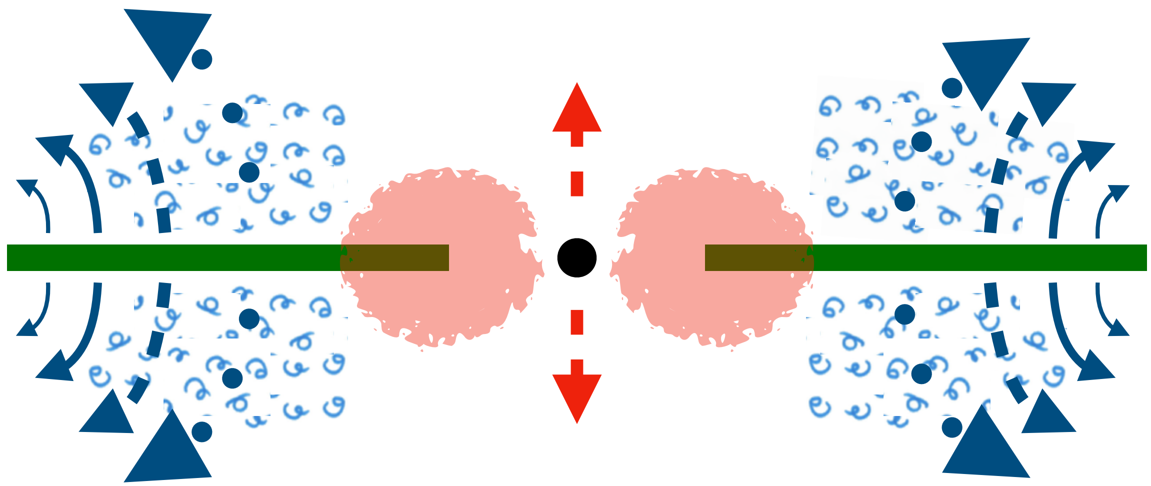
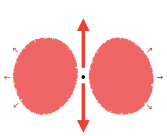
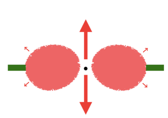
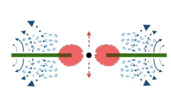
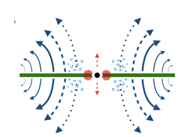
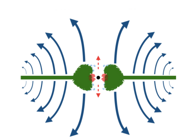
# A global view of the inner accretion and ejection flow around super massive black holes

## Radiation-driven accretion disk winds in a physical context

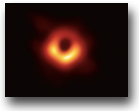


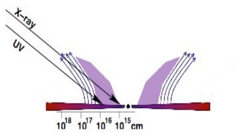
Margherita Giustini and Daniel Proga

*A&A accepted, arXiv:1904.07341*

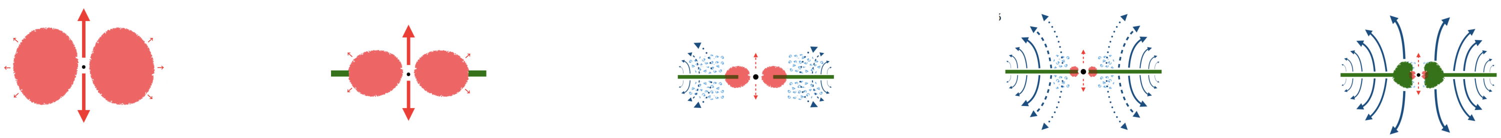
# Outline

**1**  AGN: accretion/ejection around SMBHs

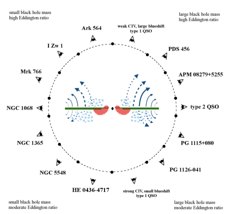
**2** 

AGN winds: theories & observations

## 3 A global scheme for accretion/ejection around SMBHs

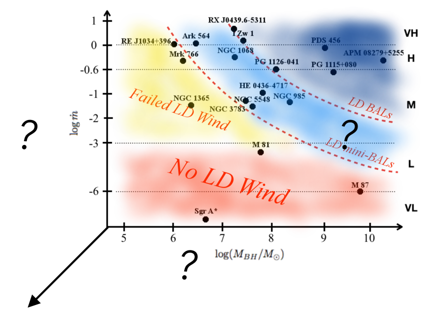


*Quiescent* | *LLAGN* | *Seyfert* | *QSO* | *Super-Eddington*

**3.1**  Accretion disk winds and geometrical effects

**3.2** Comparison with observations

**3.3** The future necessary steps



# Looking up at the night sky with optical light…

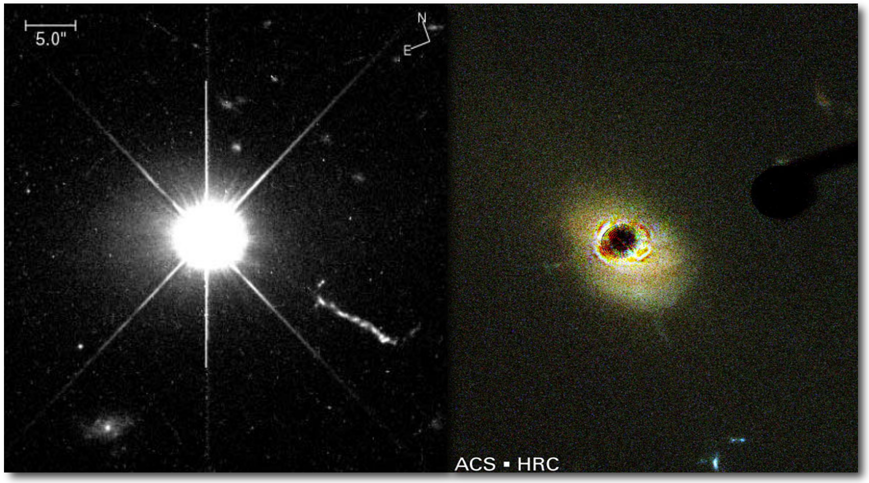
STARS

$L_{star} \approx L_{\odot}$

GALAXIES

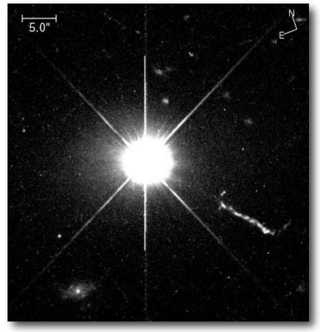
$L \approx \sum L_{stars}$

**Q**uasi **S**tellar **O**bjects ~ **A**ctive **G**alactic **N**uclei




$$L \approx 10^{10-15} L_{\odot} \neq \sum L_{stars}$$

# AGN: mass accretion onto Super Massive Black Holes



## MASS ACCRETION ONTO SUPER MASSIVE BLACK HOLES

**The most efficient mechanism for energy production**

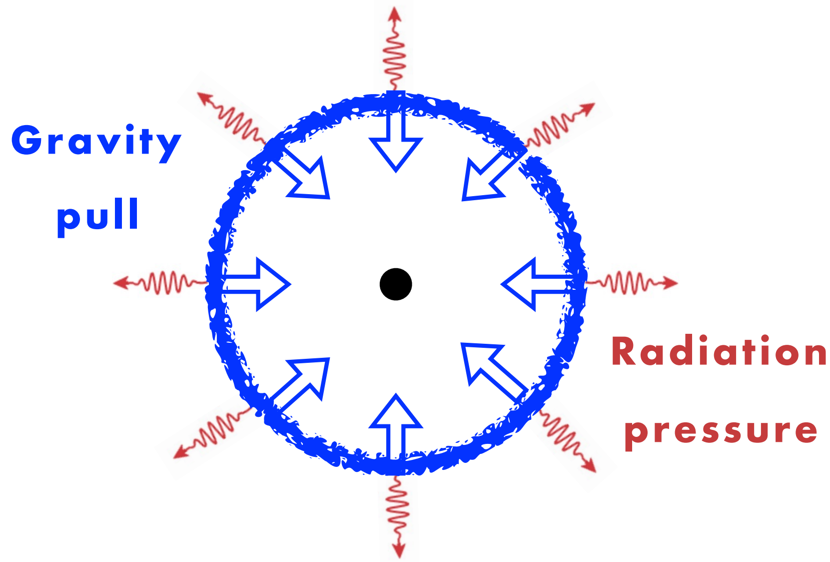
- Black Hole Mass: $M_{BH} = 10^{6-10} M_{\odot}$
- Accretion Luminosity: $L_{acc} = \eta \left( \dot{M}_{acc} \right) c^2$

$$\sim 5.7 \left( \frac{\eta}{0.1} \right) \left( \frac{\dot{\mathrm{M}}_{\mathrm{acc}}}{1\mathrm{M}_{\odot}\mathrm{yr}^{-1}} \right) \times 10^{45} \quad \mathrm{erg\ s^{-1}}$$

- Accretion Efficiency: $\eta \approx 0.06 - 0.42$

*Compare to ~0.007 maximum for nuclear fusion!*

# AGN: mass accretion onto Super Massive Black Holes




- **Eddington Luminosity:**

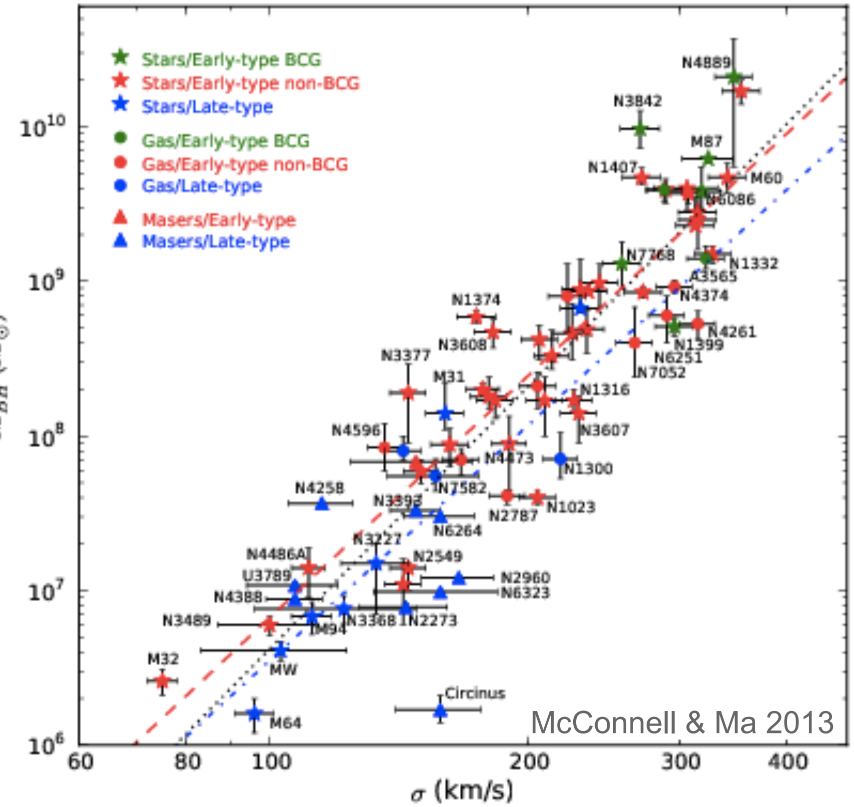
$$L_{Edd} = \frac{4\pi G M_{BH} m_p c}{\sigma_T} \sim 1.3 \left(\frac{\mathrm{M_{BH}}}{10^8 \mathrm{M_\odot}}\right) \times 10^{46} \quad \mathrm{erg\ s^{-1}}$$

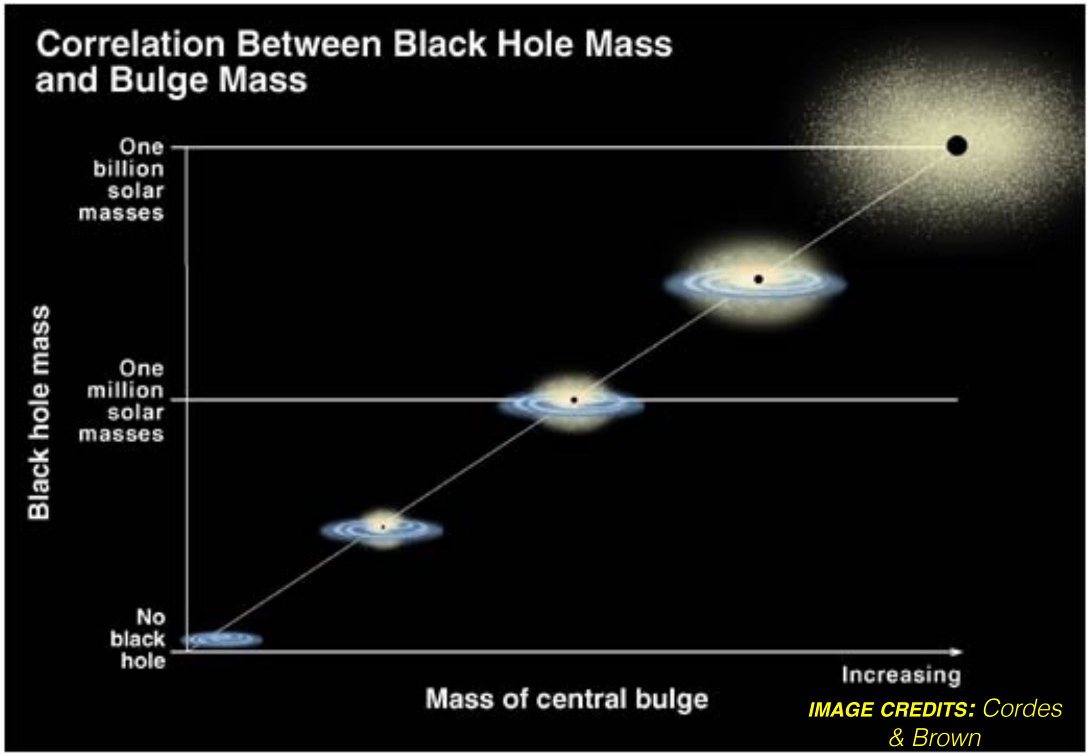
- **Eddington Ratio:** $\dot{m} = L/L_{Edd}$

- Gravitational Radius: $r_g = GM_{BH}/c^2 \sim 1.5 \left(\frac{\mathrm{M_{BH}}}{10^8 \mathrm{M_\odot}}\right) \times 10^{13} \quad \mathrm{cm}$

# The AGN phase is crucial to understand galaxy evolution

Ferrarese & Merritt 2000, Gebhardt et al. 2000



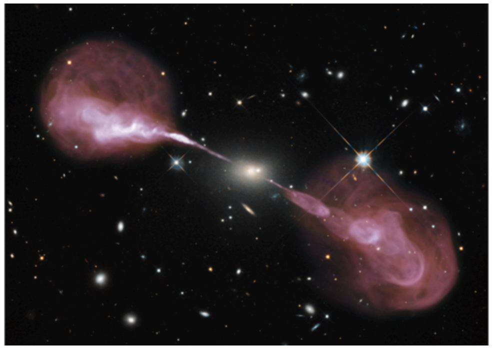




## A FEEDBACK MECHANISM BETWEEN THE CENTRAL SUPERMASSIVE BLACK HOLE AND THE HOST GALAXY

# AGN Feedback

- **Kinetic feedback**

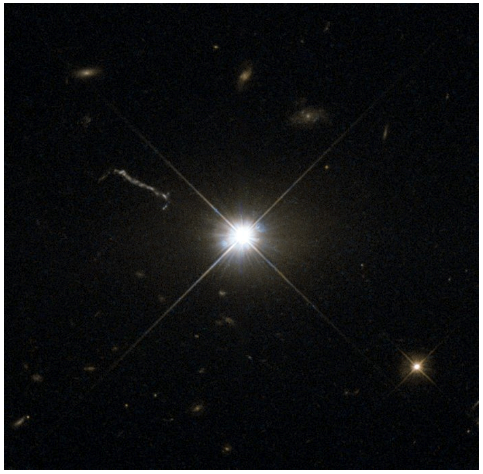
  Radio jet



"Radio mode"
LLAGN
ADAF-powered

- **Radiative feedback**

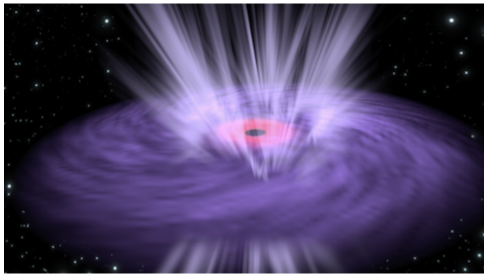
  Luminosity



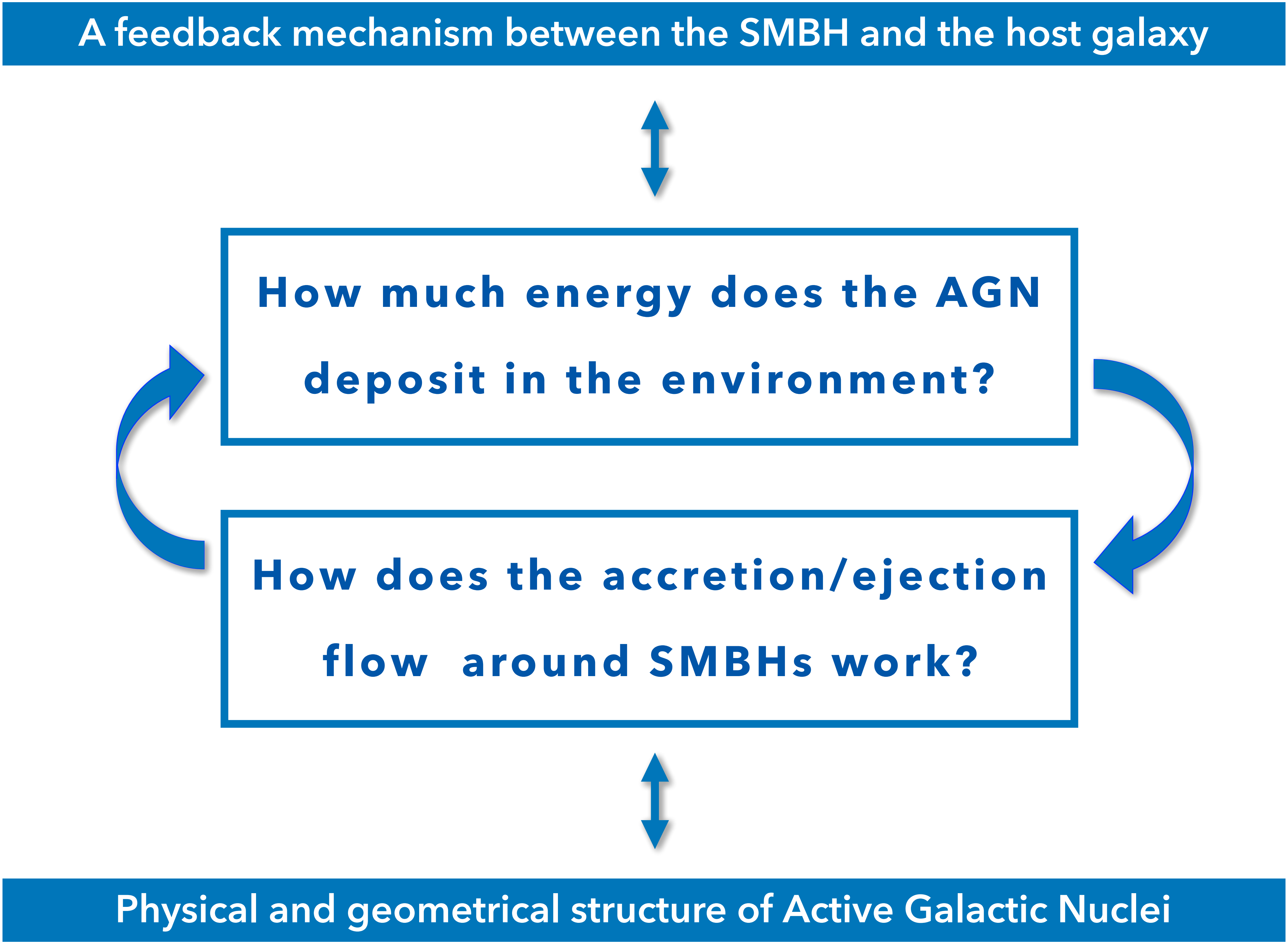
"QSO mode"
Luminous AGN
disk-powered

- **Radiative + kinetic feedback**

  Luminosity + wind



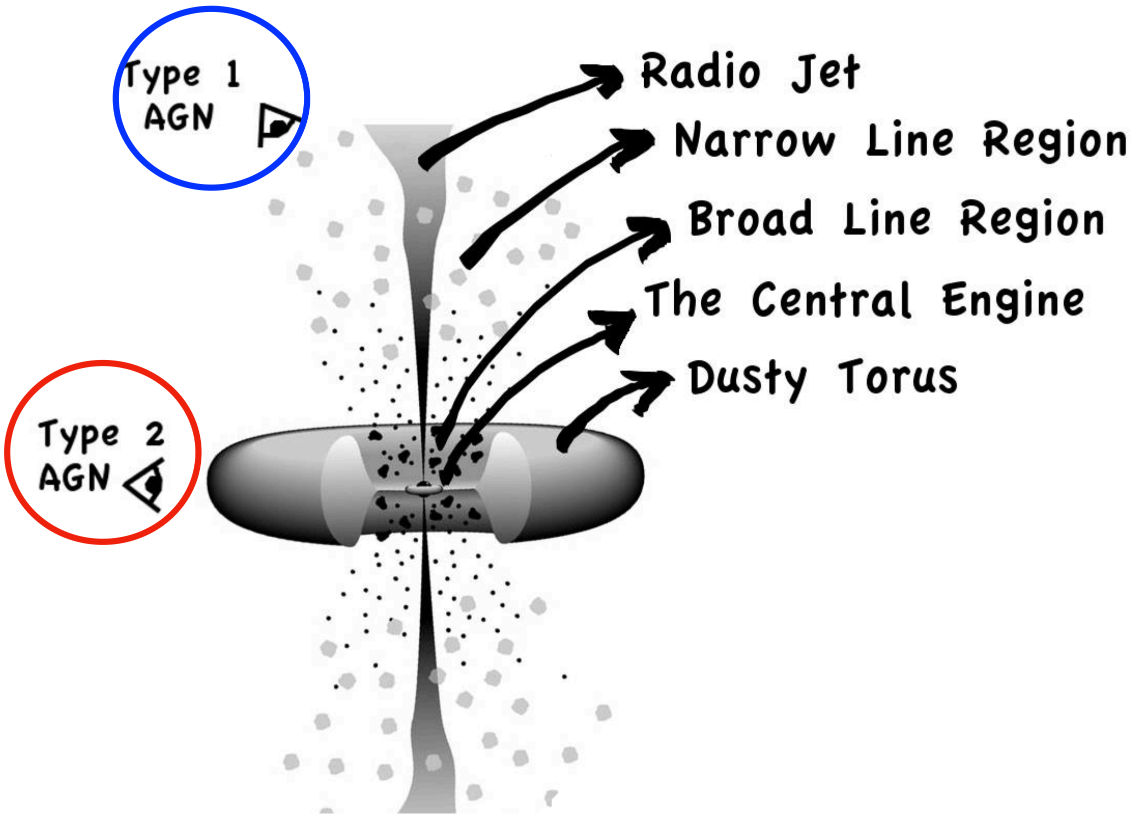
**? % of AGN**
**how and how much?**


A feedback mechanism between the SMBH and the host galaxy
How much energy does the AGN deposit in the environment?
How does the accretion/ejection flow around SMBHs work?
Physical and geometrical structure of Active Galactic Nuclei

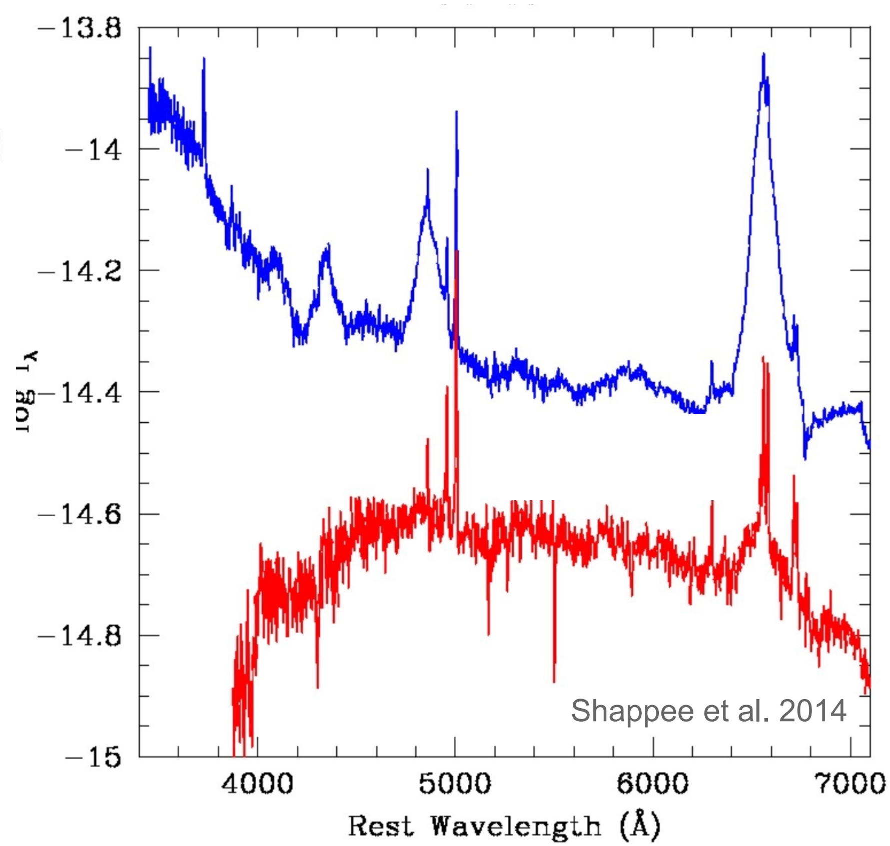
# AGN Unified Geometrical Scenario

**UNOBSTRUCTED OR OBSCURED VIEW**

**OF THE CENTRAL ENGINE OF LUMINOUS AGN**




Urry & Padovani 1995; Antonucci 1993



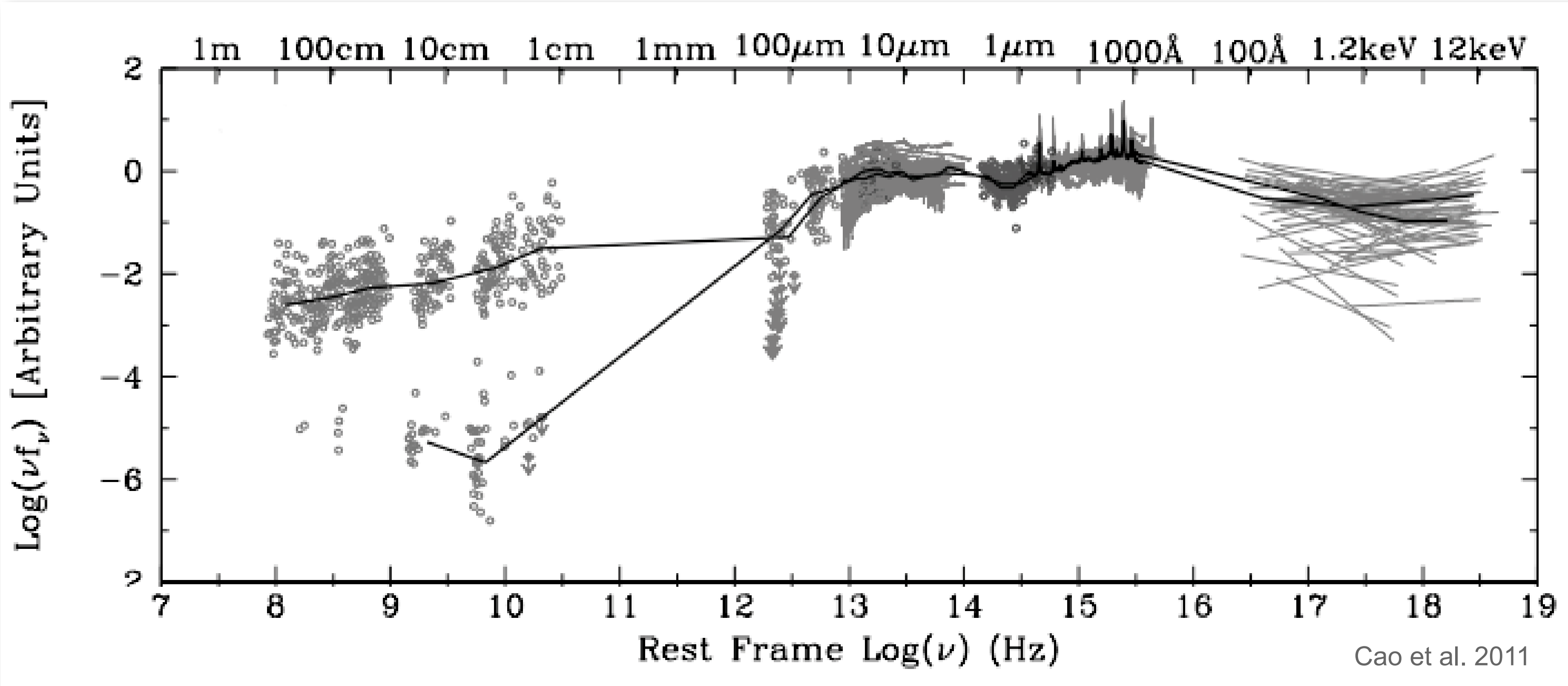

"Central engine": accretion disk + upscattering corona

*Plenty of gas and radiation around: lots of reprocessing*

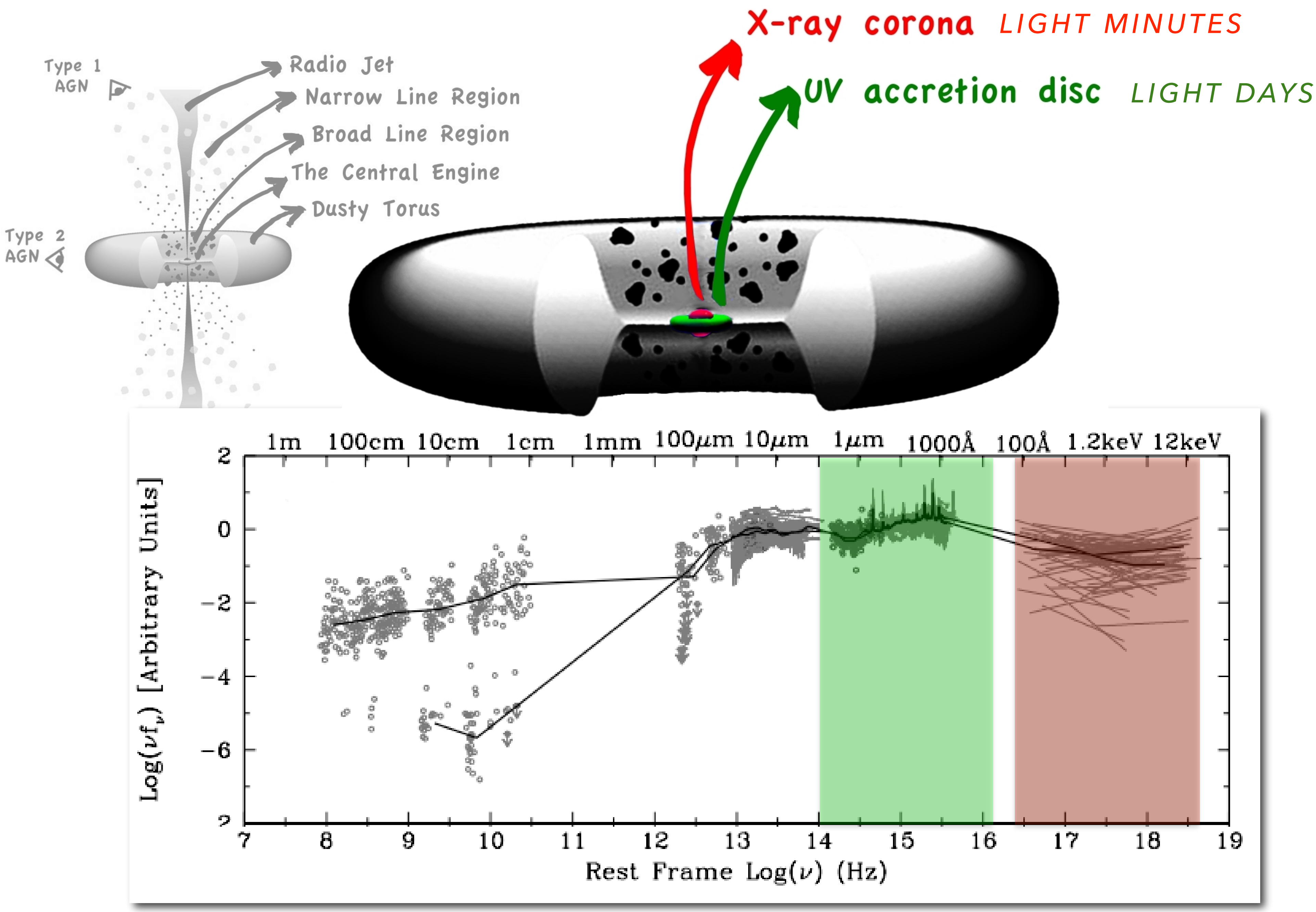
# AGN are multi wavelength messengers

## Spectral Energy Distribution (SED)

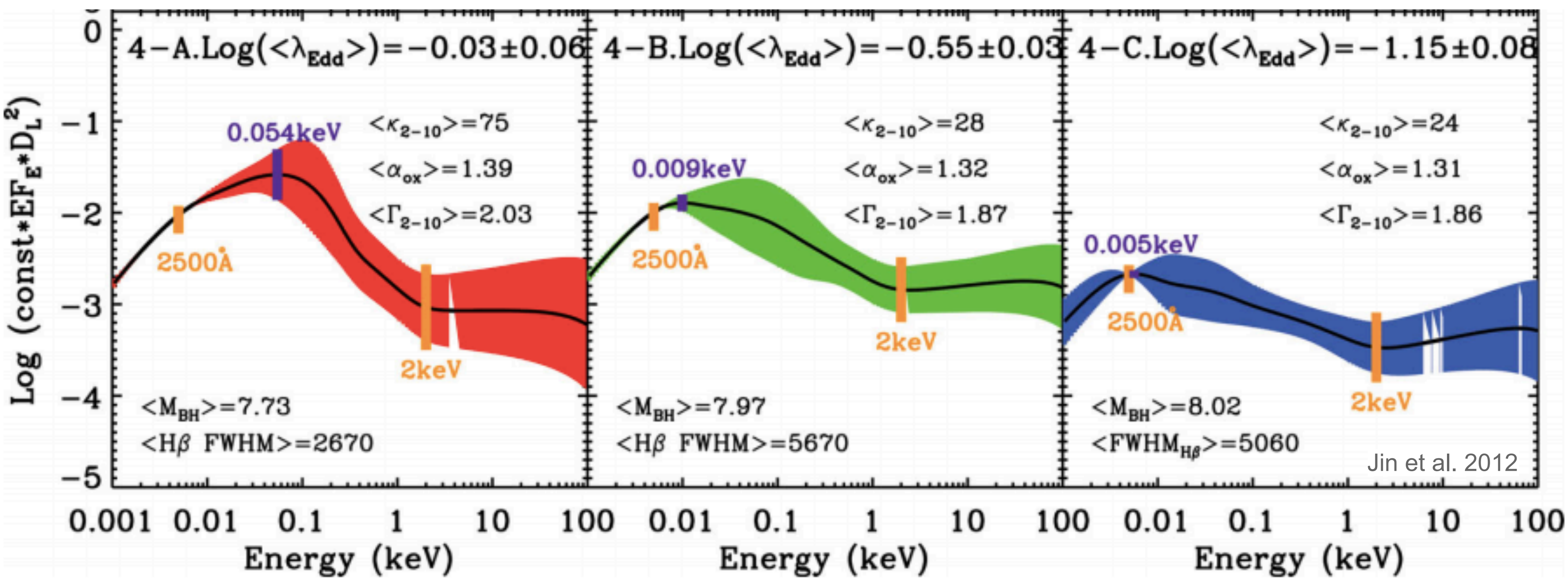
Radio Infrared UV X-ray



# UV and X-rays probe the AGN innermost regions



# The UV/X-ray SED of luminous AGN varies with mdot

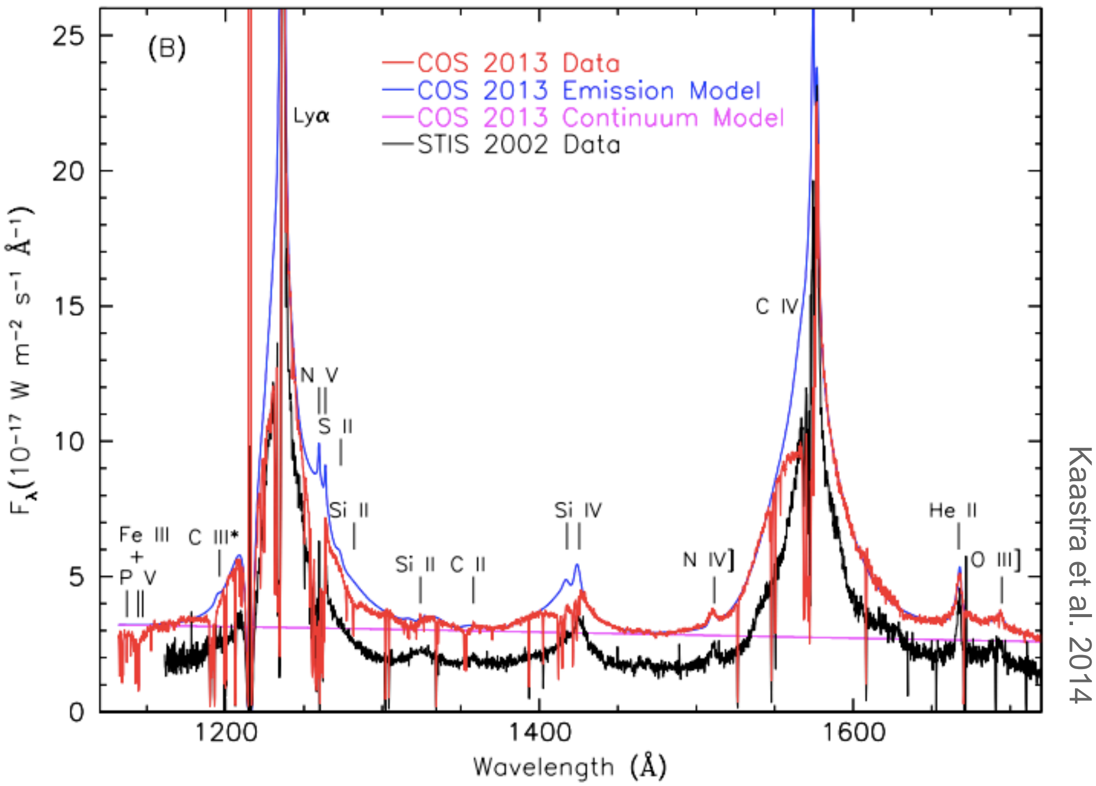


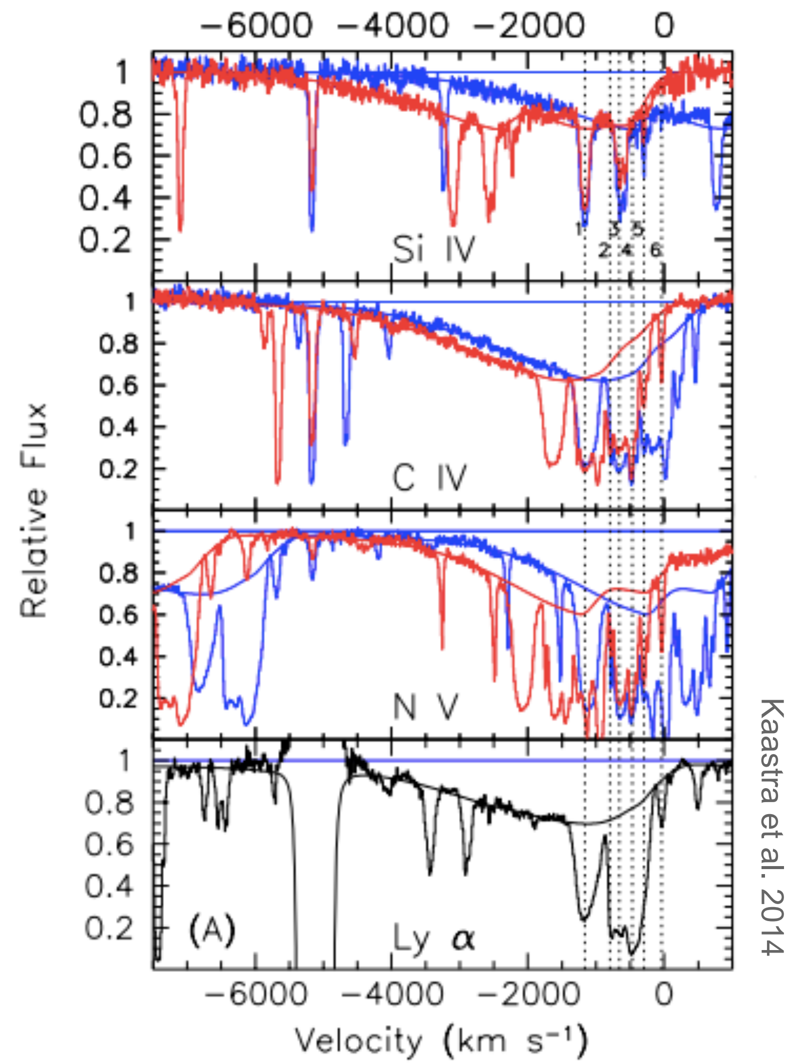

**High mdot:** Strong UV flux, weak X-ray flux

**Low mdot:** Plenty of X-ray photons compared to the UV ones

Accretion disk temperature: $T^4 \propto M_{BH}\dot{M}/R_{in}^3 \propto (\dot{m}/M_{BH}^2)(R_{in}/R_g)^{-3}$

# Blueshifted absorption lines in the UV spectra



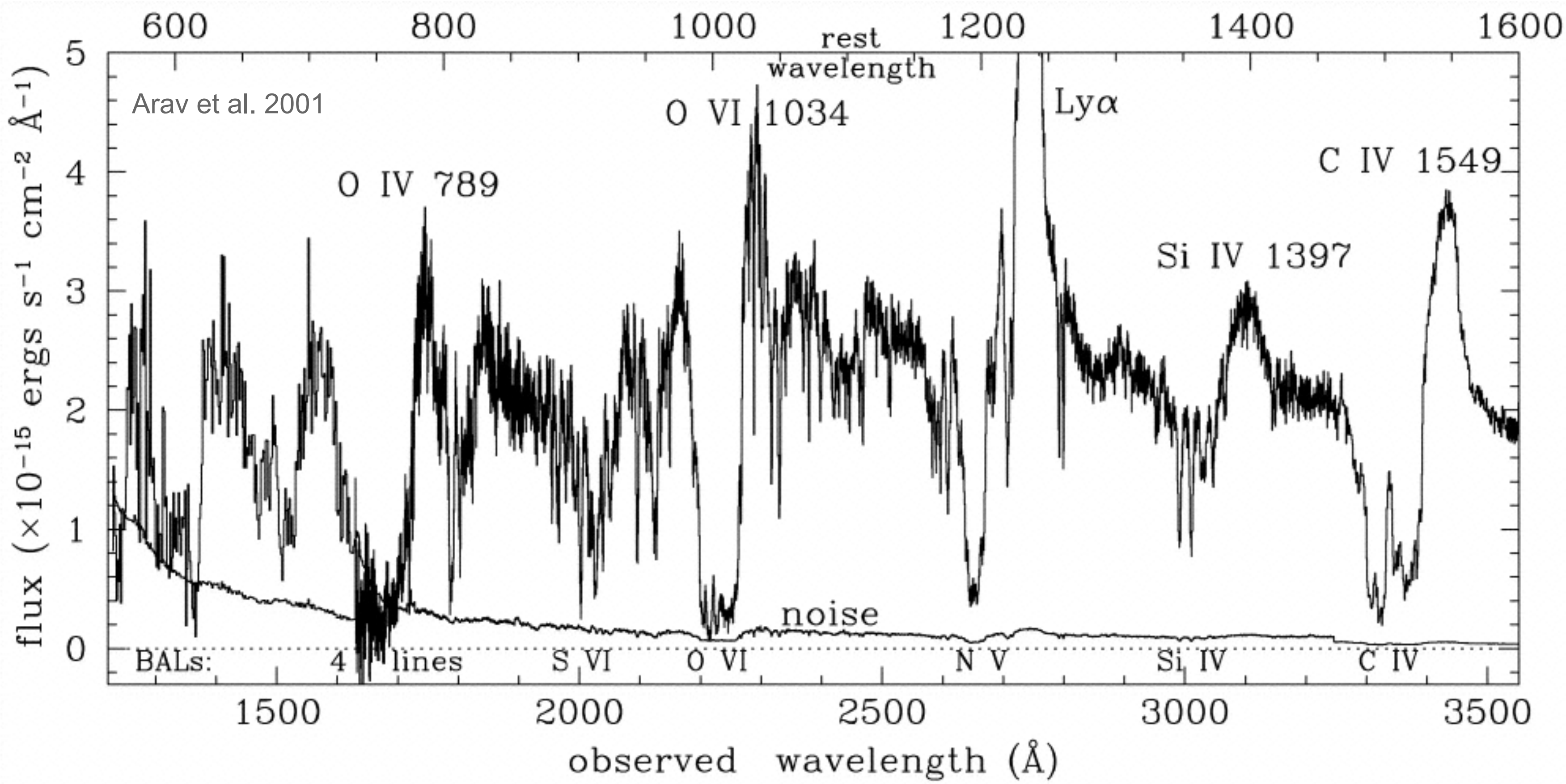




| | |
|---|---|
| "Narrow" | FWHM < 500 km/s |
| "mini-Broad" | 500 km/s < FWHM < 2000 km/s |
| "Broad" | FWHM > 2000 km/s |

**Narrow/mini-Broad UV absorption lines in >50% of AGN**

# UV Broad Absorption Lines

## The most spectacular examples: BAL QSOs

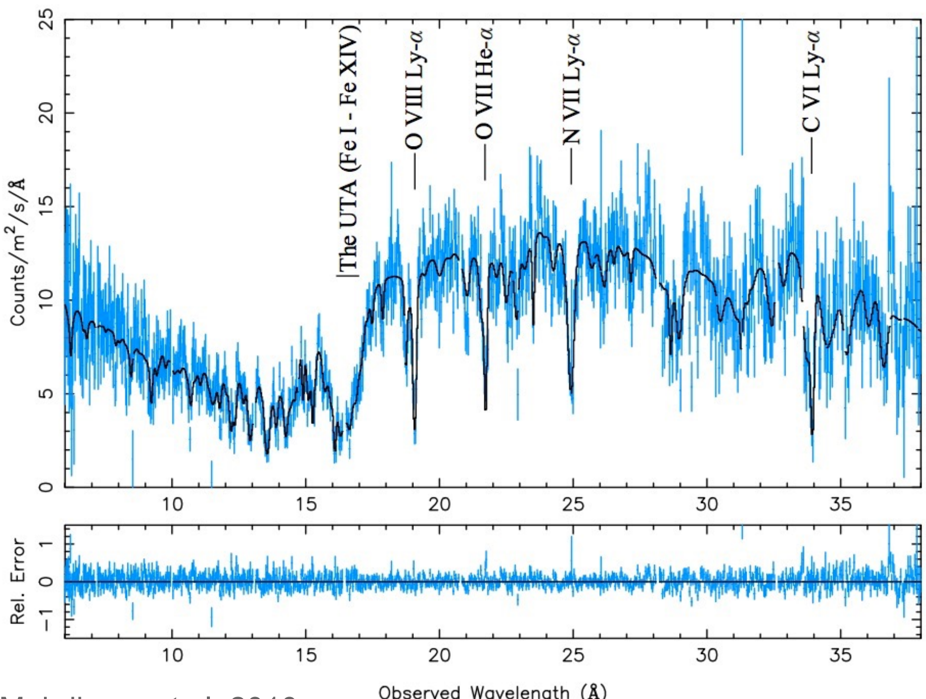



**Observed in 15-20% of optically selected QSOs**

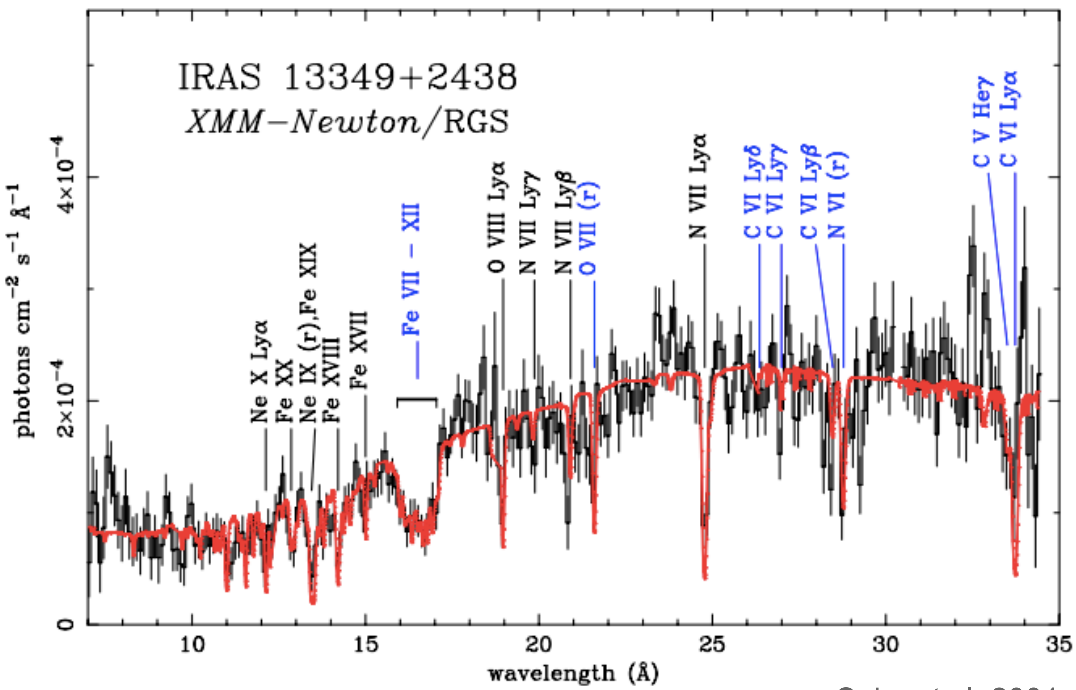
**larger intrinsic fraction (>30-40%)**

Velocity up to 0.2c

# X-ray narrow absorption lines




Mehdipour et al. 2010



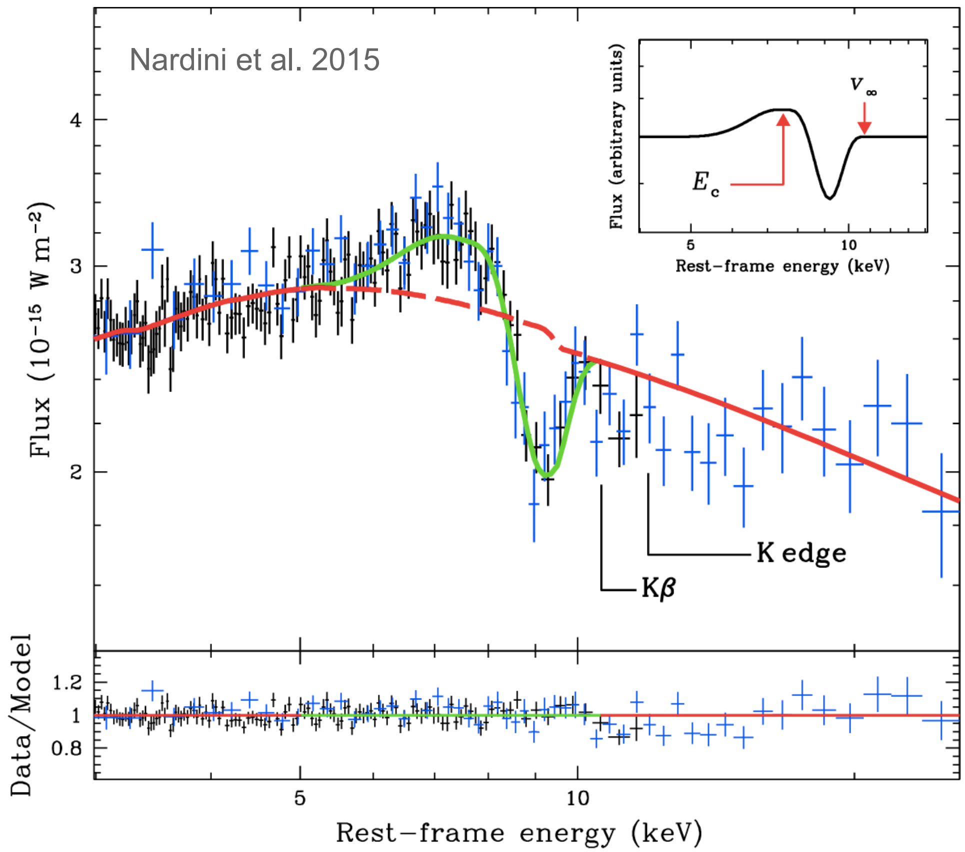

Sako et al. 2001

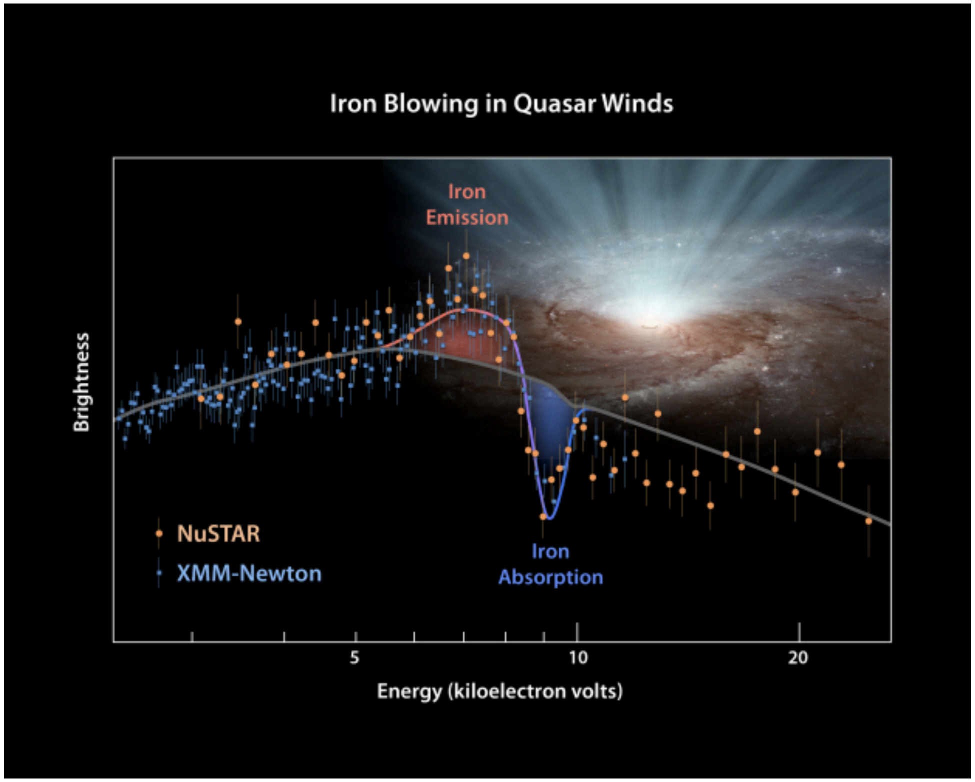
## X-ray "Warm Absorber"

## Observed in >50% of AGN

Velocity of 100-1000s km/s

# X-ray broad absorption lines




## "Ultra-fast outflows" are observed in >30% of local AGN

Tombesi et al. 2010

Large column densities > $10^{23}$ cm$^{-2}$ of highly ionized iron

Velocity >10,000 km/s, up to ~0.4-0.5c

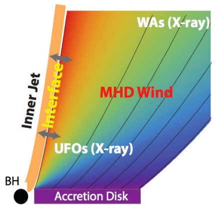
# The wind must overcome gravity to exist

**The closest to the SMBH is the wind launching point, the fastest is its terminal velocity.**

- **Thermal Pressure** can launch low-velocity winds: X-ray warm absorber, UV NALs

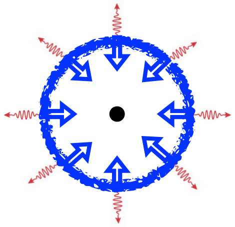
e.g., Krolik & Kriss 2001; Dorodnitsyn et al. 2008

- **Magnetic Field** can launch self-similar winds of any velocity




e.g., Königl & Kartje 1994; Fukumura et al. 2015

- **Radiation Pressure** can launch high-velocity winds through continuum and line opacity



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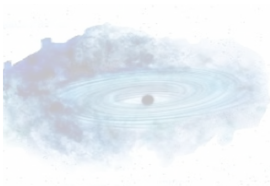

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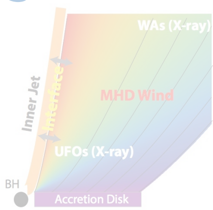


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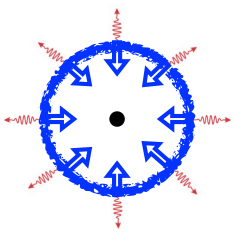

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$$L_{Edd} = \frac{4\pi G M_{BH} m_p c}{\sigma_T}$$

***$L > L_{Edd}$: Super-Eddington wind***

# Radiation-driven winds

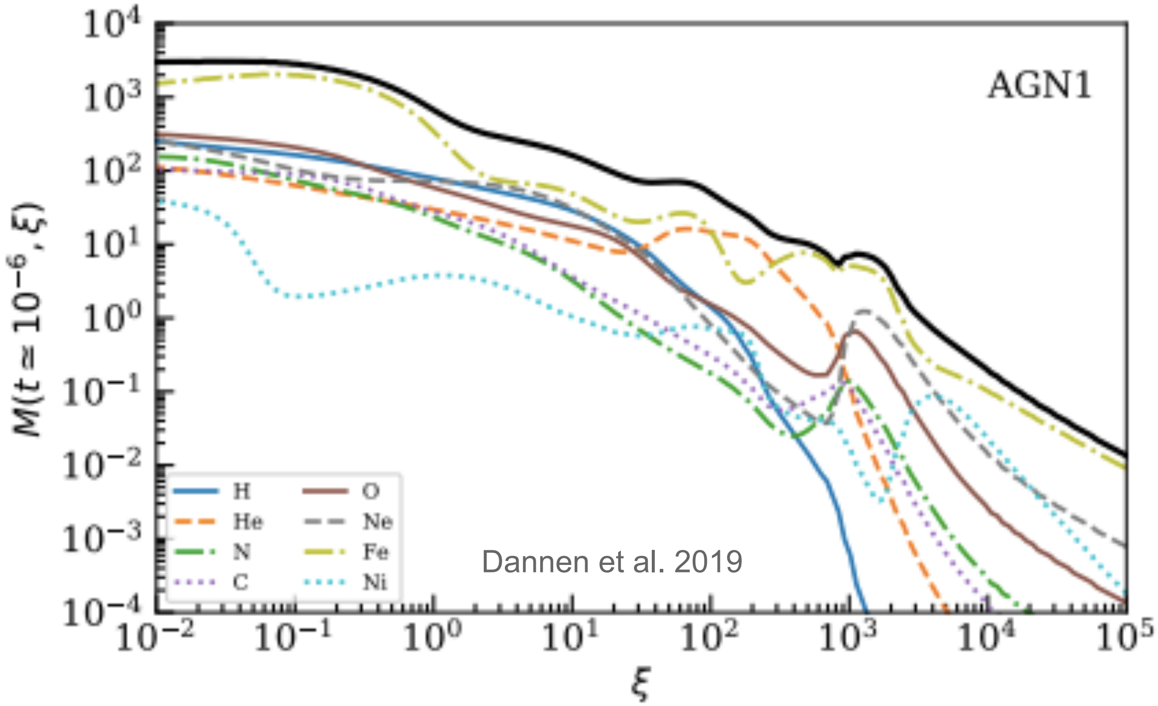
If matter is partially ionized:

effective cross section >> $\sigma_T$

"Force Multiplier" M

*Line-driven wind*

*at $L < L_{Edd}$*

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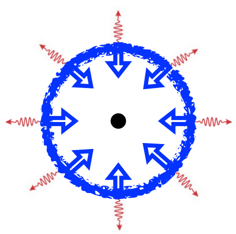


$$L_{Edd} = \frac{4\pi G M_{BH} m_p c}{\sigma_T}$$

*$L > L_{Edd}$: Super-Eddington wind*

# Line-driven accretion disk winds

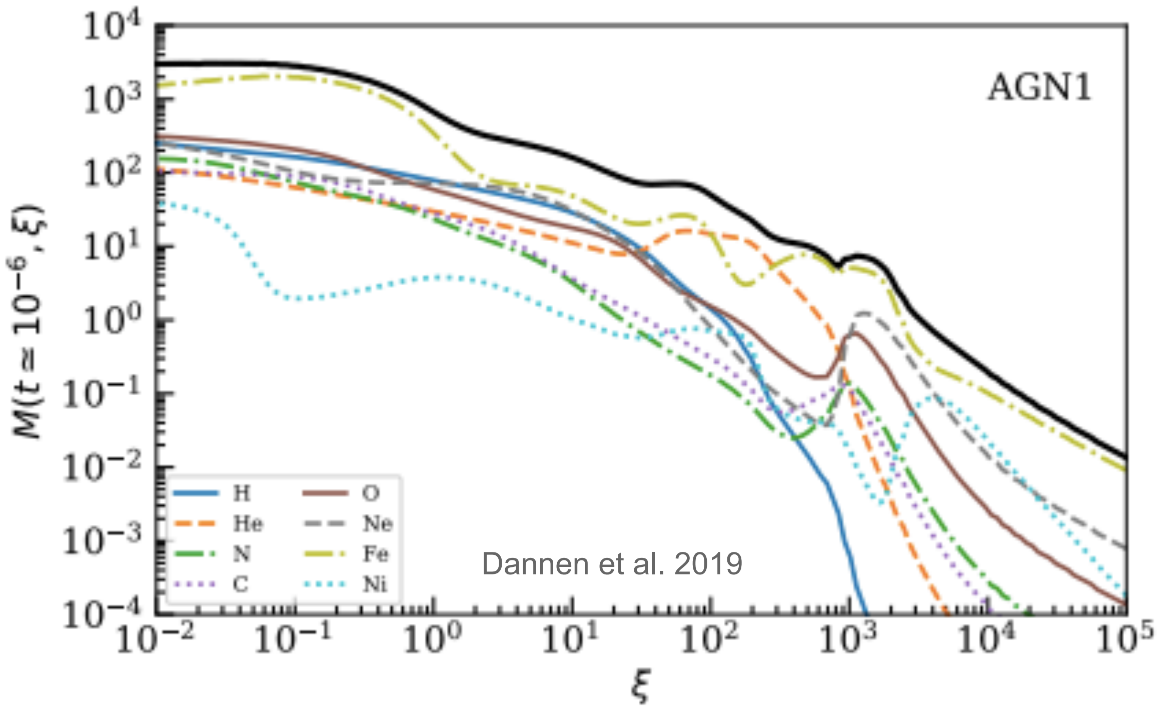
If matter is partially ionized:

effective cross section >> $\sigma_T$

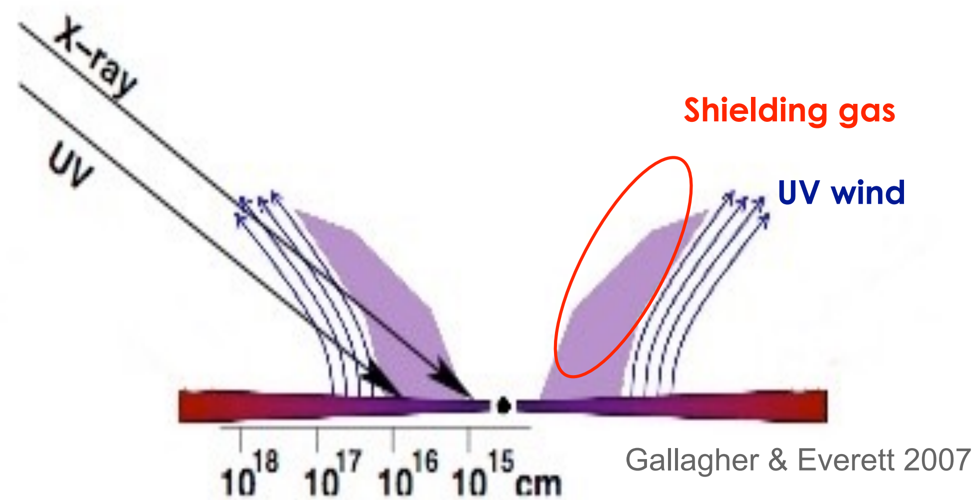
"Force Multiplier" M

***Line-driven wind***

***at $L < L_{Edd}$***




*The relative X-ray/UV photon flux is crucial for LD to be efficient in AGN: the UV-absorbing atoms need to be "shielded" against the X-ray photons in order not to lose electrons and be able to become a wind.*



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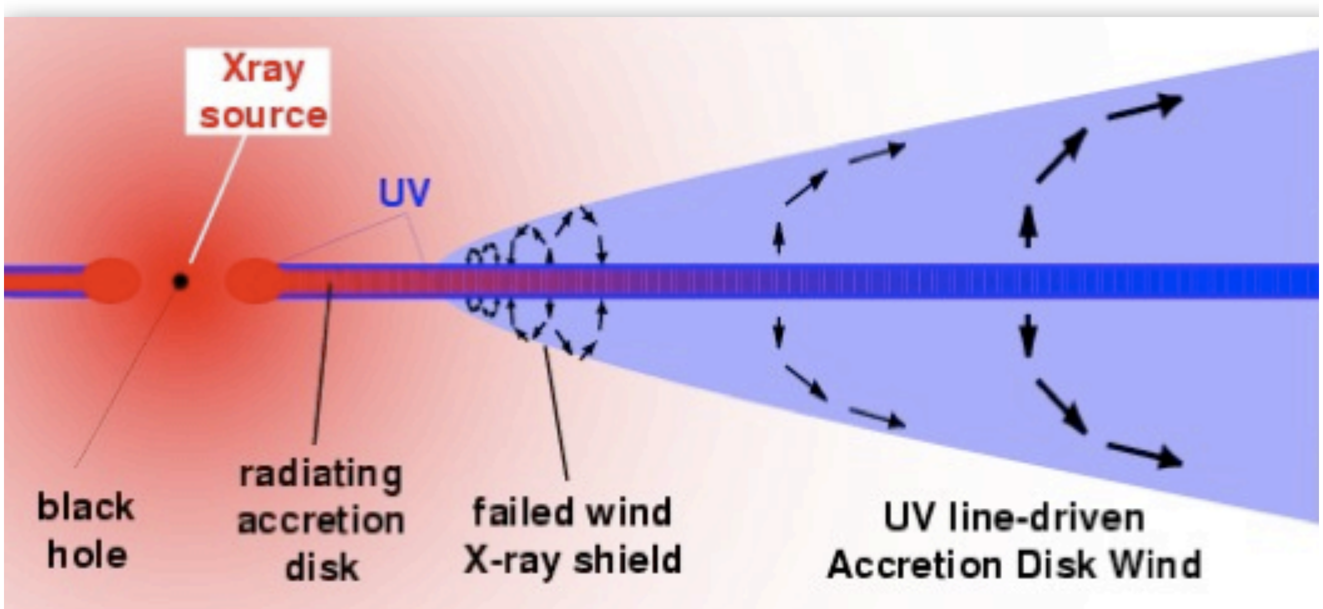


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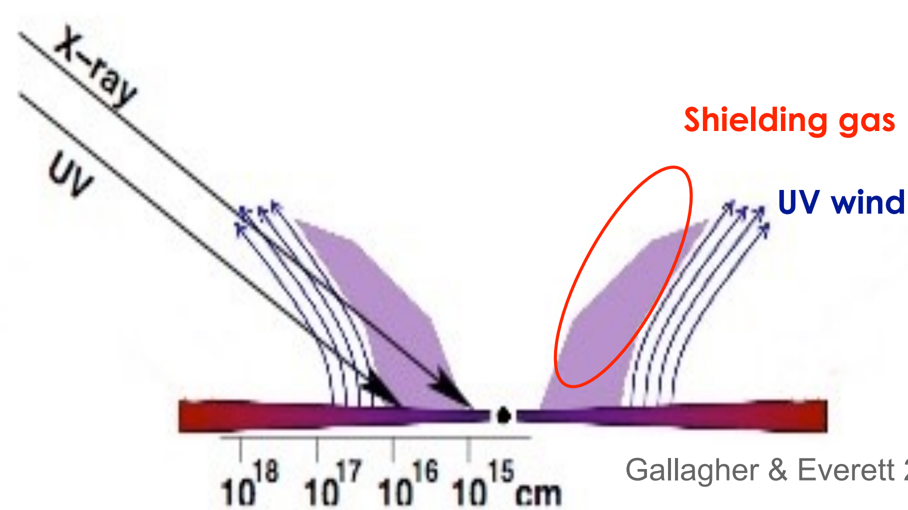
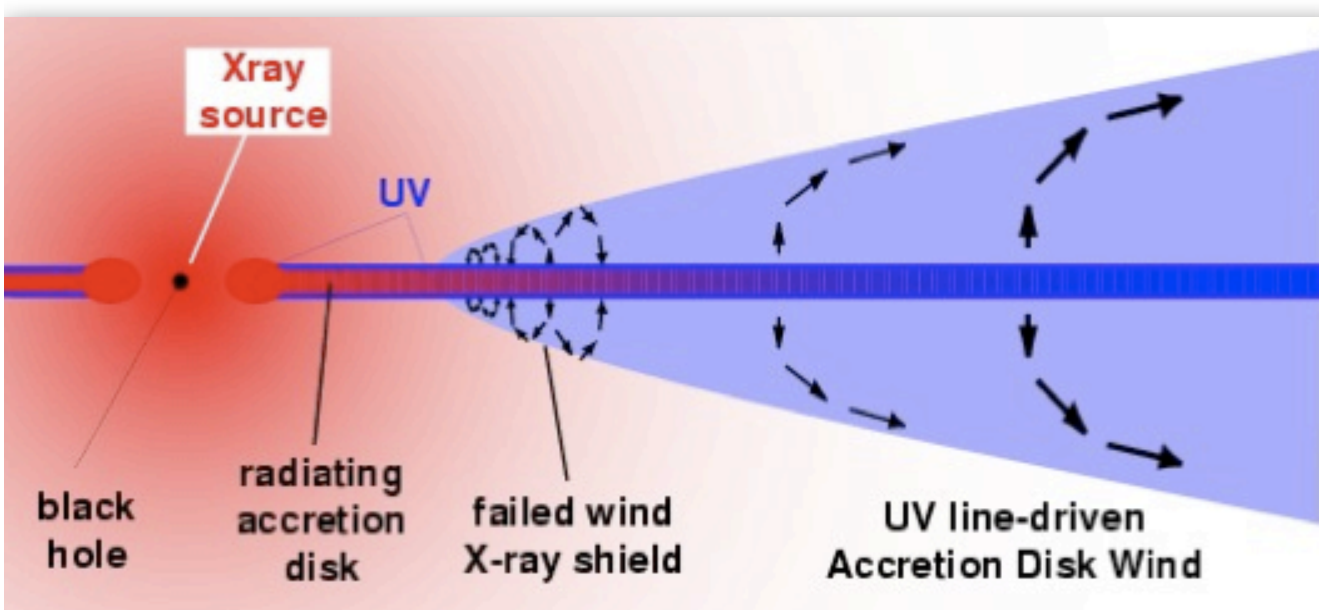



Gallagher & Everett 2007

# Line-driven accretion disk winds

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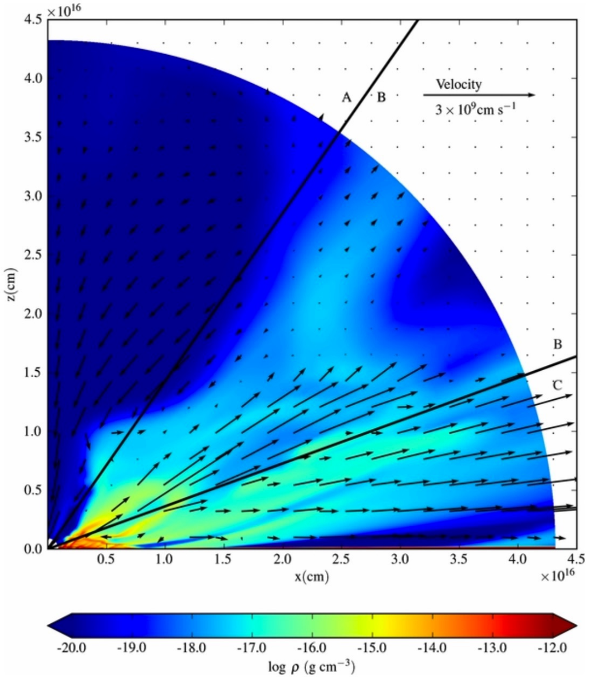



*For high Eddington ratios and large black hole masses: an inner failed wind shields the farther out portion of the flow from the central X-ray radiation. Strong equatorial disk winds are launched.*

# A global view of the inner accretion/ejection flow around SMBHs

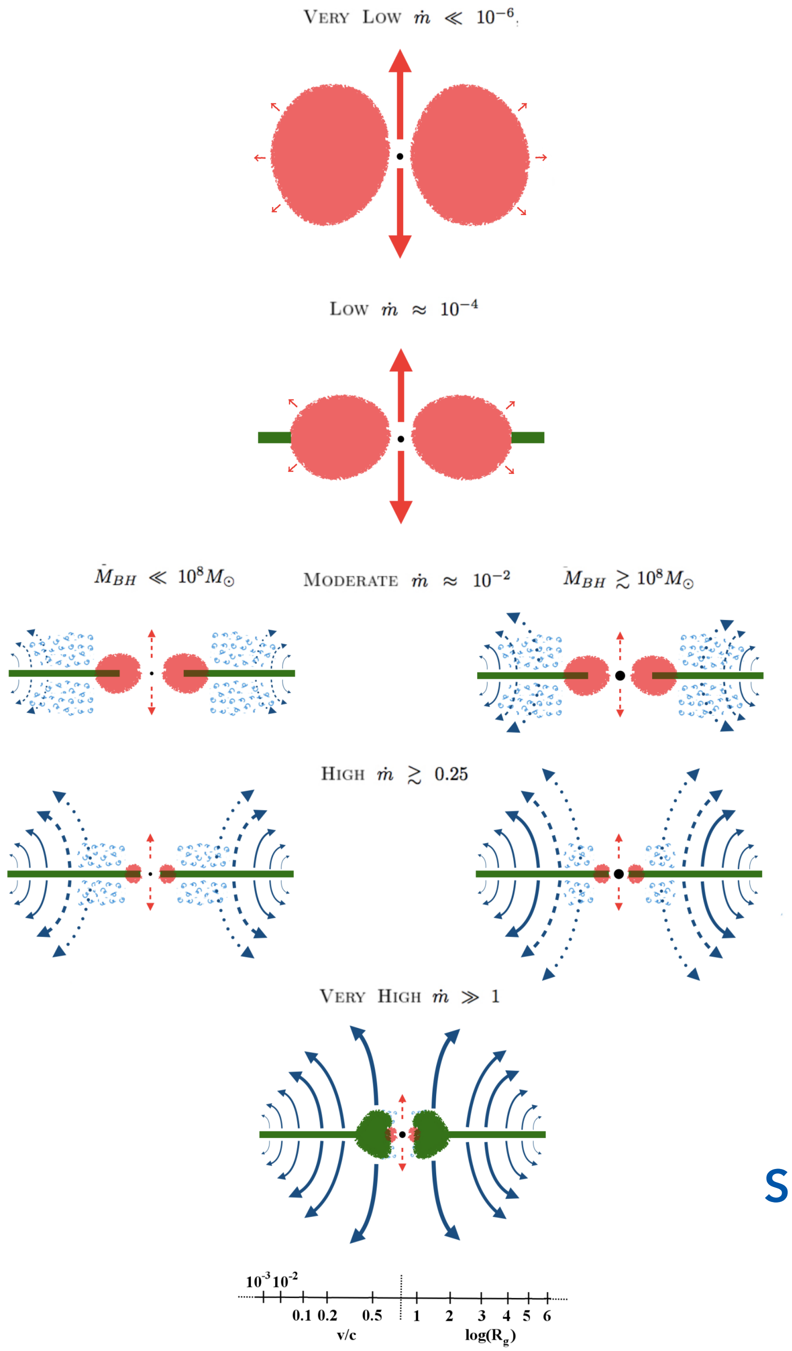
**Quiescent** **LLAGN** **Seyfert** **QSO** **super-Eddington**

| Inefficient accretion flow | | Efficient accretion flow |
|---|---|---|
| Hot ADAF | | Cold disk + corona |
| Collimated, relativistic ejection flow | ? | Wide-angle, sub-relativistic ejection flow |
| Strong jet | | Weak jet |
| Strong kinetic feedback<br>Weak radiative feedback | | Strong radiative feedback<br>Weak kinetic feedback |

**Variations of SED with black hole mass**

**Presence/absence of strong accretion disk winds**

# A global view of the inner accretion/ejection flow around SMBHs



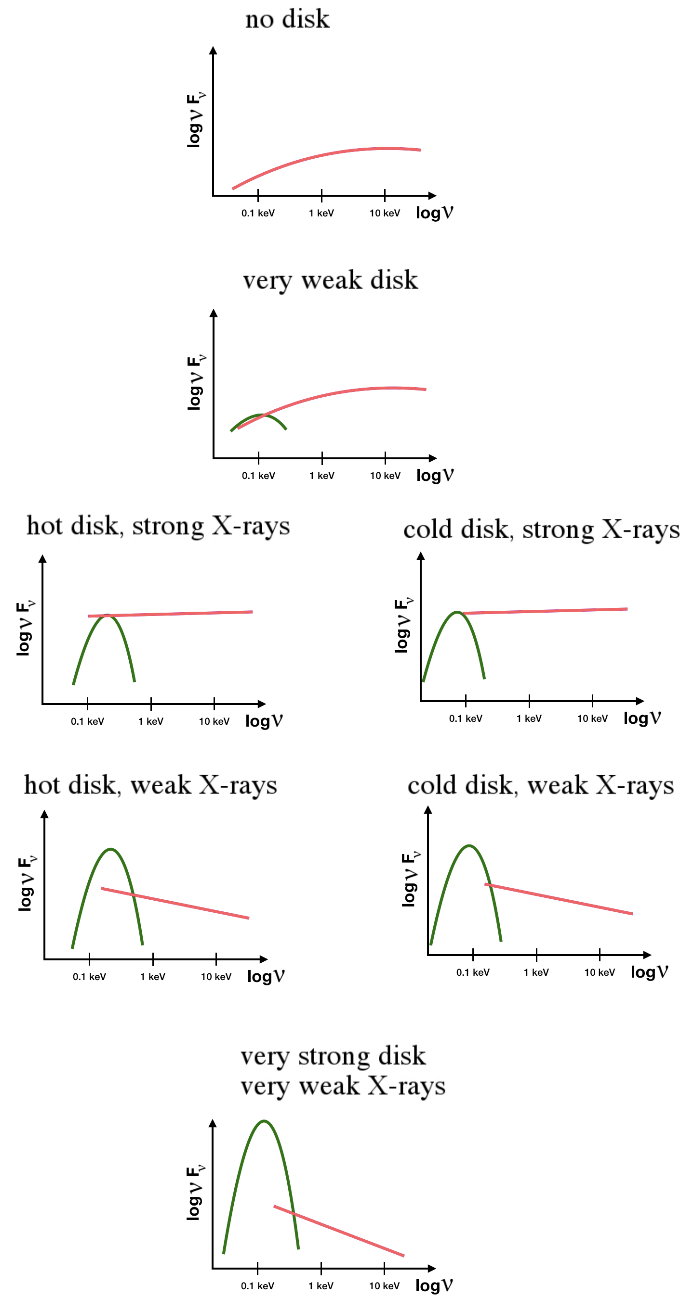

Quiescent

LLAGN

Seyfert

QSO

Super-Eddington



# Logarithmically-scaled side view of the inner parsec of an AGN

Optically thin matter

Optically thick matter

Relativistic jet

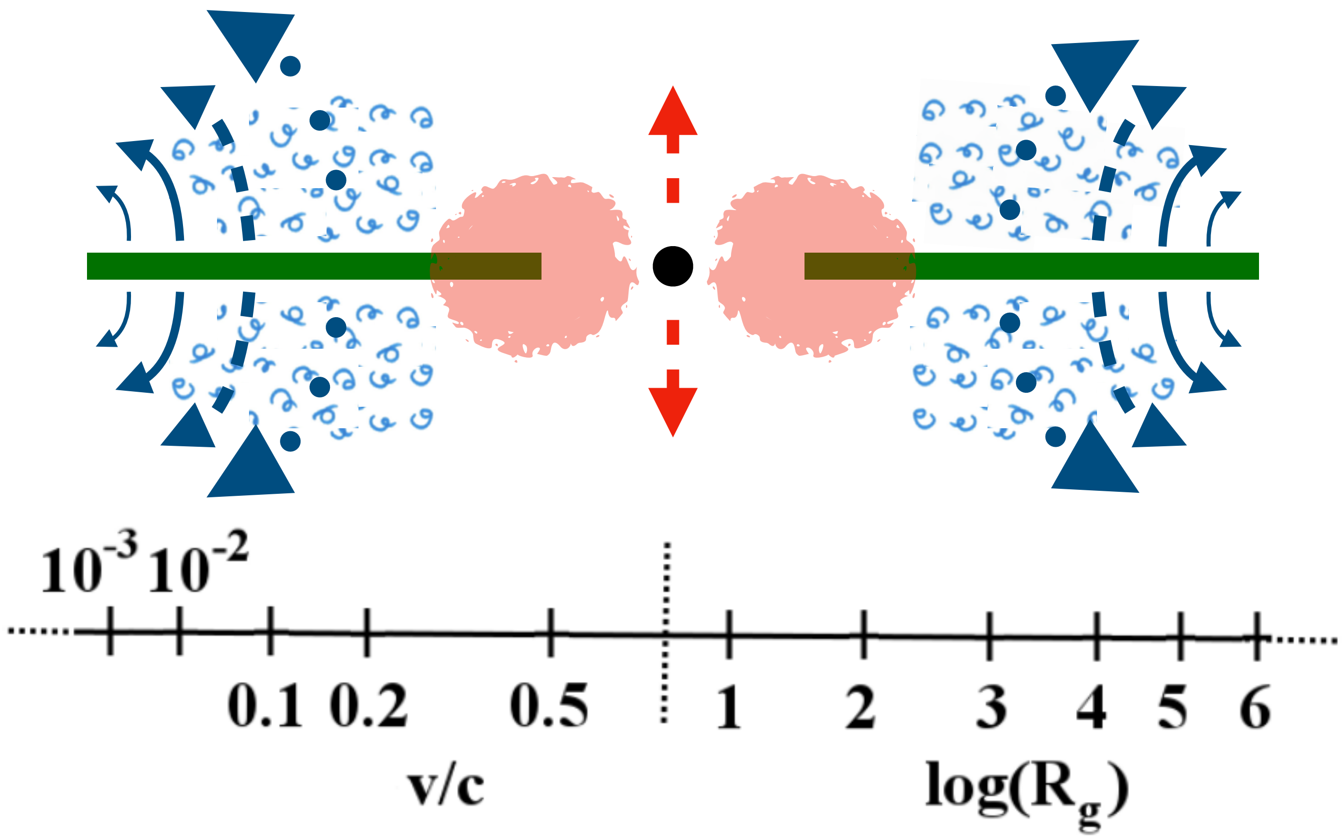
Wide-angle wind

Persistent outflow

Transient outflow

Sporadic outflow

Failed wind



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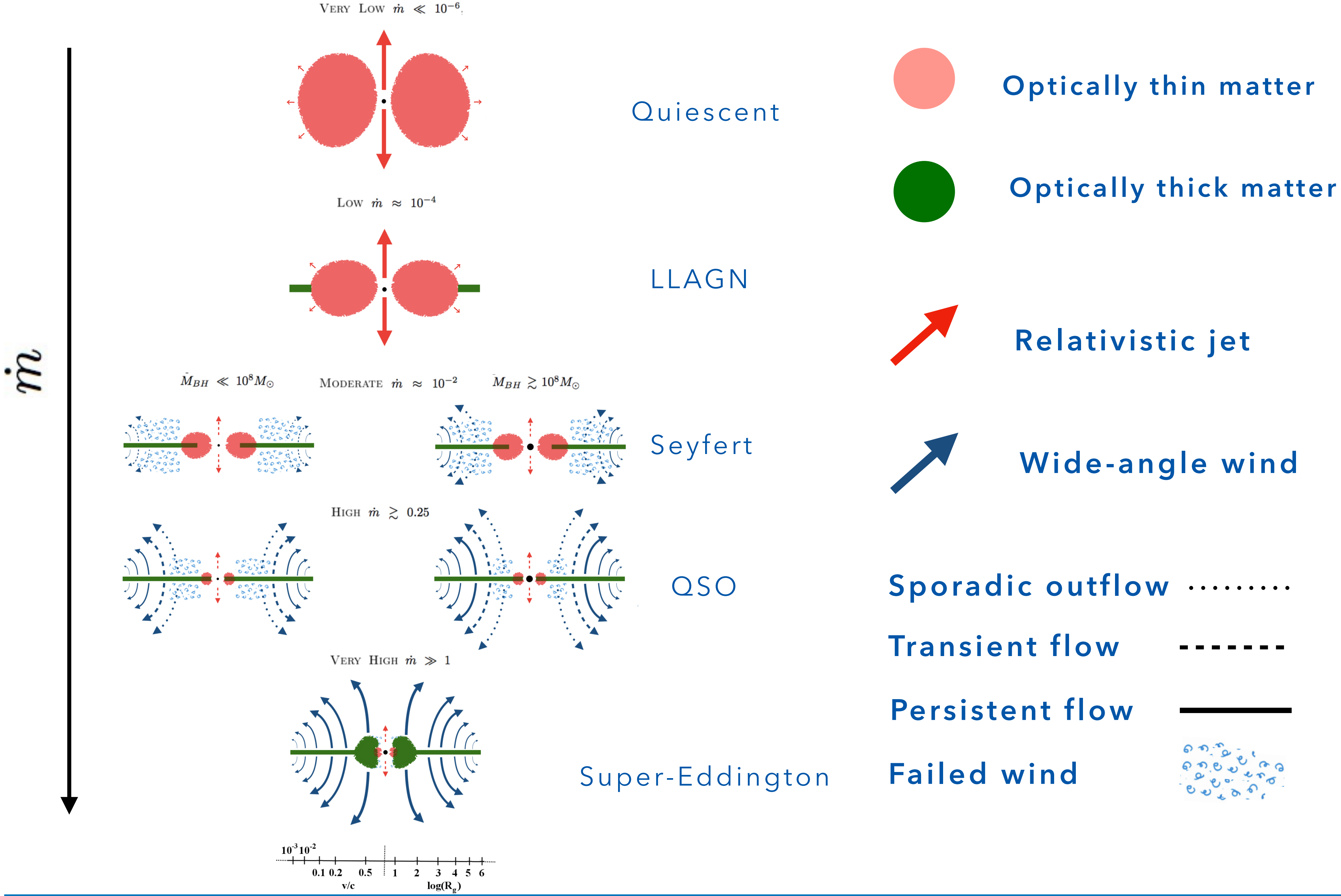
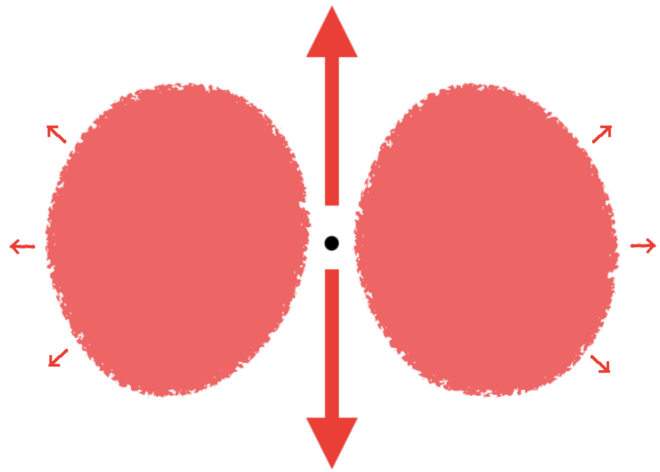
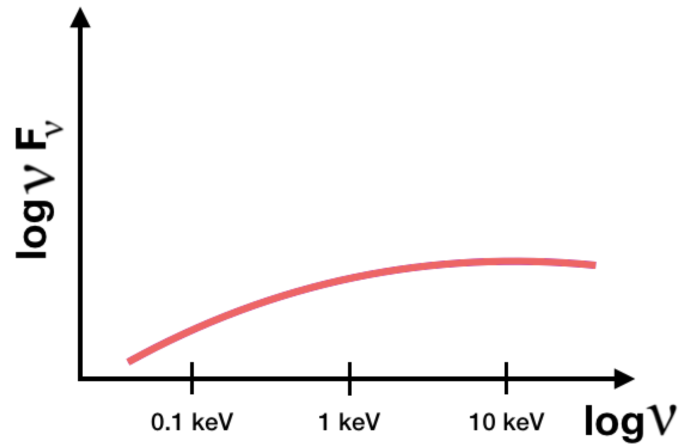


# Quiescent galactic nuclei

VERY LOW $\dot{m} \ll 10^{-6}$



no disk




Relativistic polar jet

Non-radiative accretion flow

$\eta \ll 0.1\%$

Synchrotron from the jet

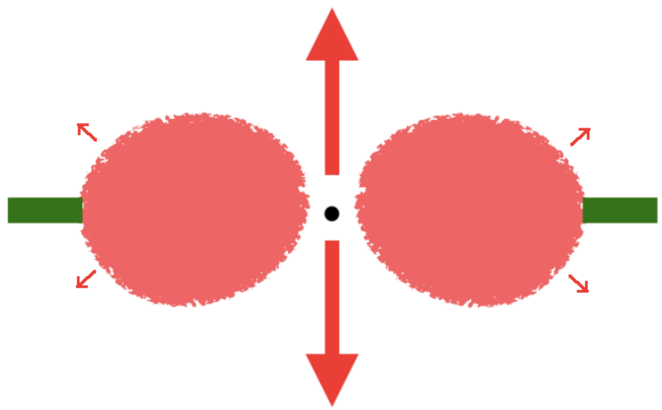
Bremsstrahlung + Compton from the accretion flow

*Thermally/magnetically driven outer winds with v~100-1000 km/s*

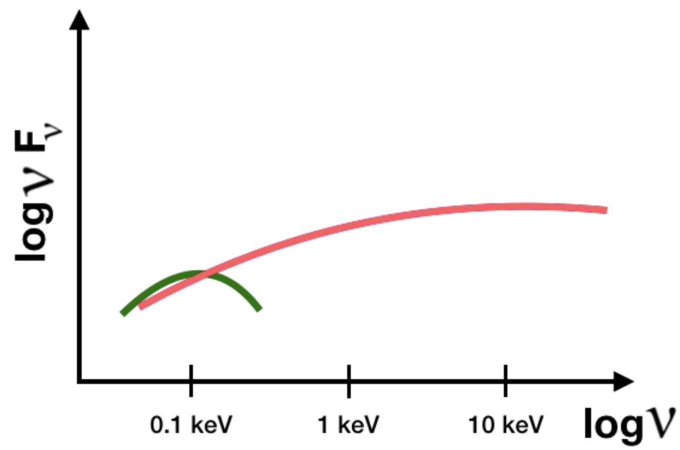
*No Line-Driven disk winds*

# Low Luminosity AGN

Low $\dot{m} \approx 10^{-4}$



very weak disk




Relativistic polar jet

Synchrotron from the jet

Radiative cooling starts in the outer 1000s $r_g$

Bremsstrahlung + Compton from the hot accretion flow

$\eta \sim 0.005 - 0.05$

Weak thermal emission from the outer disk

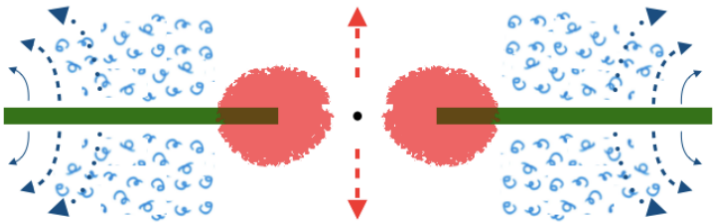
*Thermally/magnetically driven outer winds with v~100-1000 km/s*

*No Line-Driven disk winds*

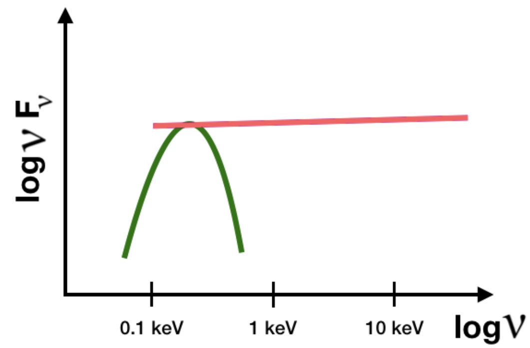
# Seyfert/mini-BAL QSO

MODERATE $\dot{m} \approx 10^{-2}$

$M_{BH} \ll 10^{8} M_{\odot}$



hot disk, strong X-rays




Moderate/transient jet

Radiative cooling is efficient

Outer thin disk and inner hot corona

Thermal emission from the disk

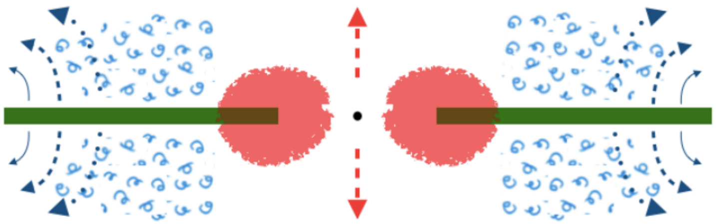
Compton up-scattering in the corona

*Line-Driven disk winds can be launched*

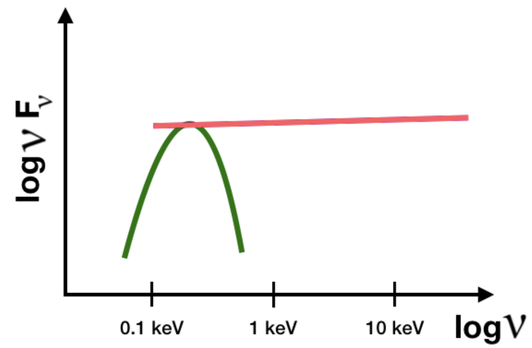
# Seyfert/mini-BAL QSO

MODERATE $\dot{m} \approx 10^{-2}$

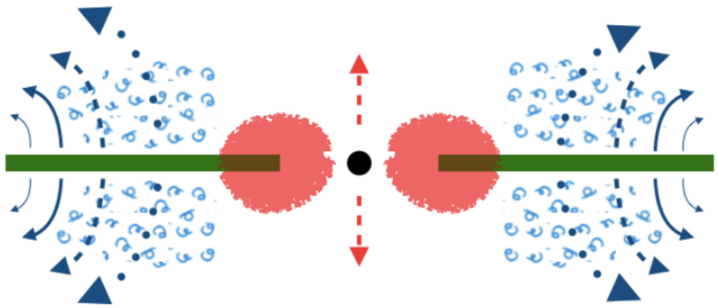
$M_{BH} \ll 10^8 M_\odot$



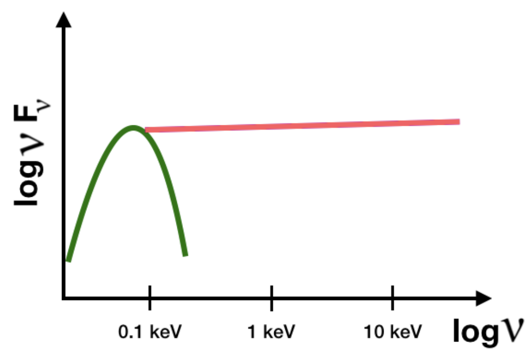
hot disk, strong X-rays




$M_{BH} \gtrsim 10^8 M_\odot$



cold disk, strong X-rays




Moderate/transient jet

Radiative cooling is efficient

Outer thin disk and inner hot corona

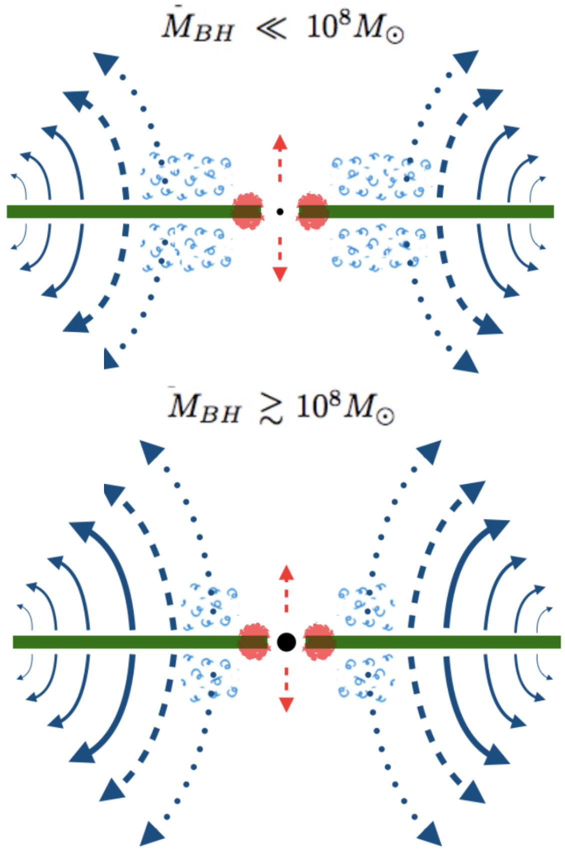
Thermal emission from the disk

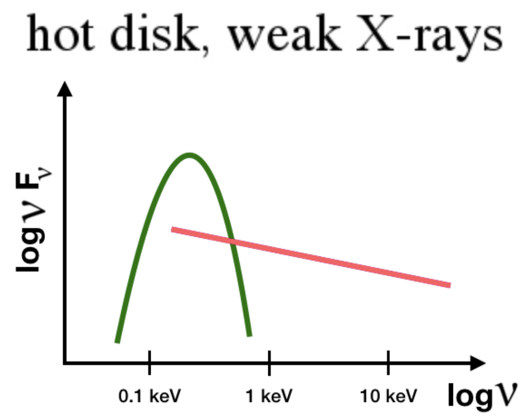
Compton up-scattering in the corona

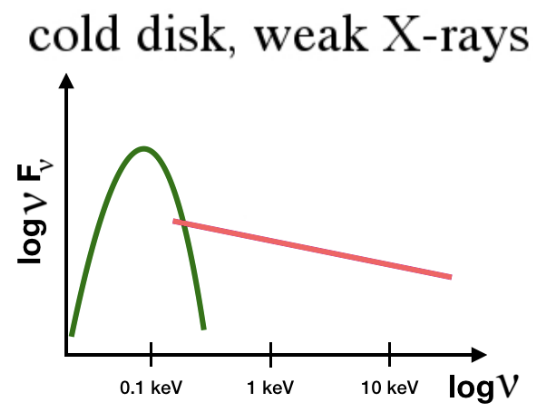
*Line-Driven disk winds can be launched*

# QSO/BAL QSO

HIGH $\dot{m} \gtrsim 0.25$




Moderate/transient jet

Radiative cooling is efficient

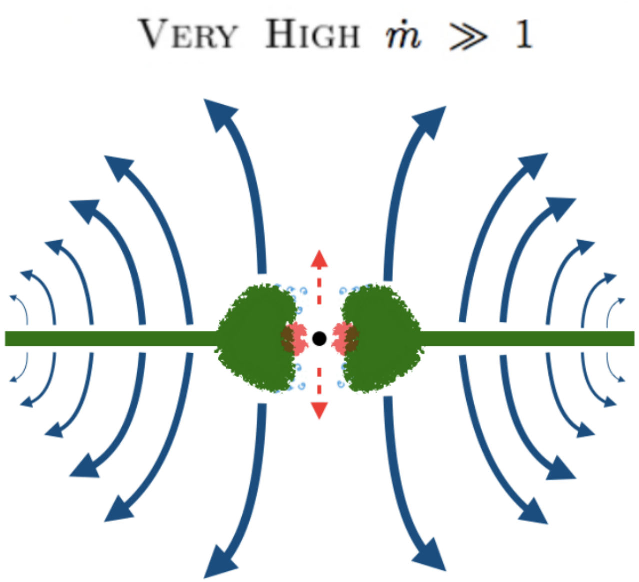
Thin disk down to ISCO, inner compact corona

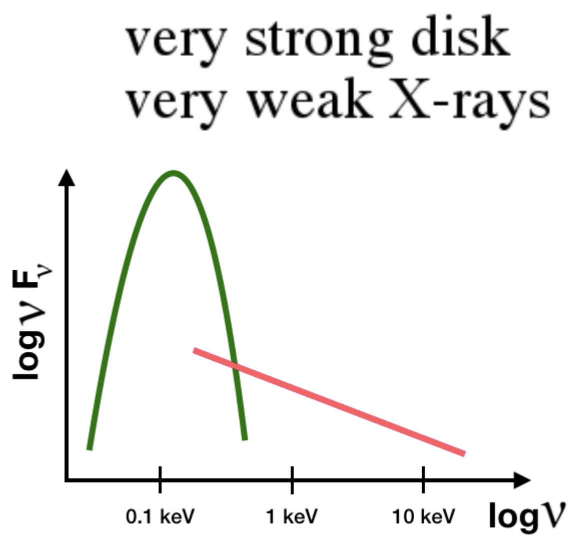
Strong thermal disk emission

Weak , steep coronal emission

*LD disk winds dominate the ejection flow*

# super-Eddington




Super-Eddington winds

The inner disk puffs up under the strong radiation pressure

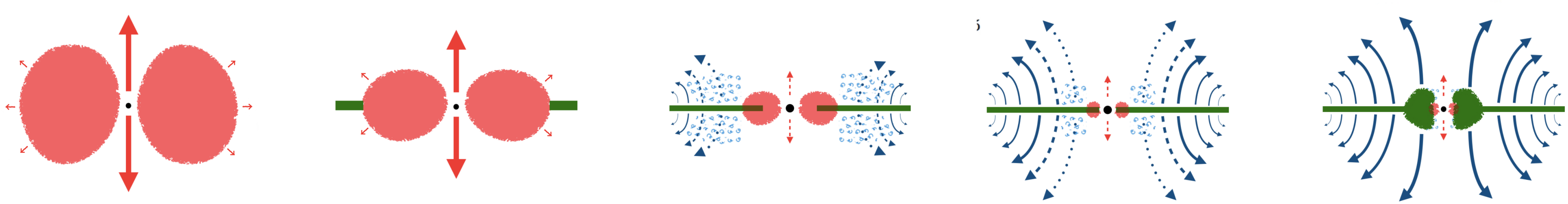
The innermost corona is very compact and (relatively)cold

*Polar and equatorial outflow, almost 4pi sr*

# A global view of the inner accretion/ejection flow around SMBHs

| $\dot{m}$ range (1) | Accretion/ejection flow (2) | Feedback (3) | Examples (4) |
|---|---|---|---|
| *very low* $\dot{m} \approx 10^{-8}$ ($\ll 10^{-6}$) | non radiative hot accretion flow<br>relativistic polar jet | $L_{kin}$ | Quiescent/inactive,<br>Sgr A* |
| *low* $\dot{m} \approx 10^{-4}$ ($10^{-6} \lesssim \dot{m} \lesssim 10^{-3}$) | outer cold disk at ≈1000s $R_g$, inner hot flow<br>relativistic polar jet | $L_{kin} \gg L_{rad}$ | LLAGN<br>M81*, M87 |
| *moderate* $\dot{m} \approx 10^{-2}$ ($10^{-3} \lesssim \dot{m} \lesssim 10^{-1}$) | outer cold disk at ≈10s $R_g$, extended hot corona<br>weak/moderate LD wind depending on small/large $M_{BH}$ | $L_{kin} \ll L_{rad}$ | Seyfert/mini-BAL QSO<br>NGC 5548/PG 1126-041 |
| *high* $\dot{m} \gtrsim 0.25$ ($0.1 \lesssim \dot{m} \lesssim 1$) | cold accretion disk down to ISCO, compact hot corona<br>moderate/strong LD wind depending on small/large $M_{BH}$ | $L_{kin} < L_{rad}$ | NLS1/BAL QSO<br>I Zw 1/PDS 456 |
| *very high* $\dot{m} \gg 1$ ($1 \lesssim \dot{m} \lesssim 100$) | outer thin disk, inner slim disk, very compact hot corona<br>strong outflows, both polar and equatorial | $L_{kin} \lesssim L_{rad}$ | Super-Eddington<br>RX J0439.6-531 |

**Notes.** (1) Nomenclature for the Eddington ratio ranges used in this work, with an indicative order of magnitude, and an indicative range of values in parenthesis. (2) Accretion/ejection flow main physical characteristics. (3) Type of energy feedback between the AGN and the environment: kin = kinetic, rad = radiative. (4) Classes of objects/individual examples of well studied local AGN.

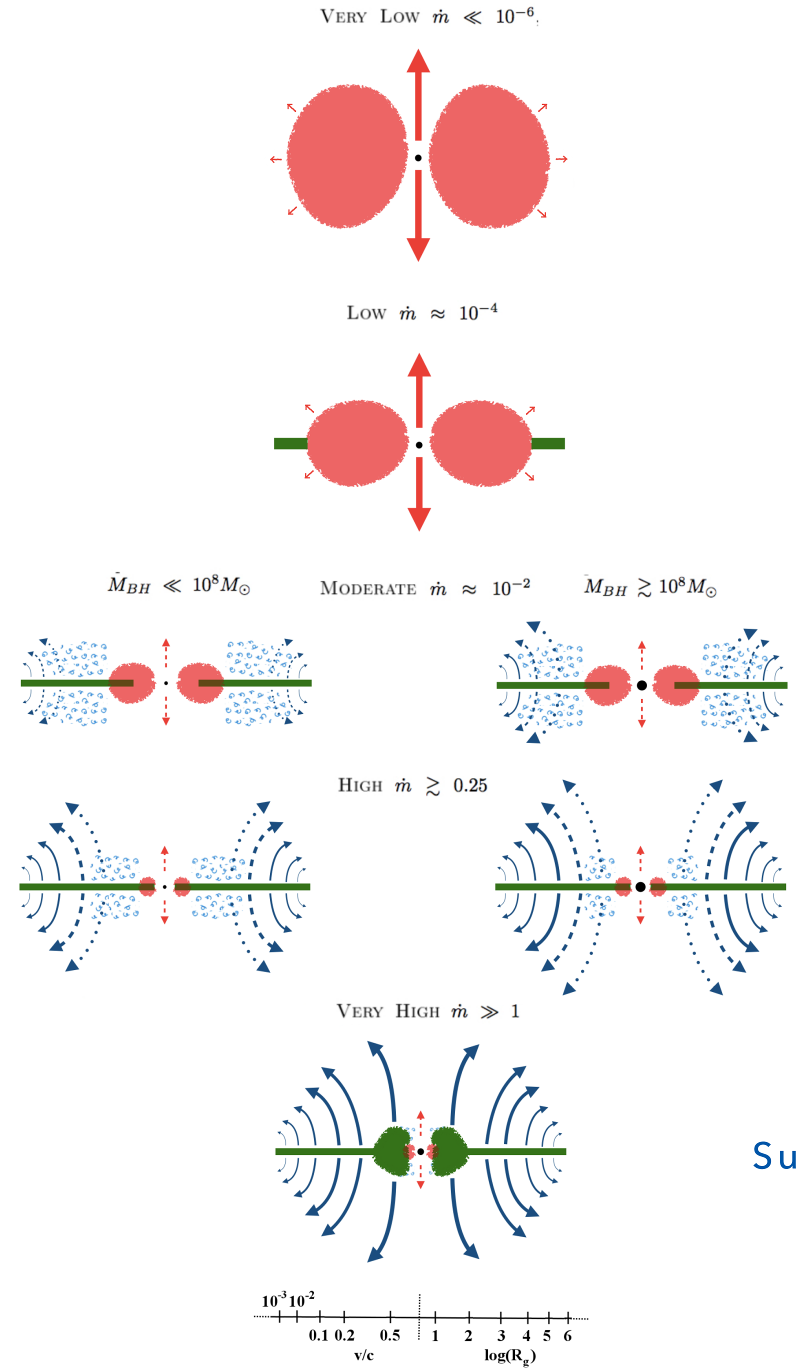


# Line of sight and geometrical effects

**Almost isotropic flow**
Weak geometrical effects

**Strongly anisotropic flow**
**Strong geometrical effects**

**Almost isotropic flow**
Weak geometrical effects




Quiescent

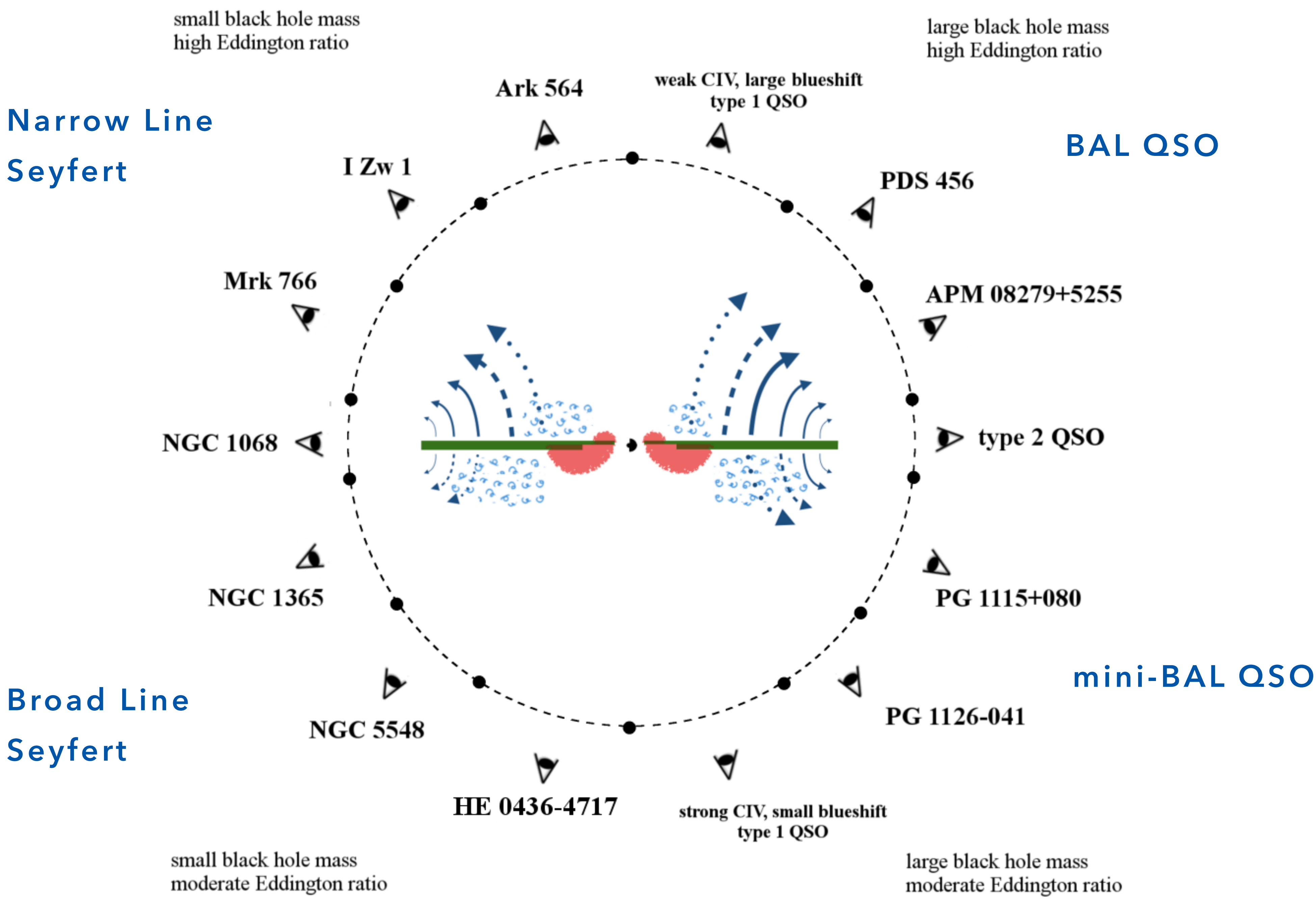
LLAGN

Seyfert

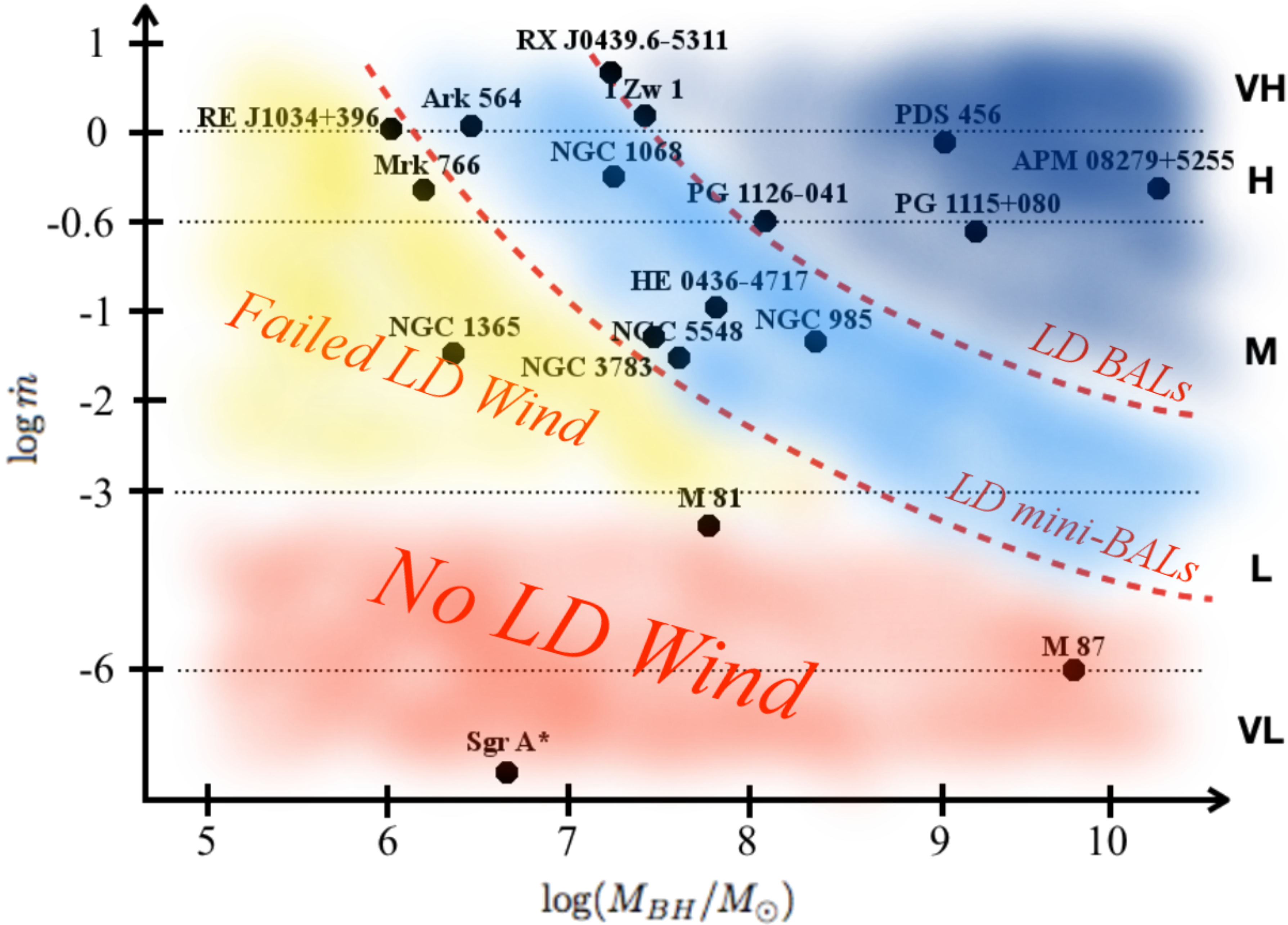
QSO

Super-Eddington

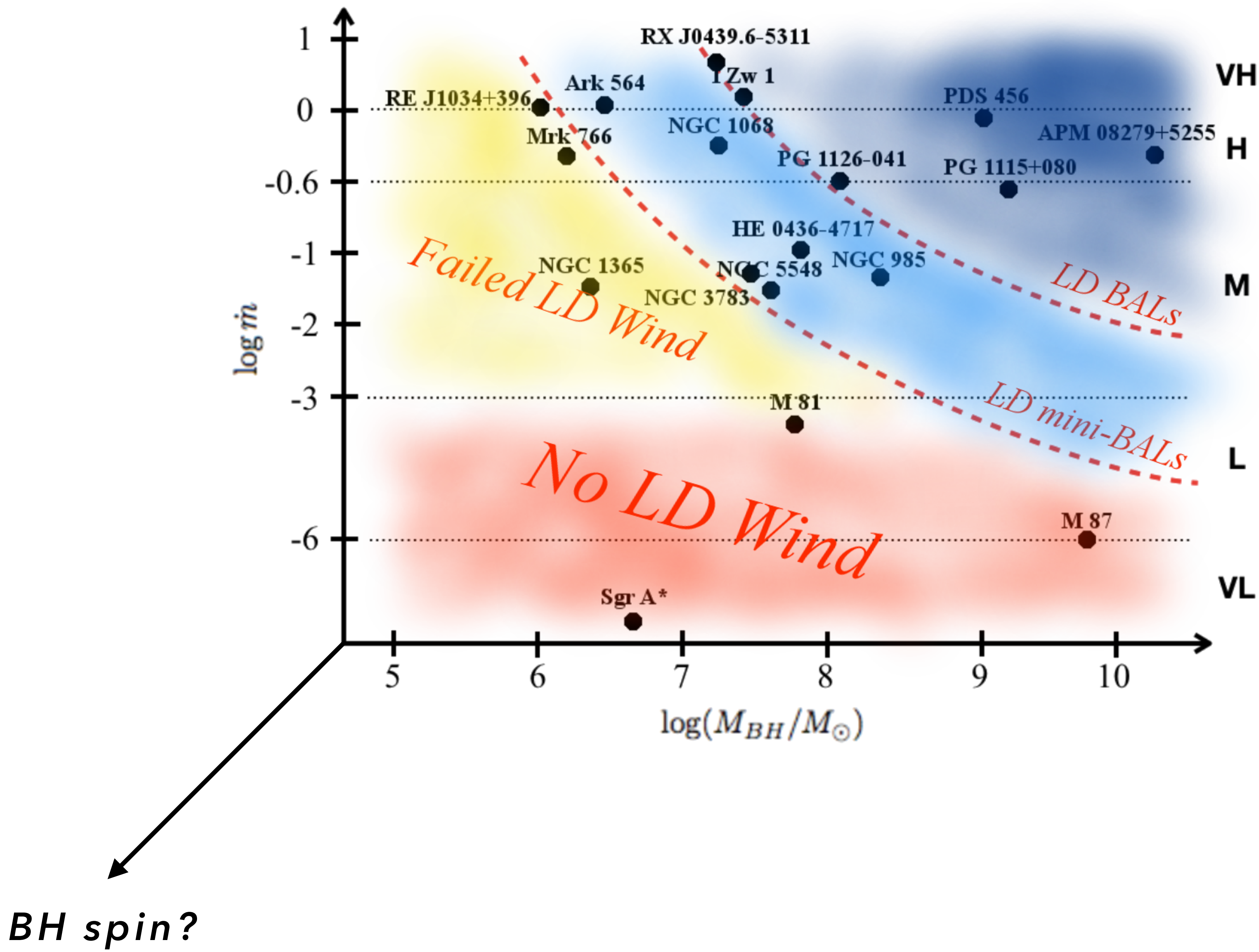
# Important geometrical effects in the Seyfert/QSO regime



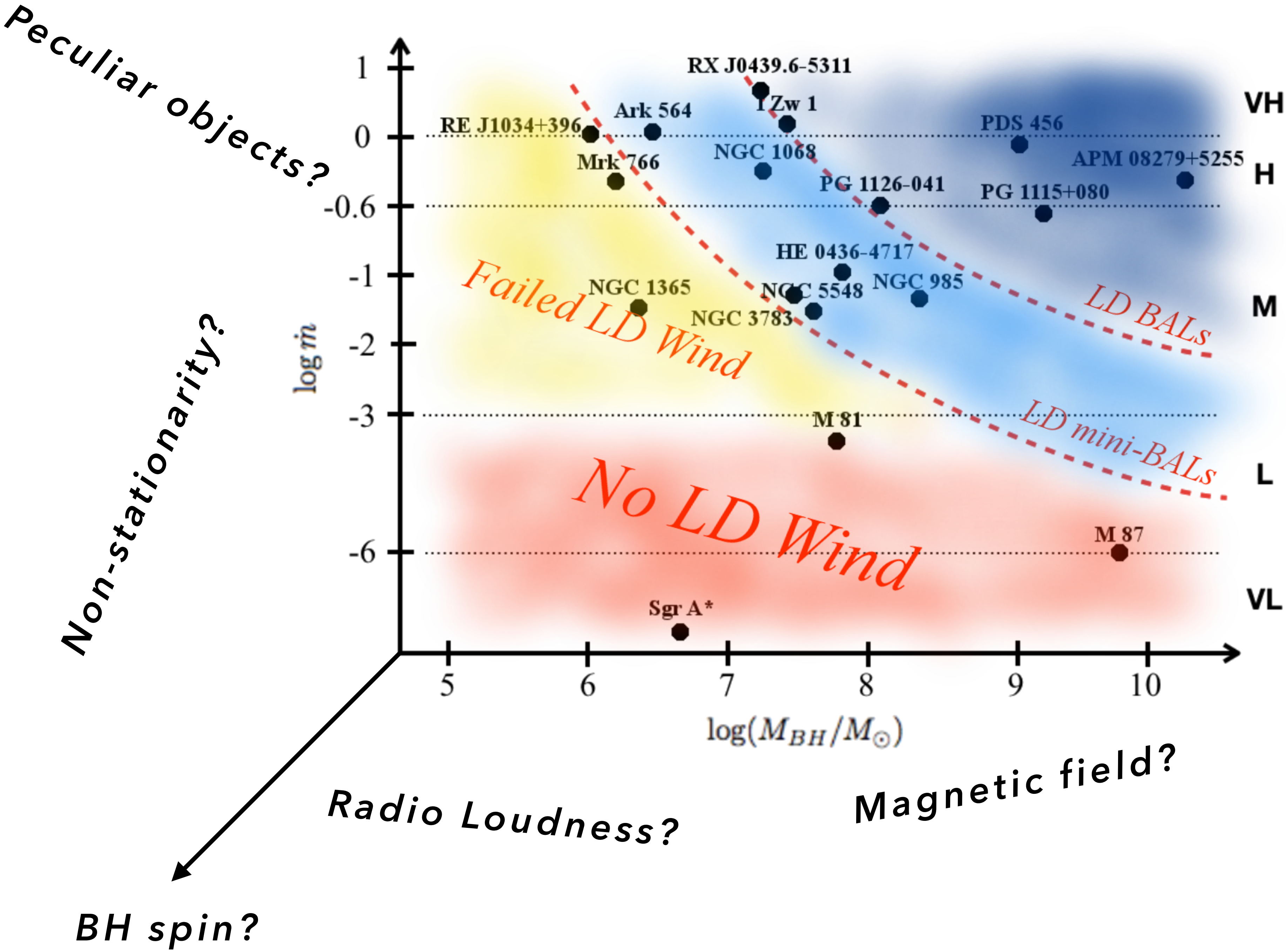
# The present and the future



# The present and the future



# The present and the future



# Mass outflow rate and kinetic efficiency

**kinetic efficiency**

$$\varepsilon_w \propto \frac{\dot{M}_{out} v_{out}^2}{L_{acc}}$$

**mass outflow rate**

$$\dot{M}_{out} \propto A(r)\rho(r)v_{out}(r)$$

Assuming spherical symmetry, isotropy, constant velocity:

$$\dot{M}_{out} = 4\pi m_H n r^2 v_{out} C_f F_V$$

Assuming photoionization equilibrium, and the absorber as a thin shell:

$$\dot{M}_{out} = 4\pi m_H \frac{L_{ion}}{\xi} v_{out} C_f F_V$$

$$\dot{M}_{out} \approx \dot{M}_{acc}$$

⇨ $\varepsilon_w \approx$ up to a few %

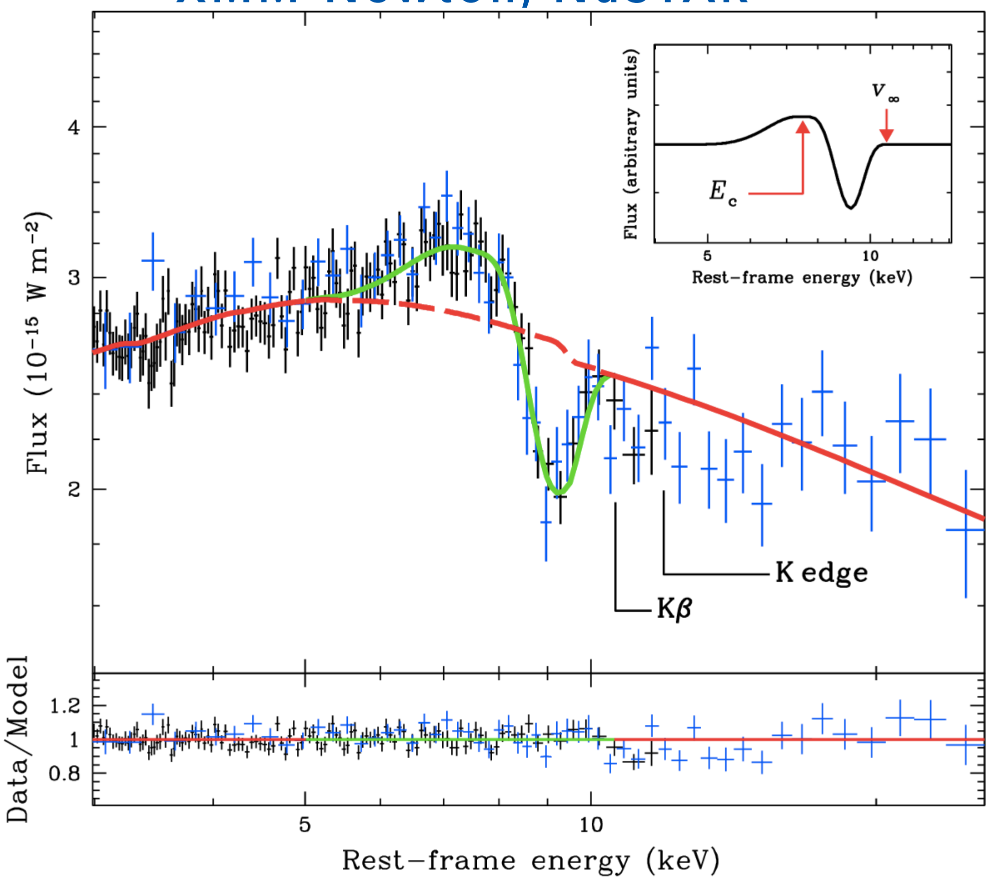
For the highly ionized, high velocity phases.

BUT

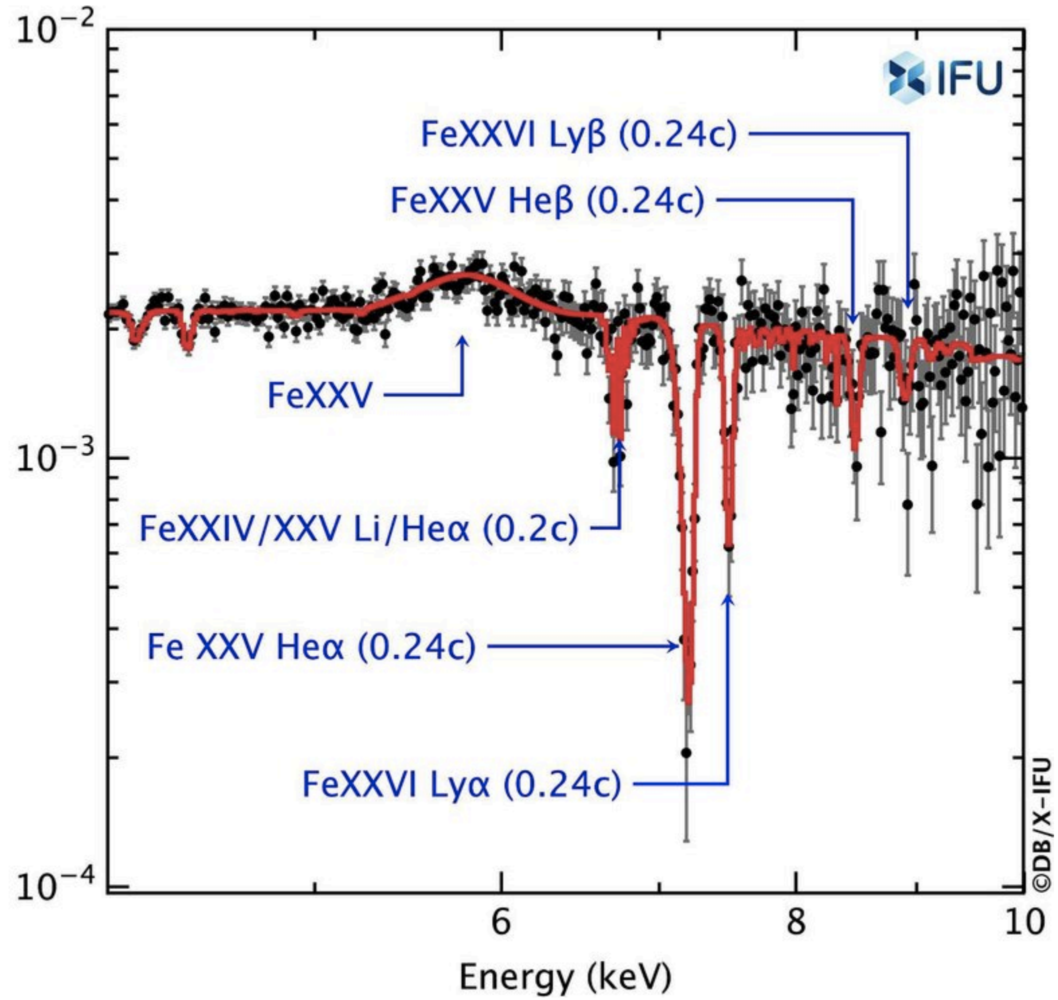
***All the assumptions are highly uncertain!***

# PDS 456 as seen by ATHENA

XMM-Newton, NuSTAR




ATHENA X-IFU




**Realistic mass outflow rate measurements will be possible!**