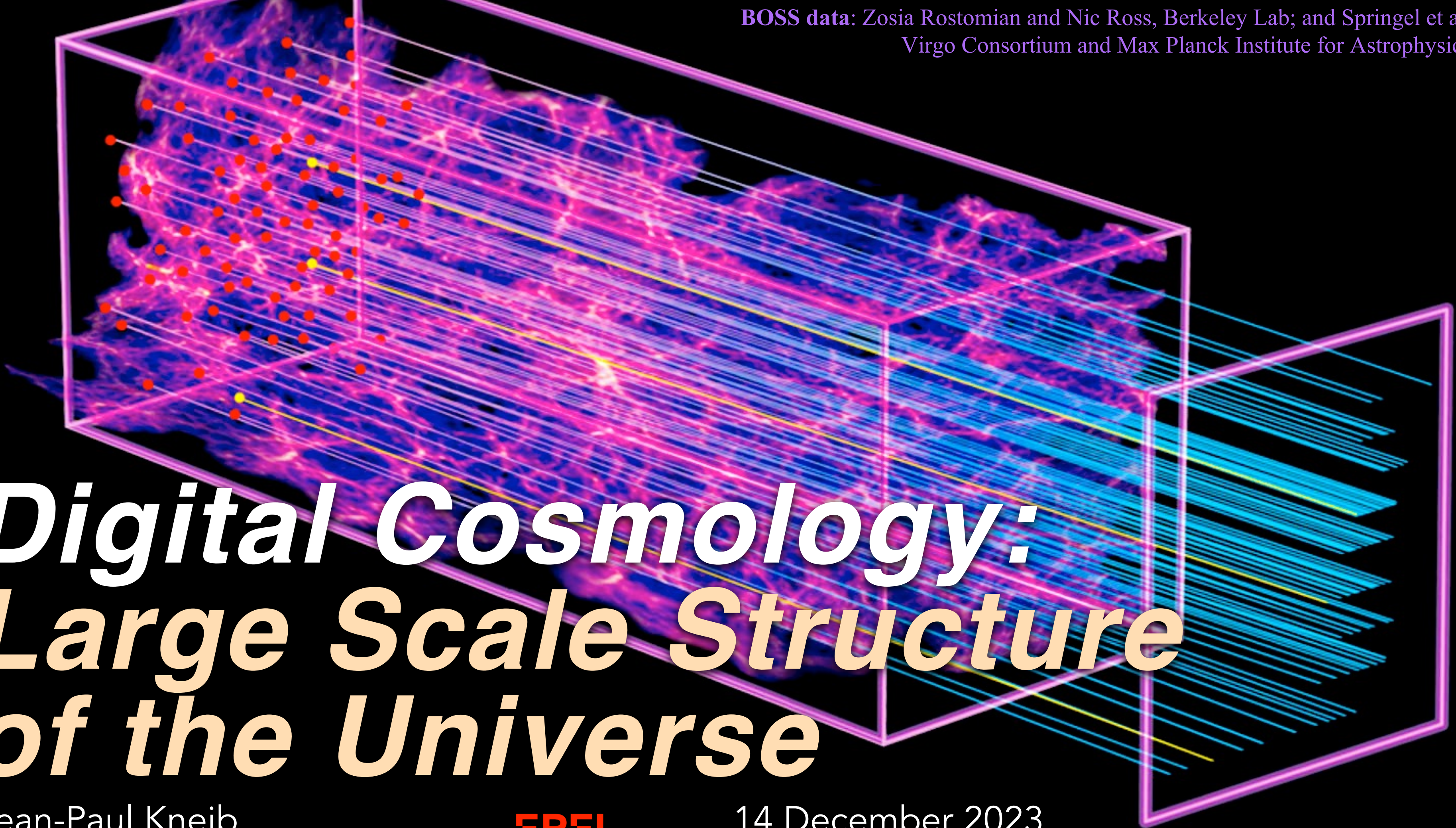


BOSS data: Zosia Rostomian and Nic Ross, Berkeley Lab; and Springel et al, Virgo Consortium and Max Planck Institute for Astrophysics

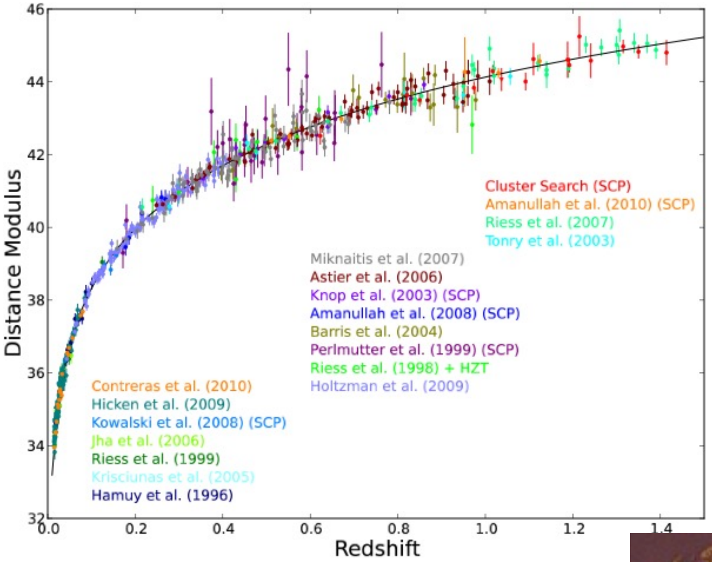
Digital Cosmology: Large Scale Structure of the Universe

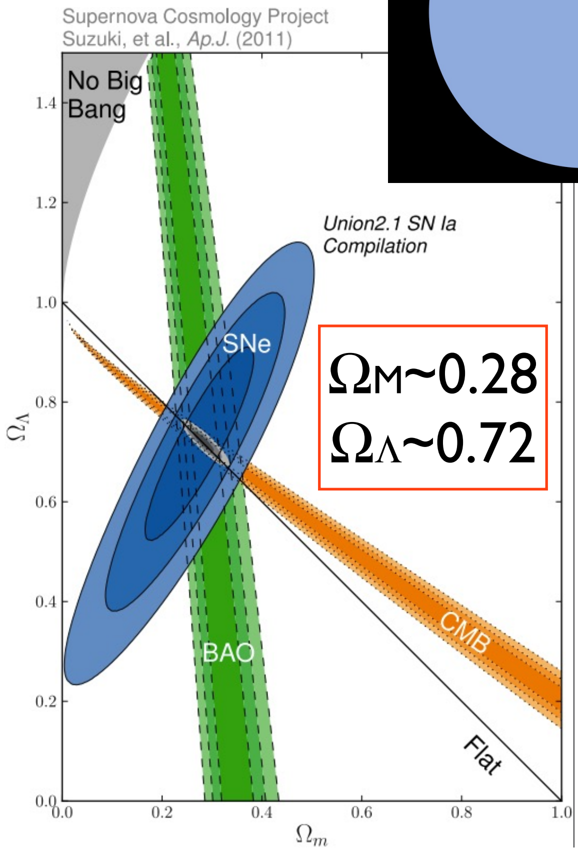
Jean-Paul Kneib

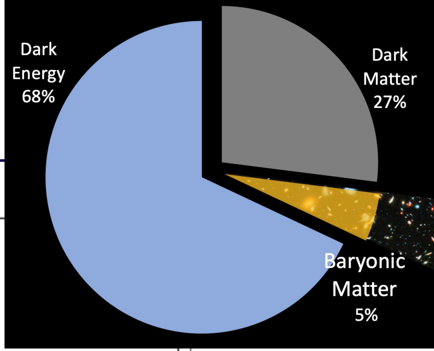
EPFL

14 December 2023

Precision Cosmology (2000-2012)



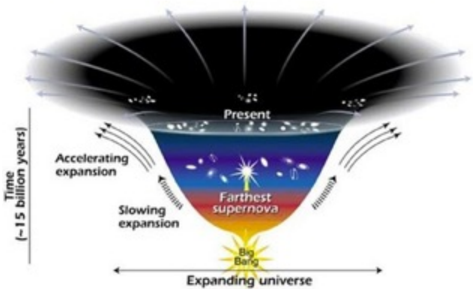


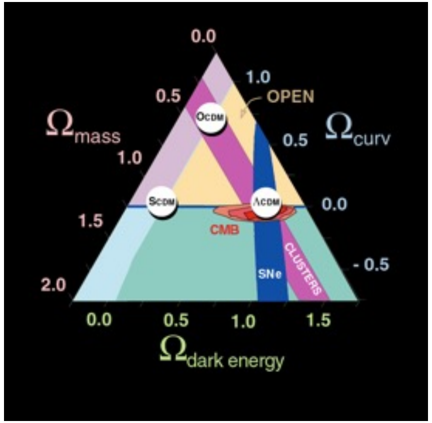


$\Omega_M \sim 0.28$
$\Omega_\Lambda \sim 0.72$

2010: ~600 SNIa
Confirmed the
Accelerated Expansion
2011: Nobel Prize

Understanding the accelerated expansion of the Universe





- **Origin of the accelerated expansion?** (many theories)
  - **Dark Energy** ? a new unknown component (probe its nature: eq. of state)
  - **Modified Gravity** ? correction of General Relativity on large scales
  - **Fractal Geometry/Scale Relativity??**
- **No good/simple/unique theory:** pragmatic approach need new observations => **precision cosmology:** requires measurement better than % level and not just at CMB redshift - ideally at any redshift !

=> NEED DATA

History of the Universe

from the ΛCDM *model*

LSS not well-known

LSS well-known

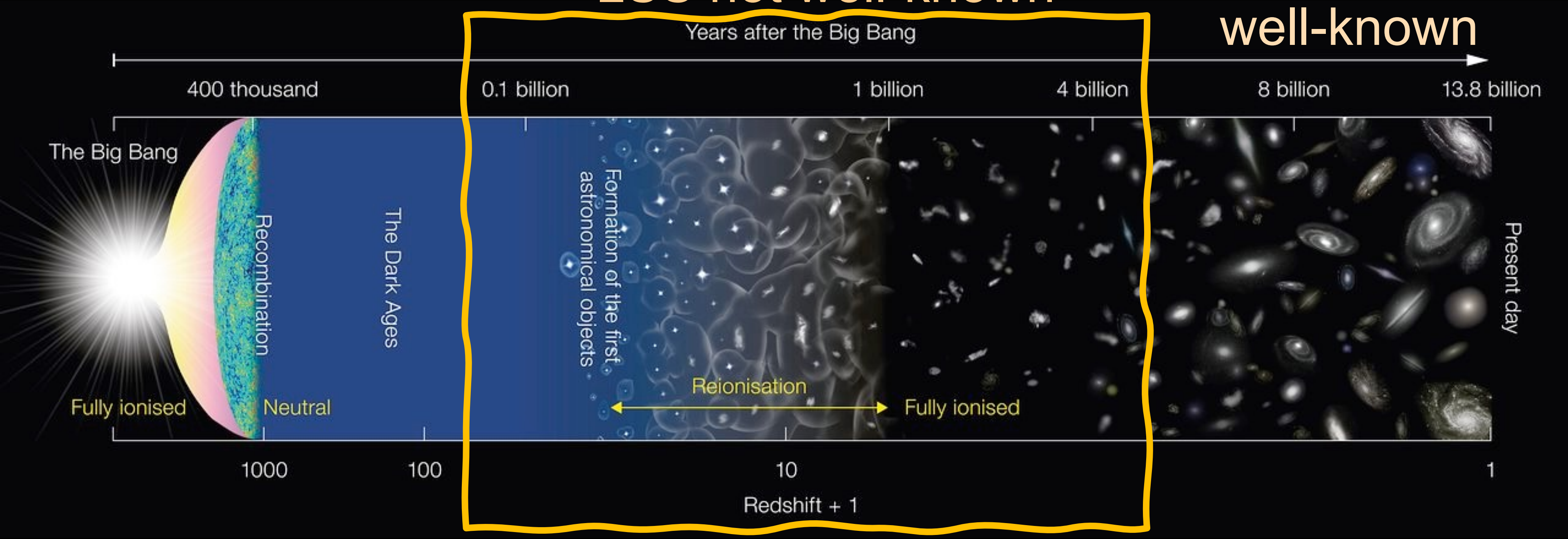
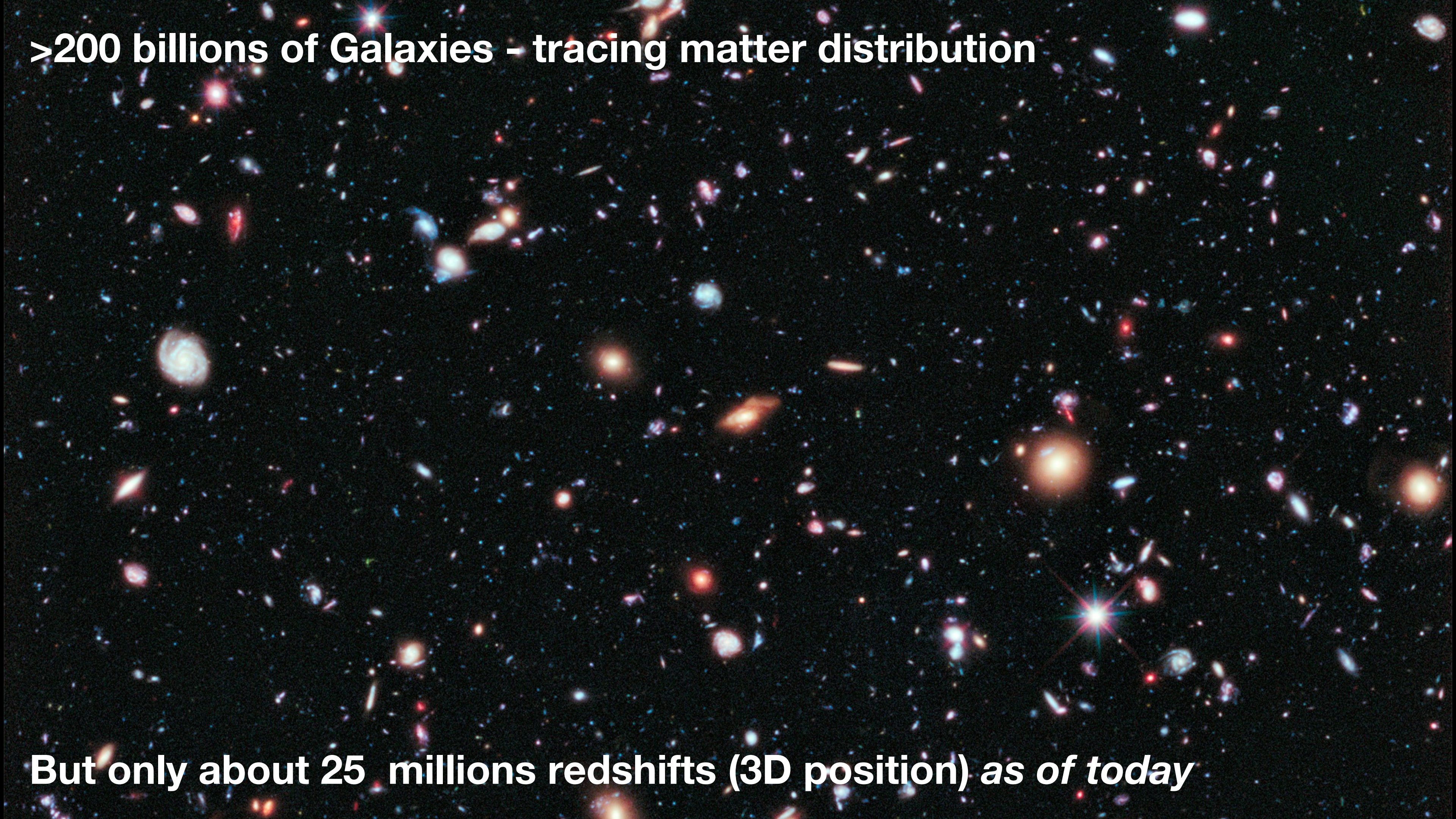
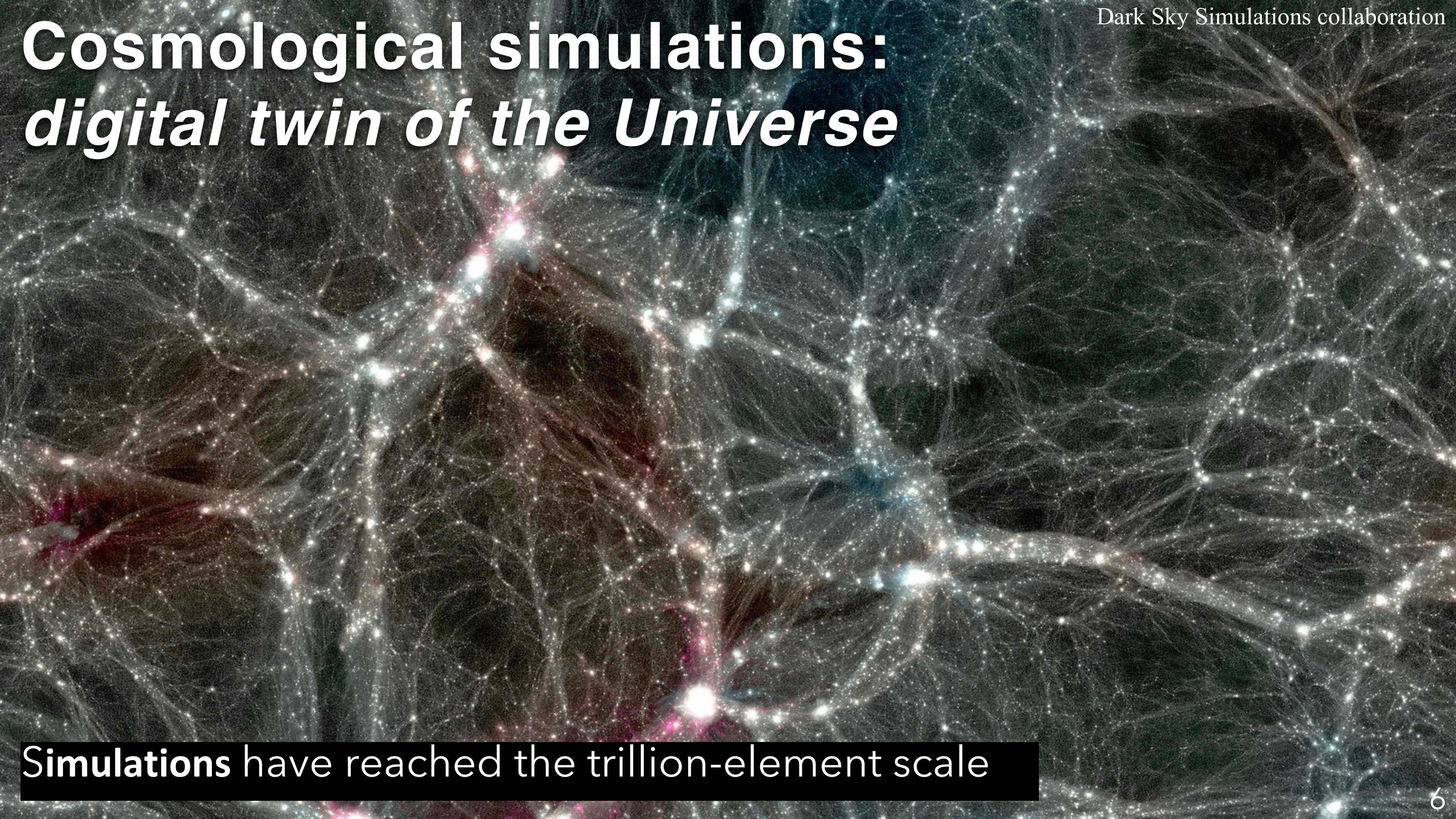


IMAGE: NAOJ


>200 billions of Galaxies - tracing matter distribution
But only about 25 millions redshifts (3D position) *as of today*

Cosmological simulations: *digital twin of the Universe*



Dark Sky Simulations collaboration

Simulations have reached the trillion-element scale

Entering a new era: >> Digital Cosmology (2020+) <<

- **Cosmology is becoming Digital:**
  - *Growth of data flow*
    - Optical/near-infrared data: growth of detector size & number of detectors
    - Radio data: growth of the number of antennas $O(N^2)$ {SKAO}
    - Gamma-ray data {CTAO}
    - Gravitational Wave data {AdvLigo, LISA, ET}
    - X-correlation between different datasets
  - *Growth of size of numerical simulations*
    - More precise simulated data to match the observations (smaller size and resolution element) + more physics in simulations (baryons, CRs, B-field …)
    - Large mocks catalogues to compute covariance matrices and evaluate measurement errors

Mapping the LSS of the Universe

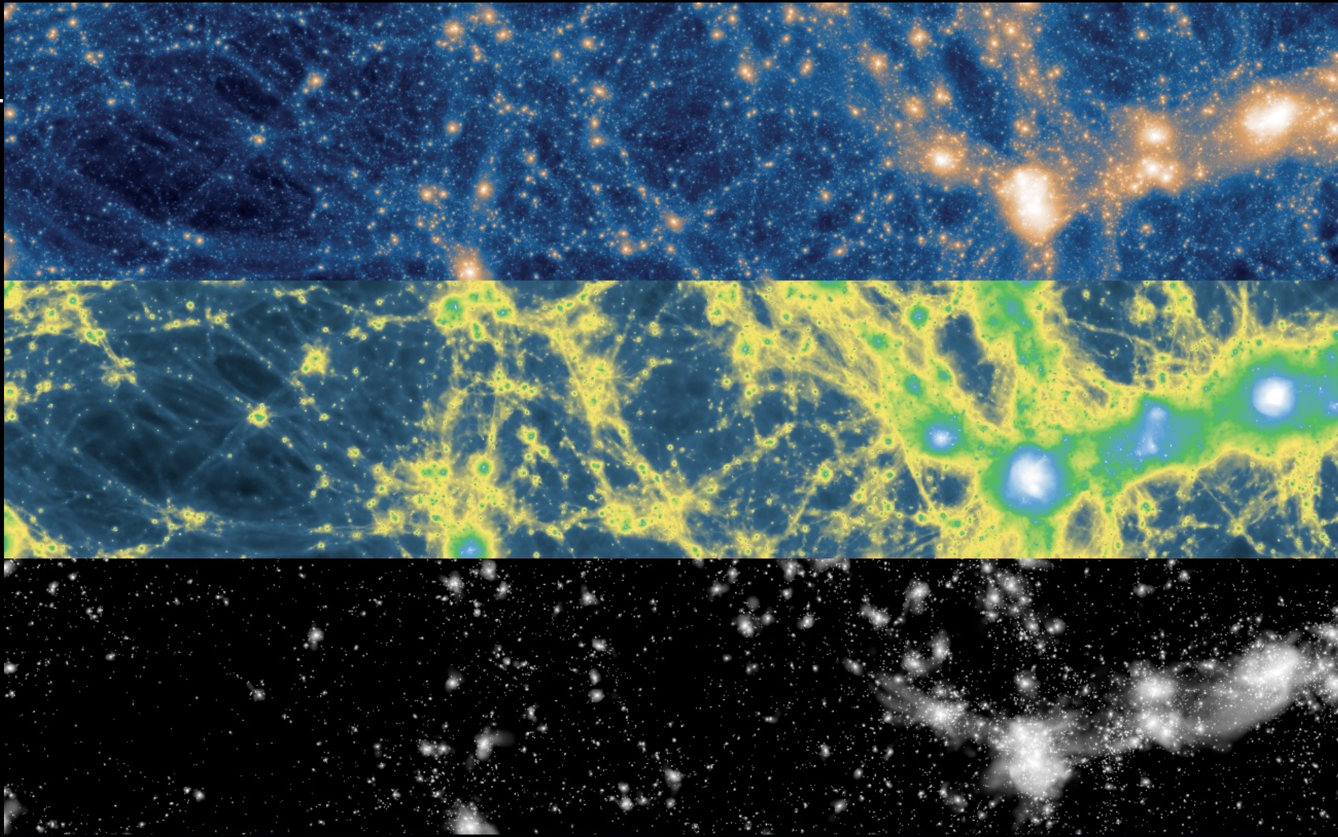
- **No simple explanation of the Dark Matter/Dark Energy/Dark Ages**
  - Precision measure shall provide answers
  - Requires Big Data

- **Improve precision is OK**
  - but also need to minimise/understand/control systematics
  - Multi-probe & multi-messenger are key elements to reduce systematics

- **Large dataset also means large computing**
  - GPU computing is key for speed-up massive data computing
  - AI/ML approaches for large dataset exploration (e.g. finding strong lensing systems) also requires GPU

Massive DATA to map the Universe in 3D

illustrisTNG collaboration



Dark Matter: the most abundant kind of matter in the Universe

=> **Euclid project**

Hydrogen: the most abundant element in the Universe

=> SKAO project

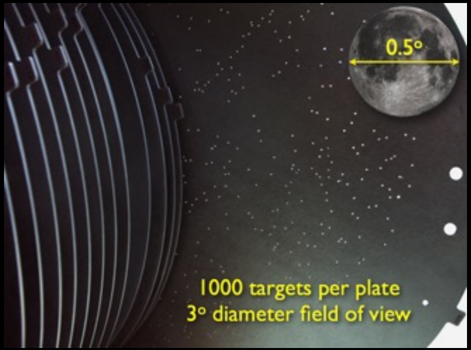
Galaxies: densest & brightest regions in the Universe

=> LSS 3D mapping

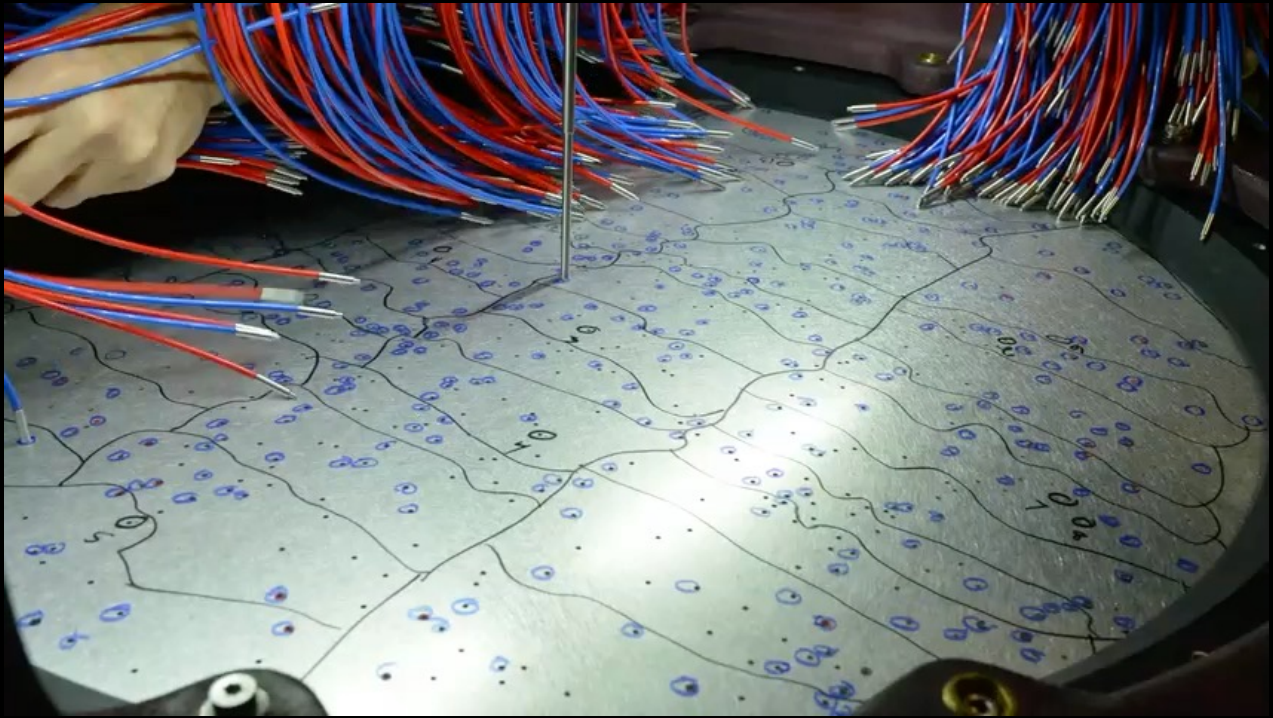
… and Transients Sources (GR, CR, FRB, GW …)

Galaxy 3D map
(In progress & roadmap)

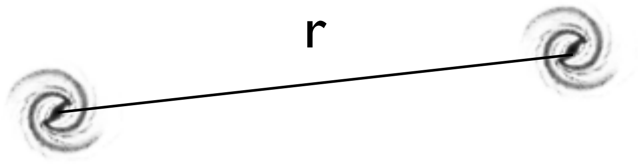
The *Sloan* Digital Sky Survey



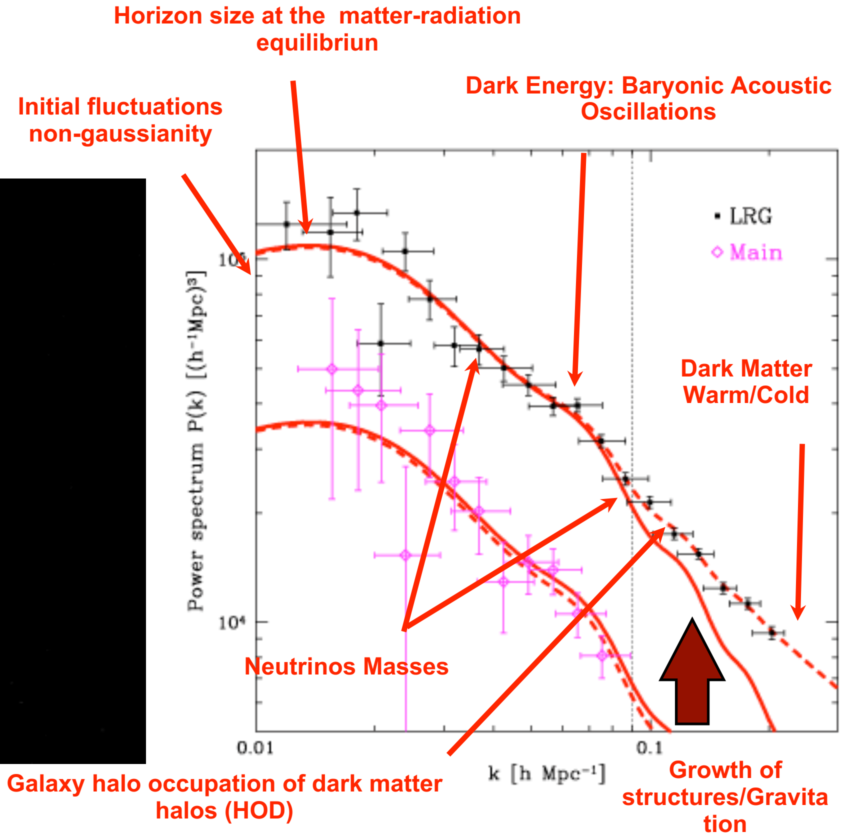
4 millions of measurements
In 20 years !



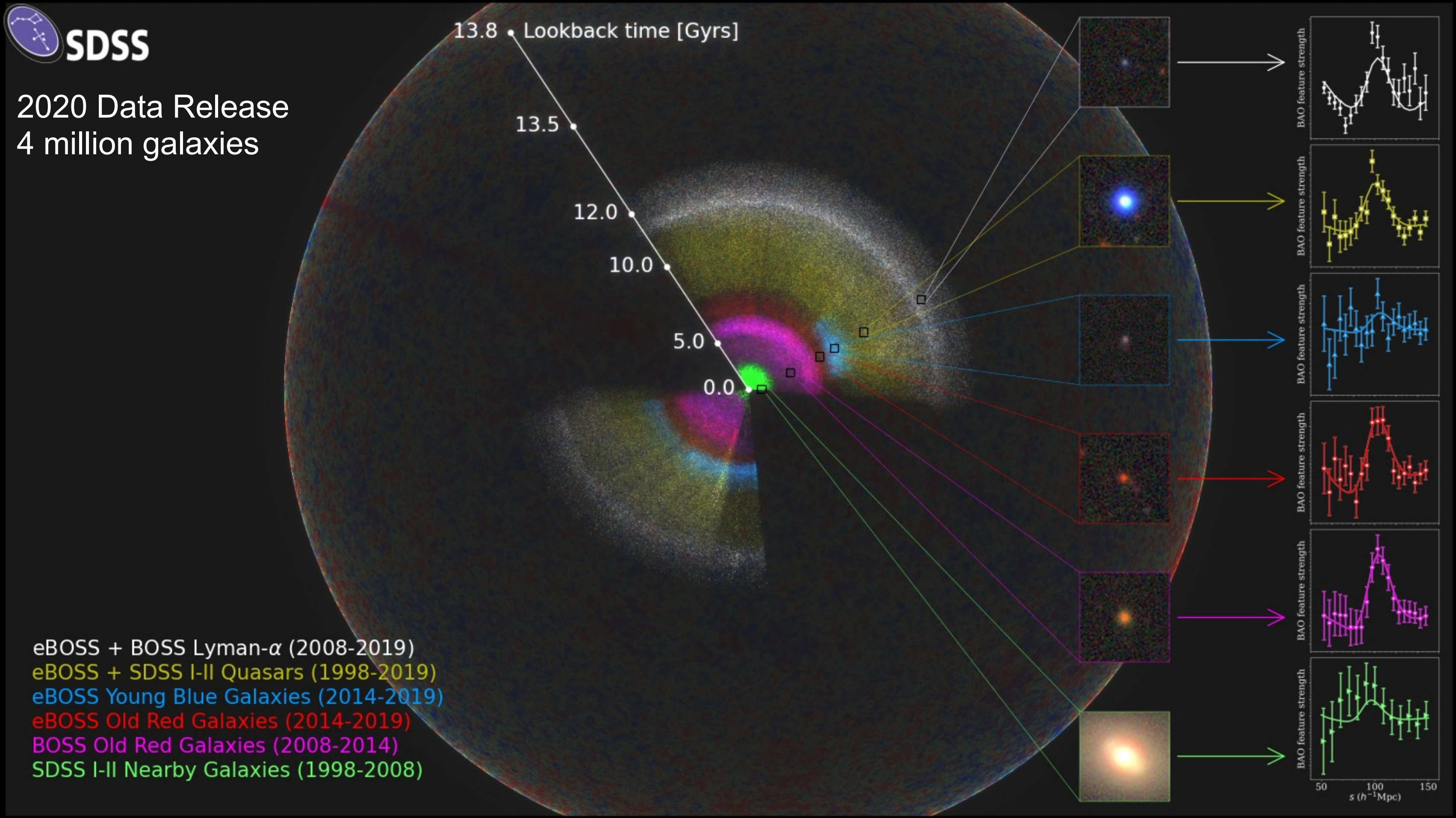
Power Spectrum of Galaxy distribution



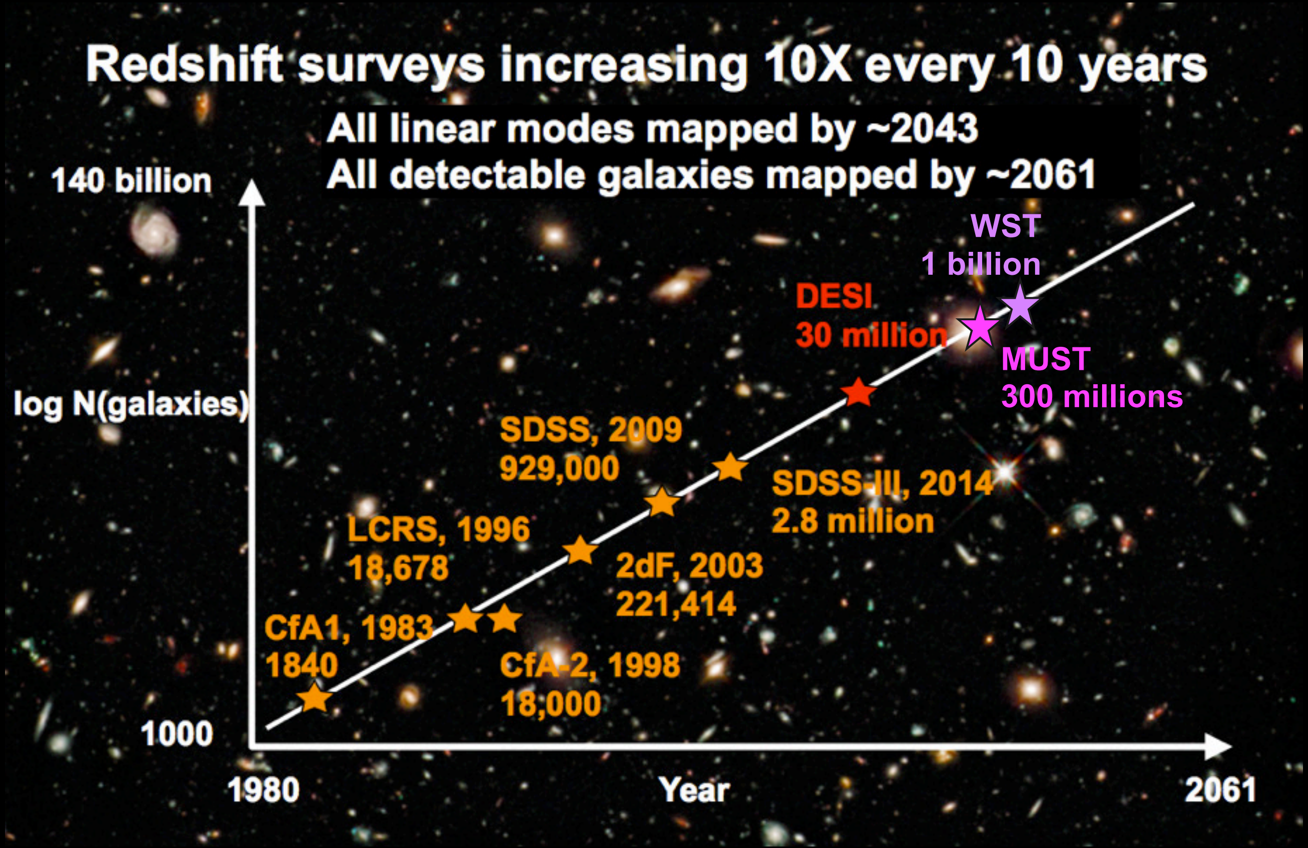
3D mapping of galaxies in the universe
(SDSS 2020)



Data-Intensive Astronomy - SDSS 20-year of data

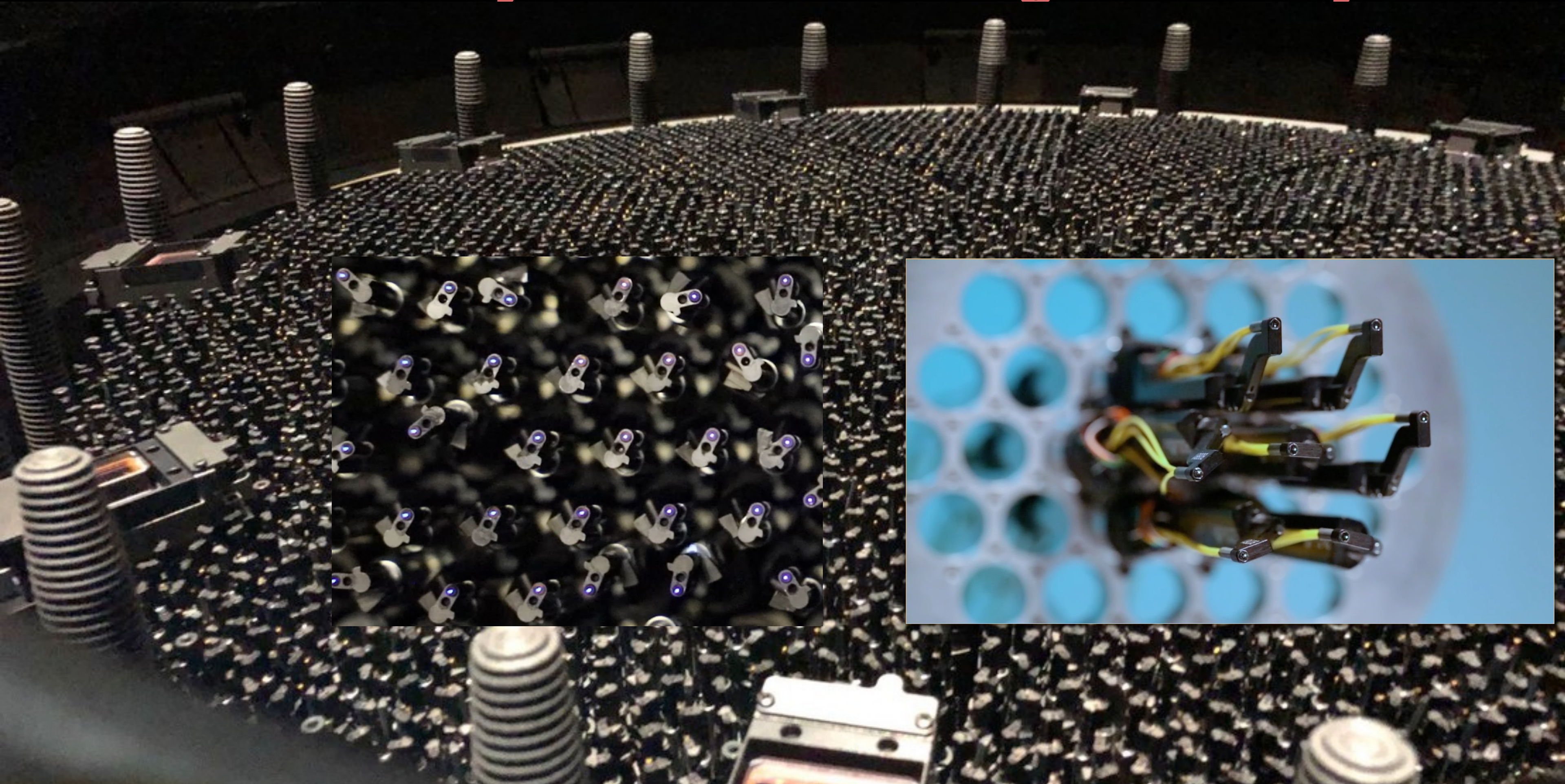


Universe in 3D: Massive Spectroscopic Surveys



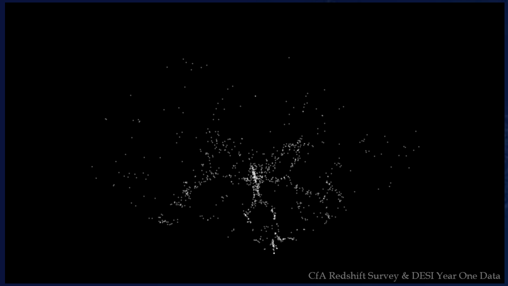
From D. Schlegel

5’000 robotic eyes … 40 million galaxies by 2025

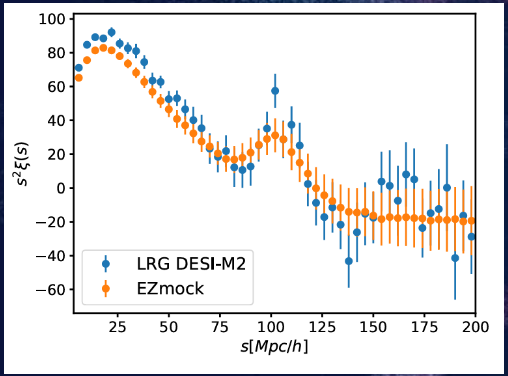


Year-1 DESI data release in summer 2024

10 million measurements

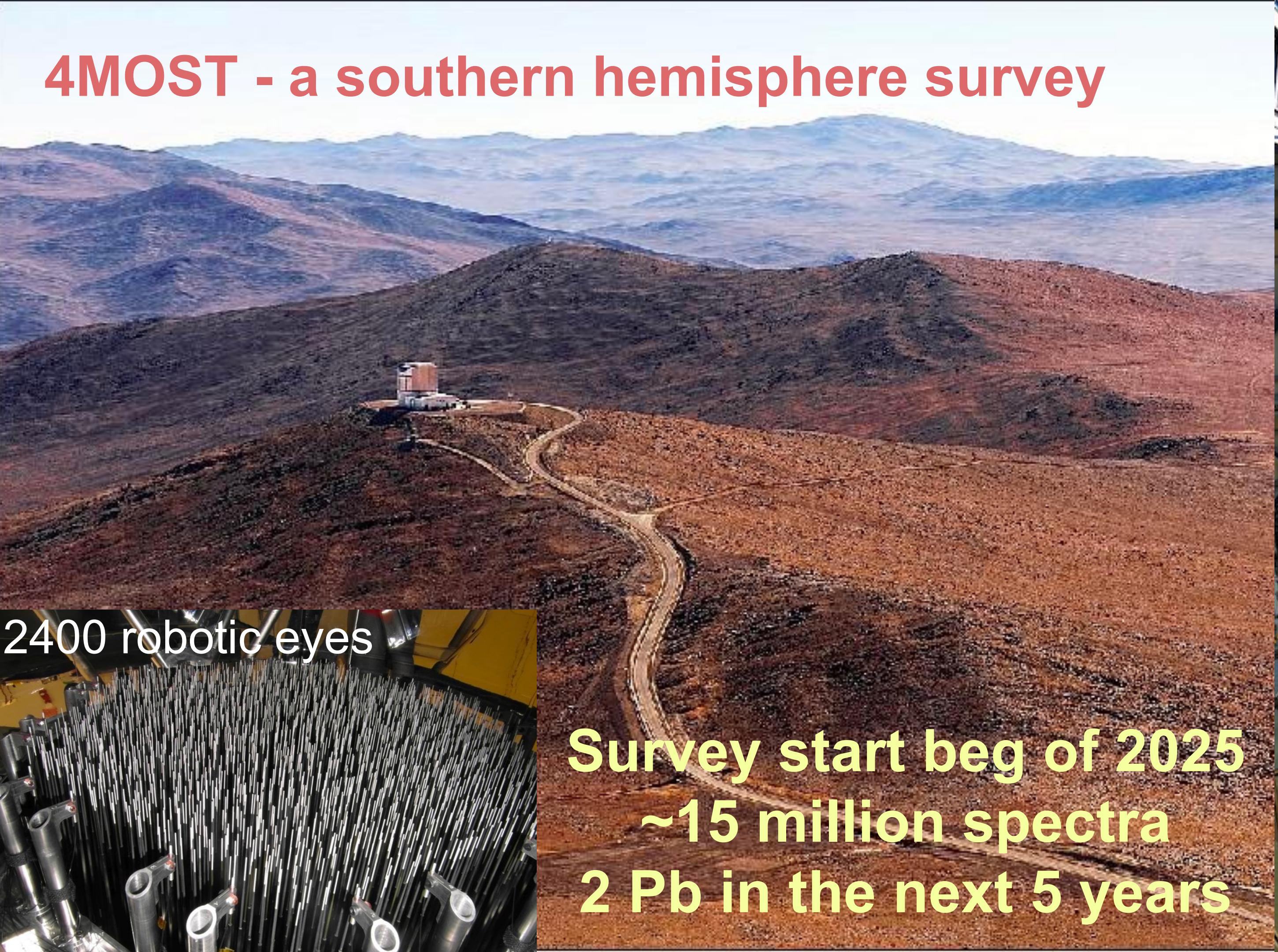


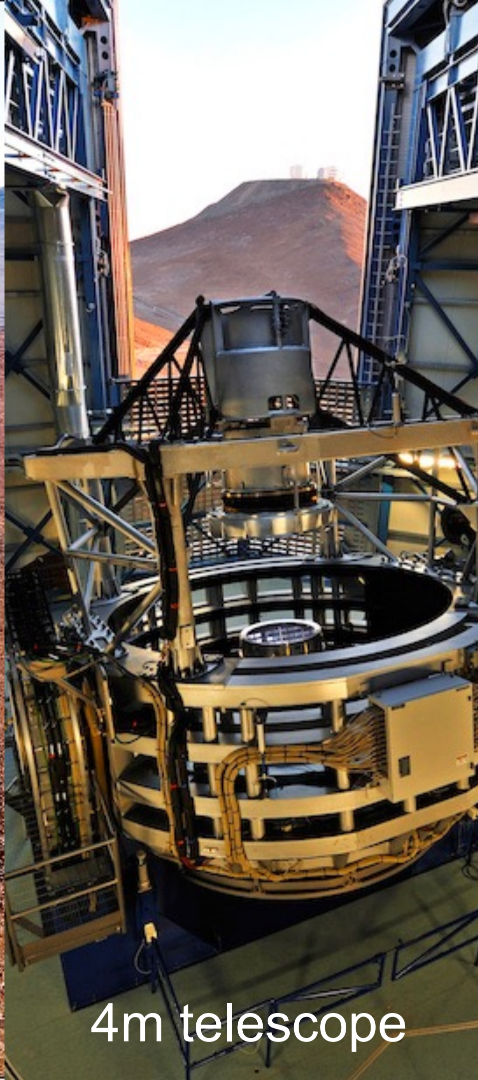
Current BAO (April 2023)
precision of 1.7% for LRG
ultimately 0.3%



After 5 year survey
40 millions measurements
and ~3 Pb of data

4MOST - a southern hemisphere survey

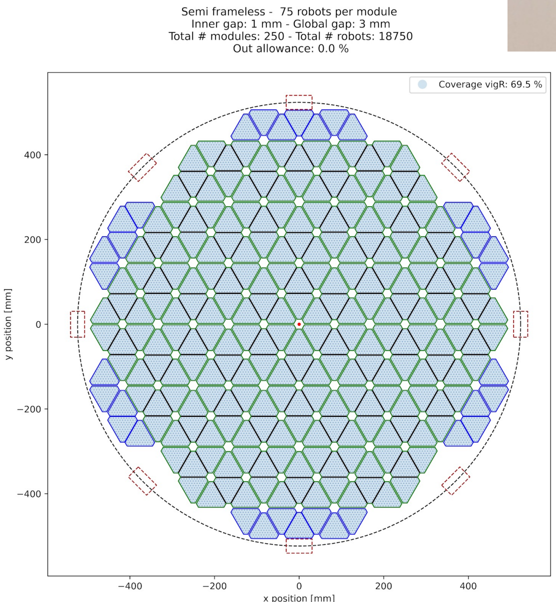


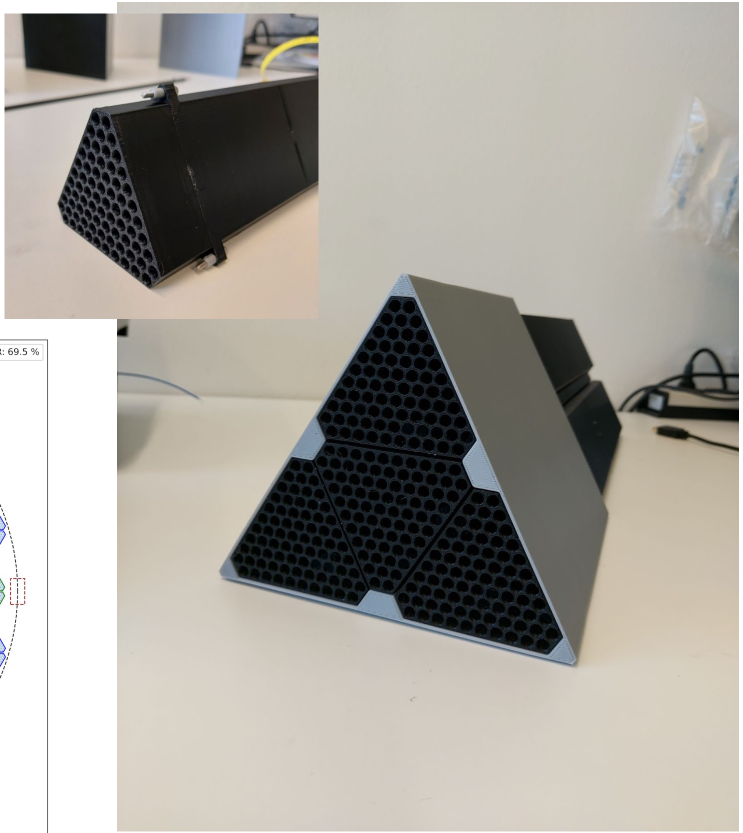


Future survey in preparation, aiming to 20’000 robotic eyes …
Miniaturisation of robots for future projects

Development in progress at EPFL.

6.2mm diameter robots to be packed
in a triangular modules to ensured robustness.





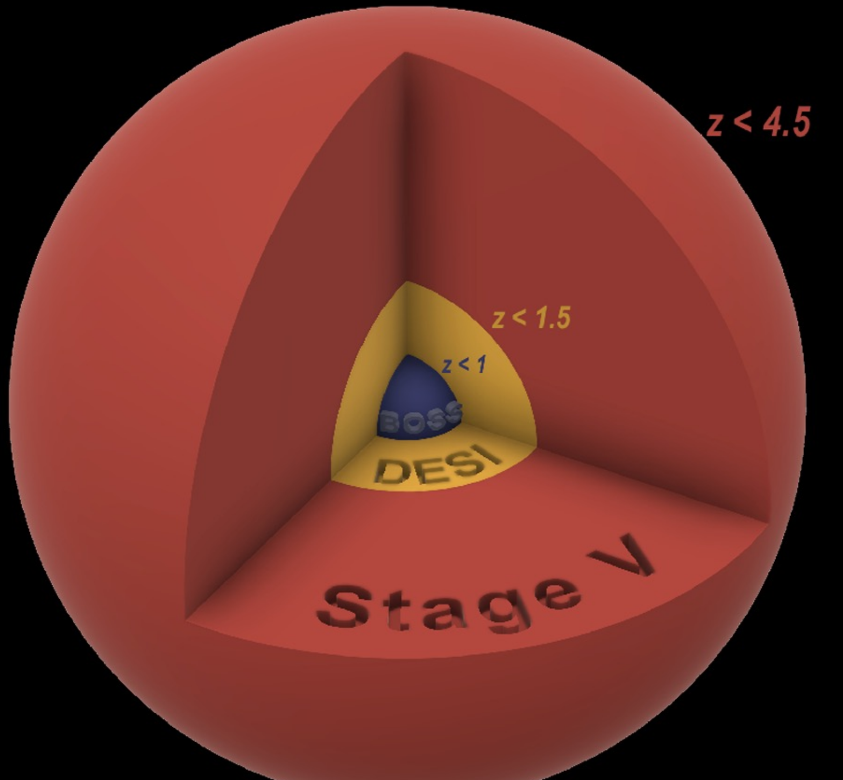
Stage 5 requires mapping the more distant universe at 2 < z < 6

— Larger volume

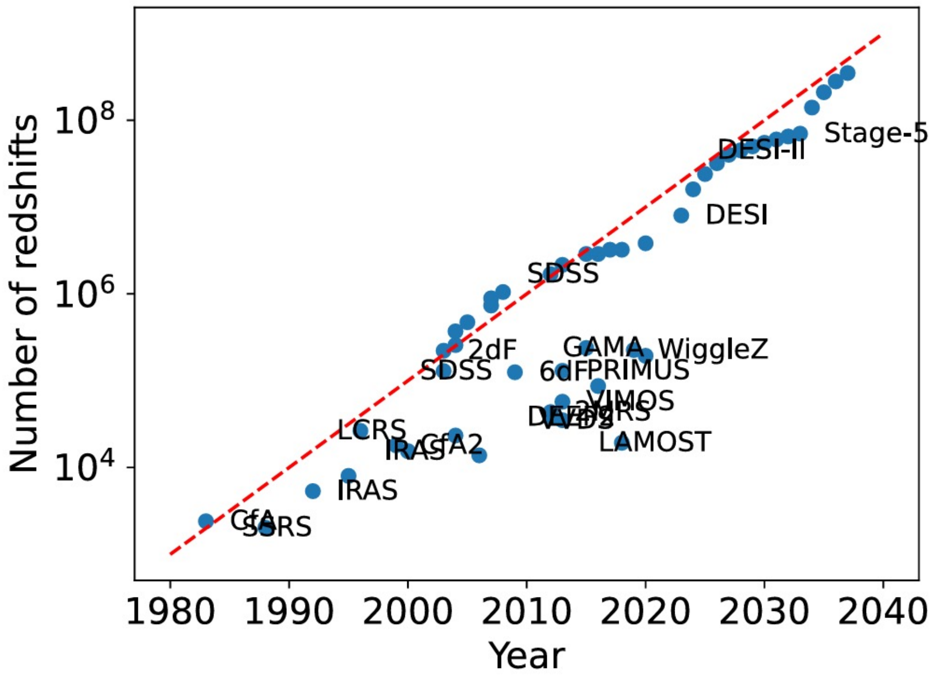
linear modes well-correlated with init. cond., less affected by late-time astrophysics

— Larger redshift range

degeneracy breaking, measures early->late Dark Energy

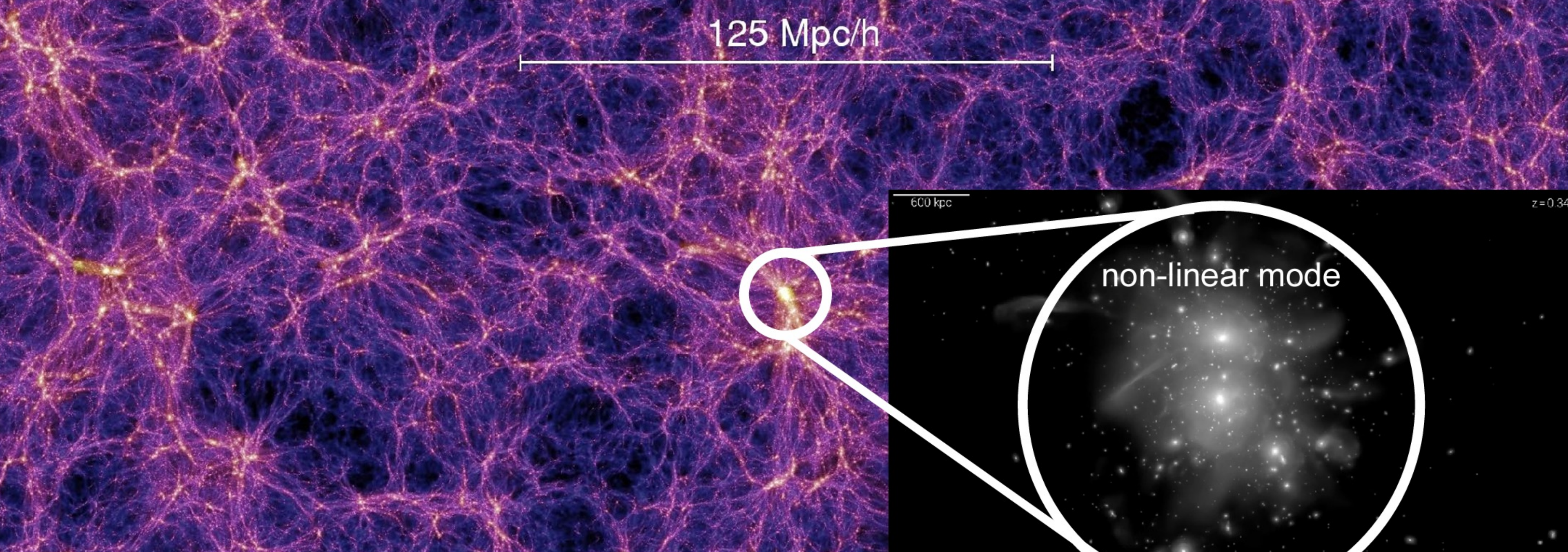


Supported by P5 report: DESI-II & R&D work for Stage-5



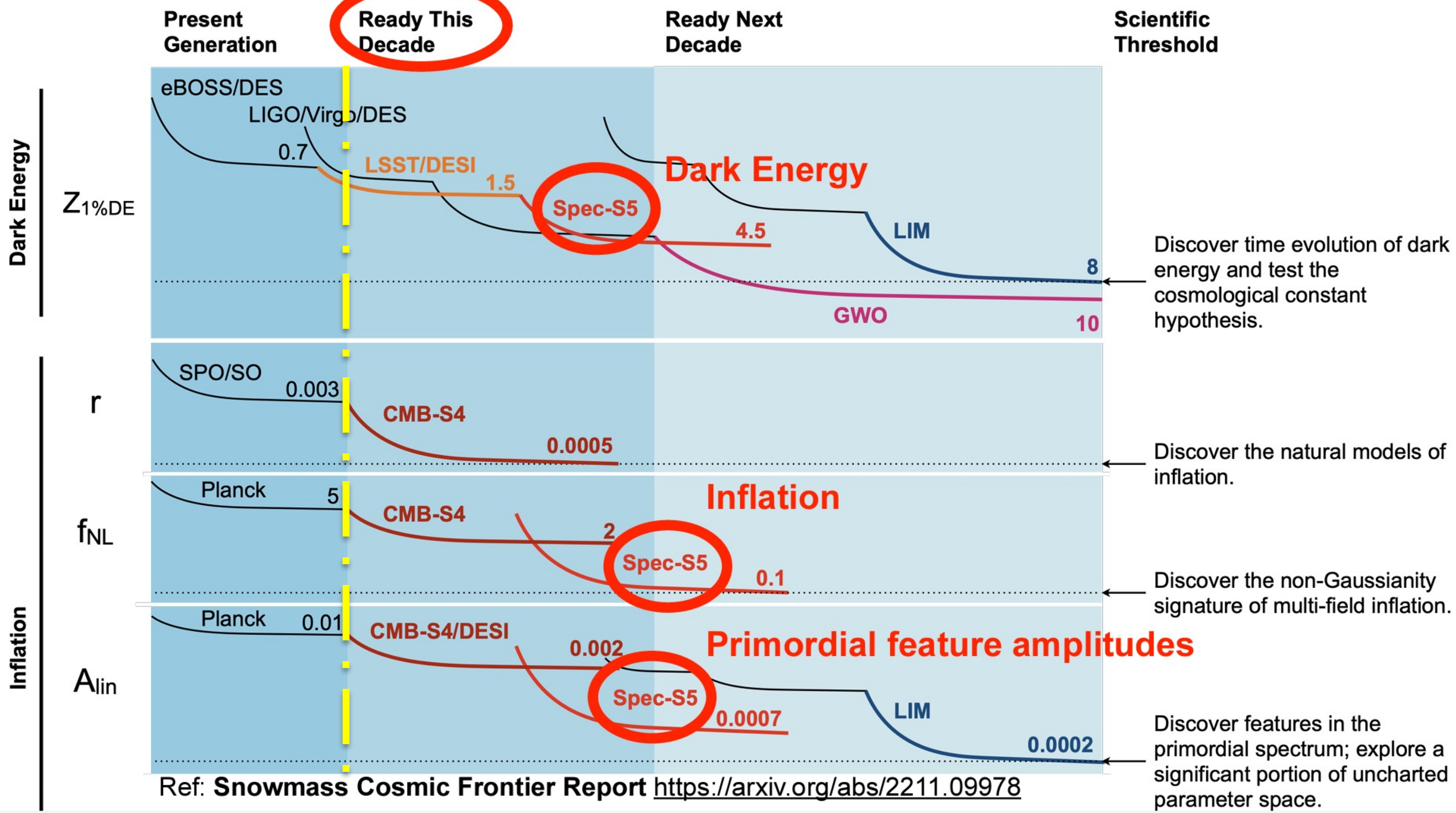
Stage 5 Spectroscopy reaches 10X the “Primordial Figure of Merit” by mapping 10X more linear modes than DESI

These are the quantum fluctuations imprinted on galaxy maps
Experimental signal-to-noise scale as √number of modes



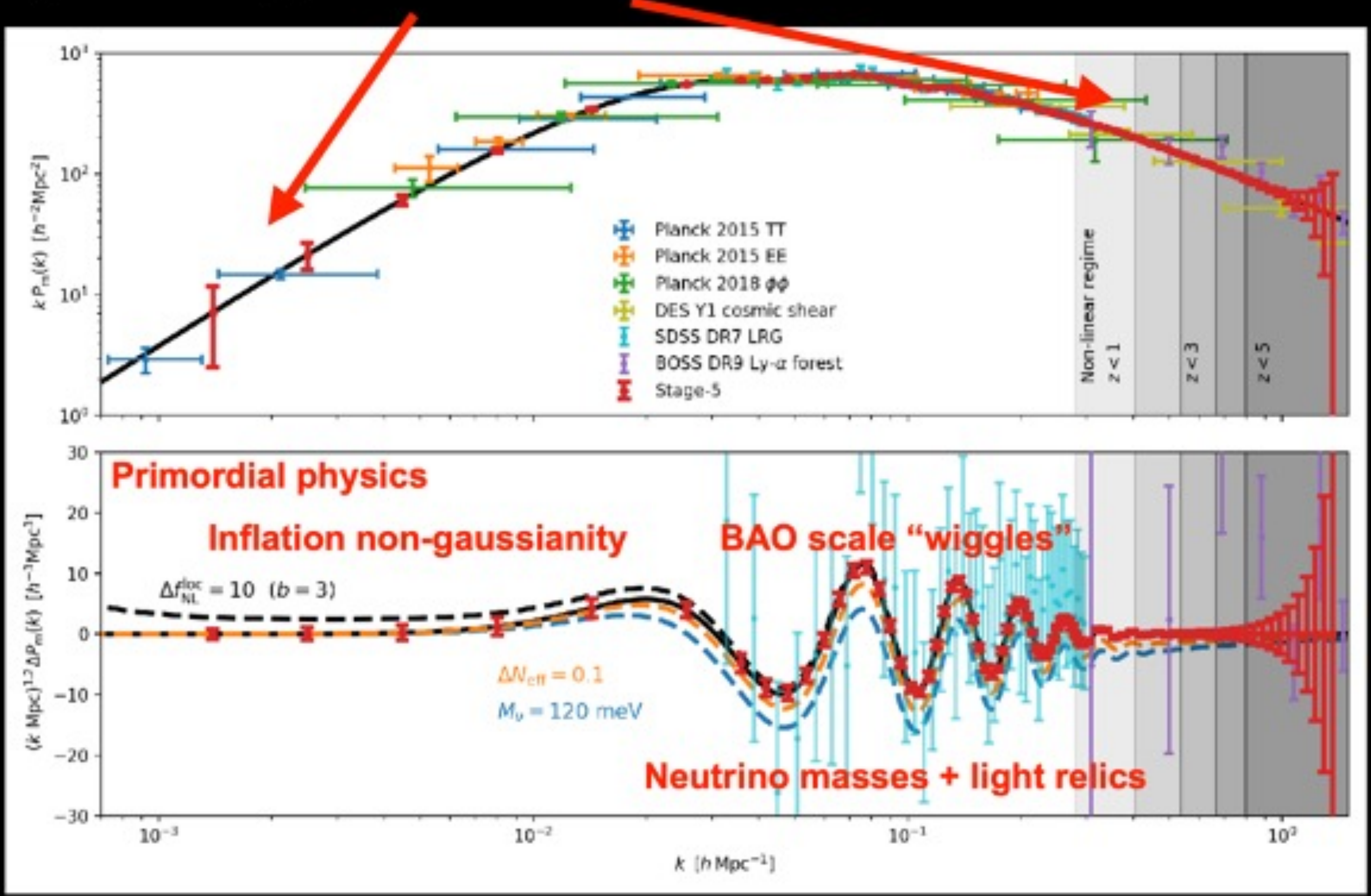
Credits: Millenium simulation, IllustrisTNG

Stage 5 Spectroscopy will probe both epochs of accelerated expansion



Ref: **Snowmass Cosmic Frontier Report** https://arxiv.org/abs/2211.09978

Stage 5 Spectroscopy extends to more volume + smaller scales than DESI



Based on Sailer, Castorina, Ferraro & White (2022)

UST: next stage-5 survey
d by Tsinghua University

6.5m telescope

MOS with 20’000 fibers

R=5000 spectroscopy

First light 2030

8 Pb per year

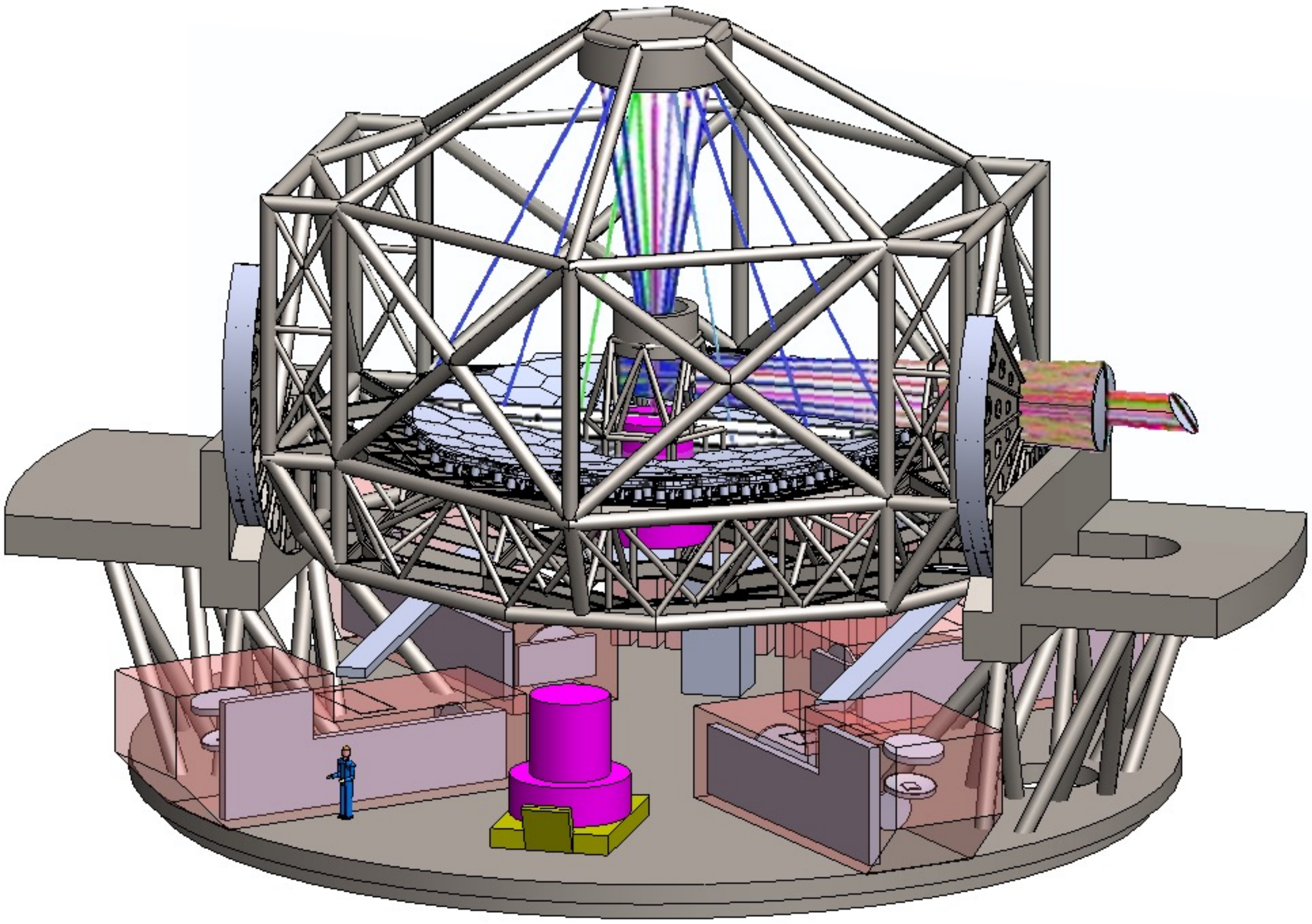
https://www.wstelescope.com/

WIDE-FIELD
SPECTROSCOPIC
TELESCOPE

European led
consortium

12m telescope
MOS+IFU
LR+HR
spectroscopy

First light 2040?
~20 Pb per year



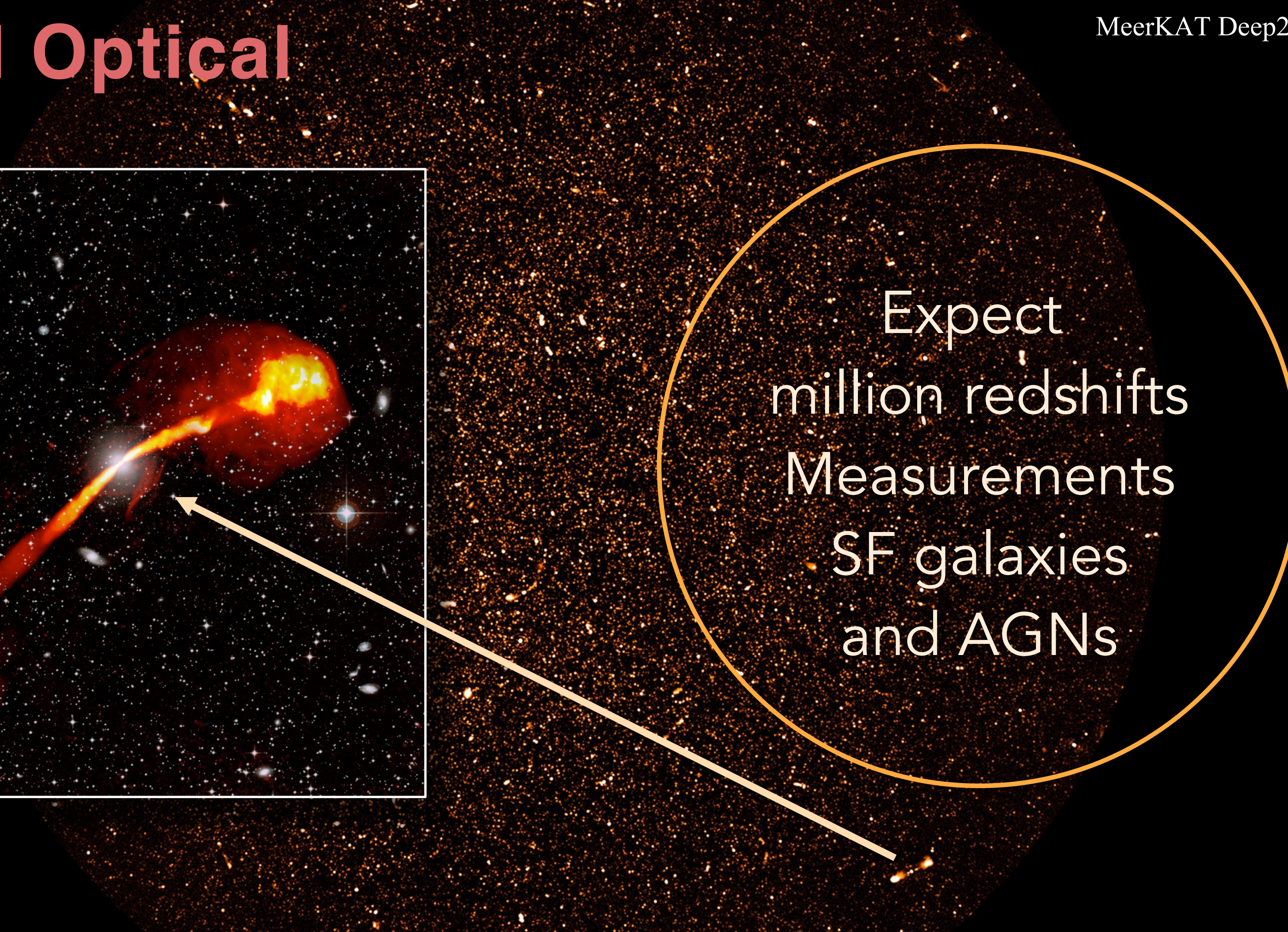
Hydrogen Mapping (Just starting)

Radio domain: a new Window on the Universe

MeerKAT Deep2 field

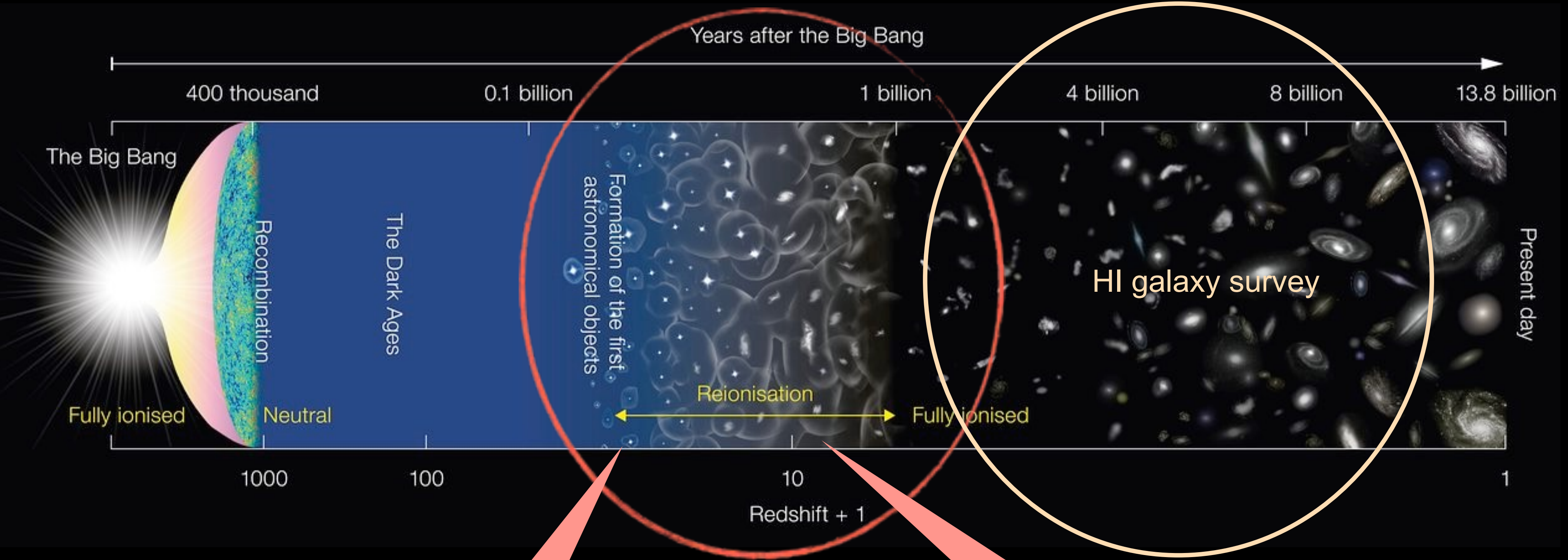
Beyond Optical

MeerKAT Deep2 field



Cosmic Reionization

Image Credit: Marcelo Alvarez, Ralf Kaehler and Tom Abel



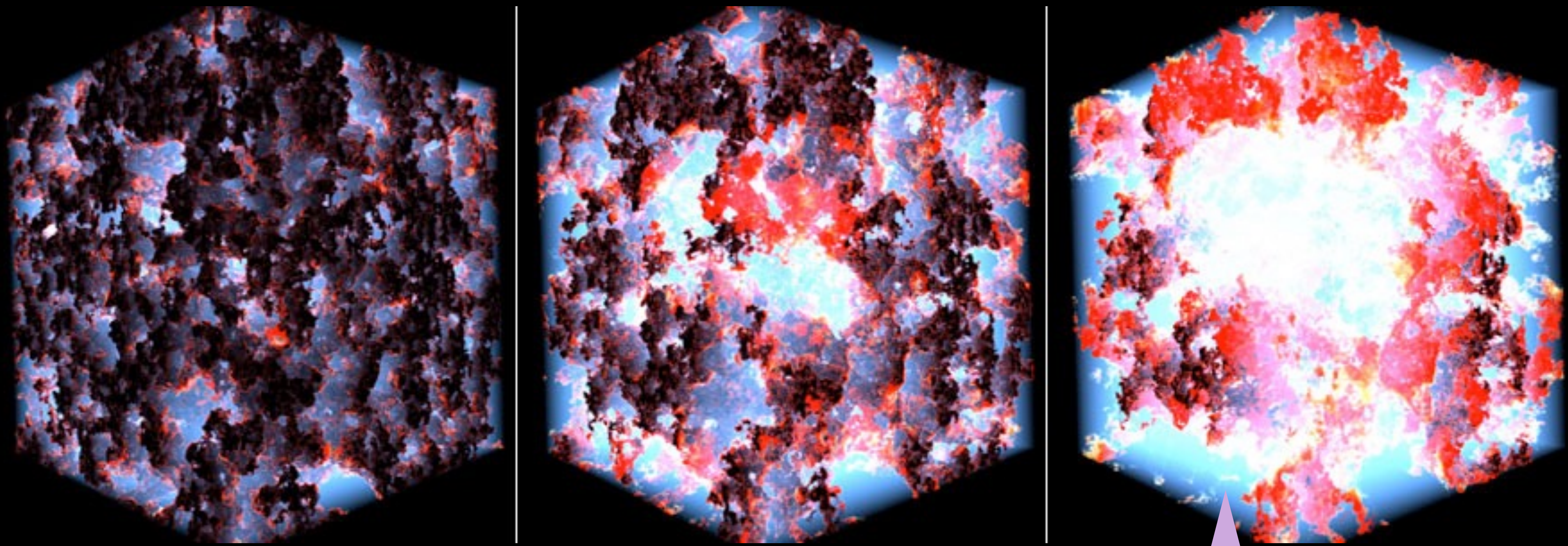
End of Dark Ages

The Epoch of Reionization

Cosmological EoR Simulations

Image Credit: Marcelo Alvarez, Ralf Kaehler and Tom Abel

time



Opaque

Transparent

Ray tracing Simulations of radiative feedback need O(10^6) core hours

Radio Astronomy - development at EPFL

Interdisciplinary approach

- **High-Performance Computing**
  - Co-design of radio astronomy pipelines
  - Tools for to evaluate energy-to-solution in addition to time-to-solution
- **Generalizable/interpretable deep learning**
  - Physics-Informed Neural Networks (PINNs) applied to cosmological simulations
  - Scattering transform for analyzing galactic morphologies
- **Imaging in Radio Astronomy**
  - Applying algorithms for quantum image processing to radio interferometry
  - New algorithms for imaging using fPCA

Summary - Digital Cosmology

- To Understand the Universe - Dark Matter, Dark Energy, Dark ages … (but also transients and gravitational waves …)
- A data deluge challenges is coming up !
- Challenges: Data handling, processing and computing - specially for the new SKA Observatory
- Need to get prepared and work on data/compute challenges!

Link with CTA Science – lots of Synergies

- 3D Galaxy mapping will collect hundreds million redshifts in the next 10 years => *huge legacy resource for transient follow-up*
- LSS put lower bound on the EBL by counting galaxies. Gamma-ray upper bounds may at some point hit into the lower bounds from galaxy counts.
- Magnetic fields play role in structure formation and reionisation, affecting dwarf galaxy abundances, modifying star formation history and affecting 21cm line
- Cosmological simulations involves more complex physics (MHD) and can synergize with modelling of gamma-ray measurements of intergalactic magnetic fields
- **Massive Dataset Computing is a big synergy between LSS/SKAO/CTAO**