Advanced utilization of High-Performance Computing
funded by NRF of Korea

DARWIN: DAzzling Realization of dWarf galaxies In the Next generation of cosmological hydrodynamic simulations

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Horizon Run 5 (HR5)

- Hydrodynamical cosmological simulation

  devised to cover **a cubic volume of ~1cGpc^3 with a spatial resolution up to 1kpc.**
- Simulation box of L~1cGpc is necessary

  to examine the BAO features and the enough number of clusters.
- Zoomed technique is used to compromise between volume and resolution.

Changbom Park

Juhan Kim

First HD simulation of the HR series

Horizon Run series (by KIAS)

	HR1	HR2	HR3	HR4	HR5
Box size (L)	9417 cMpc	10285 cMpc	15450 cMpc	4436 cMpc	1049 cMpc
# of particles	4120^3	6000^3	7200^3	6300^3	gas cells+particles
Reference	Kim et al. (2008)	Kim et al. (2011)	Kim et al. (2011)	Kim et al. (2015)	**Lee & Shin et al. (2021)**
Code	GOTPM (Dubinski, Kim, Park 2004)	GOTPM	GOTPM	GOTPM	RAMSES (Teyssier 2002)

HR5 builders

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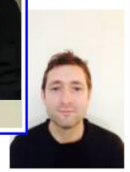
Kim, Jae-Woo (김재우) | Research Scientist



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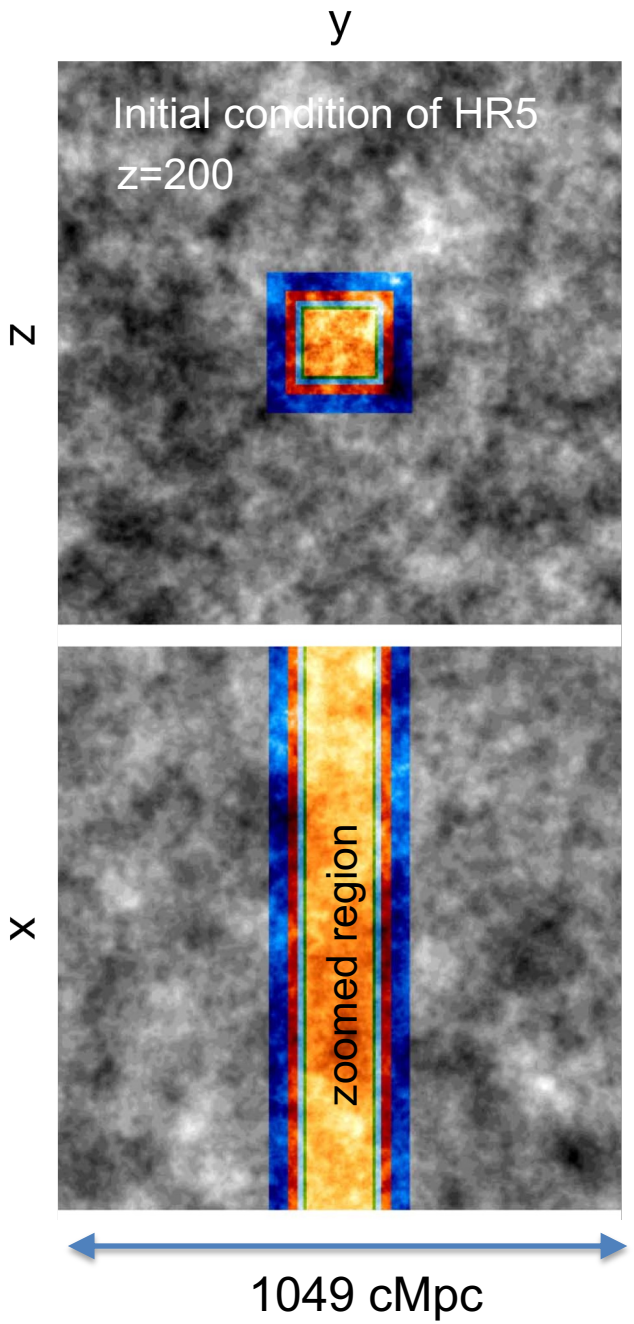
HR5 outline

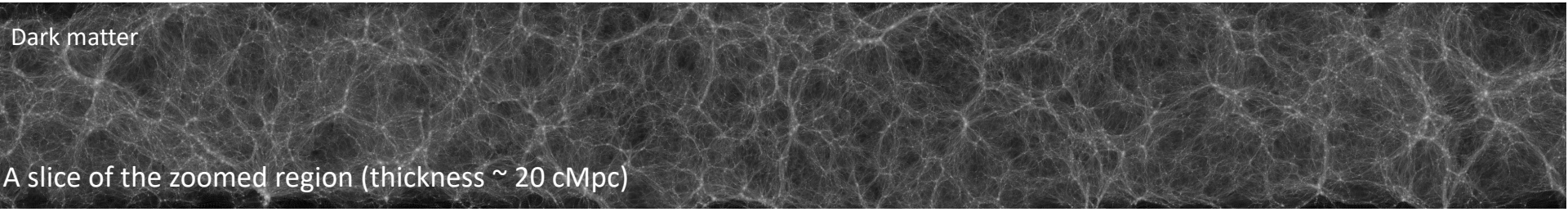
- Adaptive Mesh Refinement code, **RAMSES**
  (Teyssier 2022, Dubois et al. 2014)
- **Optimized for MPI+OMP** hybrid computing
  Simulation box - $(1049\text{cMpc})^3$
- Zoomed region - 1049 x 119 x 127 cMpc^3
  (~1/80 of the entire volume)
- Resolution - down to **1kpc in the zoomed region**
- Cosmology - h:0.684, Ω_m=0.3, Ω_Λ=0.7
  (compatible with the Planck data)
- **691 M core hours** down to z~0.625

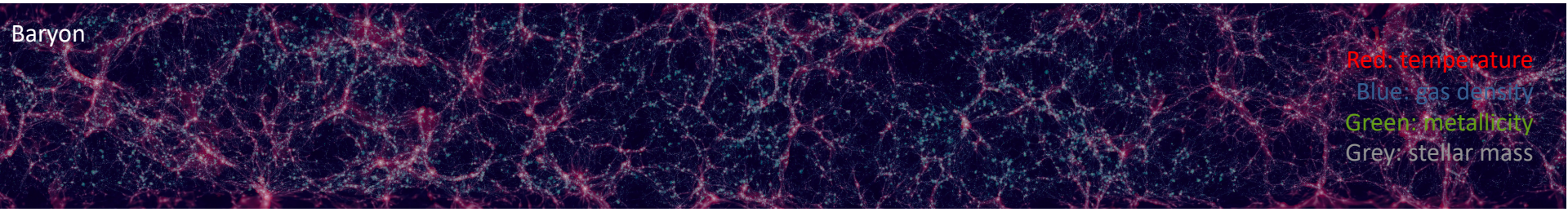
- Gas cooing down to T~750K
- Uniform reionization operates at z<10
- SNIa, SNII feedback: mechanically & radiatively
- Massive BH formation/evolution with spin:
  mechanically & radiatively



HR5 output

z~0.625





- A total of **146 snapshots**
- **Light cone space data** from 2 observers
- **5 dense regions with finer time steps**

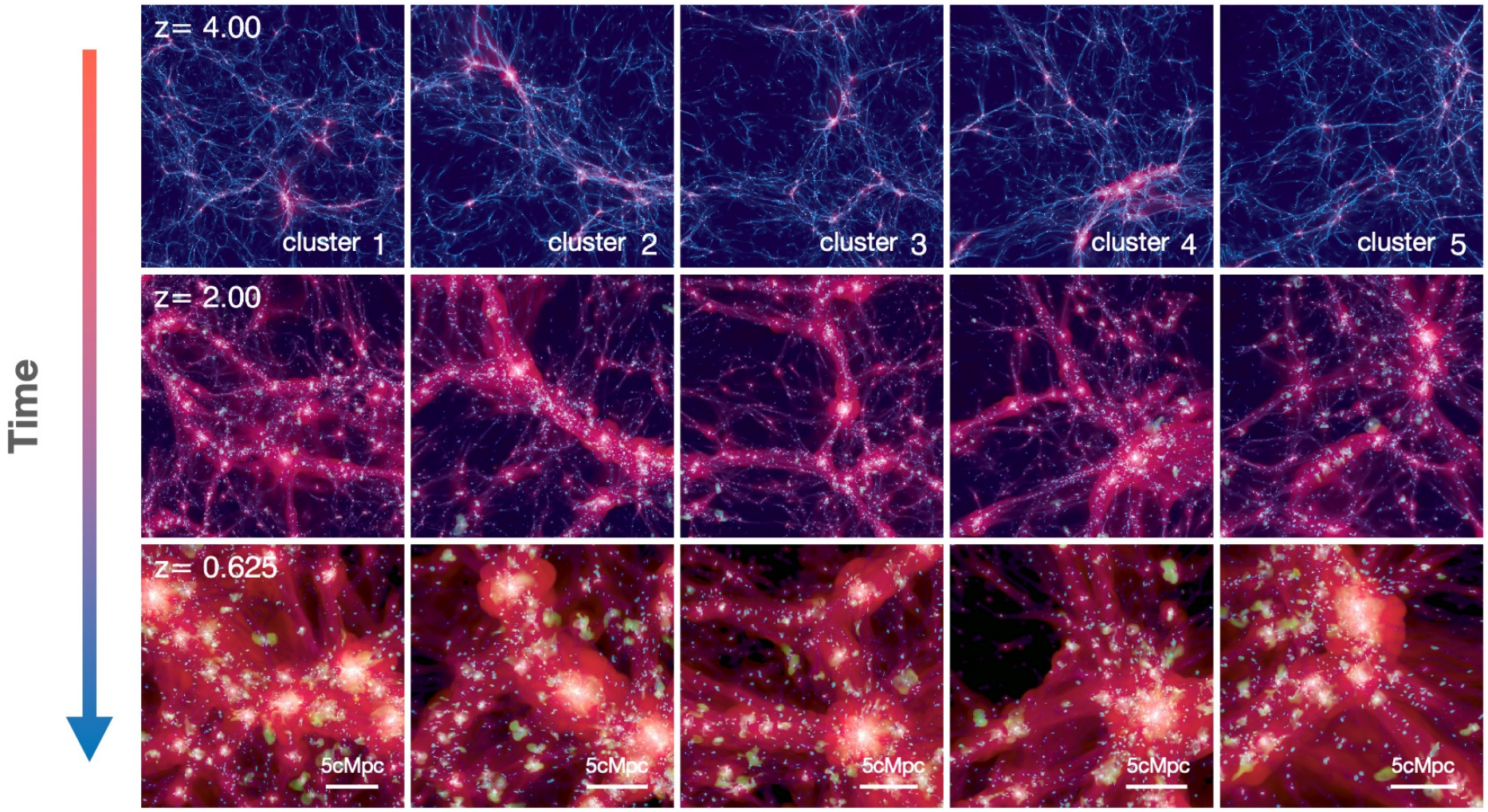
  : cluster candidate haloes
- Catalogues identified PGalF

FoF halos ($M_{\rm tot} > 10^{11}$ $\rm M_\odot$)	184,956
Cluster halos ($M_{\rm tot} > 10^{14}$ $\rm M_\odot$)	102
Galaxies ($M_* > 10^9\,\rm M_\odot$)	290,086

z=0.625

Search for 'Horizon Run 5' on Youtube ➔

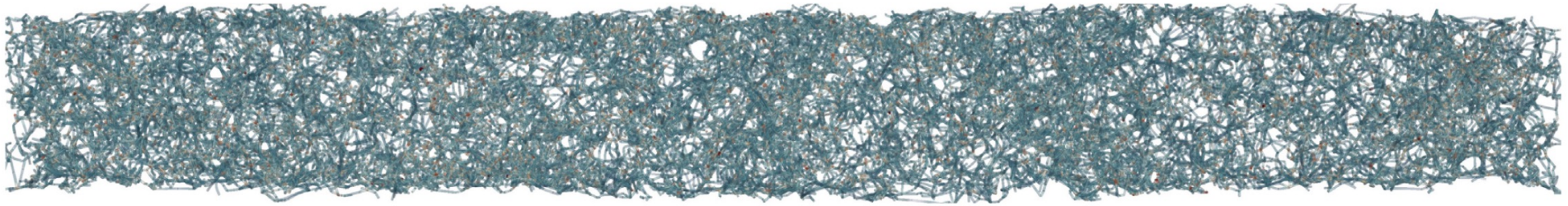
HR5 subprojects



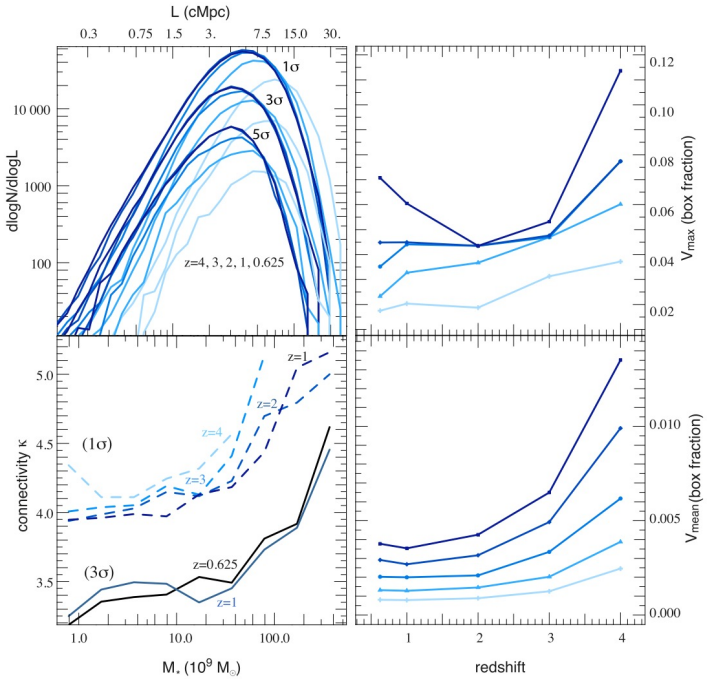
- 26 subprojects on-going
- published/accepted/submitted : more than 10 papers

Red: temperature
Blue: gas density
Green: metallicity
Grey: stellar mass

HR5 subproject on the cosmic web



Skeletons identified by DisPerSE



On-going sub-projects

- Redshift evolution of connectivity and its impact on properties of centrals
  -> leaded by Katarina Kraljic
- Influence of cosmic web environment on the galaxy cluster properties using HR5 simulation
  -> leaded by Céline Gouin

- Radius of the largest void **~ 100cMpc**

Advanced utilization of HPC program

- **Solving scientific problems** & creating innovative technologies
  - through support for large-scale group research
  - based on ultra-large data & simulation
  - using **high-performance computing**
- Major strategic fields: material science, life science, ICT, **meterology**, self-driving, **astronomy**, nuclear fusion, manufacturing technology, natural disaster, national defense
- Budget: 3.5 million dollars during 4.5 years

➔ **beginning in September of 2022**

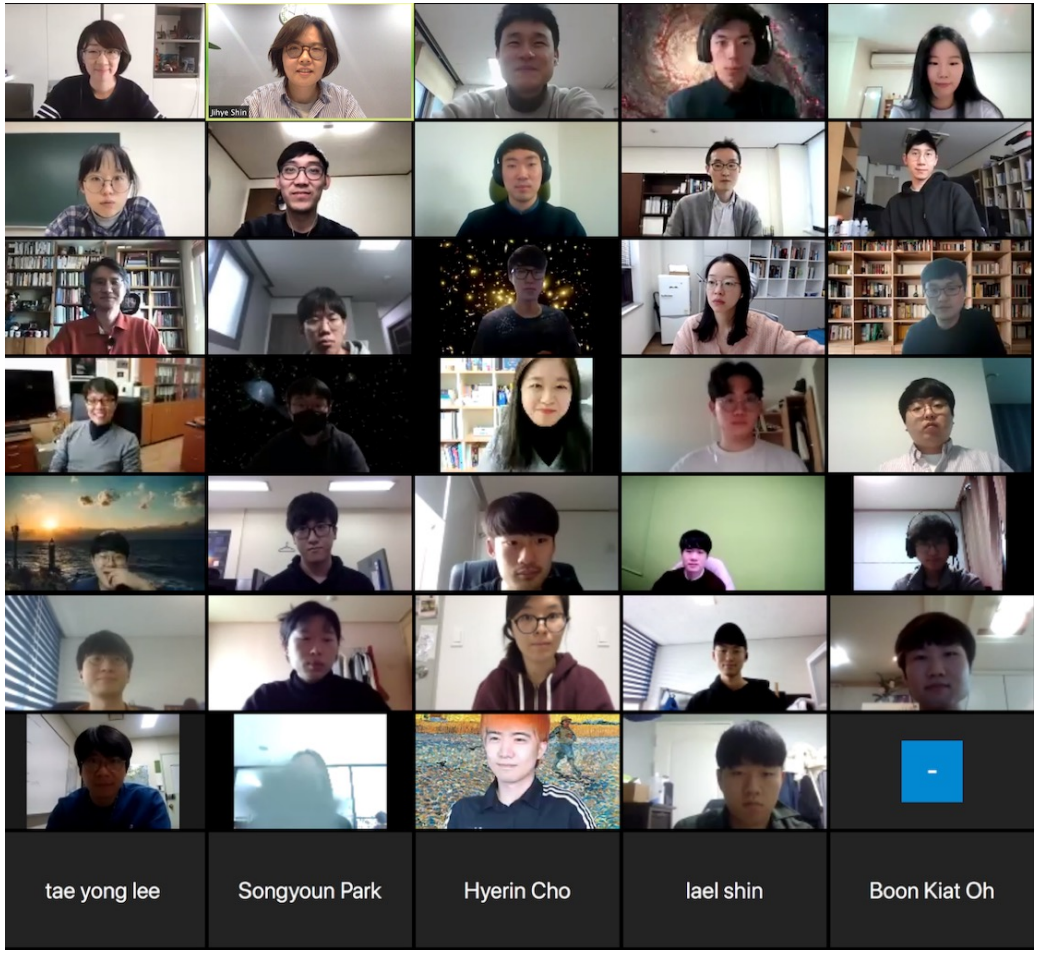
➔ **project name: DARWIN**

Numerical Galaxy Formation mini-workshop in Korea

1st - 2020.1.16

2nd - 2021.1.28

3rd - 2022. 1.25



DARWIN core members

PI: Jihye Shin

Co-PI: Jaehyun Lee

PM: Sungwook Hong

Oh-kyung Gwon

Juhan Kim

Taysun Kimm

Ji-hoon Kim

Hyunmi Song

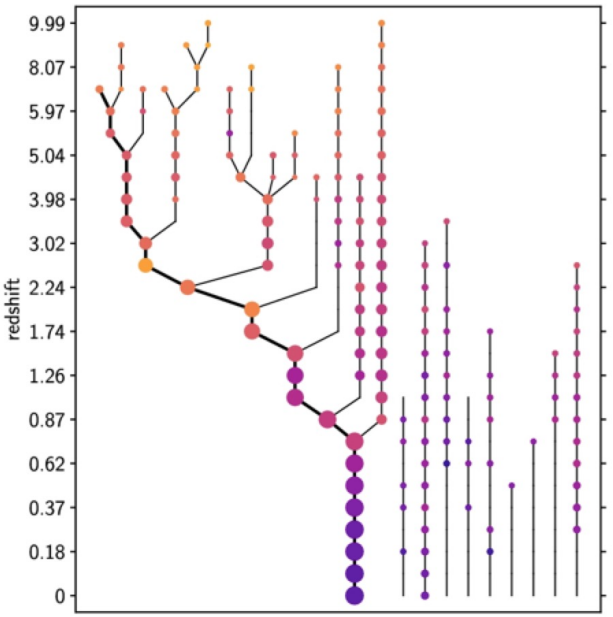
Ena Choi

Myoungwon Jeon

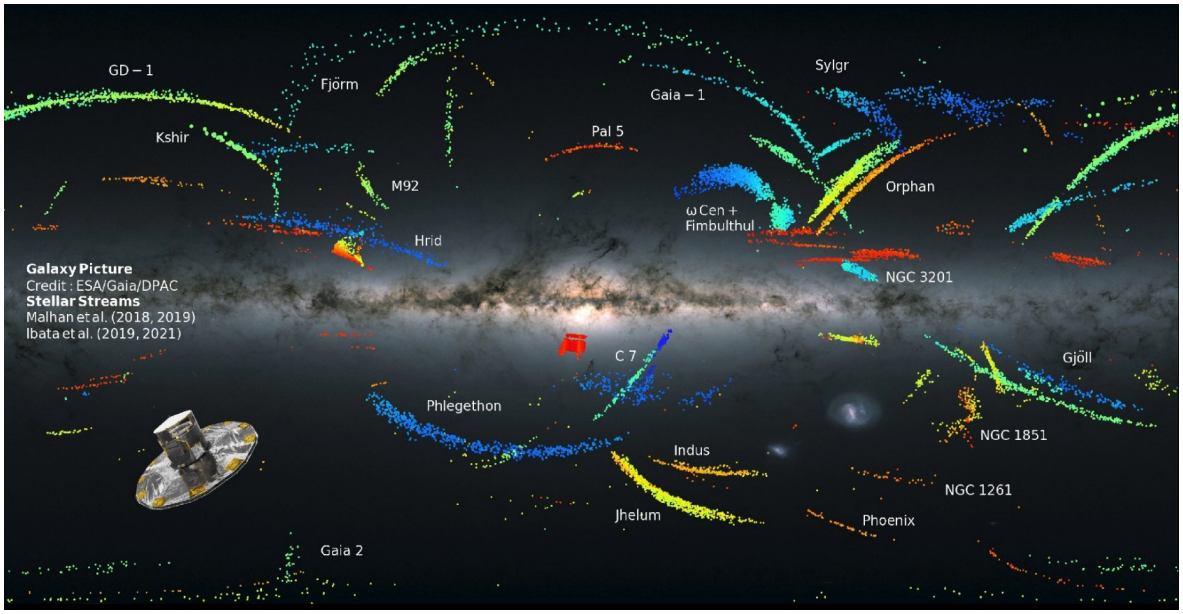
Yonghwi Kim

dwarf galaxy as target

Closely related to validity of the ΛCDM



Hierarchical merging

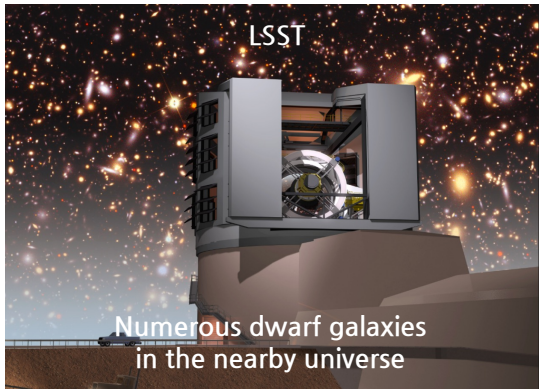


Tidal features of dwarf satellites merged with the Galaxy

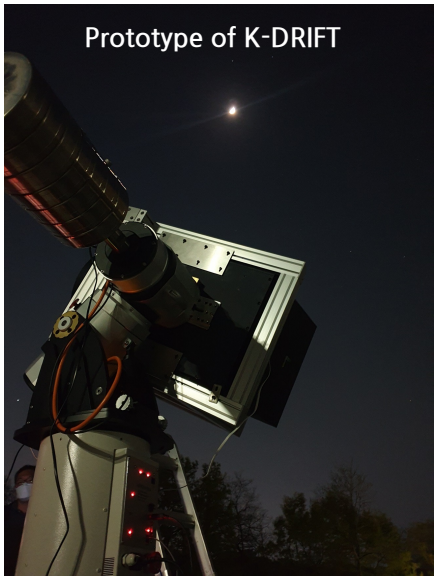
- Various origins of the dwarf galaxy: the larger scatter on mass-size relation for the more massive ($>10^{10}M_{sun}$)
  - Easily affected by baryonic physics due to the small gravitational well
- Observed properties of the dwarf galaxies: raise a crucial fundamental question about the validity of the ΛCDM

dwarf galaxy as target

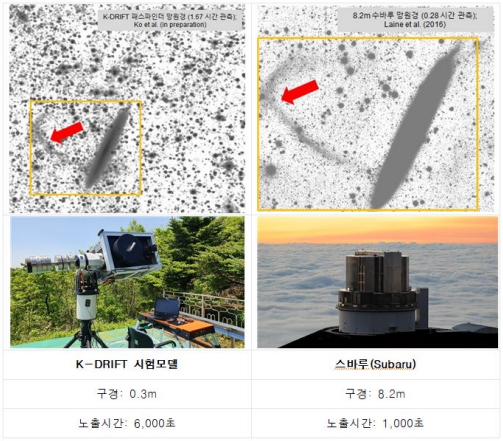
A key observation target for the next generation telescopes



➔ A new chapter in the study of dwarf galaxies in opening.



K-DRIFT
(KASI-Deep Rolling Imaging Fast-optics Telescope)



Ultra-diffuse galaxies in the nearby universe

dwarf galaxy simulation

Requirement for clarifying of the dwarf galaxy origin

- Theoretical model to interpret next-generation observations
- High resolution + precise baryonic physics + cosmological volume

  : challenging task in galaxy formation simulation

  ➔ the next-generation of the cosmological hydrodynamic simulation

한국천문연구원 Korea Astronomy & Space Science Institute

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경희대학교 KYUNG HEE UNIVERSITY

서울대학교 SEOUL NATIONAL UNIVERSITY

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KiSTi www.kisti.re.kr 한국과학기술정보연구원 Korea Institute of Science and Technology Information

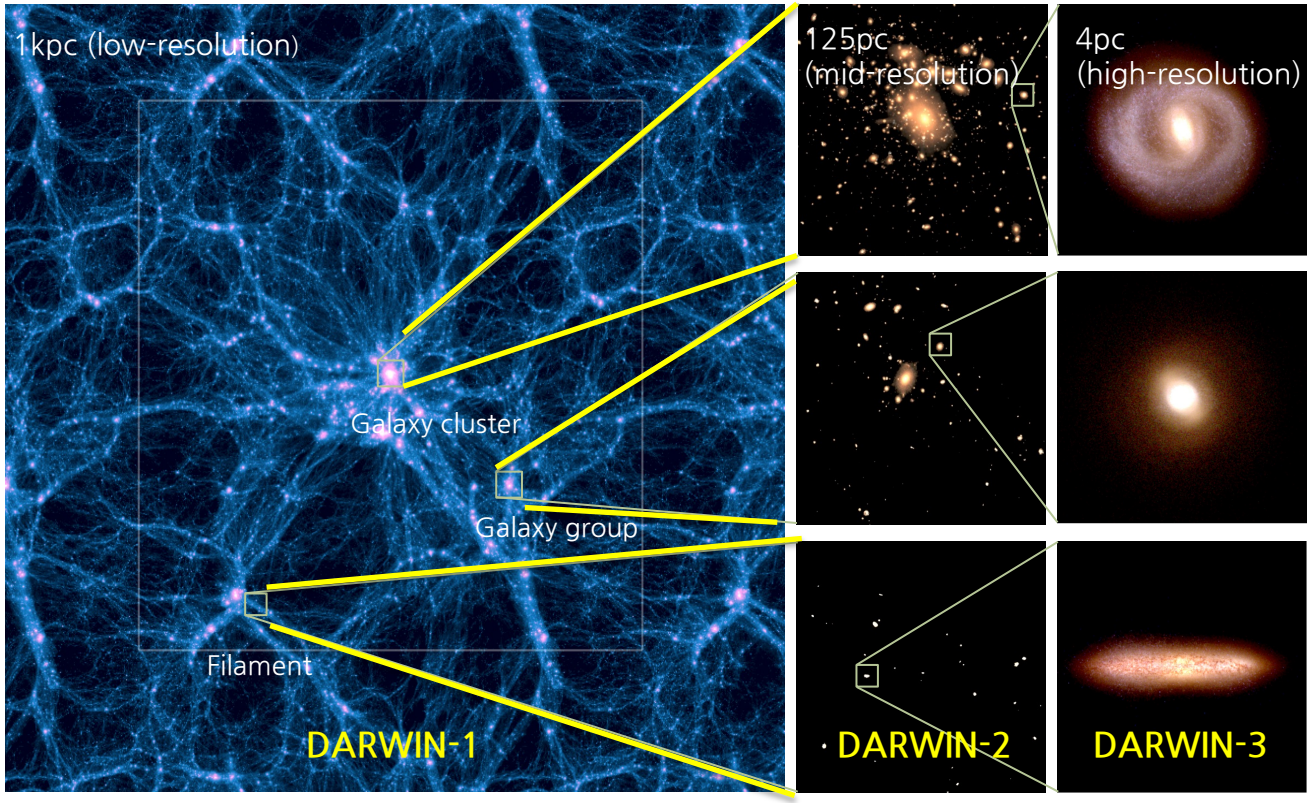
- Collaboration with Korean simulationists and HPC experts
- Utilizing experiences of the largest-scale simulations
- RAMSES-OMP optimized for the 5th Korean supercomputer
- GPU parallelization for the next-generation, the 6th supercomputer
- Implementation of high-precision baryonic physics
- Strategically designed three-step resolution simulations
- Achieving precision & statistics by using AI

DARWIN's strategy

Clarifying the formation origin of the dwarf galaxies using the DARWIN

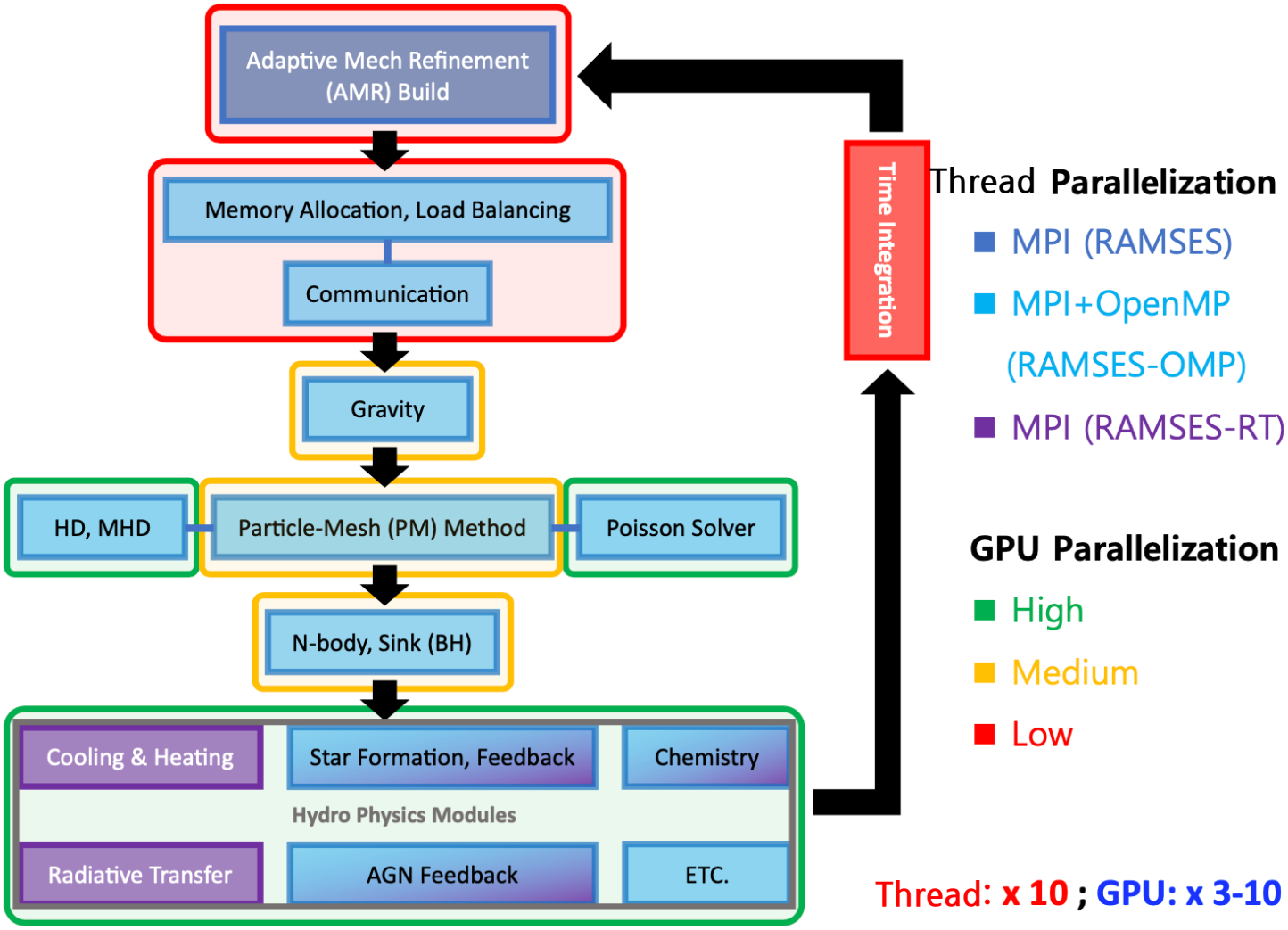
DARWIN: **DA**zzling **R**ealization of d**W**arf galaxies **I**n the **N**ext generation of cosmological hydrodynamic simulations

- High-resolution & large-volume simultaneously = 3-step resolution simulations & AI
- The highest-resolution simulation by the up-to-date baryonic
- Efficient utilization of exa-scale computing: massively-parallel supercomputer & hybrid parallelization



[1] development of optimized model for exa-scale computing

Development of RAMSES-OC (OMPCUDA)



[1] development of optimized model for exa-scale computing

Romain Teyssier

Joakim Rosdahl

Harley Katz

RAMSES → **RAMSES-RT** → **RAMSES-RTZ/PRISM**

Teyssier (2002) — **Rosdahl**, Blaizot, Aubert, Stranex, Teyssier (2013) — **Katz**, Kimm, Rosdahl..(2023)

Juhan Kim

MPI + OMP

Horizon Run 5

RAMSES-OMP

Lee, Shin et al. (2021)

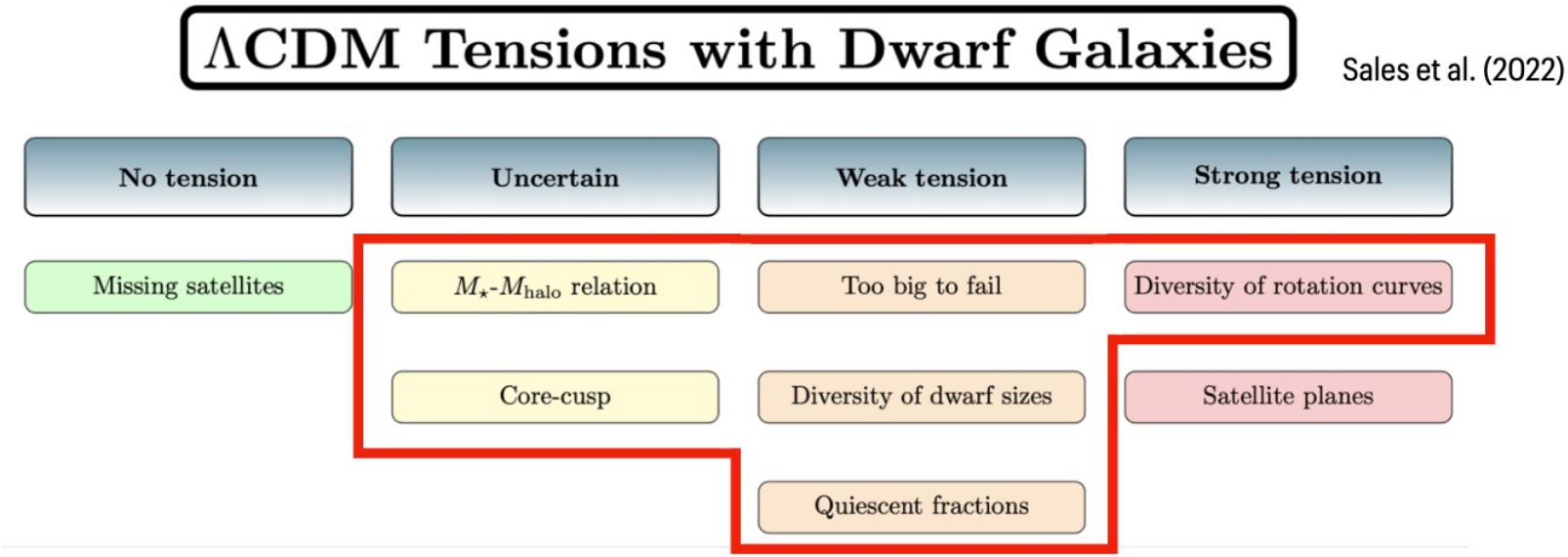
MPI + OMP + GPU

DARWIN

RAMSES-OC

Yonghwi Kim

[2] development of high-precision baryonic physics modules



➔ <u>Baryonic physics model in a self-consistent manner down to a several parsec scale</u>

= (Pop III + SN II + SN Ia + stellar winds, Gravo-thermmo-turbulent(GTT) SF model)

+ Cooling model - RAMSES-RTZ + PRISM + 4 pc resolution + large number of sample

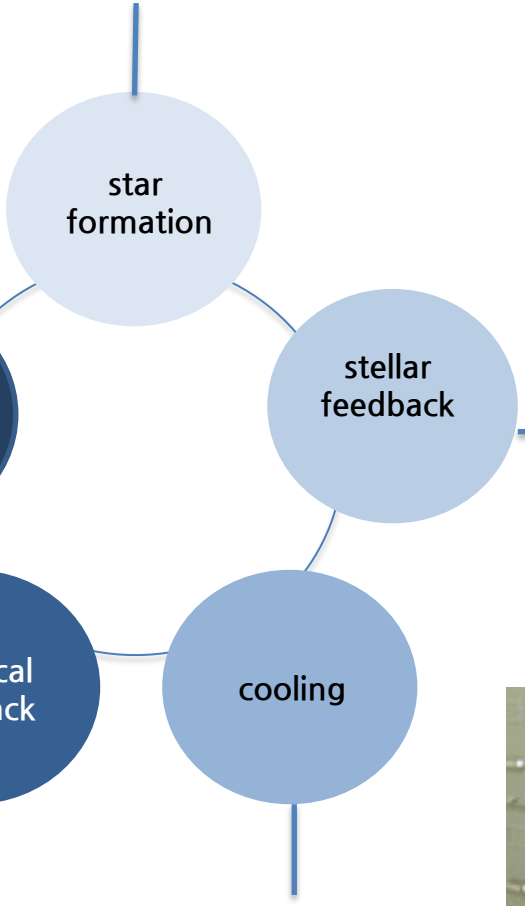
[2] development of high-precision baryonic physics modules

Ji-hoon Kim

Ena Choi

Gravo-thermo-turbulent (GTT) SF model
(Kimm et al. 2017, Applebaum et al. 2020)

Taysun Kimm



AGN feedback model and its indirect effects on dwarf galaxies
Dubois et al. 2020, Volonteri et al. 2020

Mechanical SN feedback model
Kimm et al. 2017

Myongwon Jeon

Chemical model optimized for dwarf galaxies
Heger & Woosley (2002,2010)

Gas cooling based on TIGRESS and PRISM Frameworks
Koyama & Inutsuka (2022)
Katz & Kimm et al. (2023)

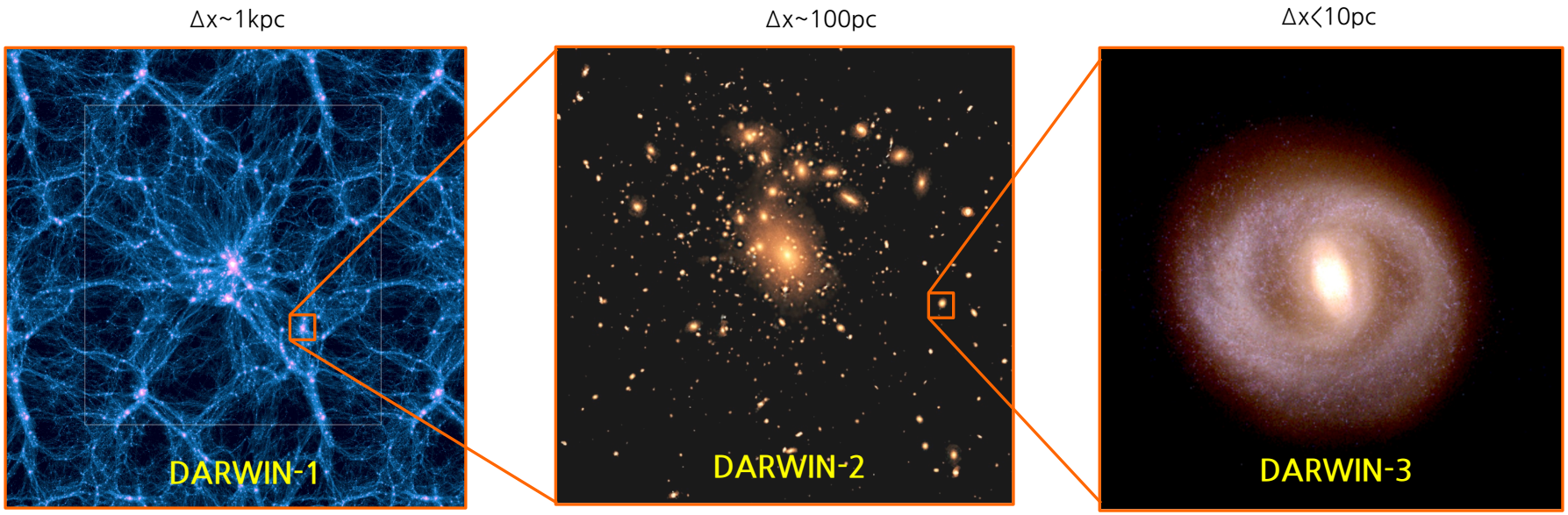
Jeong-Gye Kim

Yonghwi Kim

[3] a set of three different resolution runs, DARWIN

Three-stage run, DARWIN

	resolution	target region	features
DARWIN-1	1kpc	$(\sim 130\mathrm{Mpc})^3$	- Describing various galaxies in various environments - Searching for candidate regions of the DARWIN-2
DARWIN-2	125pc	Selected environment from DARWIN-1	- Describing various galaxies in several selected environments - Describing formation/evolution of dwarf galaxies - Searching for candidate dwarf galaxies of the DARWIN-3
DARWIN-3	4pc	Selected dwarf galaxies from DARWIN-2	- Describing ISM and internal structures of dwarf galaxies - Internal/external origin of various features of dwarf galaxies - Securing of theoretical data approaching puzzles on dwarf galaxies

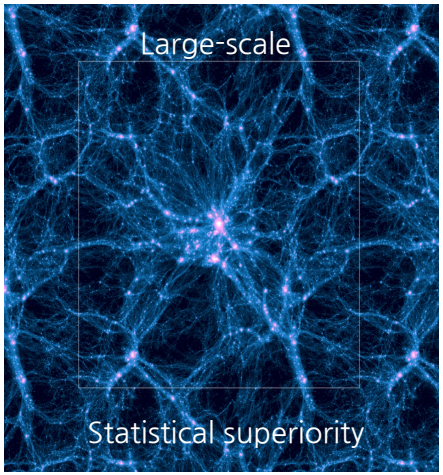


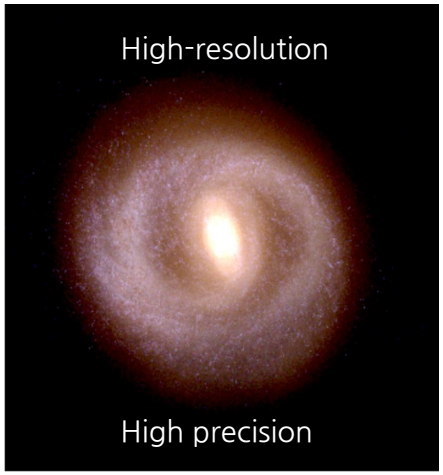
[4] data analysis using AI

Three-stage run, DARWIN

	resolution	Target region	Strength	weakness
DARWIN-1	1kpc	~ $(130\text{Mpc})^3$	Statistical analysis	Inability to describe dwarf galaxies
DARWIN-2	125pc	~ $(30\text{Mpc})^3$	Coevolution of dwarf galaxies and the cosmic web	Reduced reliability of statistical analysis
DARWIN-3	4pc	~ $(3\text{Mpc})^3$	Most realistically describe the dwarf galaxies	Inability to perform statistical analysis

- Many remaining questions about the formation/evolution of the structure of the universe
  : both “large-scale” and “high-resolution” is essential
- Impossible in the next 10 years to achieve ‘statistical superiority’ and ‘high precision’ simultaneously





Ji-hoon Kim

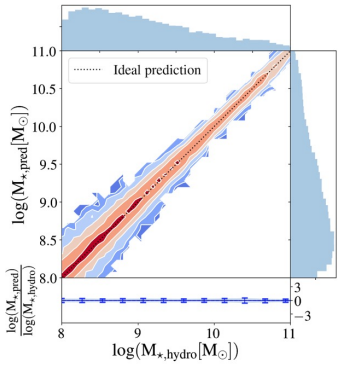
➔ artificial intelligence/machine learning

[4] data analysis using AI

Supplement of the low-resolution simulation

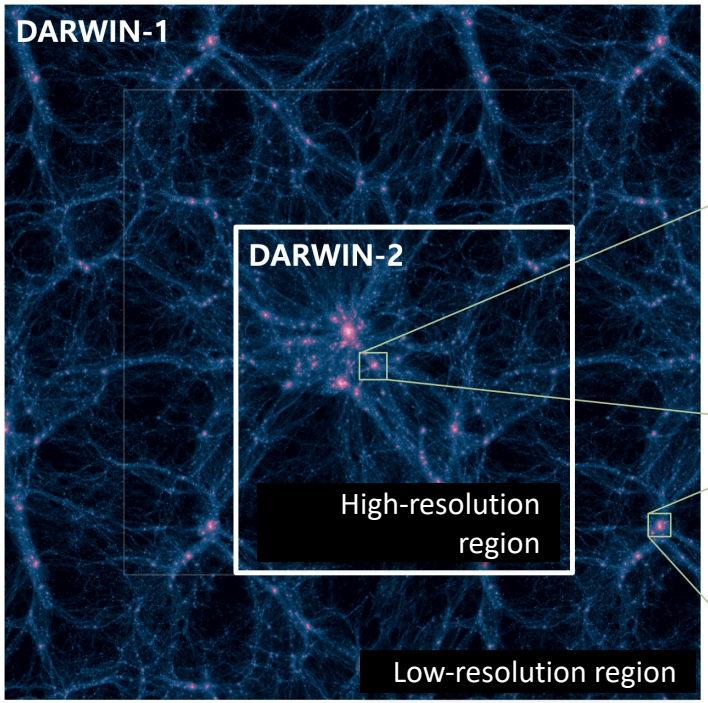
- Training from overlapped region between DARWIN-1 and DARWIN-2
- Implementing AI's prediction in the low-resolution region outside the DARWIN-2
- **Deriving de facto high-resolution results in DARWIN-1**

Validation of prediction

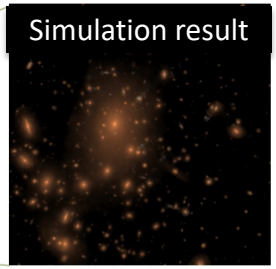


Jo & Kim (2019)

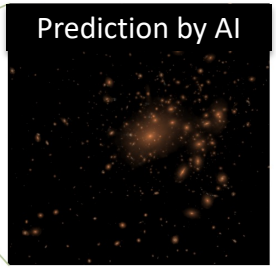
Multi-resolutions



Simulation result



Prediction by AI



AI model associating low- and high-resolution results

Trained AI

apply

Predicting high-resolution results based on low-resolution results

Trained AI

[5] studies on formation/evolution of dwarf galaxies

Research topics related to dwarf galaxies using the DARWIN

- Correlation between the diversity of dwarf galaxies and large-scale structures
- Formation/evolution channels of mysterious dwarf galaxies: ultra-diffuse galaxies, ultra-compact dwarfs
- Tracing the earliest star remnants in our Milky Way dwarf galaxies
- Relationship between primordial galaxies and supermassive black holes in the early universe
- Effects of ram pressure and hydrodynamic effects on dwarf galaxies
- Tracing the characteristics of stars and galaxies that first appear in the universe
- Internal evolution of gas instability and the impact of environmental factors
- Lyman-alpha properties of dwarf galaxies and emission/absorption lines to be compared with observations
- AI modelling to trace history of dwarf galaxies from observational characteristics of dwarf galaxies

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

➔ Maximizing synergy through collaboration with observation experts

Schedule for the DARWIN project