# XI. Observational Cosmology

## 11.1. Cosmic distance ladder

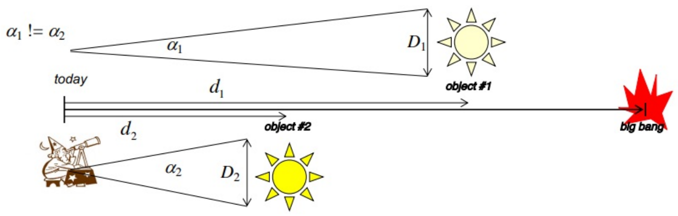
### Observations in astronomy

Astronomy consists on collecting and counting photons for different wavelengths, $N(\lambda)$. The number of photons observed depend on the wavelength and the distance to the object.
To infer the distance to an object, we can use standard candles and rulers.

### Standard candles and rulers

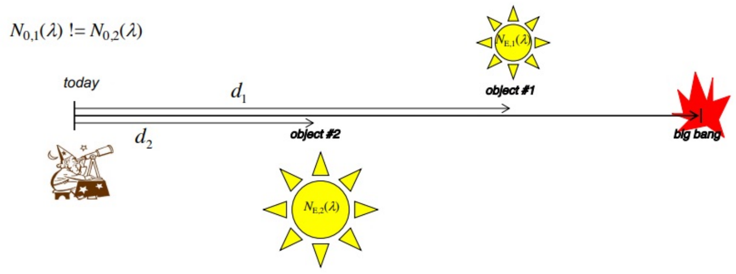
Cosmology uses standard candles and rulers to eliminate the dependence on the object.
If we know the distance to one of the objects and know their sizes (or luminosities) we can infer the distance to the other one.

Standard ruler




Objects might have different luminosities, but the same size.

Standard candle



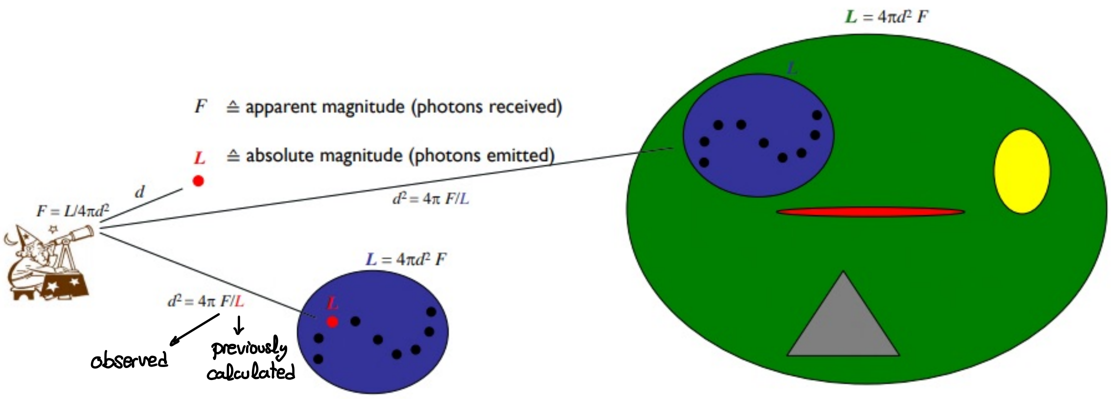

Objects might have different sizes, but the same luminosity $N_{E,1}(\lambda) = N_{E,2}(\lambda)$.

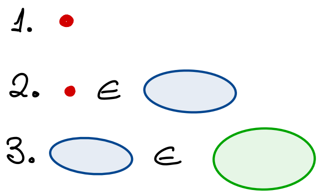
Standard candles can be used to eliminate the dependence on the object and to infer the cosmological parameters via $N(\lambda)$ (since $d = f(R(t))$).
We want equations with a dependence on the scale factor $a$ and the cosmological parameters, but first we need to have a gauge for the relation between photon counts and distance: the distance ladder

### The cosmic distance ladder

Radar → Parallax → Main sequence fitting → Cepheids
Globular clusters ← Novae ← Brightest stars ←
→ 21 cm → Supernovae

> **NOTE**
> We only observe apparent magnitudes and never absolute magnitudes, which are apparent magnitudes at a fixed distance.

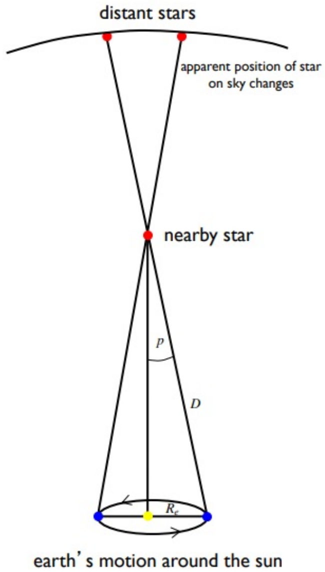



1. If we have a class of stars with identical luminosities, we can determine the distance to one such star locally (e.g. via parallax). We observe the flux F ( the luminosity L diluted on a sphere). If we measure d, we can infer L.
2. Observing such star(s) in another type of distant object (globular cluster, galaxy, etc.) we can calculate the distance to that object via $F = L/4\pi d^2$ : we still observe the flux and know L, so we can infer d.
3. If that object is "standard" in some sense, it can be used to infer the distance to another object.

## Direct parallax ($< 1$ kpc)

This method will only work if we have a zero point to start.
One of the few possibilities to directly get the distance without knowing anything about the object is direct parallax.
It consists on measuring the difference on the position of the object when the Earth is at the extrema of its orbit around the Sun:




$$\sin p = \frac{R_e}{D} \xrightarrow{\sin p \approx p\,[\text{radians}] \text{ for small } p} p'' = \frac{R_e}{D} \times \frac{360}{2\pi} \times \frac{1}{3600} \quad [\text{arcsec}]$$

We define the parsec as:

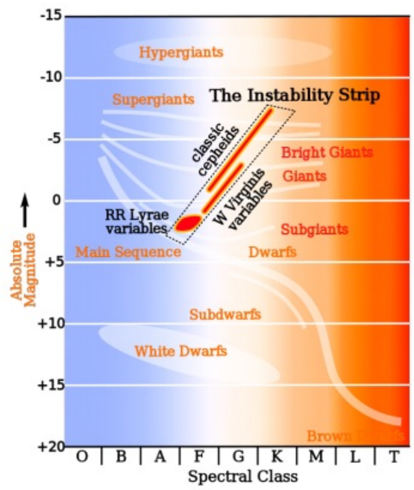
$$D = \frac{1''}{p''}\,[\text{pc}] \qquad 1\,\text{pc} = 3.0857 \times 10^{16}\,\text{m}$$

## RR Lyrae Stars ($< 1$ Mpc)

Pulsating horizontal branch stars. They have similar (mean) absolute luminosity $\longrightarrow$ Standard candles: $\langle L \rangle \approx$ const
Unfortunately, they are not very bright, but there are other objects.

## Cepheid stars ($< 20$ Mpc)

Also pulsating, but brighter than RR Lyrae. There is a relation between pulsation period and absolute luminosity: $\boxed{\log L \propto \log P}$



## H II regions. ($< 30$ Mpc)

They are large clouds of hydronized hydrogen surrounding very hot stars ($< 30$ Mpc). Since they are bright and their size is almost constant ($\langle D \rangle \approx$ const), they can be used as standard rulers.

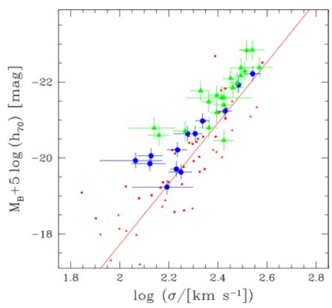
## Planetary Nebula ($< 30$ Mpc)

Reprocessed light from a central star. They can be used as standard candles $\langle L \rangle \approx$ const

## Globular clusters ($< 50 - 100$ Mpc)

Clusters of around $10^5$ to $10^7$ stars. They are standard candles.

## Elliptical galaxies - Faber Jackson relation and fundamental plane ($> 100$ Mpc)




Empirically determined

$L \propto \sigma_{los}^{\alpha}$, with $\alpha \approx 3-4$

Deduction:

$$U \propto \frac{M^2}{R} \xrightarrow[\text{virial th.}]{2T+U=0} \sigma_{los}^2 \propto \frac{M}{R} \longrightarrow \sigma_{los}^2 \propto \frac{L}{R} \longrightarrow \sigma_{los}^2 \propto \frac{L}{\sqrt{L/4\pi\Sigma}}$$

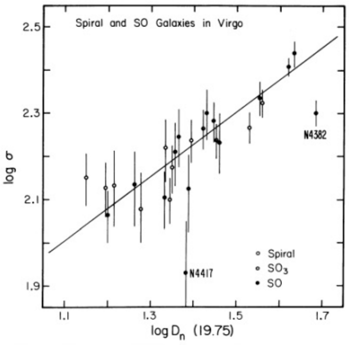
$T \propto M\sigma_{los}^2$

elliminate $M$ in favour of $L$ assuming $M/L =$ const

elliminate $R$ in favour of $\Sigma$, assuming $\Sigma =$ const

$\Sigma = L/4\pi R^2$

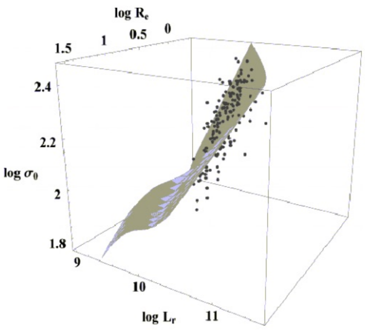
$$\Rightarrow \boxed{\sigma_{los}^4 \propto L}$$




There is also an empirically determined correlation between the size of the galaxy and $\sigma_{los}$:

$D_n \propto \sigma_{los}^{\alpha}$, $\alpha \approx 1.2$

$D_n \equiv$ diameter within which the mean surface brightness exceeds some threshold.



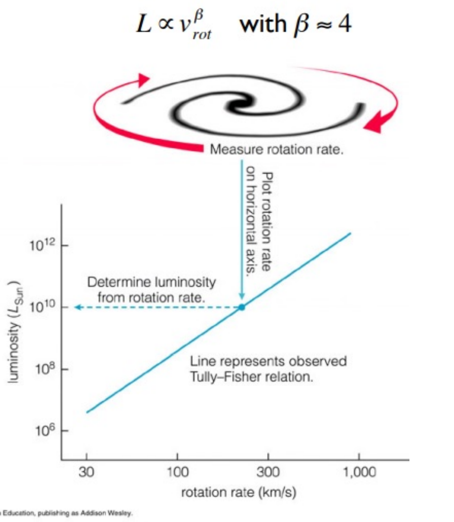

Taking into account the surface brightness profile:

$\Sigma(R) = \Sigma_0 e^{-(R/R_{eff})^{1/4}}$

we can represent:

$$\log_{10} R_{eff} = A \log_{10} \sigma_{los} + B \log_{10} \Sigma_0 + C$$

## Spiral galaxies - Tully - Fisher relation ($> 100$ Mpc)



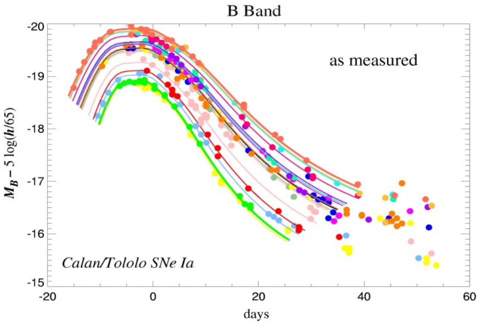

There is a similar empirically determined relation defined for spiral galaxies:

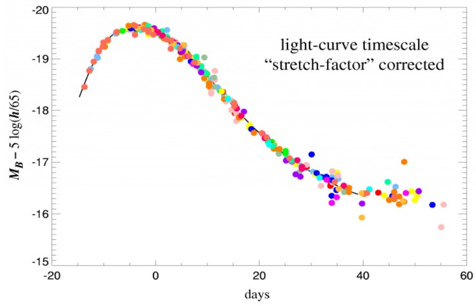
$L \propto V_{rot}^3$ with $\beta \approx 4$

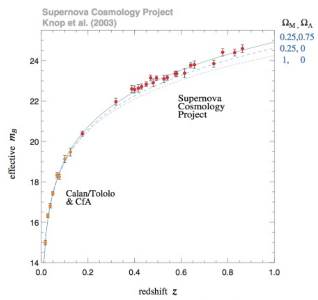
(Following the same derivation as for the Faber-Jackson relation)

## Supernovae type Ia

Their characteristic light curve is always identical once corrected from redshift.



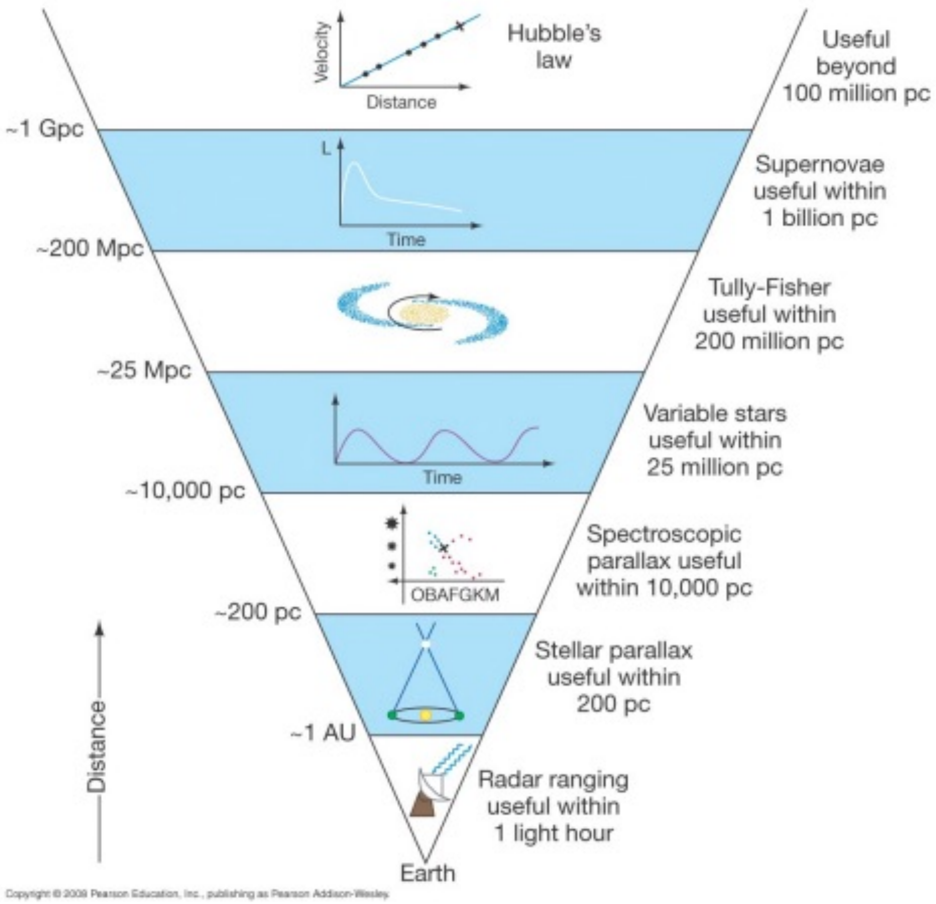




They are observable out to great distance. The relation between $L$ and $F$ is given by the distance, which is a function of the cosmological parameters. Supernova measurements showed the need of including the $\Lambda$ term. (Standard candle)

## Baryonic acoustic oscillations

As it was discussed in previous lectures, they are regular periodic fluctuations in baryonic matter. They originate from acoustic oscillations in pre-recombination plasma, and can only be seen in very large surveys. BAO can be used as a Standard ruler for very large scales.

## Summary:

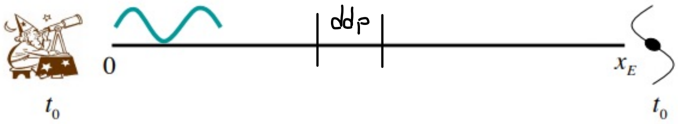


# 11.2. Cosmological distances

## Proper / comoving distance

### Proper distance


We have a galaxy at comoving coordinate $x_E$. At a time $t_E$, the galaxy emits a photon. It is important to note that the comoving coordinate is not the distance to that object: space can be curved.




Space is expanding while the photon travels to the observer. It reaches the observer at $t = t_0$ (and its wavelength has changed).

We will start calculating the physical distance that separate two events happening at constant cosmic time (which is impossible to measure, as it is defined only at one particular moment in time.

We take $dt = 0$ in the FRW metric (constant cosmic time):

$$ds^2 = R^2(t)\left[\frac{dx^2}{1-Kx^2} + x^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right)\right]$$

We are interested in the radial component. Thus, setting $d\theta = 0$ and $d\varphi = 0$ we obtain the differential distance element at constant cosmic time.

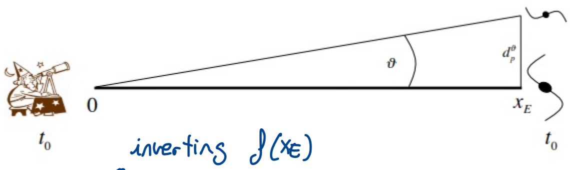
$$dd_p = ds = R(t)\frac{dx}{\sqrt{1-Kx^2}}$$

And integrating along the flightpath:

$$\boxed{d_p = R(t)\int_0^{x_E}\frac{dx}{\sqrt{1-Kx^2}} = R(t)f(x_E)} \quad \text{with} \quad f(x_E) = \begin{cases} x_E & \text{for } K=0 \\ \frac{1}{\sqrt{|K|}}\arcsin\left(\sqrt{|K|}\,x_E\right) & \text{for } K=1 \\ \frac{1}{\sqrt{|K|}}\operatorname{arcsinh}\left(\sqrt{|K|}\,x_E\right) & \text{for } K=-1 \end{cases}$$

($K=0$) → just comoving coordinate in Euclidean space

Now let us pay attention to the angular component.




If we want to calculate the distance between two objects at the same comoving coordinate, $d_p^\theta$:

$dx = 0$, $d\varphi = 0$

$$dd_p^\theta = R(t)\,x_E\,d\theta \longrightarrow \boxed{d_p^\theta = R(t)\,x_E\int_0^{\theta_E}d\theta}$$

inverting $f(x_E)$

$$\text{with} \quad x_E = \begin{cases} d_p/R & \text{for } K=0 \\ \frac{1}{\sqrt{|K|}}\sin\left(\sqrt{|K|}\,d_p/R\right) & \text{for } K=1 \\ \frac{1}{\sqrt{|K|}}\sinh\left(\sqrt{|K|}\,d_p/R\right) & \text{for } K=-1 \end{cases}$$

### Comoving distance

It is the proper distance at some pre-defined reference time (a common practice is to use today's time as reference.

$$\boxed{d_c = R(t_0) f(x_E)}$$

if we set $R(t_0) = 1$, then $f(x_E)$ is the comoving distance (convention).

The relation between proper distance and comoving distance is given by:

$$\left.\begin{aligned} d_p &= R(t) f(x_E) \\ d_c &= R_0 f(x_E) \end{aligned}\right\} \quad f(x_E) = \frac{d_p}{R(t)} = \frac{d_c}{R_0} \qquad \boxed{d_p = \frac{R(t)}{R_0} d_c} \qquad (d_p = a\, d_c)$$

Now we have to figure out how to calculate $f(x_E)$ for an object at a given redshift. To obtain this, one needs to assume null geodesics for photons in the FRW metric.

$$ds^2 = 0 = (c\,dt)^2 - R^2(t)\left[\frac{dx^2}{1-kx^2}\right]$$

And integrating:

$$f(x_E) = \int_0^{x_E} \frac{dx}{\sqrt{1-kx^2}} = \int_{t_E}^{t_0} \frac{c\,dt}{R(t)} = \text{const} \longrightarrow 0 = \frac{df(x_E)}{dt_E} = \left.\frac{c\,dt}{R(t)}\right|_{t_E}^{t_0} = \frac{c\,dt_0}{R_0} - \frac{c\,dt_E}{R(t_E)}$$

$$\Rightarrow \boxed{\frac{dt_0}{R_0} = \frac{dt_E}{R(t_E)}}$$ → This will be useful later

Time intervals are changed in proportion to the expansion

We can replace $R(t)$ using the Friedmann equation:

$$f(x_E) = \int_{t_E}^{t_0} \frac{c\,dt}{R(t)} = c\int_{R_E}^{R_0} \frac{dR}{\dot{R}R} \overset{H^2 = H_0^2 E^2(z)}{=} c\int_{R_E}^{R_0} \frac{dr}{R^2 H_0 E(z)} \overset{\frac{R}{R_0} = \frac{1}{1+z}}{=} \frac{c}{H_0}\int_{z_E}^{0} \frac{(1+z)^2}{R_0 E(z)}\left(-\frac{1}{(1+z)^2}\right) dz =$$

$$= \frac{c}{H_0}\int_0^{z_E} \frac{R_0}{R^2 E(z)} \frac{R^2}{R_0^2}\, dz = \frac{c}{H_0 R_0}\int_0^{z_E} \frac{1}{E(z)}\, dz \qquad \boxed{E^2(z) = \sum_i \Omega_{i,0}(1+z)^{3(1+\omega_i)}} \quad \omega_i \begin{cases} 0 & \text{dust} \\ 1/3 & \text{radiation} \\ -1/3 & \text{curvature} \\ -1 & \Lambda \end{cases}$$

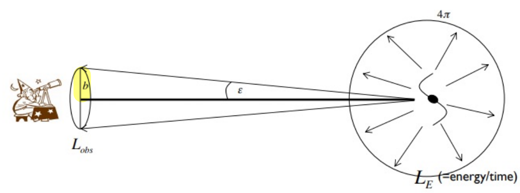
$$\boxed{f(x_E) = \frac{c}{H_0 R_0}\int_0^{z_E} \frac{1}{E(z)}\, dz}$$ → We have replaced $x_E$ with $z_E$ (which can be measured)

To calculate the comoving distance we need to know the cosmological parameters.

Now we need ways to compute distances in terms of standard candles and rulers.

## Luminosity distance - observable.

Again, we have a galaxy that emits photons. We want a definition for distance that follows $F_{obs} \overset{!}{=} \frac{L_E}{4\pi d_L^2}$, since we observe $F_{obs}$ and can theoretically obtain $L_E$.



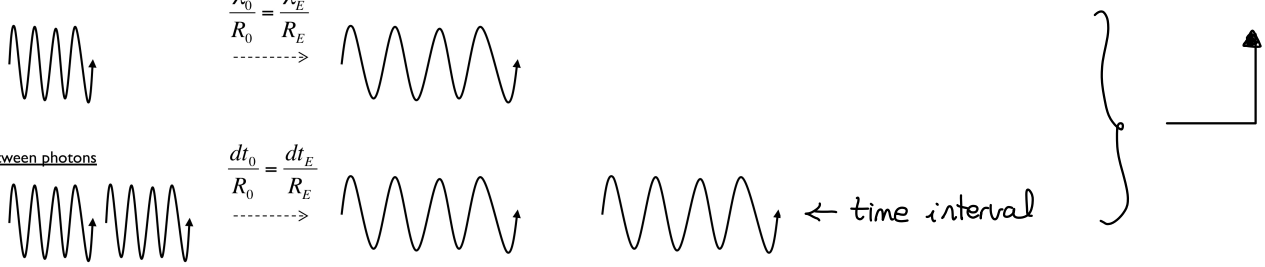

1. Photons: we find that the luminosity is changing as a function of redshift as: $L_0 = \frac{L_E}{(1+z)^2}$

1. change of wavelength

$(1+z)^{-1}$ : $\quad \frac{\lambda_0}{R_0} = \frac{\lambda_E}{R_E}$

2. change of distance between photons

$(1+z)^{-1}$ : $\quad \frac{dt_0}{R_0} = \frac{dt_E}{R_E}$



← time interval

2. Geometry: the emited luminosity $L_E$ is diminished due to the expansion of the Universe. Also, we are not collecting all photons with our telescope, only a certain fraction is collected:

$$L_{obs} = L_0 \times f \qquad \text{with} \qquad f = \frac{\pi \varepsilon^2}{4\pi} = \frac{\pi b^2}{4\pi R^2(t_0) x_E^2}$$ → ratio of solid angles

↳ due to the expansion

↳ $b = R(t_0)\, x_E \int_0^{\varepsilon} d\theta = R(t_0)\, x_E\, \varepsilon$, $R(t_0)$ because of "telescope size today", cf. proper transverse distance to calculate b ↕

3. Measurement: (energy / time / area): we observe a flux, not luminosity

$$F_{obs} = \frac{L_{obs}}{\pi b^2} = \frac{1}{\pi b^2} \frac{L_E}{(1+z)^2} \frac{\pi b^2}{4\pi R^2(t_0) x_E^2} = \frac{R^2(t_E)}{R^4(t_0) x_E^2} \frac{L_E}{4\pi}$$

We wanted to obtain $F_{obs} \overset{!}{=} \frac{L_E}{4\pi d_L^2}$. Then, we can identify and define the luminosity distance as:

$$\longrightarrow \boxed{d_L = \sqrt{\frac{L_E/4\pi}{F_{obs}}} = \frac{R^2(t_0)}{R(t_E)}\, x_E}$$

If we have objects with a known $L_E$ (standard candles), we can calculate the luminosity distance and make predictions for cosmology.

## Angular diameter distance

The same can be done for the angular diameter.

We want to define the angular diameter distance as:


$$\theta_{obs} \overset{!}{=} \frac{D}{d_A}$$

Using again the expression for the transverse distance and following the same approach as before:

$$D = R(t_E)\, x_E \int_0^{\theta_E} d\theta = R(t_E)\, x_E\, \theta_E$$

Standard ruler → $\theta_{obs} \equiv \theta_E$

$$\boxed{d_A = \frac{D}{\theta_{obs}} = R(t_E)\, x_E}$$

## Travel-time distance

$$d_T = \int_{t_E}^{t_0} c\,dt = \dots = \frac{c}{H_0} \int_0^{z_E} \frac{1}{(1+z)E(z)}\, dz$$ (for completeness)

## Summary

Comoving distance: $d_c = \frac{c}{H_0} \int_0^{z_E} \frac{1}{E(z)}\, dz$

Proper distance $d_p = \frac{R(t)}{R_0}\, d_c$

Luminosity distance $d_L = \sqrt{\frac{L_E}{4\pi F_{obs}}} = \frac{R_0}{R(t)}\, R_0\, x_E$

Angular diameter distance $d_A = \frac{D}{\theta_{obs}} = \frac{R(t)}{R_0}\, R_0\, x_E$

### Inter relation

$$\boxed{d_A = \left(\frac{R(t)}{R_0}\right)^2 d_L}$$

$x_E$ can be found inverting $f(x_E) \longrightarrow x_E = \begin{cases} \frac{1}{R_0} d_c & \text{for } k=0 \\ \frac{1}{R_0}\frac{c}{H_0\sqrt{|\Omega_{k,0}|}} \sin\left(\frac{\sqrt{|\Omega_{k,0}|}\,H_0}{c} d_c\right) & \text{for } k=1 \\ \frac{1}{R_0}\frac{c}{H_0\sqrt{|\Omega_{k,0}|}} \sinh\left(\frac{\sqrt{|\Omega_{k,0}|}\,H_0}{c} d_c\right) & \text{for } k=-1 \end{cases}$

$$\Omega_{k_0} = -\frac{c^2 k}{R_0^2 H_0^2}$$

$d_L$ and $d_A$ can be measured observationally for standard rulers/candles. The right hand side of the definition provide the link to "quantify cosmology".

### Examples for $x_E$

- $k=0$, $\Omega_r \ll \Omega_m$, $\Omega_\Lambda = 1-\Omega_m$ ($\Lambda$CDM model)

$$\boxed{x_E = \frac{c}{H_0 R_0}\int_0^{z_E} \frac{dz}{[\Omega_{m,0}(1+z)^3 + \Omega_{\Lambda 0}]^{1/2}}}$$

$$d_c(z) = \frac{c}{H_0}\int_0^z \frac{dz'}{E(z')} \rightarrow \boxed{\begin{aligned} d_L(z) &= d_c(1+z) \\ d_A(z) &= \frac{d_c}{(1+z)} \end{aligned}}$$

} simple relation of $d_L$ and $d_A$ to $d_c$

- $\Omega_\Lambda = 0$, $\Omega_r = 0$, $\Omega_m = 2q_0$

$$x_E = \frac{z_E q_0 + (q_0-1)(-1+\sqrt{2q_0 z_E + 1})}{H_0 R_0 q_0^2 (1+z_E)}$$

- $\Omega_\Lambda = 1$, $\Omega_m = 0$, $k=0$

$$x_E = \frac{c z_E}{H_0 R_0}$$

## Distance and redshift. Hubble's law - revisited

We can get a simple (approximate) relation between redshift $z$ and distance.

$$z = \frac{R(t_0)}{R(t_E)} - 1$$

Taylor-expanding $z$:

$$z = \frac{R(t_0)}{R(t_E)} - 1 = \left(\frac{R(t_0)}{R(t_E)} - 1\right)_0 + \frac{d}{dt_E}\left(\frac{R(t_0)}{R(t_E)} - 1\right)_0 (t-t_0) + \ldots \approx -\left(\frac{R(t_0)}{R^2(t_E)}\dot{R}(t_E)\right)_0 (t_E - t_0) =$$

$$= \frac{\dot{R}(t_0)}{R(t_0)}(t_0 - t_E) = H_0(t_0 - t_E)$$

Taylor expanding $d_c$: $f(x_E) = \int_{t_E}^{t_0} \frac{c\,dt}{R(t)} \approx c\,\frac{t_0 - t_E}{R(t_0)}$

Proper distance: $d_p = R(t_0) f(x_E) \approx R(t_0)\, c\, \frac{t_0 - t_E}{R(t_0)} = c(t_0 - t_E)$

$d_p \approx \frac{cz}{H_0}$

$\boxed{cz \approx H_0 d_p}$ Hubble law distance

Only valid for nearby sources

# 11.3. Cosmological horizons and volumes

## Horizons

Different bounds define different horizons. All are based upon proper distance.

### Particle horizon

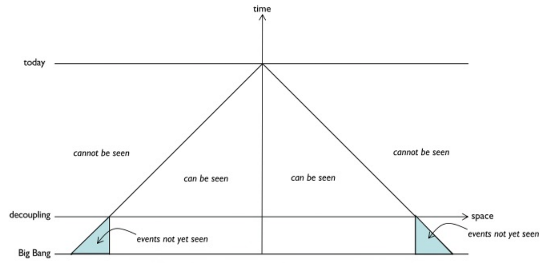
Max distance that a particle can have travelled since decoupling:

$$R_p(t) = R(t)\int_{t_{dec}}^{t} \frac{c\,dt'}{R(t')}$$

### "Particle horizon" (for some textbooks)

Max distance a photon can have travelled since Big Bang (there are events we have not seen yet).

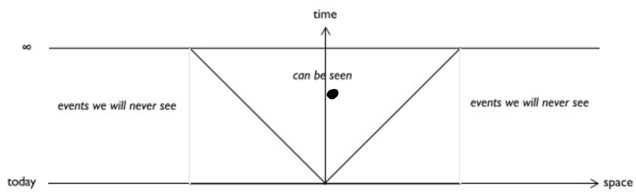
$$R_p(t) = R(t)\int_{0}^{t} \frac{c\,dt'}{R(t')}$$




### Even horizon

Max distance a particle can travel from now onwards (there are events that we will never see)

$$R_e(t) = R(t)\int_{t}^{\infty} \frac{c\,dt'}{R(t')}$$




### Hubble radius

Distance at which recessional velocity equals speed of light

$$R_H = \frac{c}{H} \qquad \underset{\text{comoving}}{R_{CH}}(t) = \frac{R_0}{R}\frac{c}{H}$$

## Volumes

Once we have distances, we can define volumes from them.

### Proper volume at $t_0$

$$dV_p(t_0) = \sqrt{\det(g_{ij})}\, dr\, d\theta\, d\varphi \leftarrow \text{general equation}$$

$t = t_0$

$d\Omega = d\theta^2 + \sin^2\theta\, d\phi^2$

$$dV_0 = R_0^3 x^2 \frac{dx}{\sqrt{1-kx^2}}\, d\Omega$$

We have to relate this to the distances we defined before:

$$dV_p(t_0) = R_0^3 x^2 \frac{-c\,dz}{H_0 R_0 E(z)}\, d\Omega = R_0^2 x^2 \frac{-c\,dz}{H_0 E(z)}\, d\Omega = R_0 x^2 \frac{R_0^2 R_E^2}{R_0 R_E^2}\frac{-c\,dz}{H_0 E(z)}\, d\Omega = \frac{R_0^4 x^2}{R_E^2}\frac{R_E^2}{R_0^2}\frac{-c\,dz}{H_0 E(z)}\, d\Omega = \frac{d_L^2}{1+z^2}\frac{-c\,dz}{H_0 E(z)}\, d\Omega$$

$$\frac{dx}{\sqrt{1-kx^2}} = \frac{c\,dz}{R(t)} = \frac{dt}{dz}\frac{c\,dz}{R(t)}, \qquad \frac{dt}{dz} = -\frac{R^2}{R_0 \dot{R}}$$

$$\to d_L = \frac{R_0^2}{R_E}x$$

And integrating:

$$\boxed{V_p(t_0) = \frac{4\pi}{H_0}\int_0^{z_E} \frac{d_L^2(z)}{(1+z)^2 E(z)}\, dz = 4\pi R_0^3 \int_0^{x_E} \frac{x^2}{\sqrt{1-kx^2}}\, dx}$$

Proper volume at $t_0$

This is interesting to normalize the volume on large surveys.
$V_p(t_0)$ is a function of $H_0$, $\Omega_m$, $\Omega_\Lambda$ and $z$.
$V_p(t_0)$ is corrected by the solid angle $\Omega$ at $z$ via:

$$V_p^{\Omega} = V_p \frac{\Omega}{4\pi}$$

$$V_p(t_0) = \begin{cases} \dfrac{4\pi}{3}\left(\dfrac{d_L}{1+z}\right)^3 & k=0 \\ \dfrac{2\pi}{H_0^3\Omega_{k,0}}\left[H_0\dfrac{d_L}{1+z}\sqrt{1+\left[\dfrac{H_0 d_L}{1+z}\right]^3\Omega_{k,0}} - \dfrac{1}{\sqrt{|\Omega_{k,0}|}}\arcsin\left(H_0 d_L\sqrt{|\Omega_{k,0}|}\right)\right] & k=1 \\ \dfrac{2\pi}{H_0^3\Omega_{k,0}}\left[H_0\dfrac{d_L}{1+z}\sqrt{1+\left[\dfrac{H_0 d_L}{1+z}\right]^3\Omega_{k,0}} - \dfrac{1}{\sqrt{|\Omega_{k,0}|}}\operatorname{arcsinh}\left(H_0 d_L\sqrt{|\Omega_{k,0}|}\right)\right] & k=-1 \end{cases}$$

### Proper volume at $t \neq t_0$

Starting again from $dV_p(t) = \sqrt{\det(g_{ij})}\, dr\, d\theta\, d\varphi$ (change to spherical coordinates), now we have:

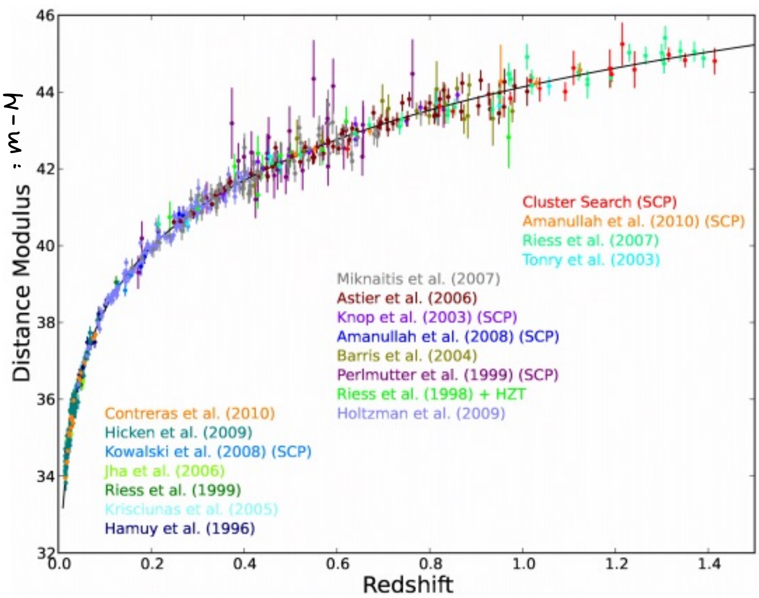
$$dV_p(t) = R^3(t)\, x^2 \frac{dx}{\sqrt{1-kx^2}}\, d\Omega = \dots = (1+z)^3\, dV_p(t_0)$$

$$\boxed{V_c(z) = \frac{V_p(z)}{R^3(t(z))}}$$

# 11.4. Supernova cosmology

## Supernovae and cosmological parameters

In the first lecture we talked about how can we determine $H_0$, $\Omega_{m,0}$ and $\Omega_{\Lambda,0}$ (since $1 = \Omega_{m,0} + \Omega_{k,0} + \Omega_{\Lambda,0}$).




This is done throug the distance-modulus equation:

$$\boxed{m - M = 25 - 5\log(H_0) + 5\log\left(D(z, \Omega_{m,0}, \Omega_{\Lambda,0})\right)}$$

# Distance-modulus equation (derivation)

We will start with the luminosity distance.

$$d_L = \sqrt{\frac{L_E}{4\pi F_{obs}}} = \frac{R_0}{R(t_E)} R_0 x_E = (1+z_E) R_0 x_E \longrightarrow x_E = \begin{cases} \frac{1}{R_0} d_c & ;k=0 \\ \frac{c}{R_0 H_0}\frac{1}{\sqrt{|1-\Omega_{m,0}-\Omega_{\Lambda,0}|}} \sin\left(\sqrt{|1-\Omega_{m,0}-\Omega_{\Lambda,0}|}\frac{H_0}{c} d_c\right) & ;k=1 \\ \frac{c}{R_0 H_0}\frac{1}{\sqrt{|1-\Omega_{m,0}-\Omega_{\Lambda,0}|}} \sinh\left(\sqrt{|1-\Omega_{m,0}-\Omega_{\Lambda,0}|}\frac{H_0}{c} d_c\right) & ;k=-1 \end{cases}$$

We also had an expresion for $d_c$:

$$d_c = \frac{c}{H_0}\int_0^{z_E} \frac{1}{E(z)}\,dz \qquad E(z) \rightarrow \text{choose cosmology}$$

The right hand side is related to cosmology, which is "under control", we need to analyse the left hand side.

$L_E$ is known from the theory of supernovae Ia explosion.

$F_{obs}$ can be obtained using apparent and absolute magnitudes.

Apparent magnitudes are defined as:

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{F_1}{F_2}\right) \qquad \text{where } F = \frac{L}{4\pi d^2}$$

And for absolute magnitudes $M$: ← placing light source at 10 pc

$$m - M = -2.5\log_{10}\left(\frac{L}{4\pi d^2}\frac{4\pi(10pc)^2}{L}\right) = -2.5\log_{10}\left(\frac{(10pc)^2}{d^2}\right) = -5\log\left(\frac{10pc}{d}\right)$$

And reversing the equation:

$$\boxed{d = 10^{1+\frac{m-M}{5}}\,pc = 10^{-5+\frac{m-M}{5}}\,Mpc \equiv d_L} \longrightarrow [d_L] = Mpc \longrightarrow m-M = 25+5\log(d_L)$$

Adding $5\log(H_0)$ (because $x_E$ contains $H_0$)

$$m-M = 25 + 5\log(d_L) - 5\log(H_0) + 5\log(H_0)$$

$$m-M = 25 - 5\log(H_0\,[Km/s/Mpc]) + 5\log(H_0 d_L)$$

↪ observation, but need to relate $m-M \leftrightarrow F \& L$ ↪ cosmology

observation $m$: $F_{obs} = 10^{-2m/5} \times 2.52\times10^{-5}\,\frac{erg}{cm^2\,sec}$

standard candle $M$: $L_E = 10^{-2M/5} \times 3.02\times10^{35}\,\frac{erg}{sec}$

} Invert to get $m$ and $M$

We end up with:

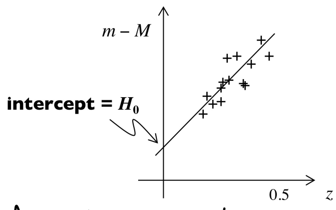
$$m - M = 25 - 5\log(H_0) + 5\log\left(D(z,\Omega_{m,0},\Omega_{\Lambda,0})\right)$$

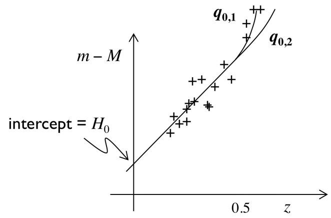
$$D(z,\Omega_{m,0},\Omega_{\Lambda,0}) = \frac{c(1+z)}{\sqrt{|k|}}\,\mathrm{sinn}\left(\sqrt{|k|}\int_0^z\left[(1+z')^2(1+\Omega_{m,0}z') - z'(2+z')\Omega_{\Lambda,0}\right]^{-1/2} dz'\right)$$

Where $m, z$ are observables, $M$ is a standard candle and $D$ comes from theory. We can plot $(m-M)$ vs. $z$ for our observations. We can also get a theoretical curve and see if it fits the observations for a chosen cosmology.

## Measuring $H_0$

The intercept with the y axis gives a value for $H_0$. It is also possible to measure $q_0$.




$$q_{0,eff} = q_0 - \frac{1}{H_0}\frac{\dot{z}}{z}$$ (which can be problematic if standard galaxies are used)

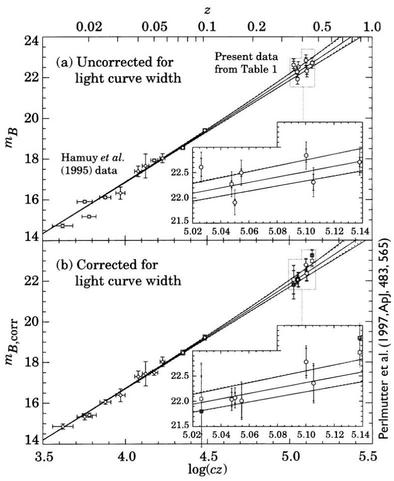
## SN and the expansion of the Universe

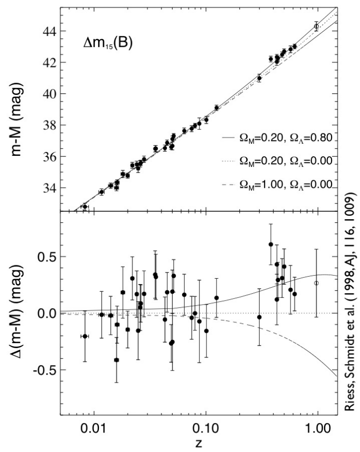
SN Ia are feasible standard candles. They are visible out to $z \approx 1$, there dispersion on the maximum of their lightcurves is small and they light curves are independent of redshift.

- Perlmutter et al. (1997)
- Garnavich et al. (1997)
- Riess, Schmidt et al. (1998)

$q_0 < 0$

$\Omega_{\Lambda,0} \neq 0$




You need something that contains $\Lambda$ to explain the observations.

# 11.5. Surveys in Cosmology

## History and motivation

A survey consist on systhematic observing and cataloging a set of objects (stars, etc.). The first star catalog in history was made by Hipparchus (190-120 BC) in 129 BC. He also:

i) Determined distances and sizes of the Moon and the Sun.

ii) Discovered the precession of equinoxes.

iii) Measured the length of year to ~6 min

Hipparchus measured the right ascension, declination (equatorial), longitude (ecliptical) to 850 stars. The original catalog was lost, but a Roman copy (150 ac) of a statue showing it survived.

Due to Weber's law we measure magnitudes: all (most) senses are logarithmic.

i) Sight: magnitudes: $m = -2.5 \log_{10}(F/F_0)$

ii) Sound: decibels (dB): $L_P = 10 \log_{10}(P/P_0)$ dB

iii) Taste: Scoville scale (pungency) : $S_c \sim \log_{10}(\rho_{capsaicin})$ (for spicyness)

iv) Sense of weight (S = sense, I = intensity of stimulus):

$$S \sim \ln(I) \rightarrow \delta S \sim \frac{\delta I}{I} \rightarrow I = mg \ , \ \delta I \sim \delta m \, g \rightarrow \delta S \sim \frac{\delta m}{m}$$

apple $\rightarrow$ $m = 100\,gr$ , $\delta m = 100\,g$ , $\delta S \sim 1$

$m = 2\,kg$ , $\delta m = 100\,g$ , $\delta S \sim 0.05$

book ↑ adding an apple ↑ $\longrightarrow$ Difficult to detect the variation

Following this, Hipparchus' catalog was in terms of magnitudes :

- Brightest star was first magnitude ($m = 1$)
- Faintest were sixth magnitude ($m = 6$)

Definition $\Delta m = 5 \rightarrow 100\,\Delta$ (brightness)

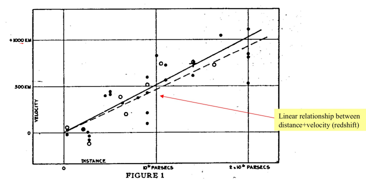
Weber's law: $m = -2.5\log_{10}(F/F_0) \longrightarrow$ Match with Hipparchus: $100^{1/5} \sim 2.5$

Ptolemy (90–186 AC) published his own catalog in Algamest with 1022 stars. It was the golden standard for more than 8 centuries.

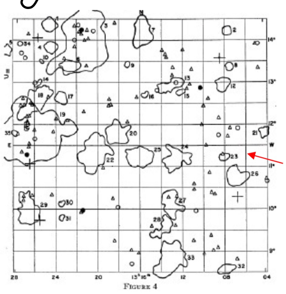
Tyco Brahe (1598 AC) ~ 1000 stars in unprecedent precision (few arcmins). He created very accurate instruments (sextant + cuadrant).

Messier published (1774 ac) a list of 110 nebulae and star clusters (e.g. M31: Andromeda galaxy).

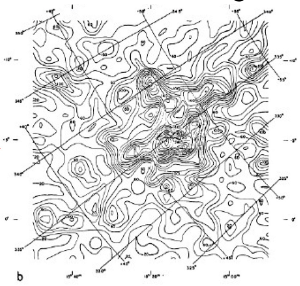
Hubble (1922) measured distances to nebulae (e.g. M31) and found that were too distant to belong to the MW. He also found that redshift (related to recession v. increases with distance (Hubble's law).




Large scale structure was discovered by Shapley and Zwicky in the 1930's.

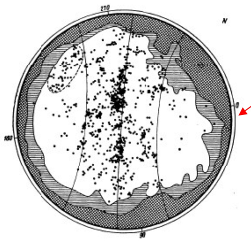



Overdensity (left) galaxy counts and density map (right)



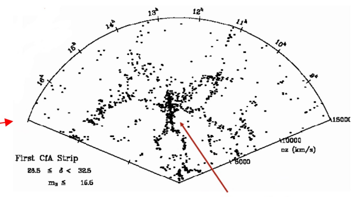
Density map for the local neighborhood

The first redshift surveys were conducted by Vaucouleurs, then CfA and Arecibo.



The Local supercluster (~60Mpc structure)

The Coma supercluster (~100Mpc structure)




Coma cluster

Measured angles, positions in the sky and redshift $\longrightarrow$ 3D

## Requirements and steps

1. Define science goals/objectives:

equation of state, growth of pert.

i) Understanding dark energy ⟶ measure cosmological parameters ($w=-1$? , $\gamma = 6/11$?)

ii) Testing homogeneity of LSS ⟶ measure fractal index $D2(r)$ and correlation function $\xi(r)$

↳ number of dimensions of the space, $D2(r)$ sets the homogeneity scale (⟶ 3)

iii) Assesing accelerating expansion of the Universe ⟶ measure Hubble parameter $H_0$ and deceleration parameter $q_0$.

iv) Is the Universe flat ⟶ measure location of 1st peak of CMB.

2. Define survey strategy

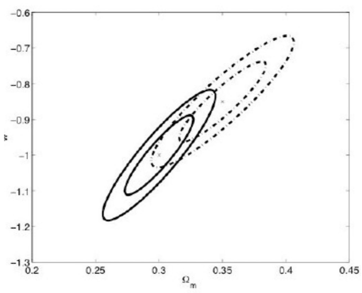
i) What kind of objects (galaxies, supernovae, CMB) should we target?

ii) At which redshift should we go? (this affects the instrument design).

iii) Should we survey a wide area at low z or a small area to a greater depth (m)?

3. Quantify the performance of the survey.

To convince funders about your ability to process the data, it is necessary to quantify the performance of the survey (number of galaxies to get a certain accuracy, etc.). There are two complementary ways to do this. If we have a likelihood that describes two parameters ($\Omega_m$, $\omega$) one can write it as an expansion around the best fit:




$$\ln \mathcal{L}(\theta) \approx \ln \mathcal{L}(\theta^{ML}) + \frac{1}{2}\sum_{ij}(\theta_{i} - \theta_i^{ML})^{t} H_{ij} (\theta_j - \theta_j)^{ML}$$

Where $H_{ij} = \frac{\partial \mathcal{L}}{\partial \theta_i}\frac{\partial \ln \mathcal{L}}{\partial \theta_j}\Big|_{\theta^{ML}}$ (Hessian matrix)

i) Fisher matrix:

Expectation value of $H_{ij}$ ⟶ $F_{ij} = \langle H_{ij} \rangle$

The inverse of the Fisher matrix is related to the errors  Errors $\sim (F_{ij})^{-1}$

ii) Figure of metric ($= 1/$Area of contour) : The higher, the better. In the figure, the best one is the solid line one (vs. dashed line). The figure of merit is defined as:

$$\left.\begin{aligned} Vol(M) &= \int_c d^M a_i \\ FoM &= Vol(M)^{-1} \end{aligned}\right\} \longrightarrow FoM(M) = |F|^{1/2} \frac{\Gamma(M/2+1)}{\pi^{M/2}} (8\chi^2)^{-M/2}$$

↳ relation to the Fisher matrix

4. Publish proposal making scientific case

eg. Euclid Definition Study Report. arXiv: 1110.3193

Goals: Map the dark Universe

Euclid Definition study (aka Red Book) contains info on: science objectives and requirements, payload (instruments), mission design, performance, data handling, management. (More details later).

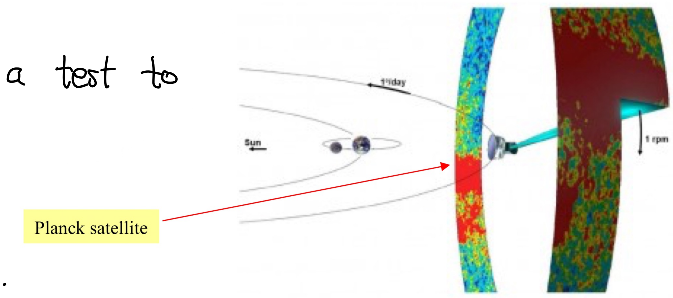
5. Request for funding : very difficult step, when most proposals fail.

6. Construction phase

7. Data adquisition

i) First light for DES telescope. Serves as a test to make sure everything is working ok.

ii) Planck satellite taking full sky map (rotating around his axis and around the Sun).




8. Pipelines and analysis (theory + data) e.g. see Planck website for maps, catalogs, ...

i) Store and analyze data

ii) Make likelihood (the $\chi^2$) to fit data

iii) Other data products and codes

9. Publish papers

i) Provide Key results

ii) Communicate science

iii) Credit authors

iv) Scientific Legacy – Discussion about the istruments, constrains, analysis, additional surveys...

v) Data product description

## CMB surveys

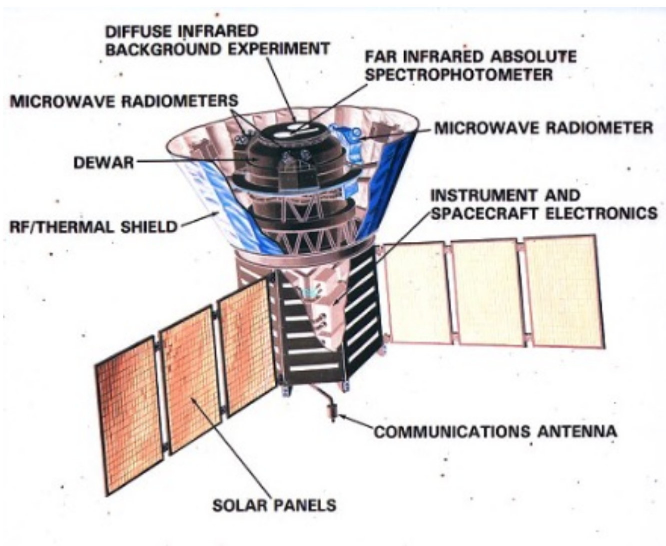
### COBE: Cosmic Background Explorer (1989 - 1993)

Instruments:

i) Differential microwave radiometer: for differential measurements of the CMB
$\hookrightarrow$ to measure the anisotropies

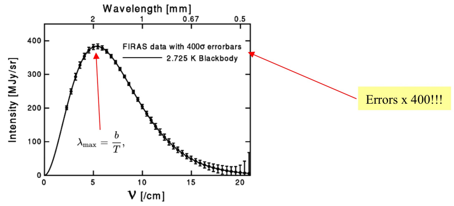
ii) Far Infra-red absolute spectrophotometer: to measure the CMB spectrum

iii) Diffuse infrared Background Experiment: to measure dust emission in Galaxy



## Key findings:

i) Black-body spectrum of the CMB



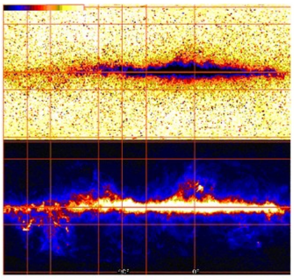

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

ii) Infrared background and galactic disc (effect of dust important).

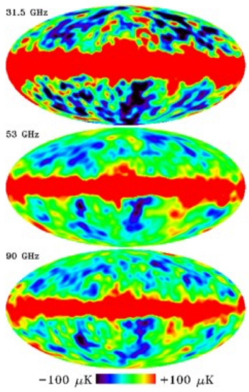
iii) CMB anisotropies (3 channels at 31.5 GHz, 53 GHz and 90 GHz).

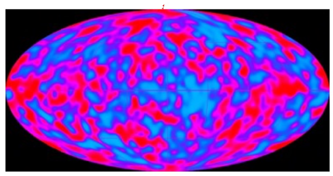
→ $T = 2.7\,K$ and $\Delta T/T \sim 10^{-5}$

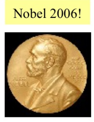
ii)



iii)






## WMAP (Wilkinson Microwave Anisotropy Probe (2001-2010)

### Instruments / probe components:

i) Passive coolers (~90 K)

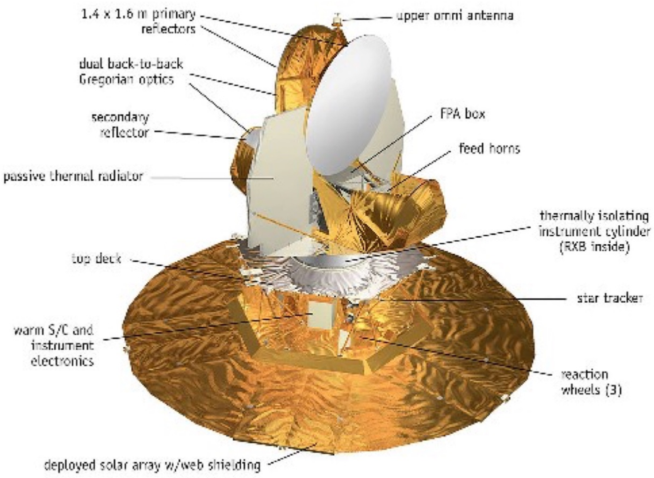
ii) 5m solar panel array

iii) Differential radiometers

iv) Low noise amplifiers

v) 5 frequency bands (23, 33, 41, 61, 94 GHz)

vi) Reaction wheels, gyroscopes

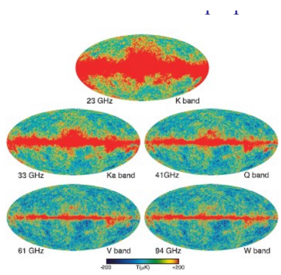


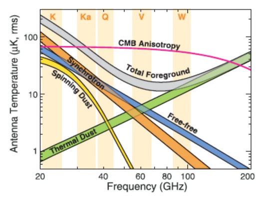

### Key findings:

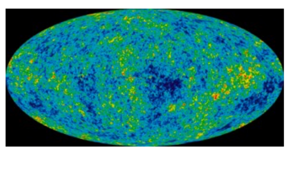
i) Most accurate CMB map up to that point

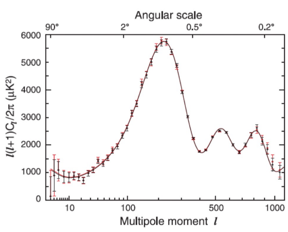
ii) Foreground spectra and CMB anisotropies →

iii) Constrains on cosmological parameters





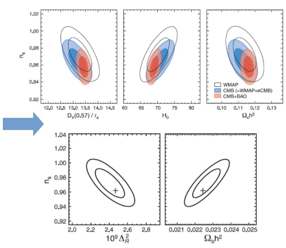



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TABLE 3

*WMAP* Seven-year to Nine-year Comparison of the Six-Parameter ΛCDM Model[a]

| Parameter | *WMAP*-only[b] Nine-year | *WMAP*-only[b] Nine-year (MASTER)[c] | *WMAP*-only[b] Seven-year | *WMAP*+BAO+$H_0$[b] Nine-year | *WMAP*+BAO+$H_0$[b] Seven-year |
|---|---|---|---|---|---|
| Fit parameters | | | | | |
| $\Omega_b h^2$ | $0.02264 \pm 0.00050$ | $0.02243 \pm 0.00055$ | $0.02249^{+0.00056}_{-0.00057}$ | $0.02266 \pm 0.00043$ | $0.02255 \pm 0.00054$ |
| $\Omega_c h^2$ | $0.1138 \pm 0.0045$ | $0.1147 \pm 0.0051$ | $0.1120 \pm 0.0056$ | $0.1157 \pm 0.0023$ | $0.1126 \pm 0.0036$ |
| $\Omega_\Lambda$ | $0.721 \pm 0.025$ | $0.716 \pm 0.028$ | $0.727^{+0.030}_{-0.029}$ | $0.712 \pm 0.010$ | $0.725 \pm 0.016$ |
| $10^9 \Delta^2_{\mathcal{R}}$ | $2.41 \pm 0.10$ | $2.47 \pm 0.11$ | $2.43 \pm 0.11$ | $2.427^{+0.078}_{-0.079}$ | $2.430 \pm 0.091$ |
| $n_s$ | $0.972 \pm 0.013$ | $0.962 \pm 0.014$ | $0.967 \pm 0.014$ | $0.971 \pm 0.010$ | $0.968 \pm 0.012$ |
| $\tau$ | $0.089 \pm 0.014$ | $0.087 \pm 0.014$ | $0.088 \pm 0.015$ | $0.088 \pm 0.013$ | $0.088 \pm 0.014$ |
| Derived parameters | | | | | |
| $t_0$ (Gyr) | $13.74 \pm 0.11$ | $13.75 \pm 0.12$ | $13.77 \pm 0.13$ | $13.750 \pm 0.085$ | $13.76 \pm 0.11$ |
| $H_0$ (km/s/Mpc) | $70.0 \pm 2.2$ | $69.7 \pm 2.4$ | $70.4 \pm 2.5$ | $69.33 \pm 0.88$ | $70.2 \pm 1.4$ |
| $\sigma_8$ | $0.821 \pm 0.023$ | $0.818 \pm 0.026$ | $0.811^{+0.030}_{-0.031}$ | $0.830 \pm 0.018$ | $0.816 \pm 0.024$ |
| $\Omega_b$ | $0.0463 \pm 0.0024$ | $0.0462 \pm 0.0026$ | $0.0455 \pm 0.0028$ | $0.0472 \pm 0.0010$ | $0.0458 \pm 0.0016$ |
| $\Omega_c$ | $0.233 \pm 0.023$ | $0.237 \pm 0.026$ | $0.228 \pm 0.027$ | $0.2408^{+0.0093}_{-0.0092}$ | $0.229 \pm 0.015$ |
| $z_{reion}$ | $10.6 \pm 1.1$ | $10.5 \pm 1.1$ | $10.6 \pm 1.2$ | $10.5 \pm 1.1$ | $10.6 \pm 1.2$ |

Planck satellite (2009-2013)

Instruments/probe components (30-857 GHz):

i) Low Frequency instrument (LFI)

ii) High frequency instrument (HFI)

iii) Passive & active (liquid He) cooling (0.1 K)

Objectives (all astro and cosmo):

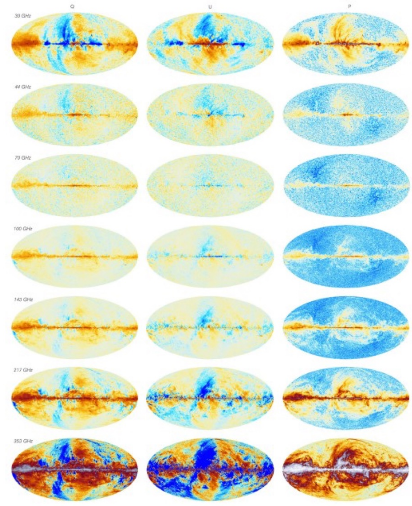
i) High resolution TT, TE and EE maps/spectra

ii) Galaxy cluster catalog

iii) Observations of Milky Way emission

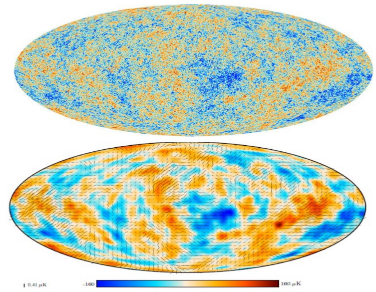
iv) Gravitational lensing and ISW effect

v) Stringent constrains on cosmological parameters



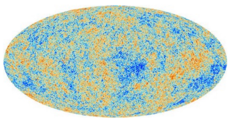
Key findings:

i) Most accurate CMB up to now →




arXiv:1807.06205, 1807.06209, 1807.06211

ii) Constrains on cosmological parameters



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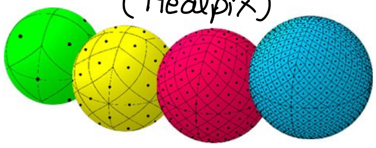
(Healpix)



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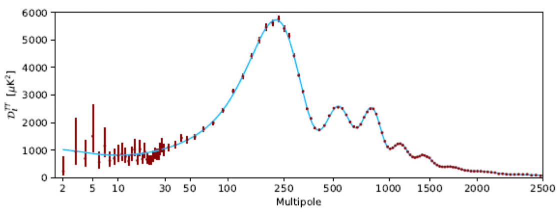
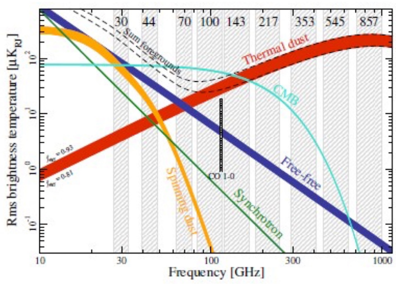


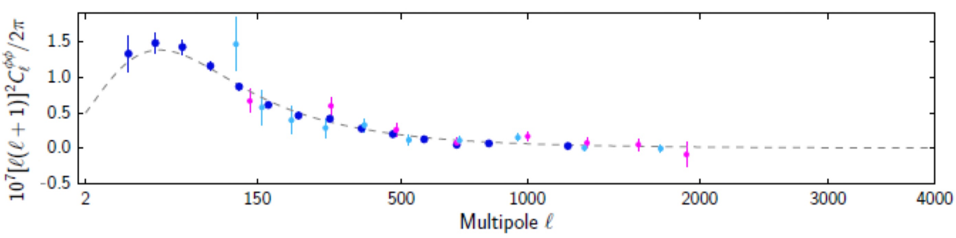

MCMC →

| Parameter | *Planck* alone | *Planck* + BAO |
|---|---|---|
| $\Omega_b h^2$ | 0.022383 | 0.022447 |
| $\Omega_c h^2$ | 0.12011 | 0.11923 |
| $100\theta_{MC}$ | 1.040909 | 1.041010 |
| $\tau$ | 0.0543 | 0.0568 |
| $\ln(10^{10}A_s)$ | 3.0448 | 3.0480 |
| $n_s$ | 0.96605 | 0.96824 |
| $H_0$ [km s$^{-1}$Mpc$^{-1}$] | 67.32 | 67.70 |
| $\Omega_\Lambda$ | 0.6842 | 0.6894 |
| $\Omega_m$ | 0.3158 | 0.3106 |
| $\Omega_m h^2$ | 0.1431 | 0.1424 |
| $\Omega_m h^3$ | 0.0964 | 0.0964 |
| $\sigma_8$ | 0.8120 | 0.8110 |
| $\sigma_8(\Omega_m/0.3)^{0.5}$ | 0.8331 | 0.8253 |
| $z_{re}$ | 7.68 | 7.90 |
| Age [Gyr] | 13.7971 | 13.7839 |

iii) Frequency dependence of temperature



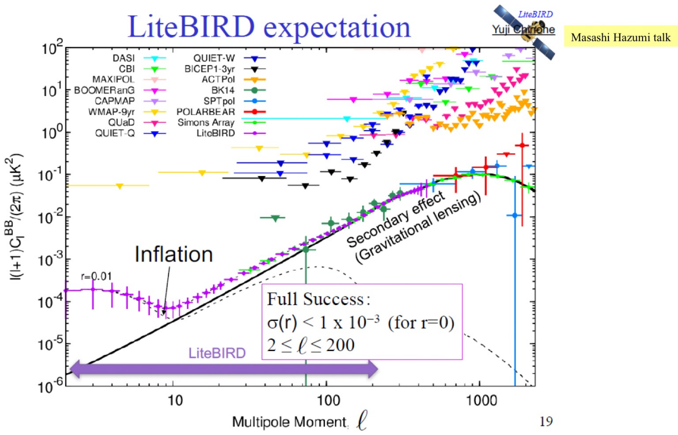

iv) Lensing power spectrum - how CMB photons are lensed by matter structures



## Lite Bird (2020's)

Light satellite for the studies of B-mode polarization and Inflation from cosmic background radiation detection.

Instruments/probe components (40-400 GHz):




i) Superconducting polarimeter

ii) Low frequency telescope (40 - 235 GHz)

iii) High frequency telescope (280 - 400 GHz)

iv) Passive and active cooling (5K)

Objectives

i) B mode detection

ii) Constrains on primordial GWs and inflation

iii) Determination of scalar to tensor ratio $r = A_t / A_s$

## Bicep/Keck array - CMB experiments in South Pole (2010 - now) [Radiotelescopes]

Instruments / probe components (various phases):

i) BICEP 1: 98 sensors (100 - 150 GHz)

ii) BICEP2: 512 @ 150 GHz

iii) Keck: 5 polarimeters with liquid Helium

iv) BICEP 3: 2560 sensors at 95 GHz (no weight limit, since it is not a satellite)

Objectives:

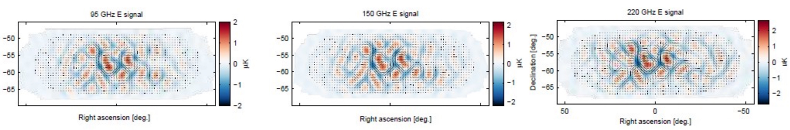
i) Measurements of polarization

ii) Emphasis on B mode

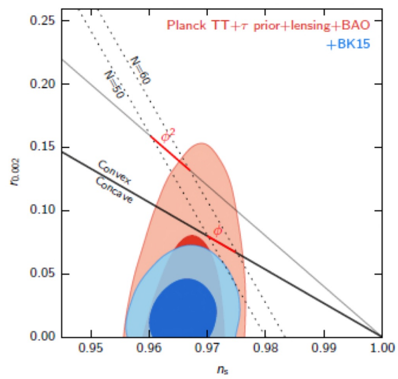
iii) Stringent constrains on tensor to scalar ratio ($r < 0.07$)

Bicep results (until 2015)

i) Maps of E-modes




ii) Constrains on $n_s$ and $r$ ⟶




## LSS surveys

LSS surveys can be spectroscopic or photometric. Spectroscopic surveys (Boss, Euclid) split light into frequency bands and match absorption/emission lines. This provides more accurate redshifts, but data are harder to get (need a fiber for every object). Photometric surveys (DES, Euclid, LSST) use the total light received by the telescope. They are easier and faster to get, but provide a worse redshift determination.

The main probes are:

i) Gravitational lensing

ii) Type Ia supernovae

iii) Galaxy cluster mass function and number counts

iv) Baryon acoustic oscillations

v) Ly$\alpha$ quasars

## 2dF - Two degree field galaxy redshift survey

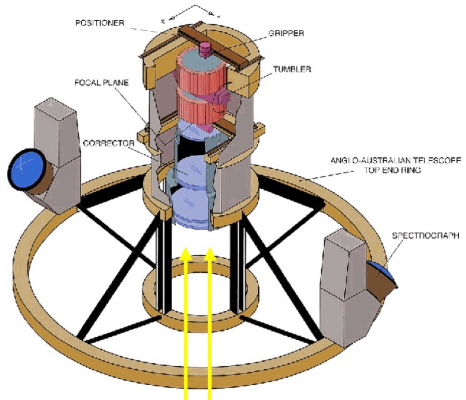
http://www.2dfgrs.net/
http://www.2dfgrs.net/Public/Survey/

Instruments and components:

i) 4m telescope at Anglo-Australian Observatory

ii) 2 degree field of view

iii) 400 fibers




Objectives:

i) Obtain spectra for 245,591 objects

ii) Cover an area of approximately 1500 degrees$^2$

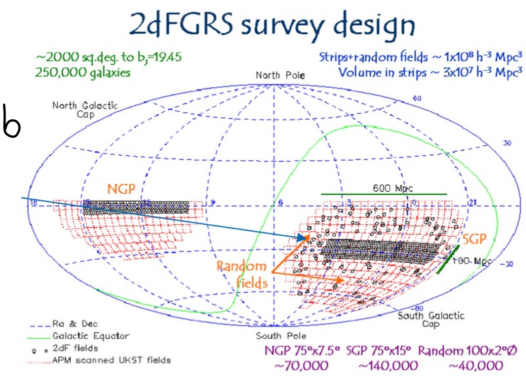
iii) Determine LSS up to 600 Mpc

iv) Determine cosmological parameters and galaxy bias b

Survey strategy:

i) Choose targets a priori

ii) Point and shoot at 2 degrees.



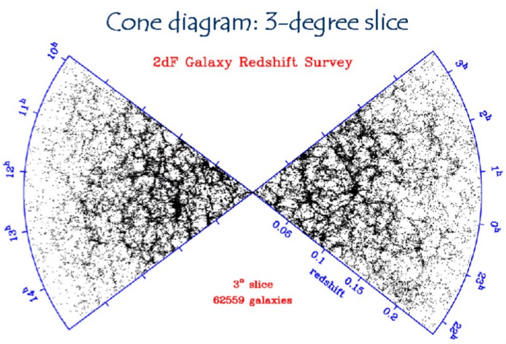

Cosmo results:

i) LSS up to 600 Mpc/h

ii) $\Omega_m = 0.3 \pm 0.06$

iii) $\Omega_b / \Omega_m = 0.17 \pm 0.06$ (PH8 : 0.156)

iv) Bias $b = 0.96 \pm 0.08$ — baryons following DM wells



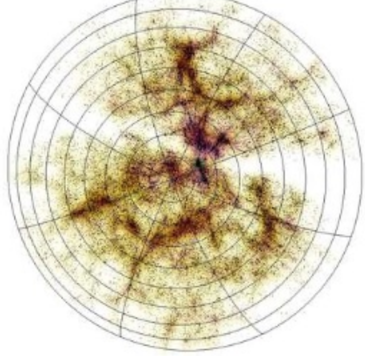

## 6dF : Six degree field Galaxy Redshift survey

Instruments and components:

i) 1.2 m Schmidt telescope at UK

ii) 6 degree field of view

iii) Spectrograph with 150 fibers



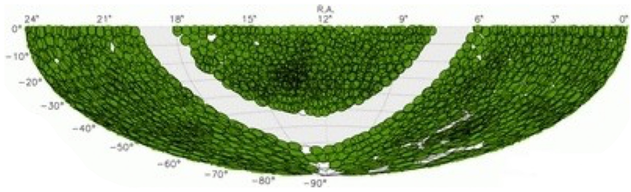
Objectives:

i) Obtain spectra for 136,304 objects

ii) Map nearby Universe over half the sky

iii) Detect BAO

iv) Determine peculiar velocity field (8885 gals)




Survey strategy:

i) Choose the targets a priori

ii) Point and shoot at 6 degrees

$$D_V(z) = \left[(1+z)^2 D_A^2(z)\frac{cz}{H_0 E(z)}\right]^{1/3},$$

Cosmo results

i) BAO detection ($2.4\sigma$) at 105 Mpc/h

ii) $\Omega_m = 0.296 \pm 0.028$

iii) $H_0 = 67 \pm 3.2$ Km/s Mpc

iv) Peculiar velocities for 8885 galaxies at $z < 0.055$

| Summary of parameter constraints from 6dFGS | | |
|---|---|---|
| $\Omega_m h^2$ | $0.138 \pm 0.020$ (14.5%) | |
| $D_V(z_{\rm eff})$ | $456 \pm 27$ Mpc (5.9%) | |
| $D_V(z_{\rm eff})$ | $459 \pm 18$ Mpc (3.9%) | [$\Omega_m h^2$ prior] |
| $\mathbf{r_s(z_d)/D_V(z_{eff})}$ | $\mathbf{0.336 \pm 0.015}$ (4.5%) | |
| $R(z_{\rm eff})$ | $0.0324 \pm 0.0015$ (4.6%) | |
| $A(z_{\rm eff})$ | $0.526 \pm 0.028$ (5.3%) | |
| $\Omega_m$ | $0.296 \pm 0.028$ (9.5%) | [$\Omega_m h^2$ prior] |
| $\mathbf{H_0}$ | $\mathbf{67 \pm 3.2}$ (4.8%) | [$\mathbf{\Omega_m h^2}$ prior] |

SDSS/BOSS: Sloan Digital Sky Survey

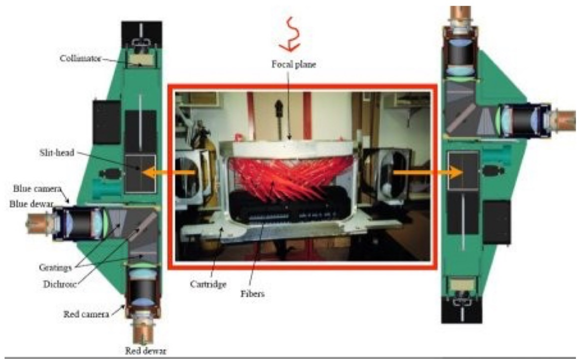
http://www.sdss3.org

SDSS - I : 2000 - 2005

SDSS - II : 2005 - 2008

SDSS - III (Boss) : 2008 - 2014

SDSS - IV : 2014 - 2020




Instruments components:

i) 2.5 m telescope at New Mexico (USA)

ii) 120 Mpixel camera

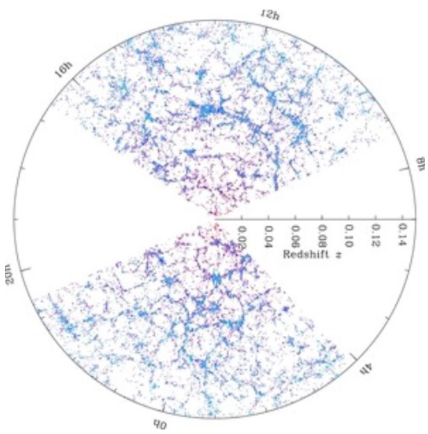
iii) Spectrograph with 1000 fibers

iv) Liquid nitrogen cooling to reduce noise (190 K)

Objectives:

i) Obtain spectra for 4355 200 objects

ii) Both photometry and spectroscopy




iii) High significance detection of BAO

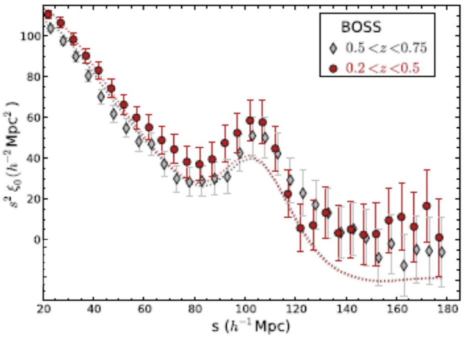
iv) Determine peculiar velocity field (8885 gal)

Observations / results:

i) Distribution of local galaxies

ii) Millions of objects and spectra

iii) Frequent data releases



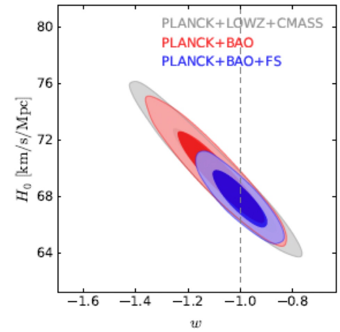

Cosmo results:

i) BAO detection (4.5σ) at ~ 105 Mpc/h

ii) $\Omega_m = 0.310 \pm 0.06$

iii) $H_0 = 67.6 \pm 0.5$ km/s/Mpc

iv) Detection of most distant quasars (160 000 objects at $2.2 < z < 3$)




## WiggleZ Dark energy survey (2006- 2011)

Instruments and components:

i) 4m telescope at Anglo-Australian Observatory

ii) 2 degree field of view

iii) Spectograph with 150 fibers

Objectives

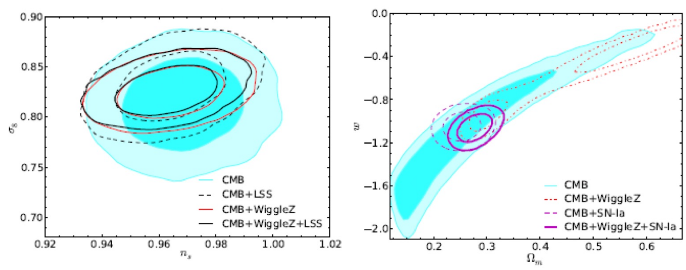
i) Improve understanding of DM

ii) Measure the BAO (hence the wiggle)

iii) Attempt to determine z 1/4 × $10^{16}$ galaxies

iv) Cover 1000 square degrees

v) Synergy with n-body sims (GiggleZ)




ArXiv: 1210.2130

http://wigglez.swin.edu.au/site/

Results:

i) Stringent constrains on ΛCDM

ii) Redshift of 240000 galaxies

iii) Constraints on $\xi(r)$ and $P(k)$

iv) Constraints on $r = A_t / A_s$

v) Systematic test of ΛCDM extensions

| Model | Parameter | CMB + WiggleZ | + $H_0$ | + SN-Ia | + BAO | + $H_0$ + BAO |
|---|---|---|---|---|---|---|
| Flat ΛCDM | $100\Omega_b h^2$ | $2.238 \pm 0.052$ | $2.255 \pm 0.050$ | $2.240 \pm 0.053$ | $2.239 \pm 0.050$ | $2.253 \pm 0.050$ |
| | $\Omega_{CDM} h^2$ | $0.1153 \pm 0.0027$ | $0.1145 \pm 0.0026$ | $0.1150 \pm 0.0028$ | $0.1152 \pm 0.0024$ | $0.1146 \pm 0.0024$ |
| | $100\theta$ | $1.039 \pm 0.002$ | $1.040 \pm 0.002$ | $1.039 \pm 0.003$ | $1.039 \pm 0.002$ | $1.039 \pm 0.002$ |
| | $\tau$ | $0.083 \pm 0.014$ | $0.084 \pm 0.014$ | $0.083 \pm 0.014$ | $0.083 \pm 0.014$ | $0.084 \pm 0.014$ |
| | $n_s$ | $0.964 \pm 0.012$ | $0.968 \pm 0.012$ | $0.965 \pm 0.013$ | $0.964 \pm 0.012$ | $0.968 \pm 0.011$ |
| | $\log(10^{10} A_s)$ | $3.084 \pm 0.029$ | $3.086 \pm 0.029$ | $3.085 \pm 0.030$ | $3.083 \pm 0.029$ | $3.086 \pm 0.029$ |
| | $\Omega_m$ | $0.290 \pm 0.016$ | $0.283 \pm 0.014$ | $0.288 \pm 0.017$ | $0.289 \pm 0.013$ | $0.284 \pm 0.012$ |
| | $H_0[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$ | $68.9 \pm 1.4$ | $69.6 \pm 1.3$ | $69.1 \pm 1.6$ | $69.0 \pm 1.2$ | $69.5 \pm 1.2$ |
| | $\sigma_8$ | $0.825 \pm 0.017$ | $0.825 \pm 0.017$ | $0.825 \pm 0.017$ | $0.825 \pm 0.017$ | $0.825 \pm 0.017$ |

Cosmo results in detail:

i) Measurement of growth at z = (0.22, 0.41, 0.60, 0.78)

ii) $\Omega_m = 0.280 \pm 0.016$

iii) $\sigma_8 = 0.825 \pm 0.017$

iv) $\sum m_\nu = 0.58$ eV

v) $r < 0{,}18$

DES - Dark energy survey (2012 - ?)

Instruments and components:

i) Visible and infrared 4m telescope at Cerro Tololo in Chile

ii) 2.2 degree field of view

iii) 5 photometric bands $(g, r, i, z, Y)$

Objectives:

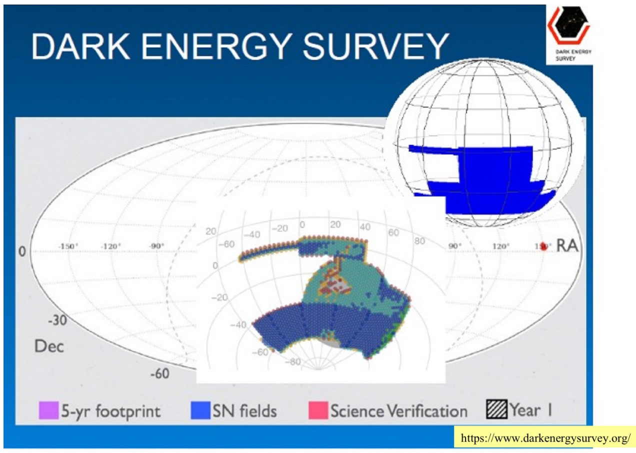
i) Obtain spectra Sn Ia $(\sim 10\,000)$

ii) Find galaxy clusters

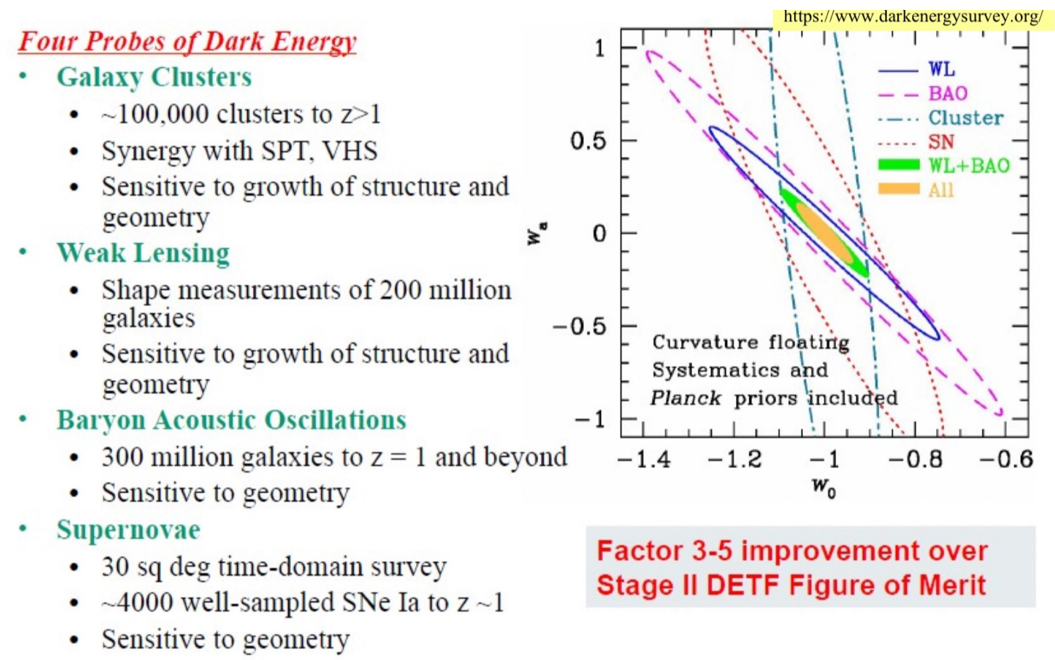
iii) Sample $300 \times 10^6$ galaxies for BAO

iv) Weak lensing constrains

v) Find deviations from GR




"weird" shape to overlap with other surveys.

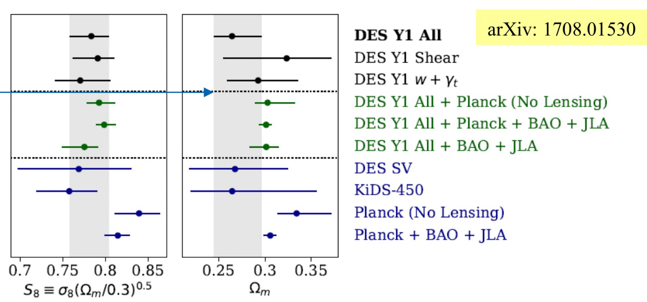



DES resolved tensions between low-z probes and Planck.

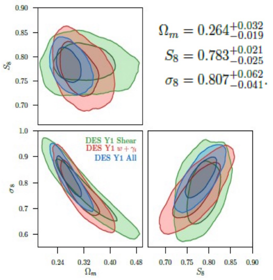
1. Planck vs. Local Hubble measurements

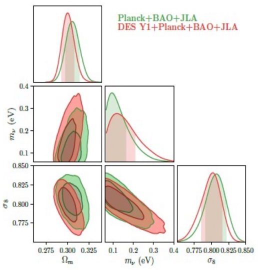
2. Planck vs. Local constraints on $\sigma_8$ (important parameter for LSS)

DES results lie in the middle

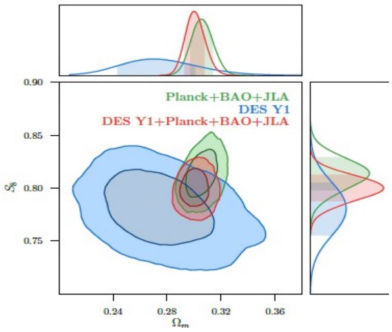


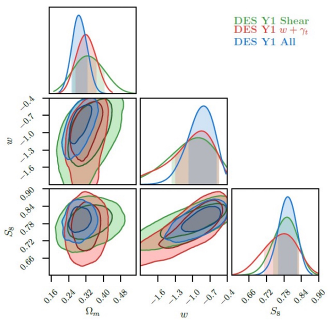
And obtained improved constraints on ΛCDM and neutrinos.




Joint DES-Planck results are astounding.
DES gave constraints on wCDM as well.




## Euclid survey by ESA (2020?)

**Characteristics:**

i) Satellite at L2 Sun-Earth position
ii) 1.2 m telescope by Airbus
iii) Wide survey : 15000 sq degrees
iv) Deep survey : 40 sq degrees
v) Wavelengths : 550 - 2000 nm
vi) Shapes of $1.5\times10^9$ galaxies
vii) Redshifts of $5\times10^7$ galaxies
viii) Cost : 1.25 billion €

**Objectives:**

i) Weak lensing
ii) Determining the BAO
iii) Galaxy clustering
iv) Goal: constrain deviations of GR

**General expectations on parameters:**

related to inflation

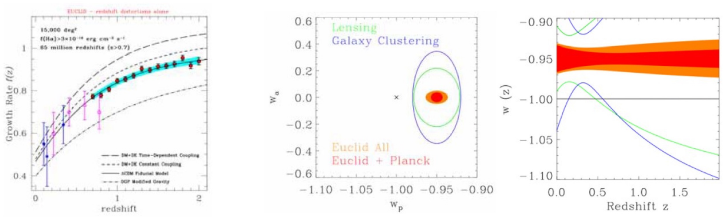
| | Modified Gravity | Dark Matter | Initial Conditions | Dark Energy | | |
|---|---|---|---|---|---|---|
| **Parameter** | $\gamma$ | $m_\nu/eV$ | $f_{NL}$ | $w_p$ | $w_a$ | FoM |
| Euclid Primary | 0.010 | 0.027 | 5.5 | 0.015 | 0.150 | 430 |
| Euclid All | 0.009 | 0.020 | 2.0 | 0.013 | 0.048 | 1540 |
| Euclid+Planck | 0.007 | 0.019 | 2.0 | 0.007 | 0.035 | 4020 |
| Current | 0.200 | 0.580 | 100 | 0.100 | 1.500 | ~10 |
| **Improvement Factor** | **30** | **30** | **50** | **>10** | **>50** | **>300** |

$$f = \frac{d\ln\delta}{d\ln a} = \Omega_m(z)^{\gamma} \qquad \gamma \approx \frac{6}{11}$$

(Improvements)

(ΛCDM)

**Expectations on growth and equation of state $\omega$**

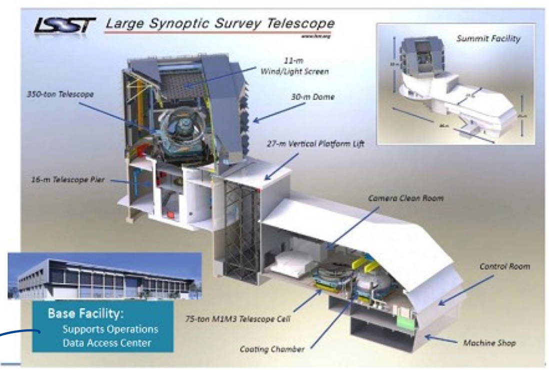



## LSST: The Large Synoptic Telescope (2020??)

Now the Vera Rubin observatory

**Instruments and components:**

i) Telescope at Cerro Pachon (Chile)
ii) 9.6 sq degrees field of view




Because of the amount of data

iii) 3.2 Gigapixels

Objectives:

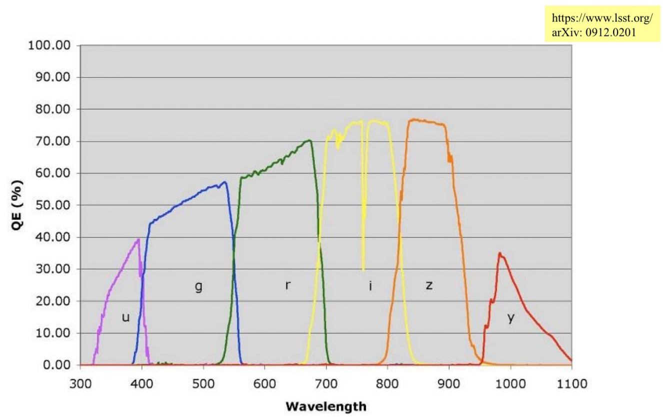
i) Supernovae, GRBs

ii) Asteroids, Comets and motion of stars

iii) Mapping the Milky Way (tidal strips and Galactic structure)

iv) DE and DM : lensing, DE properties $(w, \gamma)$, etc.

v) Overall, ~ 37 billion objects




↖ Photometric bands