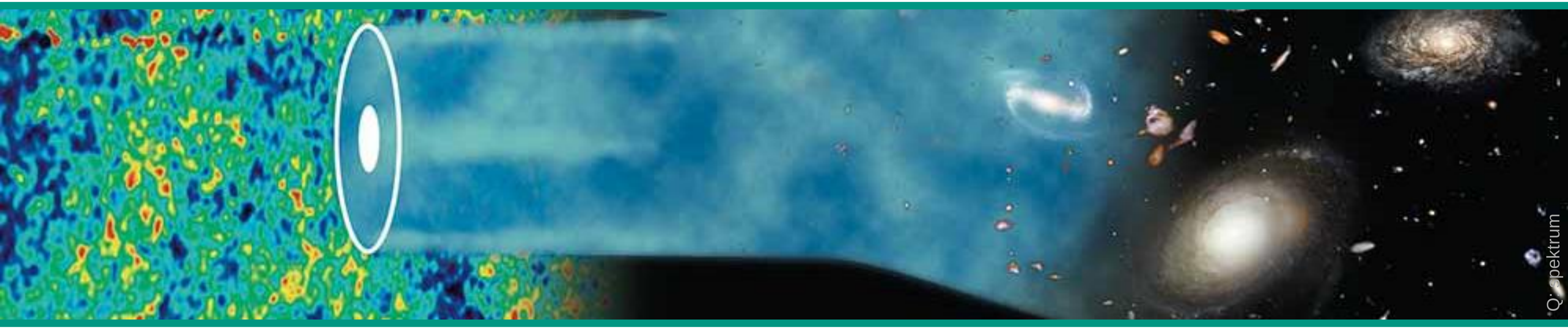
Introduction to Cosmology

Winter term 22/23 Lecture 10 Jan. 17, 2023



Recap of Lecture 9

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- **CMB-multipole expansion: a unique tool for cosmology**

  - foreground: thermal (dust) & non-thermal (synchrotron, free-free scattering)

  - BOOMERanG, **WMAP-mission** to $L2$ –point, high-resolution CMB maps

  - angular correlation function $\boldsymbol{C(\theta)}$ for $\boldsymbol{\Delta T/T}$: expansion in multipoles ℓ

  - **power spectrum**: $(\Delta T)^2 = \ell \cdot (\ell + 1) \cdot \boldsymbol{C_\ell}/2\pi$

  - large angles: flat Harrison Zel´dovich spectrum – due to zero-point fluctuations

  - small angles: BAO – **baryon acoustic oscillations** (Dark Matter signature)

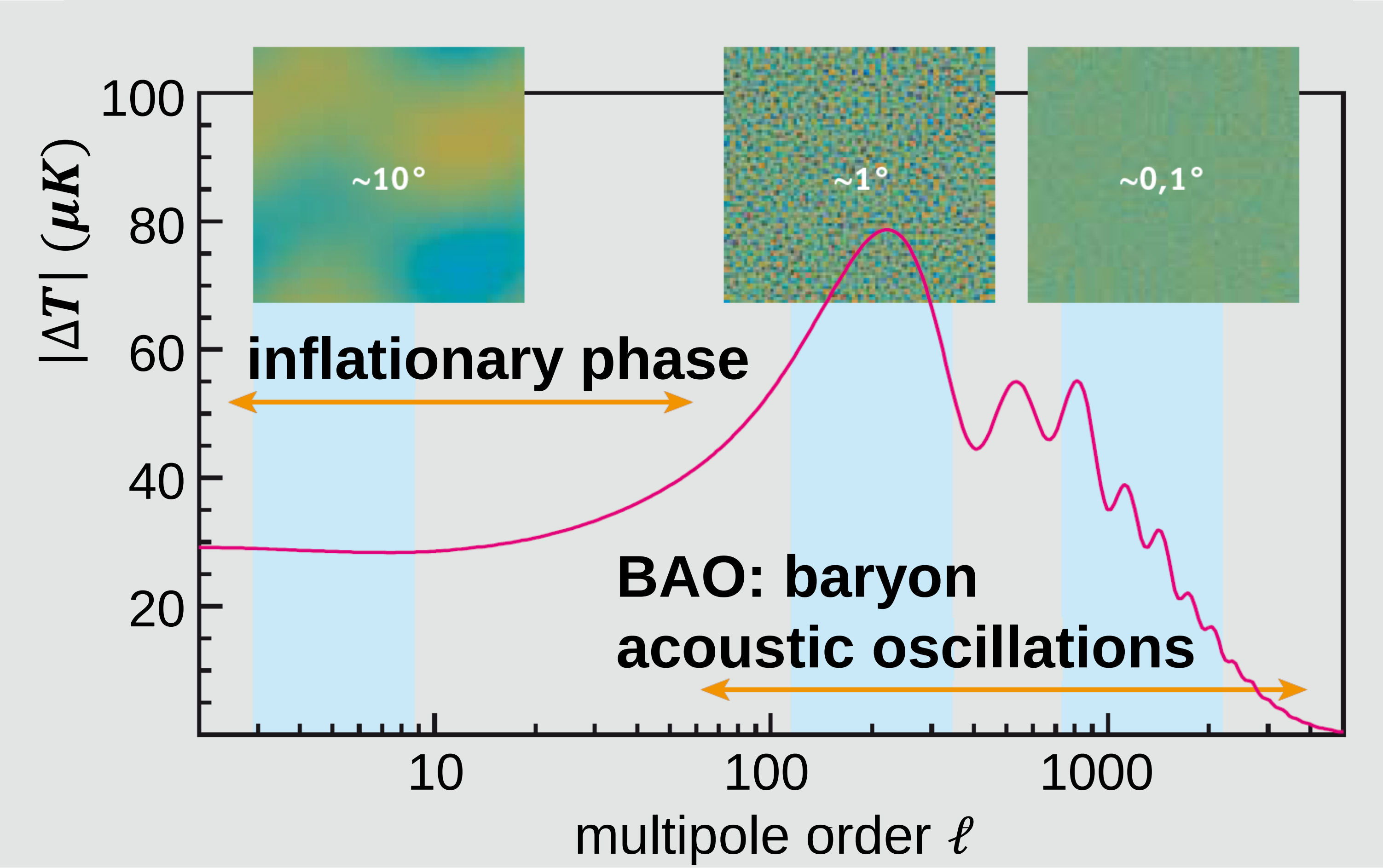
Recap/Outlook: from scale invariance to BAOs

- **CMB multipole spectrum: study physics of the early universe $t < 378000\ yr$**

- frozen fluctuations at large scales: ´QM in the sky´

- small scales: modification due to gravity & **acoustic sound waves** in plasma

- BAOs: a perfect tool to measure baryon density Ω_B & dark matter density Ω_{DM}



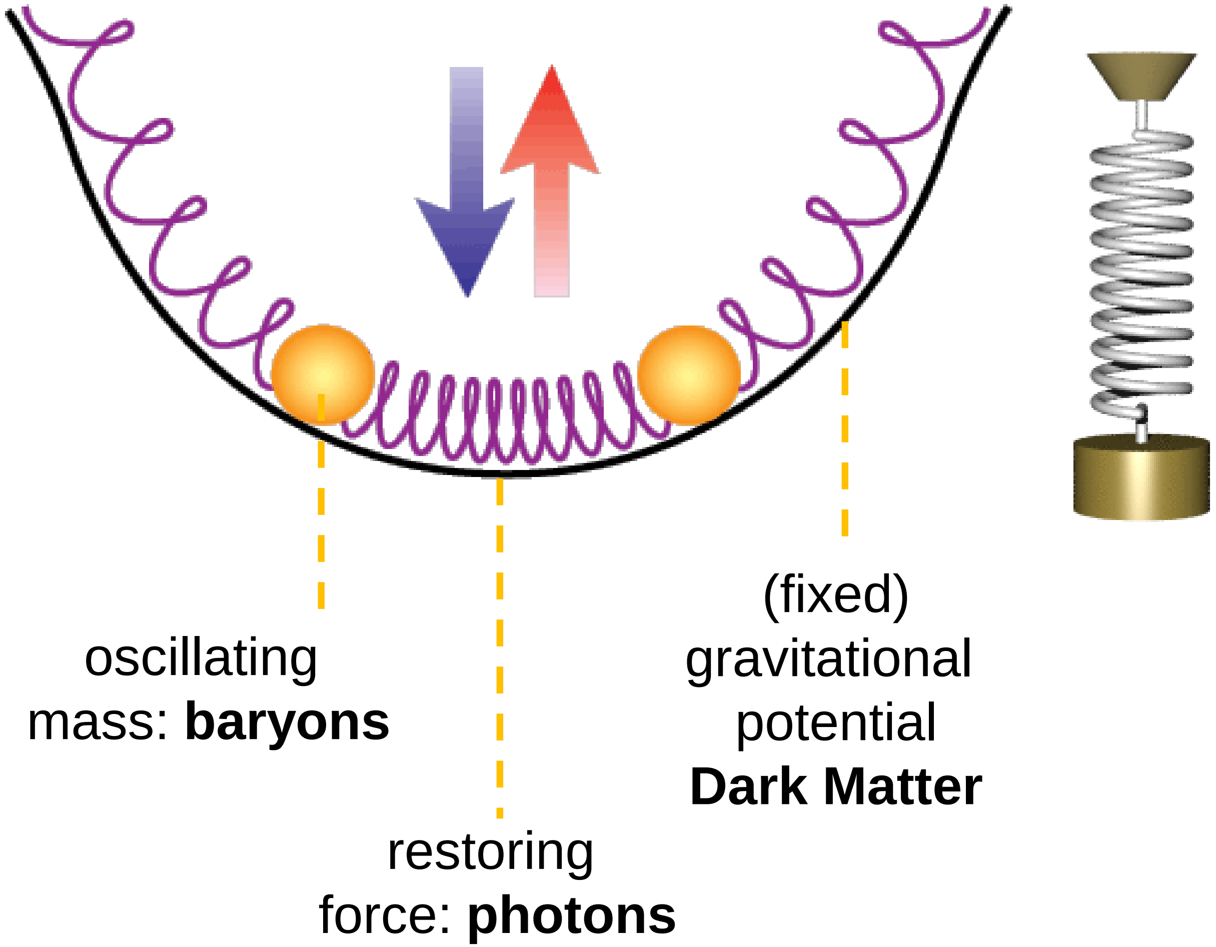
Baryon Acoustic Oscillations – BAO

- **the modification is due to close coupling of baryonic matter and radiation**

- after a density perturbation re-enters into causal contact, it will experience two forces

a) **gravitational attraction** from dark matter, forming a quasi-fixed gravity well (dark matter is dominant & does not interact with photons)

b) **radiation pressure** from photons, restoring force



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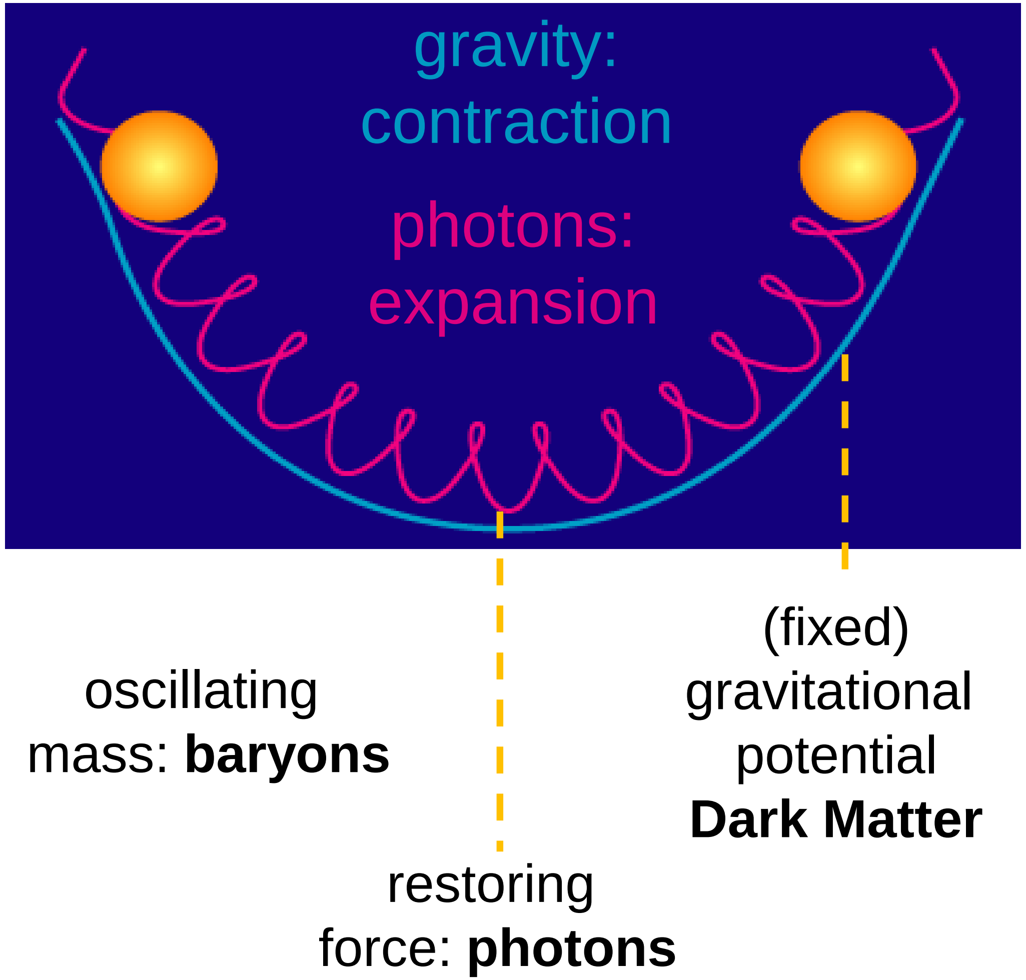
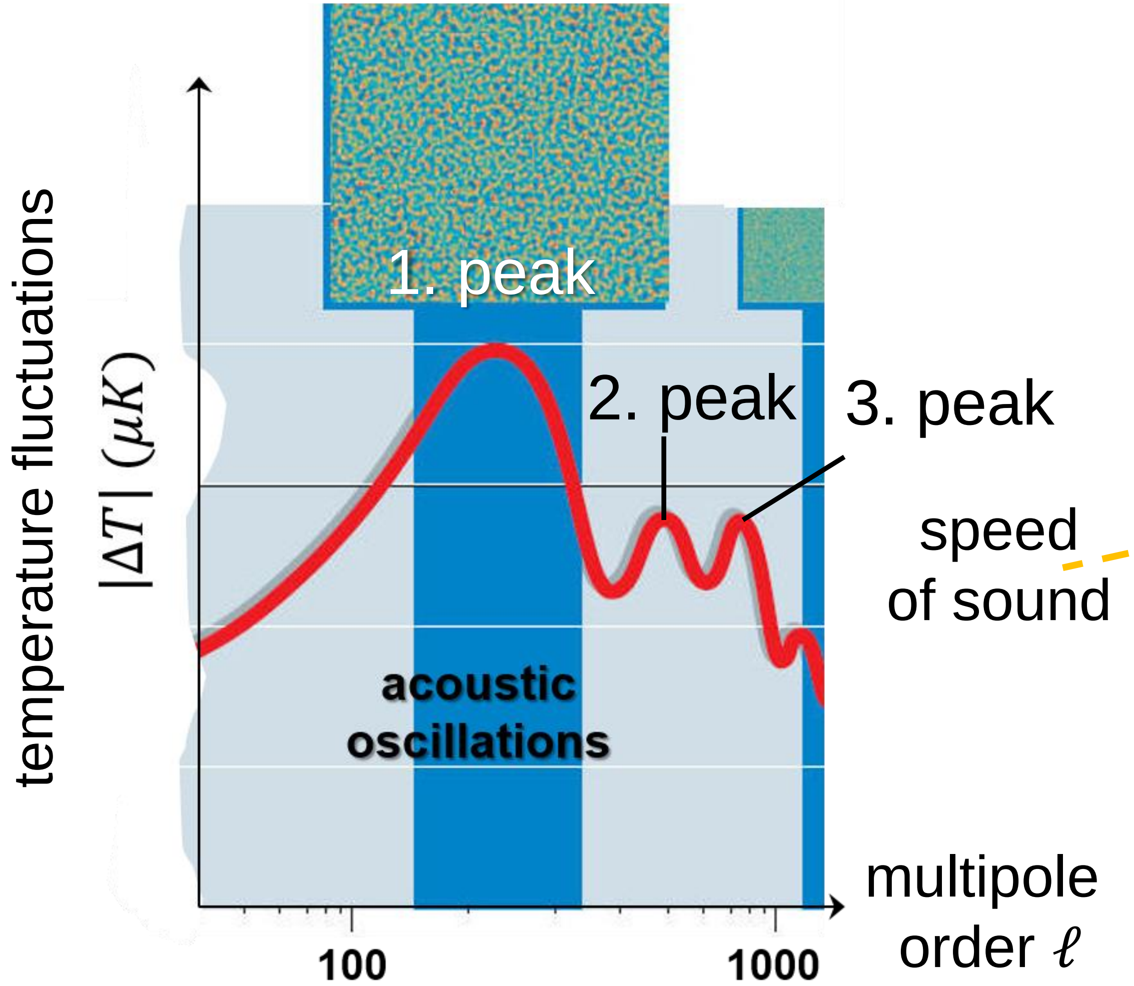
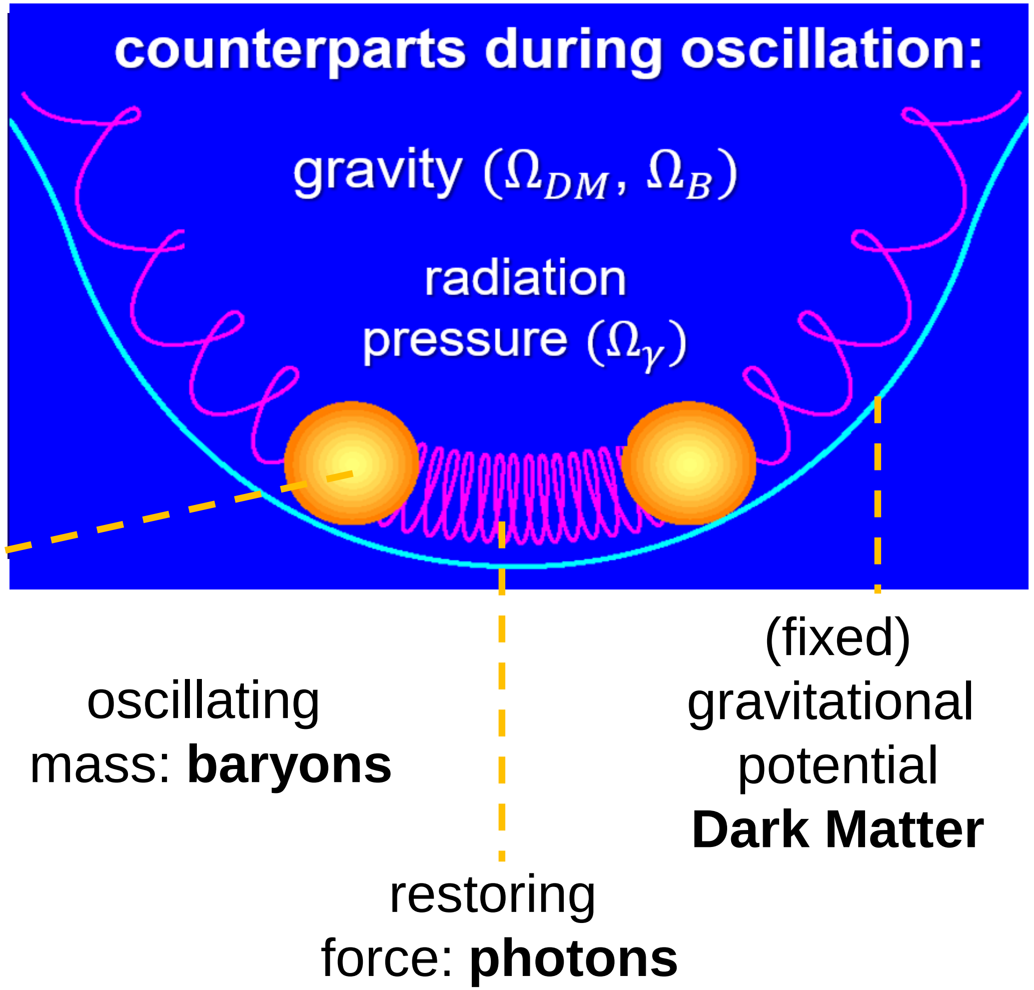


Baryon Acoustic Oscillations – BAO

- **the modification is due to close coupling of baryonic matter and radiation**



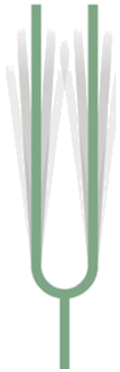


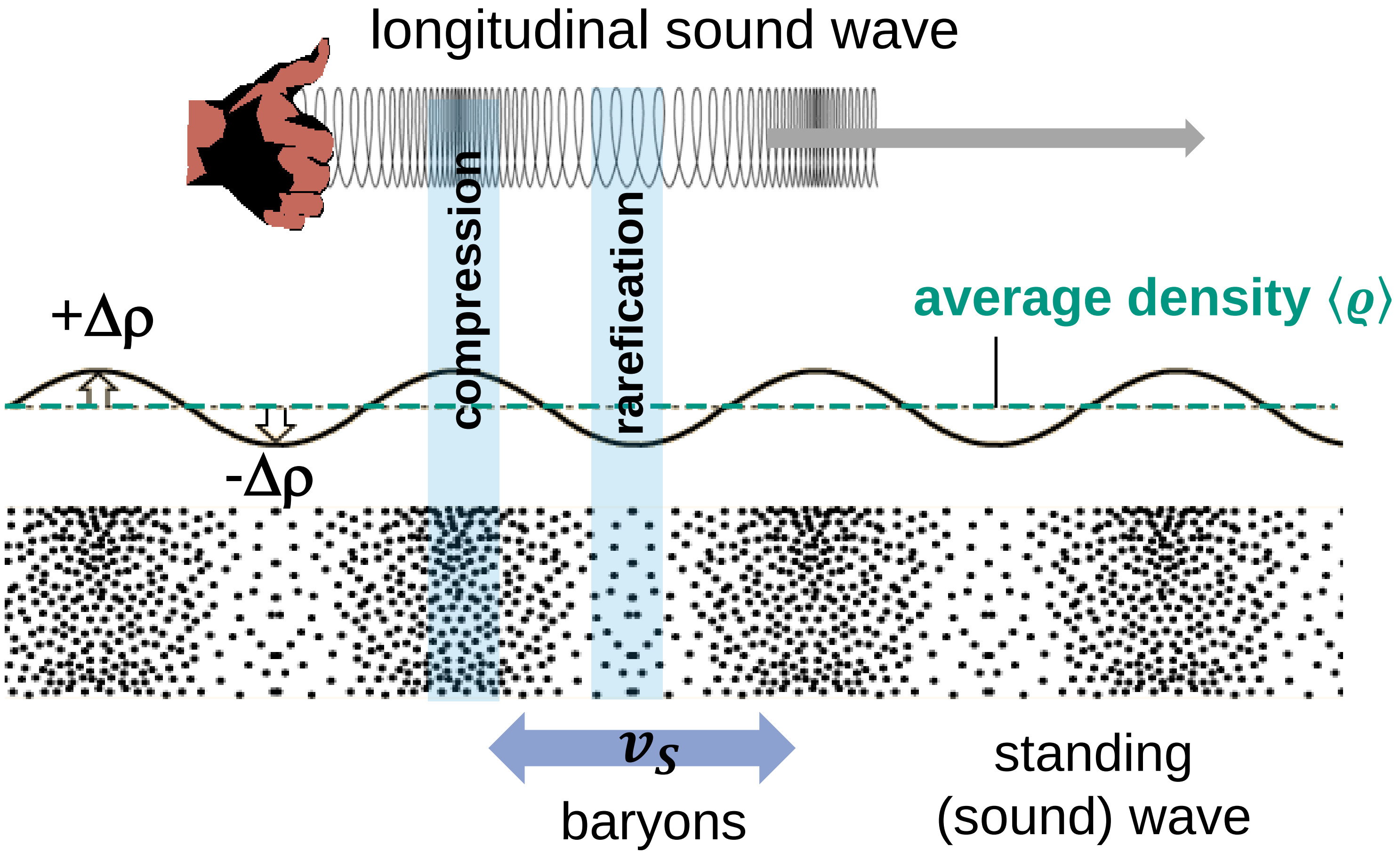
BAO – acoustic waves in the early universe

- **John Peebles:** **standing acoustic waves** **in the early primordial plasma**

- BAOs are based on well-established physics: **standing acoustic waves**

- important parameter: **the speed of sound** v_S





Recap*: speed of sound v_S during phase transition

■ **Phase transition from plasma to neutral matter: change of speed of sound**

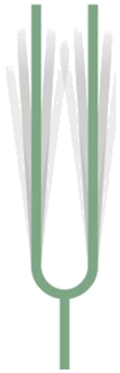
- **sound speed v_S** before (plasma) & after (neutral atoms) recombination:

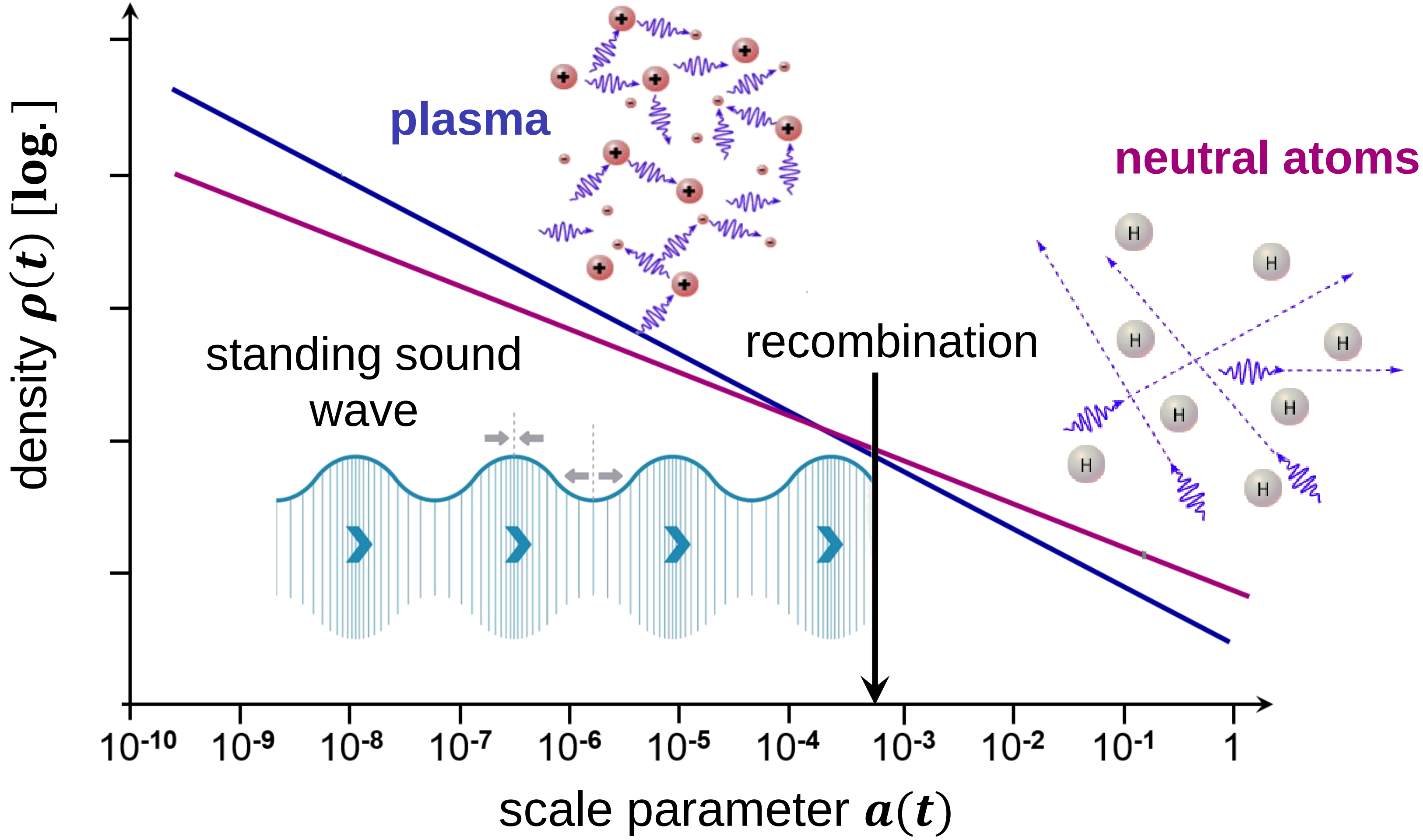
- plasma: very fast!

$$\boxed{v_S^2 = \frac{\partial p}{\partial \rho} = \frac{c^2}{3}}$$

- neutral matter:

$v_S^2 \approx 0$ ⇨ full stop!





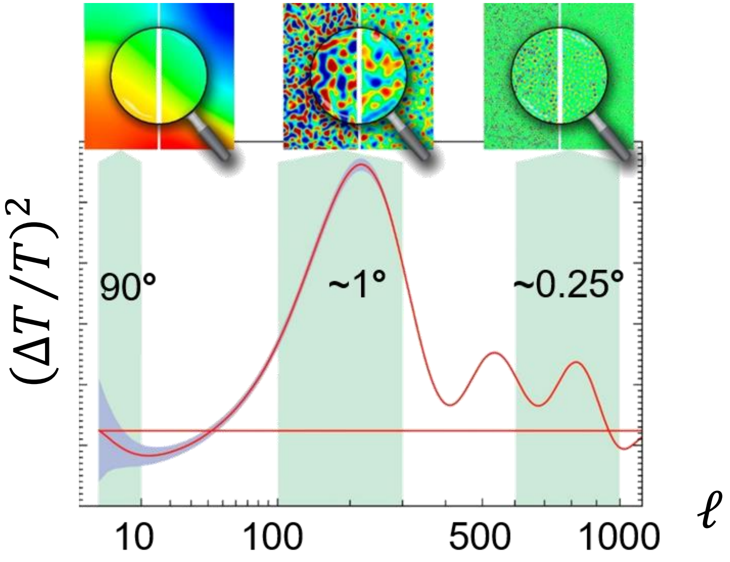
*see lecture 8, p. 31

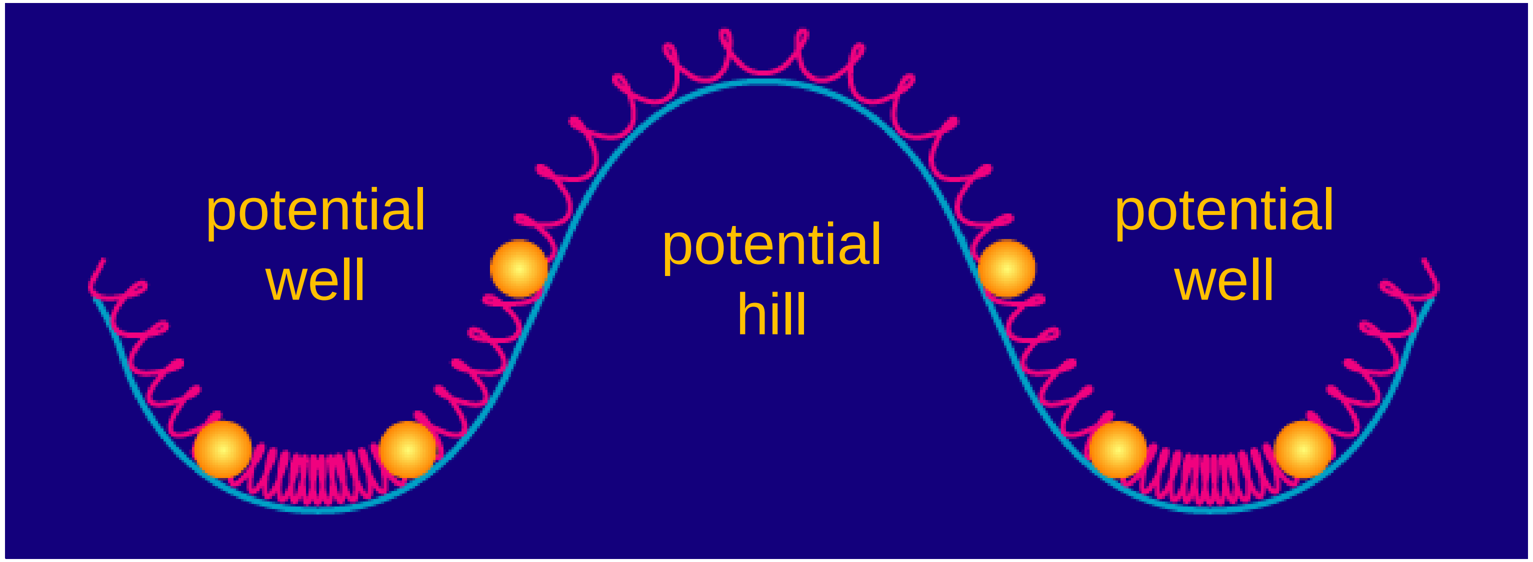
BAO – acoustic waves in the early universe

- **One more thing: acoustic oscillations are all in phase over entire universe**

  - acoustic oscillations in different (non-causally linked) regions: ⇨ *identical phases*
    ⇨ add coherently: no destructive interference (as expected for random phases)

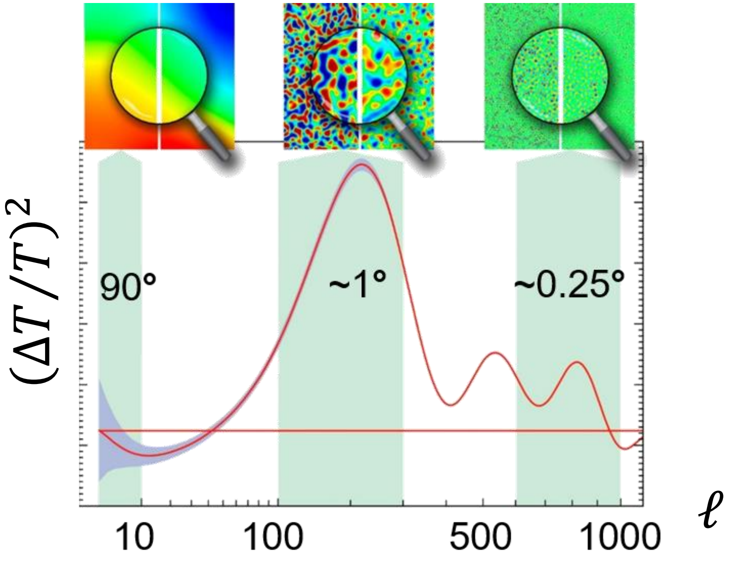
  - a possible solution, again: **inflation** in the very early universe has synchronised all density fluctuations, thus they all start with the same phase

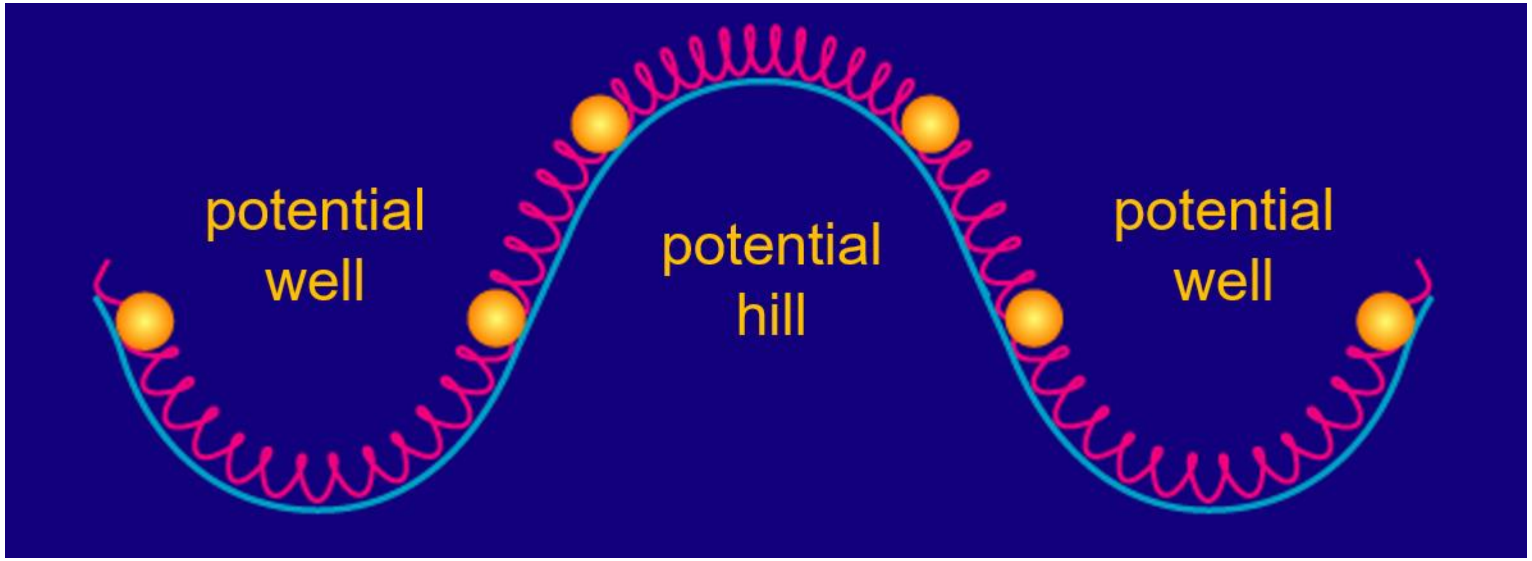




BAO – acoustic waves in the early universe

- **One more thing: acoustic oscillations only in the plasma state $t < 378000\ yr$**
  - $t = 0$: causal interaction of baryons & photons in presence of Dark Matter wells
    ⇨ a density perturbation starts to move with speed of sound $v_S = c/\sqrt{3}$
  - $t = 378000\ yr$: after recombination no baryon-photon interaction, sound wave is ´**frozen**´ as $v_S \approx 0$ (⇨ sound horizon of fundamental mode from $t = 0$ to t_{rec})





BAO – acoustic waves in the early universe

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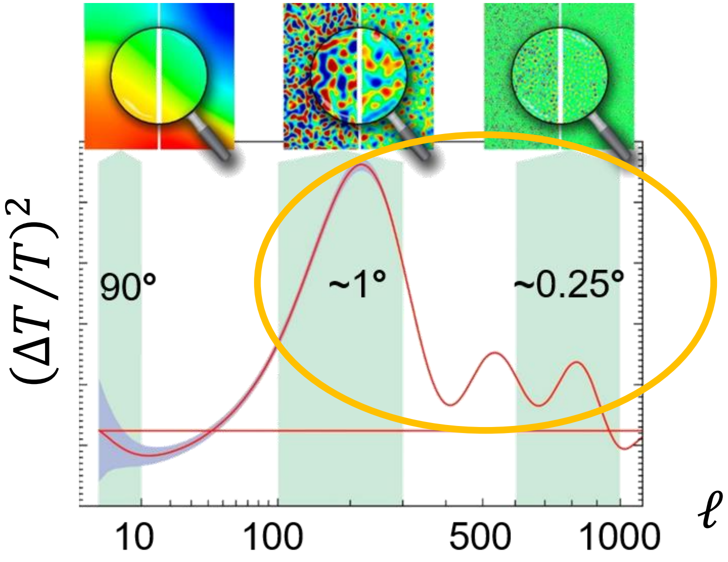
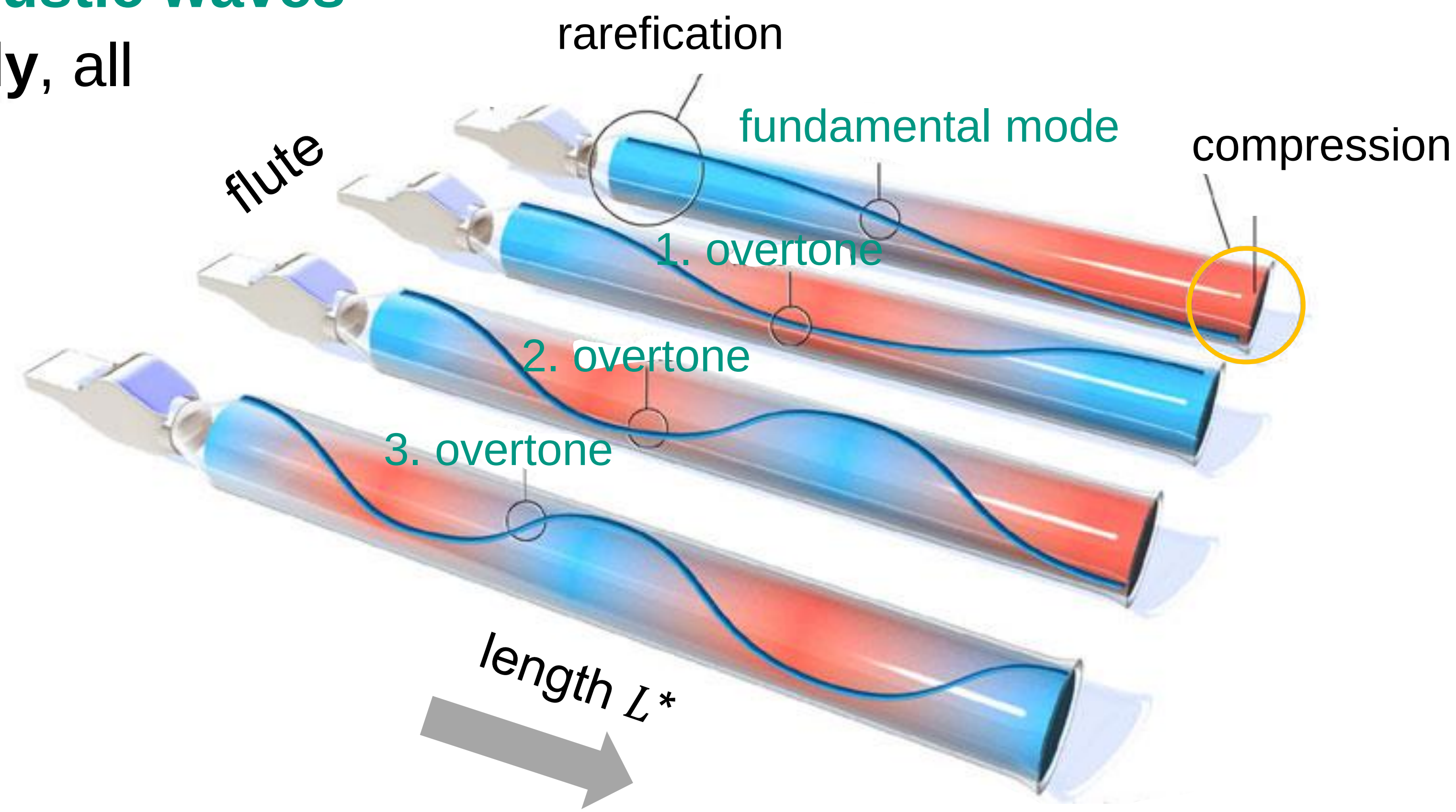
- **Analogon: fundamental mode & overtones in flute as standing acoustic wave**

  - RECAP: only **standing acoustic waves will interfere constructively**, all others will be wiped out due to destructive interference



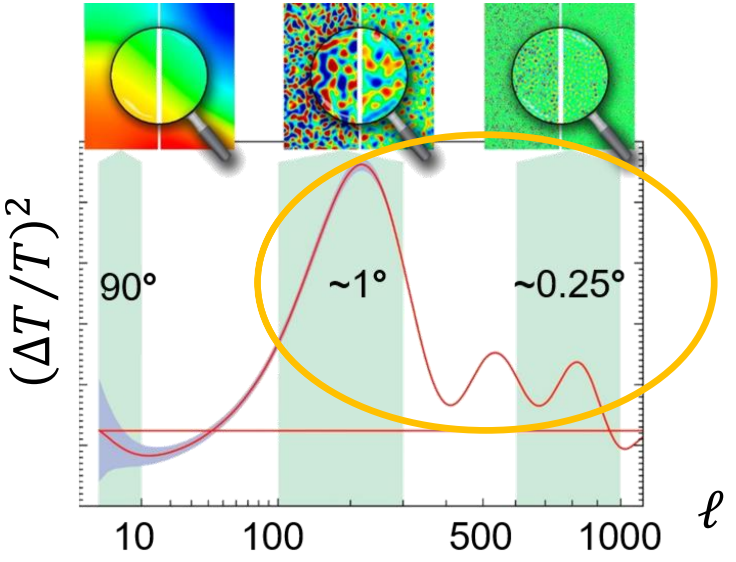


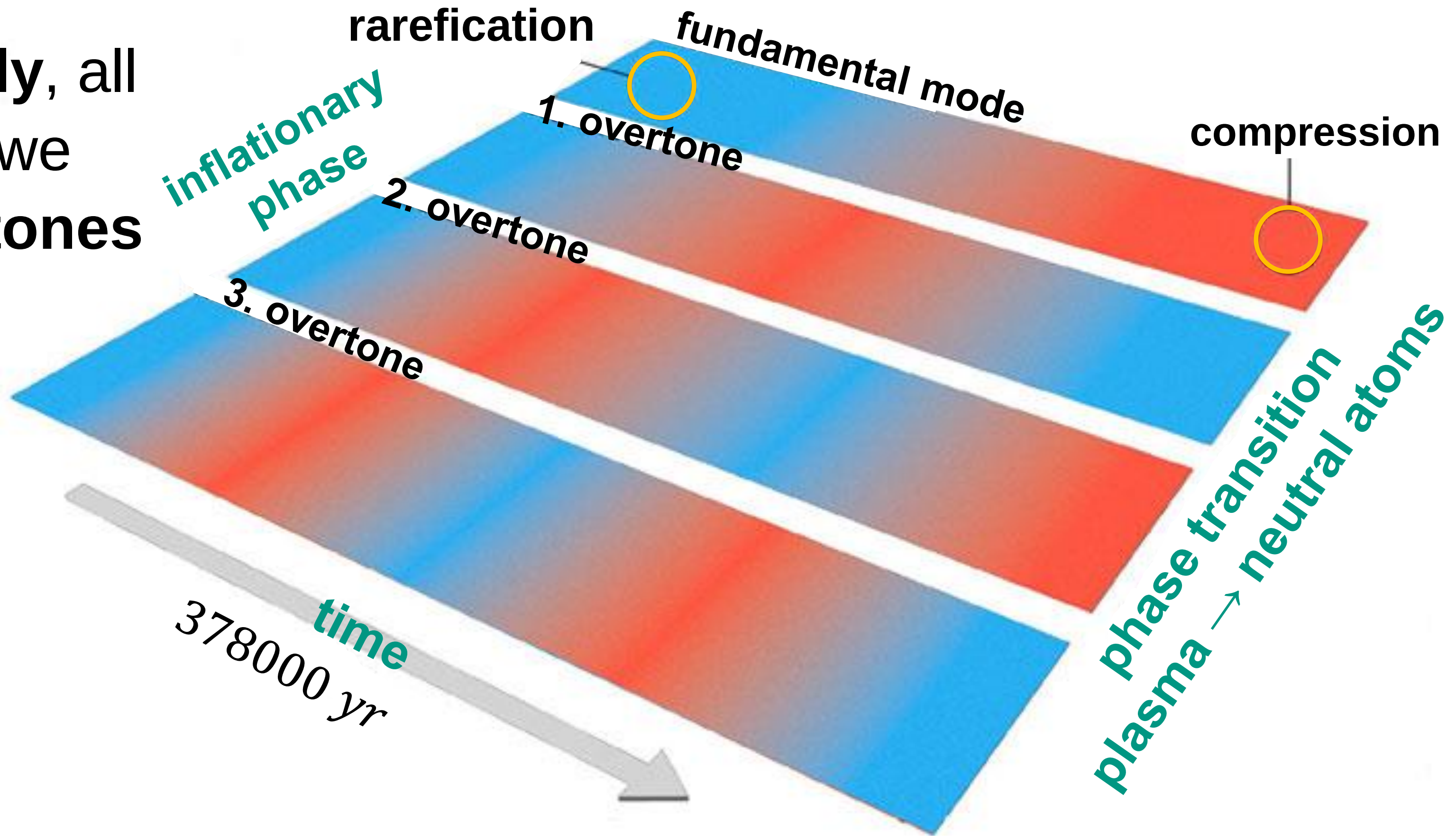
$^*L =$ sound horizon at $t = t_{rec}$

BAO – acoustic waves in the early universe

- **BAO: only fundamental mode & overtones as standing acoustic waves**

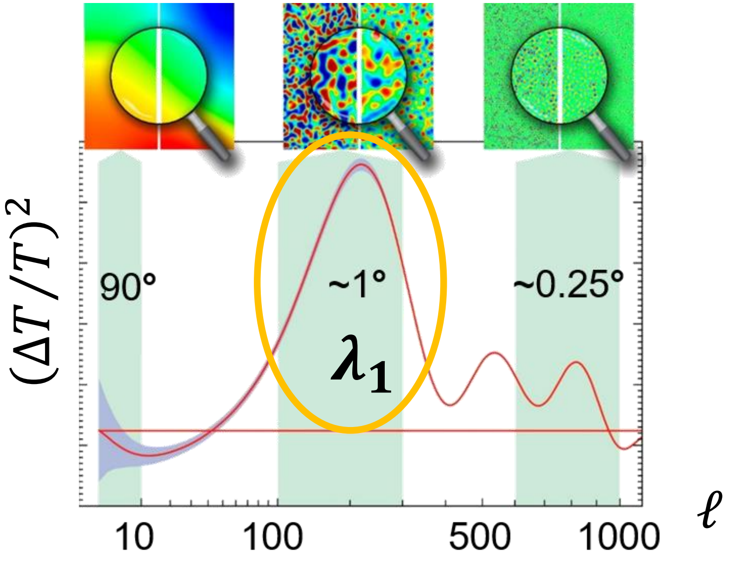
  - only standing BAO waves **will interfere constructively**, all others will be wiped out, ⇨ we have: **fundamental + overtones**

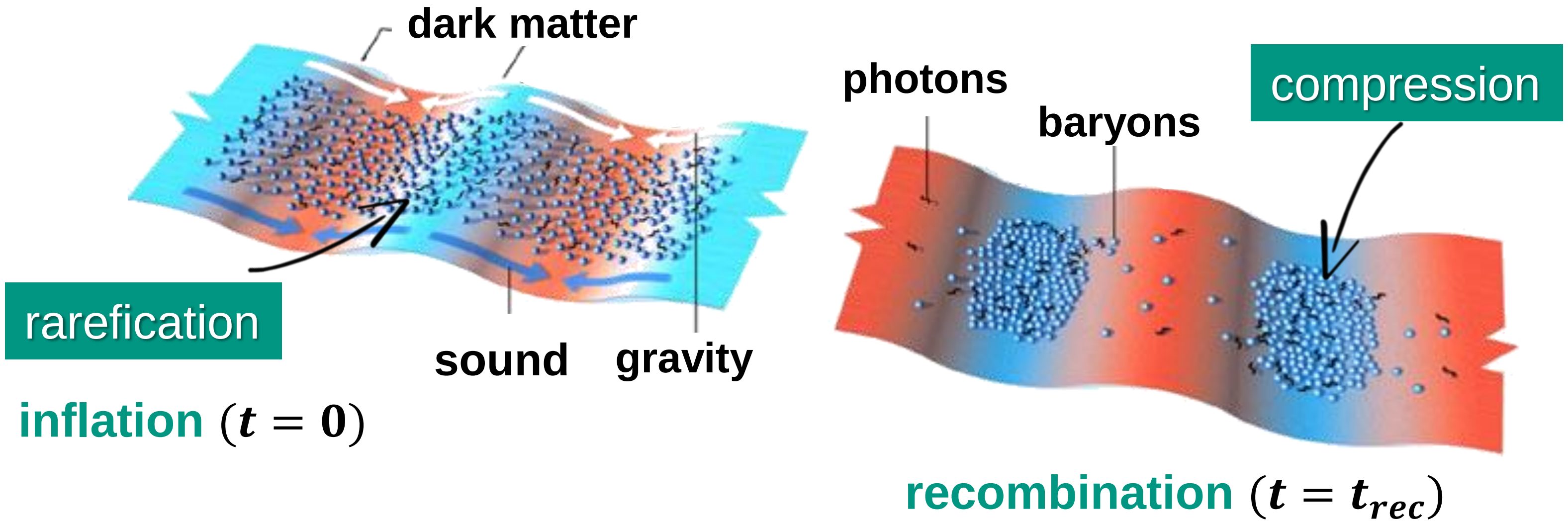




BAO – acoustic waves in the early universe

- **BAO: only fundamental mode & overtones as standing acoustic waves**
  - $t = 0$ up to $t = 378000\,yr$: fundamental mode (largest wavelength $\boldsymbol{\lambda_1}$) with multipole $\ell \approx 200$ has just gone from **rarefaction** → **compression** (one cycle)
  - the fundamental mode with $\ell \approx 200$ consists of $(m = 2\ell + 1 \approx 400)$ independent fluctuations, all add with *coherent phase* to this mode with λ_1



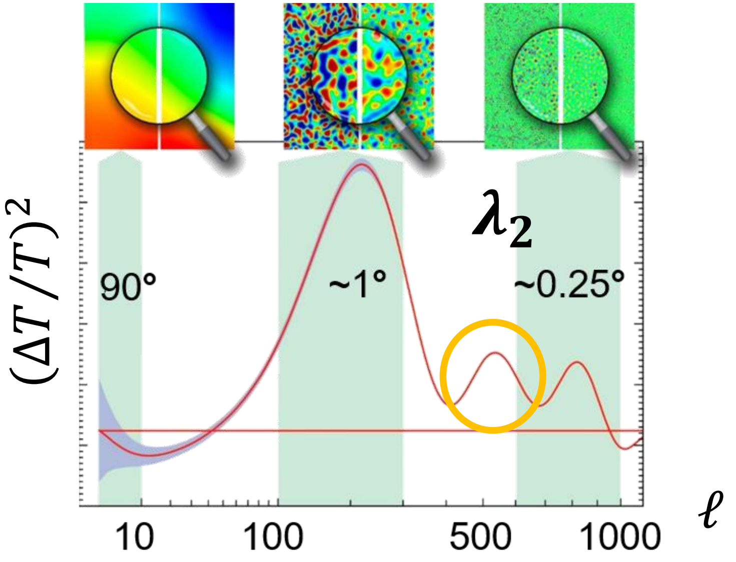


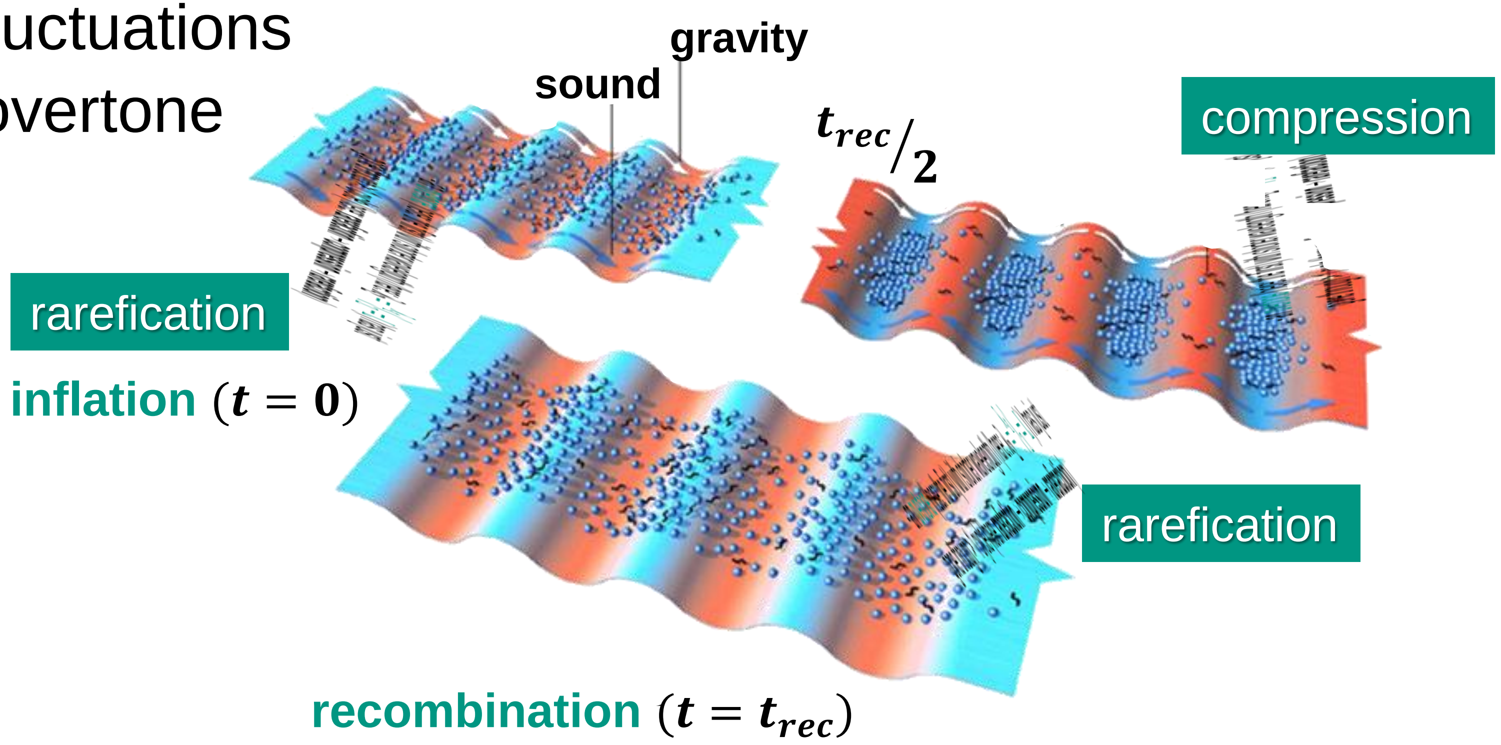
BAO – acoustic waves in the early universe

- **BAO: only fundamental mode & overtones as standing acoustic waves**

  - an overtone (here: the first) with shorter wavelength (here: $\boldsymbol{\lambda_2} = {}^{\lambda_1}/_2 = L$) has just gone through > 1 cycle (here: **rarefaction → compression → rarefaction**)

  - again: many independent fluctuations *add coherently* to a single overtone

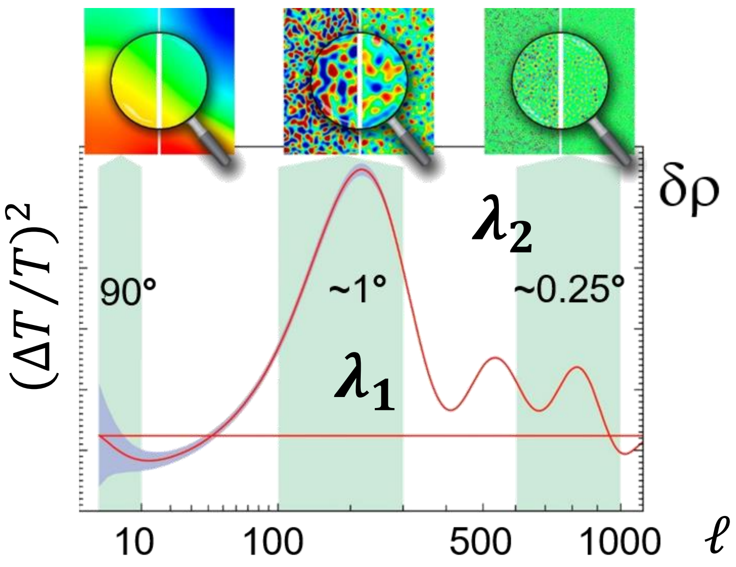


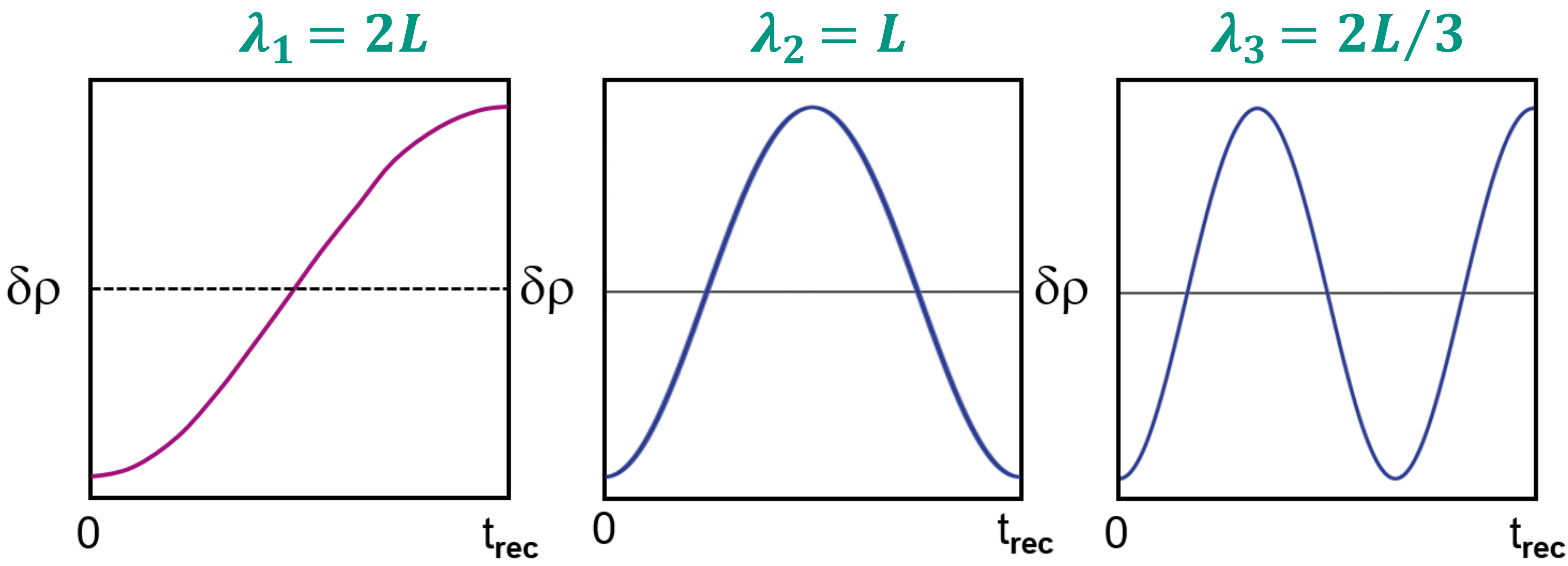


BAO – acoustic waves in the early universe

- **BAO: only fundamental mode & overtones as standing acoustic waves**

  - a ´**cosmic symphony**´ in the early universe of fundamental mode and many overtones, each composed of $2\ell + 1$ independent (coherent!) fluctuations

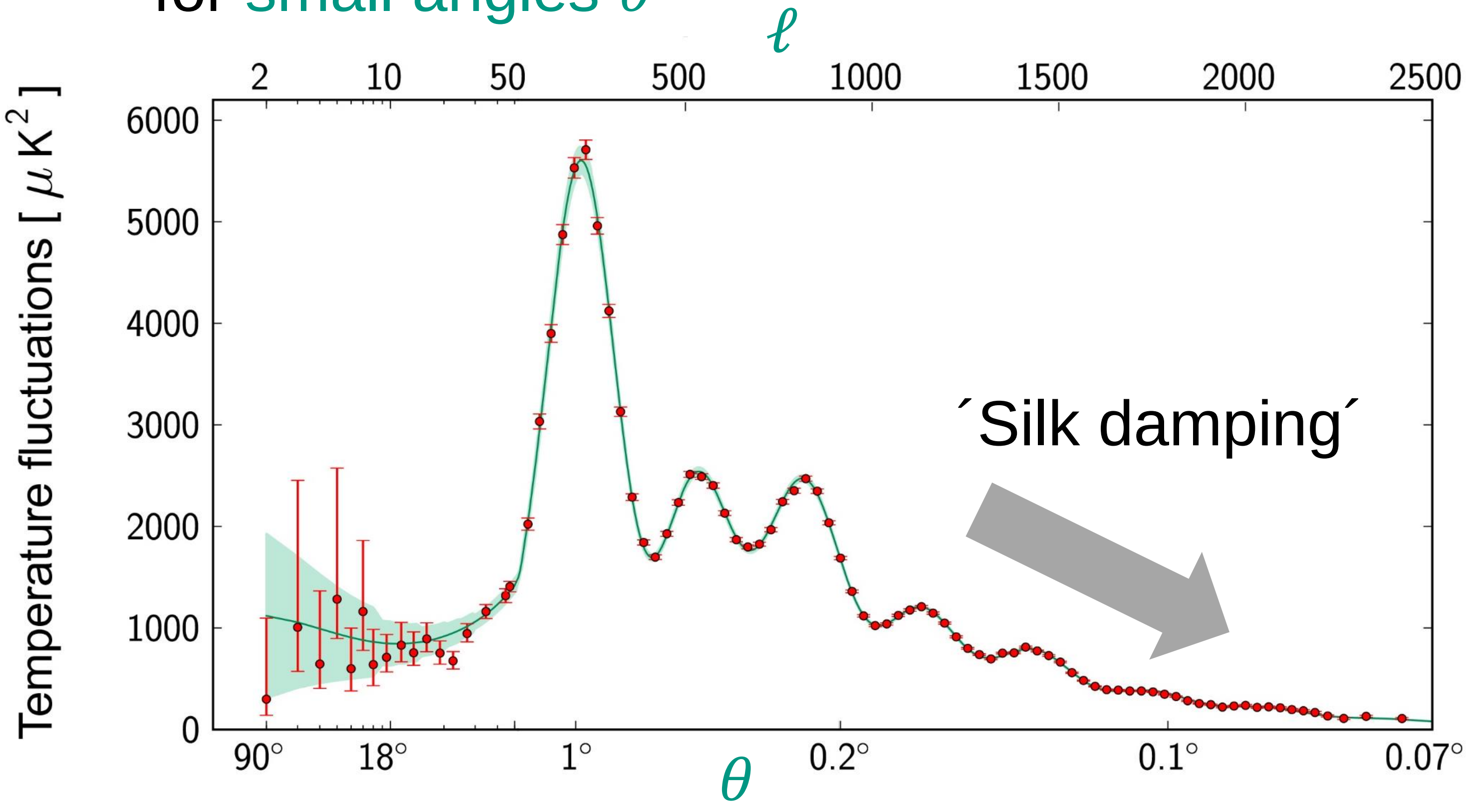




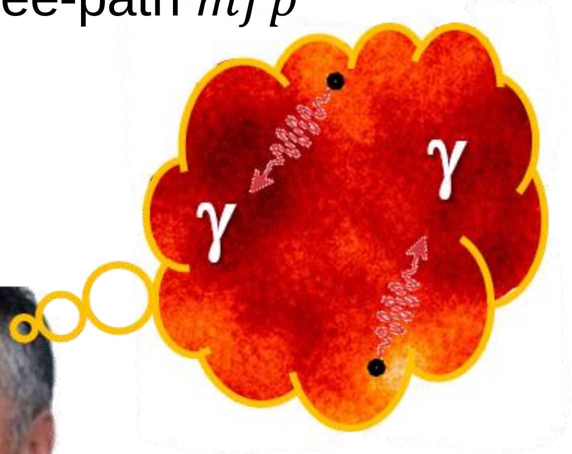
BAO – acoustic waves in the early universe

- **Why are the temperature fluctuations at large multipoles ℓ being damped?**

  - BAOs in the early universe take place in a strong heat bath, which is important for small angles θ



photons have a finite mean-free-path mfp

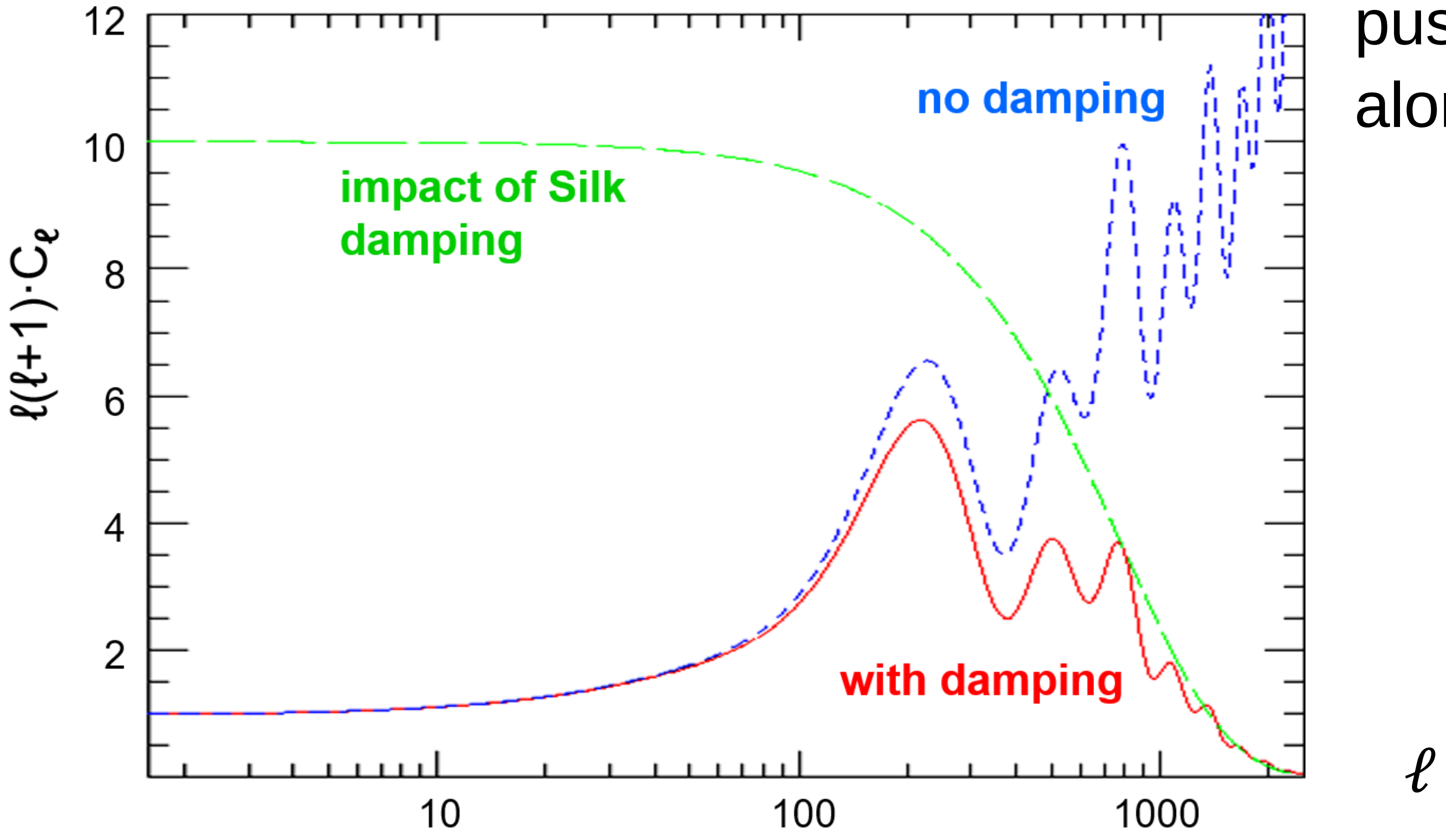


Joseph Silk

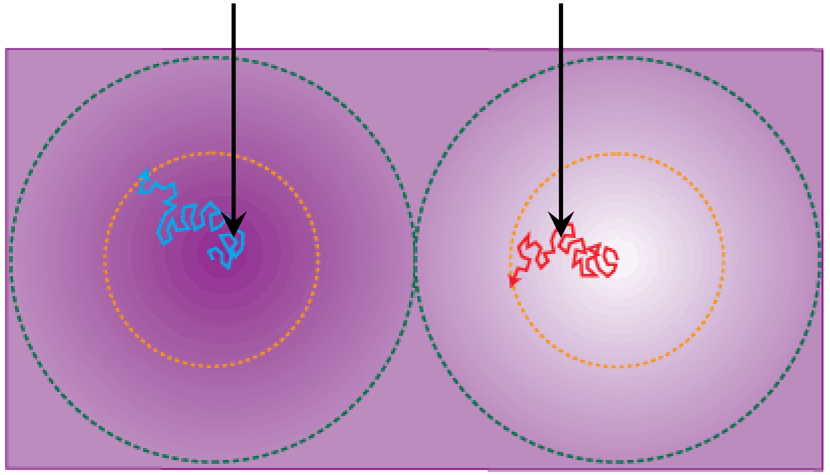
BAO – acoustic waves in the early universe

- **temperature fluctuations at large multipoles ℓ: impacted by photon diffusion**

- photons diffuse out from hotter (overdense) to colder (underdense) regions, thereby pushing electrons e^-, & thus protons p along: ⇨ damping of anisotropies at smaller scales



photons diffuse out of perturbations

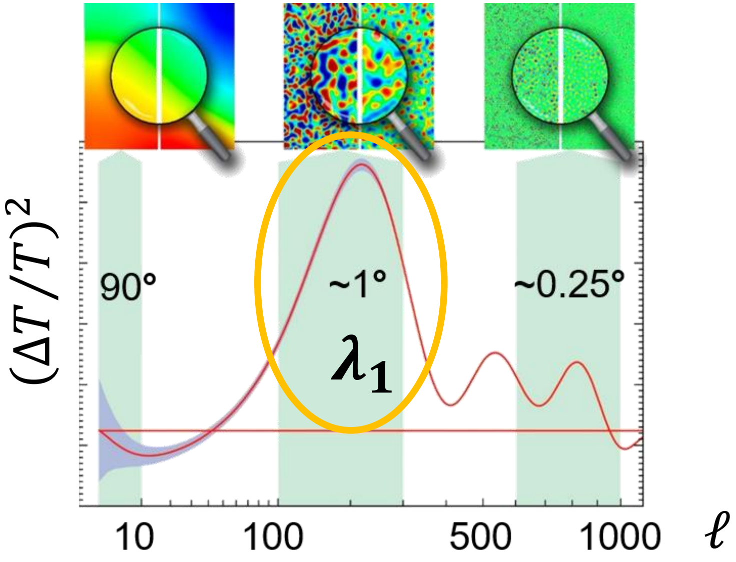


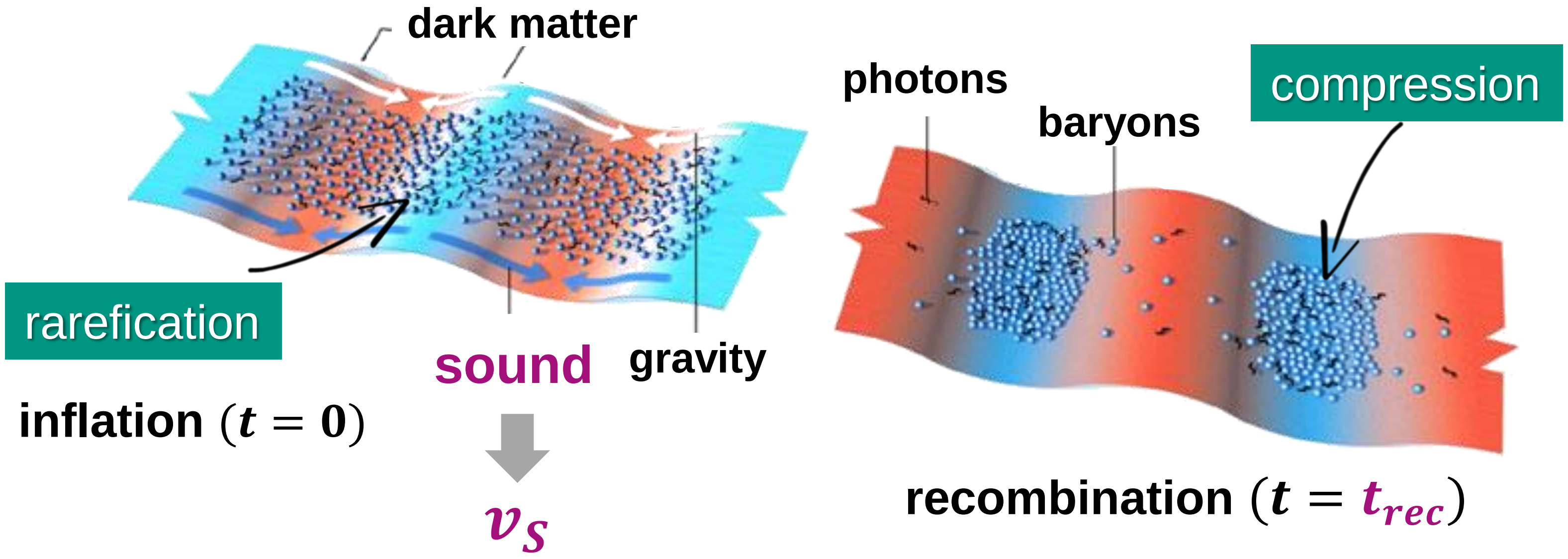
BAO – determining the topology of the universe

- **The fundamental mode revisited: the absolute sound horizon scale is known**

  - the wavelength of the fundamental mode $\lambda_1 = 2L$: ⇨ measure the absolute scale of the **sound horizon** $L \sim v_S \cdot t_{dec} = \frac{c}{\sqrt{3}} \cdot t_{dec}$

  - we measure $L = \lambda_1 /2$ via angular size (multipole order) of the fundamental mode



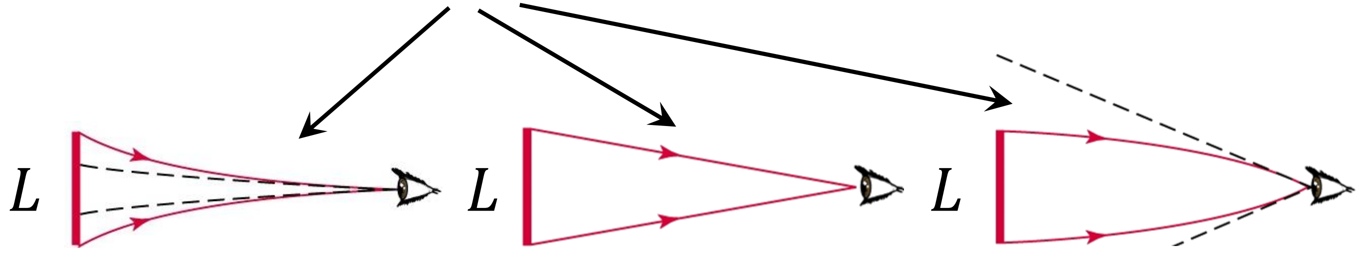


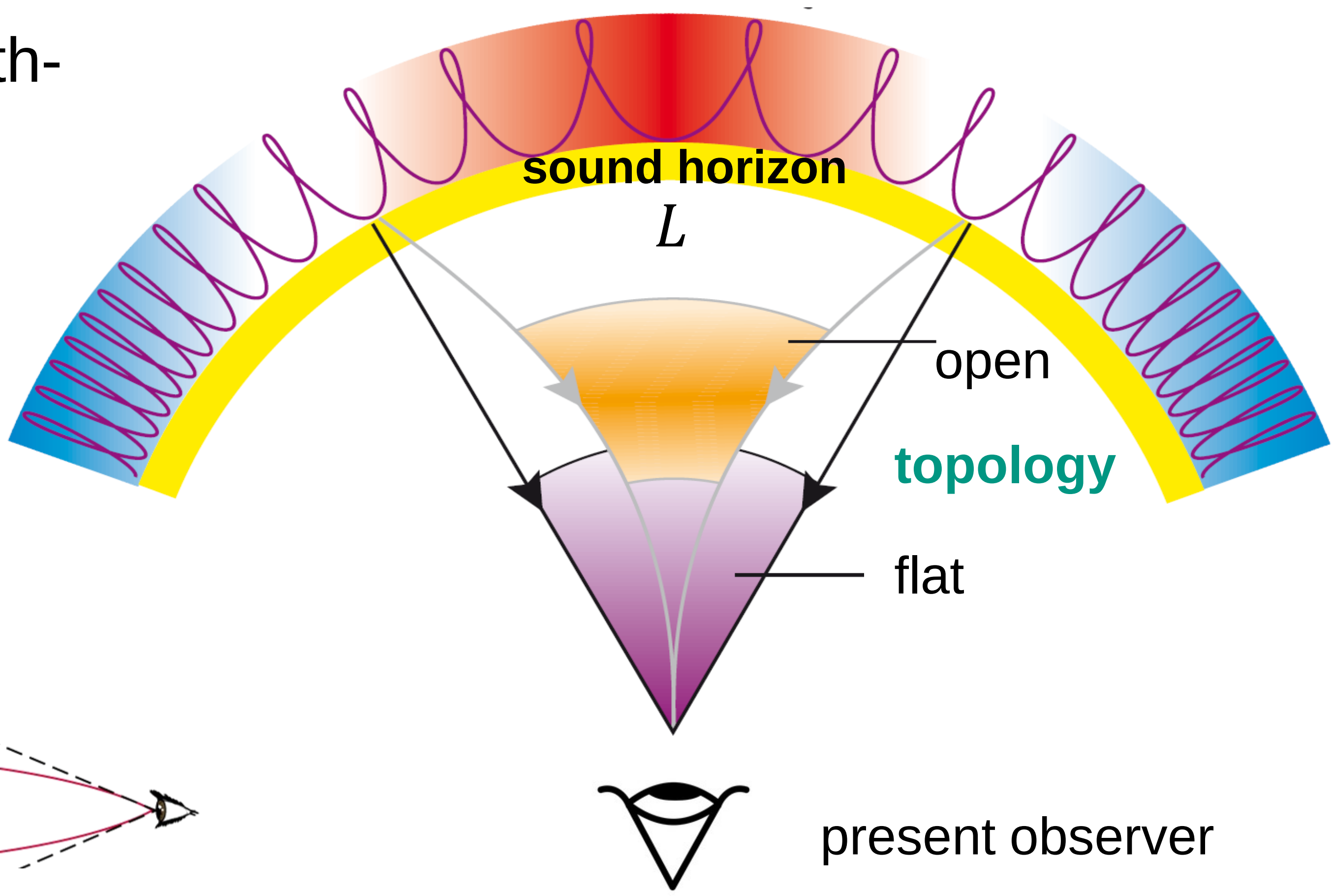
BAO – determining the topology of the universe

- **Taking into account the expansion of the universe and its topology**

  - since decoupling ($t = d_{dec}$) all length-scales (λ_1) have increased by factor $a = (1 + z_{dec}) \approx 1100$ due to the cosmic expansion since $\boldsymbol{t_{dec}}$

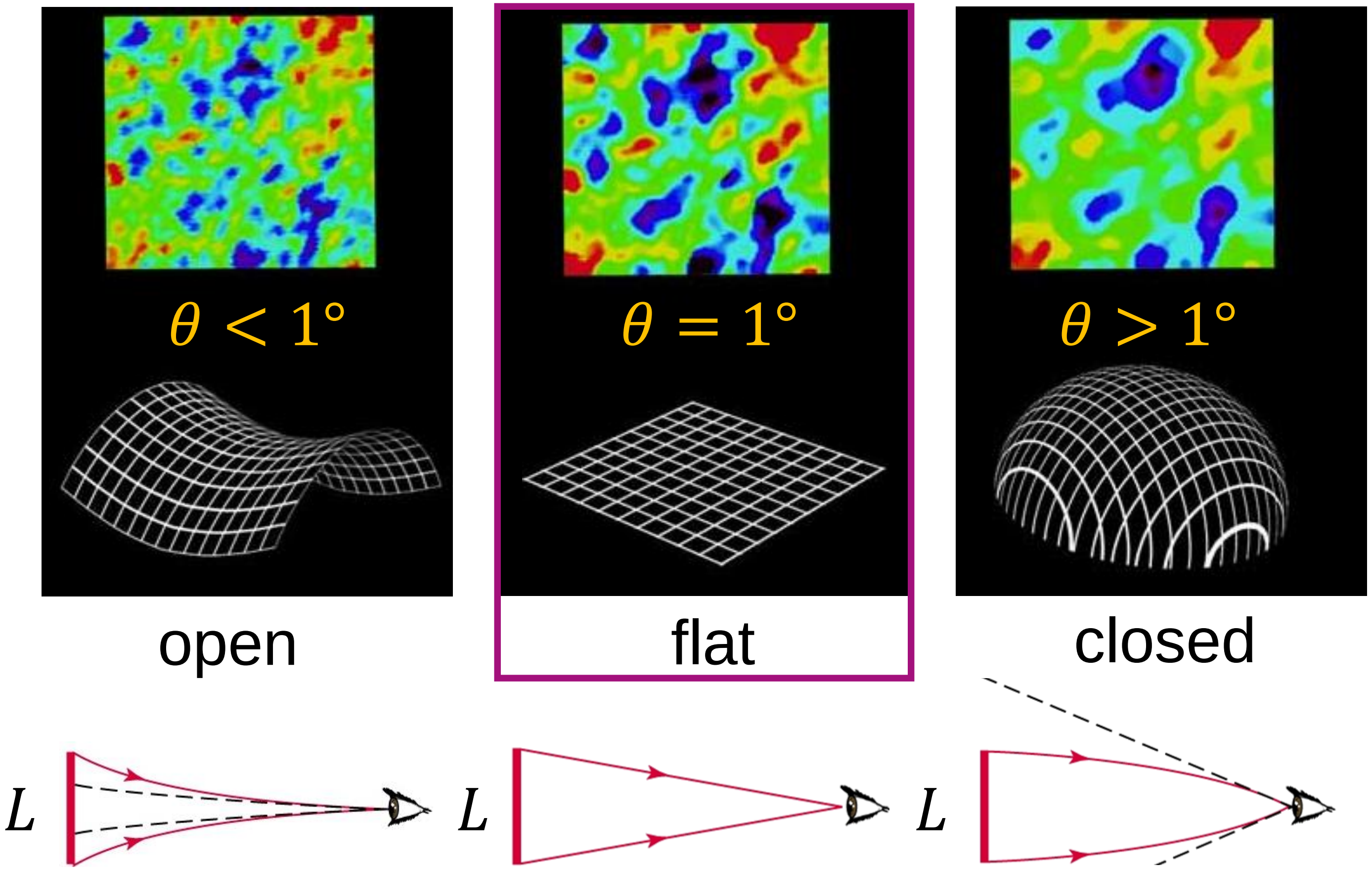
  - now: let´s determine whether the corresponding **angle** $\sphericalangle$ is modified by the topology of the universe:





BAO – determining the topology of the universe

- **Taking into account the expansion of the universe and its topology**



- for a **flat universe** we expect the fundamental mode (1. CMB peak) to appear at multipole $\ell \approx 200$

total energy Ω_{tot} of universe:

… via multipole order ℓ_1 of first acoustic CMB peak

$$\ell_1 \sim 1/\sqrt{\Omega_{tot}}$$

BAO – determining the topology of the universe

- **CMB results:**

- universe has a flat topology as **position of first acoustic peak** is at $\ell_1 \approx 200$

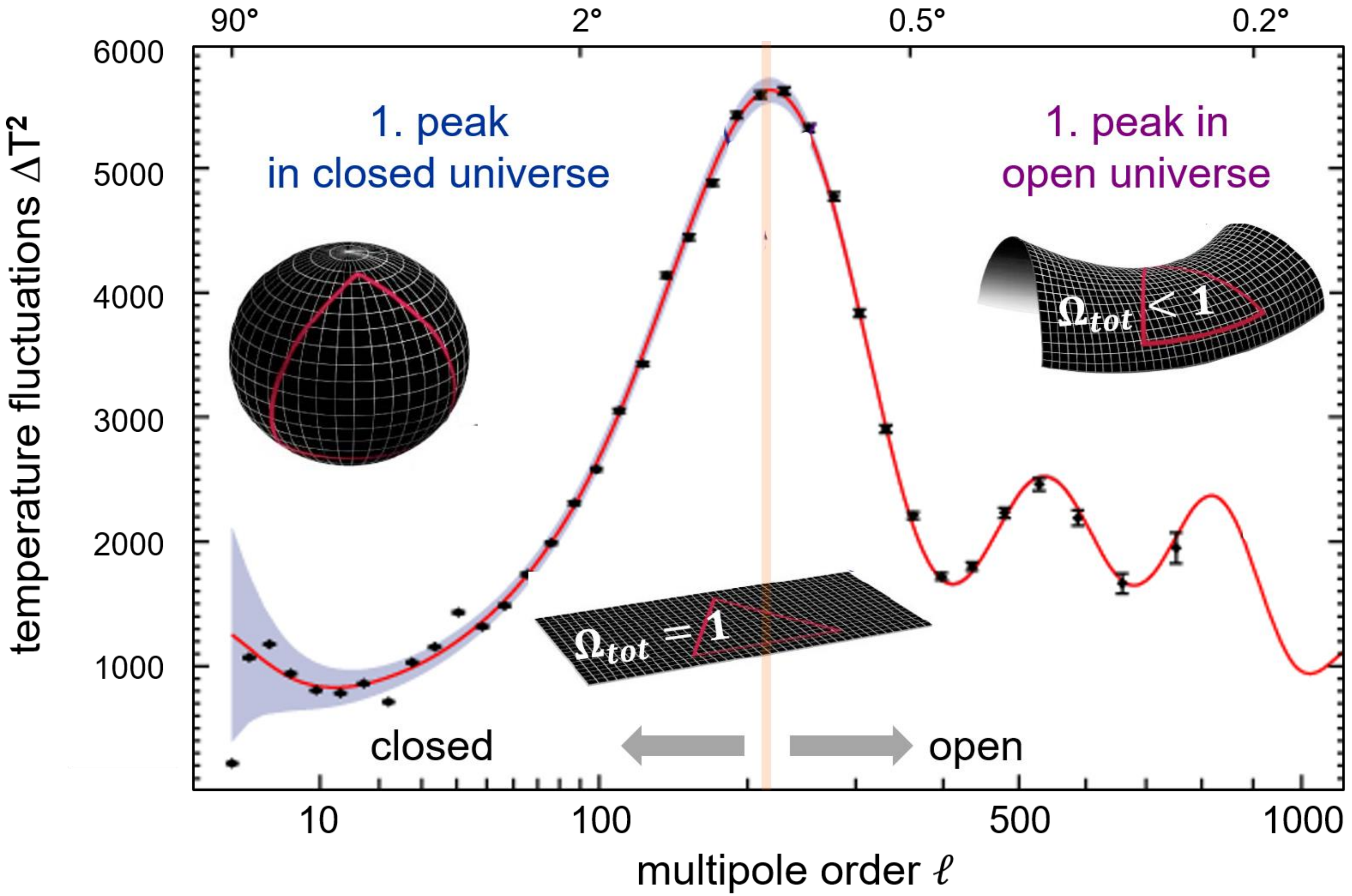
- $\Omega_k \approx 0$

Hubble constant $\boldsymbol{H_0}$

curvature radius $\boldsymbol{R_{curv}}$

curvature $\mathbf{k} = +1, 0, -1$

$$\boxed{\Omega_k = \frac{-kc^2}{H_0^2 R_{curv}^2} = 0.000 \pm 0.005}$$

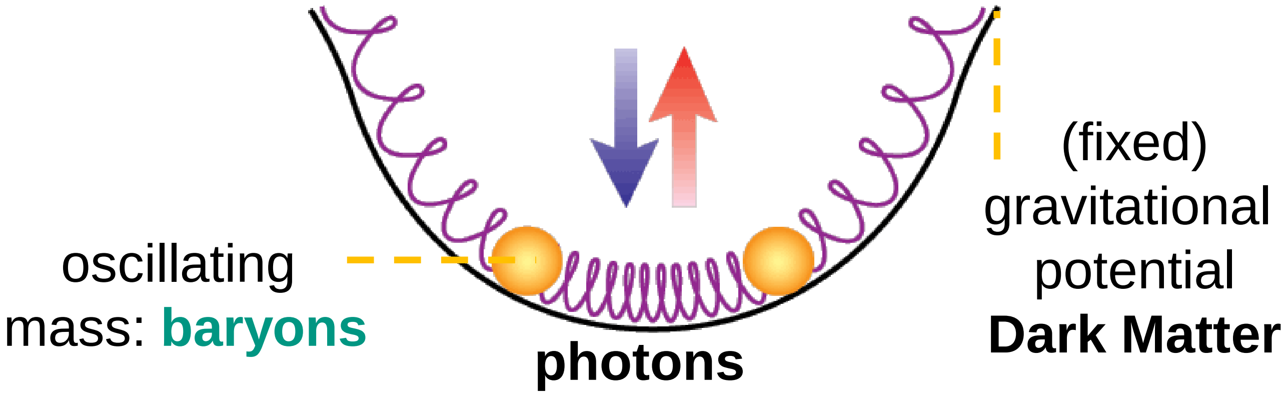


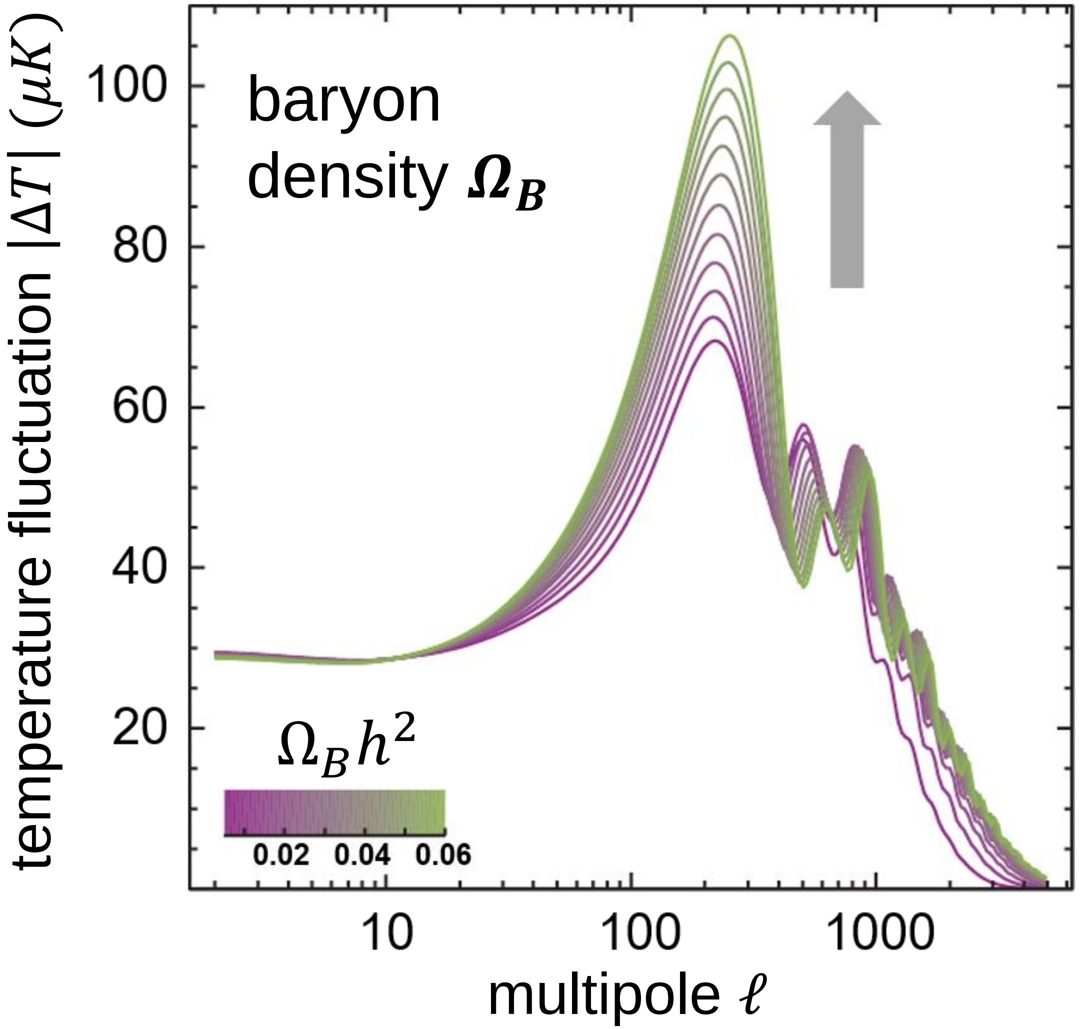
BAO – determining the baryon density Ω_B

- **BAO first peak height is sensitive to Ω_B**

- ´baryon loading´: the height of the first acoustic peak is sensitice to the total number of baryons in the universe Ω_B

- **´baryon loading´**: more baryons Ω_B
  ⇨ height of first acoustic peak increases

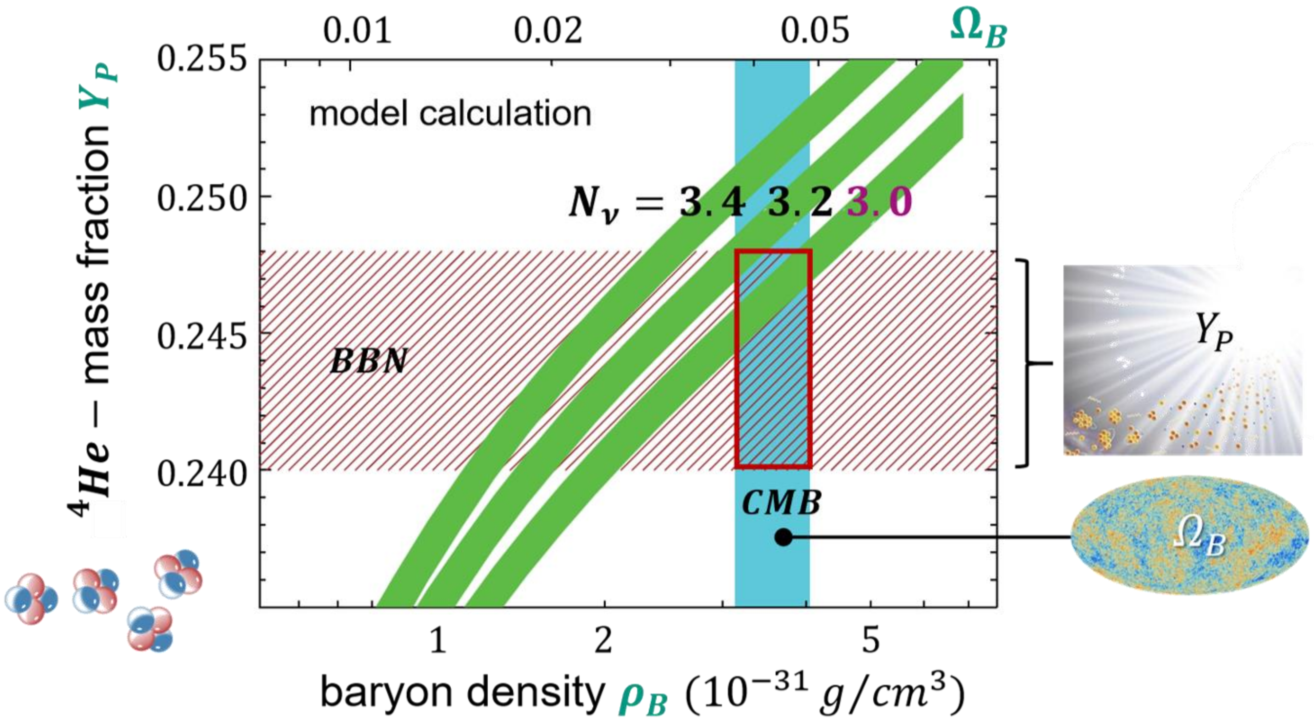


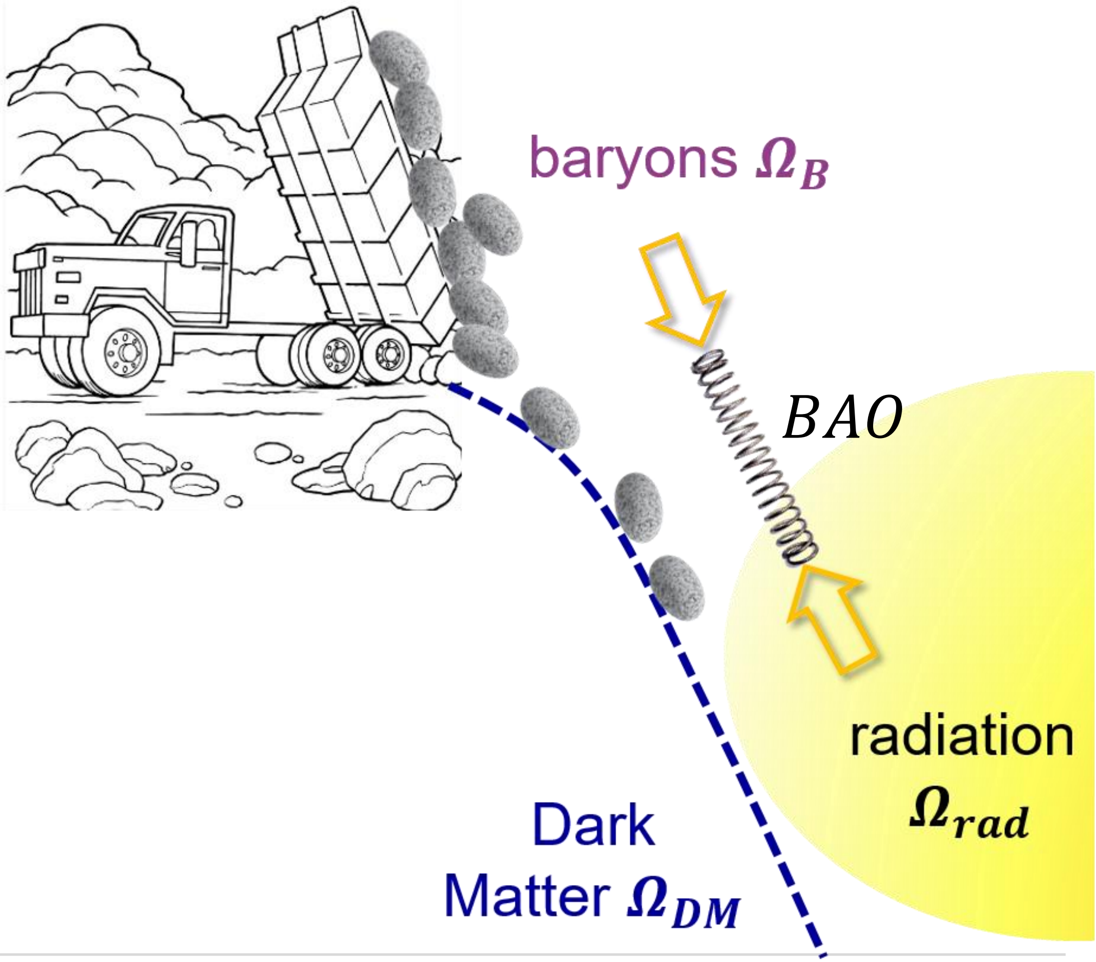


BAO – determining the baryon density Ω_B

- **BAO first peak height is sensitive to Ω_B**

- ´**baryon loading**´: the CMB value for Ω_B
  ⇔ comparison to BBN* light element yields





*see lecture #7 p. 41

BAO – determining the baryon density Ω_B

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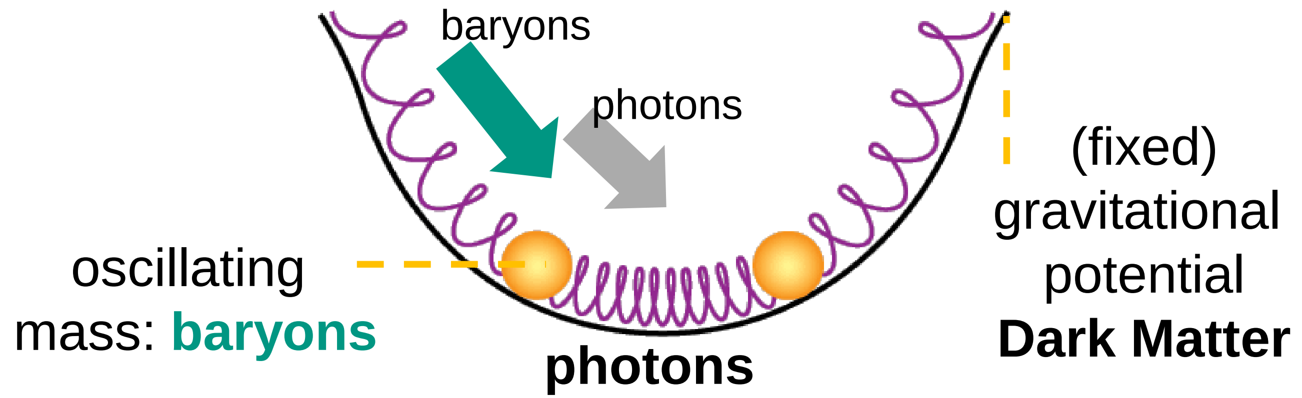
- **BAO: baryon loading & Ω_B**

- ´**baryon loading**´: baryons (matter) & radiation are ´**in phase**´ - from rarefication to compression (**first peak**)

- for each second peak (odd numbers): matter & photons are ´in phase´



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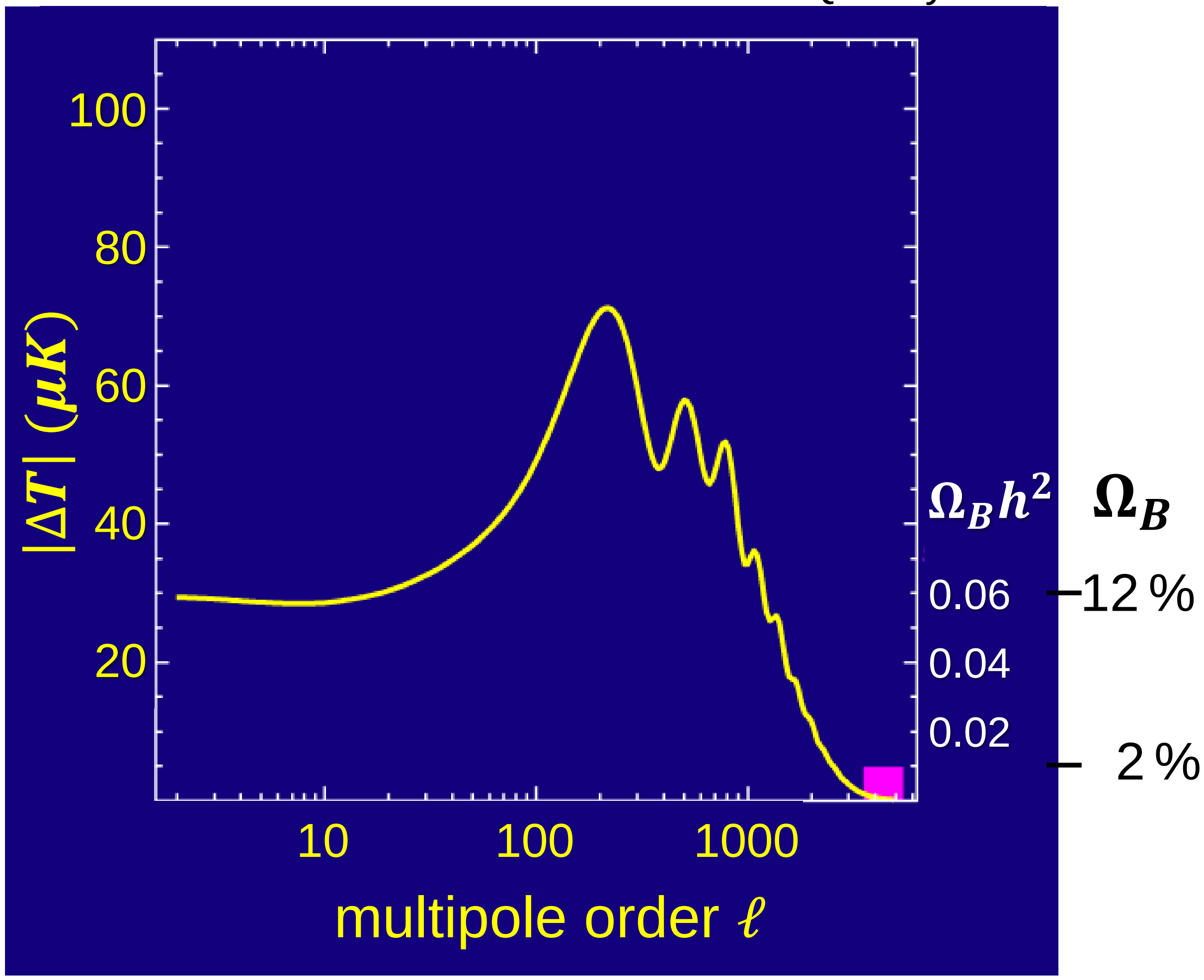
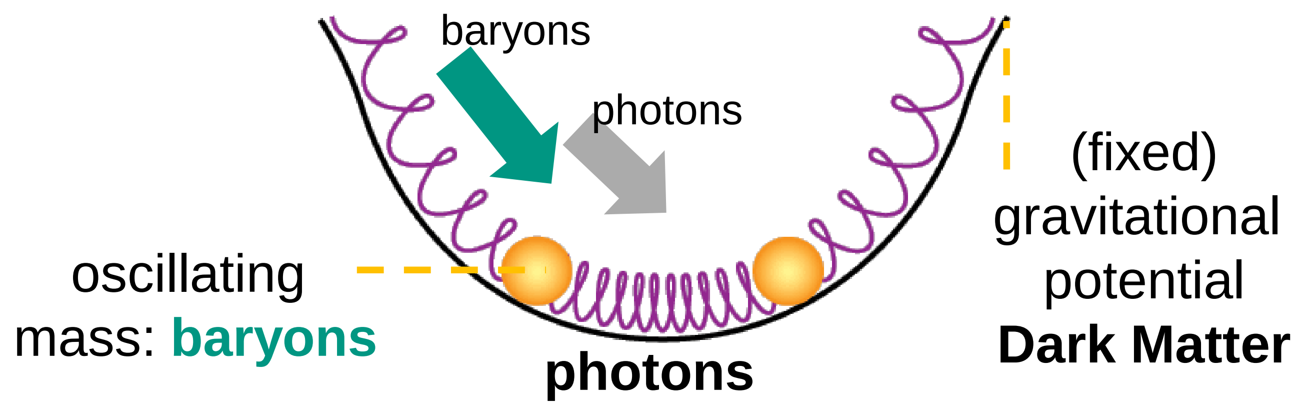


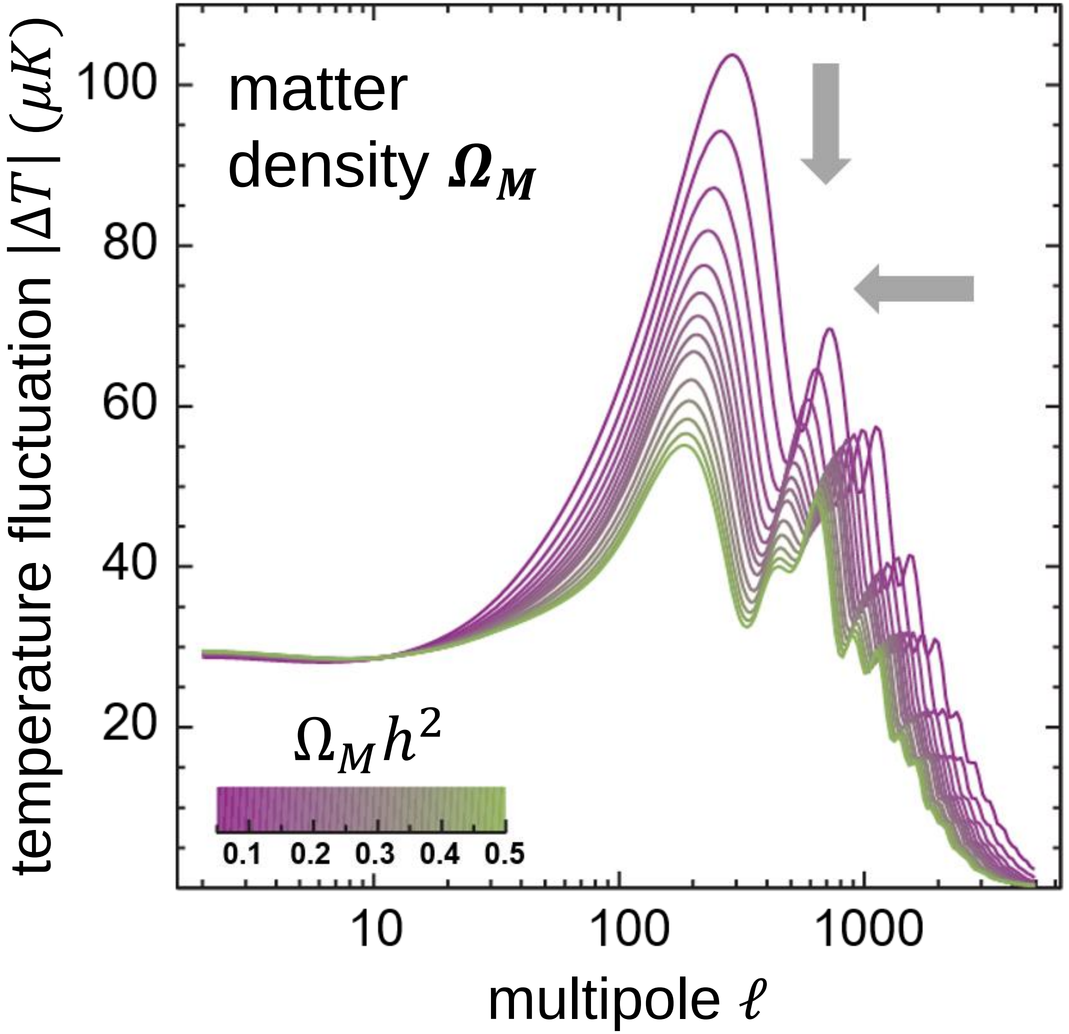
BAO – determining the dark matter density Ω_{DM}

- **BAO: a clear CMB evidence for $\Omega_{DM} \neq 0$**

- matter density Ω_M with two contributions:
  dominant Dark Matter $\boldsymbol{\Omega_{DM}}$ & baryons $\boldsymbol{\Omega_B}$

- increasing $\boldsymbol{\Omega_M}$: deeper potential wells
  ⇨ scale of ΔT –fluctuations will
  decrease, consider even & odd peaks





BAO – determining the dark matter density Ω_{DM}

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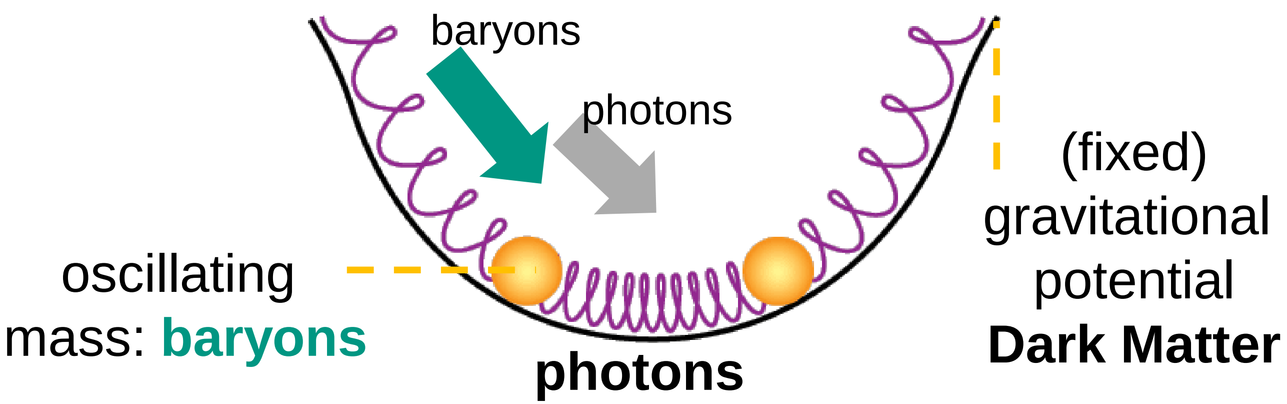
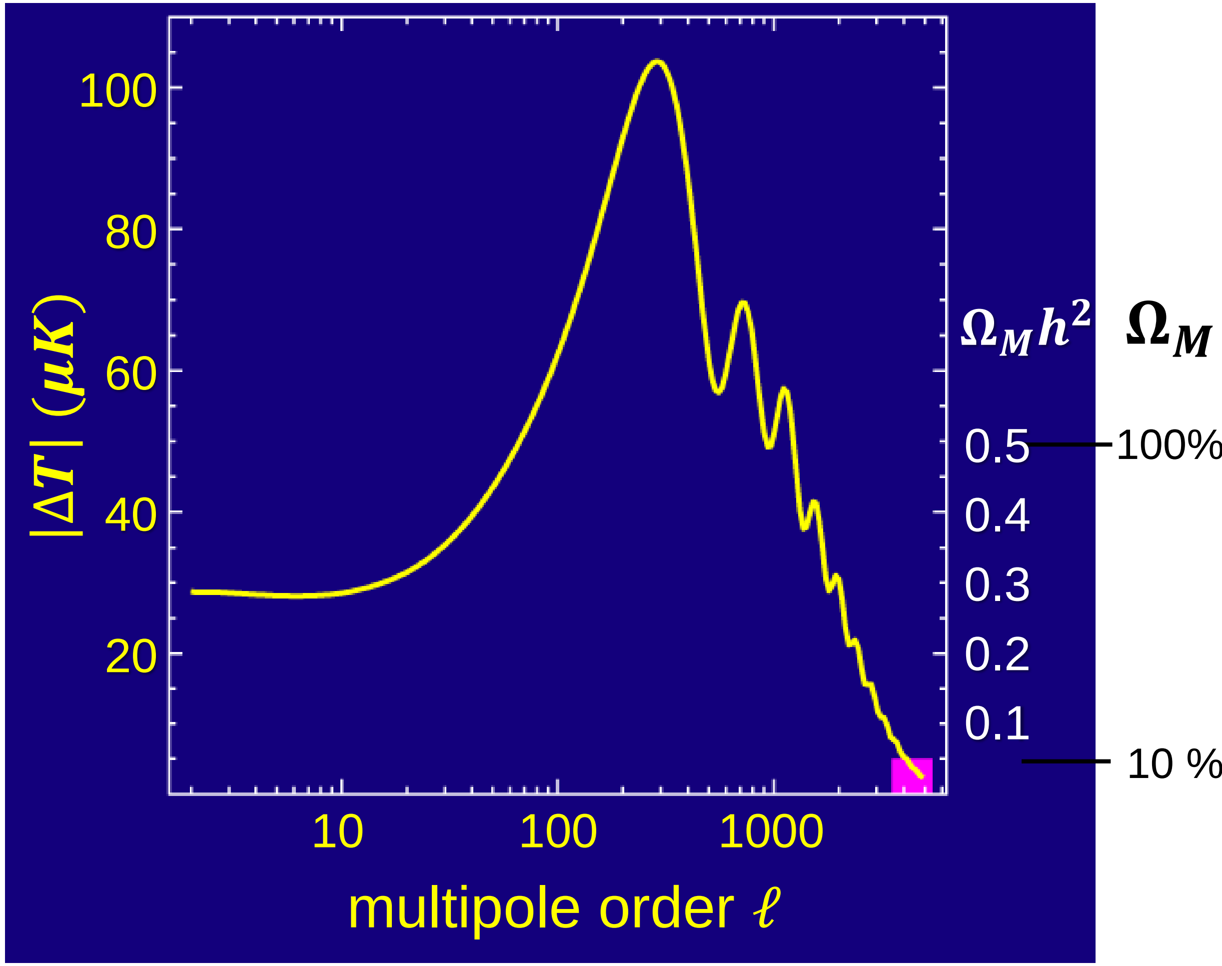
■ BAO: a clear CMB evidence for $\Omega_{DM} \neq 0$

- as $\Omega_{DM} \gg \Omega_B$: this allows to draw direct conclusions for Dark Matter density

- best indicator for Ω_{DM}: relative heights & positions of 2. and 3. acoustic peaks (of course: global fit to entire spectrum!)





BAO – a ´powerhouse´ for cosmology

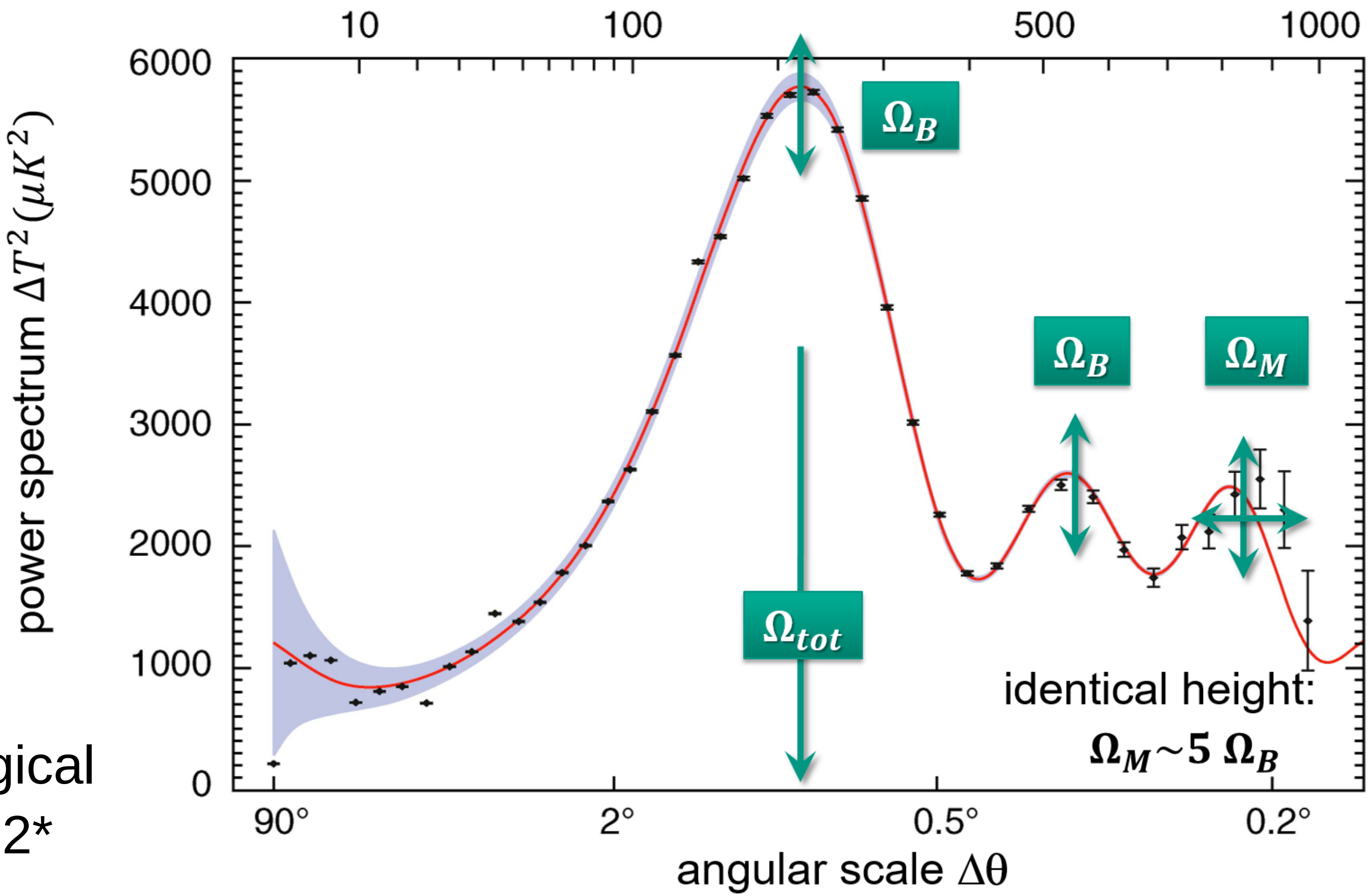
- **BAO: global analysis**

- flat, Euclidian universe
  with $\Omega_{tot} = 1$

- baryon density
  $\Omega_B h^2 = 0.02237 \pm 0.00015$

- matter density
  $\Omega_M = 0.315 \pm 0.007$

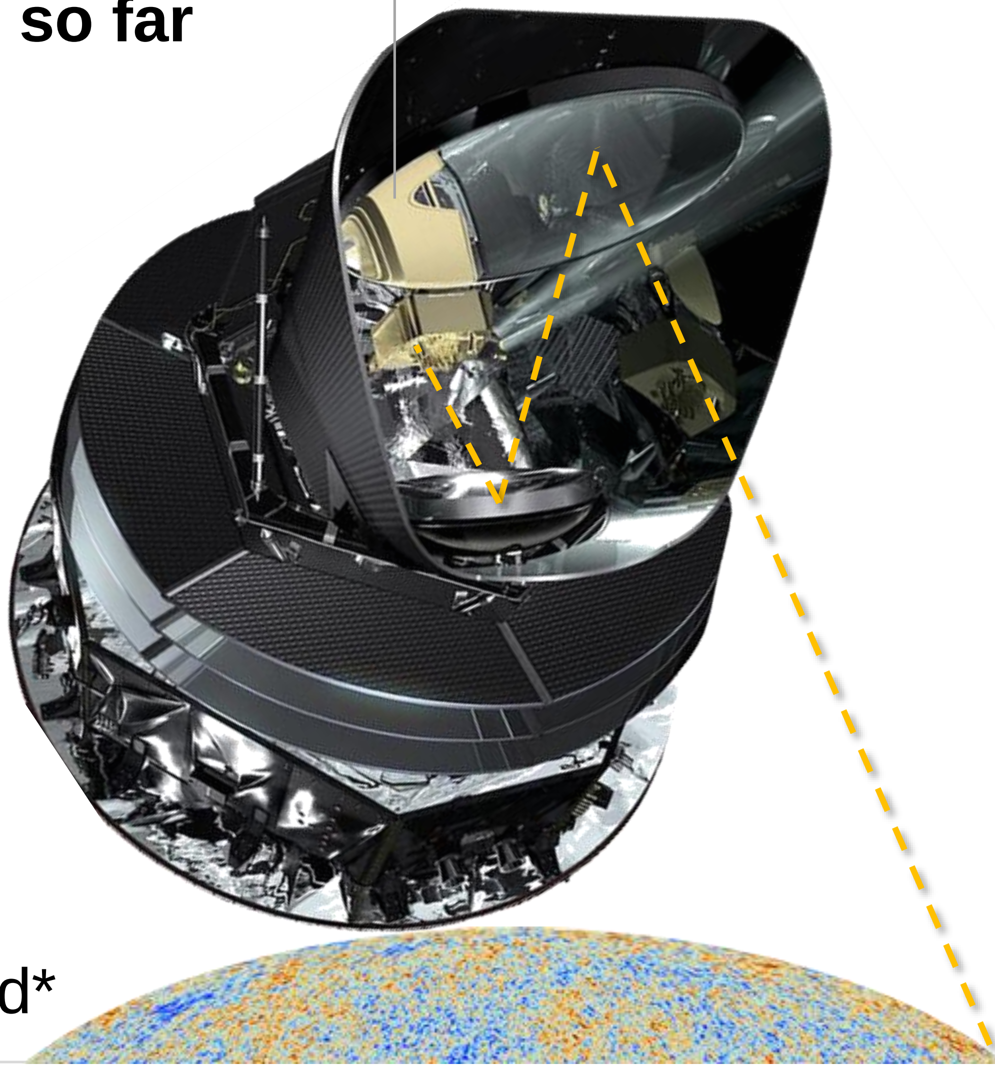
- actual values of cosmological parameters see PDG 2022*



* rpp2021-rev-cosmological-parameters.pdf (lbl.gov)

ESA´s Planck mission 2009-13

primary mirror
aperture $1.75\ m$



■ CMB measurements at the highest resolution so far

- nominal resolutions of Planck:
  - $T/T \sim 2 \cdot 10^{-6}, \Delta\theta = 4' \dots 33'$
  - frequencies: $30 \dots 857\ GHz$

- May 14, 2009: start with Ariane 5
- Aug 08, 2009: beginn data taking
- Jan 16, 2012: LHe-reservoir empty (5 *full sky surveys*)
- Mar 21, 2013: publication of first results
- Oct 23, 2013: Planck deactivated
- Aug 10, 2021: final 2018 results V4 published*

* 1807.06209.pdf (arxiv.org)

Planck – instrumentation of the focal plane

- **LFI and HFI cover 9 frequency bands**

LFI - **L**ow **F**requency **I**nstrument

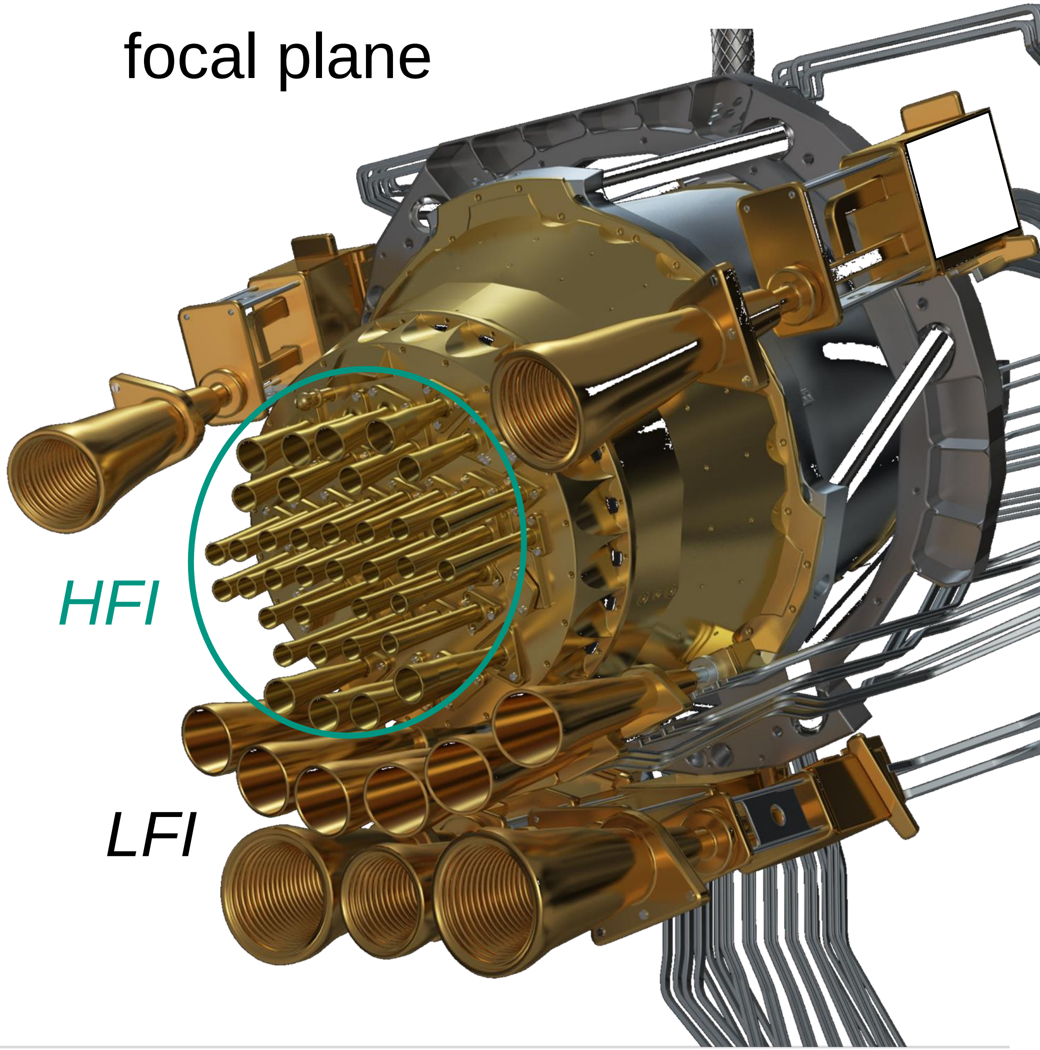
$f = 27 \ldots 77\ GHz \quad T = 20\ K$

HFI - **H**igh **F**requency **I**nstrument

$f = 100 \ldots 857\ GHz \quad T = 0.1\ K$

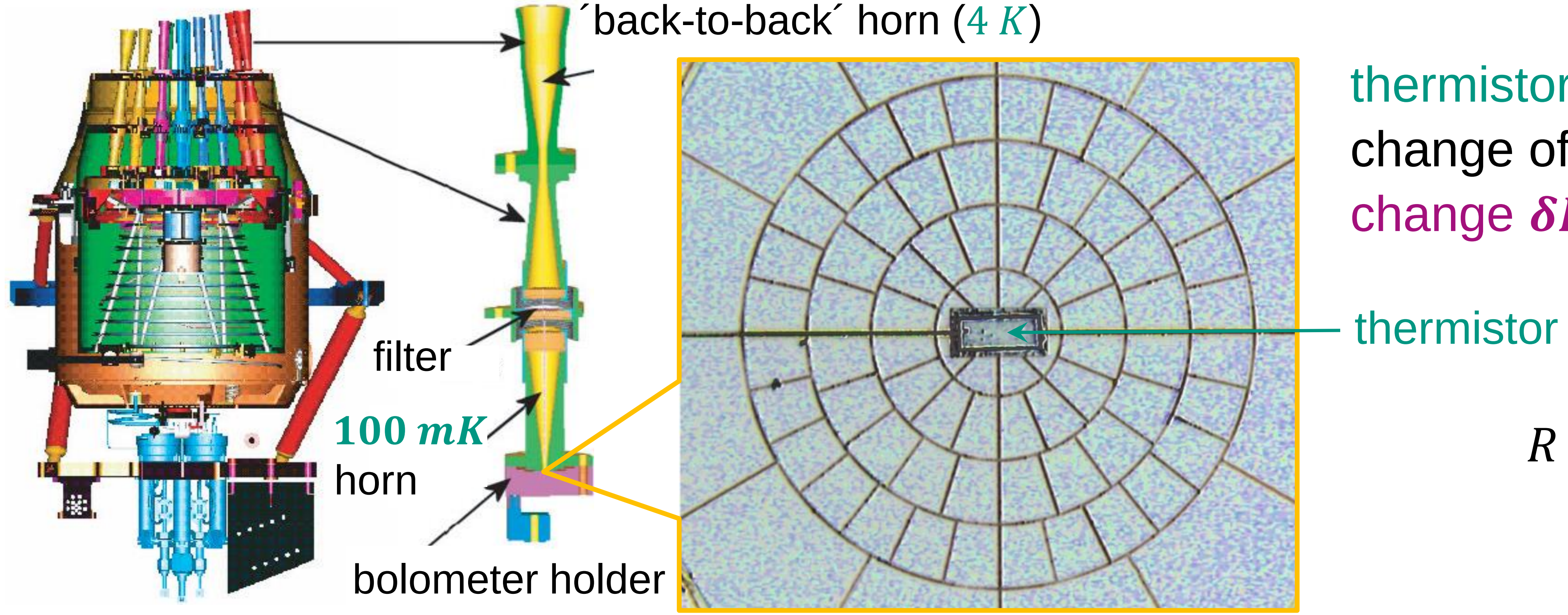
- CMB is guided via the primary & via the secondary mirrors onto the ´**focal plane**´ with instruments **LFI** and **HFI**

- **LFI** & **HFI** are cooled via LHe reservoir

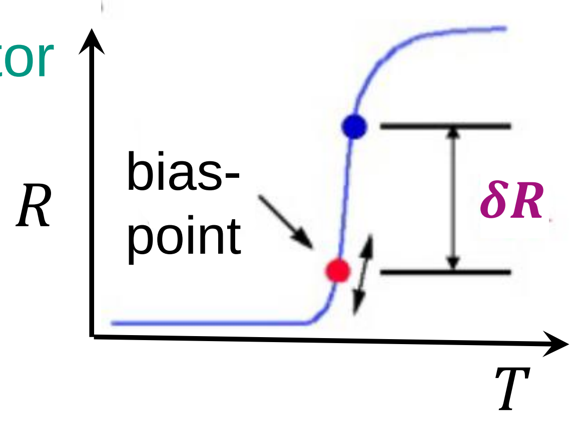


Planck – HFI: a ´spider-web´ bolometer

- **CMB microwaves are detected by super-conducting bolometer (´spider-web´)**
  - absorption of microwaves: tiny increase of bolometer temperature, read-out by thermistor

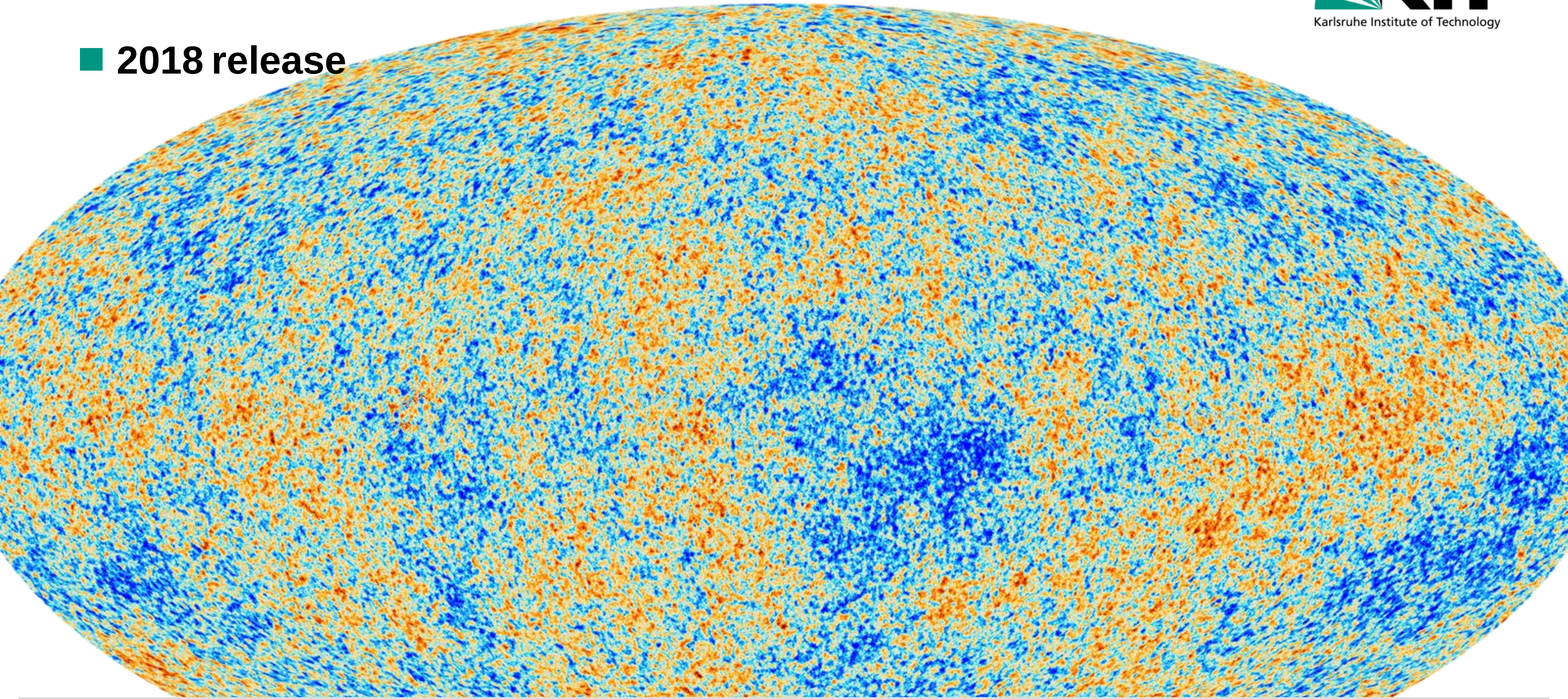


thermistor:
change of temperature T ⇨
change δR of resistivity R



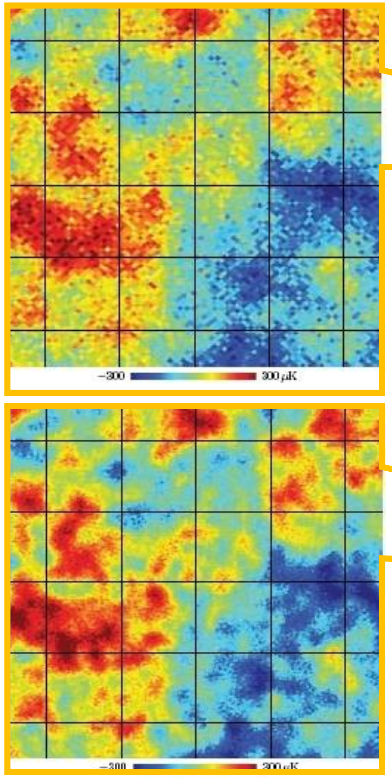
Planck – the ´definitive´ CMB temperature map

- 2018 release



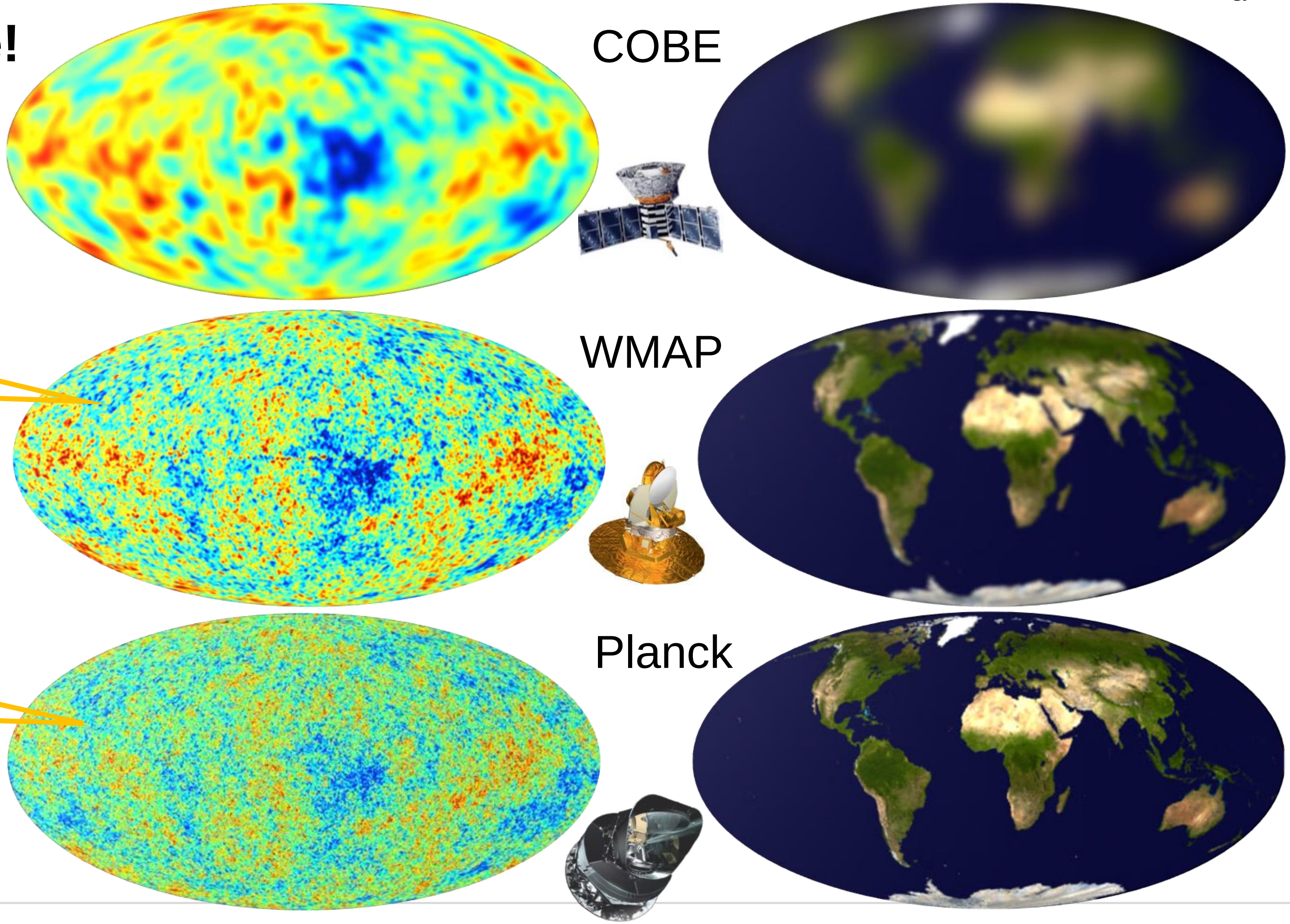
Comparing COBE … WMAP … Planck

- **Better resolution, please!**
  - exp. advances from 1989 … 2013



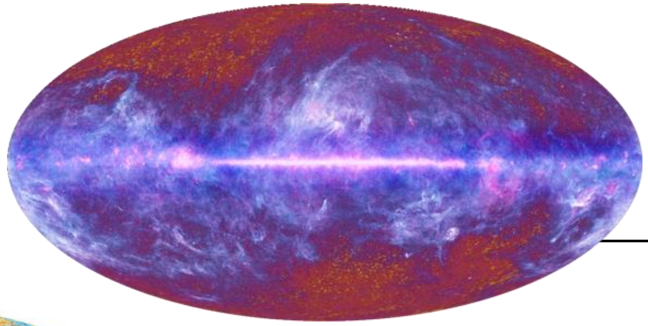
WMAP
9 years

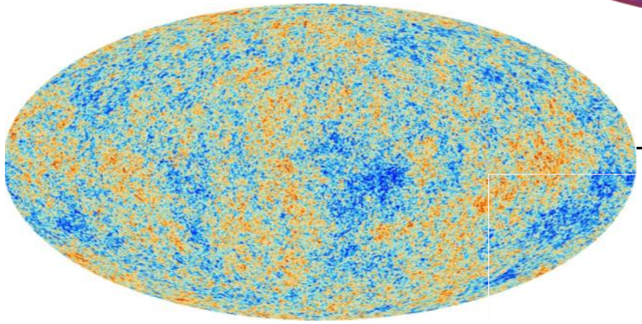
Planck
1 year

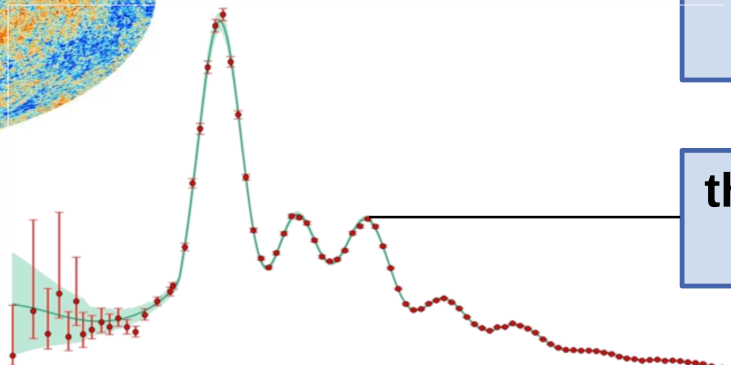


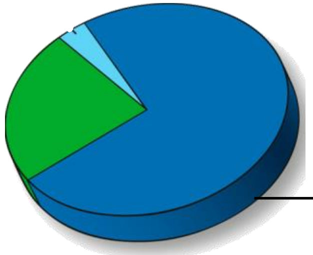
Planck – data analysis

- Chain of analysis is complex…









measurements: 72 detectors, 15000 data sets / s total: 6×10^{11} data sets

frequency cards: 9 channels total: 3×10^{7} pixels

experimental sensitivity, systematic effects

foreground maps 500 parameters

catalog of point sources $> 10^{4}$ individual objects

CMB temperature maps 5×10^{6} pixel

CMB polarization maps 10^{7} pixel

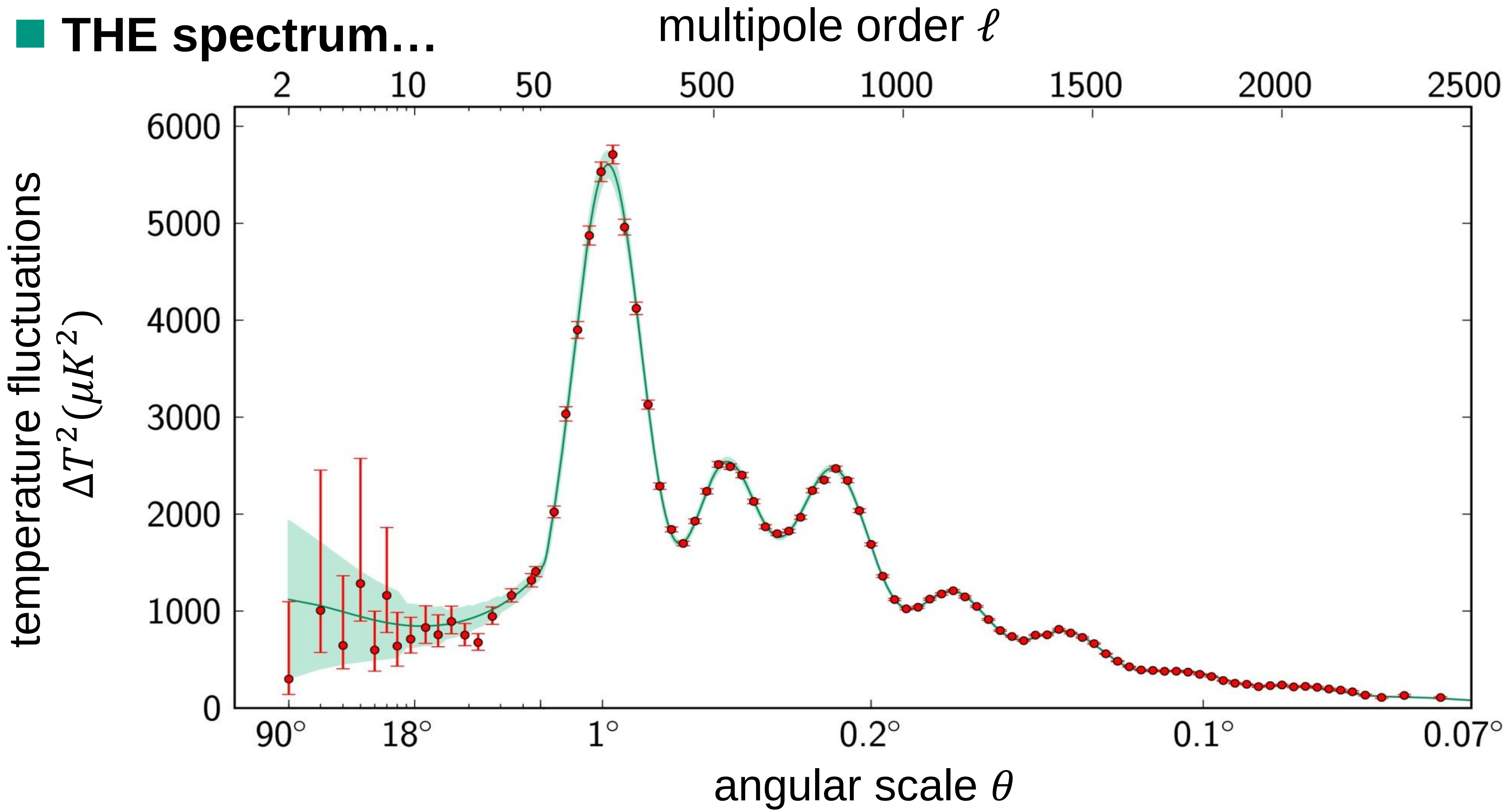
thermal power spectrum ~ 2000 numbers

power spectrum polarization ~ 1000 numbers

cosmological parameters 12 numbers

Planck – finally: the multipole spectrum for fits

- **THE spectrum…**



Planck – cosmological parameters

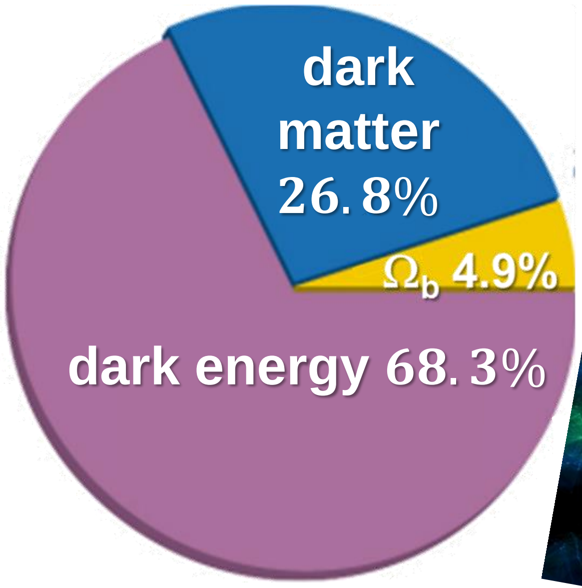
- **CMB has opened the precision age of cosmology**

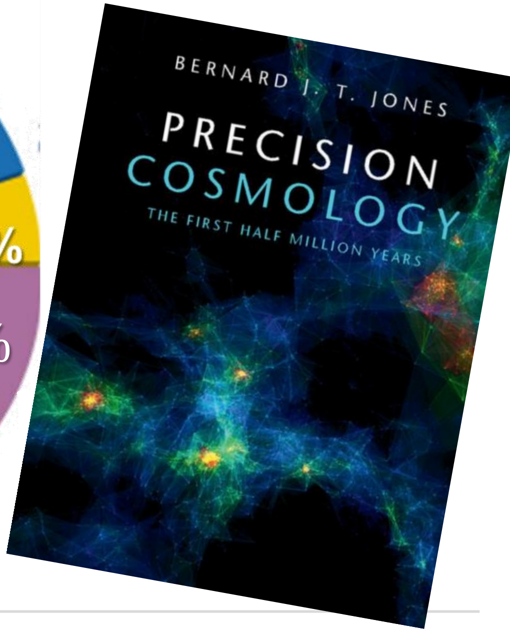
⇨ all CBM data can be described within the ΛCDM – concordance model

⇨ cosmological parameters based on CMB are derived from 2018 Planck data

- Planck data are fitted together with other data sets (galaxy surveys,…)

parameter	best fit value
age of universe t_0	$(13.80 \pm 0.04) \cdot 10^9\ yr$
Hubble constant* H_0	$(67.8 \pm 0.9)\ km\ s^{-1}\ Mpc^{-1}$
Baryon fraction $\Omega_B\ h^2$	$0.02226\ \pm 0.000230$
Dark Matter fraction $\Omega_{DM}\ h^2$	$0.1186\ \pm 0.0020$
Dark Energy Ω_Λ	$0.685\ \pm 0.017$
time of decoupling t_{rec}	$(377730 \pm 3200)\ yr$
red shift of decoupling z_{rec}	$1090.9\ \pm 0.7$





*see Hubble tension, lect. #2, p. 28-31

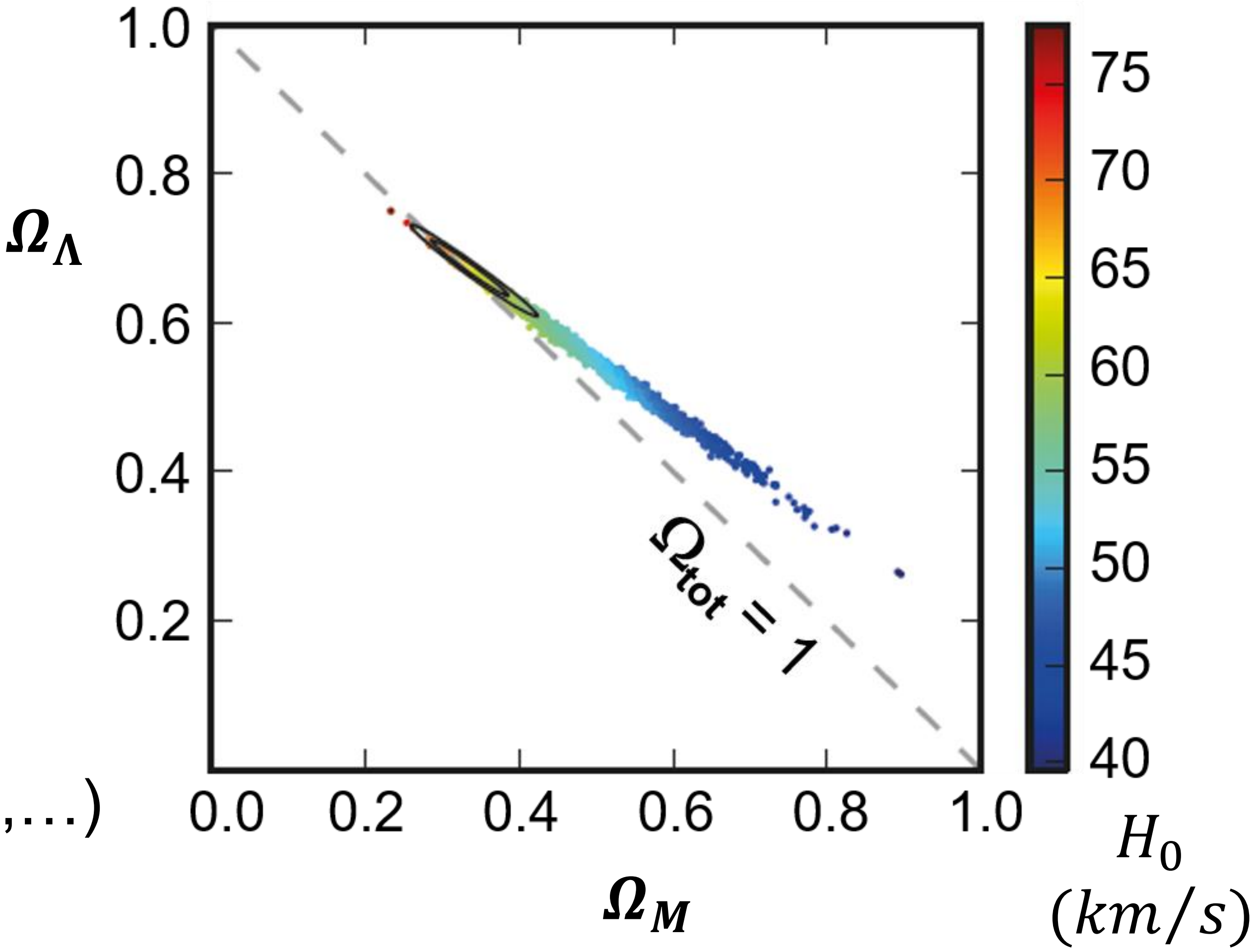
Cosmological parameters can be degenerate

- **Model fits to CMB & other data: ⇨ sets of degenerated parameters**

  - example:
    degeneracy of the three
    key cosmological parameters
    Ω_Λ Ω_M & H_0

  - **degeneracy of parameters:**
    different combinations of
    parameters yield identical fits to data

    ⇨ needs to be broken by additional
    information (orthogonal data sets,…)



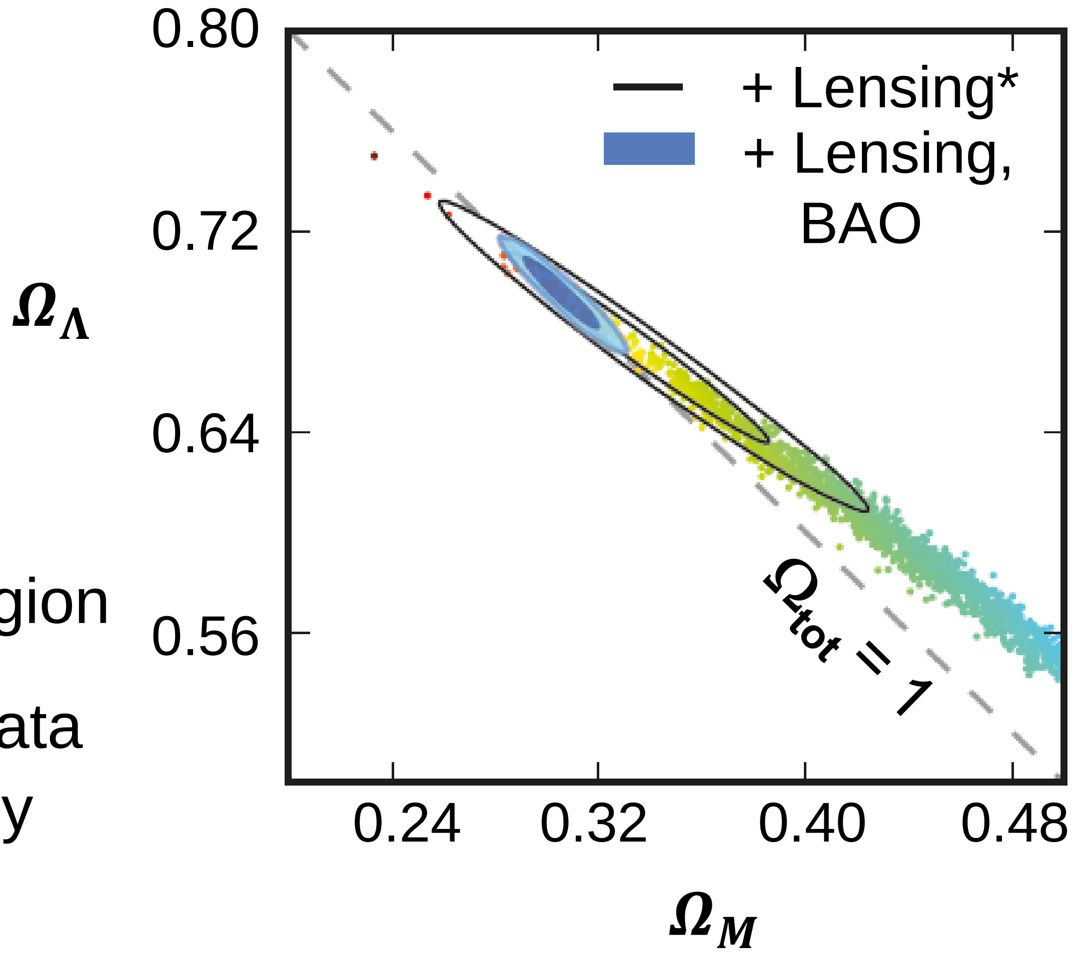
Cosmological parameters: degeneracy broken

- **Model fits to CMB & other data: ⇨ sets of degenerated parameters**

- example with additional data: **degeneracy** of the two key cosmological parameters Ω_Λ Ω_M

- **degeneracy of parameters reduced:** different combinations of parameters still good fits, but smaller region

  ⇨ additional information (orthogonal data sets,…): breaks/reduces degeneracy here - weak lensing effect*



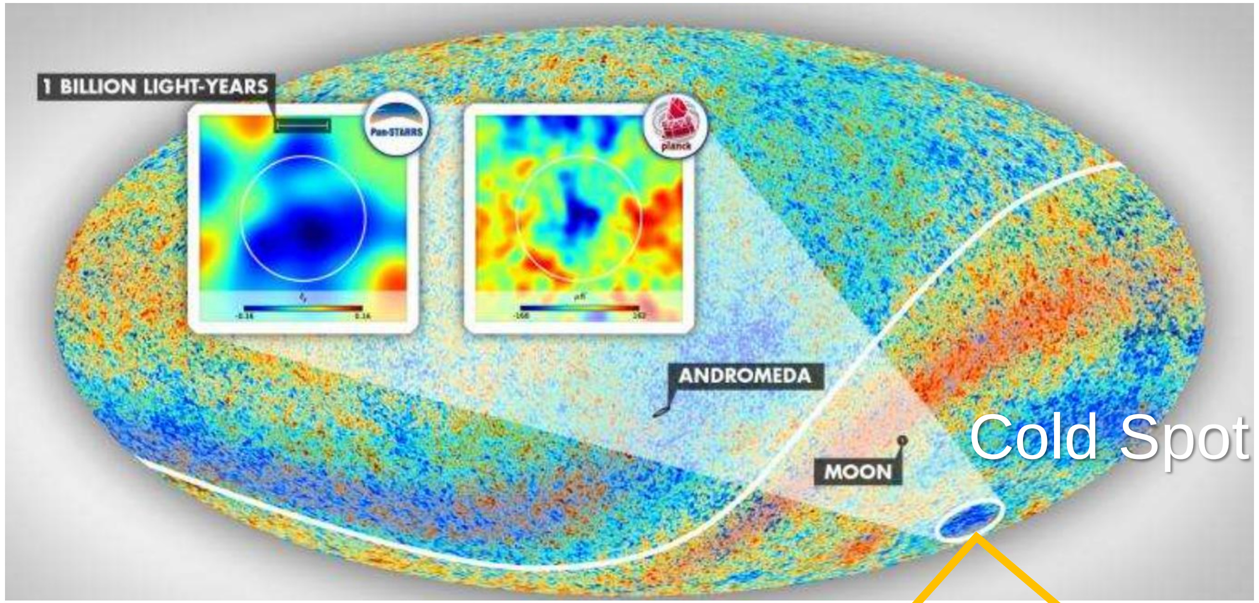
*see chapter 5.2 (lecture #14)

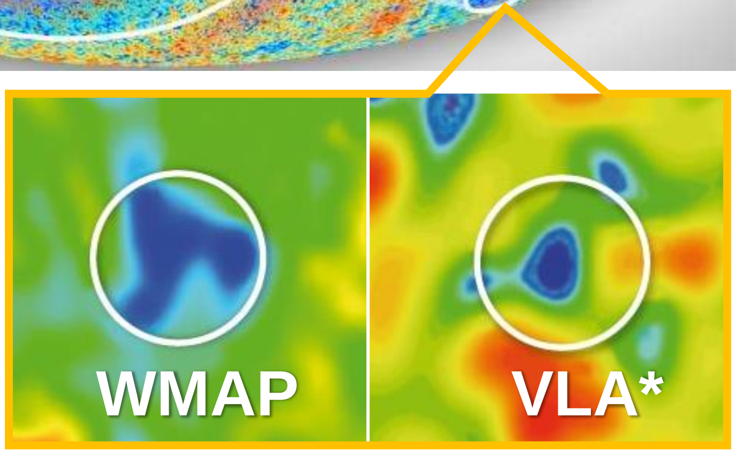
Anomalies in the CMB: WMAP ´Cold Spot´

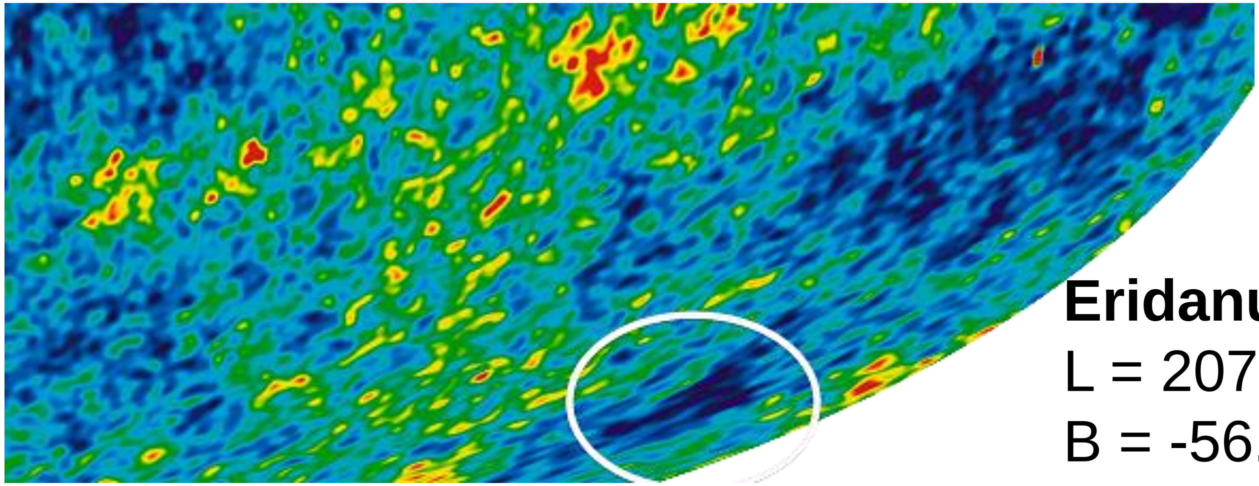
- **A large cold region revealed by WMAP: a cosmic ´super-void´?**

- WMAP data have yielded a surprise: a **5° large cold CMB region**, where $\Delta T \sim -70\ \mu K$ (below CMB-average)

- also seen in VLA* data & others







Eridanus:
L = 207.8°
B = -56.3°

*Very Large Array (radio)

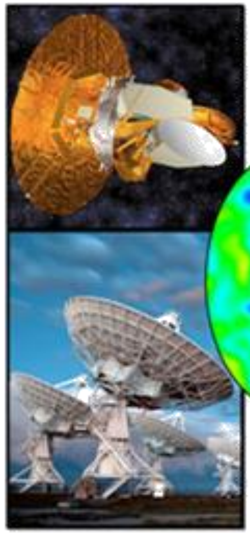
Anomalies in the CMB: WMAP ´Cold Spot´

- **Does the CMB pass a super-void with $d = 300\ Mpc$ at $z = 1$?**

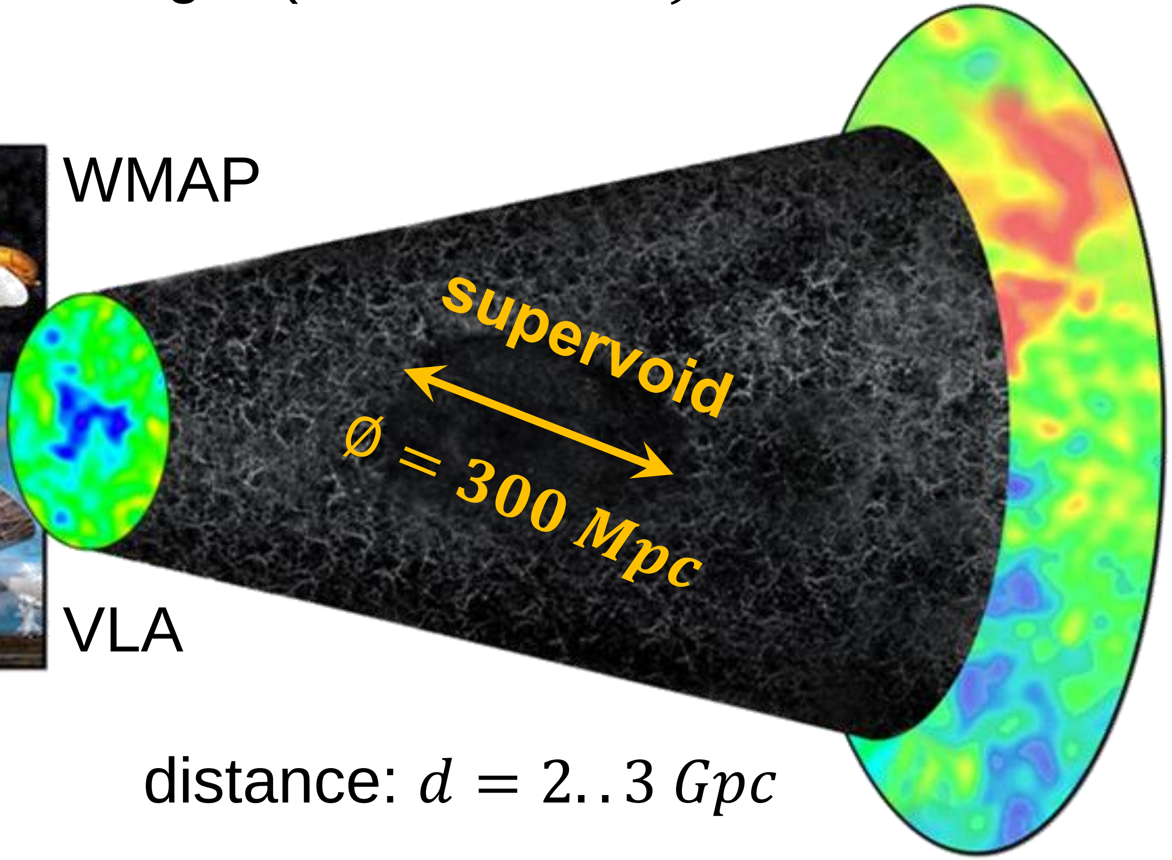
  - this super-void, if existing, would be much larger ($V \approx 30 \ldots 100$) than all other, average-size voids

- (highly speculative) interpretation of data: we are witnessing the ongoing collision with another universe ´next door´

WMAP



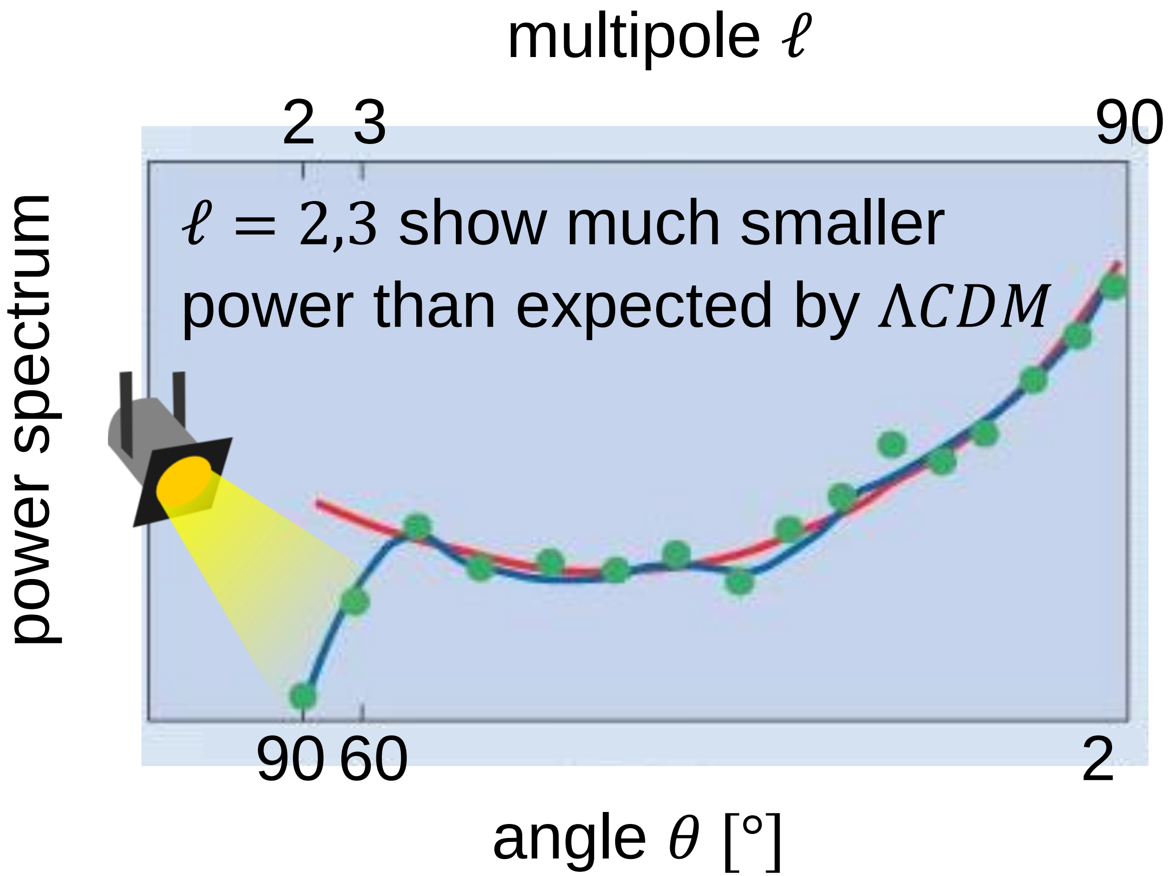
VLA



distance: $d = 2..3\ Gpc$

Anomalies in the CMB: quadrupole & octopole

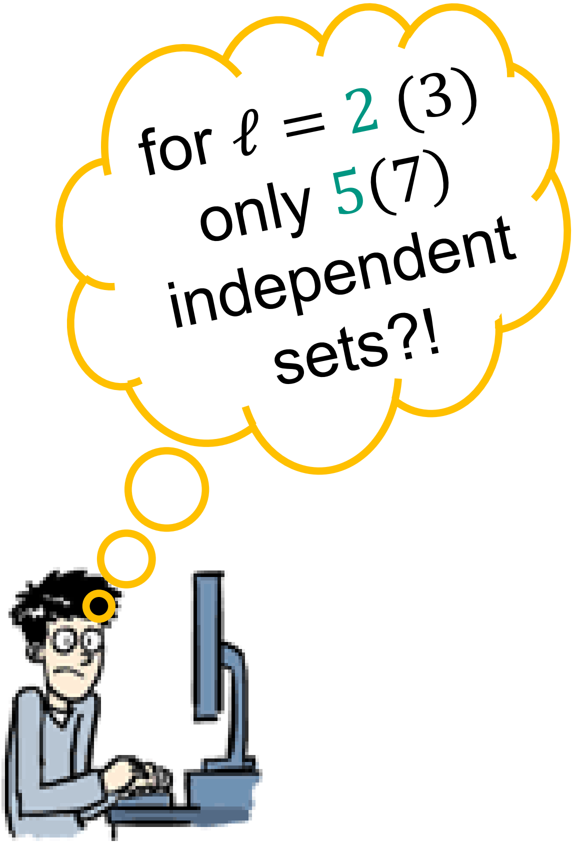
- Why is there so little power in the two lowest-order multipoles?



cosmic variance

$$\pm\sqrt{2/(2\ell+1)} \cdot C_\ell$$

- an intrinsic limit to cosmology with the CMB, does NOT depend on the resolution of my experiment!



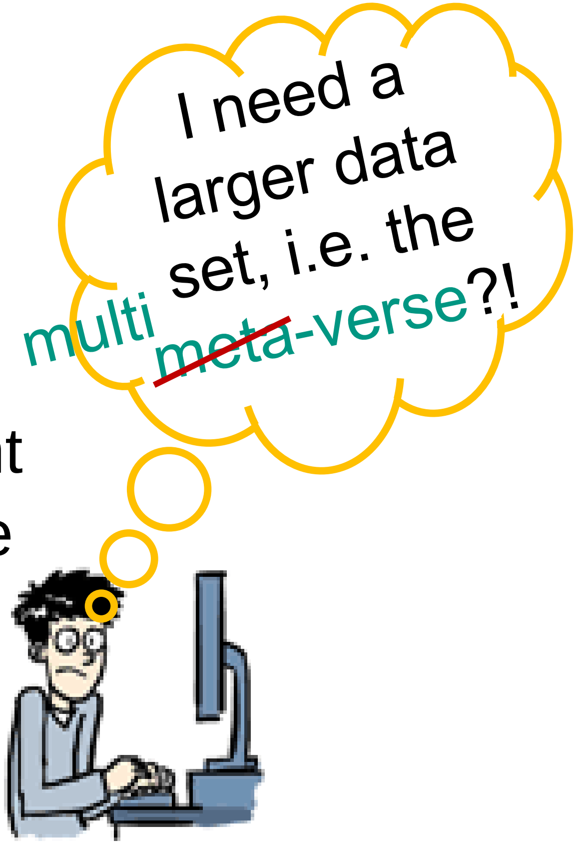
Anomalies in the CMB: quadrupole & octopole

- **Why is there so little power in these two lowest-order multipoles?**

cosmic variance

$$\pm\sqrt{2/(2\ell+1)}\cdot C_\ell$$

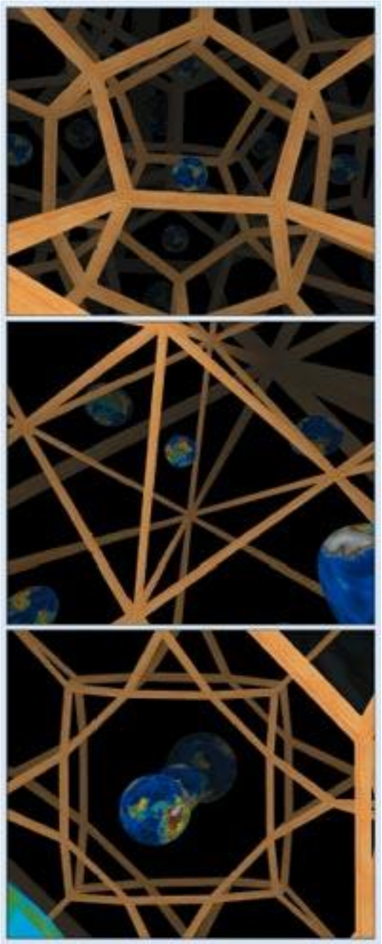
- we would need to sample* many different universes to overcome cosmic variance!

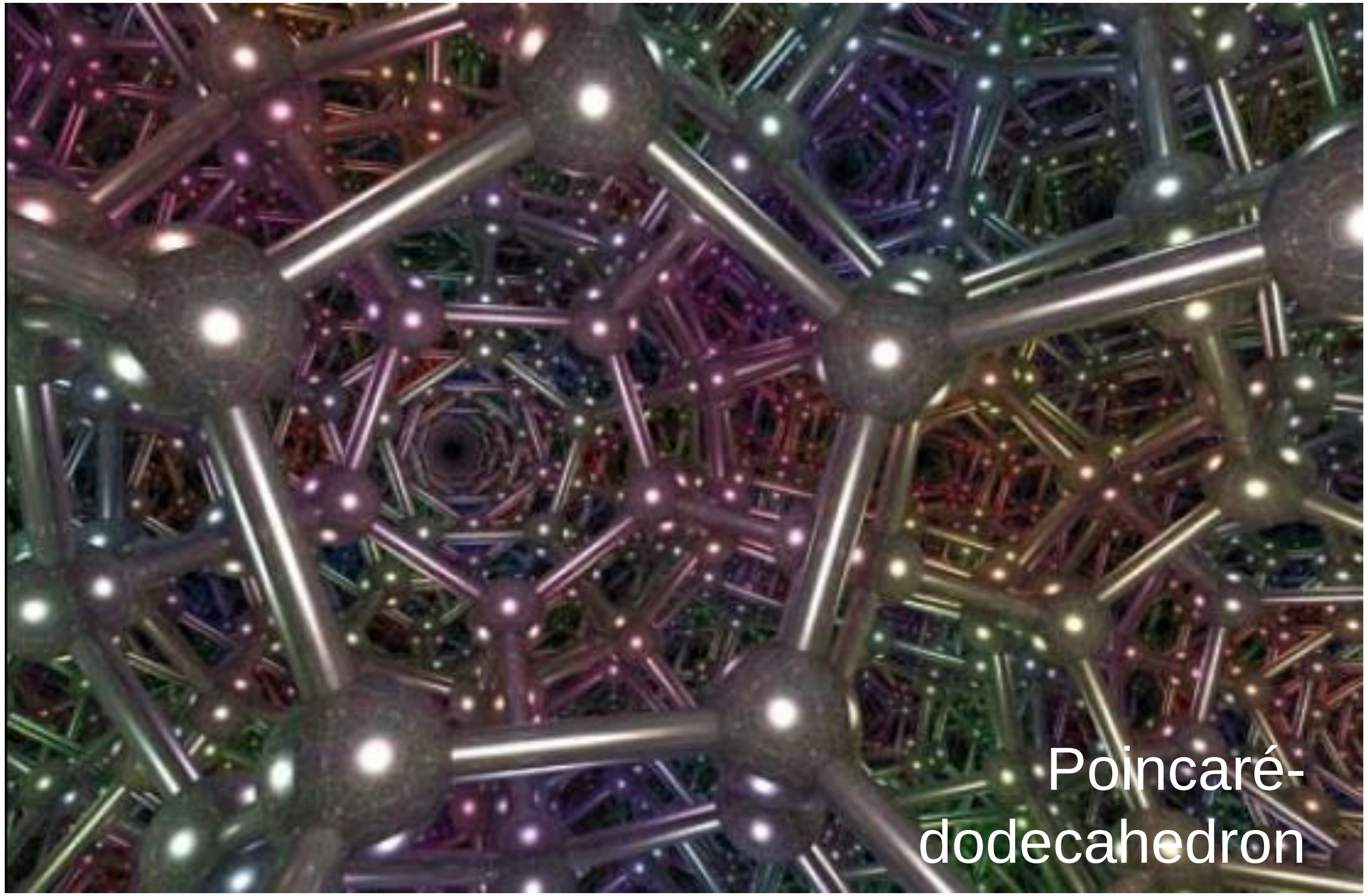


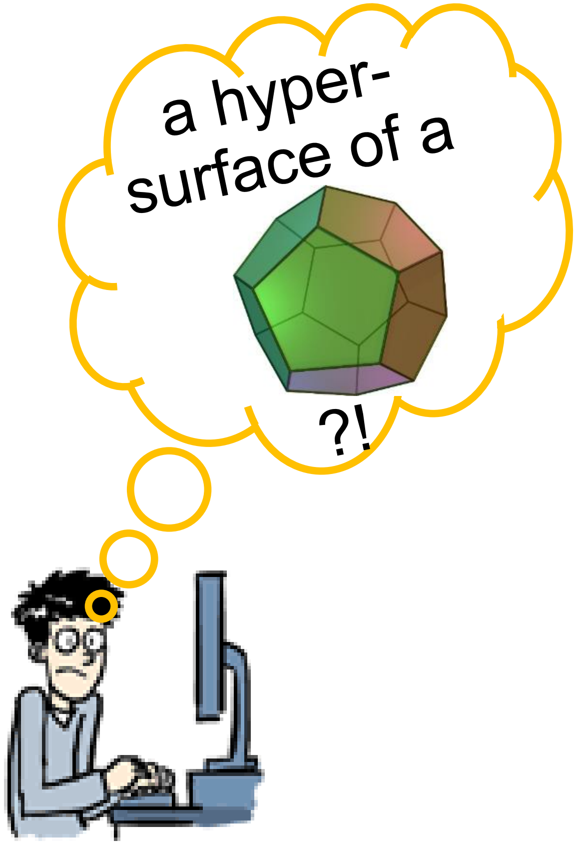
* or in our universe at different, far-off locations

Anomalies in the CMB: quadrupole & octopole

- **Answer 1: it points to the universe being a Poincaré manifold**

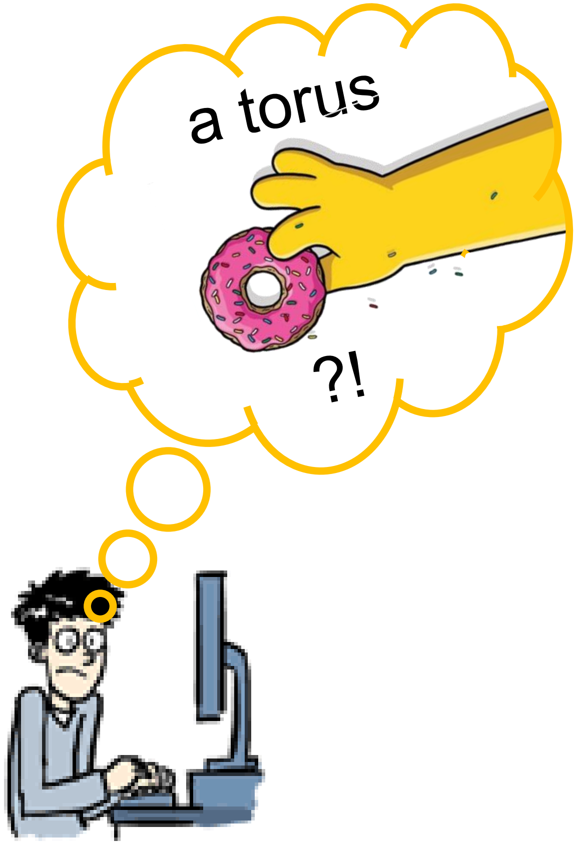






Anomalies in the CMB: quadrupole & octopole

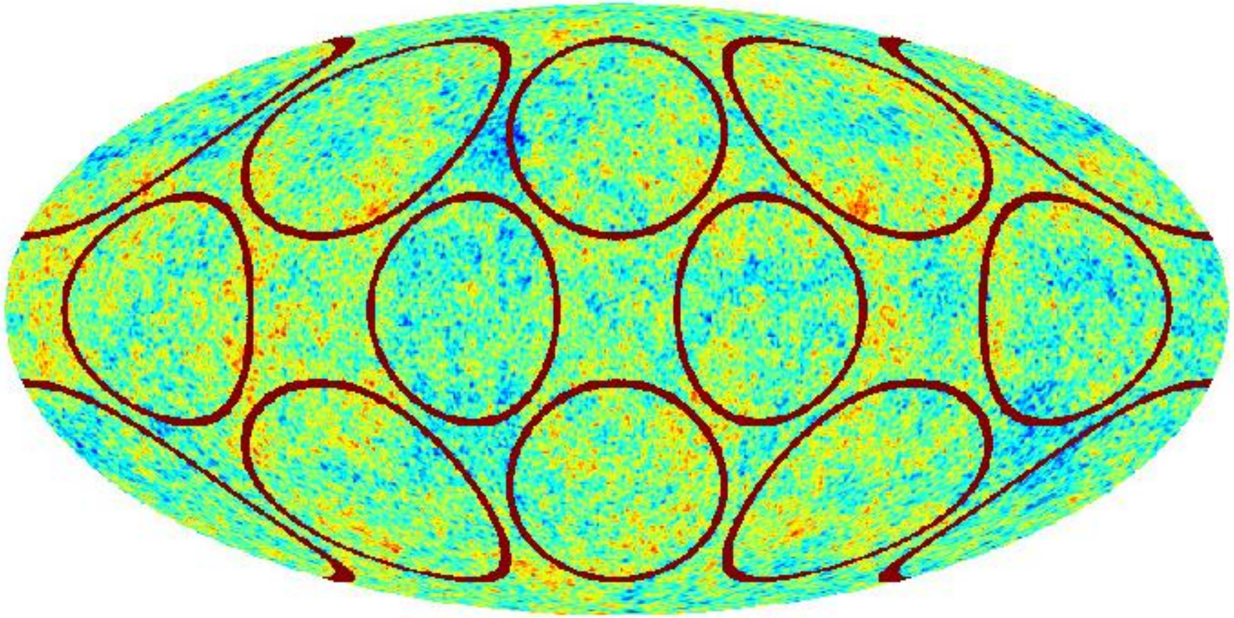
- **Answer 2: it points to the universe being a torus (not all dimensions did increase equally)**



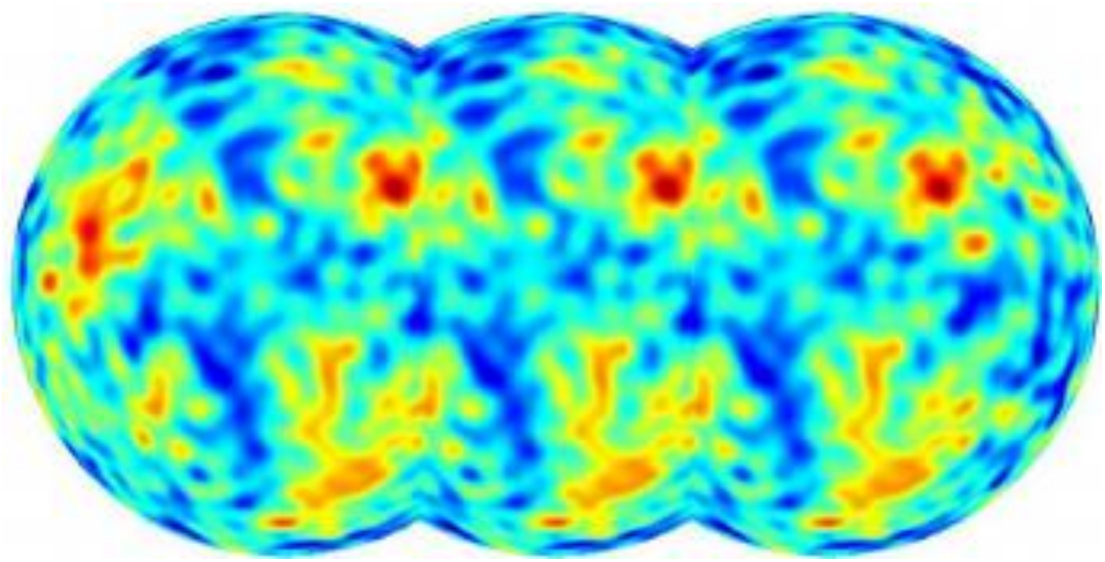
Anomalies in the CMB: circles in the sky?

- **Answer 3: universe with non-trivial topology : pairs of matching circles?**

- simulated Planck map with a [2,2,2] toroidal symmetry



- none found so far...



Anomalies in the CMB: quadrupole & octopole

- The ´**axis of evil**´: pure coincidence or systematic effect in the analysis?

The universe lines up along the 'axis of evil'. Coincidence?

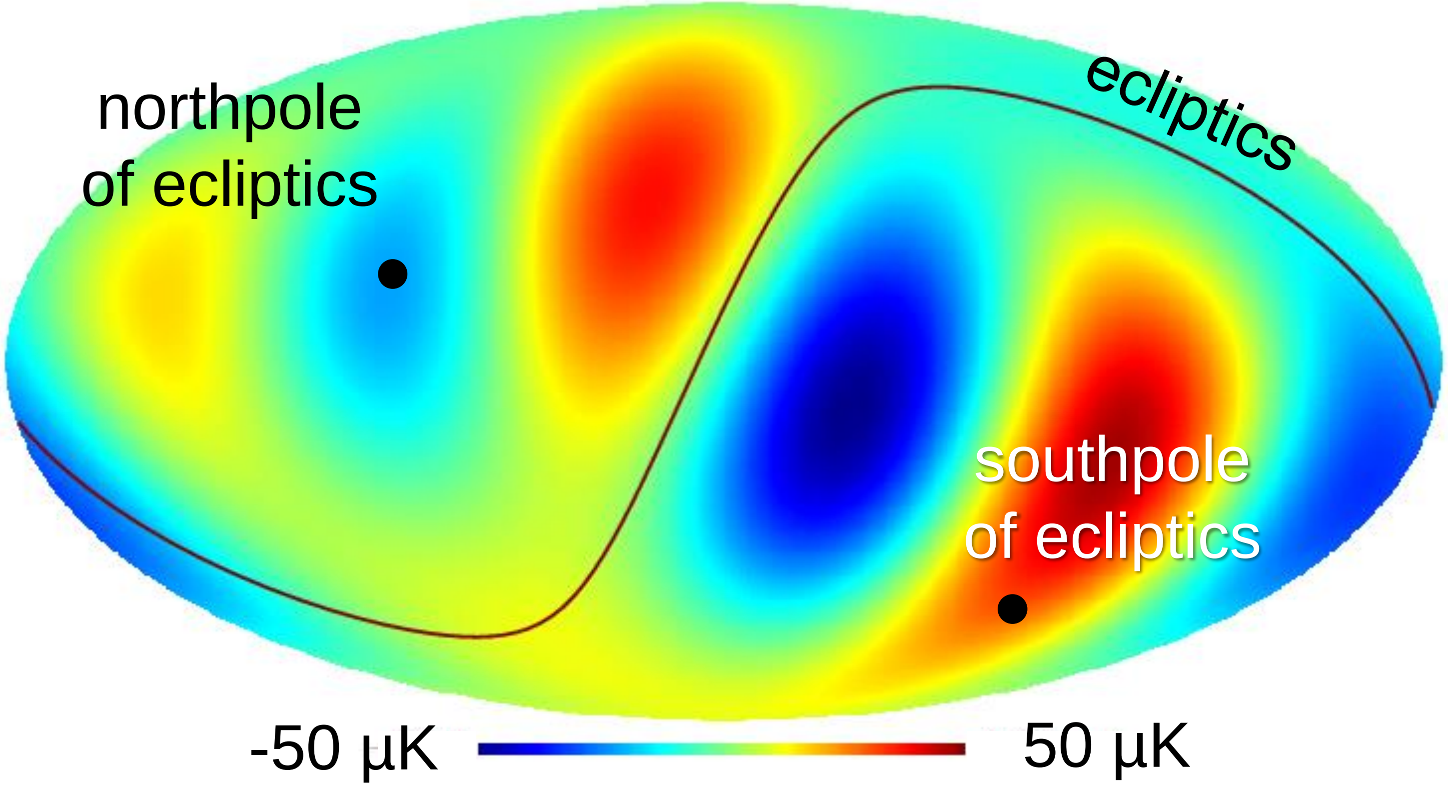
From the rotation of galaxies to cosmic expansion everything points in one direction. If only we knew why

SPACE 26 October 2016

By **Stuart Clark**

ESO/B. Tafreshi (twanight.org)

COSMOLOGISTS called it the axis of evil. Spotted in 2005 in the cosmic microwave background, the all-pervading afterglow of the big bang, the axis was a peculiar alignment of features where we would have



quadrupole & octopole alignment

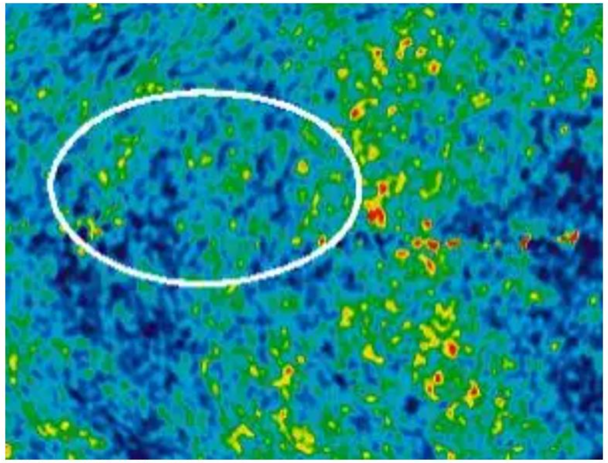
Anomalies in the CMB

- **Cosmic variance & the element of coincidence* in large data sets**

Found: Hawking's initials written into the universe

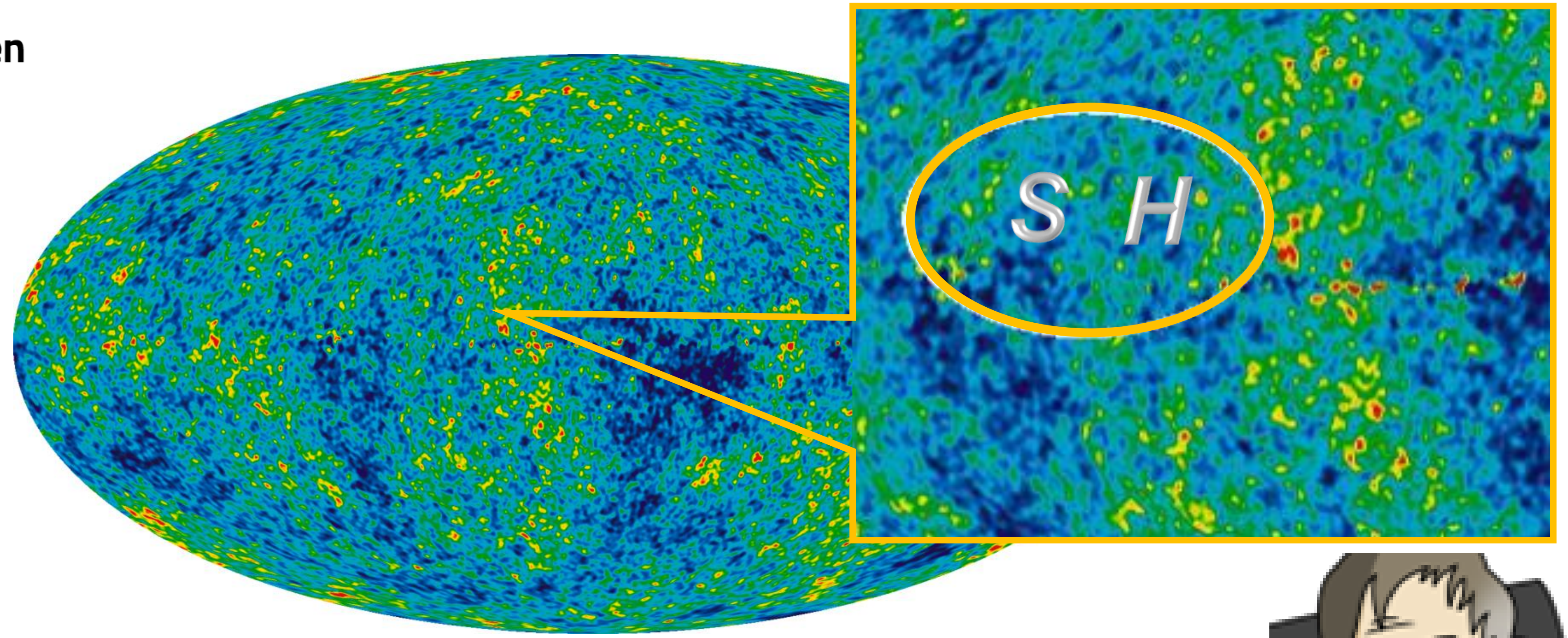
SPACE 7 February 2010

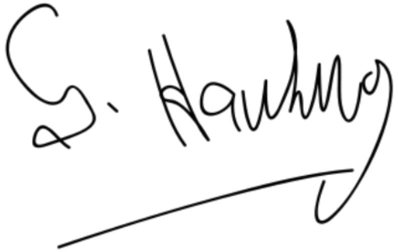
By Richard Fisher and Rachel Courtland



Stephen Hawkings leaves his mark
(Image: NASA/WMAP Science Team)

Is Stephen Hawking a galactic graffiti artist? Hidden away in the cosmic microwave background, the afterglow of the big bang, the initials "SH" are clear to view (see picture, right). We took a closer look and spotted

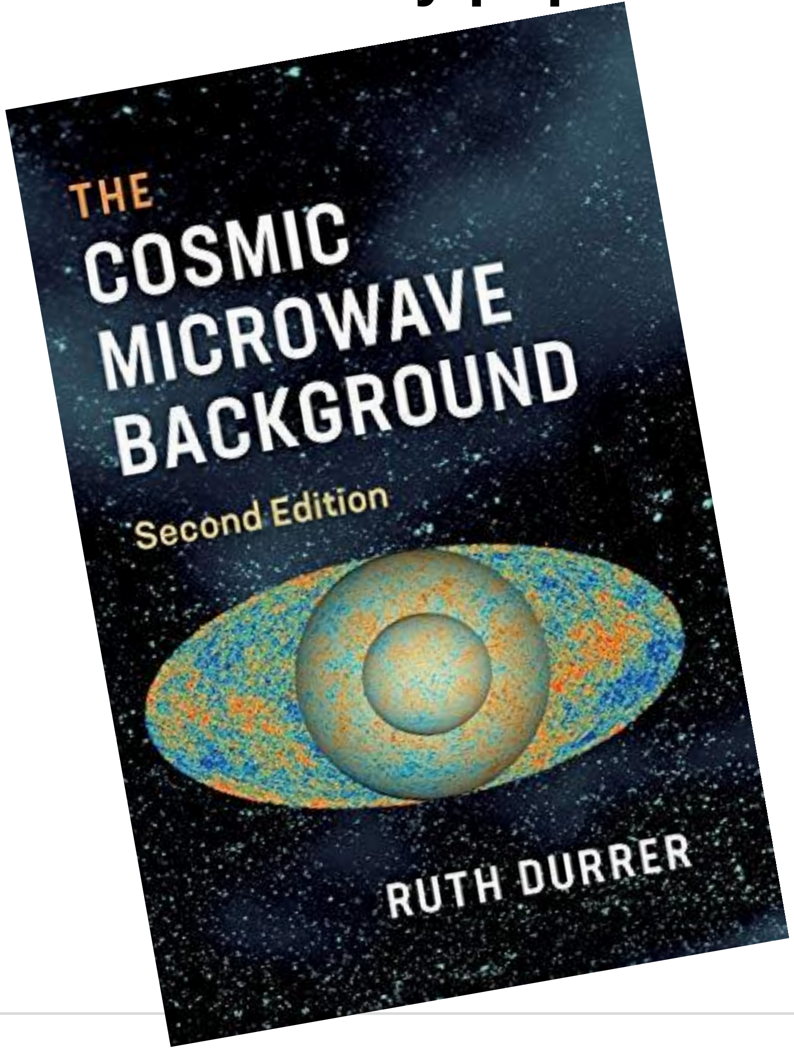


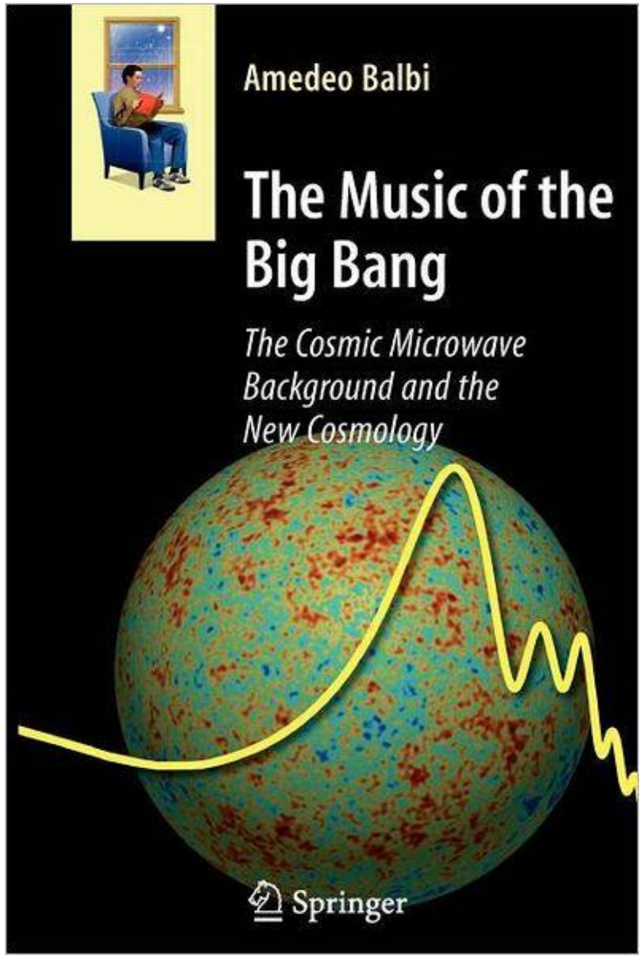


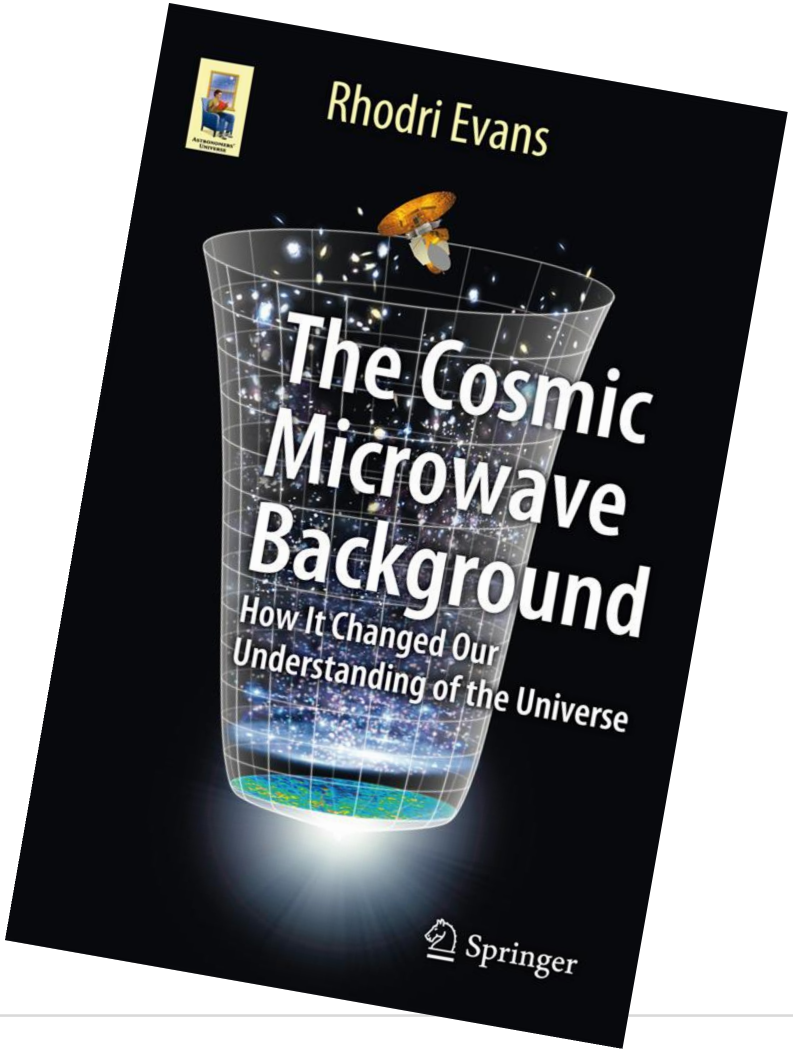
*find your own initials in the CMB

Riding early waves: interesting books for 2023…

- CMB is fairly popular: many books on the market

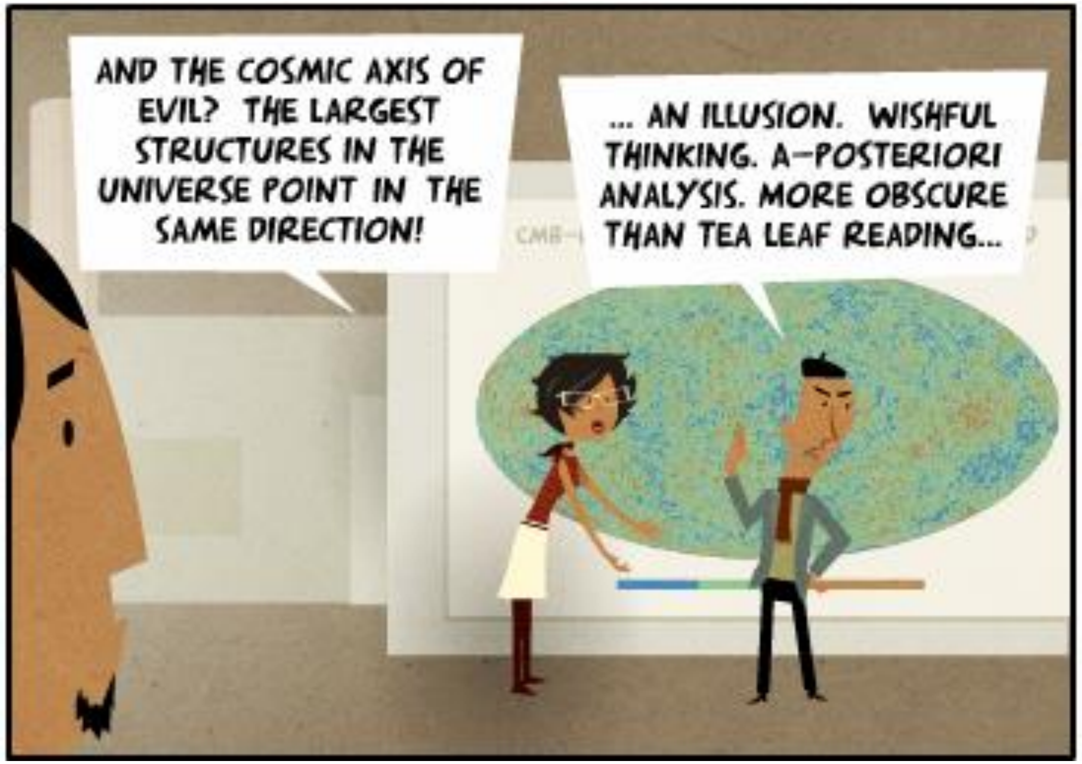






Riding early waves: two Post-docs at MPA

- Do NOT mimic: surfing on acoustic (sound) waves in the early universe



[Riding the Cosmic Waves – Pressepaket (mpg.de)]