吸积与喷流物理

袁 峰

复旦大学天文与天体物理中心

天关卫星时代的X射线天文学 2025.8.19 云南大学

Outline

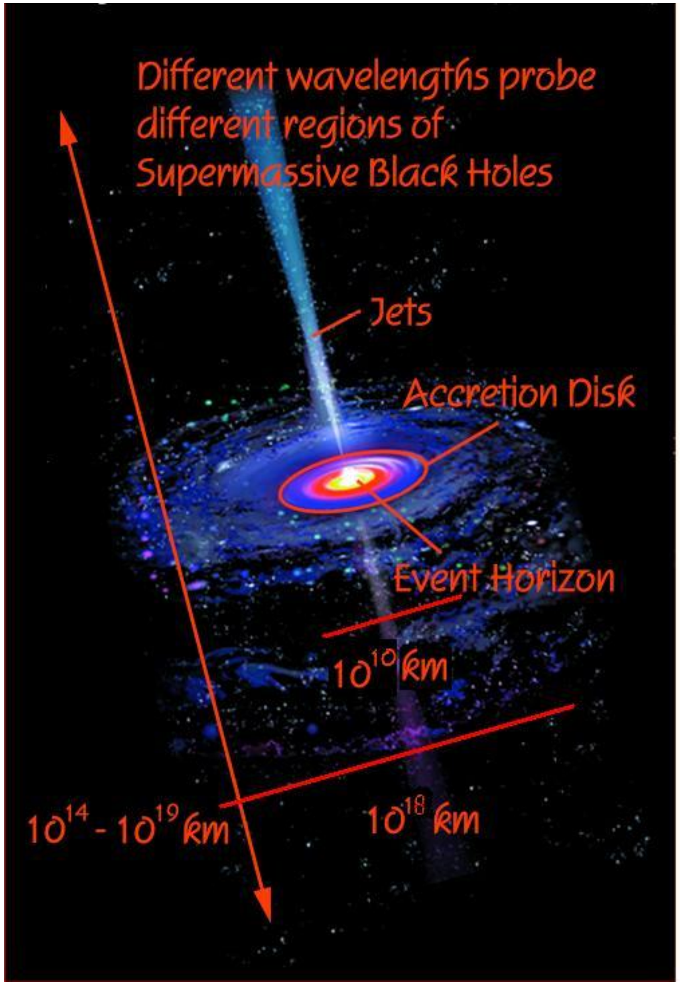
- Hot accretion flows
  - Dynamics & radiation
  - Wind & jet
  - Applications: Sgr A* & Fermi bubble
- Standard thin disk
  - Dynamics & radiation
  - Corona model
  - Wind
- Super-Eddington accretion
  - One-D dynamics & radiation
  - Modern picture of super-Eddington accretion

References

- 《Accretion power in astrophysics》: Frank, King & Raine; Cambridge University Press, 2002
- 《Hot accretion flows around black holes》: Yuan & Narayan 2014, ARA&A, 52, 529
- 《Relativistic jets from active galactic nuclei》: Blandford, Meier & Readhead, 2019, ARA&A, 57, 467
- Jiang & Dai 2024, arXiv:2408.16856; in 《New Frontiers in GRMHD Simulations》, 2025, Springer Press

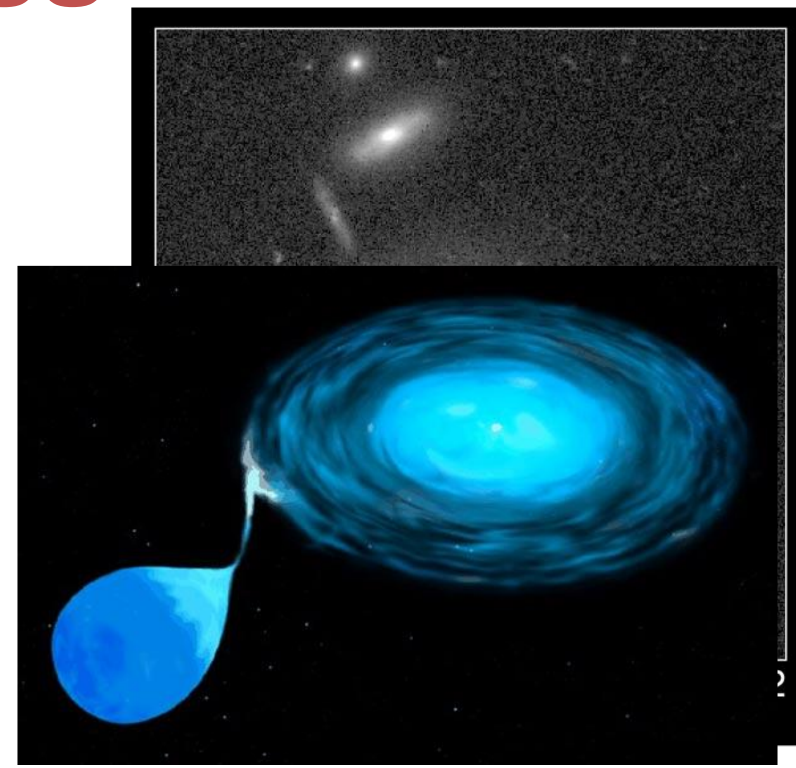
Accretion

- Rotating gas falls onto the center due to the gravitational force
- Gravitational energy → thermal energy
- Thermal energy → radiation
- High efficiency



Accretion is common in the universe

- Active galactic nuclei
- Black hole X-ray binaries
- Gamma-Ray burst
- Star formation
- Planet formation



—— **A fundamental physical process**

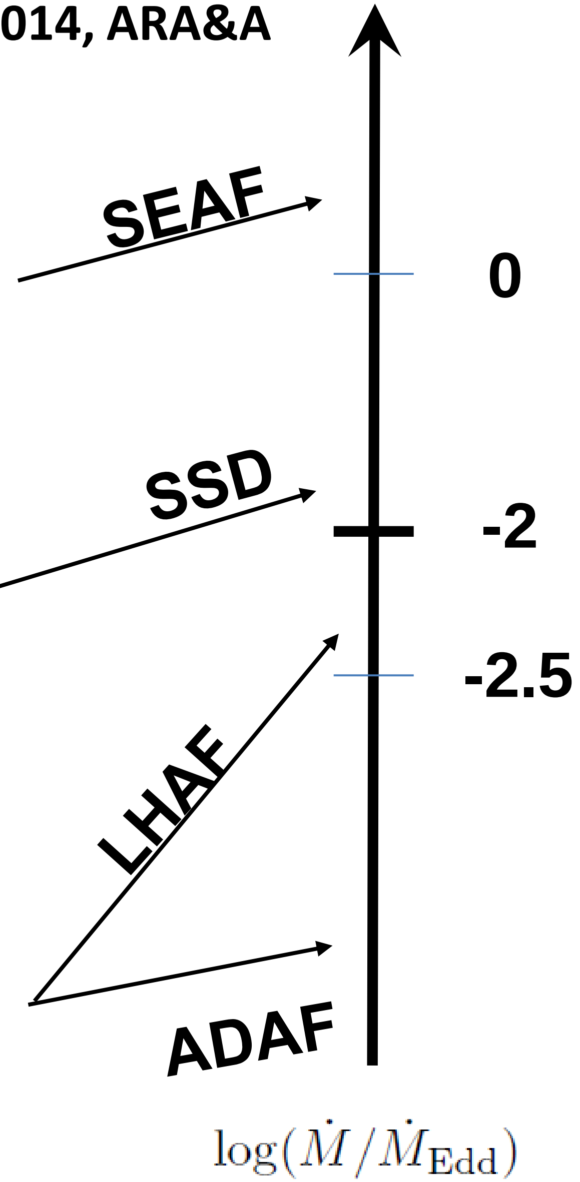
Accretion modes (models)

Pringle 1981, ARA&A; Yuan & Narayan 2014, ARA&A

Super-Eddington accretion (slim disk)
(Abramowicz et al. 1989; Sadowski et al. 2014; Jiang et al. 2014)
TDEs, ULXs, SS433

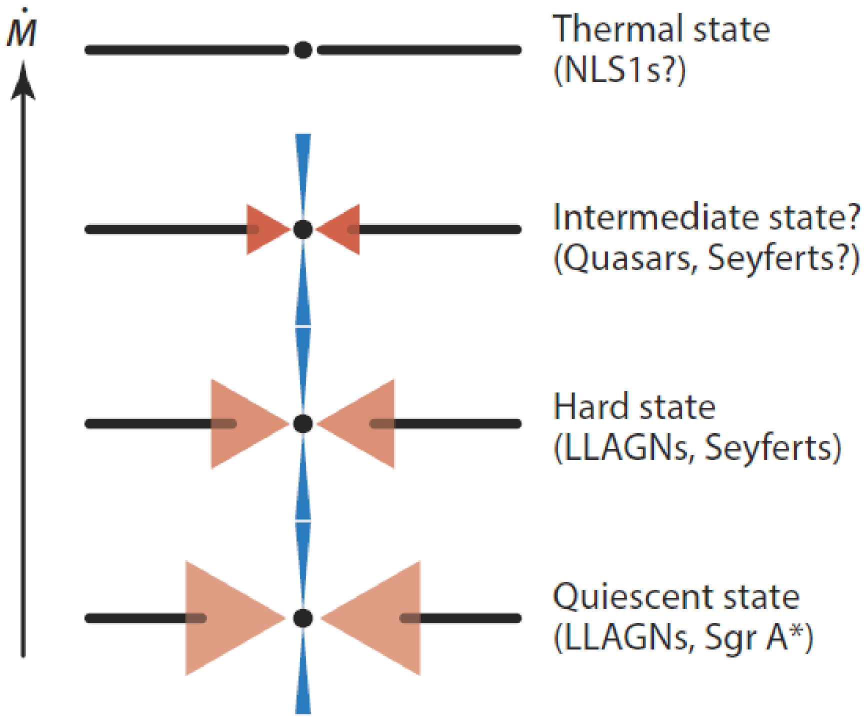
Standard thin accretion disk
(Shakura-Sunyaev 1976; Pringle 1981, ARA&A)
Typical QSOs, Seyferts; XRBs in thermal soft state

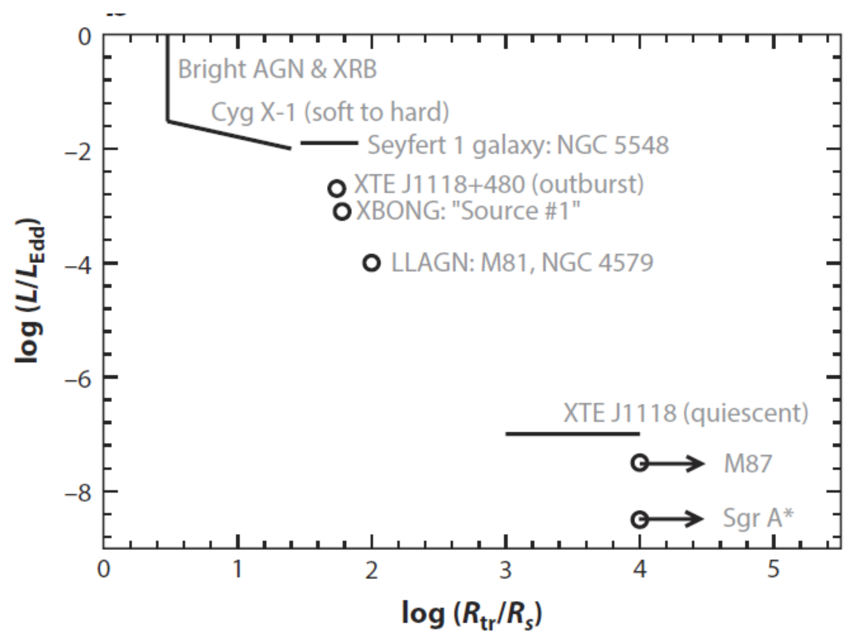
Hot Accretion: ADAF(RIAF) & LHAF
(Narayan & Yi 94; Yuan 2001; Yuan & Narayan 2014, ARA&A)
LLAGN, BL Lac objects, Sgr A*, M87
XRBs in hard & quiescent states



Models for BHXB & AGN

Yuan & Narayan 2014, ARA&A





Hot accretion flows

One-dimensional equations

$$\frac{d}{dR}(\rho R H v) = 0,$$

$$v\frac{dv}{dR} - \Omega^2 R = -\Omega_K^2 R - \frac{1}{\rho}\frac{d}{dR}(\rho c_s^2),$$

$$v\,\frac{d(\Omega R^2)}{dR} = \frac{1}{\rho R H}\frac{d}{dR}\left(\nu \rho R^3 H \frac{d\Omega}{dR}\right)$$

One-T: $$\rho v\left(\frac{de}{dR} - \frac{p}{\rho^2}\frac{d\rho}{dR}\right) = \rho\nu R^2\left(\frac{d\Omega}{dR}\right)^2 - q^-,$$

Two-T: $$q^{\rm adv,i} \equiv \rho v\left(\frac{de_i}{dR} - \frac{p_i}{\rho^2}\frac{d\rho}{dR}\right) \equiv \rho v\frac{de_i}{dR} - q^{i,c} = (1-\delta)q^+ - q^{\rm ie},$$

$$q^{\rm adv,e} \equiv \rho v\left(\frac{de_e}{dR} - \frac{p_e}{\rho^2}\frac{d\rho}{dR}\right) \equiv \rho v\frac{de_e}{dR} - q^{e,c} = \delta q^+ + q^{\rm ie} - q^-.$$

Self-similar solution

Narayan & Yi 1994;1995

Assuming power-law scaling with radius for physical quantities:

$$v \simeq -1.1 \times 10^{10}\, \alpha r^{-1/2} \quad \mathrm{cm\ s^{-1}},$$

$$\Omega \simeq 2.9 \times 10^{4}\ m^{-1} r^{-3/2} \quad \mathrm{s},$$

$$c_s^2 \simeq 1.4 \times 10^{20}\ r^{-1} \quad \mathrm{cm^2\ s^{-2}},$$

$$n_e \simeq 6.3 \times 10^{19}\ \alpha^{-1}\, m^{-1} \dot{m}\, r^{-3/2} \quad \mathrm{cm^{-3}},$$

$$B \simeq 7.8 \times 10^{8}\ \alpha^{-1/2}\, m^{-1/2} \dot{m}^{1/2}\, r^{-5/4} \quad \mathrm{G},$$

$$p \simeq 1.7 \times 10^{16}\ \alpha^{-1}\, m^{-1} \dot{m}\, r^{-5/2} \quad \mathrm{g\ cm^{-1}\ s^{-2}},$$

$$q^{+} \simeq 5.0 \times 10^{21}\ m^{-2} \dot{m}\, r^{-4} \quad \mathrm{ergs\ cm^{-3}\ s^{-1}},$$

$$\tau_{\mathrm{es}} \simeq 24\ \alpha^{-1} \dot{m}\, r^{-1/2},$$

Main features

- Large radial velocity:

$$v_r \sim \frac{\alpha c_s H}{R}$$

- Sub-Keplerian rotation: pressure-gradient support
- High temperature: $T \sim \frac{GMm_p}{6kR} \sim \frac{10^{12}}{r}$ (virial, why?)
- Geometrically thick: $(H = \frac{c_s}{\Omega_k} \sim R)$
- Optically thin (because of large radial velocity)
- Two-temperature: $T_i \gg T_e$
  - coupling between ions and electrons not strong enough
  - plasma collective behavior also too weak

Radiative efficiency is low when $\dot{M}$ is small

- The energy equation of the accretion flow:

$$\rho \upsilon T \frac{ds}{dr} \equiv q_{adv} = q^{+} - q^{-}$$

- For the standard thin disk, we have,

$$q^{+} \approx q^{-} >> q_{adv}$$

- For ADAFs, we have,

$$q^{+} \approx q_{adv} >> q^{-}$$

- Physics:
  - the density of the accretion flow is very low so: radiation timescale >> accretion timescale.
  - So most of the viscously dissipated energy is stored in the accretion flow and advected in to the black hole rather than radiated away.

The critical accretion rate of ADAF

- With increasing of $\dot{M}$, cooling increases faster than viscous dissipation and advection
- So there exists a critical accretion rate of ADAF, determined by

$$q^+ = q^- \rightarrow \dot{M}_{crit,ADAF} \sim \alpha^2 \dot{M}_{Edd}$$

What will happen when $\dot{M} > \dot{M}_{crit,ADAF}$?

Another hot accretion flow model beyond ADAF: LHAFs

Yuan 2001, MNRAS

Energy equation:

$$\rho\upsilon T_i \frac{ds_i}{dr} \equiv q_{adv,i} = q^+ - q_{ie}$$

$$q_{adv} \equiv \rho\upsilon T_i \frac{ds_i}{dr} \equiv \rho\upsilon \frac{d\varepsilon_i}{dr} - q^c$$

So we have:

$$\rho\upsilon \frac{d\varepsilon_i}{dr} = q^+ + q^c - q_{ie}$$

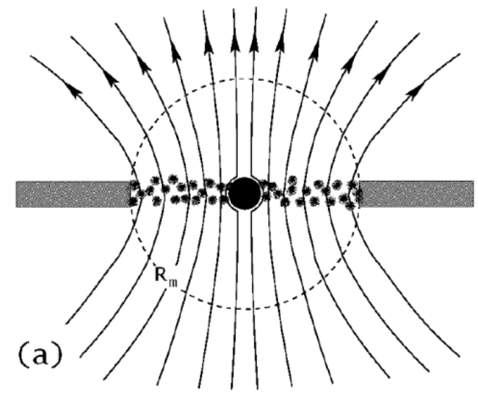
So there exists another critical rate $\dot{M}_{crit,LHAF}$, determined by:

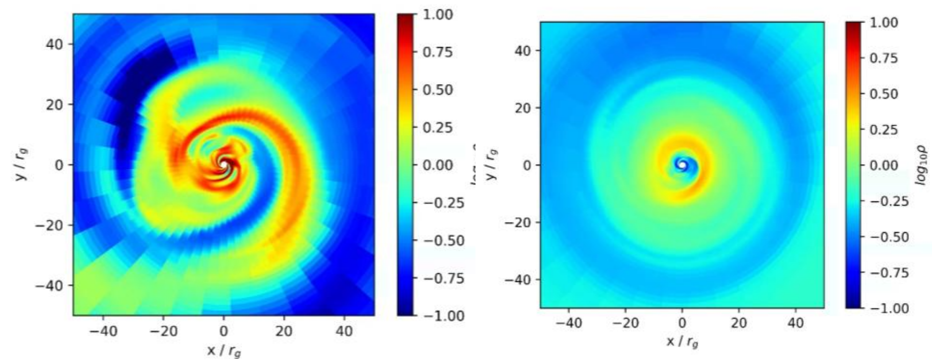
$$q^+ + q^c = q_{ie} \rightarrow \dot{M}_{crit,LHAF} \sim 0.6\,\alpha \dot{M}_{Edd}$$

Below $\dot{M}_{crit,LHAF}$, there is another model — LHAF, in which advection is a heating term

Two modes of hot accretion: SANE & MAD

- SANE: standard and normal accretion
- MAD: magnetically arrested disk
- Magnetic field lines accumulated near BH
  - Accreted magnetic flux must be large enough
  - Feasible in reality
- magnetic pressure is strong enough to stop accretion
- Gas falls in toward the BH due to interchange instability





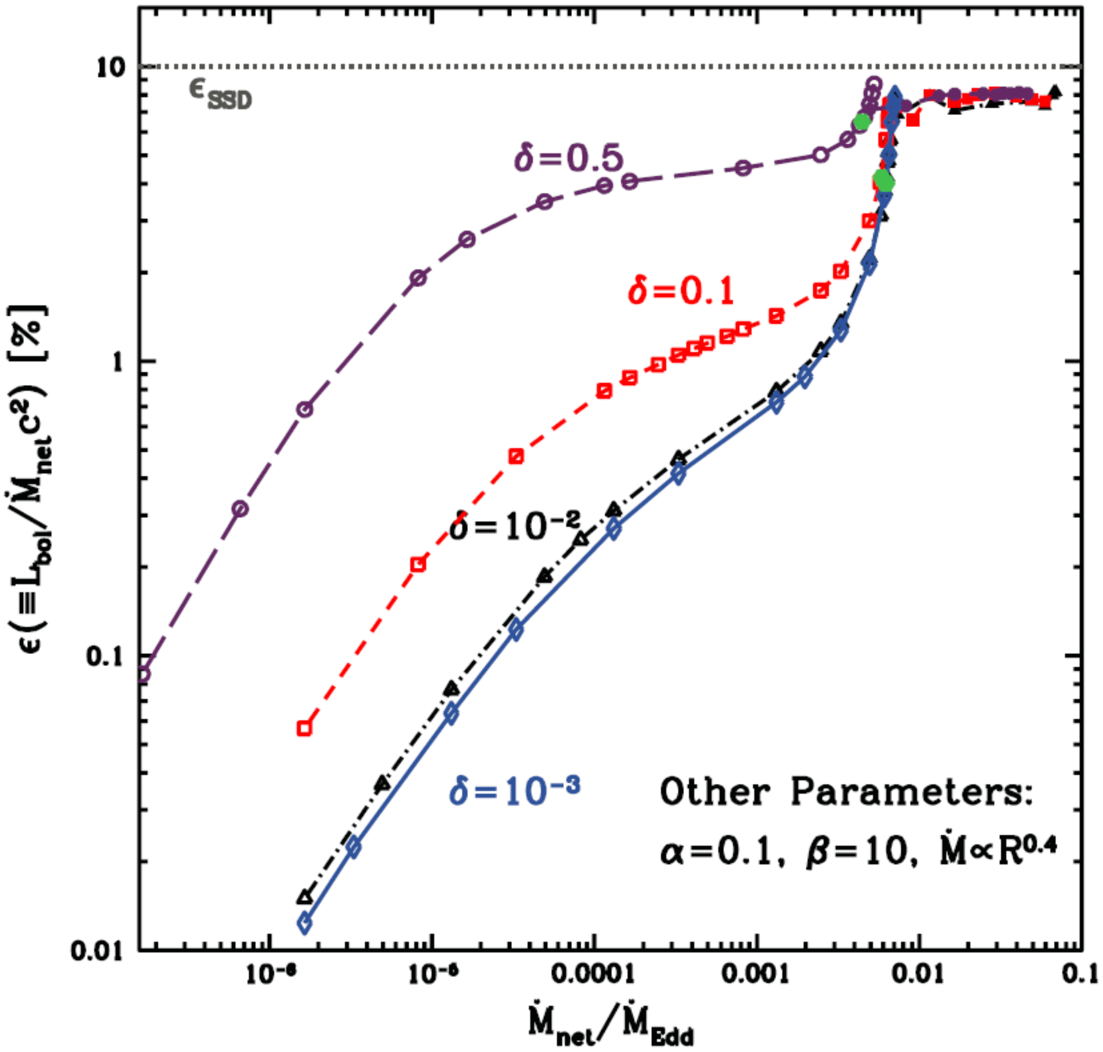
MAD SANE

Radiative processes

- Synchrotron emission:
  - relativistic electrons & B field (described by a parameter β);
  - Maxwell distribution
  - Self-absorption of synchrotron emission
- Bremsstrahlung radiation
- Comptonization
  - seed photons are synchrotron & Brem. photons
- Misc:
  - Gamma-ray emission by the decay of neutral pions created in proton-proton collisions

Radiative efficiency

Xie & Yuan 2012



Wind

Why wind is important?

- Accretion physics
  - An important ingredient of the dynamics of BH accretion
  - Determine how do we understand observations
- Affect galaxy evolution
  - Strong wind can propagate to large distance in the galaxy and modify the density & temperature of the gas
  - Star formation will be changed, even the galaxy is quenched (Zou et al. 2025)

Accretion rate decreases inward

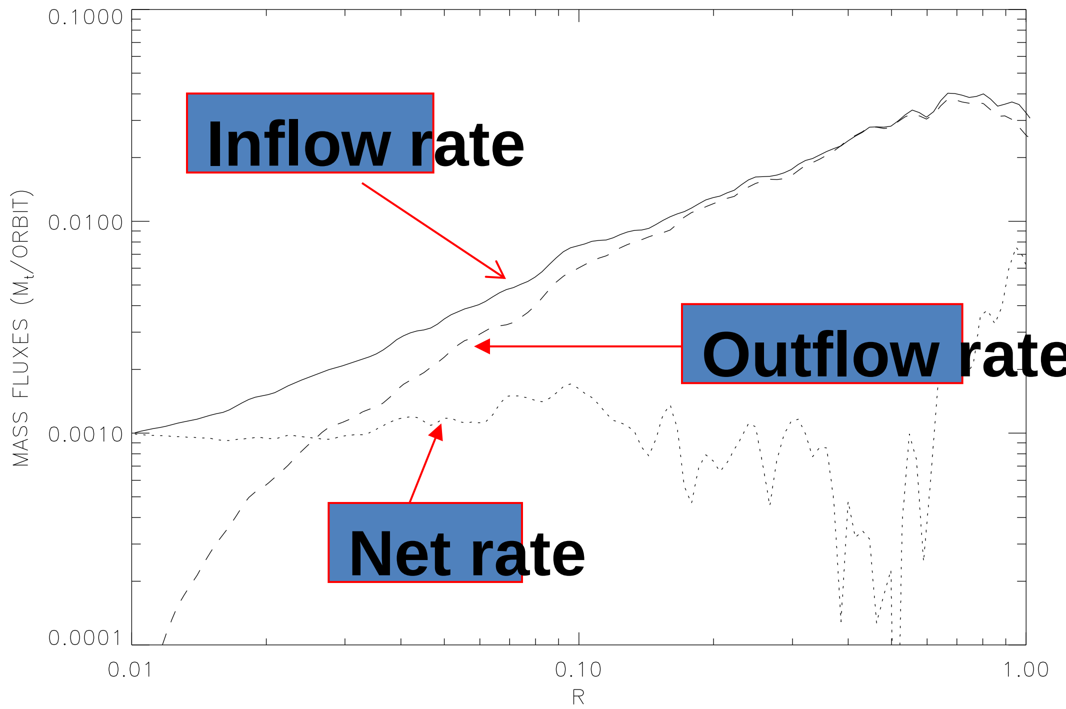
Stone, Pringle & Begelman 1999; Stone & Pringle 2001

$$\dot{M}_{\rm in}(r) = 2\pi r^2 \int_0^\pi \rho \min(v_r, 0) \sin\theta d\theta,$$

$$\dot{M}_{\rm out}(r) = 2\pi r^2 \int_0^\pi \rho \max(v_r, 0) \sin\theta d\theta,$$

$$\dot{M}_{\rm net}(r) = \dot{M}_{\rm in}(r) - \dot{M}_{\rm out}(r).$$

$$\dot{M}(r) = \dot{M}(r_{out})(r/r_{out})^{0.5-0.8}$$

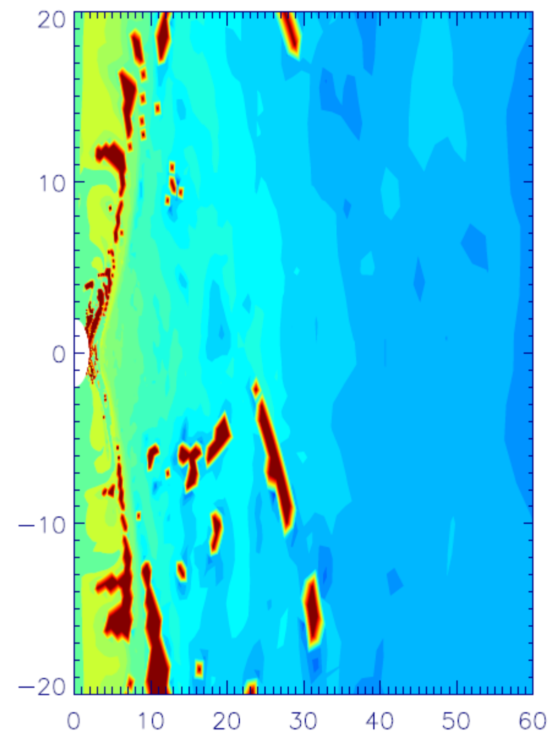


Stone, Pringle & Begelman 1999

Physical reason: convection or wind?

Yuan, Bu &Wu (2012)

- Two scenarios have been proposed:
  - Outflow (Blandford & Begelman 1999)
  - Convection (Narayan et al. 2000)
- Yuen et al. 2012:
  - If convective turbulence, we expect: inflow & outflow properties roughly same; → but we find different
  - Analyze the convective stability of *MHD* accretion flow → stable
  - Trajectory of virtual test particles
- Conclusion: strong outflow exists!



Yuan, Bu & Wu 2012

Observational evidences: Sgr A* & NGC 3115

Yuan, Quataert & Narayan 2003; Wong et al. 2011

- Chandra observations + Bondi theory give the Bondi rate:

$$10^{-5} M_{\bullet} yr^{-1}$$

(consistent with numerical simulation of Cuadra et al. 2006)

- High linear polarization at radio waveband requires innermost region accretion rate (rotation measure requirement):

$$(10^{-7} - 10^{-9}) M_{\bullet} yr^{-1}$$

- So $\dot{M}$ must decrease inward
- Density profile consistent with numerical simulation
  - Sgr A*: $\rho \propto r^{-1}$
  - NGC 3115: $\rho \propto r^{-1.03^{+0.23}_{-0.21}}$

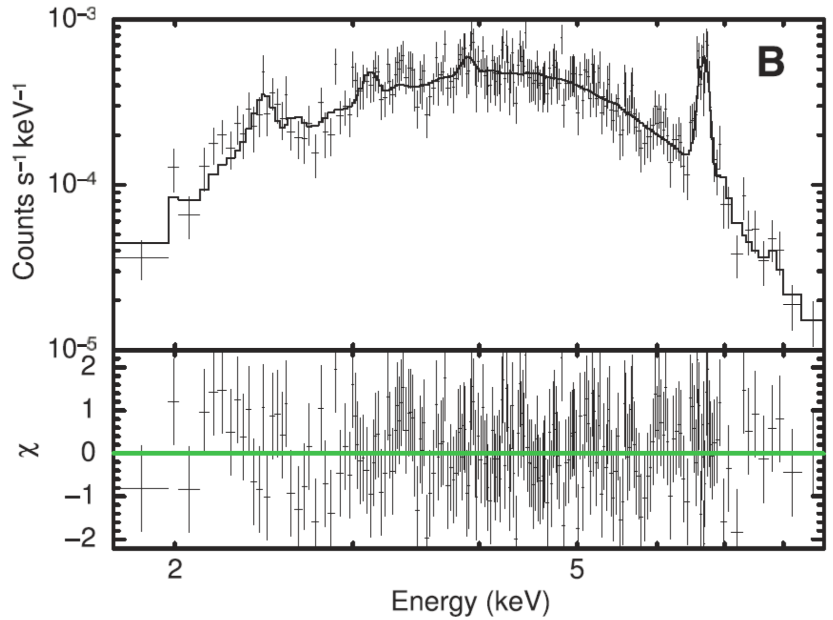
Outflow confirmed by new observations

Wang et al. 2013, Science

- 3Ms observation to the quiescent state of Sgr A* by Chandra
- H-like Fe Kα line profile fitting

→ flat density profile

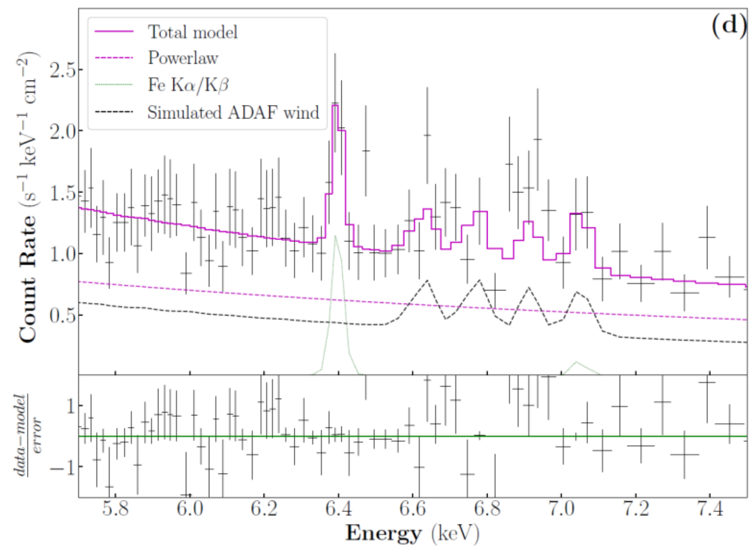
→ strong outflow

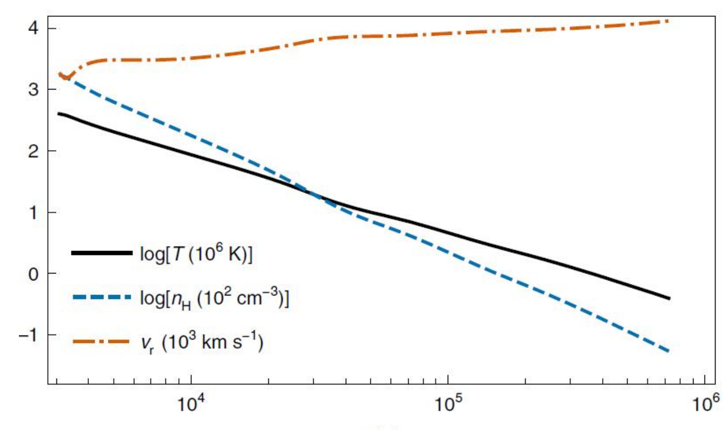


Observational evidence in M81

Shi et al. 2021, Nature Astronomy

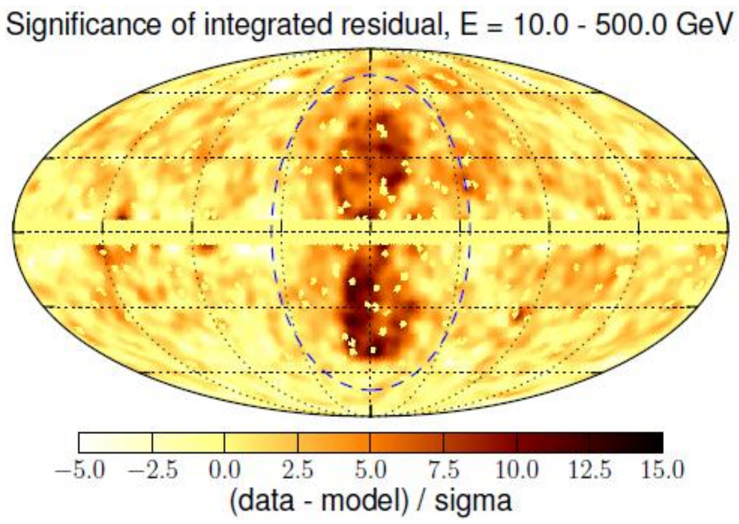
- A pair of Fe XXVI Lyα emission lines:
  - redshifted and blueshifted → v = 3000 km/s
  - Line ratio → 1.3 10^8 K
- MHD simulation of wind; use the simulation data to fit the observation



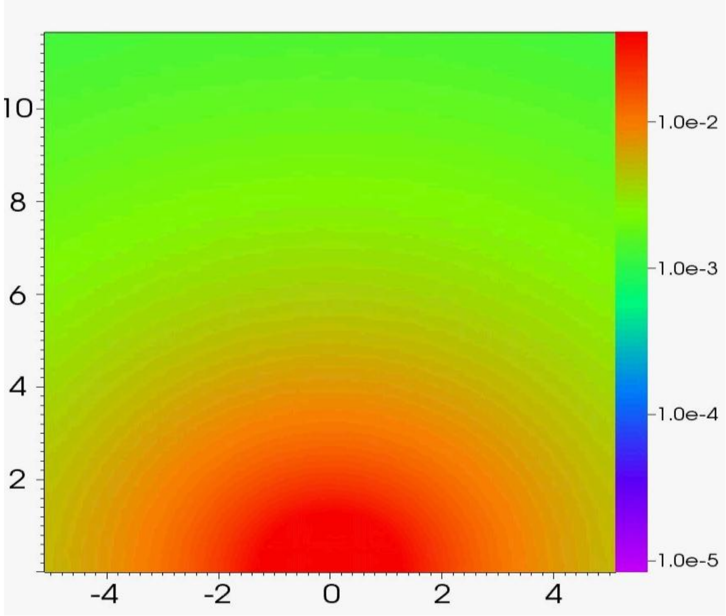


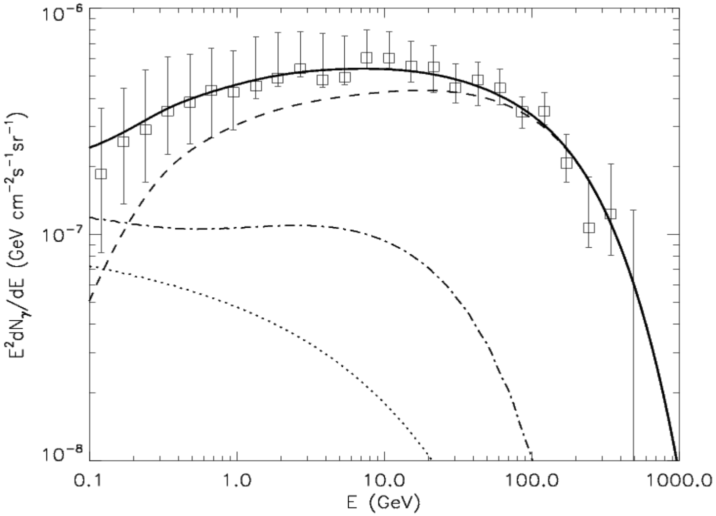
Accretion wind model for Fermi bubbles

Mou, Yuan et al. 2014; 2015



Su et al. 2010; Ackermann et al. 2014





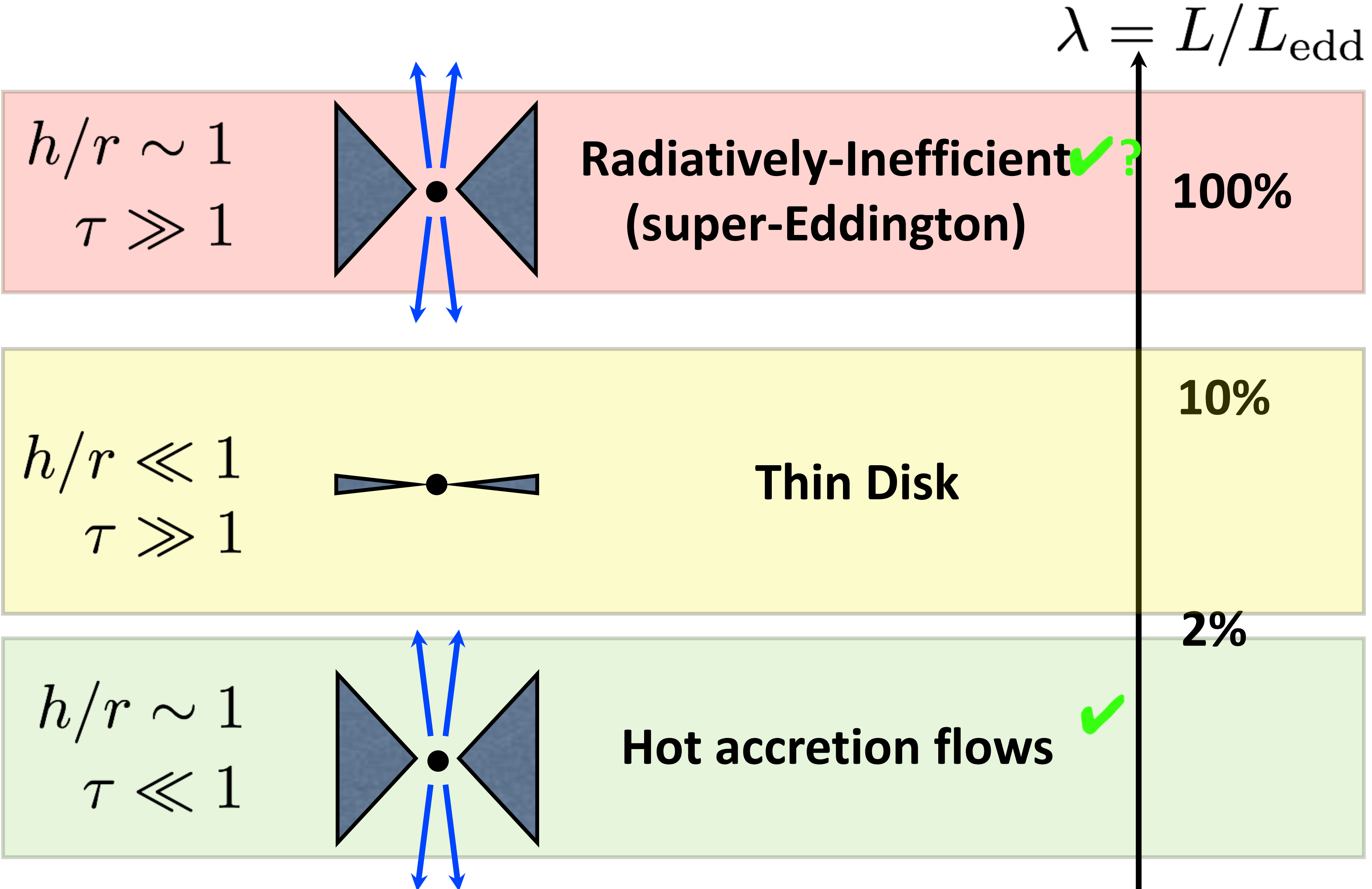
(Rossi X-ray Prize)

The wind model:

- **Int. between wind & ISM**
- **Parameters not free**
- **Simul.: 3DMHD + Two-fluid**

Jet

When Do We Observe Jets?



Three models of jet formation

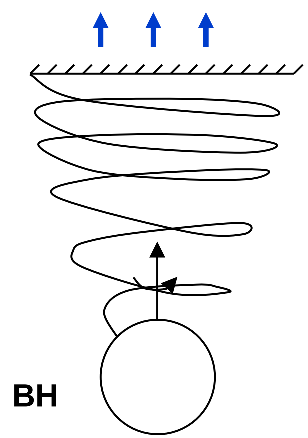
Blandford & Znajek 1976; Blandford & Payne 1982; Lynden-Bell

- Blandford & Znajek (1976).
  - Two key components: ordered magnetic field + BH spin
- Blandford & Payne (1982)
  - Large-scale B field
  - Magneto-centrifugal force
- Magnetic tower (Lynden-Bell 2003)
  - Gradient force of toroidal magnetic pressure

Jet formation models (I) : Blandford-Znajek model

- Blandford-Znajek model (Blandford & Znajek 1977)
  - Spinning black hole
  - Large-scale poloidal magnetic field anchored to the horizon
  - Extracting the spin energy of the BH with poloidal B field

$$P = \frac{B_\varphi^2}{8\pi}$$

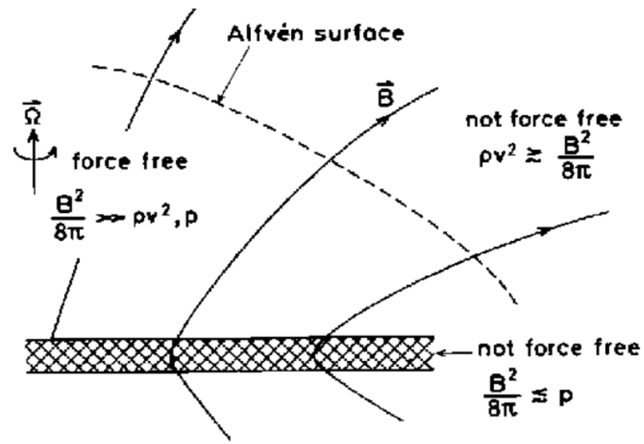


Roger Blandford

Shaw Prize in Astronomy, 2020

Jet formation models (II): Blandford-Payne and Magnetic tower models

- Blandford-Payne model (Blandford & Payne 1982)
  - Large-scale ordered poloidal field
  - Suitable inclination angle
  - Extracting the spin energy of the accretion flow via magnetocentrifugal force
- Magnetic tower model (Lynden-Bell 2003)
  - Similar to BZ model, but extracting the spin energy of the accretion flow
  - Confirmed by numerical simulations



Mon. Not. R. Astron. Soc. **341,** 1360–1372 (2003)

On why discs generate magnetic towers and collimate jets

D. Lynden-Bell[1,2,3,4★†]
[1] *The Observatories of the Carnegie Institution, 813 Santa Barbara St., Pasadena, CA, USA*
[2] *The Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA*
[3] *Clare College, Trinity Lane, Cambridge CB2 1TL*
[4] *Physics Department, The Queens University, Belfast*

Accepted 2003 February 6. Received 2003 January 16; in original form 2002 November 5

ABSTRACT
We show that accretion discs with magnetic fields in them ought to make jets provided that their electrical conductivity prevents slippage and there is an ambient pressure in their surroundings.

We study *equilibria* of highly wound magnetic structures. General Energy theorems demonstrate that they form tall magnetic towers, the height of which grows with every turn at a velocity related to the circular velocity in the accretion disc.

The pinch effect amplifies the magnetic pressures toward the axis of the towers, the stability of which is briefly considered.

We give solutions for all twist profiles $\Phi(P) = \Omega(P)t$ and for any external pressure distri-

Power of BZ jet

Blandford & Znajek 1976; Tchekhovskoy 2010

- Two key components: ordered magnetic field at the horizon and rotation of BH

$$P_{\rm BZ} = \frac{\kappa}{4\pi c}\Phi^2\Omega_{\rm H}^2$$

Φ: magnetic flux threading the horizon;
Ω_H**=ac/2**R_H**: angular velocity of the horizon;** R_H**=Rg(1+**$\sqrt{1-a^2}$**)**
κ≈0.05

- Prograde disk produces stronger jet than retrograde

Open questions in jet physics

- BZ, BP: Which dynamical model is correct?
- Whether BZ model can reproduce observations of jet?
  - Many observational constraints (not only jet power & SED)
  - Keys: electron acceleration and radiation mechanisms
- How are electrons accelerated?
  - Internal shock (Bell 1978; Blandford & Eichler 1987)?
    - Seems to be inefficient in relativistic magnetized plasma (Sironi, Spitkovsky, & Arons 2013; Bell et al. 2018)
    - Within ~ 1kpc, jet energy is mainly in the form of Poynting flux rather than kinetic energy
  - Magnetic reconnection? By what mechanism? Kink instability?
- What is the composition of jet?
  - Electron-positron pairs or normal plasma?

These questions are answered in Yang et al. 2024, Science Advances

The “magnetic reconnection” model of jet radiation: basic scenario

- Perform 3D GRMHD simulation to form a BZ jet
- Calculate electrons acceleration by reconnection
- Calculate synchrotron radiation of these energetic electrons and radiative transfer, to obtain jet radiation & morphology
- Compare with observations

Number density of nonthermal electrons accelerated by magnetic reconnection

Yang et al. 2024, Science Advances

- How to determine N_pl? the most important quantity!
- Usually it is assumed to be a constant fraction of thermal electrons or magnetic field (Ozel, Psaltis & Narayan 2000; Broderick et al. 2016; Davelaar et al. 2018; Dexter et al. 2012)
- In our model, it is determined by (based on PIC simulations; Peterson & Gammie 2020):

$$\propto \left(\frac{J}{J_0}\right)^2$$

- Calculation of J: $J^i = \partial_j F^{ij} + \Gamma^i_{j\lambda} F^{ij}$
- Steady-state distribution obtained by:

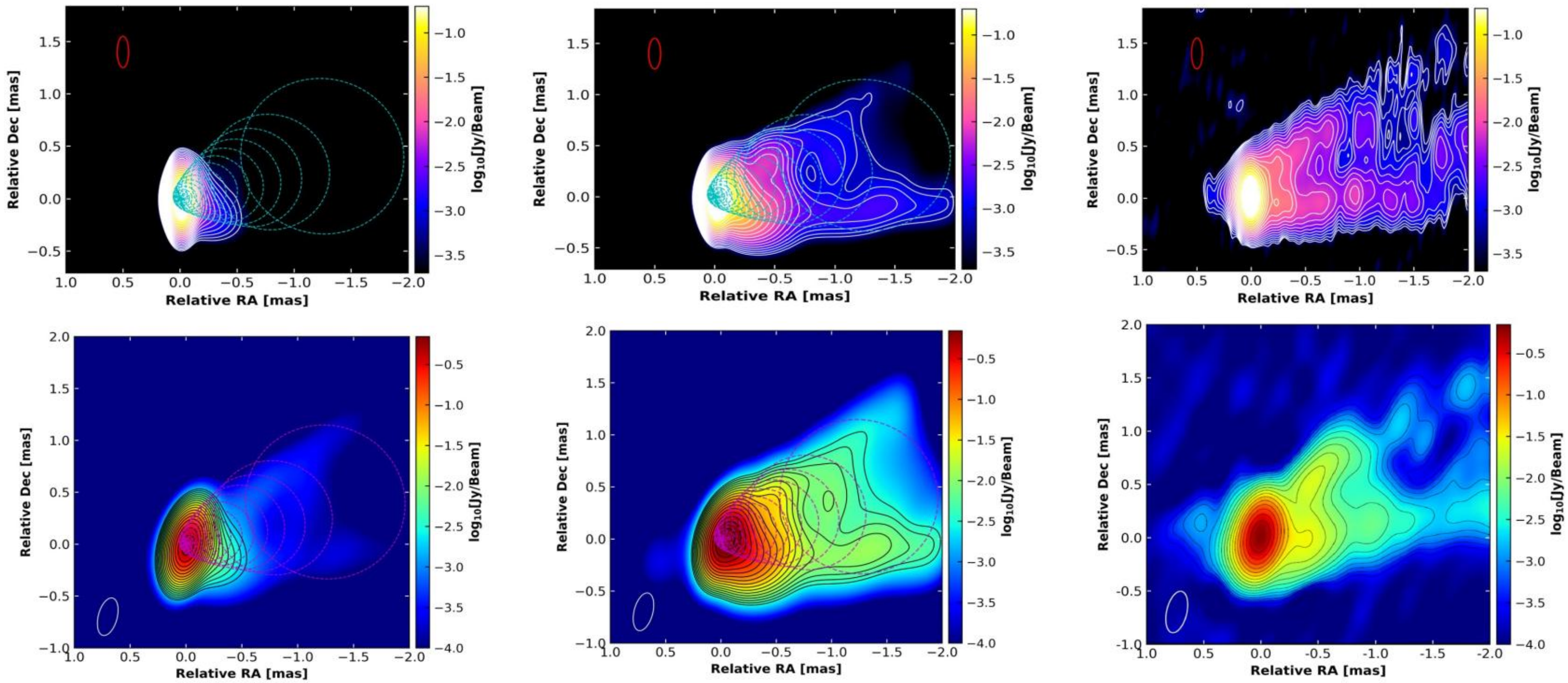
$$\eta \frac{v_A}{r_z} (N_{tot} - N_{pl}) \frac{J^2}{J_0^2} = \frac{N_{pl}}{\tau_{cool}}$$

- We then calculate radiative transfer in GR frame using ray-tracing approach

Predicted jet images

86 GHz

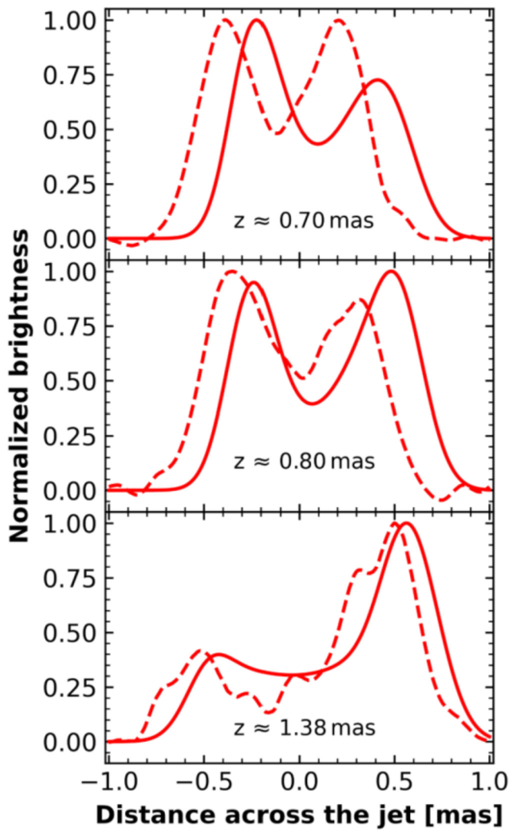
43 GHz



Thermal-only model | **Current-density model** | **observations**

The model can successfully reproduce the elongated structure of jet

Limb-brightening features



Dashed lines:
observed profiles

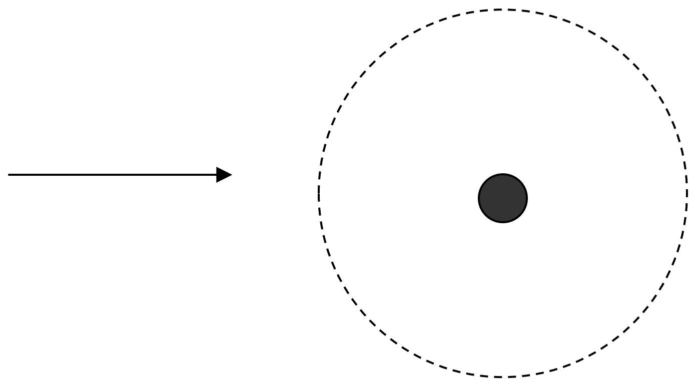
Solid lines:
predicted profiles of brightness by MAD98

Conclusion:
Well consistent with observations and much better than previous works!

Application of hot accretion flow theory in Sgr A*

Outer Boundary Conditions at Bondi Radius

- **Temperature**: 2keV; **Density**: 130cm^-3
- **Bondi radius:** $R_A \approx \frac{GM}{c_s^2} \approx 1'' \approx 10^5 R_s$

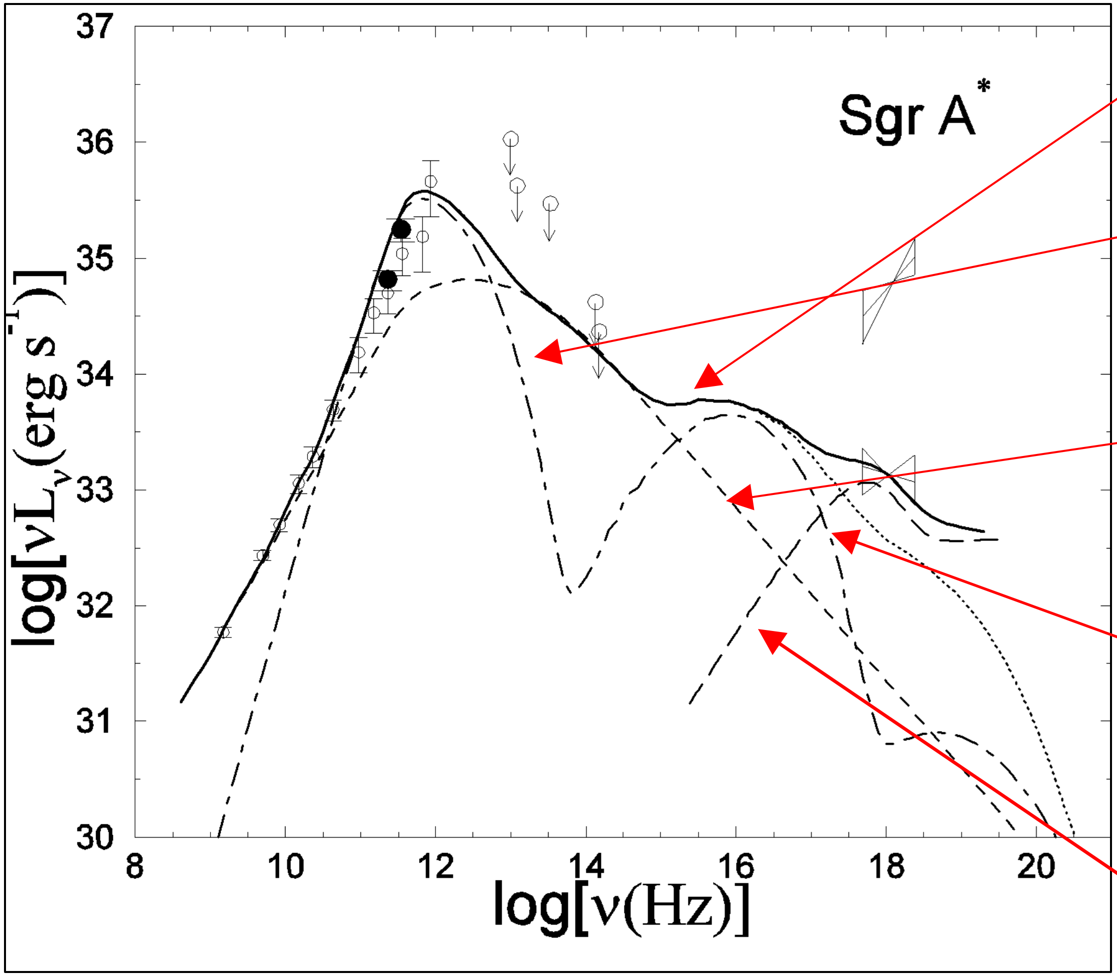


- **Mass accretion rate estimation**

$$\dot{M}_{captured} \approx 4\pi R_A^2 \rho c_s |_{R \approx R_A} \approx 10^{-5} M_{\odot} yr^{-1}$$

The standard thin disk model will predict a luminosity several orders magnitude higher than observation!

ADAF (RIAF) model of quiescent state of Sgr A*



Total emission

Synchrotron emission thermal electrons)

synchrotron emission power-law electrons)

Comptonization (from thermal electrons)

Bremsstrah lung

Yuan, Quataert & Narayan 2003

The standard thin disk model

Equations

- Mass conservation: $\dot{M}=4\pi r H\rho v_r$
- Momentum: $\frac{1}{\rho}\frac{dP}{dr}-(\Omega^2-\Omega_k^2)r+v_r\frac{dv_r}{dr}=0$
- Angular momentum: $\dot{M}(l-l_0)=4\pi r^2 H\alpha P$
- Energy equation: $H\rho v_r T\frac{dS}{dr}=H\alpha P r\frac{d\Omega}{dr}-F^-$

  Here the vertical radiation flux is:

$$F^- = \frac{c}{k\rho}\frac{aT^4}{3H}$$

Overview of the thin disk model

- Cool: ~10^6 K → Geometrically thin & Keplerian rotation
- Slow radial velocity
- "Optically thick":
- Spectrum: black body spectrum
- Radiative efficiency is high, ~0.1

A thin disk

Radiation

- We should have: $\sigma T^4(R) = D(R)$

- Thus: $$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \left(\frac{R_*}{R} \right)^{1/2} \right] \right\}^{1/4}$$

- Emitted spectrum:

$$I_\nu = B_\nu[T(R)] = \frac{2h\nu^3}{c^2(e^{h\nu/kT(R)} - 1)} (\mathrm{erg\ s^{-1}\ cm^{-2}\ Hz^{-1}\ sr^{-1}})$$

- Integrate over radius,

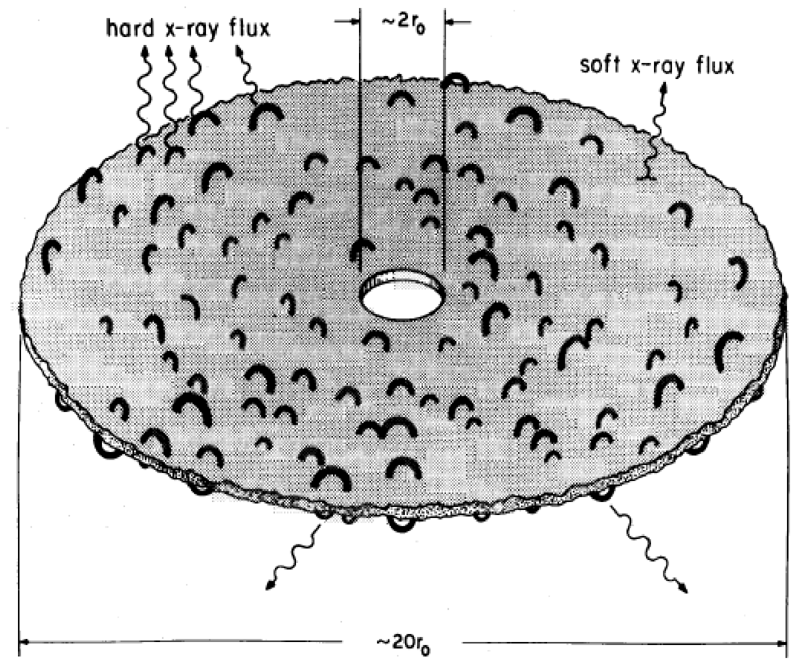
$$F_\nu = \frac{4\pi h \cos i\, \nu^3}{c^2 D^2} \int_{R_*}^{R_{\mathrm{out}}} \frac{R\, \mathrm{d}R}{e^{h\nu/kT(R)} - 1}$$

Thermal stability: an open issue

- Observations to the soft state of BHBs show that they are stable!
- RMHD simulations:
  - Hirose, Krolik & Blaes (2009): thermally stable
  - Jiang, Stone & Davis (2013): thermally unstable
  - So it is not understood how to explain observations

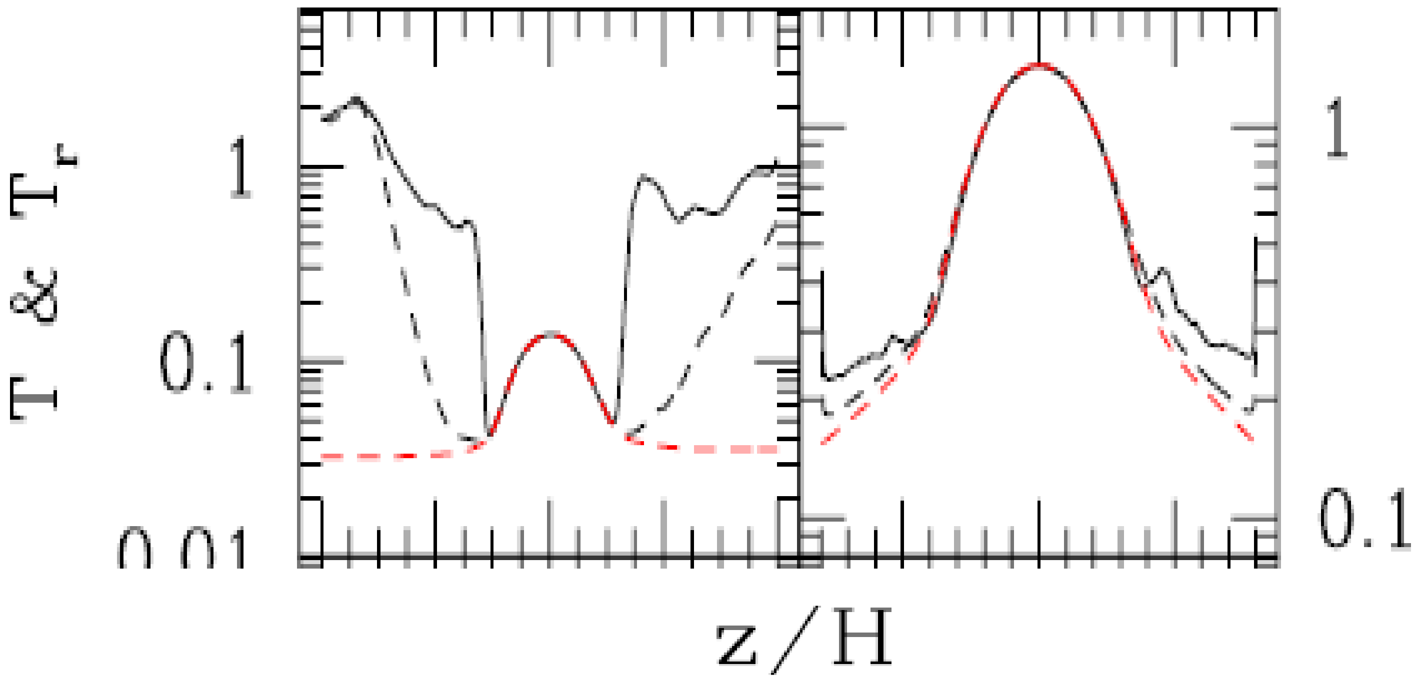
Disc-corona model

- Motivation
  - To explain X-ray radiation
  - Analogy with solar corona
- Formation mechanism of corona
  - Emergence of magnetic field from disk to corona
  - Magnetic reconnection heating
- MHD simulation to Corona:
  - Magnetically supported
  - High temperature



Radiative MHD simulation of corona

Jiang, Stone & Davis 2014



Low Σ high Σ

- The strength of the corona depends on surface density of the disk!
- Temperature of corona can be 30 times higher than that of the disk;

Wind launching mechanisms (I)

- **Thermally driven** (Begelman et al. 1983; Woods et al. 1996; Done et al. 2018)
  - Photons from very inner region compton heating accretion disk and driven wind.
  - $T_{Compton} \sim 10^7$K, wind can only be driven outside 10^5 Rs.
- **Magnetically driven**
  - Magneto-centrifugal driven (Blandford & Payne 1982)
    - Wind is driven by magneto-centrifugal force.
    - Large scale open B field is required & angle between B and rotational axis > 30^o.
  - Magnetic tower model (Lynden-Bell 2003, Kato et al. 2004)
    - Wind is driven by magnetic pressure gradient force.

Wind launching mechanisms (II)

- Radiation pressure driven
  - Tomson scattering: only works when luminosity close to Eddington value.
  - Line force (Proga et al. 2000; Liu et al. 2013; Yang & Bu 2018):
    - Works when $T < 10^5$K and ionization parameter < 100.
    - Works only for AGN, but not X-ray binary.
  - Radiation pressure on dust (Dorodnitsyn et al. 2016):
    - IR radiation on dust, opacity can be 30 times of Thomson scattering.
    - Works in regions > 1pc.

Super-Eddington accretion

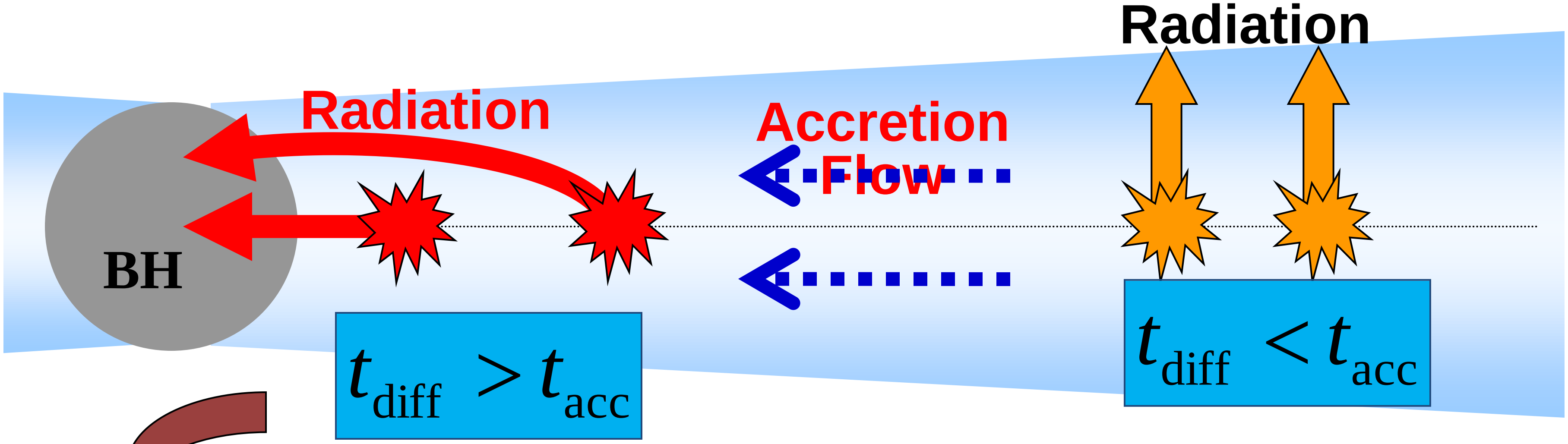
Traditional one-dimensional slim disk model

- Recall energy eq:

$$H\rho v_r T\frac{dS}{dr}=H\alpha P r\frac{d\Omega}{dr}-F^{-}$$

- When accretion rate is above Eddington, advection because dominant ("photon trapping" effect)
- Thus radiative efficiency is low
- And T is much higher, the disk is slim

Traditional scenario: Photon Trapping



$$\frac{r}{r_S} < \left(\frac{\dot{M}}{L_E c^2}\right)\left(\frac{H}{r}\right)$$

$$t_{diff} \sim \frac{H}{\tau c}; \quad t_{acc} \sim \frac{r}{v_r}$$

$$\left(\frac{R_{\rm tr}}{r_g}\right) = \frac{\kappa_{\rm es}\dot{M}}{\pi c}\left(\frac{H}{r}\right) = 7.2 \times 10^2 \left(\frac{\dot{m}}{50}\right)$$

So photon-trapping occur in the super-Eddington flow

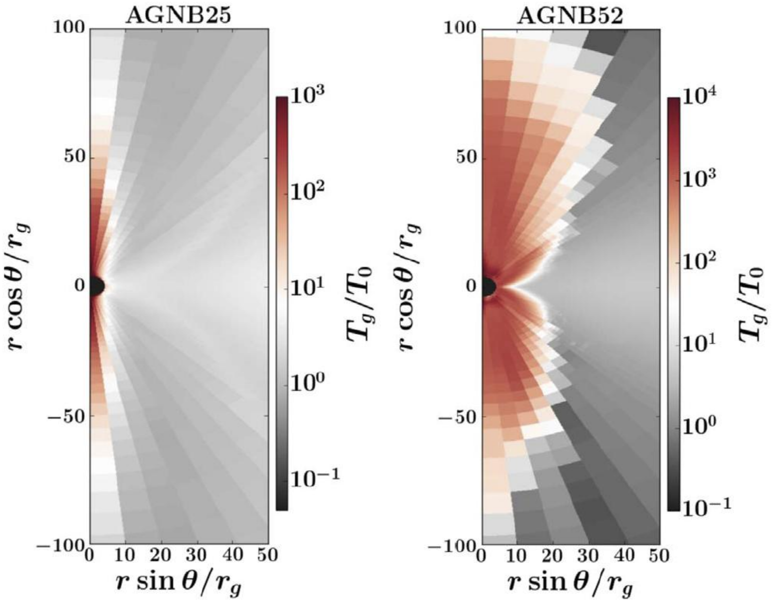
Modern Picture of Super-Eddington accretion

Jiang, Stone & Davis 2014, 2019; Narayan et al. 2017; Curd & Narayan 2019

- By RMHD simulation
- Super-Eddington luminosity is achieved by larger emission area and smaller effective temperature compared to thin disk.
- A new radiative transfer mechanism identified: magnetic buoyancy of photon bubbles
  - Transfer speed: local Alfven speed; >> photon diffusion speed
- Radiative efficiency much higher than previously thought
  - $\dot{M} < 50\,\dot{M}_{Edd}$: $\eta \sim 0.05 - 0.07$ → $25 - 35 L_{Edd}$
  - $\dot{M} \sim 150\,\dot{M}_{Edd}$: $\eta \sim 0.01$
- Luminosity saturation at higher Mdot?

Super-Eddington accretion

- Hot gas embedded within cooler gas, so in general X-ray weak
  - Can explain the X-ray weakness of 50% LRD
- But extremely X-ray bright for pole-on observer (Curd & Narayan 2019)
- Jet can be produced if MAD and BH is spinning (Narayan et al. 2017) (why no jet in most TDEs?)



復旦大學
FUDAN UNIVERSITY

Thanks!

日月光華 旦復旦兮