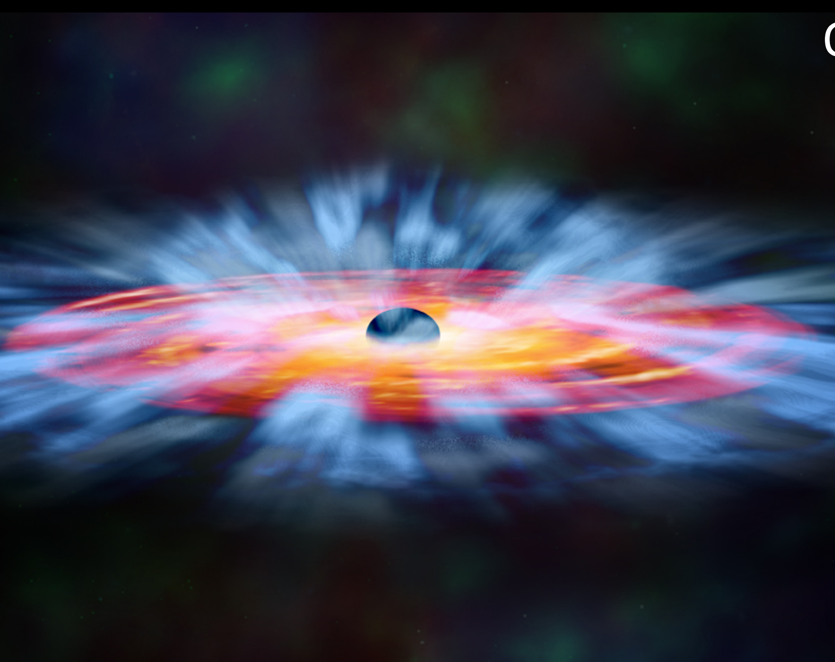
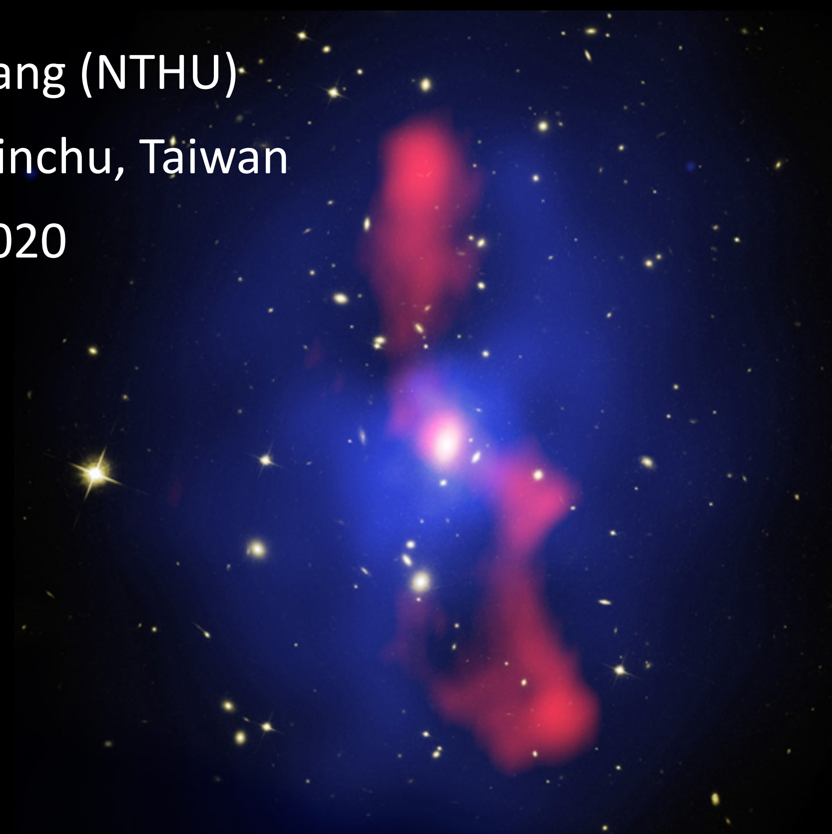
AGN Feedback on Galaxy Evolution – Theoretical Perspective

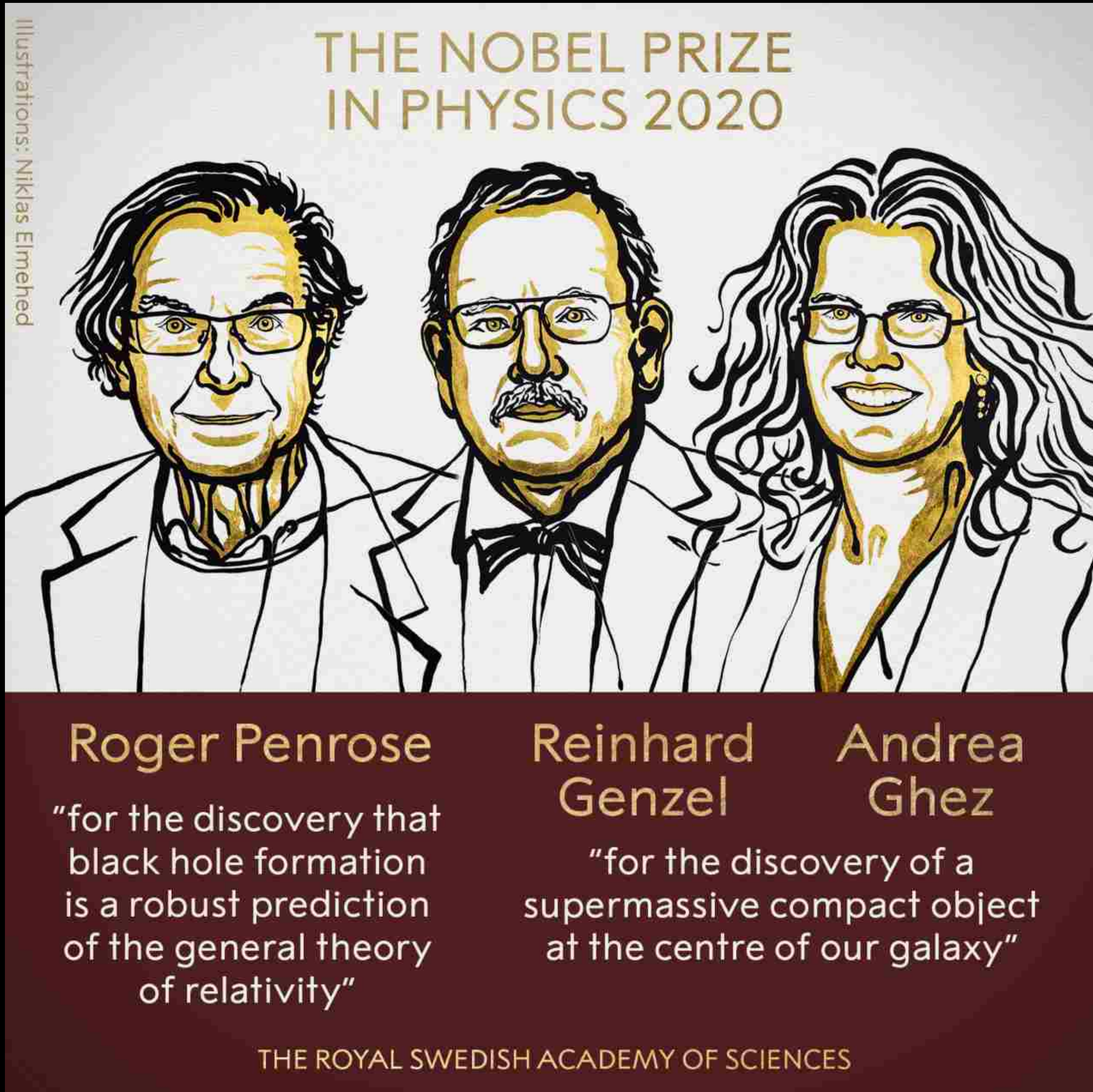
Hsiang-Yi Karen Yang (NTHU)

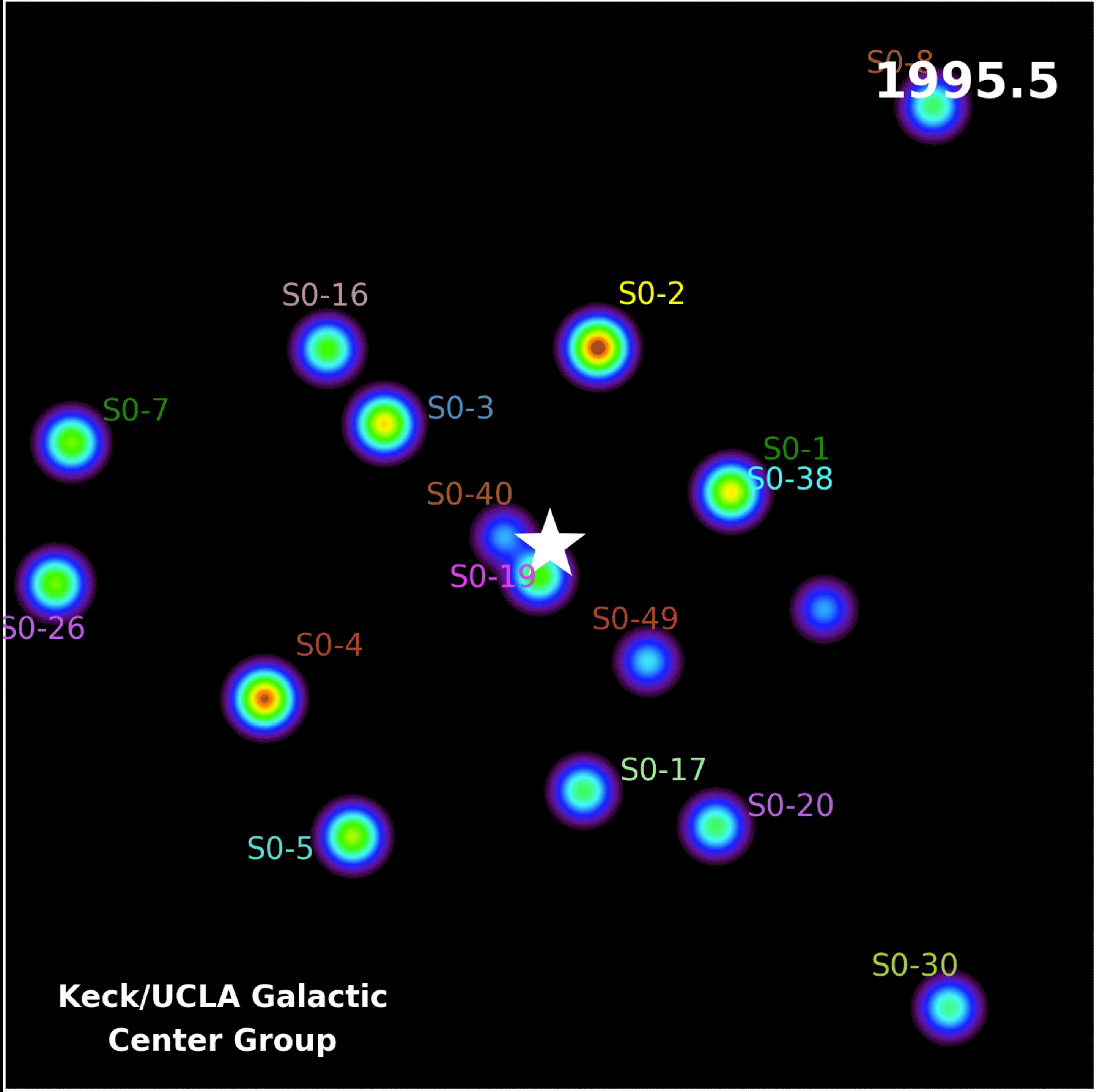
NCTS Workshop, Hsinchu, Taiwan

Oct 20, 2020






Illustrations: Niklas Elmehed
THE NOBEL PRIZE
IN PHYSICS 2020
Roger Penrose
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"
Reinhard Genzel
Andrea Ghez
"for the discovery of a supermassive compact object at the centre of our galaxy"
THE ROYAL SWEDISH ACADEMY OF SCIENCES



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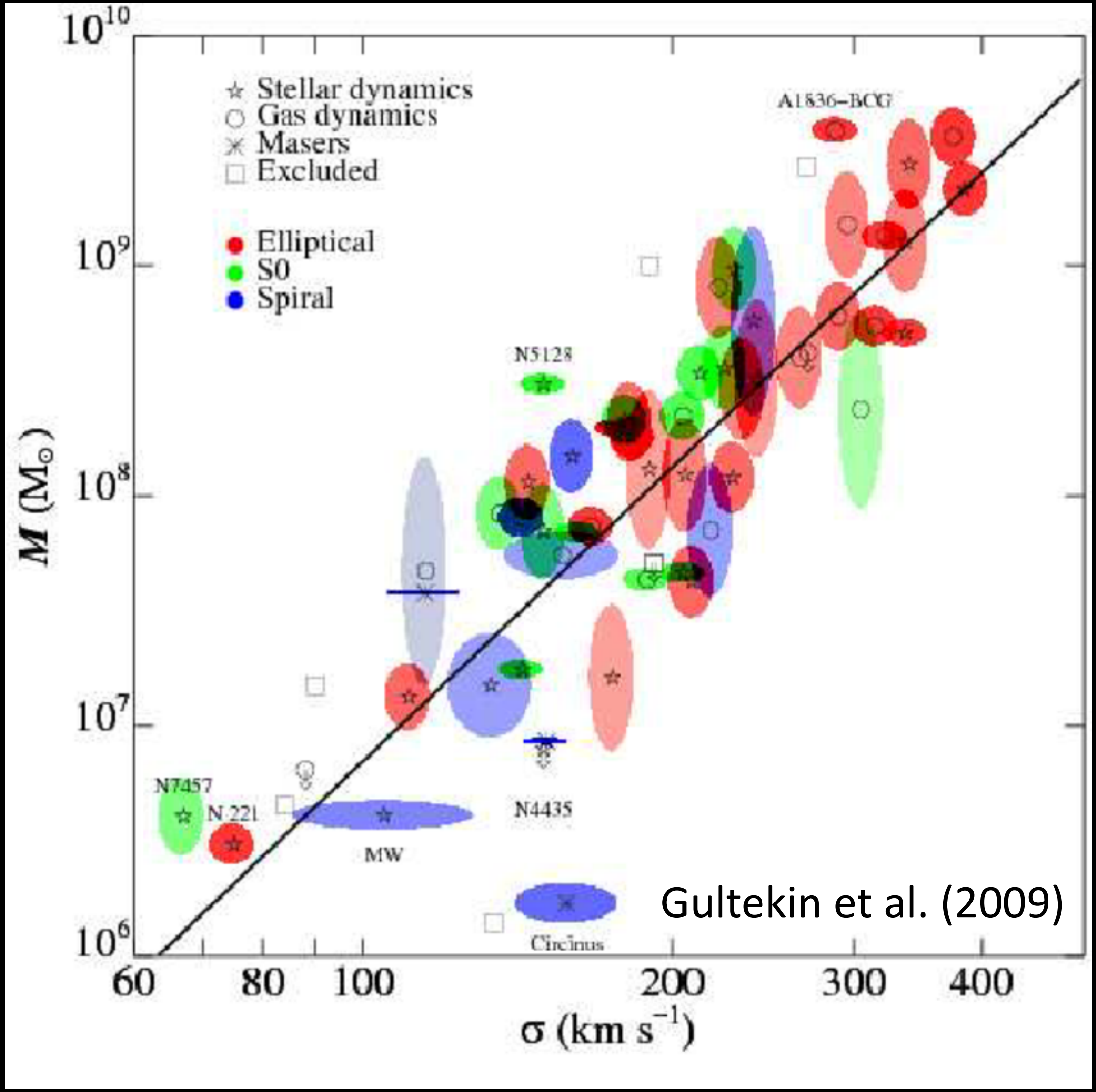
Keck/UCLA Galactic
Center Group

The M-σ relation hints SMBH-galaxy coevolution



THE ASTRONOMICAL JOURNAL, 115:2285–2305, 1998 June

Citation >3000 to date!

THE DEMOGRAPHY OF MASSIVE DARK OBJECTS IN GALAXY CENTERS

JOHN MAGORRIAN,[1] SCOTT TREMAINE,[1,2] DOUGLAS RICHSTONE,[3] RALF BENDER,[4] GARY BOWER,[5] ALAN DRESSLER,[6]
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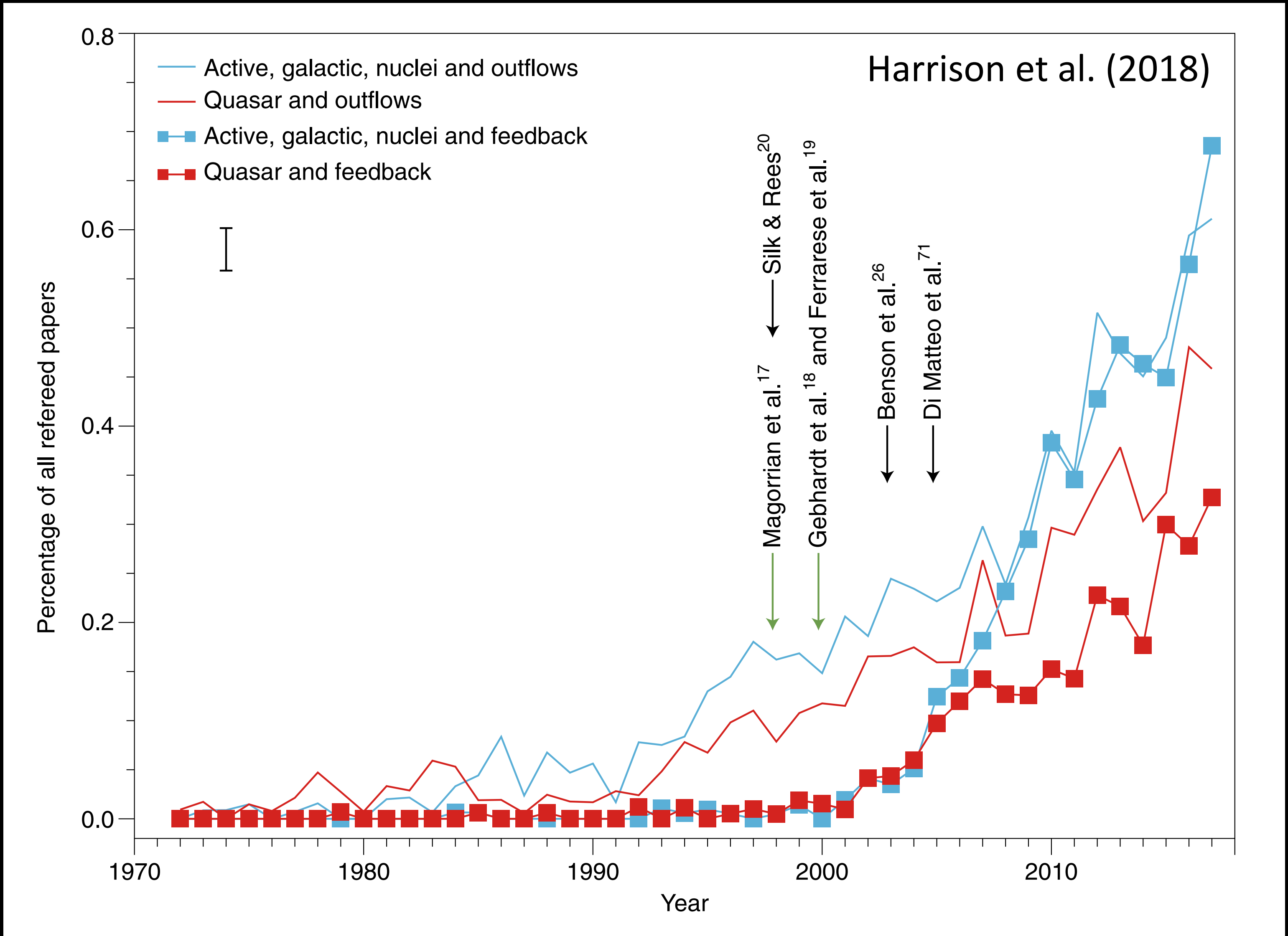
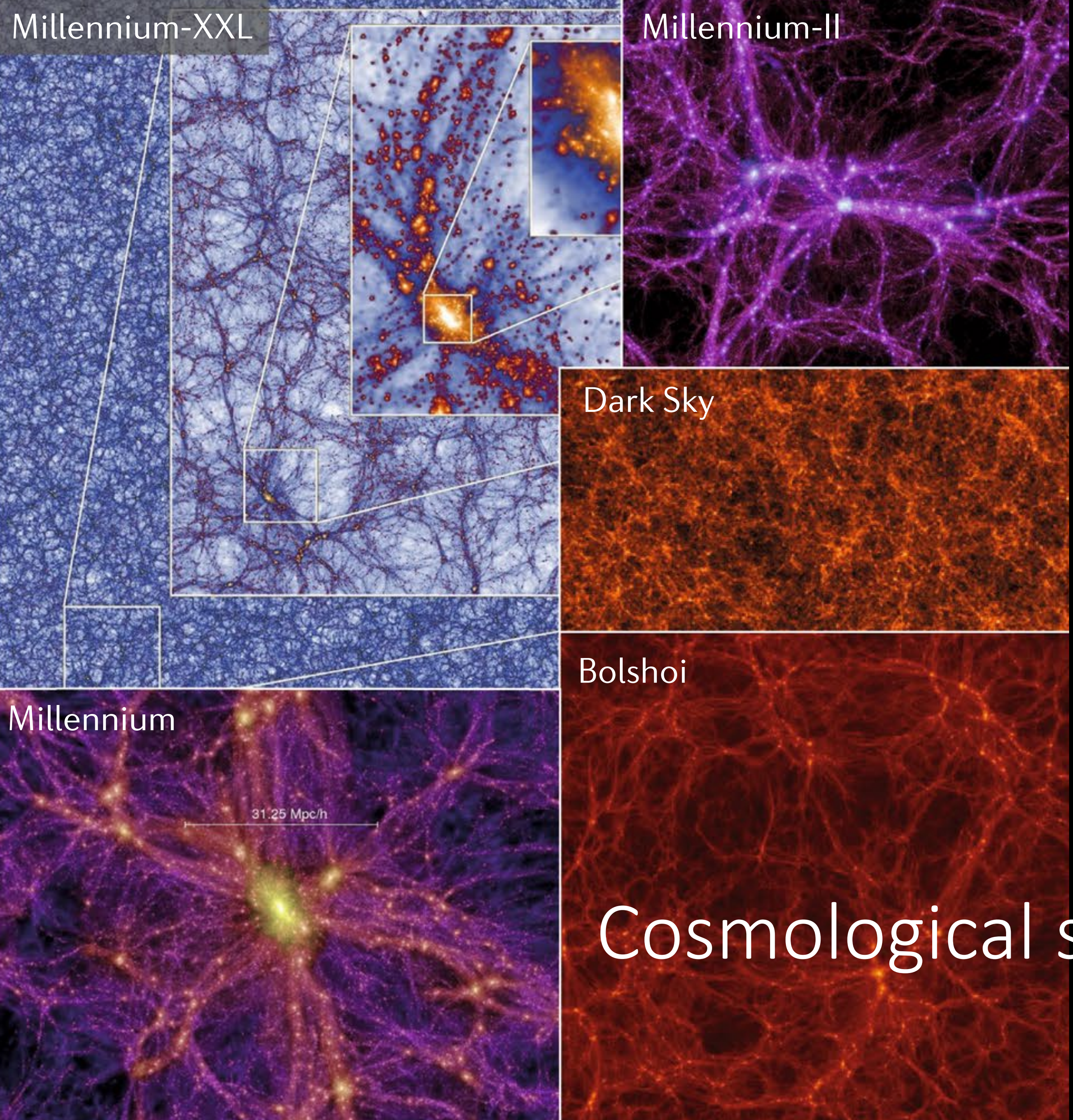
JOHN KORMENDY,[9] AND TOD LAUER[5]
Received 1997 August 7; revised 1998 March 2

The birth of the field of AGN feedback



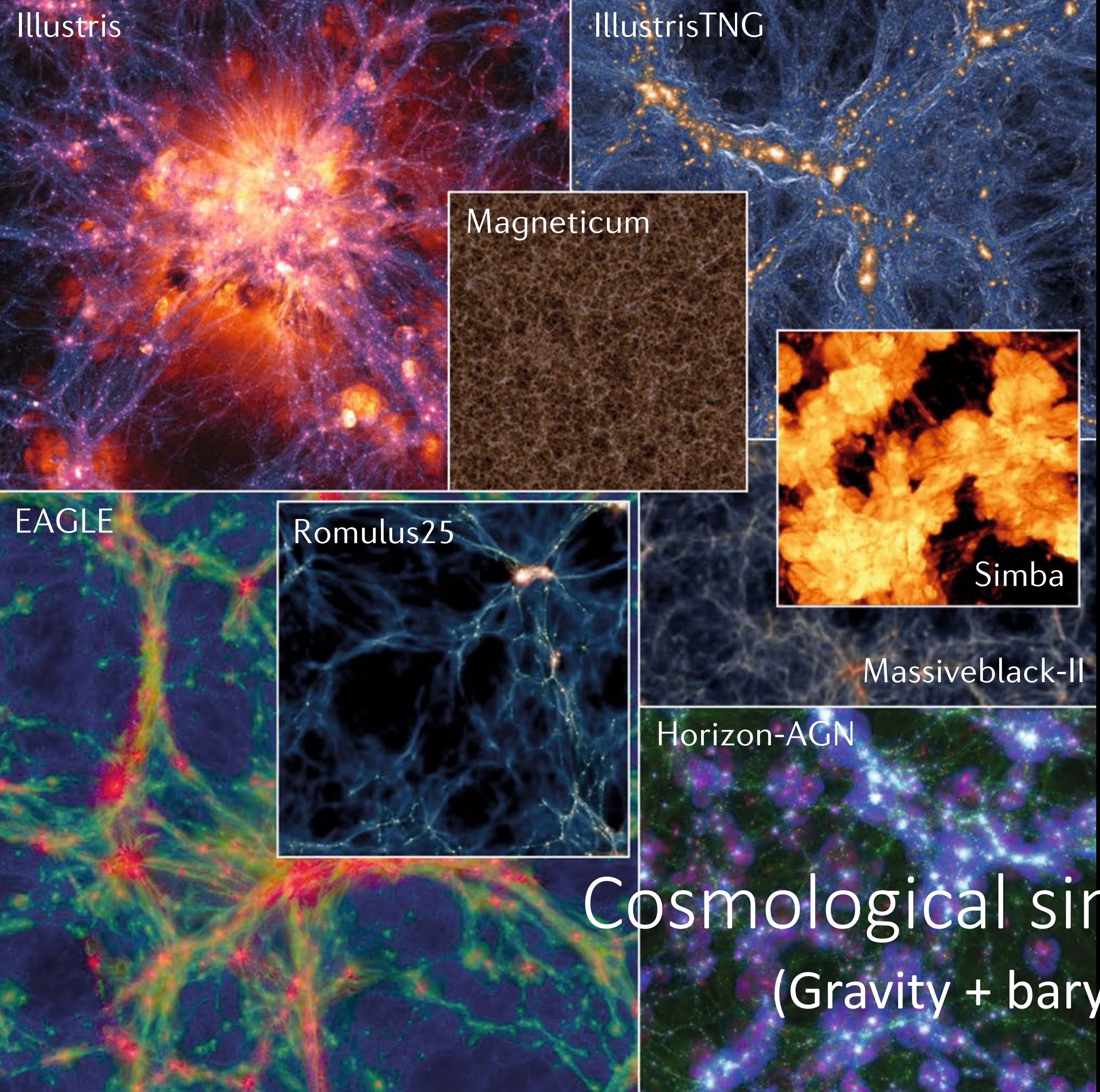
Outline

- Why AGN feedback is needed in galaxy evolution
- How AGN feedback is modeled in state-of-the-art cosmological simulations
  - Conventional paradigm
  - Limitations
- Current understanding of how AGN feedback works
  - Accretion onto the black holes
  - Quasar- and radio-mode feedback of the black holes
- Open questions and possible future directions



Cosmological simulations

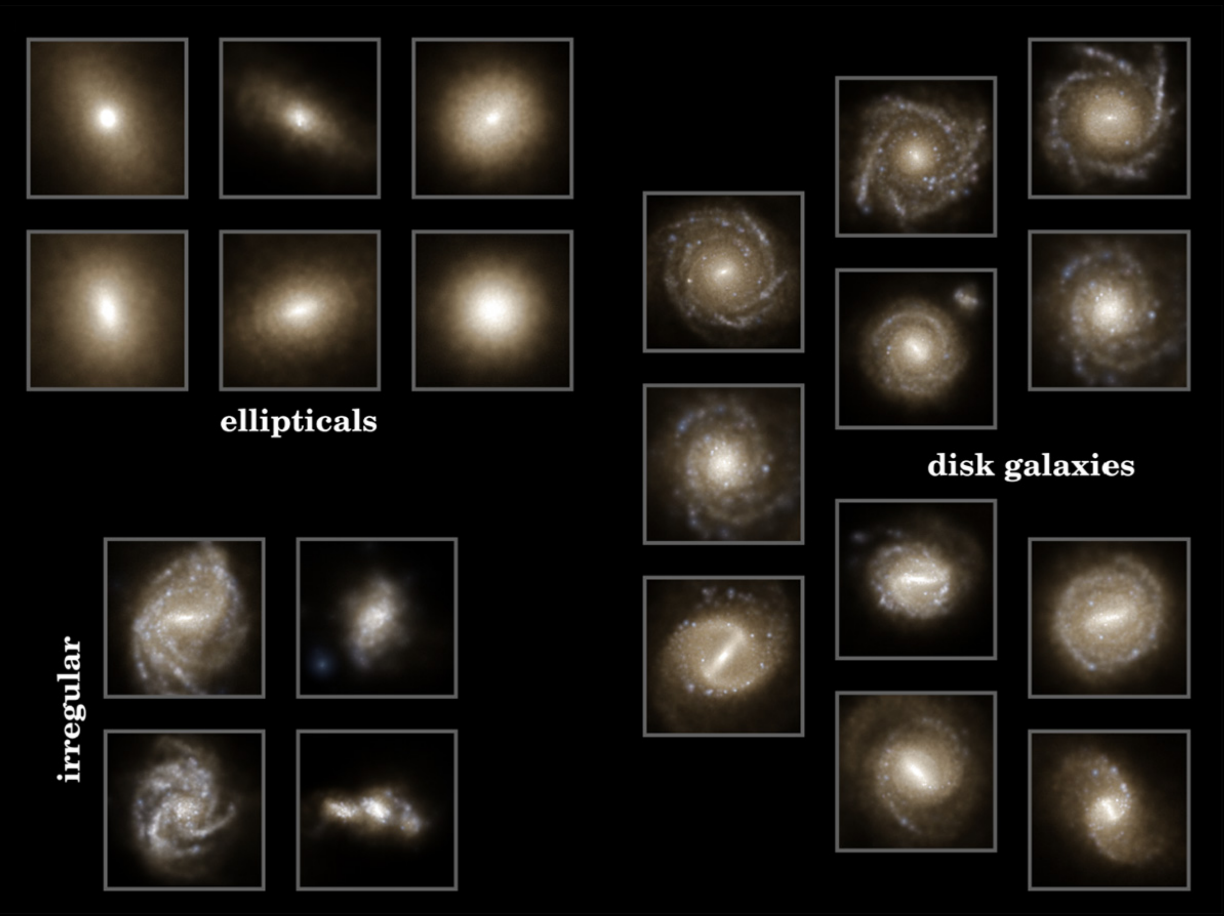
(Gravity only)



Cosmological simulations

(Gravity + baryonic physics)

Success of state-of-the-art cosmological hydro simulations

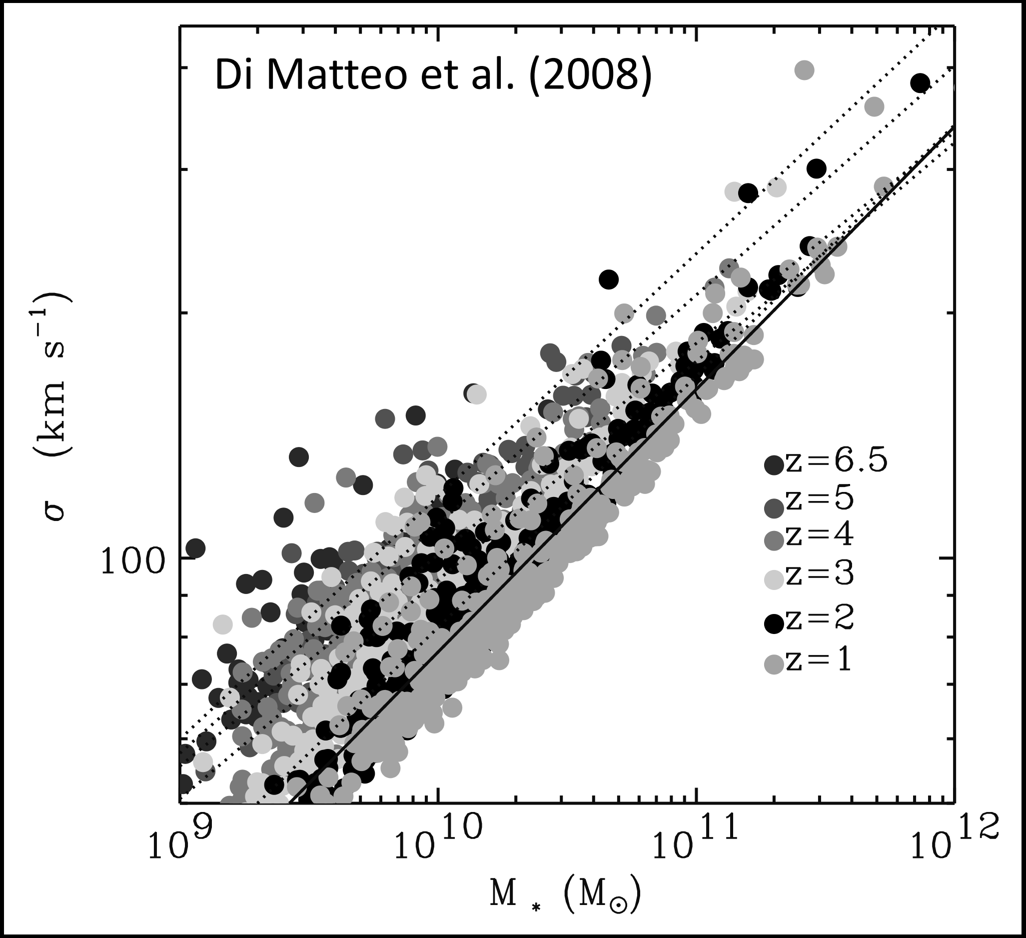


Galaxy gallery from Illustris

Baryonic physics

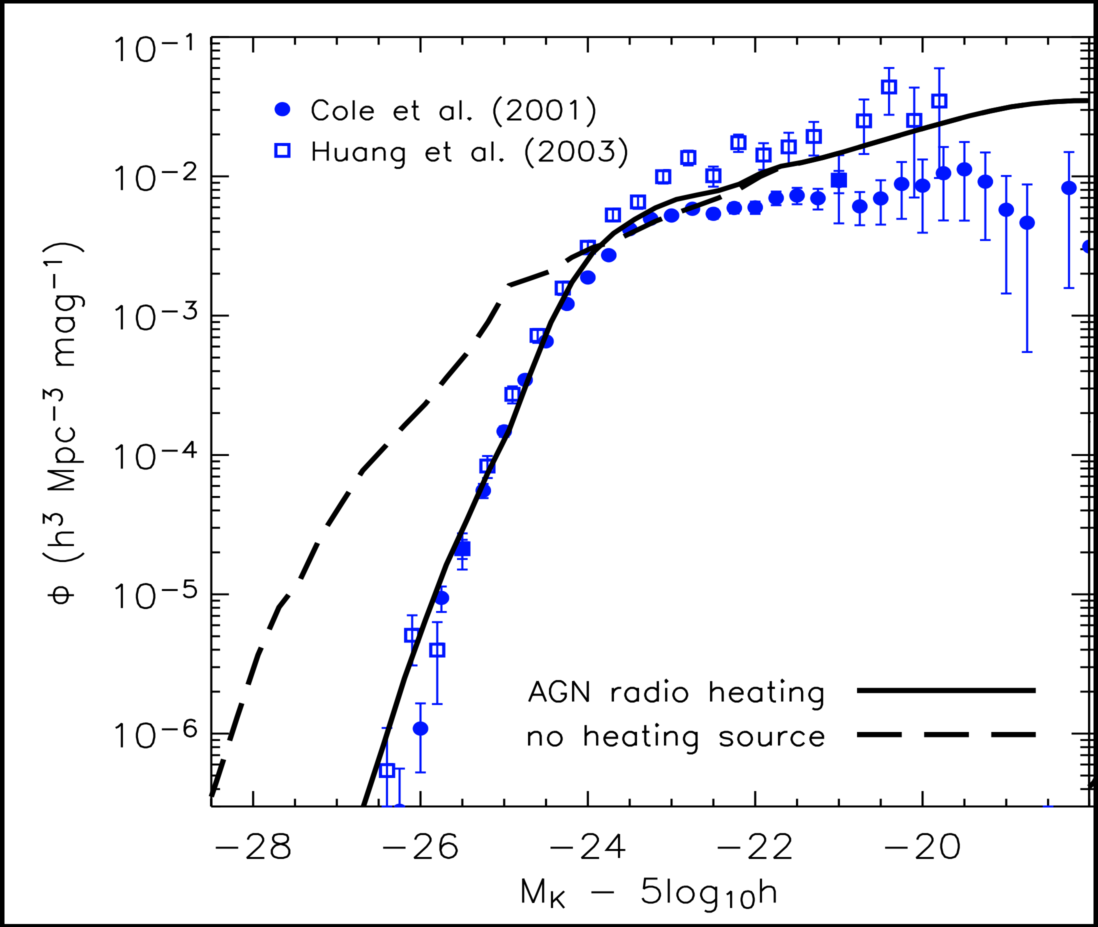
- Radiative cooling
- Star formation
- Stellar feedback
- SMBH growth
- AGN feedback
    - Quasar mode
    - Radio mode

Quasar feedback is needed…



- To reproduce the M-σ relation
- To quench the galaxies
- Quasar/radiative mode

Radio feedback is needed…



More luminous

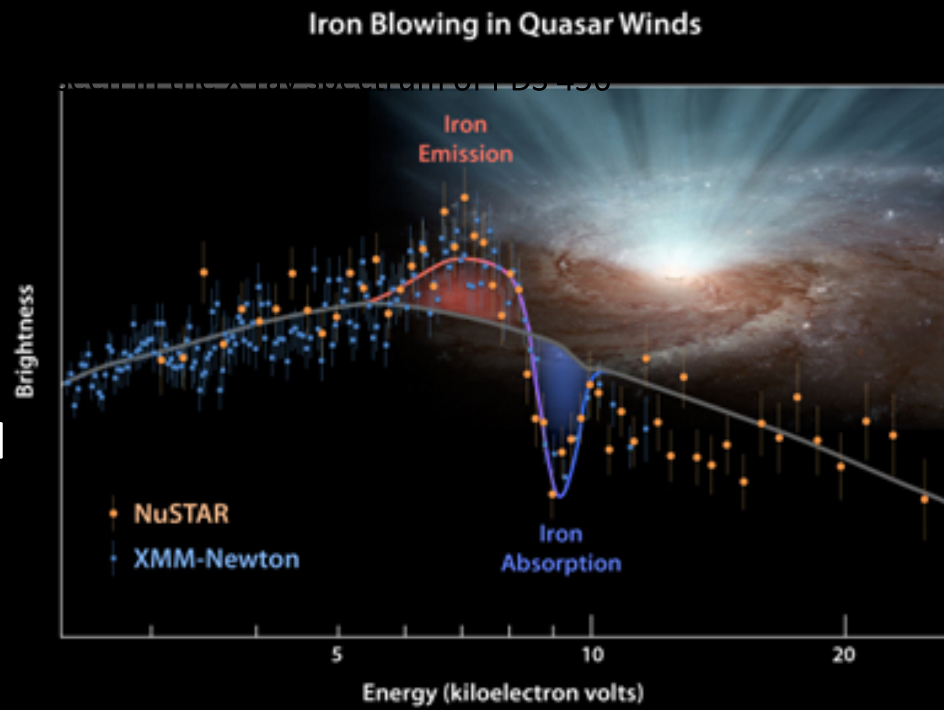
Croton et al. (2006)

- To halt cooling and SF in massive galaxies
- Radio/mechanical/ maintenance mode

Observational evidence for quasar feedback

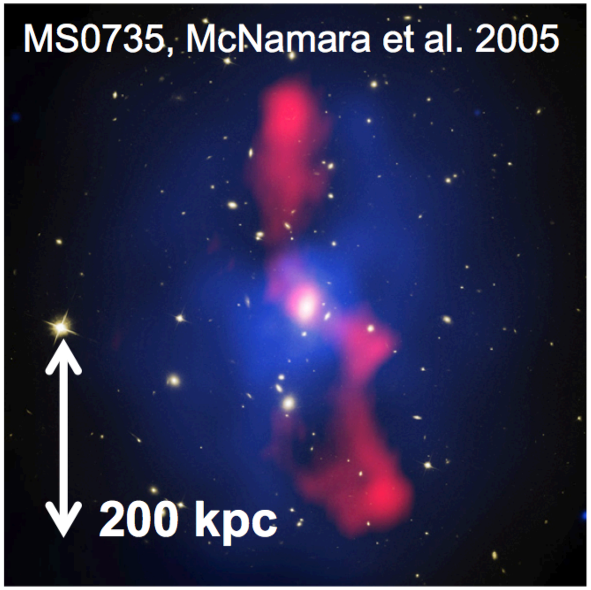
- ***Multi-scale, multi-phase AGN winds!***
- On scales of accretion disk (<pc), ultra fast outflows (UFOs) are observed
    - Velocity ~ 0.05c - 0.3c
    - Power ~ 0.5 – 5% L_{edd}
- On kpc scale, warm ionized and molecular outflows are also observed
    - Mass outflow rate > SFR
    - Depletion time < 100 Myr

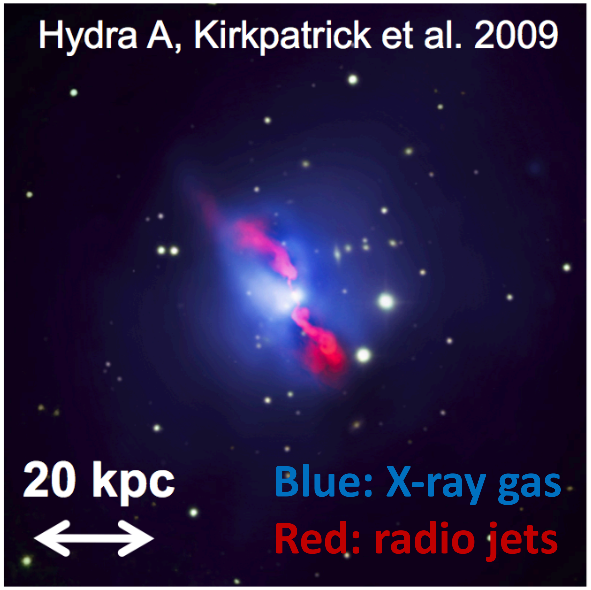
  ⇒ imply ***feedback***!!
- Kpc winds may be driven by pc winds (e.g., Tombesi et al. 2015)

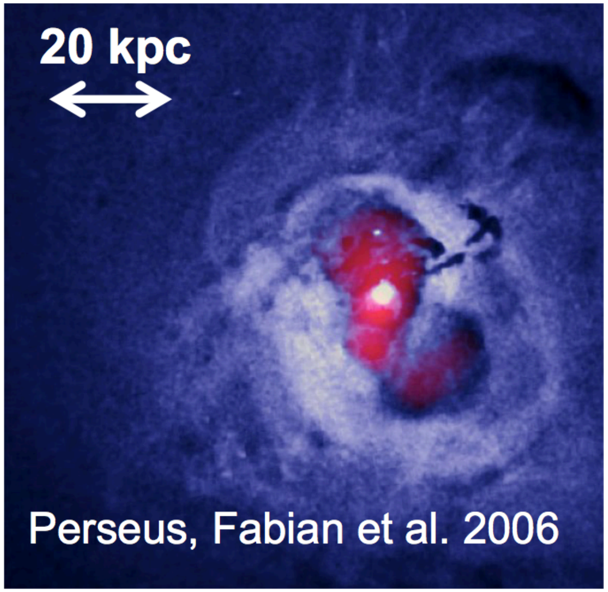


Strong evidence for radio-mode feedback

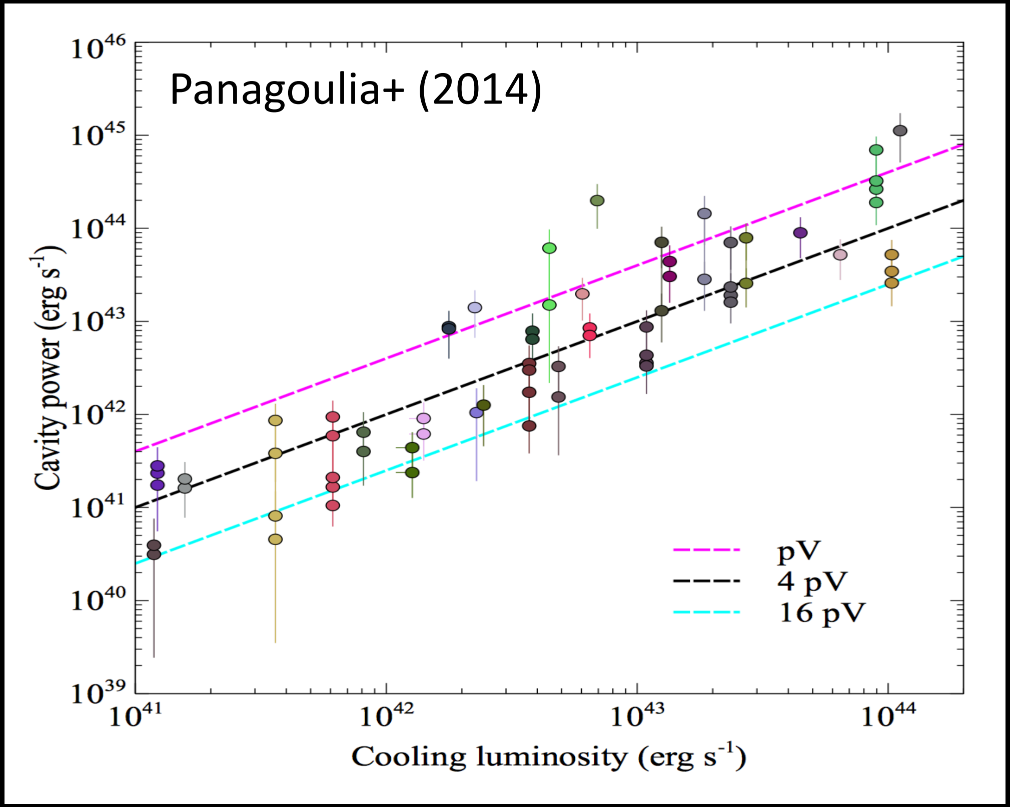
- In massive galaxy clusters with strong cooling, clear interactions between AGN jets and gas are seen
- For CC clusters, expected SFRs >> observed SFRs





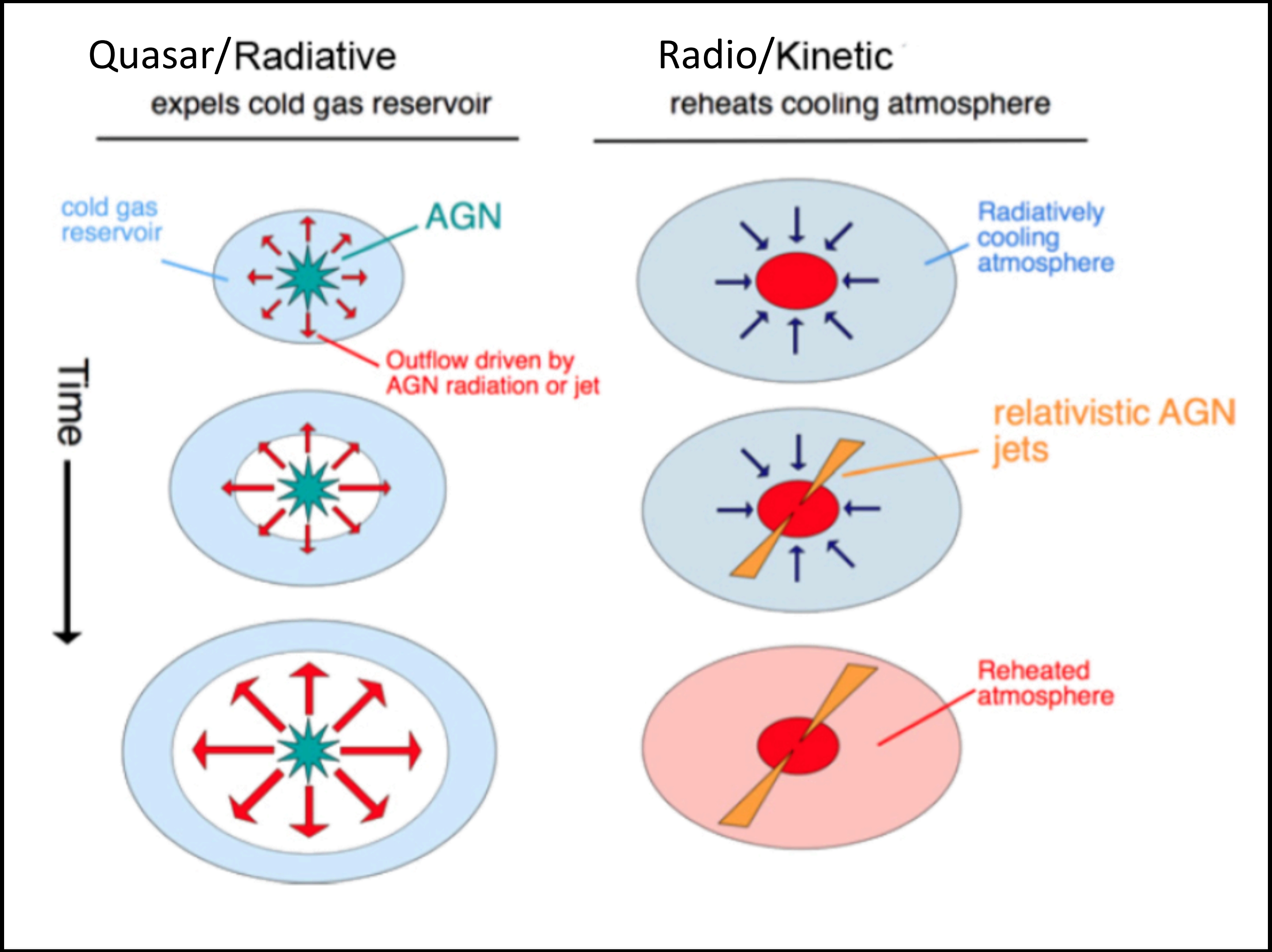


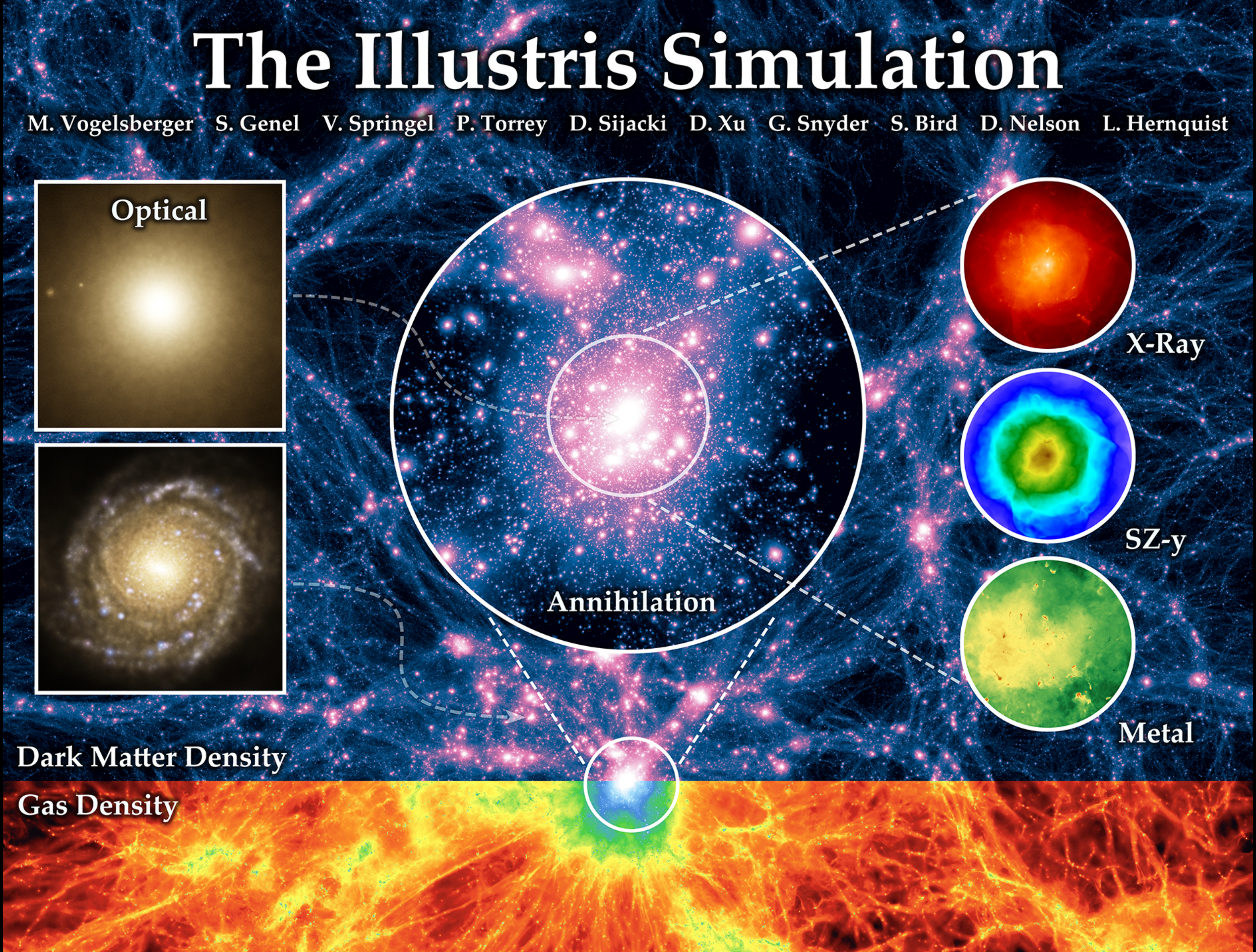
Strong evidence for radio-mode feedback



- $P_{jet} \sim L_X$
- Heating ~ cooling within cluster CCs
- Just enough to suppress SFRs and maintain the quenched galaxies

Conventional paradigm of AGN feedback




The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
X-Ray
SZ-y
Metal
Annihilation
Dark Matter Density
Gas Density

However…

- Spatial resolution of state-of-the-art cosmological hydro simulations ~ 0.1 kpc ~ ***10^{20} cm***
- Schwarzschild radius of 10^{6-9} M_{sun} SMBH ~ ***10^{11-14} cm***

=> ***Subgrid*** models of AGN feedback

Ingredients of subgrid AGN models

- SMBH seeding
- SMBH growth due to mergers and accretion
- SMBH accretion
  - ***Eddington-limited modified Bondi accretion***:

$$\dot{M}_{\rm BH} = \min\left[\frac{4\pi\alpha G^2 M_{\rm BH}^2 \rho}{(c_{\rm s}^2 + v_{\rm BH}^2)^{3/2}}, \dot{M}_{\rm Edd}\right]$$

  - Boosting factor α ~ 100 (Sijacki+2007, Booth & Schaye 2009)

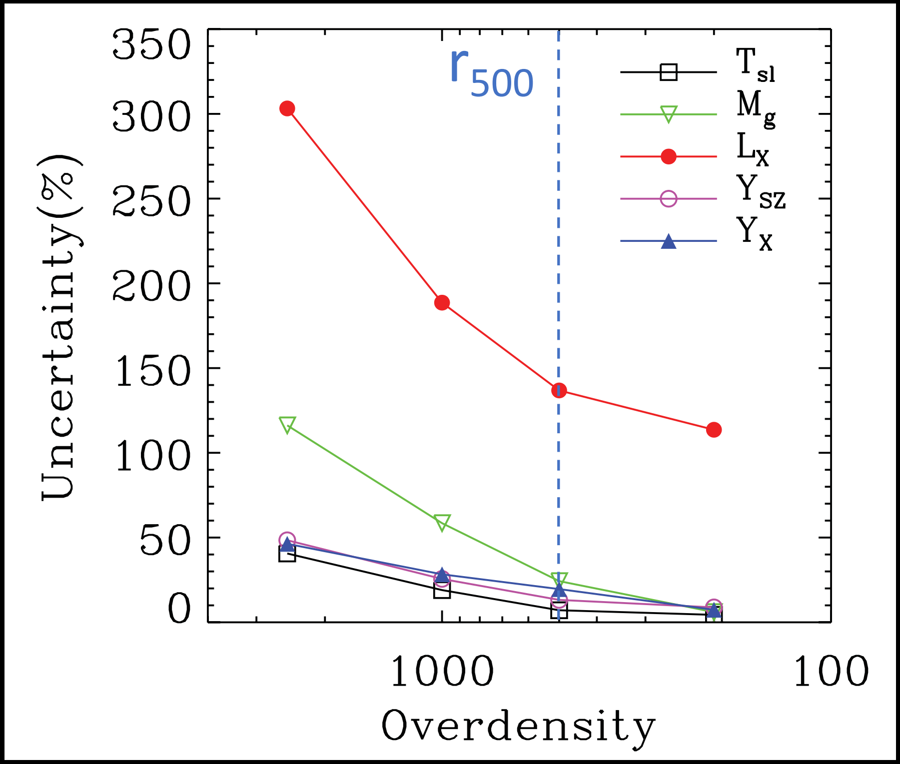
Ingredients of subgrid AGN models

- ***Two-mode feedback*** with threshold ~ % Eddington
- Quasar-mode:
  - Injection of thermal energy $\dot{E}_{\rm feed} = \epsilon_{\rm f} L_{\rm r} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{M}_{\rm BH}c^2$
  - E_r ~ 0.1, E_f ~ 5%
- Radio-mode:
  - Injection of thermal energy or kinetic energy (Weinberger+2017)

$$\Delta\dot{E}_{\rm low} = \epsilon_{\rm f,kin}\dot{M}_{\rm BH}c^2$$

  - E_f ~ 0.02 (thermal) or 0.2 (kinetic)
  - Random displacements or momentum kicks

Uncertainties due to AGN subgrid models are *BIG*!



Yang et al. (2012)

- Cluster integrated properties could vary by 15-150% at r_{500}
- Uncertainties are even larger close to cluster centers

To go beyond the simplistic subgrid AGN models, we need to…

1. Understand the subgrid physics better, using both high-resolution simulations and observations
2. Identify minimal, essential parameters and build a robust, physically-motivated AGN model

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1. Understand the subgrid physics better, using both high-resolution simulations and observations
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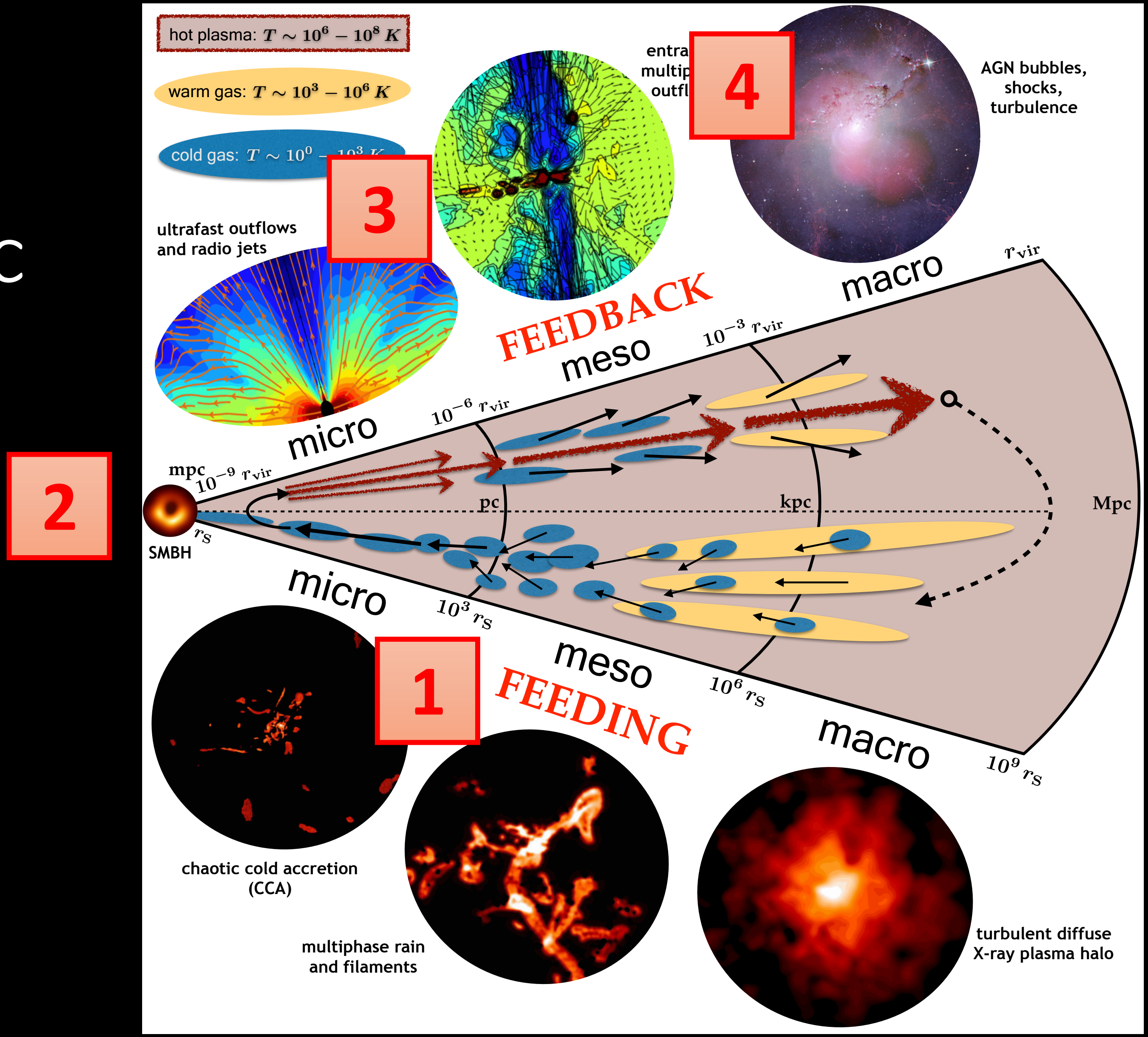
Complex physics below kpc



Gaspari (2020)

1 SMBH feeding

Option 1: Bondi accretion

- Currently implemented in most cosmological simulations, with a boosting factor

$$\dot{M}_{\rm Bondi} = 4\pi\alpha_{\rm B} \frac{G^2 M_{\rm BH}^2 \rho_{\rm gas}}{c_{\rm s}^3}$$

- May feed SMBHs in some massive ellipticals and clusters (Allen et al. 2006)
- Assume spherically symmetric, steady-state accretion from fluids with ***no angular momentum*** and ***no B field***

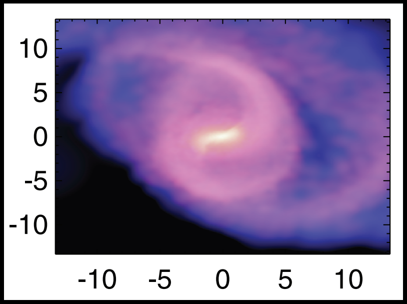
1 SMBH feeding

Option 2: Accretion by gravitational torque

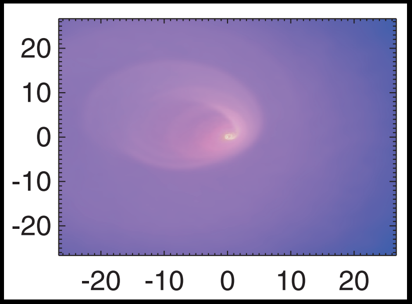
- Applies to gas with angular momentum, e.g., disk galaxies, mergers, etc
- Outward angular momentum transport needed to flow in to the vicinity of the BH
- Torque can be provided by ***non-axisymmetric perturbations*** to the stellar gravitational potential
- Analytical prescription:

$$\dot{M} \sim \frac{-|a|\, m\, \Sigma_{\rm gas}\, R^2\, \Omega}{1 + \partial \ln V_{\rm c} / \partial \ln R} \sim -|a|\, \Sigma_{\rm gas}\, R^2\, \Omega$$

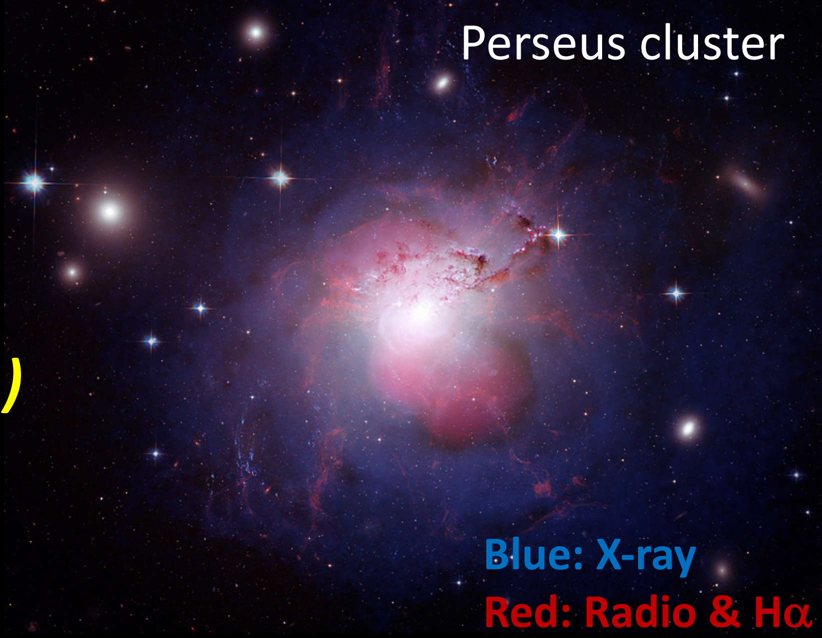
Bars (0.01-1kpc)



Lopsided disks (<10 pc)



Hopkins & Quataert (2011)



1 SMBH feeding

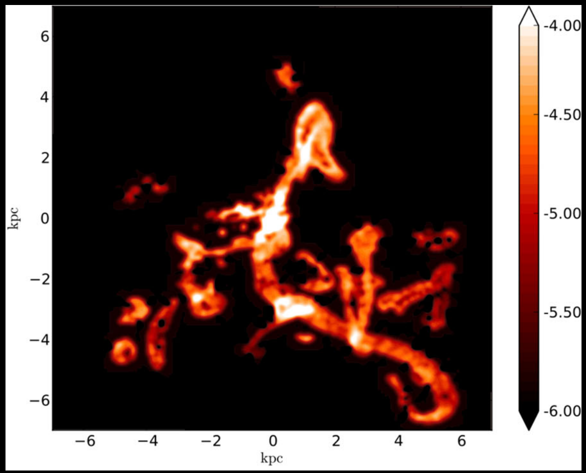
Option 3: Chaotic cold accretion (CCA)

- Multiphase cold gas/filaments are ubiquitous in clusters
- Applies to gas satisfying criteria for precipitation (McCourt et al. 2012, Voit et al. 2015, Gaspari et al. 2017):

$$t_{\rm cool}/t_{\rm ff} \lesssim 10.$$

- During CCA, gas collisions and tidal forces allow angular momentum cancellation (Gaspari et al. 2013, 2017)
- Accretion rate can reach ~100 x Bondi rate
- May be relevant in violently accreting, irregular systems at high redshifts too

Simulated cold gas



1 SMBH feeding – open questions

Q: How well does each theory compare with the data?

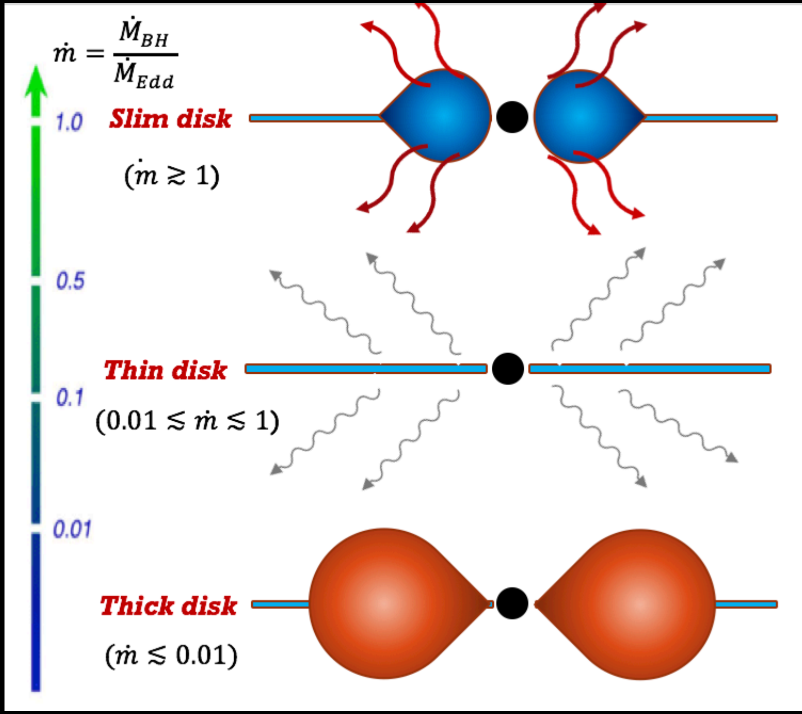
- What powers the AGNs? Observational evidence for accretion by secular processes?

Q: How to determine which BH accretion mechanism is dominant depending on galaxy types/environments?

2 On the scales of BH accretion disks

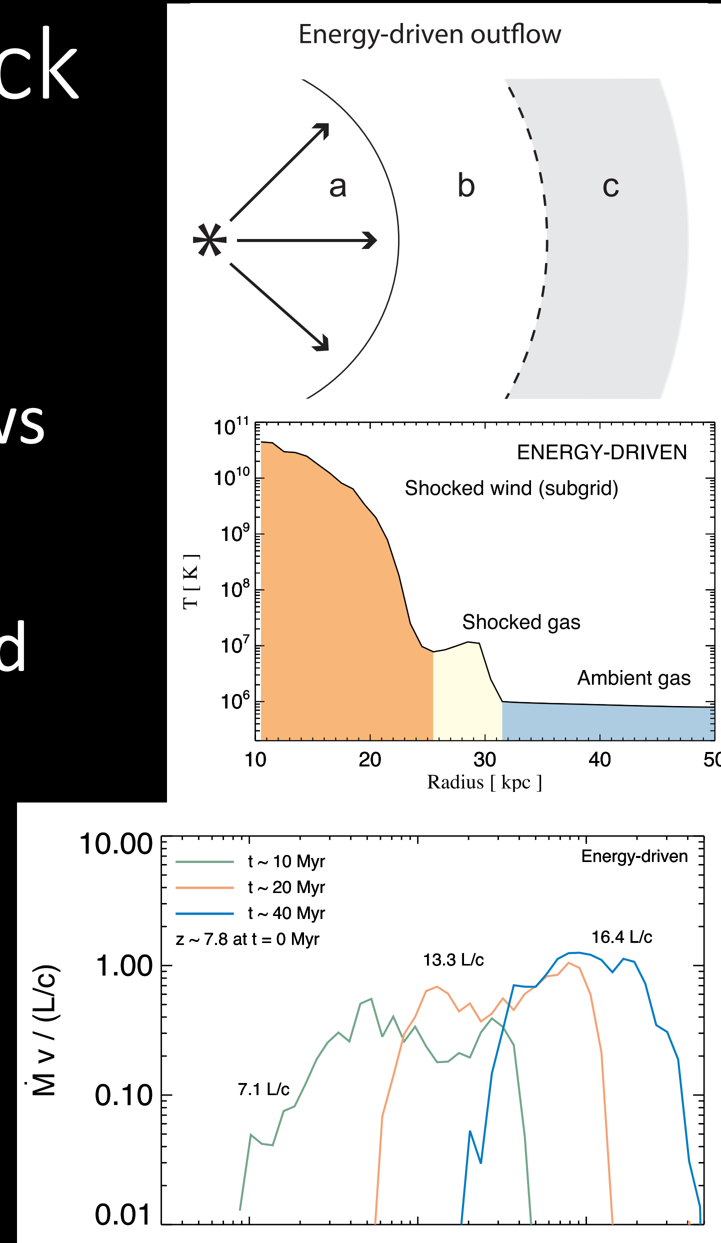
(see HY Pu's talk on Thursday!)

- Successes:
  - Thin disk theory confirmed
  - For thick disks, jets are launched as described by the Blandford-Znajek mechanism
  - For slim disks, AGN accretion disk winds produced by strong radiation pressure
- Goal: obtain ***efficiencies of radiation/winds/jets*** as a function of Eddington ratio, BH spin, B field flux, etc
  - GRMHD/GRrMHD simulations are both simple and hard



3 Quasar wind feedback

Costa et al. (2014)



- ***Energy-driven outflows*** could produce momentum injection ~ ***5-20 L/c*** seen in observed outflows (Cicone et al. 2014, Tombesi et al. 2015)

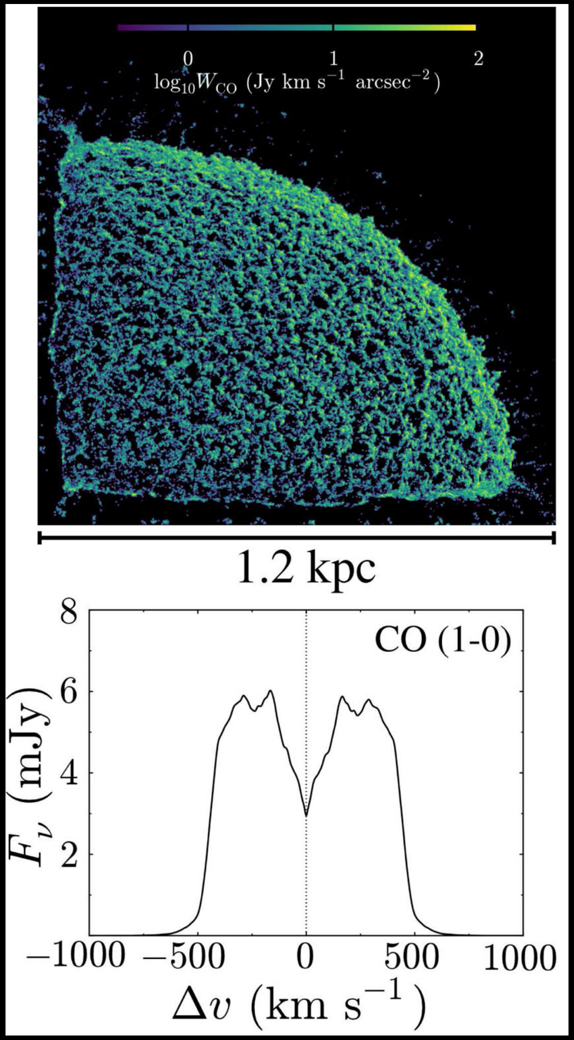
- Such energy driven outflows could originate from shock-heated gas from the ***accretion-disk winds***

- Justified injection of thermal energy for quasar feedback

3 Quasar wind feedback

- The ***kpc molecular outflows*** could be driven by the accretion disk winds, but molecular clouds should be quickly destroyed during entrainment

- Recent simulations including time-dependent chemistry have successfully shown ***in situ formation of molecular clouds***



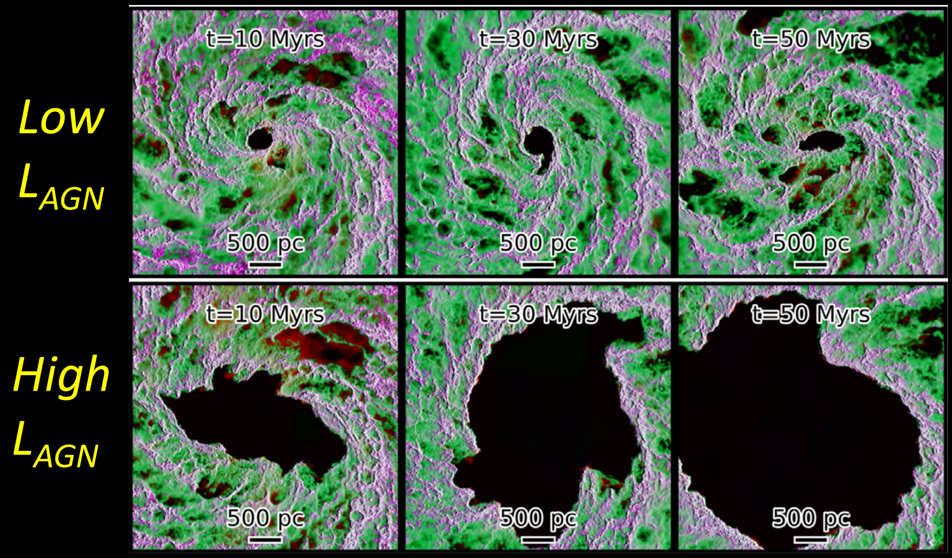
Richings & Faucher-Giguere (2018)

3 Quasar feedback – open questions

(see TC Chen's talk on tomorrow!)

Q: How does the wind energy couple to the ISM/CGM and ***suppress star formation***? What exactly causes quenching (ejection/heating/turbulence)?

- May depend on AGN luminosity, clumpiness of the ISM, and geometry



Torrey et al. (2020)

3 Quasar feedback – open questions

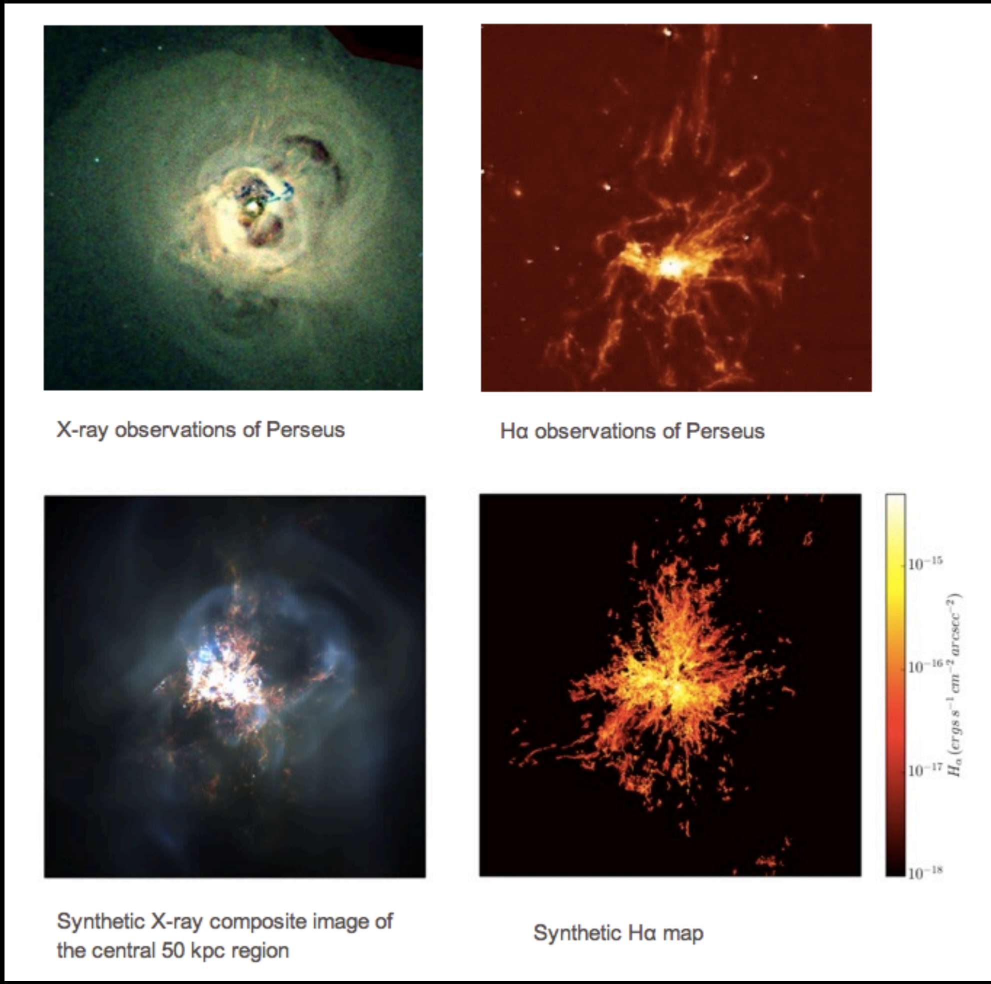
Q: What is the role of ***radiation driving on dust*** on the scale of dusty torus? (Murray et al. 2005, Ciotti & Ostriker 2007, 2012, Costa et al. 2018)

Q: Do ***jets*** play a role in quenching galaxies? (Wagner & Bicknell 2011)

4 Radio jet feedback

- Early simulations including Bondi accretion & thermal injections from AGNs successfully prevented runaway cooling of clusters and reach self-regulation (Sijacki et al. 2007)

- Isolated simulations with ***CCA & kinetic jets*** further reproduced the properties of CC clusters (Gaspari 2011, Li & Bryan 2014, Yang & Reynolds 2016)



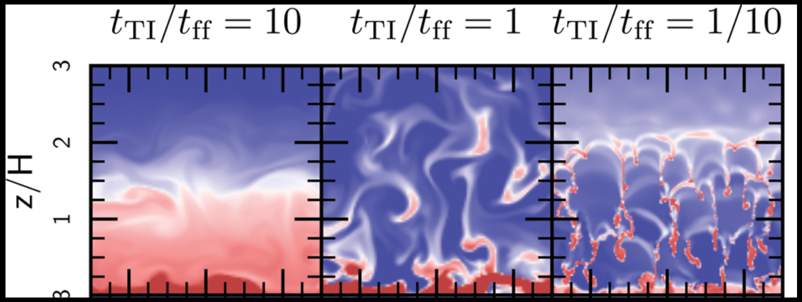
Li et al. (2015)

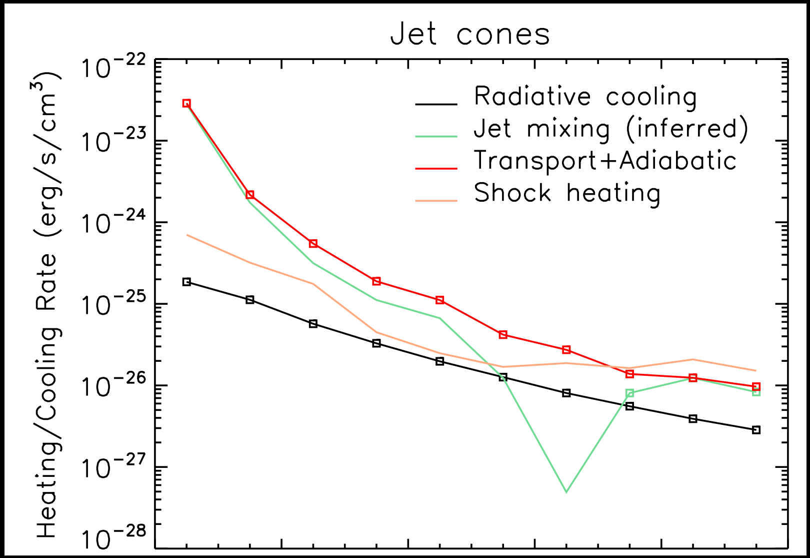
4 Radio jet feedback

- Understanding the processes of ***local thermal instabilities*** in producing cold filaments (McCourt et al. 2012, Voit et al. 2015, 2017)

- Understanding the ***thermalization*** processes of kinetic jets (Yang & Reynolds 2016, Li et al. 2017)

McCourt et al. (2012)





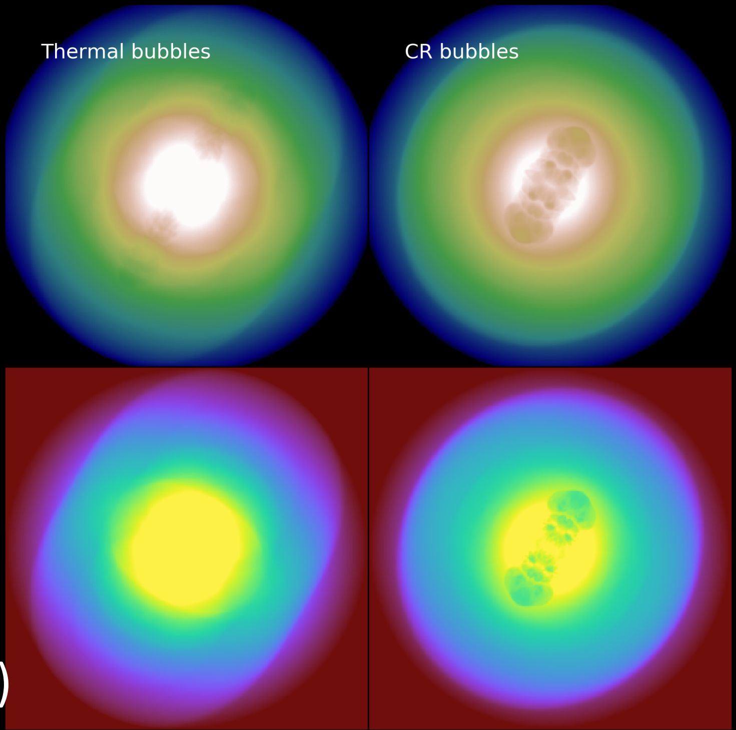
Yang & Reynolds (2016)

4 Radio feedback – open questions

Q: What about cosmic-ray ***(CR) dominated jets***? How do they heat the clusters differently? How to distinguish kinetic vs. CR jets? (Guo & Oh 2008, Pfrommer 2013, Ruszkowski et al. 2017, Yang et al. 2019)

X-ray

SZ



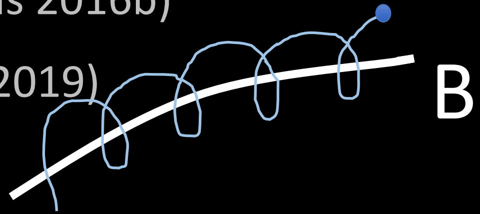
Yang et al. (2019)

Lu-Cheng Sie
(NTHU)

4 Radio feedback – open questions

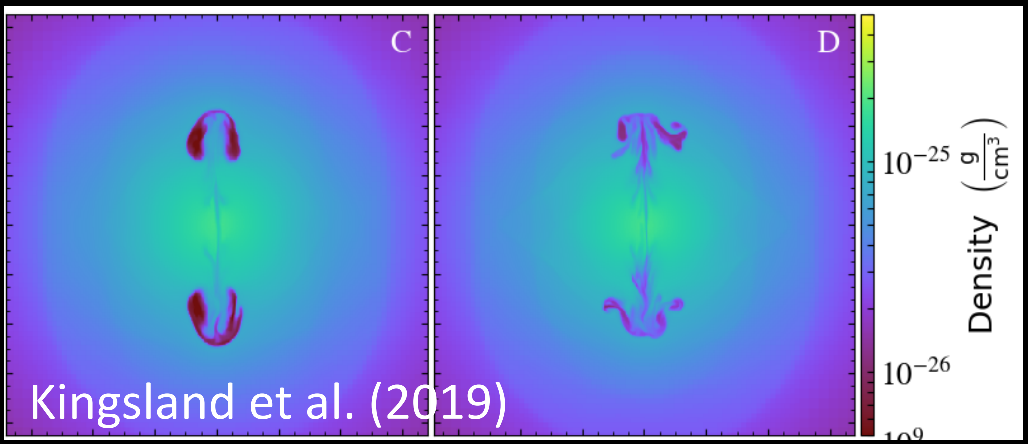
Q: ICM is a magnetized, weakly collisional plasma. How do the ***plasma properties of ICM*** affect the feedback processes?

- Anisotropic thermal conduction (Yang & Reynolds 2016b)
- Anisotropic/Braginskii viscosity (Kingsland et al. 2019)

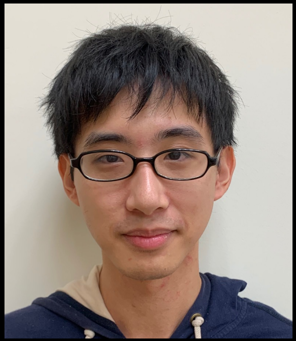


Full Braginskii viscosity

Viscosity suppressed by micro-instabilities



Kingsland et al. (2019)



Shiang-Chih Wang (NTHU)

Summary

- State-of-the-art cosmological simulations have had tremendous success in reproducing the properties of galaxies, and AGN feedback is one of the essential ingredients
- Due to the huge separation of scales, subgrid AGN models are simplistic, limiting the predictive power
- Detailed observations and multi-scale simulations have significantly improved understanding of the SMBH feeding and feedback processes on <kpc scales

Open questions and future prospects

- What is the urgent next step to improve subgrid AGN models?
- What additional simulations are needed to answer the open questions or to interpret controversial observational results?

1 Q: What is the dominant mechanism for powering the AGNs? How does it depend on galaxy types/environments?

2 Q: What are the efficiencies of radiation/winds/jets as a function of Eddington ratio, BH spin, B field flux, etc?

3 Q: Whether/how do the winds suppress star formation? Do jets play a role in quenching?

4 Q: How are the feedback processes affected by CR-dominated jets and the fact that ICM is weakly collisional?