AGN研究の進展

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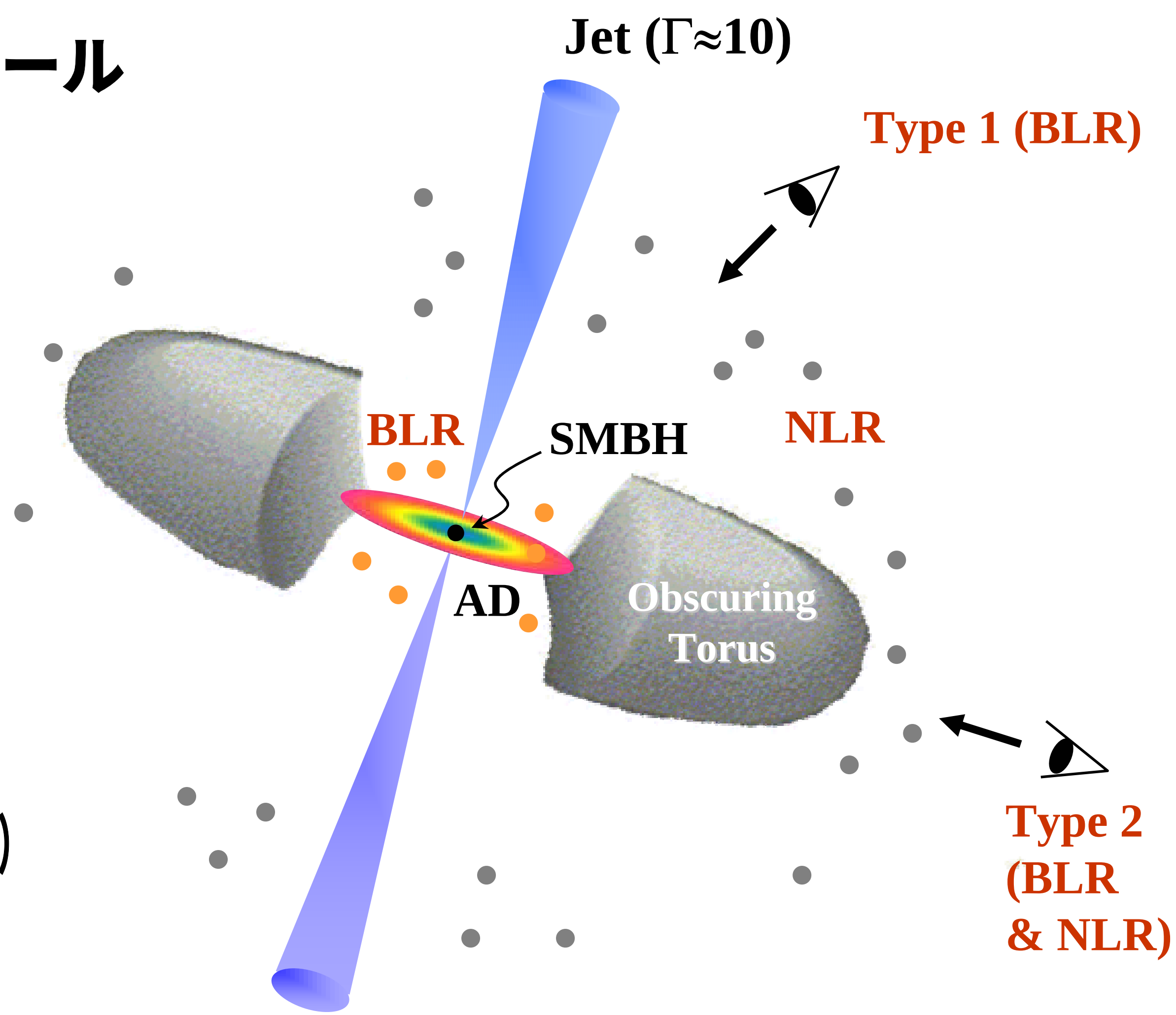
AGN GUT

３０年来のパラダイム

① 超巨大ブラックホール
(SMBH)

② 降着円盤
(AD)

③ 遮蔽トーラス
(Obscuring Torus)



BLR: Broad Line Regions, NLR: Narrow Line Regions

Part 1　超巨大ブラックホール形成

Rees Diagram
(1984)

Supermassive Star ?

or

Cluster ?

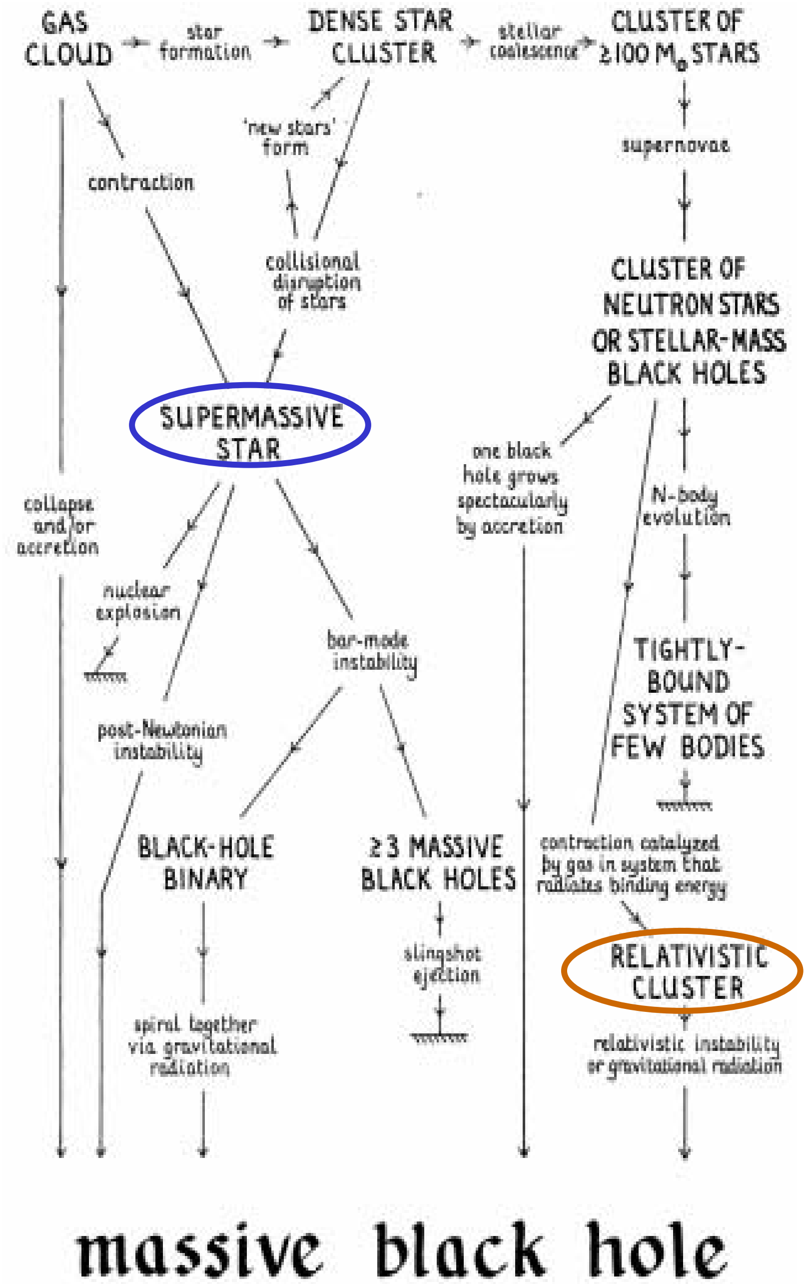
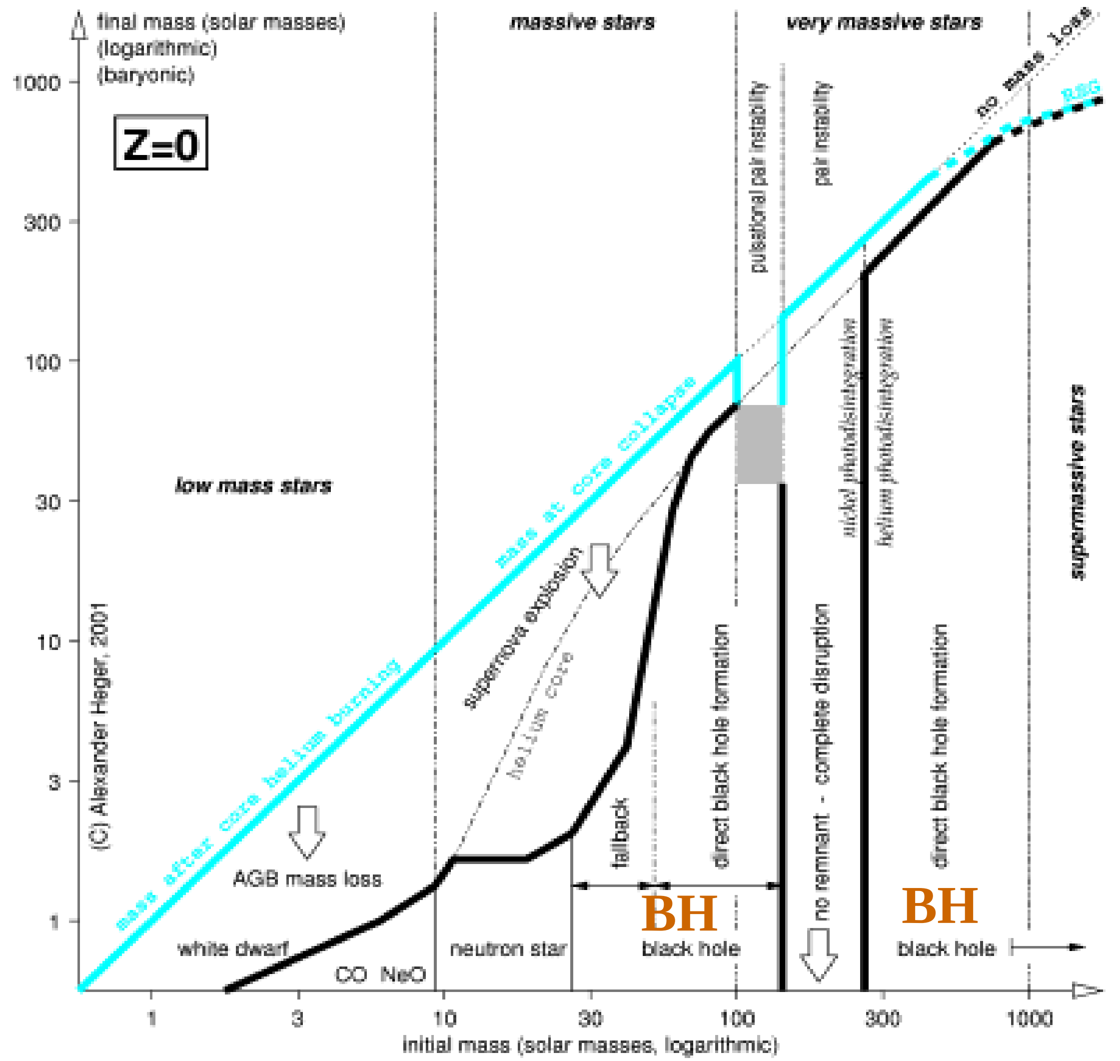


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Seed BHs

Pop III Stars

Heger & Woosley 2002, ApJ, 567, 532



Supermassive Star

General Relativistic Instability

Rapidly rotating supermassive star
in equilibrium

- rigid rotation
- mass-shedding limit
- unstable at $R < 640 GM / c^2$

Baumgarte & Shapiro 1999, ApJ, 526, 941

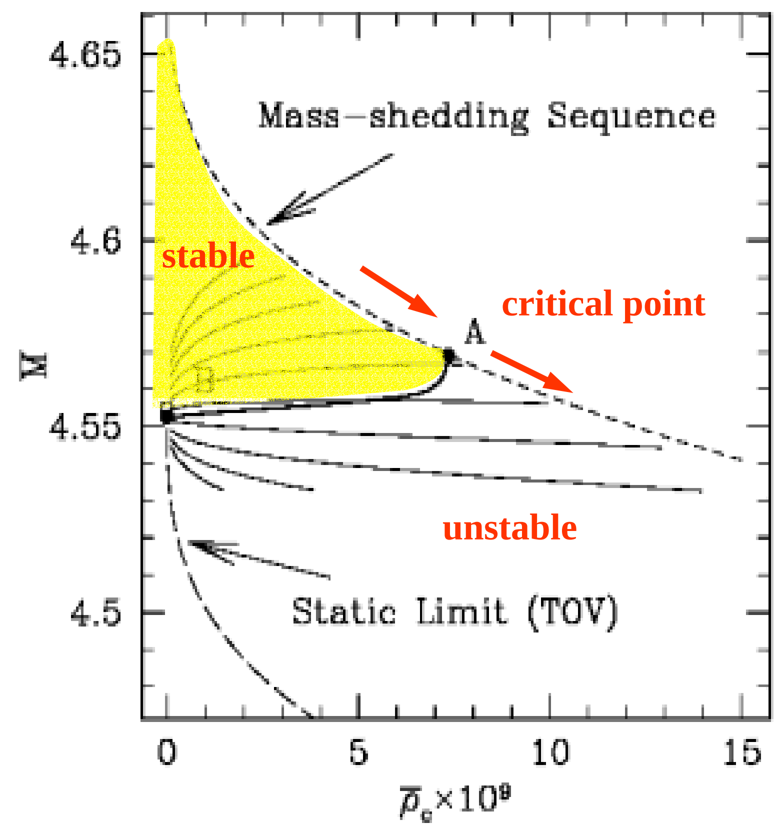


FIG. 2.—Mass vs. central density plot for relativistic, rotating $n = 3$ polytropes. The long-dashed curve is the Tolman-Oppenheimer-Volkoff (TOV) solution for nonrotating, static configurations, and the short-dashed curve marks the mass-shedding limit. The thin solid lines denote sequences of constant angular momentum, ranging from $\bar{J} = 15$ (*lowest curve*) to $\bar{J} = 24$ (*highest curve*) in increments of $\Delta \bar{J} = 1$. Turning points of these curves mark the onset of instability. The thick solid line connects these turning points (see also Fig. 3) and hence separates a region of stable configurations (*above this line*) from a region of unstable configurations (*below this line*). In particular, all nonrotating $n = 3$ polytropes are unstable to radial perturbations. A configuration evolving along the mass-shedding sequence with increasing central density becomes unstable at the critical point A. All sequences of constant angular momentum connect the mass-shedding limit with point B for $\rho_c \to 0$ (and hence $R \to \infty$). The mass of this configuration should agree with the mass $\bar{M} = 4.5525$ of a Newtonian $n = 3$ polytrope (eq. [26]; *open circle*). The deviation of the solid point B from the analytical value is a measure of our numerical accuracy.

Dynamical Collapse (Post Newtonian)

Saijyo, Shibata, Baumgarte, & Shapiro (2001, ApJ, 548, 919)

Differentially rotating SMS
⇒ bar instability

Saijyo, Baumgarte, Shapiro & Shibata (2002, ApJ, 569, 349)

Rigid rotating SMS
⇒ collapse

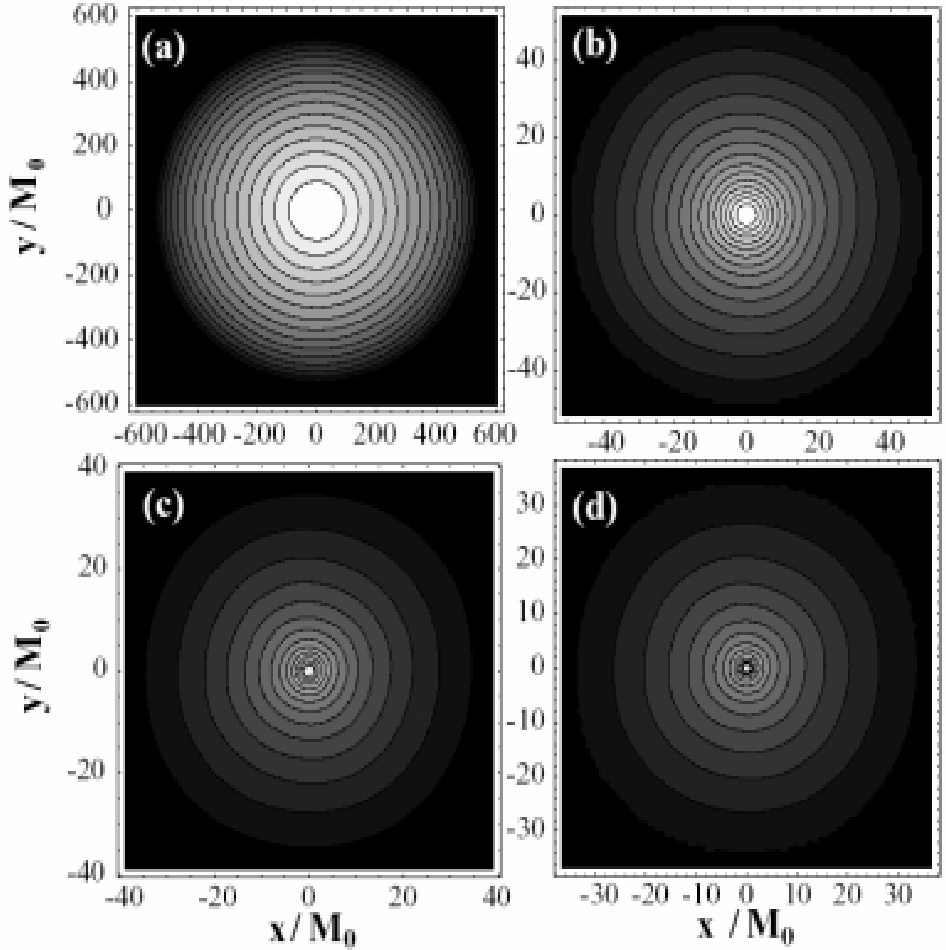


FIG. 14.— Density contours ρ_* in the equatorial plane at selected times during rotating SMS collapse. Snapshots are plotted at $(t/t_{\mathrm{P}}$ … $d)$ = (a) $(5.0628\times10^{-4}, 8.254\times10^{-9}, 10^{-7})$, (b) $(2.50259, 1.225\times10^{-4}, 10^{-5})$, (c) $(2.05360, 8.328\times10^{-3}, 5.585\times10^{-7})$, (d) (2.5… $3.425\times10^{-2}, 1.357\times10^{-7})$, respectively. The contour lines denote densities $\rho^* = \rho_c^* \times d^{(1-i/16)}$ $(i = 1, \cdots, 15)$.

Dynamical Collapse (Full General Relativity)

Shibata & Shapiro 2002, ApJ, 572, L39

Dnamical collapse ⇒ Apparent Horizon

Kerr parameter ≈ 0.75 (Kerr BH)

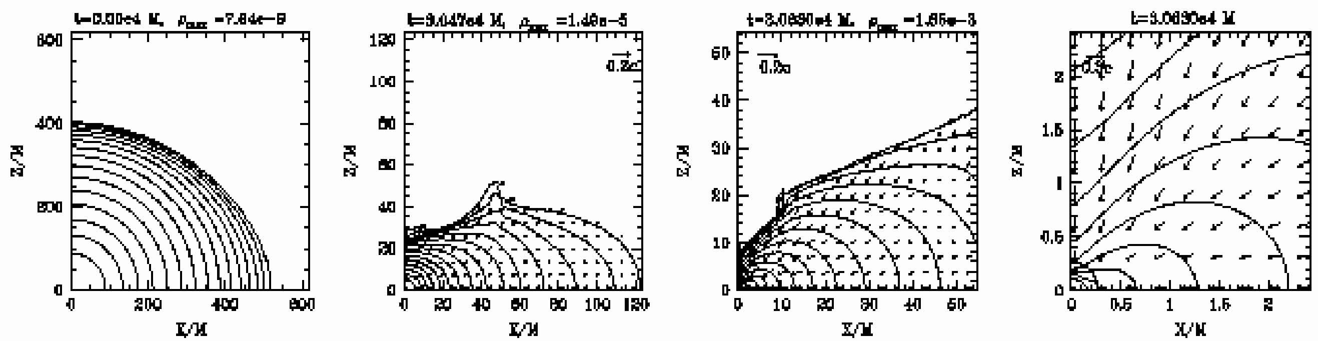


FIG. 1.— Snapshots of density contour lines and velocity vectors in the x-z plane at selected time slices. The contour lines are drawn for $\rho/\rho_{max} = 10^{-0.4j}$ ($j = 0 \sim 15$), where ρ_{max} denotes the maximum density. The fourth figure is the magnification of the third one: The thick solid curve at $r \approx 0.3M$ denotes the location of the apparent horizon.

Supermassive star (rigidly rotating) M t $10^6 M_\odot$

↓ $R < 640\, GM/c^2$

General relativistic instability (Baumgarte & Shapiro 1999, ApJ, 526, 941)

↓

Dynamical collapse (Post Newtonian) → **Apparent horizon (Full GR)**

(Saijyo, Baumgarte, Shapiro & Shibata 2002, ApJ, 569, 349)

Kerr BH with spin parameter of 0.75

(Shibata & Shapiro 2002, ApJ, 572, L39)

Mechanisms due to *N*-Body Process

Dynamical Friction (Makino 2002)

$$t_{\rm fric} \simeq \frac{1.17}{\log\Lambda}\frac{r^2 v_c}{Gm} = 6\times10^8\,{\rm yr}\left(\frac{r}{\rm kpc}\right)^2\left(\frac{v_c}{100{\rm km\ s^{-1}}}\right)\left(\frac{m}{5\times10^6 M_\odot}\right)^{-1}$$

IMBH formation in a dense cluster

↓

Infall by dynamical friction

↓

Stripping of stellar envelop

↓

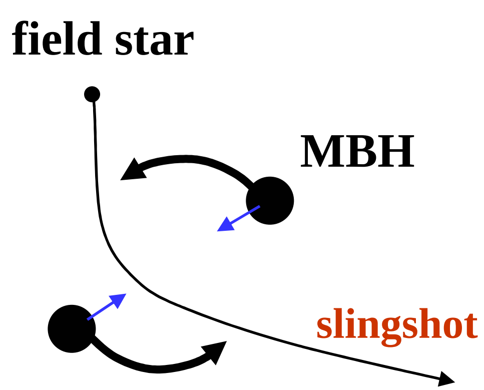
Multiple IMBH

↓

Binaries by slingshot (three-body reaction)

↓

Merger by gravitational wave



(1) Dynamical Friction

effective at $M_{\mathrm{BH}}<M_*$

$$\rho_* \propto r^{-2} \quad (M_* \propto r)$$

$$M_* = 10^6 M_\odot \left(\frac{r}{0.1\mathrm{pc}}\right)\left(\frac{M_{\mathrm{gal}}}{10^{10} M_\odot}\right)\left(\frac{R_{\mathrm{gal}}}{1\mathrm{kpc}}\right)$$

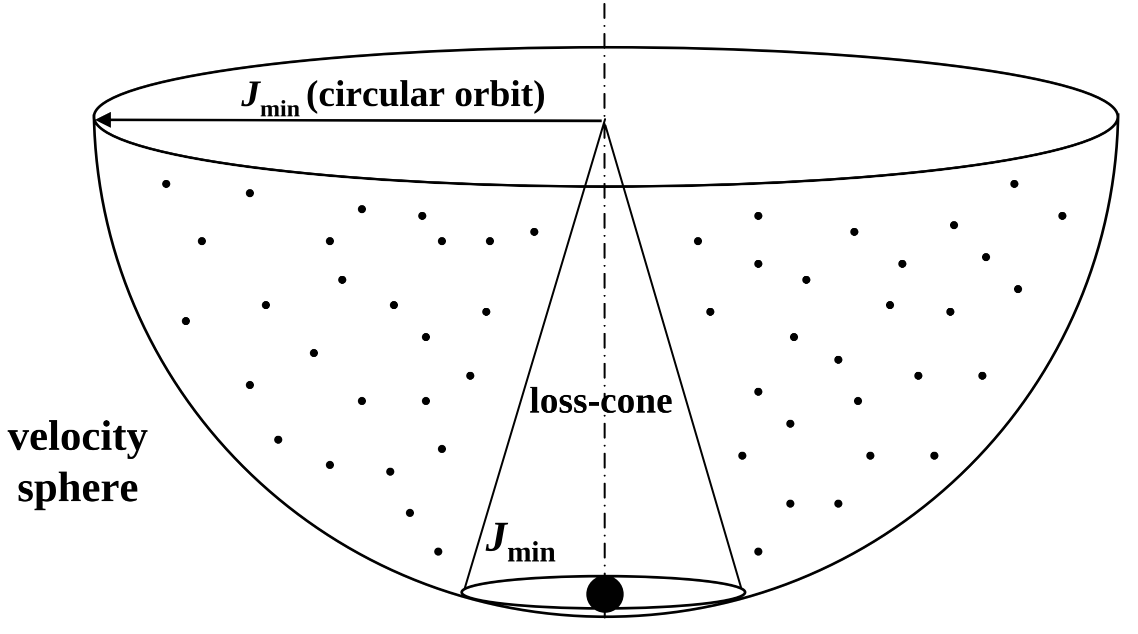
(2) Gravitational wave

$$t_{GW} \;;\; \frac{r}{c}\left(\frac{r}{r_g}\right)^3 = 2\times 10^{18}\,\mathrm{yr}\left(\frac{r}{0.1\mathrm{pc}}\right)^4\left(\frac{M_{\mathrm{BH}}}{10^6 M_\odot}\right)^{-3}$$

(3) Loss-cone depletion by slingshot

Loss-cone Depletion in Binary

Begelman, Blandford, Rees, 1980, Nature, 287, 307



ejection by slingshot

Loss-cone Depletion in MBH Binary

Makino & Funato, 2004, ApJ, 602, 93

MBH binaryは, slingshotによるhardening では,
Hubble time 内に重力波放出の軌道まで縮まらない

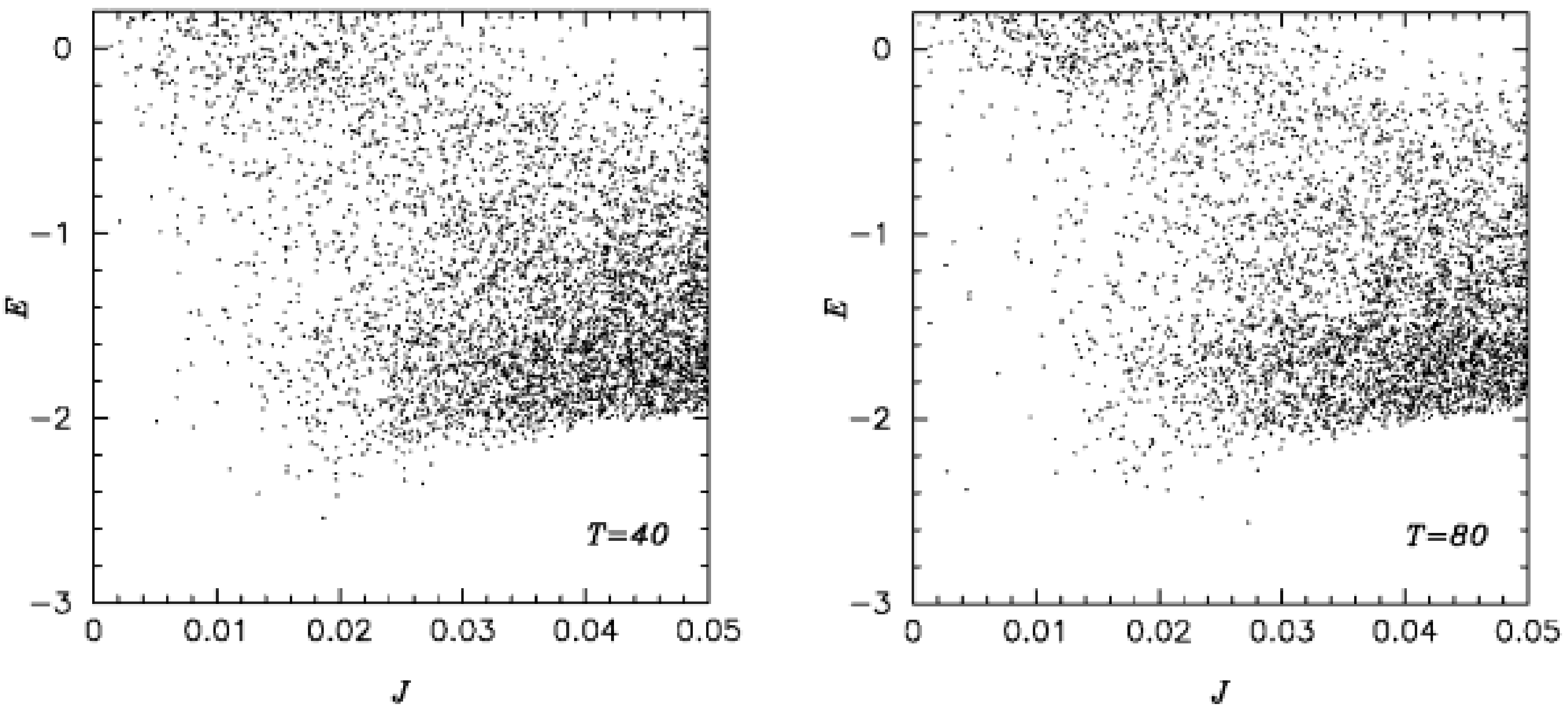
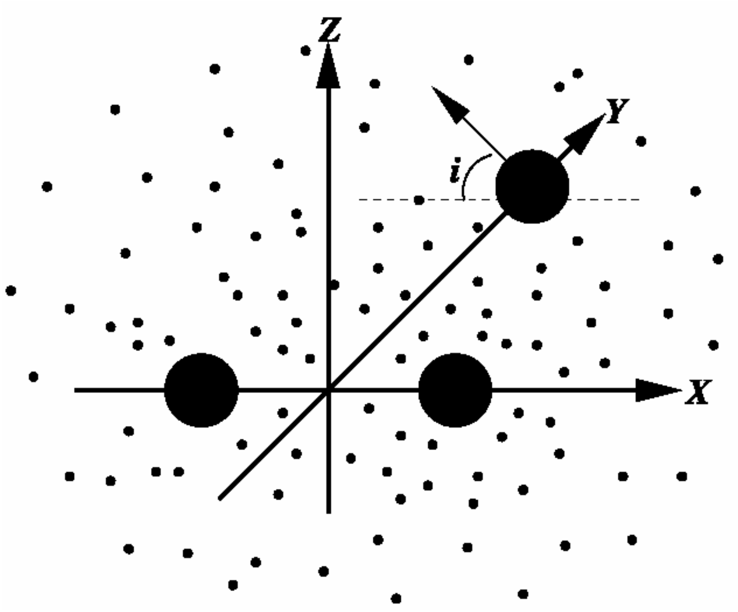


FIG. 8.—Distribution of particles in the (*E*, *J*) plane at times $T = 10, 20, 40$ and 80 (*top left to bottom right*). The number of particles is 10^6.

MBH Triplet

Iwasawa, Funato, &Makino, 2006, ApJ, 651, 1059

Eccentricity の大きいBH binaryは, single BH との
3体相互作用で重力波放出の軌道まで縮まる



High eccentricity BH binary形成

① 強3体相互作用による eccentricity thermalization

② Kozai メカニズムによる経年的変化

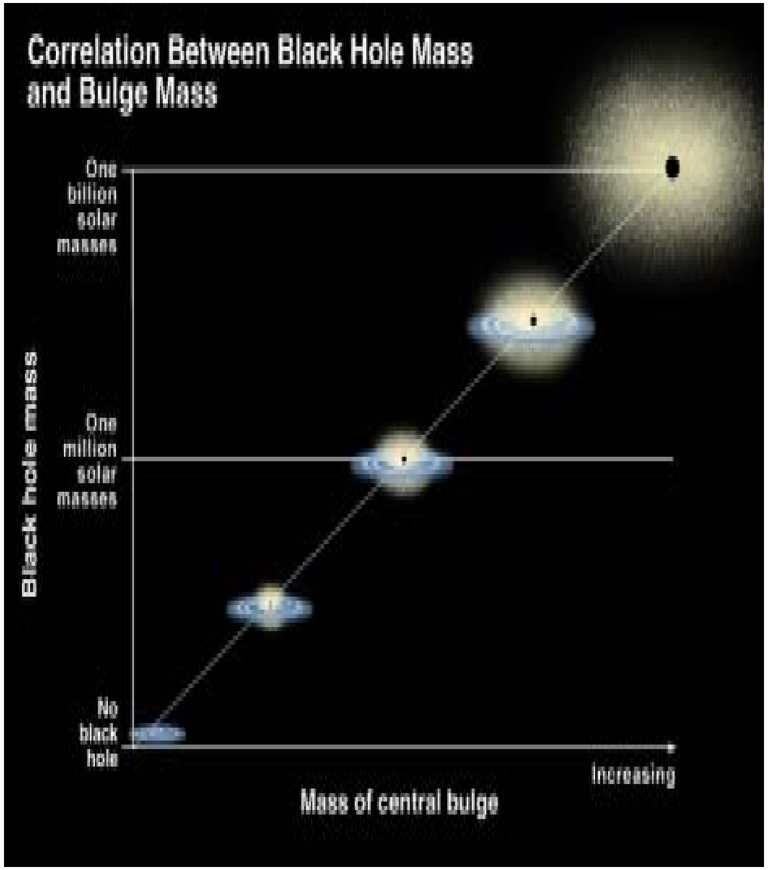
←

多くのMBH は, binaryとして残る

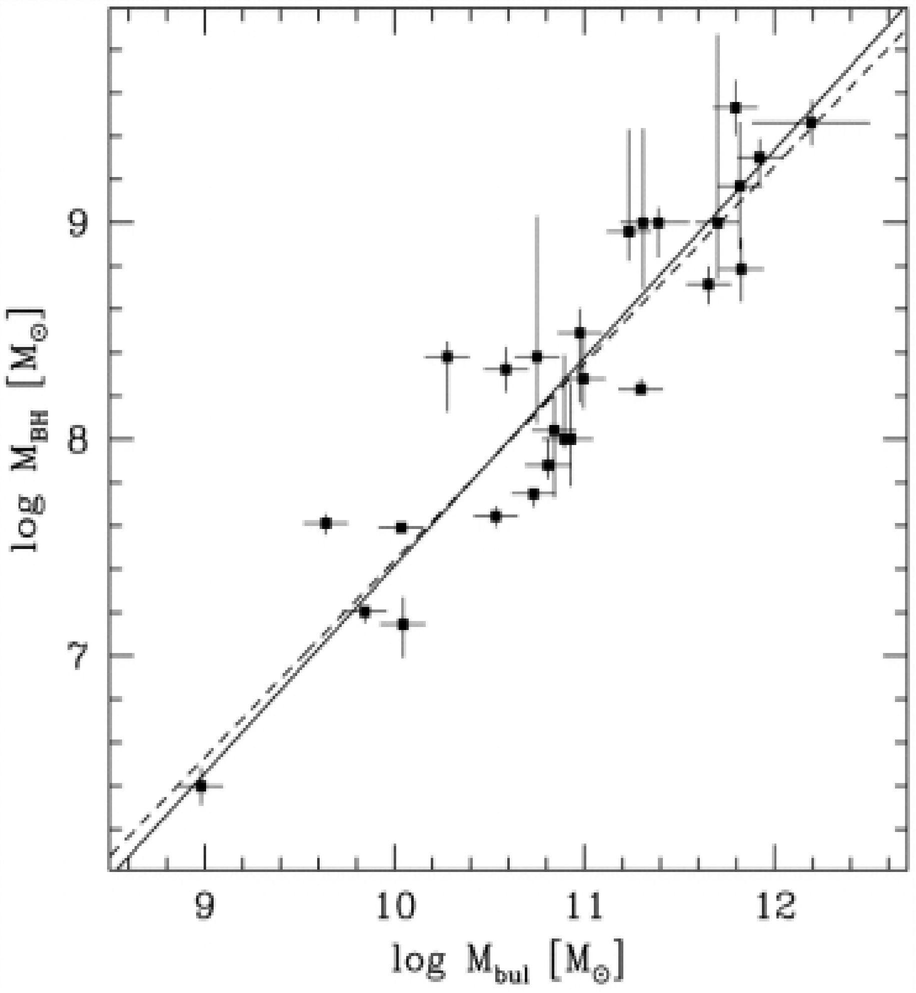
超巨大BH－銀河バルジ関係

$$M_{BH} / M_{bulge} \approx 0.001$$

Kormendy & Richstone 1995
Magorrian et al. 1998
Merritt & Ferrarese 2001
Marconi & Hunt 2003



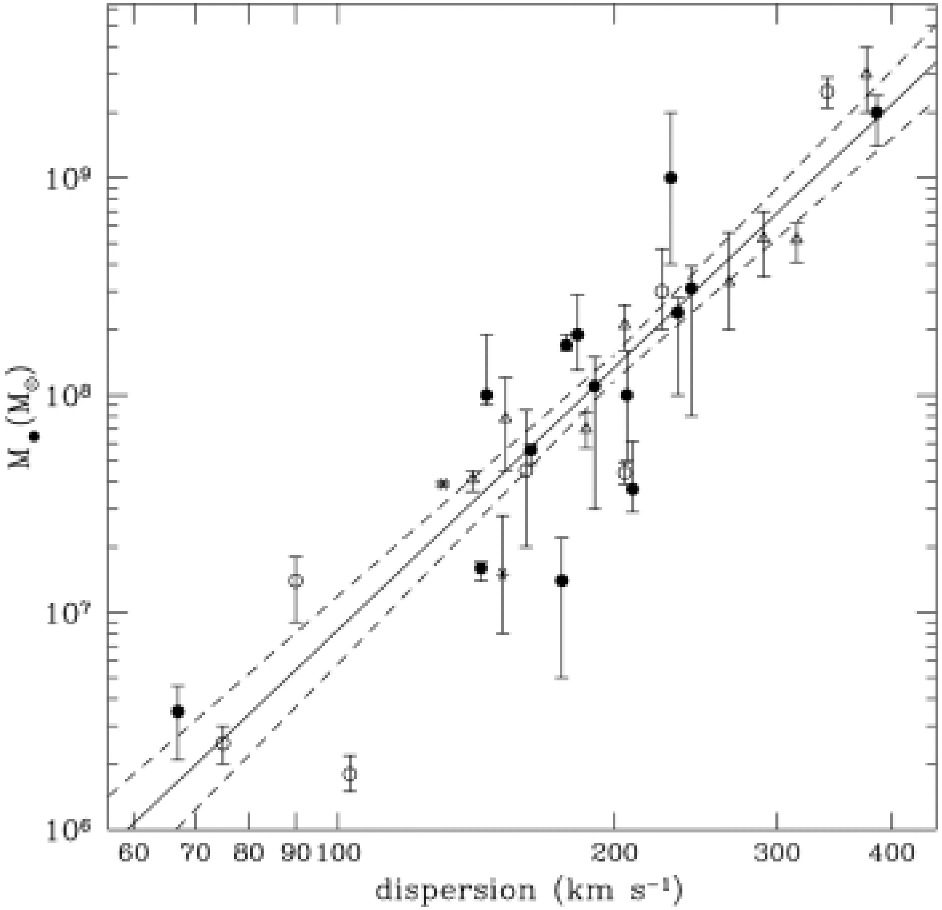
Marconi & Hunt 2003, ApJ, 589, 21



M_{BH}-σ Relation

$$M_{BH} \approx 10^8 M_{\odot} \left(\frac{\sigma}{200\mathrm{km/s}} \right)^4$$

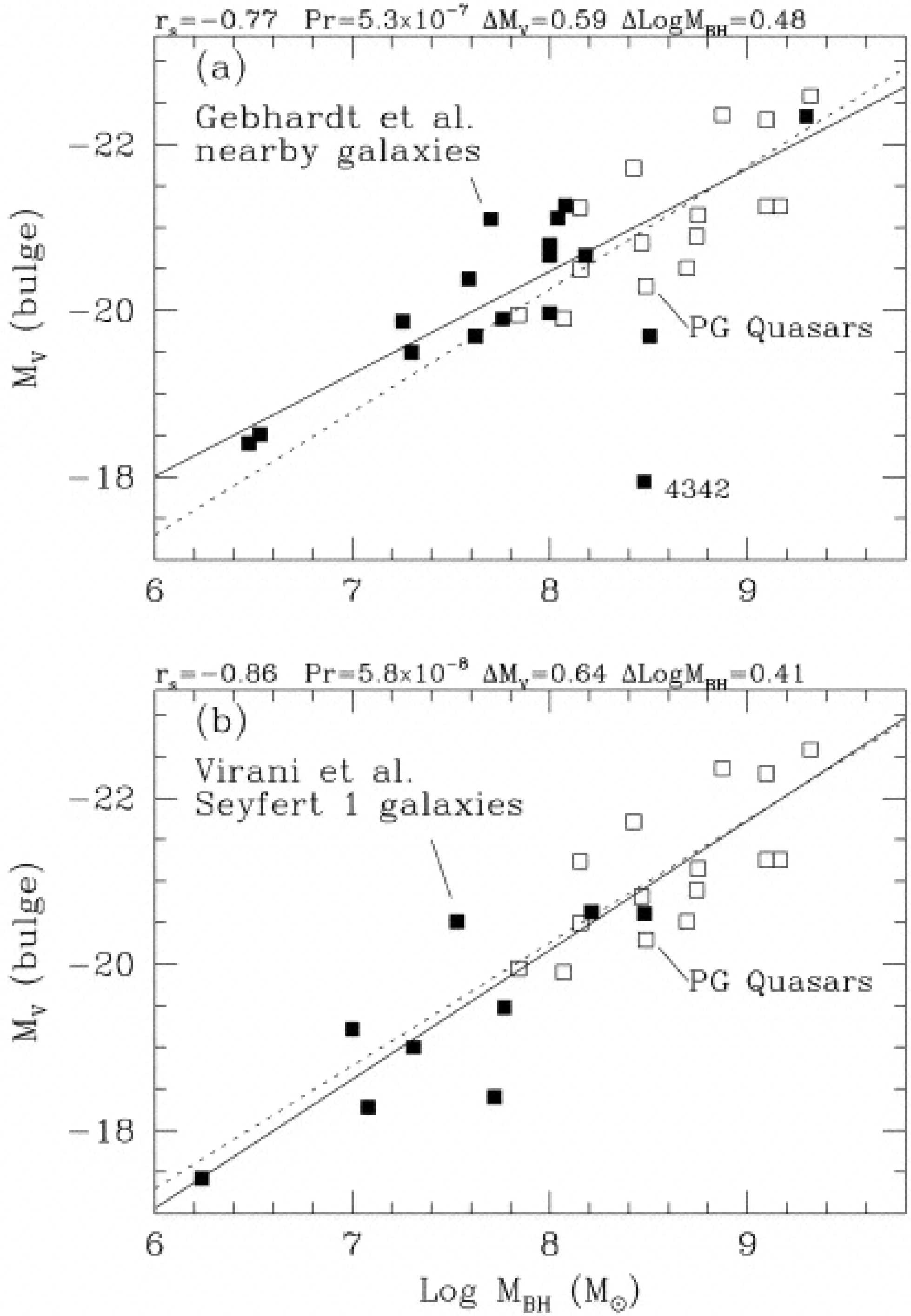
σ: バルジの速度分散



Tremaine et al. 2002, ApJ, 574, 740

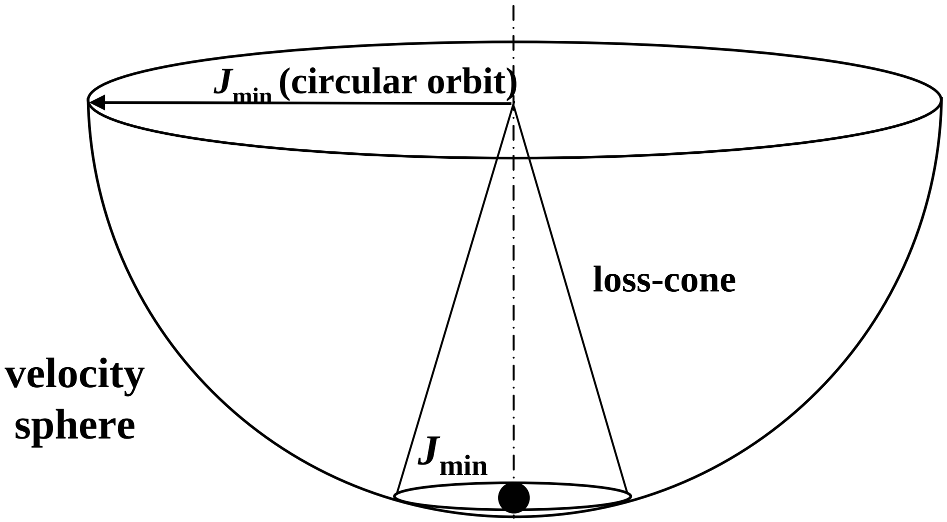
クェーサー

Laor 2001, ApJ, 553, 677



Direct Capture of Stars

Adams et al. 2003, ApJ, 591, 125



stellar density

$$\rho = \frac{\sigma_V^{\,2}}{4\pi G r^2}, \quad M(r) = \frac{\sigma_V^{\,2}}{G} r$$

$$r_p = \frac{j^2}{2GM_{\rm BH}} = \frac{(GM_{\rm BH})^3 \Omega^2}{2\sigma_V^{\,4}}$$

spin parameter

$$\lambda = \frac{J\left|E\right|^{1/2}}{GM^{5/2}} = 0.035$$

direct capture

$$r_p < 4 r_S$$

$$\Rightarrow \; M_{BH} = \frac{4\sigma_V^{\,4}}{Gc\Omega} \approx 10^8 M_\odot \left(\frac{\sigma_V}{200\rm km/s}\right)^4$$

Tidal Disruption & Capture of Star by SMBH

Tidal disruption radius

$$\frac{GM_{BH}M_{\odot}}{r_{disr}{}^{3}} = \frac{GM_{\odot}}{R_{\odot}^{2}} \quad \Rightarrow \quad r_{disr} = R_{\odot}\left(\frac{M_{BH}}{M_{\odot}}\right)^{1/3}$$

Direct capture

$$J \le \frac{4GM_{BH}}{c}$$

$$r_{disr} < r_{S} \quad \Rightarrow \quad r_{disr} = \left(\frac{M_{BH}}{10^{8}M_{\odot}}\right)^{-2/3} r_{S}$$

$10^{8}M_{\odot}$以上のBHでは，星は潮汐破壊の前にBH horizonに吸い込まれる

←

輻射を出さない（AGNにならない）

QSO Luminosity Functionからの制限

Integration of QSO LF

$$\Omega_{BH}(\mathrm{QSO}) \approx 1.8 \times 10^{-6}$$

Yu & Tremaine 2002, MNRAS, 335, 965

$$\Omega_{BH}(\mathrm{QSO}) \approx (2.4 - 4.8) \times 10^{-6}$$

Marconi et al. 2004, MNRAS, 351, 169

SMBH-bulge mass relation at z=0

$$\Omega_{BH}(\mathrm{bulge}) \approx 2.1 \times 10^{-6}$$

$$\Downarrow$$

QSO BHの最終フェーズはガスアクリーションで太った

Relativistic Radiation Hydrodynamics

Equation of motion O(v/c)

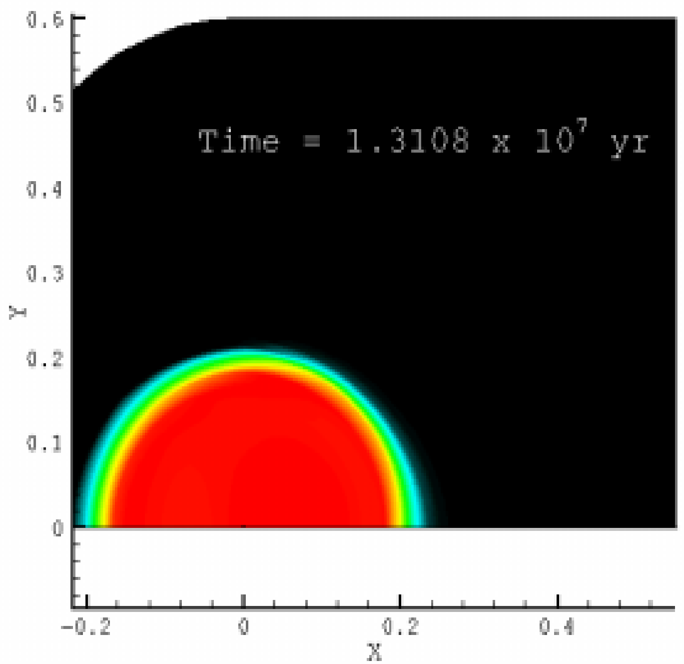
absorption

scattering

$$\rho \frac{d\mathbf{v}}{dt} = \boldsymbol{f} - \nabla p + \frac{1}{c}(\kappa_0 + \sigma_0)\left[\mathbf{F} - (E + \mathbf{P})\mathbf{v}\right]$$

Radiation drag

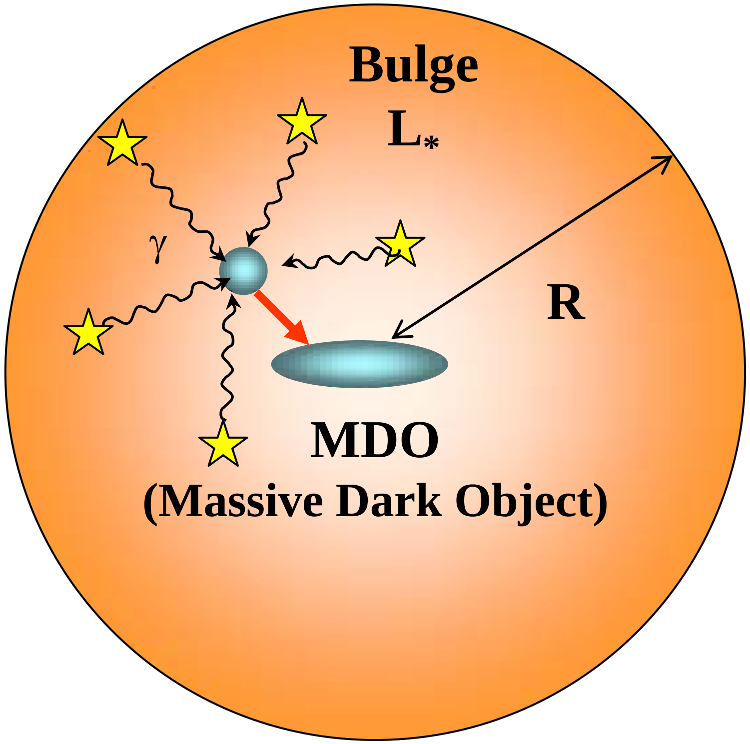
e.g. Poynting-Robertson effect in solar system



Sato, MU, Sawada, Matsuyama, 2004, MNRAS, 354, 176

SMBH Formation by Radiation Drag in Bulge

Umemura, 2001, ApJ, 560, L29
Kawakatsu & Umemura, 2002, MNRAS, 329, 572



Angular Momentum Extraction

Poynting-Robertson Effect

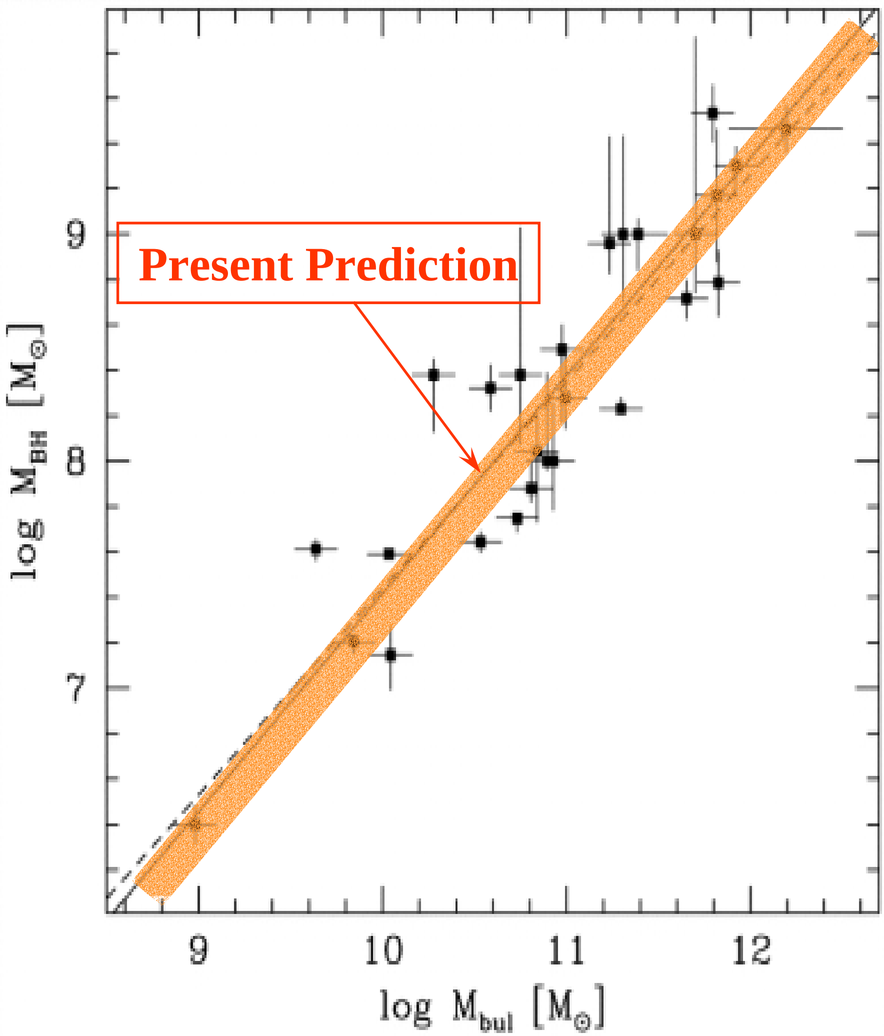
$$\frac{d\ln J}{dt} \simeq -\frac{\chi E}{c} \simeq -\frac{\chi L_*}{c^2 R^2} = -\frac{L_*}{c^2 M_g}\left(1-e^{-\tau}\right)$$

(τ: optical depth by dust)

photon number conservation

Mass Accretion Rate

$$\dot{M} \equiv -M_g \frac{d\ln J}{dt} \simeq \frac{L_*}{c^2}\left(1-e^{-\tau}\right)$$

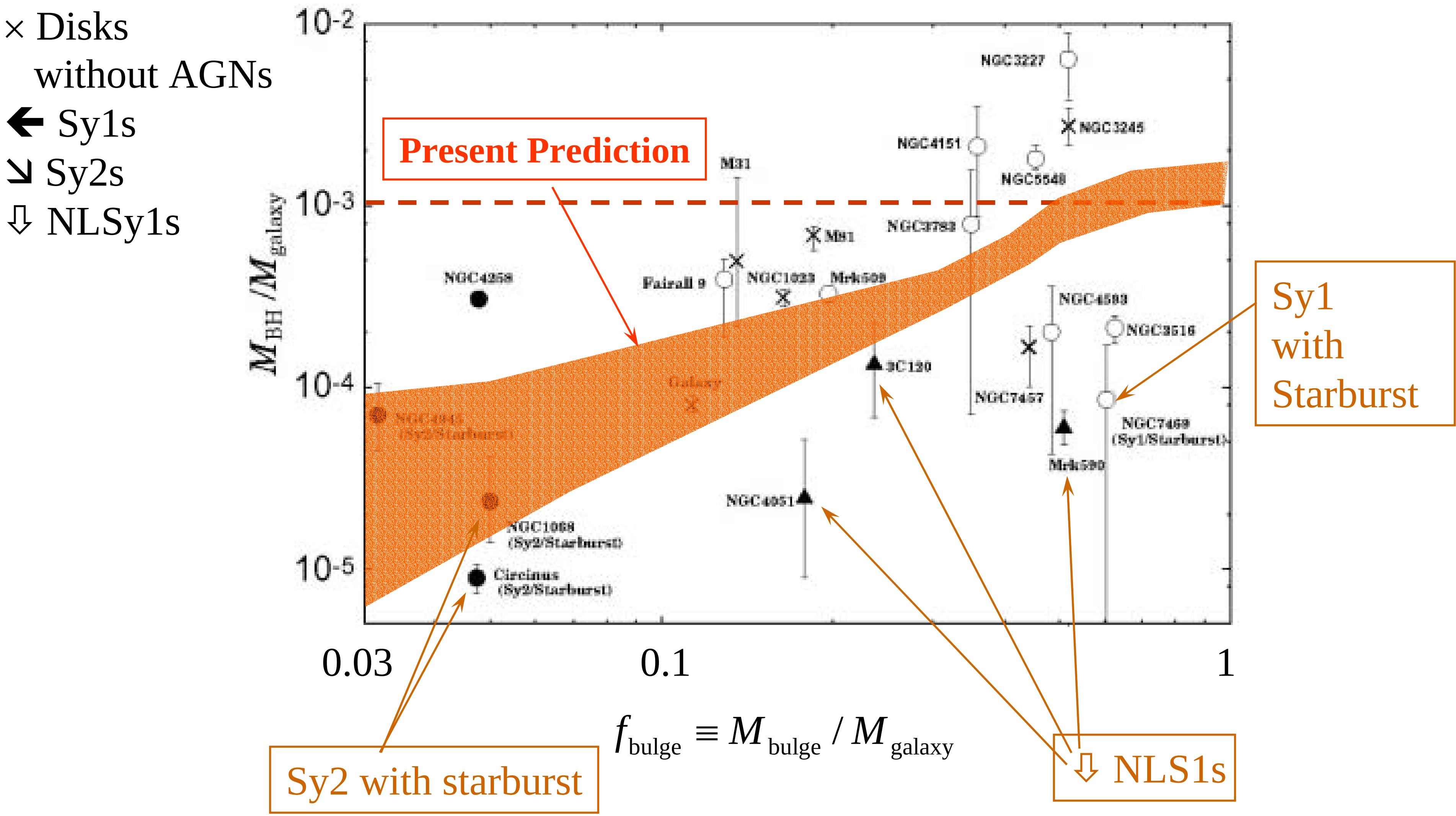


$$\frac{M_{BH}}{M_{bulge}} \approx 0.14\varepsilon = 0.001$$

ε = 0.007 : Hydrogen burning energy conversion efficiency

$$(e_{rad} = l_* t_* \approx 0.14\varepsilon \cdot m_* c^2)$$

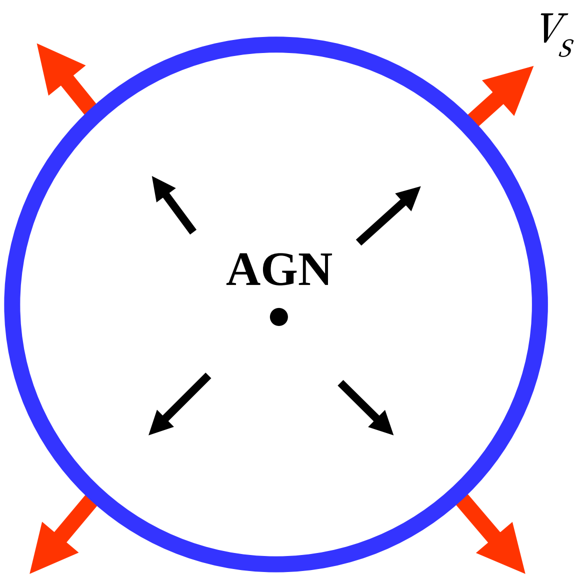
Why small BHs in disks?



Kawakatu & Umemura 2004, ApJL, 601, L21

AGN Feedback Regulation

Silk & Rees 1998, A&A, 331, L1



gas density

$$\rho = f_{gas}\frac{\sigma^2}{2\pi G r^2},\ M(r) = f_{gas}\frac{2\sigma^2}{G}r$$

velocity of expanding shell driven by AGN

$$V_s = \left(\frac{8\pi^2 G f_w L_E}{f_{gas}\sigma^2}\right)^{1/3}$$

feedback condition

$$V_s > \sigma\ (=\sqrt{2}\sigma_V)$$

$$\Rightarrow\ M_{BH} = \frac{\sigma^5\kappa}{G^2 c} \approx 10^8 M_\odot \left(\frac{\sigma_V}{200\mathrm{km/s}}\right)^5$$

Downsizing

SMBH 大きなＢＨほど先にできた

Ueda et al. 2003, ApJ, 598, 886
Hasinger et al. 2003, astro-ph/0302574
Marconi et al. 2004, MNRAS, 351, 169
Merloni, 2004, MNRAS, 353, 1035

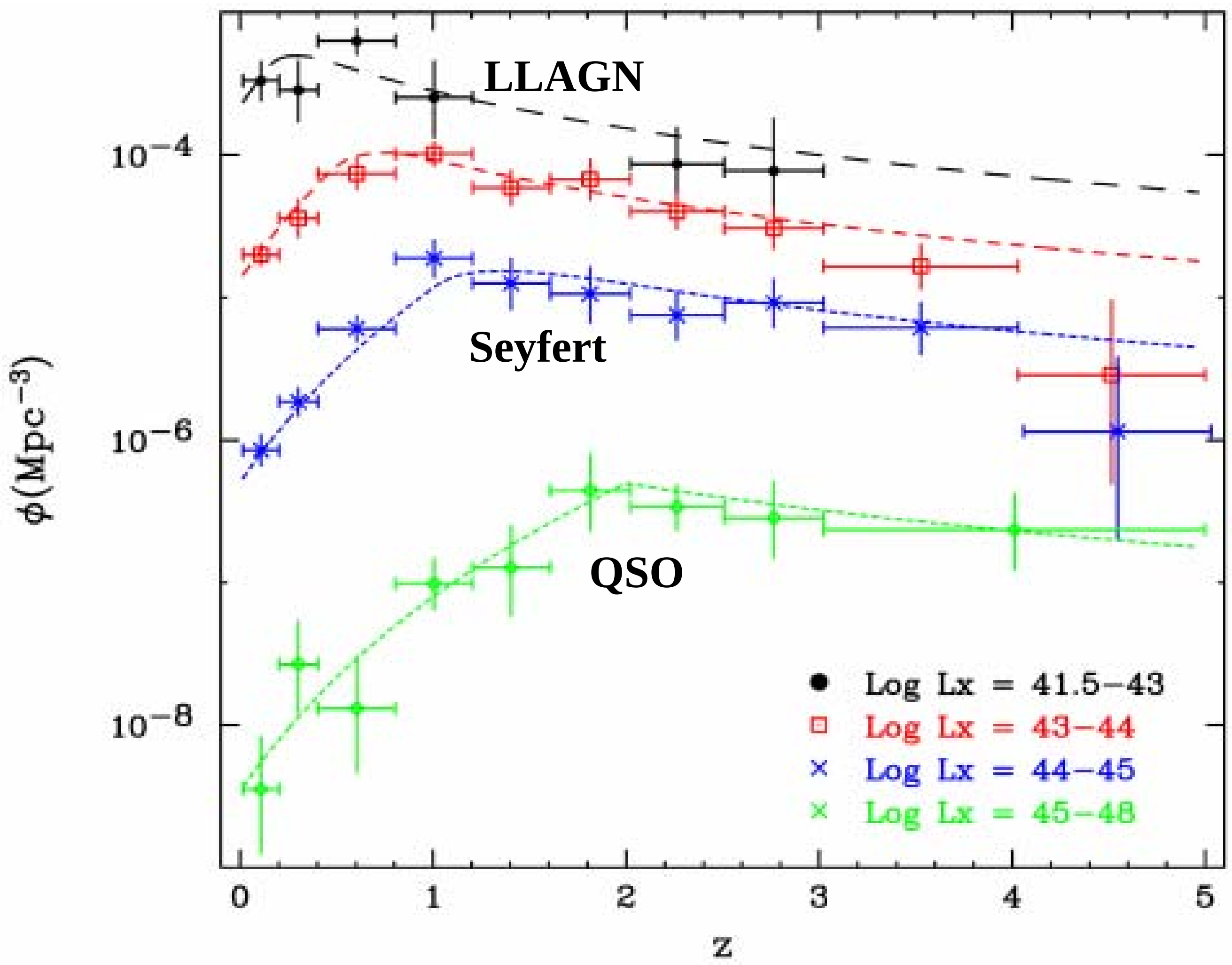
Galaxies 大きな銀河ほど先に生まれた

Cowie et al. 1996, AJ, 112, 839
Kauffmann et al. 2003, MNRAS, 341 54
Kodama et al. 2004, MNRAS, 350, 1005
Glazebrook et al. 2004, Nature, 430, 181

“Downsizing” in SMBH Formation

More massive BHs formed at higher redshifts.

Ueda et al. 2003, ApJ, 598, 886; Ueda et al. 2006



超巨大ブラックホールのダウンサイジング

+

SMBH-bulge 関係

=

重いバルジほど昔星形成を終了した

早期型銀河は早期に出来た

銀河と超巨大BH の共進化

ブラックホール形成と成長
課題

Seed BH

$M_{\mathrm{BH}} = 1 - 10^5 M_{\odot}$

SN/GRB remnant (Pop III remnant) (1-10^{3}M$_{\odot}$)
Supermassive star (10$^{4\text{-}5}$M$_{\odot}$)

ガス降着(Super/Sub-Eddington)

合体成長 $t \approx 10^8\,\mathrm{yr}$

$M_{\mathrm{BH}} = 10^6 M_{\odot}$

ガス降着 $t \approx 10^{7-9}\,\mathrm{yr}$

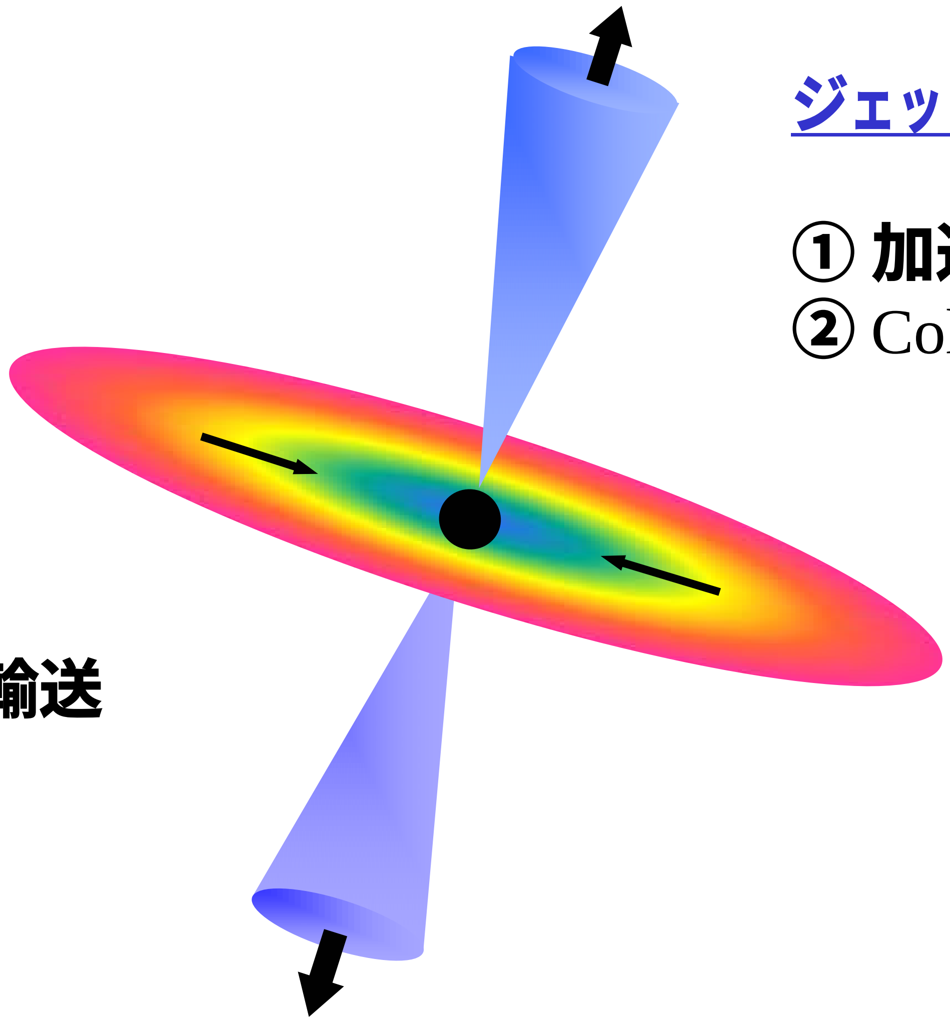
$M_{\mathrm{BH}} = 10^{8-9} M_{\odot}$

銀河との共進化

銀河スケールからサブパーセックへのアクリーション

Part 2　降着円盤＆ジェット

Accretion & Jet



ジェット

① 加速メカニズム
② Collimation

降着円盤

①角運動量輸送
②定常解

α-Prescription

viscosity coefficient $\nu = \alpha c_s^2 \Omega^{-1}$

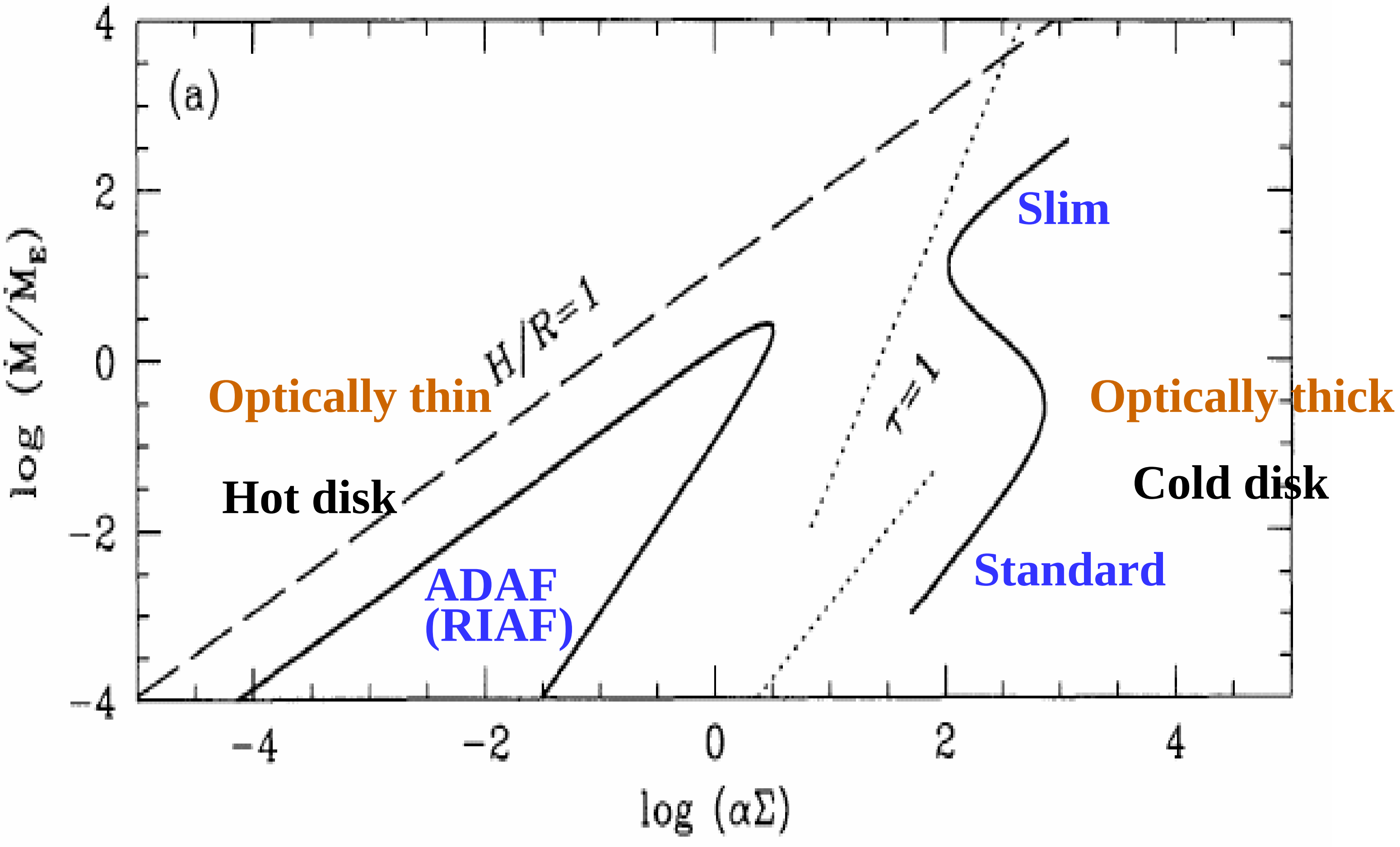
角運動量輸送

$$\frac{dJ}{dt} = -\frac{d}{dr}\left(\frac{\alpha c_s^2}{\Omega} r \frac{dv_\varphi}{dr}\right) \quad \left(= -\frac{\alpha c_s^2}{2} \text{ for Kepler}\right)$$

分子粘性: α≈10^{-10}
乱流粘性(K-H shear 不安定): α≈10^{-4}
磁気粘性: α≈10^{-2} - 1

Accretion Flows

Abramowicz et al. 1995



Accretion Flows

$$L = \eta \dot{m} \dot{M}_{\mathrm{E}} c^2, \quad \dot{M}_{\mathrm{E}} = 10 L_E / c^2 = 10 \cdot \frac{4\pi G c m_p M}{\sigma_T c^2}$$

① Sub-Eddington: ADAF(Advection-Dominated Accretion Flow)

RIAF (Radiatively Inefficient Accretion Flow)

high energy photons (strong X-ray)

$$\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\mathrm{E}}} = 1 \quad \Rightarrow \quad \eta \approx 0.1 \dot{m}$$

② Eddington: Standard Disk

low energy photons

$$\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\mathrm{E}}} \approx 1 \quad \Rightarrow \quad \eta \approx 0.1$$

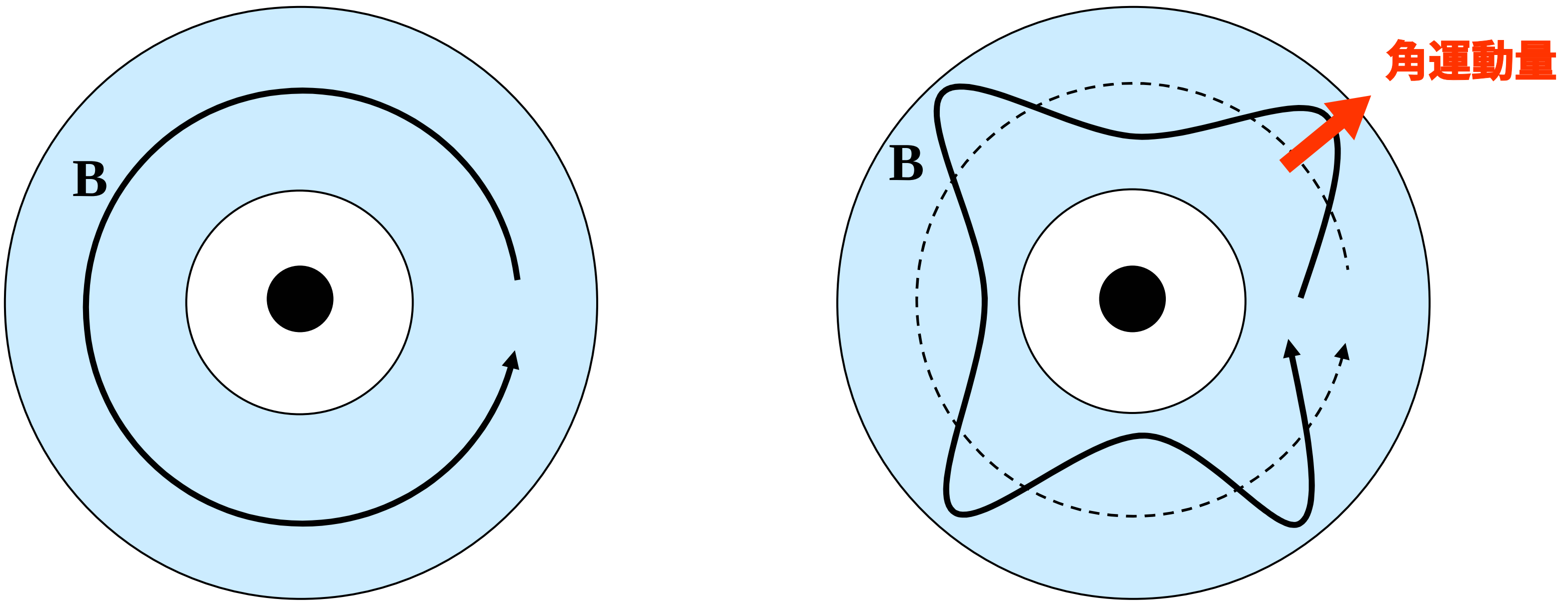
③ Super-Eddington: Slim Disk (Photon trapping)

lower energy photons

$$\dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\mathrm{E}}} > 1 \quad \Rightarrow \quad \eta \approx 0.1 \dot{m}^{-1/2}$$

MRI (Magneto-Rotational Instability)

(Velinhov 1959, Chandrasekhar 1961, Balbus & Hawley 1991)



重力 $= \dfrac{GM\rho}{r^2}\left(1 + 2\dfrac{dr}{r}\right)$　　**遠心力** $= (r - dr)\rho\Omega^2$　　**磁気張力** $= 2B^2 dr\left(\dfrac{\lambda}{4}\right)^{-2}$

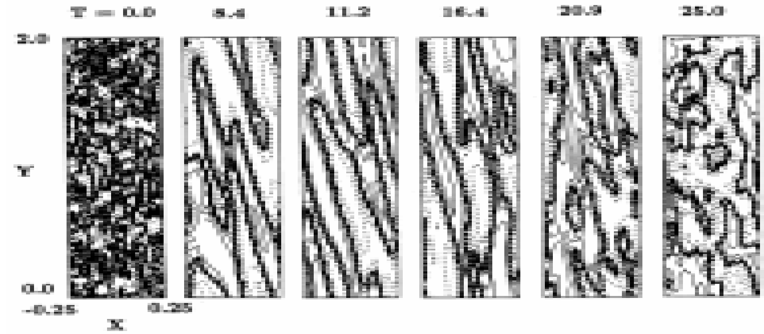
($\Omega =$ **一定**)

<u>不安定条件：　重力＋遠心力＞磁気張力</u>

$$\lambda > 4\sqrt{\frac{2}{3}}c_A\Omega^{-1}$$ (c_A =Alfven velocity)

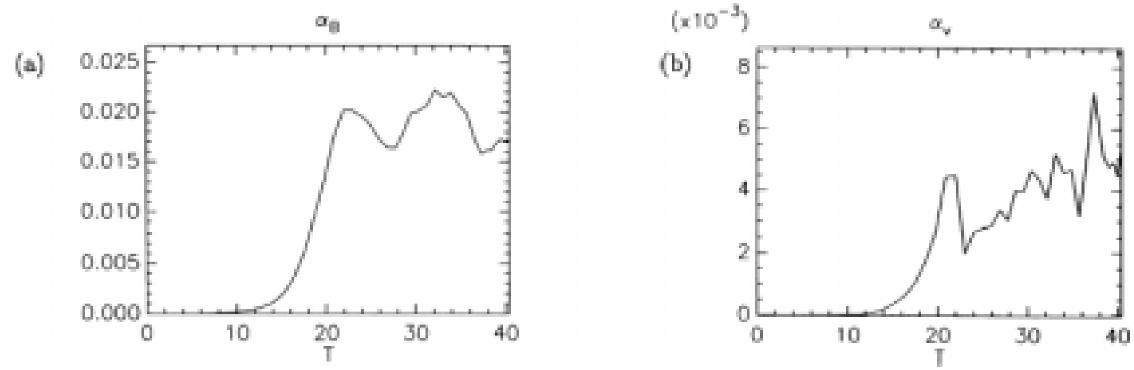
Magnetic Viscosity

Matsumoto & Tajima 1995, ApJ, 445, 767

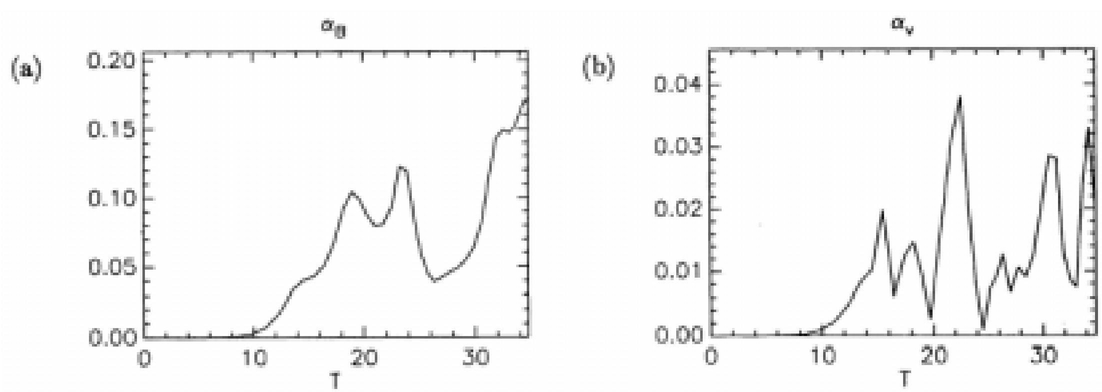


$$\alpha_B = \langle B_x B_y \rangle / 4\pi P \qquad \alpha_V = \rho \langle v_x v_y \rangle / P$$

toroidal field model



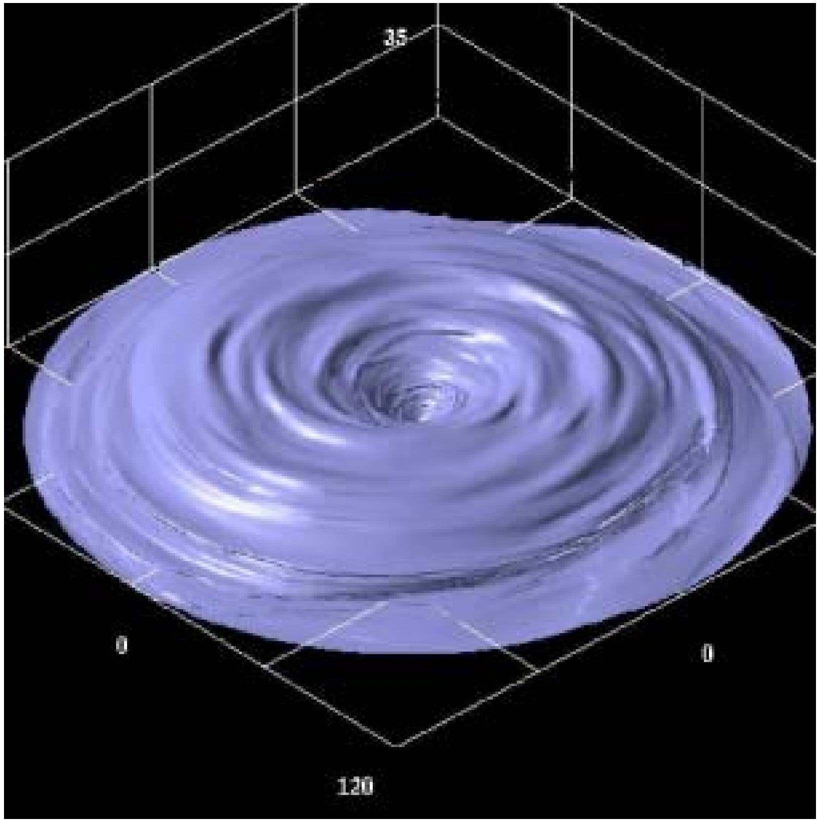
vertical field model



MHD Simulation of ADAF

Machida, Nakamura, Matsumoto, 2004, PASJ, 56, 671

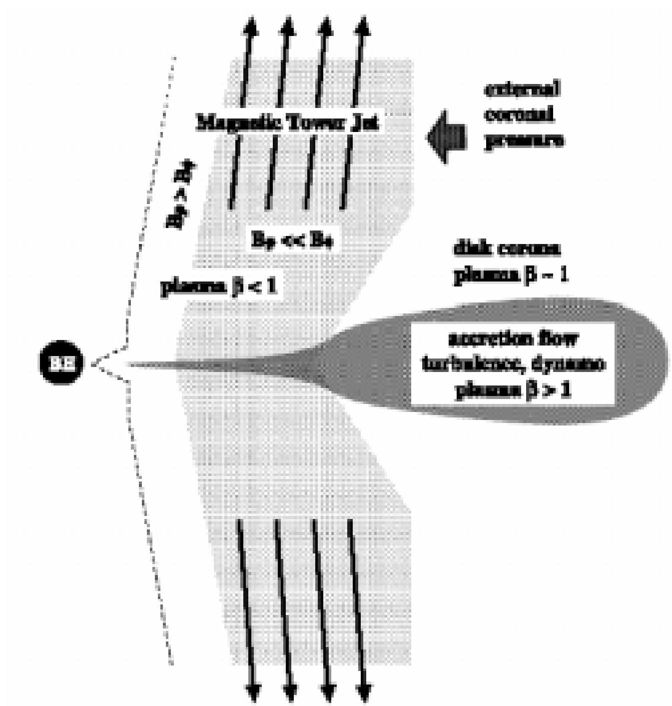
光学的に薄いaccretion flow
の global structure についてMHD計算

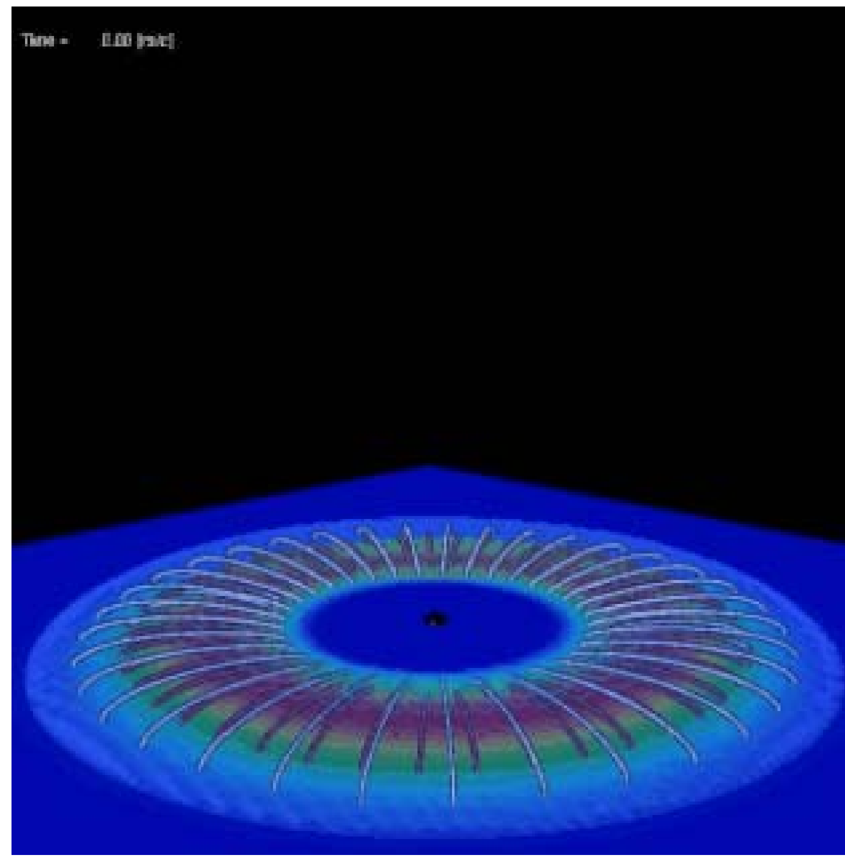


<15r_g で, optically-thin
hot disk を形成
||
ADAF解に一致

Magnetic-Tower Jet

Lynden-Bell, 1996, MNRAS, 279, 389
Kato, Mineshige, Shibata, 2004, ApJ, 605, 307



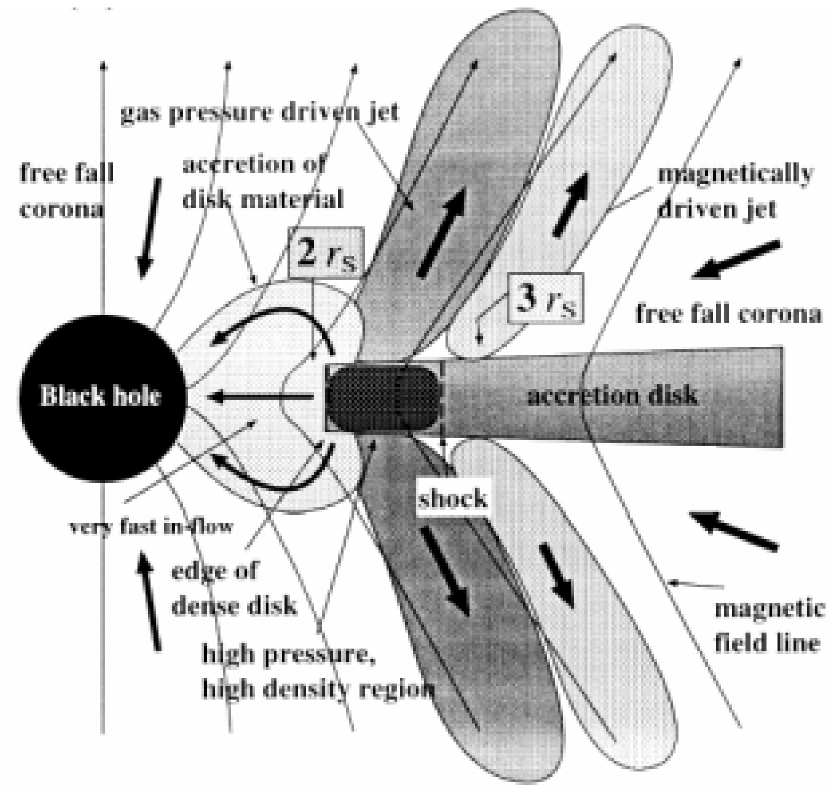


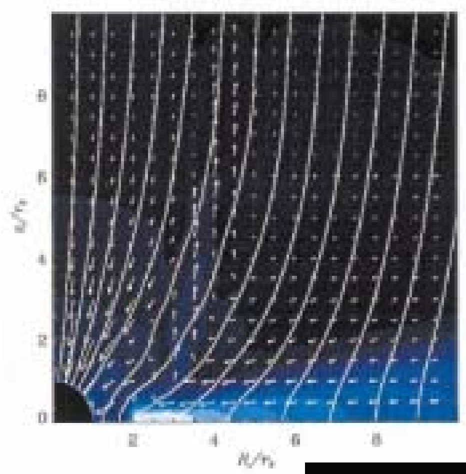
MRI → 強いトロイダル磁場形成と浮上
→ 磁気タワー形成
→ 磁気圧によりジェット加速（≈ 0.5c）

Y. Kato et al. 2004

GR-MHD

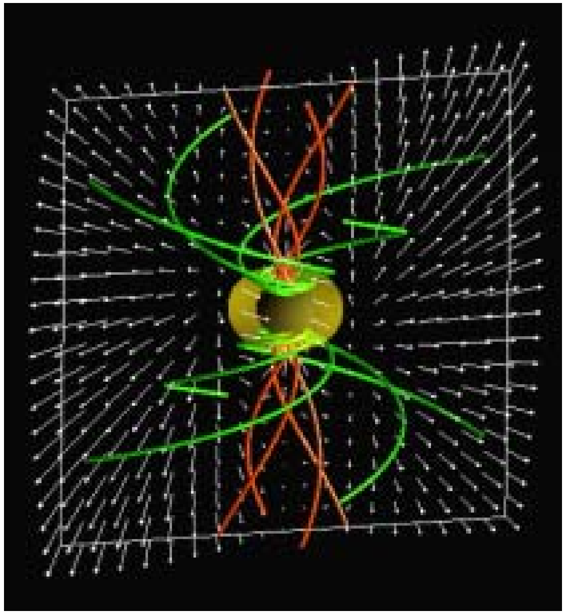
Koide, Shibata, Kudoh, 1999, ApJ, 522, 727 (Schwartzshild)
Koide, 2004, ApJ, 606, L45 (Kerr)





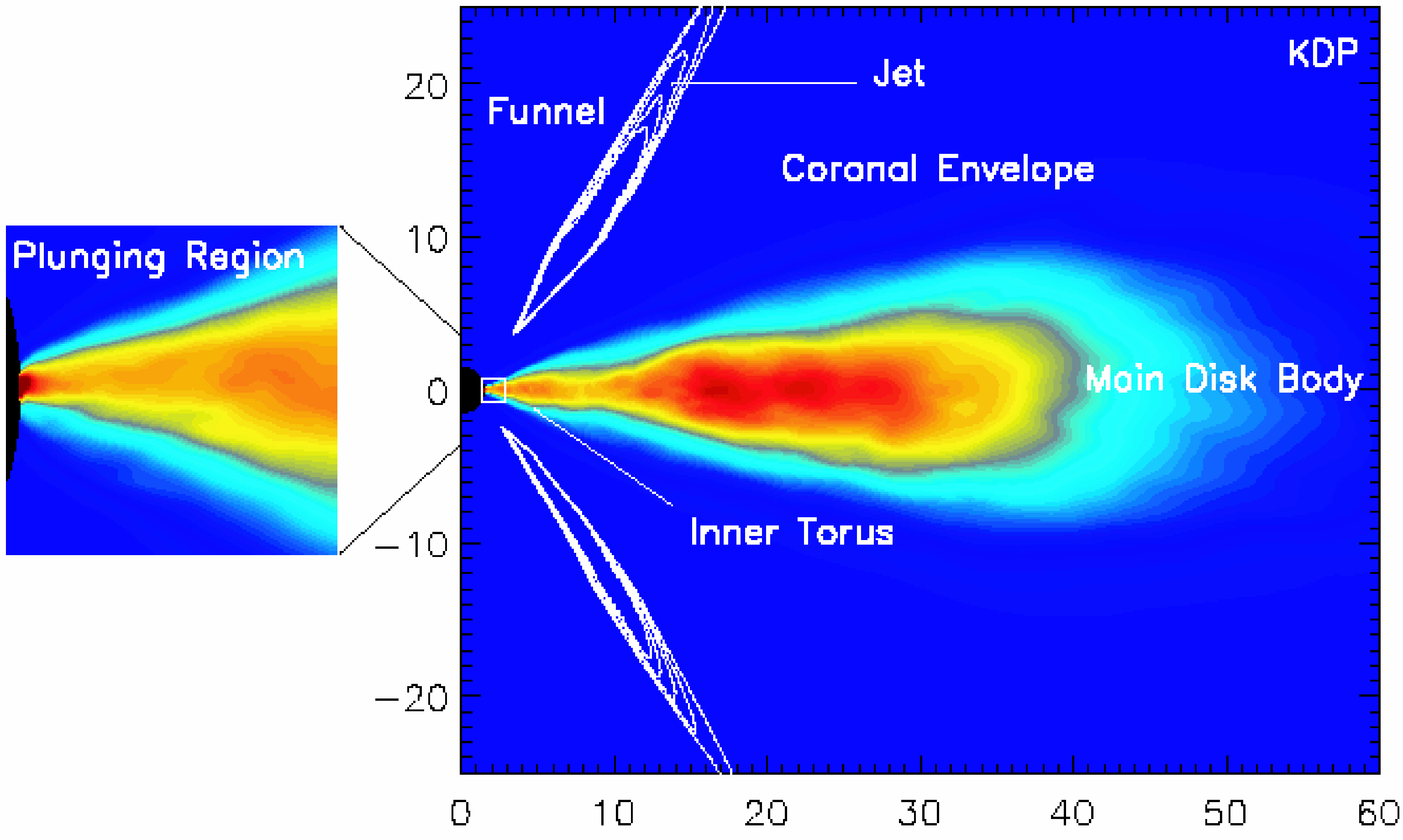
Schwartzshild

Kerr



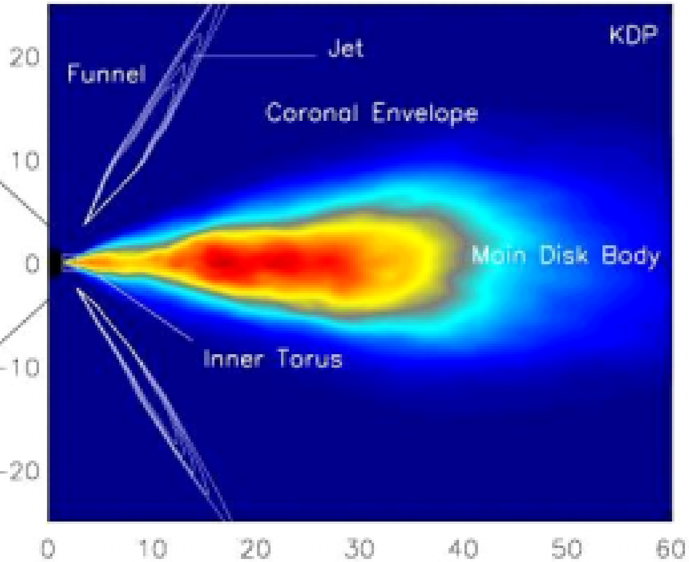
Accretion Flow around Kerr BH

De Villiers et al. 2003, ApJ, 599, 1238



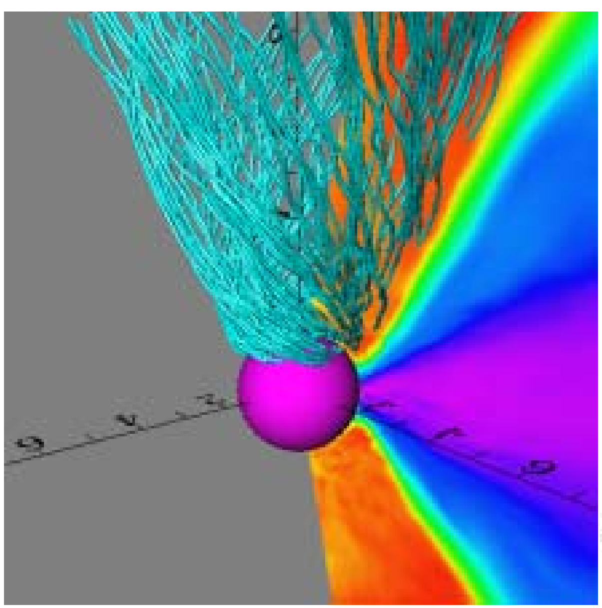
MHD Jet around Kerr BH

Hawley & Krolik 2006, ApJ, 641, 103



BH spin によってToroidal 磁場が生成
→ 外向きのPoynting flux
→ funnel wall に沿ってout-flowを生成
~0.4 - 0.6 c

BH spin が上がるとoutflow増大



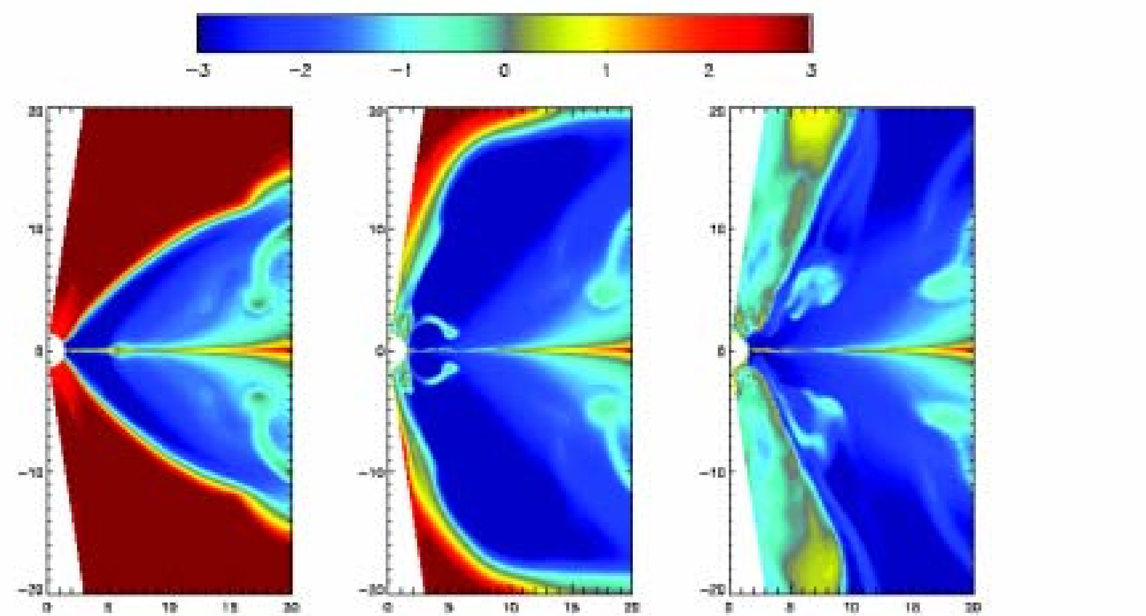


FIG. 2.—Ratio of the azimuthally averaged gas to magnetic pressure β at $t = 560M$, $640M$, and $720M$ in KDPg. The color contours are in a logarithmic scale: dark red is gas pressure–dominated ($\beta = 10^3$) and dark blue is magnetic field–dominated ($\beta = 0.001$).

Supercritical Accretion

- **高赤方偏移クェーサーからの要請**

  (Haiman 2004, astro-ph/0403225)

  SDSS QSO z=6.4, $M_{\rm BH} \approx 10^9 M_\odot$

$$t_{\rm growth} \simeq 7 \times 10^8 \eta_{0.1} \ {\rm yr}$$

$$t_{\rm H} \simeq 9 \times 10^8 \ {\rm yr \ at} \ z=6$$

$$\Rightarrow \dot{m} \equiv \frac{\dot{M}}{\dot{M}_{\rm E}} > 1$$

- **Narrow Line Sy 1 & Narrow Line QSOs**

  (Kawaguchi et al. 2004, A&A, 420, 23L)

  $<10^8 M_\odot$ **のBH成長は,** Super-Eddington

Slim Disk Model for NLS1

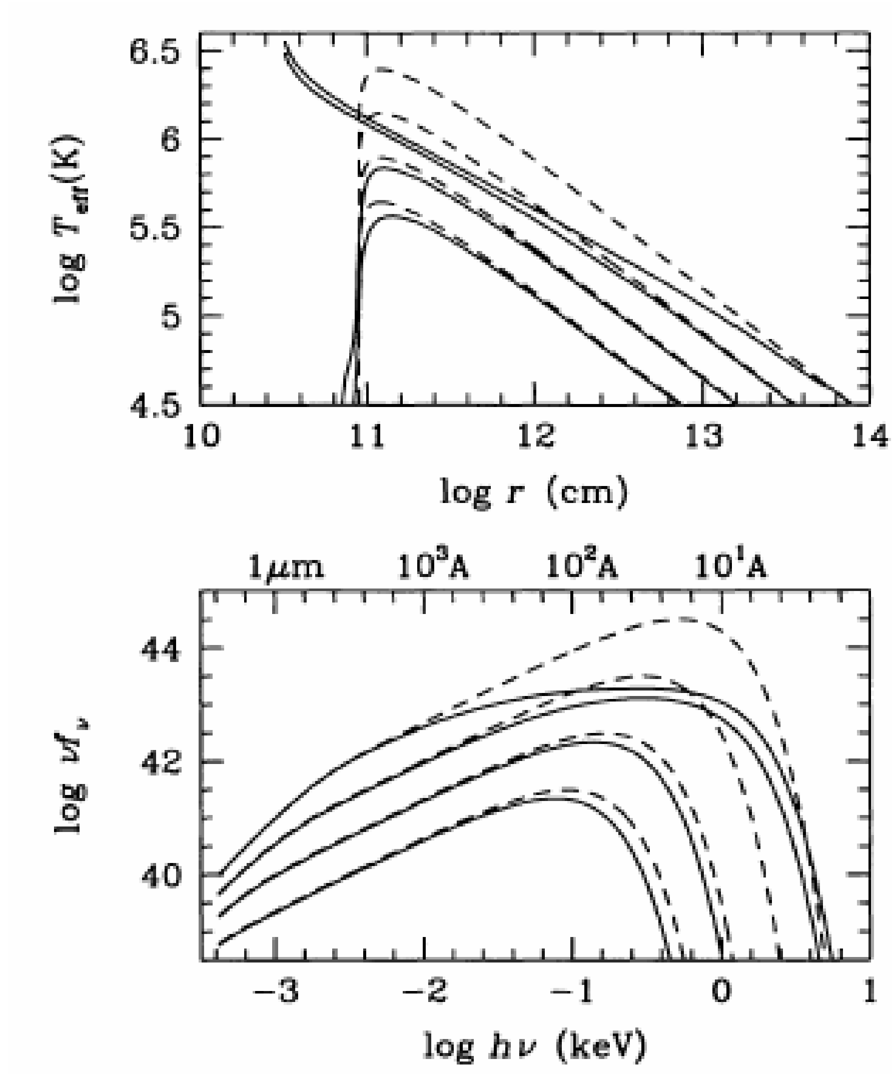
Mineshige et al. 2000, PASJ, 52, 499

Multi-color spectra

NLS1**の観測は**

$\dot{m} > 10$

で説明できる



Photon Trapping in Supercritical Accretion

mass accretion: $t_{acc} = r / v_r, \quad \dot{M} = 2\pi r v_r \Sigma$

photon diffusion: $t_{diff} = h / (c / 3\tau), \quad \tau = \sigma_T \Sigma / 2m_p$

photon trapping condition: $t_{acc} < t_{diff}$

$$\left(\frac{\dot{M}}{\dot{M}_E}\right) > 2\left(\frac{r}{3r_S}\right)\left(\frac{h}{r}\right)^{-1}$$

Supercritical accretion では, photon trapping が起こる
Outflow ⇒ BH accretion rate はどこまで上がれるか

大須賀氏講演

Accretion Disk & Jet
課題

- 磁気粘性ディスクとスペクトル

- 磁場の回転と, BHスピンで, どの程度の angular momentum と mass がoutflowで運ばれるか

- BH mass accretion rate は, どこまで大きくなれるか

⇓

RMHD (Radiation Magneto-Hydrodynamics)が必要

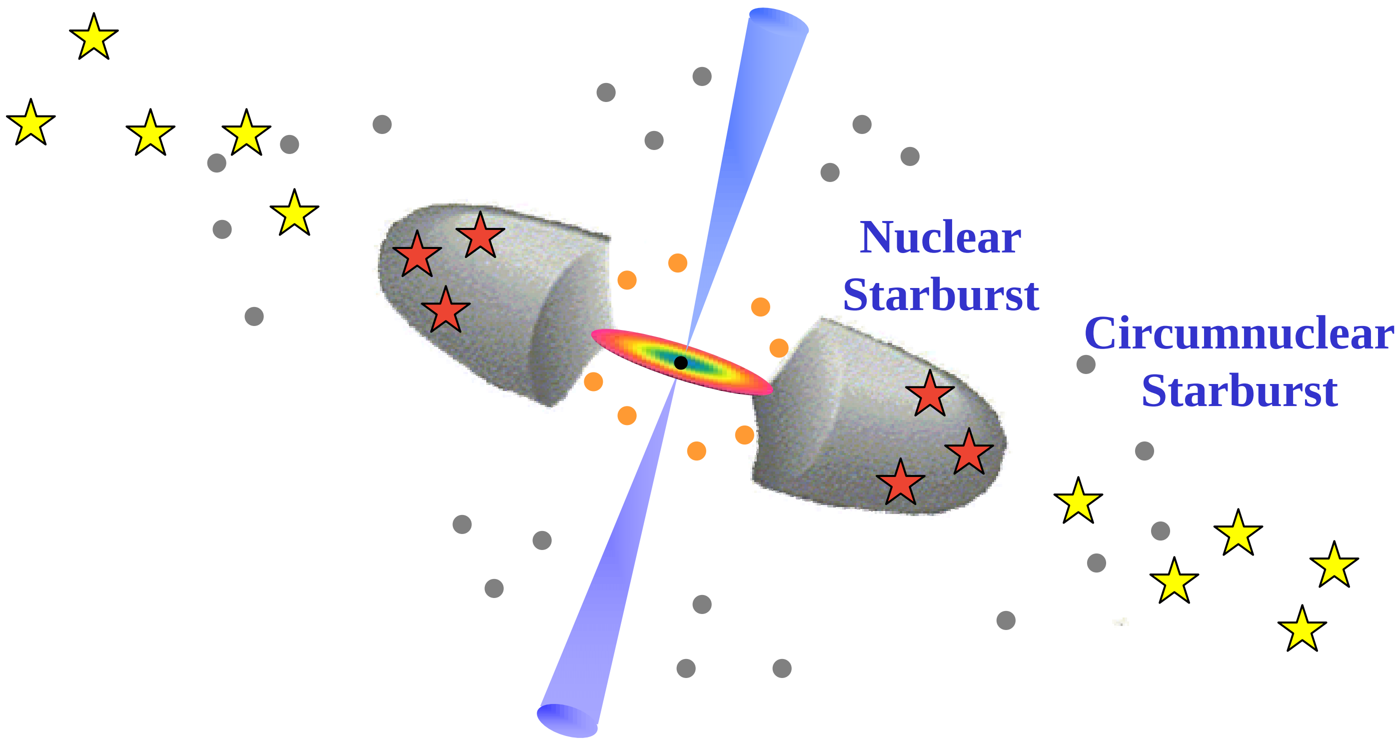
Part 3　遮蔽とAGNタイプ

AGN-Starburst Connection

① Circumnuclear Starburst (数10pc-1kpc) は2型に多い

② Nuclear Starburst (1-10pc) は1型, 2型にあまりよらない
(Hidden Starburst)

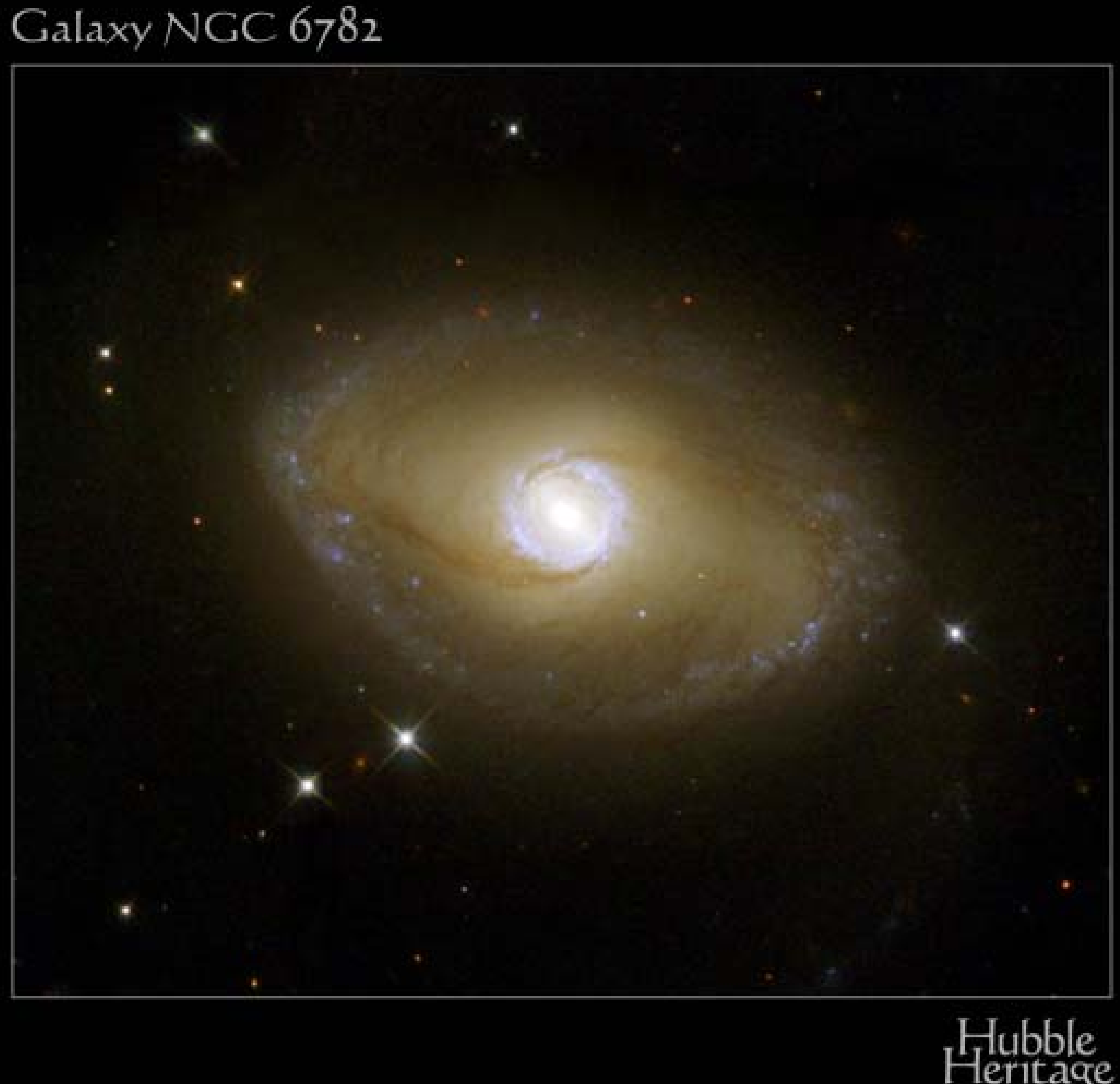
単純なトーラスモデルでは説明がつかない！



Starburst Rings

NGC1300

NGC6782

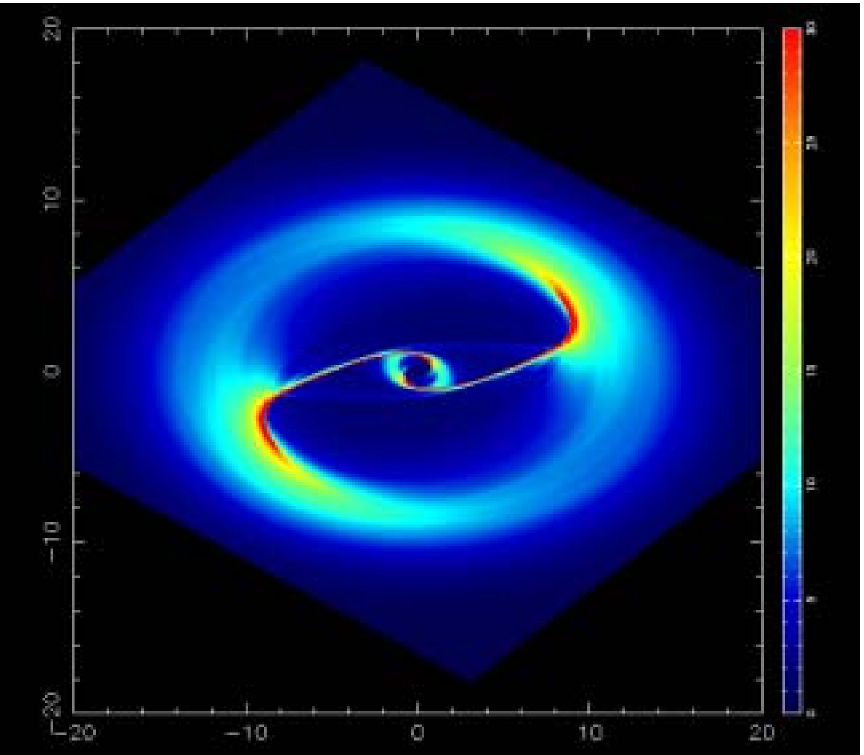


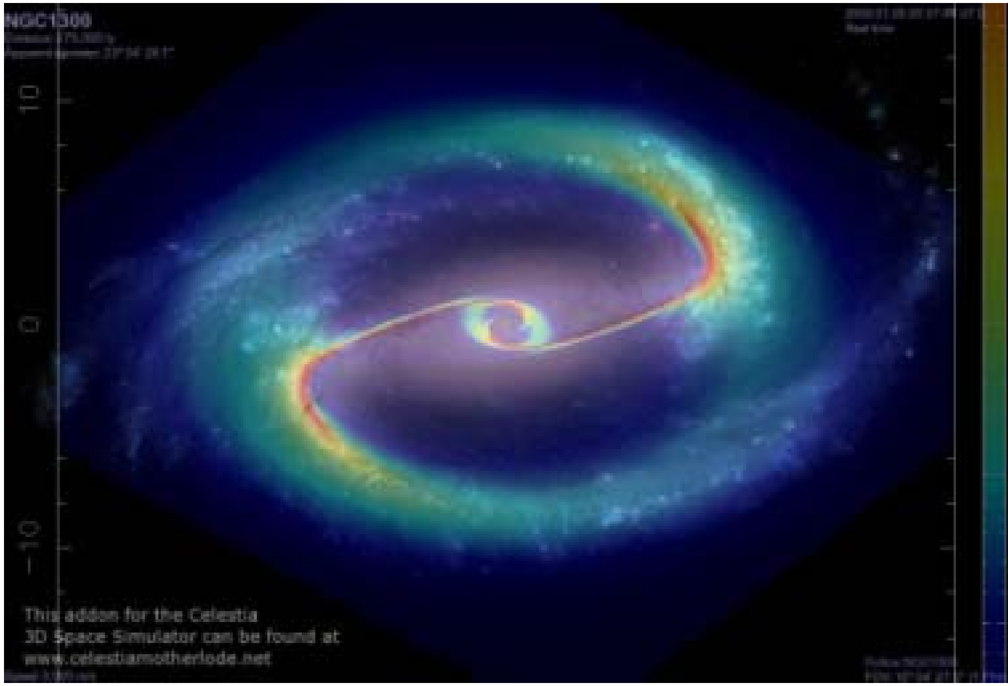
NGC1300

Yen et al 2006

OILR=8.62kpc

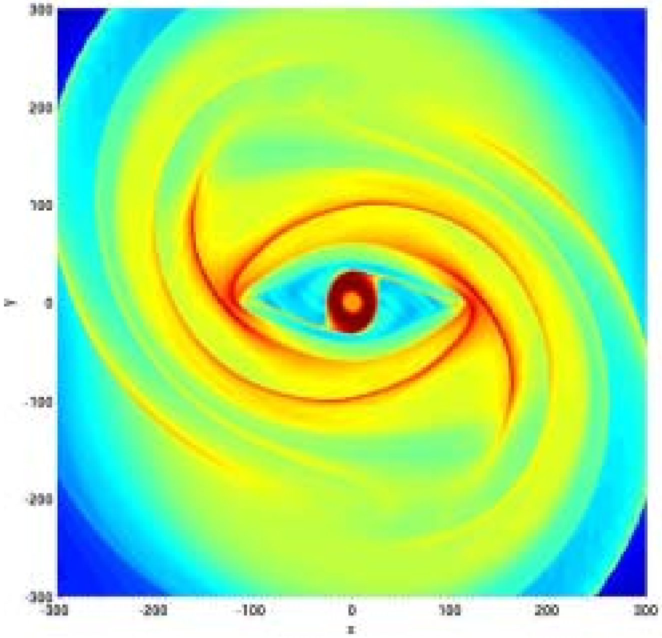
$$\Omega_p = 4.1\ km/s \cdot kpc$$



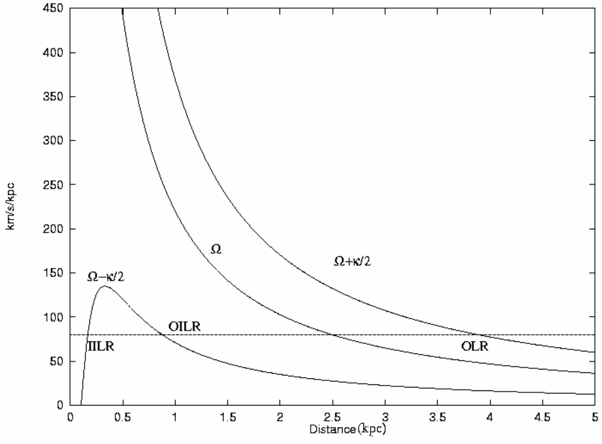


Double Ring Feature

Yen et al 2006



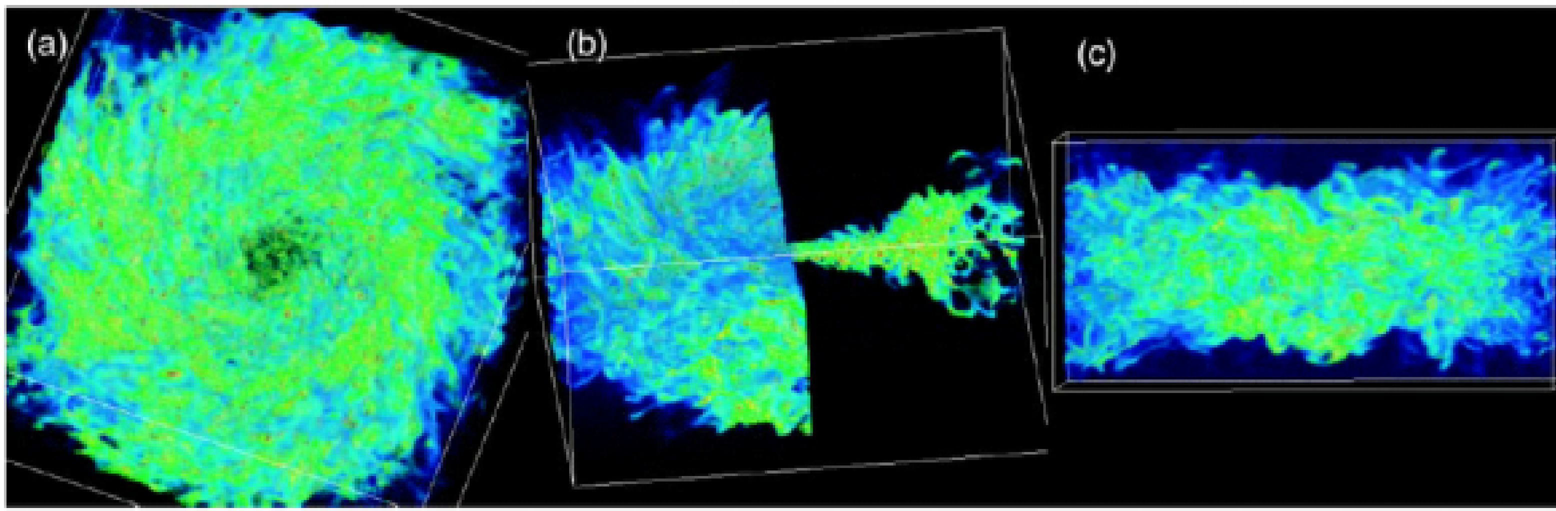
OLR & OILR

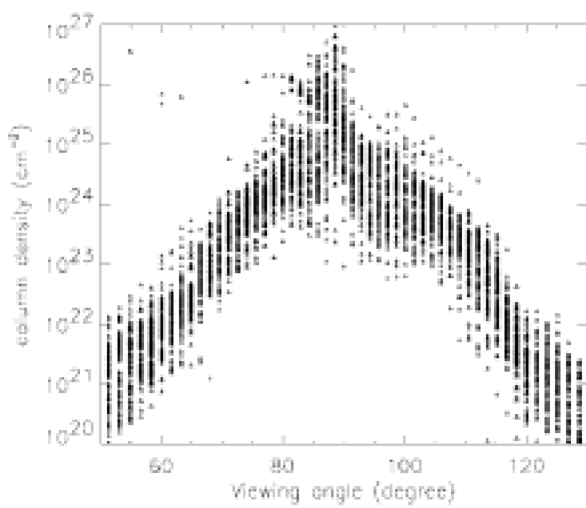


Turbulent-Supported Obscuring Torus

Wada & Norman, 2002, ApJ, 566, L21

SN feedback による遮蔽トーラス形成と乱流粘性発生





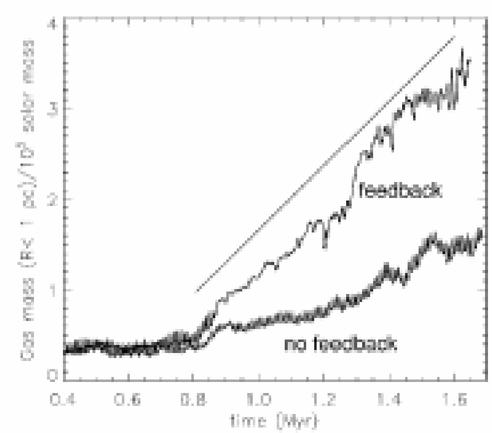


FIG. 3.—Time evolution of the gas mass inside $R < 1$ pc for two models (with and without energy feedback). Solid line represents the mass accretion rate 0.3 $M_{\odot}$ yr^{-1}.

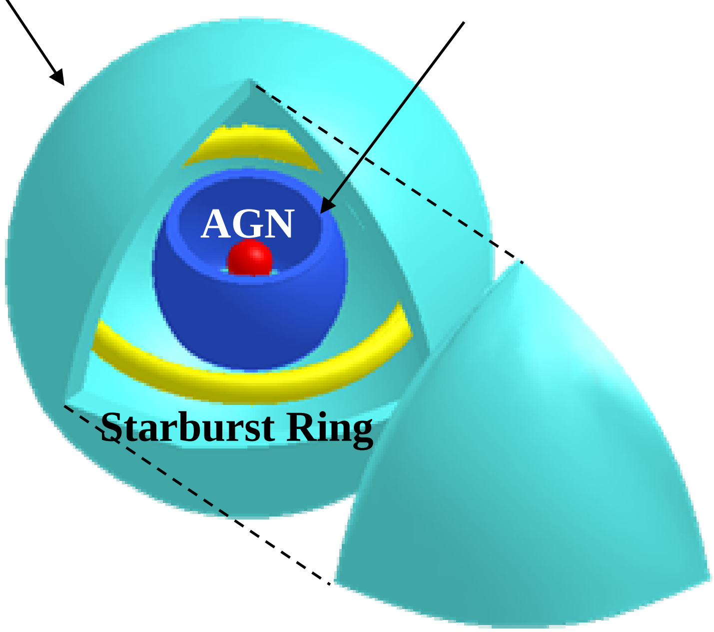
Obscuring Wall Model

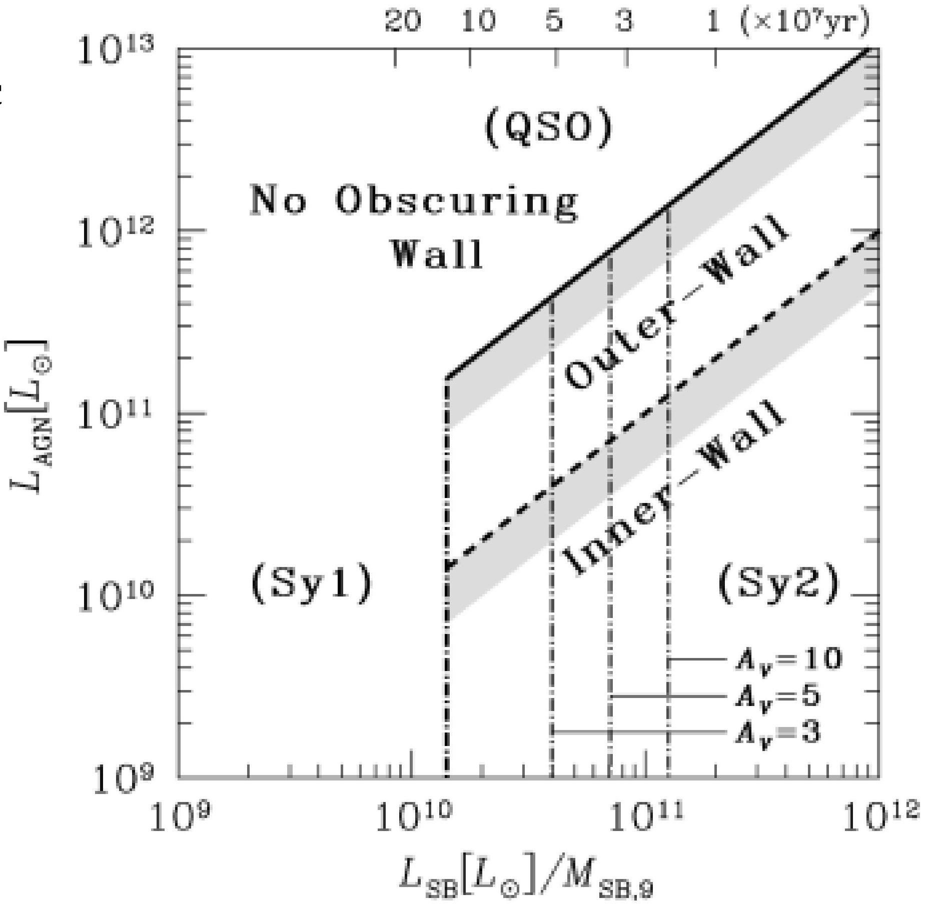
Ohsuga & MU, 2001, ApJ, 559, 157

スターバーストの輻射圧で形成される Stable Gas Wall
AGNが明るくなると平衡解はなくなる（QSO）

Outer Obscuring Wall
Size ~ several 100pc
A_V **~ 1**

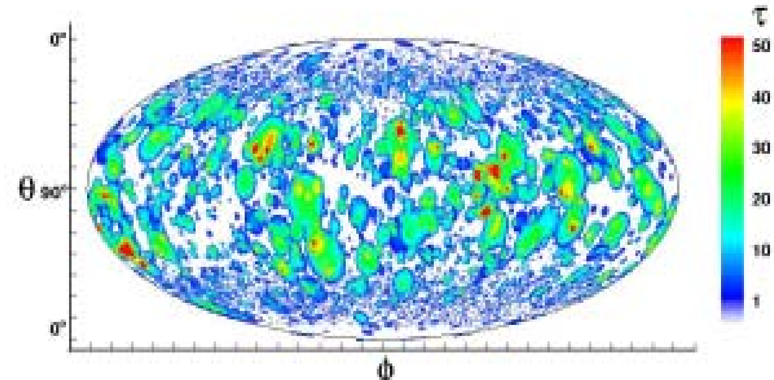
Inner Obscuring Wall
Size ~ several 10pc
A_V **~ several - 10**





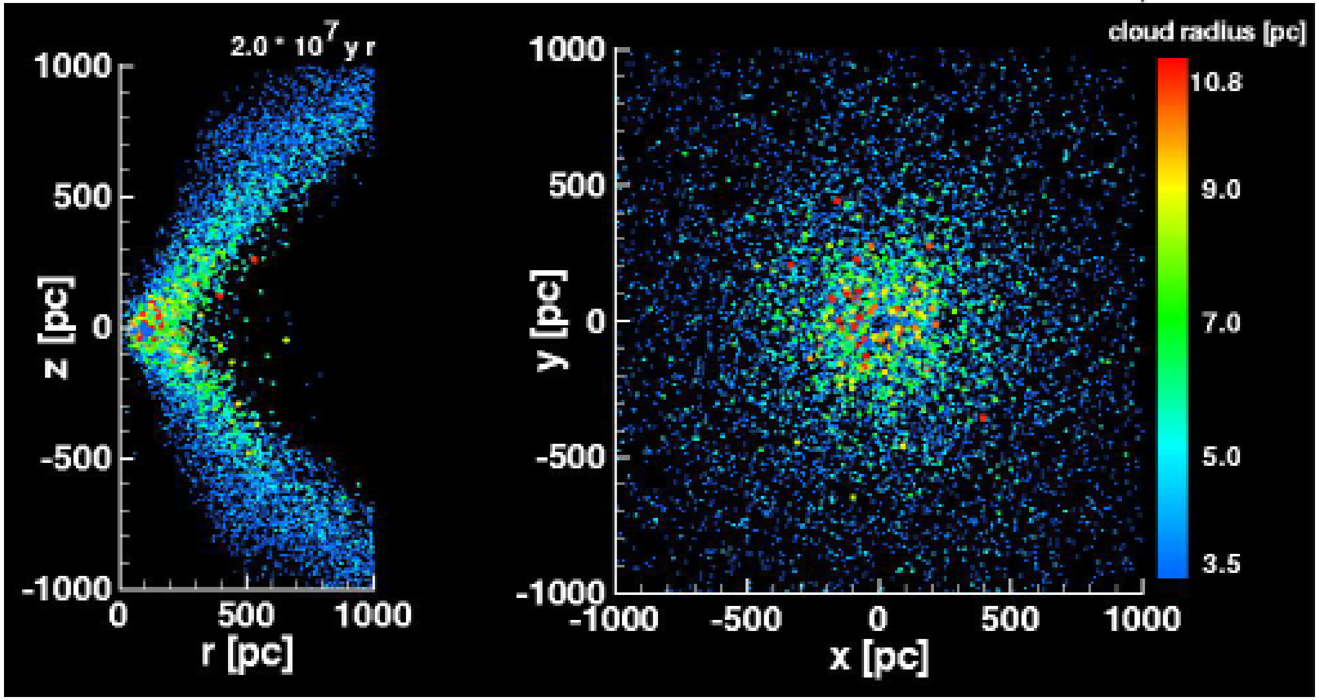
Radiation-Pressure Driven Obscuring Clouds

Watabe & MU, 2005, ApJ, 618, 649



スターバースト輻射圧によるガス雲の巻上げと非一様遮蔽構造発生

$A_V \sim$ **1-50**



遮蔽 & AGNタイプ
課題

- スターバーストとAGN遮蔽, AGN活動の関係は？

- 観測
  可視光　$A_V \sim$ 1-10
  X線　$A_V \sim$ 100
  遮蔽は一元論でよいか

- ブラックホール降着とどのように関係しているか

Conclusions

① 超巨大ブラックホール

key physics はかなりわかってきた

銀河スケールからサブパーセックまでつながったわけではない

② 降着円盤＆ジェット

磁気粘性降着円盤のモデルが確立しつつある

輻射の役割はまだ十分にわかっていない

③ 遮蔽&AGNタイプ

単純なトーラスモデルは行き詰まっている（？）

スターバーストとの関係

ブラックホールへの降着との関係

END