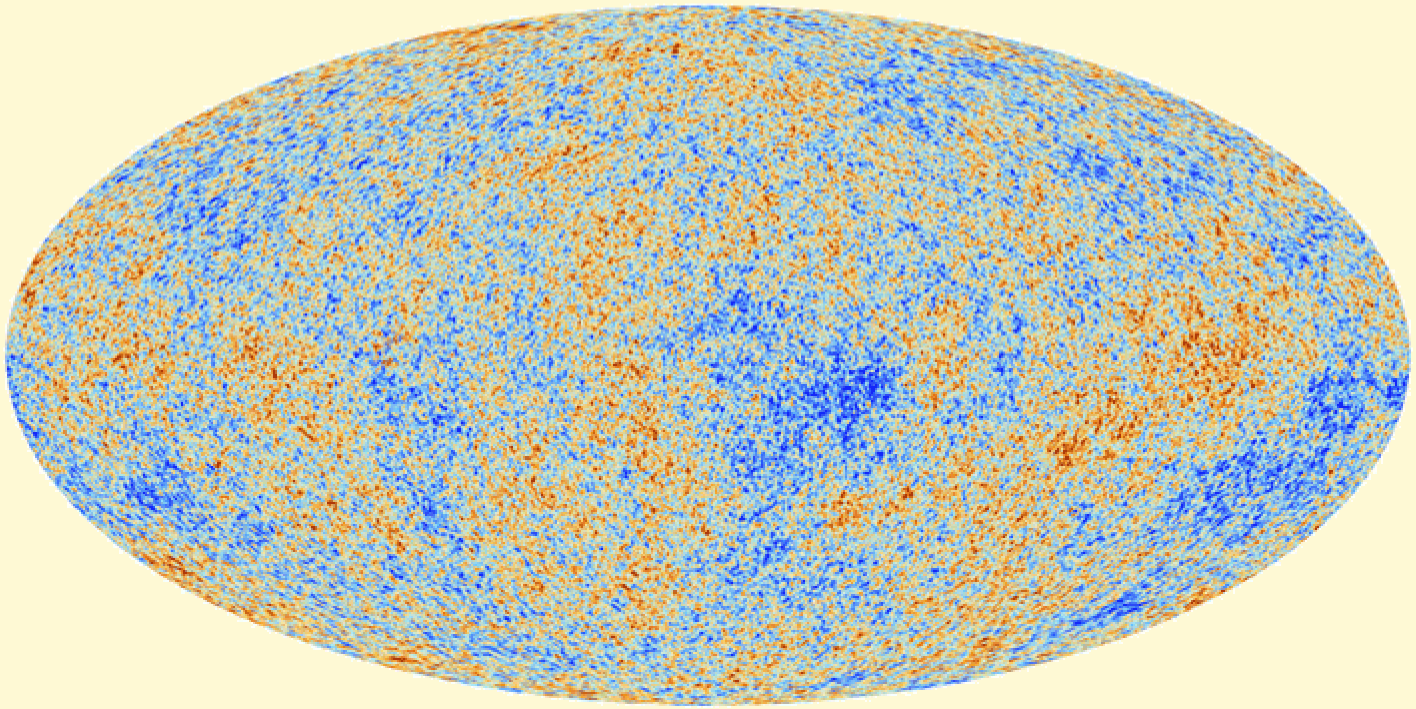
Het vroege en late heelal

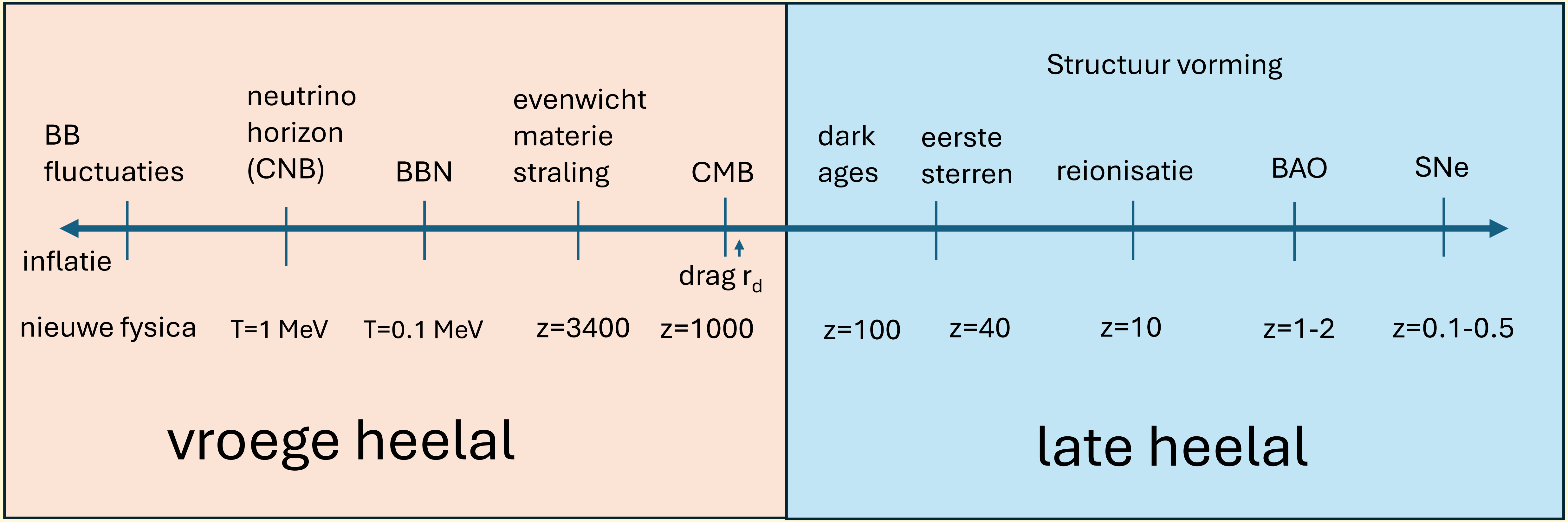
It’s all about energy densities

Processen in het vroege heelal laten hun sporen na in het late heelal



De ‘baby foto’ van het heelal – temperatuur uit de microgolf achtergrond straling door de Planck satelliet

Tijdlijn evolutie (definitie vroeg/laat)



Verhaal van de materie (en in het begin ook van de straling)

Energiedichtheden

Fysisch meten we ρ_i of $\Omega_i h^2$

maar voor de **evolutie** willen we Ω_i

De **Hubble constante** verbindt beide

relativistisch	Niet relativistisch
fotonen	baryonen
neutrino's	(koude) donkere materie

$\Omega_{rel} = \Omega_\gamma + \Omega_\nu$

$\Omega_m = \Omega_b + \Omega_c$

$(\Omega_m = \Omega_{bar} + \Omega_{cdm})$

ρ_i fysische energiedichtheid

Ω_i relatieve energiedichtheid

$$\Omega_i = \frac{\rho_i(t)}{\rho_c} = \frac{8\pi G \rho_i(t)}{3H_0^2}$$

$$\Omega_i h^2 = \frac{8\pi G \rho_i(t)}{30000}$$

$$h = \frac{H_0}{100}$$

We kennen vaak de fysische energie dichtheden, maar niet de relatieve omdat we H_0 niet goed kennen

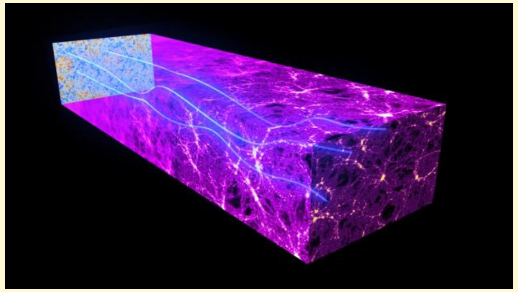
$$H(z) = H_0 E(z)$$

$$E(z) = \sqrt{\Omega_{rel,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}$$

In het vroege heelal vnl. Ω_{rel} en Ω_m

In het late heelal vnl. Ω_m en Ω_Λ

Isotroop en homogeen & **vlak** heelal (gemiddeld geen kromming)



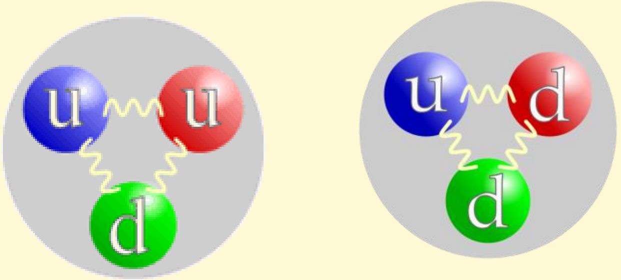
$\Omega_{rel} + \Omega_m + \Omega_\Lambda = 1$

Roodverschuiving: $z = \frac{\lambda_0}{\lambda(t)} - 1$

$\Omega_{rad} = \Omega_{rel}$ (radiation (straling) versus relativistisch, hier $\Omega_{rad} = \Omega_\gamma$)

Gewone materie: baryonen, dwz protonen en neutronen (samenstelsel van 3 quarks):

- Hoeveel is er?
- Waar komen vandaan?
- Wat maken ze mee?



proton
stabiel

neutron
15 min

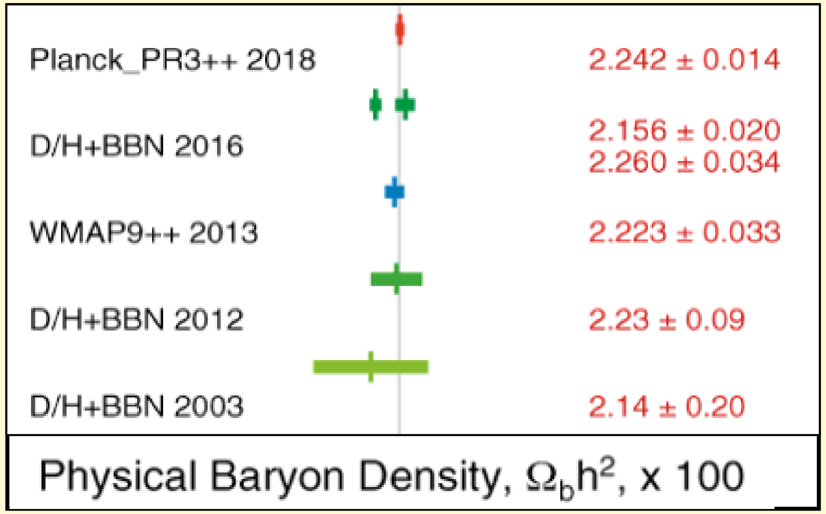
relative baryon density

$$\Omega_b = \frac{\rho_b(t)}{\rho_c} = \frac{8\pi G \rho_b(t)}{3H_0^2}$$

physical baryon density

$$\Omega_b h^2 = \frac{8\pi G \rho_b(t)}{30000}$$

- Hoe weten we hoeveel er is?
  - BBN theorie
  - D/H meting oerwolken rond quasars
  - CMB theorie



$$m_p c^2 = 938 \text{ MeV rust massa proton}$$

$$n_b \propto \frac{\Omega_{b,0} h^2}{m_p c^2} \approx 2.3\ 10^{-7} cm^{-3}$$

LAMBDA - Baryonic Density

Bartelmann-7.pdf

Fotonen

relative photon density

$$\Omega_{\gamma,0} = \frac{\rho_\gamma(t_0)}{\rho_c} = \frac{8\pi G \rho_\gamma({}_0t)}{3H_0^2}$$

physical photon density

$$\Omega_{\gamma,0}h^2 = \frac{8\pi G \rho_\gamma({}_0t)}{30000}$$

$\rho_\gamma \sim T_\gamma^4$ $\qquad \rho_\gamma \sim n_\gamma T_\gamma$ $\qquad T_\gamma \sim (z+1)$

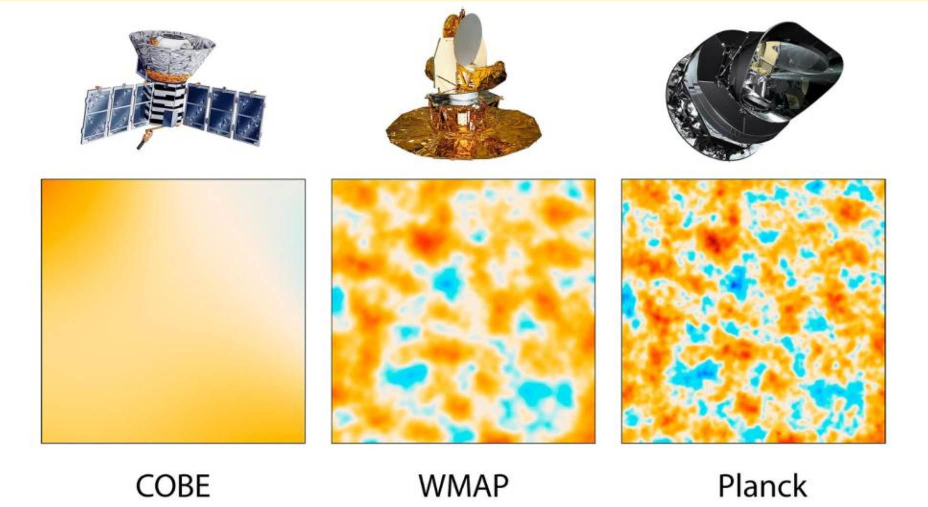
Stefan-Boltzmann

$n_\gamma \sim T_\gamma^3$ $\qquad n_\gamma = 410\ \mathrm{cm}^{-3} \left(\frac{T_\gamma}{2.725\mathrm{K}}\right)^3$

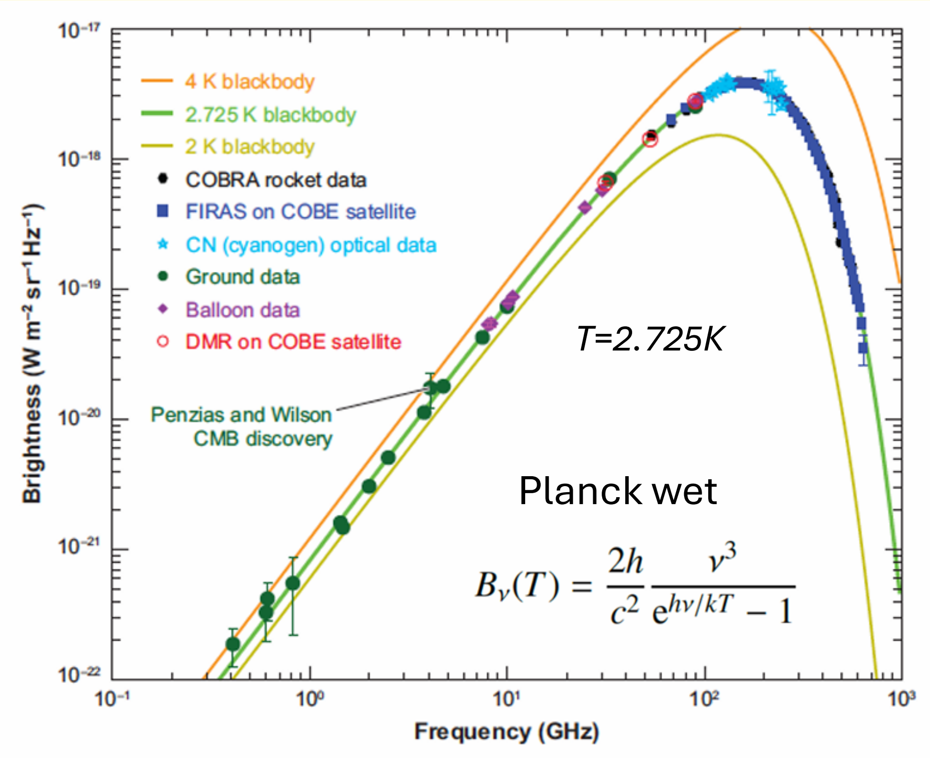
Waar komen de fotonen van de achtergrond straling vandaan?

Radiation Energy Density

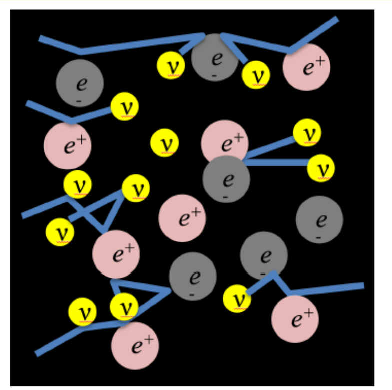
The Cosmic Microwave Background Radiation - E. Gawiser & J. Silk



Wat meet COBE?



Zwakke interactie ontkoppeling & CNB

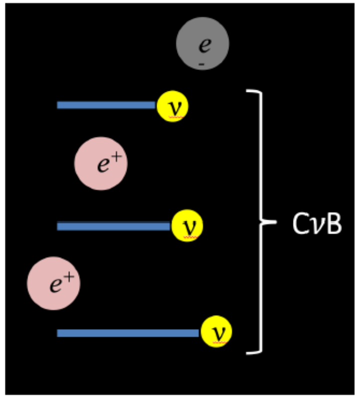


Voor ontkoppeling evenwicht:

$$p + e^- \longleftrightarrow n + \nu_e, \quad n + e^+ \longleftrightarrow p + \bar{\nu}_e, \quad n \longleftrightarrow p + e^- + \bar{\nu}_e$$

Na ontkoppeling alleen:

$$n \longrightarrow p + e^- + \bar{\nu}_e$$



Neutrinos "free-stream" to infinity.

Gevolgen ontkoppeling:

Neutrino's ontkoppeld → CνB
(cosmic neutrino background)

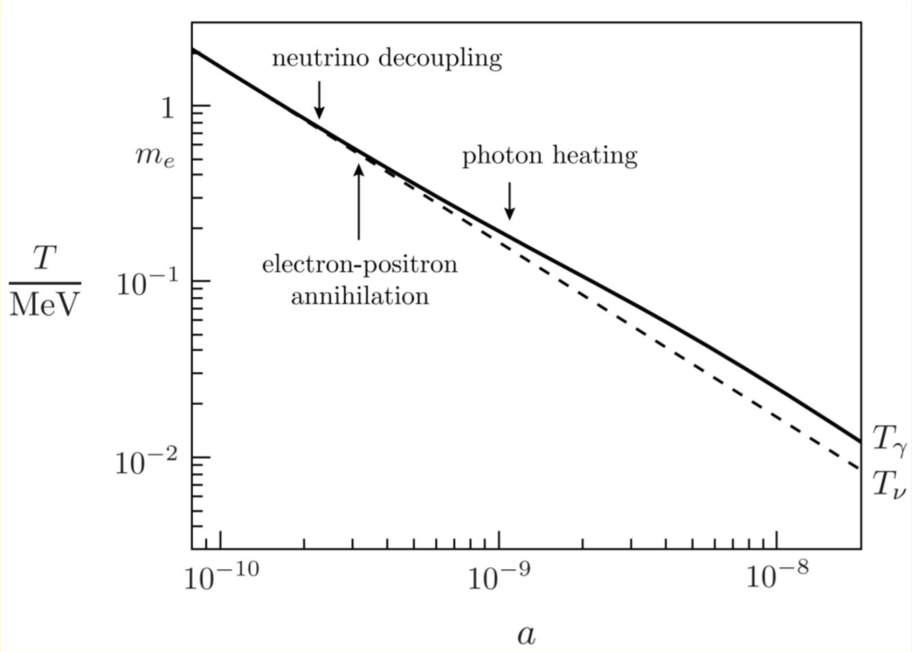
Vaste neutron/proton verhouding

$$\left(\frac{n}{p}\right)_{eq} \propto exp\left(-\frac{\Delta mc^2}{kT}\right) \approx \frac{1}{6} \rightarrow \frac{1}{7}$$

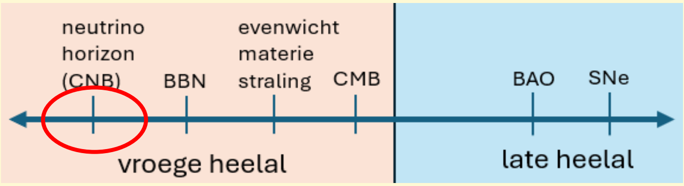
e^+, e^- annihilatie bij kT~0.8 MeV
→ boost foton temperatuur

$$T_\nu = T_\gamma \longrightarrow T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma$$

$$\rho_\nu = N_{eff}\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}}\rho_\gamma \qquad N_{eff}\sim 3$$



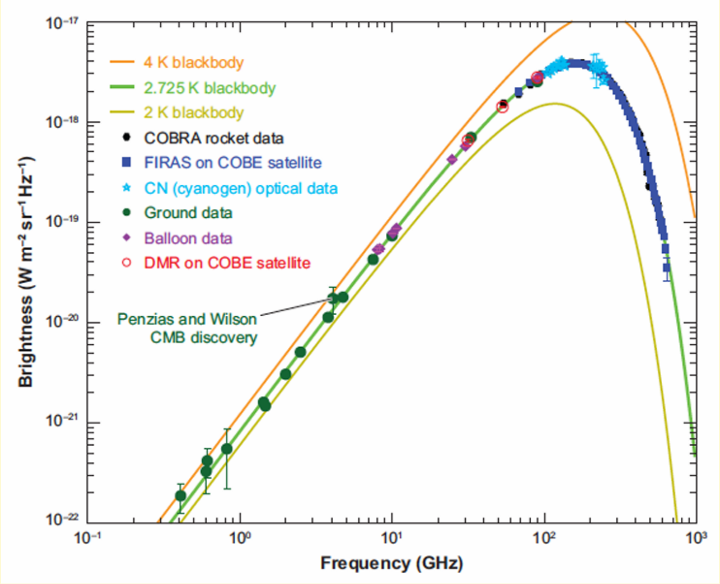
Relativistisch heelal	Ontkoppeling bij
$T(t) \sim 10^{10}$ K $(t/1sec)^{-1/2}$	t ~1sec
$kT(t) \sim 1$ MeV $(t/1sec)^{-1/2}$	kT ~ 1 MeV

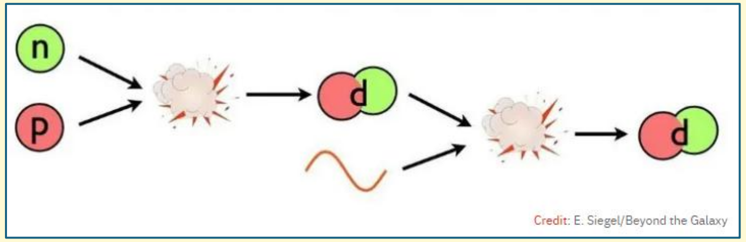


BBN - Deuterium bottleneck

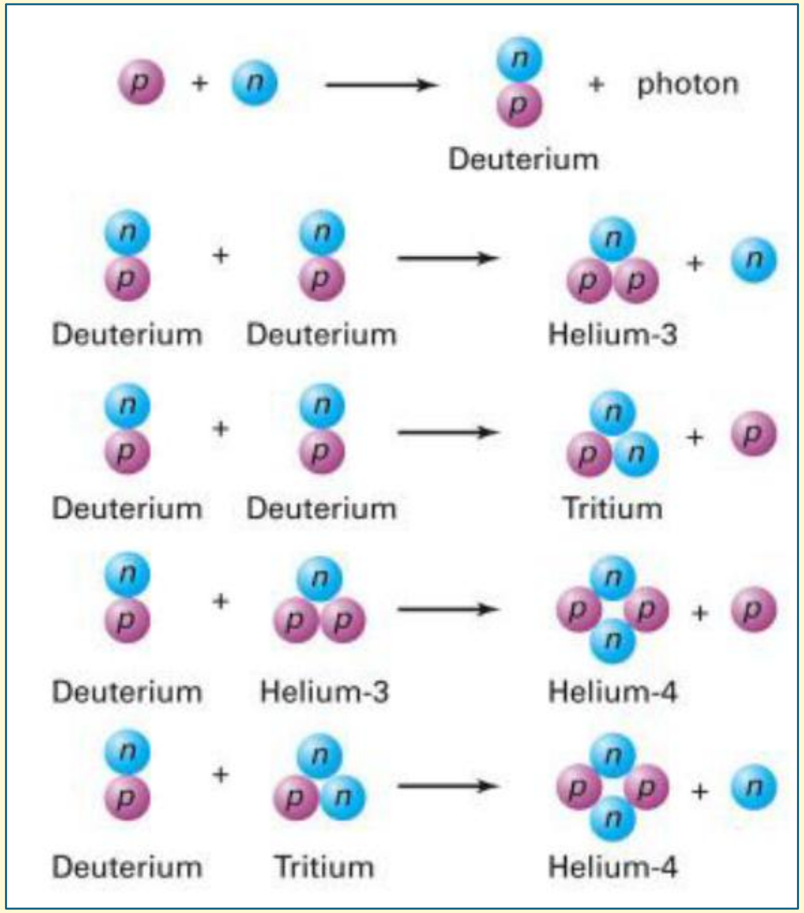
$\Delta_D = 2.23\ \mathrm{MeV}$ bindings energie deuterium

$\eta = \frac{n_b}{n_\gamma} = 6.1\ 10^{-10}$ aantal baryonen t.o.v. fotonen





hoge energie staart



Bij T~0.1 MeV $\eta^{-1}\exp\left(-\frac{\Delta_D}{kT}\right) < 1$

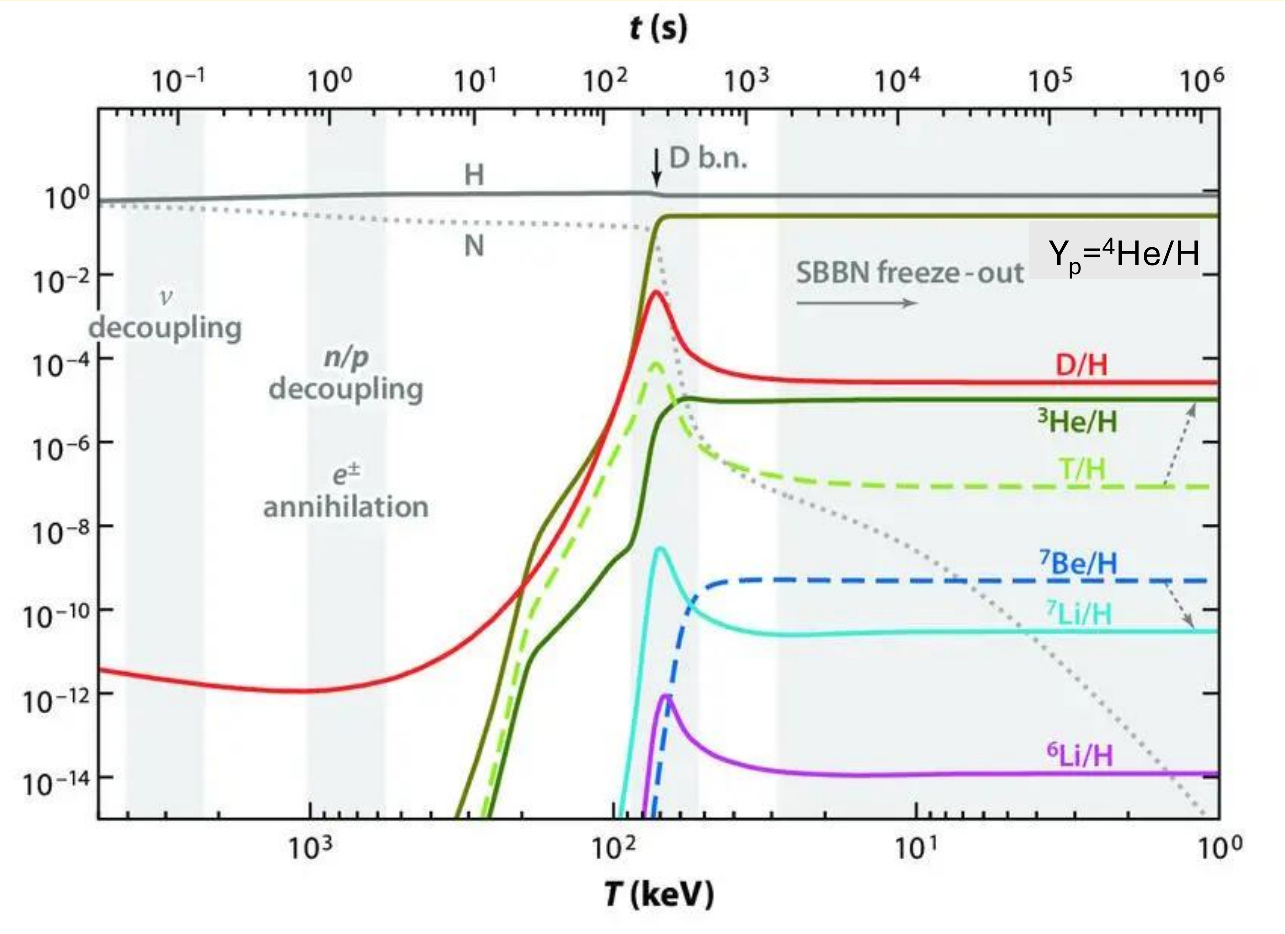
kT(t) ~ 1 MeV $(t/1\mathrm{sec})^{-1/2}$ → t~100sec

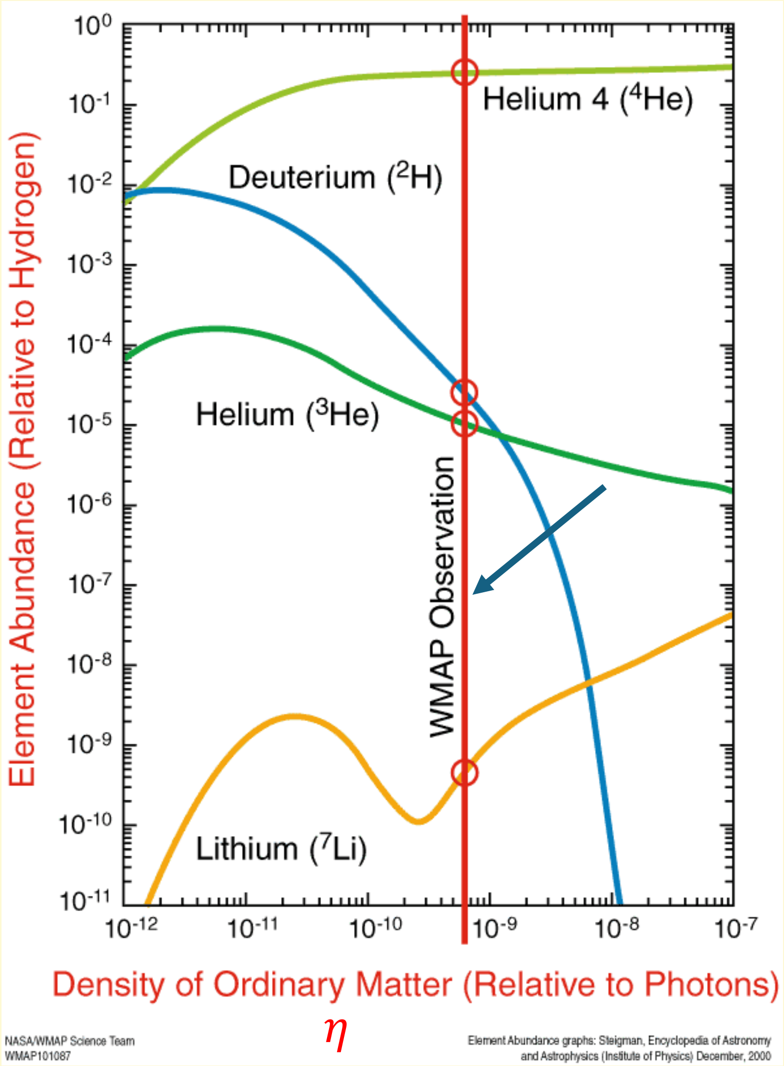
Na deuterium gaat vervolg snel en worden meeste neutronen weggevangen

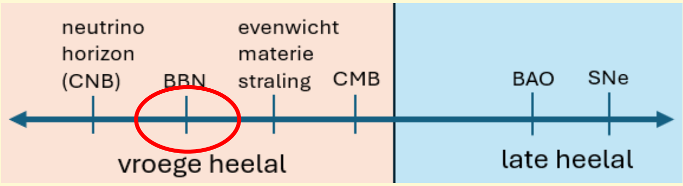
nuclear physics - Why is the deuterium bottleneck temperature 0.1 MeV? - Physics Stack Exchange

BBN - Baryon afhankelijkheid

deuterium vorming is erg gevoelig voor η en dus ook voor $\frac{\Omega_{b,0}}{\Omega_{\gamma,0}}$

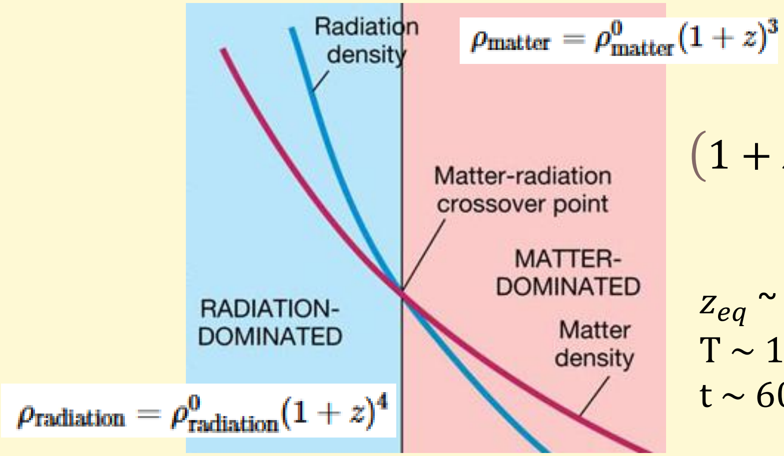






Uitdijing meten (m.b.v. de geluidshorizon)

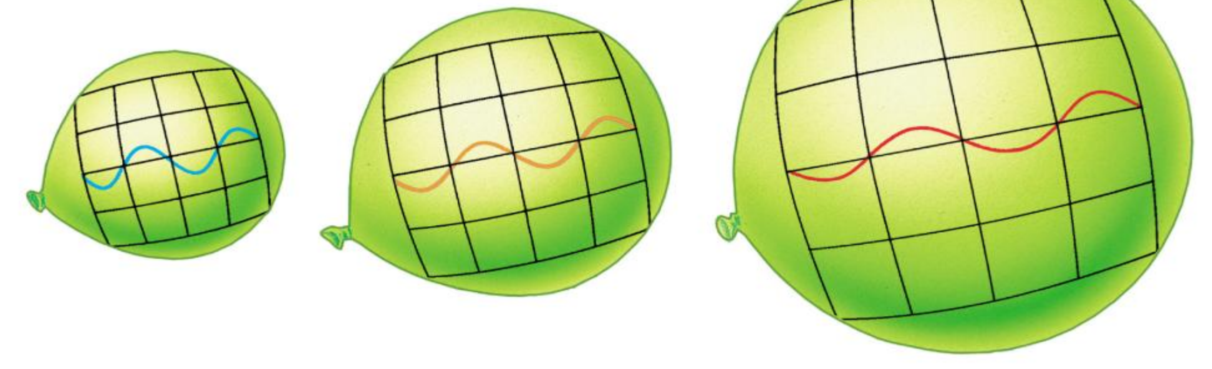
Uitdijing (overgang naar materie dominant)



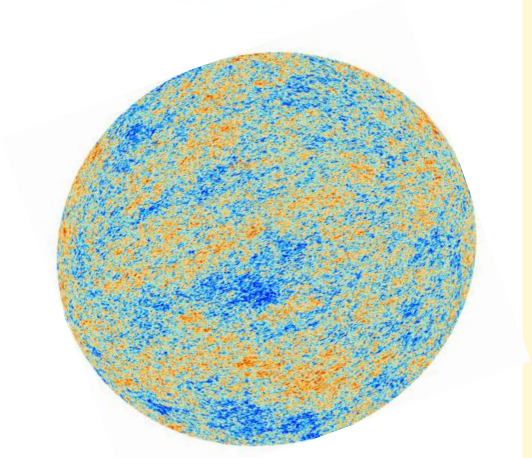
$$\left(1+z_{eq}\right)^{-1} = \frac{\rho_\gamma + \rho_\nu}{\rho_b + \rho_{cdm}}$$

z_{eq} ~ 3400
T ~ 10000 K (~1eV)
t ~ 60000 jaar

Comoving grid



Ballon metafoor met sinaasappelhuid (dichtheidsfluctuaties)

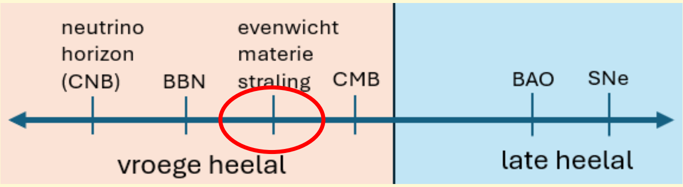


Straling dominantie

Verdichtingen trekken nog niet (goed) samen

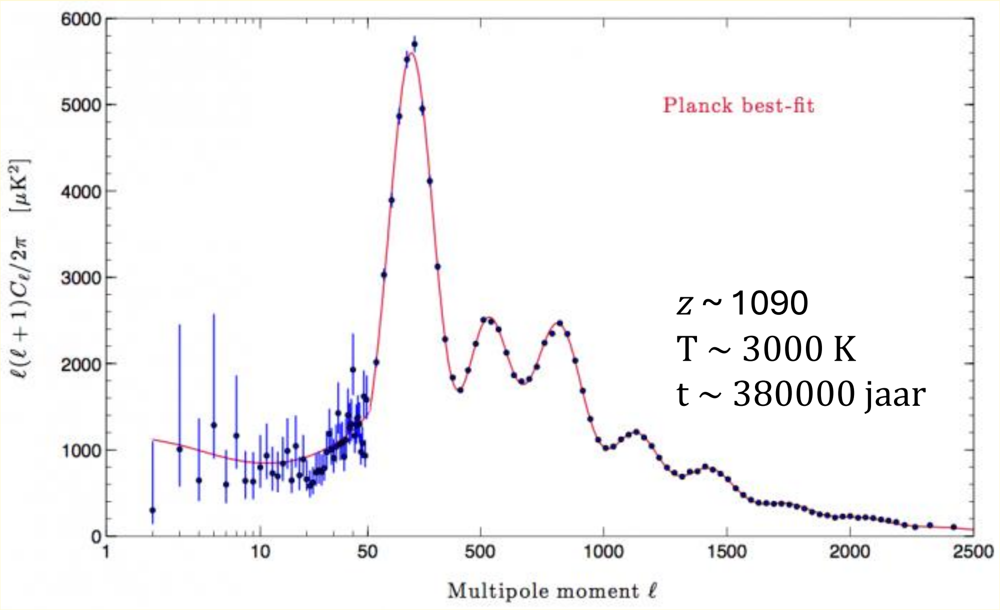
Materie dominantie

Verdichtingen trekken wel samen door zelf gravitatie



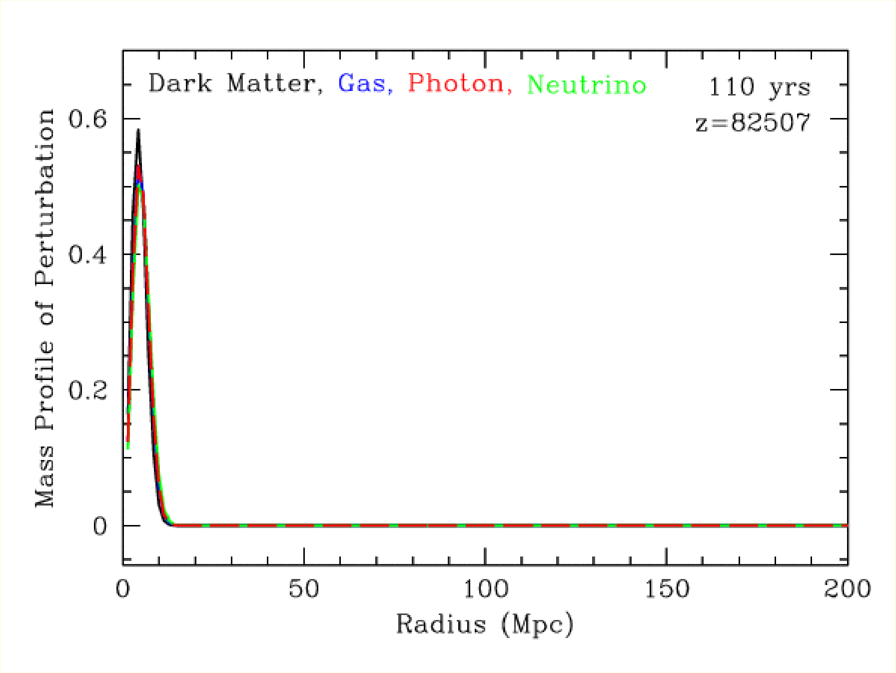
CMB sound horizon

CMB temperature power spectrum



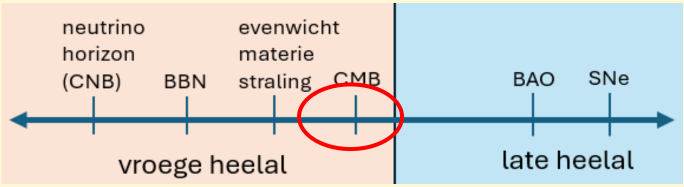
Fotonen slepen (drag) de baryonen mee
→ geluidsgolf (**massa**)

Massa profiel



Baryonen volgen ook de donkere materie
→ Samentrekken → verhitting → tegendruk→ afkoeling → weer samen trekken etc. → oscillatie.

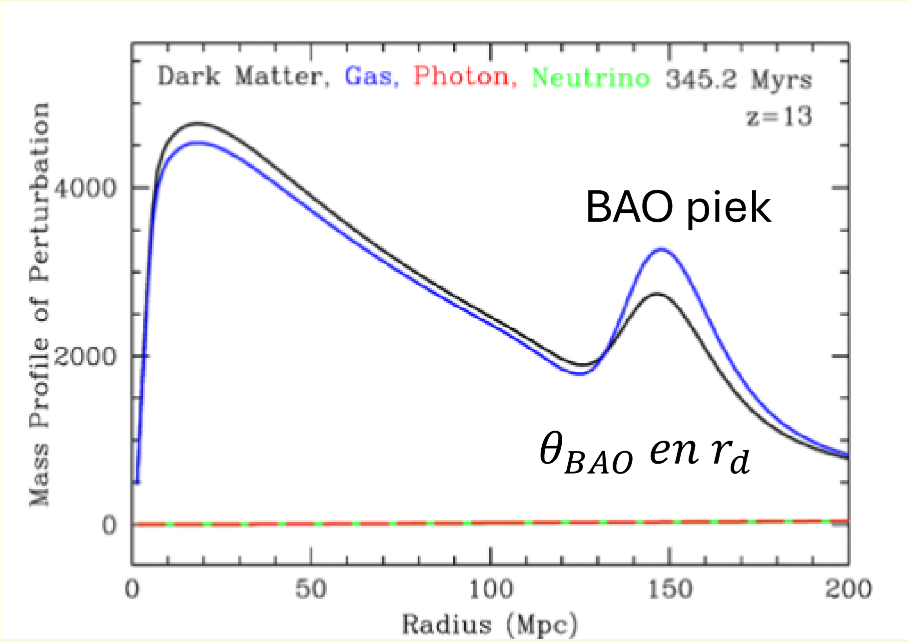
Temperatuur verschillen terug te zien bij de fotonen



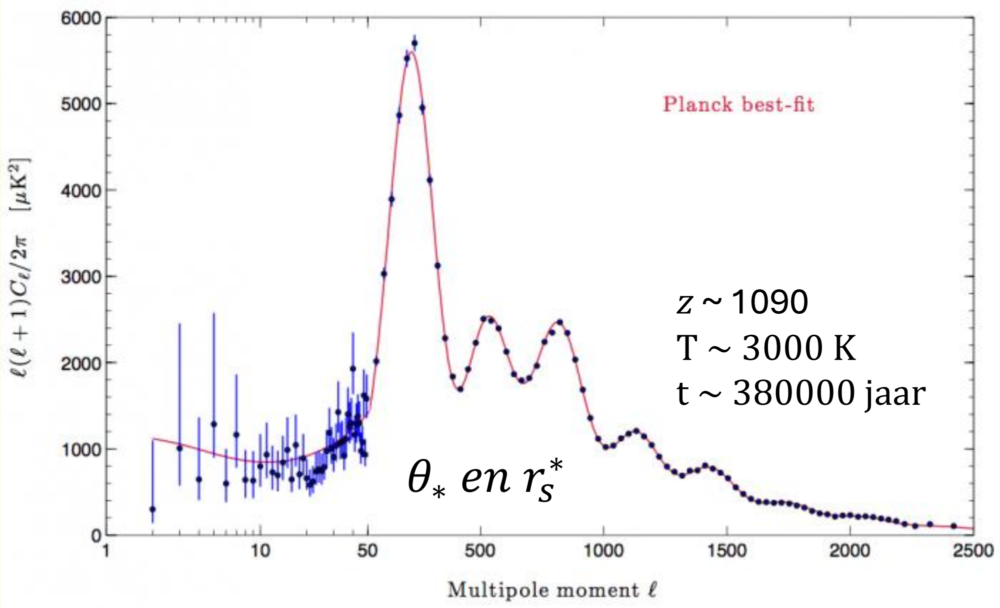
CMB geluidshorizon

Fotonen slepen (drag) de baryonen mee
→ geluidsgolf (**massa**)

Massa profiel



CMB temperature power spectrum



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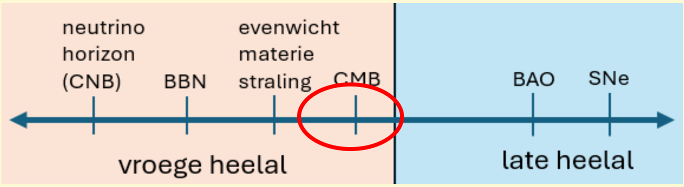


Geluidshorizon berekenen bij recombinatie (r_s^*) en drag (r_d)

$$r_s^*(z_*) = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$

z~1090, r_s*~144 Mpc

Is niet afhankelijk van H0, alleen van de energiedichtheden zelf (materie en straling)

$$r_d(z_d) = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

z~1060, r_d~147 Mpc

Geluidssnelheid in baryon/fotonen plasma

$$c_s(z) = \frac{c}{\sqrt{3(1+R(z))}} \qquad R(z) = \frac{3\rho_b}{4\rho_\gamma} = \frac{3\Omega_{b,0}h^2}{4\Omega_{\gamma,0}h^2(z+1)}$$

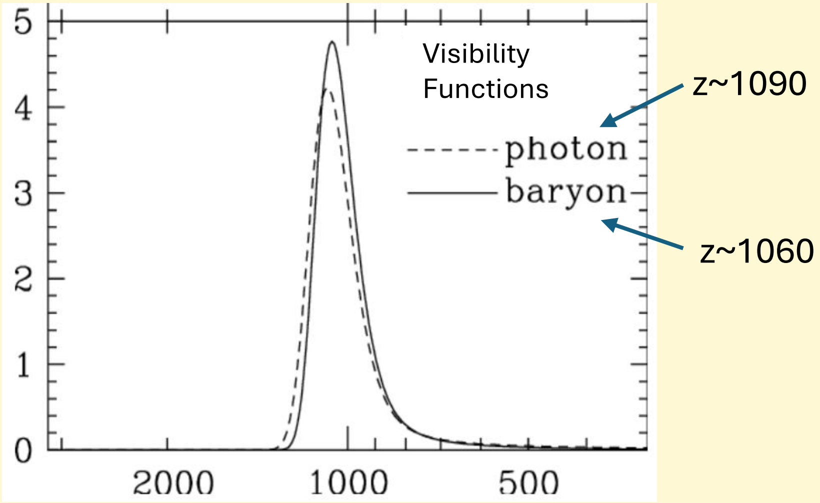
Cosmology Lecture 19 - AstroBaki

$$H(z) = H_0 E(z)$$

$$E(z) = \sqrt{\Omega_{rel,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}}$$

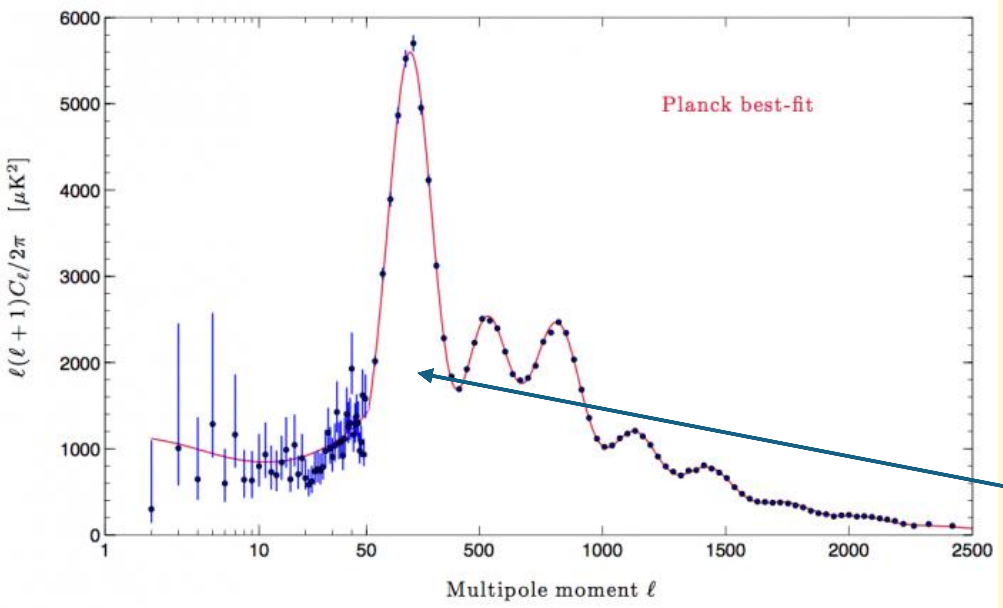
$$H(z) = \sqrt{\Omega_{rel,0}h^2(1+z)^4 + \Omega_{m,0}h^2(1+z)^3}$$

Vroege heelal



roodverschuiving z

Resultaten CMB temperatuur power spectrum (totale materiedichtheid)



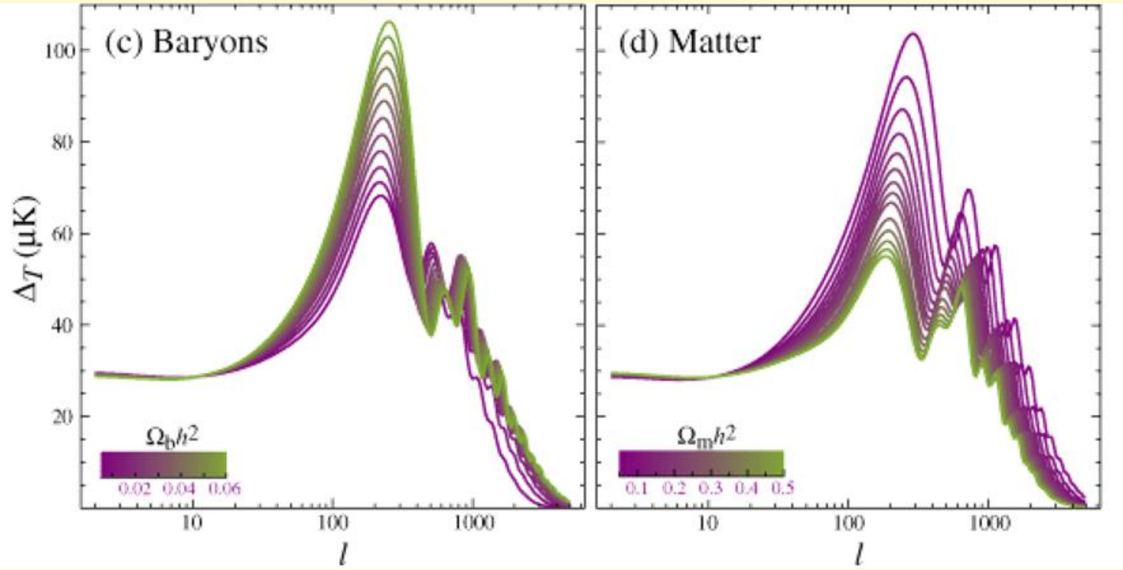
Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_*$	1.041085
τ	0.0543
$\ln(10^{10}A_s)$	3.0448
n_s	0.96605

$\Omega_{m,0}h^2 = \Omega_{b,0}h^2 + \Omega_{c,0}\,h^2 = 0.1425$

vroege heelal

$$\theta_* = \frac{r_s^*(z_*)}{D_M(z_*)}$$

late heelal



Verhouding pieken geven info over $\Omega_{b,0}h^2$ & $\Omega_{c,0}h^2$

$$D_M(z_*) = \frac{c}{H_0}\int_0^{z_*}\frac{dz}{E(z)}$$

Comoving angular diameter distance (transverse)

$$E(z) = \sqrt{\Omega_{rel,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}} \Rightarrow \sqrt{\Omega_{m,0}(1+z)^3 + 1 - \Omega_{m,0}}$$

late heelal

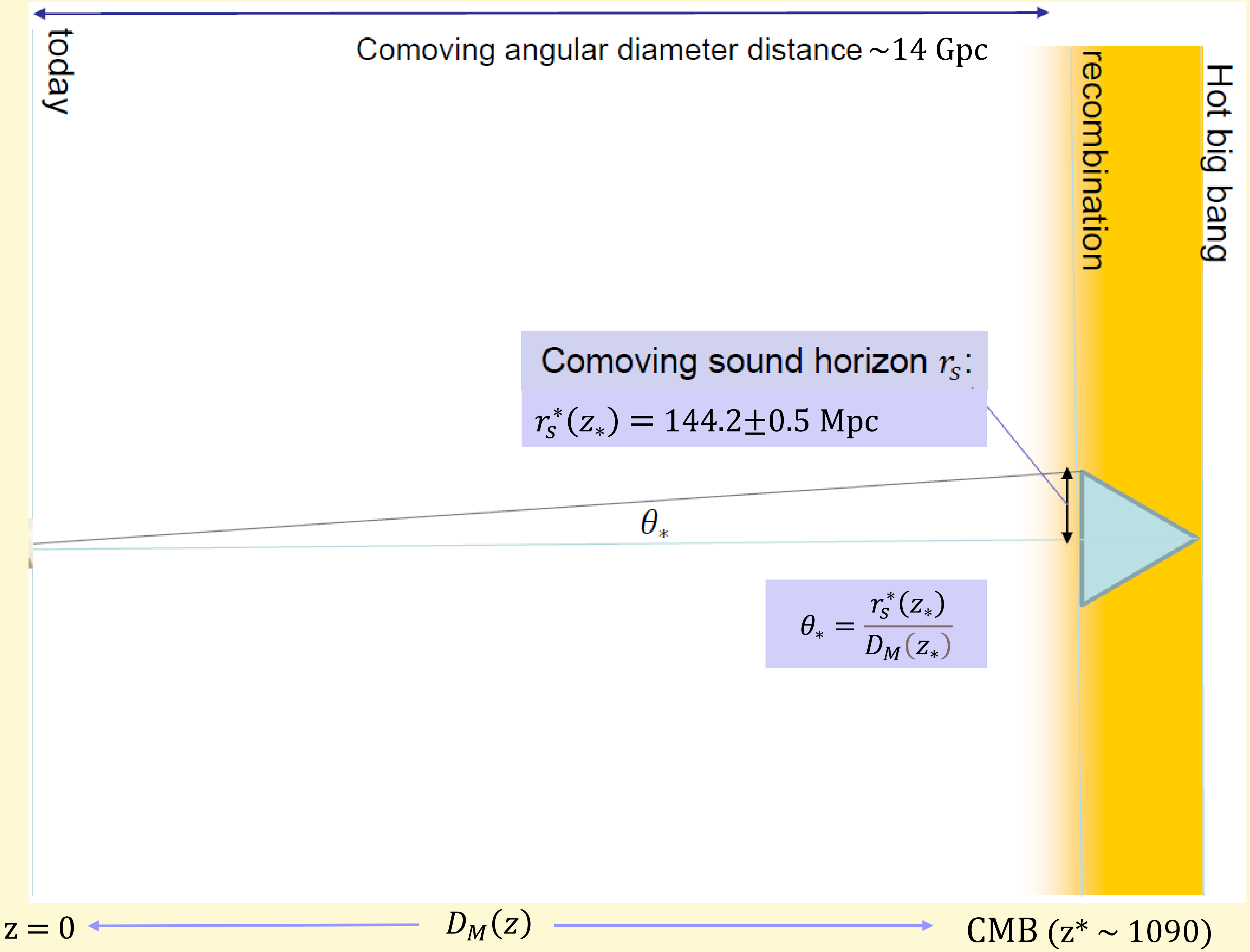
$\Omega_{\Lambda,0} = 1 - \Omega_{m,0}$

vlak heelal

z_* =1090, dus best een lang stuk evolutie in $D_M(z_*)$

Distance Measures in Cosmology

r_s als spil



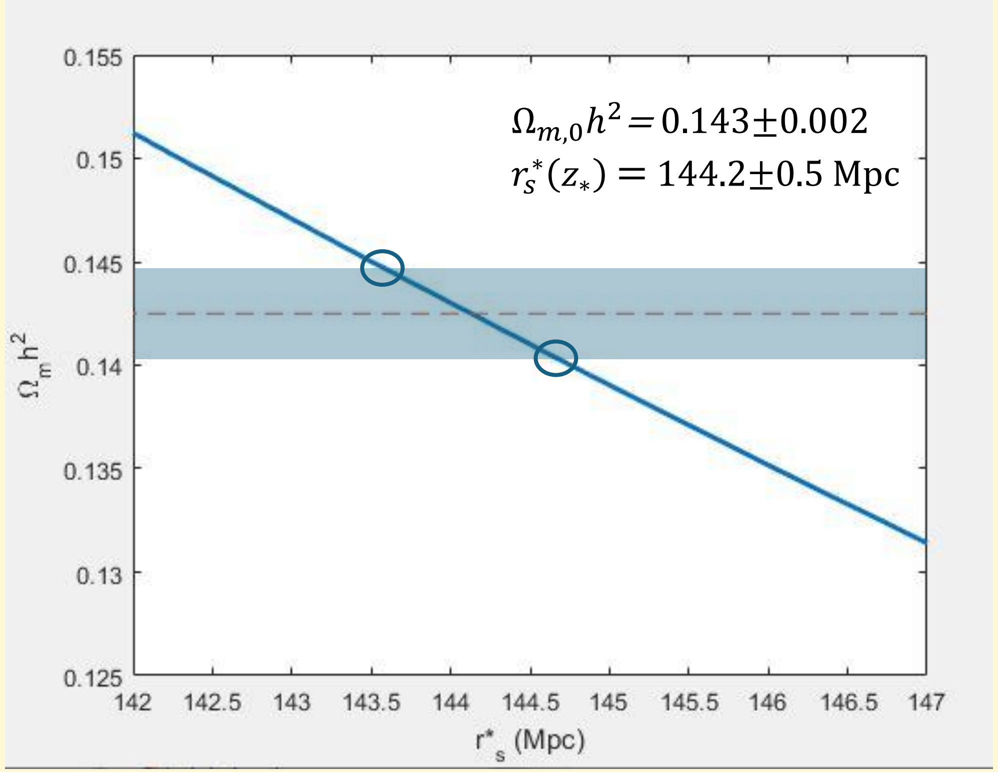
Comoving angular diameter distance ~14 Gpc
today
recombination
Hot big bang
Comoving sound horizon r_s:
$r_s^*(z_*) = 144.2 \pm 0.5$ Mpc
θ_*
$\theta_* = \frac{r_s^*(z_*)}{D_M(z_*)}$
z = 0
$D_M(z)$
CMB ($z^* \sim 1090$)

Afleiding H0 uit CMB resultaten

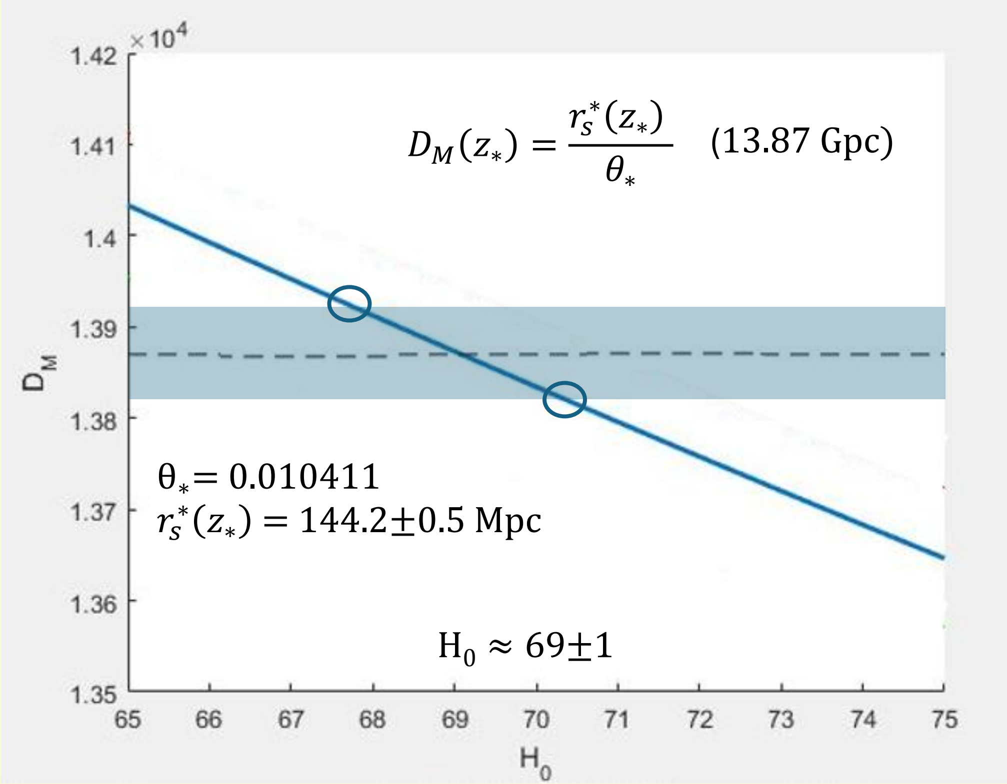
late heelal

$$D_M(z_*) = c\int_0^{z_*}\frac{dz}{H(z)} \qquad H_0 = 100h$$

$$H(z) = \sqrt{\Omega_{m,0}h^2(z+1)^3 + h^2 - \Omega_{m,0}h^2}$$



$$D_M(z_*) = \frac{r_s^*(z_*)}{\theta_*}$$



$$r_s^*(z_*) = \int_{z_*}^{\infty}\frac{c_s(z)}{H(z)}dz$$

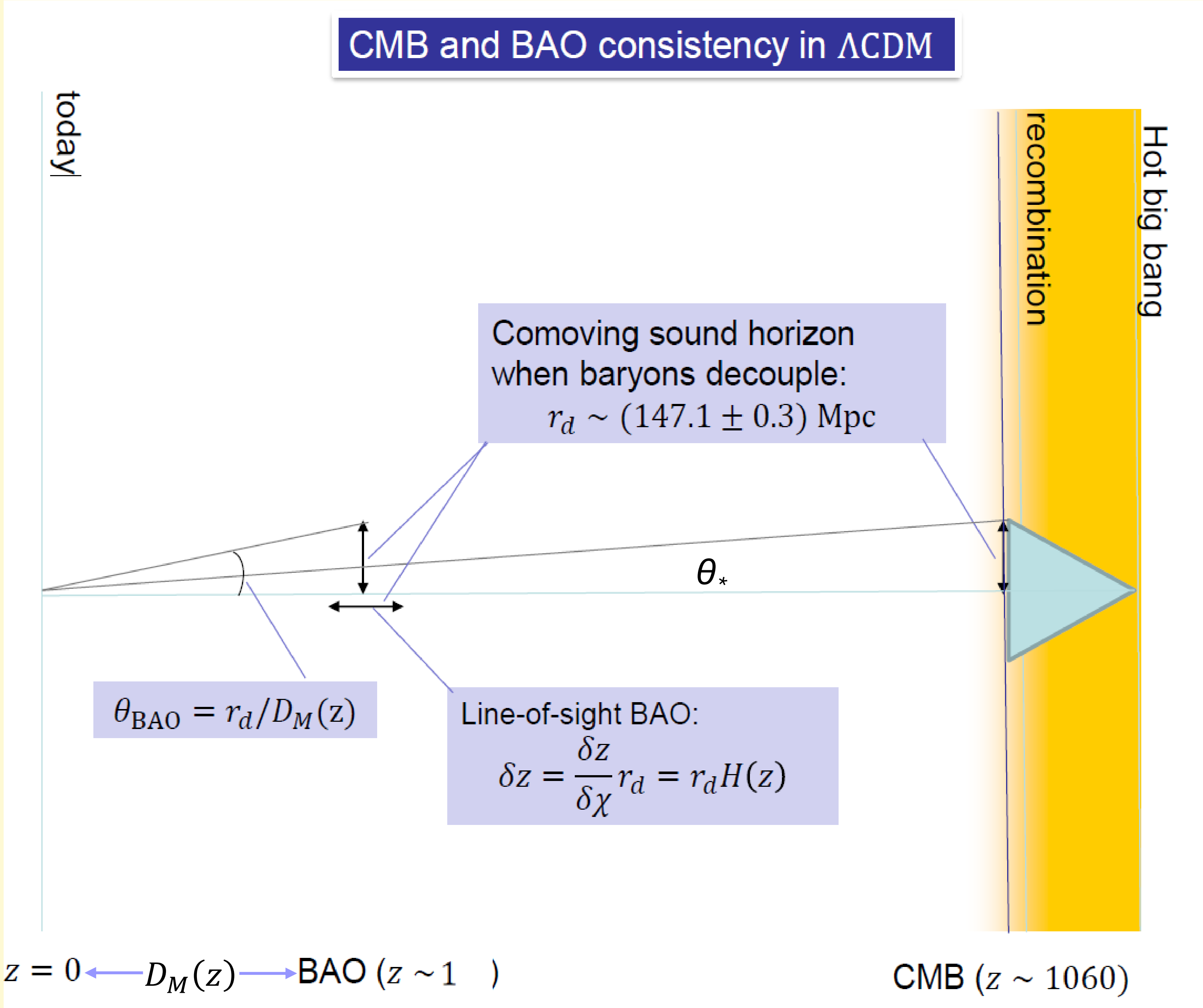
vroege heelal

$$H(z) = \sqrt{\Omega_{\mathrm{rel},0}h^2(z+1)^4 + \Omega_{m,0}h^2(z+1)^3}$$

$\Omega_{m,0}h^2$ is hier de cruciale parameter en ook het minst ‘betrouwbaar’ bekend

z_* =1090, dus best een lang stuk evolutie in $D_M(z)$

Nu r_d als spil



BAO pieken in late heelal

BAO piek (in het late heelal)

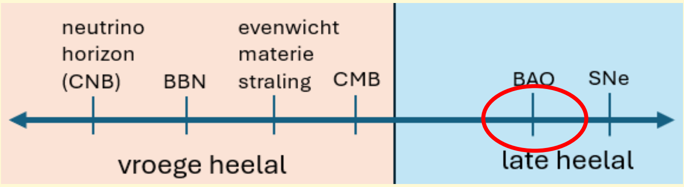
$$\theta_{BAO} = \frac{r_d(z_d)}{D_M(z_{BAO})}$$

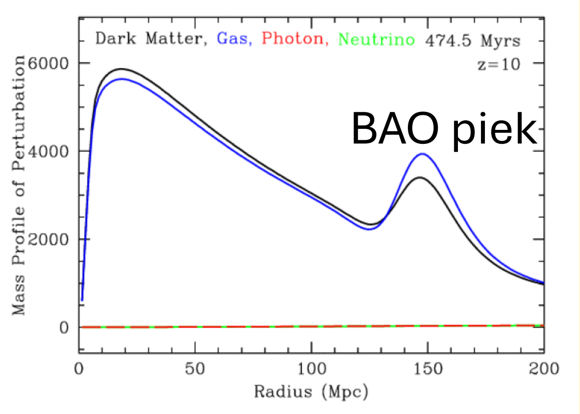
Comoving distance (transverse, flat universe)

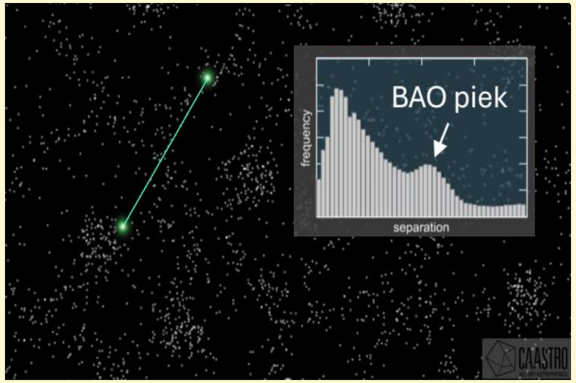
$$D_M(z_{BAO}) = \frac{c}{H_0}\int_0^{z_{BAO}} \frac{dz}{E(z)}$$

$$E(z) = \sqrt{\Omega_{m,0}(z+1)^3 + 1 - \Omega_{m,0}}$$

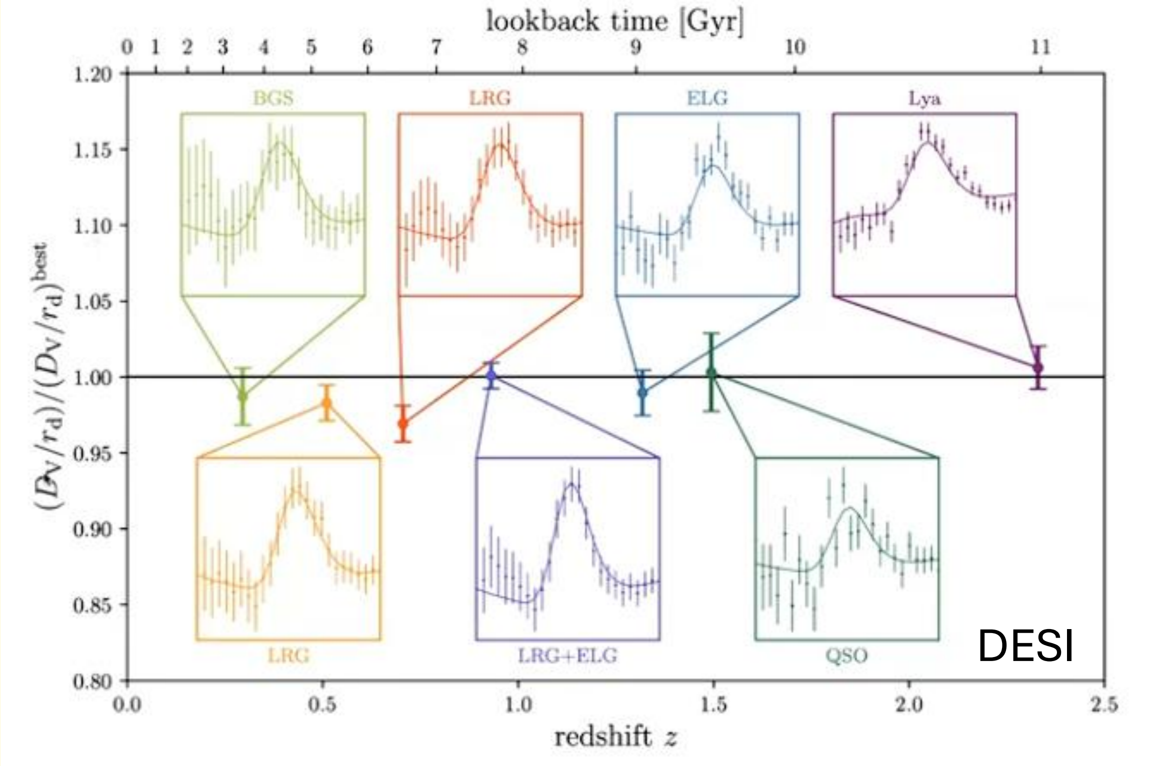
z~1, dus een klein stuk evolutie bij D_M







Correlation function (astronomy) - Wikipedia



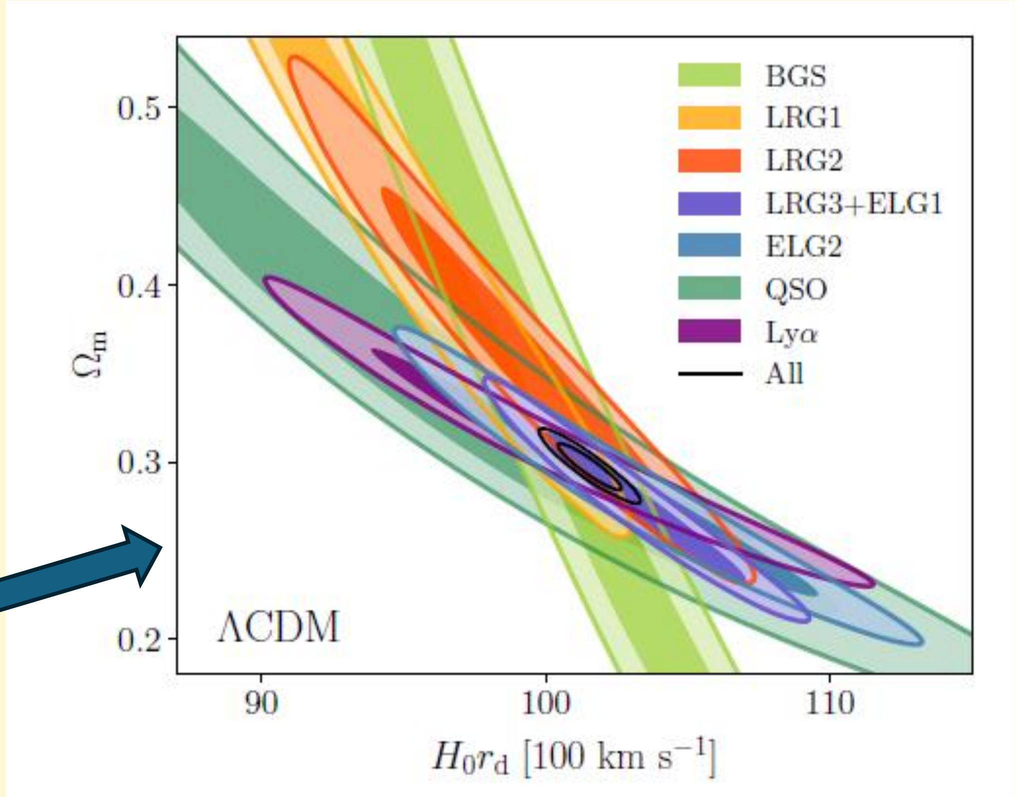
Verschillende z → meer controle

Degeneracy $H_0 r_d$ en Ω_m – (afhankelijkheid van Ω_m)

$$\theta_{BAO} = \frac{r_d(z_d)}{D_M(z_{BAO})}$$

$$H_0 r_d = \theta_{BAO} \int_0^{z_{BAO}} \frac{dz}{E(z)}$$

$$E(z) = \sqrt{\Omega_{m,0}(z+1)^3 + 1 - \Omega_{m,0}}$$



Setjes $\{\theta_{BAO}, z_{BAO}\}$ gemeten → diverse curven $\{H_0 r_d, \Omega_{m,0}\}$

gemeten

$$\frac{H_0 r_d(z_d)}{r_d} = \frac{102 \text{ x } 100}{147} \quad \sim 69 \text{ km/s/Mpc}$$

berekend

Snijpunt →

$$\left.\begin{aligned} \Omega_m &= 0.2975 \pm 0.0086, \\ h r_d &= (101.54 \pm 0.73) \text{ Mpc}, \end{aligned}\right\} \text{ DESI DR2}$$

Onafhankelijk van CMB parameters θ_* , $\Omega_{c,0}\, h^2$ en $\Omega_{b,0}\, h^2$

[2503.14738] DESI DR2 Results II: Measurements of Baryon Acoustic Oscillations and Cosmological Constraints

Samenvattend

De evolutie van het heelal wordt gedreven door de volgende *energiedichtheden*

- Fotonen (Ω_γ)
- Neutrino's in vaste verhouding tot de fotonen (Ω_ν)
- De baryonen (gewone materie) (Ω_b)
- Donkere materie (Ω_c)
- De rest is donkere energie in een vlak heelal (Ω_Λ)

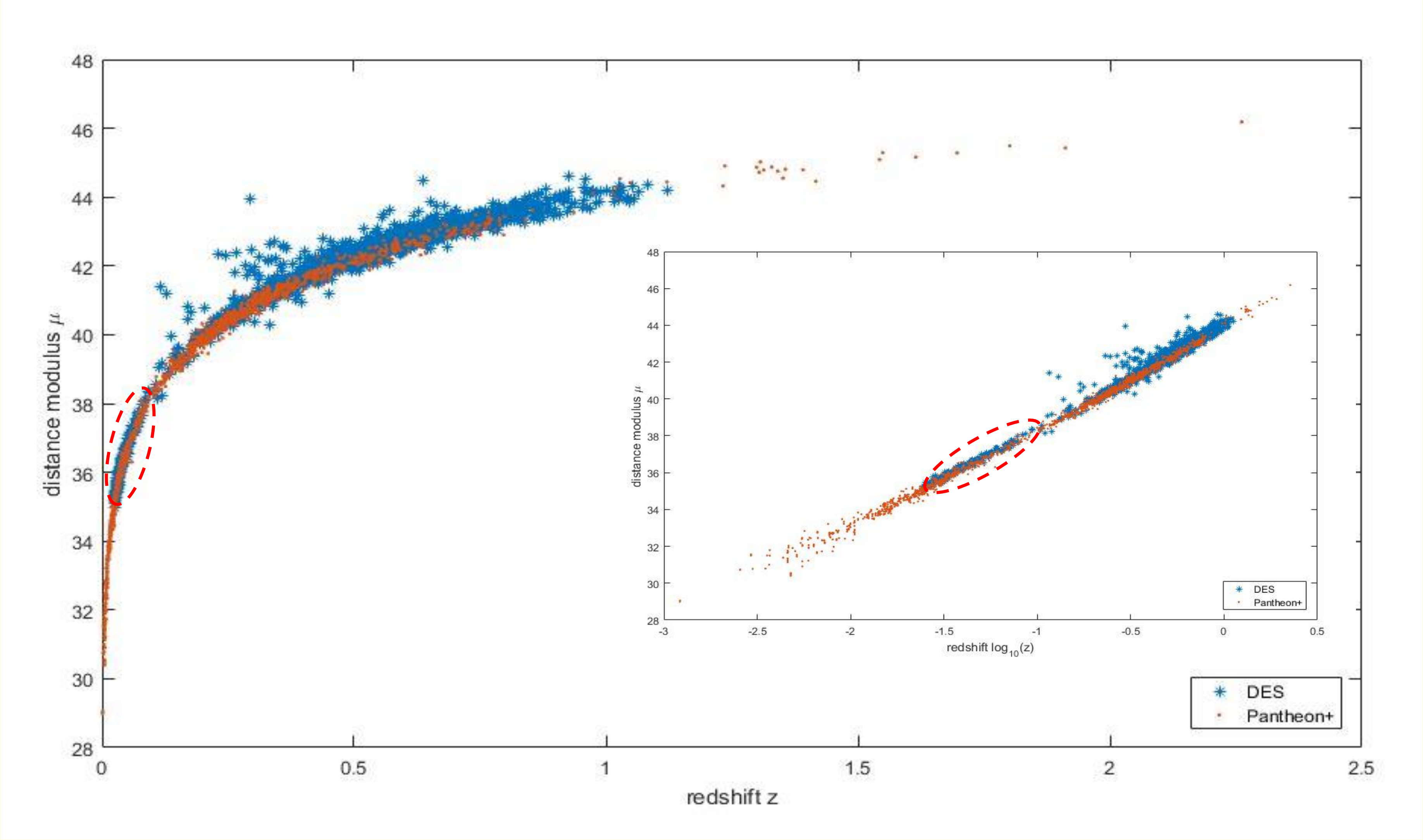
Er is een *ankerpunt* dat we kunnen berekenen en meten: de sound horizon (geluidshorizon) n.a.v. de geluidsgolf van baryonen.

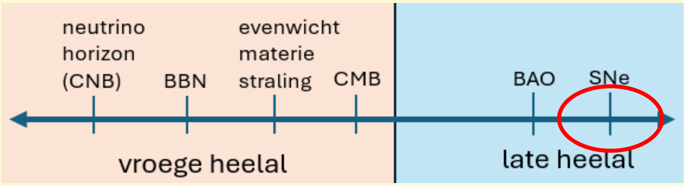
- M.b.v. fotonen bij de CMB (iets hogere temperatuur in de geluidsgolf)
- M.b.v. baryonen (en indirect de donkere materie) de booggolf van de baryonen weerspiegeld in de distributie van sterrenstelsels (BAO)

Dit geeft een tempo van uitdijing weerspiegeld in de *Hubble contante* < 70 Mpc/km/s (H_0~67-69)

Nu lokaal uitdijing meten

High redshift Hubble diagram samples (Pantheon+ en DES)





High redshift Hubble diagram (theorie)

Distance modulus

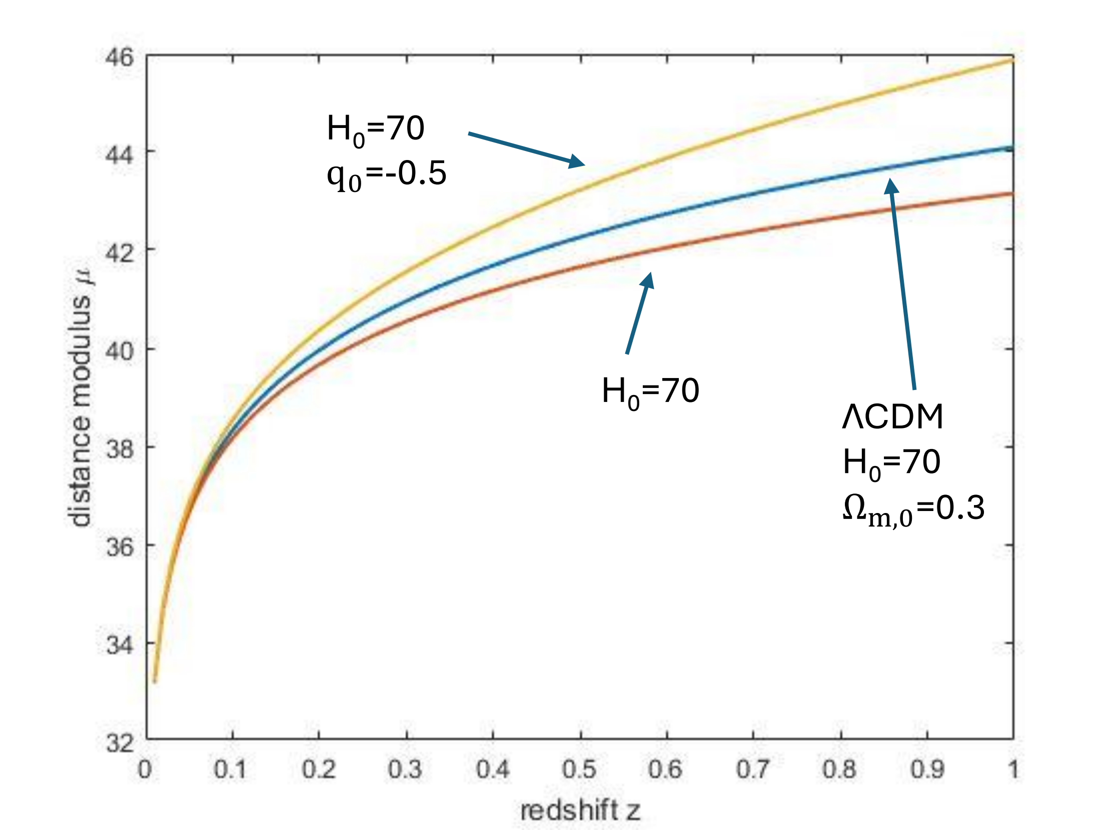
$$S = \frac{L}{4\pi d_L^2}$$

$$\mu_0 = m - M_B = 5\log\left(\frac{d_L(z)}{Mpc}\right) + 25$$

ΛCDM model

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

$$E(z) = \sqrt{\Omega_{m,0}(z+1)^3 + 1 - \Omega_{\mathrm{m},0}}$$

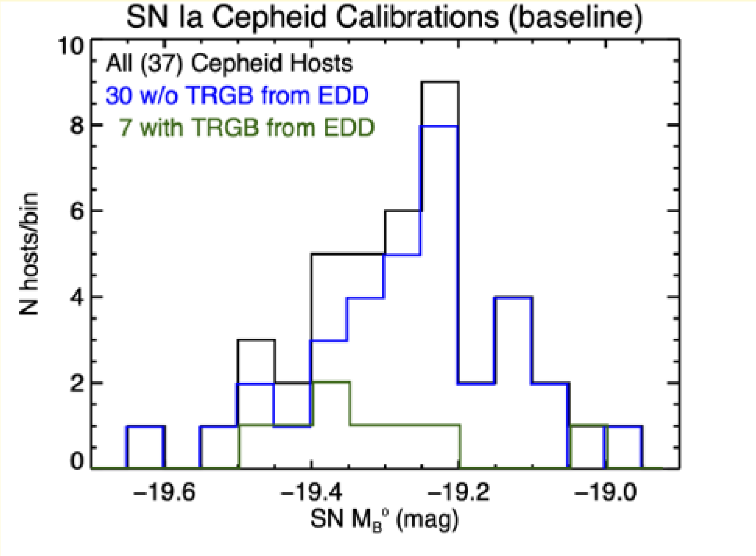


Cosmography – Taylor reeks

$$d_L(z) = \frac{c}{H_0}\left(z + \frac{1}{2}(1-q_0)z^2 + O(z^3) + \cdots\right)$$ als z→0 $$d_L(z) = \frac{cz}{H_0}$$ *($v = H_0 * r$)*

$$q_0 = \frac{3}{2}\Omega_{m,0} - 1$$

Calibration with the distance ladder (Cepheids)

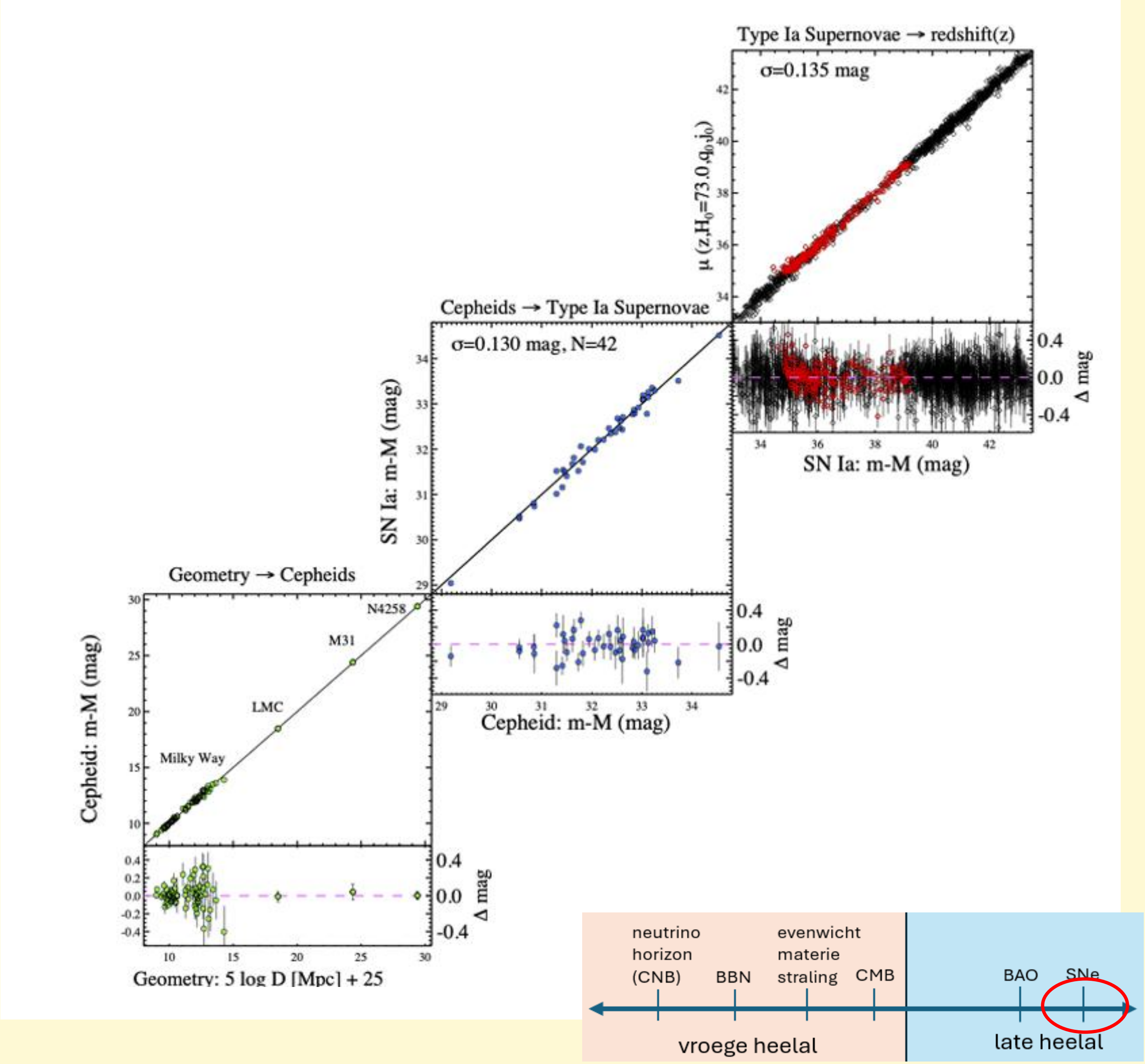


$$M_B^0 = -19.253 \pm 0.027 \text{ mag}$$

$$H_0 = 73.04 \pm 1.01 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

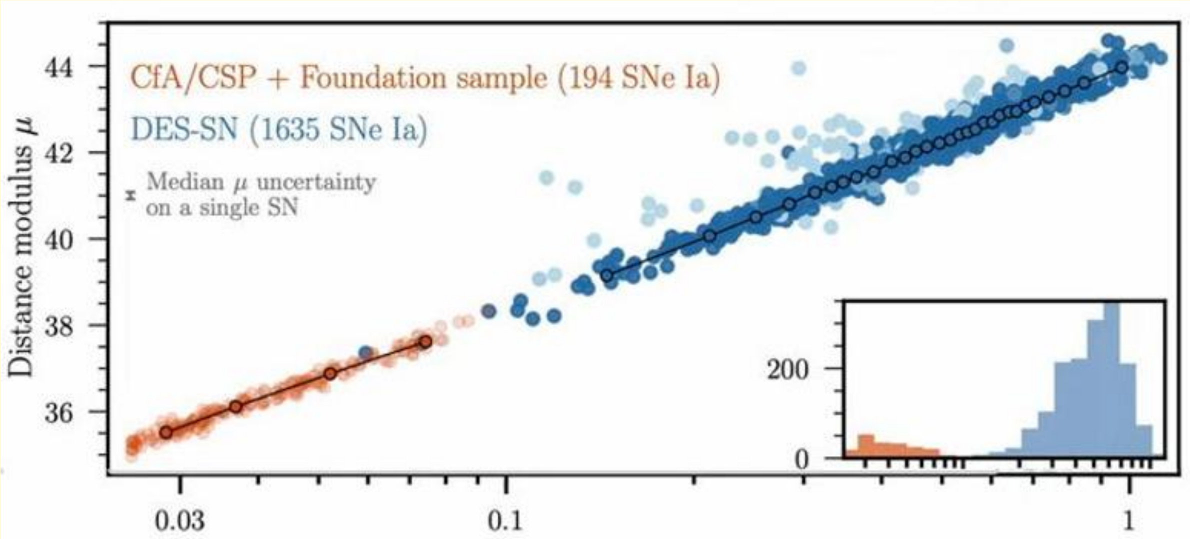
$$0.03 \text{ mag or } 1 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

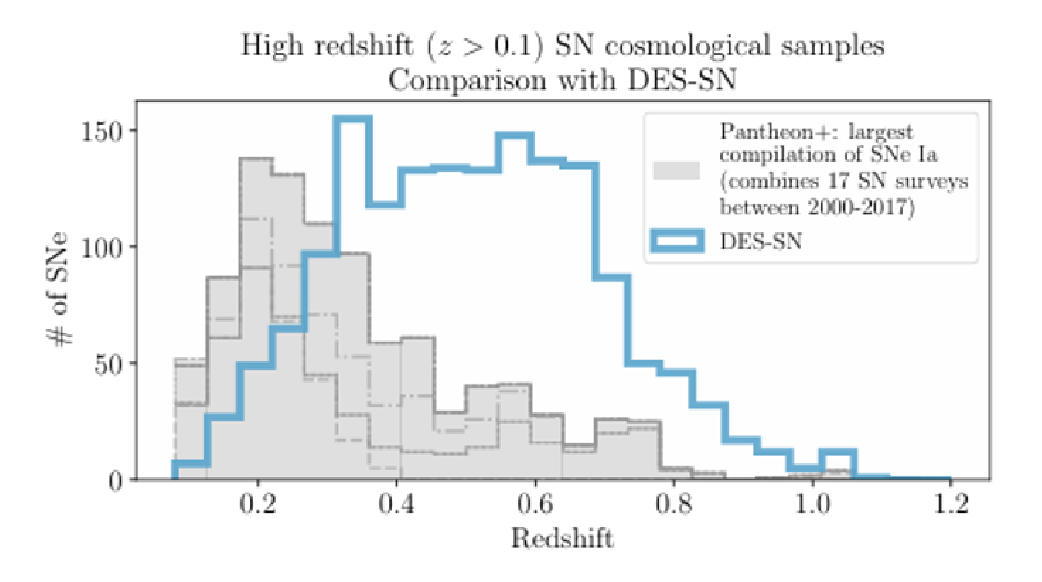
$$q_0 = -0.51 \pm 0.024$$



Riess_2022_2112.04510

Dark energy survey (DES) sample, nadruk op z>0.1, single telescope, single camera



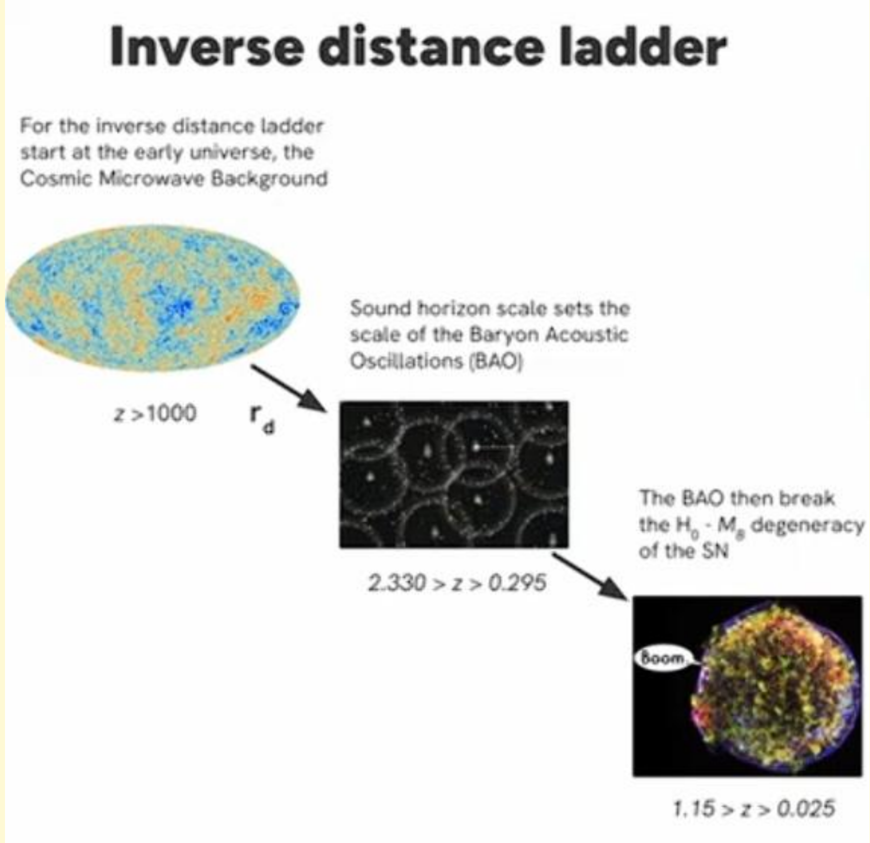


DES is een dieper (meer hogere roodverschuiving) sample dan Pantheon+

DES is waargenomen is diverse specifieke bundels

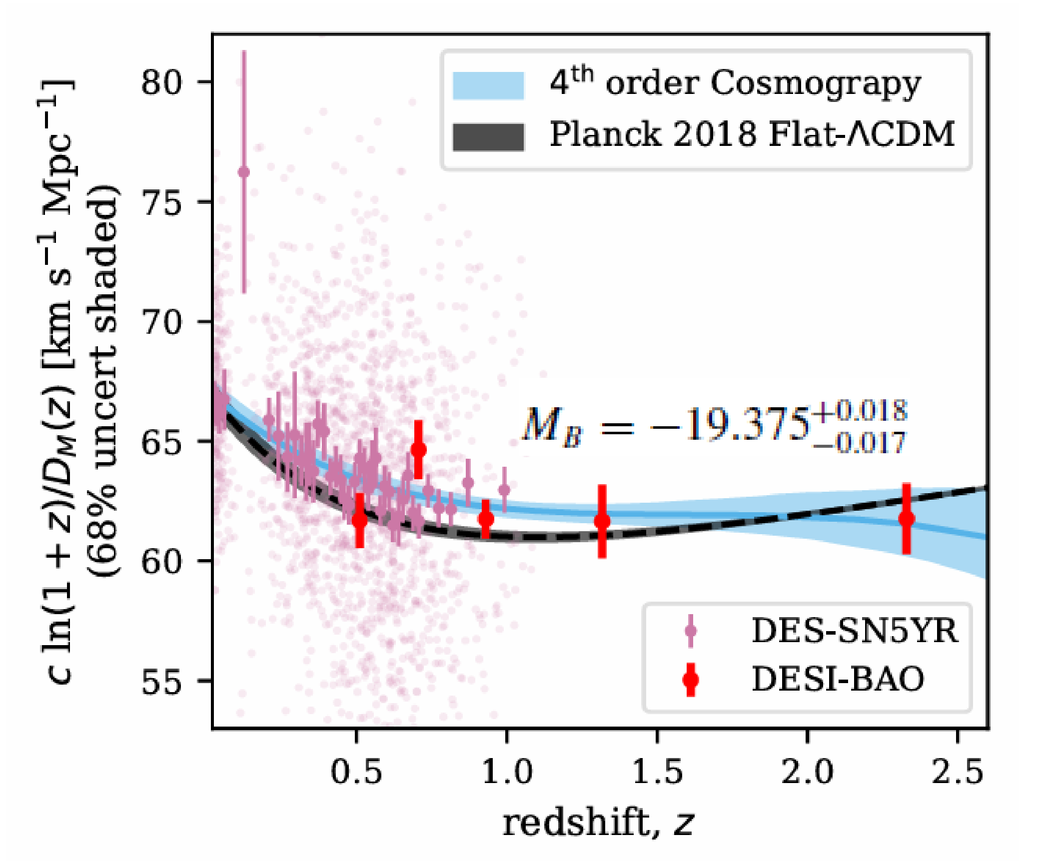
[2401.02945] The Dark Energy Survey Supernova Program: Cosmological Analysis and Systematic Uncertainties

Calibration with the inverse distance ladder



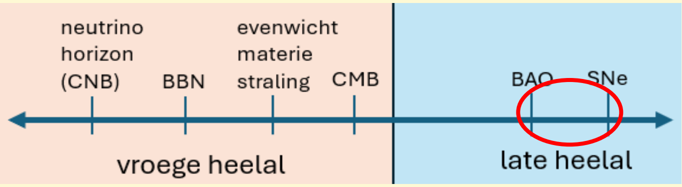
r_d → afstand BAO bij z → een fit geeft SNe afstand bij waargenomen z van bijbehorende stelsel.
Geen kalibratie met Cepheïden nodig.

Illustration of the inverse distance ladder method
2406.05049

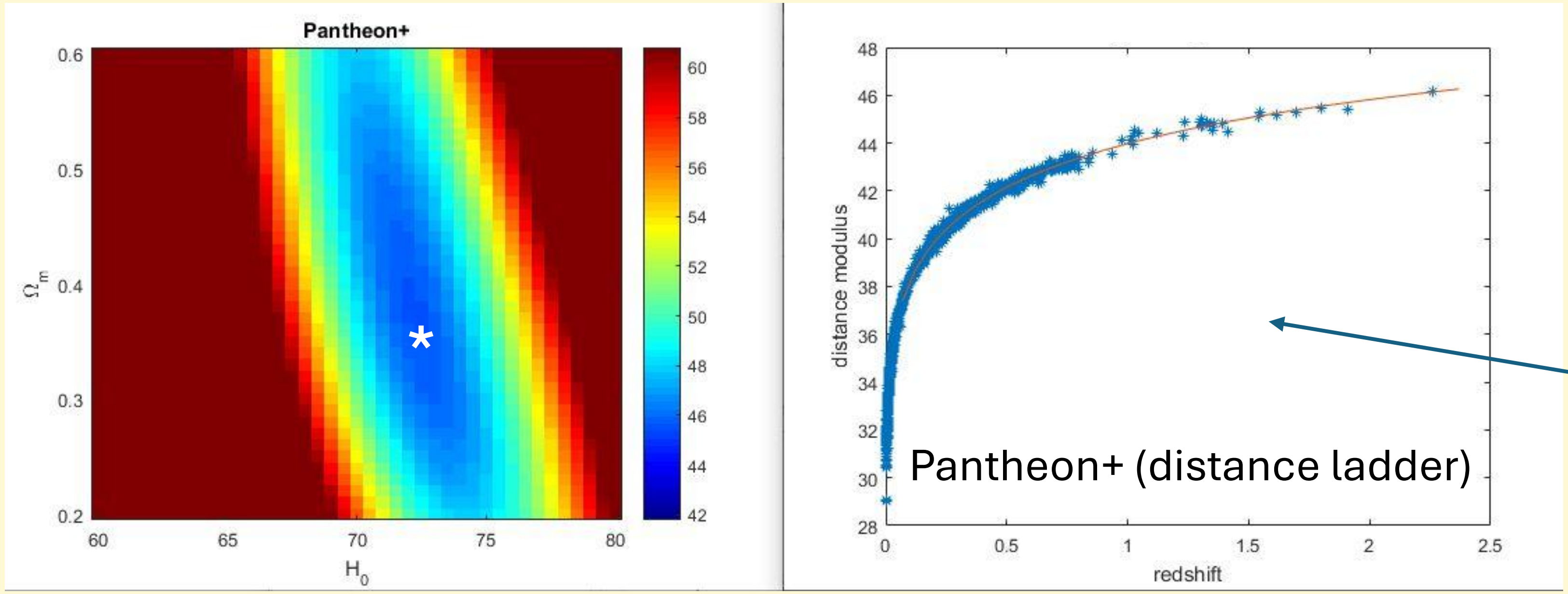


Known are: θ_{BAO}, z_{BAO} en r_d → $D_M(z_{BAO})$ for various redshift bins
M_B as free parameter → fit & calibrate

M_B=-19.375 ⟶ H_0~69 km s^{-1} Mpc^{-1}



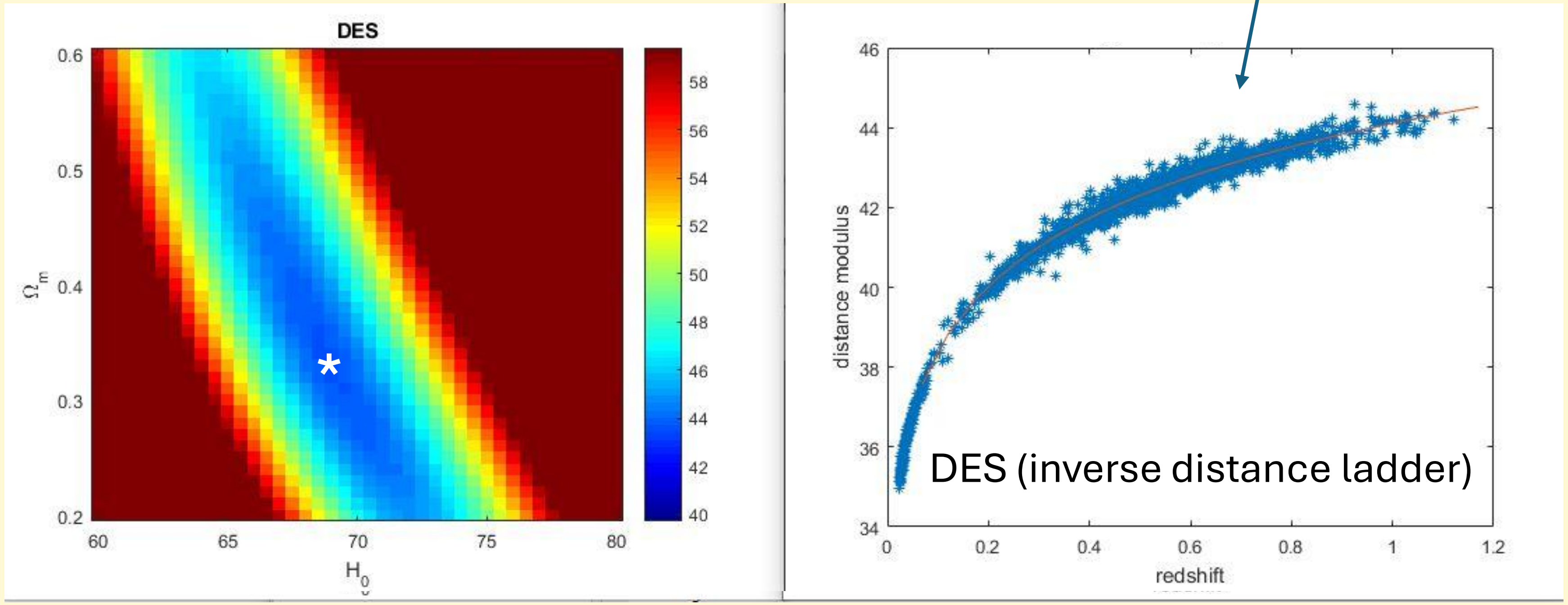
Degeneratie, hubble diagrammen lokaal - distance modulus (ΛCDM model)



*
$H_0 = 72$
$\Omega_{m,0} = 0.36$

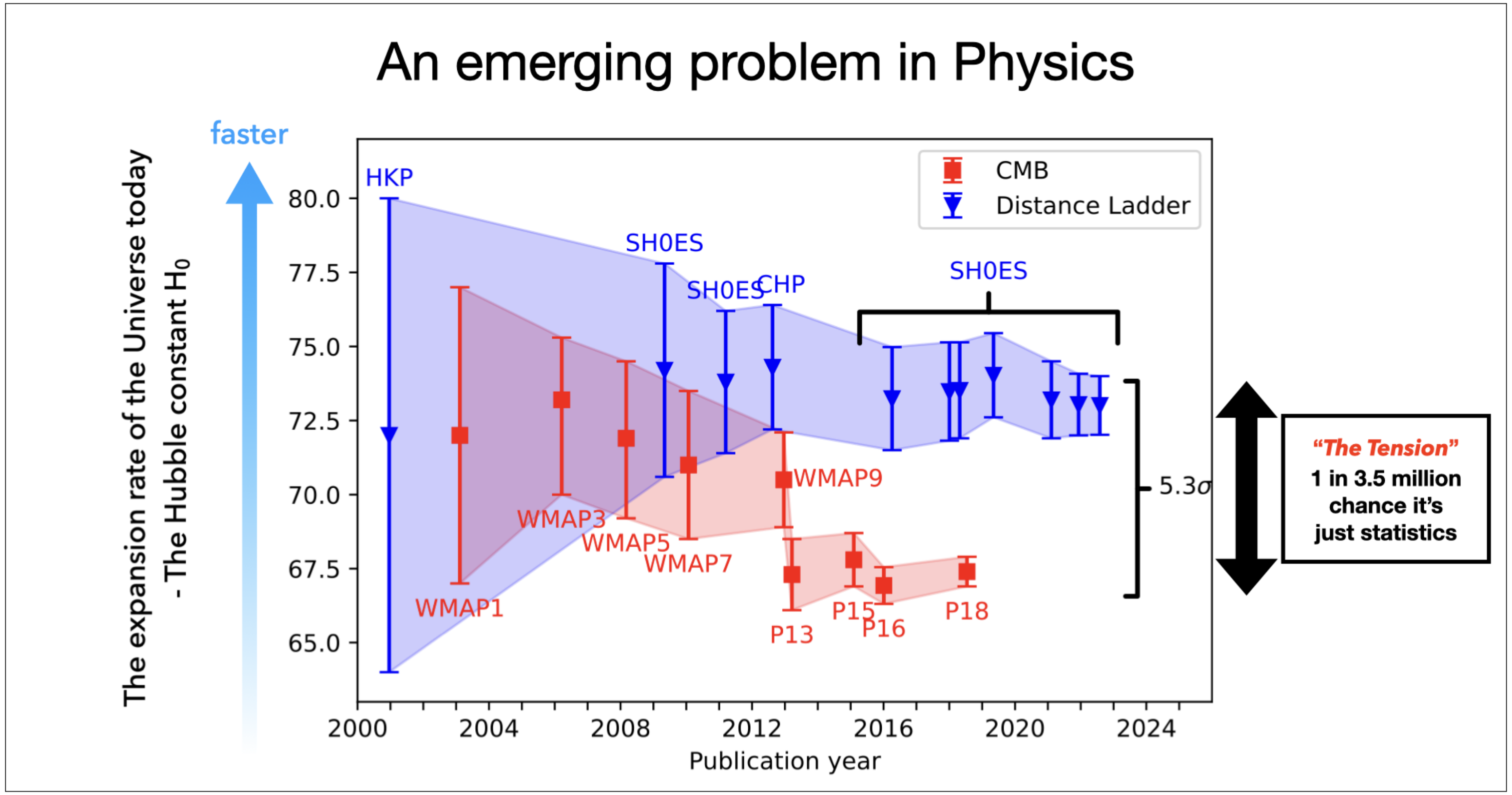
Verschillende kalibraties:

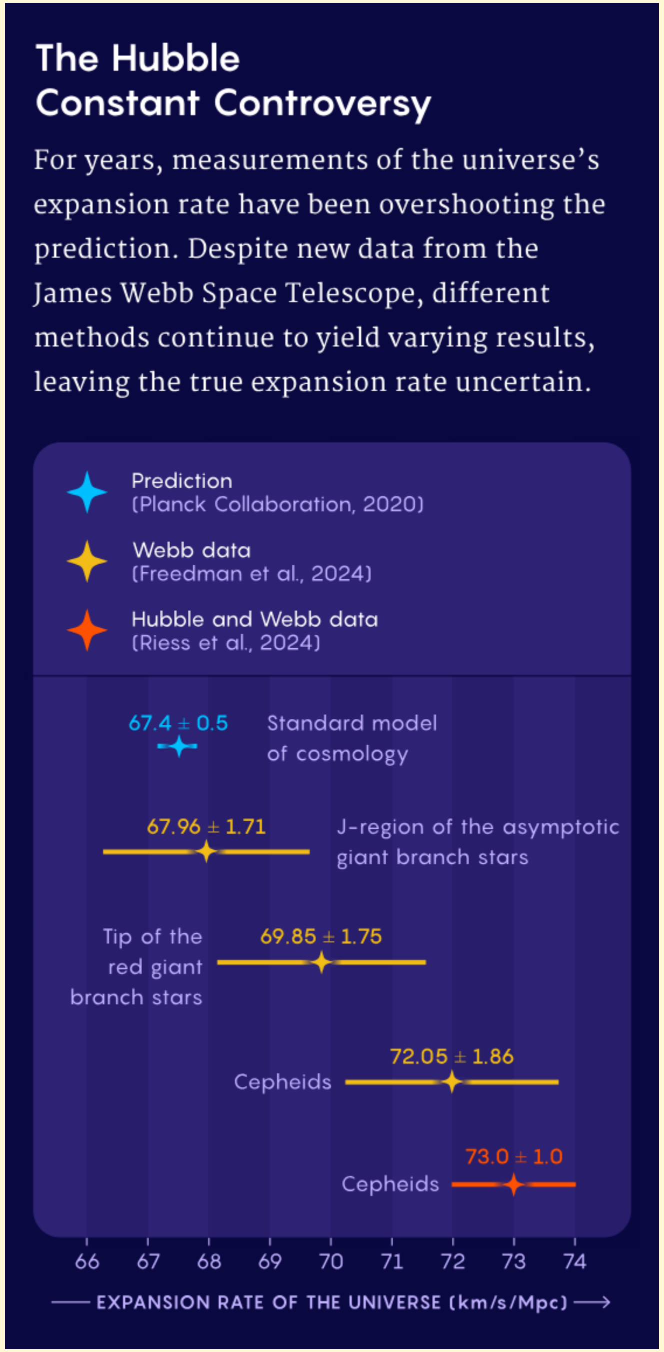
- Cepheiden
- Sound horizon r_d



*
$H_0 = 69$
$\Omega_{m,0} = 0.33$

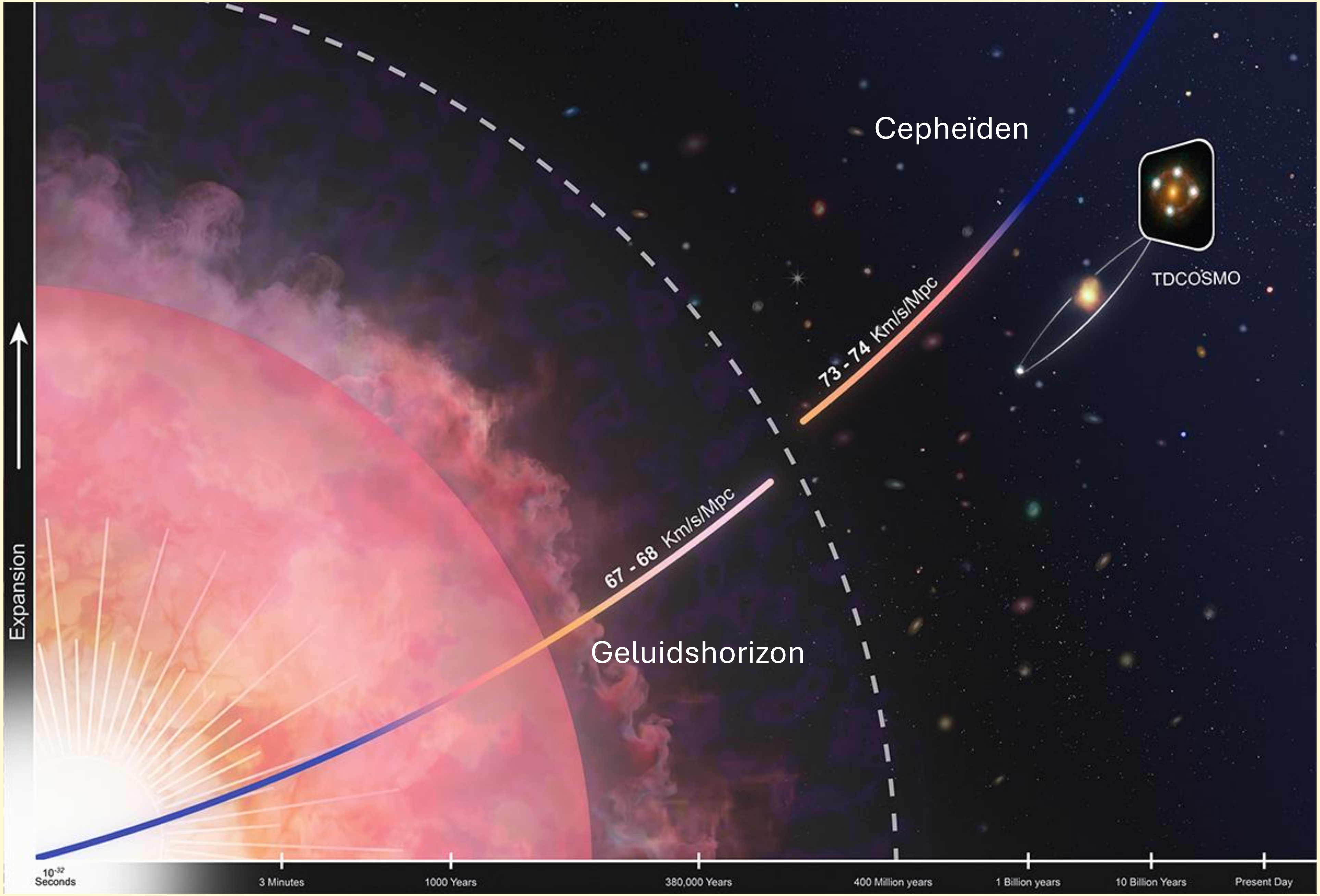
Hubble tension





The Hubble tension – CERN Courier

Samenvattend



[Astronomers Sharpen the Universe's Expansion Rate, Deepening a Cosmic Mystery – W. M. Keck Observatory]

Tot slot

Andere methoden:

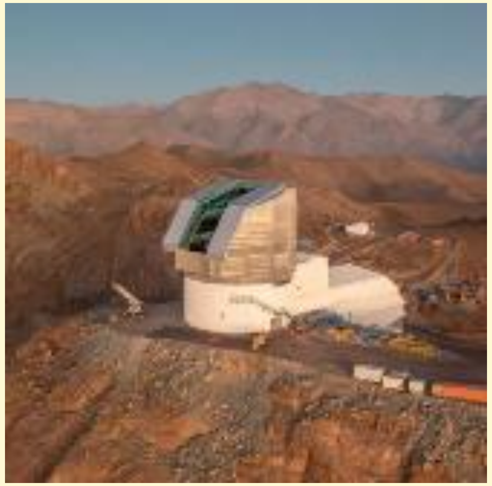
- Lensing (quasars, supernovae)
- Zwaartekrachtgolven (merging neutron stars)
- Piek massa power spectrum (matter-radiation equality)

Mogelijke verklaringen verschil:

- Locale afwijkingen van vlak heelal
- Decaying or interacting dark matter
- Early dark energy
- Dynamical dark energy $w_0 w_a$
- Iets anders onderweg ...

Toekomstige waarnemingen:

- DESI
- Euclid
- Vera Rubin telescoop (LSST) Legacy Survey of Space and Time
- Roman Grace space telescope



cosmology - What are the current theoretical solutions to the Hubble Tension? - Physics Stack Exchange

Gravitational lensing is amazing, but won't solve the Hubble tension - Big Think

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