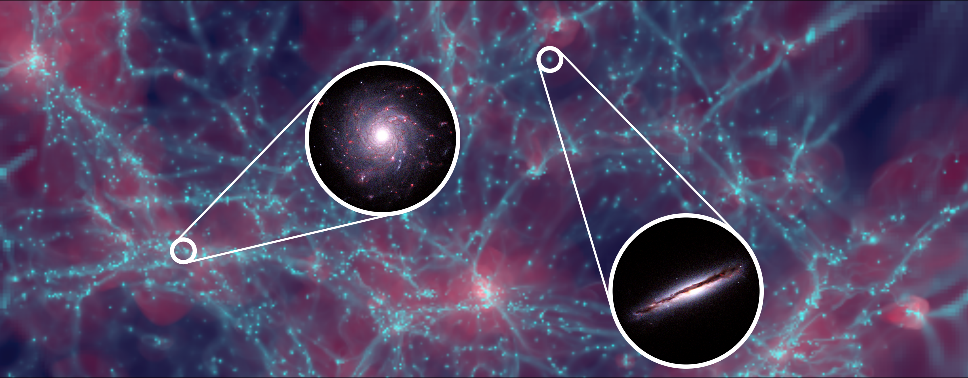
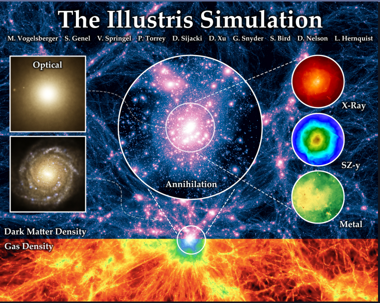
The NewHorizon Project: Resolving disks in cosmic environment



Katarina Kraljic
&
NewHorizon collaboration

Laboratoire d'Astrophysique de Marseille
June 15th, 2022, Montpellier

Simulations



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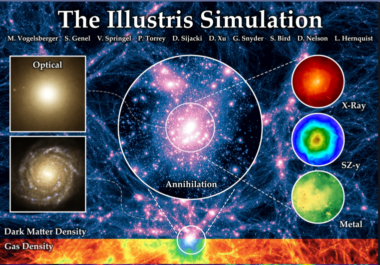

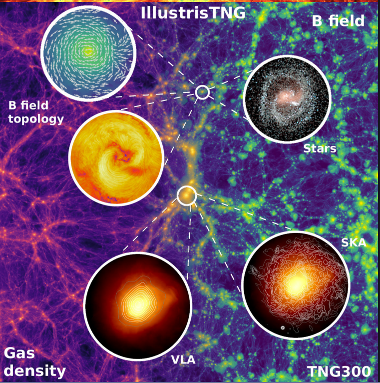

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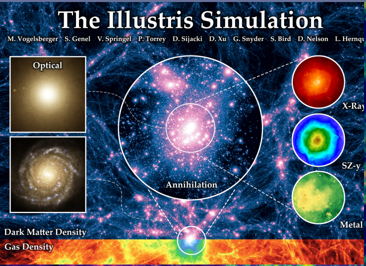
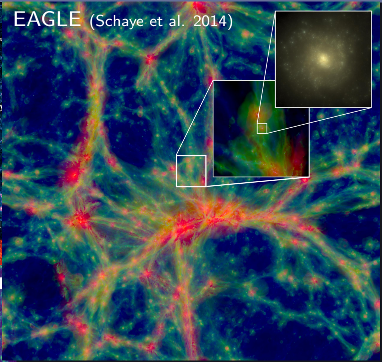
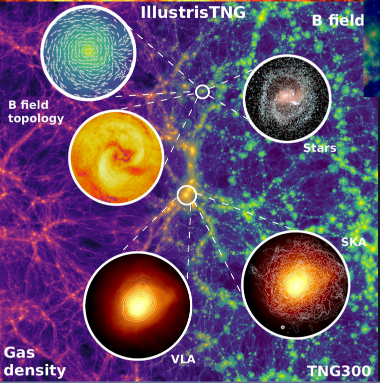
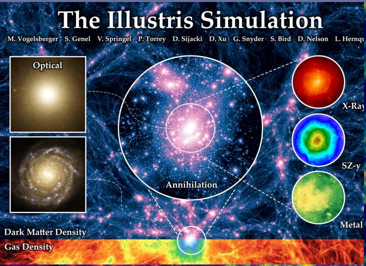
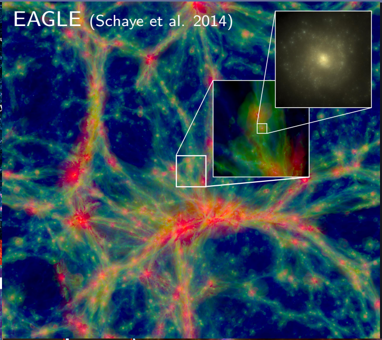




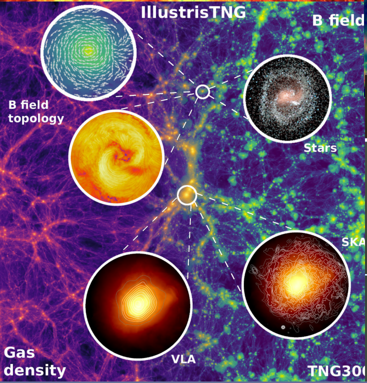




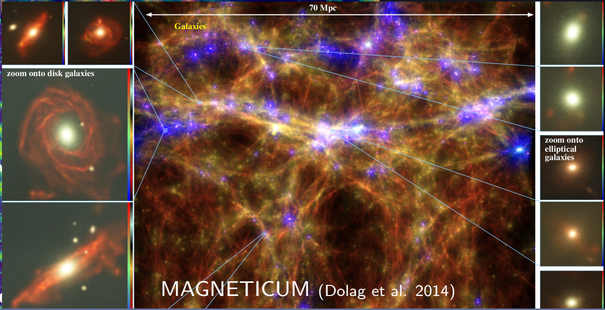
The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernqu
Optical
Annihilation
X-Ray
SZ-y
Metal
Dark Matter Density
Gas Density



EAGLE (Schaye et al. 2014)

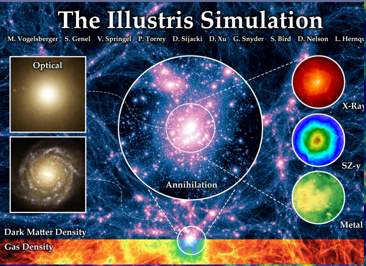


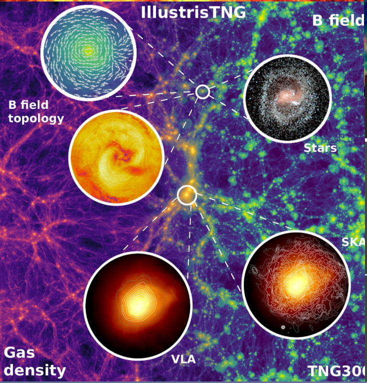
IllustrisTNG
B field
B field
topology
Stars
SKA
Gas
density
VLA
TNG30

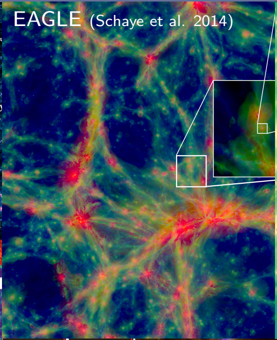


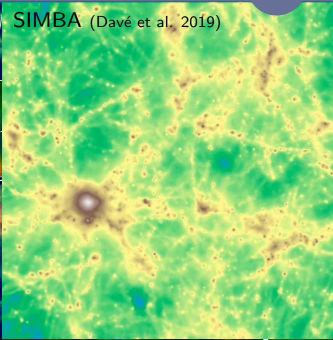
70 Mpc
Galaxies
zoom onto disk galaxies
zoom onto
elliptical
galaxies
MAGNETICUM (Dolag et al. 2014)

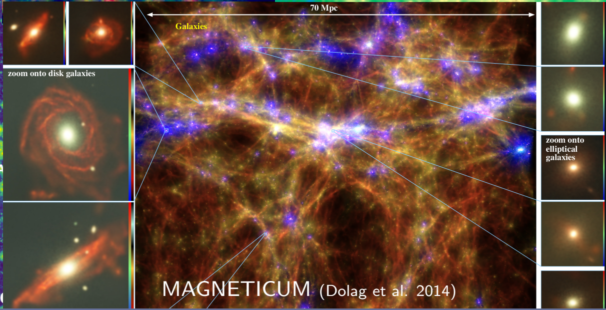
Simulations



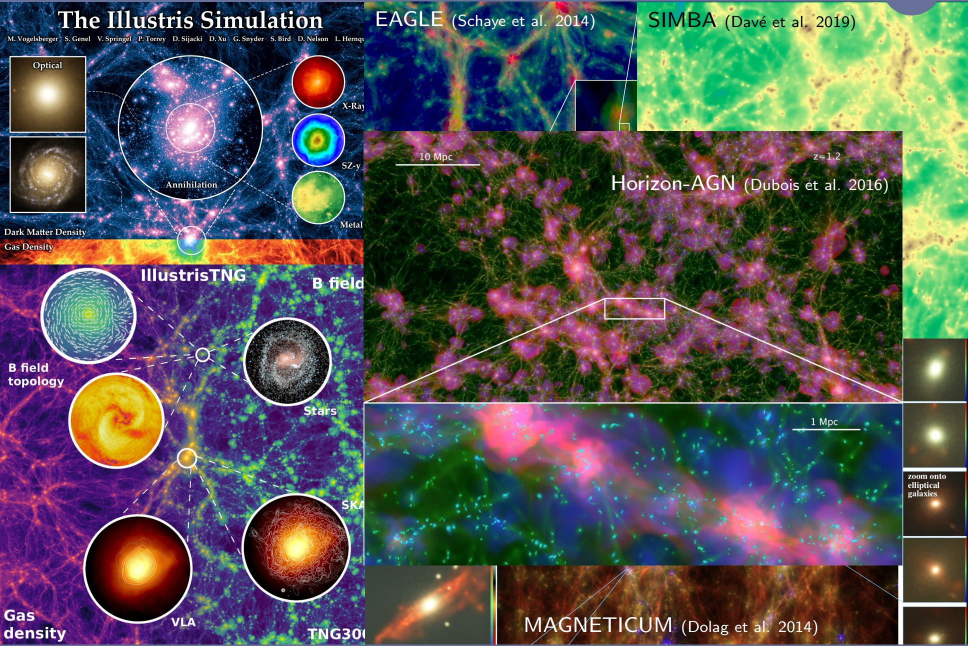








Simulations



Simulations

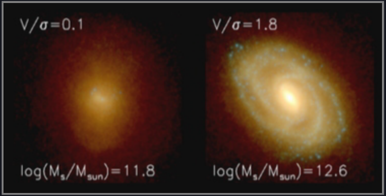
ellipticals irregular disk galaxies

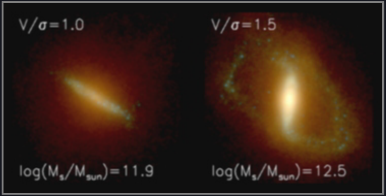
Illustris (Vogelsberger et al. 2014)

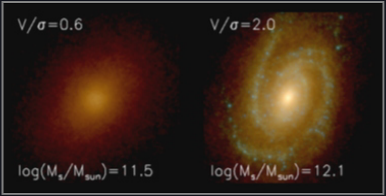
see also Horizon-AGN (Dubois et al. 2014)
Eagle (Schaye et al. 2015)

Simulations

AGN no AGN AGN no AGN

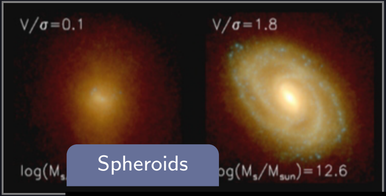






HORIZON-AGN/HORIZON-NOAGN (Dubois et al. 2014, 2016)

AGN no AGN



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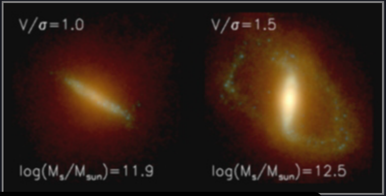

Spheroids

- *formation*: 'easy' (?) $\Longleftrightarrow$ mergers (Toomre 1977)

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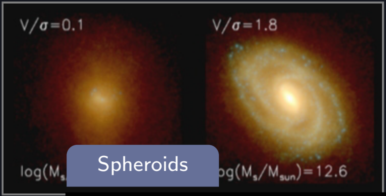

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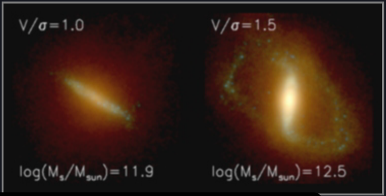

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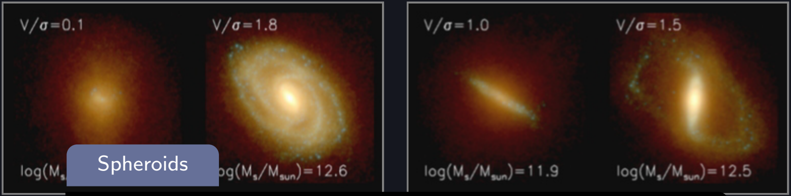
Simulations

AGN	no AGN	AGN	no AGN



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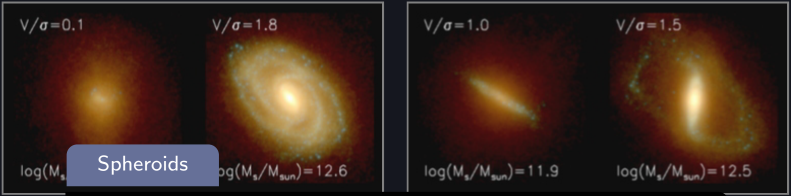

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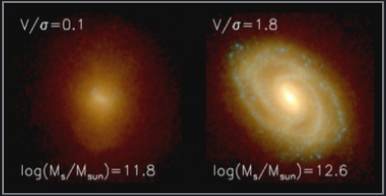
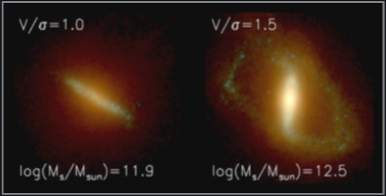
- *problems*: too massive, central SFR too high, 'cooling-flow problem', gas-rich mergers
- *origin*: too-efficient cooling & SF
- *solution*: consume or remove gas early $\longrightarrow$
  - ejective AGN feedback ('jet mode')
  - preventive AGN feedback ('radiative mode')

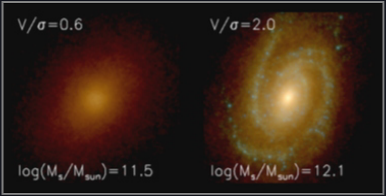
Horizon-AGN/Horizon-noAGN (Dubois et al. 2014, 2016)

Simulations

AGN no AGN AGN no AGN







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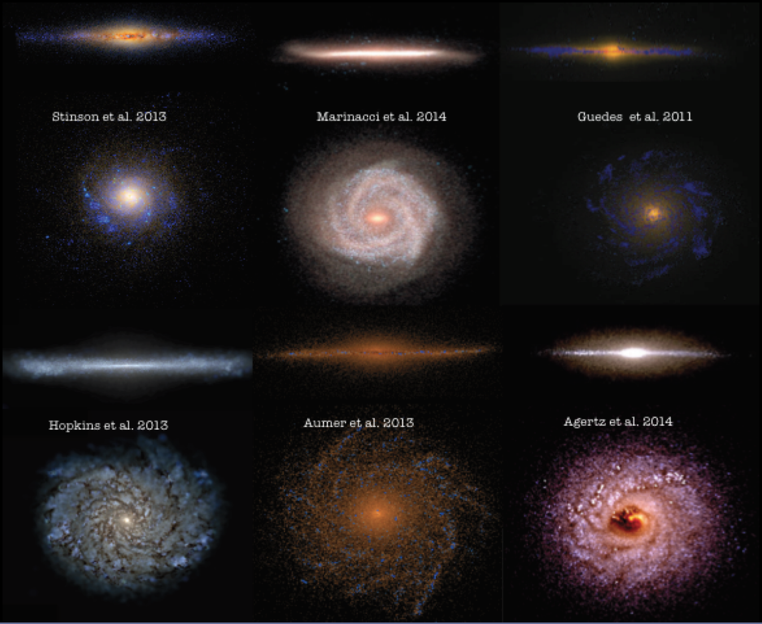
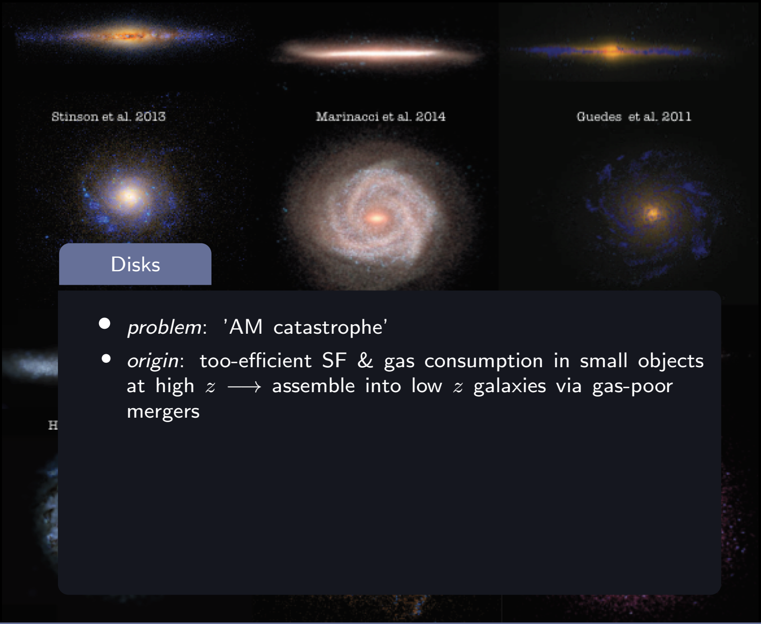


Naab & Ostriker 2016

Disks

- *problem*: 'AM catastrophe'

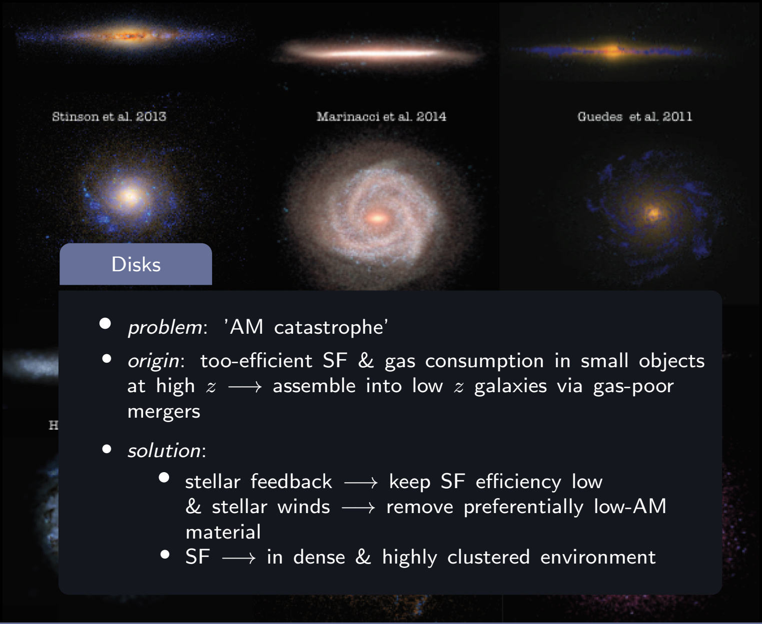


Naab & Ostriker 2016

Disks

- *problem*: 'AM catastrophe'
- *origin*: too-efficient SF & gas consumption in small objects at high $z \longrightarrow$ assemble into low z galaxies via gas-poor mergers

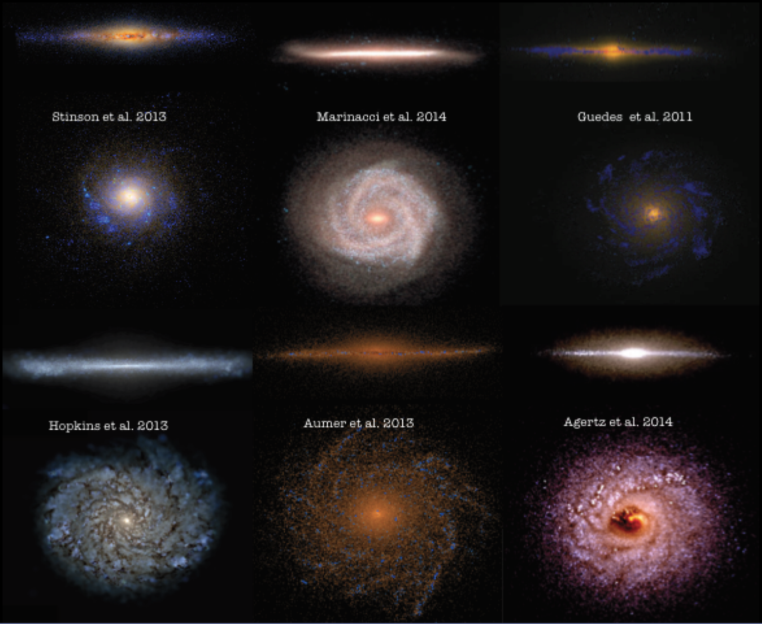
Simulations



Disks

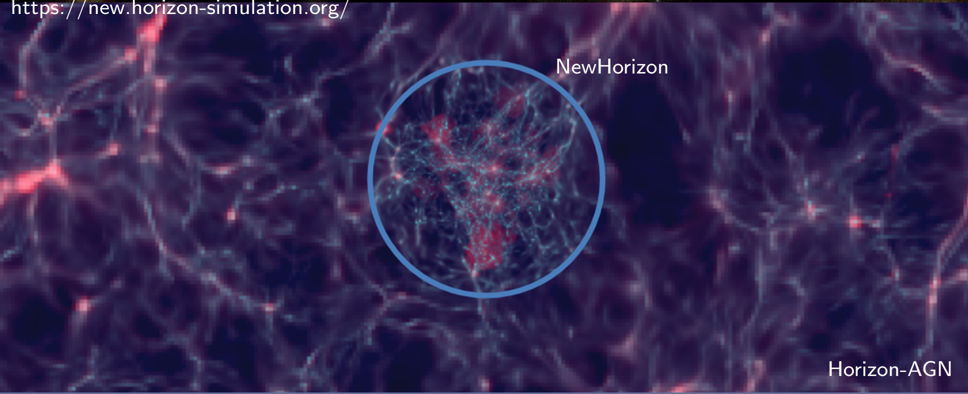
- *problem*: 'AM catastrophe'
- *origin*: too-efficient SF & gas consumption in small objects at high $z \longrightarrow$ assemble into low z galaxies via gas-poor mergers
- *solution*:
  - stellar feedback $\longrightarrow$ keep SF efficiency low
    & stellar winds $\longrightarrow$ remove preferentially low-AM material
  - SF $\longrightarrow$ in dense & highly clustered environment

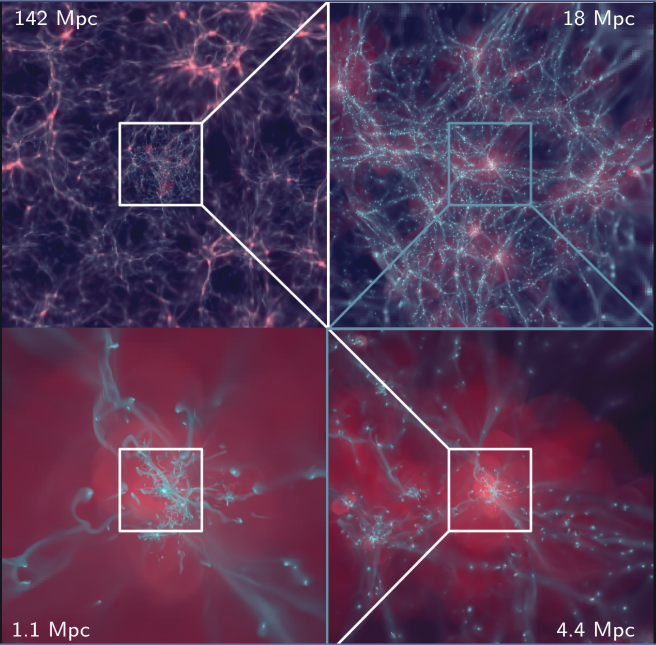
Naab & Ostriker 2016



Naab & Ostriker 2016

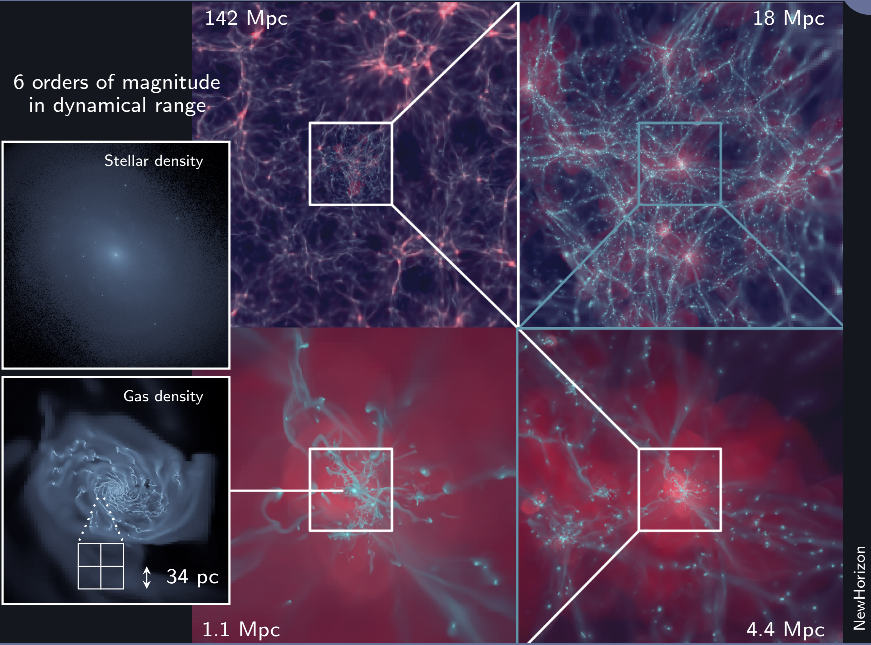
https://new.horizon-simulation.org/





NewHorizon

6 orders of magnitude
in dynamical range



- hydrodynamical cosmological simulation
- RAMSES (Teyssier 2002)

Dubois et al. 2021

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- $\mathrm{R_{sphere}} = 10\ h^{-1}$ Mpc
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Dubois et al. 2021

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Dubois et al. 2021

Turbulent star formation

SFR: $\dot{\rho_\star} = \epsilon_\star \rho_{\rm g}/t_{\rm ff}$, if $\rho_{\rm g} > 10$ H/cc
(Schmidt 1959)

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- set up by ISM properties
(no more ad hoc, const $\sim$ 1 %)

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SFE: $\epsilon_\star = f(\mathcal{M}, \alpha_{vir})$
- set up by ISM properties
(no more ad hoc, const ~ 1 %)

$$\epsilon_\star \propto \epsilon \exp \sigma_s^2 \left[1 + \mathrm{erf}\left(\frac{\sigma_s^2 - s_{crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

$$\sigma_s^2 = \ln(1 + b^2 \mathcal{M}^2)$$

- variance of the density PDF

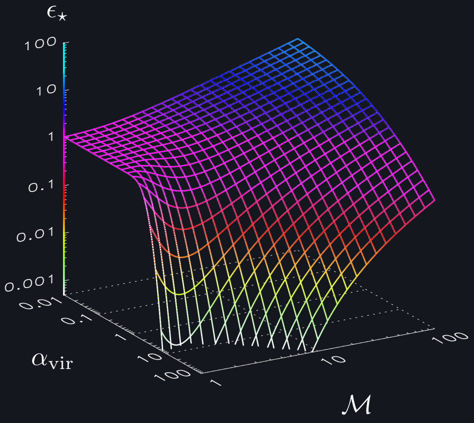
$$s_{crit} \propto \ln(\alpha_{vir} \mathcal{M}^2)$$

- critical density contrast

$$\epsilon = 0.5$$

- proto-stellar feedback parameter

multi-freefall PN model



Federrath & Klessen 2012
see also Padoan & Nordlund 2011, Hennebelle & Chabrier 2011

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Dubois et al. 2021

Mechanical Supernovae feedback

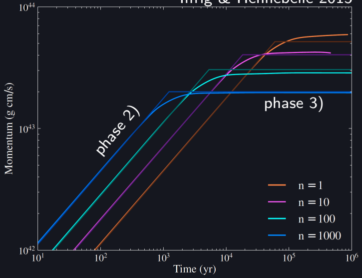
(Kimm & Cen 2014)

Three phases of SN explosions:

1) **Free expansion phase**
   - mass of the remnant dominates the swept-up mass (never resolved in practice)
2) **Energy-conserving (Sedov-Taylor) phase**
   - swept-up mass comparable to the mass of ejecta
   - the initial energy of SN is conserved
3) **Momentum-conserving (snowplough) phase**
   - the internal energy of the shocked shell has been radiated away & momentum is set up according to gas properties and energy of the explosion:

$$p_{\rm SN,snow} \approx 3 \times 10^5\,{\rm km\,s^{-1}}\,{\rm M_\odot}\,{\rm E}_{51}^{16/17}\,{\rm n}_{\rm H}^{-2/17}\,{\rm Z'}^{-0.14}$$

Iffrig & Hennebelle 2015



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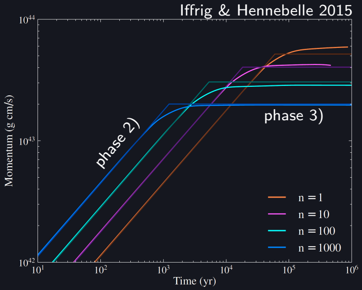
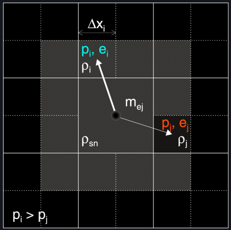
Implementation:

- if in 2) deposit internal energy
- if in 3) deposit right amount of momentum ($p_{\rm SN,snow}$)
  2 × momentum (UV from OB stars)
  (Geen et al. 2014)





Kimm & Cen 2014

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Dubois et al. 2021

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- AGN feedback & BH spin-dependent model
  (Dubois et al. 2014)

Dubois et al. 2021

Black holes & AGN feedback

BH formation:

- density $>$ SF threshold
- stellar $\sigma > 20$ km/s
- distance ≥ 50 ckpc from $\exists$ BH

Black holes & AGN feedback

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BH growth:

$\dot{M}_{\rm MBH} = (1 - \epsilon_{\rm r})\dot{M}_{\rm Bondi}$

$\epsilon_{\rm r}$ - spin-dependent radiative efficiency

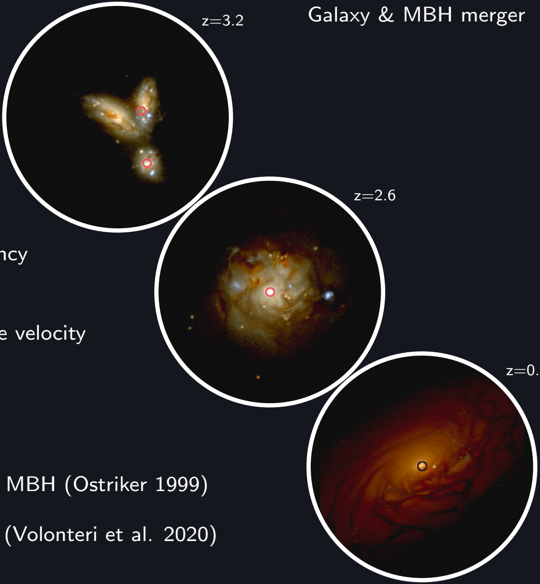
$\dot{M}_{\rm Bondi} = \frac{4\pi\bar{\rho}(GM_{\rm MBH})^2}{(\bar{u}^2+\bar{c}_s^2)^{3/2}}$

$\bar{u}$ - average MBH-to-gas relative velocity
$\bar{\rho}$ - average gas density
$\bar{c_s}$ - average gas sound speed

- capped at the Eddington rate

Black holes & AGN feedback

Galaxy & MBH merger



Volonteri et al. 2020

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BH dynamics:

- explicit drag force of the gas onto the MBH (Ostriker 1999)
- allowed to merge when: $d_{\rm rel} < 4\Delta x$
  $v_{\rm rel} < v_{\rm esc}$ (Volonteri et al. 2020)

Black holes & AGN feedback

BH spin evolution:

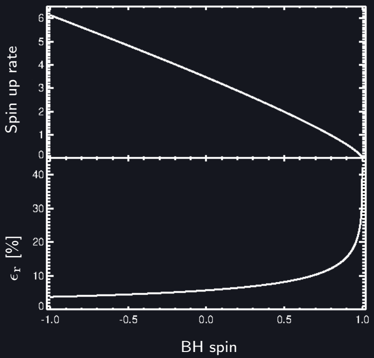
- followed on-the-fly
- takes into account: gas accretion
  MBH-MHB mergers

Black holes & AGN feedback

BH spin evolution:

- followed on-the-fly
- takes into account: gas accretion
  MBH-MHB mergers
- at high accretion rate ($\chi = \dot{M}_{\rm MBH}/\dot{M}_{\rm Edd} \geq 0.01$):
  - thin accretion disk solution (Shakura & Sunyaev 1973)
  - AM of accreted gas spins up (down) co-rotating (counter-rotating) systems

thin disc

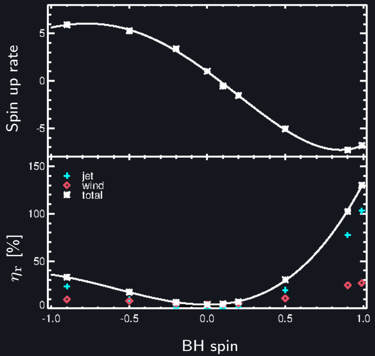


Black holes & AGN feedback

BH spin evolution:

- followed on-the-fly
- takes into account: gas accretion
  MBH-MHB mergers
- at high accretion rate ($\chi = \dot{M}_{\rm MBH}/\dot{M}_{\rm Edd} \geq 0.01$):
    - thin accretion disk solution (Shakura & Sunyaev 1973)
    - AM of accreted gas spins up (down) co-rotating (counter-rotating) systems
- at low accretion rate ($\chi < 0.01$):
    - jets powered by energy extraction from MBH rotation (Blandford & Znajek 1977)
    - MBH spin magnitude can only decrease

thick disc



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$\Leftrightarrow$ controls radiative and feedback efficiency

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AGN feedback:

- released power

$$\dot{E}_{\rm AGN,R,Q} = \eta_{\rm R,Q}\dot{M}_{\rm MBH}c^2$$

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quasar thermal mode

- thermal energy released only

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- thermal energy released only
  $$\eta_{\rm Q} = 0.15\epsilon_{\rm r}$$

radio jet mode

- bipolar jets: 10^4 km/s; $0°$ angle
- deposit mass
  momentum
  energy

- hydrodynamical cosmological simulation
- RAMSES (Teyssier 2002)
- $R_{sphere} = 10\ h^{-1}$ Mpc
  $\Delta x = 34$ pc (vs 1 kpc in Horizon-AGN)
- $M_{DM} = 10^6\ M_\odot$ (vs $10^8\ M_\odot$ in Horizon-AGN)
  $M_\star = 10^4\ M_\odot$ (vs $10^6\ M_\odot$ in Horizon-AGN)
- SF: turbulent criterion (Padoan & Nordlund 2011)
  $\epsilon_\star = f(\mathcal{M}, \alpha_{vir})$ (vs const $\sim$ 1% in Horizon-AGN)
- mechanical SNII feedback (Kimm & Cen 2014)
- AGN feedback & BH spin-dependent model
  (Dubois et al. 2014)

Dubois et al. 2021

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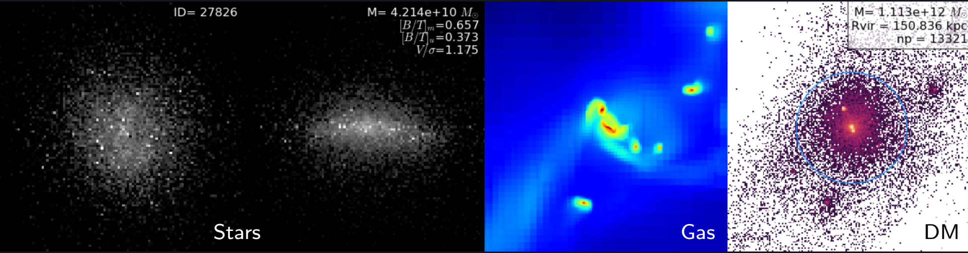
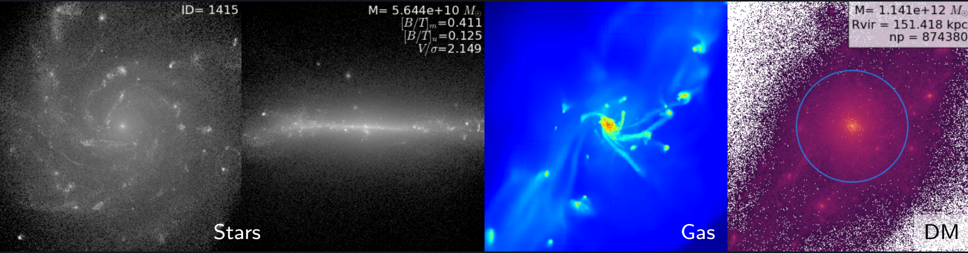
- mechanical SNII feedback (Kimm & Cen 2014)
- AGN feedback & BH spin-dependent model (Dubois et al. 2014)
- outputs every 15 Myr ($\sim$ 150 GB each)
- to z~ 0.8, French & Korean effort: 25 Mhr
  to z~ 0.17, Grand Challenge project
  Extreme-Horizon: 65 Mhr at TGCC

Dubois et al. 2021

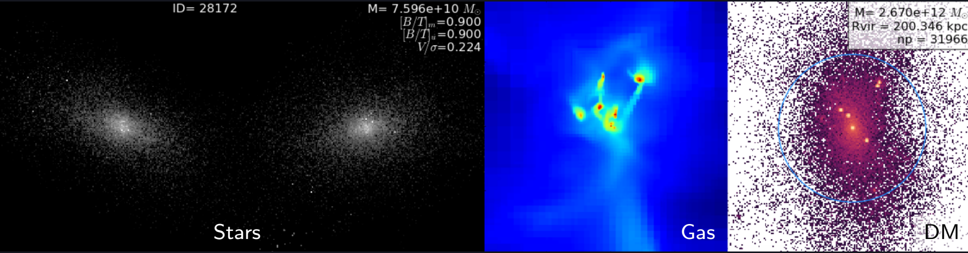
Horizon-AGN



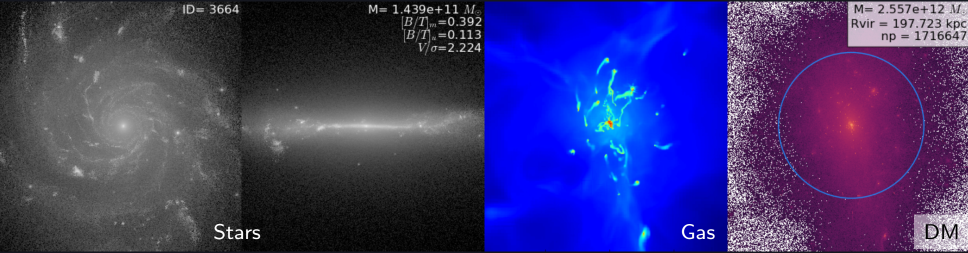
NewHorizon

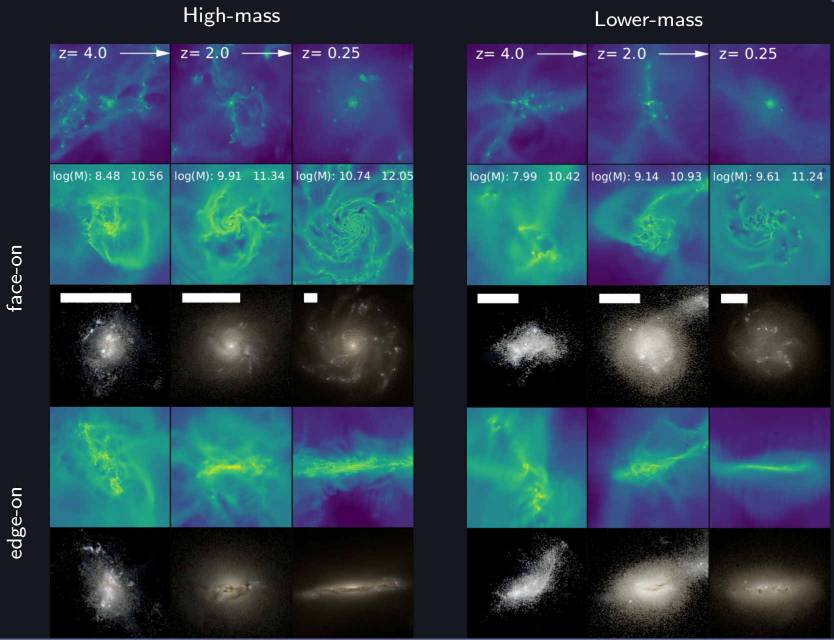


Horizon-AGN

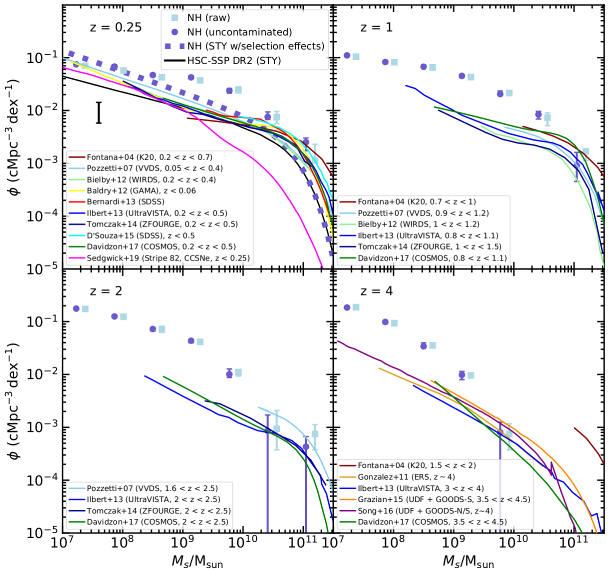


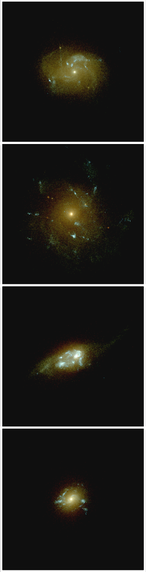
NewHorizon



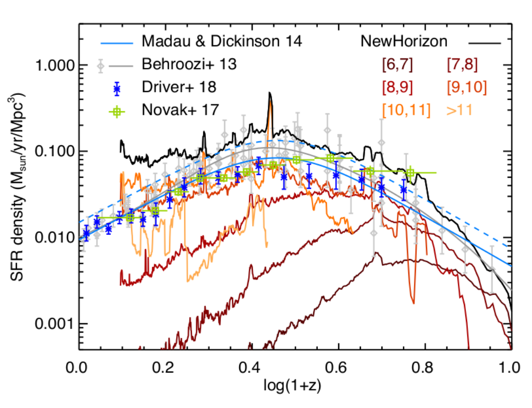

High-mass
Lower-mass
z= 4.0
z= 2.0
z= 0.25
z= 4.0
z= 2.0
z= 0.25
log(M): 8.48 10.56
log(M): 9.91 11.34
log(M): 10.74 12.05
log(M): 7.99 10.42
log(M): 9.14 10.93
log(M): 9.61 11.24
face-on
edge-on

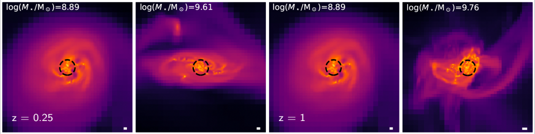
NewHorizon

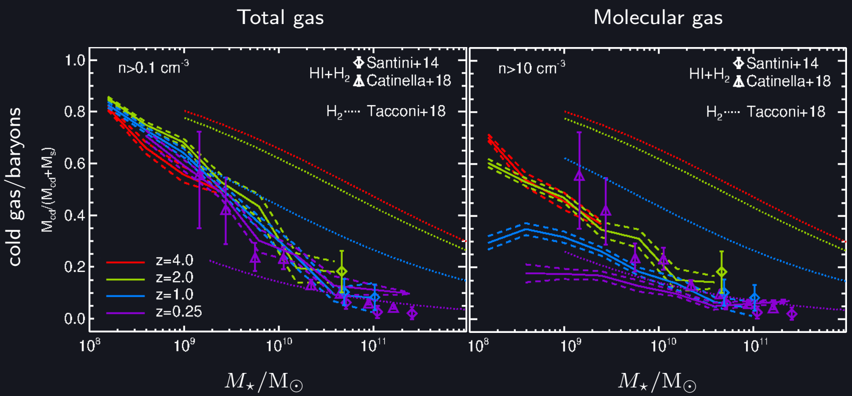




Dubois et al. 2021

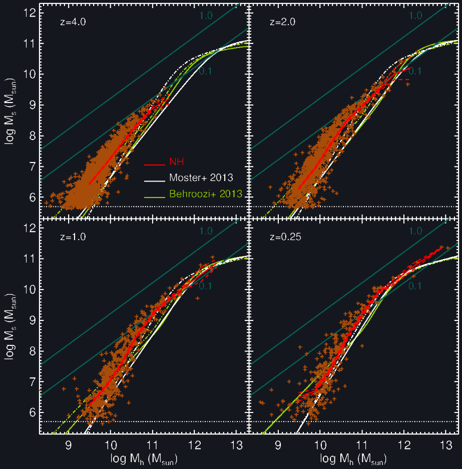

Madau & Dickinson 14
Behroozi+ 13
Driver+ 18
Novak+ 17
NewHorizon
[6,7] [7,8]
[8,9] [9,10]
[10,11] >11
SFR density (M_sun/yr/Mpc^3)
1.000
0.100
0.010
0.001
0.0
0.2
0.4
0.6
0.8
1.0
log(1+z)


log(M*/M☉)=8.89
z = 0.25
log(M*/M☉)=9.61
log(M*/M☉)=8.89
z = 1
log(M*/M☉)=9.76



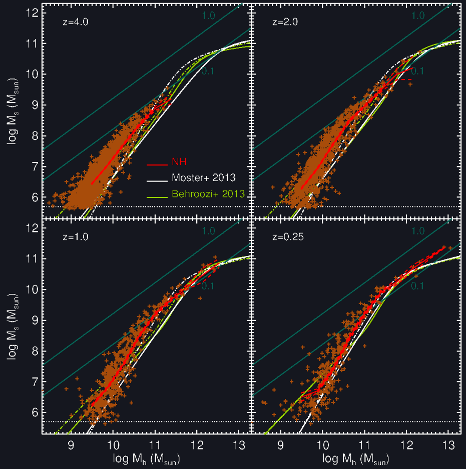
- less gas rich at high $M_\star$ and low z: qualitative agreement
- significantly less molecular gas at low $M_\star$ and high z

Stellar-to-halo mass

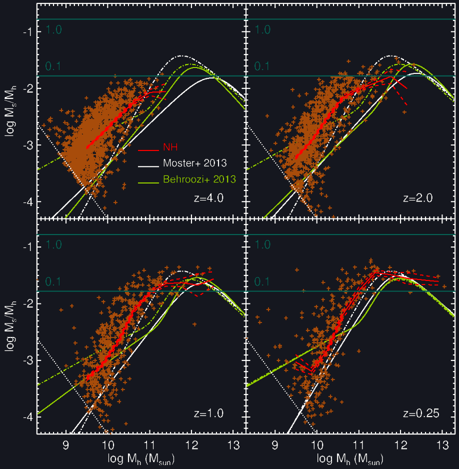


- fairly good qualitative agreement

Stellar-to-halo mass

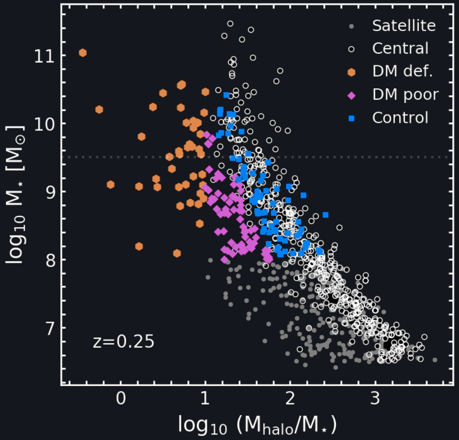


Baryon conversion efficiency

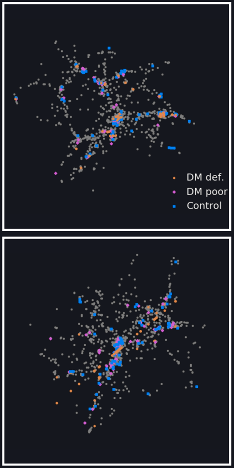


- fairly good qualitative agreement

- overestimated below the peak

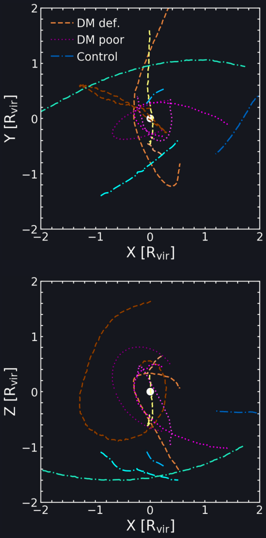


Cosmic web



Jackson et al. 2021

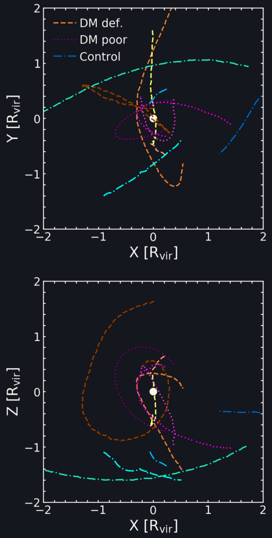
Orbits



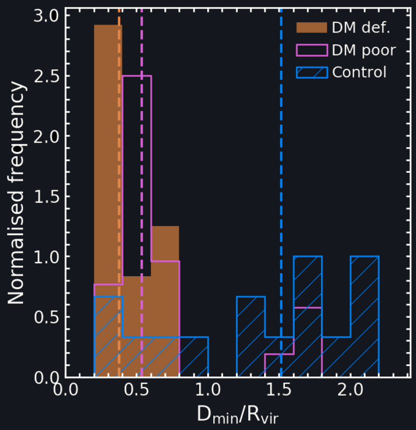
- DM deficient/poor exhibit closer orbits than control

Jackson et al. 2021

Orbits



Minimum distance satellite-central



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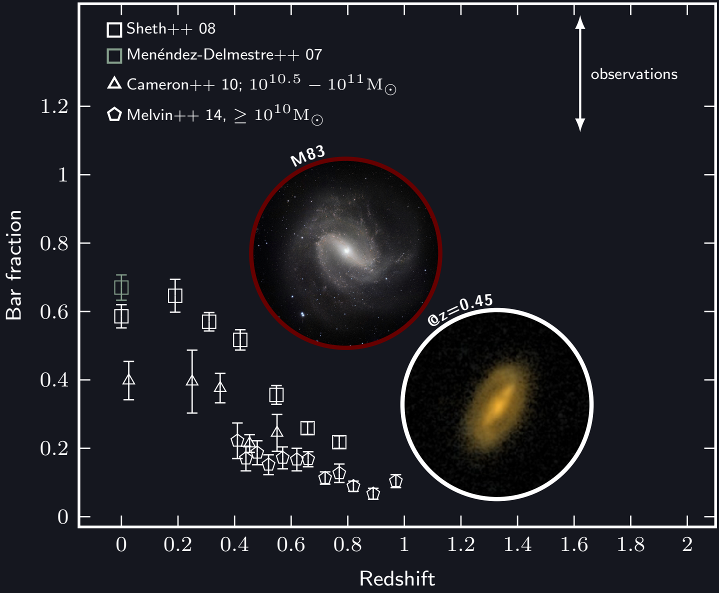
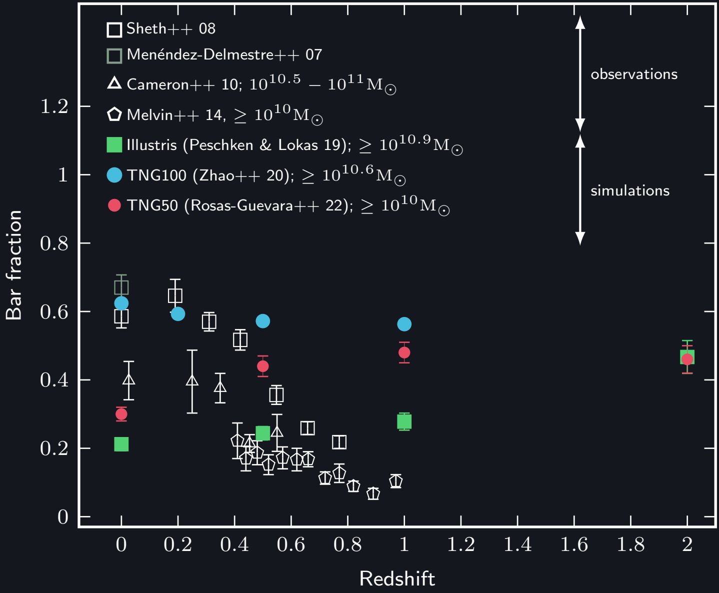
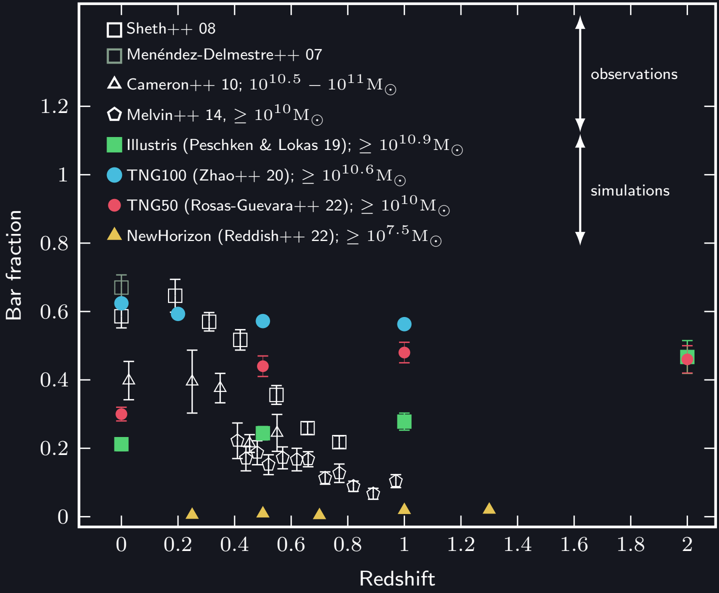
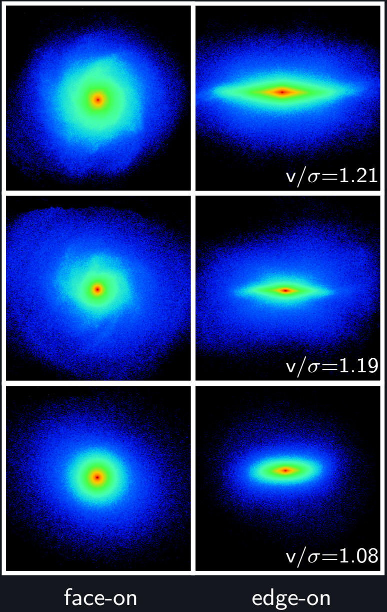
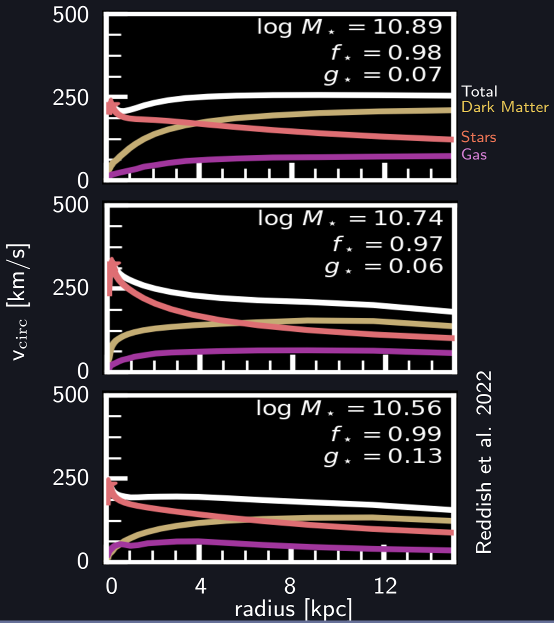
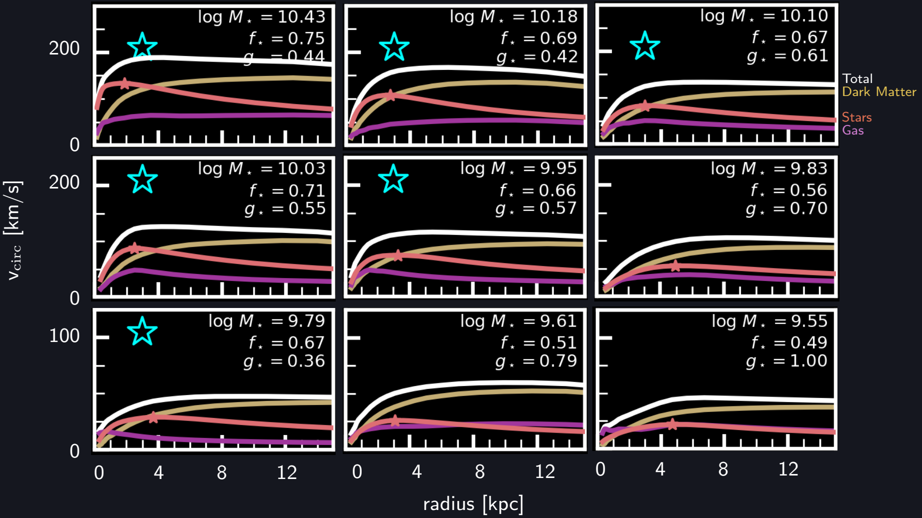

Sheth++ 08
Menéndez-Delmestre++ 07
Cameron++ 10; $10^{10.5} - 10^{11} M_\odot$
Melvin++ 14, $\geq 10^{10} M_\odot$
observations
M83
@z=0.45
Bar fraction
Redshift
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

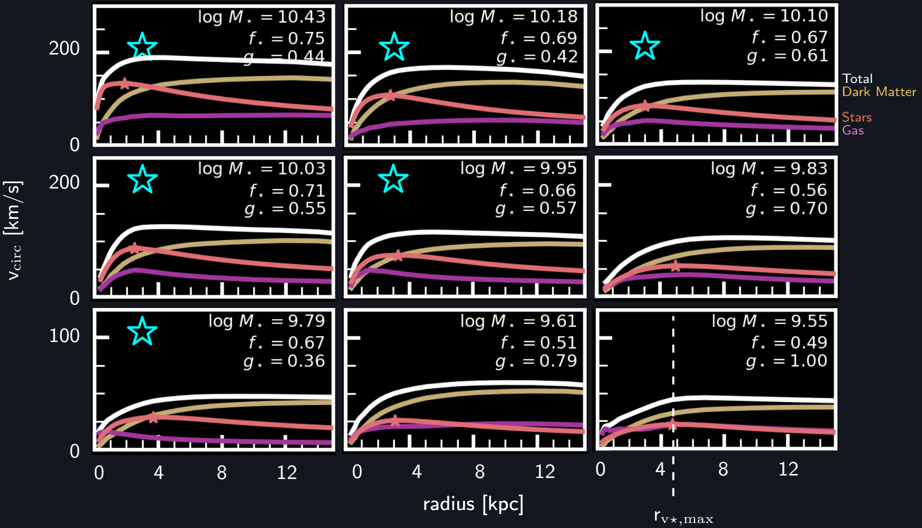

Sheth++ 08
Menéndez-Delmestre++ 07
Cameron++ 10; $10^{10.5} - 10^{11} M_\odot$
Melvin++ 14, $\geq 10^{10} M_\odot$
Illustris (Peschken & Lokas 19); $\geq 10^{10.9} M_\odot$
TNG100 (Zhao++ 20); $\geq 10^{10.6} M_\odot$
TNG50 (Rosas-Guevara++ 22); $\geq 10^{10} M_\odot$
observations
simulations
Bar fraction
0
0.2
0.4
0.6
0.8
1
1.2
Redshift
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


Sheth++ 08
Menéndez-Delmestre++ 07
Cameron++ 10; $10^{10.5} - 10^{11} M_\odot$
Melvin++ 14, $\geq 10^{10} M_\odot$
Illustris (Peschken & Lokas 19); $\geq 10^{10.9} M_\odot$
TNG100 (Zhao++ 20); $\geq 10^{10.6} M_\odot$
TNG50 (Rosas-Guevara++ 22); $\geq 10^{10} M_\odot$
NewHorizon (Reddish++ 22); $\geq 10^{7.5} M_\odot$
observations
simulations
Bar fraction
Redshift
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


v/σ=1.21
v/σ=1.19
v/σ=1.08
face-on
edge-on


log M⋆ = 10.89
f⋆ = 0.98
g⋆ = 0.07
log M⋆ = 10.74
f⋆ = 0.97
g⋆ = 0.06
log M⋆ = 10.56
f⋆ = 0.99
g⋆ = 0.13
Total
Dark Matter
Stars
Gas
v_circ [km/s]
radius [kpc]
0
250
500
4
8
12
Reddish et al. 2022


log $M_\star$ = 10.43
$f_\star$ = 0.75
$g_\star$ = 0.44
log $M_\star$ = 10.18
$f_\star$ = 0.69
$g_\star$ = 0.42
log $M_\star$ = 10.10
$f_\star$ = 0.67
$g_\star$ = 0.61
log $M_\star$ = 10.03
$f_\star$ = 0.71
$g_\star$ = 0.55
log $M_\star$ = 9.95
$f_\star$ = 0.66
$g_\star$ = 0.57
log $M_\star$ = 9.83
$f_\star$ = 0.56
$g_\star$ = 0.70
log $M_\star$ = 9.79
$f_\star$ = 0.67
$g_\star$ = 0.36
log $M_\star$ = 9.61
$f_\star$ = 0.51
$g_\star$ = 0.79
log $M_\star$ = 9.55
$f_\star$ = 0.49
$g_\star$ = 1.00
Total
Dark Matter
Stars
Gas
v_{circ} [km/s]
200
0
200
0
100
0
0
4
8
12
radius [kpc]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$g_\star$ = 0.44
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$g_\star$ = 0.42
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log $M_\star$ = 10.03
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log $M_\star$ = 9.83
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$g_\star$ = 0.70
log $M_\star$ = 9.79
$f_\star$ = 0.67
$g_\star$ = 0.36
log $M_\star$ = 9.61
$f_\star$ = 0.51
$g_\star$ = 0.79
log $M_\star$ = 9.55
$f_\star$ = 0.49
$g_\star$ = 1.00
Total
Dark Matter
Stars
Gas
v_{circ} [km/s]
200
0
200
0
100
0
0 4 8 12
0 4 8 12
0 4 8 12
radius [kpc]
$r_{v\star,max}$

$$f_\star \equiv \frac{v_\star(r\star,\max)}{v_{tot}(r\star,\max)}$$

- how 'maximal' the galaxy is

$$f_\star \equiv \frac{v_\star(r\star,\max)}{v_{tot}(r\star,\max)}$$

- how 'maximal' the galaxy is

$$g_\star \equiv \frac{v_{gas}(r\star,\max)}{v_\star(r\star,\max)}$$

- gas fraction in galaxy

$$f_\star \equiv \frac{v_\star(\mathrm{r}\star,\mathrm{max})}{v_{\mathrm{tot}}(\mathrm{r}\star,\mathrm{max})}$$

- how 'maximal' the galaxy is

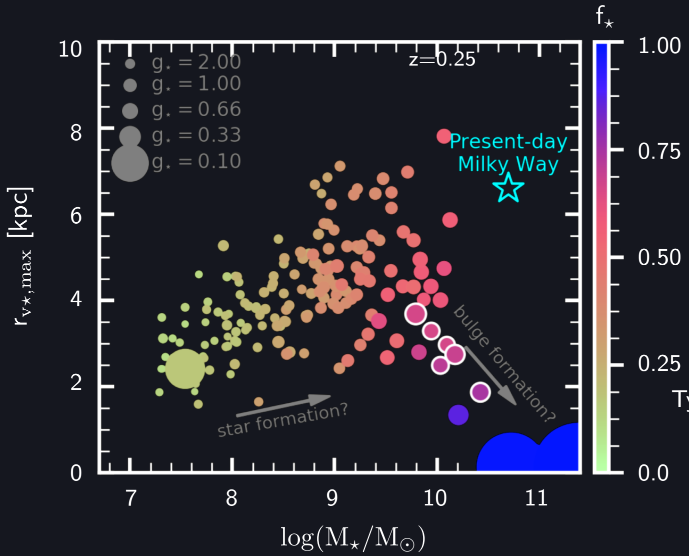
$$g_\star \equiv \frac{v_{\mathrm{gas}}(\mathrm{r}\star,\mathrm{max})}{v_\star(\mathrm{r}\star,\mathrm{max})}$$

- gas fraction in galaxy

Typical values promoting bar formation

$$g_\star < 0.66$$

$$0.4 < f_\star < 0.8$$



$$f_\star \equiv \frac{v_\star(r\star,max)}{v_{tot}(r\star,max)}$$

- how 'maximal' the galaxy is

$$g_\star \equiv \frac{v_{gas}(r\star,max)}{v_\star(r\star,max)}$$

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Typical values promoting bar formation

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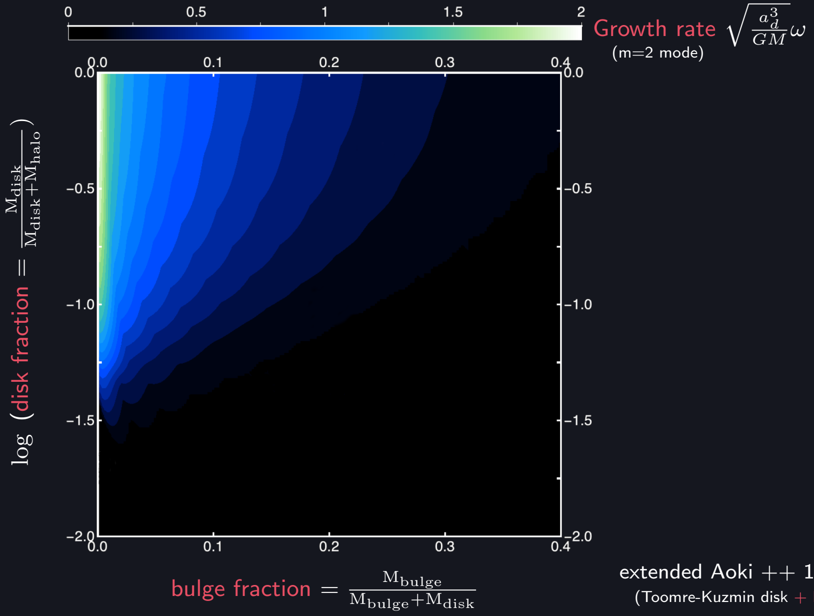
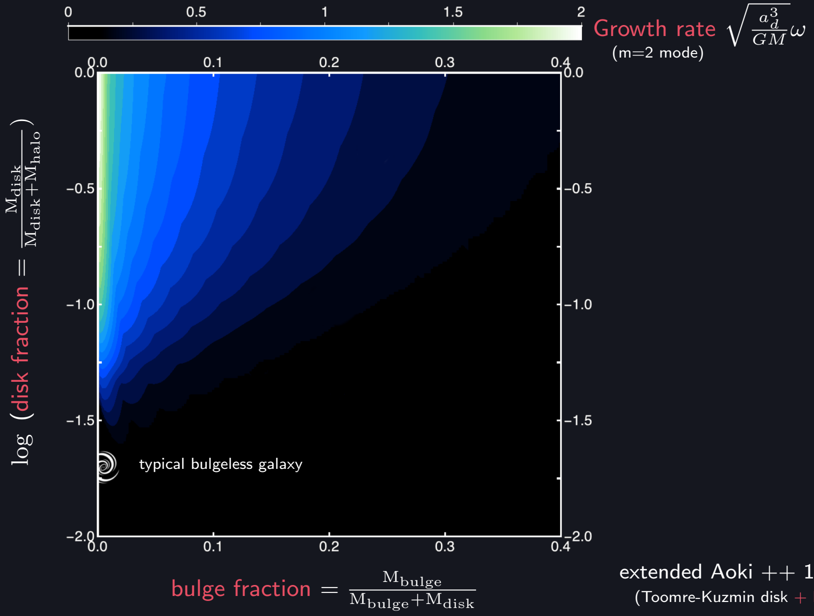
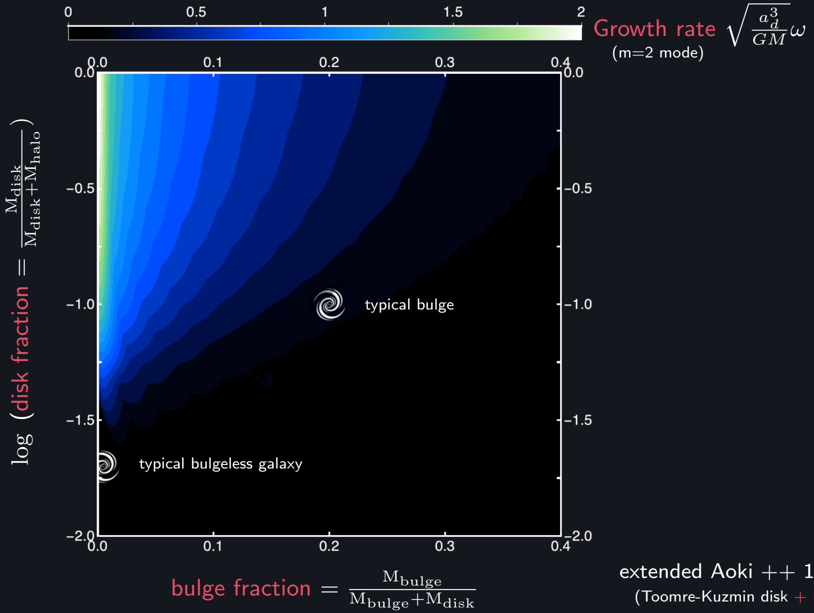


extended Aoki ++ 1979 model

(Toomre-Kuzmin disk + halo + bulge)



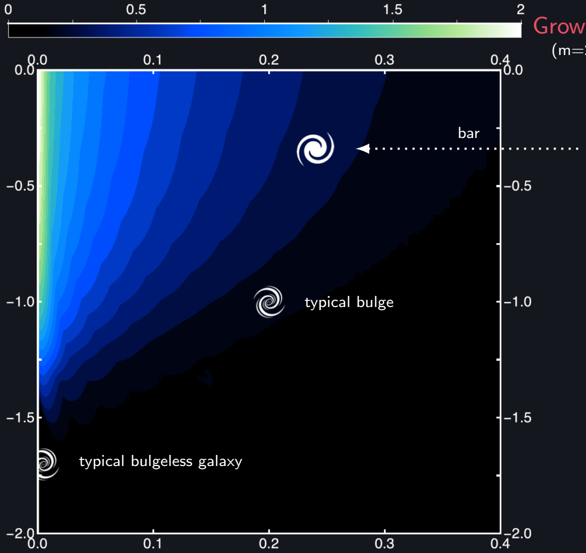
extended Aoki ++ 1979 model
(Toomre-Kuzmin disk + halo + bulge)



extended Aoki ++ 1979 model

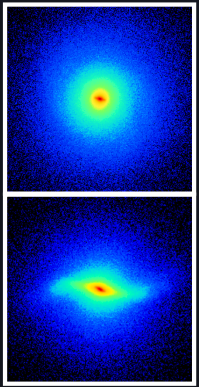
(Toomre-Kuzmin disk + halo + bulge)

Growth rate $\sqrt{\frac{a_d^3}{GM}}\omega$
(m=2 mode)



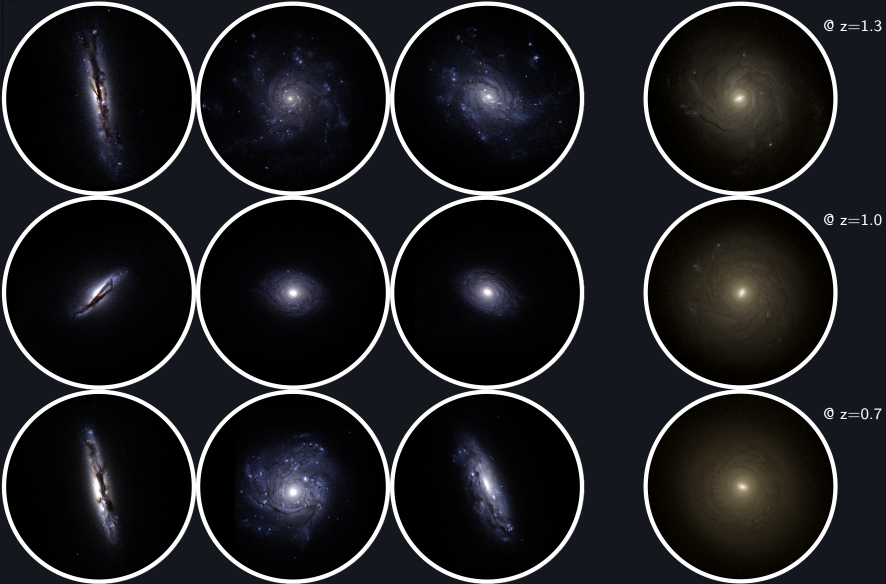
log (disk fraction $= \frac{M_{disk}}{M_{disk}+M_{halo}}$)

bulge fraction $= \frac{M_{bulge}}{M_{bulge}+M_{disk}}$



@ z=1.3

extended Aoki ++ 1979 model
(Toomre-Kuzmin disk + halo + bulge)



@ z=1.3
@ z=1.0
@ z=0.7