DARWIN: Formation and evolution of dwarf galaxies in various environments

Recent progress of the DARWIN project

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Introduction

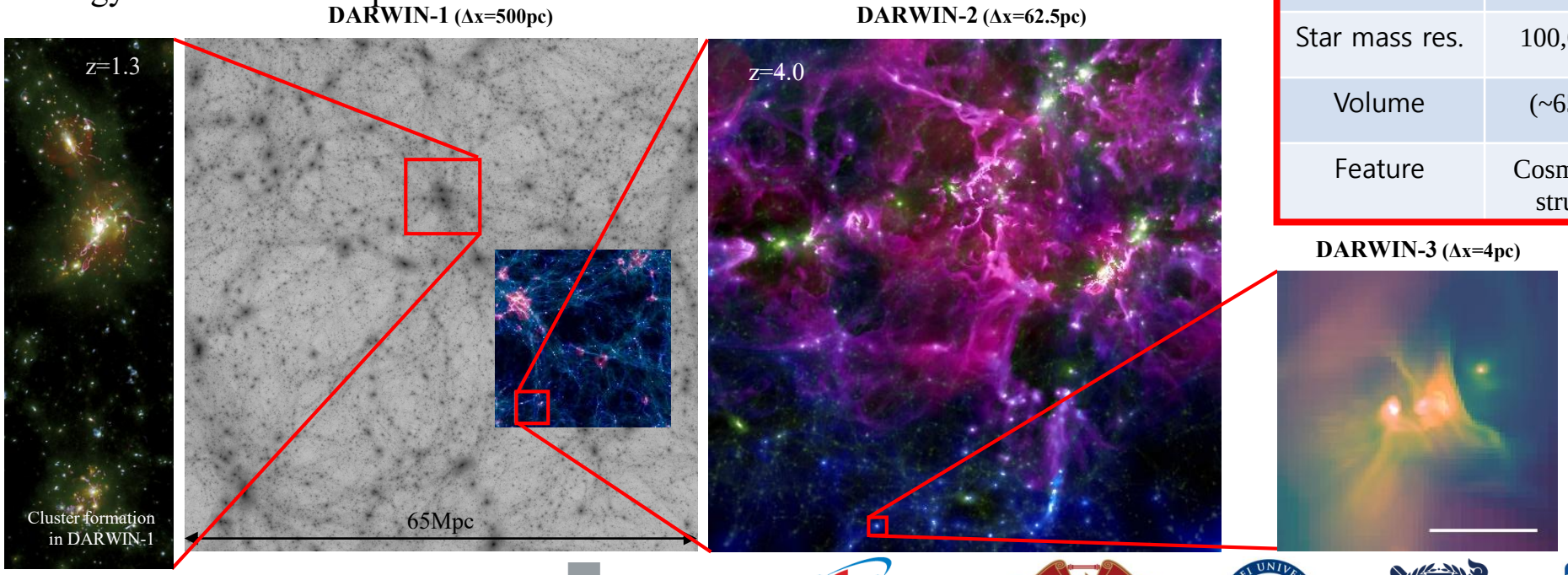
DARWIN project

Aim: **simulating the formation & evolution of dwarf galaxies** using gigantic computing resources

Support: ‘advanced utilization of Korean supercomputer’ program

strategy: a series of 3-step zoom-in simulations

	DARWIN-1	DARWIN-2	DARWIN-3
Spatial res.	500pc	62.5pc	4pc
Star mass res.	100,000 $M_\odot$	10,000 $M_\odot$	500 $M_\odot$
Volume	$(\sim 65\mathrm{Mpc})^3$	$(4\text{-}20\mathrm{Mpc})^3$	$< (1\mathrm{Mpc})^3$
Feature	Cosmological structures	dwarf galaxies in various env.	internal structures of dwarf galaxies



Korea Astronomy and Space Science Institute
KIAS KOREA INSTITUTE FOR ADVANCED STUDY
KiSTi www.kisti.re.kr Korea Institute of Science and Technology Information
KYUNG HEE UNIVERSITY
YONSEI UNIVERSITY
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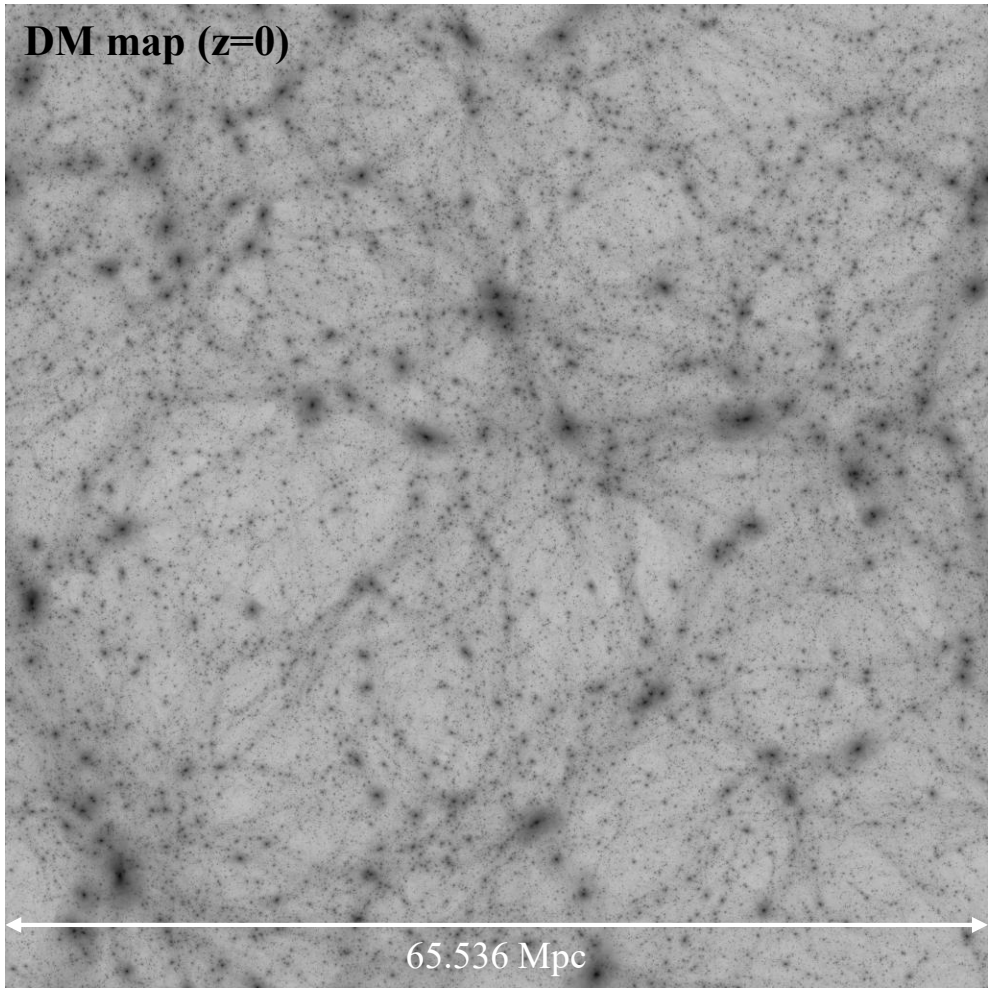
서울시립대학교 UNIVERSITY OF SEOUL
CHUNGNAM NATIONAL UNIVERSITY

Simulation

DARWIN-1



Base Simulation for DARWIN-2 & 3

Size - L_{box}=65.536cMpc

Resolution - Δx=500pc (Stellar particle = $10^5\,M_\odot$)

Cosmology - h=0.674, Ω_m=0.315, Ω_Λ=0.685 (Planck 2018)

Star formation - Density threshold/convergence flow (Cen & Ostriker92)

SN feedback - Thermal/mechanical feedback for SNII

- thermal mode for SNIa (Kimm & Cen 14)

AGN feedback - BH spin traced

- QSO & radio modes (Dubois+21)

- drag (BH particle) implemented

Elements - H, O, Fe traced (SNII: Portinari+98, SNIa: Seitenzahl+13)

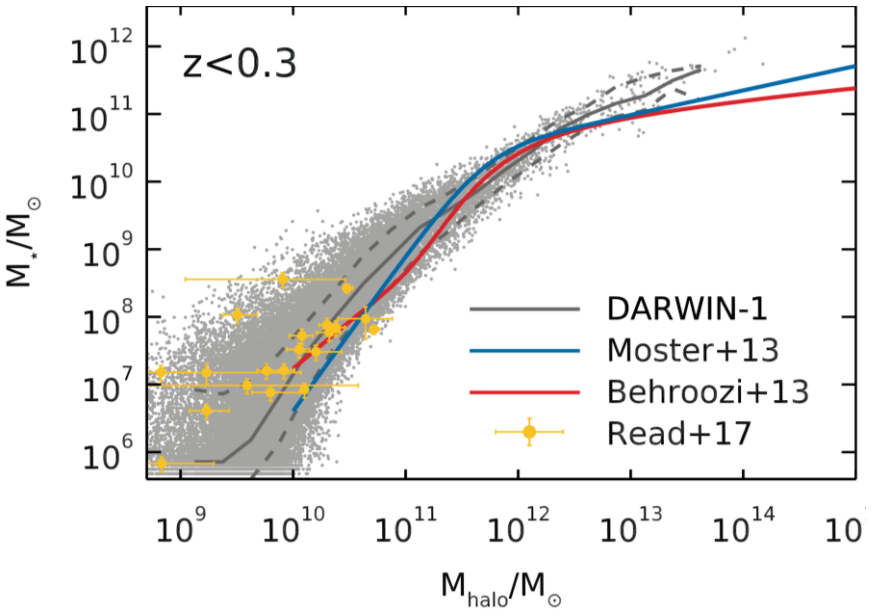
Now approaching z=0.3

Simulation performed by Jaehyun Lee

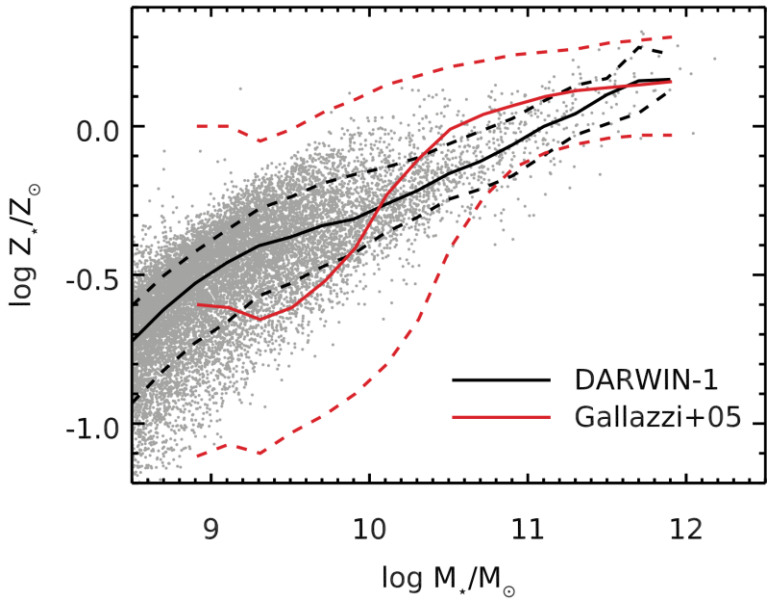
DARWIN-1

Properties @ z~0.3

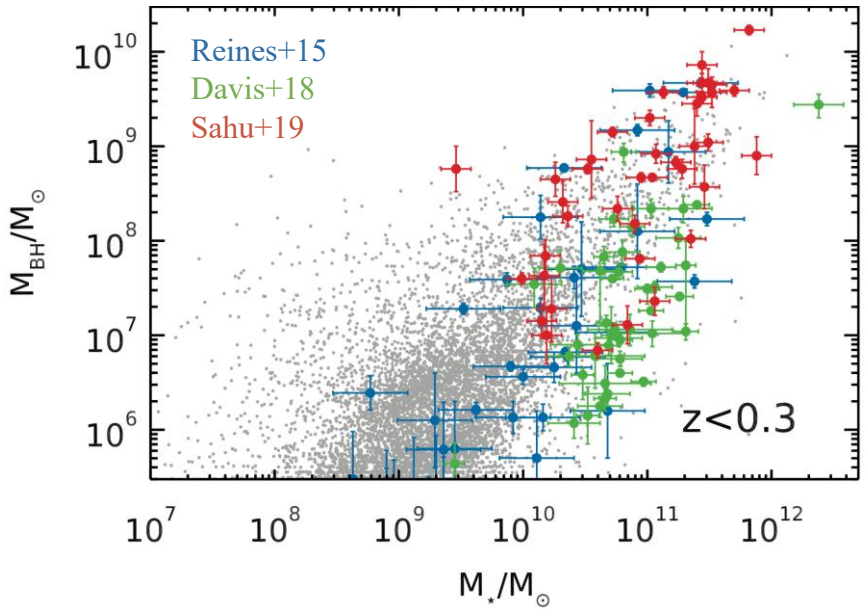
$M_\star$-M_{halo} relation



$M_\star$-$Z_\star$ relation

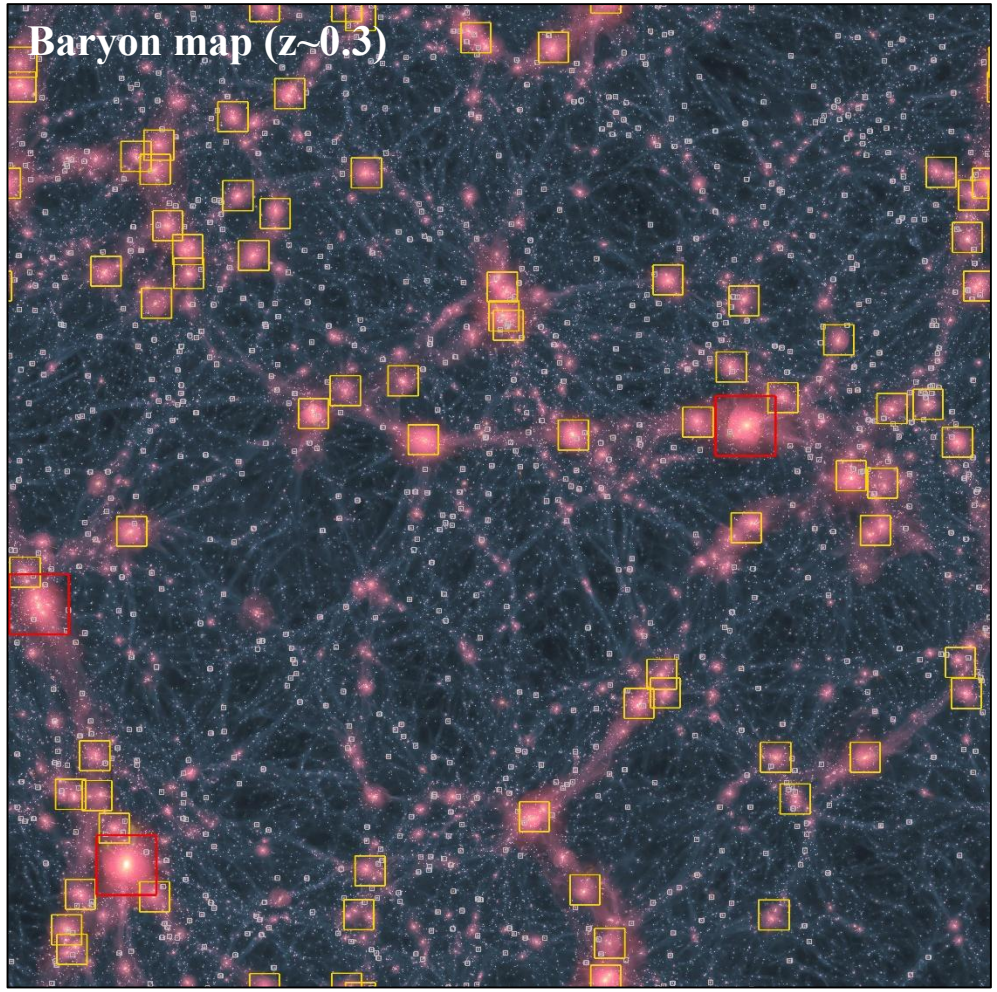


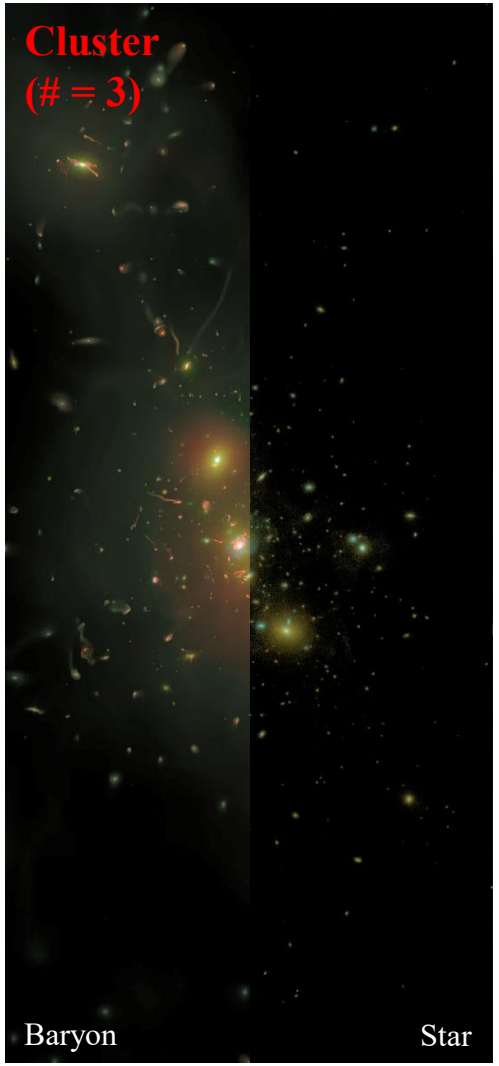
M_{BH}-$M_\star$ relation

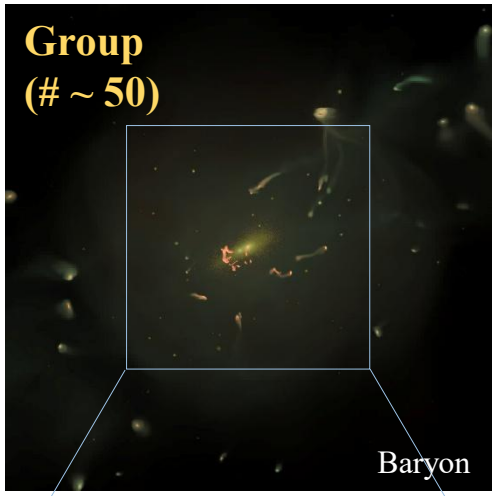


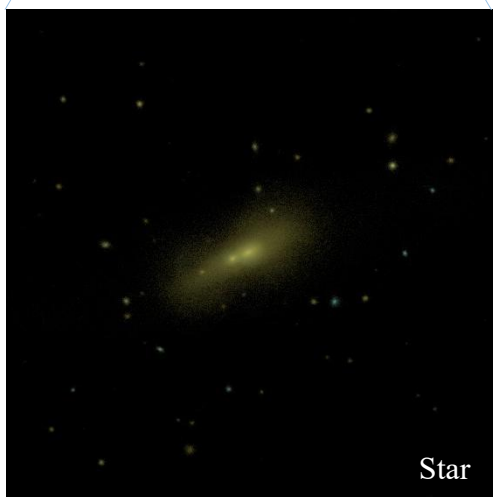
DARWIN-1

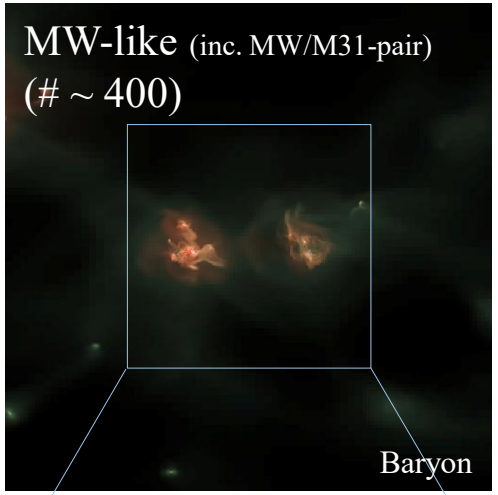
Various environments

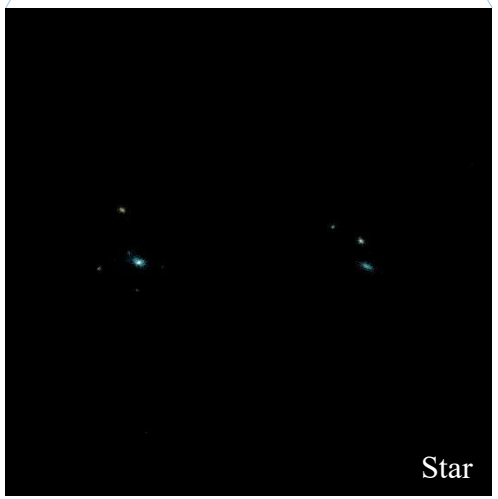






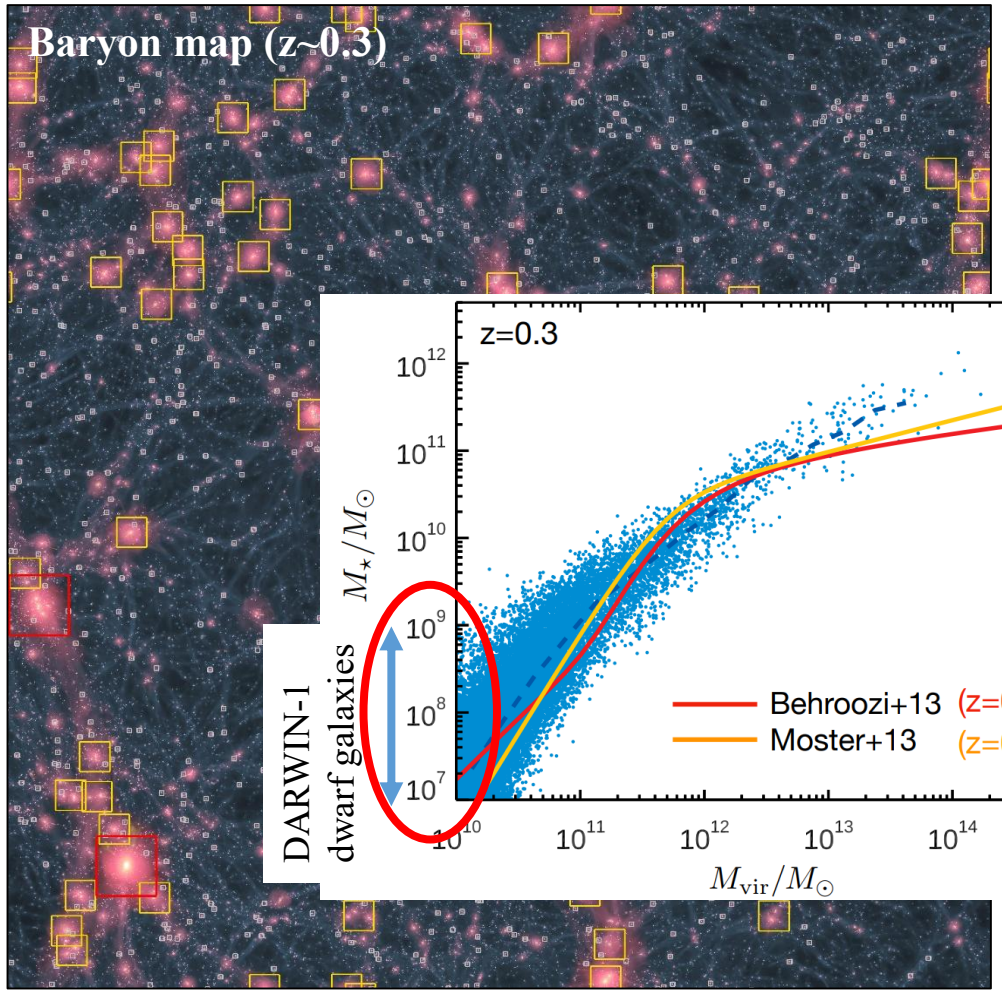


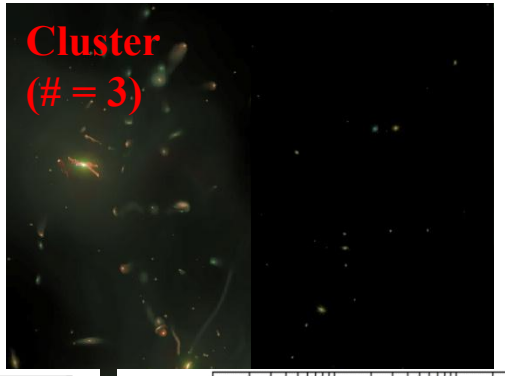


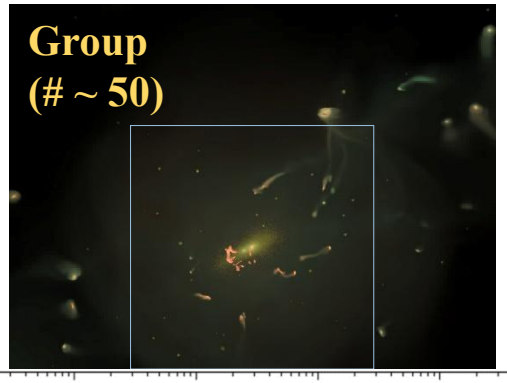


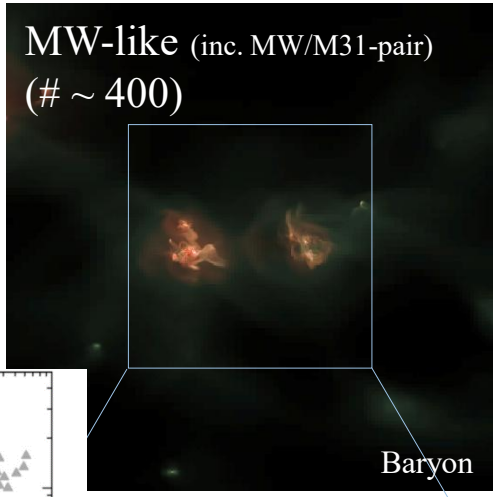
DARWIN-1

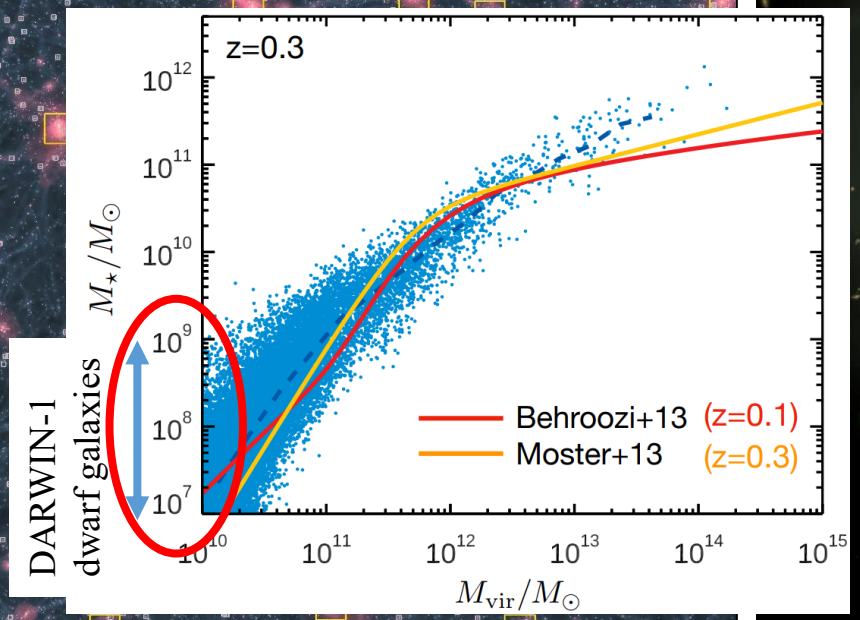
Various environments

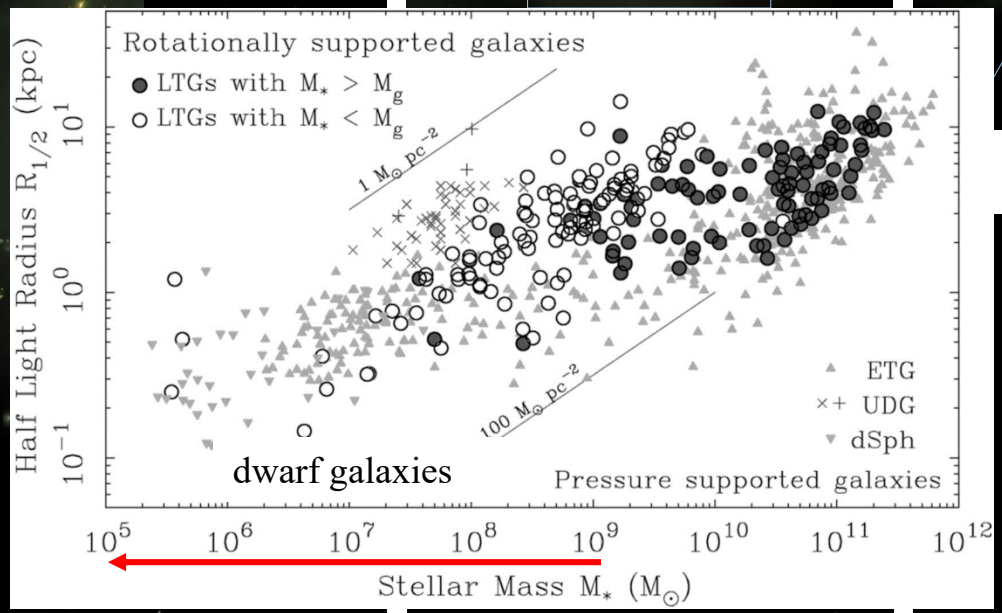


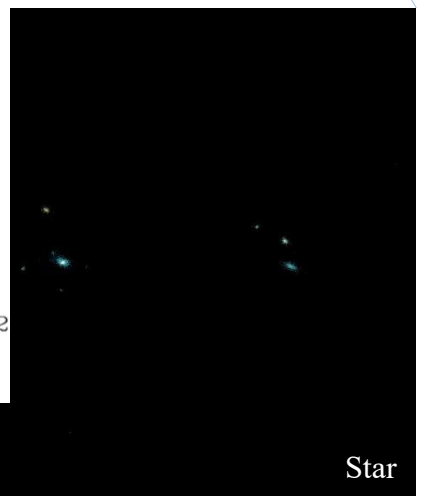


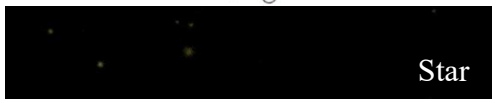






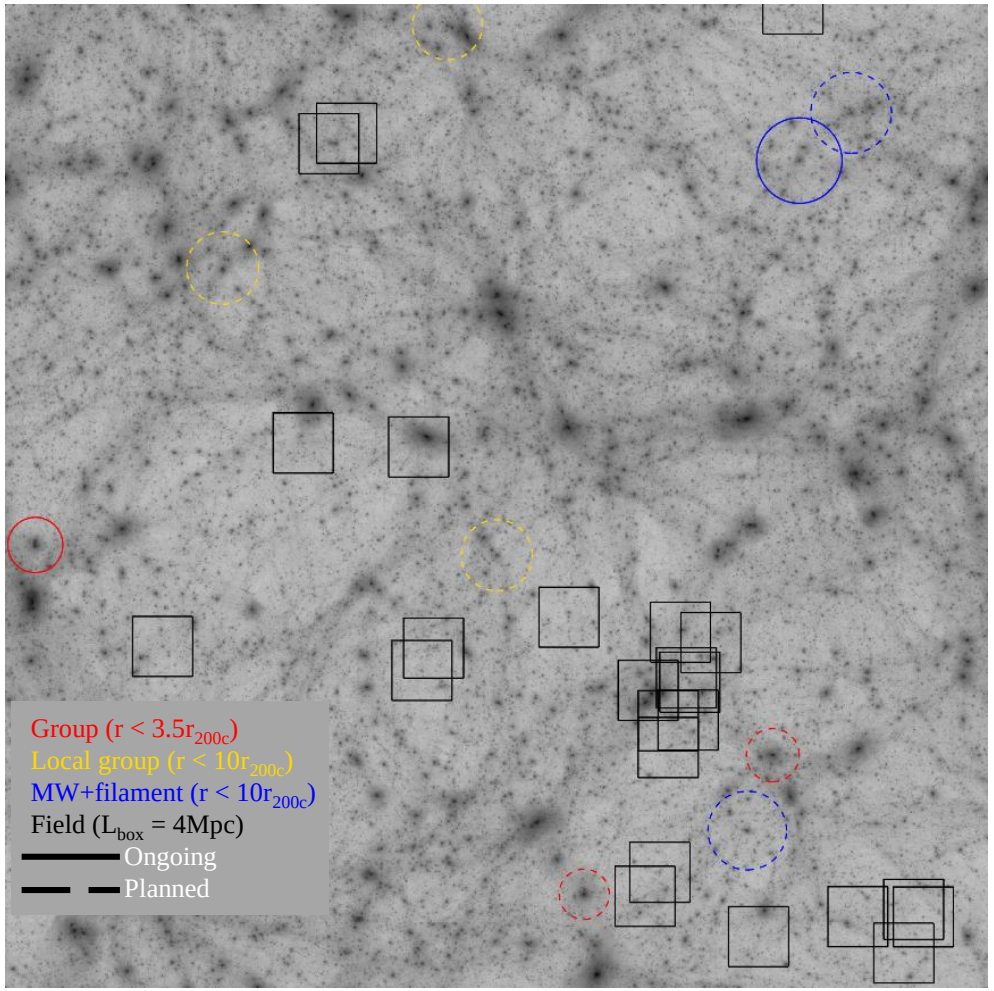


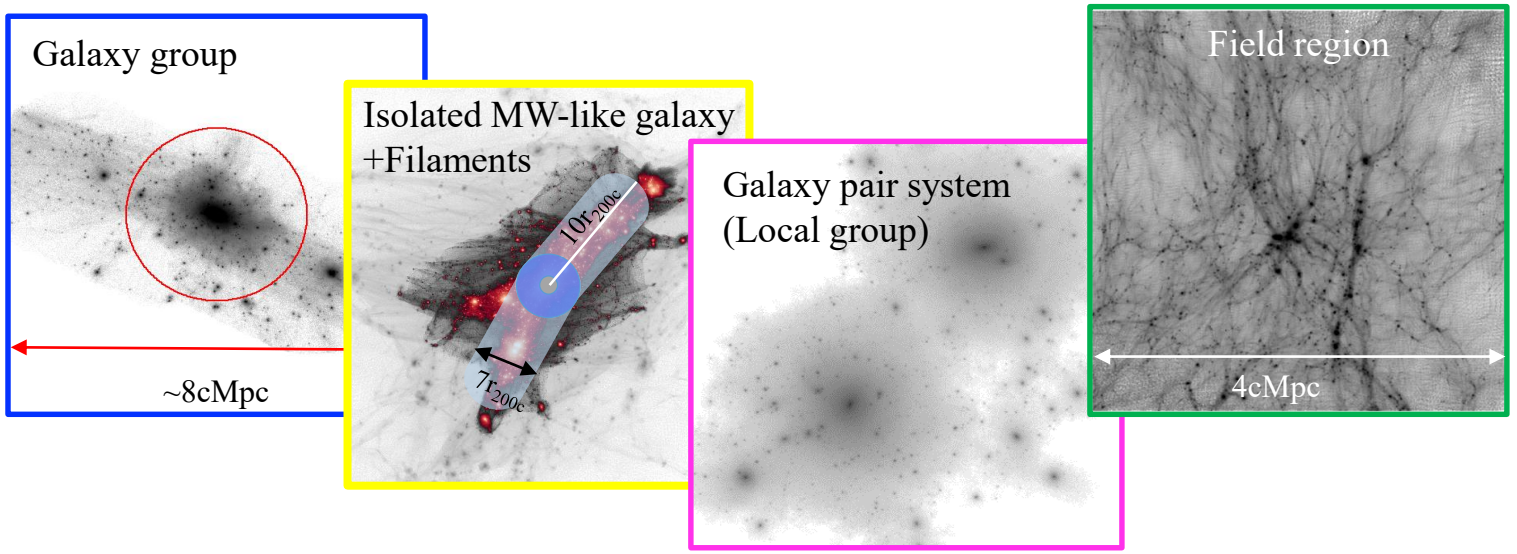




Simulation

DARWIN-2 (RHD zoom-in)





Target - various environments from DARWIN-1 DM-only uniform box

Resolution - Δx=62.5 pc (stellar particle = $10^4\,M_\odot$)

Star formation - Gravo-thermo-turbulent (Kimm+17)

RT - 3 bands (13.6, 24.6, 54.42eV)

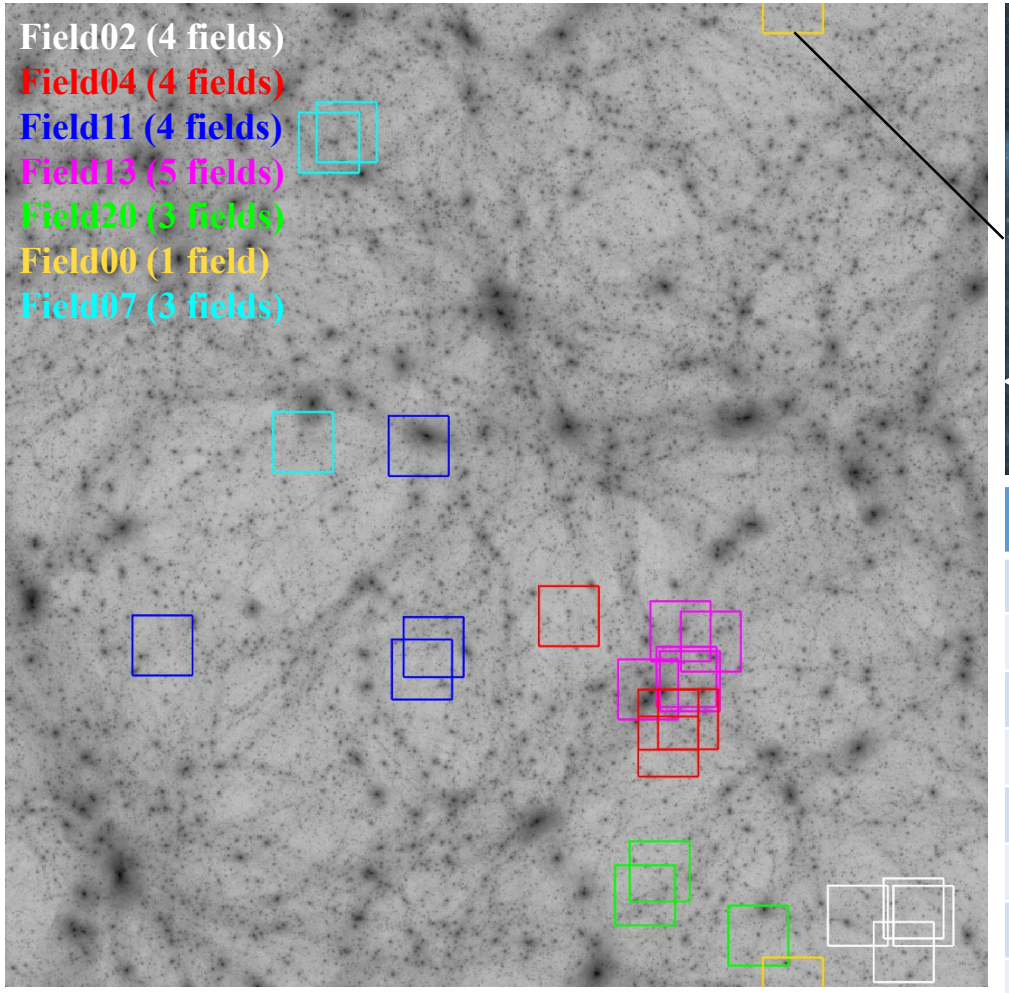
Elements - H, O, Fe, N, Mg traced (SNII: Portinari+98, SNIa: Seitenzahl+13)

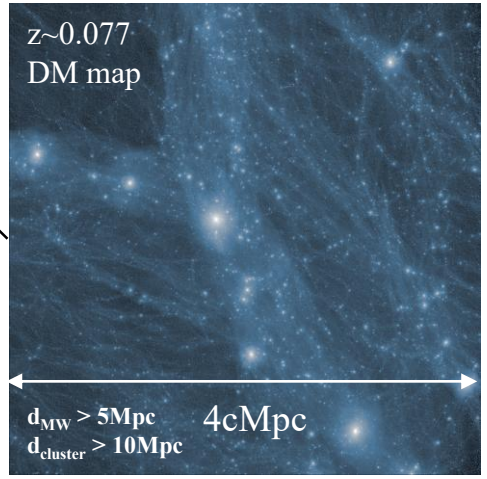
Now running calculation for field regions and MW+filaments cases

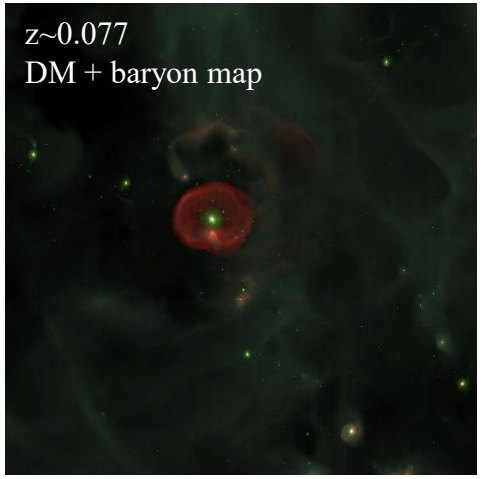
Simulation performed by Jaehyun Lee & Kyungwon Chun

DARWIN-2

Field regions



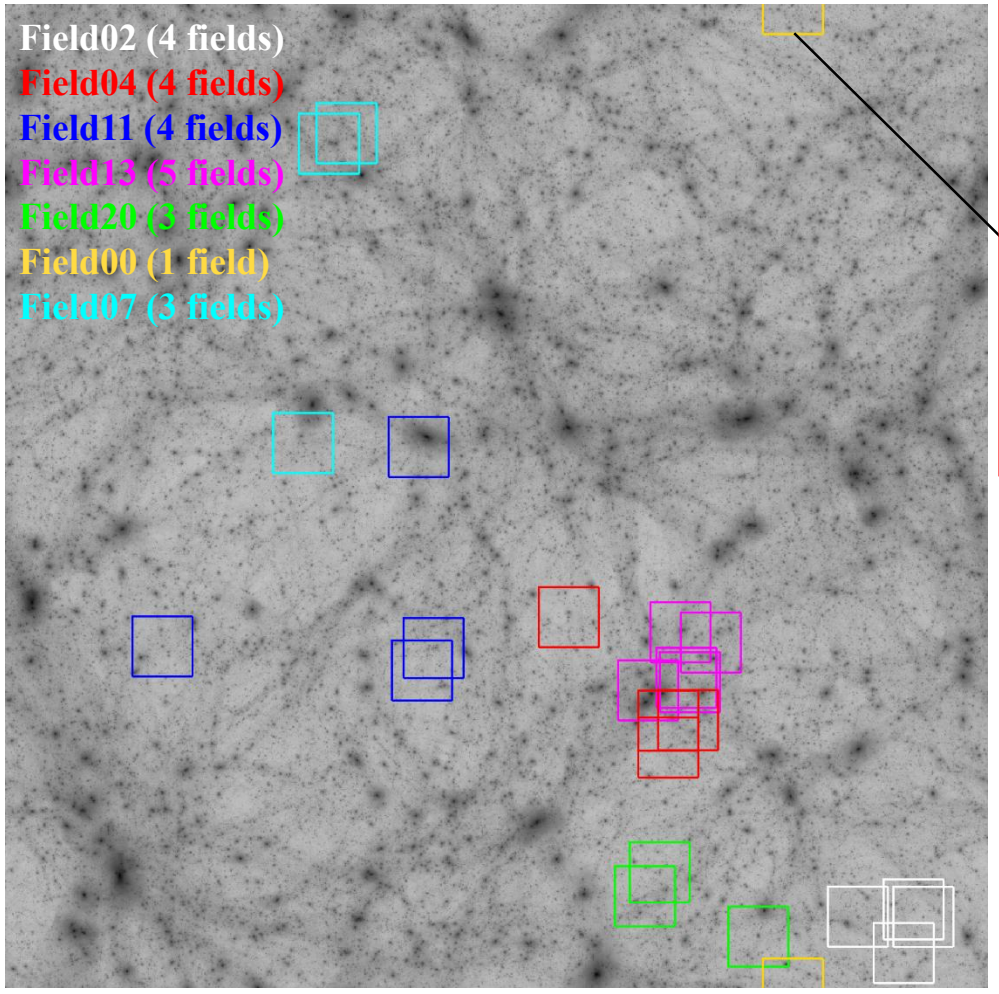


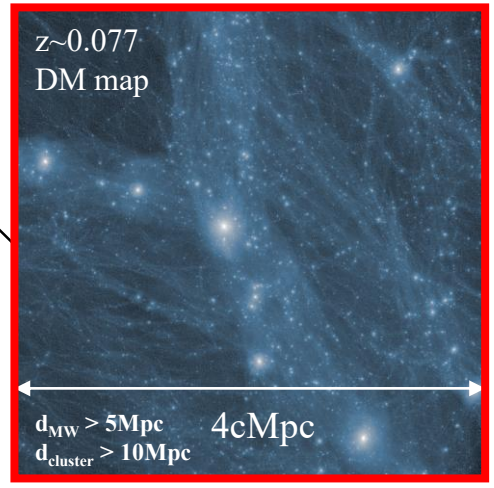


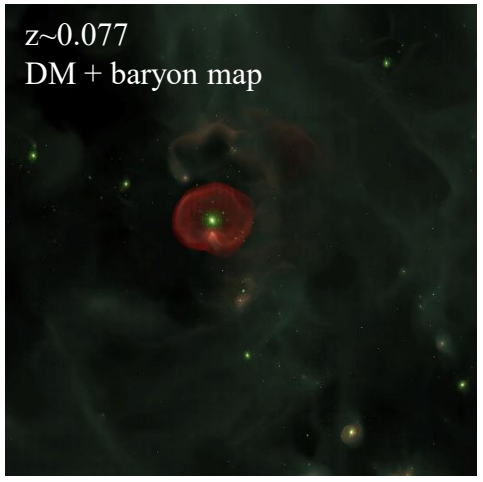
Name	Current z	# of fields	N_{gal} (M_{star} > 5×10^5 $M_\odot$ @ z~3.0)
Field02	2.881	4	55
Field04	2.714	4	20
Field11	1.990	4	27
Field13	2.266	5	55
Field20	3.132	3	42 (z~3.1)
Field00	**0.000**	1	11
Field07	0.965	3	33
		24	**243**

DARWIN-2

Field regions







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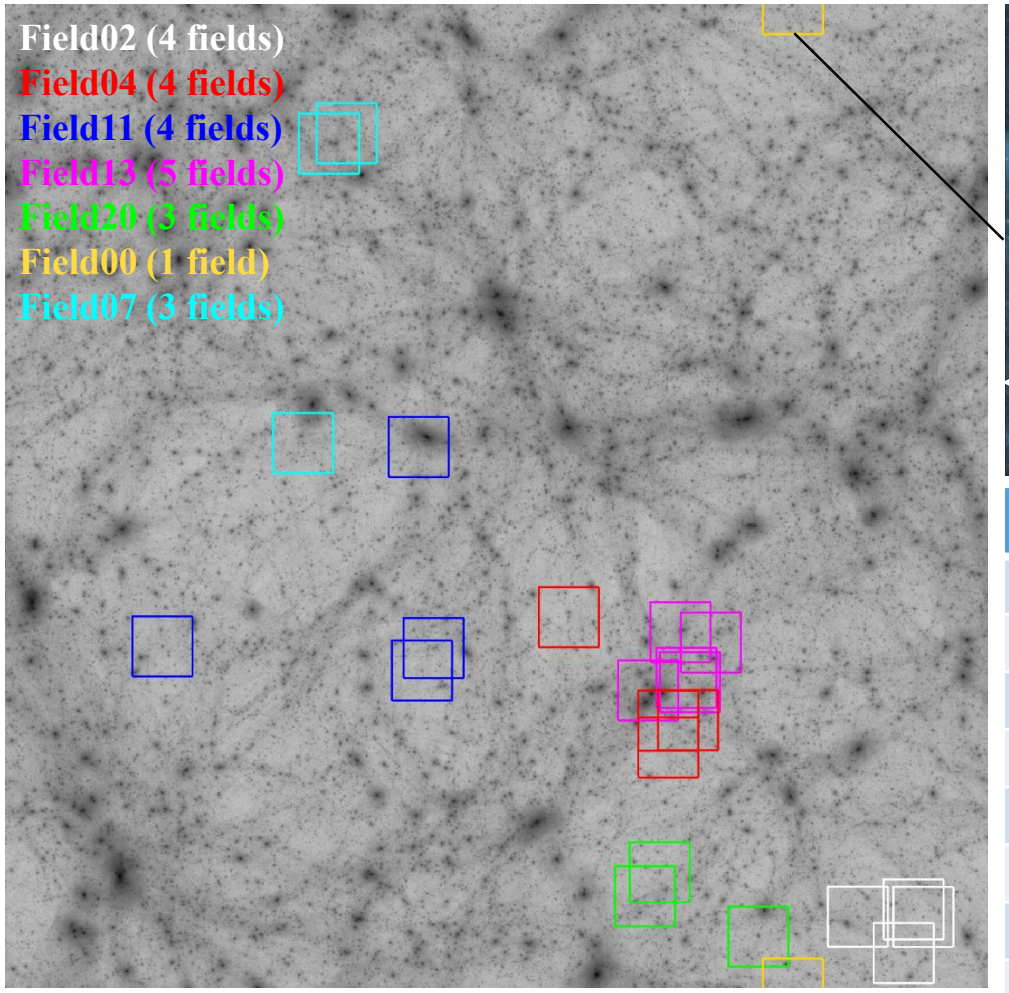
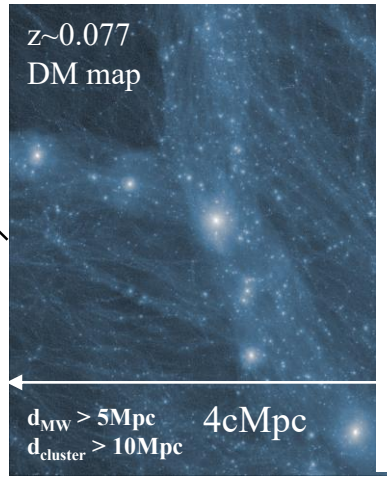
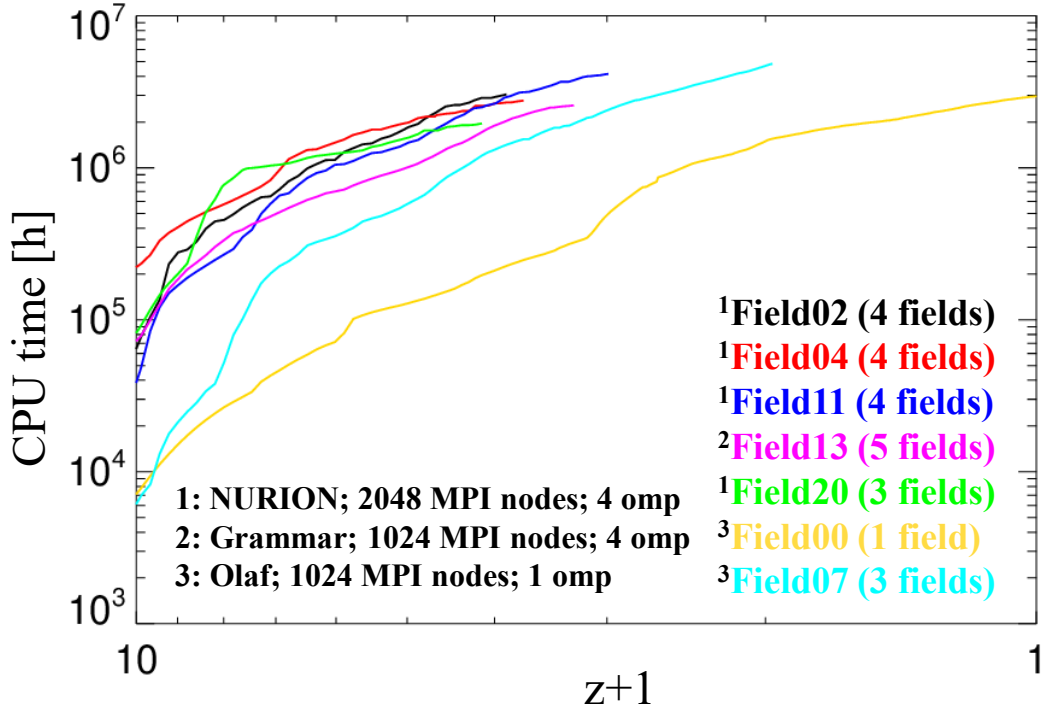
DARWIN-2

Field regions



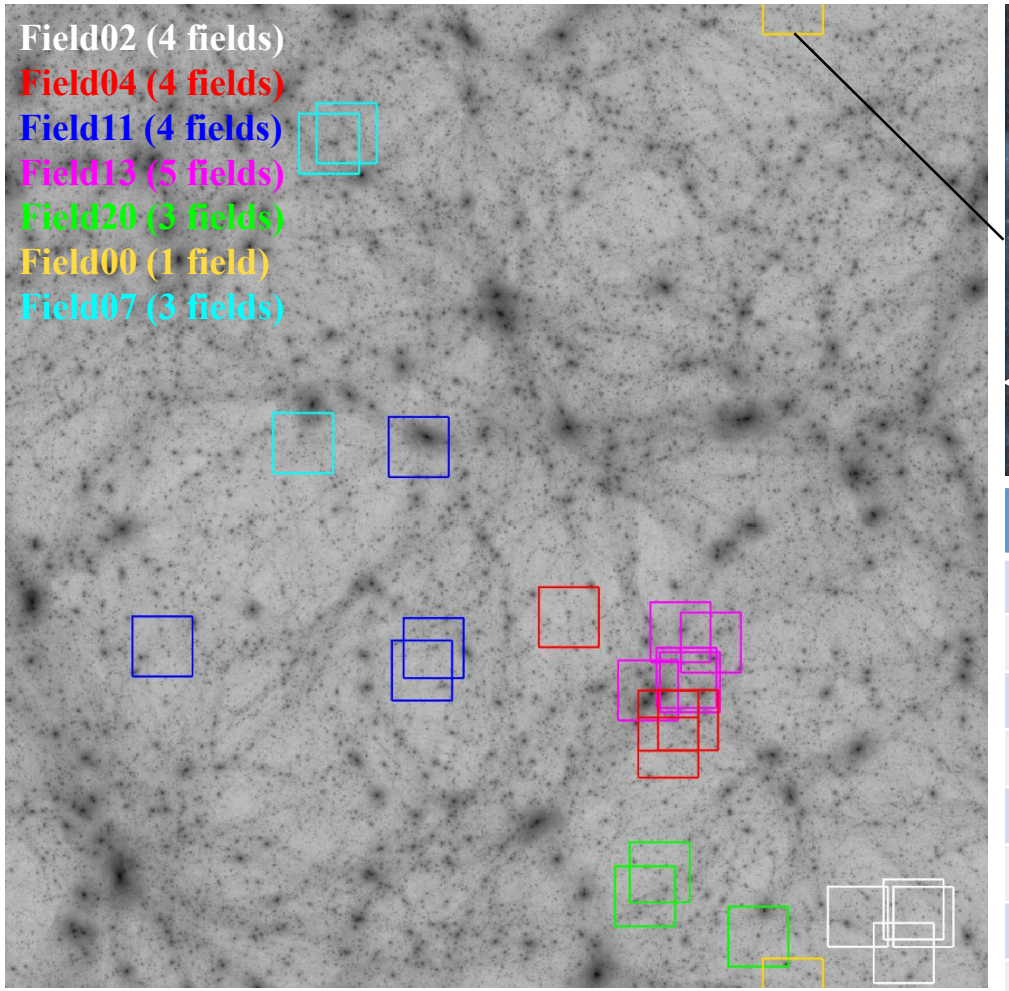


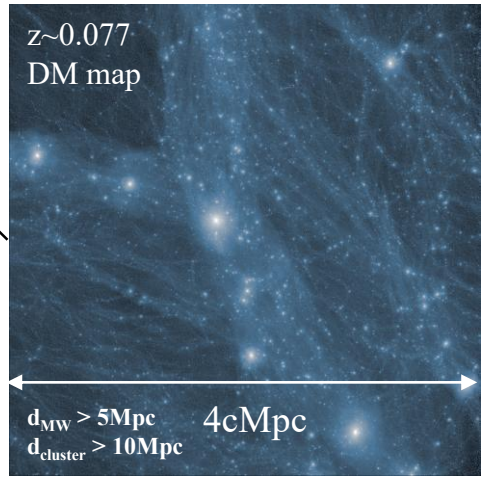


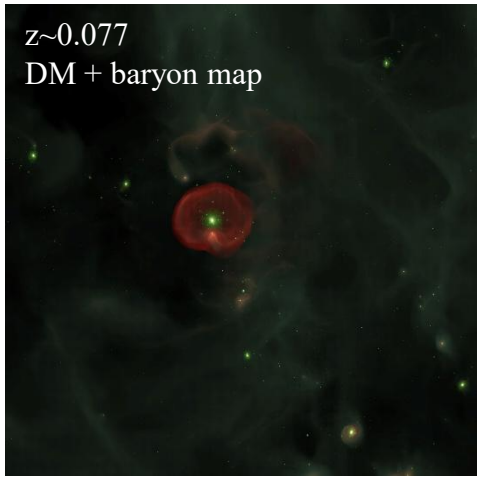
Name	Current z	# of fields	CPU time [h] (up to current z)
Field02	2.881	4	3.04×10^6
Field04	2.714	4	2.77×10^6
Field11	1.990	4	4.15×10^6
Field13	2.266	5	2.58×10^6
Field20	3.132	3	1.96×10^6
Field00	**0.000**	1	2.96×10^6
Field07	0.965	3	4.84×10^6
		24	

DARWIN-2

Field regions







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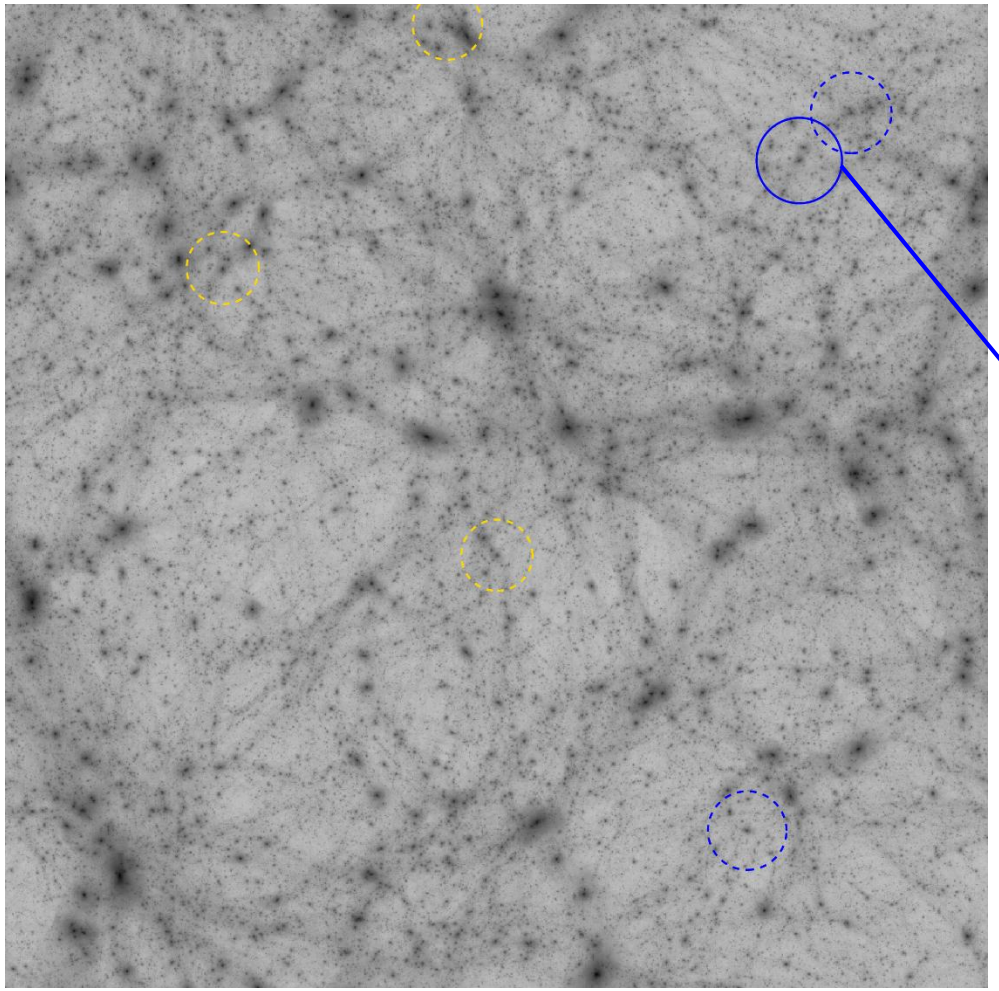
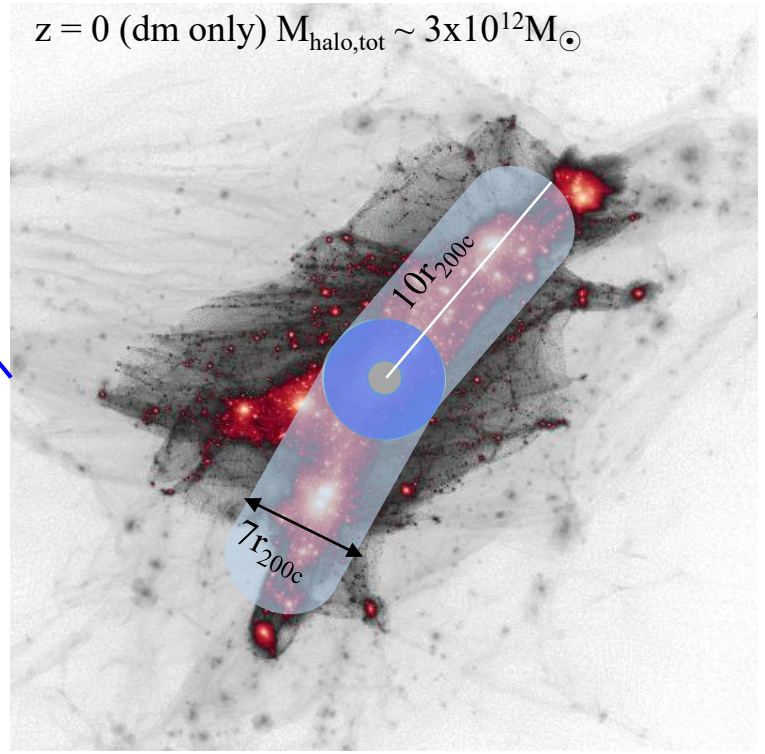
DARWIN-2

MW + filaments



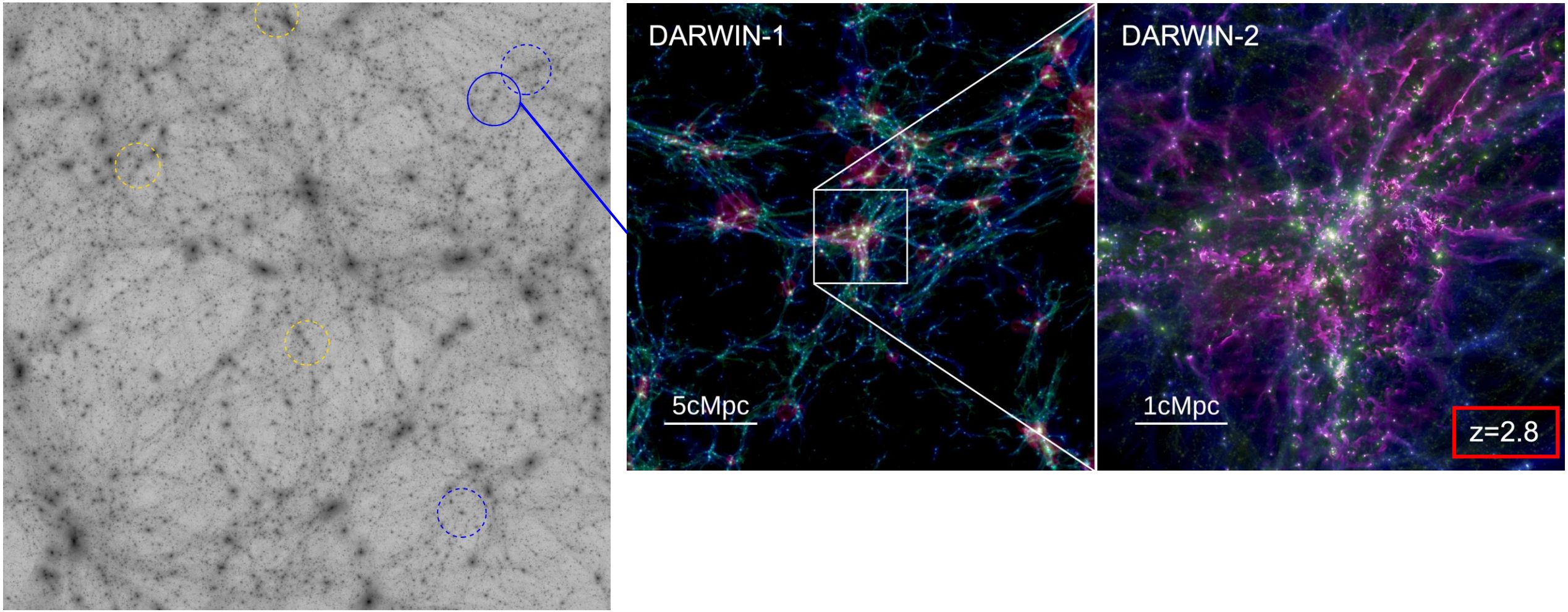


Filamentary structures

- Detection: DisPerSE (Sousbie et al. 2011)
- Zoom region: < 10 r_{200c} of the host galaxy

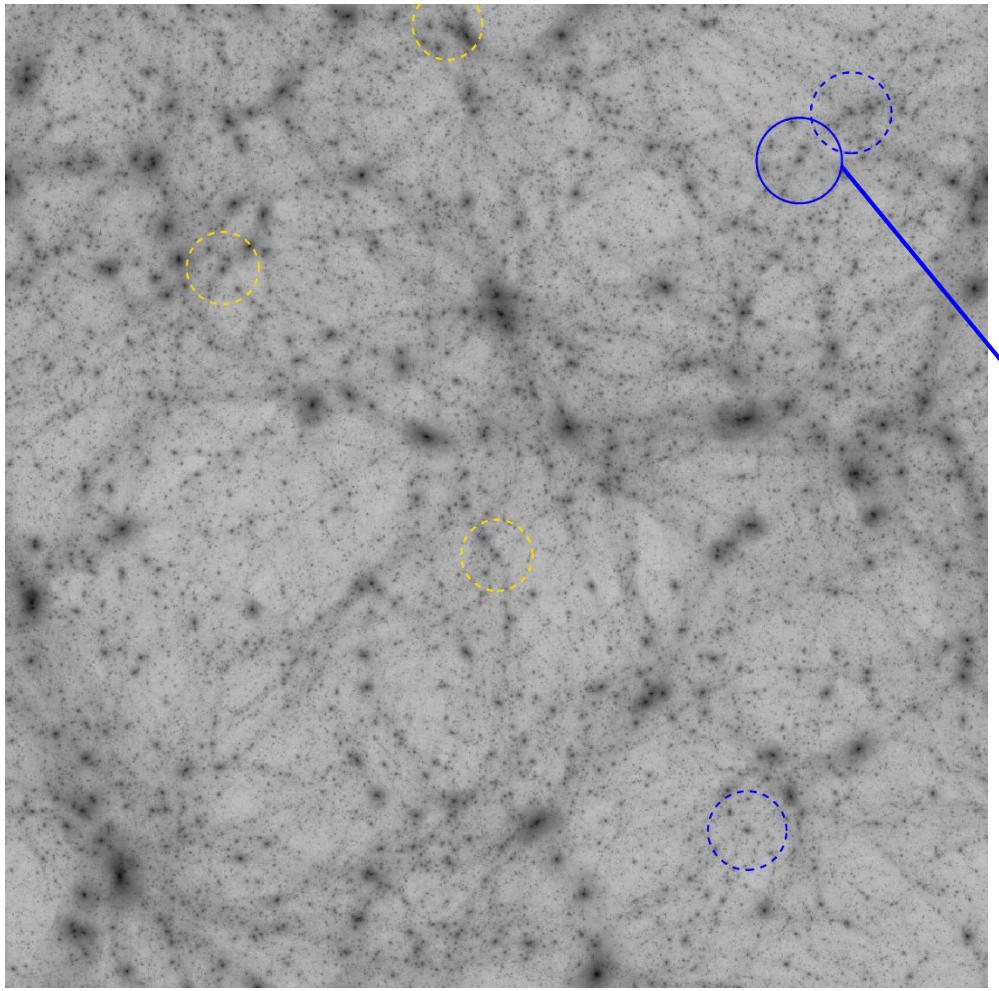
DARWIN-2

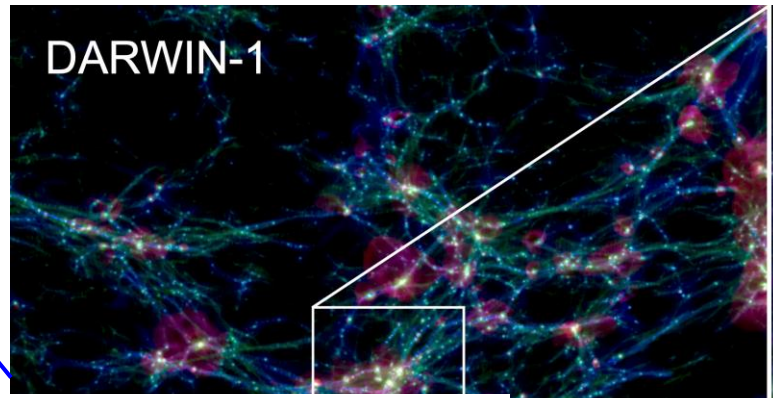
MW + filaments

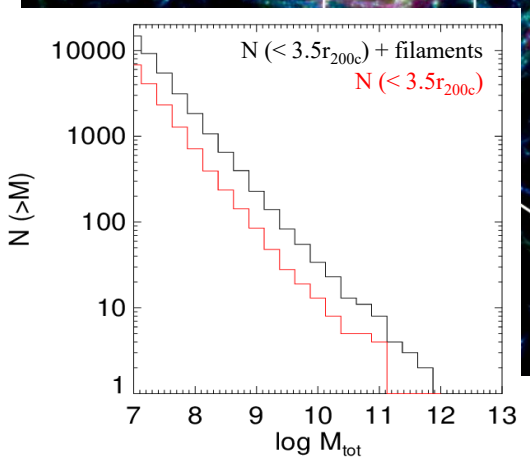


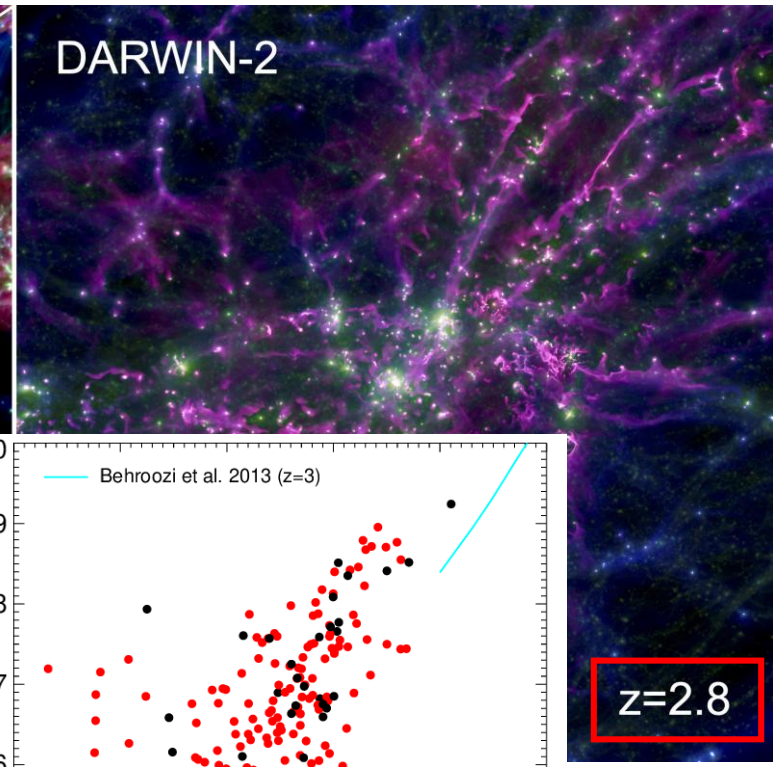
DARWIN-2

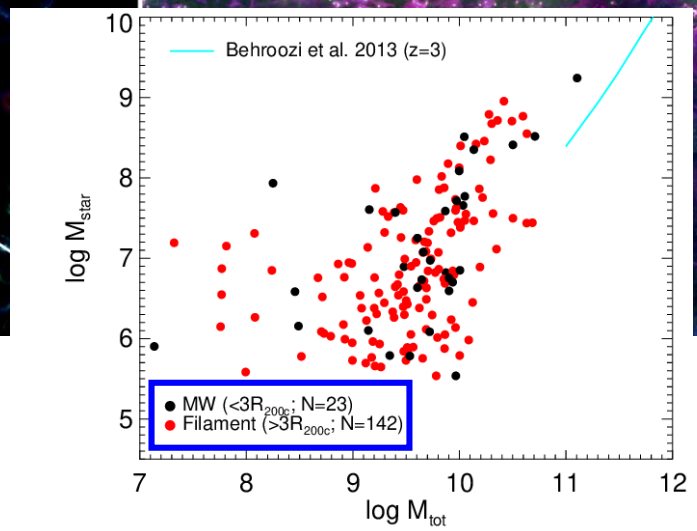
MW + filaments







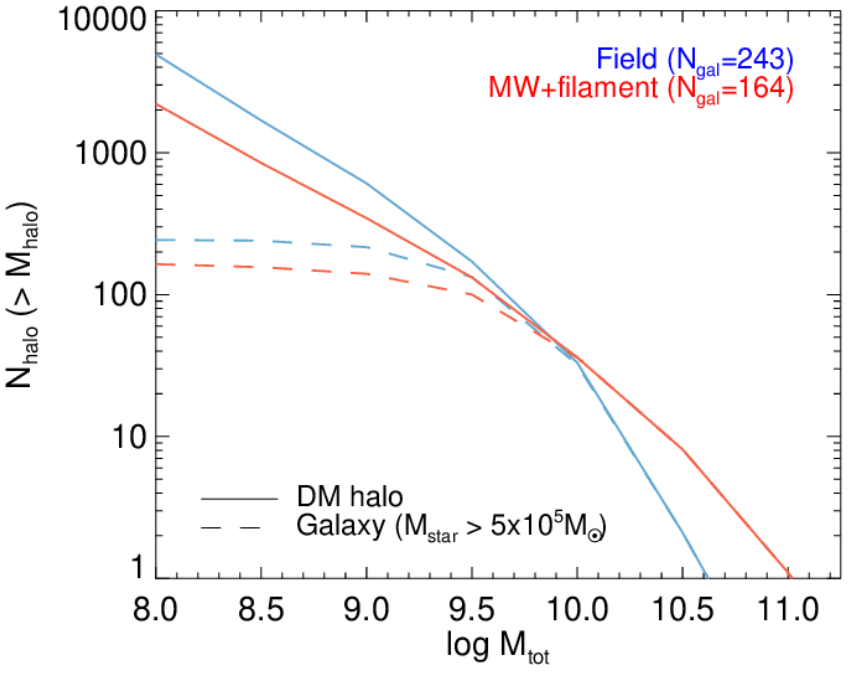




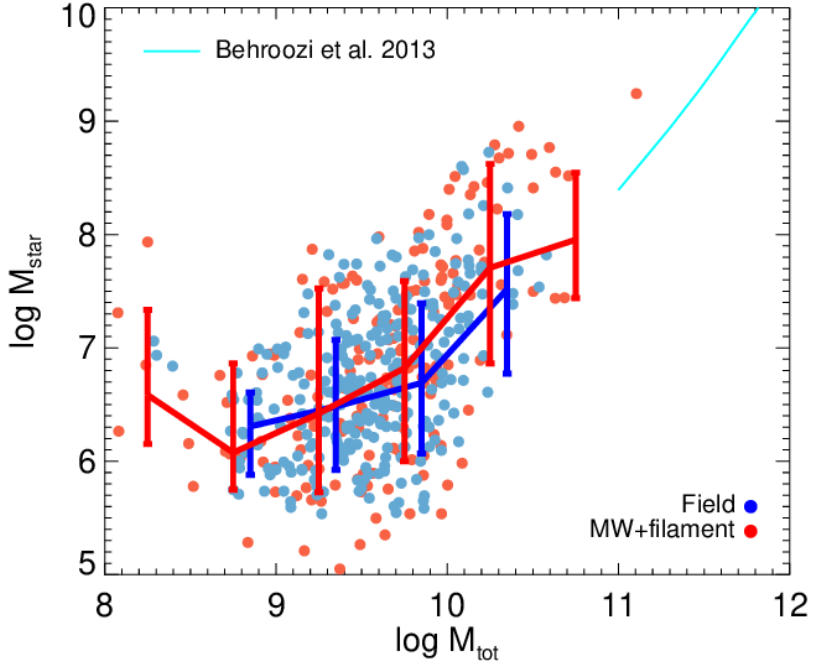
DARWIN-2

Properties @ z~3

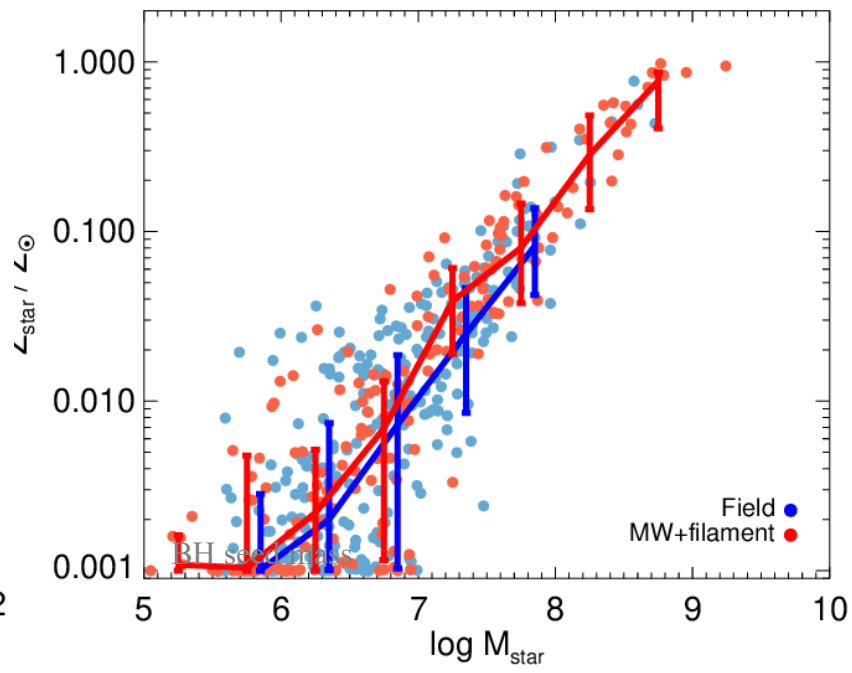
Halo (galaxy) mass function



M∗-M_{halo} relation

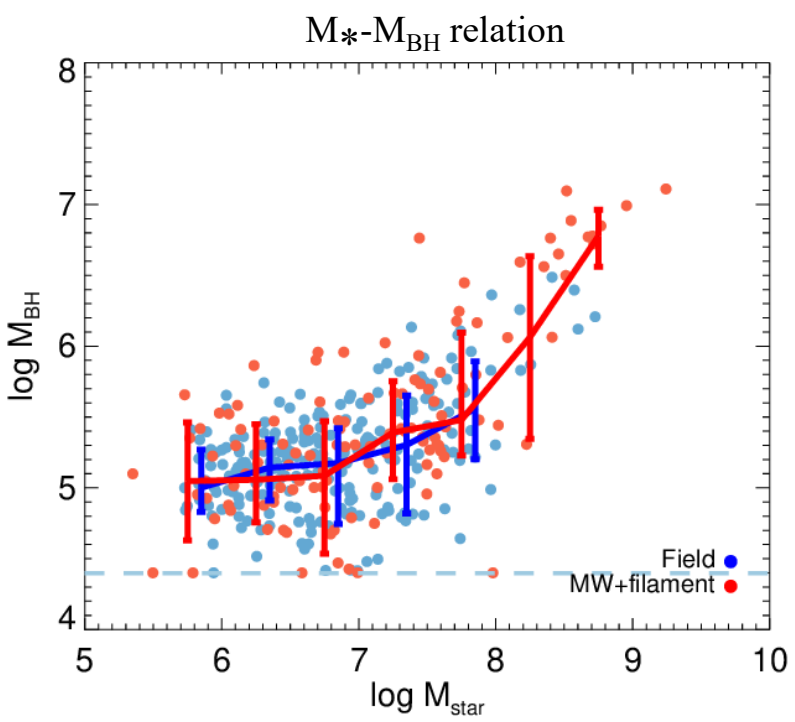


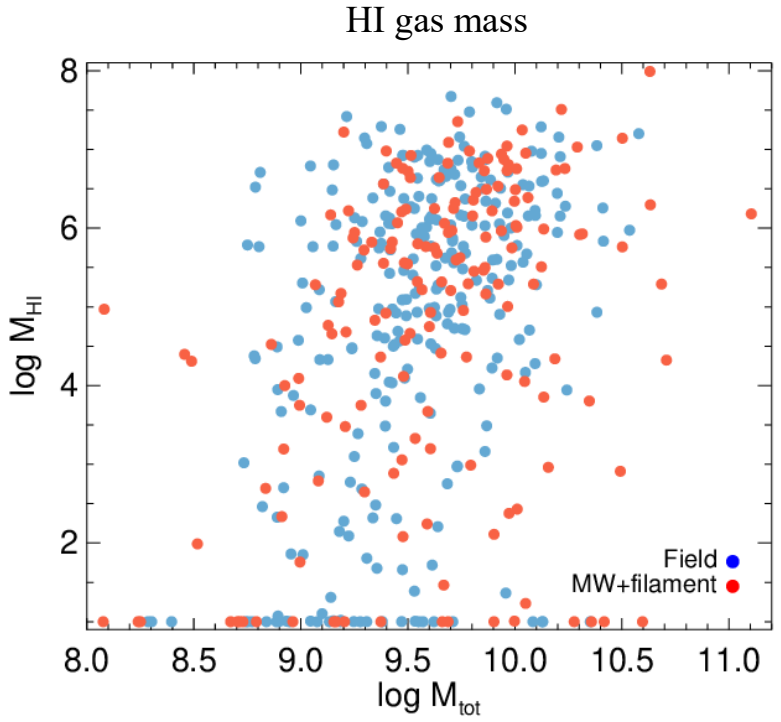
M∗-Z∗ relation

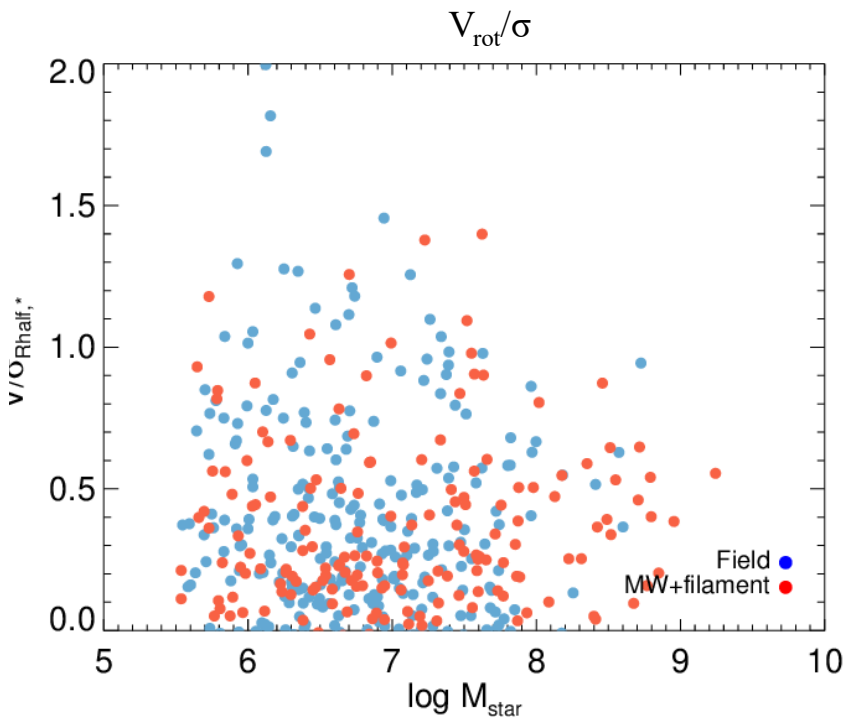


DARWIN-2

Properties @ z~3



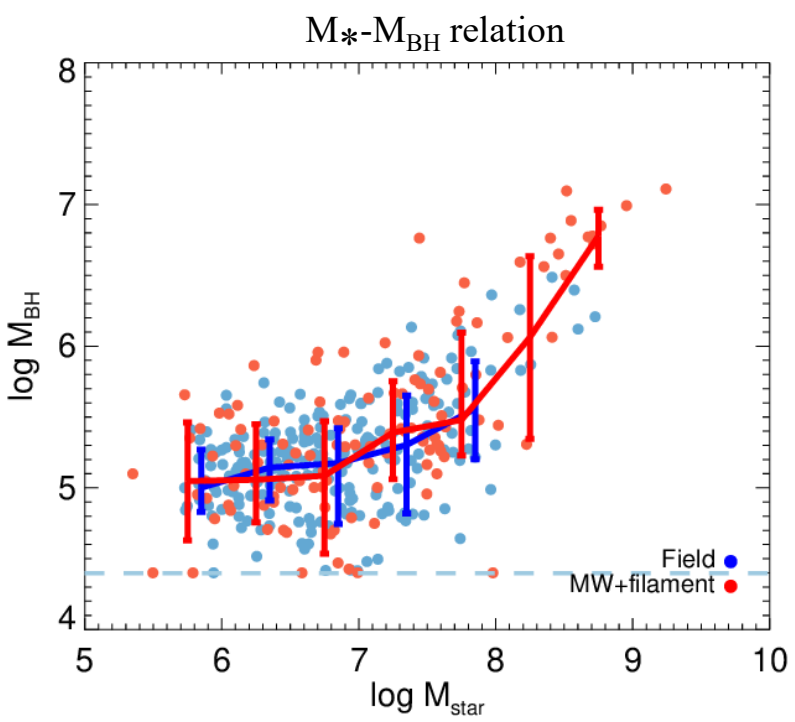


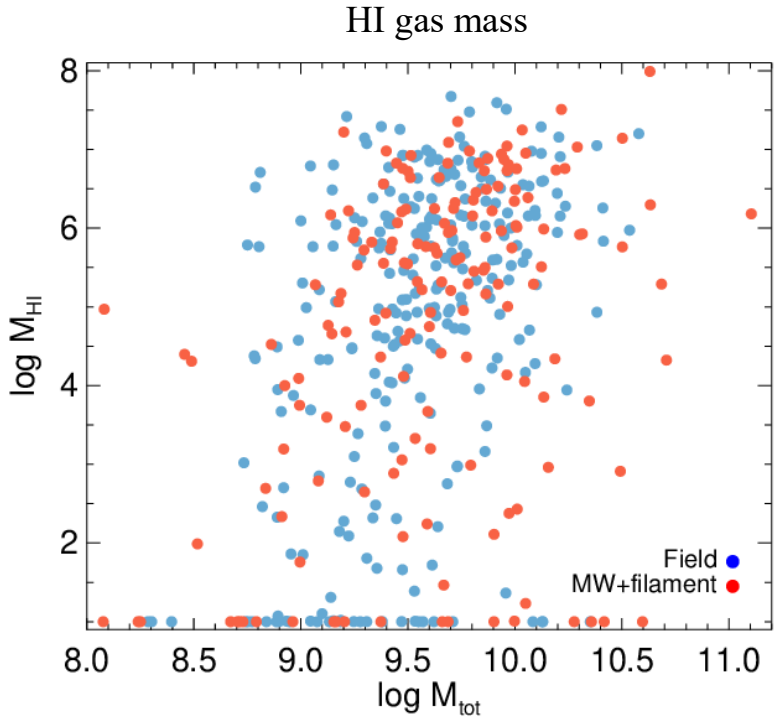


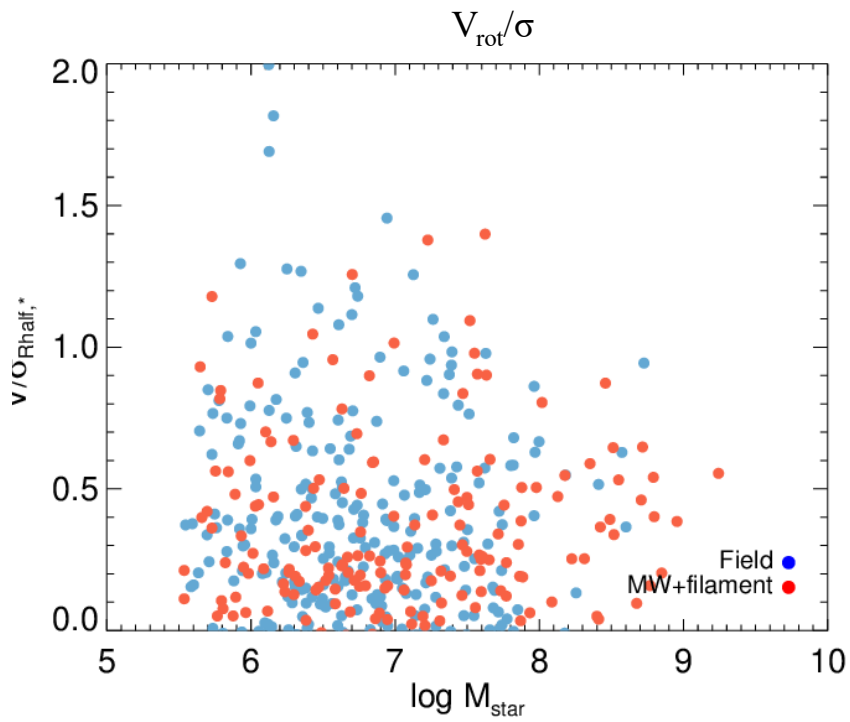
No significant differences in properties depending on environments

DARWIN-2

Properties @ z~3



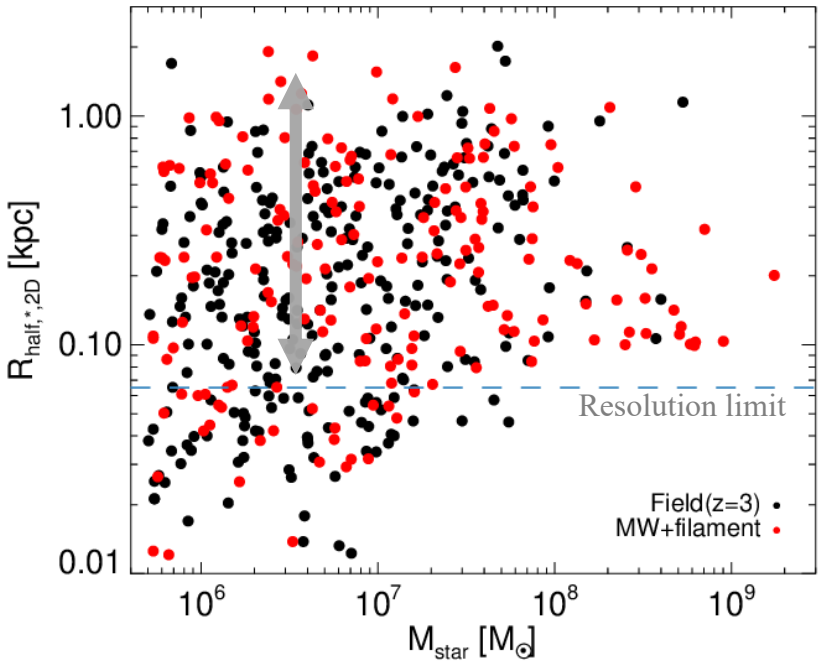




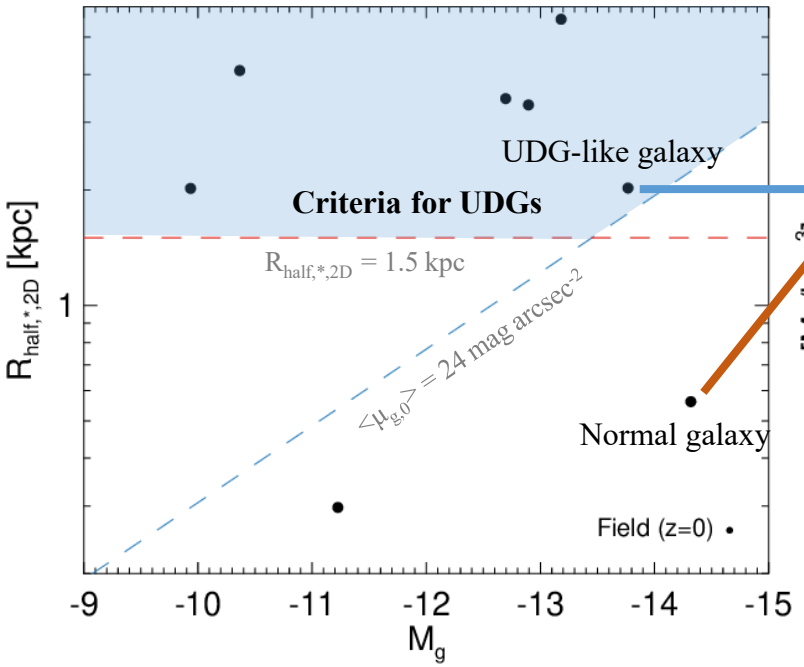
However, the DARWIN-2 simulations produce a variety of dwarf galaxies.

DARWIN-2

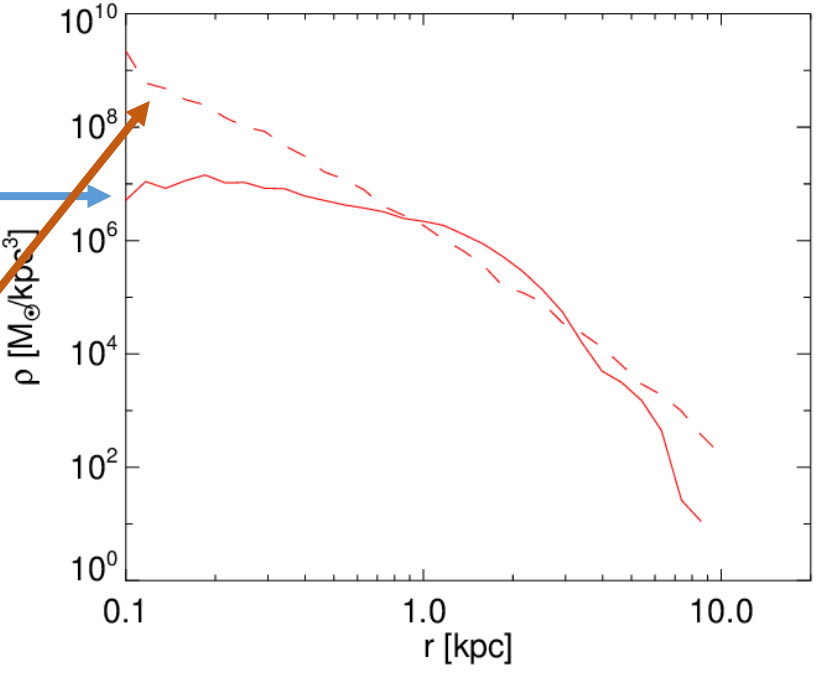
A wide range of sizes



Size vs. magnitude (z=0)

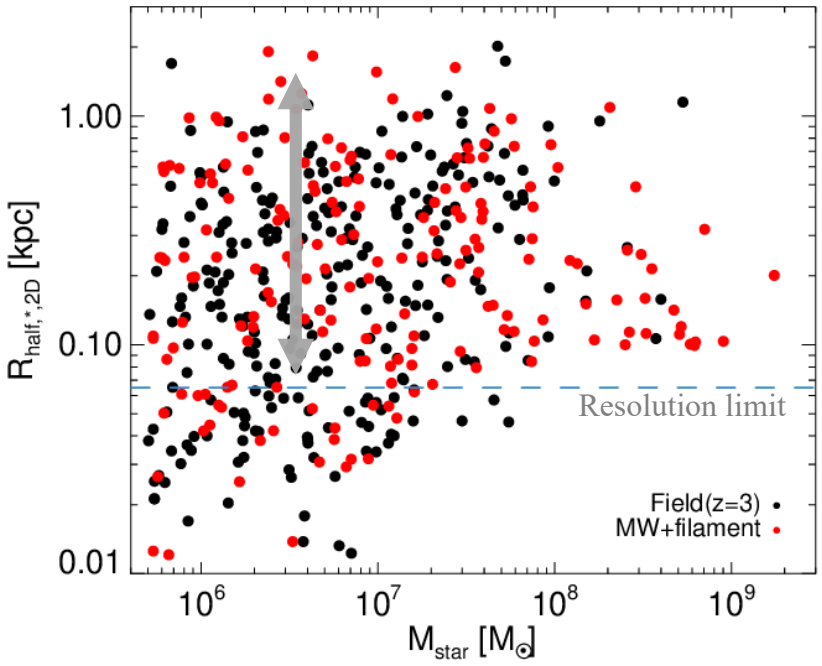


The stellar density profile

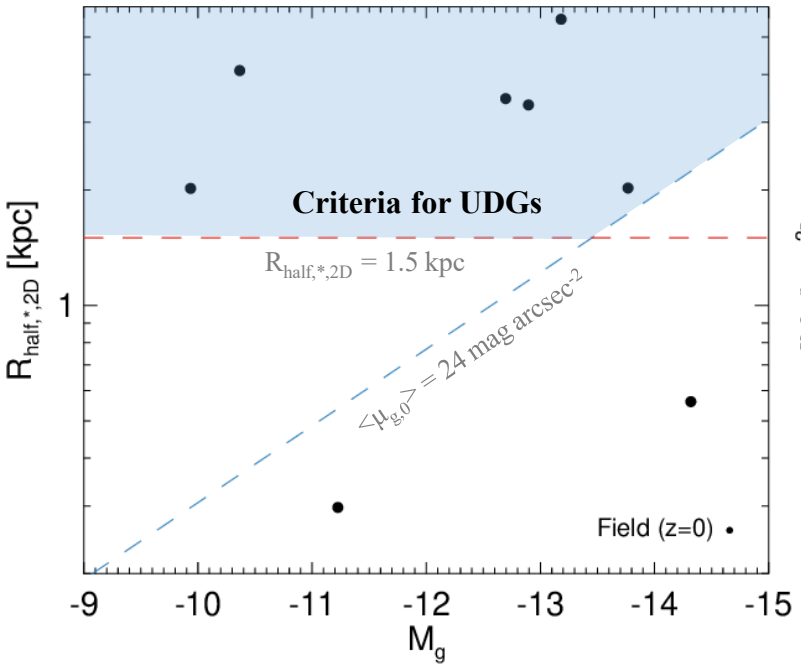


DARWIN-2

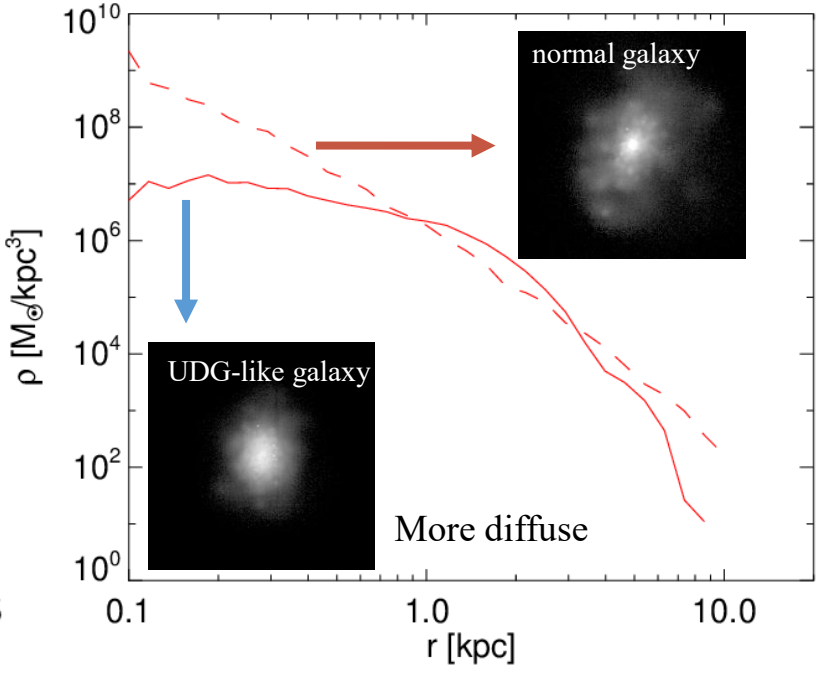
Diffuse galaxies



Size vs. magnitude (z=0)

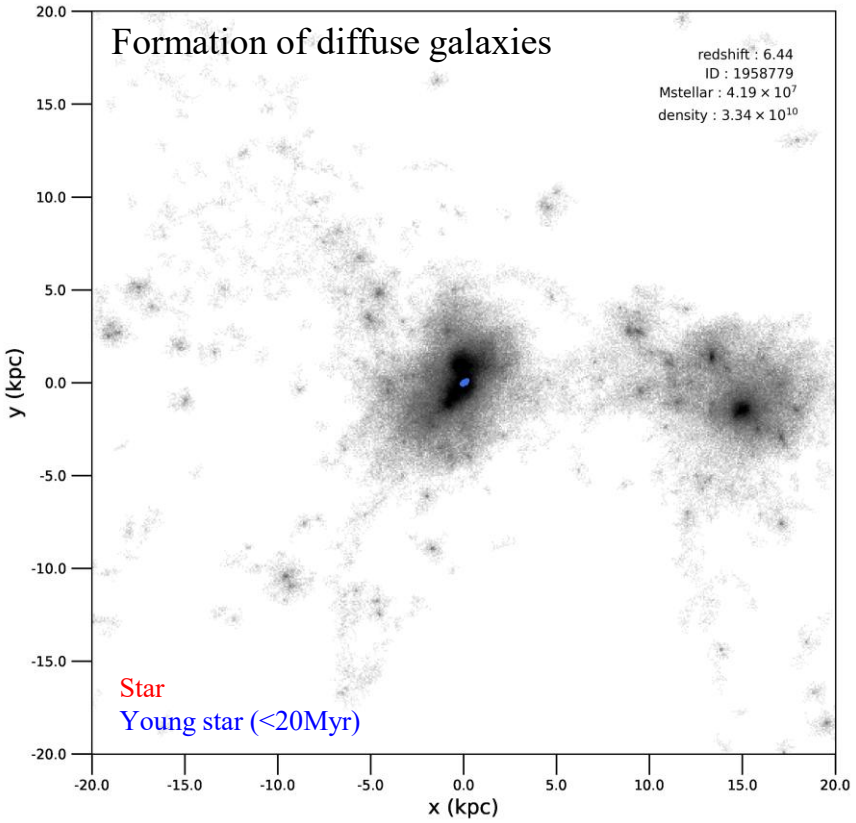


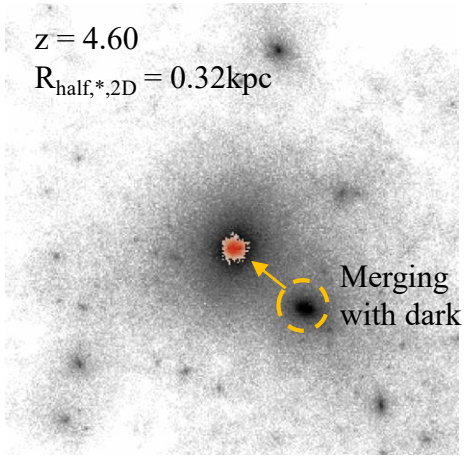
The stellar density profile

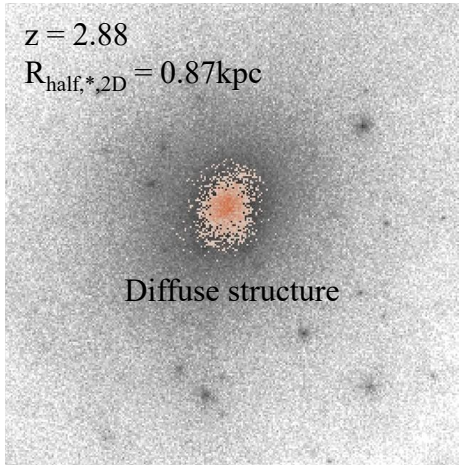


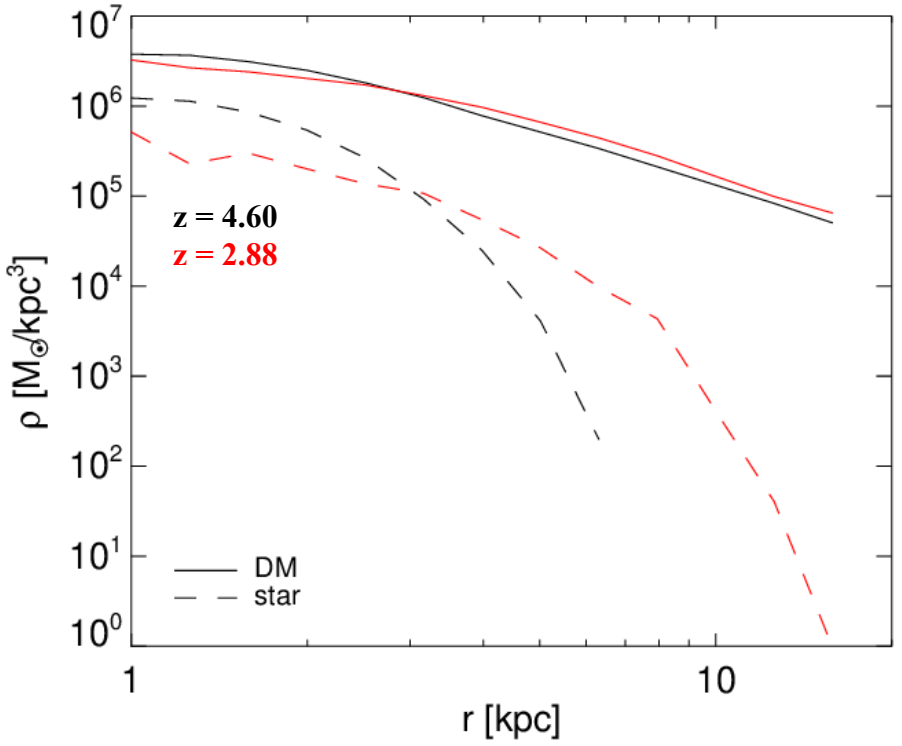
DARWIN-2

Diffuse galaxies



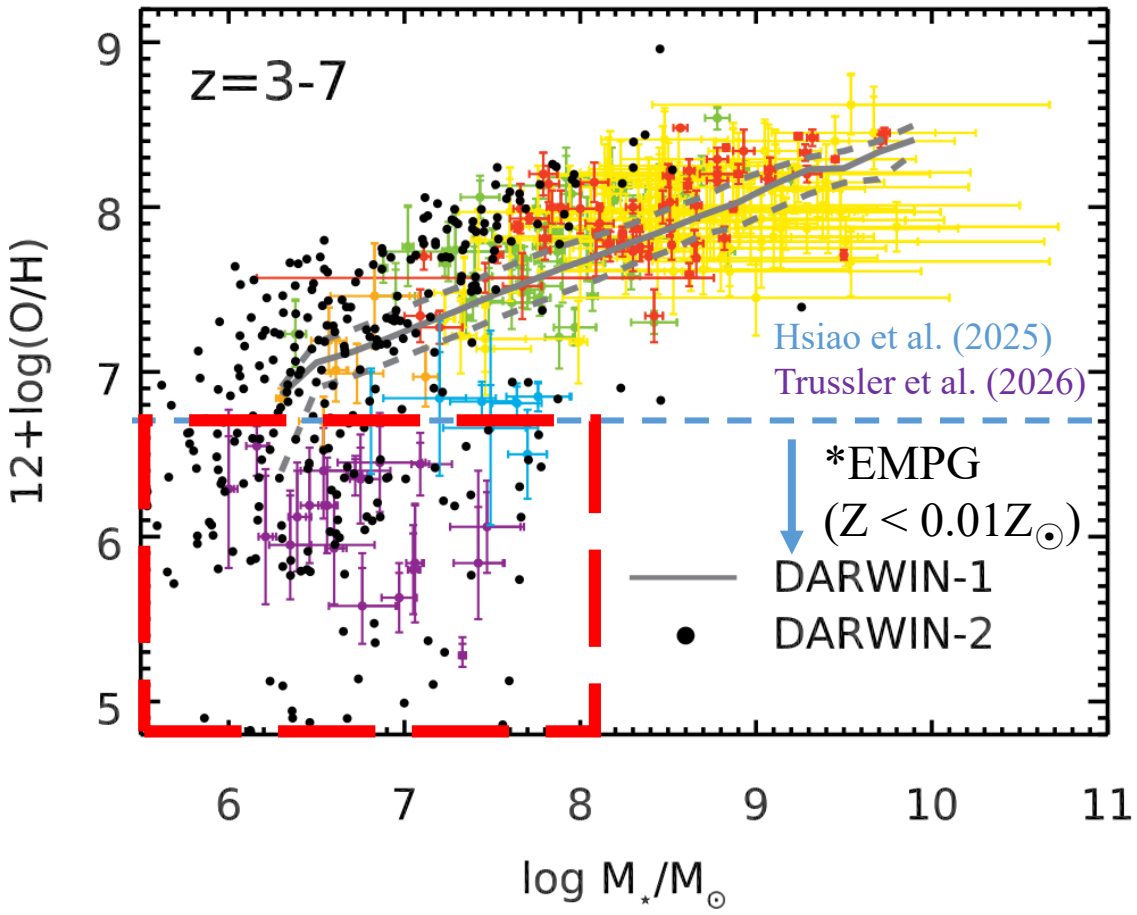


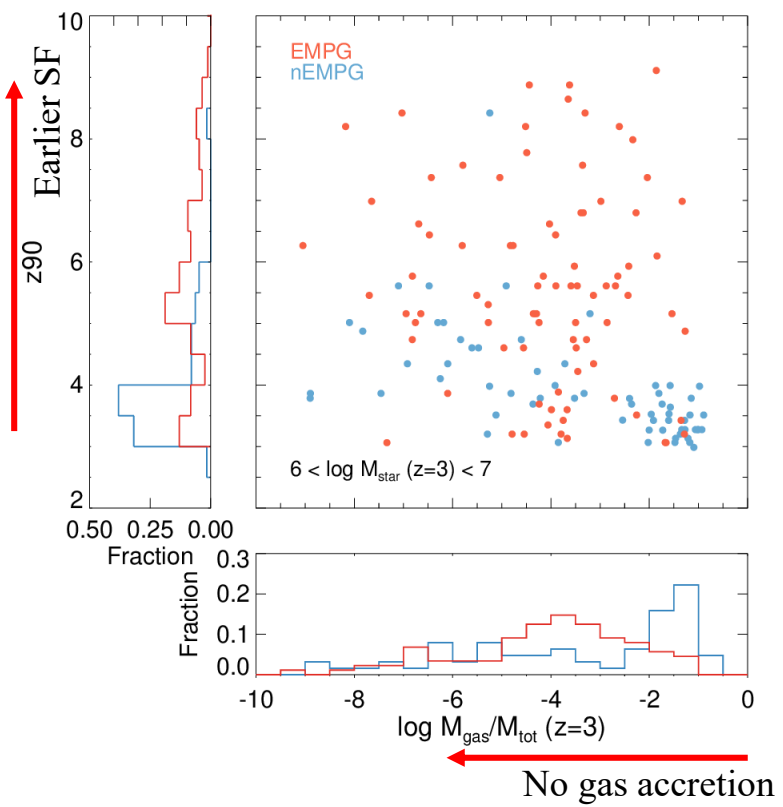




DARWIN-2

Metallicity of galaxies





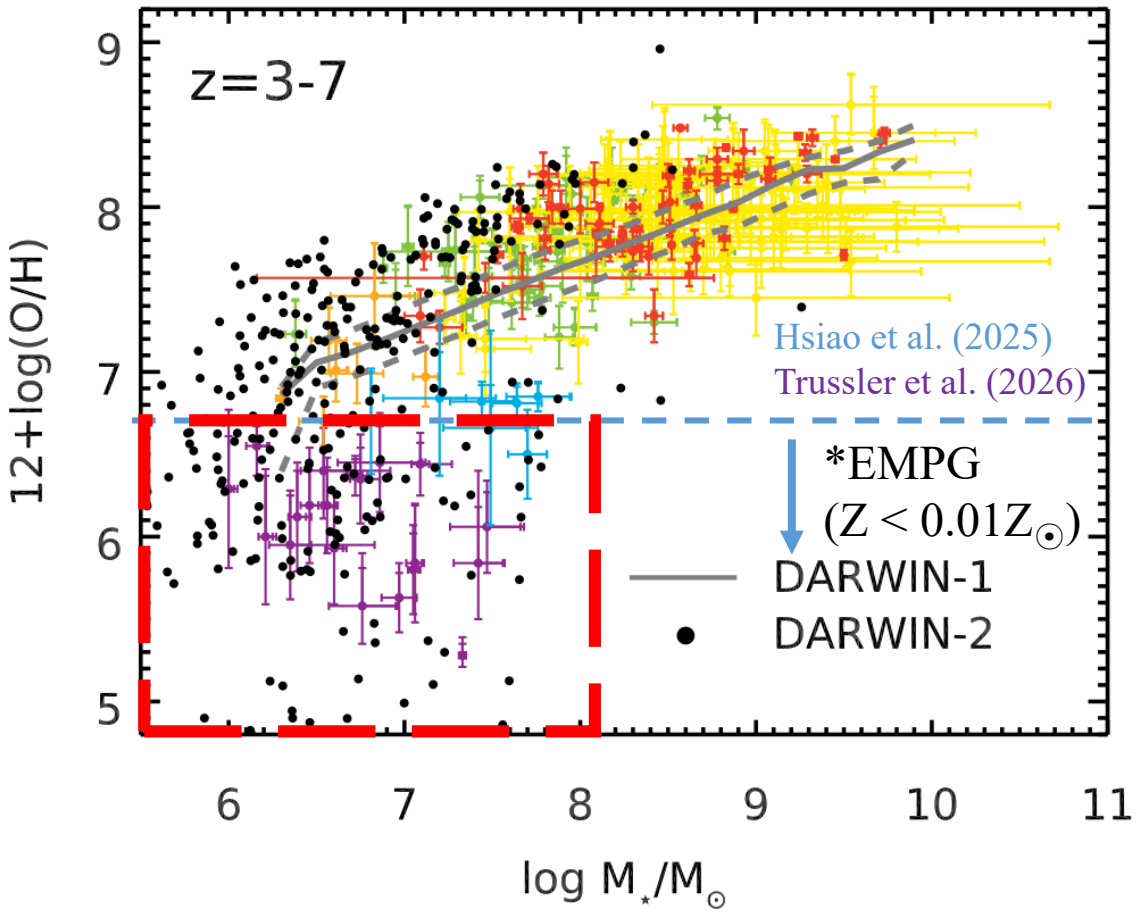
EMPG
→ early SF & no gas accretion
nEMPG
→ late SF

z_{90}: the redshift when a galaxy form 90% of its stars(z~3).

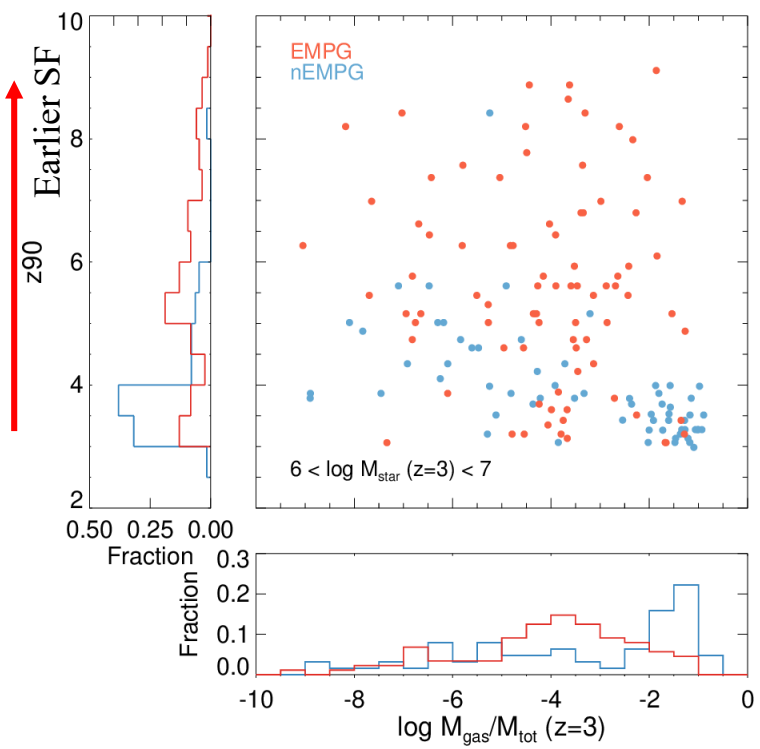
*EMPG: extremely metal poor galaxy

DARWIN-2

Metallicity of galaxies



*EMPG: extremely metal poor galaxy



EMPG
→ early SF & no gas accretion
nEMPG
→ late SF

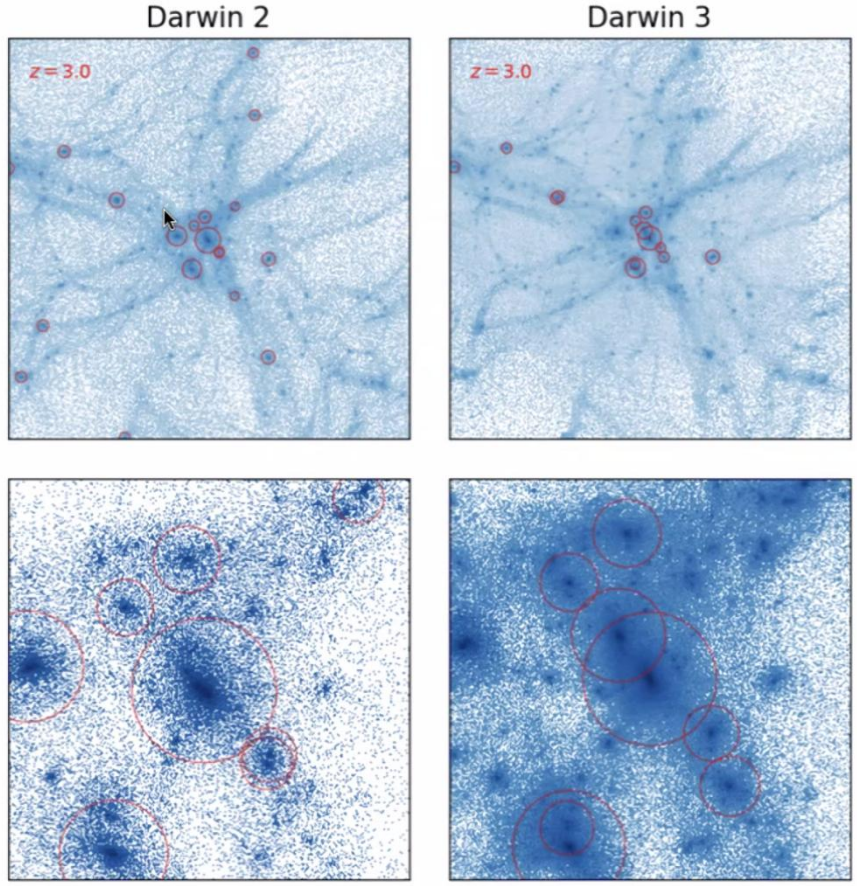
z_{90}: the redshift when a galaxy form 90% of its stars(z~3).

	Field	Filament (>3R_{MW})	MW (<3R_{MW})
f_{EMPG}	0.46	0.49	0.05

f_{EMGP}: The fraction of EMPGs among galaxies in each environment

Simulations

DARWIN-3 (RHD zoom-in)



Simulation performed by Jongwon Park

Target - dwarf galaxies from DARWIN-2 zoom region

Resolution - Δx=3.9 pc (stellar particle = 500 $M_{\odot}$)

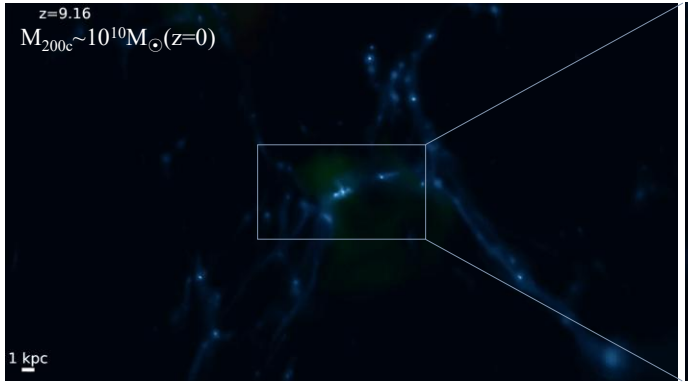
RT – 6 bands (5.6, 11.2, 13.6, 15.2, 24.59, 54.42eV)

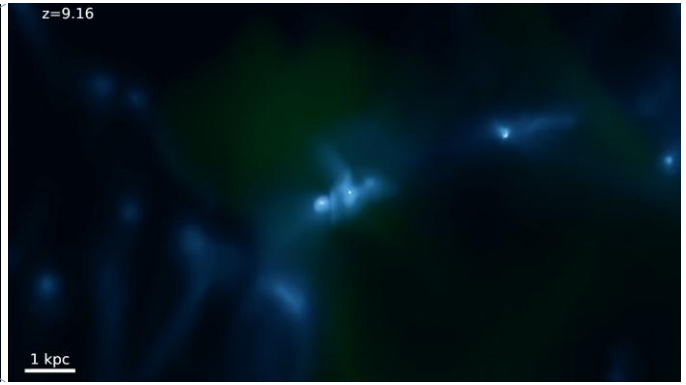
Star formation – sink particle based model (Blueuer & Teyssier 15; Kang+25)

Elements - H, He, Fe, O, N, Mg, Ne, Si, Ca, C, S traced (SNII: Limongi & Chieffi (18), SNIa: Seitenzahl+13)

Now running calculations for field dwarfs

Credit by Jongwon Park





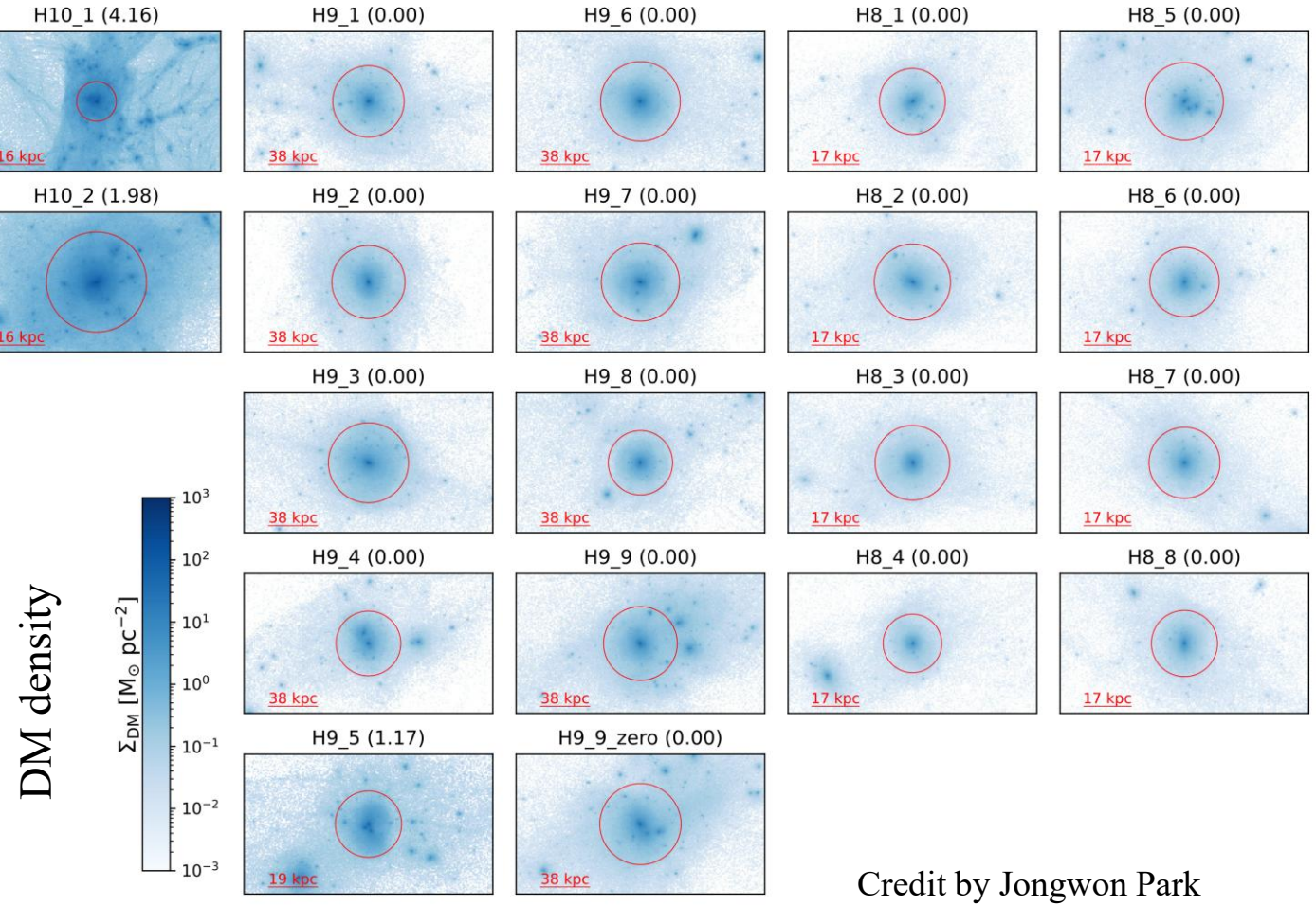
DARWIN-3

Target dwarf galaxies

- $M_{vir}(z=0) \sim 10^{8\text{-}10} M_\odot$
- H10: 2 runs
- H9: 10 runs (2 of them for genetIC)
- H8: 8 runs

→ 20 runs
(selected directly from DARWIN-2 field regions)

- $\Delta x = 3.9$ pc
- $m_{DM} = 2{,}180\ M_\odot$ (H10, H9)
- $m_{DM} = 273\ M_\odot$ (H8)
- $m_{star} = 500\ M_\odot$



Credit by Jongwon Park

DARWIN-3

Target dwarf galaxies

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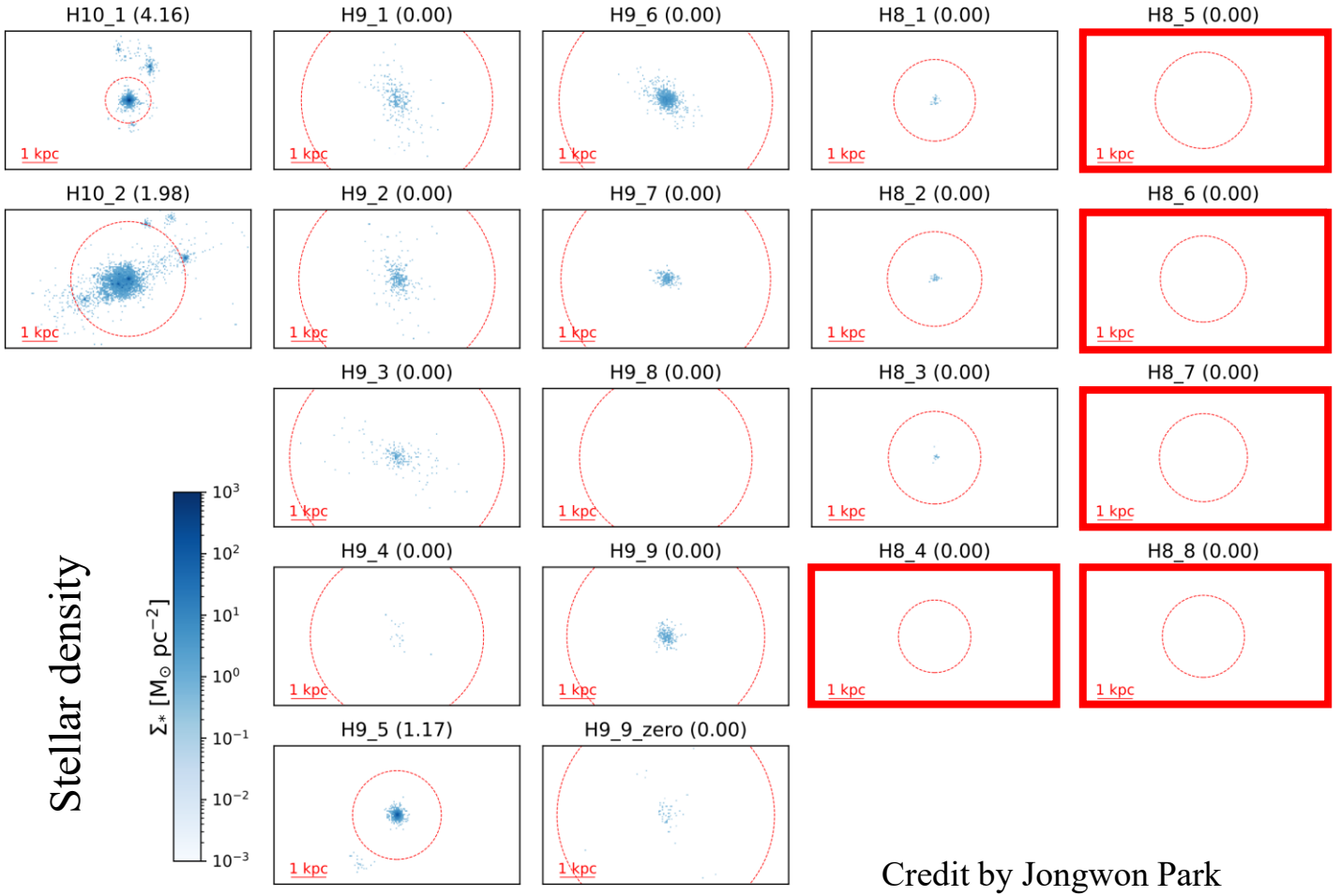


Credit by Jongwon Park

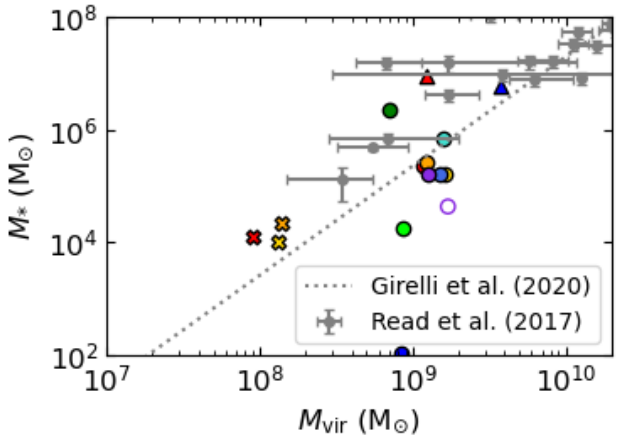
DARWIN-3

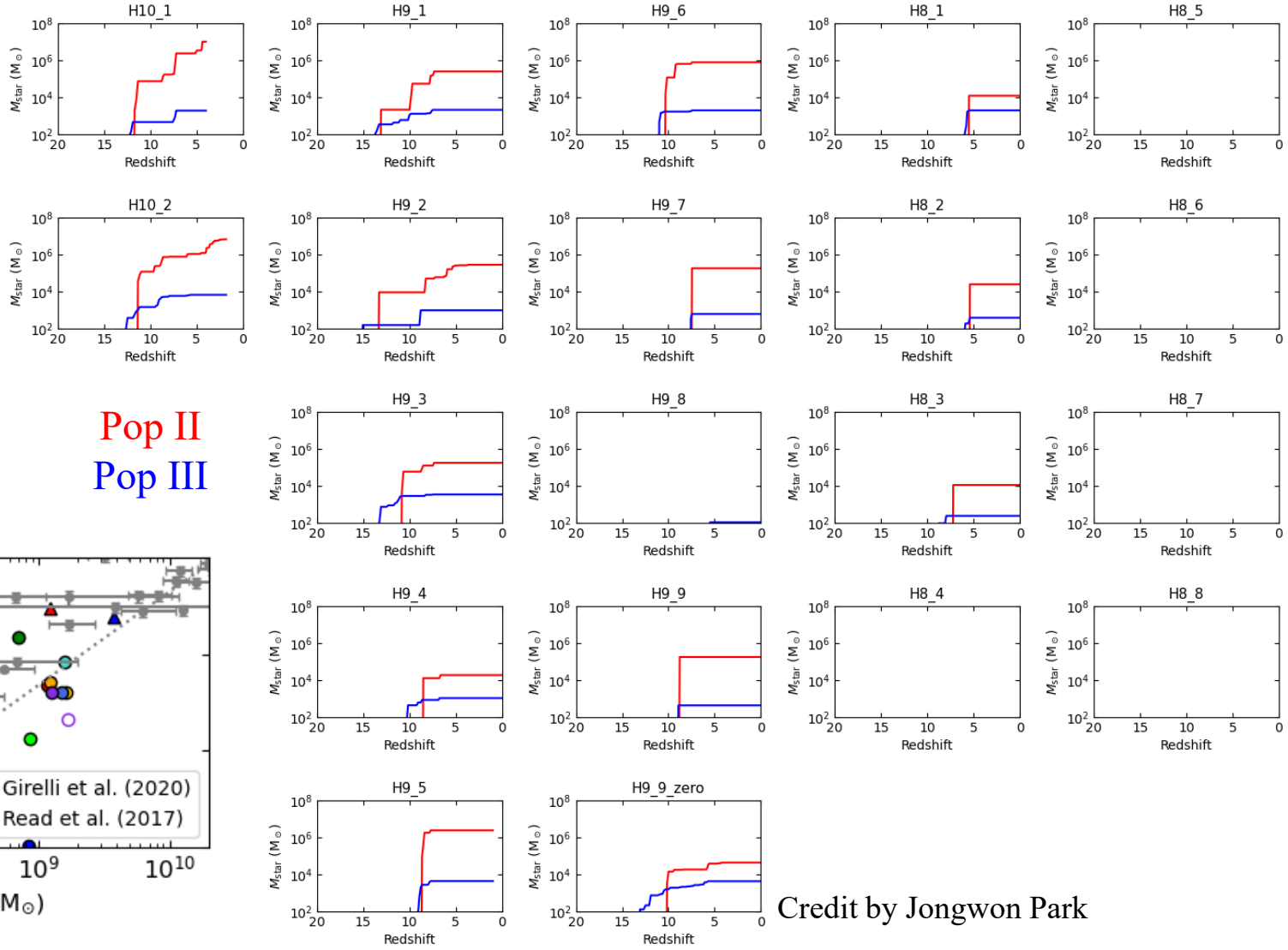
Pop III star formation

- $M_{vir}(z=0) \sim 10^{8\text{-}10} M_\odot$
- H10: 2 runs
- H9: 10 runs (2 of them for genetIC)
- H8: 8 runs

→ 20 runs
(selected directly from DARWIN-2 field regions)

- $\Delta x = 3.9$ pc
- $m_{DM} = 2{,}180\ M_\odot$ (H10, H9)
- $m_{DM} = 273\ M_\odot$ (H8)
- $m_{star} = 500\ M_\odot$





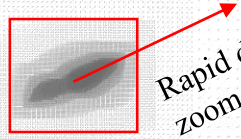
Pop II
Pop III

Credit by Jongwon Park

DARWIN-3

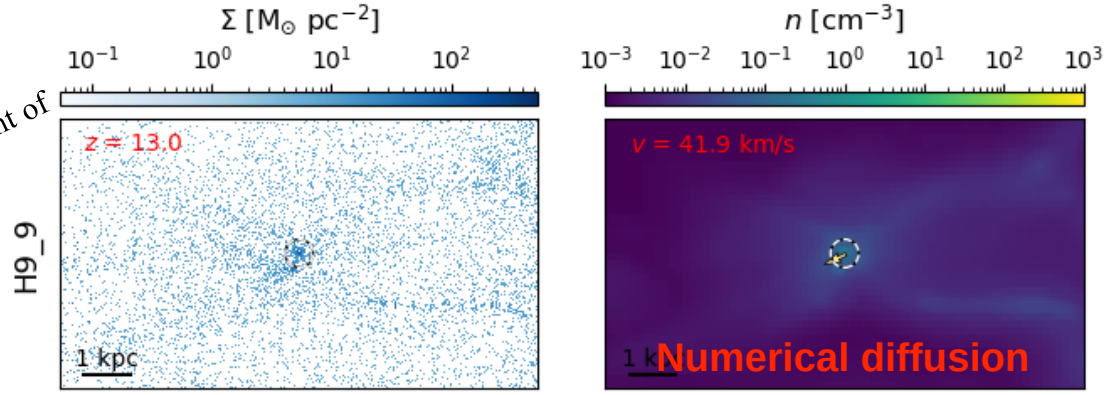
Velocity zeroing (using genetIC)

Unmodified IC

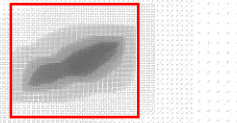


Rapid displacement of zoom-in region

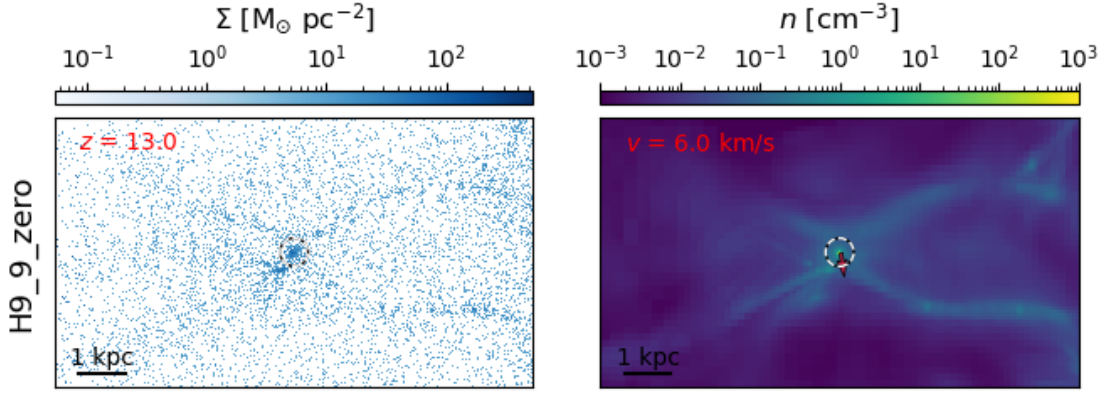
Initial zoom region



Velocity-zeroed IC



Initial zoom region



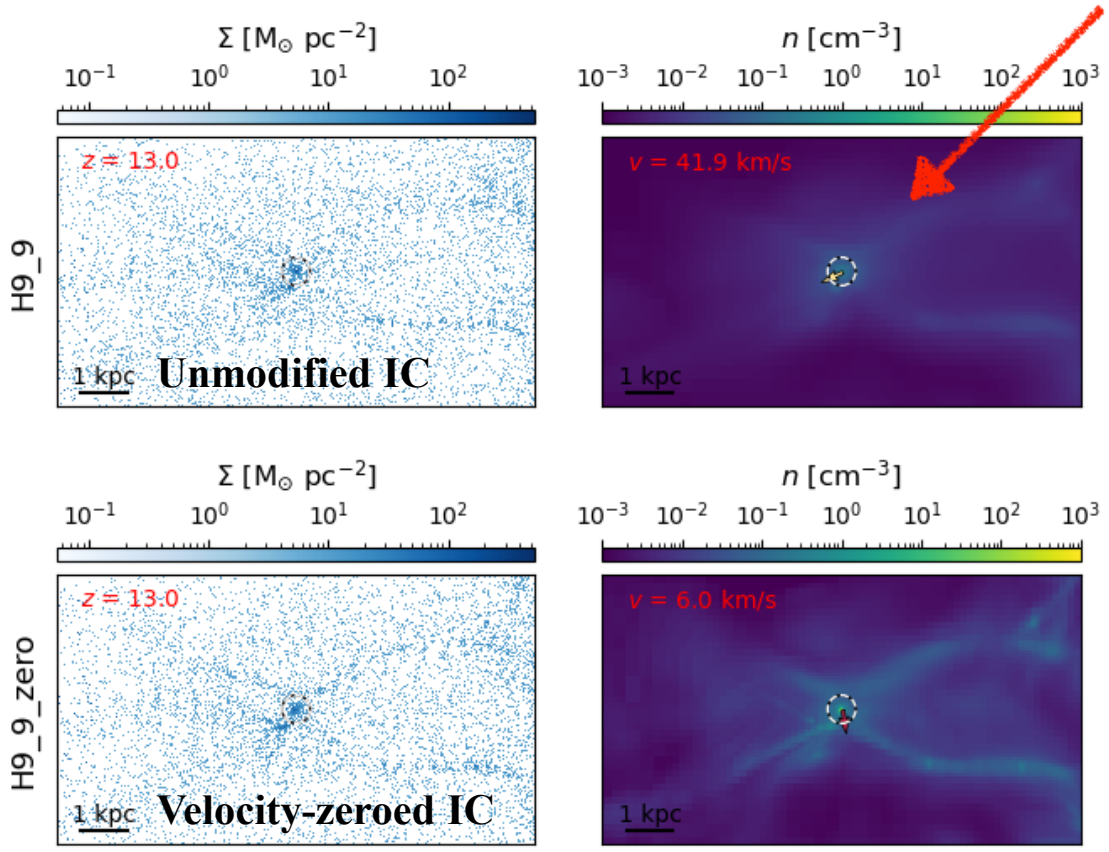
Rapid displacement of zoom-in region
→ Surrounding gas suffers from numerical diffusion.

To understand this effect,
we make a modified(velocity-zeroed) IC using GenetIC (Stopyra et al. 2021).

Credit by Jongwon Park

DARWIN-3

Velocity zeroing (using genetIC)



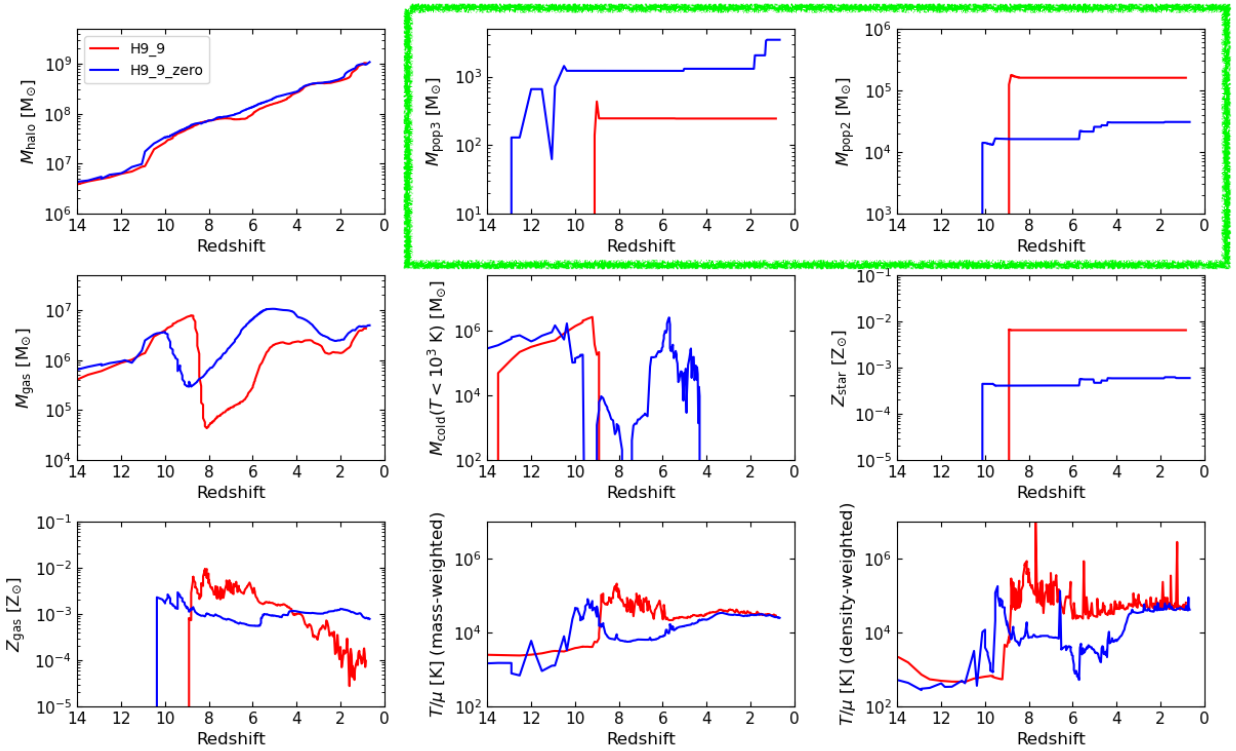
more diffuse

H9_9: The displacement control (x)

H9_9_zero: The displacement control (o)

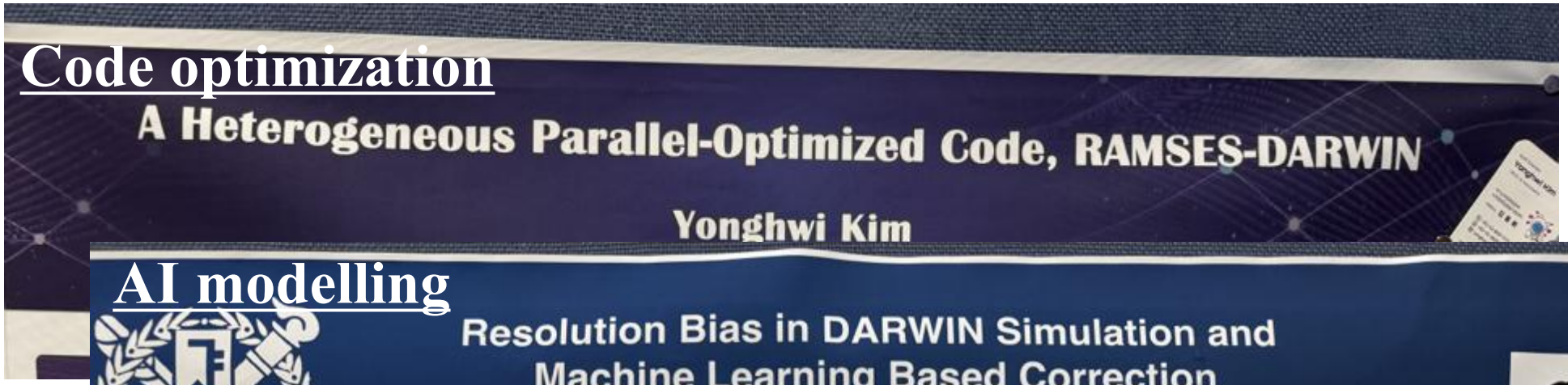
Delayed Pop III formation

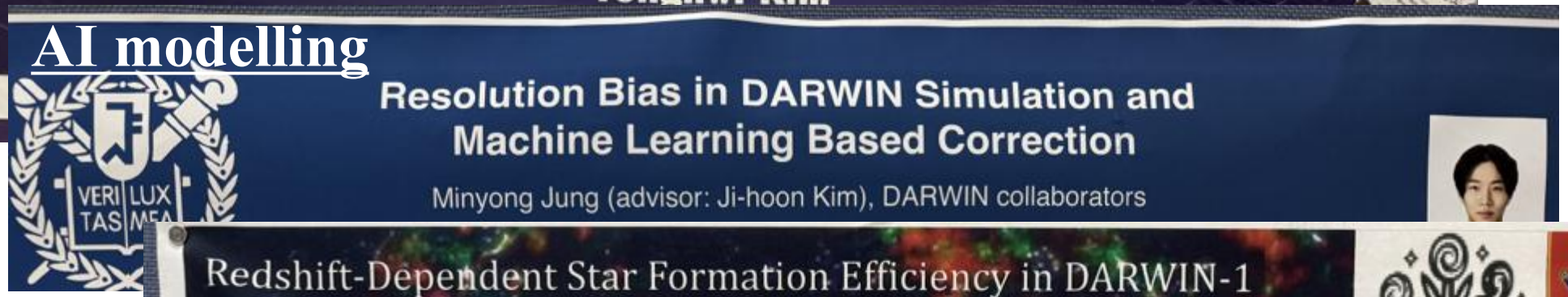
Enhanced Pop II formation

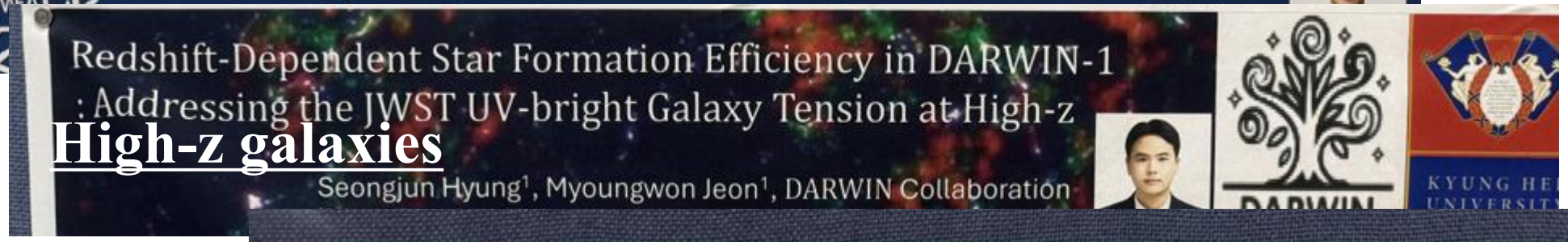


Credit by Jongwon Park

Research topics

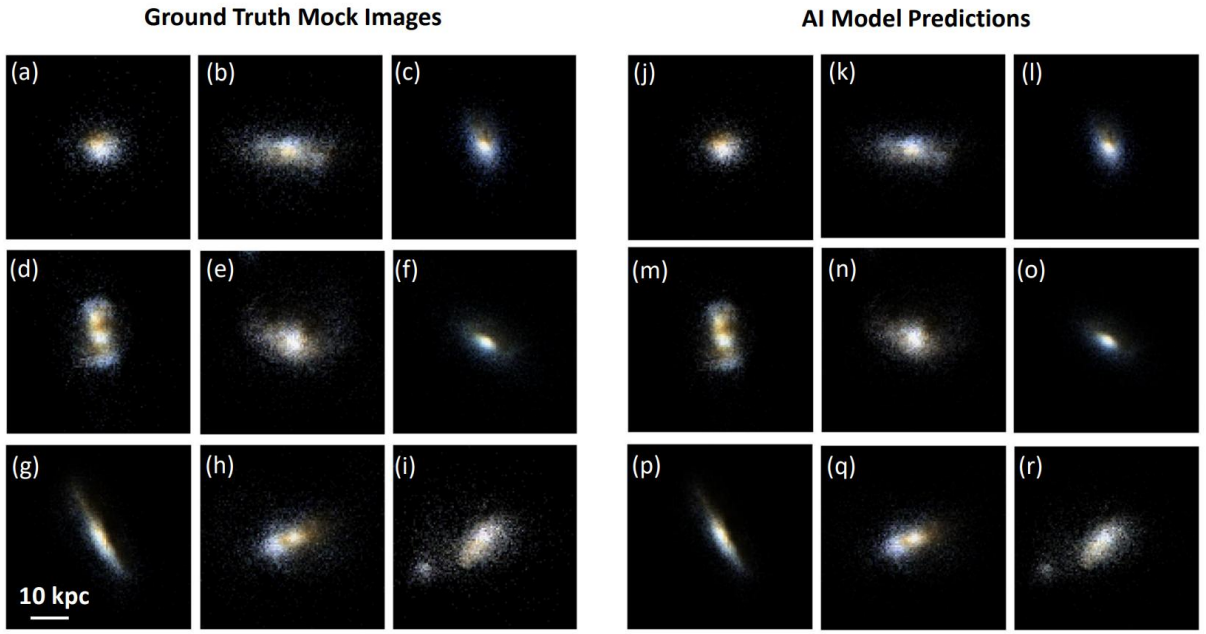






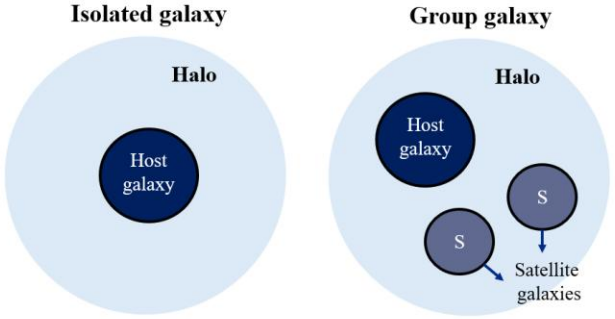
Research topics

AI based Mock image generation (DARWIN-1)



Ji-Hoon Ha et al. in prep.

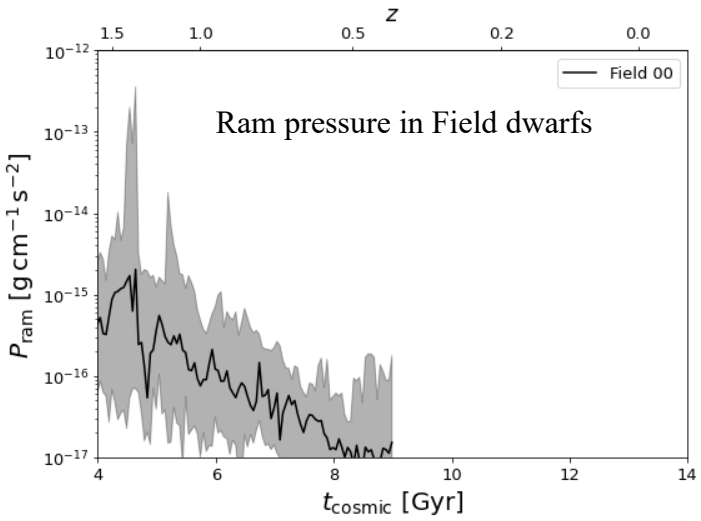
Environmental effects in DARWIN-2

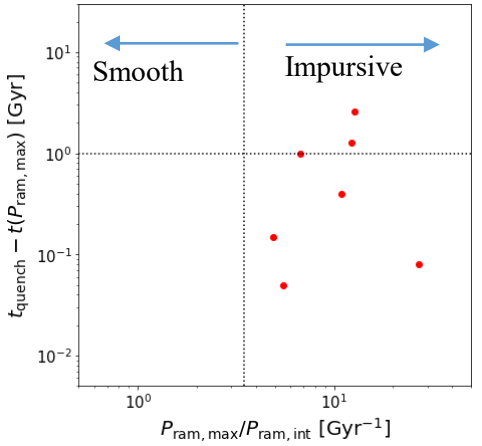


Group information in z ~ 4

Region	# of groups	# of group galaxies	# of total galaxies	Group ratio [%]	Max # of satellites
Field	15	40	163	24.5	5
MW	29	81	164	49.3	9

Seungyeon Kim et al.





Research topics

Many research topics related to dwarf galaxies

- Correlation between **the diversity of dwarf galaxies and large-scale structures** (DARWIN-1, 2)
- Tracing **the earliest star remnants in MW dwarf galaxies** (DARWIN-1, 2)
- Relationship between **primordial galaxies and supermassive black holes** in the early universe (DARWIN-1, 2)
- **Effects of ram pressure and hydrodynamic effects** on dwarf galaxies (DARWIN-1, 2)
- Formation/evolution channels of mysterious dwarf galaxies: **UFD, UCD, UDG**, etc. (DARWIN-2, 3)
- Tracing the characteristics of **first stars and galaxies** in the universe (DARWIN-3)
- The role of z, M_*, and SFR in observable properties of **the cool CGM** (DARWIN-3)
- **Cusp-core** transformation in dwarf galaxies (DARWIN-3)
- **Lyman-α properties** of dwarf galaxies and emission/absorption to be compared with observations (DARWIN-1, 2, 3)
- **AI modelling** to trace history of dwarf galaxies from observational characteristics of dwarf galaxies (DARWIN-1, 2, 3)

➔Various in-depth/detailed research topics from the DARWIN

Simulation summary

		DARWIN-1	DARWIN-2	DARWIN-3
Boxsize		65 Mpc	Zoom-in (from DARWIN-1)	Zoom-in (from DARWIN-1 or 2)
Min (res)		500pc	62.5 pc	4 pc
Min (m_{DM})		900,000 $M_\odot$	17,000 $M_\odot$	2,200 M_{sun}
Min (m_{star})		100,000 $M_\odot$	10,000 $M_\odot$	500 $M_\odot$
Star formation	model	Density-based	Gravo-thermo-turbulent (Kimm+17)	SINK-based (Blueuer & Teyssier 15; Kang+25)
	SFE_ff	100%	Variable	On the fly
Chemical species		H, Fe, O	H, Fe, O, N, Mg	H, He, Fe, O, N, Mg, Ne, Si, Ca, C, S
Radiative transfer		X	O	O
Target		Full box	Field, Filament, Isolated (or paired) MW, Group	Isolated dwarf galaxies
Progress		z~0.31	DARWIN-2 table	DARWIN-3 table

DARWIN-2 table

	Current z	# of targets	N_{gal} ($M_{star} > 5\times10^5 M_\odot$ @ z~3.0)
Field(L~4Mpc)	0.0~3.1	24	243
MW+Filament	2.8	1	164

DARWIN-3 table

	Current z	# of targets	N_{gal} ($M_{star} > 10^4 M_\odot$)
M_{200c}~$10^{10}M_\odot$	1.9~4.1	2	2
M_{200c}~$10^{9}M_\odot$	0.0~1.1	10	9
M_{200c}~$10^{8}M_\odot$	0.00	8	3