The WINE photoionisation and spectroscopic model

*W*inds in the *I*onised *N*uclear *E*nvironment

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In collaboration with:

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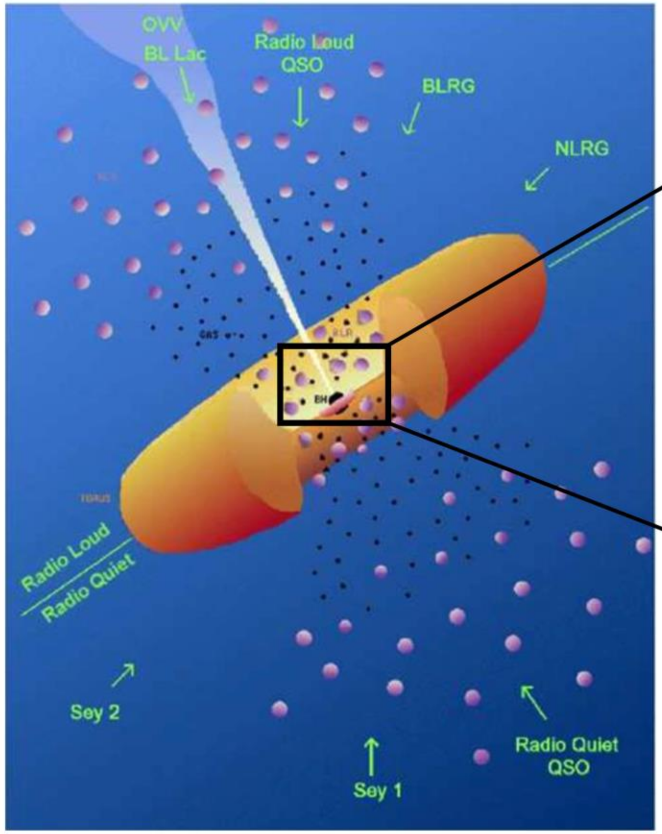
The WINE model

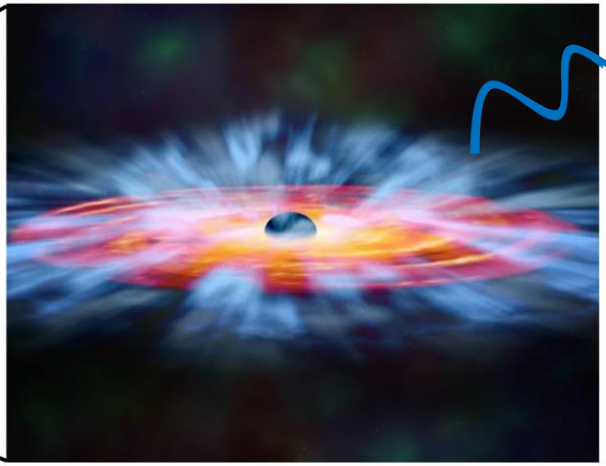
Outline

i. *X-ray Outflows in AGNs: where we stand now*
ii. *The WINE photoionisation model:*
    a. *Radiative transfer*
    b. *Relativistic effects*
iii. *WINE at play:*
    a. *Location, geometry and energetic of the UFO in PG1448+273*
    b. *The variable 0.3 c UFO in the low-luminosity Seyfert NGC 2992*
iv. *Conclusions*

i. X-ray Ultra Fast Outflows in AGNs: where we stand now

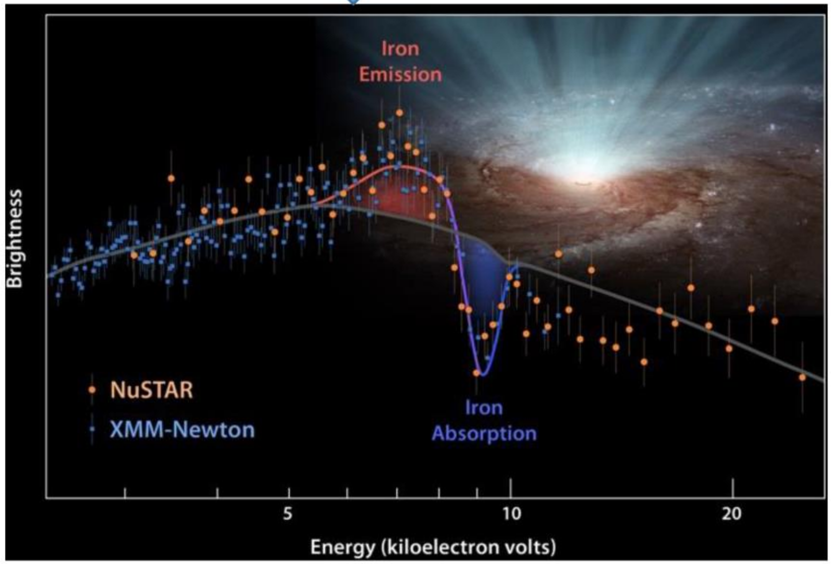
AGN





Accretion disk

X-ray spectrum

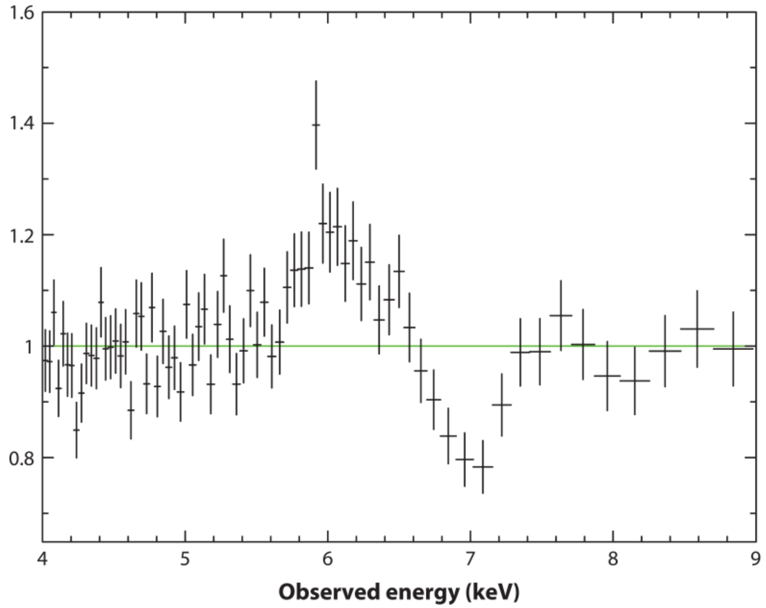


P-Cygni profile (PDS456; Nardini+15)

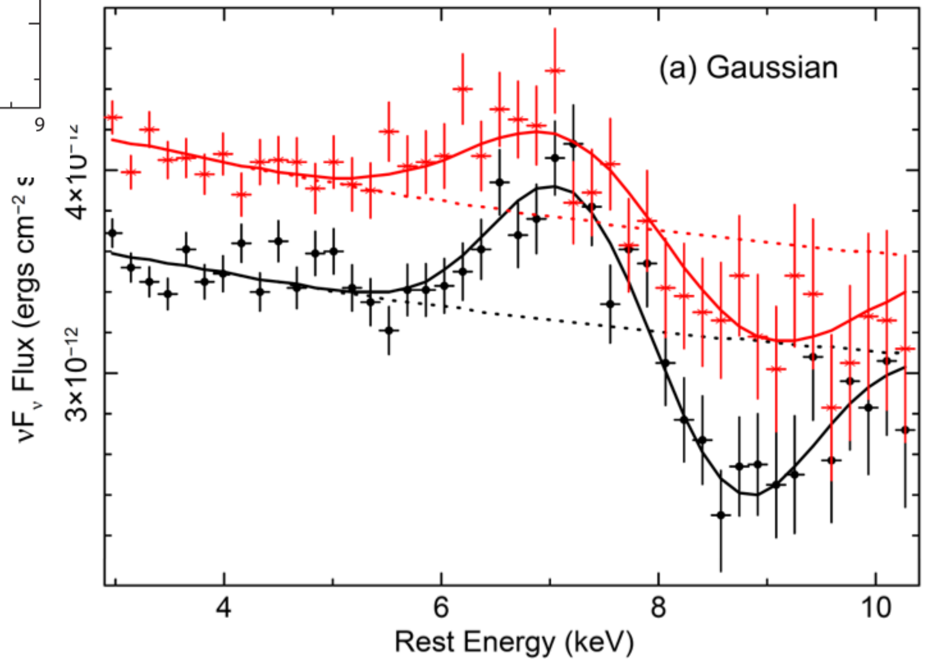
Relativistic winds at accretion disk scales.
Observed through spectroscopy, as blueshifted absorption/emission imprinted on the continuum spectrum of the AGN, mainly at $E \geq 5\ keV$

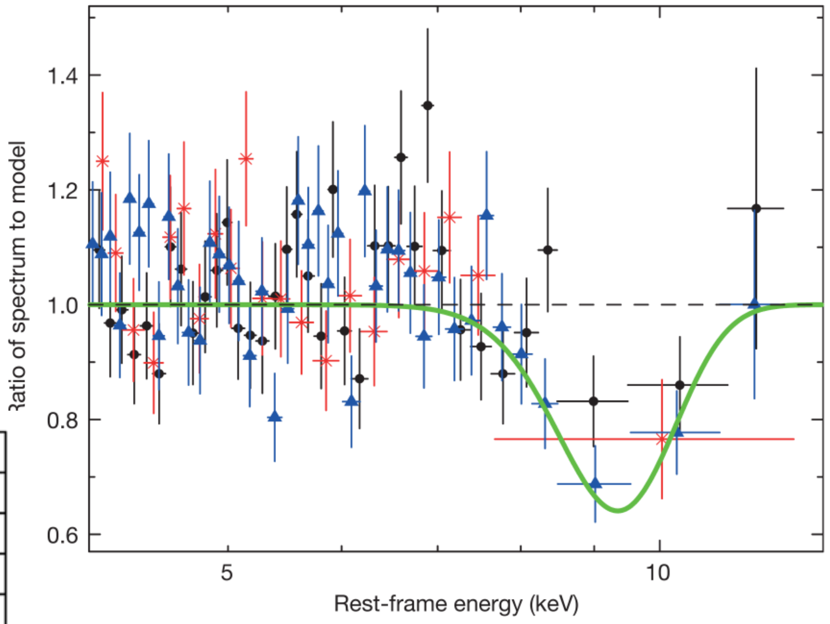
i. X-ray UFO in AGNs

Emission/absorption features imprinted on the $4-10\ keV$ spectrum:



PG 1211+143: $v_{out} = 0.15\ c$
(Pounds+09)





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

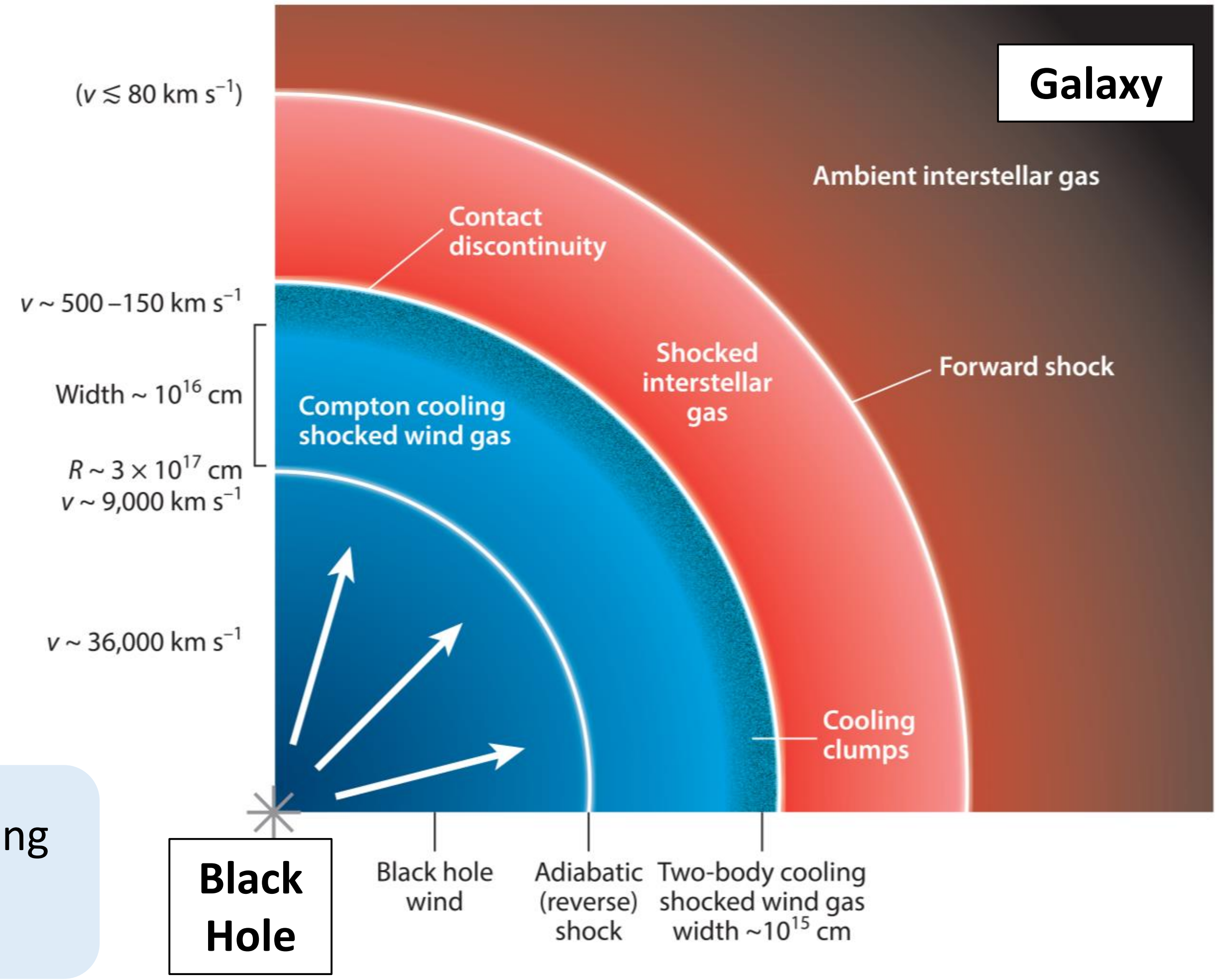
I Zwicky1: $v_{out} = 0.27\ c$
(Reeves+19)

i. X-ray UFO in AGNs

Key properties:

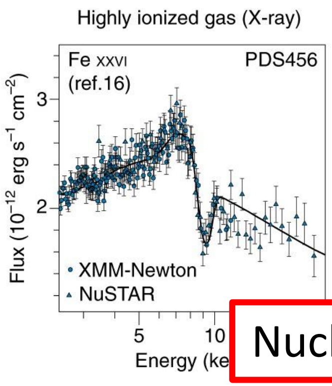
- Outflowing velocity $v_{out} = 0.1 - 0.4\ c$
- Column density $N_H = 10^{22} - 10^{24}\ cm^{-2}$
- Opening angle $\theta = 45 - 60\ deg$
- Energy flux $\dot{E}_{out}$ up to $20 - 40\%\ L_{AGN}$

__FEEDBACK__: UFO expands to the host galaxy, sweeping its gas reservoir and quenching star formation

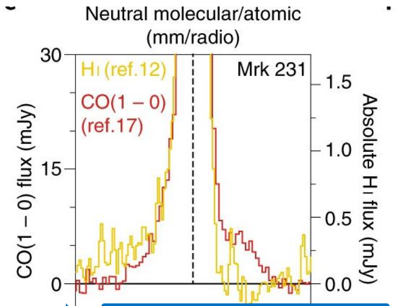


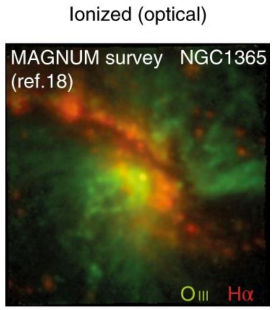
Fiore+17, King & Pounds 15 , Di Matteo+05, Faucher-Giguère+12, Menci+19, Tombesi+10,+13

i. Why do we need UFOs?



Nuclear → … → Galaxy-scale





Two-phase model:

1. Momentum driven outflow

shock front is cooled -> thermal energy is lost, only wind momentum is conserved

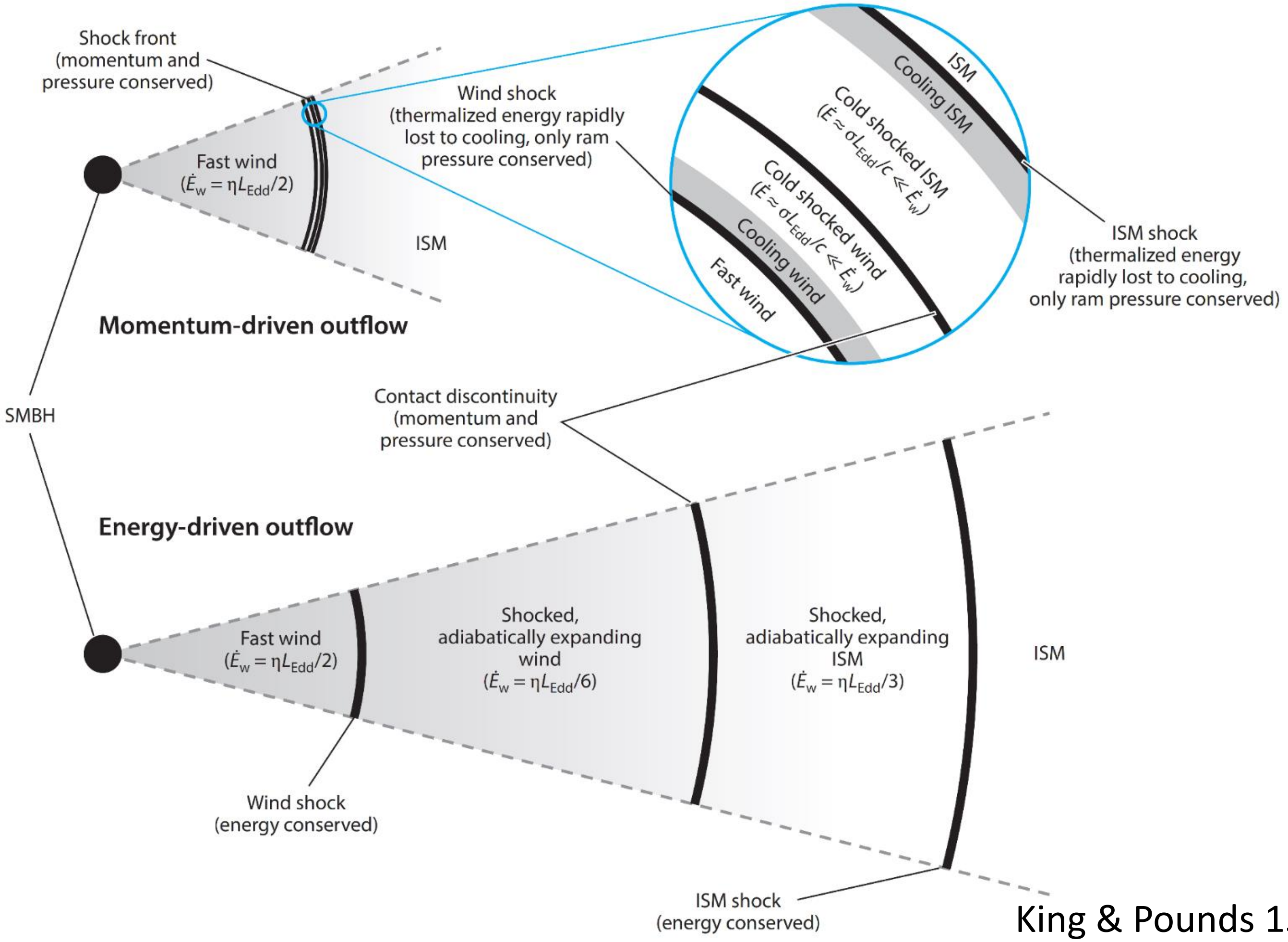
$$\rightarrow \dot{P}_{gal} = \dot{P}_{UFO}$$

2. Energy driven outflow

shock front expands adiabatically -> energy is conserved during propagation

$$\rightarrow \dot{E}_{gal} = \dot{E}_{UFO}$$

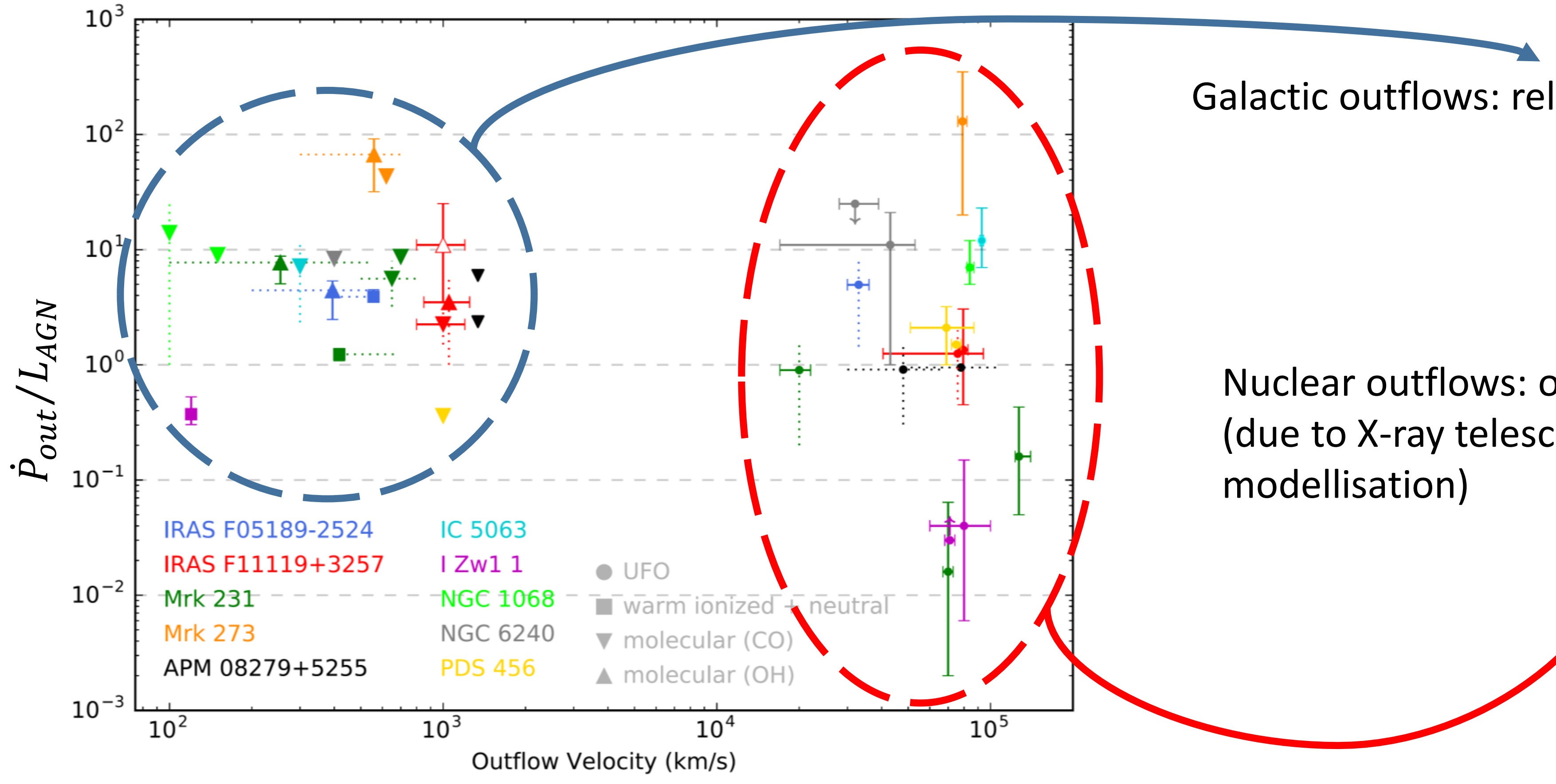
$$\rightarrow \dot{P}_{gal} = \dot{P}_{UFO} \cdot \frac{v_{UFO}}{v_{gal}} \approx 50\, \dot{P}_{UFO}$$



King & Pounds 15

i. Why do we need UFOs?

Energy of galactic and nuclear outflows:



Galactic outflows: relatively small errors

Nuclear outflows: order-of-magnitude errors (due to X-ray telescopes limitations and basic modellisation)

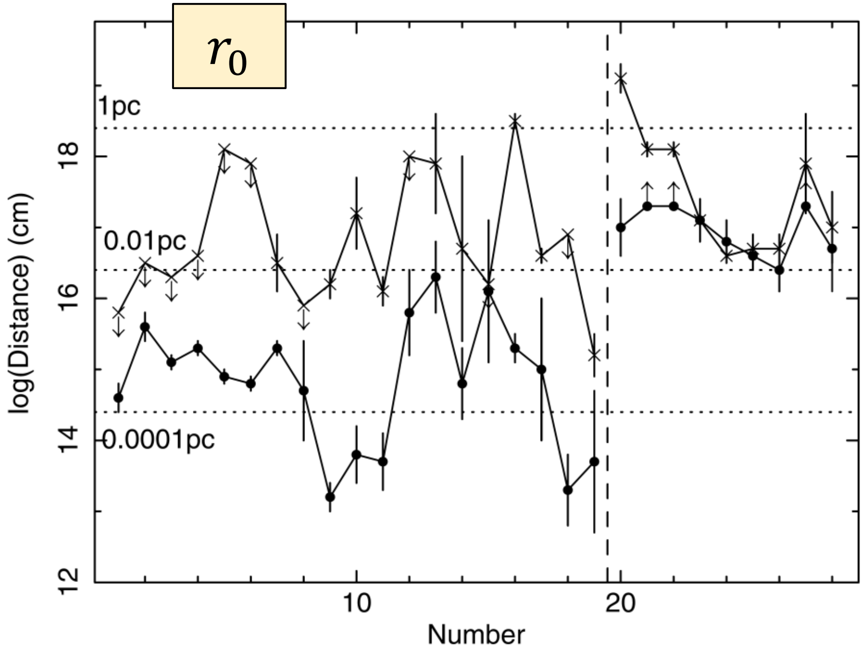
Smith+19

i. Where do we stand now?

Most uncertain quantities

Mass transfer rate is calculated as: $\dot{M}_{out} \propto r_0 C_f N_H v_{out}$

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

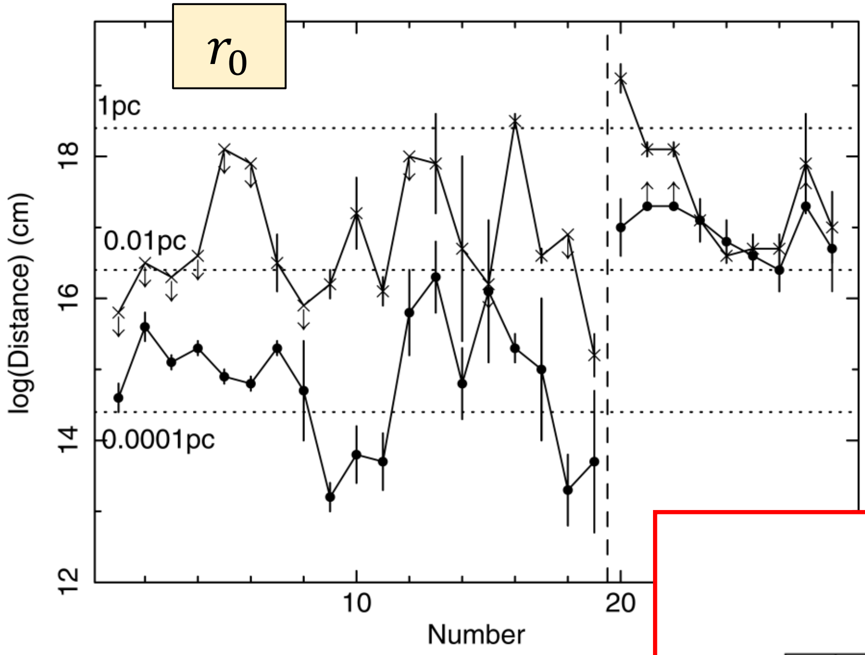


Lower and upper limits
estimated through indirect arguments and assumptions
(e.g. $r_{min} = \frac{2\,G\,M_{BH}}{v^2}$, $r_{max} = \frac{L}{\xi N_H}$)

C_f **Unknown for many UFOs**
assumed from statistical arguments or by phenomenologically fitting wind emission with Gaussian profiles

Tombesi+12, Gofford+15

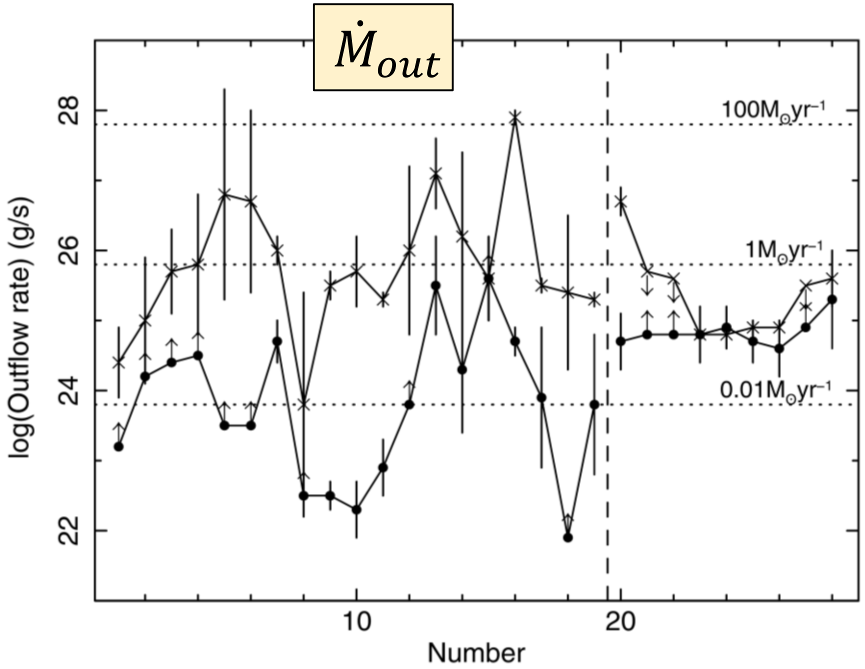
i. Where do we stand now?

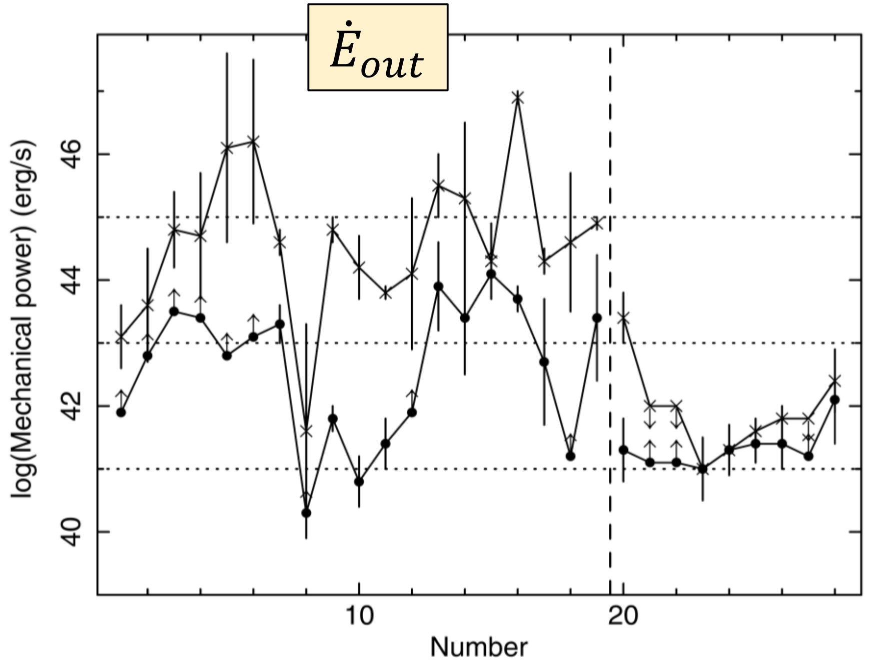


Lower and upper limits
estimated through indirect arguments and assumptions

C_f **Unknown for many UFOs**
statistical arguments or phenomenologically fitting

Wind energetic has order-of-magnitude uncertainties!





Tombesi+12, Gofford+15

ii. The WINE spectroscopic model

Current approach:

General-purpose photoionisation codes (*Cloudy, XSTAR, ...*)

i. Photoionisation simulations **do not accurately reproduce** the properties of the source

ii. Simulated spectra rely on several assumptions on the **geometry** and the **kinematics** of the **wind**

iii. The wind is modeled as a **layer of gas at rest** with turbulent broadened features, which are a posteriori blue-shifted to account for the wind velocity smearing

WINE model

*W*inds in the *I*onised *N*uclear *E*nvironment

i. WINE is a **self-consistent model** for absorption and emission from disk winds. It is highly customizable and can mimic different launching scenarios.

ii. The **physical, kinematical and geometrical parameters** are determined fitting the model to the observed spectra and minimizing the χ^2 statistic

iii. R**elativistic effects** are taken into account in the radiative transfer calculations. Absorption and emission profiles are directly built according to the geometry and velocity profiles.

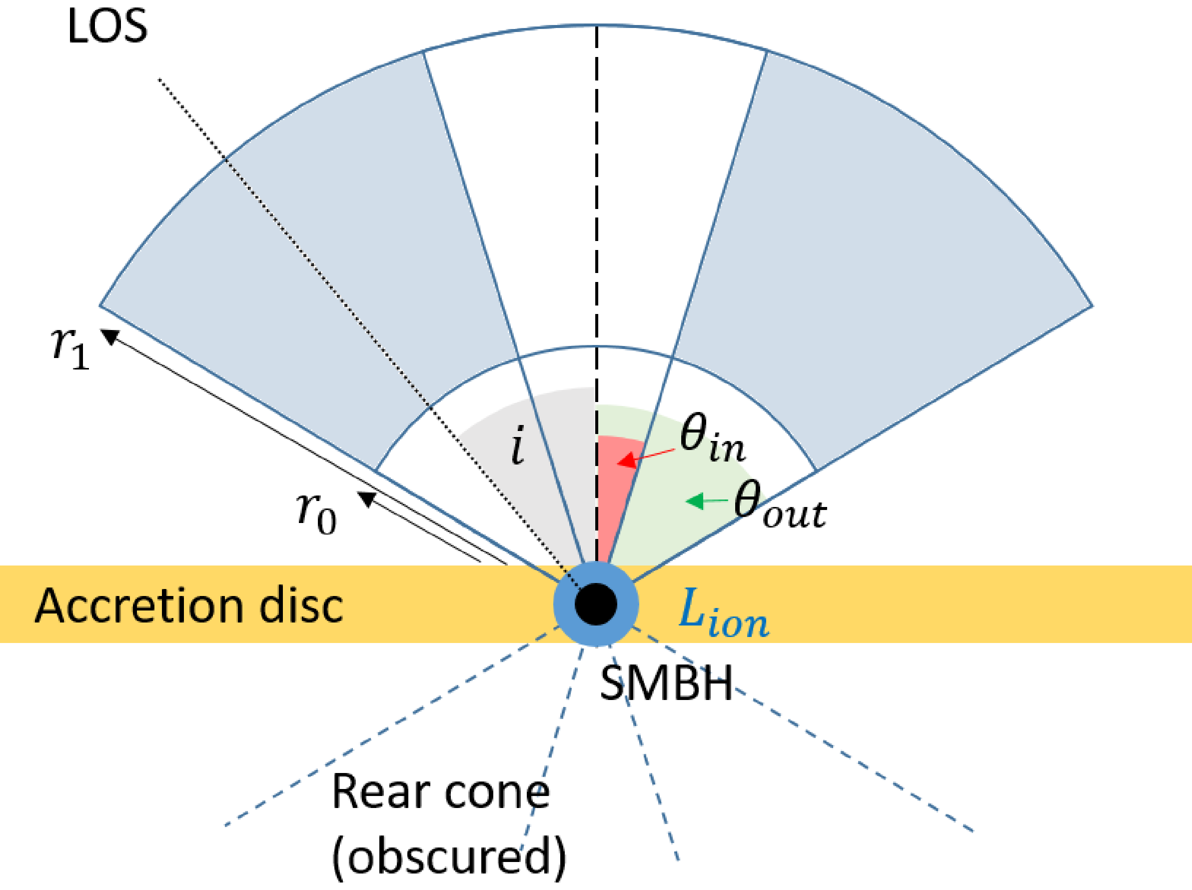
ii. The WINE spectroscopic model

Parameters of the model:

1. Incident spectrum (SED and luminosity)
2. Ionization parameter $\xi(r)$
3. Column density N_H
4. Launching radius r_0
5. Density and velocity profiles:

$$n(r) = n_0 \left(\frac{r_0}{r}\right)^{\alpha}, v(r) = v_0 \left(\frac{r_0}{r}\right)^{\beta}$$

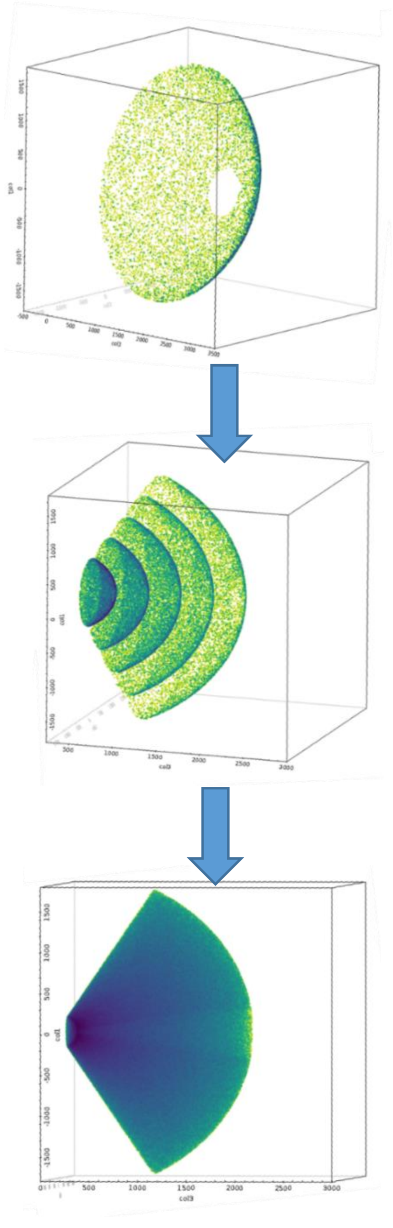
5. Geometry of the source: $\theta_{out}, \ \theta_{in}, i$

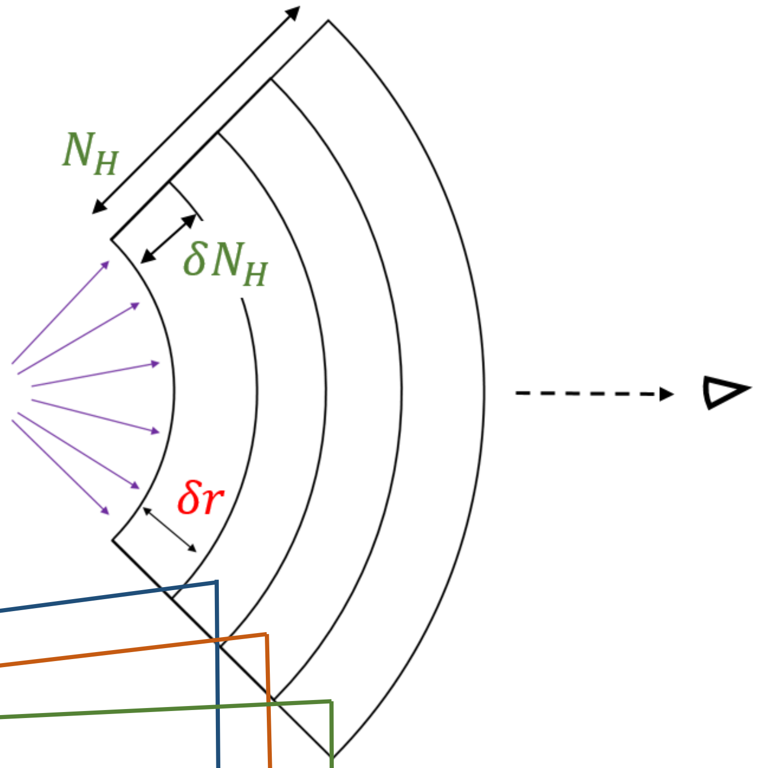


Best-fit values are determined comparing the model with the data and minimizing the χ^2 statistic.

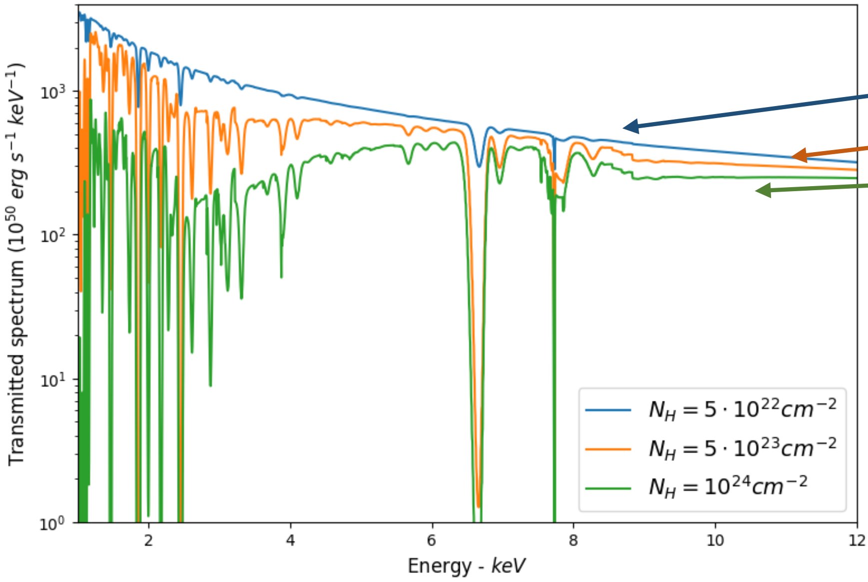
→ C_f , $\dot{M}_{out}$, $\dot{E}_{out}$ are determined self-consistently

ii a. Radiative transfer

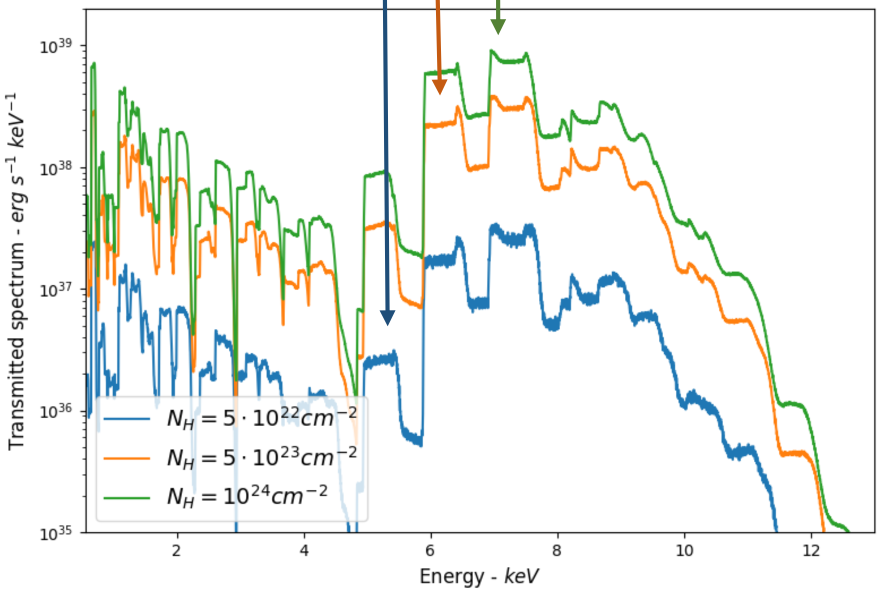




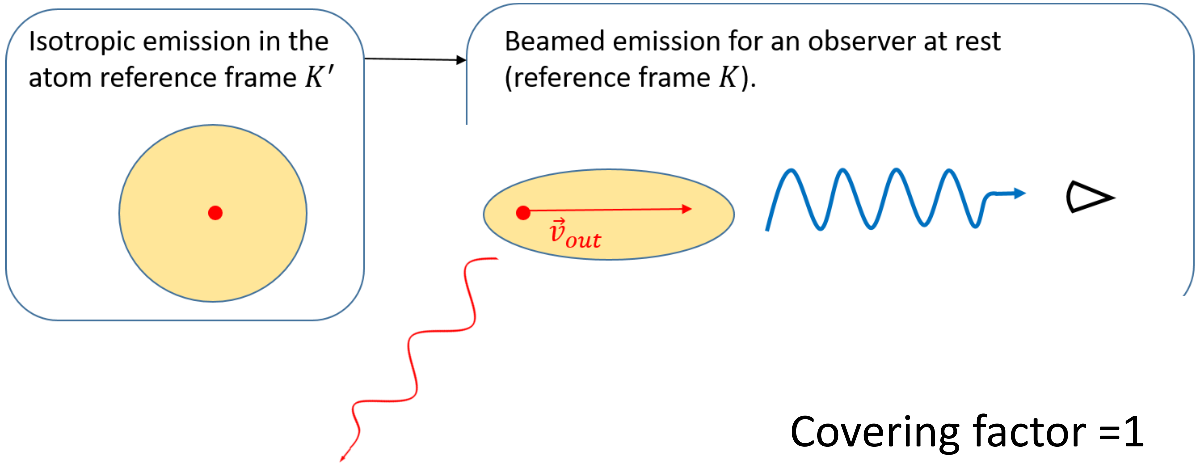
Multi-shell radiative transfer with a public code (e.g. XSTAR) to account for the ionisation, velocity, density profiles



Monte Carlo modellisation of emission profiles

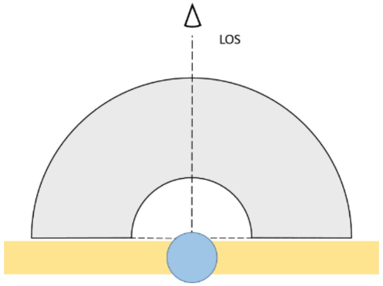


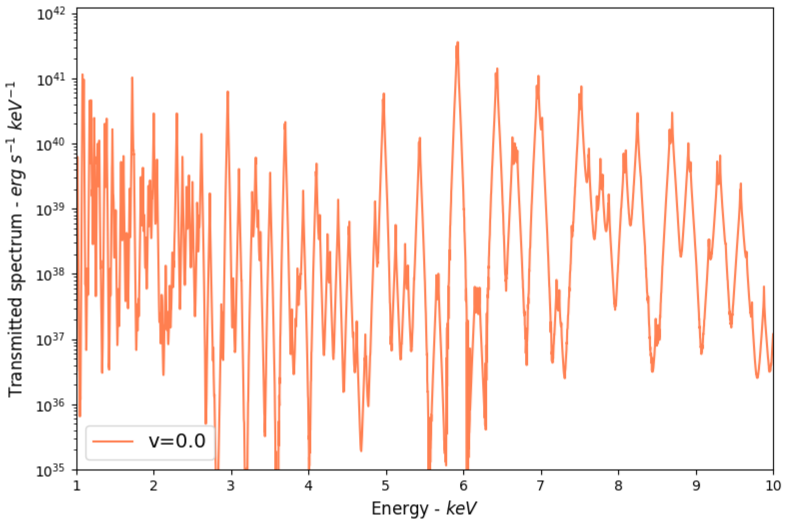
ii b. Relativistic effects



Emission: relativistic beaming

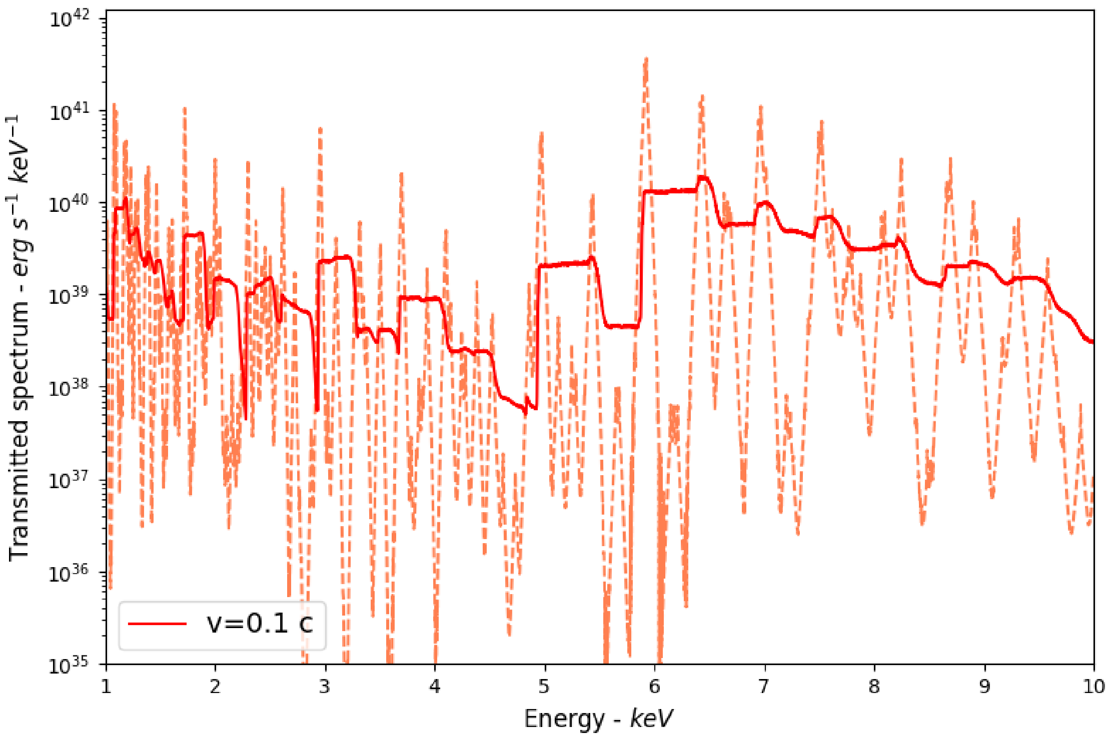
Covering factor =1
$v_0 = 0.0$





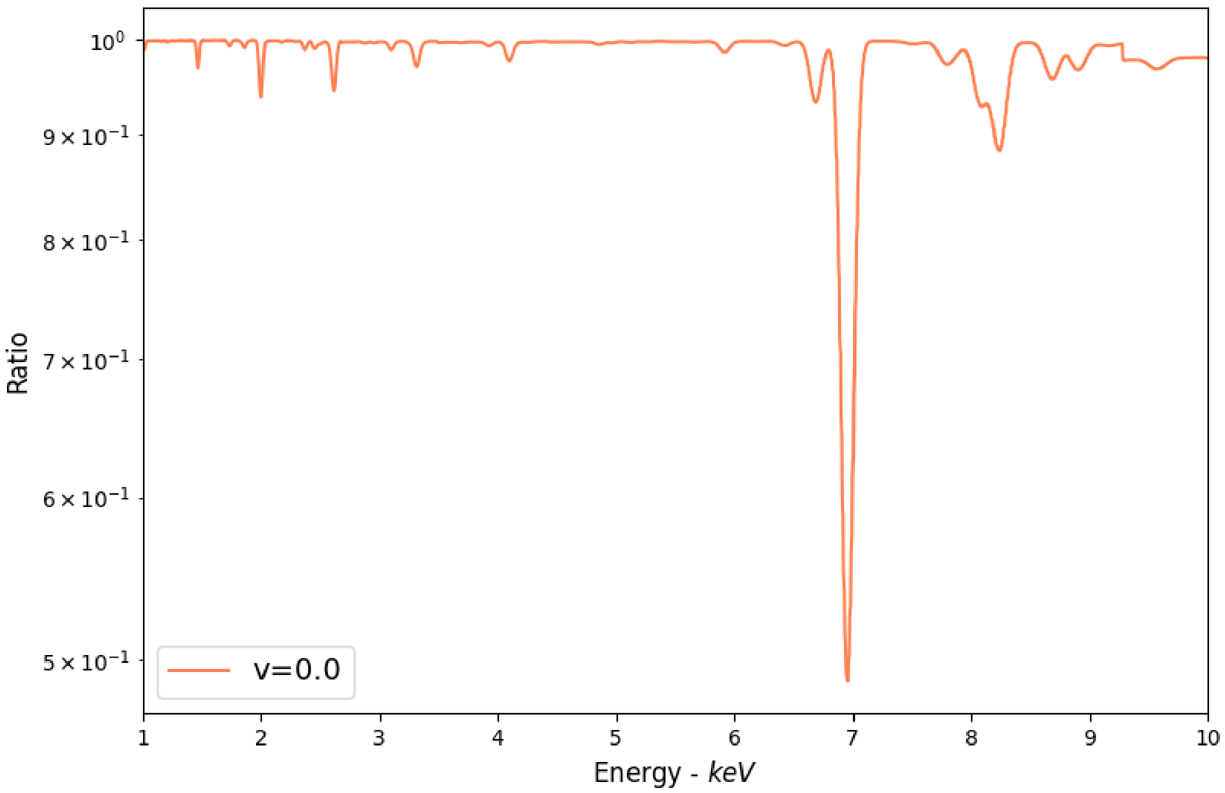
$v_0 = 0.1$ c

Covering factor =1
$v_0 = 0.1\ c$



ii b. Relativistic effects

Absorption spectrum for $\underline{v = 0}$

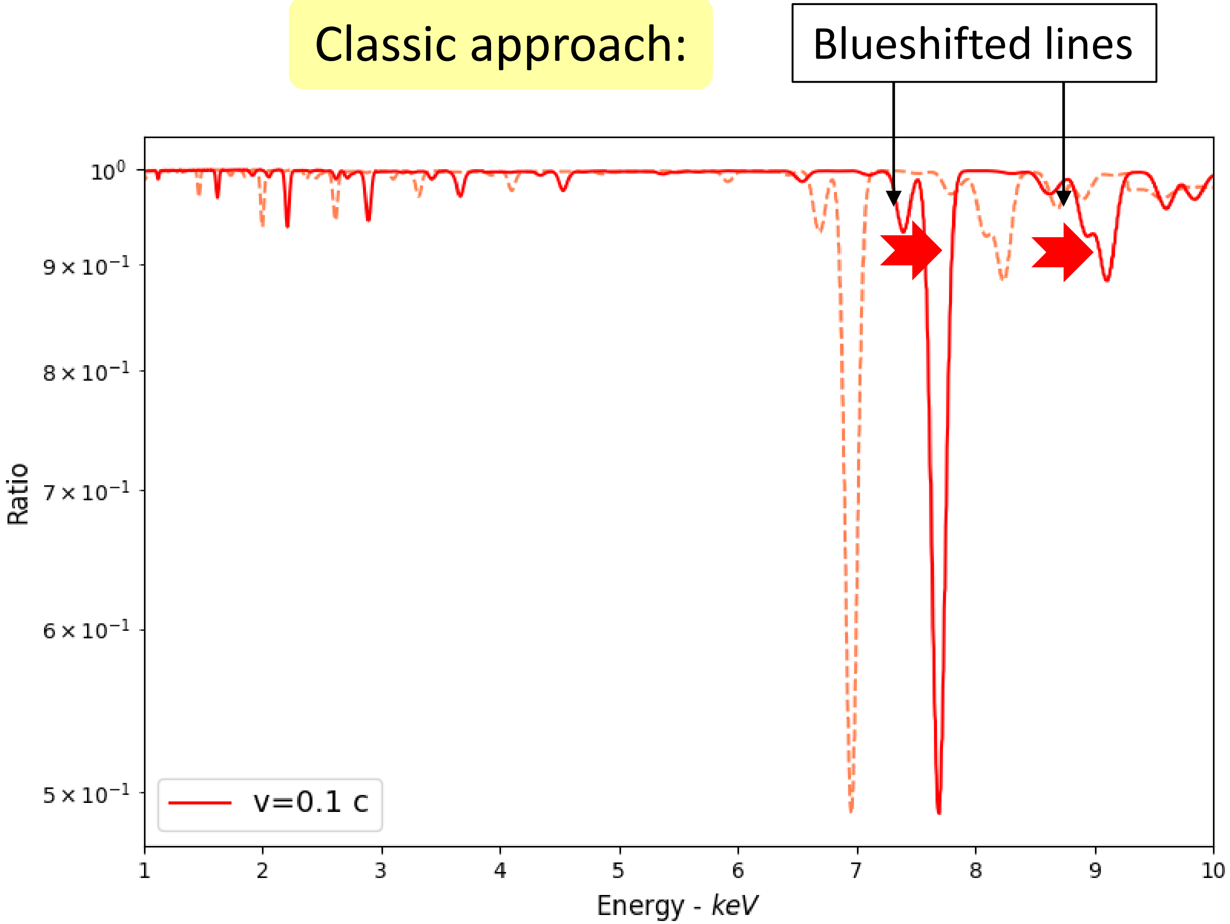


ii b. Relativistic effects

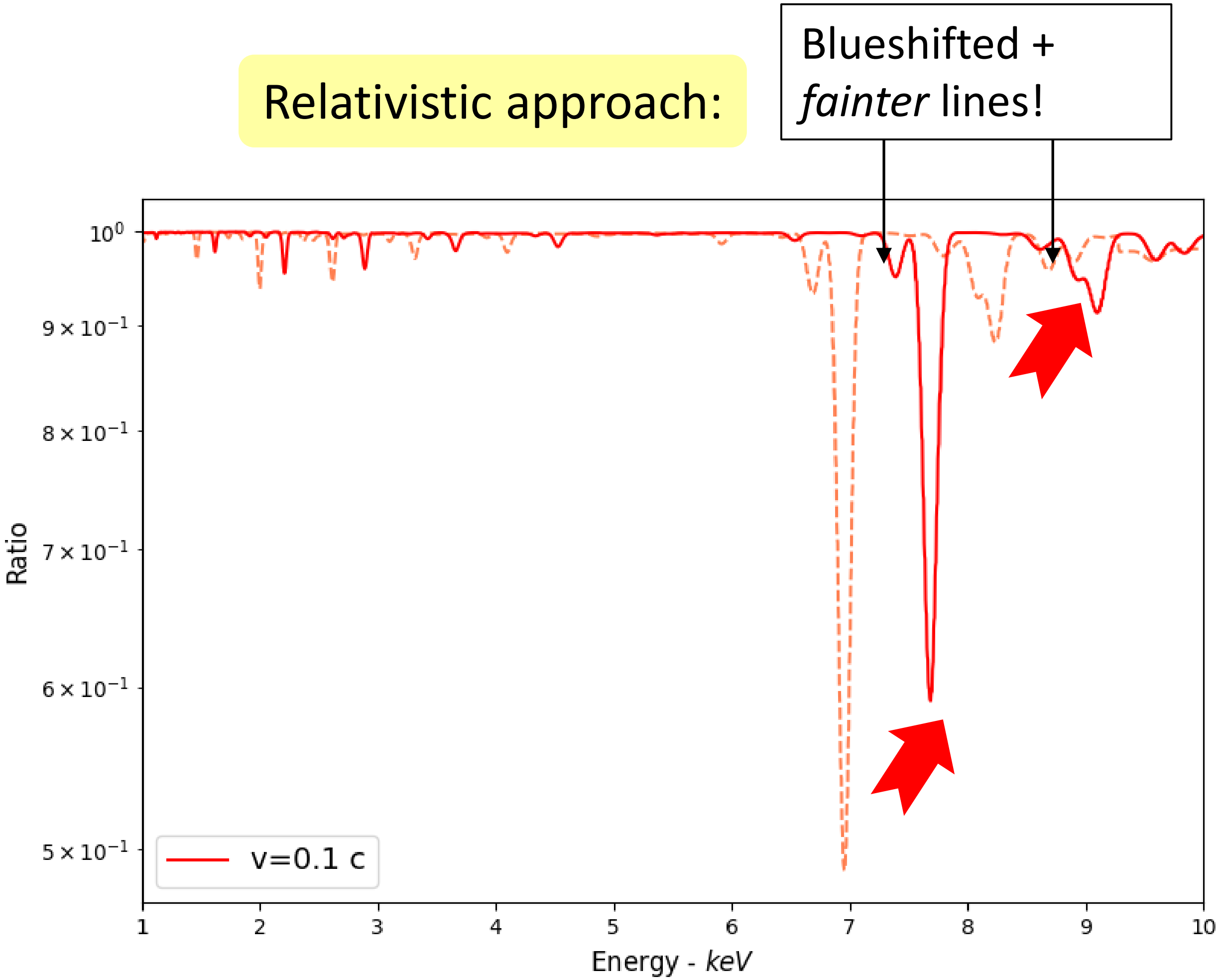
Luminari+20

Absorption spectrum for $\underline{v = 0.1\ c}$

Classic approach:



Relativistic approach:

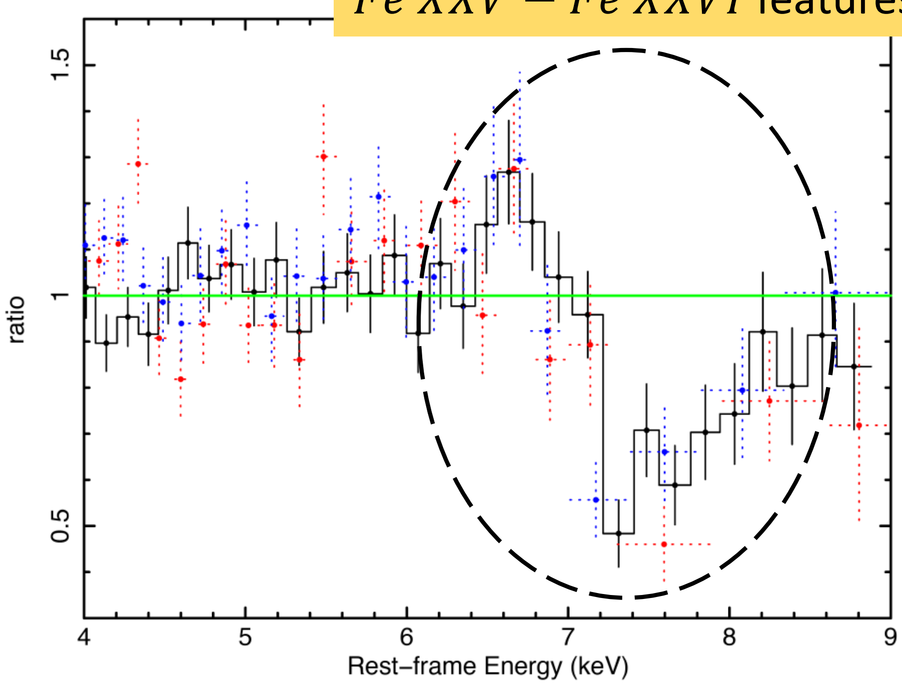


iii. WINE at play: The UFO in PG1448+273

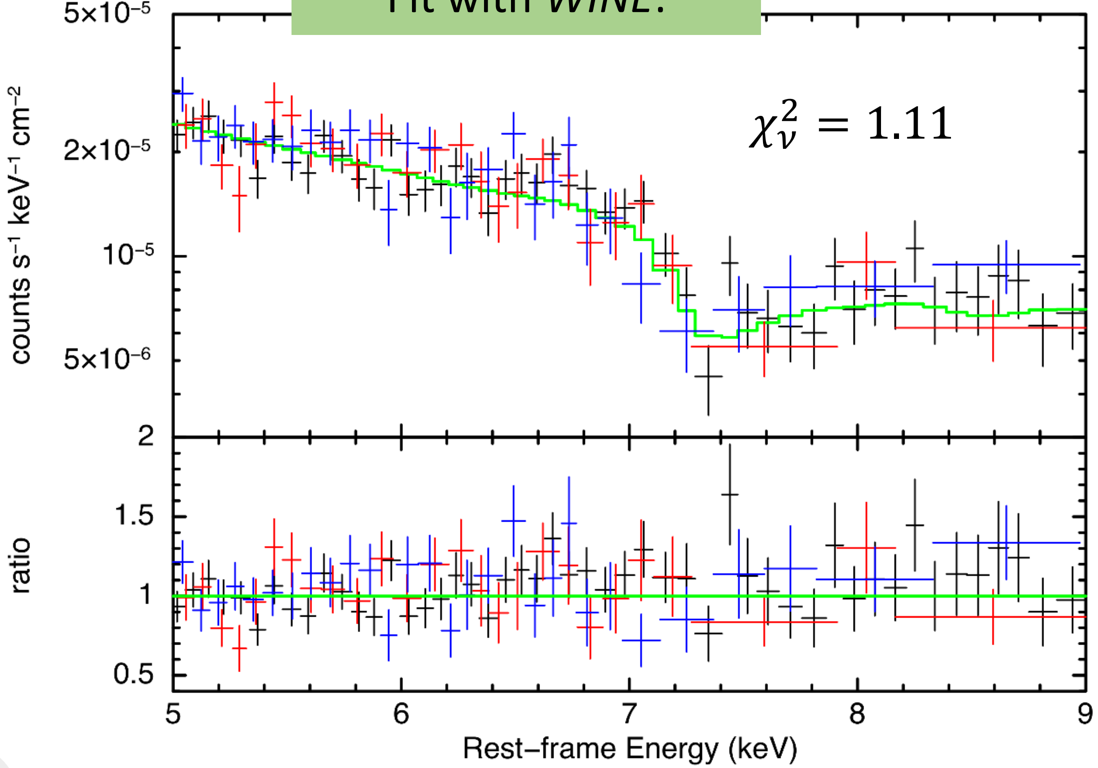
Laurenti, AL+21

A new, powerful UFO from a luminous quasar: $L_{bol} = 0.75\ L_{Edd}$

$Fe\ XXV - Fe\ XXVI$ features



Fit with *WINE*:



Fit with WINE

- $N_H = 4.5 \cdot 10^{23} cm^{-2}$
- $v_{avg} = 0.15\ c$
- $\log(\xi) = 5.5$
- $R_0 = 77\ r_S$
- $\theta_{out} > 72° \ \rightarrow C_f > 0.69$

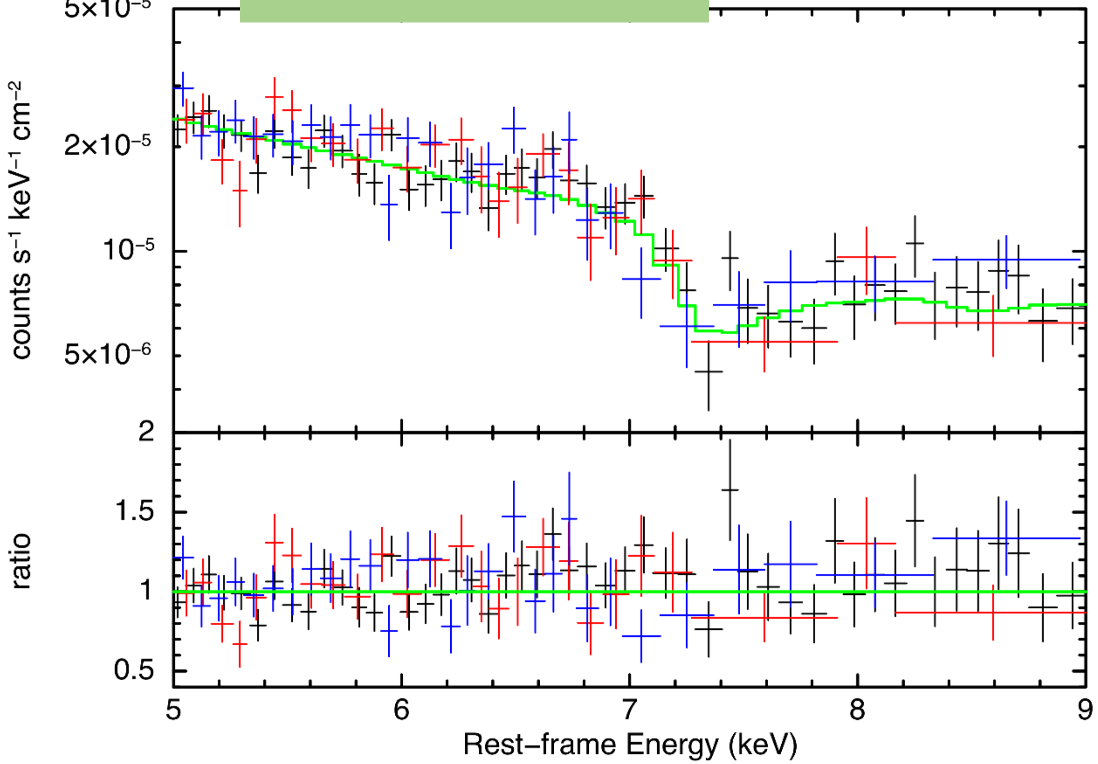
without relativistic effects:

$N_H^{norel} = 2 \cdot 10^{23} cm^{-2}$

iii. WINE at play: The UFO in PG1448+273

Laurenti, AL+21

Fit with *WINE*:



- $R_0 = 77\ r_S$
- $N_H = 4.5 \cdot 10^{23} cm^{-2}$
- $v_{avg} = 0.15\ c$
- $\theta_{out} > 72° \rightarrow C_f > 0.69$
- $\chi^2_\nu = 1.11$

Zero-th order formulas for the wind energetic:

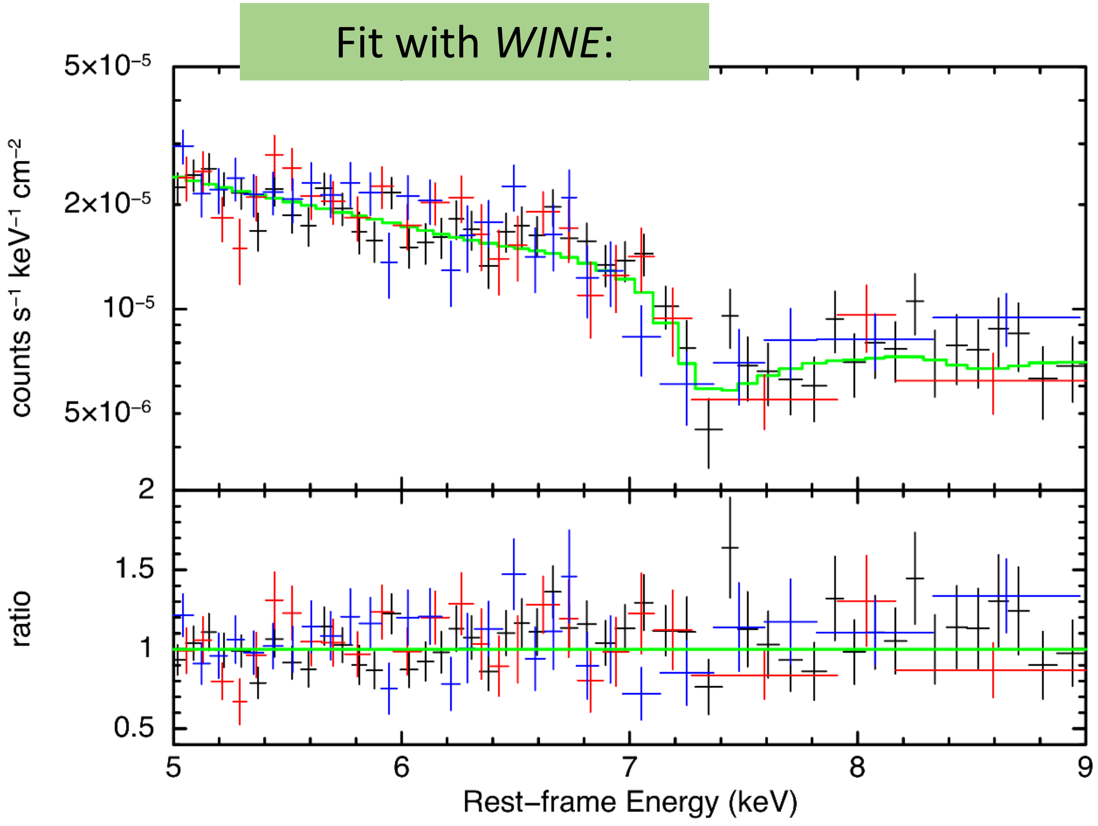
$$\dot{M}_{out} = 4\,\pi r_0 C_f N_H\,\mu\, m_P\, v_{out} = 0.25\, M_\odot\, yr^{-1}$$

$$\dot{E}_{out} = \frac{1}{2}\dot{M}_{out}\cdot\ v_{out}^2 = 1.7\cdot 10^{44} erg\ s^{-1}$$

Assuming: constant wind density, spherical symmetry, no relativistic effects

iii. WINE at play: The UFO in PG1448+273

Laurenti, AL+21



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$$\dot{E}_{out} = \frac{1}{2}\dot{M}_{out} \cdot v_{out}^2 = 1.7 \cdot 10^{44} erg\ s^{-1}$$

Updated formulas:

$$\dot{M}_{out} = 2\ \mu\ m_P \int_0^{2\pi} d\ \phi \int_0^{2\pi} \sin\theta\ d\ \theta \int_{r_0}^{r_1} n(r) v(r) r\ dr$$

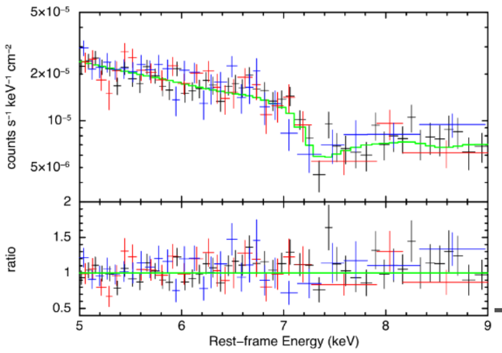
$$= 0.65\ M_\odot\ yr^{-1} = 2.0 \dot{M}_{acc}$$

$$\dot{E}_{out} = (\gamma - 1)\dot{M}_{out} c^2 = 4.4 \cdot 10^{44}\ erg\ s^{-1} = 24\%\ L_{bol}$$

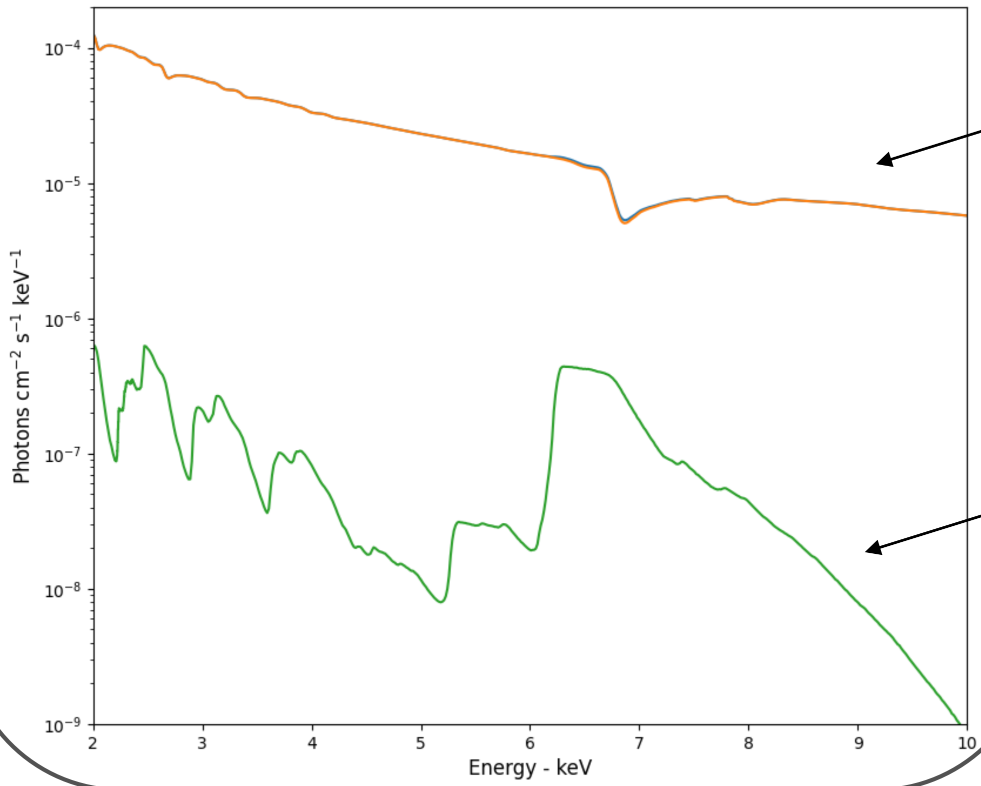
- $\dot{M}_{out} > \dot{M}_{acc}$: impact on disc stability?
- $\dot{E}_{out}$ enough to trigger galactic feedback!

iii. WINE at play: The UFO in PG1448+273

Laurenti, AL+21



Best fit model:

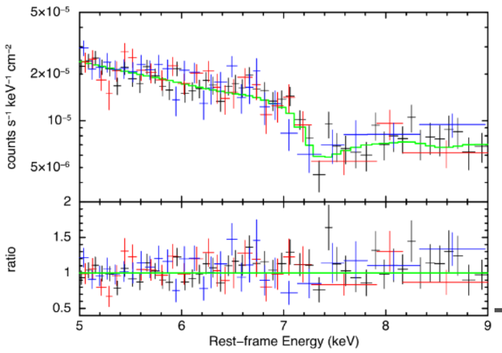


Total spectrum

Emission

iii. WINE at play: The UFO in PG1448+273

Laurenti, AL+21



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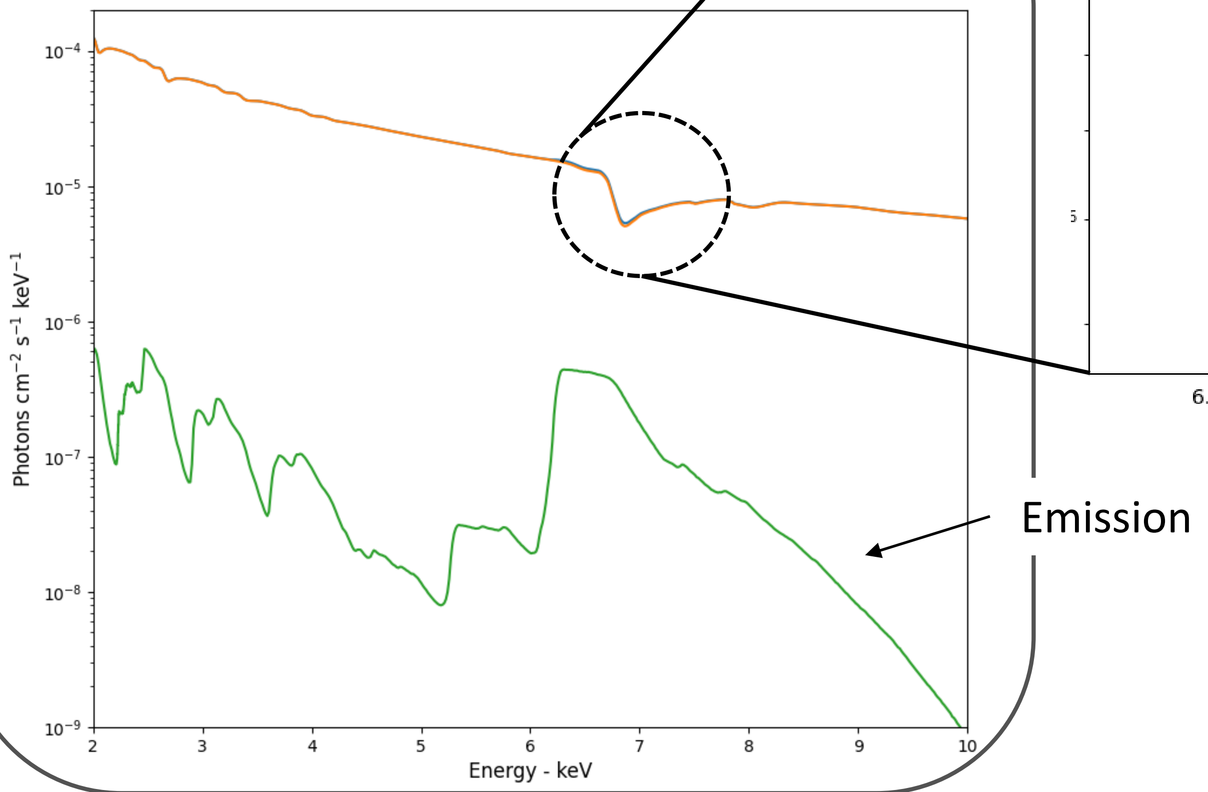
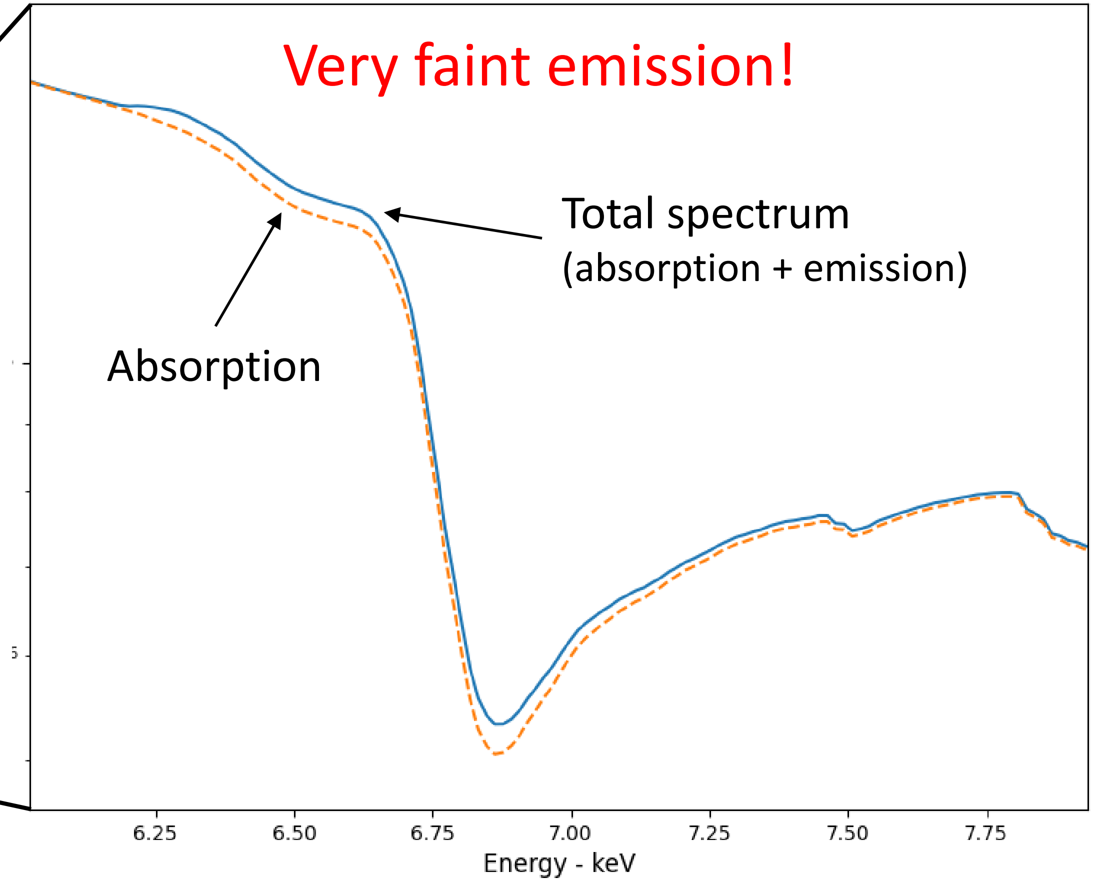




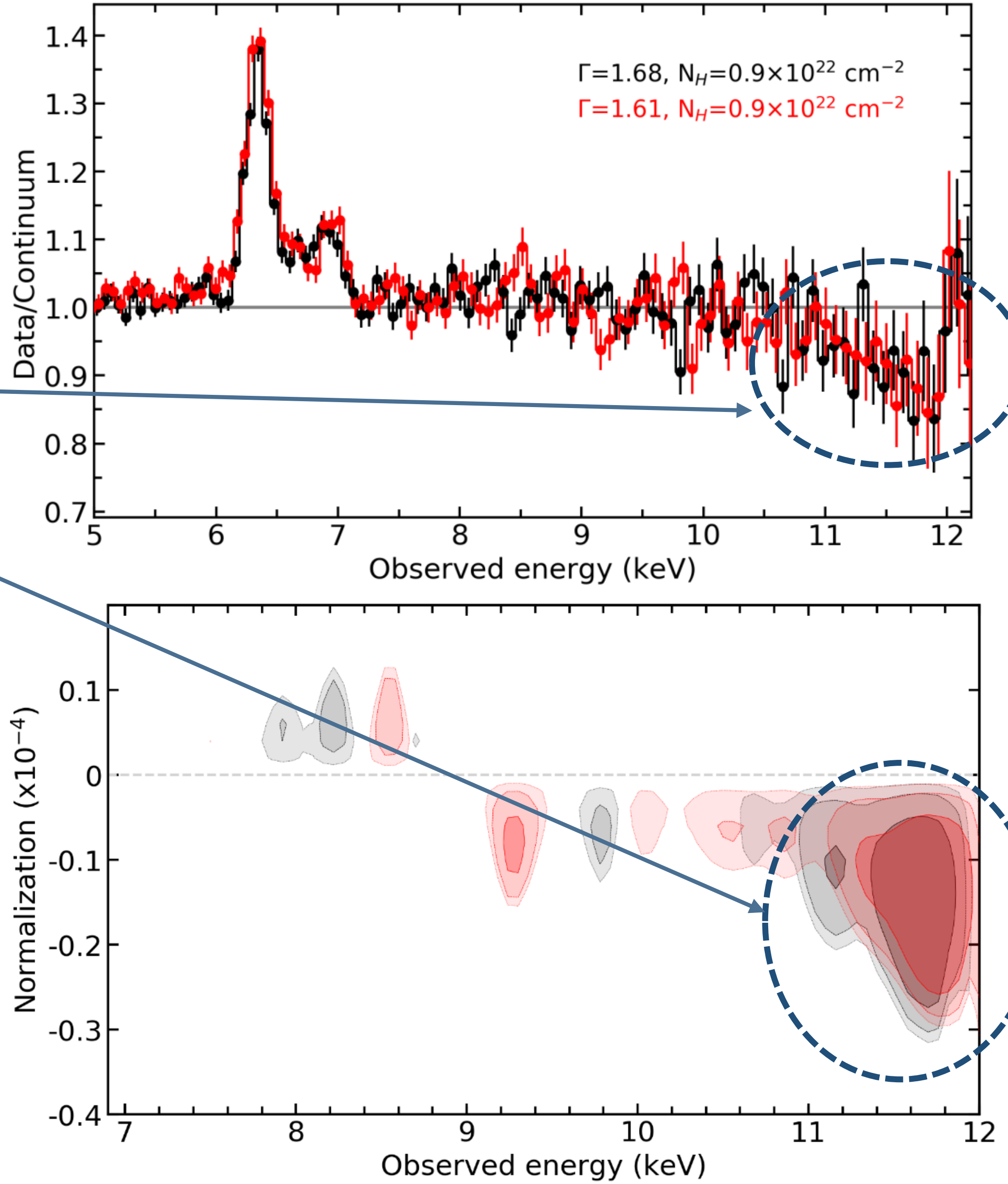
Why this? High v!

- relativistic beaming
- geometrical projection

iii. WINE at play: a 0.3c UFO in the low-luminosity Seyfert NGC 2992

A variable, fast UFO in the low-luminosity Seyfert NGC 2992 : $L_{bol} = 0.04\ L_{Edd}$

Time averaged spectra show UFO absorption features:

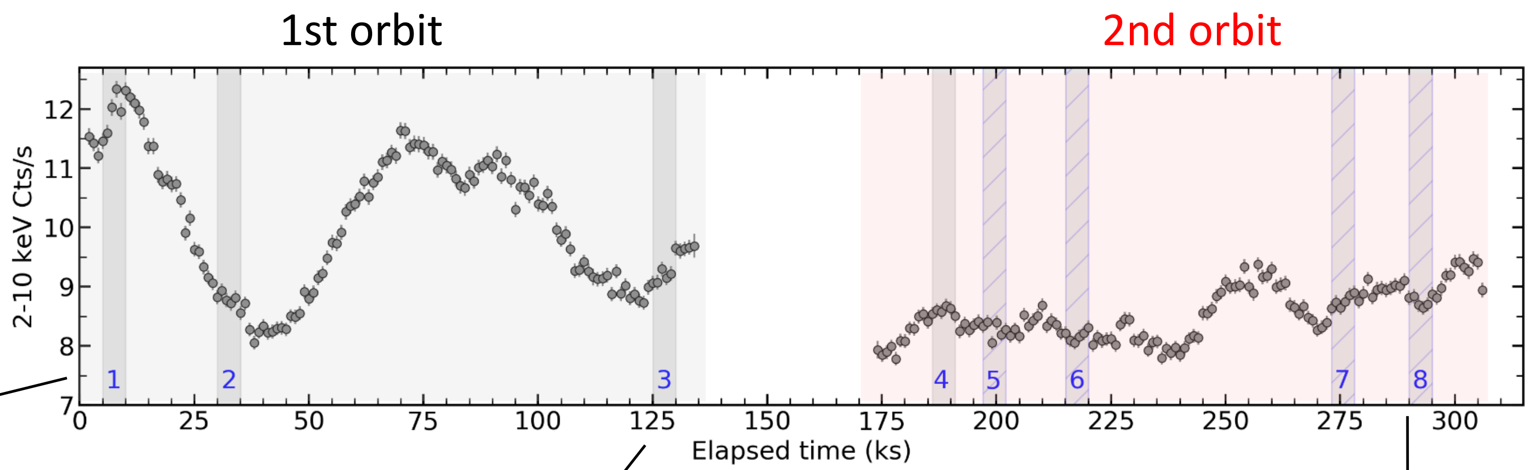


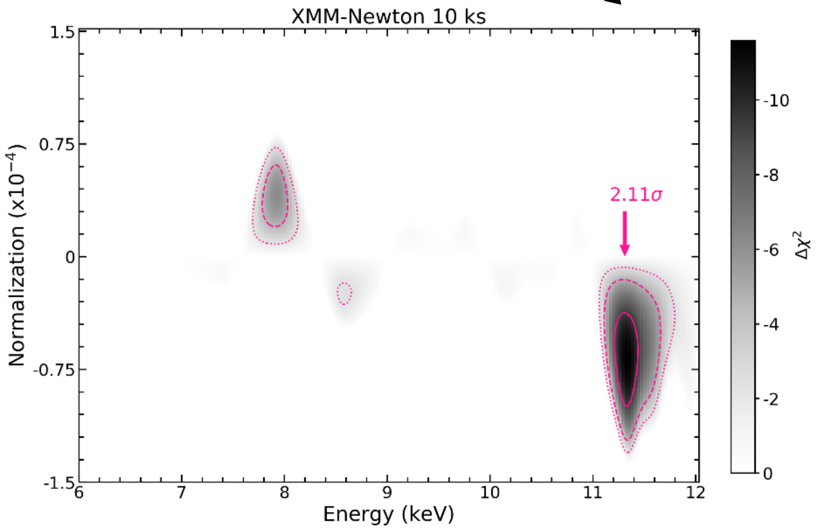
Luminari, Marinucci+22 (submitted)

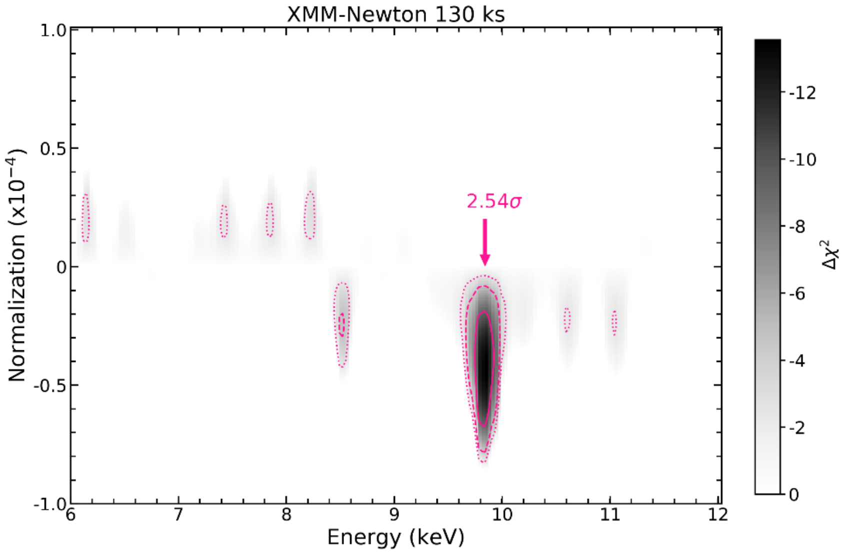
iii. WINE at play: a 0.3c UFO in NGC 2992

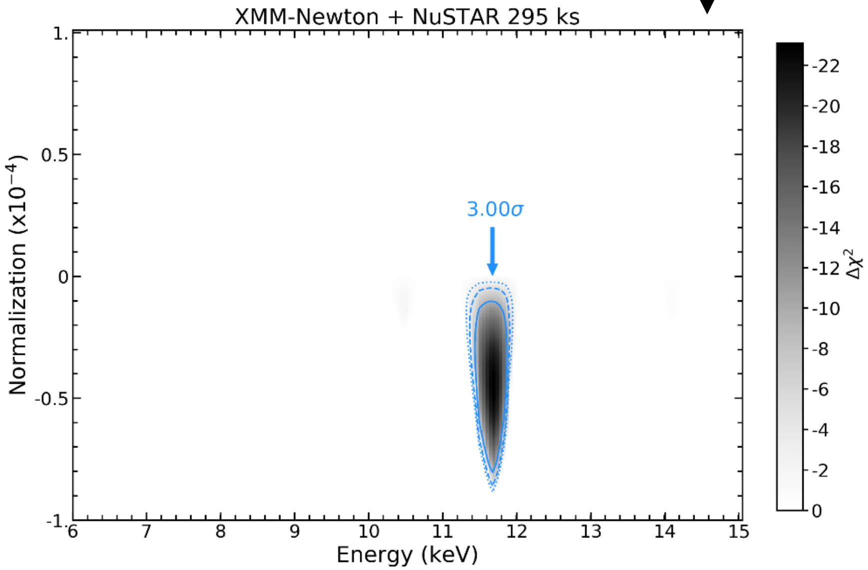
<u>Time resolved spectroscopy:</u>

observations are binned in 5 ks slices and Gaussian-scanned for UFO features





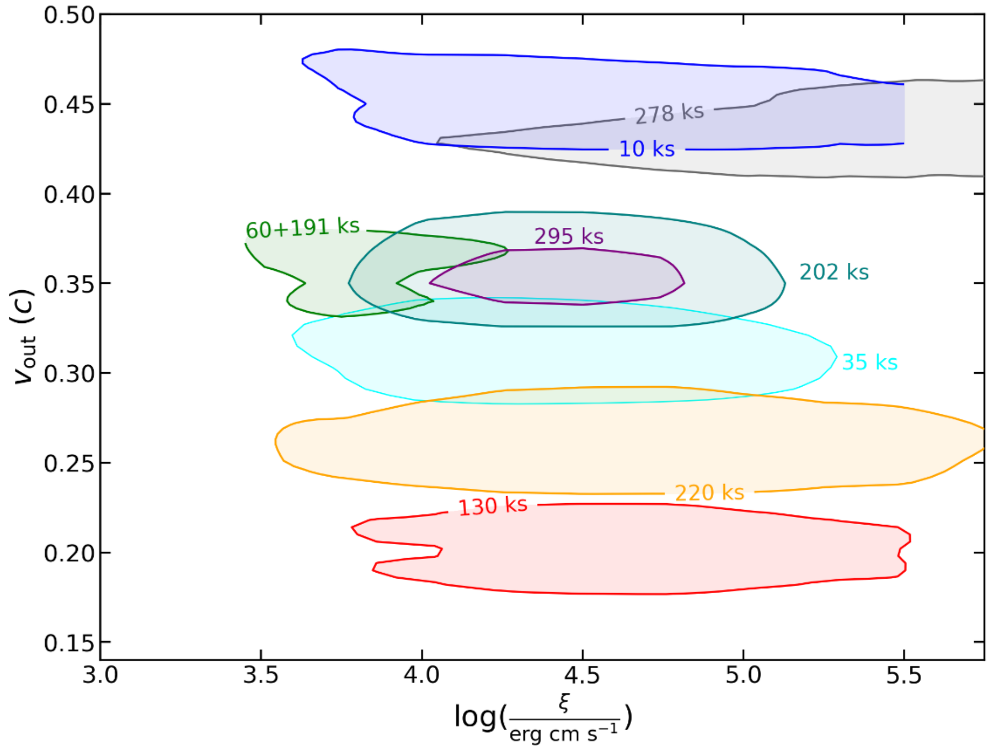


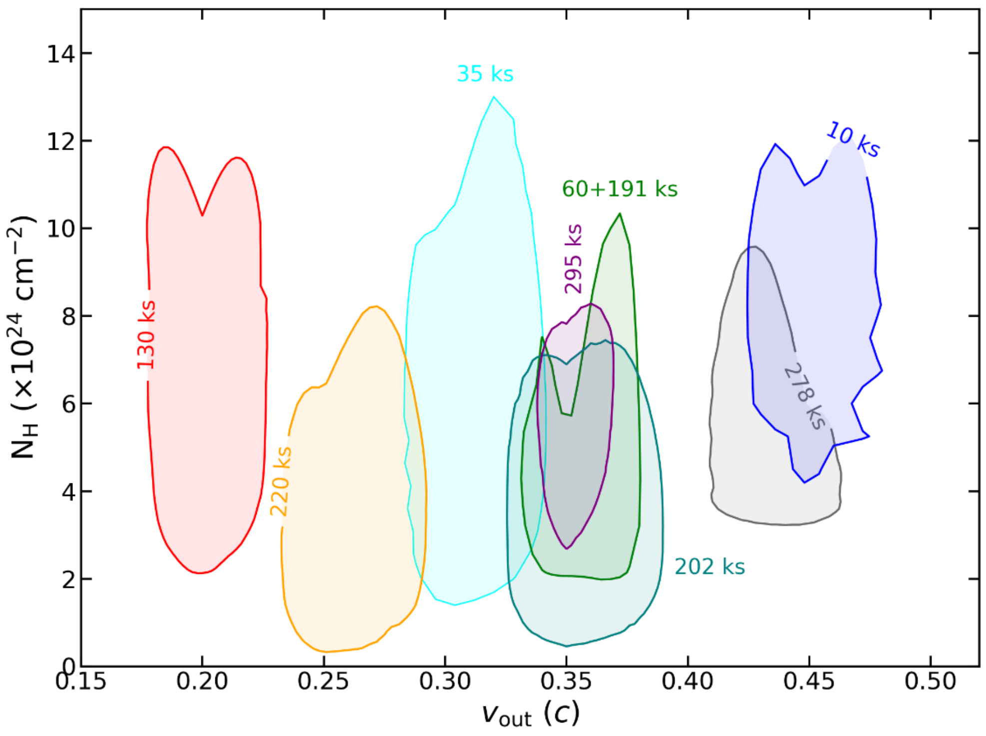


Luminari, Marinucci+22 (submitted)

iii. WINE at play: a 0.3c UFO in NGC 2992

thanks A. Marinucci for the plots!



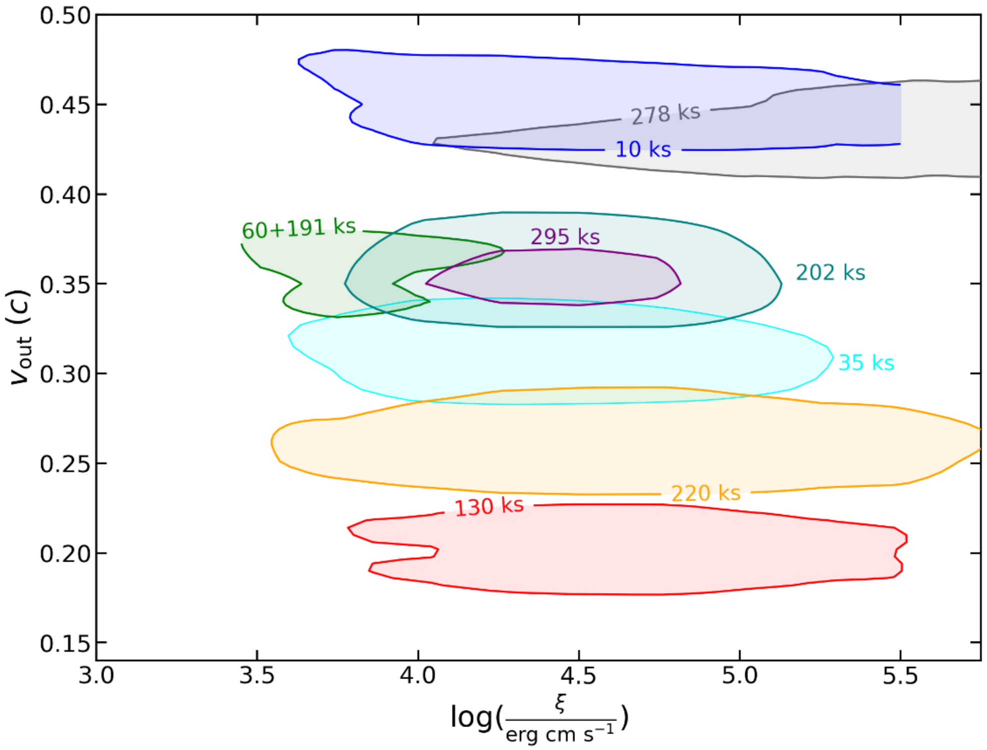


<u>Time resolved best fit values with WINE:</u>
a powerful, Quasar-like UFO!

- $v \approx 0.30\ c$
- $\log(\xi) \approx 4.5$
- $N_H \approx 6 \cdot 10^{24} cm^{-2}$
- $\chi^2_\nu \approx 1.0$

Luminari, Marinucci+22 (submitted)

iii. WINE at play: a 0.3c UFO in NGC 2992



What about the launching radius r_0?

Cannot be directly probed due to the limited spectral S/N

→ *However:*

By requiring that the best fit intervals for ξ encompass the variation of $\xi(r)$ along the wind column, we obtain an ***upper limit*** for the launching radius r_0:

$$r_0 \leq 5 \text{ Schwarzschild radii}$$

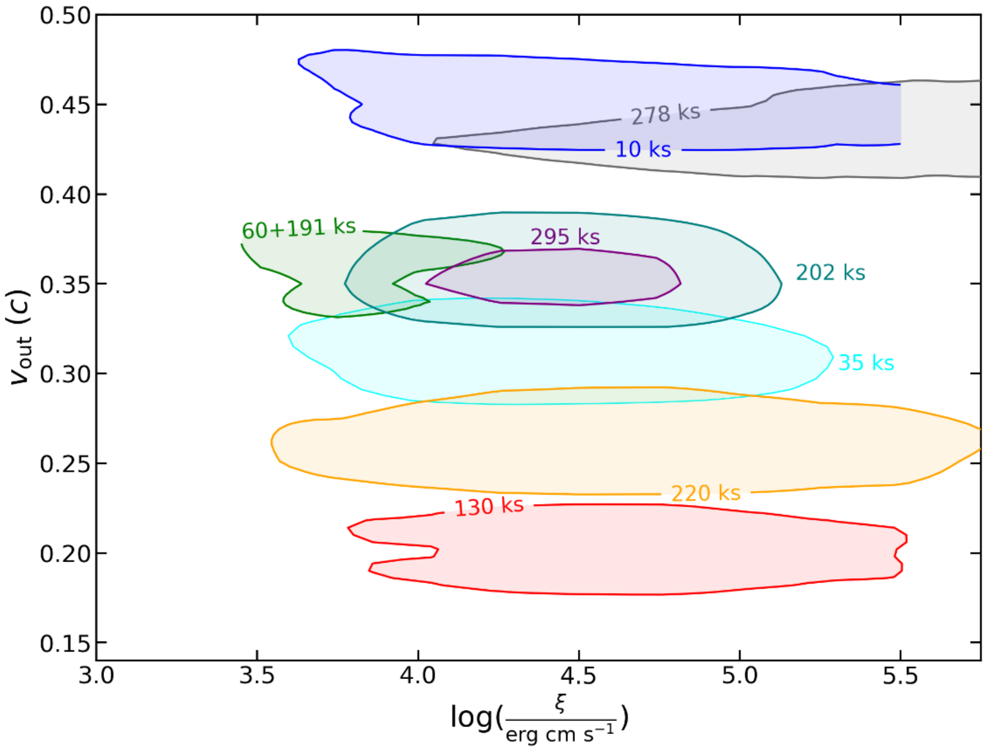
Also matches the UFO typical crossing scale!

Best fit values:

- $v \approx 0.30\, c$
- $\log(\xi) \approx 4.5$
- $N_H \approx 6 \cdot 10^{24} cm^{-2}$

Luminari, Marinucci+22 (submitted)

iii. WINE at play: a 0.3c UFO in NGC 2992



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$\mathrm{r}_0 \lesssim 5$ Schwarzschild radii

Best fit values:

- $v \approx 0.30\, c$
- $\log(\xi) \approx 4.5$
- $N_H \approx 6 \cdot 10^{24} cm^{-2}$

Wind energetic:

$\dot{M}_{out} \approx 0.4\, M_{\odot}/yr$

$\dot{E}_{out} \approx 10\, L_{bol}$

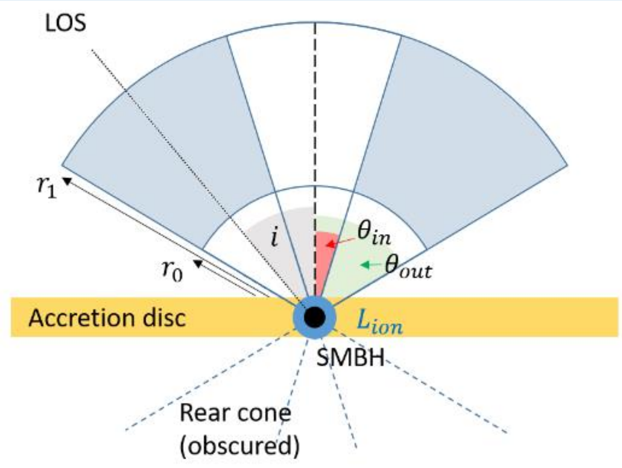
+ *Lower limit* on wind density: $n \lesssim 10^{11}\, cm^{-3}$

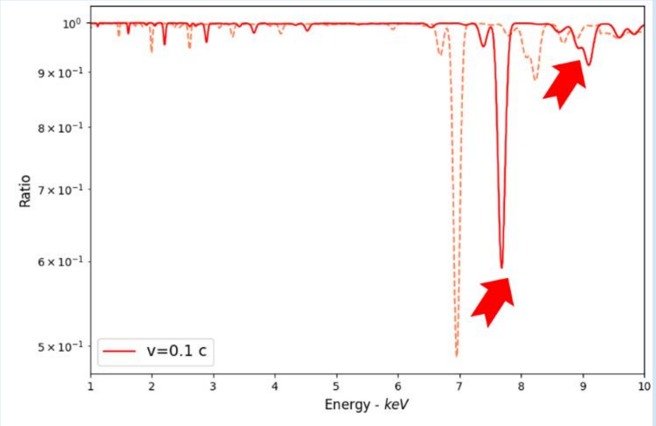
Luminari, Marinucci+22 (submitted)

Conclusions

The WINE model

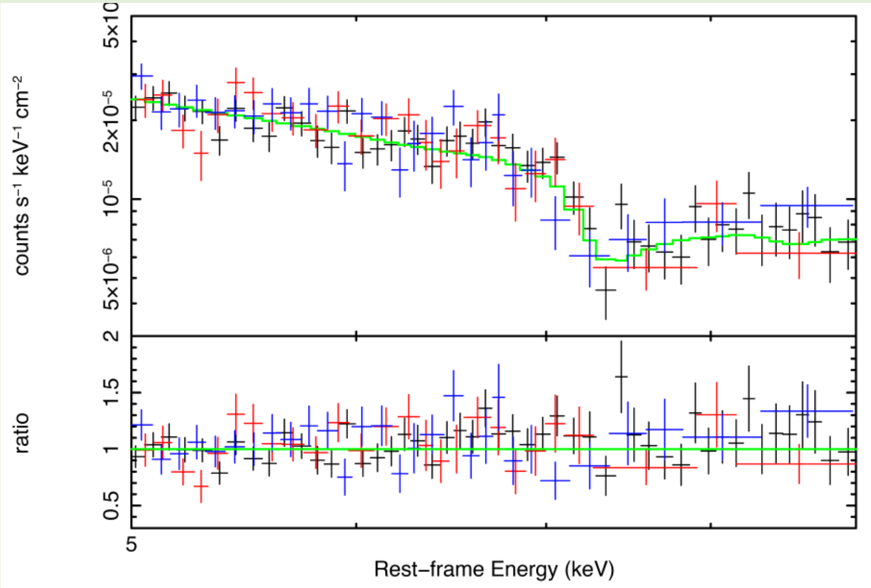
- Constrain the physics and the geometry of the wind
- Derive $\dot{M}_{out}, \dot{E}_{out}$ and estimate the impact on the galaxy
- Radiative transfer, Monte Carlo emission, special relativity



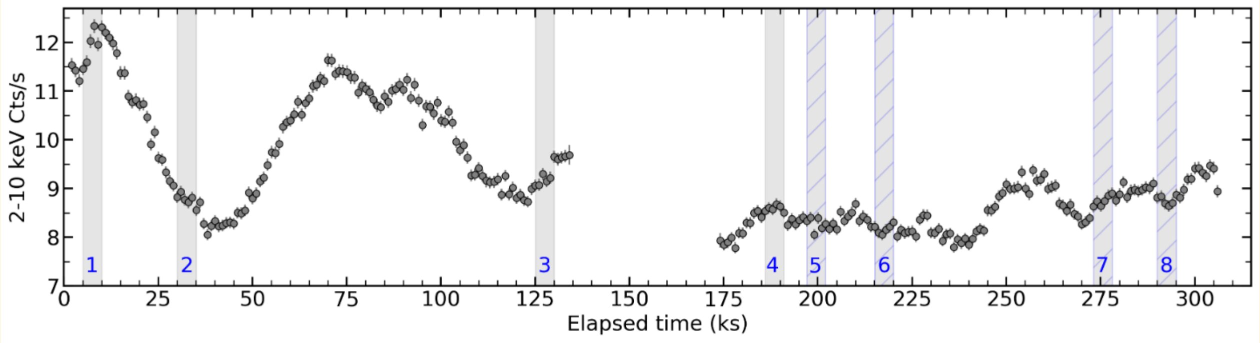


Velocity, location and energetic of the UFO in PG1448+273

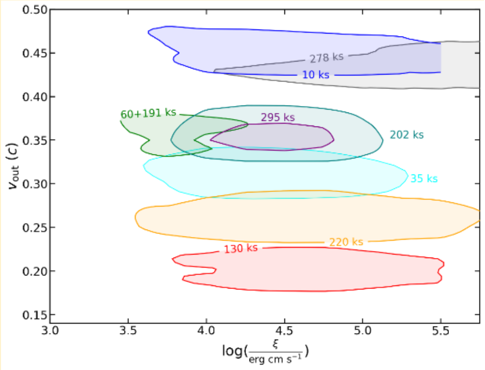
- v, ξ, N_H, r_0, C_f directly constrained from the fit
- High mass outflow
- Galactic feedback
- UV - X-ray interplay?

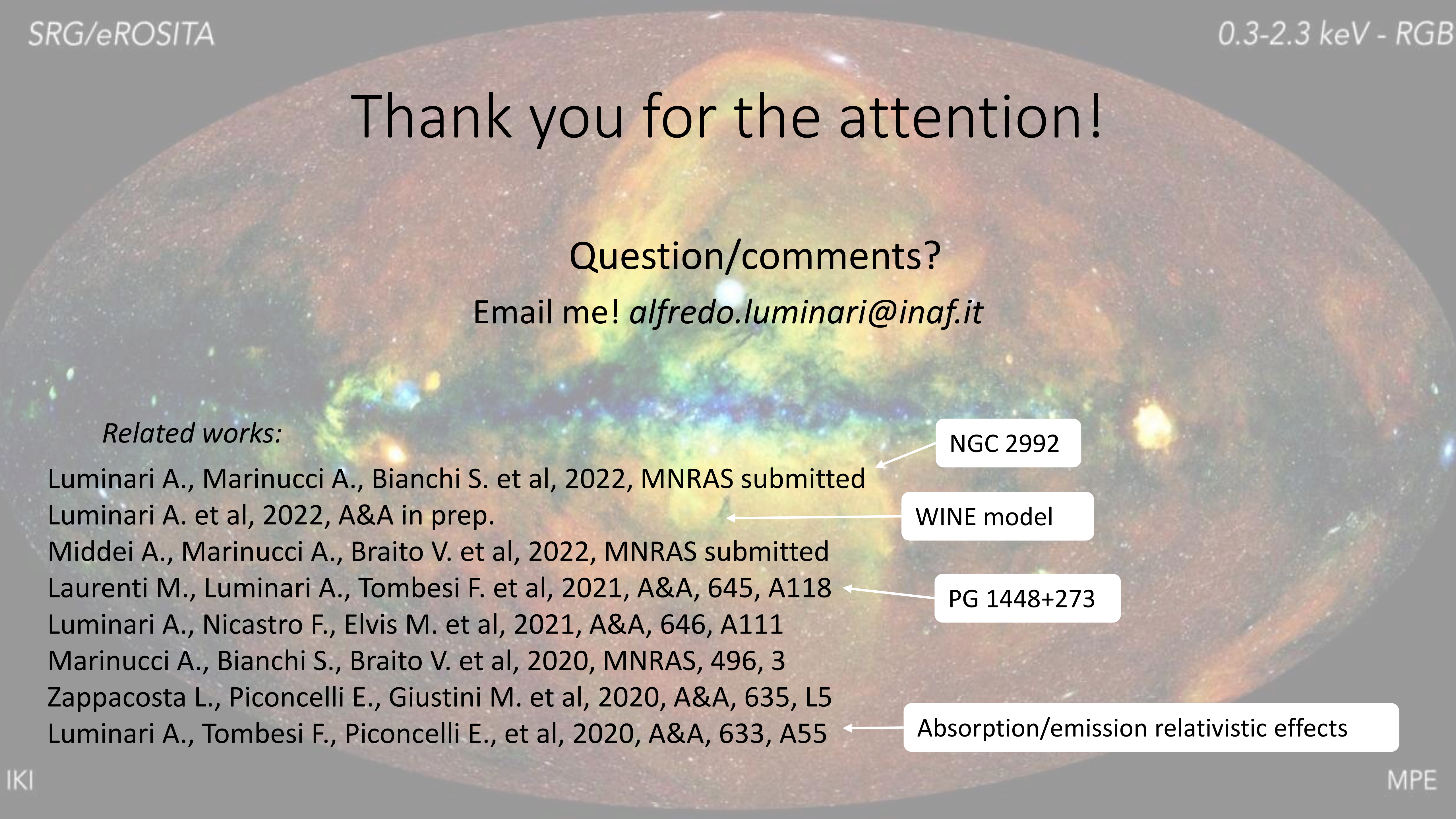


Variable 0.3 c UFO in the Seyfert NGC 2992



- ➢ Wind characterisation on 5ks time scale
- ➢ v, ξ, N_H determined with WINE
- ➢ Limits on r_0, n
- ➢ Powerful, ''quasar-like'' UFO





Thank you for the attention!

Question/comments?

Email me! *alfredo.luminari@inaf.it*

Related works:

Luminari A., Marinucci A., Bianchi S. et al, 2022, MNRAS submitted ← NGC 2992
Luminari A. et al, 2022, A&A in prep. ← WINE model
Middei A., Marinucci A., Braito V. et al, 2022, MNRAS submitted
Laurenti M., Luminari A., Tombesi F. et al, 2021, A&A, 645, A118 ← PG 1448+273
Luminari A., Nicastro F., Elvis M. et al, 2021, A&A, 646, A111
Marinucci A., Bianchi S., Braito V. et al, 2020, MNRAS, 496, 3
Zappacosta L., Piconcelli E., Giustini M. et al, 2020, A&A, 635, L5
Luminari A., Tombesi F., Piconcelli E., et al, 2020, A&A, 633, A55 ← Absorption/emission relativistic effects