Wind and Jet from Black Hole Accretion

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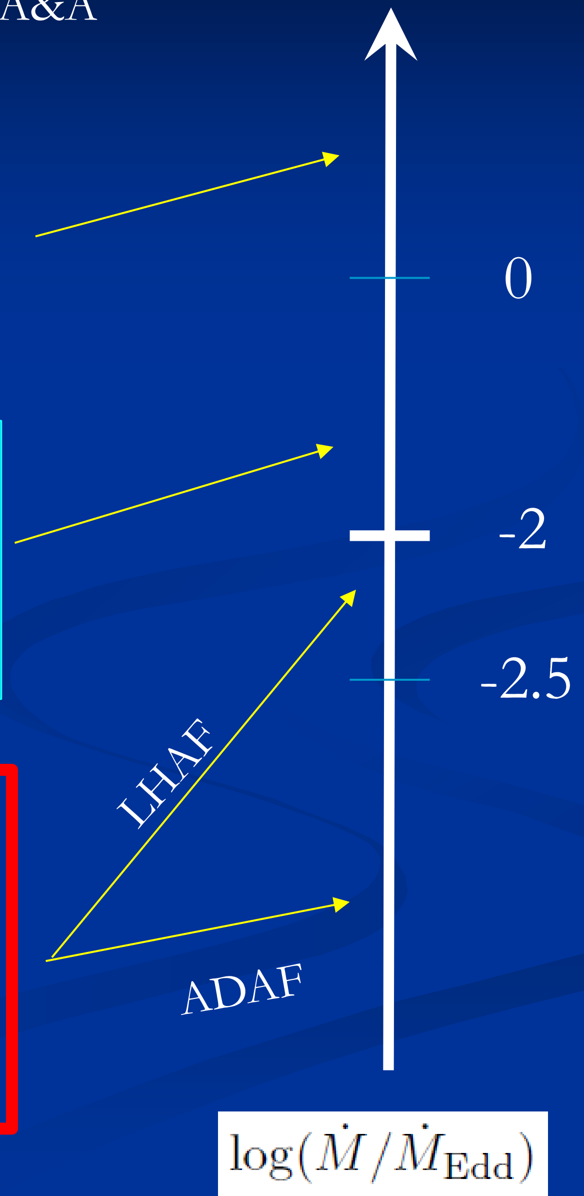
Accretion Regimes

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)
Typical QSOs, Seyferts; XRBs in thermal soft state

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



Wind exists in all regimes

- Super-Eddington accretion
  - Strong wind found in simulations (Ohsuga et al.; Sadowski et al. 2014; Jiang et al. 2014; Yang, Yuan et al. 2013)
  - Mechanisms: radiation + ?
- Standard thin disk
  - Many observations (by absorption lines)
  - Radiation line-force (Proga et al., many works; Liu, Yuan et al. 2013)
  - MHD mechanism? (next talk by Defu Bu)
- Hot accretion flow: this talk

OUTLINE

- Wind exists or not in hot accretion flow?
- Properties of wind
- Driving mechanism of wind
- Disk-jet (vs. Blandford-Znajek jet)
- Wind model for the formation of Fermi bubbles

Outflow (wind): why interesting?

- Accretion physics
  - Outflow: exists or not? important ingredient of accretion physics
  - Crucial to explain many observations of AGNs & BH binaries
- AGNs feedback
  - Outflow plays an important role in AGN feedback
  - Need to constrain their properties: mass flux, velocity, density…

Observations of wind

- AGNs
  - Frequently detected in luminous AGNs: BAL quasar
  - But also in LLAGN; e.g. NGC 4395: $L_{bol} = 10^{-3} L_{Edd}$ (Crenshaw & Kraemer 2012)
  - Wind and jet coexist in radio loud galaxies (Tombesi et al. 2014)
- Black hole X-ray binaries
  - Previously: wind exits in soft state
  - Recently: also in hard state (Homan, Neilsen et al. 2016)

Brief history of study of wind

- Narayan & Yi (1994) speculate there should be outflow
- Blandford & Begelman (1999): construct ADIOS
- HD & MHD simulations (Yuan, Bu & Wu 2012; Narayan et al. 2012; Li, Ostriker & Sunayev 2013):
  - Self-consistently simulate both disk and outflow
  - show the existence of MHD outflow
- Analytical works:
  - 1D: Begelman (2012); Gu (2015)
  - 2D: Jiao & Wu (2011); Mosallanezhad, Bu & Yuan (2016)

Accretion rate decreases inward

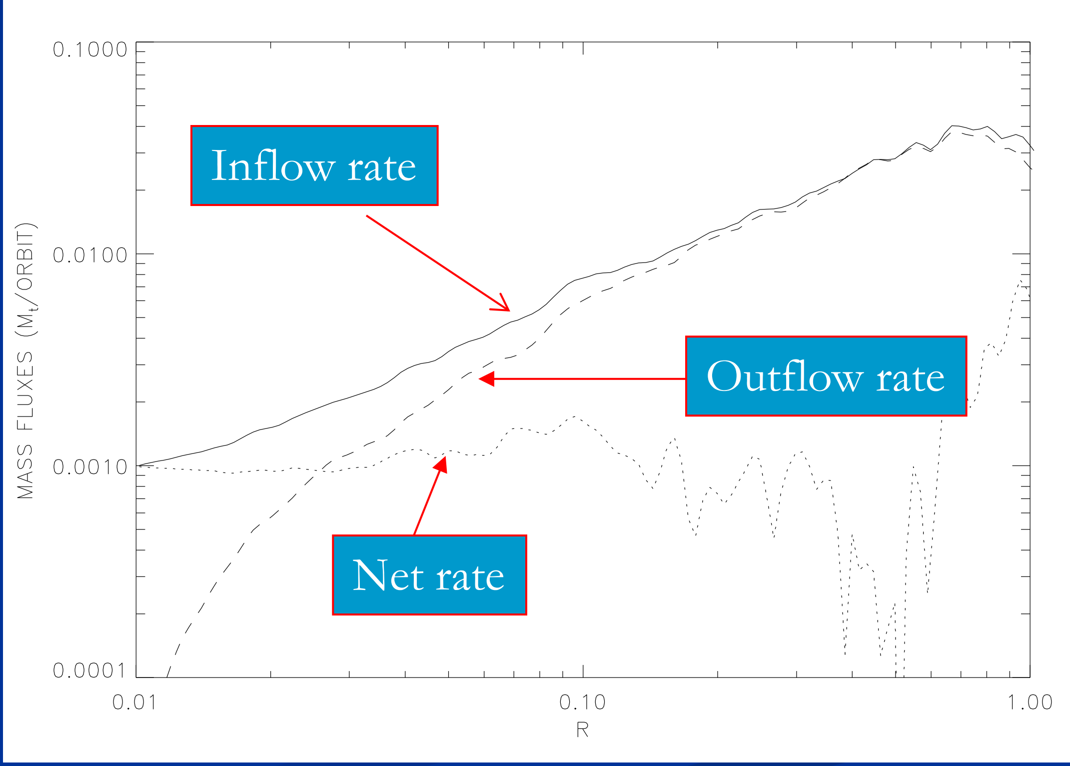
Stone, Pringle & Begelman 1999; Stone & Pringle 2001; Hawley & Balbus 2002; Machida et al 2003; Pen et al. 2003; Igumenshchev, Narayan & Abramowicz 2003; Pang et al. 2010; Yuan & Bu 2010; Yuan, Wu & Bu 2012; Narayan et al. 2012; Li, Ostriker & Sunyaev 2013

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

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

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

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



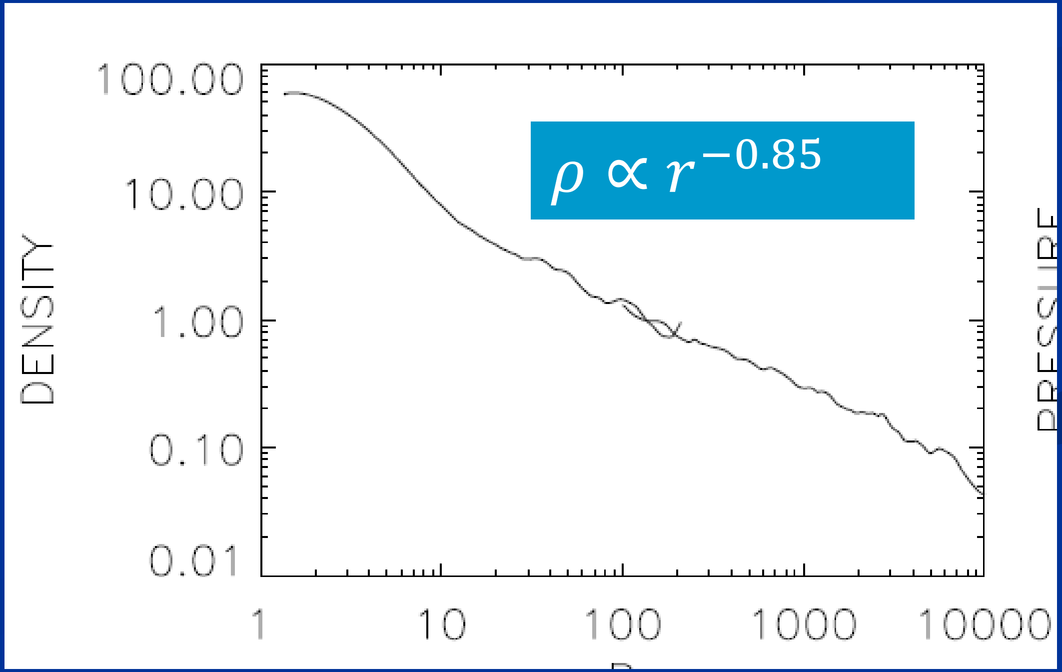
Stone, Pringle & Begelman 1999

Density profile flattens

If Mdot is constant, then:

$$\rho \propto r^{-3/2}$$

When Mdot decreases inward →



Yuan, Wu & Bu 2012

Confirmed by Observations of Sgr A*

Aitken et al. 2001; Bower et al. 2003, 2005; Yuan, Quataert & Narayan 2003

- Chandra observations + Bondi theory give the Bondi rate:

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

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

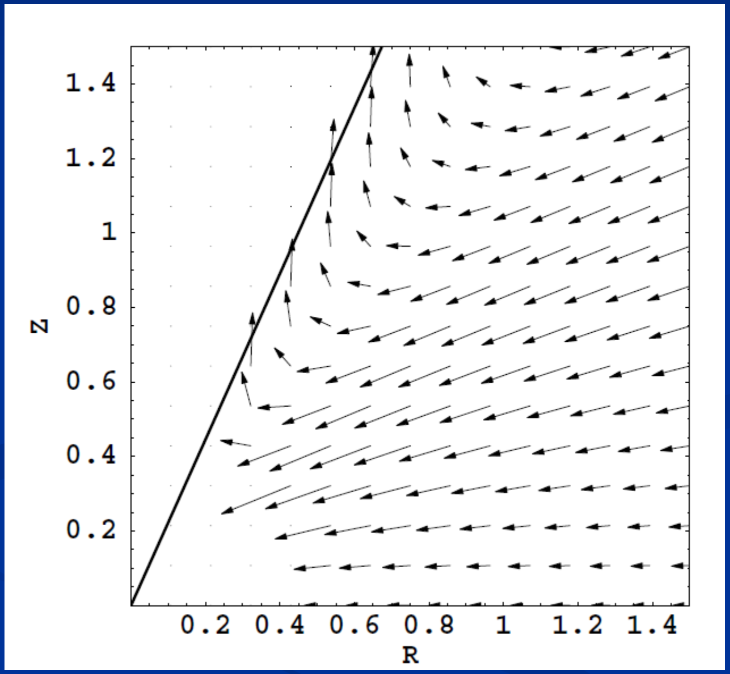
- High linear polarization at radio waveband requires innermost region accretion rate (rotation measure requirement):

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

- So Mdot must decrease inward!

Two Models proposed to explain the simulation

- Adiabatic Inflow-Outflow Solution (Blandford & Begelman 1999; 2004)
  - Assumption: Mass loss in outflow → Mdot decreases
- Convection-Dominated Accretion Flow (Narayan et al. 2000; Quataert & Gruzinov 2000)
  - basis: accretion flow is convectively unstable
  - Gas is locked in convective eddies → Mdot decreases
  - MHD flow is convectively unstable?



Blandford & Begelman 1999

ADIOS or CDAF?

Yuan et al. (2012, 2015)

- Performed HD & MHD simulations
- Theoretical analysis:
  - If convective turbulence, inflow & outflow properties should roughly same; → but different!
  - Analyze the convective stability of *MHD* accretion flow → stable!
  - Study the trajectory of virtual particles in the acc. flow
- Conclusion: strong outflow exists!

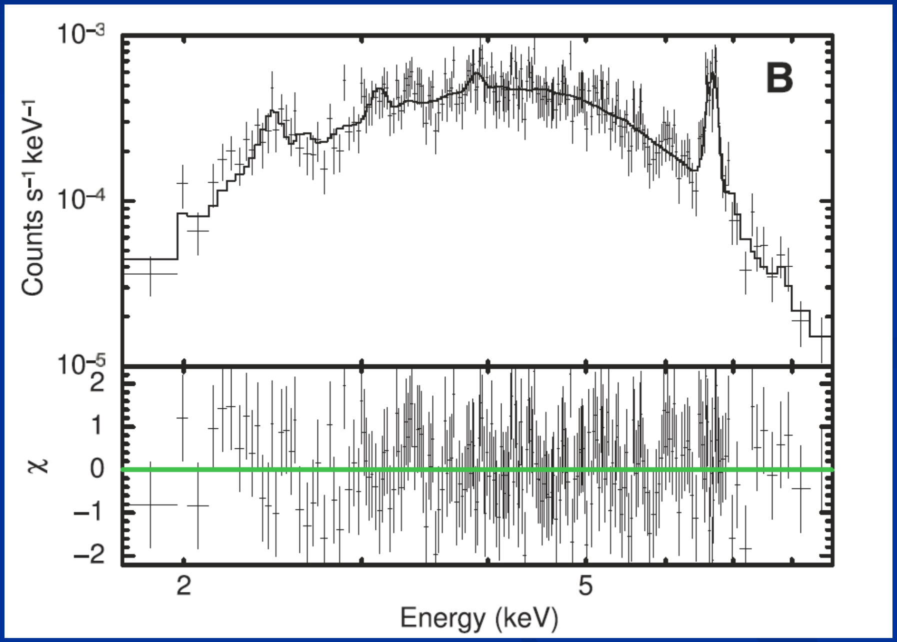
Outflow confirmed by new observations

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

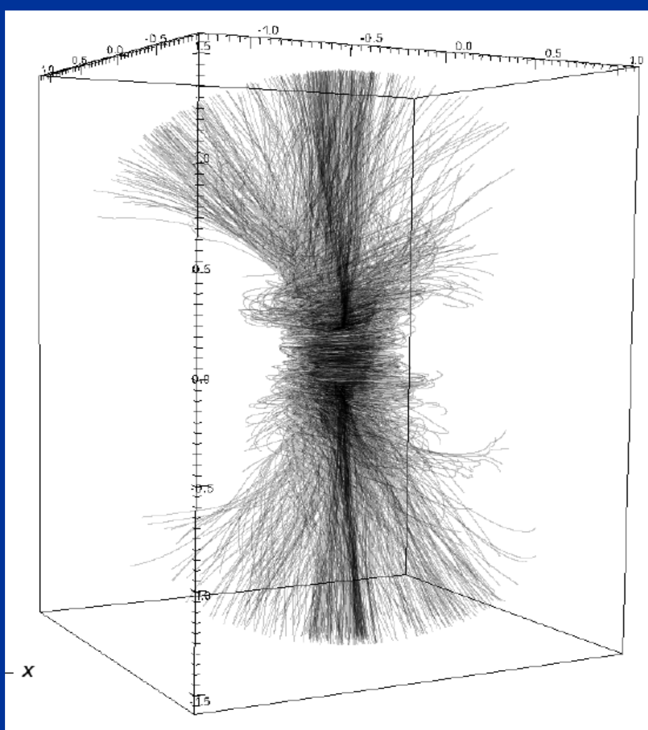
→ outflow



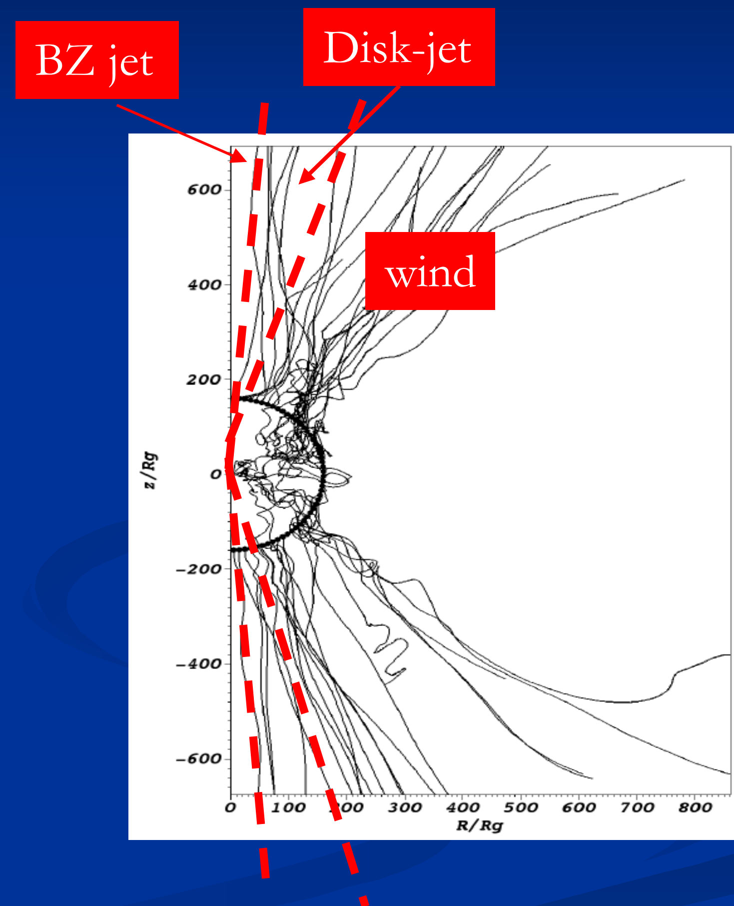
“Virtual particle trajectory”

Yuan et al. 2015, 2016

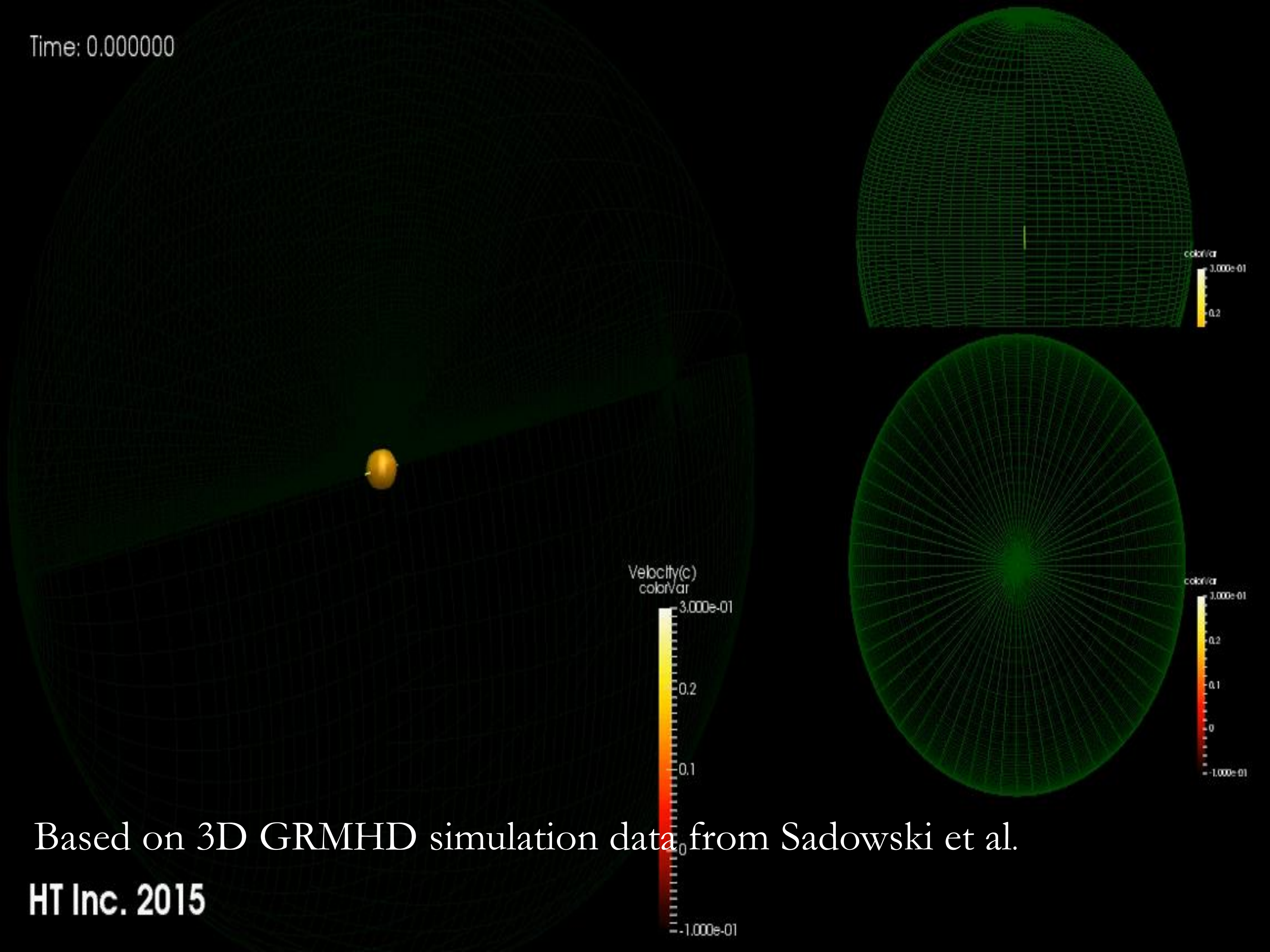
- Trajectory approach
  - Firstly used in BH accretion
  - What & why?
  - Based on 3D GRMHD data



3D



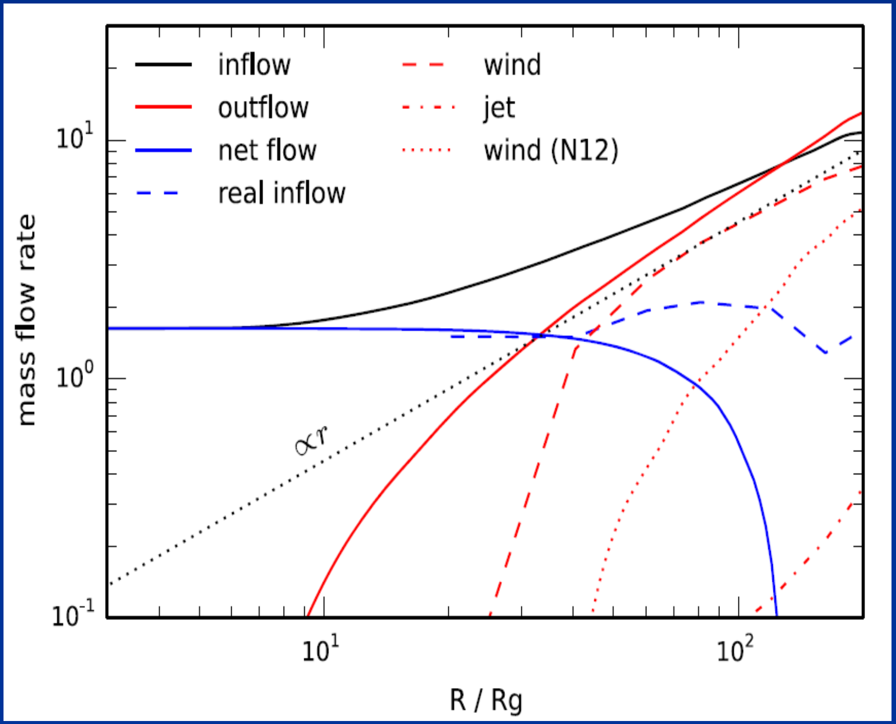
2D



Based on 3D GRMHD simulation data from Sadowski et al.

Properties of wind: mass flux

Yuan et al. 2015, 2016



"Normal" magnetic field:

$$\dot{M}_{wind} = \dot{M}_{BH}(r)\left(\frac{r}{20r_s}\right), \quad a = 0$$

$$\dot{M}_{wind} = \dot{M}_{BH}(r)\left(\frac{r}{10r_s}\right), \quad a = 0.9$$

"Strong" magnetic field (MAD):

$$\dot{M}_{wind} = \dot{M}_{BH}(r)\left(\frac{r}{5r_s}\right), \quad a = 0.9$$

Properties of wind: poloidal speed

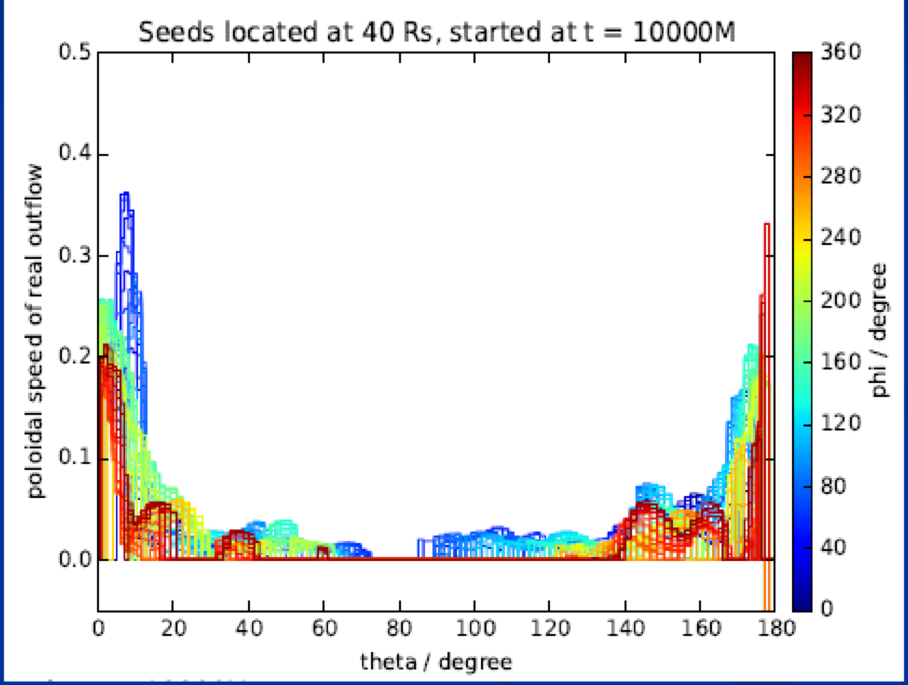
Yuan et al. 2015; 2016

- Angular distribution
  - Disk-jet: *(0.3-0.4)c*
- Poloidal speed:

$$v_p(r) \sim (0.2 - 0.7) v_k(r)$$

(*a* has little effect but *B* does!)

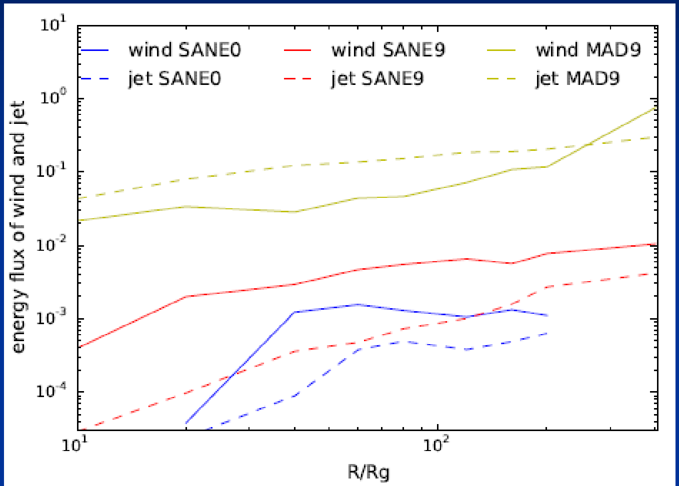
- Conserve or even slightly increase along trajectories

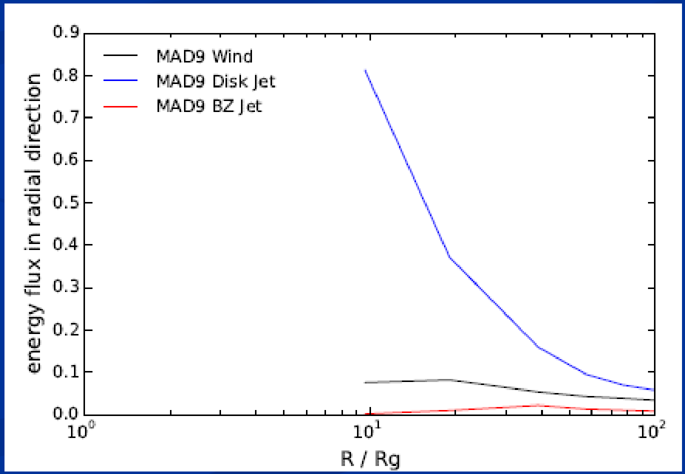


Properties of outflow: energy flux

Yuan et al. 2015; 2016

- Contribution from: plasma & Poynting flux
- Energy flux *(temporary results)*
  - For MAD & *a=0.9*:
    - wind < jet (for both plasma & Poynting flux)
    - Disk-jet vs. BZ jet ?
  - For all other cases (SANE & any *a*):
    - wind > jet
    - Disk-jet > BZ jet
- Energy flux of wind vs. accretion:





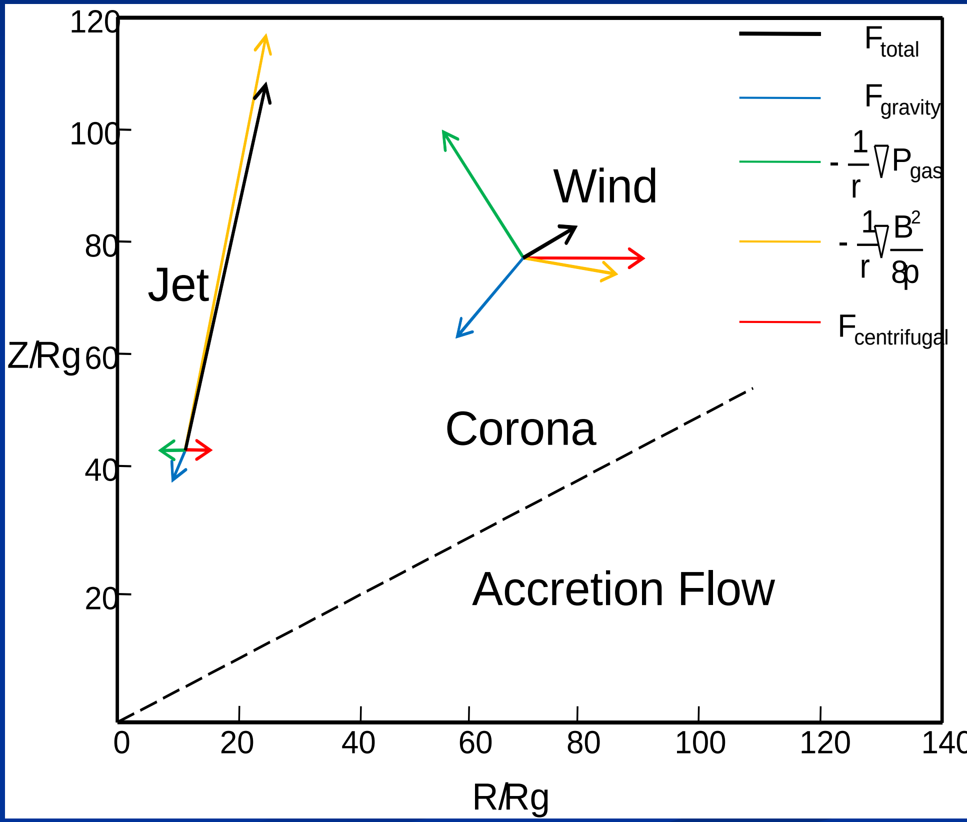
$$\dot{E}_{wind} = \frac{1}{1000}\dot{M}_{BH}c^2$$

→ consistent with AGN feedback simulations

Mechanism of wind production

Yuan et al. 2015

- Driving forces:
  - Centrifugal force
  - Gradient of gas & magnetic pressure
- Comparison with Blandford & Payne (1982)
  - BP82: large-scale field + only centrifugal
  - We don't have large-scale poloidal field, we have both centrifugal & magnetic force (since $\hat{v} \neq \hat{B}$!)



Wind vs. jet: summary

- Mass flux: wind >> jet
- Velocity: wind < jet
- Energy flux: wind < jet only for MAD & a=0.9
- Momentum flux: jet at most comparable to wind (?)

Given that the opening angle of wind is much larger than jet,
Wind may be more important than jet in AGN feedback

Disk-jet (versus BZ jet)

Yuan & Narayan 2014; Yuan et al. 2015, 2016

- Matter dominated
- Powered by the rotation of disk → so present even a=0
- Power of disk-jet vs. BZ jet?

  (Livio, Ogilvie & Pringle 1999)
- not powered by Blandford-Payne, but by the magnetic tower mechanism proposed by Lynden-Bell (gradient of the pressure of toroidal magnetic field)

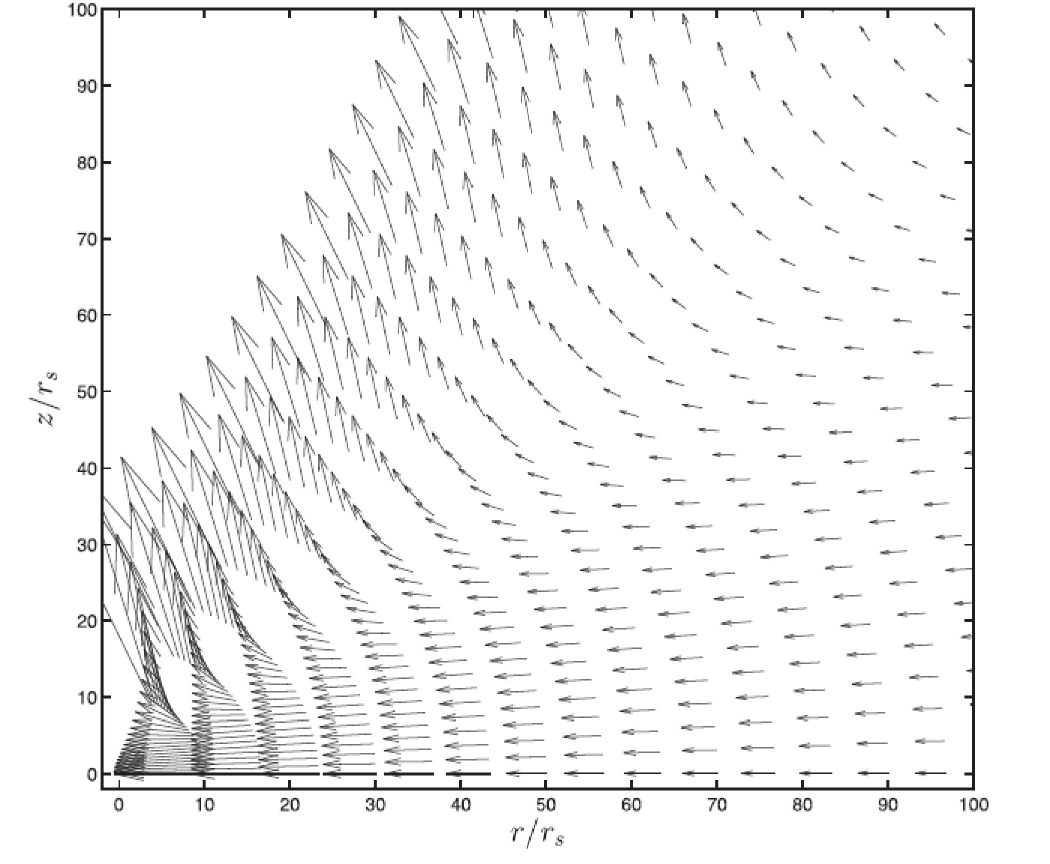
Question:

Disk jet & BZ jet, which one is associated with the observed jet?

2D MHD analytical solution with winds

Mosallanezhad, Bu & Yuan 2016

- Including B field
- Reproducing the main simulation results
  - Strong wind found
  - Wind can transport *l*
  - Wind velocity
  - But: direction

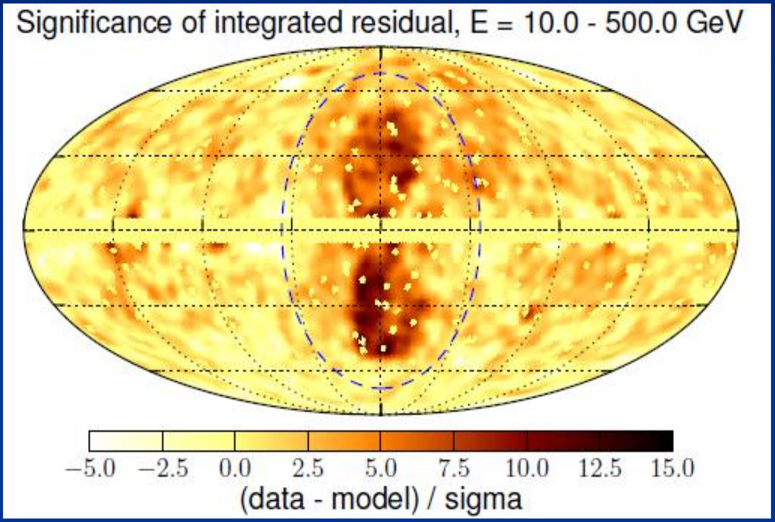


Does the same mechanism produce wind from a thin disk?

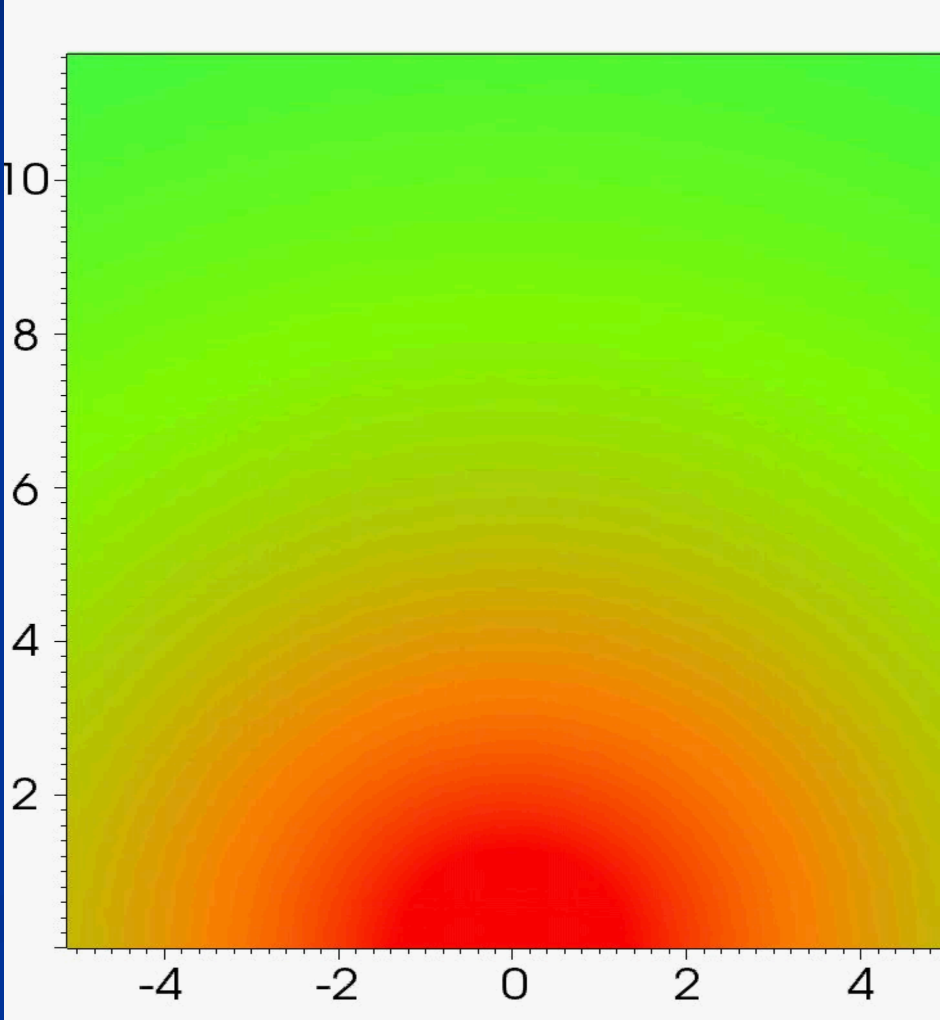
→ Next talk by Defu Bu

Application: "accretion wind" model for Fermi bubbles

Mou, Yuan et al. 2014; 2015



Su et al. 2010; Ackermann et al. 2014

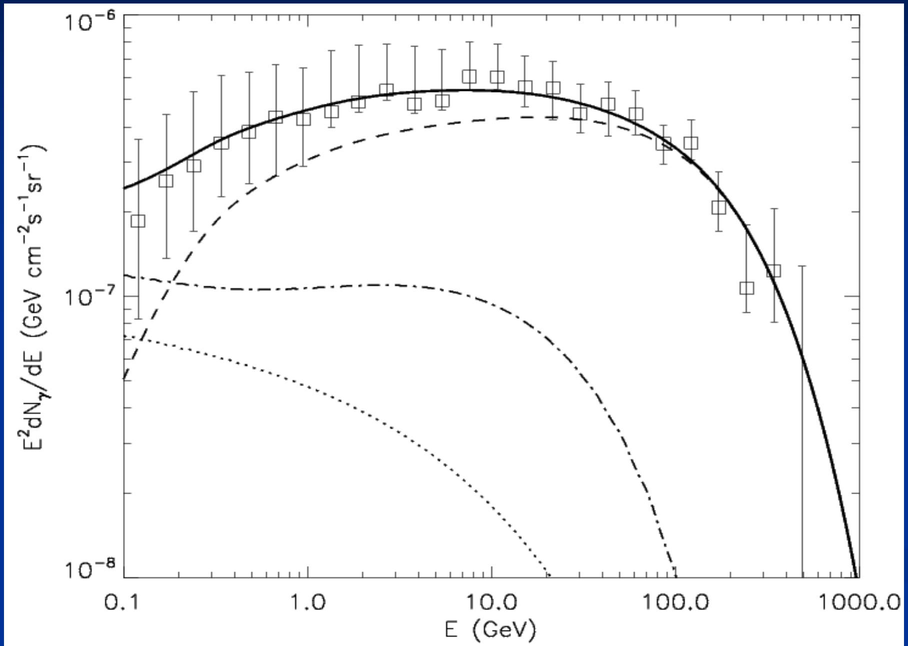


Our wind model:

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

Results: γ-ray radiation and others

- Total γ-rays:



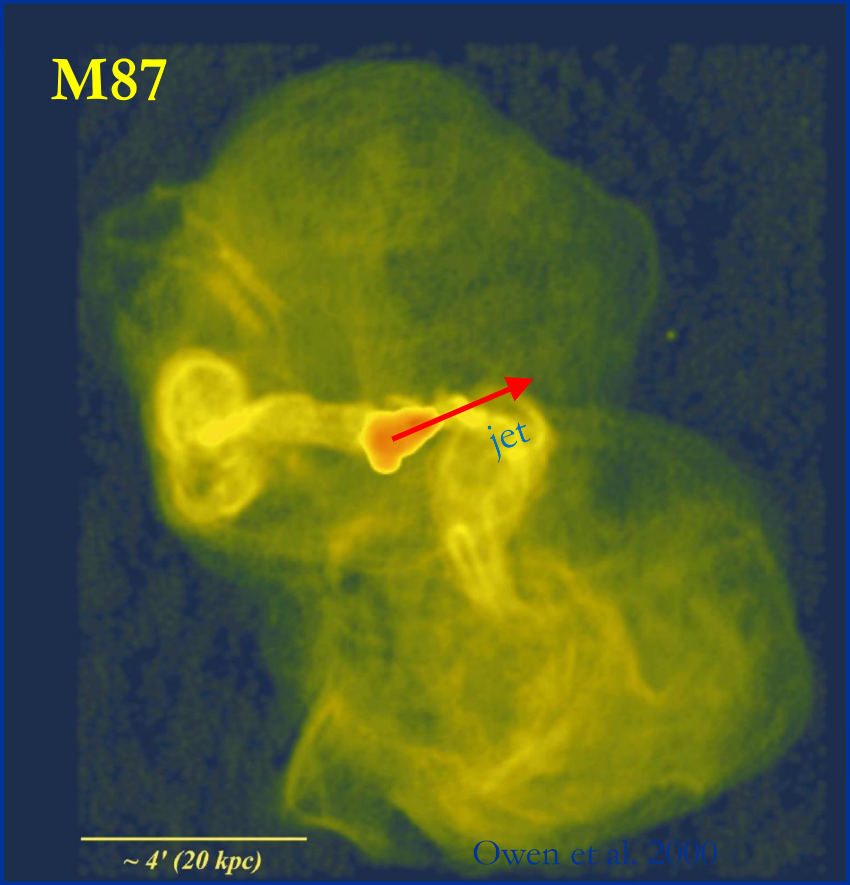
- Other features:
  - Surface brightness
  - Temperature of shocked ISM (observed: 0.3 kev):

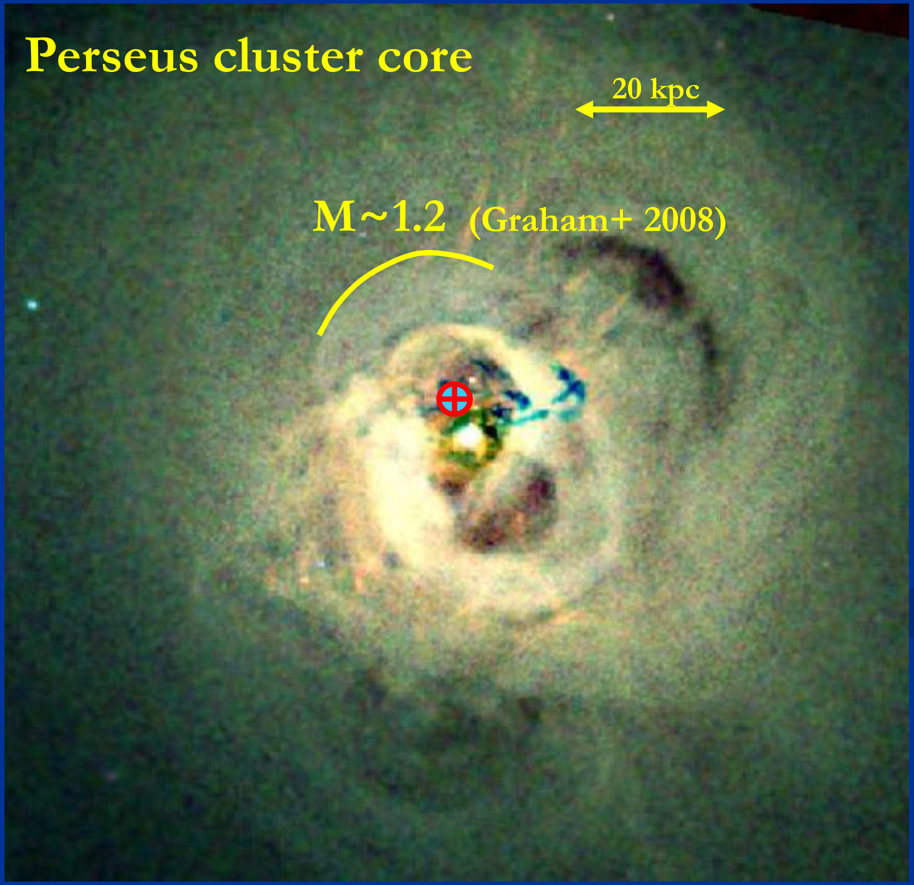
Models	Jet	Radiation-driven wind	SF-driven Wind	Hot Accretion Wind
Temperature (NPS)	> 5 keV	~ 1 keV	N	0.4-1 keV
Age	1-2 Myr	6 Myr	10^2-10^3 Myr	7-12 Myr

  - Velocity of bubble edge --- consistent with observations

Implication: roles of wind in other aspects

- Formation of X-ray cavities and bubbles: by wind?
- Solving the cooling flow problem with wind ?(Mou & Yuan 2016)





Summary

- Strong wind exists in hot accretion flows
- Properties of wind obtained with trajectory method
- Perhaps in most cases, energy & momentum flux of wind > jet, so wind may more important for AGN feedback than jet
- Disk-jet identified, powered by magnetic tower mechanism → associated with the observed jet?

Thank you!