Why is the Universe accelerating?

Observational constraints

instituto de astrofísica
e ciências do espaço

Summer program

Supernovae

Hubble parameter for a flat ΛCDM neglecting the radiation (good for late times):

$$H^2(z) = \Omega_m(1+z)^3 + 1 - \Omega_m$$

We normally use:

$$E^2(z) = \frac{H(z)}{H_0}$$

The luminosity distance in Mpc is:

$$d_L = \frac{c}{H_0}\,(1+z)\int_0^z \frac{dz'}{E(z')} = \frac{c}{H_0}\,\hat{d}_L$$

with

$$\frac{c}{H_0} \simeq 3000\,h^{-1}\,\mathrm{Mpc} \quad \text{and} \quad h \simeq 0.7$$

Supernovae

Supernovae data:

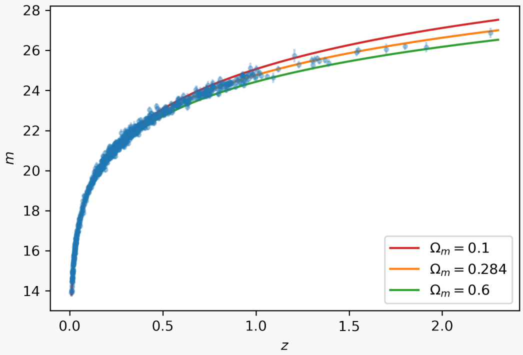
```
#name zcmb zhel dz mb dmb
03D1au 0.50309 0.50309 0.0 22.93445 0.12605
03D1ax 0.4948 0.4948 0.0 22.8802 0.11765
03D1co 0.67767 0.67767 0.0 24.0377 0.2056
03D1ew 0.8665 0.8665 0.0 24.34685 0.17385
03D1fq 0.79857 0.79857 0.0 24.3605 0.17435
03D3ay 0.37144 0.37144 ......
```

distance modulus (or apparent magnitude):

$$m = M + 5\log_{10}(d_L/10\text{pc}) = M + 25 + 5\log_{10} d_L$$

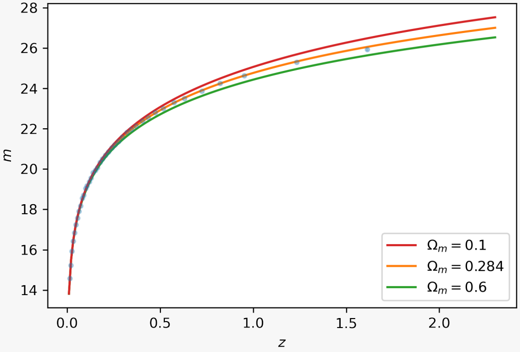
Supernovae

$$h = 0.7 \qquad M = -19.36$$



Supernovae

$$h = 0.7 \qquad M = -19.36$$



Supernovae

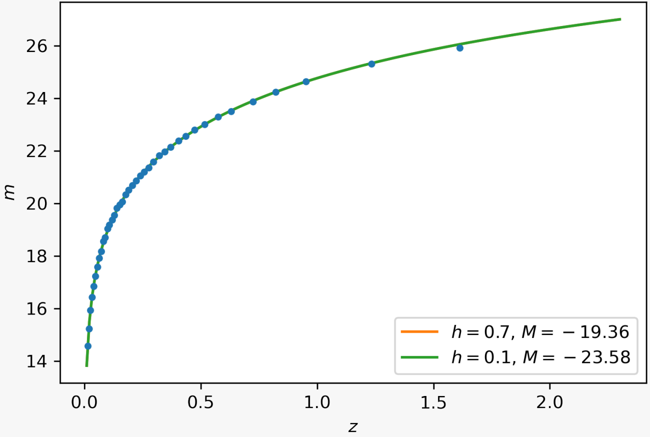
Likelihood $\mathcal{L} \propto e^{-\chi^2/2}$:

$$-2\ln\mathcal{L} = \underbrace{\sum_i \left(\frac{m_i - m_{\text{th}}}{\sigma_i}\right)^2}_{\chi^2} + \underbrace{\sum_i \left(\ln(2\pi\sigma_i^2)\right)}_{\text{constant (usually)}}$$

$$\begin{aligned} m_{\text{th}} &= M + 25 + 5\log_{10}(d_L) \\ &= \underbrace{M + 25 + 5\log_{10}(c/H_0)}_{=\mathcal{M}=?} + 5\log_{10}\hat{d}_L \end{aligned}$$

Supernovae

$$\Omega_{\mathrm{m}} = 0.284$$



Supernovae

$$\mathcal{M} = M + 25 + 5\log_{10}(c/H_0)$$

$$m_i - m_{\rm th} = \underbrace{m_i - 5\log_{10}\hat{d}_L}_{=\Delta_i} - \mathcal{M}$$

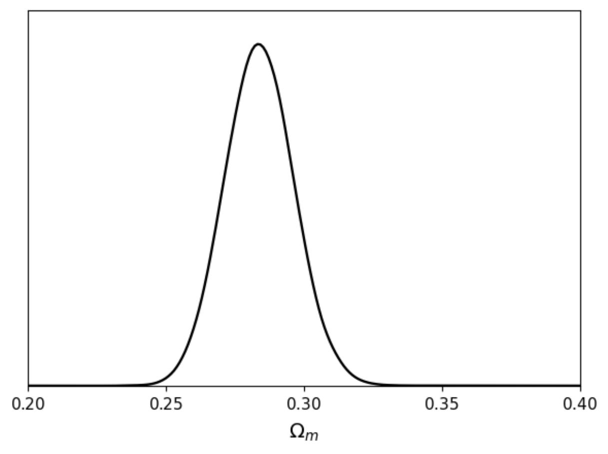
$$A = \sum_i \frac{\Delta_i^2}{\sigma_i^2} \qquad B = \sum_i \frac{\Delta_i}{\sigma_i^2} \qquad C = \sum_i \frac{1}{\sigma_i^2}$$

and the chi-square to use is:

$$-2\ln\mathcal{L} = A - \frac{B^2}{C}$$

Supernovae

$\Omega_m = 0.285 \pm 0.013$

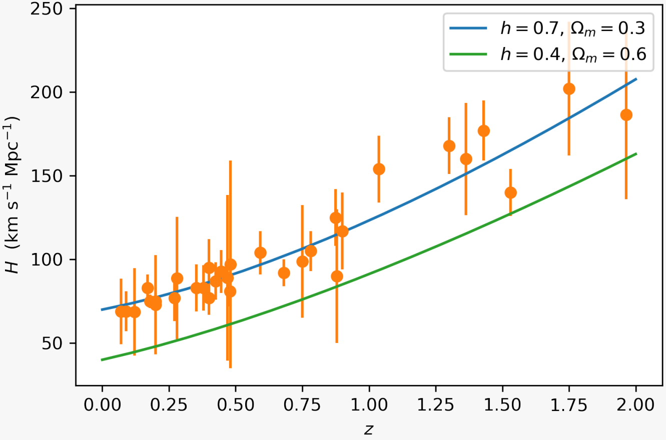


Cosmic chronometers

Cosmic chronometers data:

```
# z H(z) σH(z)
0.07 69 19.6
0.09 69 12
0.12 68.6 26.2
0.17 83 8
0.179 75 4
0.199 75 5
0.2 72.9 29.6
0.27 ......
```

Cosmic chronometers

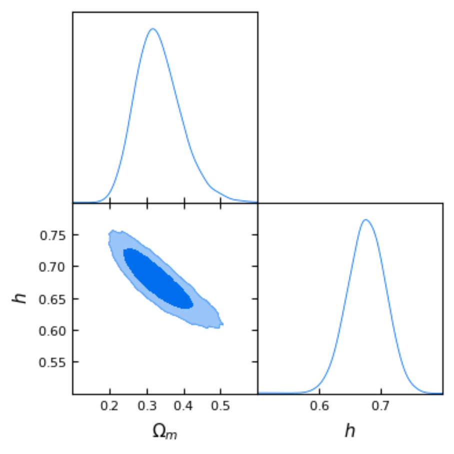


Cosmic chronometers

log-likelihood:

$$-2\ln\mathcal{L} = \underbrace{\sum_i \left(\frac{H_i - H_{\mathrm{th}}}{\sigma_i}\right)^2}_{\chi^2} + \underbrace{\sum_i \left(\ln(2\pi\sigma_i^2)\right)}_{\text{constant (usually)}}$$

Cosmic chronometers



$$\Omega_m = 0.33^{+0.05}_{-0.07}$$

$$h = 0.68 \pm 0.03$$

Baryon Acoustic Oscillations

Baryons decouple from radiation at the drag epoch: z_d

“standard ruler”: sound horizon at the drag epoch $r_d \approx 150\mathrm{Mpc}$

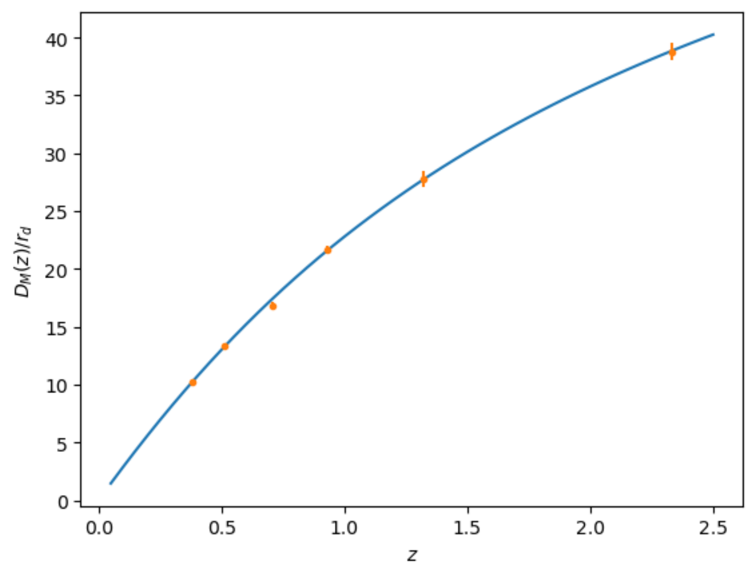
Comoving distance: $D_M(z) = \dfrac{c}{H_0} \displaystyle\int_0^z \dfrac{dz'}{E(z)}$

Hubble distance: $D_H(z) = \dfrac{c}{H_0 E(z)}$

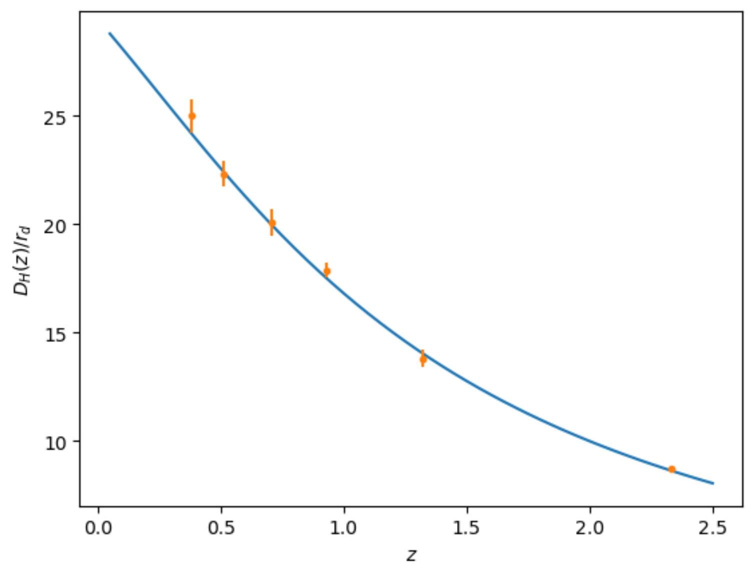
Effective “dilation scale” distance: $D_V(z) = \left[z D_M^2(z) D_H(z) \right]^{1/3}$

BAO constrains D_M/r_d, D_H/r_d or D_V/r_d.

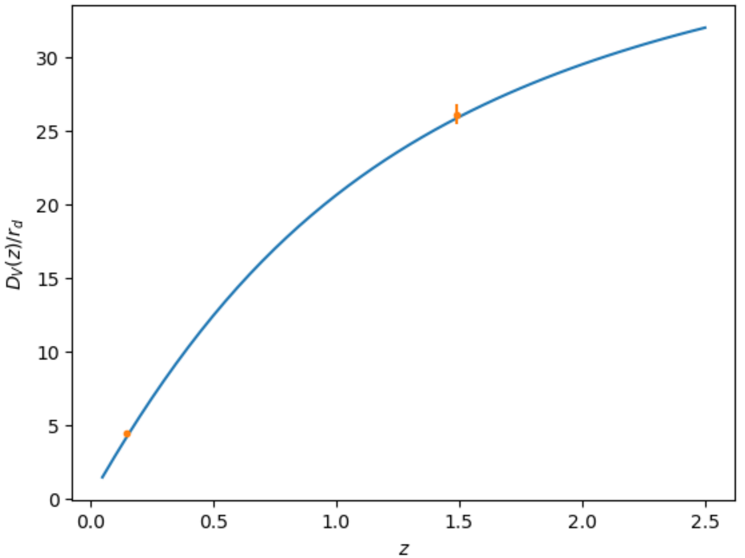
Baryon Acoustic Oscillations



Baryon Acoustic Oscillations



Baryon Acoustic Oscillations

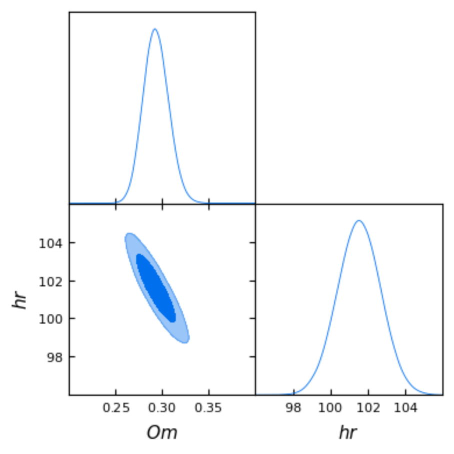


Baryon Acoustic Oscillations

(ignoring correlations)

$$-2\ln\mathcal{L} = \sum_i \left(\frac{D_{Mi} - D_{M\mathrm{th}}}{\sigma_{Mi}}\right)^2 + \sum_i \left(\frac{D_{Hi} - D_{H\mathrm{th}}}{\sigma_{Hi}}\right)^2 + \sum_i \left(\frac{D_{Vi} - D_{V\mathrm{th}}}{\sigma_{Vi}}\right)^2$$

Baryon Acoustic Oscillations



$$\Omega_m = 0.294^{+0.013}_{-0.015}$$

$$h\, r_d = 101.5 \pm 1.30$$