• The smoking gun: the $L_X - L_{UV}$

• The disk-corona model

• The methodology: an observational test

• Results & Conclusions
The smoking gun of the Disk-Corona interplay

Relation between the Disk and the Corona

- Known for ~40 yrs, mostly as $\alpha_{ox}$ (Tananbaum+79 and many others)
The smoking gun of the Disk-Corona interplay

Relation between the Disk and the Corona

- Known for ~40 yrs, mostly as $\alpha_{OX}$ (Tananbaum+79 and many others)
- Used for many applications: CXRB, XLF, $L_{BOL}$, SEDs... (e.g. Marconi+04, Hopkins+07, Lusso+10)
  even for cosmology (e.g. Risaliti & Lusso 15, 18)
- But no conclusive physical explanation yet
  (but see Lusso & Risaliti 17, Kubota & Done 18)

$L_X$  $L_{UV}$

Arcodia+2019

Lusso+19
The smoking gun of the Disk-Corona interplay

The emission from the Corona increases less than the Disk emission

Slope $\approx 0.65$

$\sigma_{phys} \lesssim 0.2$ dex

Lusso & Risaliti 16
Chiaraluce+ 18

Some mechanism regulates their energetic connection

Arcodia+2019
Outline

• The smoking gun: the $L_X - L_{UV}$

• The **disk-corona model**

• The methodology: an **observational test**

• Results & Conclusions
The disk-corona model

- Prescriptions from the standard accretion theory (Shakura&Sunyaev73, Pringle81)
- Modified with:

  \( \rightarrow \) Generalised viscosity law: \( \tau_{r\phi} \propto P_{gas}^\mu P_{tot}^{1-\mu} \)

\( \mu = \) DISK ACCRETION PRESCRIPTION

AGN in a sweet spot of accretion \( \dot{m} \approx (0.0x - 1) \)
The disk-corona model

- Prescriptions from the standard accretion theory (Shakura & Sunyaev 73, Pringle 81)
- Modified with:

  \[ \tau_r \propto P_{\text{gas}} P_{\text{tot}}^{1-\mu} \]

  \[ f = \frac{Q_{\text{cor}}}{Q_{\text{accr}}} = f_{\text{max}} \left(1 + \frac{P_{\text{rad}}}{P_{\text{gas}}}\right)^{-\mu/2} \]

AGN in a sweet spot of accretion \( \dot{m} \approx (0.0x - 1) \)

- Generalised viscosity law:
- X-ray corona:
- Prescriptions from the standard accretion theory
- Modified with:

  \[ \mu = \text{DISK ACCRETION PRESCRIPTION} \]

  \[ f_{\text{max}} = \text{MAX CORONAL STRENGTH} \]

  (Haardt & Maraschi 91,93)
  (Svensson & Zdziarski 94)
  (Merloni & Fabian 02; Merloni 03)
The disk-corona model

\[ \mu = \text{DISK PHYSICS} \]

\[ f_{\text{max}} = \text{MAX CORONAL STRENGTH} \]
The disk-corona model

\[ \mu = \text{DISK PHYSICS} \]

\[ f_{\text{max}} = \text{MAX CORONAL STRENGTH} \]

Radial profiles: \( P, \rho, T, h, f \)

\[ L_X \propto f Q_{\text{accr}} \]

\[ L_{\text{UV}} \text{ multicolor BB} \]
The disk-corona model

\[ \mu = \text{DISK PHYSICS} \]

\[ f_{\text{max}} = \text{MAX CORONAL STRENGTH} \]
The disk-corona model

\[ \mu = \text{DISK PHYSICS} \]

\[ f_{\text{max}} = \text{MAX CORONAL STRENGTH} \]

\[ L_X \propto f Q_{\text{accretion}} \]

Arcodia+2019
Qualitative prediction: $L_X - L_{UV}$ slope < 1
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$$f = f_{\text{max}} \left(1 + \frac{P_{\text{rad}}}{P_{\text{gas}}}\right)^{-\mu/2}$$
Qualitative prediction: $L_X - L_{UV}$ slope < 1

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Arcodia+2019
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• Results & Conclusions
Observational test: methodology

• We built a sample of radiatively-efficient BL AGN

  - Starting from 1787 BL AGN in XMM-XXL (Liu+16, Menzel+16)
  - Minimizing contamination from extinction, X-ray absorption, X-ray reflection
  - \( N = 379 \) (referred to as XMM-XXL)
Observational test: methodology

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• We take all the BH IDs of XMM-XXL \( (m, \dot{m}, \Gamma_x) \)
Observational test: methodology

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  - Starting from 1787 BL AGN in XMM-XXL (Liu+16, Menzel+16)
  - Minimizing contamination from extinction, X-ray absorption, X-ray reflection
  - $N = 379$ (referred to as XMM-XXL)

- We take all the BH IDs of XMM-XXL ($m, \dot{m}, \Gamma$)

- Mock $L_X - L_{UV}$ for every $\mu, f_{max}$

  Match in normalization, slope and scatter
Outline

• The smoking gun: the $L_X - L_{UV}$

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• Results & Conclusions
Results: a complete picture

\[ \log L_X = \hat{\alpha} + \hat{\beta} \log L_{UV} \]
Results: $L_X - L_{UV}$ normalization

\[ \mu = \text{DISK PRESCRIPTION} \quad f_{\text{max}} = \text{MAX CORONAL STRENGTH} \]
Results: $L_X - L_{UV}$ normalization

$\mu = \text{DISK PRESCRIPTION}$  
$f_{\text{max}} = \text{MAX CORONAL STRENGTH}$
Results: $L_X - L_{UV}$ slope

Disk-corona diagram

What influences the slope of the $L_{corona} - L_{disk}$?

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slope=1

same $f$ across accretion regimes

slope<1

lower $f$ for higher accretion regimes
Results: a complete picture

\[ \log L_X = \hat{\alpha} + \hat{\beta} \log L_{UV} \]
Results: the role of BH spin

Flux-limited samples are biased in detecting high-spin sources preferentially!

(Brenneman+11; Vasudevan+16; Baronchelli+18; Reynolds19)
Future prospects: what about soft-states in XRBs?

Similar behavior as in QSOs?

$F_{\text{COR}} @ 15 \text{ keV}$

$F_{\text{DISK}} @ 0.2 \text{ keV}$
Conclusions

• The gap between simulations and observations needs to be reduced
  
  → Simplified but motivated analytic prescriptions are still a powerful tool

• Disk-corona models should be tested against the observed $L_X - L_{UV}$
  
  → We modeled the observed sources $(m, \dot{m}, \Gamma_x)$ one by one
  
  → Match in normalization, slope and scatter of the $L_X - L_{UV}$

• Why is the slope of the $L_X - L_{UV} < 1$?
  
  → Our model can explain it in terms of modified accretion prescriptions

• Is the observed $L_X - L_{UV}$ recovered?
  
  → In a spin=0 case, models that get the slope right show too weak coronae
  
  → More realistic spin distributions can relax the tension

Thank you!
Results: peak of the X-ray emission

- **X-ray reverberation** and **microlensing** studies predict a corona peaking close to the BH (e.g. Mosquera+13, Reis & Miller 13, Wilkins +16)
The smoking gun of the Disk-Corona interplay

AGN in a sweet spot of accretion \( \dot{m} \approx (0.0x - 1) \)

\( m \approx (0.0x - 1) \)

Very similar properties (in X and UV separately)

Adapted from Liu+2016

Menzel+2016

Arcodia+ subm.
The disk-corona model

\[ f P_{\text{accr}} \]

\[ \mu = \text{DISK PRESCRIPTION} \]

\[ f_{\text{max}} = \text{MAX CORONAL STRENGTH} \]
The disk-corona model

\[ f(1 - \eta)P_{accr} \]

\[ fP_{accr} \]

\[ f\eta P_{accr} \]

\[ (1 - f)P_{accr} \]

\[ \mu = \text{DISK PRESCRIPTION} \]

\[ f_{max} = \text{MAX CORONAL STRENGTH} \]

\[ \frac{m}{\dot{m}} = \Gamma_x \]

Black, Hole

\[ P_{gas} >> \]

\[ P_{rad} >> \]
The disk-corona model

\[ f \cdot \frac{P_{\text{gas}}}{P_{\text{accr}}} \]

\[ f(1 - \eta)P_{\text{accr}} \]

\[ f \eta a_{\text{disk}} P_{\text{accr}} \]

\[ f P_{\text{accr}} \]

\[ (1 - f)P_{\text{accr}} + f \eta (1 - a_{\text{disk}}) P_{\text{accr}} \]

\[ \mu = \text{DISK PRESCRIPTION} \]

\[ f_{\max} = \text{MAX CORONAL STRENGTH} \]
\[
\rho \propto [\alpha_0 m]^{-\frac{4}{\mu+4}} [\dot{m}J(r)] \frac{2(3\mu-4)}{\mu+4} r^{3(2-3\mu)} (1 - f)^{\frac{6(\mu-2)}{\mu+4}} \\
T_{\text{mid}} \propto [\alpha_0 m]^{-\frac{1}{\mu+4}} [\dot{m}J(r)] \frac{2\mu}{\mu+4} r^{\frac{3(2\mu^2-3\mu-2)}{2(\mu-\mu(\mu+4))}} (1 - f)^{\frac{2\mu-1}{\mu+4}} \\
h = 9.14 \dot{m}J(r)(1 - f) \\
P \propto [\alpha_0 m]^{-\frac{4}{\mu+4}} [\dot{m}J(r)] \frac{8\mu}{\mu+4} r^{\frac{6(2\mu^2-3\mu-2)}{(2-\mu)(\mu+4)}} (1 - f)^{\frac{4(2\mu-1)}{\mu+4}} \\
\frac{(2\alpha_0)^{1/\mu} - f^{2/\mu}}{f^{2/\mu}} = \frac{P_{\text{rad}}}{P_{\text{gas}}} \propto [\alpha_0 m]^{\frac{4}{\mu+4}} [\dot{m}J(r)] \frac{8}{\mu+4} r^{-\frac{21}{2(\mu+4)}} (1 - f)^{\frac{9}{\mu+4}}
\]

The disk-corona model

\[
\rho = 14.44 k_0^{-3/5} \xi^{3/10} [\alpha_0 m]^{-7/10} [\dot{m}J(r)]^{2/5} r^{-33/20} (1 - f)^{-3/10} \\
T = 8.01 \times 10^8 k_0^{-4/15} \xi^{-1/5} [\alpha_0 m]^{-1/5} [\dot{m}J(r)]^{2/5} r^{-9/10} (1 - f)^{1/5} \\
h = 1.72 \times 10^{-2} k_0^{-7/15} \xi^{-1/10} [\alpha_0 m]^{-1/10} [\dot{m}J(r)]^{1/5} r^{21/20} (1 - f)^{1/10} \\
P = 1.91 \times 10^8 k_0^{-13/15} \xi^{1/10} [\alpha_0 m]^{-9/10} [\dot{m}J(r)]^{4/5} r^{-51/20} (1 - f)^{-1/10} \\
\frac{4\alpha_0^2 - f^4}{f^4} = \frac{P_{\text{rad}}}{P_{\text{gas}}} = 5.41 \times 10^2 k_0^{-1/5} \xi^{-9/10} [\alpha_0 m]^{1/10} [\dot{m}J(r)]^{4/5} r^{-21/20} (1 - f)^{9/10}
\]
The disk-corona model

The disk-corona model is a theoretical framework used to describe the structure of accretion disks around compact objects, such as black holes and neutron stars. It combines the disk model, which describes the inner region of the disk where material accretes onto the central object, with the corona model, which describes the outer, hotter region of the disk where the magnetic field is strong and radiative losses are significant.

In the disk-corona model, the pressure and density of the disk are described as a function of the radial distance from the central object, while the temperature and opacity are determined by the balance between inward gravitational and outward pressure forces. The model also incorporates the effects of magnetic fields and radiative cooling, which are crucial for understanding the observed properties of accretion disks.

The diagrams in the image illustrate various properties of the disk-corona model, such as the radial profiles of density, opacity, and temperature, and how they vary with different parameters such as the mass accretion rate and disk inclination.
Results: $L_X - L_{UV}$ normalization

$f_{\text{max}} = \text{MAX CORONAL STRENGTH}$
Results: $L_X - L_{UV}$ normalization

$f_{\text{max}} = \text{MAX CORONAL STRENGTH}$
Comparison with other models
The cleaned sample
The model-mock comparison
Results: $L_X - L_{UV}$ scatter

\[ \sigma_{\text{phys}} \lesssim 0.2 \text{ dex} \]

Controlling for calibration issues, variability, non-simultaneity.. 
(Lusso & Risaliti 16; Chiaraluce+ 18)

- The intrinsic scatter is given by the diversity in $m, \Gamma_x$ at a given $\dot{m}$ ($L_{3000}$)
Results: high-spin case
Results: the role of a dynamic corona

\[ L_{2\,\text{keV}} \propto f(1 - \eta) P_{\text{acocr}} \]

\( \eta = 0.55 \) was adopted, we then tested different \( \eta \) (also mimicking outflowing coronae)

(Haardt\&Maraschi93) (Beloborodov 99; Janiuk 00)