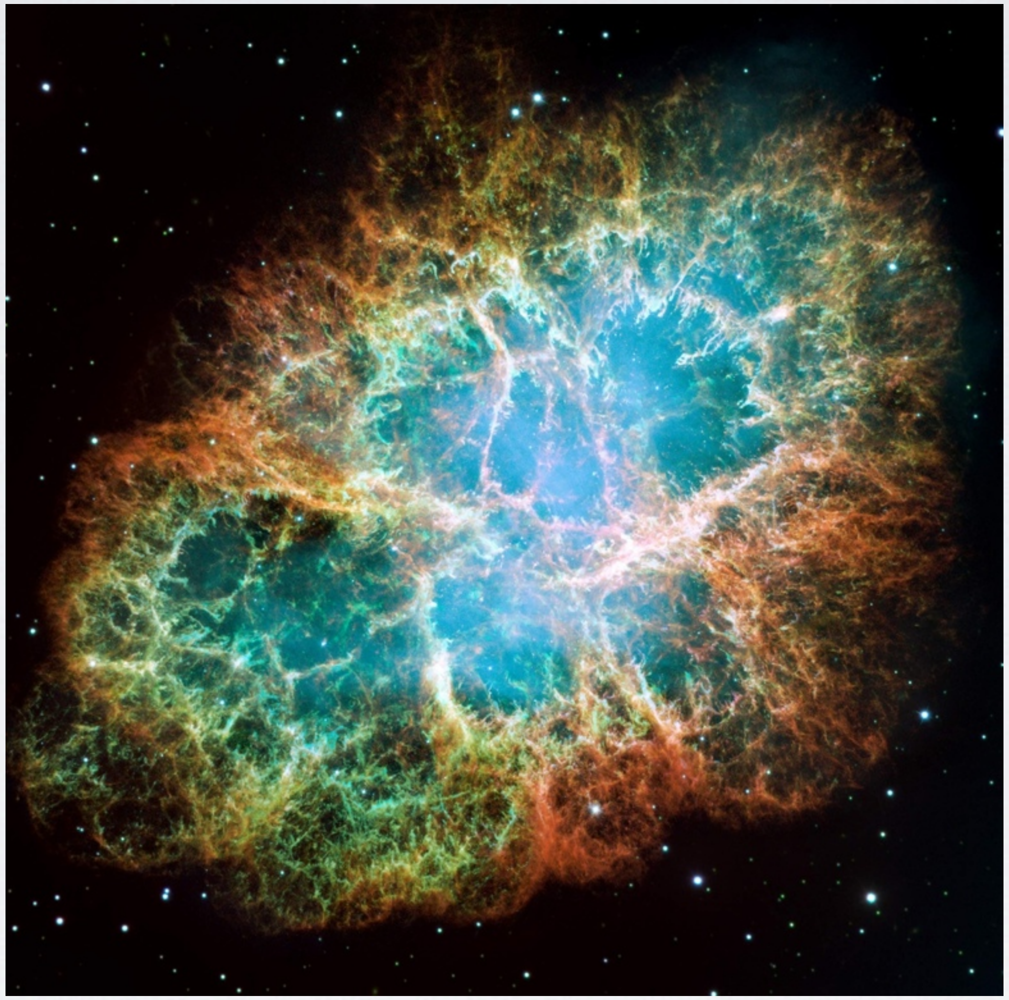
What do supernovae tell us about the accelerated expansion of the Universe?



remnant of a supernova, HST

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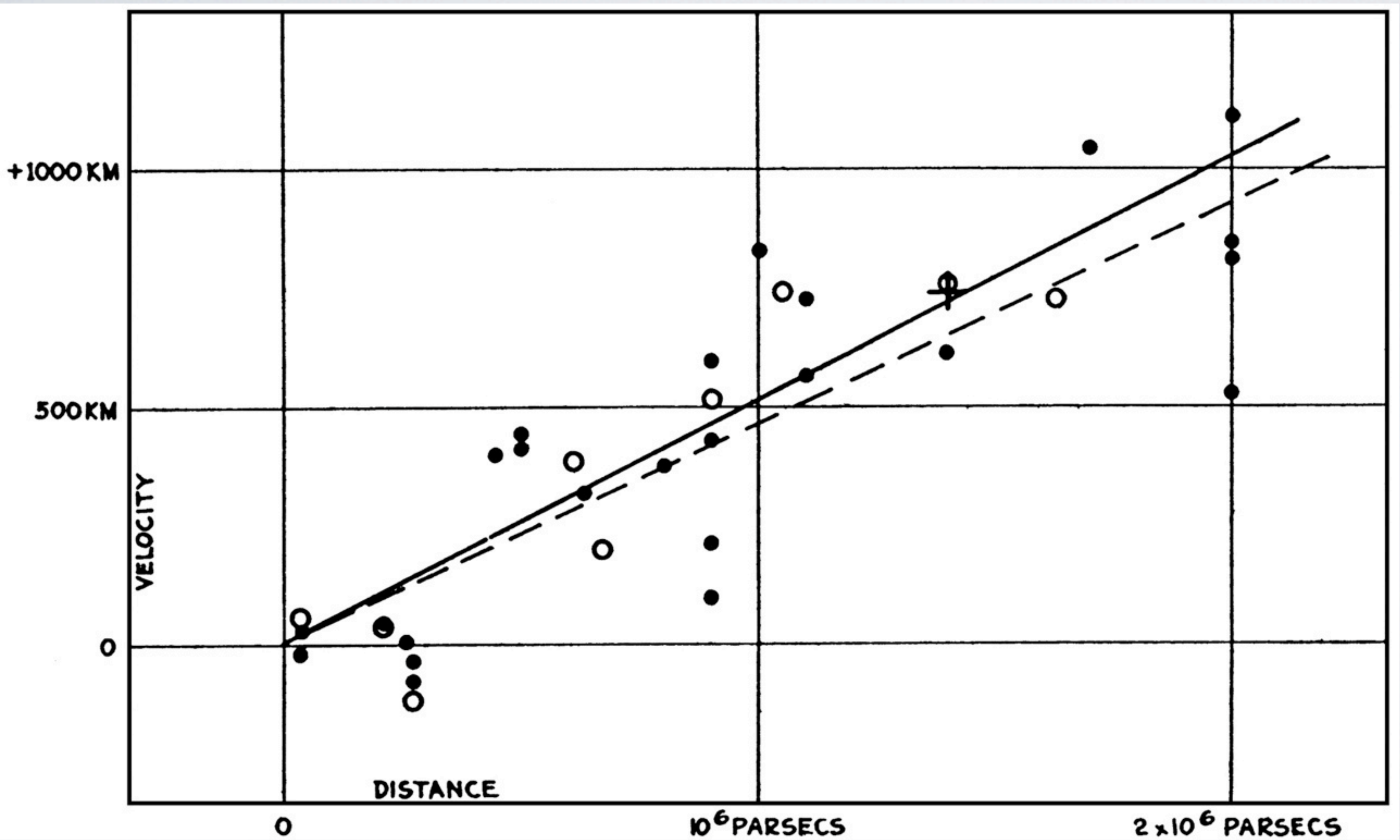
The universe is in expansion

In 1930, Hubble discovered that the Universe is expanding.



The galaxies that are further away are moving faster.

The Universe is **expanding**.

It is a solution of Einstein's equations.

Astrophysicists decided to measure the expansion rate **in the past**, in order to find the matter energy density.

Measuring distances

Velocities are easy to measure, using the **redshift**.

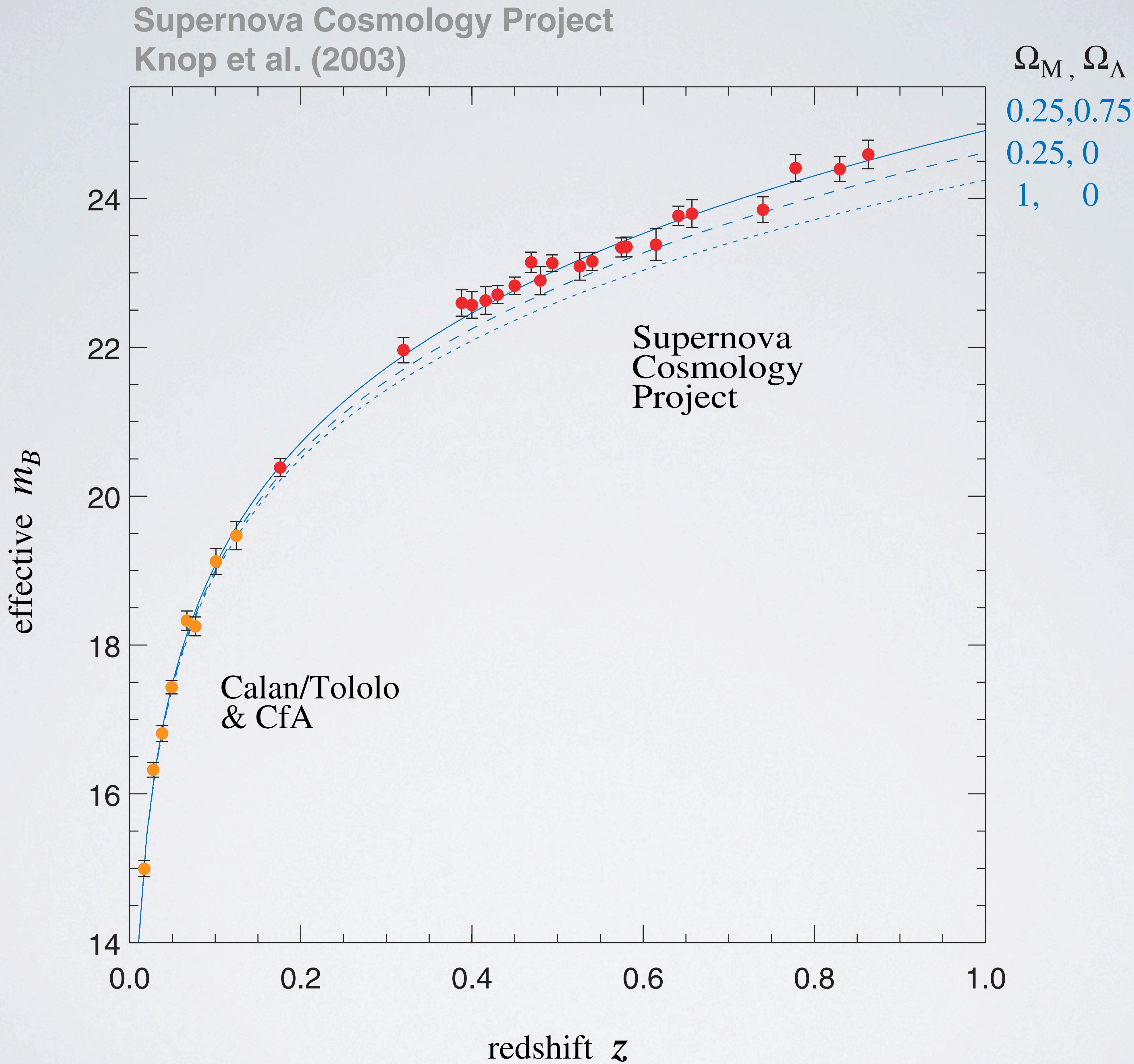
Distances are very difficult to measure.

If we know the luminosity, and measure the flux, we can infer the distance.

Supernovae are **standard candles**.

They are extremely bright.

supernova and galaxy, HST



The Universe expansion is accelerating.

The acceleration of the Universe

The acceleration is in **contradiction** with a Universe governed by General Relativity and the Standard Model.

There are two classes of solution → **Dark Energy**

→ **Modified gravity**

There exist a large number of models able to reproduce the acceleration. But none is completely convincing.

We need extra **observational information**.

The observations

We need an **accurate measurement** of the evolution of the acceleration of the Universe.

Nowadays, **400** SNe have been observed. In the future, JEDI, ALPACA, SNAP plan to observe **100'000** SNe.

This is not sufficient to find unambiguously the solution.

The **evolution of large-scale structures** can place stringent constraints.

General relativity predicts a link between the expansion rate and the growth rate of structure that is violated by modified theories of gravity.

Luminosity distance

Supernovae allow to measure the **background evolution** and the **growth rate** of structures.

$$\boxed{\textbf{Luminosity distance} \quad d_L = \sqrt{\frac{L}{4\pi F}}}$$

L Luminosity

F Flux

For nearby SNe: $H(z) = H_0 \qquad d_L = \frac{z}{H_0}$

For distant SNe: $d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$

This has been used in 1998 to show that the expansion of the Universe is accelerating.

This relation is valid in a **homogeneous** and **isotropic** Universe.

An inhomogeneous Universe

The **light** feels the **inhomogeneities** of the matter distribution when it travels from the supernova to the observer.

Density perturbations modify the distance between the supernova and the observer.

Usually these modifications are regarded as **noise** on the signal.

Our idea: use them as a **new signal** that contains information on the distribution of matter.

We can measure the evolution of **large-scale structures** with the luminosity distance.

Perturbations of the luminosity distance

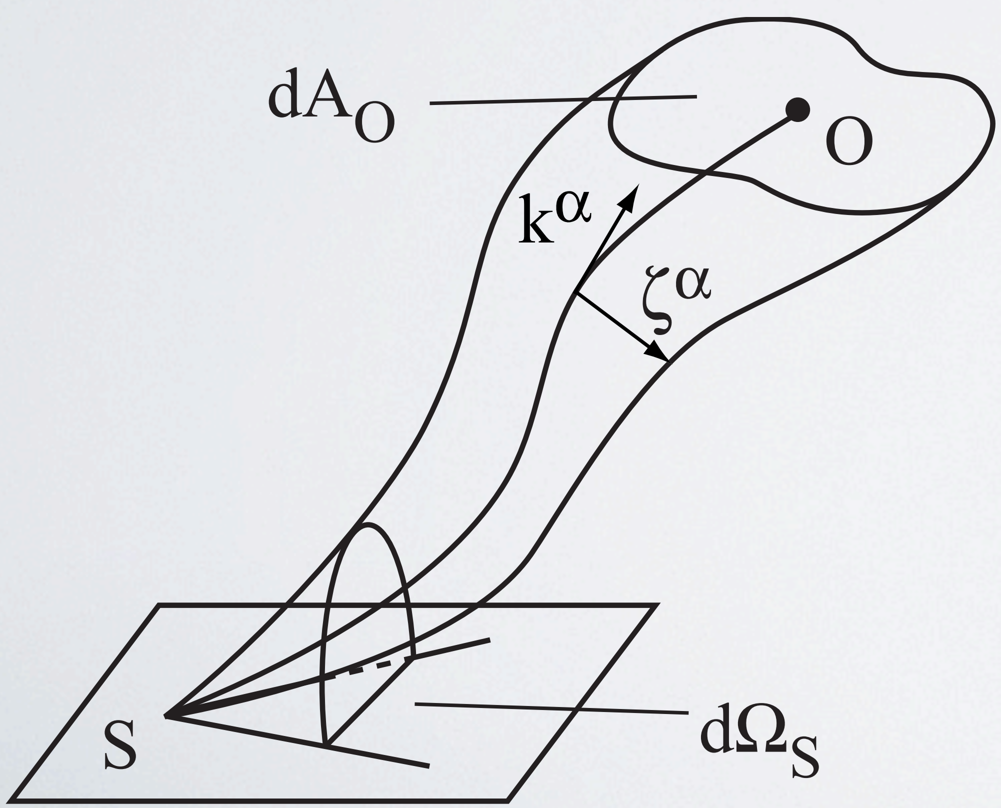
Bonvin, Durrer and Gasparini, PRD 2006

We need

A large number of SNe. JEDI, ALPACA, SNAP 100'000 SNe.

Theoretical predictions for d_L in a perturbed Universe.

Propagation of light in an inhomogeneous Universe.



$$d_L(z) = (1+z)\sqrt{\frac{dA_O}{d\Omega_S}}$$

$$\frac{dk^\alpha}{d\lambda} = -\Gamma^\alpha_{\mu\nu} k^\mu k^\nu$$

$$\frac{D^2\xi^\alpha(\lambda)}{D\lambda^2} = R^\alpha_{\ \beta\mu\nu} k^\beta k^\mu \xi^\nu$$

Sachs 1961

The result

$$d_L(z_S,\mathbf{n}) = (1+z_S)(\eta_O-\eta_S)\cdot$$

$$\Bigg\{1-\frac{1}{(\eta_O-\eta_S)\mathcal{H}_S}\mathbf{v}_O\cdot\mathbf{n}-\left(1-\frac{1}{(\eta_O-\eta_S)\mathcal{H}_S}\right)\mathbf{v}_S\cdot\mathbf{n}$$

$$-\left(2-\frac{1}{(\eta_O-\eta_S)\mathcal{H}_S}\right)\Psi_S+\left(1-\frac{1}{(\eta_O-\eta_S)\mathcal{H}_S}\right)\Psi_O$$

$$+\frac{2}{(\eta_O-\eta_S)}\int_{\eta_S}^{\eta_O}d\eta\,\Psi+\frac{2}{(\eta_O-\eta_S)\mathcal{H}_S}\int_{\eta_S}^{\eta_O}d\eta\,\dot{\Psi}$$

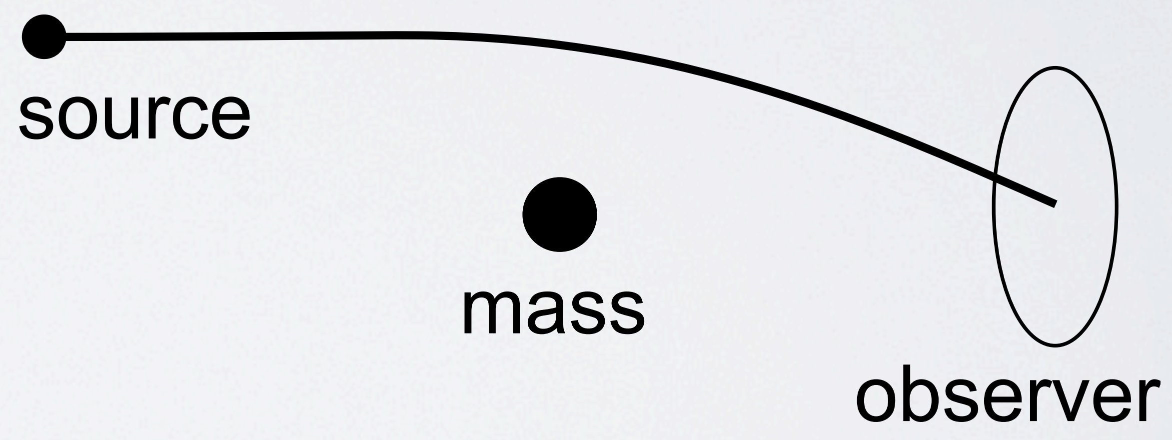
$$-2\int_{\eta_S}^{\eta_O}d\eta\,\frac{(\eta-\eta_S)}{(\eta_O-\eta_S)}\dot{\Psi}+\int_{\eta_S}^{\eta_O}d\eta\,\frac{(\eta-\eta_S)(\eta_O-\eta)}{(\eta_O-\eta_S)}\ddot{\Psi}$$

$$-\int_{\eta_S}^{\eta_O}d\eta\,\frac{(\eta-\eta_S)(\eta_O-\eta)}{(\eta_O-\eta_S)}\nabla^2\Psi\Bigg\}$$

Various contributions

Ψ is the **gravitational potential**; it describes the geometry.

- Local terms: $\Psi_O \;\; \Psi_S$
- Integrated terms along the trajectory: $\Psi \;\; \dot{\Psi} \;\; \ddot{\Psi}$
- Lensing term: $\nabla^2\Psi$



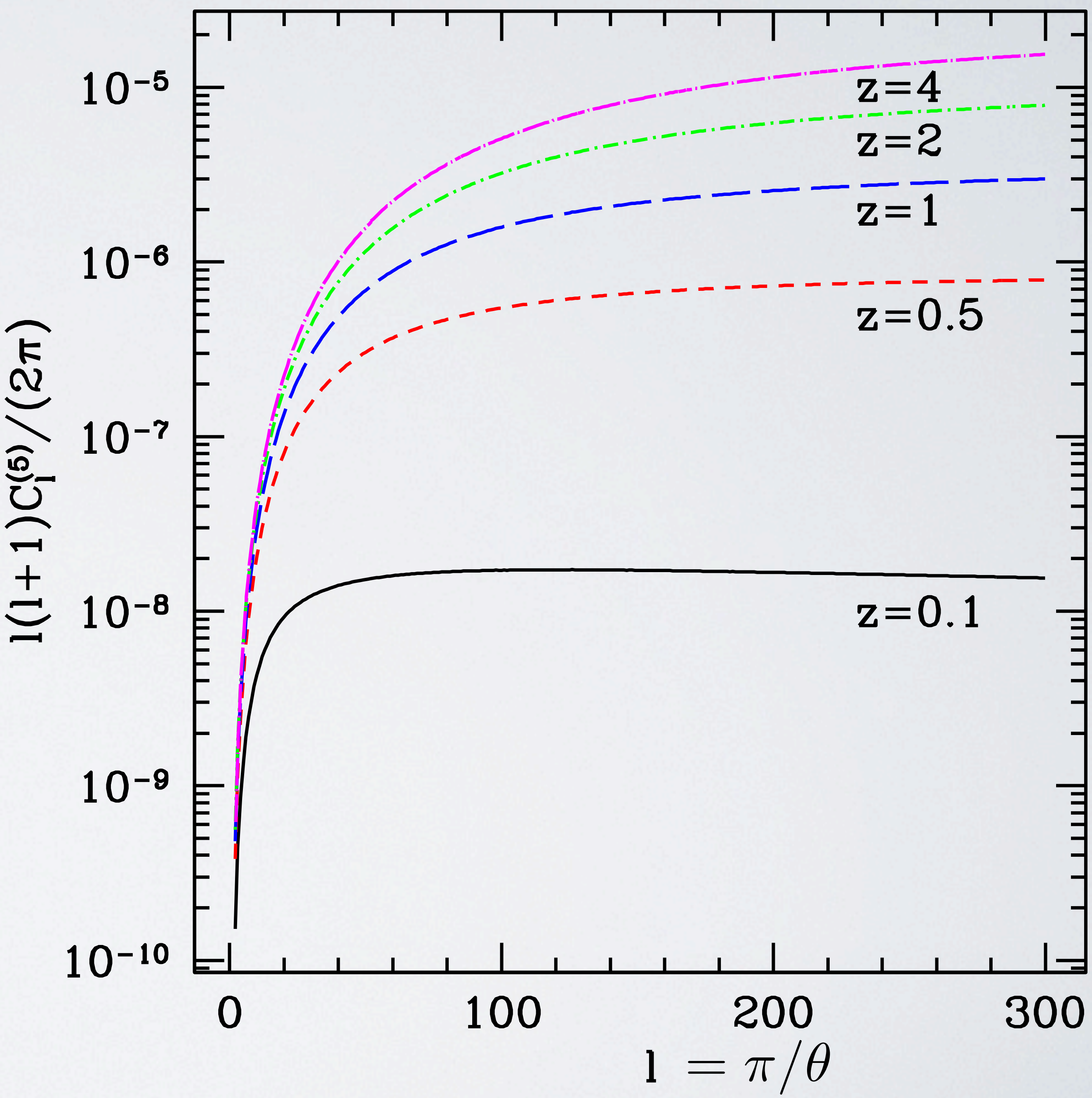
- Doppler terms: $\mathbf{v}_O \;\; \mathbf{v}_S$

The lensing term

$$d_L^{\text{lens}}(z,\mathbf{n}) = \int_{\eta_O}^{\eta_S} d\eta\, \frac{(\eta-\eta_S)(\eta_O-\eta)}{\eta_O-\eta_S}\nabla^2\Psi$$

Correlations $\langle d_L(z,\mathbf{n})d_L(z,\mathbf{n}')\rangle$

- Effect increases with z
- At large z, almost one percent $\gg \Psi \sim 10^{-5}$



It will be **observed** in the future and used to **reconstruct** $\Psi(z)$

The dipole

Bonvin, Durrer and Kunz, PRL 2006

The observer velocity generates a dipole in d_L

Amplitude: $$d_L^{\text{dipole}}(z) = \frac{(1+z)^2 \cdot v_O}{H(z)}$$

Monopole: $$d_L(z) = (1+z)\int_0^z \frac{dz'}{H(z')}$$

The dipole is much more sensitive to **local variation** of the expansion rate than the monopole.

Large amplitude 10% at $z = 0.1$ and 1% at $z = 0.4$

We have seen the dipole in a set of 44 SNe (SNLS sample)

In the future we will **measure** $H(z)$

Conclusion

We studied the effect of **inhomogeneities** on the **luminosity** distance of supernovae.

- The **lensing** contribution will allow to measure **growth rate** of structures.
- The **dipole** contribution will allow to measure the **expansion rate** more precisely.

The perturbations of d_L are extremely powerful to **discriminate** between dark energy and modified gravity.

In 1998, supernovae have revealed the problem of acceleration. In the future, they will help us to solve it.