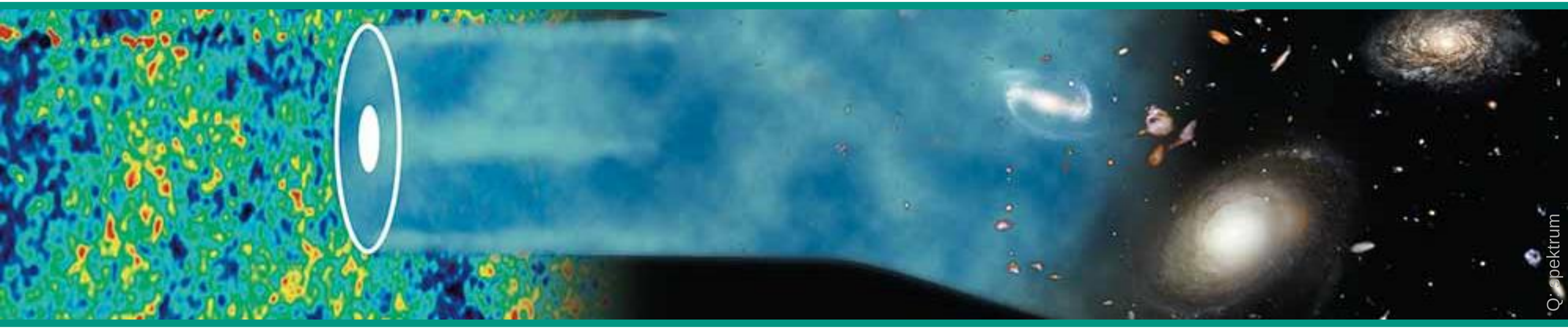
Introduction to Cosmology

Winter term 23/24 Lecture 11 Jan. 16, 2024



Recap of Lecture 10

- $\boldsymbol{CMB}$: $\boldsymbol{B}$**aryon** $\boldsymbol{A}$**coustic** $\boldsymbol{O}$**scillations (**$\boldsymbol{BAO}$**)** & **the** $\boldsymbol{Planck}$ **mission**

  - $\boldsymbol{BAO}$: (standing) **acoustic waves** in the primordial plasma (⇨ sound horizon)

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

    height is impacted by **baryon loading:** $\boldsymbol{\Omega_B h^2 = 0.022}$

  - **overtones**: $\mathbf{2.}$ & $\mathbf{3.}$ peaks ⇨ ratio to determine **dark matter** $\boldsymbol{\Omega_{DM} \approx 5 \times \Omega_B}$

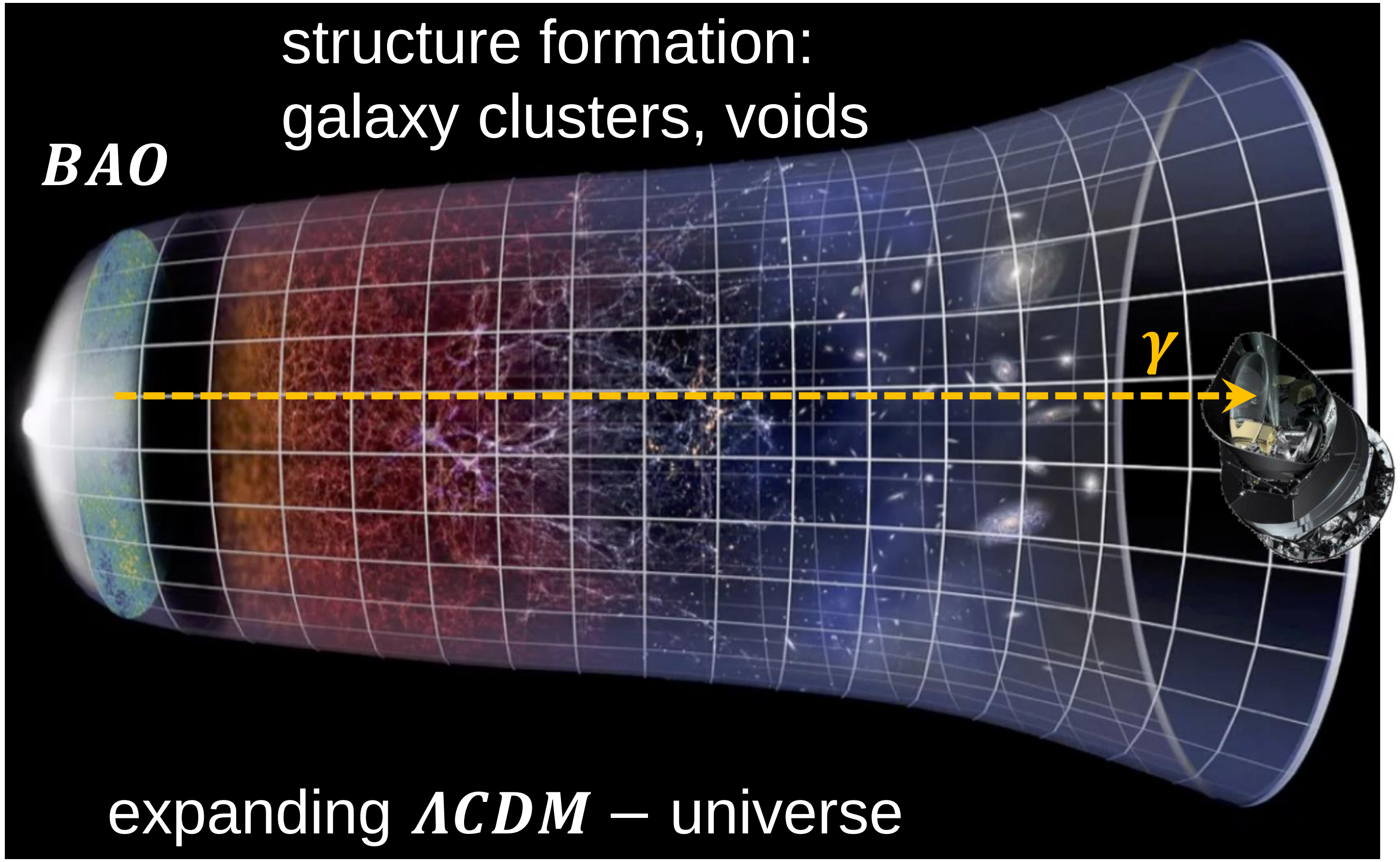
  - $\boldsymbol{Planck}$ – definitive $\boldsymbol{CMB}$ map, yielding **fundamental parameters** for $\boldsymbol{\Lambda CDM}$

  - $\boldsymbol{CMB}$ anomalies seem to persist: low power & alignment of small multipoles,...

Secondary CMB anisotropies

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

- **secondary CMB anisotropies**:
  - due to **large−scale structures** in an expanding $\Lambda CDM -$ universe with
    - ⇨ ISW – **effect** due to non−zero Λ
    - ⇨ SZ – **effect** due to CMB – scattering off e^- in galaxy clusters



Secondary CMB anisotropies

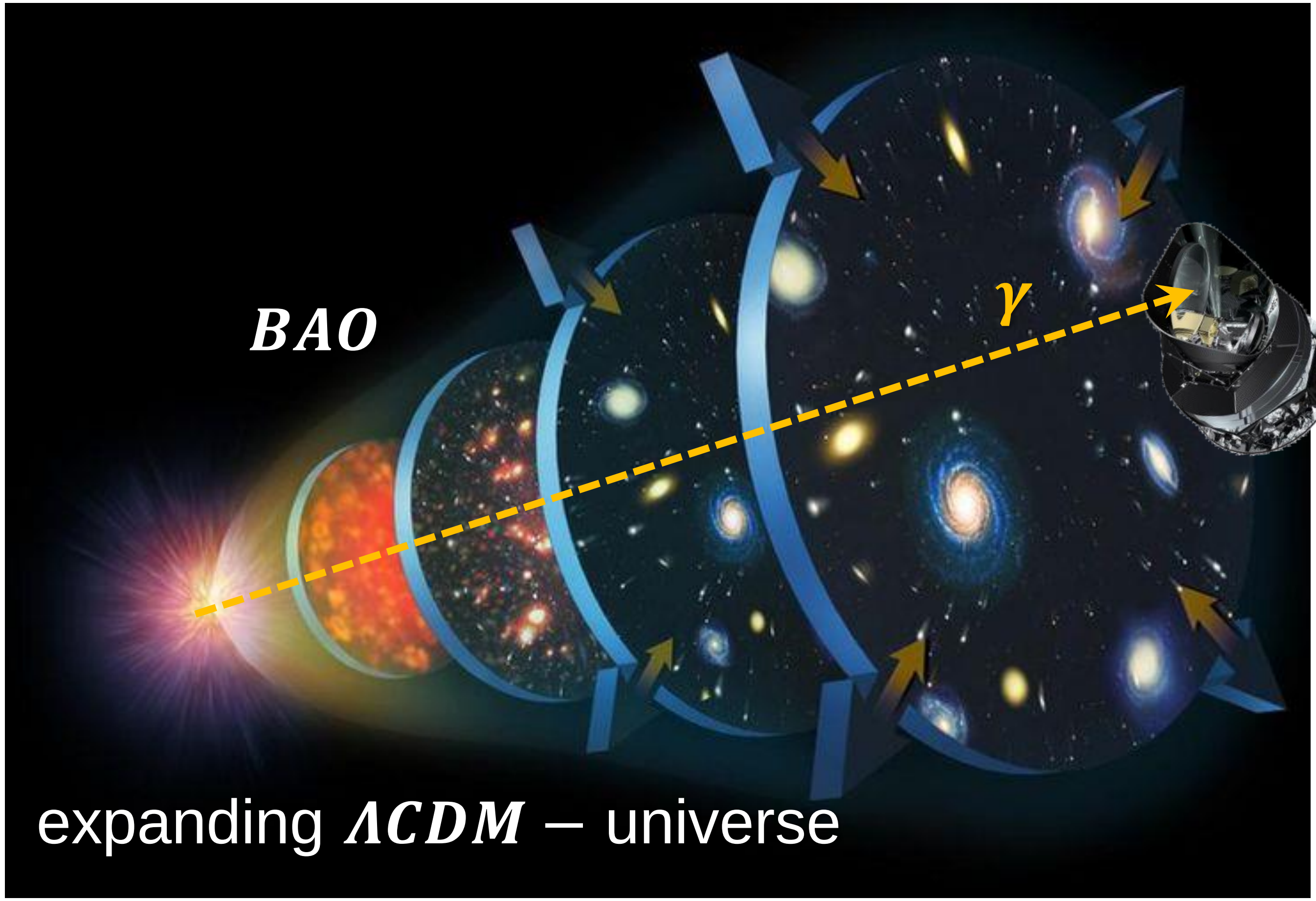
- **CMB anisotropies due to photon propagation over $t = 13.8 \cdot 10^9\ yr$**

- **secondary CMB anisotropies**:

how are the **primary CMB anisotropies** being influenced...

- topic $\mathbf{1}$:
  ... by the **accelerated expansion** of the universe?

- topic $\mathbf{2}$:
  ... by **matter in galaxy clusters**?



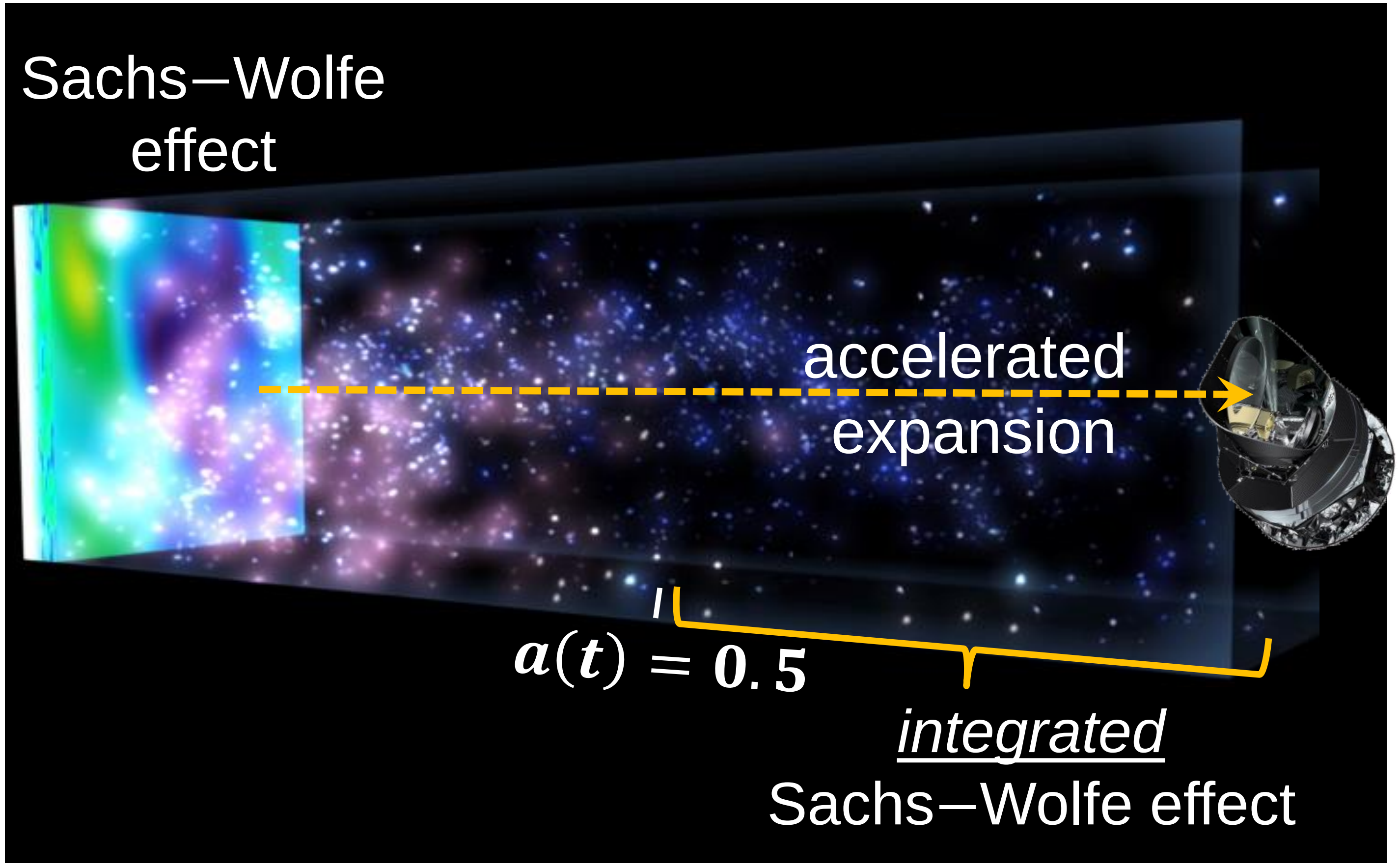
$\boldsymbol{I}$ntegrated $\boldsymbol{S}$achs–$\boldsymbol{W}$olfe $(\boldsymbol{ISW})$ effect

- **Secondary anisotropy due to accelerated expansion of $\boldsymbol{\Lambda CDM}$ – universe**

- $\boldsymbol{ISW}$ – **effect**: propagation of the $\boldsymbol{CMB}$ in late $\boldsymbol{\Lambda}$ – dominated universe $\boldsymbol{a(t) > 0.5}$ with an accelerated cosmic expansion:

⇨ a (further) evidence for a non–zero value of the vacuum energy density $(\boldsymbol{\Lambda \neq 0})$

⇨ manifests as a **secondary anisotropy** $\boldsymbol{\Delta T / T}$ at **large scales** $\boldsymbol{\theta > 2°}$



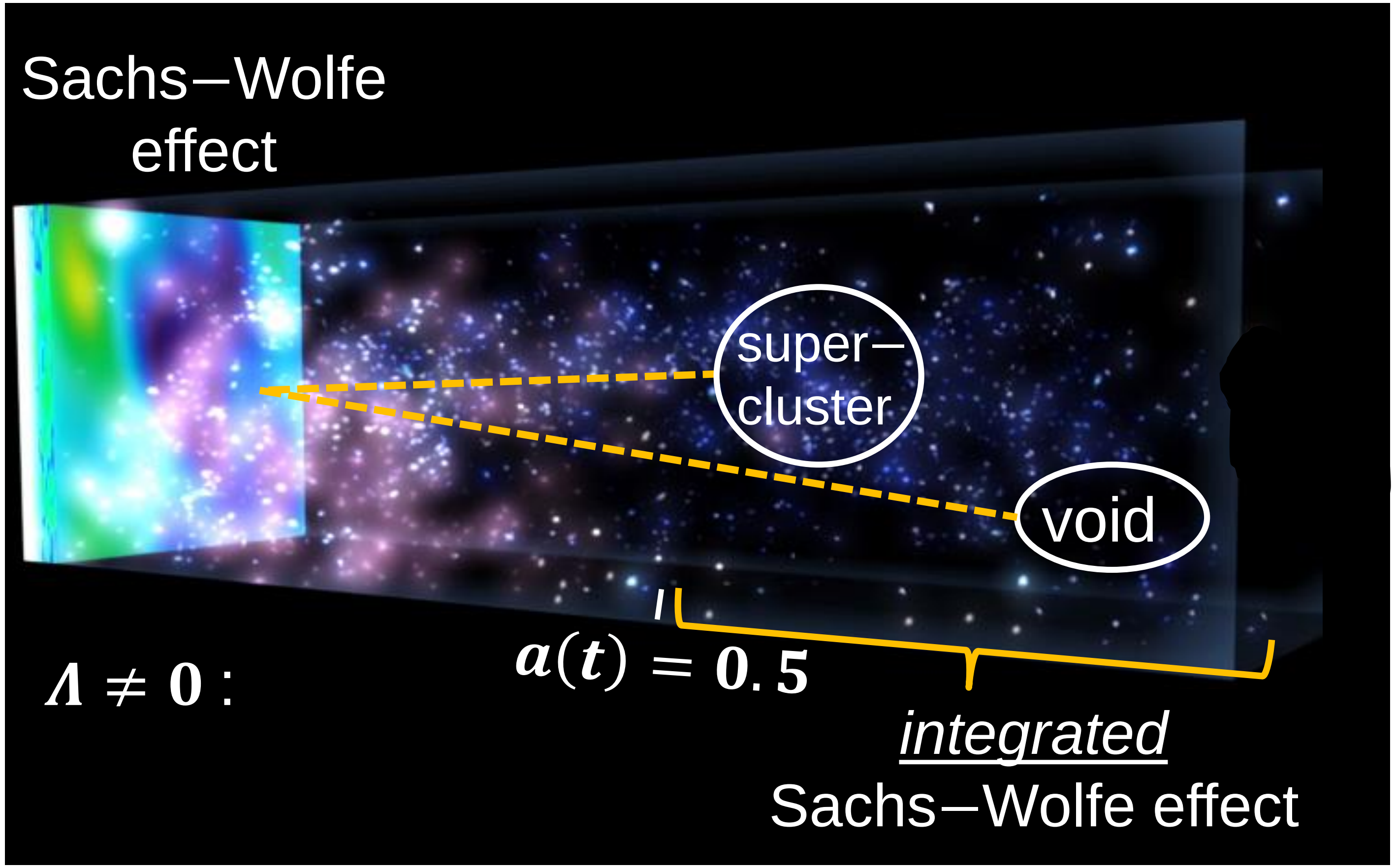
$\boldsymbol{I}$ntegrated $\boldsymbol{S}$achs–$\boldsymbol{W}$olfe ($\boldsymbol{ISW}$) effect

- **Secondary anisotropy due to accelerated expansion of $\boldsymbol{\Lambda CDM}$ – universe**

- let´s consider propagation of $\boldsymbol{CMB}$ in a time–dependent gravity $\boldsymbol{\Phi(t)}$ **well** (**cluster**) & in a **hill** (**void**) for an epoch dominated by $\boldsymbol{\Lambda \neq 0}$:

⇨ **galaxy super–cluster**:
local **overdensity**
how is $\boldsymbol{CMB}$ affected by $\boldsymbol{\Lambda \neq 0}$?

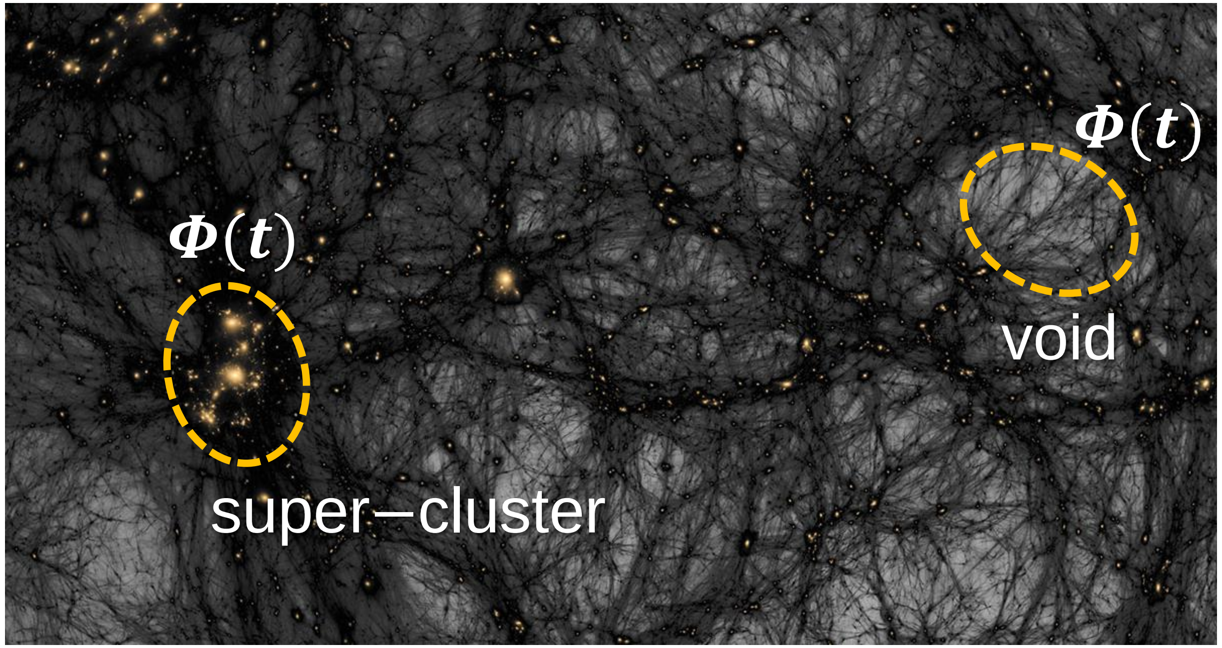
⇨ **cosmic void**:
local **underdensity**
how is $\boldsymbol{CMB}$ affected by $\boldsymbol{\Lambda \neq 0}$?

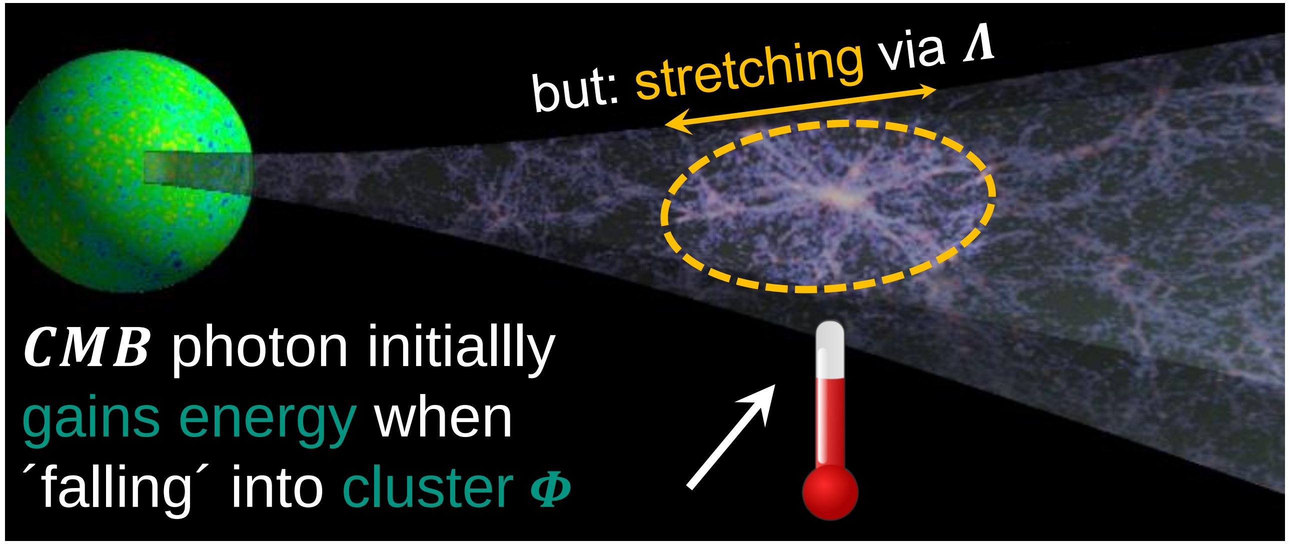


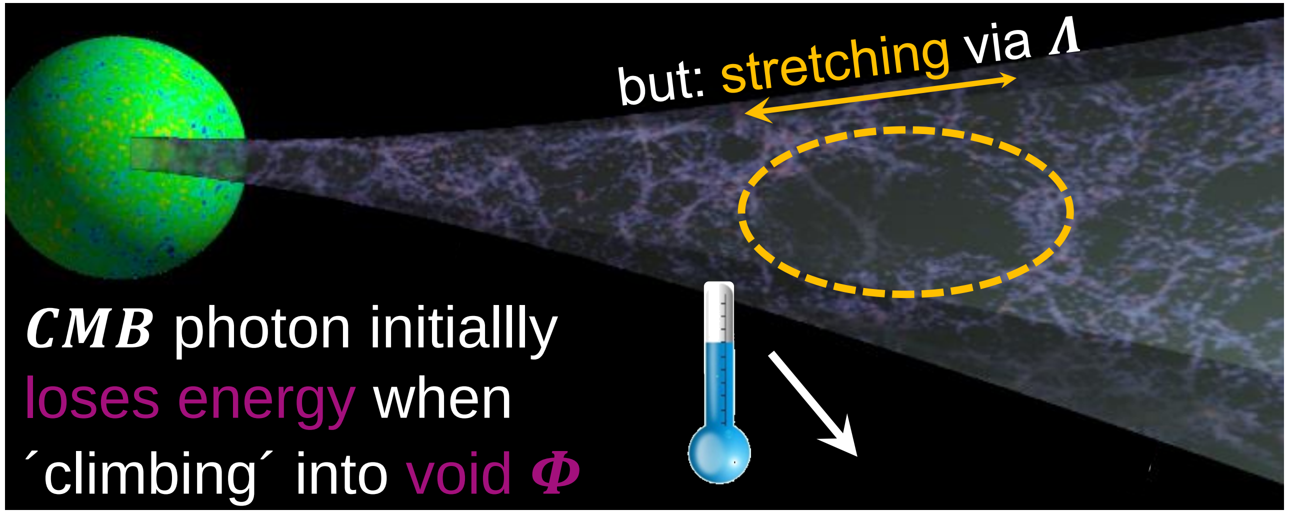
ISW: CMB propagation in super–clusters / voids

- **Secondary anisotropies due to Λ**

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







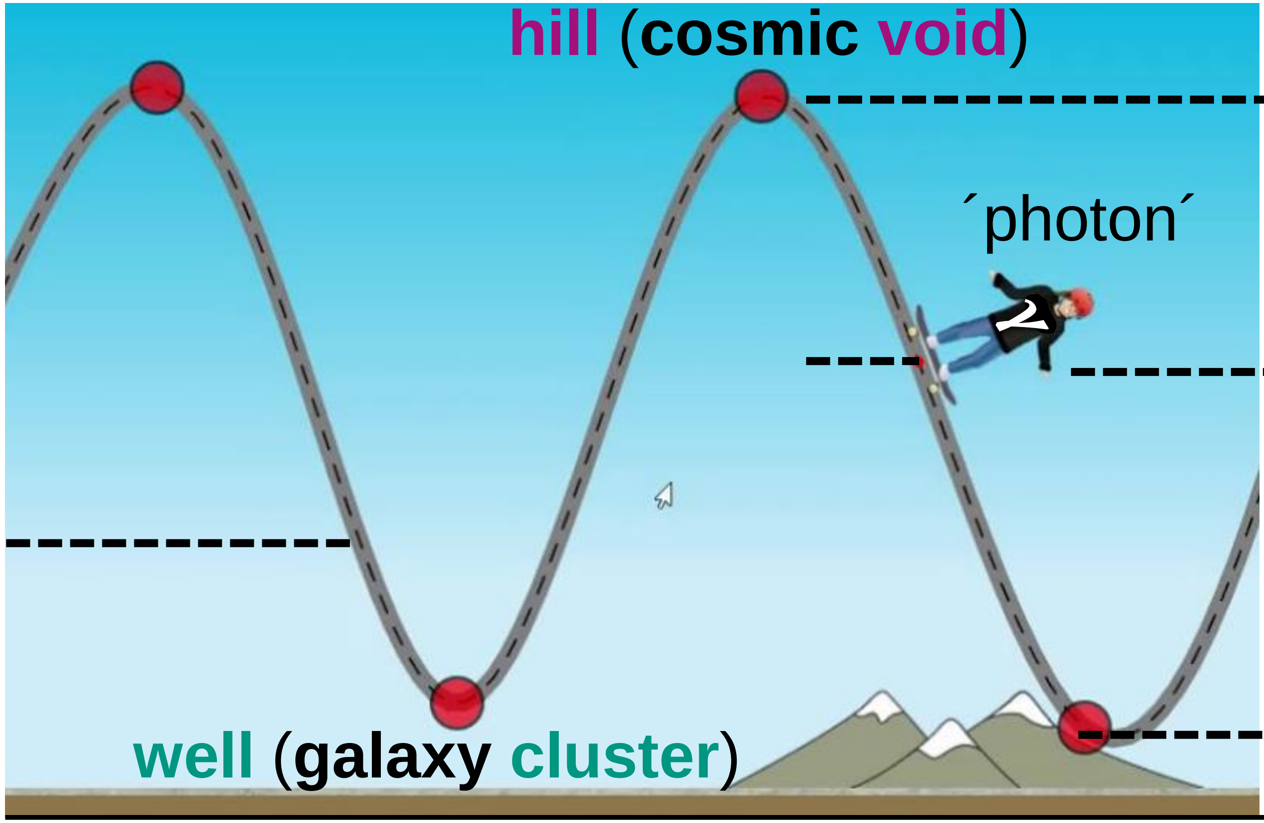
RECAP: photons travelling in static potential $\Phi(x)$

- **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}

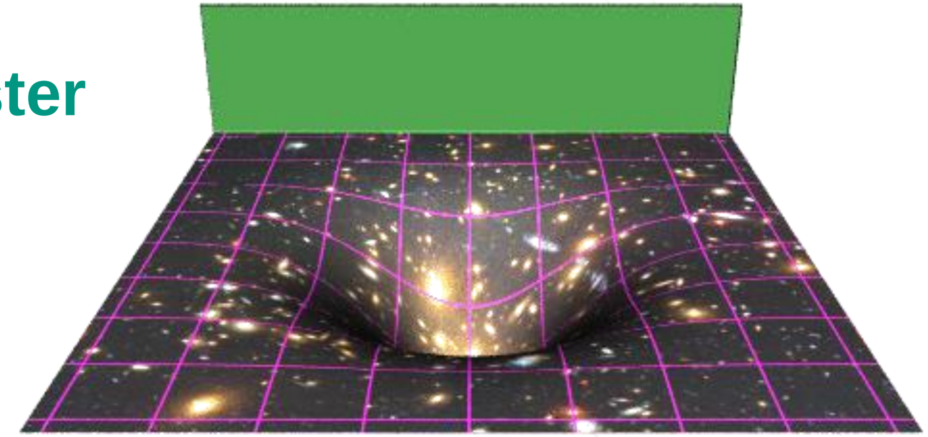
x

photon has no interaction with particles

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

Karlsruhe Institute of Technology

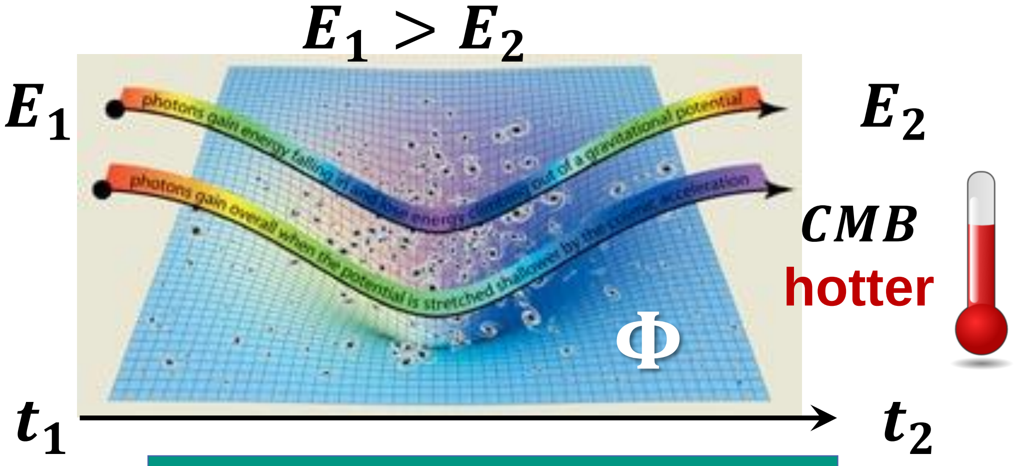
- **Secondary CMB anisotropy after photons have propagated an overdense super−cluster**



- entry: energy E_1
CMB gains an amount 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

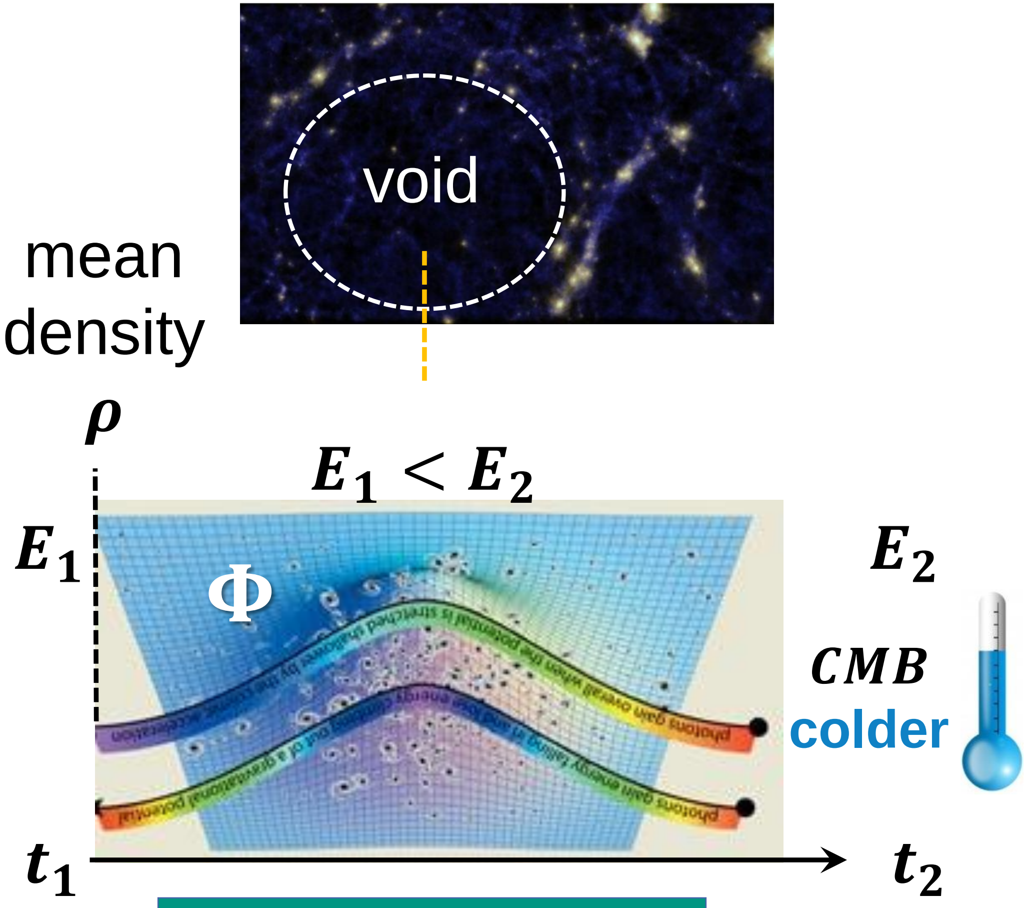
ISW effect: CMB propagation in $\Lambda \neq 0$ universe

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

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

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

- **exit: energy E_2**
  CMB obtains a **net loss** of E_{kin} after falling out of the **gravity hill** with **shallower** potential Φ

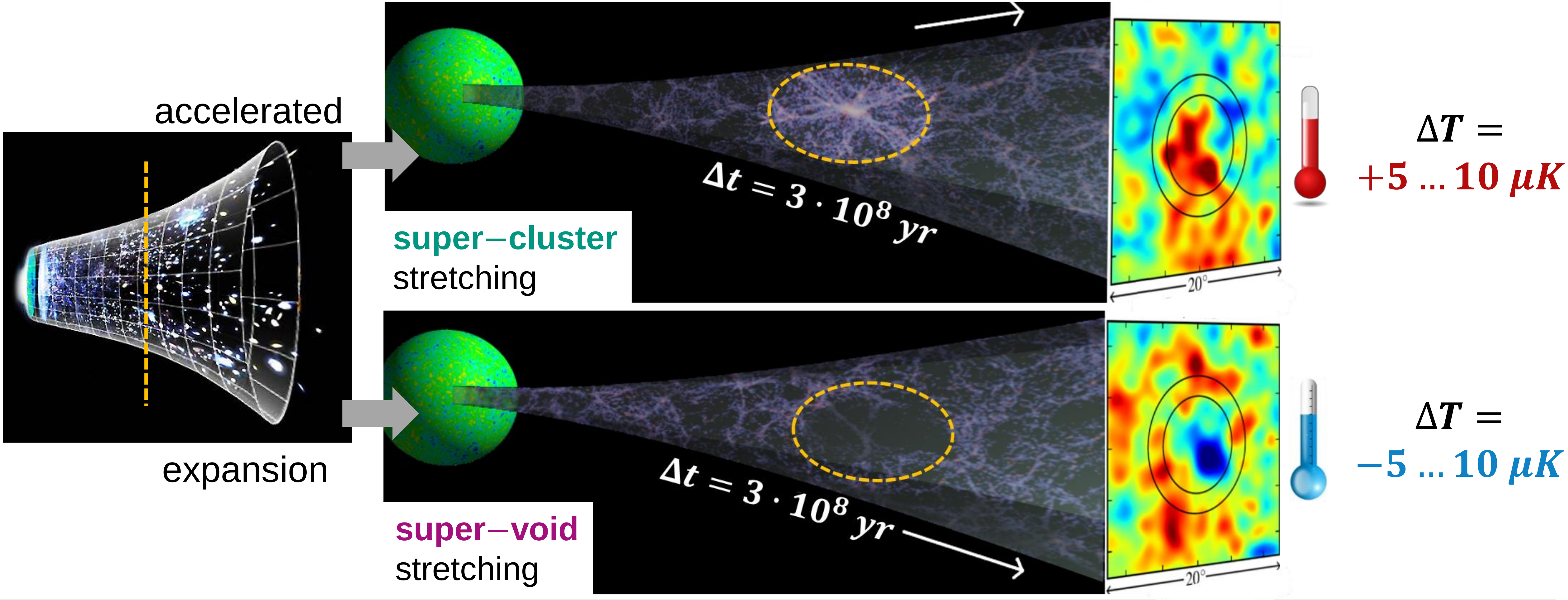


ISW in large void

ISW effect: scale of the photon energy gain / loss

Karlsruhe Institute of Technology

- non−adiabatic photon propagation: only in a vacuum−dominated universe

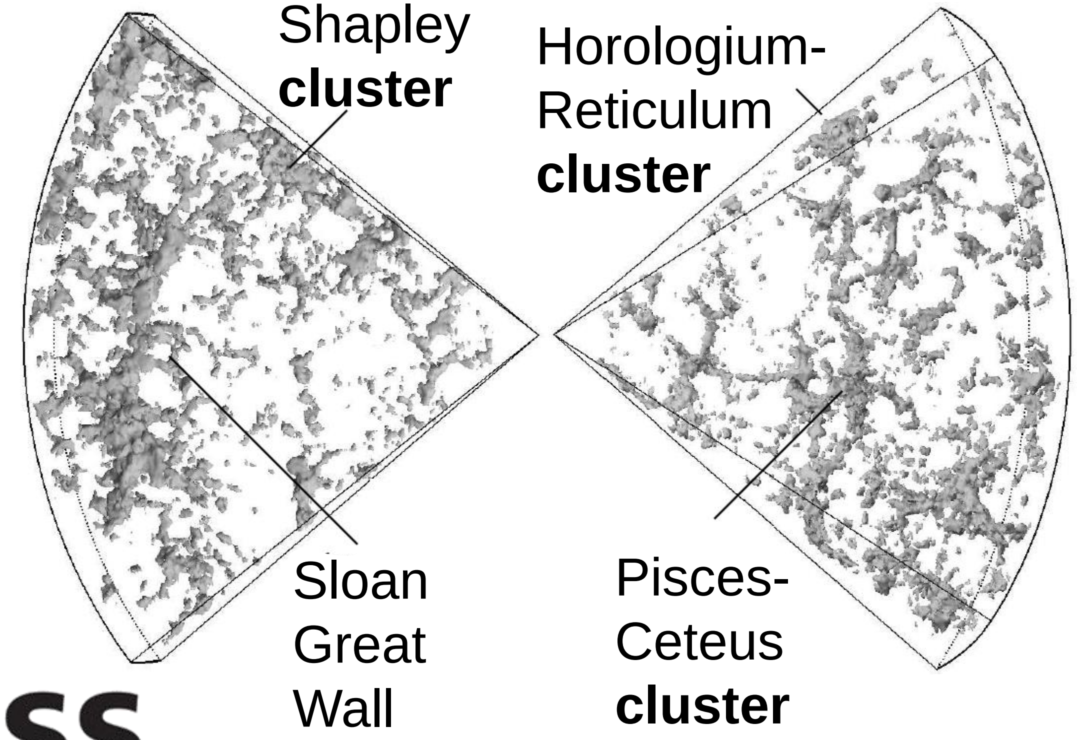


ISW effect: we now correlate ΔT with LSS data sets

- ***L*arge *S*cale *S*tructure (LSS) data show distribution of super–clusters & voids**

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

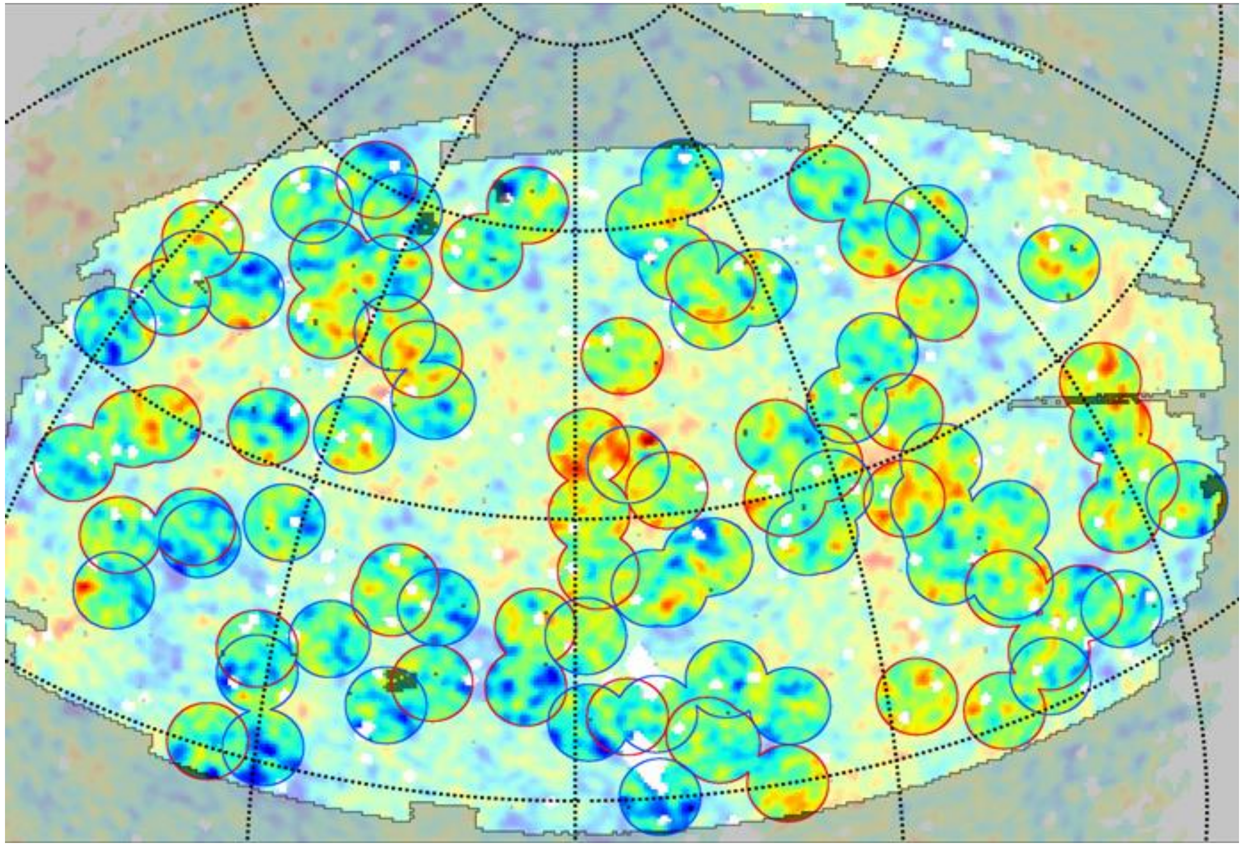
SDSS

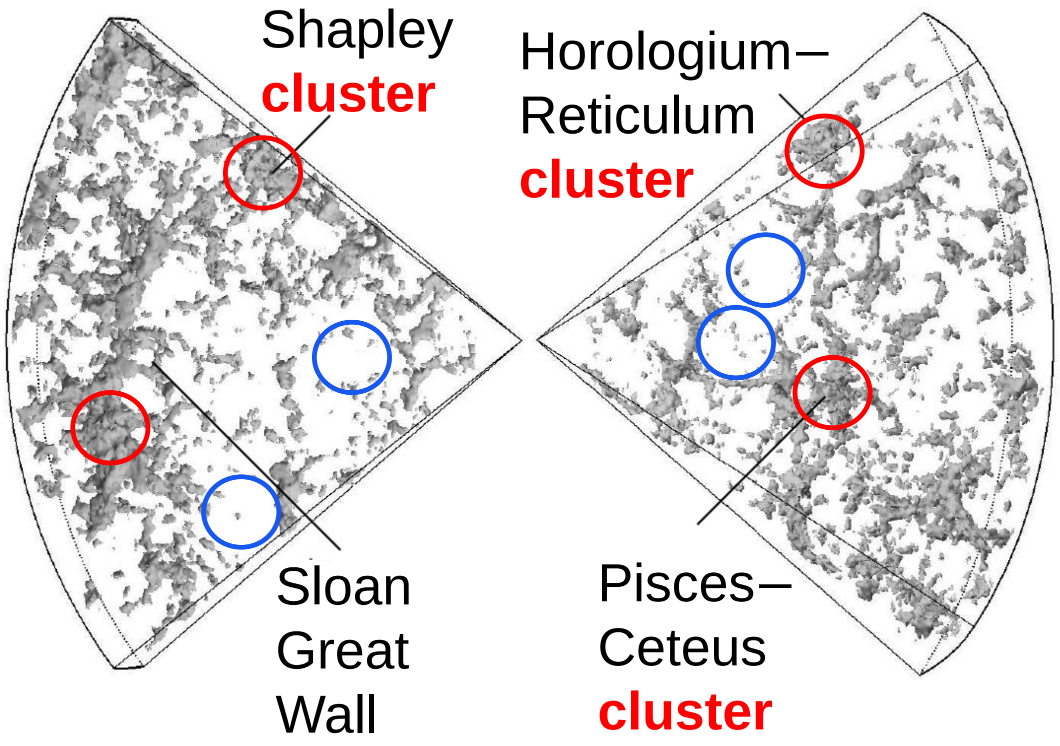


ISW effect: we perform a correlation analysis

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

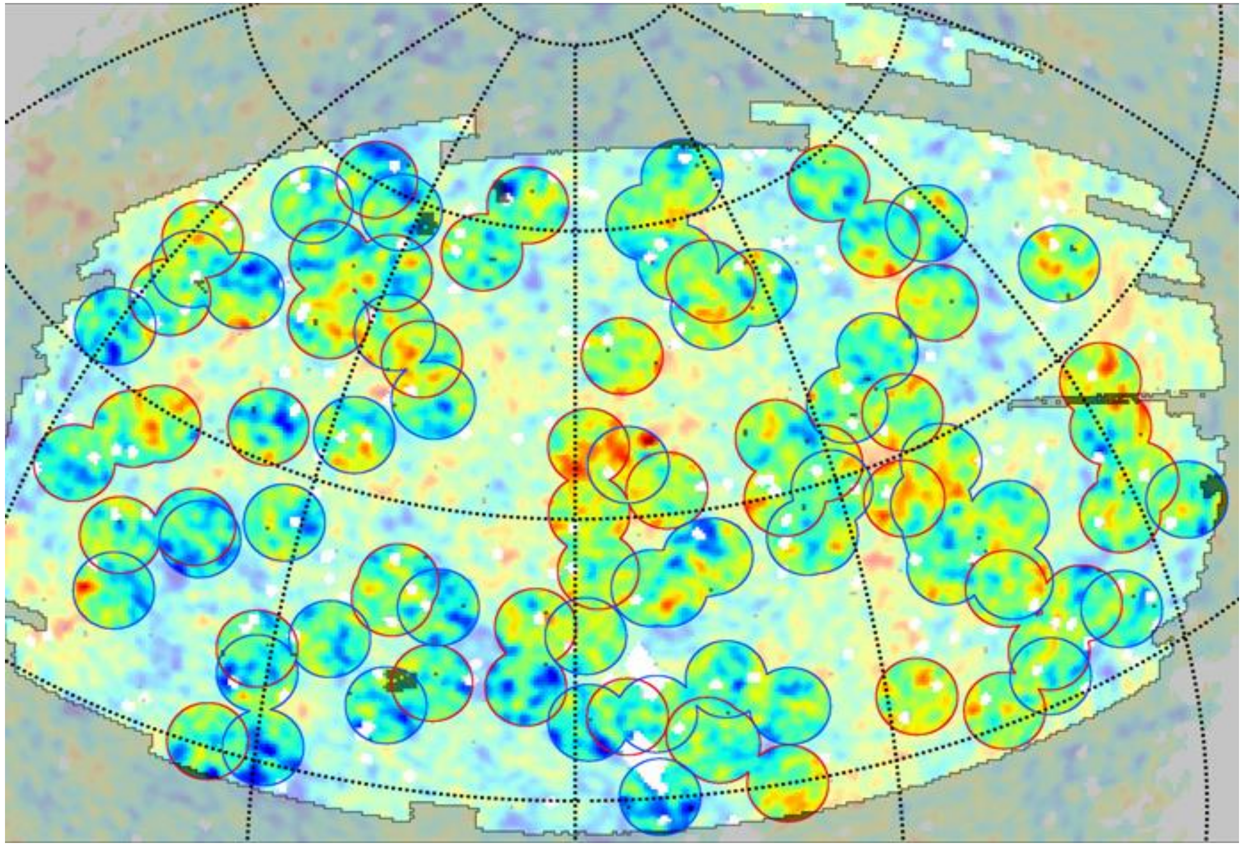
  - can we confirm the expectation of the ISW – effect via a **correlation analysis**?

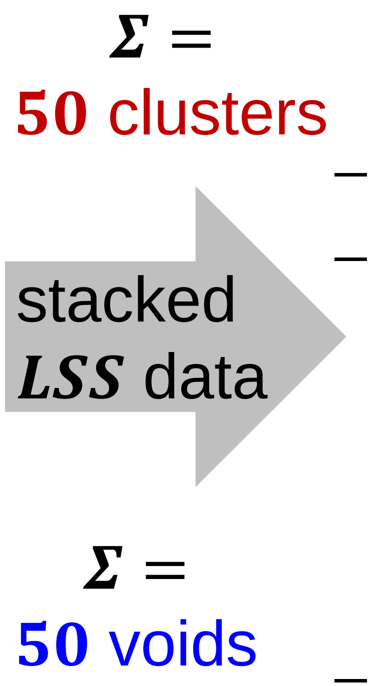


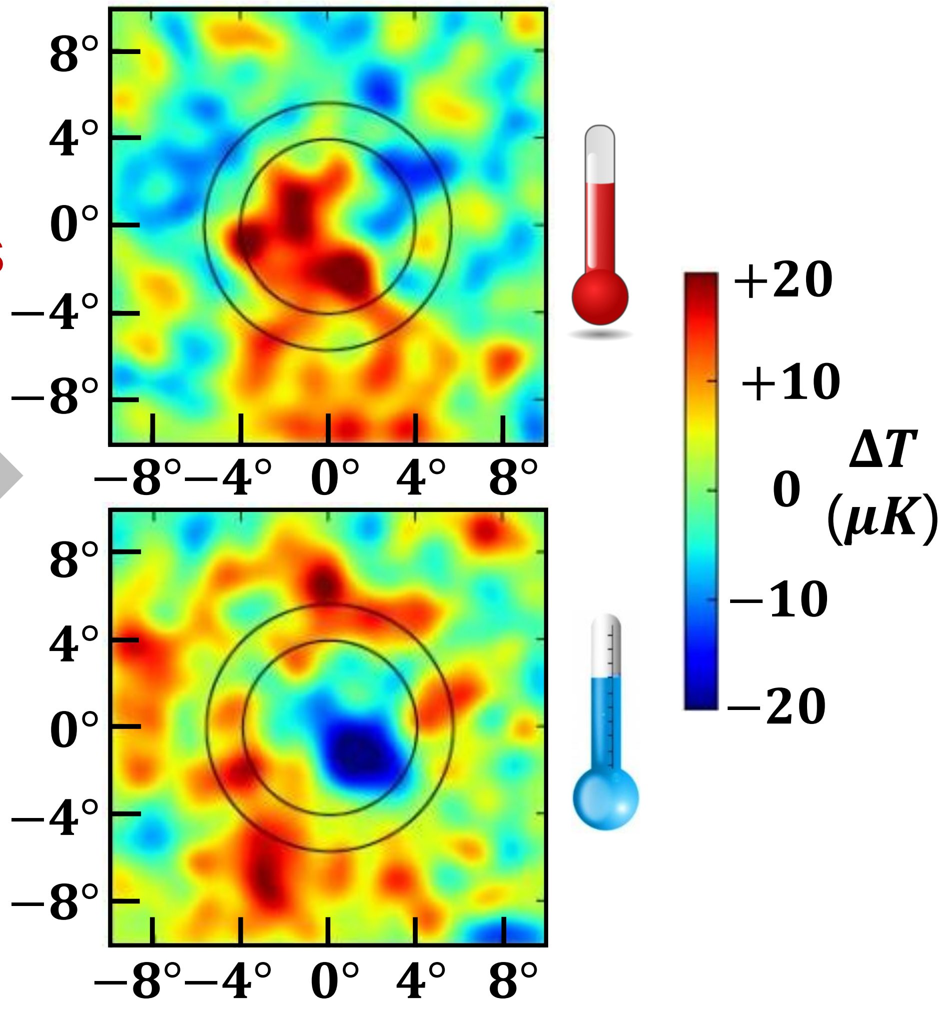


ISW effect: we see a strong correlation signal!

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







ISW effect: further evidence for dark energy !

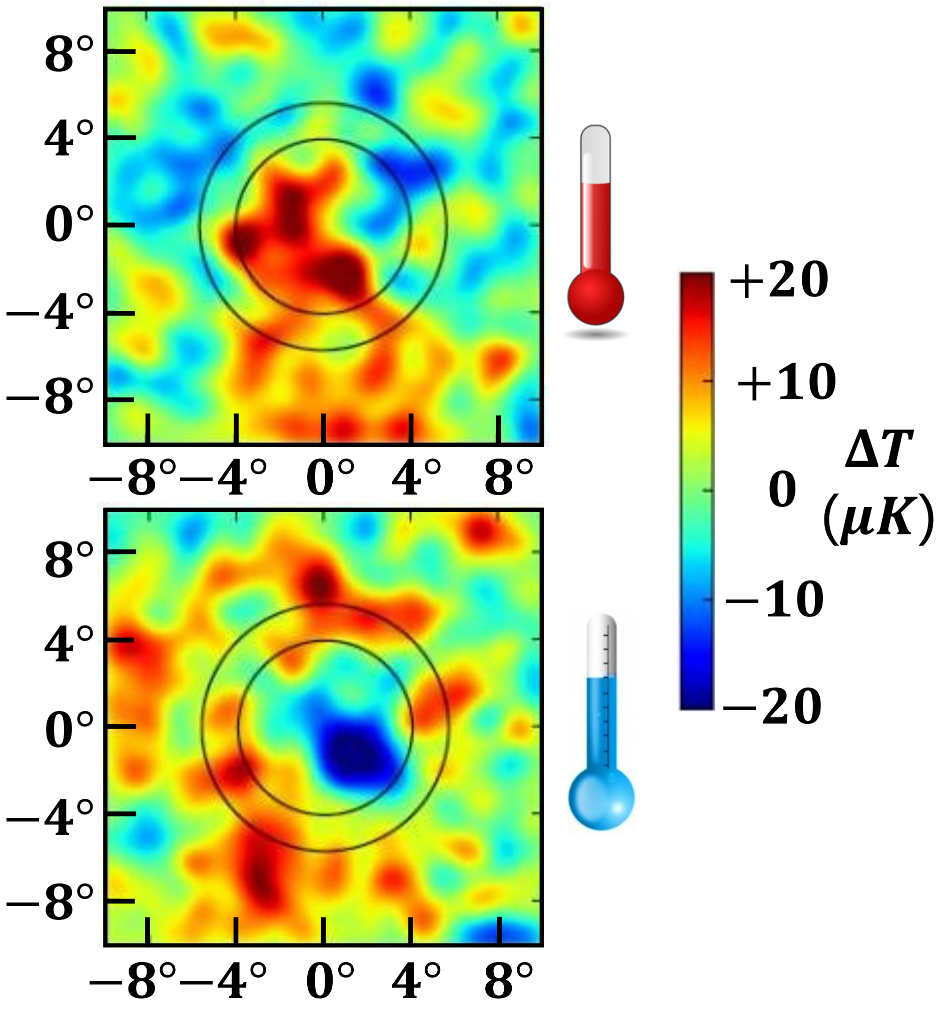
Karlsruhe Institute of Technology

- **Confirmation: 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 LSS: $\delta\theta = 4°/100\ h^{-1}\ Mpc$

↳ $|\Delta T| = (9.6 \pm 2.2)\ \mu K$ due to the ISW effect (~$4\ \sigma$ evidence)

↳ **accelerated** cosmic stretching of super–clusters & voids



ISW: independent $evidence$ for Dark Energy

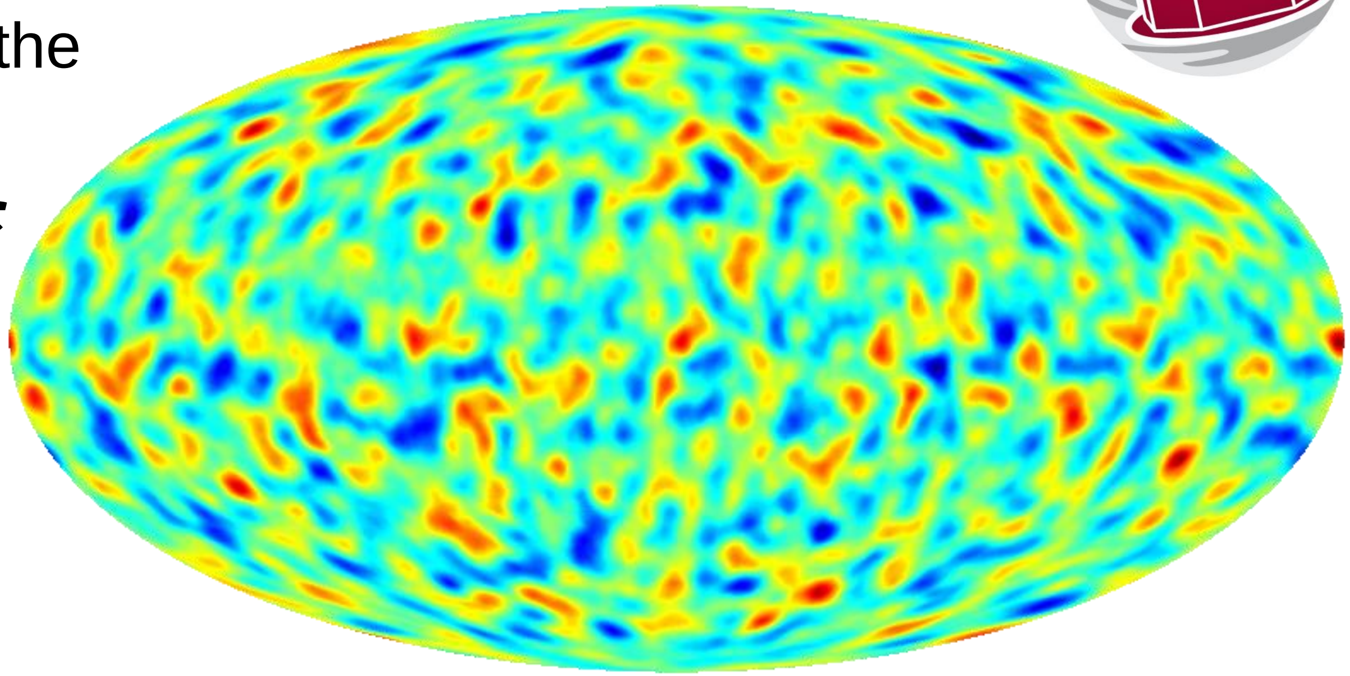
ISW effect: further evidence for dark energy!

- **Confirmation: 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 LSS: $\delta\theta = 4°/100\ h^{-1}\ Mpc$

↳ $|\Delta T| = (9.6 \pm 2.2)\ \mu K$ due to the ISW effect (~$4\ \sigma$ evidence)

↳ **accelerated** cosmic stretching of super–clusters & voids



$Planck$: global ISW map

ISW: independent *evidence* for Dark Energy

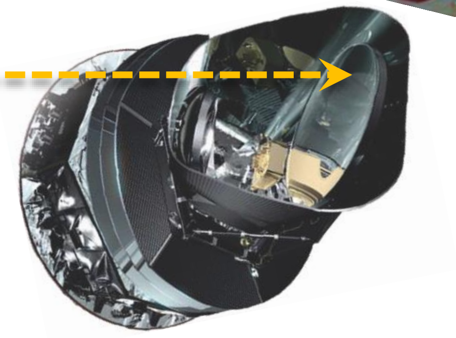
Sunyaev – Zel´dovich effect: CMB effect in clusters

- **further effect of 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 also is a **secondary anisotropy**, which has to be accounted for as a **noise effect** in CMB analyses

SZ = Sunyaev-
Zel´dovich*

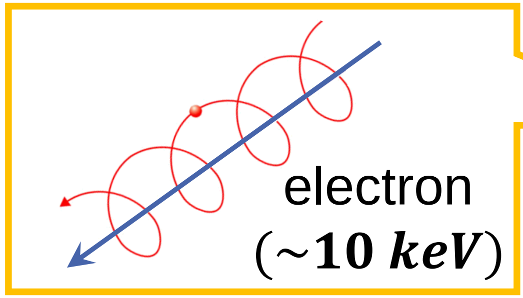


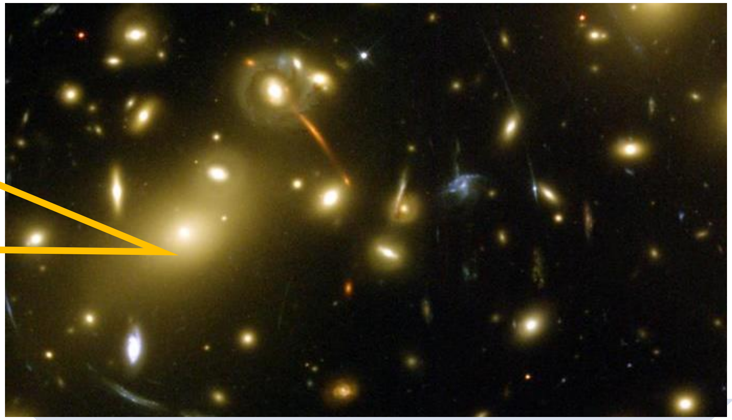
 *remember *me* from last lecture? This flat CMB part…

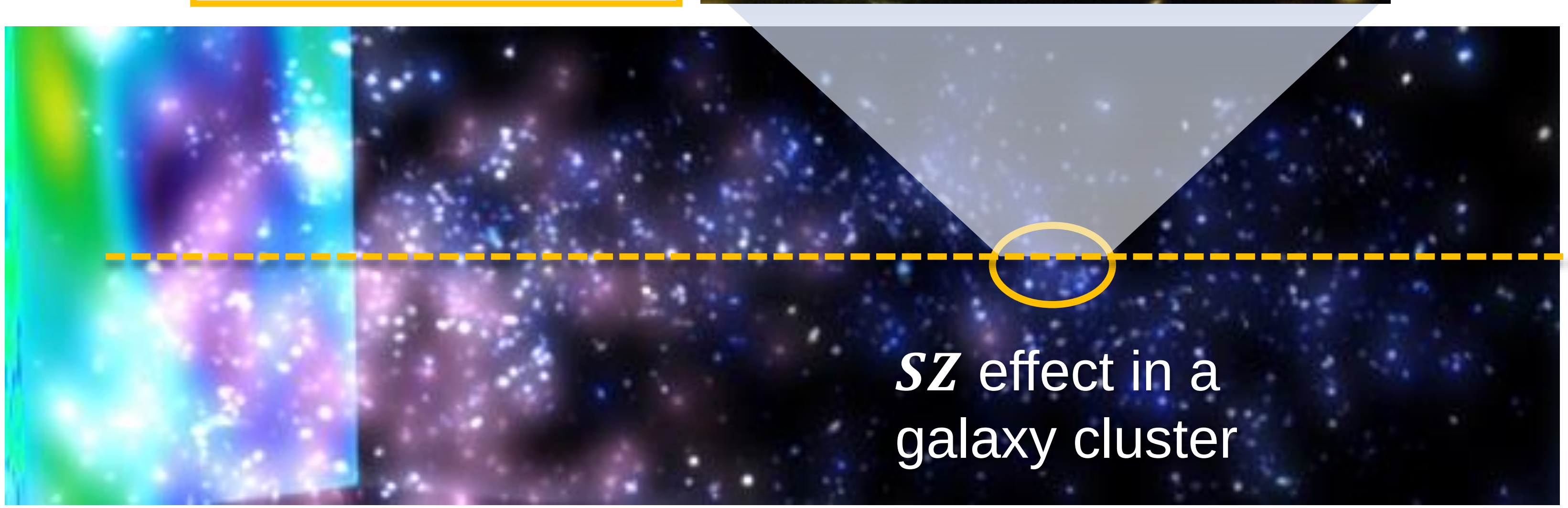
Sunyaev – Zel´dovich effect: CMB scattering off e^-

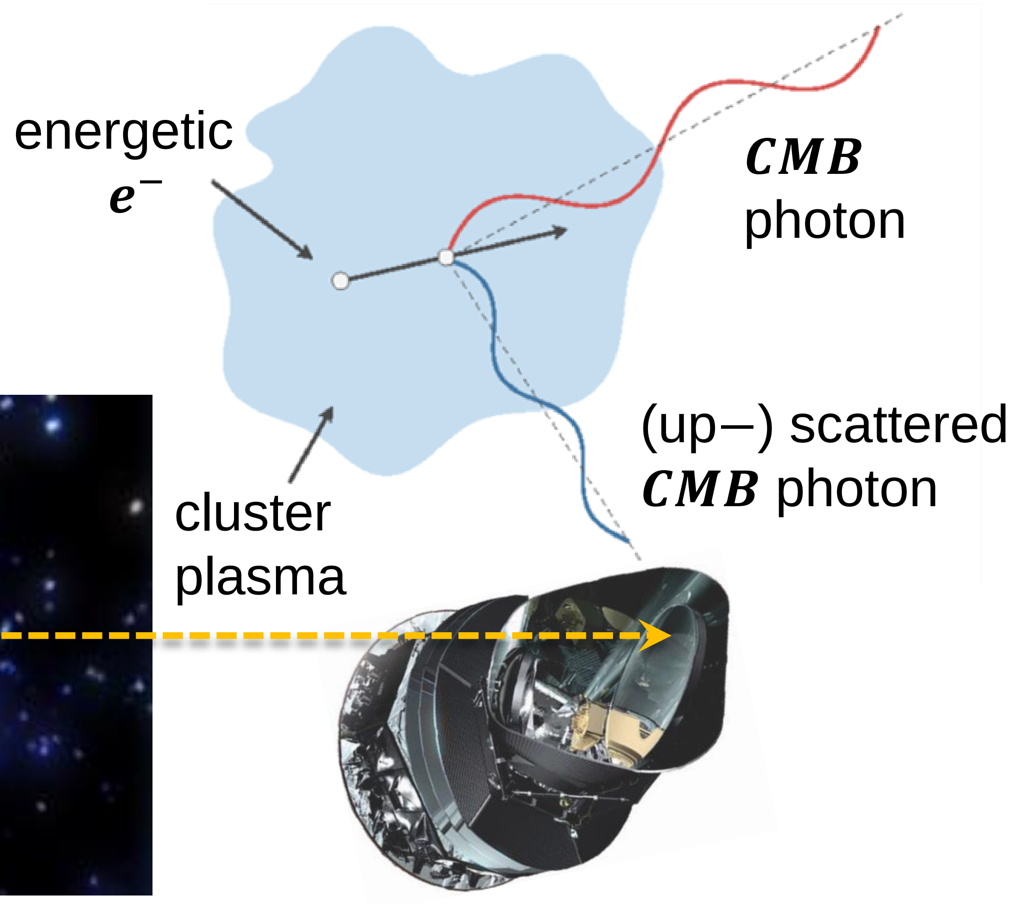
- **secondary anisotropies: CMB undergoes** inverse Compton* scattering

- hot ionized **cluster gas**









*see also lectures on astroparticle physics I

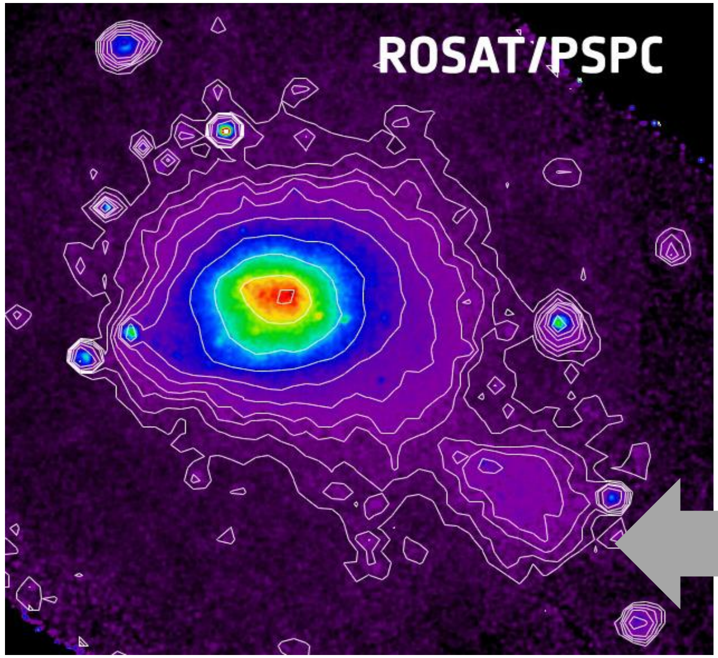
$SZ-$ effect: scaatered CMB photons are hotter

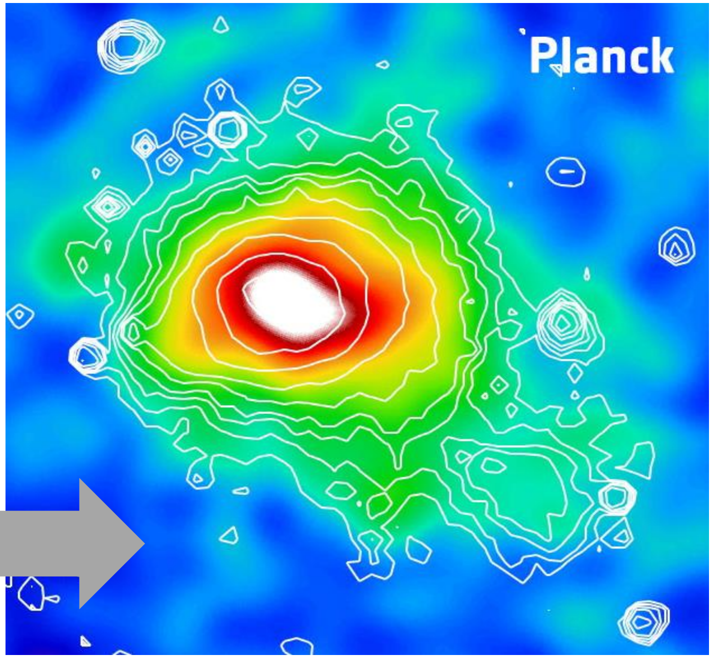
Karlsruhe Institute of Technology

- **Next correlation analysis: CMB photons that are crossing galaxy clusters**

- $\boldsymbol{SZ}-$ example: **Coma galaxy cluster** (**Abell 1656**) at $\boldsymbol{d} \sim \mathbf{100}\ \boldsymbol{Mpc}$ ($\emptyset = 2°$)

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





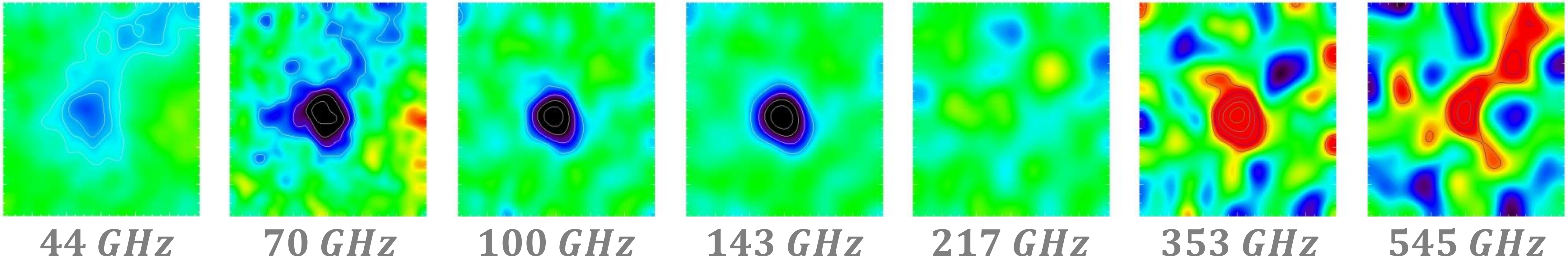
SZ – signature: specific frequency dependence

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

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

  - $\sim 1\%$ of all CMB photons passing this cluster interact via the SZ – **effect** with the hot cluster gas (inverse Compton scattering)

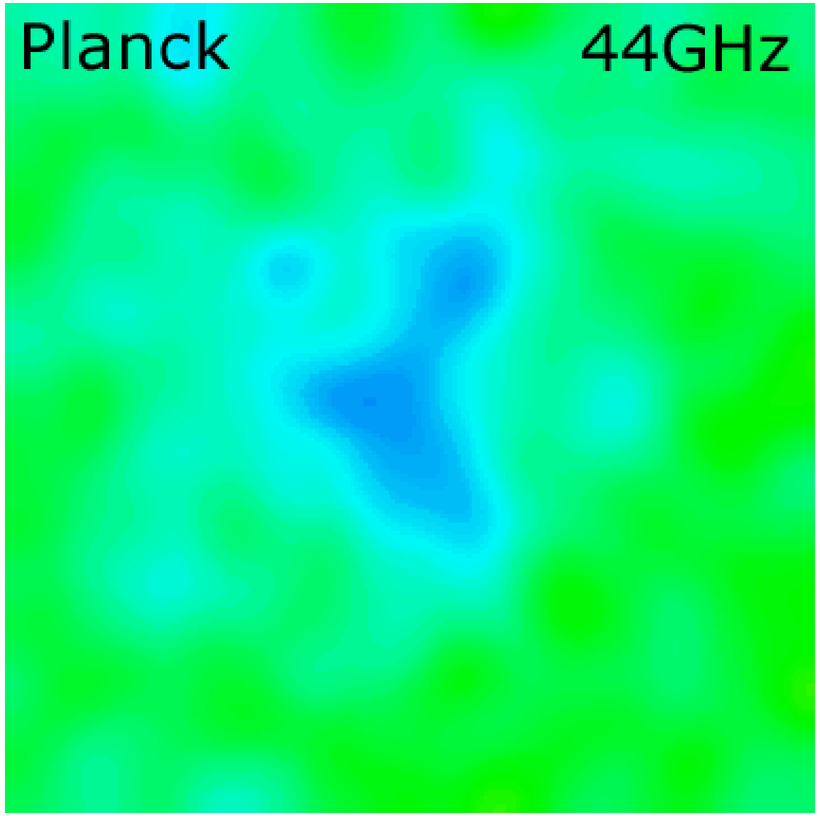
  - $Planck$ data show **characteristic** SZ – **dependence** on **photon frequency** f ⇨ photons **gain energy** via inverse Compton effect (´**up–scattering**´)

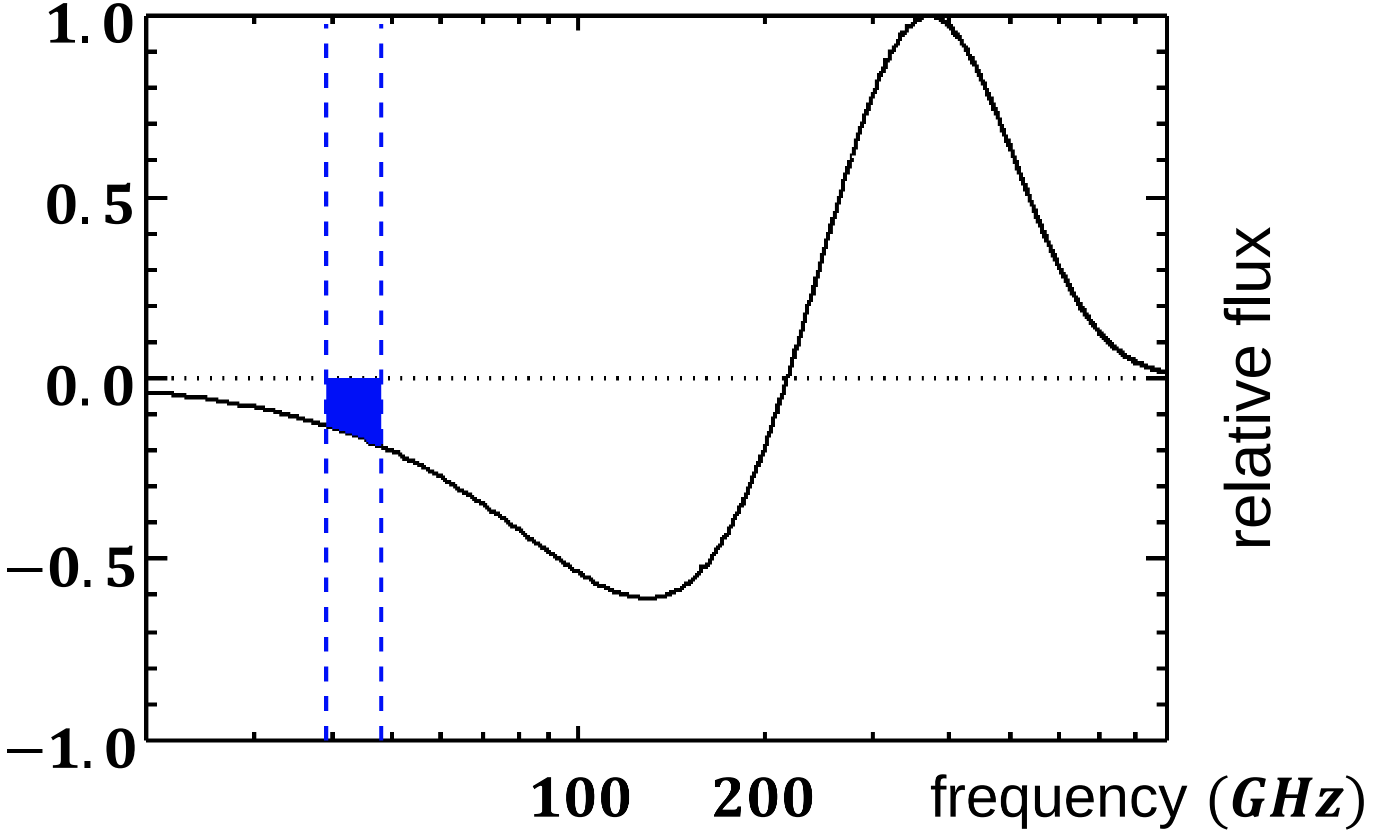


SZ – signature: specific frequency dependence

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

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

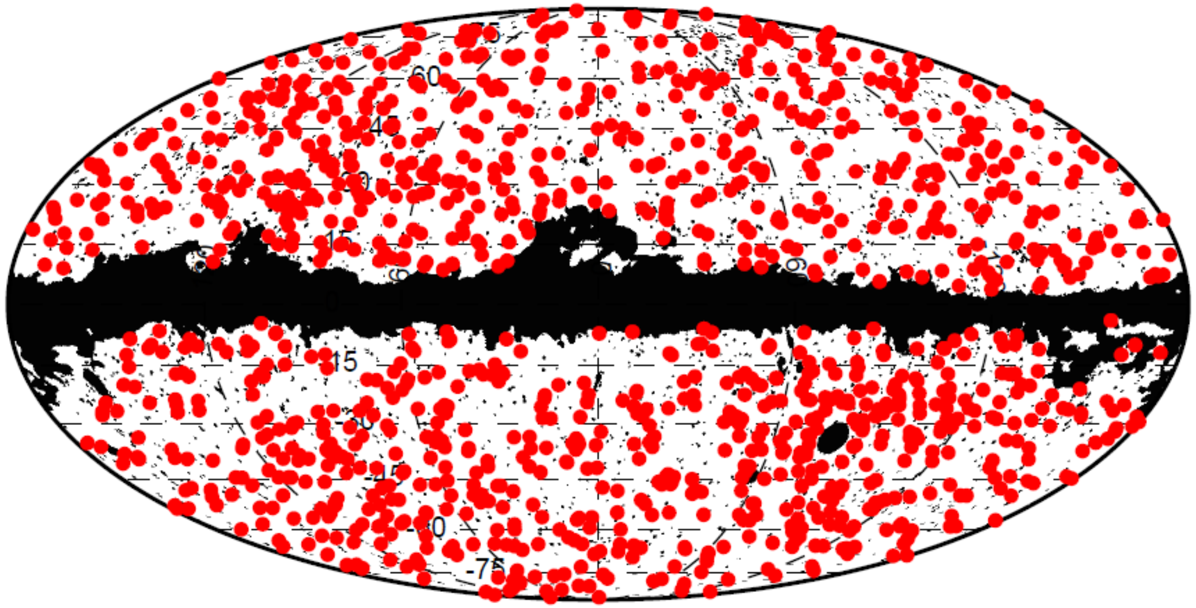


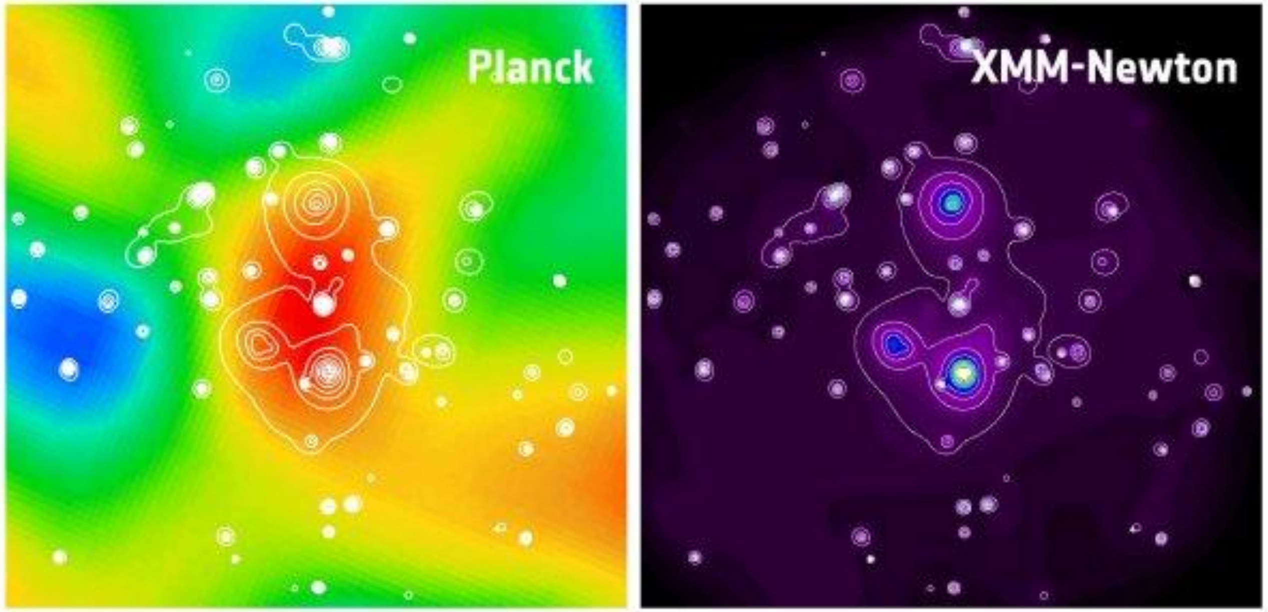


SZ – effect as noise signal: eliminate clusters

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

- identified dense clusters (LSS) & analyses by $Planck$: new clusters seen via CMB





> 1000 SZ sources (galaxy clusters) are known at present & excluded from analysis

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

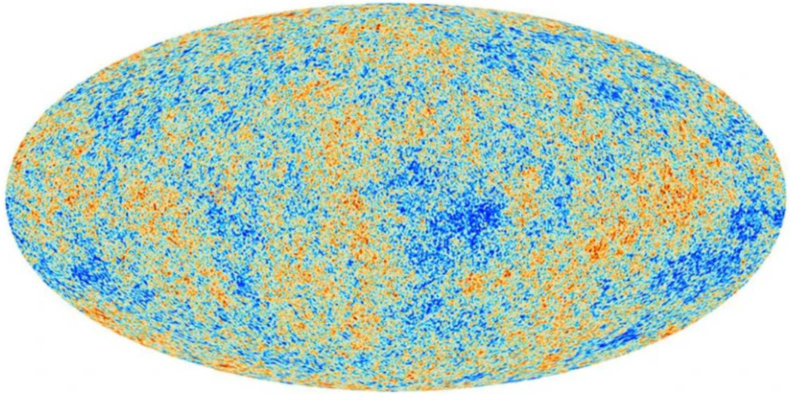
Beyond $Planck$ – future CMB challenges

Karlsruhe Institute of Technology

- **$CMB - S4$: next–generation CMB experiment at South Pole & Chilean Andes**

  - plans to deploy **21 telescopes** with ~ **550 000 cryo–cooled bolometers**

Nature explores the P5 report's five leading proposals, ranked in order of importance, as well the panel's discussion of future accelerators.



Studying the cosmic microwave background (CMB) is the lead priority of the US particle-physics community. Credit: ESA and the Planck Collaboration

Ripples from the Big Bang

The goal of CMB-S4 is to study radiation that was created around 380,000 years after the Big Bang, when the nearly uniform broth of particles in the Universe transitioned from plasma to gas. Microwave antennas will

NEWS | 07 December 2023

Big Bang observatory tops wish list for big US physics projects

Report also supports projects of unprecedented scale to study dark matter, neutrinos and the Higgs boson.

By Davide Castelvecchi

nature

Beyond $Planck$ – future CMB challenges

- $\boldsymbol{CMB-S4}$: **next−generation $\boldsymbol{CMB}$ experiment at South Pole** & **Chilean Andes**
  - plans to deploy **21 telescopes** with ~ **550 000 cryo−cooled bolometers**

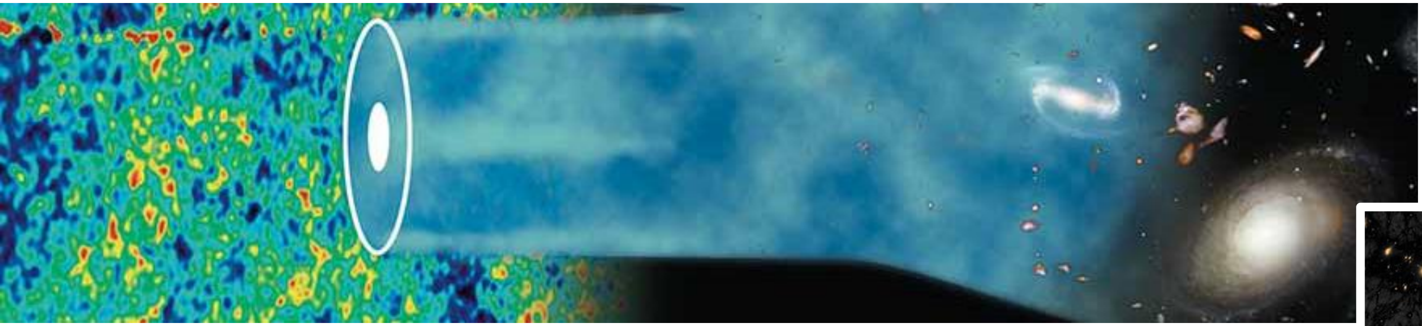
South Pole

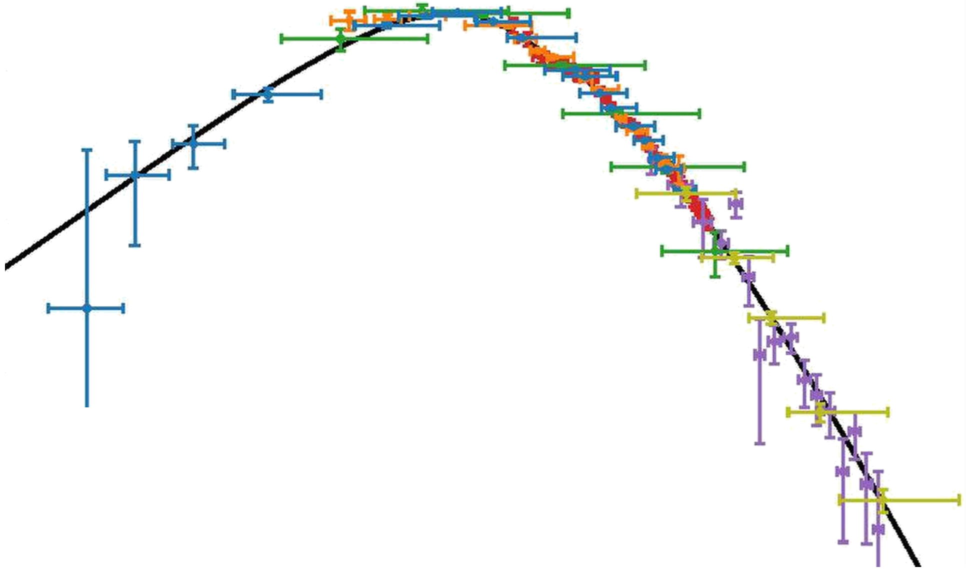
Atacama desert

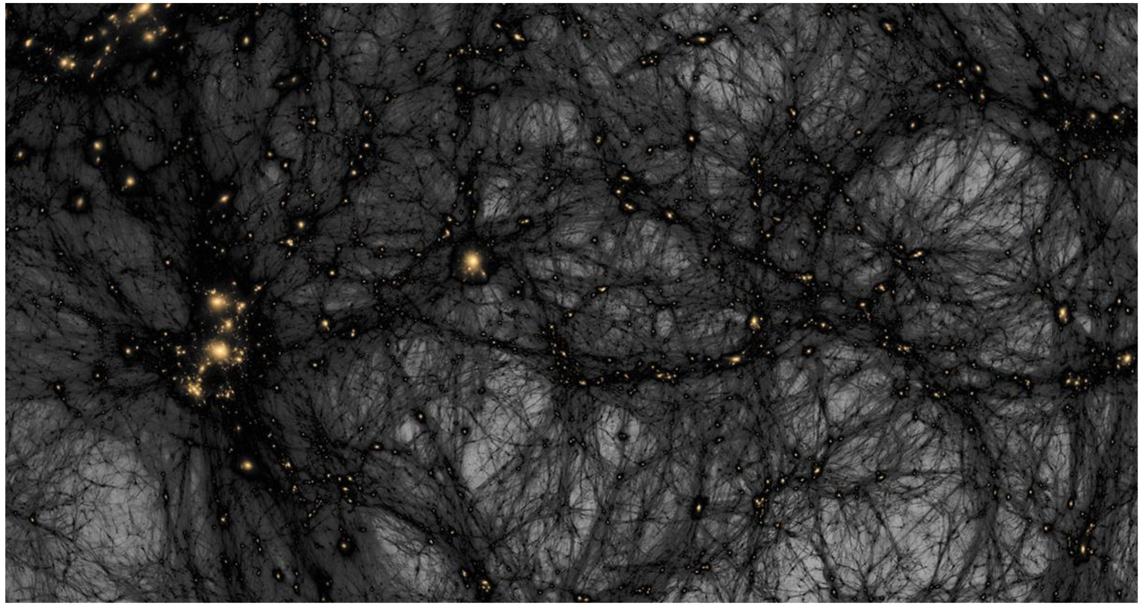
- probe the nature of **Dark Matter** & **Dark Energy** ...
- capture **transient** phenomena ...
- signatures of **primordial gravitational waves** from inflationary phase ...
- map the **matter** through−out the sky...

Beyond $Planck$ – future CMB challenges

- $CMB - S4$: next−generation CMB experiment at South Pole & Chilean Andes







CHAPTER 4 – STRUCTURE FORMATION IN THE UNIVERSE

4. 1 Inflation & Early Universe

- **RECAP: inflationary phase of early universe would – if confirmed – cause a rapid, huge increase of the scale factor $a(t)$**

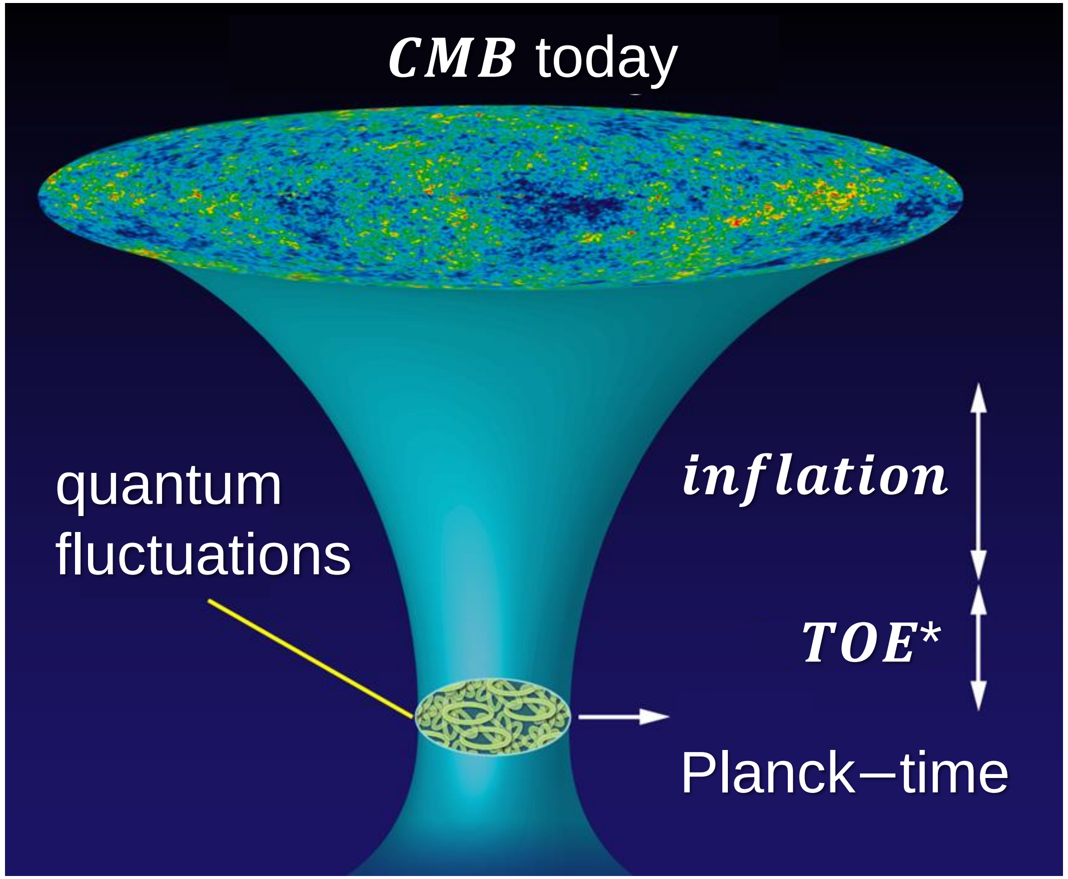
- **short** time period $t = 10^{-36} \ldots 10^{-32}\ s$

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

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

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

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

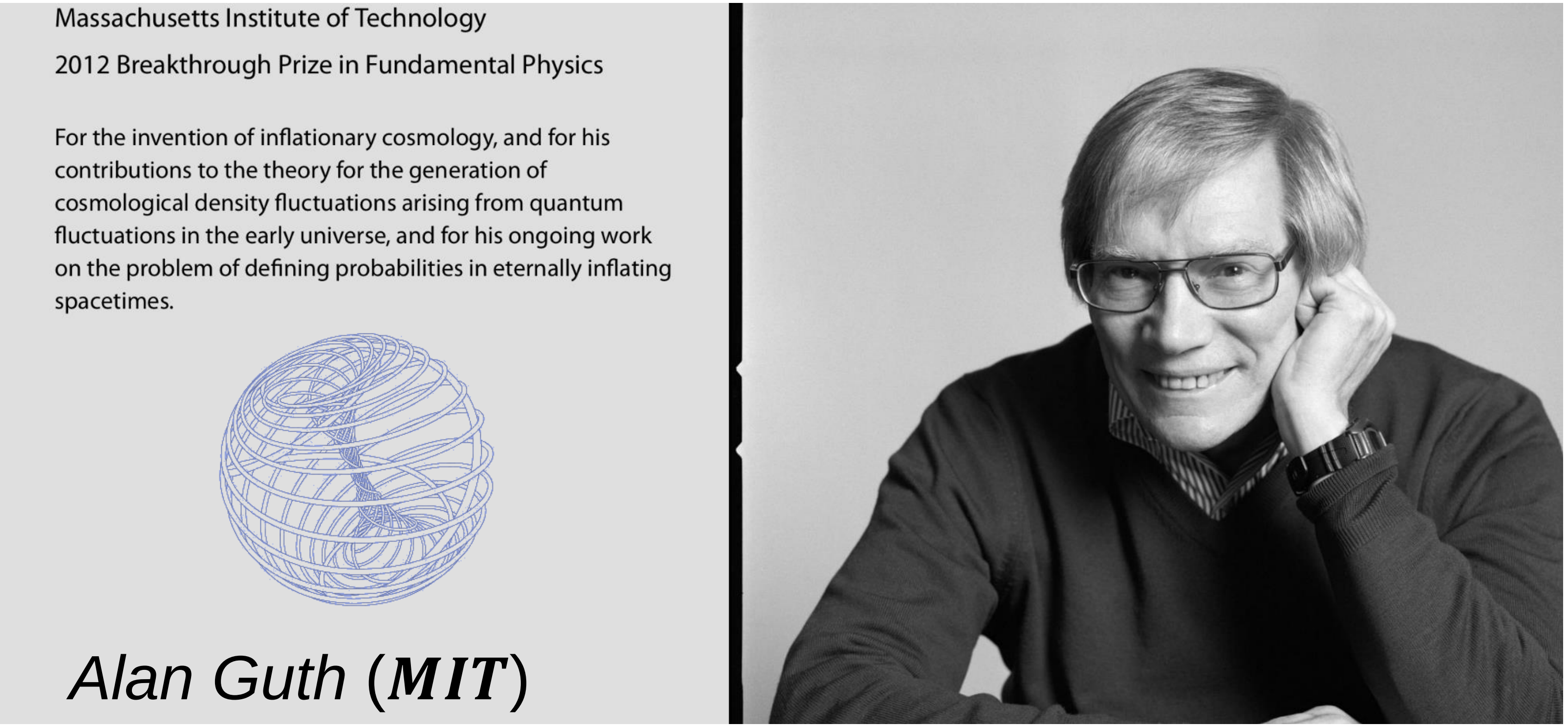


*Theory-Of-Everything

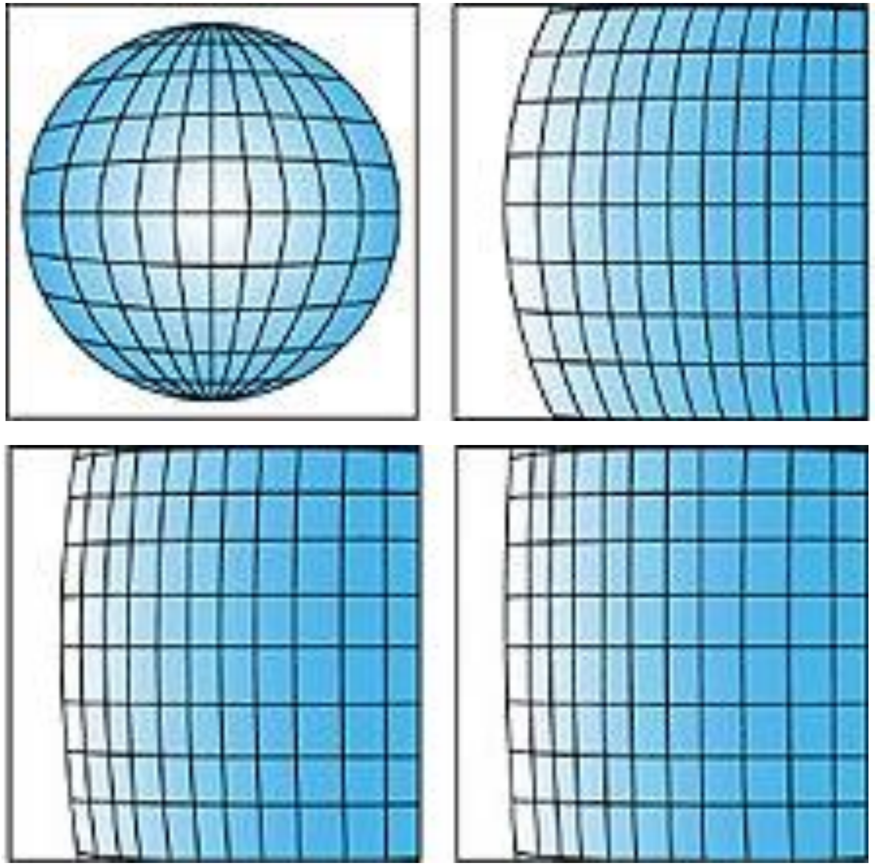
Inflation – Breakthrough Prize 2012 …

- **A. Guth: inflationary phase of early universe with rapid increase of the scale factor $a(t)$**

- solves the horizon problem, HZ – spectrum of CMB



Alan Guth (MIT)

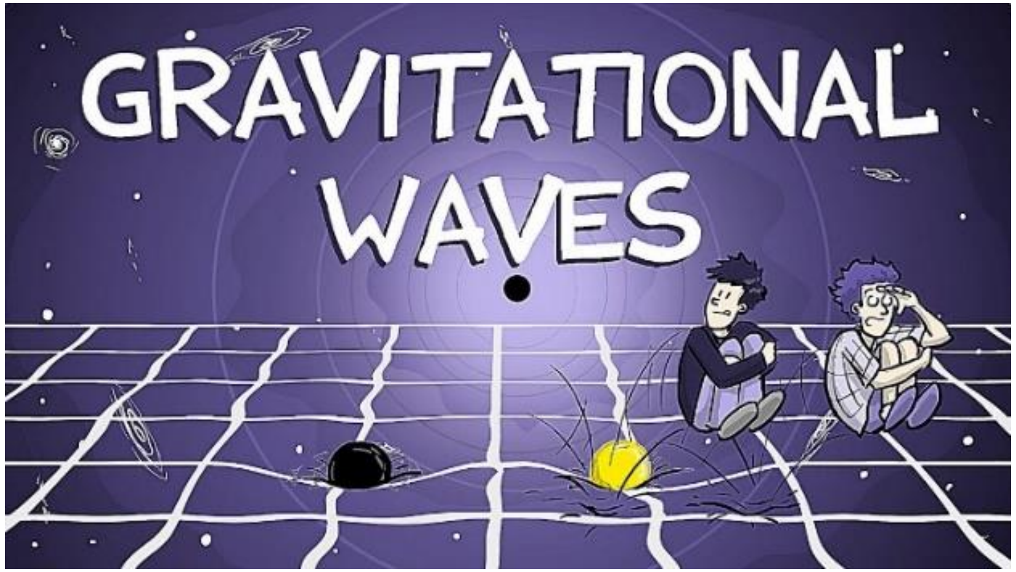


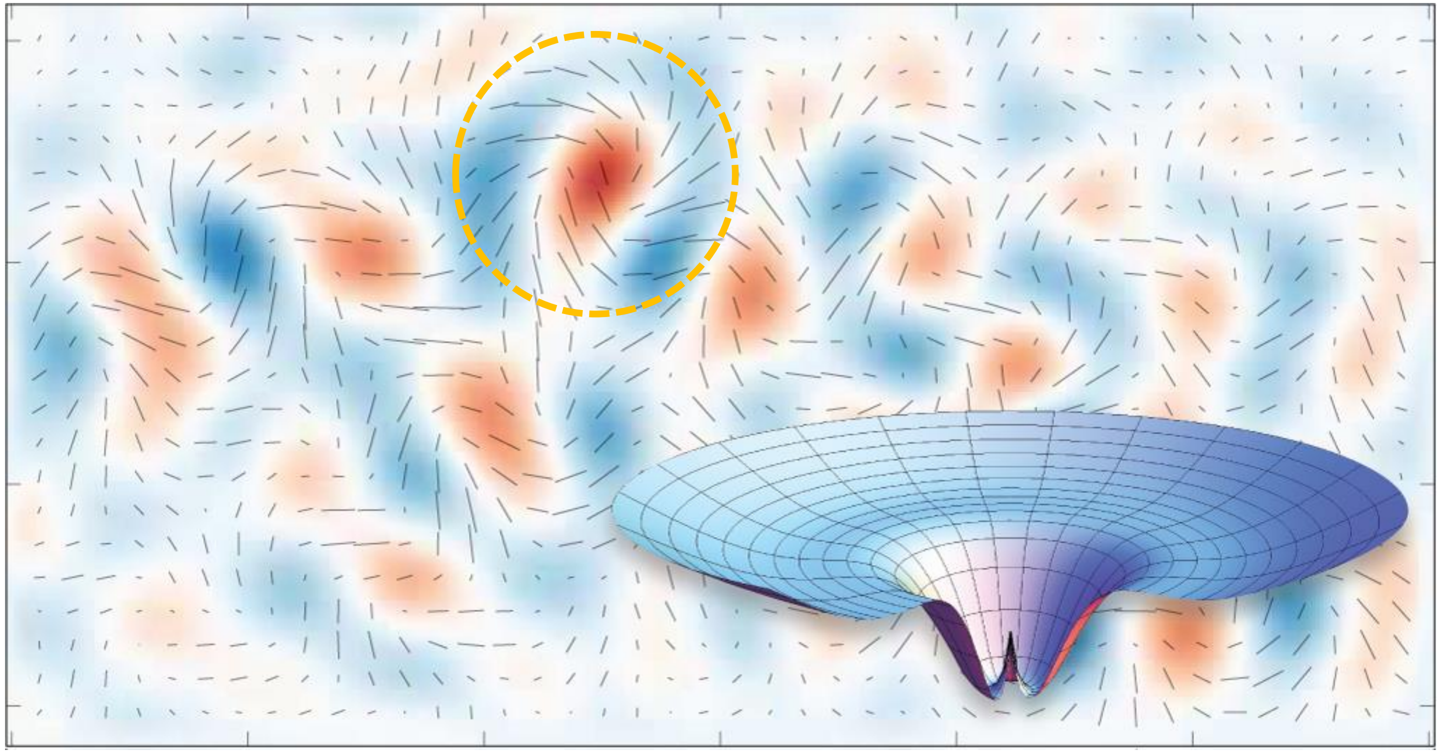
Inflation – can we verify it experimentally?

- 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)





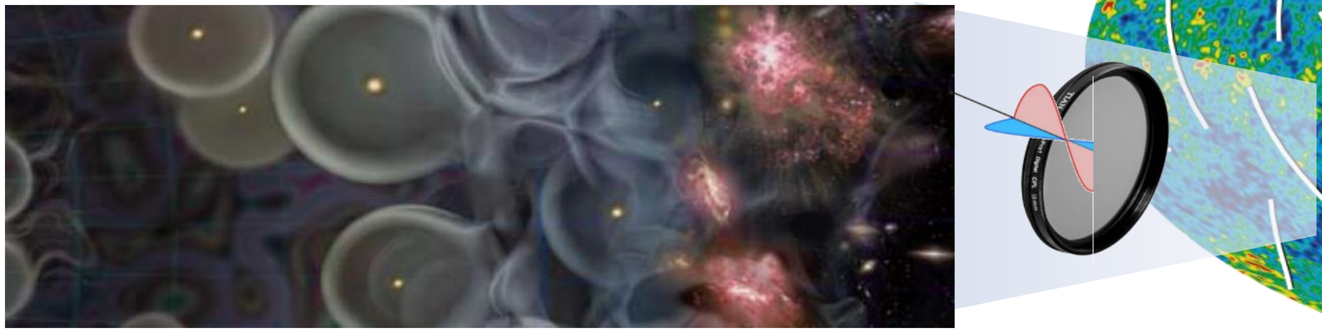
Inflation – not so easily verified experimentally

Karlsruhe Institute of Technology

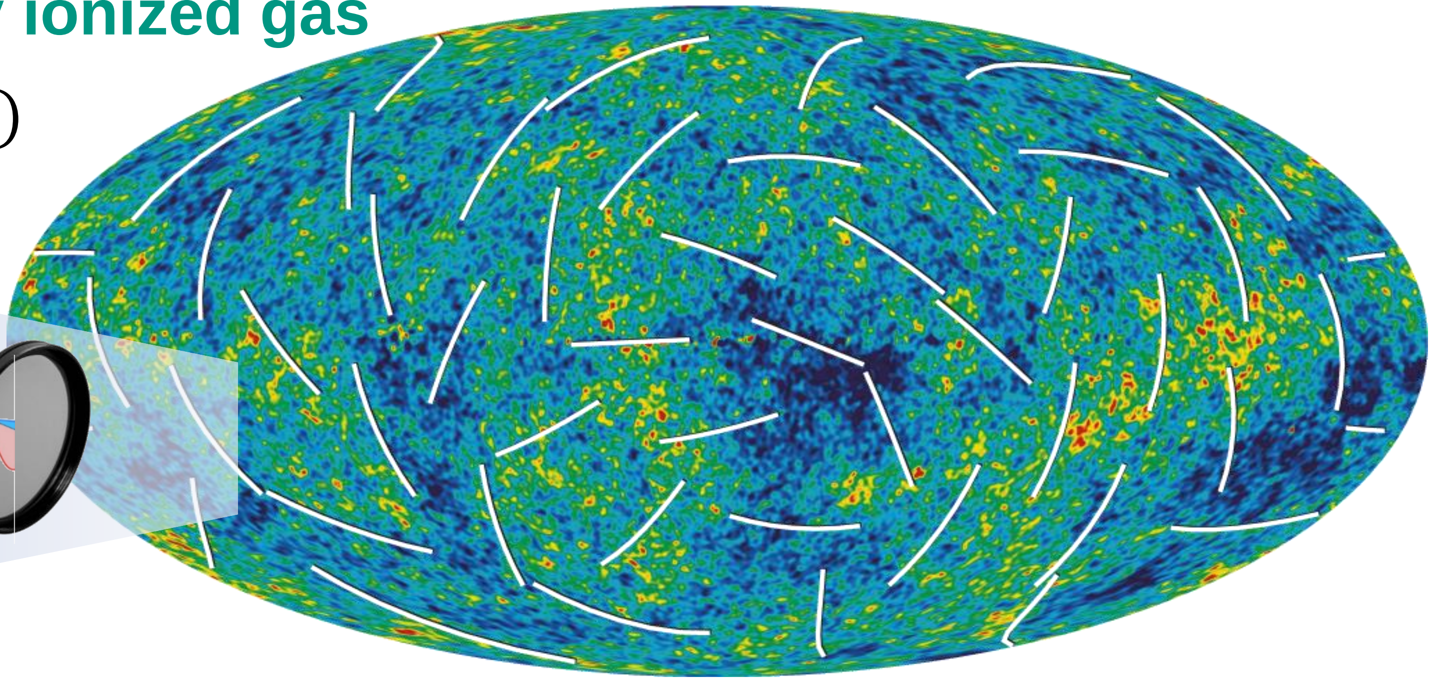
- **Polarization pattern of the $\boldsymbol{CMB}$ due to classical Thomson scattering off $\boldsymbol{e^-}$**

- **no signal without noise**, here: we expect a **polarization** of the $\boldsymbol{CMB}$ due to **scattering processes** off **nearby ionized gas**

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



$\boldsymbol{CMB}$ scatters off re−ionised regions
⇨ large−scale **linear** polarization pattern



first sky map of $\boldsymbol{CMB}$ polarization from $\boldsymbol{WMAP}$:
nearby ionised gas (**non−primordial origin**!)

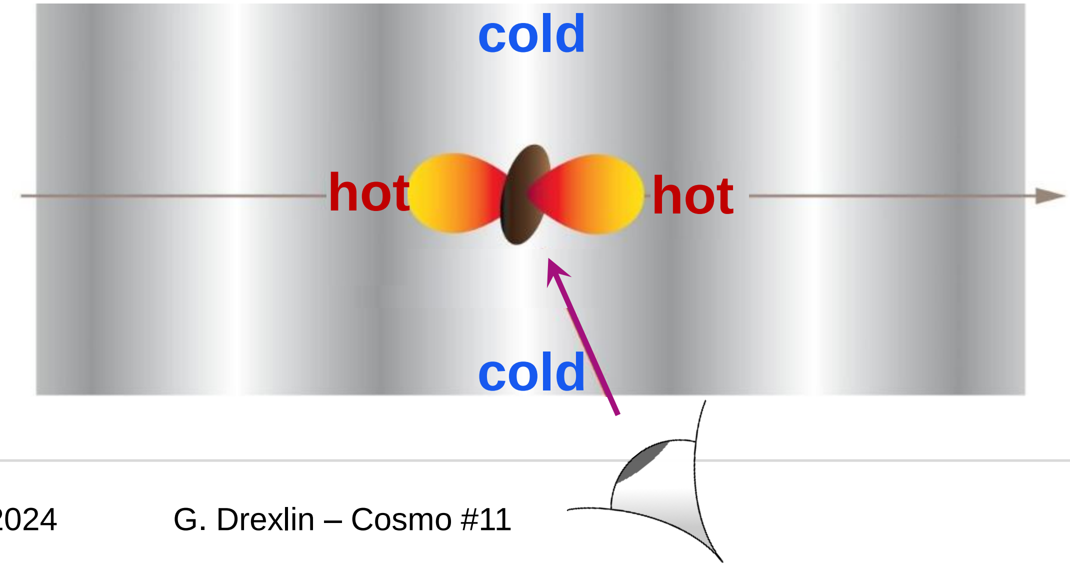
Classical Thomson scattering: primordial plasma

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

  - more interesting for cosmology: $\boldsymbol{CMB}$ **scattering off primordial plasma**

  - expected primordial **polarization level $\sim 1\ \%$** due to Thomson scattering at last surface, before decoupling **(´last surface of scattering´)**

  - from **density fluctuations** $\Delta\rho/\rho$ we expect a **linear $\boldsymbol{CMB}$ polarization**



local $\boldsymbol{quadrupole}$ moment

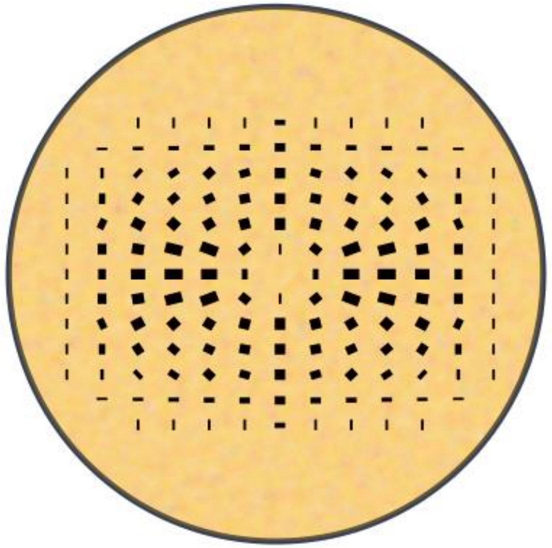
standing acoustic density wave

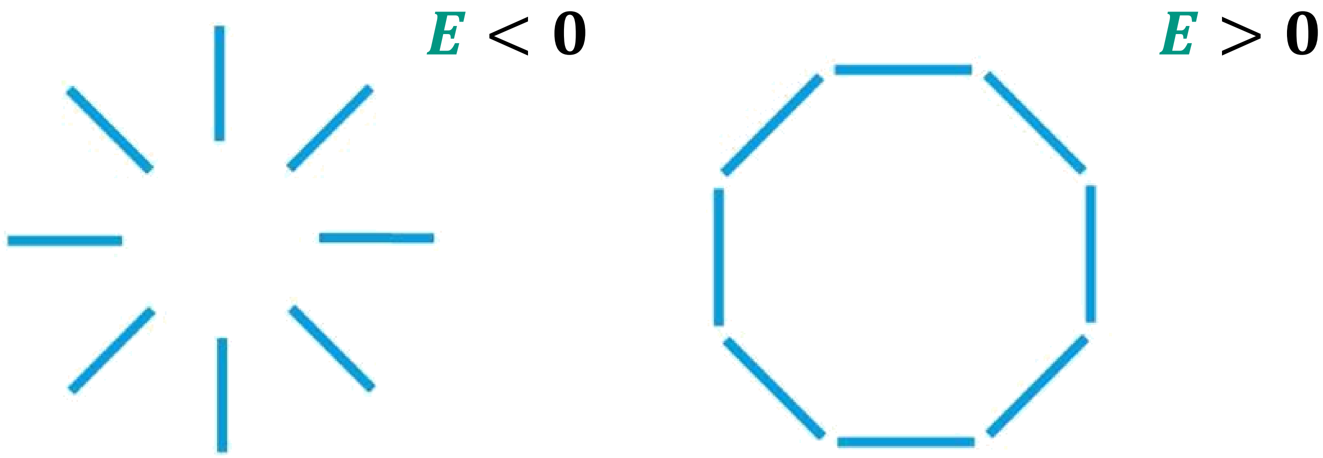
Classical Thomson scattering: primordial plasma

- **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**)

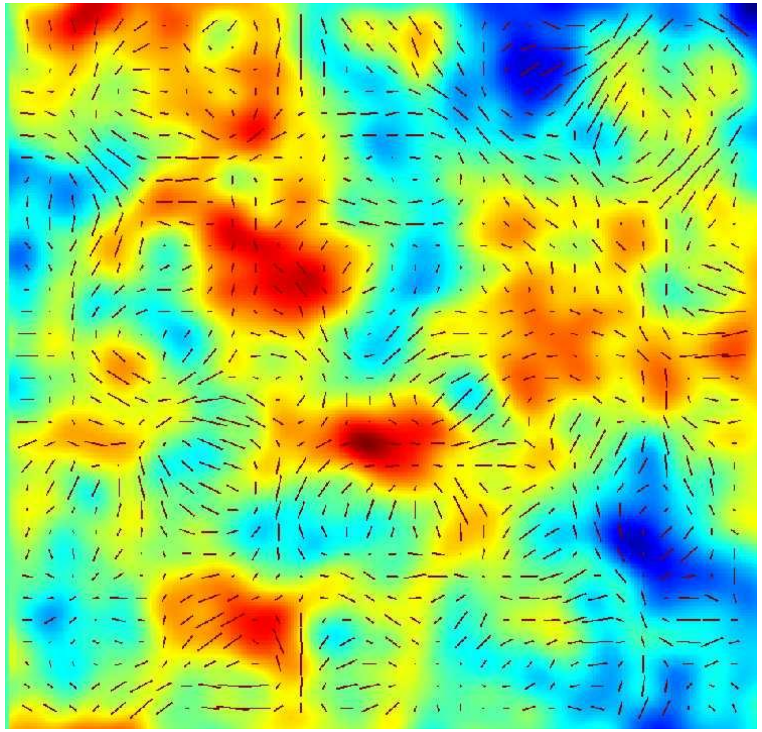




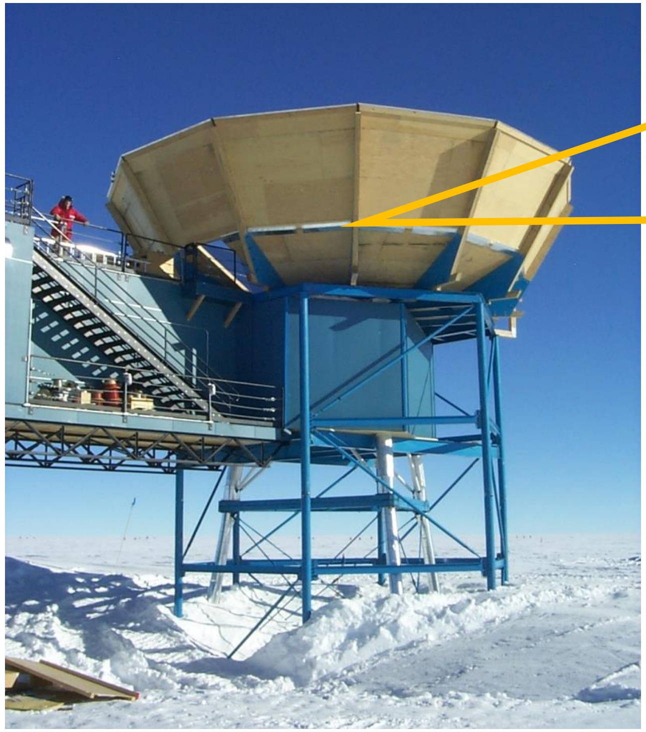
⇨ **linear CMB polarization** analogy to E – field: vanishing rotation

Classical Thomson scattering: primordial plasma

- **First experimental verification of CMB polarization by $DASI$* at South Pole**



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



$\mathbf{12/2002}$: $\boldsymbol{DASI}$ reports $\boldsymbol{E}$ – modes in $\boldsymbol{CMB}$ – polarization

$\mathbf{11}\ \boldsymbol{m}$ tower with bottom dome to prevent interference from ground heat

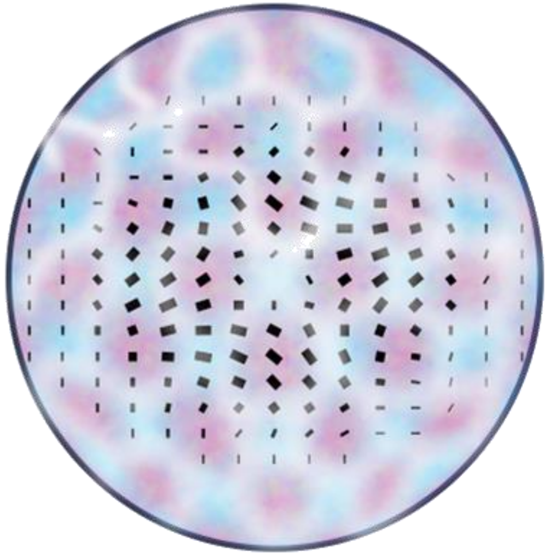
*$DASI$ – Degree Angular Scale Interferometer

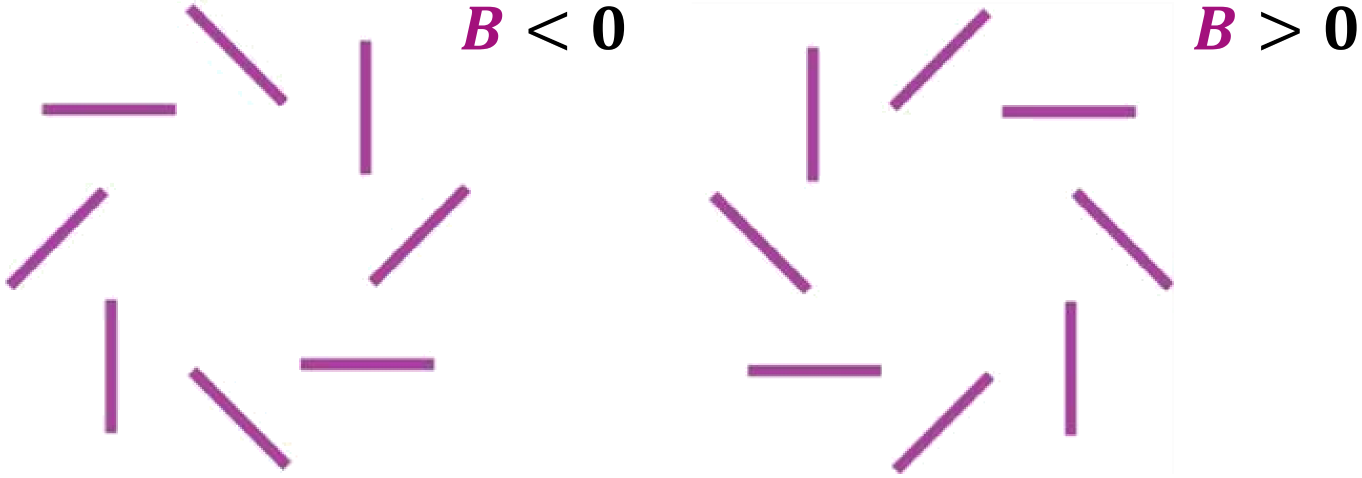
Holy Grail: curl–like CMB polarization (inflation)

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

  - CMB waves are **streched / squeezed** by **primordial gravitational waves**

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





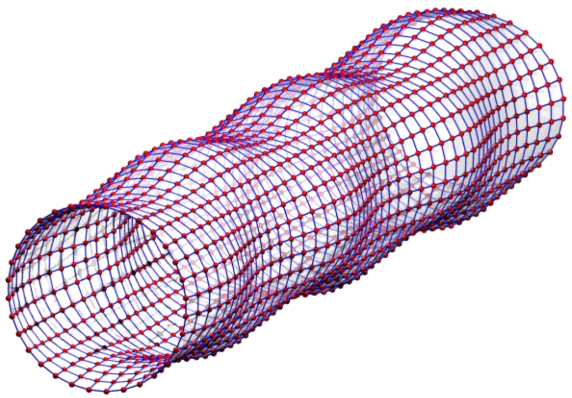
⇨ **tensor CMB polarization**

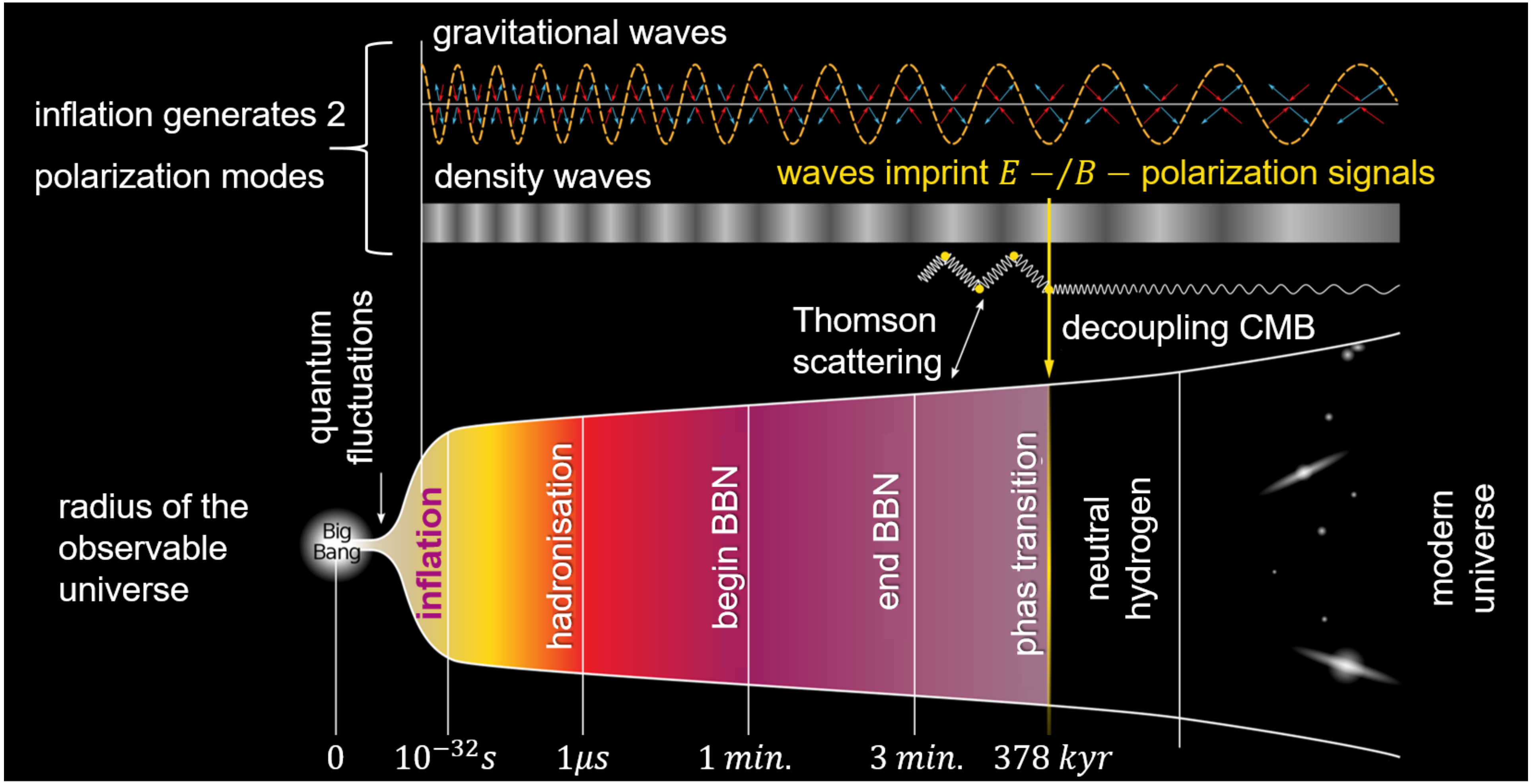
analogy to $\boldsymbol{B}$ – **field**: non–vanishing rotation

Early inflationary phase & CMB polarizations

- accelerated masses during inflation: emission of gravitational waves

- gravitational waves stretch and squeeze space & time

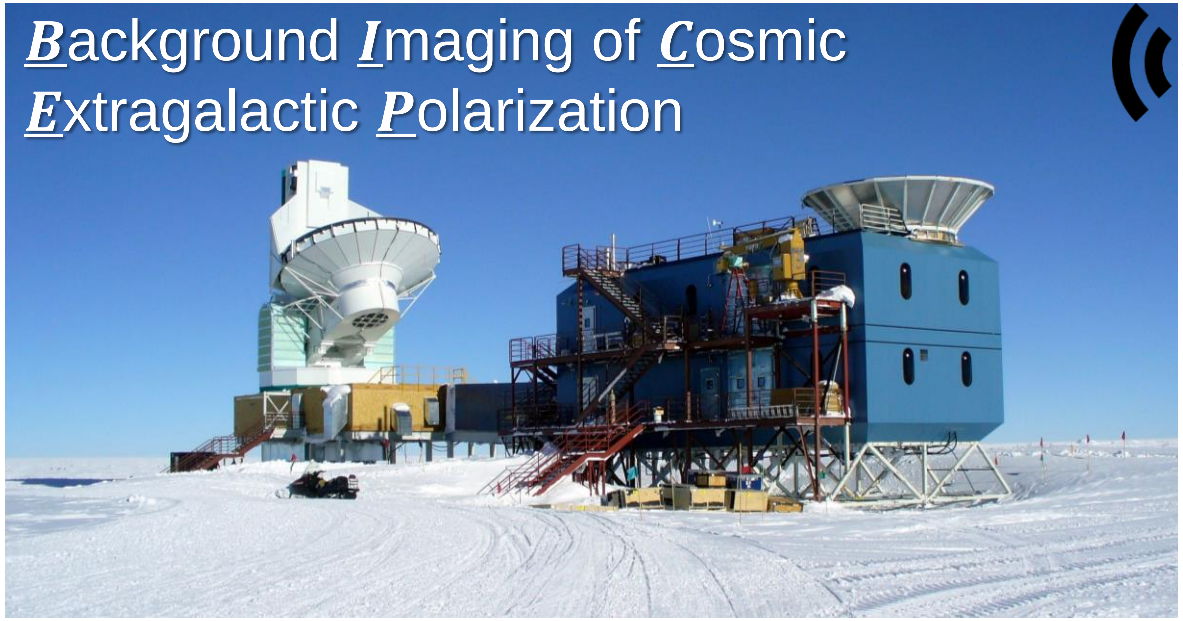




Hunting primordial curls in the CMB: $BICEP2$

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

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



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

arXiv:1403.3985v1 [astro-ph.CO] 17 Mar 2014

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

[1] School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, UK
[2] Department of Physics, California Institute of Technology, Pasadena,

 ***extraordinary** claims demand **extraordinary** evidence

Hunting primordial curls in the CMB: $BICEP2$

- **March $17, 2014$: sensational news from the South Pole**

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

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

Polarization measurement detects primordial gravitational waves

Cosmic inflation is bolstered, but some inconsistencies await resolution.

Alan Chodos

PHYSICS TODAY

'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.

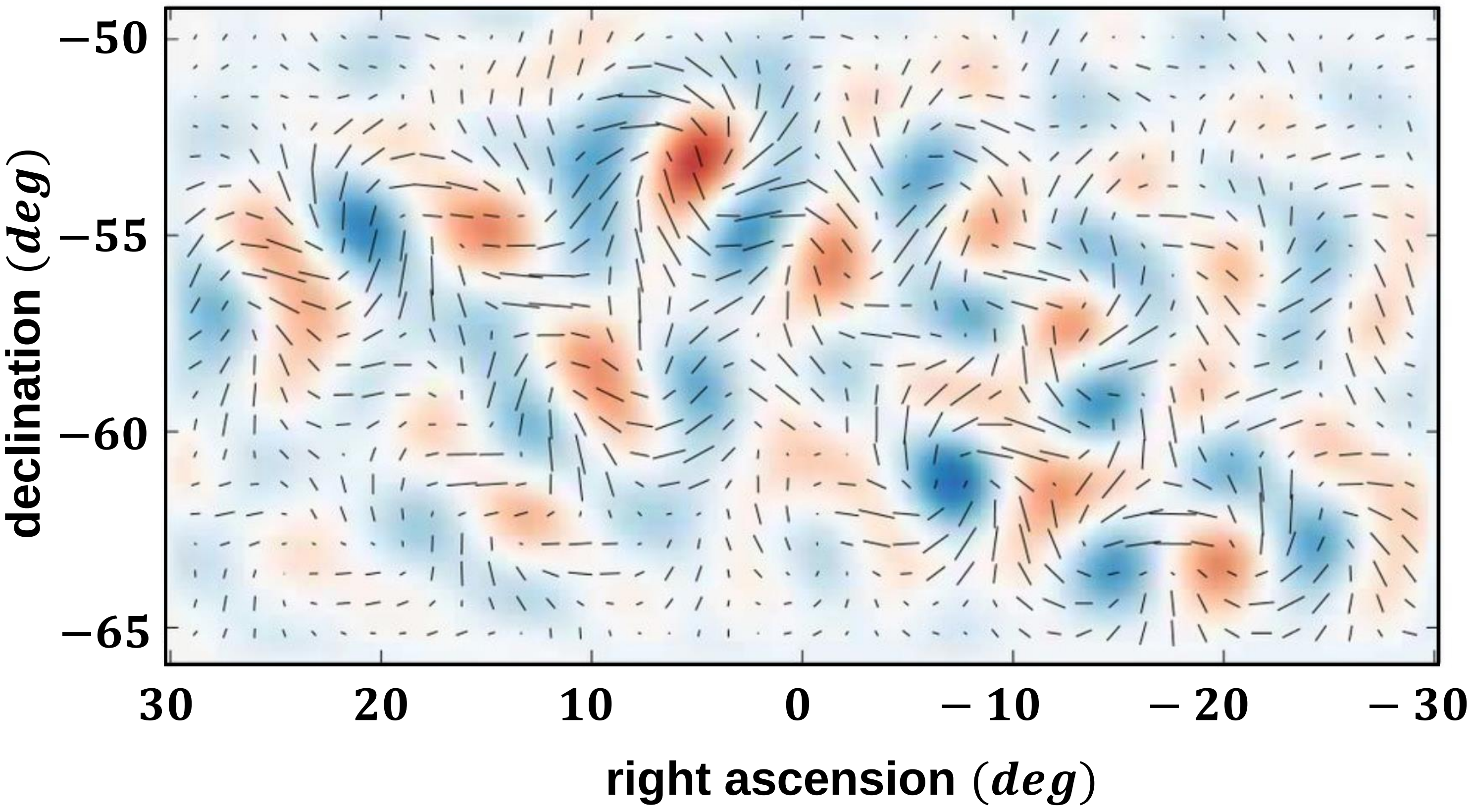
Researchers believe they have found the signal left in the sky by the super-rapid expansion of space that must have occurred just fractions of a second after everything came into being.

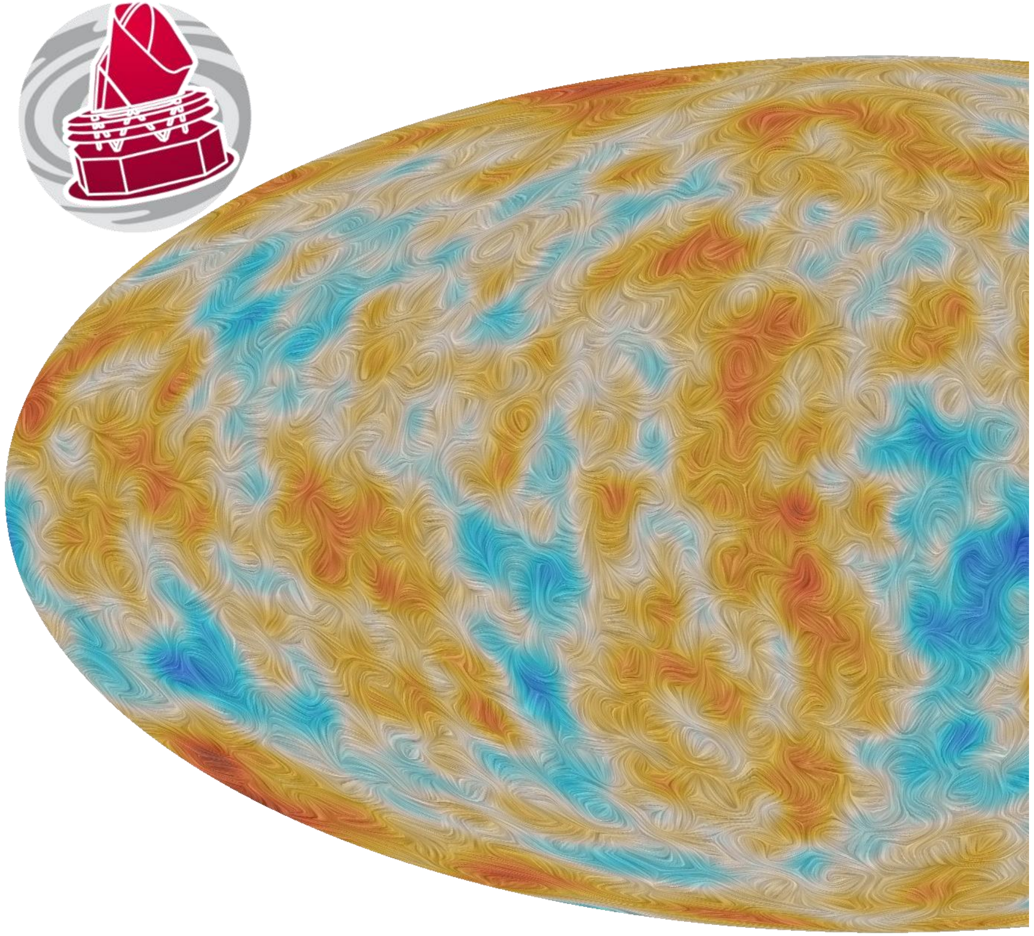
It takes the form of a distinctive twist in the oldest light detectable with

Hunting primordial curls in the CMB: $BICEP2$

- sensational news from the South Pole, but wait: news from $Planck$

\- $BICEP2$: non−zero curls!





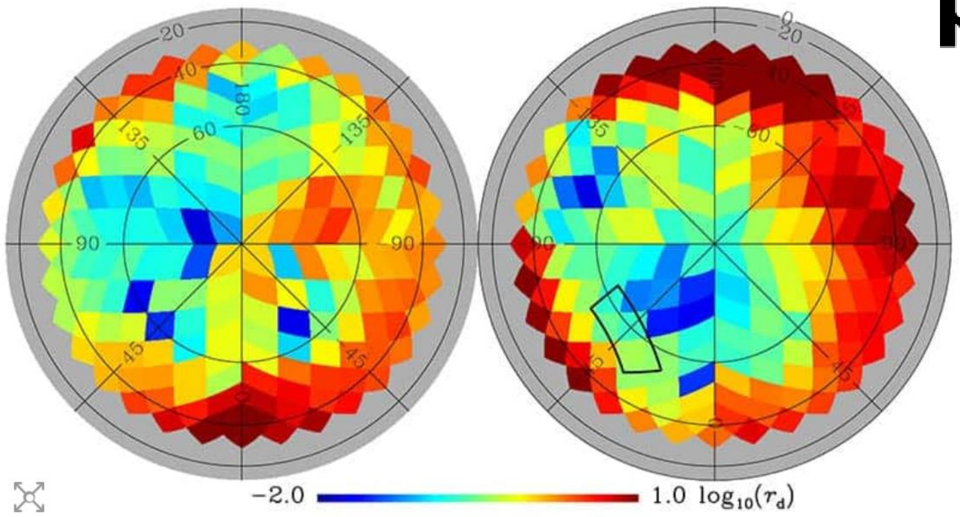
Primordial curls in the CMB: it´s just dust …

- **Sept. 2014: sensational news from the South Pole – bites the dust…**

TELESCOPES AND SPACE MISSIONS | RESEARCH UPDATE

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

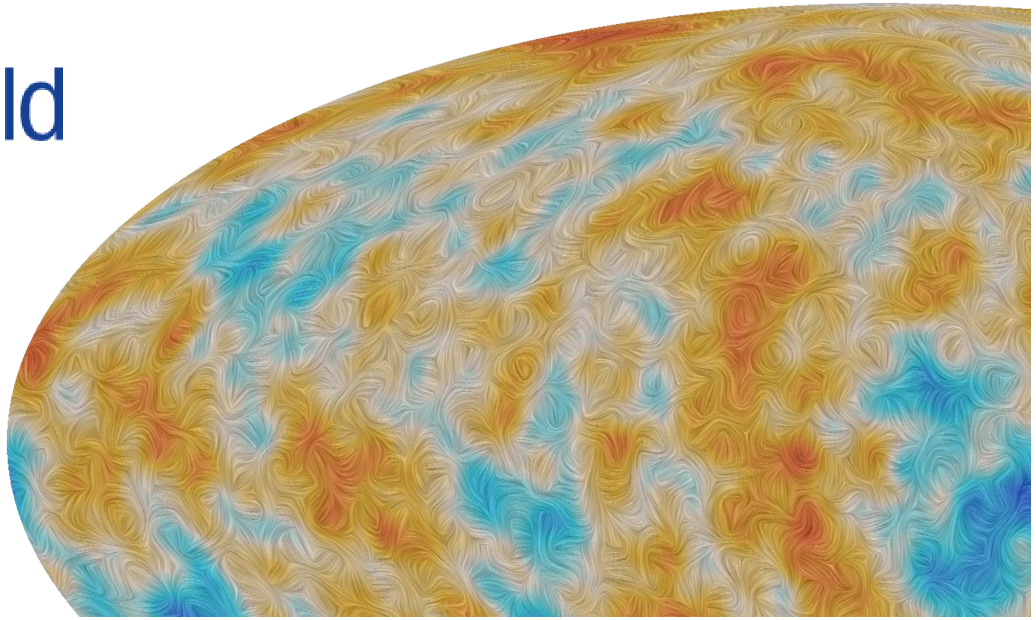
22 Sep 2014 Tushna Commissariat



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

physicsworld



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 $\boldsymbol{Planck - BICEP2}$:
  no evidence for cosmological $\boldsymbol{B}$ – mode (tensor) signal due to $\boldsymbol{GW}$

- contribution due to **noise** (**dust rings**) substantially larger than assumed by $\boldsymbol{BICEP2}$ in original publication

- polarization data **confirm** earlier measurements $\boldsymbol{\Omega_B}$ & $\boldsymbol{\Omega_{DM}}$ 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**!