AGNアウトフローの理論研究とSMBHの進化

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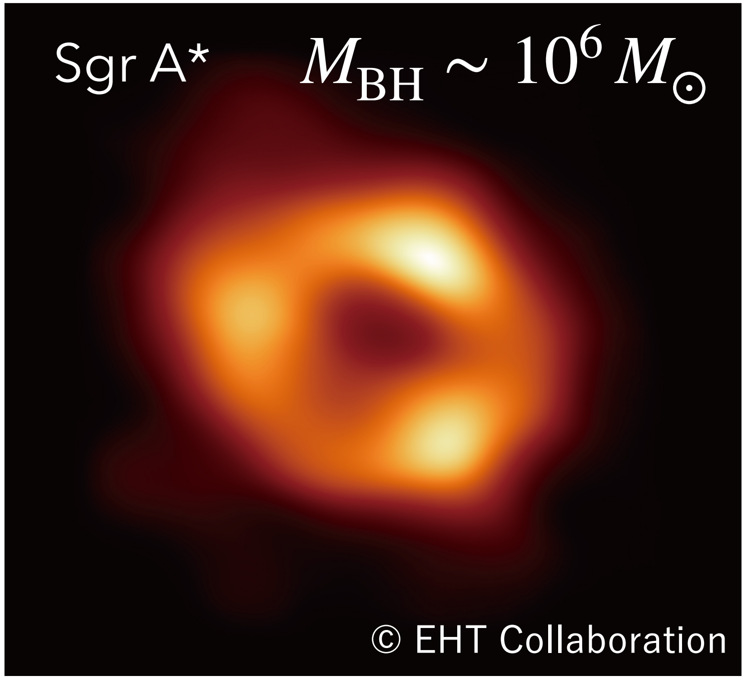
  - Suppression of mass accretion at the disk scale
  - Feedback onto the interstellar medium and multi-scale outflows

Supermassive black holes

- Supermassive black holes (SMBHs, $M_{\rm BH} \sim 10^{6-10}\,M_\odot$) are found in the center of almost all large galaxies.

- $M_{\rm BH} \sim 10^9\,M_\odot$ @ $z \gtrsim 6$ → Heavy seed BHs of $\sim 10^{3-5}\,M_\odot$ and/or rapid gas accretion close to the Eddington rate are preferred, but the specific process of growth from seeds to SMBHs is not known.



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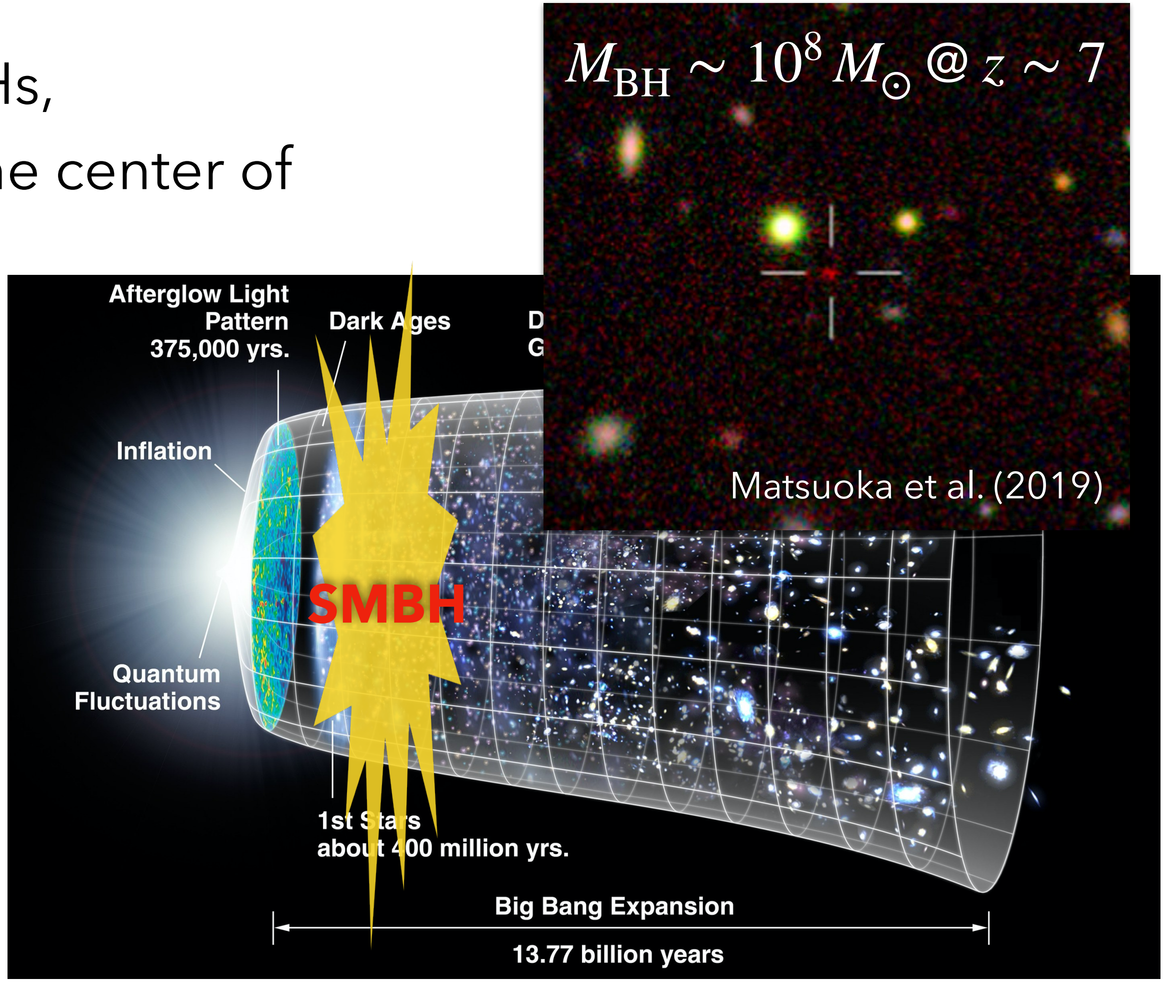
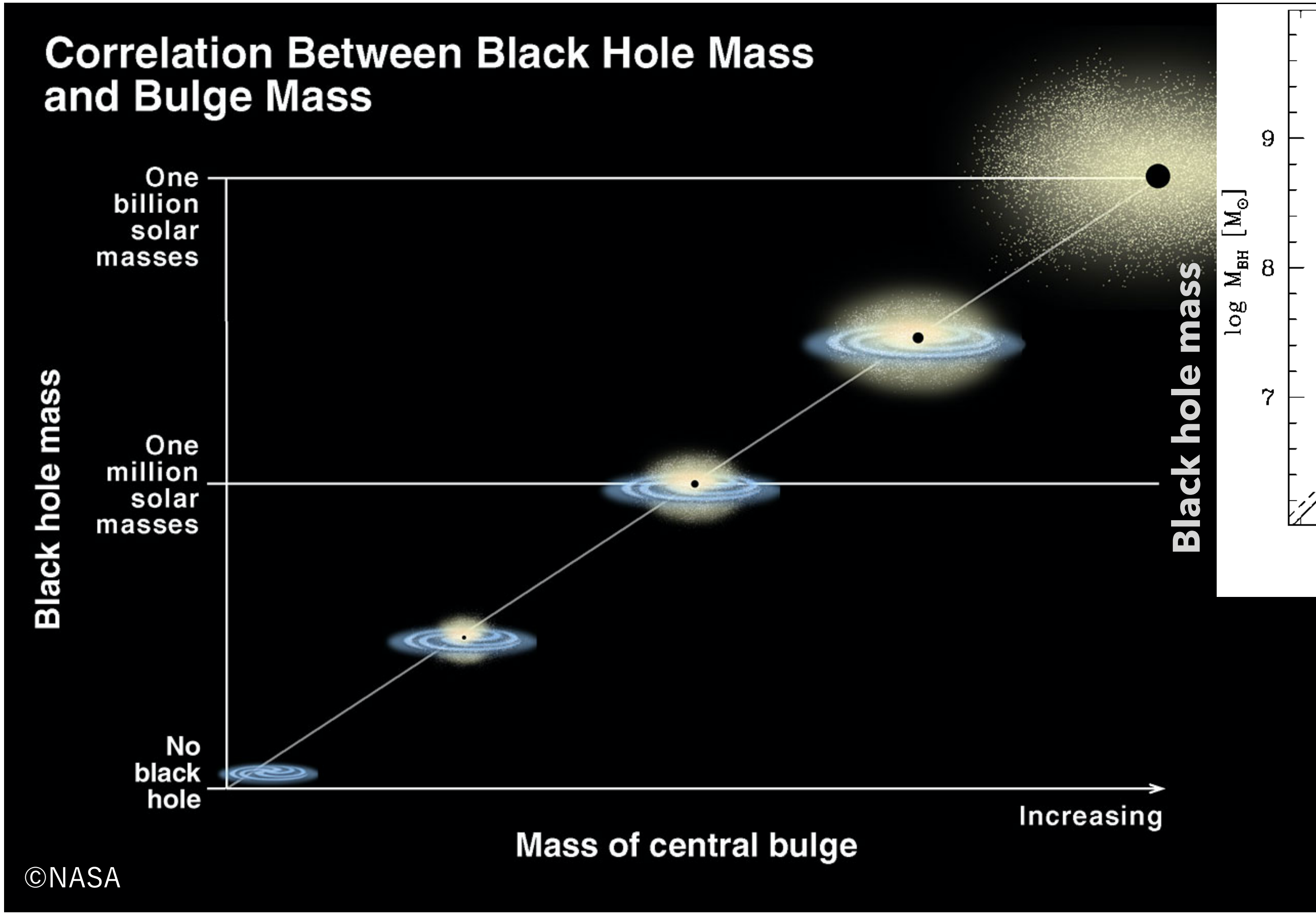
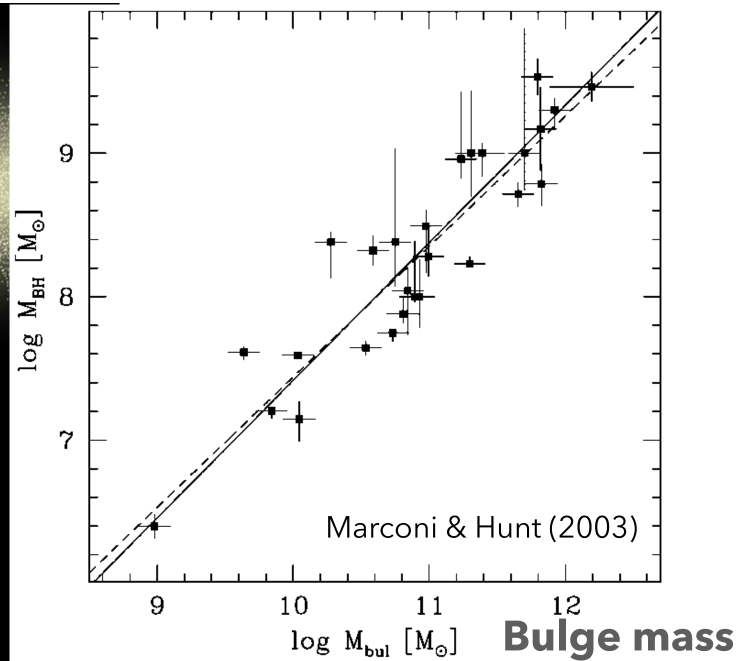


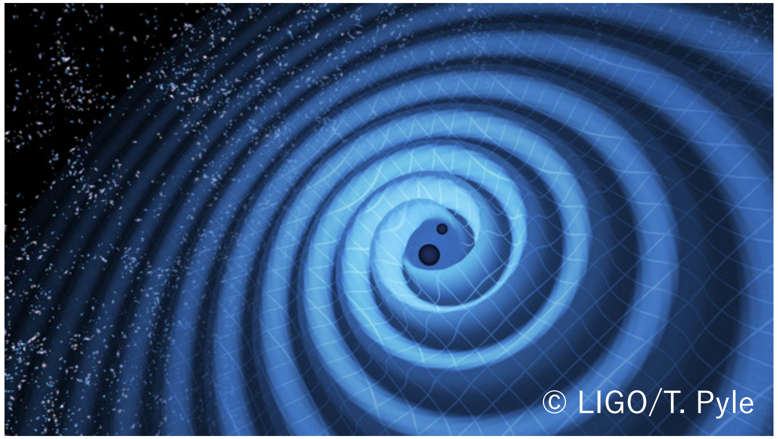
Co-evolution between SMBHs and galaxies



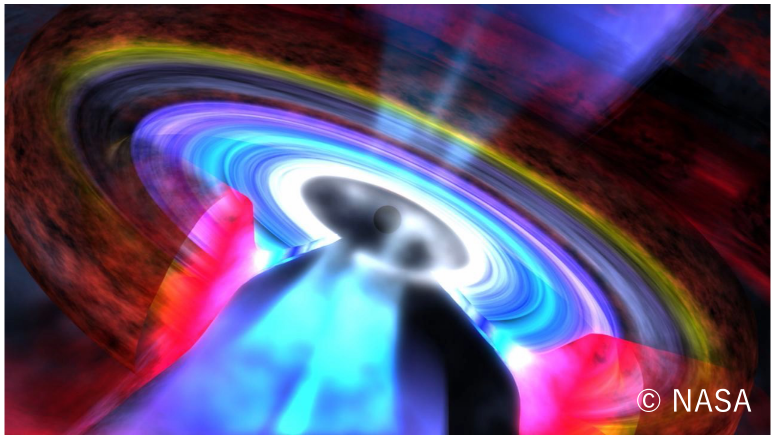


→ SMBH and host galaxies influence each other.

What is the evolution process of SMBH?



✦ Growth by merging of black holes

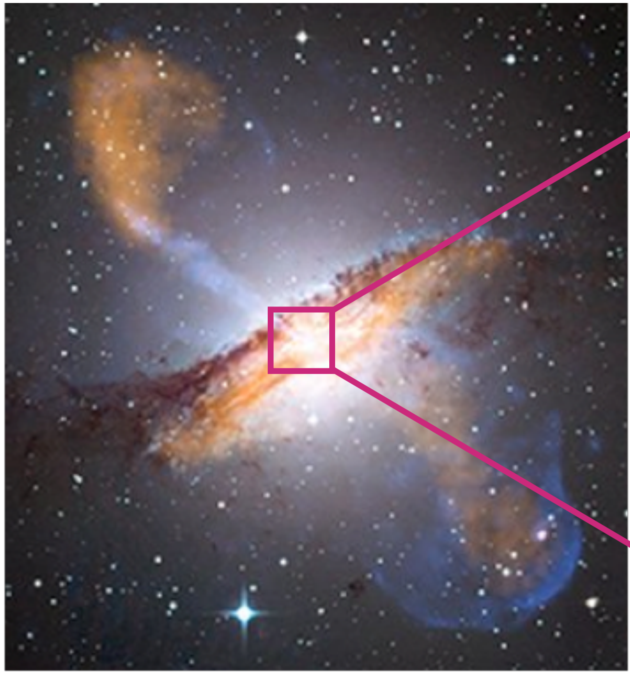


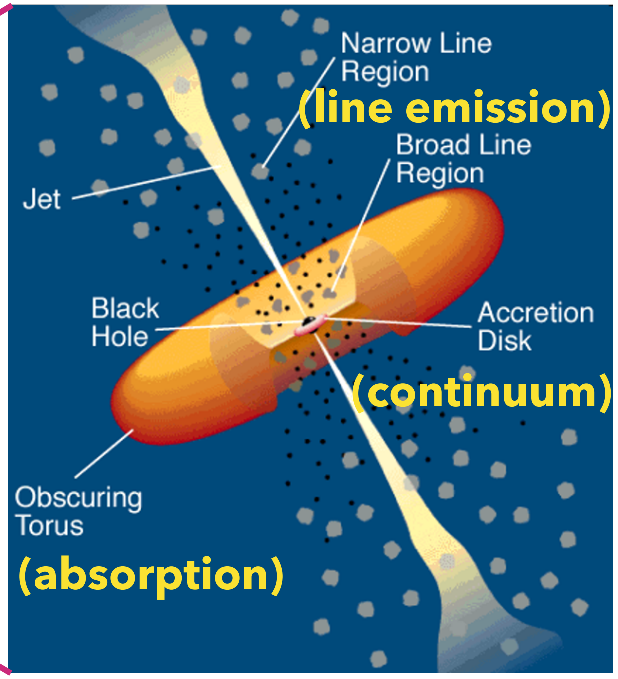
✦ Growth due to the fall of surrounding gas into the black hole (mass accretion) → Understanding the **activity galactic nuclei (AGNs)** is important.

Active galactic nuclei (AGNs)

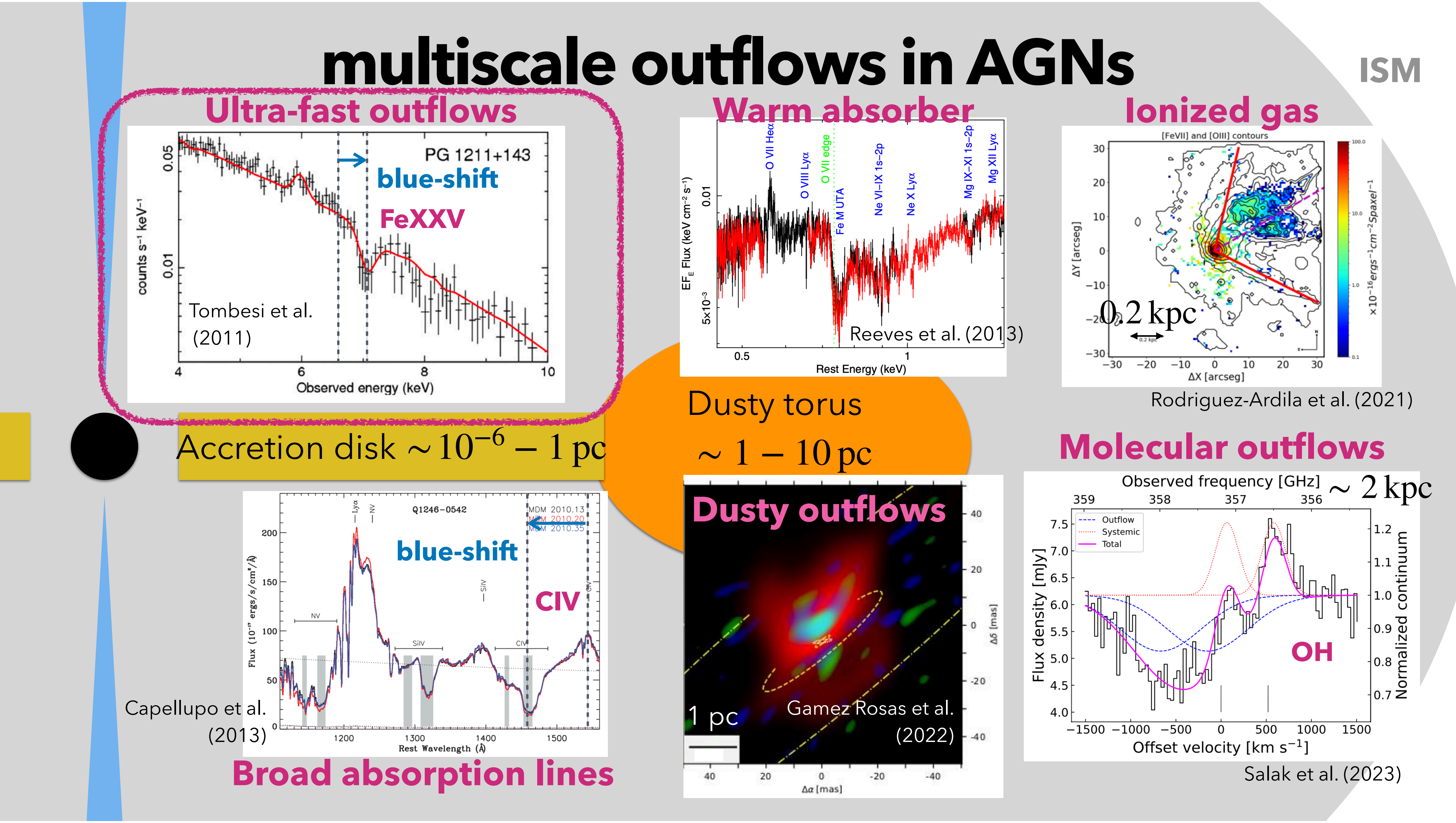
- The accretion of a large amount of mass onto a SMBH releases the gravitational energy via radiation and jets.
- The classical phenomenological model can explain basic spectral features (continuum, emission lines, absorption) of AGNs.

host galaxy



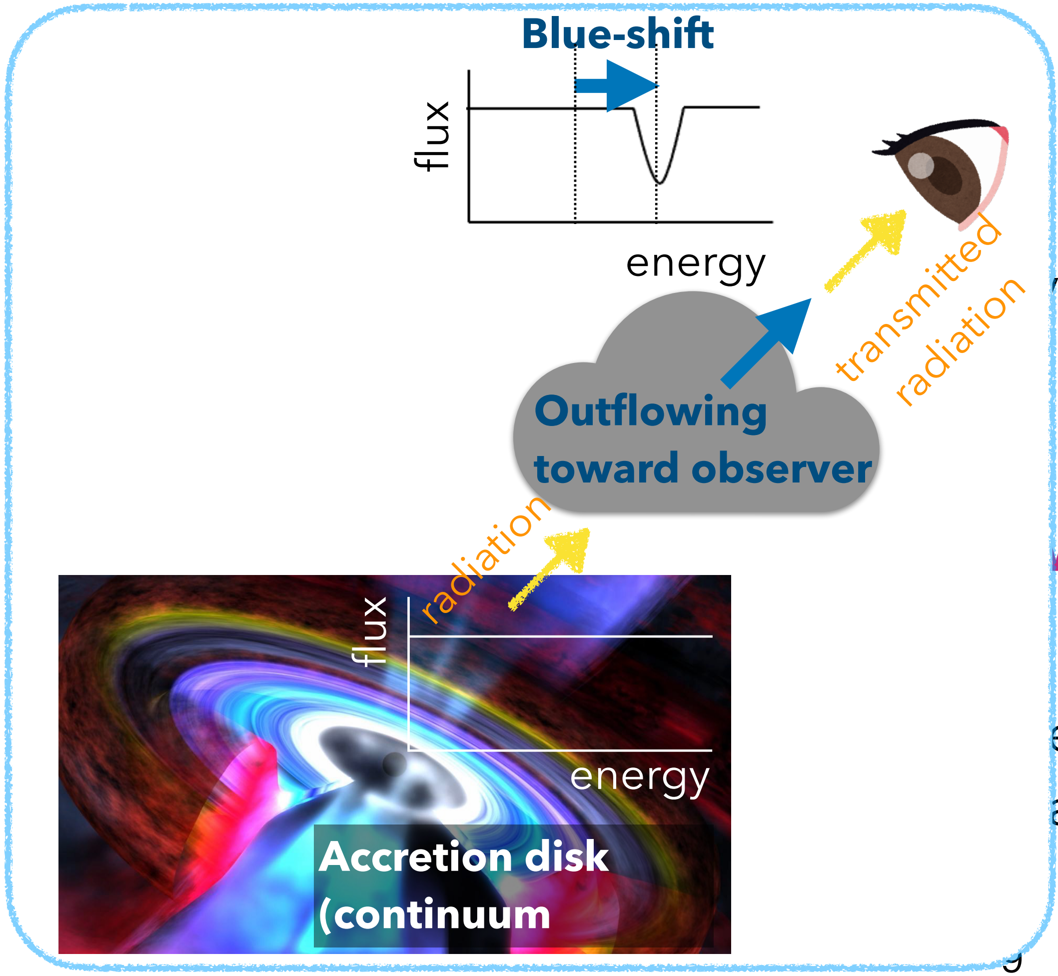


unified model of AGNs


multiscale outflows in AGNs
ISM
Ultra-fast outflows
PG 1211+143
blue-shift
FeXXV
Tombesi et al. (2011)
counts s⁻¹ keV⁻¹
Observed energy (keV)
Warm absorber
O VII Heα
O VIII Lyα
O VII edge
Fe M UTA
Ne VI–IX 1s–2p
Ne X Lyα
Mg IX–XI 1s–2p
Mg XII Lyα
Reeves et al. (2013)
Rest Energy (keV)
Ionized gas
[FeVII] and [OIII] contours
0.2 kpc
ΔX [arcseg]
ΔY [arcseg]
Rodriguez-Ardila et al. (2021)
Accretion disk $\sim 10^{-6} - 1$ pc
Dusty torus
$\sim 1 - 10$ pc
Dusty outflows
1 pc
Gamez Rosas et al. (2022)
Δα [mas]
Δδ [mas]
Molecular outflows
~ 2 kpc
Observed frequency [GHz]
Outflow
Systemic
Total
OH
Flux density [mJy]
Normalized continuum
Offset velocity [km s⁻¹]
Salak et al. (2023)
Q1246−0542
blue-shift
CIV
Capellupo et al. (2013)
Rest Wavelength (Å)
Broad absorption lines

Ultra-Fast outflows

✦ Bule-shifted absorption lines suggest the outflows.



es

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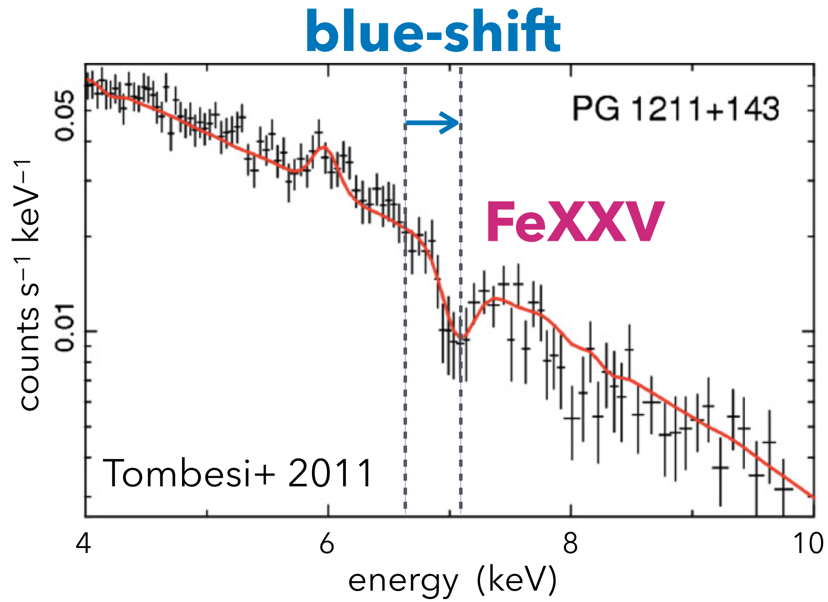
wind

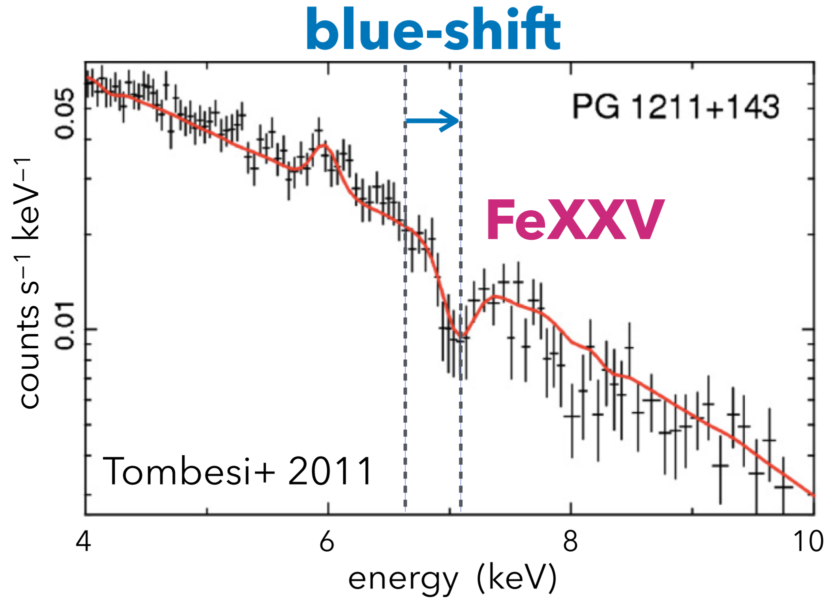
ess SMBH growth

alaxy co-evolution



Ultra-Fast outflows

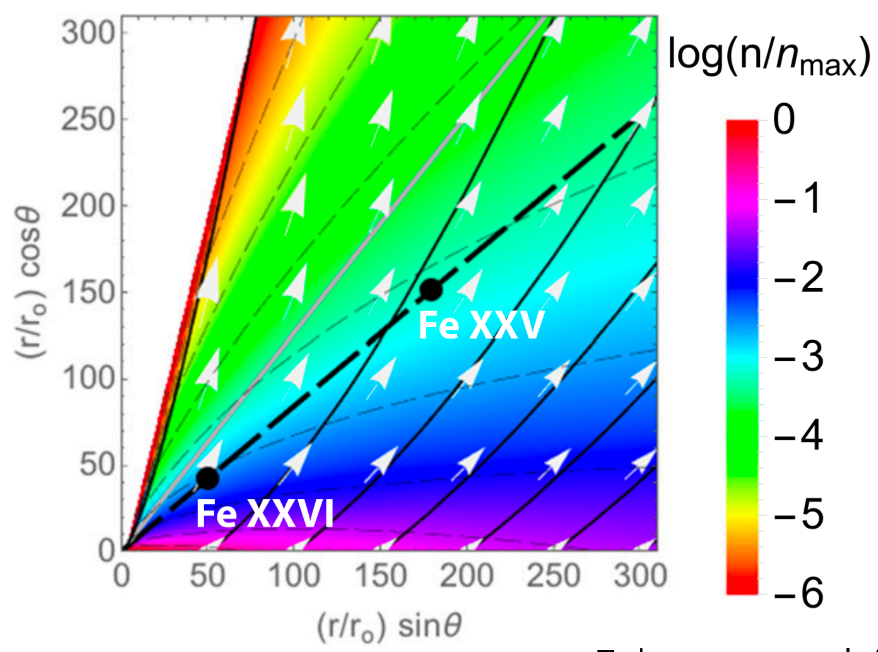
- ✦ Bule-shifted absorption lines suggest the outflows.
- ✦ **Ultra-fast outflows (UFOs)**
  - outflow speed ~0.1-0.3c
  - detected in 40% of nearby AGN samples
  - large mass loss rate and kinetic energy
    $\dot{M}_{\rm wind}/\dot{M}_{\rm Edd} \sim 0.01 - 1,$
    $L_{\rm wind}/L_{\rm Edd} \sim 0.1 - 10\,\%$



- ✦ Location of UFOs is $\sim 100 R_{\rm S}$ → **disk wind**
- ✦ Effects on the SMBH growth
  - decrease mass accretion rate → suppress SMBH growth
  - feedback onto host galaxy → SMBH-galaxy co-evolution

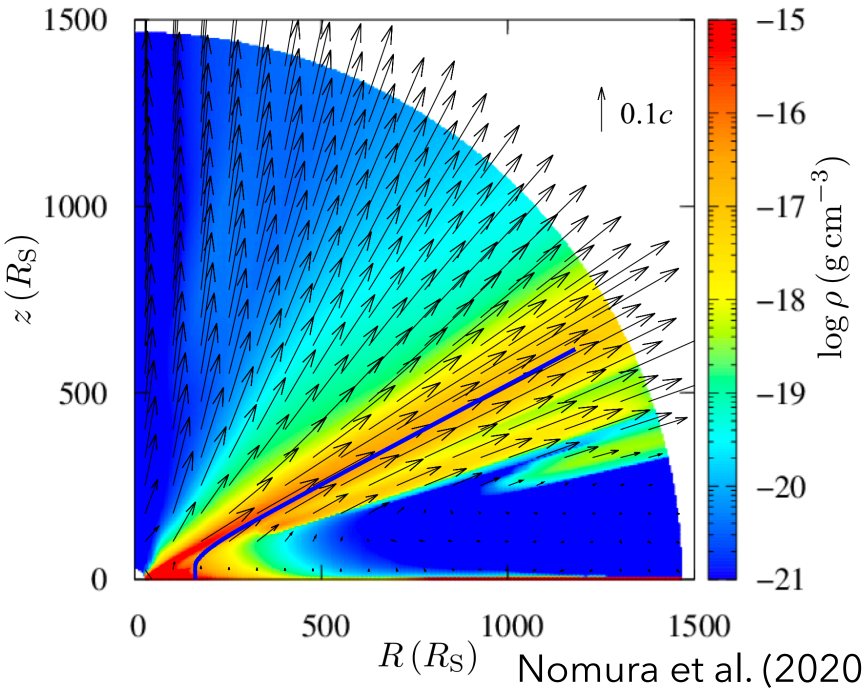
Possible launching mechanism of UFOs

1. Magnetically driven wind



Fukumura et al. (2015)

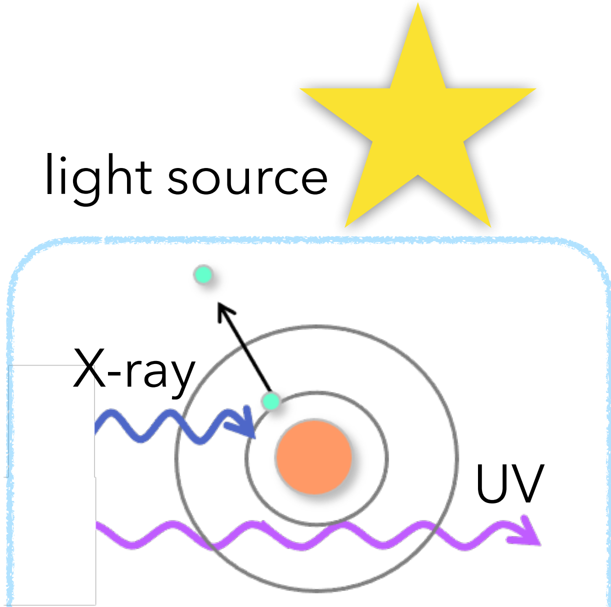
2. Radiation-driven wind
   - Continuum-driven wind is unlikely in the sub-Eddington AGNs
   - **Line-driven wind** is preferred.



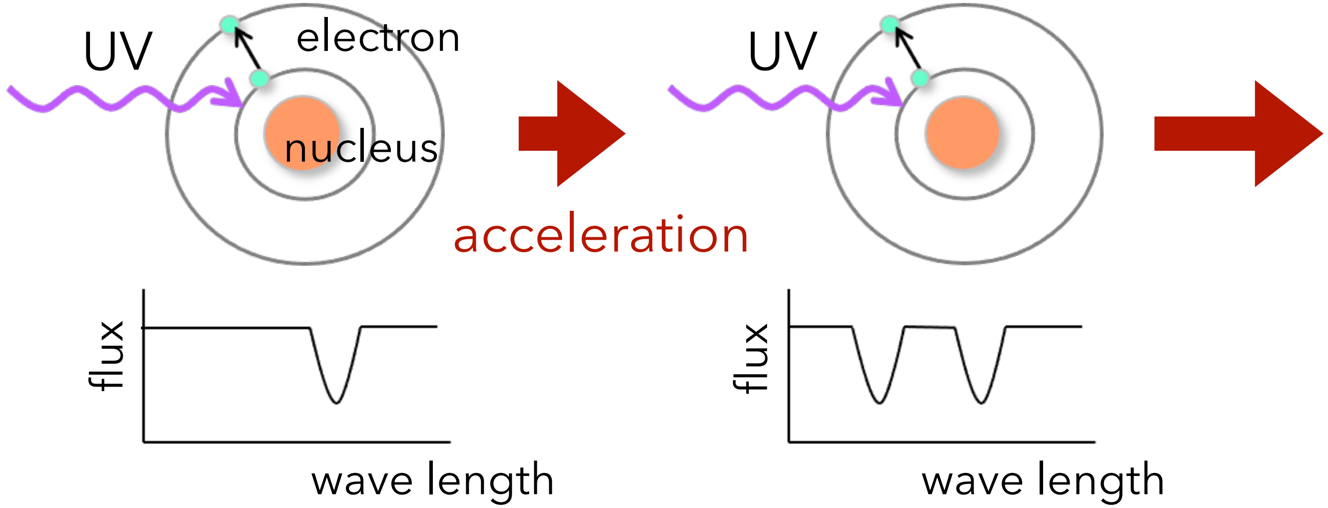
Nomura et al. (2020)

Line-driving mechanism

✦ line-driven winds are accelerated by radiation force due to absorbing UV radiation through the bound–bound transitions of metals (**line force**)



X-ray ionizes the metal and suppresses the line force.

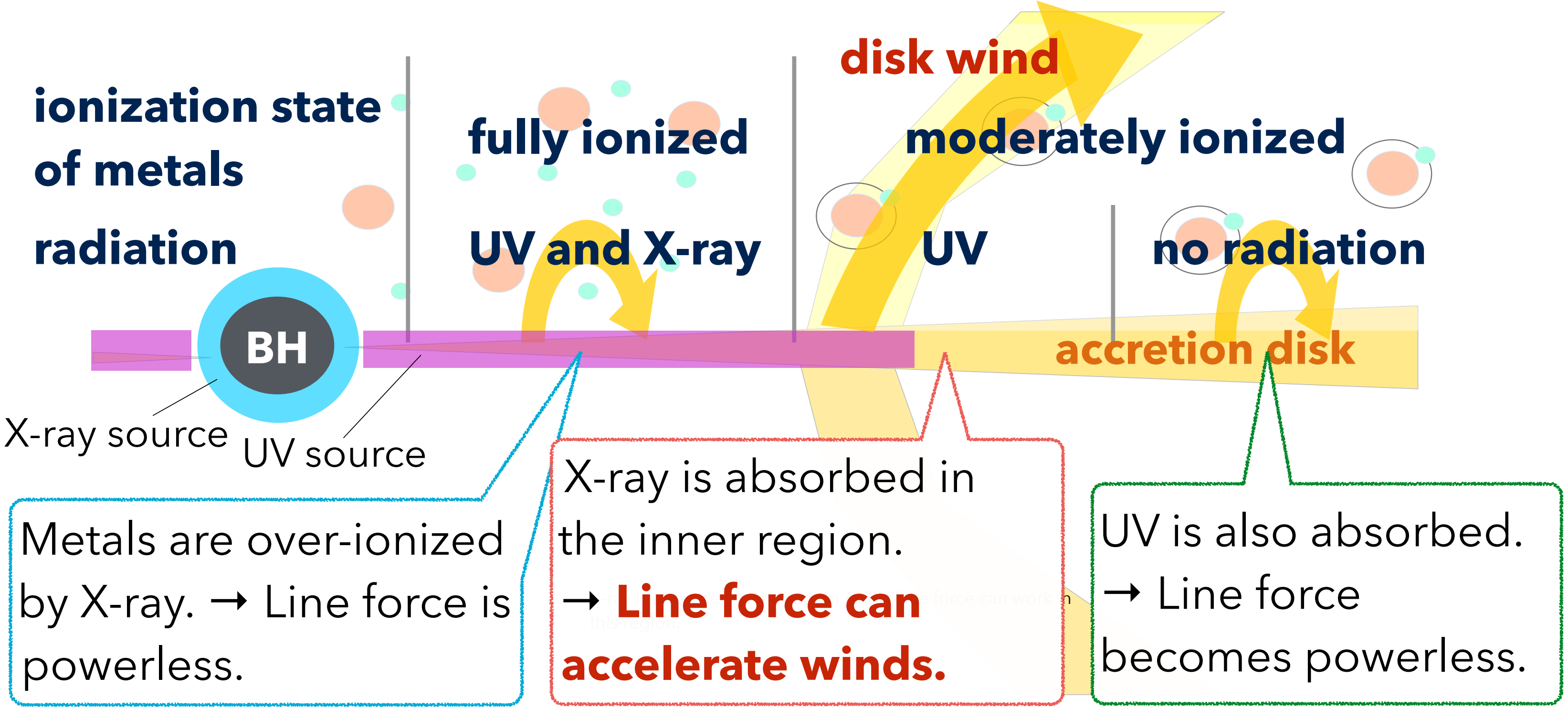


Momentum is transferred from radiation to the metal ion through the **bound-bound transition.**

Matter is accelerated even in the downstream because of the **Doppler shift.**

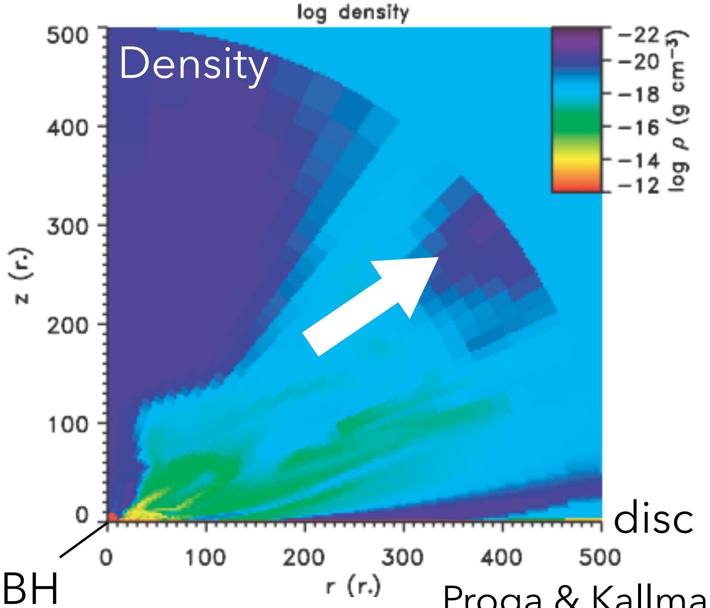
line-driven winds in AGNs

- ✦accelerated by radiation force due to absorbing UV radiation through the bound–bound transition of metals (**line force**)
- ✦Line force can accelerate the moderately ionized matter effectively.

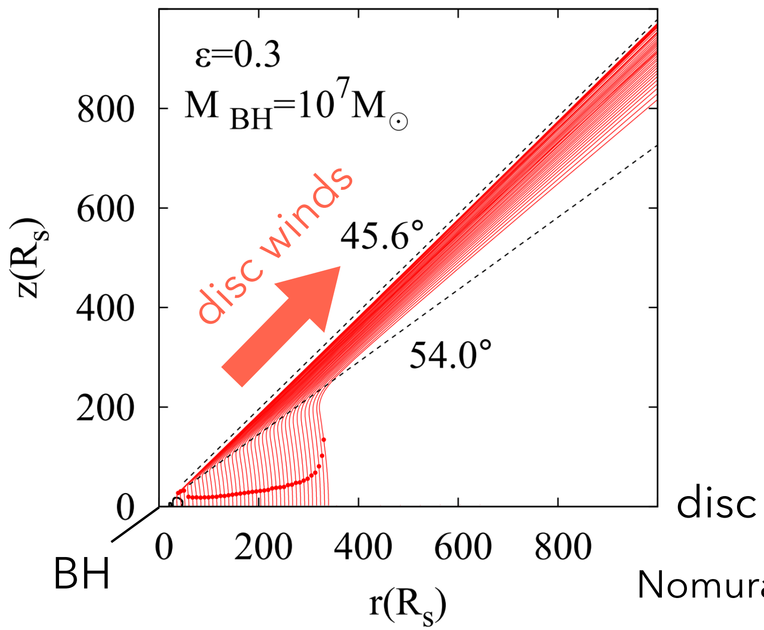


Early theoretical works of line-driven winds

- Hydrodynamics simulations
  2D：Proga et al. (2000), Proga & Kallman (2004), 3D：Dyda & Proga (2017)
- Calculations of steady structure: Risaluti & Elvis (2010), Nomura et al. (2013)



Proga & Kallman (2004)



Nomura et al. (2013)

Do the line-driven winds reproduce the UFOs?

Method: basic equations & setup

- Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

- Equations of motion

Radiation force

$$\frac{\partial(\rho v_r)}{\partial t} + \nabla \cdot (\rho v_r \mathbf{v}) = -\frac{\partial p}{\partial r} + \rho \left[\frac{v_\theta^2}{r} + \frac{v_\varphi^2}{r} + g_r + f_{\mathrm{rad},\, r} \right]$$

$$\frac{\partial(\rho v_\theta)}{\partial t} + \nabla \cdot (\rho v_\theta \mathbf{v}) = -\frac{1}{r}\frac{\partial p}{\partial \theta} + \rho \left[-\frac{v_r v_\theta}{r} + \frac{v_\varphi^2}{r} \cot\theta + g_\theta + f_{\mathrm{rad},\, \theta} \right]$$

$$\frac{\partial(\rho v_\varphi)}{\partial t} + \nabla \cdot (\rho v_\varphi \mathbf{v}) = -\rho \left[\frac{v_\varphi v_r}{r} + \frac{v_\varphi v_\theta}{r} \cot\theta \right]$$

- Energy equation

Radiative heating/cooling

$$\frac{\partial}{\partial t}\left[\rho \left(\frac{1}{2} v^2 + e \right) \right] + \nabla \cdot \left[\rho \mathbf{v} \left(\frac{1}{2} v^2 + e + \frac{p}{\rho} \right) \right] = \rho \mathbf{v} \cdot \mathbf{g} + \rho \mathbf{v} \cdot \mathbf{f}_{\mathrm{rad}} + \rho \mathscr{L}$$

radiation force due to Thomson scattering

line force

$$f_{\mathrm{rad}} = \frac{\sigma_e \boldsymbol{F}_{\mathrm{UV}}}{c} + \frac{\sigma_e \boldsymbol{F}_{\mathrm{UV}}}{c} M$$

force multiplier

ionization parameter $\xi = 4\pi F_X / n$ ↘

density ρ ↘

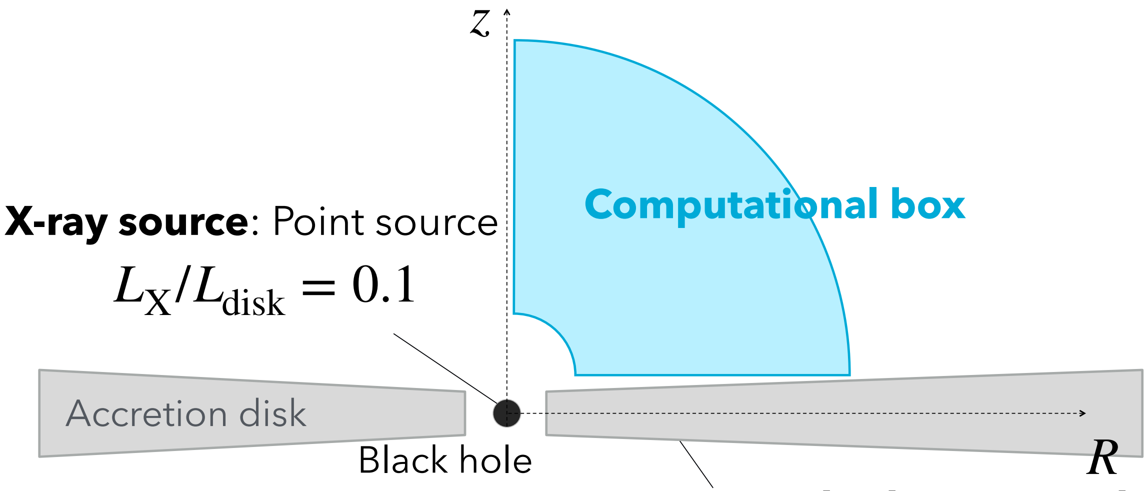
velocity gradient $\left| \frac{dv}{dr} \right|$ ↗

metallicity Z ↗

$\Rightarrow M$ ↗

Stevens & Kallman (1990)
Kudritzki et al. (1989)

Method: basic equations & setup



UV source: Standard accretion disk
(Radiation in the range of 300–3200Å contributes the line force.)
ignore X-ray emitted from the disk

- Accretion disk surface is the boundary.
- Radiation source is located outside the computational box.

radiation force due to Thomson scattering

line force

$$f_{rad} = \frac{\sigma_e F_{UV}}{c} + \frac{\sigma_e F_{UV}}{c} M$$

force multiplier

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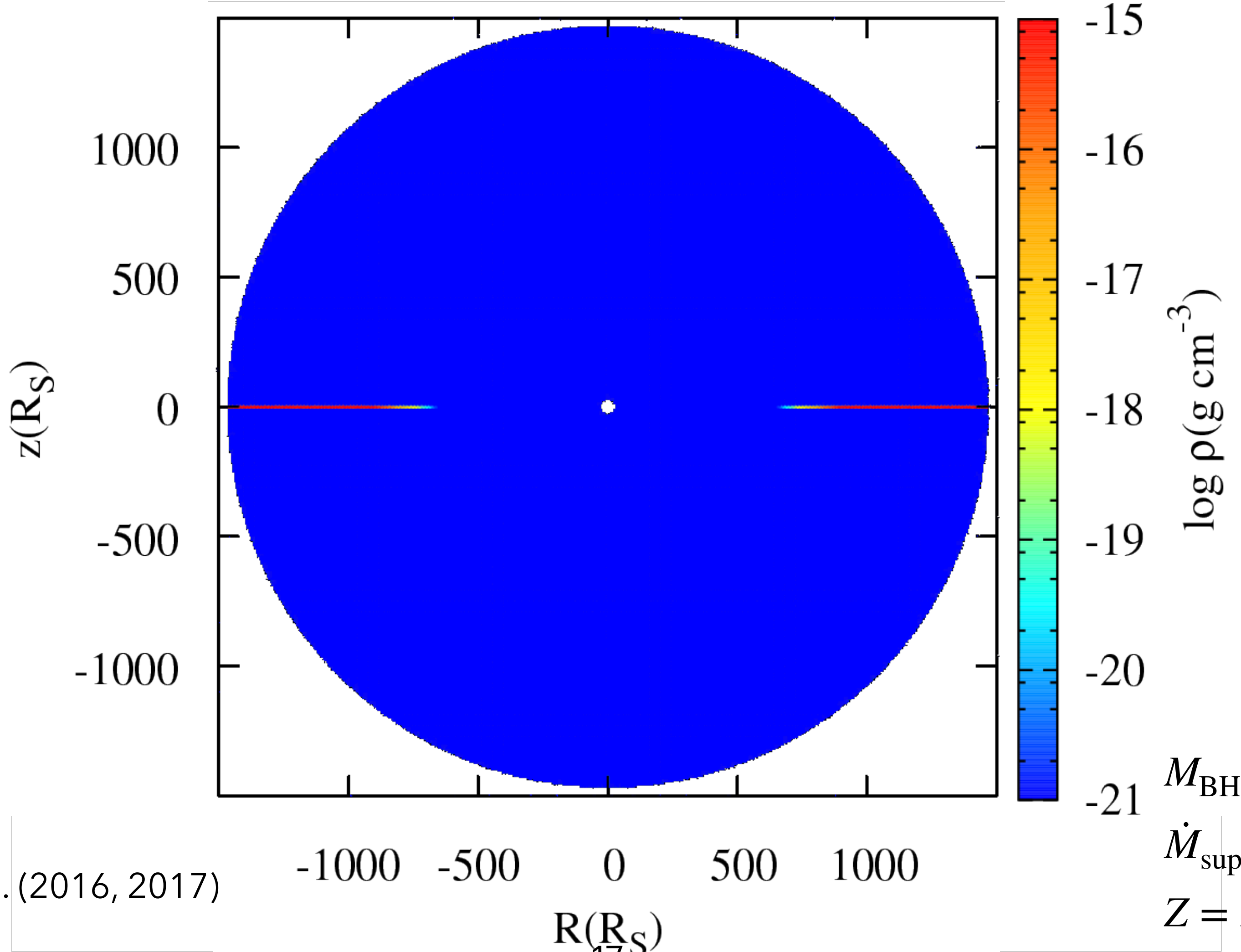
Results



$M_{\rm BH} = 10^8\, M_\odot$

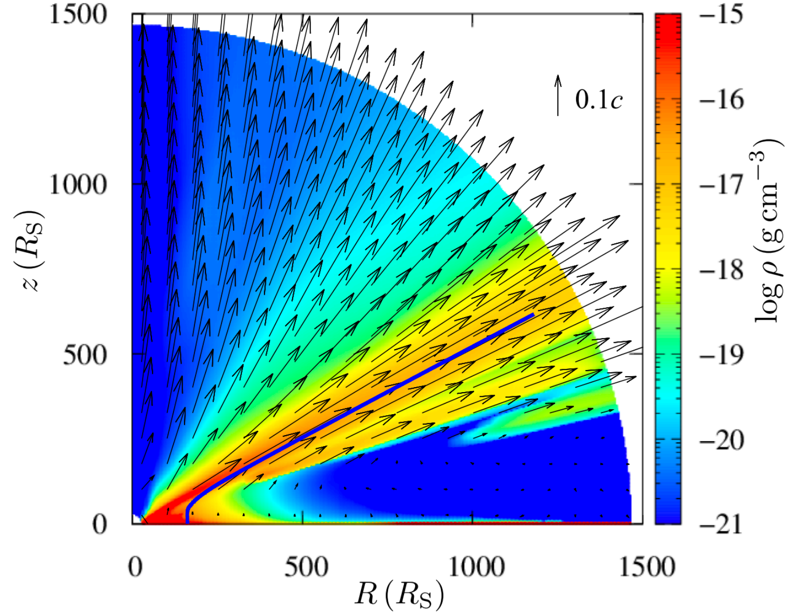
$\dot{M}_{\rm sup}/(L_{\rm Edd}/0.06c^2) = 0.5$

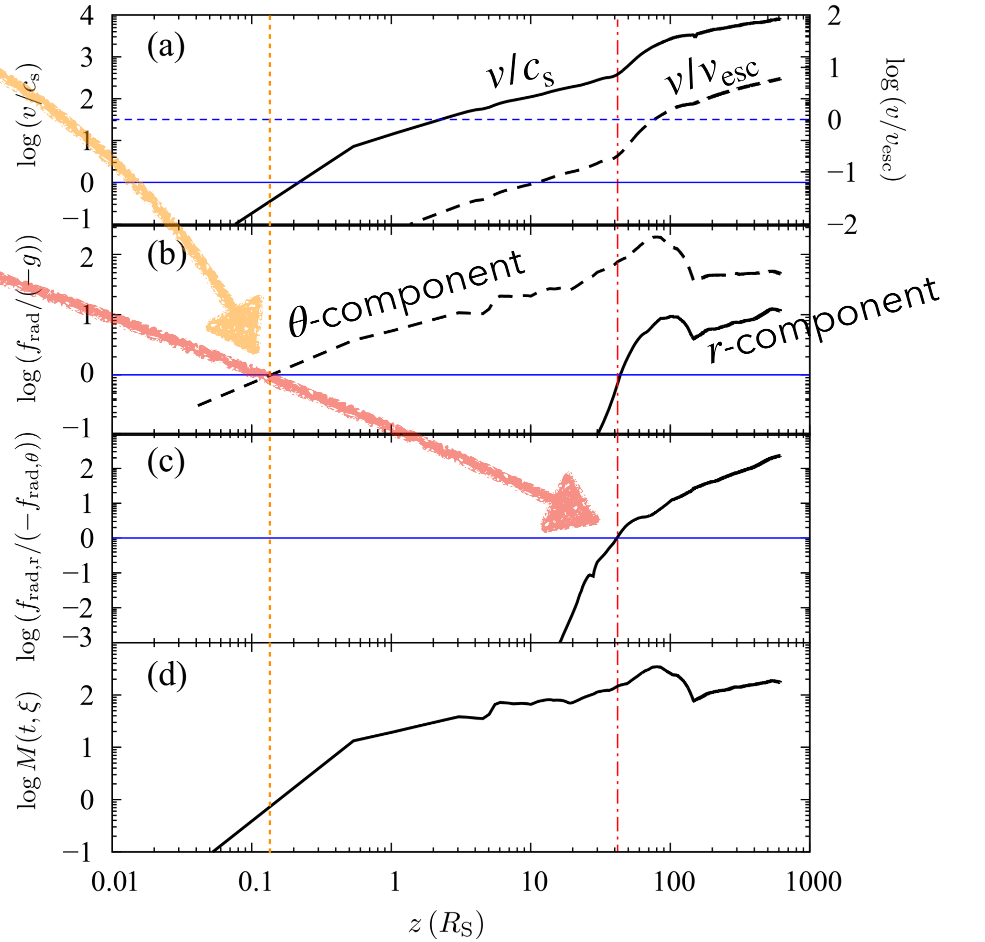
$Z = Z_\odot$

Nomura et al. (2016, 2017)

Acceleration mechanisms

- ✦ The upward radiation force exceeds the gravity due to line force.
- ✦ The wind is bent in radial-direction and its velocity exceeds escape velocity.
- ✦ **Velocity ~ 0.2c, consistent with UFO**



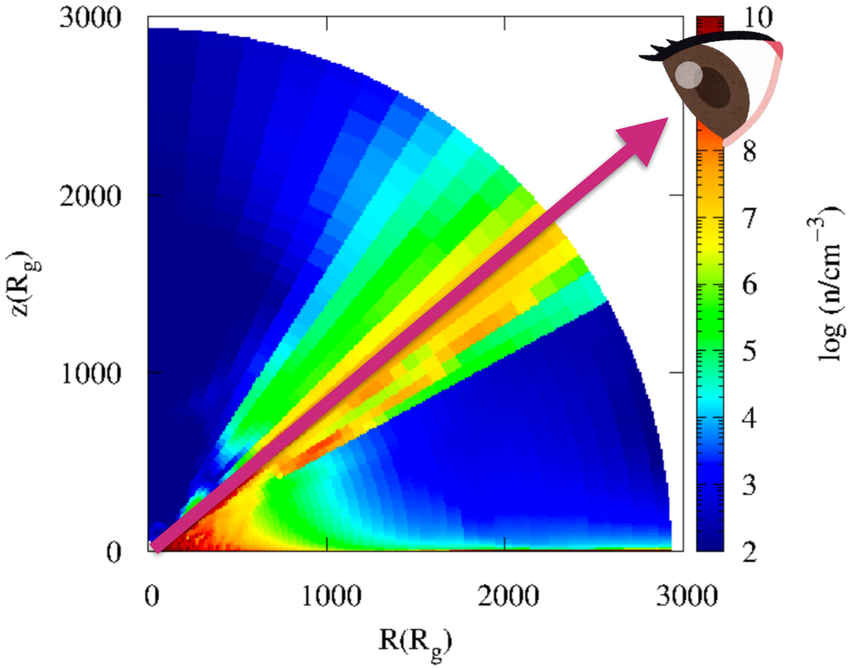


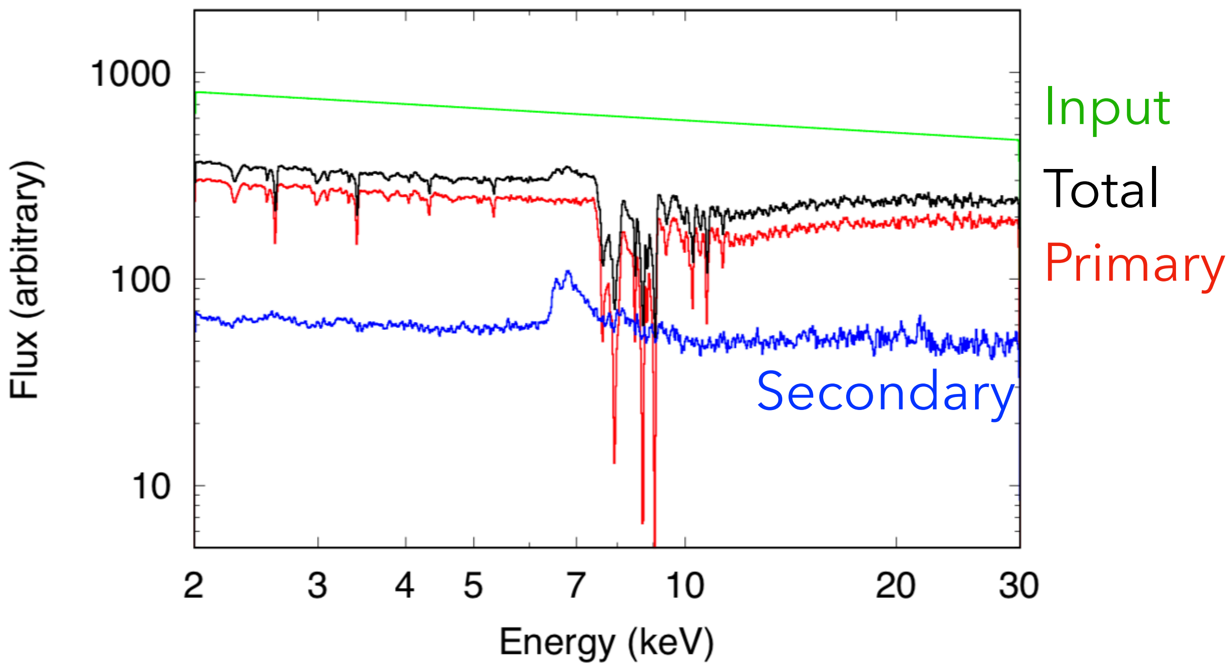
$M_{BH} = 10^8 M_\odot$, $\dot{M}_{sup}/(L_{Edd}/0.06c^2) = 0.5$, $Z = Z_\odot$

X-ray spectra synthesis

X-ray spectra synthesis based on the simulations

1. Along the line of sight, ion populations are calculated using XSTAR.
2. Monte-Carlo simulations with MONACO code.





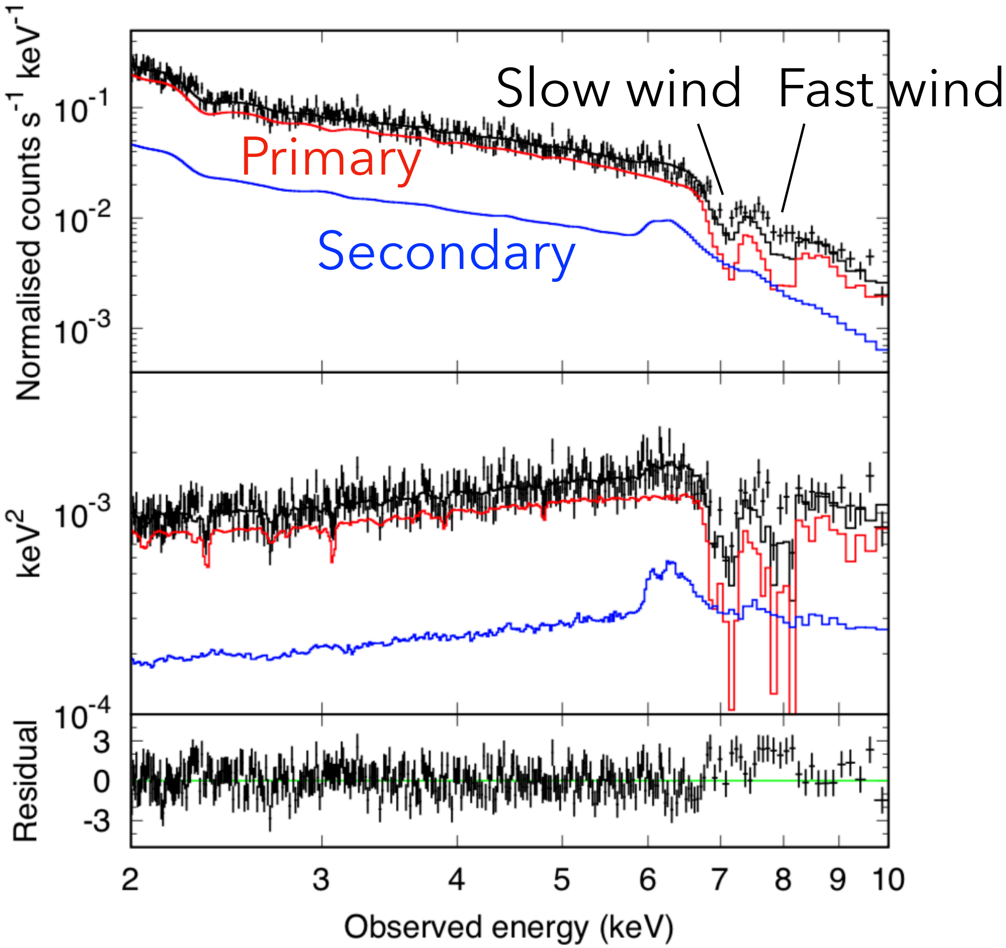
Mizumoto, MN, Done, Ohsuga, Odaka (2020)

vs PG1211+143

- Typical UFO target PG 1211+143
  - observed with XMM-Newton/EPIC-pn
  - $M_{\rm BH} \sim 10^8\, M_\odot$, $L_{\rm bol}/L_{\rm Edd} \sim 0.9$

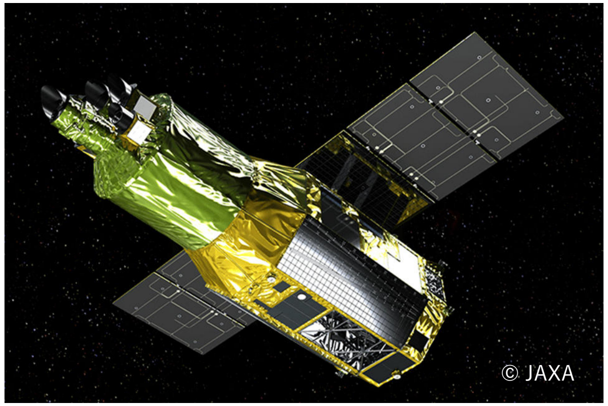
- X-ray spectrum can be well described by our model, showing that **both the two sets of absorption lines and the strong emission line can be explained by line-driven disc wind.**

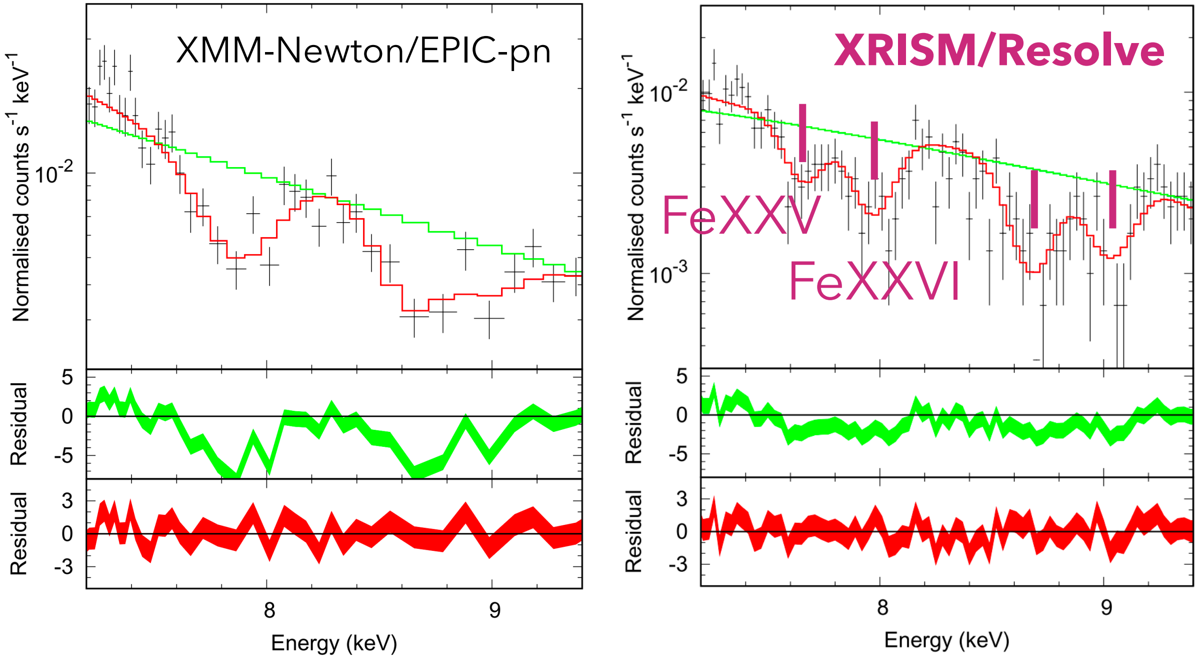
Black line: our model (total)



Mizumoto, MN, Done, Ohsuga, Odaka (2020)

Expectations for XRISM

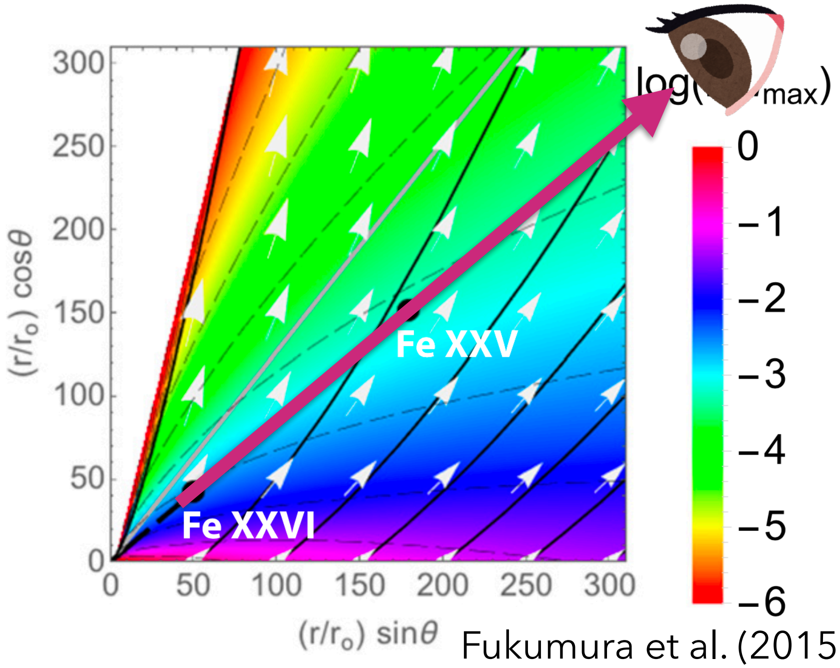




- ✦ Blended absorption lines of different ionization states can be resolved by XRISM observations.

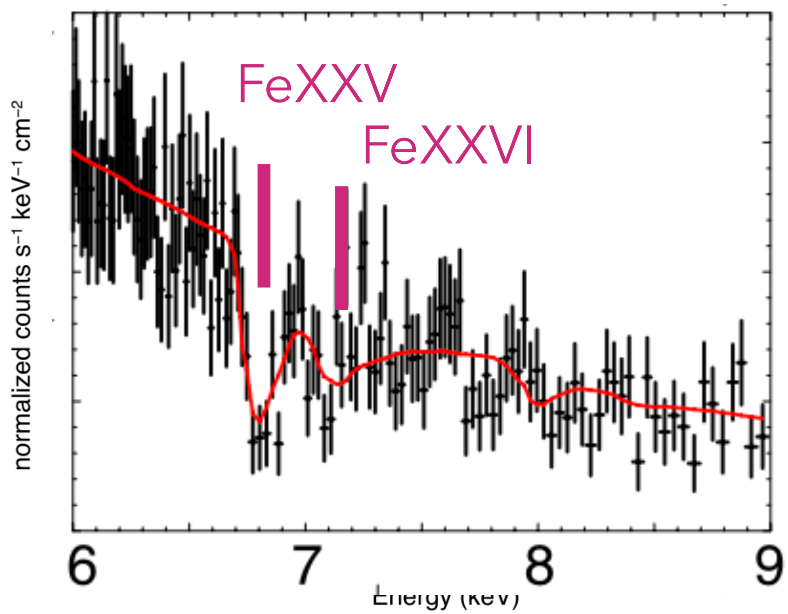
Magnetically-driven wind

- ✦ Self-similar MHD wind



Fukumura et al. (2015)

- ✦ synthetic spectra simulated for **XRISM/Resolve**



MHD winds produce **absorption lines with tails on the blue side.**

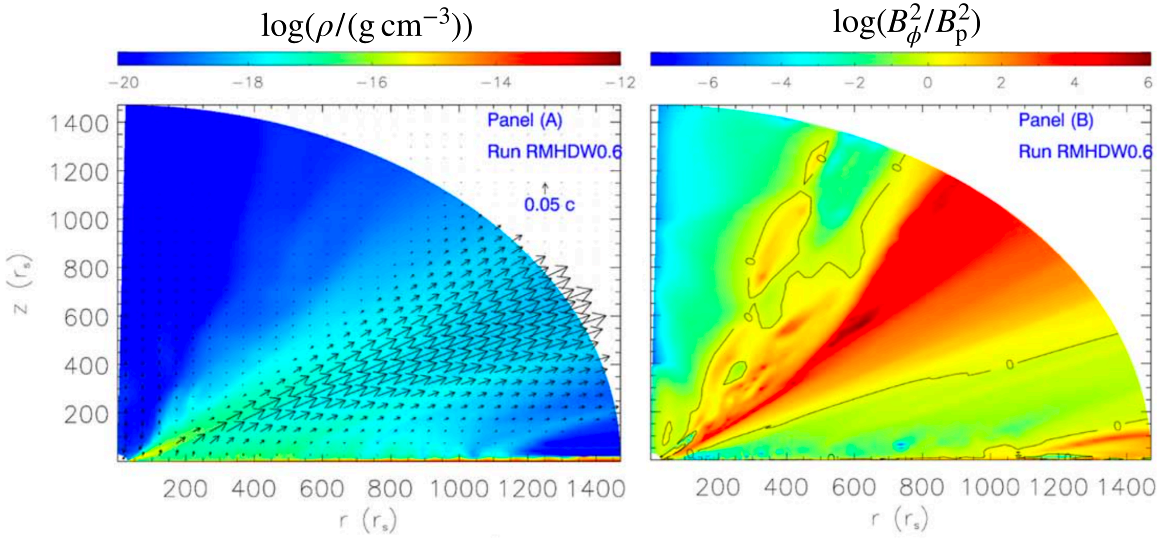
Toward a more precise theoretical model

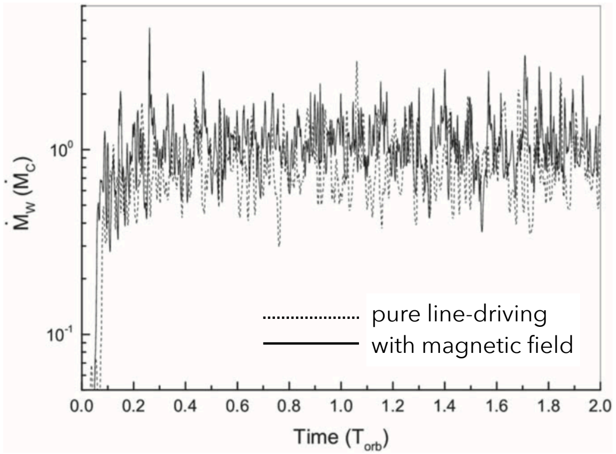
✦ **MHD+line force**

The toroidal magnetic field suppresses mass inflow from the disk surface to the pole direction.

→ High density and low ionization in the launch area

→**Line force is greater than pure line-driving**





Mass loss rate is several times larger than that of pure line-driving model

Yang et al. (2021)

Toward a more precise theoretical model

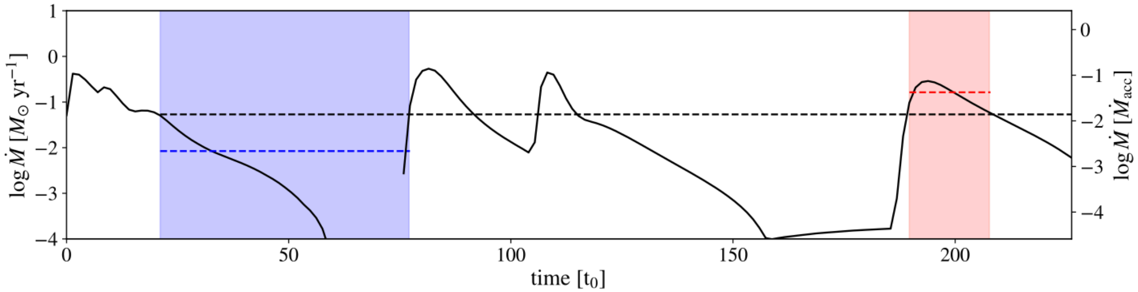
- More realistic radiation transfer: **including scattered and reprocessed X-ray**

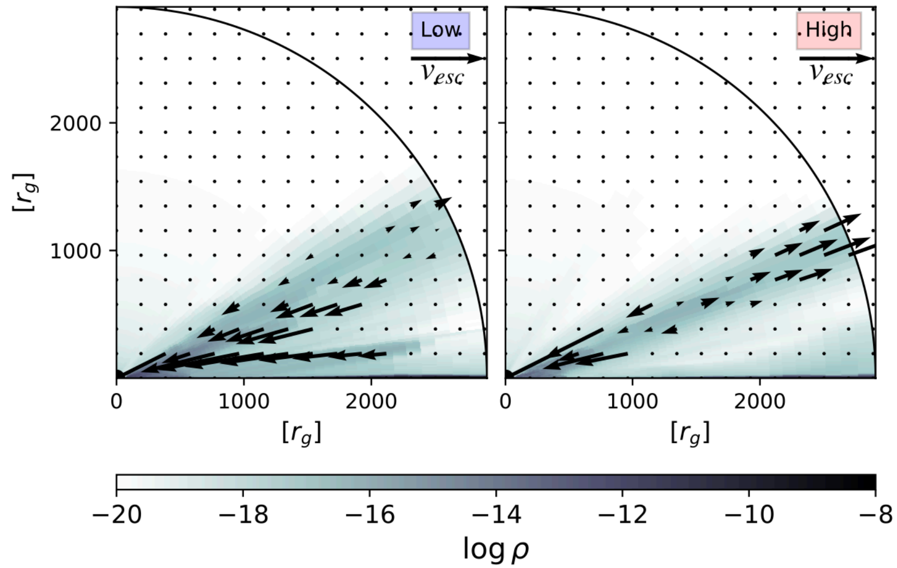
  Ionization parameter increases the launch of the wind fails.

  → "Failed wind" returns to the disk surface and the density of the launch area increases.

  → Ionization decreases and wind is accelerated by line forces.

  Periodic wind eruptions are obtained.





Dyda et al. (2023)

Current state of the theoretical model

✦ Theoretical model for **sub-Eddington AGN disc winds**

model \ Physics taken into account	line transition	magnetic flied	scattering/ reprosesstion	mass conservation (decrease of mass accretion rate)
Proga et al. 2000, Proga & Kallman 2004	⭕	❌	❌	❌
Yang et al. 2021 (Proga et al. 2003 for YSO)	⭕	⭕	❌	❌
Dyda et al. 2023 (Higginbottom et al. 2024 for CV)	⭕	❌	⭕	❌
Nomura et al. 2020, 2021	⭕	❌	❌	⭕
Fukumura et al. 2015, Wang et al. 2022	❌	⭕	❌	❌

前半のまとめ

UFOの重要性とその加速メカニズム

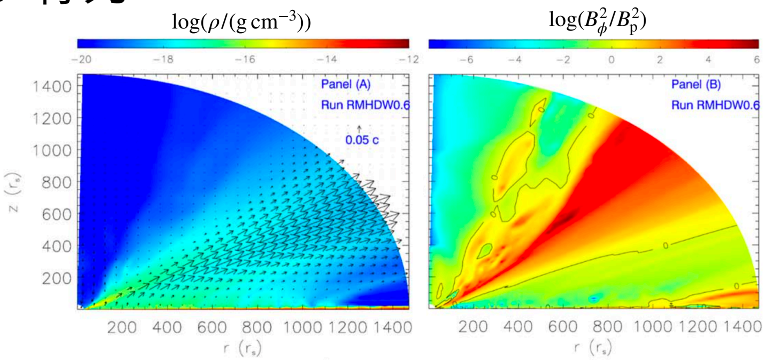
✦ 観測からわかること

- UFOは降着円盤から噴出するdisk wind, 速度 $\sim 0.1c$, 高い電離状態
- 質量放出率，エネルギー放出率が大きく，SMBHの進化過程に影響を及ぼしている可能性がある.

✦ 理論研究の現状

- 磁気駆動型円盤風/ラインフォース駆動型円盤風が有力
- XRISMによる吸収線の観測
(multi-component, line profile)で決着がつく？？
- おそらく実際は複雑
→より現実的なモデル構築が急務

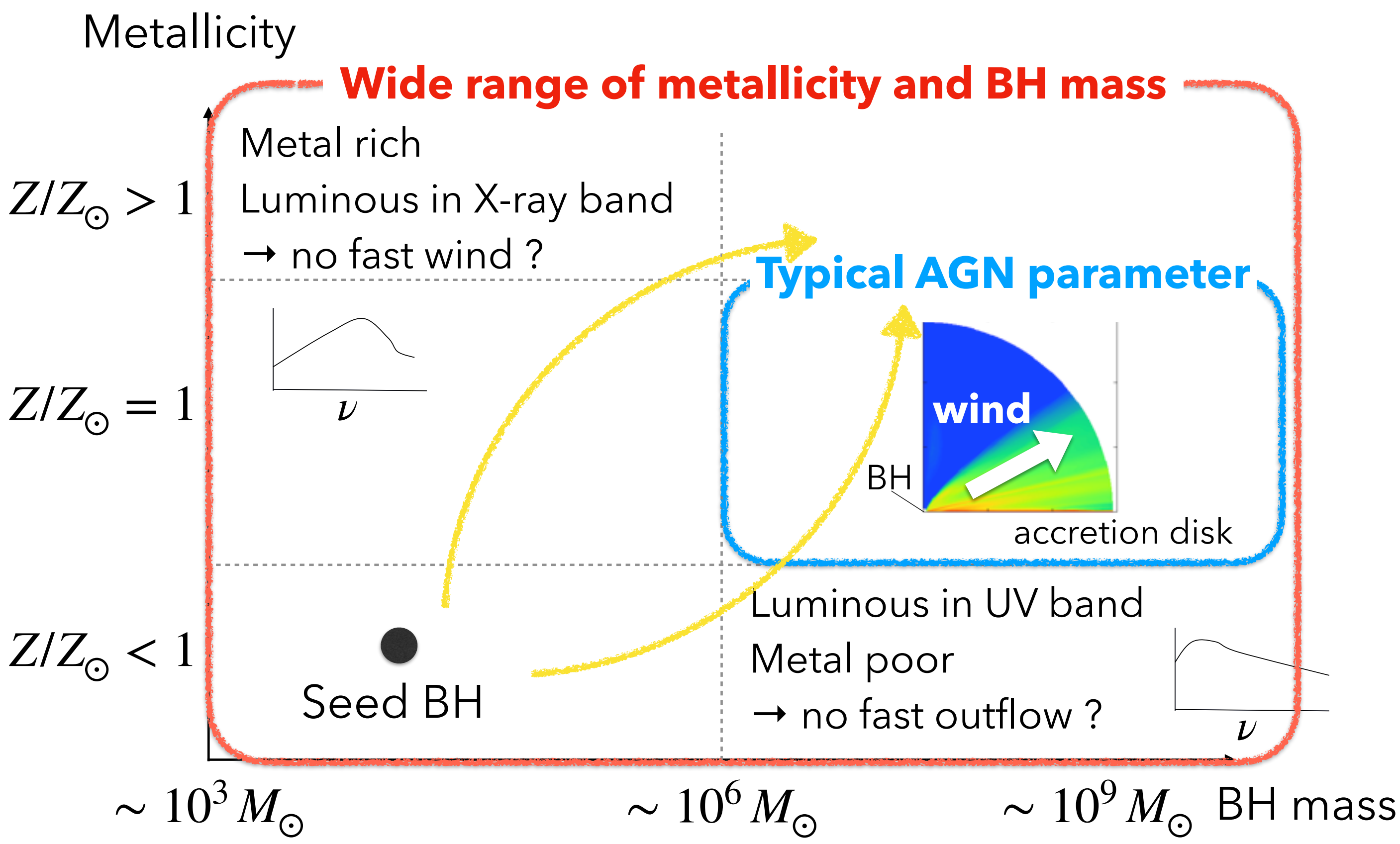
MHD+line force



Yang et al. (2021)

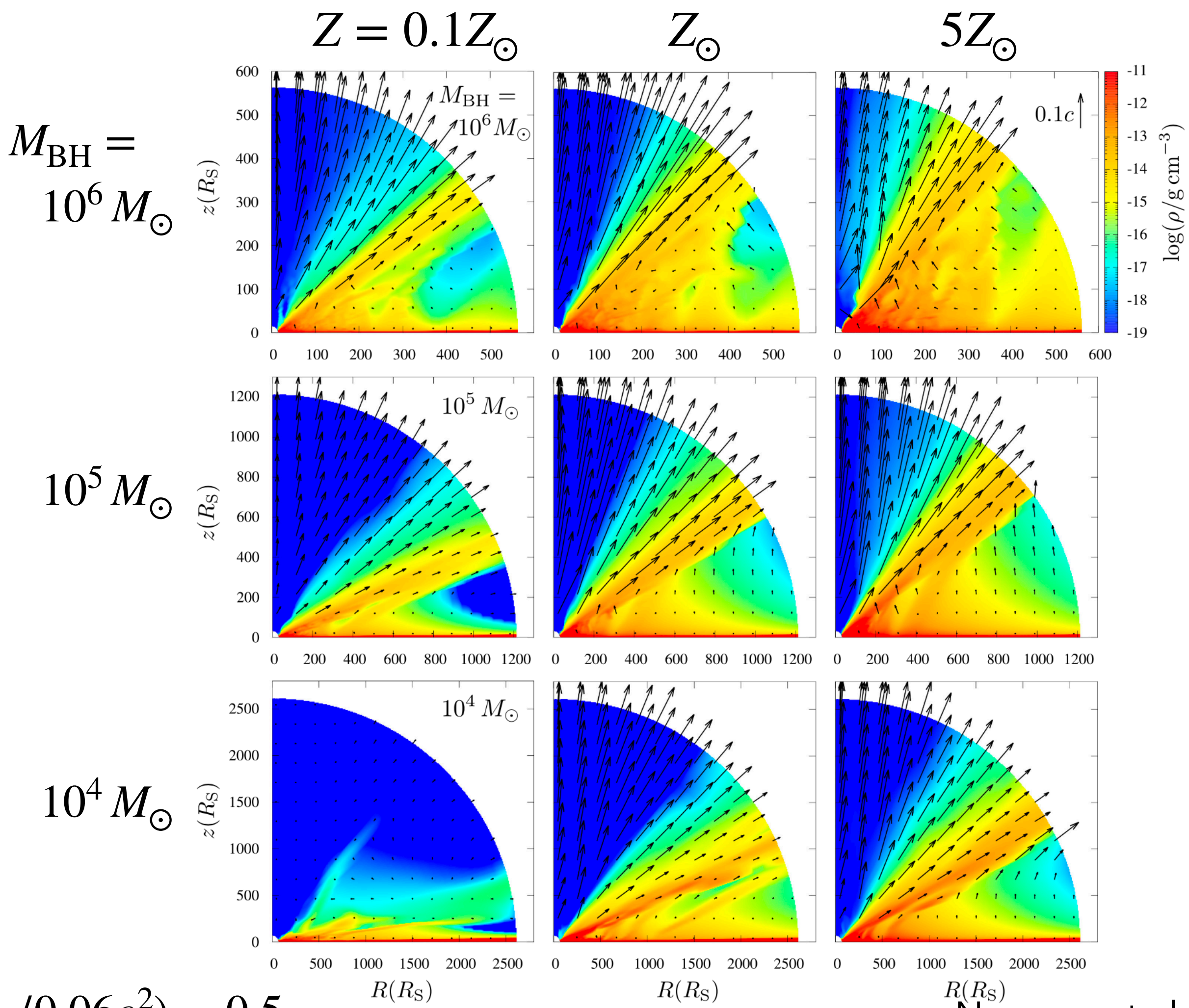
Outflows in SMBH evolution: the case of line-driven

- Question: Do the line driven winds suppress the mass accretion on the evolutional pass from seeds to SMBHs?
- This work explores **the role of line-driven winds in a wide range of BH mass and metallicity**.



Metallicity and BH mass dependencies

- Denser and faster winds appear for higher metallicity and larger BH mass.

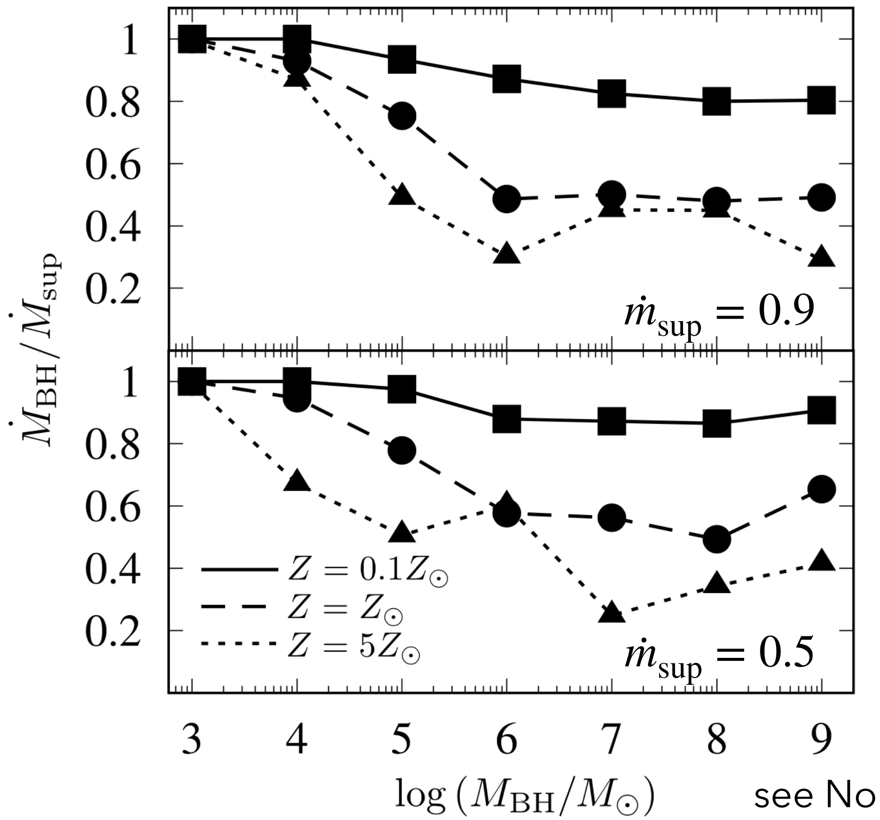


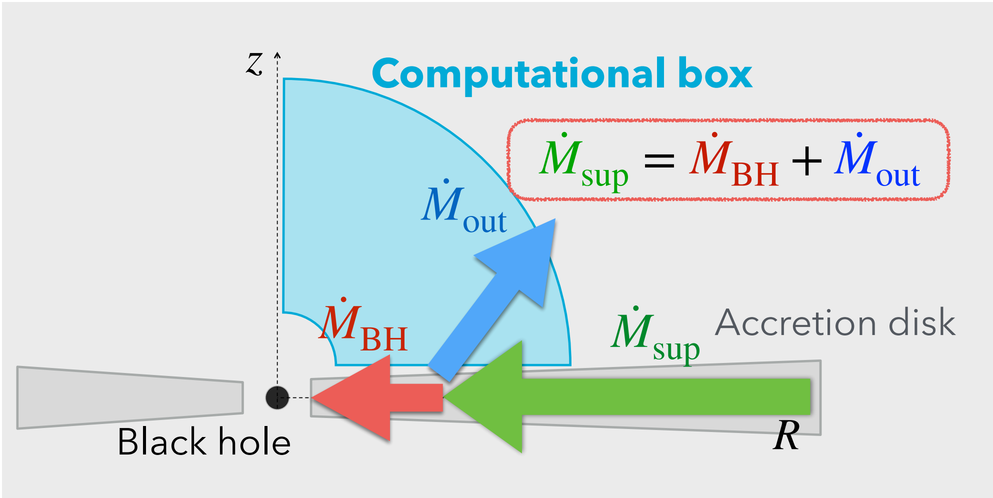
$\dot{M}_{sup}/(L_{Edd}/0.06c^2) = 0.5$

Nomura et al. (2021)

Reduction of mass accretion rate

Ratio of mass accretion rate onto BH to mass supply rate onto the disk.





✦ The line-driven winds may **suppress the mass accretion for $M_{\rm BH} \gtrsim 10^5 M_\odot$ in high-metallicity environments**.

$\dot{m}_{\rm sup} = \dot{M}_{\rm sup}/(L_{\rm Edd}/0.06c^2)$

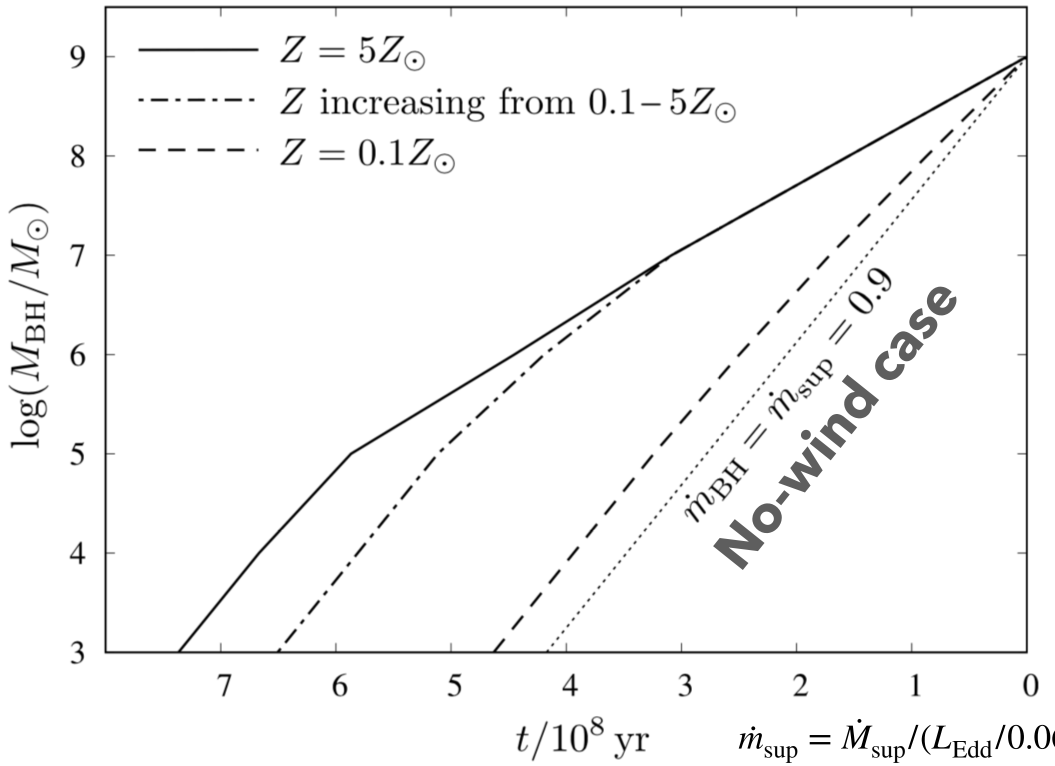
see Nomura et al. (2021) for details

Effects on the growth time of BHs

- In metal poor environment ($Z = 0.1Z_\odot$), the growth time is not different from that for the no-wind case, and relatively fast evolution is possible.

- Growth times for $Z = 5Z_\odot$ at all the time or for Z increasing from $0.1-5Z_\odot$ are 1.6 and 1.8 times larger than that for no-wind case respectively.

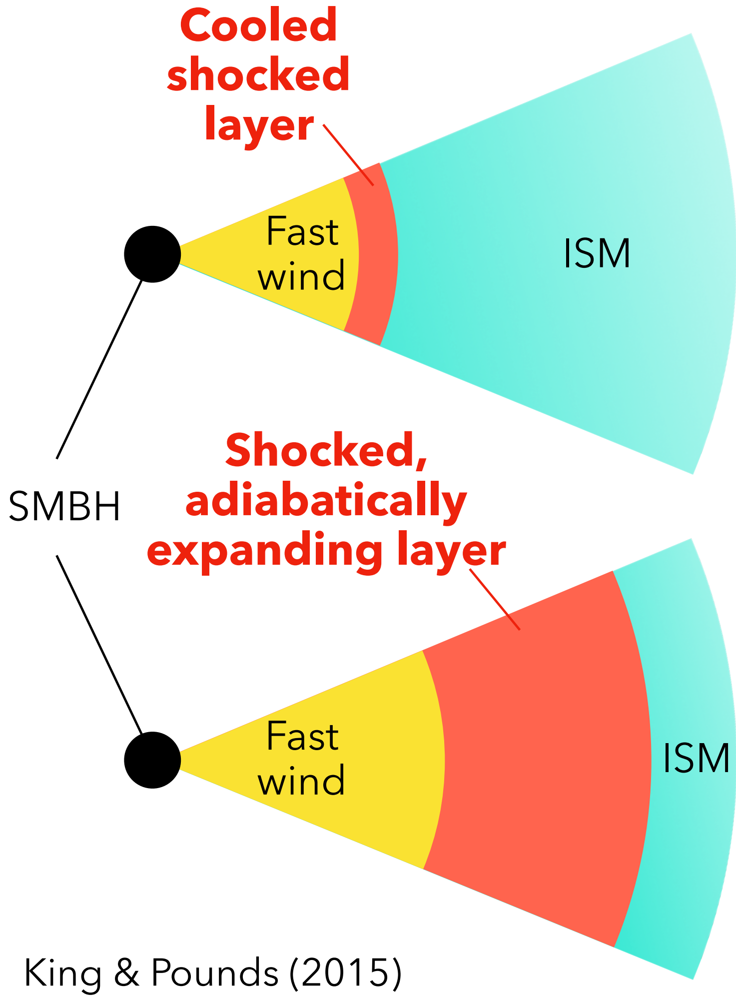
  → Line-driven wind has an impact on the evolution of SMBHs.



$\dot{m}_{\rm sup} = \dot{M}_{\rm sup}/(L_{\rm Edd}/0.06c^2)$

Nomura et al. (2021)

Feedback onto ISM

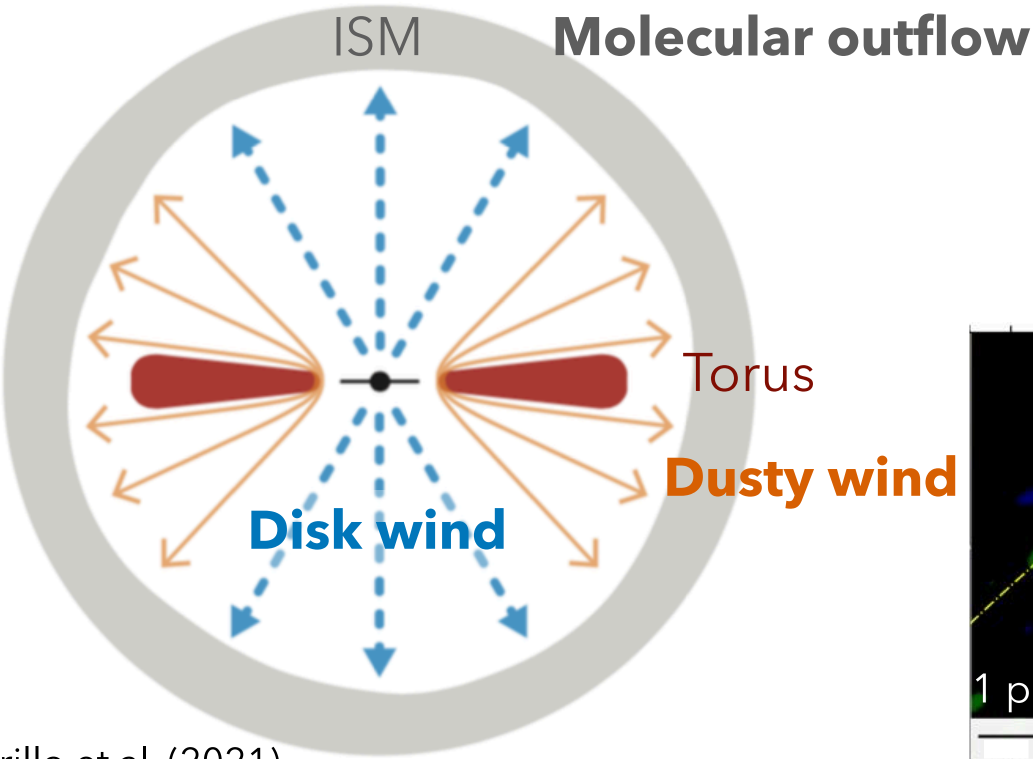


King & Pounds (2015)

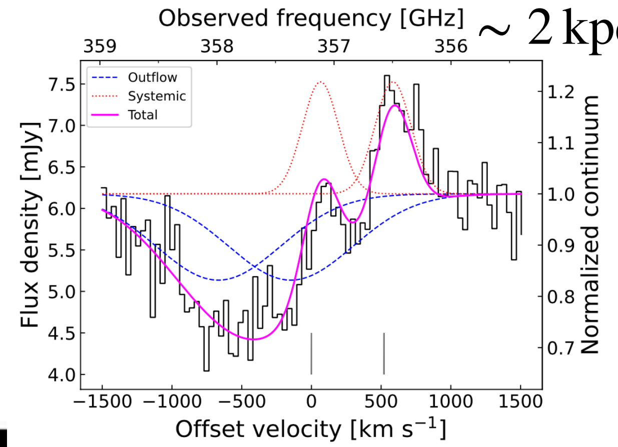
- ✦ **Momentum driven wind**
  - Thermal energy of the shocked gas is rapidly cooled via radiative cooling.
  - Momentum is conserved between the wind and ISM.
  - A portion of ISM is affected by wind ram pressure and BH accretion can continue.
- ✦ **Energy driven wind**
  - Cooling time scale is larger than the dynamical time scale of the wind.
  - Energy is conserved between the wind and ISM.
  - Powerful feed back suppresses the mass accretion onto BH.

UFOs and large-scale outflow

- Accretion disk winds (such as UFOs) can accelerate the molecular outflows and local dusty winds

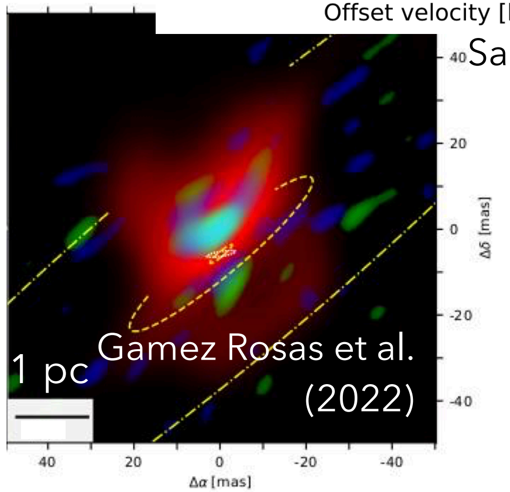


Garcia-Burillo et al. (2021)



~ 2 kpc

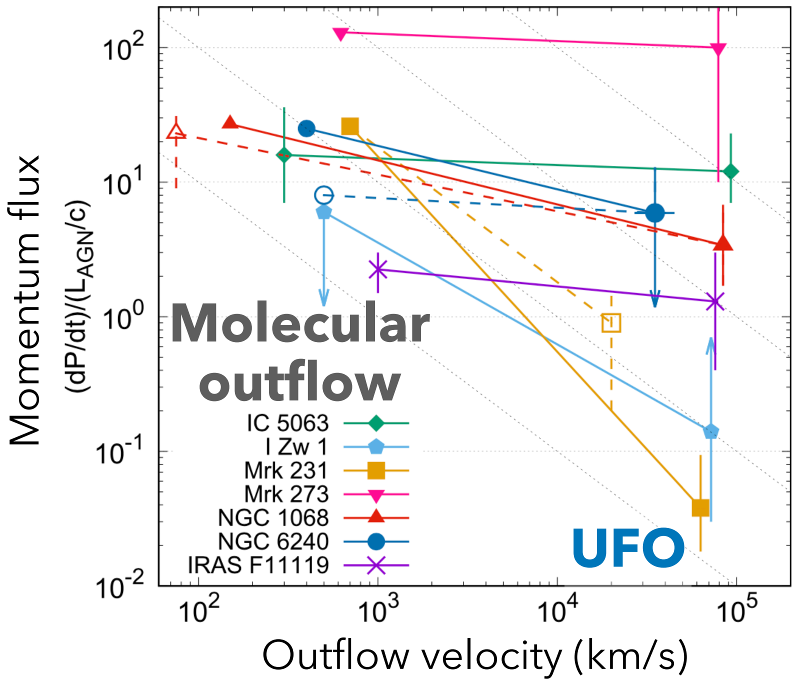
Salak et al. (2023)

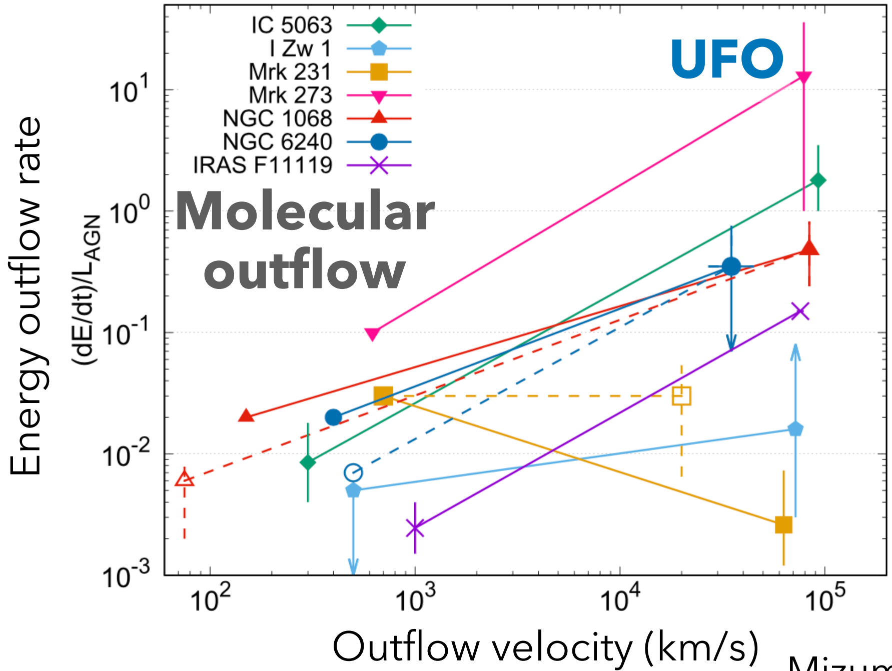


Gamez Rosas et al. (2022)

Momentum driven or Energy driven?

✦ Compare momentum and energy between molecular outflows and UFOs.





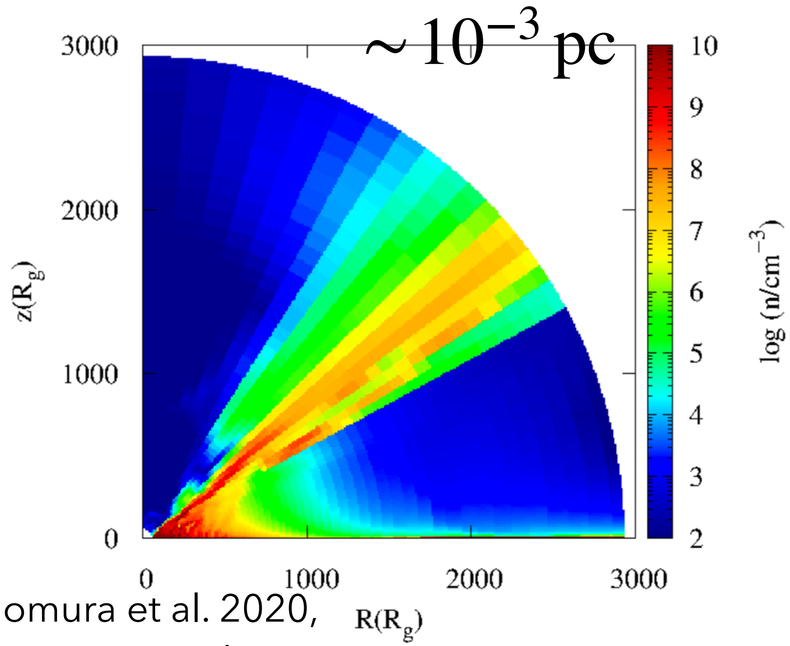
Mizumoto et al. (2019)

In many objects, energy is lost in molecular outflows.

Energy transfer rate is ~0.007–1

Remaining Issues in Theoretical Research

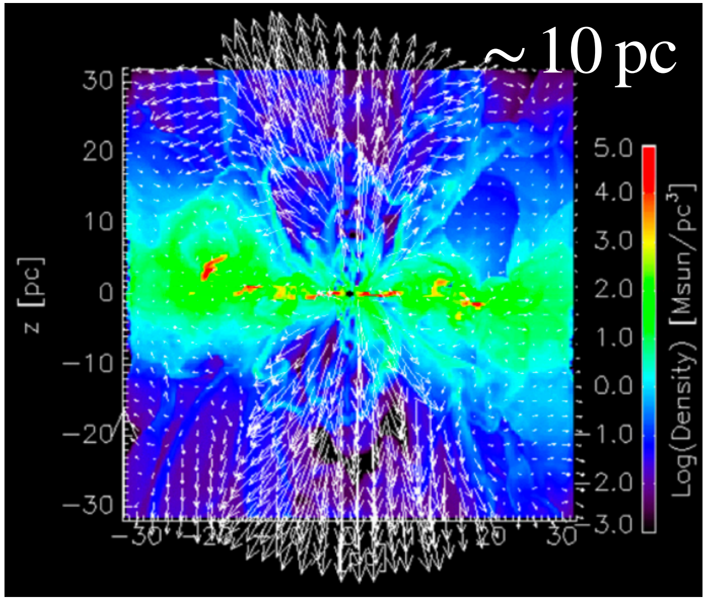
- ✦ Multi-scale simulations are necessary for comprehensive understanding of multi-scale outflows.
- ✦ Each scale simulation has been developed, but the calculations connecting them have not yet been accomplished.



Nomura et al. 2020, Mizumoto at al. 2021

Dynamical torus model

“Radiation fountain” driven by X-ray heating and radiation force



Wada 2012, 2015

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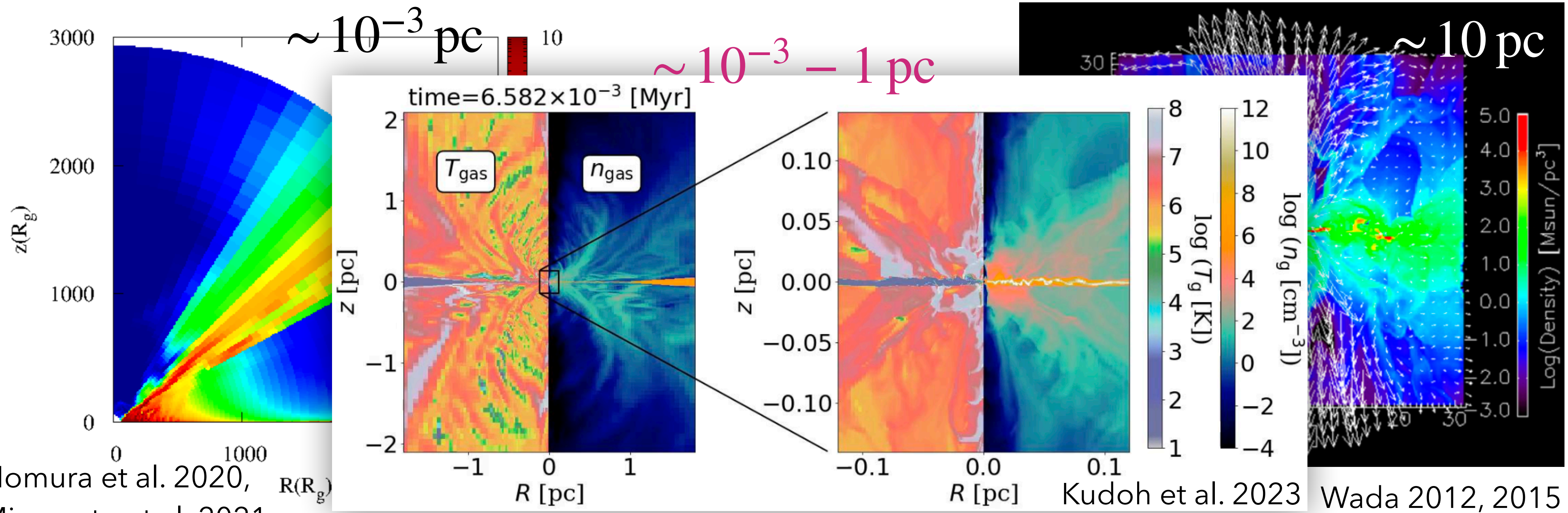


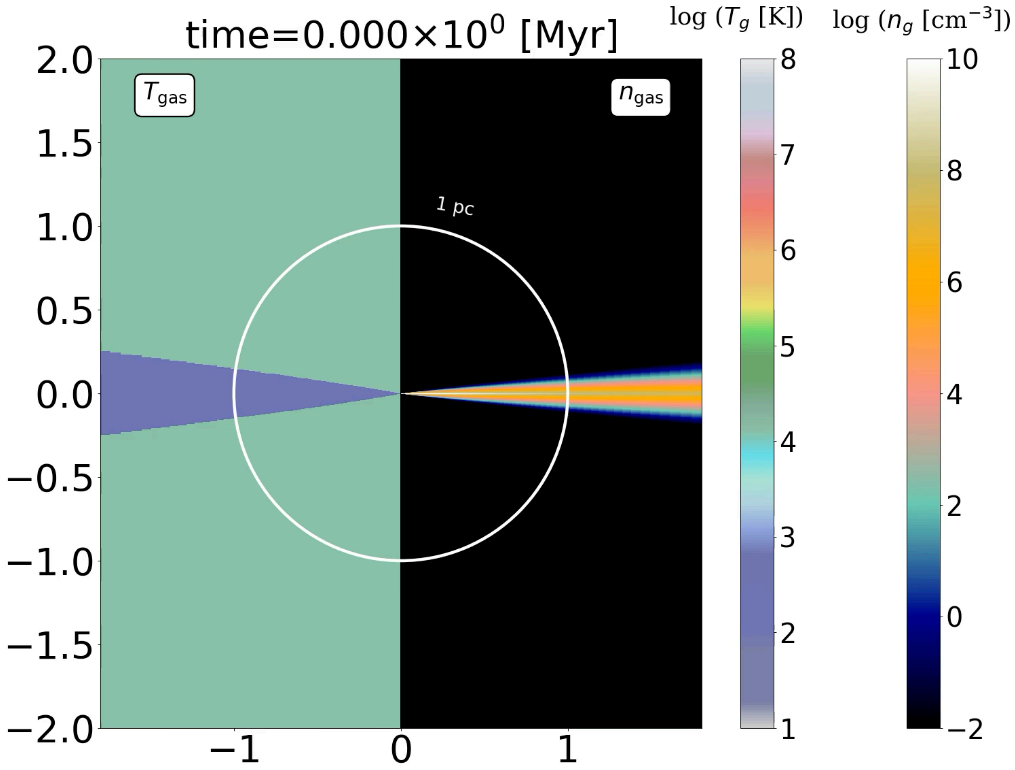
Nomura et al. 2020, Mizumoto at al. 2021

Kudoh et al. 2023

Wada 2012, 2015

Dusty outflow

- ✦ Radiation-hydrodynamic simulations including dust opacity.
  - Dust-gas mass ratio = 0.01. Dust sublimation and sputtering are included.



$M_{\rm BH} = 10^7 \, M_\odot$

Assuming the stationary radiation field $L = 0.1 L_{\rm Edd}$

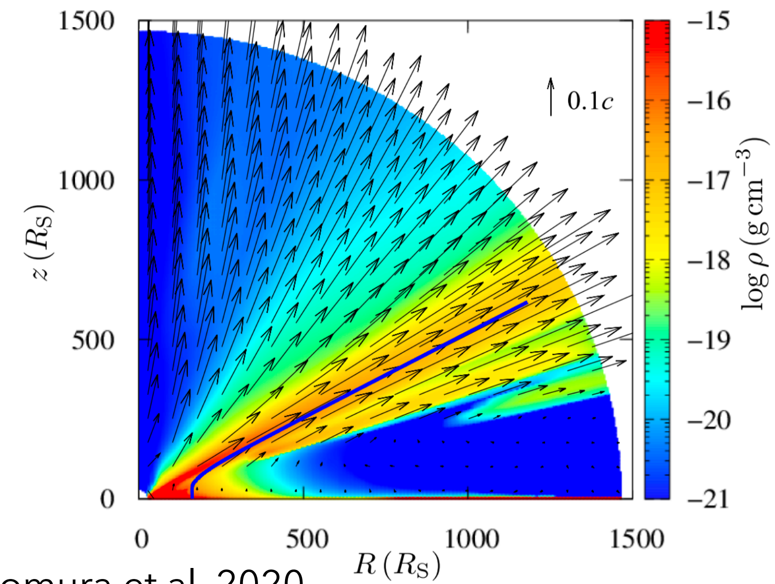
Dusty gas can escape from the nucleus.

Dust-free gas ($r \lesssim 0.04$) is bound.

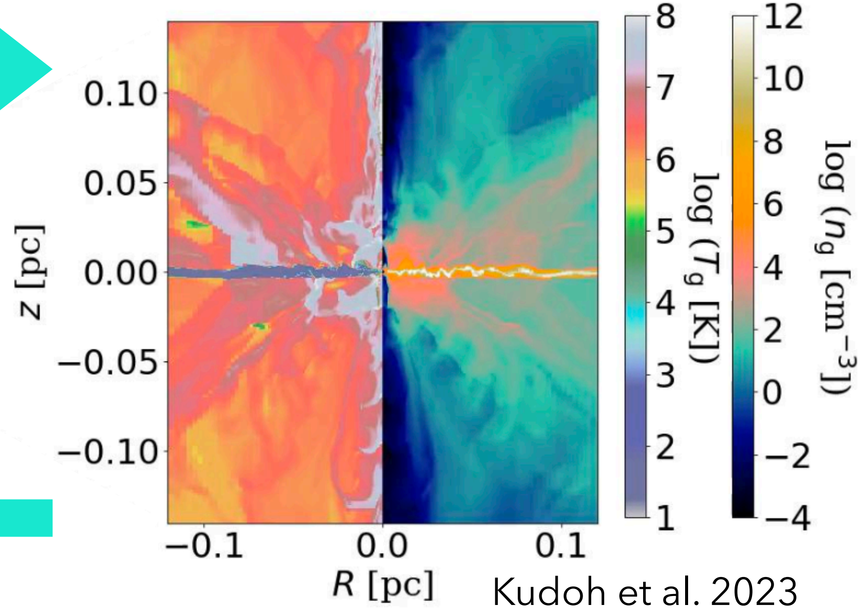
UFO+Dusty outflow (future work)

Input velocity, density, and temperature

UFO changes the structure and mass outflow rate of dusty outflow.



Nomura et al. 2020



Kudoh et al. 2023

Mass accretion onto accretion disc is regulated by dusty winds.

Simulations connecting the different scale from $10^{-5}\,\mathrm{pc}$ to $1\,\mathrm{pc}$

後半のまとめ

UFOがSMBHの成長に与える影響

✦ 降着円盤からの質量の引き抜き

- ラインフォース駆動型円盤風を考えた場合，金属量が高く，BH質量が大きい ($M_{\rm BH} \gtrsim 10^5\,M_\odot$)の場合に質量降着率を減少させ，SMBHの成長時間に影響を与える可能性がある.

✦ 周辺環境へのフィードバック

- UFO (円盤風) がISMに衝突し，分子アウトフロー，ダストアウトフローなどの多層構造の起源になっている可能性？
- 広いダイナミックレンジに渡って，ローカルに加速されるアウトフローや, UFOの伝搬を調べる必要性がある.