Vision on the new trends on astrophysics and cosmology: from large ground base surveys to space missions

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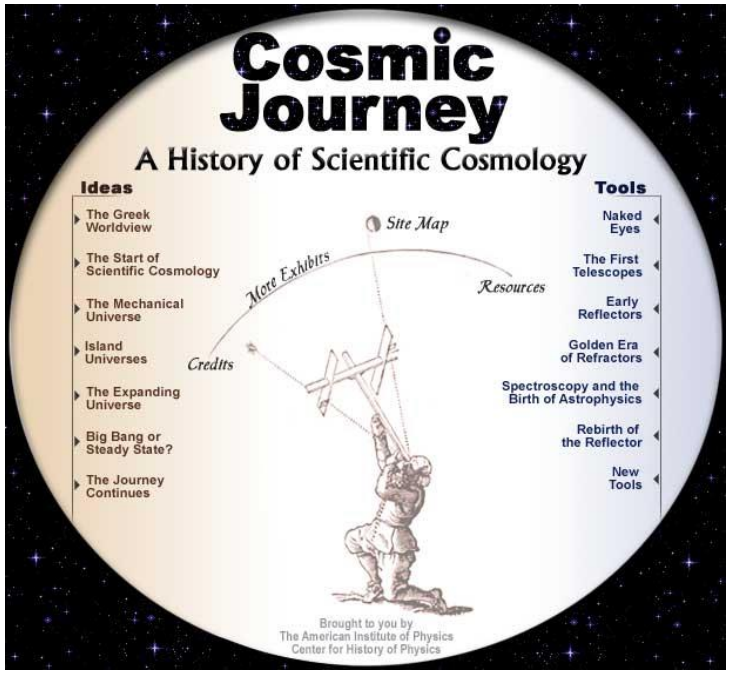
Outline

- **Introduction**
- **Knowns and unknowns about the Universe**
- **Expectations/surprises from next generation of large surveys and the challenges therein**
- **Discussions**

• Introduction

Astronomy is one of the fundamental disciplines in science, aiming to probe the nature and the laws governing the cosmic evolution



An active field in all ancient civilizations for different purposes

-- Human life related

-- Understanding the laws objectively

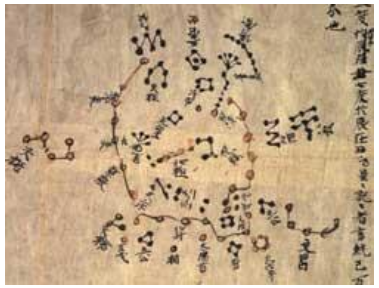
Methodologically, it is different from other fields. We cannot produce signals (not entirely true), but receive them from the heaven.

-- *cons: somewhat passive*

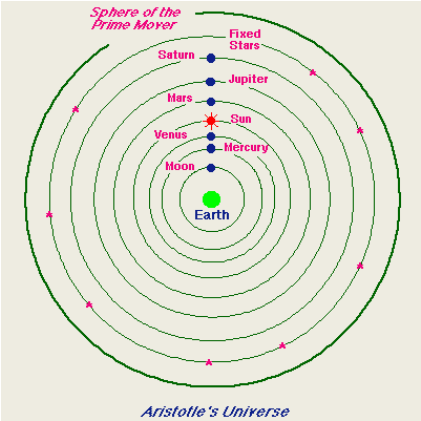
-- *pros: discovery of the unexpected*

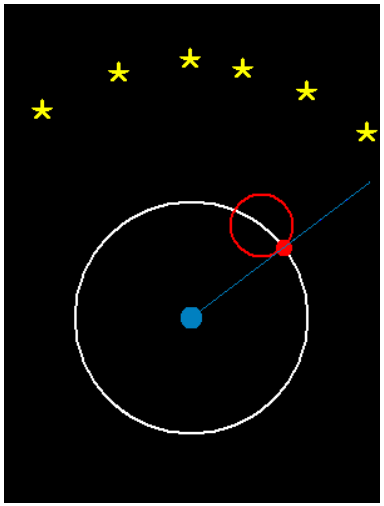
It is one of the fields that have benefitted the most from technology developments

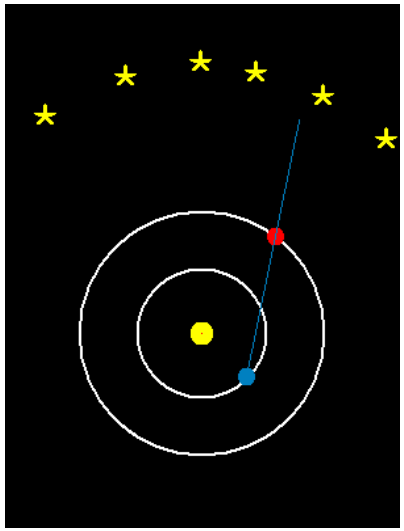
In old times, people relied on eyes and later mechanical instruments
to measure the position and variability of planets and nearby stars



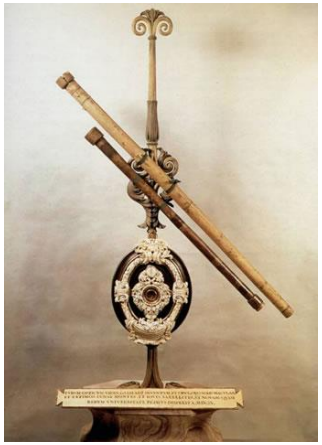
Geocentric theory to Heliocentric theory





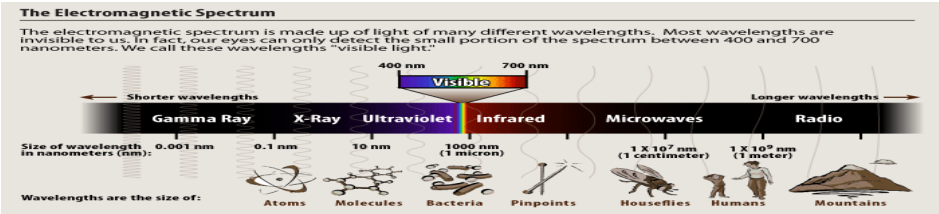


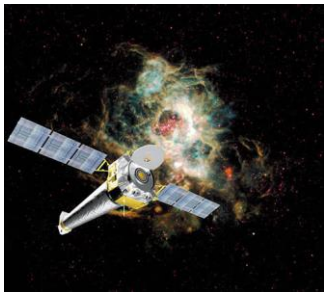
The invention and use of telescope have changed completely the horizon we can probe



Galileo first pointed the telescope to the sky (1608-1609)

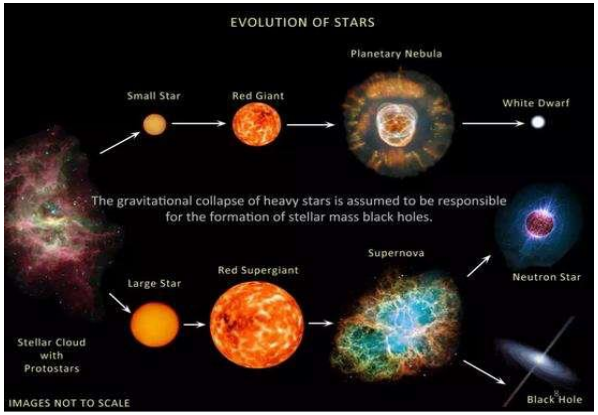
Since the 20th century, observational and theoretical developments have led to many new discoveries and improved our understanding of the Universe

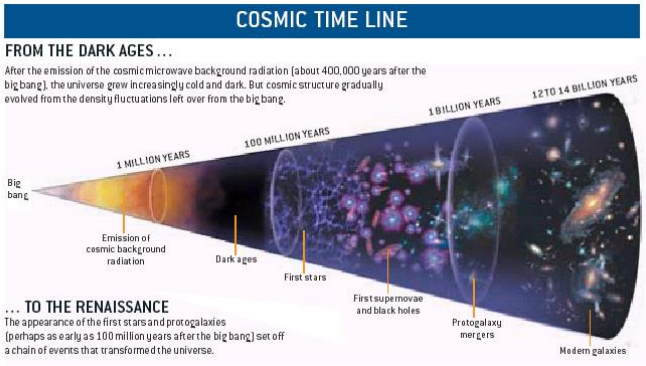


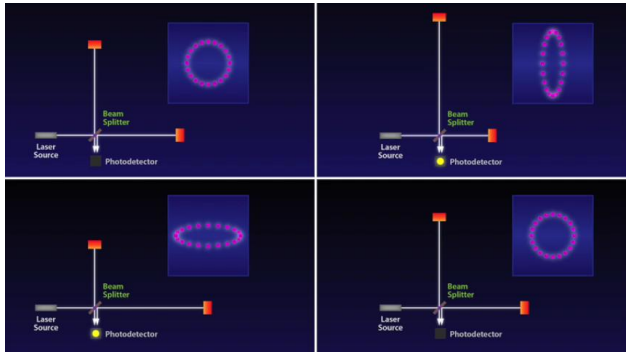


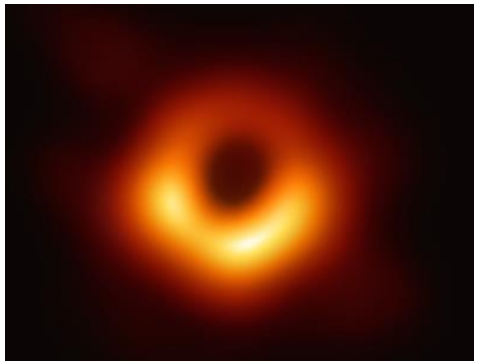
Gravitational waves, neutrinos, cosmic rays – multi-messenger era!!

-- Stellar evolution
-- Big Bang theory for the cosmic evolution
-- Pulsar/Neutron star
-- Dark matter
-- Inflation theory for the early Universe
-- Galaxy formation and large-scale structures
-- Dark energy
-- Exsoplanet detections
-- Gravitational wave detections
-- Black hole studies
-- Neutrino and cosmic rays



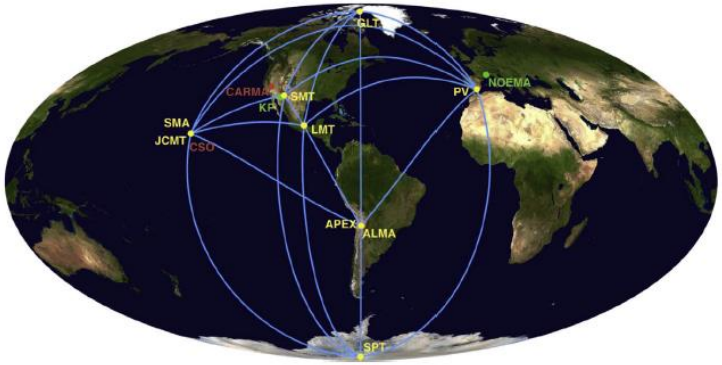






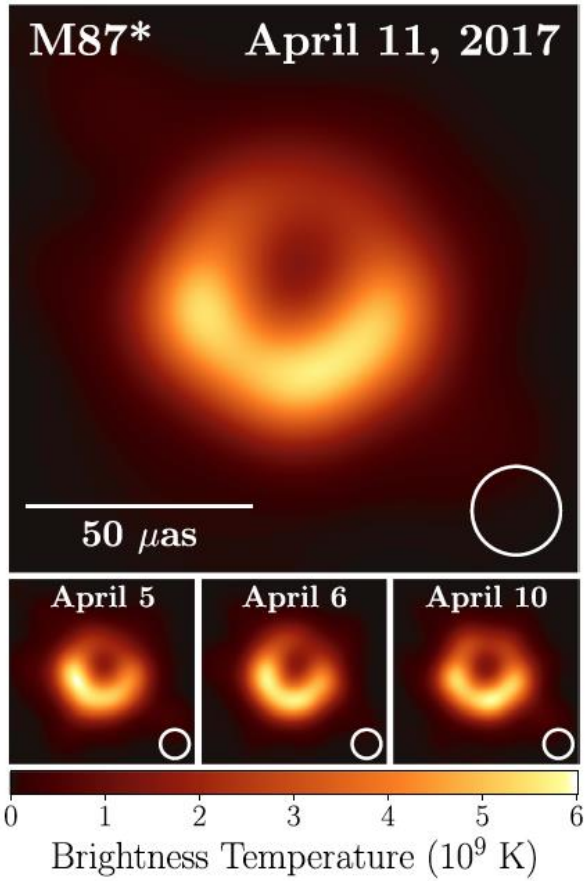
Astronomy is in its golden stage

-- multi-messenger era
-- high precision measurements
-- data volume is increasing continuously



EHT project director Sheperd S. Doeleman of the CfA, Harvard Univ.:

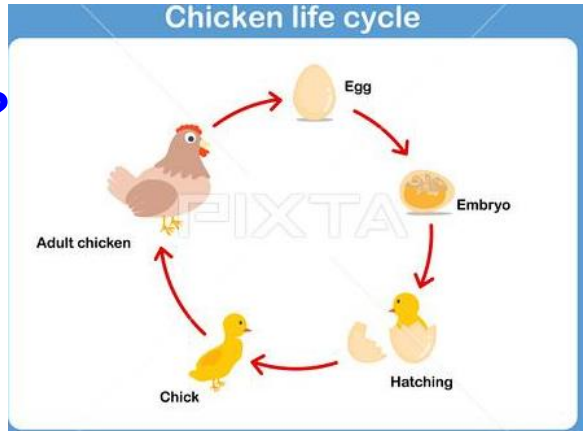
"We have achieved something presumed to be impossible just a generation ago," "Breakthroughs in technology, connections between the world's best radio observatories, and innovative algorithms all came together to open an entirely new window on black holes and the event horizon."



• Knowns and unknowns about the Universe

Cosmology is a branch of science aiming to understand the origin and evolution of the universe and the matter therein

How can we probe the cosmic evolution?



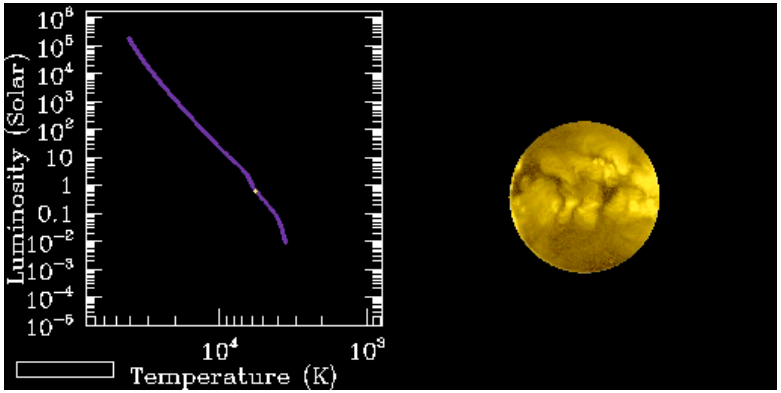
Animal/human life cycle

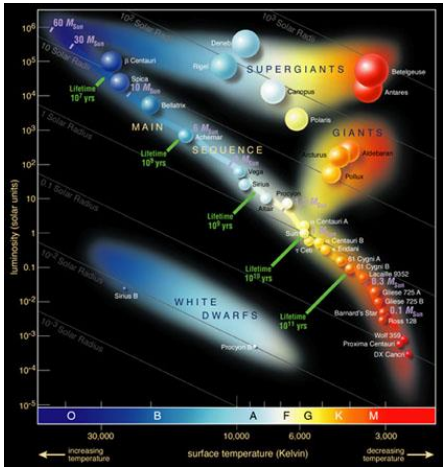
– follow individuals through their life time
(It is possible because we have longer or comparable life duration)

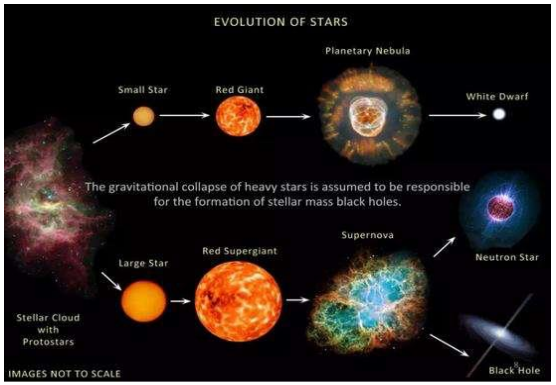
-- population studies by analyzing a group of individuals at different ages
(It is possible because we have a large sample)

Astronomical objects normally have much longer life time than our human being.
It is impossible for us to follow an individual object through its life time
(The life duration of the Sun is about 9 billion years, and it is now in its middle age)

In stellar studies, we can observe a large number of stars at different evolutionary stage → a global picture of stellar evolution







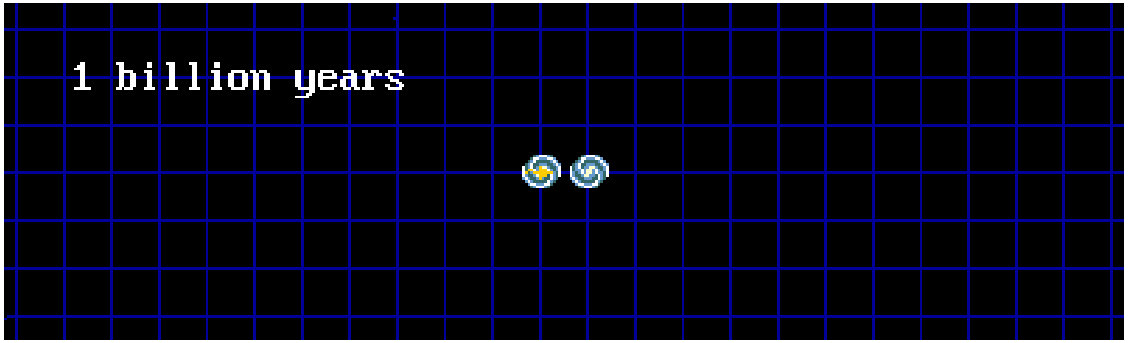
We have only one Universe, and it is now about 14 billion years old.

-- to study the old relics, similar to archaeological studies of the human civilization. Detailed studies of Milky Way and nearby galaxies -- near field cosmology

-- The Universe is huge in size. Light travels with a finite speed

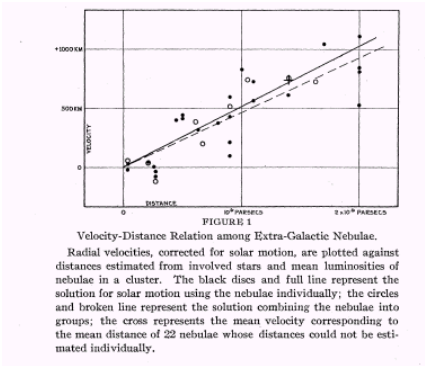
→ The light signals we received today actually emitted some time ago
The farther the object, the earlier the light emitted

→ Therefore we can indeed "see" the evolution of the Universe by observing light signals from different distances

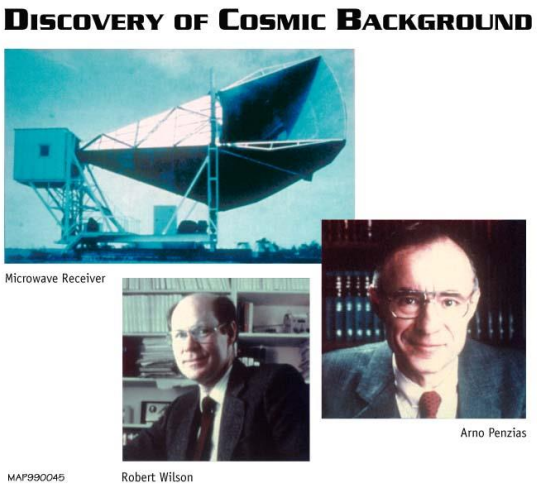


Follow the life of the Universe statistically

1920s Expansion of the Universe

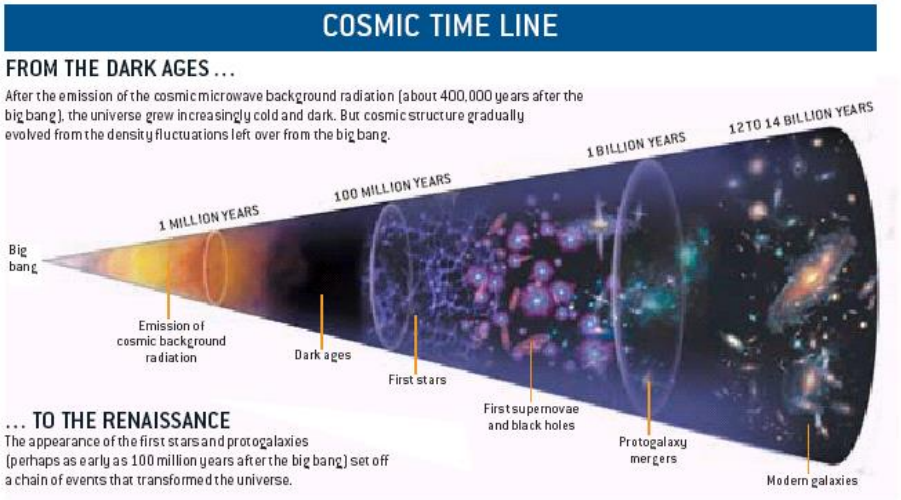


1965 CMB was detected

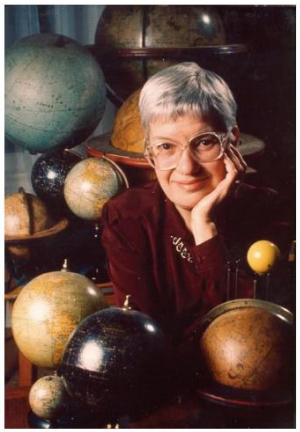


1940s Big bang theory was proposed to explain the element abundances predicted the existence of CMB

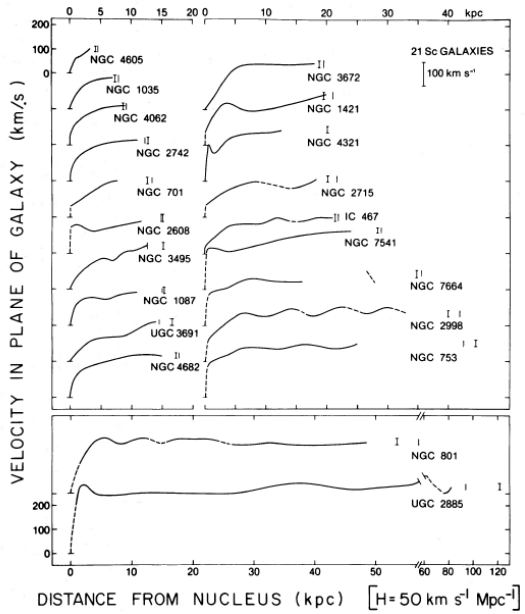
Cosmic thermal history

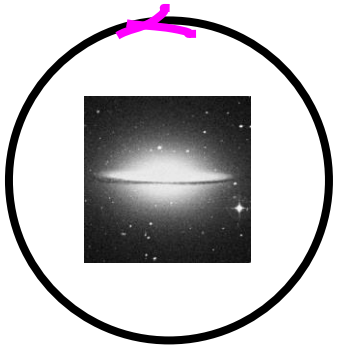


1970s -- Systematic studies of disk galaxies



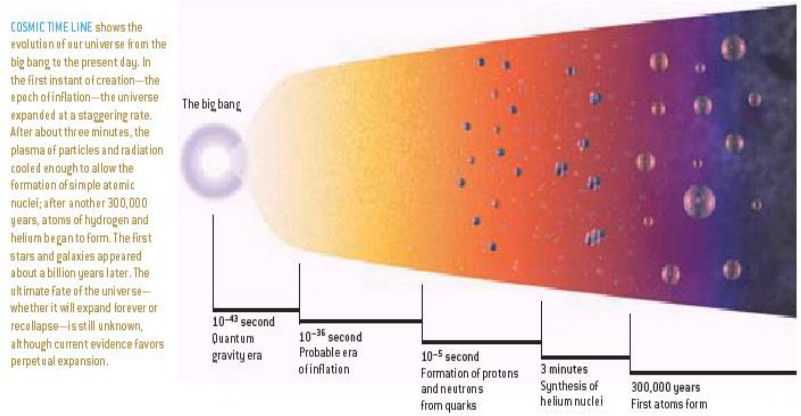
Vera C. Rubin





The flat rotation curve at outer disk → existence of ***dark matter***

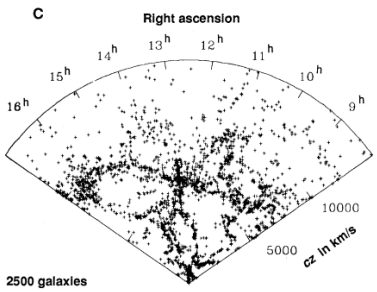
Late 1970s and early 1980s – **Inflation theory** was proposed to remedy the defects of Big Bang theory – horizon problem, flatness problem, origin of large-scale structures

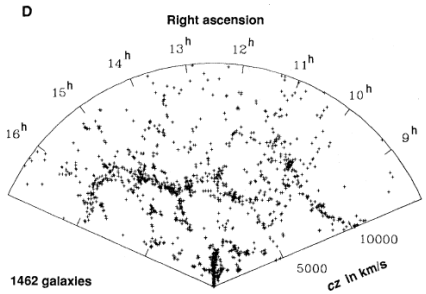


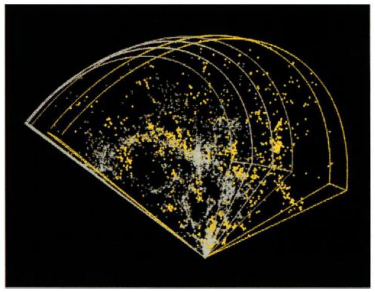
1980s

– Galaxy redshift surveys → map the 3D distribution of galaxies

spectral line shift → redshift → radial distance of a galaxy



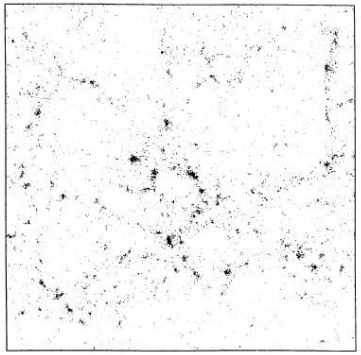


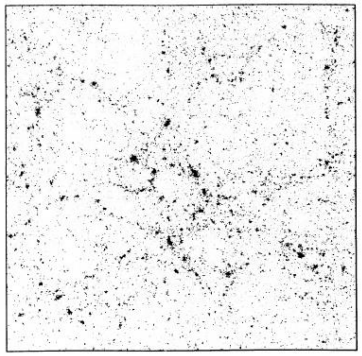


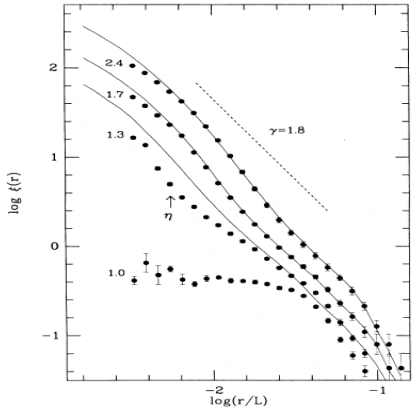
CfA survey

-- Computer simulations to confront the observed large-scale structures with theoretical predictions

Numerical simulations (Davis, M. et al. 1985)



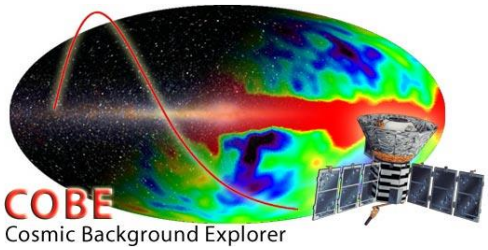


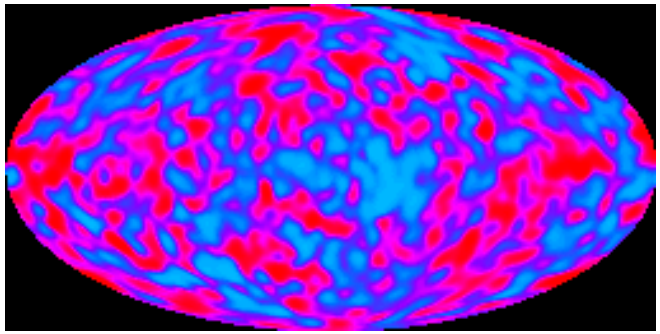


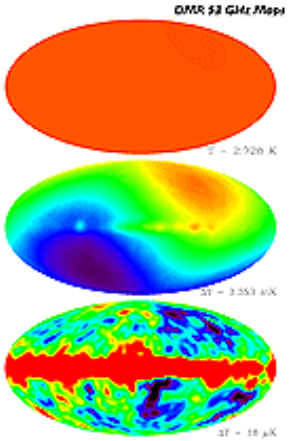
1992 COBE satellite observations of CMB

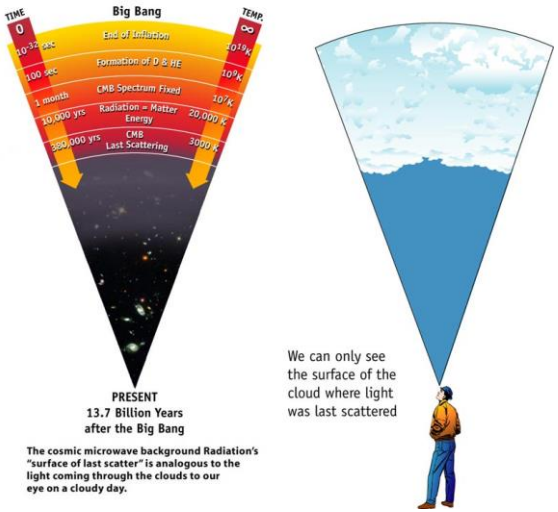
-- blackbody spectrum to high accuracy → Big Bang theory

-- first detection of CMB anisotropy → seed of large-scale structures and support the inflation theory







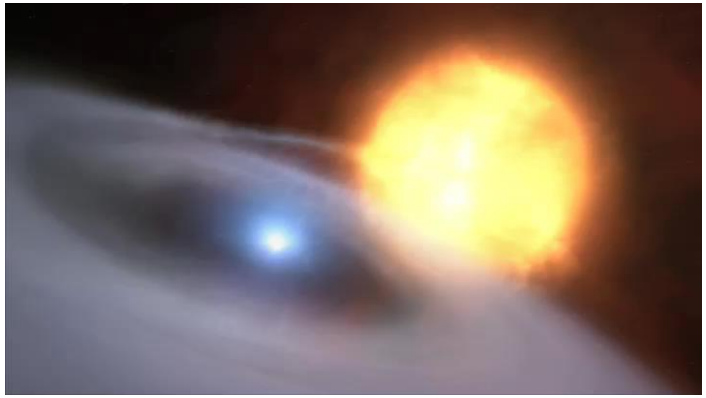


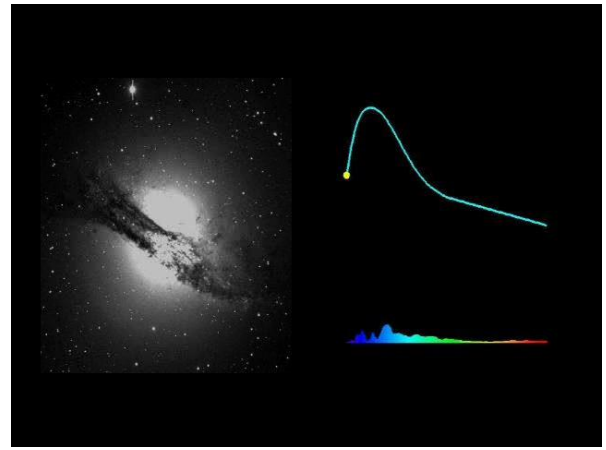
CMB is the thermal relics of hot Big Bang.
It started traveling to us at redshift z~1100, corresponding to age ~400,000 year
(note currently the Universe is ~14 billion years old)

We can see directly the Universe at its baby age!!

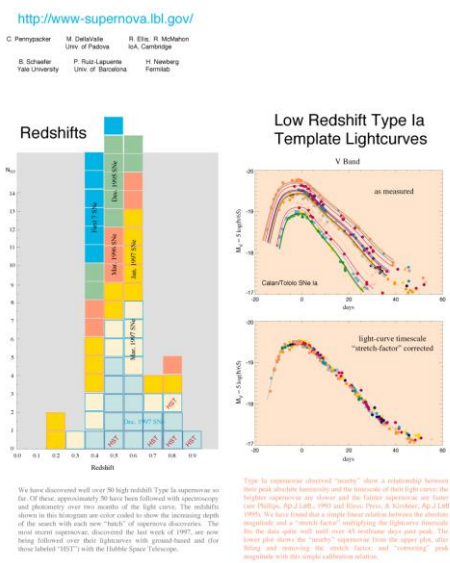
1998-1999 – SNeIa observations → cosmic accelerating expansion !! **– dark energy**

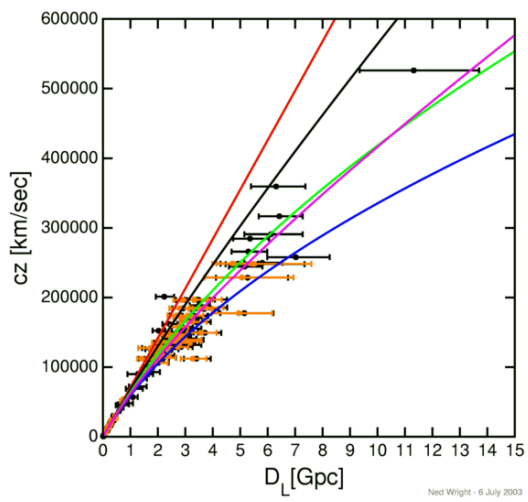
white dwarf explosion when its mass exceeds the Chandrasekhar limit

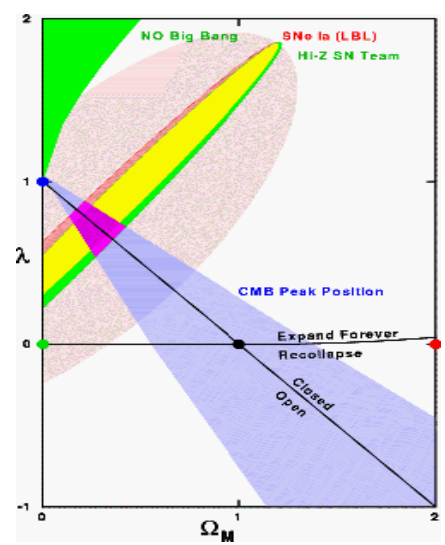




Standardizable candles -- can be used to measure distance



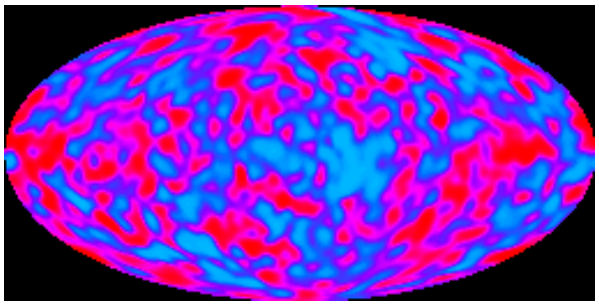




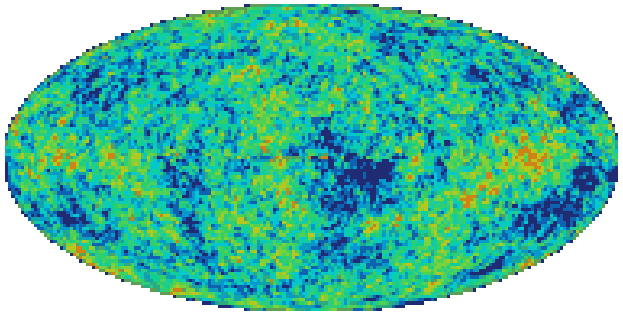
Since 21st century, the cosmological observations have been developing rapidly, in terms of both quantity and quality

CMB observations

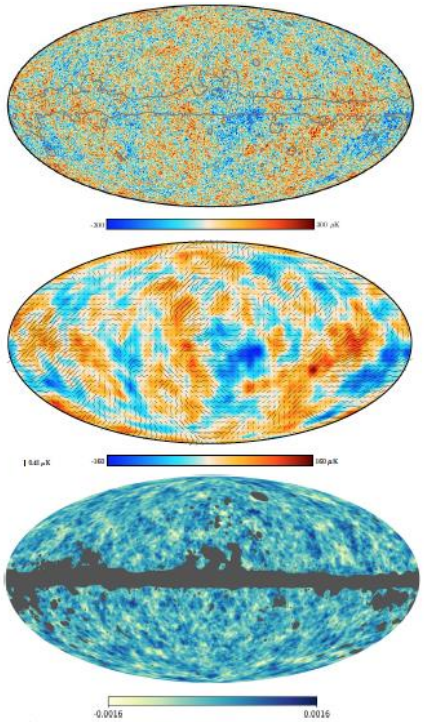
COBE ~7deg resolution

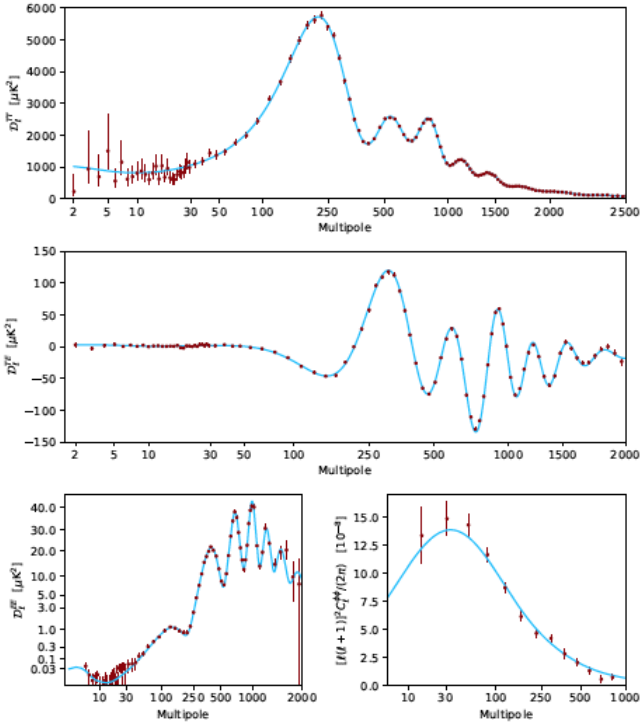


WMAP ~20 arcmin



Planck ~10 arcmin





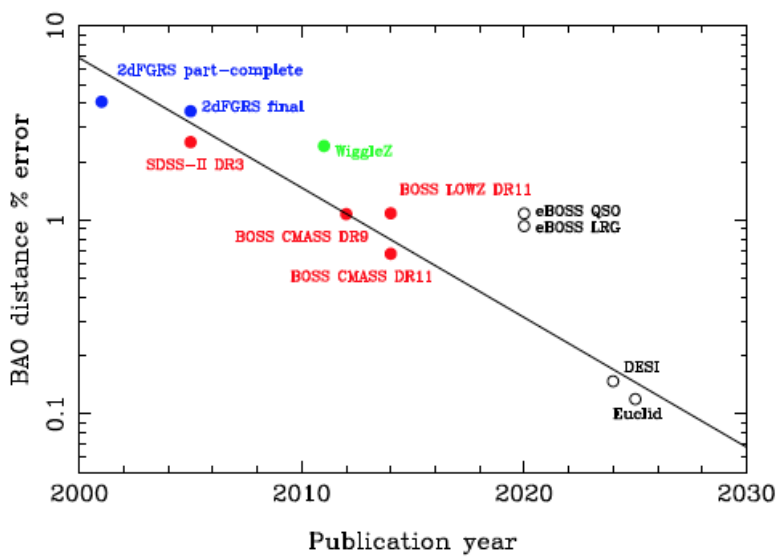
CMB observations lead to the field into the era of precision cosmological studies

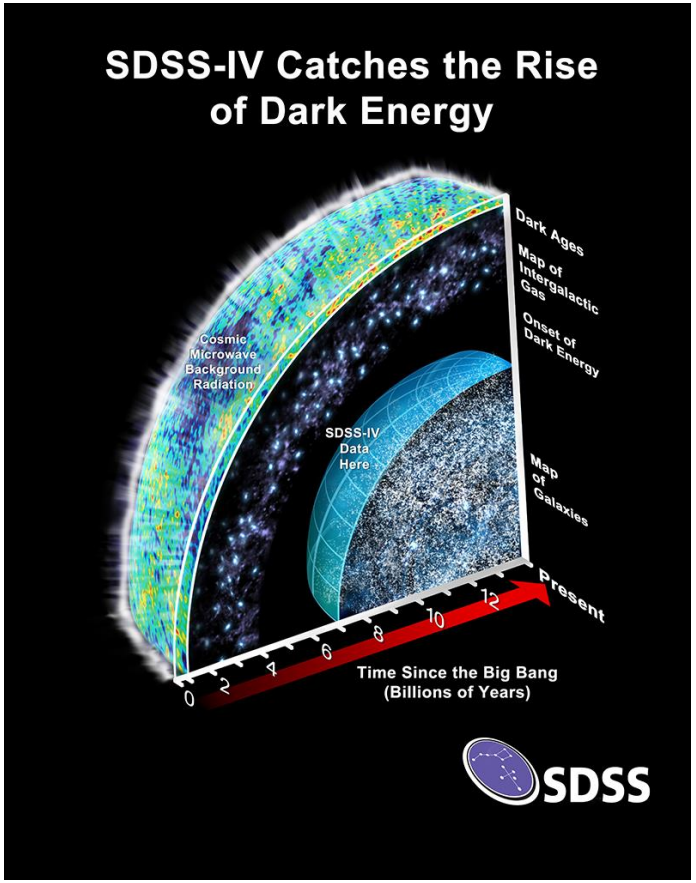
Galaxy redshift surveys

From a few thousand galaxies in CfA survey, to SDSS DR1 to DR 15 with over a million galaxies and also quasars

eBOSS Technical Details

eBOSS at a glance
Dark-time observations
Fall 2014 - Spring 2020
1000 fibers per 7 deg^2 plate
Wavelength: 360-1000 nm, resolution R~2000
375,000 luminous red galaxies over 7500 deg^2, $0.6 < z < 0.8$
375,000 luminous red galaxies over 7500 deg^2, $0.6 < z < 0.8$
260,000 emission line galaxies over 1500 deg^2, $0.6 < z < 1.0$
740,000 quasars over 7500 deg^2, $0.9 < z < 3.5$
1--2% distance measurements from baryon acoustic oscillations between $0.6 < z < 2.5$





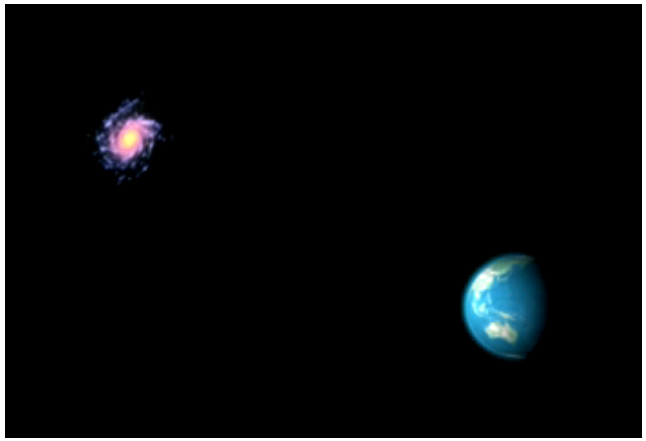
Probe large-scale structures to z~3

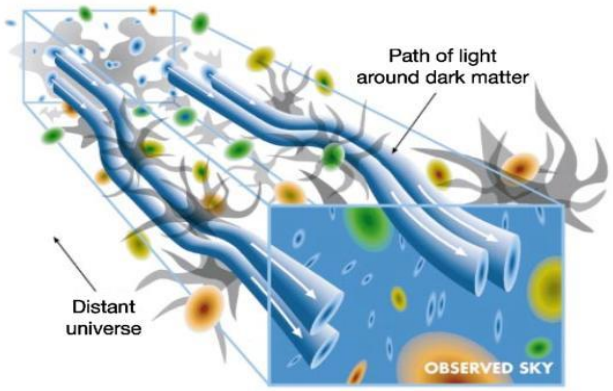
Weak lensing surveys have come to the stage

The mass of the Universe is dominated by dark matter

Galaxy distribution is a biased tracer of the underlying matter distribution

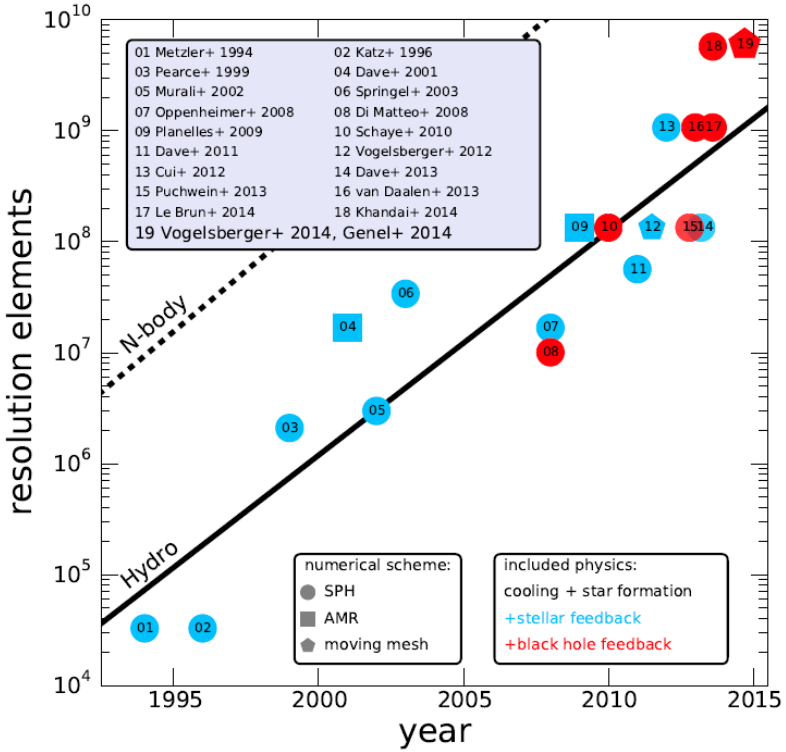
Gravitational lensing effect provides us a way to directly map the total matter distribution in the Universe

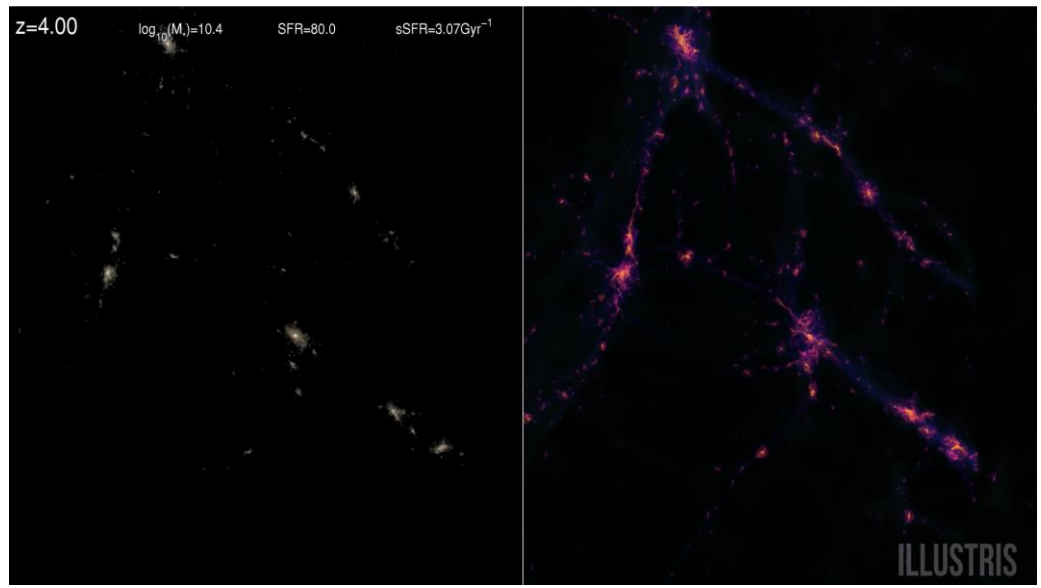




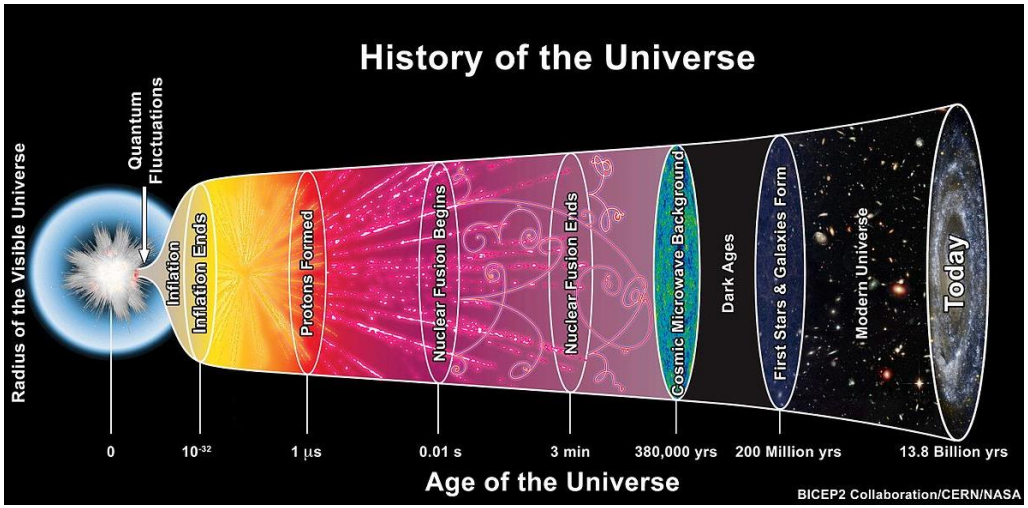
While strong lensing effects occur in the central region of galaxies
or clusters of galaxies, weak lensing effects can probe the large-scale structures

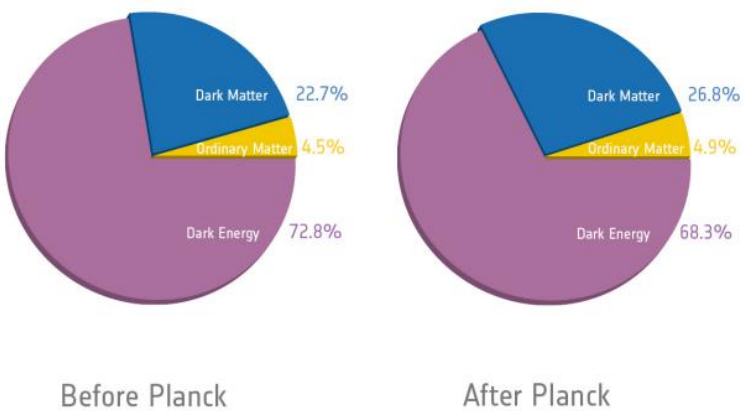
With the technical development, numerical simulations have become an integral part of the cosmological research

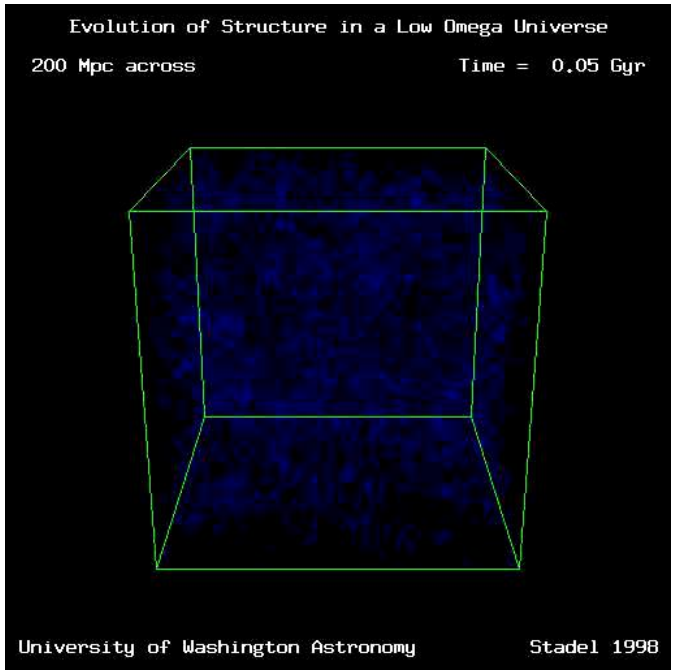




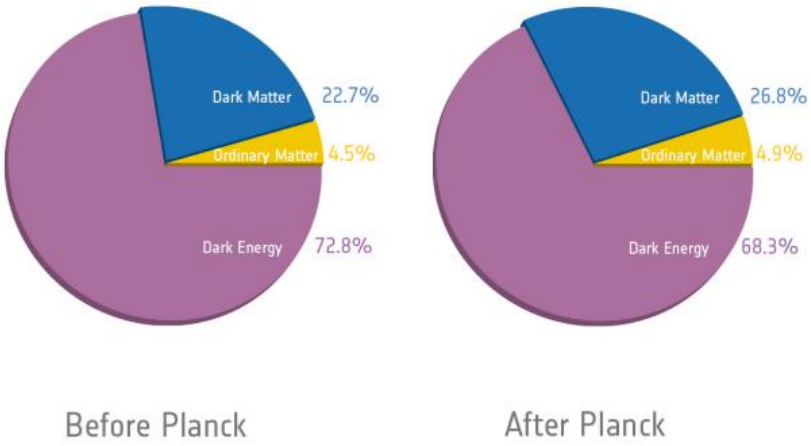
With all the observations and the theoretical framework of general relativity, we now know the evolutionary picture of the Universe







In this picture, we need ~25% dark matter to provide enough gravity to form structures in the Universe, and ~70% of dark energy to drive the cosmic accelerating expansion

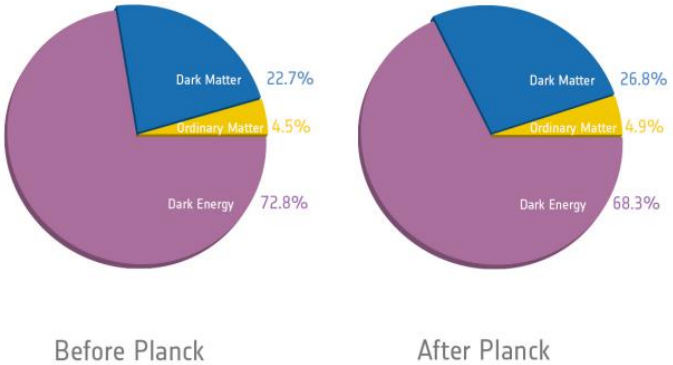


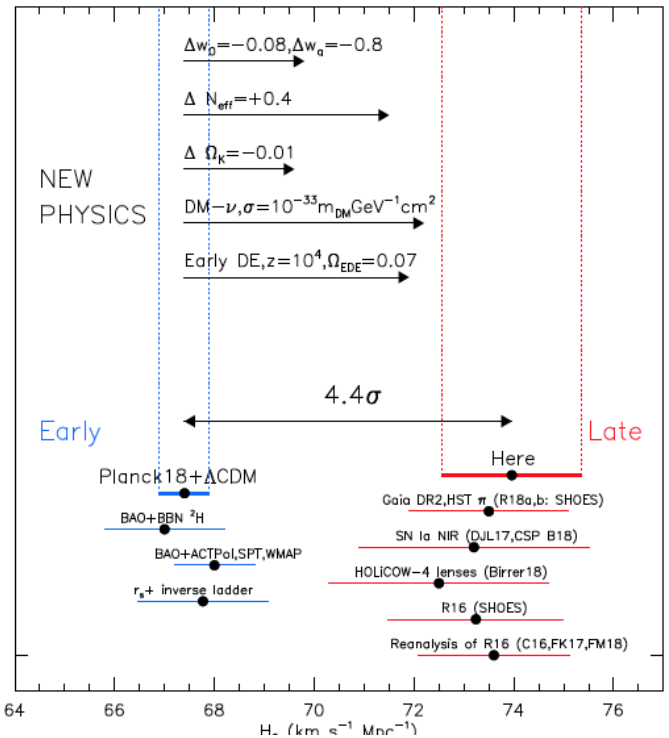
But the physical nature of dark matter and dark energy is still largely unknown

That is the great challenge in the field, which can influence our fundamental understanding about the nature of matter and force

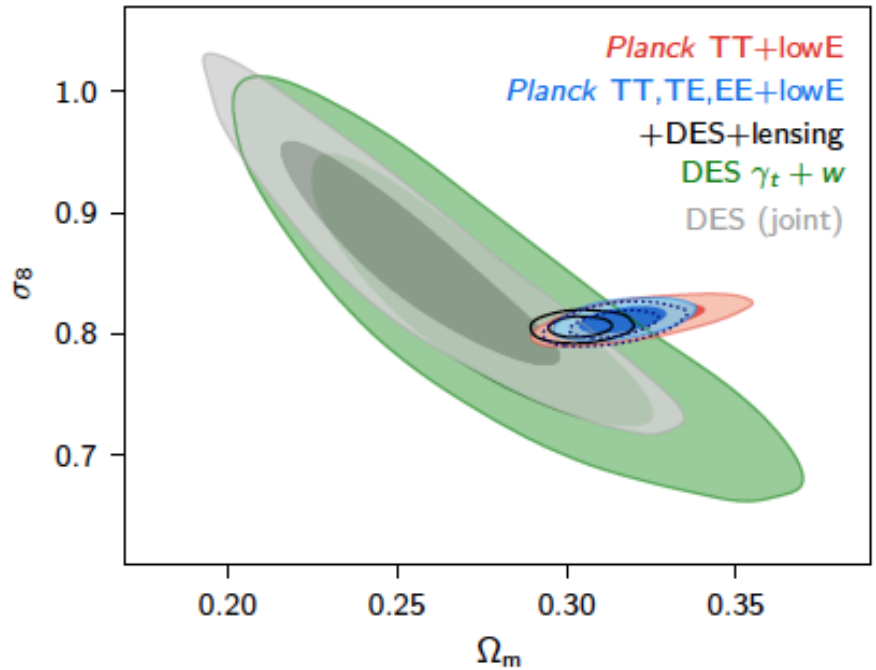
Inconsistency within the concordance picture?

Hubble constant H_0 discrepancy (Riess et al. 2019)





Ω_m-σ_8 discrepancy (Planck 2018)



New physics or systematics?

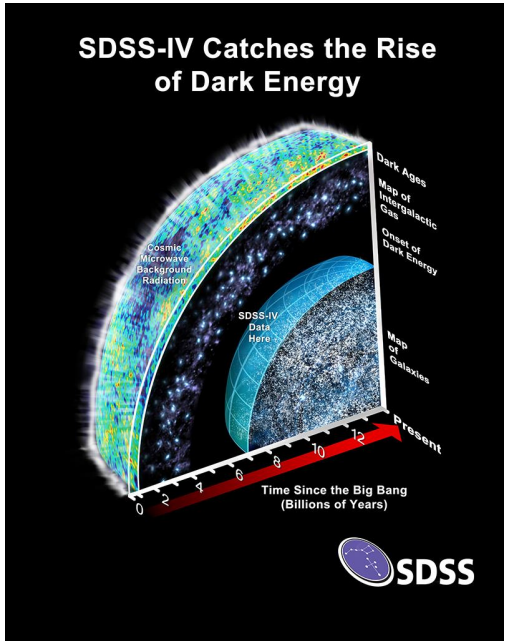
Quantitative improvements can lead to qualitatively new discoveries

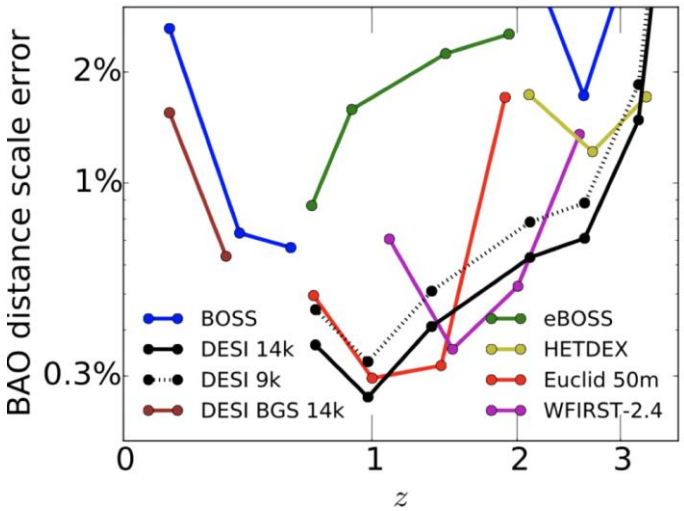
- **Next generation of large surveys and the challenges**

In next 5-10 years, new surveys will be in operation

-- increase in data volume
-- increase in data quality

DESI redshift survey

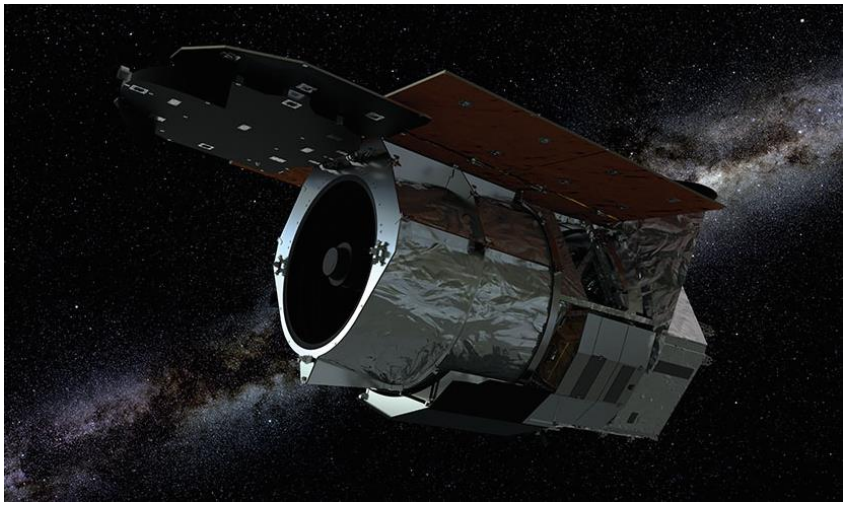




LSST, US

Euclid, ESA

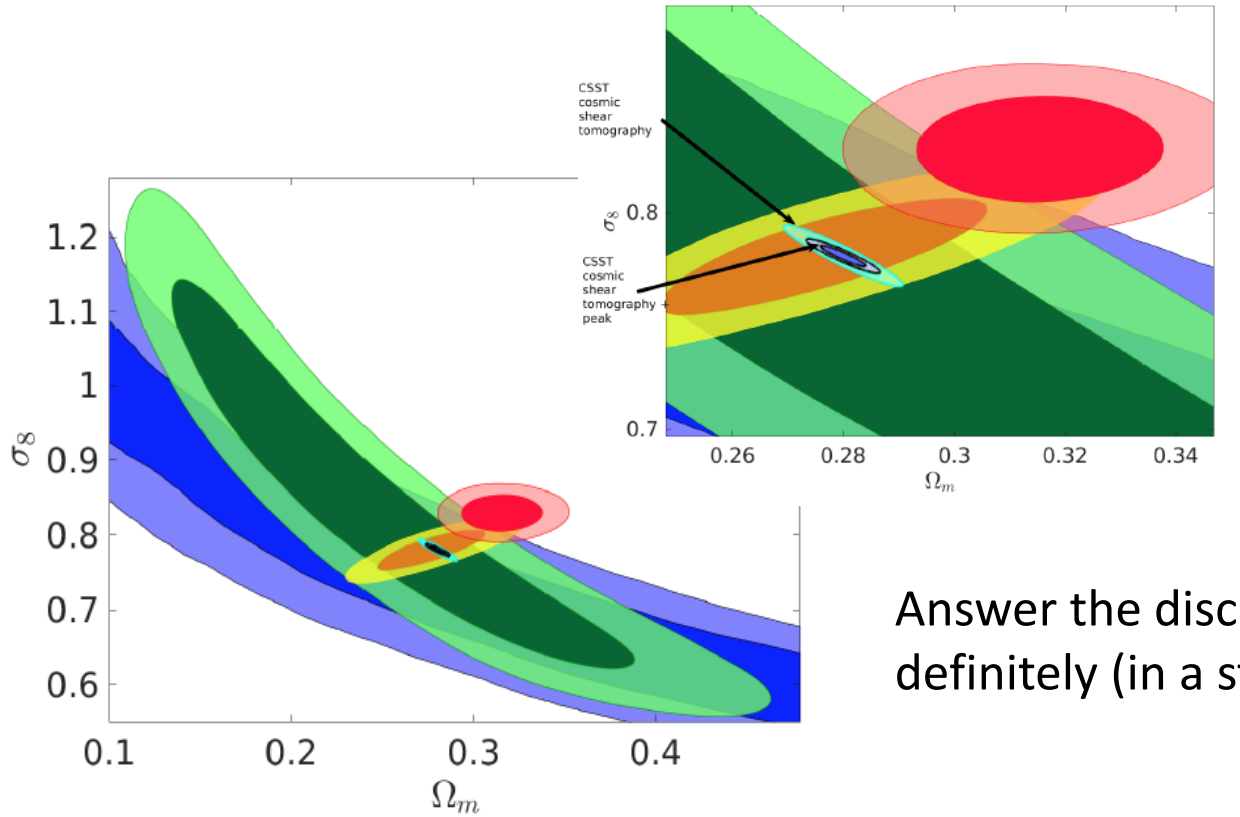
WFIRST, NASA



CSST, China

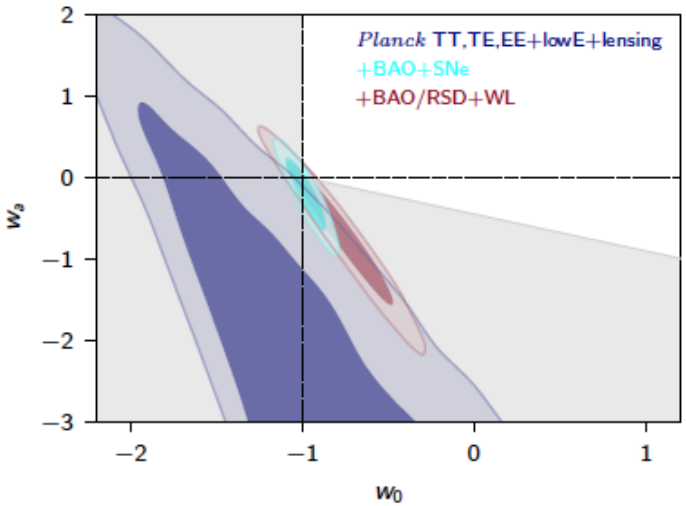
In terms of weak lensing observations, these surveys will increase the number of observed galaxies to ~10^9, comparing to the current surveys of a few times 10^7

Statistical power will increase enormously



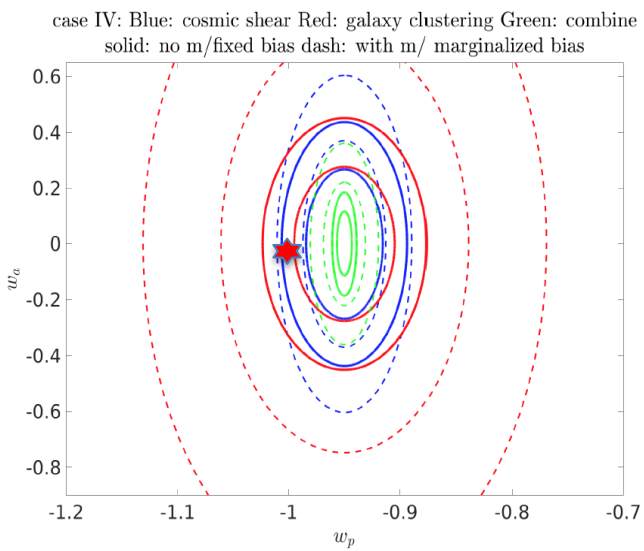
Answer the discrepancy questions definitely (in a statistical sense)

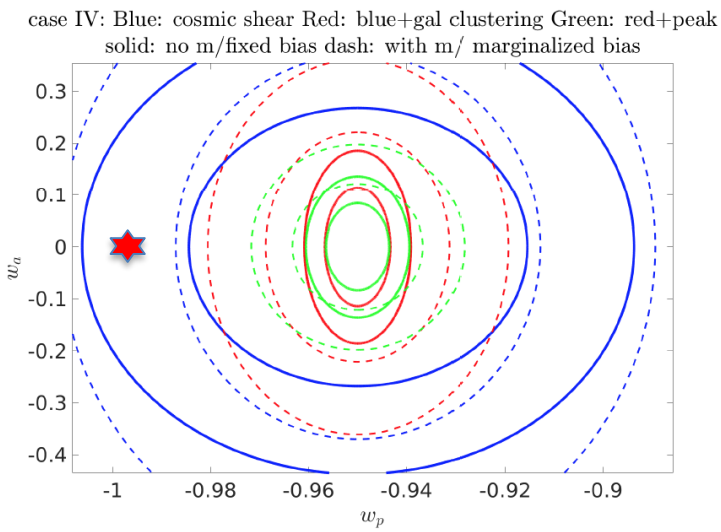
Constrain dark energy properties: Is dark energy dynamical?



Current constraint (Planck 2018)

Expected from future surveys





Observing weak lensing signals is very challenging

The signal is very weak with the induced shape distortion (cosmic shear) at the level of 1%

Weak lensing cosmological studies need to observe a large number of far-away galaxies and measure their light distribution very accurately

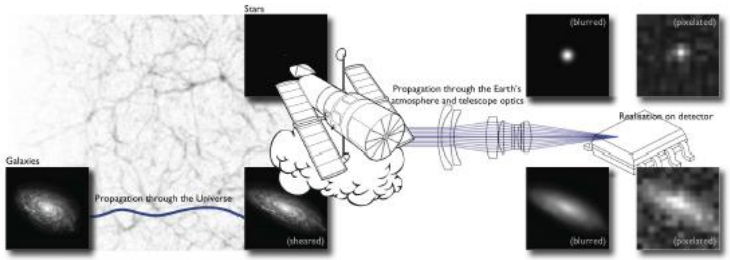
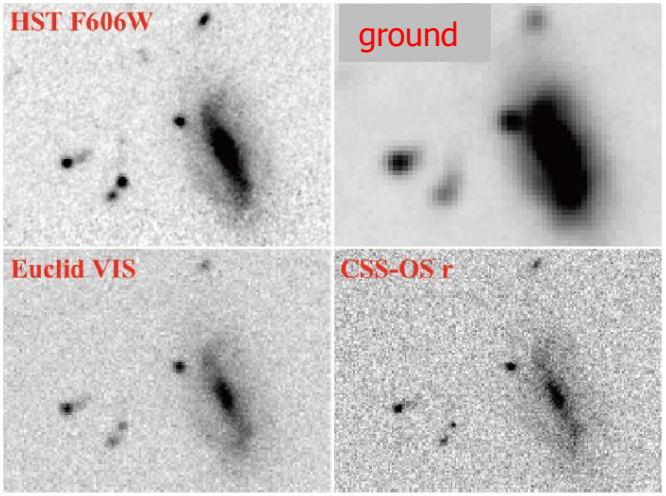


FIG 8. **Summary of the main effects on an individual galaxy or star.** *This is the* forward process *described in Bridle et al. (2008), although GREAT10 includes additional realism in that both the induced gravitational shear distortion and the PSF vary as a function of position. The GREAT10 'Galaxy Challenge' is to estimate the shear distortion applied to a galaxy image, correcting for the additional effects in the Earth's atmosphere and telescope optics, which are also experienced by the images of stars; for space-based telescopes the atmospheric effects are not present so that telescope and detector effects alone induce a PSF.*

Go to space can be advantageous:

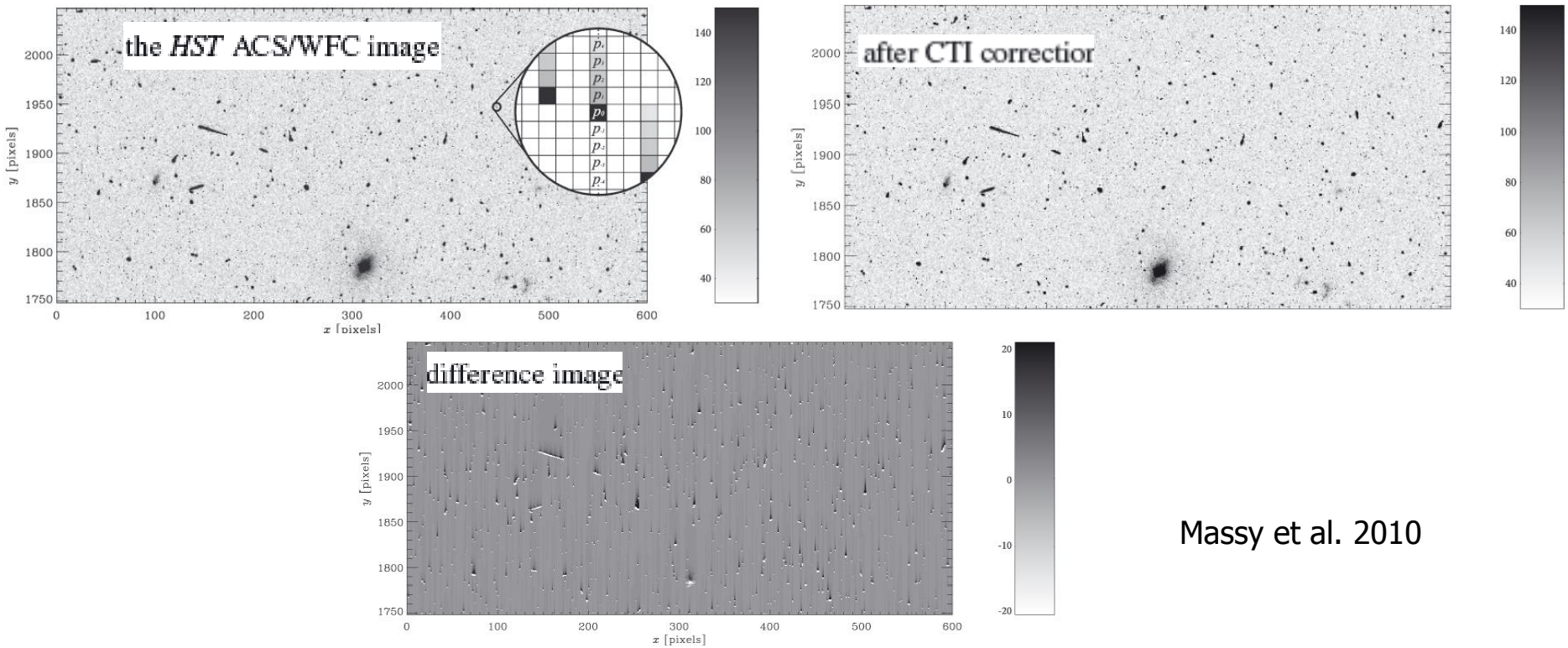
-- higher resolution
-- wider observable bands



To realize the statistical power of future large surveys, we need to control the systematics to an extremely high accuracy --- major challenges

Hardware: e.g., CCD detectors' defect affect galaxy shape measurements significantly

brighter fatter effects, charge transfer inefficiency (CTI=1-CTE)



Massy et al. 2010

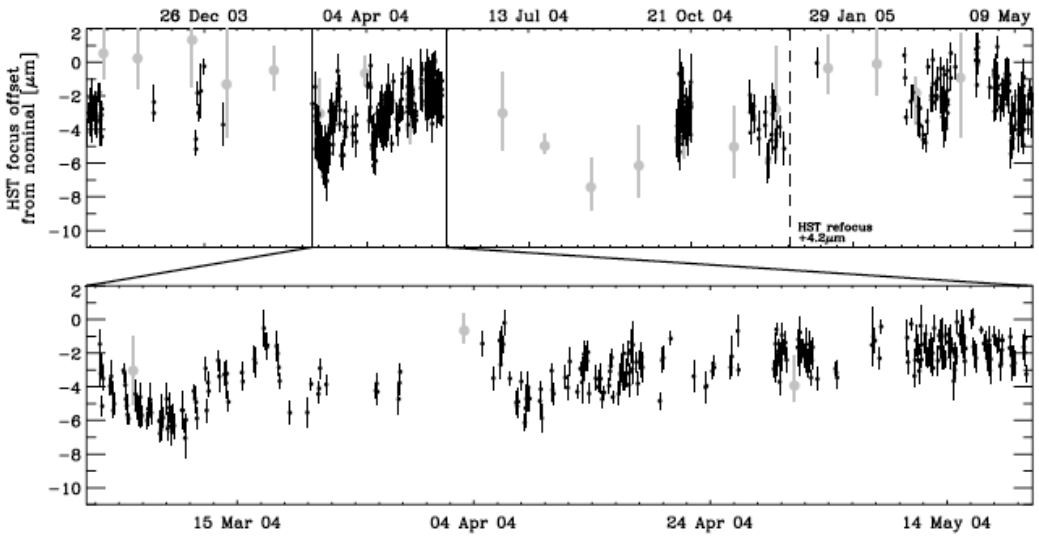
Fast CCD read out technique

real-time signal process– important for time-domain observations

Materials, e.g., temperature variation sustainability

E.g., HST and CSST, low earth orbit with the rotating period of ~90mins

-- induce focus change, and thus affect the images



Rhodes, J. et al. 2007

Computer hardware and software developments

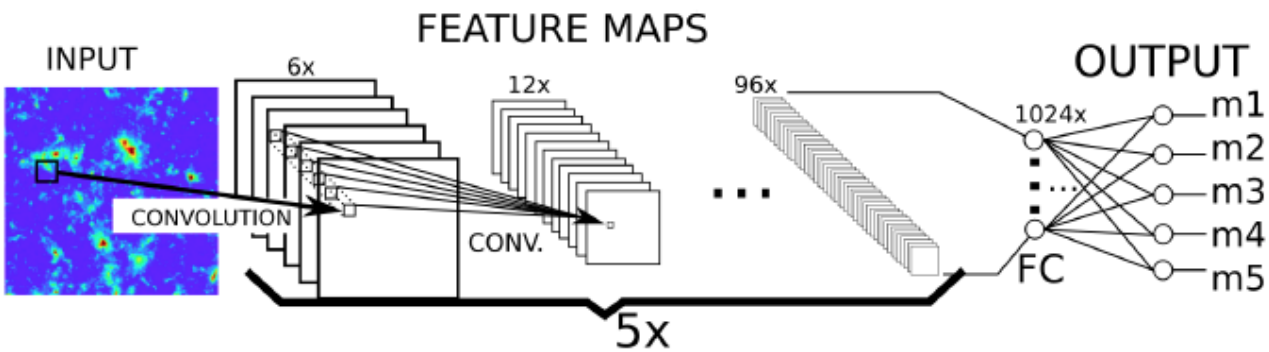
Big data analyses: accurate shear measurement methods

accurate photometric redshift measurements

extract cosmological information accurately and as much as possible

Benefitted from all the advances in the field of data analyses

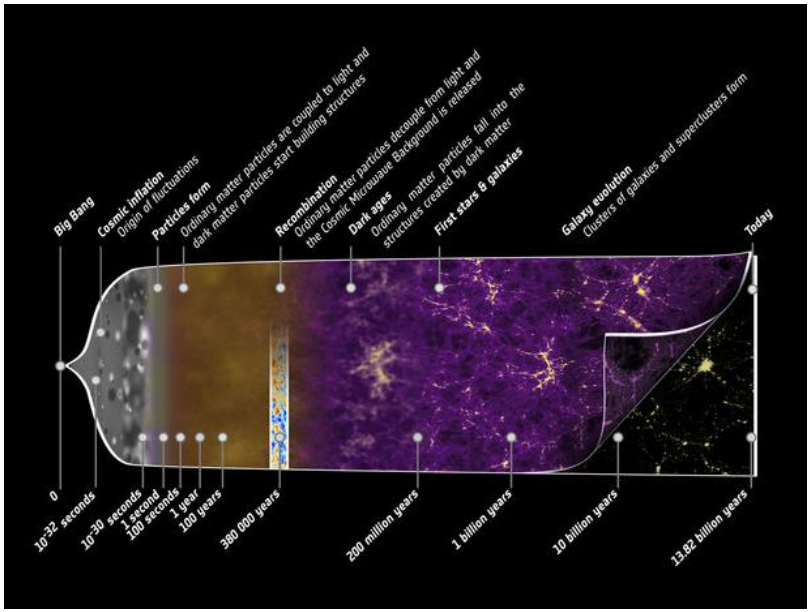
Machine learning techniques have been applied in many studies



Schmelzle et al. 2017

• Discussions

* We have known the Universe in depth from its origin to what it is like today
* Along the way, we have discovered new ingredients, dark matter/dark energy
* New generation of surveys will target at probing the physical nature of these new ingredients
* Astronomical observations are developing rapidly, thanks to the developments of new technologies – cross-disciplinary
* Intelligent signal processing has played and will continue play important roles in astronomy studies



"We have achieved something presumed to be impossible just a generation ago," "Breakthroughs in technology, connections between the world's best radio observatories, and innovative algorithms all came together to open an entirely new window on black holes and the event horizon."

Thank you