Torque-limited growth of massive black holes in galaxies

Daniel Anglés-Alcázar
CIERA Fellow
Northwestern University

with: Romeel Davé, Feryal Özel, Neal Katz, Juna Kollmeier, Ben Oppenheimer

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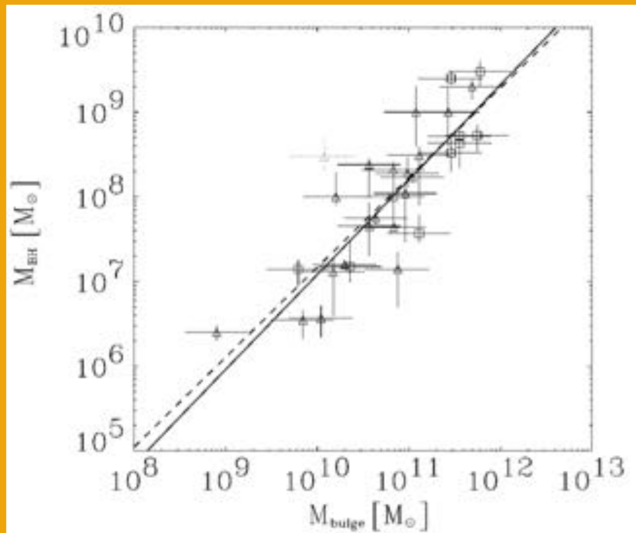
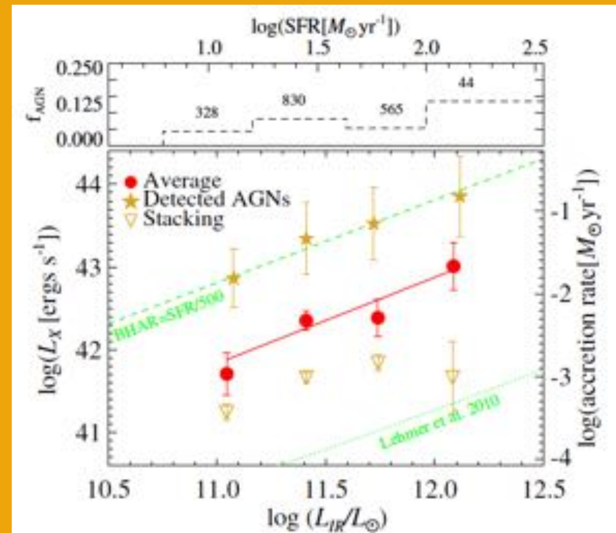
Massive black holes and galaxies

Häring & Rix 04





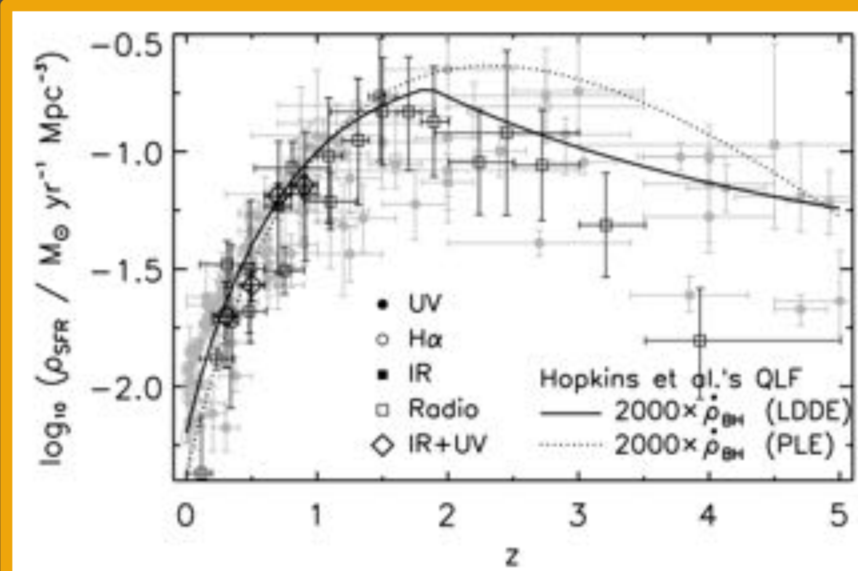
Chen+13

Average black hole accretion in star-forming galaxies

Correlations between black hole mass and galaxy properties in the local universe

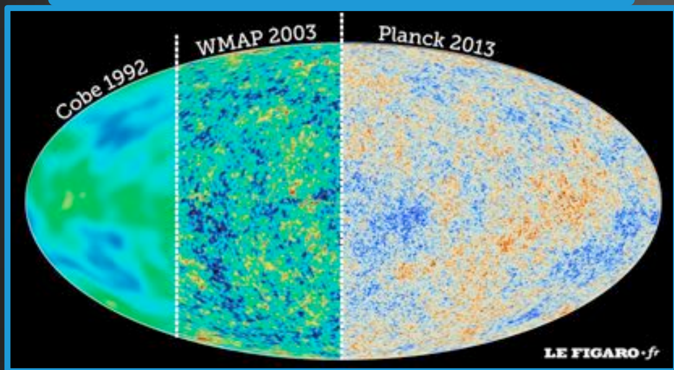
Global cosmic evolution of star formation rate and black hole accretion rate densities

Zheng+09



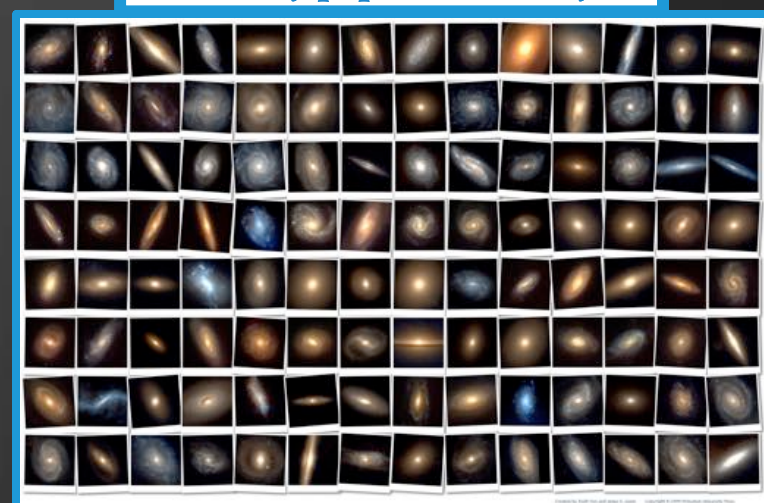
How do galaxies form?

Cosmic Microwave Background



?

Galaxy population today



BASIC INGREDIENTS

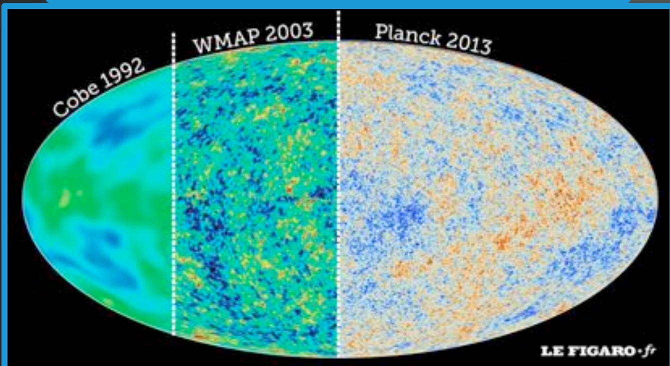
Initial conditions
→ primordial density fluctuations

Background cosmology
→ LCDM

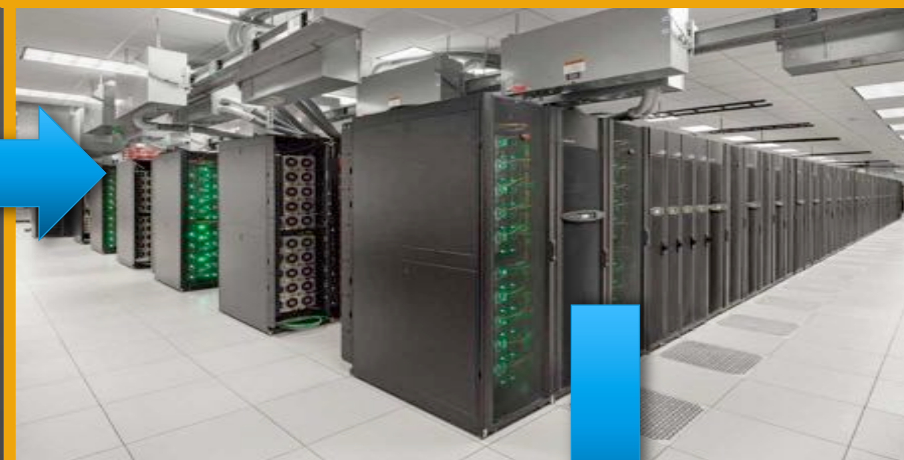
And lots of physics!
→ self-gravitating fluid dynamics, gas cooling, star formation, stellar feedback, supermassive black holes,…

Cosmological hydrodynamic simulations

Cosmic Microwave Background



Cosmological hydrodynamic simulations



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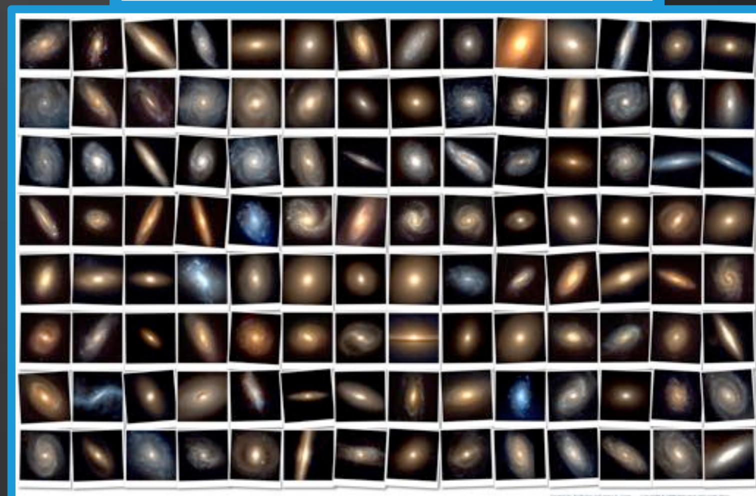

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Cosmological hydrodynamic simulations

Initial conditions
→ primordial density fluctuations

Background cosmology
→ LCDM

} Assumed to be known

Dark matter dynamics
→ Collisionless Boltzmann equation

→ Well constrained by current N-body methods

Baryonic physics
→ Hydrodynamic forces
→ Gas cooling
→ Star formation
→ Stellar Feedback
…

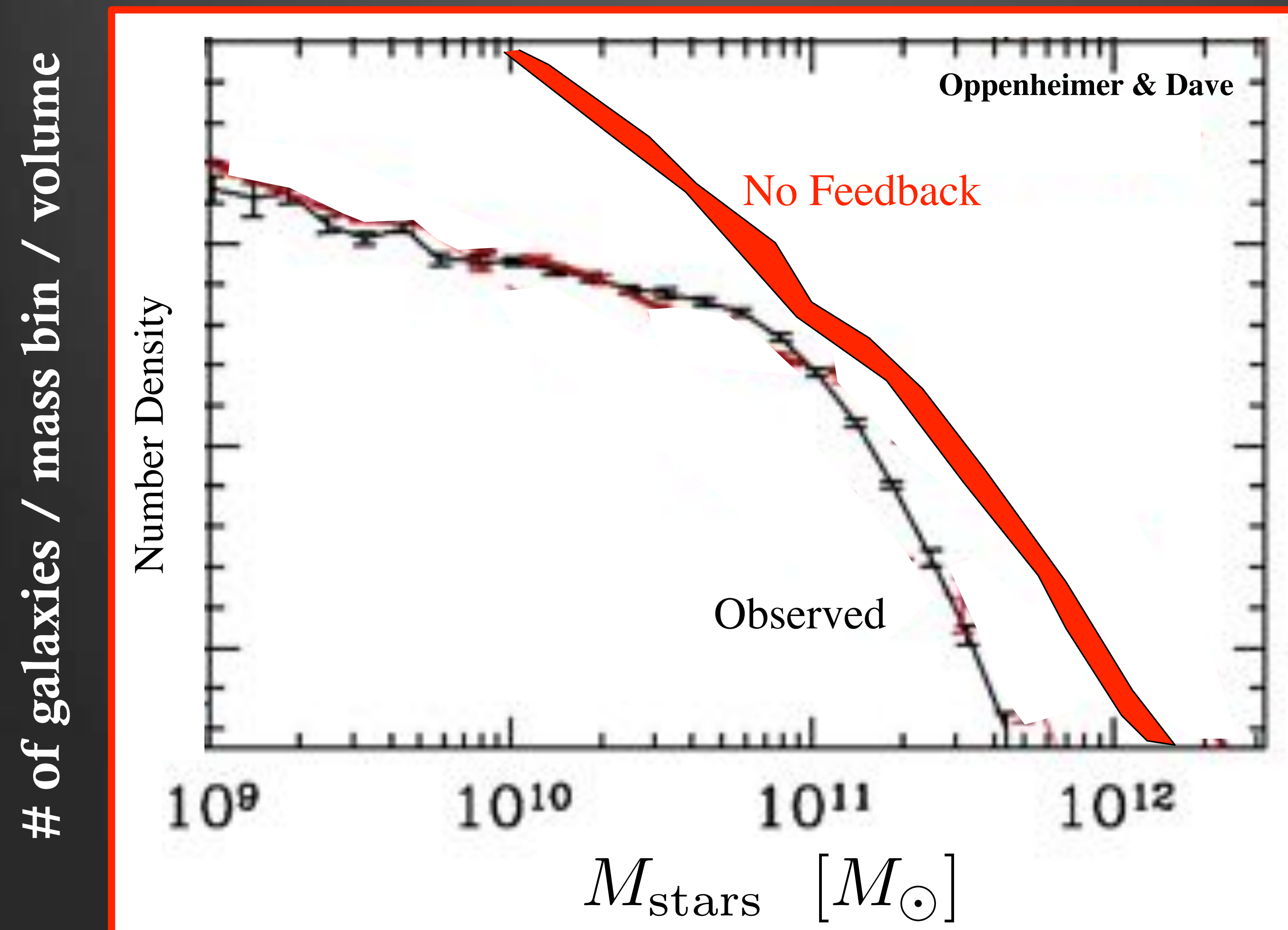
} Major challenge!

→ **BLACK HOLE GROWTH AND FEEDBACK!**

ARAA review by
Somerville & Davé

Massive black holes and galaxies

Need to suppress star formation in massive galaxies!!



Massive black holes and galaxies

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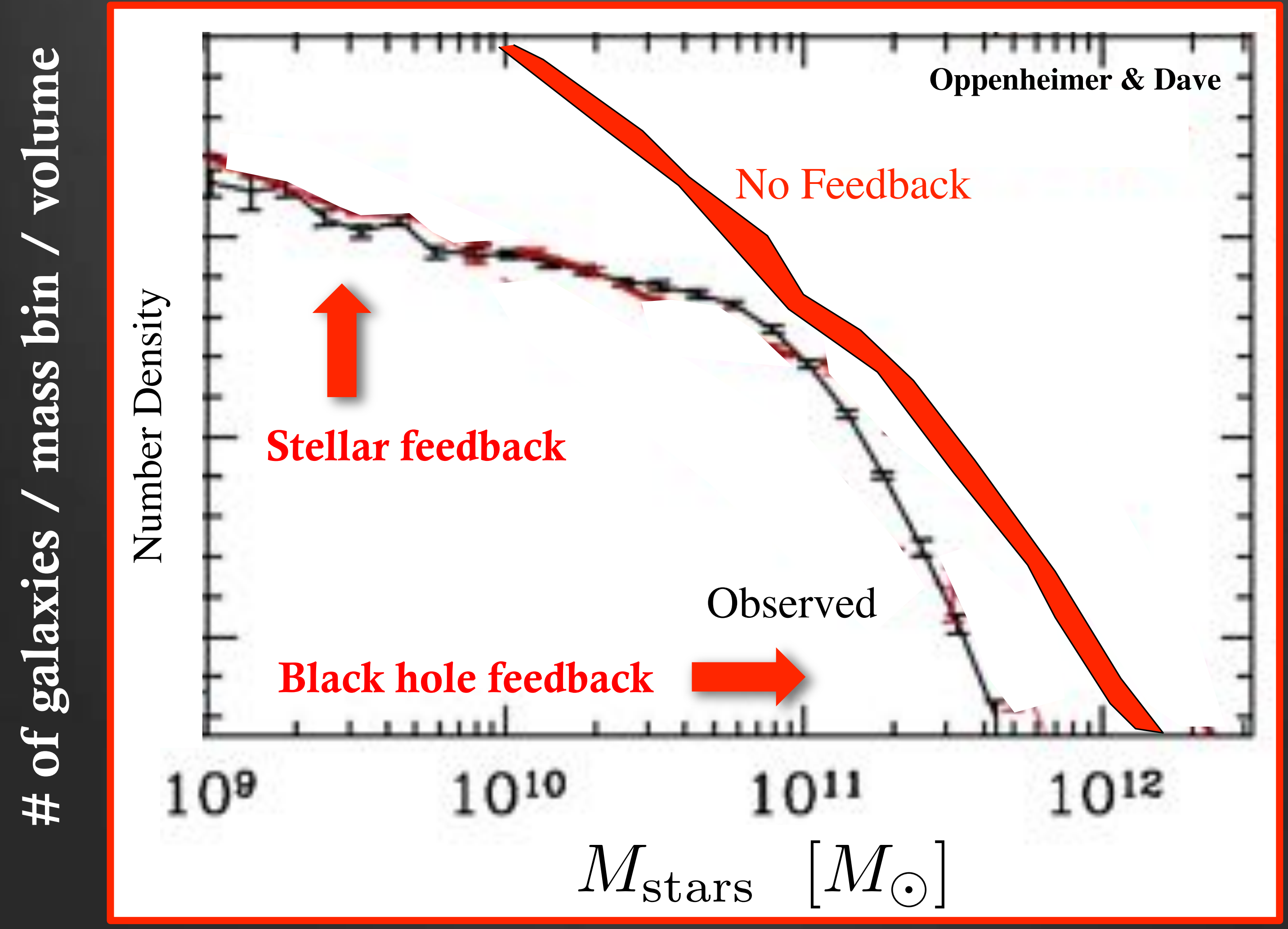
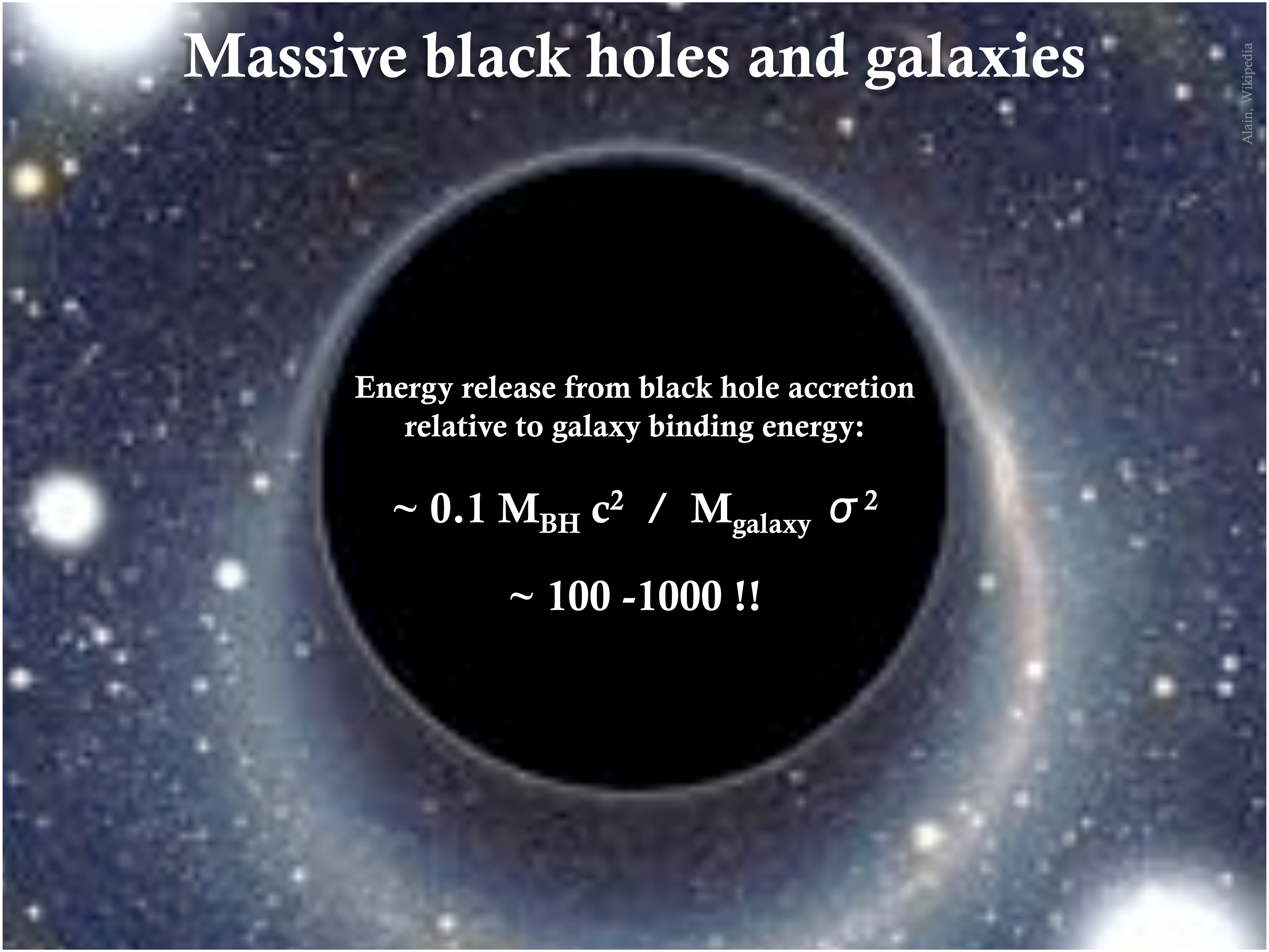


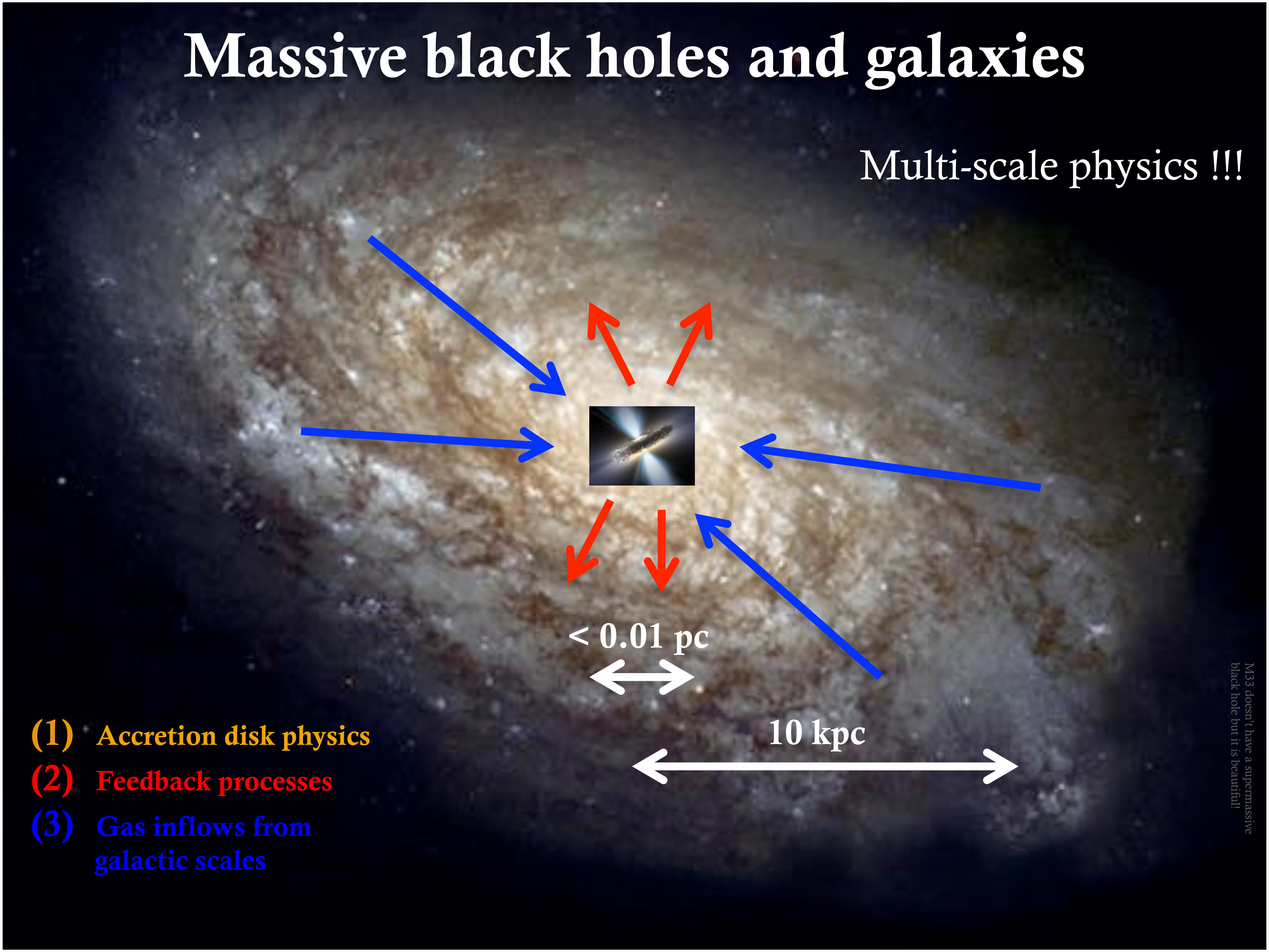
Massive black holes and galaxies

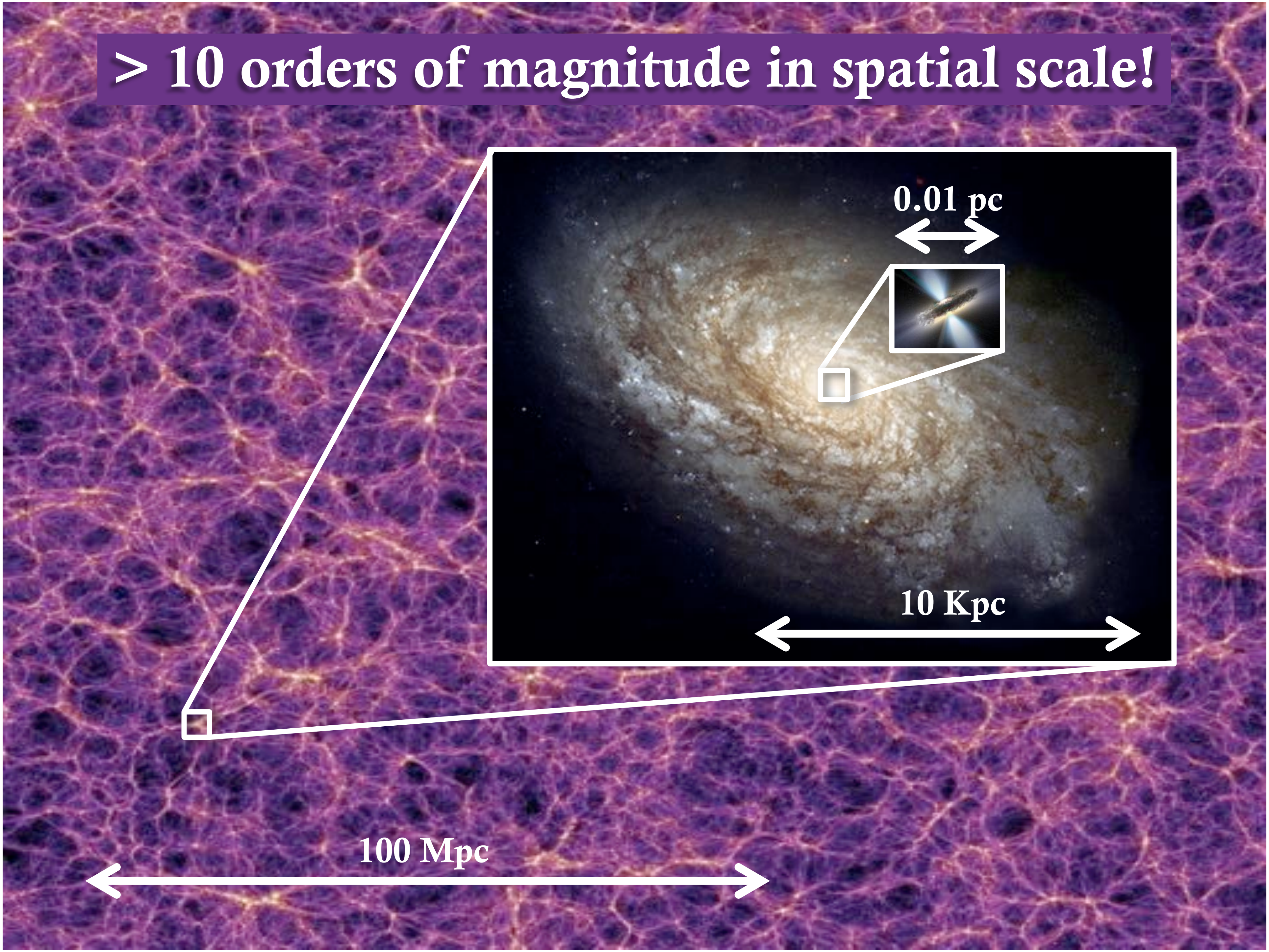


Energy release from black hole accretion relative to galaxy binding energy:

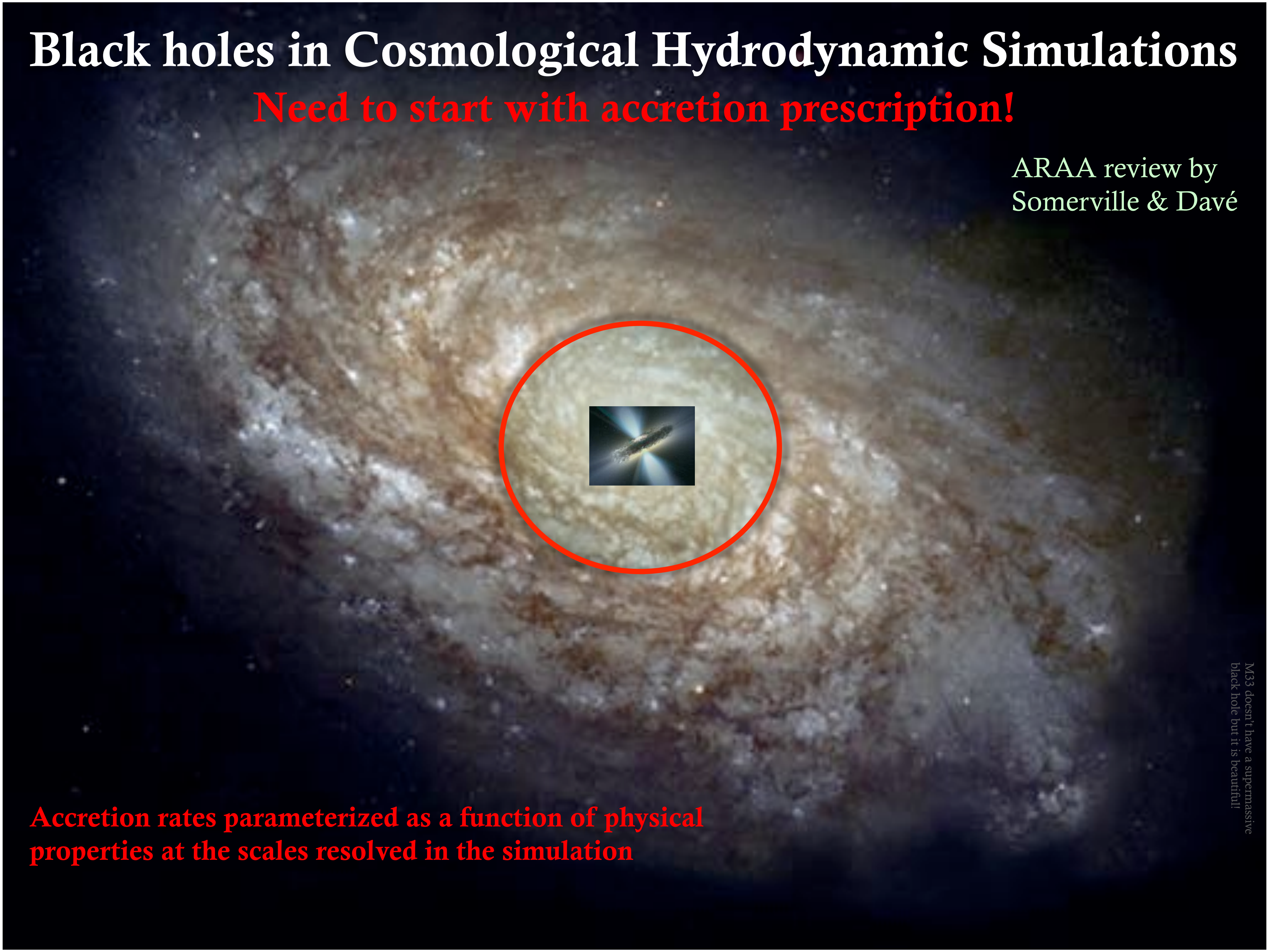
$$\sim 0.1\, M_{BH}\, c^2 \;/\; M_{galaxy}\, \sigma^2$$

~ 100 -1000 !!


Massive black holes and galaxies
Multi-scale physics !!!
< 0.01 pc
10 kpc
(1) Accretion disk physics
(2) Feedback processes
(3) Gas inflows from galactic scales
M33 doesn't have a supermassive black hole but it is beautiful!



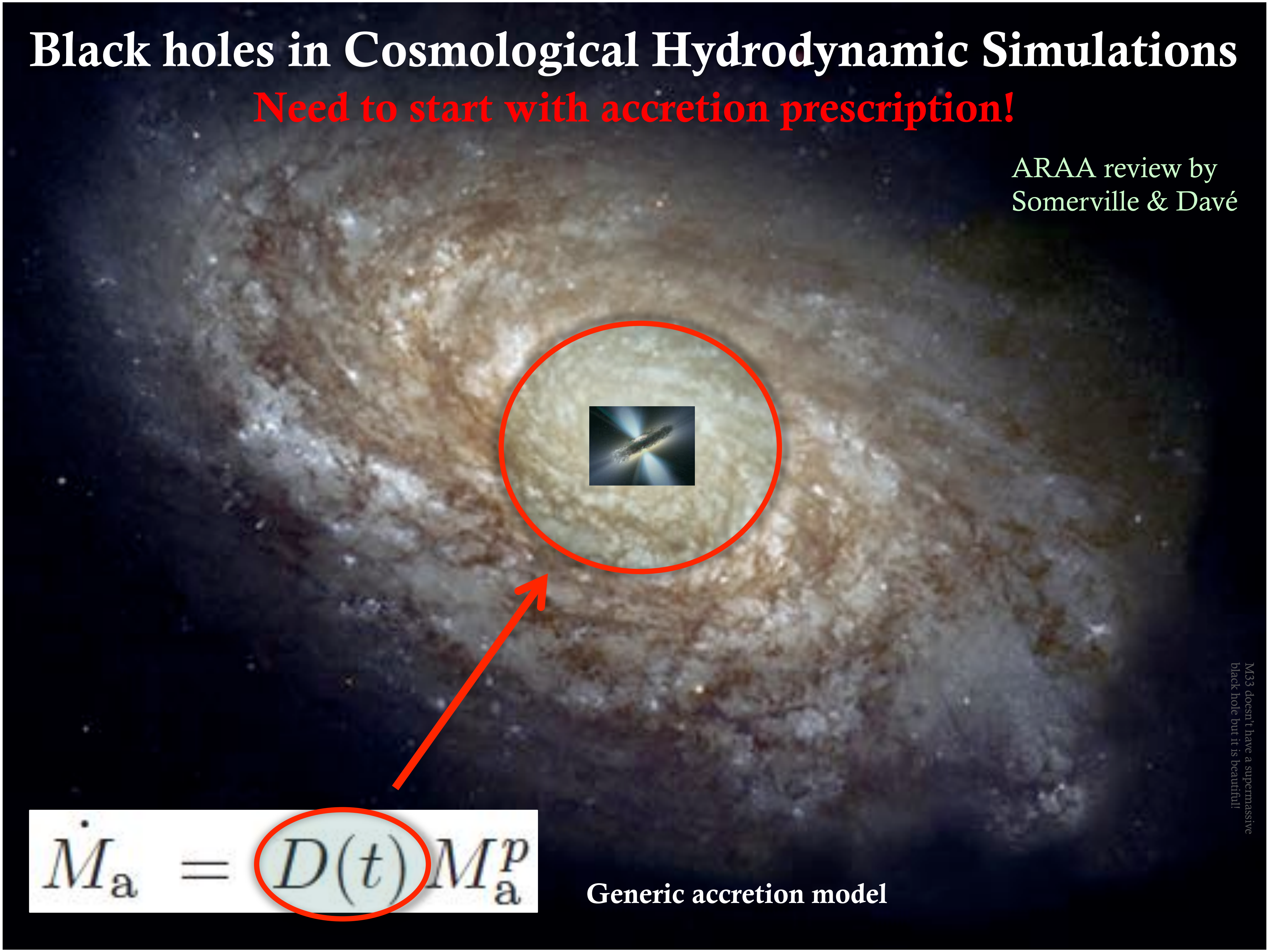
> 10 orders of magnitude in spatial scale!
0.01 pc
10 Kpc
100 Mpc


Black holes in Cosmological Hydrodynamic Simulations
Need to start with accretion prescription!
ARAA review by Somerville & Davé
Accretion rates parameterized as a function of physical properties at the scales resolved in the simulation
M33 doesn't have a supermassive black hole but it is beautiful!

Black holes in Cosmological Hydrodynamic Simulations

Need to start with accretion prescription!

ARAA review by Somerville & Davé

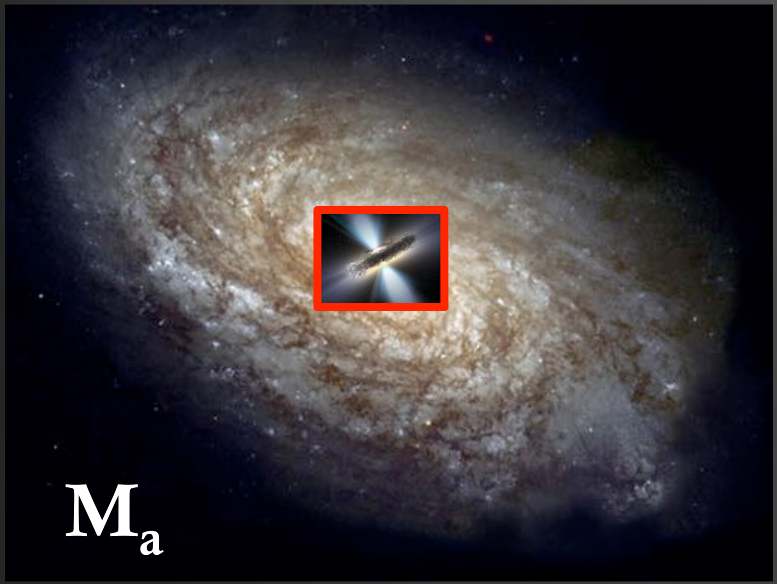


$$\dot{M}_{\rm a} = D(t) M_{\rm a}^{p}$$

Generic accretion model

Dependence on black hole mass…

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

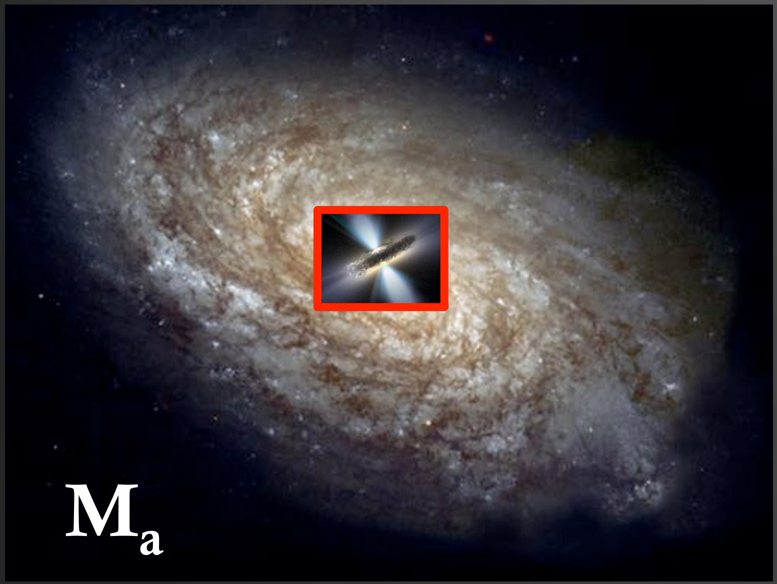


Assume same physical conditions D(t) – different initial black hole mass

Subsequent Evolution of M_a and M_b ?

Dependence on black hole mass…

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



Subsequent Evolution of M_a and M_b ?

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

Dependence on black hole mass…

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

Subsequent Evolution of M_a and M_b ?

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

Dependence on black hole mass…

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

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

Subsequent 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…

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

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

Subsequent Evolution depends on power index p

M_a and M_b diverge 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) !!

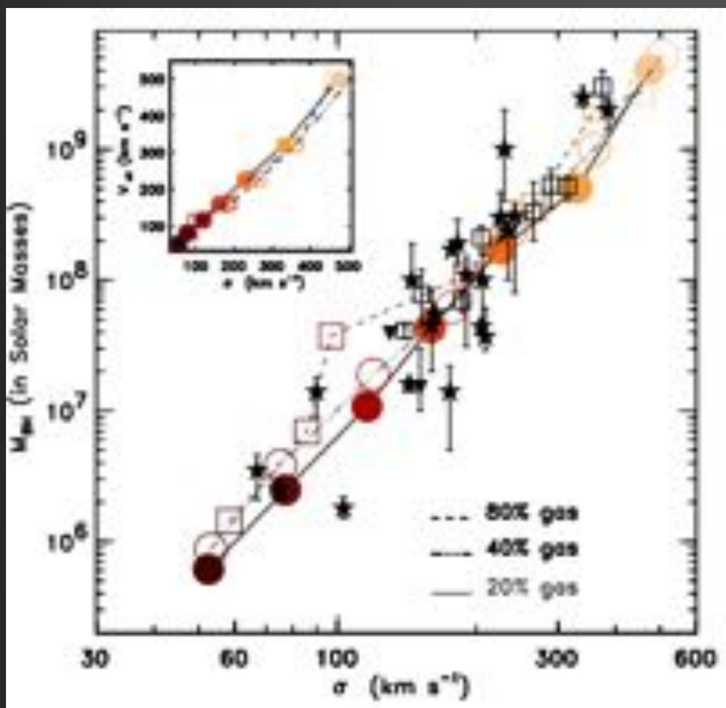
Massive black holes in simulations

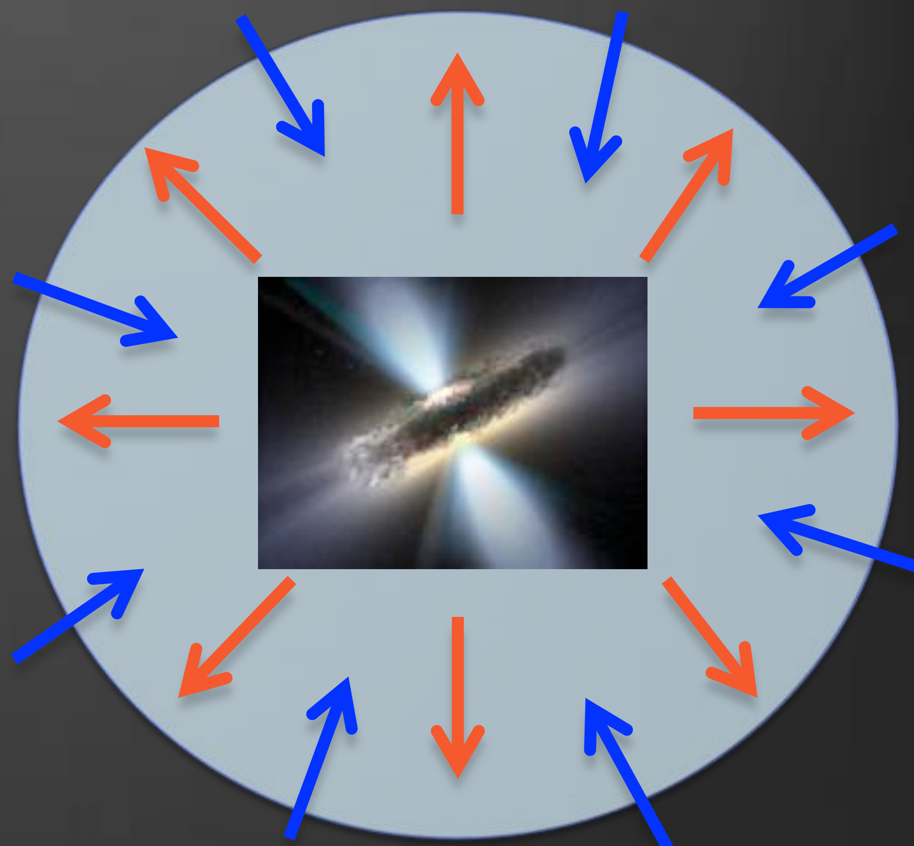
Bondi accretion + thermal feedback

Springel+05, Di Matteo+05,08, and many others

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

Black hole mass vs. velocity dispersion





→ **Feedback self-regulation drives the BH-galaxy connection**

Dependence on black hole mass…

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

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

Subsequent Evolution depends on power index p

M_a and M_b diverge if $p > 1$

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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

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

Springel+05
Di Matteo+05
and many others

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

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

Anglés-Alcázar et al. (2015)

Dependence on black hole mass…

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

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

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

Anglés-Alcázar et al. (2015)

Feedback loop required !!

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

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

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

→If so, can we break the degeneracy between black hole accretion and feedback?

→ Need to improve the accretion parameterization

Bondi neglects angular momentum!!

Physics of gas inflows

"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"

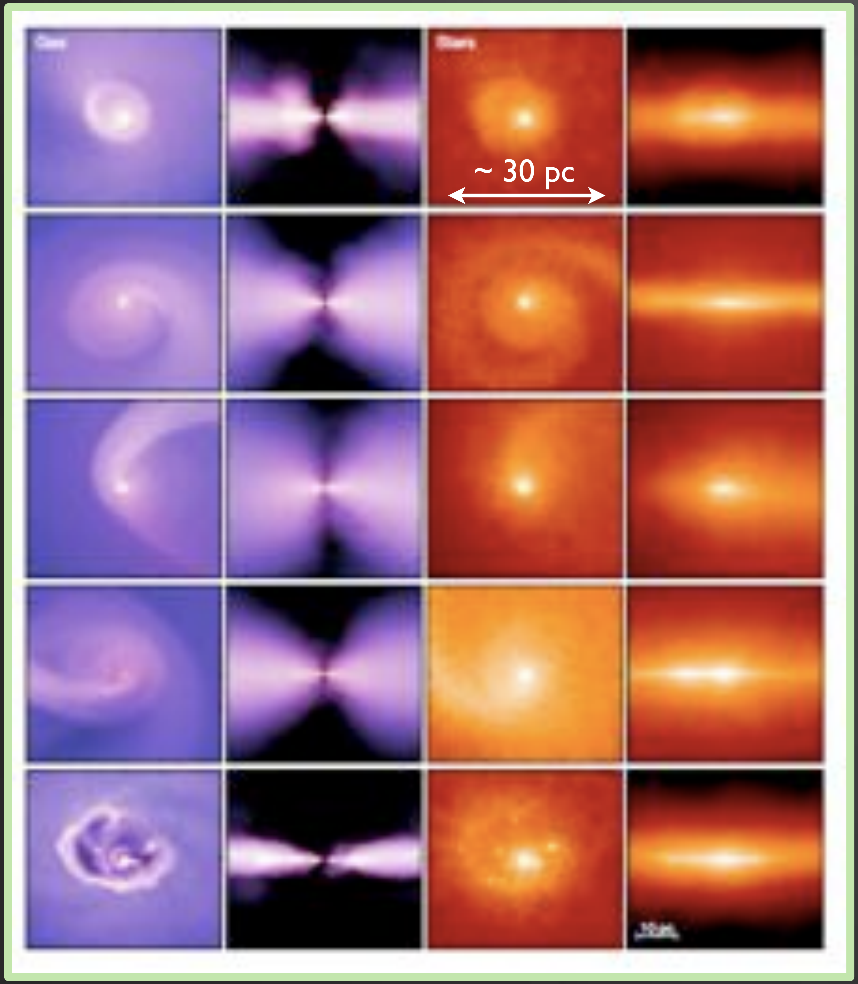
Shlosman et al. 1989, 1990

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

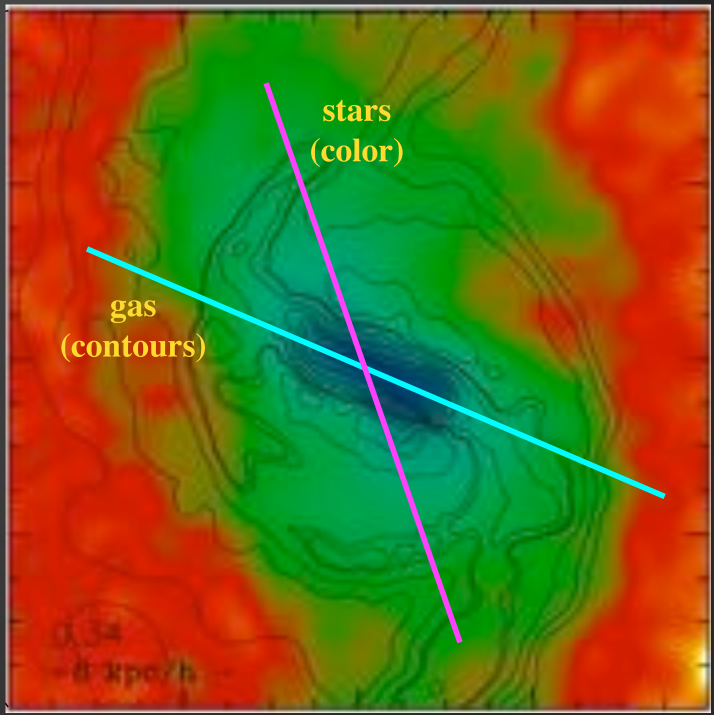
Analytic gravitational torque model

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



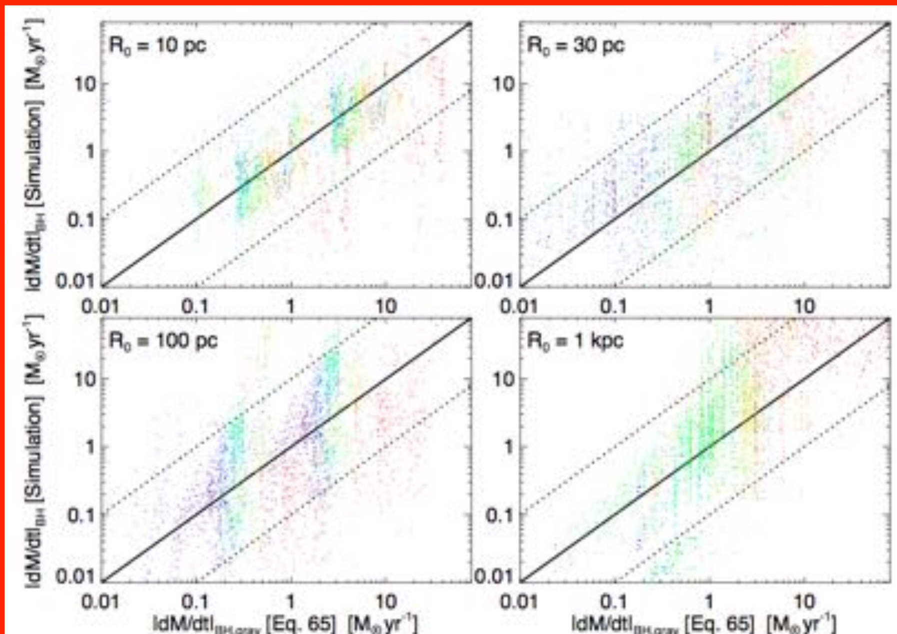
Perturbations to the stellar component drive the gas into shocks that dissipate energy and angular momentum



Simulations vs. analytic models

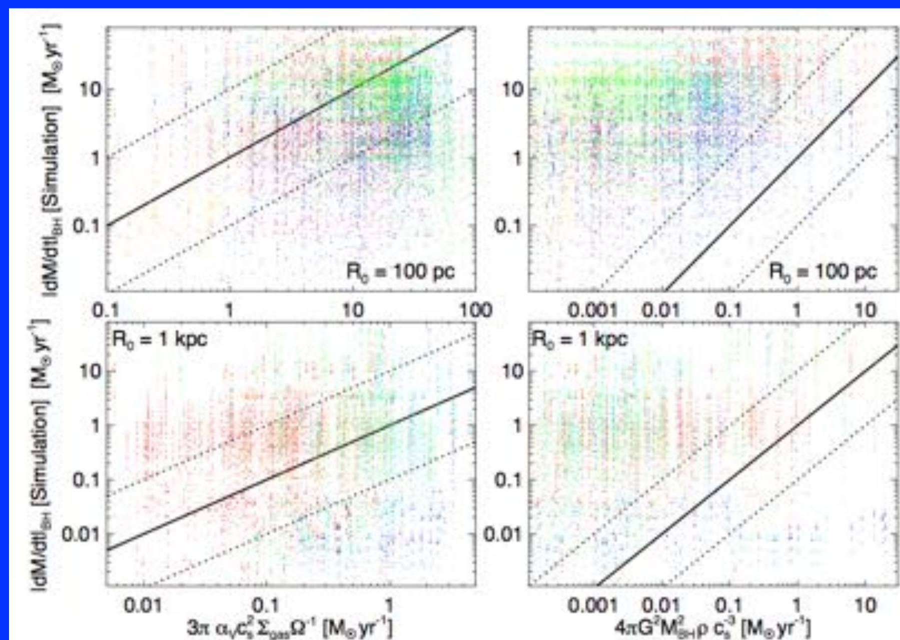
Multi-scale simulations of gas rich disks

Hopkins & Quataert 2010,2011



Bondi

Neglects angular momentum!

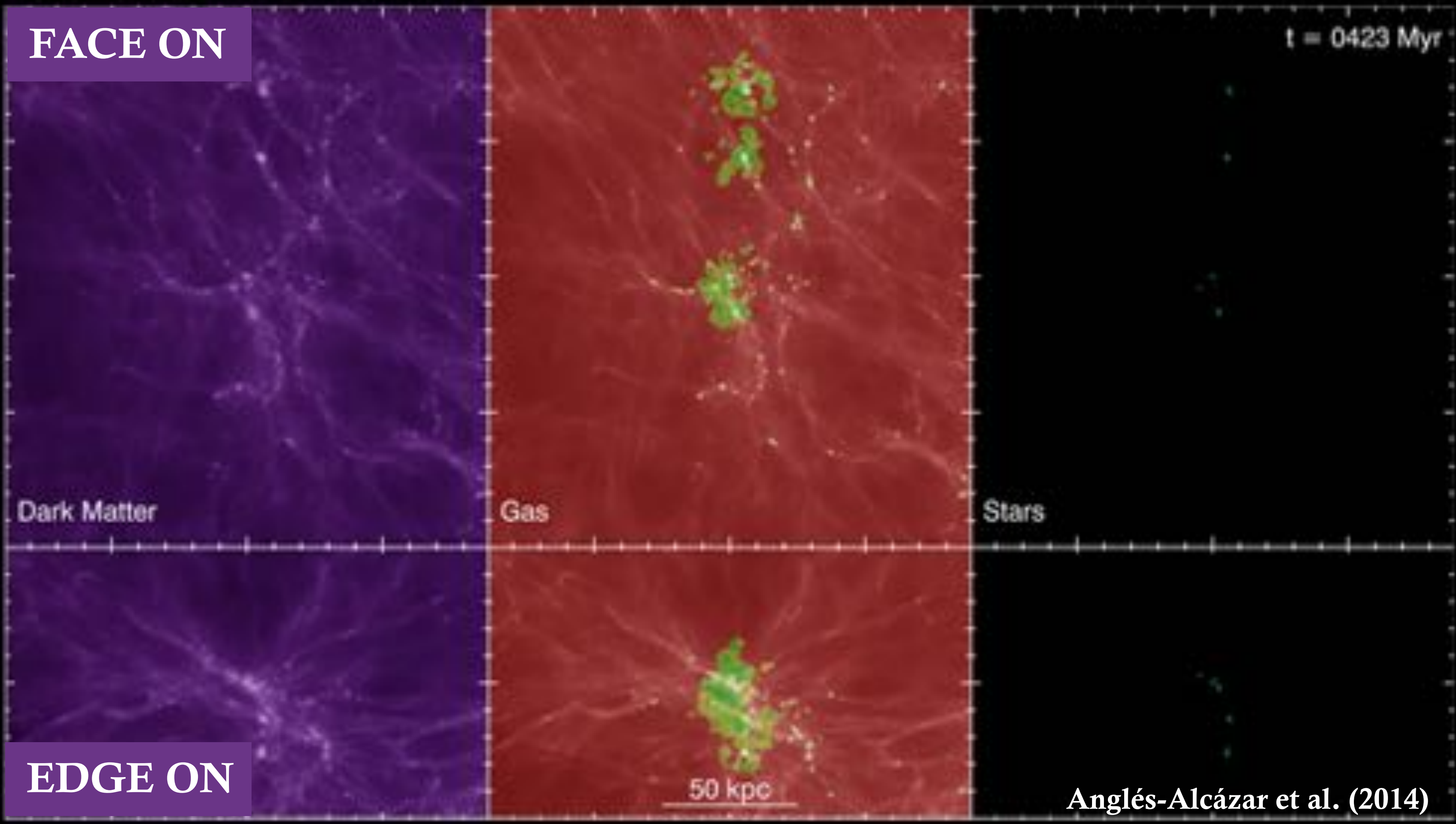


Gravitational torques provide angular momentum transport

Cosmological hydrodynamic simulations

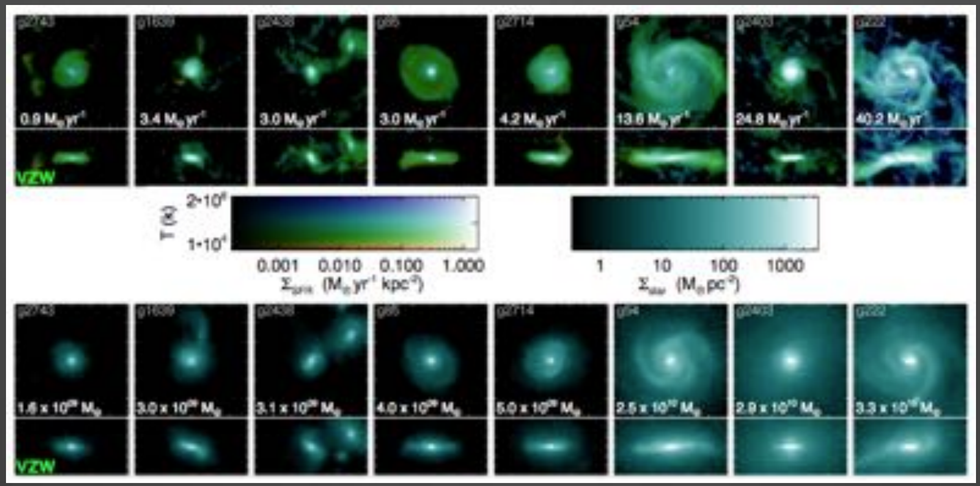
→Gadget2 code (Springel05) extended (Oppenheimer & Davé)

Multi-phase ISM, metal cooling, UV background, feedback (energy, mass, metals) from type Ia-II SNe, AGB stars, momentum-driven winds,…



Anglés-Alcázar et al. (2014)

Cosmological zoom simulations



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Central black hole accretion rate in post-processing:

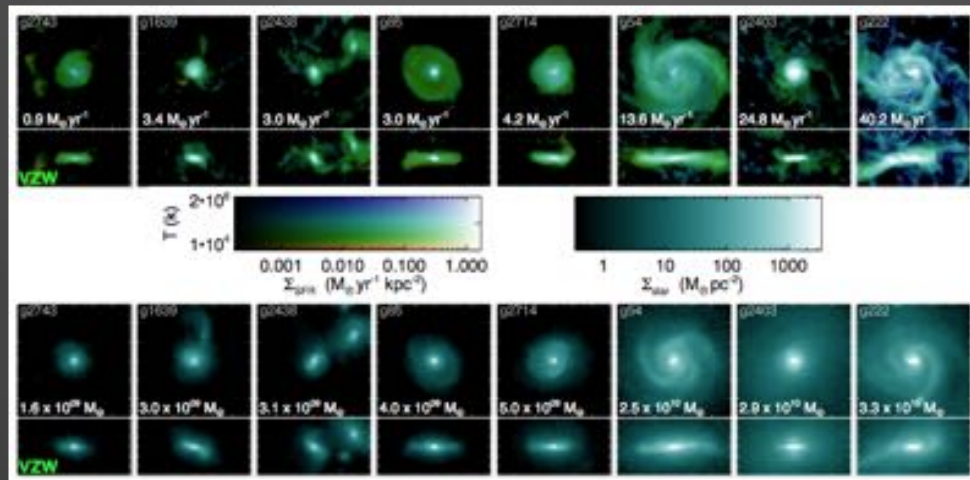
Gravitational torque model

Hopkins & Quataert 2010,2011

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

- Parameterize angular momentum transport below resolution
- Gas inflows down to 0.01 pc scales as a function of galaxy properties

Cosmological zoom simulations



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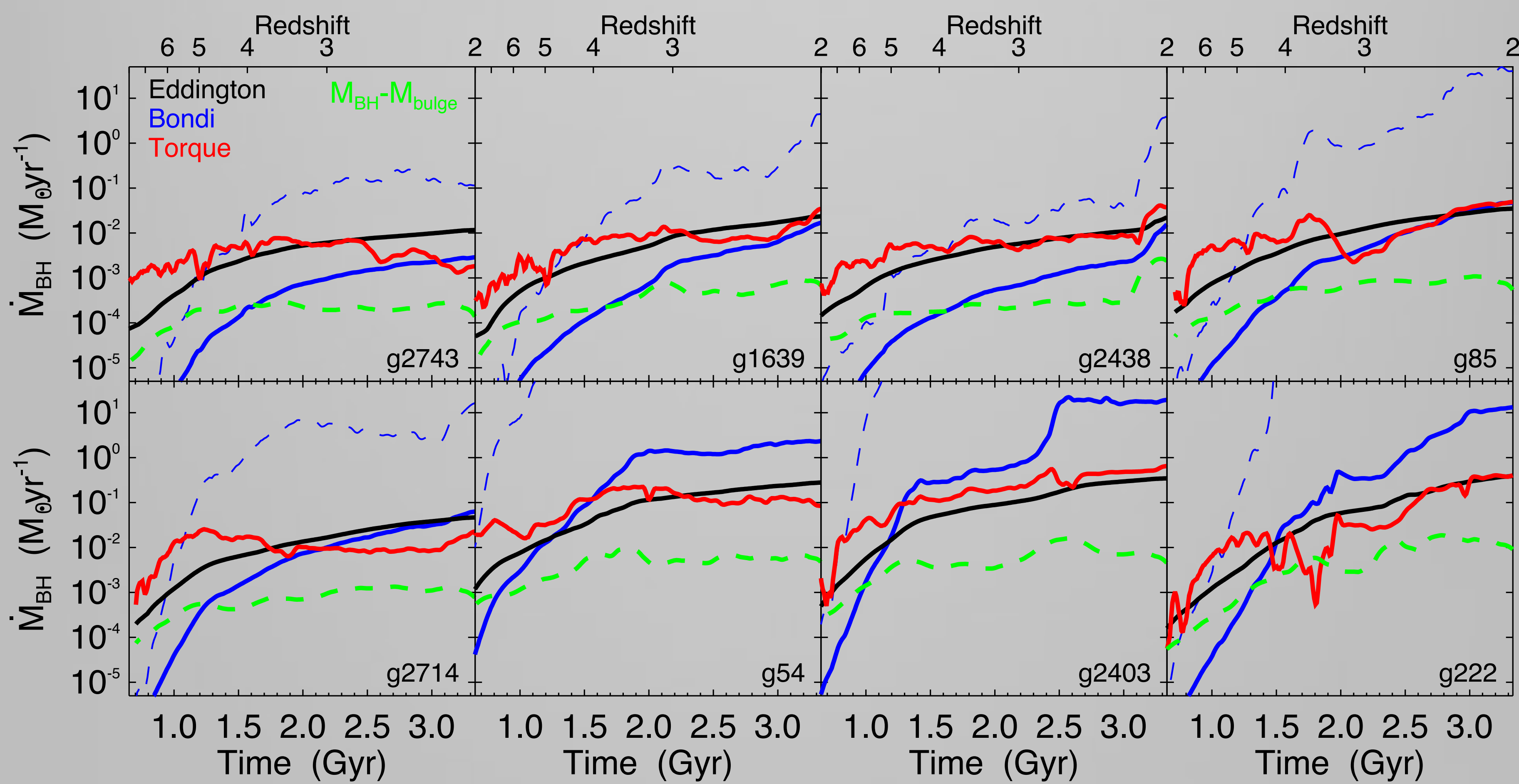
Bondi

Bondi 1952,...

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

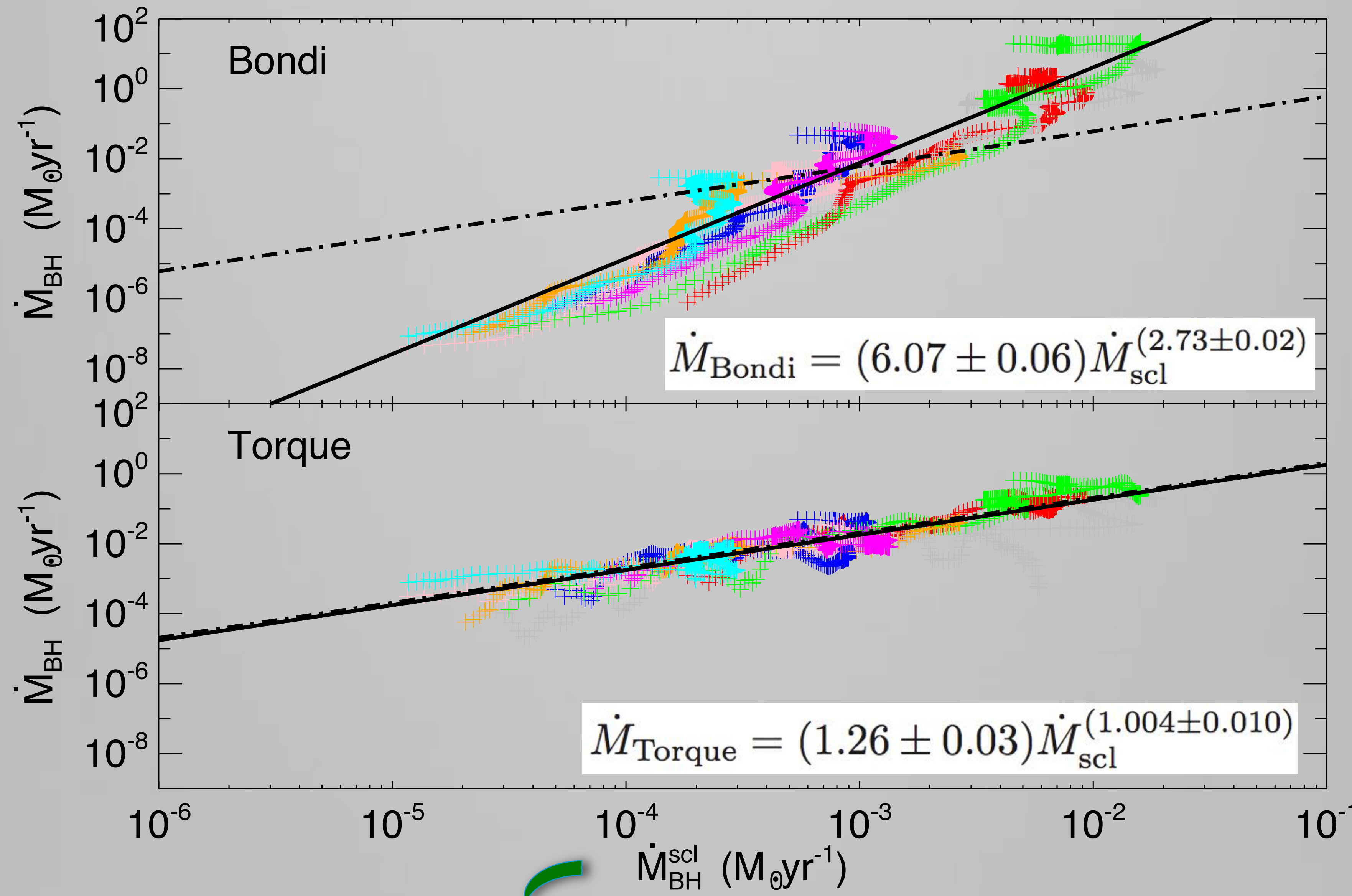
Black hole accretion rates

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



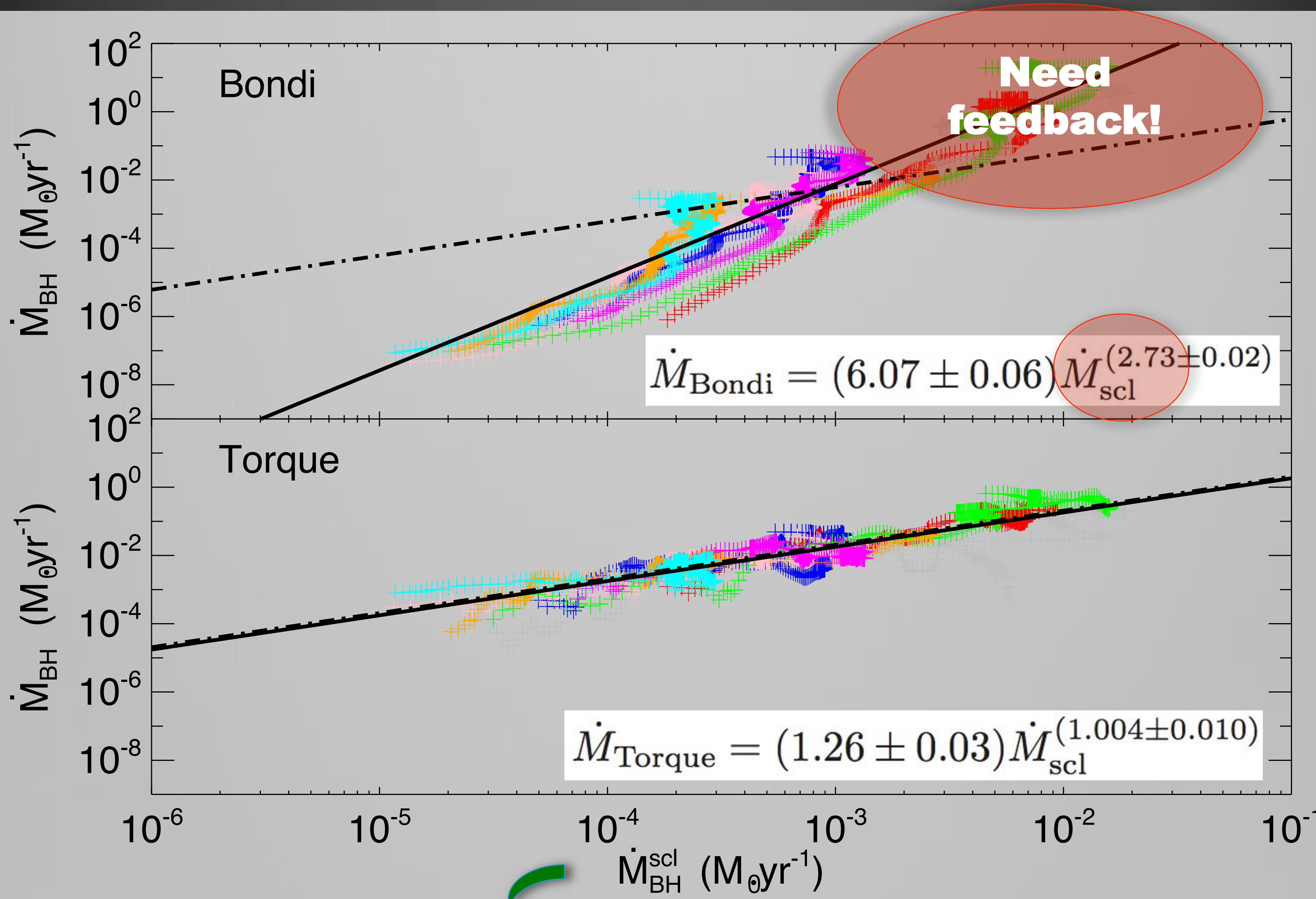
→ **Accretion rate if growing along M_{BH}–M_{bulge} relation**

Anglés-Alcázar et al. (2013)



Anglés-Alcázar et al. (2013)

BH growth according to scaling relation



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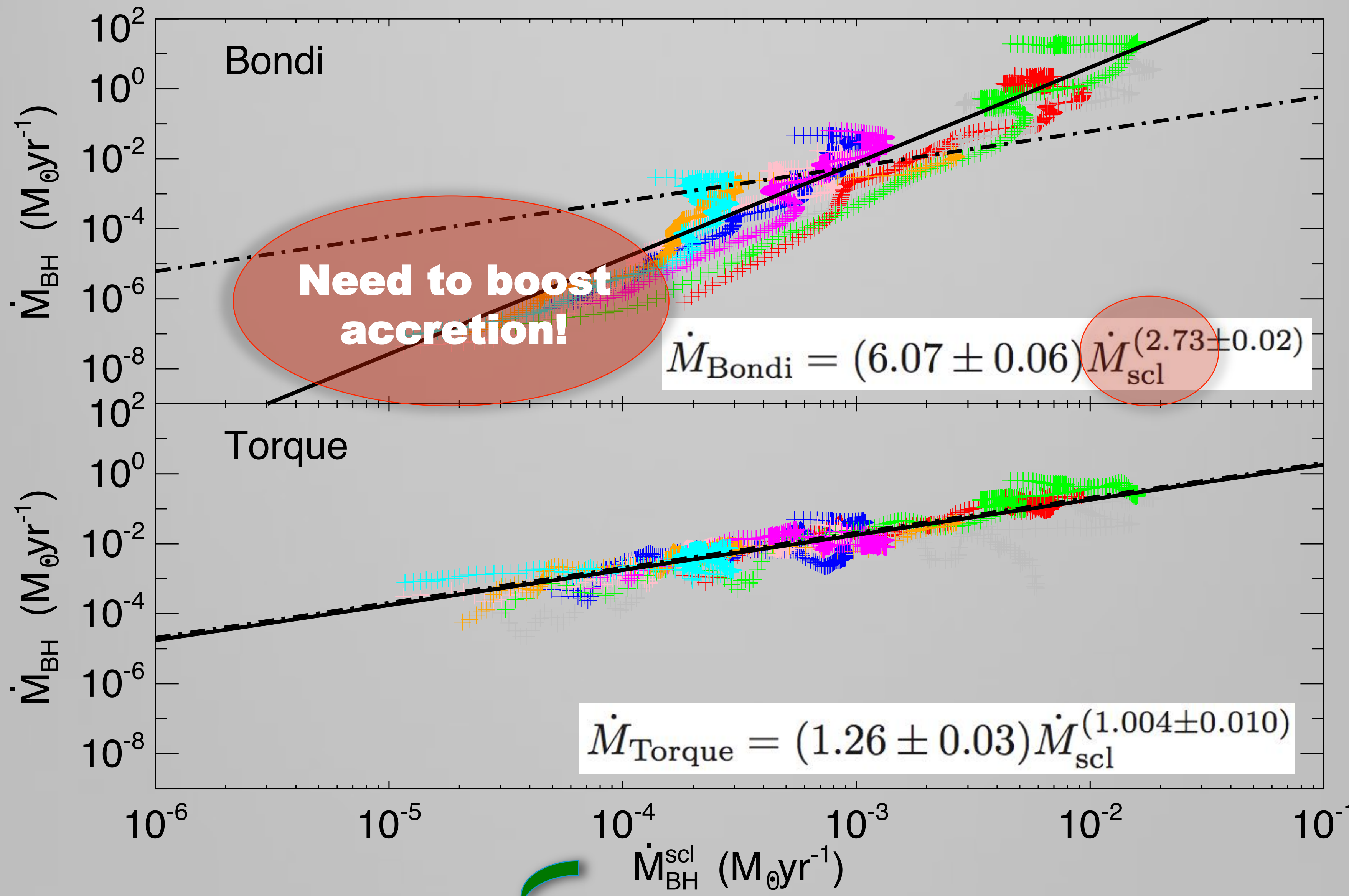
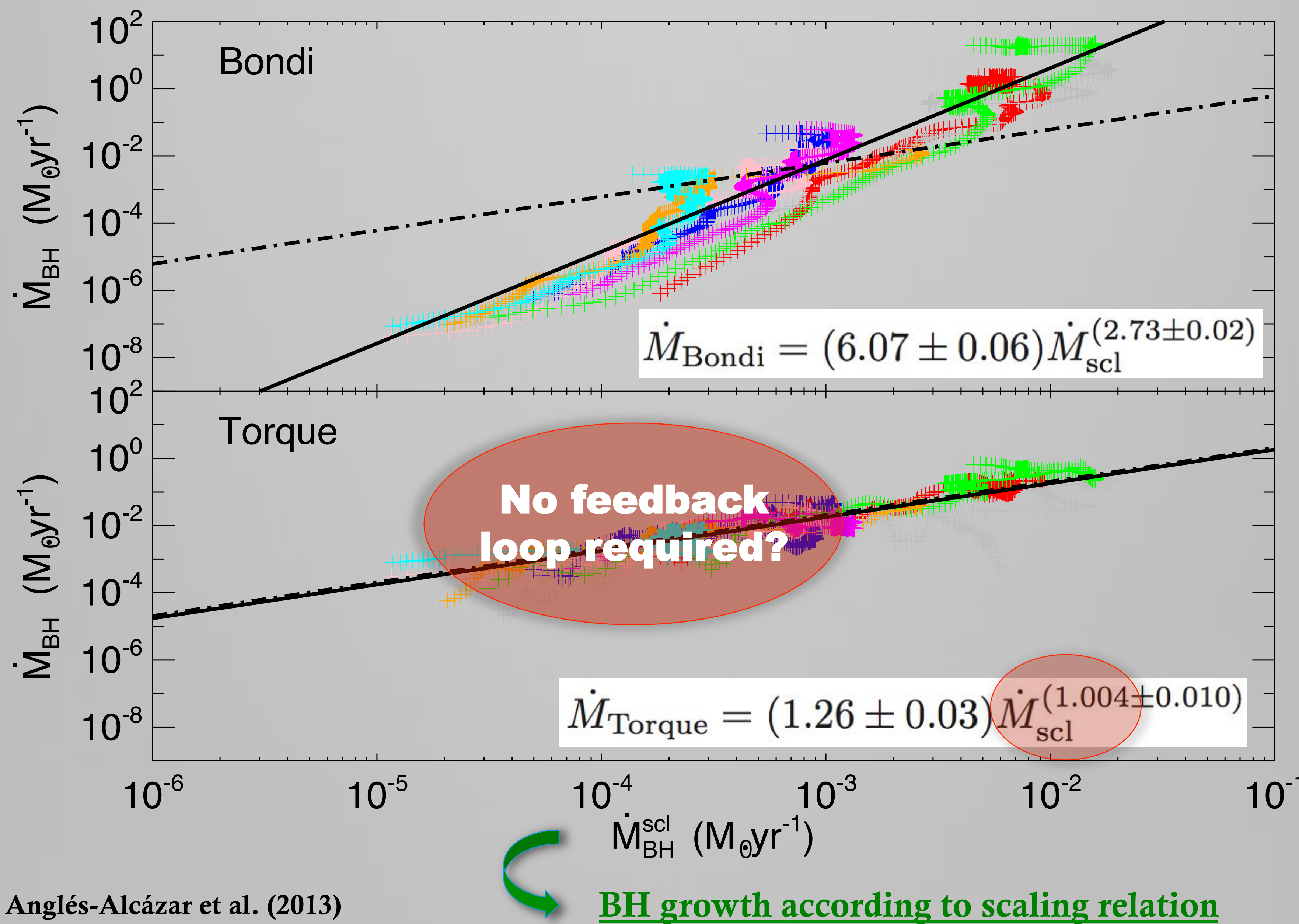


Anglés-Alcázar et al. (2013)

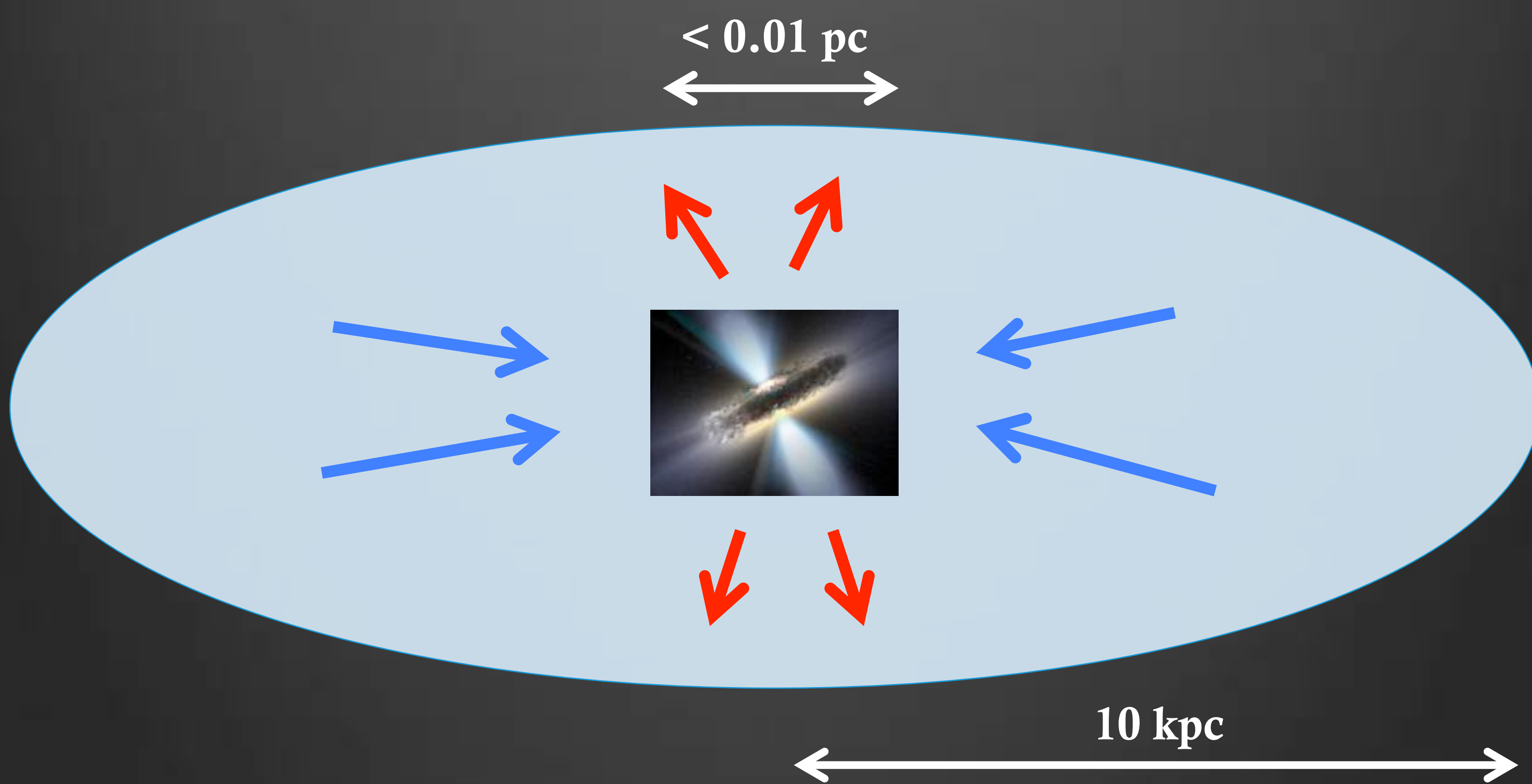
<u>BH growth according to scaling relation</u>



Anglés-Alcázar et al. (2013)

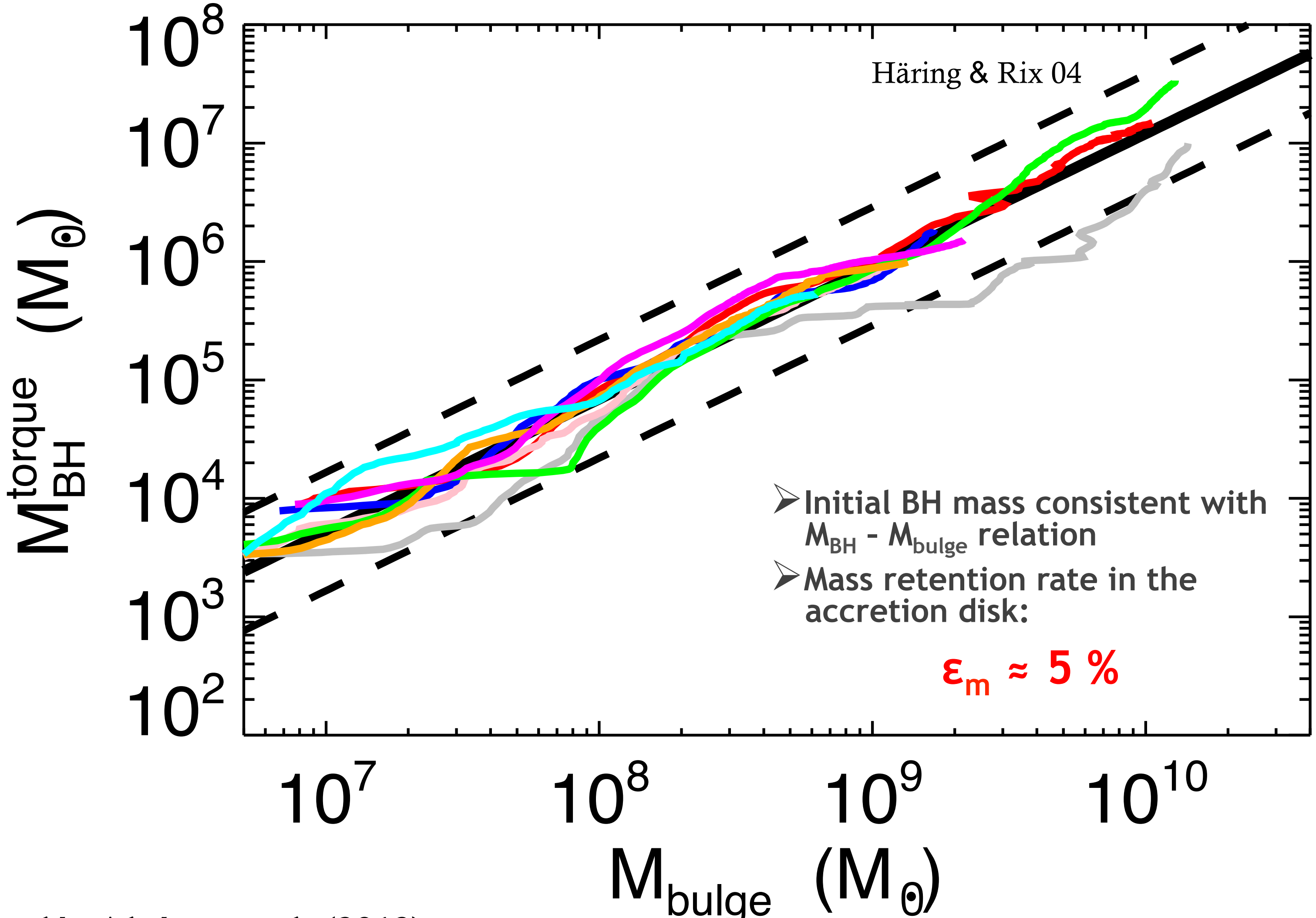
Torque-limited growth

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



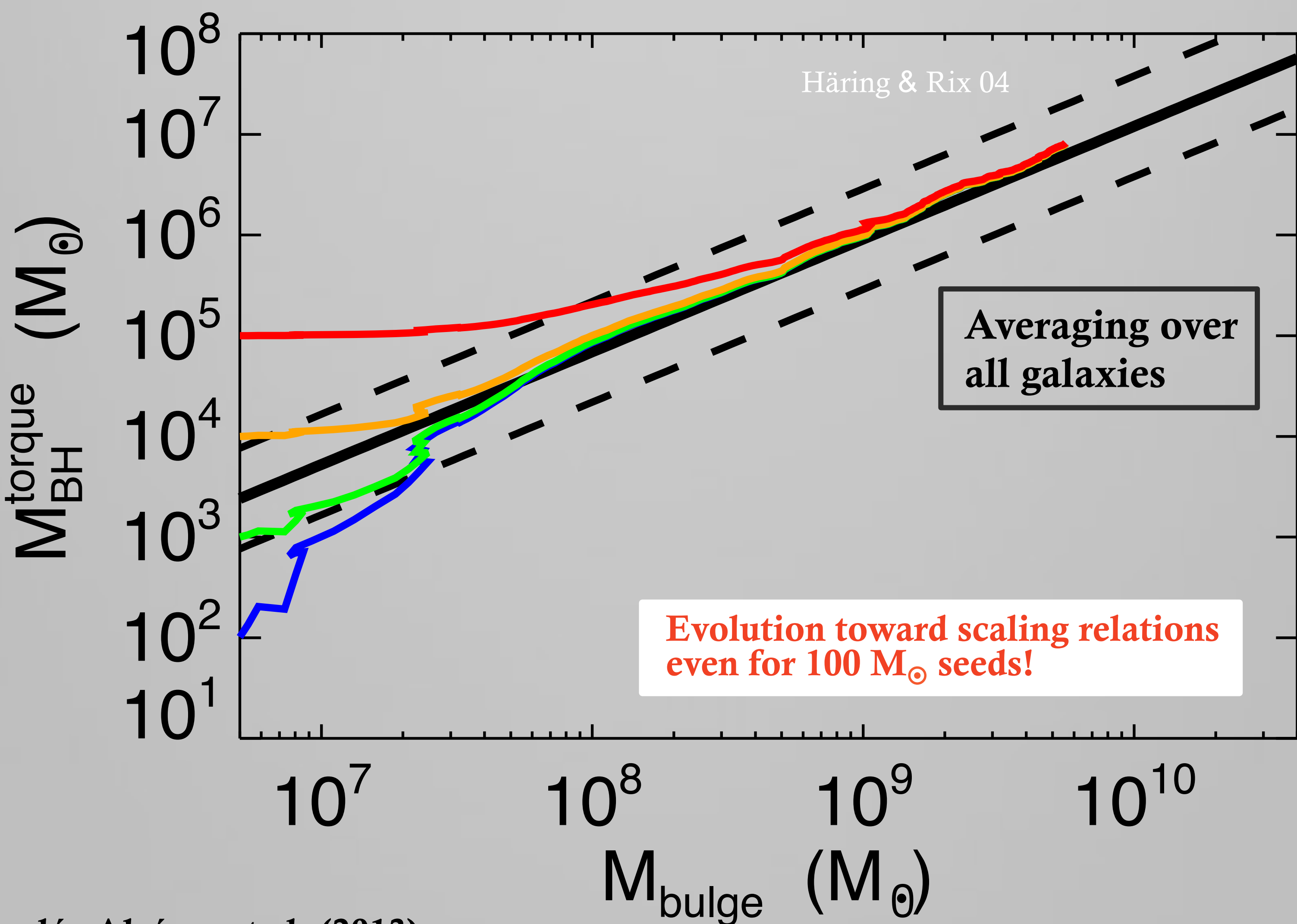
OUTFLOWS = (1 - ε) INFLOWS

Torque-limited growth



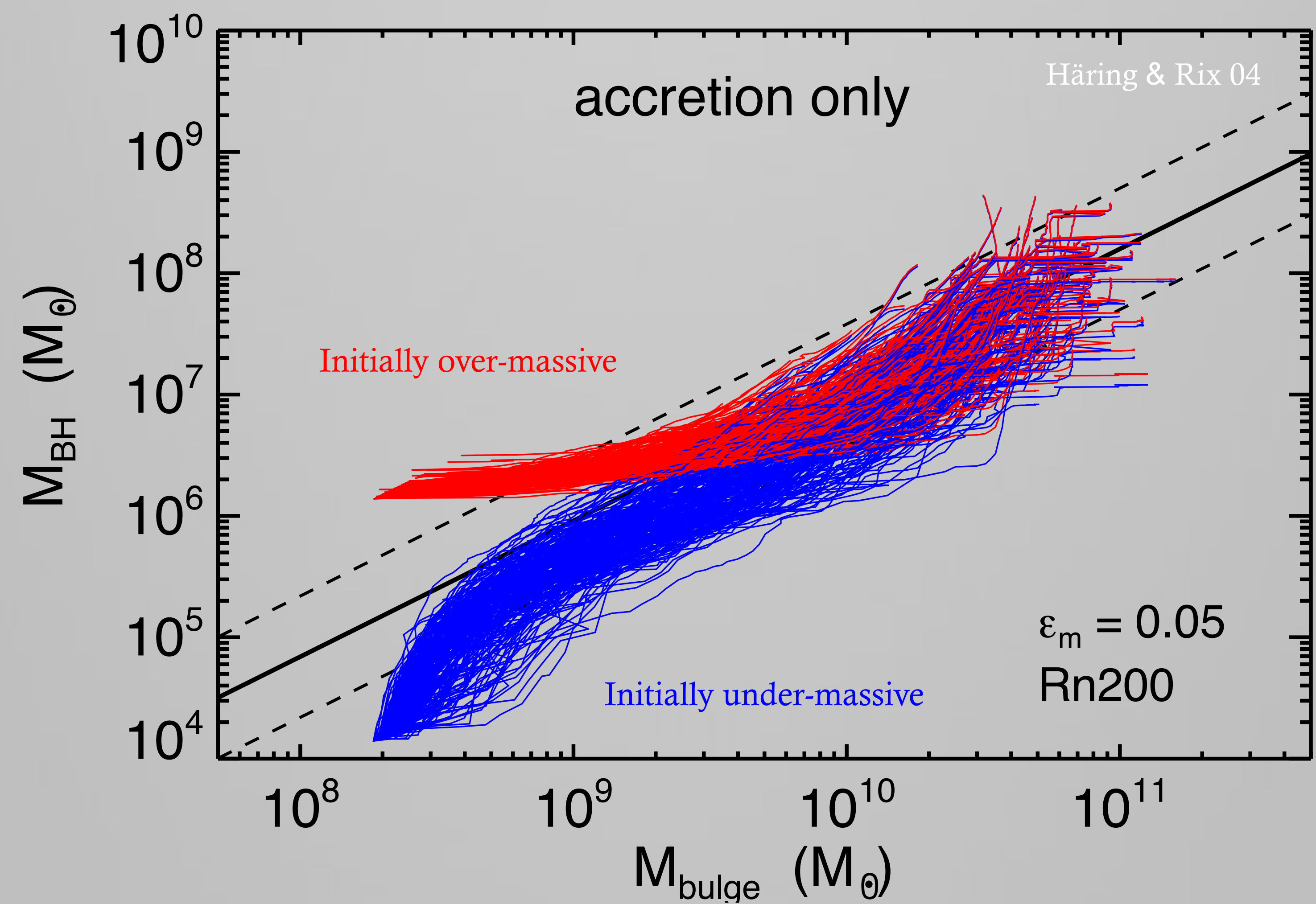
Anglés-Alcázar et al. (2013)

Torque-limited growth



Anglés-Alcázar et al. (2013)

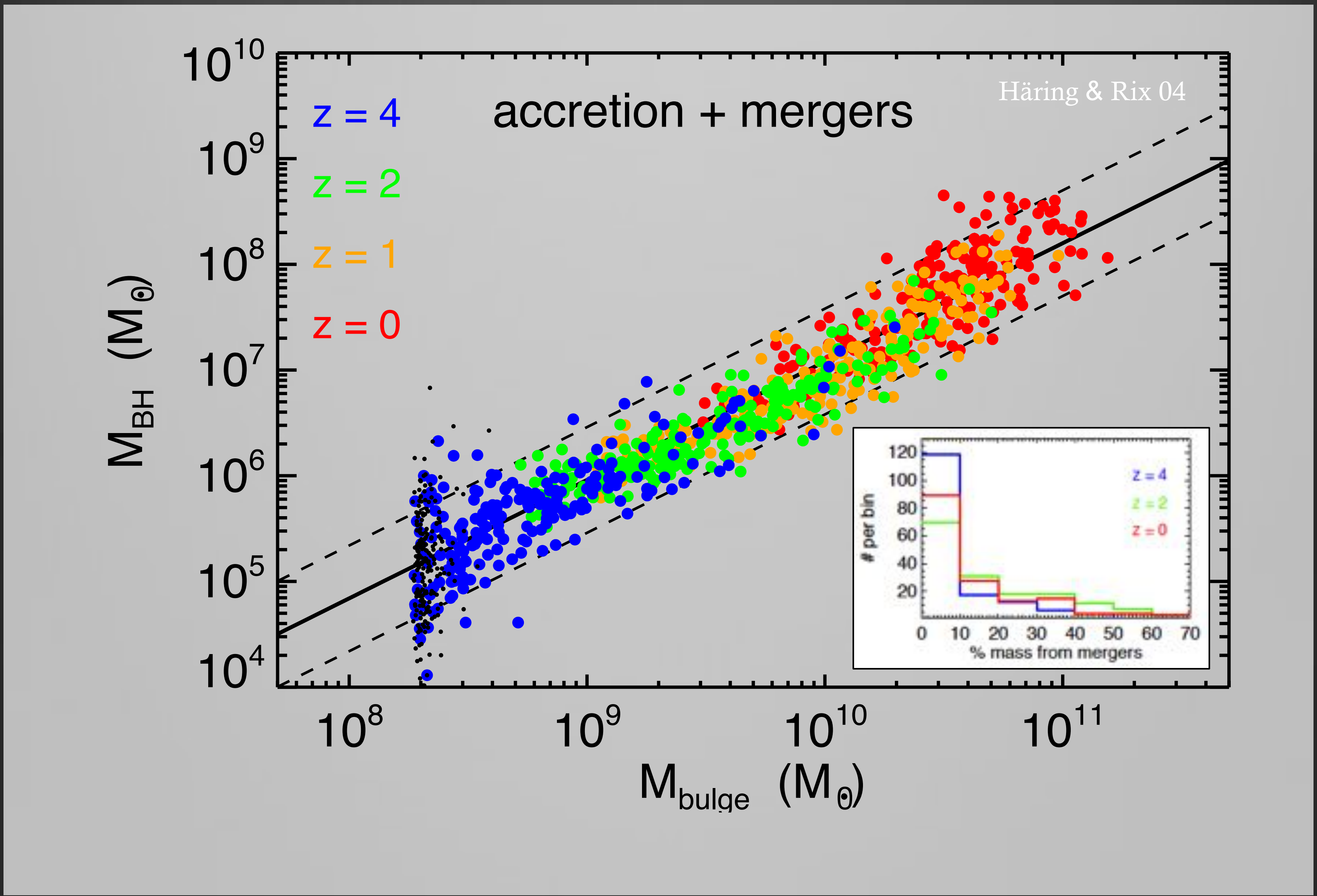
Torque-limited growth



Evolutionary tracks of >200 BHs/galaxies from early times down to z = 0

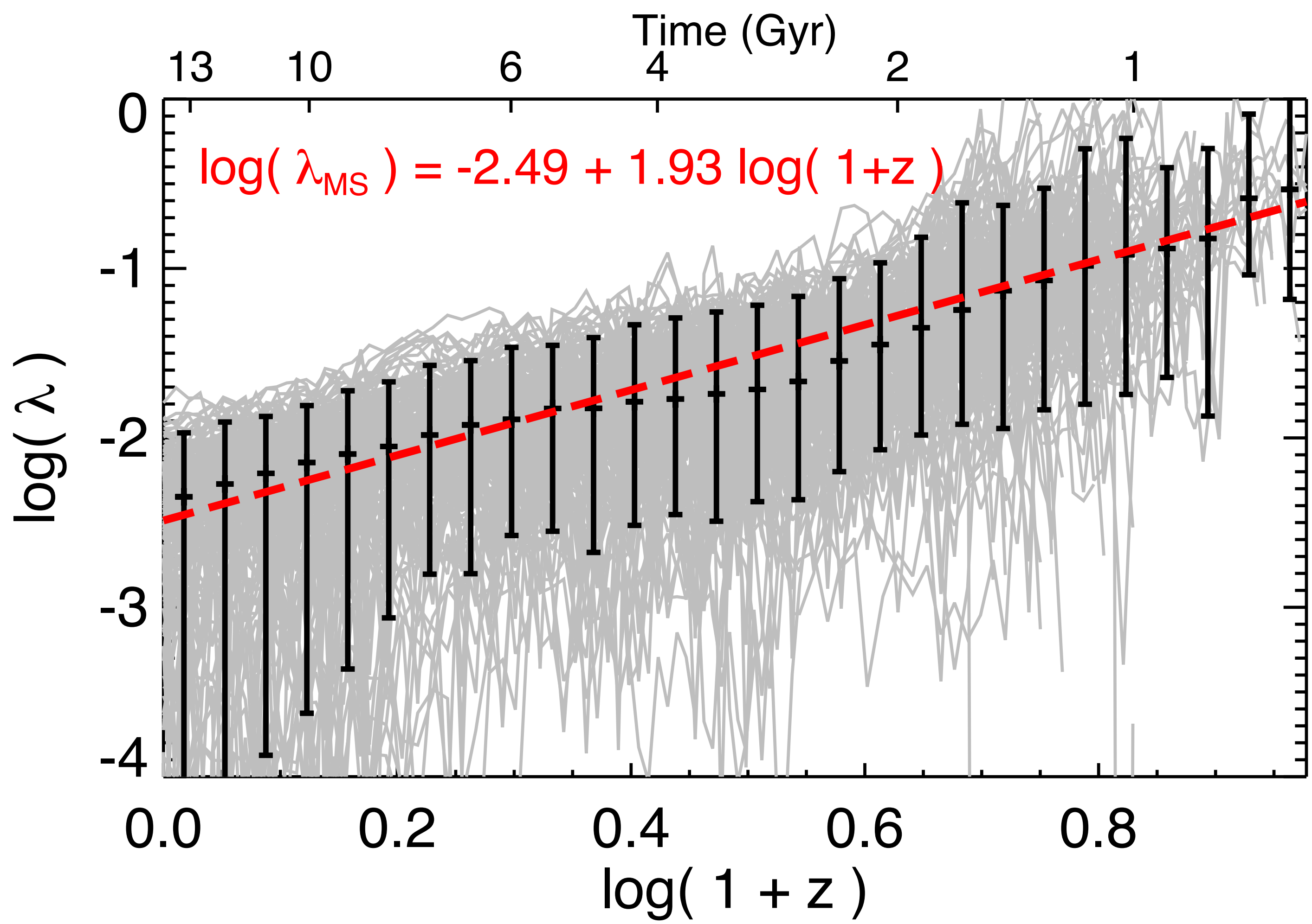
Anglés-Alcázar et al. (2015)

Torque-limited growth



Anglés-Alcázar et al. (2015)

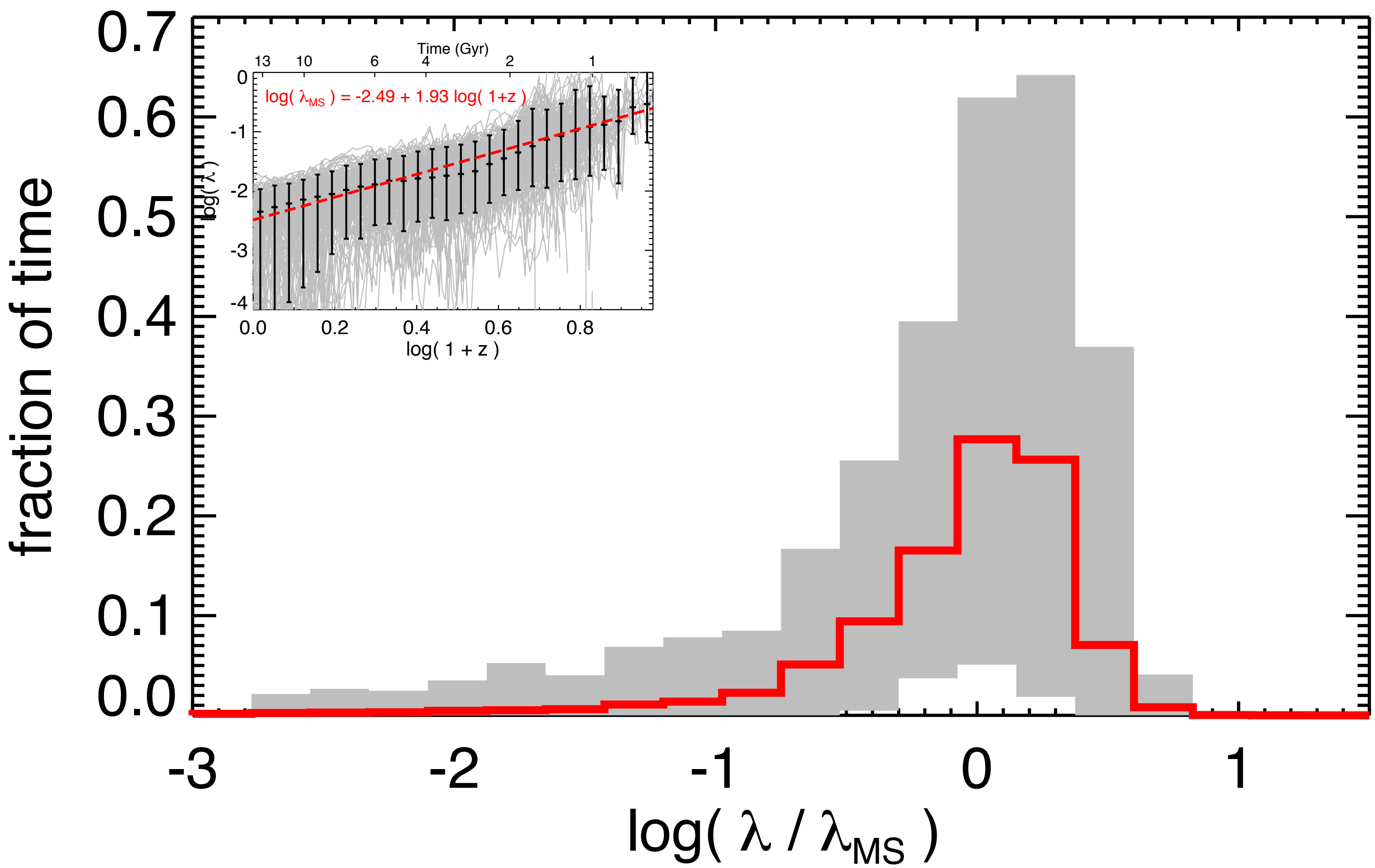
Evolution of Eddington ratios



Anglés-Alcázar et al. (2015)

Evolution of Eddington ratios

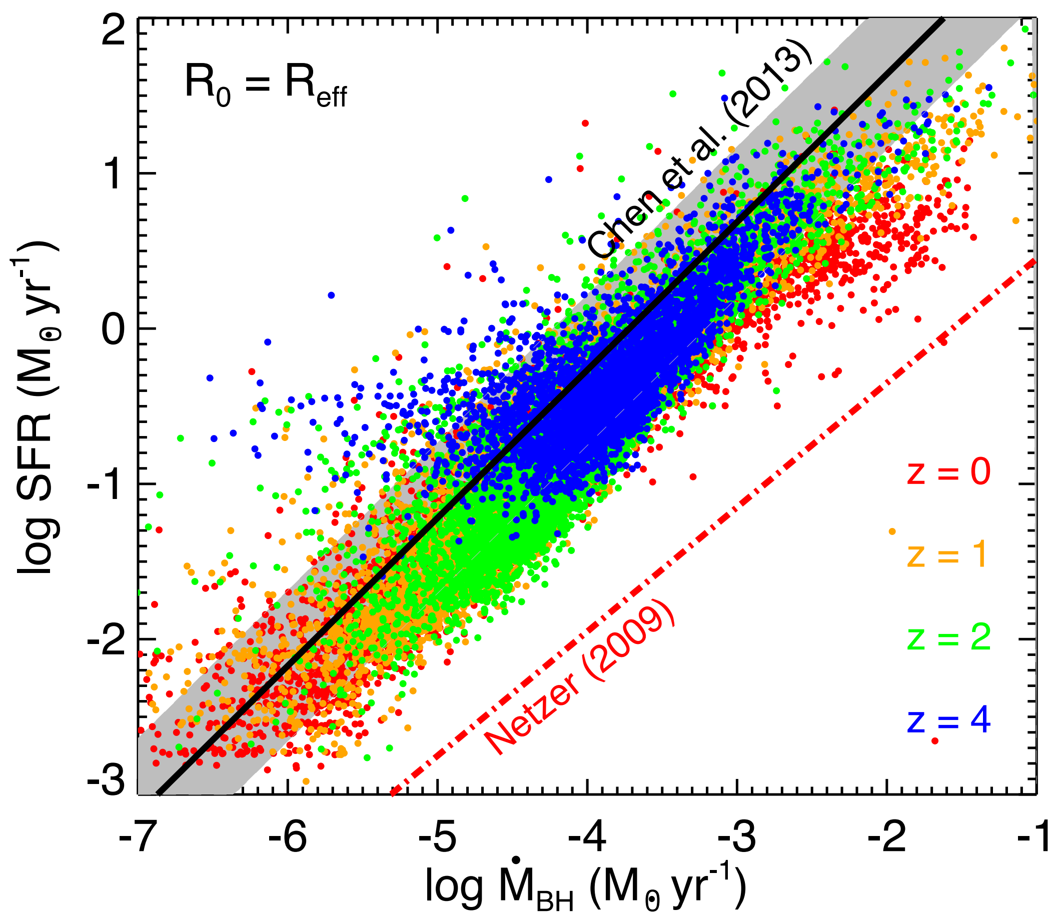
Main sequence for black hole growth?



Anglés-Alcázar et al. (2015)

SFR – AGN connection

Average black hole growth proportional to star formation



Anglés-Alcázar et al. (2015)

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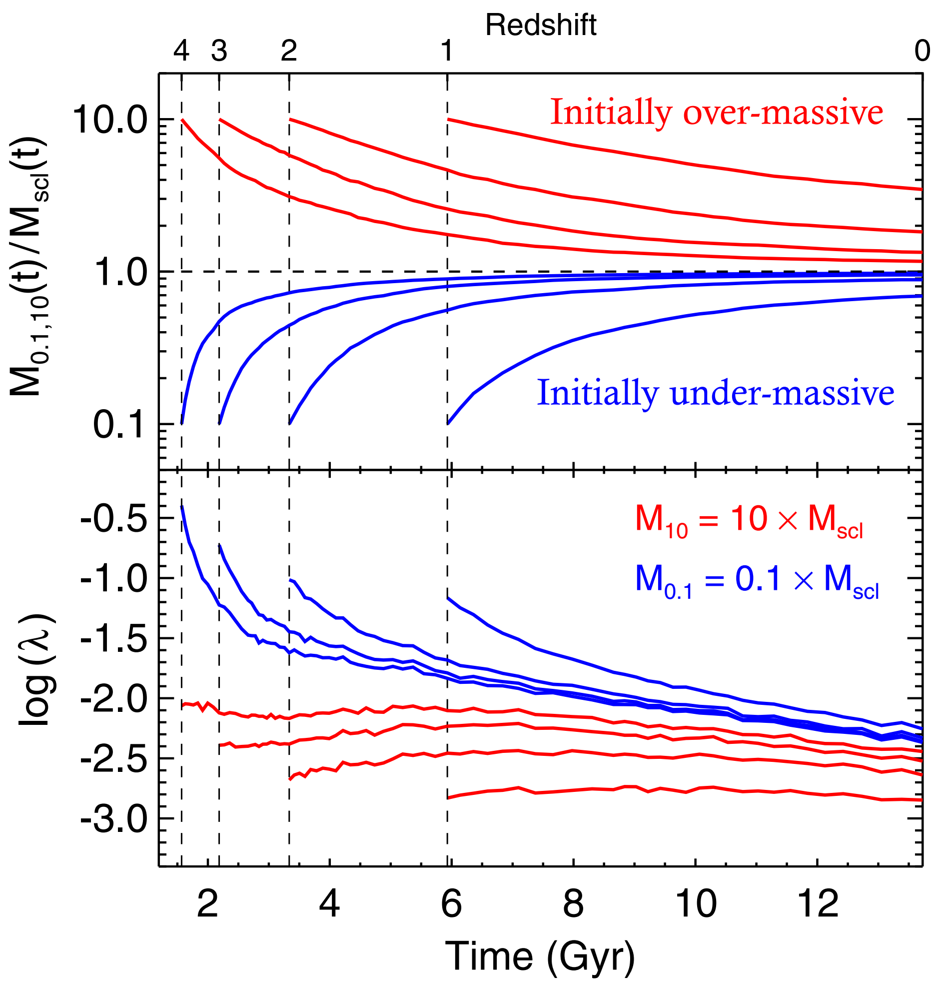
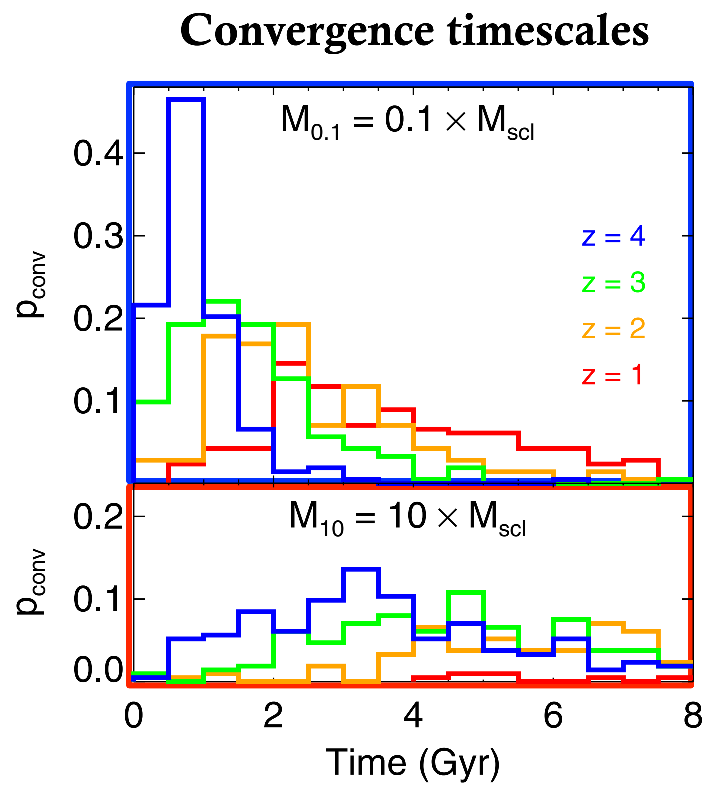




Significant offset in M_{bh}/M_{gal} ratios at high-z may have implications for the evolution of Eddington ratios

Anglés-Alcázar et al. (2015)

Torque-limited growth of BHs in Galaxies

1. Black holes and galaxies evolve on average toward the observed scaling relations, regardless of the initial conditions, and with no need for mass averaging through mergers or additional self-regulation processes.

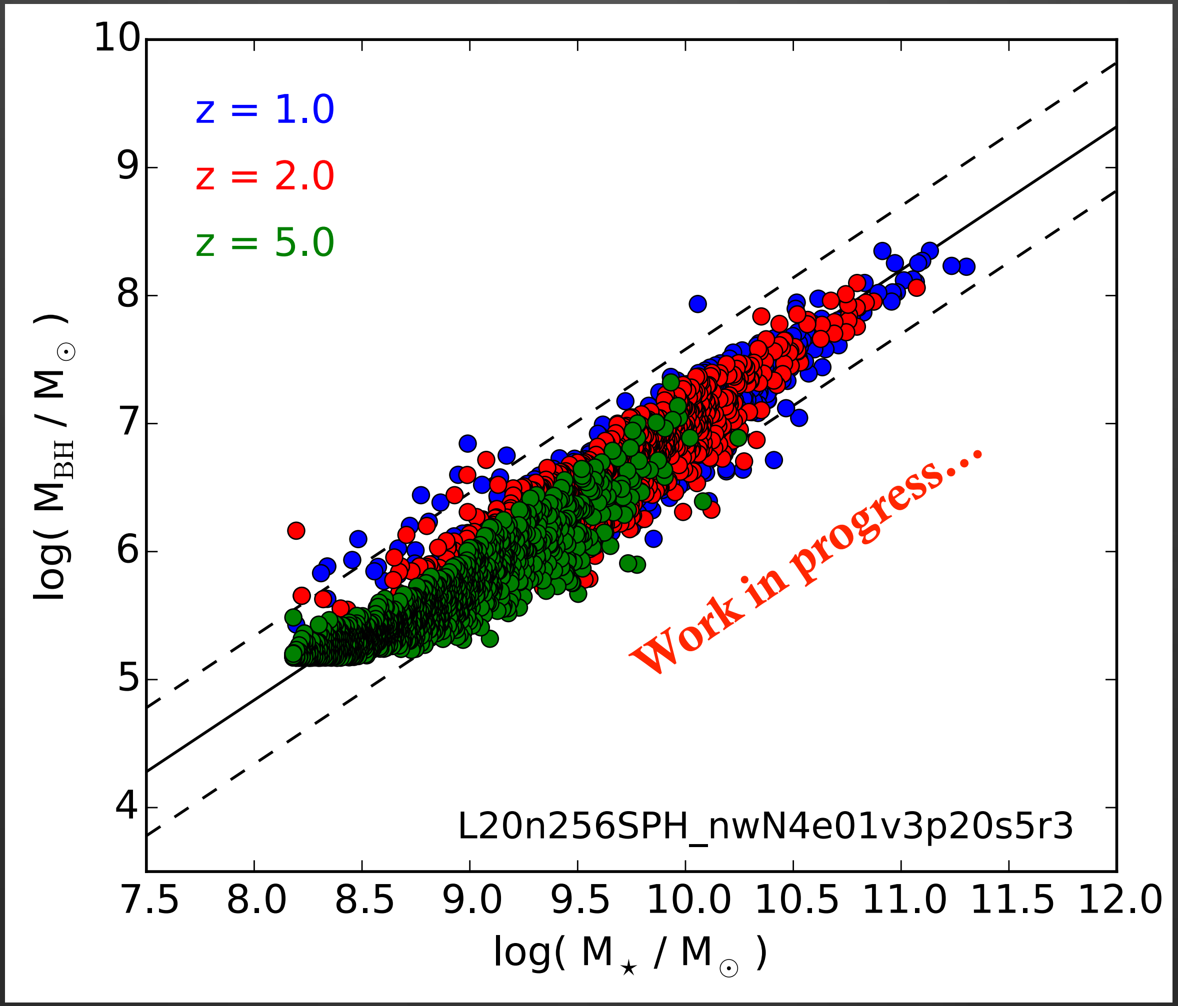
2. Cosmological gas infall and transport of angular momentum in the galaxy by gravitational instabilities drive the observed connection between black holes and galaxies. Common gas supply modulated by gravitational torques! (Escala).

3. SFR~BHAR correlation when averaging over galaxy evolution time scales (Rosario, Mullaney, LaMassa, Diamond-Stanic, Juneau, Daddi, Delvecchio, Ruschel Dutra, …). AGN Main Sequence?

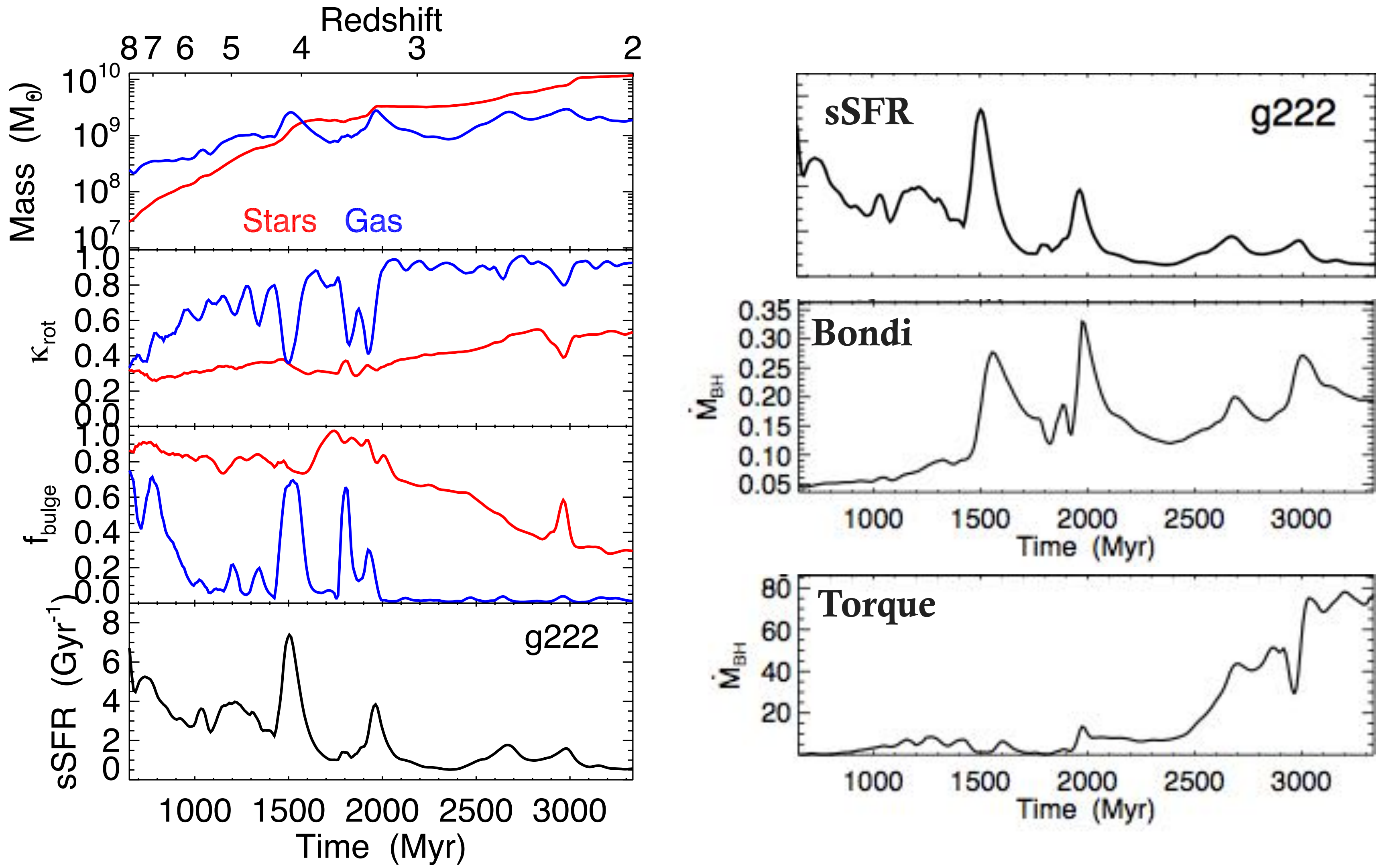
4. Outflows powered by the accretion disk may have a strong impact on the host galaxy (Harrison, Veilleux, Kewley, Rupke,…): key role in this model by providing significant mass loss but no need for strong interaction with the inflowing gas to regulate black holes in a non-linear feedback loop.

Torque-limited growth of BHs in Galaxies

Self-consistent simulations with GIZMO including black hole seed formation, black hole mergers, torque-limited growth and outflows…



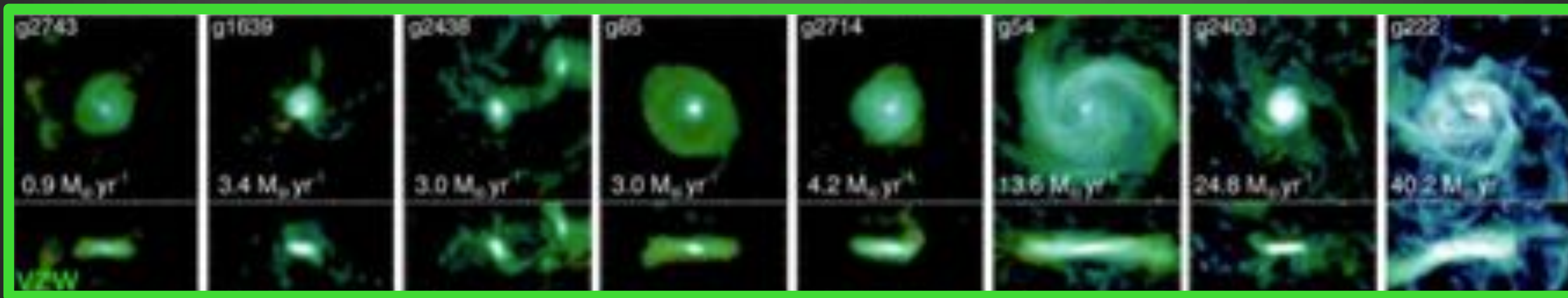
AGN-merger connection



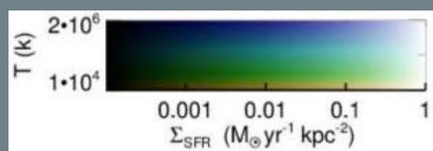
Anglés-Alcázar et al. (2013)

Effects of winds: gas

Anglés-Alcázar et al. (2014)

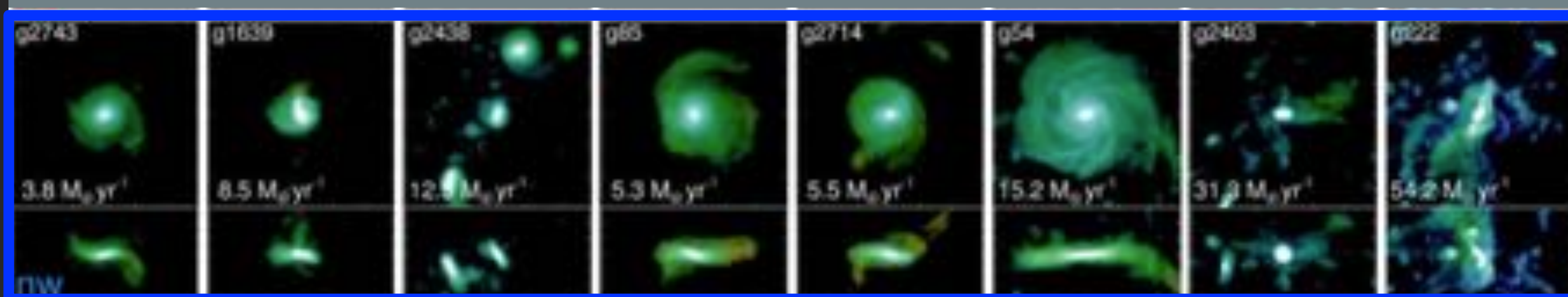


Simulations with galactic winds



SFR surface density

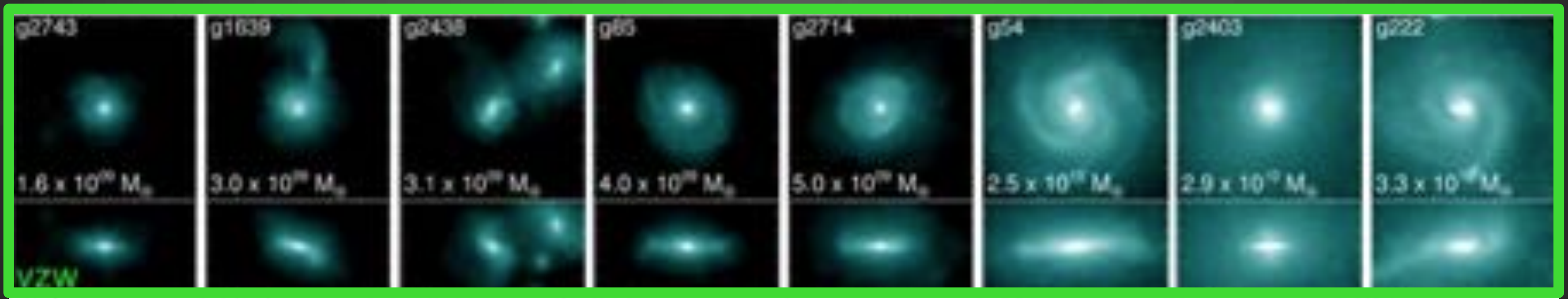
Simulations with no winds



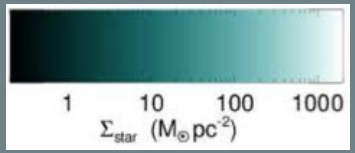
2D maps made with great help from Brant Robertson

Effects of winds: stars

Anglés-Alcázar et al. (2014)

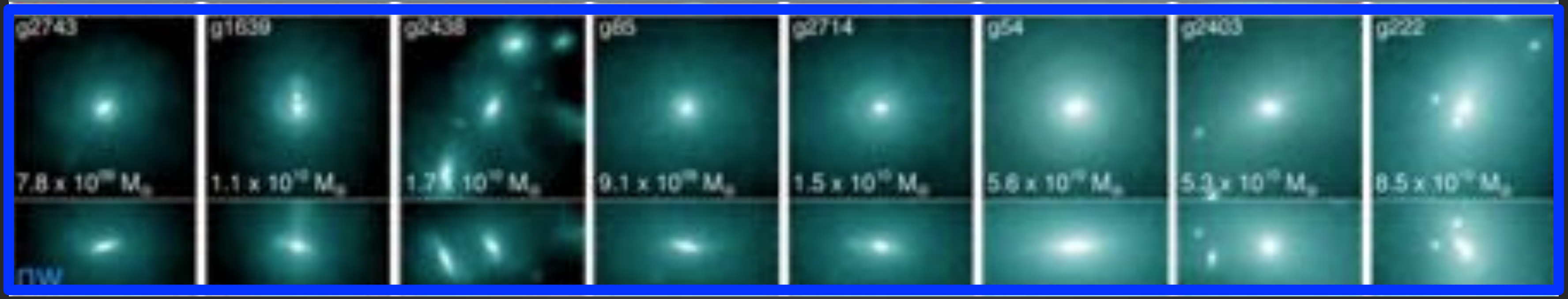


Simulations with galactic winds



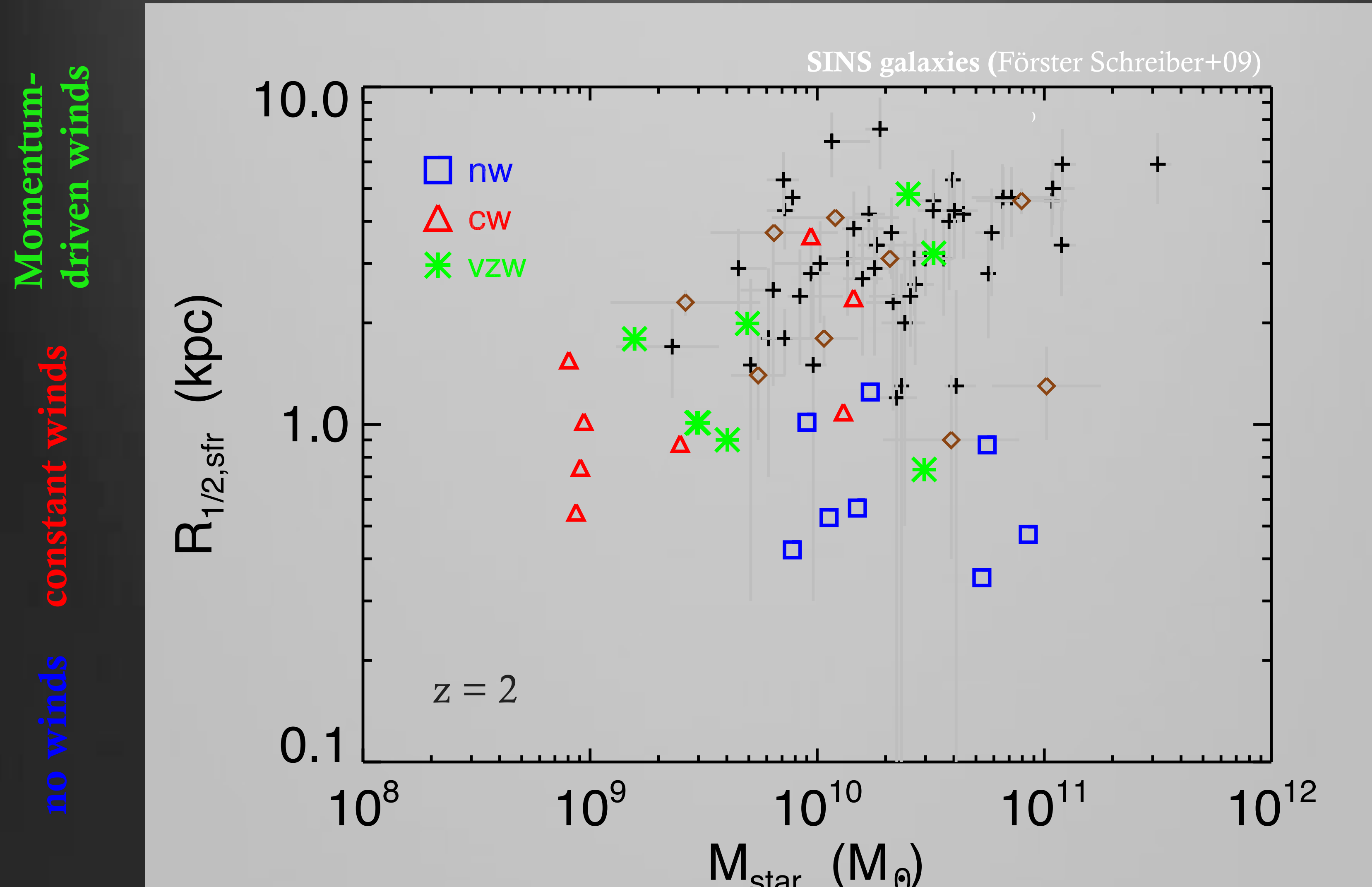
Stellar mass surface density

Simulations with no winds



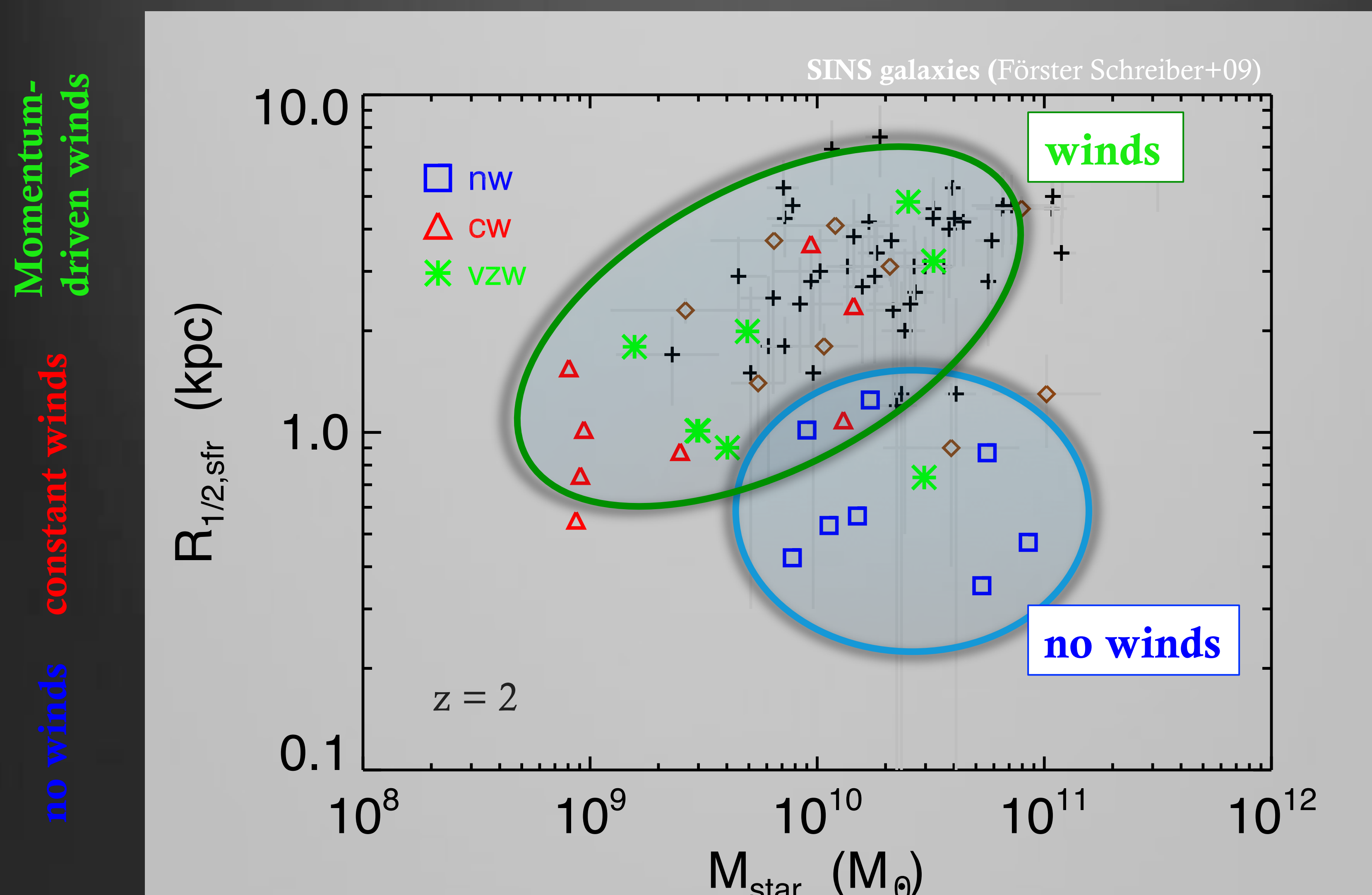
2D maps made with great help from Brant Robertson

Simulations vs. observations



Anglés-Alcázar et al. (2014)

Simulations vs. observations



Anglés-Alcázar et al. (2014)