AGN feedback

Carlos S. Frenk
Institute for Computational Cosmology, Durham

University of Durham

... and the curious case of the Milky Way

The new Ogden Centre at Durham

AGN Feedback & gal formation

AGN feedback solves three major problems:

Why is there a bright cutoff in the galaxy luminosity function?

Why are there no cooling flows in clusters ?

Why are the brightest galaxies old, red and elliptical ?
(The "hierarchy" problem)

An answer to these questions was proposed 15 years ago

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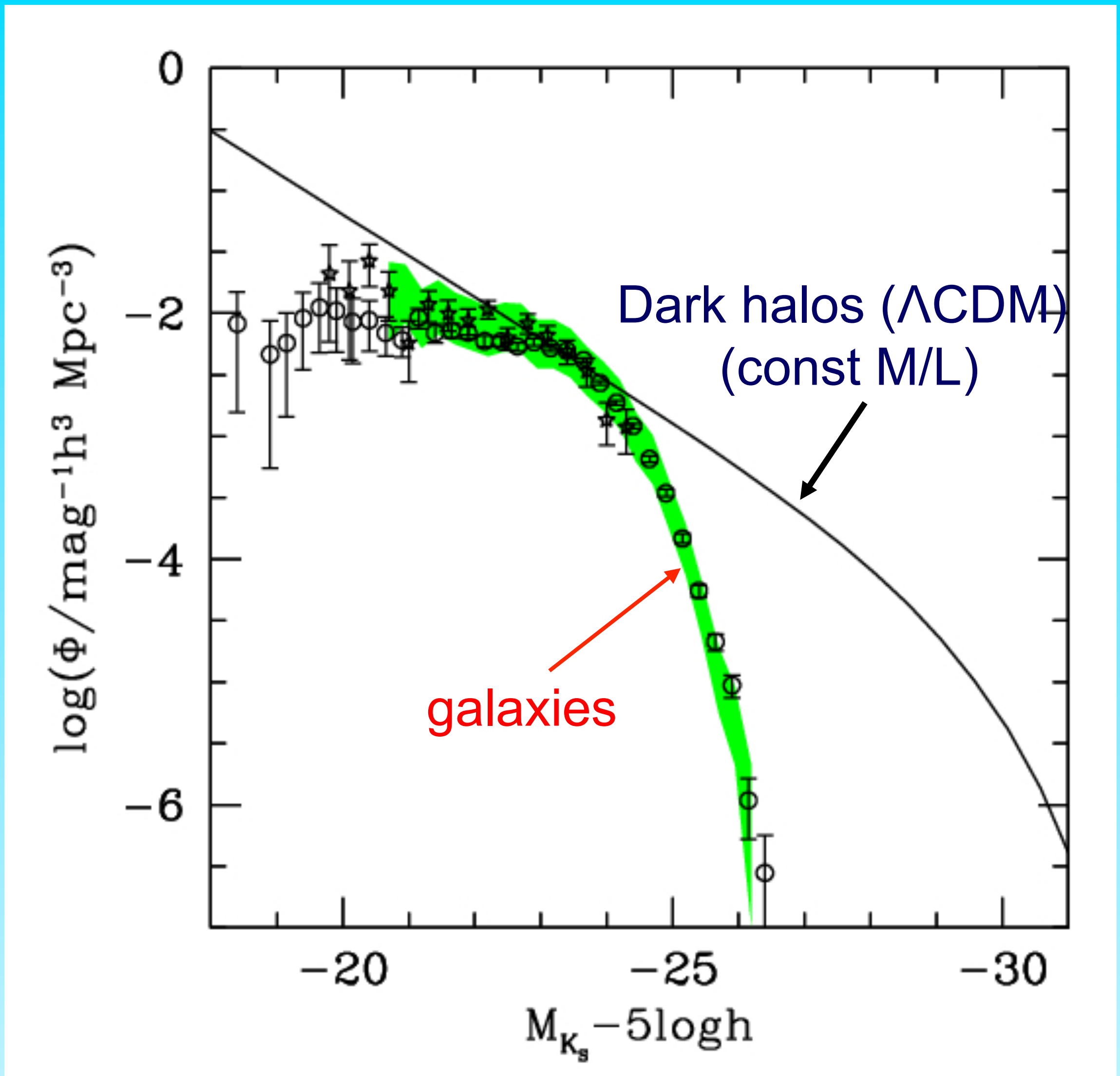
The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes

Complicated variation of M/L with halo mass



Benson, Bower, Frenk, Lacey, Baugh & Cole ‘03

University of Durham

The faint end of the galaxy luminosity function

The main physical processes that determine the masses and abundance of galaxies were laid out in 2 classic papers:

Mon. Not. R. astr. Soc. (1977) **179**, 541–559

Cooling, dynamics and fragmentation of massive gas clouds: clues to the masses and radii of galaxies and clusters

M. J. Rees *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*
J. P. Ostriker *Department of Astronomy, Princeton University, Princeton, New Jersey 08540, USA*

Received 1976 November 5; in original form 1976 July 7

Mon. Not. R. astr. Soc. (1978) **183**, 341–358

Core condensation in heavy halos: a two-stage theory for galaxy formation and clustering

S. D. M. White and M. J. Rees *Institute of Astronomy, Madingley Road, Cambridge*

Received 1977 September 26

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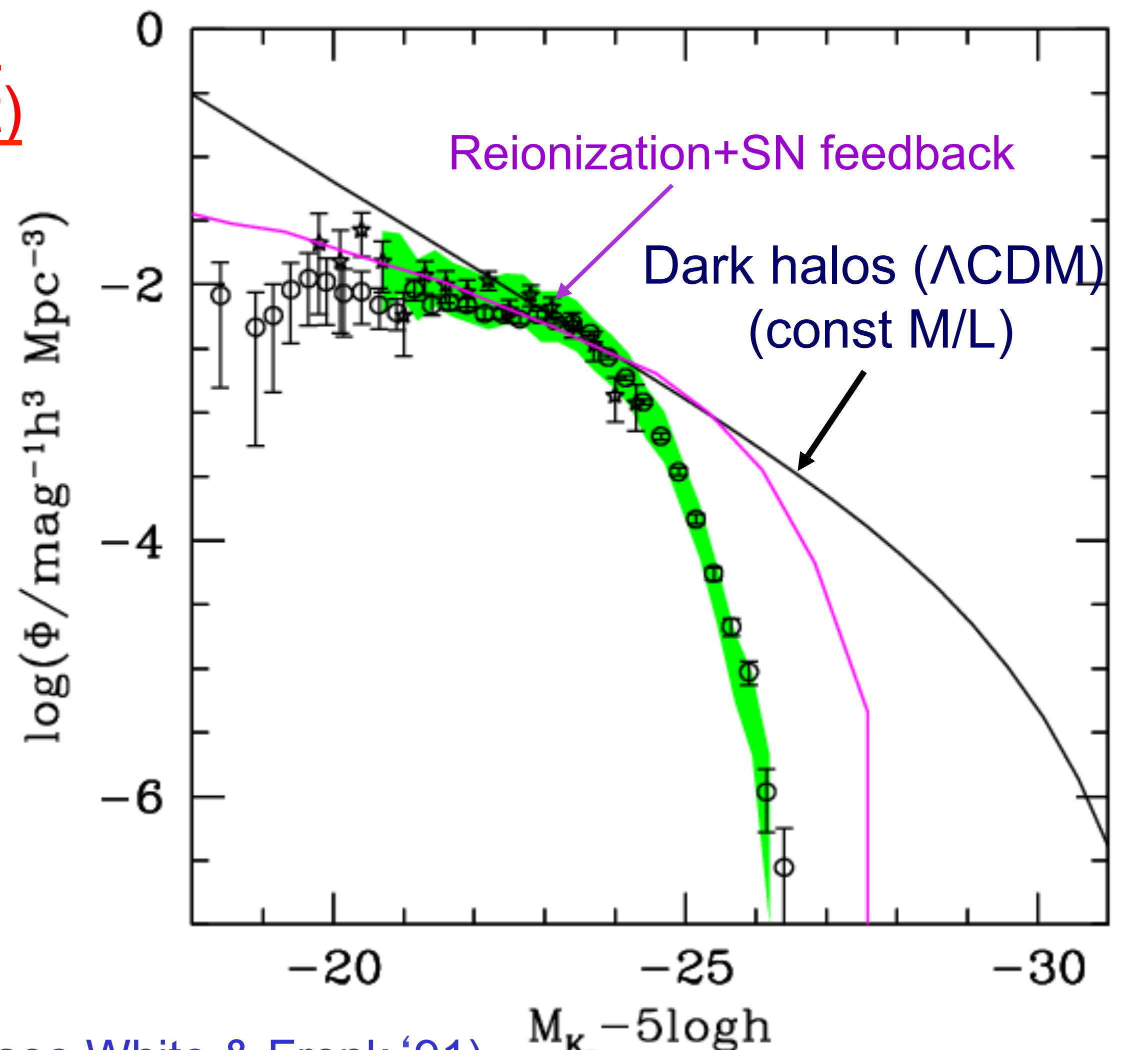
Deconstructing the galaxy LF

Cooling + photoionisation +energy feedback (reheat)



Faint end:

Can be explained by

✓ Reionization

✓ SNe feedback

Bright end:

→ Too many bright galaxies

Need to prevent too much gas cooling in large halos

(see White & Frenk '91)

Benson, Bower,Frenk, Lacey, Baugh & Cole '03

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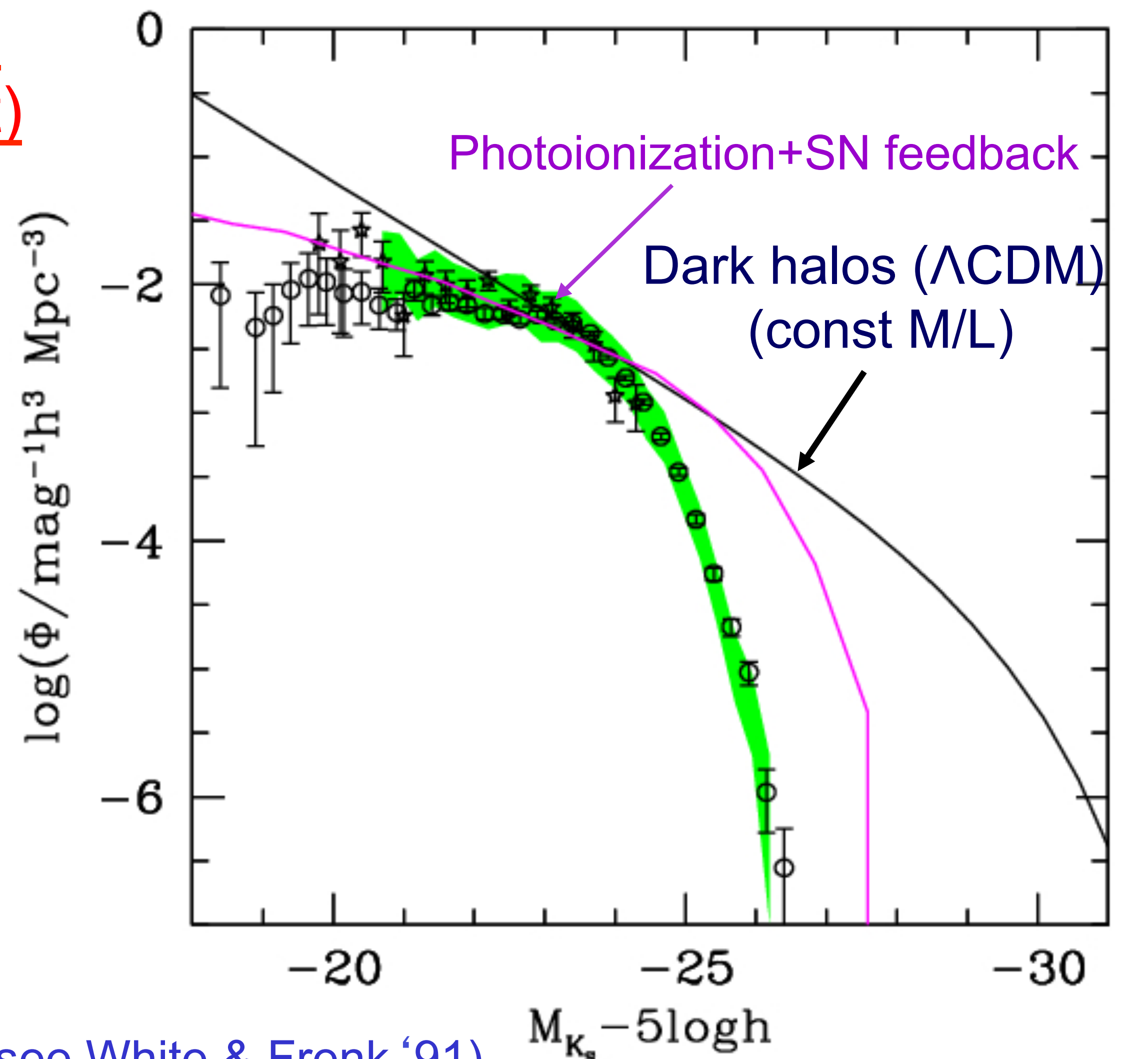


(see White & Frenk '91)

Benson, Bower, Frenk, Lacey, Baugh & Cole '03

A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
02(02.13.5; 09.13.2; 12.03.4)

ASTRONOMY
AND
ASTROPHYSICS

Quasars and Galaxy Formation

Joseph Silk[1] and Martin J. Rees[2]

[1] Institute of Astronomy, Cambridge, UK, Institut d'Astrophysique de Paris, France, and Departments of Astronomy and Physics, University of California, Berkeley, CA 94720 USA
[2] Institute of Astronomy, Cambridge, UK

Received October 9, 1997 / Accepted

Deconstructing the galaxy LF

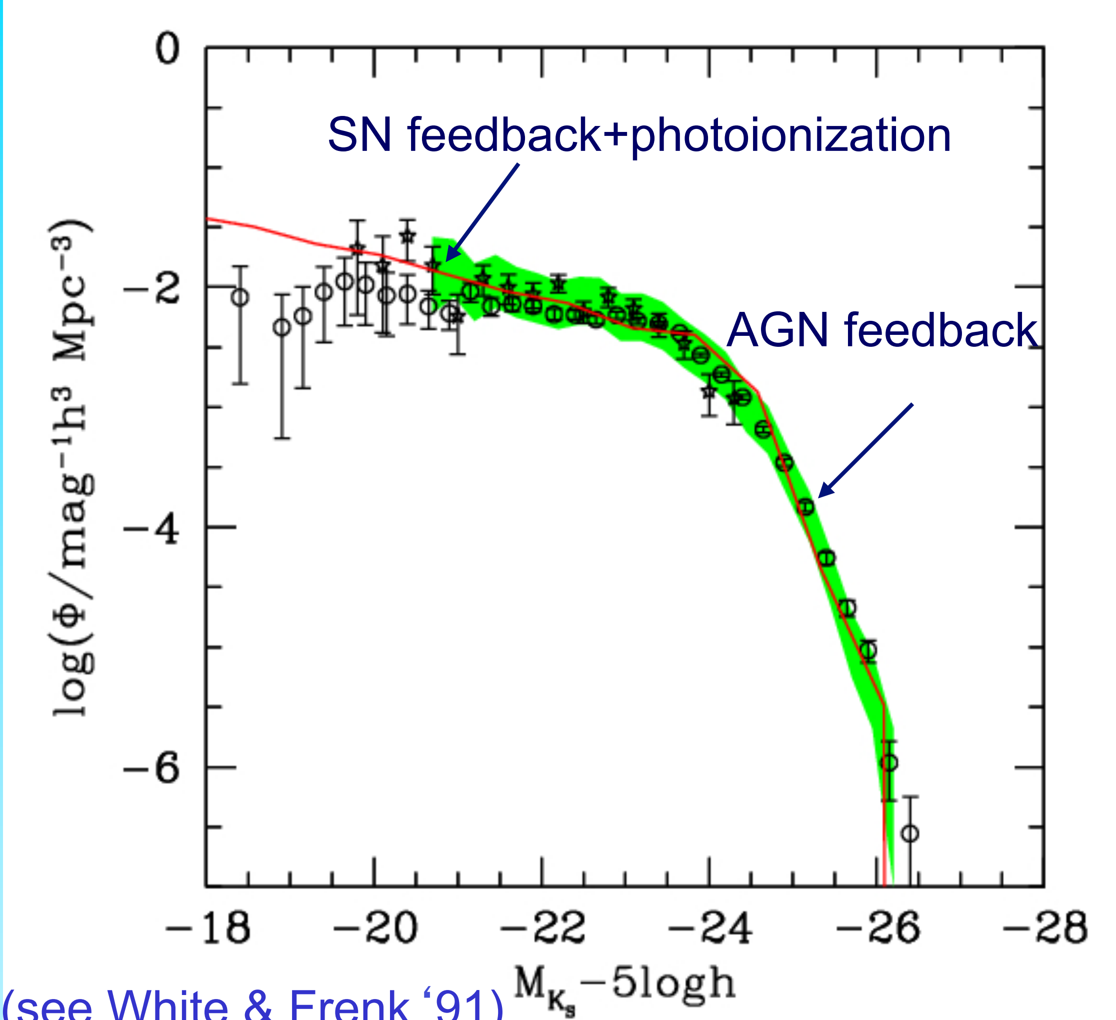
University of Durham

Faint end:

Photoionization + reheating of cold disk gas by SN

Bright end:

AGN feedback: energy transported by bubbles



(see White & Frenk '91)

Croton et al '06, Bower et al '06

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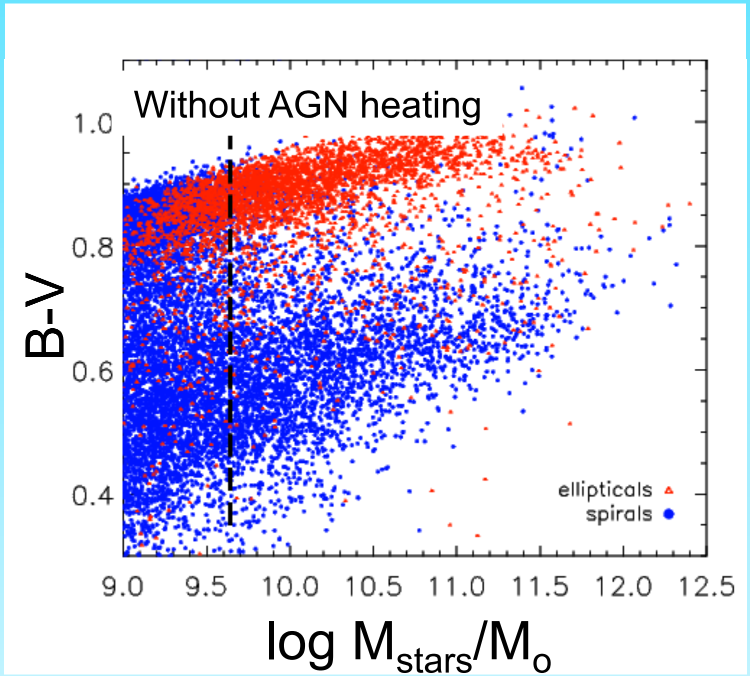
AGN feedback and the properties of ellipticals

The most massive galaxies are red, elliptical



Croton et al ‘06

AGN feedback and the properties of ellipticals

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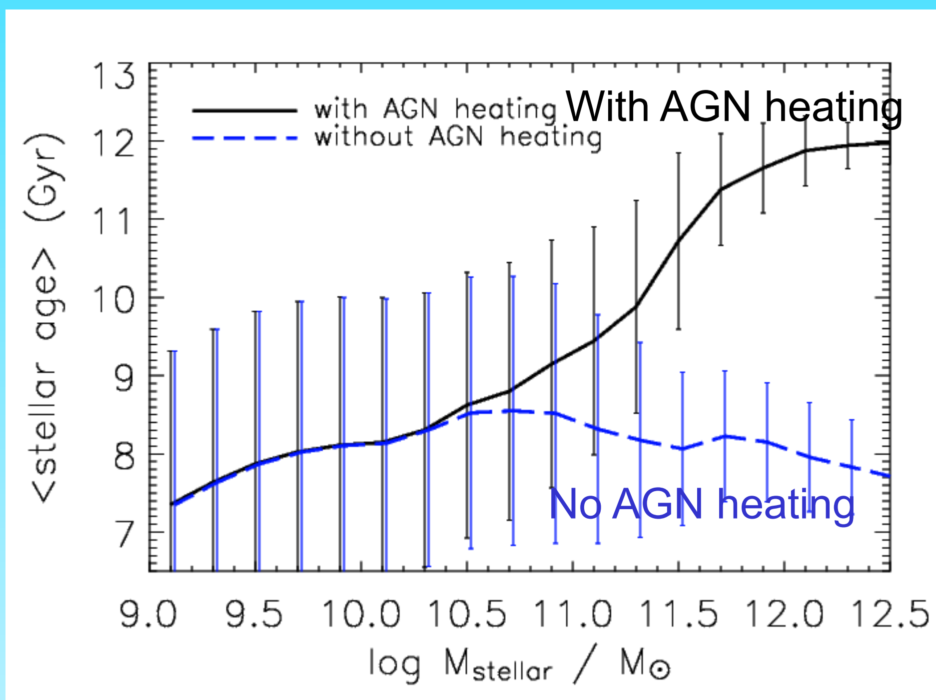
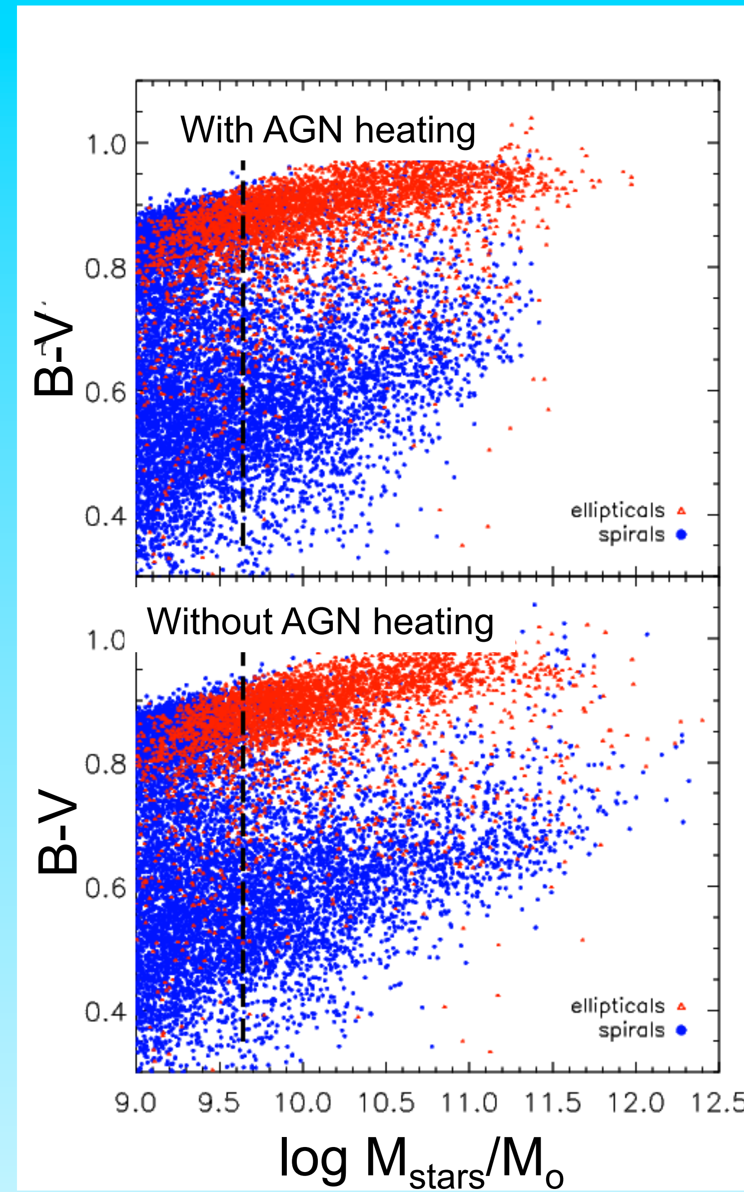
The most massive galaxies are red, elliptical



and old!!



Croton et al 05

Institute for Computational Cosmology

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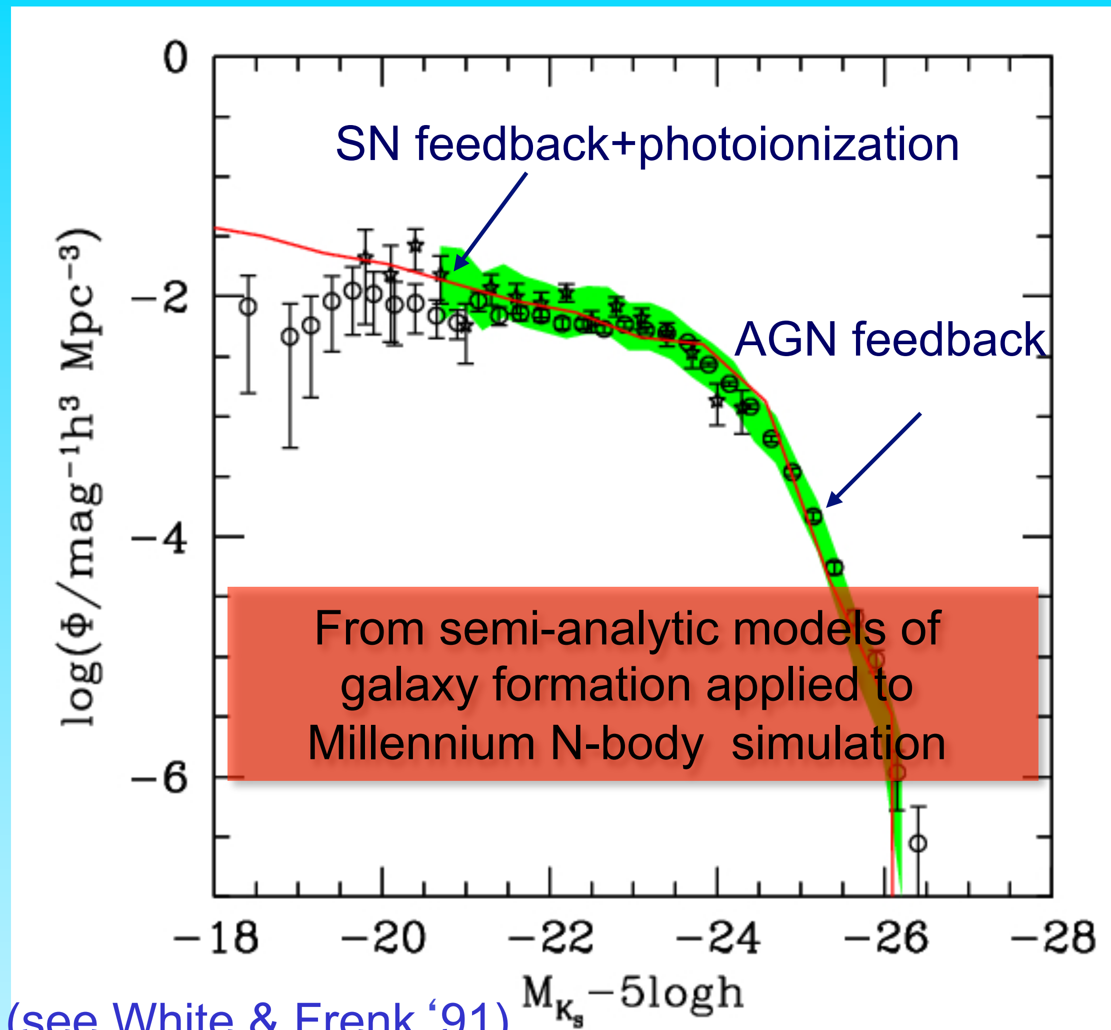


(see White & Frenk ‘91)

Croton et al ‘06, Bower et al ‘06

VIRGO

The "Evolution and assembly of galaxies and their environment" **(EAGLE)** simulation project

Durham: Richard Bower, Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

Other: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

\+ Virgo Consortium

NAM 2014

DiRAC

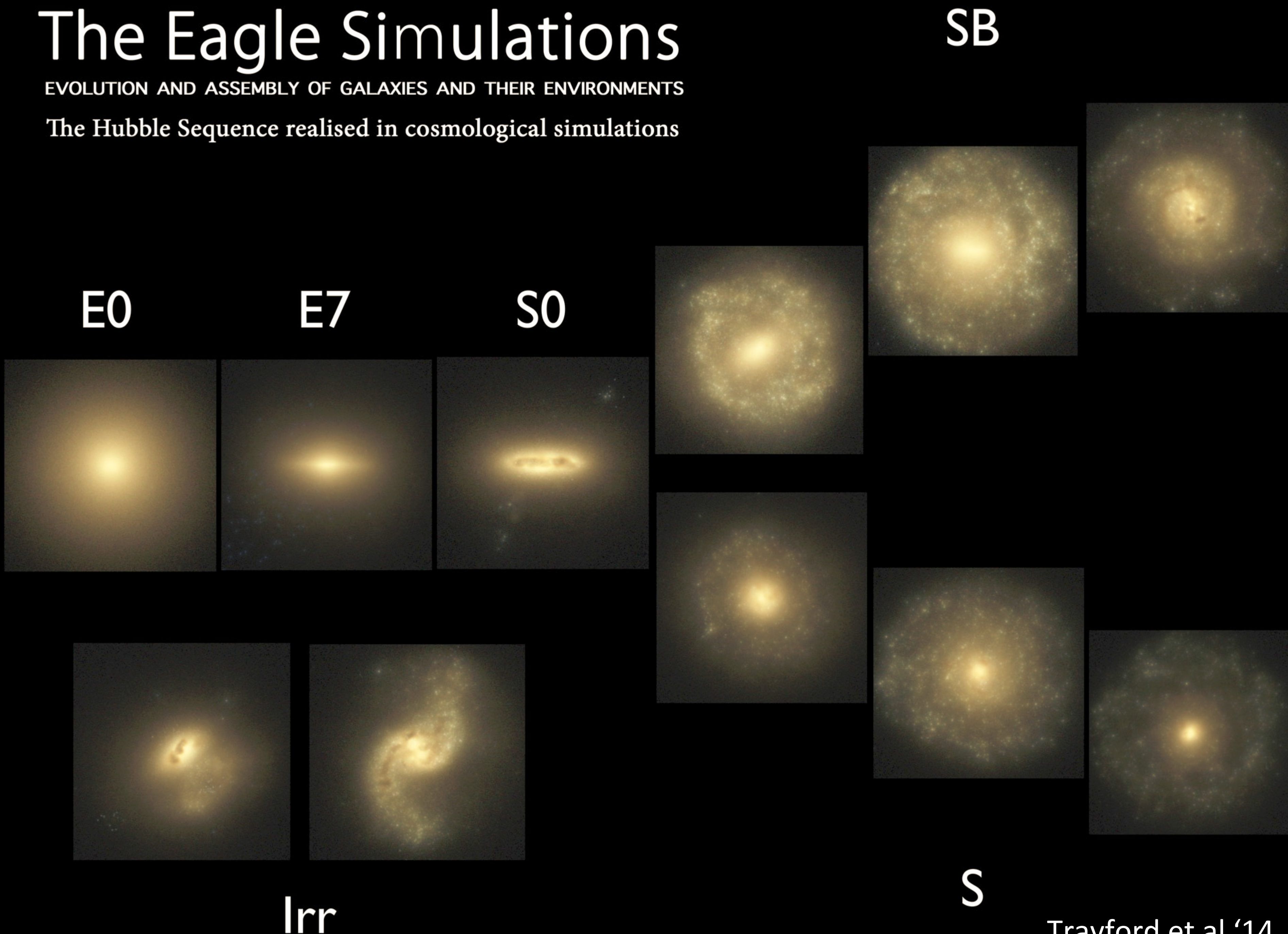
ICC Institute for Computational Cosmology

PRACE

The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

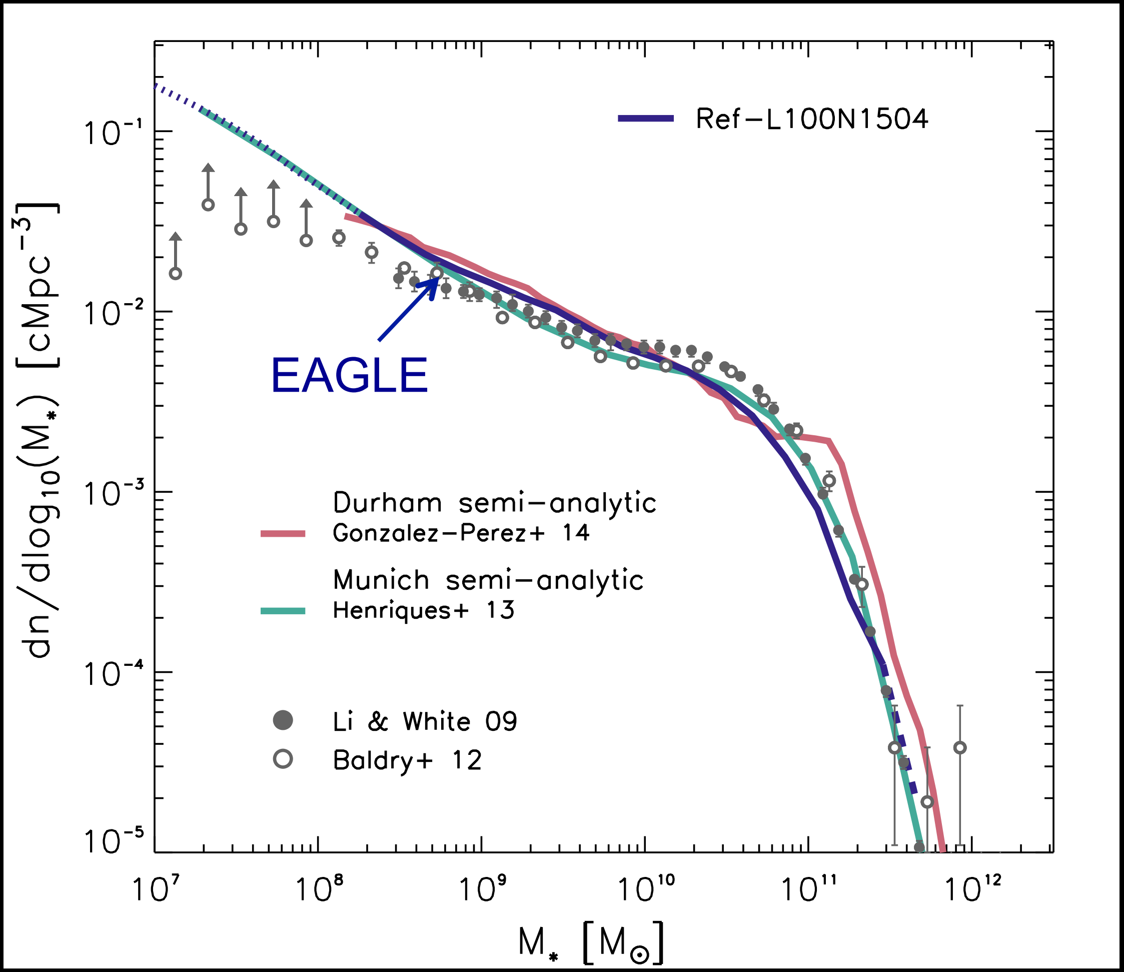
The Hubble Sequence realised in cosmological simulations



Trayford et al '14

Galaxy stellar mass function

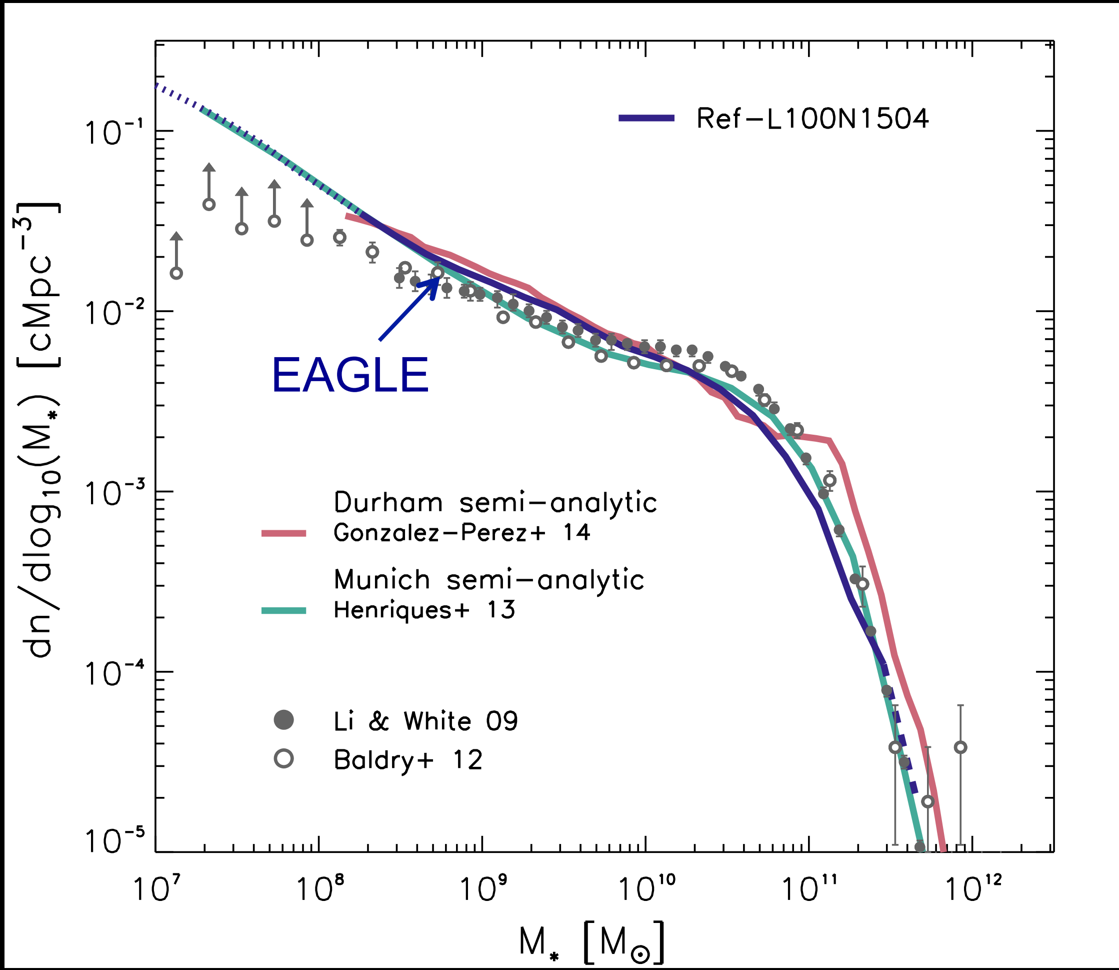
Comparison to semi-analytic models



Schaye et al '15

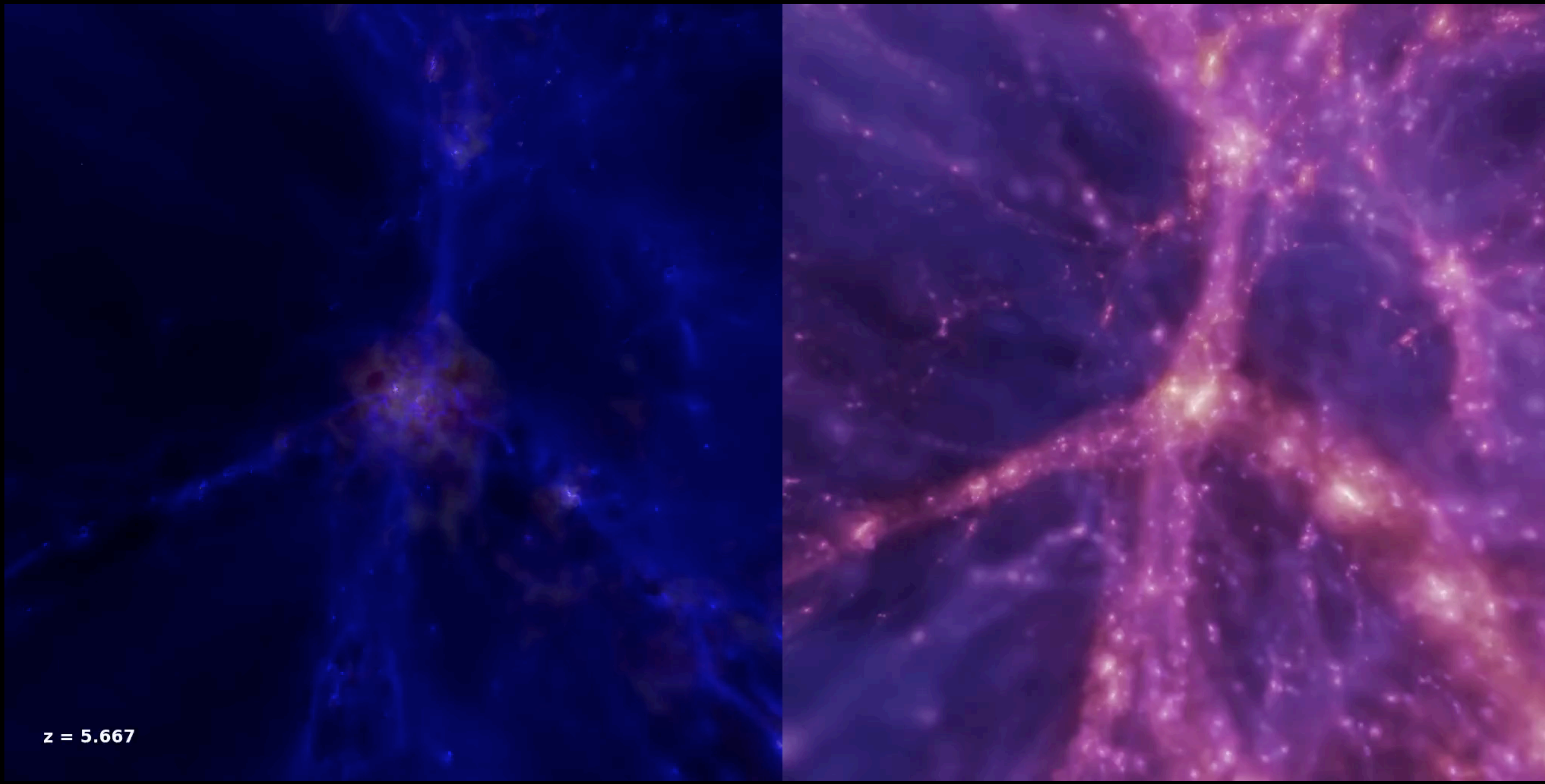
Galaxy stellar mass function

- In EAGLE, seed BHs ($M=1.5x10^5 M_o$) are placed in halos of $M=10^{10} M_o$
- BH grow by Bondi accretion and mergers
- As the BH grows, 1.5% of rest mass energy of accreted gas is injected thermally



Rosas Guevara et al '16

Schaye et al '15



AGN feedback in action – an example

MNRAS 000, 1–?? (2016) Preprint 7 November 2016 Compiled using MNRAS LATEX style file v3.0

The dark nemesis of galaxy formation: why hot haloes trigger black hole growth and bring star formation to an end

Richard G. Bower[1⋆], Joop Schaye[2], Carlos S. Frenk[1], Tom Theuns[1], Matthieu Schaller[1], Robert A. Crain[3], Stuart McAlpine[1].

[1] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK*
[2] *Leiden Observatory, Leiden University, PO Box 9513, 2300 RA Leiden, The Netherlands*
[3] *Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool, L3 5RF, UK*

A model of AGN feedback

- In low mass halos, supernovae regulate build up of gas in disk
  - Gas heated by SNe is buoyant compared to gas corona
  - Cold clouds are evaporated by the hot wind, not accelerated
    (Robertson 2016, Scannapieco 2016)
  - Reheated gas is ejected from the galaxy

- In halos more massive than 10^{12} $M_\odot$
  - Disk outflow is no longer hot enough to be buoyant → stalls
  - Corona increases in mass
  - Density near BH increases → BH accretion rate increases rapidly
  - AGN is triggered (often aided by a merger)

For related ideas, based on energetics, see Keller et al 2015; Dubois et al 2015; Habouzit et al 2016

A simple analytic model

- Black hole accretion in the Bondi regime

Growth is highly non-linear

$$\dot{M}_{bh} \propto M_{bh}^{2} \rho^{1/2}$$

Note: Eddington accretion rate is linear in BH mass

- BH will grow to infinite mass in finite time

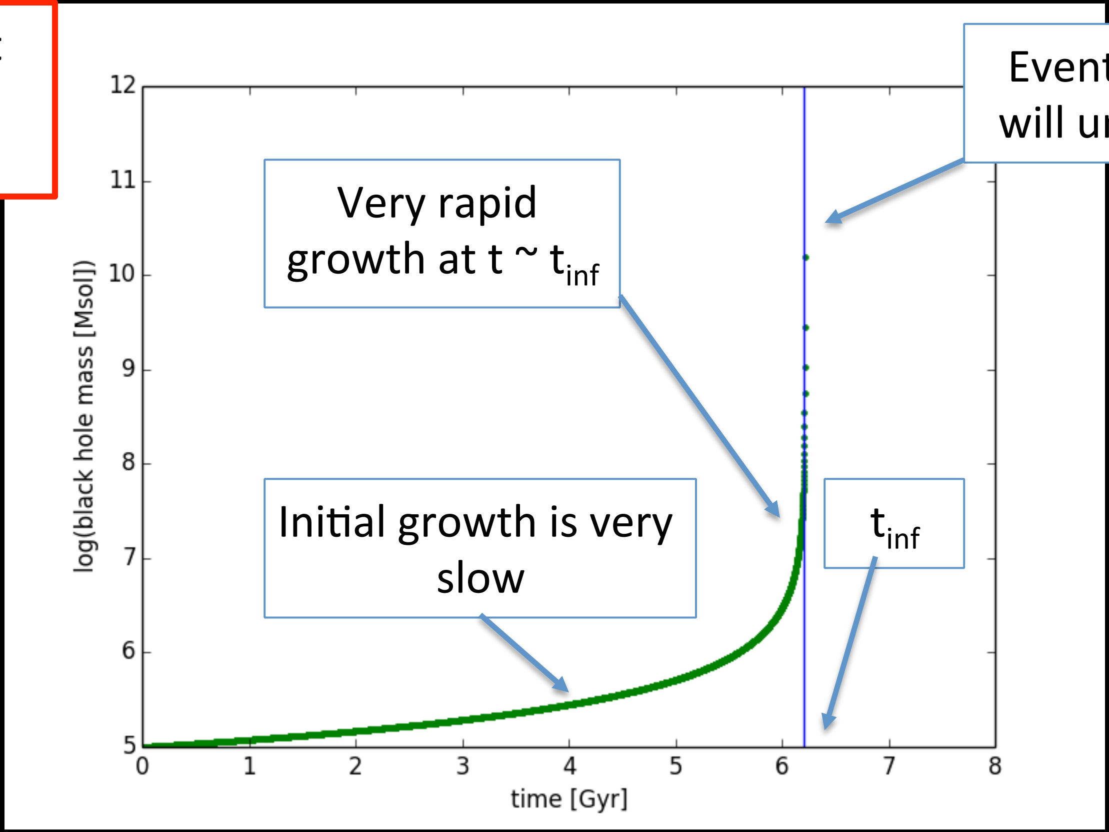
$$t_{\infty} = \frac{1}{\kappa \rho^{1/2}}$$

Const that depends on EOS, M_{seed}, effective disk viscosity

Density of surrounding gas drives timescale

A simple analytic model

For a constant density gas environment



Eventually, the BH will unbind the halo

$$t_\infty = \frac{1}{\kappa \rho^{1/2}}$$

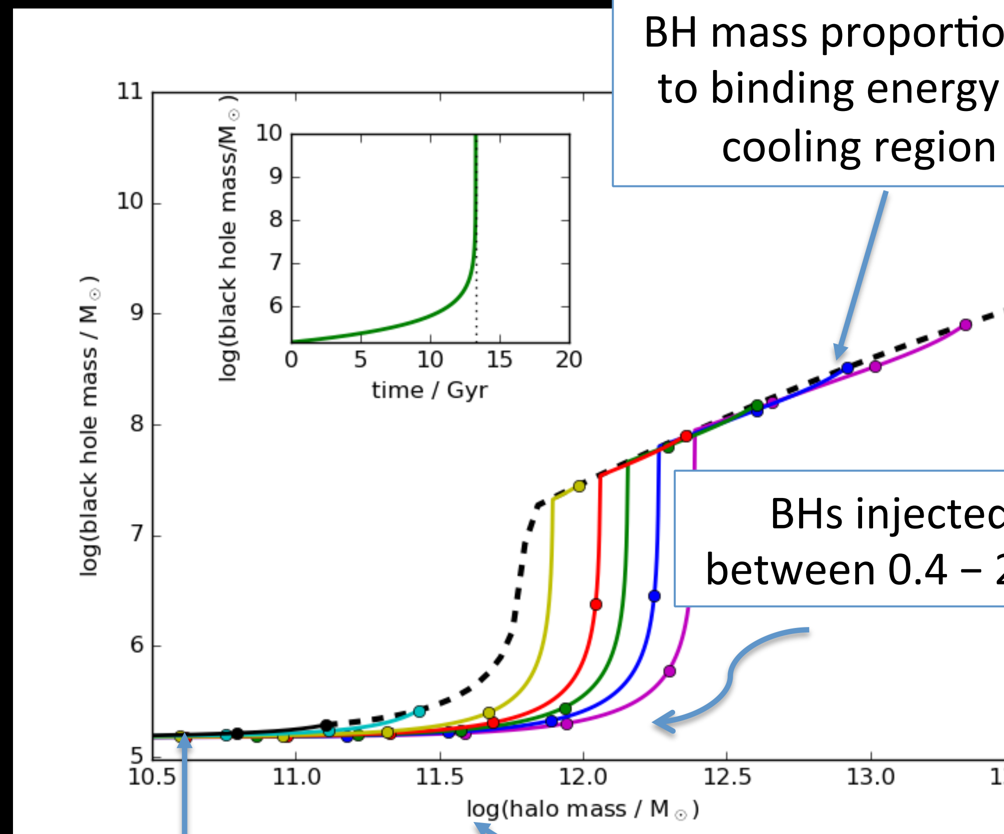
- a small increase in density causes reduction of t_{inf}
- acts as a switch, making BH growth (and feedback) efficient.

A simple analytic model

- BH spends most of its time in slow growth and suddenly switches to rapid growth
- Density around the BH increases:

$$\rho_{\mathrm{bh}} = \rho_{\mathrm{bh}}^{0}(1+z)^{2}\left(\frac{M_{\mathrm{halo}}}{M_{\mathrm{crit}}}\right)^{2}$$

- BH grows until energy output exceeds halo binding energy



Black hole mass growth in EAGLE

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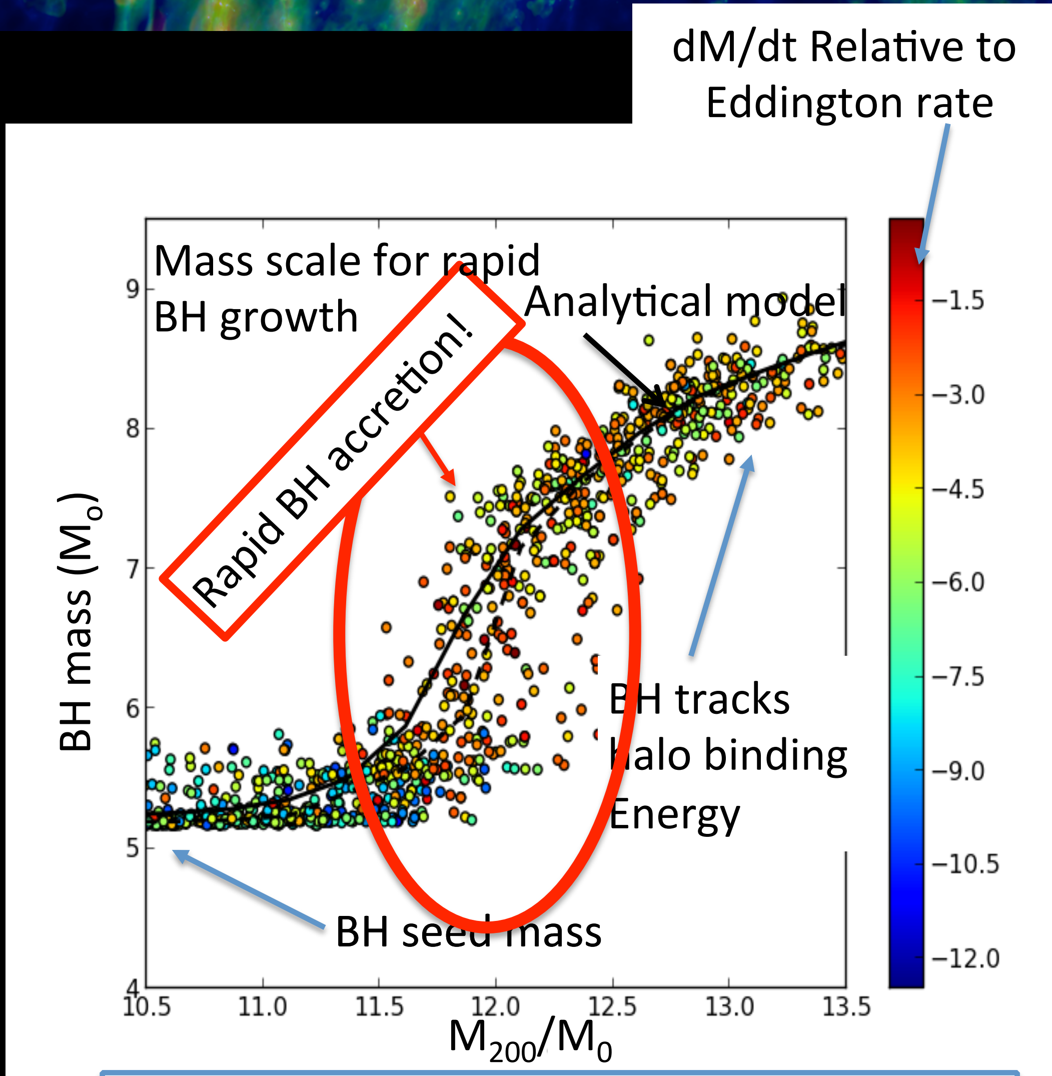
- Transition mass corresponds to rapid BH accretion

Rosas-Guevara et al '15

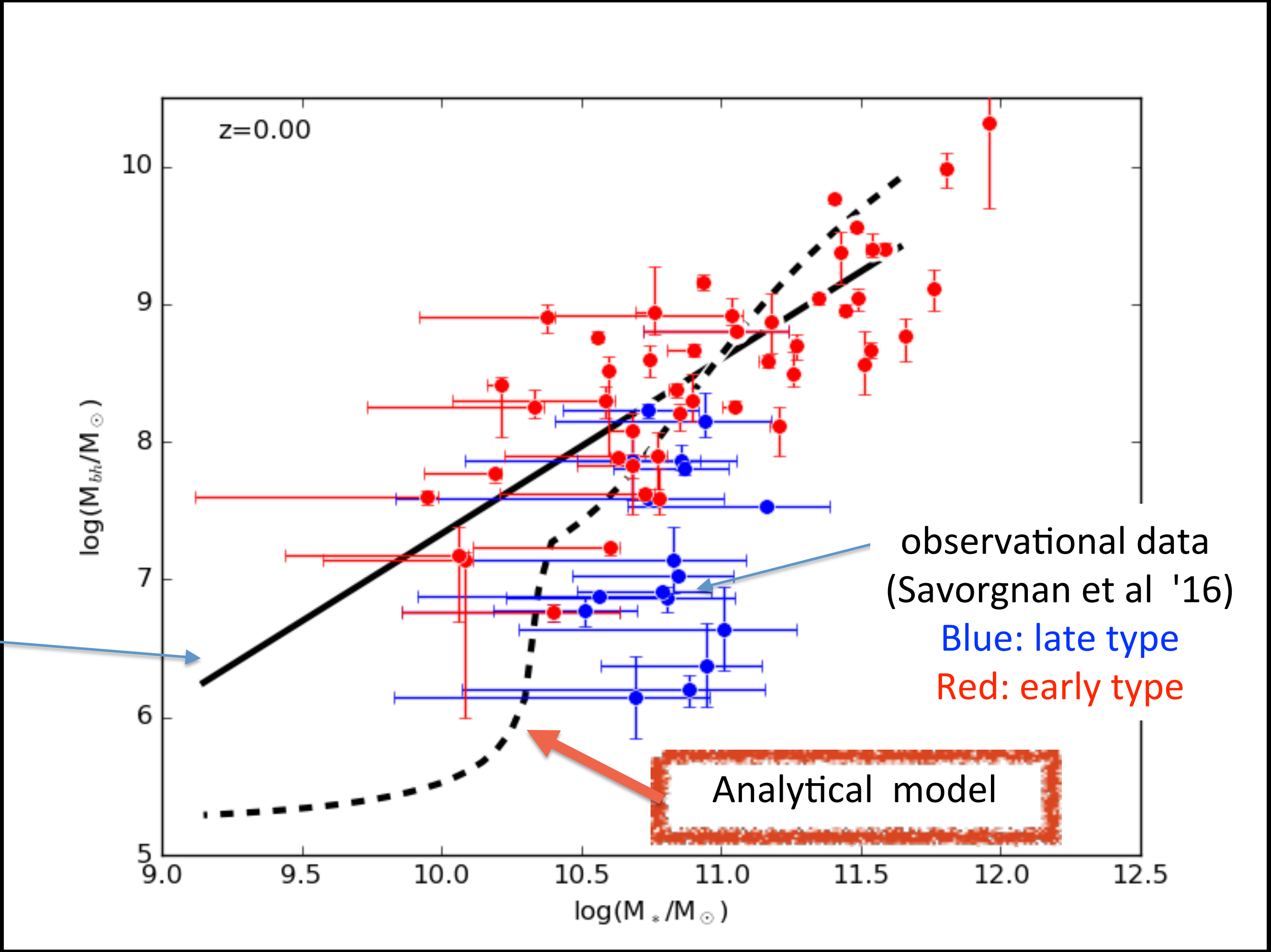


see also Larson 2010, Keller et al 2015; Dubois et al 2015

Simple model – comparison with observations and EAGLE

Convert M_{200} to M_* using abundance matching

$M_{200} \rightarrow M_*$



Extrapolated relation from high mass (McConnel & Ma '13)

Bower et al '17

See also Volonteri & Reines, 2015

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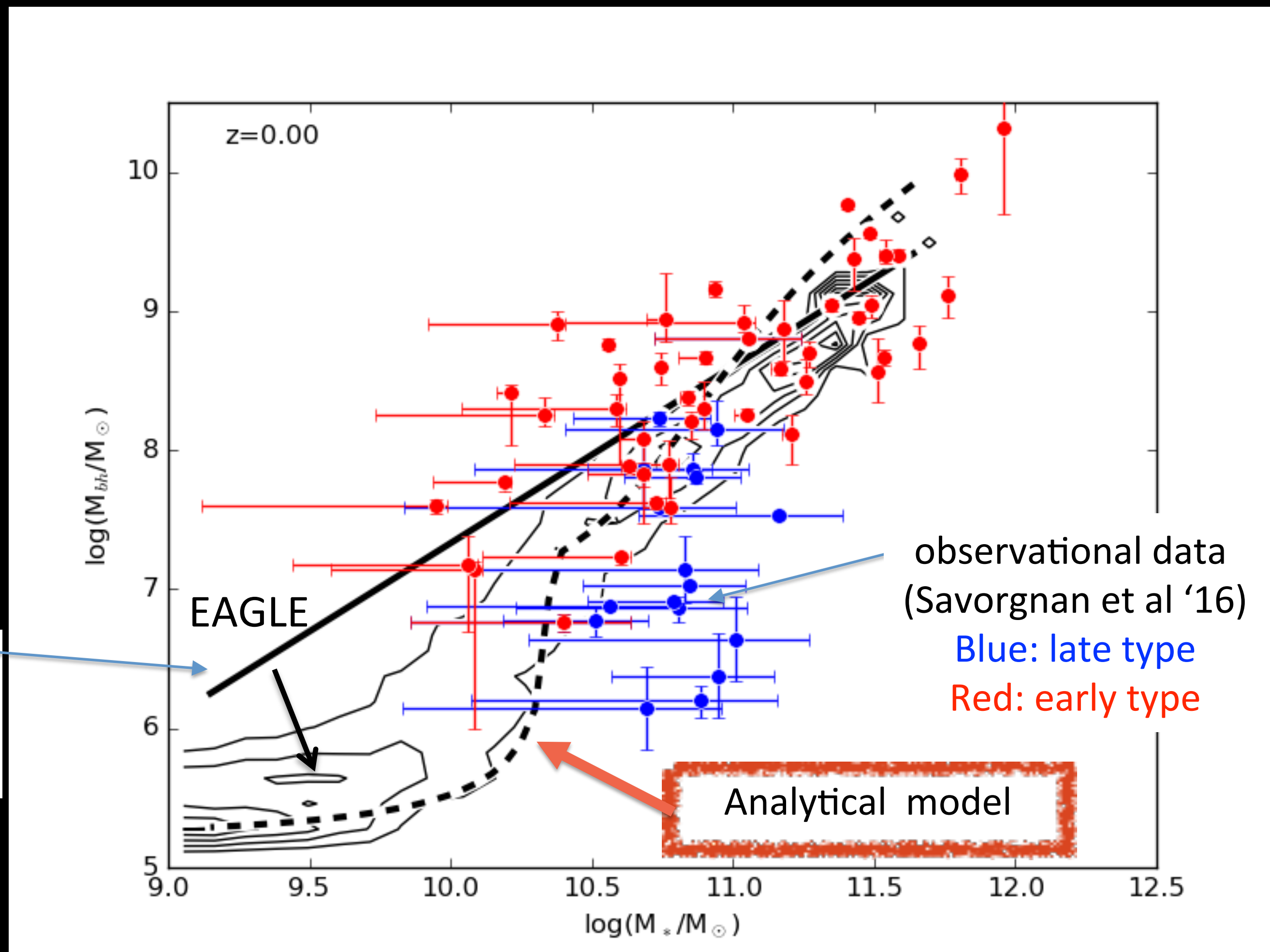

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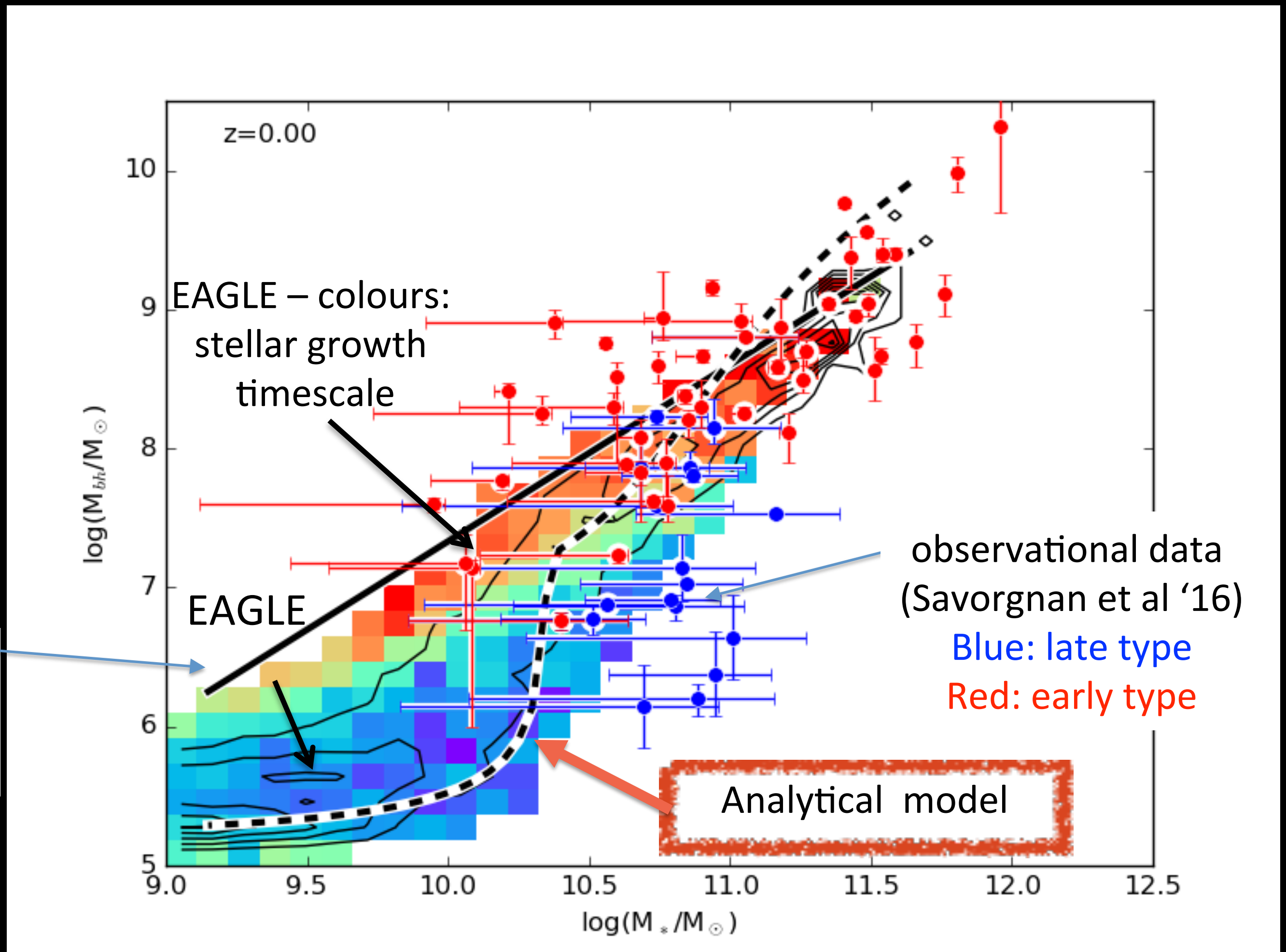
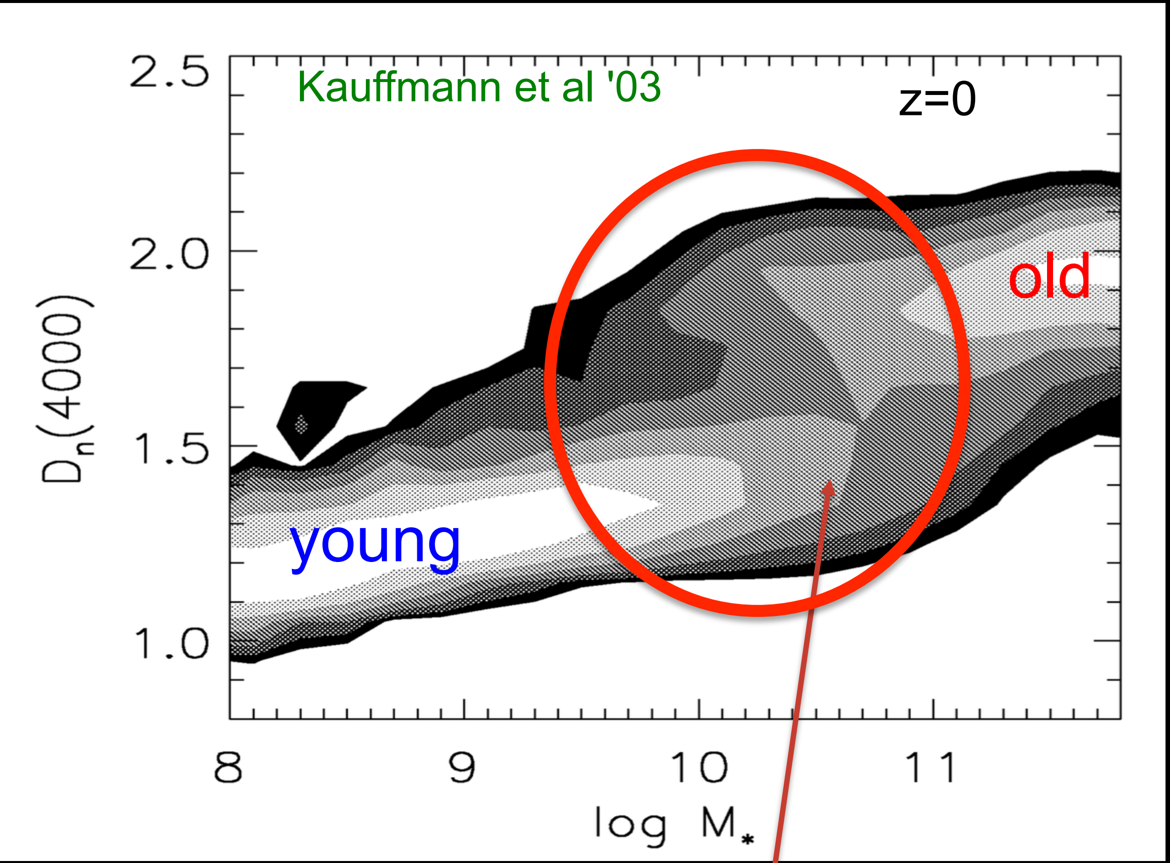


Bower et al '17

See also Volonteri & Reines, 2015

A transition mass in galaxy properties

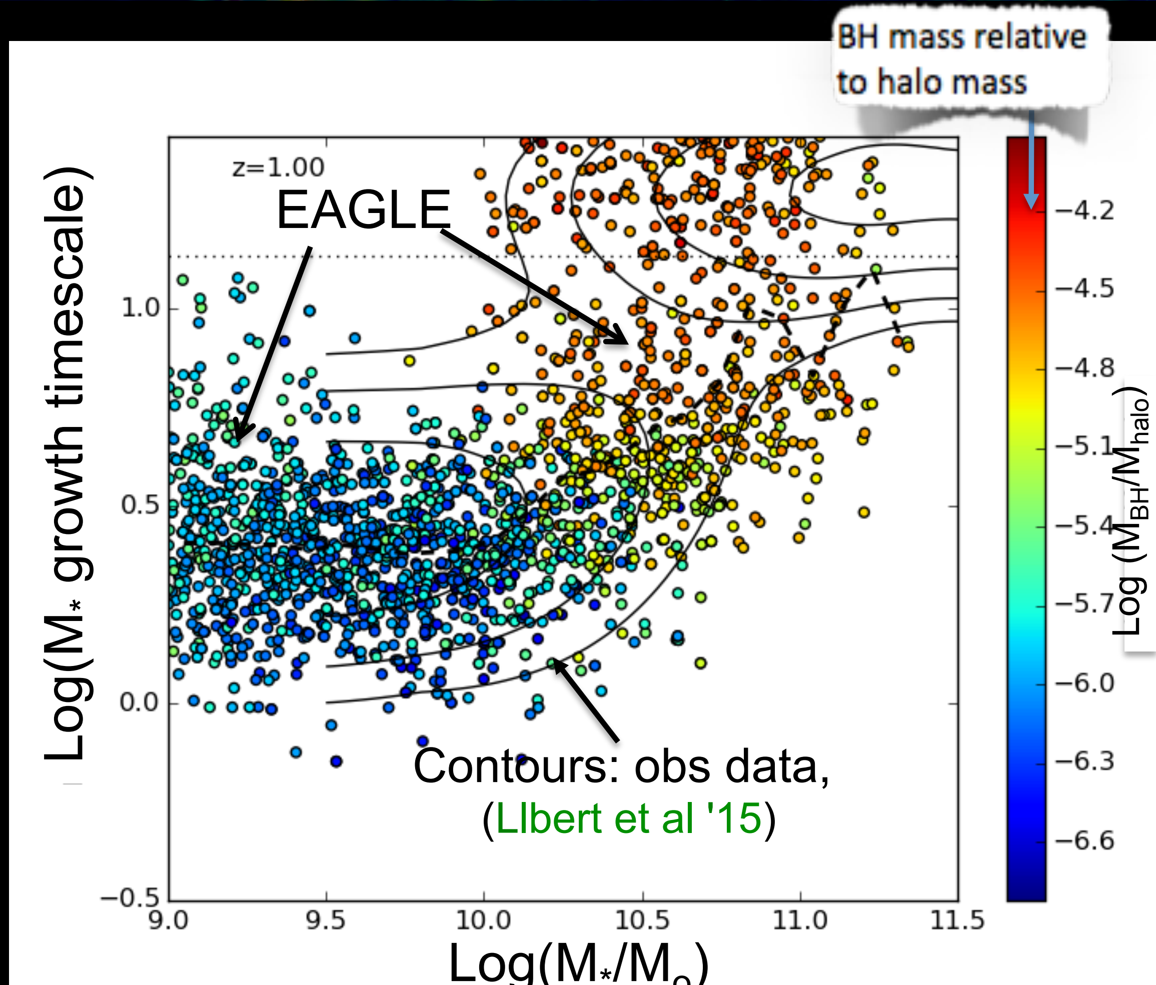
- Galaxy properties exhibit a sharp transition
- This transition occurs at a similar halo mass at all redshifts



Transition mass scale

A transition mass in galaxy properties

- Galaxy properties exhibit sharp transition
- Reproduced in Eagle
- In Eagle, at a fixed halo mass, galaxies with large BH have a long SF growth timescale
- Transition occurs at similar halo mass at all redshifts



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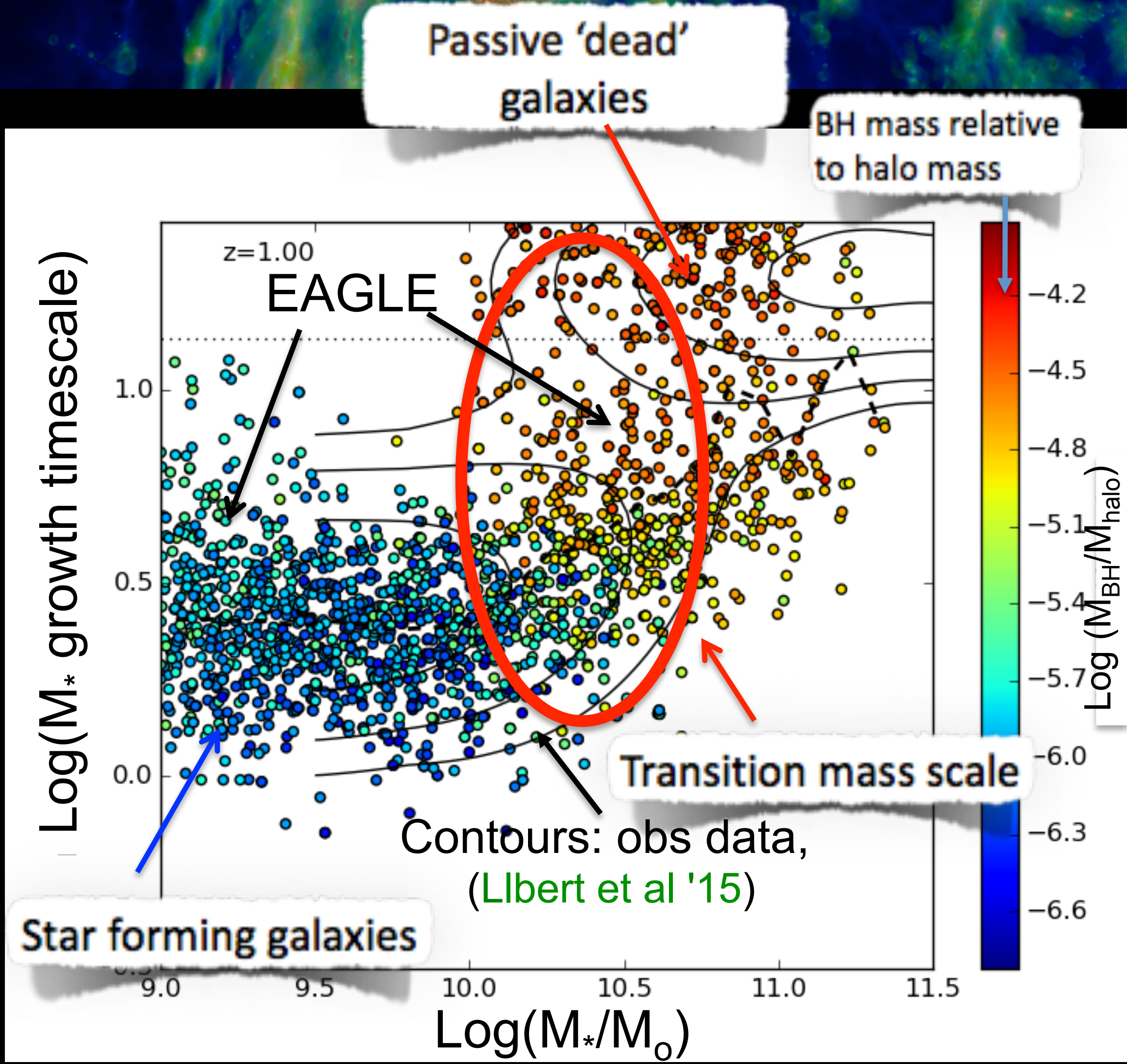
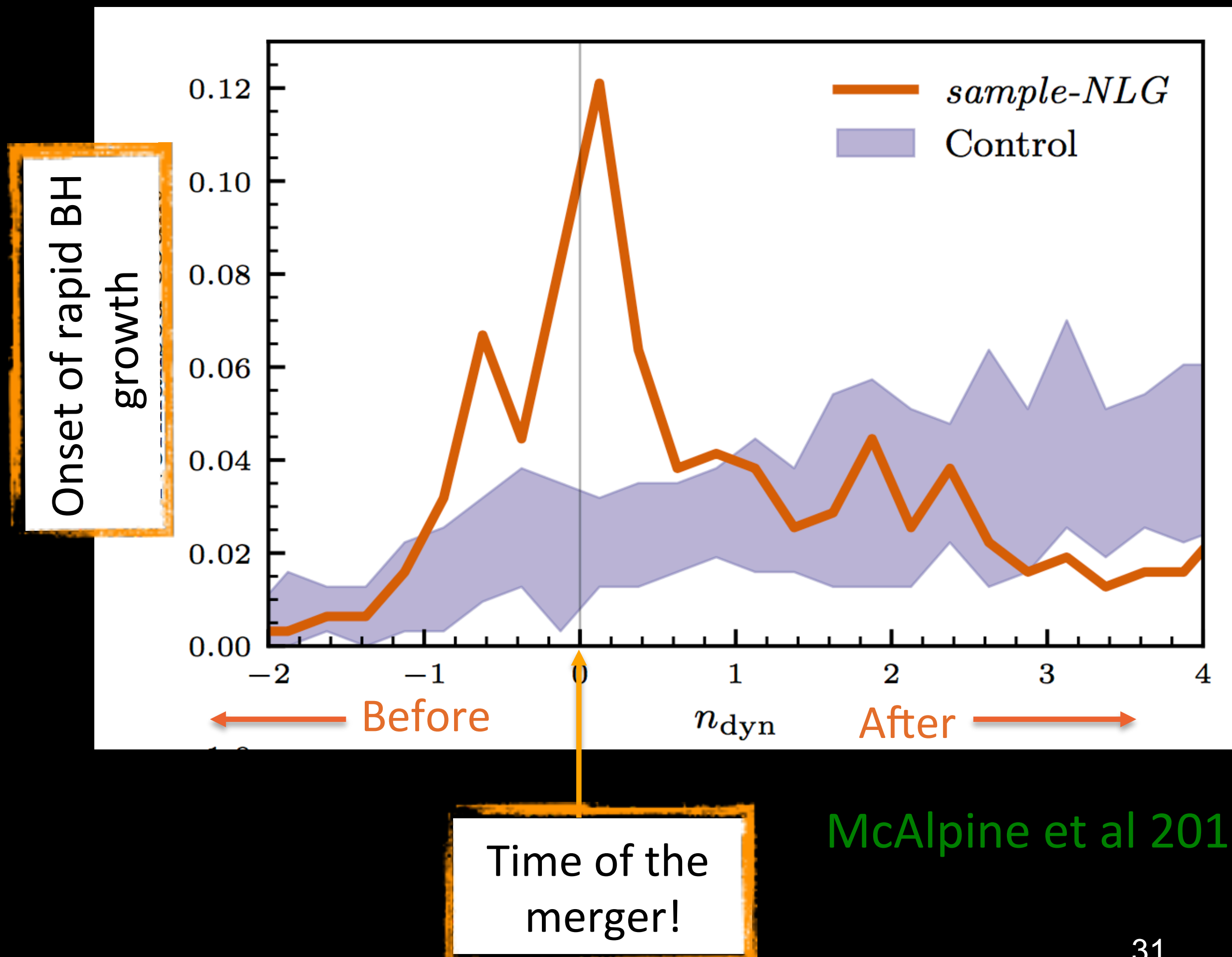


The role of mergers

Mergers are the trigger!

- Time difference (in dynamical times) between rapid growth phase and major merger
- Responsible for the onset of growth in ~40% of cases
- But halo mass is critical too!!



McAlpine et al 2017

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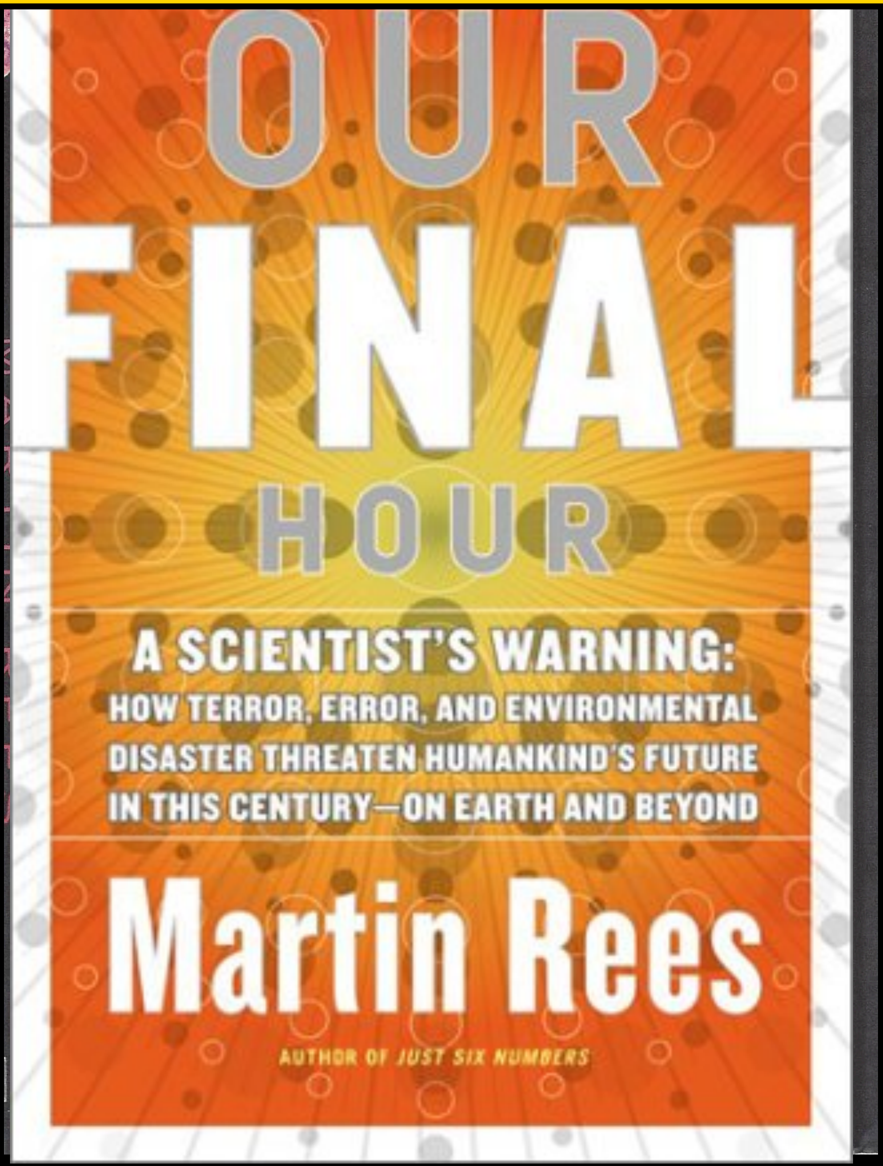
Main points (so far)

- Transition mass scale emerges when SN-driven outflow stalls
- In the Bondi accretion regime, BH growth is highly non-linear → a small increase in density can trigger rapid BH growth
- Break in galaxy mass function, & transition mass that separates red/blue galaxy sequences are the result of rapid BH growth
- Major mergers play a role, often (not always) triggering this growth

The curious case of the Milky Way



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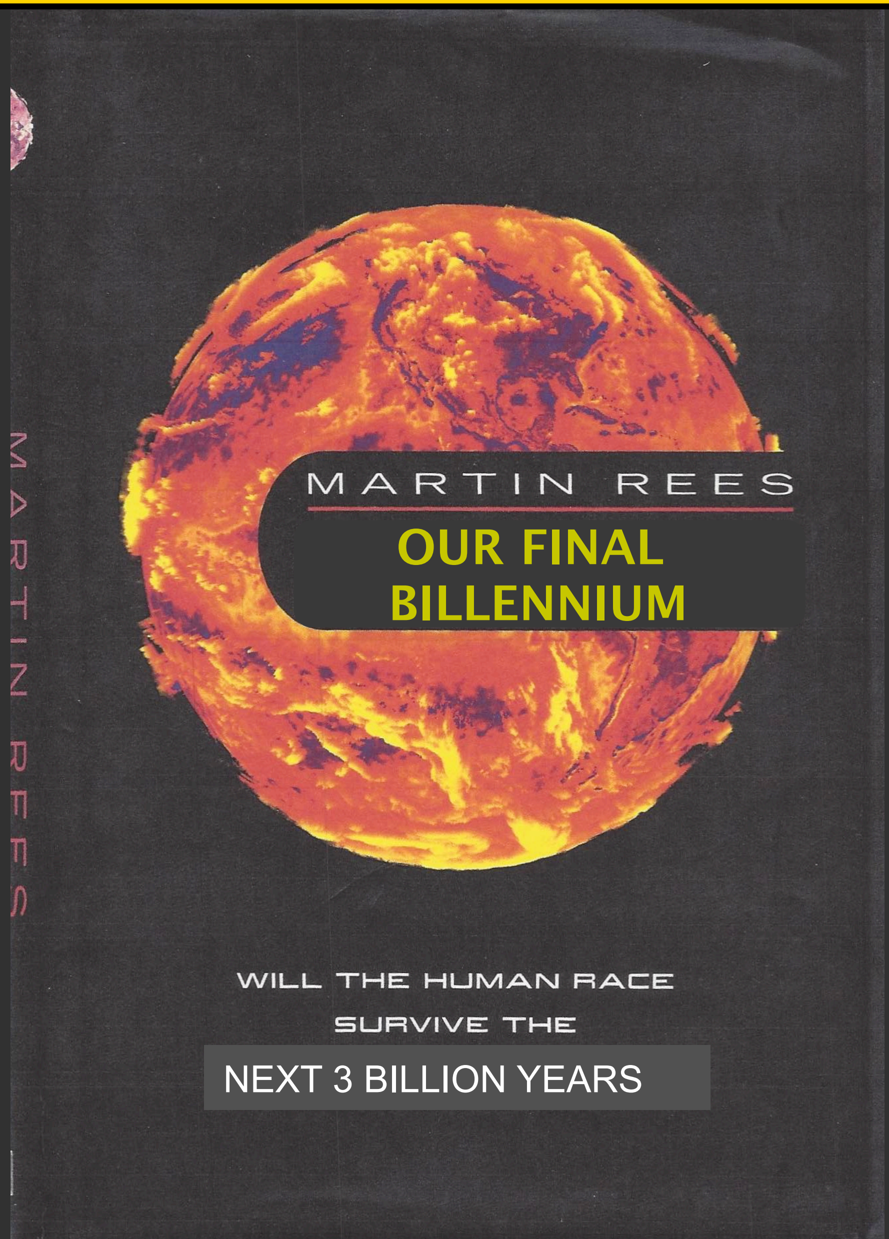

The curious case of the Milky Way

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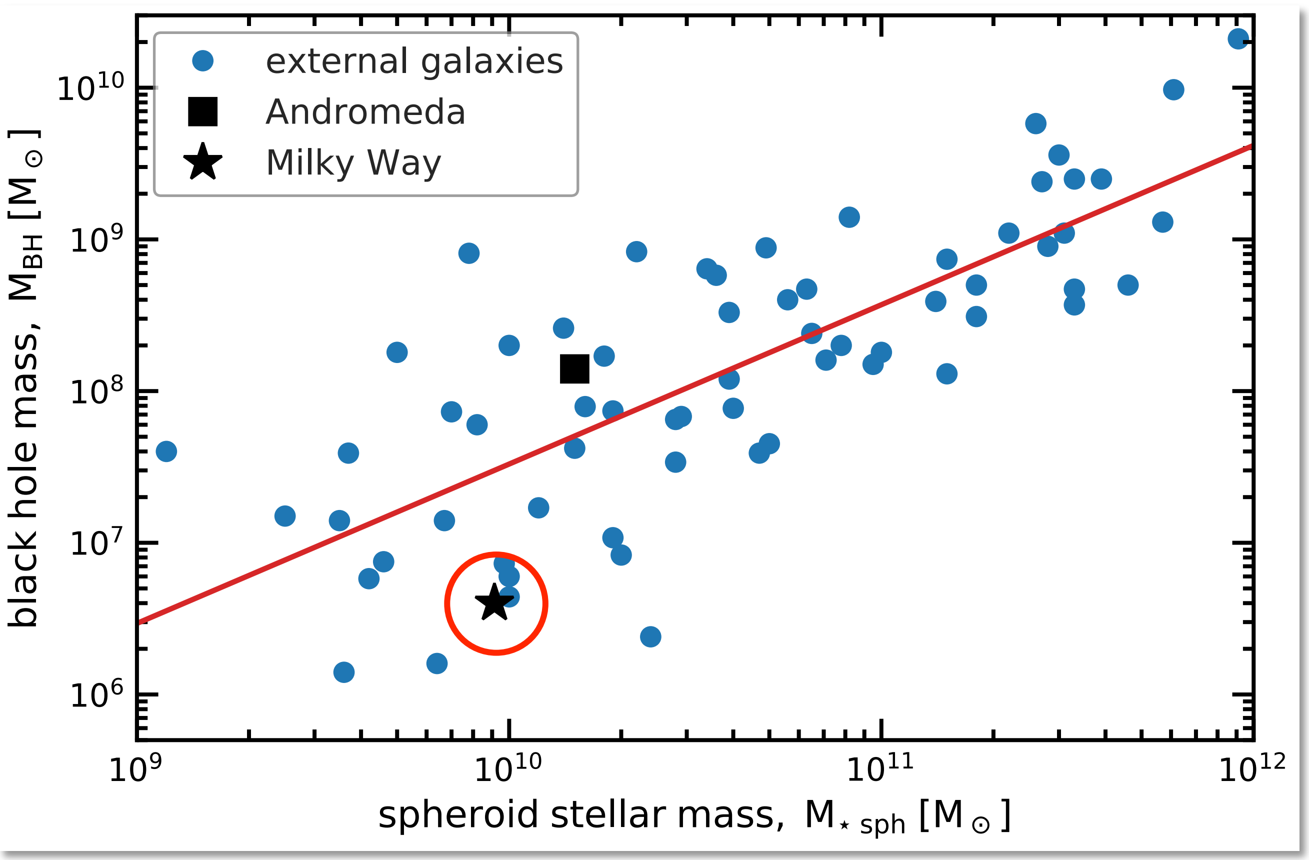
The Milky Way is an outlier in the $M_{BH} - M^*_{spheroid}$ relation



In the MW:

$M_{BH} = 4\times10^6\ M_0$ is ~10 × smaller than average

Cautun & Frenk '17

The curious case of the Milky Way

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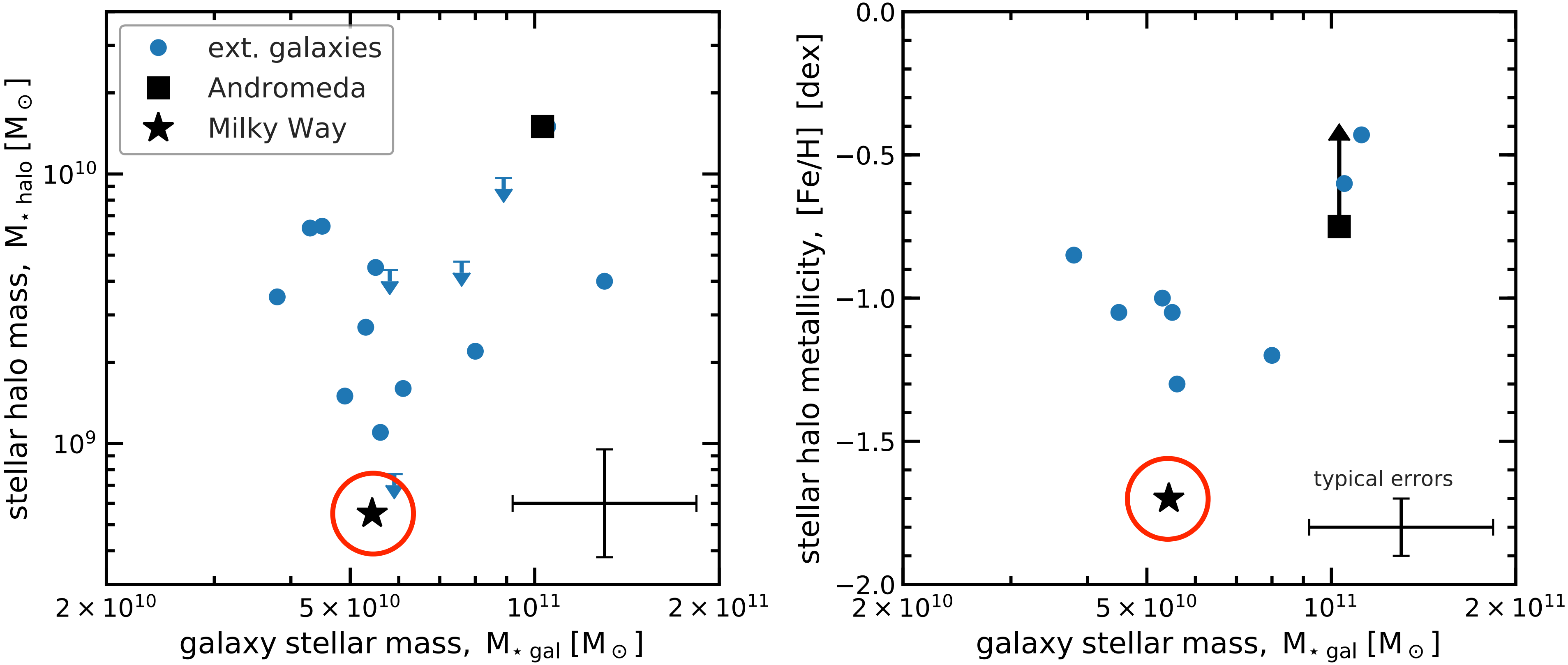
The MW stellar halo is also underdevolped

- Its stellar mass, $M_{*,halo}=5\times10^8 M_0$, is 10 × smaller than average
- Its metallicity, [Fe/H]=-1.7, is 0.7 dex smaller than average



Cautun & Frenk ‘17

Institute for Computational Cosmology

What is wrong with the Milky Way?

Black hole mass growth in EAGLE

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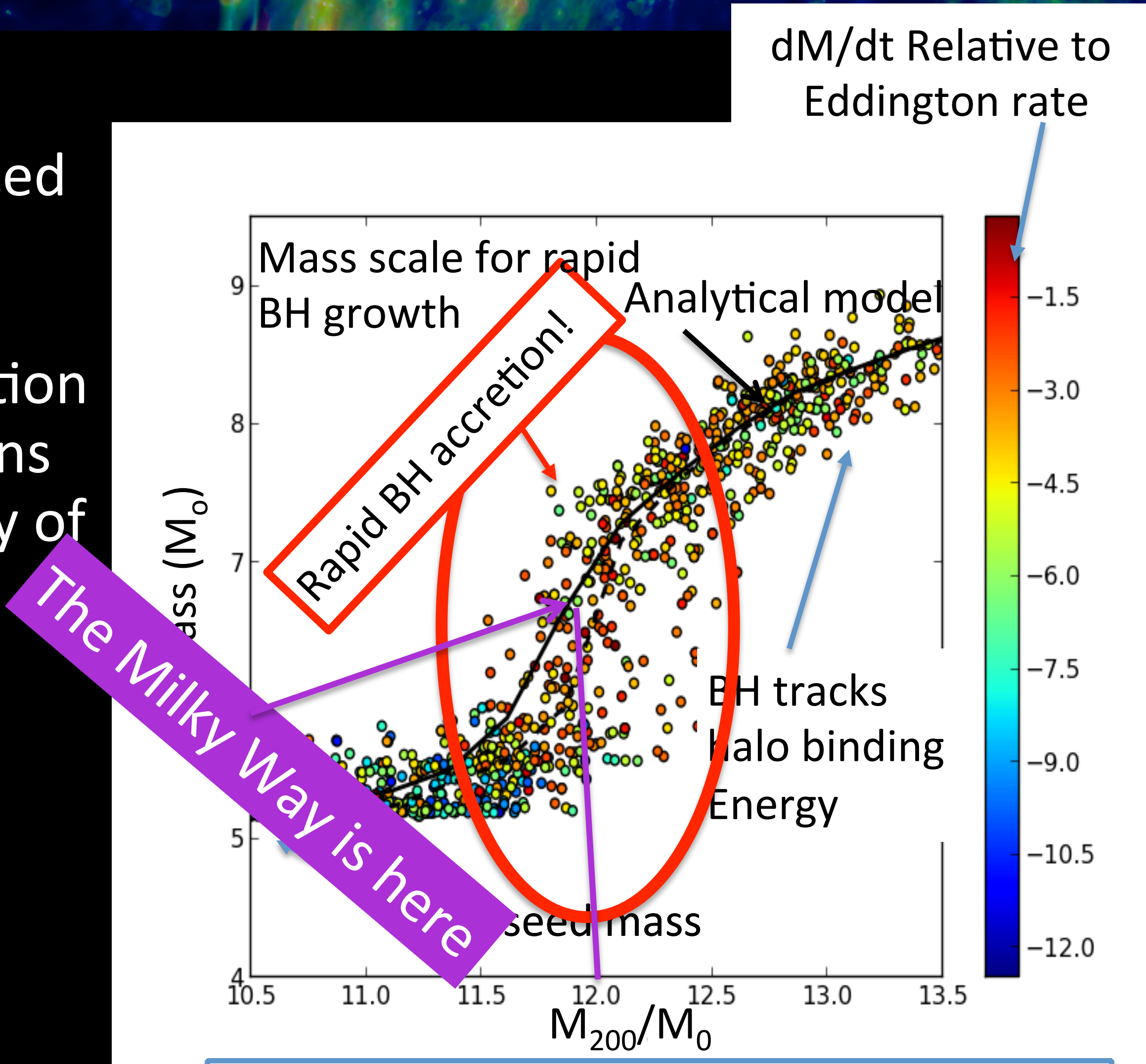
Rosas-Guevara et al '15



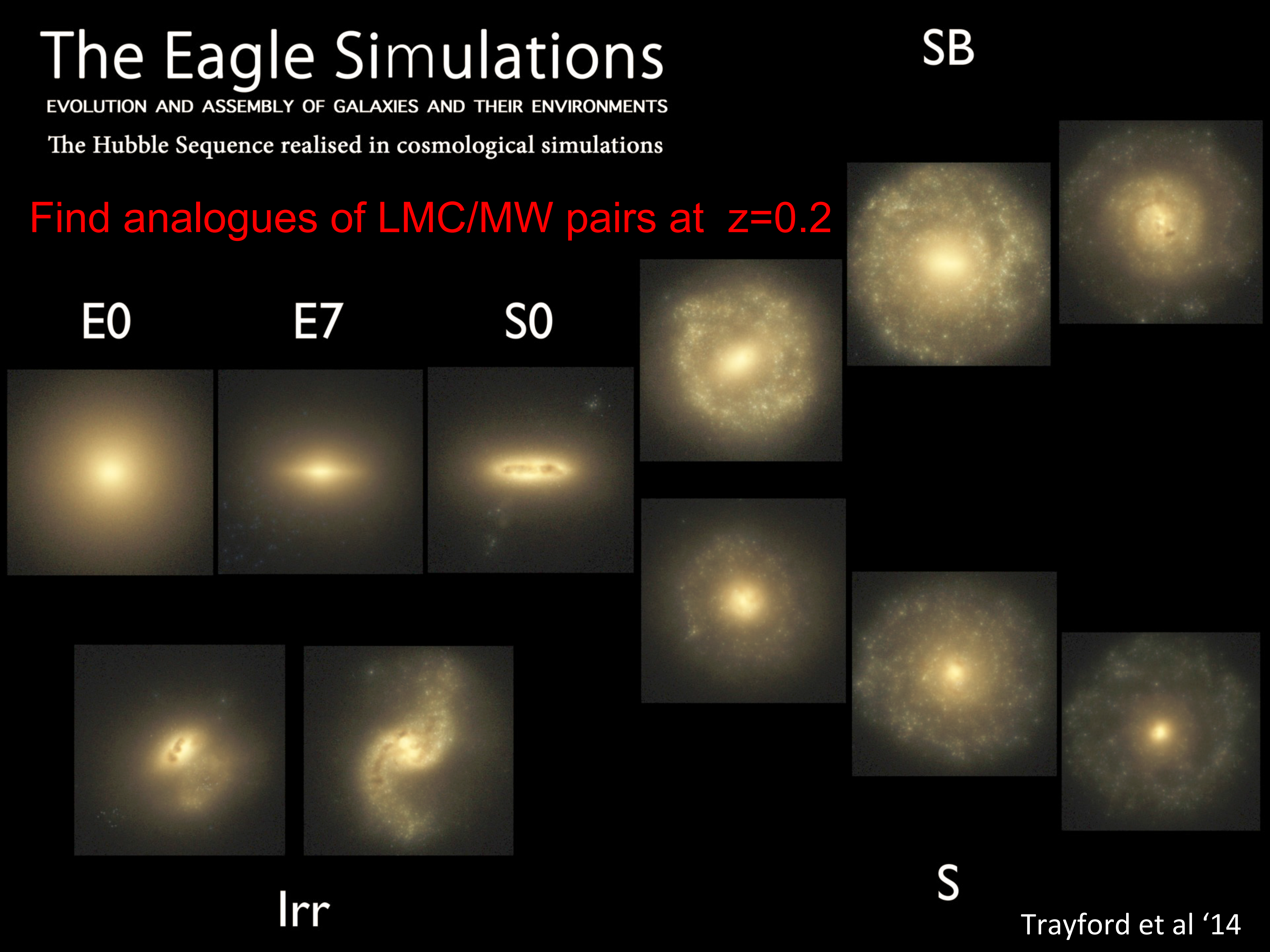
see also Larson 2010, Keller et al 2015; Dubois et al 2015

The strange case of the Milky Way

The Large Magellanic Cloud

- M_{LMC}=2.5 ± 0.1 ×$10^{11}M_0$
- Galactocentric distance = 50 kpc
- V_{LMC-MW} = 327 km/s
- Orbital eccentricity = 0.88 ± 0.07
- (Peñarrubia et al '16; Bajkova, V.V. Bobylev '17)

The LMC will crash at the Galactic Centre in 2.5 Gys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EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
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Find analogues of LMC/MW pairs at z=0.2
SB
E0
E7
S0
Irr
S
Trayford et al '14

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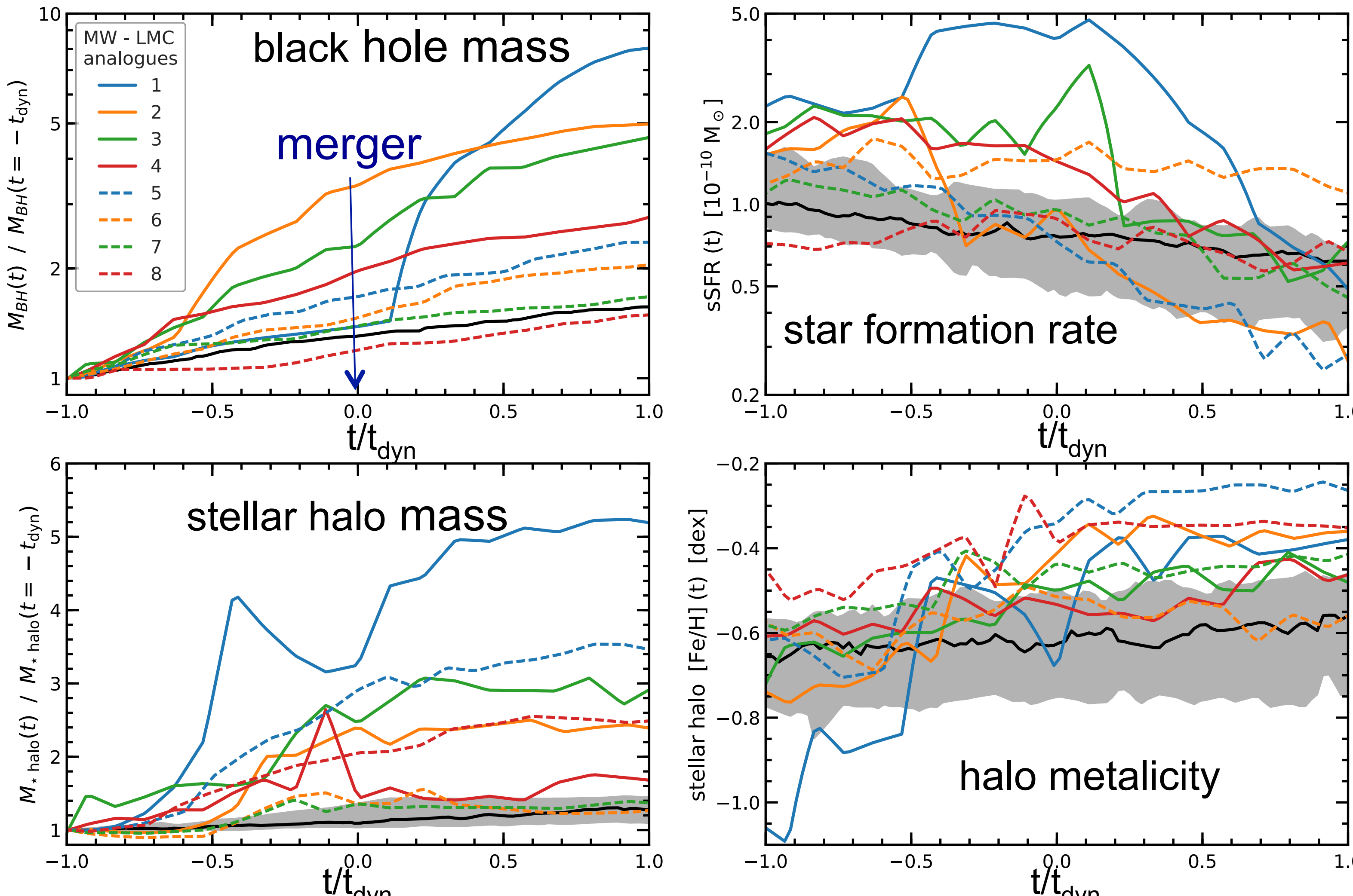
The strange case of the Milky Way

Found 8 MW-LMC analogues in EAGLE



Cautun & Frenk '17

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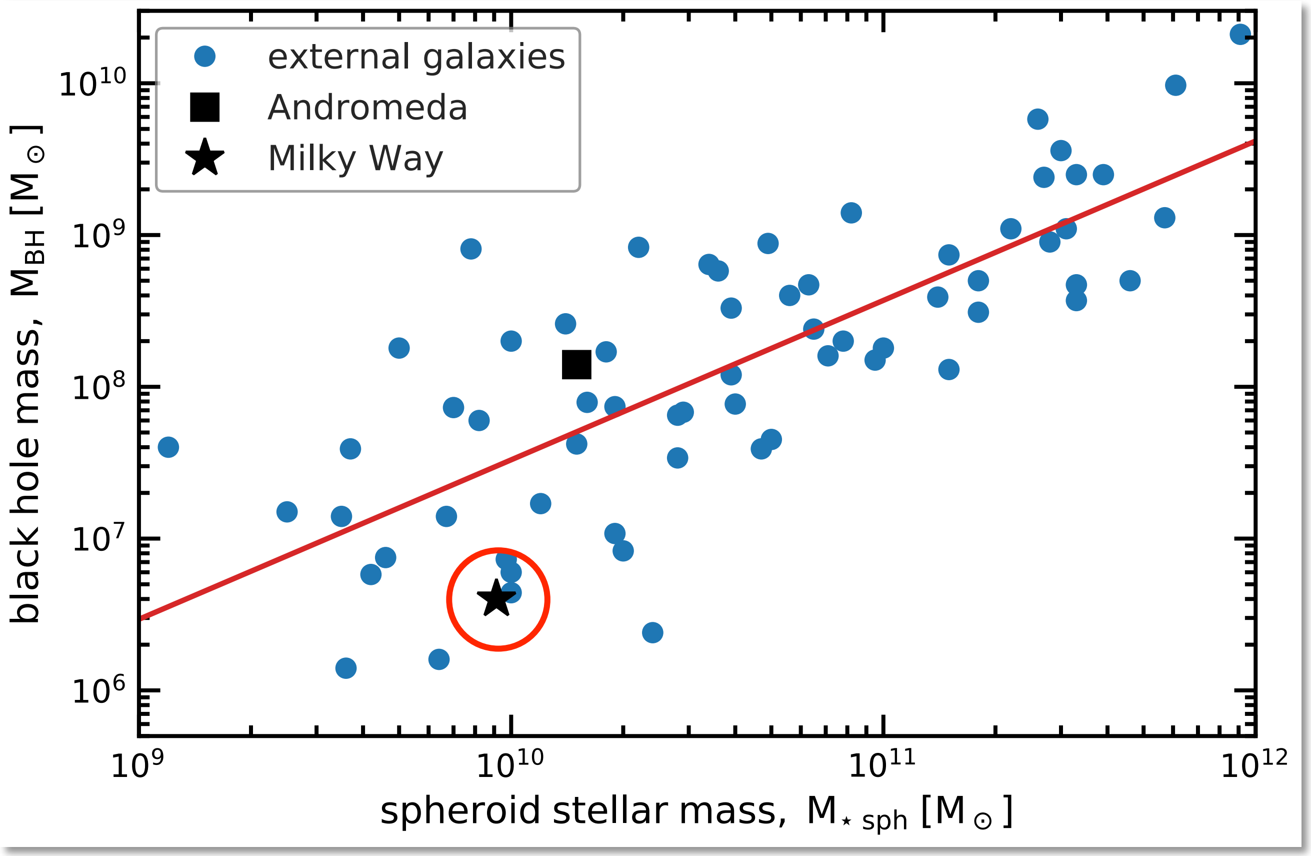

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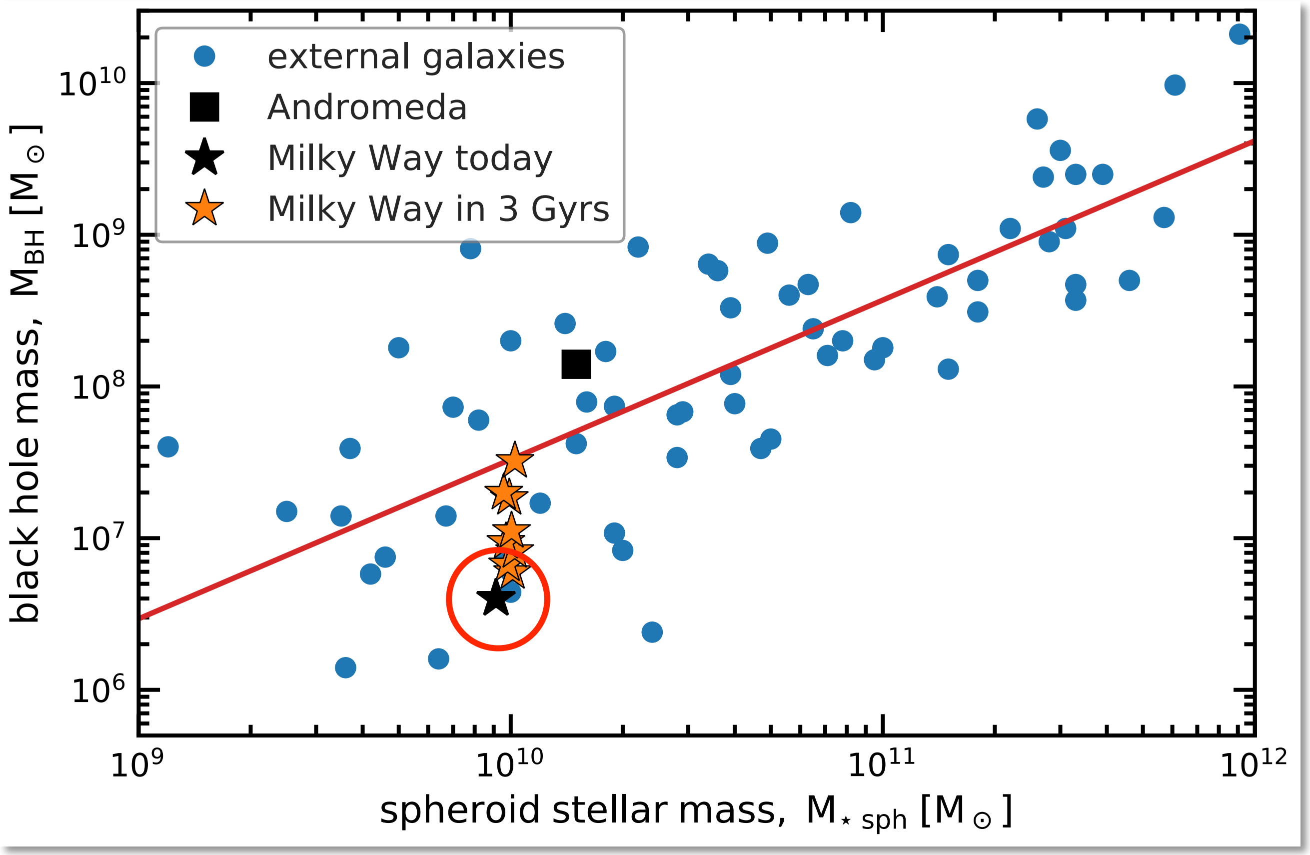
Milky Way BH can grow by up to × 10



Our BH will become typical of those in galaxies like the MW

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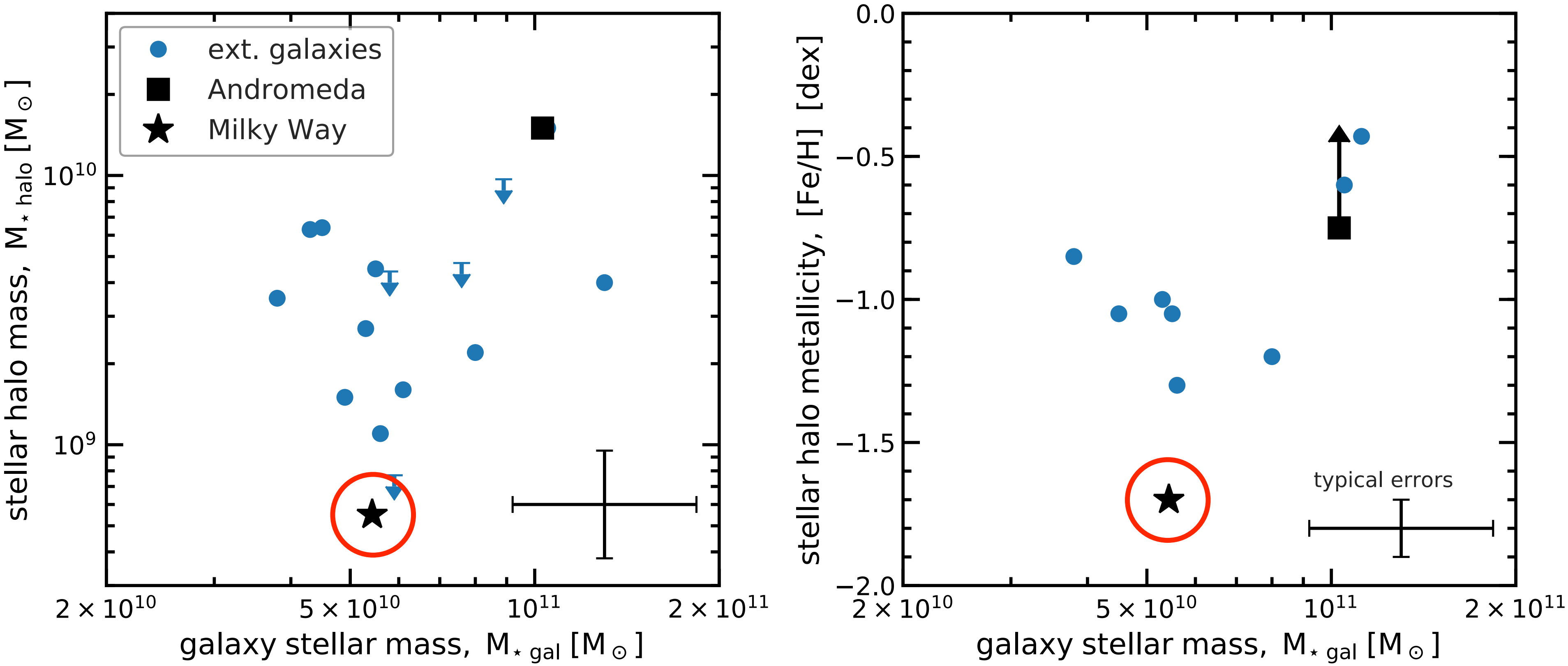

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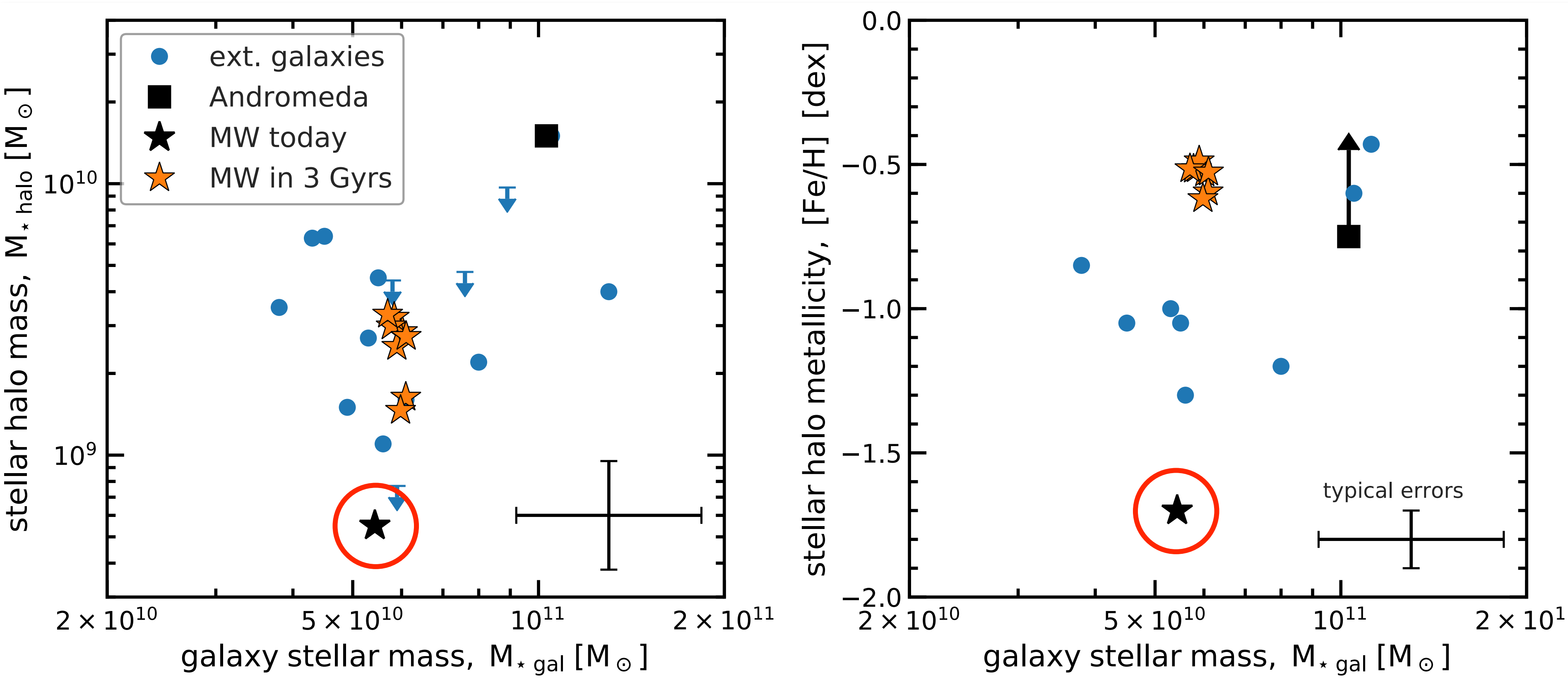
The mass and metalicity of the MW stellar mass will also become typical



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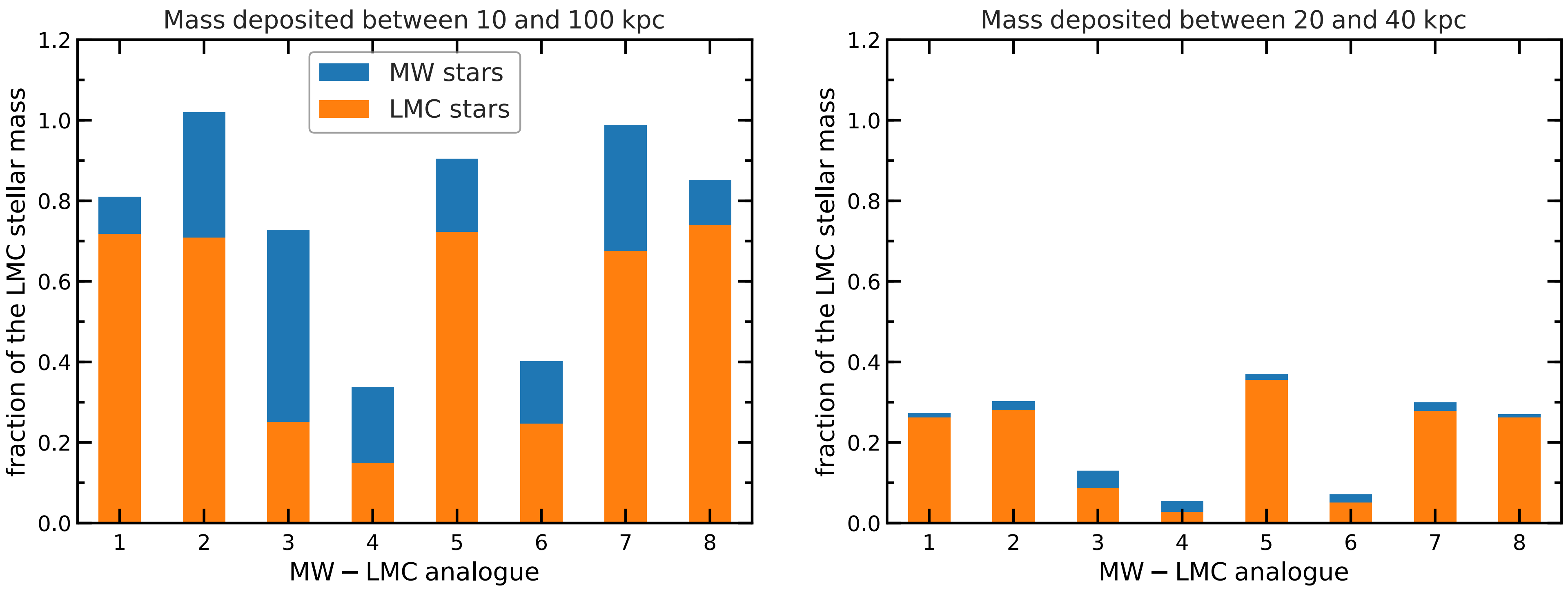
In most examples, the stellar halo will be made of LMC stars although a fraction will be scattered from the MW disk



Cautun & Frenk '17

Martin@75

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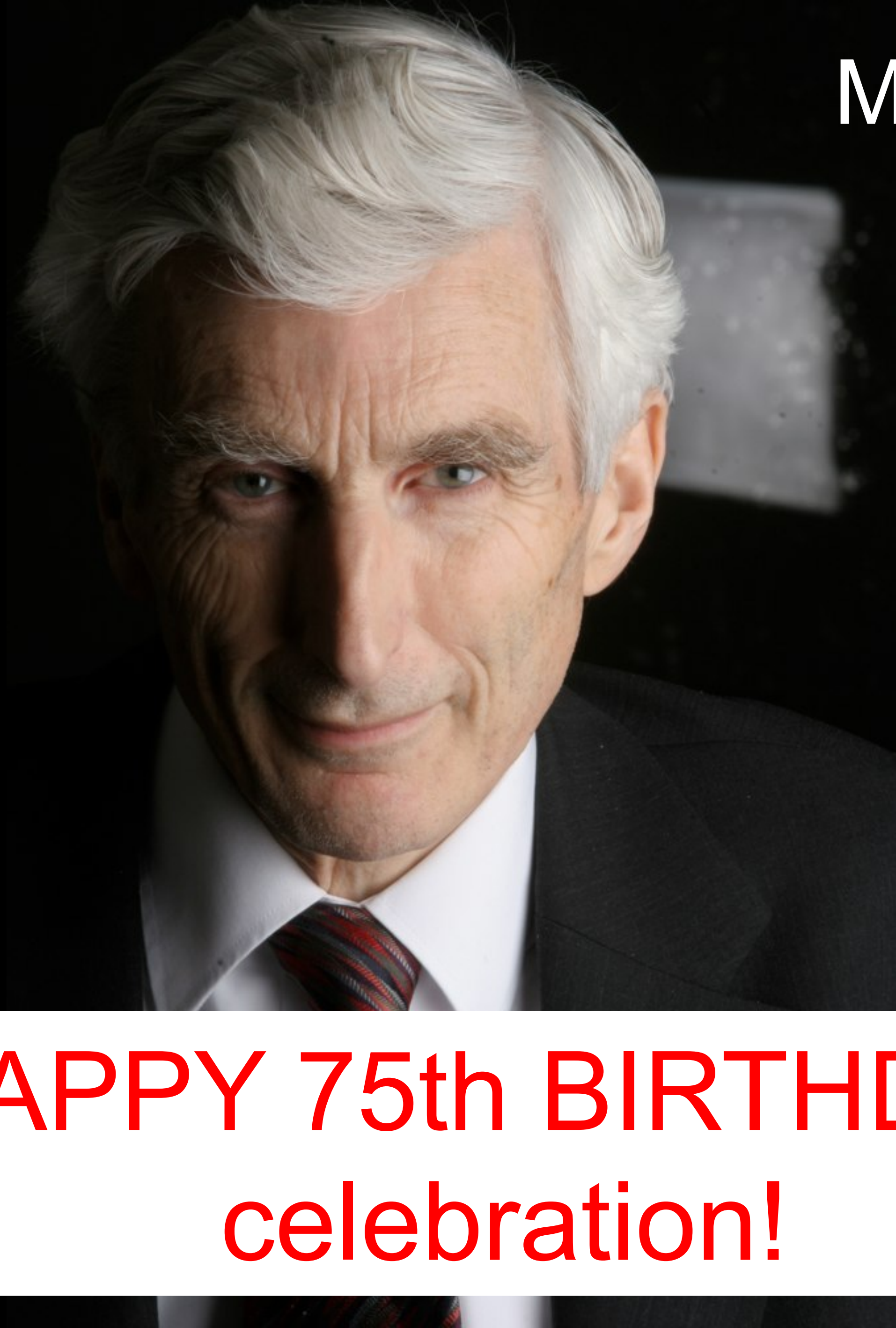

HAPPY 75th BIRTHDAY celebration!