Torque-Limited Black Hole Growth and Feedback in Cosmological Simulations

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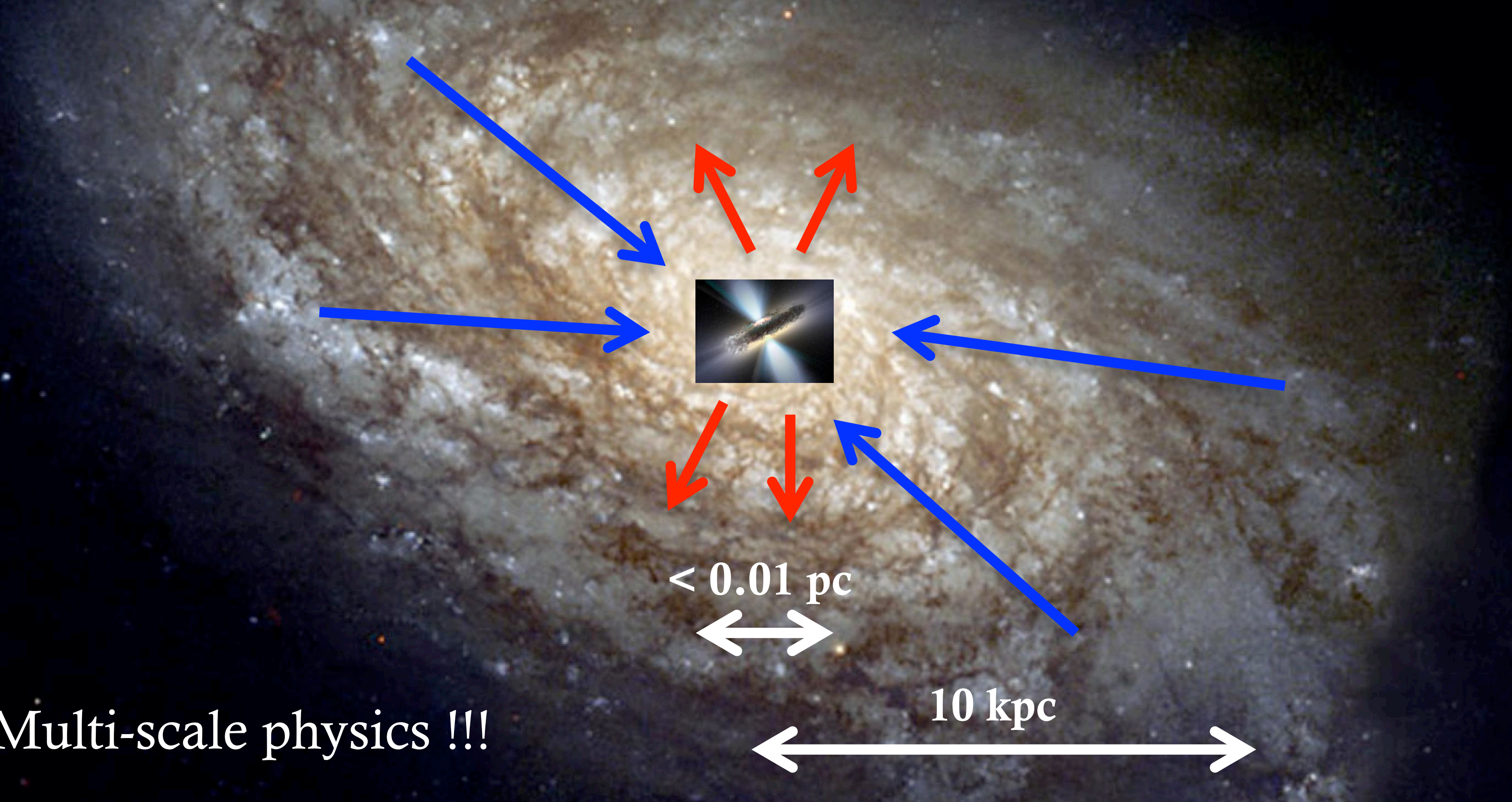
Black holes in Cosmological Hydrodynamic Simulations

Springel+05; Di Matteo+05,08; Hopkins+05,06; Sijacki+07,15; Booth & Schaye 09; Johansson+09; Bellovary+10,11; Teyssier+11; Choi+12,15; Debuhr et al. 2012; Dubois+12,13; Vogelsberger+14; Rosas-Guevara+15; Schaye+15; Steinborn+15; …



M33 doesn't have a supermassive black hole but it is beautiful!

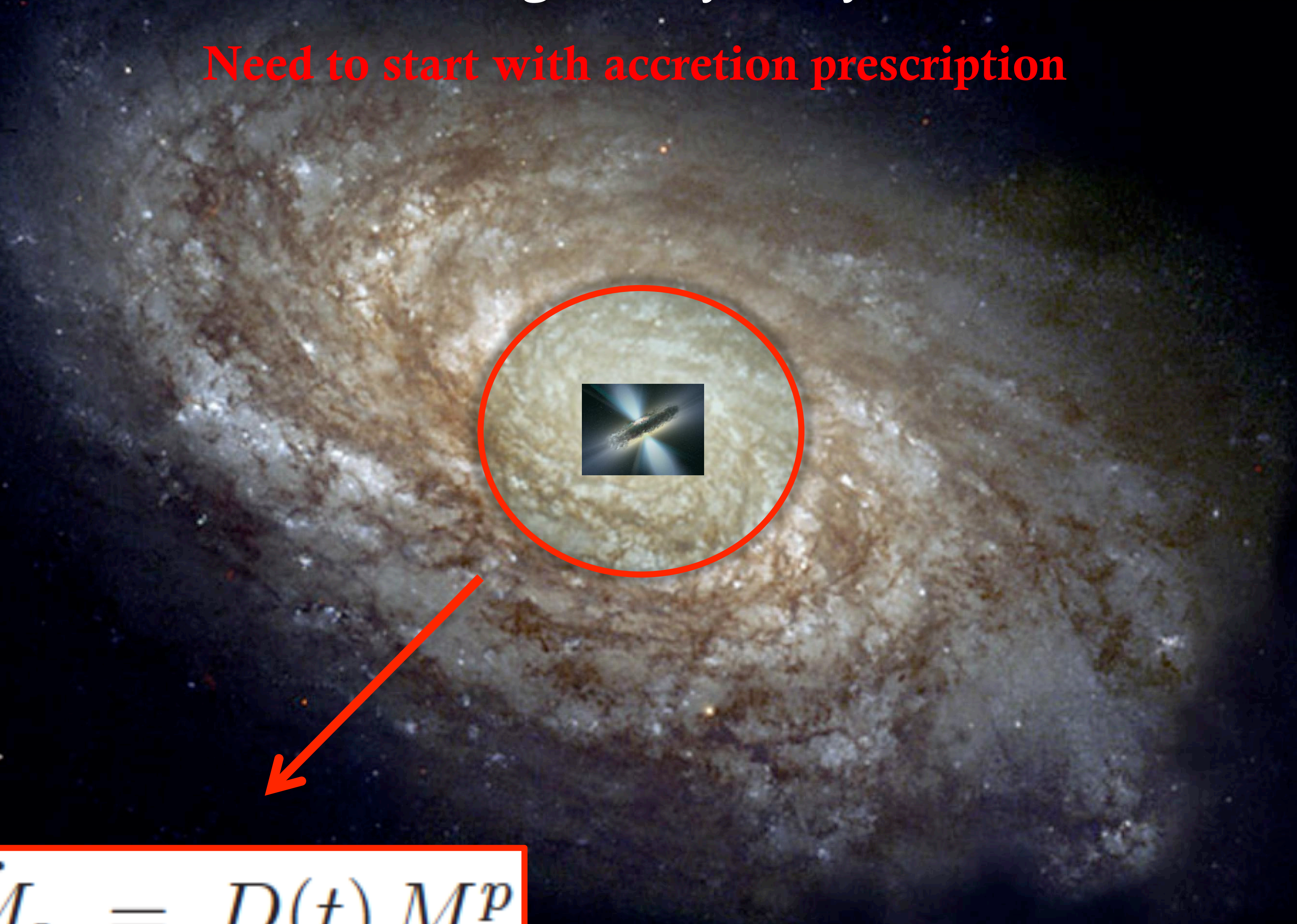
Multi-scale physics !!!

(1) Gas inflows from galactic scales

(2) Feedback acting at galactic scales

Black holes in Cosmological Hydrodynamic Simulations

Need to start with accretion prescription

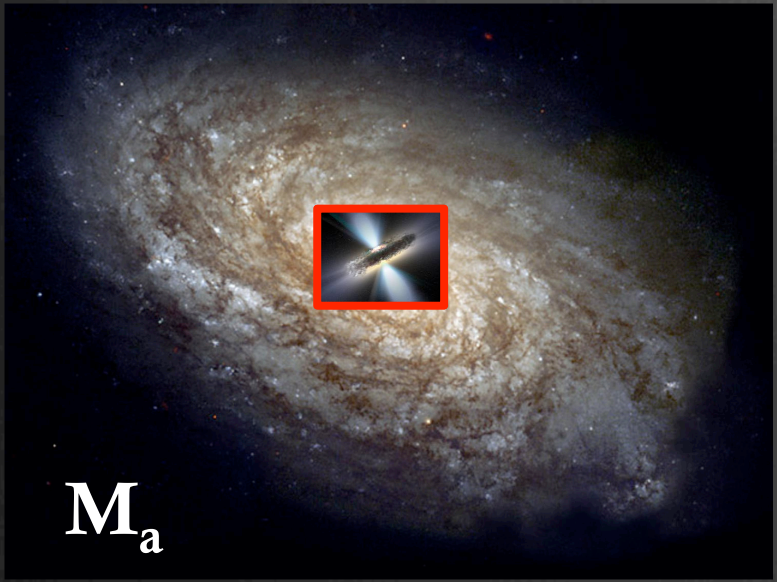


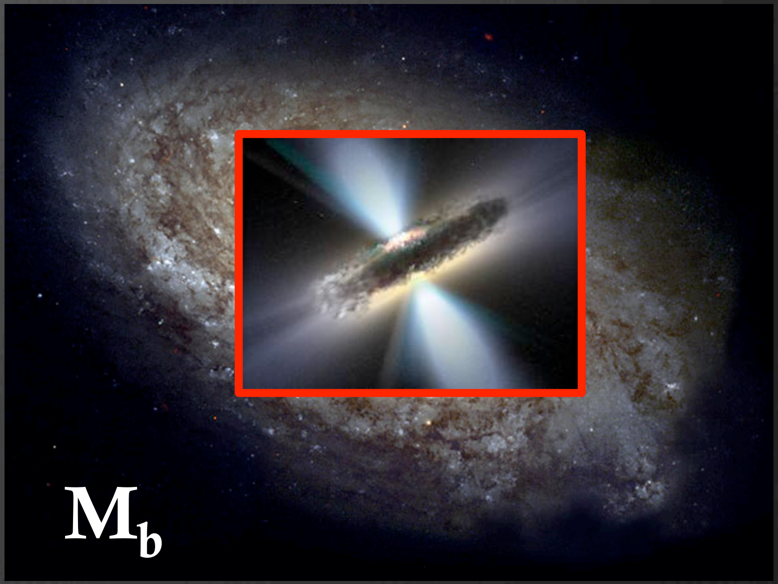
$$\boxed{\dot{M}_{\rm a} \;=\; D(t)\, M_{\rm a}^{p}}$$

M33 doesn't have a supermassive black hole but it is beautiful!

Dependence on black hole mass…

$$\boxed{\dot{M}_{\mathrm{a}} = D(t)\, M_{\mathrm{a}}^{p}}$$



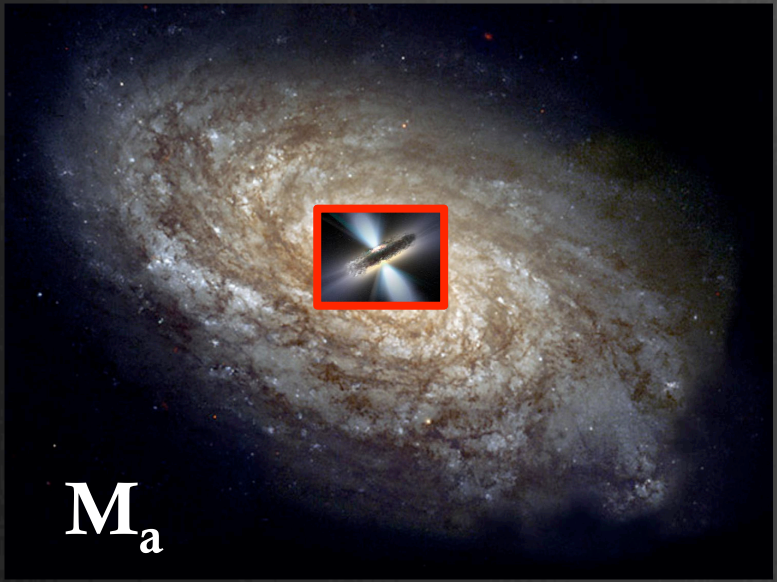


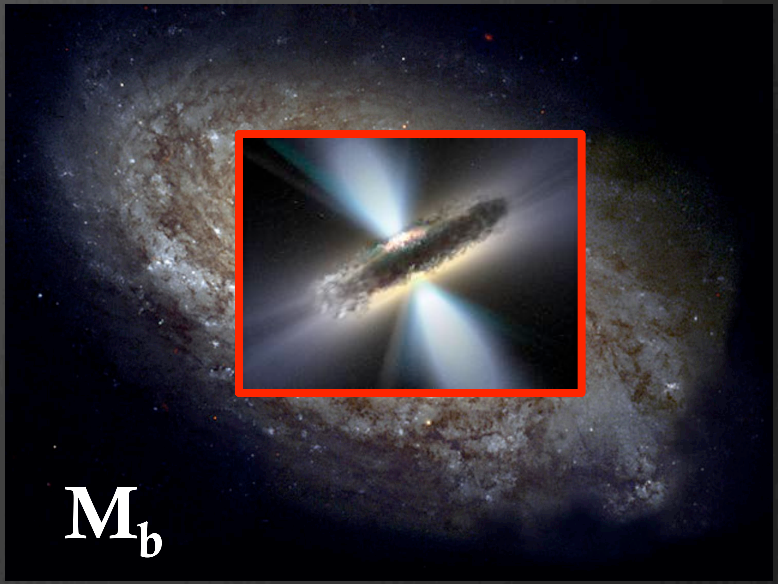
Assume same physical conditions D(t) – different initial black hole mass

→Evolution of M_a and M_b ?

Dependence on black hole mass…

$$\boxed{\dot{M}_{\mathrm{a}} = D(t)\, M_{\mathrm{a}}^{p}}$$





→Evolution of M_a / M_b ?

$$\boxed{\frac{d}{dt}\left(\frac{M_{\mathrm{a}}}{M_{\mathrm{b}}}\right) = D(t)\,\frac{M_{\mathrm{a}}^{p}}{M_{\mathrm{b}}}\left[1 - \left(\frac{M_{\mathrm{a}}}{M_{\mathrm{b}}}\right)^{1-p}\right]}$$

Dependence on black hole mass…

$$\dot{M}_{\rm a} = D(t)\, M_{\rm a}^{p}$$

$$\boxed{\frac{d}{dt}\left(\frac{M_{\rm a}}{M_{\rm b}}\right) = D(t)\,\frac{M_{\rm a}^{p}}{M_{\rm b}}\left[1 - \left(\frac{M_{\rm a}}{M_{\rm b}}\right)^{1-p}\right]}$$

Evolution depends on power index **p**

M_a and M_b converge if $p < 1$

- $dm_{\rm ab}/dt < 0, \quad \text{if } m_{\rm ab} > 1$
- $dm_{\rm ab}/dt > 0, \quad \text{if } m_{\rm ab} < 1$

Anglés-Alcázar et al. (2015)

Independent of D(t) !!

Dependence on black hole mass…

$$\dot{M}_{\mathrm{a}} = D(t)\, M_{\mathrm{a}}^{p}$$

$$\boxed{\frac{d}{dt}\left(\frac{M_{\mathrm{a}}}{M_{\mathrm{b}}}\right) = D(t)\,\frac{M_{\mathrm{a}}^{p}}{M_{\mathrm{b}}}\left[1-\left(\frac{M_{\mathrm{a}}}{M_{\mathrm{b}}}\right)^{1-p}\right]}$$

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Anglés-Alcázar et al. (2015)

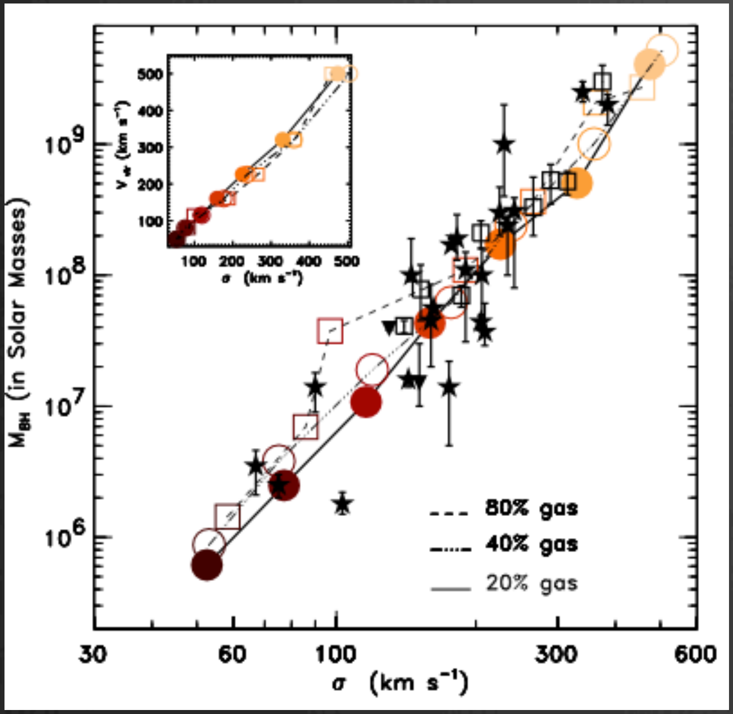
Independent of D(t) !!

Massive black holes in simulations

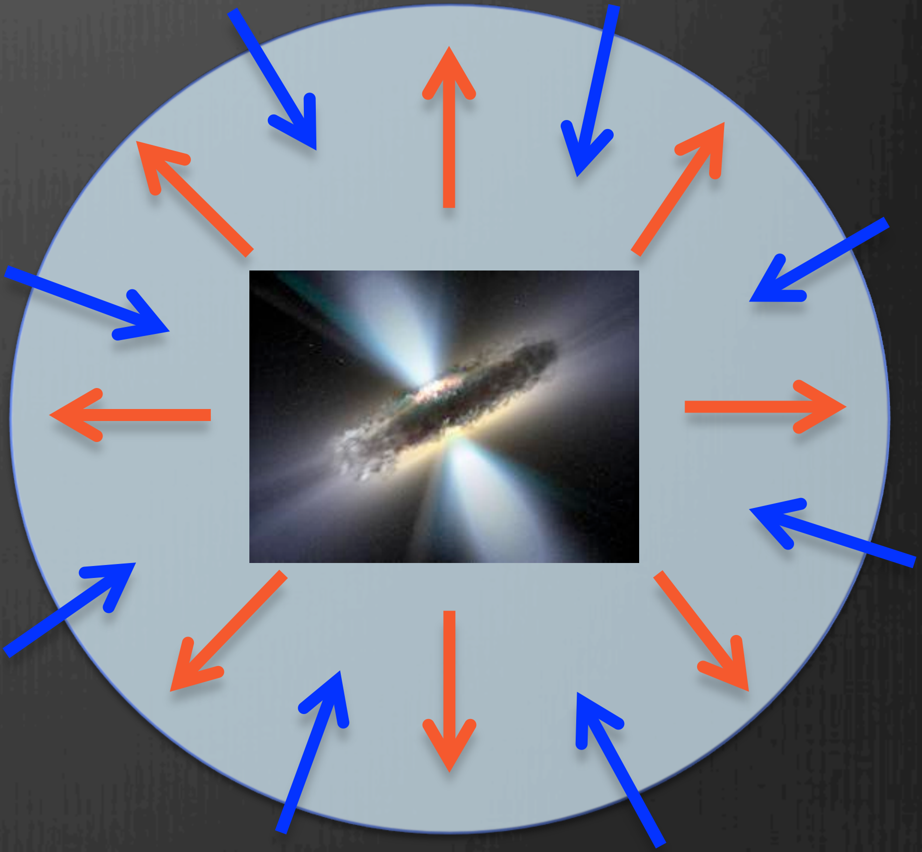
Bondi accretion + thermal feedback

$$\dot{M}_{\rm Bondi} = \alpha \frac{4\pi\, G^2\, M_{\rm BH}^2\, \rho}{(c_s^2 + v^2)^{3/2}}$$

Black hole mass vs. velocity dispersion



Di Matteo+05 and many others



→ Feedback self-regulation drives BH-galaxy connection

Analytic models: Silk & Rees 1998, King 2003, Murray et al. 2005

Dependence on black hole mass…

$$\dot{M}_{\mathrm{a}} = D(t)\, M_{\mathrm{a}}^{p}$$

$$\frac{d}{dt}\left(\frac{M_{\mathrm{a}}}{M_{\mathrm{b}}}\right) = D(t)\,\frac{M_{\mathrm{a}}^{p}}{M_{\mathrm{b}}}\left[1 - \left(\frac{M_{\mathrm{a}}}{M_{\mathrm{b}}}\right)^{1-p}\right]$$

Subsequent Evolution depends on power index p

M_a and M_b diverge if $p > 1$

- $dm_{\mathrm{ab}}/dt > 0, \quad \text{if } m_{\mathrm{ab}} > 1$
- $dm_{\mathrm{ab}}/dt < 0, \quad \text{if } m_{\mathrm{ab}} < 1$

Anglés-Alcázar et al. (2015)

Independent of D(t) !!

Dependence on black hole mass…

$$\dot{M}_{\rm a} = D(t)\, M_{\rm a}^{p}$$

p = 2 in Bondi prescription

$$\dot{M}_{\rm Bondi} = \alpha\, \frac{4\pi\, G^2 M_{\rm BH}^2 \rho}{(c_{\rm s}^2 + v^2)^{3/2}}$$

Need to break dependence on M_{BH} for convergence !!

$$\boxed{\dot{M}_{\rm BH} = D(t, \dot{M}_{\rm BH}) \times M_{\rm BH}^{p}}$$

Anglés-Alcázar et al. (2015)

Dependence on black hole mass…

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$$\dot{M}_{\rm BH} = D(t, \dot{M}_{\rm BH}) \times M_{\rm BH}^{p}$$

Anglés-Alcázar et al. (2015)

Feedback loop required !!

$$\boxed{\dot{M}_{\mathrm{BH}} = D(t, \dot{M}_{\mathrm{BH}}) \times M_{\mathrm{BH}}^{p}}$$

?

1. Is black hole growth self-regulated by a non-linear feedback loop?

2. Is the observed connection between black holes and galaxies driven by feedback self-regulation?

3. Can we break the degeneracy between black hole accretion and feedback?

$$\boxed{\dot{M}_{\rm BH} = D(t, \dot{M}_{\rm BH}) \times M_{\rm BH}^{p}}$$

?

1. Is black hole growth self-regulated by a non-linear feedback loop?

2. Is the observed connection between black holes and galaxies driven by feedback self-regulation?

3. Can we break the degeneracy between black hole accretion and feedback?

Do we want Bondi to tell us what to do with feedback…
…while neglecting angular momentum?

Gas inflows from galactic scales

"Gas at galactic scales must loose > 99.9% of angular momentum to get to the black hole accretion disk"

Jogee 2006

- Galaxy interactions and internal gravitational instabilities trigger non-axisymmetric perturbations to the gravitational potential on galactic scales

- Gravitational torques drive gas inflows to smaller scales, triggering further instabilities and driving gas to ever smaller scales

"Bars within Bars"

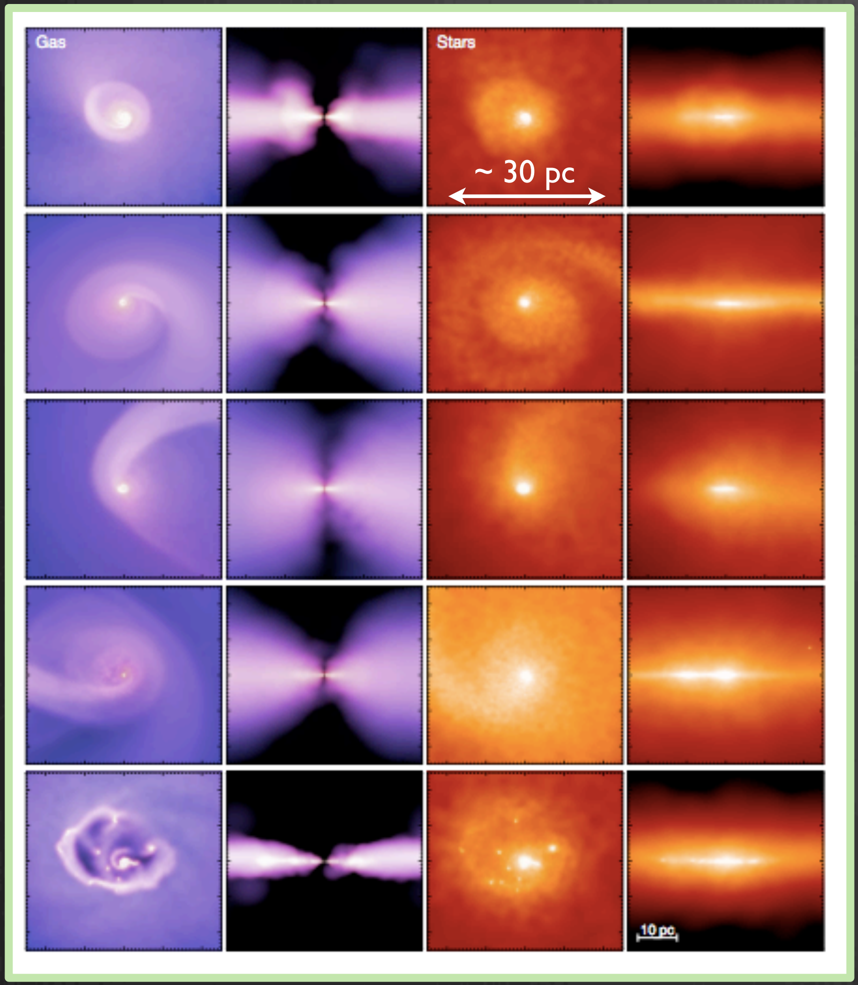
Shlosman et al. 1989, 1990

But transport of gas by bars is not efficient within BH radius of influence…

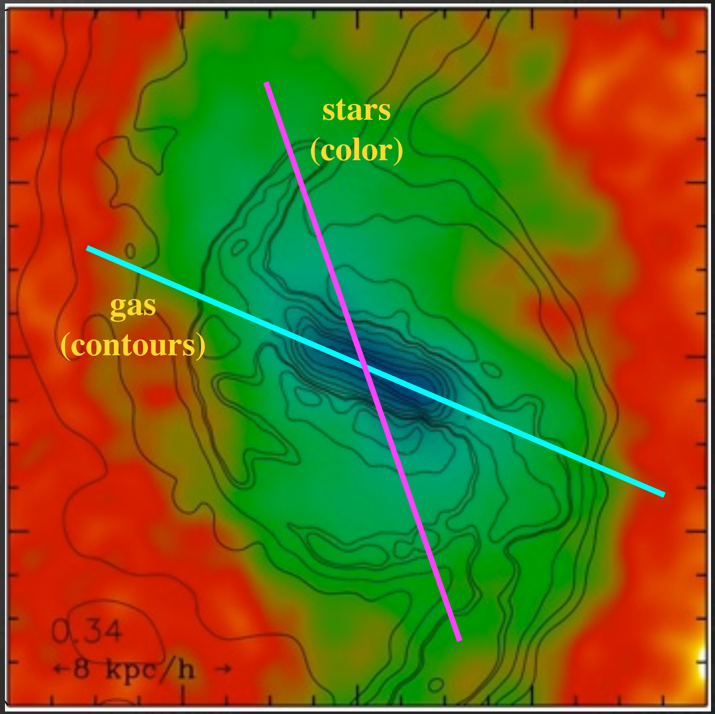
Analytic gravitational torque model

Hopkins & Quataert 2010, 2011

Inside BH potential the dominant asymmetries driving gas inflows are eccentric / lopsided disk (m=1), not bar-like (m=2) modes



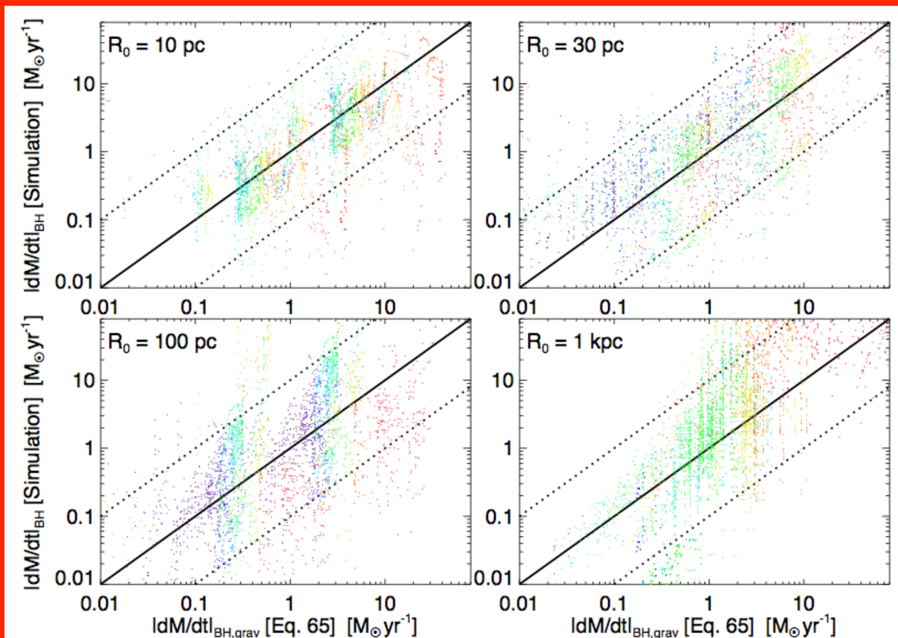
Perturbations to the stellar component drive the gas into shocks that dissipate energy and angular momentum



Simulations vs. analytic models

Multi-scale simulations of gas rich disks

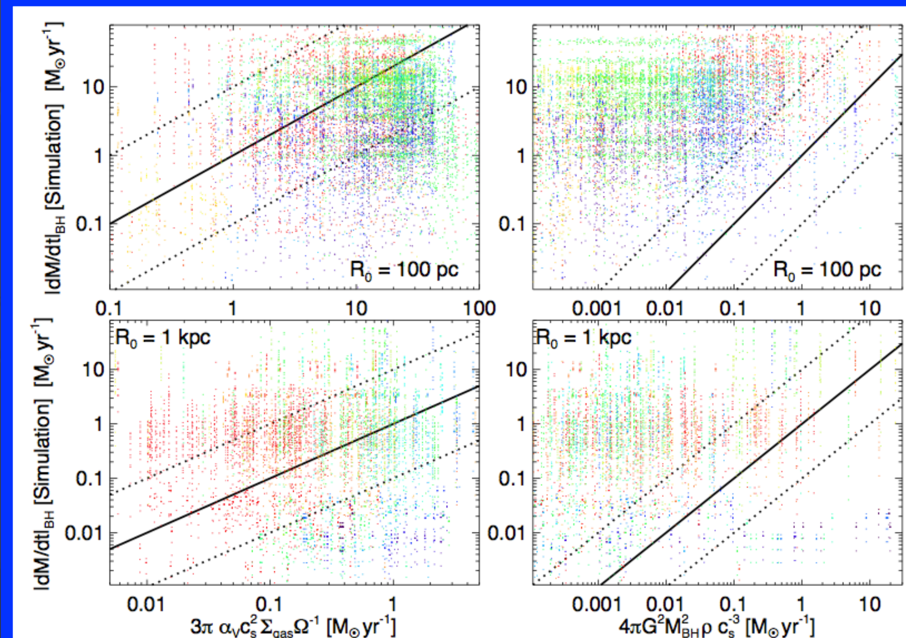
Hopkins & Quataert 2010,2011



Gravitational torques provide angular momentum transport

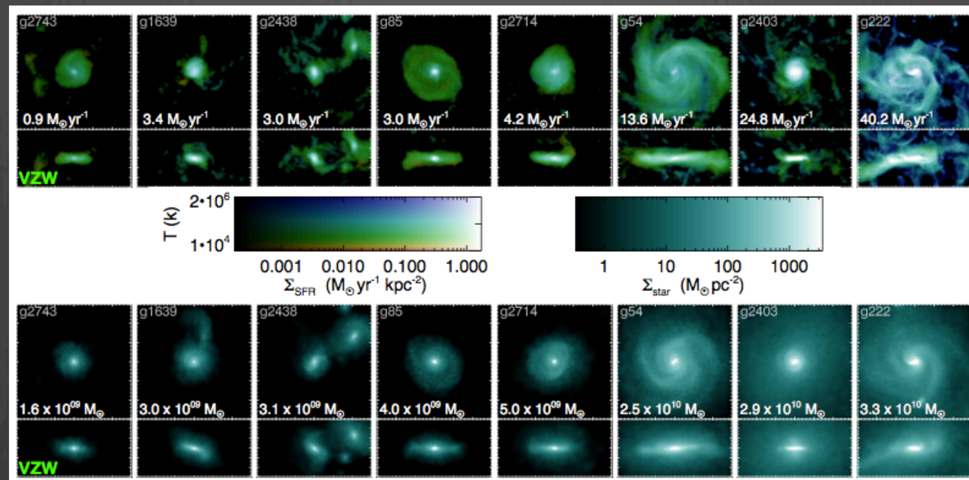
Bondi

Neglects angular momentum!



Zoom-in simulations of z=2 galaxies

Anglés-Alcázar et al. (2014)



Central black hole accretion rate in post-processing:

Gravitational torque model

Hopkins & Quataert 2011

$$\dot{M}_{\rm Torque} \approx \alpha_{\rm T}\, f_{\rm disk}^{5/2} \times \left(\frac{M_{\rm BH}}{10^8\,{\rm M_\odot}}\right)^{1/6} \left(\frac{M_{\rm disk}(R_0)}{10^9\,{\rm M_\odot}}\right) \times \left(\frac{R_0}{100\,{\rm pc}}\right)^{-3/2} \left(1+\frac{f_0}{f_{\rm gas}}\right)^{-1} {\rm M_\odot\,yr^{-1}}$$

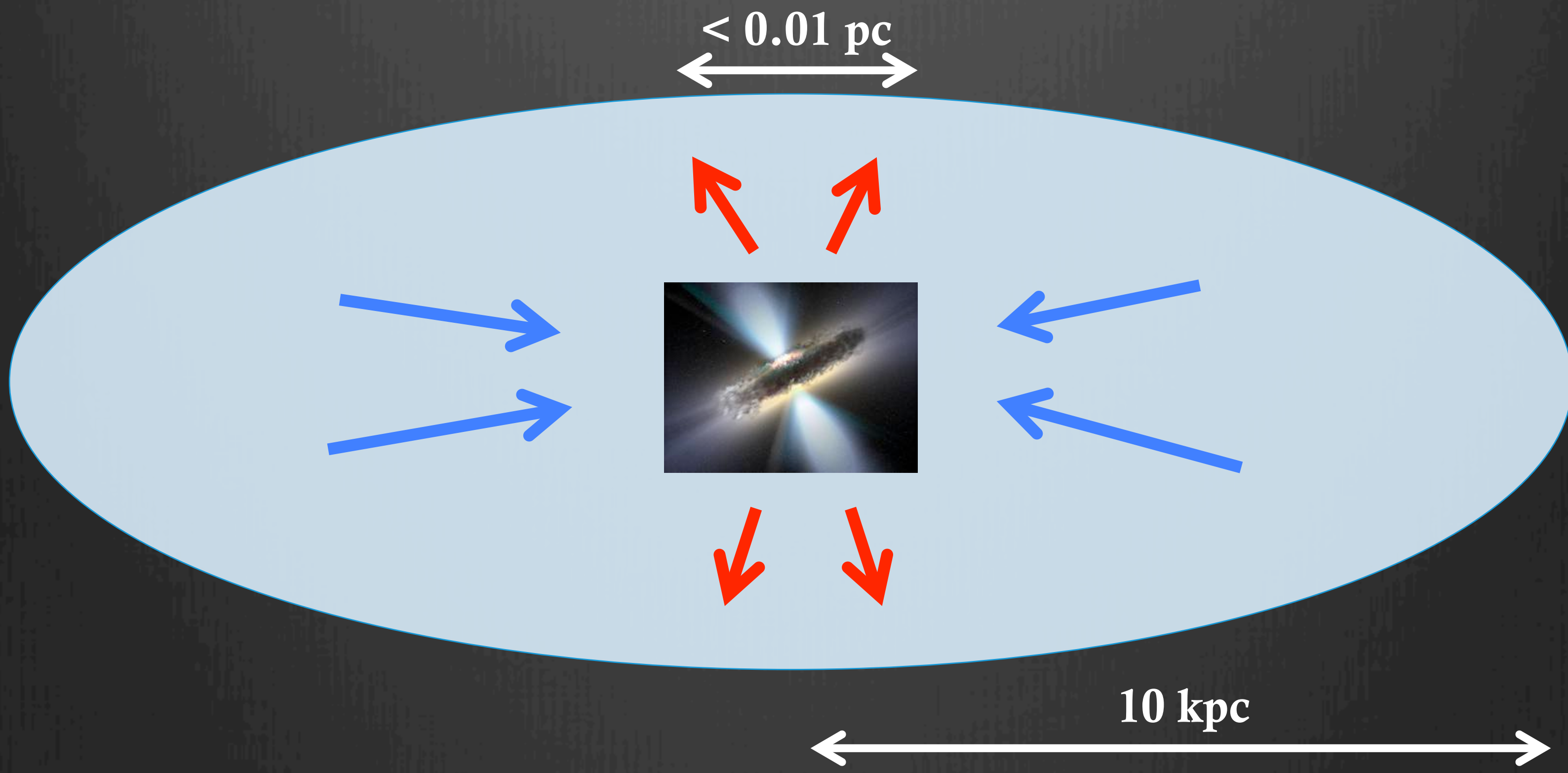
Bondi

Bondi 1952,…

$$\dot{M}_{\rm Bondi} = \alpha\, \frac{4\pi\, G^2\, M_{\rm BH}^2\, \rho}{(c_{\rm s}^2 + v^2)^{3/2}}$$

Black hole growth limited by inflows and mass loss in outflows

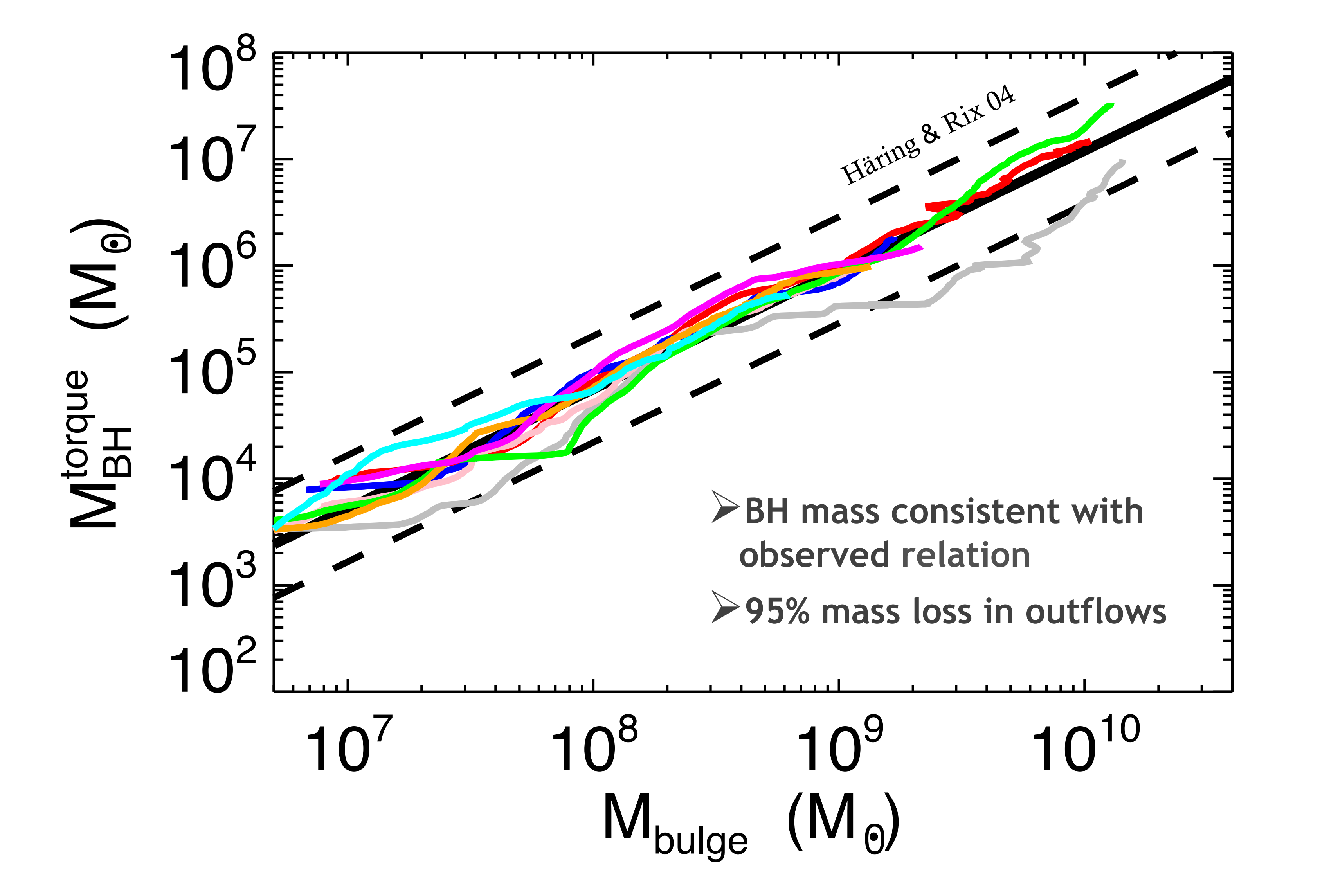
$$dM_{\mathrm{BH}}/dt = \epsilon_{\mathrm{m}}\, \dot{M}_{\mathrm{Torque}}(t)$$



OUTFLOWS = (1 - ε) INFLOWS

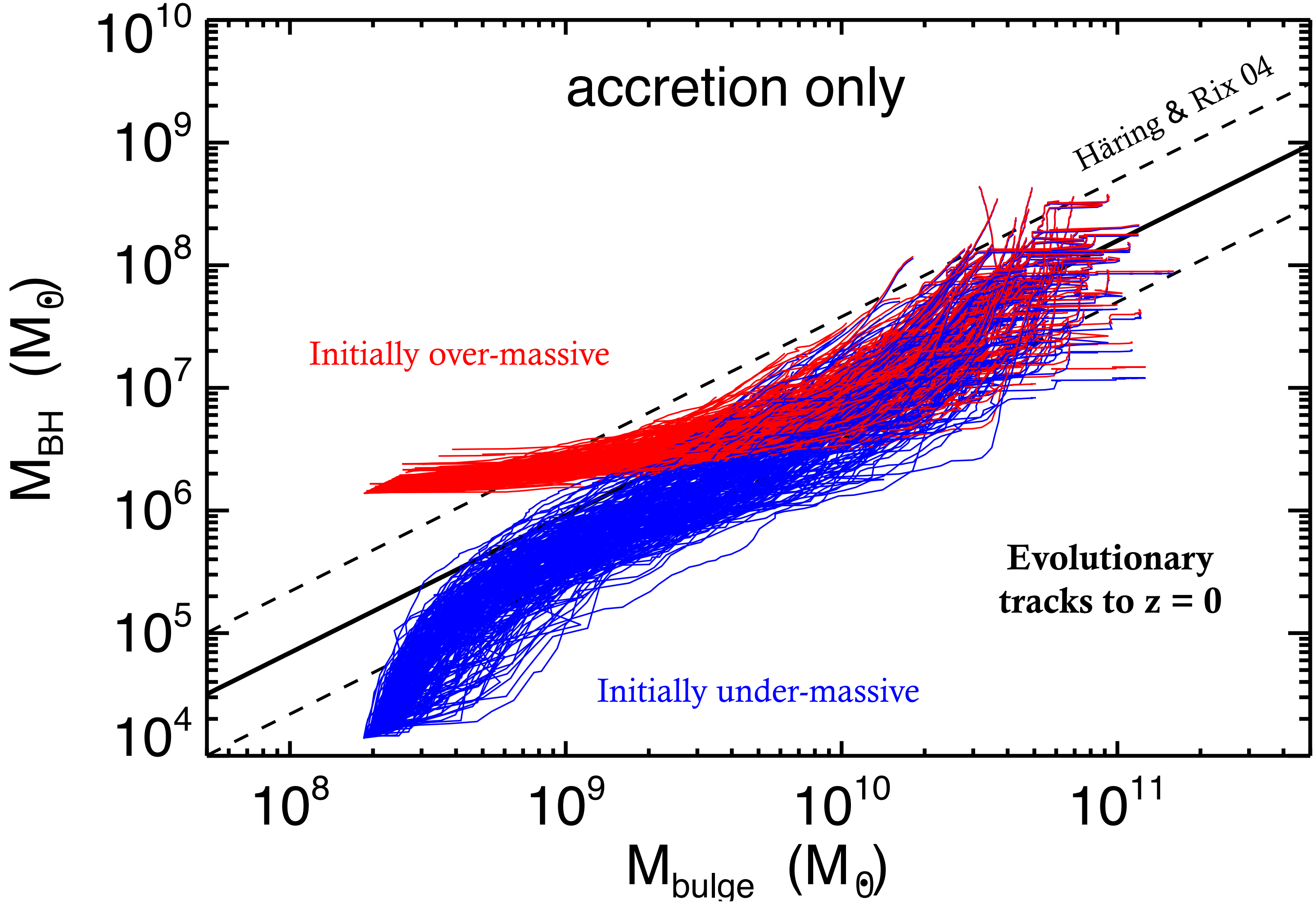
… but no feedback loop included!

Black hole growth limited by inflows and mass loss in outflows



Anglés-Alcázar et al. (2013)

Black hole growth limited by inflows and mass loss in outflows

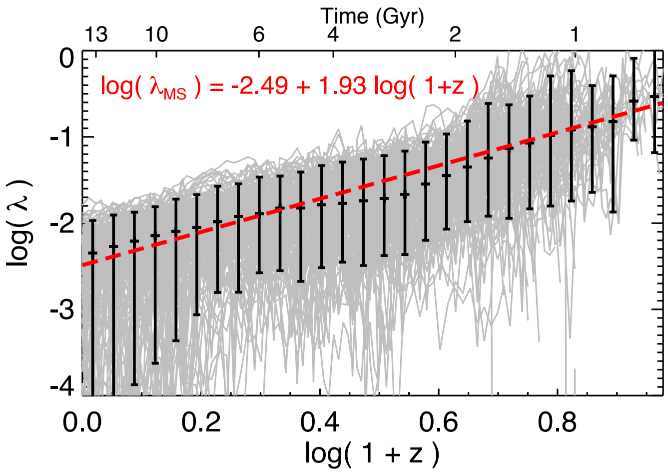


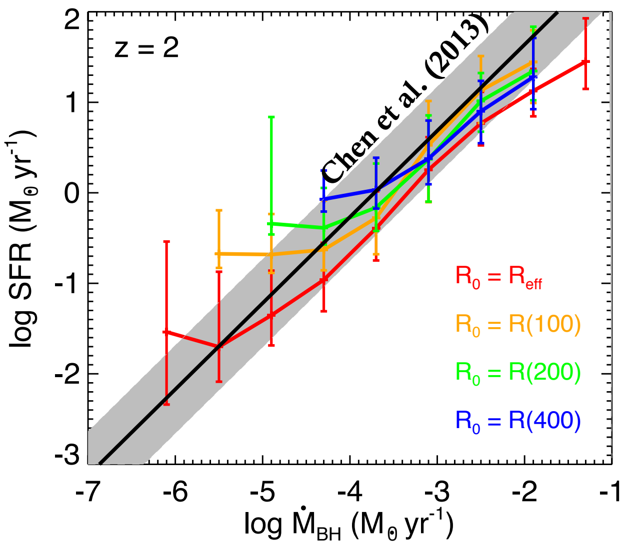
Post-processing full box simulations from Davé+13

Anglés-Alcázar et al. (2015)

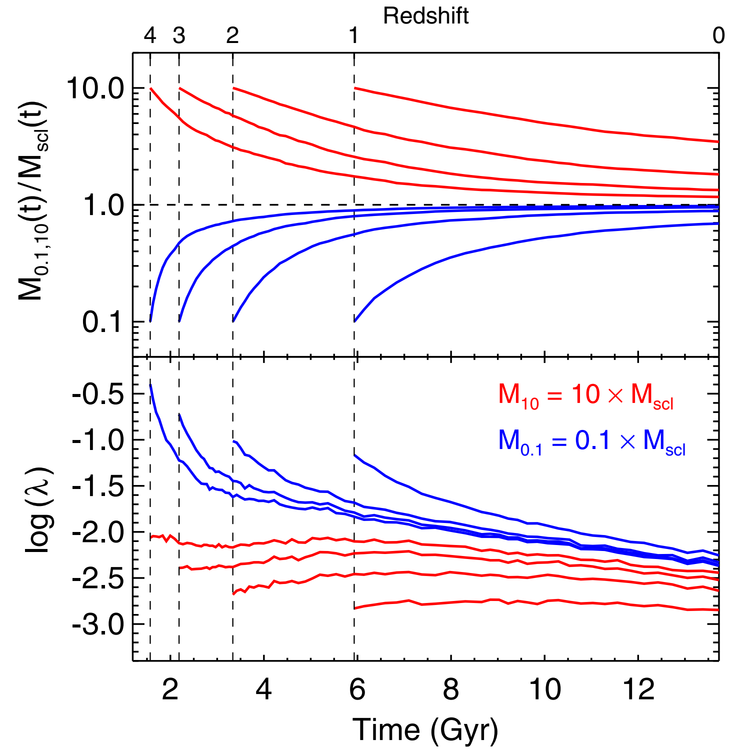
Black hole growth limited by inflows and mass loss in outflows

Evolution of Eddington ratios





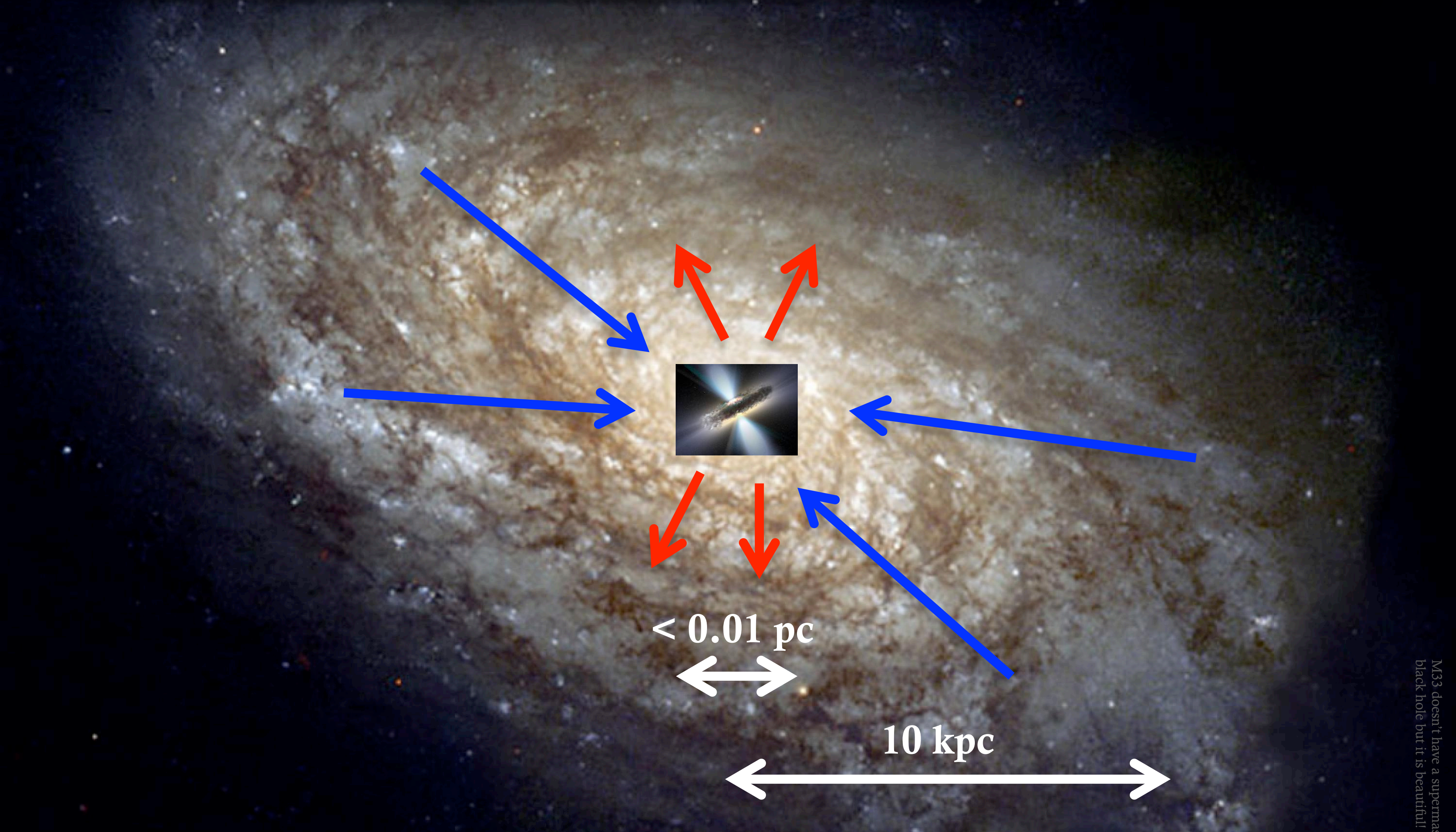
SFR – AGN connection



Timescale for convergence onto scaling relations

Anglés-Alcázar et al. (2015)

What about black hole feedback?

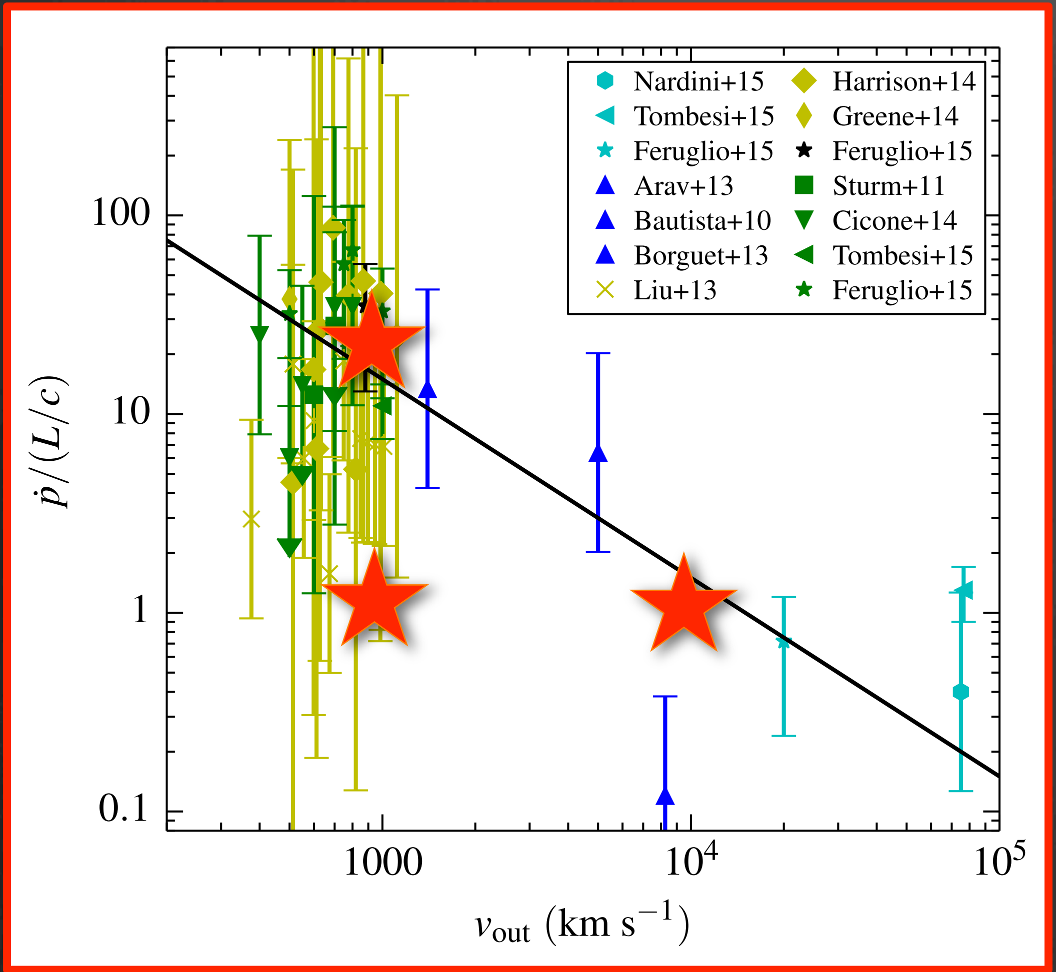


(1) Gas inflows from galactic scales

(2) Feedback acting at galactic scales

What about black hole feedback?

GIZMO (Hopkins 2015) in PSPH and MFM, adaptive softenings
metal cooling, subgrid ISM (Springel & Hernquist 2003), no galactic winds



Stern+2016; Faucher-Giguere & Quataert (2012)

[20 Mpc/h]^3 volume,
2x256^3 particles,
$m_g = 10^7\ M_\odot$
ε = 2 kpc (DM)

→ On-the-fly gravitational torque accretion + standard BH seeding,BH mergers

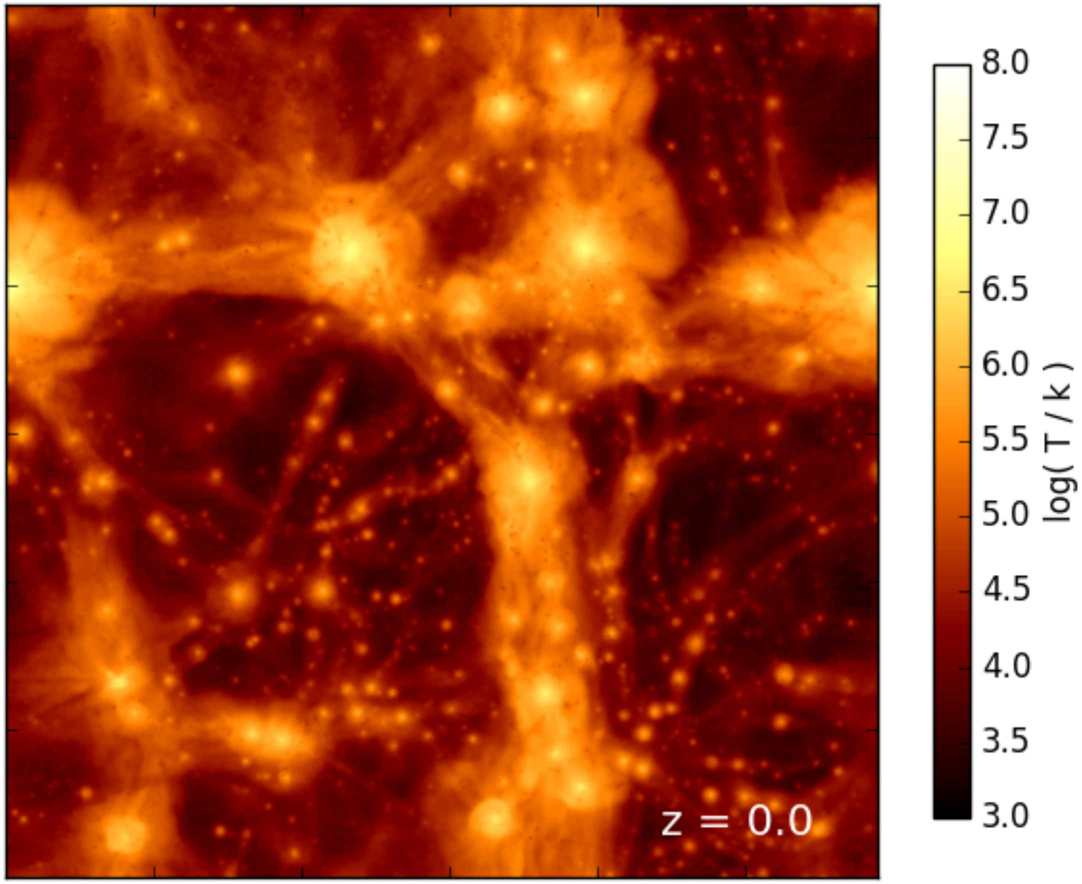
→ Kinetic outflows with prescribed velocity and total momentum flux

Debuhr+12
Choi+12,15
Hopkins+15

What about black hole feedback?

Same black hole accretion model and different feedback strengths

Temperature distribution in [20 Mpc/h]^3 volume



NO FEEDBACK

Anglés-Alcázar et al. (2016), arXiv:1603.08007

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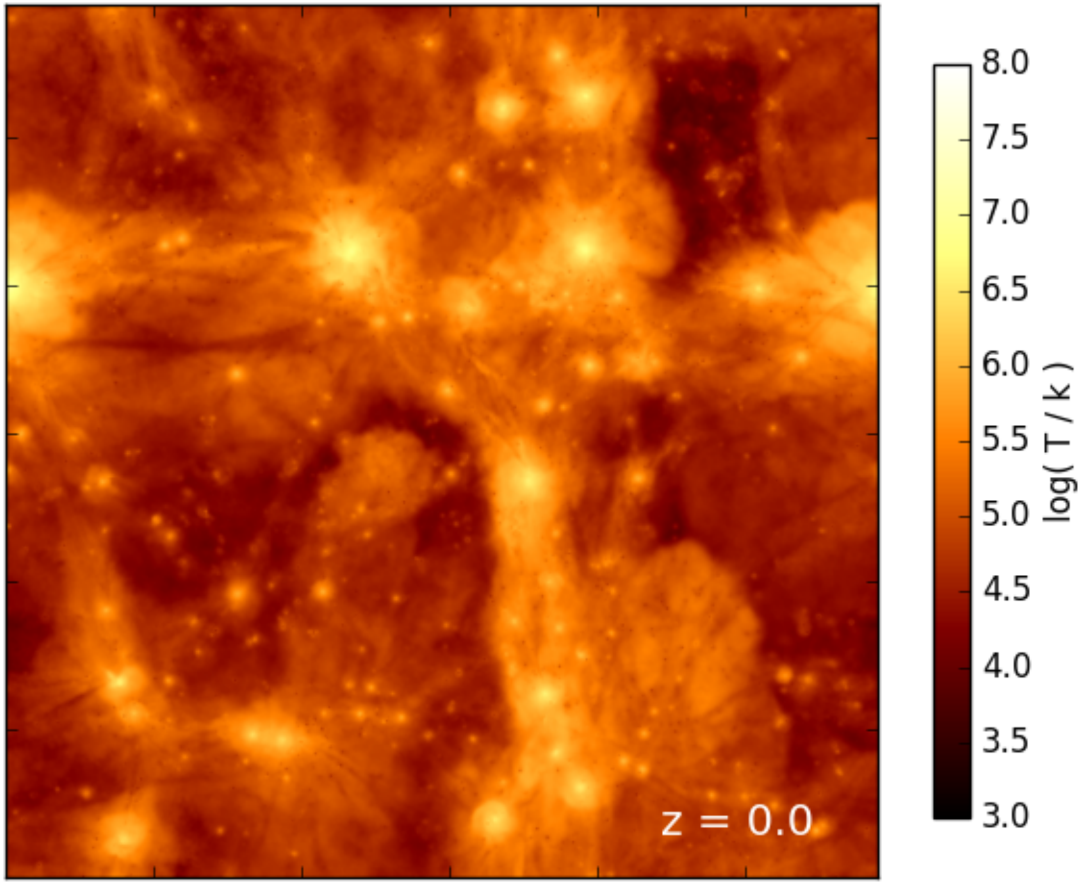
Same black hole accretion model and different feedback strengths

Temperature distribution in [20 Mpc/h]^3 volume



FEEDBACK: v = 1000 km/s, P = L_{bol}/c

Anglés-Alcázar et al. (2016), arXiv:1603.08007

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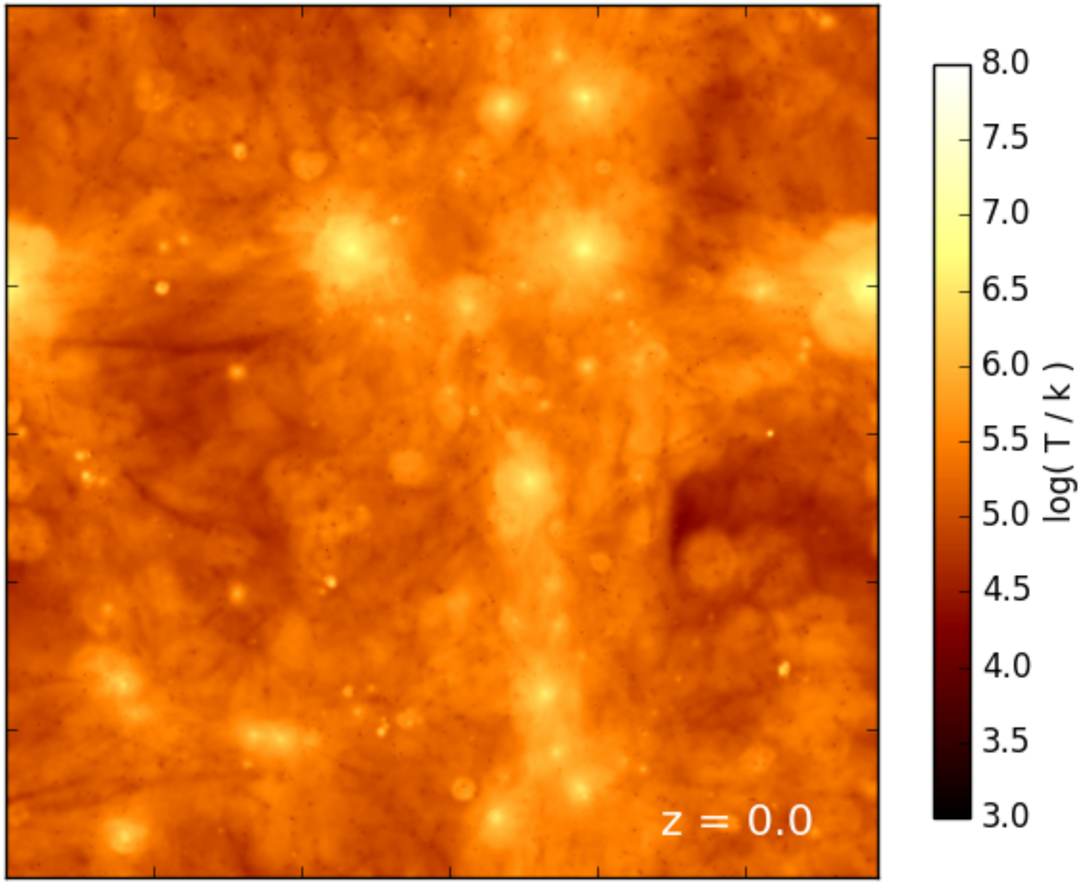
Temperature distribution in [20 Mpc/h]^3 volume



FEEDBACK: v = 10000 km/s, P = L_{bol}/c

Anglés-Alcázar et al. (2016), arXiv:1603.08007

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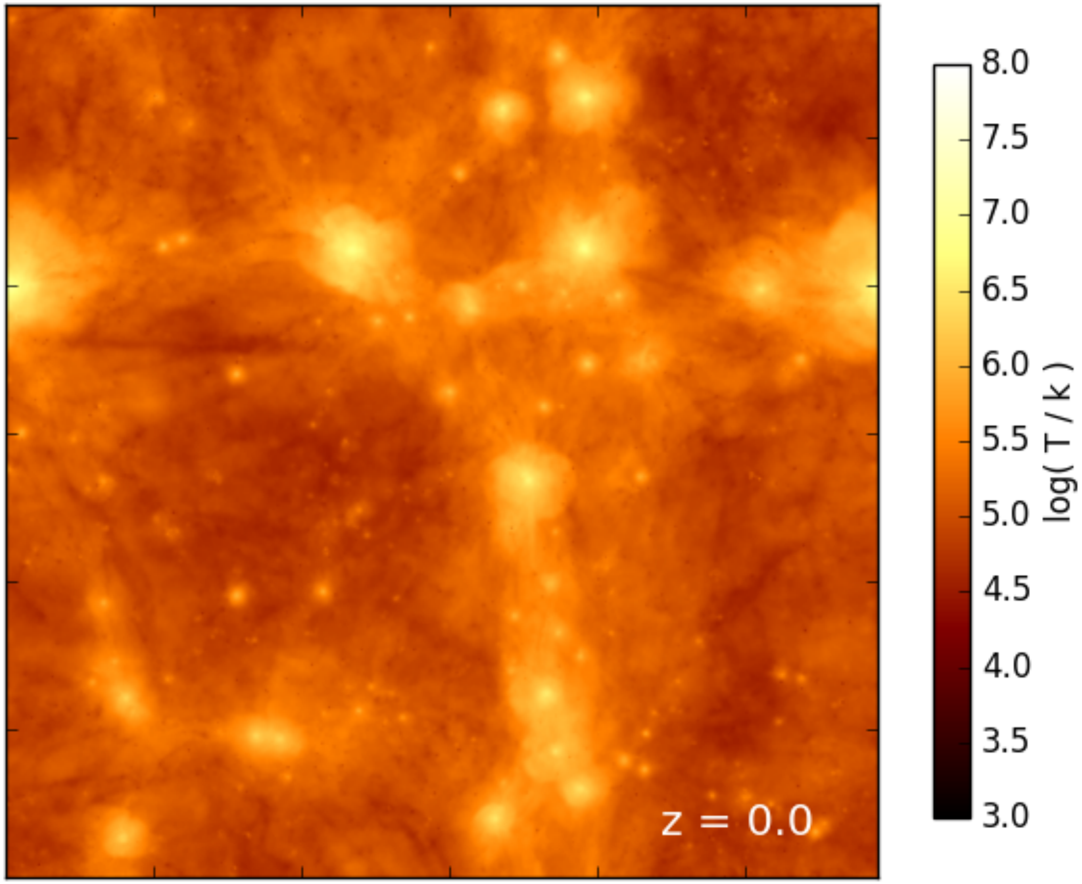
Temperature distribution in [20 Mpc/h]^3 volume



FEEDBACK: $v = 1000$ km/s, $P = 20\ L_{bol}/c$

Anglés-Alcázar et al. (2016), arXiv:1603.08007

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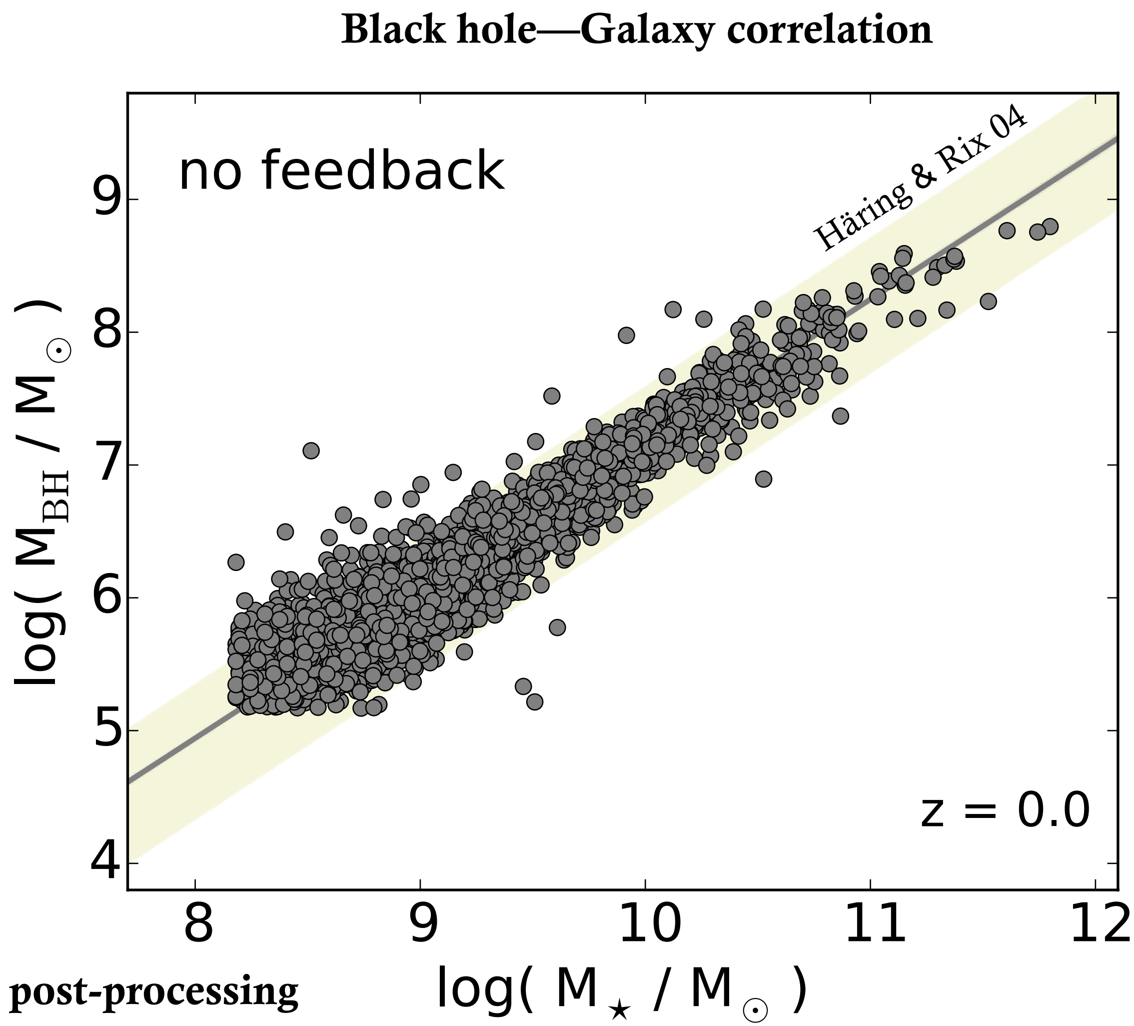

Reproducing post-processing calculations!

Anglés-Alcázar et al. (2016), arXiv:1603.08007

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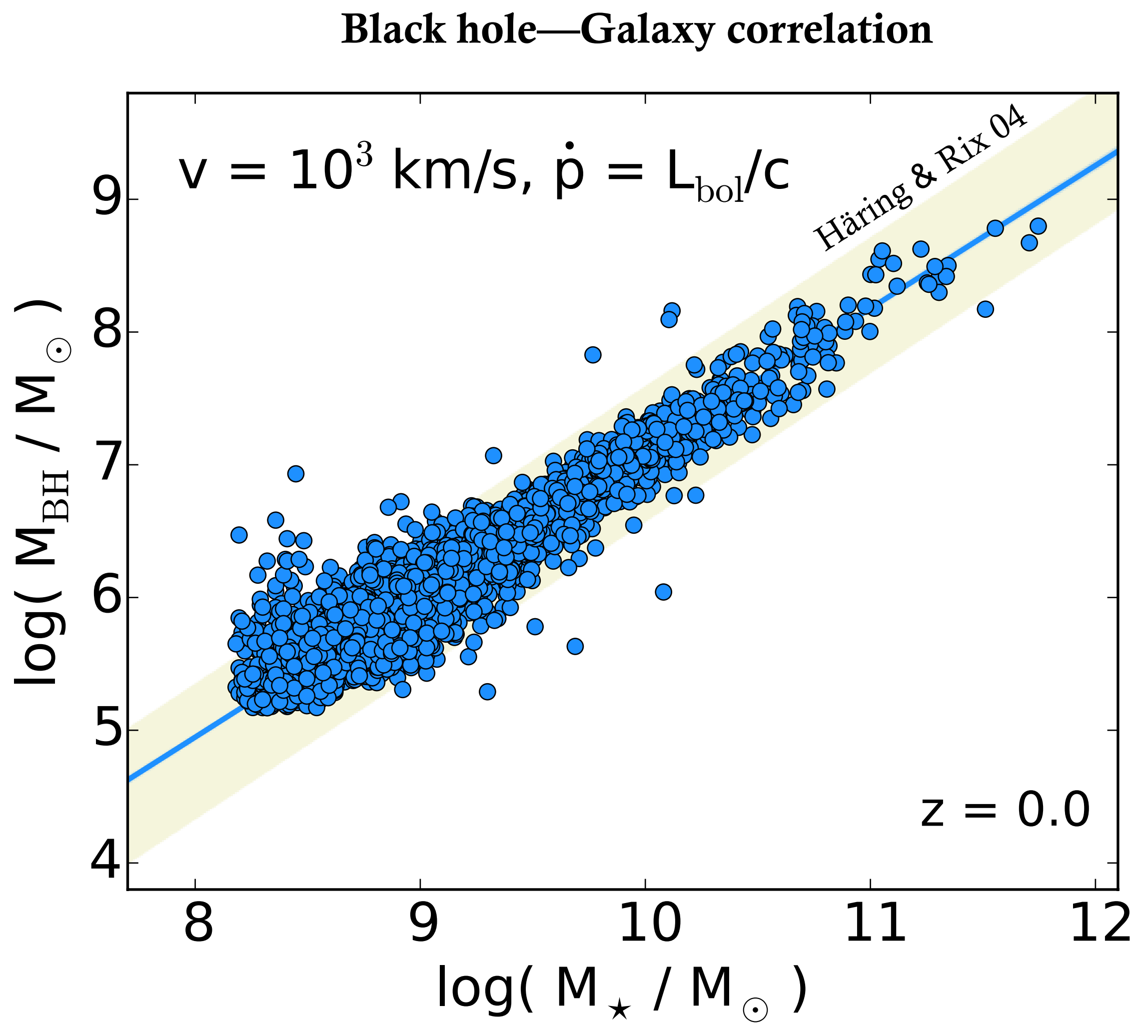
Same black hole accretion model and different feedback strengths



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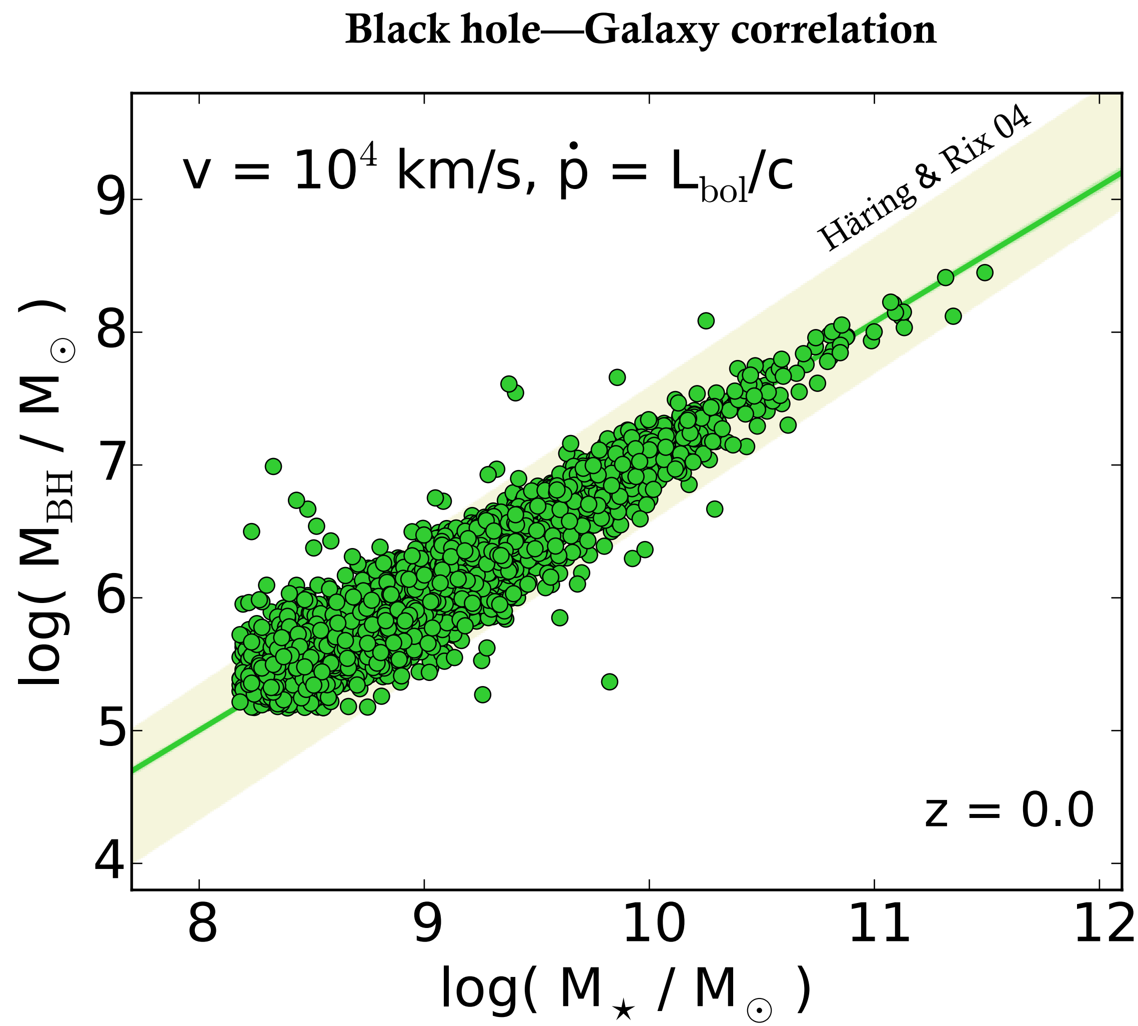

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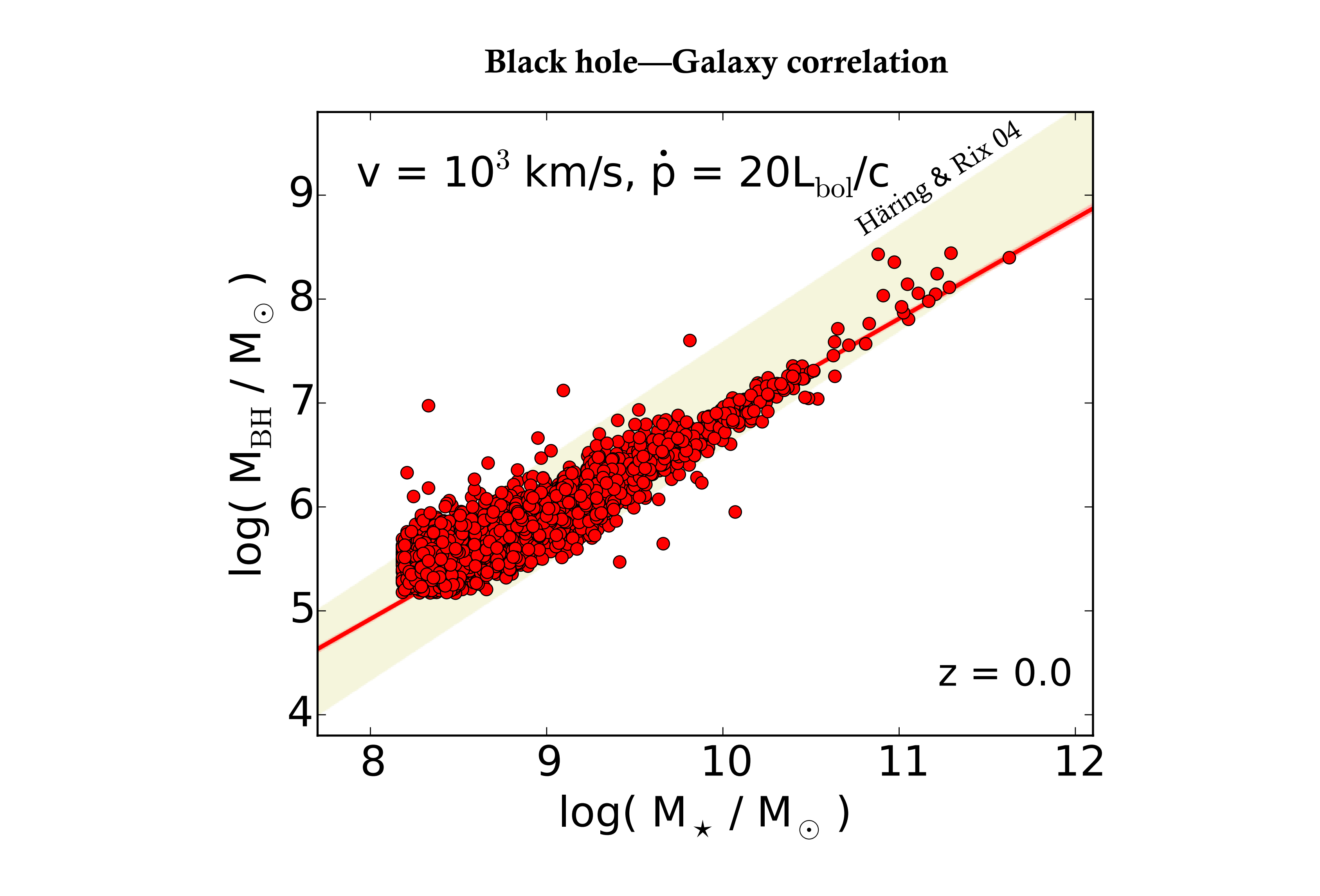

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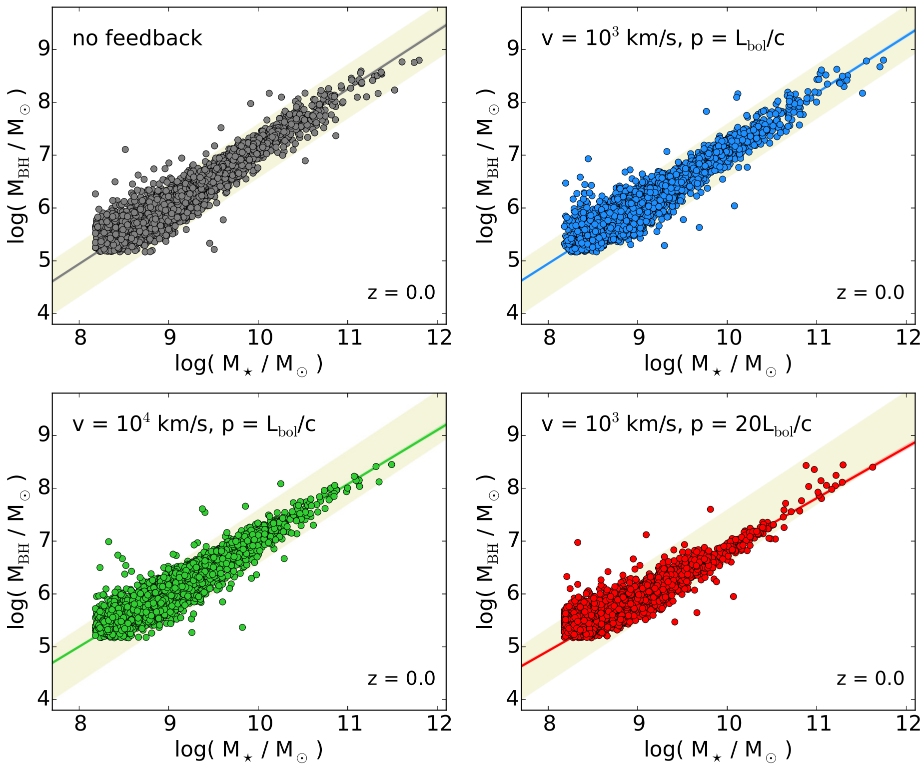

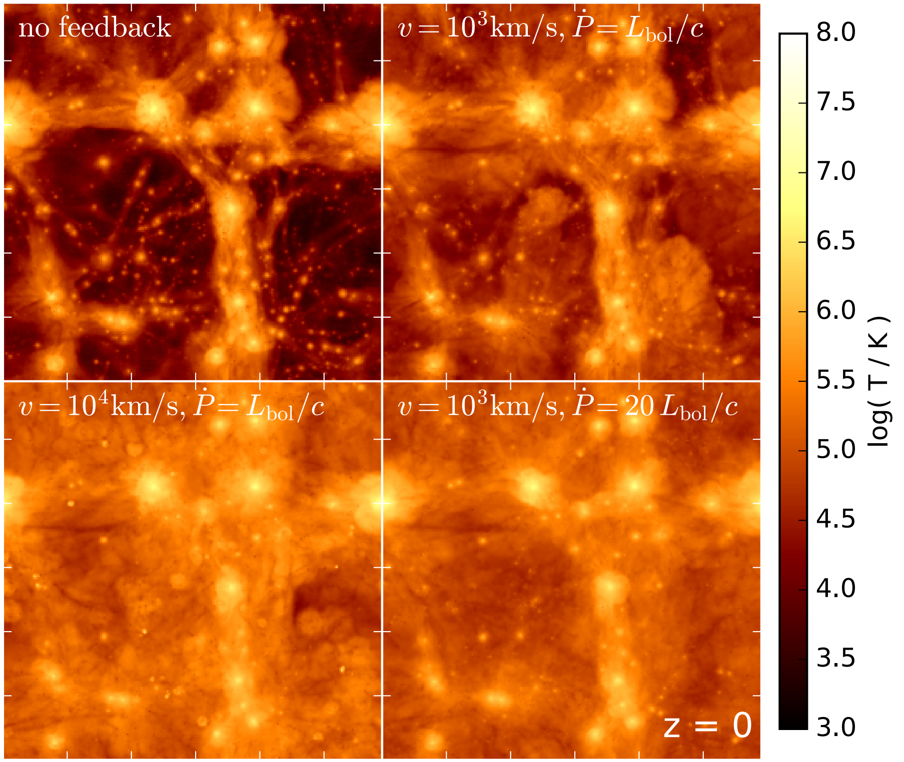

Black hole—galaxy correlation

→Driven by gas inflow rates and not by feedback self-regulation on large scales

Temperature distribution on large scales

→Significant impact of black hole feedback on IGM / galaxy evolution

Anglés-Alcázar et al. (2016), arXiv:1603.08007

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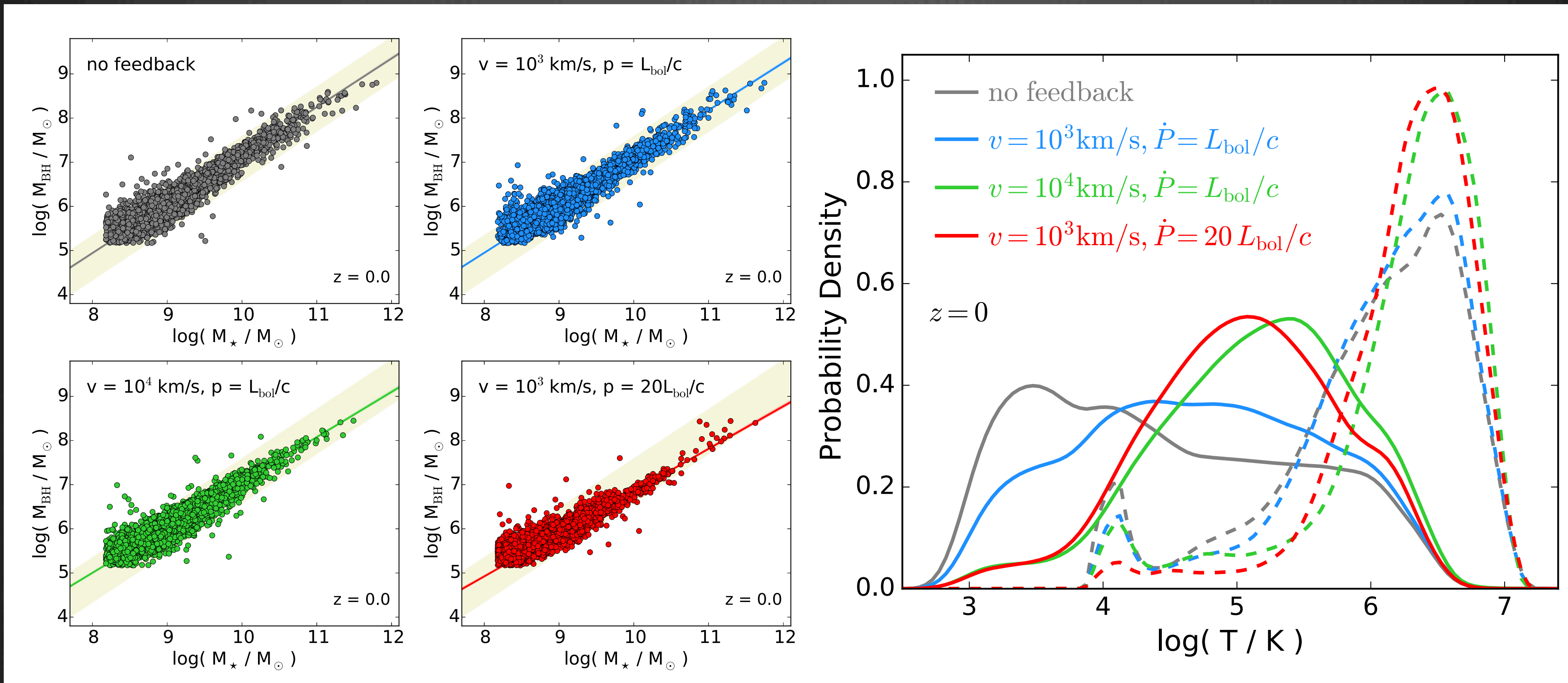
Same black hole accretion model and different feedback strengths



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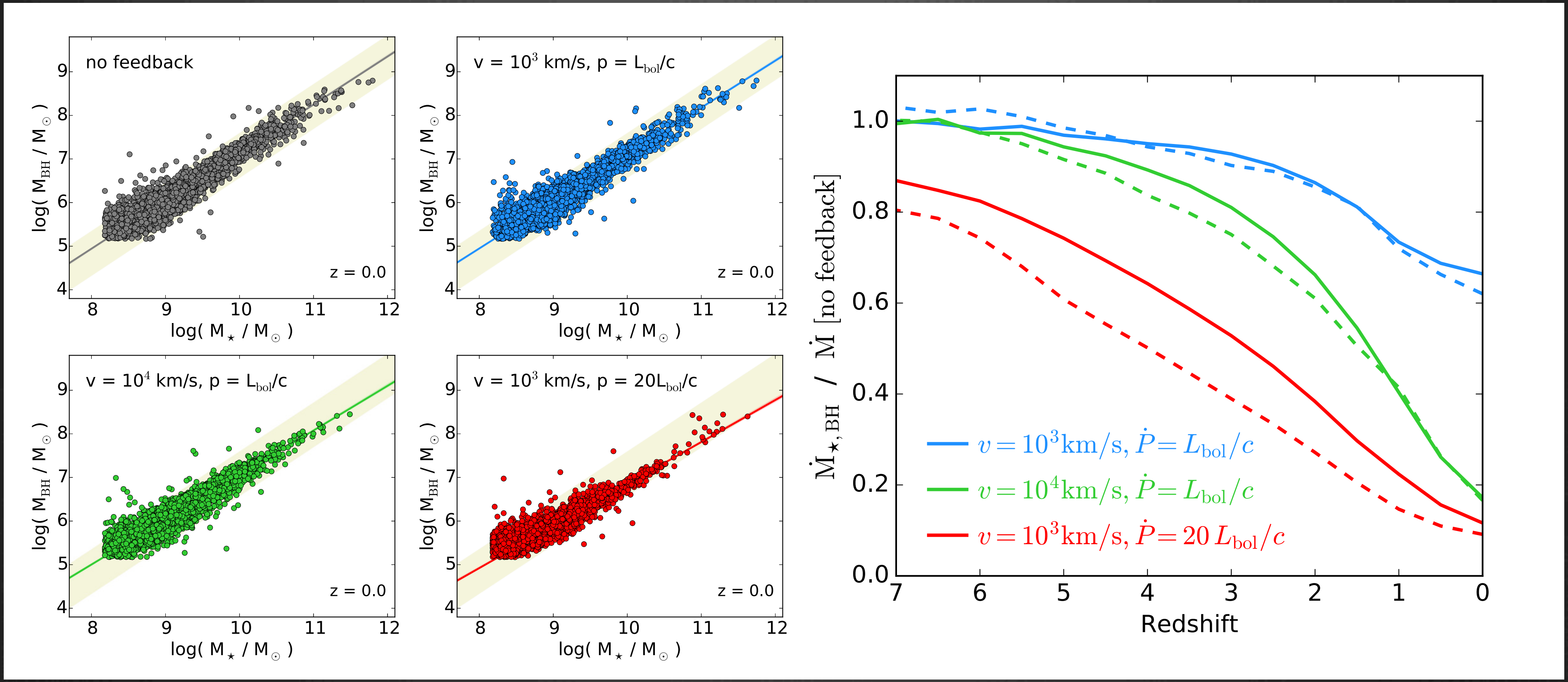


Black hole—galaxy correlation

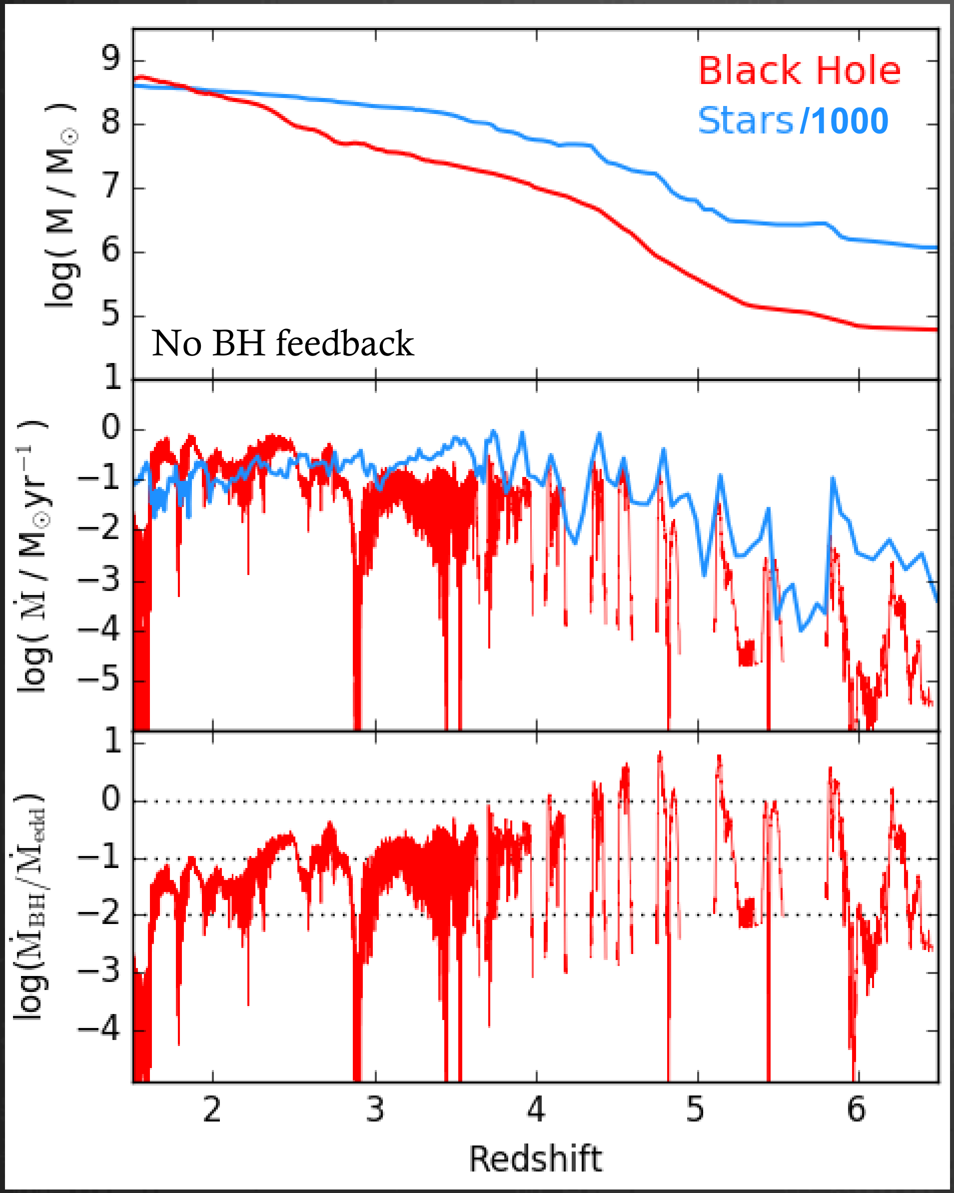
→Driven by gas inflow rates and not by feedback self-regulation on large scales

Mass growth suppressed by feedback

→Significant impact of black hole feedback on IGM / galaxy evolution

Anglés-Alcázar et al. (2016), arXiv:1603.08007

Torques growing BHs on FIRE (in progress)



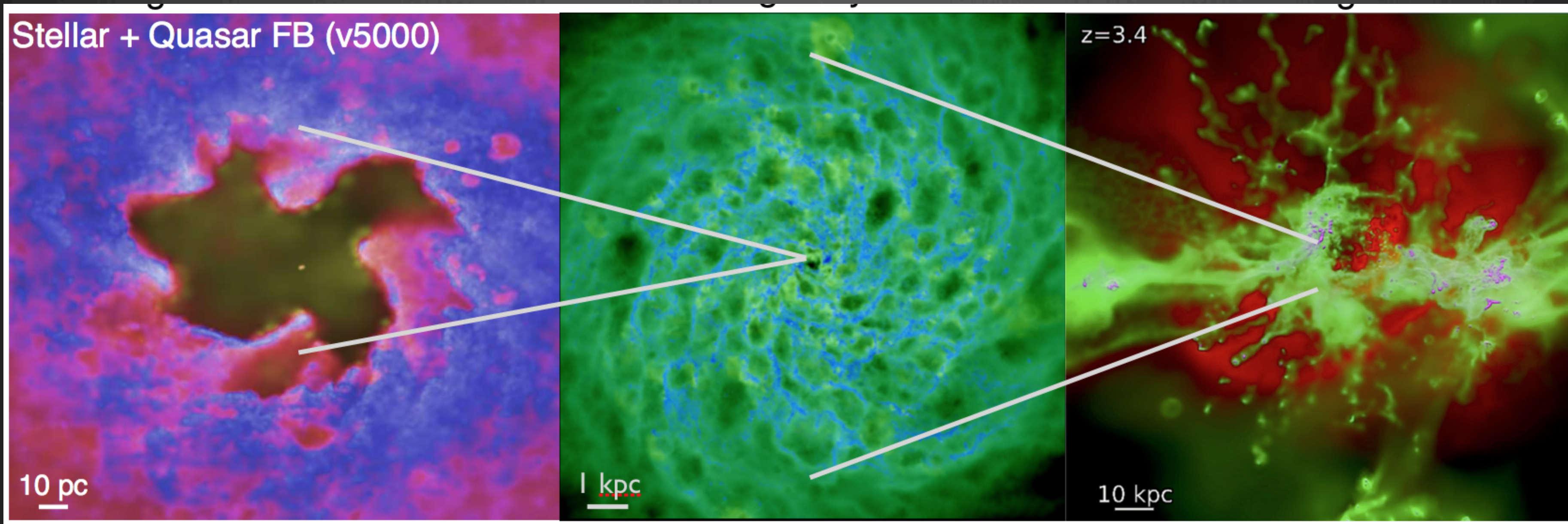
Hopkins+2014

Extremely rich simulations!
BH growth/feedback at <100 pc,
BH dynamics, bursty star formation,
violent stellar feedback…

"More physics, more resolution, more problems!"

(R. Teyssier)

Multi-scale BH growth/feedback on FIRE



Hopkins+2015 Torrey+ (in prep) Anglés-Alcázar+ (in prep)

→Nuclear/galaxy scale simulations with FIRE star formation/stellar feedback + explicit BH growth/feedback

→Calibrate accretion/feedback for cosmological simulations

Summary

1. Torque-limited growth: black holes and galaxies evolve on average towards observed scaling relations, regardless of the initial conditions, and with no need for mass averaging through mergers or additional self-regulation processes.

2. Large-scale AGN feedback can have a significant effect on galaxy evolution while only weakly affecting BH-host scaling relations.

3. Common gas supply regulated by gravitational torques is the primary driver of the observed co-evolution of black holes and galaxies.

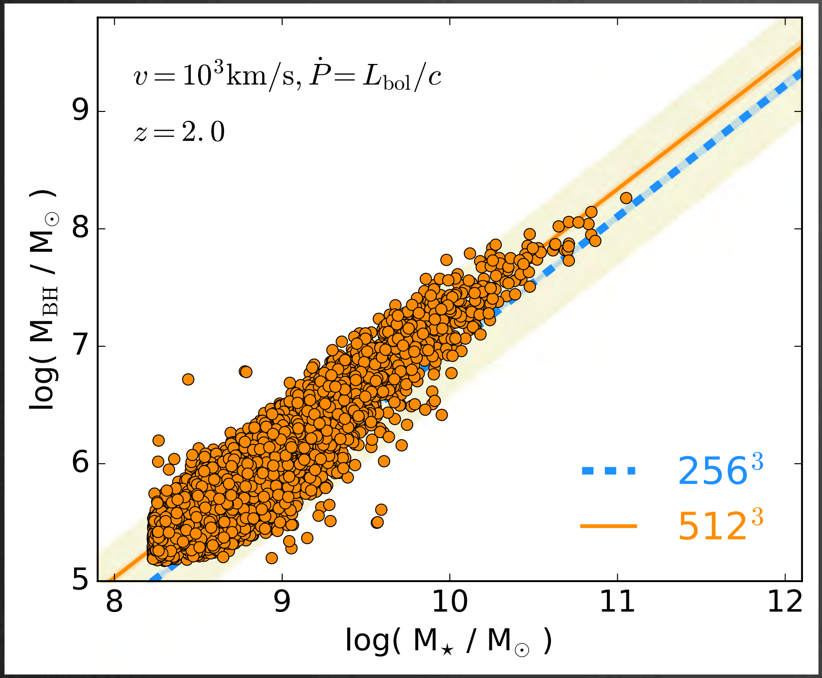
4. Calibrating AGN feedback efficiency to match BH-host correlations can be severely biased by the accretion model!

Anglés-Alcázar et al. (2013), ApJ, 770, 5

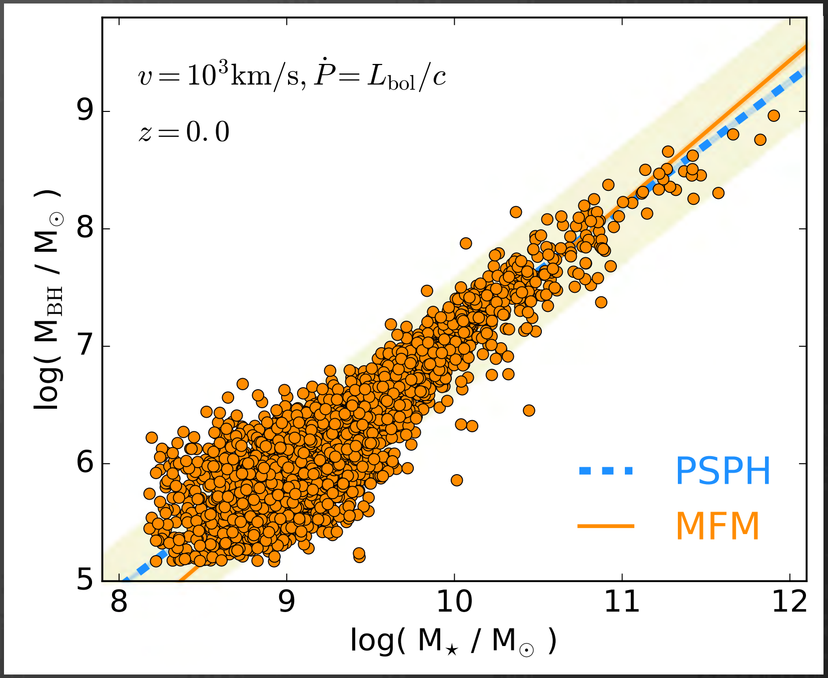
Anglés-Alcázar et al. (2015), ApJ, 800, 127

Anglés-Alcázar et al. (2016), arXiv:1603.08007

Resolution convergence

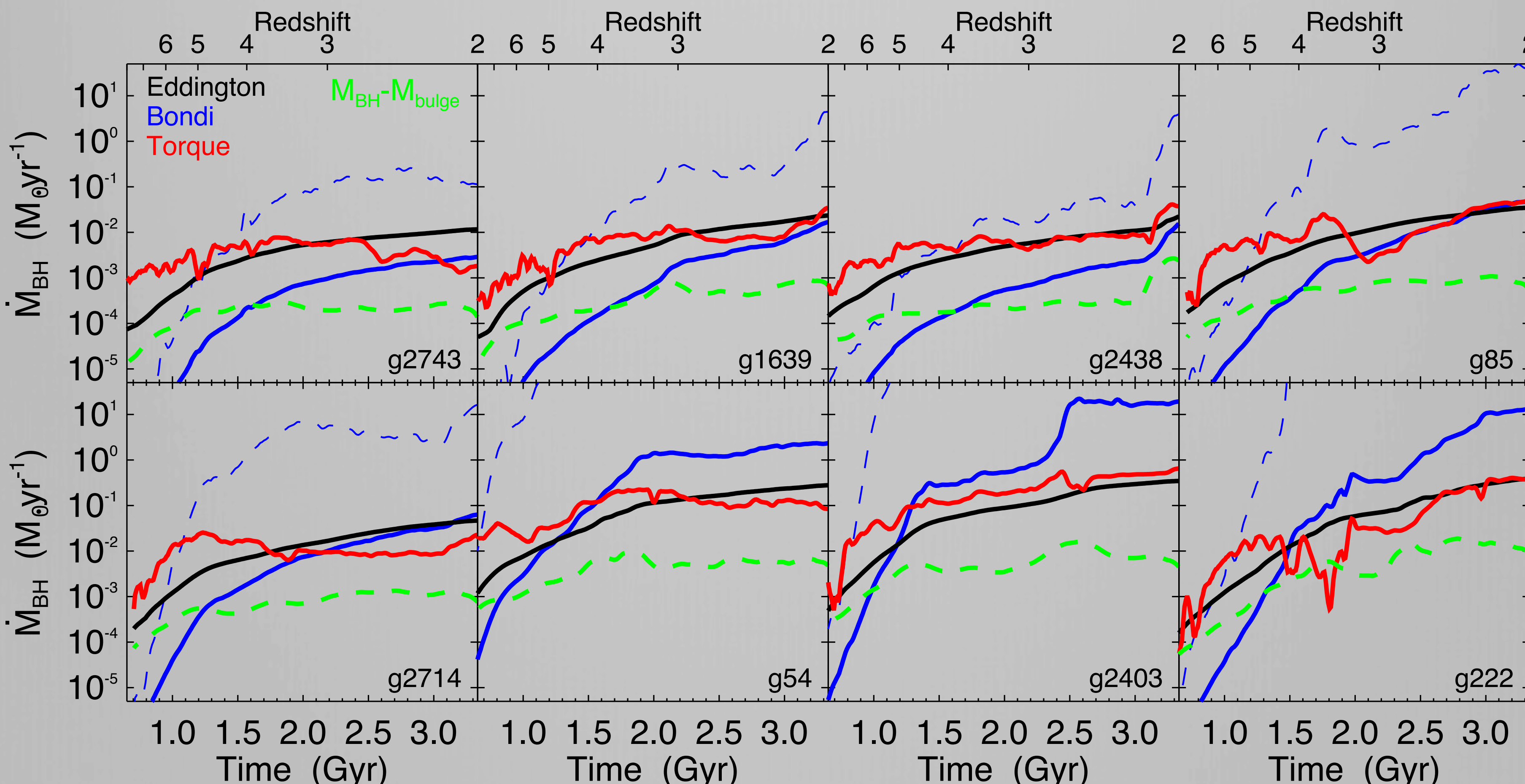


Hydrodynamics



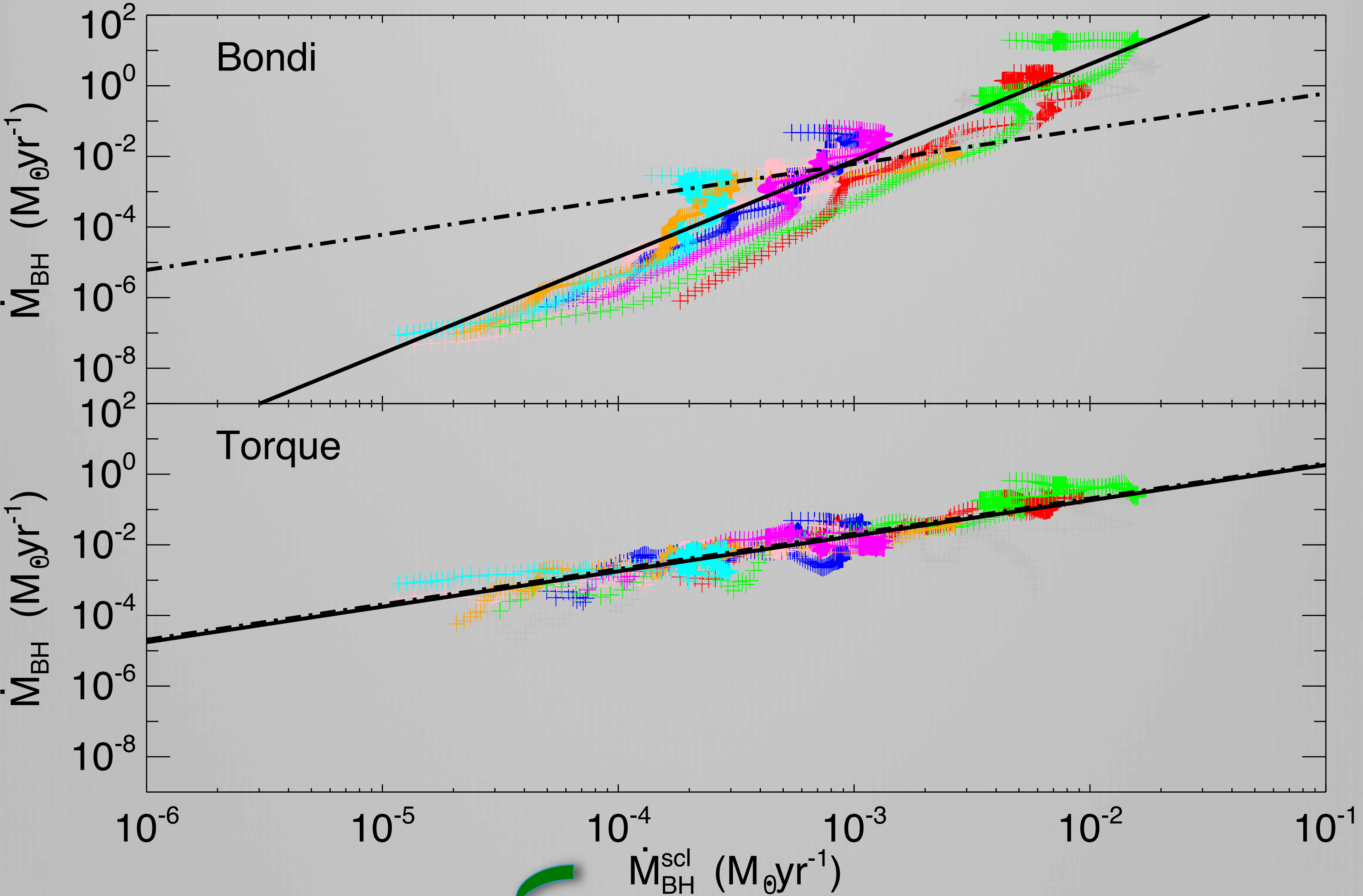
Black hole accretion rates

→ **Bondi** → **Gravitational torque** → **Eddington**



→ **Accretion rate if growing along M_{BH}–M_{bulge} relation**

Anglés-Alcázar et al. (2013)



Anglés-Alcázar et al. (2013)

BH growth according to scaling relation