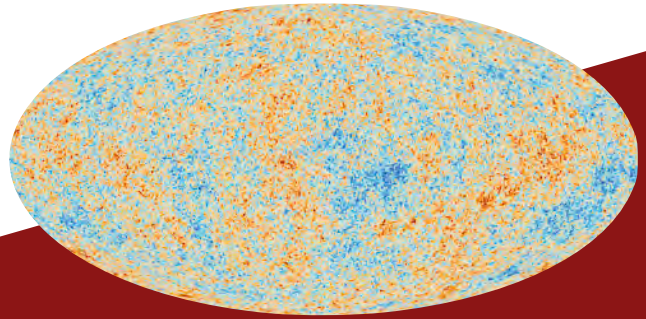
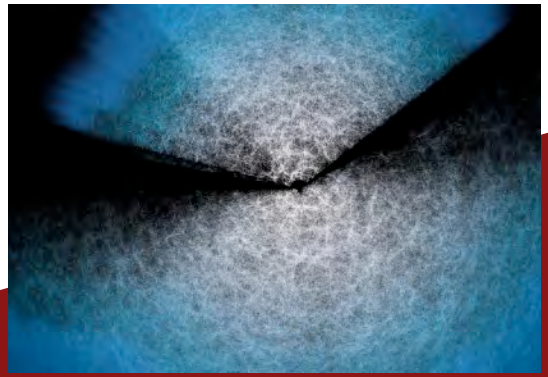
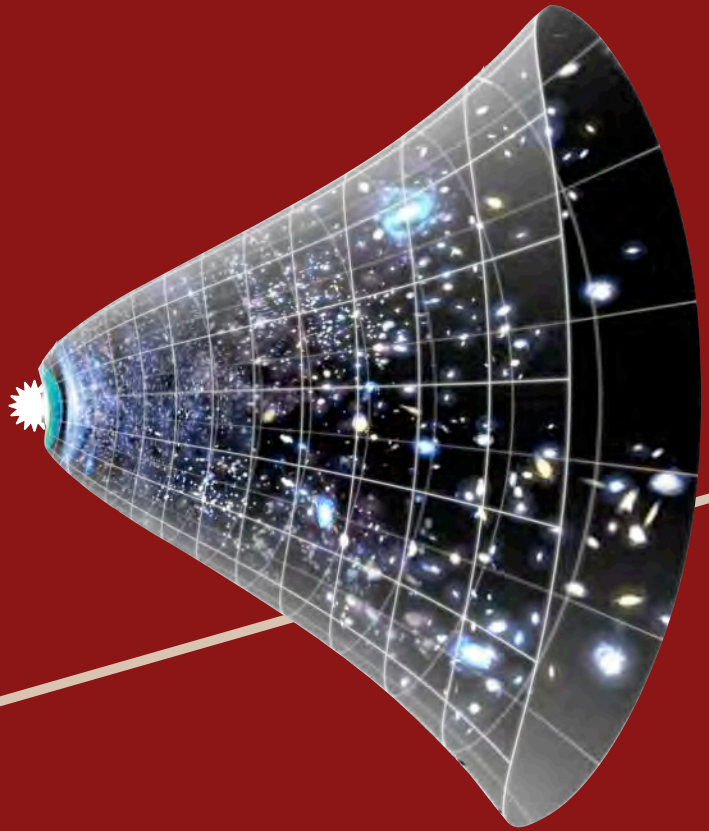
Unraveling the Universe with High Performance Computing



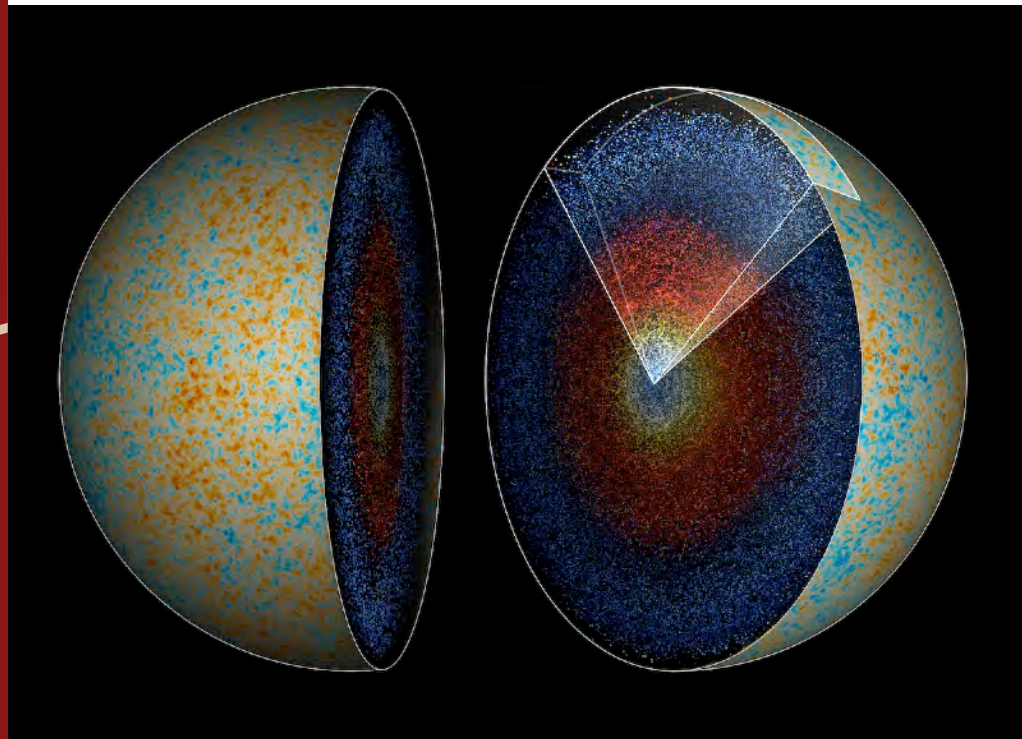


Marcelo Alvarez
Kavli Institute for Particle Astrophysics & Cosmology

The Observable Universe



The observable universe is a sphere roughly 90 billion light-years across with us at the center



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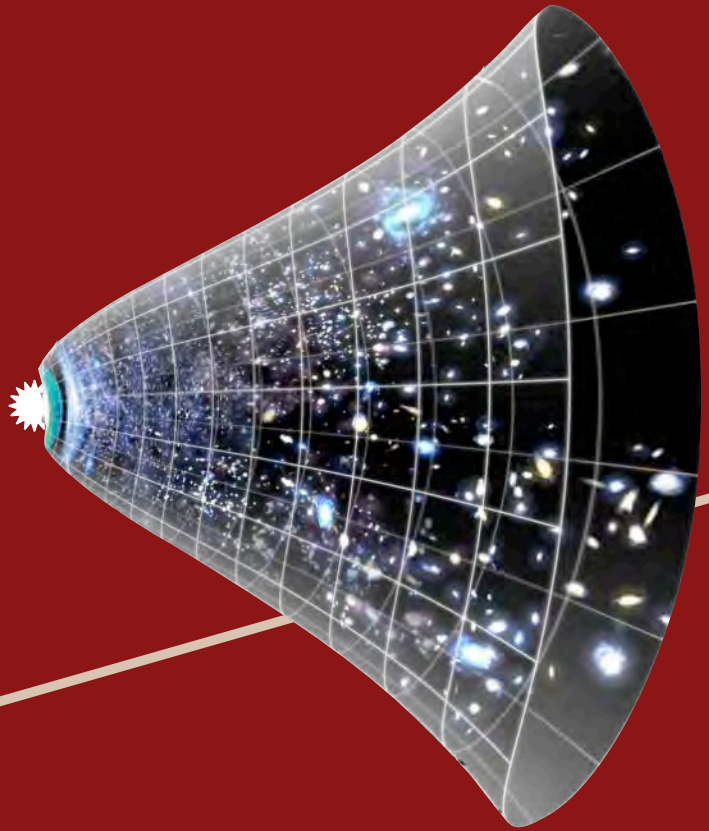
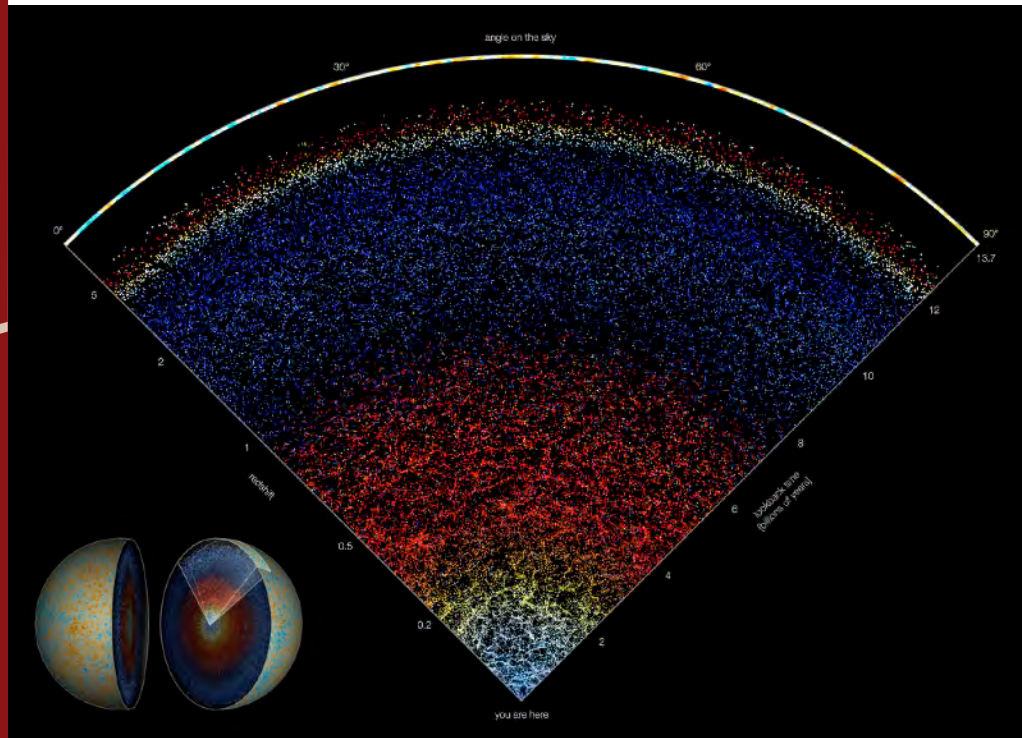
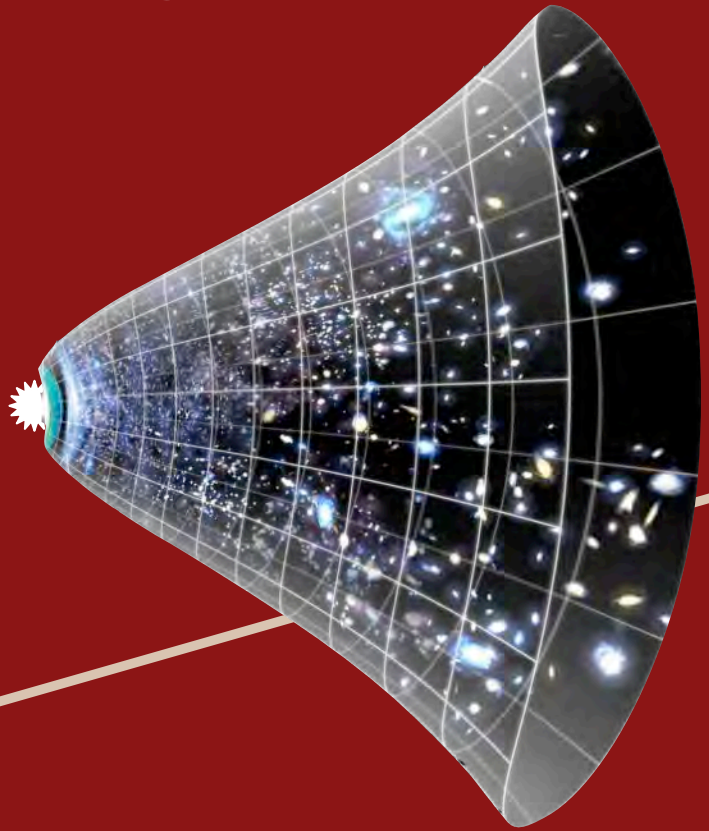


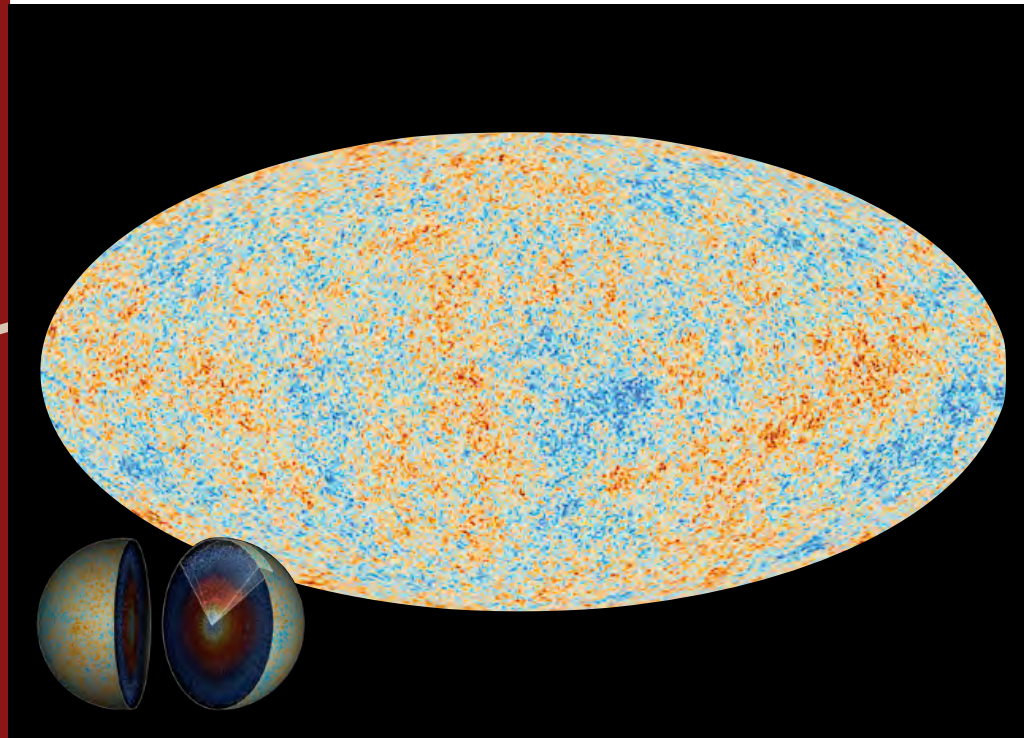
The further away we look, the further back in time, all the way back to t=0, which defines the radius of the sphere



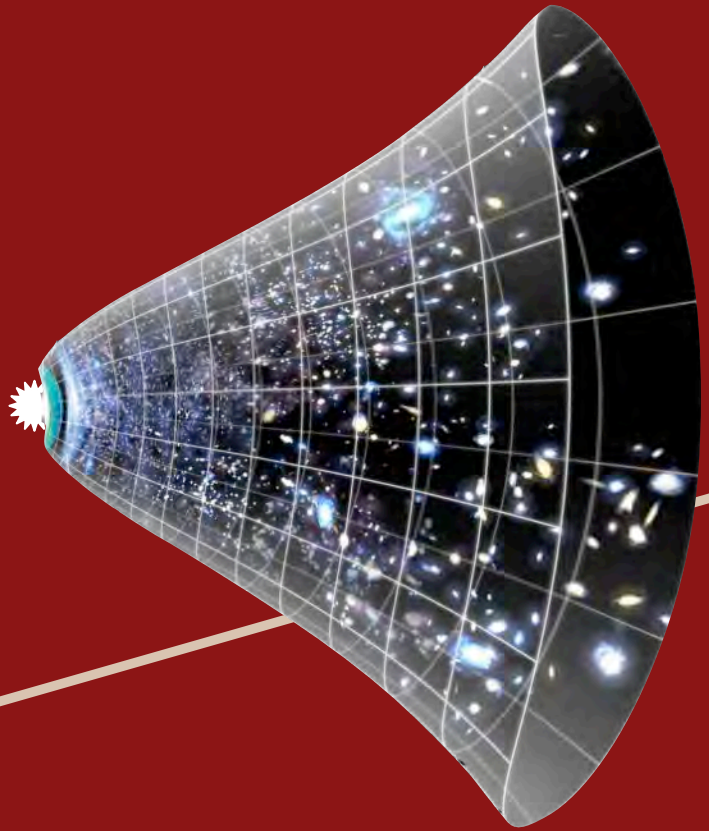
The Cosmic Microwave Background



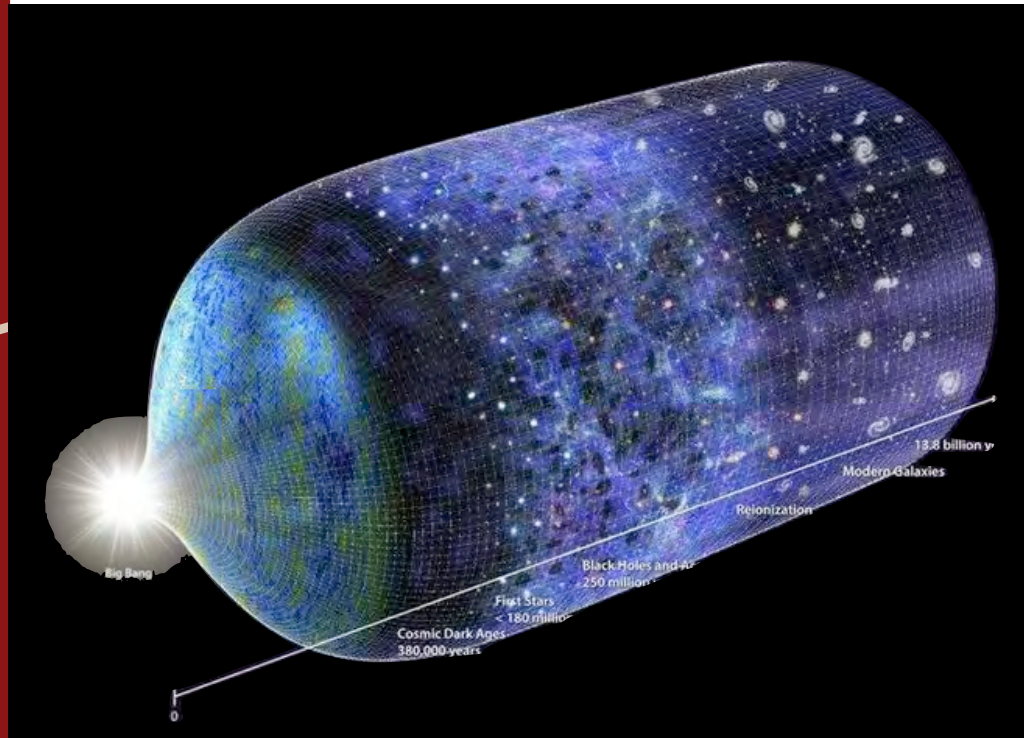
For now the farthest back we can look is the cosmic microwave background, the afterglow of the big bang



Before the Big Bang Inflation



Cosmic inflation is an elegant theory but its connection to fundamental physics is unknown



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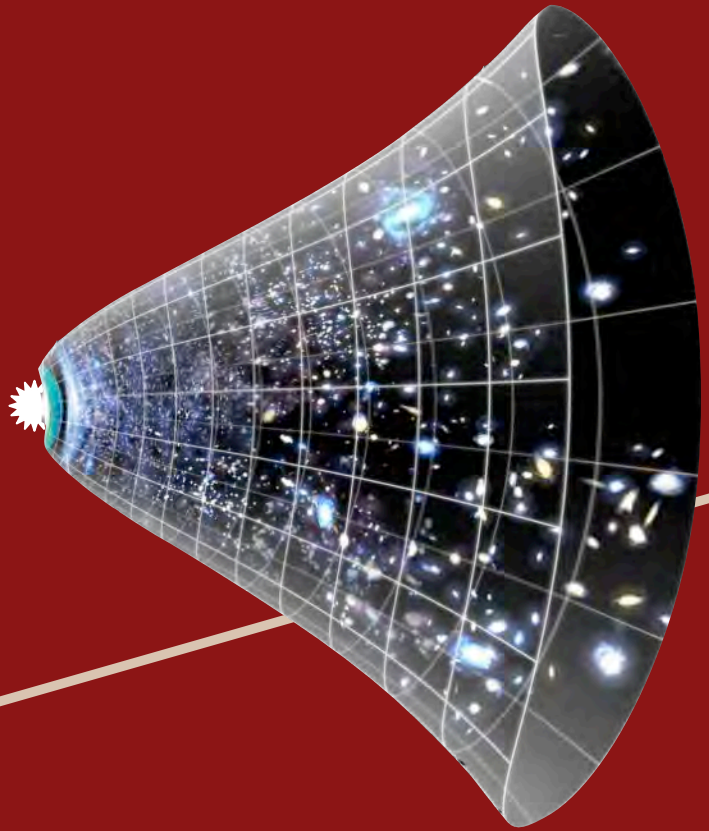
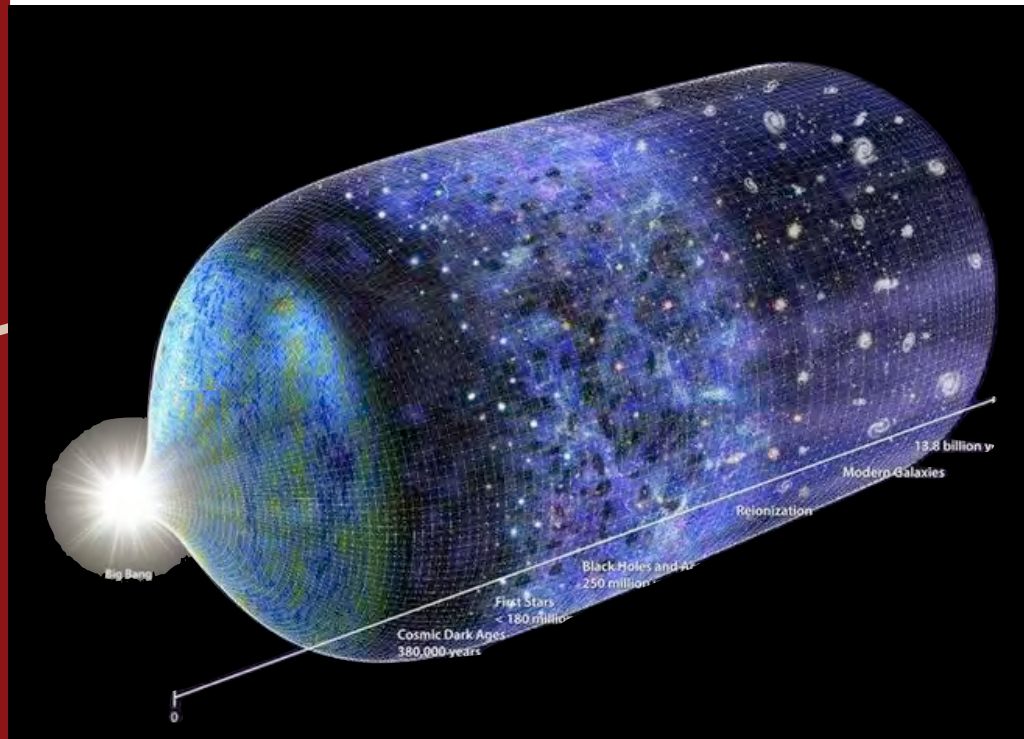
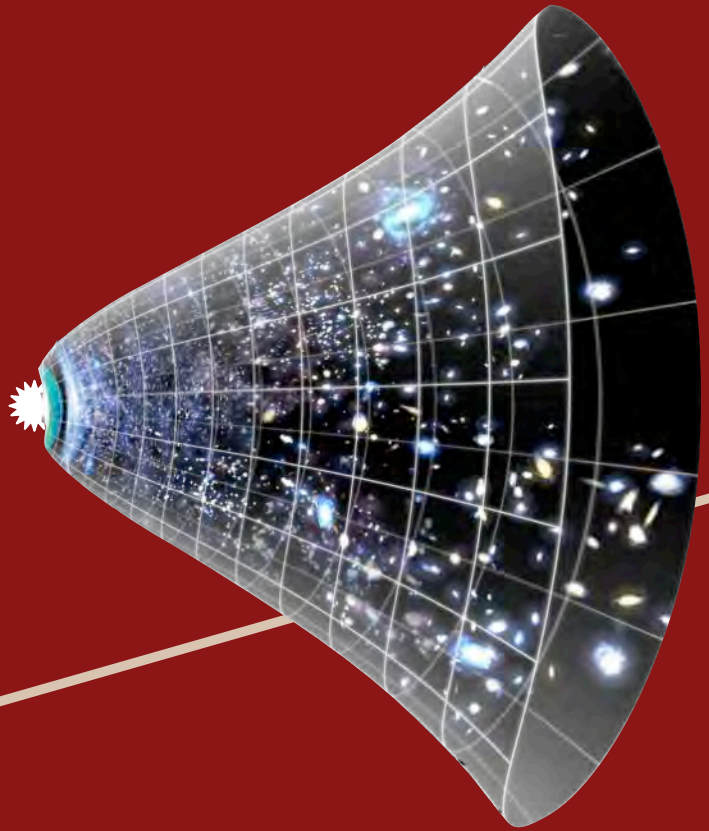


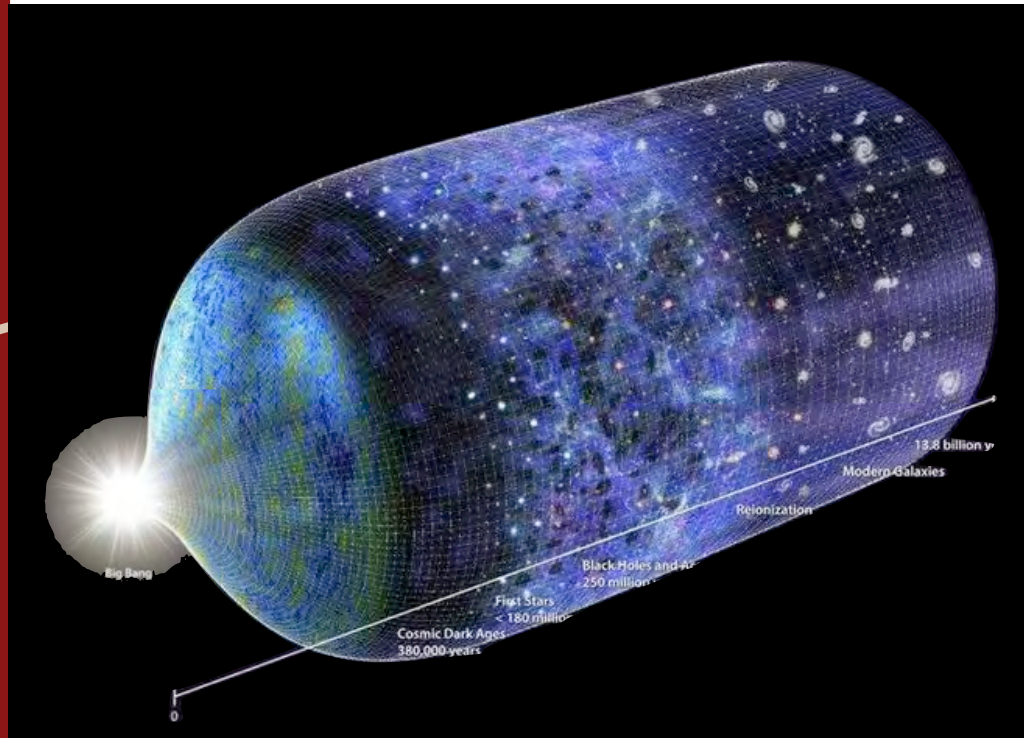
During inflation the universe expanded from the size of a nucleus to a meter in a trillionth of a femtosecond!



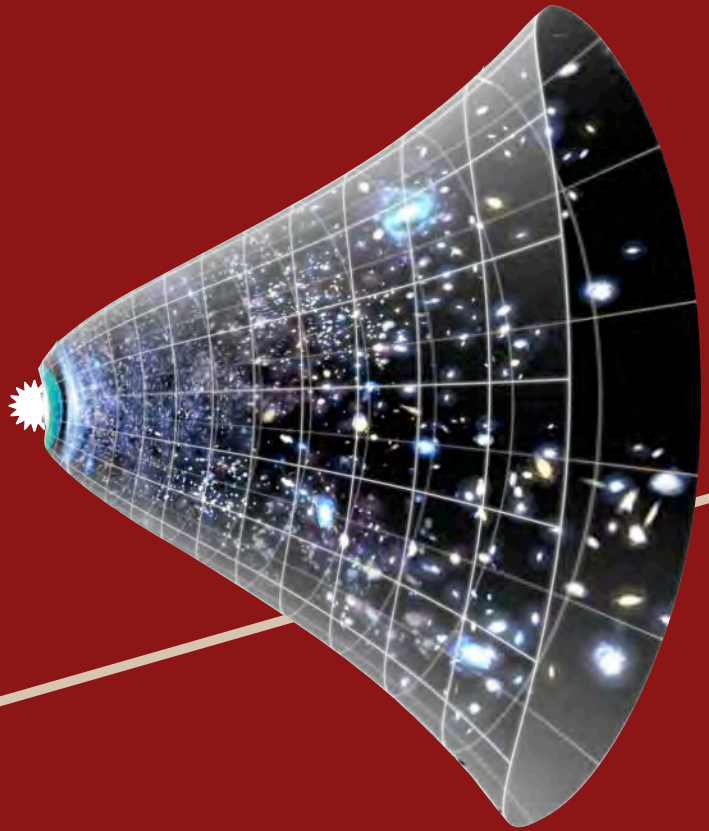
Quantum Noise and Seeds of Structure



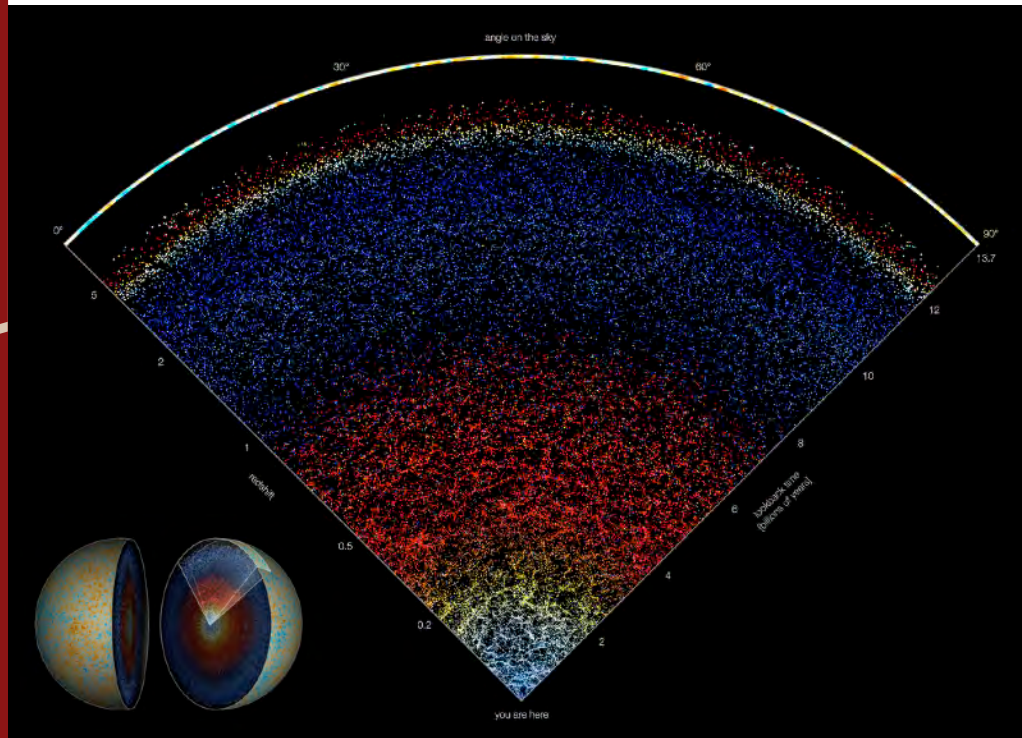
Quantum fluctuations from inflation are the leading theory for the origin of structure in the Universe



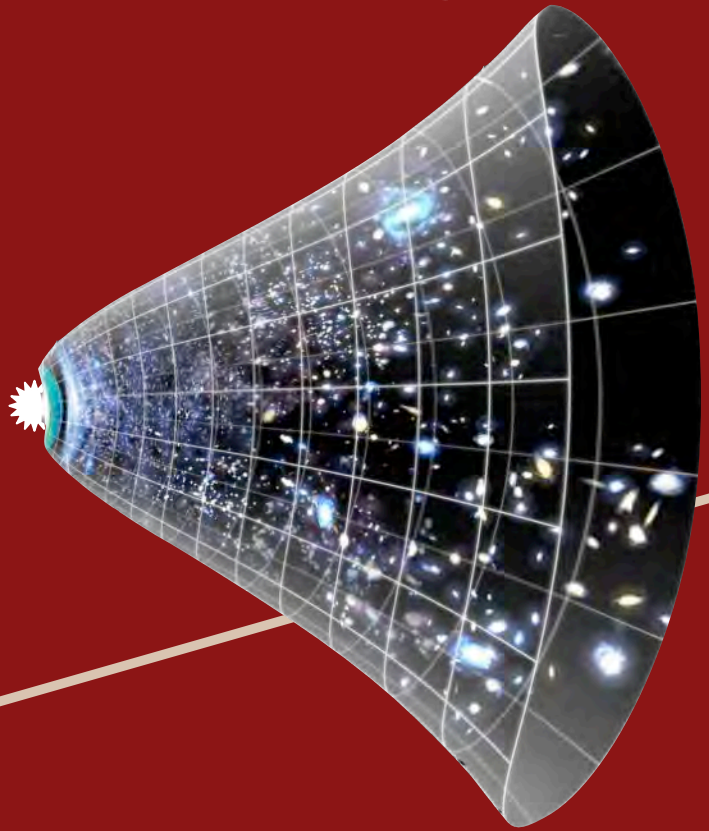
The Cosmic Expansion History



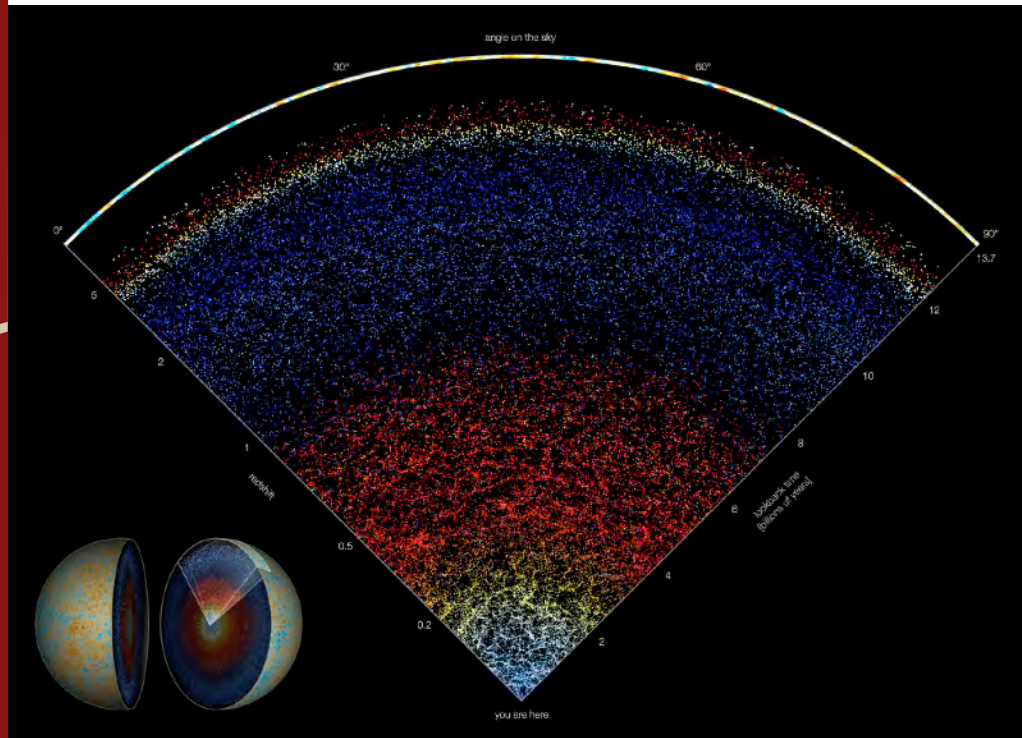
By measuring the degree to which galaxy light redshifts vs distance, we can recreate the expansion history



Accelerated Expansion and Dark Energy



The expansion should decelerate because of gravity, but instead it is accelerating, known as “dark energy”



Unanswered Questions

Standard Model is "ΛCDM"

Hubble parameter	h
Total matter density	$\Omega_{\rm m}$
Baryon density	$\Omega_{\rm b}$
Cosmological constant	Ω_Λ
Density perturbation amplitude	σ_8
Density perturbation spectral index	n

INFLATION $f_{\rm NL}$

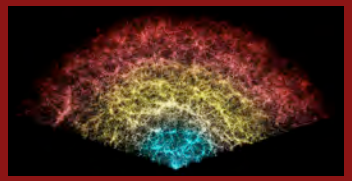
Is inflation the correct description for the initial conditions of the observable universe and, if so, what is the connection to high energy physics?

DARK ENERGY w

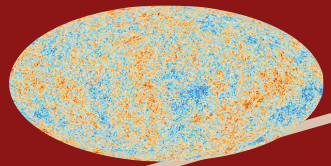
What is causing the accelerated expansion of the universe? Is it a constant vacuum energy (i.e. cosmological constant Λ), some undiscovered new field, or something else entirely?

Data Holds the Key

DESI



Simons Observatory



Rubin Observatory

INFLATION

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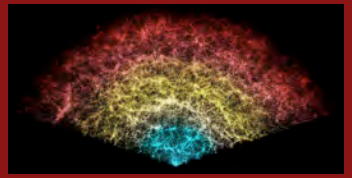
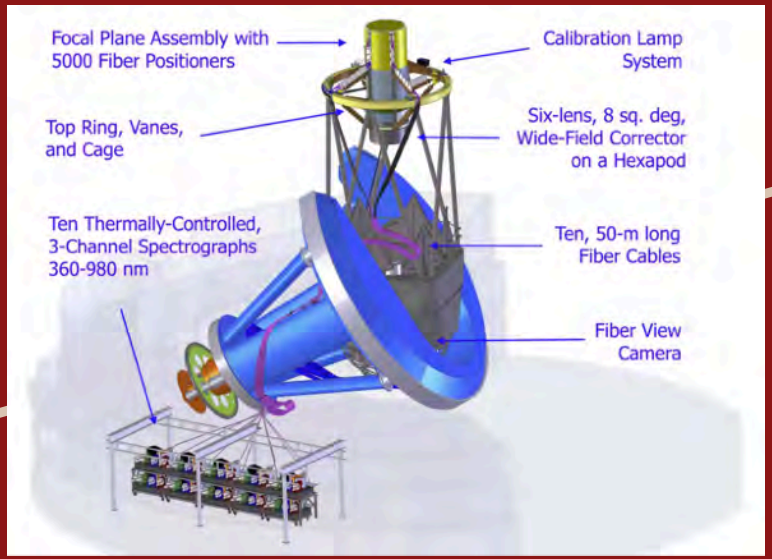
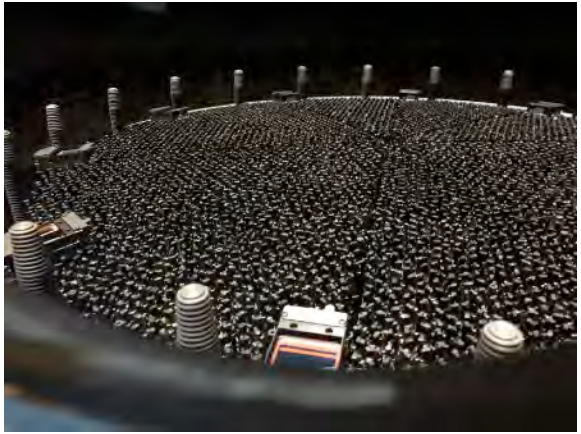
DESI: The Dark Energy Spectroscopic Instrument

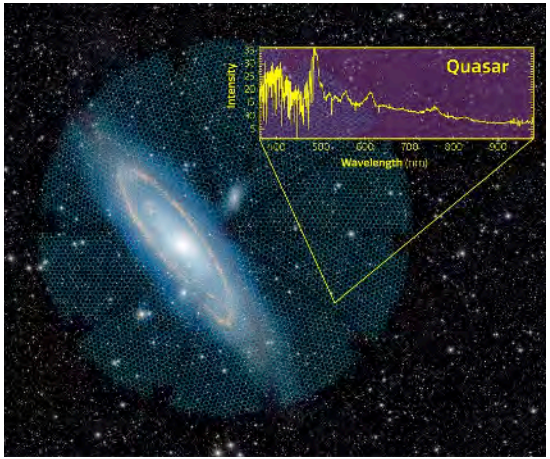


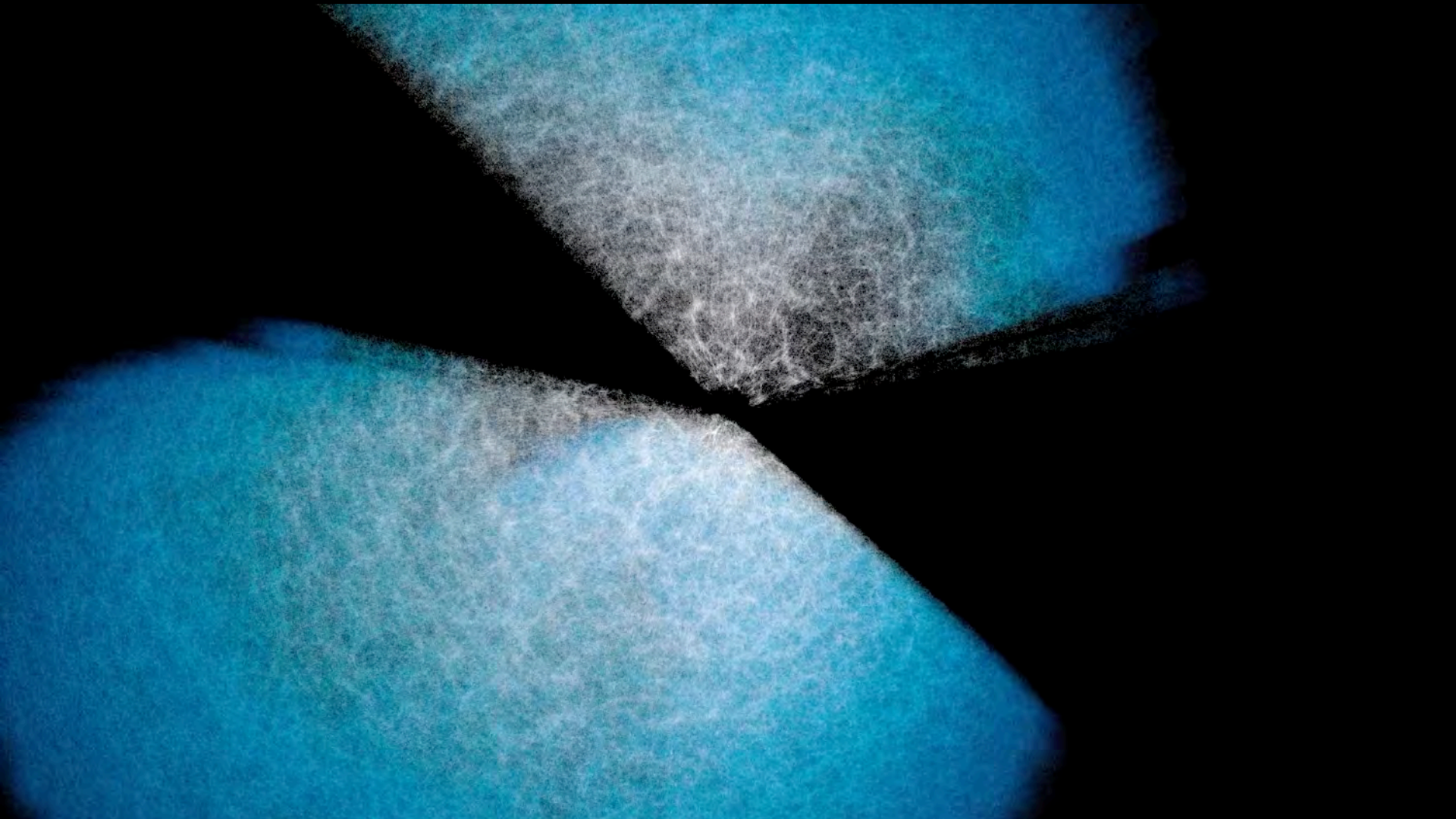




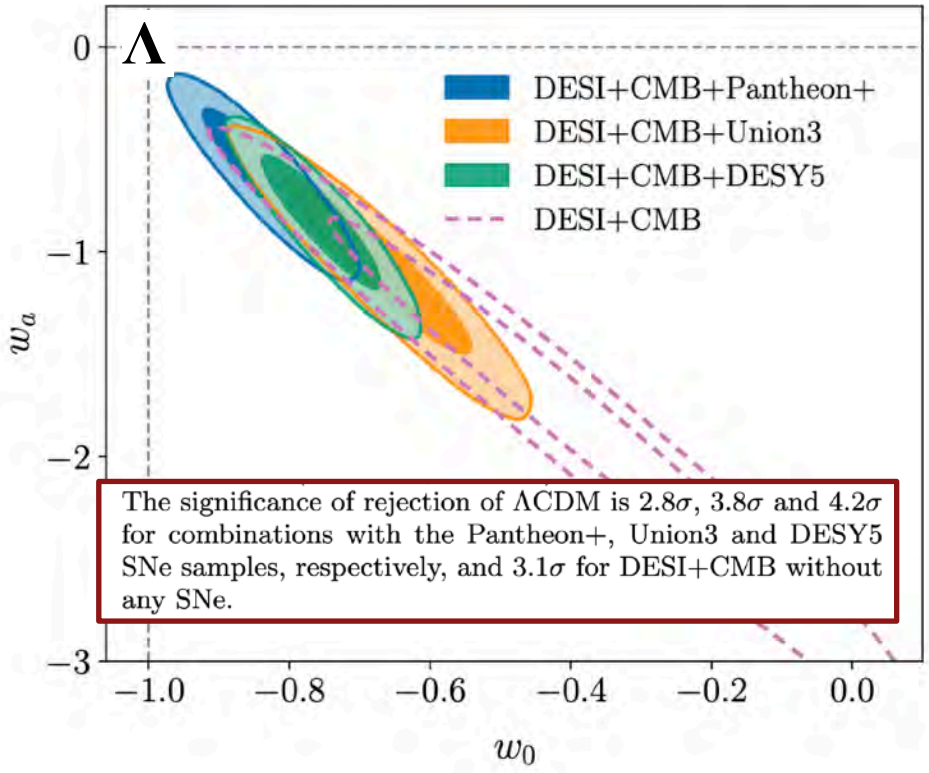
5,000 individual robotic fibers move independently in the focal plane to the position of each galaxy or quasar to be observed for each pointing of the telescope.

Each “tile” in the survey is observed for a few minutes at a time; over a few years, individual spectra have been obtained for millions of objects, creating the largest 3D map of the universe ever made





Dark Energy in the News



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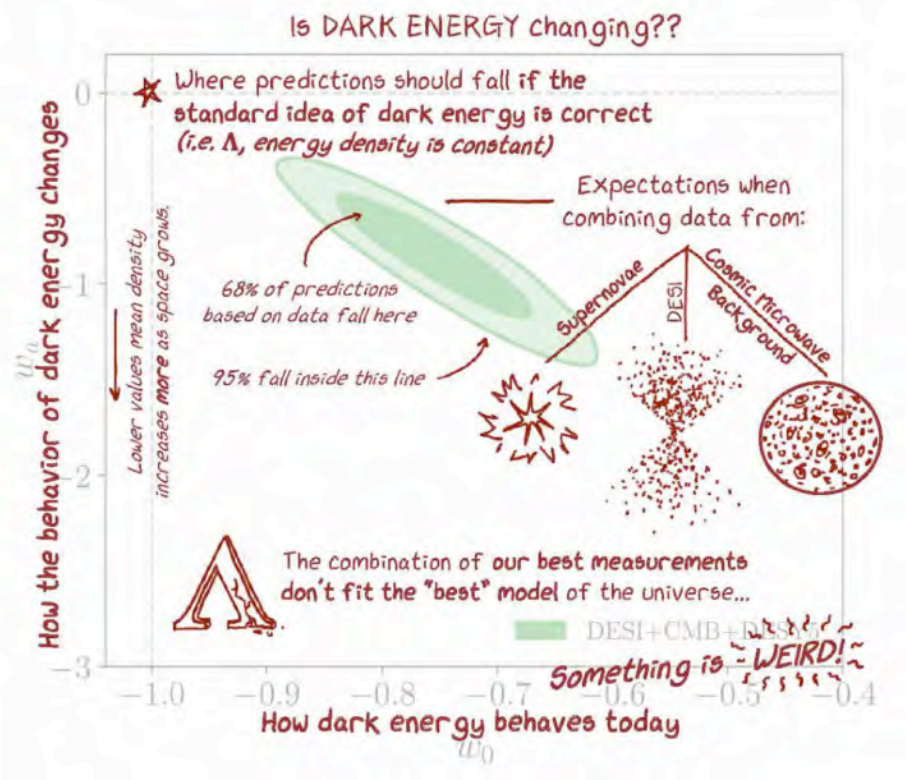
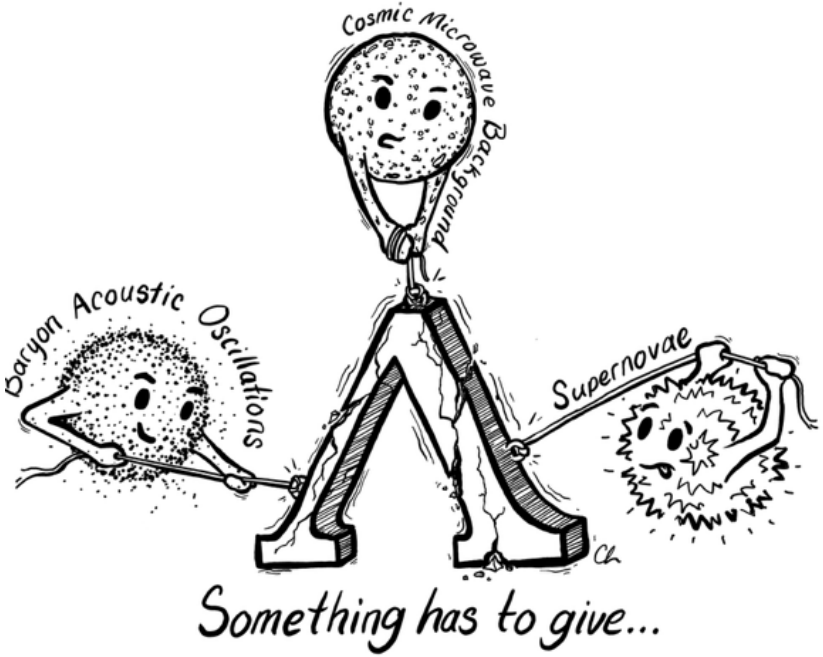
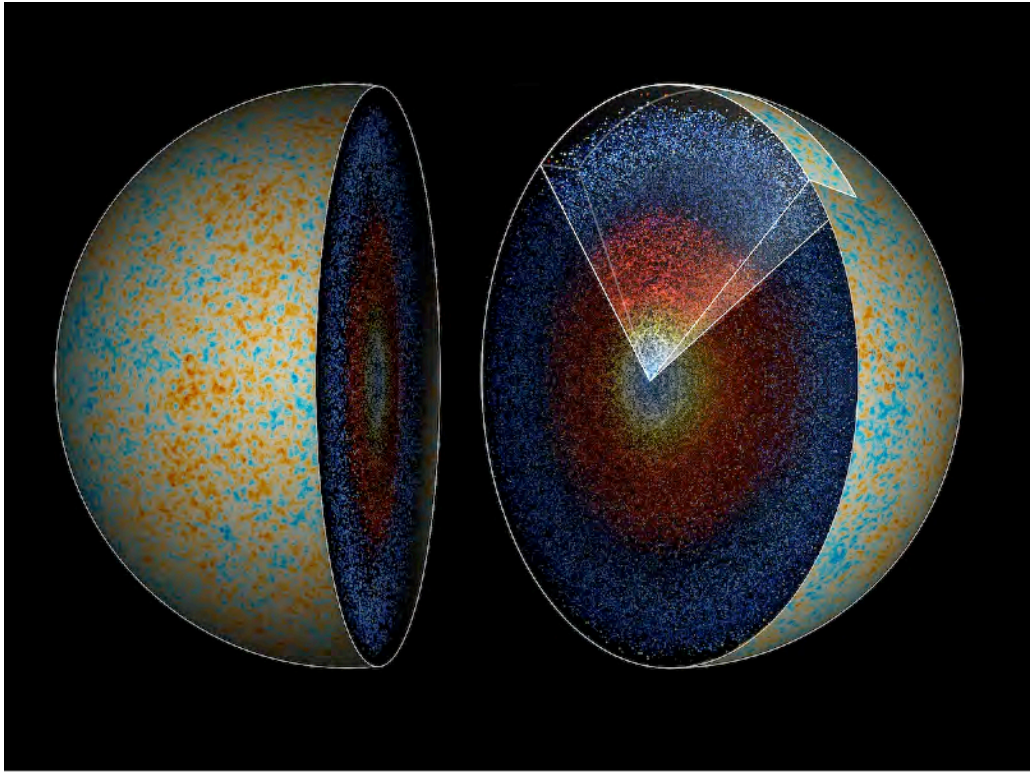
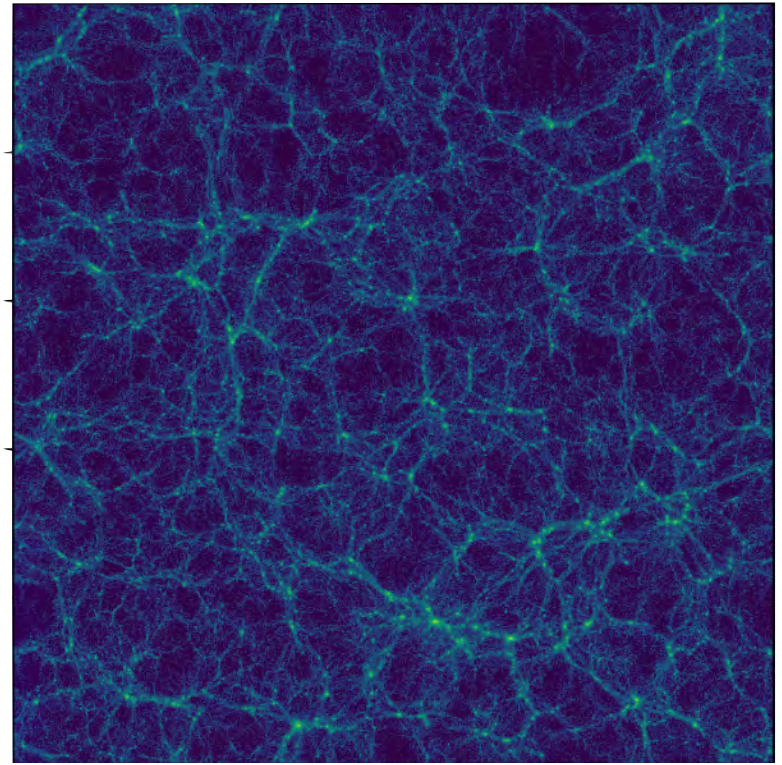




Simulations for Cosmology





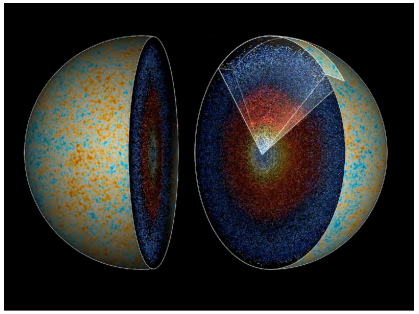
Simulations for Cosmology

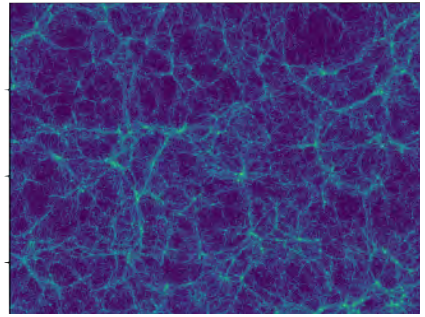
survey volume ~ 2000 Gpc^3

scales that form galaxies ~ 0.2 Mpc

# of resolution elements ~ $65{,}000^3$

initial conditions alone ~ 1 PB





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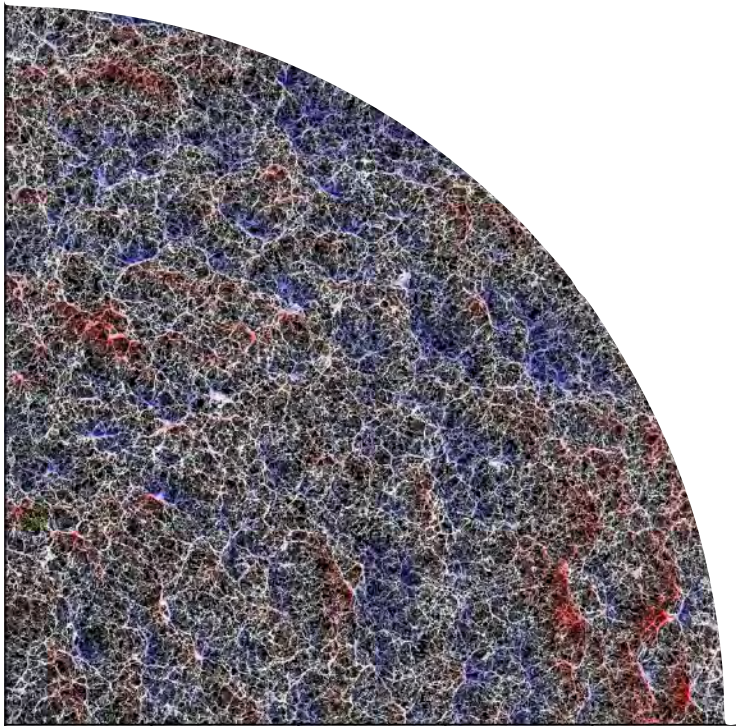

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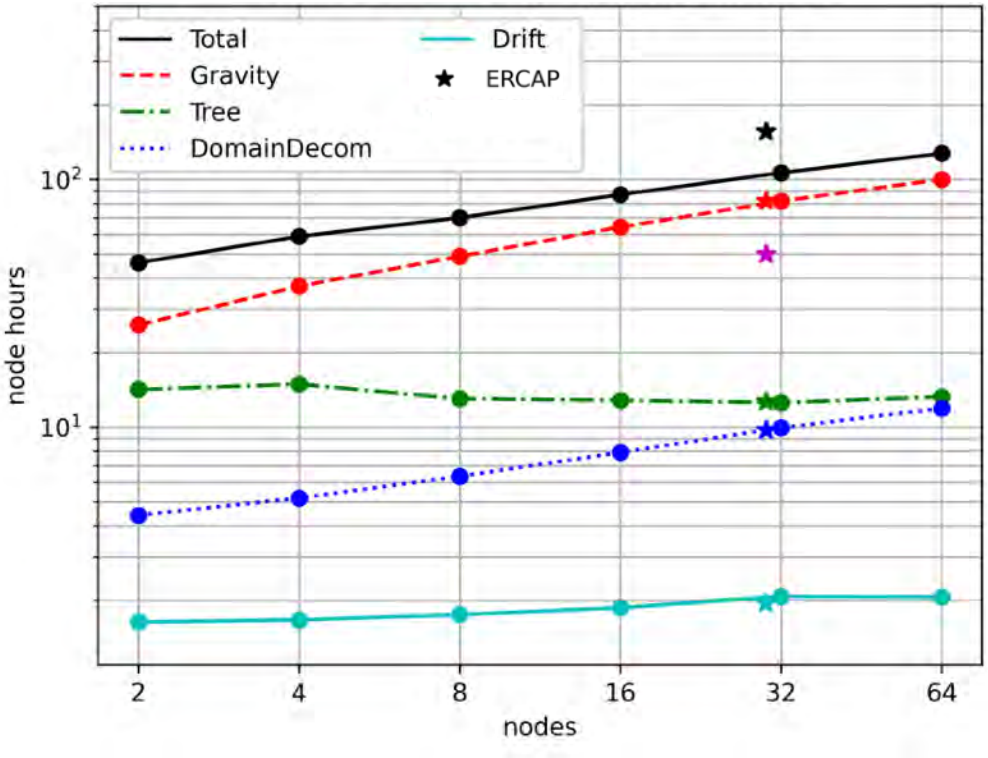
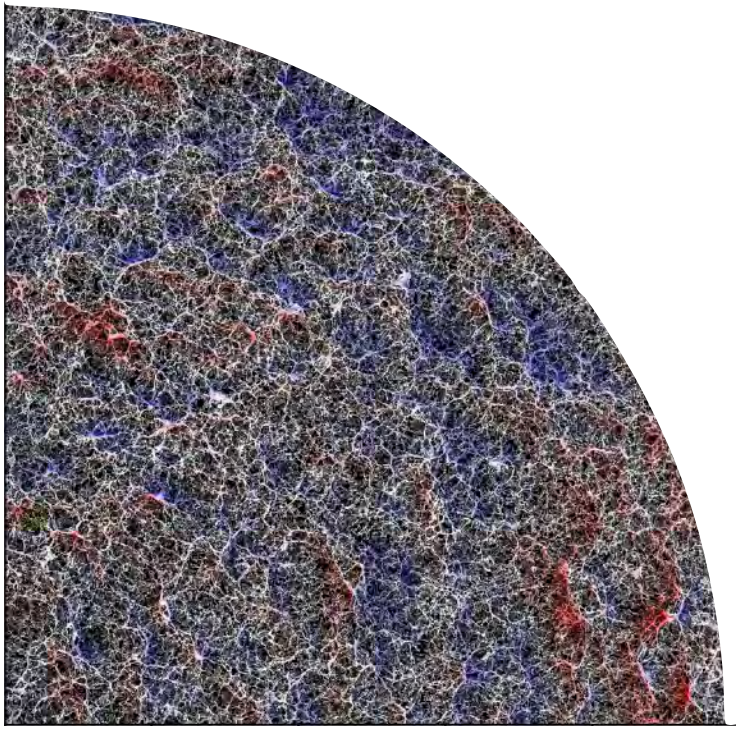
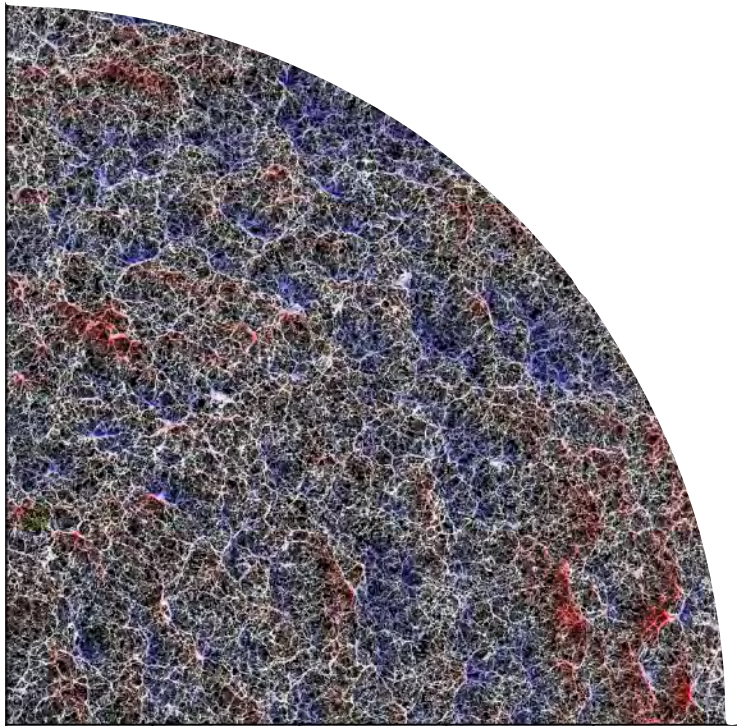




Simulations for Cosmology

name	z_{min}	z_{max}	L_{box}	N_{part}	wall	node	Nodes
			Gpc/h		hrs	hrs	
scale			1	1400^3	20	40	2
L1	0	1.5	3	4200^3	20	1100	54
L2	1.4	4.1	5	4200^3	10	550	54
S0	0	4.1	5	7000^3	20	5000	250



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S0	0	4.1	5	7000^3	20	5000	250

Largest simulation of our current campaign is expected to use 20,000 GPU hours, but…

it is only one set of cosmological parameters and the resolution is still too low by a factor of ~10

Training Models with Simulations

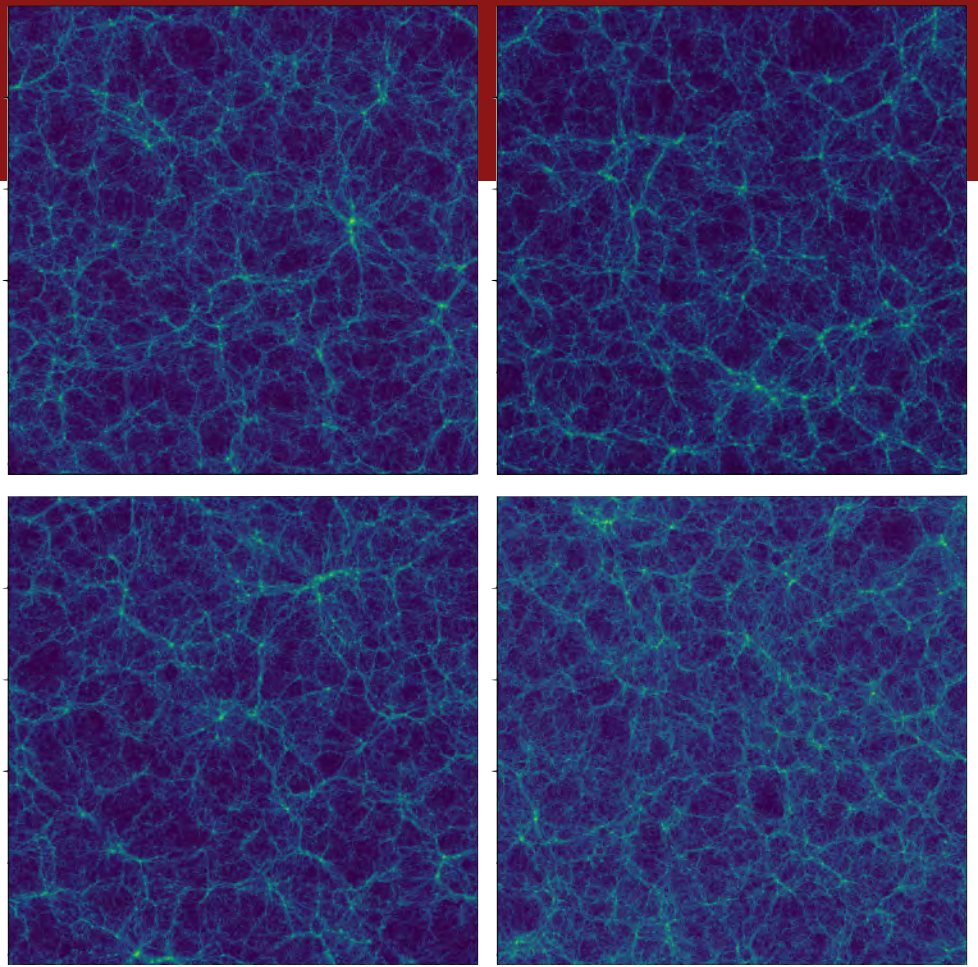
High resolution simulations of large scale structure

25 sets of cosmological parameters using a modified version of the N-body code Gadget with MPI+OpenMP

CPU hours: 4M
Data: 1.25 PB

Completed December 2024 on Sherlock
Data products stored at Oak

Being used for current and upcoming galaxy surveys including:
DESI, SPHEREx, Simons, Rubin, and Roman



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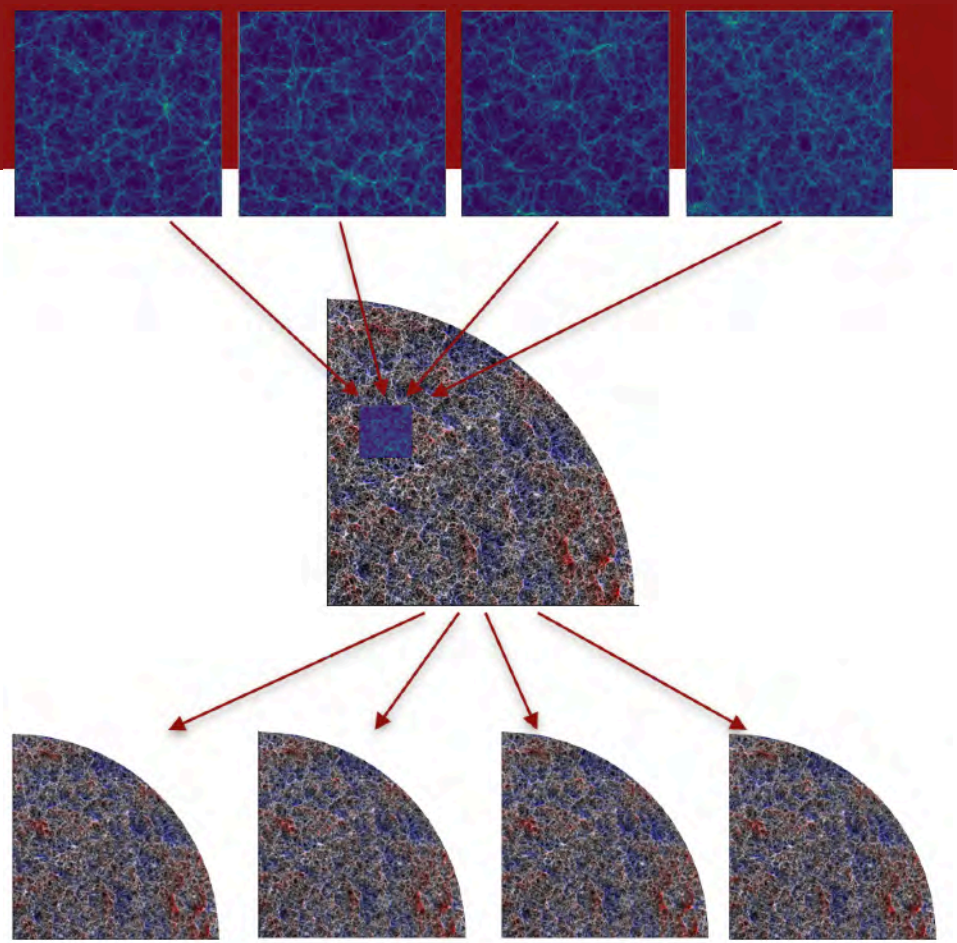
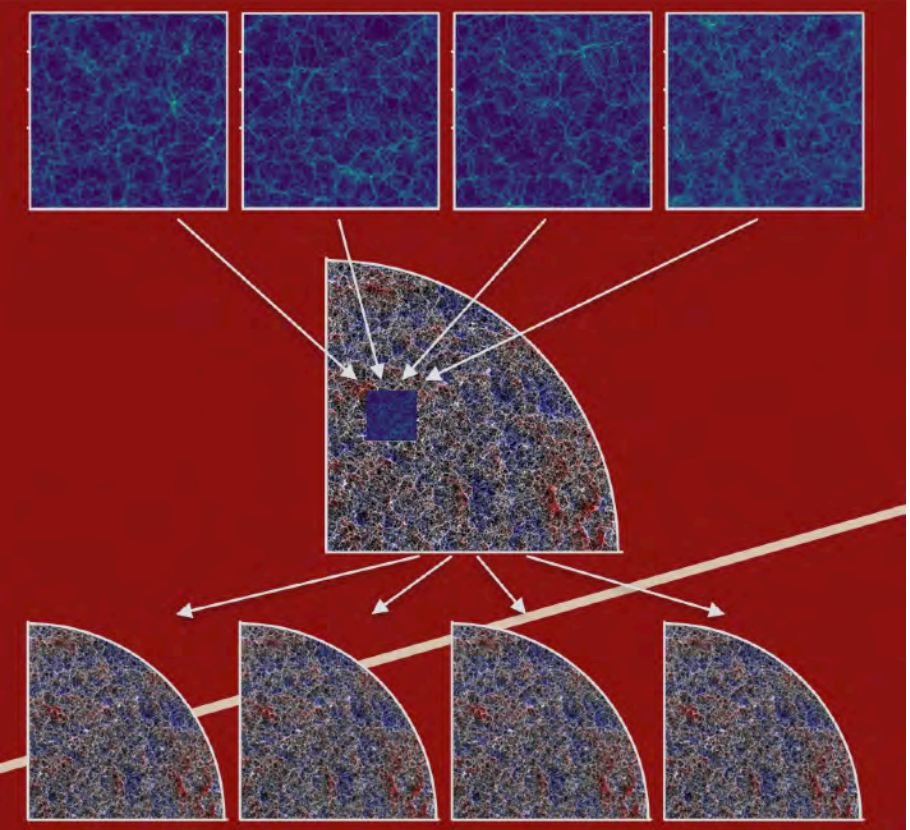


Outlook



I/O intensive simulations will play a key role in training foundation models for the large scale structure of the universe

New survey data coming soon from
Rubin, Simons (Chile) and
Euclid, SPHEREx, Roman (space)
will shed light on inflation and dark energy

We are on the cusp of developing “digital twins” of the universe based on data from astronomical sky surveys