X-ray winds with the WINE model: a detailed photoionization treatment of relativistic outflows

Alfredo Luminari[1,2,*], F. Tombesi[1,2,3,4], E. Piconcelli[2], F. Fiore[5], K. Fukumura[6], D. Kazanas[4], F. Nicastro[2], L. Zappacosta[2]

[1] Univ. of Rome Tor Vergata, Italy; [2] INAF- Observatory of Rome; [3] Univ. of Mariland;
[4] NASA-GSFC; [5] INAF- Observatory of Trieste; [6] J. Madison Univ., USA; * *alfredo.luminari@roma2.infn.it*

Abstract Ultra-Fast Outflows are often observed in X-ray spectra of Active Galactic Nuclei (AGN) and represent a powerful tool to probe the innermost regions surrounding the SMBH. However, up to now very little is known about the physics and the launching mechanisms driving them.
To gain new insights from the data, **we developed a new spectral model** for disk winds, that includes both absorption and emission. Particular attention is devoted to the **wind kinematics and geometry** and to the photoionization equilibrium.
Special relativistic effects have also been included, leading to a velocity-dependent optical depth. This, in turn, implies that the measured column density of the wind N_H must be corrected according to the outflow velocity. This correction applies also to the derived mass and energy flux rates, which linearly depend on N_H.
The model can be applied as well to **all kinds of compact sources**, such as stellar BHs, X-Ray Binaries, etc. Its spectral diagnostics will allow to fully exploit the energy resolution of the upcoming XRISM and ATHENA.

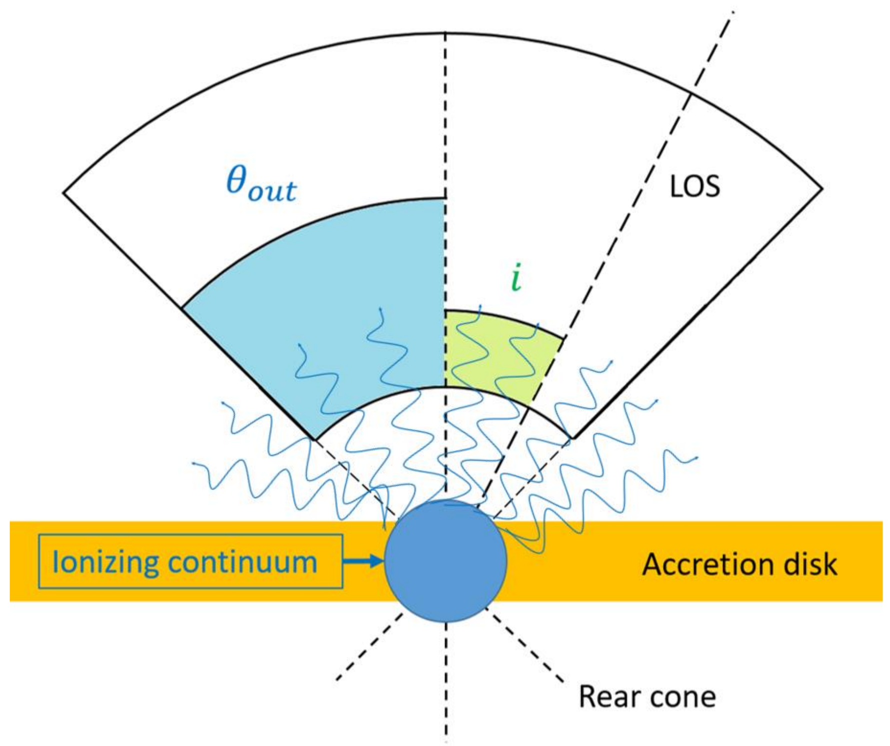
Current status of the field

i. Spectral analysis of X-ray winds is done mainly through simulated absorption and emission spectra. P-Cygni profiles are modeled *ad hoc* combining emission and absorption spectra.

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

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

The WINE model



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

ii. The **physical, kinematical and geometrical parameters** are:
1. Ionization parameter $\xi(r)$
2. Column density N_H
3. Density and velocity profiles as functions of the radius:
$$n(r) = n_0\left(\frac{r_0}{r}\right)^{\alpha},\ v(r) = v_0\left(\frac{r_0}{r}\right)^{\beta}$$
4. Geometry of the source: θ_{out}, i

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

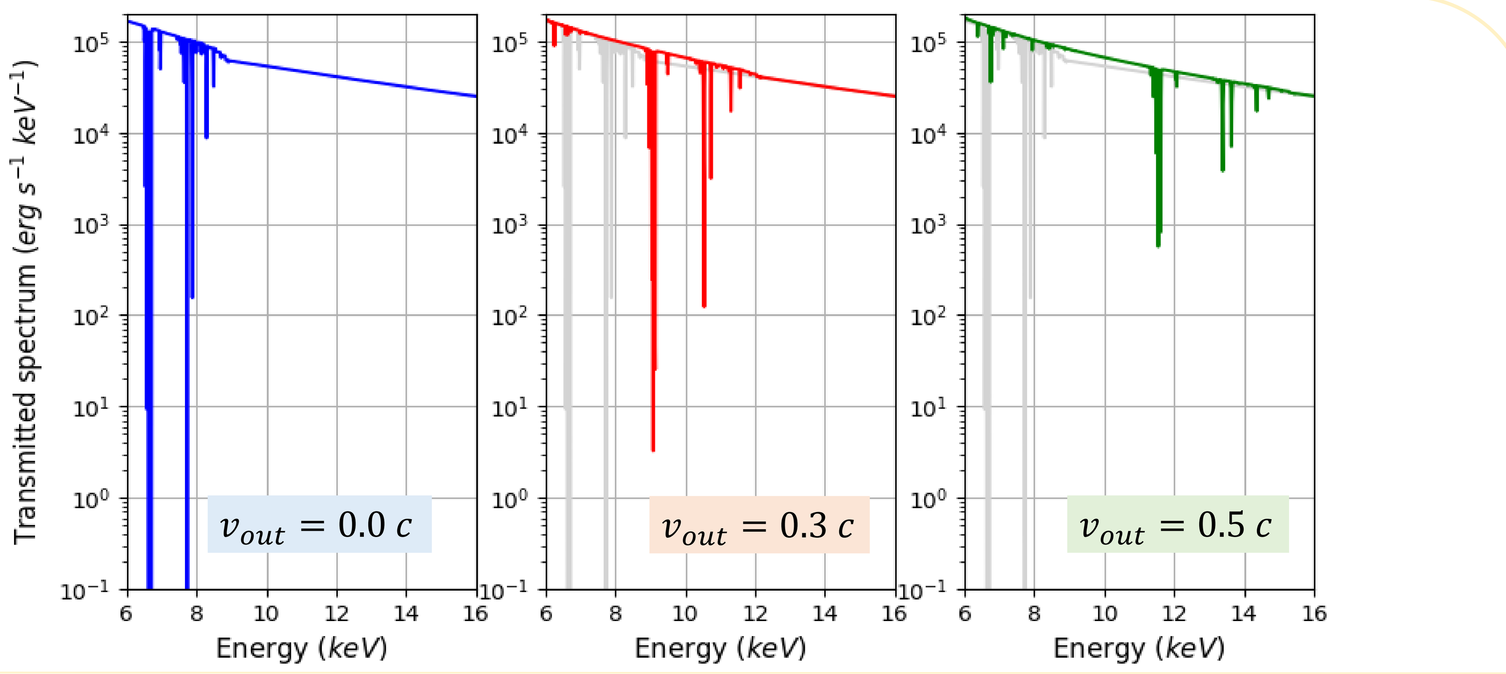
iii. **Relativistic effects** are taken into account in the radiative transfer calculations. Absorption and emission profiles are directly built according to the geometry and the velocity profile.

Special relativity effects on the wind features

When approaching relativistic velocities, the space-time reference frame of the wind is transformed. This has a double effect:

Wind emission is relativistically beamed, as commonly observed in relativistic systems such as AGN jets, Blazars, GRB, where the outflow points toward the observer.

Wind absorption is reduced for increasing wind velocity:

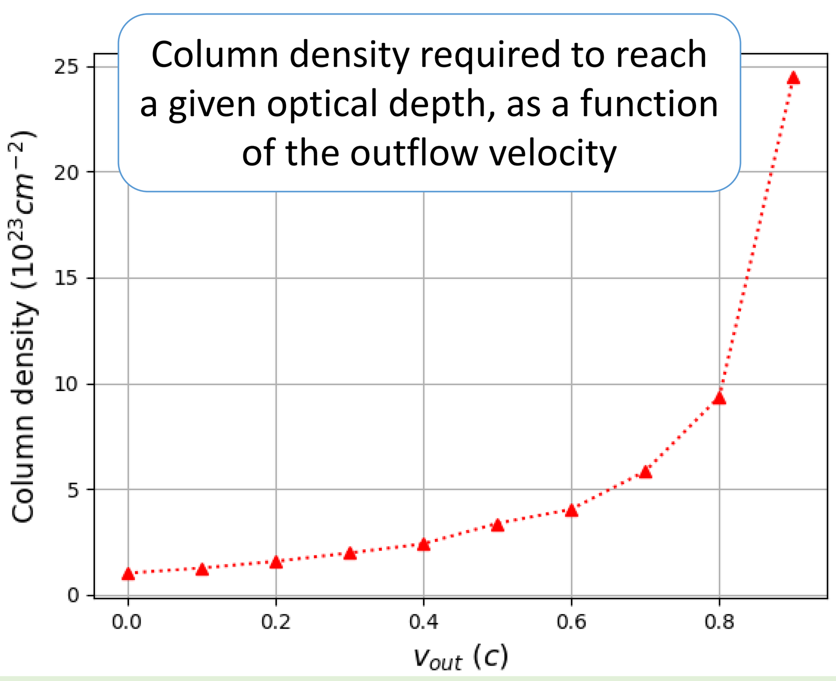


Absorption spectra with increasing v_{out} and fixed $N_H = 6\times10^{23}cm^{-2}$ and $\xi = 10^{4.5} erg\ s^{-1}cm^{-2}$.

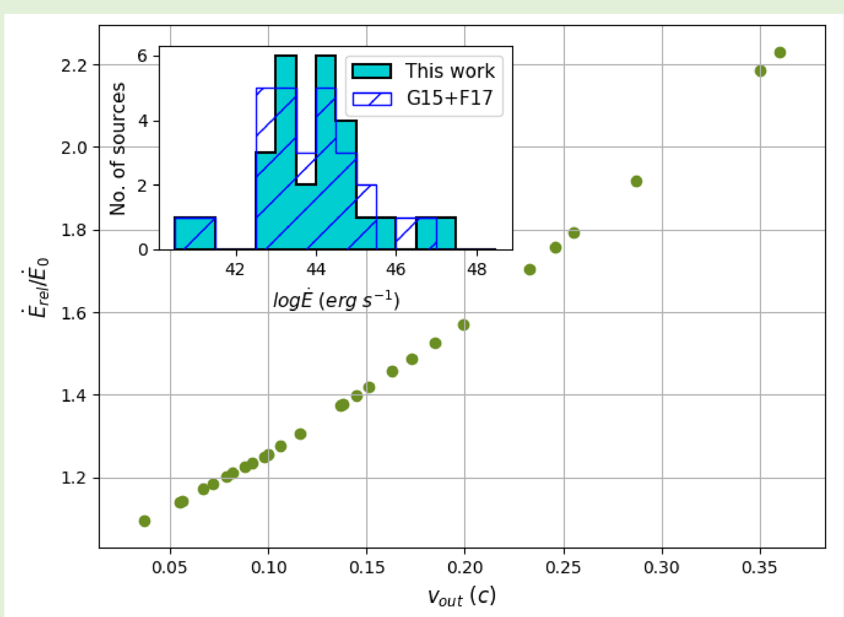
The observed optical depth depends on the wind velocity v_{out}. Hence, the measured column density of the wind must be corrected according to the velocity.

This correction is already significant ($\approx 50\%$) for a velocity of $v_{out} = 0.1\ c$, and increases to a factor ≈ 10 for $v_{out} = 0.8\ c$:

Neglecting this effect leads to a systematic underestimate of N_H, that linearly propagates in the derived $\dot{M}_{out}$ and $\dot{E}_{out}$.



Effect on the UFO population:



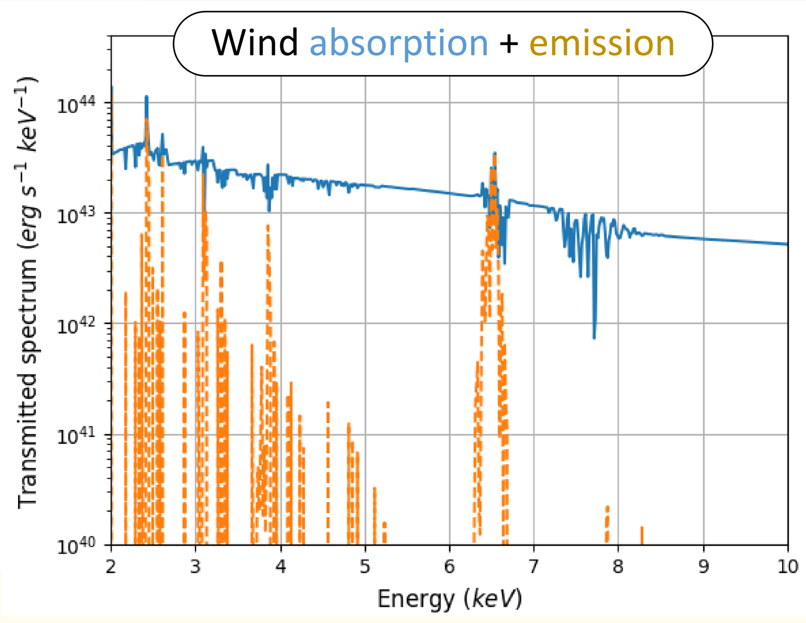
Main panel: Ratio between the relativistic-corrected energy transfer rates $\dot{E}_{rel}$ and the original values $\dot{E}_0$ as a function of the outflow velocity, for a sample of Ultra Fast Outflows in AGNs (from Gofford+15, Fiore+17).

Inset: cumulative distributions of $\dot{E}_{rel}$ and $\dot{E}_0$.

How they are implemented in WINE:

Wind absorption

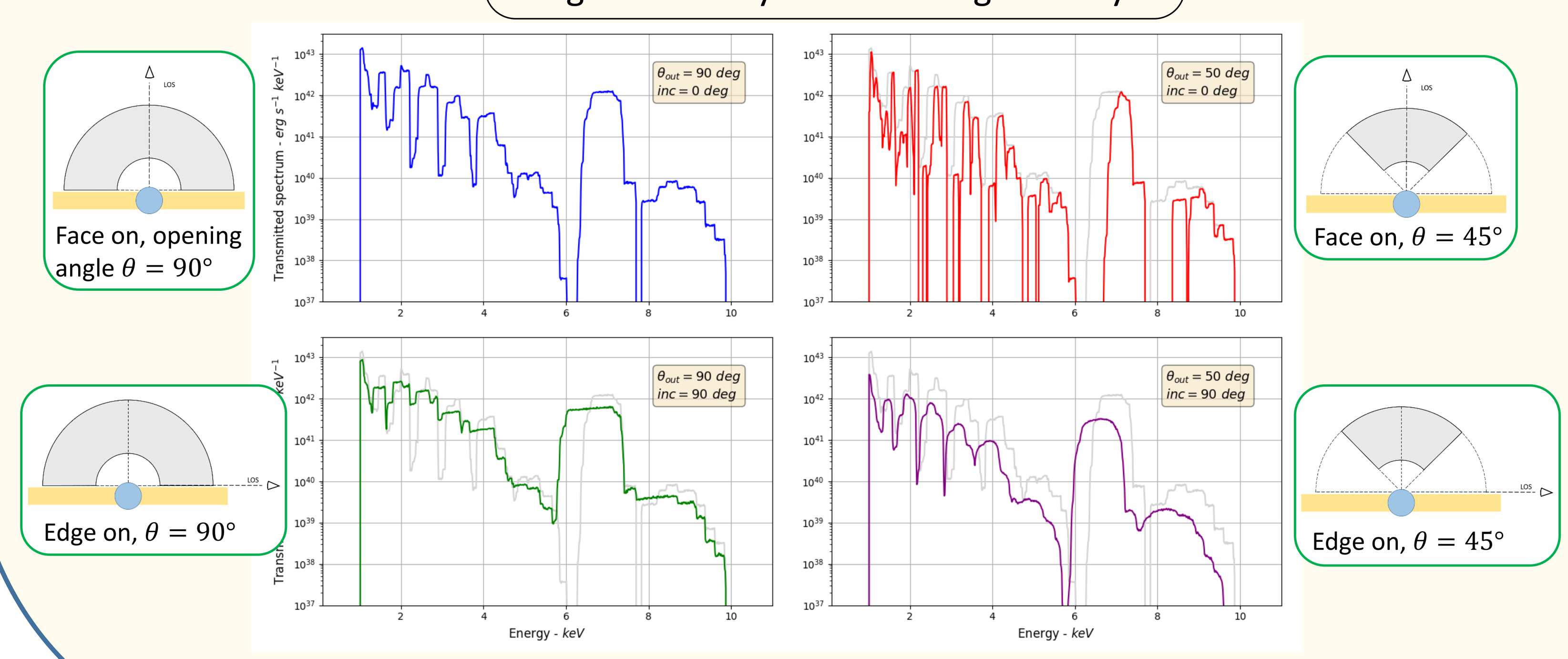
i. The wind is divided in thin shells to sample the gradient of $\xi(r), v(r), n(r)$
ii. Calculation is started from the innermost shell with *XSTAR*, using incident spectrum and ξ_0, v_0 and including relativistic effect
iii. Simulation is propagated to the 2nd shell using data from the transmitted spectrum and computing $\xi(r), v(r)$
iv. Iterate until the total column density N_H is reached



Wind emission

i. Sample each shell with n random points
ii. Compute emission from each point, using *XSTAR* line emissivities and calculating the relativistic beaming toward the observer
iii. Compute emission from each shell
iv. Total emission is the composition of all the shells

High sensitivity to emission geometry:



Emission spectra for $v_{out} = 0.10c, N_H = 6\times10^{23}cm^{-2}, \log(\xi) = 4.5\ erg\ s^{-1}cm^{-2}$

Summary

The WINE model allows to:

- derive **energy and mass flux** of the wind, with particular attention to geometry, kinematics and relativistic effects
- mimic **different wind launching scenarios** and compare them with the data
- constrain the **density and ionization structures** of the wind
- test the geometry of **P-Cygni profiles**

Bibliography

i. *Constraining the geometry of the nuclear wind in PDS 456 using a novel emission model* (Luminari, A. *et al.*, 2018 A&A 619 A149)
ii. *On the importance of special relativistic effects in modeling ultra-fast outflows* (Luminari, A. *et al.*, 2019, submitted)