionisation:

Ionisation parameter dictates the physical status of the gas:

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

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

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

→ measure U through the ratio of different absorption lines

→ measure N_H from line depth

→ measure v_{out} from line blueshift

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. Current efforts

TEPID:
Time-Evolving PhotoIonisation Device

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

Variable ionisation source ($t_{var} < t_{eq}$):
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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
[2] INAF - Osservatorio Astronomico di Roma, Via Frascati 33, 00078 Monteporzio, Italy
[3] Instituto de Astronomía, Universidad Nacional Autónoma de México, Circuito Exterior, Ciudad Universitaria, Ciudad de México 04510, México
[4] Dipartimento di Fisica, Università degli Studi di Roma "Tor Vergata", Via della Ricerca Scientifica 1, 00133 Roma RM, Italy

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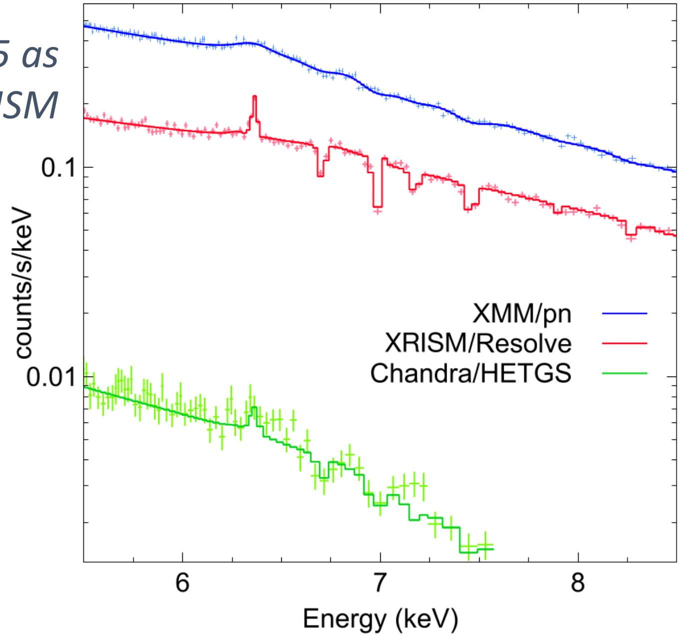
ABSTRACT

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.

iii. Current efforts

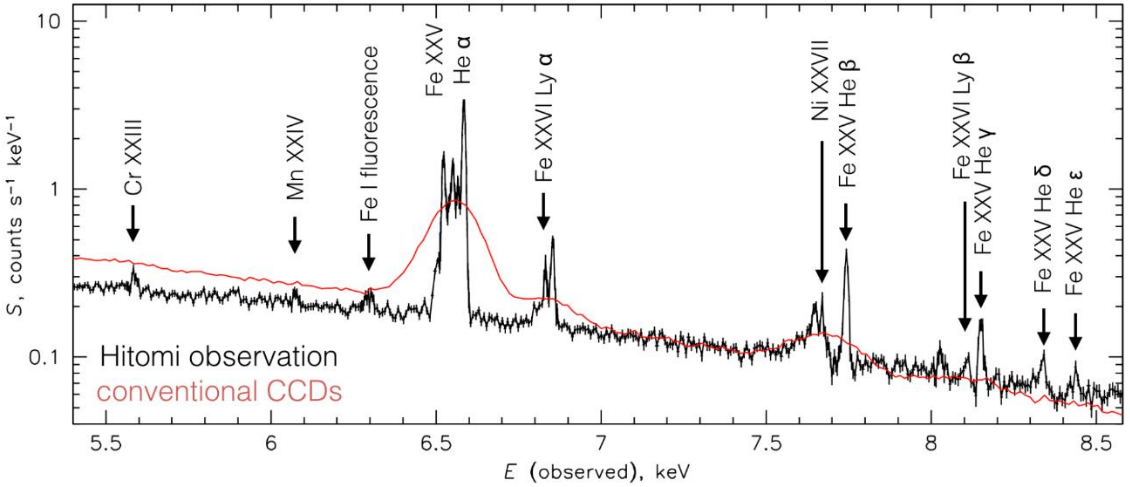
The X-ray spectrum of AGN MCG-6-30-15 as seen by current instruments and XRISM



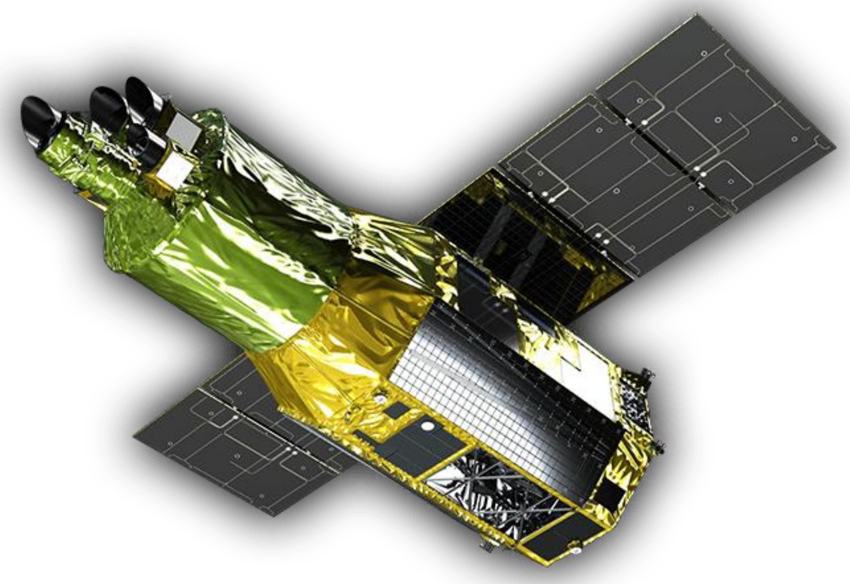
Images from XRISM WP

The XRISM X-ray telescope (launch due May 2023) will lead to a breakthrough in X-ray astronomy using microcalorimeters for the first time, leading to an improvement in the spectral resolution from today's $\sim 100\ eV$ to $7\ eV$.

Its unprecedented spectral resolution will make current time-equilibrium codes obsolete and will require accurate time-evolving ionisation codes.



The Perseus cluster X-ray spectrum with CCD-like resolution and with XRISM microcalorimeters



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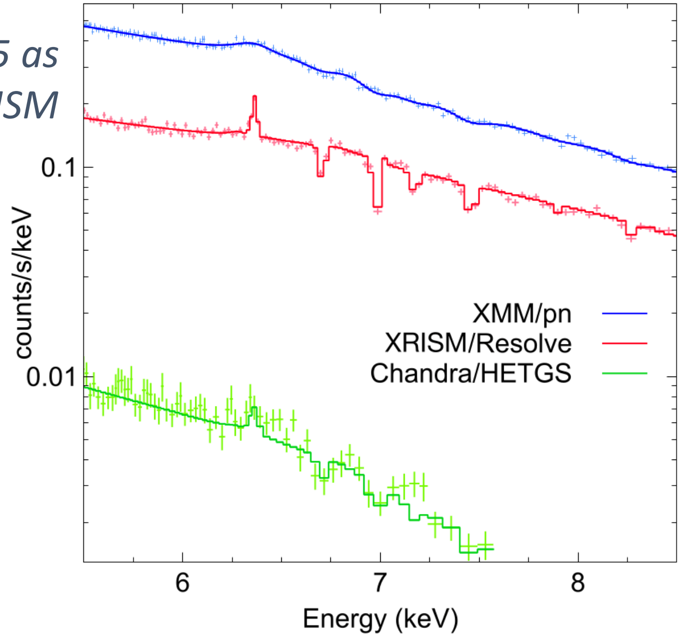

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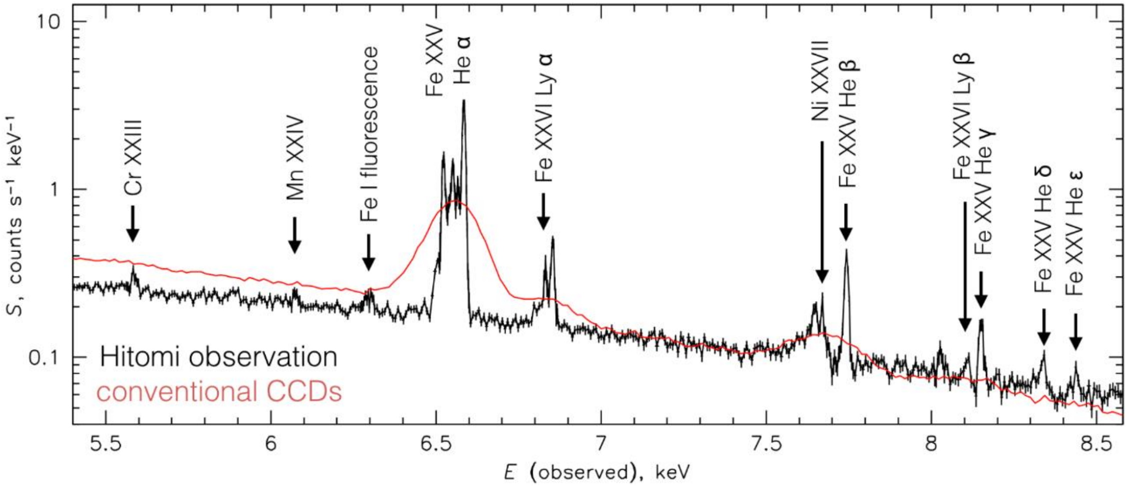


The Perseus cluster X-ray spectrum with CCD-like resolution and with XRISM microcalorimeters

Time-evolving codes will (soon!) be necessary to meaningfully analyse observed spectra and to gain new insights from the data.

Present codes are at a prototypical stage:

i. they are <u>numerically fragile</u> (prone to non-convergence, need very high temporal resolution and oversampling)

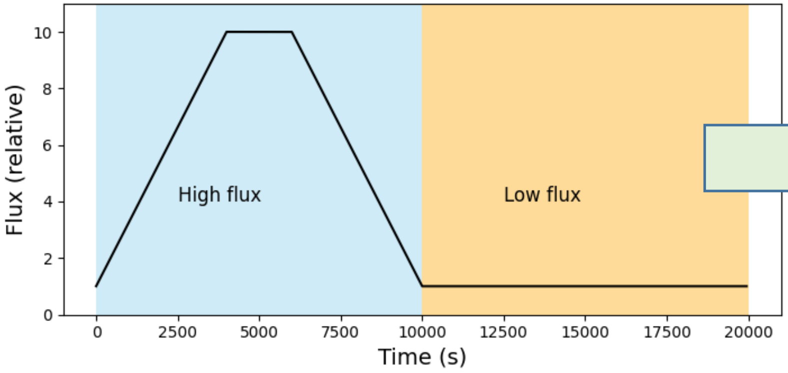
ii. <u>cannot accurately propagate</u> radiation through the gas cloud

iii. do not have any <u>predictive power</u> (i.e. you have to integrate over all the timespan to properly follow the time evolving photoionisation)

iii. Current efforts. TEPID

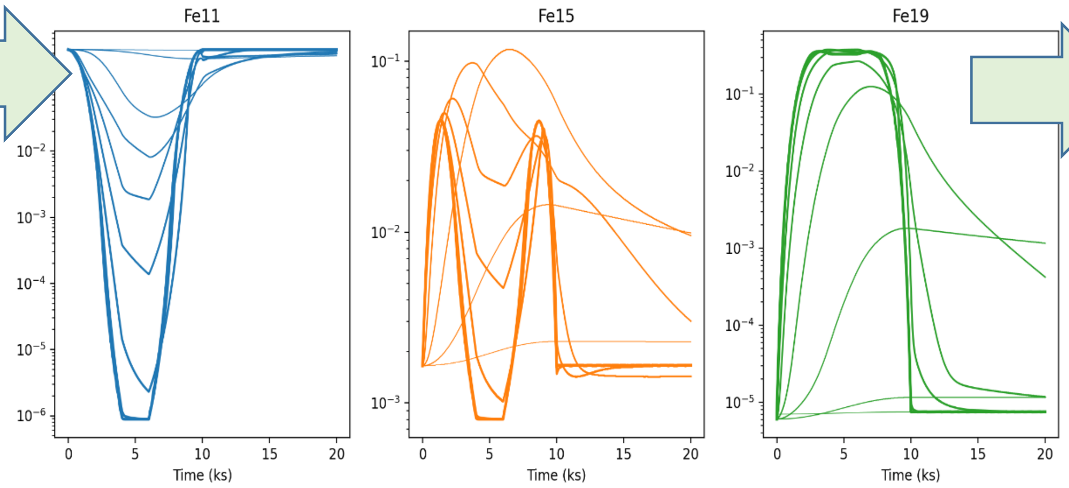
Work flow of TEPID:

1. Initial conditions:



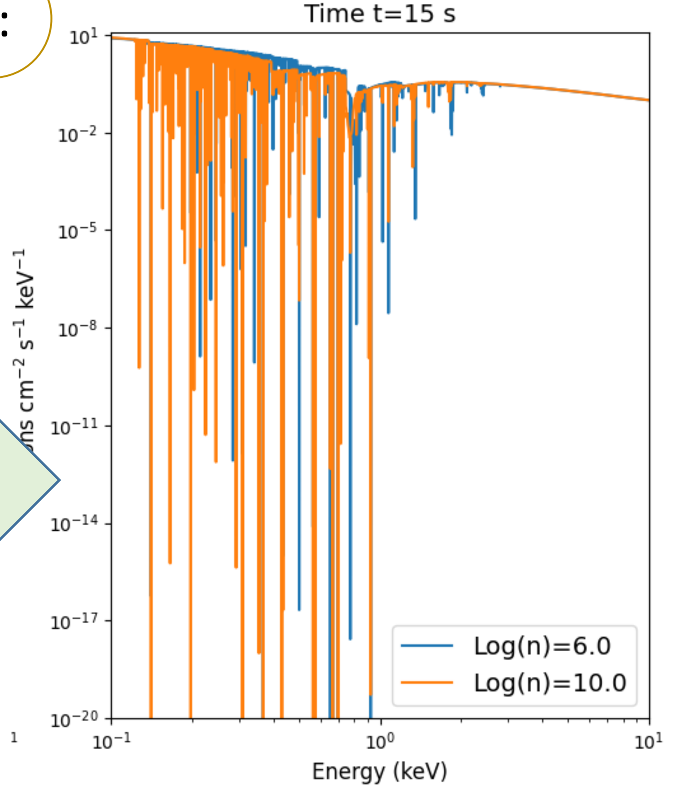
i. Lightcurve
ii. Gas density n_e
iii. Initial $\log(\xi)$

2. Time evolving computation:



Temporal evolution of the gas ionisation n_{X^i} and temperature T

3. Absorption spectrum:



Time-resolved X-ray spectra as a function of n_e and the other gas properties *iii. TEPID* 1. Initial conditions

Temporal resolution

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

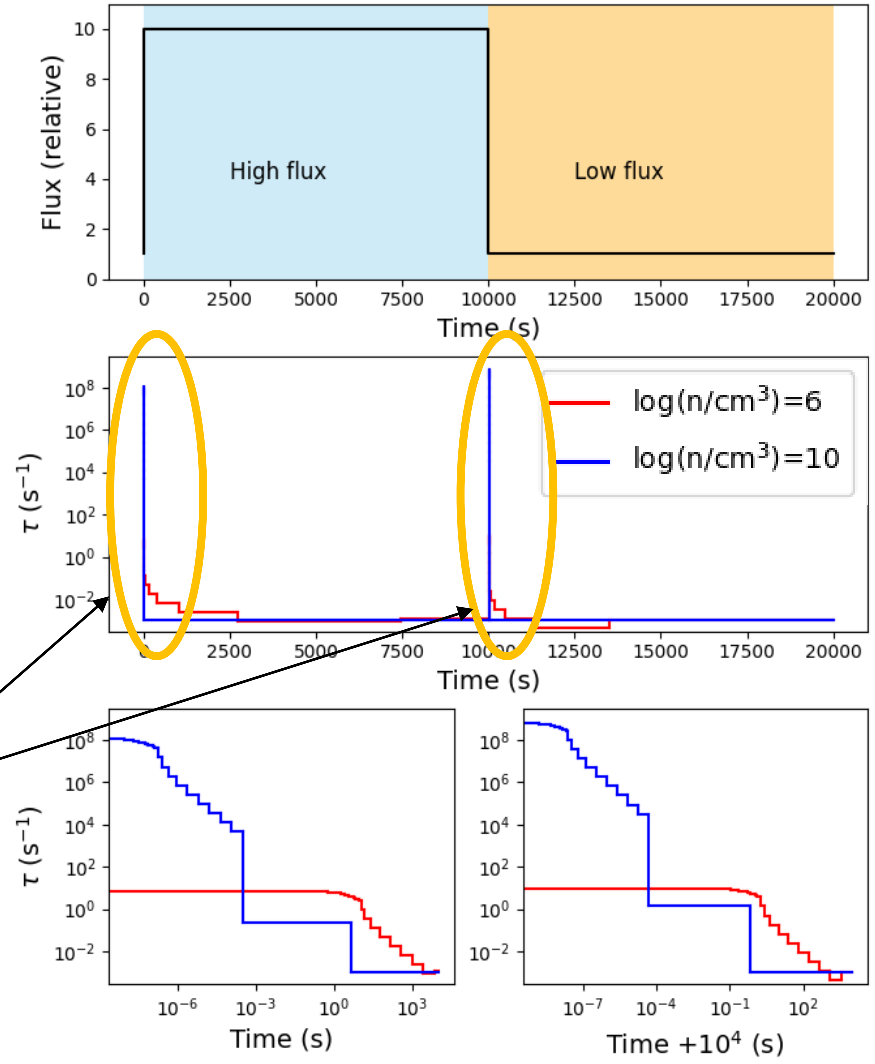
i) Lightcurve

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

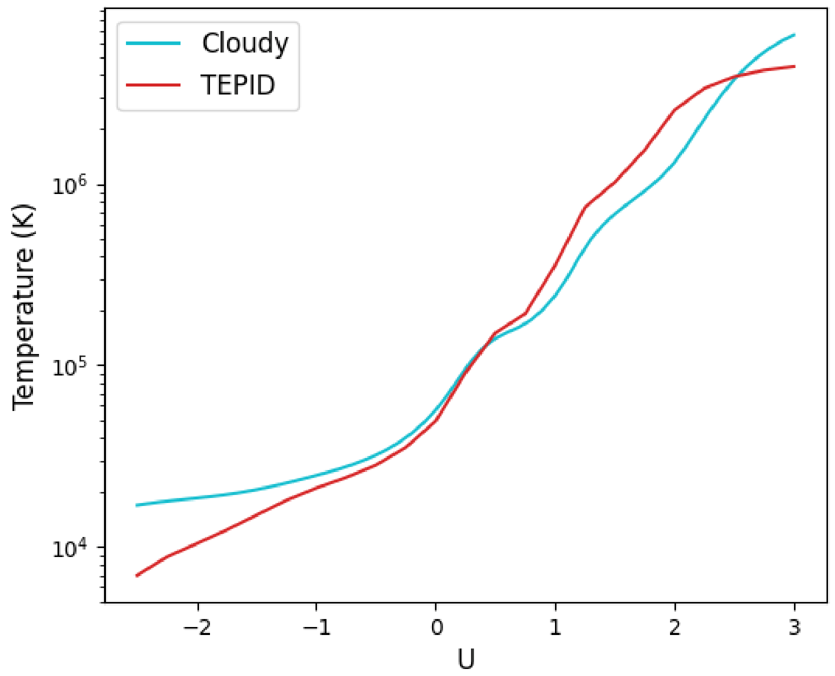
2. Resolution $\omega \propto 1/\mathrm{t_{err}}$ (error on numerical integration)
   Lower density → slower gas reaction → lower ω
   Higher density → faster gas reaction → higher ω



iii. TEPID

1. Initial conditions

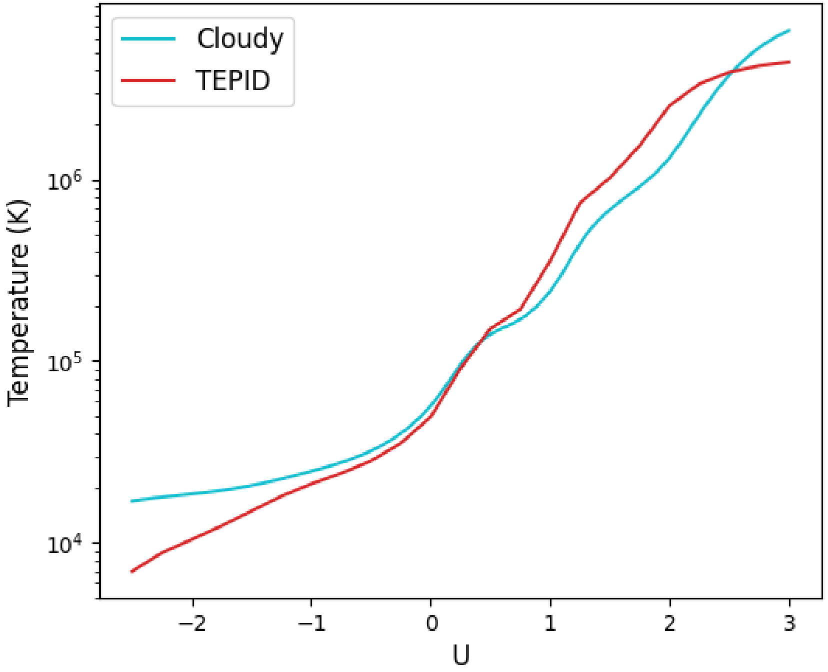
To compute the initial temperature and ionic abundances, TEPID assumes ionisation equilibrium at $t = 0$:



Note: fixed $U = \frac{Q_{ion}}{r^2 n}$ implies higher $\frac{Q_{ion}}{r^2}$ for high n, and viceversa

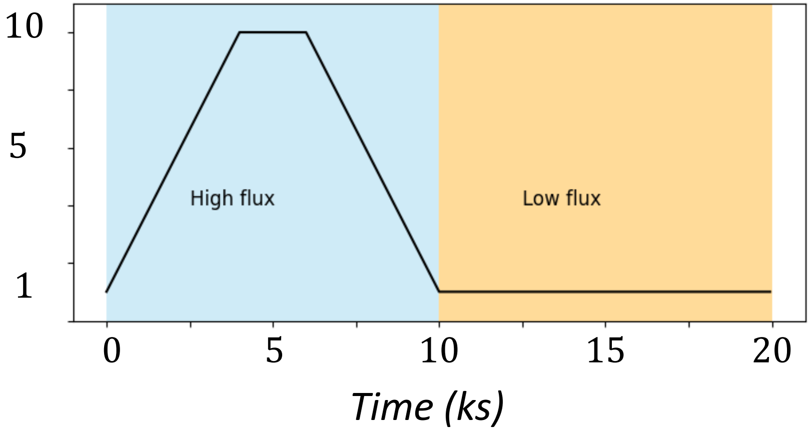
iii. TEPID 1. Initial conditions

To compute the initial temperature and ionic abundances, TEPID assumes ionisation equilibrium at $t = 0$:



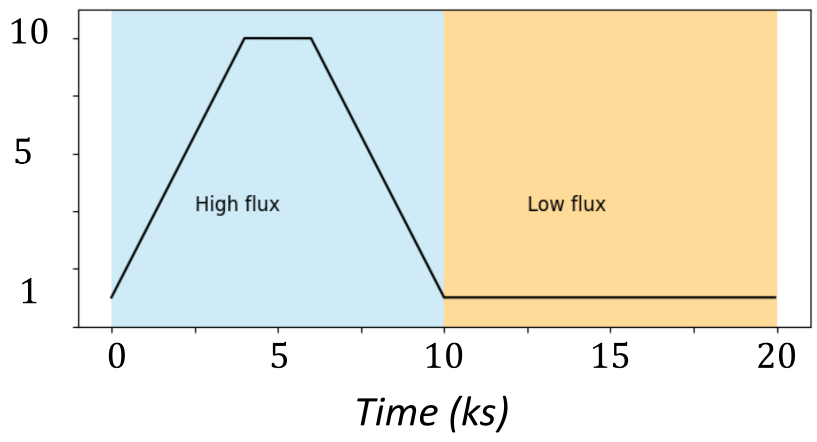
+

The lightcurve dictates the temporal evolution of the impinging radiation:



iii. TEPID

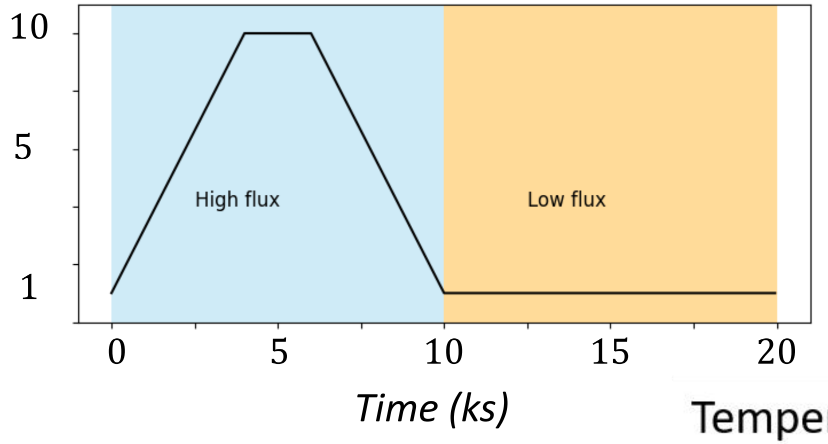
2. Time evolving computation:



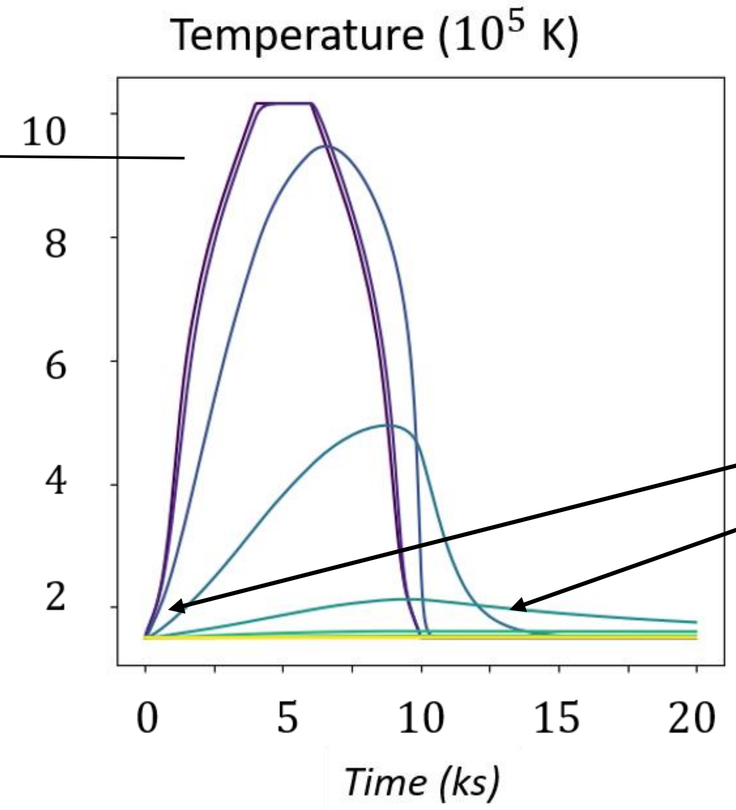
Once initial conditions are set, computation is performed via *brute force*: first-order integration of the set of differential equations with "sufficiently small" temporal resolution, over all the time interval.

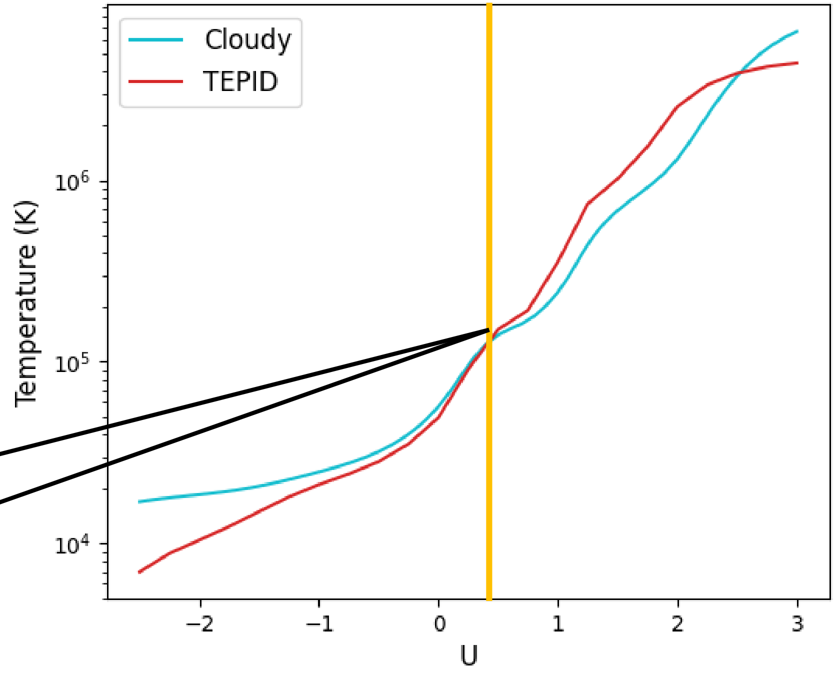
iii. TEPID

2. Time evolving computation:



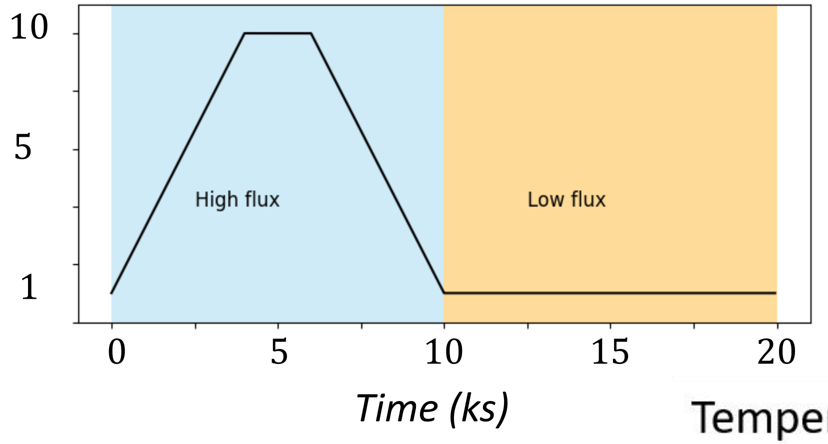
$n_e = 10^{12} cm^{-3}$:
instantaneous response (ionisation equilibrium)





iii. TEPID

2. Time evolving computation:



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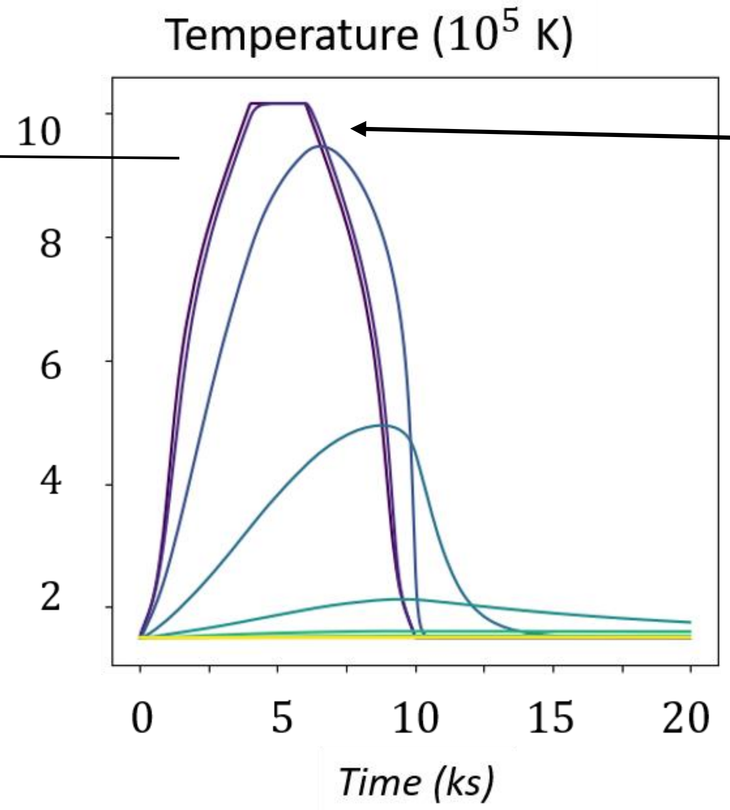
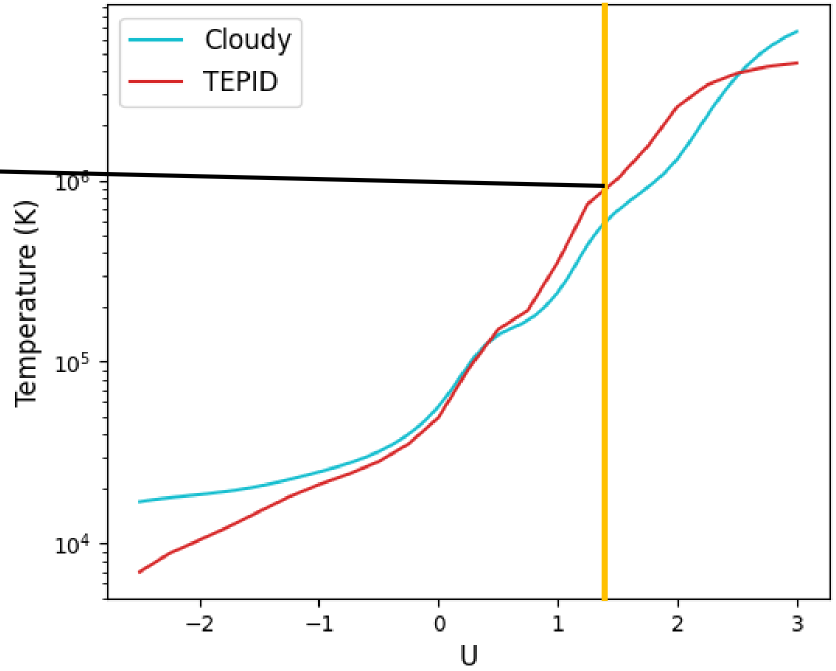
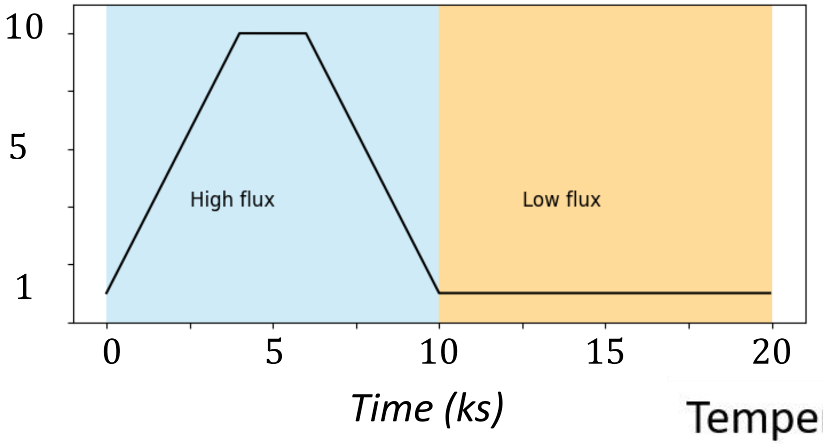
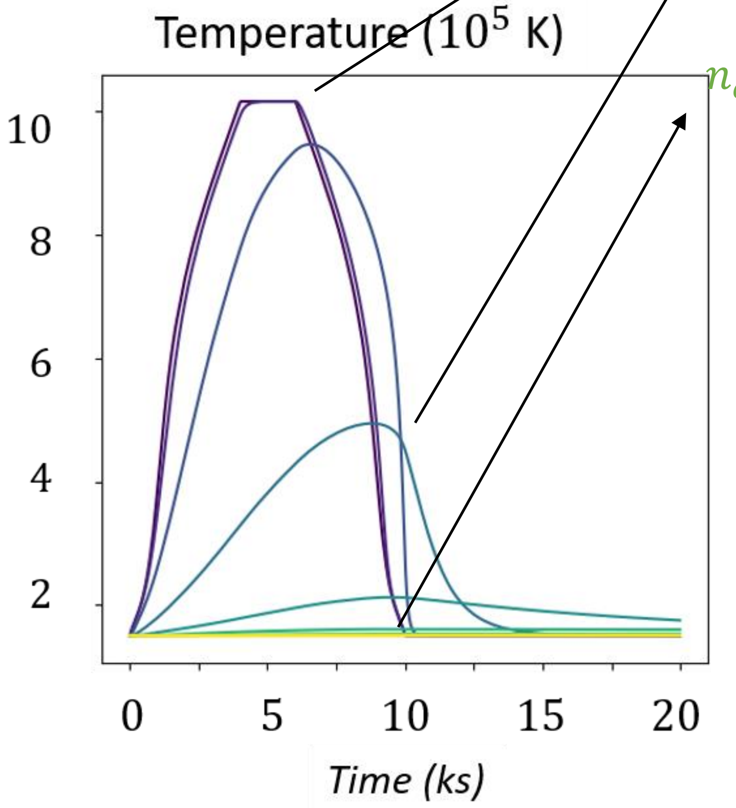




iii. TEPID

2. Time evolving computation:





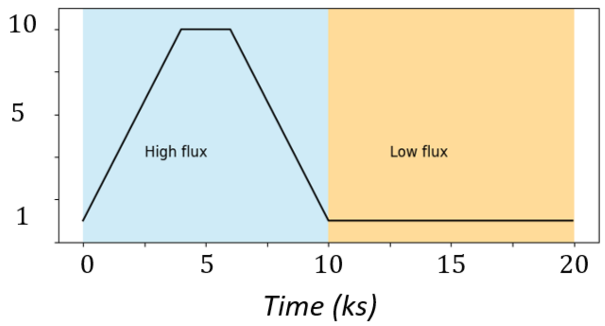
$n_e = 10^{12} cm^{-3}$: *instantaneous response (ionisation equilibrium)*

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

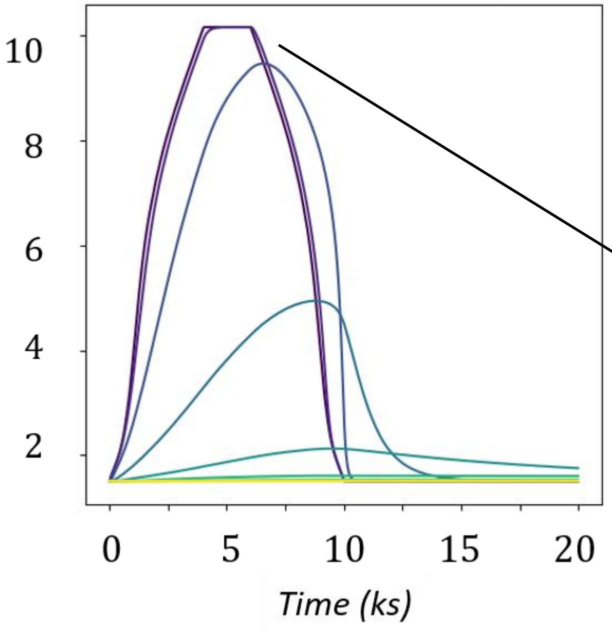
$n_e = 10^{4} cm^{-3}$: *always out of equilibrium (no gas response)*

iii. TEPID

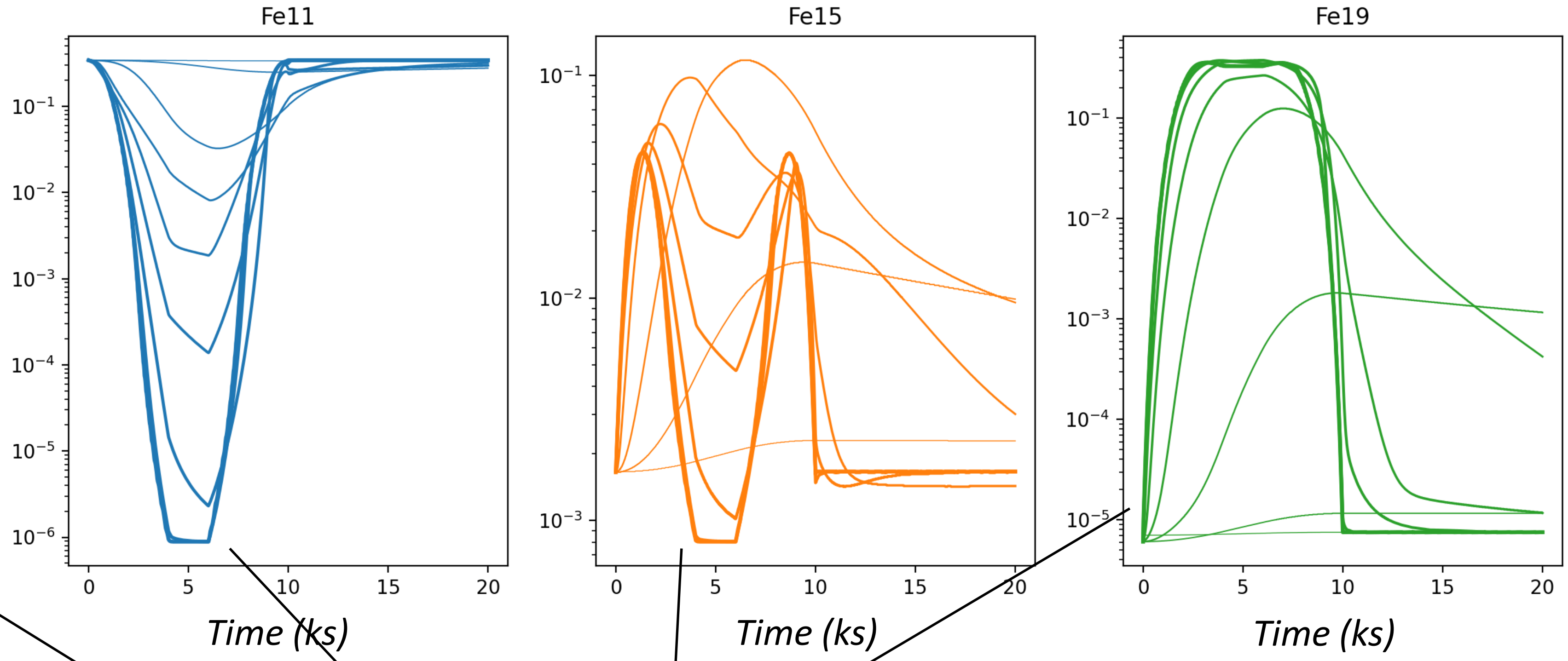
2. Time evolving computation:



Temperature (10^5 K)



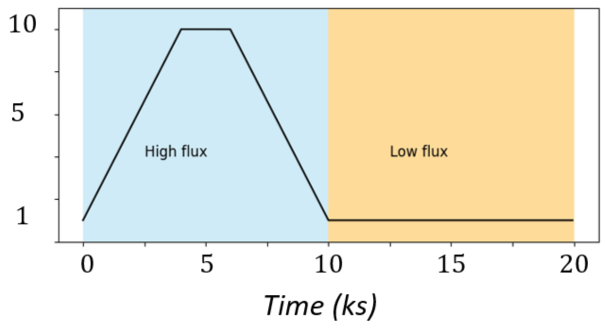
Iron ionic abundances (ratio)



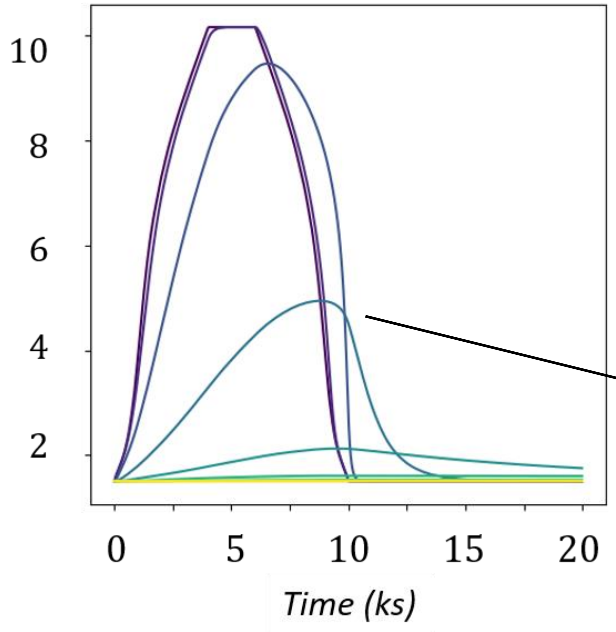
$n_e = 10^{12} cm^{-3}$: temperature and ionic abundances adjust instantaneously to the lightcurve

iii. TEPID

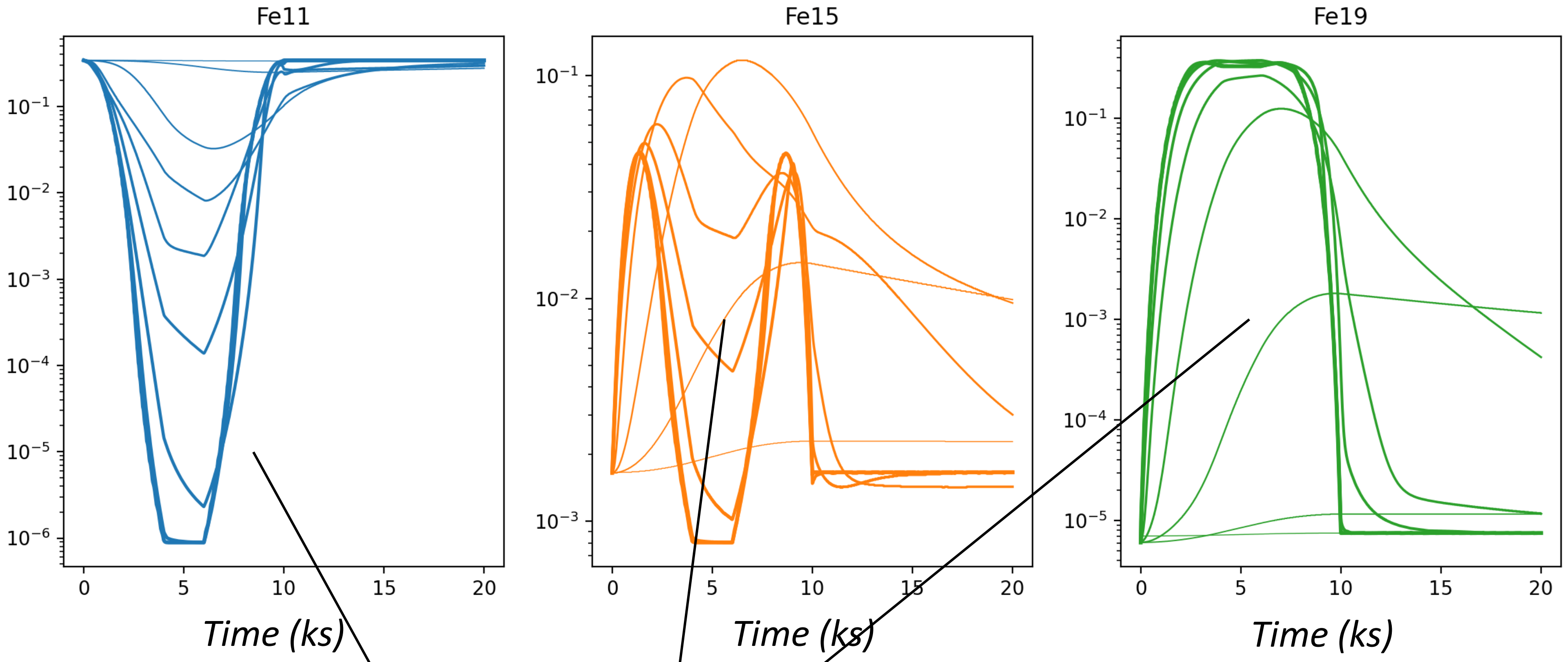
2. Time evolving computation:



Temperature (10^5 K)



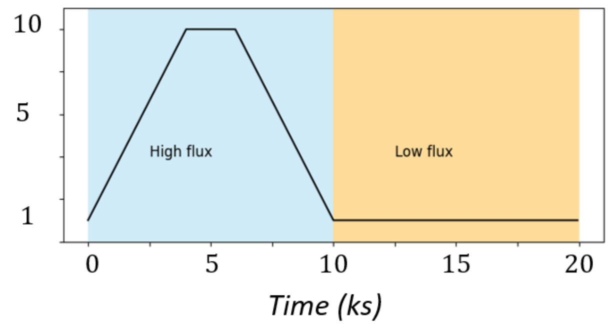
Iron ionic abundances (ratio)



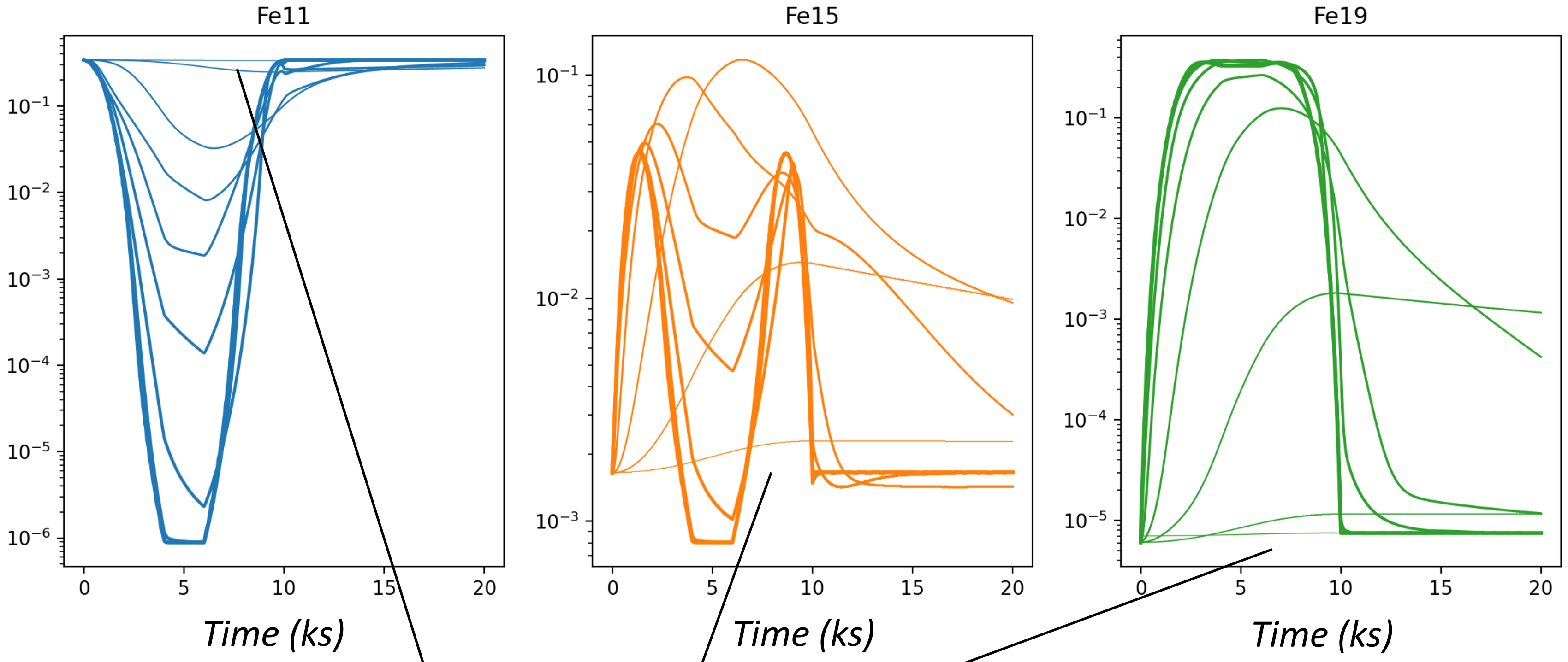
$n_e = 10^6 - 10^{10} cm^{-3}$: gas response to the lightcurve is *damped* and *delayed*

iii. TEPID

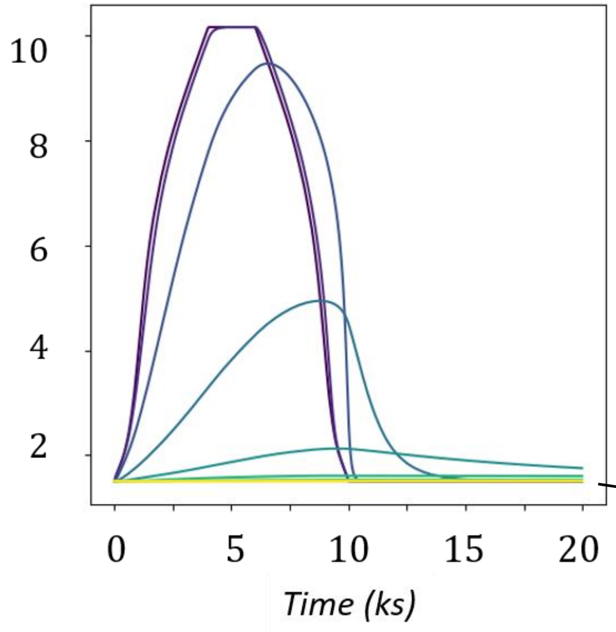
2. Time evolving computation:



Iron ionic abundances (ratio)



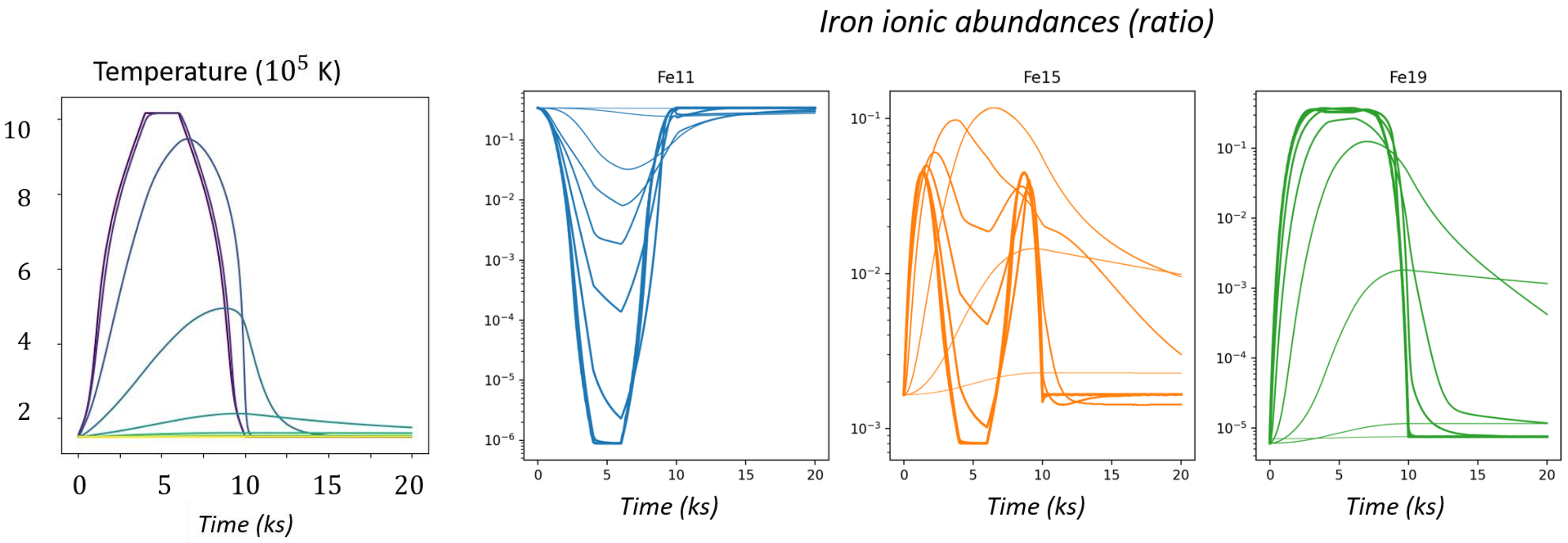
Temperature (10^5 K)



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

iii. TEPID

2. Time evolving computation:



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

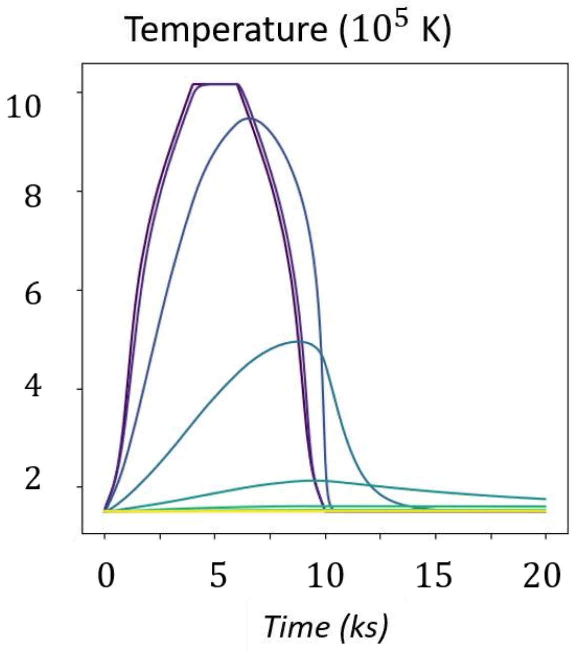
For decreasing n_e the gas response is:

i. Damped: for given L_{ion}, both photoionisation and recombination rates linearly depends on n_e
ii. Delayed: recombination decreases faster than photoionisation, due to its dependence on T (which, in turn, depends on n_{X^i} via the heating/cooling balance)

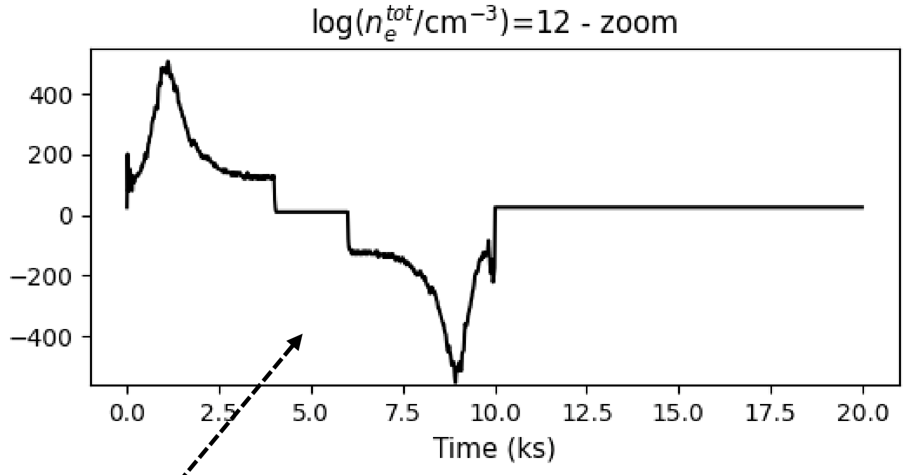
→ gas is over ionised with respect to ionisation equilibrium

iii. TEPID

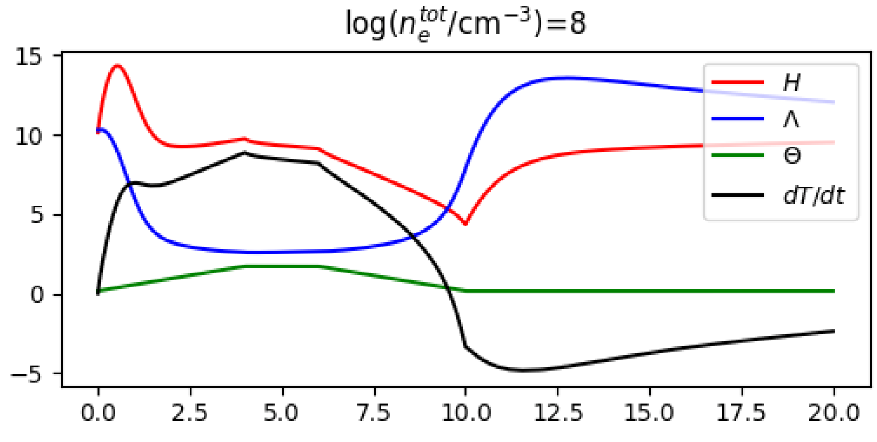
2. Time evolving computation:

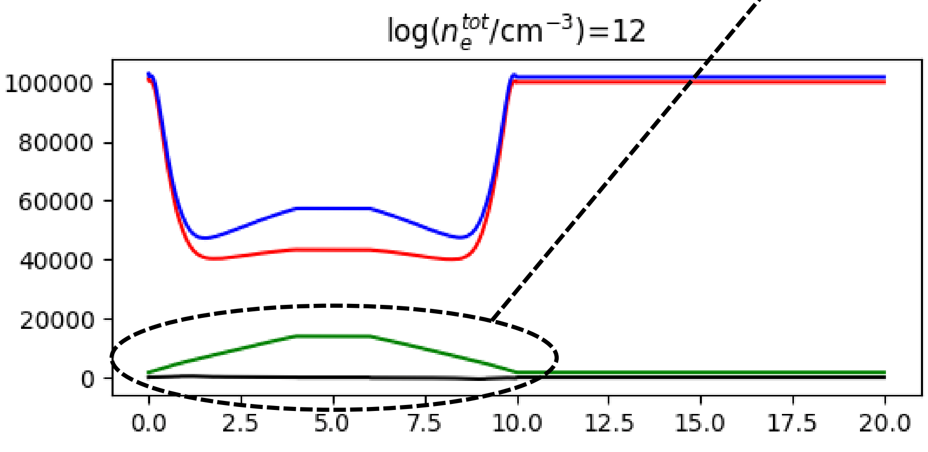


Heating *photonionisation+Auger*
Cooling *gas emission (incl. lines)*
Compton *photon-electron interaction*
Sum *total temperature derivative* $= \frac{dT}{dt}$



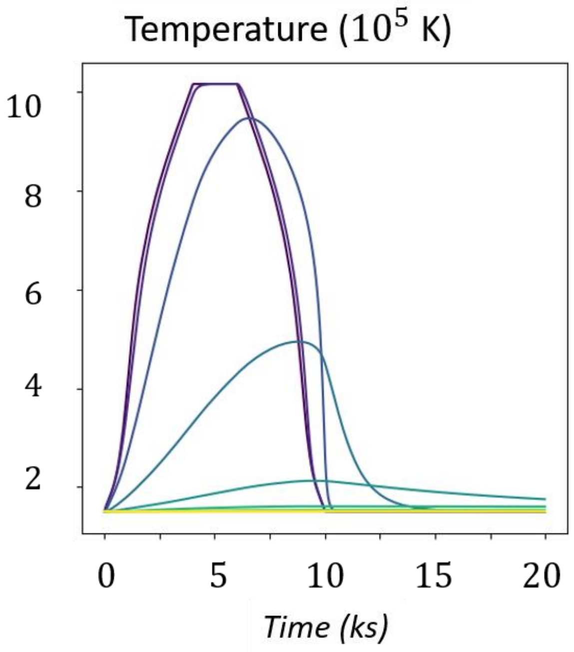
Energy Balance (Kelvin/second):





iii. TEPID

2. Time evolving computation:



Heating *photonionisation+Auger*

Cooling *gas emission (incl. lines)*

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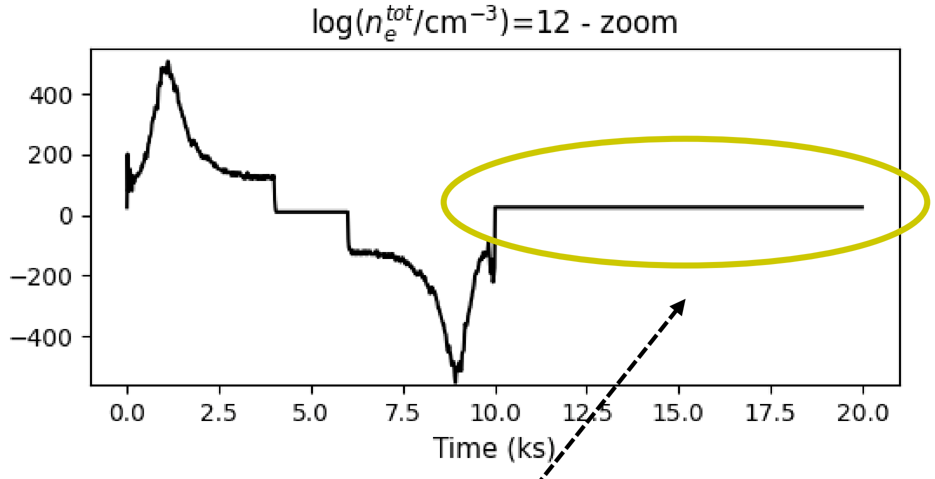
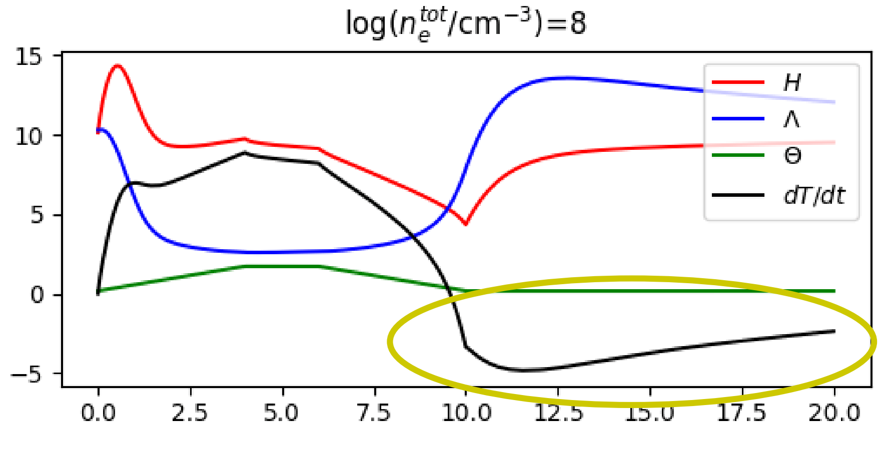
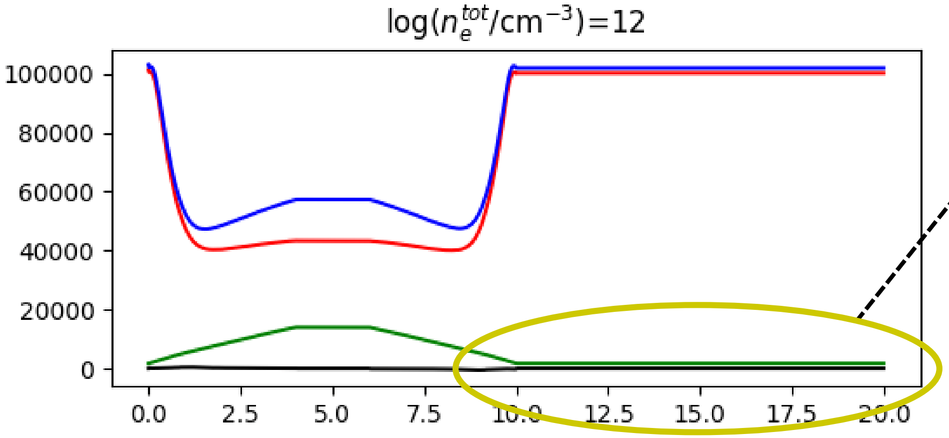


Energy Balance (Kelvin/second):

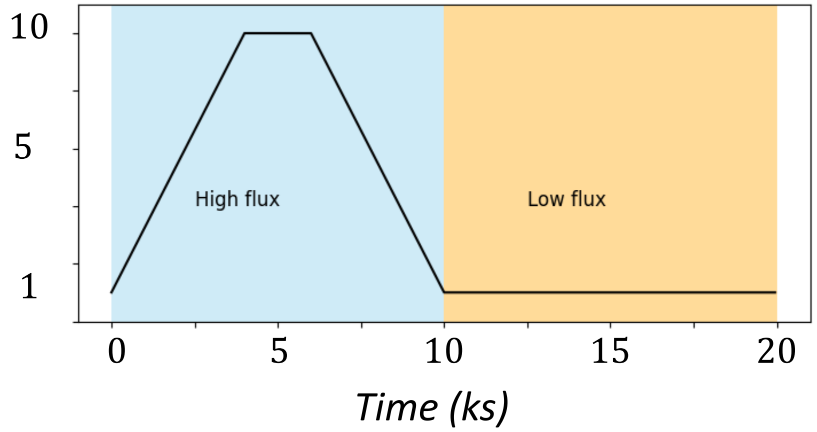


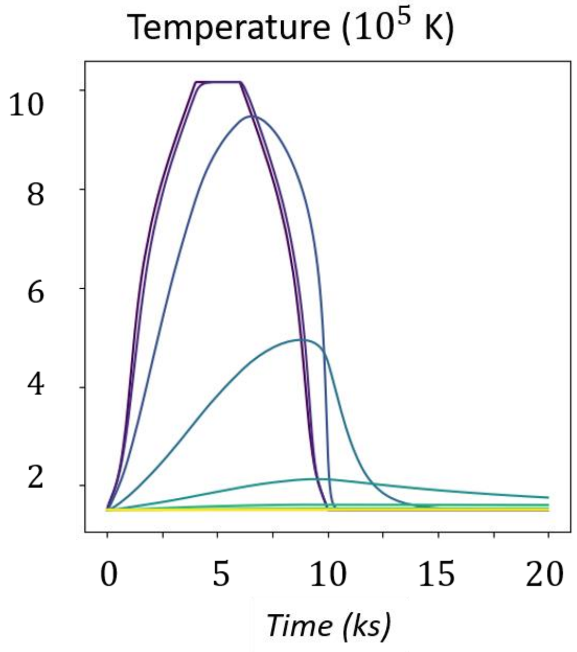


$\frac{dT}{dt} < 0$ when $L_{ion} = const$: gas is over ionised

$\frac{dT}{dt} = 0$: gas is in equilibrium

iii. Can we do (statistically) better?





From a mathematical point of view, time-evolving photoionisation is a set of non-linear differential equations:

$$
\begin{cases}
n_{X^i}(t=0) = n_{X^i}(t_0) \\
T(t=0) = T_0 \\
Q_{ion}(t) \text{ given by the lightcurve} \\
\\
n_{X^i}(t) = f(n_X, T, Q_{ion}) \\
T = f(T, n_X)
\end{cases}
$$

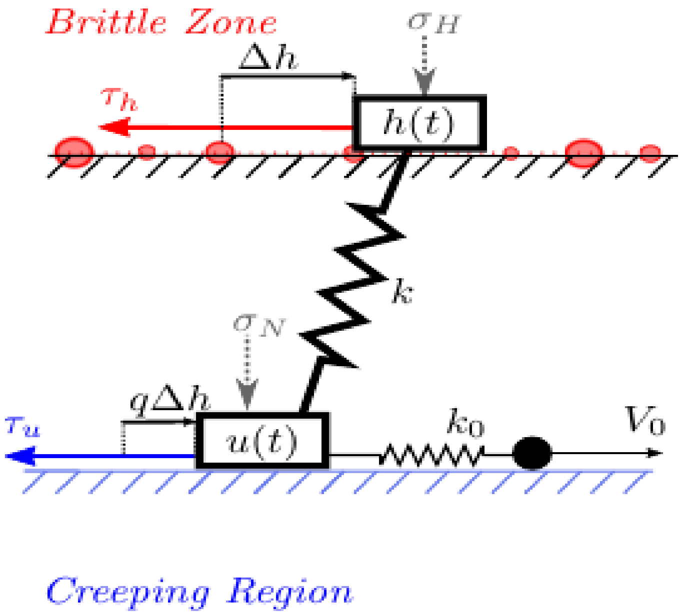
However, the evolution is marginally constrained and the space phase is finite:

i. Temperature variation range is always within the photoionisation equilibrium limit
ii. Gas is always in-between totally neutral and totally ionised
iii. Gas goes towards equilibrium ionic abundances, but following non-equilibrium trajectories in the $T - n_X$ hyperplane due to the mutual dependence between these terms

iii. Can we do (statistically) better?

Courtesy E. Lippiello – Thanks!!

Two block model (Lippiello et al. 2018)



Photoionisation

Recombination

Separation of time scales

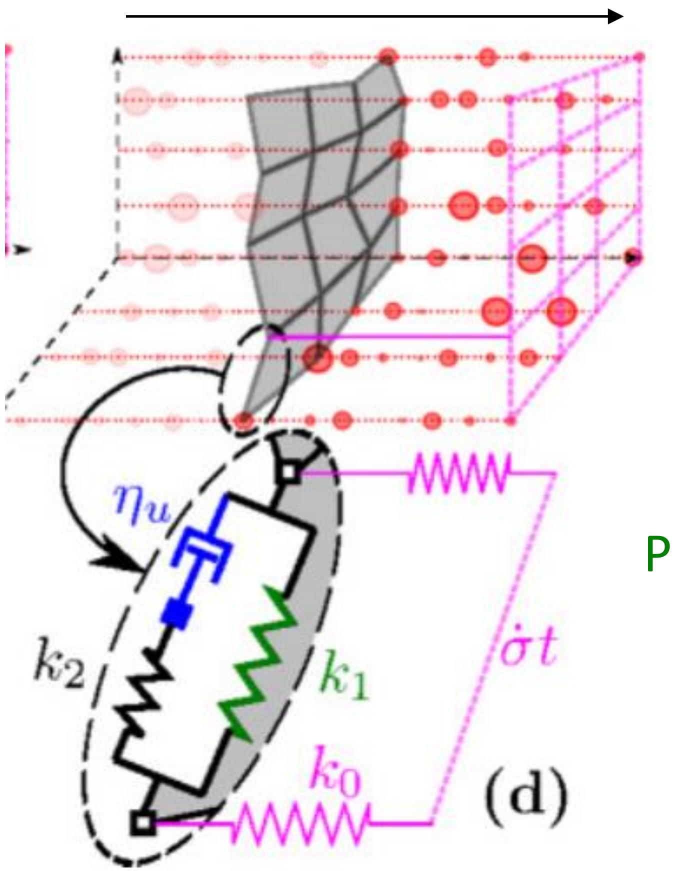
- Strain accumulation rate cm/year → Recombination rate
- Post seismic defomation velocity cm/day → Photoionisation rate
- Strain propagation velocity km/sec → Luminosity variation

iii. Can we do (statistically) better?

Courtesy E. Lippiello – Thanks!!

The Viscoelastic or 2L qEW model

Time arrow



Luminosity variation

Photoionisation rate

Recombination rate