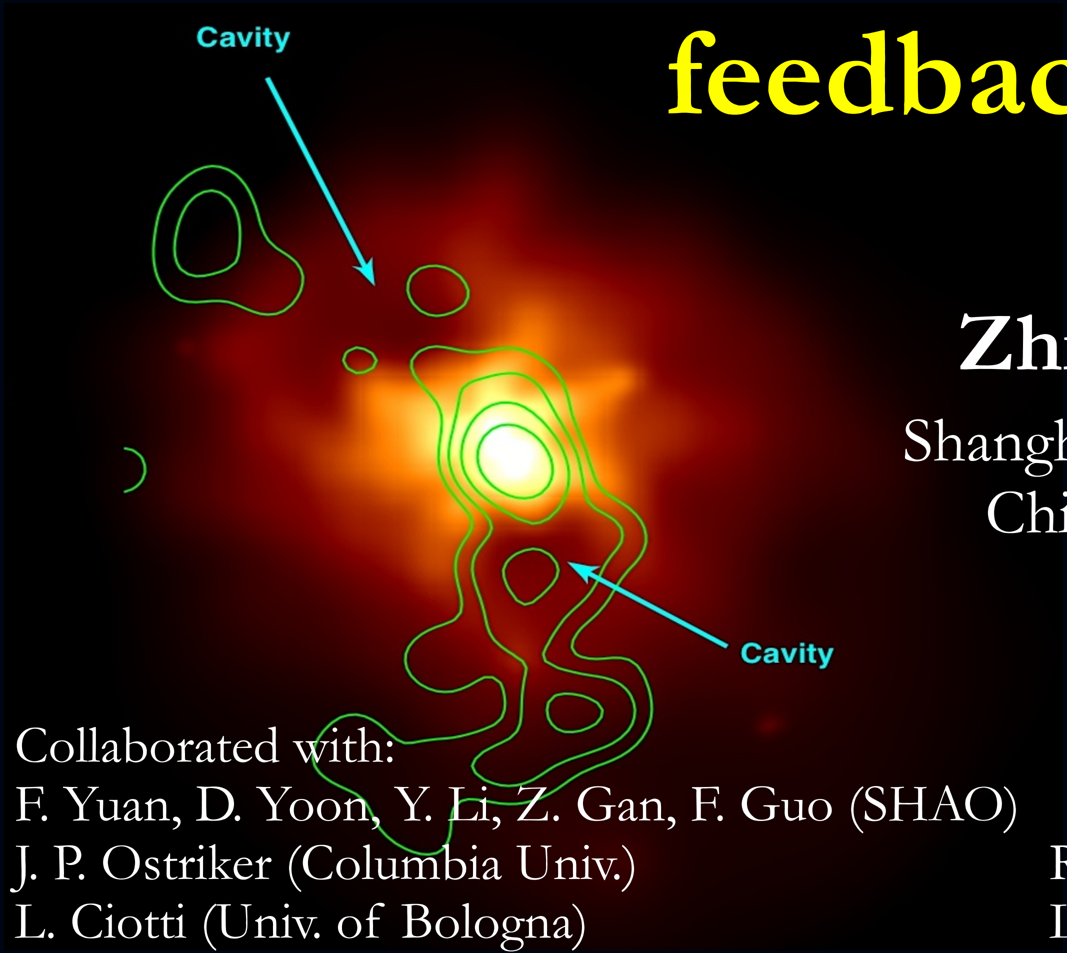
Numerical study of AGN feedback



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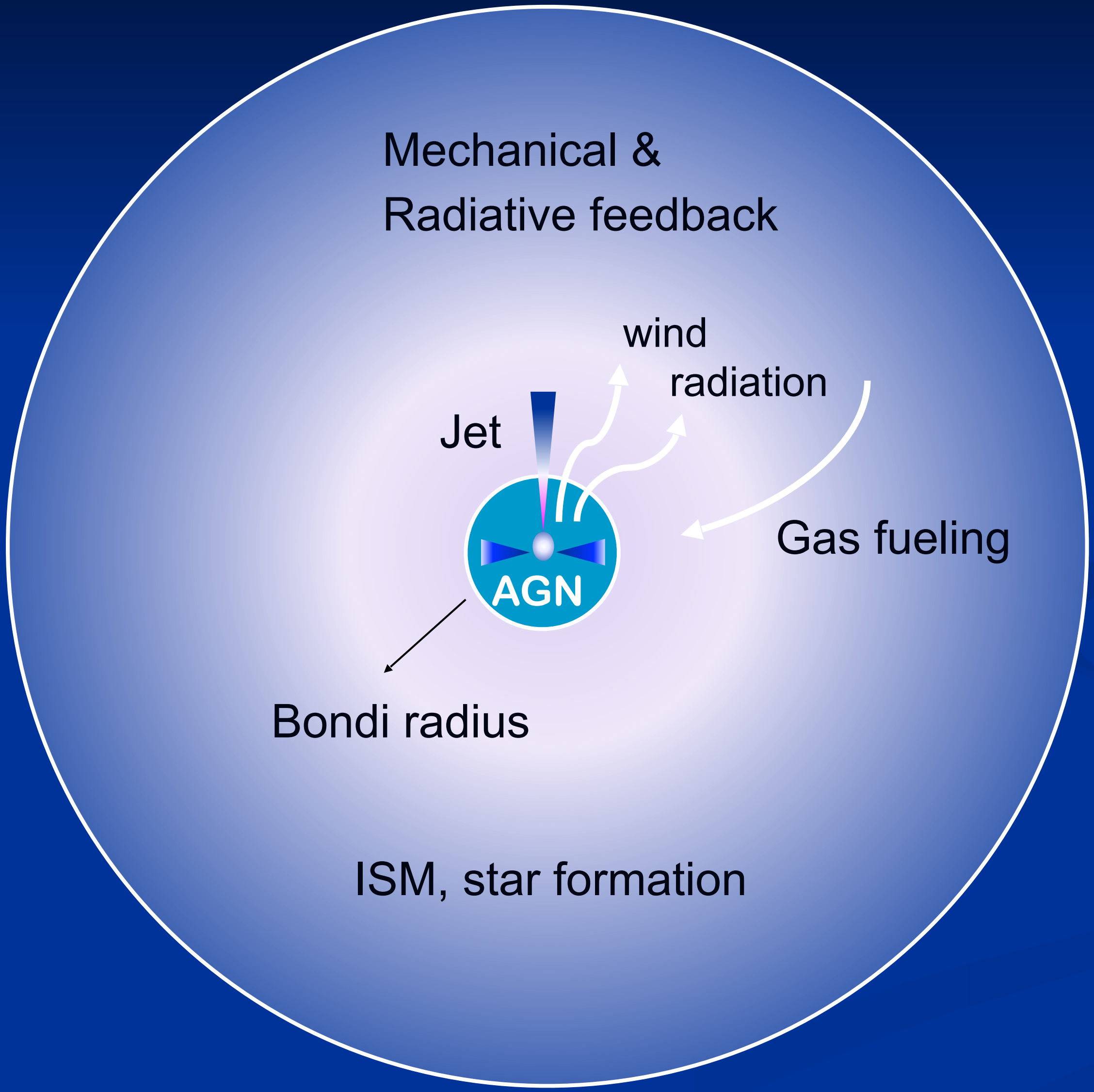
AGN feedback



Key issues of AGN feedback:

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

Current situation and our approach

- Many 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…), thus:
  - only resolve galactic scale, not the accretion scale
  - Model of AGN feedback: subgrid & simple
- To better understand feedback, we focus on galaxy scale
  - Can resolve the Bondi scale
  - Adopt the most updated AGN physics: radiation + outflow
  - Calculate the interaction between wind & radiation with ISM

Outline

- Review of accretion physics:
  - Two accretion modes: cold & hot
  - Descriptions of wind & radiation in each mode
- Model setup: AGN feedback in an isolated galaxy
- Results: light curve; duty-cycle; star formation; BH growth

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

Cold accretion(feedback) mode (I)

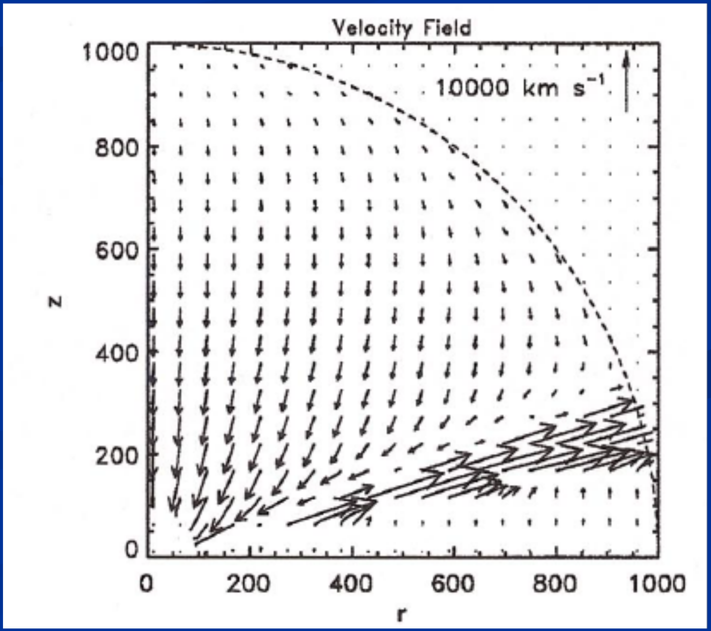
Shakura & Sunyaev 1976; Pringle 1981, ARA&A; Blaes 2013; Omer and Mitch's talks

- Correspond to quasar (thermal/radiative) feedback mode
- Cool: ~10^6 K, Geometrically thin & Optically thick
- Outputs: strong wind & radiation, but no jet (?)
- Radiation
  - Efficiency high: ~0.1
  - Spectrum: quasar spectrum (big blue bump et al.)

Cold accretion mode (II): wind

Crenshaw et al. 2003, ARA&A; Tombesi et al. 2010, 2014; Gofford et al. 2015…

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

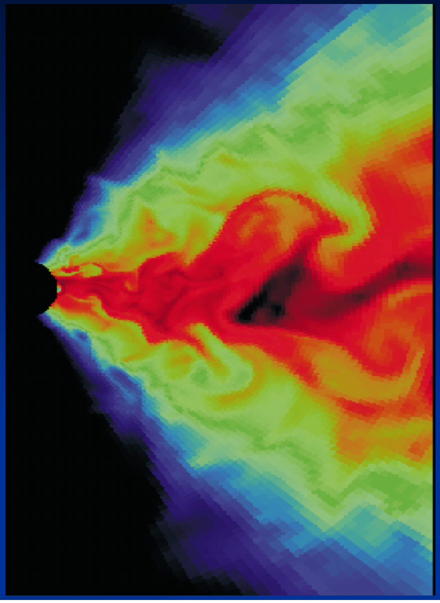


$$\dot{M}_{\rm W,C} = 0.28 \left(\frac{L_{\rm BH}}{10^{45}\,{\rm erg\,s^{-1}}}\right)^{0.85} M_\odot\,{\rm yr}^{-1}$$

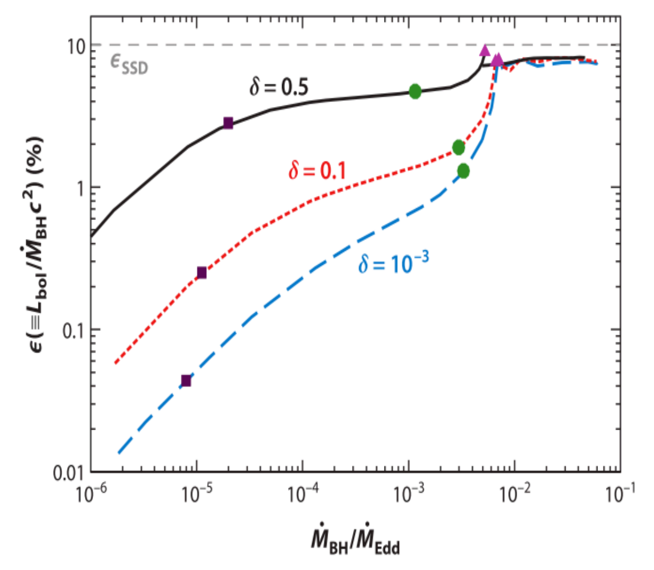
$$v_{\rm W,C} = 2.5\times10^{4} \left(\frac{L_{\rm BH}}{10^{45}\,{\rm erg\,s^{-1}}}\right)^{0.4} {\rm km\,s^{-1}}$$

Hot accretion (feedback) mode (I)

Narayan & Yi 1994, 1995; Yuan & Narayan 2014, ARA&A



- Correspond to kinetic (radio/jet/ maitanence) feedback mode
- Hot, geometrically thick; Optically thin;
- Outputs: radiation, wind & jet
- Radiation:
  - Efficiency: a function of Mdot →
  - Spectrum: complicated; different from luminous AGN



Xie & Yuan 2012

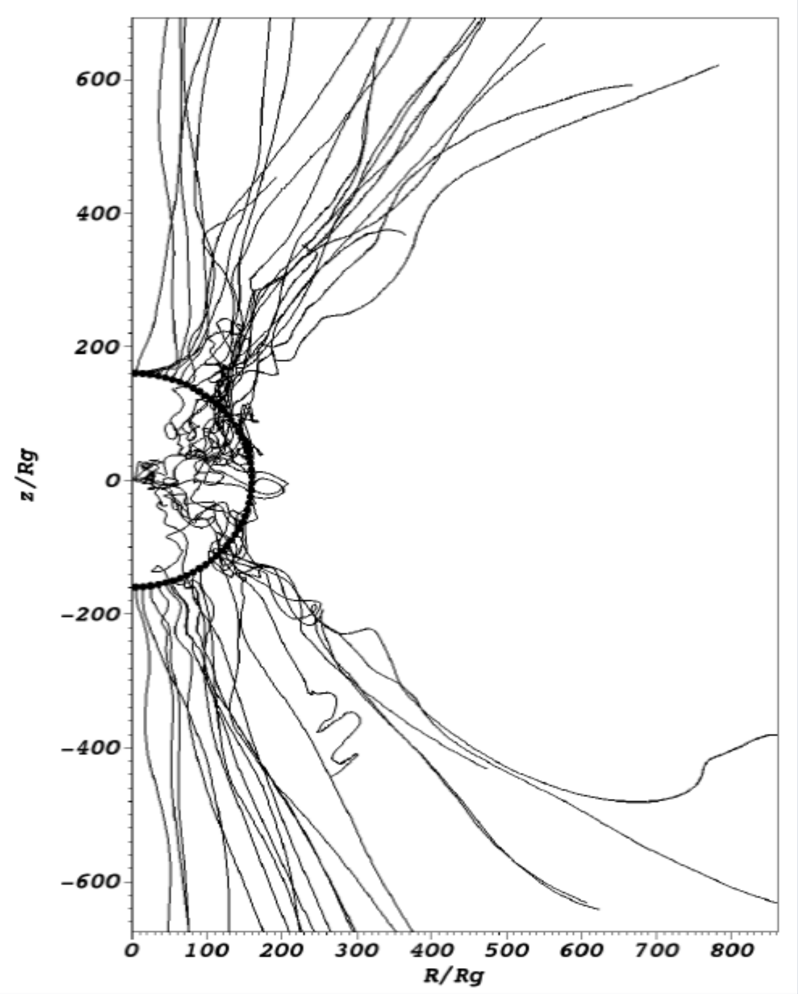
Hot accretion flow (II): wind

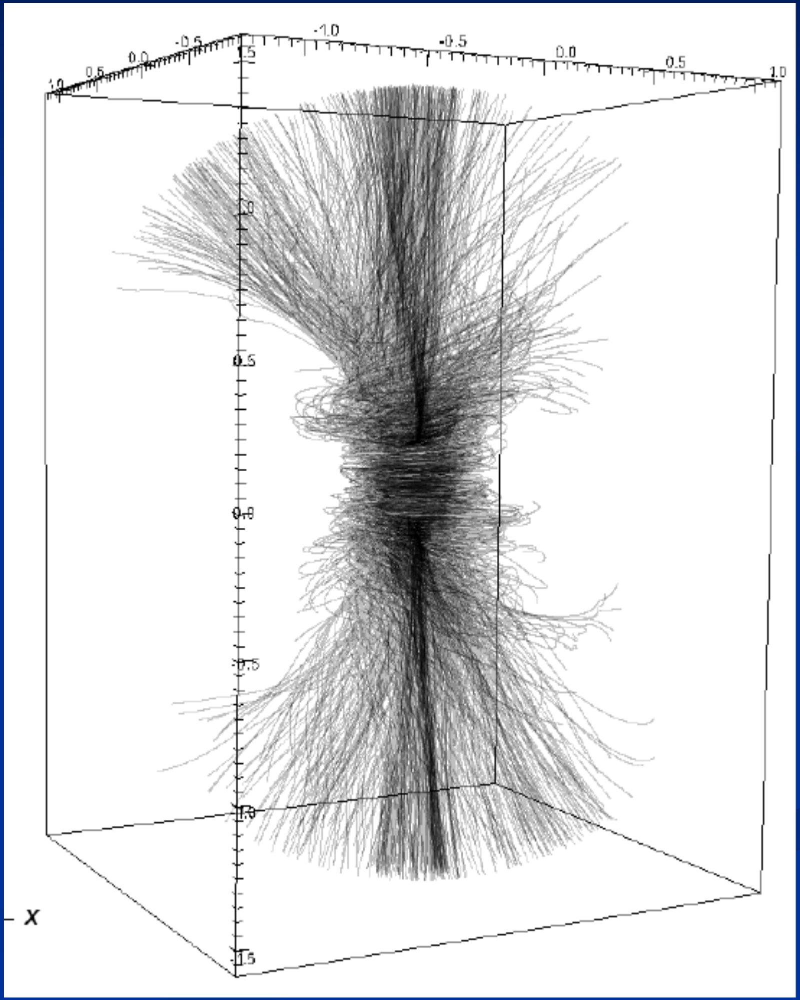
Yuan et al. 2012; Narayan et al. 2012; Yuan et al. 2015

- Observational evidence:
  - Hard state of black hole X-ray binaries (Homan et al. 2016)
  - Sgr A* (Wang et al. 2013, Science)
  - LLAGN (Cheung et al. 2016, Nature)
  - Radio galaxy (Tombesi et al. 2010, 2014)
- But wind properties still poorly constrained
- Theoretical studies:
  - Yuan et al. (2012), Narayan et al. 2012: show the existence of wind
  - Yuan et al. (2015): calculate wind properties

Trajectory of wind based on GRMHD simulation

Yuan et al. 2015





Properties of wind from hot accretion flow

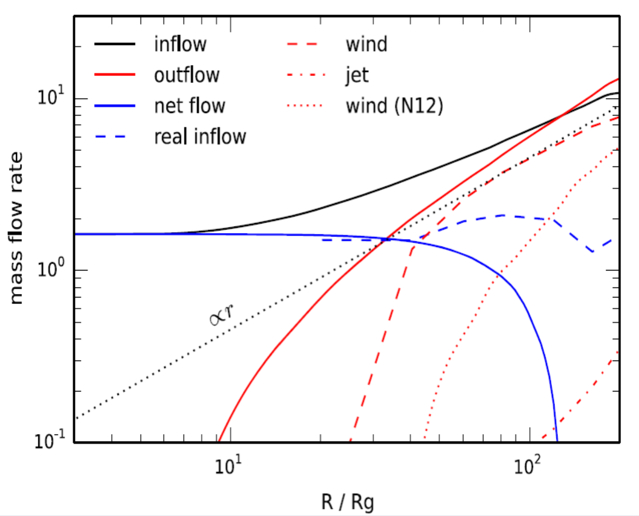
Yuan et al. 2015

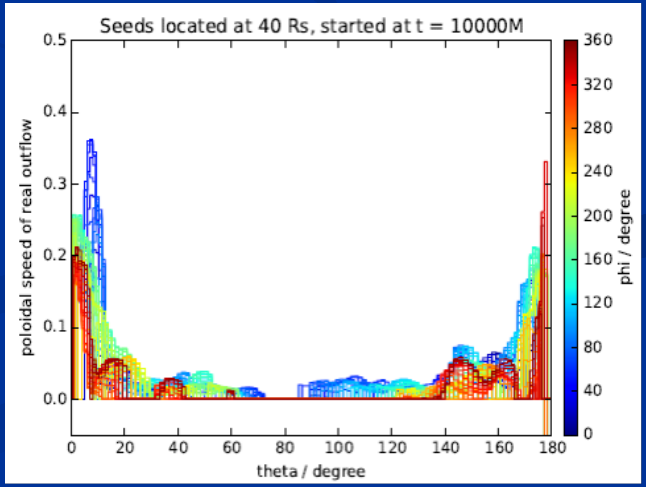
- Use trajectory approach
  - Different from stream line
- Mass flux

$$\dot{M}_{\rm W,H}(r) = \dot{M}_{\rm BH}(\frac{r}{20r_s})$$

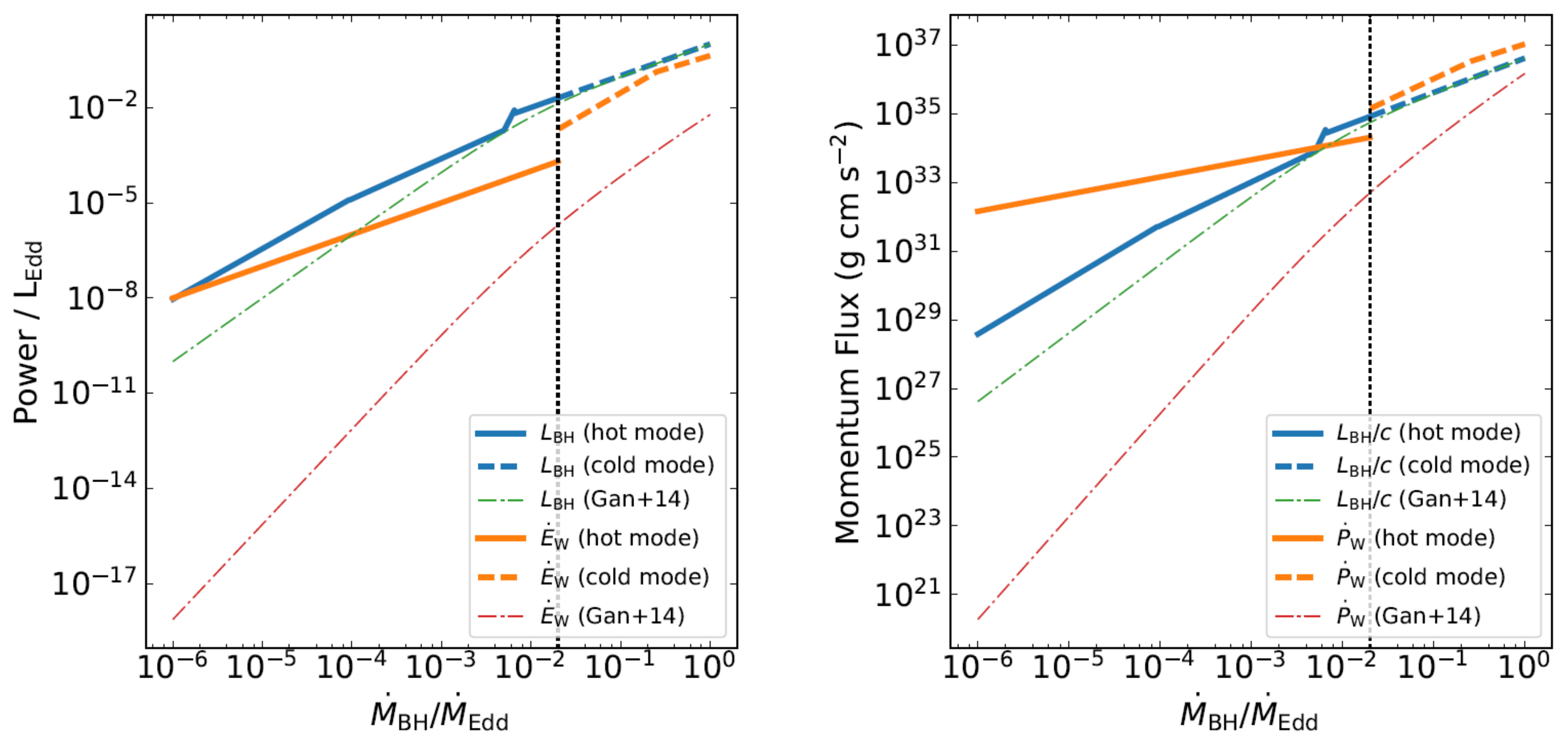
- Wind speed

$$v_{\rm W,H}(r) \sim 0.2 v_K(r)$$




Seeds located at 40 Rs, started at t = 10000M

Momentum/energy fluxes of wind/radiation in cold/hot accretion(feedback) modes



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

Galaxy Model

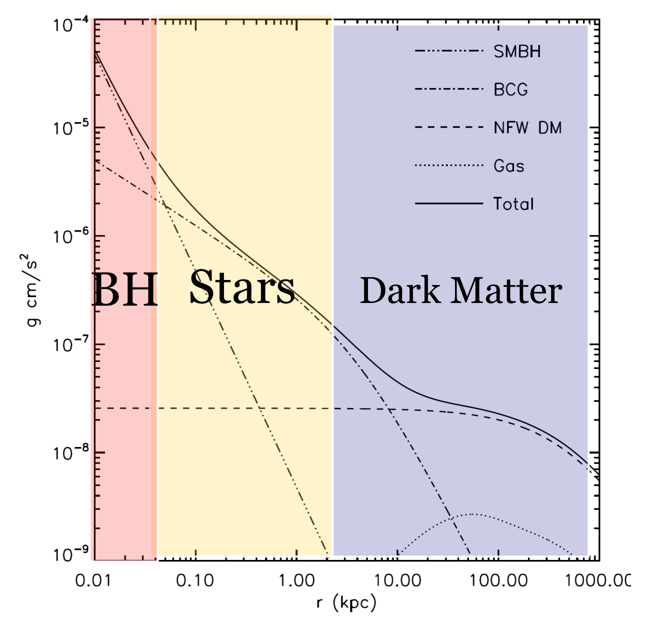
We focus on the **cosmological evolution** of an **isolated elliptical galaxy.**

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**,

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

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

Star Formation

We estimate SFR using the standard Kennicut-Schmidt 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**.

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

Radiative Heating & Cooling

Sazonov et al. 2005

Net energy change rate per unit volume:

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

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

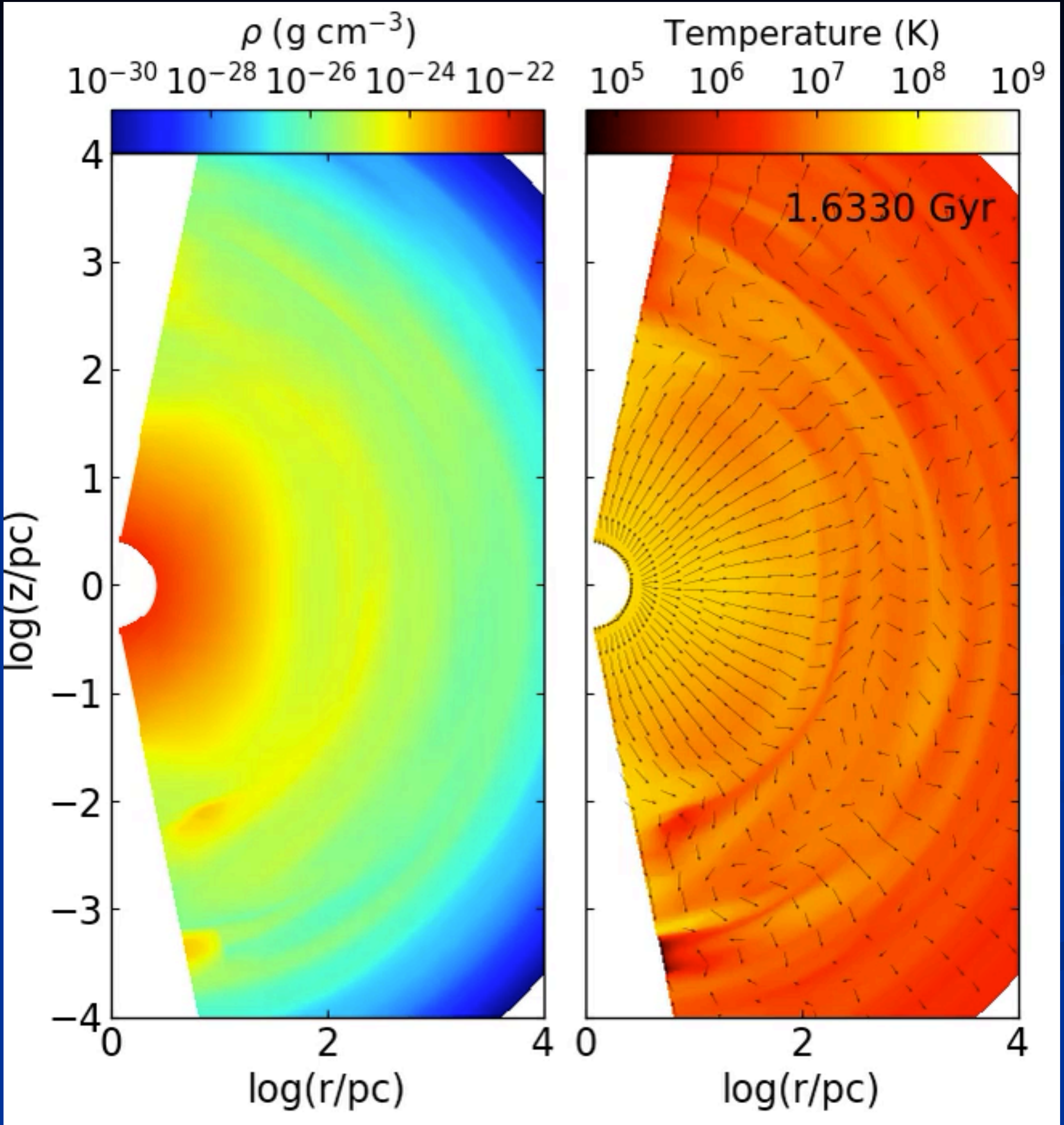
$$S_3 = 10^{-23} \times \frac{a + b(\xi / \xi_0)^c}{1 + (\xi / \xi_0)^c}$$

Setup of *MACER* code

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

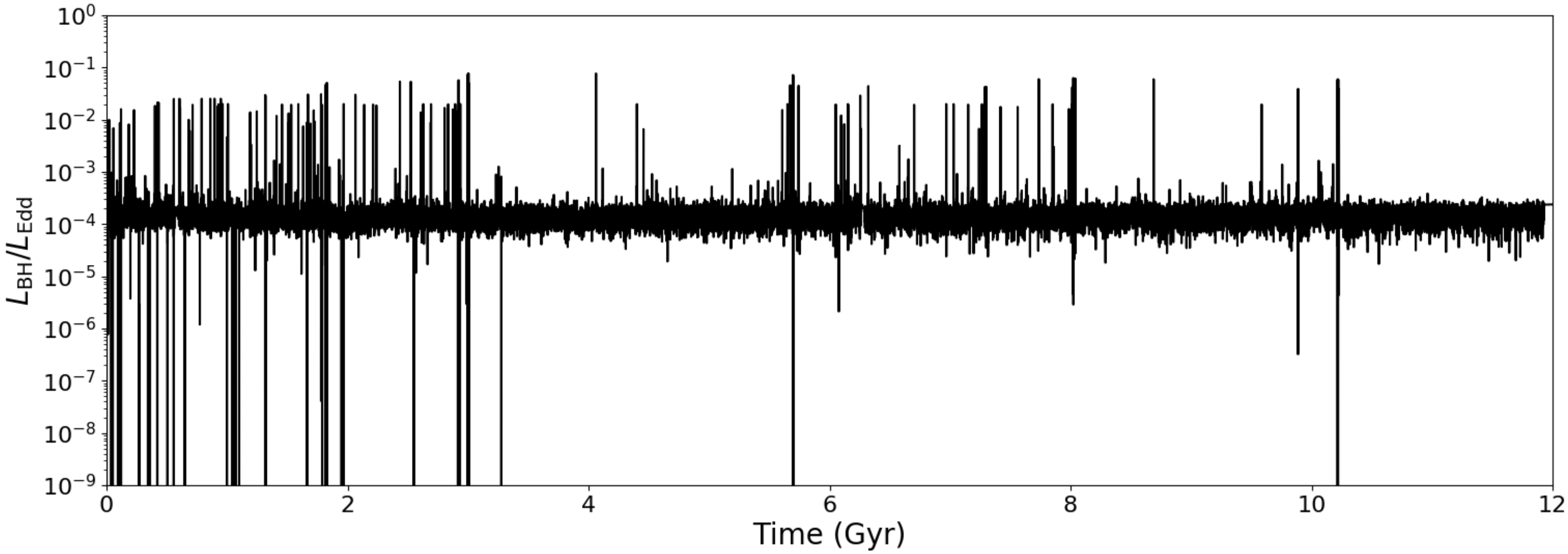
Yuan et al. 2018; Ciotti & Ostriker 2001, 2007; Novak et al. 2012; Gan et al. 2014

- 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
log(r/pc)
0
2
4
log(r/pc)
0
2
4

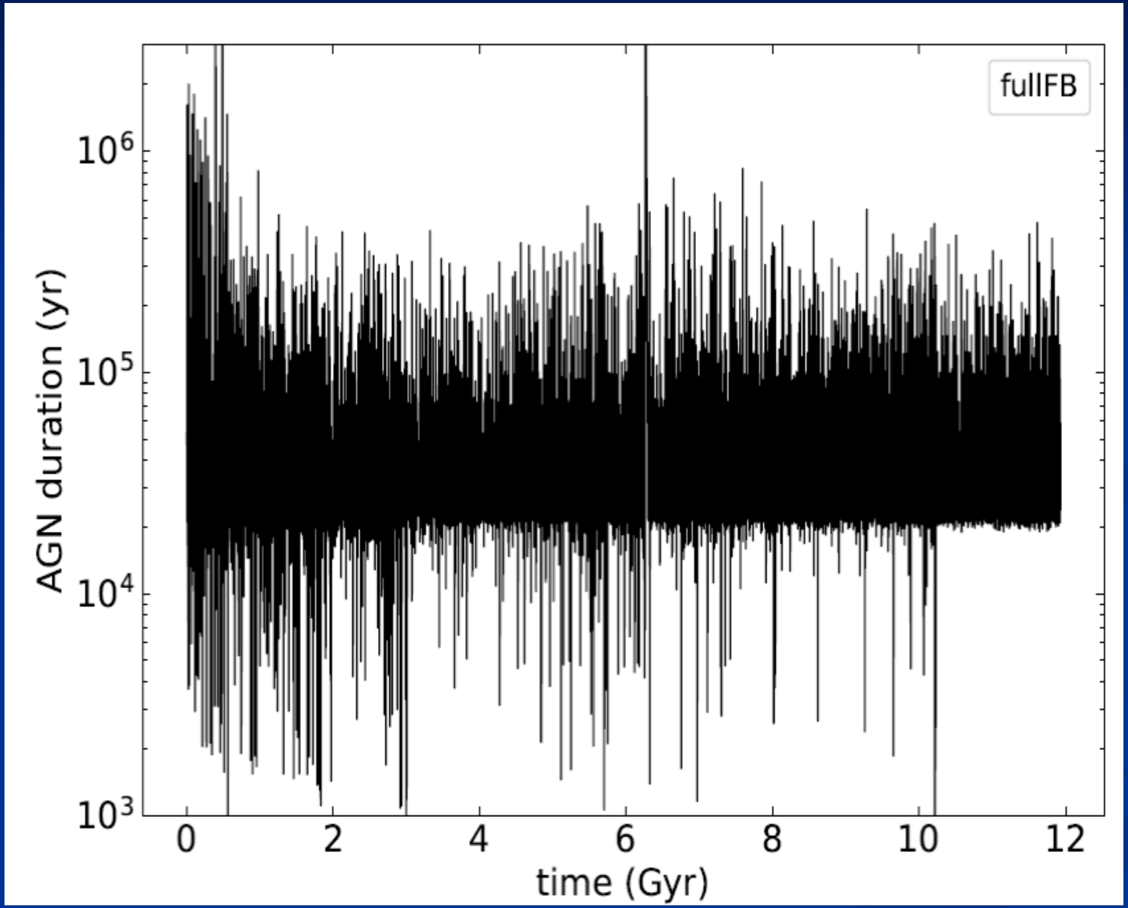
Light curve of AGN (I)

Yuan et al. 2018



Most of time, AGN stays in LLAGN phase

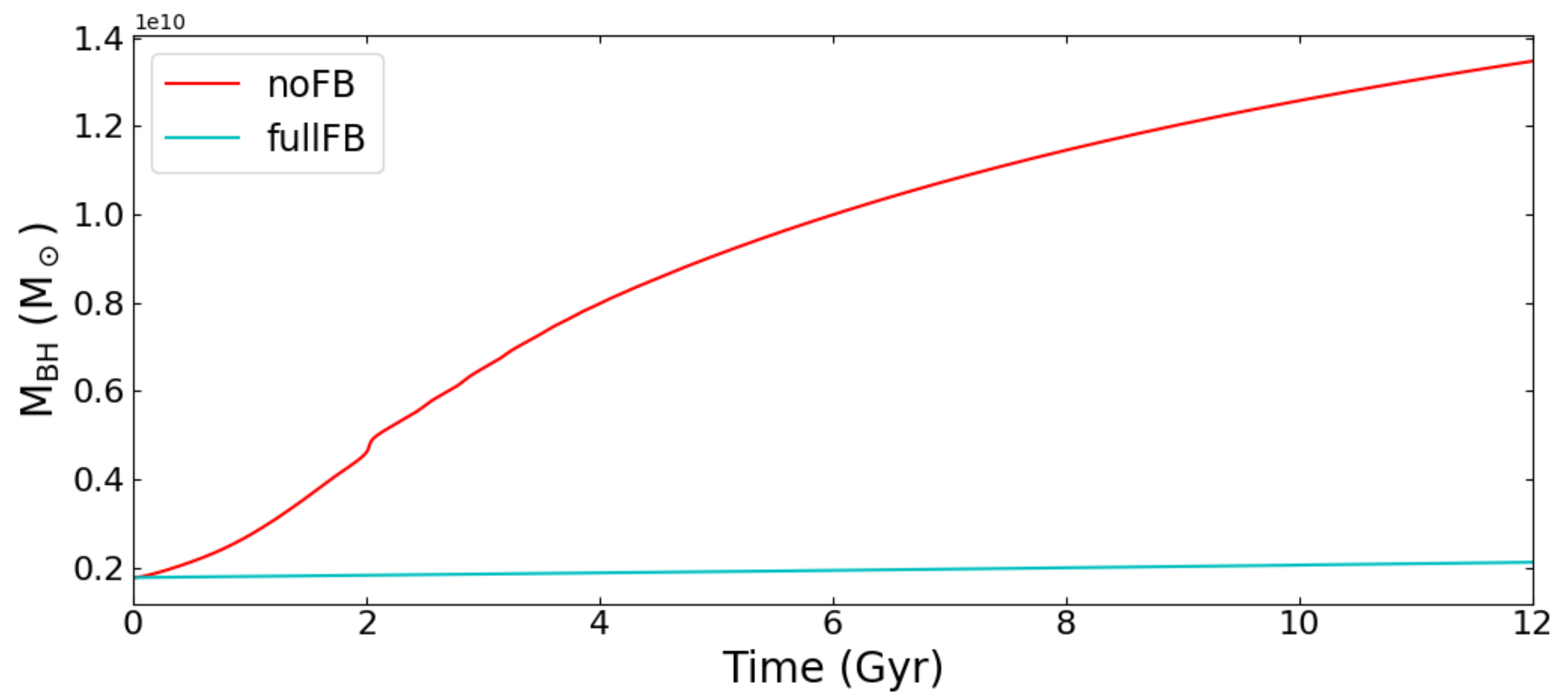
Light curve of AGN (II): AGN lifetime



Lifetime of AGN: 10^5 yr, consistent with observations (e.g., Keel et al. 2012; Schawinski et al. 2015; King & Nixon 2015)

Growth of black hole mass

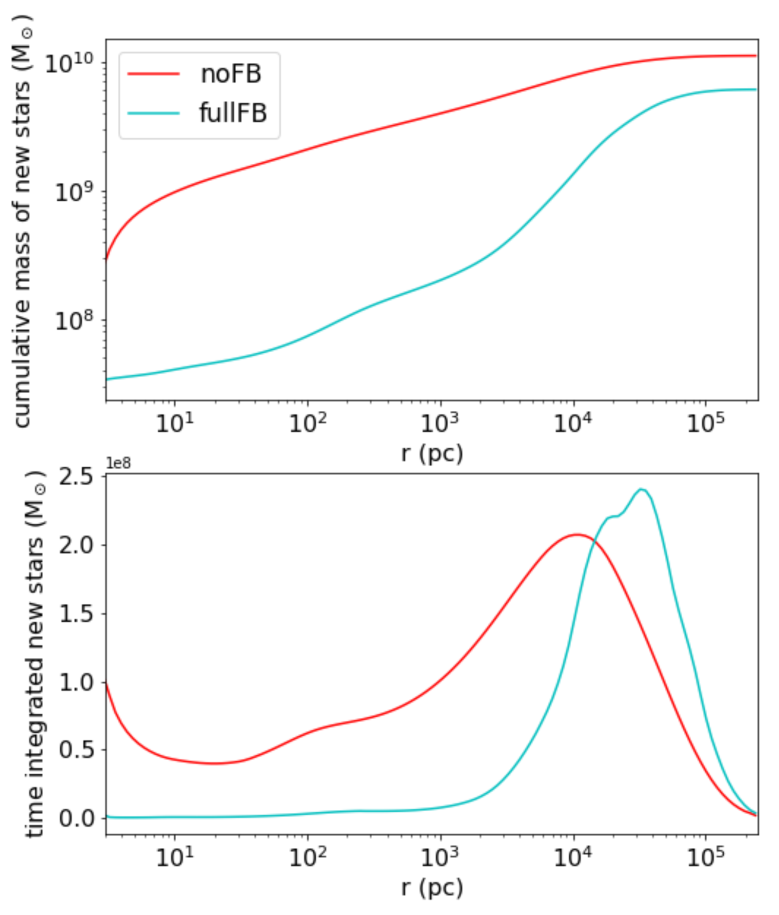
Yuan et al. 2018



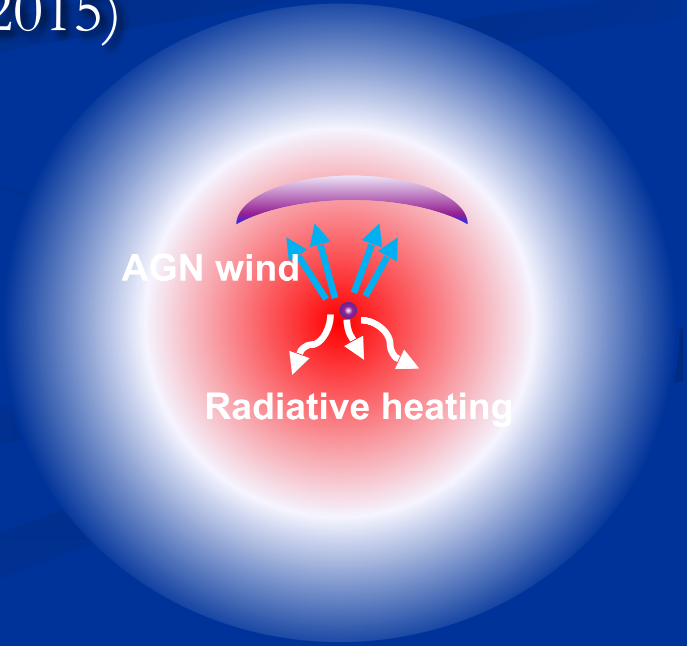
AGN feedback regulates BH mass growth.

Star formation

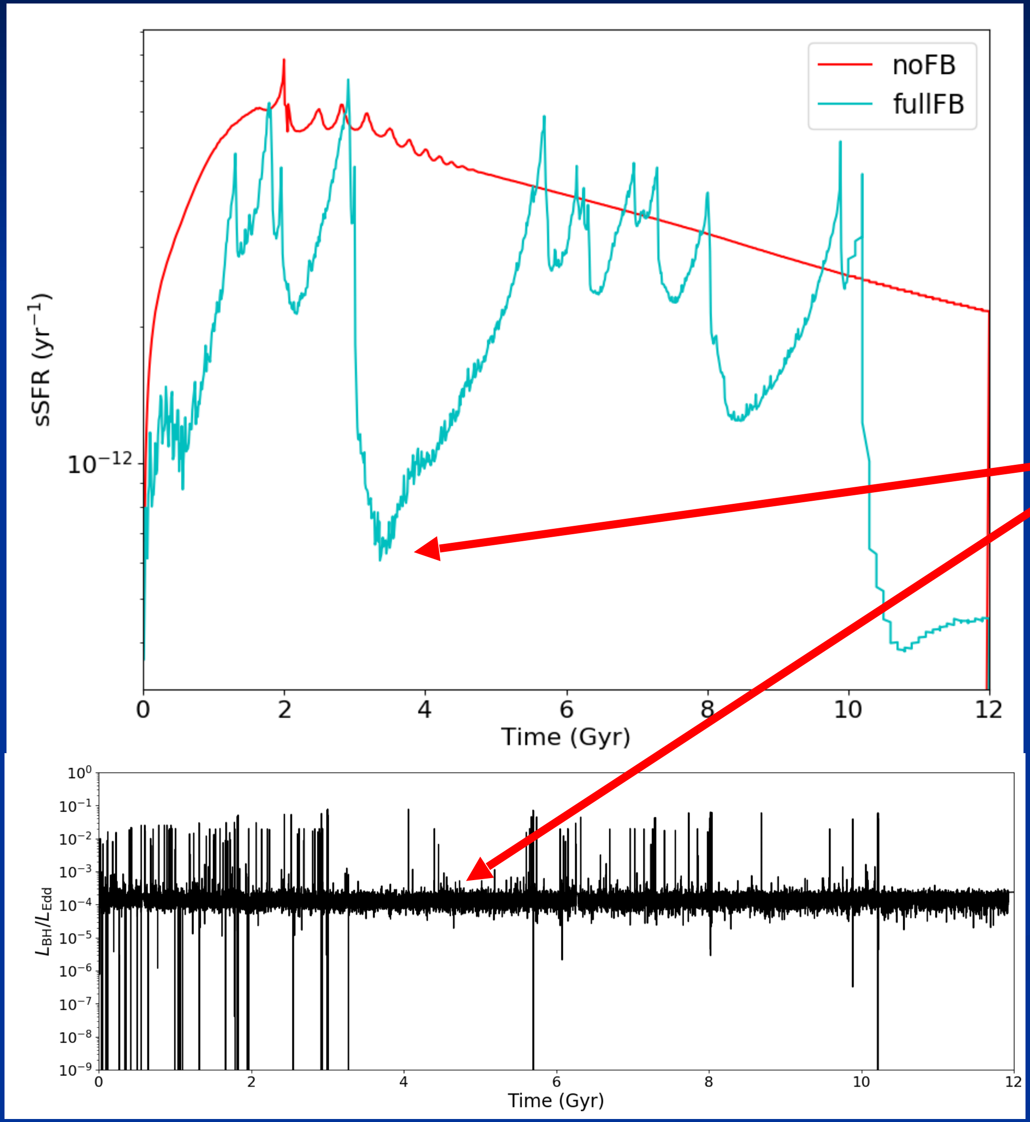
— suppressed or enhanced?



- Overall, star formation is suppressed
- 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; again consistent with observation (e.g., Cresci et al. 2015)



Specific Star Formation Rate



Relation between AGN & SFR:

* Negative or positive?

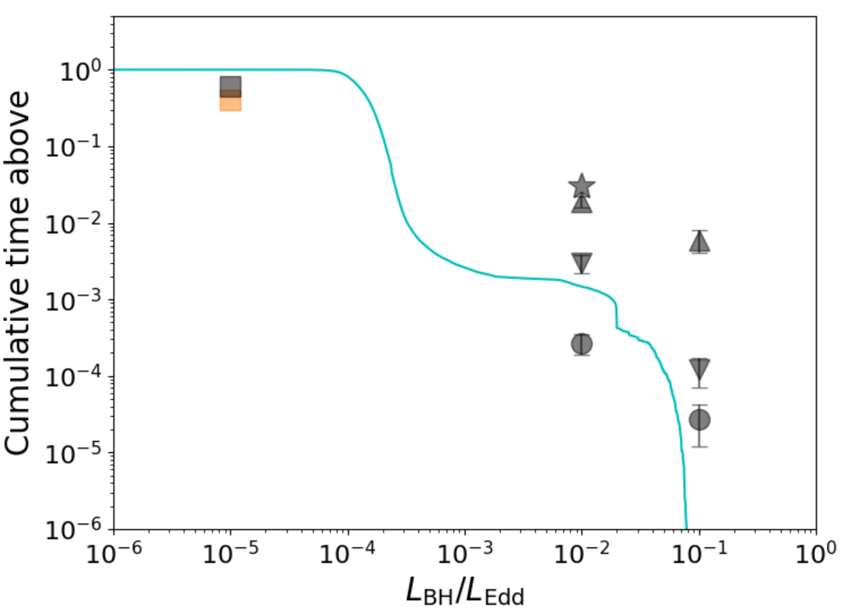
Depending on location and time !

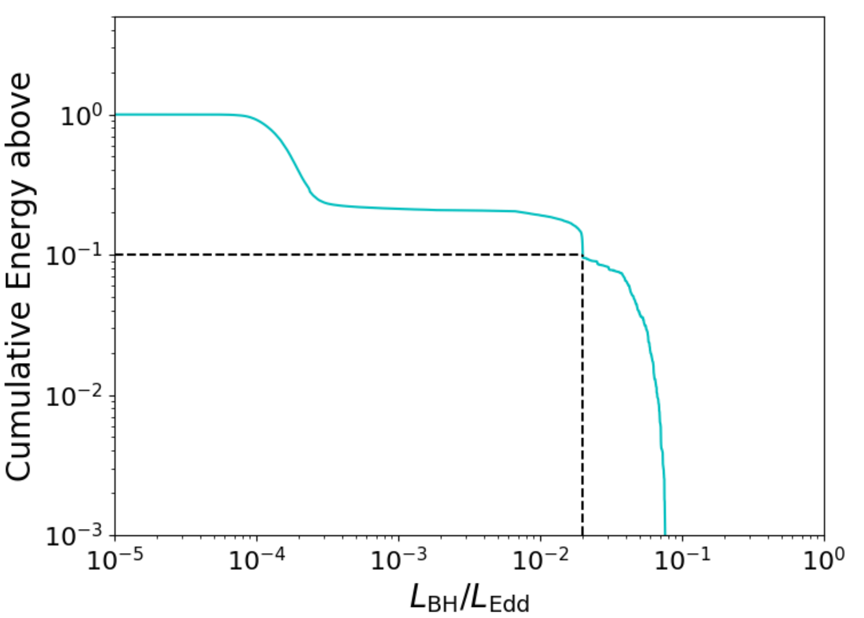
* Compare light curves of AGN with sSFR: to be studied

Question:

How to study effect of feedback on SF from observation?

AGN duty-cycle

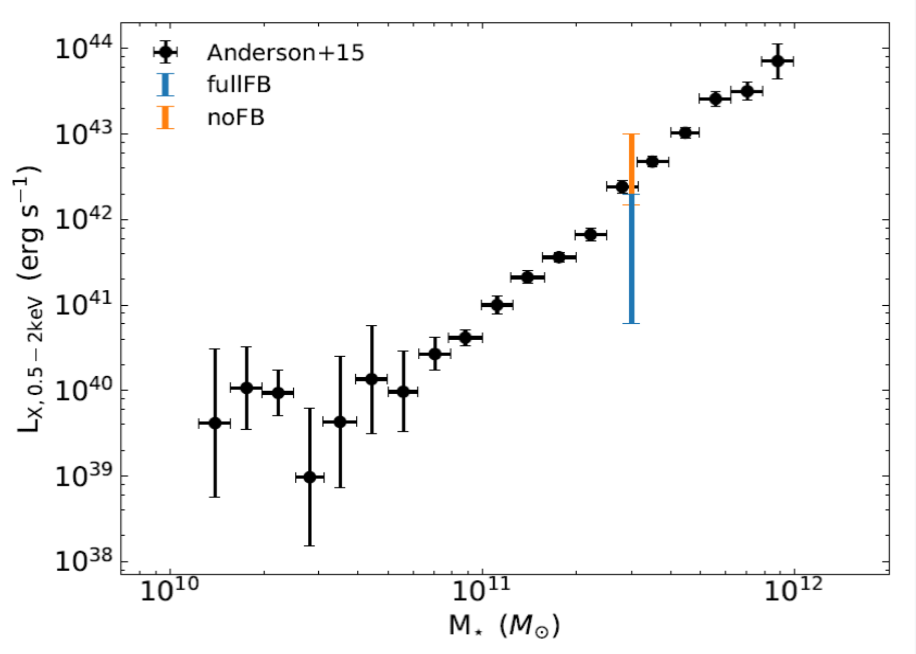


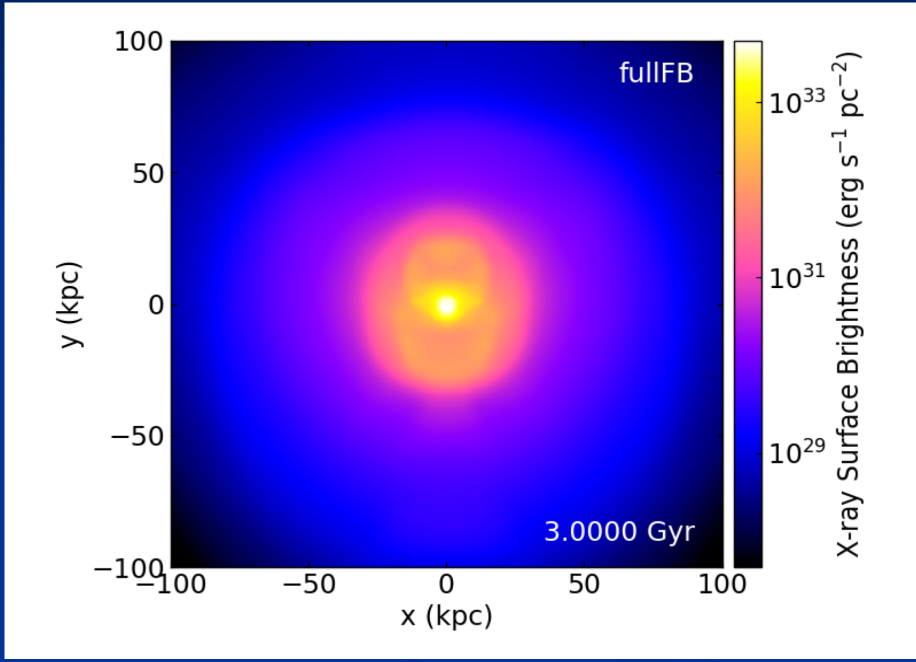


Percentage of the total simulation time spent above an Eddington ratio
Consistent with observations

Percentage of the total energy emitted above 2% Eddington ratio: ~10%
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 studied by high-res. simulation: Bondi radius resolved
- Exact AGN physics adopted:
  - two accretion/feedback modes: cold & hot
  - proper descriptions of radiation & wind
- Include: interaction between wind & radiation and ISM; SNe; SF
- AGN light curve, BH growth, star formation, surface brightness
- Comparison with other works indicates the importance of *exact AGN physics*

Thank you for your attention!