KIAS Workshop on Cosmology and Structure Formation



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

Jihye Shin

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Background image: Horizon Run 5 (Lee & Shin et al. 2021)

DARWIN project

- Aim: simulating the **formation and evolution of dwarf galaxies** in a cosmological context using gigantic computing resources
- Support: ‘advanced utilization of Korean supercomputer’ program
- Budget: 3.5 million dollars during 4.5 years (2022-2027)
- Collaboration: 16 young scientists from 7 institutes



DARWIN core members

Horizon Run 5 members



PI: Jihye Shin



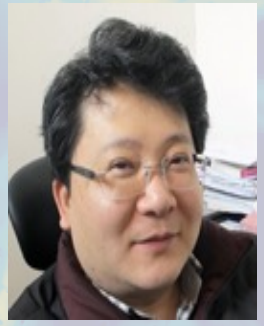
Co-PI: Jaehyun Lee



PM: Sungwook Hong



Yonghwi Kim



Juhan Kim



Oh-kyung Kwon



Myoungwon Jeon



Taysun Kimm



Ji-hoon Kim



Ena Choi



Hyunmi Song

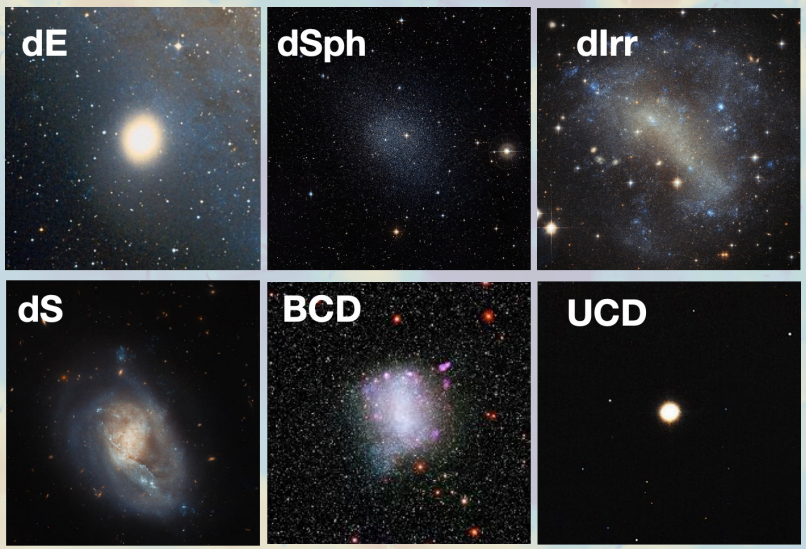


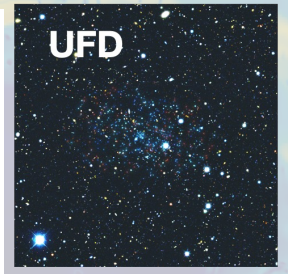
Kyoungwon Chun

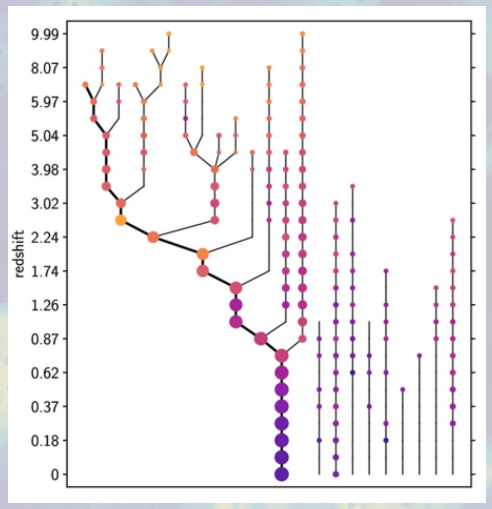
Dwarf galaxy as DARWIN's target

- The smallest galaxy type (10^4 – 10^9 M_{sun})
- Building blocks of massive galaxies and cosmic large-scale structures
- **<u>Diversity in types and characteristics</u>**
  - sensitive to internal physics
  - environmental effects

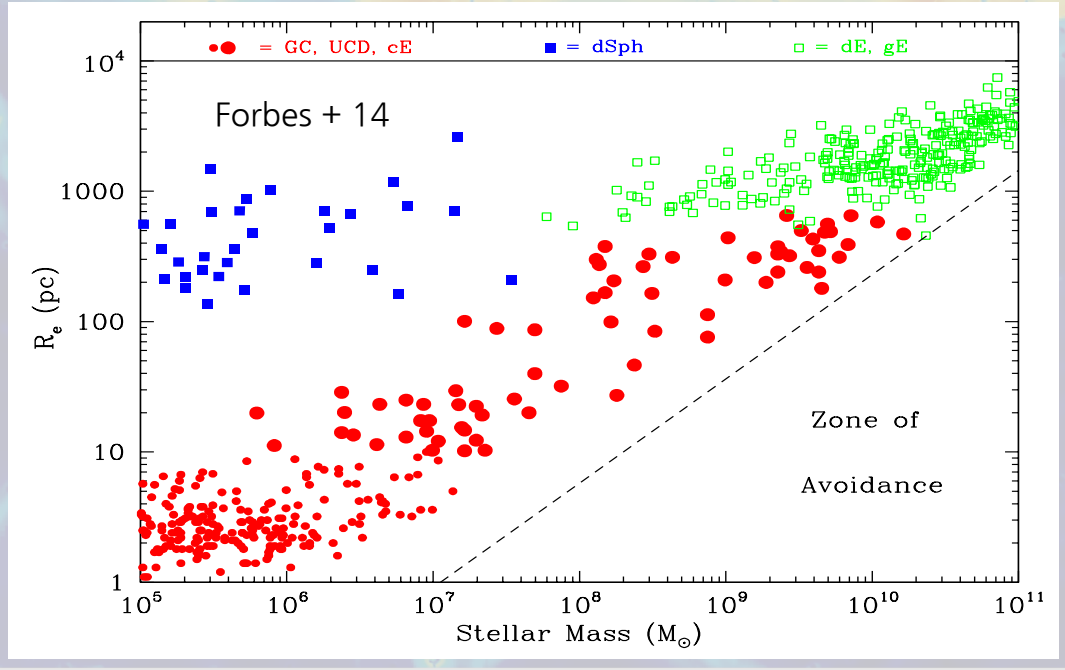
various types of dwarf galaxies







Hierarchical merging

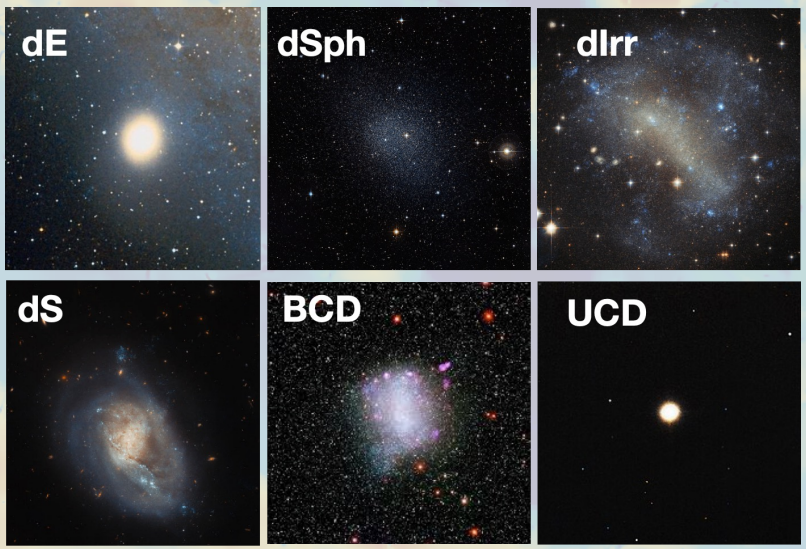


Sales + 22

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various types of dwarf galaxies



ΛCDM Tensions with Dwarf Galaxies

No tension	Uncertain	Weak tension	Strong tension
Missing satellites	$M_\star$-$M_{\rm halo}$ relation	Too big to fail	Diversity of rotation curves
	Core-cusp	Diversity of dwarf sizes	Satellite planes
		Quiescent fractions	

Sales + 22

DARWIN's strategies

- Required conditions to describe dwarf galaxies

  : a very wide dynamic range is necessary (~10^6)

  - effective radius $R_{1/2} \lesssim$ 1kpc: resolution $\lesssim$ 0.1kpc

  - diversity across different environments: volume ~ $(100\mathrm{Mpc})^3$

S1. **Efficient utilization of exa-scale computing**

- massively-parallel supercomputer (MPI + OpenMP + CUDA/OpenACC)

S2. **Three-step zoom-in simulation**

- aggressive application of the zoom-in technique

S3. **Implementing ML's prediction**

- deriving high-resolution galaxy properties, hybrid calculation (ML on-the-fly)

S4. **High-precision baryonic physics**

- self-consistent manner down to several parsec scale

S1. Exa-scale computing



Romain Teyssier



Joakim Rosdahl



Harley Katz

RAMSES (**Teyssier** (2002)) → + Radiative Transfer → **RAMSES-RT** (**Rosdahl**, Blaizot, Aubert, Stranex, Teyssier (2013)) → + Chemistry → **RAMSES-RTZ/PRISM** (**Katz**, Kimm, Rosdahl..(2023))

MPI + OpenMP



Juhan Kim

RAMSES-OMP

Horizon Run 5

MPI+OpenMP+CUDA/OpenACC

RAMSES-DARWIN-OC

DARWIN



Yonghwi Kim



Oh-kyoung Kwon

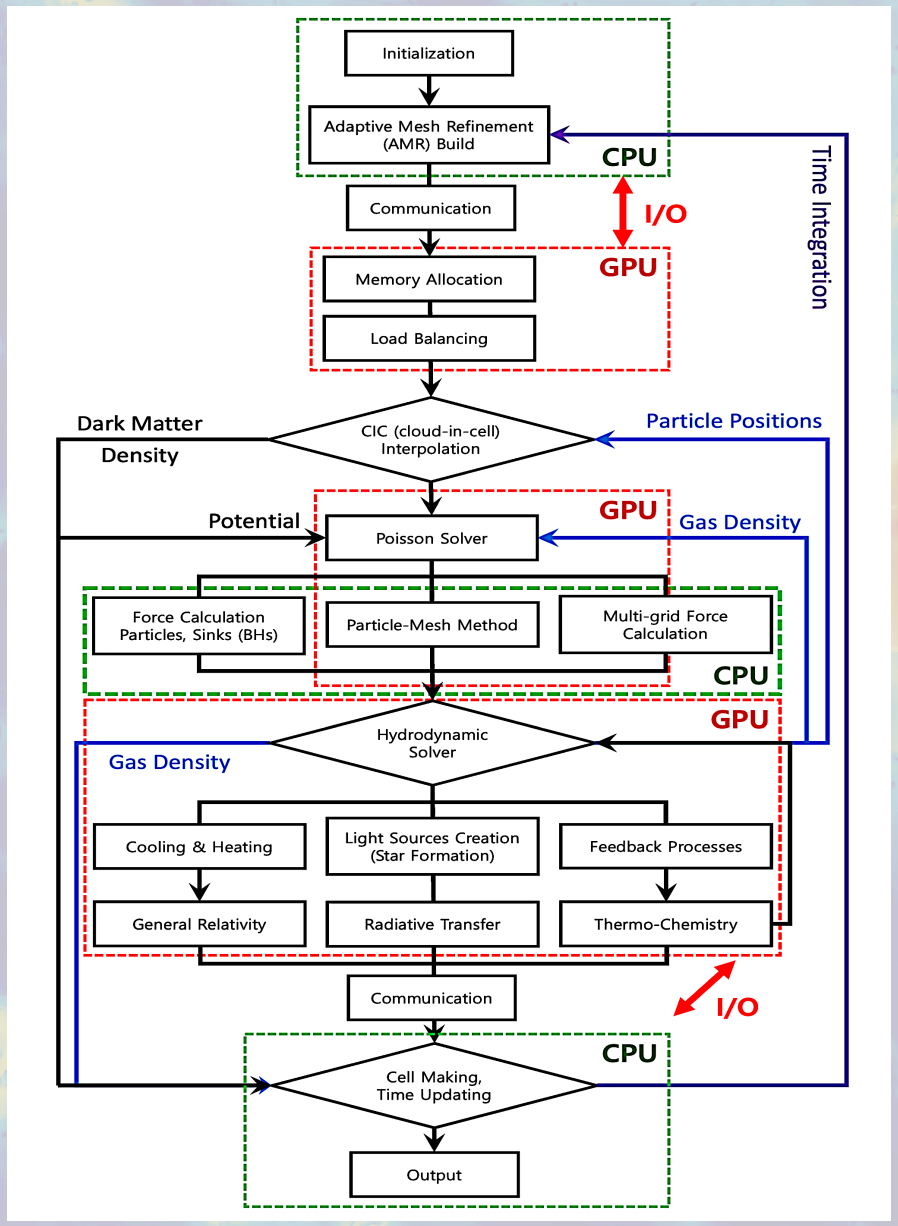
5th supercomputer (based on manycore CPUs)

6th supercomputer (two GPUs for each node, 600Pflops)

2024 2025 2026 2027 2028

S1. Exa-scale computing



RAMSES-DARWIN-OC (OMPCUDA)

- Loop parallelization (w/ OpenMP) can be easily ported using OpenACC.
- Core parts (AMR, Poisson, PM) will be using CUDA Fortran.
- Dynamics (80k lines) : mainly CUDA
  - AMR – CUDA / OpenACC
  - Load balancing – OpenACC
  - Poisson – CUDA
  - PM – CUDA / OpenACC
  - I/O
- Physics (50k lines) : mainly OpenACC
  - N-body / Tree – OpenACC / CUDA
  - Hydro – OpenACC / CUDA
  - ETC – OpenACC / CUDA

S1. Exa-scale computing

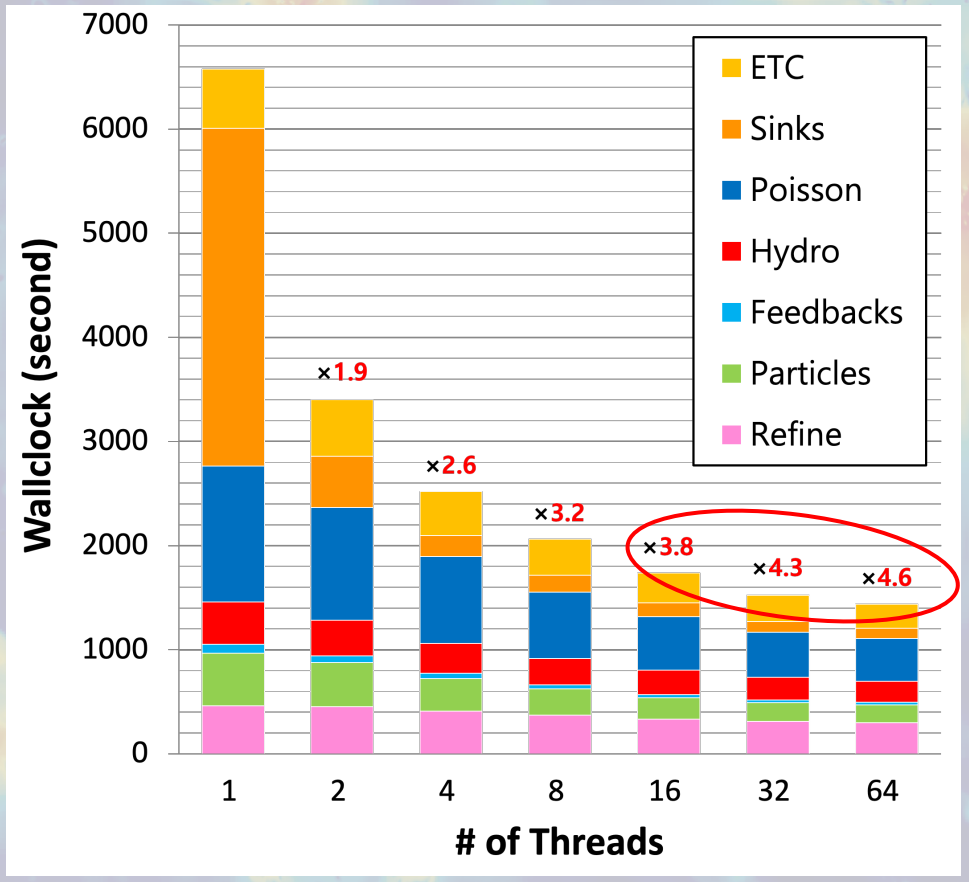



IC: 32^3 Mpc^3 with 512^3 grids (levels 9-16)

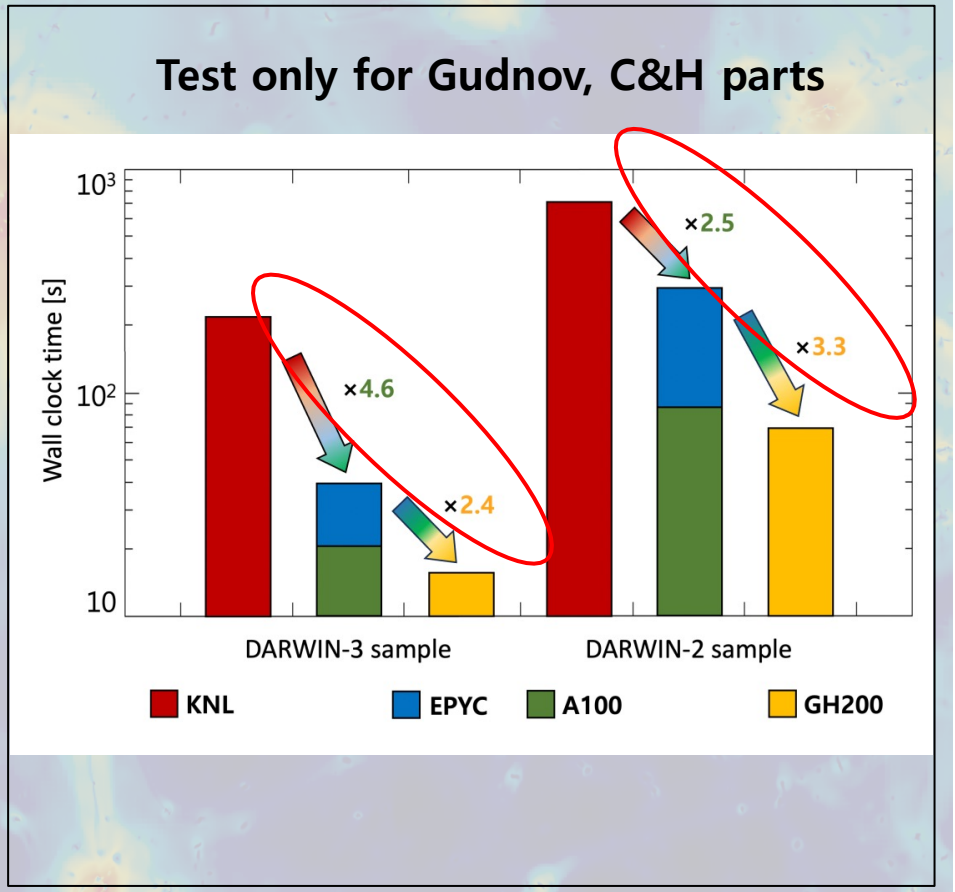
# of MPI tasks = 1024

# of OMP threads = 1, 2, 4, 8, 16, 32, 64

# of nodes = 16, 32, 64, 128, 256, 512, 1024



RAMSES-DARWIN (MPI + OMP)



RAMSES-DARWIN (MPI + OMP + GPU)

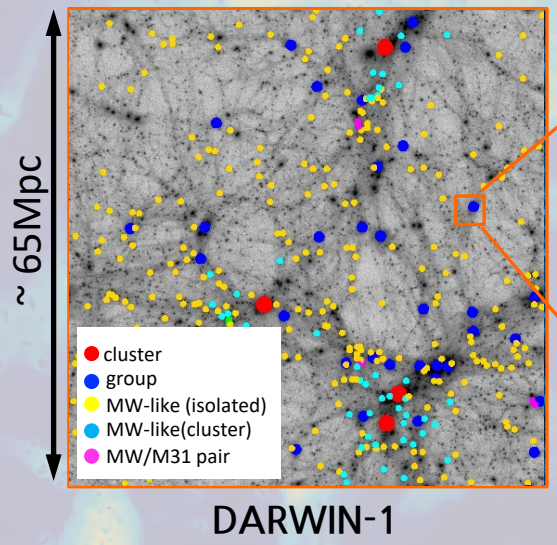
S2. 3-step zoom-in simulation

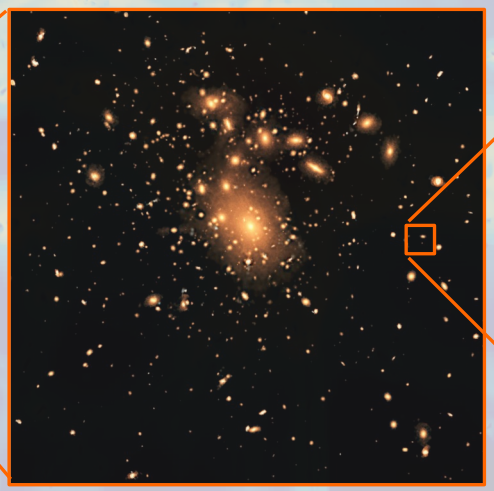


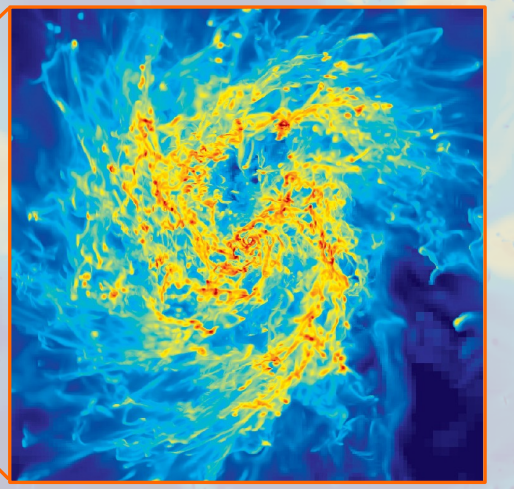

Δx=500pc

Δx=125pc, 62.25pc

Δx=4-8 pc







DARWIN-1

DARWIN-2

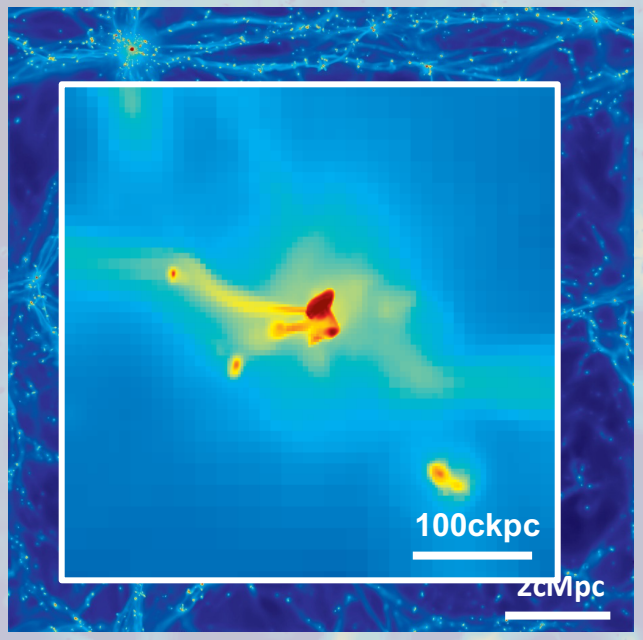
DARWIN-3

	spatial res.	star mass res.	volume	feature
DARWIN-1	500pc	10^5 M_{sun}	$(\sim 65Mpc)^3$	various galaxies in various environments
DARWIN-2	125pc, 62.25pc	$2x10^3$ M_{sun}	$(5\text{-}20Mpc)^3$	formation/evolution of dwarf galaxies in various env.
DARWIN-3	4-8pc	$1x10^3$ M_{sun}	$< (1Mpc)^3$	ISM and internal structures of dwarf galaxies

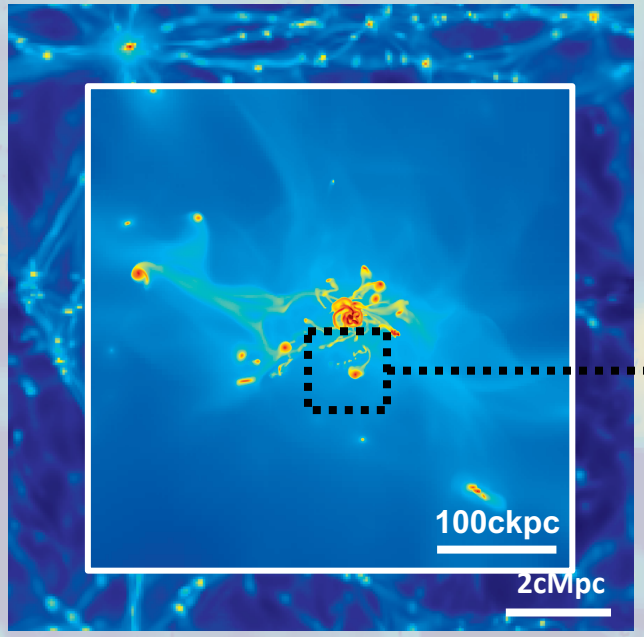
S2. 3-step zoom-in simulation



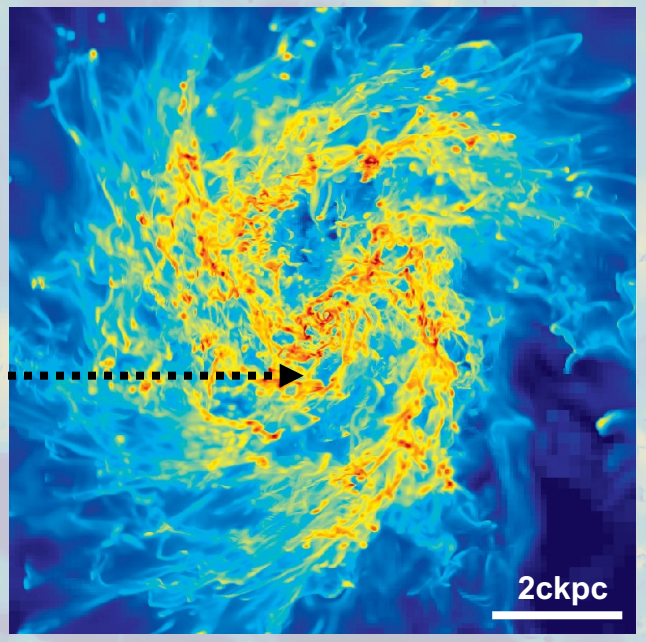

DARWIN-1 analogue (Δx= 500pc)



DARWIN-2 analogue (Δx=125, 62.5pc)



DARWIN-3 analogue (Δx=16pc)

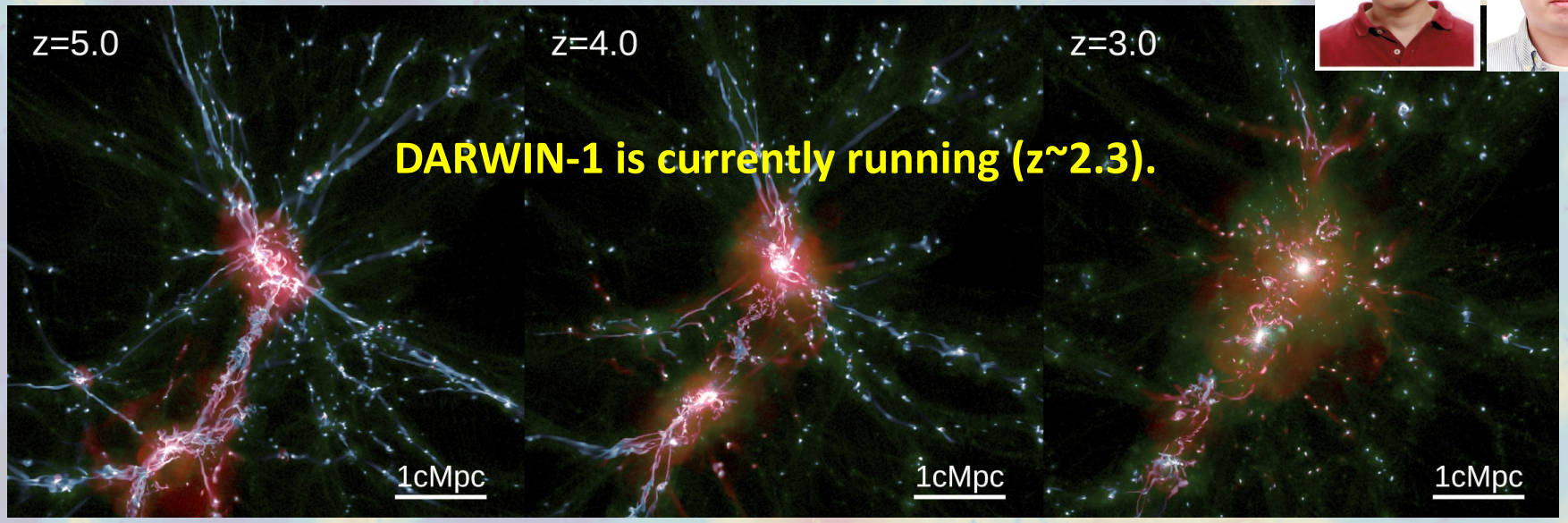


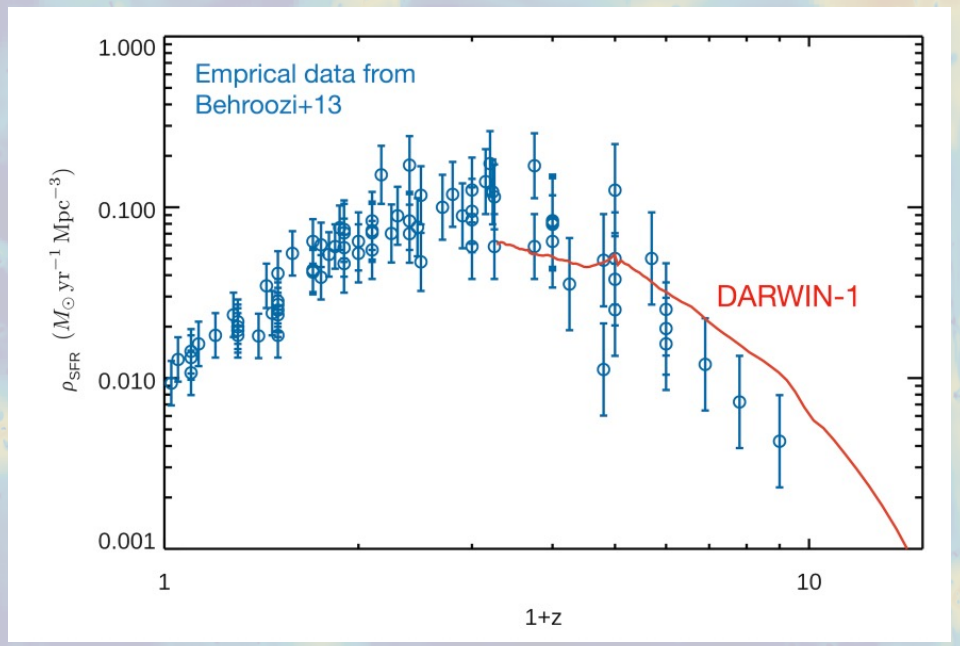
< Resolution difference of DARWIN-1, -2, and -3 >

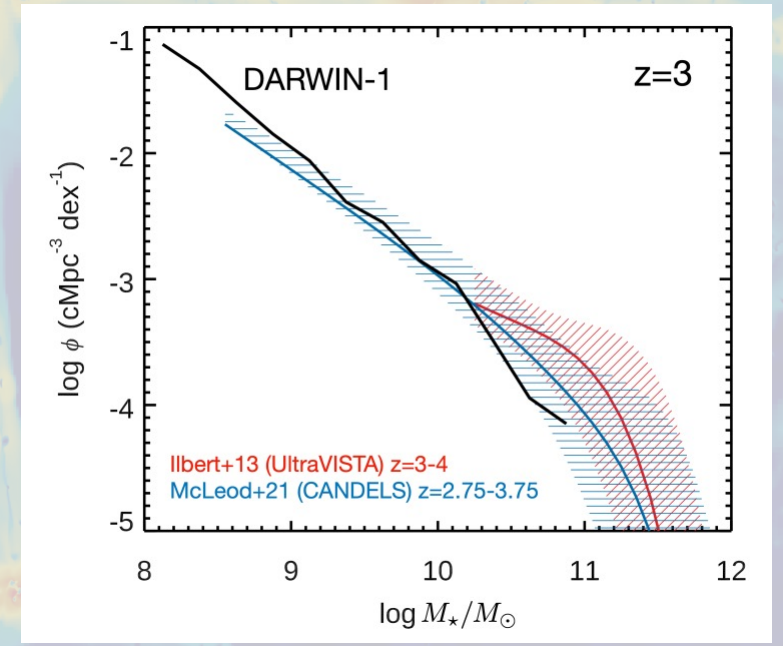
DARWIN-1	Detailed internal properties of galaxies (roughly $M_{star} \gtrsim 3 \times 10^7 M_{sun}$) in various environments
DARWIN-2	Formation of dwarf galaxies (global: $M_{star} \gtrsim 10^5 M_{sun}$, internal: $M_{star} \gtrsim 10^6 M_{sun}$) in various environments
DARWIN-3	ISM and formation of internal structures of dwarf galaxies

S2. 3-step zoom-in simulation



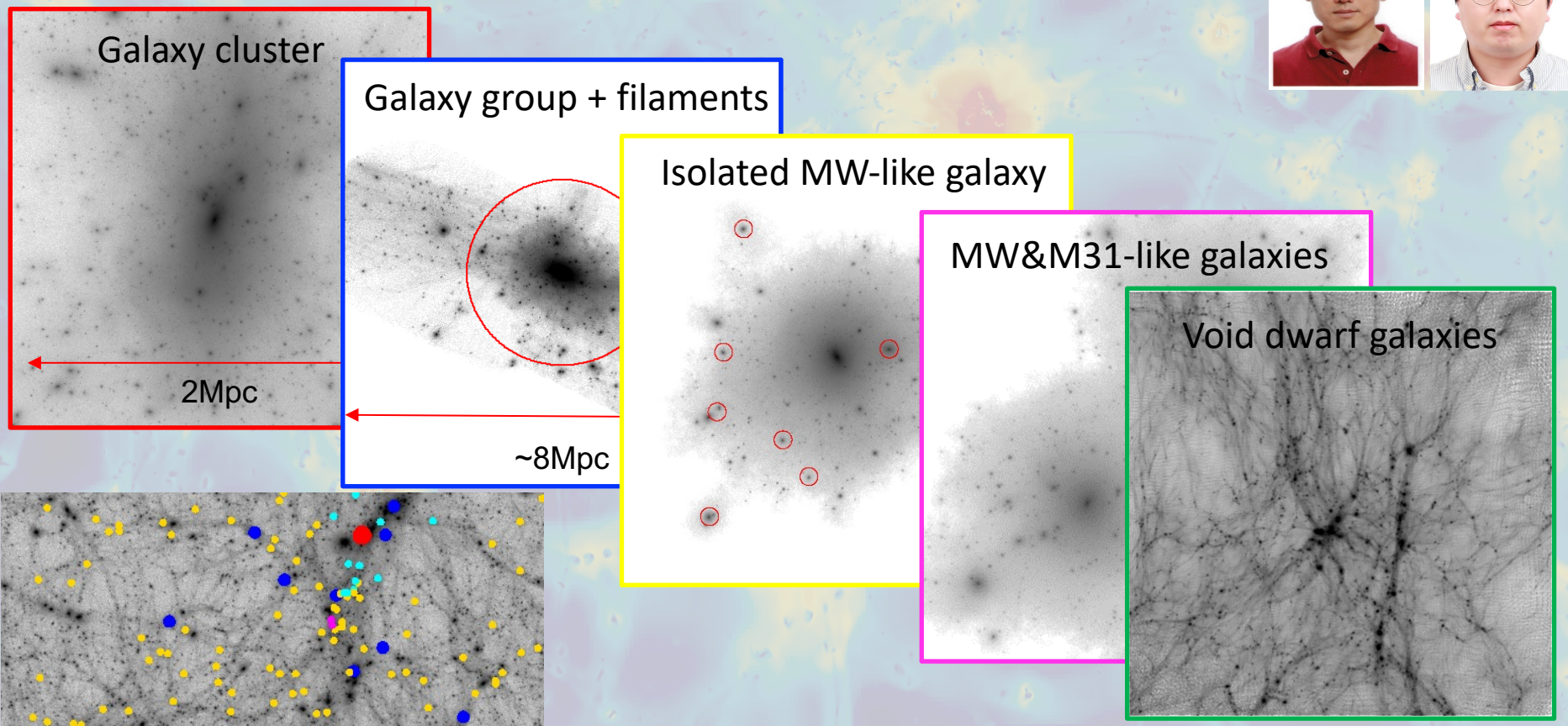



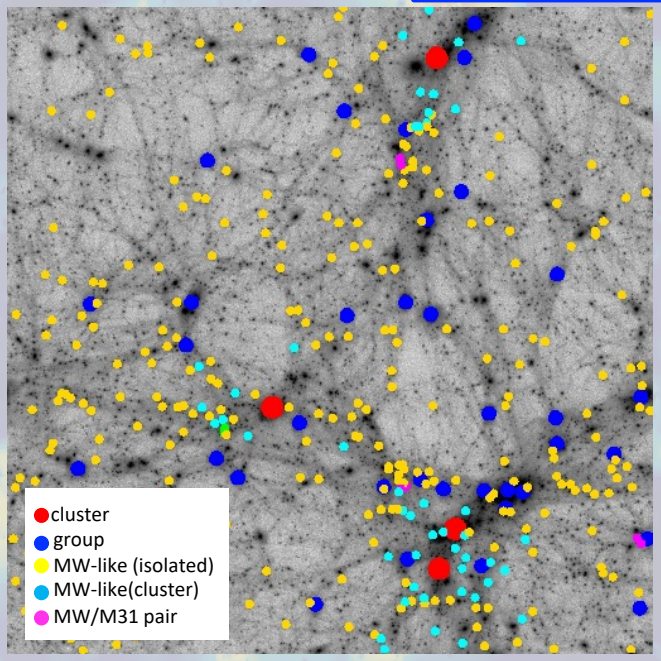




S2. 3-step zoom-in simulation





DARWIN-1-DMonly

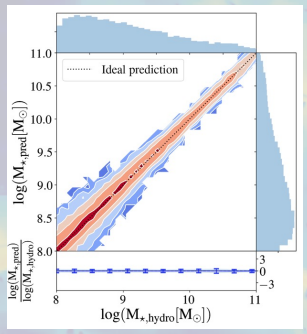
Target regions of DARWIN-2	Mass range	# of sim.
Galaxy cluster	1~2 x 10^{14} M_{sun}	1 (or 0)
Galaxy group + filaments	1~5 x 10^{13} M_{sun}	5~10
MW-like galaxy (LG-like)	1~3 x 10^{12} M_{sun}	> 20
Field (or isolated dwarfs)	< 10^{12} M_{sun}	> 100

S3. Prediction with AI

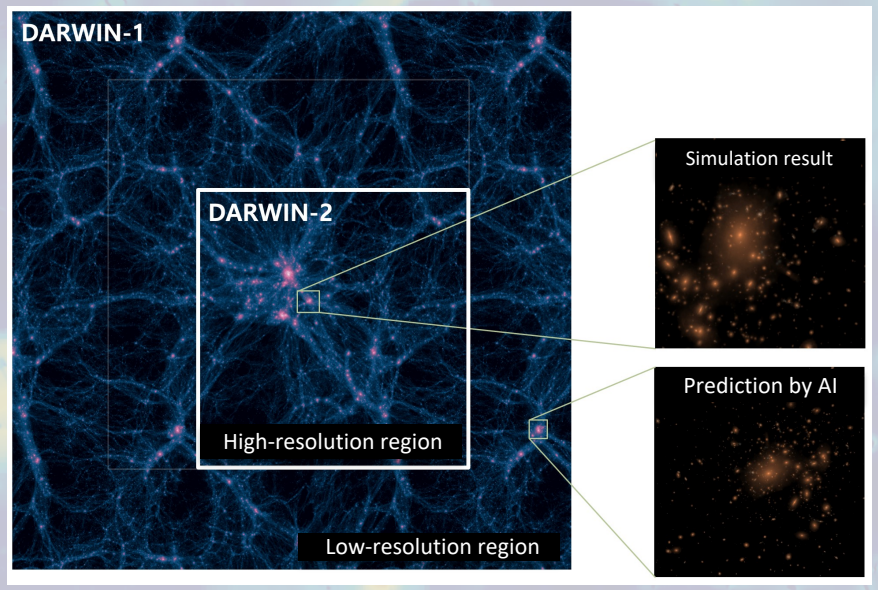


	spatial res.	strength	weakness
DARWIN-1	500pc	statistical analysis	inability to describe dwarf galaxies
DARWIN-2	125pc, 62.25pc	dwarf galaxies in various environments	reduced reliability of statistical analysis
DARWIN-3	4-8pc	most realistically describe the dwarf galaxies	inability to perform statistical analysis

- Training from overlapped region between DARWIN-1 and DARWIN-2
- Implementing AI prediction in the low-resolution regions
- **<u>Deriving de facto high-resolution results in the entire region of DARWIN-1</u>**
- Preliminary study using TNG were recently published (Jung+24)



Jo & Kim (2019)



AI model associating low- and high-resolution results

Trained AI

validation

apply

Trained AI

Predicting high-resolution results based on low-resolution results

S4. High-precision baryonic physics



Ji-hoon Kim



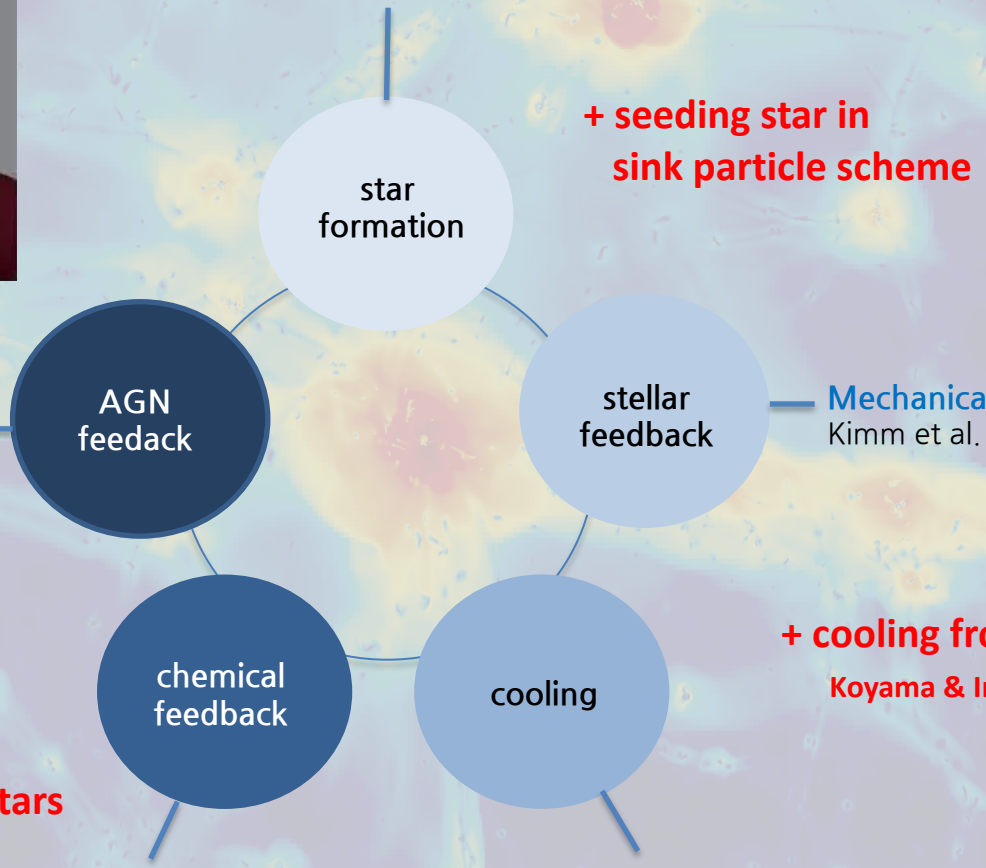
Ena Choi



Taysun Kimm



Myongwon Jeon



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

+ seeding star in sink particle scheme

Mechanical SN feedback model
Kimm et al. 2017

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

+ AI model for 'central engine'

+ cooling from TIGRESS
Koyama & Inutsuka 2002

+ PoP III stars

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

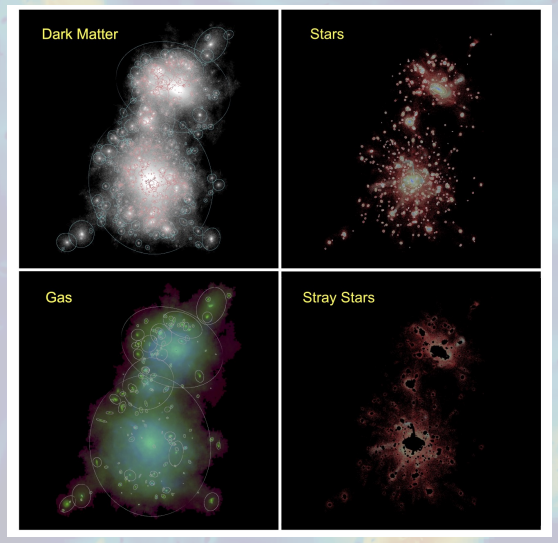
Gas cooling based on PRISM
Katz & Kimm et al. (2023)

➔ RAMSES-RTZ + TIGRESS/PRISM cooling model + stars seeded in sink scheme + AI model + Pop III + SN II + SN Ia + stellar winds + 4 pc resolution + large number of sample

DARWIN's output







Snapshots : 300 from z=200 to 0

Halo/galaxy catalog: Pgalf (PSB-based Galaxy Finder)

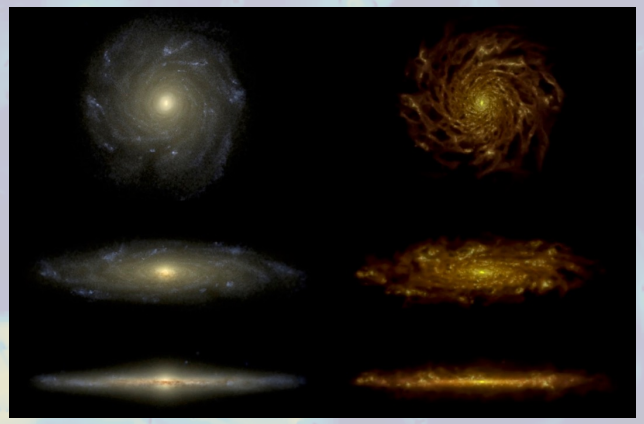
- developed by Juhan Kim

- gravitationally self-bound and tidally stable

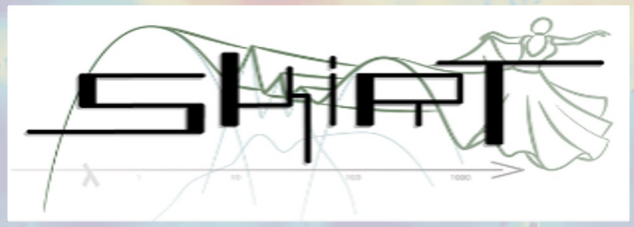
Mock image: SKIRT and/or Powderday

Cosmic web: DisPeRSE

Optical Far-infrared



A galaxy with different viewing angles (from SKIRT homepage)



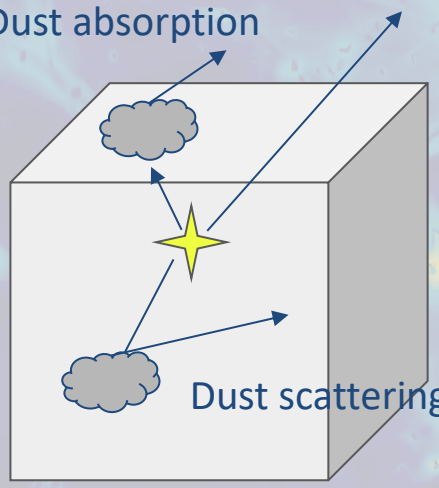
An Advanced Dust Radiative Transfer code (Camps & Baes 2014)

- multi-wavelength (0.1-1000 um)
- images viewed at different angles
- **customized for various instruments**

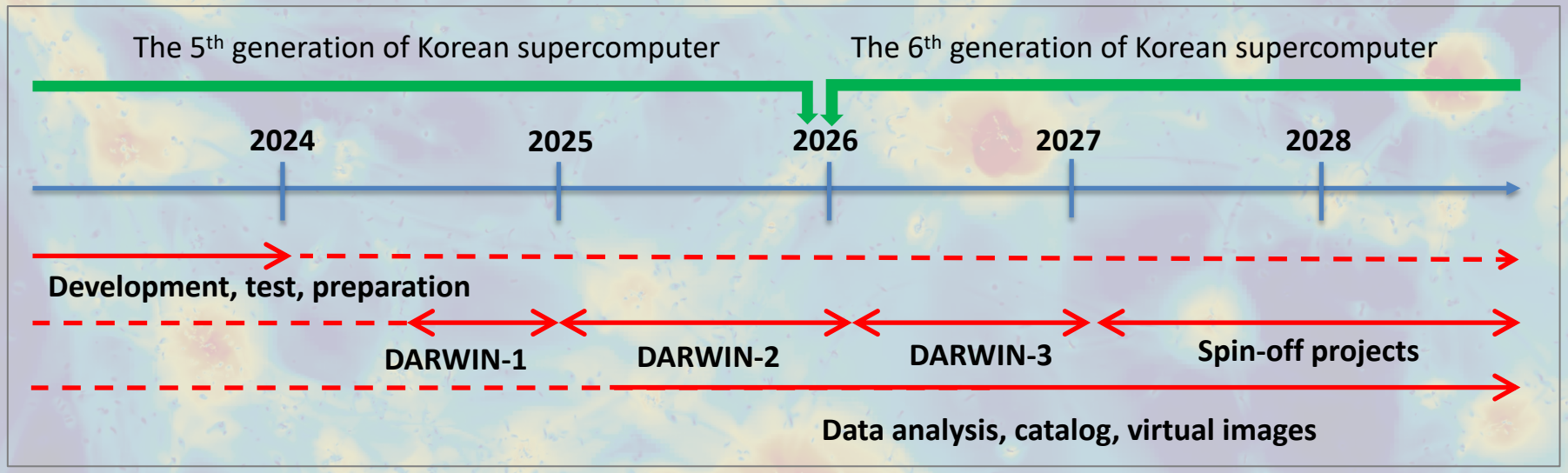
  :K-DRIFT, LSST, JWST, SKA, HST, etc.

Emission from Single Stellar Population

Dust absorption



DARWIN's timeline



- rotation curve to be compared with SKA
- mock images targeting JWST, LSST, K-DRIFT, Euclid, SKA
- mock spectra, absorption/emission lines
- Lyman-alpha properties of dwarf galaxies, reionization
- exotic tidal and/or ram-pressure features of void dwarfs
- origin of exotic dwarf galaxies: UFD, UDG, UCD, etc.
- origin of diverse characteristics of dwarf galaxies: mass-size, luminosity-metallicity, etc.

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

➔ Maximizing synergy through collaboration with observation experts

Thank you very much.