Hydrodynamic Simulation of AGN Feedback and its impact on the evolution of ETGs:

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Outline

- Introduction
  - Observational evidences and theoretical concept of AGN feedback
- Key Questions
- Numerical Setup
- Result:
  - Tailored sub-grid model for the proper accretion physics
  - The effects of AGN feedback on the co-evolution between the black hole and the host galaxy
- Future Work
- Summary
Introduction

Chandra X-ray observations for AGN feedback
(Fabian 12, reference therein)

(Kormendy & Ho 2013)
AGN Feedback & Accretion Physics

Mechanical feedback
Radiative feedback

Jet
Gas fueling

ISC

Thermal state
(NLSTs?)

Intermediate state?
(Quasars, Seyferts?)

Hard state
(LLAGNs, Seyferts)

Truncation of thin disk (Yuan & Narayan 14)

In addition, we adopt updated
• radiative efficiency profile
• Compton temperature depending on BH accretion rate.
Angular Momentum Transport

- Magneto-rotational Instability (MRI; Stone+99,01)
- Gravitational Instability (Gammie 01)
- Anisotropic Gravitational Torque (Hopkins+10,11)
Models & Physics of Interest

\[
\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = \alpha \rho_* + \dot{\rho}_{II} - \dot{\rho}_* .
\]

\[
\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \rho g - \nabla p_{rad} - \dot{m}_* .
\]

\[
\rho \frac{D}{Dt} \left( \frac{e}{\rho} \right) = -p \nabla \cdot \mathbf{v} + H - C + E_S + E_I + E_{II} - \dot{E}_* .
\]

- Galactic Model
  - Spherically symmetric distribution of stellar population (Jaffe profile) and dark matter halo
  - Initial \( M_{BH} \sim M_*^{-3} \) (Magorrian+98)
  - Gas supply \( \leftarrow \) stellar evolution + Supernova
  - AGN Feedback
    - Radiative Feedback (radiation pressure, radiative heating)
    - Mechanical Feedback (BLR wind)

- 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
Numerical Configuration

- **ZEUS-MP code** (Hayes+05)
- 2.5-dimensional **Hydrodynamic simulation**
- Spherical coordinate \((r, \theta)\)
- Logarithmic mesh in \(r\)-direction **[from 2.5 pc (< \(R_{\text{Bondi}}\)) to 250 kpc]**
  - finest resolution close to the BH – 0.25 pc
- Inject wind & radiation from the inner boundary & calculate their interaction with ISM
- Time coverage: **2 Gyr ~ 14 Gyr**
Light curves

- AGN variability timescales ($\tau_{\text{AGN}}$): $10^2 - 10^7$ yr (Martini+03, Novak+11)
- Conventional treatment (e.g. Gan+14)
  $\tau_{\text{AGN}}$: $10^5 - 10^8$ yr
- Updated sub-grid model
  $\tau_{\text{AGN}}$: $10^2 - 10^6$ yr
BH Mass Growth

AGN feedback (mainly mechanical feedback) regulates BH mass growth.
Newly born stars

Does AGN feedback suppress star formation ??
Specific Star Formation Rate

- Negative or positive effect on SFR?
Dynamical evolution of low & high ang.
BH Mass Growth w/ Galactic Rotation

$M_{BH} (M_\odot)$ vs Time (Gyr)

- k00
- k01
- k05
- k09
- k05noFB
- k05windFB
- k05radFB
Newly born stars

Faster the host galaxy rotates,
→ more stars forms at the central region of the galaxy
   (mostly at the mid-plane disk).
Comparison of timescales

\[ \tau_{\text{infall}} = \frac{\tau}{v_r} \]

\[ \tau_{\text{SF}} = \max(\tau_{\text{cool}}, \tau_{\text{dyn}}) \]

where \( \tau_{\text{dyn}} = \min(\tau_{\text{Jeans}}, \tau_{\text{rot}}) \)
Comparison of timescales

\[ \tau_{\text{infall}} = \frac{r}{v_r} \]

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Future Work

• Isolated evolution
  → zoom-in simulation using the data from cosmological simulation as an initial condition
• No magnetic field → MHD simulation
• No jets → self-consistent jet
• 2.5D axisymmetric simulation → full 3D simulation
Summary

• Under the **improved the sub-grid model of black hole accretion disk** based on well established accretion physics, we found that
  • the dynamical evolution of the galaxy (i.e. the self-regulation of black hole growth, AGN duty-cycle, star formations) is different from the previous studies.
  • AGN-variable timescales is more broadly consistent with observation.
• We also found that **if the host galaxy rotates faster**,  
  • the black hole accretion is more suppressed, and the star formation is more enhanced.
  • the dynamics of AGN feedback loop becomes significantly altered: cooling and inflowing at random direction $\rightarrow$ falling into mid-plane and accreting through the disk channel
Thanks very much for your attention.

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Chandra X-ray observations for AGN feedback (Fabian 12, reference therein)

M87 (Forman+07; McNamara+09)
Why isolated ETGs?

- **Collisional fluid** is an important ingredient for shaping universe → Cosmological simulation with hydrodynamics
- **AGN feedback** must be treated carefully.

(Credited by ILLUSTRIS team)

EAGLE Project (Schaye+14)
Rotating ETGs

82% of 260 ETG samples are regular rotators (Krajnović+11)
Primary goals of two projects

1. Role of **hot accretion flow** on the effects of AGN feedback
   - Develop sub-grid model for hot accretion flow
   - Update radiative efficiency profile
   - Update Compton temperature profile

2. How does the feedback work when the high angular momentum?
   - Develop rotation & angular momentum
Primary goals of two projects

1. Role of **hot accretion flow** on the effects of AGN feedback
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![Diagram showing thermal states and truncation of thin disk](image-url)
Backup Slide – Primary goals of two projects

1. Role of **hot accretion flow** on the effects of AGN feedback
   - Develop sub-grid model for hot accretion flow
   - Update radiative efficiency profile

2. How does the role of high accretion on AGN feedback change?
   - Develop new models

(Xie & Yuan 2012)
Primary goals of two projects

1. Role of **hot accretion flow** on the effects of AGN feedback
   - Develop sub-grid model for hot accretion flow
   - Update radiative efficiency profile
   - Update Compton temperature profile

2. How does the feedback work when the galaxy has an intrinsic **high angular momentum**?
   - Develop rotation & angular momentum transport
Backup Slide – Achievements

• Actively done by Ciotti, Ostriker and their collaborators
  2-D (Novak+2011, 2012; Ciotti+2015, 2016; Negri+2014; Gan+2014 …)
  3-D ?

• Mechanical feedback
  – be efficient in regulating the BH growth

• Radiative feedback
  – balance cooling/heating on the galactic scale

• Stellar feedback
  – play an important role in producing galactic outflow along with AGN feedback
Models & Physics of Interest

• Galactic Model
  • Spherically symmetric distribution of stellar population (Jaffe profile) and dark matter halo

• Initial $M_{\text{BH}} \sim M_*^{-3}$ (Magorrian+98)

• Gas supply $\leftrightarrow$ stellar evolution + Supernova

• AGN Feedback
  • Radiative Feedback (radiation pressure, radiative heating)
  • Mechanical Feedback (BLR wind)

• Star formation
• Stellar Feedback (SNI, SNII, AGB, thermalization …)

• Self-gravity, magnetic field and jet are not taken into account.
Backup Slide – Models & Physics of Interest

• Galactic Model
  • Spherically symmetric distribution of stellar population (Jaffe profile) and dark matter halo

• Initial $M_{BH} \sim M_*^{-3}$ (Magorrian+98)

• Gas supply $\leftarrow$ stellar evolution + SN Ia

• AGN Feedback
  • Radiative Feedback
  • Mechanical Feedback

• Star formation
• Stellar Feedback

\[ \dot{M} = \dot{M}_* + \dot{M}_{SN} \]
Backup Slide – Models & Physics of Interest

• Galactic Model
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• AGN Feedback
  • Radiative Feedback
  • Mechanical Feedback

• Star formation
• Stellar Feedback

\[ L_{BH} = \epsilon_{EM} \dot{M}_{BH} c^2 \]
\[ \dot{M}_w = 2 \epsilon_w \dot{M}_{BH} c^2 / v_w^2 \]
\[ \dot{E}_w = \epsilon_w \dot{M}_{BH} c^2 \]
\[ \dot{P}_w = 2 \epsilon_w \dot{M}_{BH} c^2 / v_w \]
Sub-grid model of Truncated Hot Accretion Flow

\[ R_{tr} \approx 3 R_g \left( \frac{2 \times 10^{-2} \dot{M}_{Edd}}{\dot{M}(r_{Bondi})} \right)^2 \]

Yuan & Yoon et al. 2017 in preparation
Backup Slide – Newly born stars

- HotAcc, Gan+14
- Log(r/pc) vs. Log(z/pc)
- Integ. star new (g cm⁻³)
  - 10⁻³⁰, 10⁻²⁷, 10⁻²⁴, 10⁻²¹, 10⁻¹⁸
- Time integrated new star M(⊙)
- Cumulative mass of new stars M(⊙)

- fullFB
- windFB
- radFB
- fullFBem03
- noFB
Backup Slide – Duty cycle of AGN feedback

Sotan’s argument:
Most of the energy is emitted with high Eddington ratio.
Backup Slide – Light curves
X-ray Luminosity & Surface Brightness

- X-ray cavity can be reproduced by wide-angle AGN wind even if the jet is absent.
Light Curves

\[ \alpha = 10^{-1} \]

\[ \alpha = 10^{-2} \]
Newly born stars
Backup Slide – Comparison of timescales

\[ \tau_{\text{infall}} = \frac{r}{v_r} \]

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\end{align*}
\]
Backup Slide – Specific Star Formation Rate

- More rapidly rotating galaxy $\rightarrow$ higher star formation rate
Backup Slide – X-ray Luminosity