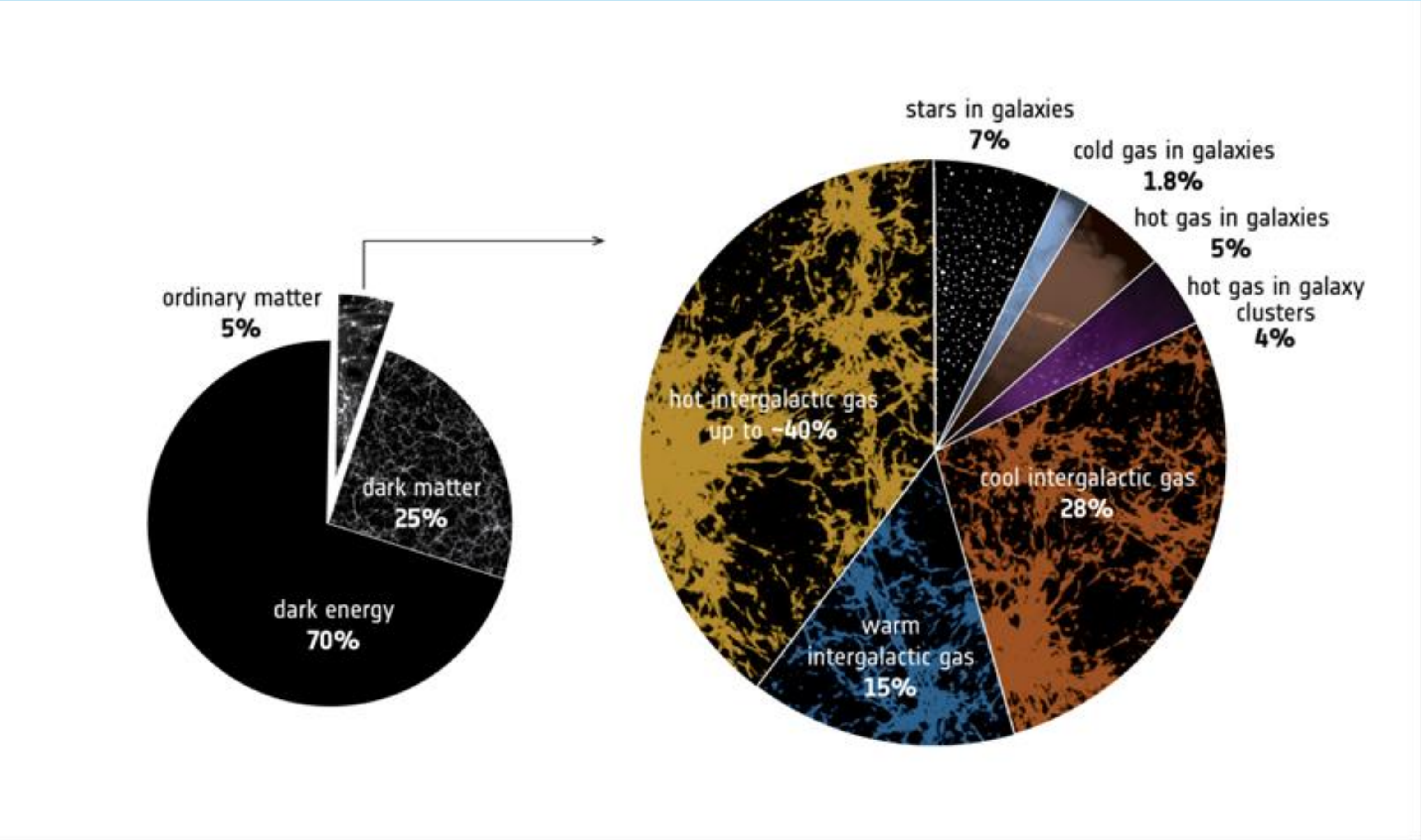
Donkere energie, van idee naar realiteit?

Wat denken jullie is het verschil tussen donkere materie en donkere energie?

Wat zit er in het heelal ?



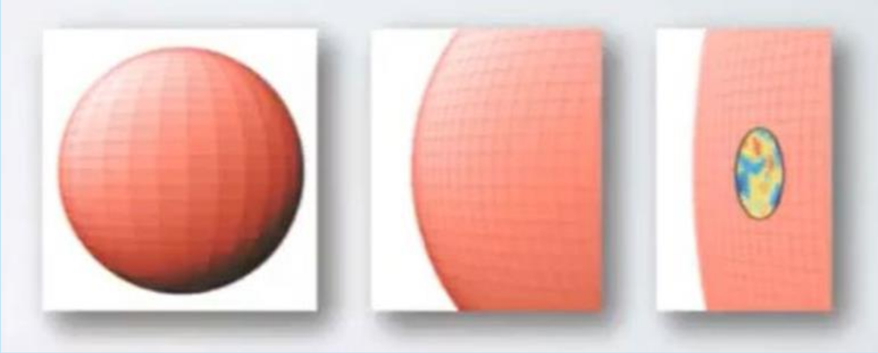
- Straling
- Materie
- Donkere materie
- Donkere energie

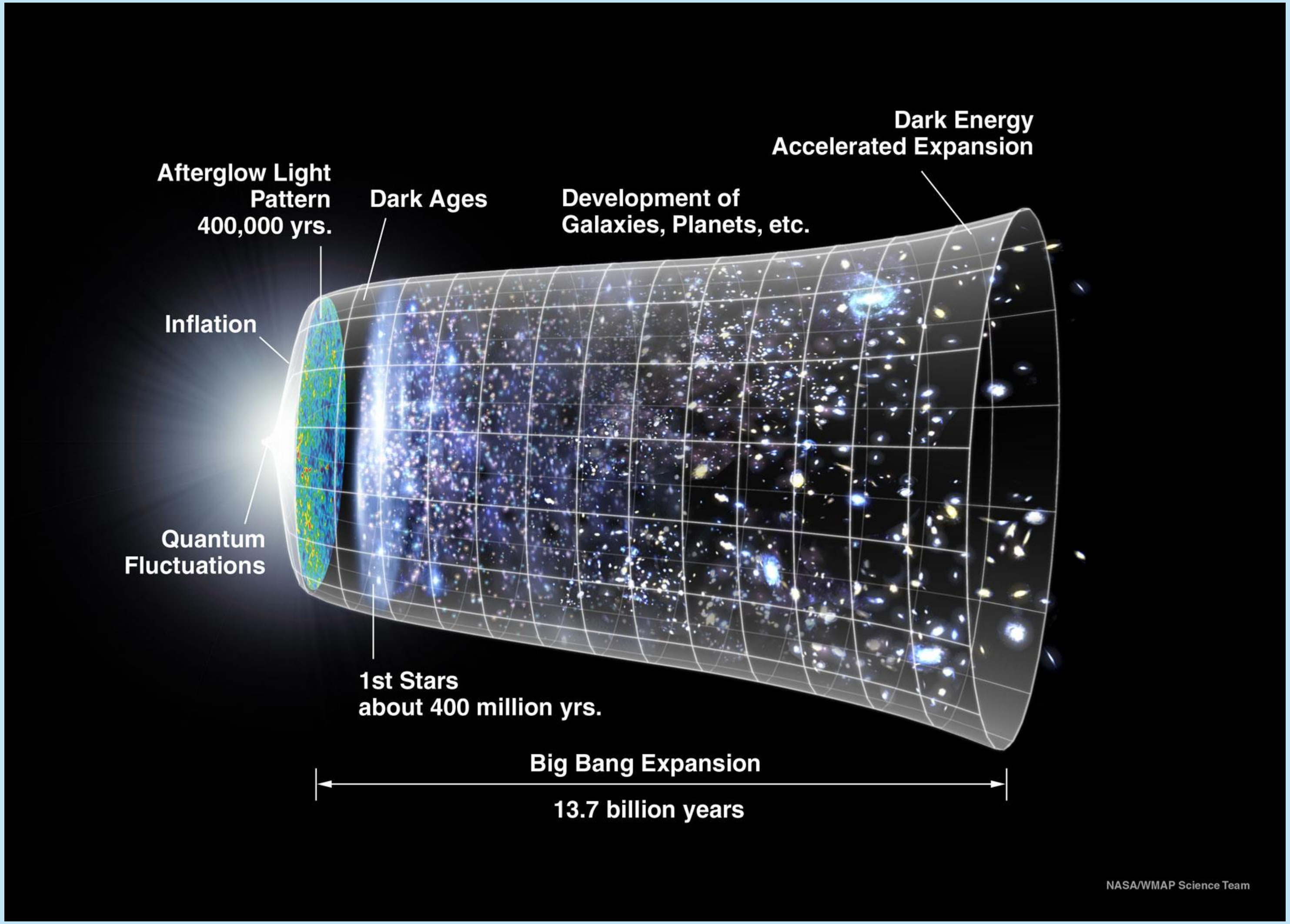
Donkere materie en Donkere energie: Dark sector

[ESA - The cosmic budget of ‘ordinary’ matter]

Hot big bang model

- Heet dicht begin (niet in evenwicht)
- Proces van afkoeling (streven naar evenwicht) via diverse overgangen.
- Afkoeling gaat gepaard met uitdijing
- In het begin inflatie → heelal is vlak



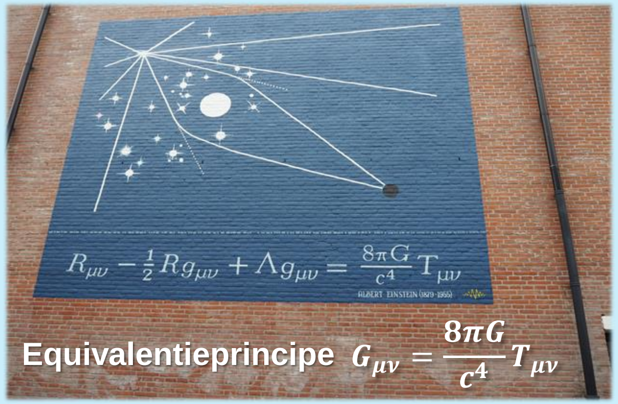


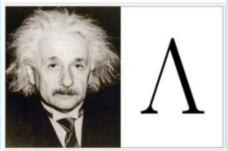
Theorie huidige heelal model

***isotroop** & **homogeen** (bewegende) ideale ‘vloeistof’*

⊕

Algemene relativiteitstheorie





Kosmologische constante
1917

metriek $ds^2 = g_{\mu\nu}dx^{\mu}dy^{\nu}$

$$T_{\mu\nu} = \begin{pmatrix} -\rho(t)c^2 & 0 & 0 & 0 \\ 0 & p(t) & 0 & 0 \\ 0 & 0 & p(t) & 0 \\ 0 & 0 & 0 & p(t) \end{pmatrix}$$

toestandsvergelijking
$p(t) = wc^2\rho(t)$

***Schaal factor** als functie v.d. tijd*

$$ds^2 = -c^2dt^2 + a(t)^2\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + sin^2\theta d\phi^2)\right)$$

Alg. krommingsparameter

Evolutie wordt ‘eenvoudig’ beschreven door een schaal parameter a(t) en energie dichtheden Ω_i

$$\Omega_i = \frac{\rho_i(t)}{\rho_c} = \frac{8\pi G\rho_i(t)}{3H_0^2} \qquad \sum_i \Omega_i = 1$$

Hubble parameter:

$$H(a) = \frac{1}{a(t)}\frac{da(t)}{dt} = H_0\sqrt{\sum_i \Omega_i a^{-3(1+w_i)}}$$

Meten met roodverschuiving $z + 1 = \frac{1}{a(t)}$

$$H(z) = H_0E(z) \qquad E(z) = \sqrt{\sum_i \Omega_i(z+1)^{3(1+w_i)}}$$

Evolutie van de componenten

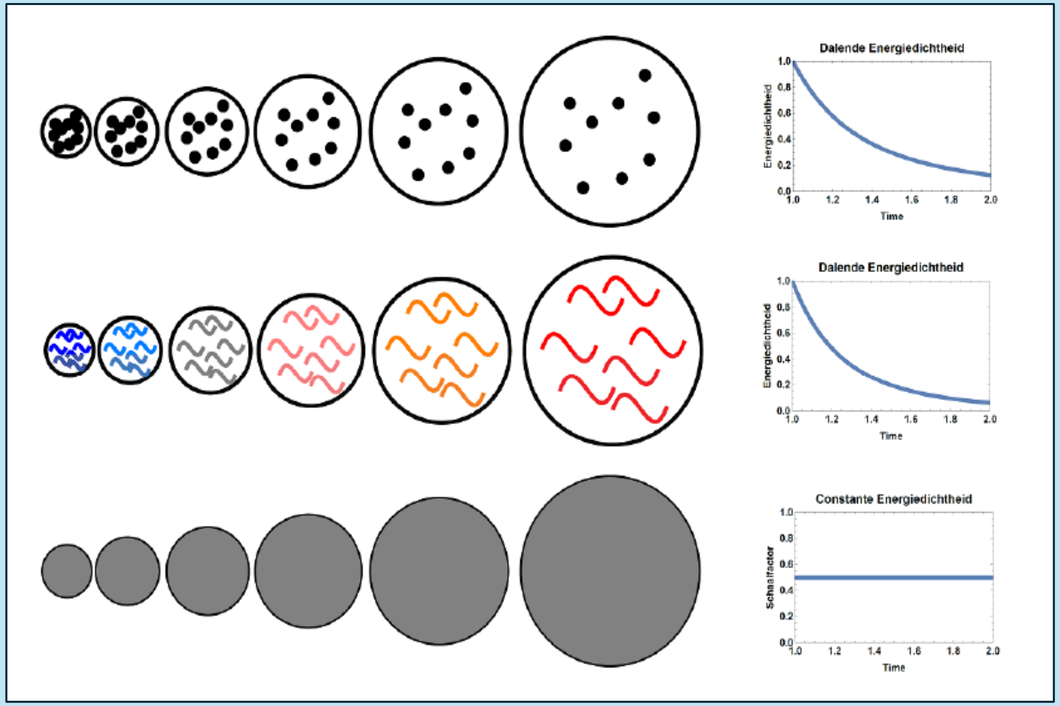
$$p(t) = wc^2\rho(t)$$

$$\Omega_i(t) = \frac{\rho_i(t)}{\rho_c}$$

Ω_m niet relativistisch (materie)

Ω_{rel} relativistisch (straling)

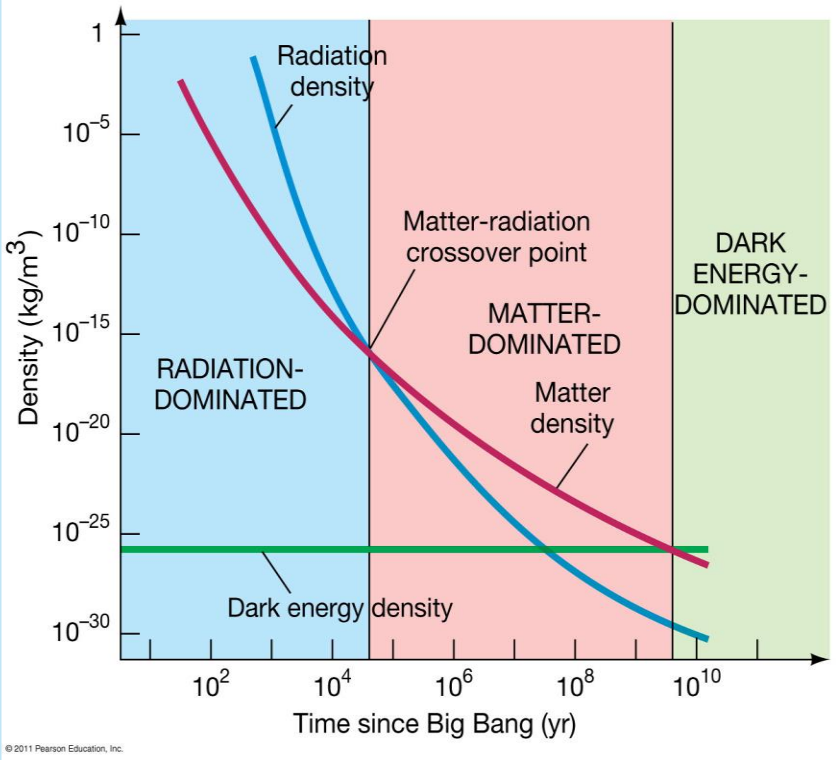
Ω_Λ vacuüm (kosmologische constante)



w=0

w=1/3

w=-1

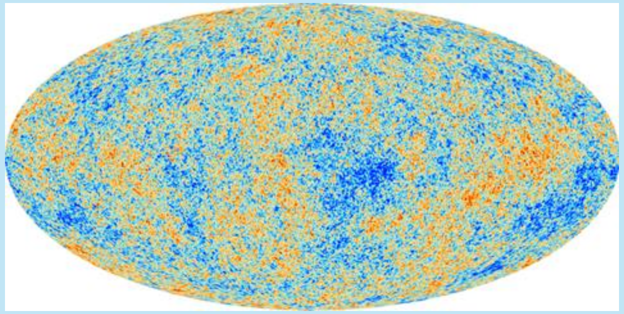


'vlak' heelal: $\Omega_m + \Omega_{rel} + \Omega_\Lambda = 1$

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

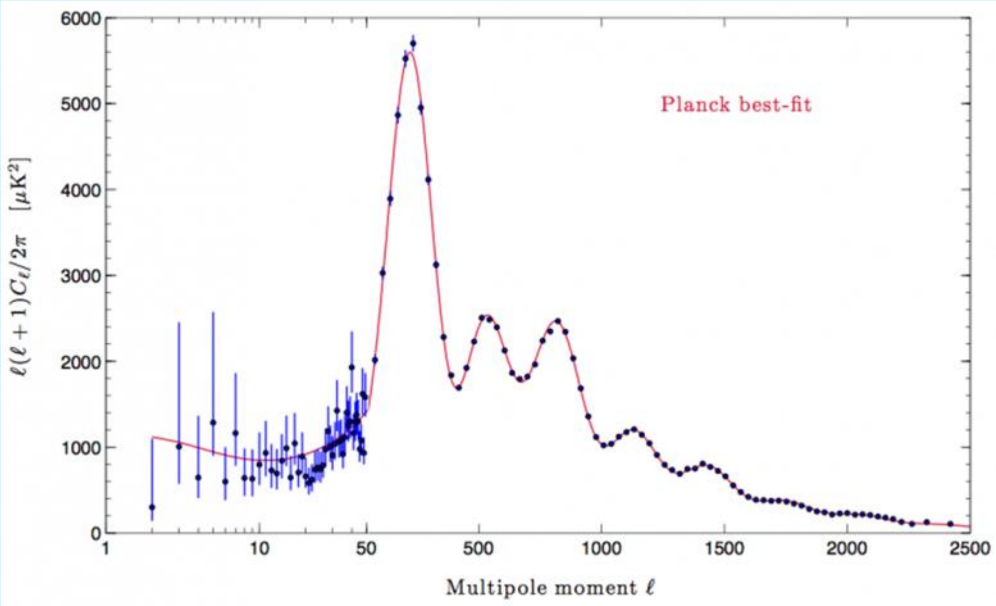
$$E(z) = \sqrt{\sum_i \Omega_i (z+1)^{3(1+w_i)}} \Rightarrow E(z) = \sqrt{\Omega_{rel,0}(1+z)^4 + \Omega_{\mathrm{m},0}(1+z)^3 + \Omega_{\Lambda,0}}$$

Cosmic microwave background



Plank satelliet (2009 -2013)

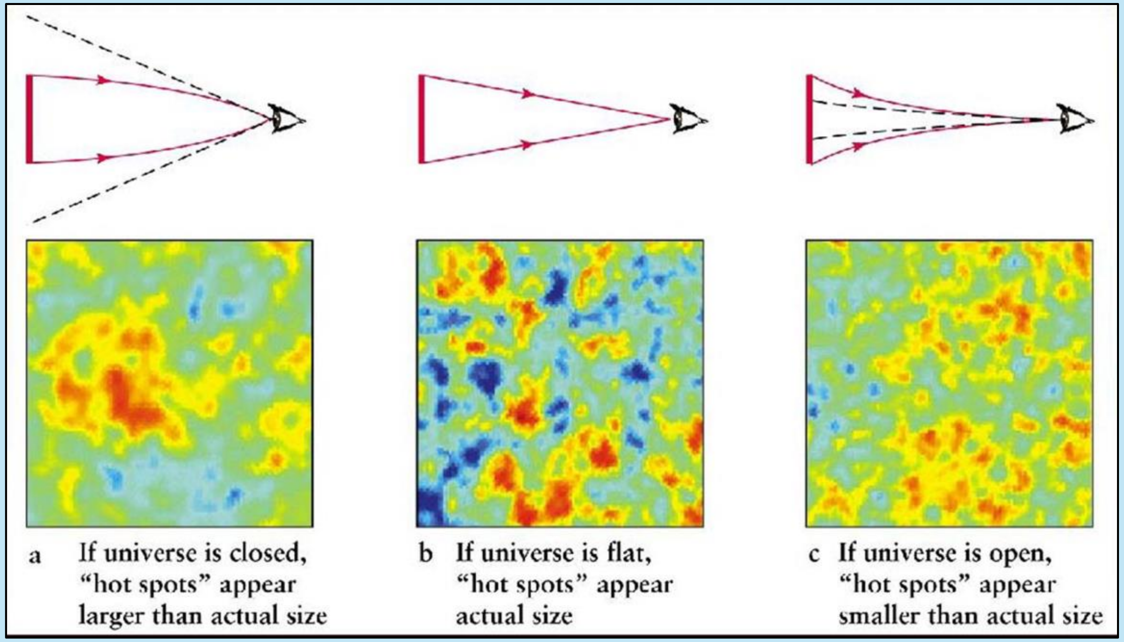
Kaart van de 3 Kelvin achtergrond straling (baby foto heelal)



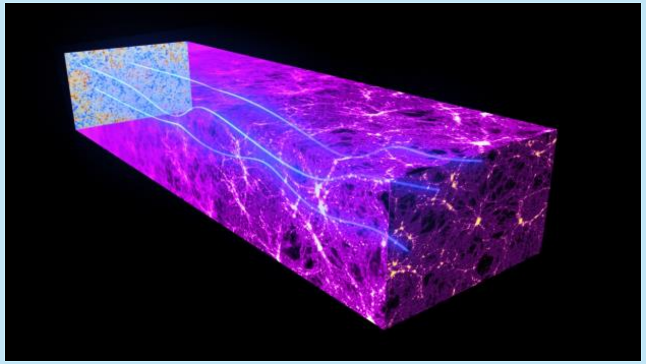
Piek 1: totale energie dichtheid
Piek 2: verhouding piek 2 en piek 3: baryonische materie
Piek 3: dichtheid (donkere) materie

Positie grote piek ←

CMB: ondersteuning vlak heelal



Vlak heelal: evenwijdige lichtbanen blijven evenwijdig



[Shape of the universe - Wikipedia]

Heropleving kosmologische constante Λ → Ω_Λ

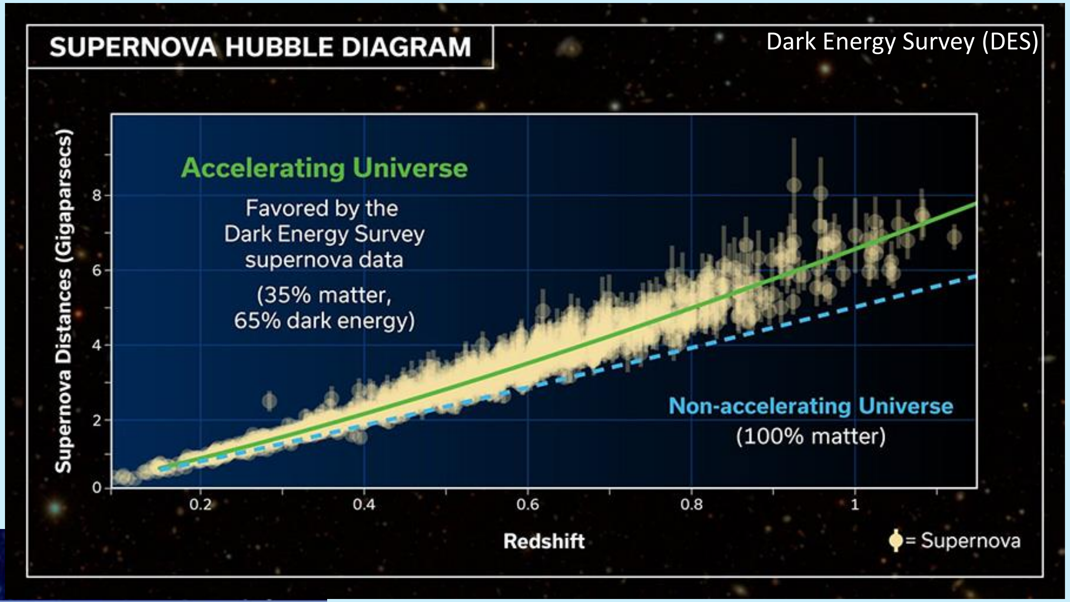
Λ terzijde geschoven want expanderend heelal → Einstein-De Sitter heelal (vlak heelal met alleen materie, 1932)

Jaren 60/70: $\Omega_{tot} \approx 1$ & $\Omega_m \sim 0.2-0.3$ → heelal vlak dus 'missing mass'

Zoeken naar deze massa met preciezere waarnemingen (terugkijken met hogere roodverschuiving z)

The high-z team (Adam Riess) meten Type Ia supernovae

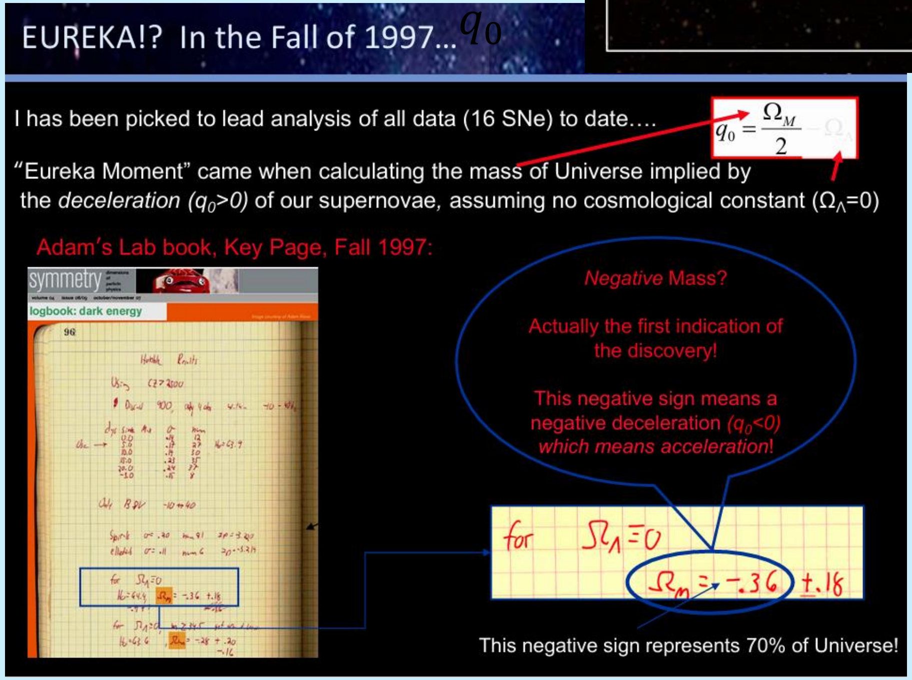
$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} = \frac{1}{2}\Omega_m$$

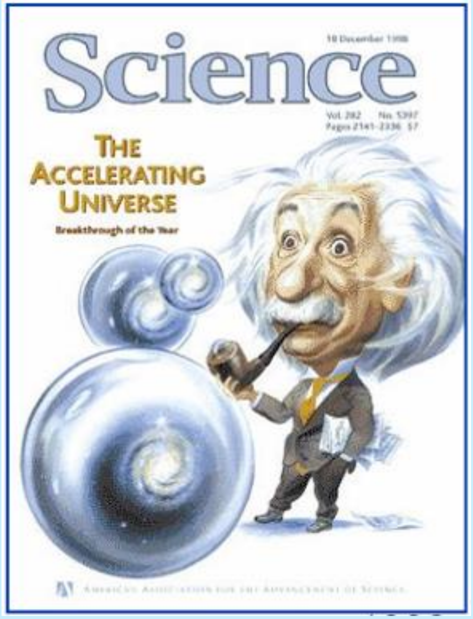


Riess mat een negatieve massa
→ Ω_Λ weer een optie

$$q_0 = \frac{1}{2}\Omega_m - \Omega_\Lambda$$

Ω_Λ werkt tegen (w=-1). Tegendruk



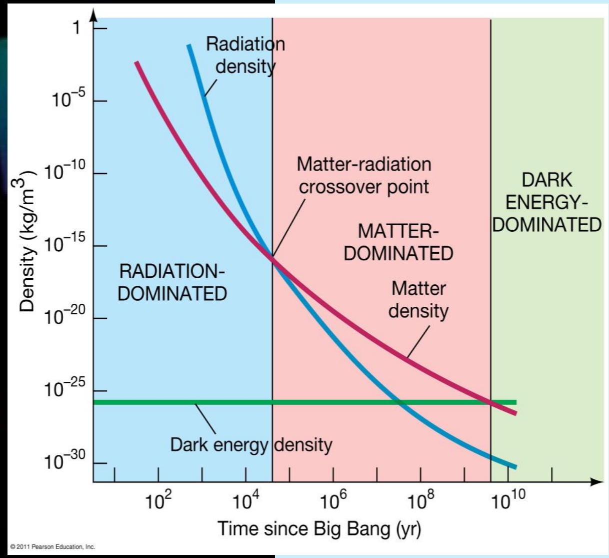


Dec.1998

Microsoft Word - shawlecture.doc
An interview with Nobel Laureate Adam Riess | EP News

Interpretatie Λ als Dark energy

$w \equiv p/\rho$

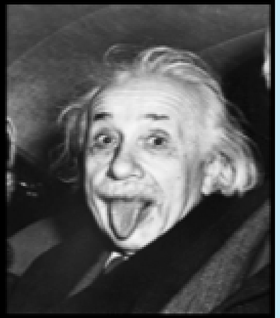


1. **Static Vacuum Energy, (the cosmological constant)**

A constant energy of empty space, expected in QM, consequence in GR--repulsive gravity, now $\Omega_{DE} \geq \Omega_M$ (but the coincidence problem & the 10^{120} problem)

2. **Dynamical dark energy**

A field with energy pervades space, changes with time (e.g., “inflation-lite”)



3. **Modification to GR—long range**

Maybe GR fails at long range, modification as scale approaches present horizon

Tests of all 3: is DE strength constant, evolving, scale-dependent?

Donkere energie als vacuüm energie (een echte kosmologische constante)?

Vacuüm energie als nulpuntsenergie van 'alle' kwantumvelden.

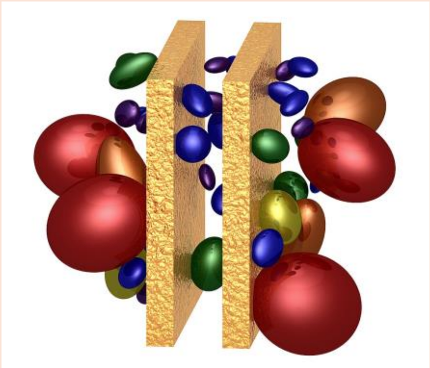
Kwantumveld met hoogste energie meeste impact
→ Planck of GUT schaal

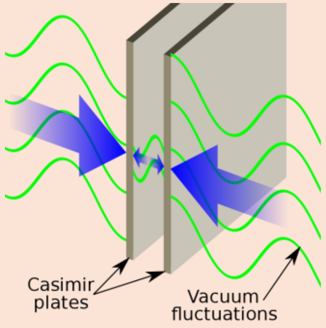
Nulpuntsenergie door onzekerheid

$$\Delta p \Delta r \sim h \xrightarrow[\Delta r = l_{pl}]{p = \frac{E}{c}} \Delta E \sim \frac{hc}{l_{pl}}$$

Vacuüm energiedichtheid

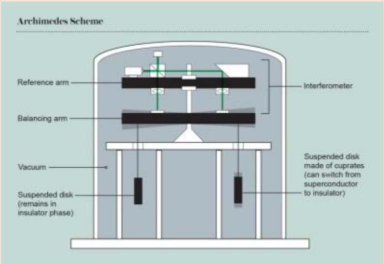
$$\rho_{vac} \sim \frac{\Delta E}{{l_{pl}}^3} \sim \frac{hc}{{l_{pl}}^4} \quad \& \quad l_{pl} = \sqrt{\frac{hG}{c^3}}$$





The Casimir effect, aantrekkende werking

Vacuüm energie 120 orde groter dan waargenomen Ω_Λ



Archimedes experiment

Heeft deze 'energie' wel invloed op de gravitatie?

[Cosmological constant problem - Wikipedia]

[The Cosmological Constant - Sean M. Carroll]

[How Much Does 'Nothing' Weigh? | Scientific American]

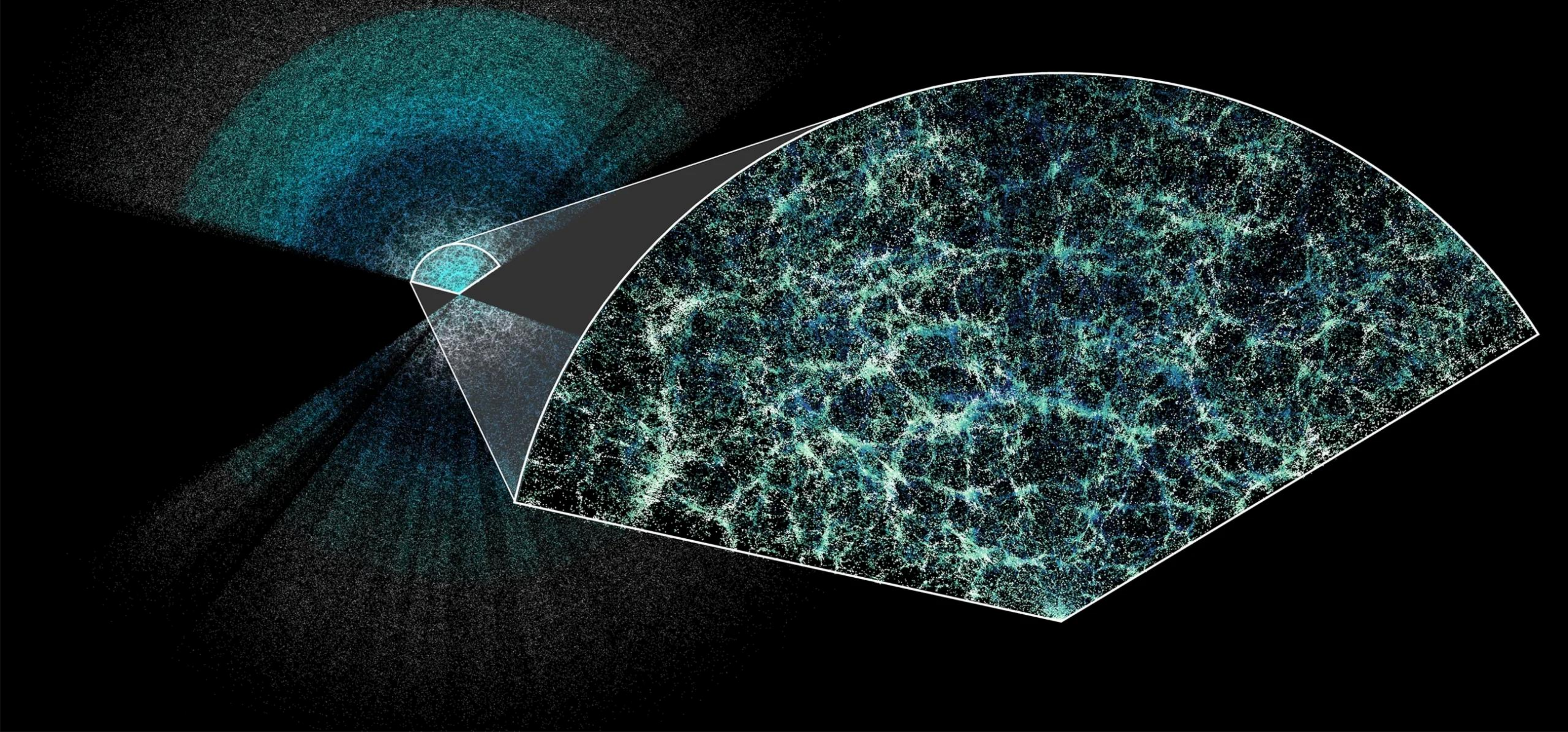
Hoe zouden we DE en eventuele verandering dan kunnen waarnemen, wat zouden we dan moeten doen?

NRC 10 april 2024:

``Opwindend nieuws voor fysici: donkere energie gedraagt zich mogelijk anders dan verwacht''

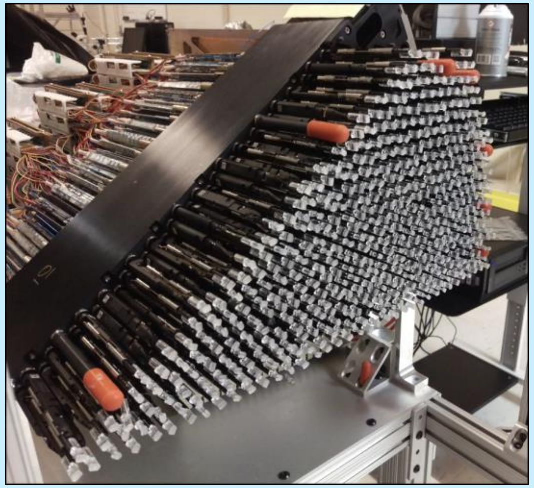
Dark Energy Spectroscopic Instrument (DESI):

3D kaart van 40 miljoen sterrenstelsels in 5 jaar tijd tot een roodverschuiving van ongeveer 2.4 (11 miljard jaar terug)

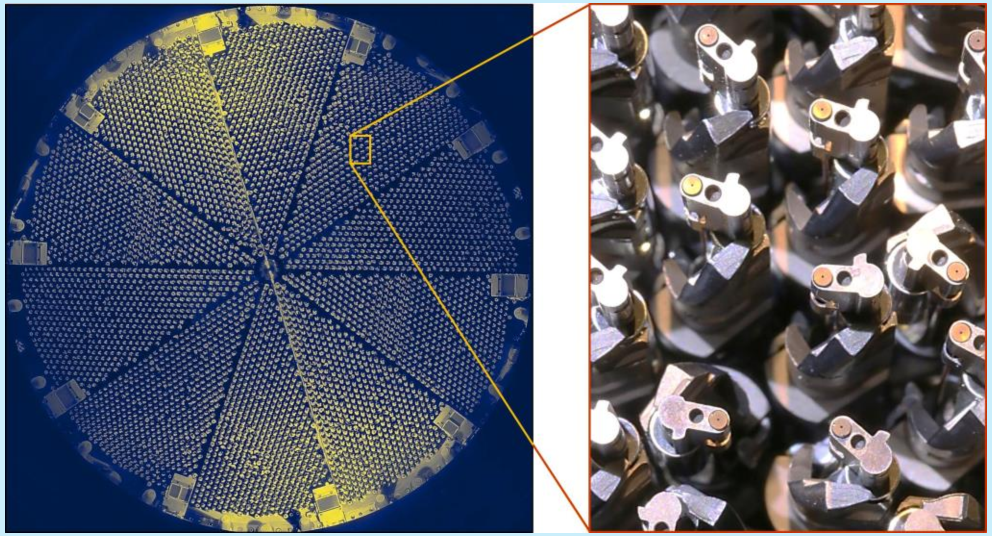


The DESI instrument is equipped with thousands of robotic fibers to dramatically speed up data collection

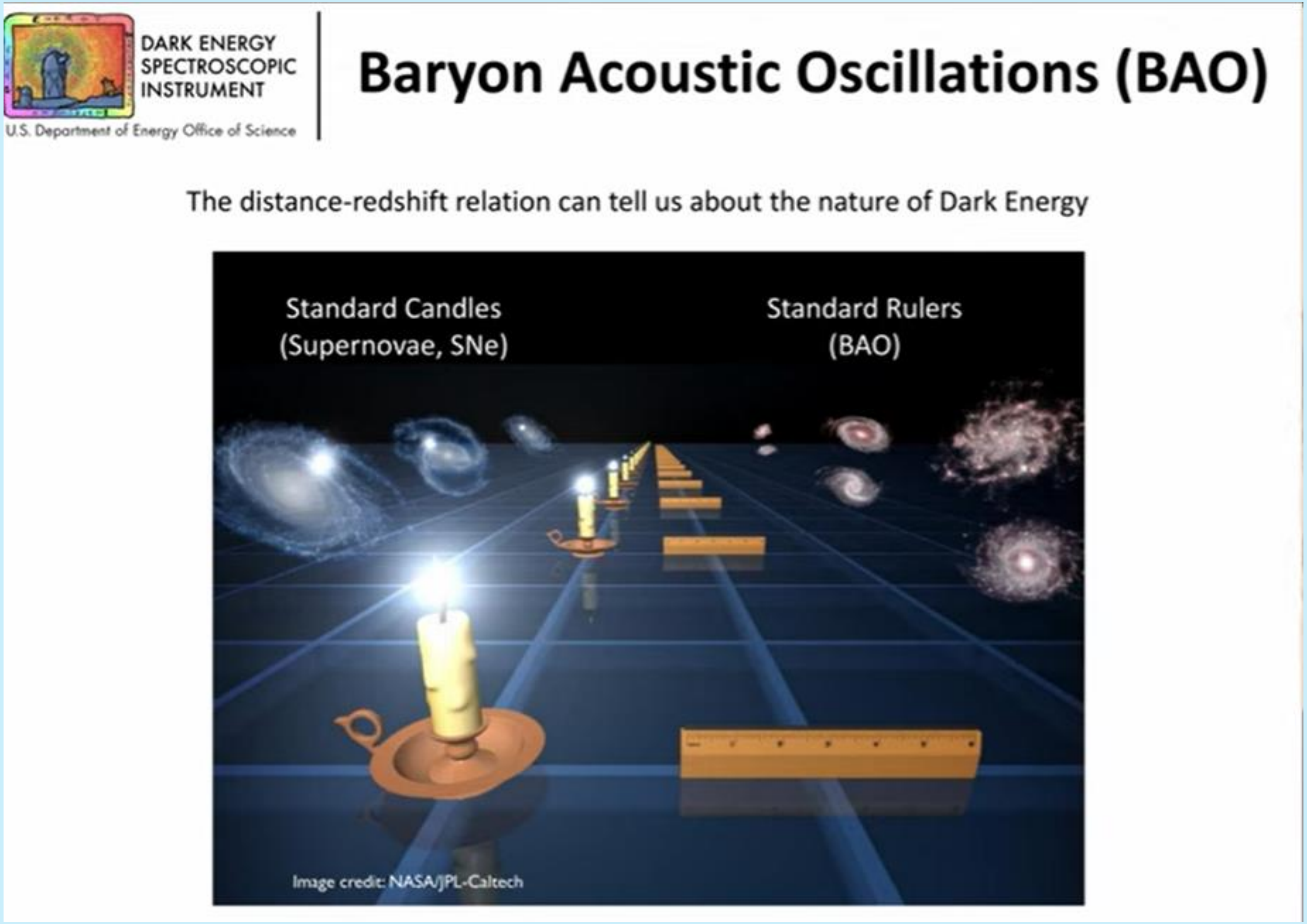
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science



5000 robotic positioners

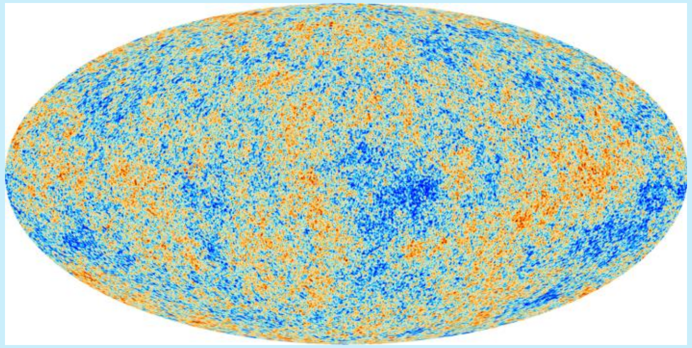


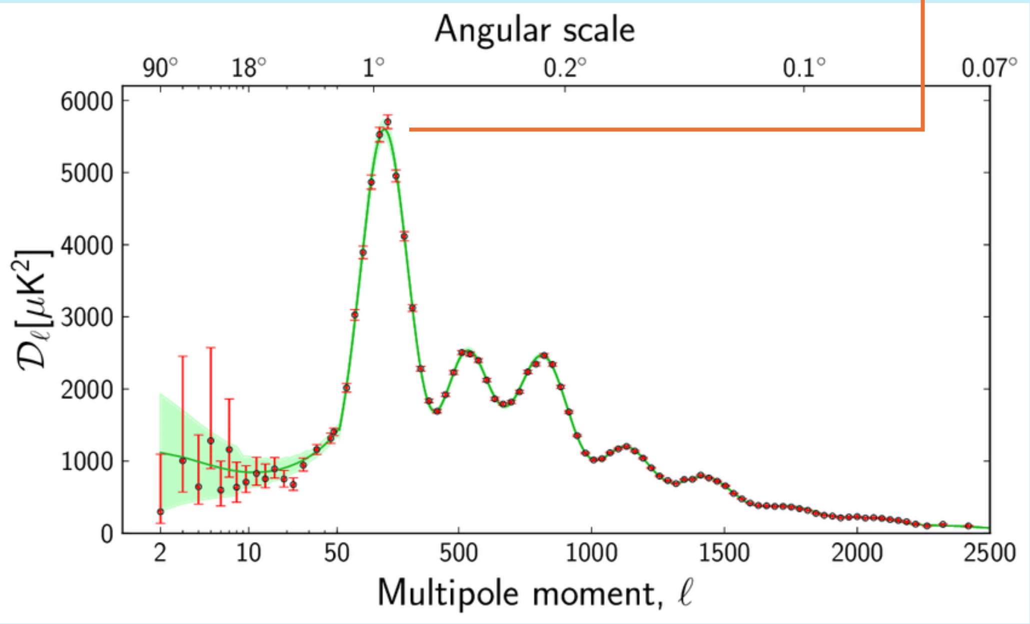
Baryon Acoustic Oscillations (BAO) and type-Ia supernovae

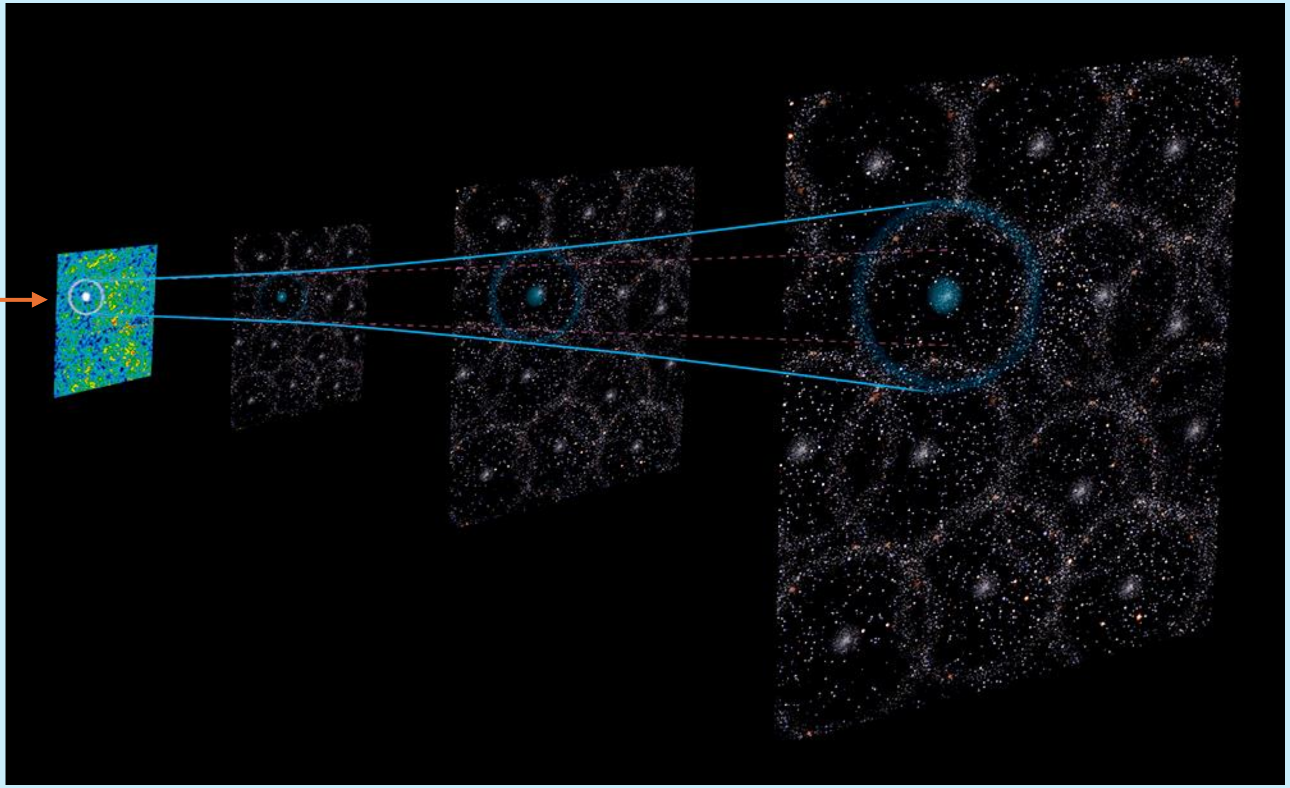


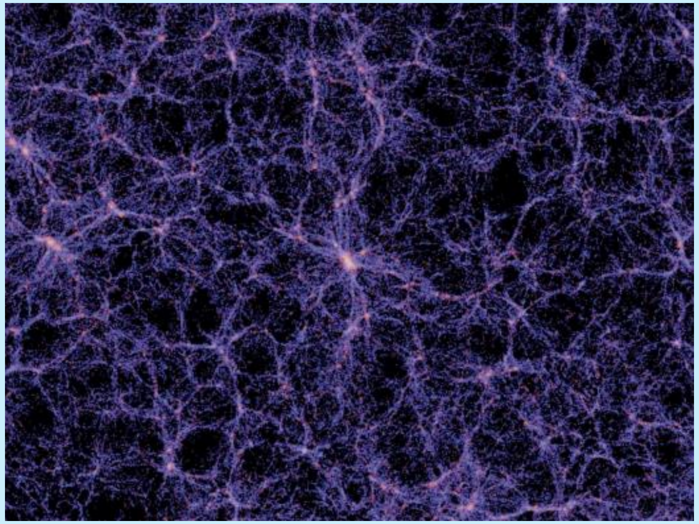
Wat zijn de verschillen tussen een Standard Candle en een Standard Ruler?

Cosmic Ruler (BAO)
‘’BAO bubbles”





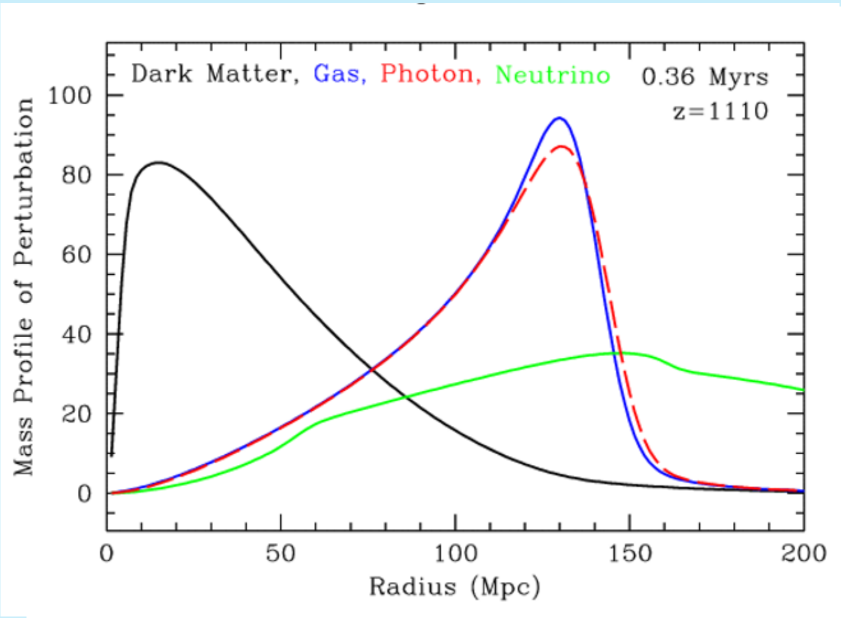




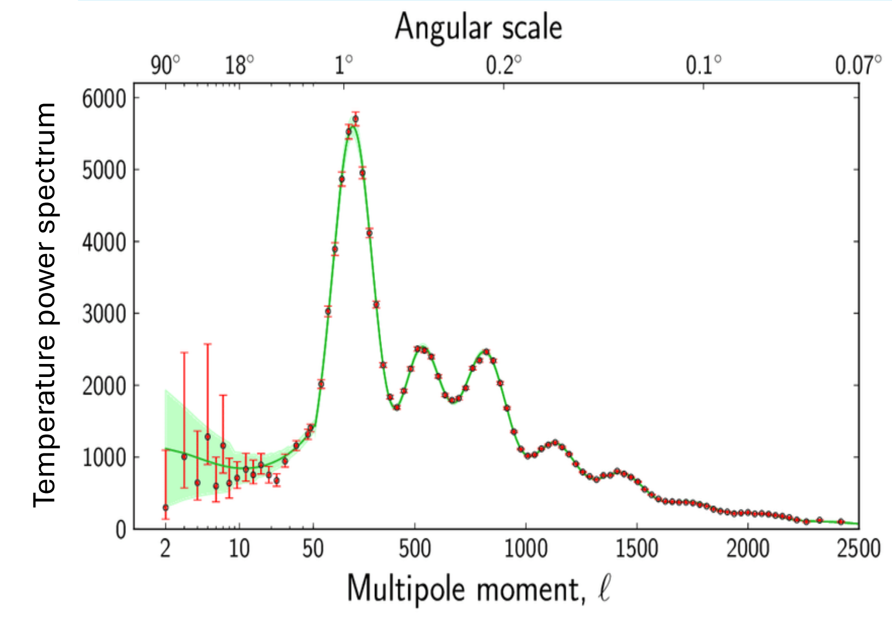
Cosmic web

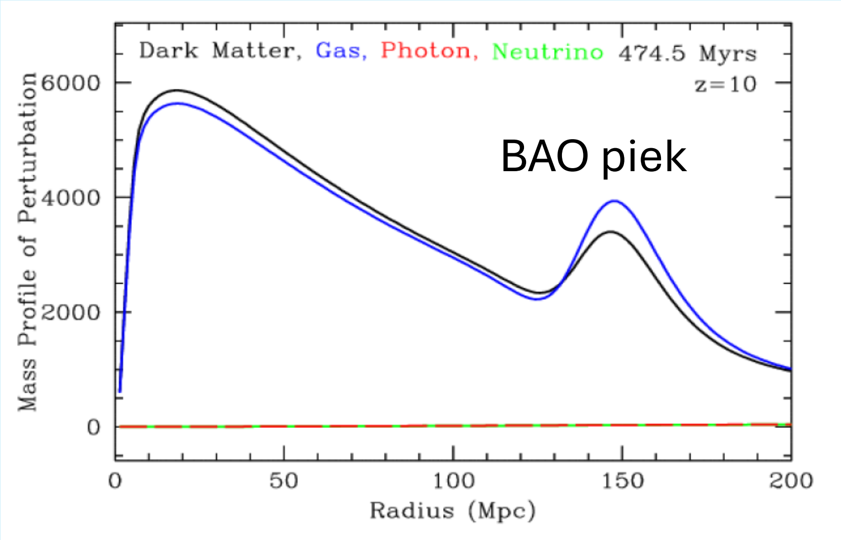
A characteristic scale is imprinted in the distribution of matter at the sound horizon
$r_d \approx 150$ Mpc

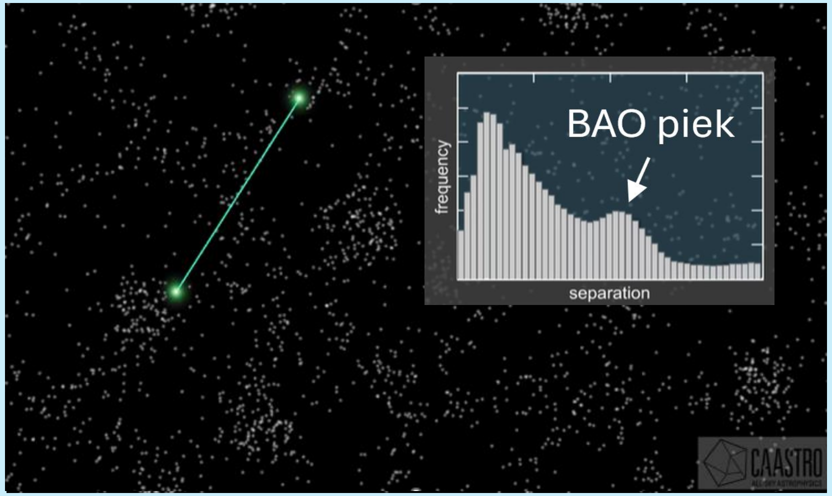
Cosmic Ruler (BAO)



sound horizon

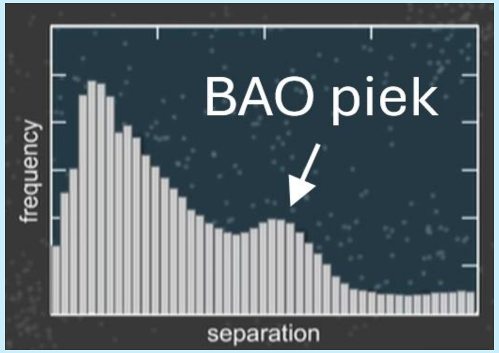






Cosmology Research   What is the Acoustic Peak?   Correlation function (astronomy) - Wikipedia

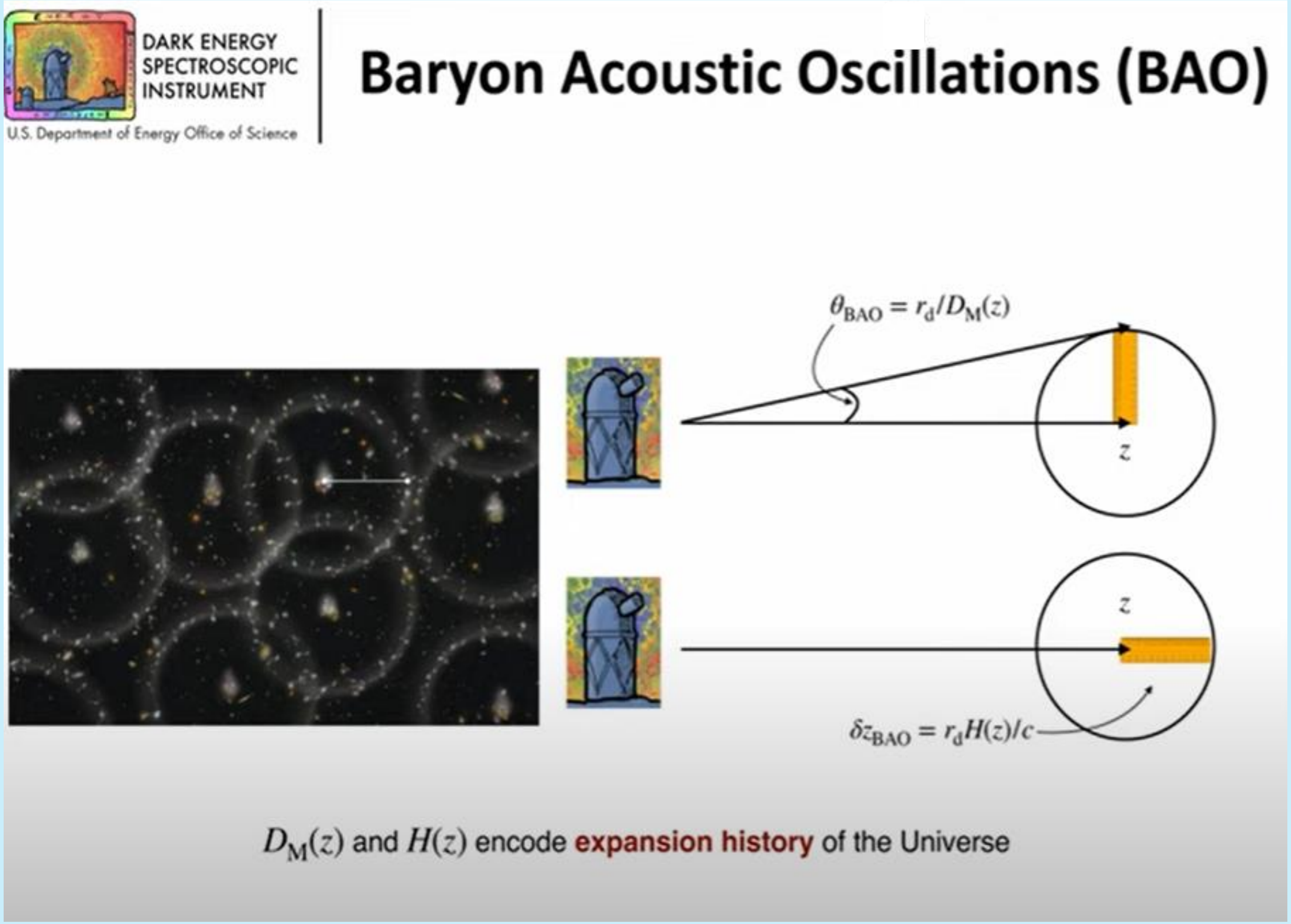
BAO bubbles: hoe te meten?



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

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

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

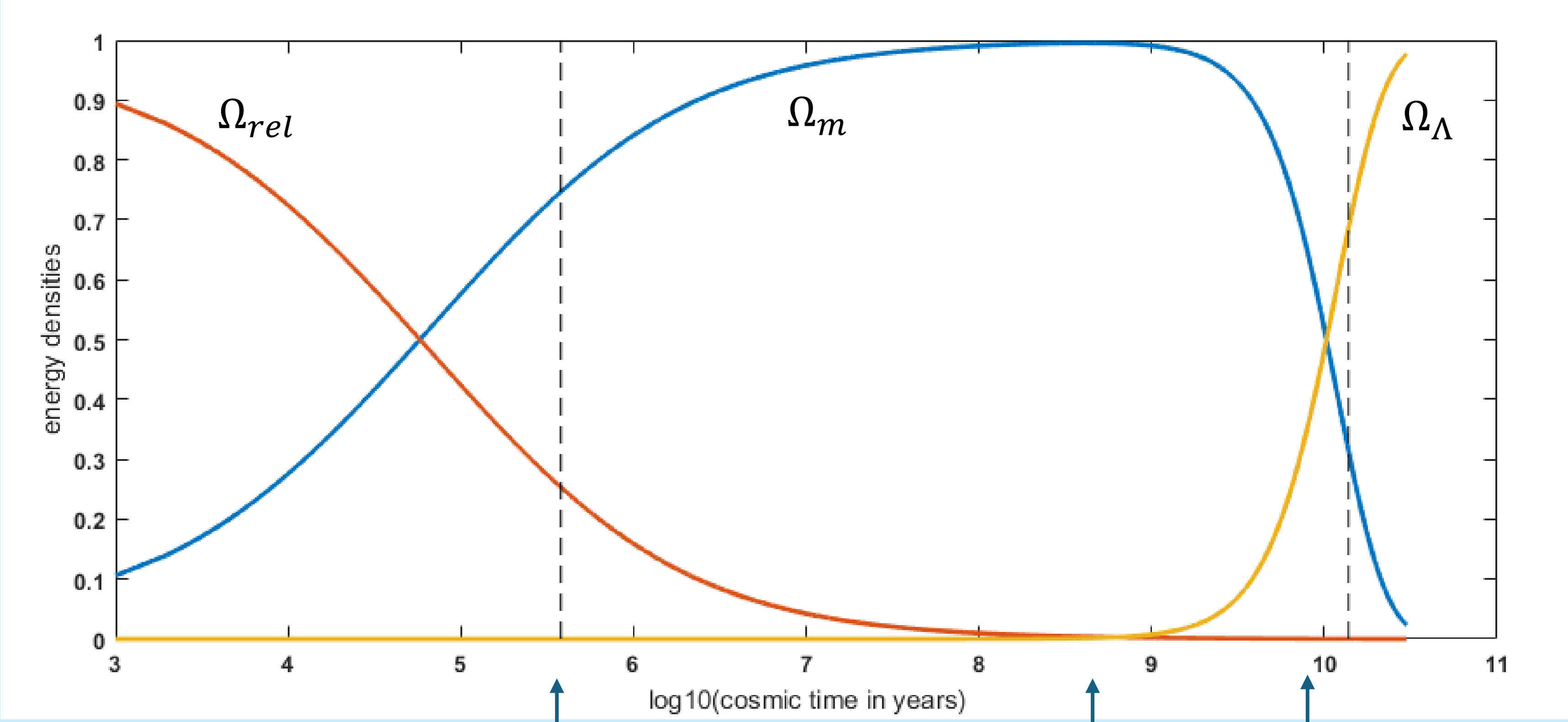


Invloed donkere energie is alleen ‘recentelijk’ te merken

Planck waarneming CMB:

- gevoelig voor inflatie en materie versus straling,
- niet zozeer donkere energie (wel late time SW effect)

BAO



Inital conditions

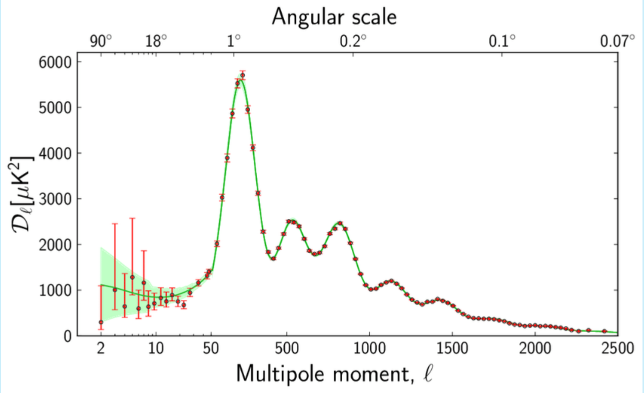
End of inflation &
Quantum Fluctuations
BBN
Neutrino decoupling

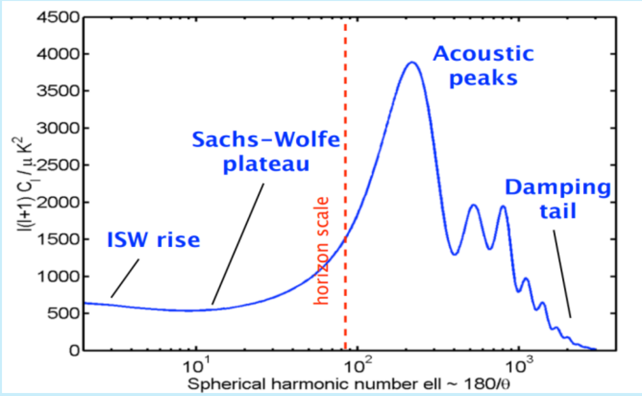
CMB
Photon decoupling
380,000y

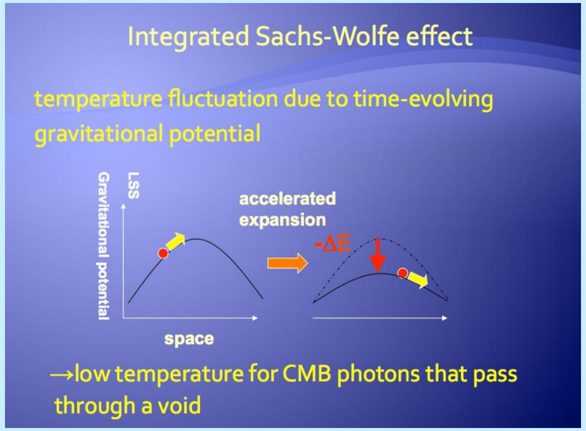
Reionisation
(600 My – 1GY)

late-time
integrated Sachs–
Wolfe

Late time SW invloed op CMB

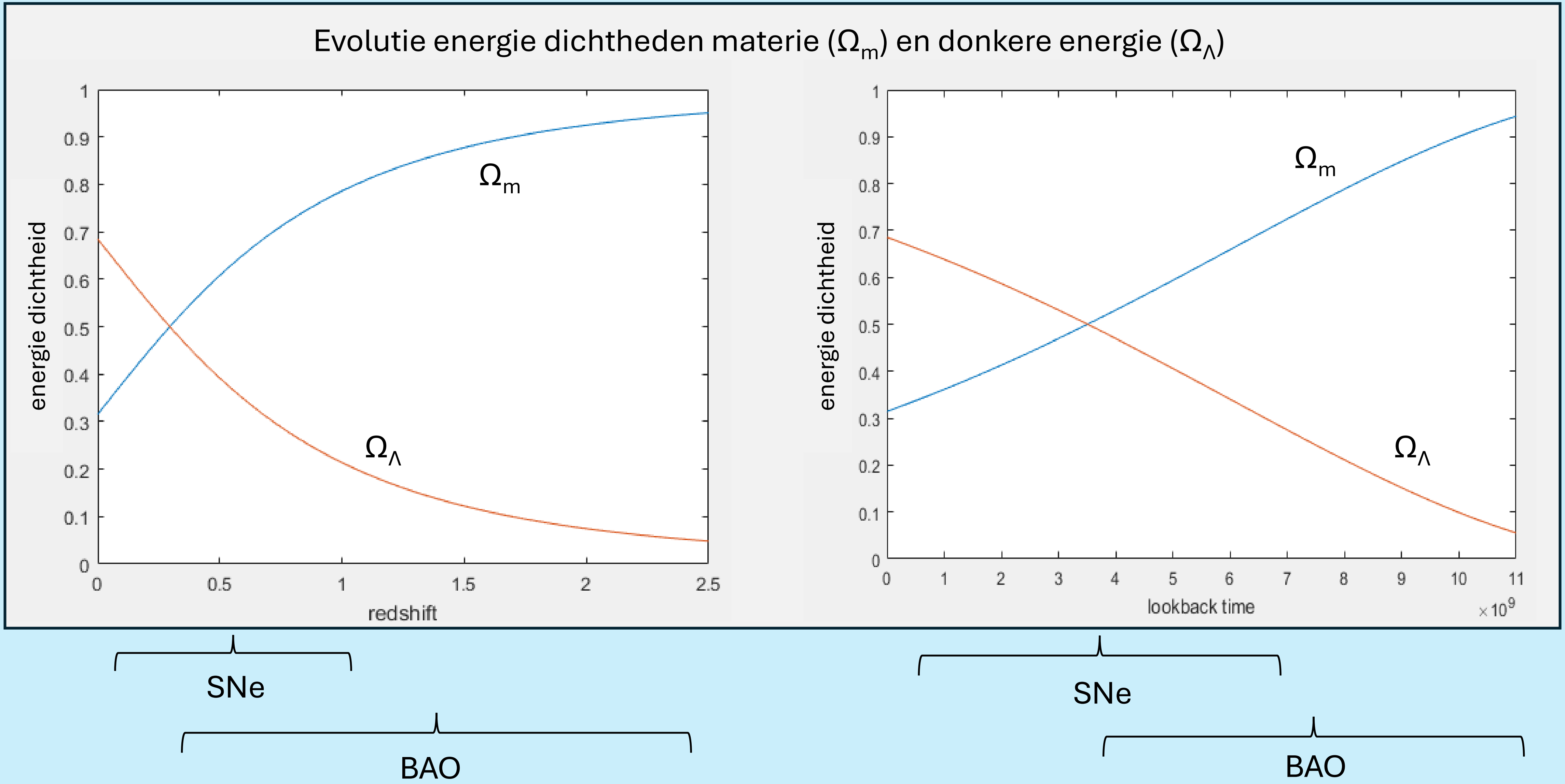






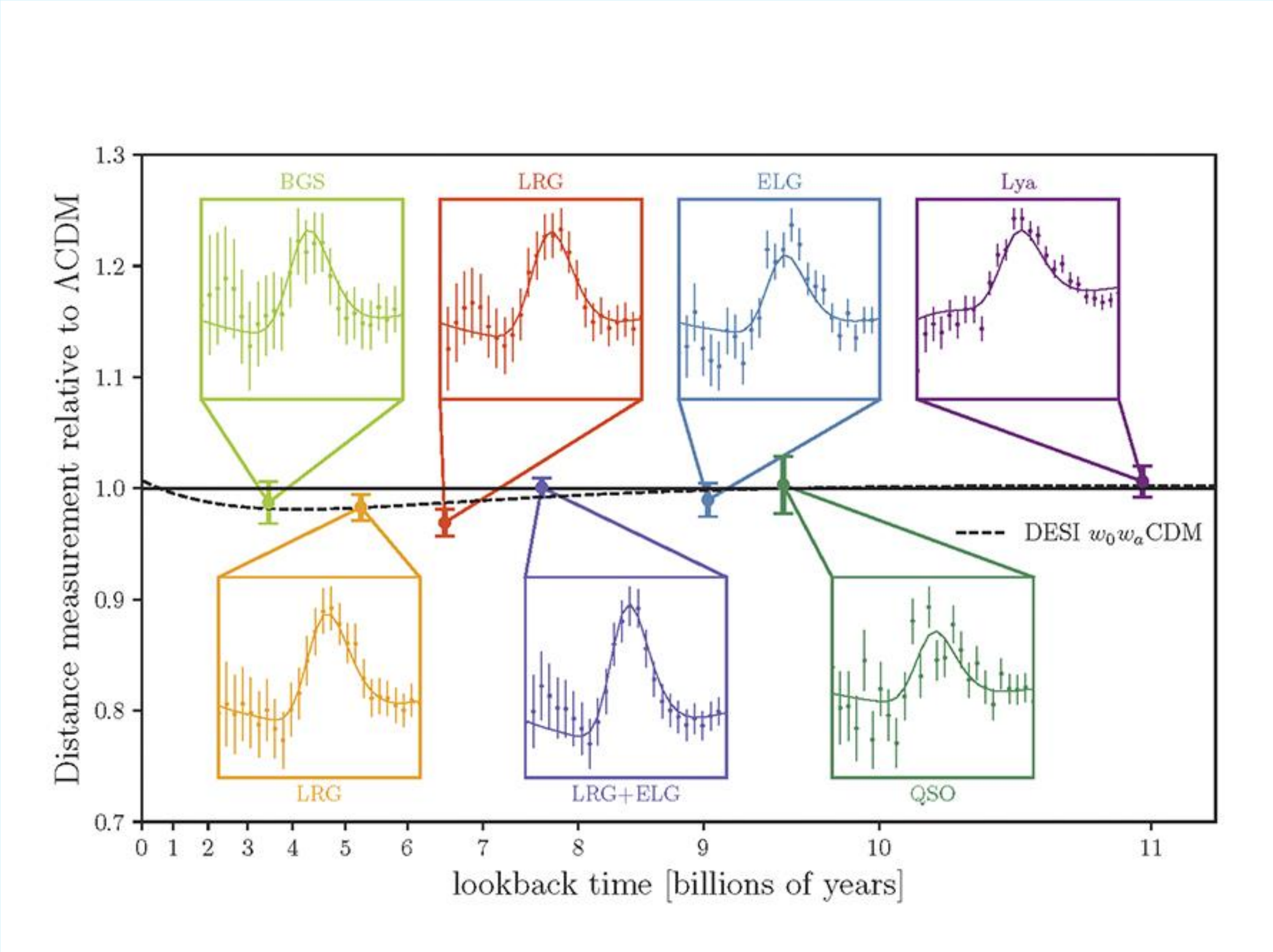
Sachs–Wolfe effect - Wikipedia

Waarneembereik supernovae techniek en BAO techniek



Waarom zijn BAO en SNe complementair?

“Vereenvoudigd” overzicht resultaten van de eerste data release DESI



BGS: Bright Galaxy Sample (0.1 < z < 0.4)

LRG: Luminous Red Galaxy Sample (0.4 < z < 0.6)

LRG: The Luminous Red Galaxy Sample (0.6 < z < 0.8)

LRG+ELG: The combined LRG and ELG Sample (0.8 < z < 1.1)

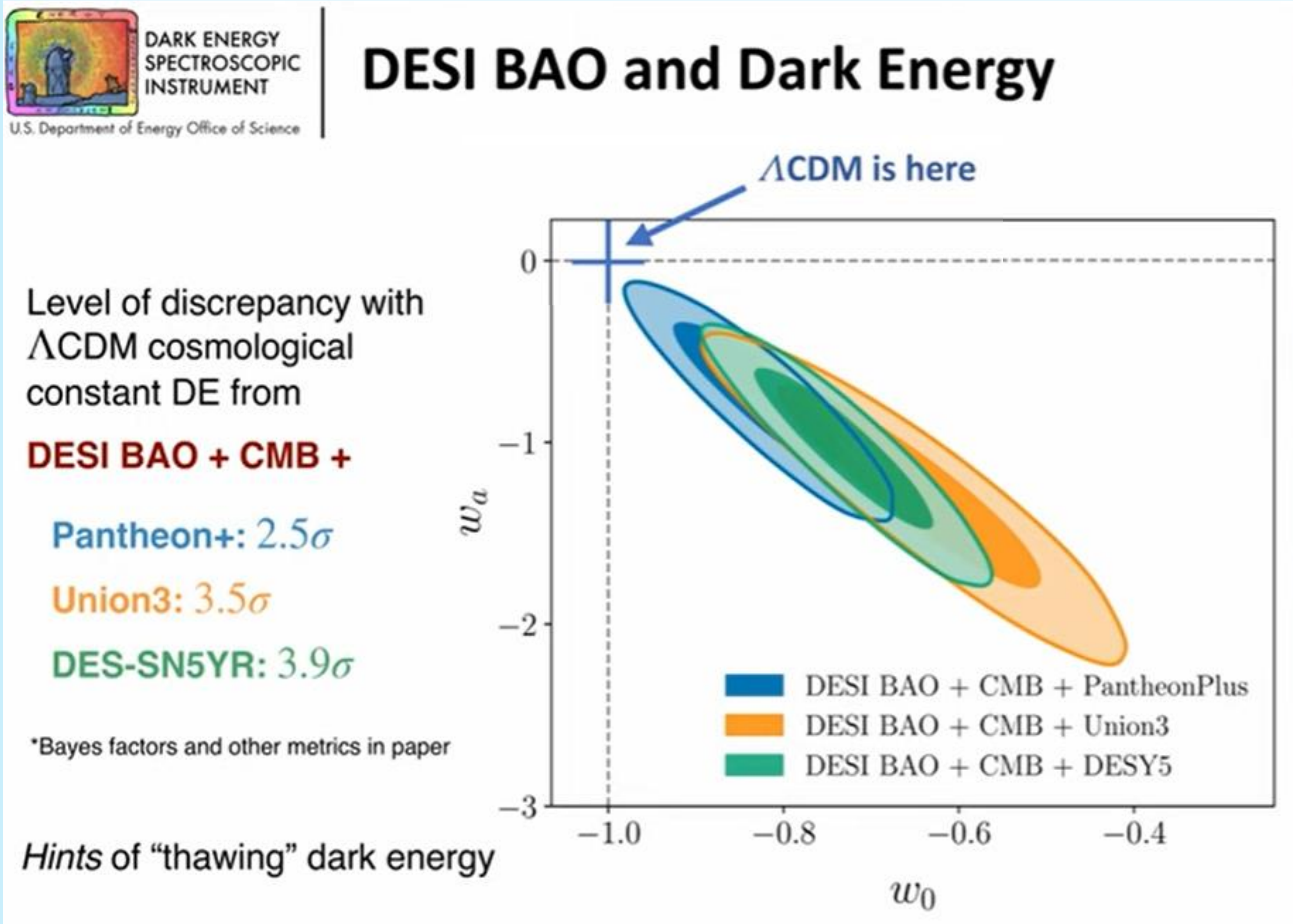
ELG: Emission Line Galaxy Sample (1.1 < z < 1.6)

QSO: Quasar Sample (0.8 < z < 2.1)

Lyα: Lyman-α Forest Sample (1.77 < z < 4.16)

DESI’s Hubble diagram plots a characteristic pattern – baryon acoustic oscillations, or BAO “bubbles” – at different ages of the universe. The amount of dark energy determines how fast the universe grows, and therefore the size of the bubbles. The solid line is how big Lambda CDM predicts the bubbles will be, while the dashed line shows the prediction from a different model where dark energy evolves with time. DESI will gather more data to determine which model is a better description of the universe. (Credit: Arnaud de Mattia/DESI collaboration)

Hint van afzwakkende donkere energy



SNe Ia surveys: PantheonPlus, Union3 and DESY5

CPL parametrisatie om verandering te testen, niet om een fysische verklaring te geven

$$w(a) = w_0 + w_a(1 - a) = w_0 + w_a \frac{1}{1+z}$$

Chevallier-Polarski-Linder (CPL) parametrization *(2001)*

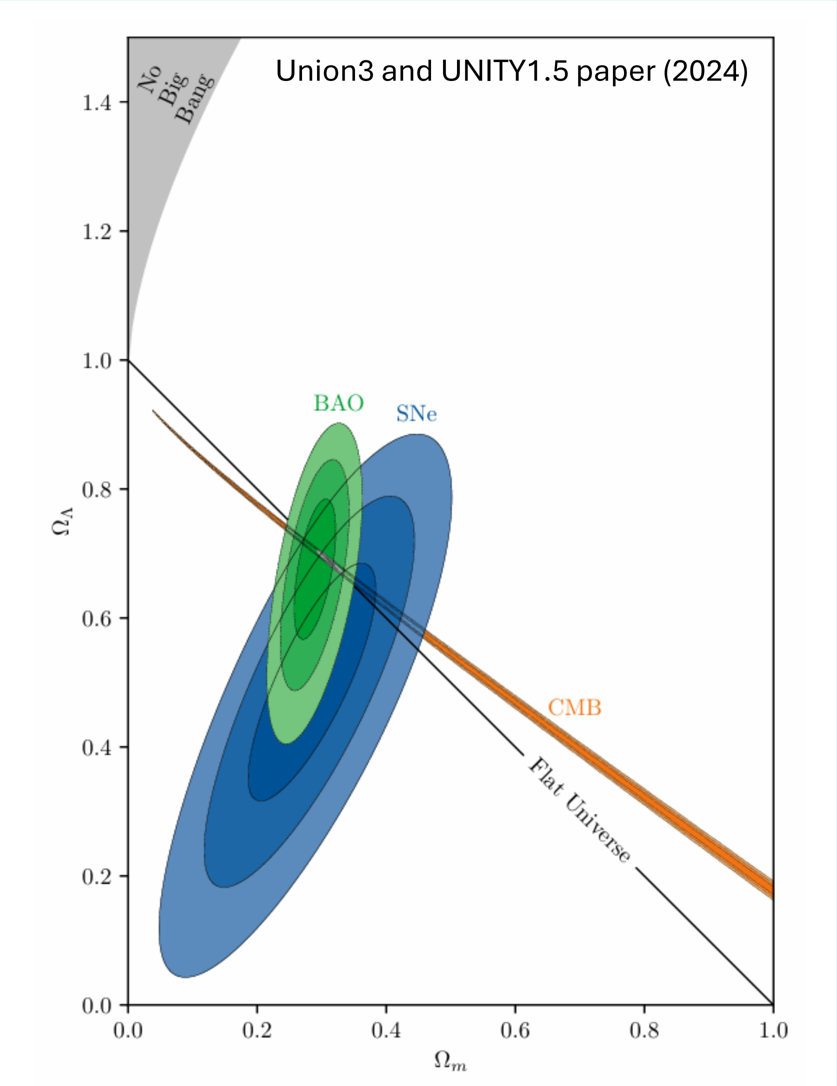
$$H(z) = H_0 E(z)$$

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

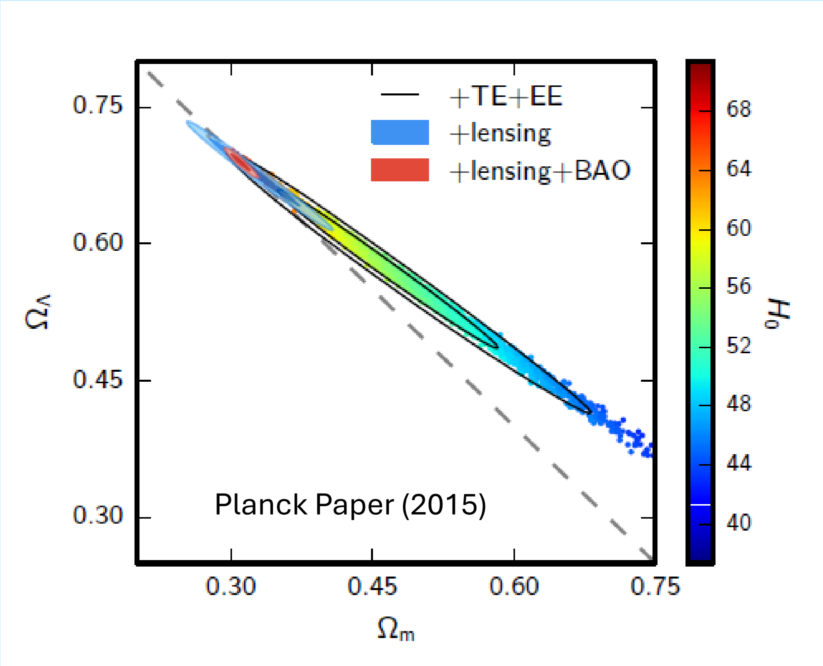
Evoluerende donkere energie?

$$\Omega_{\Lambda,0} \rightarrow \Omega_{\Lambda,0}(1+z)^{3(1+w_0+w_a)} e^{-3w_a z/(z+1)}$$

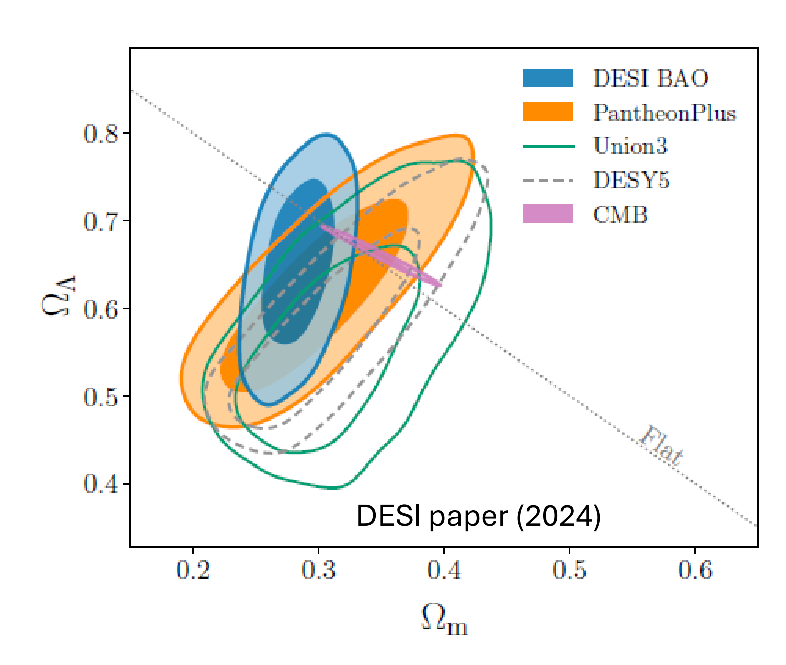
Nauwkeuriger bepaling Ω_Λ door combineren diverse waarneembronnen



Supernovae cosmology projects



Flat → $\Omega_m + \Omega_\Lambda = 1$



Inverse cosmic distance ladder (redshift drift i.p.v. BOA)

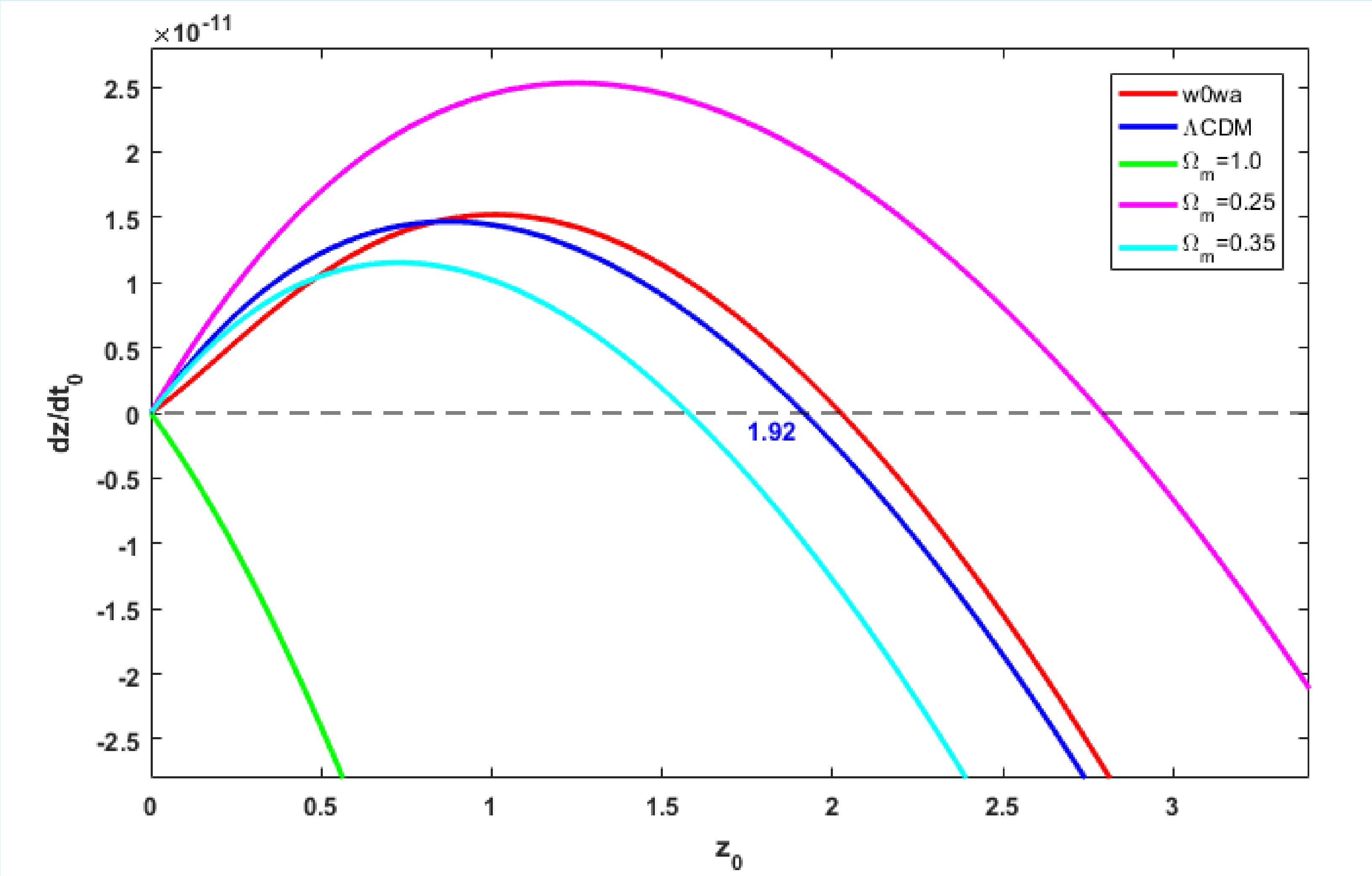
Directe meting van $H(z)$

Redshift drift:

$$\dot{z} = H_0(z+1) - H(z)$$

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

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



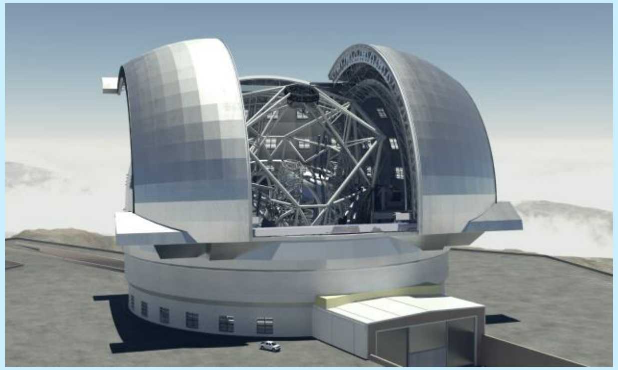
Standard rulers, however, use a **reverse distance ladder** which does not directly measure H0. Instead, measurements are made of H(z) (the Hubble parameter at redshift z), and a cosmological model is used to infer the value of H0.

Toekomstige waarnemingen

- **DESI**
- **EUCLID**
- **Rubin**
- **Roman**
- **ELT**
- ….

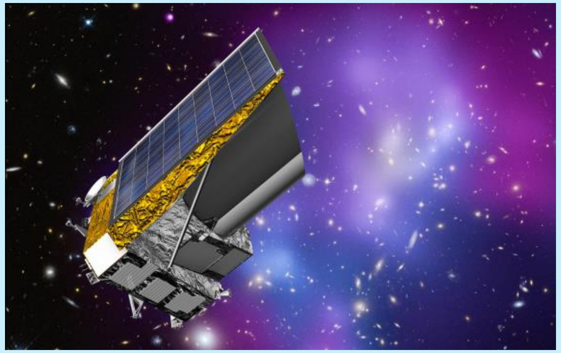
DESI with combined efforts of **Euclid, ELT, Roman, and Rubin** will usher in a new “golden age” of cosmology

DESI (survey, BAO, 2019)



Extremely Large Telescope (**ELT**)
(redshift drift, SNe, BAO, weak lensing, 2028)

Vera C. **Rubin** Observatory
(survey, SNe, BAO, weak lensing, 2025)



EUCLID (survey, weak lensing, BAO, 2023)

Nancy Grace **Roman** Space Telescope
(survey, weak lensing, BOA, SNe, 2027)

Is donkere energie een idee of werkelijkheid?

Wat vinden jullie?

Welke fysische verklaringen zouden er kunnen zijn voor DE denken jullie?

Mogelijkheden voor DE

- Scalaire velden, Quintessence
- Interacting (decaying) dark energy/dark matter
- Early dark energy (EDE)
- Modifications to General Relativity
- Timescape/inhomogeneous cosmology (loslaten homogeniteit/isotropie)
- Non singular BH coupling to DE (cosmologically coupled black holes - CCBH)
- …

Rekening houdend met de ruimte die de waarnemingen (CMB, BOA, SNe, etc) bieden

Dark sector
(boeket van componenten en interacties)

Changing DE

Early DE

Inflaton

[Inhomogeneous cosmology - Wikipedia]

[New supernova analysis reframes dark energy debate]

[Nonsingular black hole models - Wikipedia]

[Black holes that form in 'reverse Big Bang replays' could account for dark energy | Space]

Changing DE, fysische interpretatie

An Introduction to Cosmological Inflation - A.R. Liddle

Quintessence (physics) - Wikipedia

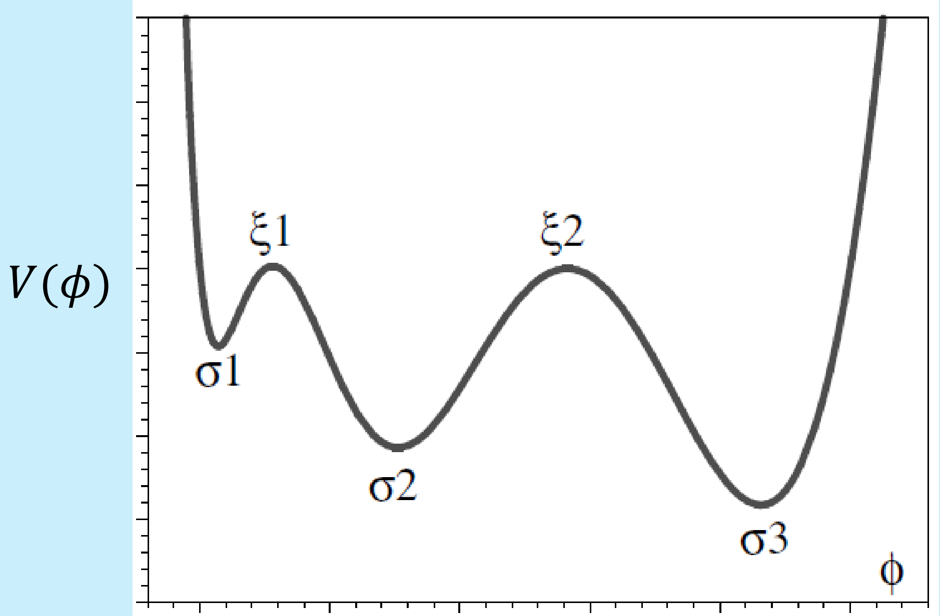
Scalaire velden,

- Quintessence
- Inflatie
- Higgs

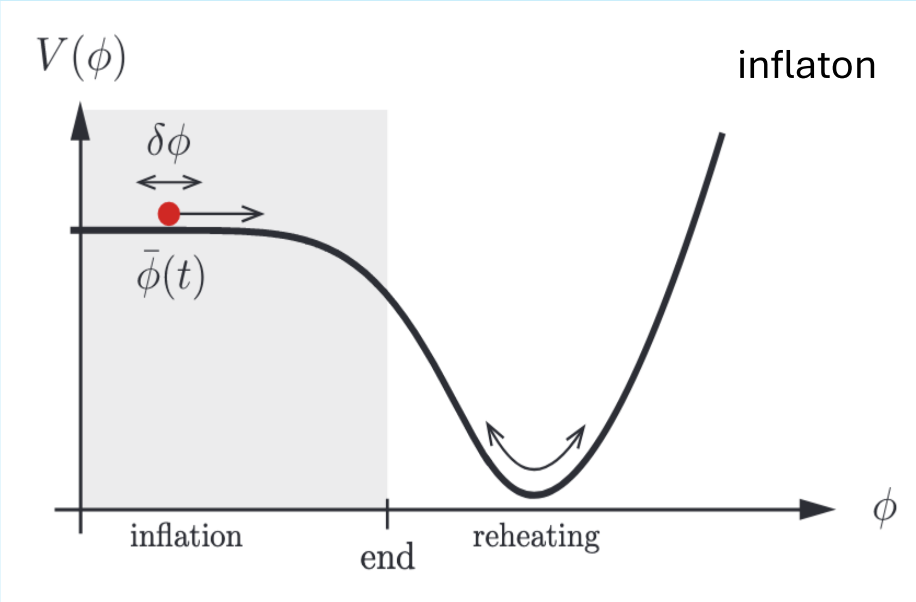
$$w = \frac{p}{\rho} = \frac{E_{kin} - Epot}{E_{kin} + Epot} = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)}$$

The kosmologische constante heeft een constante w=-1 terwijl quintessence een dynamische w heeft

w<-1 geeft negatieve kinetische energy, ook fantoom energie genoemd. Omhoog rollen in het diagram



Quintenessence voorbeeld potentiaal



Phantom energy – Sean Carroll