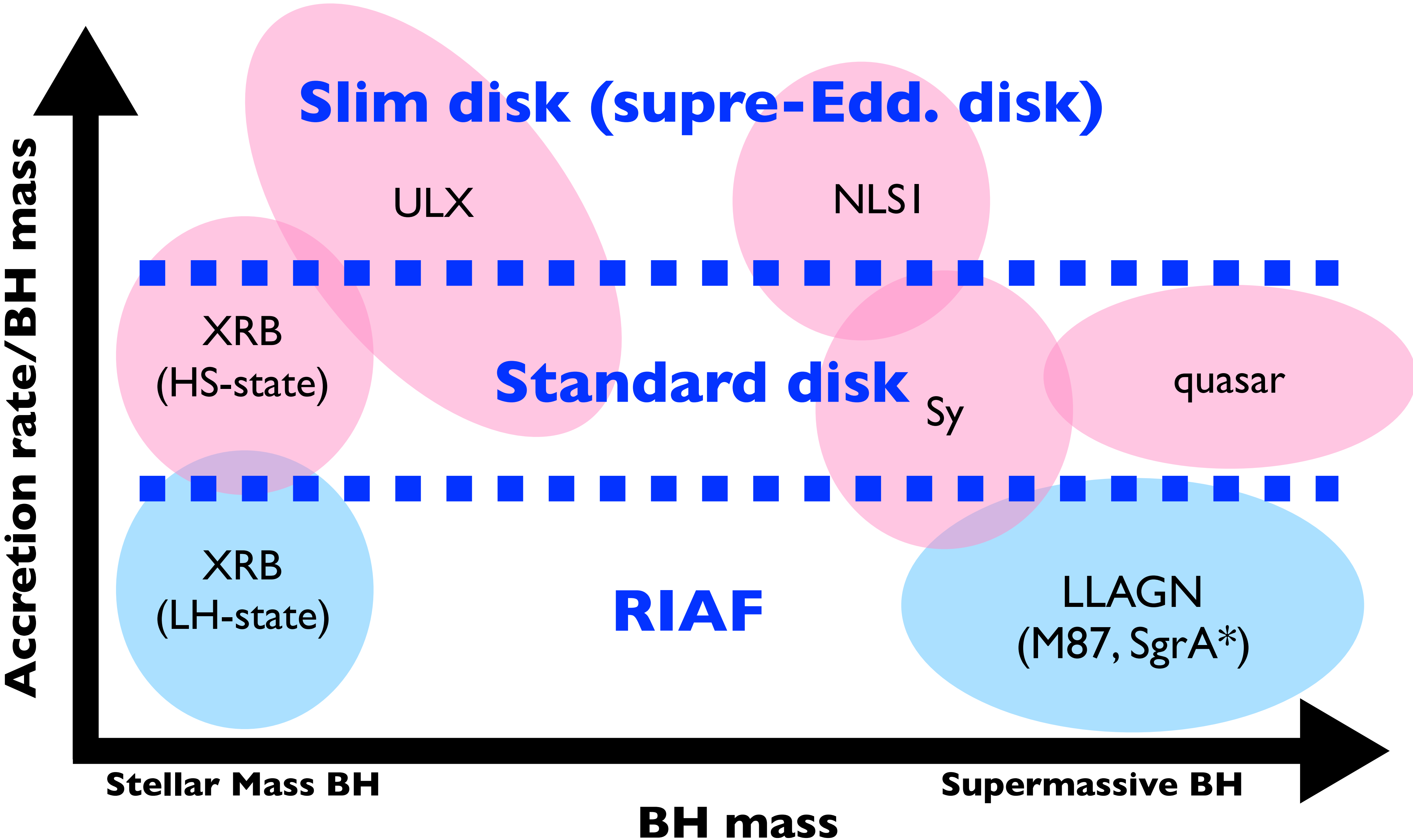
Numerical Simulations of Accretion Flows and Outflows around BHs (NSs)

Ken OHSUGA (Univ. of Tsukuba)

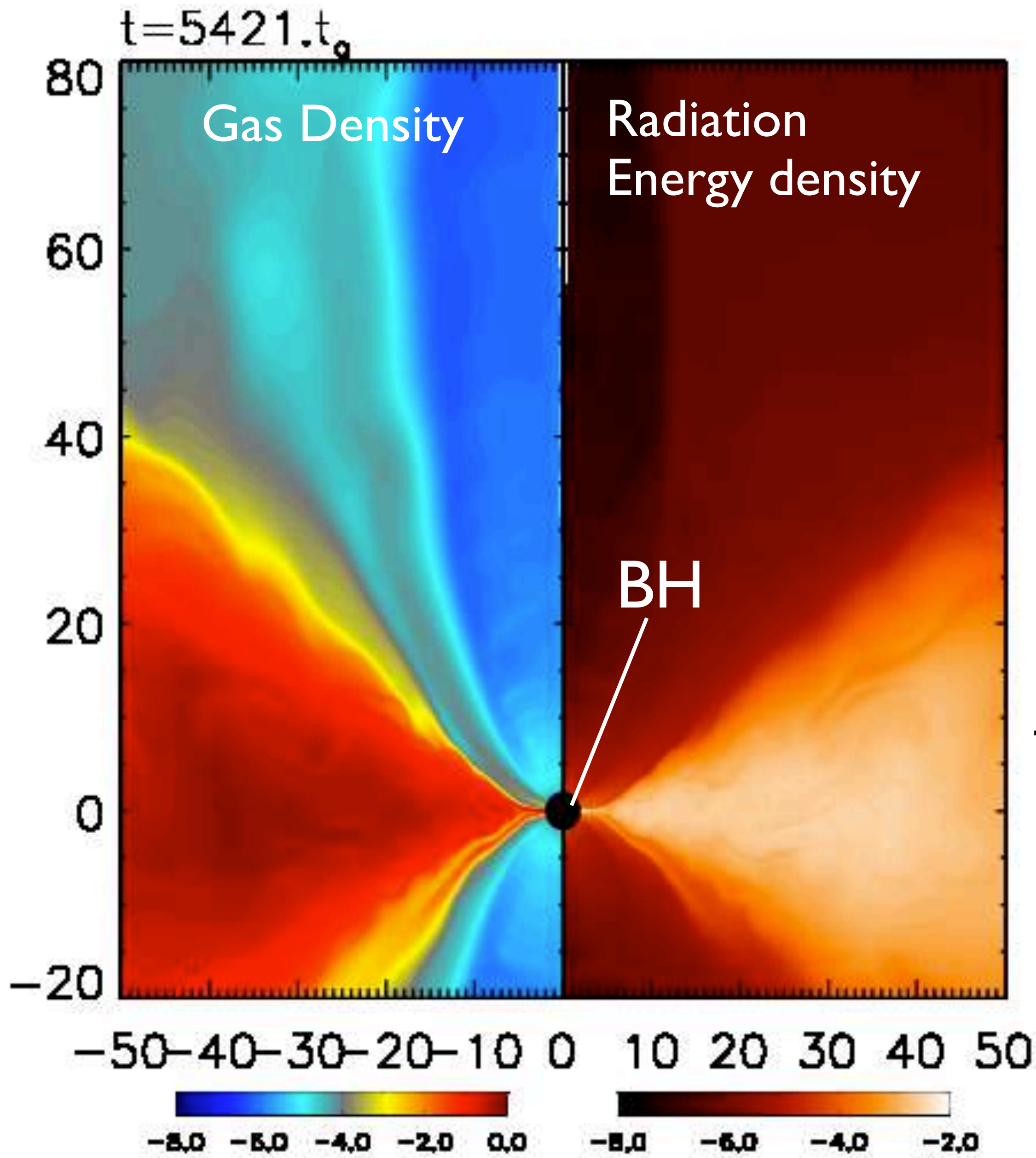
A. Inoue, A. Utsumi, T. Ogawa, Y. Asahina (Univ. of Tsukuba),
H.R. Takahashi (Komazawa Univ.), T. Kawashima (Univ. of Tokyo),
M. Nomura (Kure-NCT), M. Mizumoto (Kyoto Univ.),
R. Tomaru, C. Done (Durham Univ.)

BH mass vs Accretion rate



(c)Kawashima

Super-Edd. disk & radiatively-driven jets



General relativistic Radiation-MHD (GR-RMHD) simulations with using M1-closure scheme & Kerr-shild metric.

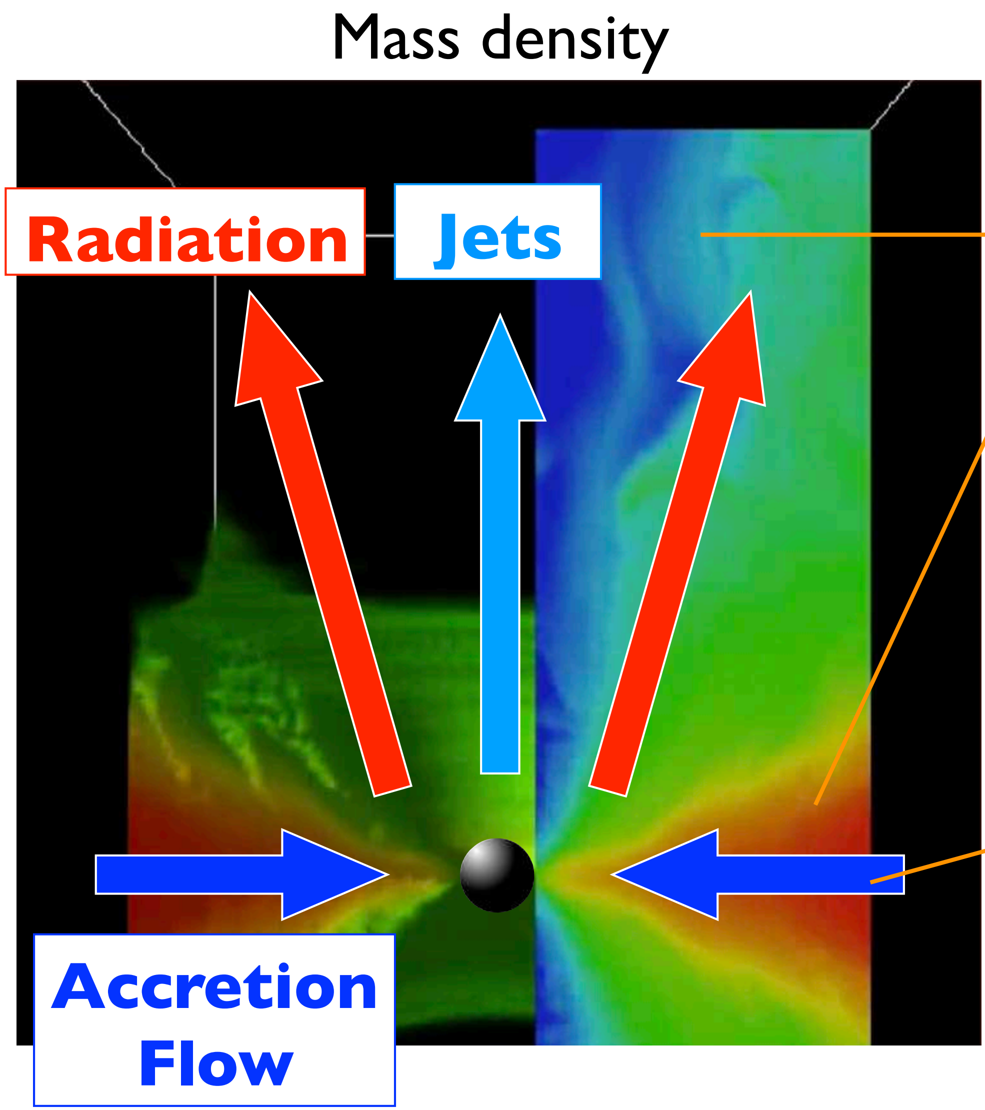
L_{rad} ($>L_{kin}$) $\geq L_{Edd}$

Mdot ~ a few $100L_{Edd}/c^2$

Takahashi, Ohsuga et al. 2016

see also Sadowski et al. 2014, Jiang et al. 2014

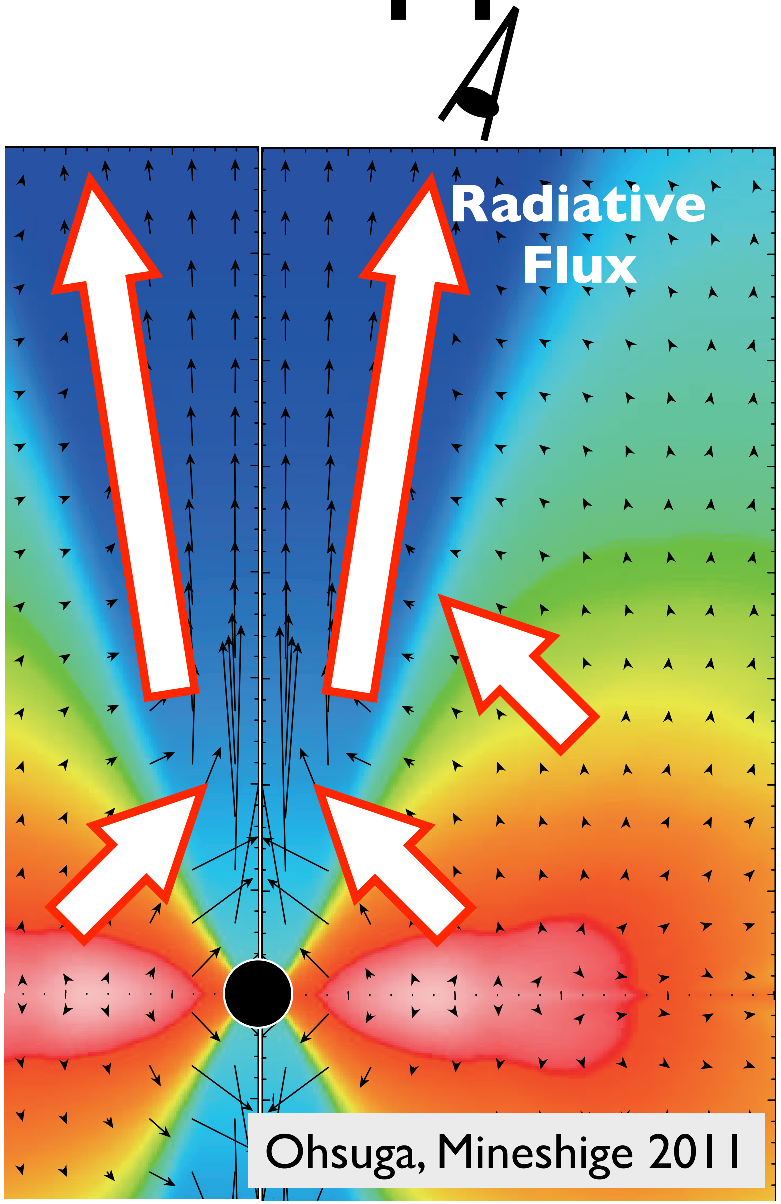
Super-Edd. disk & radiatively-driven jets



Strong radiation pressure supports the thick disk and generates the jets, ~0.3-0.7c.

Photons mainly escape through the region around the rotation axis, so that the radiation pressure cannot prevent the accreting motion.

Apparent Luminosity

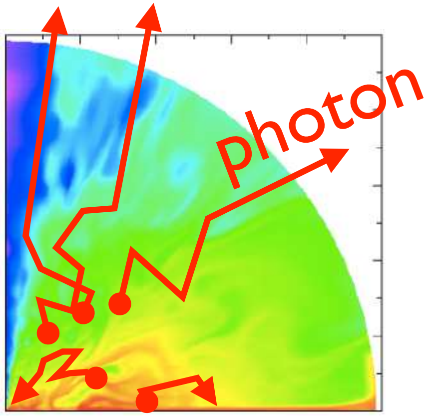


The radiative flux is mildly collimated since the disk is optically and geometrically thick.

The apparent luminosity becomes highly super-Eddington for the face-on observers (**$22L_{Edd}$** for $\lesssim 20°$ in the case of Mdot~$100L_{Edd}/c^2$, L_{disk}~$3L_{Edd}$).

Large luminosity of ULXs ($>10^{39\text{-}40}$erg/s) can be explained for the face-on case.

X-RAY SPECTRA (≲10-20keV)

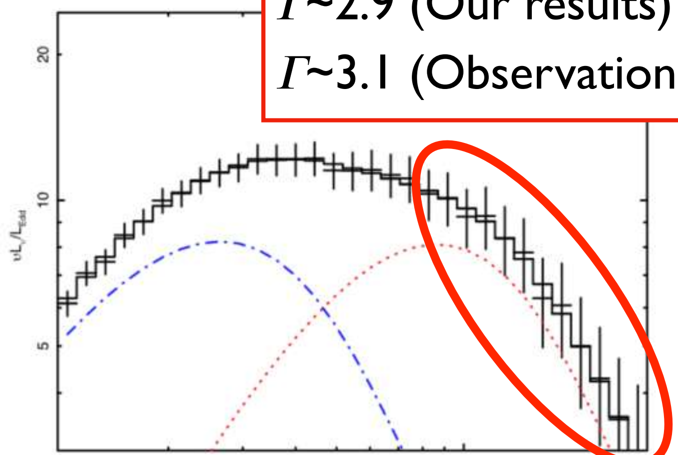


Simulated spectra nicely fit the observations of ULXs.

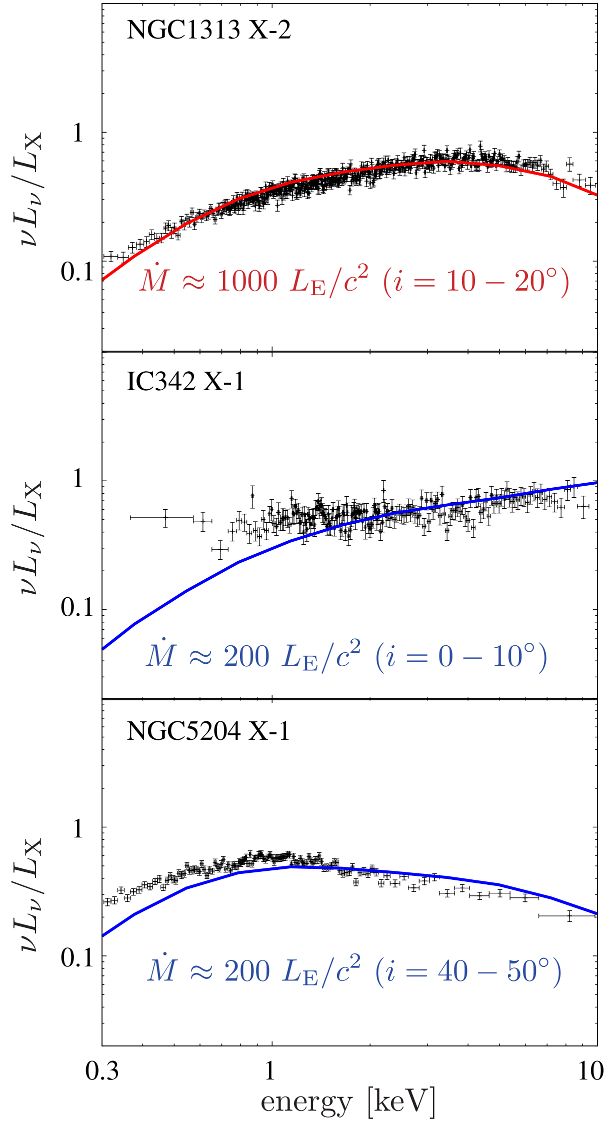
Kitaki, Mineshige, Kawashima, Ohsuga+ 2017

Γ~2.9 (Our results)

Γ~3.1 (Observations by Walton+15)

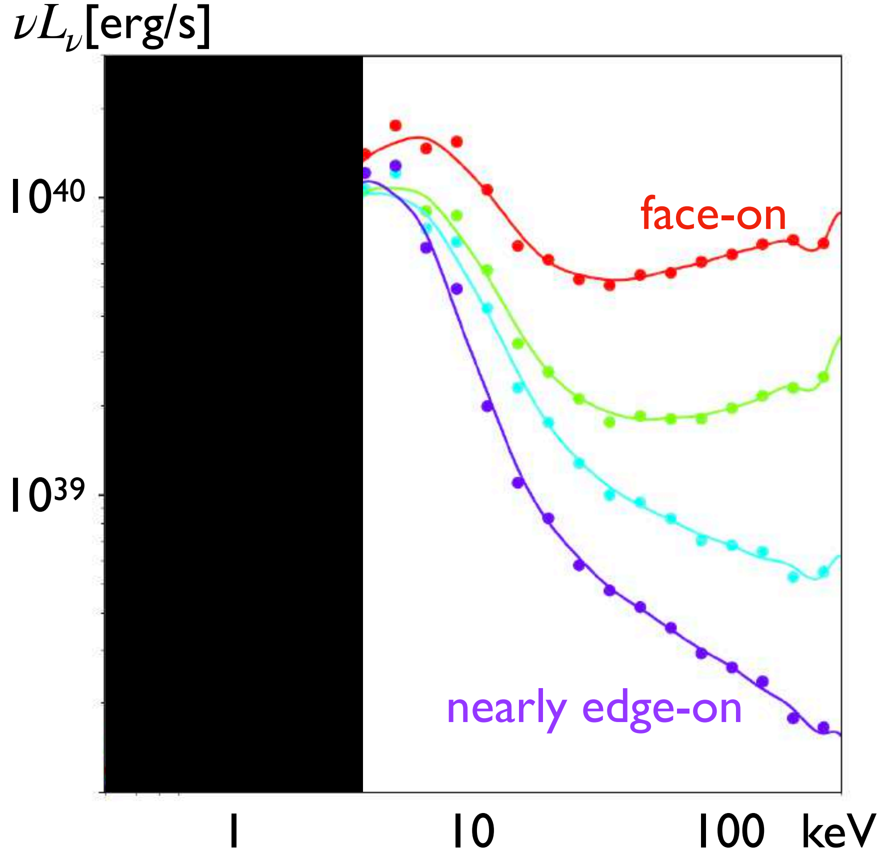


Kawashima et al. 2012
(data; Gladstone 2009)



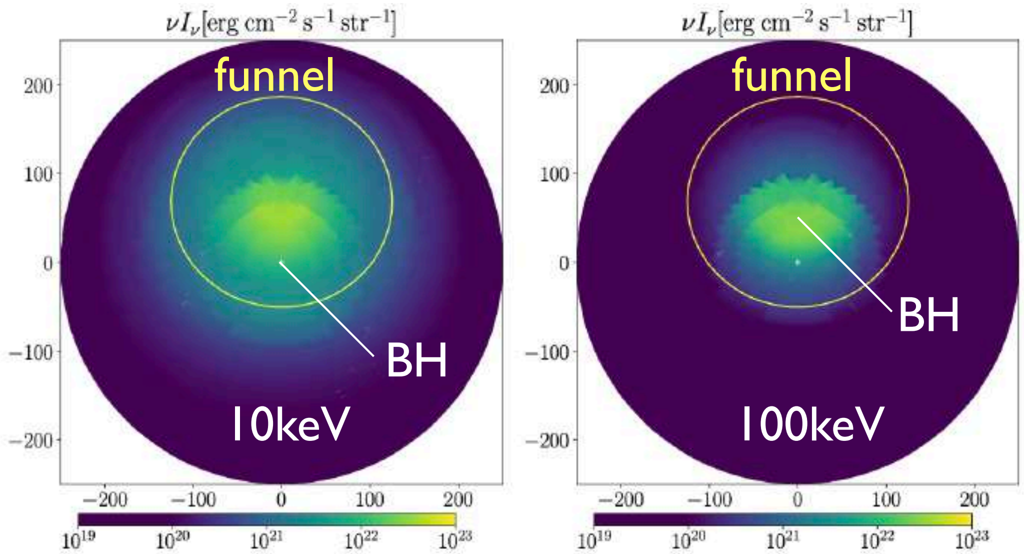
X-RAY SPECTRA (10-100keV)

Spectra



Very high-energy photons would be observed for the face-on observer.

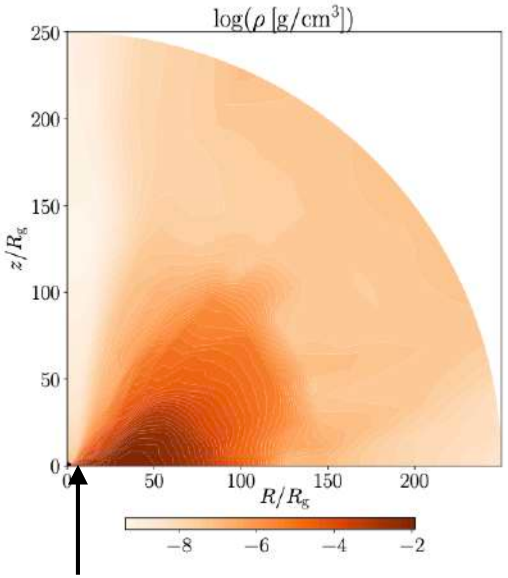
Intensity Map ($i = 20^\circ$)



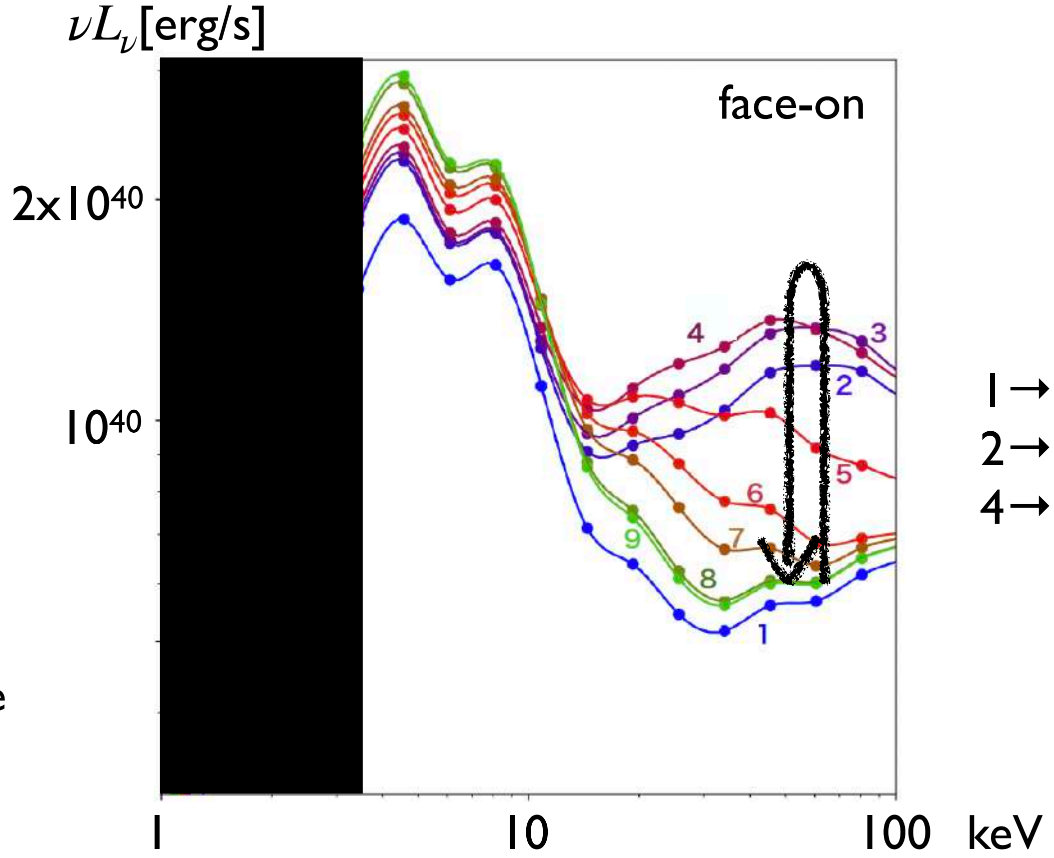
Very high-energy photons come through the region around the rotation axis (funnel).

Ogawa, Ohsuga, et al. 2021

X-ray flare



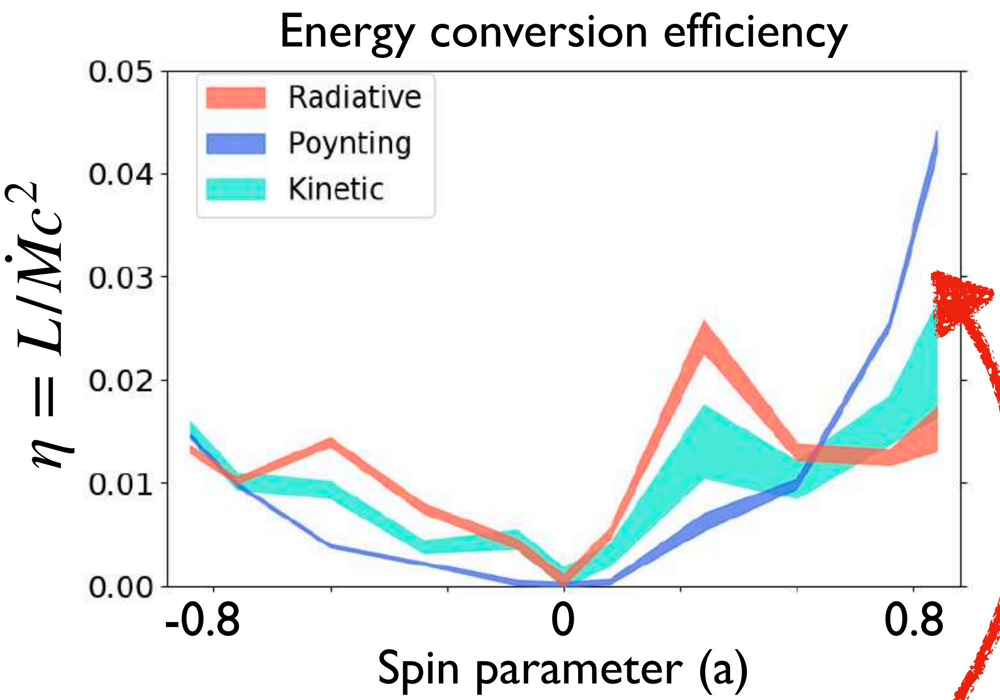
Simple flare model:
Increase the gas temperature in the vicinity of BH (<20Rg) by a factor of 10 for 200Rg/c sec.

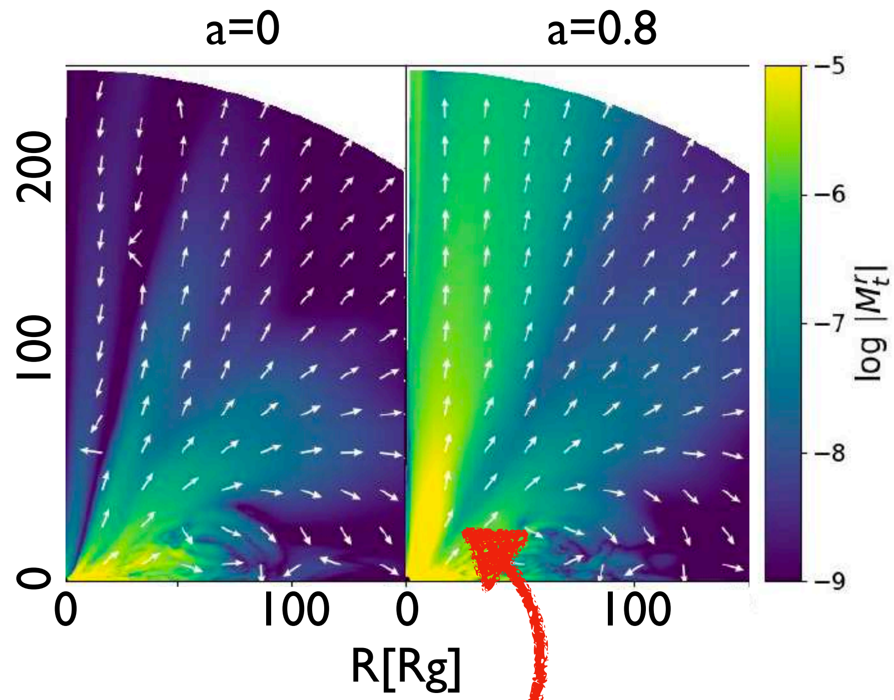


1→2: Rising phase
2→4: Luminous phase
4→9: Decay phase

Luminosity at 20-100keV fluctuates.
Response of the luminosity at around 20-40keV is delayed.

Effect of BH spin





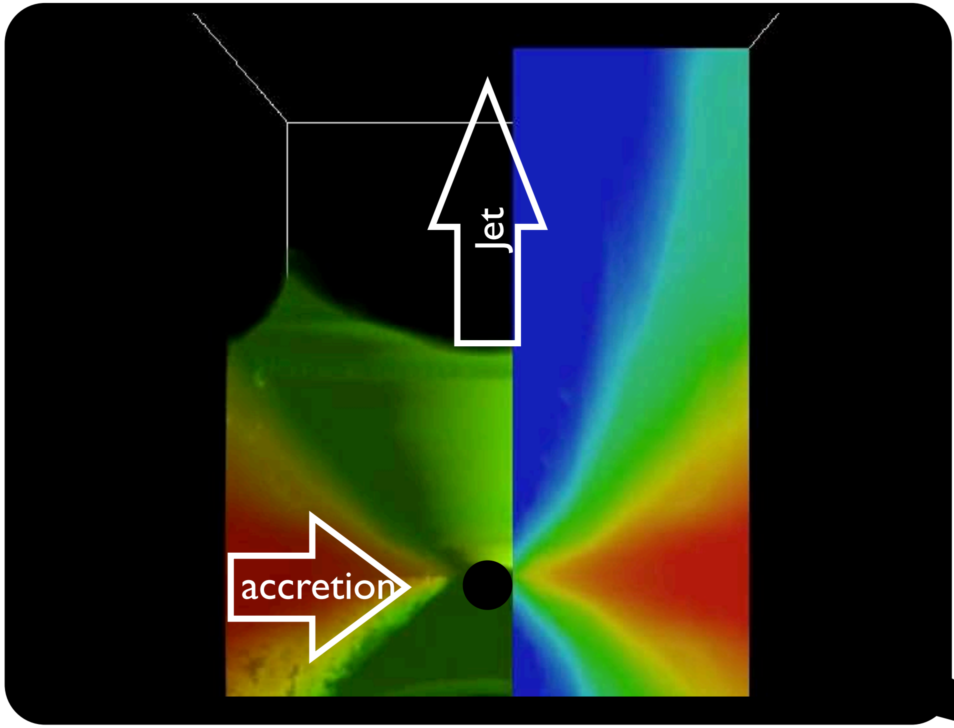
Energy conversion efficiency (η) increases with an increase of the BH spin. Especially, poynting flux is enhanced if BH spin is large.

Magnetic flux is large in the vicinity of the BH and within the funnel. Enhancement of η is probably caused by the BZ effect.

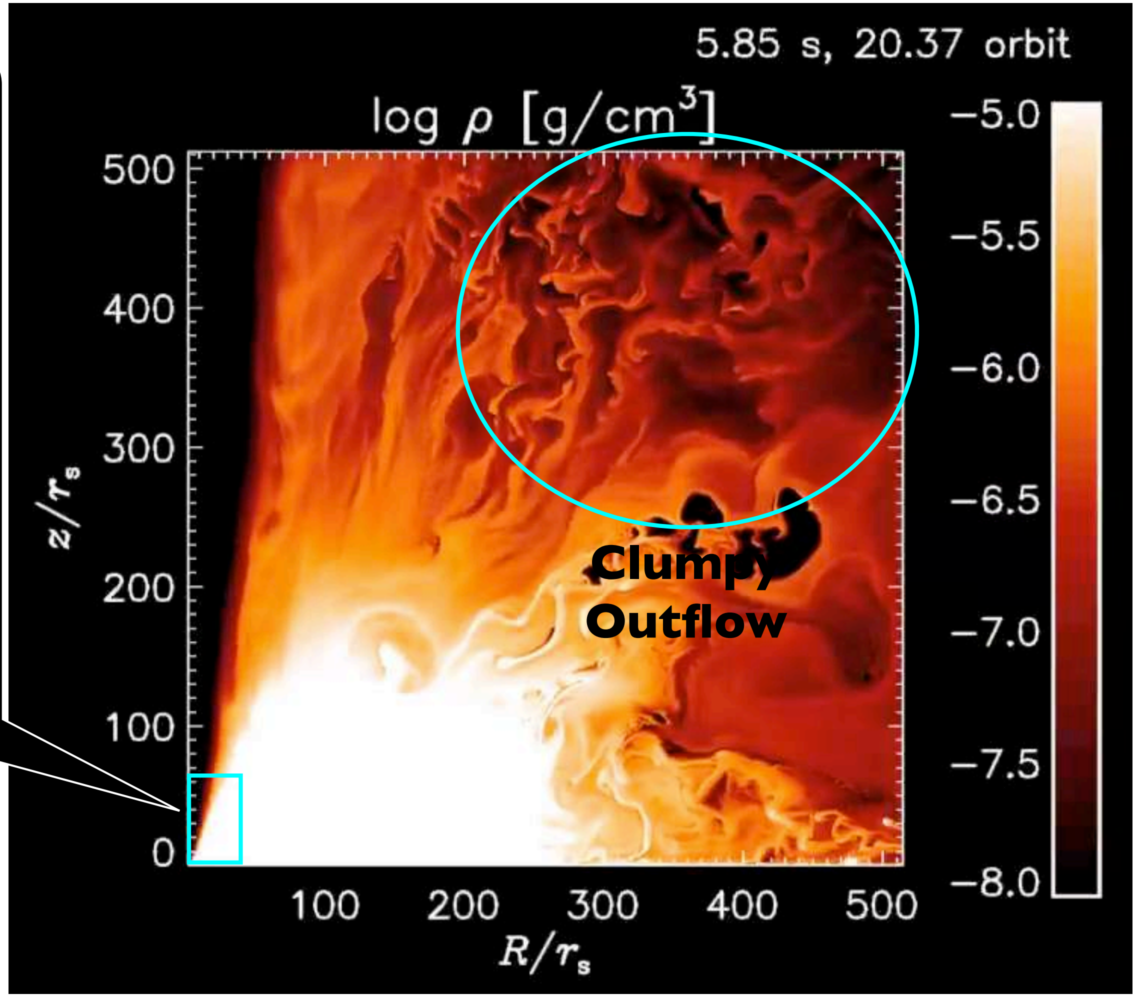
Utsumi, Ohsuga, et al. in prep

Clumpy Outflow

Super-Eddington disk+ Jet



Takeuchi, Ohsuga, Mineshige 2013



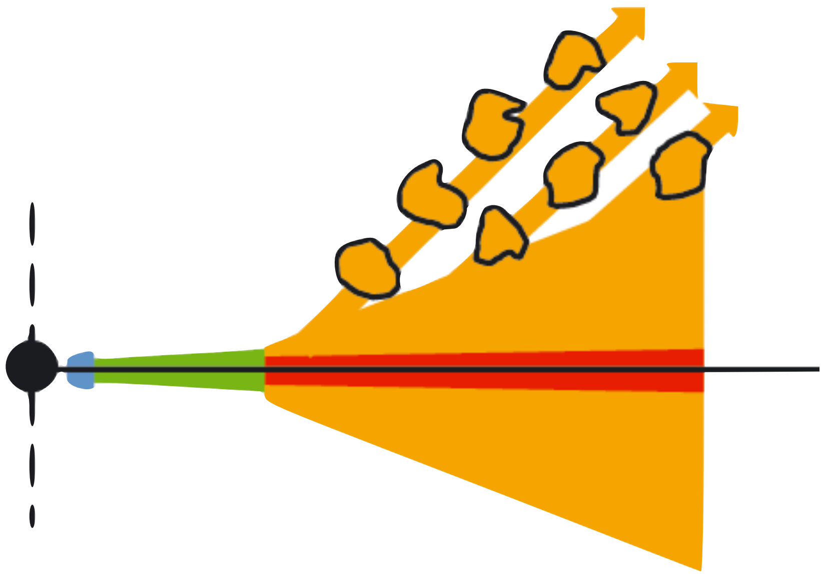
see also 3D version;
Kobayashi, Ohsuga et al. 2018

Time-dependent, Clumpy outflow with wide angle

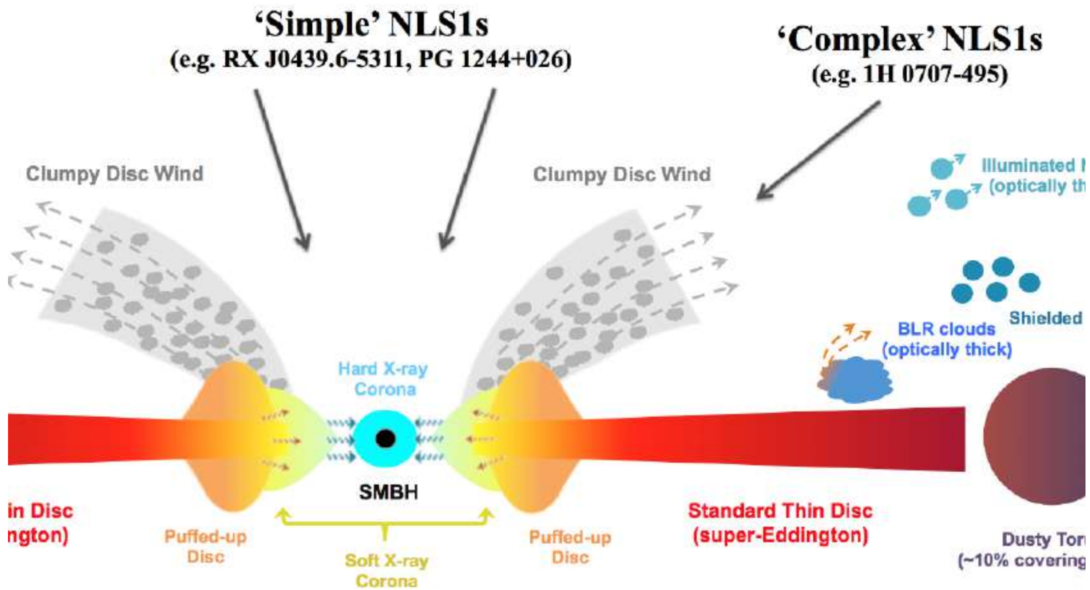
Clumpy outflows

Some ULXs exhibit the time variations of X-ray luminosity, implying the launching of clumpy outflows.

Launching of clumpy winds is also reported by observations of NLS1s or V404 Cyg.



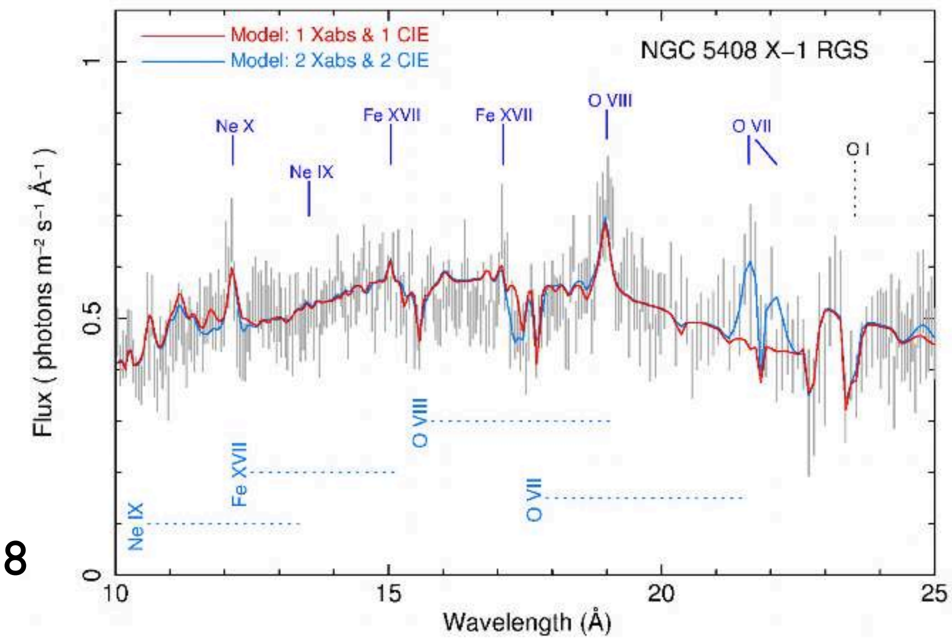
Middleton+11



Jin+17 see also Motta+17

Absorption lines

Outflow velocity of ~0.1-0.2c agrees with the observations of blueshifted absorption lines.



Pinto+16,
see also Kosec+18

Time variation

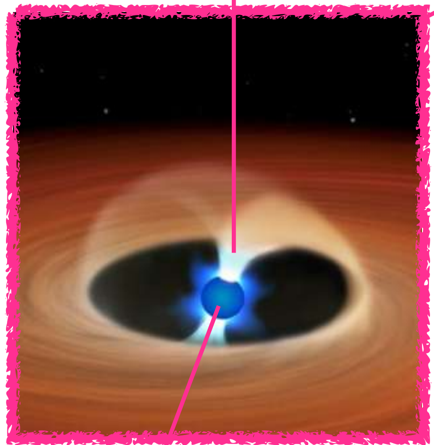
Timescale of the luminosity variation ($100R_s/0.3V_{kep}$) is

$$\sim 2.5 \left(\frac{M_{\rm BH}}{10\, M_\odot}\right) \left(\frac{\ell_{\rm cl}^{\theta}}{10^2\, r_{\rm S}}\right) \left(\frac{r}{10^3\, r_{\rm S}}\right) {\rm s}$$

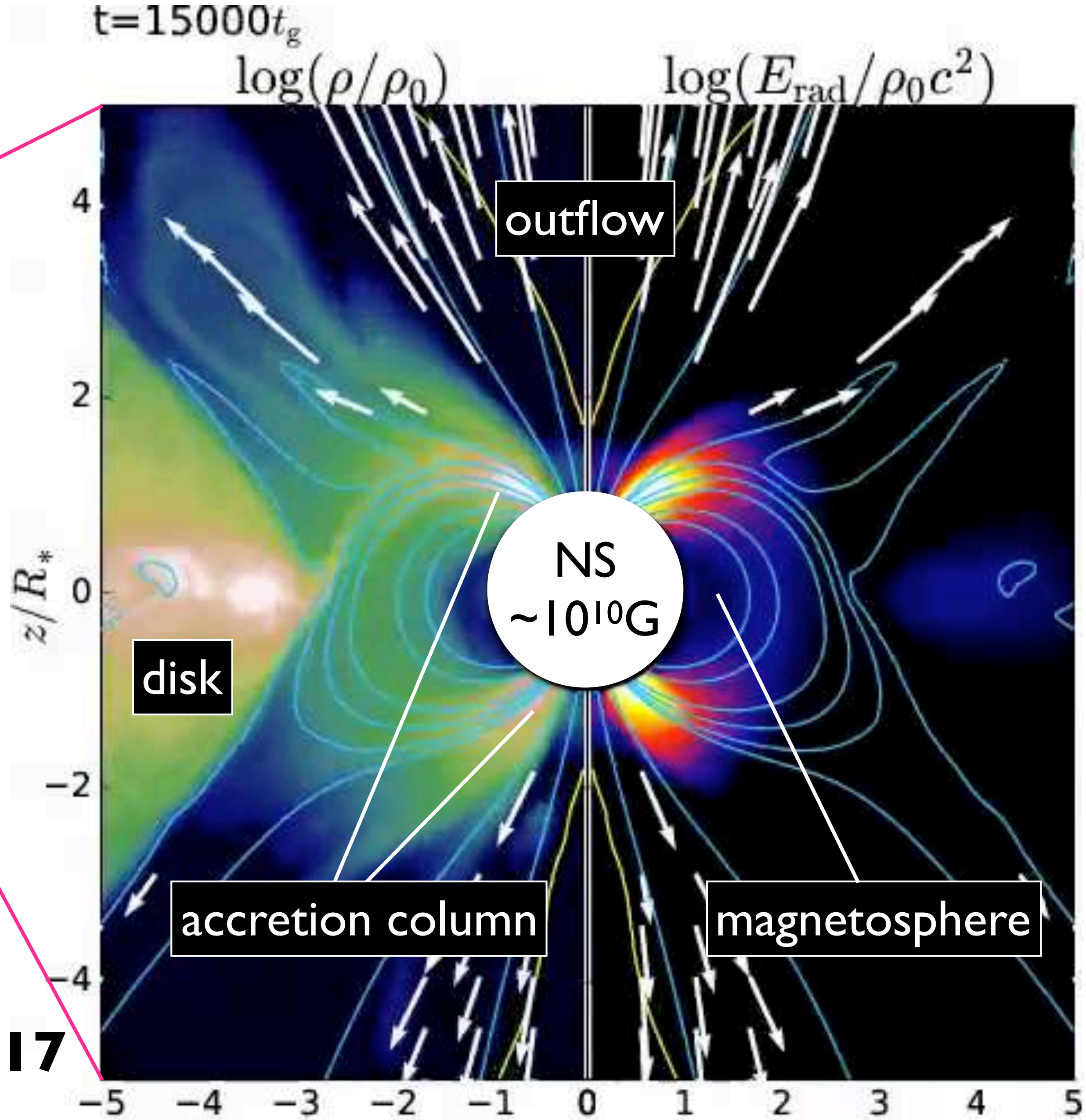
Our result is consistent with the observations of ULXs (Middleton+11) and V404 Cyg (Motta+17) in the case of M_{BH}~10-100Msun.

Super-Edd. flows onto NSs

Accretion column



Magnetized NS

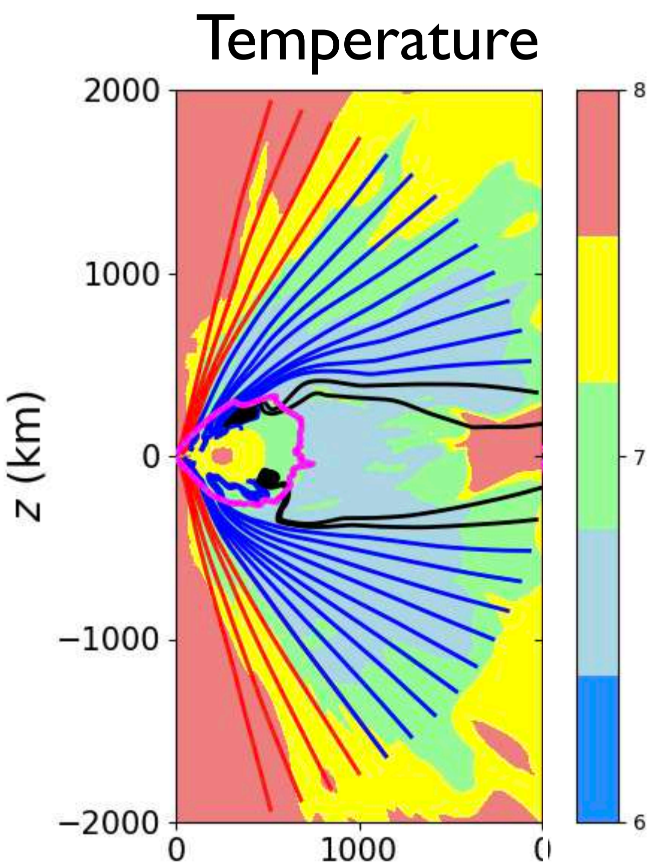


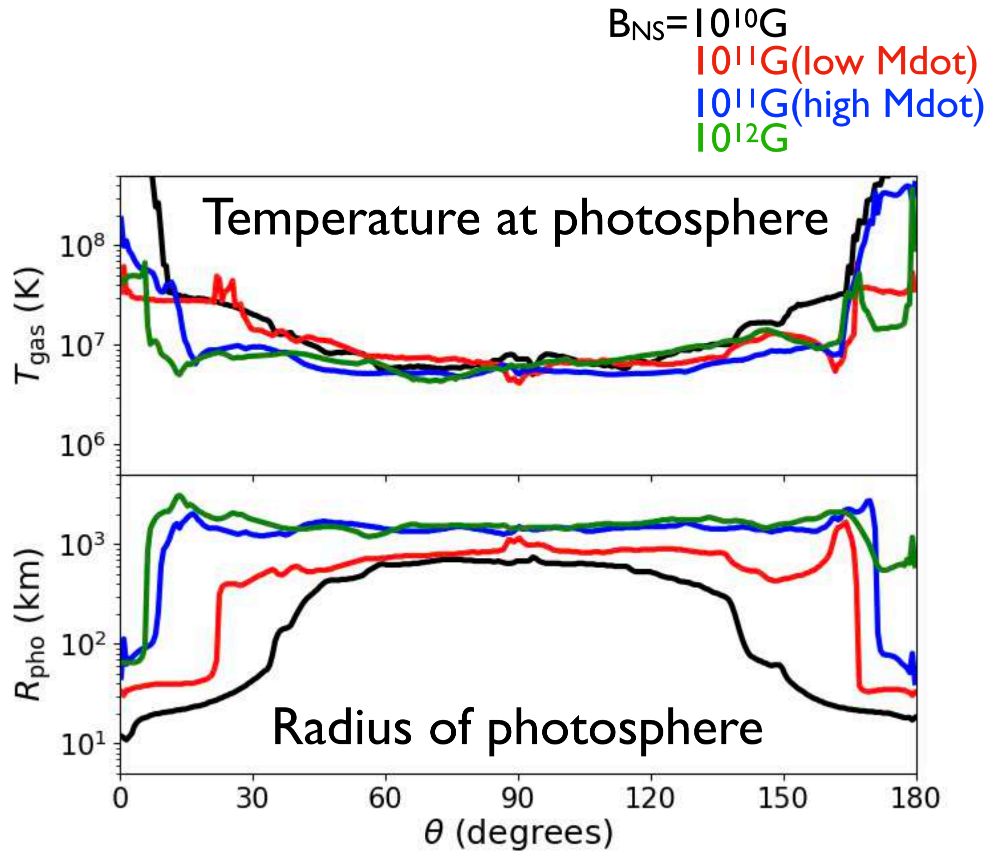
Mdot~$100L_{Edd}/c^2$

L~several L_{Edd}

Takahashi, Ohsuga 2017

Super-Edd. flows onto NSs





Size of photosphere is
~ several 10^2-a few 10^3km

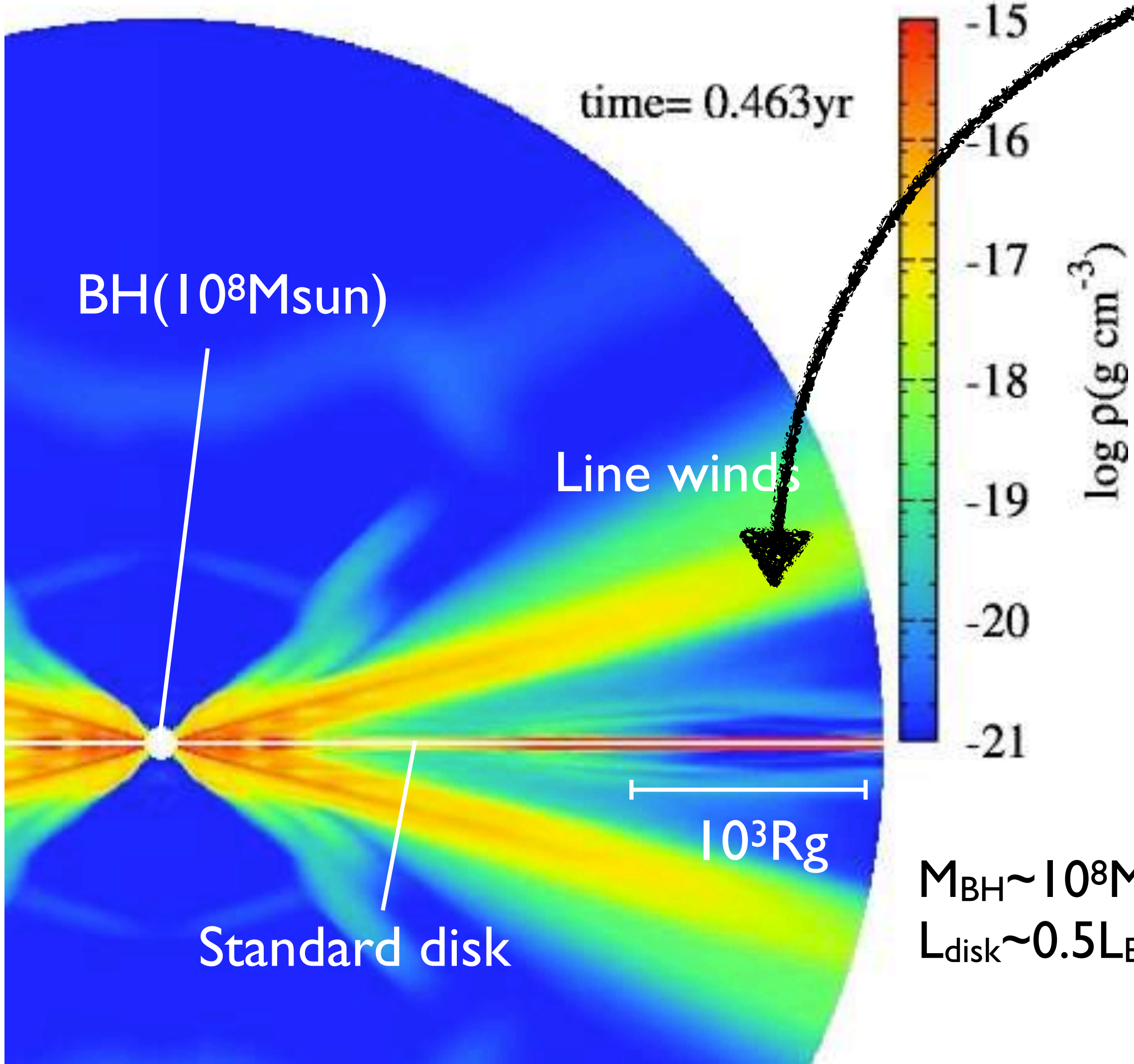
Temperature at
photosphere is ~ 10^7K.

Our model is consistent with observations of ULXP (Tao et al. 19, Beri et al. 20)

Inoue, Ohsuga, et al. in prep

Line-winds

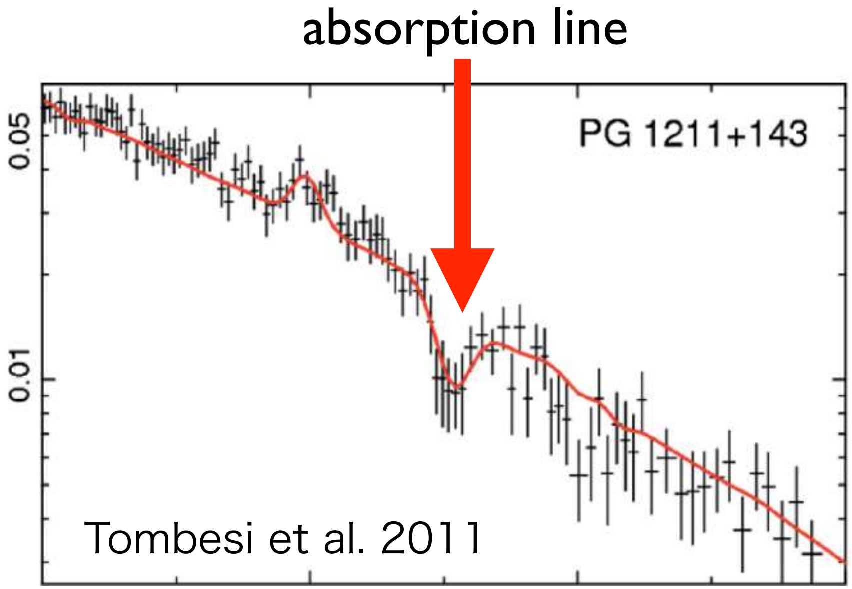
Nomura et al. 2016, 2017, 2020
(see also Proga et al. 00, 04)



From the standard disk, the disk wind is launched by the radiation force for spectral lines (line-force).

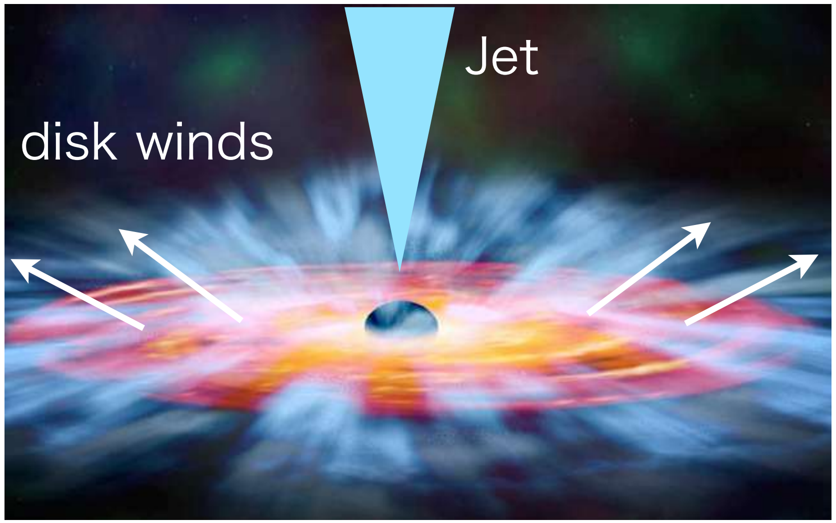
$M_{BH} \sim 10^8$Msum
$L_{disk} \sim 0.5 L_{Edd}$

Ultra Fast Outflows (UFOs)

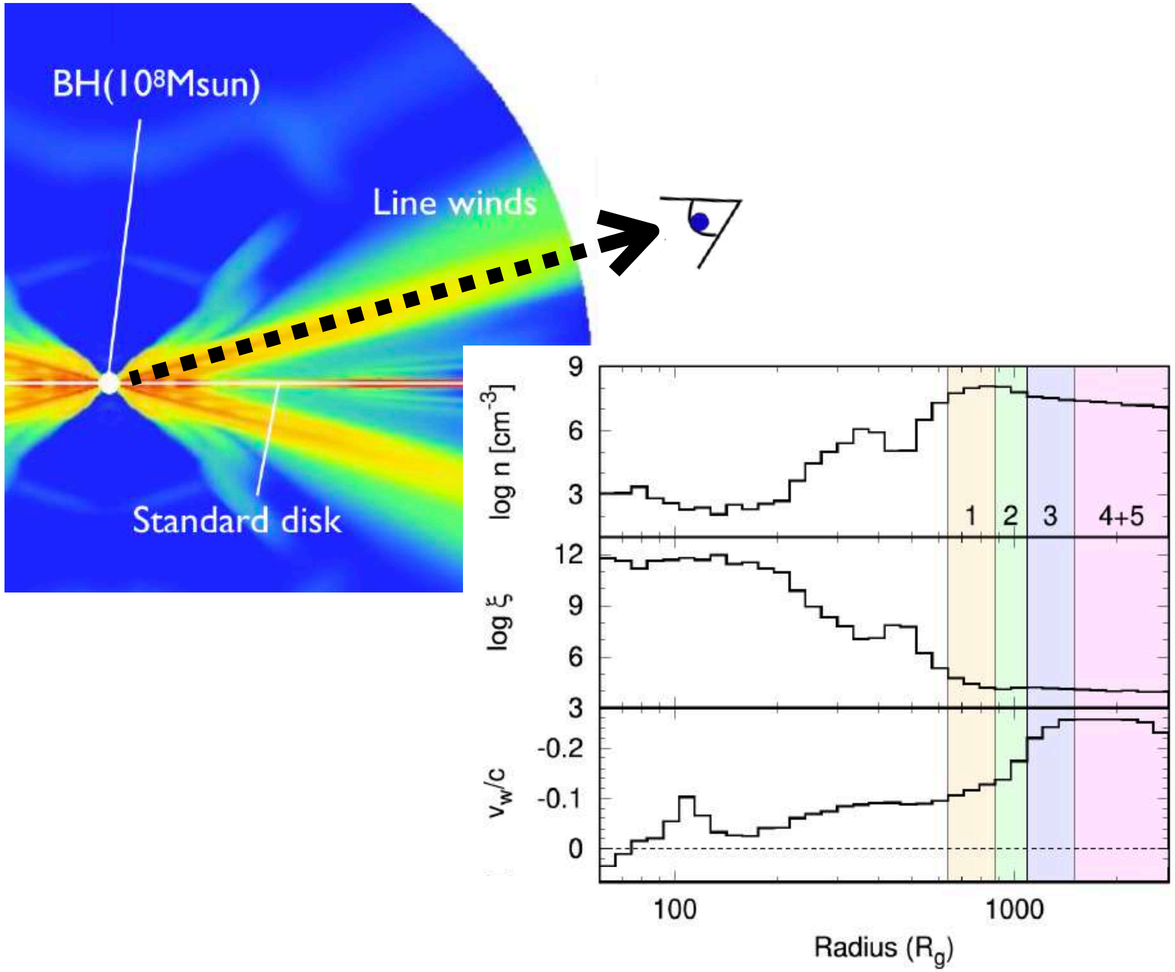


- Blueshifted Fe absorption lines are detected in **40% of Sy galaxies**.
- Typical velocity is **0.1-0.3c**.
- **Outflow rate ~ Accretion rate**
- **Kinetic power ~ Jet power**

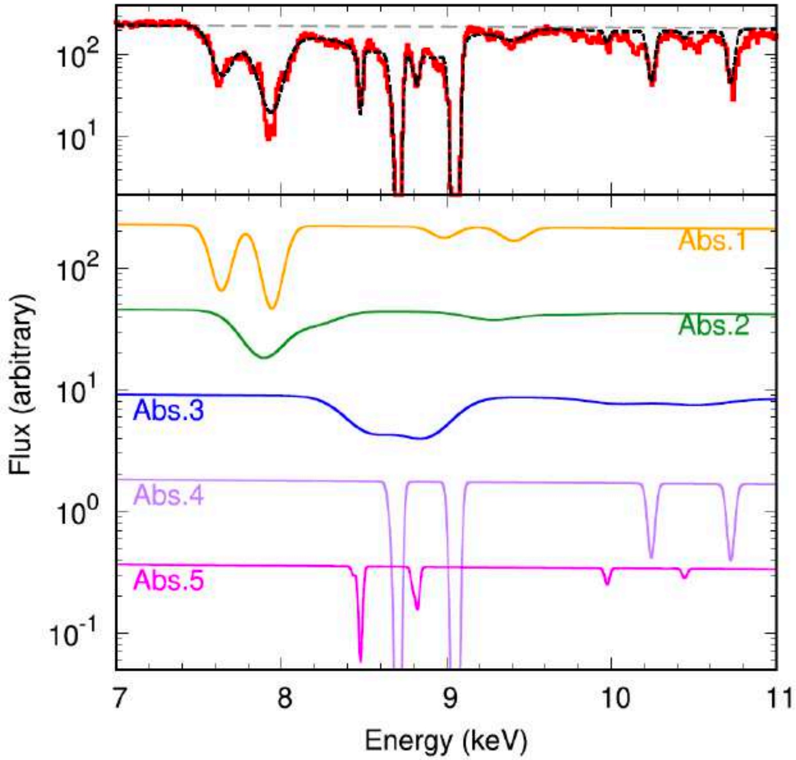
One of the important candidates of the origin of the AGN FEEDBACK



Simulated spectra



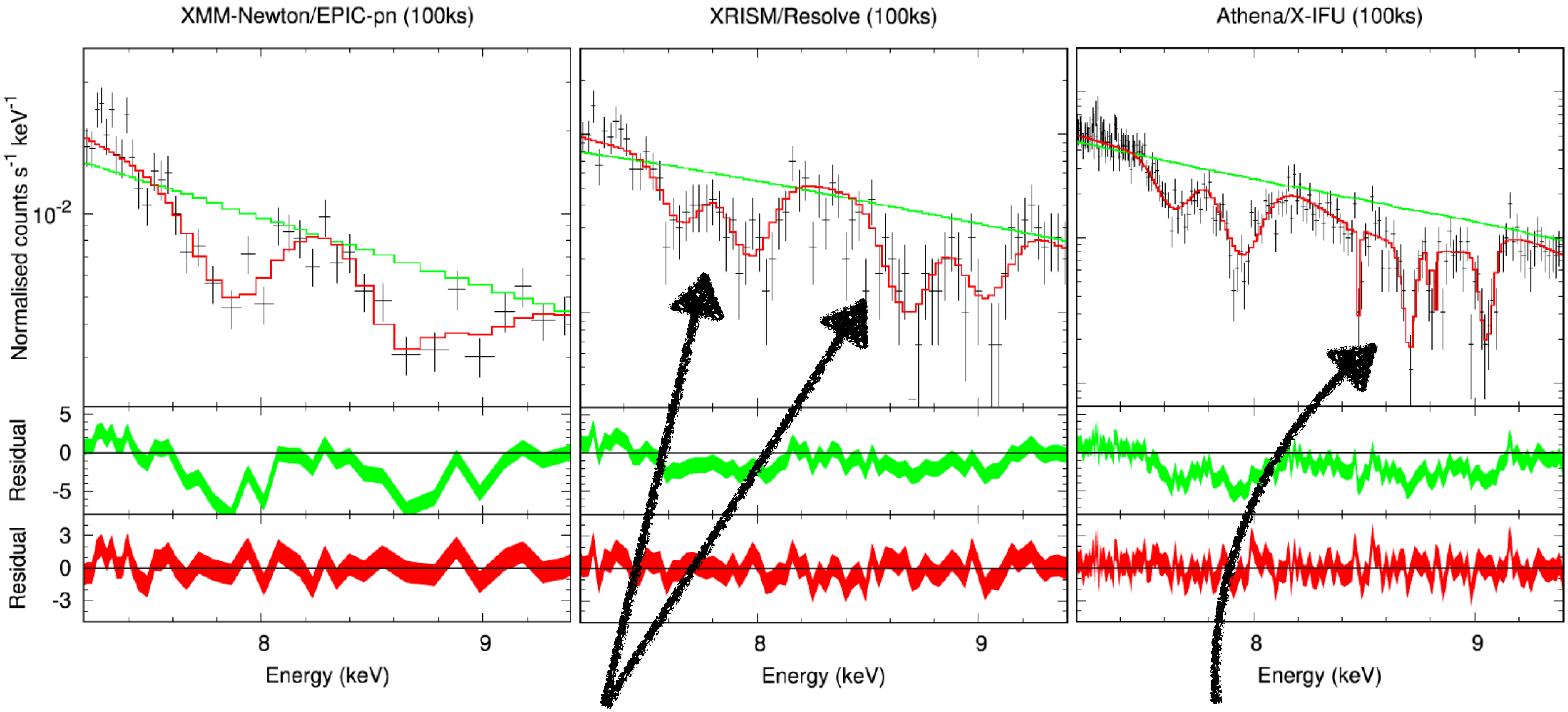
Mizumoto et al. 2021



Density, ionization parameter, velocity drastically change, and there are five absorbing regions along the line of sight.

Complicated Fe absorption lines (H-like and He-like iron) would appear.

Simulated spectra

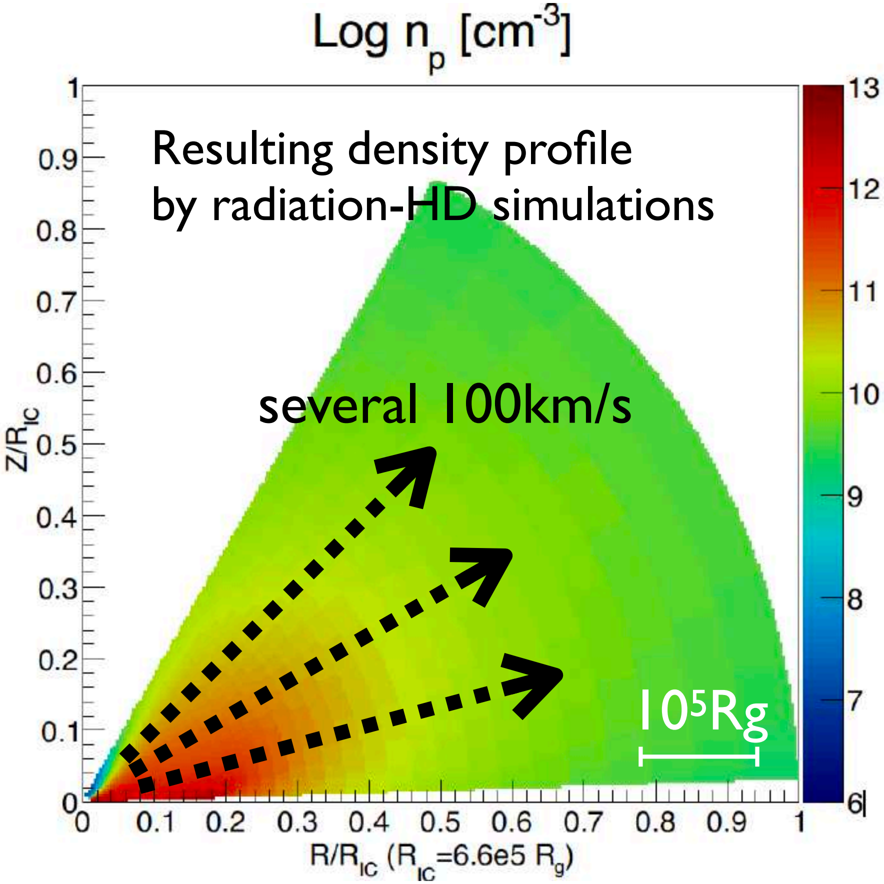


Absorption lines from H-like and He-like iron are resolved by XRISM.

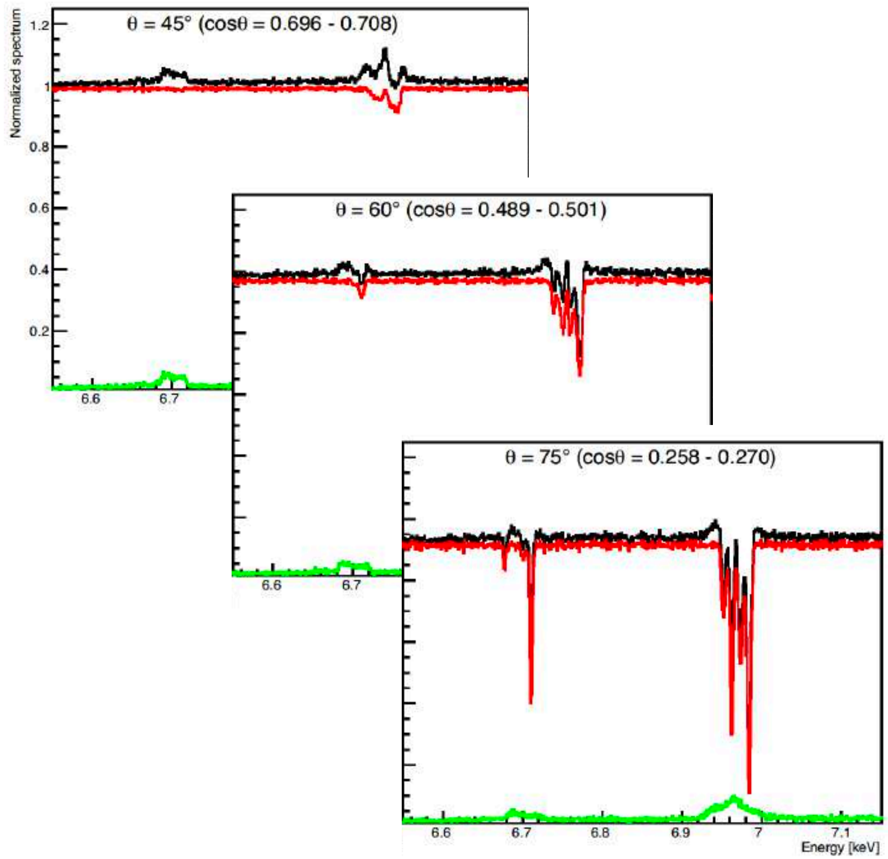
More detailed absorption profiles can be understood by Athena.

Mizumoto et al. 2021

Thermal-radiative wind



Gas is heated up via the Comptonization and blown away by the gas pressure force and the radiation force.

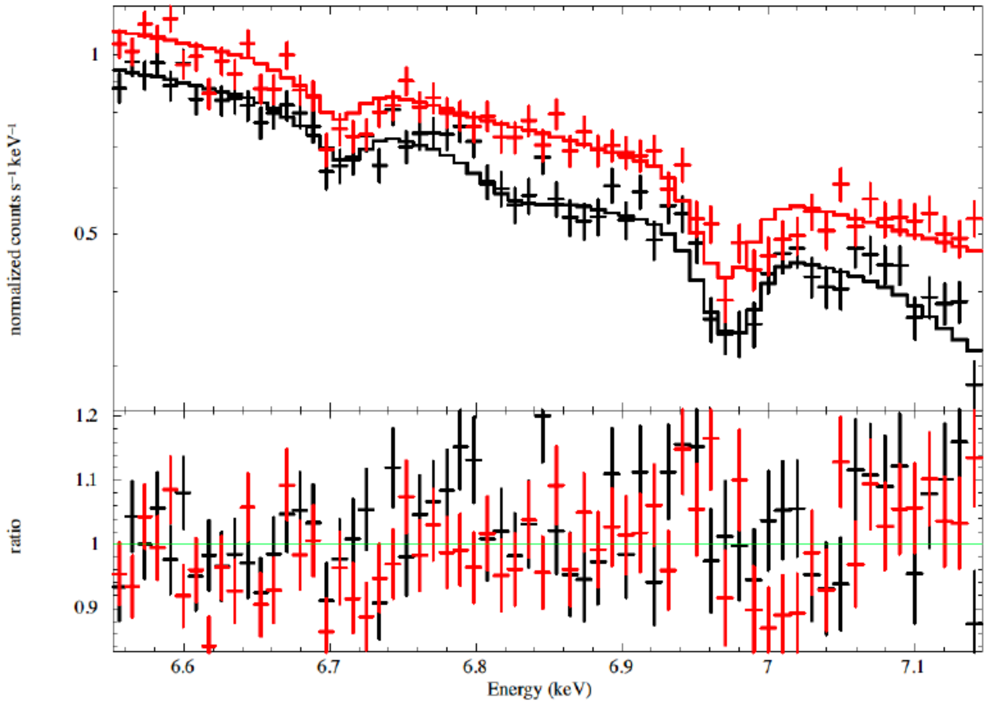


Simulated absorption features (Fe XXVI Ly α_1 & Ly α_2) are obtained by MONACO.

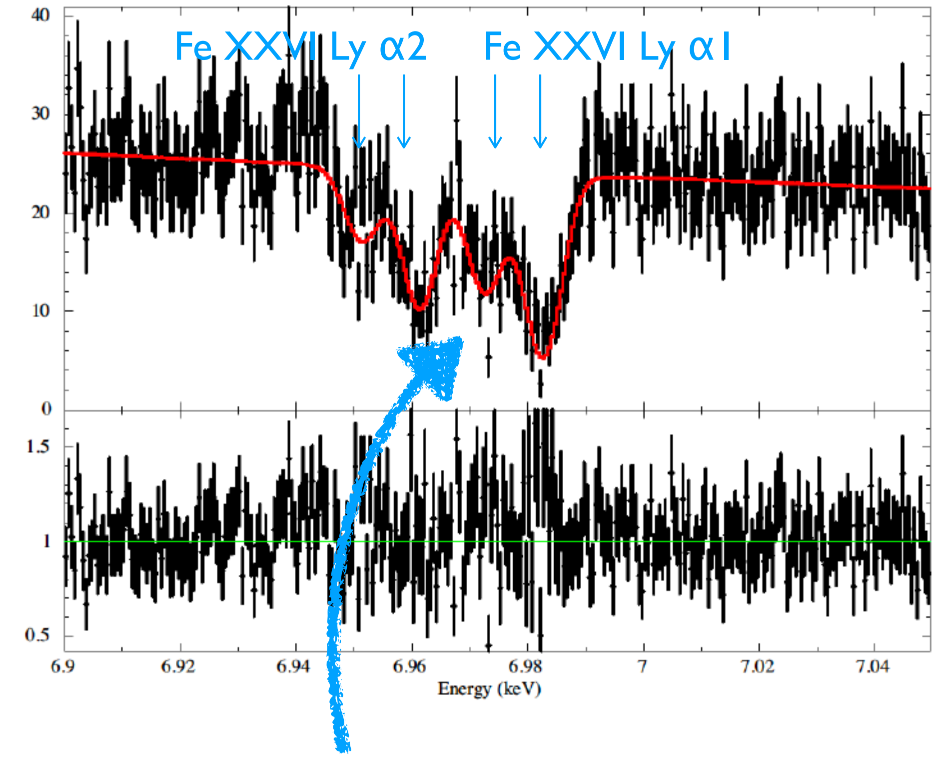
Tomaru et al. 2020

Thermal-radiative wind

Chandra/HETGS data with best-fitting model



Simulated spectrum of a 30 ks XRISM observation



Simulation results are consistent with observations of BH binary, H1743−322.

Separation of Fe absorption lines due to velocity difference would be detected by XRISM.

Tomaru et al. 2020

Summary

Outflow from Super-Eddington Disks

- Outflow is accelerated by the radiation force for electron scattering.
- Our model is consistent with observations of ULXs; Luminosity, X-ray spectra, outflow velocity, relatively low-temperature BB radiation, and so on.

Disk winds from near-Eddington Disks

- Matter is blown away by radiation force for spectral lines and gas pressure force.
- Simulated Fe spectral lines are consistent with observations of AGNs (UFOs) and XRBs.
- Detailed line structure is expected to be resolved by XRISM/Athena.