AGN Feedback in an Isolated Elliptical Galaxy

—elaborating the AGN physics

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Outline

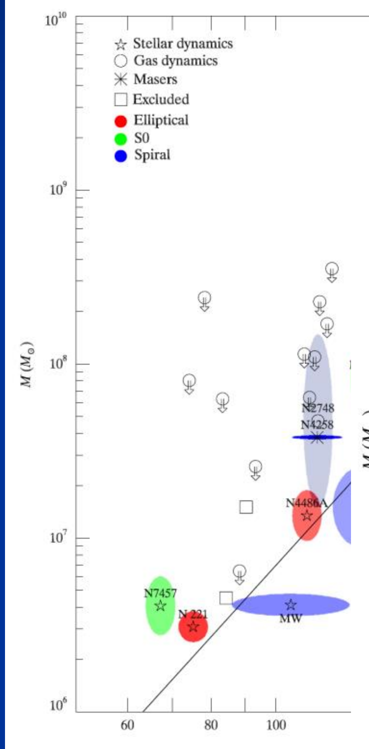
- Brief introduction to AGN feedback
- Accretion physics
  - Two accretion modes: cold & hot
  - Wind & radiation in the two modes
- Numerical study of AGN feedback
- Results: lightcurve; duty-cycle; star formation; BH growth

Observational evidence of AGN Feedback (I):

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

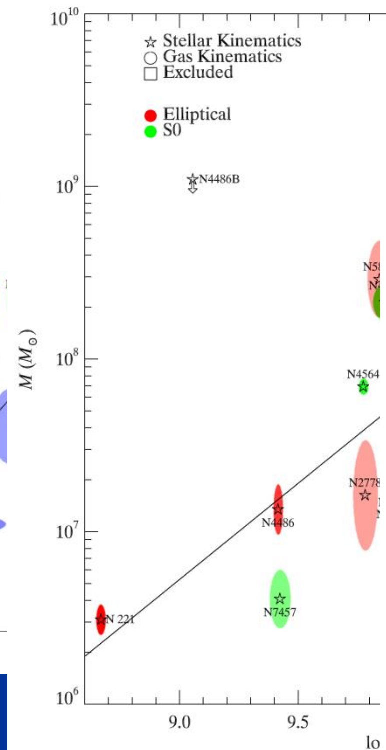
Coevolution of AGNs and Their Host Galaxies

$M_{BH}-\sigma$ relation



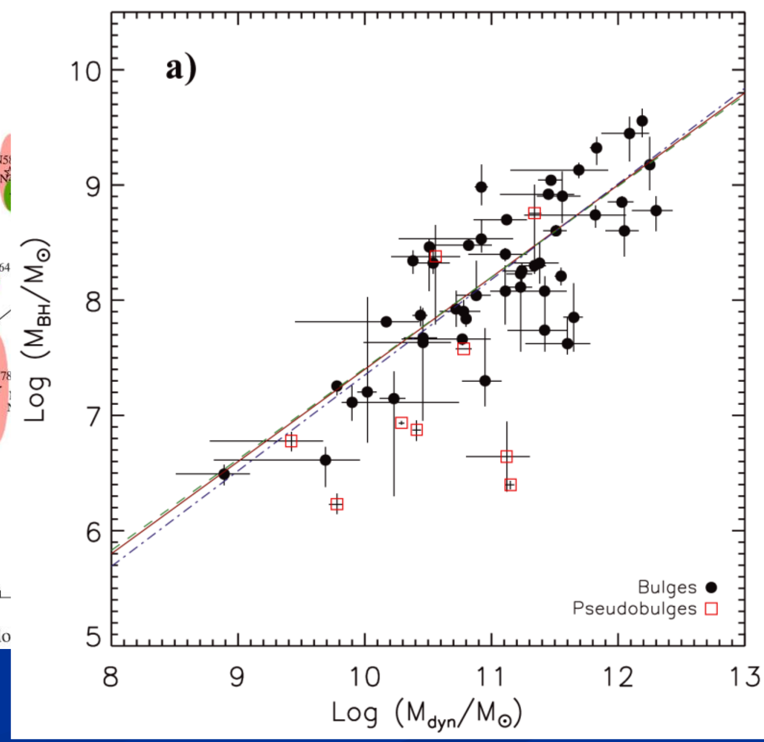
Gultekin et al. 2009

$M_{BH}-L$ relation



Gultekin et al. 2009

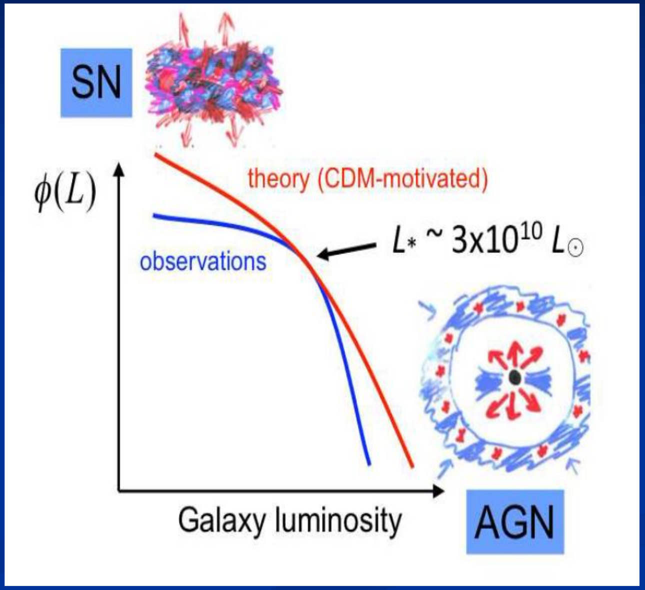
ation



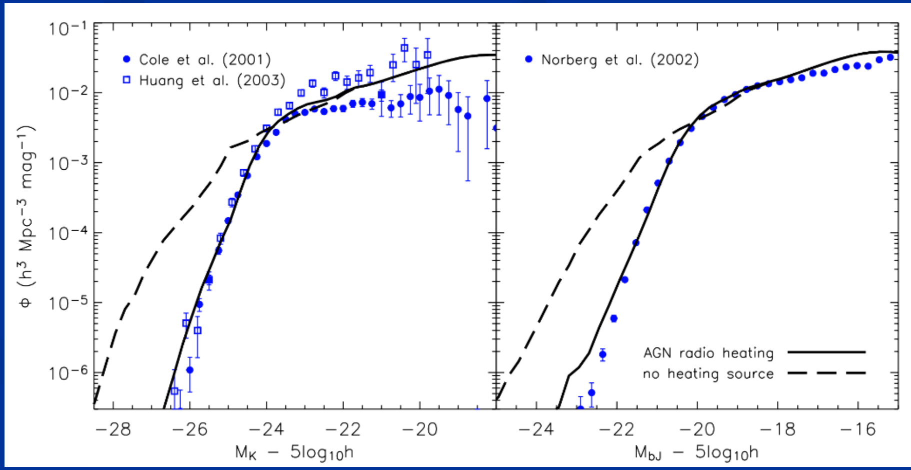
Sani et al. 2011

Galaxy Luminosity Function

- Main problem: gas in simulated galaxies to transform into stars **too efficiently**.
- How to make the overall galaxy formation inefficient with self-consistent models?
- Solution: **SN, AGN or other possibilities?**

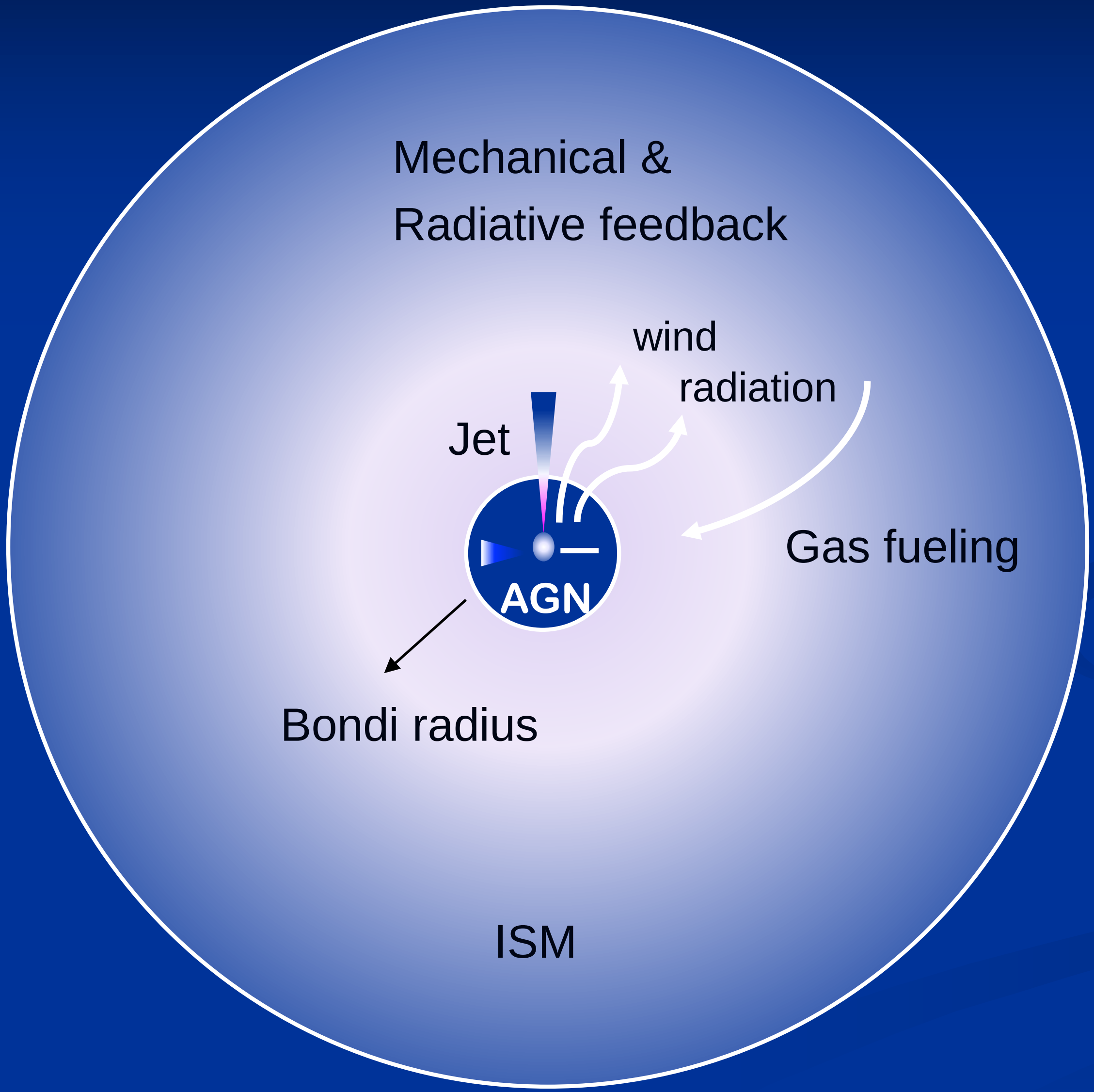


Silk & Mamon 2012



(Croton+2016)

What is AGN feedback?



Key issues for feedback:

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

Previous works & our motivations

- Often focus on very large (e.g., cosmological) scale (Di Matteo et al. 2005; Springel et al. 2005; Debuhr et al. 2010, 2011; Johansson et al. 2009; Li et al. 2015; Illustris…)
  - only resolve galactic length and timescale
  - Model for feedback physics:
    - Mdot estimated
    - Subgrid; parameterized; outputs not properly described
- Our goals:
  - Resolve the accretion (Bondi) and galaxy scales
  - Adopt the most updated sub-grid AGN physics
  - Calculate the interaction between wind & radiation with ISM

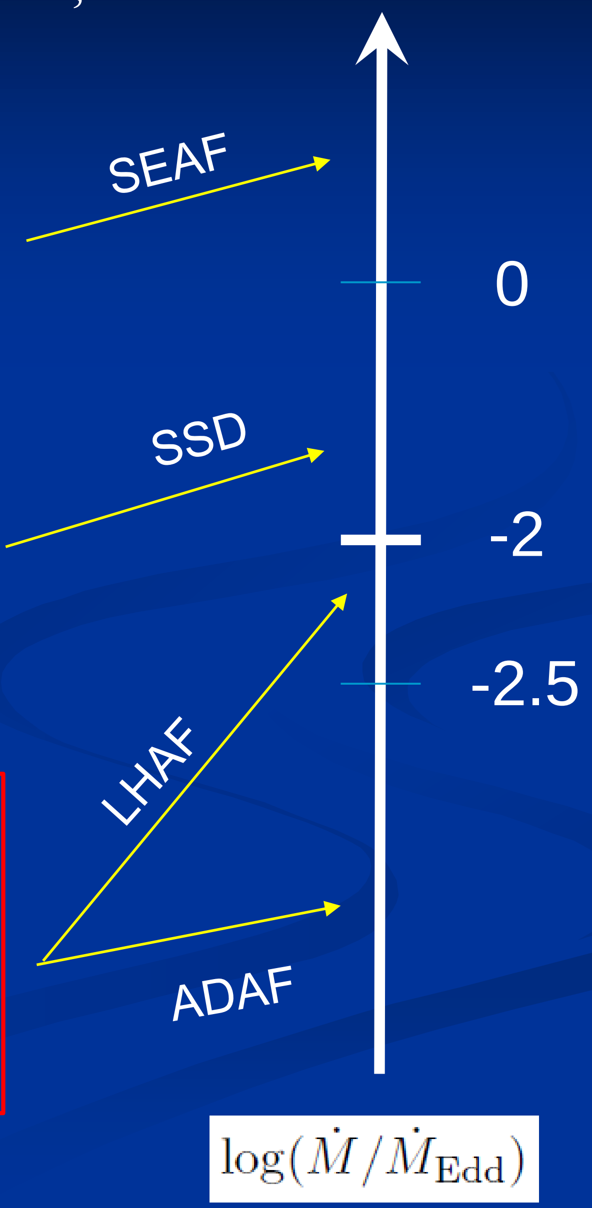
Two accretion modes: cold & hot

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



Cold accretion mode (I)

Shakura & Sunyaev 1976, A&A; Pringle 1981, ARA&A

- Correspond to quasar ***(cold)*** feedback mode
- Cool: ~10^6 K, Geometrically thin & Optically thick
- Outputs: strong wind & radiation, but no jet (?)
- Radiative efficiency
  - standard thin disk: ~0.1
  - Super-Eddington: ~0.1 (?)

Cold accretion mode (II): wind

Shakura & Sunyaev 1976, A&A; Pringle 1981, ARA&A; Gofford et al. 2015

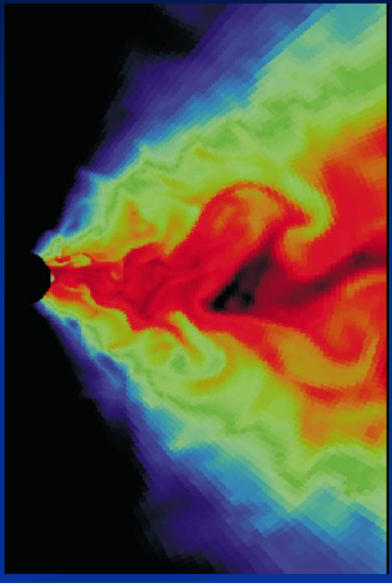
- Many observations: BAL quasar, UFO, warm observer…
- Wind production mechanisms:
  - thermal+magnetic+radiation (line force)
- Wind properties: mass flux & velocity (from observations, e.g., Gofford et al. 2015)

$$\dot{M}_{\rm W,C} = 0.28 \left(\frac{L_{\rm BH}}{10^{45}\,{\rm erg\,s^{-1}}} \right)^{0.85} M_{\odot}\,{\rm yr}^{-1}$$

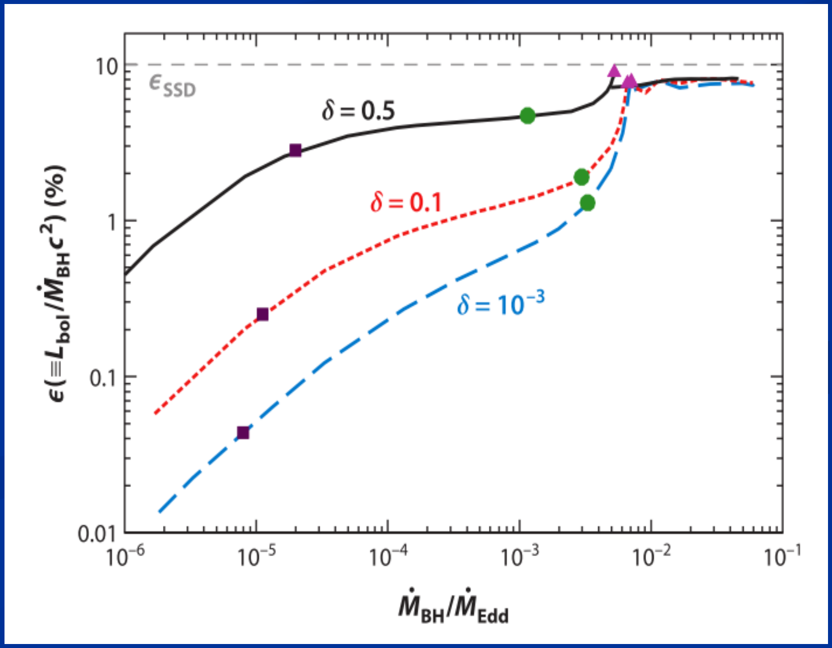
$$v_{\rm W,C} = 2.5 \times 10^{4} \left(\frac{L_{\rm BH}}{10^{45}\,{\rm erg\,s^{-1}}} \right)^{0.4} {\rm km\,s^{-1}}$$

Hot accretion flow (I)

Yuan & Narayan 2014, ARA&A



- Correspond to kinetic (radio/jet) ***(hot)*** feedback mode
- Hot, geometrically thick; Optically thin; Spectrum: complicated
- Outputs: radiation, wind & jet
- Radiative efficiency
  - A function of Mdot →



Xie & Yuan 2012

Global simulation of hot accretion flow: Accretion rate decreases inward

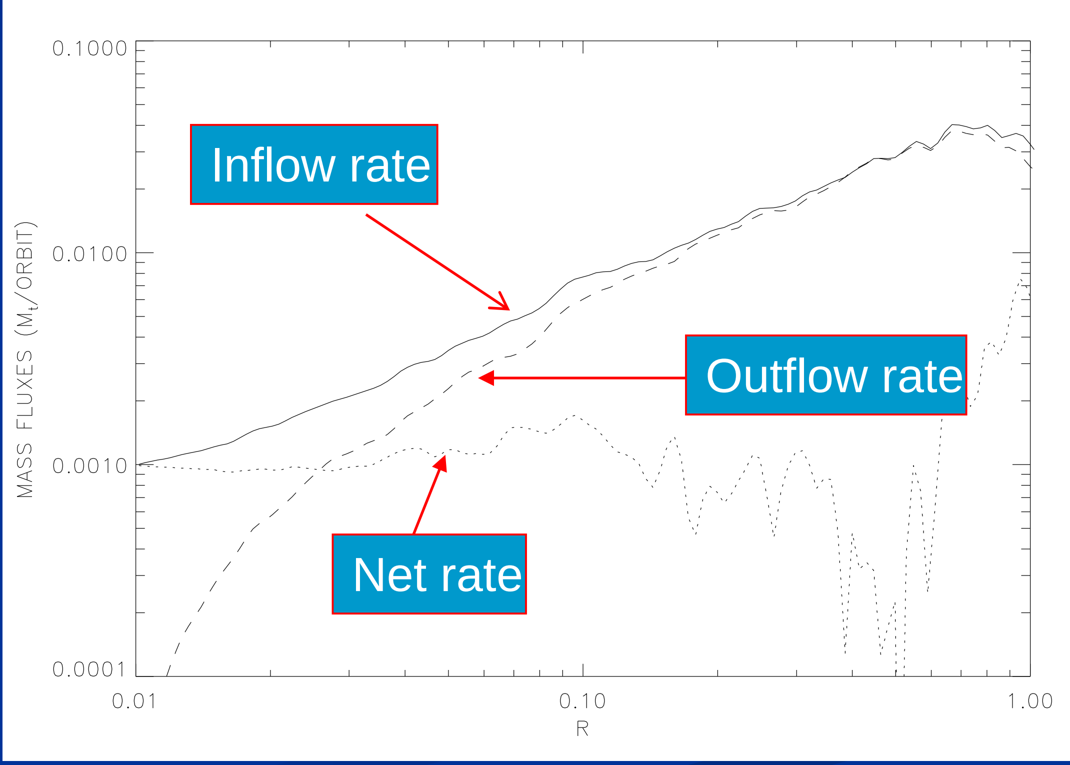
Stone, Pringle & Begelman 1999; Stone & Pringle 2001; Hawley & Balbus 2002; Machida et al 2003; Pen et al. 2003; Igumenshchev, Narayan & Abramowicz 2003; Yuan & Bu 2010; Yuan, Wu & Bu 2012; Li, Ostriker & Sunyaev 2013

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

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

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

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



Stone, Pringle & Begelman 1999

Confirmed by Observations of Sgr A*

Aitken et al. 2001; Bower et al. 2003, 2005; Yuan, Quataert & Narayan 200

- Chandra observations + Bondi theory give the Bondi rate:

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

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

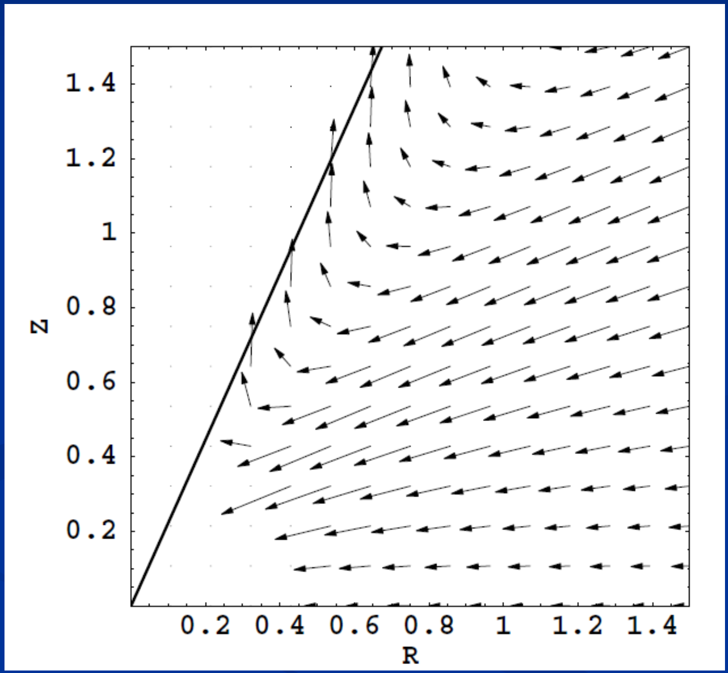
- High linear polarization at radio waveband requires innermost region accretion rate (rotation measure requirement):

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

- So Mdot must decrease inward

Two models 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
- Which one is correct? Debated for more than 10 years (Blandford, Stone, Narayan, Hawley…)



Blandford & Begelman 1999

Convection or wind?

Yuan et al. (2012a; 2012b; 2015) ; Narayan et al. 2012

- Performed HD & MHD simulations
- Theoretical analysis:
  - If convective turbulence, we expect: inflow & outflow properties roughly same; → different!
  - Analyze the convective stability of *MHD* accretion flow → stable!
  - Trajectory analysis
- Conclusion: strong outflow exists

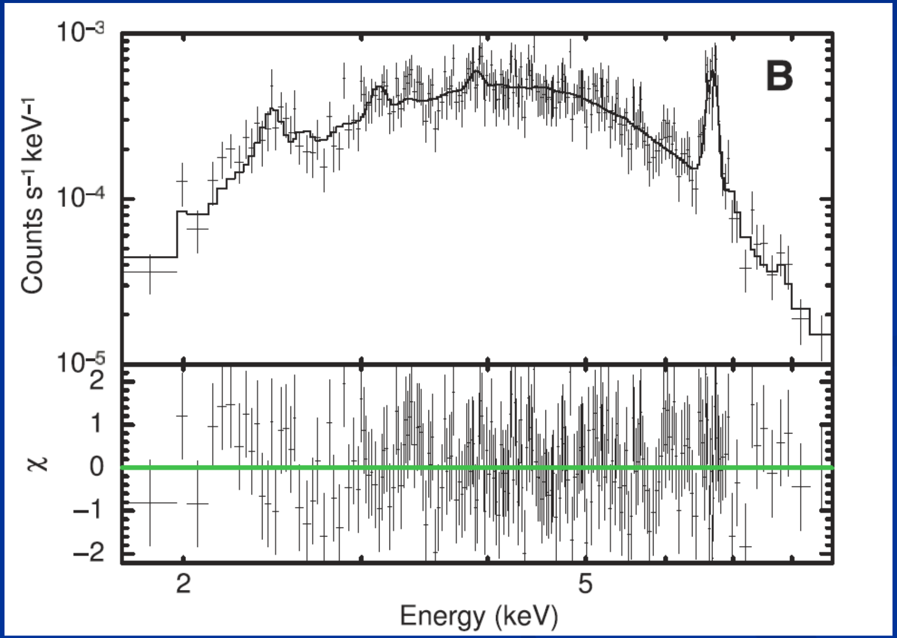
Outflow confirmed by new observations

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



Additional observation evidences for wind from hot accretion flows

- Low-luminosity AGN (Cheung et al. 2016, Nature)
  - They find evidence for wind in LLAGNs with, e.g., L ~ $4 \times 10^{-4} L_{Edd}$
- Radio galaxy (Tombesi et al. 2010, 2014)
  - Blue-shifted iron absorption lines
  - Winds co-exist with jets
- Hard state of black hole X-ray binaries (Homan et al. 2016)
- But: still no good observational constraint on wind properties

Properties of wind from hot accretion flow

Yuan et al. 2015

- Trajectory approach
  - Different from stream line
- Mass flux

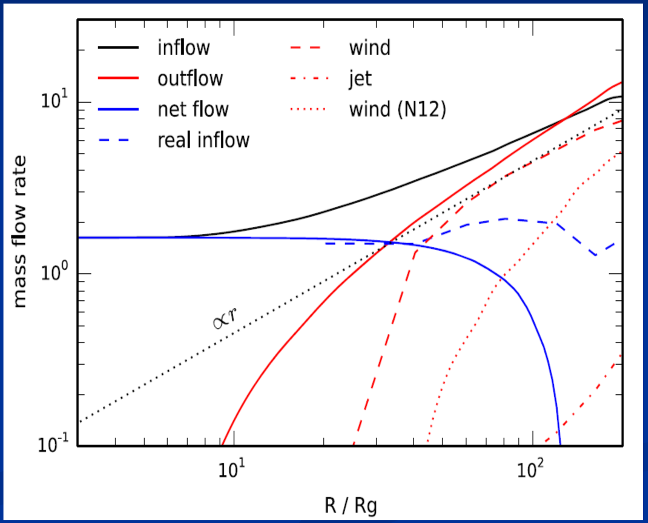
$$\dot{M}_{wind} = \dot{M}_{BH}(r)\left(\frac{r}{20r_s}\right), \quad a = 0$$

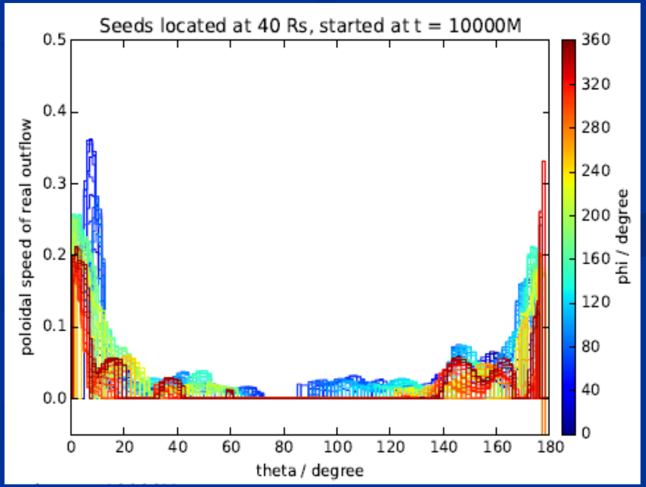
- Poloidal speed:

$$v_{term}(r) \sim 0.3 v_k(r)$$

- Energy & momentum flux:

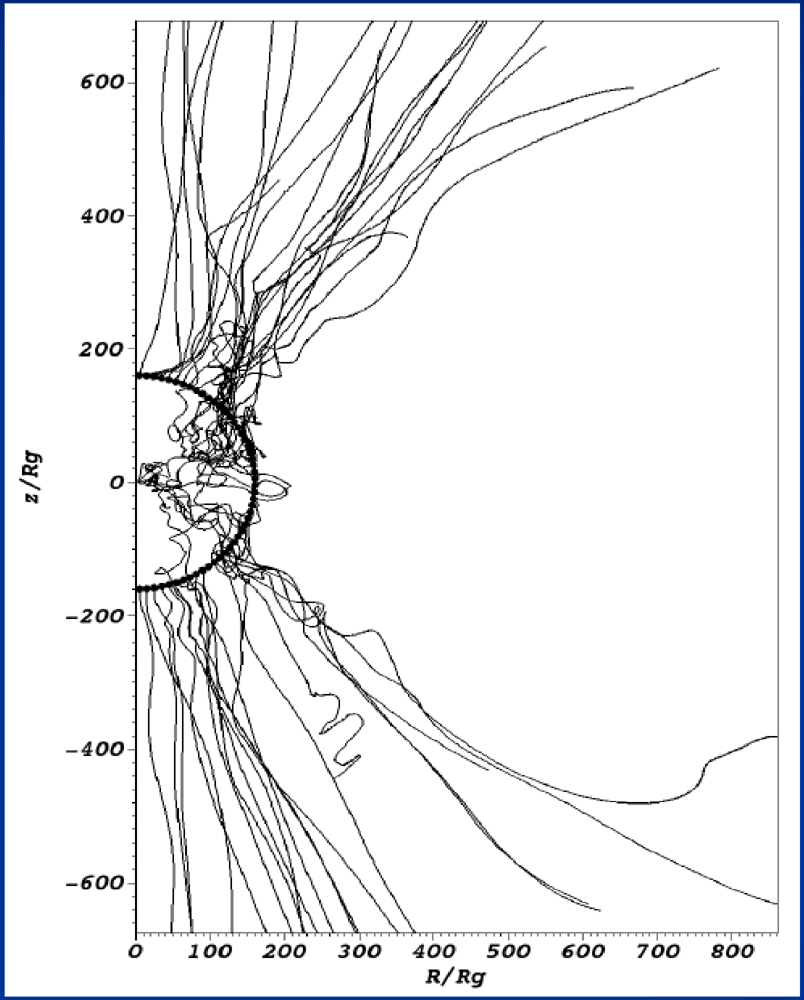
$$\dot{E}_{wind} = \frac{1}{1000}\dot{M}_{BH}c^2$$

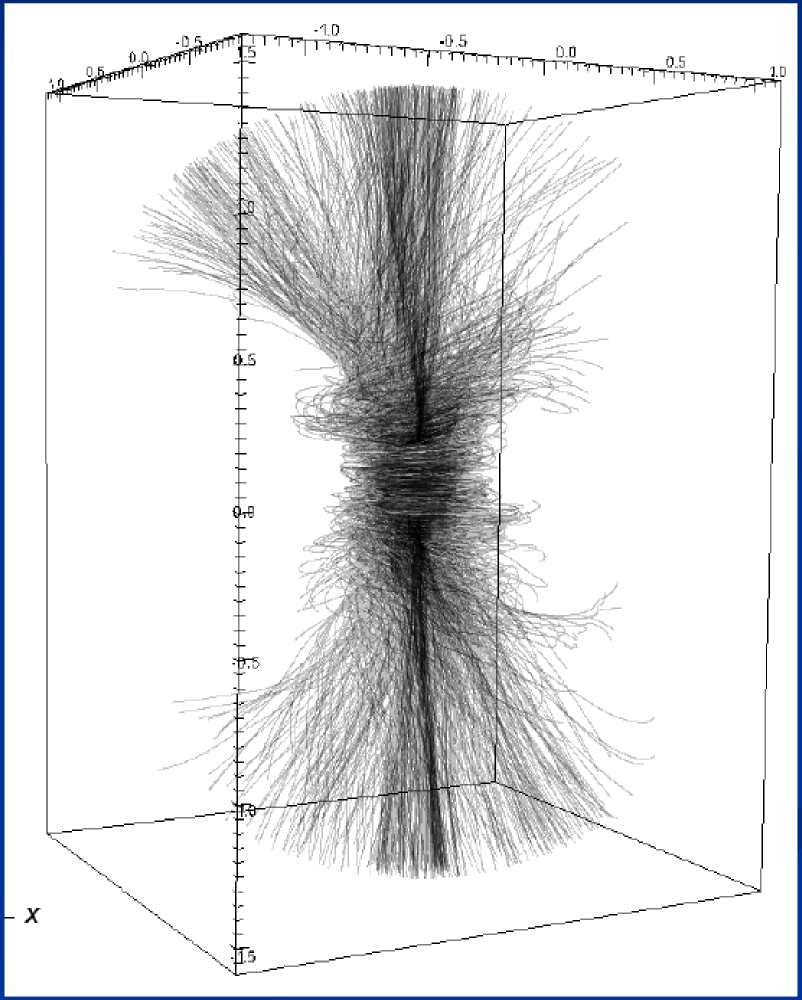


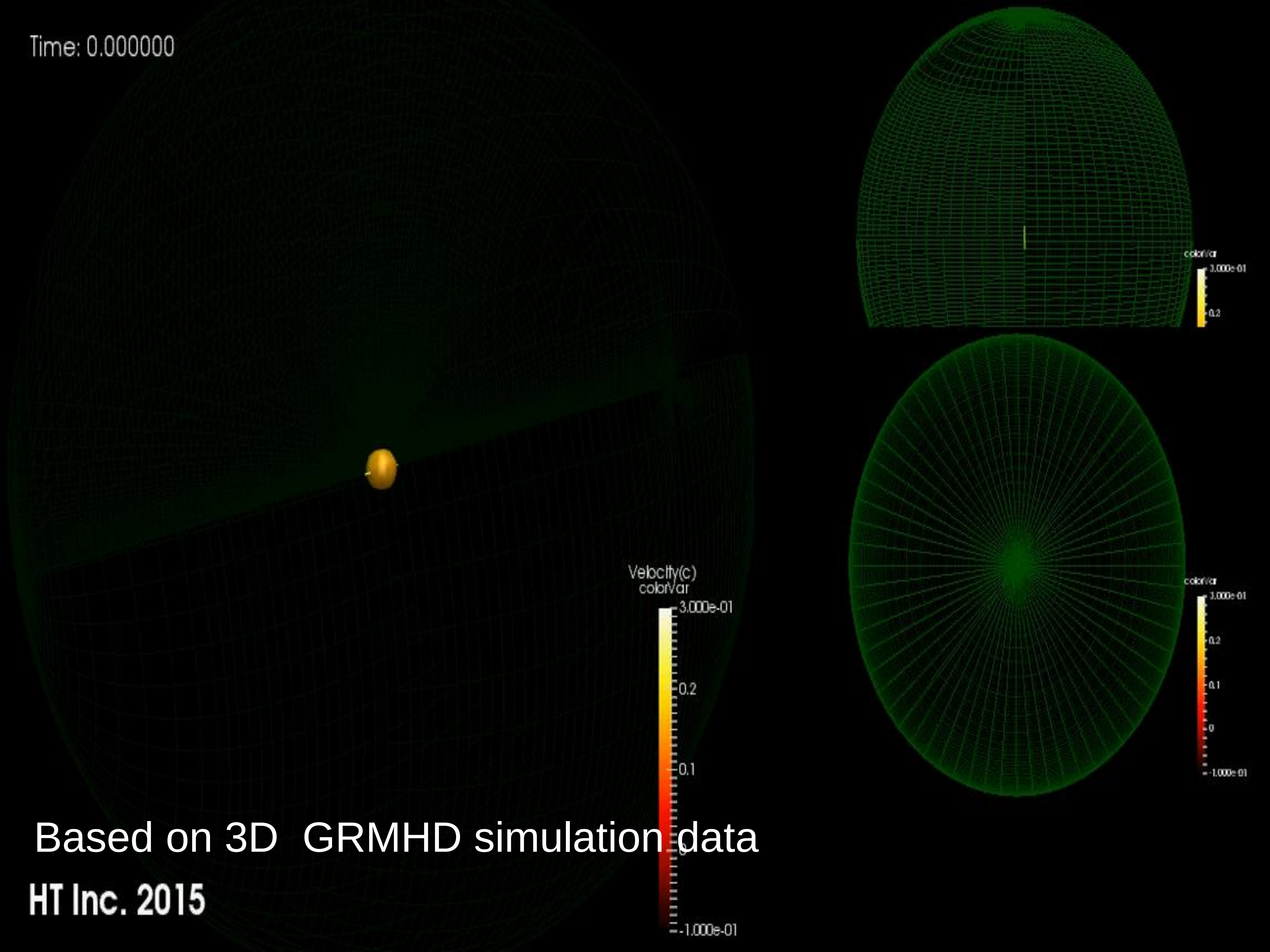


Trajectory of ``virtual test particles”

Yuan et al. 2015







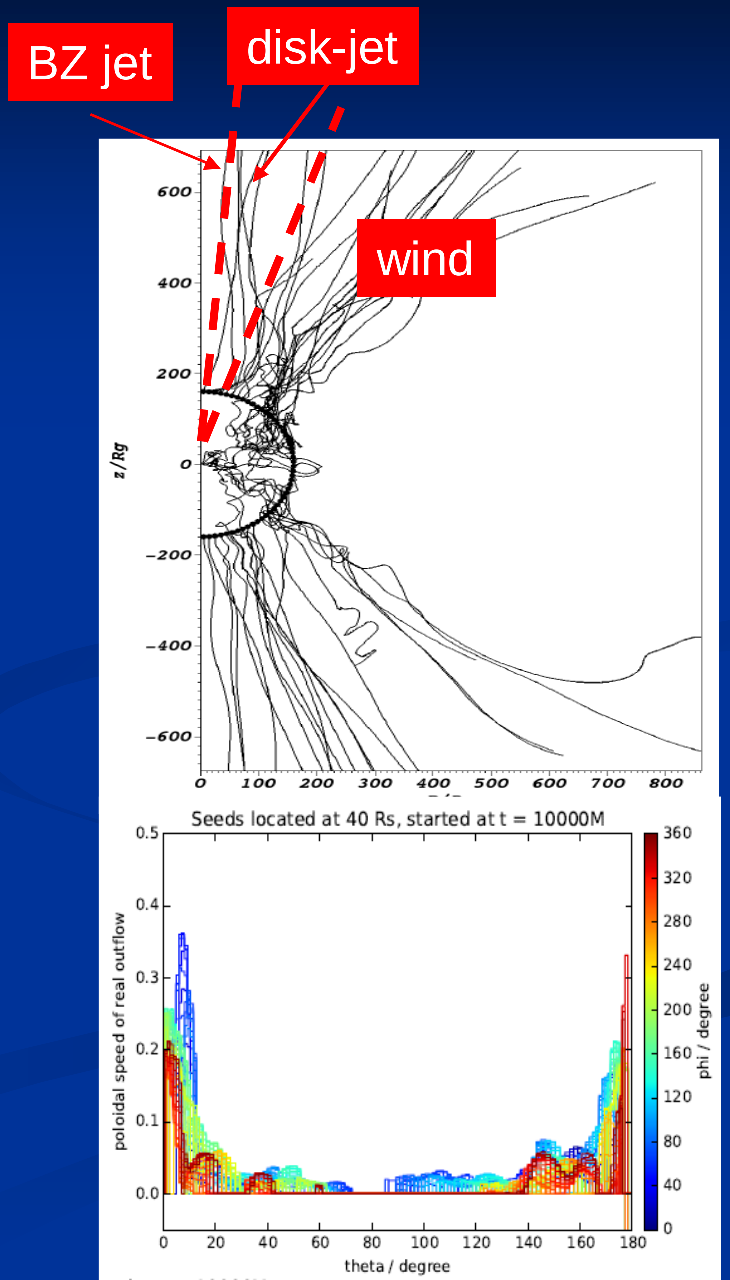
Based on 3D GRMHD simulation data

HT Inc. 2015

Special wind — disk-jet — jet sheath??

Yuan et al. 2015; Yuan & Narayan 2014,ARA&A

- Angular distribution of wind
- Angular distribution of wind speed
- Disk-jet
  - Originate from disk (not BH); present even for a=0
  - Gas-rich (not Poynting flux)
  - v~0.2-0.4 c
  - Accelerated by gradient of toroidal magnetic field; ***so not BZ nor BP***, but Lynden-Bell (1996) mechanism
  - Just outside of BZ jet --- sheath?



Hydrodynamical Equations

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

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

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

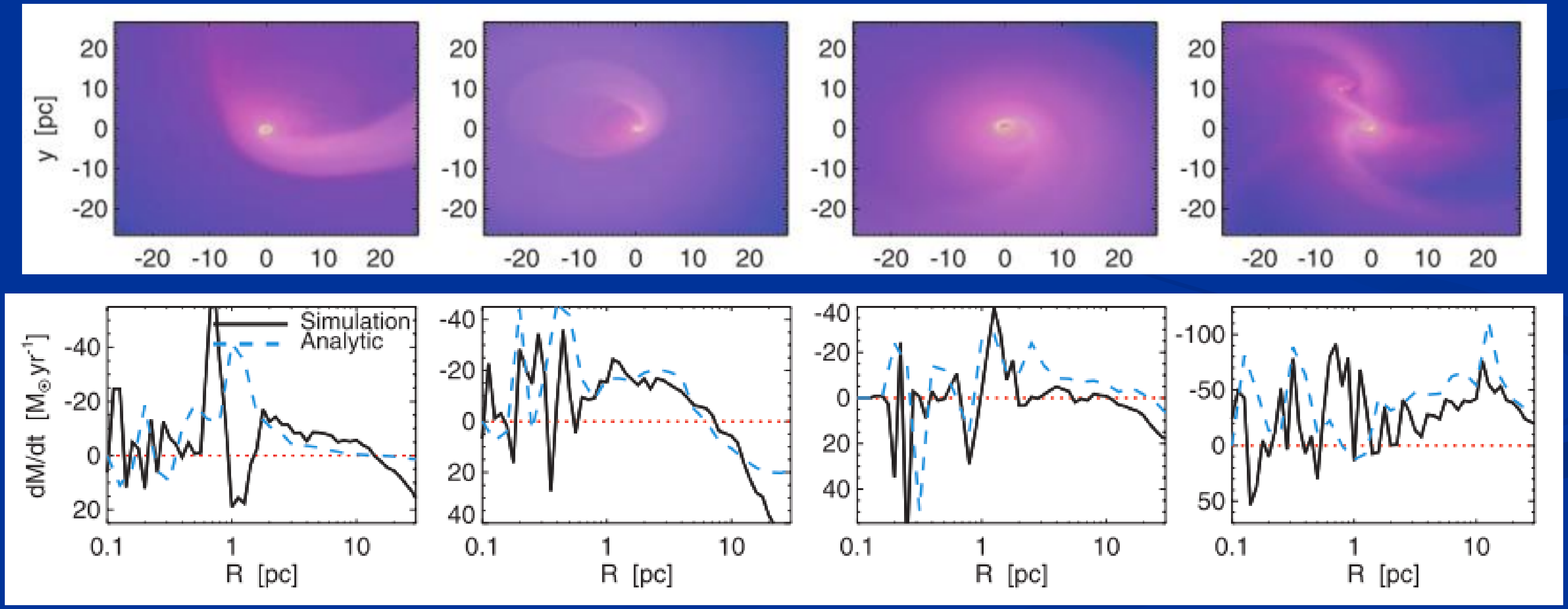
Physics included in the model:

- Stellar mass loss from dying stars
- Gas depletion of 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

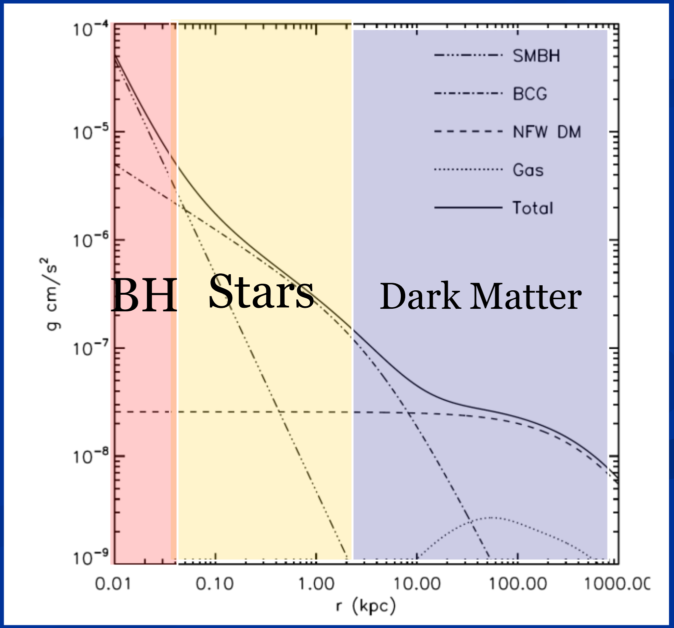
We focus on the **cosmological evolution** of an **isolated elliptical galaxy.**

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**,

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

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:

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

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

- 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):

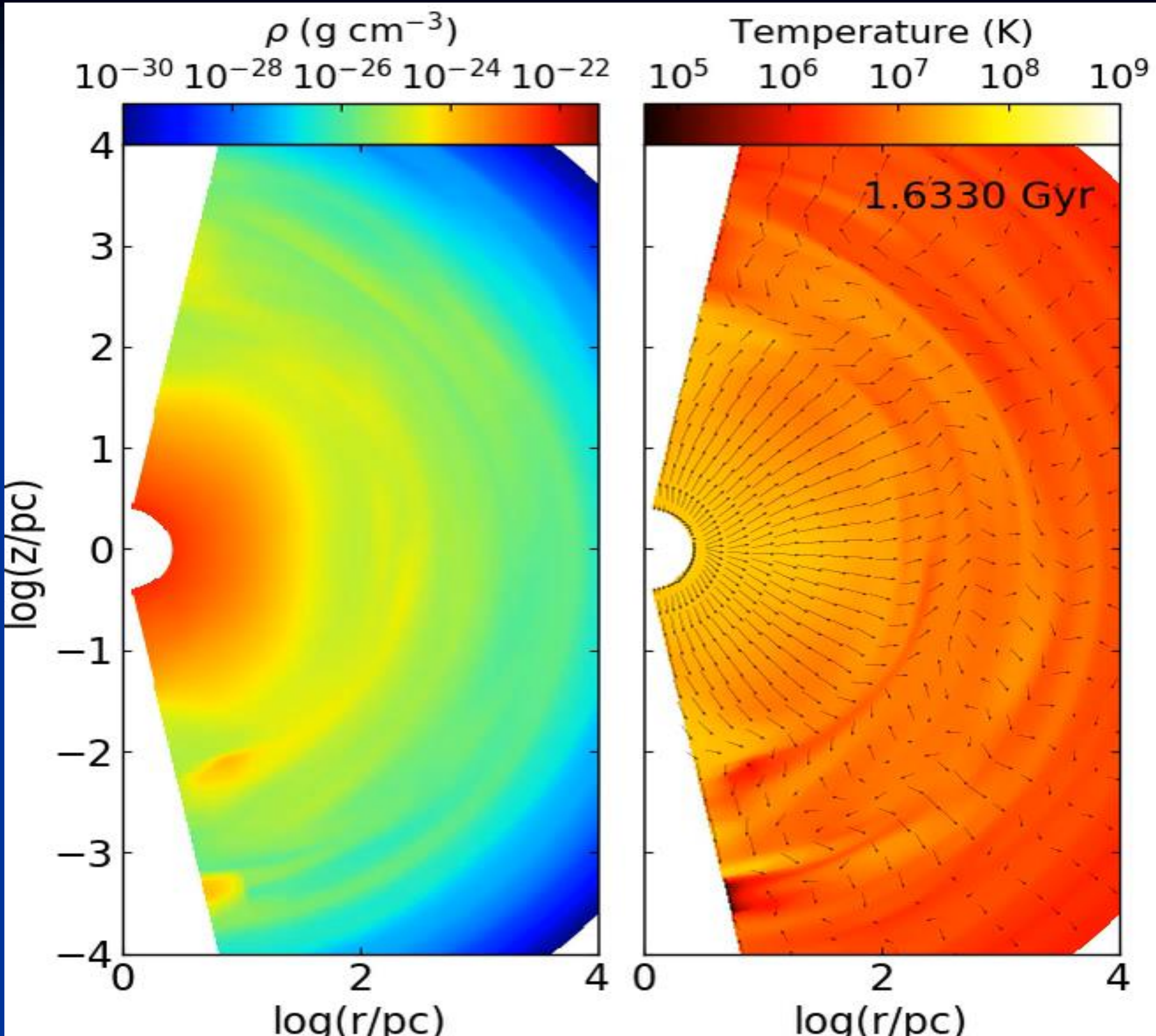
$$T_c \sim 10^8 \text{ K}$$

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

Setup of Numerical Simulation

Yuan et al. 2018; Yoon et al. 2018

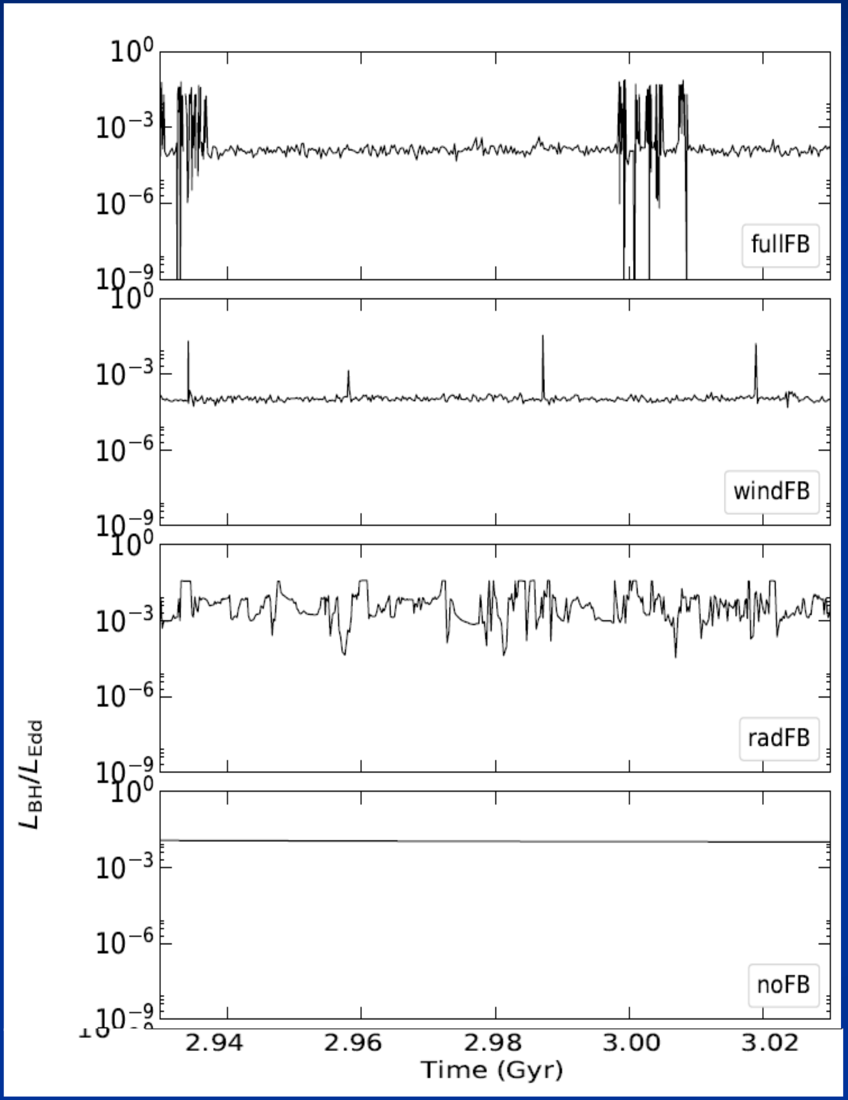
- ZEUS-MP code: 2D + hydro + radiation
- From 2.5 pc (~0.1 Bondi radius) to 250 kpc
- Evolve for cosmological time (~12 Gyr)
- Mdot self-consistently determined
- Two accretion/feedback modes discriminated
- Inject wind & radiation from inner boundary & calculate their int. with ISM



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)
log(r/pc)
log(r/pc)

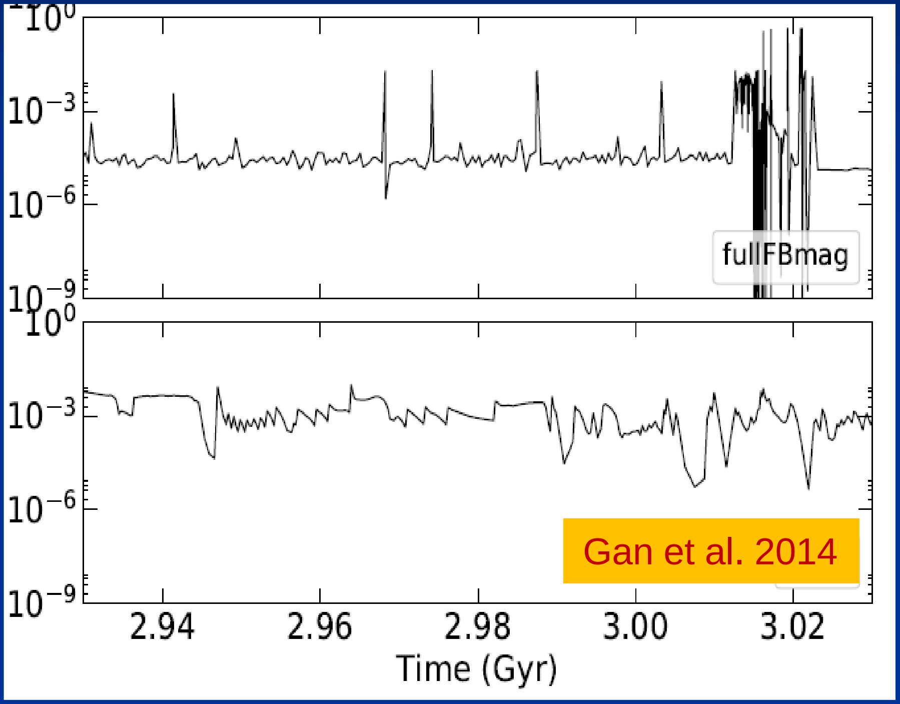
Light curve of AGN (I)

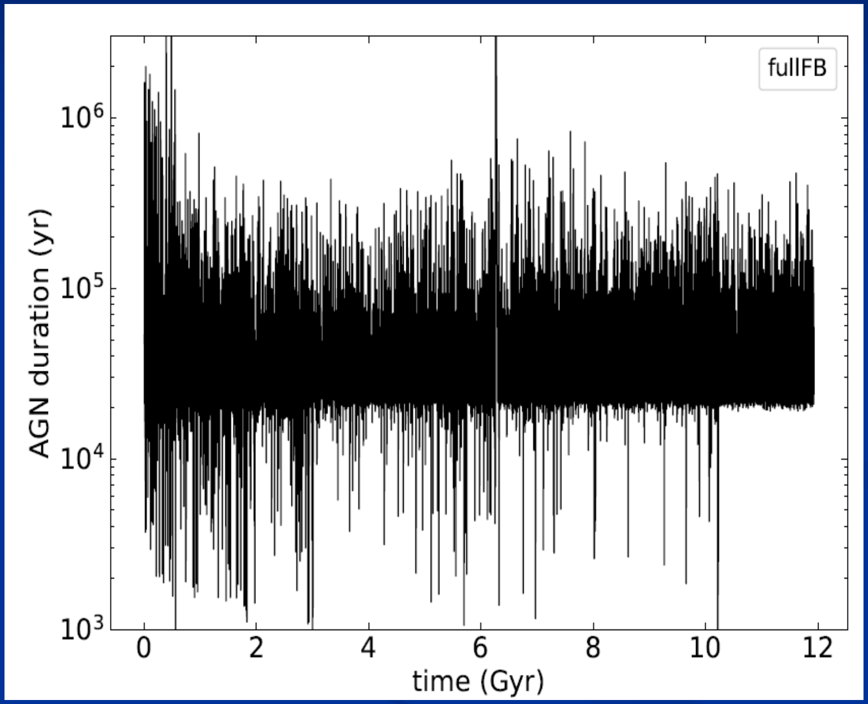
Yuan et al. 2018



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

Lightcurve of AGN (II): effect of AGN physics

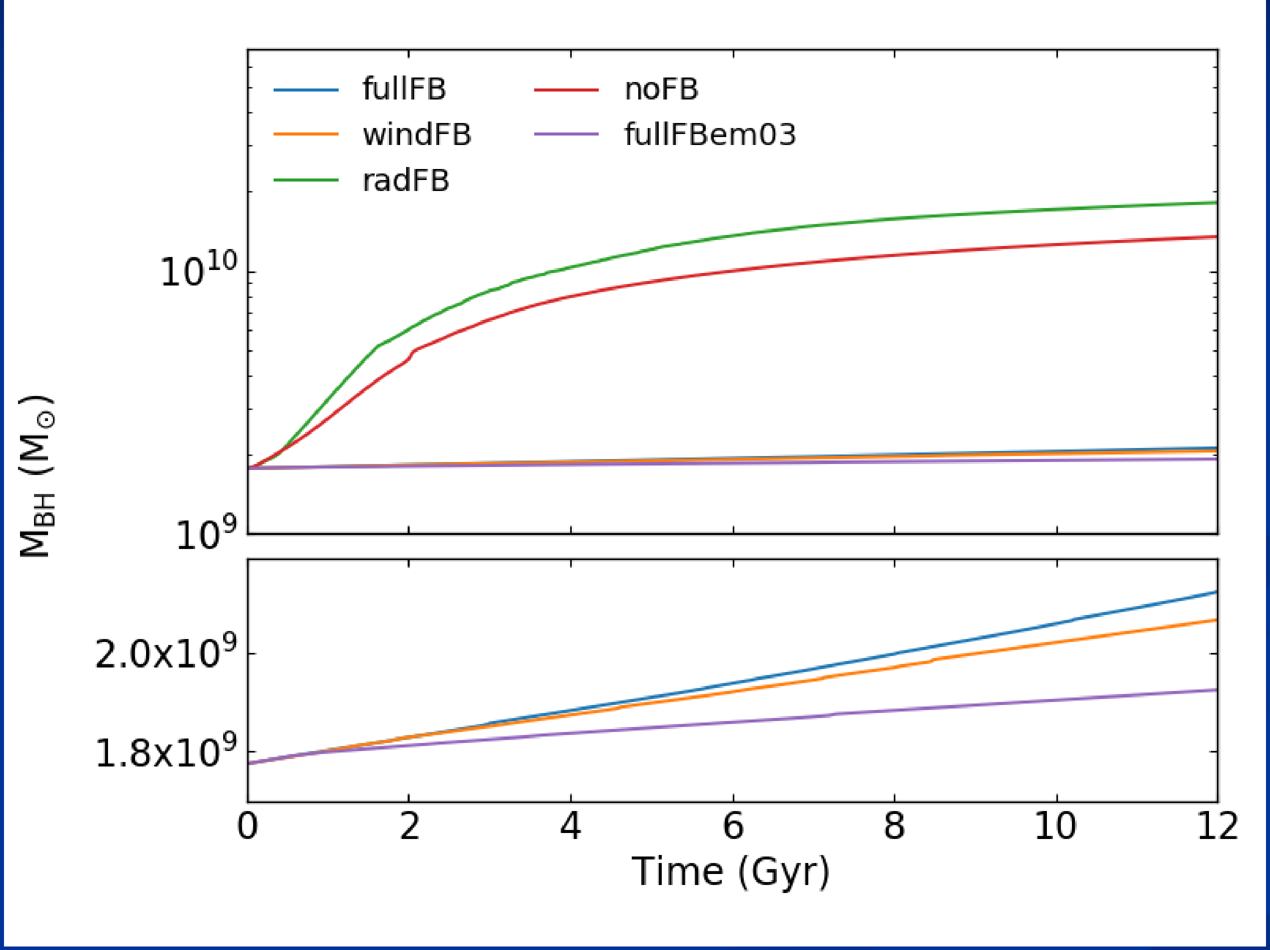




- Difference between two models: Wind strength
- Typical *L* differs by 2 orders of magnitude
- Lifetime of AGN: 10^5 yr (vs. 10^7 yr), consistent with observations (e.g., Keel et al. 2012; Schawinski et al. 2015)

Growth of black hole mass

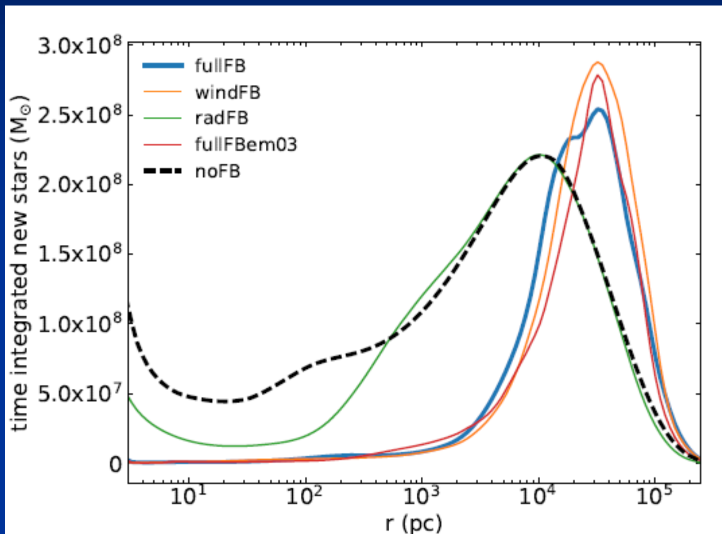
Yuan et al. 2018

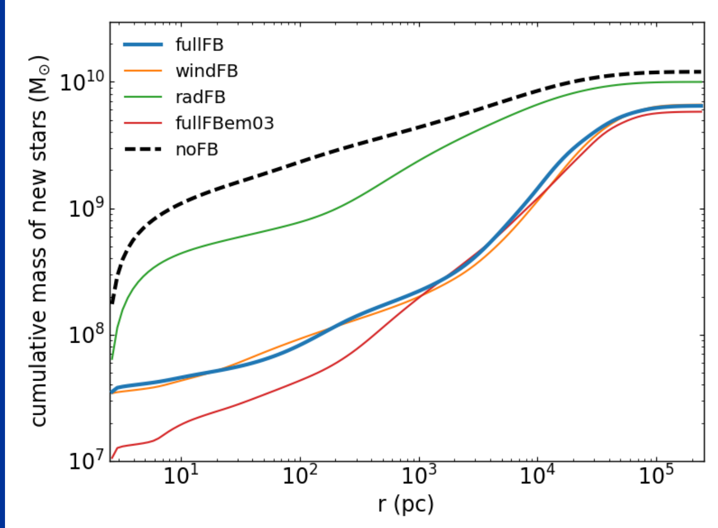


AGN feedback (mainly by wind) regulates BH mass growth.

Star formation

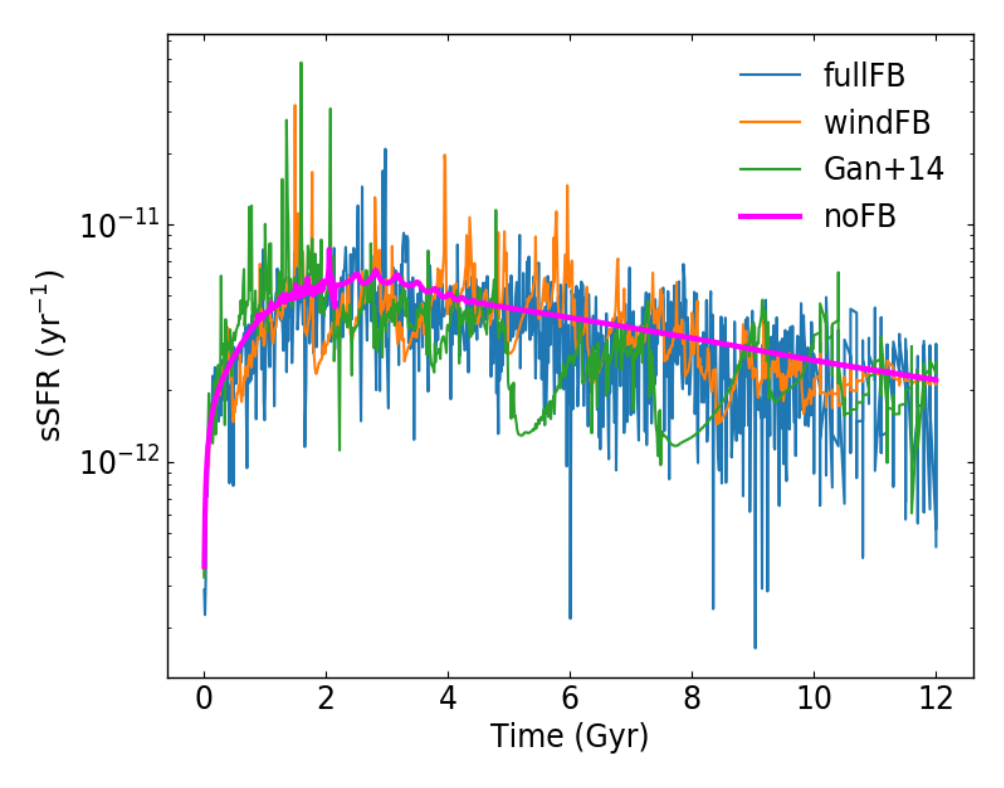
— suppressed or enhanced?





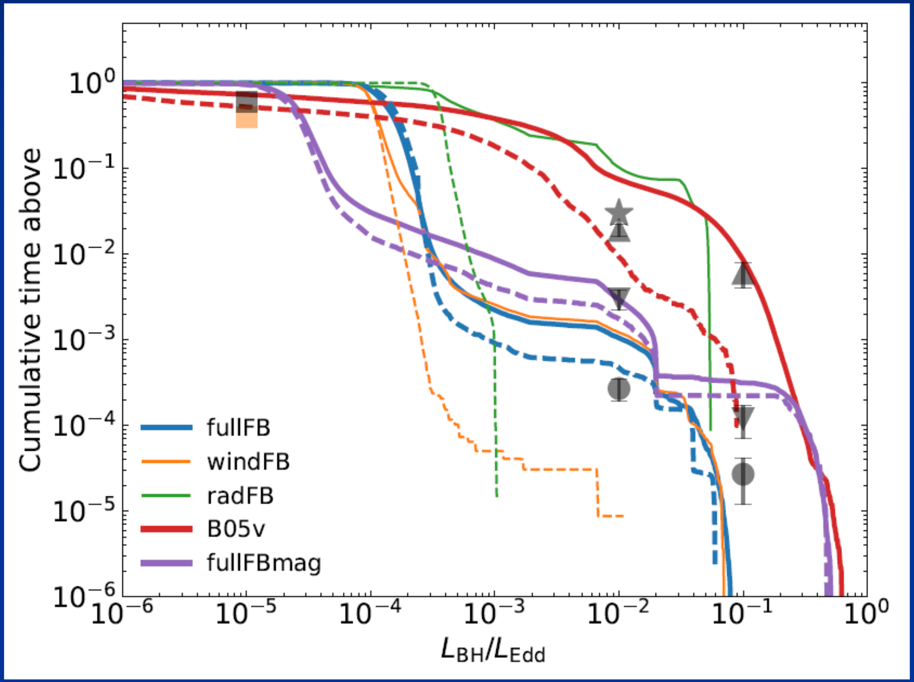
- Wind feedback is dominant
- Wind can reach & suppress SF up to 20 kpc , consistent with observation (e.g., Liu et al. 2013)
- But beyond ~20 kpc, SF is enhanced
- consistent with observation (e.g., Cresci et al. 2015)

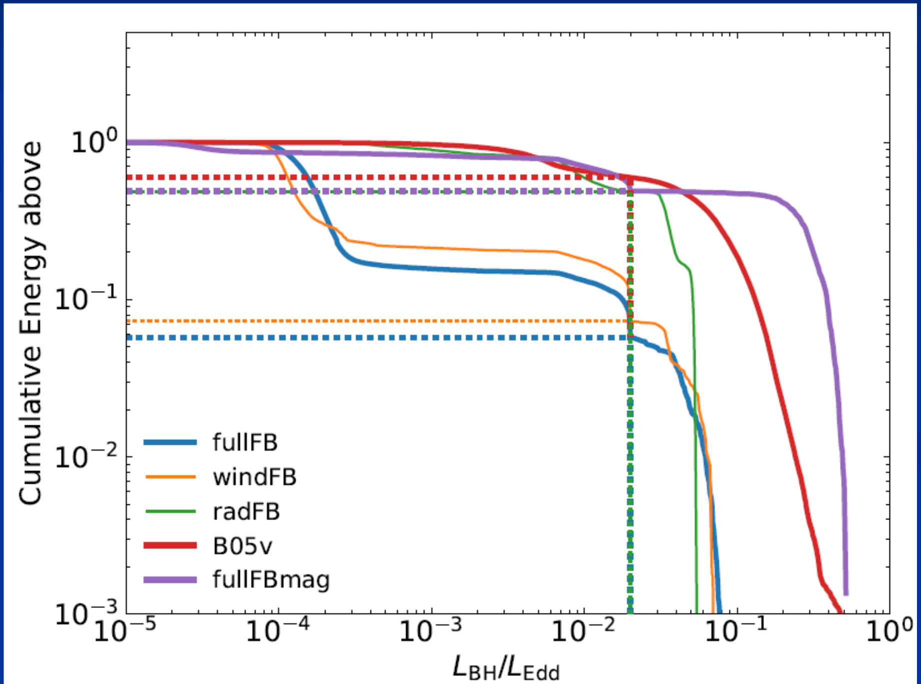
Specific Star Formation Rate



Negative or **positive** effect on SFR? Difficult to answer, depending on location and time !

AGN duty-cycle

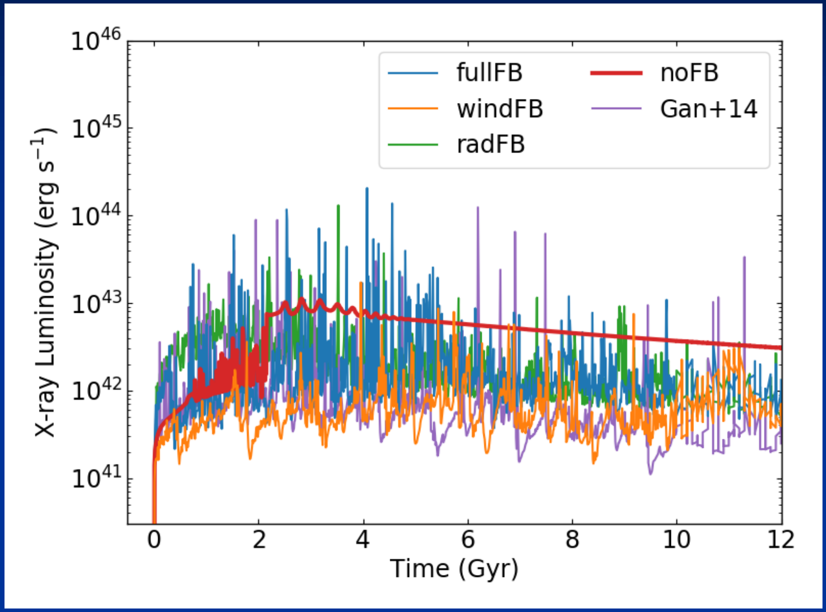


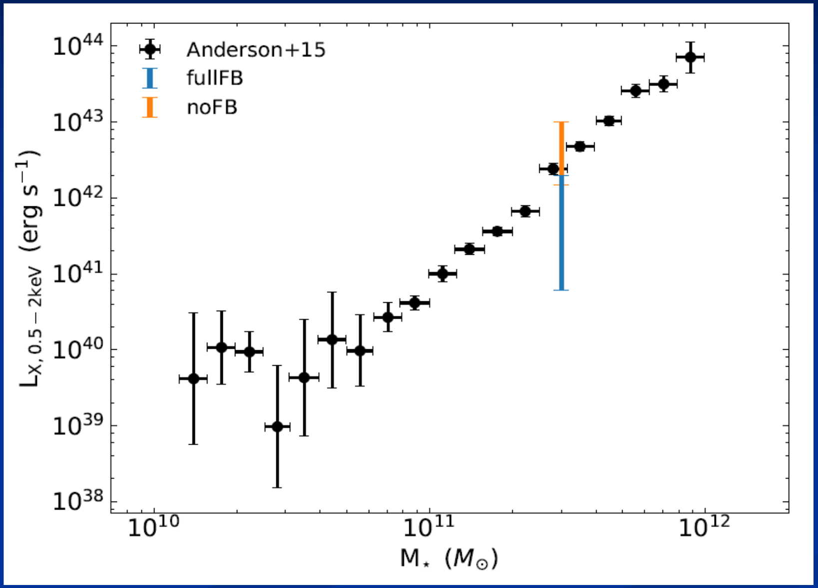


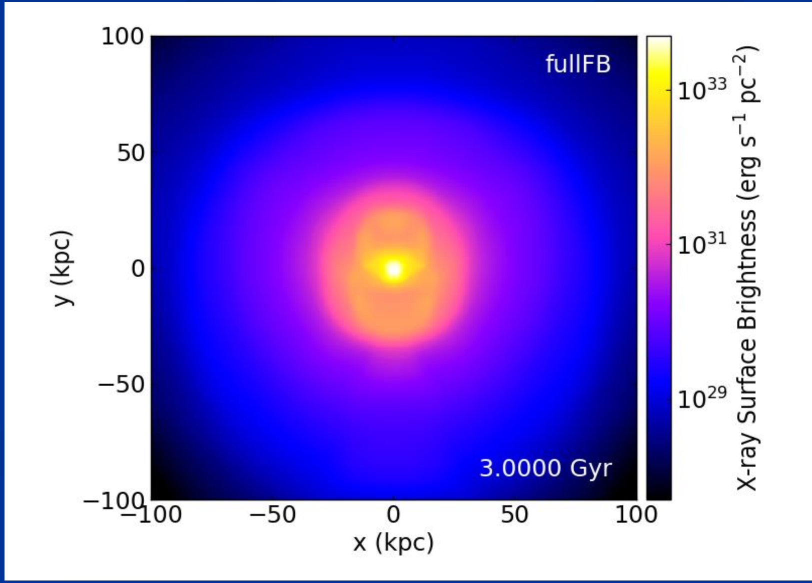
Percentage of the total simulation time spent above an Eddington ratio; consistent with observations

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

X-ray Luminosity & Surface Brightness







X-ray cavity can be produced by AGN wind even if the jet is absent!

Summary

- AGN feedback considered by 2D HD simulation; Bondi radius resolved
- Physical processes like SNe, SF, int. between radiation & wind with ISM considered
- Exact AGN physics adopted:
  - two accretion/feedback modes: cold & hot
  - Correct description of radiation & wind in each mode
- Light curve, BH growth, AGN Duty-cycle, star formation, surface brightness
- Comparison with other works indicates the importance of exact AGN physics

END