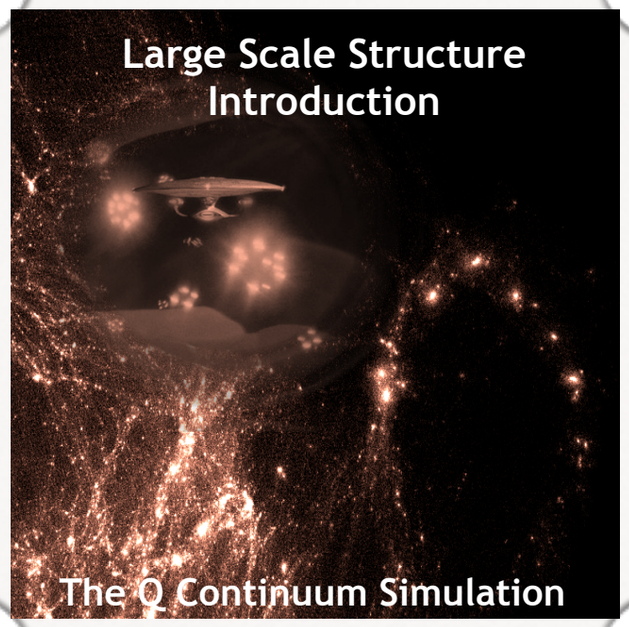
Testing the LCDM Paradigm with Large-Scale Structure Probes

Katrin Heitmann

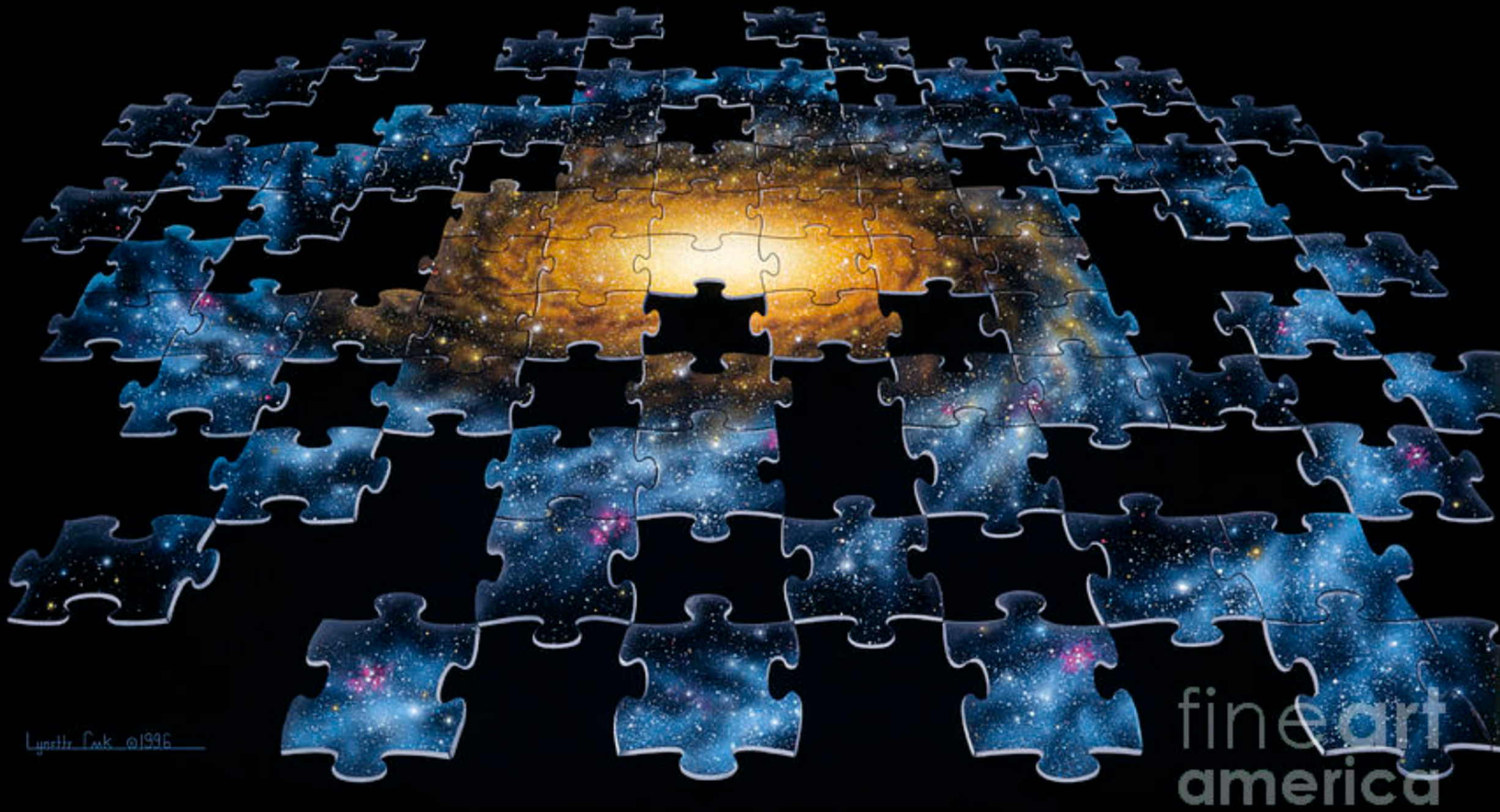
In Search of New Paradigms

Brookhaven Forum, October 13, 2017



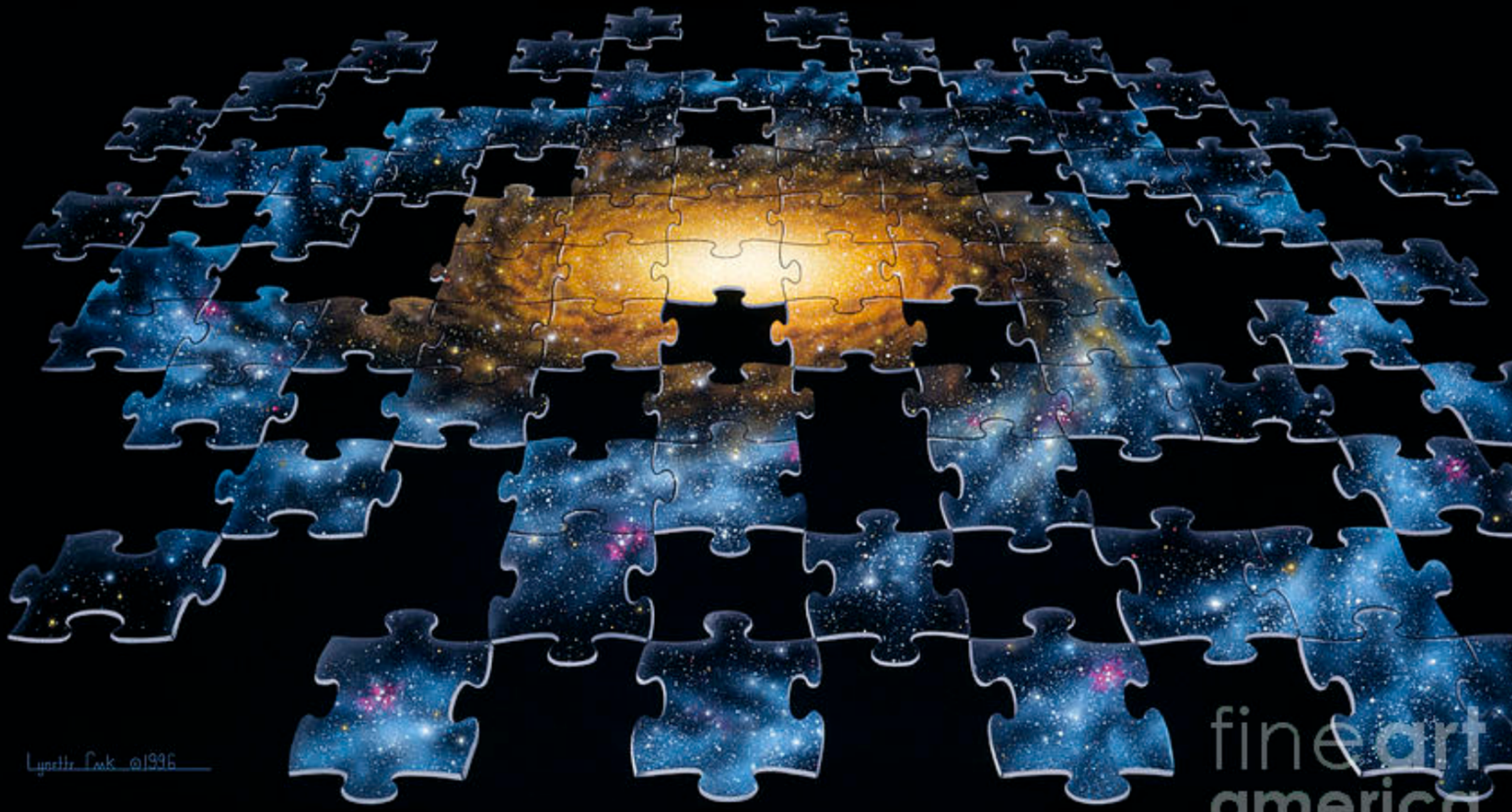
Disclaimers: (i) I am a theorist! (ii) There are a large number of observations and analysis efforts going on, results are continuously updated with new data releases, I can only show a glimpse of what is out there — apologies in advance if your favorite survey or probe is missing!

In Search of New Paradigms…



Galaxy Puzzle by Lynette Cook

In Search of New Paradigms…
… Physics Beyond the Standard Model of Cosmology



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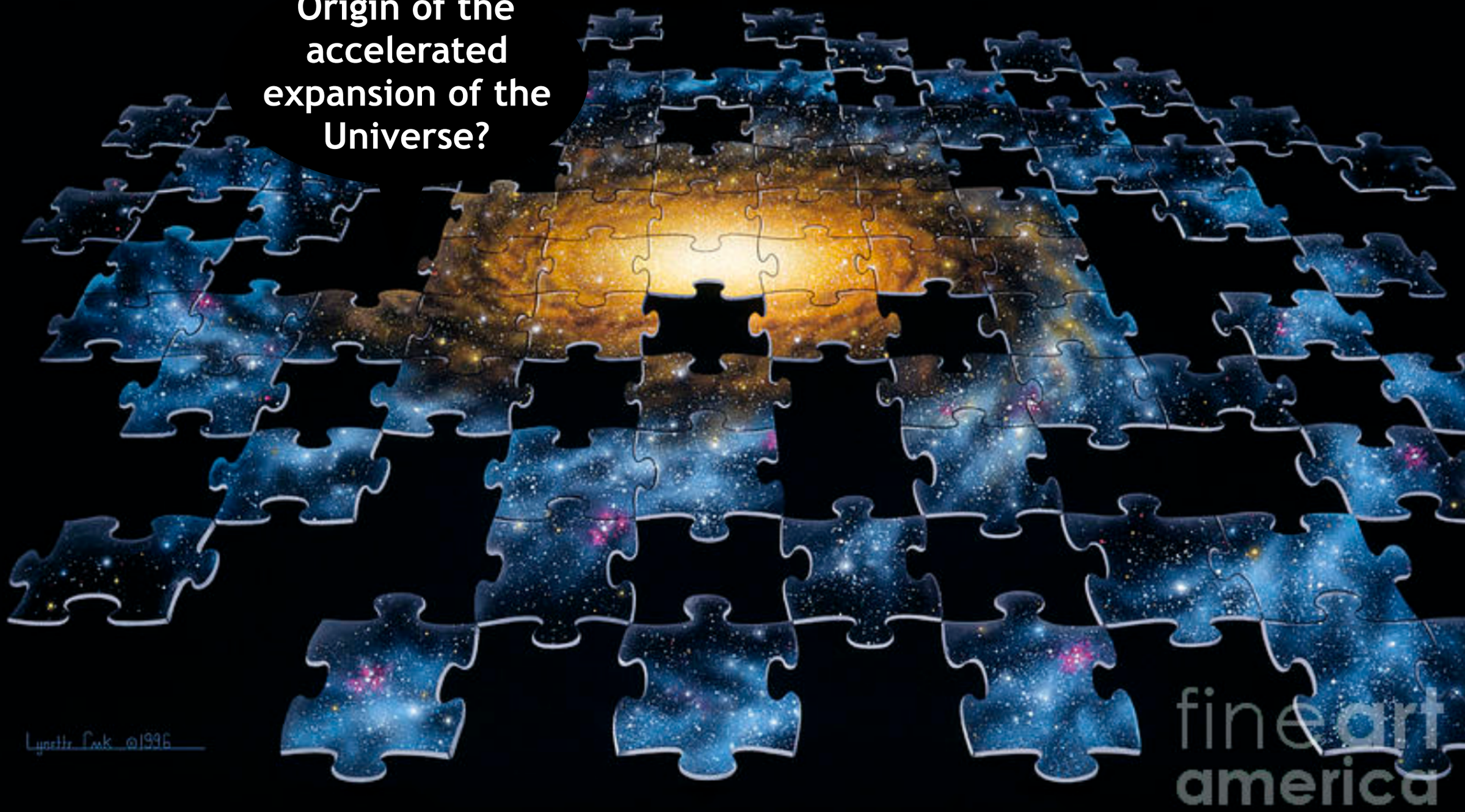
In Search of New Paradigms…

Origin of the accelerated expansion of the Universe?



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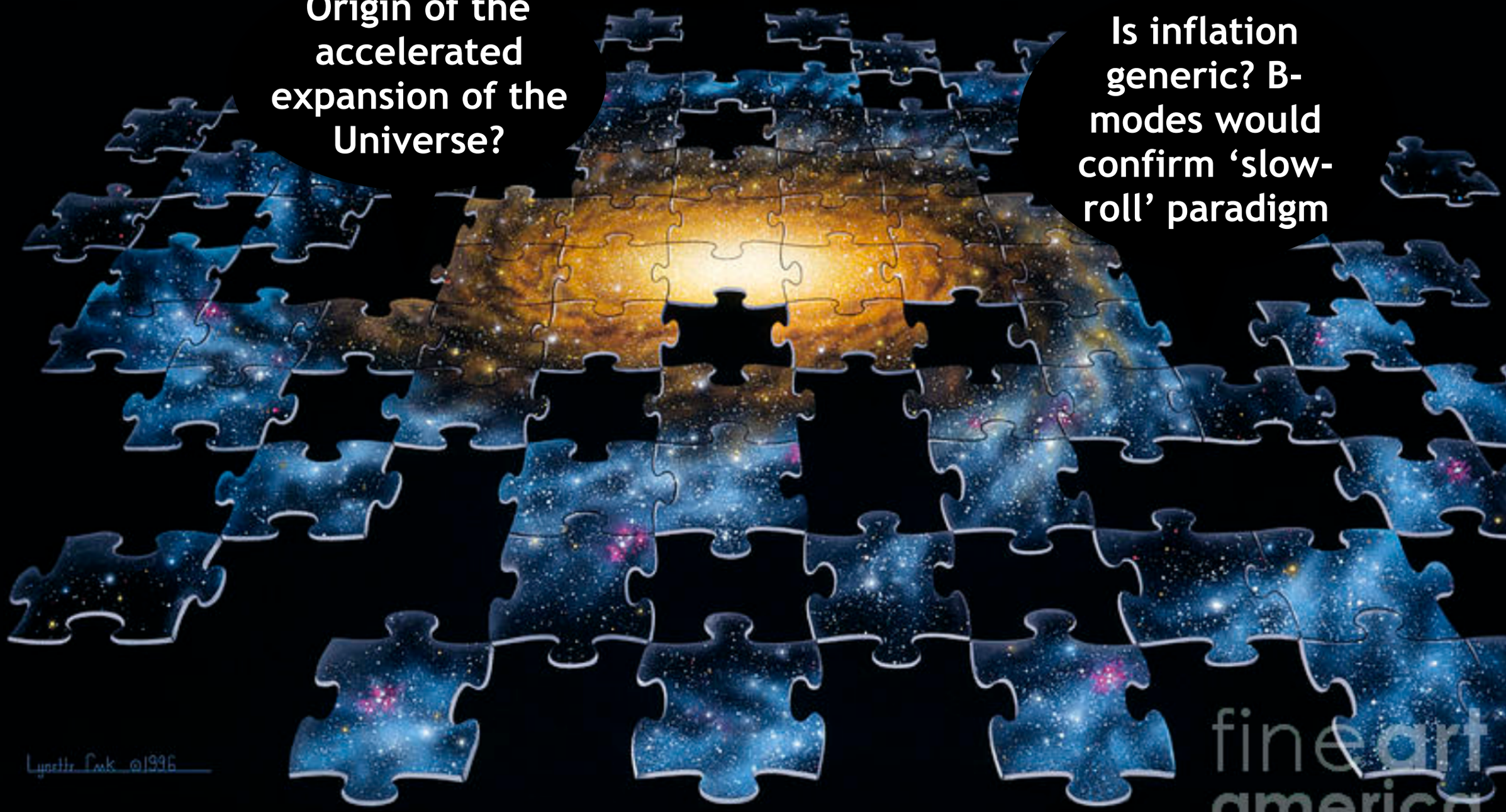
In Search of New Paradigms…

Origin of the accelerated expansion of the Universe?

Is inflation generic? B-modes would confirm ‘slow-roll’ paradigm



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In Search of New Paradigms…

Origin of the accelerated expansion of the Universe?

Signatures of dark matter non-gravitational physics?

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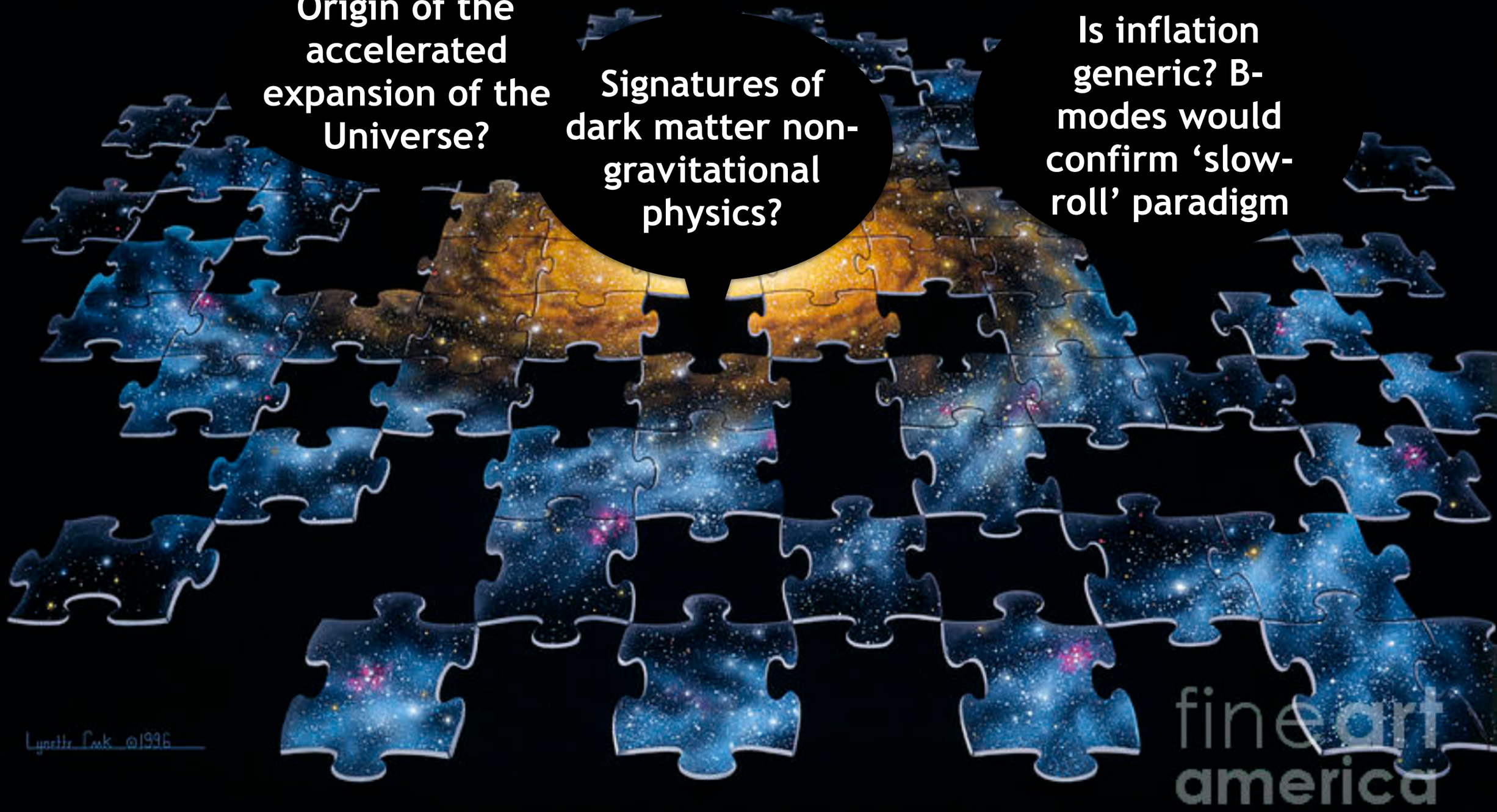

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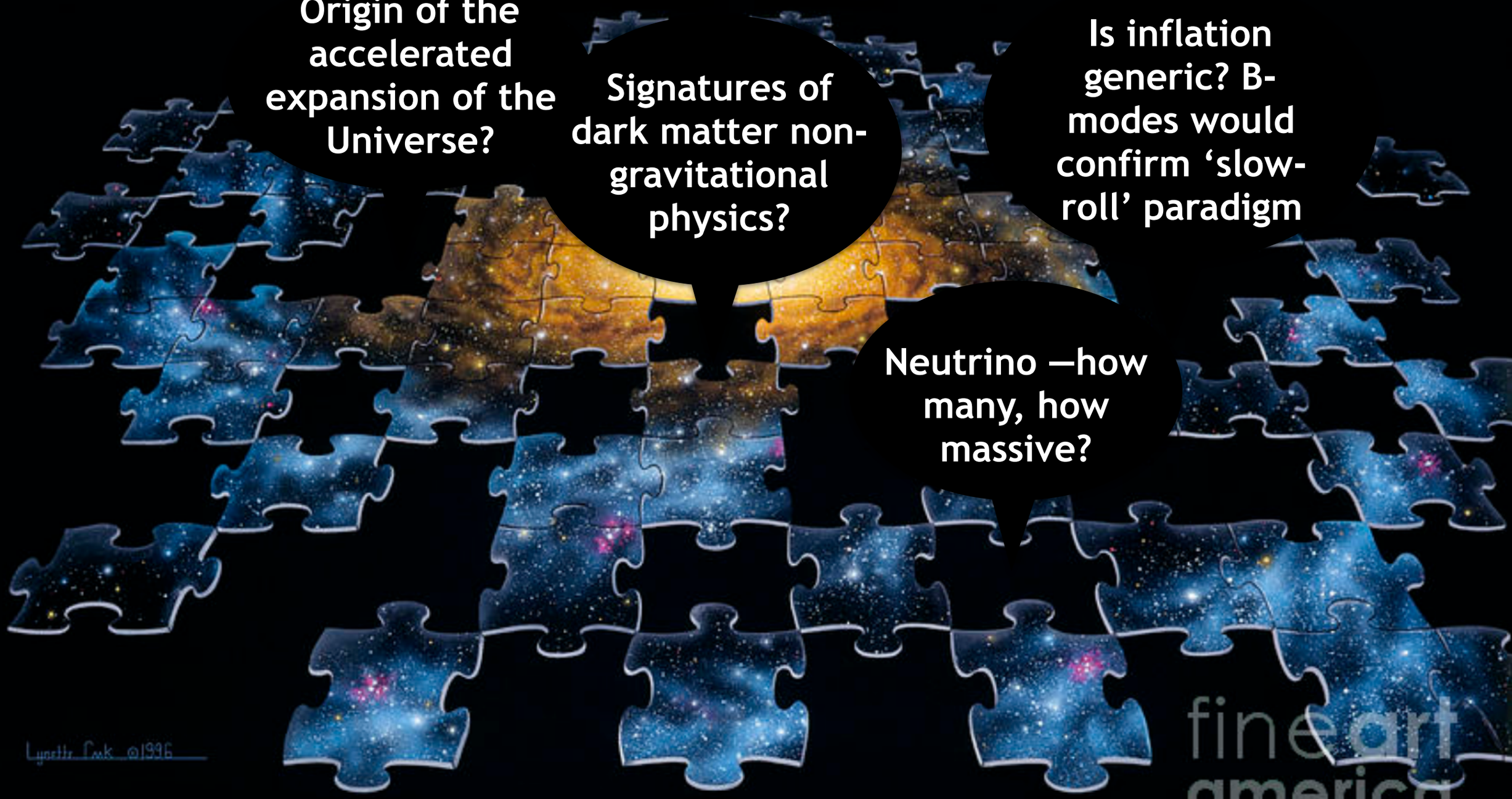

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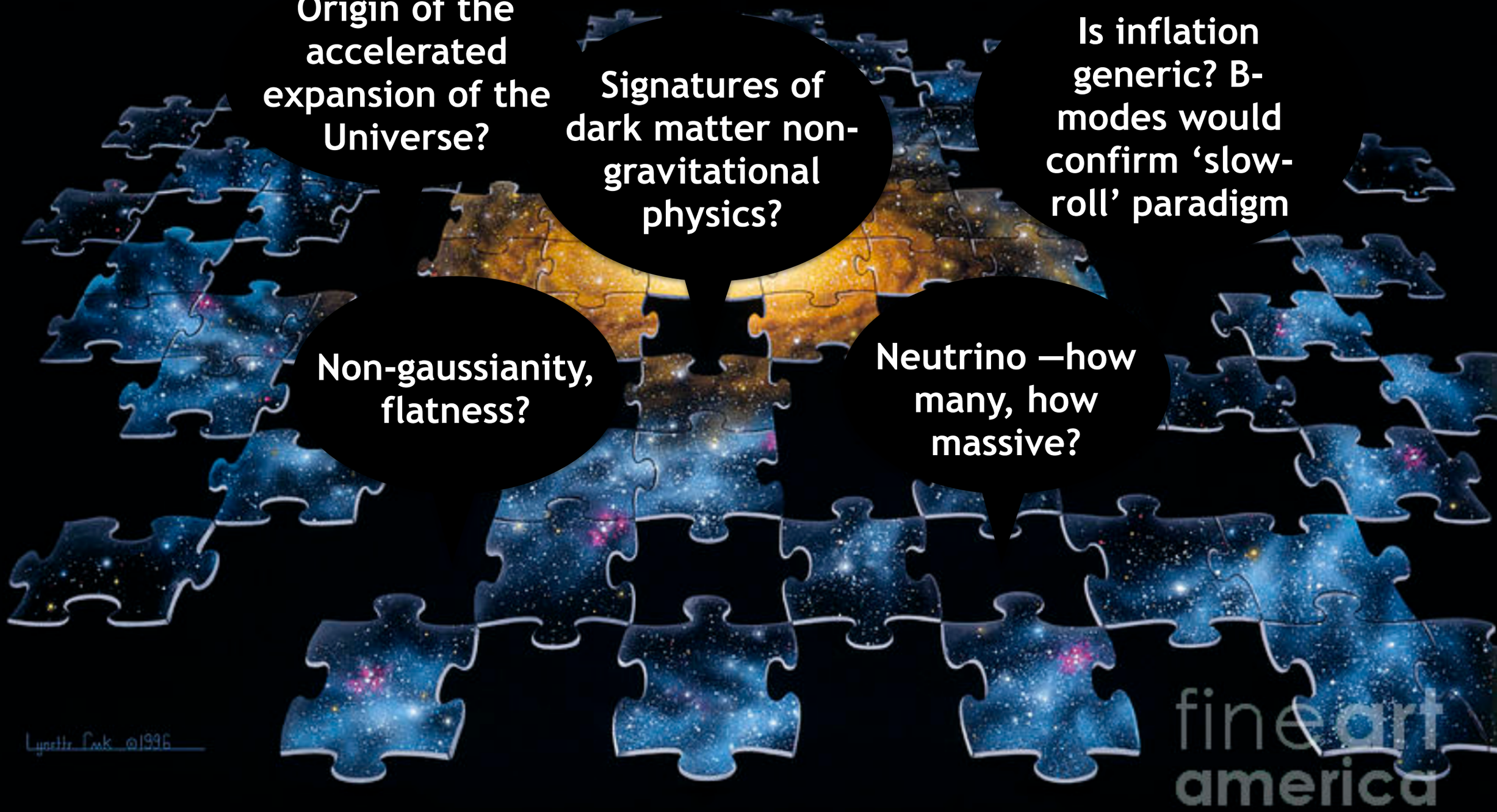

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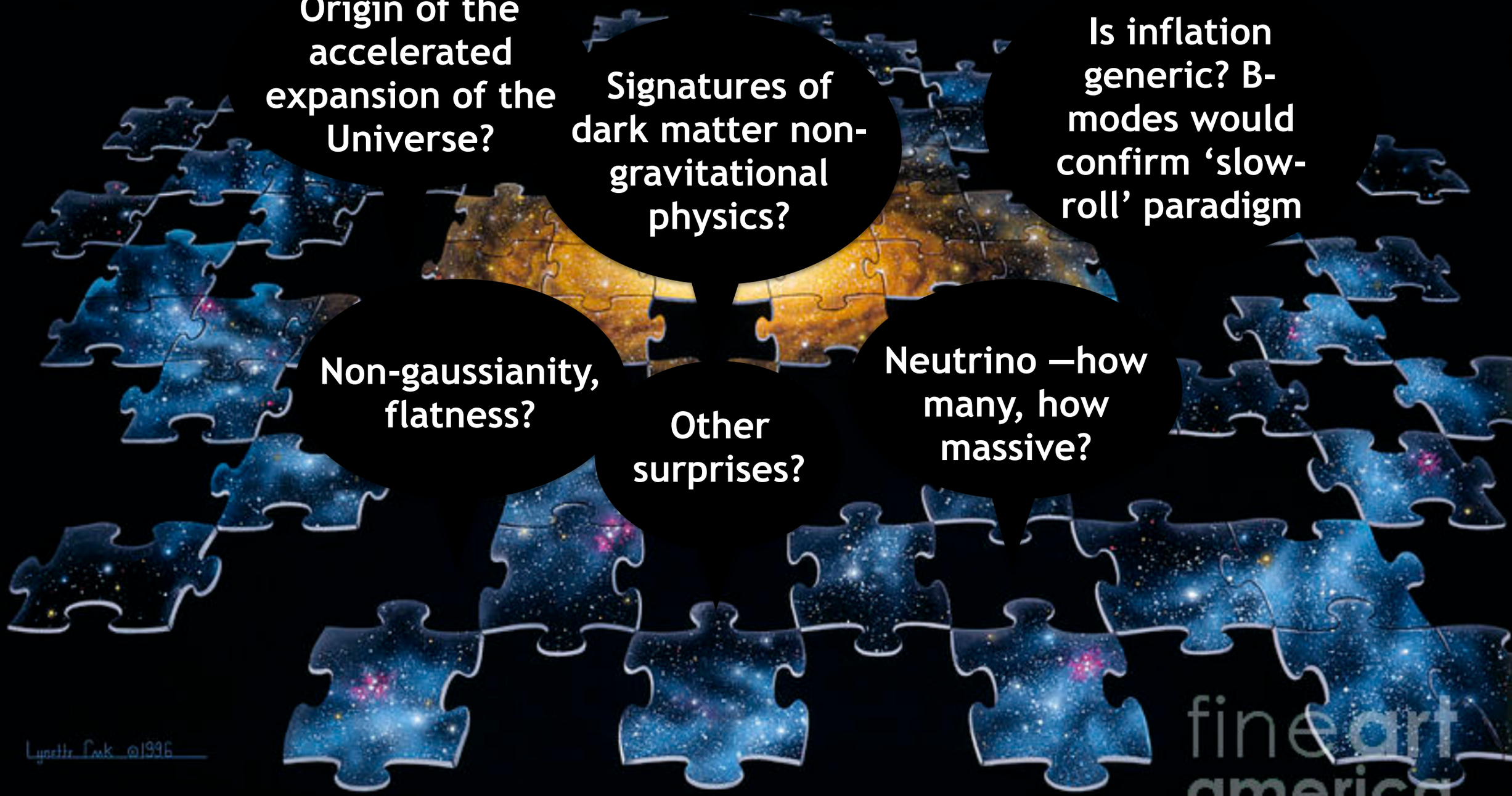
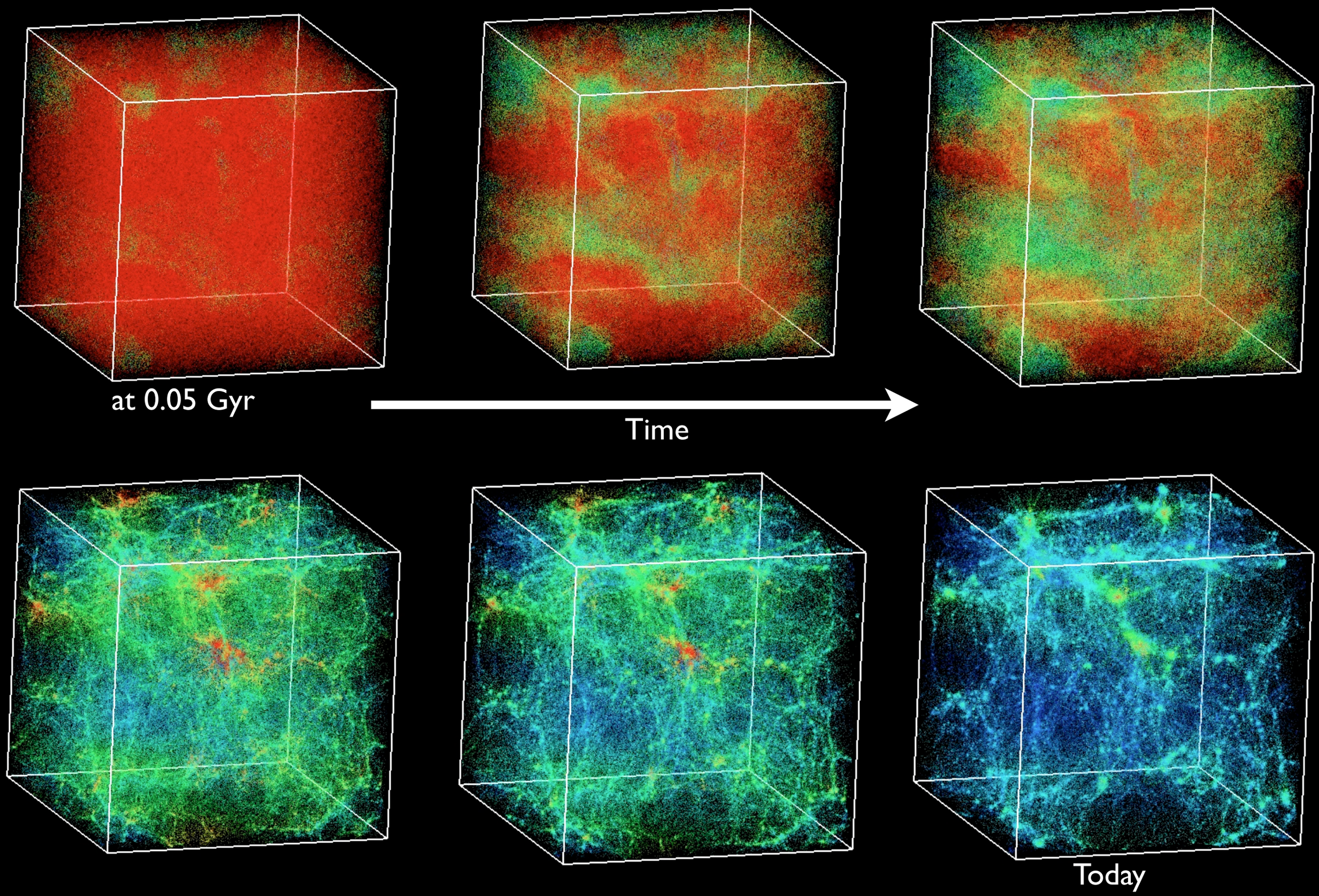


Galaxy Puzzle by Lynette Cook

Large-Scale Structure in the Universe

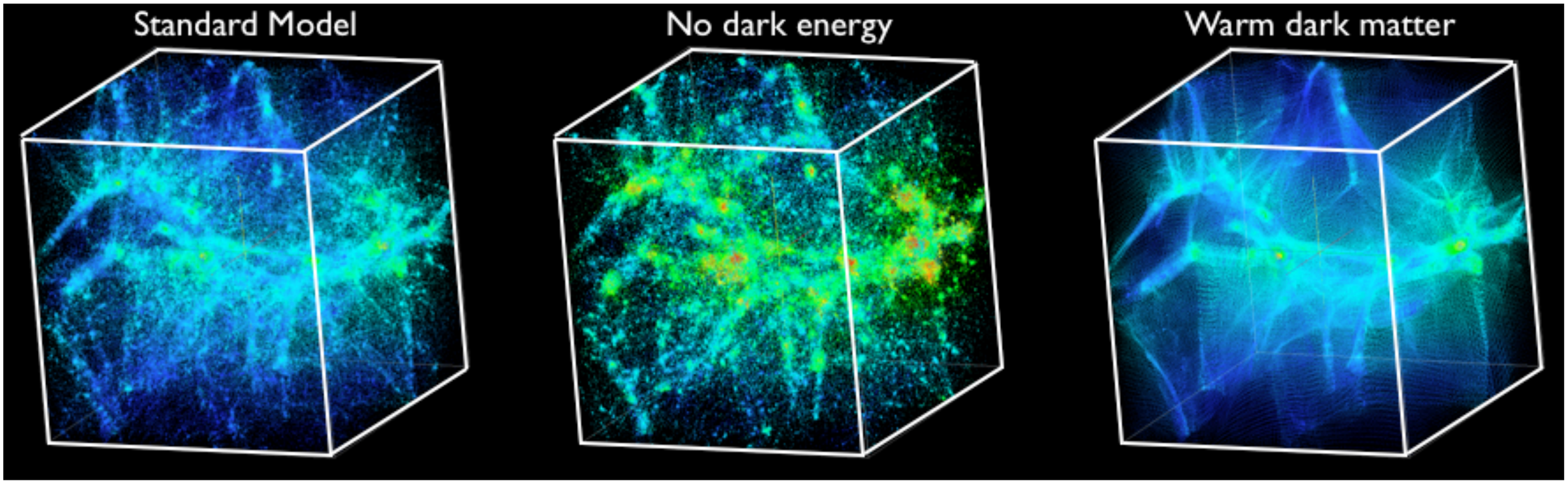
- Cosmological structure forms from small primordial fluctuations, which grow and collapse under the force of gravity
- Small dark matter clumps (halos) form, halos merge and form larger halos
- Voids, clusters, and filaments form; the building blocks of the cosmic web
- The cosmic web and its elements hold a wealth of cosmological information, (at least for the theorist … will come back to this later), different initial conditions/cosmologies lead to different structure formation scenarios …

The Theorist's Universe

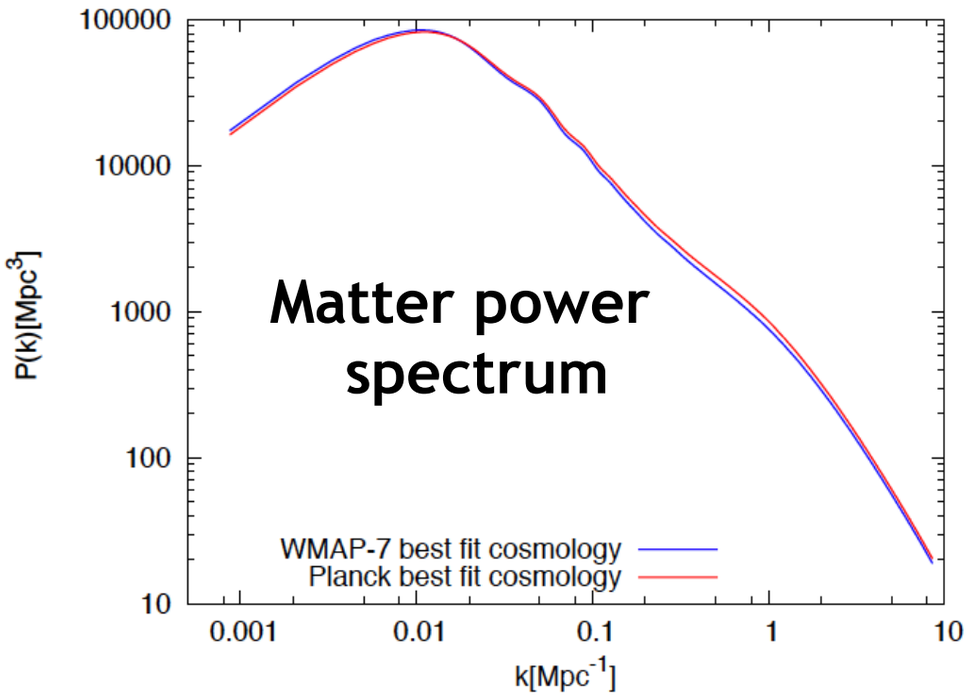


View of the evolution of dark matter tracer particles under the influence of dark energy

Exploring Structure Formation in the Dark Universe



- **Exploration of different dark energy models:** How would a dark energy model beyond Einstein's cosmological constant alter the distribution of matter (and galaxies) in the Universe?
- **Exploration of dark matter and neutrinos in the Universe:** What can cosmology tell us about different matter components in the Universe?
- **Inflation:** What are the properties of the primordial power spectrum? A running spectral index?



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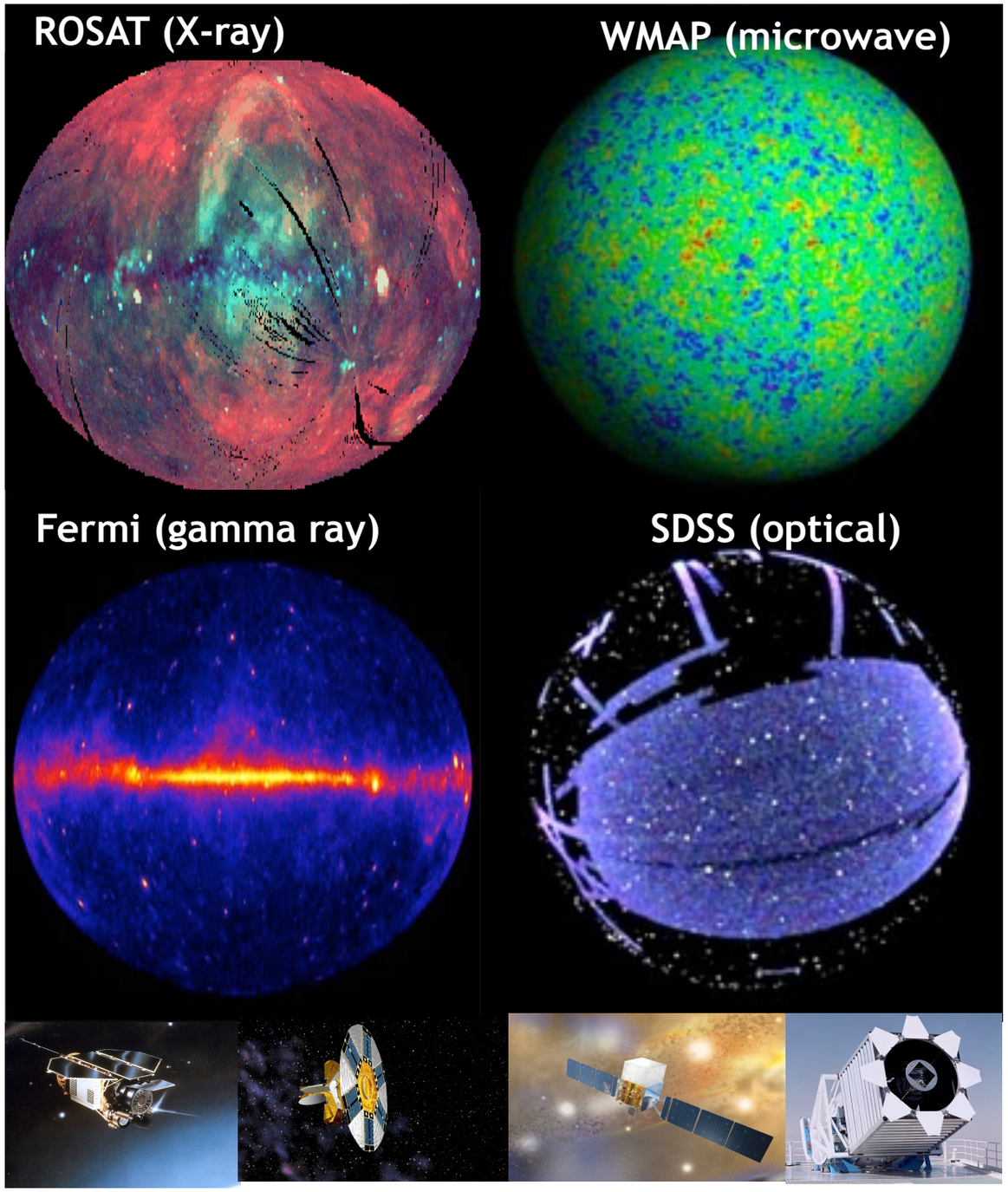
- … Baryons (gas) falls into potential wells of halos
- Gas heats up, star formation gets triggered, galaxies form
- Distribution of galaxies and the growth of structure contain a wealth of information on cosmology

Modern Cosmology and Sky Maps

- Modern cosmology is the story of mapping the sky in multiple wavebands
- Maps cover measurements of objects (stars, galaxies) and fields (temperature)
- Maps can be large (Sloan Digital Sky Survey recorded >500 million photometric objects, many billions for planned surveys)
- Statistical analysis of sky maps
- All precision cosmological analyses constitute a statistical inverse problem: **from sky maps to scientific inference**



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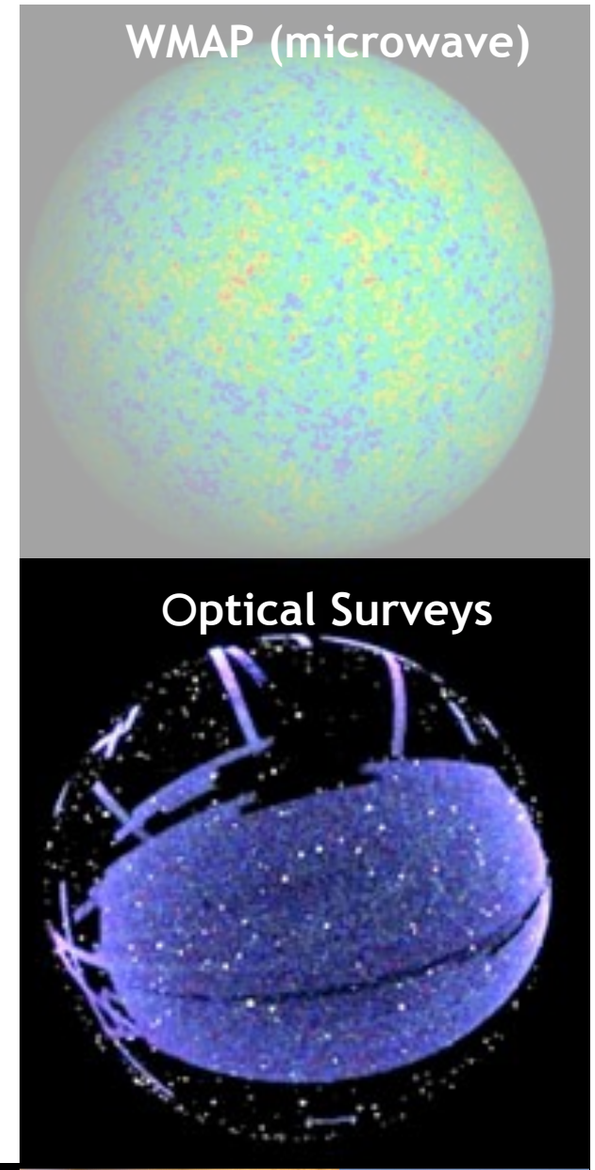
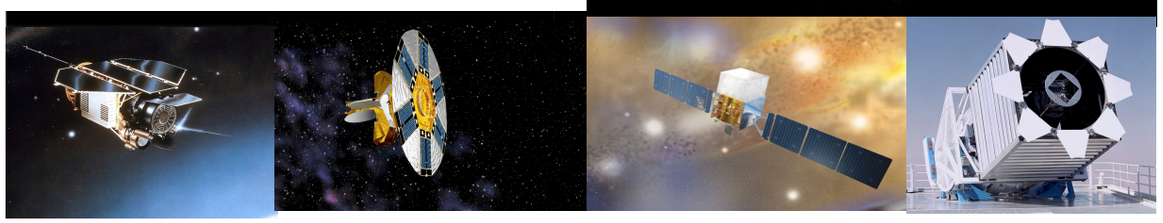
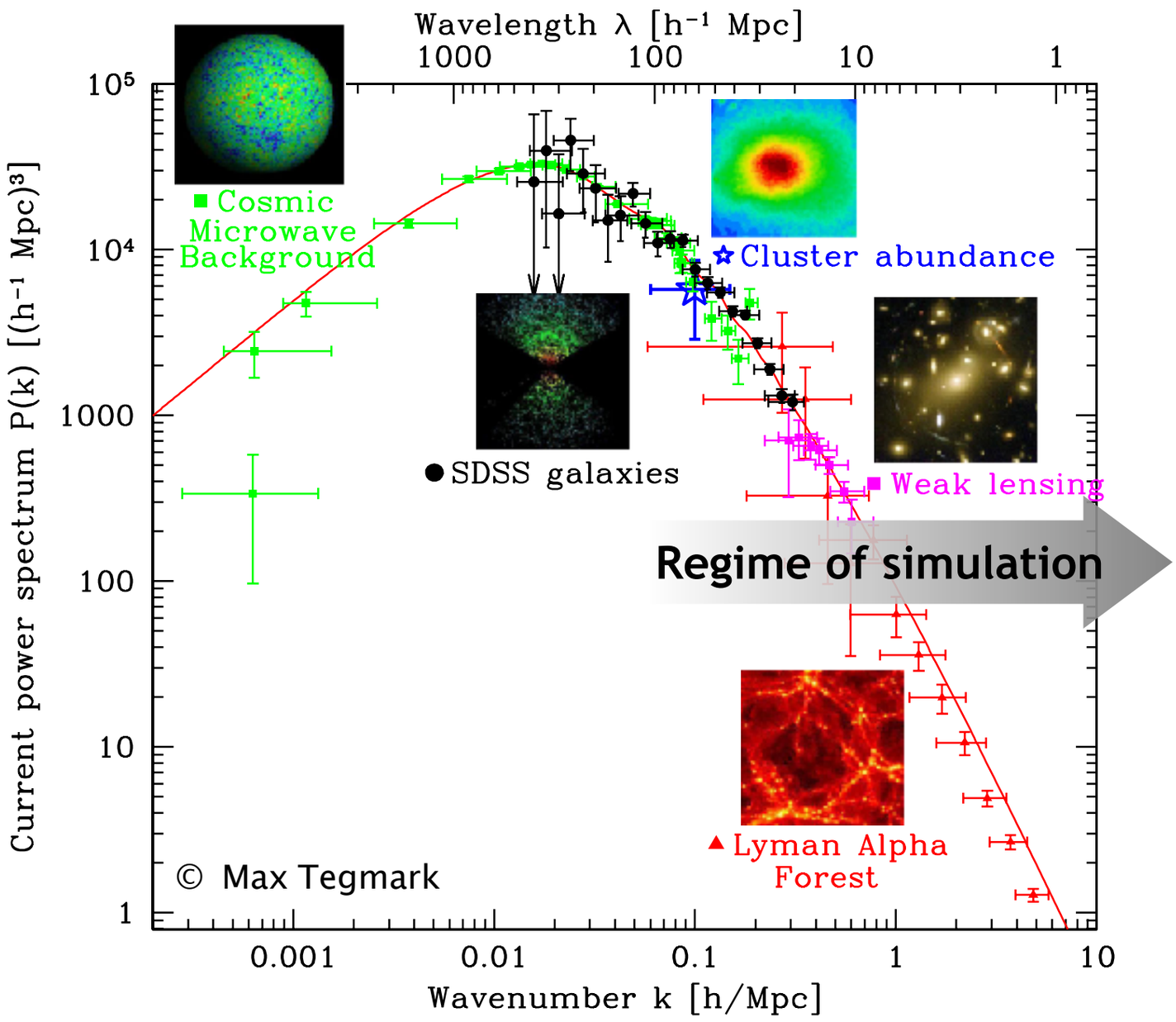




The Matter Power Spectrum



$$\theta = \{\Omega_{cdm}, \Omega_b, h, \sigma_8, n_s, \Omega_\nu, w\}$$

2-point correlation function:

$$\xi(\vec{x}) = \int \frac{d^3\vec{y}}{V}\delta(\vec{y}-\vec{x})\delta(\vec{y}) = \int \underbrace{\frac{d^3\vec{k}}{(2\pi)^3 V}|\delta_k|^2}_{\text{power spectrum}} e^{i\vec{k}\cdot\vec{x}}$$

- 2-point correlation function: excess probability of finding an object pair separated by a distance r_{12} compared to that of a random distribution
- P(k): power spectrum, Fourier transform of correlation function

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

- Power spectrum very sensitive to physics of interest: amount and properties of dark matter, dark energy, neutrino mass, ...
- Many different probes for measuring P(k)

Cosmology: An Observational Science

- Fundamental requirements of precision measurements — **controllability, repeatability, and isolation** — not available
- **Observations** often dictated by circumstances ("LSST in space"), not always by optimal design for statistical inference
- **Cross-checks** required to control systematic errors
- **Theory and modeling** limitations can be a serious source of bias in the inverse problem
- Aim is to systematically check and refine the cosmological 'Standard Model' even in the absence of fundamental guidance

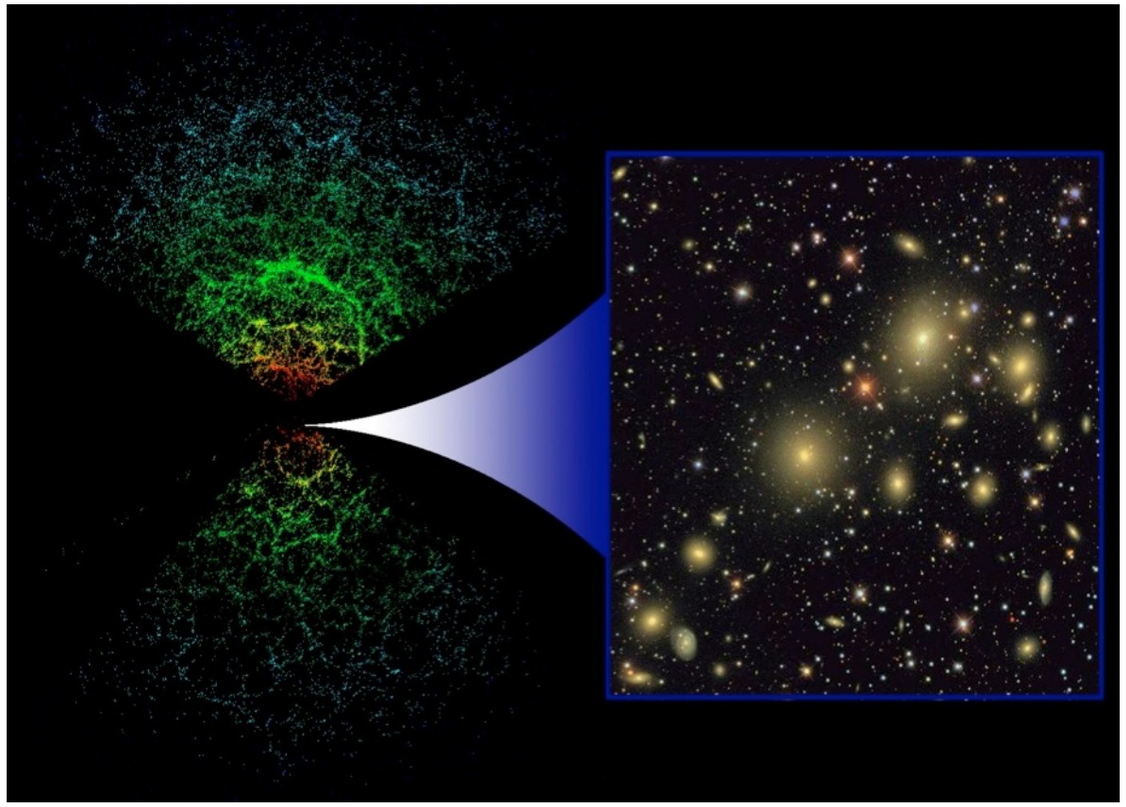
New Physics or Systematic Uncertainties?

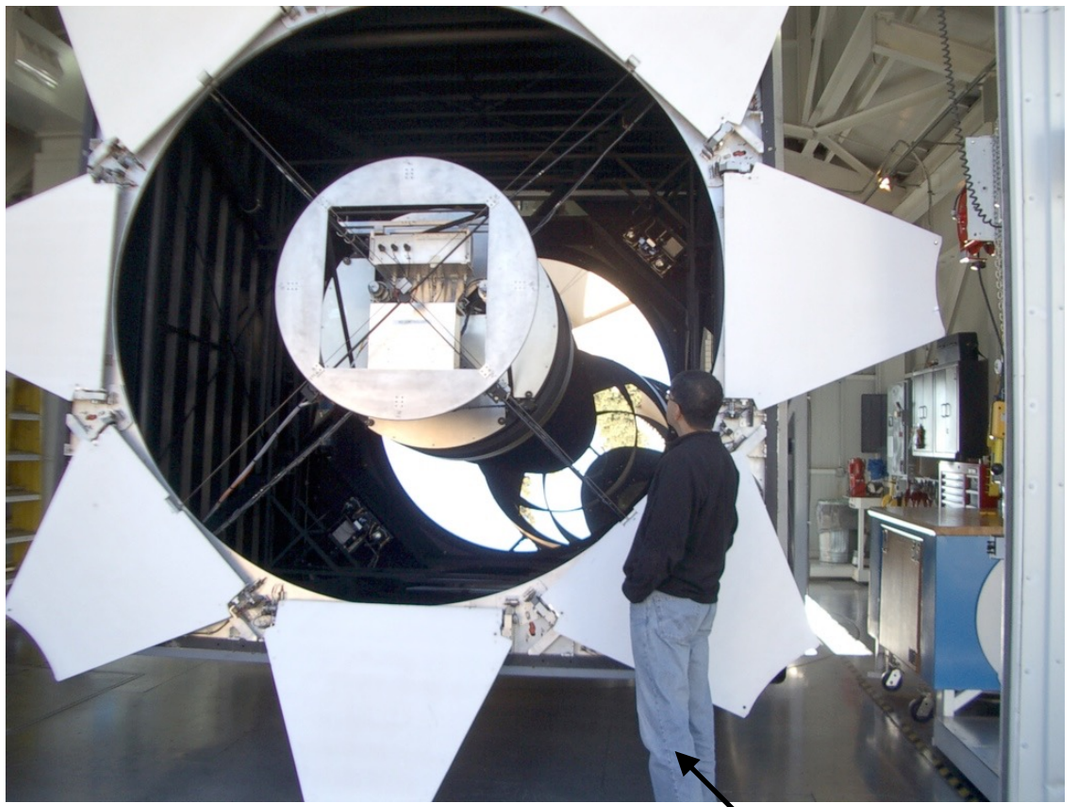
Theorist, modeler

Observer

Large Scale Structure in the Universe — As Measured by the Sloan Digital Sky Survey

- 2.5m telescope located in NM, optical imaging and spectroscopy to create 3-d map of the Universe (quarter of the sky)
- Images from over 100 million objects, including more than 100,000 quasars and spectra from a million galaxies

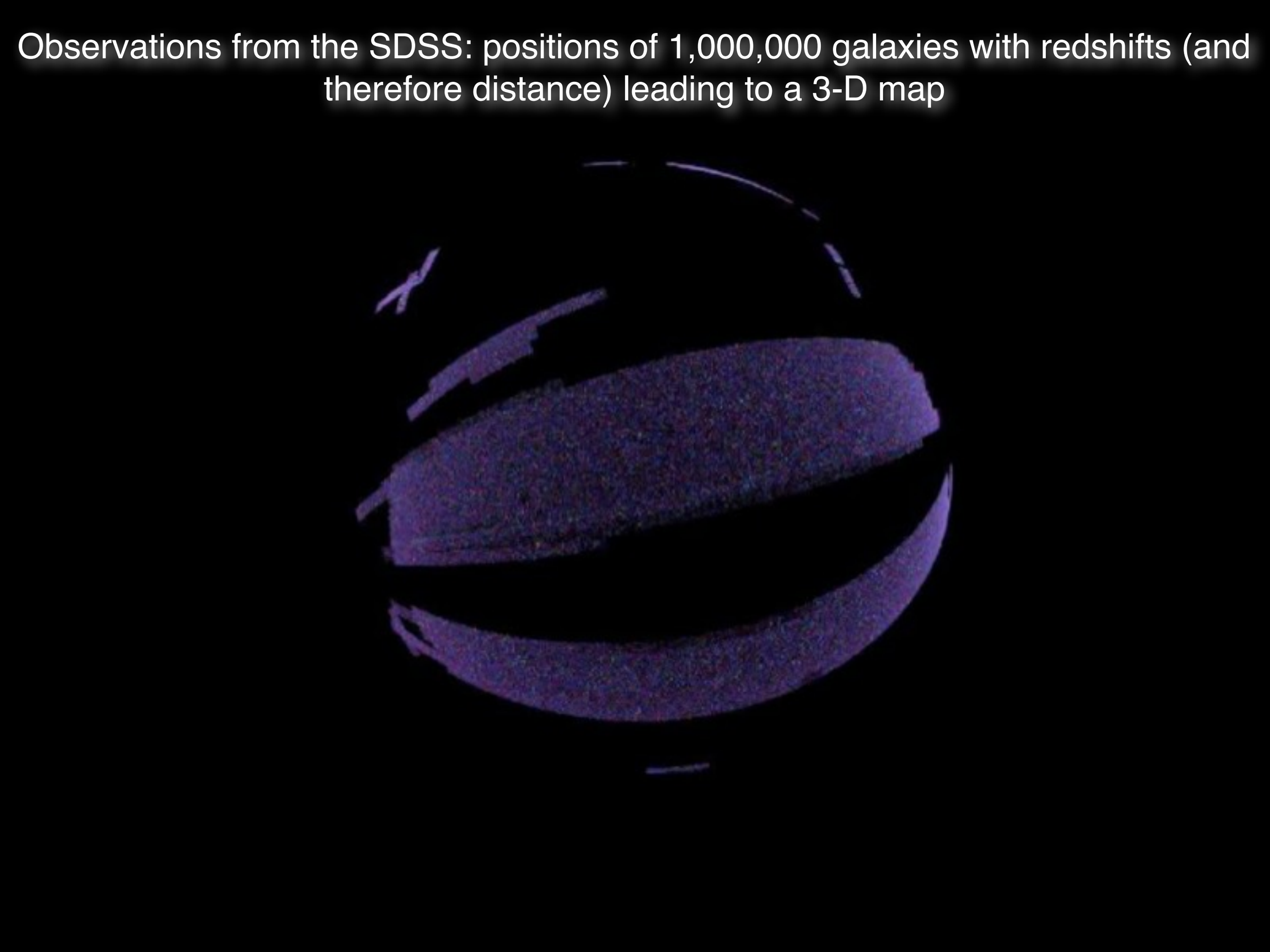


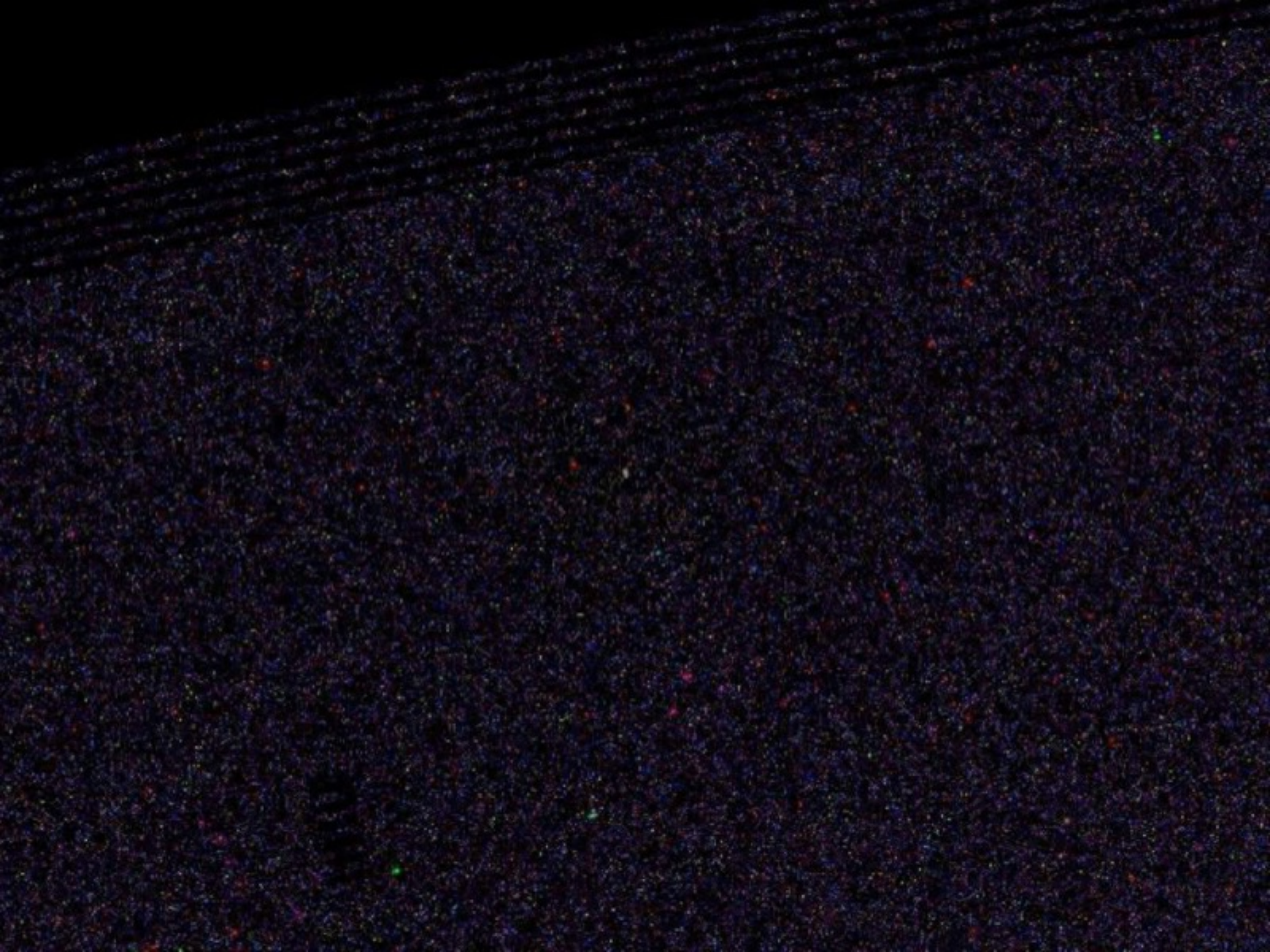


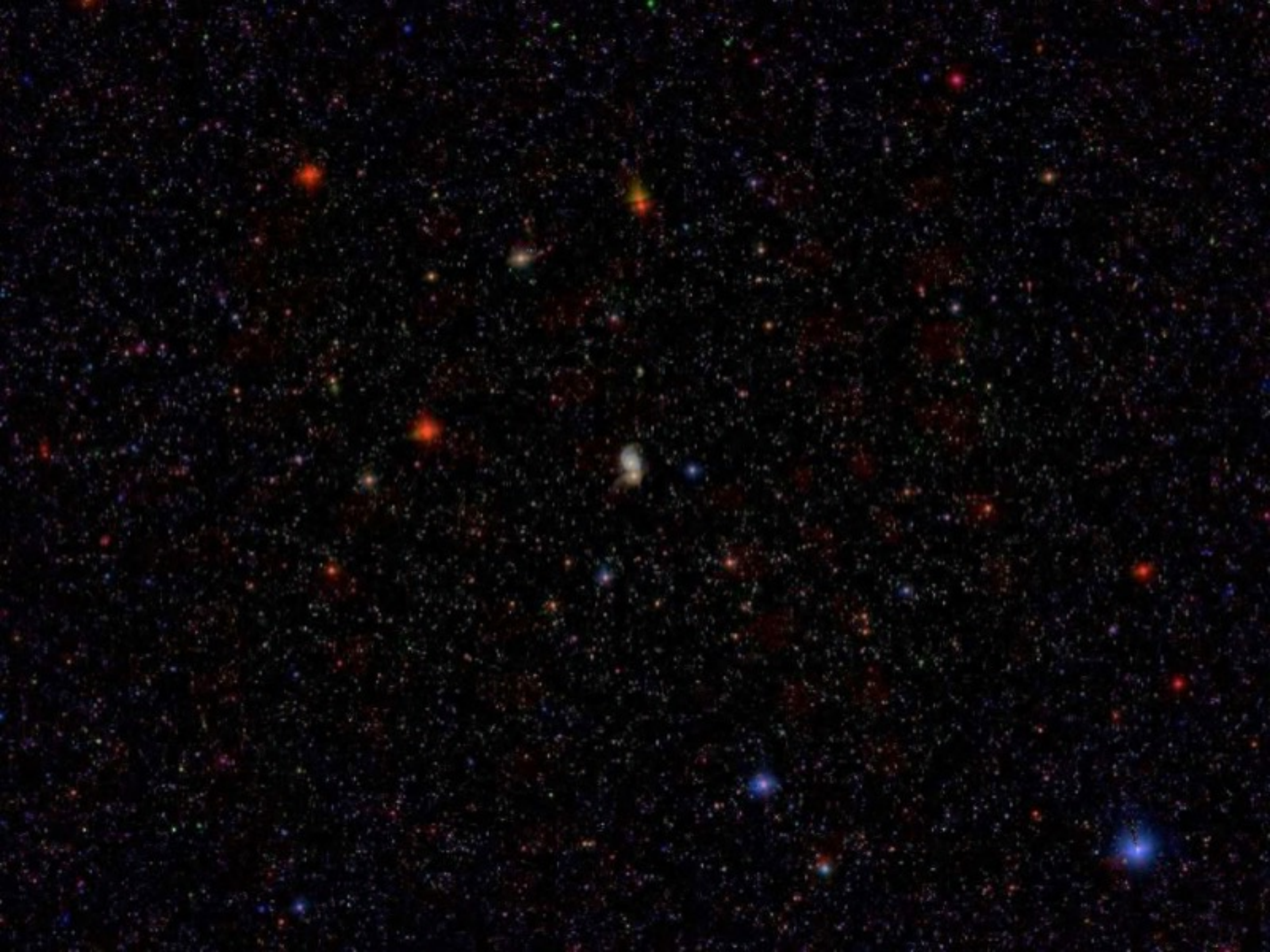
Theorist, inspecting the telescope

- First light in 1998, now SDSS-IV
- Baryon Oscillation Spectroscopic Survey (BOSS) provides precision measurements for cosmology (finished data taking in 2014), eBOSS is current stage (2014-2020)

Observations from the SDSS: positions of 1,000,000 galaxies with redshifts (and therefore distance) leading to a 3-D map

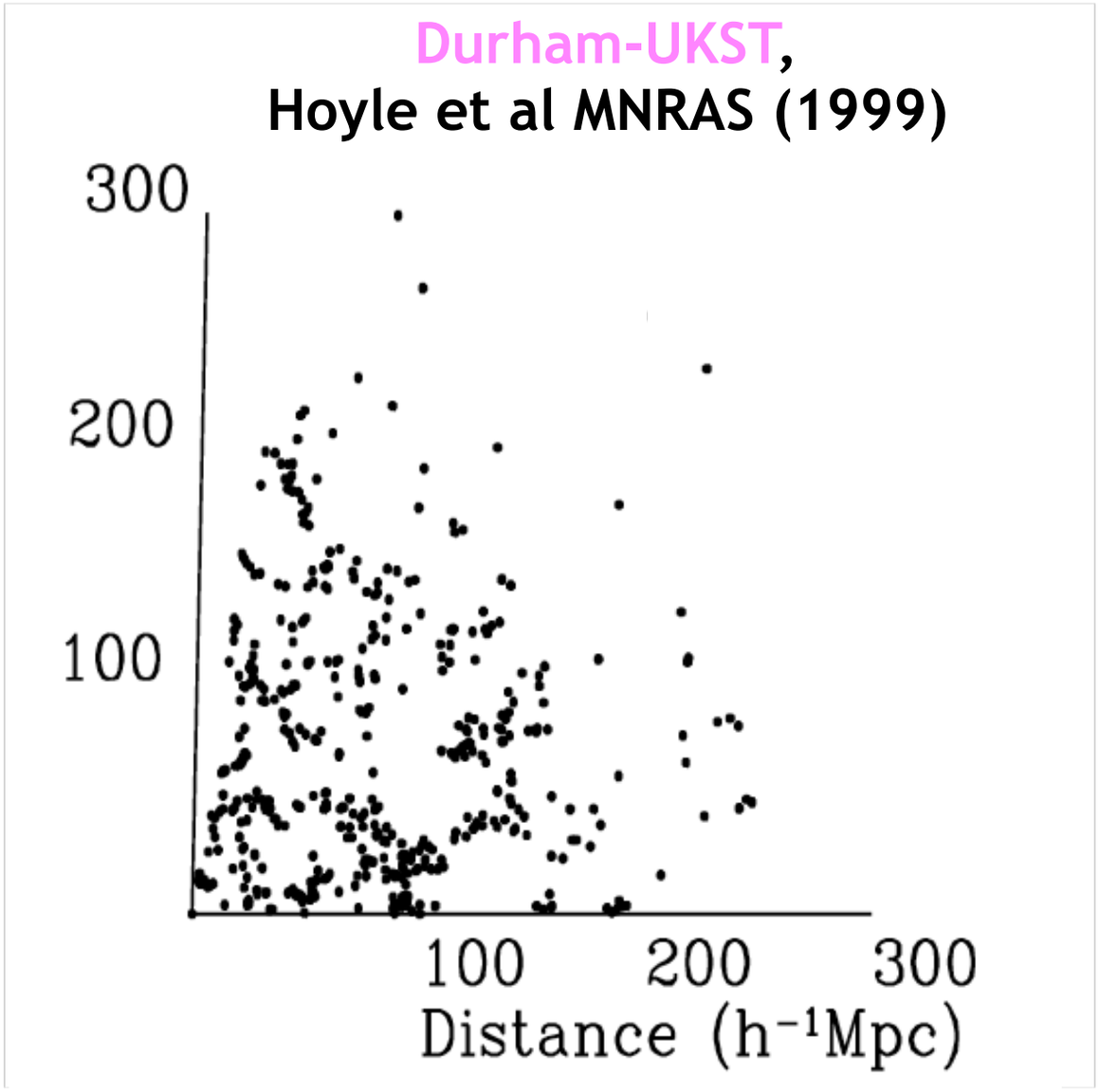




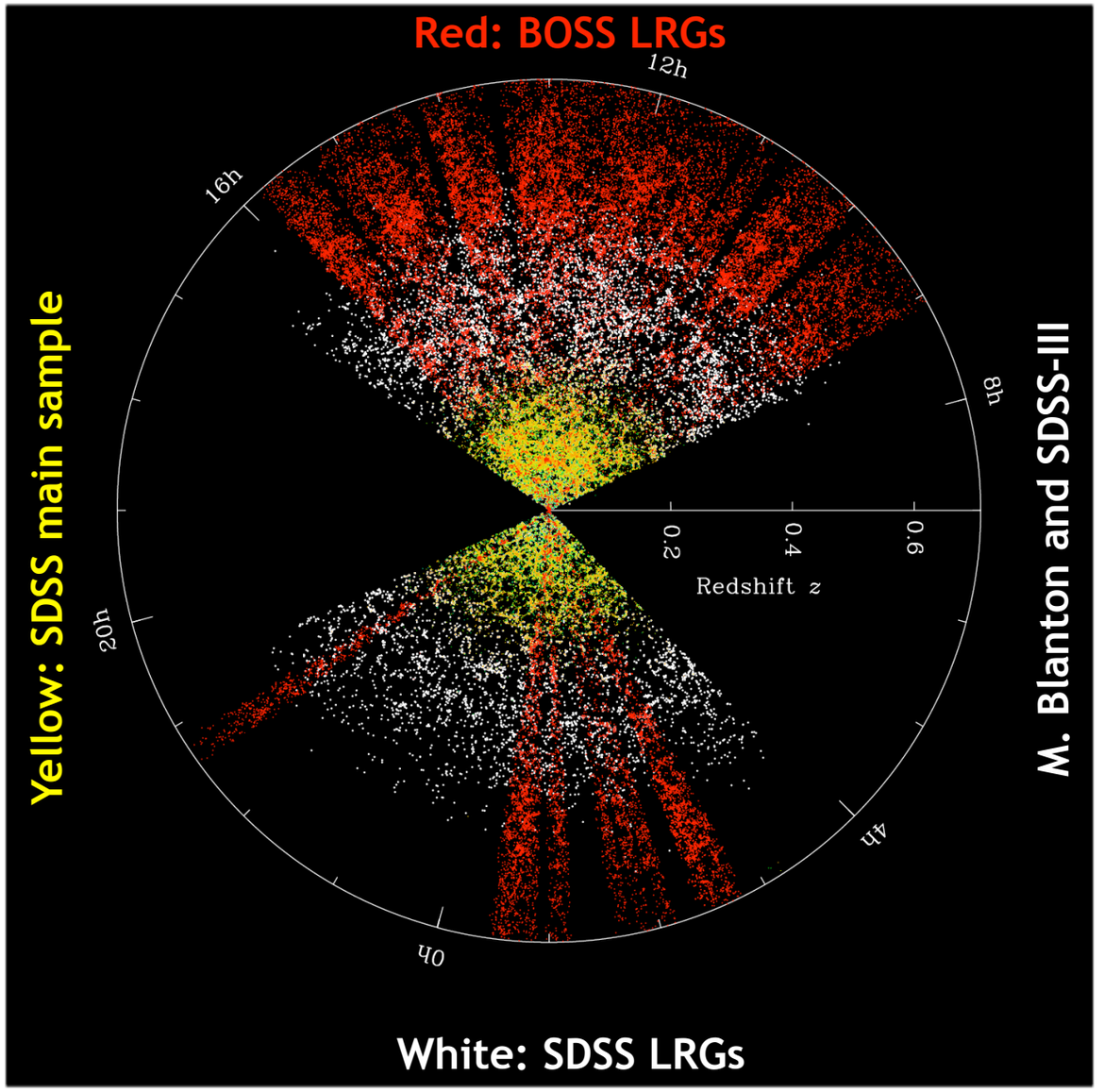


Credit: David Hogg, NYU

Galaxy Surveys



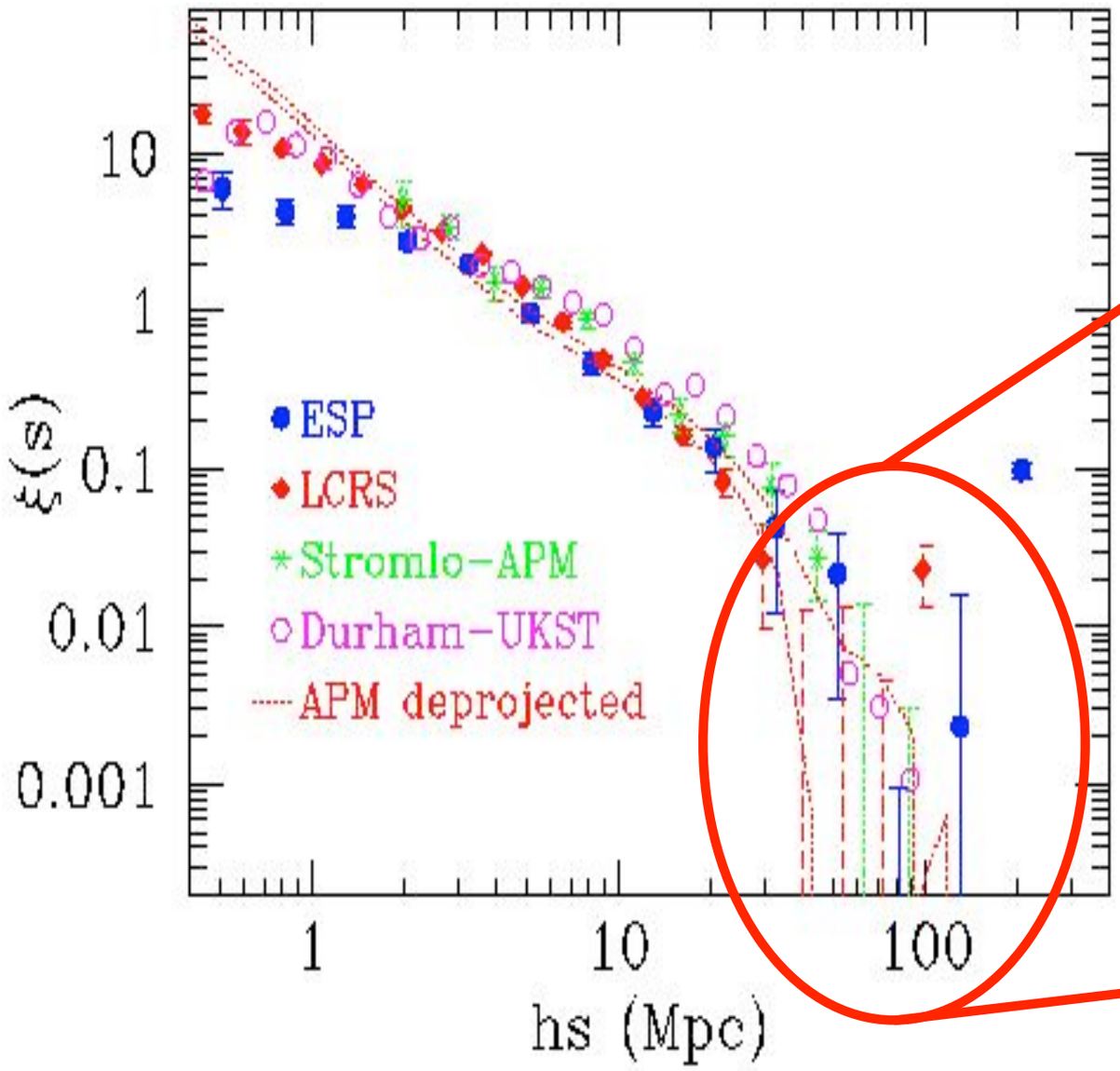
1999



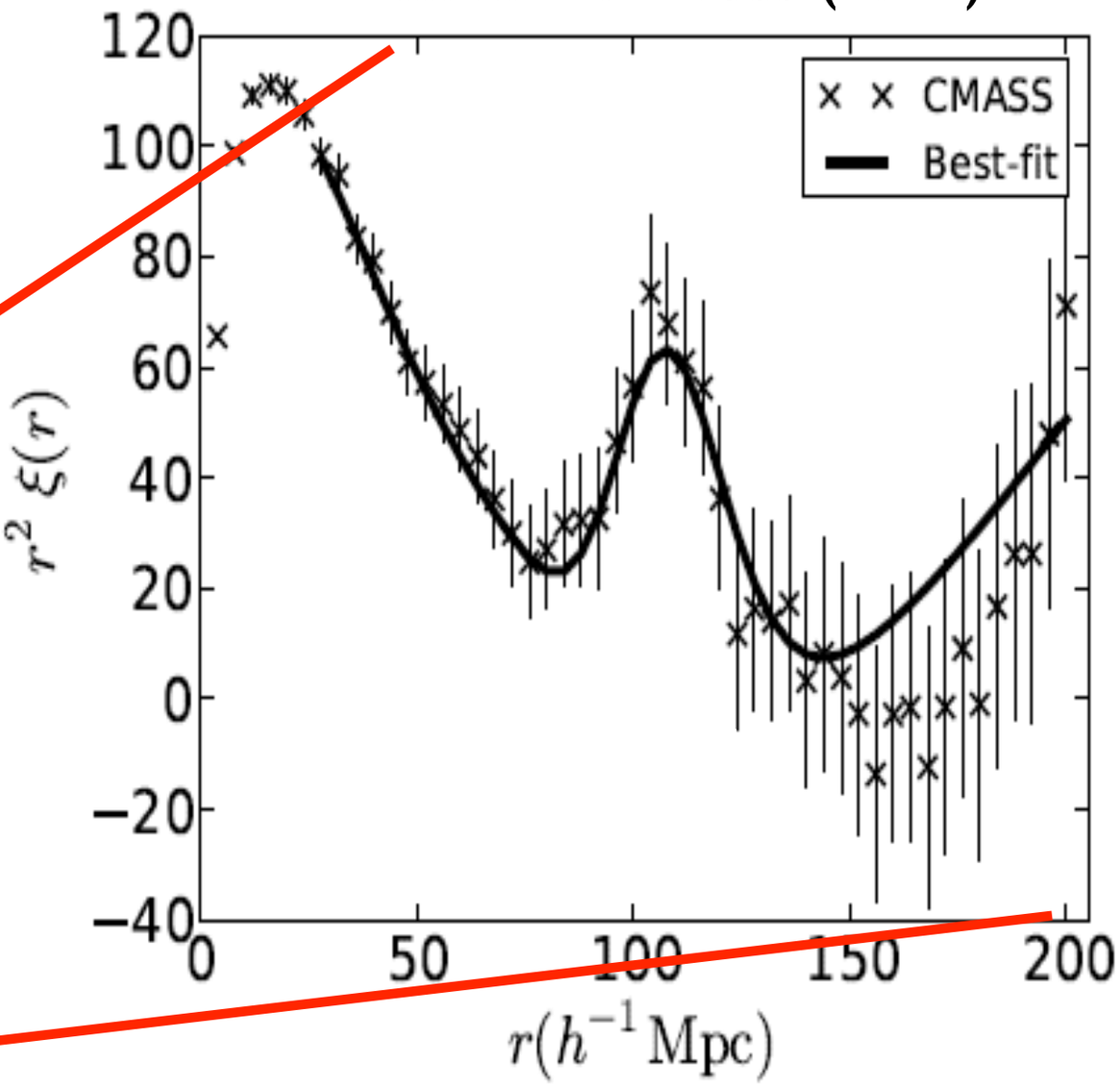
2012

Correlation Function

Results compilation (1999)



Results from BOSS (2012)



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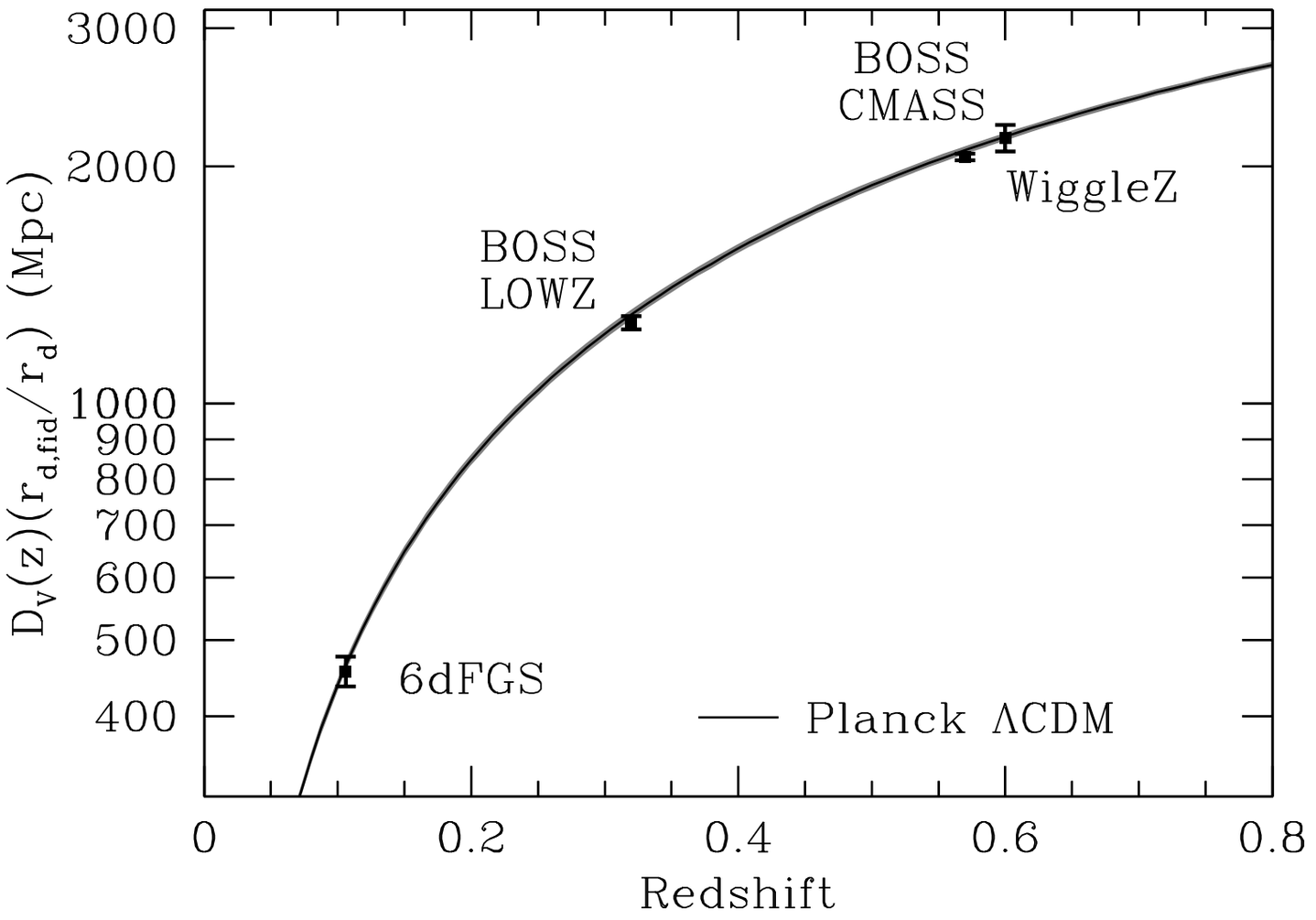
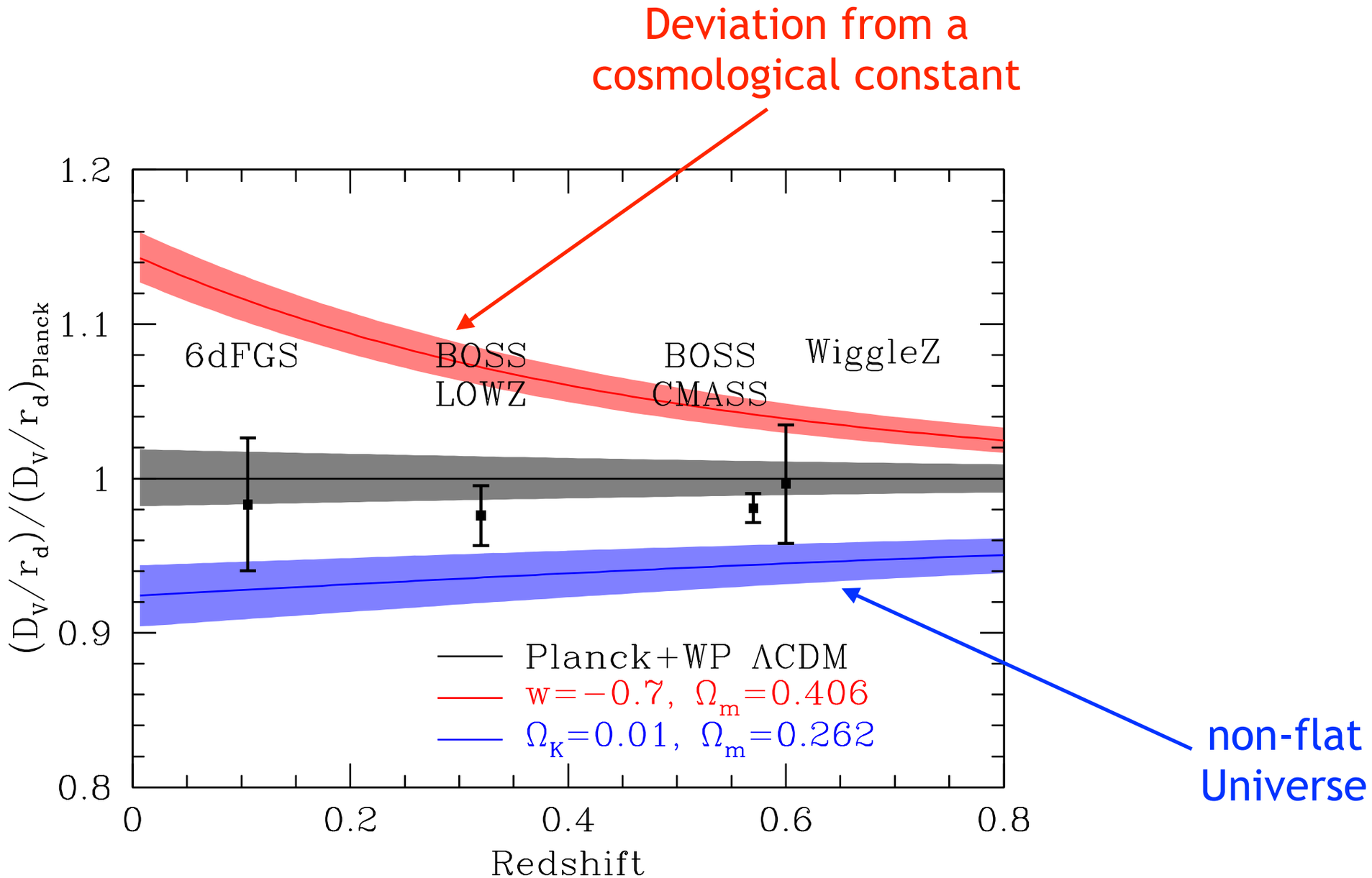
Some BOSS Results: BAO Hubble Diagram



Distance-redshift relation

Anderson et al. 2014

Some BOSS Results: BAO Hubble Diagram

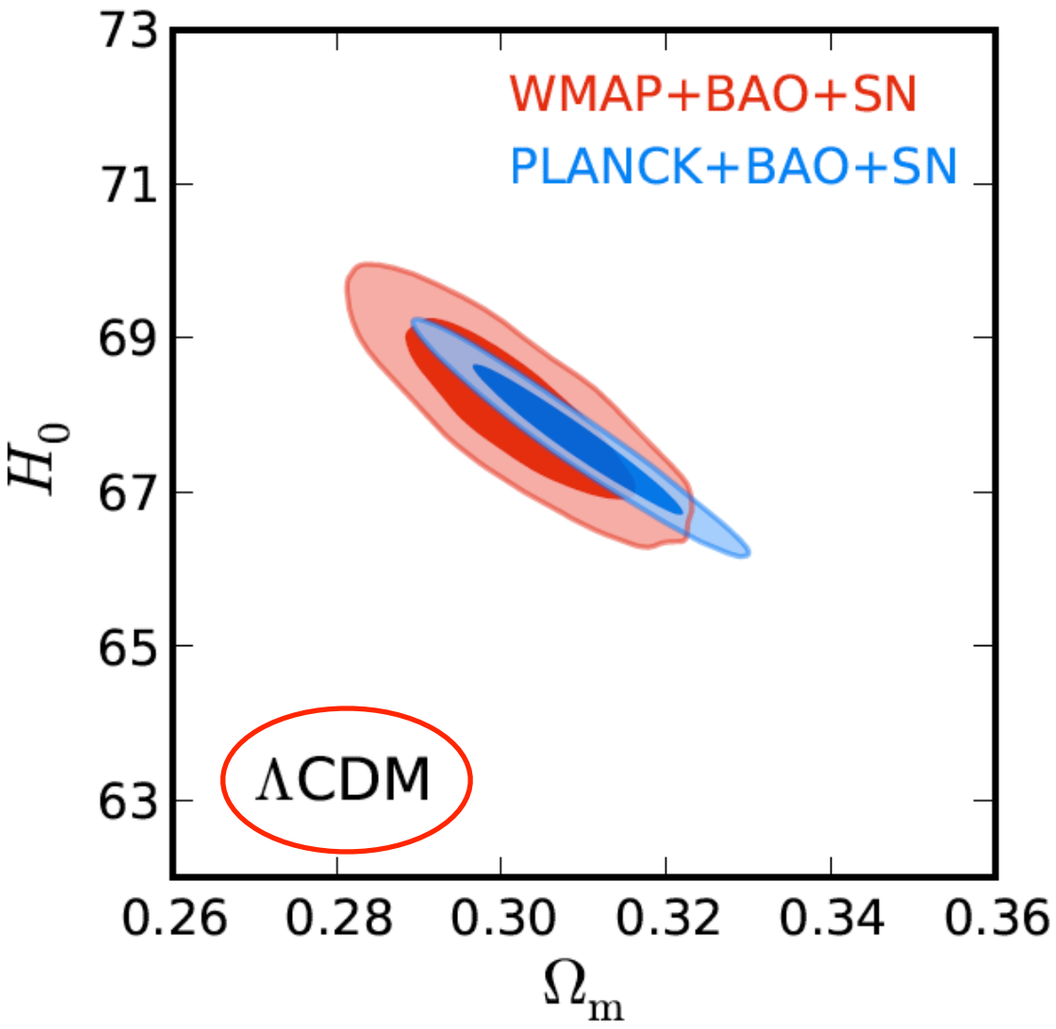


Same as previous figure but divided by LCDM

Anderson et al. 2014

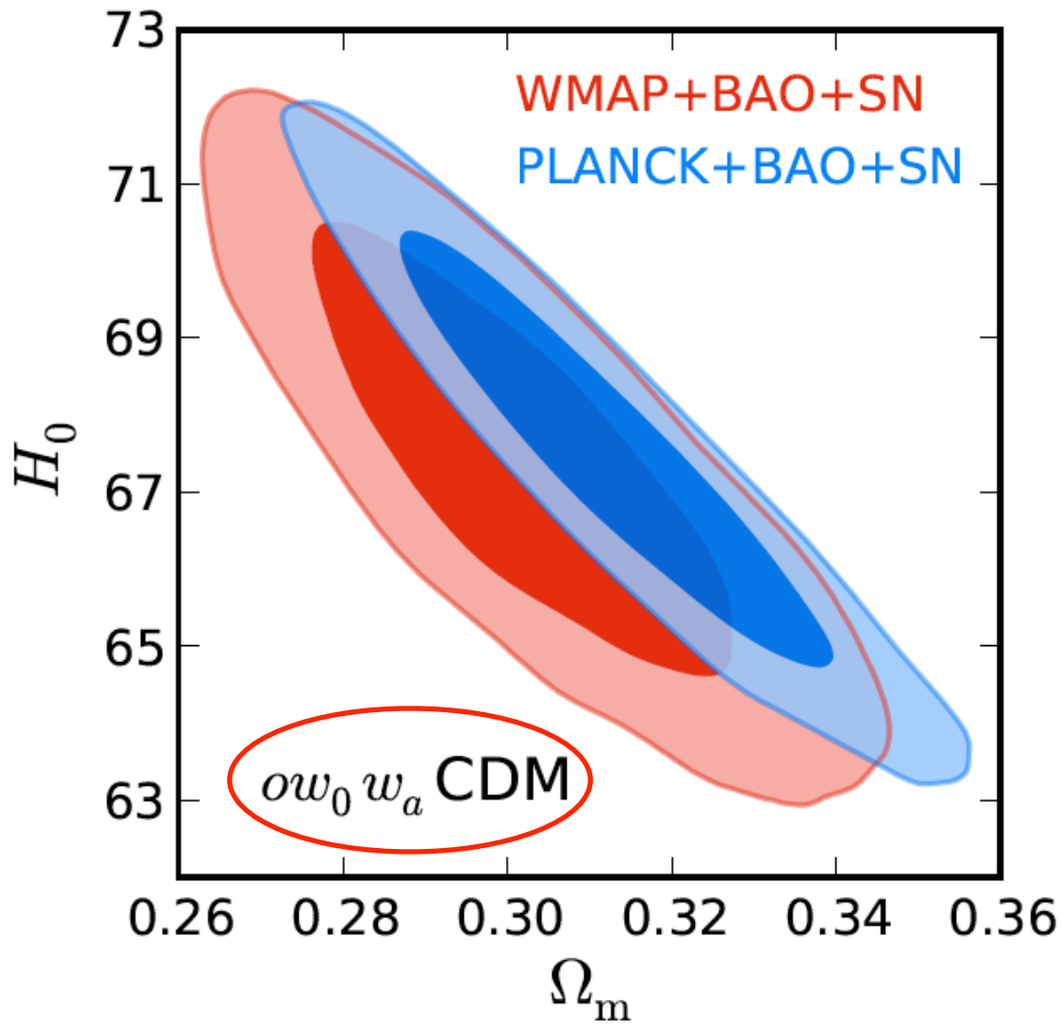
Some BOSS Results: Parameter Constraints

Anderson et al. 2014



$\Omega_m = 0.302(8); H_0 = 68.1(7)\mathrm{km/s/Mpc}$

$\Omega_m = 0.309(8); H_0 = 67.7(6)\mathrm{km/s/Mpc}$



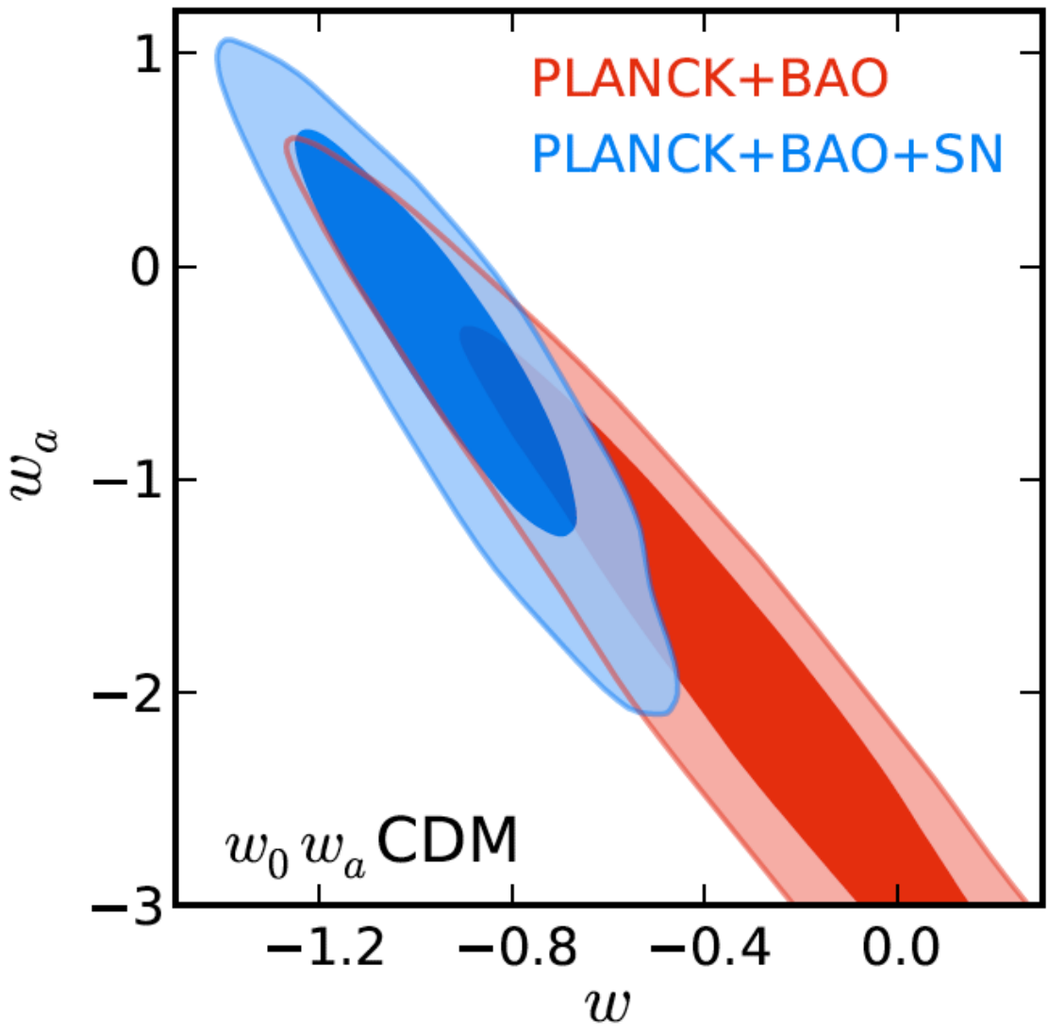
$\Omega_m = 0.302(16); H_0 = 67.4(18)\mathrm{km/s/Mpc}$

$\Omega_m = 0.313(16); H_0 = 67.5(17)\mathrm{km/s/Mpc}$

Some BOSS Results: Parameter Constraints

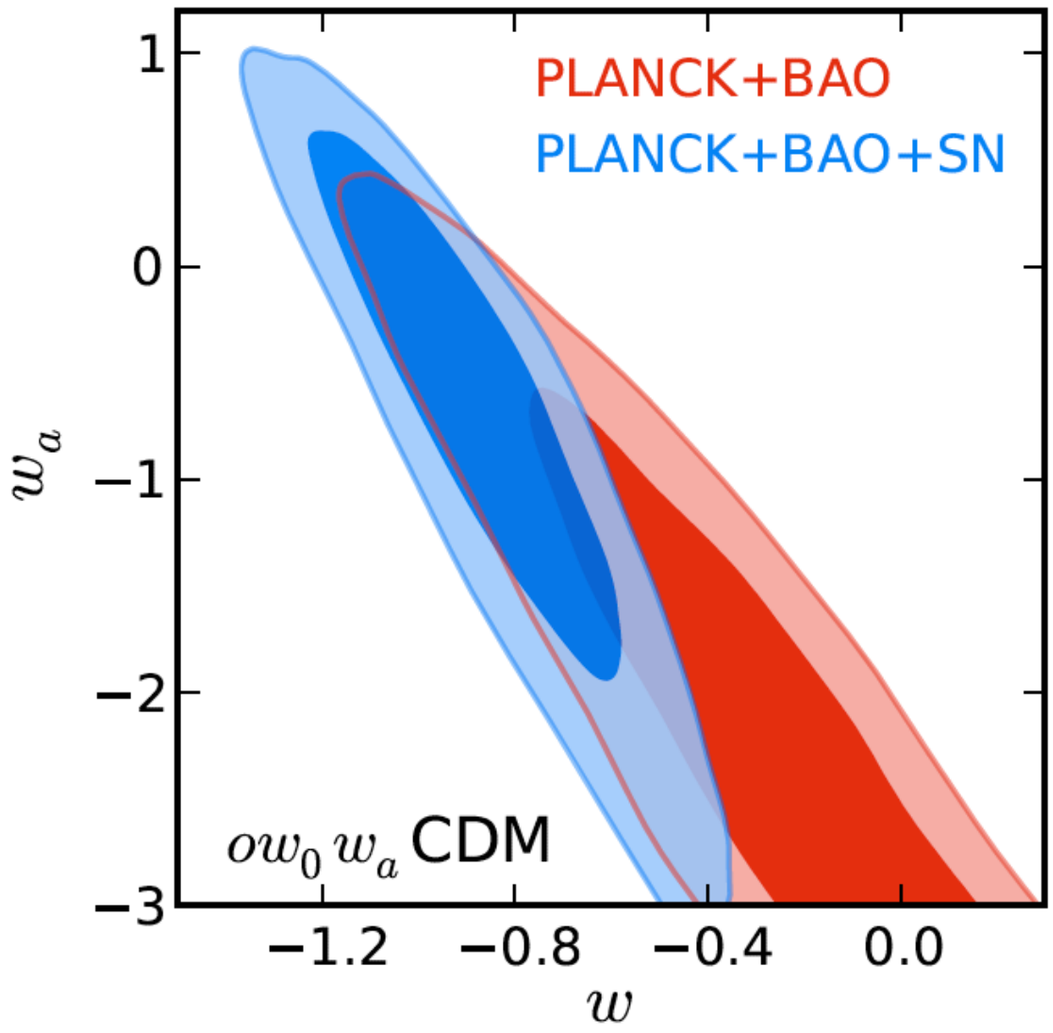
Dynamical dark energy, parameterized via: Anderson et al. 2014

$$w(a) = w_0 + (1-a)w_a$$



$w_0 = -1.0(16); w_a = 0.16(59)$

$w_0 = -0.93(18); w_a = -0.41(62)$



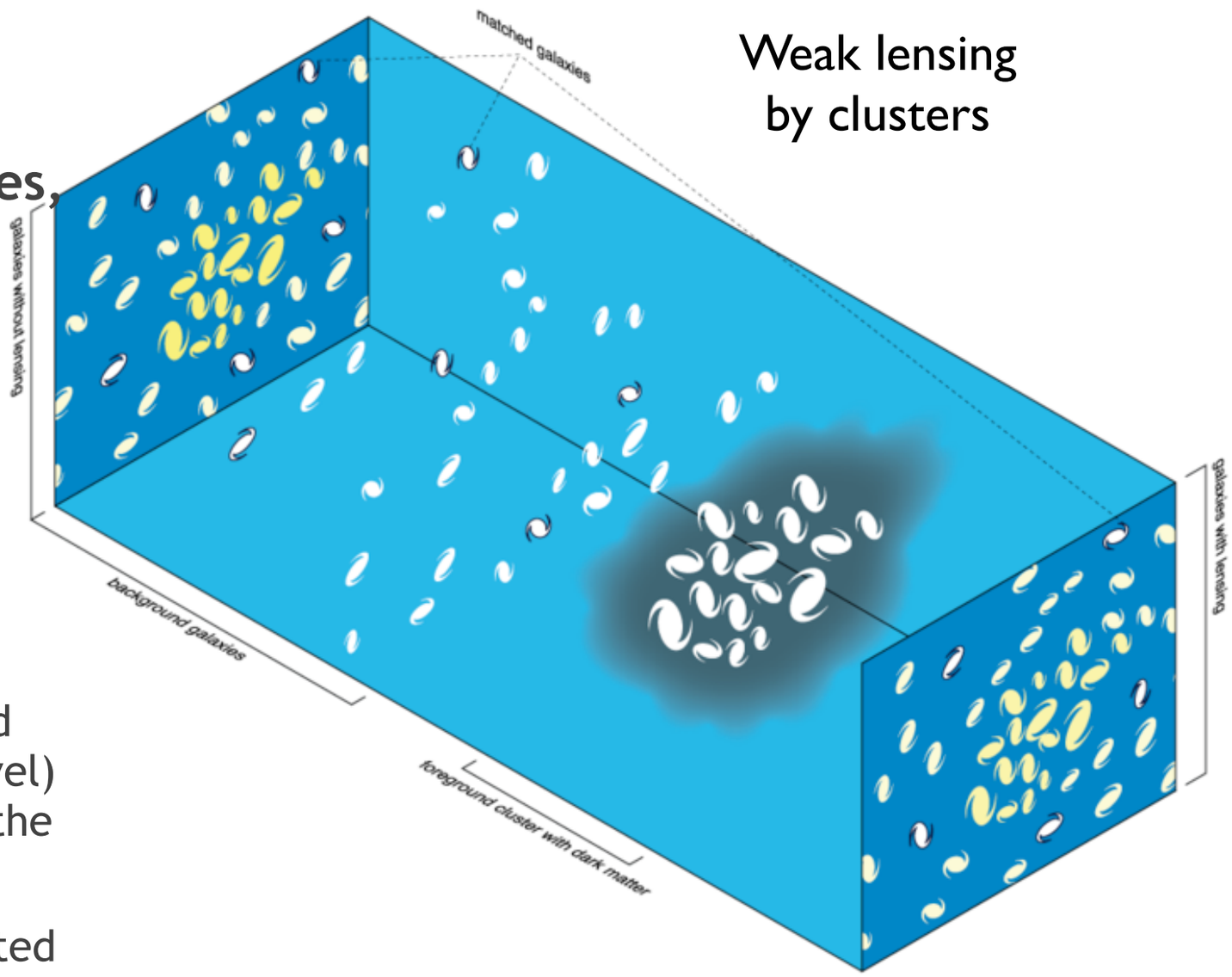
$w_0 = -1.0(18); w_a = 0.22(73)$

$w_0 = -0.87(20); w_a = -0.74(83)$

Weak Lensing Basics

- Intervening matter between a galaxy and an observer magnifies the image (convergence) and stretches the image (shear)

- Weak lensing by clusters of galaxies, 10% signal
- Galaxy-galaxy lensing, 1% signal
- Cosmic shear
  - Gravitational lensing by large scale structure
  - Since we do not know the size of the object that is lensed and the effect in general is small (for sources at z=1 and structures at 0.1<z<1 at the 0.1-1% level) we can only measure the statistics of the effect, shear correlation function
  - Shear correlation function can be related to dark matter density correlation function/power spectrum



Weak lensing by clusters

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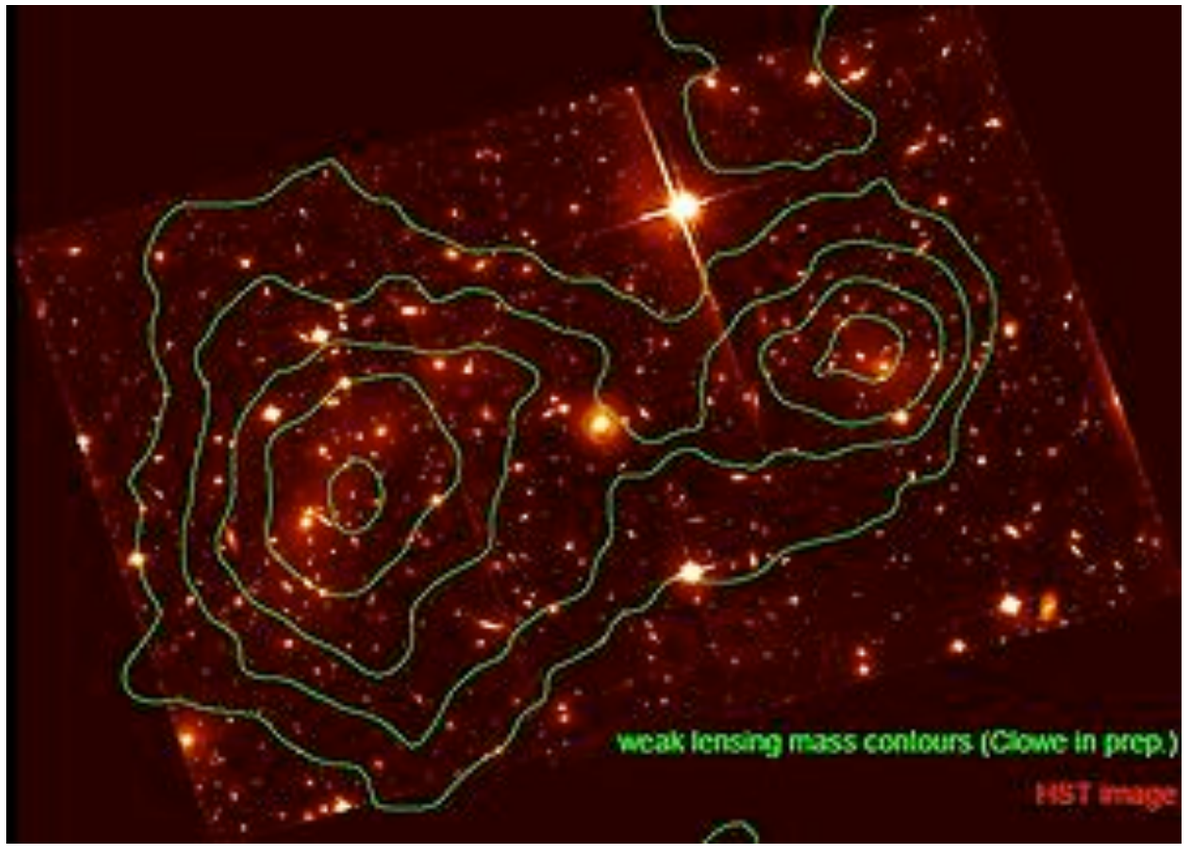
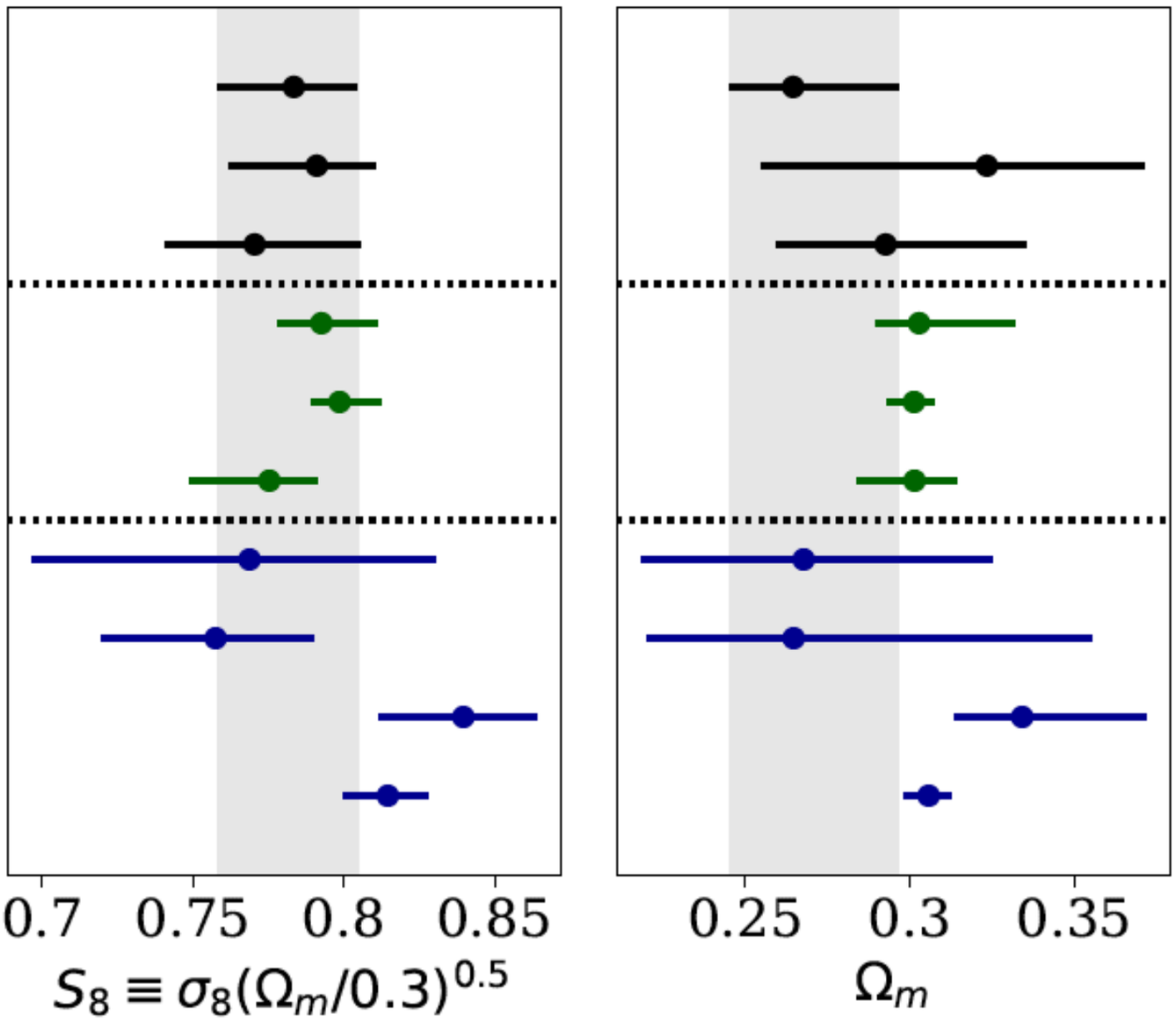


The Dark Energy Survey

- Optical and near-infrared imagine survey carried out on the 4m Blanco telescope in Chile
- 5000 square degrees in the southern sky, 525 nights, 300M galaxies
- Data taking started officially in August 2013 and is now in its fifth (last?) season
- First set of Y1 (year 1) papers recently were posted to the arXiv
- Main science focus: dark energy, but much more science is coming out (dwarf galaxies, solar system, …)
- Dark energy probes: Supernovae, lensing, clusters, clustering

Compilation of DES Results

Abbott et al. 2017



DES Y1 All
DES Y1 Shear
DES Y1 $w + \gamma_t$
DES Y1 All + Planck (No Lensing)
DES Y1 All + Planck + BAO + JLA
DES Y1 All + BAO + JLA
DES SV
KiDS-450
Planck (No Lensing)
Planck + BAO + JLA

LCDM

Compilation of DES Results

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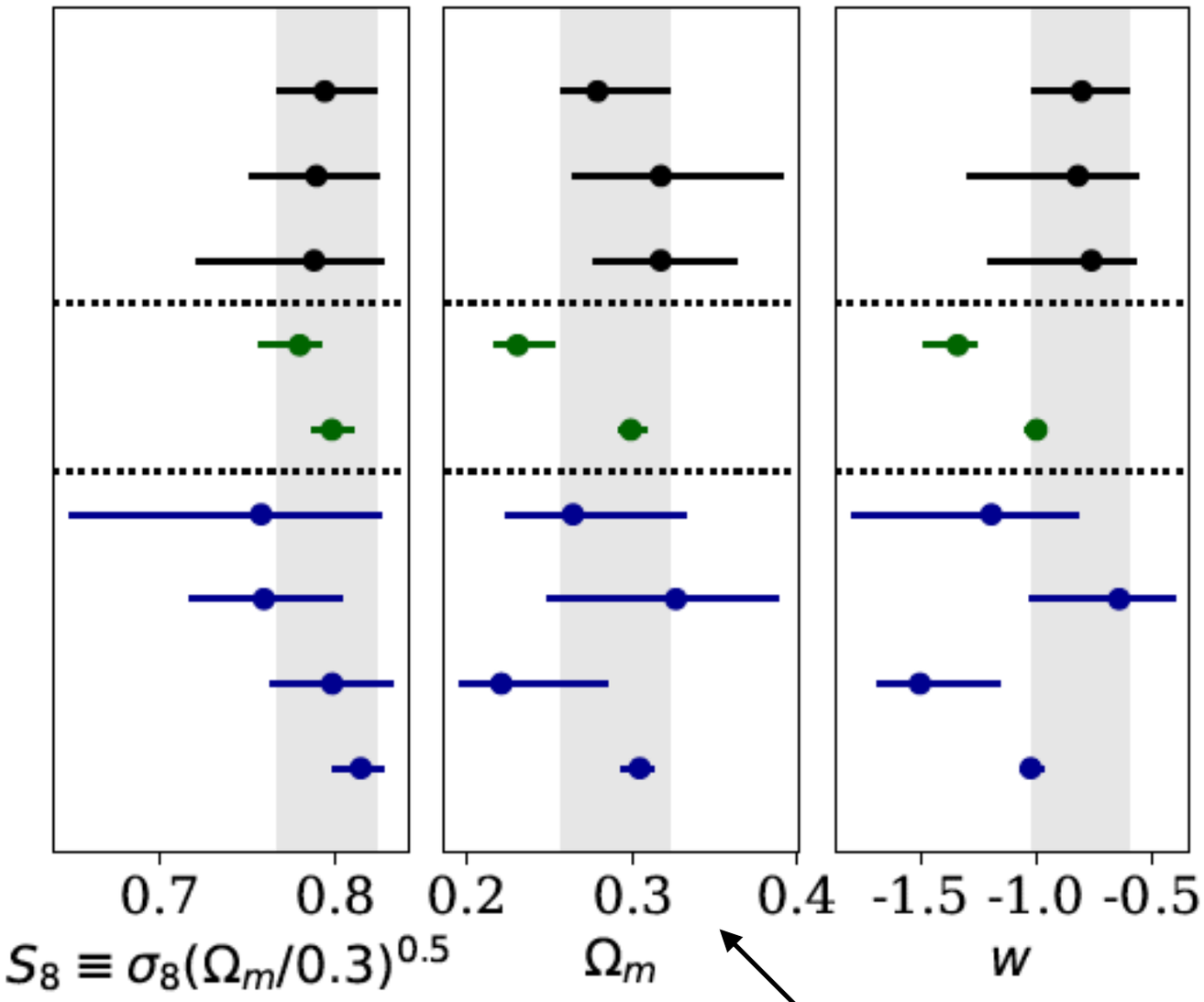


DES Y1 All

DES Y1 Shear

DES Y1 $w + \gamma_t$

DES Y1 All + Planck (No Lensing)

DES Y1 All + Planck + BAO + JLA

DES SV

KiDS-450

Planck (No Lensing)

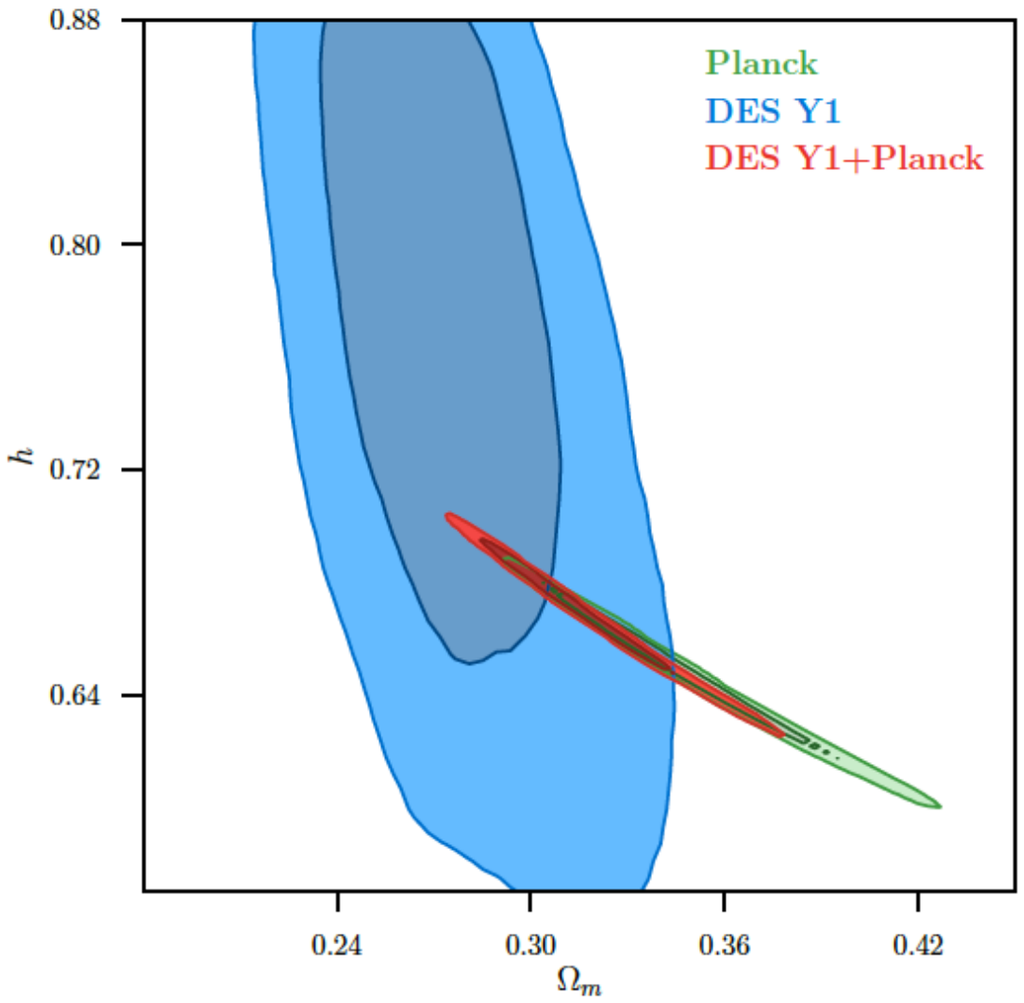
Planck + BAO + JLA

Note, wider range compared to previous slide

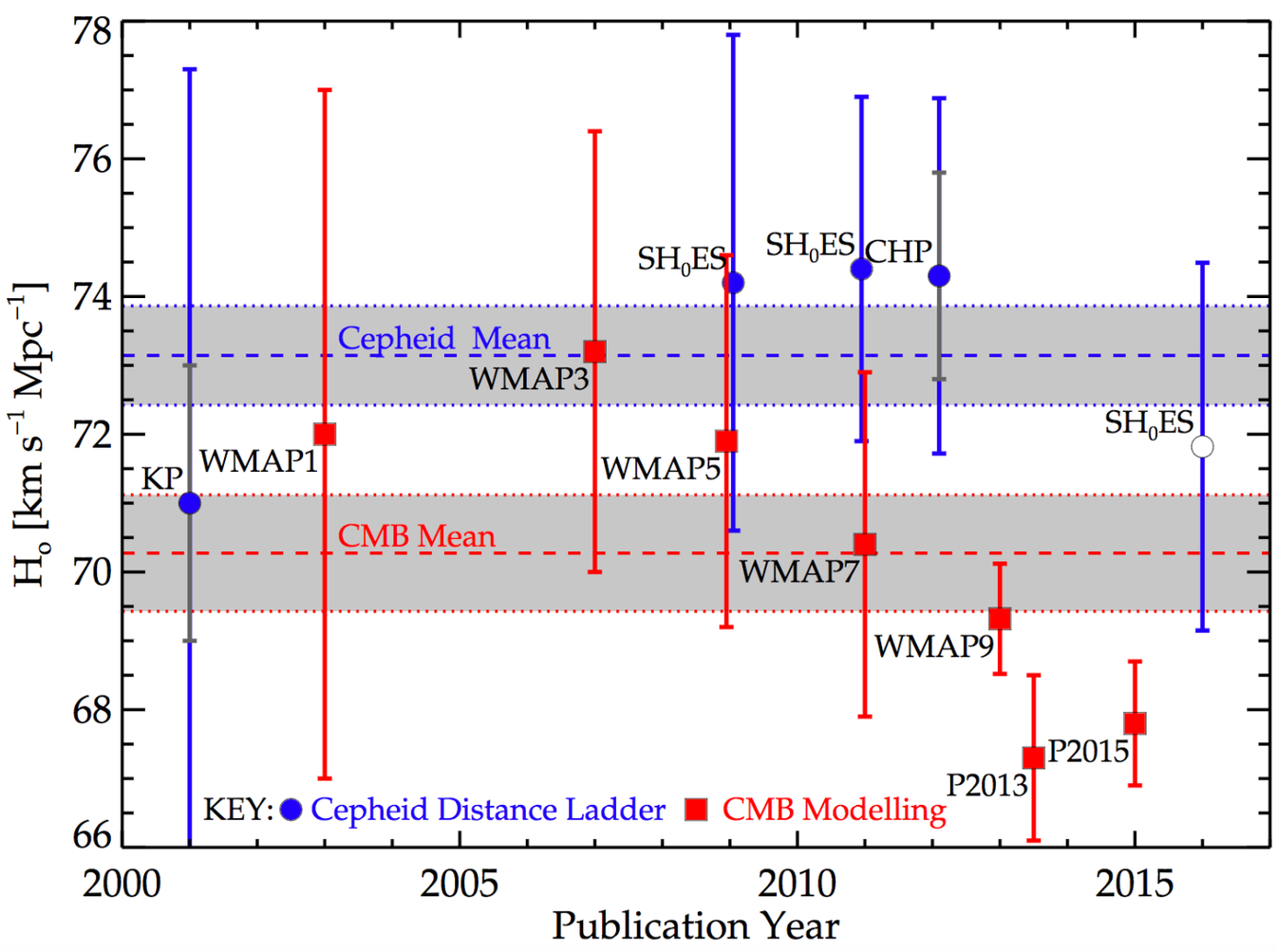
wCDM

Compilation of DES Results

Abbott et al. 2017



Beaton et al. 2016



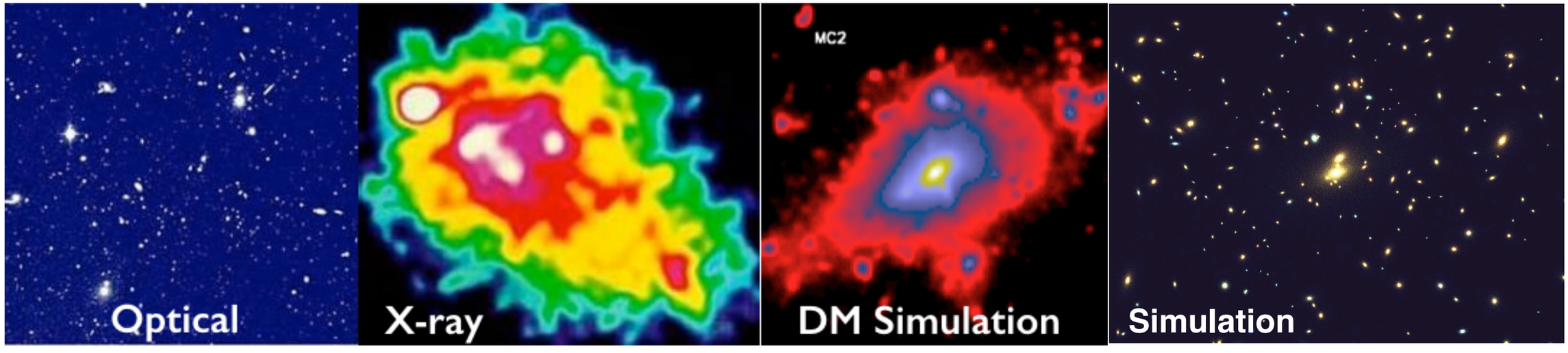
LCDM

New Physics or Systematic Uncertainties?

Theorist, modeler

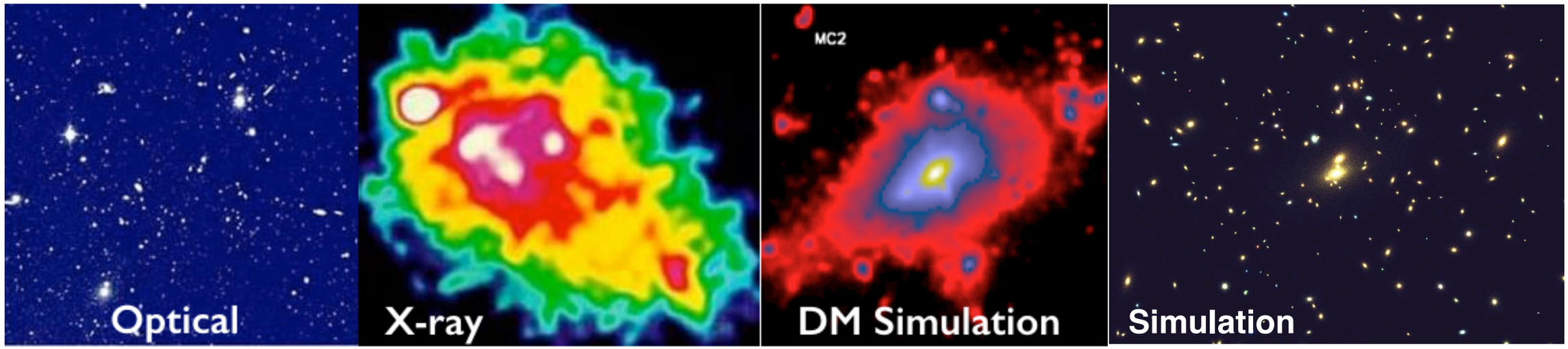
Observer

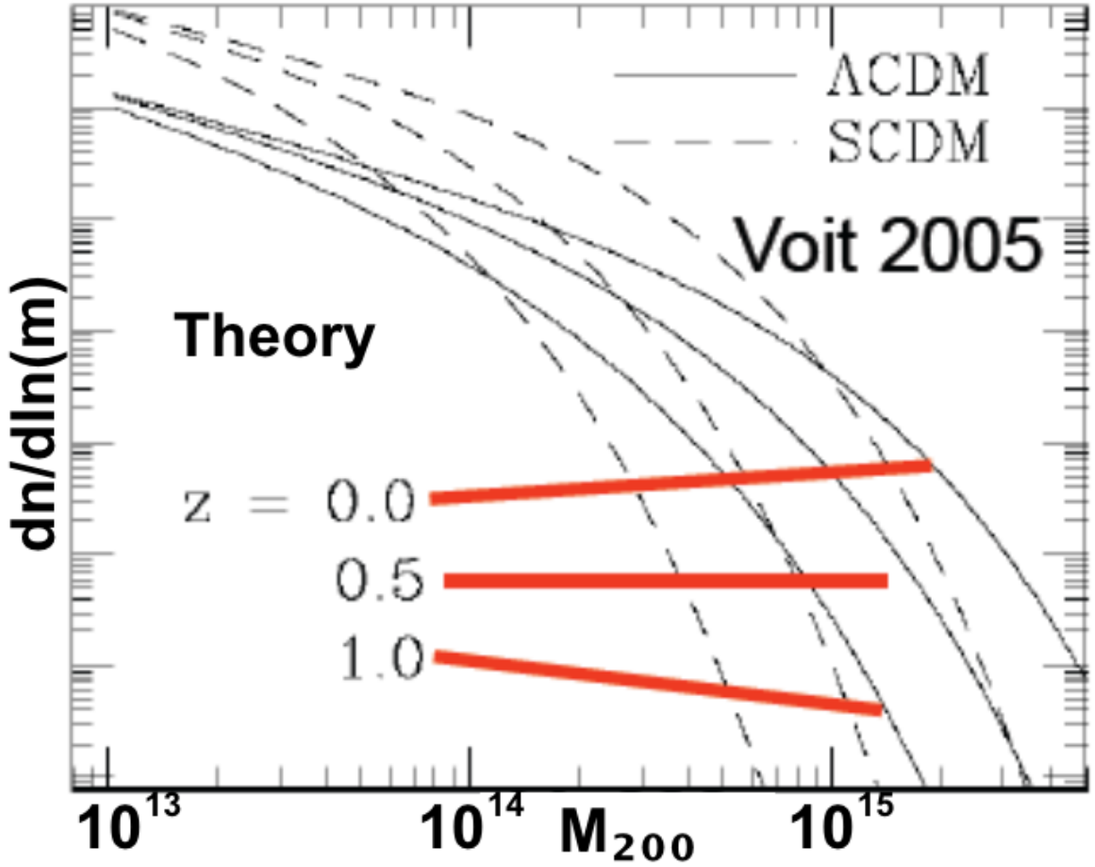
Clusters of Galaxies



- **Clusters of galaxies are largest bound objects in the Universe**
  - mass: $\sim 10^{14} - 10^{15} \mathrm{M}_{\odot}$
  - temperature: $\sim 10^{7} \mathrm{K}$
- **Redshift distribution of clusters in a survey is sensitive to geometry and growth of structure via redshift dependence of mass function**
  - Mass function: count of clusters as function of their mass
- **Exponentially sensitive to cosmology**
- **Major difficulties**
  - Finding clusters (optical, x-ray, SZ), measuring their mass and redshift
  - Predictions for mass function and mass-observable relations from simulations; complicated physics, simulations costly

Clusters of Galaxies





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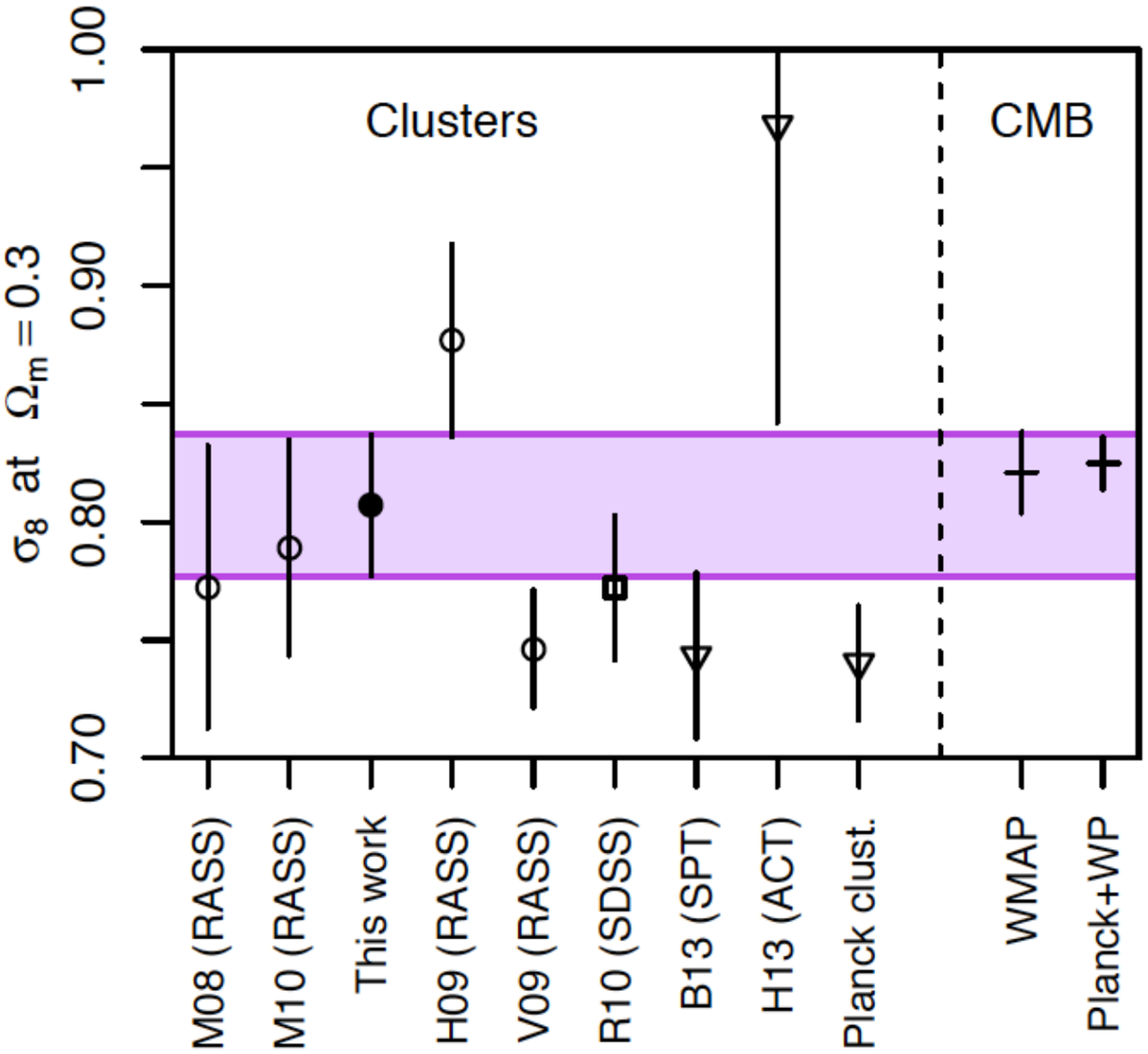
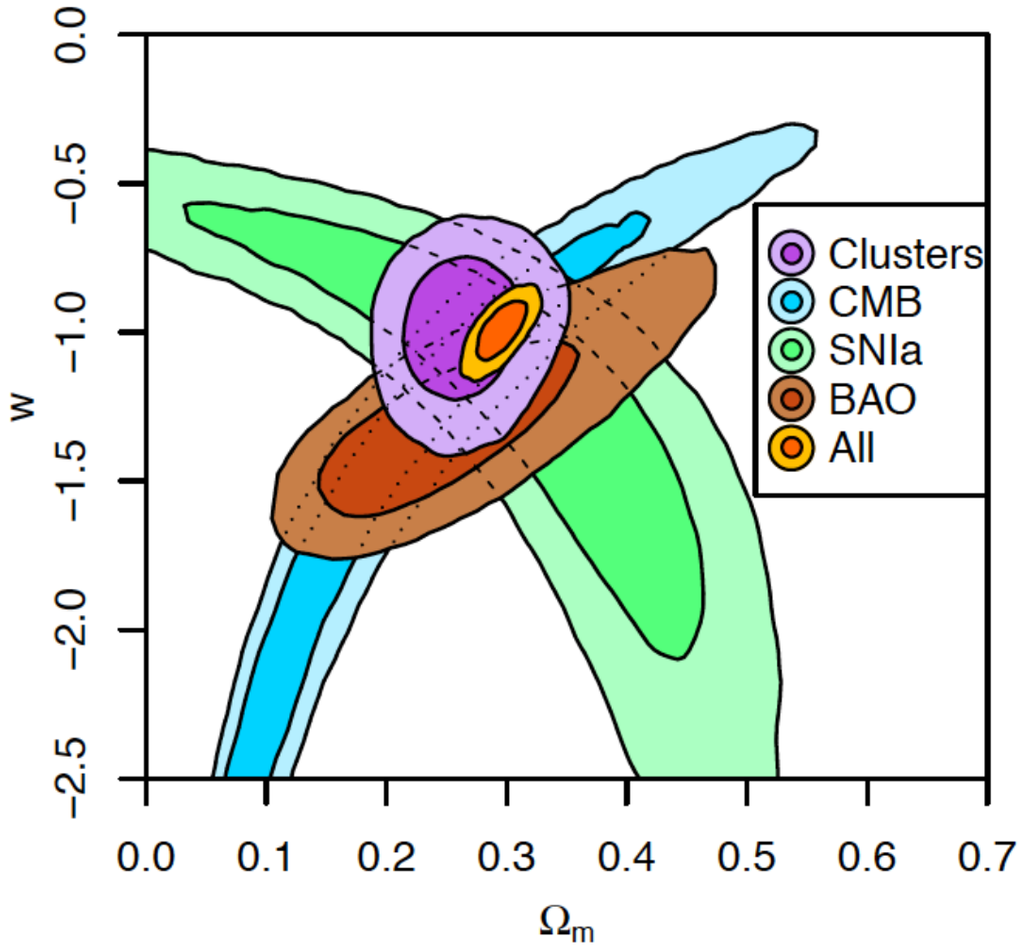




Mantz et al. 2015

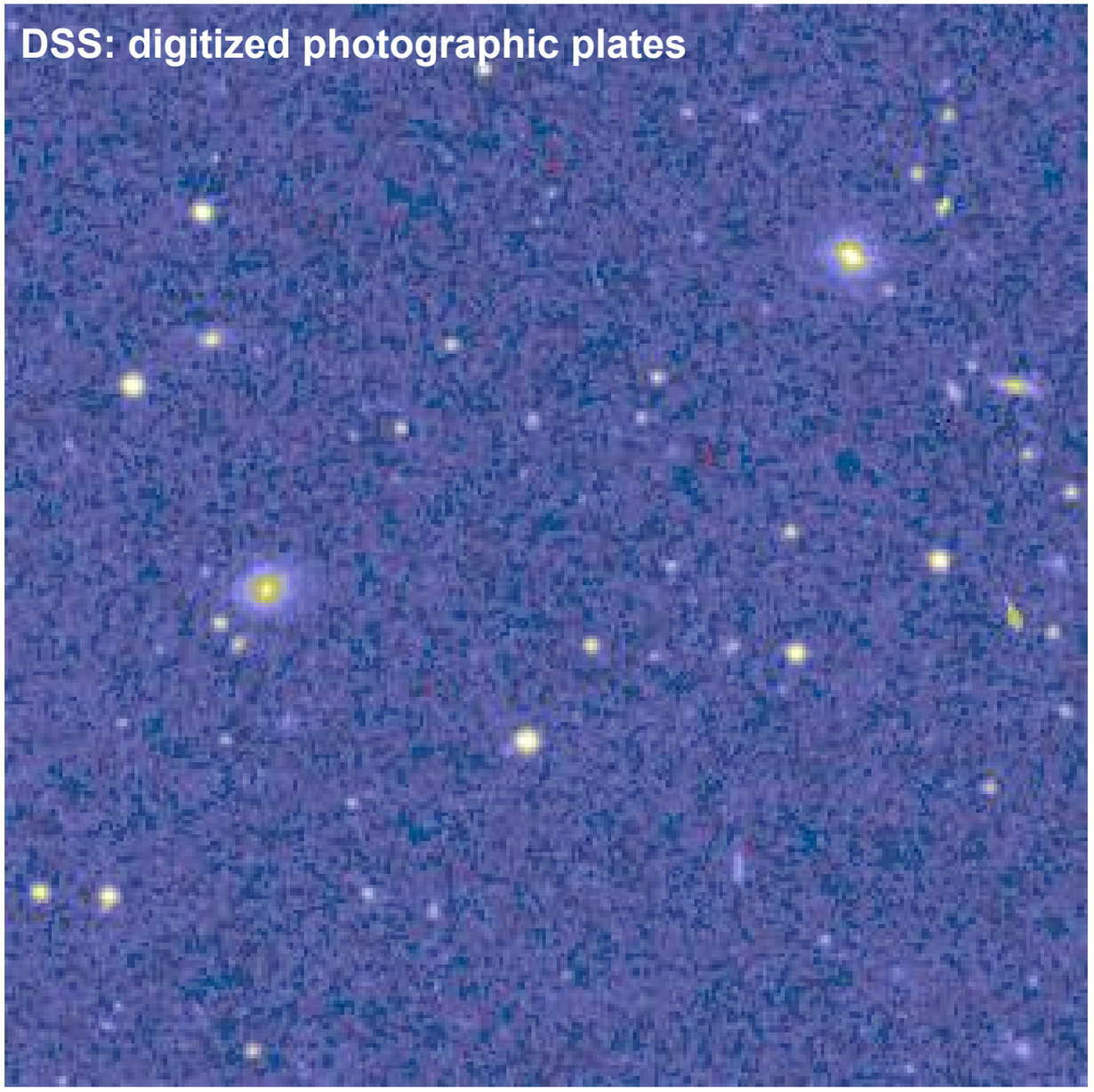
What's next —

The Large Synoptic Survey Telescope

- The deepest, widest, image survey of the Universe
- 8.4-m mirror
- 37 billion stars and galaxies
- 10 year survey of the sky
- 15 Terabytes of data .. every night

Dark Energy Science Collaboration (DESC): 600+ members, focusing on dark energy constraints, everybody with LSST data right (=everybody in the US! Some european institutions) is welcome to join us!

What’s next —



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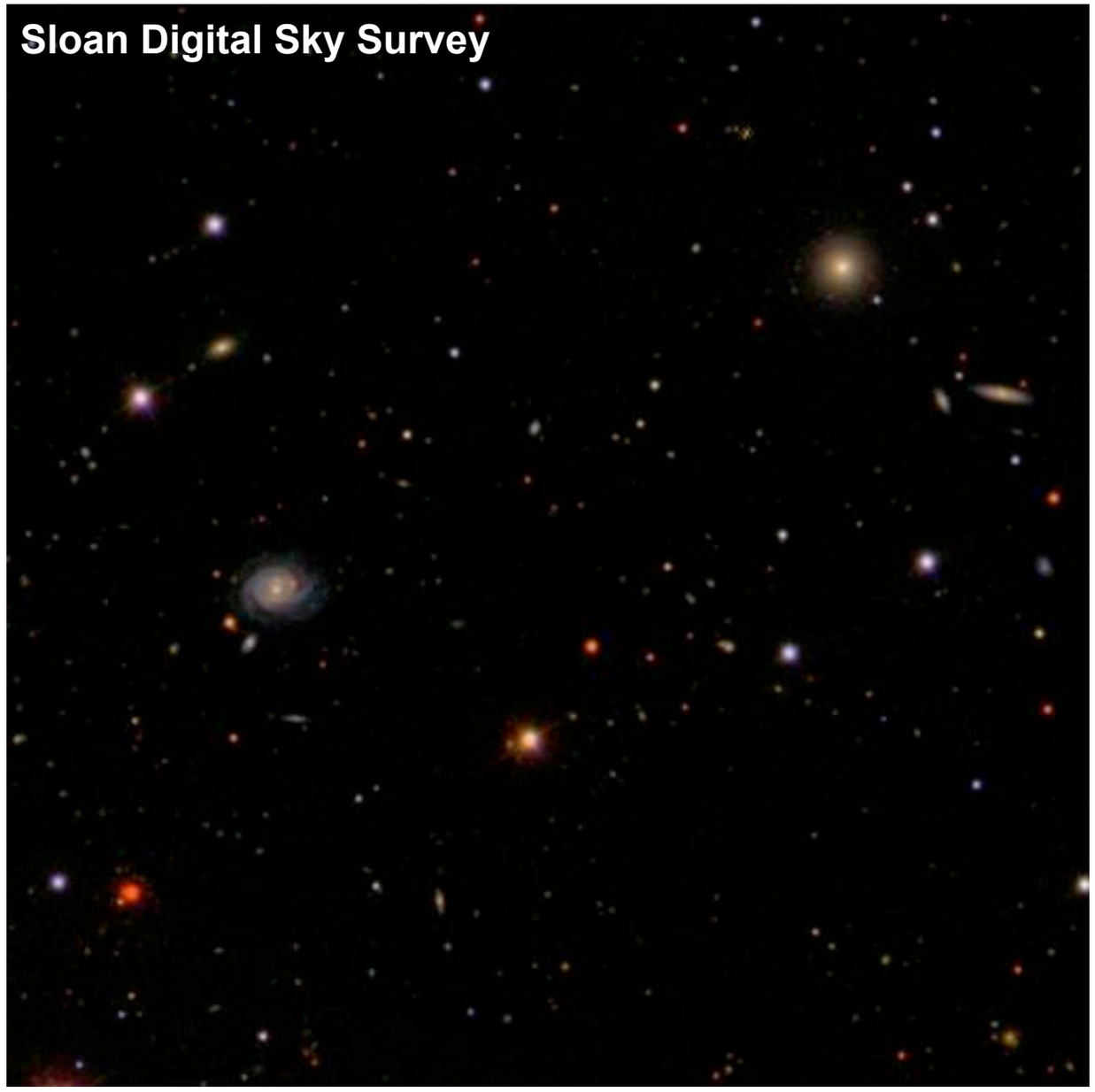

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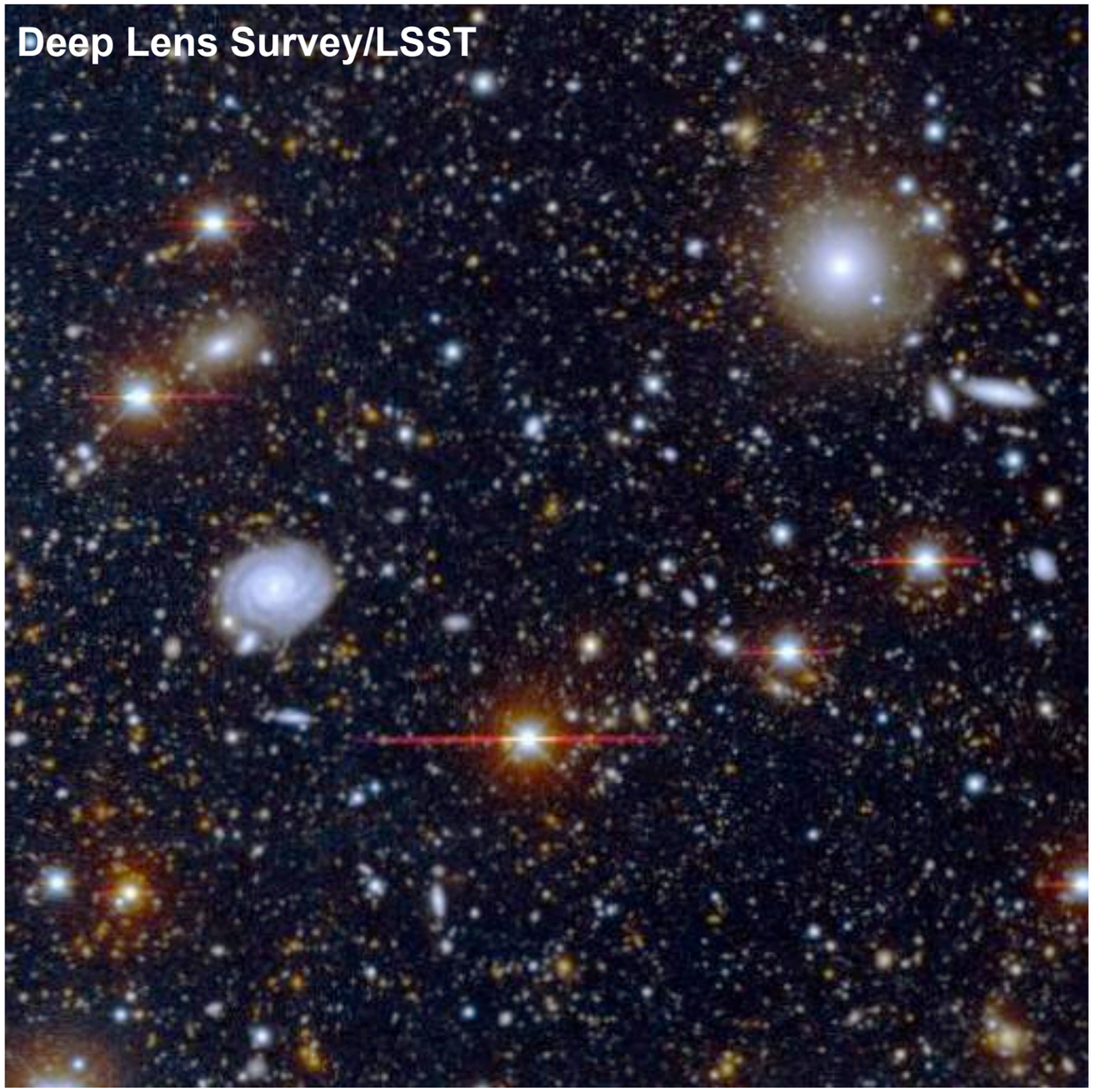
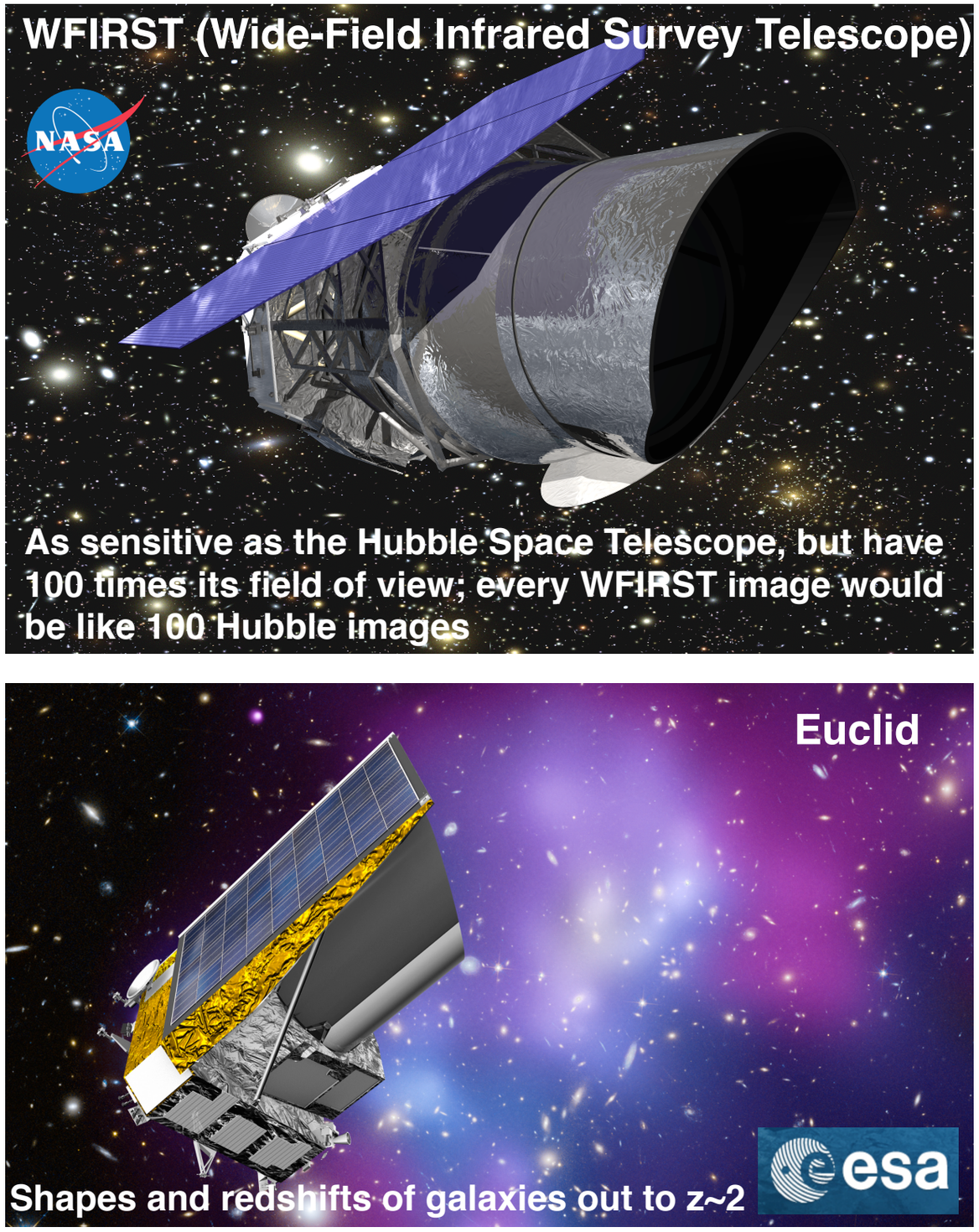
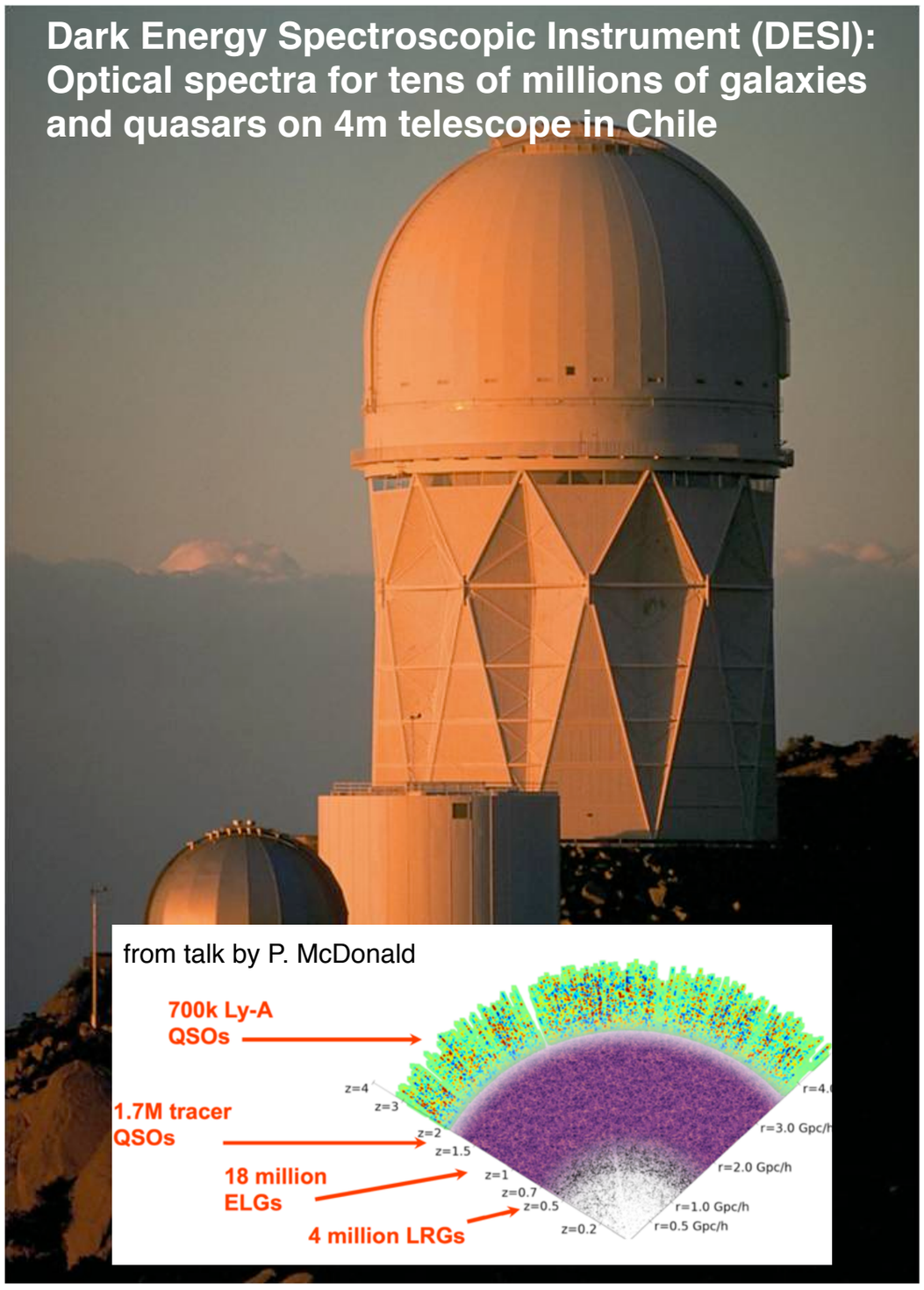


What's next —


WFIRST (Wide-Field Infrared Survey Telescope)
NASA
As sensitive as the Hubble Space Telescope, but have 100 times its field of view; every WFIRST image would be like 100 Hubble images

Euclid
esa
Shapes and redshifts of galaxies out to z~2


Dark Energy Spectroscopic Instrument (DESI):
Optical spectra for tens of millions of galaxies and quasars on 4m telescope in Chile
from talk by P. McDonald
700k Ly-A QSOs
1.7M tracer QSOs
18 million ELGs
4 million LRGs
z=4
z=3
z=2
z=1.5
z=1
z=0.7
z=0.5
z=0.2
r=3.0 Gpc/h
r=2.0 Gpc/h
r=1.0 Gpc/h
r=0.5 Gpc/h

Building Virtual Universes

Building the Universe in the Lab

- Without controlled experiments: **Build your own Universe(s)**!
- Create simulations that are as close to the real Universe as possible with regard to images and statistical properties
- **Explore fundamental theories** as well as the effects of **systematic errors** in a **controlled** way; hunting for small deviations
- Develop new cosmological probes to further our understanding of the Universe

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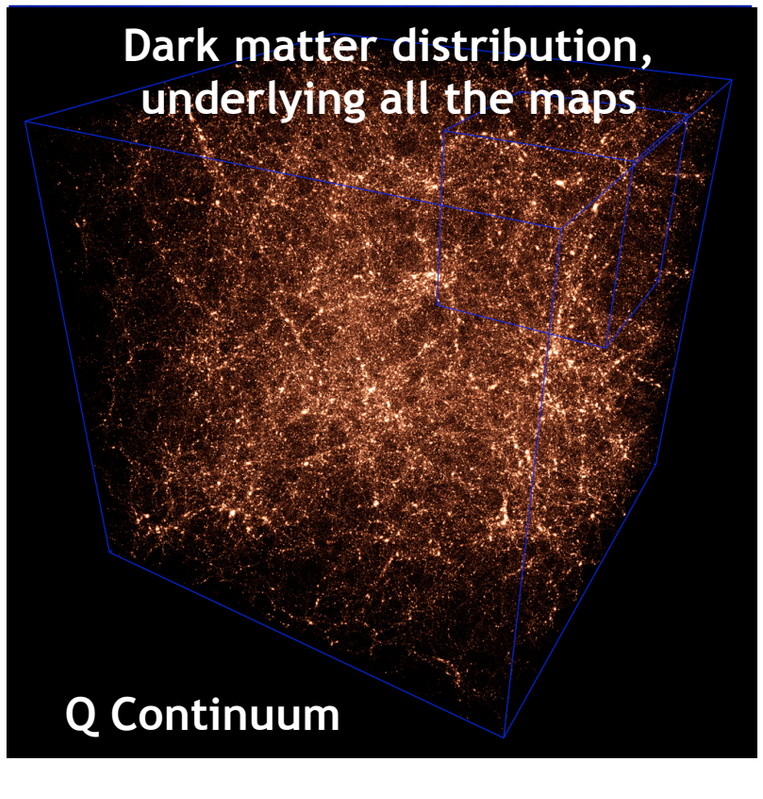
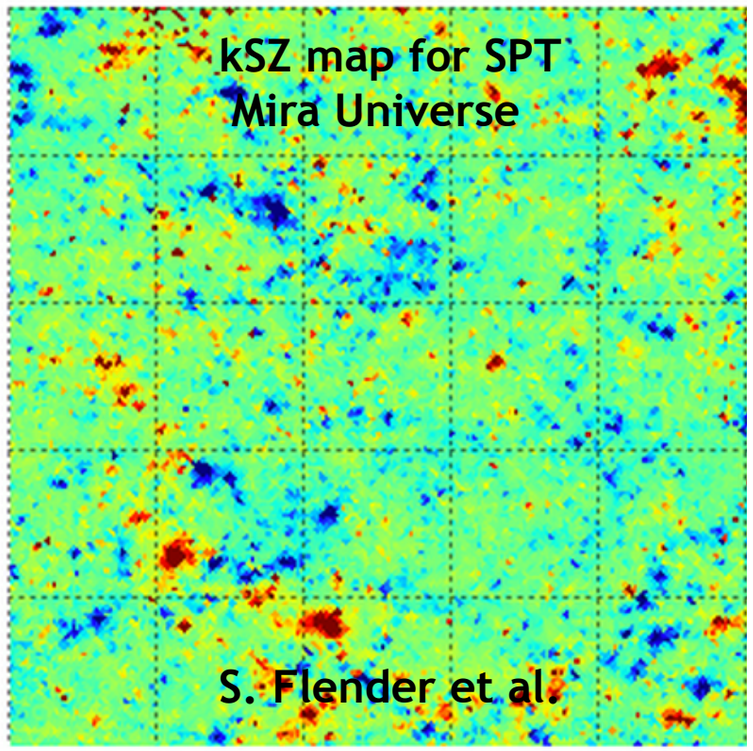
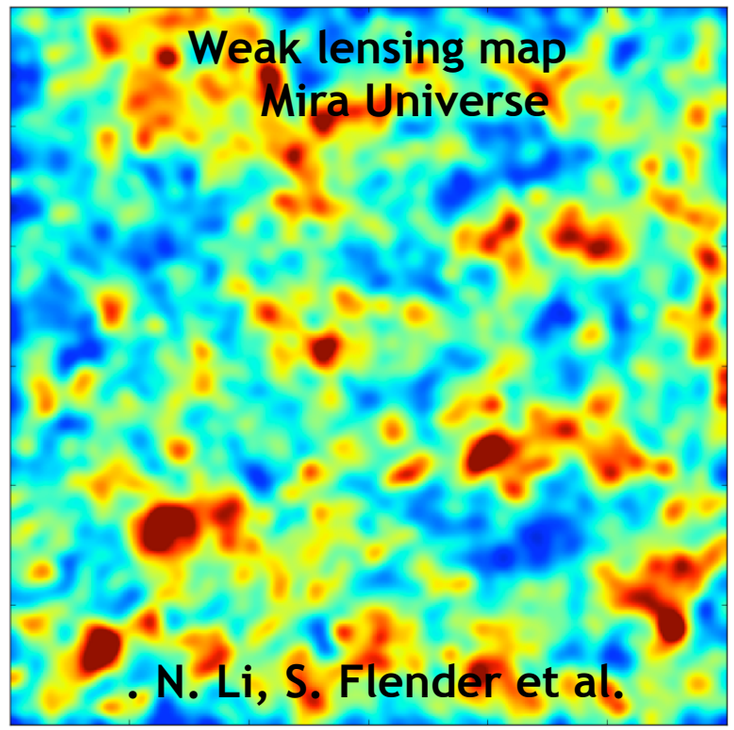
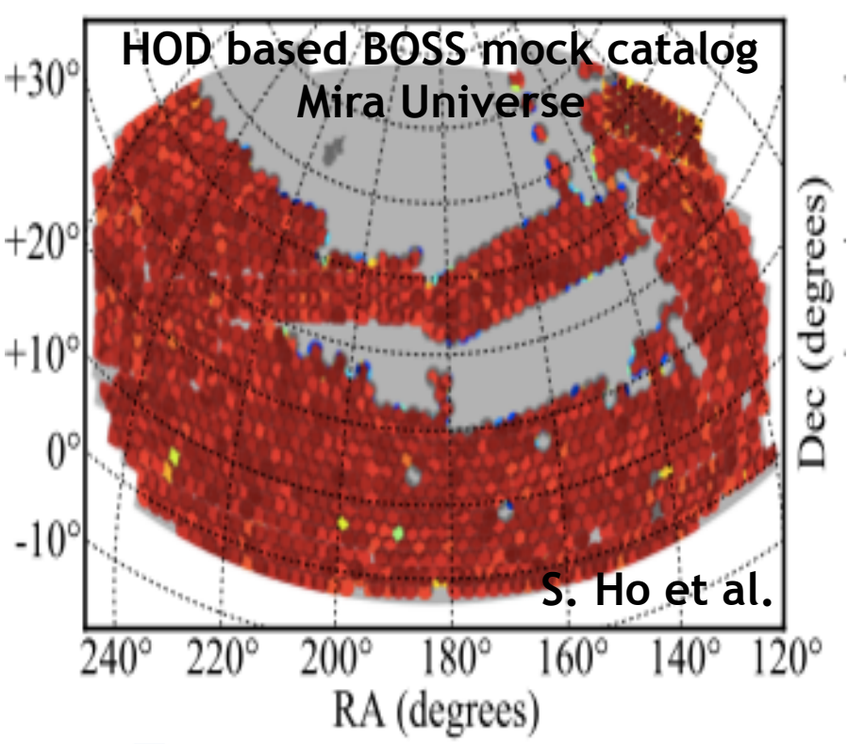
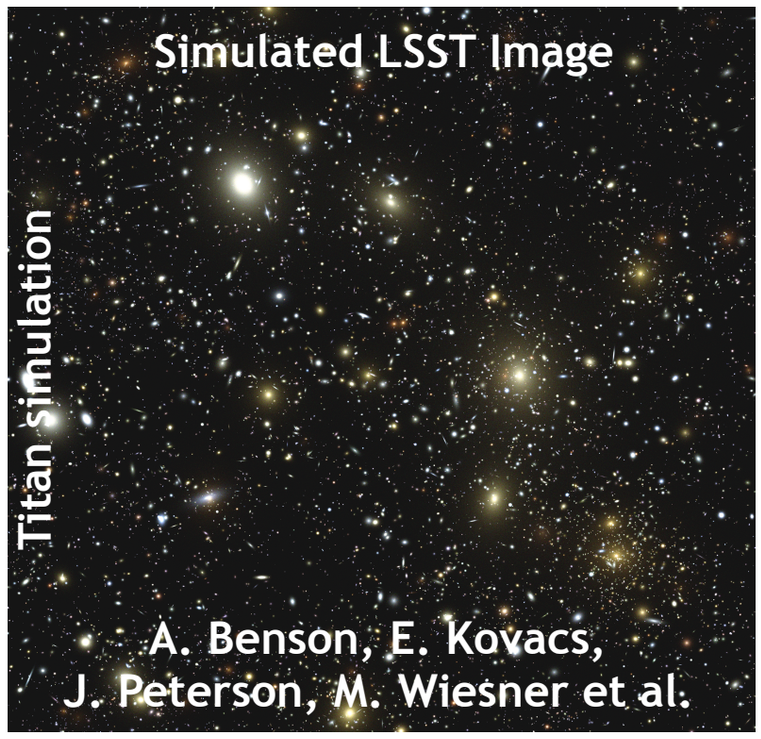
Virtual Skies for Cosmological Surveys

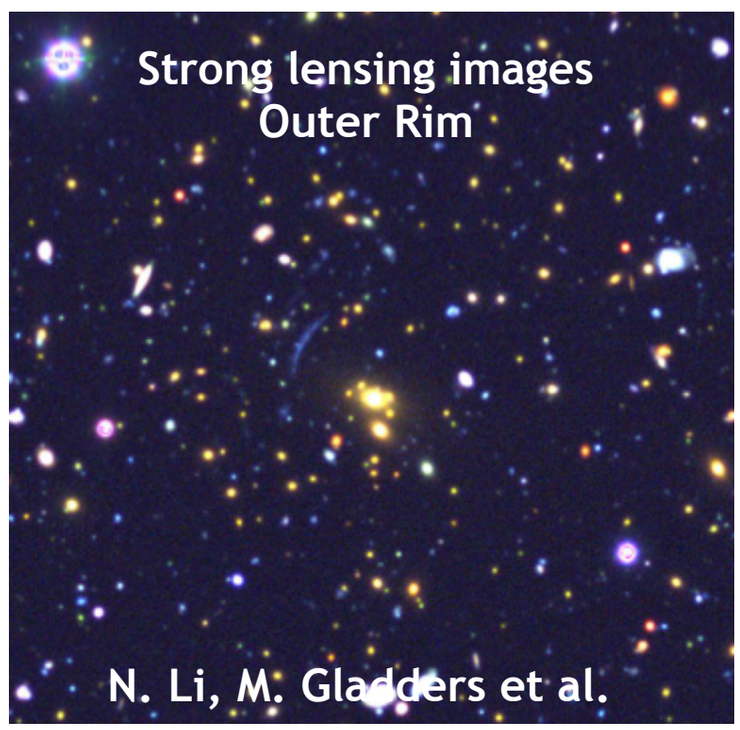












Summary and Outlook

- **Exciting times for cosmology!**
- **Dark energy program for the next decade and beyond:**
  - Experiments have been categorized into Stage I-IV depending on their constraining power
  - Stage III is currently being analyzed (DES, eBOSS, …), ~2020
  - Stage IV is being built (DESI, LSST, WFIRST, Euclid, …), ~2030
  - Stage V ideas are developing … ~2030+
- **Development of new probes and cross-correlating of measurements ongoing, program provides a range of different ways of looking at the dark energy/modified gravity question**
- **Accuracy of measurements is improving impressivly!**
- **Understanding of possible systematics and accurate predictions is critical to push to the next level!**