降着円盤およびジェットの一般相対論的輻射磁気流体力学シミュレーション

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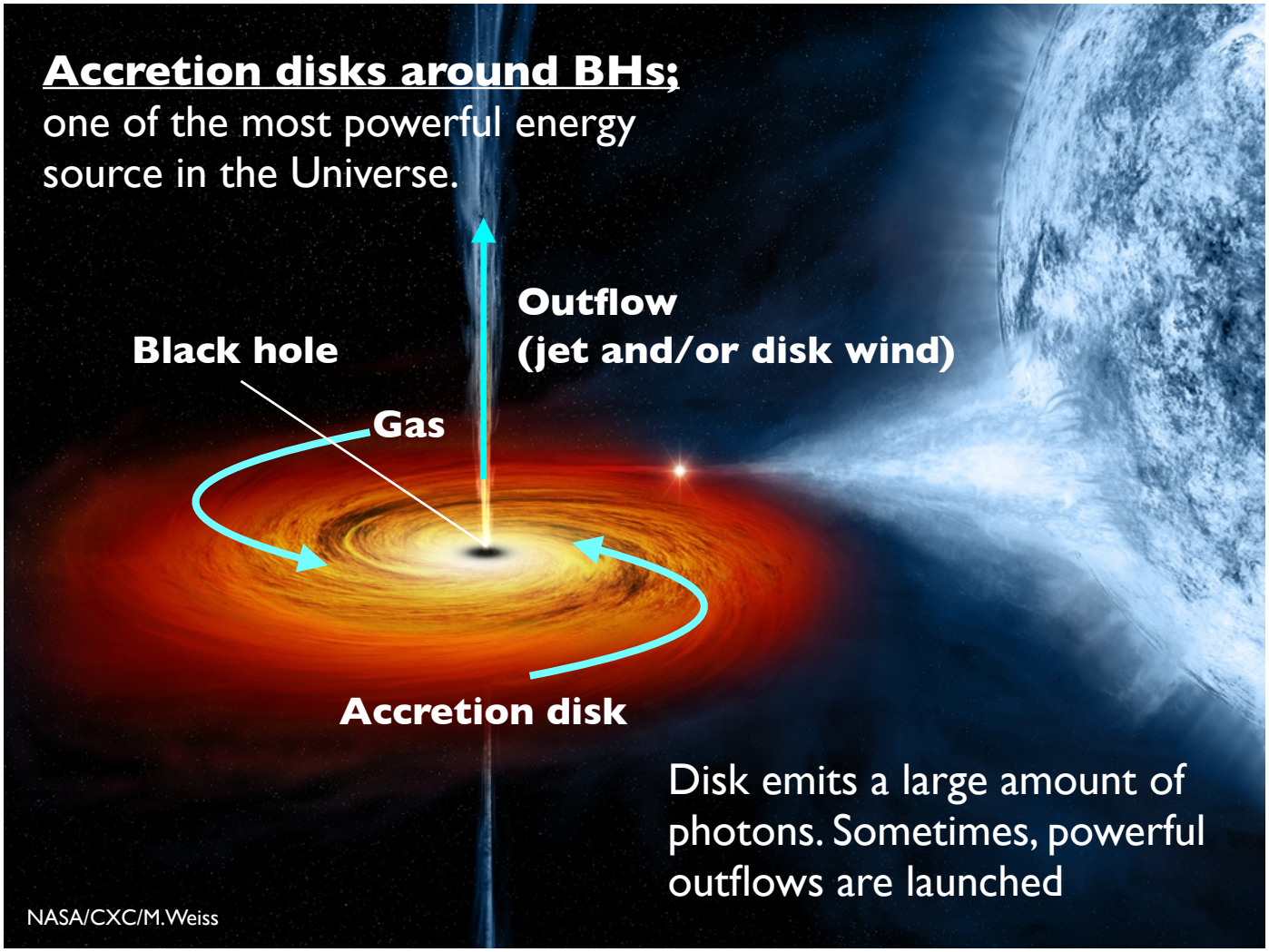
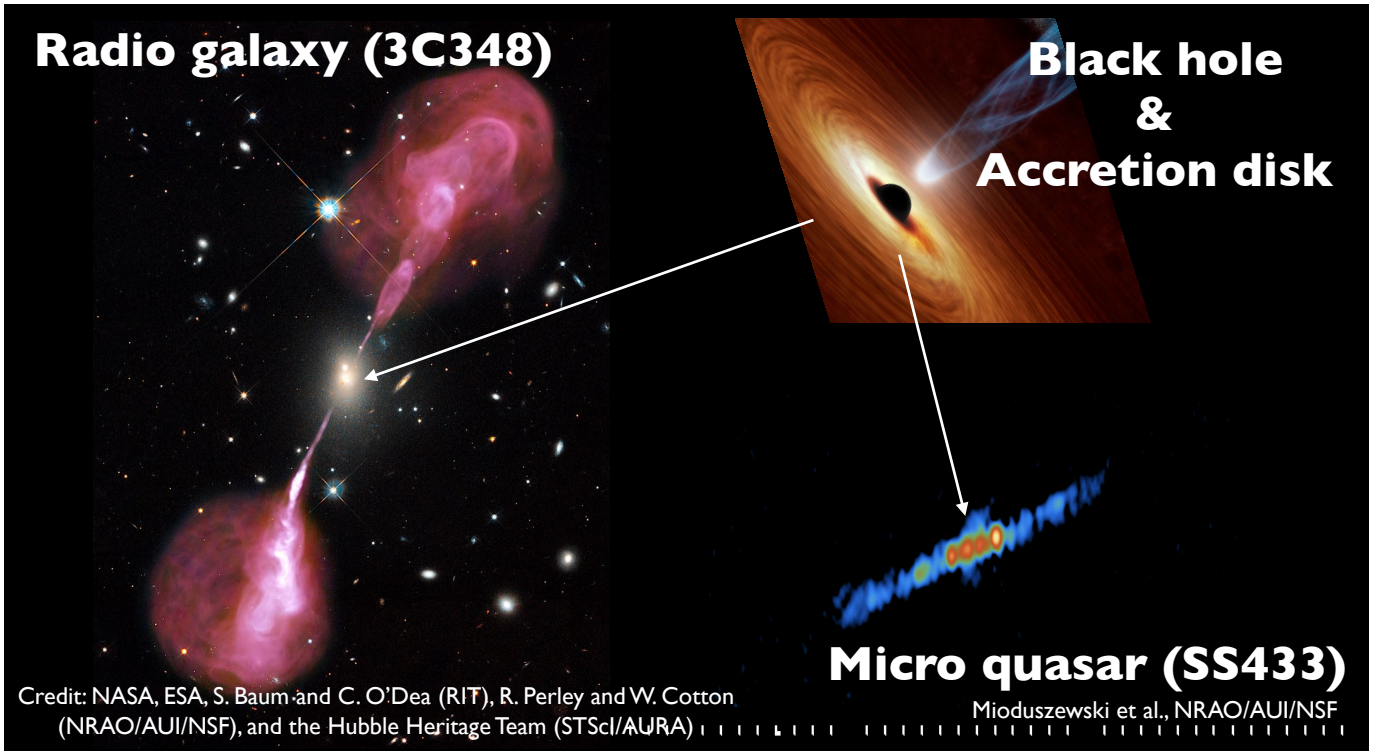
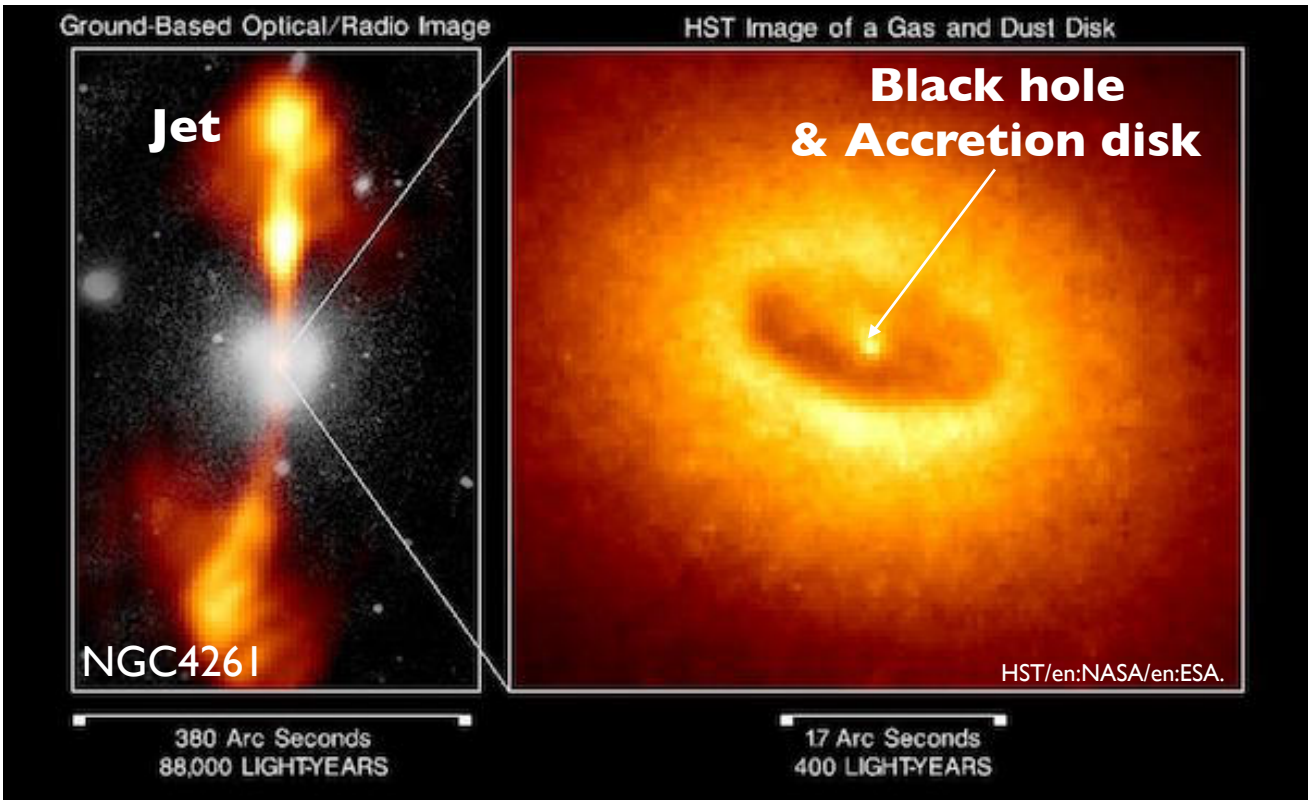
野村真理子（呉高専）, 嶺重慎, 北木孝明, 恒任優（京大宇物）



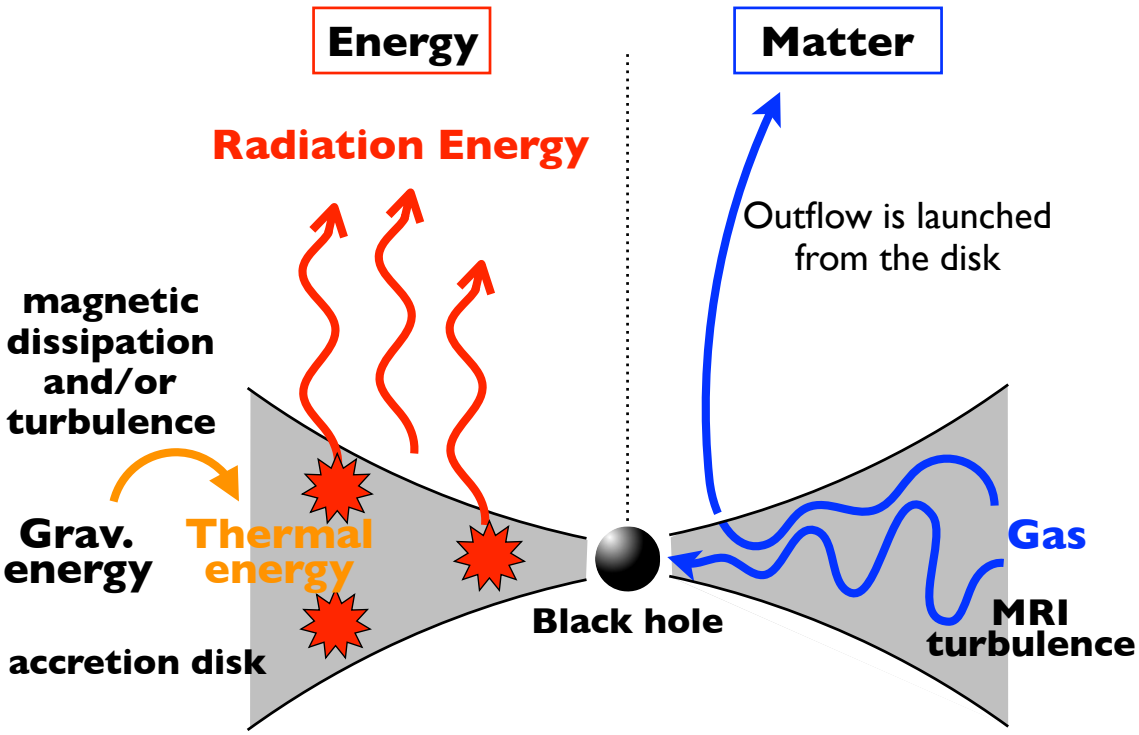
宇宙最高のエンジン



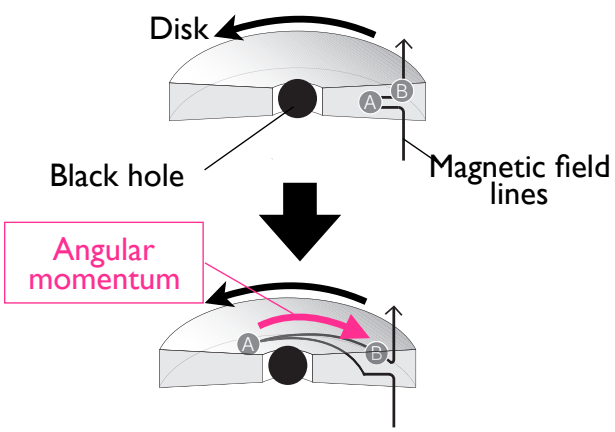
宇宙最高のエンジン

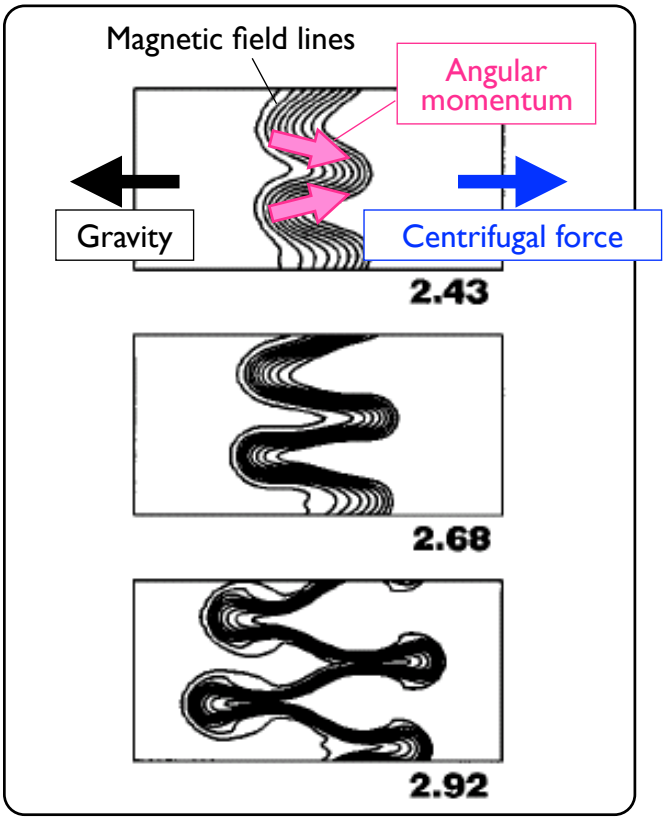


Role of Radiation and Magnetic Fields



Magneto-rotational instability (MRI)





Angular momentum transport induced by magnetorotational instability (MRI) leads to mass accretion

Hawley & Balbus 1991
See also Velikhov 1959

Basic Eq. (GR-version)

Magneto-hydro

mass cons. $\partial_t\left(\sqrt{-g}\rho u^t\right)+\partial_i\left(\sqrt{-g}\rho u^i\right)=0$

Gauss's law $\partial_i\left(\sqrt{-g}B^i\right)=0$

Induction eq. $\partial_t\left(\sqrt{-g}B^i\right)=-\partial_j\left[\sqrt{-g}\left(b^j u^i-b^i u^j\right)\right]$

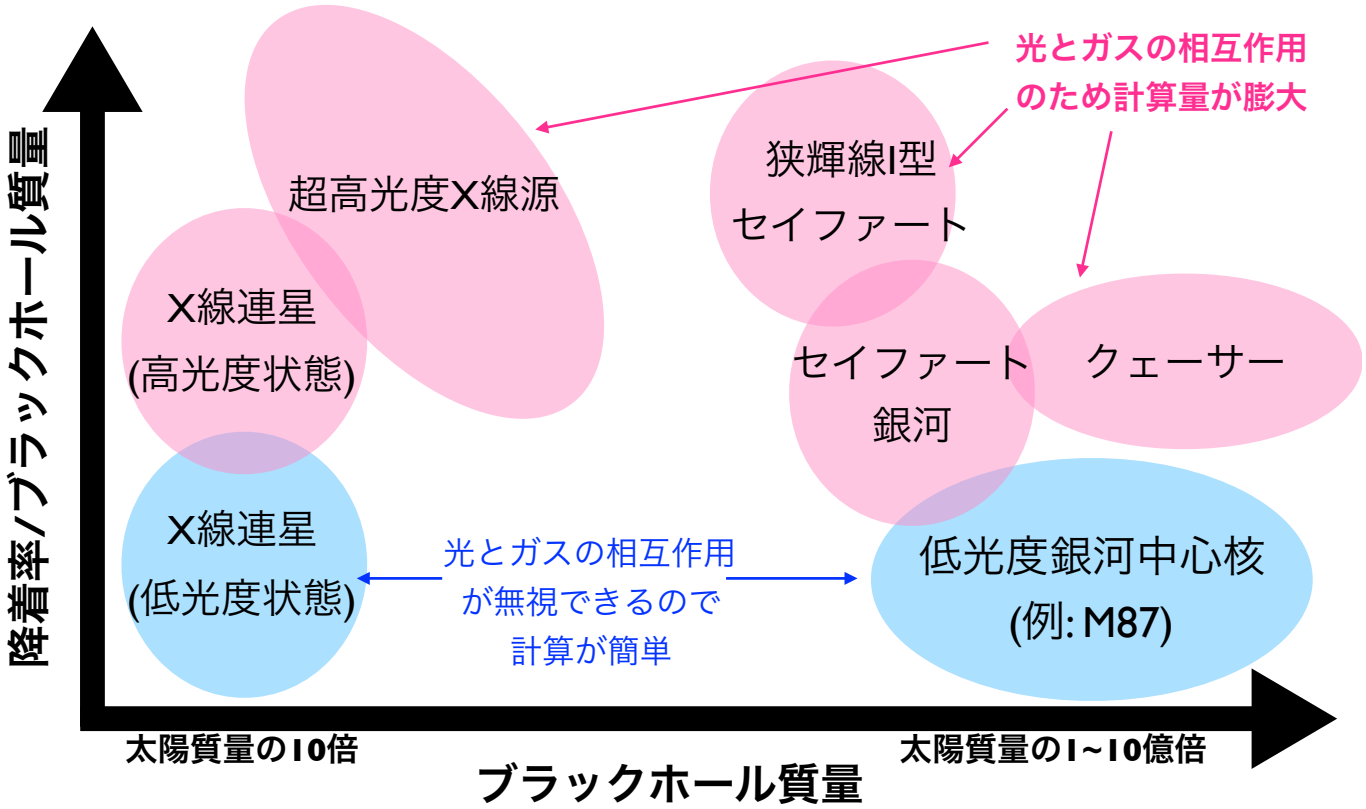
energy momentum cons. for MHD $\partial_t\left(\sqrt{-g}T^t_\nu\right)+\partial_i\left(\sqrt{-g}T^i_\nu\right)=\sqrt{-g}T^\kappa_\lambda\Gamma^\lambda_{\nu\kappa}-\sqrt{-g}G_\nu$

energy momentum cons. for radiation $\partial_t\left(\sqrt{-g}R^t_\nu\right)+\partial_i\left(\sqrt{-g}R^i_\nu\right)=\sqrt{-g}R^\kappa_\lambda\Gamma^\lambda_{\nu\kappa}-\sqrt{-g}G_\nu$

Radiation Fields

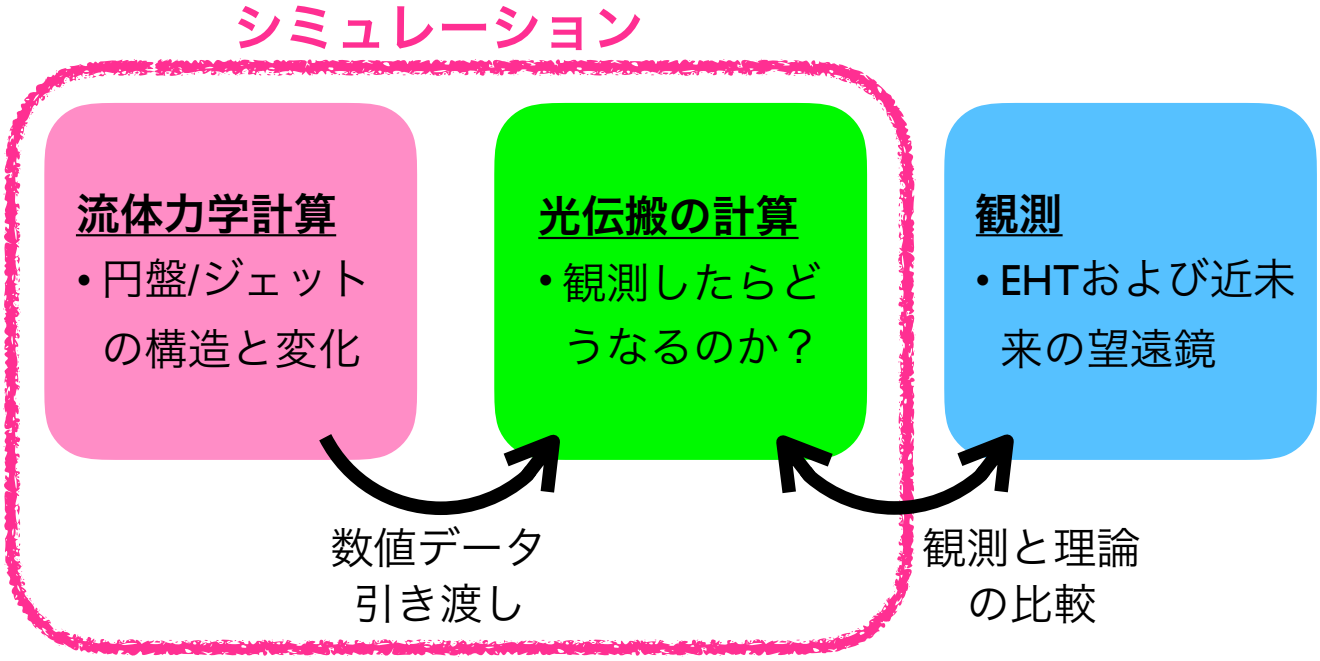
We use Kerr-Schild metric

ブラックホール天体の多様性



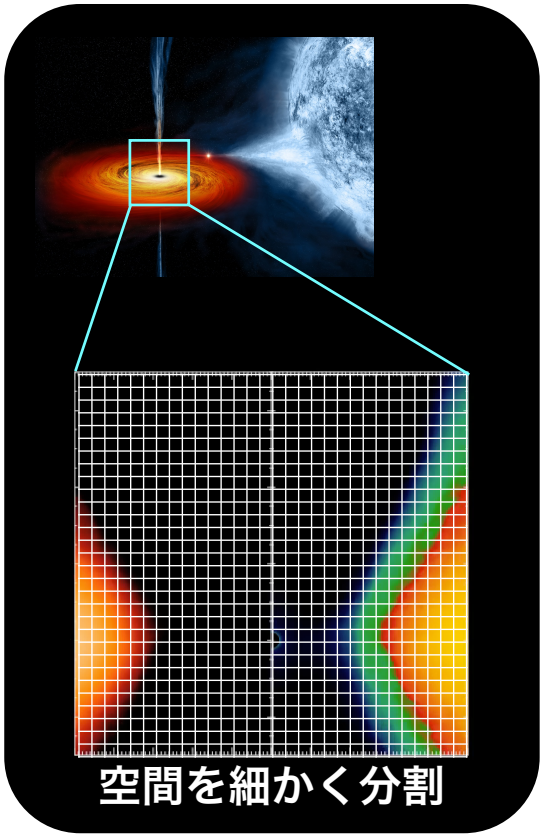
川島さんの資料を改変

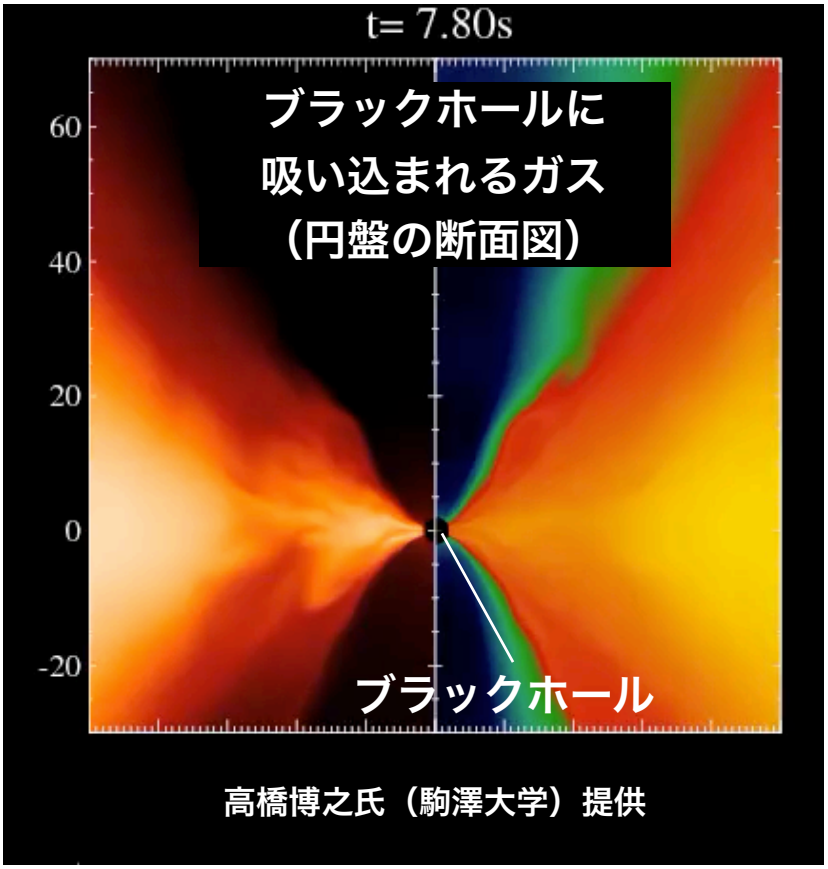
シミュレーションと観測の協力

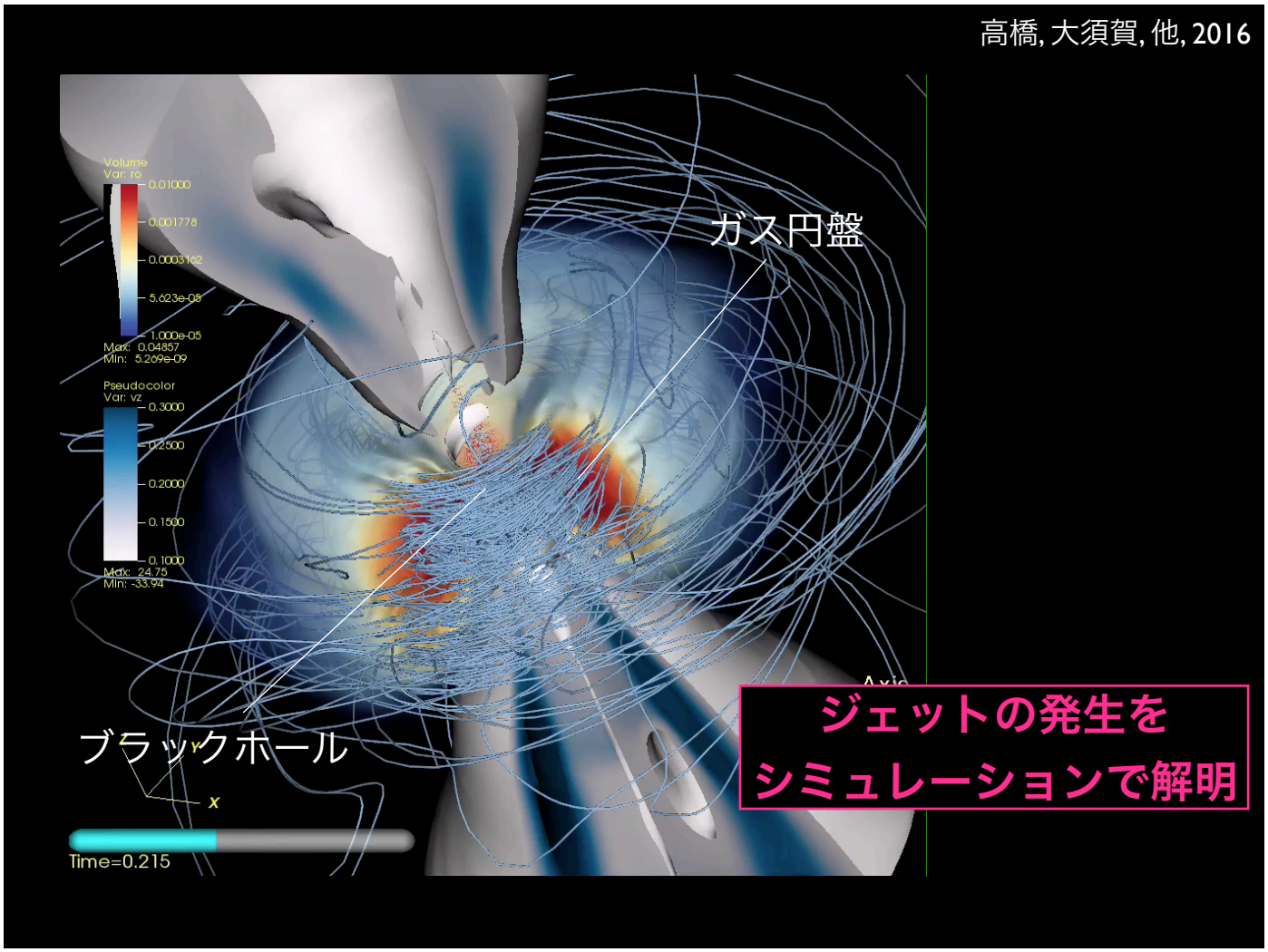


理論と観測の融合による研究の推進

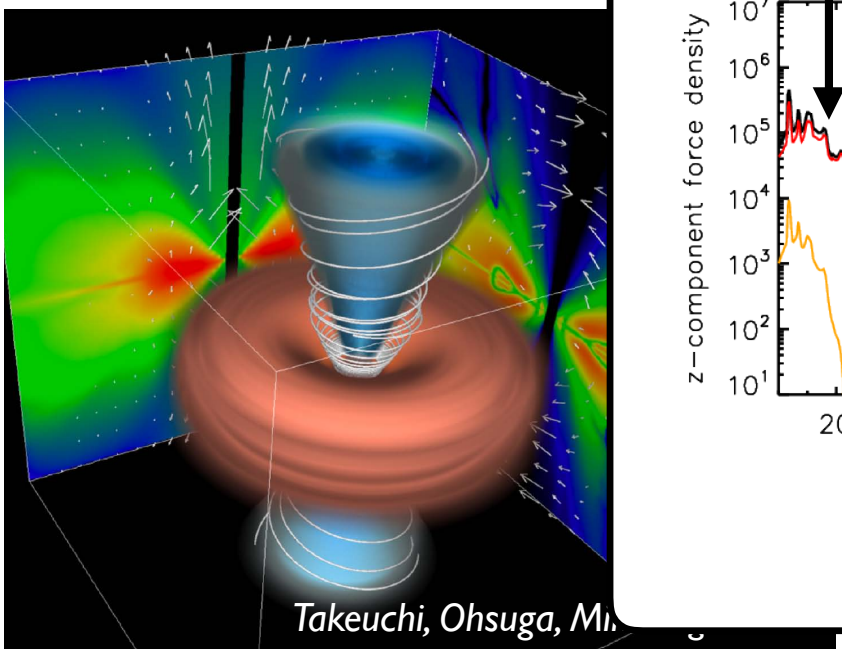
降着円盤＆ジェットのシミュレーション

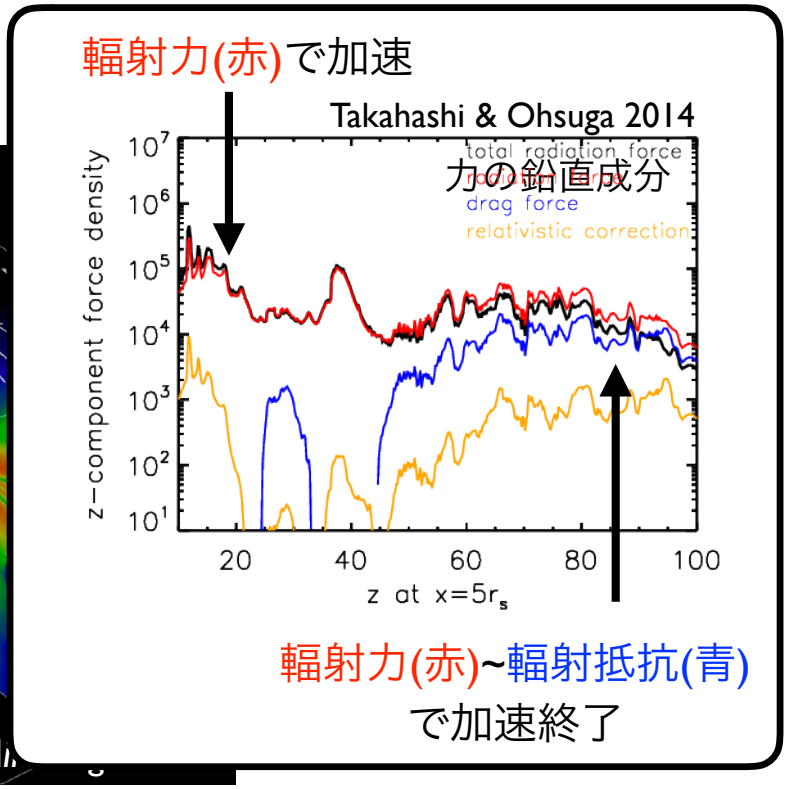




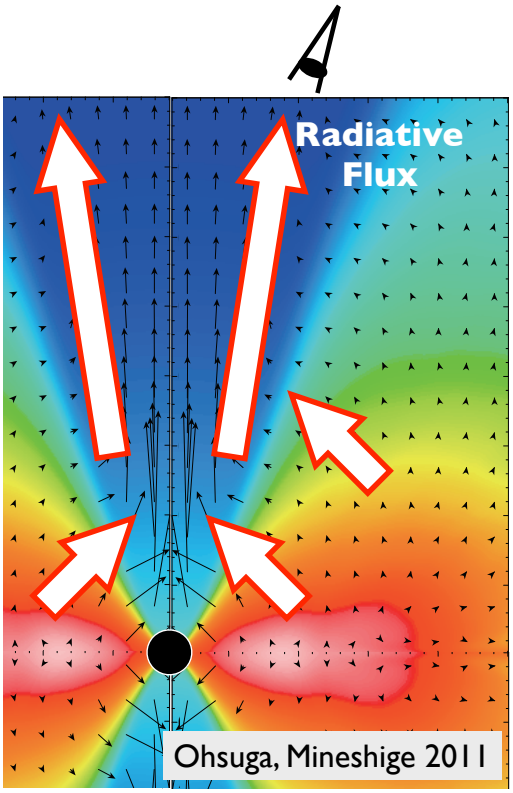


RADIATIVELY DRIVEN JET





APPARENT LUMINOSITY



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

Thus observed luminosity is very sensitive to the observer's viewing angle.

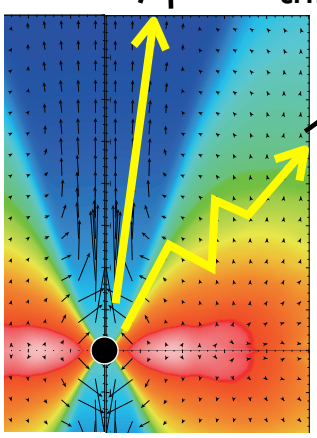
The apparent luminosity becomes highly super-Eddington for the face-on observers (**$22L_{Edd}$** for ≲20° in the case of Mdot~$100L_{Edd}/c^2$, L_{disk}~$3L_{Edd}$).

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

X-RAY SPECTRA

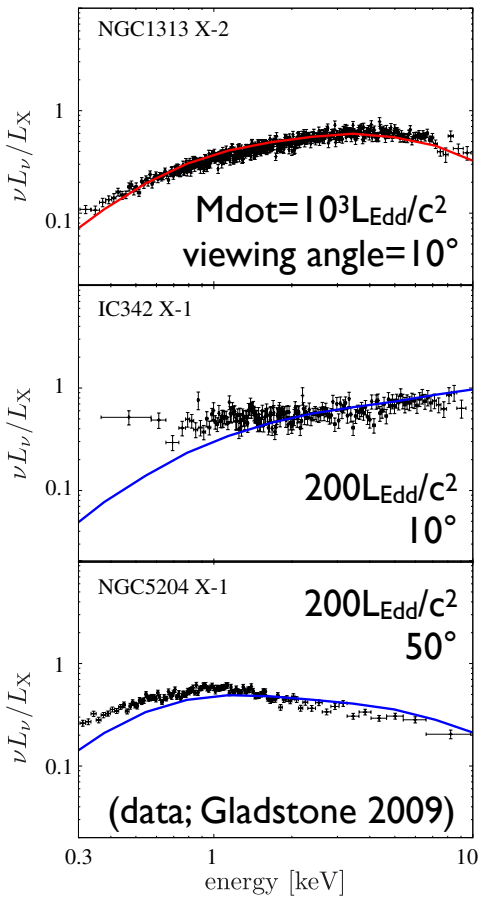
X-ray spectra, calculated by the post-processing radiation transfer, nicely fit the observations (ULXs).

hard X-ray is observed since high-energy photons escape through the funnel



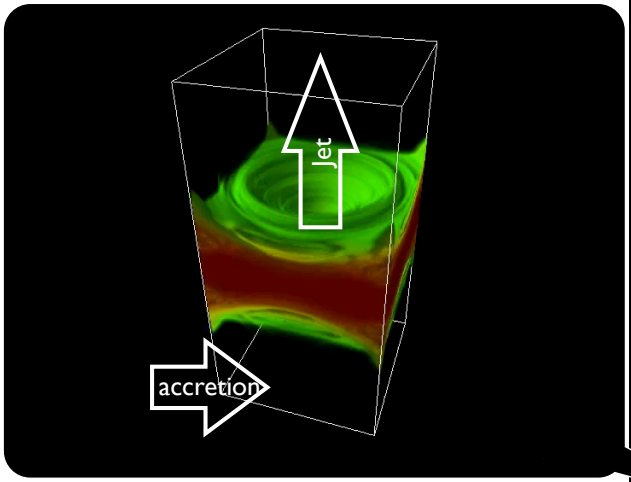
hard X-ray is reduced by Compton down-scattering

Kawashima et al. 2012

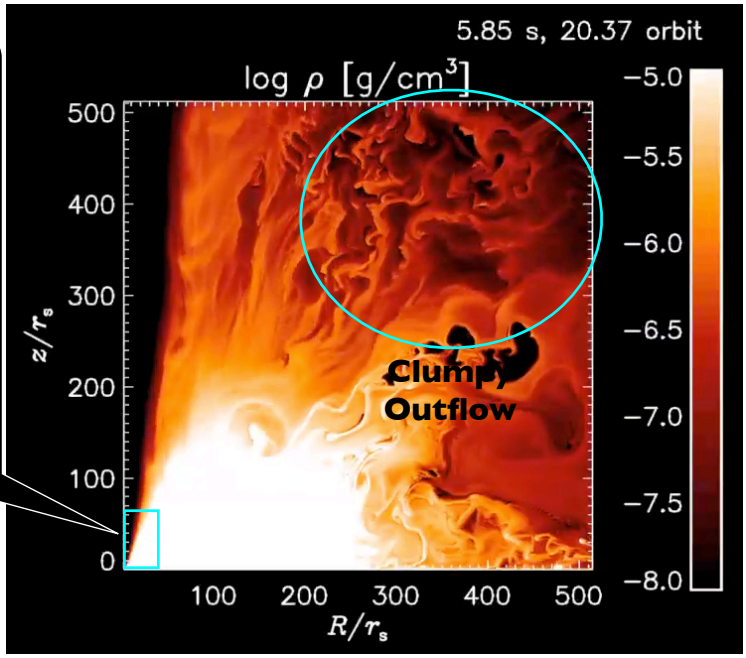


SIMULATION OF CLUMPY WIND

Super-Eddington disk+ Jet



Takeuchi, Ohsuga, Mineshige 2013

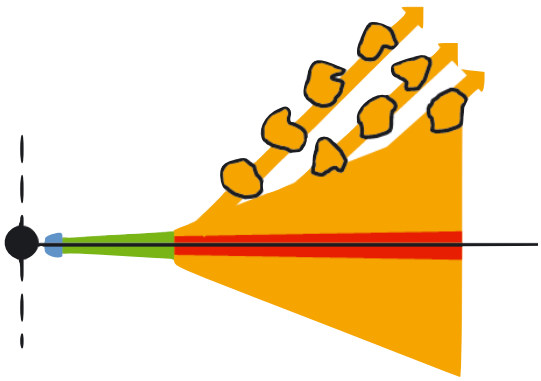


Time-dependent, Clumpy outflow with wide angle

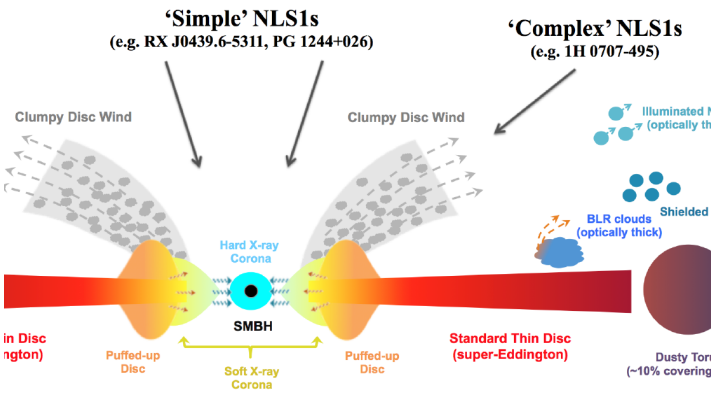
CLUMPY OUTFLOWS

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.

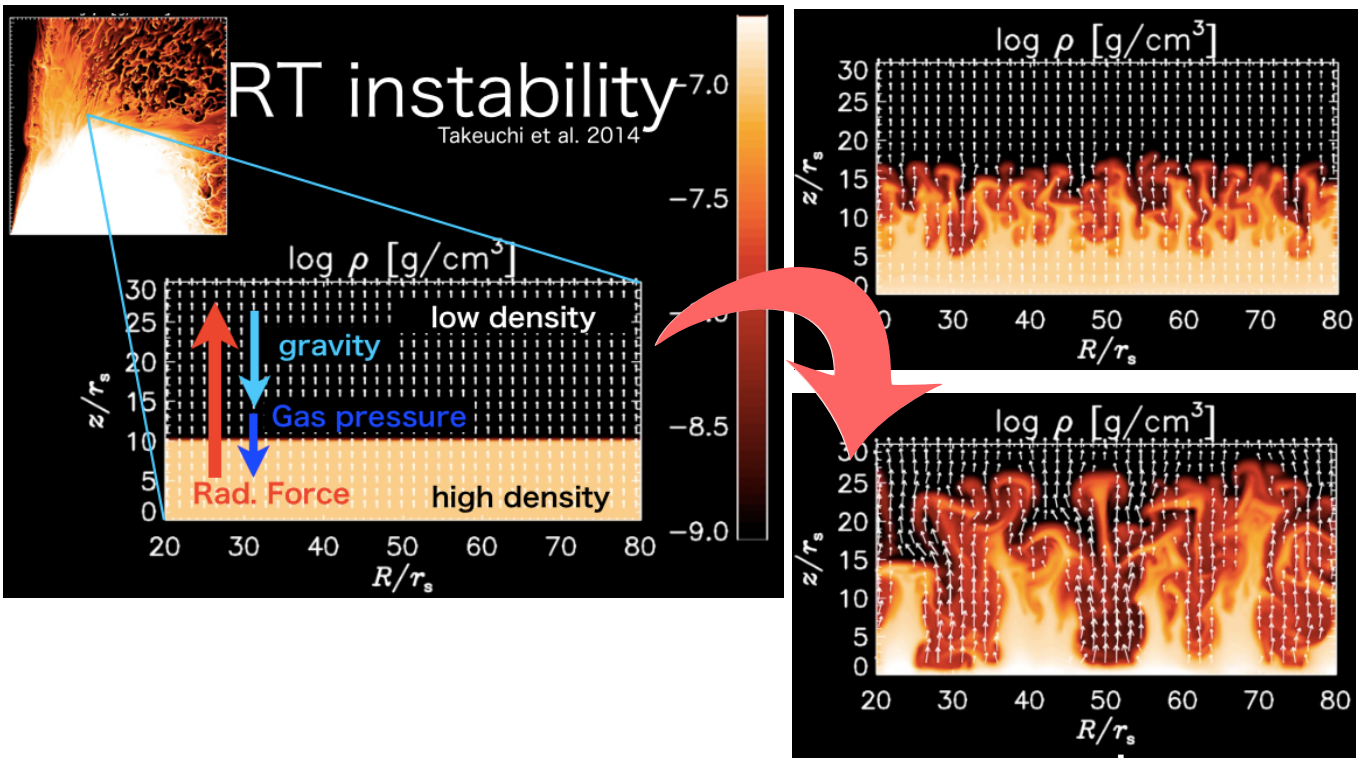


Middleton+11



Jin+17 see also Motta+17

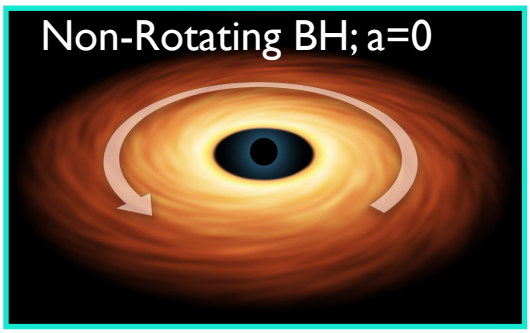
RT INSTABILITY

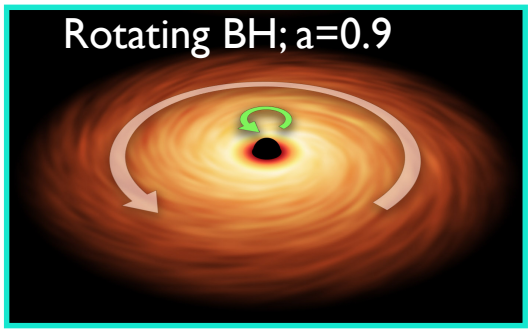


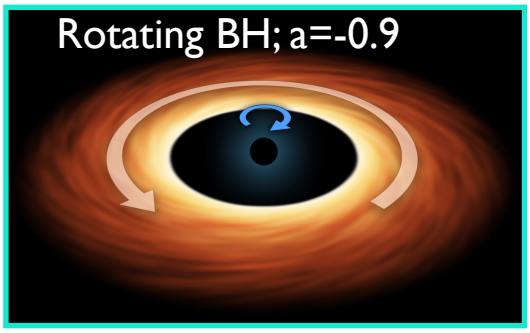
EFFECT OF BH SPIN

Disk luminosity and jet power might depend on the BH spin. We perform simulations of the super-Eddington flows around BHs with a=0.9, 0, -0.9.

*a: spin parameter



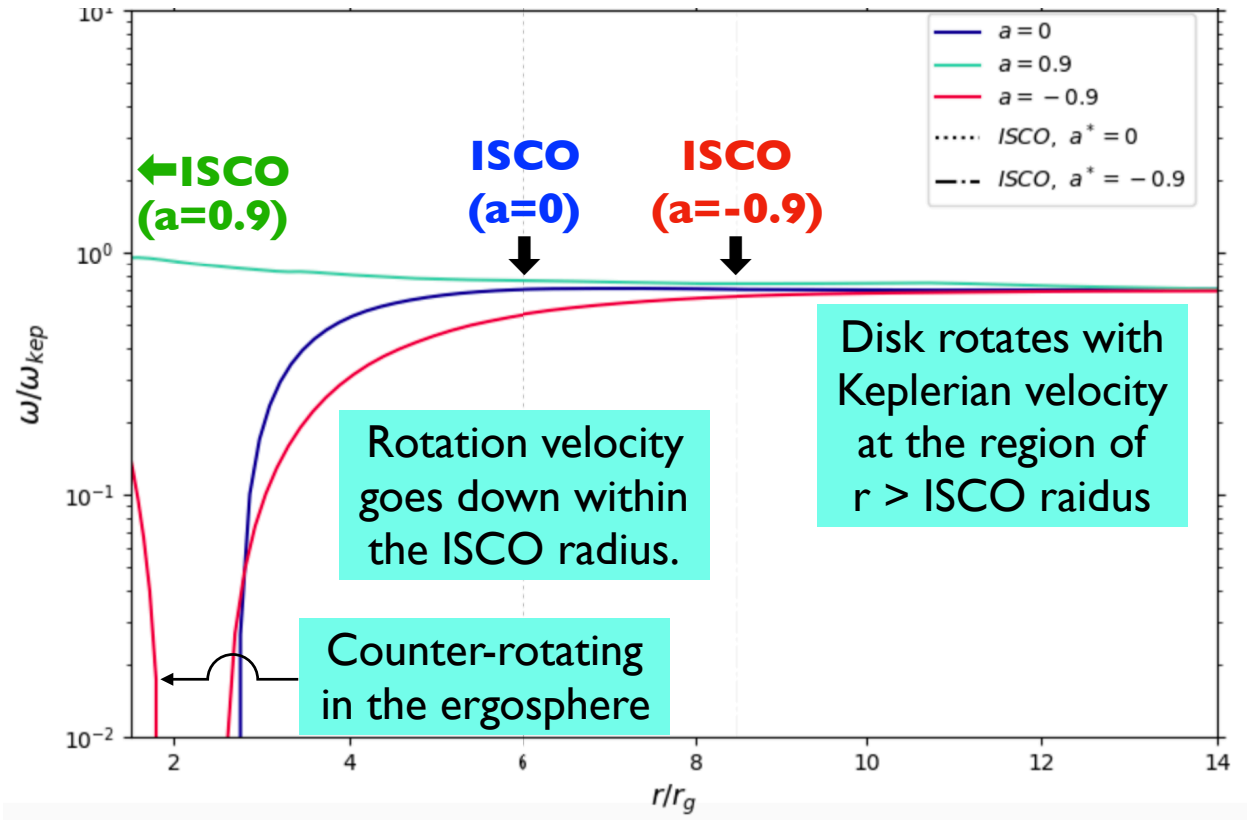




DISK ROTATION

Preliminary

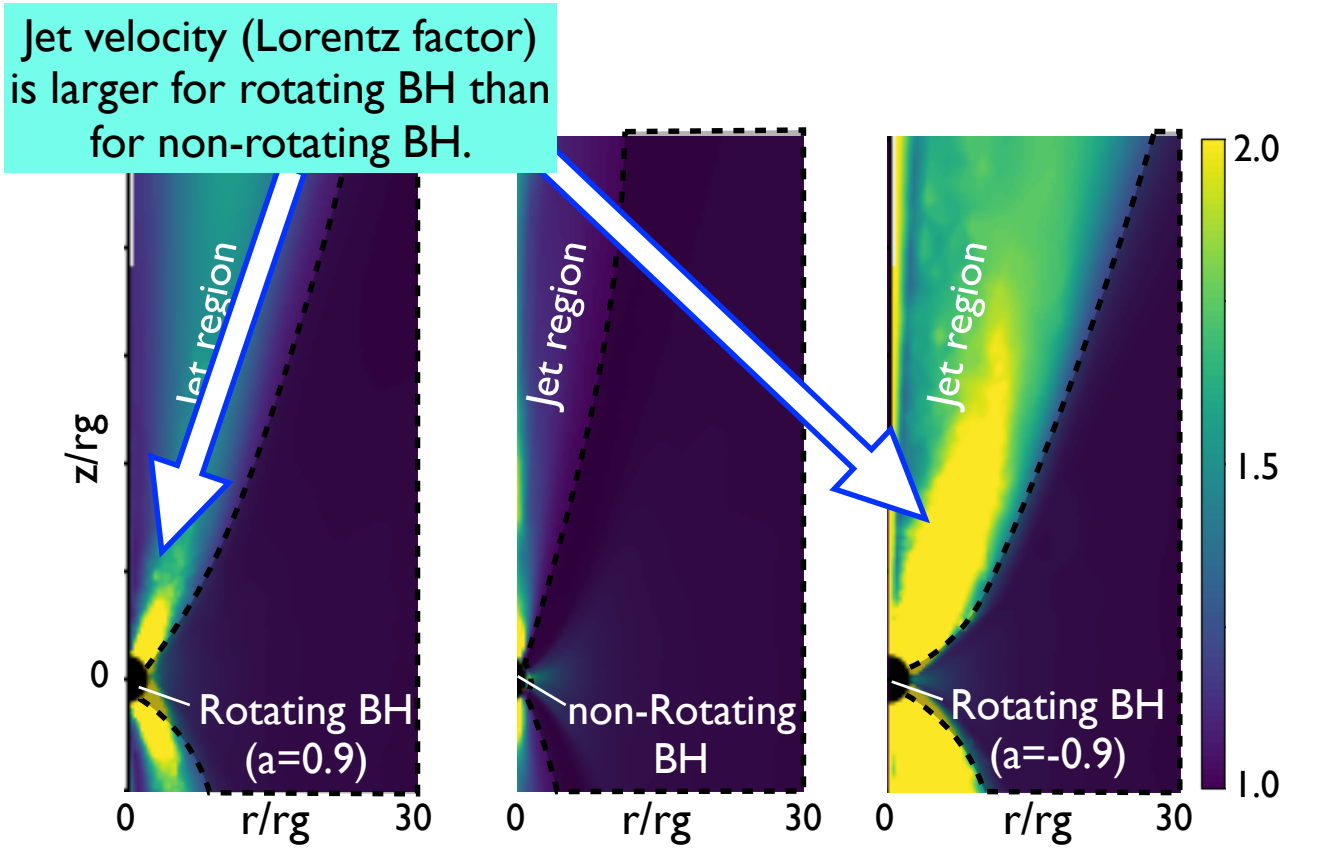
Utsumi et al. in prep.



LORENTZ FACTOR OF JETS

Preliminary

Utsumi et al. in prep.



BH SPIN & JETS

Preliminary

Utsumi et al. in prep.

	Conversion Efficiency (Jet) [%]	Conversion Efficiency (radiation) [%]
a=0.9	7.5	11
a=0	0.7	0.5
a=-0.9	1.5	2

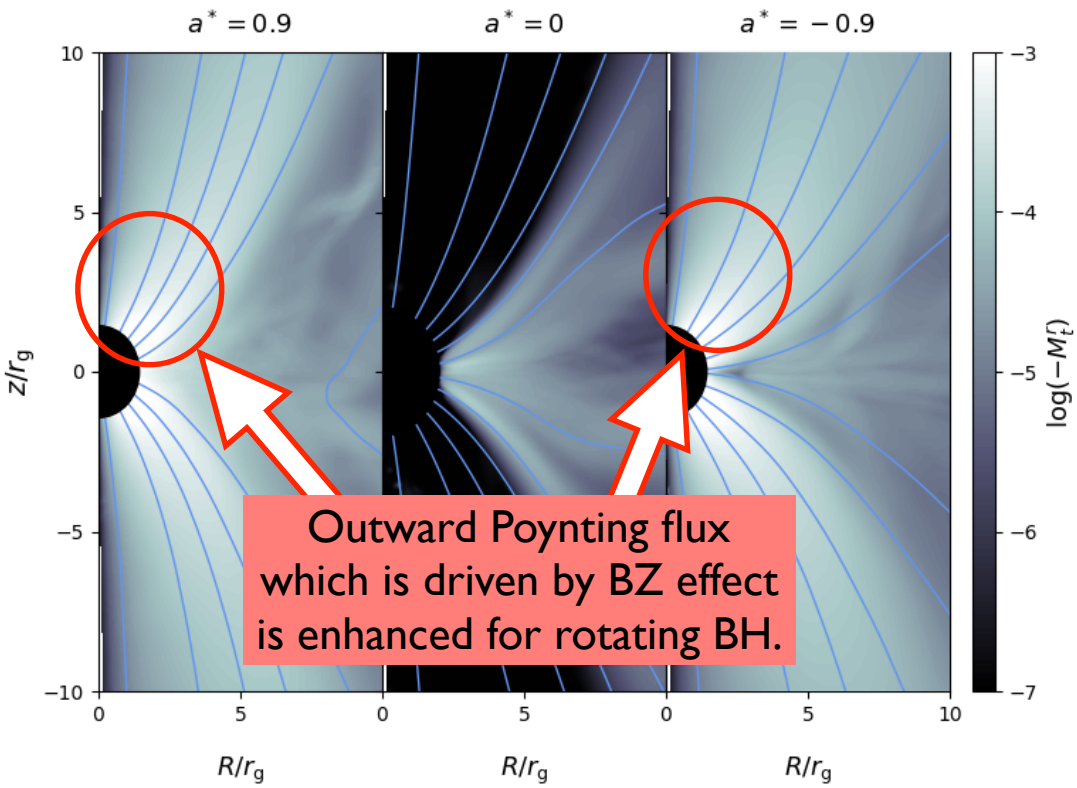
BZ effects drive powerful jet and large luminosity ?

BH SPIN & JETS

Preliminary

Utsumi et al. in prep.

Outward Poynting Flux



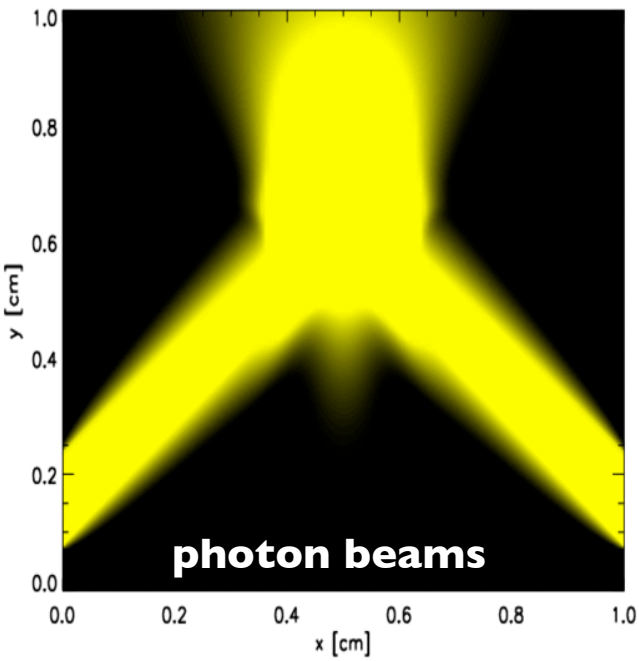
Outward Poynting flux which is driven by BZ effect is enhanced for rotating BH.

輻射流体力学計算の世界情勢

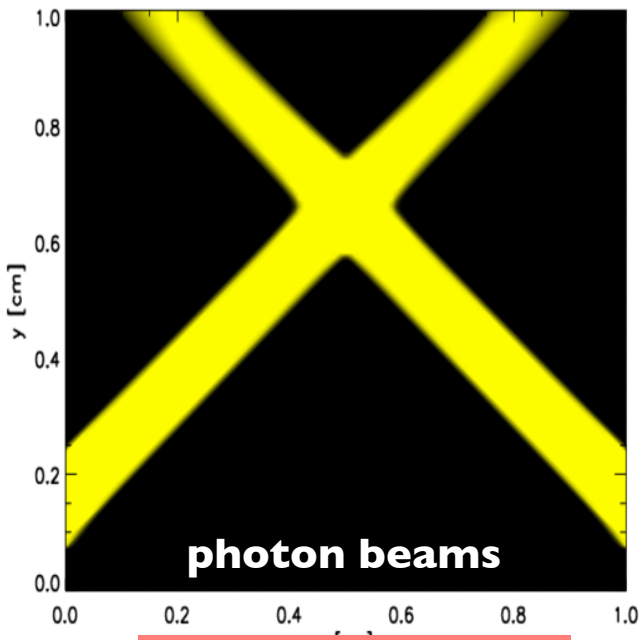
	Newtonian or O(v/c)	Special relativity	General relativity
VET Full Transfer	Stone et al. 92 Jiang et al. 14a Jiang et al. 14b	Ohsuga, Takahashi 16	under development Asahina+ in prep.
厳密 / 近似			
M1	Gonzalez et al. 07	Takahashi, Ohsuga 17	Sadowski+ 14,15 McKinney+ 14 Takahashi, Ohsuga+16 Takahashi & Ohsuga 17
Eddington /FLD	Ohsuga et al. 09, 11	Takahashi, Ohsuga, et al. 13	Farris et al. 08

Two-beam TEST

M1

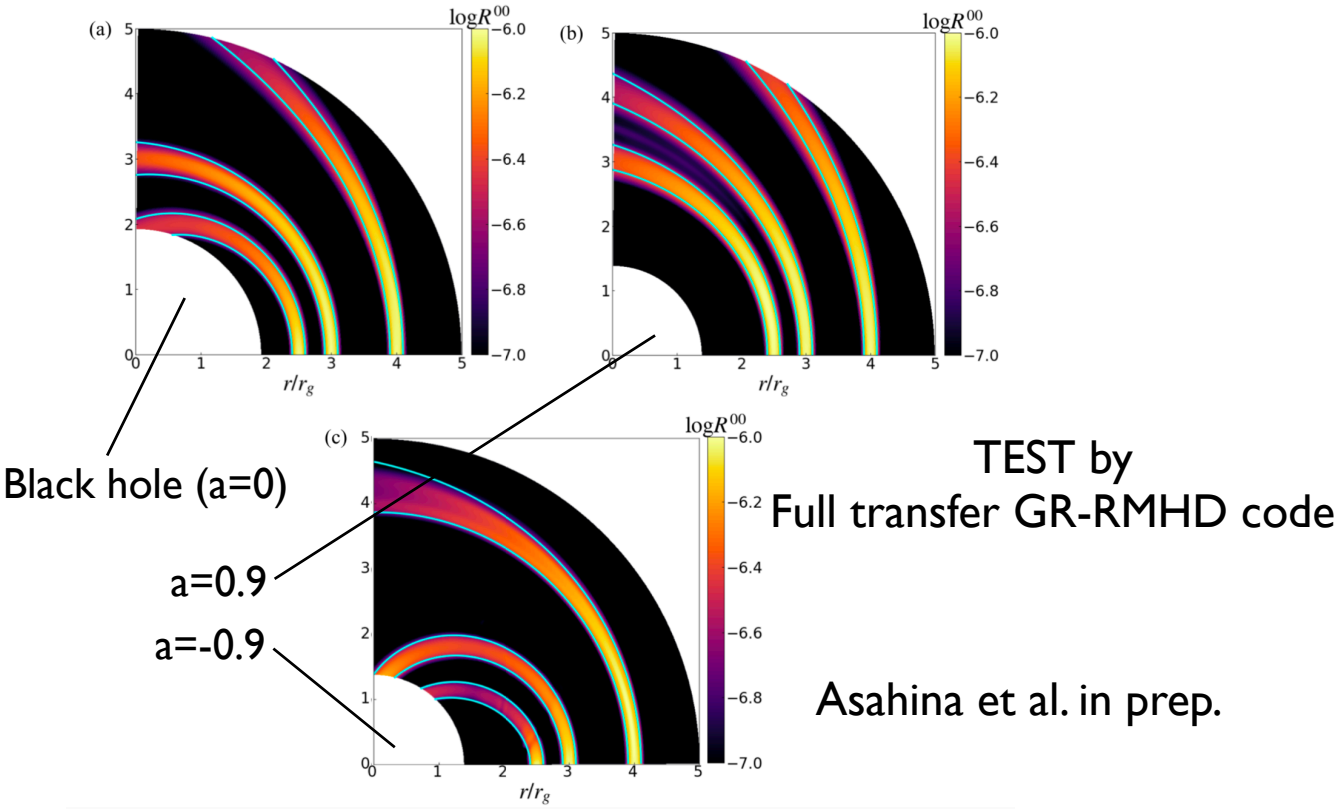


full transfer



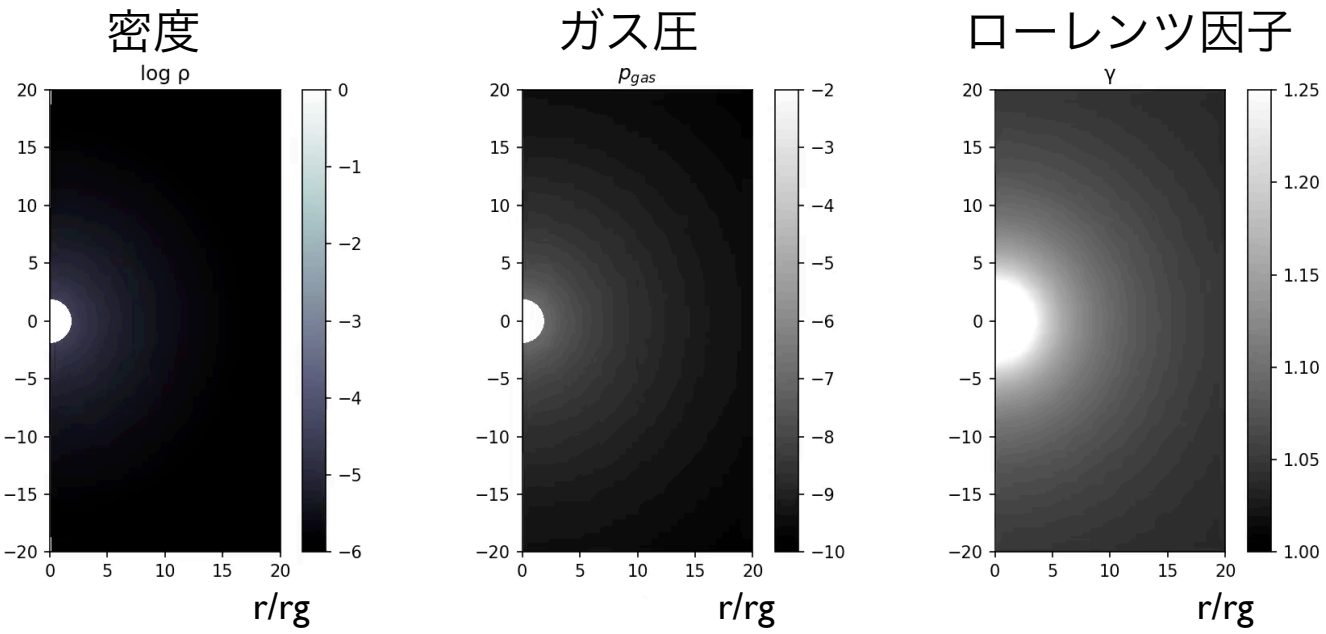
Full transfer method gives correct answer.

Photon Beam TEST around BH



Asahina et al. in prep.

New Simulations; Disk & Jet

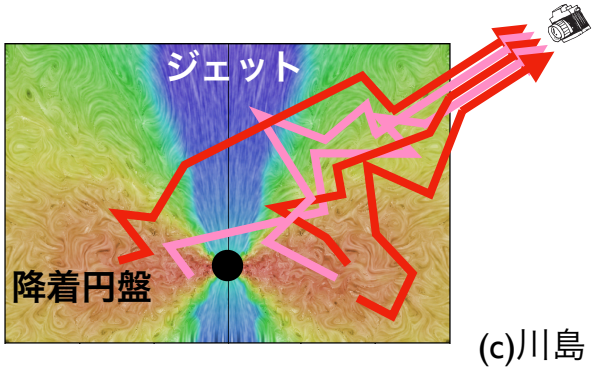


過去の研究（MI近似）と比較すると, ジェットのパワーや
輻射エネルギーの流れにおいて, 定量的な違いが見られる.

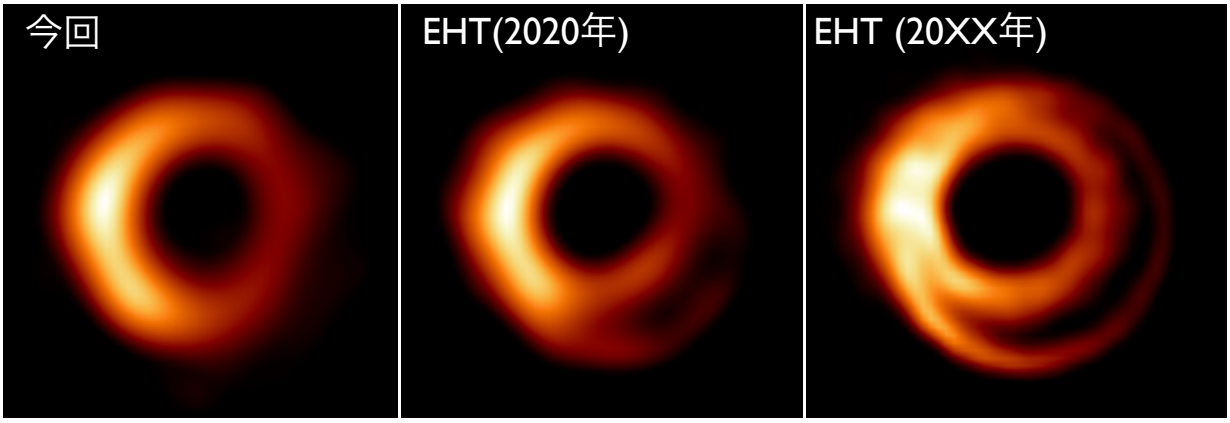
次世代観測を見据えて(EHT)

一般相対論的放射輸送計算コード（RAIKOU）の開発に成功

今回のEHT観測の再現に成功し，近未来のEHT観測を予言

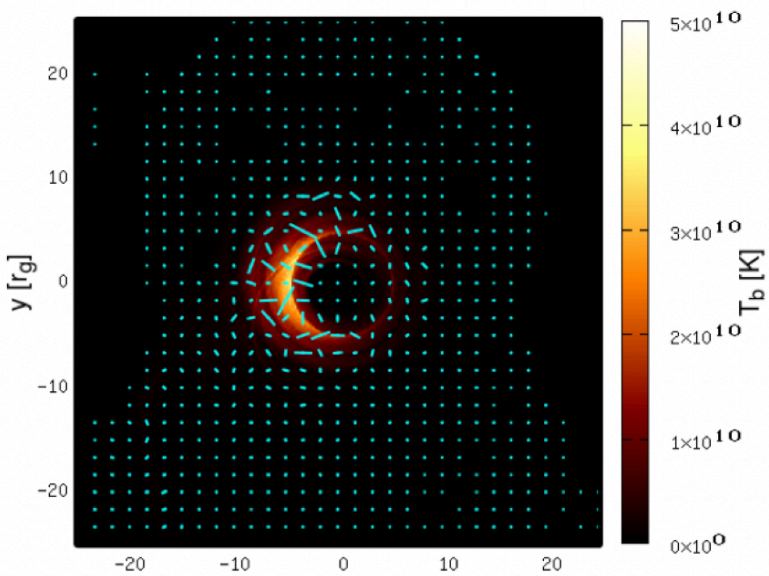


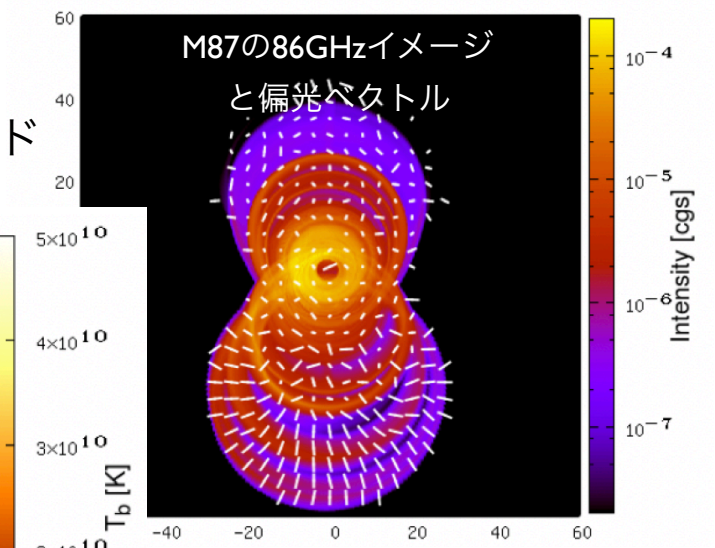
(c)川島



次世代観測を見据えて(EHT)

恒任さん（京都大学M2）作：
一般相対論的偏光輻射輸送コード

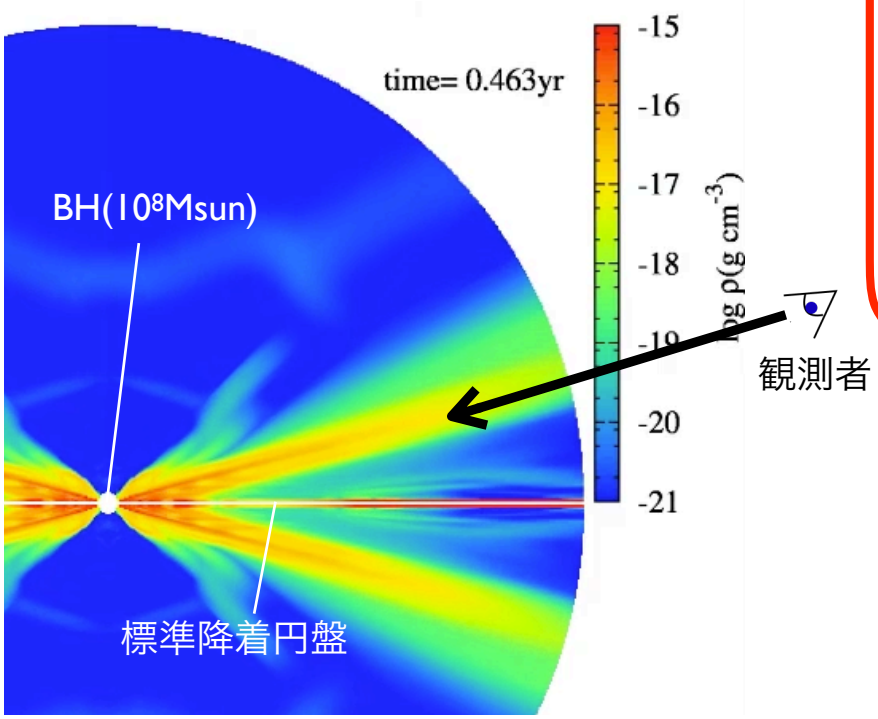




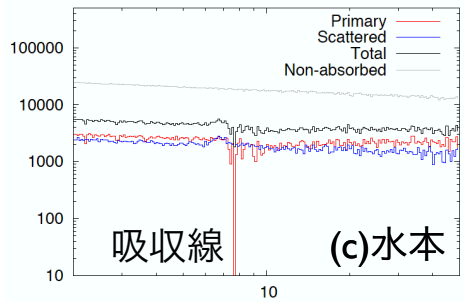
Tsuneto et al. submitted

次世代観測を見据えて(XRISM)

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



X線スペクトルの計算例



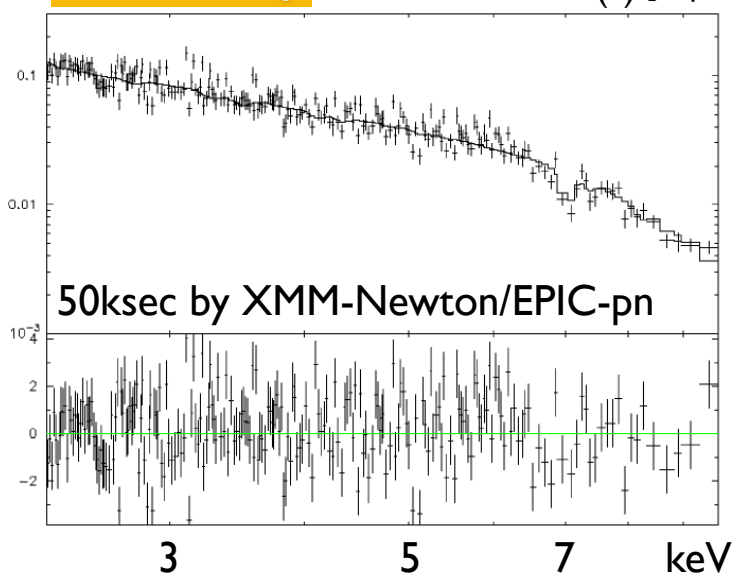
輻射スペクトル計算
by MONACO

次世代観測を見据えて(XRISM)

疑似観測(XMM)

Preliminary

(c)水本



フィッティング
-Log[電離度] ~ 3.5
-速度 ~ 0.13c (位置~120Rg)
-数密度 ~ $10^{10.1}$cm^{-3}

正解（シミュレーション）
-Log[電離度] ~ 4.0-5.0
-速度 ~ 0.15c
-位置~300Rg
-数密度~$10^{8\text{-}9}$cm^{-3}

理論と観測が協力しないと真実はわからない！

まとめと今後

- ブラックホール降着円盤とジェットの一般相対論的輻射磁気流体力学(GR-RMHD)シミュレーションに成功した.
- 高光度ブラックホール天体の性質をおよそ再現することに成功した.
- 富岳で, Full Transfer (Boltzmann based) GR-RMHDシミミュレーションを実施する予定である.
- 近未来の観測計画とも密接に連携し, ブラックホール周囲のガスダイナミクスを解明する計画である.