Cosmology with Sky Surveys

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Eduardo José Barroso

Post-doc@LAPP

Summary

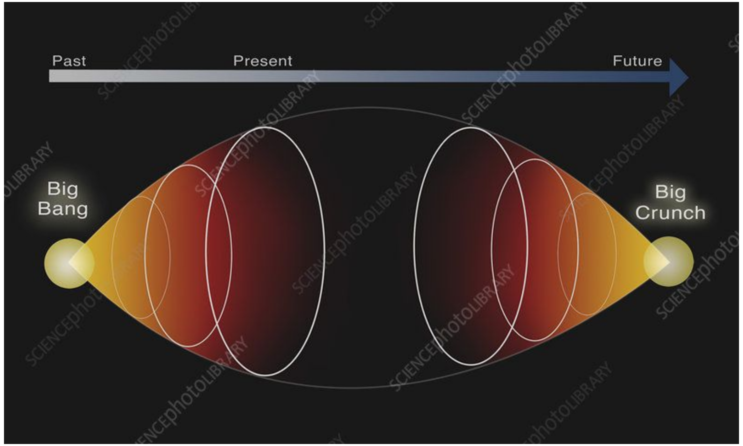
1. Cosmology 101
2. The standard cosmology model (Λ-CDM)
3. Cosmology with sky surveys
4. Euclid and LSST sky surveys

Cosmology 101

What is Cosmology — and Why Study It?

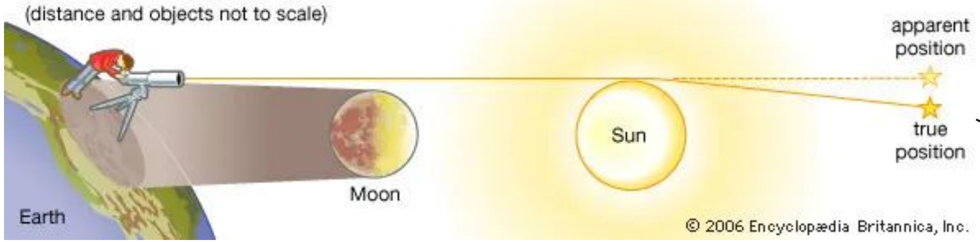
- Cosmology is the scientific study of the universe as a whole — its origin, evolution, structure, and ultimate fate.
- One of the main goals of modern cosmology is to explain the structure of the Universe on the scale of galaxies and beyond

- Some questions that we want to answer:
  - **What is the universe made of?**
  - **How did structures form?** — galaxies, clusters, and cosmic filaments
  - **What were the initial conditions after the Big Bang**?
  - **What is the ultimate fate of our universe**?



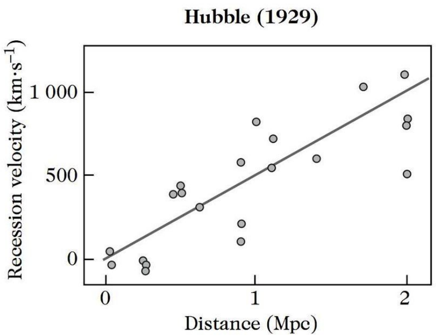
Schematic representation of the Big Crunch

Some Facts about the Universe

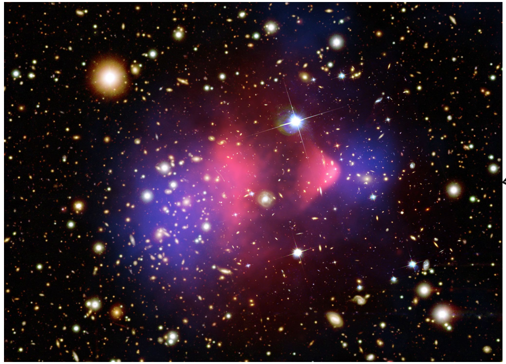


In the 1919 starlight passing near the Sun was deflected exactly as Einstein’s theory predicted → one of the earliest tests of GR.

Initial plot of the Hubble law



In 1929 Hubble showed that galaxies are receding away from us with a velocity that is proportional to their distance from us: more distant galaxies recede faster than nearby galaxies.



Around 1998, two independent teams discovered that distant Type Ia supernovae appeared fainter than expected in a decelerating universe. That implied the expansion of the universe is **accelerating**

In 1930s, during a collision of two galaxy clusters, the hot X-ray gas (baryonic matter, pink X-rays) is separated spatially from total mass peaks determined by gravitational lensing (blue lensing map)

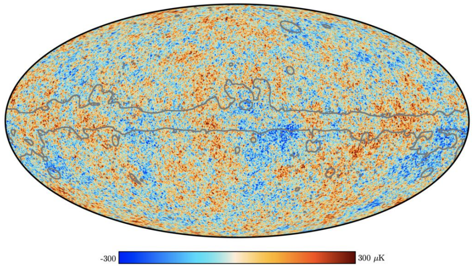
Cosmological Problems

Flatness

- The universe is a 4-dimensional space such that we can measure its curvature Ω_k.
- The results from the Planck satellite show that the Universe is nearly flat today ($\Omega_k \cong 0$).
- The dynamics imply that a positive curvature would always increase, thus we need to set initial conditions up to $\Omega_k \leqq 10^{-63}$, which is a strong fine-tuning.

Horizon

- The particle horizon is the maximum distance that a photon could have traveled since the origin of the universe. Quantities separated by distances higher than the horizon could never have been in casual contact.
- Yet, regions separated by higher distances were seen to have similar properties, like the CMB.



Large-Scale Structure Problem

- The universe contains large scale structures locally (galaxies and clusters).

- The origin of these initial fluctuations.
- Why modes behave differently on different scales
  a. Short-wavelength modes evolve dynamically (oscillate).
  b. - Long-wavelength modes remain frozen beyond the Hubble radius.

Standard Cosmology Model

What ingredients would you put to model the universe we observe?

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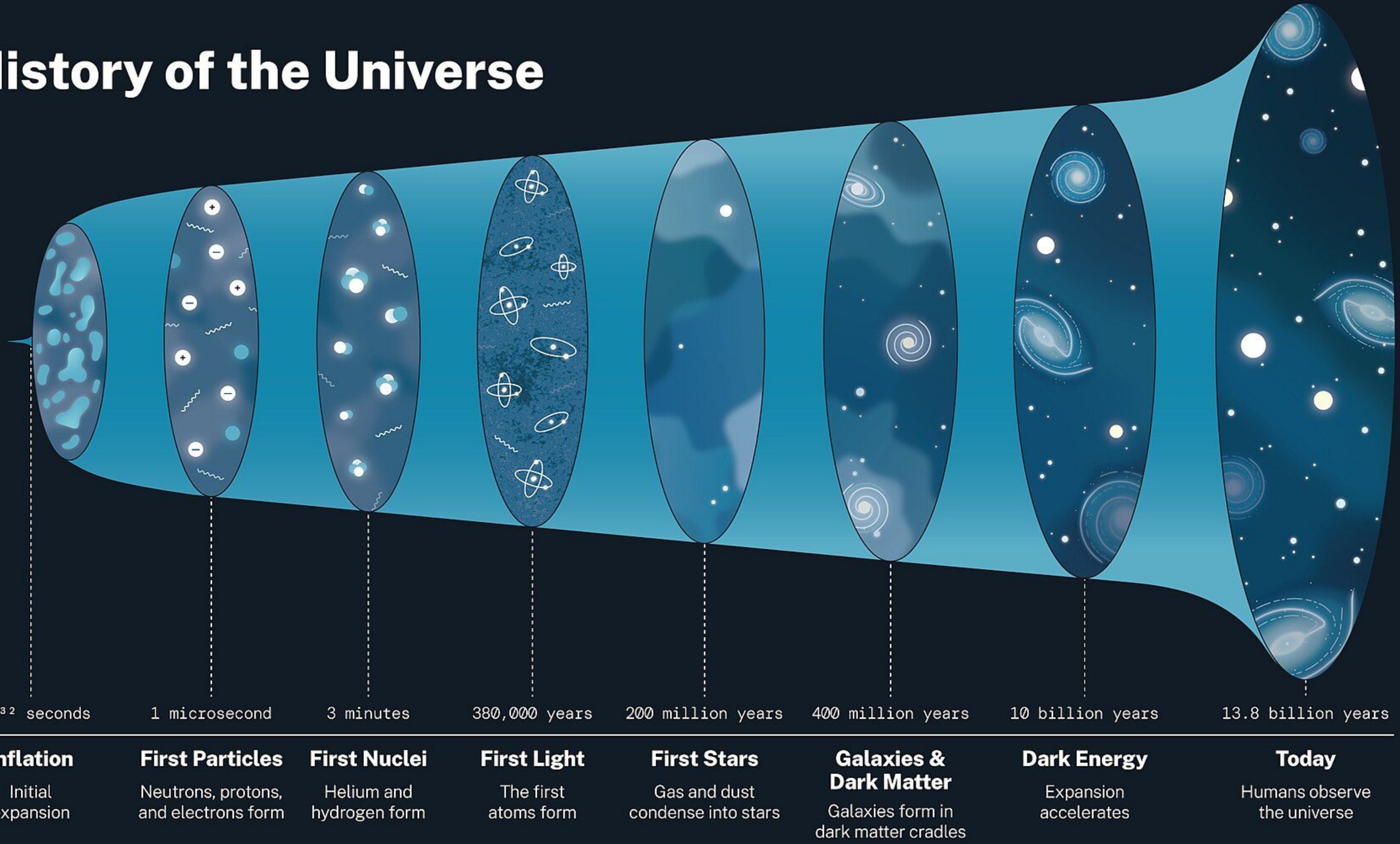
- **Inflation:** Explains the initial conditions of the Universe (flatness, homogeneity, isotropy, and origin of structure).

- **Big Bang Model:** Universe expanded from a hot, dense state → describes expansion and thermal history
  - **Expansion of the Universe:** Space itself is stretching, galaxies move away from each other.

- **ΛCDM Model:**
  - **Λ (Lambda):** Dark energy, responsible for the observed accelerated expansion today.
  - **CDM (Cold Dark Matter):** Non-relativistic dark matter, explains structure formation (galaxies, clusters).
  - **Matter Content:** Combination of ordinary matter, dark matter, and dark energy.
  - **Cosmological Principle:** Universe is homogeneous and isotropic on large scales.
  - **Predicts:** Detailed evolution of the Universe, structure formation, and present-day acceleration.

History of the Universe



ΛCDM Model

a_0 / a
Expansion parameter

$$\bar{E}(t) \equiv \frac{\bar{H}(t)^2}{\bar{H}_0^2} = \Omega + \Omega_k = \Omega_{\gamma 0} x^4 + \Omega_{m0} x^3 + \Omega_{k0} x^2 + \Omega_{\Lambda 0}$$

Radiation

Matter (Baryons + Dark Matter)

Curvature

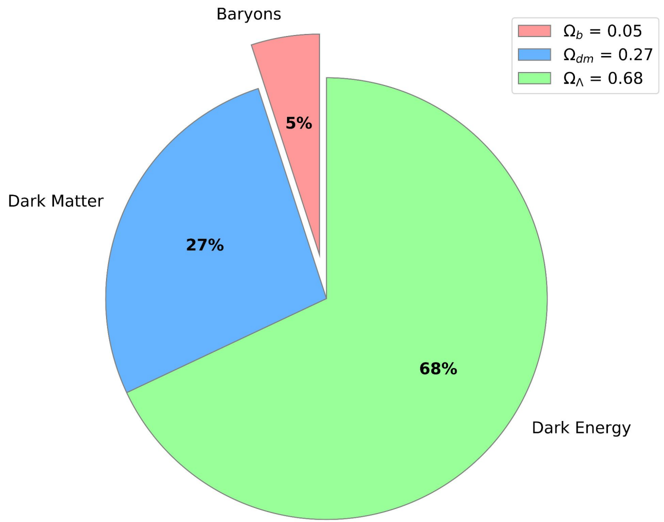
Dark Energy

These parameters appear in the Einstein Field equations

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Geometry

Matter

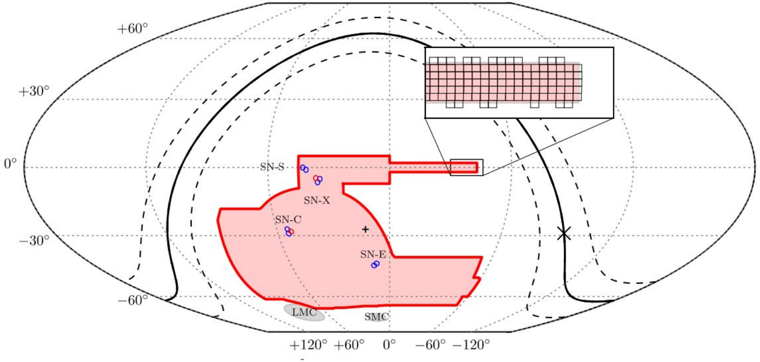


Cosmology with Sky Surveys

Sky surveys

- Sky surveys have the objective of scanning the universe with the goal of characterizing different objects
- We may classify surveys in regard to their scientific motivation and strategy, their wavelength, regime, ground-based vs. space-based, the type of observations (e.g., imaging, spectroscopy, polarimetry, etc.), etc.
- We can have different types of sky surveys
  - Optical → Image based surveys
  - Infrared → Good for exoplanets and cool clouds of cosmic dust
  - Gamma-ray → Gamma-ray spectroscopy. Good for supernovae and particles falling into black holes
  - Multi-wavelength, etc.

Image of the sky from the Dark energy Survey

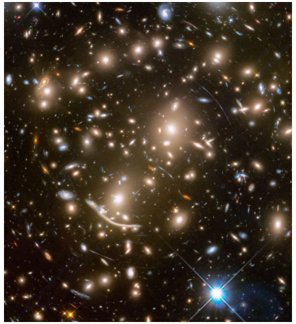


Dark energy Survey footprint

How would you do cosmology with sky surveys?

How would you do cosmology with sky surveys?

1. **Choose probes of the Universe:**
   - Large-scale structure formation: galaxy clusters, galaxy clustering
   - Cosmic expansion: Type Ia supernovae
   - Other tracers: weak lensing, BAO, CMB



The massive galaxy cluster Abell 370 as seen by Hubble Space Telescope

2. **Develop theoretical predictions:**
   - Use cosmological models (ΛCDM) to predict how these observables behave.

$$N_\alpha^\beta = \int_{z_\alpha}^{z_{\alpha+1}} \mathrm{d}z \frac{dV}{dz d\Omega} \int_{\ln \lambda_\beta}^{\ln \lambda_{\beta+1}} \mathrm{d}\ln\lambda \int_0^\infty \mathrm{d}M \frac{dn}{dM} P(\ln\lambda | M, z)$$

3. **Compare theory with observations:**
   - Collect data from telescopes and surveys
   - Measure what we can directly observe; use **proxies** for quantities we cannot measure directly

We cannot measure directly:
- masses
- Dark matter
- initial density fluctuations

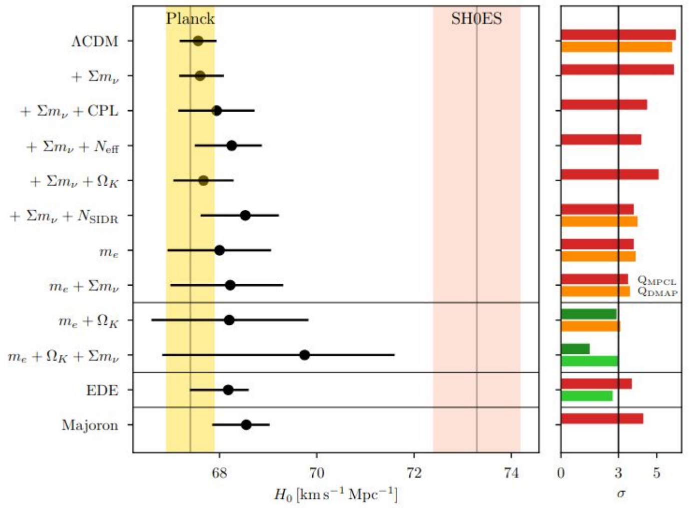
4. **Perform likelihood inference:**
   - Treat the unknowns statistically because we cannot control everything in the Universe
   - Model observables and uncertainties as **random variables**
   - Use statistical techniques to constrain cosmological parameters θ = (H_0, **Ω**, σ_8 , …)

$$L(D|\vec{\theta}) = exp^{(\text{Data vector})^T \text{Cov}(\text{Theory vector}(\vec{\theta}))}$$

Current Survey Results

- Two sets of observations for LSS:
  - homogeneous cosmological background → geometry and the expansion history of the Universe (BAO)
  - inhomogeneous universe → LSS formation (Galaxy Clusters)

- We have already made some surveys and the results were inconsistent!!!
  - Measurements from different probes led to different results that do not agree with each other. This is called the Hubble tension



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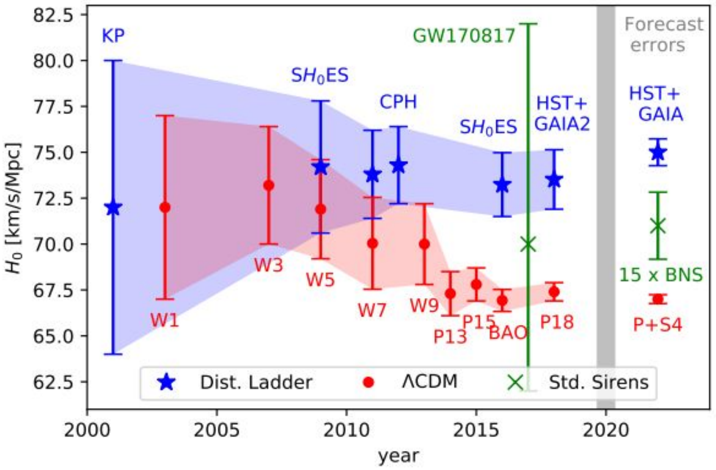


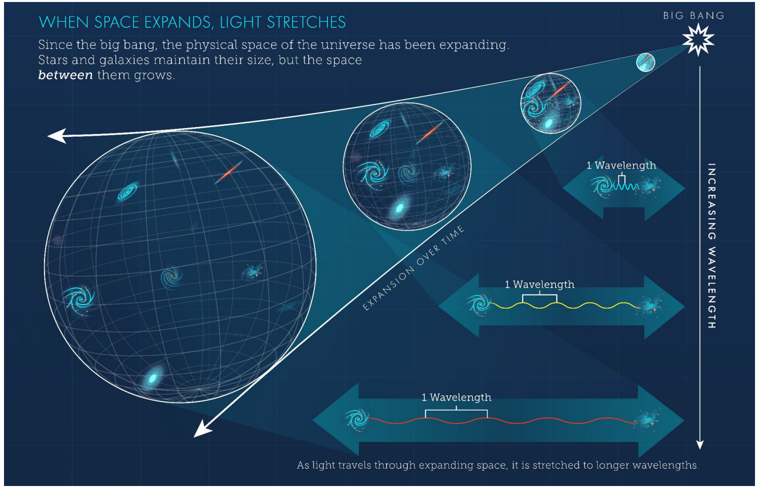
Redshift

What is redshift? (z)

- Light from distant objects is stretched as the Universe expands.
    - Redshift is the key evidence that **the universe is expanding.**
    - It is defined as the stretch of a source wavelength from its emitted light
    - Wavelengths increase (In an expanding universe, $a_{obs} > a_{rest}$, being the observation today)
    - z is a **cosmic clock**: Higher z → earlier in the universe.
    - z is a **distance indicator**: Combined with Hubble's law, it tells us how far galaxies are.

$$z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}}$$

$$1 + z = \frac{a_{obs}}{a_{rest}}$$

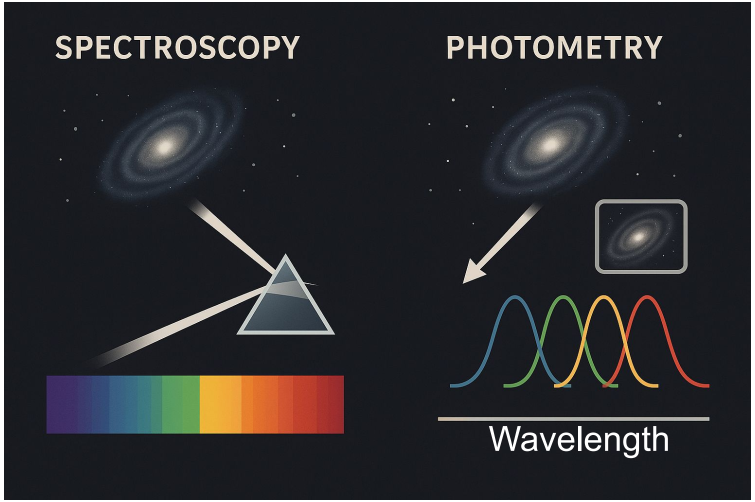


How to get redshift information with Sky Surveys?

Redshift Estimation

Spectroscopy

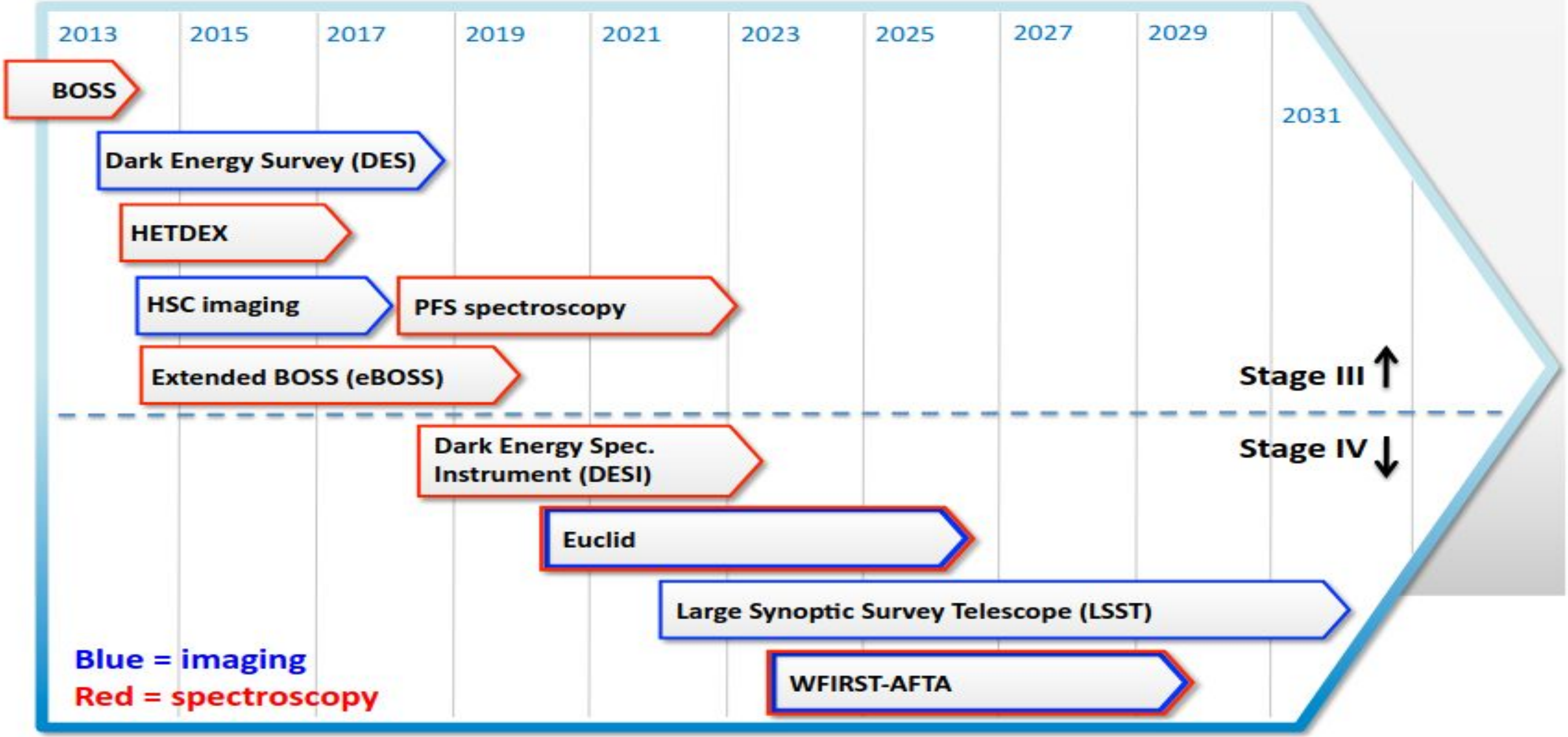
- The light passes through (or reflect from) a dispersive element (a prism or diffraction grating) and then you record the dispersed light.
- You have a record of the intensity of the light as a function of wavelength.
- **Pros**: record the light of one or more objects over a very wide wavelength range and have excellent fine discrimination between different wavelengths
- **Cons**: You spread the light from the source thinly over the detector and it can be difficult to obtain spectra of many sources in one go (maybe 10s to 100s if you use multi-slit of multi-fibre spectrographs).



Photometry

- Record images of your sources where the light is allowed to pass through coloured filters. The only wavelength information you have is the intensity of the light admitted through the filter Focused on light intensity
- **Pros**: The light from a source over your filter band is concentrated onto a spot on your detector - giving better signal-to-noise ratios. You also get data for as many sources are in the image - potentially thousands.
- **Cons**: The effective wavelelength resolution is only as good as how narrow the filter bandpasses are. You lose the ability to see individual spectral features.

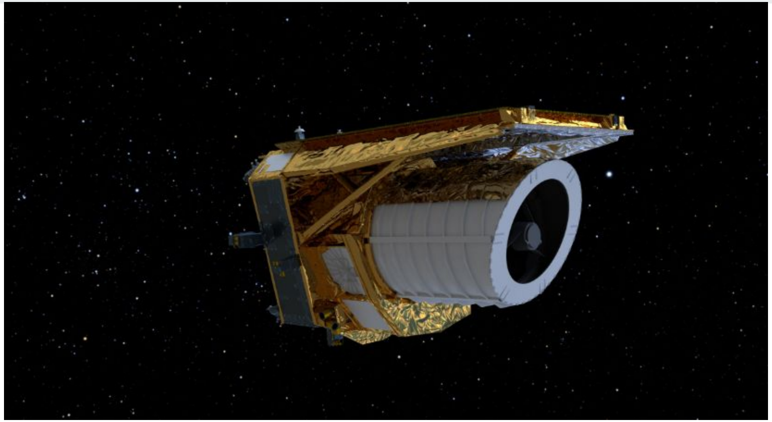
Dark Energy Experiments: 2013 - 2031

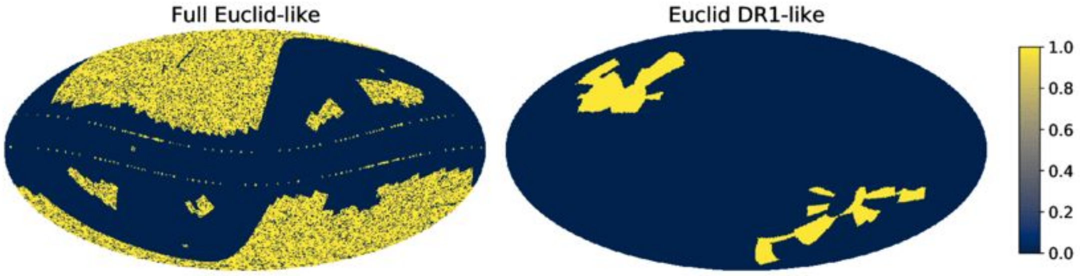


Euclid and LSST

Euclid

- Space-based wide-field cosmological survey.
- Launched: July 1, 2023, by the European Space Agency (ESA).
- Uses visible imaging and near-infrared photometry and spectroscopy.
- The Euclid Wide Survey is designed to cover both the **Northern and Southern Hemispheres**.
- However, it ends up slightly **more weighted toward the Northern Hemisphere**, mainly because the Galactic bulge and plane take a larger fraction of the Southern sky.





Legacy Survey of Space and Time (LSST)

The Survey

- 10-year survey covering the entire visible southern sky (~18,000 deg²)
- Will image the whole sky every 3 nights → creating a *"video of the sky"*

Telescope & Camera:

- World's largest digital camera – 3.2 gigapixels, 189 sensors
- Wide field of view: 9.6 deg² per exposure
- Uses a 3-mirror design and quick-swap filter system

Filters & Observing

- 6 filters: *u, g, r, i, z, y* (covering ultraviolet to near-infrared)
- Short exposures (15–30 sec), combined for deep images

Starts soon: Entering full survey mode in the next year!!

Why do we need ground and space surveys?

Why do we need ground and space surveys?

- **Ground-based telescopes provide wide, statistical surveys** — billions of galaxies.
  - Limited wavelength (optical to near IR)
  - Affected by atmosphere distortion
  - Limited to night observations
  - Cheaper, easier to maintain

- **Space-based telescopes** provide **precision and full spectral coverage**.
  - Observing wavelengths blocked by the atmosphere (UV, far IR, X-ray)
  - Very expensive, limited lifetime, no direct maintenance
  - Small field of view
  - Obtaining sharp, stable imaging and accurate photometry/spectroscopy
  - Calibrating and complementing ground-based observations

Together, they give a complete picture:

- **Ground → breadth (big samples, wide coverage)**
- **Space → depth and precision (clear, multiwavelength data)**

Properties	LSST	EUCLID
Sky Area	18000 sq. deg.	15000 sq. deg.
Field of View	9.6 sq. deg.	0.5 sq. deg.(VIS)
Wavelength	320 - 1050 nm (u,g,r,i,z,y)	550 - 900 nm (VIS) 1100 - 2000 nm (NISP)
Camera Resolution	3.2 Gpx, 0.2”/pixel	600 Mpx VIS, 0.3”/pixel
Exposure per image	15 - 30 sec	565 - 780 sec
Sky Coverage	Southern Sky	Northern mainly plus Southern

Links:

https://skyviewer.app/explorer

https://rubinobservatory.org/gallery/collections/first-look-gallery

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