Black hole accretion

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Outline

- Chapter 1: Introduction to some basic concepts and Review of accretion models
- Chapter 2: The standard thin disk and slim disk
- Chapter 3: Hot accretion flow: dynamics & radiation
- Chapter 4: Hot accretion flow: applications
- Chapter 5: Wind and jet
- Chapter 6: AGN feedback

Chapter 6:
Interaction between AGN and ISM

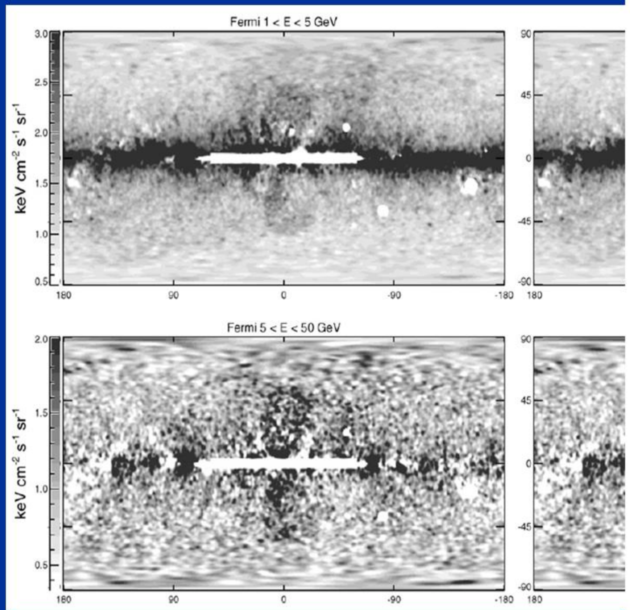
6.1 Fermi bubbles

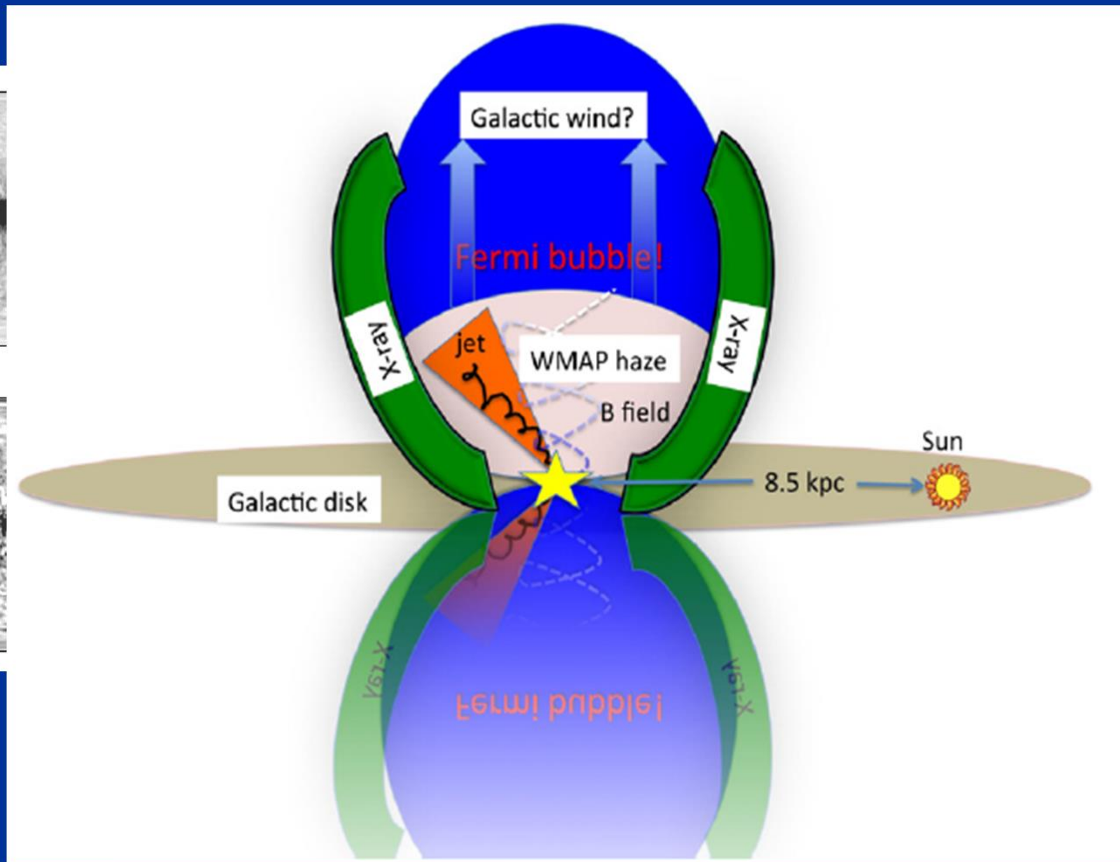
The Fermi Bubbles

Su et al. 2010

Two giant γ-ray bubbles discovered by Fermi-LAT

- Morphology, Surface brightness, Spectrum

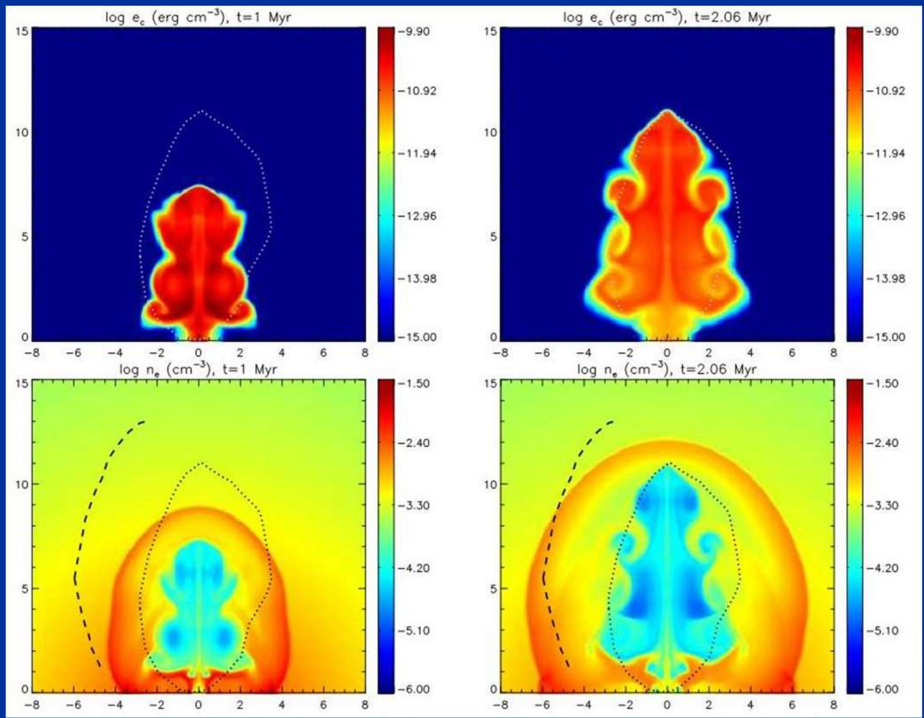




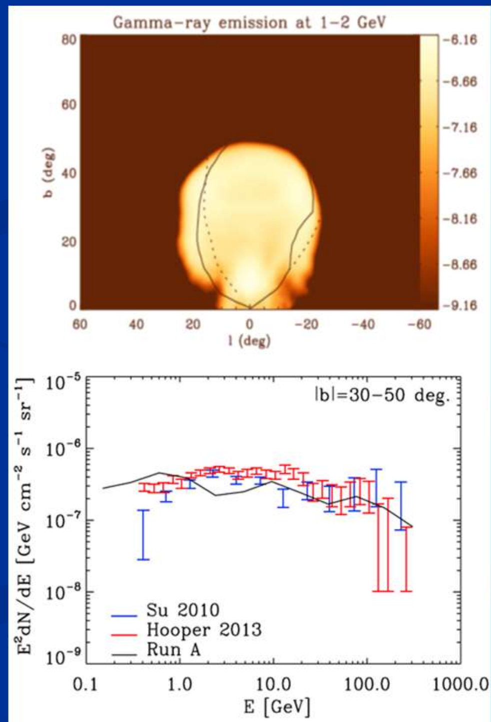
Jet Model (I)

Guo & Mathews 2012; Guo et al. 2012; Yang et al. 2012, 2013

- Jet lasted for ~0.3 Myr, quenched 1-2 Myr ago
- Jet interacts with ISM and form the bubbles
- Gamma-rays: IC scatterings of ISRF by CRe.



Guo & Mathews 2012



Yang et al. 2013

Jet Model (II)

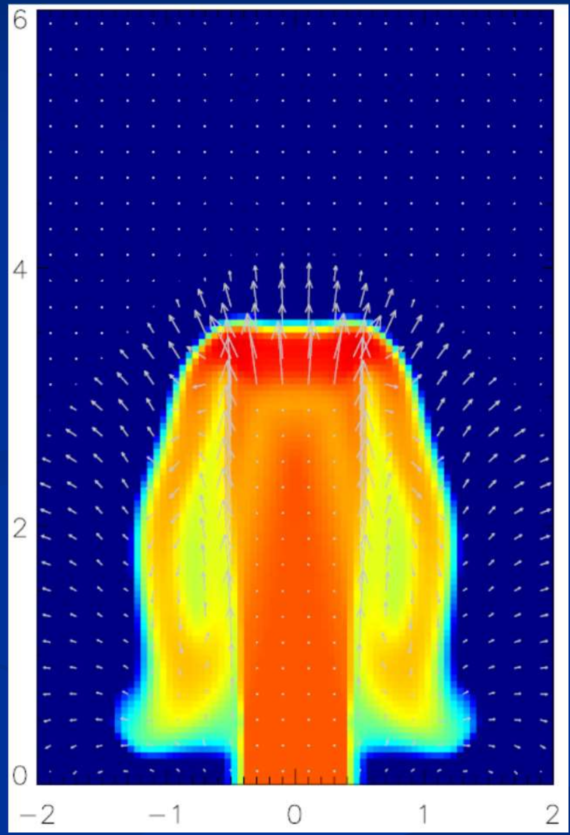
Guo & Mathews 2012; Guo et al. 2012; Yang et al. 2012, 2013

Assumptions:

- Jet direction $\perp$ Galactic plane
- Jet velocity too low: $\leq 0.1c$
- Jet mass loss rate too large:
  - Guo et al. 2012: $0.3\dot{M}_{Edd}$ (one jet)
  - Guo & Mathews 2012, Yang et al. 2012, 2013: 3 or $170\dot{M}_{Edd}$ (one jet)

v_{jet}	Jet speed	0.025	c
R_{jet}	Radius of cross section	0.5	kpc
t_{jet}	Duration of injection	0.3	Myr

Yang et al. 2013

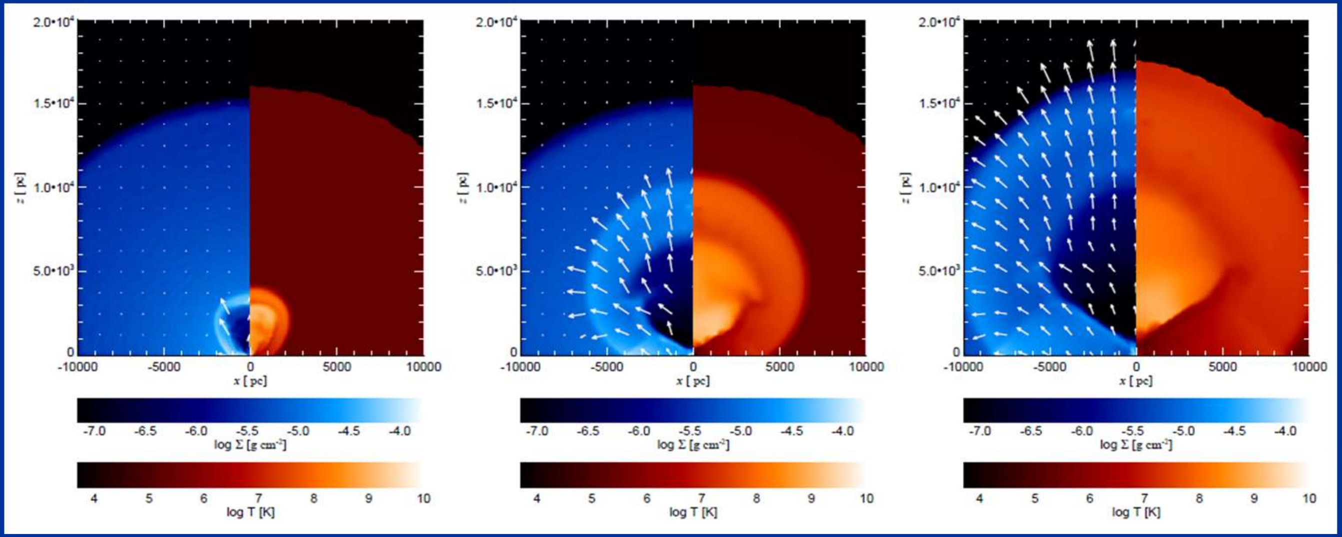


Guo et al. 2012

Models (II): Quasar outflow model

Zubovas, Nayakshin & King 2011; Zubovas & Nayakshin 2012

- Assume Sgr A* was a quasar; lasting for 1Myr; quenched 5 Myr ago
- Strong wind from quasar
- Parameters of wind: v~0.1c , $\dot{M}_{out} \sim \dot{M}_{Edd}$, $P_{wind} \sim 5\% \; L_{Edd}$



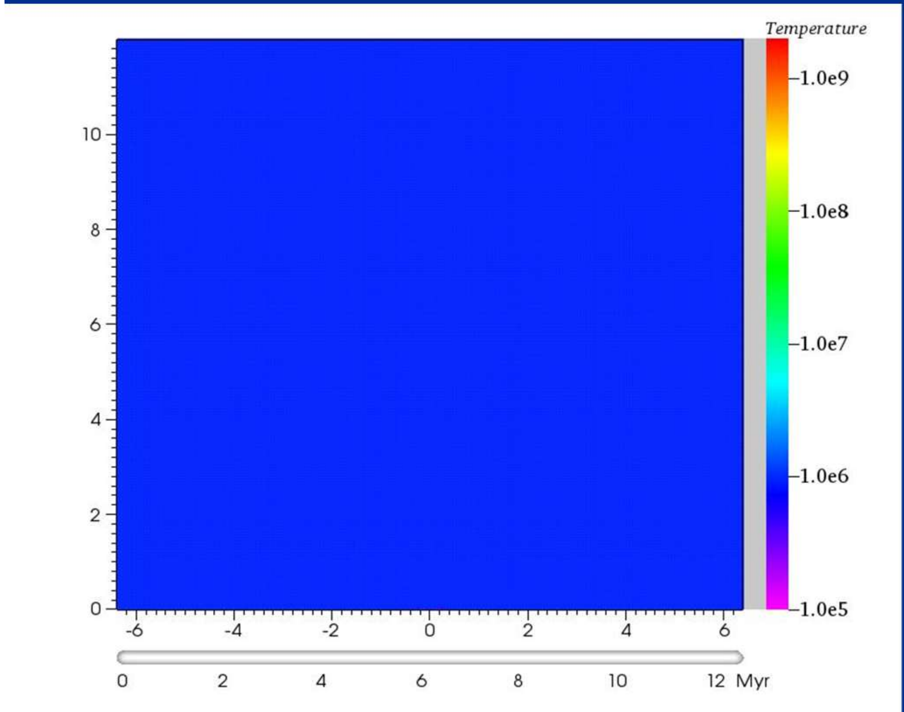
Problems:

M*ildly super-Eddington* – too large?

- Totani (2006) shows that $P_{wind} \sim 10^{41}$ erg/s (~10^{-3} L_{Edd}).
- Suzaku observation: confirm the above value (Kataoka et al. 2013).

Our model: Inflated by accretion wind

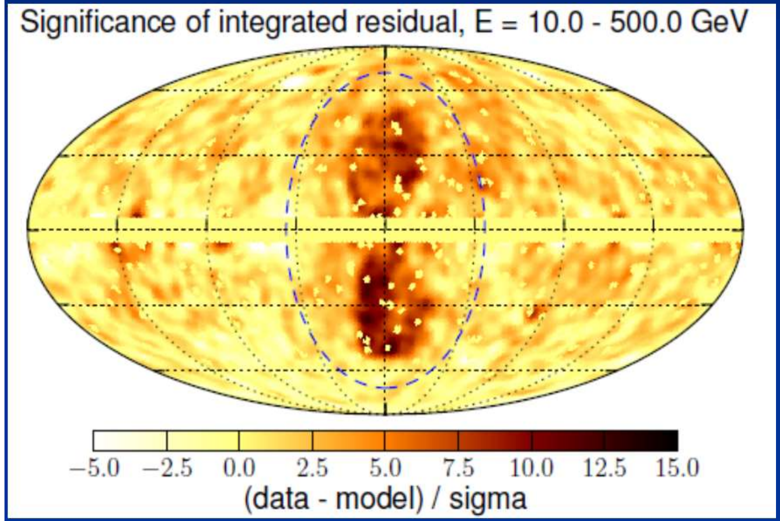
Mou et al. 2014, 2015



- Past activity of Sgr A*
  - Independent constrain on Mdot: 10^4 times higher
  - Still a RIAF
- Detailed numerical simulation
  - Accretion rate: from other independent constrain
  - Properties of outflow: determined by MHD simulation of accretion flow
  - 3DMHD+two-fluid
- Consistent with observations

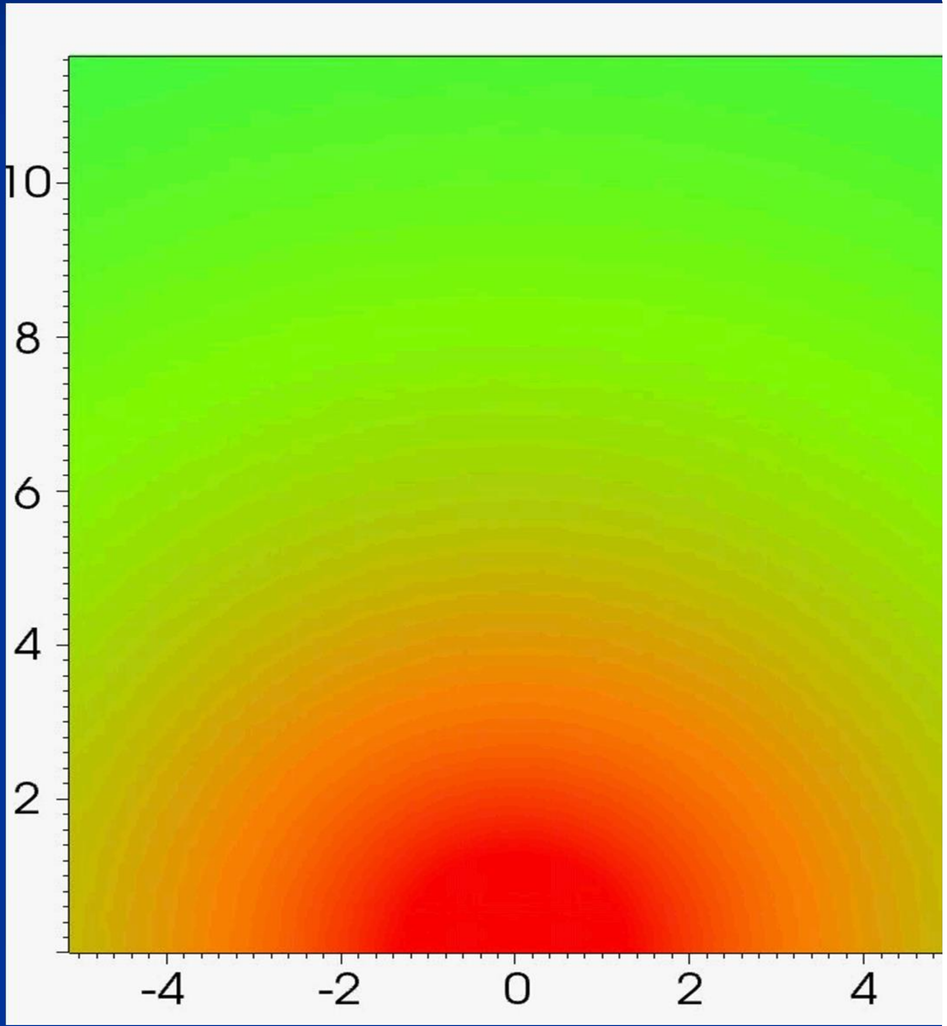
Application I: "accretion wind" model for Fermi bubbles

Mou, Yuan et al. 2014; 2015



Su et al. 2010; Ackermann et al. 2014

(Rossi X-ray Prize)

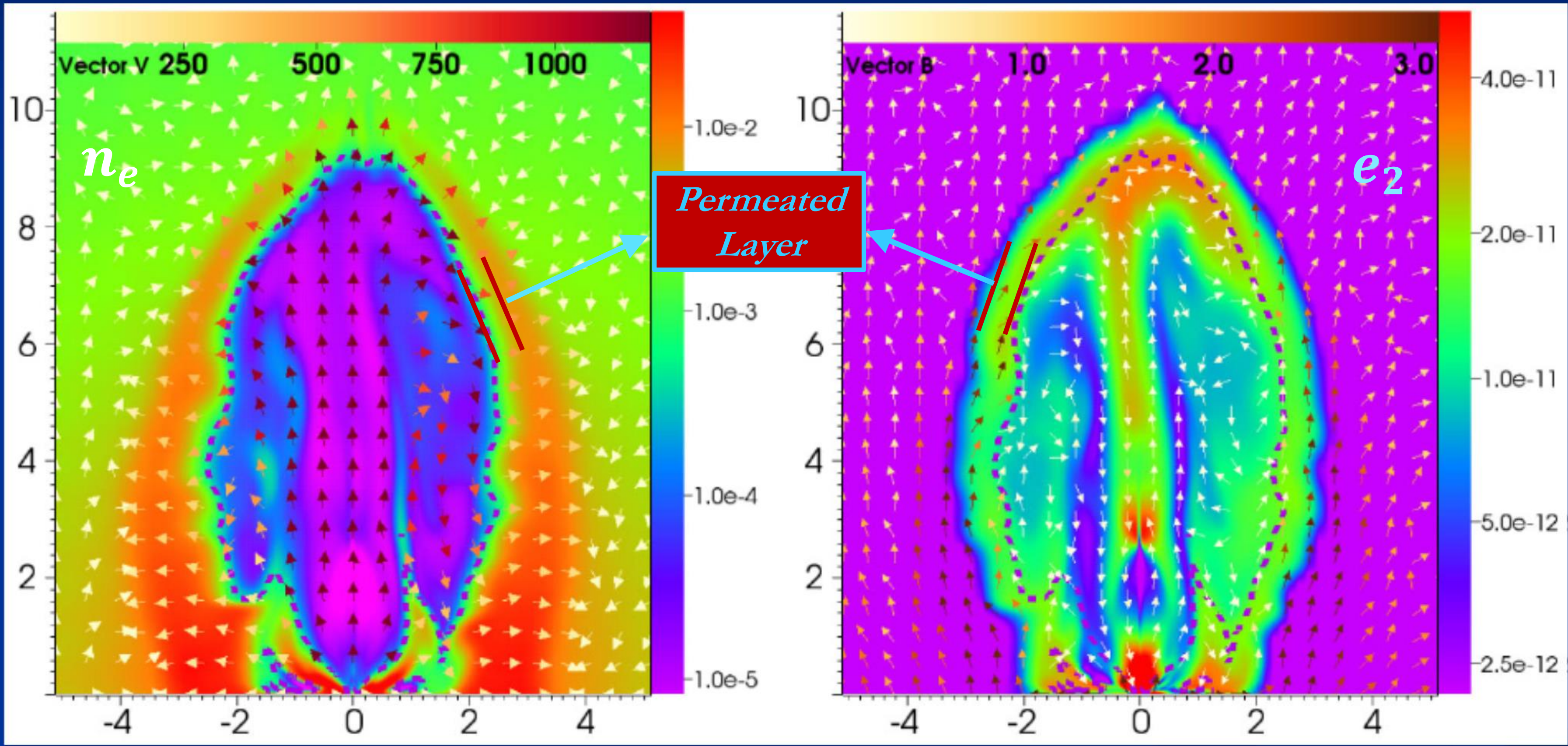


Our wind model:

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

Results: γ-ray radiation

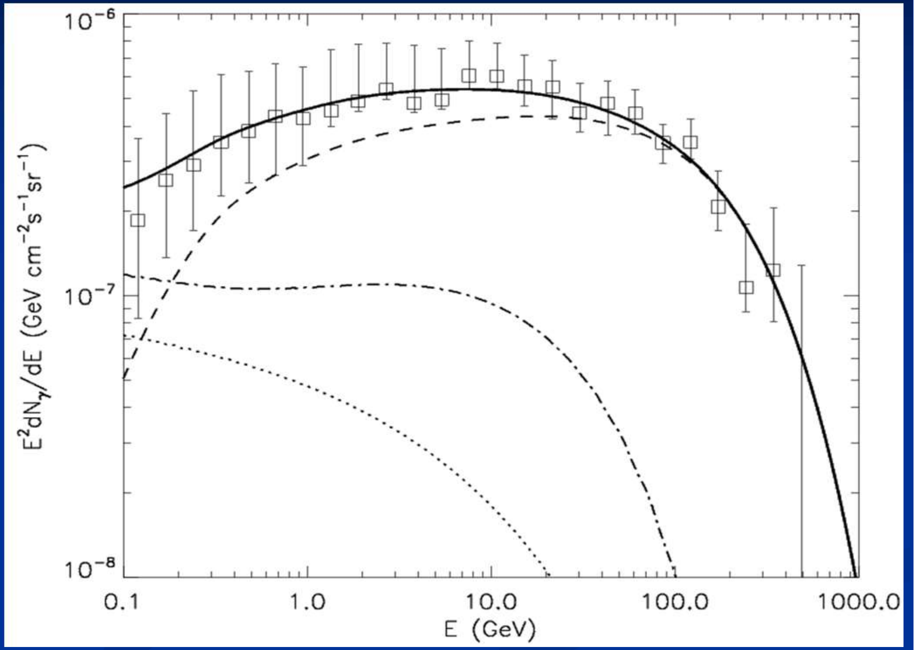
Mou et al. 2015



Left: density and velocity. *Right:* CR energy density and magnetic field.

Results: γ-ray spectrum and others

- γ-rays spectrum:
- 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

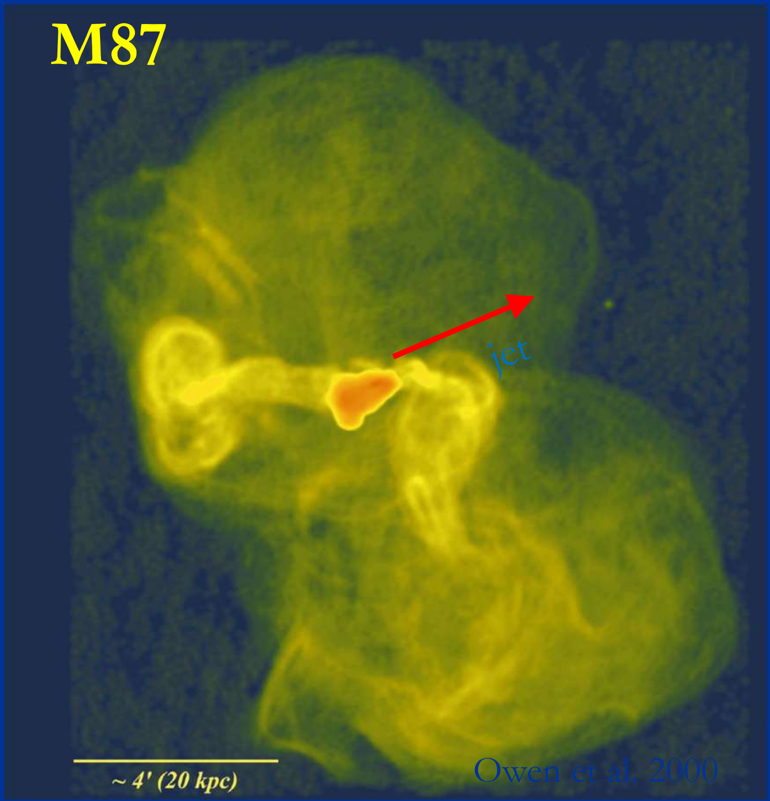
- Velocity of bubble edge --- consistent with observations

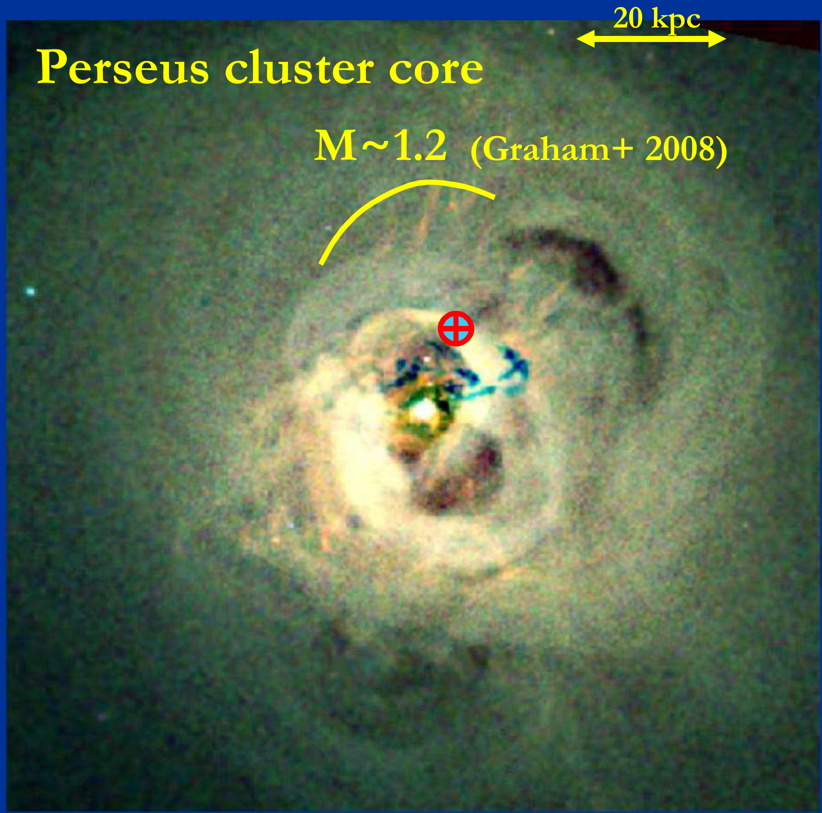
Example & Implication: roles of wind in other aspects

Example: Heliosphere: by solar wind

Implications:

- Formation of X-ray cavities and bubbles: by wind?
- Solving the cooling flow problem with wind ?



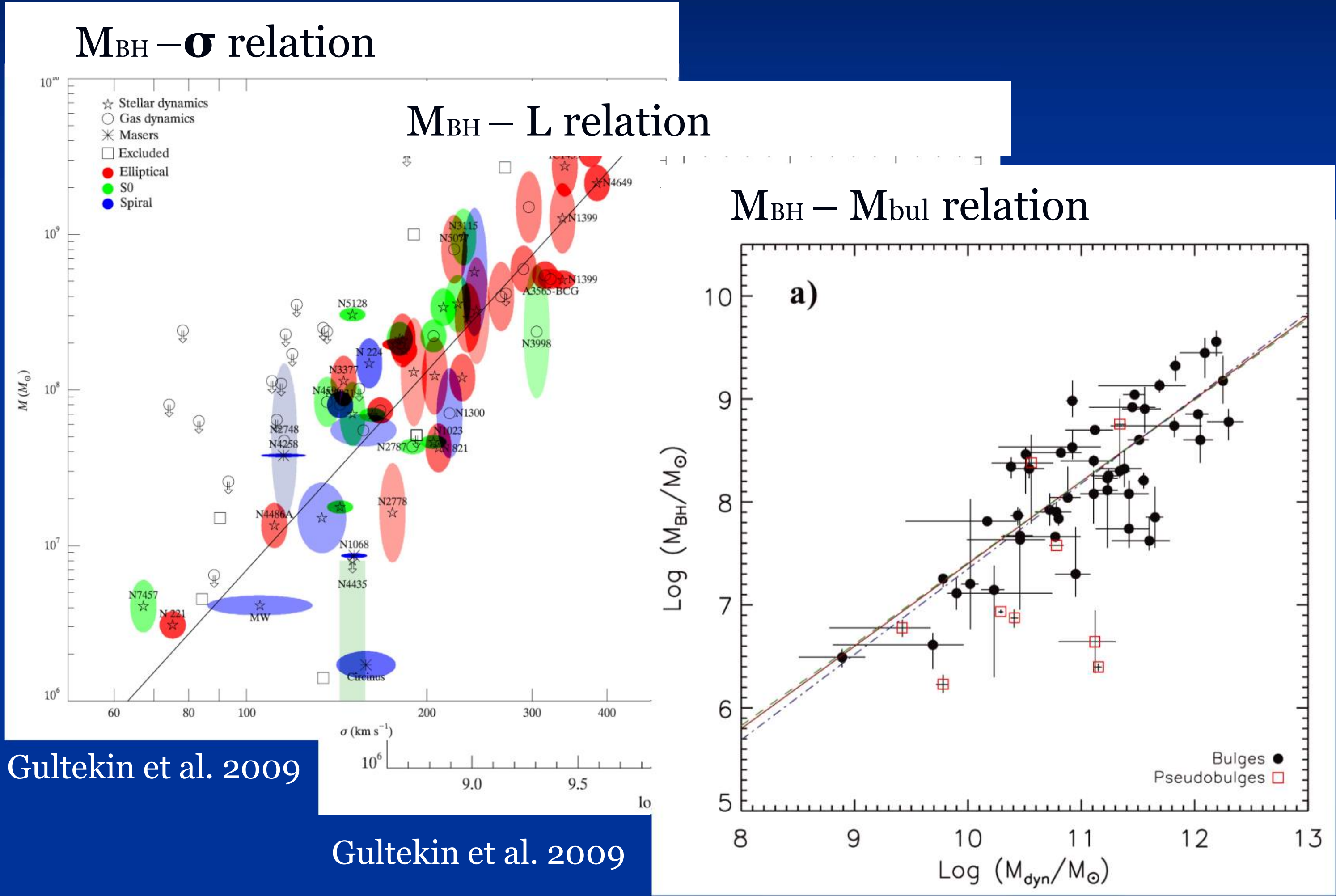


6.2 AGN feedback

Observational evidence of AGN Feedback

(Fabian 2012, ARAA; Kormendy & Ho 2013, ARAA)

(I): Coevolution of AGNs and Their Host Galaxies



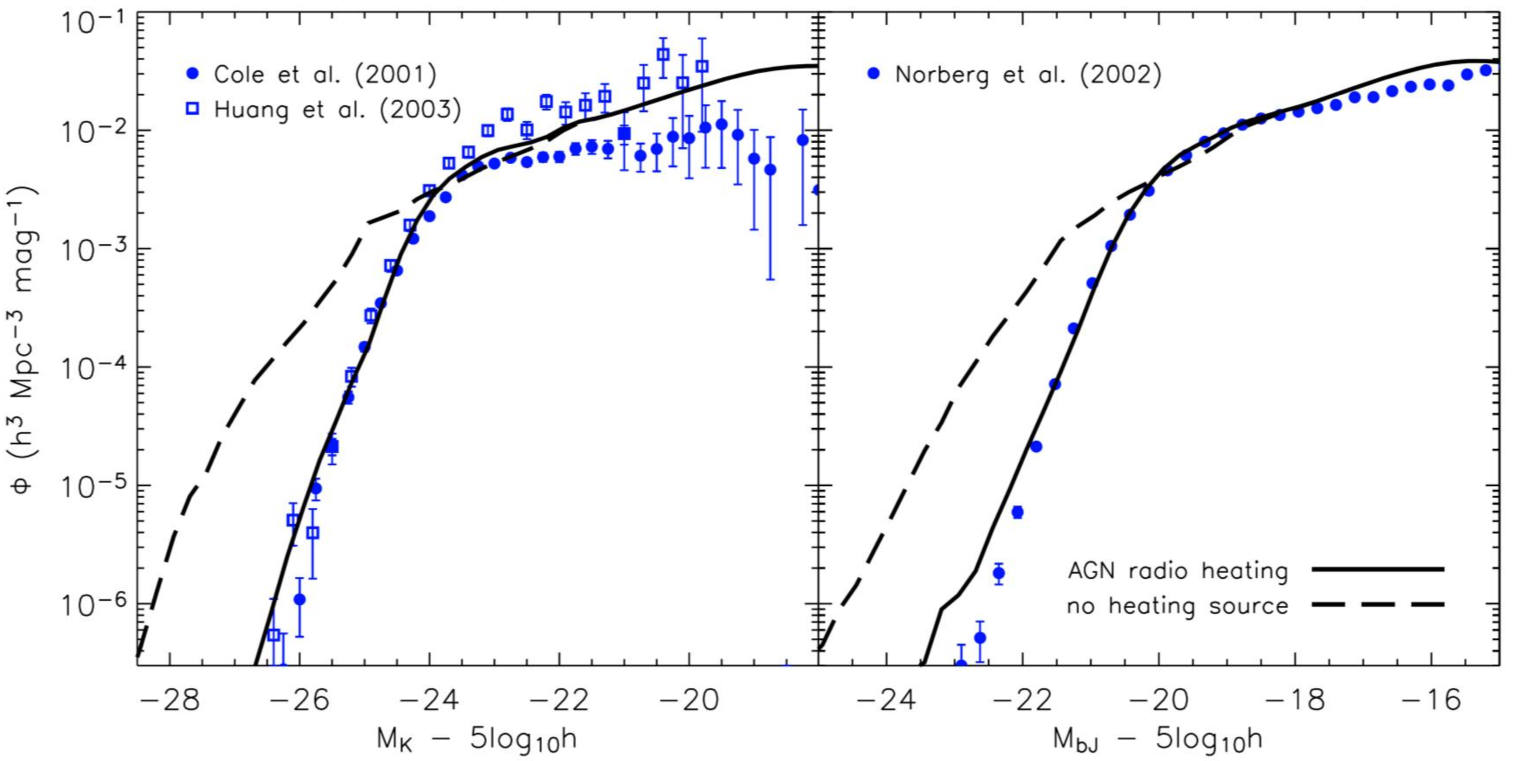
Gultekin et al. 2009

Gultekin et al. 2009

Sani et al. 2011

Observational evidence for AGN Feedback:
(II) High-mass end truncation of galaxy luminosity function

Galaxy luminosity function



Croton Springel et al. 2006

Other evidences of AGN feedback

- Downsizing puzzle (Cowie et al. 1996)
  - The most massive galaxies and BHs are the oldest
- Cooling flow problem in galaxy clusters (Peterson et al. 2001)
  - Lack of significant cooling in cluster cores
  - AGN heating may be the key

Why AGN Feedback Important ?

--- Energetic estimation

The total energy emitted by the black hole during its growth:

$$E_{tot} = \varepsilon M_{BH} c^2$$

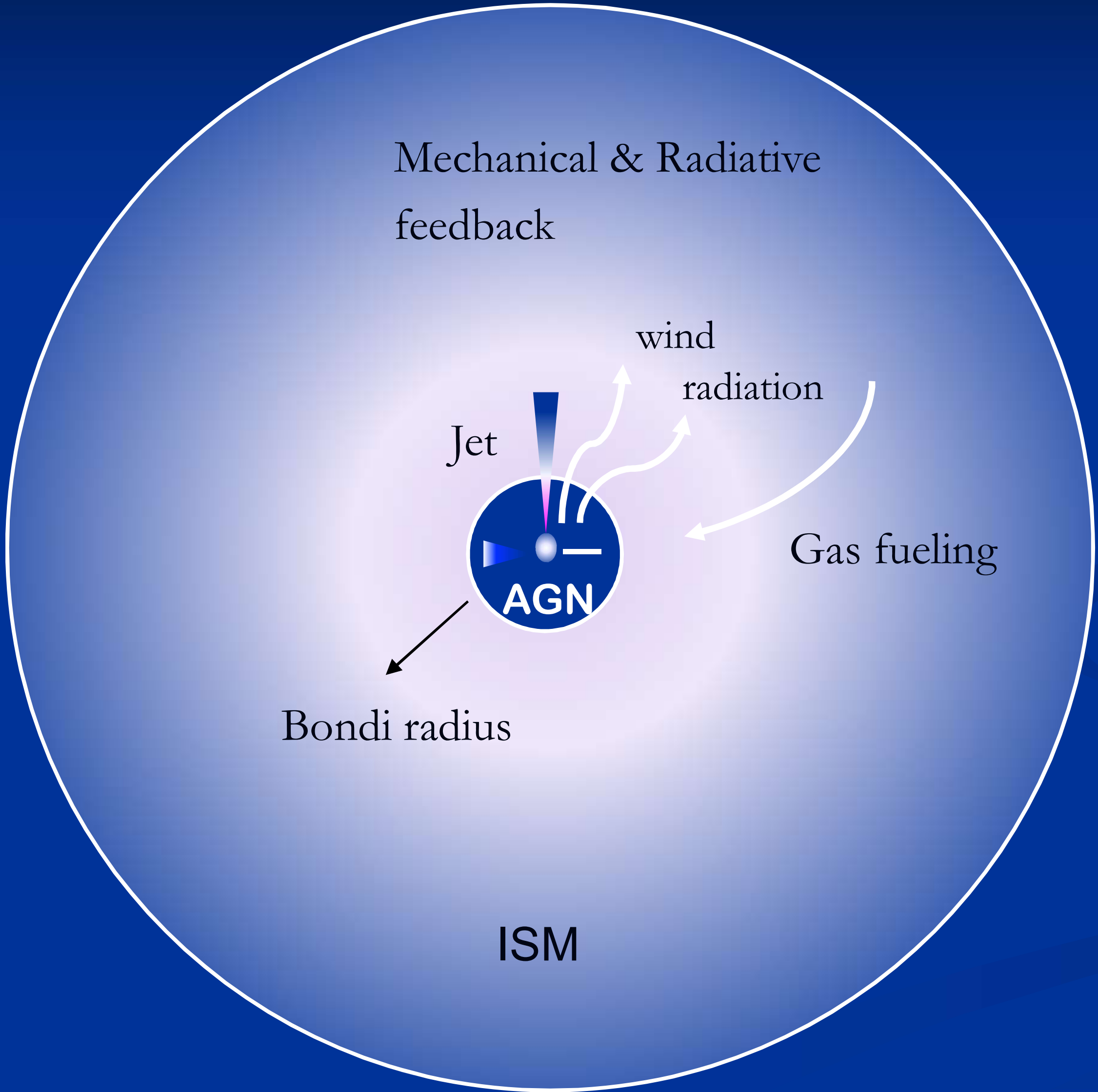
The gravitational energy of a virialized sphere (e.g., the stellar bulge):

$$E_{grav} \approx M_{sph} \sigma_*^2$$

The ratio is

$$E_{tot}/E_{grav} >> 1$$

AGN feedback



Key issues of AGN feedback:

- How to determine BH accretion rate ?
- For a given rate, what are the outputs from AGN?

Hydrodynamical Equations

$$\frac{D\rho}{Dt} + \rho\nabla \cdot \mathbf{v} = \alpha\rho_* + \dot{\rho}_{II} - \dot{\rho}_*^+,$$

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p + \rho\mathbf{g} - \nabla p_{\mathrm{rad}} - \dot{m}_*^+,$$

$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -p\nabla \cdot \mathbf{v} + H - C + \dot{E}_S + \dot{E}_I + \dot{E}_{II} - \dot{E}_*^+.$$

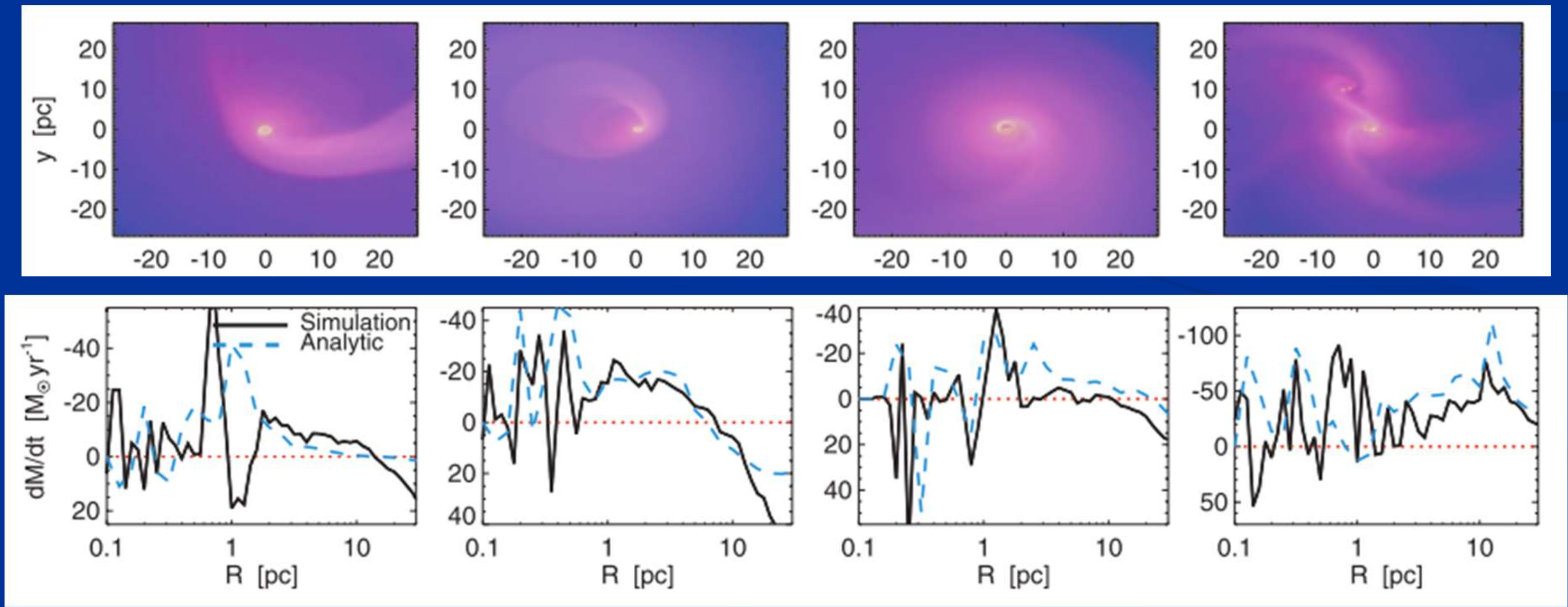
Physics included in the model:

- Stellar mass loss from dying stars
- Gas depletion from star formation
- Feedback of Type II supernovae
- Feedback of Type Ia supernovae
- Thermalization due to stellar dispersive motion

Angular Momentum Transport

Yoon et al. 2018

- Magneto-rotational Instability (MRI; Stone+99,01)
- Gravitational Instability (Gammie 01)
- Anisotropic Gravitational Torque (Hopkins+10,11)
  - This is what we adopt
  - We use alpha description to mimic it



Galaxy Model

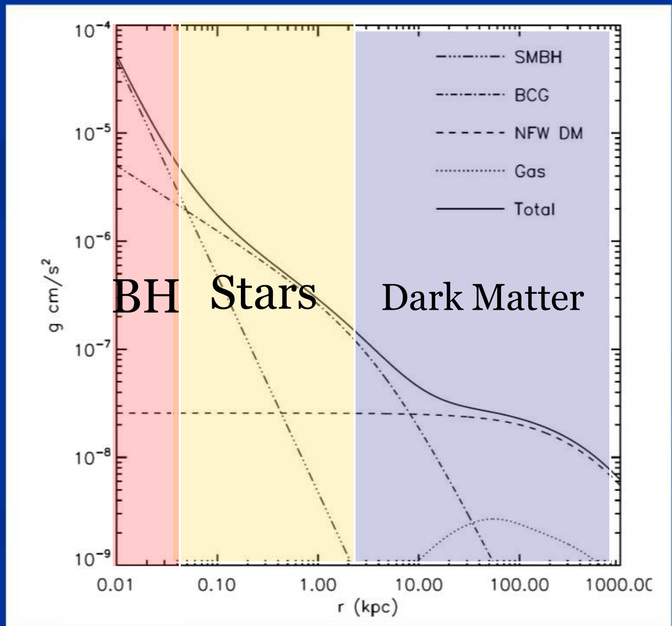
We focus on the **cosmological evolution** of an **isolated elliptical galaxy.**

Gas source

- only stellar mass loss during their cosmological evolution

Gravity

- Super massive black hole
- Stellar population
- Dark matter halo
- But no gravity from interstellar medium



Li&Bryan2012

Contribution of SN Ia to energy

Ciotti, Ostriker et al. 2009

Massive stars (SNe II) died before the simulation starts due to their short lifetime.

But **SNe Ia** can be triggered by **accretion or merger events of neutron stars/white dwarfs**,

$$R_{\mathrm{SN}}(t) \approx 0.32 \times 10^{-12} h^2 \frac{L_{\mathrm{B}}}{L_{\mathrm{B,sun}}} \left(\frac{t}{13.7\,\mathrm{Gyr}} \right)^{-1.1} \quad \mathrm{yr}^{-1}$$

Each SN Ia releases energy in an order of 10^51 erg

Star Formation

We estimate SFR using the standard Schmidt-Kennicut prescription:

$$\dot{\rho}_{\rm SF} = \frac{\eta_{\rm SF}\,\rho}{\tau_{\rm SF}} \qquad \tau_{\rm SF} = \max(\tau_{\rm cool}, \tau_{\rm dyn})$$

We also consider **SNe II** among the **newly formed stars**.

$$N_{\rm II} = \int_{M_{\rm II}}^{\infty} \frac{dN}{dM} dM = \left(1 - \frac{1}{x}\right)\left(\frac{M_{\rm inf}}{M_{\rm II}}\right)^{x} \frac{M_{sun}}{M_{\rm inf}} \frac{\Delta M_*}{M_{sun}} \approx 7 \times 10^{-3} \frac{\Delta M_*}{M_{sun}}$$

Radiative Heating & Cooling

Sazonov et al. 2005

Net energy change rate per unit volume:

$$\dot{M} = n^2 (S^1 + S^2 + S^3)$$

Bremsstrahlung cooling

$$S_1 = -3.8 \times 10^{-27} \sqrt{T}$$

Compton heating/cooling

$$S_2 = 4.1 \times 10^{-35} (T_X - T)\xi$$

photoionization heating, **line and recombination** cooling

$$S_3 = 10^{-23} \times \frac{a + b(\xi / \xi_0)^c}{1 + (\xi / \xi_0)^c}$$

Compton temperature T_c

Sazonov et al. 2004; Xie, Yuan & Ho 2017

- Compton heating ~ $(T_c - T_{ISM})$
- Definition of T_c

$$T_C = \frac{1}{k} \cdot \frac{\int F_\nu \cdot h\nu d\nu}{\int F_\nu \cdot d\nu}$$

- In cold (radiative/quasar) mode (Sazonov et al. 2004):

$$T_c \sim 10^7 \text{ K}$$

- In hot (kinetic/radio) mode (Xie, Yuan & Ho 2017):

$$T_c \sim 10^8 \text{ K}$$

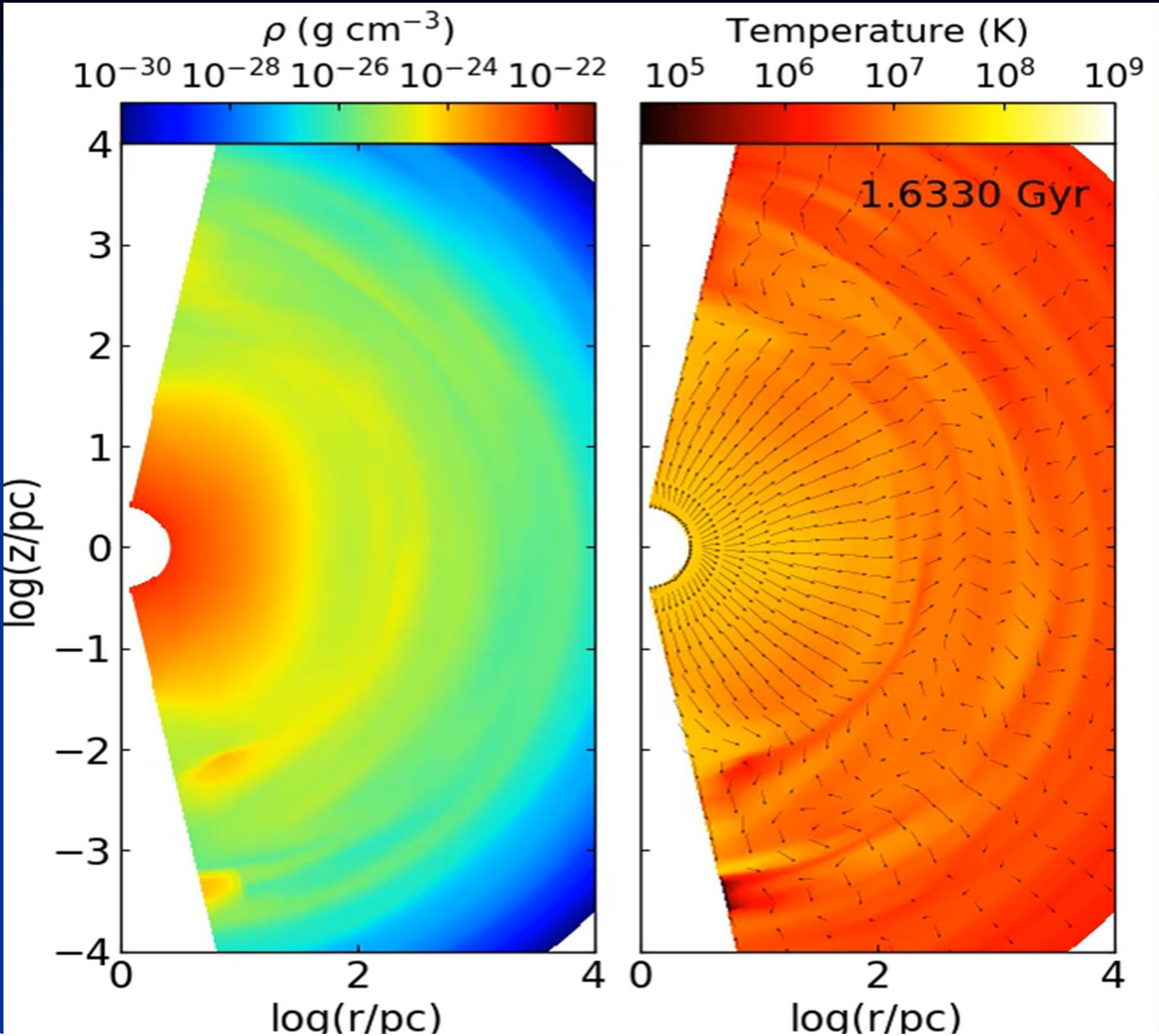
(This is because the SED of LLAGN is different from luminous AGNs: more hard photons)

Setup of *MACER* code

(*M*assive *A*GN *C*ontrolled *E*llipticals *R*esolved)

Yuan et al. 2018; Ciotti & Ostriker 2001, 2007; Novak et al. 2012; Gan et al. 2014

- Based on ZEUS-MP; 2D + hydro + radiation
- Resolution: 0.3 pc
- Simulation domain (spherical coordinate):
  - R_in=2.5 pc (~0.1 Bondi radius);
  - R_out=250 kpc
- Evolve for cosmological time (~12 Gyr)
- Mdot self-consistently determined (not Bondi!)
- Two accretion/feedback modes discriminated
- Inject wind & radiation from R_in then calculate their interaction with ISM

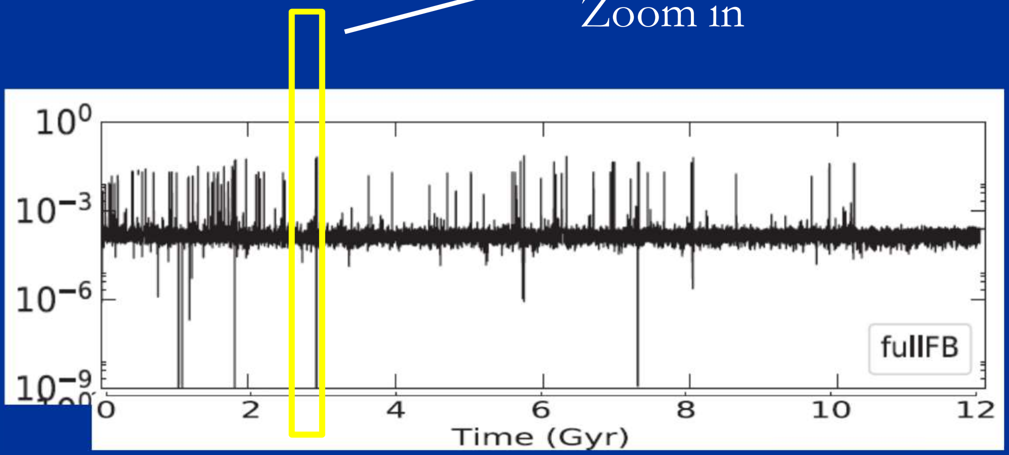


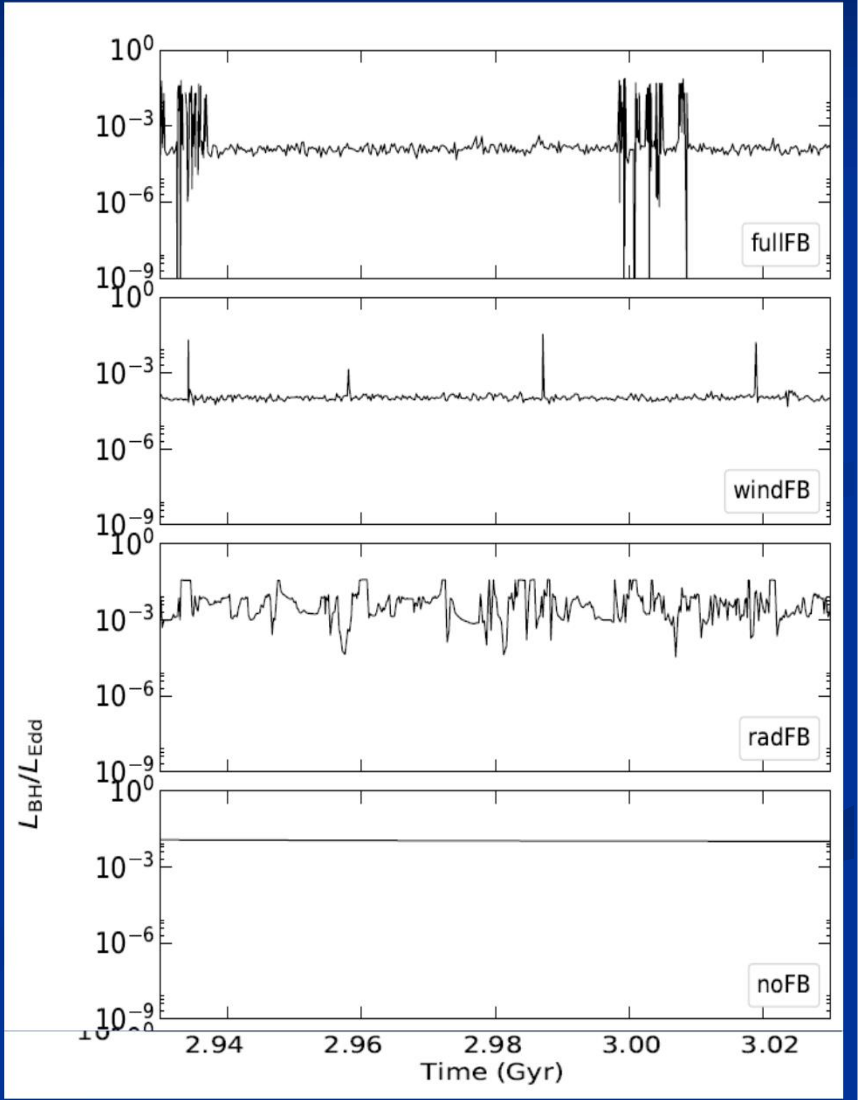
ρ (g cm^{-3})
10^{-30} 10^{-28} 10^{-26} 10^{-24} 10^{-22}
Temperature (K)
10^5 10^6 10^7 10^8 10^9
1.6330 Gyr
log(z/pc)
4 3 2 1 0 −1 −2 −3 −4
0 2 4
log(r/pc)
0 2 4
log(r/pc)

Light curve of AGN (I)

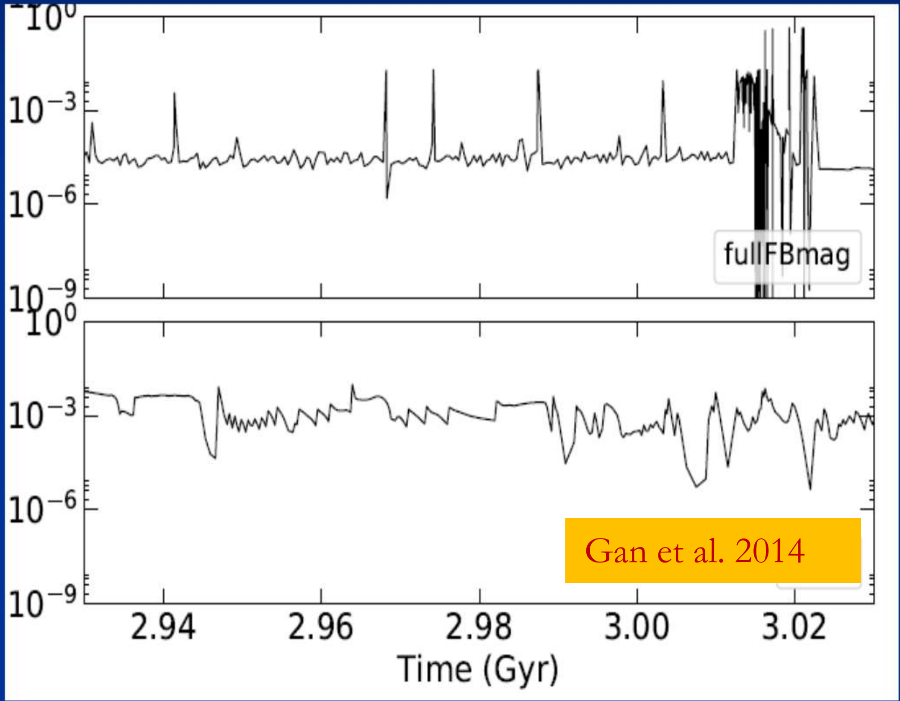
Yuan et al. 2018

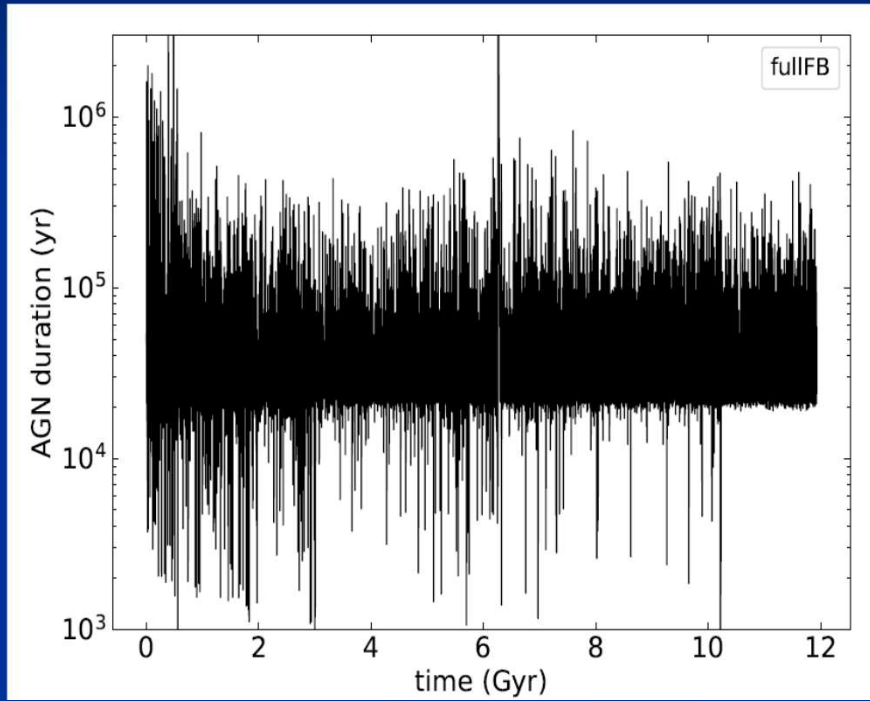
- Most of time, AGN stays in LLAGN phase
- Wind rather than radiation controls Mdot & BH growth
  - Why?





Lightcurve of AGN (II): AGN lifetime

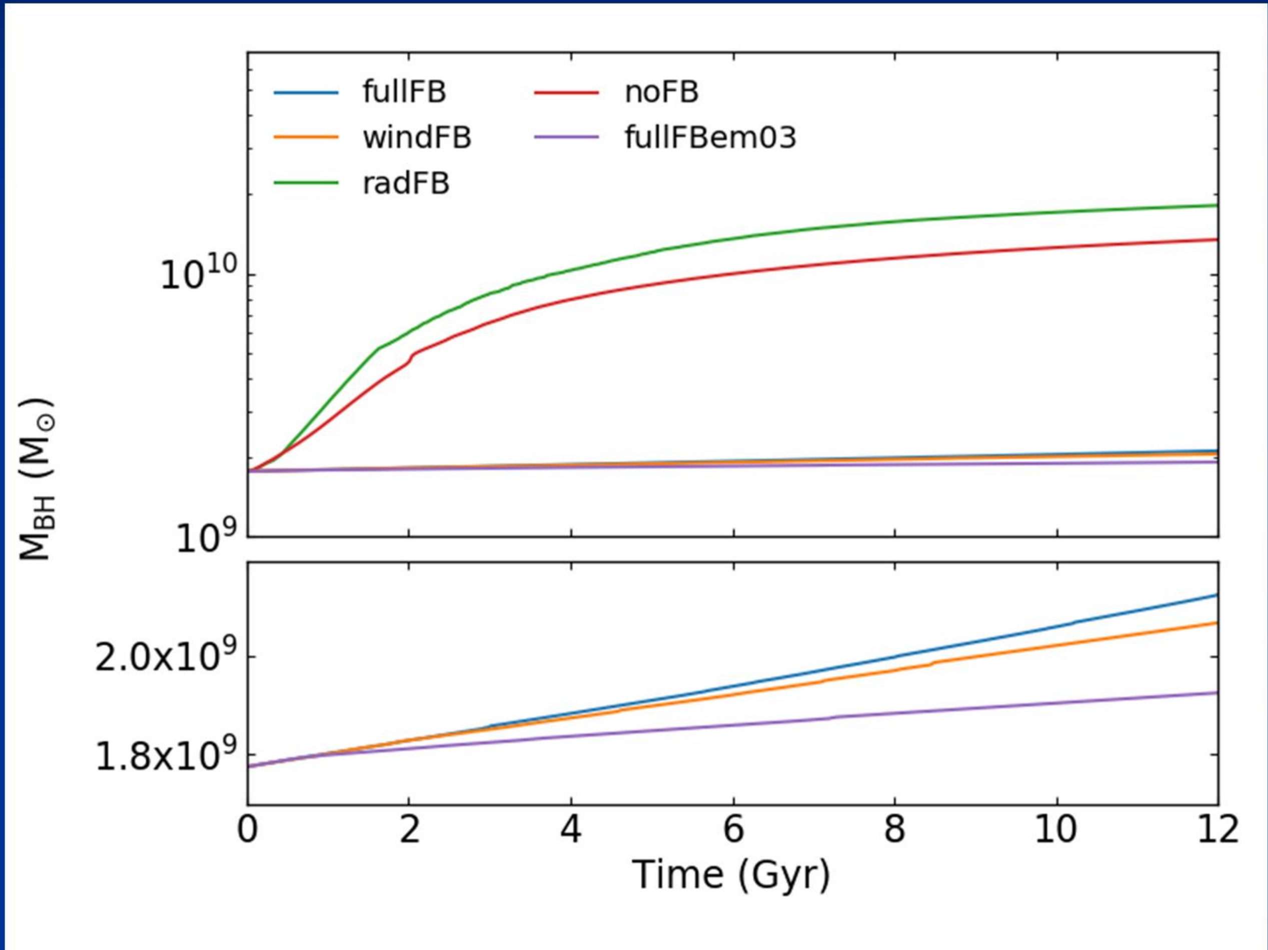




- Difference between Gan et al. (2014) & Yuan et al. (2018): Wind strength
- Typical *L* differs by ~100 times
- Lifetime of AGN: 10^5 yr (vs. 10^7 yr), consistent with observations (e.g., Keel et al. 2012; Schawinski et al. 2015; King & Nixon 2015)

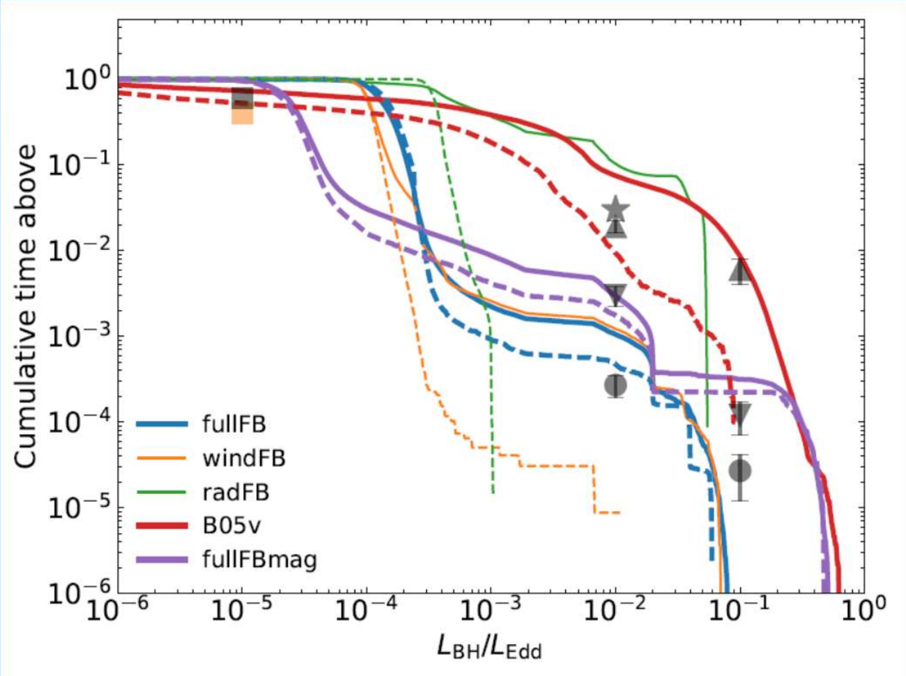
Growth of black hole mass

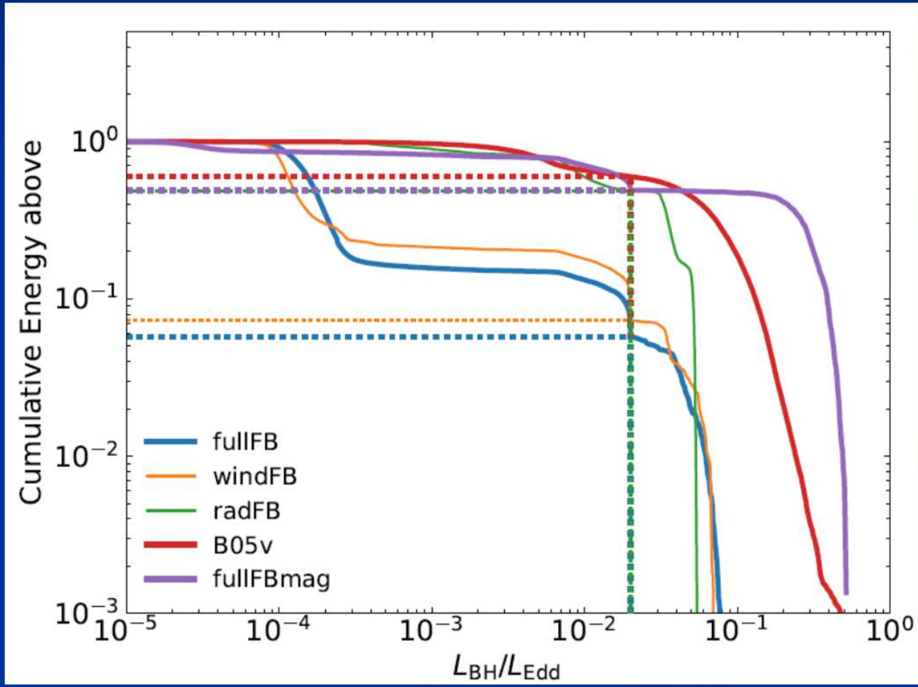
Yuan et al. 2018



AGN feedback (mainly by wind) regulates BH mass growth.

AGN duty-cycle





Percentage of the total simulation time spent above an Eddington ratio; Consistent with observations

Percentage of the total energy emitted above an Eddington ratio
NOT consistent with observations: why?

END