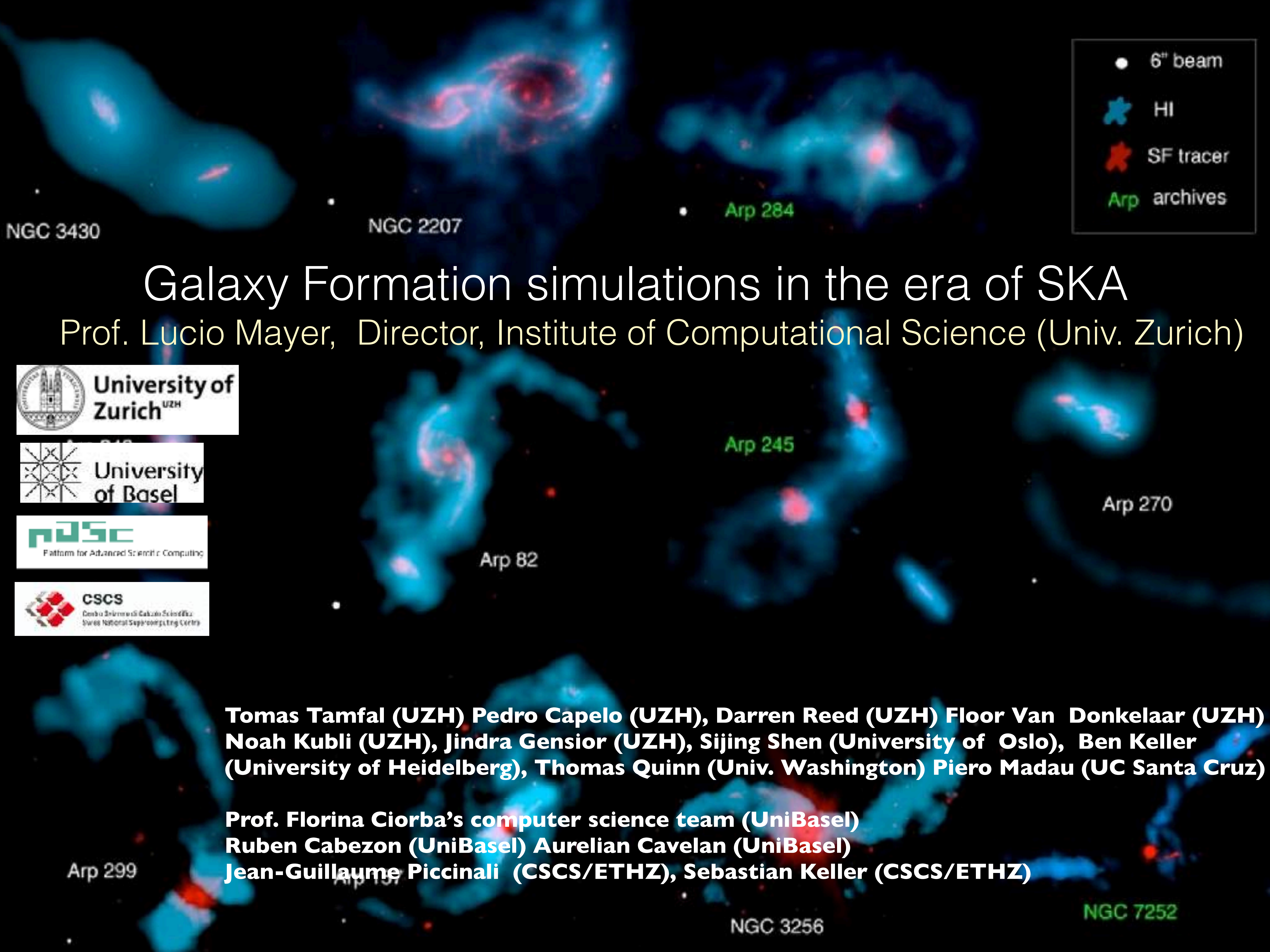

Galaxy Formation simulations in the era of SKA

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Simulations of galaxy formation and SKA

Central theme: **HI in galaxy evolution**

SKA1: HI to z=1; SKA2: to z=2—3 (potentially)
Pathfinder observations from precursors, eg MIGHTEE-HI Meerkat Survey (up to z ~ 0.6, see Maddox et al. 2021)

HI in galaxy evolution encompasses a rich phenomenology at various scales that simulations will need to capture:

- **()inside galaxies**: HI phase in cold star forming disk, ~ 1kpc scales

- **()around galaxies**:cold neutral phase in Circumgalactic Medium (CGM) 10-100 kpc scales

- **()between galaxies**: cold filaments/flows feeding galaxies from intergalactic cosmic web (100 kpc to Mpc scales)
  AND gas stripped from galaxy satellites as signature of environmental effects (ram pressure, tidal interactions, etc..)

At the Institute of Computational Science (ICS) of the University of Zurich we carry out galaxy formation simulations on all scales as well as dark matter-only state-of-the-art cosmological simulations (eg EUCLID Flagship Simulations, Potter et al. 2017)

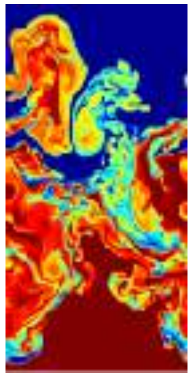
Four different SPH and AMR cosmological hydro codes developed within international collaboration frameworks: **ChaNGa, GASOLINE2, GIZMO, RAMSES**

Also **SPH-EXA** from collaboration with Prof. Florina Ciorba's HPC research group at UniBasel (Dept. Math and Computer Science)

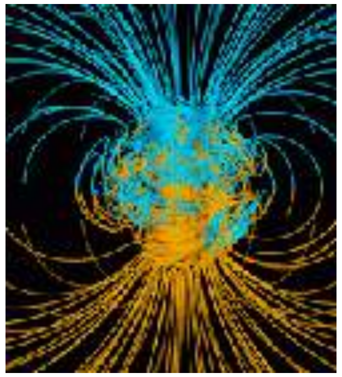
New SPH+N-body code ready to scale on upcoming Exascale supercomputers, co-design with CSCS

SPH-EXA: Smoothed Particle Hydrodynamics at Exascale

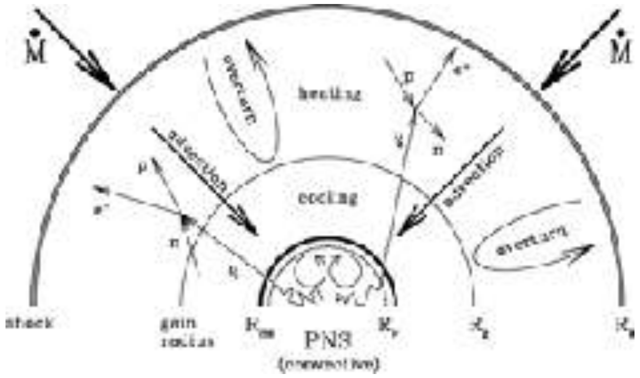
University of Basel | University of Zurich[UZH] | pasc Platform for Advanced Scientific Computing | CSCS Centro Svizzero di Calcolo Scientifico Swiss National Supercomputing Centre



Hydrodynamics



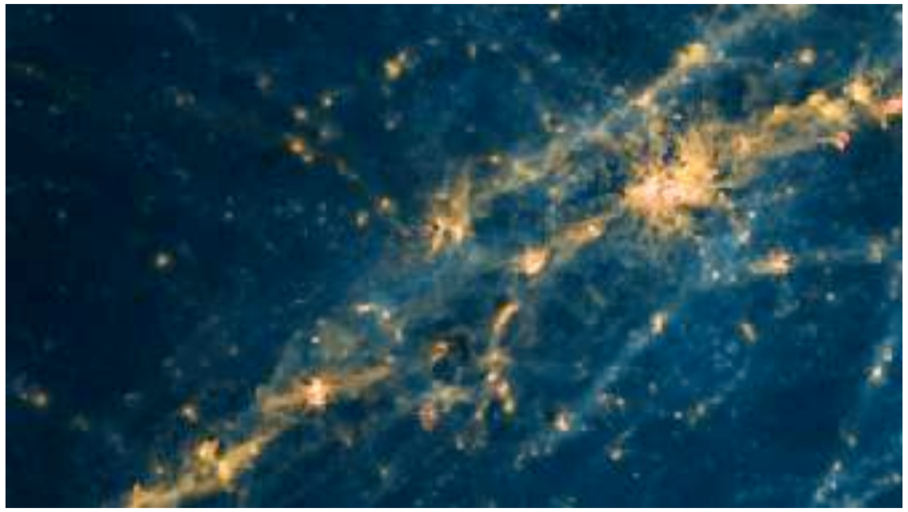
Magnetic fields



Neutrino transport

General Relativity

Nuclear Physics



Galaxy formation

Vision

Development of a scalable and fault tolerant SPH framework that executes at Exascale to perform for the first time trillion particle galaxy formation simulations with SPH, gravity, and radiation (ExaPHOEBOS).

SPH-EXA: From Mini-App to Framework

Synthesizes the characteristics of state-of-the-art SPH codes
Provides an MPI+X (OpenMP/OpenACC/CUDA) reference optimized C++ (header only) implementation
Employs adaptive load balancing and fault-tolerance
Implements basic to advanced SPH operands
Explores new programming paradigms (e.g., HPX)
Works with Cray, Clang, GCC and Intel compilers
70% efficiency at 65bn particles on 2048 GPU nodes @ Piz Daint

SPH-EXA project:
Project (2017-2020) + extension 2021
Continues as SPH-EXA2 (2021-2024)
Combines with the Swiss participation in the SKA Observatory (2021-2025)
Targets simulation > 1 trillion particles with SPH, gravity, radiation

https://hpc.dmi.unibas.ch/en/research/pasc-sph-exa2/
https://hpc.dmi.unibas.ch/en/research/sph-exa/

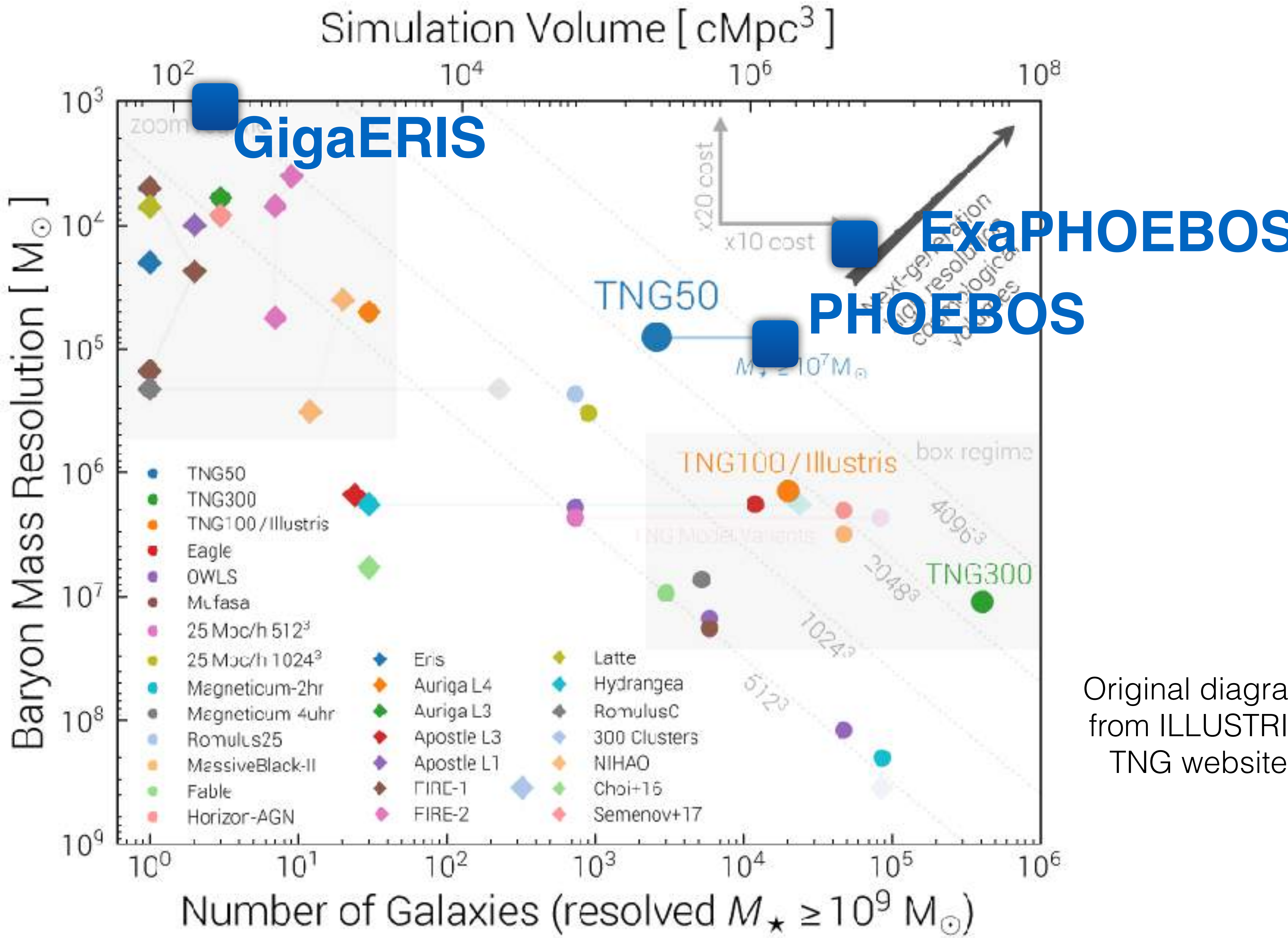
Two types of cosmological hydro simulations

Solve gravity, hydrodynamics and radiation, plus account for sub-grid physics (star formation, stellar/SN feedback, massive black hole formation, accretion and feedback etc.)

- **Hi-res zoom-in simulations**. Recent state-of-the art example is **GigaEris** **(Tamfal et al. 2021)** first ever billion particle SPH simulation of an individual galaxy. Run with **ChaNGa** on
- hybrid CPU+GPU PizDaint nodes.

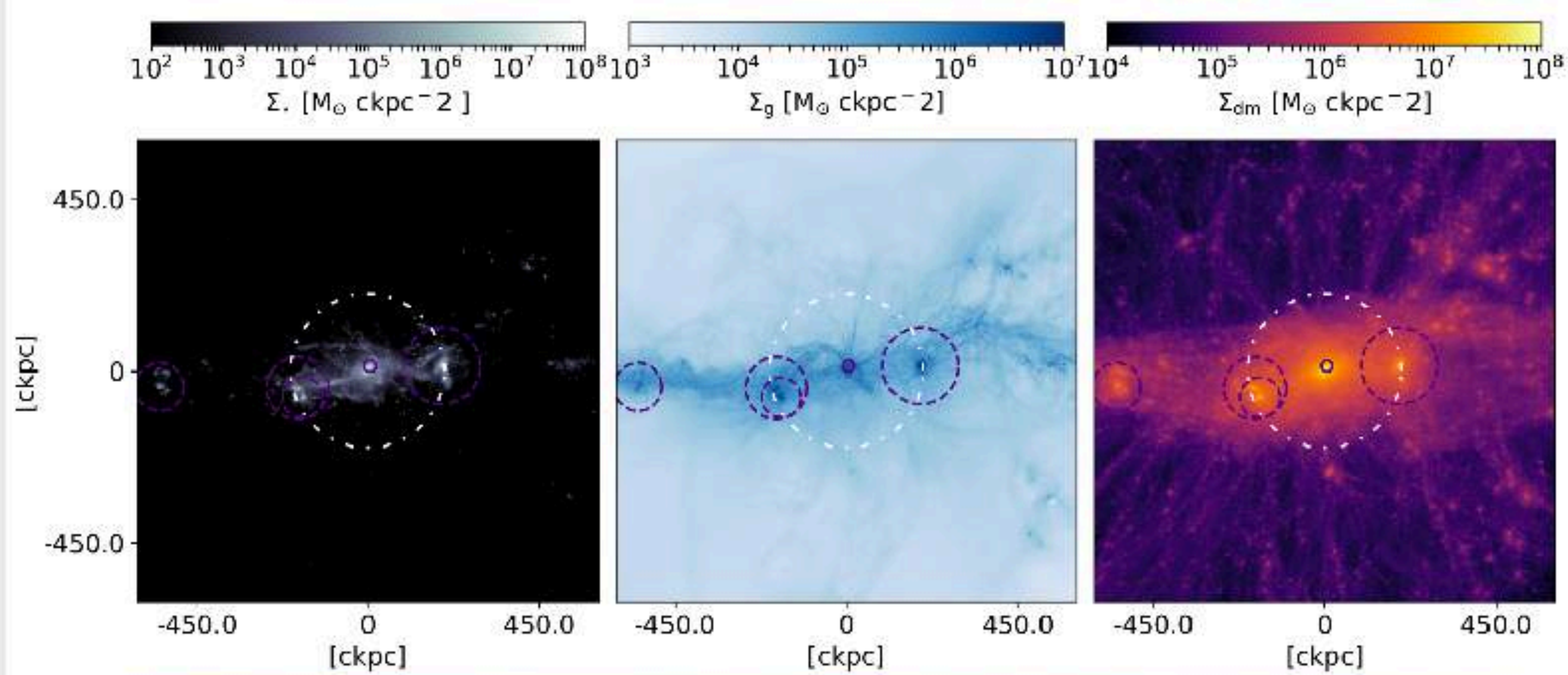
- **Large cosmological volumes:** The **PHOEBOS simulations**. Advancing beyond simulations such as **ILLUSTRIS, EAGLE and HORIZON-AGN.** Current runs with **ChaNGa**, future
- ones with **SPH-EXA**

Our new generation cosmological simulations (performed/to be performed on PizDaint and Alps/Eiger)

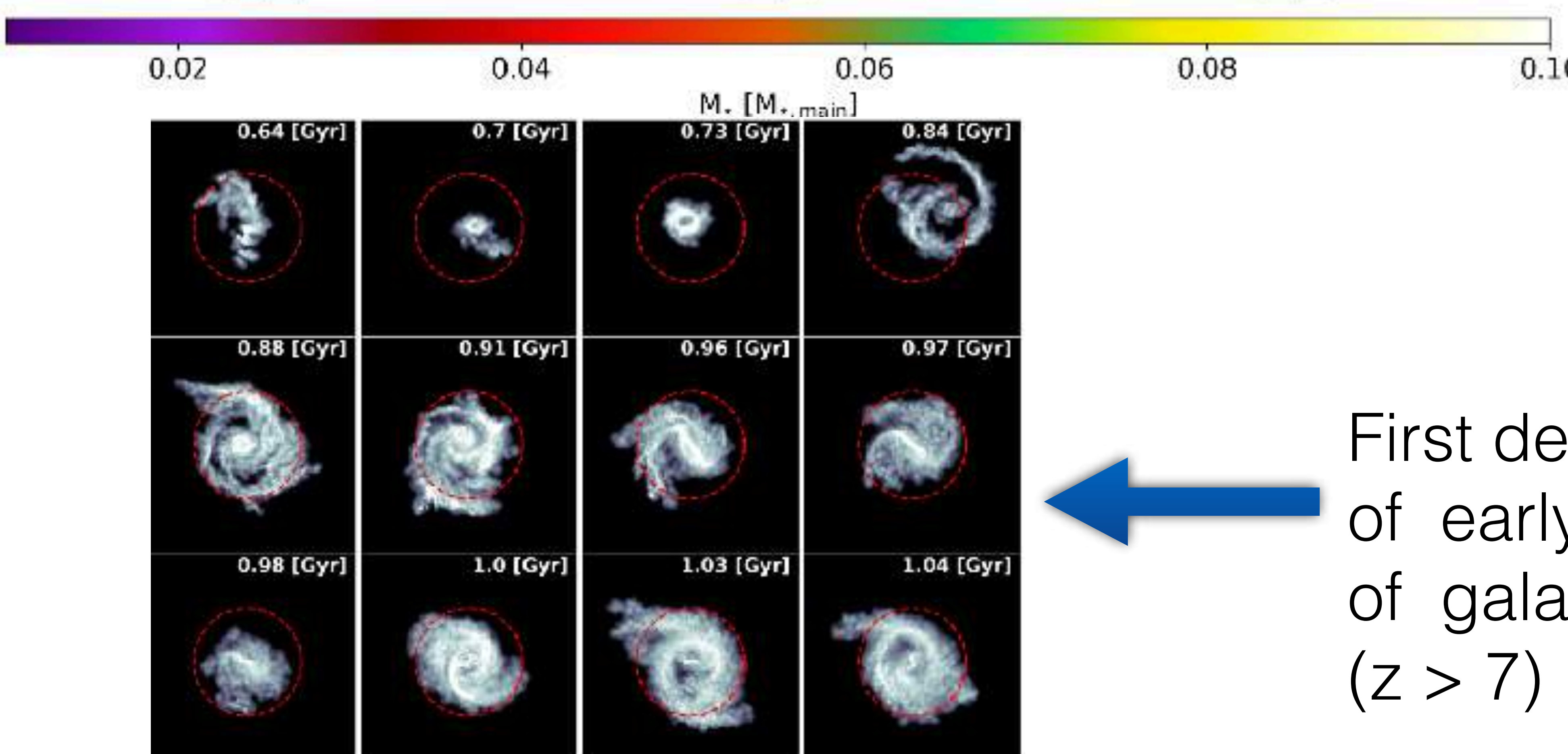


Original diagram from ILLUSTRIS TNG website

Increased resolution enables new science



GigaERIS

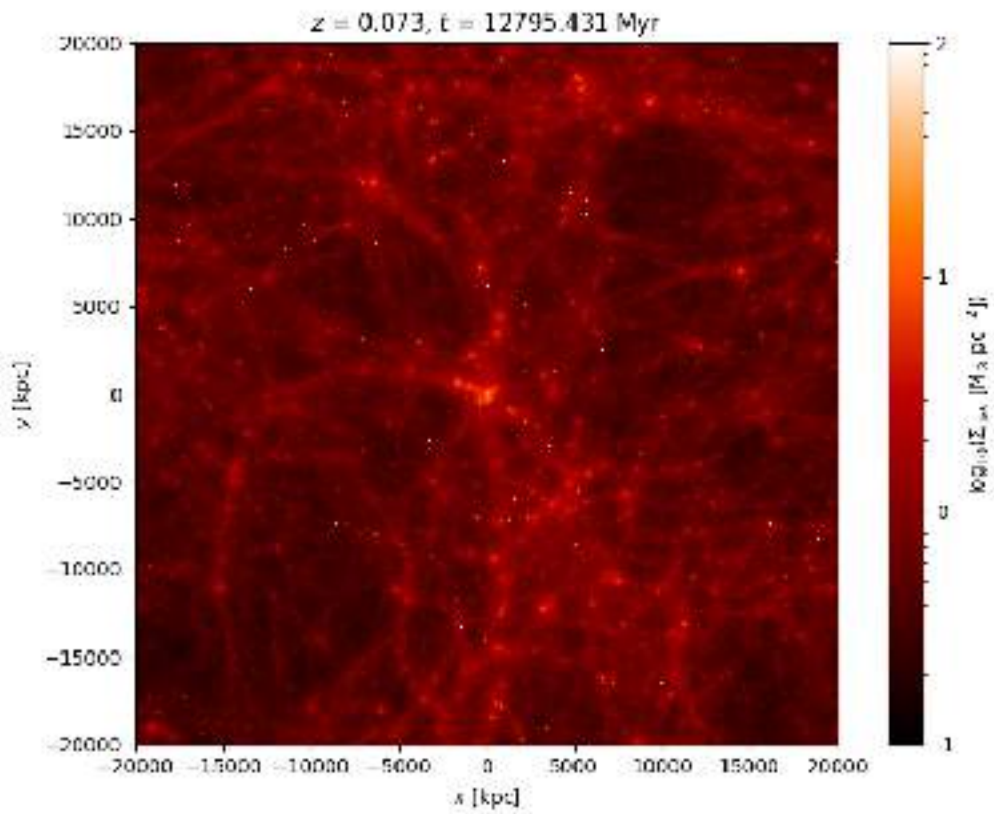


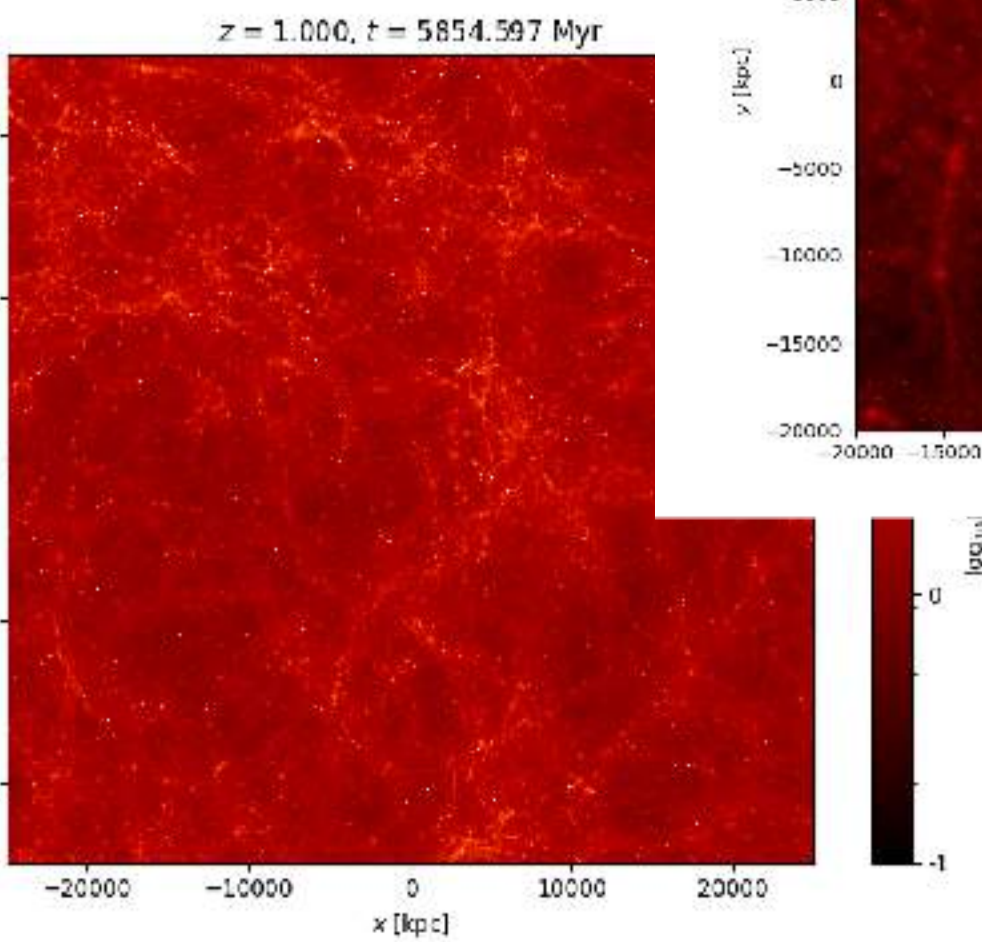
Tamfal et al. 2021

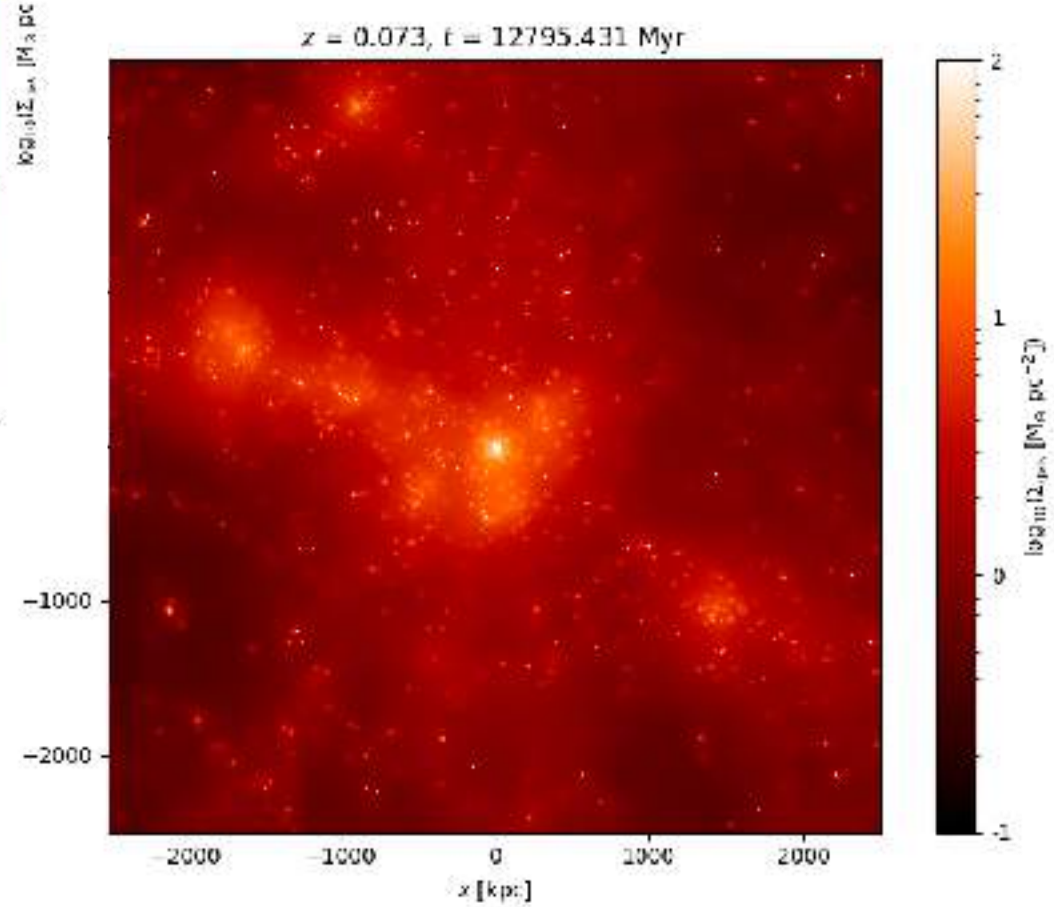
First detailed study of early disk assembly of galactic disks ($z > 7$)

The PHOEBOS simulations: nearing resolution of zoom-in galaxy simulations in a large cosmological volume (100 comoving Mpc)

Run:	# DM	# gas	# tot	m_{DM} [M$_\odot$]	m_{gas} [M$_\odot$]	ϵ [kpc]	memory [kB]	# nodes
PhoebosHR	5808^3	3888^3	2.547×10^{11}	1.699×10^5	1.059×10^5	0.15	3.135×10^{11}	4898
PhoebosMR	2904^3	1944^3	3.184×10^{10}	1.360×10^6	8.473×10^5	0.30	3.918×10^{10}	612
PhoebosLR	1452^3	972^3	3.980×10^9	1.088×10^7	6.778×10^6	0.60	4.898×10^9	77
PhoebosULR	726^3	486^3	4.974×10^8	8.701×10^7	5.423×10^7	1.20	6.122×10^8	10



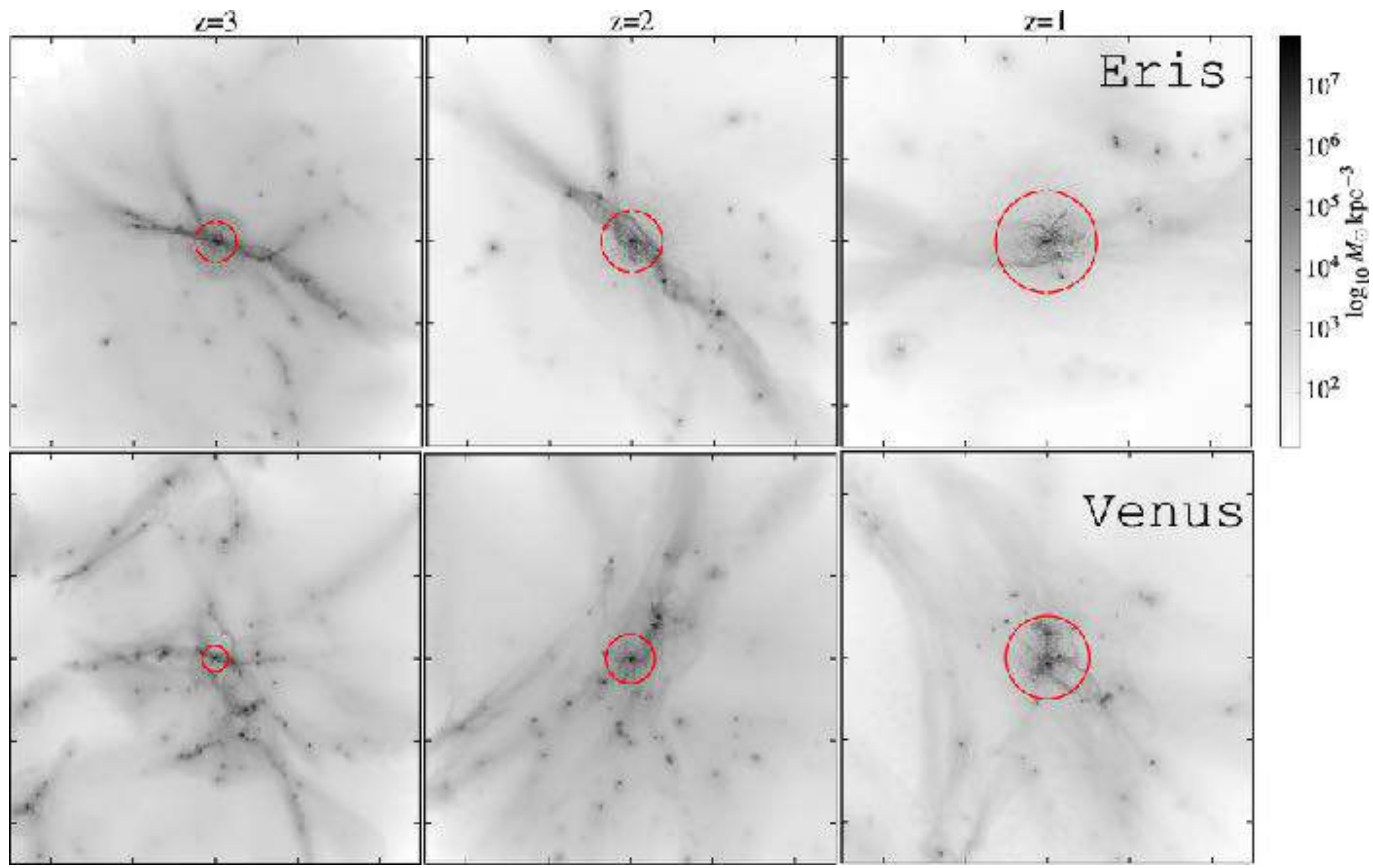




An important **SKA-related** science driver is understanding ***"how galaxies get their gas"***. Continued gas accretion needed as gas consumption timescale <~ 1Gyr).

The current paradigm is "cold flow accretion" (Keres et al. 2005; Dekel & Birnboim 2006): cold gas filaments (<~ 10^4 K) are believed to be the raw material that builds galactic disks (Brooks et al. 2009).

Sokolowska et al. 2018



Cold flows have never been observed convincingly.
SKA can can be transformative in this area.
Simulations such as PHOEBOS are best designed to study cold flows with enough resolution to study their impact on a large population of galaxies

The unexpected impact of galaxy merging history on cold flows **(Sokolowska et al. 2018)**