Numerical simulations of galaxies: (biased) status

Cosmological simulations of “Milky Way-like” galaxies

Emmanuel Nezri

Laboratoire d’Astrophysique de Marseille

News from the dark

Episode 8: from particle physics and cosmology

11-13 september 2023, ULB Brussels

Some references :

- **Cosmological Simulations of Galaxy Formation**

  Mark Vogelsberger[1], Federico Marinacci[2], Paul Torrey[3], and Ewald Puchwein[4]

  arXiv:1909.07976

- **Theoretical Challenges in Galaxy Formation**

  Thorsten Naab[1] & Jeremiah P. Ostriker[2,3]

  arXiv:1612.06891

- *GISM 2021 Florent Renaud*

  https://ismgalaxies2021.sciencesconf.org/

GRAVITY: Dark matter (+Stars)

Modeling dark matter

collisionless Boltzmann equation: $$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \frac{\partial \Phi}{\partial \mathbf{r}}\frac{\partial f}{\partial \mathbf{v}} = 0$$

Poisson's equation: $$\nabla^2\Phi = 4\pi G \int f \mathrm{d}\mathbf{v}$$

The collisionless Boltzmann equation describes the evolution of the phase-space density or distribution function of dark matter, $f = f(\mathbf{r}, \mathbf{v}, t)$, under the influence of the collective gravitational potential, Φ, given by Poisson's equation. The collisionless Boltzmann equation states the conservation of the local phase-space density; i.e. Liouville's theorem.

HYDRO: Gas

Modeling cosmic gas

Eulerian formulation:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

$$\frac{\partial \rho\mathbf{v}}{\partial t} + \nabla\cdot(\rho\mathbf{v}\otimes\mathbf{v} + P\mathbb{1}) = 0$$

$$\frac{\partial \rho e}{\partial t} + \nabla\cdot(\rho e + P)\mathbf{v} = 0$$

Lagrangian formulation:

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho\nabla\cdot\mathbf{v}$$

$$\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla P$$

$$\frac{\mathrm{D}e}{\mathrm{D}t} = -\frac{1}{\rho}\nabla\cdot P\mathbf{v}$$

Arbitrary Lagrangian-Eulerian formulation:

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho \mathrm{d}V = -\int_S \rho(\mathbf{v}-\mathbf{w})\cdot\mathbf{n}\mathrm{d}S$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho\mathbf{v} \mathrm{d}V = -\int_S \rho\mathbf{v}(\mathbf{v}-\mathbf{w})\cdot\mathbf{n}\mathrm{d}S - \int_S P\mathbf{n}\mathrm{d}S$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\int_V \rho e \mathrm{d}V = -\int_S \rho e(\mathbf{v}-\mathbf{w})\cdot\mathbf{n}\mathrm{d}S - \int_S P\mathbf{v}\cdot\mathbf{n}\mathrm{d}S$$

Different forms of the hydrodynamical equations. $\mathrm{D}/\mathrm{d}t \equiv \partial/\partial t + \mathbf{v}\cdot\nabla$ denotes the Lagrangian derivative and $e = u + \mathbf{v}^2/2$ the total energy per unit mass. The equations are closed through $P = (\gamma - 1)\rho u$ with $\gamma = 5/3$. For the arbitrary Lagrangian-Eulerian formulation the grid moves with velocity $\mathbf{w}$ and cell volumes evolve as $\mathrm{d}V/\mathrm{d}t = \int_V (\nabla\cdot\mathbf{w})\,\mathrm{d}V$.

arXiv:1909.07976

Some codes

Table 1: Major galaxy formation simulation codes

code name	gravity treatment[a]	hydrodynamics treatment[b]	parallelization technique[c]	code availability[d]	primary reference
ART	PM/ML	AMR	data-based	public	Kravtsov (1997)[27]
RAMSES	PM/ML	AMR	data-based	public	Teyssier (2002)[38]
GADGET-2/3	TreePM	SPH	data-based	public	Springel (2005)[39]
Arepo	TreePM	MMFV	data-based	public	Springel (2010)[40]
Enzo	PM/MG	AMR	data-based	public	Bryan et al. (2014)[41]
ChaNGa[e]	Tree/FM	SPH	task-based	public	Menon et al. (2015)[42–44]
GIZMO[f]	TreePM	MLFM/MLFV	data-based	public	Hopkins et al. (2015)[45]
HACC	TreePM/P^3M	CRK-SPH	data-based	private	Habib et al. (2016)[46]
PKDGRAV3	Tree/FM	–	data-based	public	Potter et al. (2017)[47]
Gasoline2	Tree	SPH	task-based	public	Wadsley et al. (2017)[48]
SWIFT	TreePM/FM	SPH	task-based	public	Schaller et al. (2018)[49]

[a] PM: particle-mesh; TreePM: tree + PM, FM: fast multipole, P^3M: particle-particle-particle-mesh; ML: multilevel; MG: multigrid

[b] SPH: smoothed particle hydrodynamics, CRK-SPH: conservative reproducing kernel smoothed particle hydrodynamics , AMR: adaptive-mesh-refinement, MMFV: moving-mesh finite volume, MLFM/MLFV: mesh-free finite mass / finite volume

[c] data-based: data parallelism focuses on distributing data across different nodes, which operate on the data in parallel; task-based: task parallelism focuses on distributing tasks concurrently performed

[d] private: private code; public: publicly available code (in some cases with limited functionality)

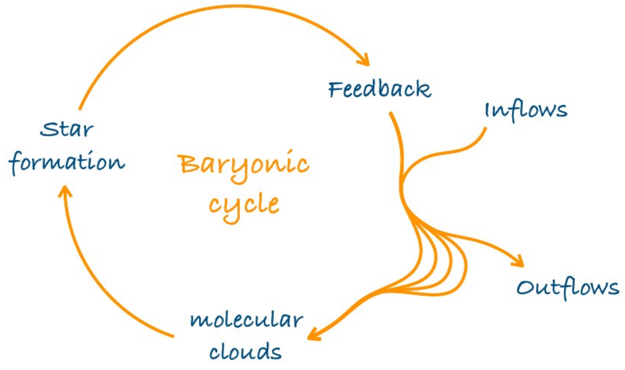
[e] gravity solver is based on PKDGRAV3

[f] based on the GADGET-3 code

arXiv:1909.07976

Baryonic physics

- *Sub resolution effective modeling/recipes*
- *Calibration, parameters, resolution dependent*



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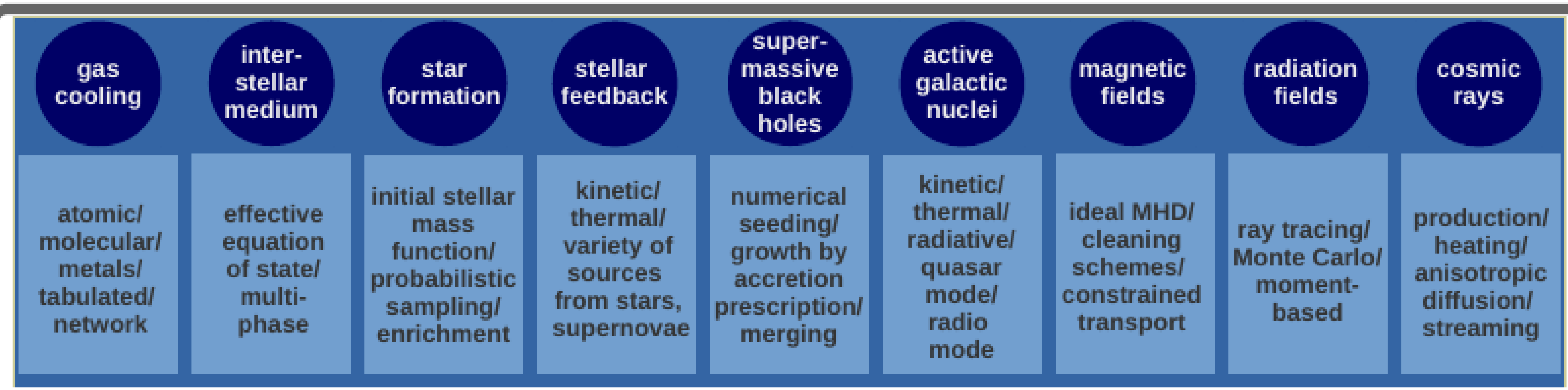
https://ismgalaxies2021.sciencesconf.org/



arXiv:1909.07976

(some) Relevant baryonic physics reciepes (for MW-size galaxies)

- *Star formation:*

  ISM conditions, physical state of gas: cold dense gas

  - Kennicut-Schmidt law (Shmidt 1959), star formation above a density threshold, constant efficiency (~1%)

  - Multifree-fall: efficiency = function of gas properties (density, turbulence …)

  (Federath & Klessen 2012, Padoan & Nordlund 2011, Henebelle & Chabrier 2011)

  Q: Universal IMF ? Impact of spirals, bars ? Environment ? Interaction and mergers ? Turbulence description Redshift dependence ? Multi-scale and multi-physics topic.

- *Stellar feedback*

  Death of heavy stars

  release energy and momentum (thermally, kinematically)

  - Delayed Cooling: stop cooling (Teyssier et 2013, Dubois et al 2015)

  - Mechanical FB: mimic Sedov blast phases (Kimm & Cen 2014)

  Q: Coupling to galactic scale ? Drift of stars ? Expansion and volume of SN bubbles ?

- *AGN feedback ?*

  - BH growth $\propto$ *Bondi accretion (and < Eddington rate)*

  - AGN released power $\propto$ *BH growth : quasar thermal and radio jet modes*

  (Dubois et al 2014)

  Q: Centering of BH ?

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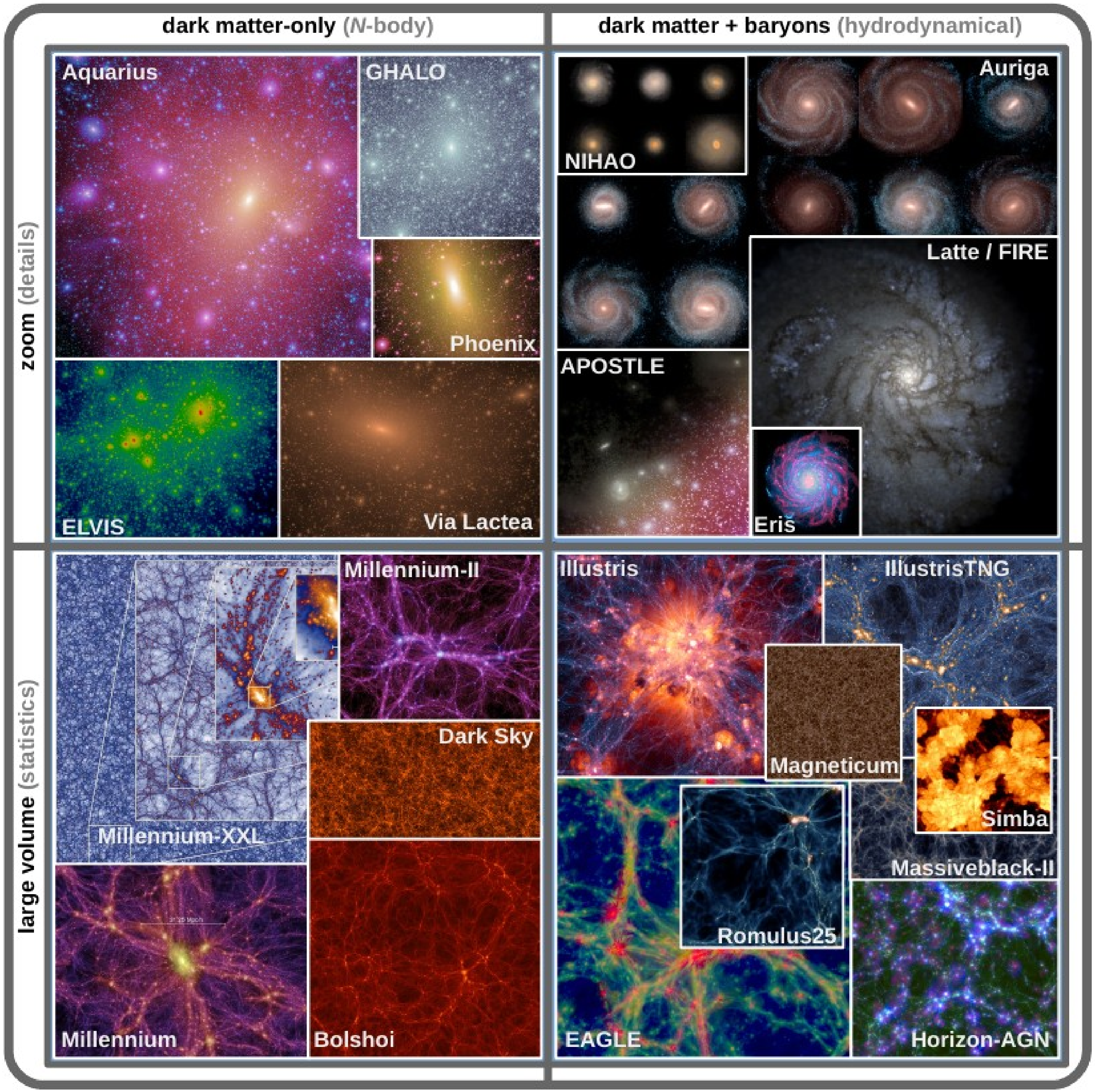
Q: Centering of BH ?

Effective models, parameters, calibration, resolution in (cosmological) simulations ?

Cosmological Simulations of Galaxy Formation

Mark Vogelsberger[1], Federico Marinacci[2], Paul Torrey[3], and Ewald Puchwein[4]



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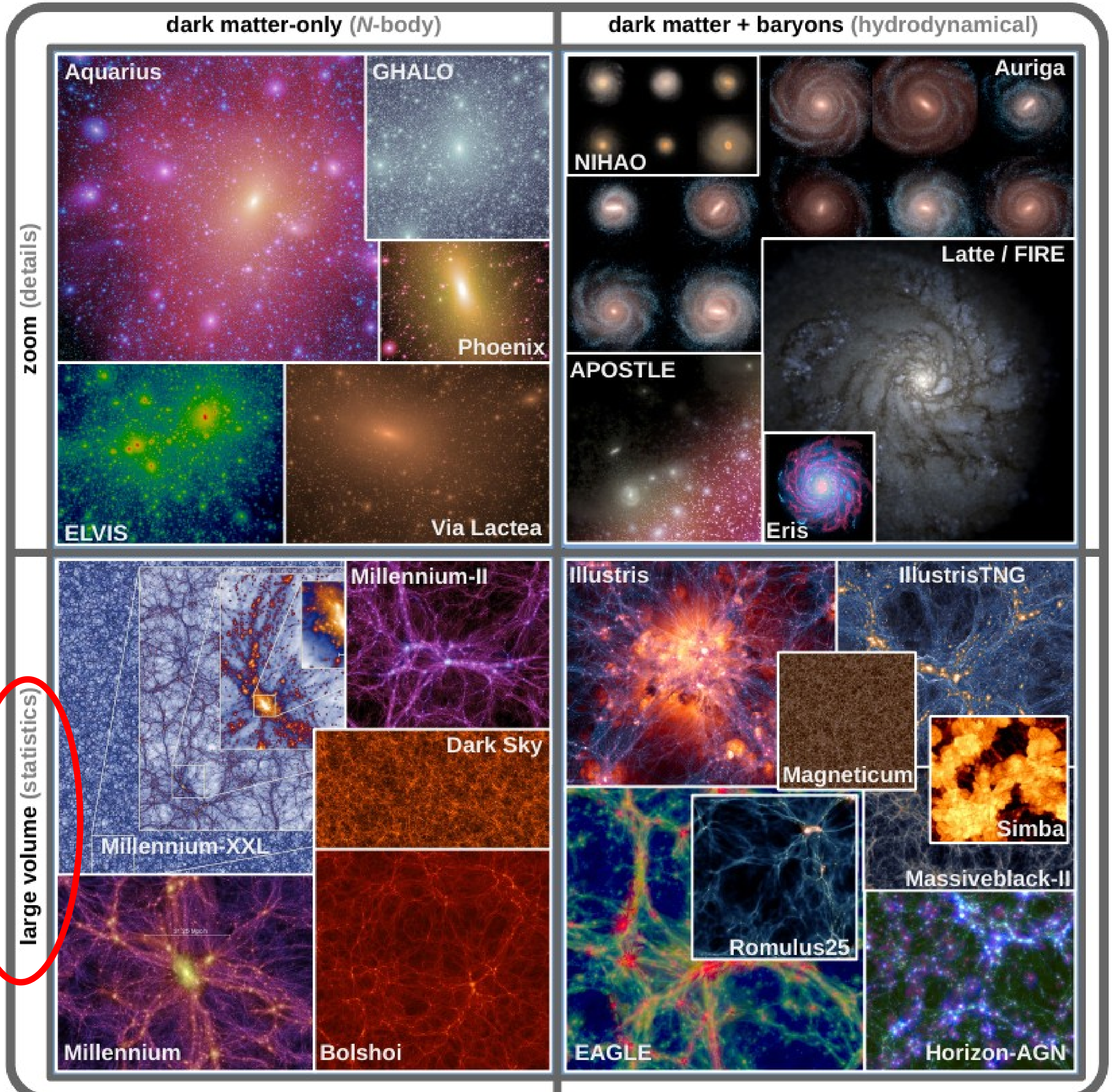

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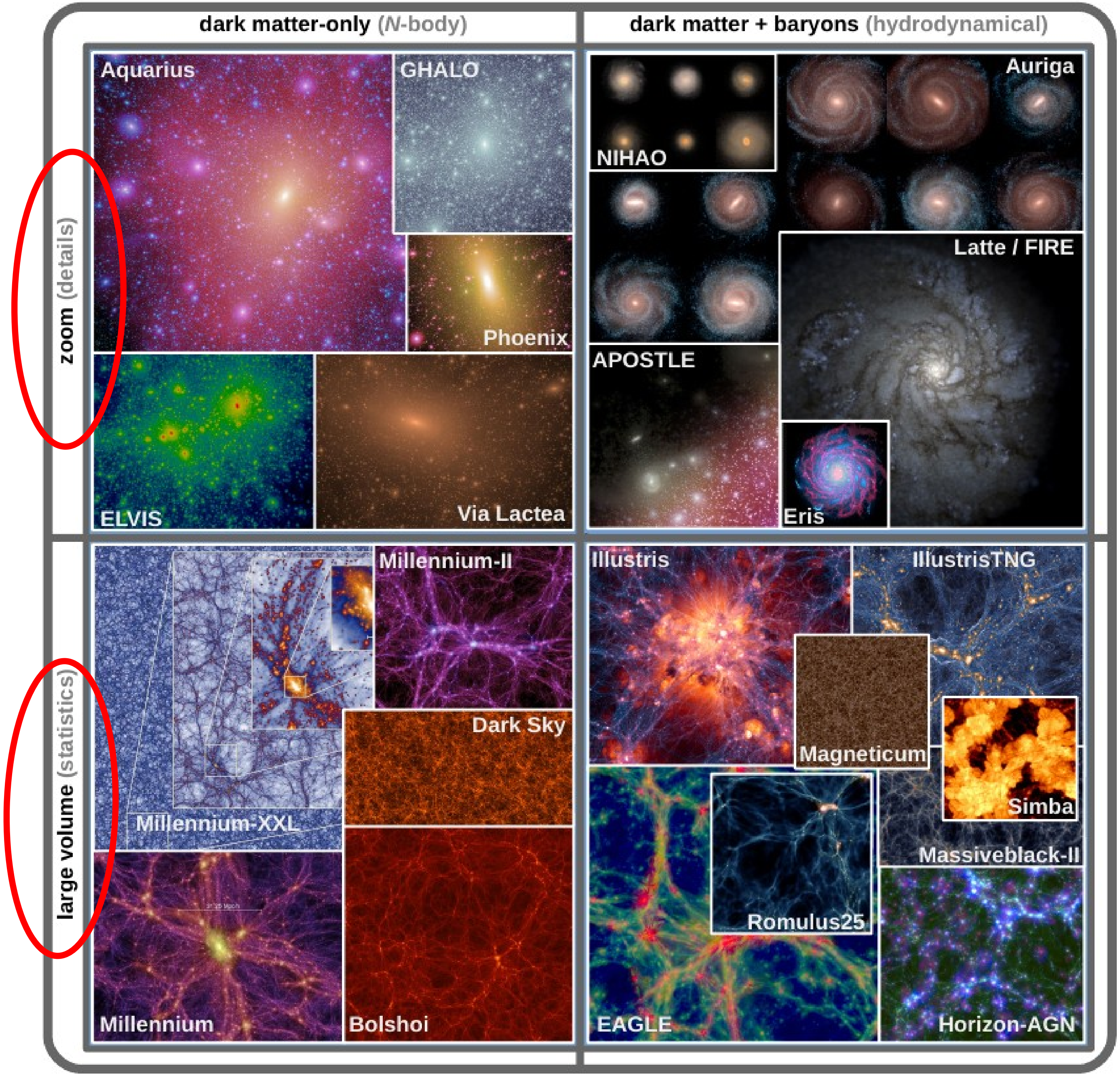

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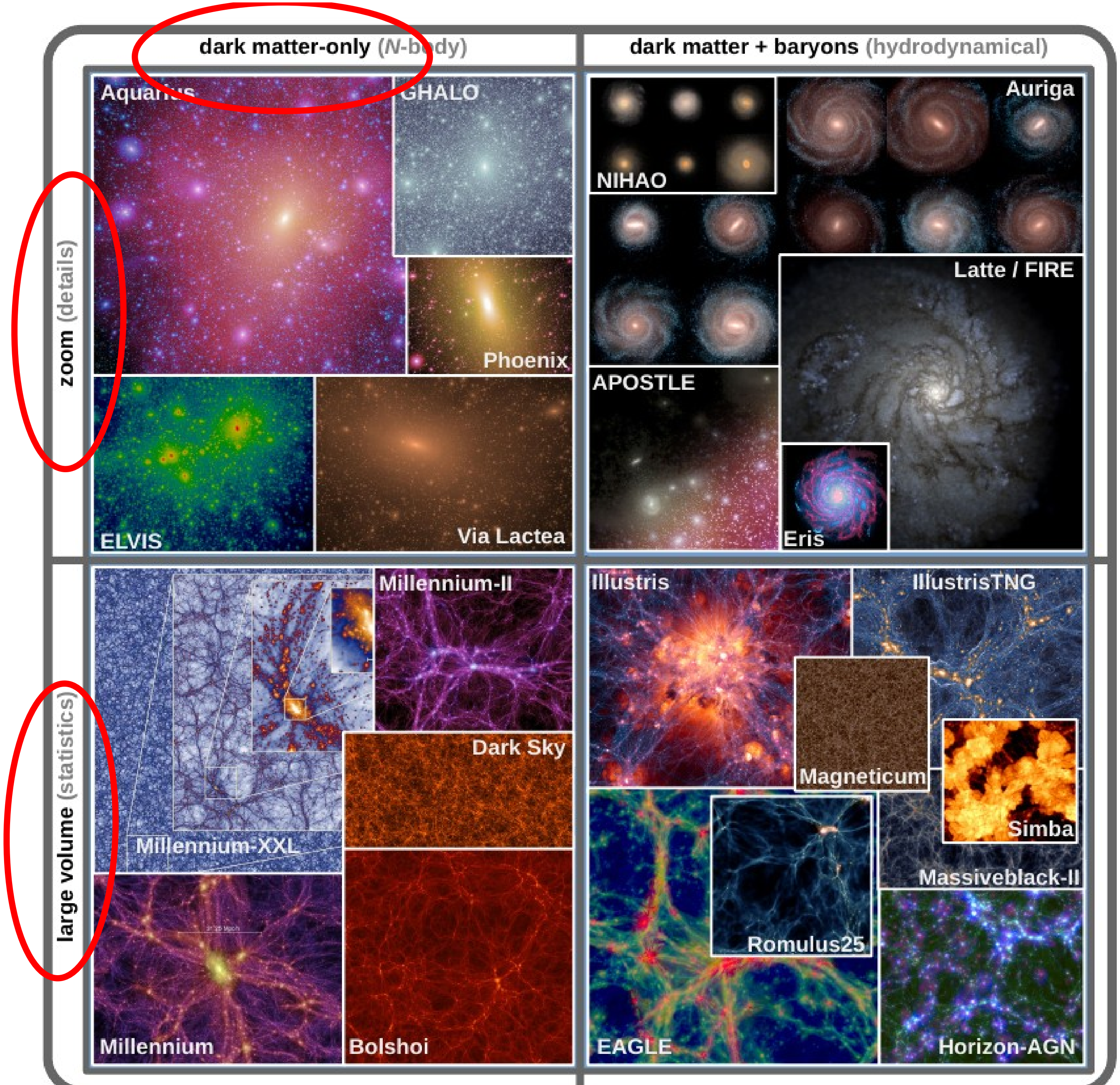

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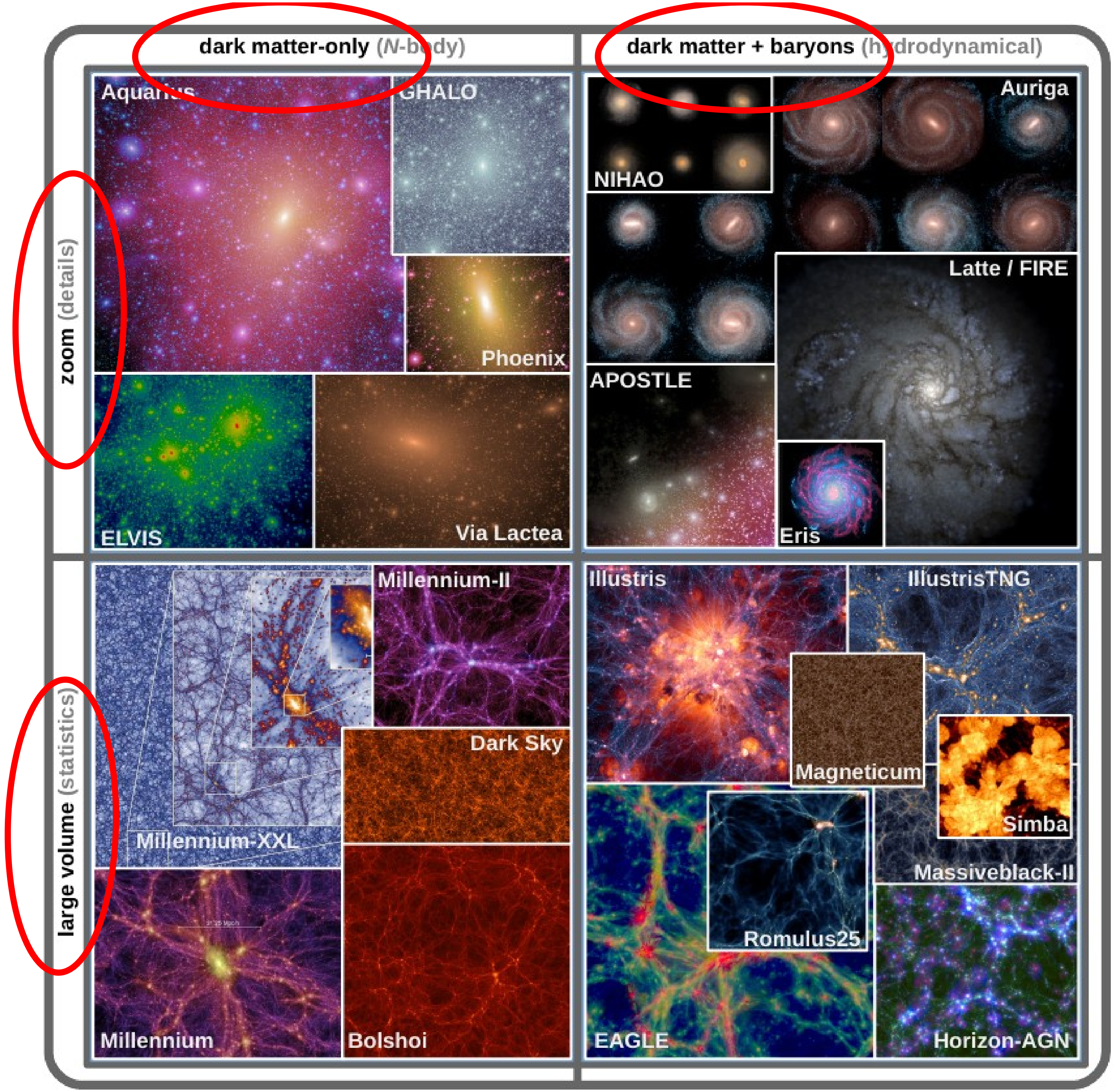


arXiv:1909.07976

Big volume simulations

Big volume simulations

Dark matter only (DMO)

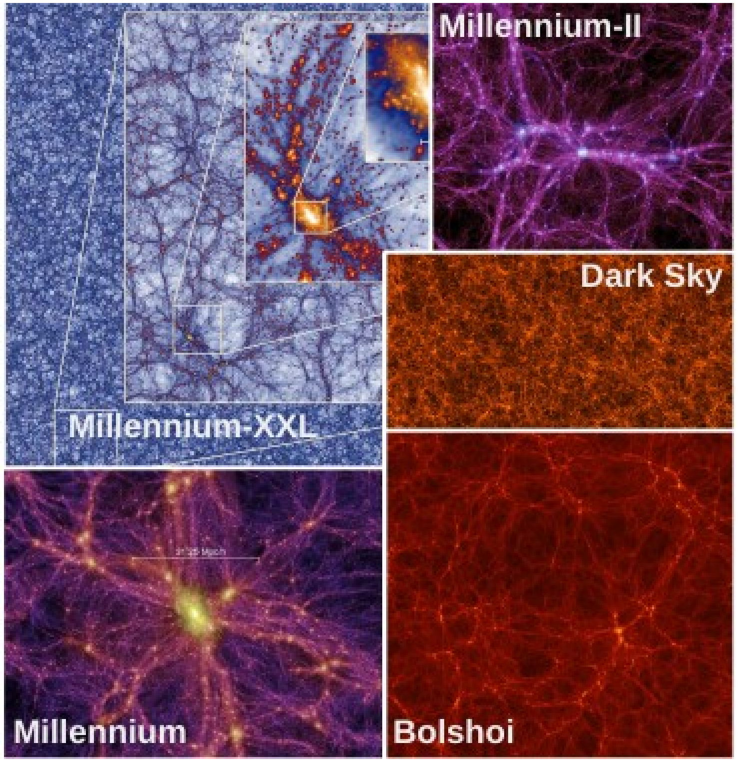
- cosmic web (filaments, voids, halos ...)

- Large scale structure (matter distribution)

- halo mass function

- cosmological scenario

....



Big volume simulations

Dark matter only (DMO)

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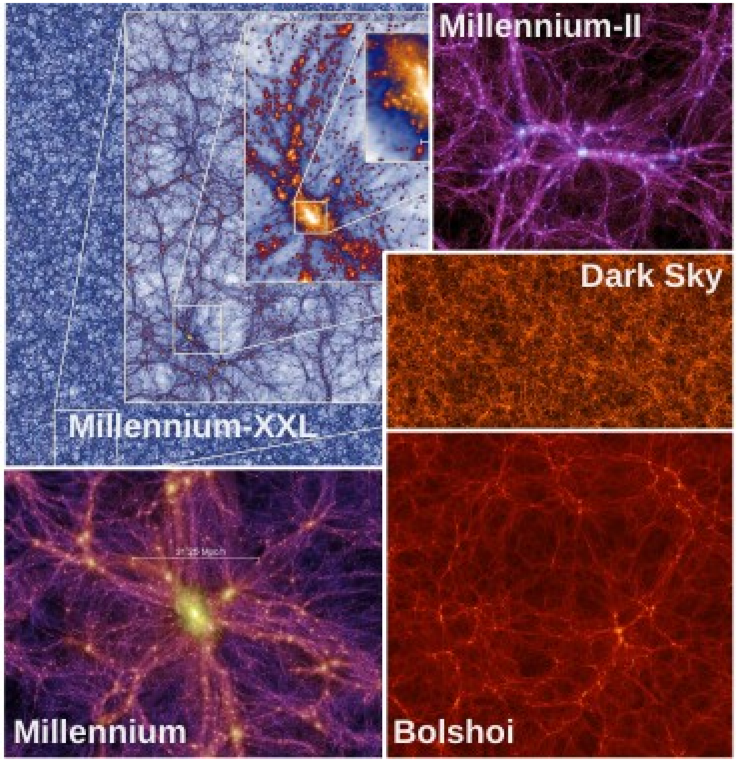
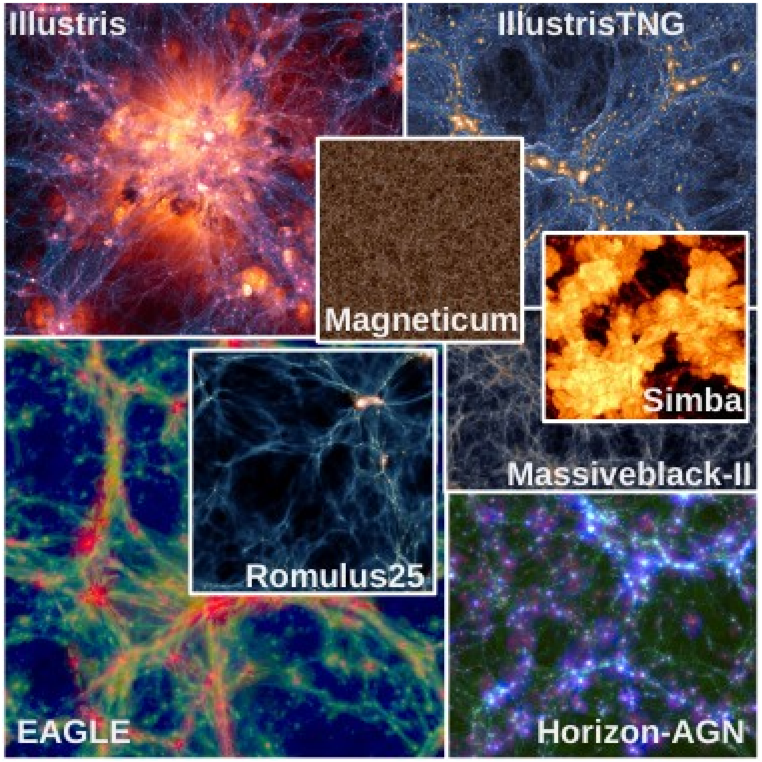
….

Hydrodynamical

- galaxies population
- stellar(-to-halo) mass function
- gas around galaxie
- clustering
- scaling relations

….





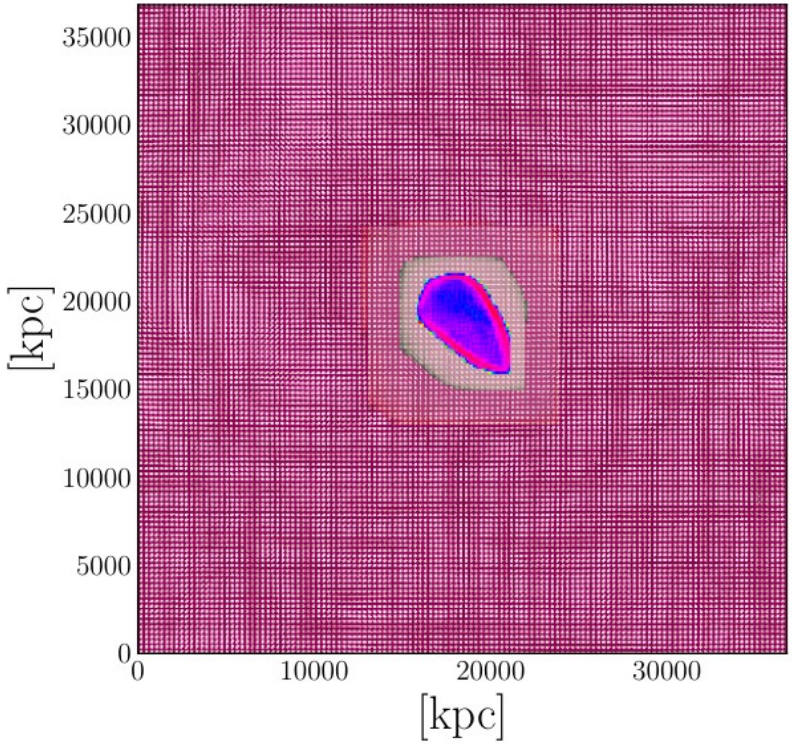
Zoom-in simulations of "Milky Way size objects"

Zoom-in simulations of "Milky Way size objects"

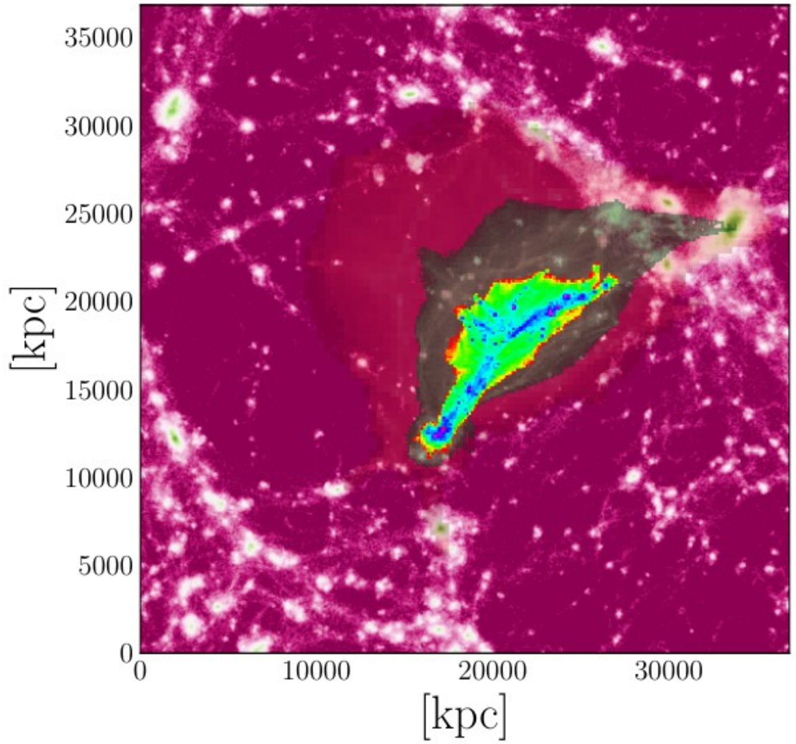
Increase resolution around the initial Lagrangian volume of interest

(Gradual levels of zoom)

Begining of the simulation



End of the simulation



A. Nunez-Castineyra PhD

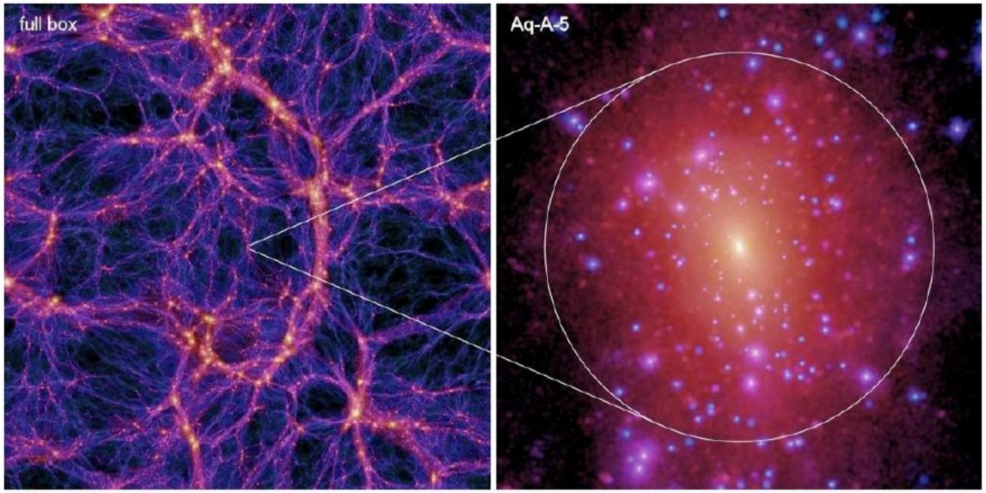
Density maps

Zoom-in simulations of “Milky Way size objects”

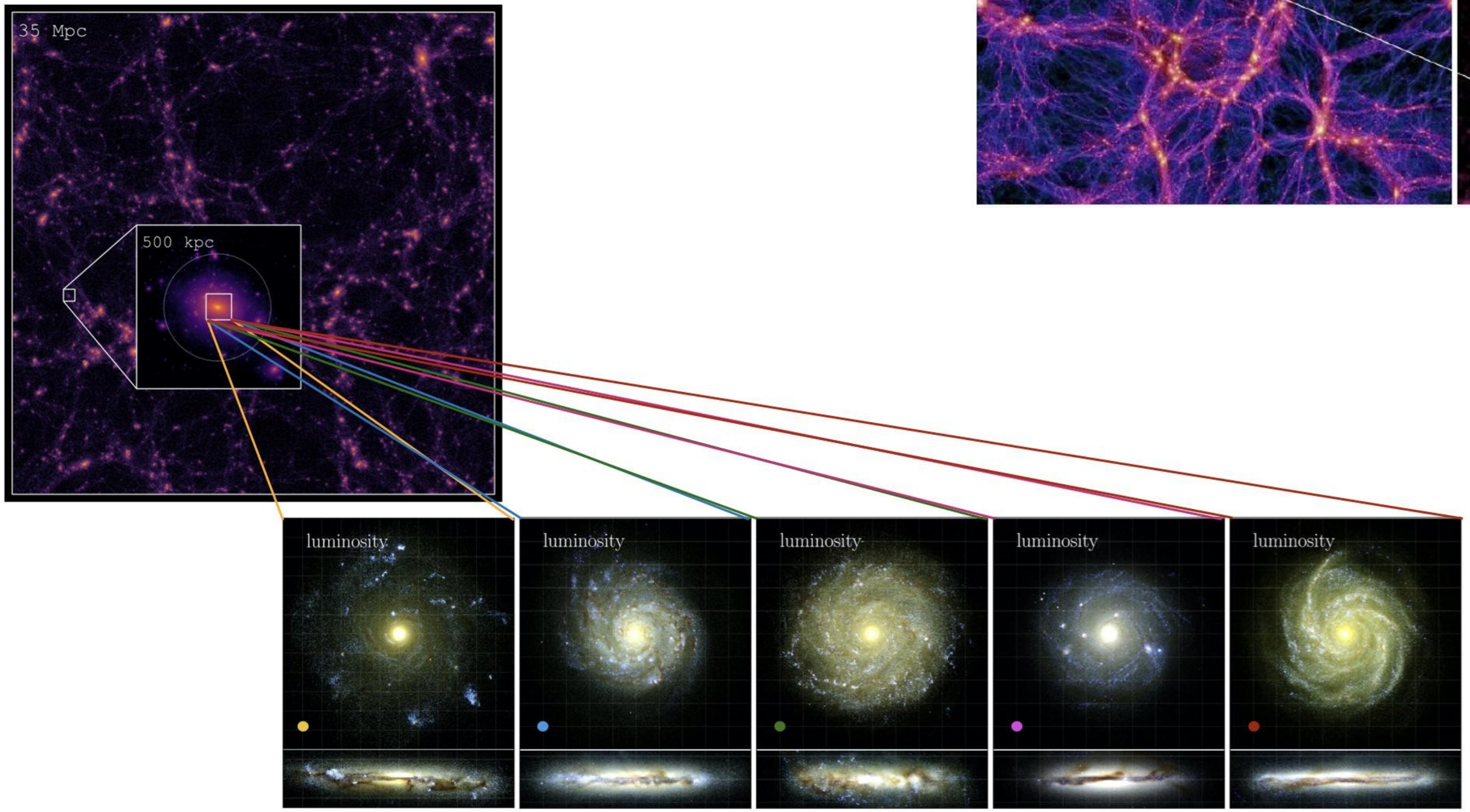
Increase resolution around the initial Lagrangian volume of interest

Aquarius

Springel et al 2009



arXiv:0809.0898



Mochima

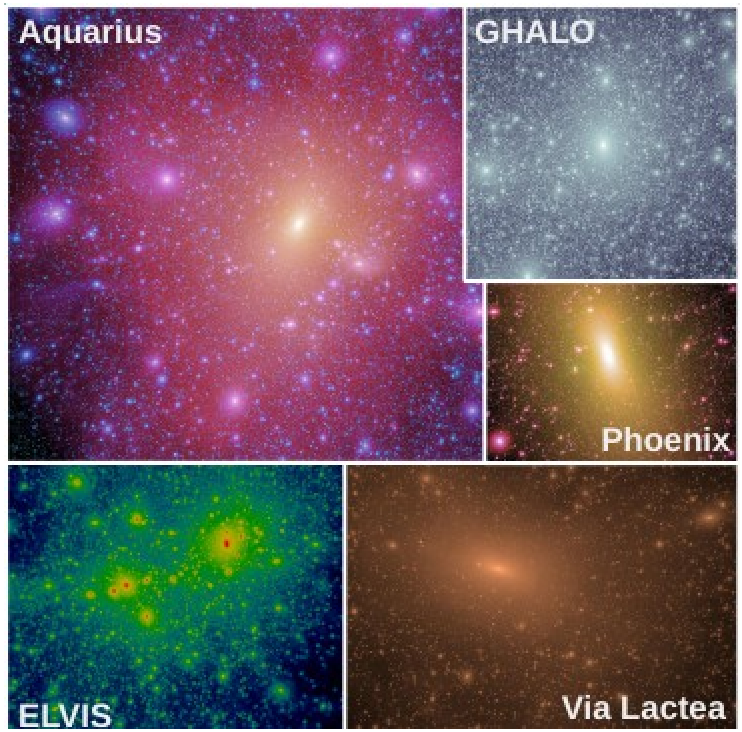
Nunez- Castineyra,

EN, Devriendt, Teyssier 2020

arXiv:2004.06008

Zoom-in simulations of “Milky Way size objects”

- Dark matter only (DMO): Zoom simulations of Milky Way size halos



Zoom-in simulations of “Milky Way size objects”

- Dark matter only (DMO): Zoom simulations of Milky Way size halos

Dark matter distribution ?

Substructures

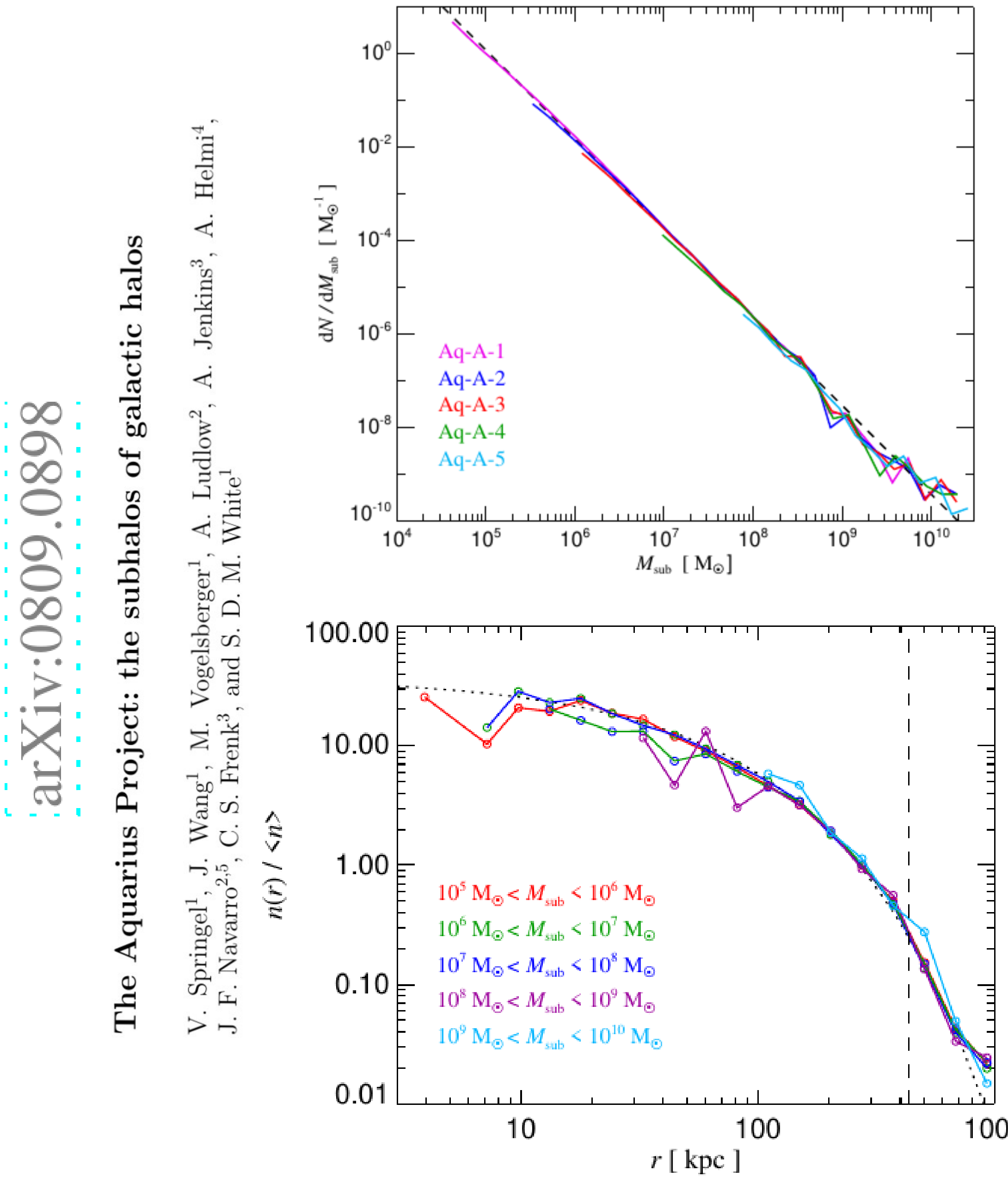
Subhalos
Mass spectrum
Concentration
Spatial distribution

Streams

Main halo

Density profile
Cusp/NFW
Einasto

Velocity distribution



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Dark matter distribution ?

Substructures

Subhalos
Mass spectrum
Concentration
Spatial distribution

Streams

Main halo

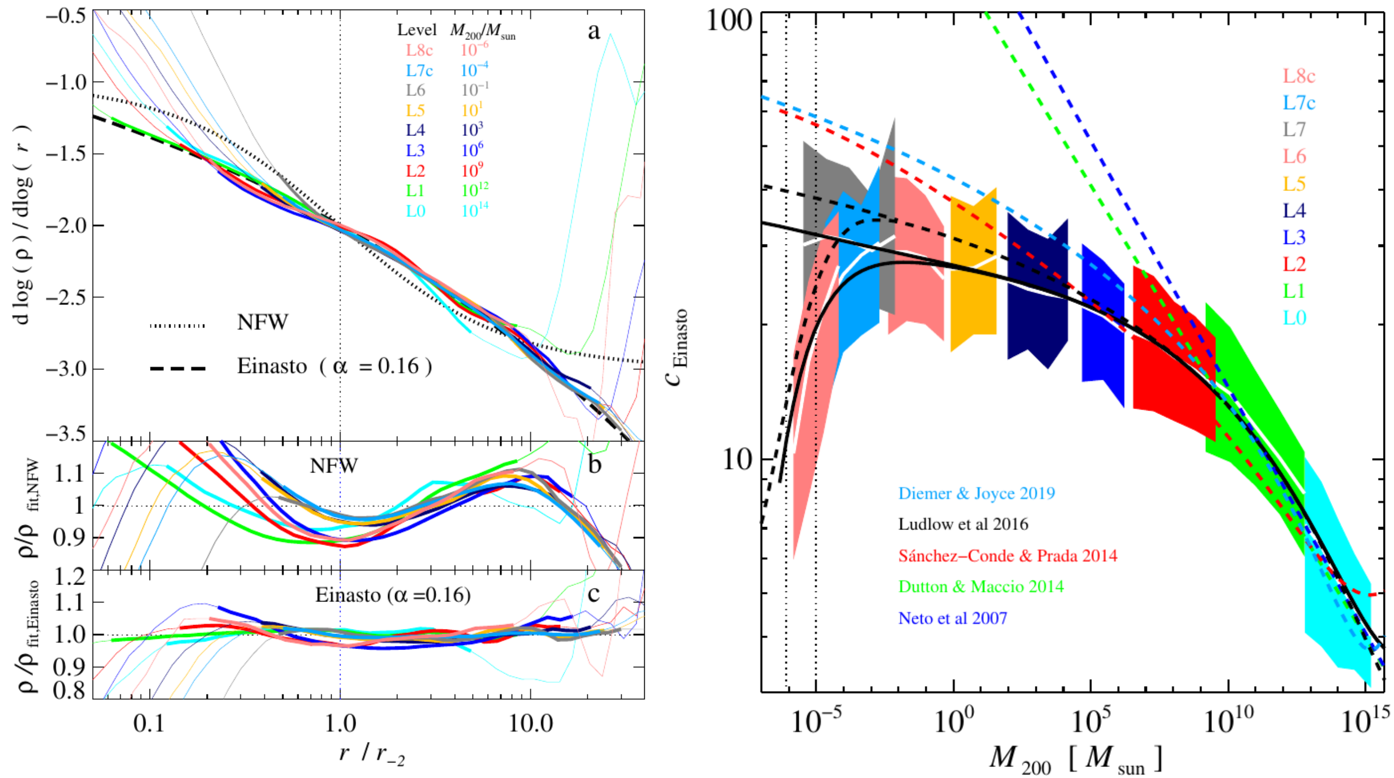
Density profile
Cusp/NFW
Einasto

Velocity distribution

arXiv:1911.09720

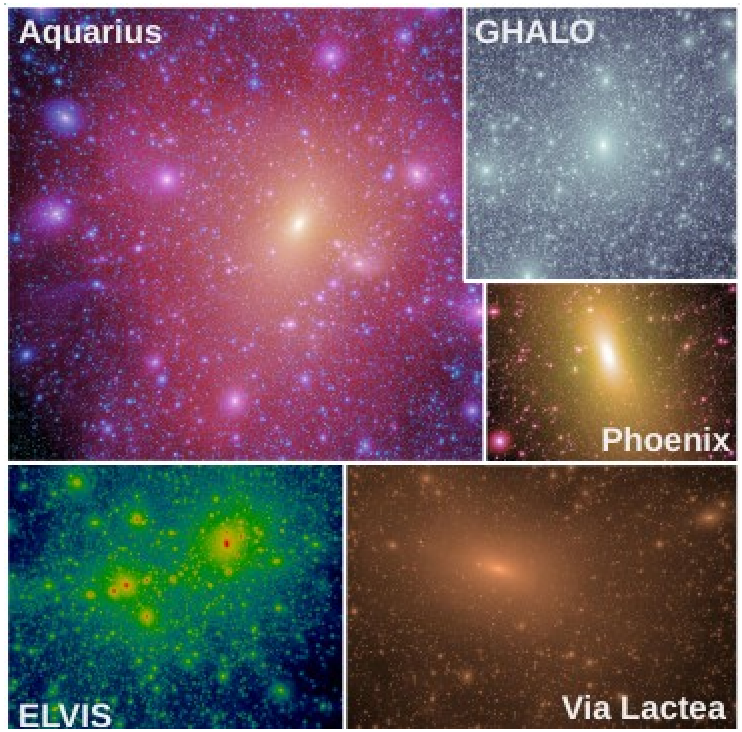
Universal structure of dark matter haloes over a mass range of 20 orders of magnitude

Wang, J.[1,5*], Bose, S.[2], Frenk, C. S.[3†] Gao, L.[1,5], Jenkins, A.[3], Springel, V.[4] & White, S. D. M.[4‡]



Zoom-in simulations of “Milky Way size objects”

- Dark matter only (DMO): Zoom simulations of Milky Way size halos



Zoom-in simulations of “Milky Way size objects”

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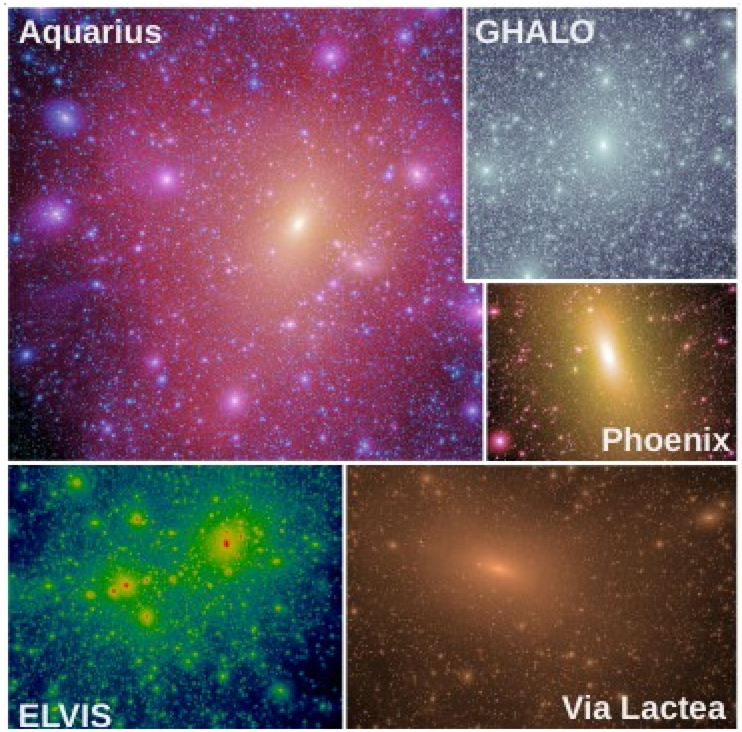
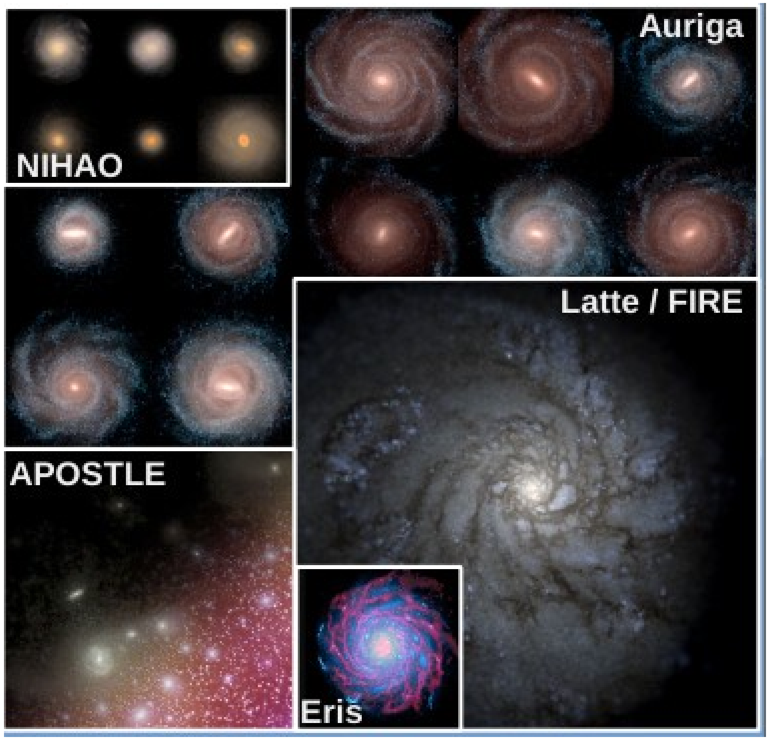


- Hydro: Zoom-in simulations of “Milky Way like” spiral galaxies

ERIS, NIHAO,EAGLE,FIRE, AURIGA,APOSTLE,GIMIC,ARTEMIS,VINTERGATAN, MOCHIMA, NEW HORIZON, ILLUSTRIS TNG …



Milky-Way “analog” = Spiral galaxie in ~ 10^{12} M⊙ halo

Zoom-in simulations of “Milky Way like” spiral galaxies

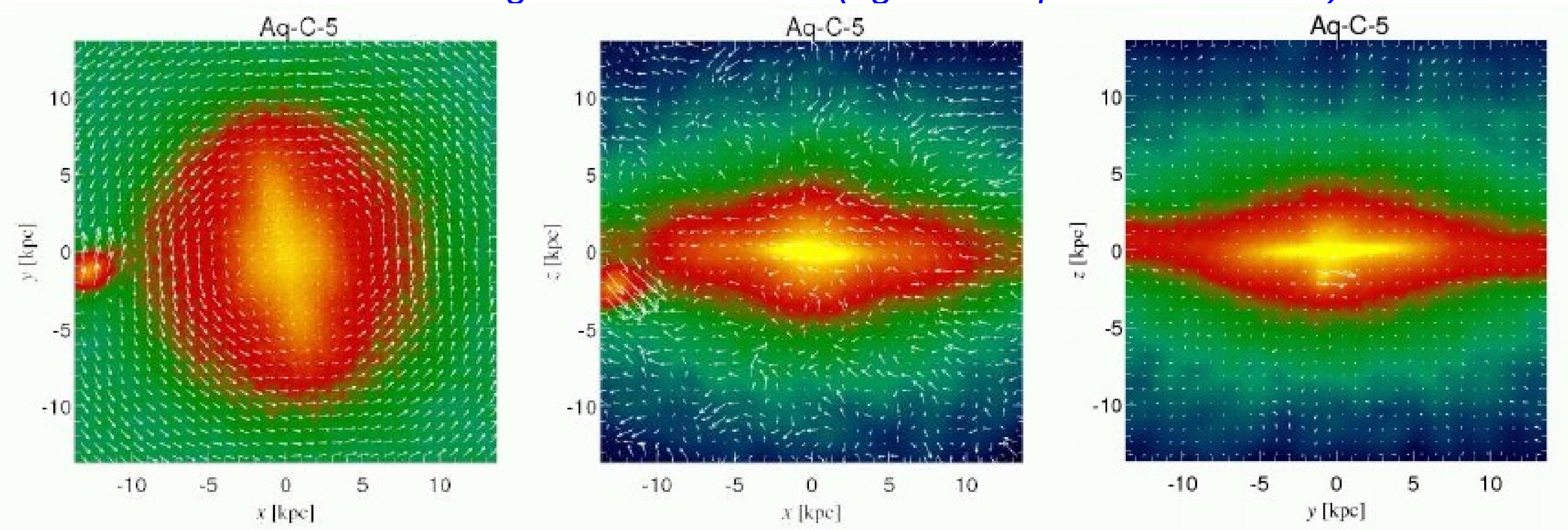
- Some time ago:

Gas cooling, star formation

Angular momentum catastrophe/overcooling problem (Balogh et al 2001, Brook et al 2011)

Too efficient SF and gas consumption at high redshift

→ Thick and not enough extended disks (eg Scannapieco et al 2009)



Zoom-in simulations of “Milky Way like” spiral galaxies

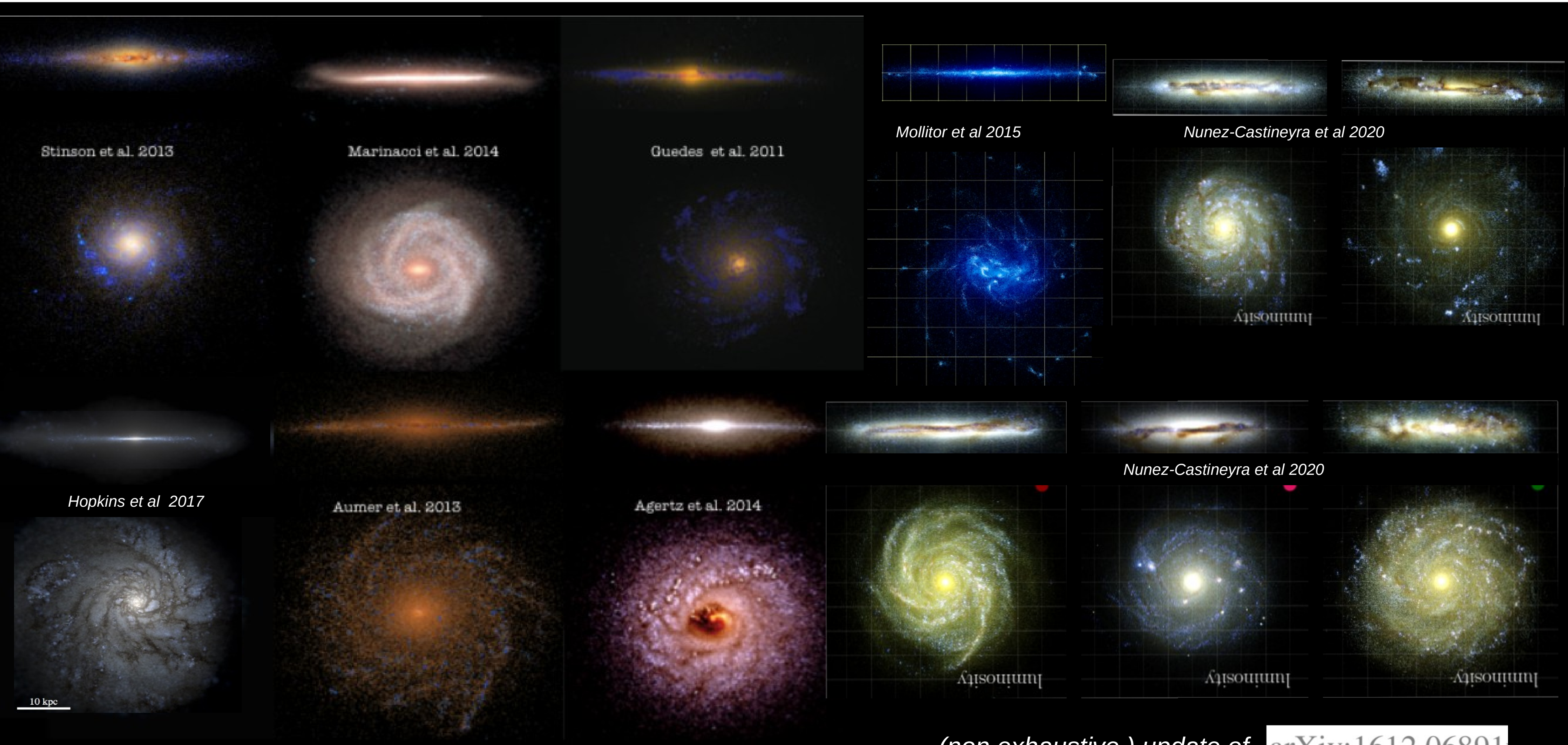
Improve star formation modeling + Including (strong enough) stellar feedback (+wind)

reduce early star formation

better stellar-to-halo mass ratio

close to 1977-78 predictions *(Binney, Rees,Ostriker,Silk)*

ERIS, NIHAO,EAGLE,FIRE,
AURIGA,APOSTLE
ARTEMIS,VINTERGATAN,MOCHIMA,
NEW HORIZON, ILLUSTRIS TNG ...



(non exhaustive) update of arXiv:1612.06891

Zoom-in simulations of "Milky Way like" spiral galaxies

Adapted from

Table 2: Recent structure and galaxy formation simulations arXiv:1909.07976

simulation	volume	method[a]	mass resolution[b]	spatial resolution[c]	primary reference
	[Mpc^3]		[$M_\odot$]	[kpc]	
Eris	zoom	Tree+SPH	$9.8\times10^4/2\times10^4$	0.12/0.12	Guedes et al. (2011)[349]
VELA	zoom	PM/ML + AMR	$8.3\times10^4/1.9\times10^5$	0.03/0.03[g]	Ceverino et al. (2014)[386]
NIHAO	zoom	Tree+SPH	$3.4\times10^3/6.2\times10^2$	0.12/0.05	Wang et al. (2015)[125]
APOSTLE	zoom	TreePM+SPH	$5.0\times10^4/1.0\times10^4$	0.13/0.13	Sawala et al. (2016)[387]
Latte/FIRE	zoom	TreePM+MLFM	$3.5\times10^4/7.1\times10^3$	0.02/0.001	Wetzel et al. (2016)[352]
Auriga	zoom	TreePM+MMFV	$4.0\times10^4/6.0\times10^3$	0.18/0.18[h]	Grand et al. (2017)[297]
Artemis	*zoom*	*SPH*	*$2x10^4$*	*0.125*	*Font et al 2020*
Vintergatan	*zoom*	*PM/ML+AMR*	*$3.5x10^4$ / $7.07x10^3$*	*0.02*	*Agertz et al 2020*
Mochima	*zoom*	*PM/ML+AMR*	*$1.9x10^5$ / $5x10^4$*	*0.035/0.035*	*Nunez-Castineyra et al 2020*

Zoom-in simulations of “Milky Way like” spiral galaxies

Picked-up results:

- Properties of simulated galaxies

- Dark matter distribution features of haloes

Galaxies

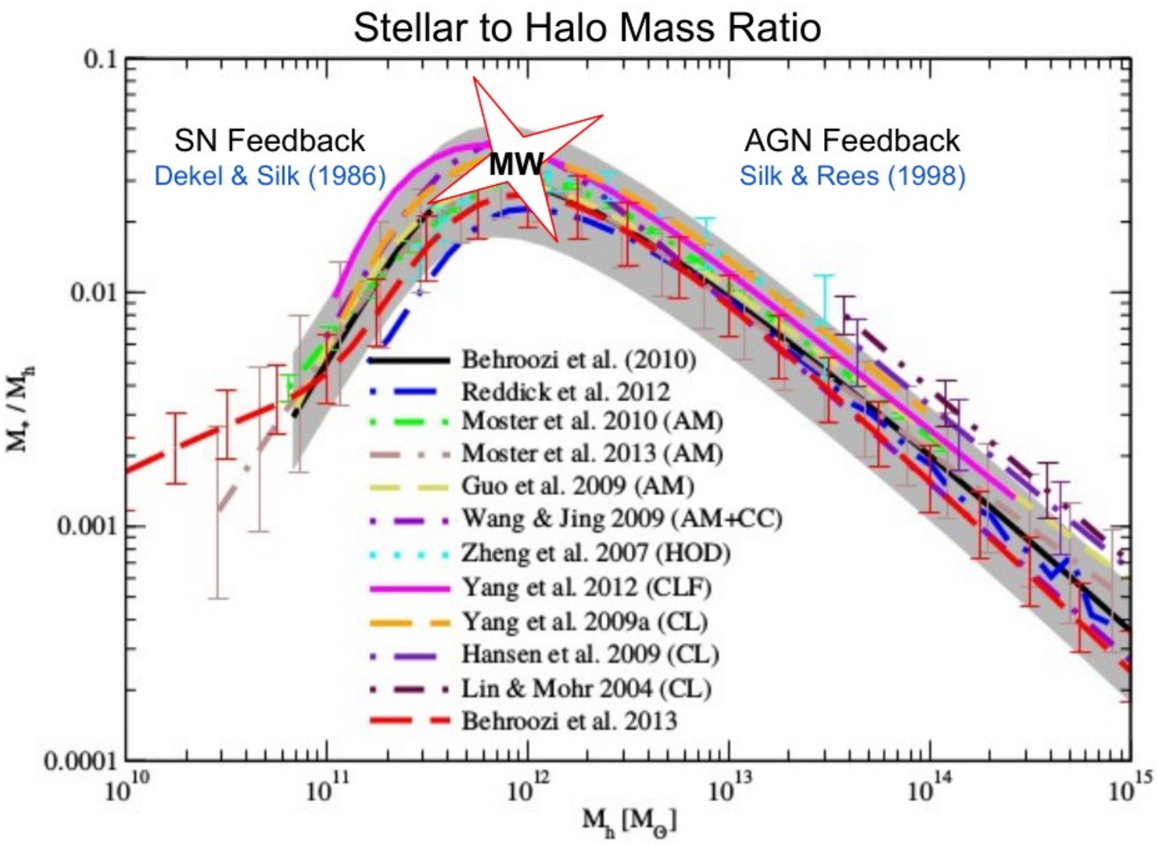
- ***Stellar-to-halo mass ratio***

- *Star formation history*

- *Disk, bulge properties Surface density*

- *Chemistery*

- *Star forming gas region properties*



Stellar mass for 10^{12} M⊙ haloes

Galaxies

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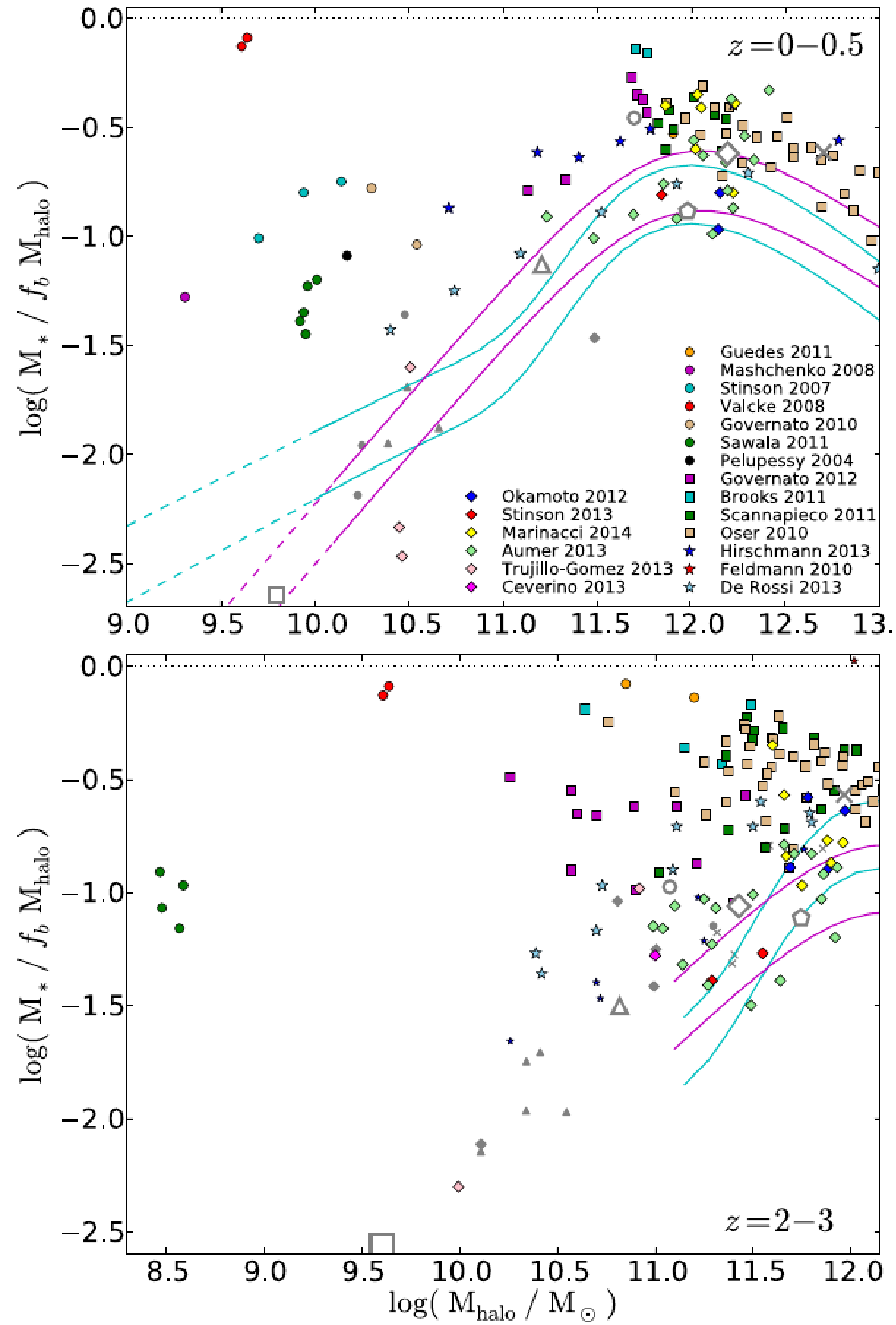

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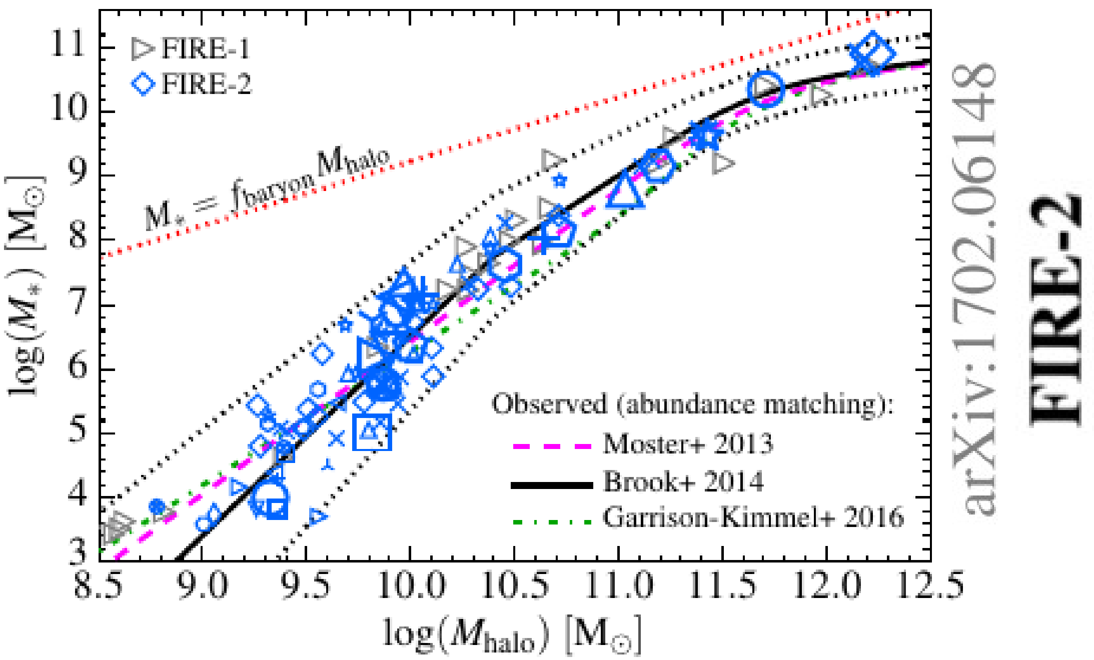

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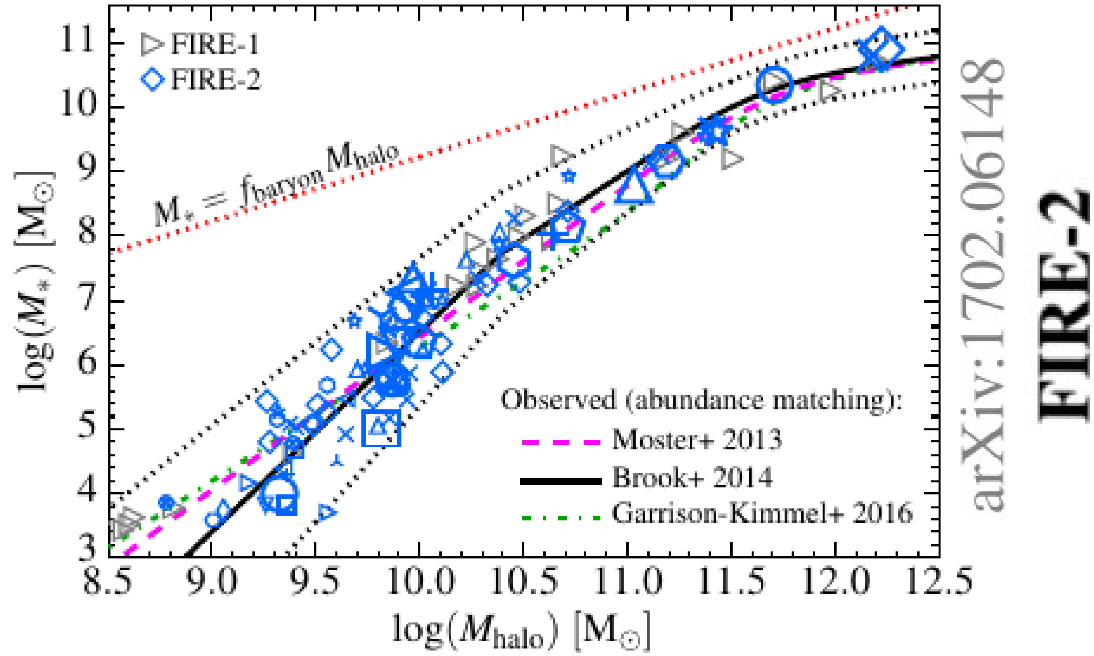

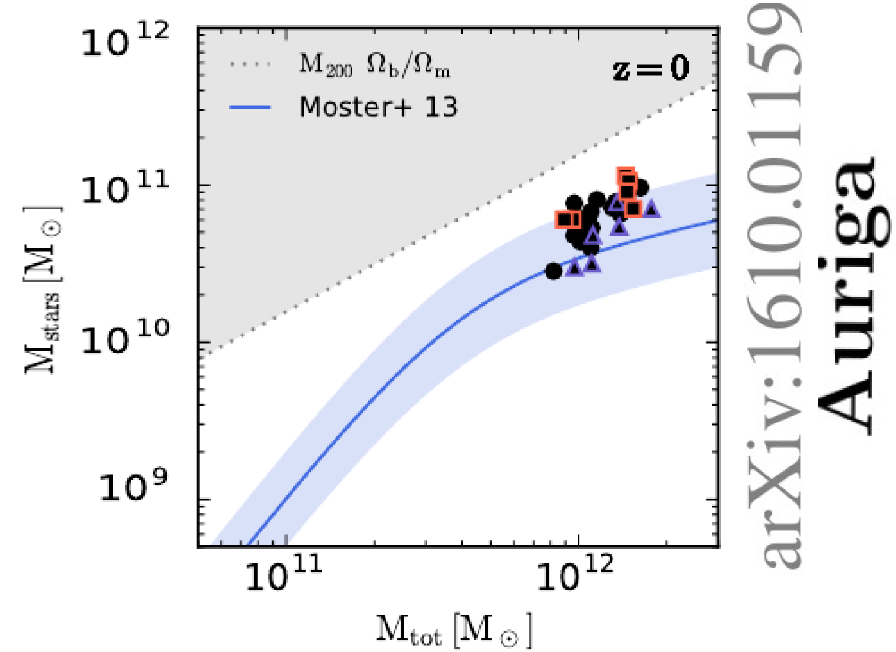

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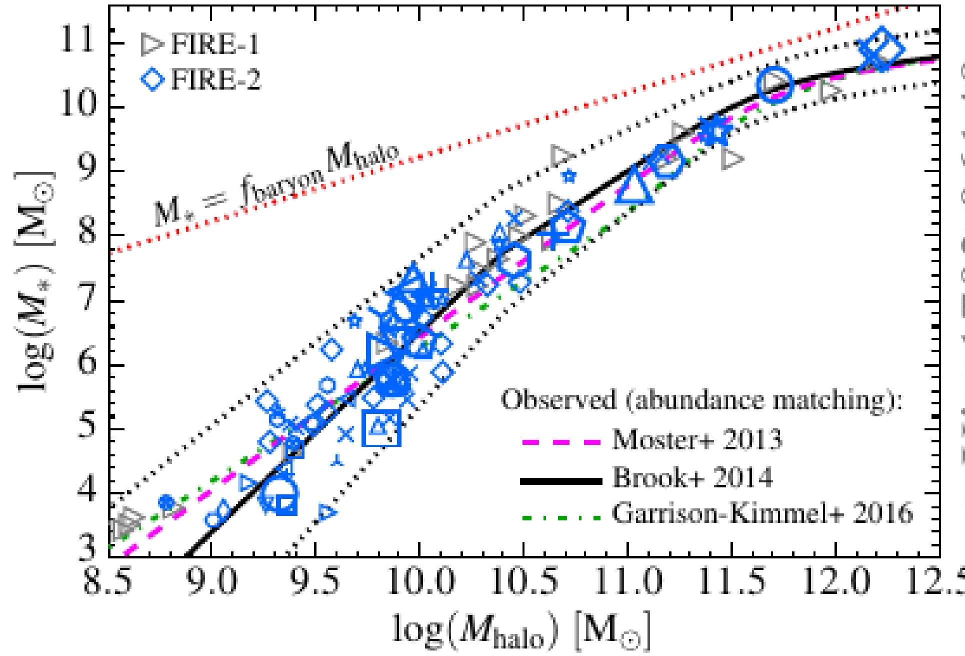
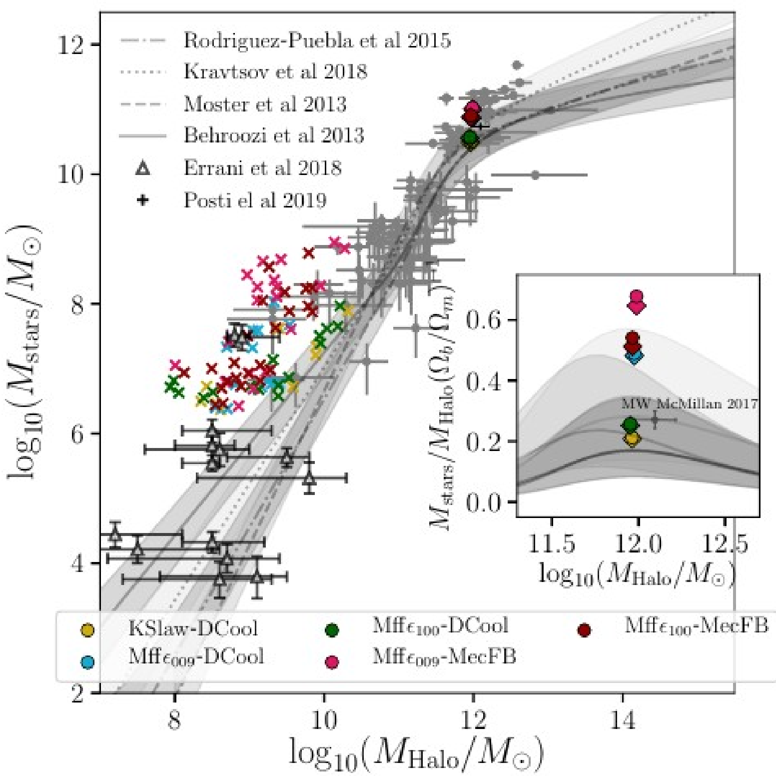
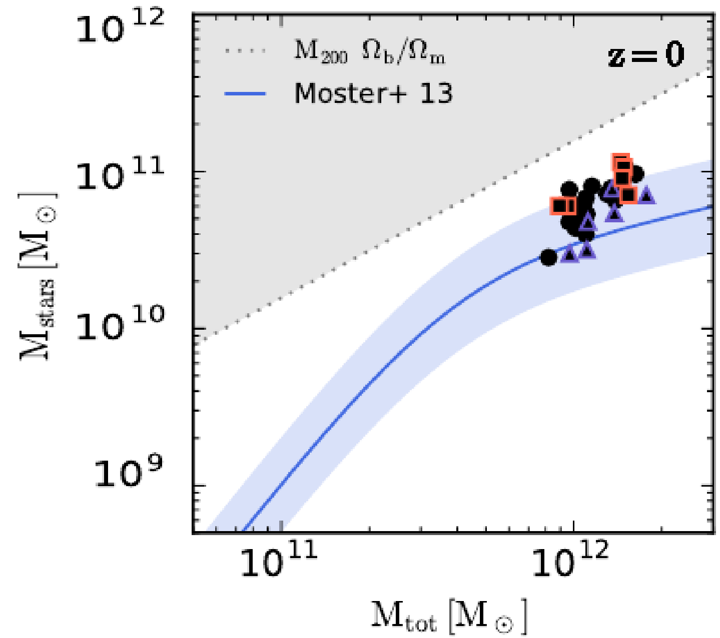


arXiv:1702.06148 **FIRE-2**



arXiv:2004.06008 Mochima

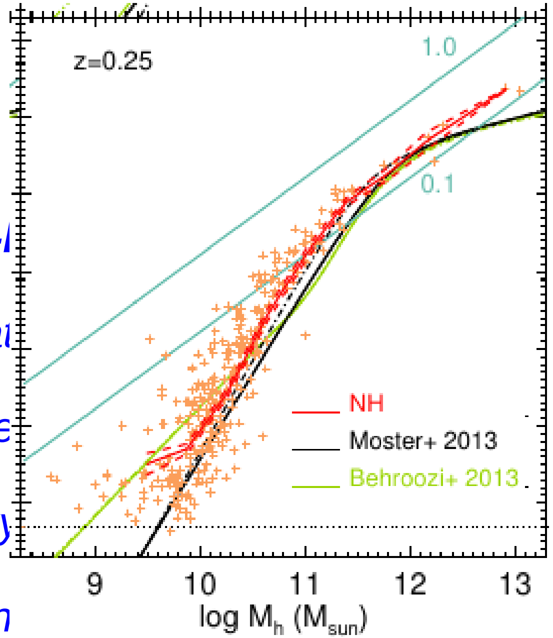


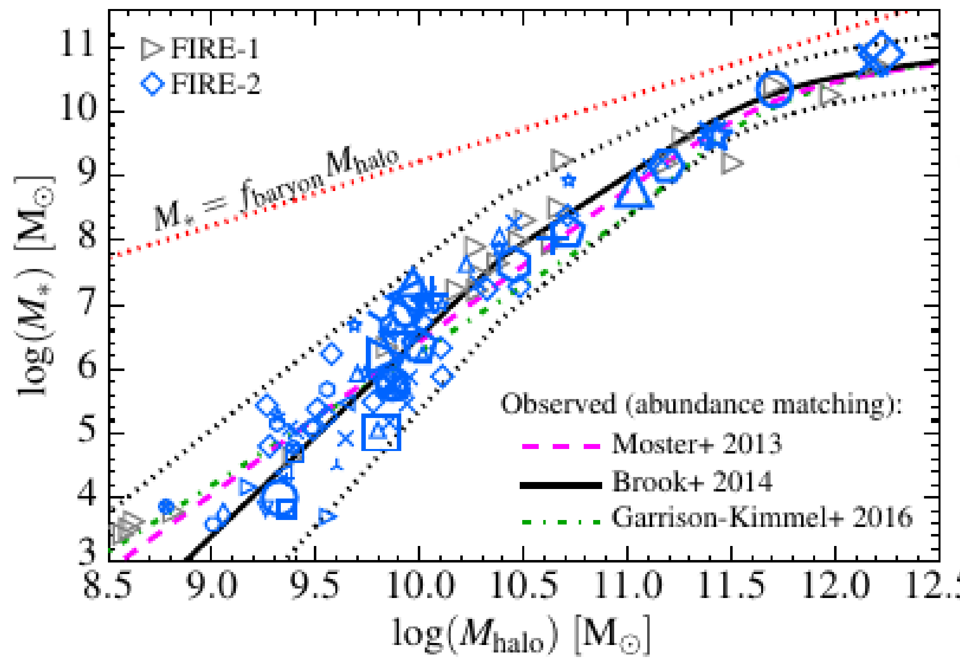
arXiv:1610.01159 **Auriga**

Galaxies

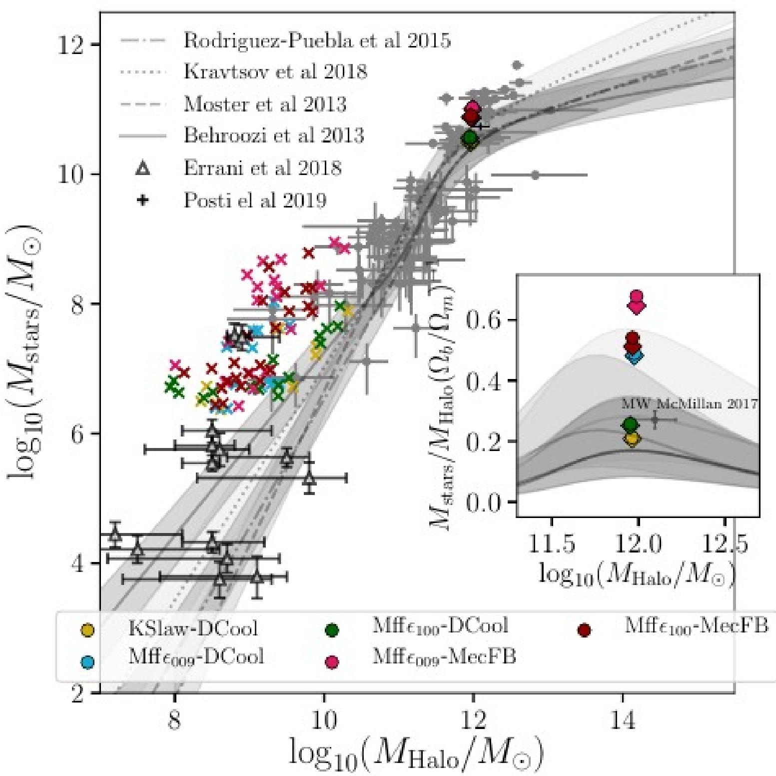
NewHorizon

- bulge
- Chemistery
- Star formin





arXiv:1702.06148
FIRE-2



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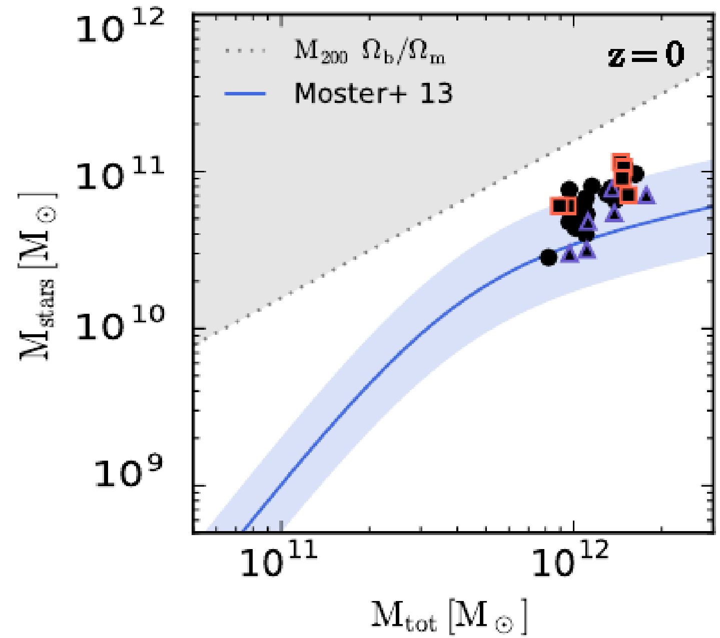
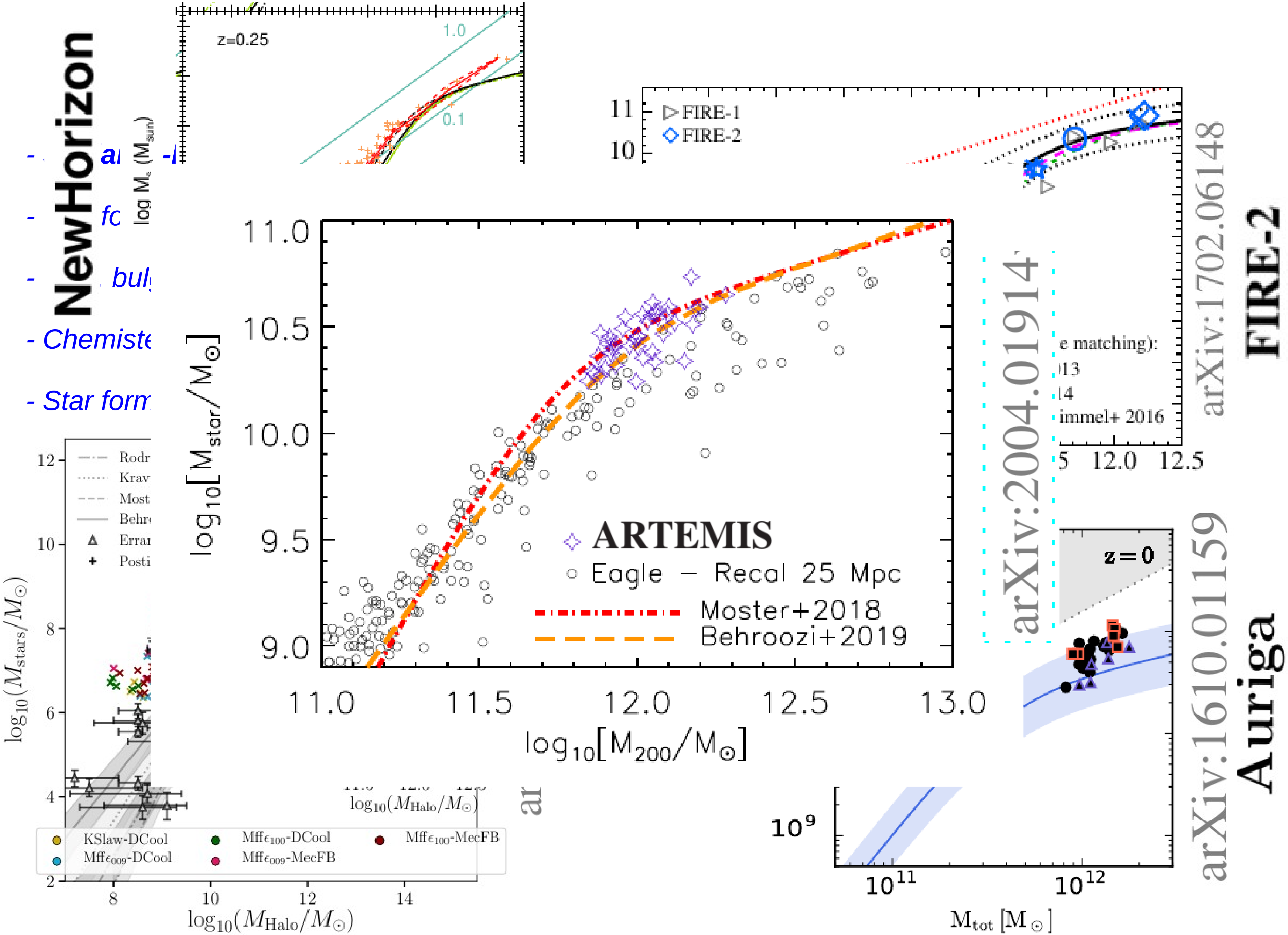


arXiv:1610.01159
Auriga

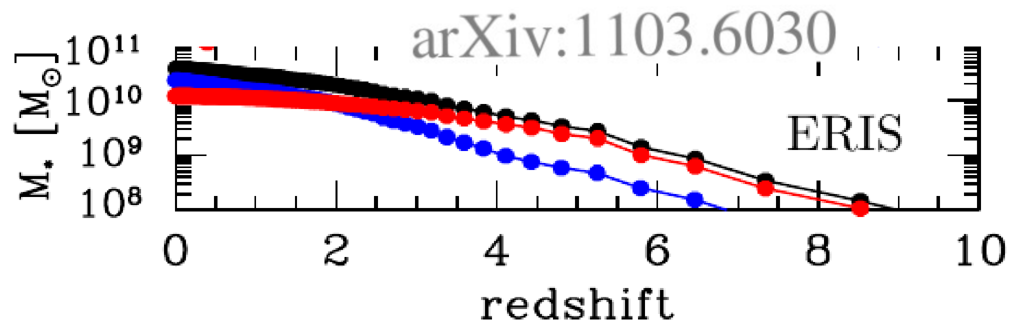
Galaxies

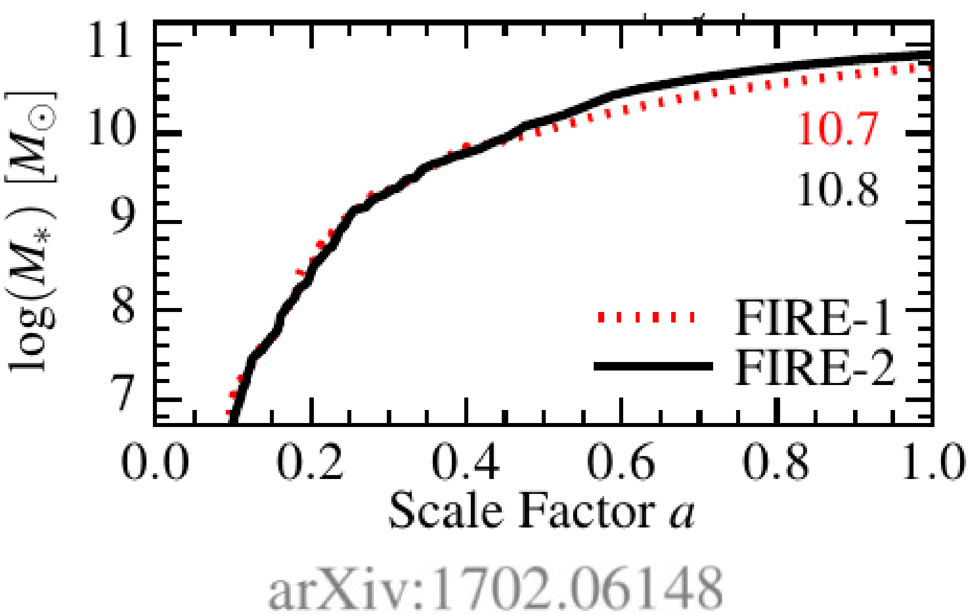


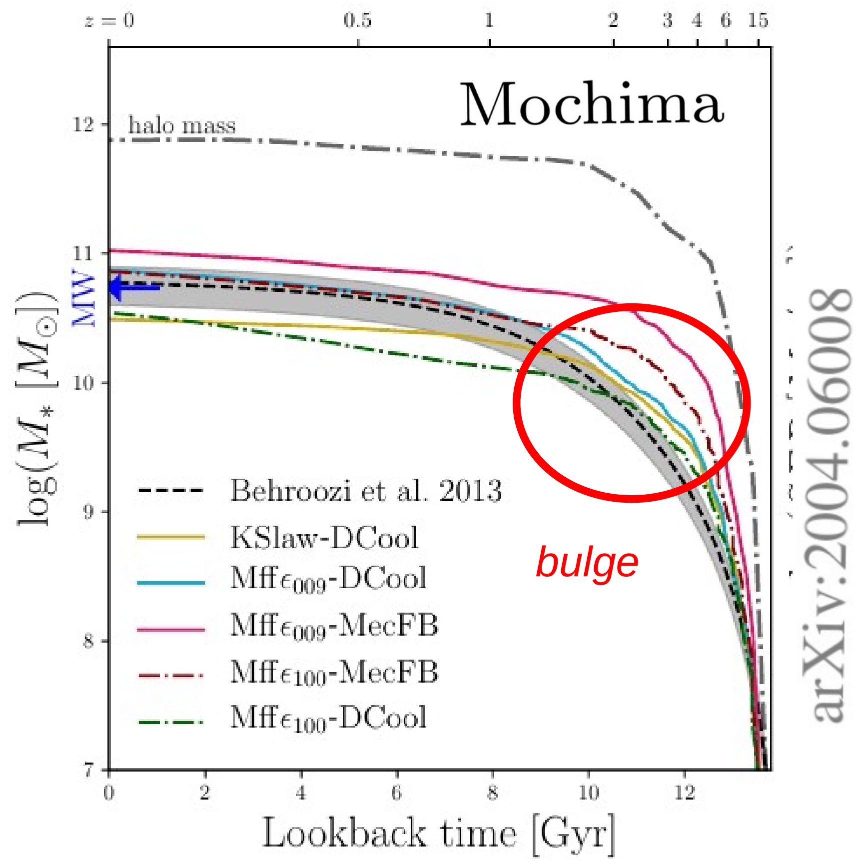
NewHorizon
z=0.25
1.0
0.1
log M* (M_sun)
- Chemiste
- Star form
Rodr
Krav
Most
Behr
Errar
Posti
$\log_{10}(M_{\rm stars}/M_\odot)$
$\log_{10}(M_{\rm Halo}/M_\odot)$
KSlaw-DCool
Mffε009-DCool
Mffε100-DCool
Mffε009-MecFB
Mffε100-MecFB
FIRE-1
FIRE-2
e matching):
immel+ 2016
arXiv:1702.06148
FIRE-2
ARTEMIS
Eagle – Recal 25 Mpc
Moster+2018
Behroozi+2019
$\log_{10}[M_{\rm star}/M_\odot]$
$\log_{10}[M_{200}/M_\odot]$
arXiv:2004.01914
z = 0
$M_{\rm tot}$ [$M_\odot$]
arXiv:1610.01159
Auriga

Galaxies

- *Stellar-to-halo mass ratio*
- ***Star formation history***
- *Disk, bulge properties Surface density*
- *Chemistery*
- *Star forming gas region properties*

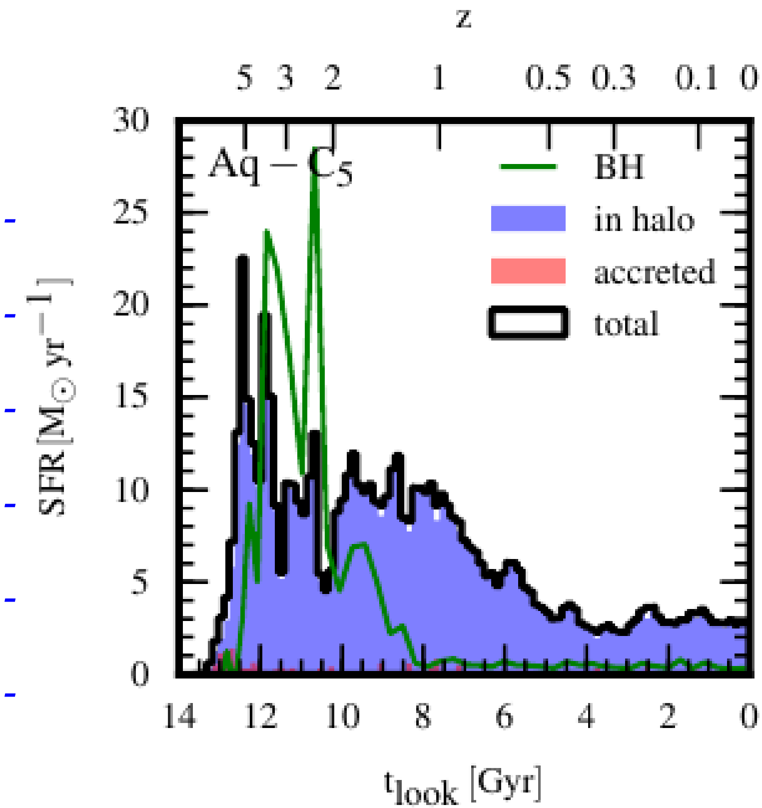


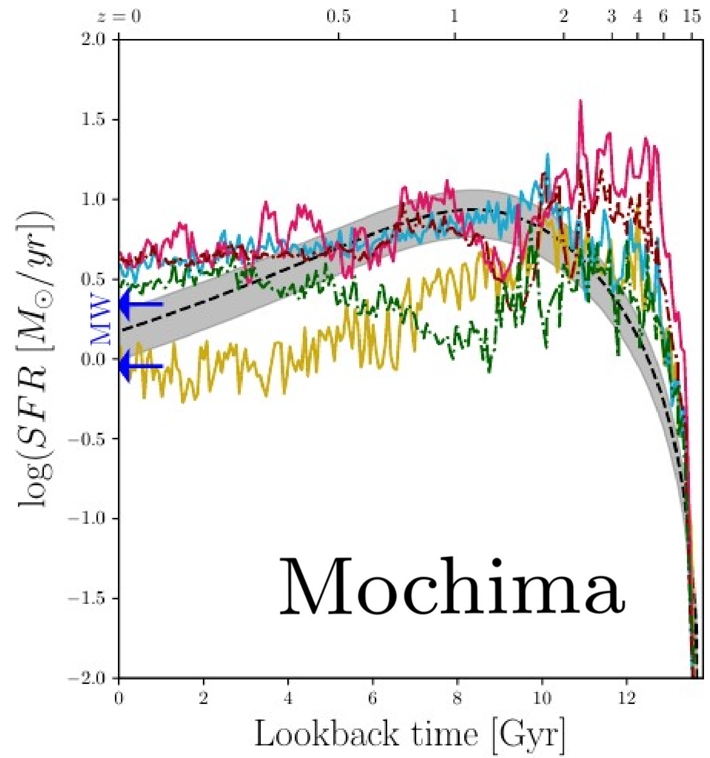




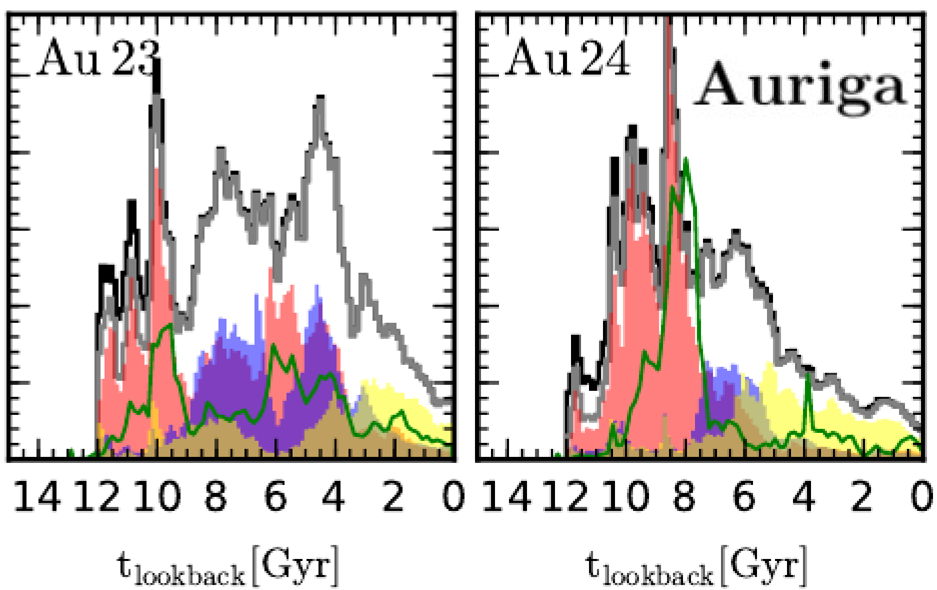
Galaxies

arXiv:1305.5360



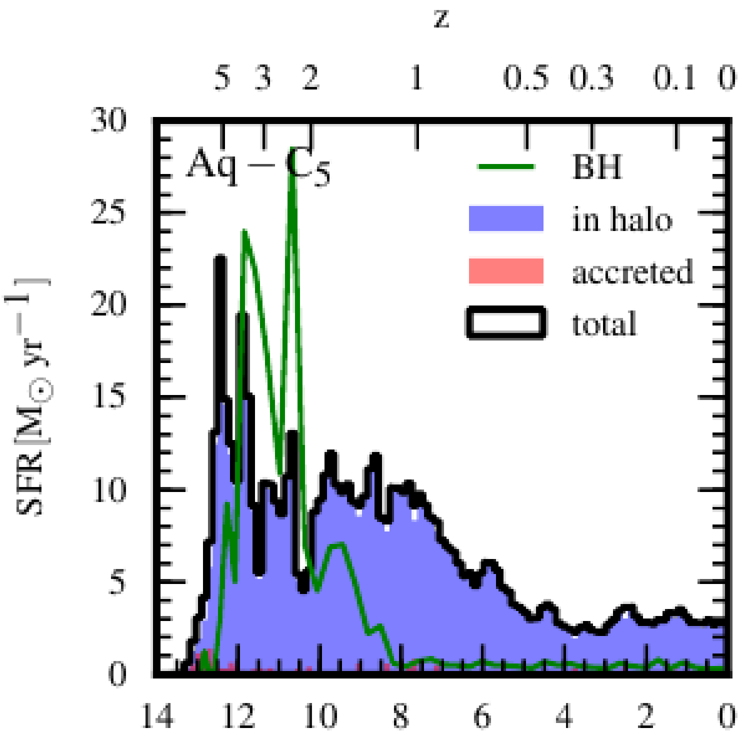


arXiv:2004.06008

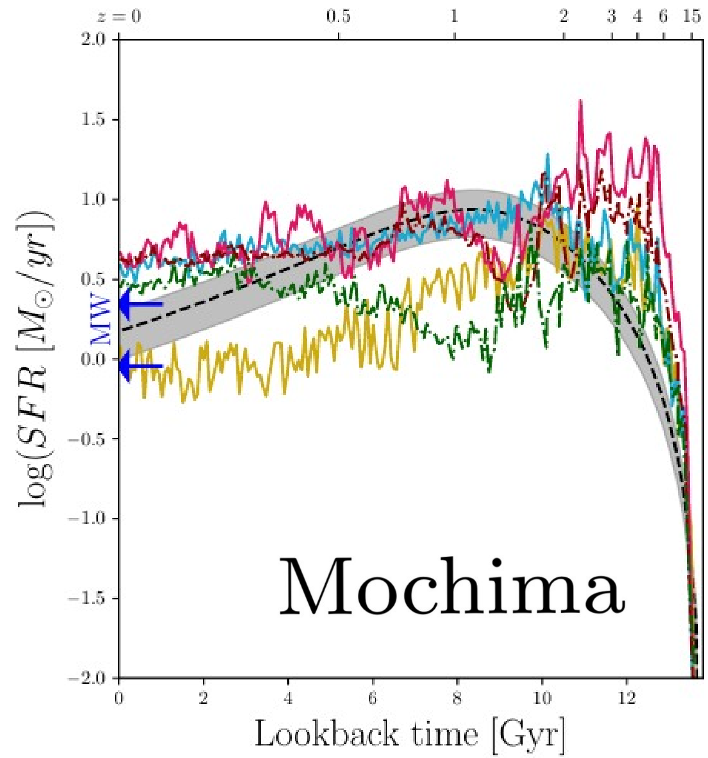


arXiv:1610.01159

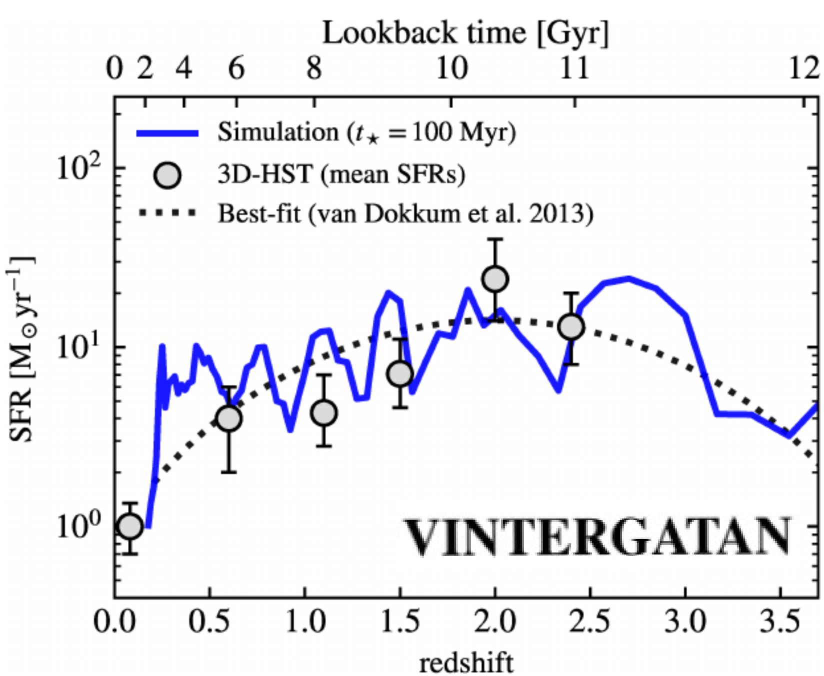
Galaxies



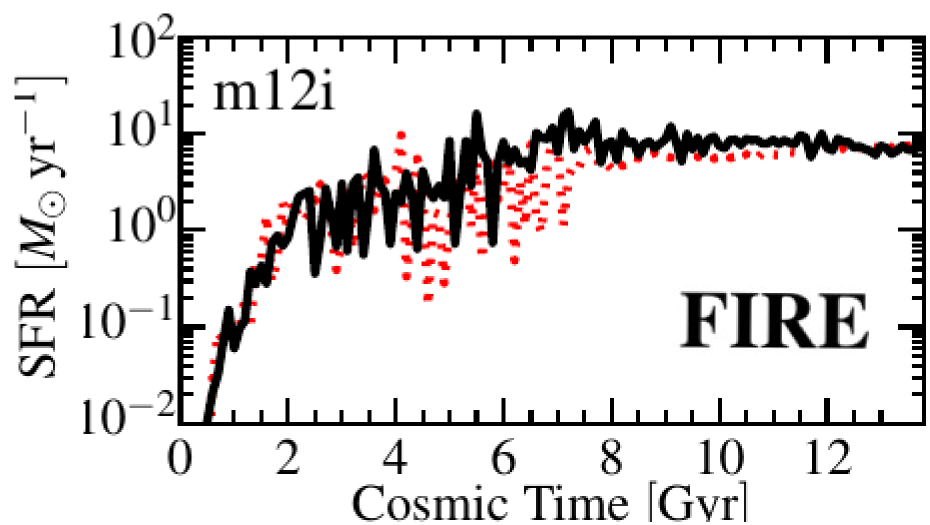
arXiv:1305.5360



arXiv:2004.06008



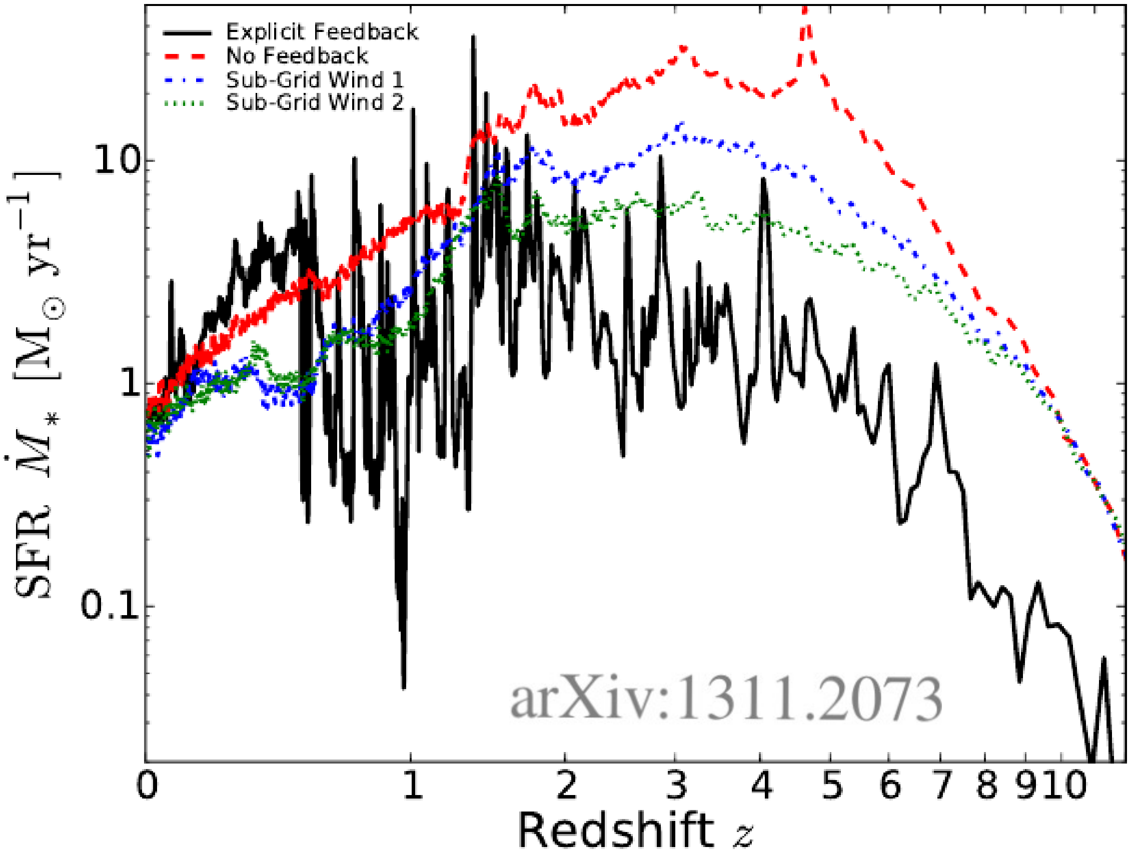
arXiv:2006.06008

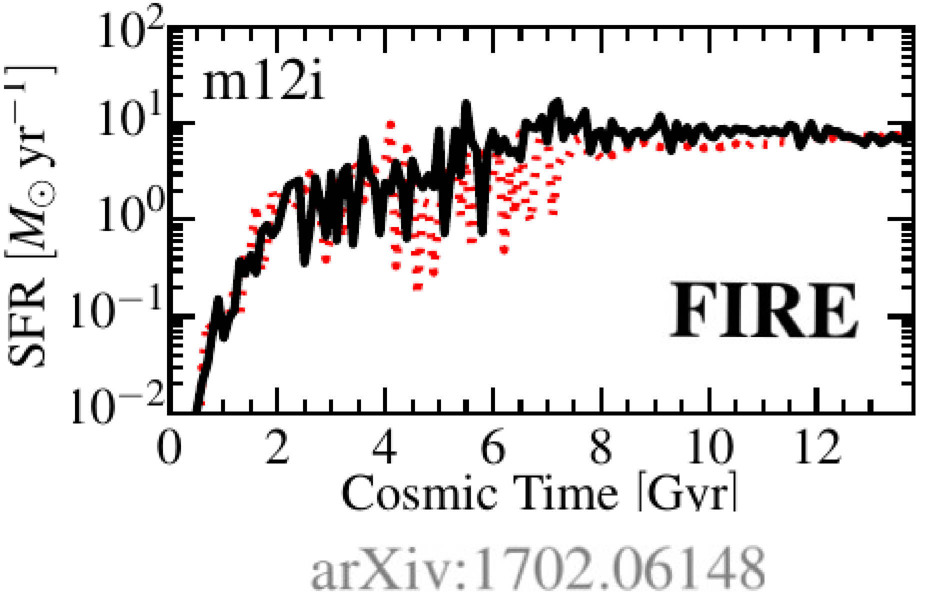


arXiv:1702.06148

Galaxies

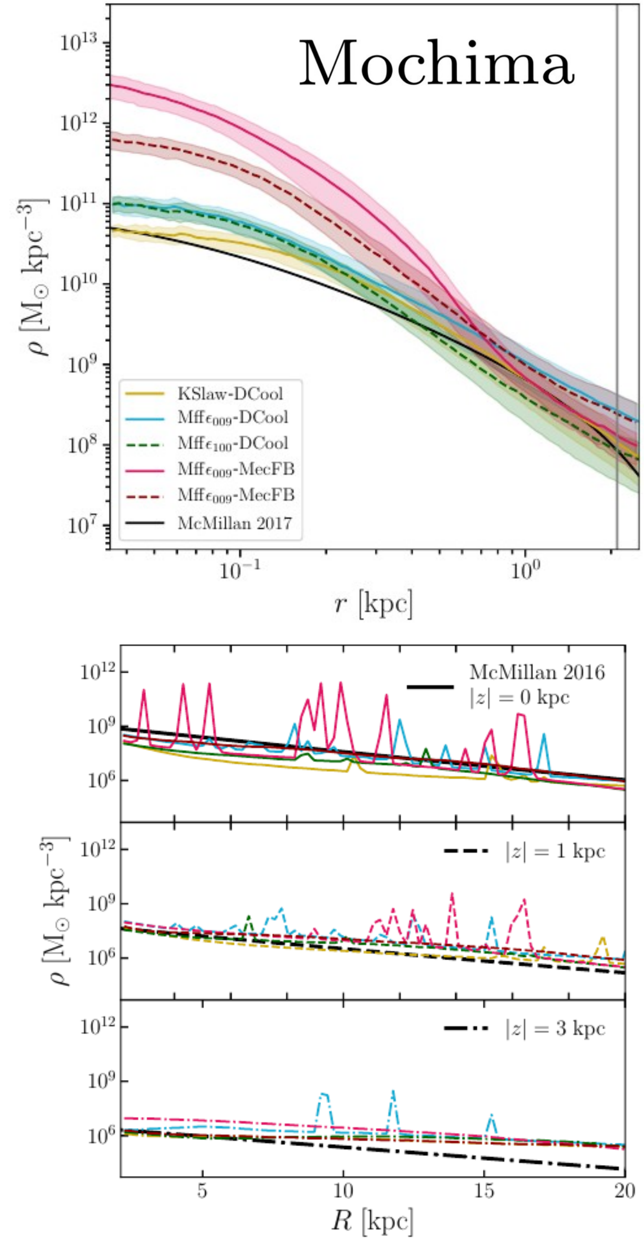
- *Stellar-to-halo mass ratio*
- ***Star formation history***
- *Disk, bulge properties Surface density*
- *Chemistery*





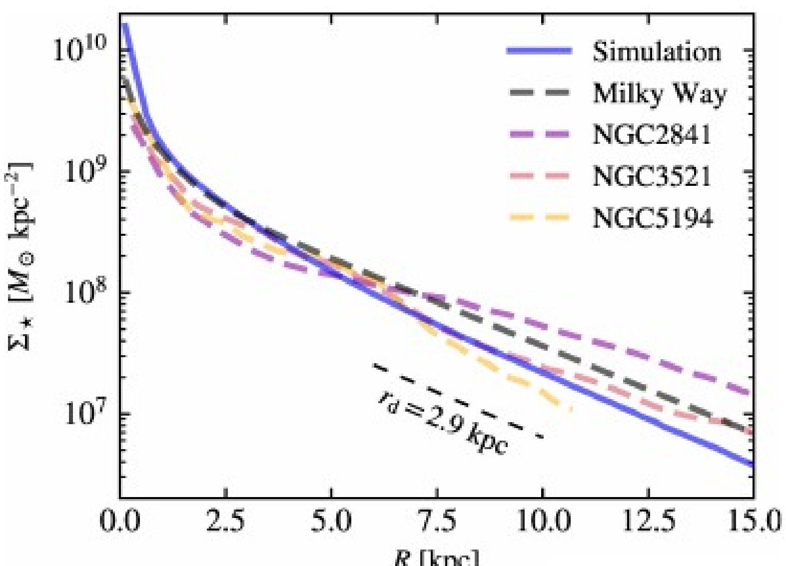
Galaxies

- *Stellar-to-halo mass ratio*
- *Star formation history*
- ***Disk, bulge properties Surface density, Rotation curve***
- *Chemistery*
- *Star forming gas region properties*



arXiv:2004.06008

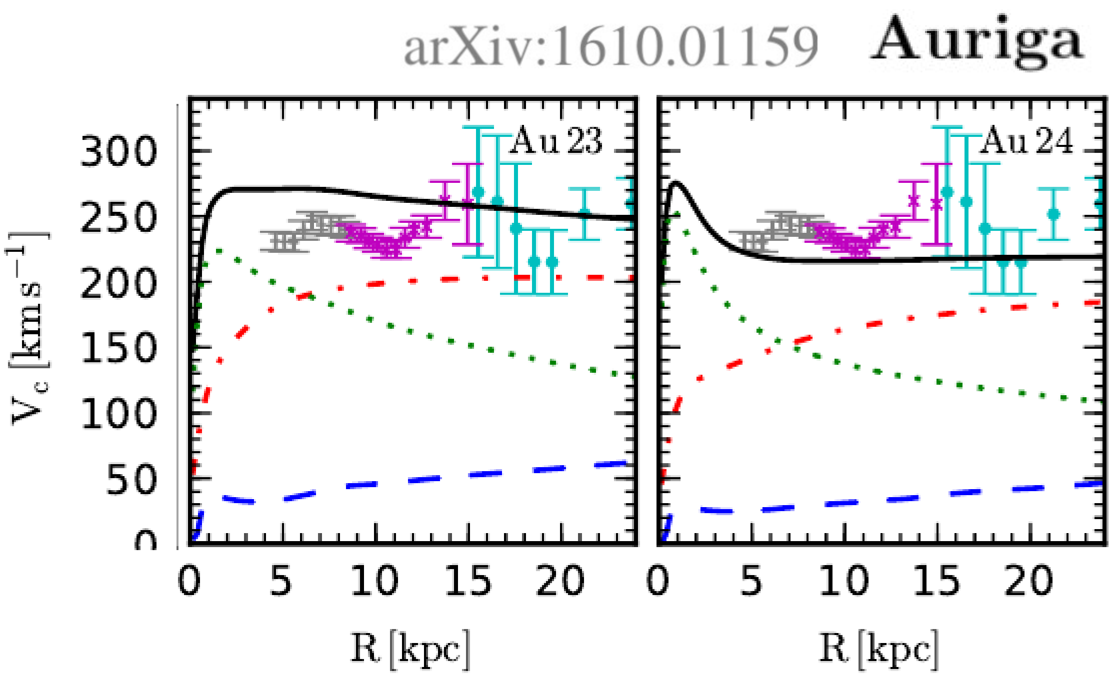
arXiv:2006.06008

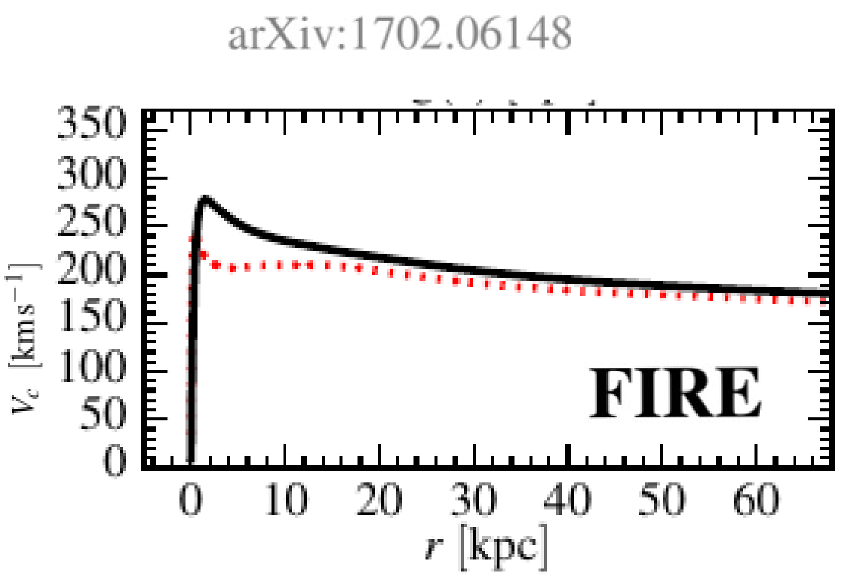


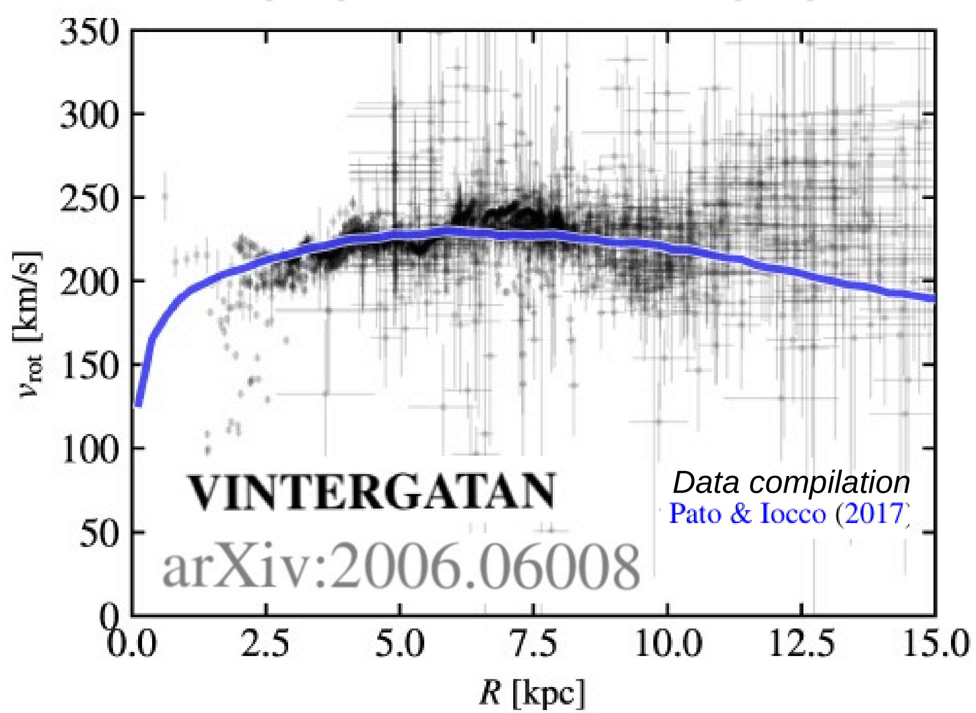
VINTERGATAN

Galaxies

- *Stellar-to-halo mass ratio*
- *Star formation history*
- ***Disk, bulge properties Surface density,***
- *Chemistery*
- *Star forming gas region properties*





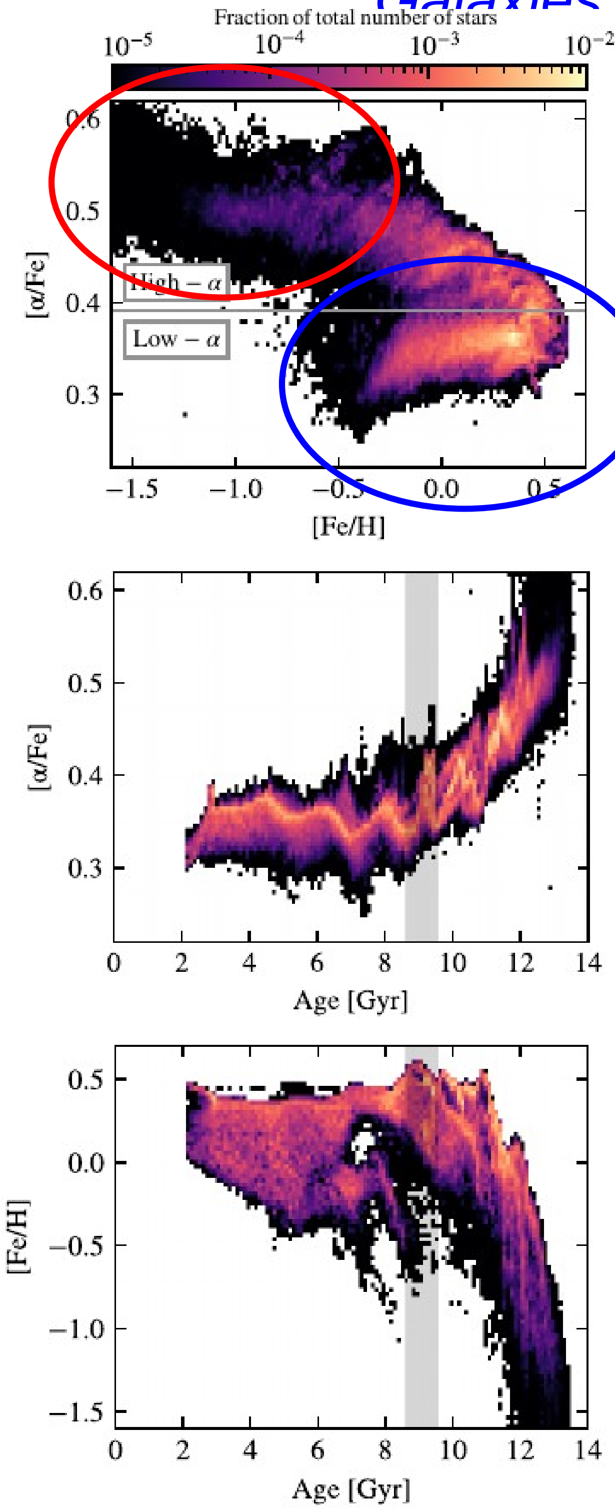


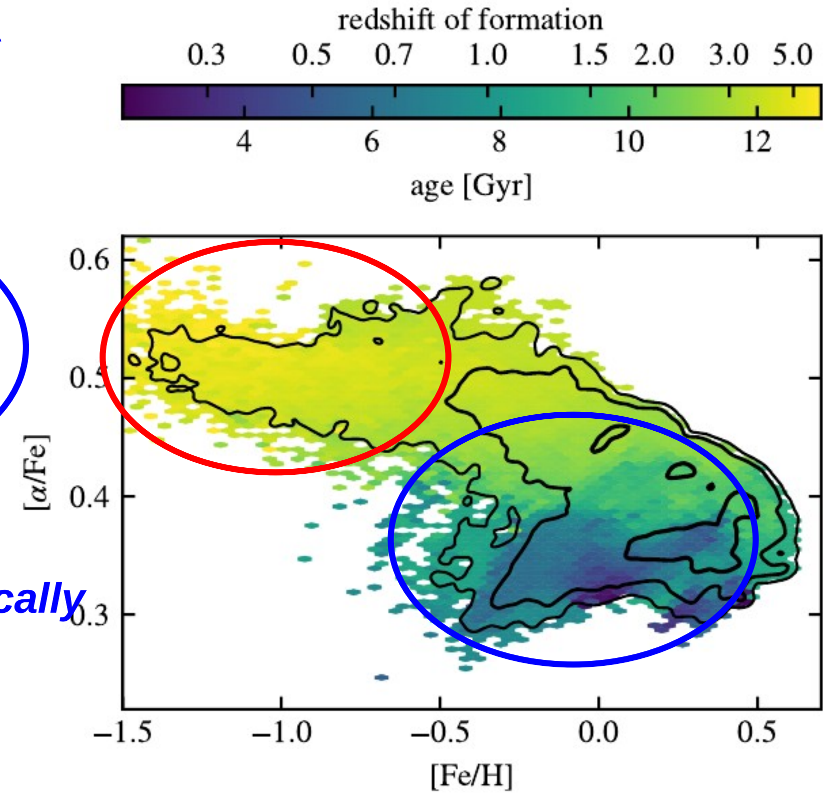
Galaxies

- *Stellar-to-halo mass ratio*
- *Star formation history*
- *Disk, bulge properties Surface density, Rotation curve*
- ***Chemistery: identifying thin and thick discs chemically***
- *Gas cycle, Star forming gas region properties*

Galaxies

- Stellar-to-halo mass r
- Star formation history
- Disk, bulge properties
- **Chemistery: identify** ... **cally**
- Gas cycle, Star formi





Thick disc

Thin disc

Abundance elements (Fe, O, Mg, Si, Ca, and Ti)

Similar to the observed MW bimodality

VINTERGATAN

arXiv:2006.06008

arXiv:2006.06011

Galaxies

- Stellar-to-halo mass ratio

- Star formation history

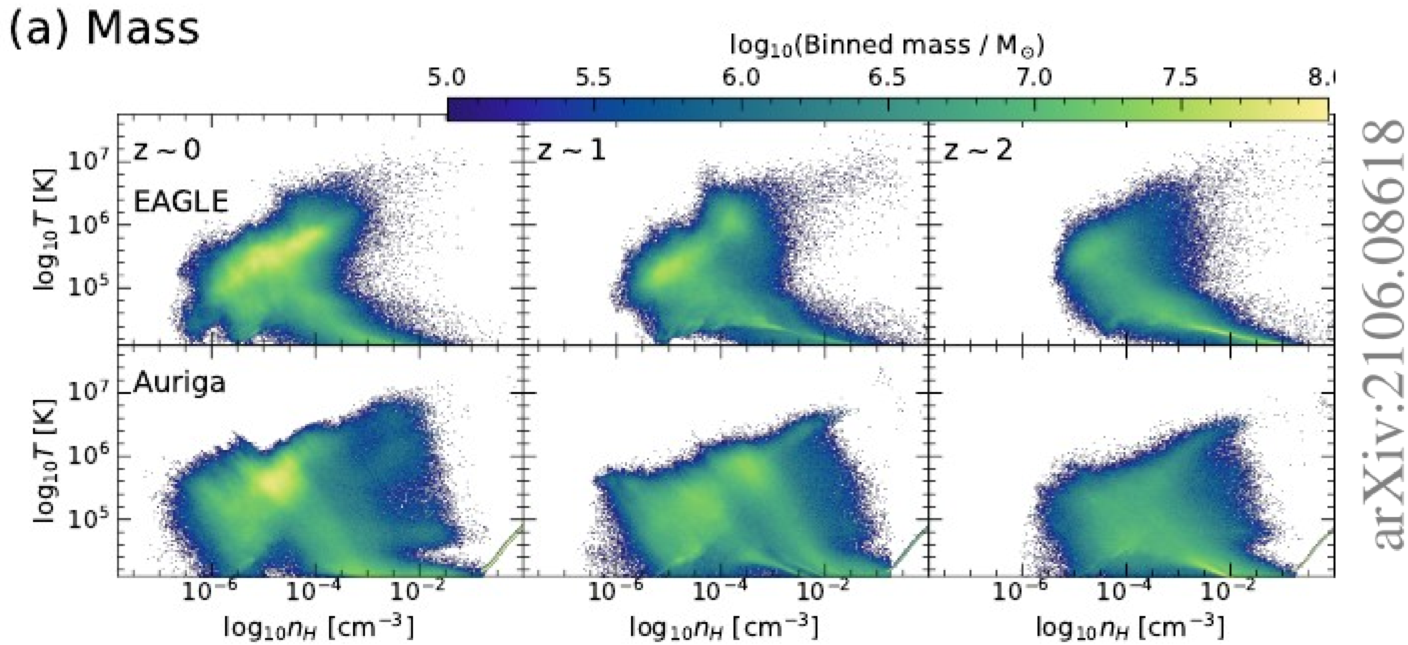
- Disk, bulge properties Surface density, Rotation curve

- Chemistery

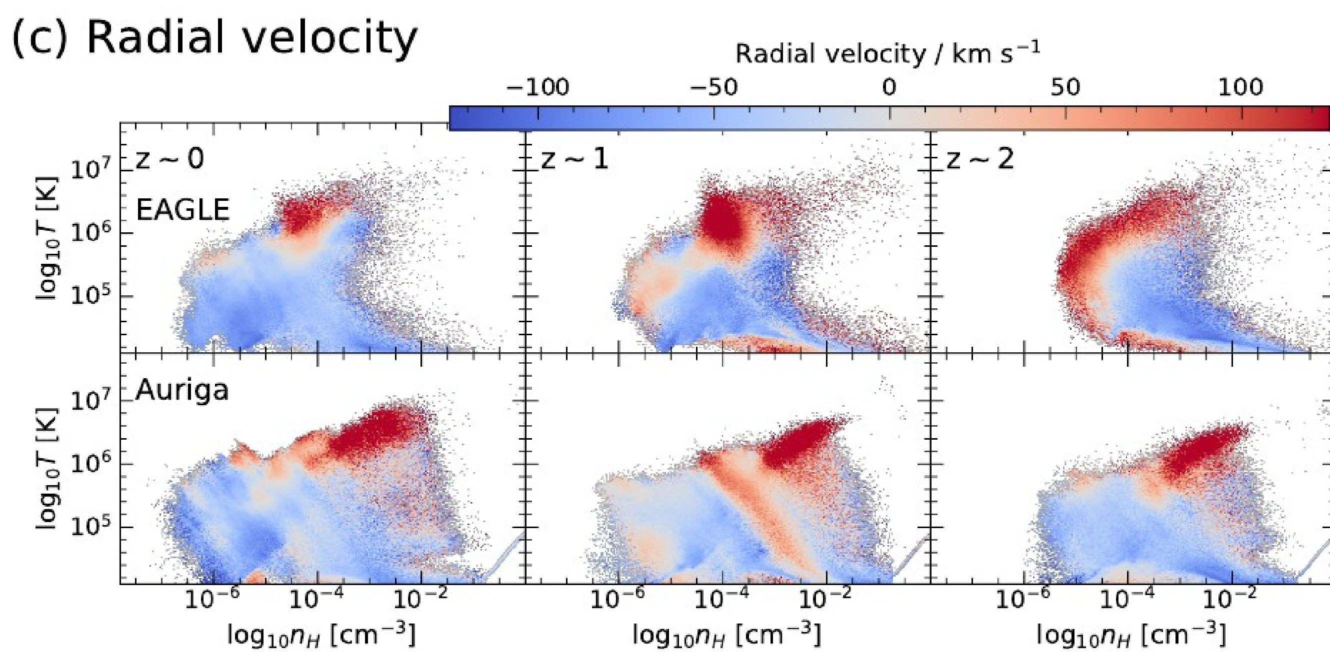
- Gas cycle, Star forming gas region properties

- Bars ? Eagles? Illustris ? Auriga !?

Galaxies



- *Stellar-to-halo mass ratio*
- *Star formation history*
- *Disk, bulge properties Surfac*
- *Chemistery*
- ***Gas cycle, Star forming gas region properties***

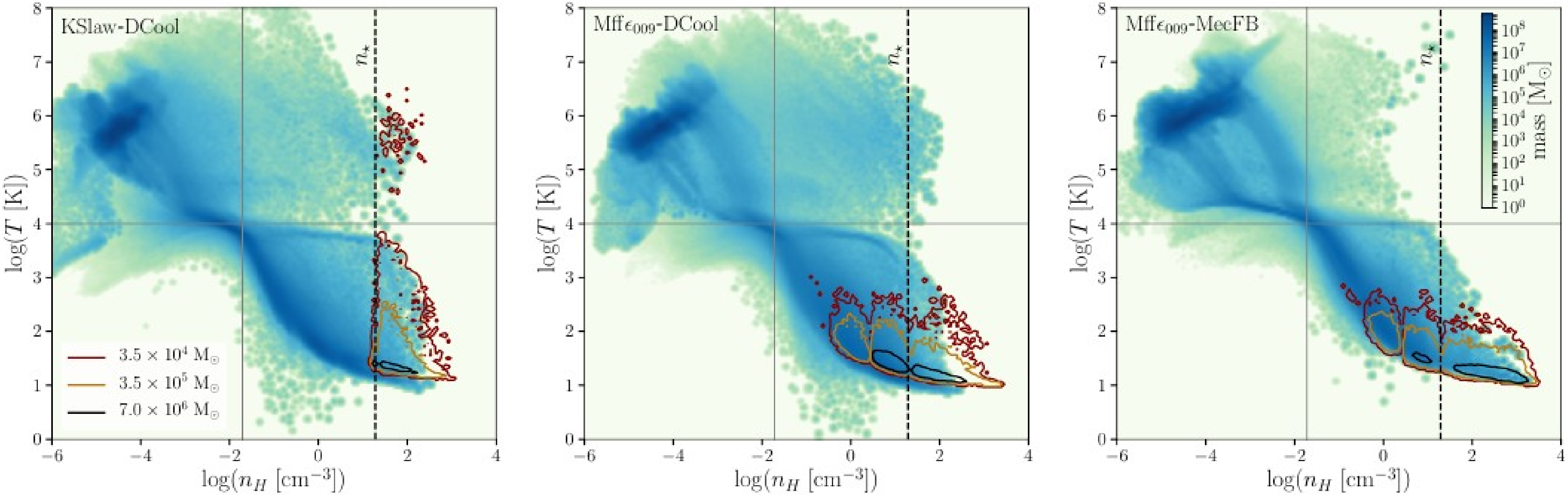


Same initial conditions and different baryonic physics → different gas properties

Galaxies

- *Stellar-to-halo mass ratio*
- *Star formation history*
- *Disk, bulge properties Surface density, Rotation curve*
- *Chemistery*
- ***Gas cycle, Star forming gas region properties***

Mochima



Galaxies

- Stellar-to-halo mass ratio

- Star formation history

- Disk, bulge properties Surface density, Rotation curve

- Chemistery

- Gas cycle, Star forming gas region properties

- (no) Bars ?

Why ?
- Stabilization by the bulge or the halo (Debattista & Sellwood 2000; Kataria & Das 2017) ?
- Gas fraction/accretion (Kraljic et al. 2012) ?
...

Some bar effects:
Trigger star formation at its extremities (Renaud et al. 2015; Motte al. 2018),
Reduce star formation inside the bar (Longmore et al. 2013; Emsellem et al. 2015)
Fuel nuclear star formation in the very center where the gas accumulates
Affect the overall kinematics of the disk (resonances) Lynden-Bell & Kalnajs 1972).
...

Dark matter

Dark matter

- *Mass density profiles*
- *Halo shape*
- *Phase-space/velocity distributions*
- *Substructures, subhaloes, streams*

Dark matter

- ***Mass density profiles***

- *Halo shape*

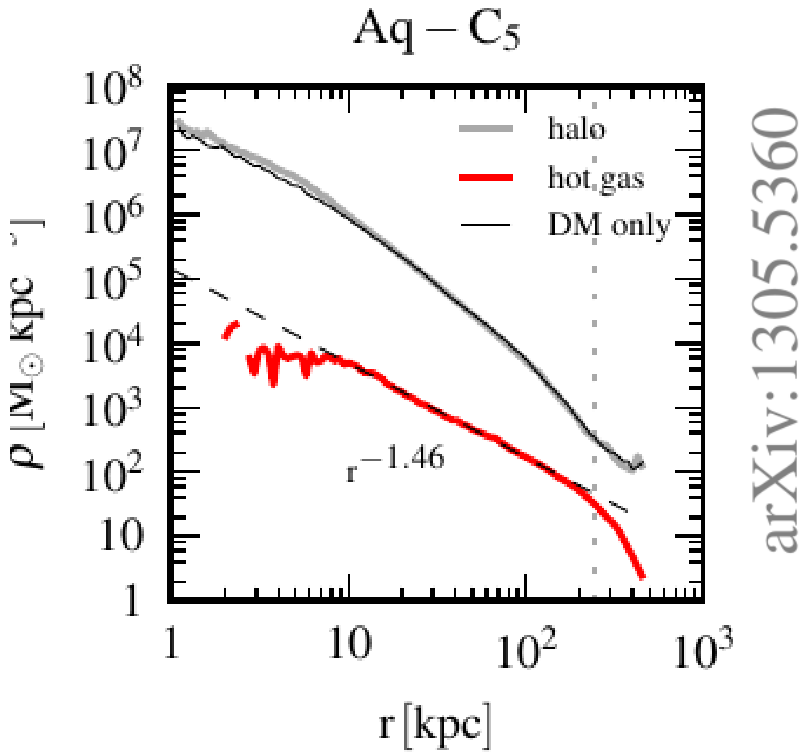
- *Phase-space/velocity distributions*

- *Substructures, subhaloes, streams*

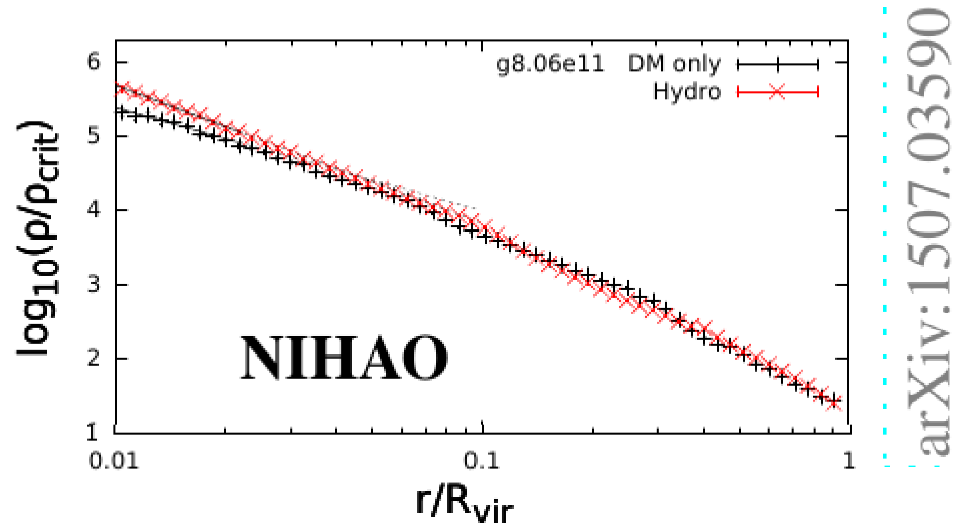
Contraction with baryon ? Steep cusp ?

Feedback induced core ?

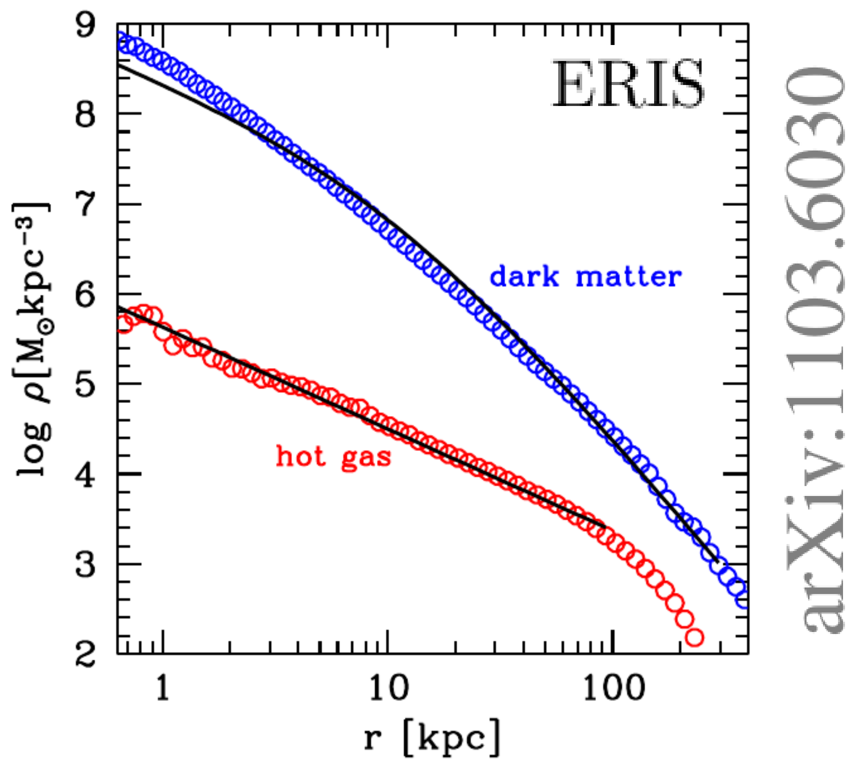
Dark matter



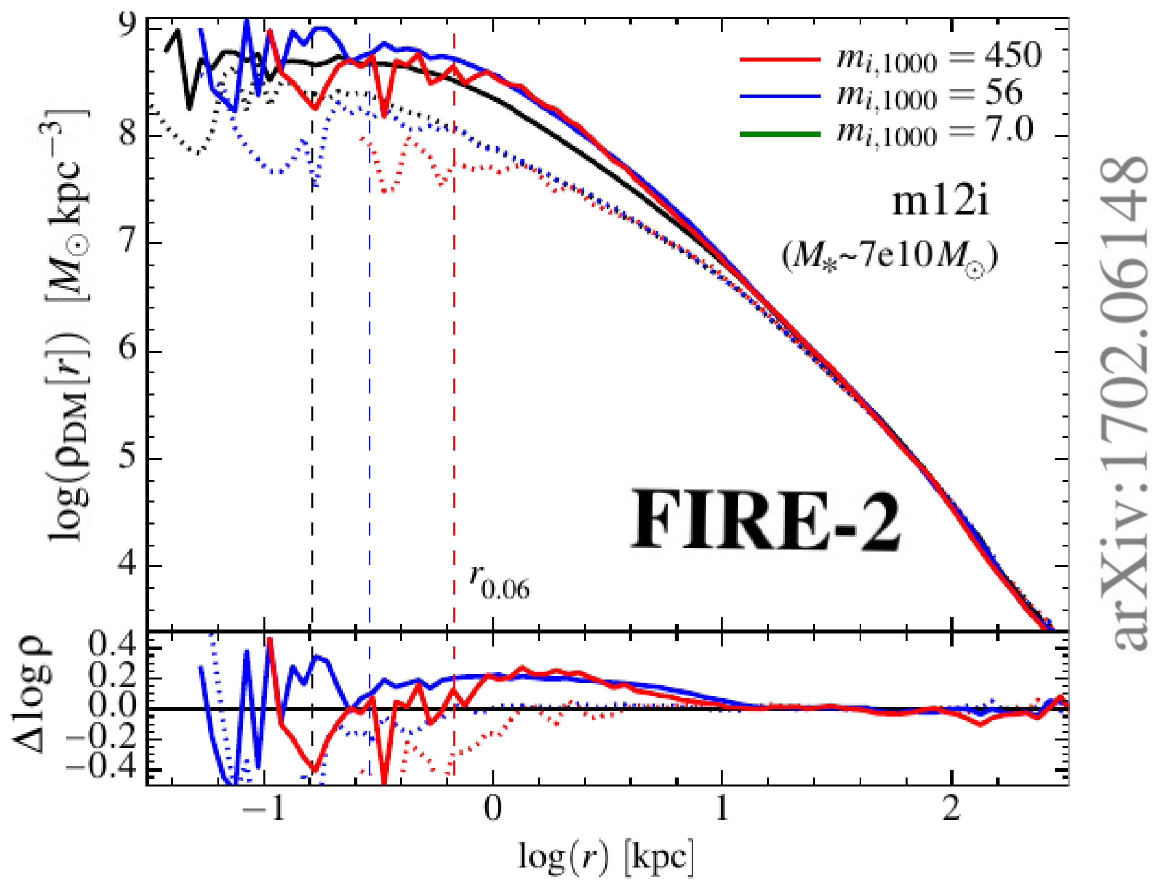
Aq – C5
halo
hot gas
DM only
$r^{-1.46}$
ρ [M$_\odot$ kpc^{-3}]
r [kpc]
arXiv:1305.5360



g8.06e11 DM only
Hydro
NIHAO
$\log_{10}(\rho/\rho_{crit})$
r/R_{vir}
arXiv:1507.03590



ERIS
dark matter
hot gas
log ρ[M$_\odot$kpc^{-3}]
r [kpc]
arXiv:1103.6030



$m_{i,1000} = 450$
$m_{i,1000} = 56$
$m_{i,1000} = 7.0$
m12i
($M_* \sim 7e10 M_\odot$)
FIRE-2
$r_{0.06}$
$\log(\rho_{DM}[r])$ [$M_\odot$ kpc^{-3}]
$\Delta\log\rho$
$\log(r)$ [kpc]
arXiv:1702.06148

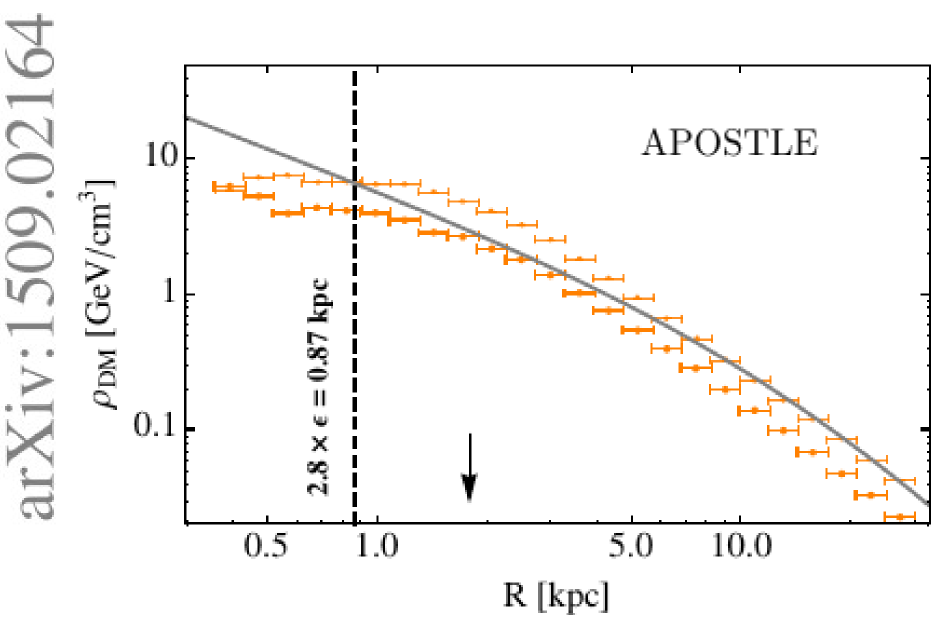
Dark matter

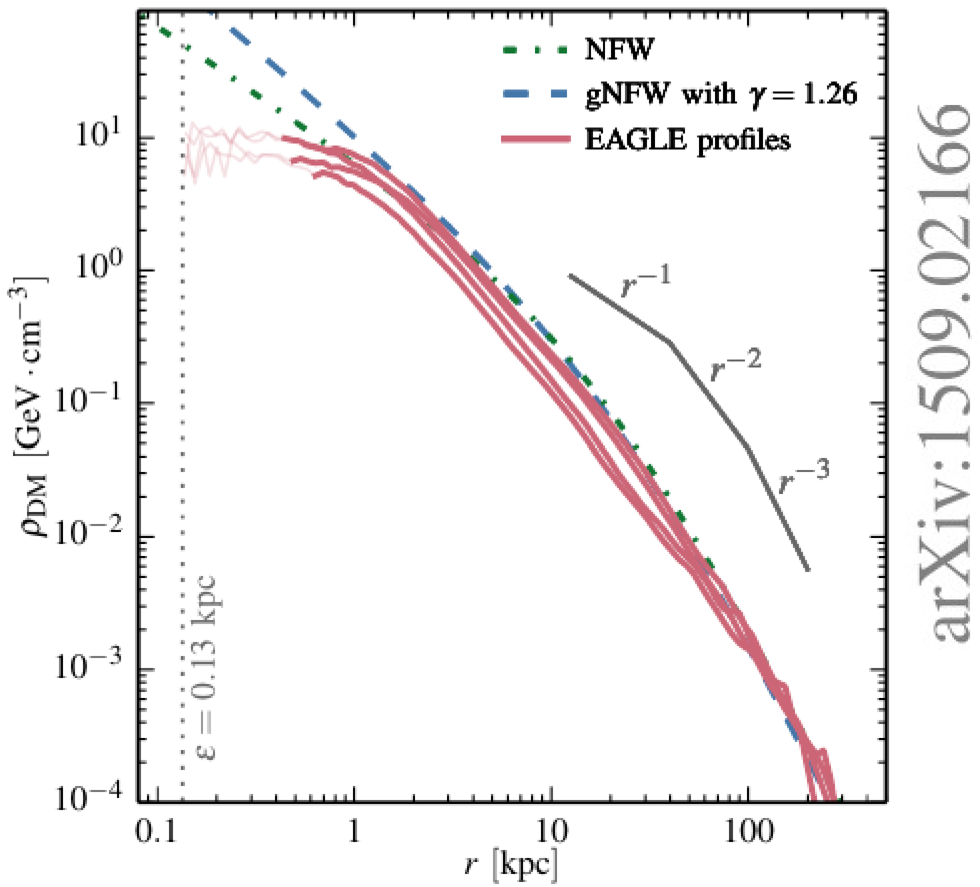
- ***Mass density profiles***

- *Halo shape*

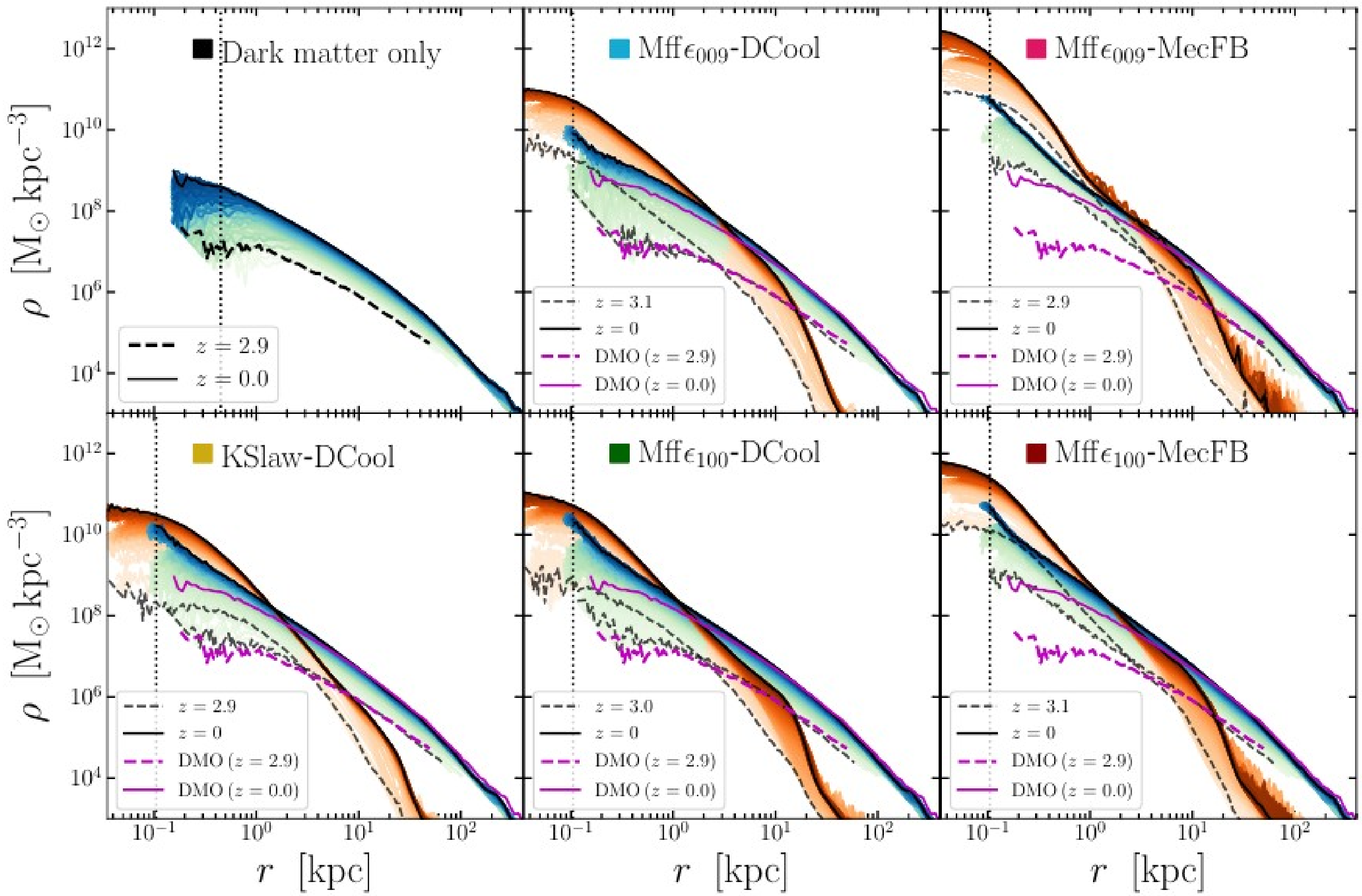
- *Phase-space/velocity distributions*

- *Substructures, subhaloes, streams*





Dark matter

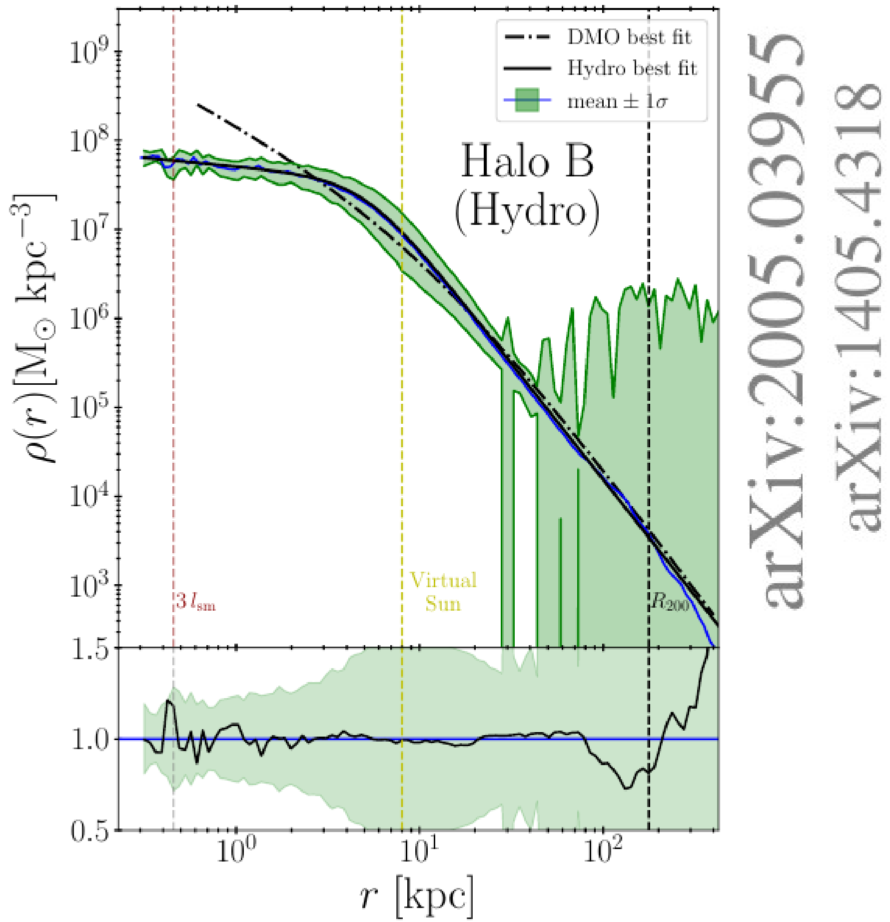


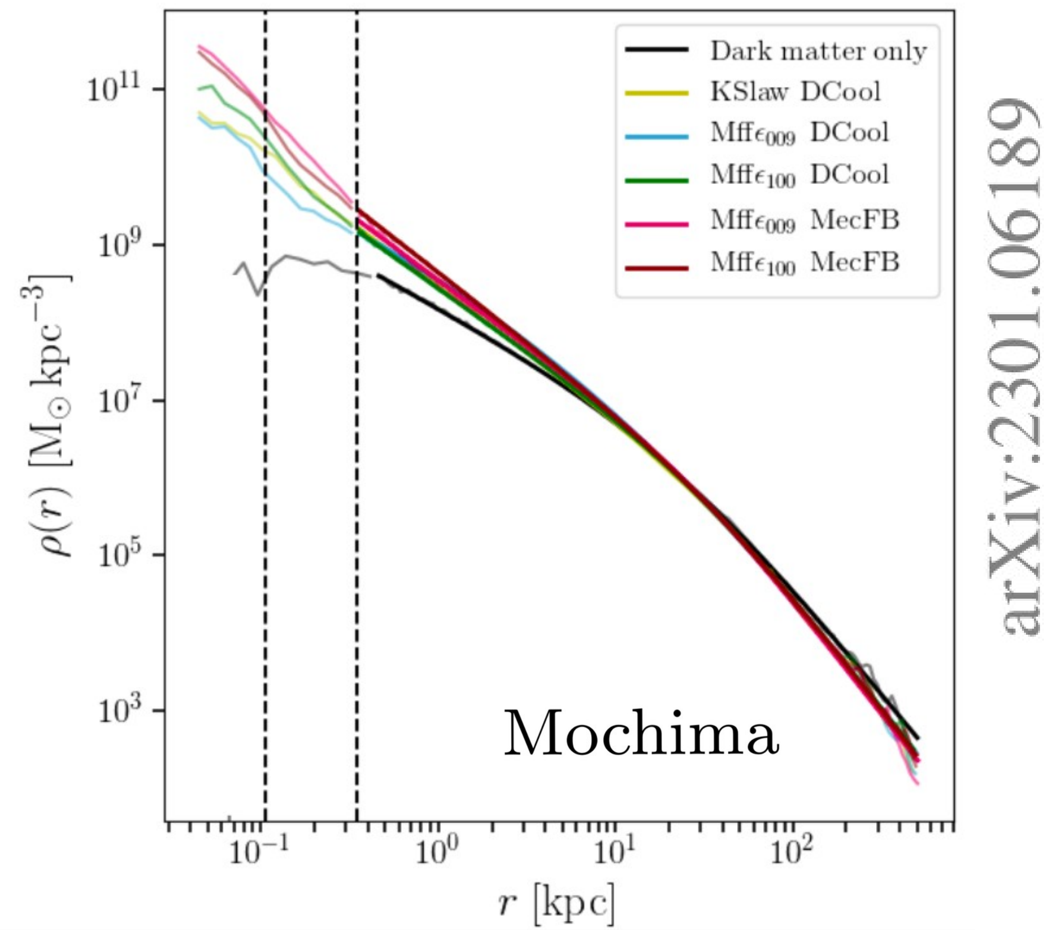
Mochima
arXiv:2301.06189

Response of DM halo driven by the history of assembly of baryons
(e.g Pedrosa et al 2009)

→ DM profile depends on baryonic physics. SF and feedback reciepes (model, parameters, resolution ...)

Dark matter





Response of DM halo driven by the history of assembly of baryons
(e.g Pedrosa et al 2009)

→ DM profile depends on baryonic physics. SF and feedback reciepes (model, parameters, resolution ...)

NFW ? Einasto ?

Dark matter

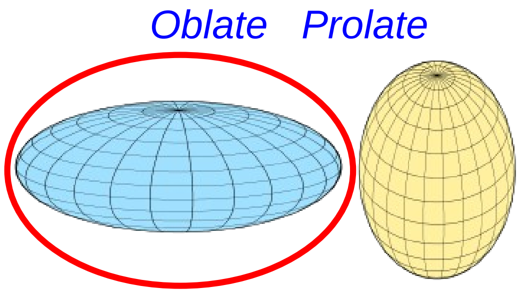
- *Mass density profiles*

- ***Halo shape***

- *Phase-space/velocity distributions*

- *Substructures, subhaloes, streams*

Dark matter

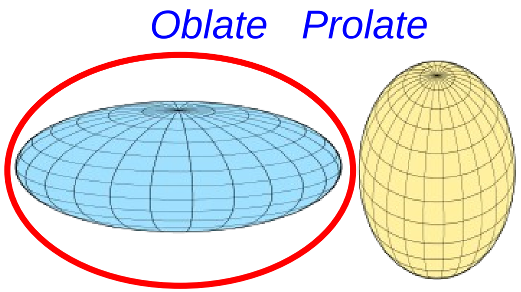


- Mass density profiles

- Halo shape

(Uncertain) observations suggest slightly oblate halo in the center and become triaxial at large distances (Law and Majewski 2010, Ibata et al 2013, Vera-Ciro and Helmi 2013)

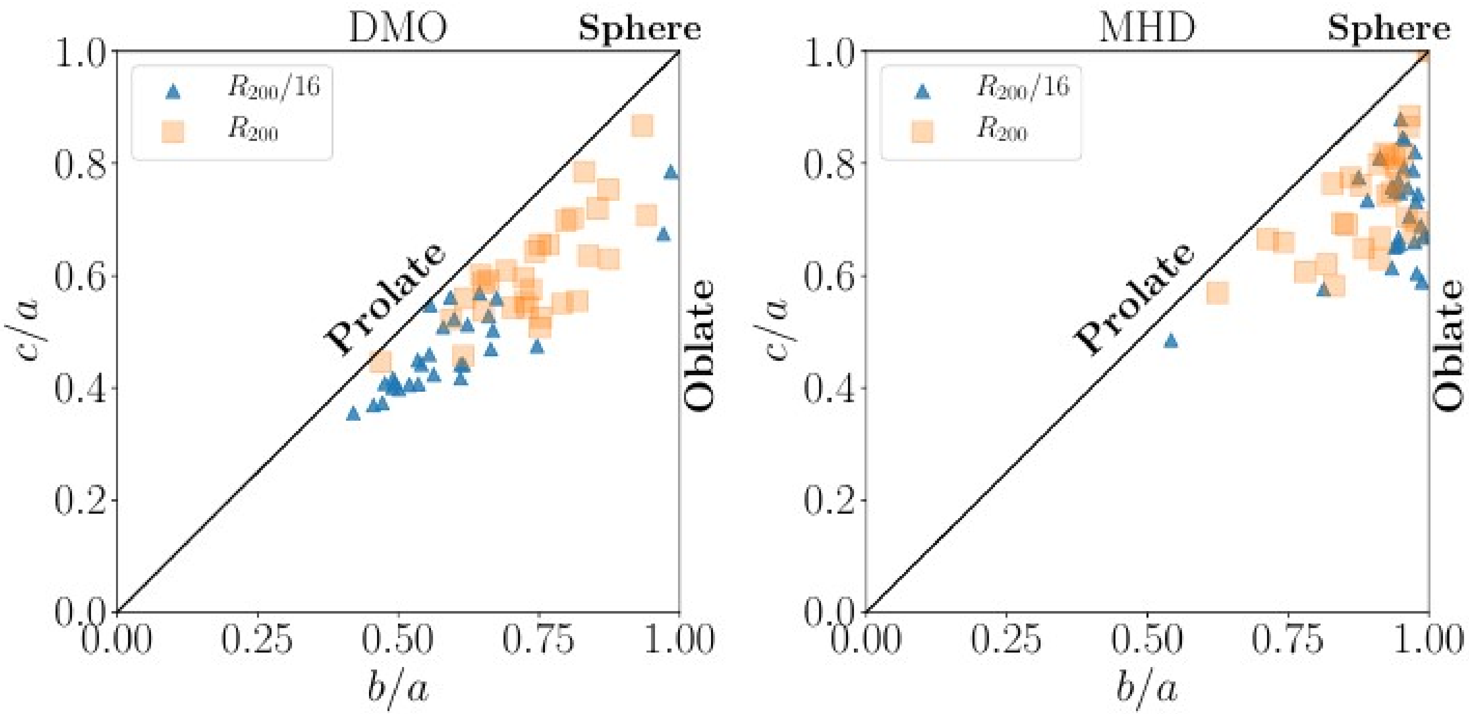
Dark matter



- *Mass density profiles*

- ***Halo shape: rounder halo than DMO***

(Uncertain) observations suggest slightly oblate halo in the center and become triaxial at large distances (Law and Majewski 2010, Ibata et al 2013, Vera-Ciro and Helmi 2013)



arXiv:1910.04045

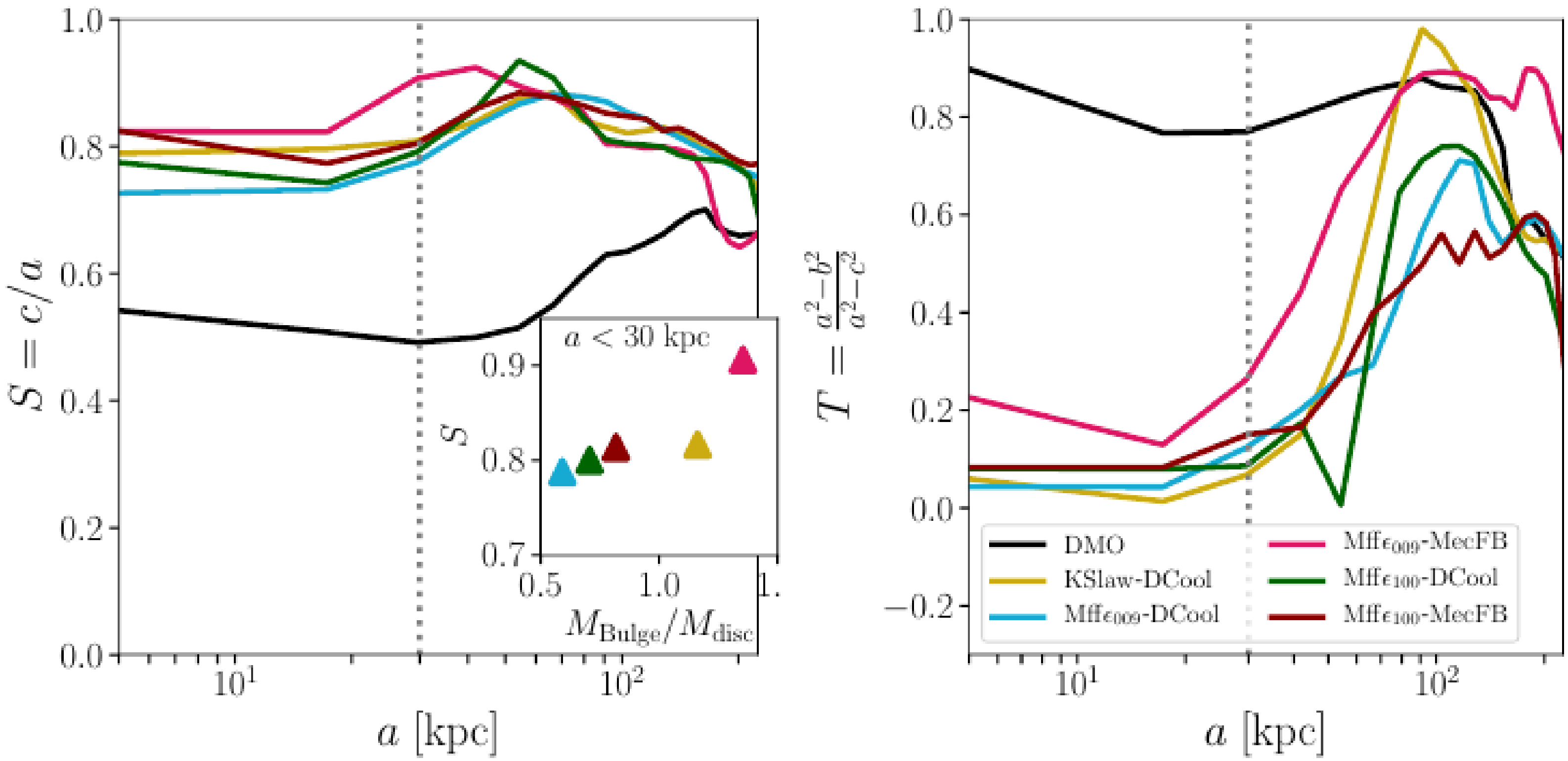
Auriga

Dark matter

- *Mass density profiles*

- ***Halo shape**: **rounder halo than DMO***

- *Phase-space/velocity distributions*



arXiv:2301.06189

Mochima

Same halo, varying baryonic physics. Results might change with weaker bulge, bar ...

Dark matter

- Mass density profiles

- Halo shape

- Phase-space/velocity distributions (complex/realistic ?)

- Substructures, subhaloes, streams

Accretion history → Distribution features
beyond analytical functions ?
Dark disc ?

Fit ? Maxwellian, Tsallis … ? SHM ?

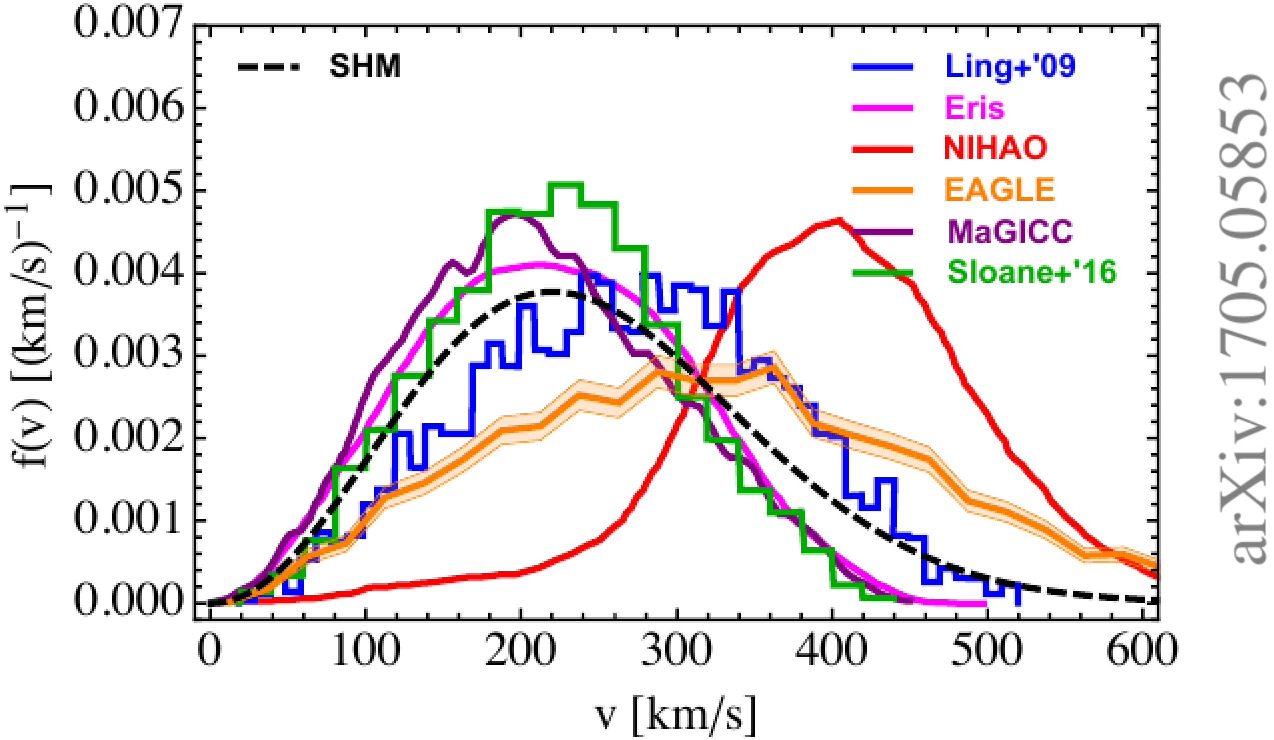
Agreement with analytical predictions ?
(e.g Eddington inversion)

Dark matter

- *Mass density profiles*

- *Halo shape*

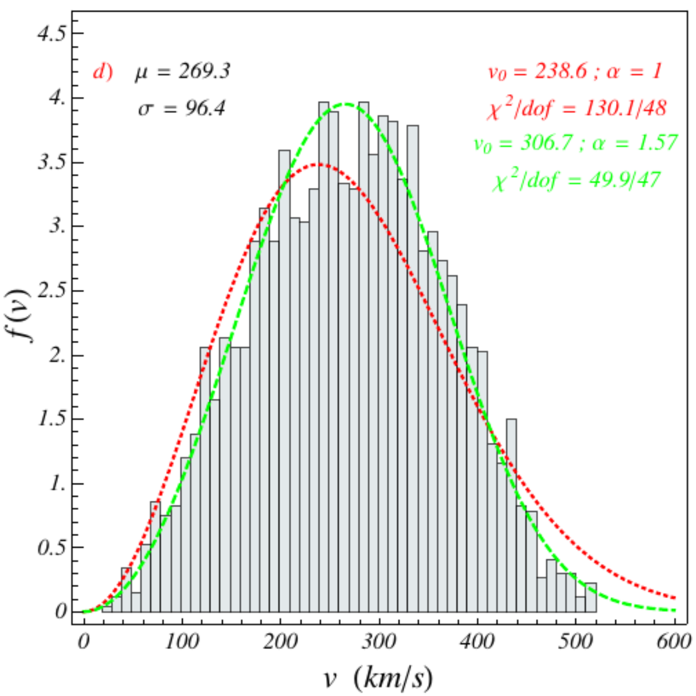
- ***Phase-space/velocity distributions (complex/realistic ?)***



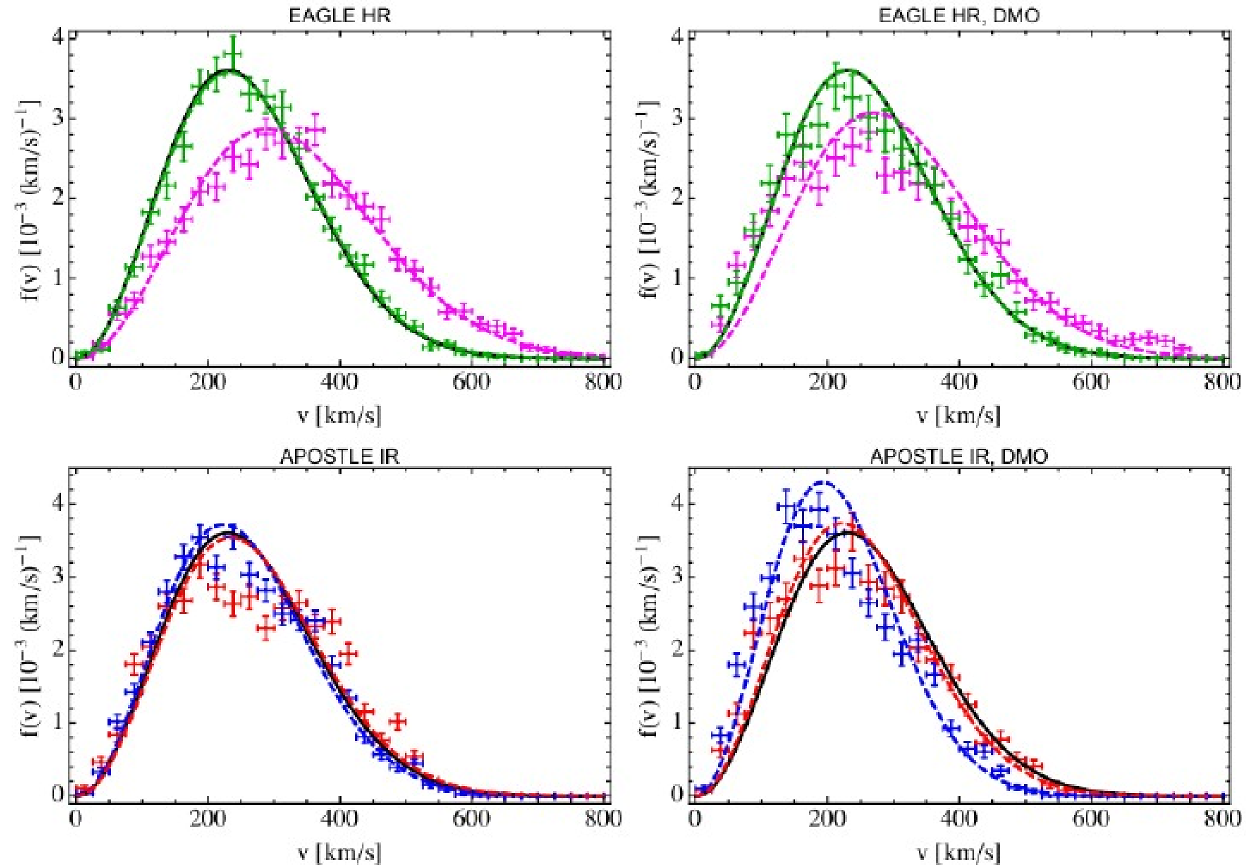
Methods (meaning !) of particle selections ?

Dark matter

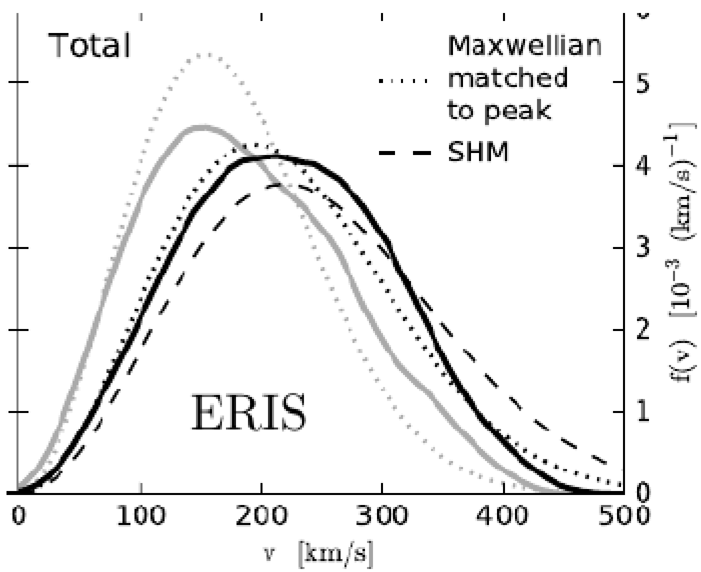
arXiv:0909.2028



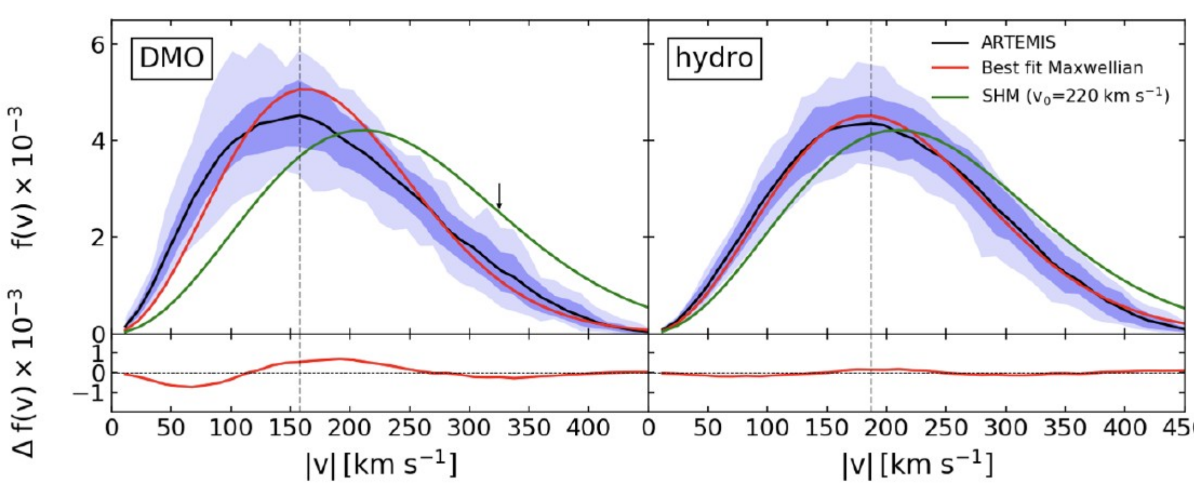
arXiv:1601.04707



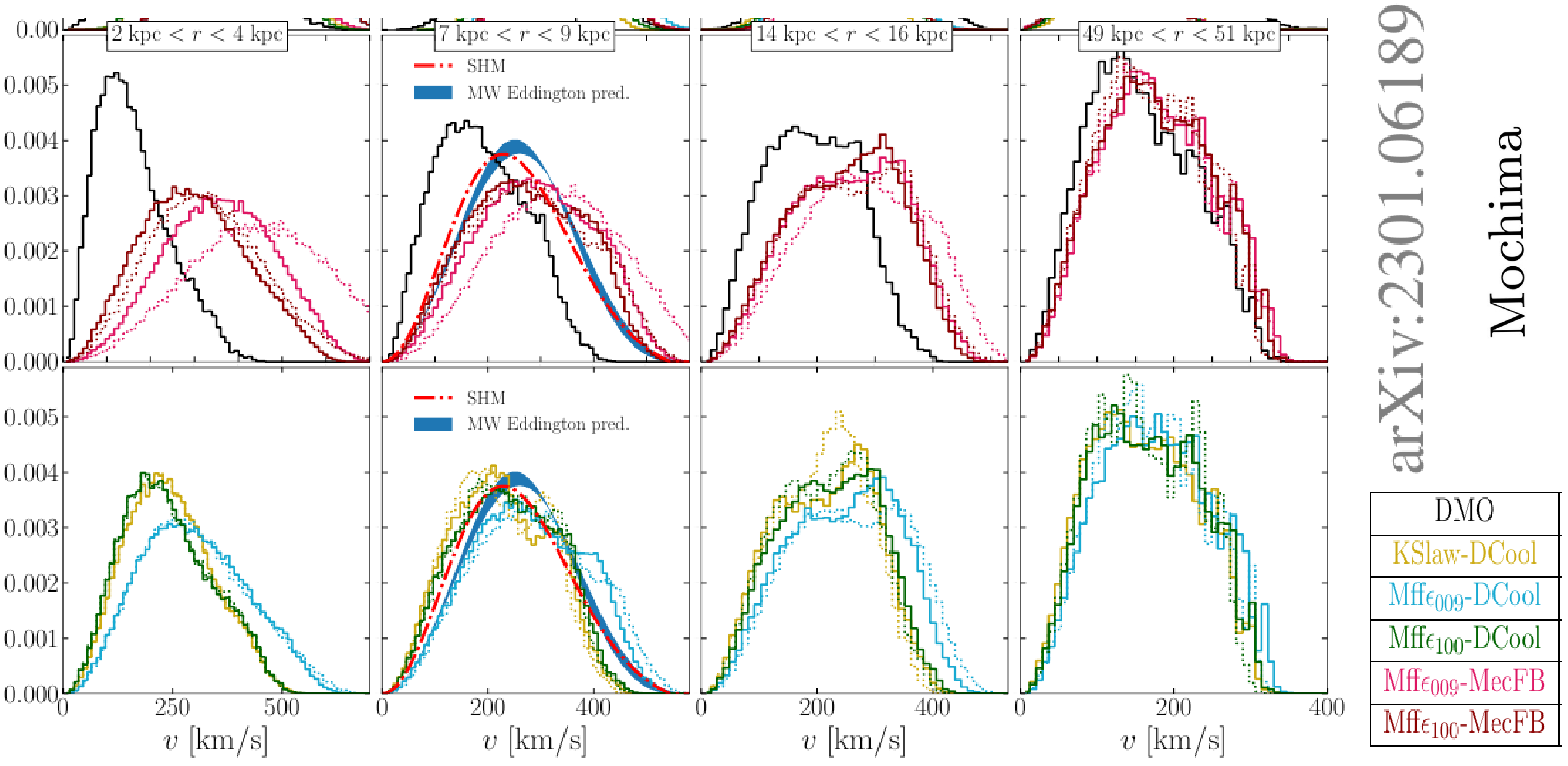
arXiv:1308.1703



arXiv:2006.15159



Dark matter



Features from formation history

Baryons : shift central value and broader distributions in central part.

Dark matter

- *Mass density profiles*

- *Halo shape*

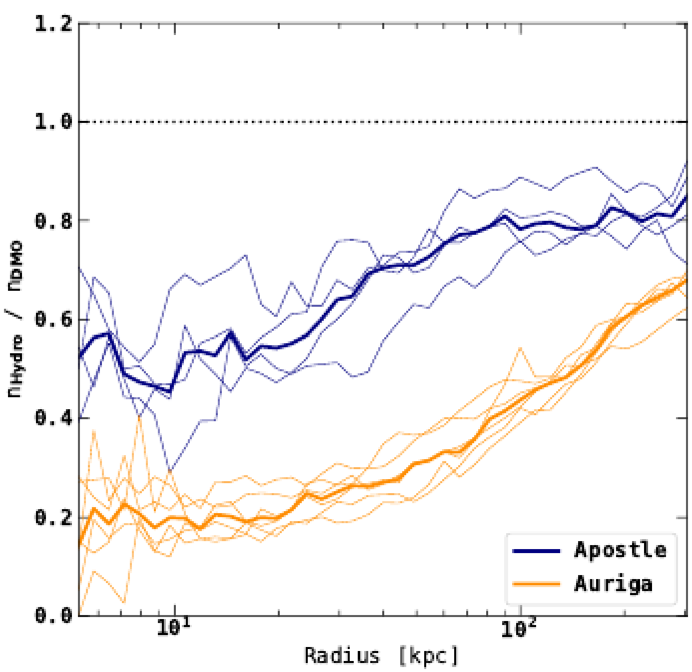
- *Phase-space/velocity distributions*

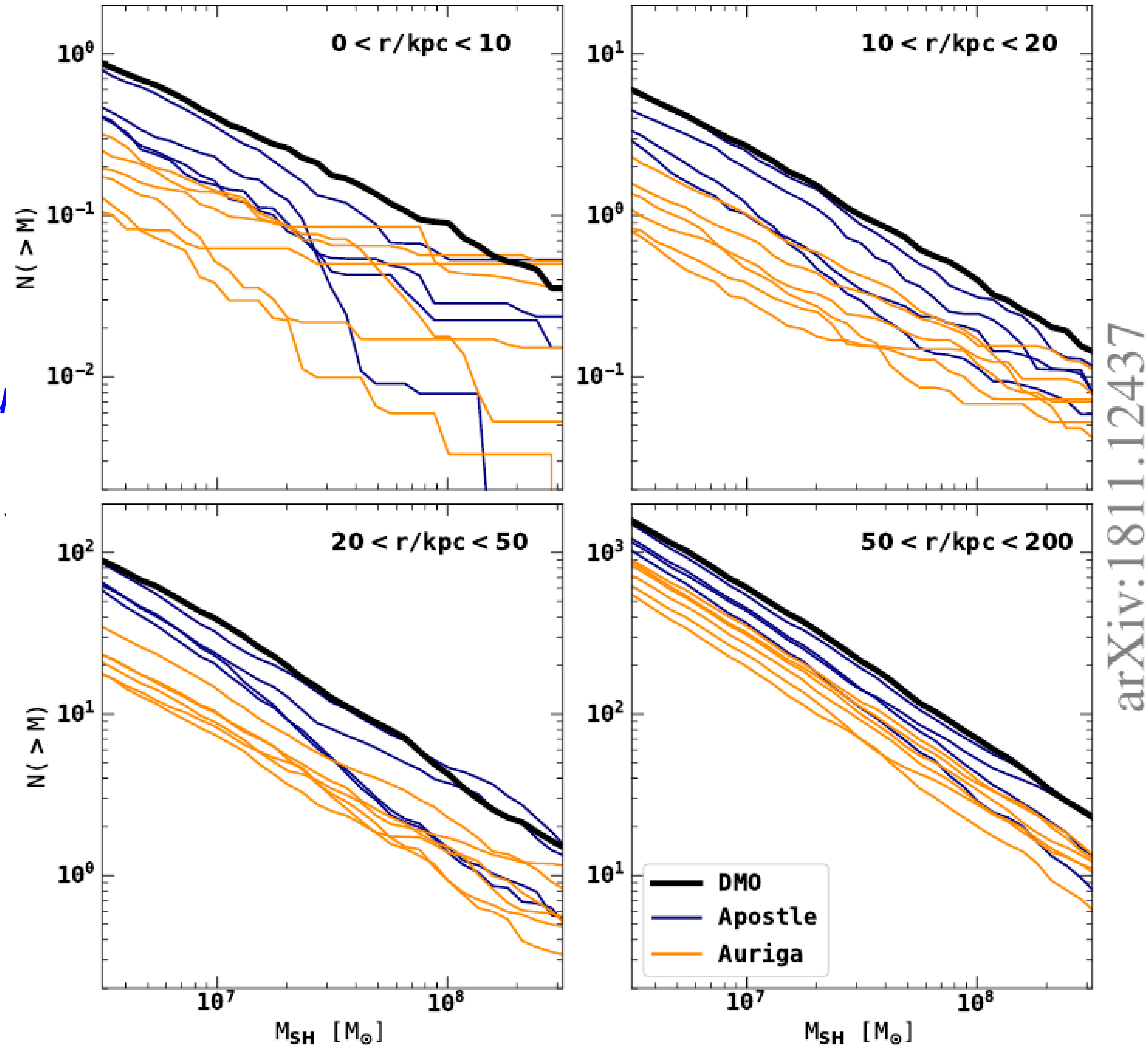
- ***Substructures, subhaloes, streams***

Mass spectrum modified by baryons (tidal effects, disc, concentration …) ?

Dark matter

- *Mass density profiles*
- *Halo shape*
- *Phase-space/velocity distribu*
- ***Substructures, subhaloes, .***





APOSTLE and AURIGA

Relative to DMO simulation, the abundance of subhalos is reduced.
APOSTLE: by 50% near the centre and by 10% within r200 .
AURIGA: 80% and 40%

Dark matter

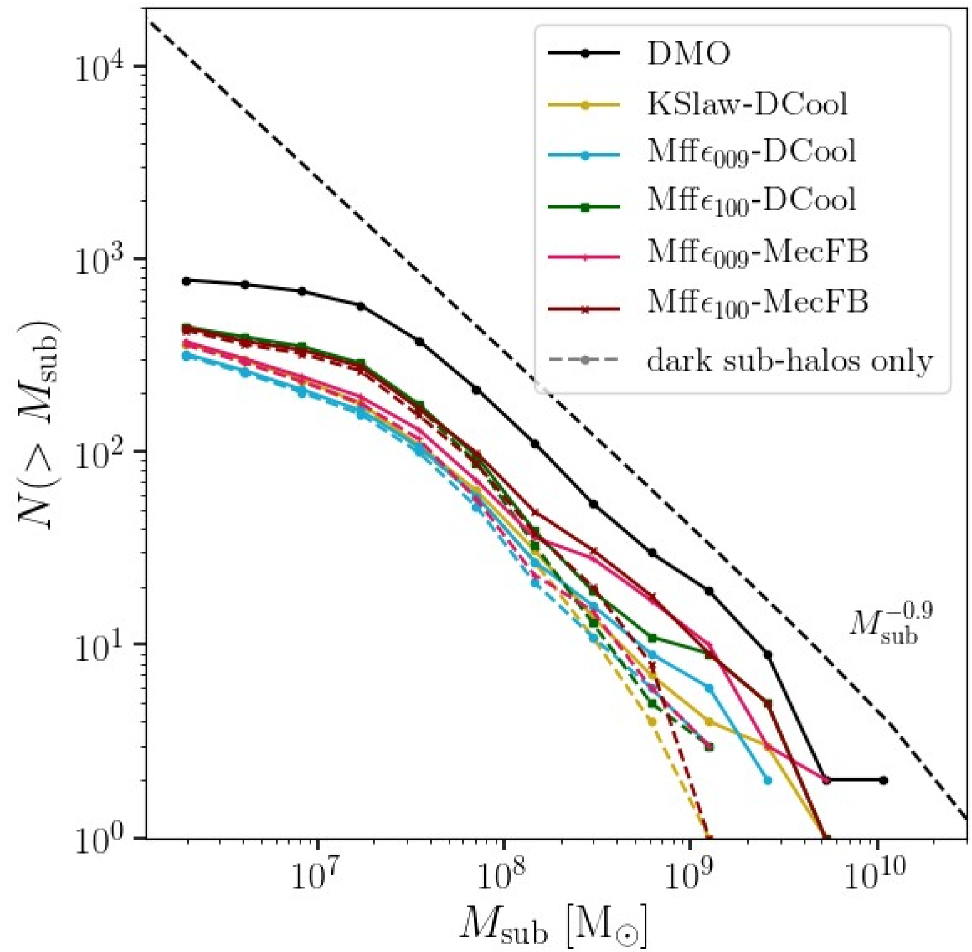
- *Mass density profiles*

- *Halo shape*

- *Phase-space/velocity distributions*

- ***Substructures, subhaloes, strea***

Mass spectrum mc
effects, disc shock



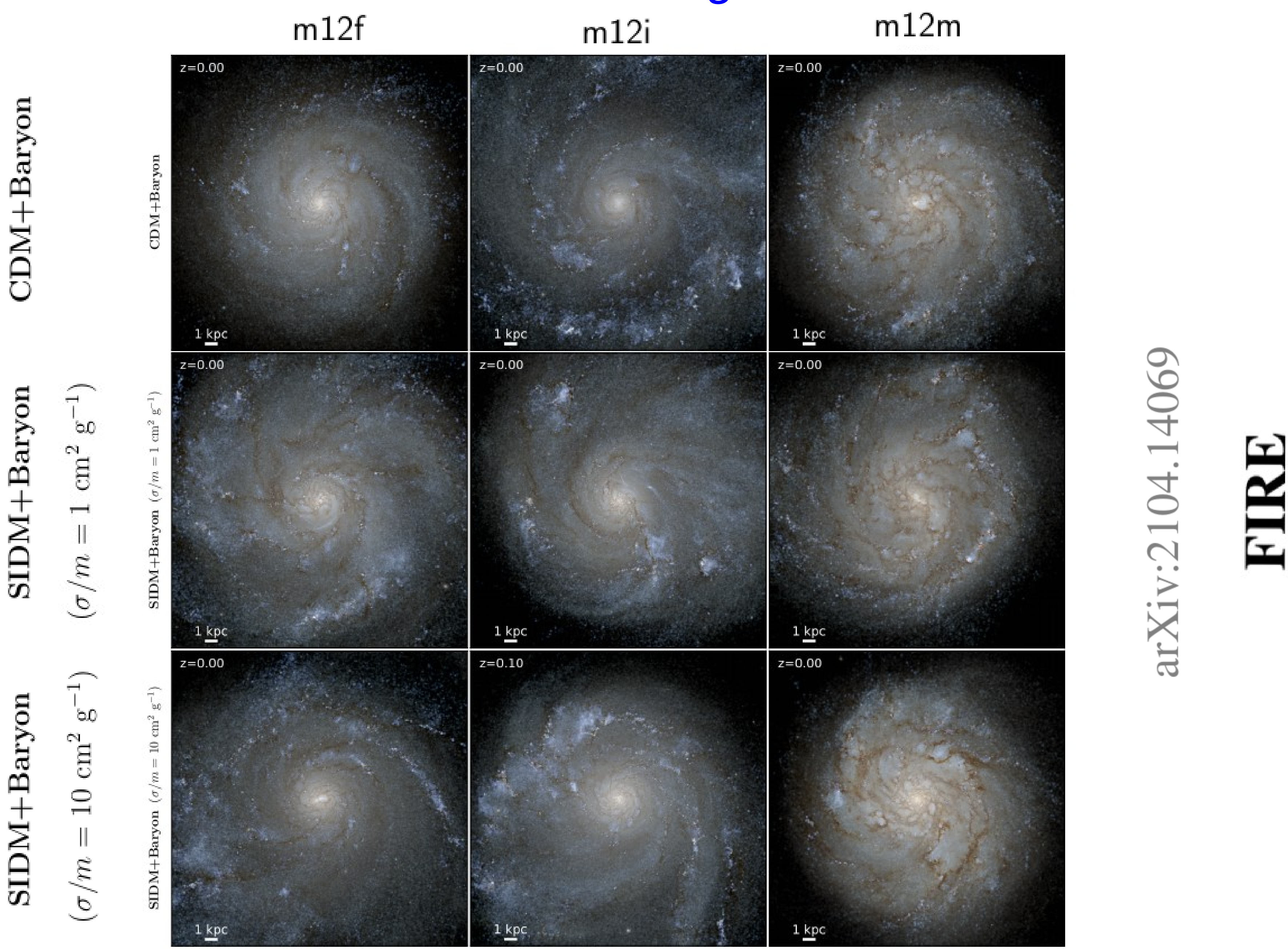
Mochima

Nunez-Castineyra, EN et al in prep

Beyond CDM ?

Self-Interacting DM

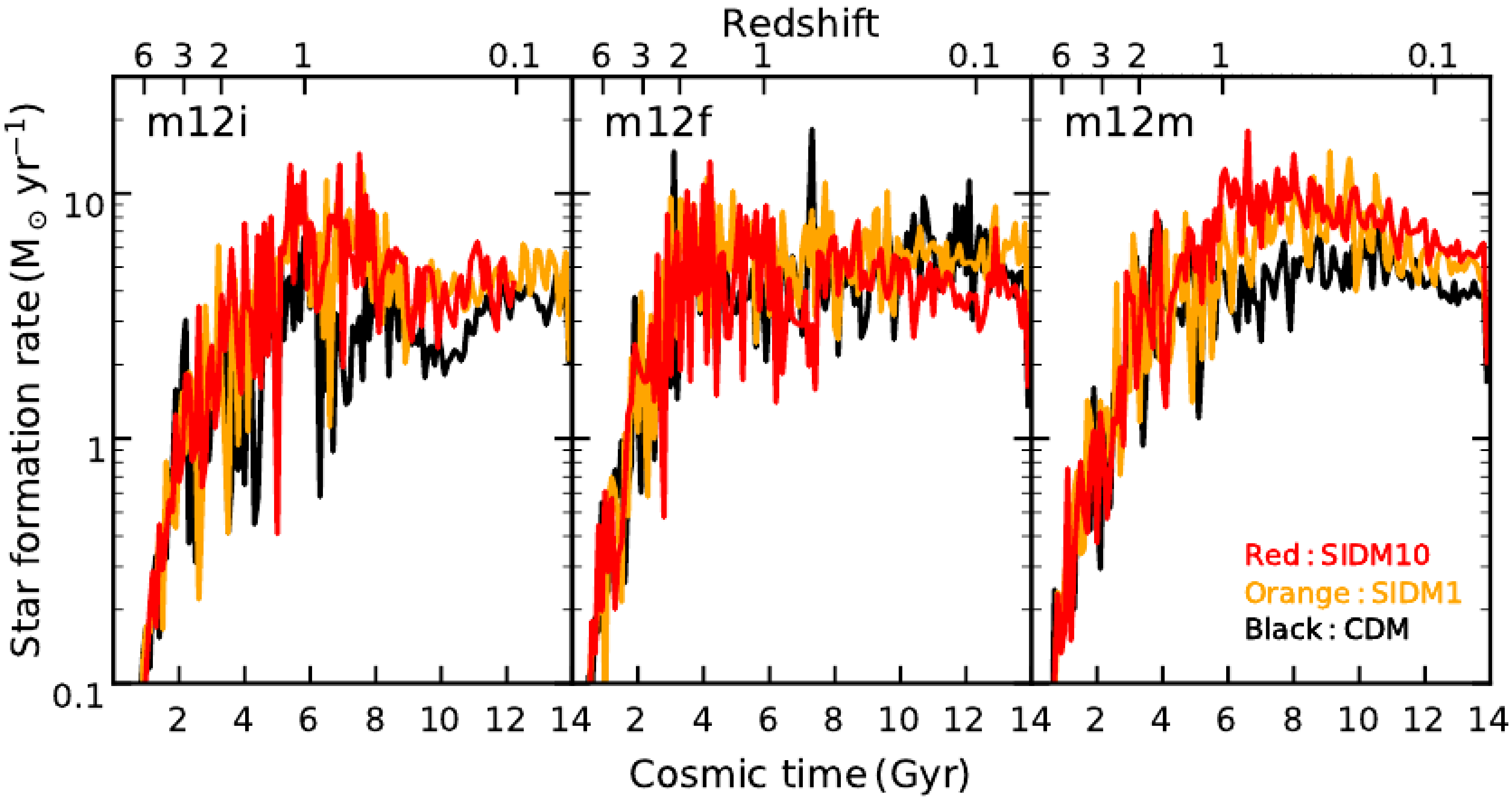
Self-Interacting DM



Similar galaxies

Self-Interacting DM

- Star formation rate



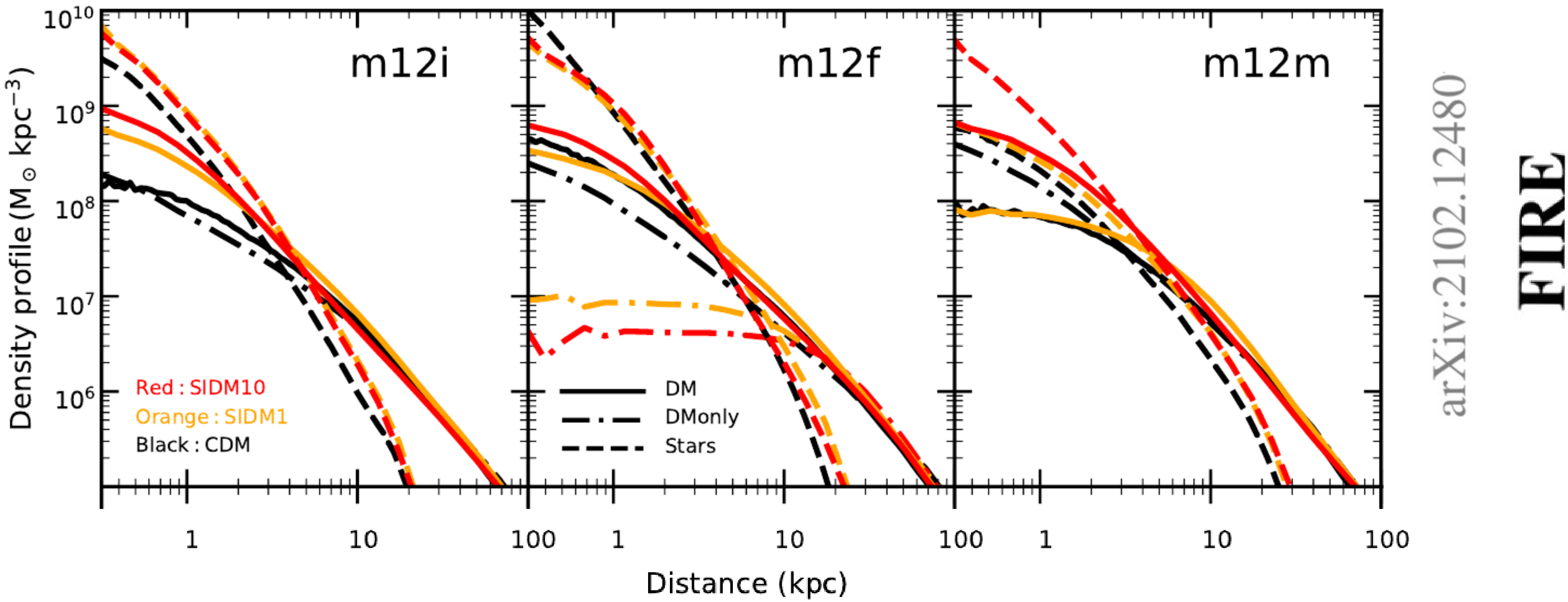
arXiv:2102.12480

FIRE

Higher SFR

SIDM

- *Mass density profiles*



Strong(er) stellar cusp than CDM

SIDM profile responds more significantly to presence/contraction by baryons than CDM

SIDM	$\bar{V}_{2\mathrm{kpc,\,DMO}}/\bar{V}_{2\mathrm{kpc,\,Hydro.}} \sim 0.10$	*Strong cusp*
CDM	$\bar{V}_{2\mathrm{kpc,\,DMO}}/\bar{V}_{2\mathrm{kpc,\,Hydro.}} \sim 0.25\text{–}0.35$	*Contraction + flattening*

FuzzyDM

(No Hydro)

FuzzyDM
(No Hydro)

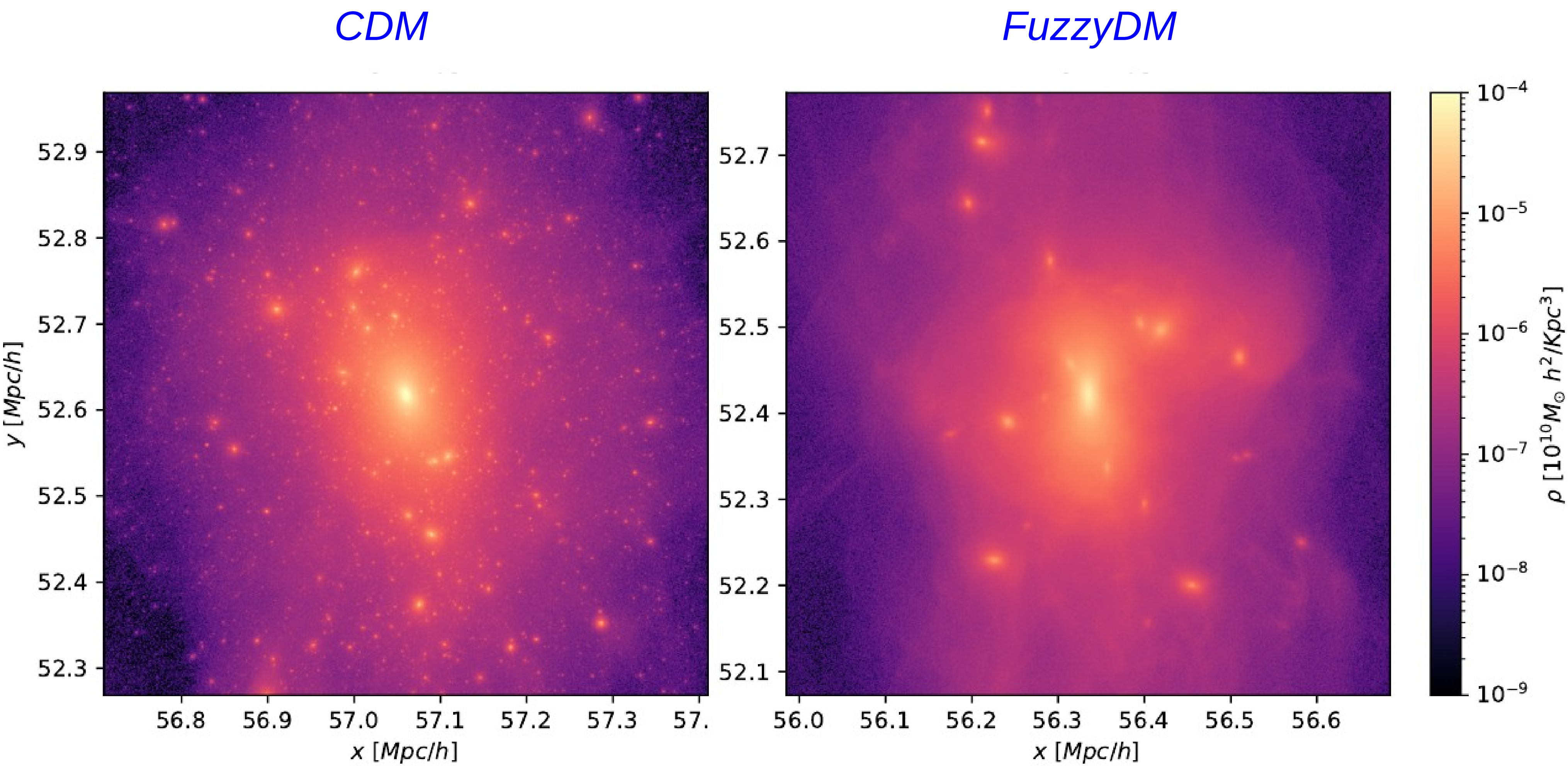
Name	$m_{\rm p}$ $[\rm M_\odot]$	ϵ [pc]	$N_{\rm hr}$	$N_{\rm lr}$	M_{200} $[\rm M_\odot]$
Aq-A-1	1.712×10^3	20.5	4,252,607,000	144,979,154	1.839×10^{12}
Aq-A-2	1.370×10^4	65.8	531,570,000	75,296,170	1.842×10^{12}
Aq-A-3	4.911×10^4	120.5	148,285,000	20,035,279	1.836×10^{12}
Aq-A-4	3.929×10^5	342.5	18,535,972	634,793	1.838×10^{12}
Aq-A-5	3.143×10^6	684.9	2,316,893	634,793	1.853×10^{12}

arXiv:2210.08022

Fuzzy Aquarius

FuzzyDM
(No Hydro)

- Density maps



Suppress small mass objects

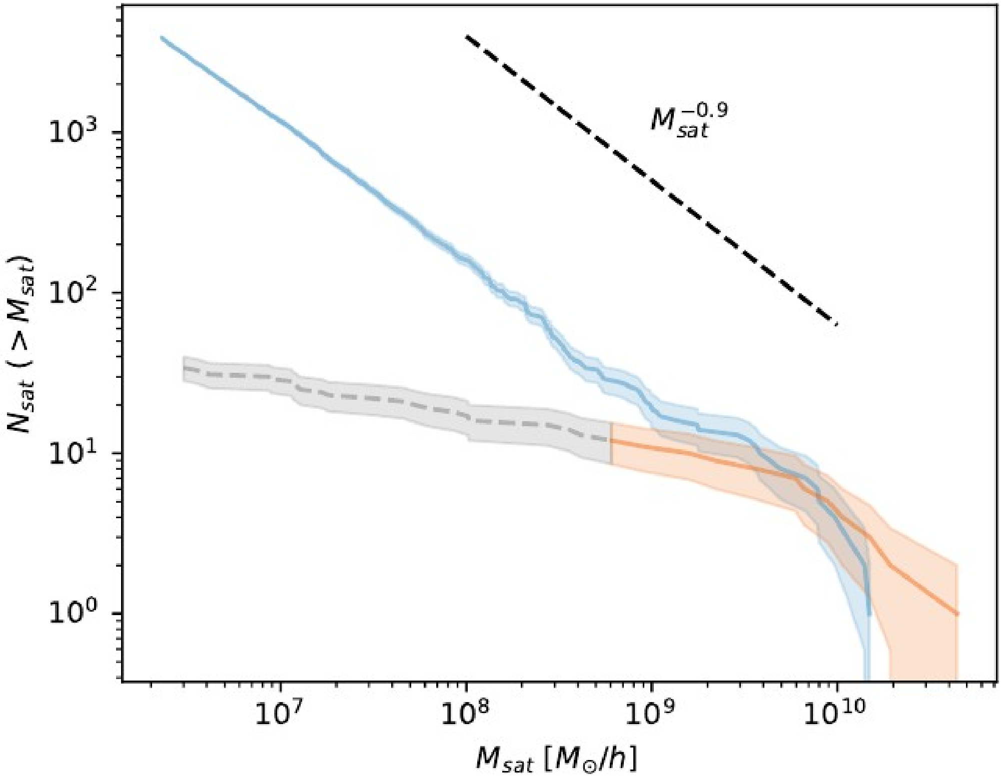
Cored profiles

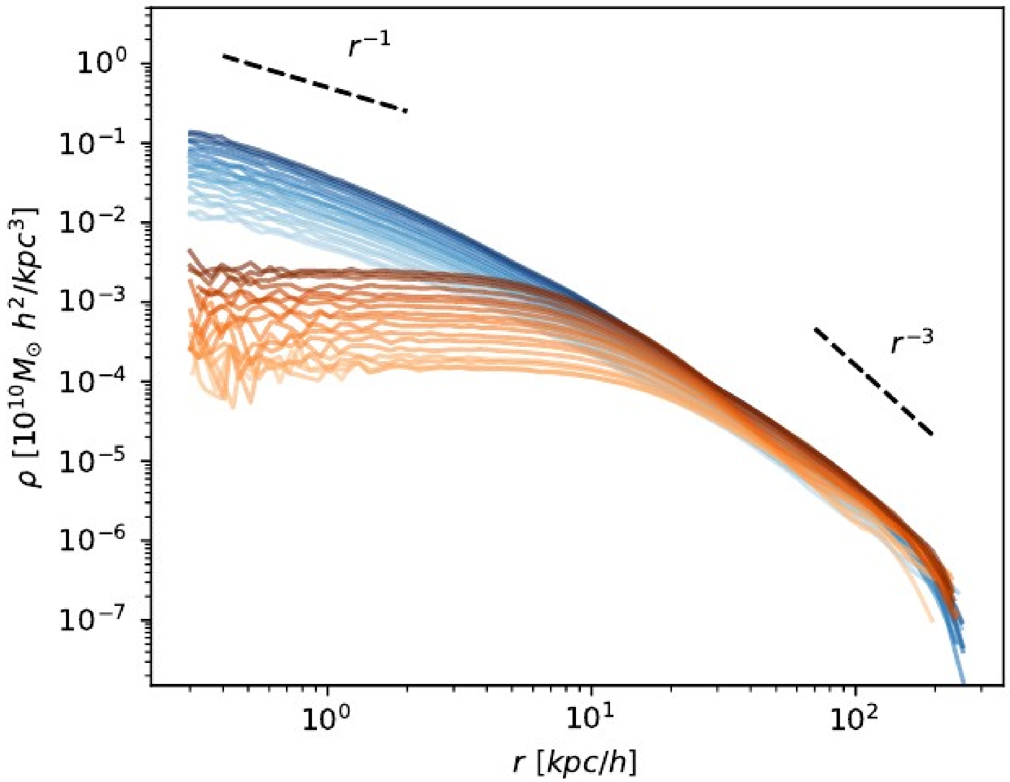
arXiv:2210.08022

Fuzzy Aquarius

FuzzyDM (No Hydro)

- *Sub halo mass function (left)*
- *Mass density profiles (right)*





cosmology. Full hydro simulations will be needed to probe the effects of the different dynamical evolution of the stellar content of the satellites, since dark matter and stars react differently to stellar stripping (Peñarrubia et al. 2008; Macciò et al. 2021).

arXiv:2210.08022

Fuzzy Aquarius

Status

- Different baryonic physics change the resulting galaxie and the DM distribution in halo

- Add more physics not necessarily give better agreement with observations (!)

(recipes/models, parameters, calibration, resolution ...)

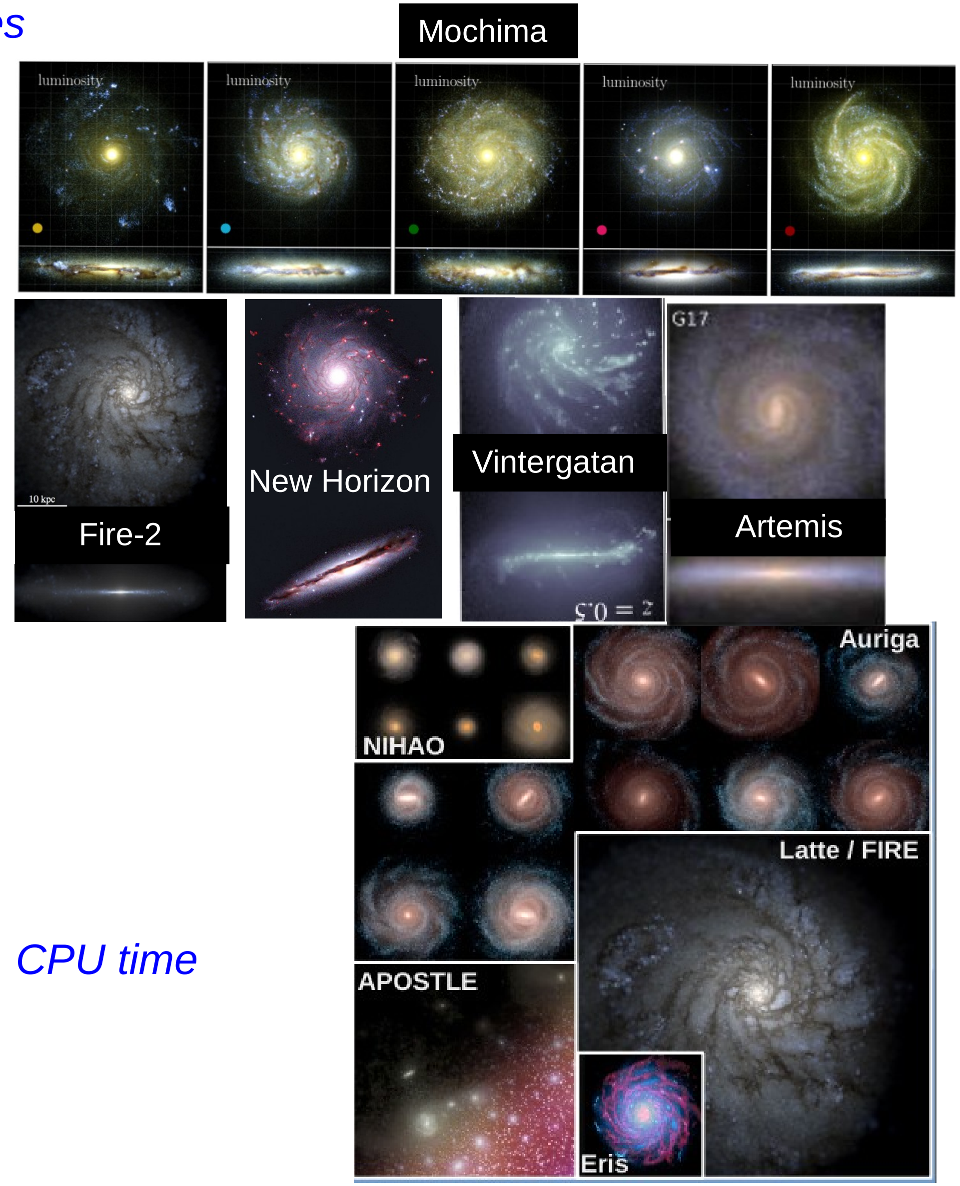
And even if baryonic physics under control → formation history changes the galaxy morphology and DM distribution

Summary-Conclusion

Successes

- Consistent (realistic !?) galaxies from first principles
- Numerical experiment to understand physical processes
- Comparisons with observations
- Test against theoretical models and

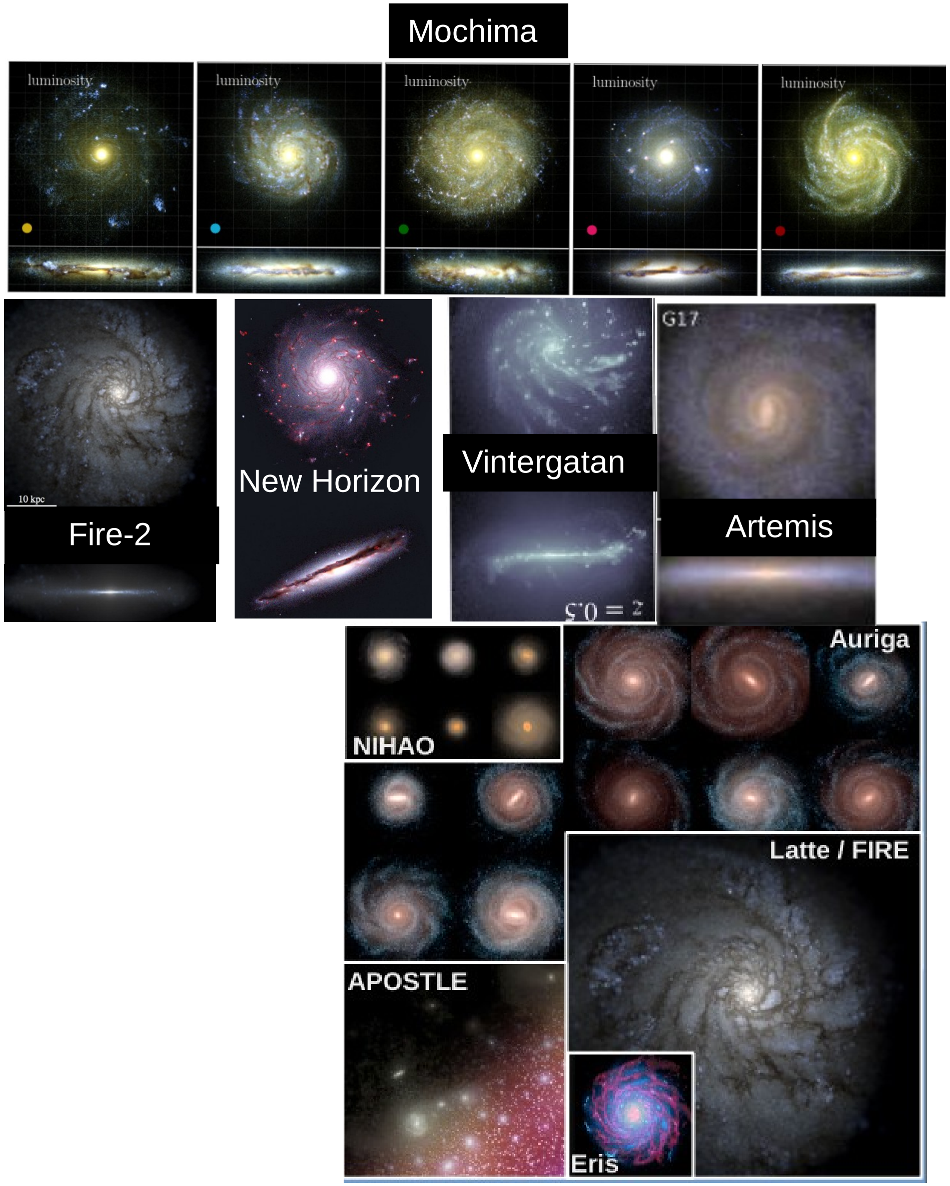
  calibration of semi-analytical models
- Dynamical studies
- Useful for DM detection rate predictions/uncertainties



Challenges

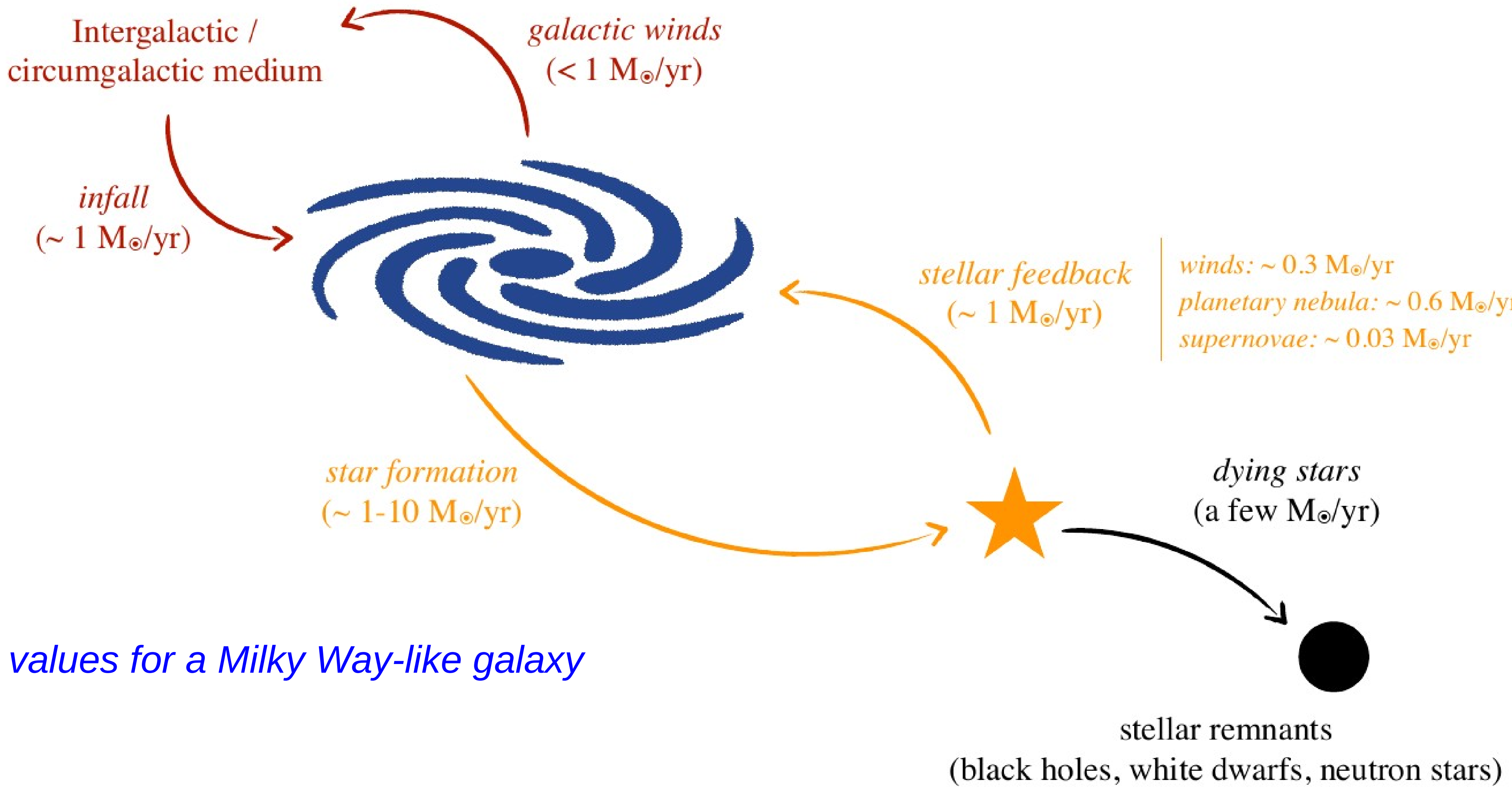
- Improve baryonic physics modeling
- Increase resolution, reach individual star formation ?
- Additionnal relevant processes (MHD ? cosmic rays ?). CPU time
- Early star formation, Bar ? Bulge ? core/cusp ?

Thanks


Mochima
luminosity
luminosity
luminosity
luminosity
luminosity
Fire-2
10 kpc
New Horizon
Vintergatan
z = 0.5
G17
Artemis
NIHAO
Auriga
Latte / FIRE
APOSTLE
Eris

Back-up

Gas flows: some numbers



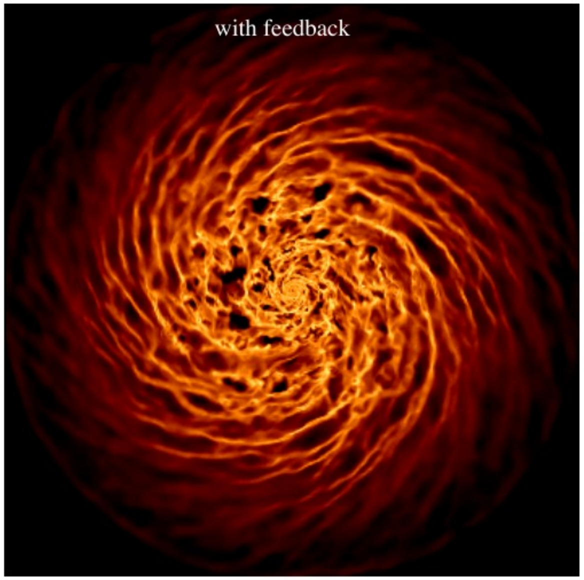
Typical values for a Milky Way-like galaxy

https://ismgalaxies2021.sciencesconf.org/

Isolated simulations of galaxies

Renaud et al. (2021c)

Grisdale et al. (2017)



Renaud et al 2013, 2021, Grisdale 2017 ...

Size~ 100 kpc
Res ~ 0.1-10 pc

+ Control parameters
+ resolution

- Environment (mergers, gas inflows/outflows)
- Initial conditions