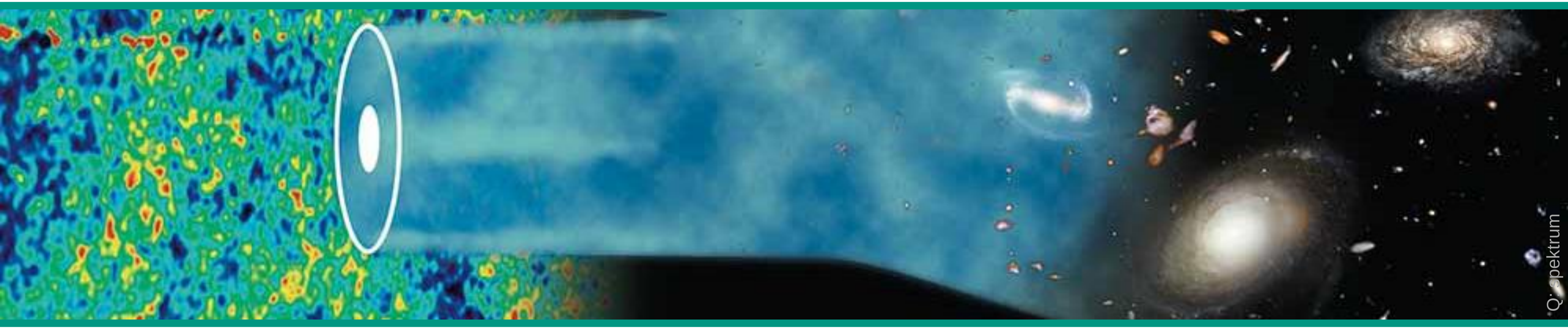
Introduction to Cosmology

Winter term 22/23 Lecture 11 Jan. 24, 2023



Recap of Lecture 10

- **CMB: Baryon Acoustic Oscillations (BAO) & the Planck mission**

  - **BAO**: (standing) acoustic waves in the primordial plasma (sound horizon)

  - fundamental mode: position $\ell_1 = 1/\sqrt{\Omega_{tot}}$ - flat, Euclidean universe $\Omega_{tot} = 1$

  - fundamental mode: height impacted by **baryon loading** $\Omega_B h^2 = 0.022$

  - overtones: impacted also by **dark matter**, $\Omega_{DM} \approx 5 \times \Omega_B$

  - **Planck** – definitive CMB map, yielding fundamental parameters for ΛCDM

  - CMB anomalies persist: low power & alingment in small multipoles,…

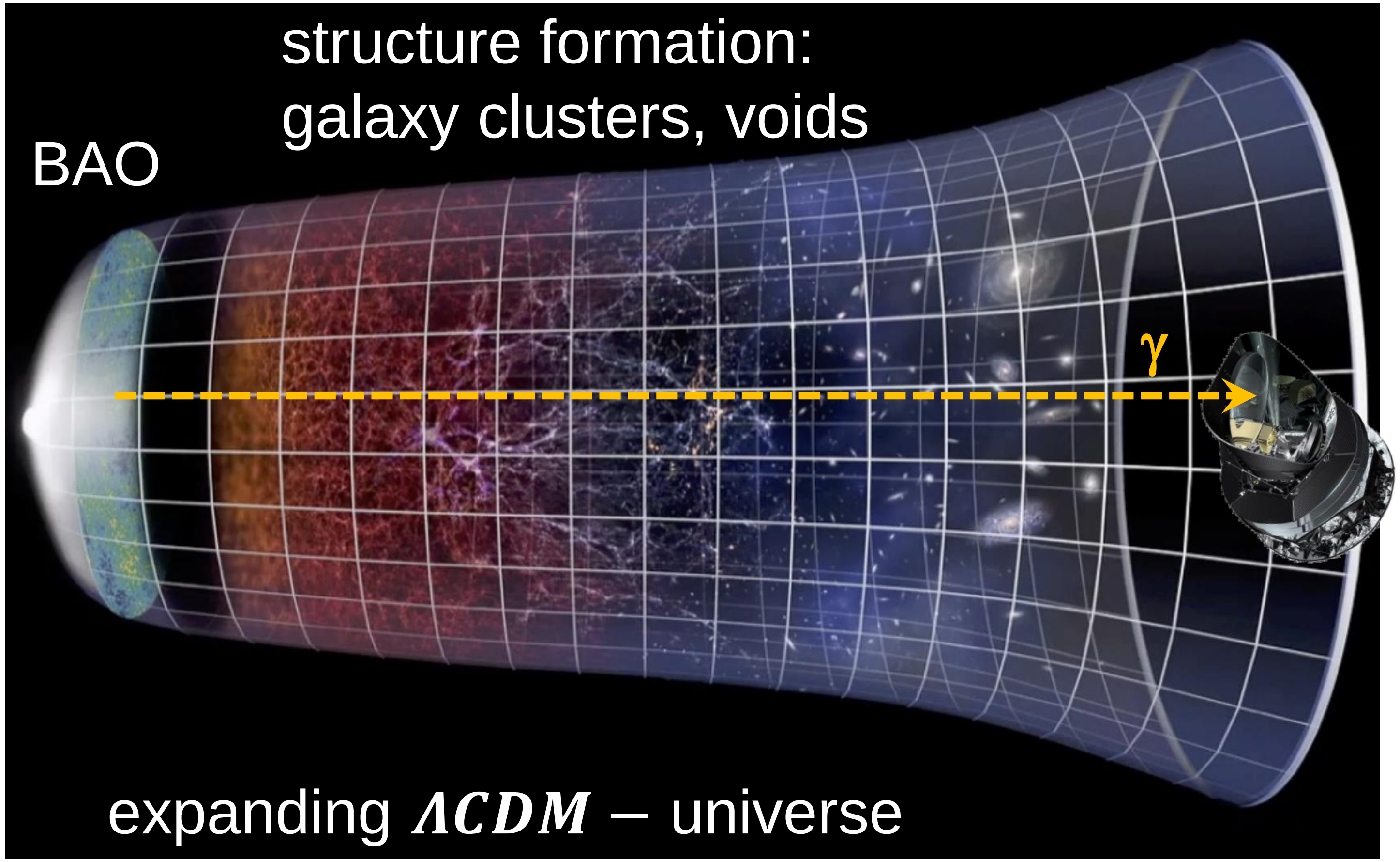
Secondary CMB anisotropies

- **CMB anisotropies due to photon propagation over $t = 13.8 \cdot 10^9\ yrs$**

- **secondary CMB anisotropies**:
  - due to large-scale structures in an expanding ΛCDM – universe
    - galaxy clusters
    - voids

⇨ **ISW-effect** due to non-zero Λ

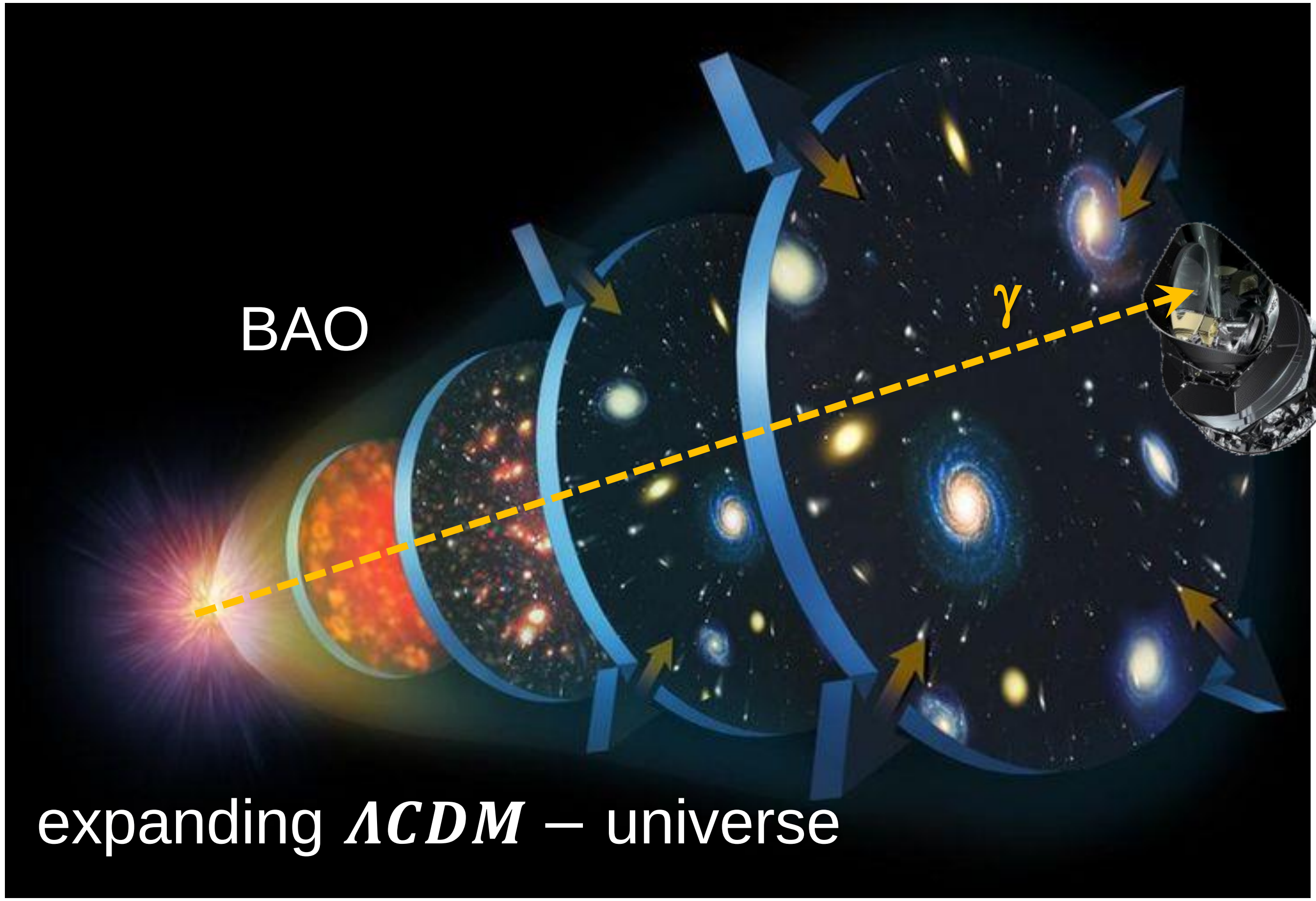
⇨ **SZ-effect** from to scattering off e^- in galaxy clusters



Secondary CMB anisotropies

- CMB anisotropies due to photon propagation over $t = 13.8 \cdot 10^9\ yrs$

- **secondary CMB anisotropies**:
  - question 1:
    how are the primary CMB anisotropies being influenced by the **accelerated expansion** of the universe?
  - question 2:
    how are the primary CMB anisotropies being influenced by **matter in galaxy clusters**?



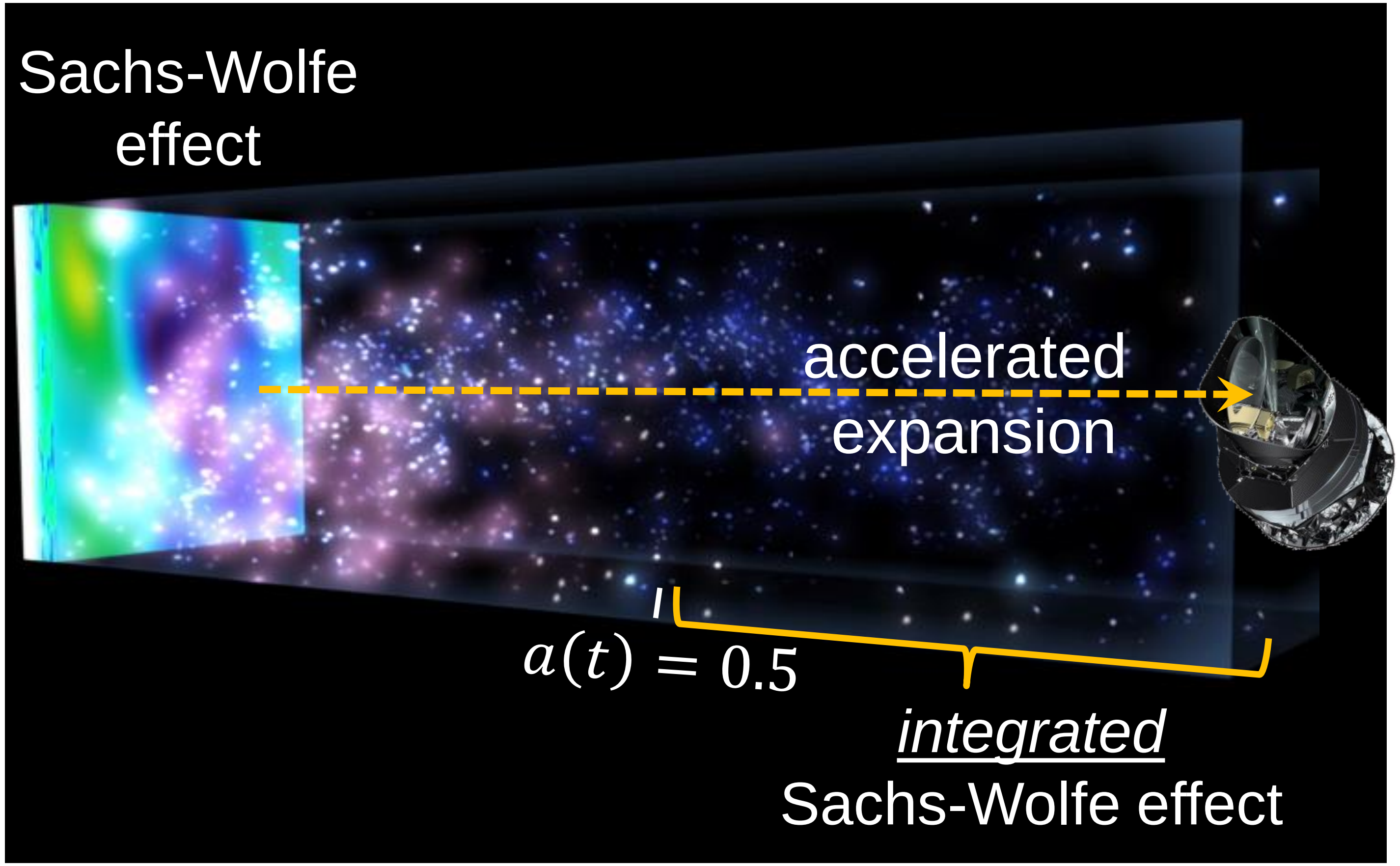
Integrated Sachs-Wolfe (ISW) effect

- **Secondary anisotropy due to accelerated expansion of ΛCDM –universe**

- let´s now consider propagation of CMB in late Λ – dominated universe $a(t) > 0.5$ with an accelerated cosmic expansion:

⇨ ISW-effect of CMB as (further) evidence for a non-zero value of vacuum energy density ($\Lambda \neq 0$)

⇨ ISW-effect of CMB manifests as secondary anisotropy $\Delta T/T$ at **large scales $\theta > 2°$**



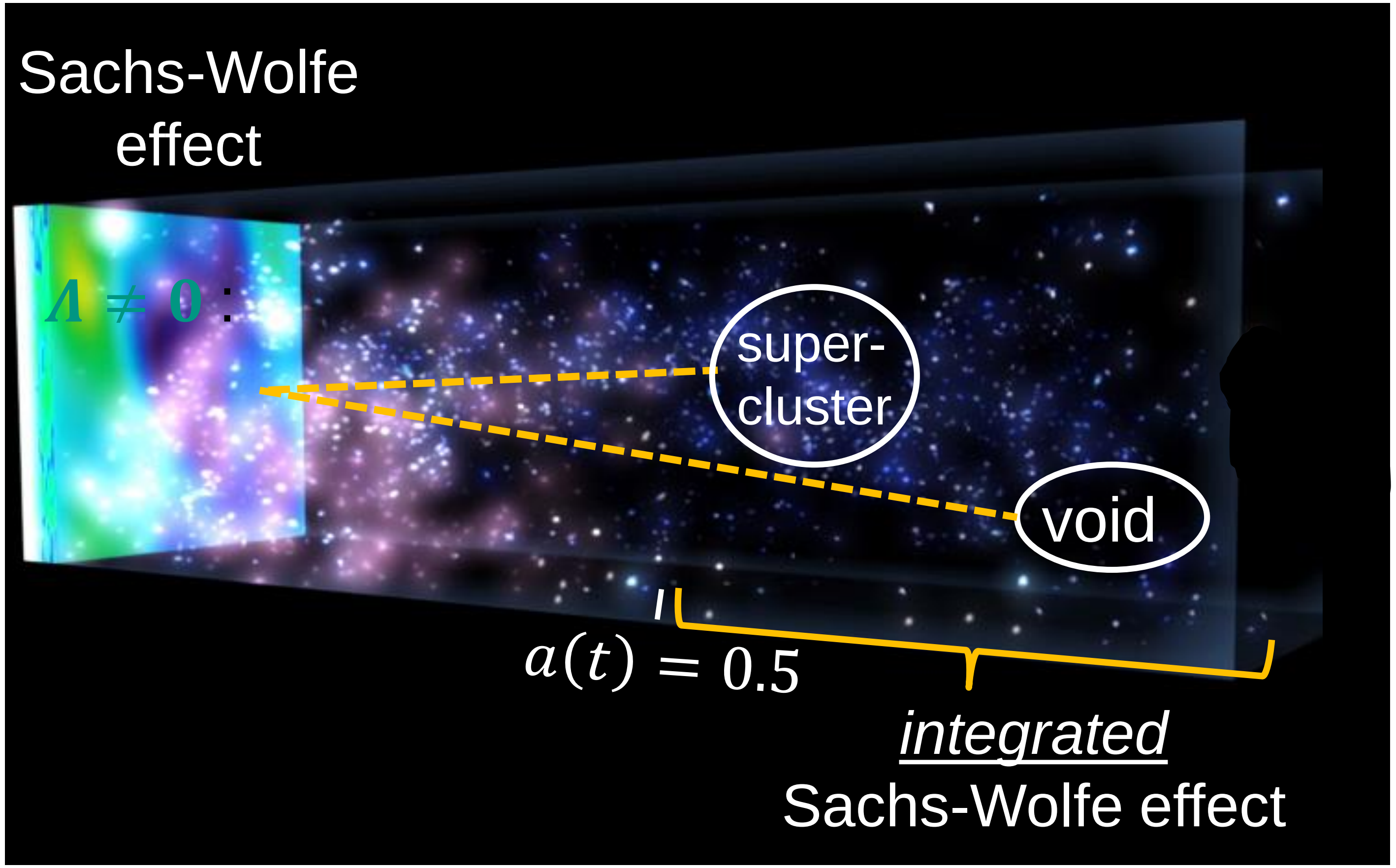
Integrated Sachs-Wolfe (ISW) effect

■ **Secondary anisotropy due to** **accelerated expansion** **of ΛCDM – universe**

- let´s now consider propagation of CMB in time-dependent gravity $\Phi(t)$ wells (clusters) and hills (voids) in a universe with dominant $\Lambda \neq 0$:

⇨ **galaxy super-cluster**:
local overdensity
how is CMB affected by $\Lambda \neq 0$?

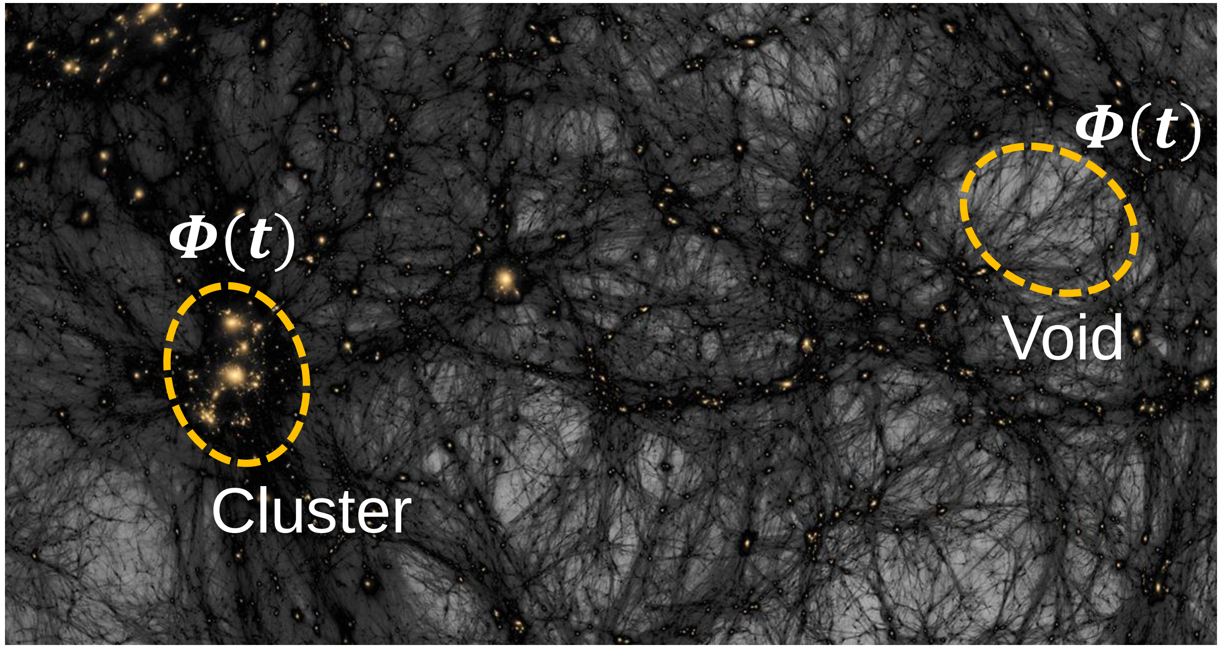
⇨ **cosmic void**:
local underdensity
how is CMB affected by $\Lambda \neq 0$?

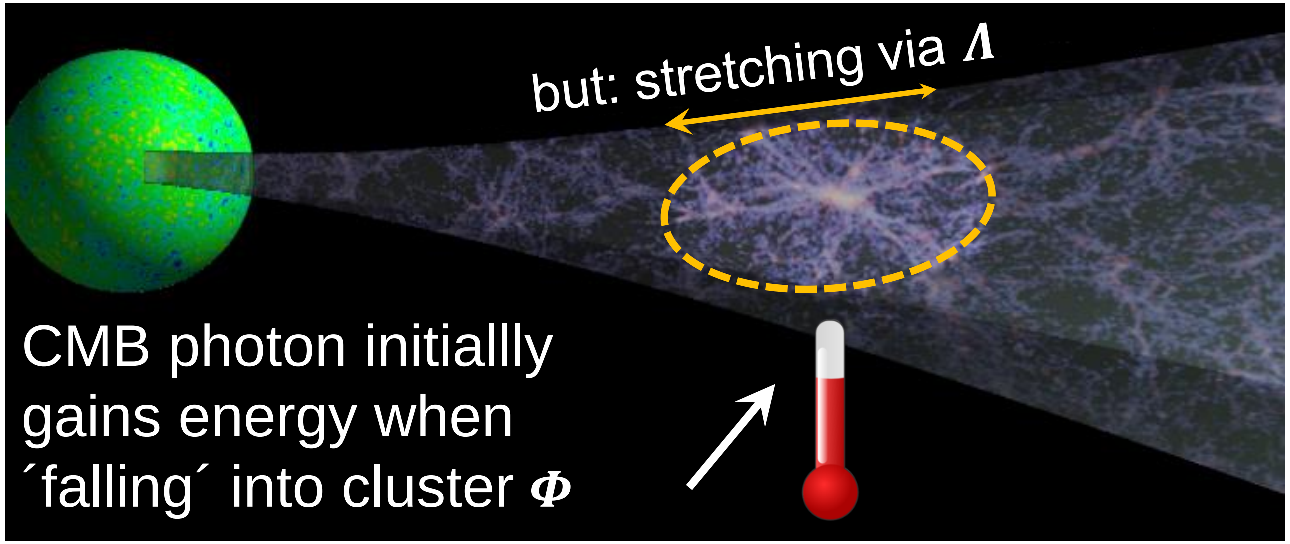


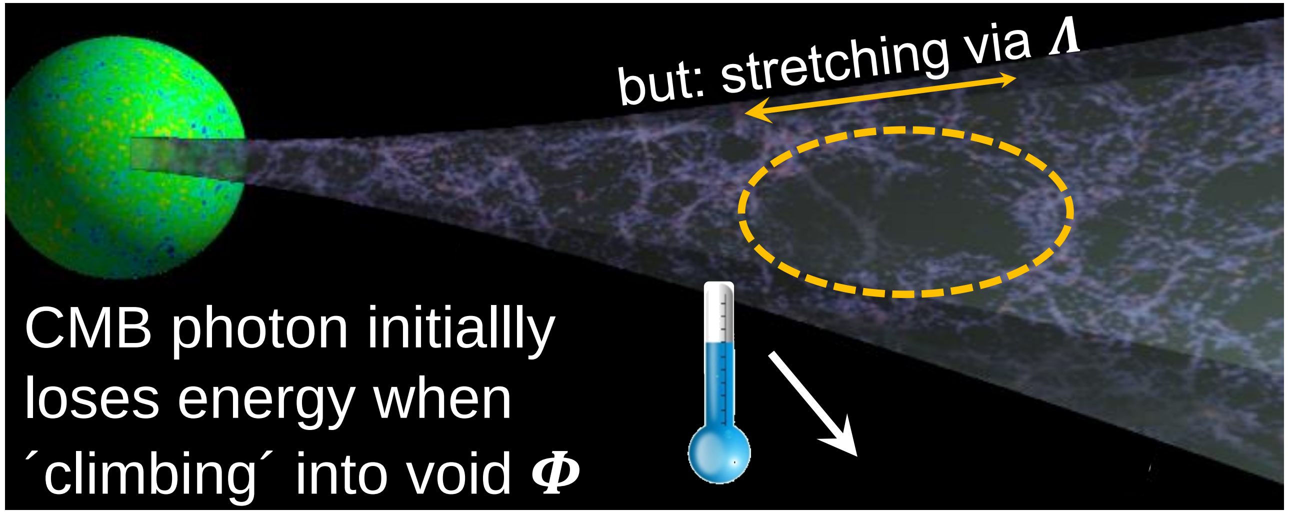
ISW: CMB propagation in super-clusters/voids

- **Secondary anisotropies due to Λ**

- in time-dependent gravity potentials $\boldsymbol{\Phi(t)}$: the propagation of CMB photons is non-adiabatic with $\boldsymbol{\Delta E \neq 0}$







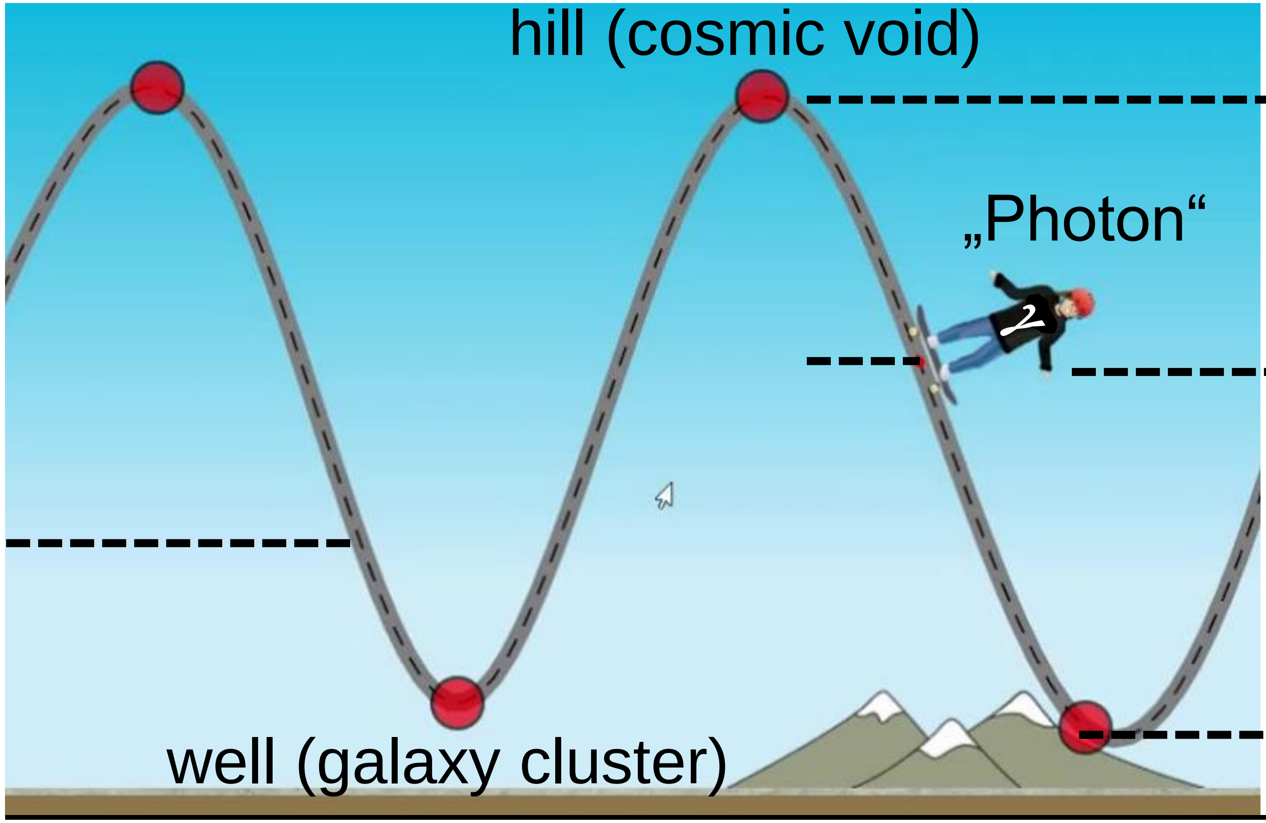
RECAP: photons travelling in static potential $\Phi(x)$

- **Classcial case: adiabatic photon propagation with interchange $E_{pot} \leftrightarrow E_{kin}$**

\- case of $\Lambda = 0$

static case, Φ independent of time t

gravitational potential $\Phi(x)$



E_{pot}

adiabatic transformation $E_{pot} \leftrightarrow E_{kin}$

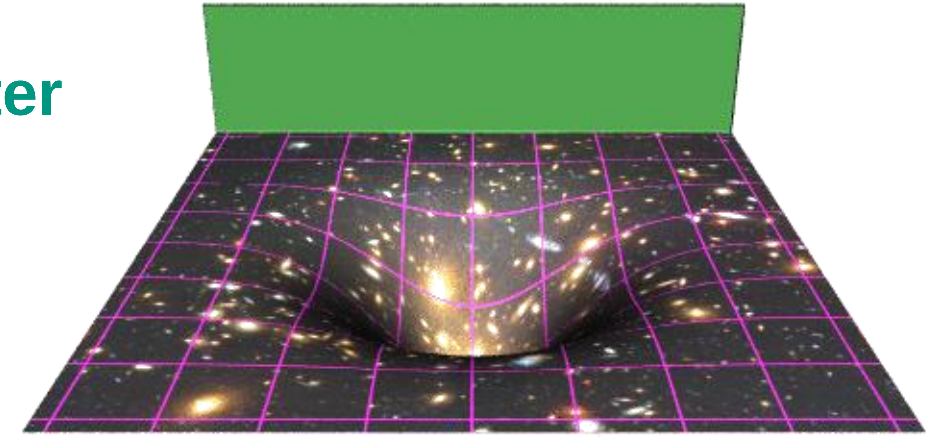
E_{kin}

x

photon has no interaction with particles

ISW effect: CMB propagation in $\Lambda \neq 0$ universe

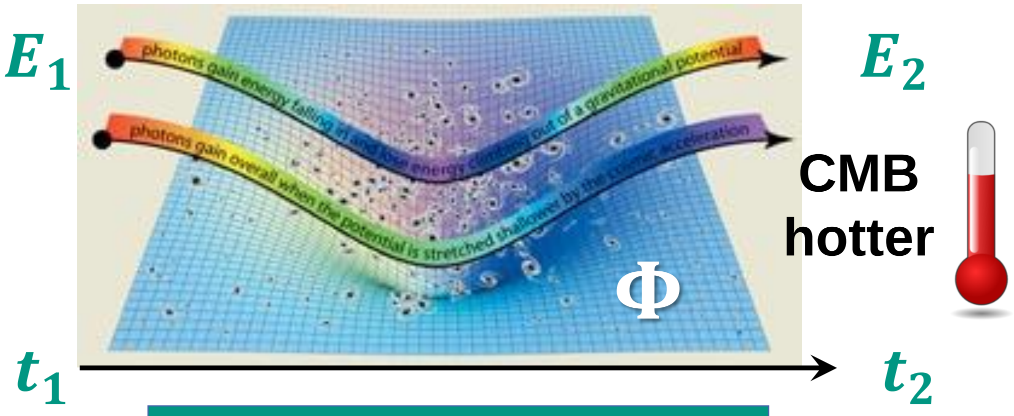
- **Secondary CMB anisotropy after photons have propagated an overdense super-cluster**



- **entry: energy E_1**
  CMB obtains a gain of E_{kin} when falling into the **gravity well** with potential Φ

- **passage: energy between $E_1 \dots E_2$**
  vacuum energy Λ results in a stretching of the **gravity well** with potential $\Phi(t)$

- **exit: energy E_2**
  CMB obtains a net gain of E_{kin} after climbing out of the **gravity well** with shallower potential Φ



ISW in super-cluster

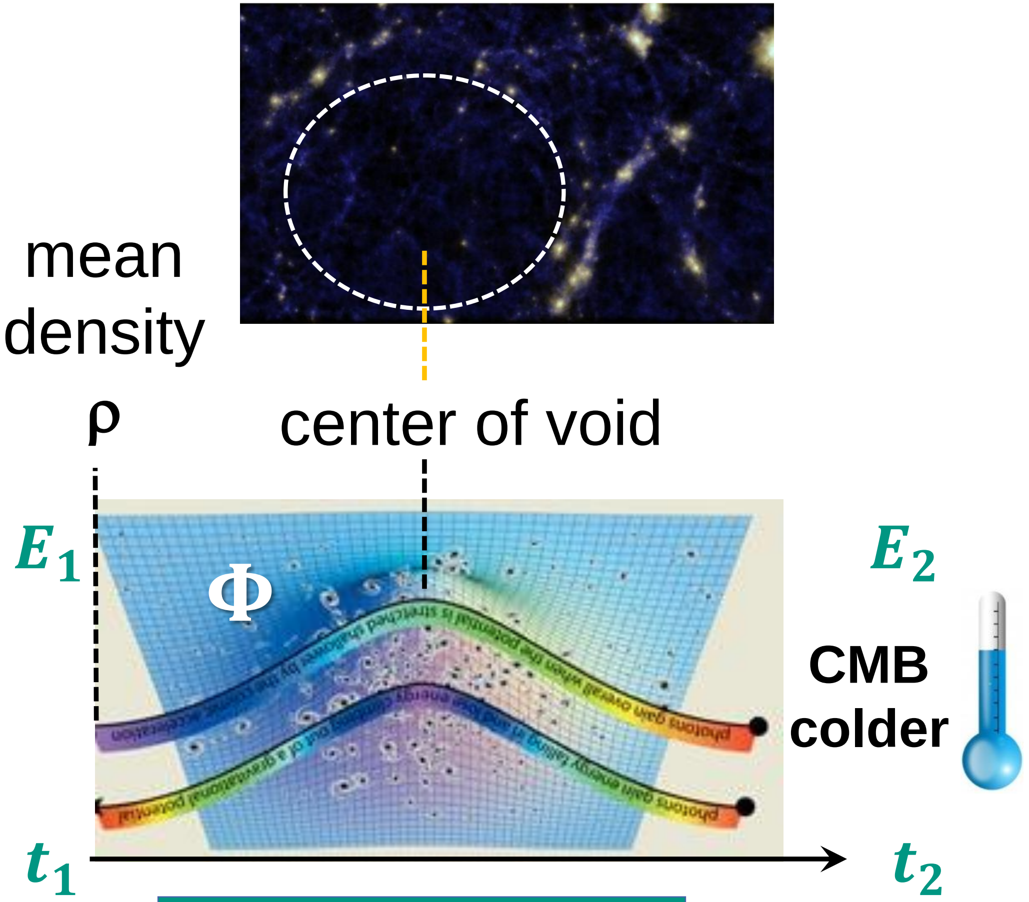
ISW effect: CMB propagation in $\Lambda \neq 0$ universe

- **Secondary CMB anisotropy after photons have propagated underdense void**

\- **entry: energy E_1**
CMB loses an amount of E_{kin} when climbing into the **gravity hill** with potential $\boldsymbol{\Phi}$

\- **passage: energy between $E_1 \ldots E_2$**
vacuum energy Λ results in a stretching of the **gravity hill** with potential $\boldsymbol{\Phi(t)}$

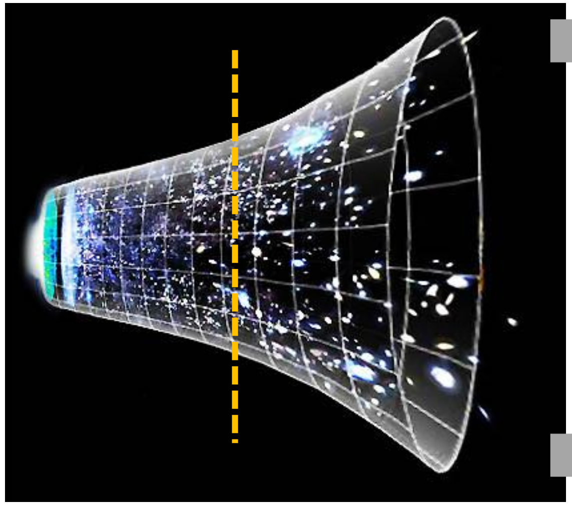
\- **exit: energy E_2**
CMB obtains a net loss of E_{kin} after falling out of the **gravity well** with shallower potential $\boldsymbol{\Phi}$

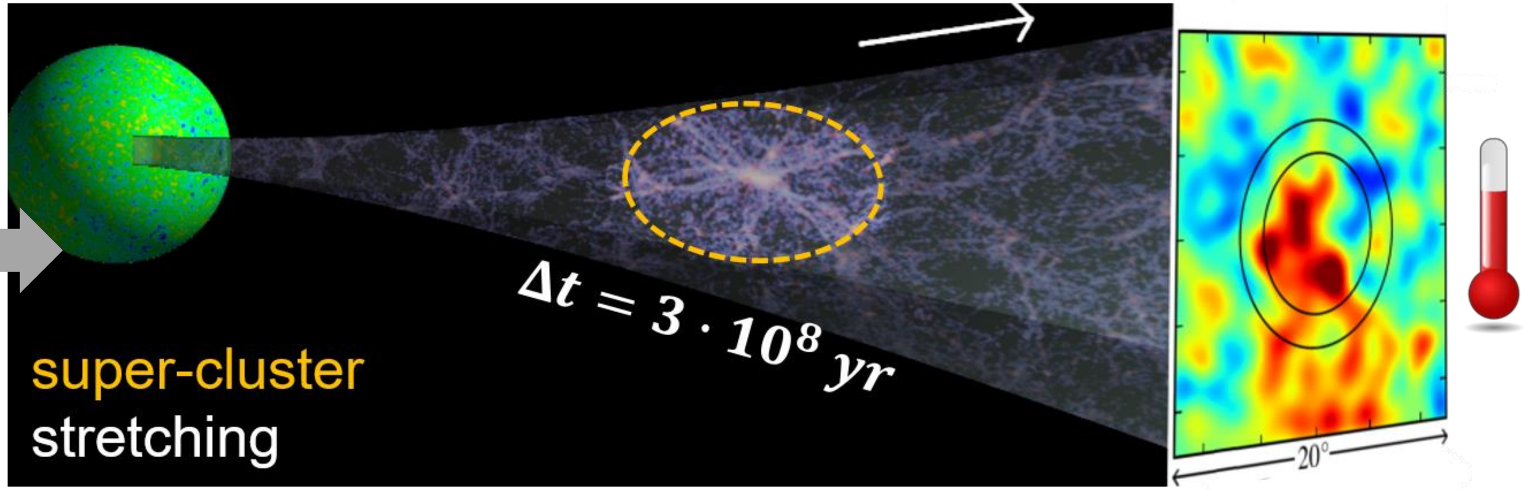


ISW in large void

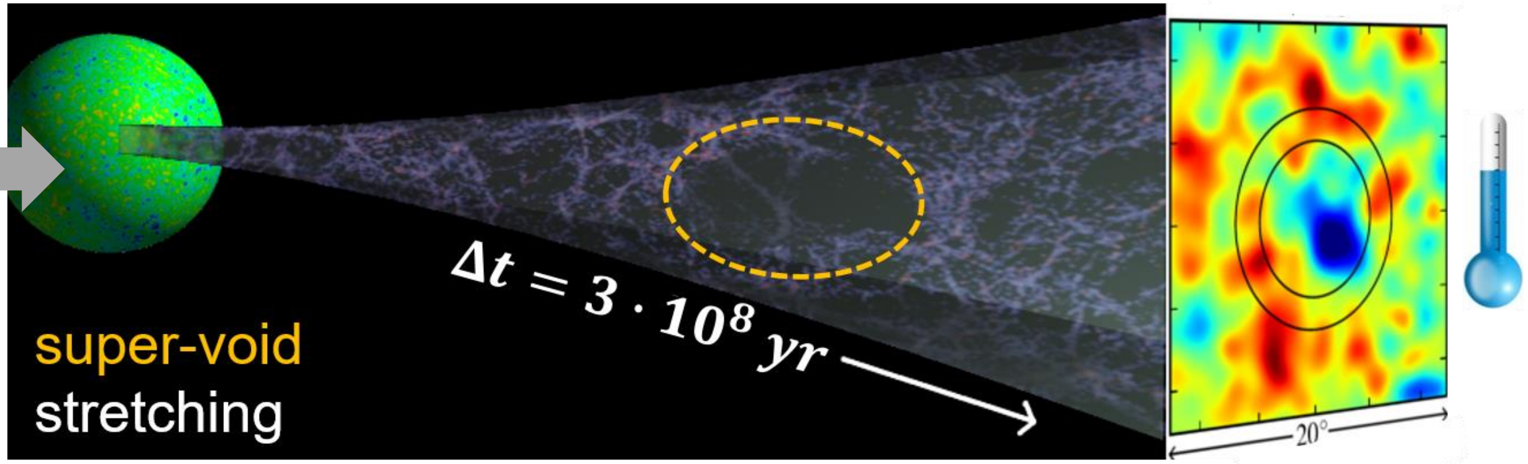
ISW effect: scale of the photon energy gain/loss

- **non-adiabatic photon propagation only in vacuum-dominated universe**





$\Delta T =$
$+5 \ldots 10\ \mu K$



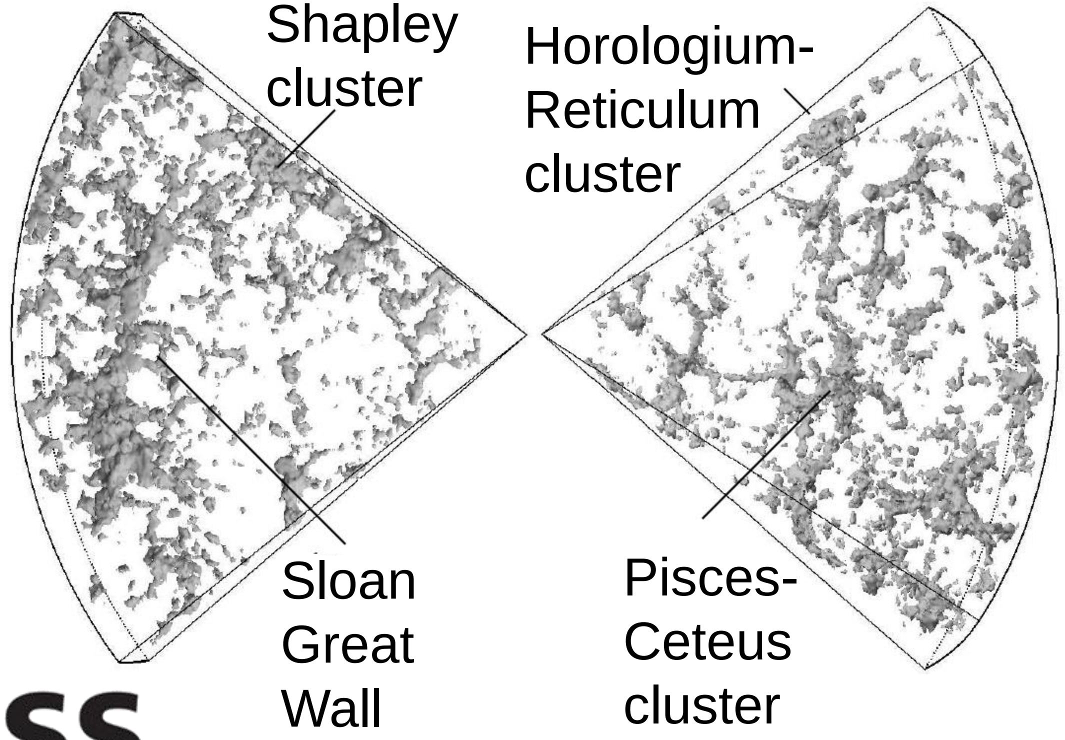
$\Delta T =$
$-5 \ldots 10\ \mu K$

ISW effect: we correlate ΔT with LSS data sets

- **Large Scale Structure (LSS) data show distribution of super-clusters & voids**

  - large-scale galaxy surveys such as SDSS* reveal regions with over- (under-) density

SDSS

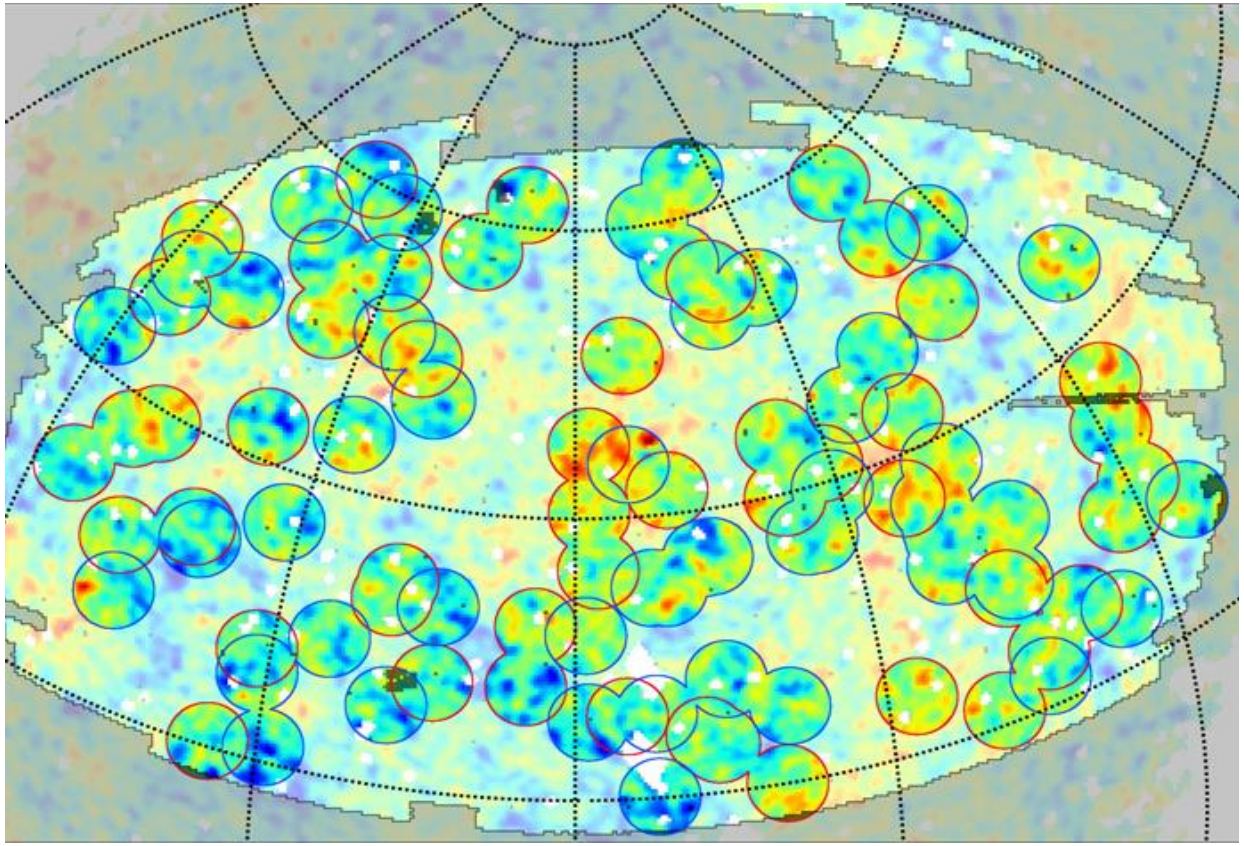


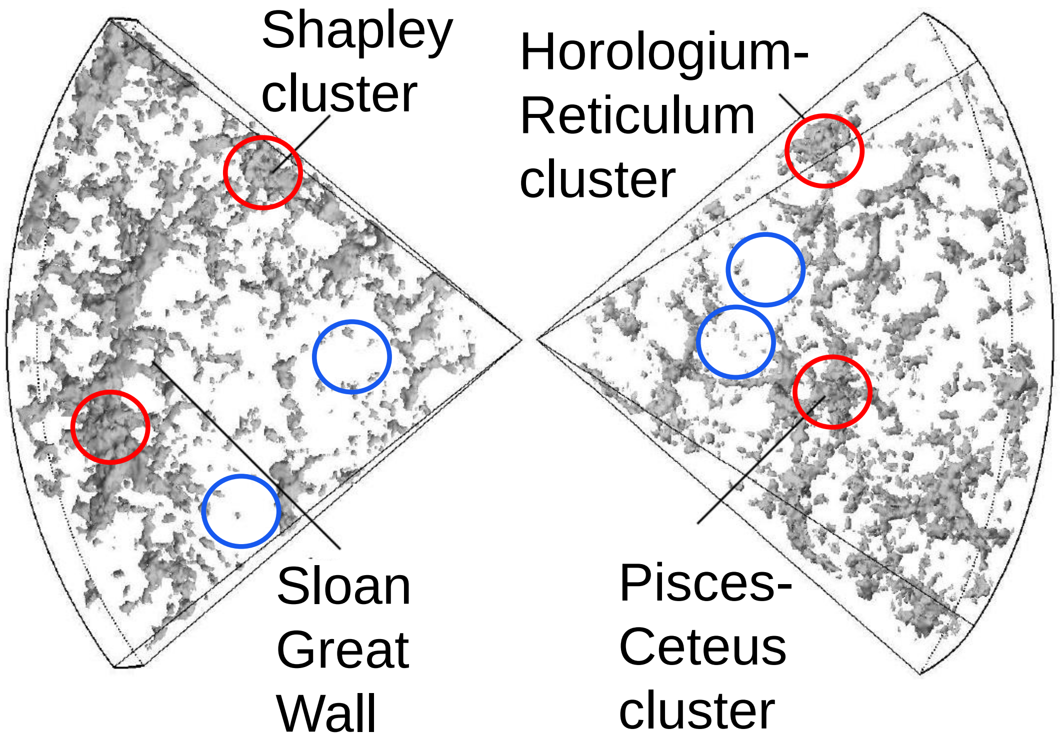
*Sloan Digital Sky Survey (see also next lecture)

ISW effect: we perform a correlation analysis

- **Correlating LSS data on super- clusters ○ and super-voids ○ with CMB**

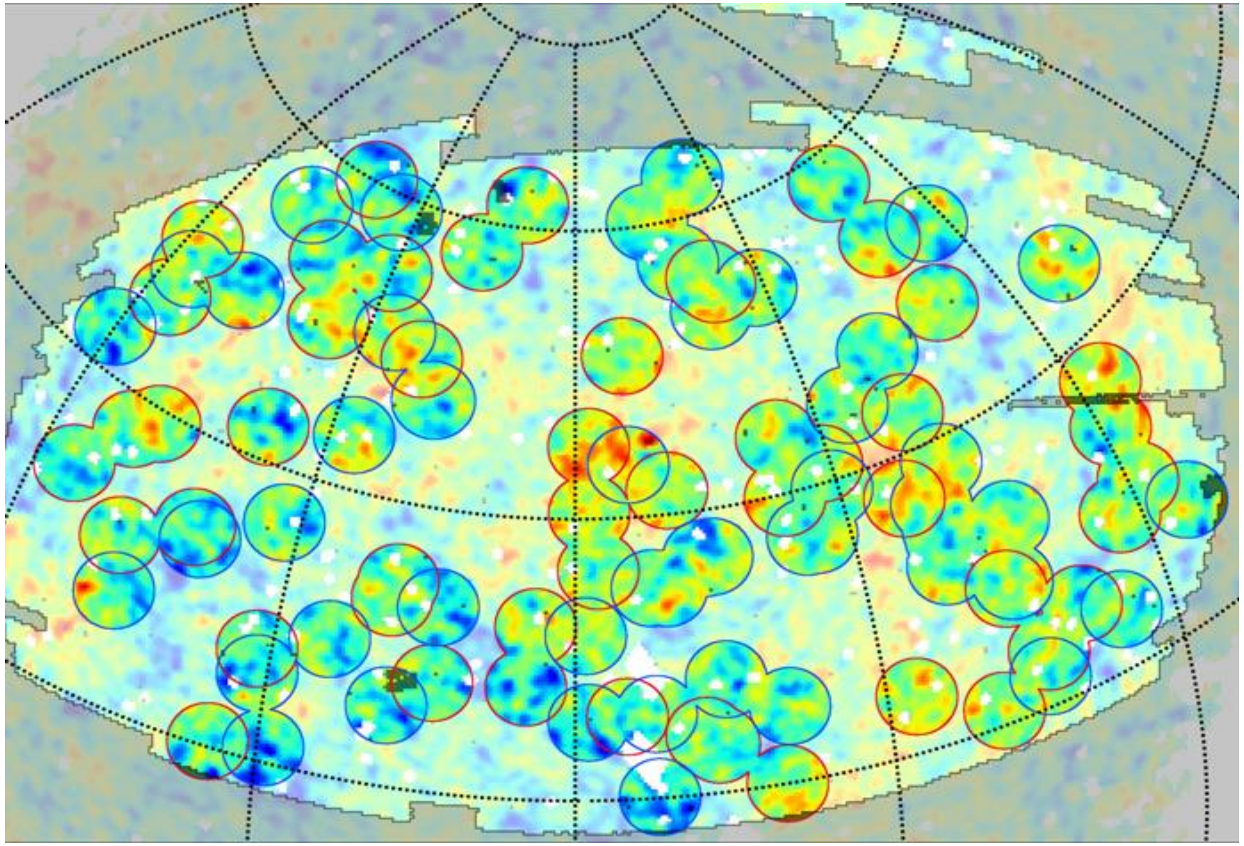
  - can we confirm the expectation of the ISW-effect via a correlation analysis?

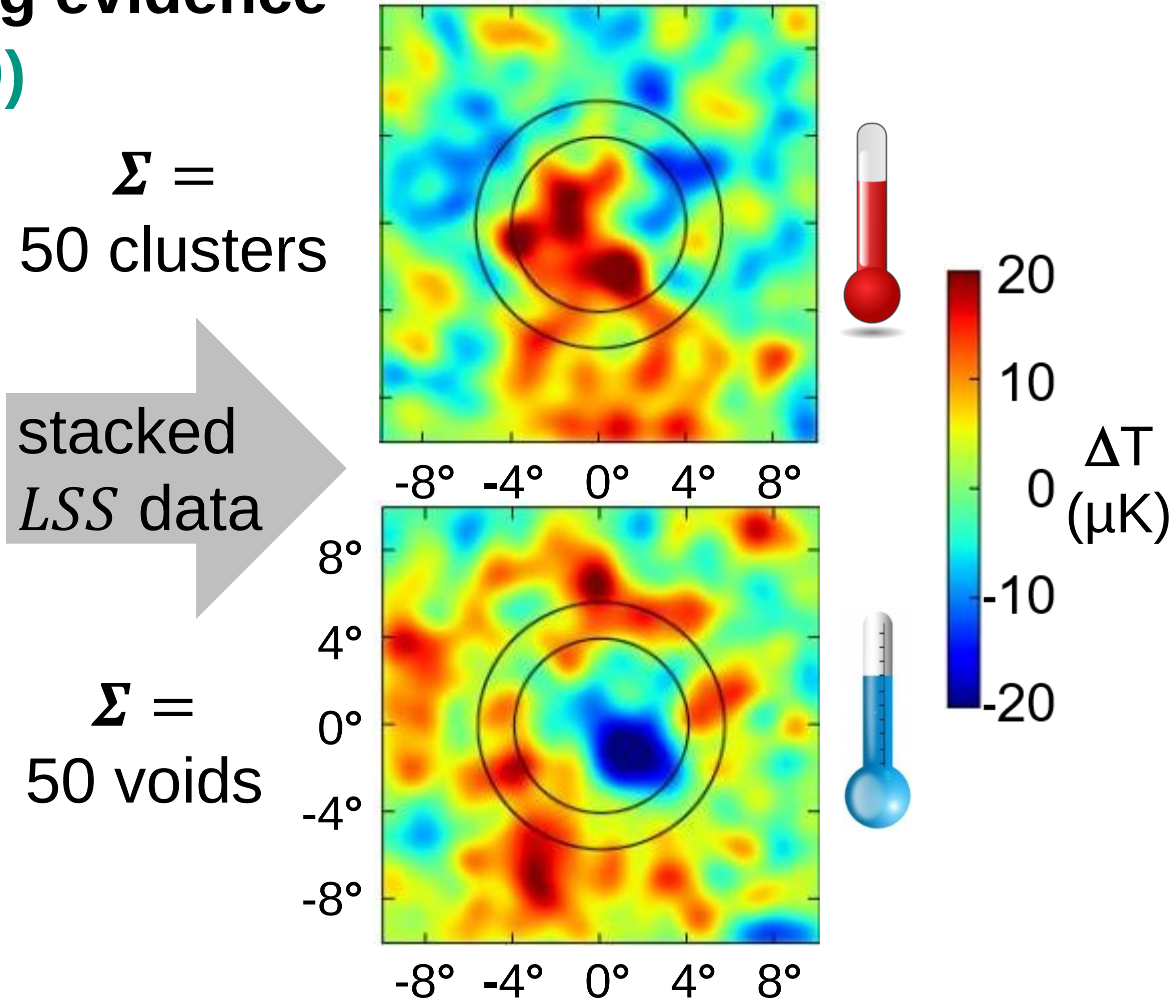




ISW effect: we see a strong correlation signal!

- **Confirmation of the ISW effect as strong evidence for the existence of Dark Energy ($\Lambda \neq 0$)**





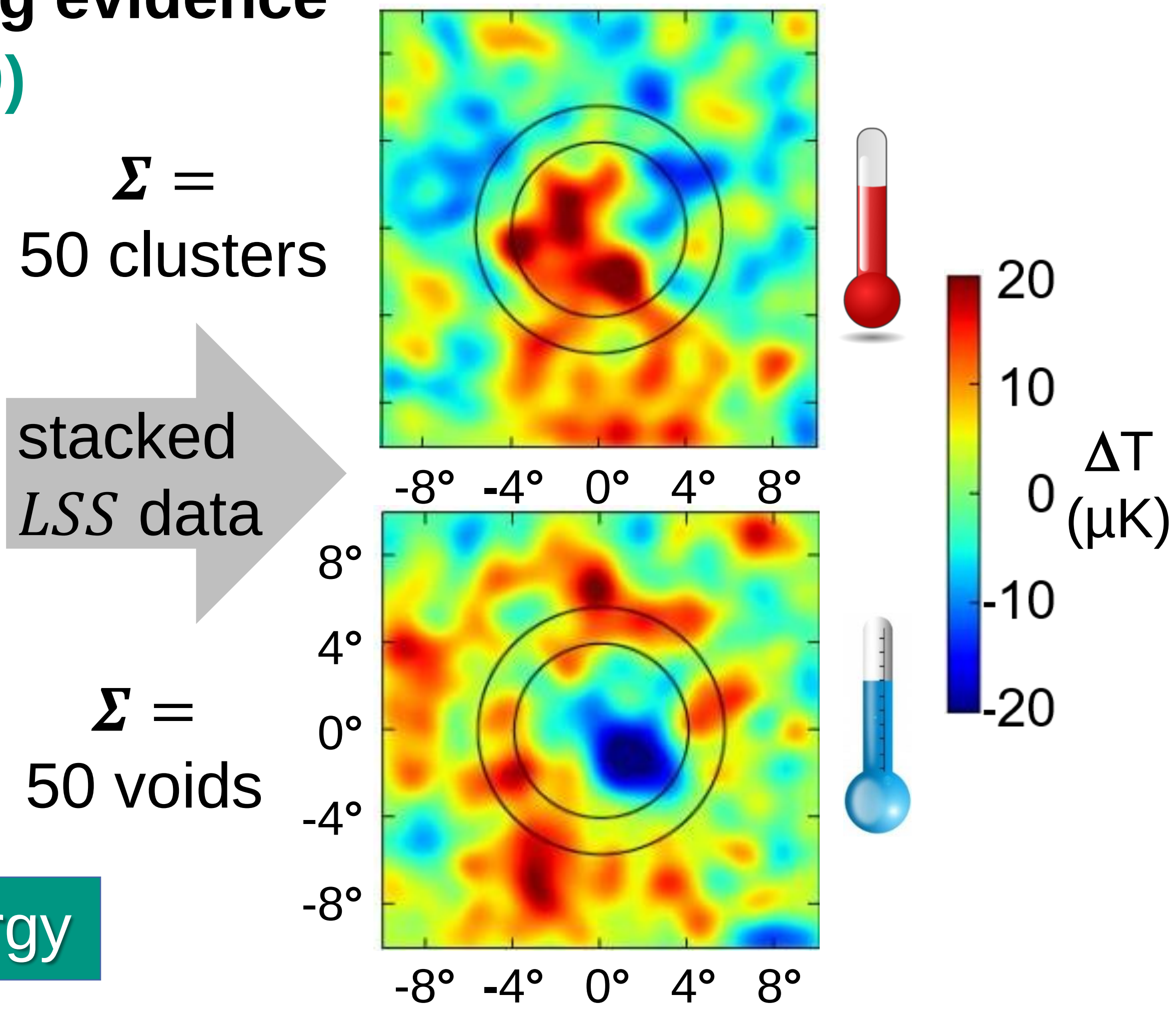
ISW effect: we see a strong correlation signal!

- **Confirmation of the ISW effect as strong evidence for the existence of Dark Energy ($\Lambda \neq 0$)**

- analysis of statistical correlation of the CMB-temperature with large-scale structures $\boldsymbol{LSS}$: $(\delta\theta = 4°/100\ h^{-1}\ Mpc)$

  ↳ $\boldsymbol{\Delta T = (9.6 \pm 2.2)\ \mu K}$ due to the ISW effect ($\sim 4\ \sigma$ evidence)

  ↳ accelerated cosmic stretching of super-clusters & voids



ISW: an independent evidence for Dark Energy

ISW effect: we see a strong correlation signal!

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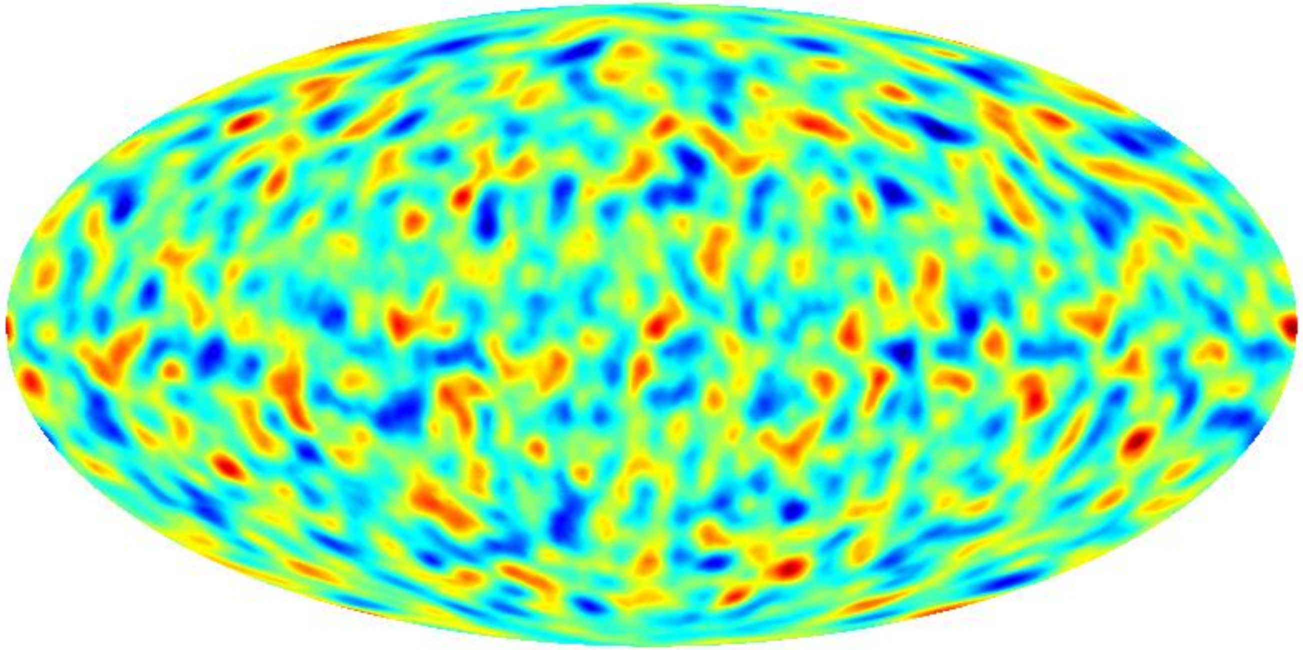


Planck: global ISW map

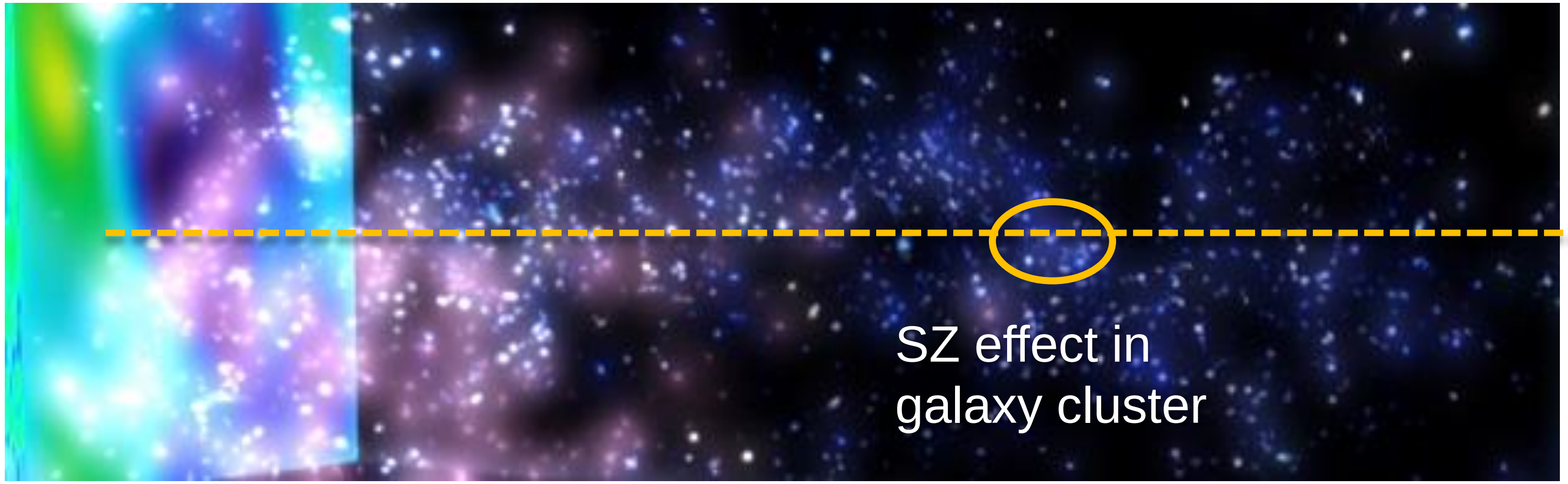
ISW: an independent evidence for Dark Energy

Sunyaev – Zel´dovich effect: CMB scattering off e^-

- **further effect causing secondary anisotropies: CMB interactions in clusters**

  - in dense galaxy clusters: CMB scatters off hot cluster electrons e^- on the keV – scale via the **inverse Compton effect** ⇨ **net energy gain**

  - the SZ-effect in a galaxy cluster is a **secondary anisotropy**, which has to be accounted for as a **noise effect** in CMB analyses



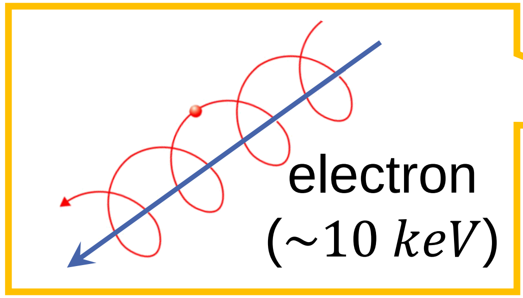
SZ = Sunyaev-
Zel´dovich*

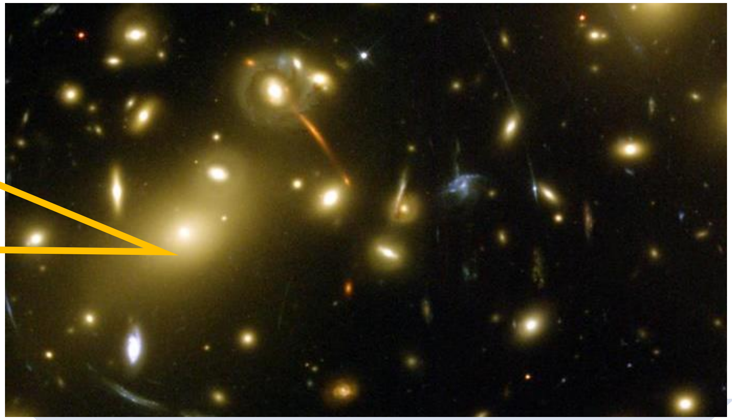
*remember me from last lecture? This flat CMB part…

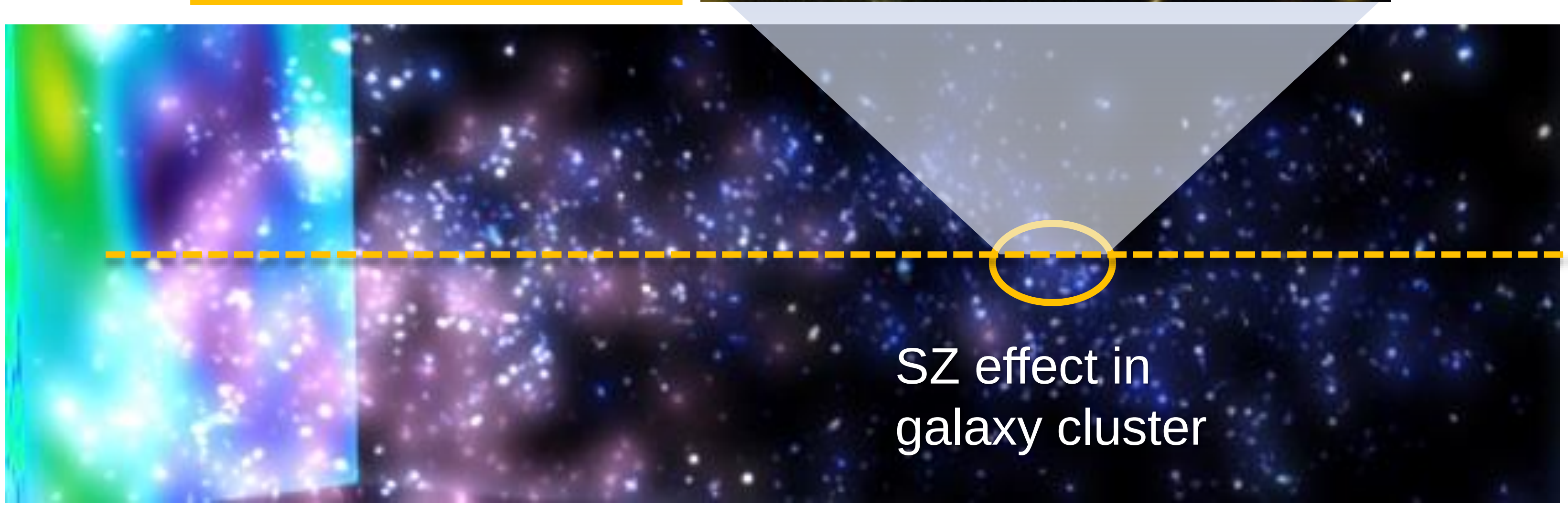
Sunyaev – Zel´dovich effect: CMB scattering off e^-

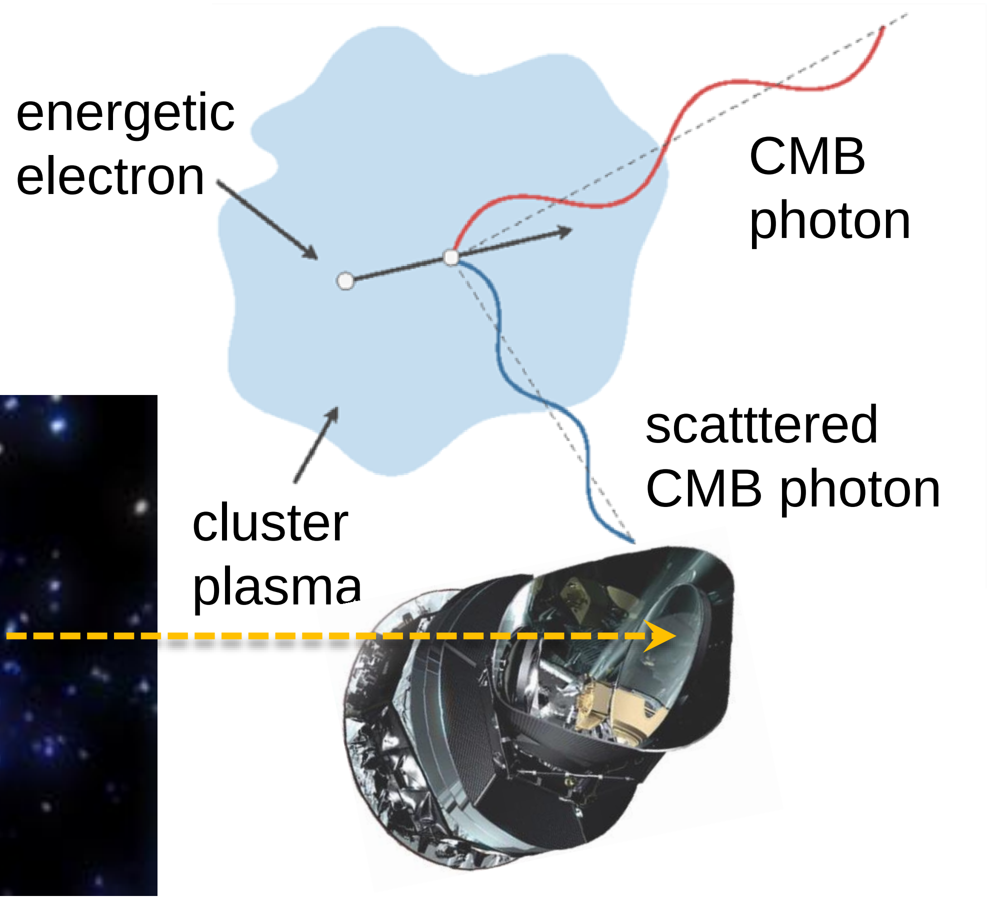
- **secondary anisotropies:** **CMB undergoes inverse Compton* scattering**

- hot ionized cluster gas









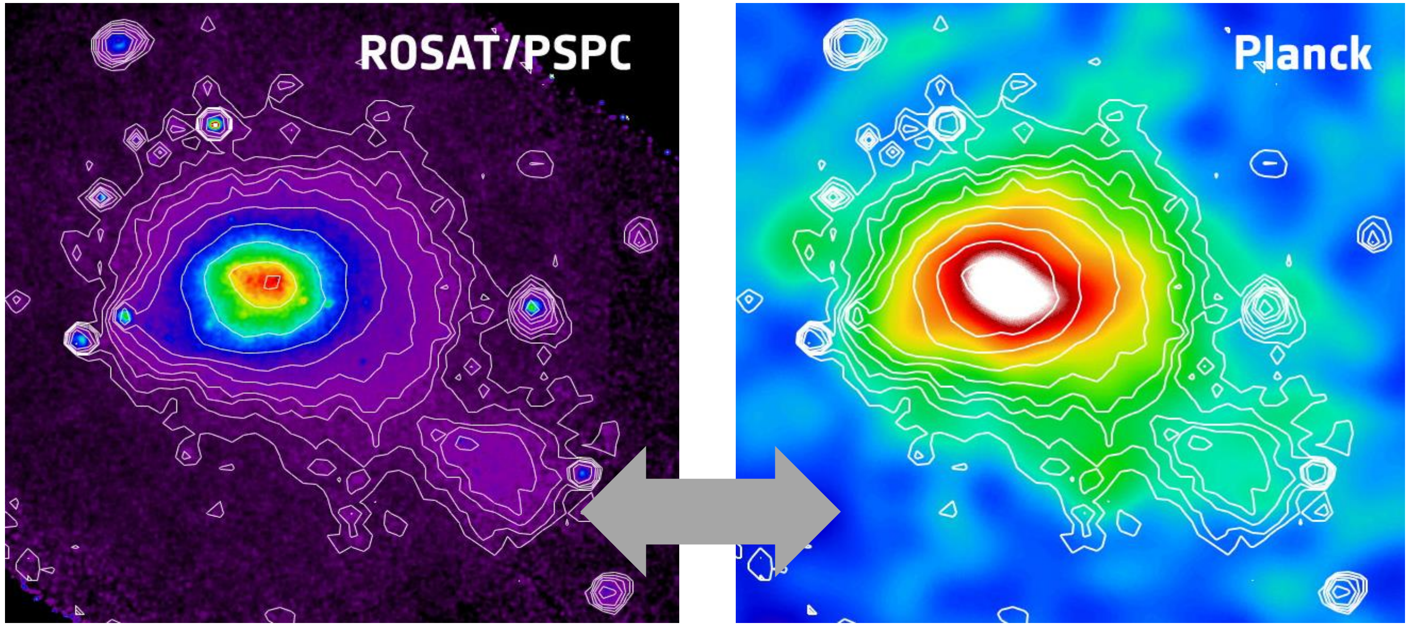
*see also lectures on astroparticle physics, if interested

SZ-effect: CMB photons are much hotter

- **Our next correlation analysis: CMB photons that cross galaxy clusters**

  - SZ-example: **Coma galaxy cluster** (Abell 1656) in $d \sim 100\ Mpc$ ($\emptyset = 2°$)

optical	**X-rays**	**CMB-temperature**
cluster of $\sim$1000 galaxies	hot cluster gas	SZ effect



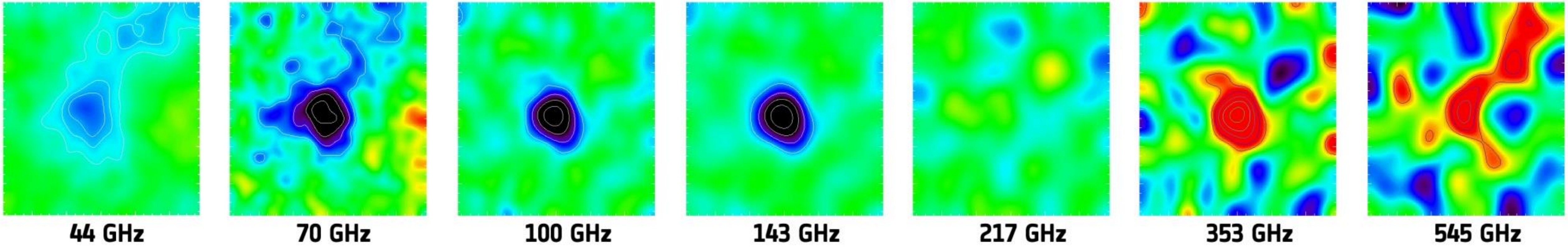
SZ-signature: specific frequency dependence

- **Effect of scattering:** **deficit at low f ⇨ excess at high f (energies)**

  - SZ-example: **galaxy cluster** Abell 2319 in $d \sim 250\ Mpc\ (\emptyset = 2°)$

  - ~1% of all CMB photons passing this cluster interact via the SZ-Effekt with the hot cluster gas (inverse Compton scattering)

  - Planck data show the characteristic SZ-dependence on photon frequency f photons gain energy via inverse Compton effect (´up-scattering´)



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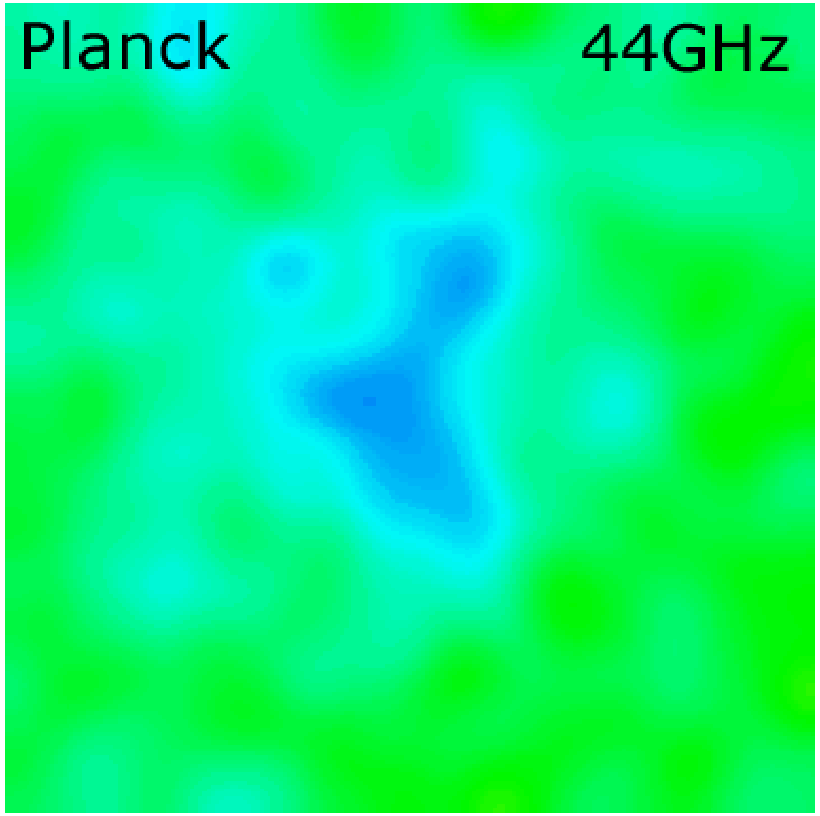
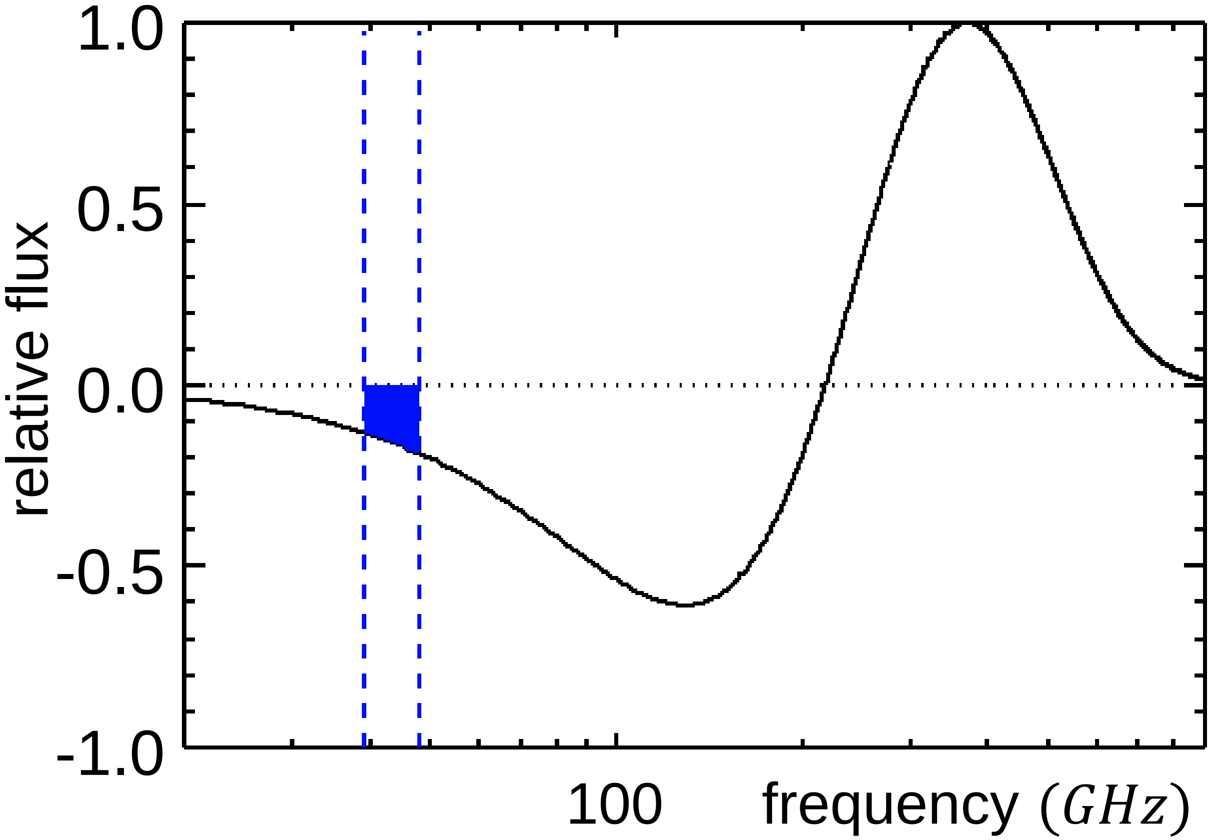
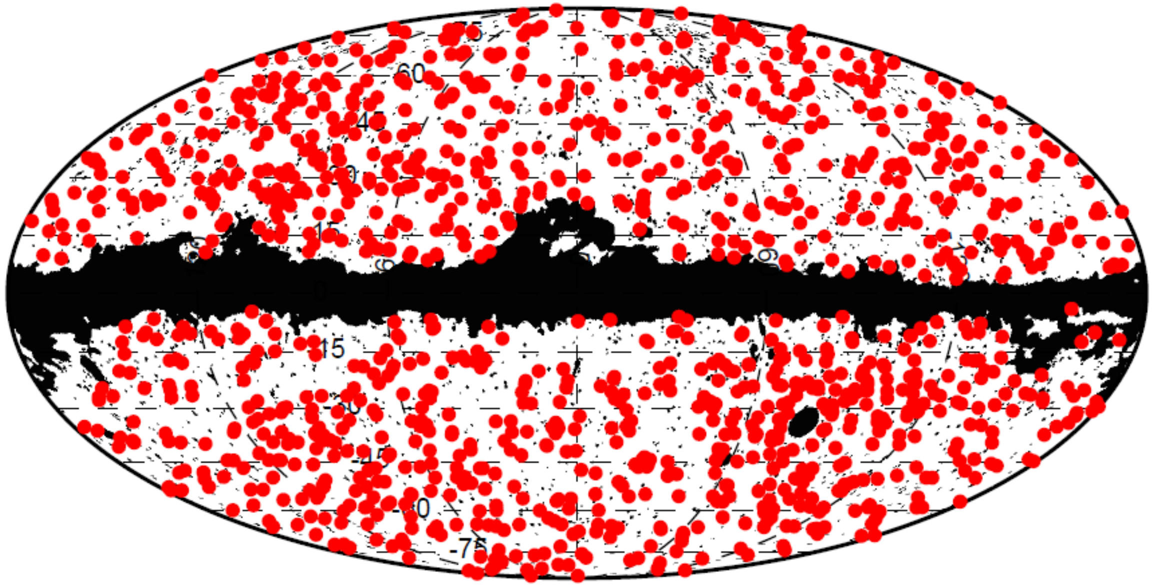




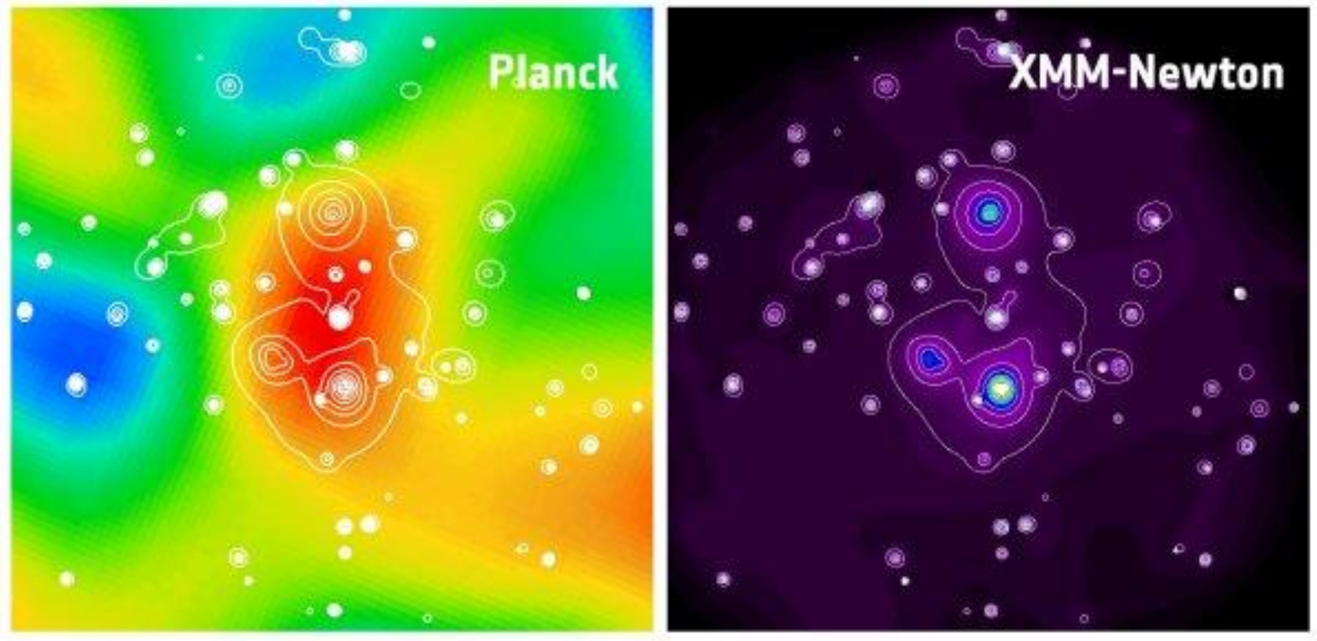
SZ-effect is a noise signal: eliminate clusters

- **Remove effect of scattering: cut out all galaxy clusters identified**

- removal: identified dense clusters & LSS – analyses by Planck: new cluster via CMB



> 1000 SZ sources (galaxy clusters) are know at present & excluded from CMB



galaxy cluster PLCK G214.6+37.0 –
first cluster identified via SZ – effect

Beyond Planck – future CMB challenges

- **CMB-S4: next-generation CMB experiment at South Pole & Chilean Andes**
  - plans to deploy 21 telescopes with 500 000 cryo-cooled bolometers

South Pole

- probe the nature of Dark Matter & Dark Energy …

- capture transient phenomena …

- signatures of primordial gravitational waves from inflationary phase …

- map the matter through-out the sky…

Atacama desert

Beyond Planck – future CMB challenges

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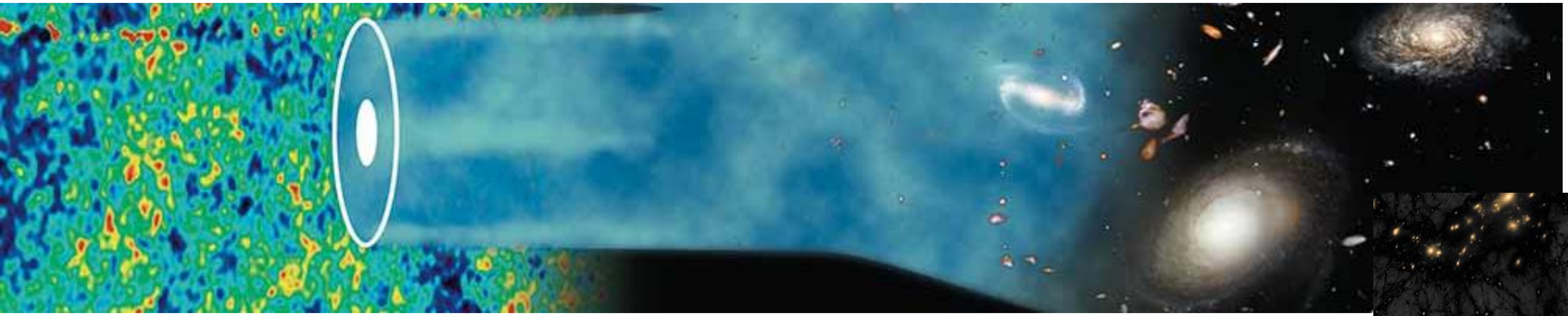

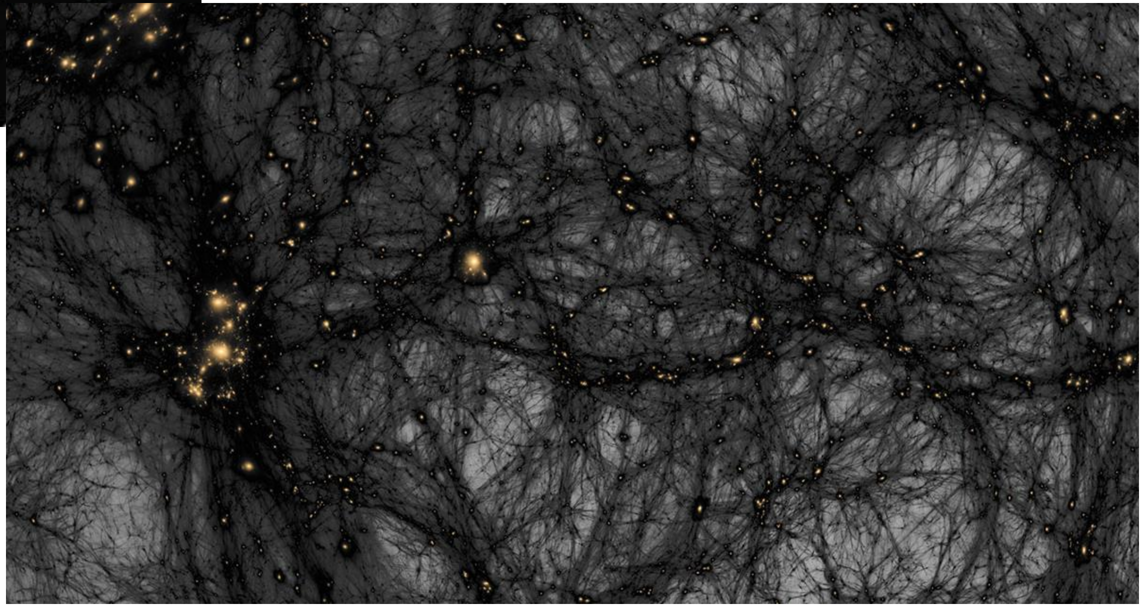

CHAPTER 4 – STRUCTURE FORMATION IN THE UNIVERSE

4.1 Inflation & Early Universe

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- **Inflationary phase of early universe with rapid increase of scale factor $a(t)$**

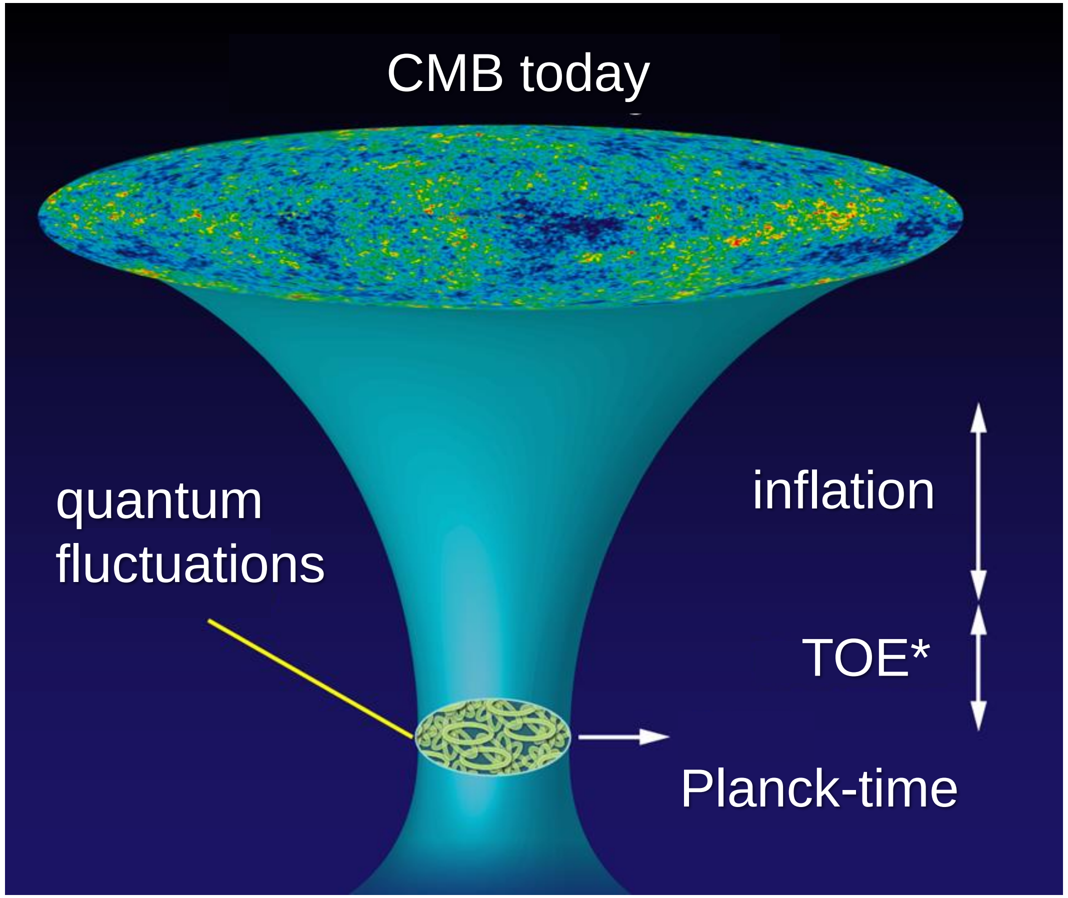
- short time period $t = 10^{-36} \ldots 10^{-32} s$

- huge increase of scale factor $a(t)$ by value of $> 10^{26}$

- proposed origin: time evolution of scalar inflaton field (Higgs mechanism)

- solves flatness problem, eliminates (dilutes) number density of monopoles

- agrees with observed $\Delta T / T$ of the CMB

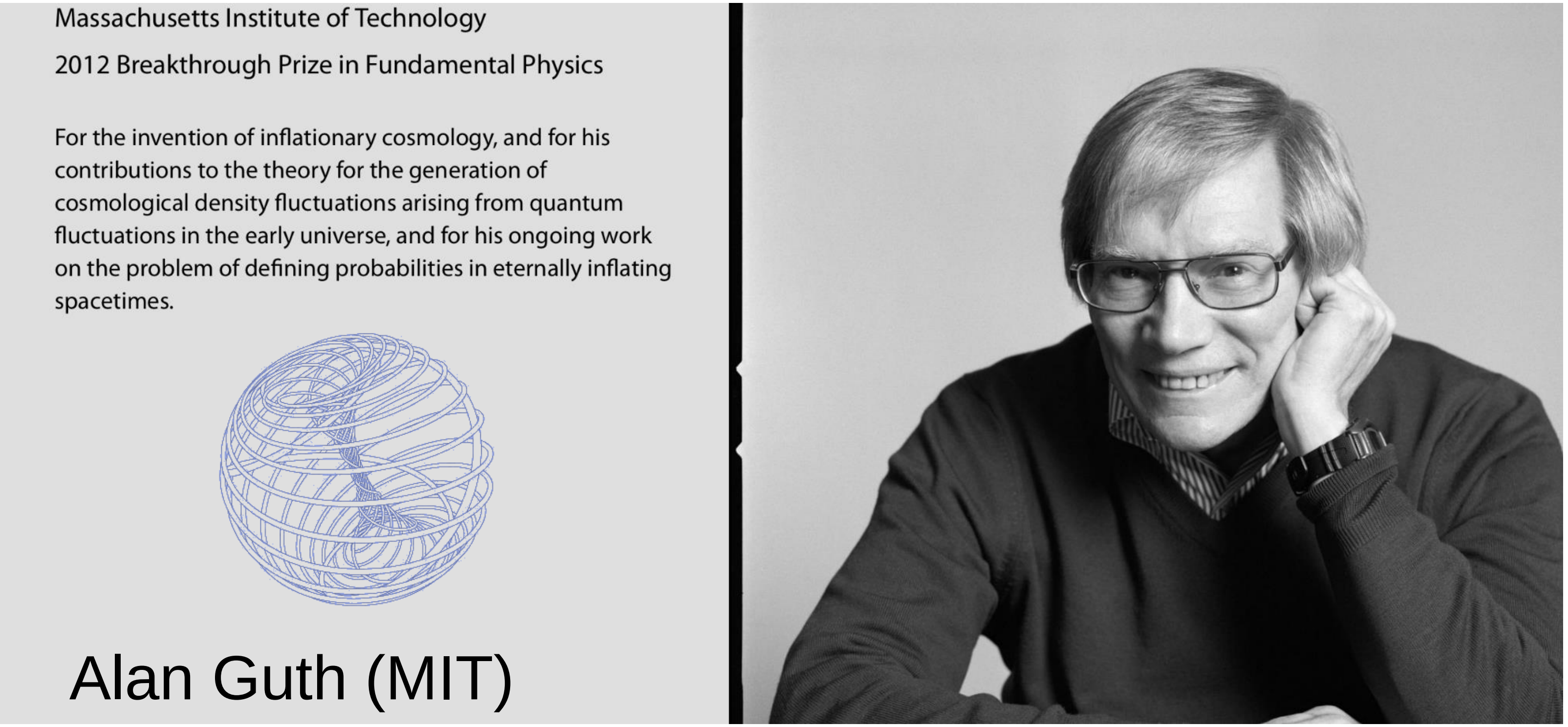


*Theory-Of-Everything

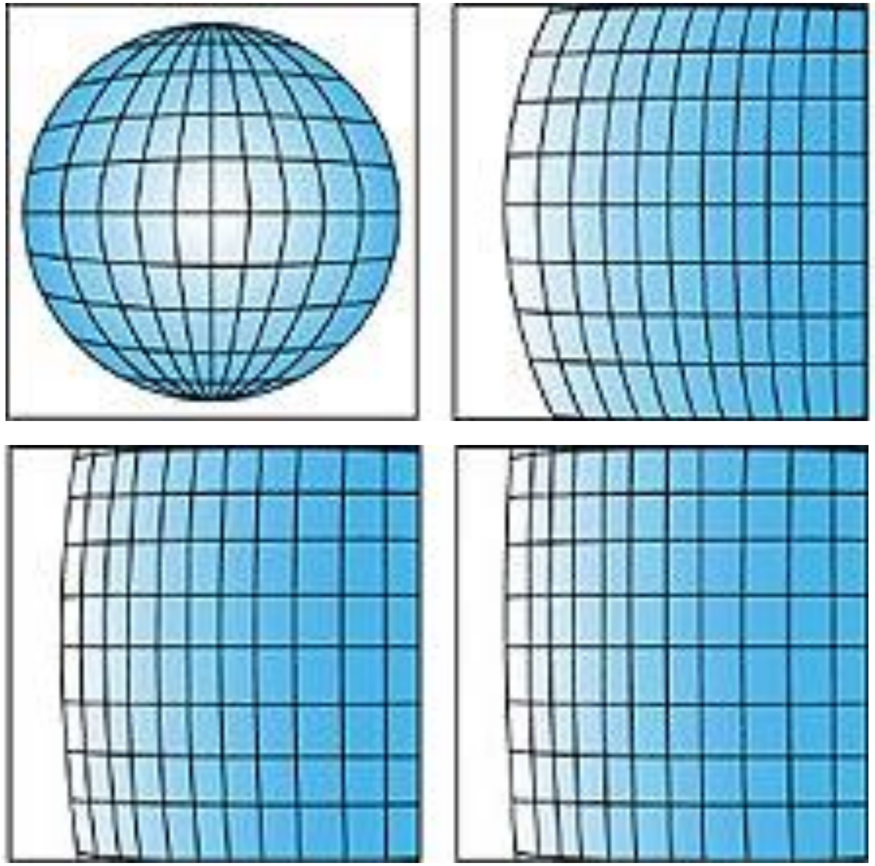
Inflation – Breakthrough Prize 2012….

- **Inflationary phase of early universe with rapid increase of scale factor $a(t)$**

  - solves the horizon problem, HZ-spectrum of CMB



Alan Guth (MIT)

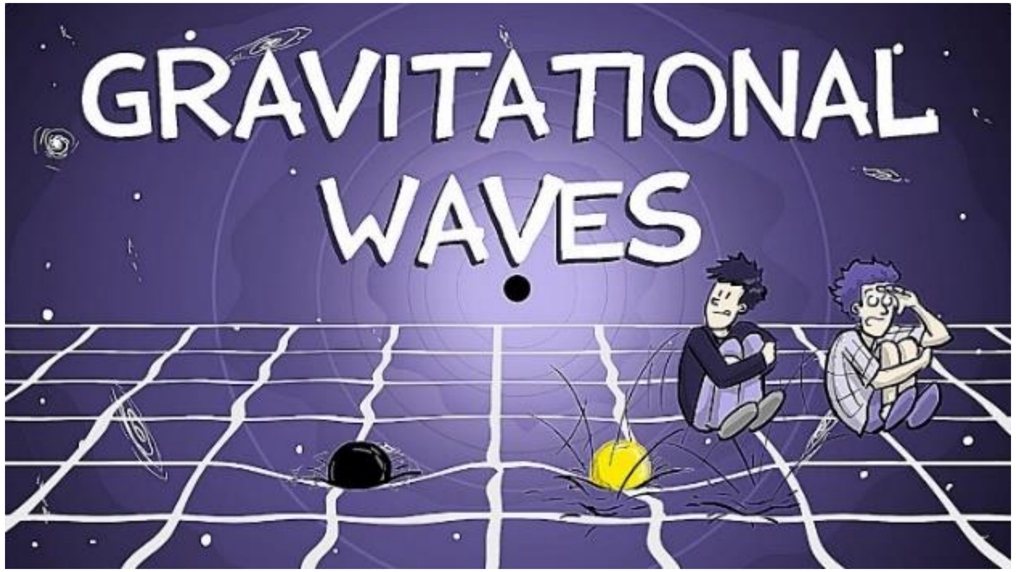


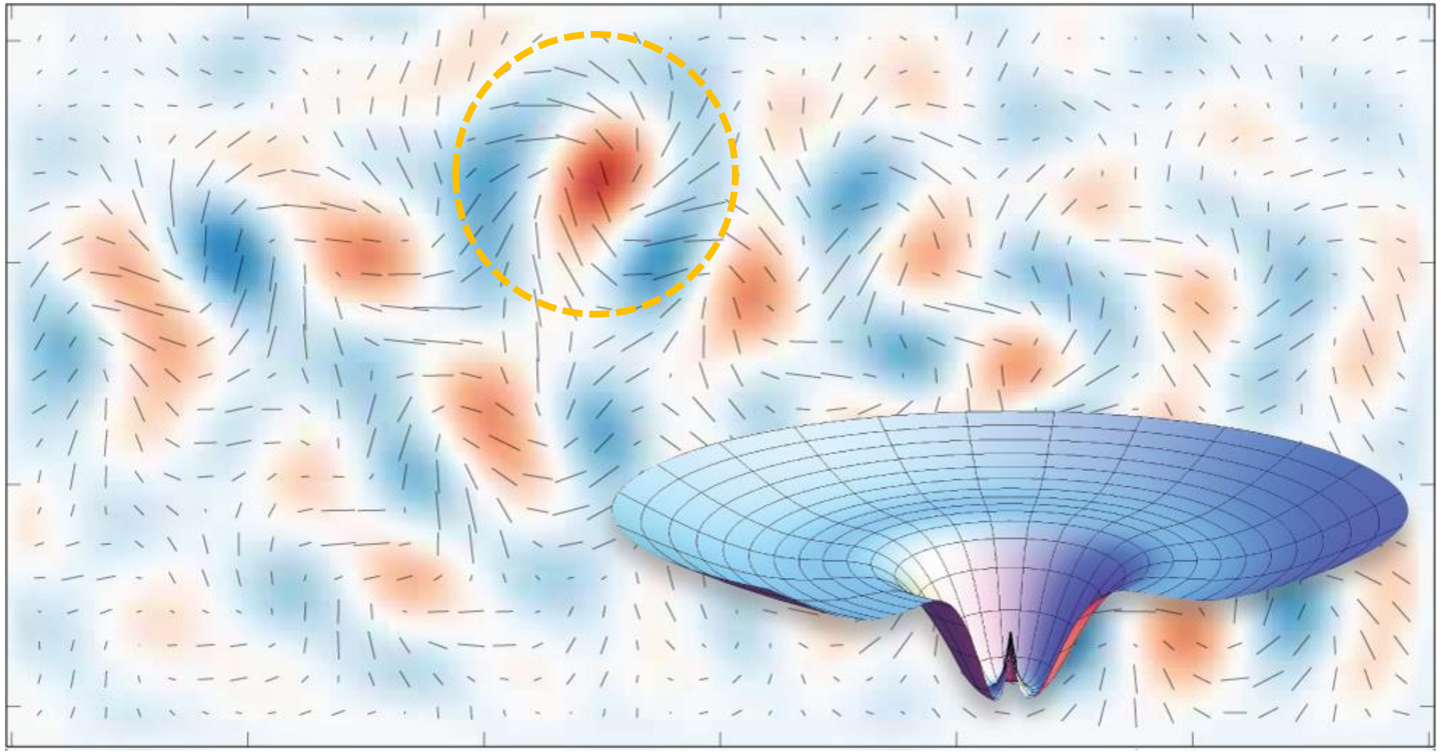
Inflation – can we verify it experimentally?

- **The ´Holy Grail´ of Cosmology: imprint of inflation on polarisation of CMB**

  - key realisation – fast expansion phase of early universe $a(t)$ leaves behind an imprint on CMB: ⇨ distinct polarization pattern of CMB due to gravitational waves

  - **curl-like polarization** of the CMB: $rot\,\vec{B} \neq 0\ (LH/RH)$



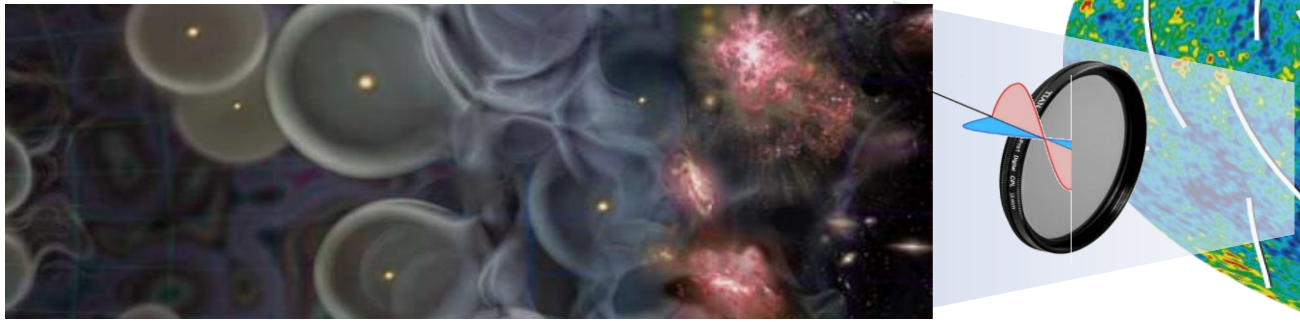


Inflation – not so easily verified experimentally

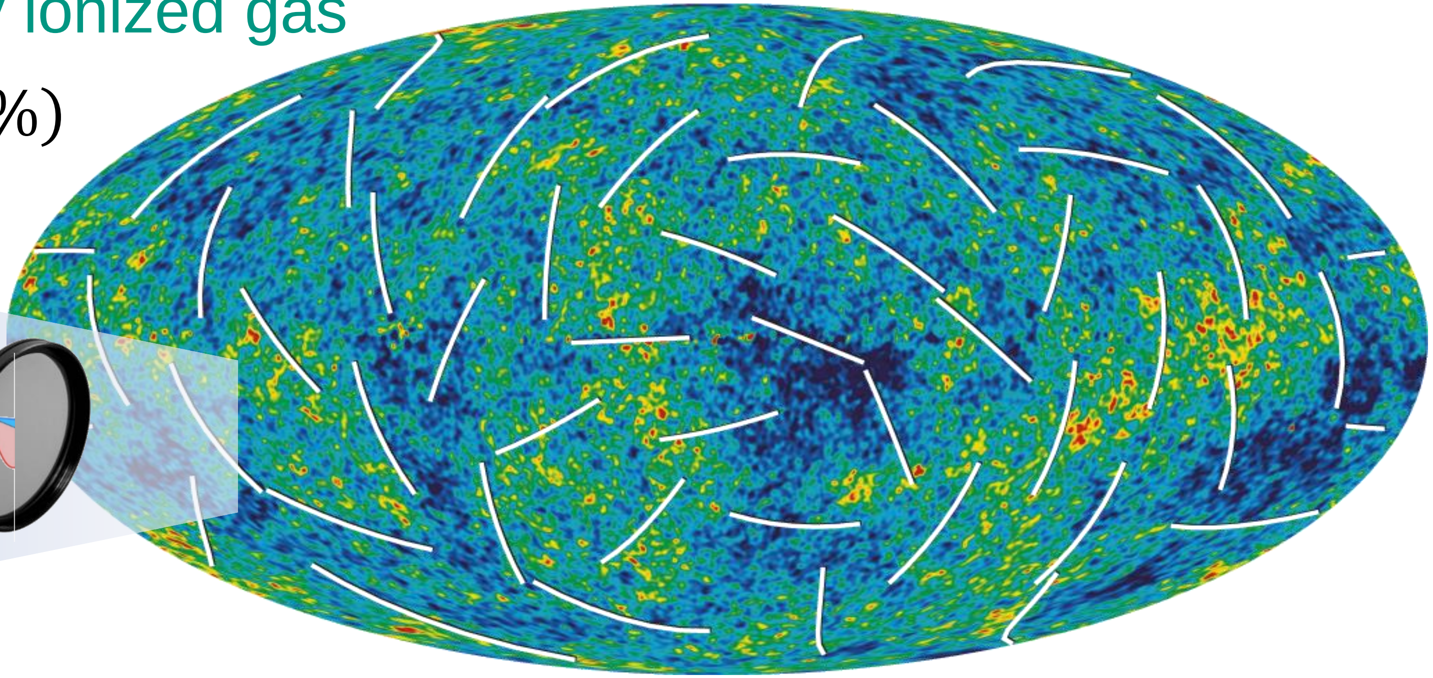
- **Polarization pattern of the CMB due to classical Thomson scattering off e^-**

  - no signal without noise, here: we expect a polarization of the CMB due to scattering processes off nearby ionized gas

  - **linear polarization** $(\sim 10 \ldots 20\ \%)$ of the CMB: $rot\ \vec{B} = 0$



CMB scatters off re-ionised regions
⇨ large-scale linear polarization pattern



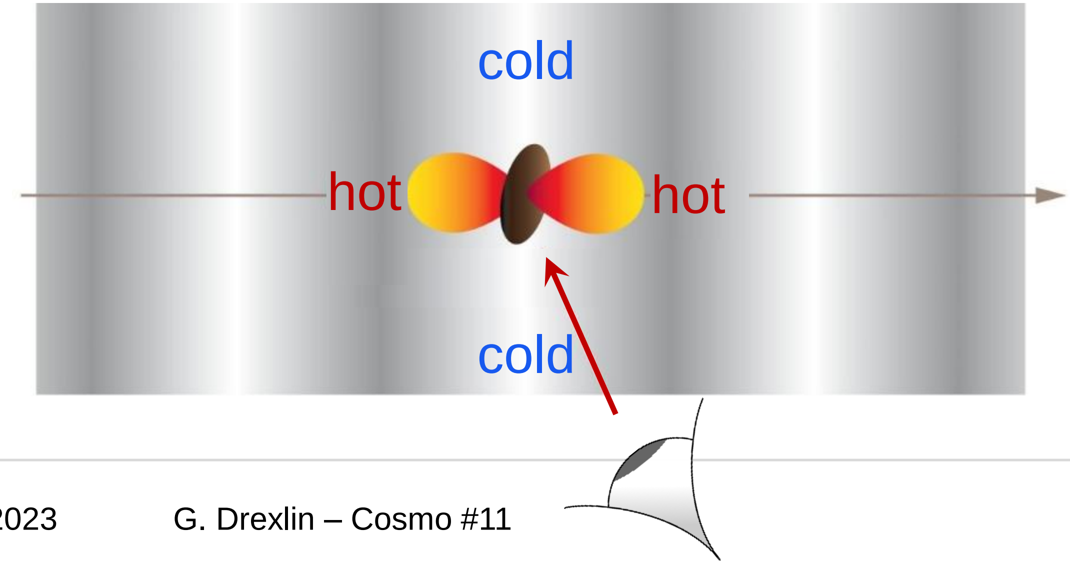
first sky map of CMB polarization from WMAP:
nearby ionised gas (non-primordial origin!)

Classical Thomson scattering: primordial plasma

Karlsruhe Institute of Technology

- **Polarization pattern of the CMB due to classical Thomson scattering off e^-**

  - more interesting for cosmology: **CMB scattering off primordial plasma**
  - expected primordial polarization level ~1 % due to Thomson scattering at last surface, before decoupling **(´last surface of scattering´)**
  - from density fluctuations $\Delta\rho/\rho$ we expect a **linear CMB polarization**



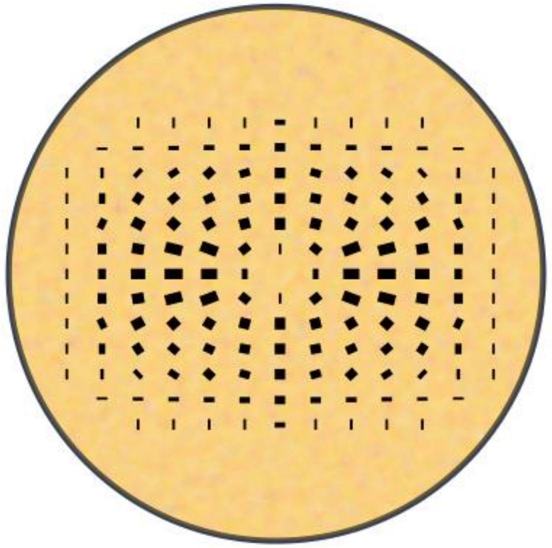
local quadrupole moment

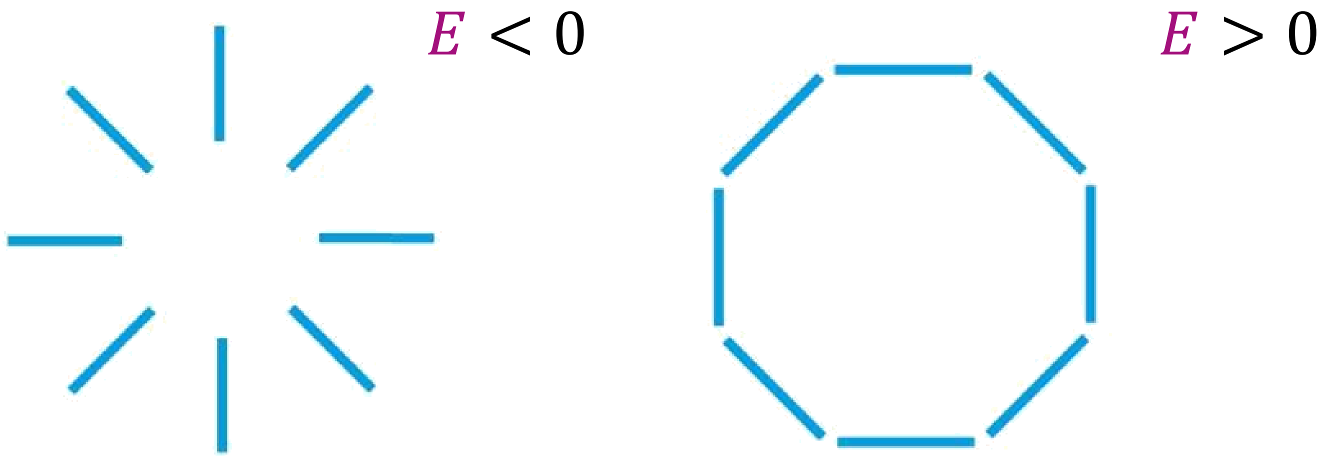
standing acoustic density wave

Classical Thomson scattering: primordial plasma

- **Polarization pattern of the CMB due to classical Thomson scattering off e^-**

  - CMB scattering off **primordial plasma with anisotropic density distribution**
  - linear or ´**scalar**´ polarization character (analogy: electric field E)



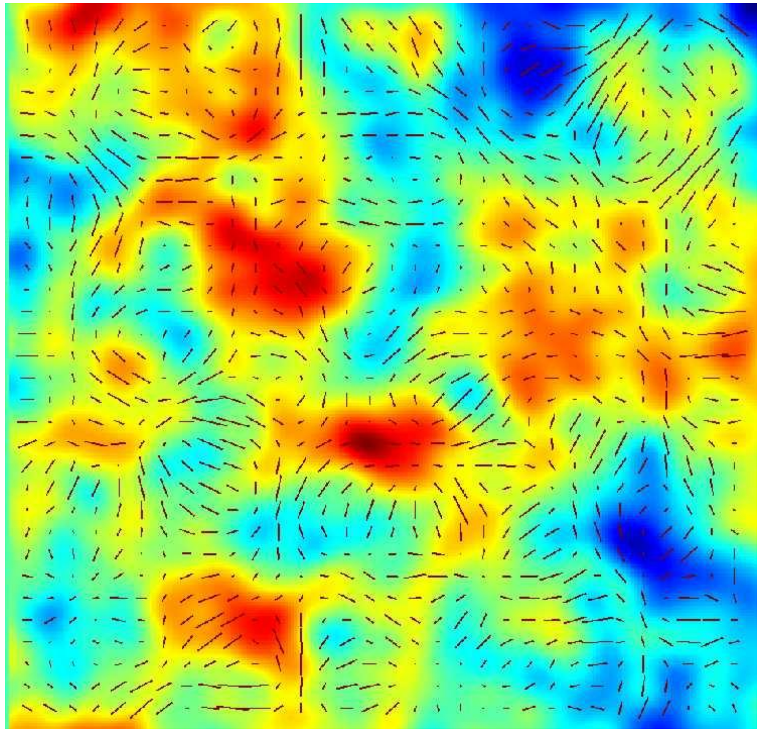


⇨ **linear CMB polarization**

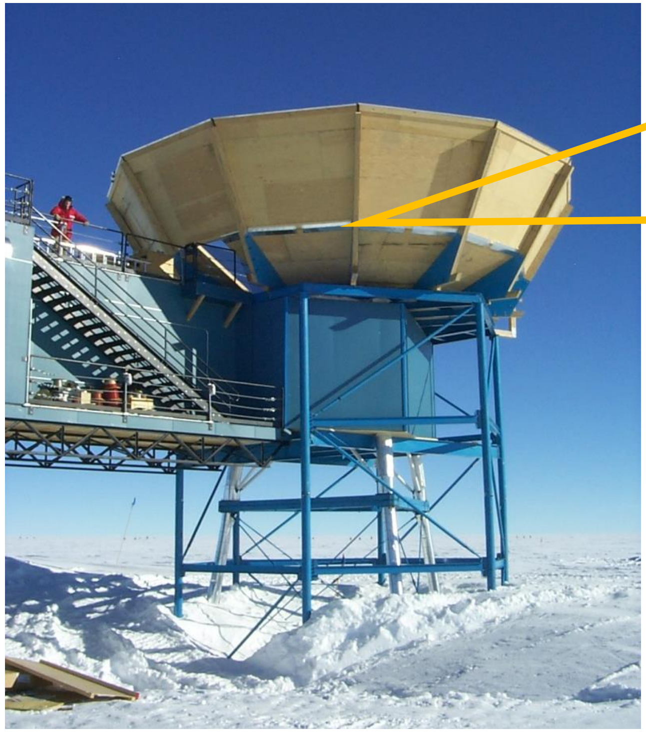
analogy to E –field: vanishing rotation

Classical Thomson scattering: primordial plasma

- **First experimental verification of CMB polarization by DASI* at the Southpole**



polarization from scattering off primordial plasma is only visible at small scales



12/2002: DASI reports CMB-polarization with E –modes

11 m tower with bottom dome to prevent interference from ground heat

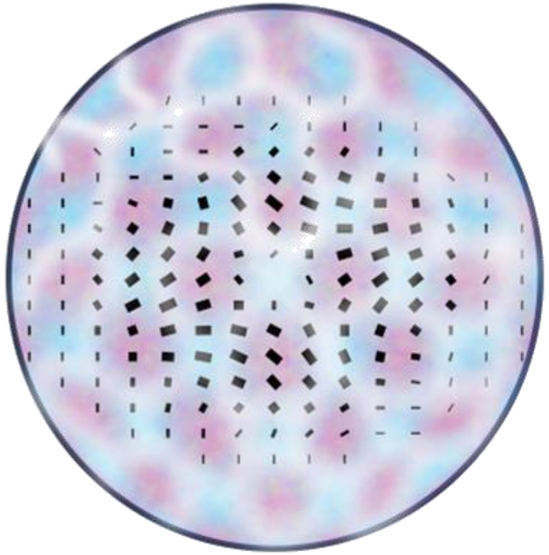
***DASI – Degree Angular Scale Interferometer**

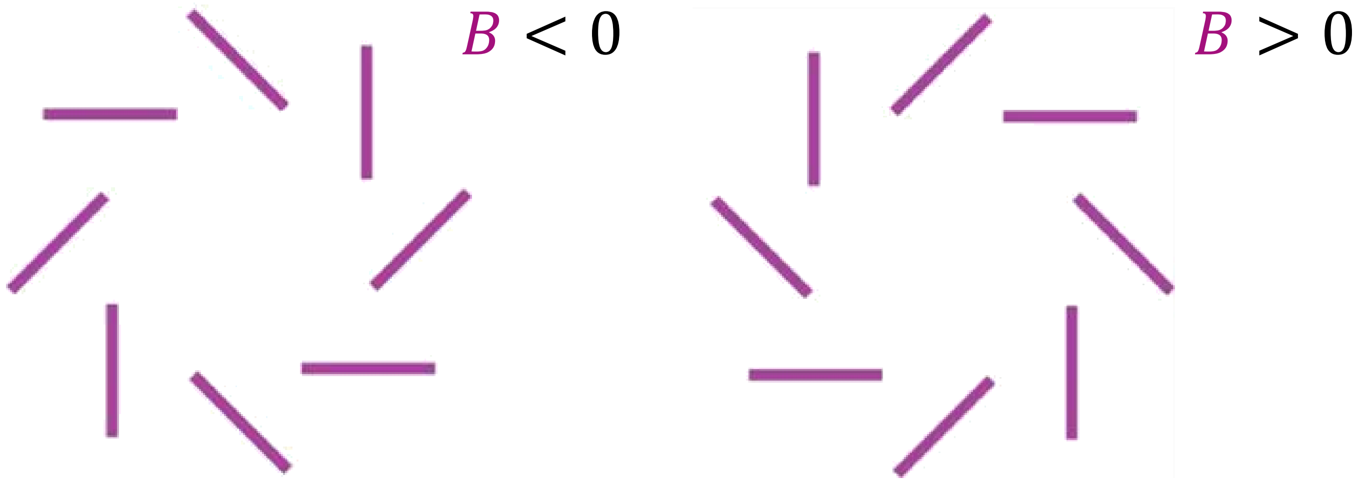
Holy Grail: curl-like CMB polarization from inflation

- **Curls in the CMB polarization patterns due to very early gravitational waves**

  - CMB radiation is strechted / squeezed by primordial gravitational waves

  - ´**tensor**´ polarization character (analogy: magnetic field B with $\mathrm{rot}\, B \neq 0$)





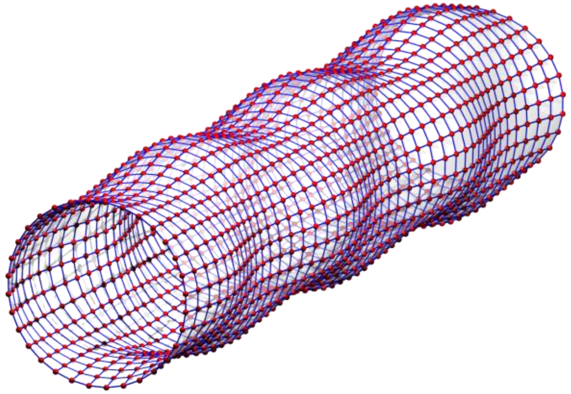
⇨ **tensor CMB polarization**

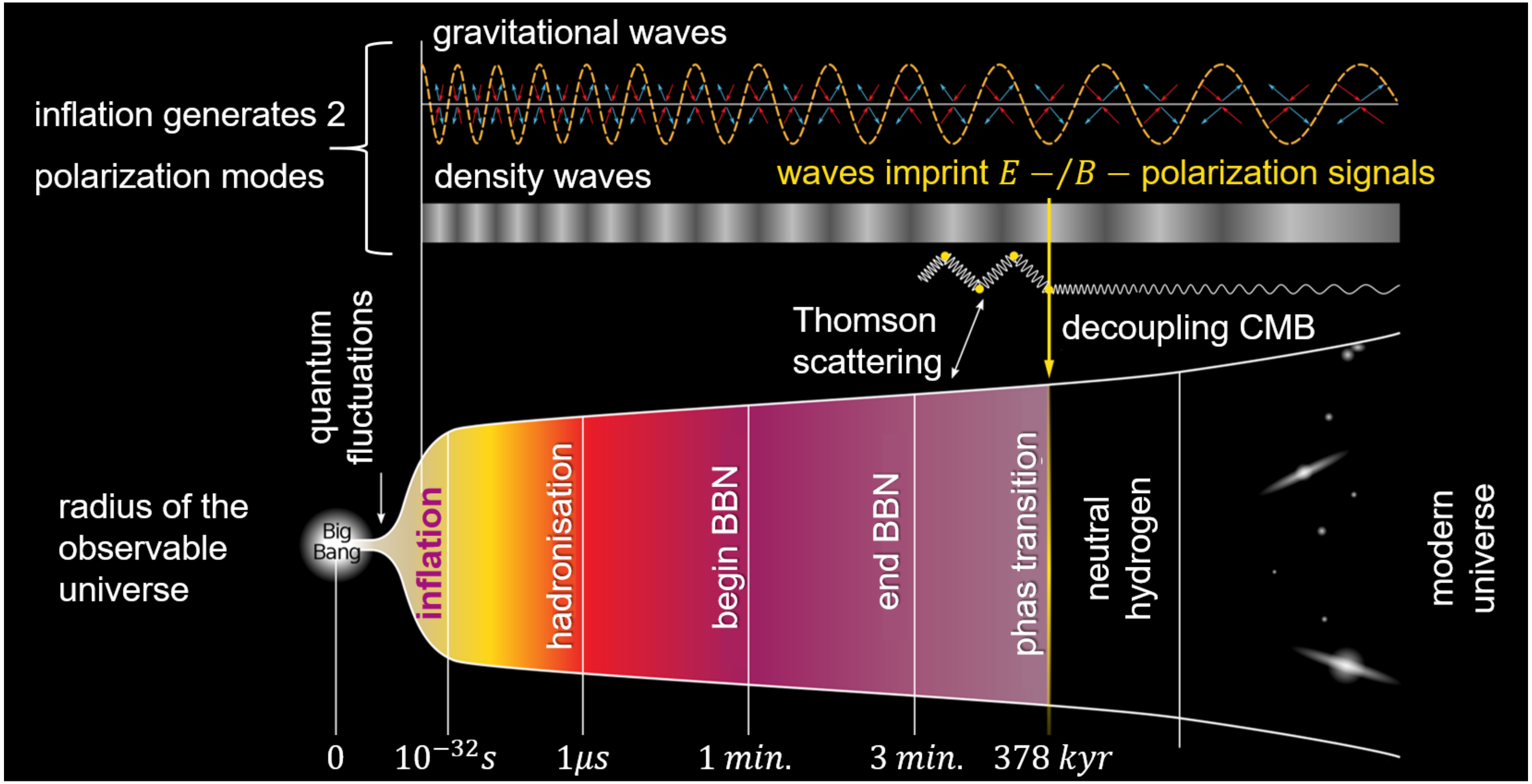
analogy to B –field: non-vanishing rotation

Early inflationary phase & CMB polarizations

- **Accelerated masses during inflation: emssion of gravitational waves**

- gravitational waves stretch & squeeze space & time

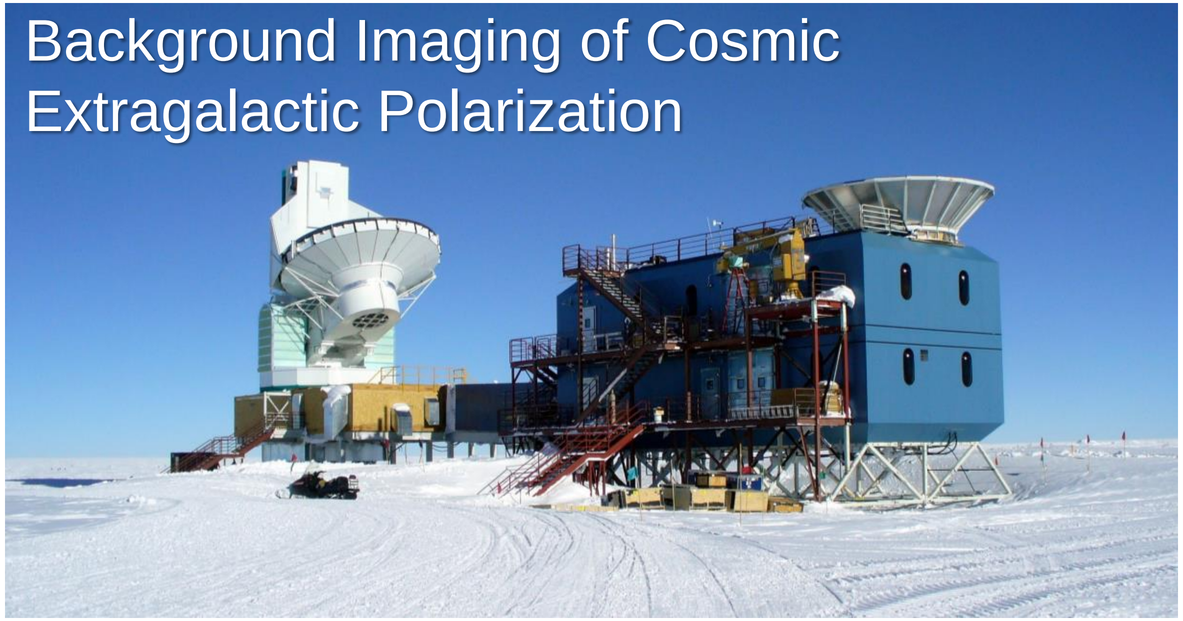




Hunting primordial curls in the CMB: BICEP2

- **March 17, 2014: interesting news from the Southpole: we have a signal!!**

- BICEP2 reports on the detection of a B – mode (tensor) signal of the CMB polarization with $7\,\sigma$ from 2010-12 data*



TO BE SUBMITTED TO A JOURNAL TBD
Preprint typeset using LaTeX style emulateapj v. 04/17/13

BICEP2 I: DETECTION OF *B*-mode POLARIZATION AT DEGREE ANGULAR SCALES

BICEP2 COLLABORATION - P. A. R. ADE[1], R. W. AIKIN[2], D. BARKATS[3], S. J. BENTON[4], C. A. BISCHOFF[5], J. J. BOCK[2,6], J. A. BREVIK[2], I. BUDER[5], E. BULLOCK[7], C. D. DOWELL[6], L. DUBAND[8], J. P. FILIPPINI[2], S. FLIESCHER[9], S. R. GOLWALA[2], M. HALPERN[10], M. HASSELFIELD[10], S. R. HILDEBRANDT[2,6], G. C. HILTON[11], V. V. HRISTOV[2], K. D. IRWIN[12,13,11], K. S. KARKARE[5], J. P. KAUFMAN[14], B. G. KEATING[14], S. A. KERNASOVSKIY[12], J. M. KOVAC[5,16], C. L. KUO[12,13], E. M. LEITCH[15], M. LUEKER[2], P. MASON[2], C. B. NETTERFIELD[4], H. T. NGUYEN[6], R. O'BRIENT[6], R. W. OGBURN IV[12,13], A. ORLANDO[14], C. PRYKE[9,7,16], C. D. REINTSEMA[11], S. RICHTER[5], R. SCHWARZ[9], C. D. SHEEHY[9,15], Z. K. STANISZEWSKI[2,6], R. V. SUDIWALA[1], G. P. TEPLY[2], J. E. TOLAN[12], A. D. TURNER[6], A. G. VIEREGG[5,15], C. L. WONG[5], AND K. W. YOON[12,13]

to be submitted to a journal TBD

ABSTRACT

We report results from the BICEP2 experiment, a Cosmic Microwave Background (CMB) polarimeter specifically designed to search for the signal of inflationary gravitational waves in the *B*-mode power spectrum around $\ell \sim 80$. The telescope comprised a 26 cm aperture all-cold refracting optical system equipped with a focal plane of 512 antenna coupled transition edge sensor (TES) 150 GHz bolometers each with temperature sensitivity of $\approx 300\ \mu K_{CMB}\sqrt{s}$. BICEP2 observed from the South Pole for three seasons from 2010 to 2012. A low-foreground region of sky with an effective area of 380 square degrees was observed to a depth of 87 nK-degrees in Stokes Q and U. In this paper we describe the observations, data reduction, maps, simulations and results. We find an excess of *B*-mode power over the base lensed-ΛCDM expectation in the range $30 < \ell < 150$, inconsistent with the null hypothesis at a significance of $> 5\sigma$. Through jackknife tests and simulations based on detailed calibration measurements we show that systematic contamination is much smaller than the observed excess. We also estimate potential foreground signals and find that available models predict these to be considerably smaller than the observed signal. These foreground models possess no significant cross-correlation with our maps. Additionally, cross-correlating BICEP2 against 100 GHz maps from the BICEP1 experiment, the excess signal is confirmed with 3σ significance and its spectral index is found to be consistent with that of the CMB, disfavoring synchrotron or dust at 2.3σ and 2.2σ, respectively. The observed *B*-mode power spectrum is well-fit by a lensed-ΛCDM + tensor theoretical model with tensor/scalar ratio $r = 0.20^{+0.07}_{-0.05}$, with $r = 0$ disfavored at 7.0σ. Subtracting the best available estimate for foreground dust modifies the likelihood slightly so that $r = 0$ is disfavored at 5.9σ.
Subject headings: cosmic background radiation — cosmology: observations — gravitational waves — inflation — polarization

1. INTRODUCTION

The discovery of the Cosmic Microwave Background (CMB) by Penzias & Wilson (1965) confirmed the hot big bang paradigm and established the CMB as a central tool for the study of cosmology. In recent years, observations of its temperature anisotropies have helped establish and refine the "standard" cosmological model now known as ΛCDM, under

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 *extraordinary claims demand extraordinary evidence

Hunting primordial curls in the CMB: BICEP2

Karlsruhe Institute of Technology

- **March 17, 2014: sensational news from the Southpole**

- BICEP2 reports on the detection of a $B-$mode (tensor) signal of the CMB polarization with $7\,\sigma$ from 2010-12 data

Home > May 2014 (Volume 67, Issue 5) > Page 11, doi:10.1063/PT.3.2367

PHYSICS TODAY

Polarization measurement detects primordial gravitational waves

Cosmic inflation is bolstered, but some inconsistencies await resolution.

Alan Chodos

'Smoking Gun' Reveals How the Inflationary Big Bang Happened

New findings show that the universe underwent a burst of inflation that was seemingly faster than the speed of light in the first instant of its existence.

NBC NEWS

Cosmic inflation: 'Spectacular' discovery hailed

17 March 2014

BBC

The measurements were taken using the BICEP2 instrument at the South Pole telescope facility

By Jonathan Amos

Science correspondent, BBC News

Scientists say they have extraordinary new evidence to support a Big Bang Theory for the origin of the Universe.

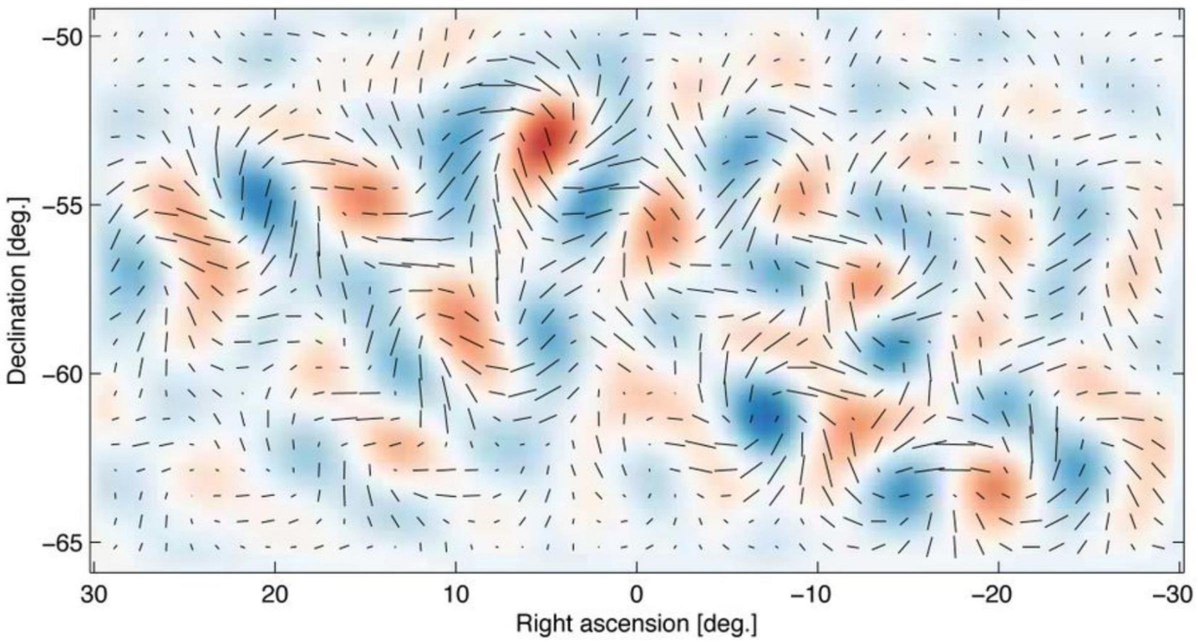
Researchers believe they have found the signal left in the sky by the super-rapid expansion of space that must have occurred just fractions of a second after everything came into being.

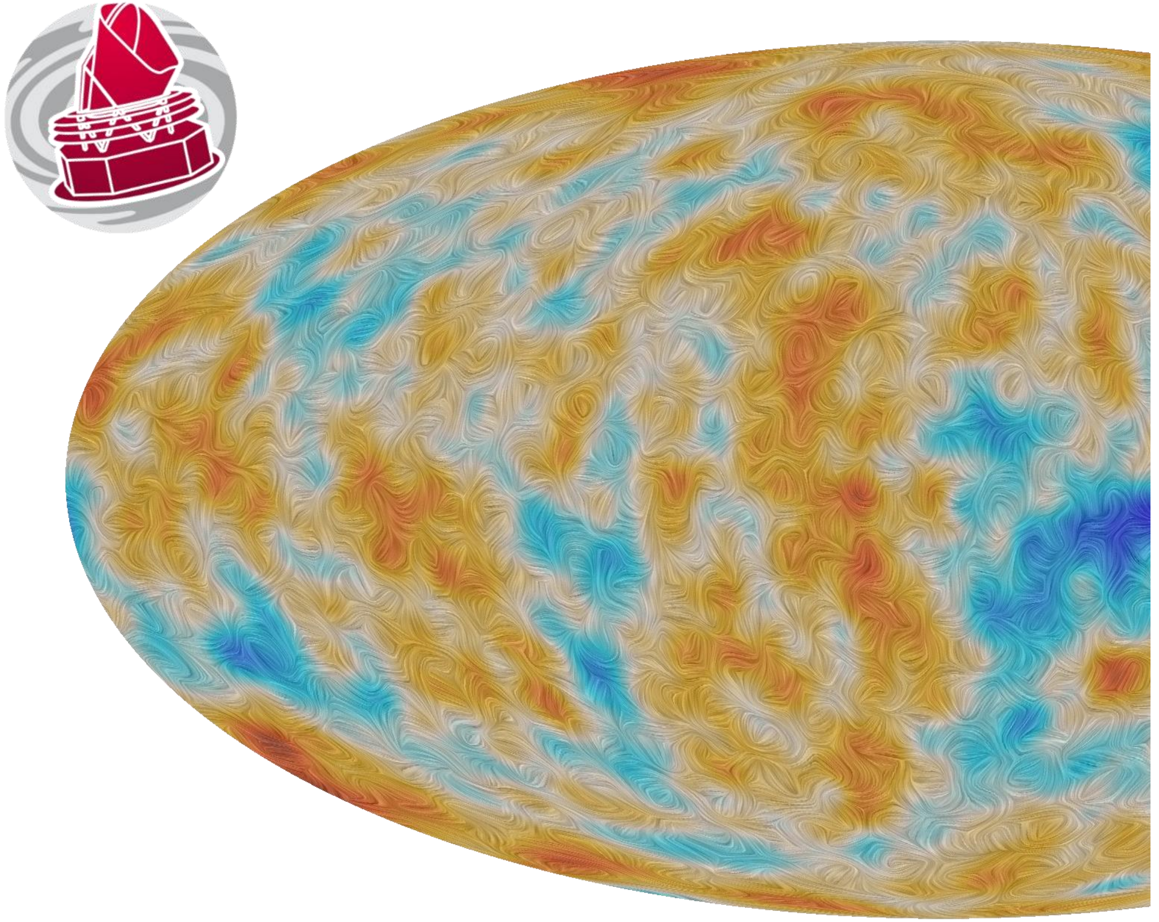
It takes the form of a distinctive twist in the oldest light detectable with

Hunting primordial curls in the CMB: BICEP2

- **March 2014: sensational news from the Southpole, but wait: news by Planck**

- BICEP2 reports on the detection of a B – mode (tensor) signal of the CMB polarization with $7\,\sigma$ from 2010-12 data





Primordial curls in the CMB: it´s just dust…

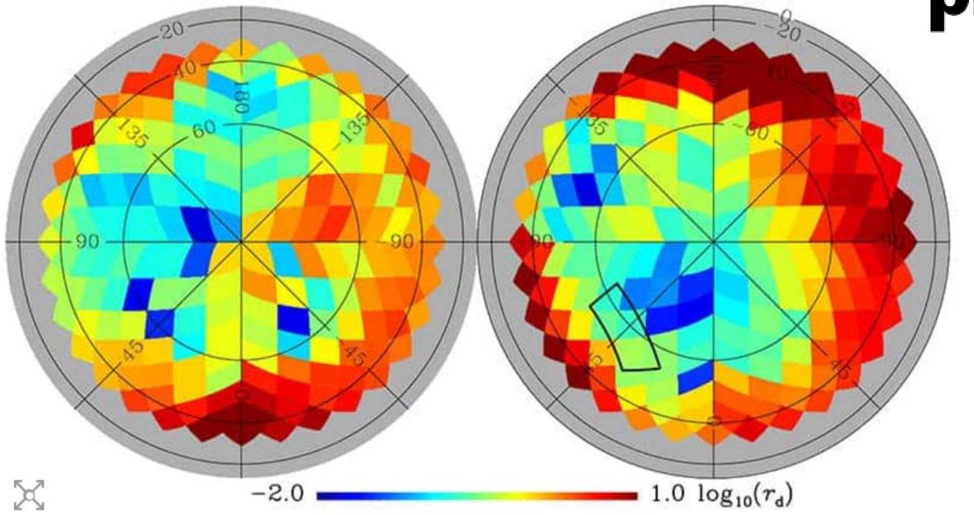
- **Sept. 2014: sensational news from the Southpole bites the dust…**

TELESCOPES AND SPACE MISSIONS | RESEARCH UPDATE

BICEP2 gravitational wave result bites the dust thanks to new Planck data

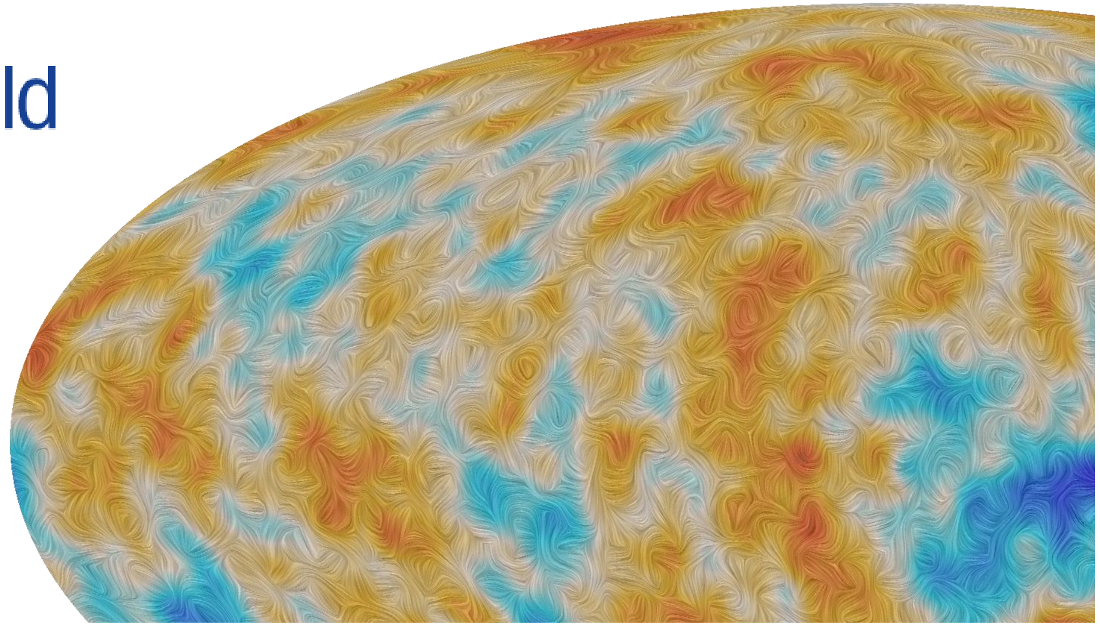
22 Sep 2014 Tushna Commissariat

physicsworld



Dirty window: The 'dusty' sky as seen by Planck

Astronomers working on the Background Imaging of Cosmic Extragalactic Polarization (BICEP2) telescope at the South Pole hit the headlines earlier this year when they claimed to have seen the first evidence for the primordial “B-mode” polarization of the cosmic microwave background (CMB). But a new analysis of polarized dust emission in our galaxy, carried out by the Planck collaboration, has shown that the part of the sky observed by BICEP2 has much



thermal emission from dust: Planck shows that BICEP2 had just measured …dust…

Combined analysis from BICEP2 & Planck

Karlsruhe Institute of Technology

- **Jan. 2015 joint publication: entire ´GW-signal´ can be explained by dust…**

  - combined analysis Planck-BICEP2: **no evidence for cosmological B – mode (tensor) signal due to GW**

  - contribution due to **noise** (dust rings) substantially larger than assumed by BICEP2 in original publication

  - polarization data confirm earlier measurements Ω_B & Ω_{DM} based (unpolarized) ΔT – data sets

nature

Dust to dust

What lessons can be learned from the presentation of the gravitational-waves story? *

More than six months after the initial announcement that scientists had found evidence of gravitational waves — echoes of the Big Bang itself — the claim is hanging by a thread. Subsequent analysis showed that much of the signal could have been contaminated by galactic dust. The predictions of Nobel prizes for the team have faded. The champagne has gone flat.

Extraordinary claims, as the saying almost goes, demand more scrutiny than usual to make sure they stand up. That is how science works. Claim and counter-claim: intellectual thrust and experimental parry.

16 OCTOBER 2014 | VOL 514 | NATURE | 273

*always very carefully study your noise!