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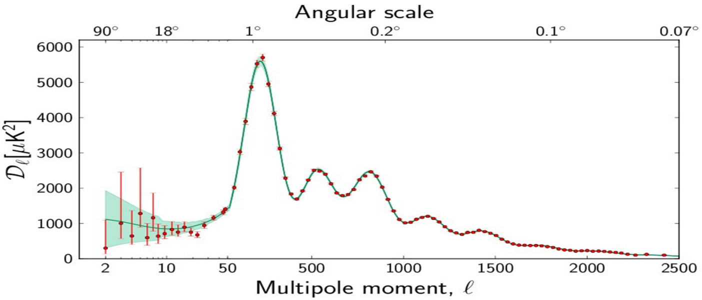
$SU(2)_{CMB}$ at high redshifts and the value of H_0

Steffen Hahn | March 22, 2017 | 5th Winter Workshop on Nonpertubative Quantum Field Theory, IN ΦNI

KARLSRUHE INSTITUTE OF TECHNOLOGY (IPS-KIT)



Outline

1. Motivation
   - tension between H_0 values
   - CMB anomalies
2. H_0 from high-z ΛCDM
   - sound horizon r_s
   - ΛCDM model
3. H_0 from high-z $SU(2)_{CMB}$
   - differences between $SU(2)_{CMB}$ and ΛCDM
   - straight-forward calculation of r_s in $SU(2)_{CMB}$
   - reinterpretation of v_b freeze out condition
4. Speculative interpolation of high- and low-z models
   - Planck-scale axion
   - PSA vortices: perculation/deperculation model
5. Summary and outlook

Motivation

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Tension between H_0 values

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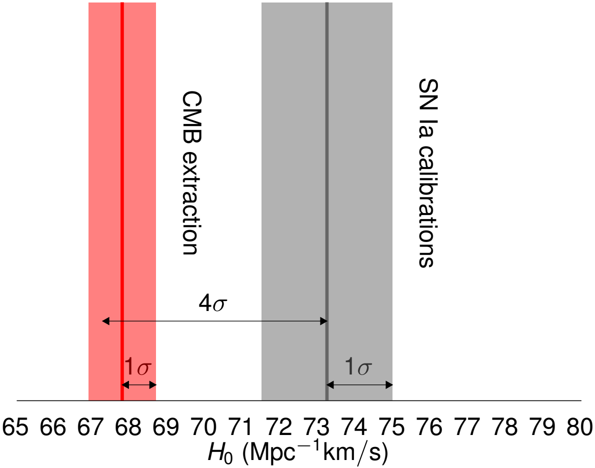

Figure 1 : CMB (red, [AAA+16]) vs. local cosmological observation (gray, [RMH+16]).

Tension between H_0 values

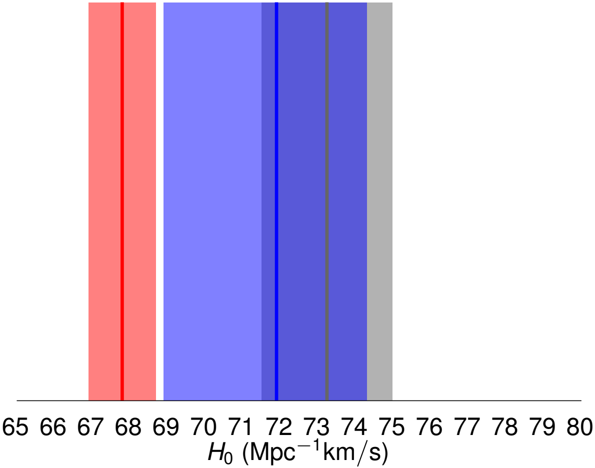

Figure 2 : H0LiCOW measurement of H_0 (blue, [BCS+16]).

What is H_0?

Definition: Hubble parameter

$$H_0 = \left.\frac{\dot{a}(t)}{a(t)}\right|_{t_0}, \ \mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\,\mathrm{d}r^2 \ \text{(FLRW metric, } a_0 = a(t_0) = 1) \quad (1)$$

- current expansion rate of the universe
- measure for the age of the universe
- important for cosmologically local distance calibrations

Definition: cosmological redshift

$$z = \frac{1}{a} - 1, z(t_0) = 0, z(0) = \infty \quad (2)$$

- redshift due to cosmological expansion (the earlier the higher)

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CMB anomalies: radio excess

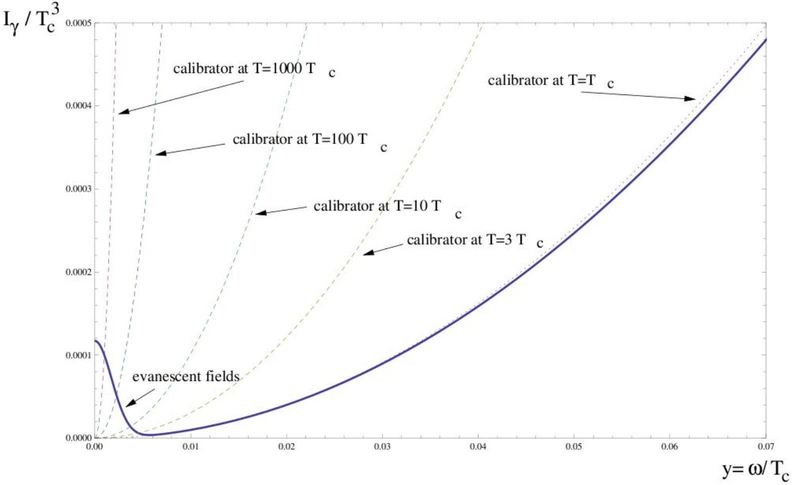

Figure 3 : Different Rayleigh-Jeans line temperature fits [FKL+11].

CMB anomalies: early reionization

What is reionization?

- late time effect due to non-linear structure growth
- ignition of star-like objects (e. g. quasars...)
- ionizing spectral components of radiation $\Rightarrow$ reionization

Detection using quasar light

- quasars are very old and have a very high luminosity
- emission during reioniz. implies Gunn-Peterson trough in spectrum

  $\Rightarrow z_i \sim 6$ ([BFW$^+$01])

Calculation out of CMB anisotropies

- CMB photons scatter off free electrons (Thomson)
- fit of optical depth to TT angular power spectrum of CMB

  $\Rightarrow z_i \sim 8.8$ ([AAA$^+$16]), $z_i \sim 11$ ([AAAC$^+$14])

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CMB anomalies: large angles

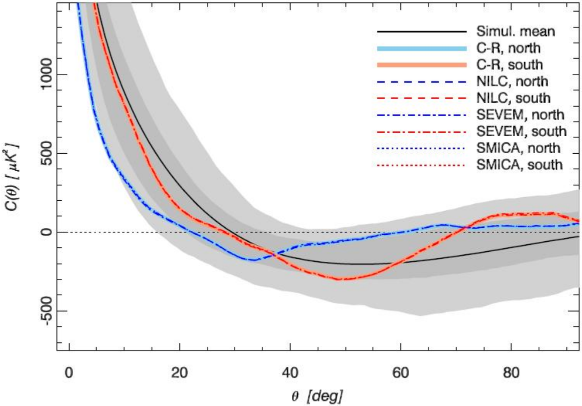

Figure 4 : Large angle suppression in TT(θ) [SH08], [CHSS10]. (Low variance of temperature fluctuations in ecliptic northern hemisphere.)

CMB anomalies: large angles

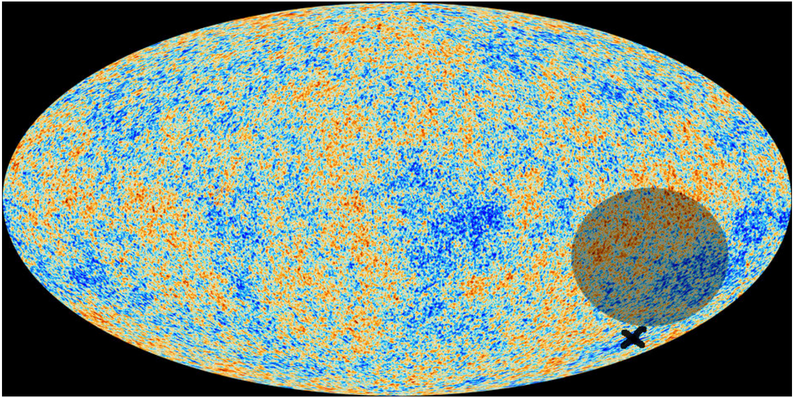

Figure 5 : CMB cold spot (non-gaussianity of temperature fluctuations) [Vie10].

CMB anomalies: large angles

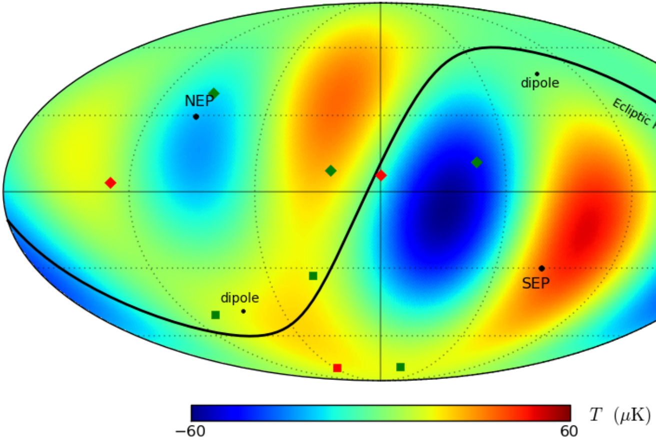

Figure 6 : Alignment low-l CMB multipoles [TOCH03, OCTZH04, CHSS06]

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Sound horizon r_s

Definition: sound horizon

$$r_s(z) = \int_z^\infty \mathrm{d}z' \, \frac{c_s(z')}{H(z')}, \; c_s(z) = \frac{1}{\sqrt{3(1+R(z))}} \tag{3}$$

- computable in high-z model
- c_s sound velocity that propagates baryonic acoustic oscillations

Definition

$$R(z) = \frac{3}{4}\frac{\rho_{b,0}}{\rho_{\gamma,0}} \cdot \frac{(z+1)^3}{(z+1)^4} = 111.019\eta_{10} \cdot \frac{(z+1)^3}{(z+1)^4}, \; \eta_{10} = \frac{n_{b,0}}{n_{\gamma,0}} 10^{-10} \tag{4}$$

- $n_{\gamma,0}$ out of T_0
- η_{10} z-independent in ΛCDM (no longer z-independent if CMB photons subject to $SU(2)_{CMB}$)

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Nearly model independ. extract. of $r_s H_0$

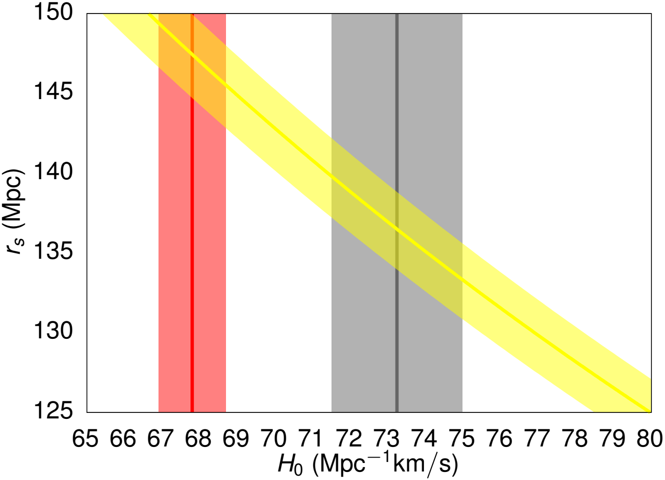

Figure 7 : r_s-H_0 relation (yellow) [BVR16].

Which value of decoup. z determines r_s?

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Definition: optical depth

$$\tau(z_*) = \int_{t(z_*)}^{t_0} \mathrm{d}t\,\dot{\tau} = \sigma_T \int_0^{z_*} \mathrm{d}z\,\frac{\chi_e(z)\,n_e^b(z)}{(z+1)\,H(z)} \stackrel{!}{=} 1 \tag{5}$$

- $\dot{\tau}$ from Thomson scattering (without reionization!)
- decoupling of photons at recombination

Definition: drag depth

$$\tau_\mathrm{d}(z_\mathrm{d}) = \int_{t(z_\mathrm{d})}^{t_0} \mathrm{d}t\,\dot{\tau}_\mathrm{d} = \sigma_T \int_0^{z_\mathrm{d}} \mathrm{d}z\,\frac{\chi_e(z)\,n_e^b(z)}{(z+1)\,H(z)\,R(z)} \stackrel{!}{=} 1 \tag{6}$$

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- corresponding r_s visible in todays matter correlation function

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Clarification

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Definition: electron number density

$$n_e^b = (1 - Y_p)\, n_{b,0}\, (z+1)^3\ \mathrm{cm}^{-3} \tag{7}$$

- electrons before recombination II (hydrogen)
- Y_p Helium mass fraction in baryons

Definition: ionization fraction

$$\chi_e(z) = \frac{n_e(z)}{n_e^b} \tag{8}$$

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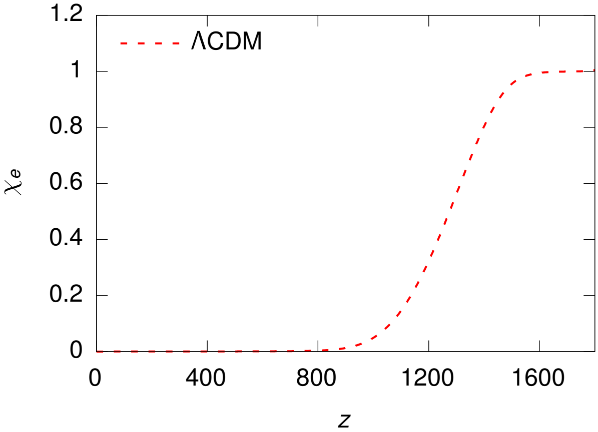

Figure 8 : χ_e marks recombination epoch.

ΛCDM model

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Definition: critical density (today)

$$\rho_{C,0} = \frac{3}{8\pi G} H_0^2 \tag{9}$$

- out of Hubble equation in limit of flat universe
- G denotes Newton's constant

Definition: z dependence of $H(z)$

$$\frac{H(z)}{H_0} = \sqrt{\Omega_{\Lambda,0} + (\Omega_{b,0} + \Omega_{\mathrm{DM},0})(z+1)^3 + \Omega_{\mathrm{r},0}(z+1)^4} \tag{10}$$

- $\Omega_{x,0}$: proportion of stuff x normalized to critical density $\rho_{C,0}$
- matter scaling: $(z+1)^3$, radiation scaling: $(z+1)^4$

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What is $\Omega_{r,0}$? High-z approximation.

Definition: radiative fraction (ΛCDM)

$$\Omega_{r,0} = \Omega_{\gamma,0} + \Omega_{\nu,0} = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right)\Omega_{\gamma,0} \tag{11}$$

- $7/8$ correction due to neutrinos being Fermions and Photons Bosons
- $4/11$ can be obtained out of entropy conserv. of e^+e^- annihilation
- N_{eff} fit parameter (represents effective number of massless neutrinos)

High-z approximation

$$\frac{H(z)}{H_0} \approx \sqrt{\left(\Omega_{b,0} + \Omega_{\mathrm{DM},0}\right)(z+1)^3 + \Omega_{r,0}(z+1)^4} \tag{12}$$

- since $\Omega_{\Lambda,0} < 1$ it can be neclected for $100 < z$

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Calculation of r_s in ΛCDM

Parameters with errors ([AAA+16])

- $\Omega_{\mathrm{b},0} h^2 = 0.0222 \pm 0.0002$
- $\Omega_{\mathrm{DM},0} h^2 = 0.1199 \pm 0.0022$
- $N_{\mathrm{eff}} = 3.15 \pm 0.23$
- $Y_p = 0.252 \pm 0.041$

Parameters without errors (calculated out of $T_0 = 2.725\,\mathrm{K}$)

- $\Omega_{\gamma,0} h^2 = 2.468 \times 10^{-5}$

Definition: h

$$H_0 = h \cdot 100\,\mathrm{km/s/Mpc} \tag{13}$$

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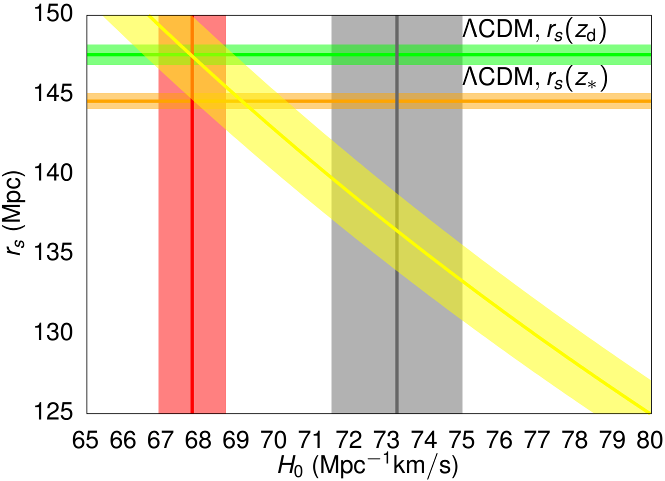
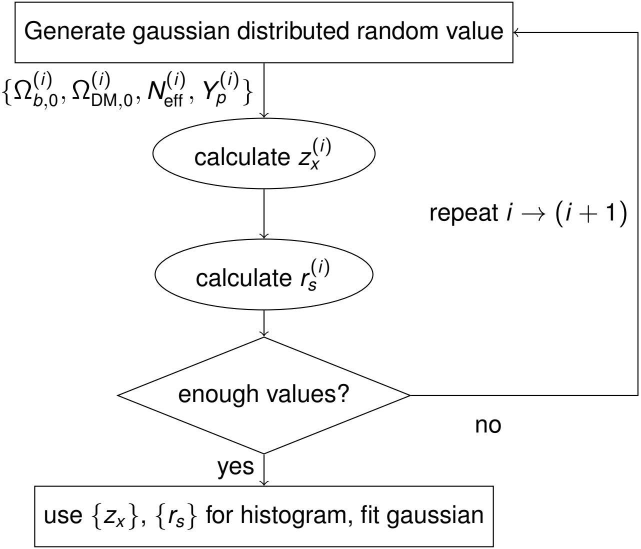


Figure 9 : ΛCDM, $r_s(z_*)$ (orange, lower), ΛCDM, $r_s(z_d)$ (green, upper)

Error estimation



H_0 from high-z $SU(2)_{CMB}$

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Differences betw. $SU(2)_{CMB}$ and ΛCDM

Table 1 : Cosmological high-z models: ΛCDM versus $SU(2)_{CMB}$.

	ΛCDM	$SU(2)_{CMB}$
$\frac{T}{T_0}$	$z+1$	$0.63\,(z+1)$
Ω_{DM}	Ω_{DM}	0
N_ν	N_{eff}	3
$\frac{T_\nu}{T}$	$\left(\frac{4}{11}\right)^{1/3}$	$\left(\frac{16}{23}\right)^{1/3}$

$T(z)$-scaling

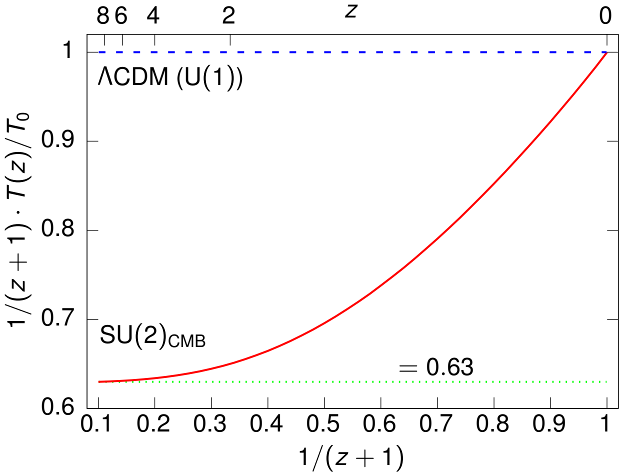

Figure 10 : ΛCDM behaviour (blue, dashed), SU(2)$_{\mathrm{CMB}}$ behaviour (red solid, [Hof15])

$T(z)$-scaling

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Definition: high z behaviour

$$T(z)/T_0 \xrightarrow{z \gg 10} 0.63\,(z+1) \qquad (14)$$

- fundamental different $T(z)$ scaling (curvature in T divided by $z+1$ which reflects presence of Yang Mills scale $\Lambda_{\mathrm{CMB}} \sim 1 \times 10^{-4}\,\mathrm{eV}$)
- recovery of linear relation at high z albeit subject to lower slope
- $\mathrm{SU}(2)_{\mathrm{CMB}}$ gas has 8 instead of 2 relativistic degrees of freedom

Today's checks of $T(z)$

$$T(z) = T_0\,(z+1)^{1-\beta} \qquad (15)$$

- thermal Sunyaev-Zeldovich effect [LGSM+15]
- molecular rotation spectra [MBB+13]

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$T(z)$-scaling?!

Sunyaev-Zeldovich effect

$$\Delta I_{\mathrm{tSZ}} = \frac{T_0^3}{2\pi^2} \frac{x^4\, e^x}{(\mathrm{e}^x - 1)^2} \tau \left(\theta f(x) - v_r + R(x, \theta, v_r)\right), x = \omega / T \tag{16}$$

- electrons of hot plasma scatter off CMB photons
- first order approximation (deviation of Planck spectrum)

  $\Rightarrow \beta \approx 0$!?
- adiabatically slow expansion implies that photon spectra depend on one mass scale only: T

  $\Rightarrow \omega$ scales as T does (prejudice of ω implies prejudice of T)
- analogous argumentation for rotation spectra

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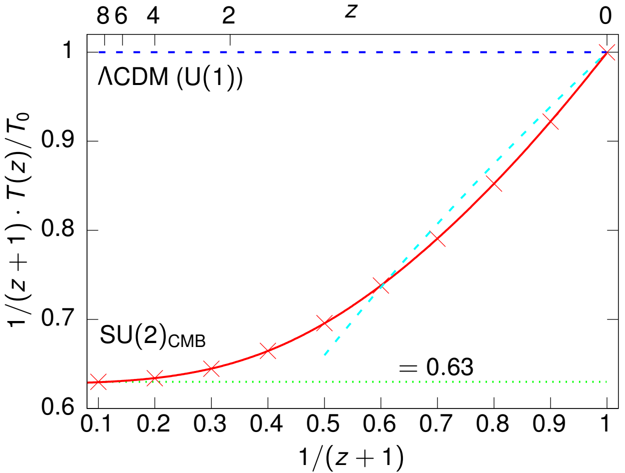

Figure 11 : New scaling can be fitted by even function:
$y \approx 0.2\pi + 0.1x^2 + 0.9x^4 - 1.4x^6 + 1.1x^8 - 0.3x^{10}$ (red solid), checked scaling (cyan, dashed, $\beta \approx 0.6$)

Ω_{DM} at high z

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With recombination $T_* \sim 3000\,\mathrm{K}$

$$1800 \sim z_{\mathrm{dec}}^{(\mathrm{SU}(2)_{\mathrm{CMB}})} > z_{\mathrm{dec}}^{(\Lambda\mathrm{CDM})} \sim 1100 \tag{17}$$

- $\left(\frac{1100}{1800}\right)^3 \sim \frac{\Omega_{b,0}}{\Omega_{b,0}+\Omega_{\mathrm{DM},0}}$
- matter domination, radiation doesn't play a role at decoupling

Neutrino N_ν and T_ν

- here not a fit parameter (N_{eff})
- $N_\nu = 3$ (missing width in Z_0 decay)

Conversion neutrino to photon T

$$\left(\frac{T_\nu}{T}\right)^3 = \frac{g_1}{g_0} = \begin{cases} \frac{4}{11}, g_1 = 2, g_0 = 2 + \frac{7}{8}4 & (\Lambda\text{CDM}) \\ \frac{16}{23}, g_1 = 8, g_0 = 8 + \frac{7}{8}4 & (\text{SU}(2)_{\text{CMB}}) \end{cases} \tag{18}$$

- change in relativistic degrees of freedom
- g_1 relativistic degrees after, g_0 relativistic degrees before e^+e^- annihilation

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$SU(2)_{CMB}$ model

High-z Hubble parameter

$$\frac{H(z)}{H_0} \approx \sqrt{\Omega_{b,0}(z+1)^3 + \Omega_{\gamma,0}\frac{8}{2}\left(1+\frac{7}{32}\left(\frac{16}{23}\right)^{\frac{4}{3}} N_\nu\right)(z+1)^4} \qquad (19)$$

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$$\frac{H(z)}{H_0} \approx \sqrt{\Omega_{b,0}(z+1)^3 + \Omega_{\gamma,0}\frac{8}{2}\left(1+\frac{7}{32}\left(\frac{16}{23}\right)^{\frac{4}{3}} N_\nu\right)(z+1)^4} \qquad (19)$$

Parameters with errors [AAA$^+$16]

- $\Omega_{\mathrm{b},0}h^2 \quad = 0.0222 \pm 0.0002$
- $Y_p \quad = 0.252 \pm 0.041$

Parameters without errors (calculated out of $T_0 = 2.725\,\mathrm{K}$)

- $\Omega_{\gamma,0}h^2 \quad = 2.468 \times 10^{-5}$, out of $T_0 = 2.725\,\mathrm{K}$

Straight-forward calc. of r_s in $SU(2)_{CMB}$

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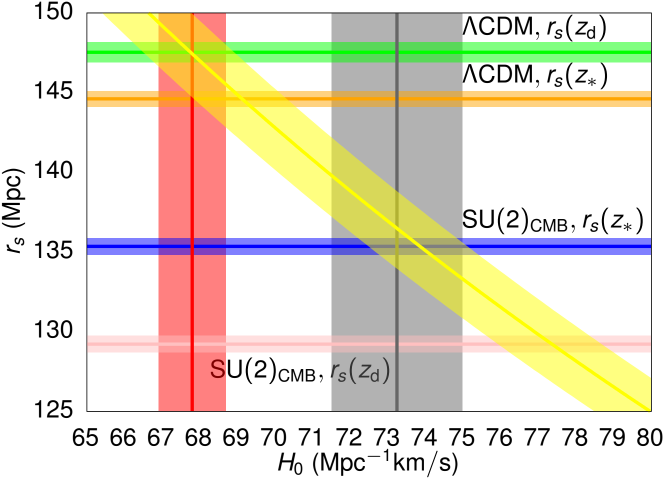

Figure 12 : $SU(2)_{CMB}, r_s(z_*)$ (blue, upper), $SU(2)_{CMB}, r_s(z_d)$ (pink, lower)

Look at baryon freeze out

Karlsruhe Institute of Technology

Baryonic Euler equation [PW68, HS96]

$$\frac{\mathrm{d}v_\mathrm{b}}{\mathrm{d}z} = -\frac{1}{a}\frac{\mathrm{d}a}{\mathrm{d}z}v_\mathrm{b} + \frac{k}{H(z)}\Psi + \frac{1}{H(z)}\sigma_T n_e^b \chi_e a\left(\Theta_1 - v_\mathrm{b}\right)/R \tag{20}$$

- describes baryon velocity v_b of perfect baryon-photon fluid
- Θ_1 dipole in temperature via Doppler effect
- Ψ gravitational potential

Look at baryon freeze out

Karlsruhe Institute of Technology

Solution: $\Psi \approx 0$

$$\frac{v_b(z)}{z+1} \sim \lim_{Z \nearrow \infty} \int_z^Z dz' \, \frac{\mathrm{e}^{-\tau_\mathrm{d}(z',z)}}{H(z')(z'+1)} \dot{\tau}_\mathrm{d}(z') \Theta_1(z') \,, \tag{21}$$

- justified by absence of dark matter

Definition

$$D_\mathrm{d}(z', z) = \frac{\mathrm{e}^{-\tau_\mathrm{d}(z',z)}}{H(z')(z'+1)} \dot{\tau}_\mathrm{d}(z') \tag{22}$$

- analogous in the photon case $\tau_\mathrm{d} \to \tau$

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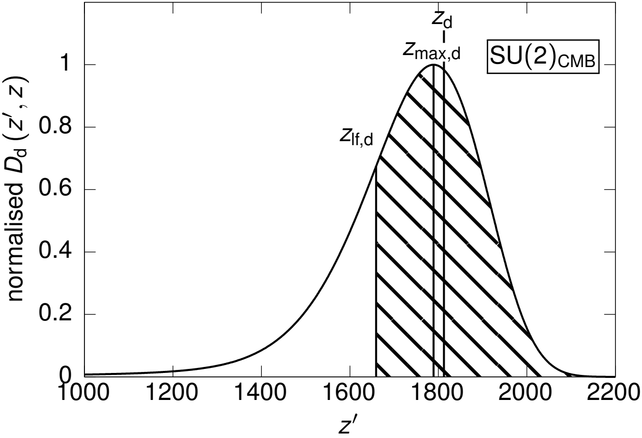

Figure 13 : The lf in $z_{lf,d}$ denotes left flank. Optical depth definition at maximum.

Look at baryon freeze out

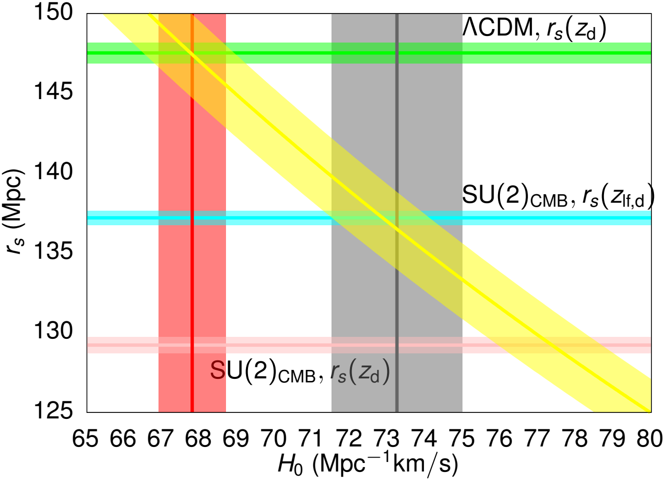

Figure 14 : SU(2)$_\mathrm{CMB}$, $r_s(z_\mathrm{lf,\,d})$ (cyan).

Final result

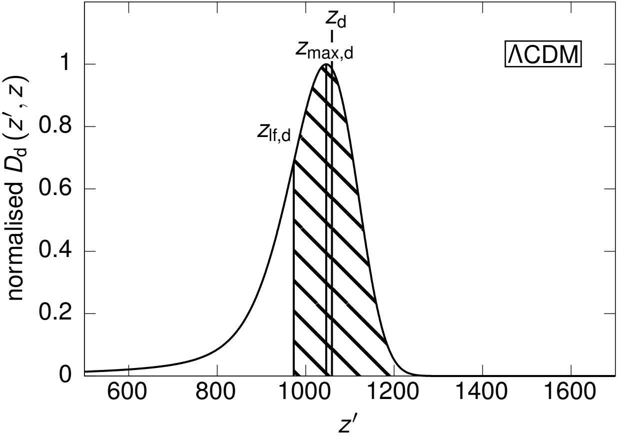

Figure 15 : $z_{lf,d}$ of ΛCDM.

Final result

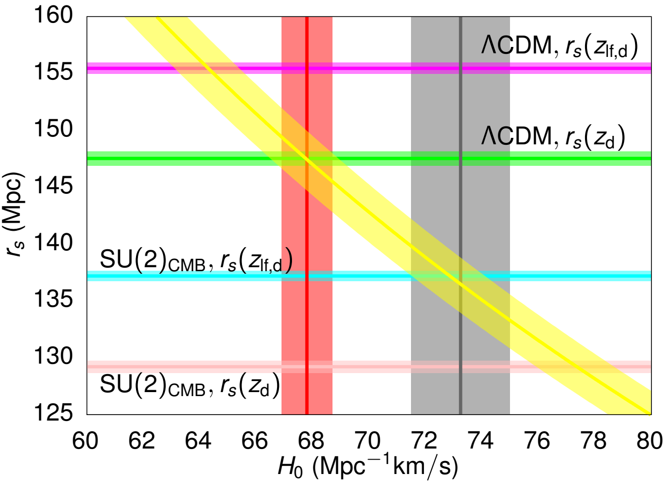

Figure 16 : ΛCMB, $r_s(z_{\mathrm{lf,\,d}})$ (magenta).

Speculative interpolation of high- and low-z models

1. Motivation
   - tension between H_0 values
   - CMB anomalies
2. H_0 from high-z ΛCDM
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4. Speculative interpolation of high- and low-z models
   - Planck-scale axion
   - PSA vortices: perculation/deperculation model
5. Summary and outlook

Planck-scale axion

Karlsruhe Institute of Technology

Definition: axion energy density, axion pressure

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)\,, p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \tag{23}$$

- dynamical chiral symmetry breakdown induced by gravitational torsion at Planck scale ([FHSW95, GH07, GHN08])

Axion potential (Peccei-Quinn)

$$V(\phi) = (\kappa\Lambda_{\text{CMB}})^4 \cdot \left(1 - \cos\left(\frac{\phi}{m_P}\right)\right), \; m_P = \frac{1}{\sqrt{8\pi G}} \tag{24}$$

- anomalous breaking of symmetry $U_A(1) \to 1$ induced by thermal ground states of Yang Mills theories
- κ dimensionless fudge factor, $\Lambda_{\text{CMB}} \sim 10^{-4}$eV
- spatially homogeneous field: frozen to slope of V at high z, damped oscillations at low z

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The Planck-scale axion (PSA)

Definition: equation of motion (minimal coupling to gravity)

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\mathrm{d}}{\mathrm{d}\phi}V(\phi) = 0 \tag{25}$$

- $3H\dot{\phi}$ damping "force"
- $\frac{\mathrm{d}}{\mathrm{d}\phi}V(\phi)$ driving "force"

Definition

$$H^2 = \frac{8\pi G}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho_{\mathrm{DM,e}} + \rho_b + \rho_r\right) \tag{26}$$

- $\rho_{\mathrm{DM},0} = \lim_{z\to 0}\left(\dot{\phi}^2 + \rho_{\mathrm{DM,e}}\right)$
- $\Omega_{\Lambda,0}\rho_{C,0} = \lim_{z\to 0}\left(V(\phi) - \frac{1}{2}\dot{\phi}^2\right)$
- not conserved separately

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Fitting

Fitting:

1. critical density $\rho_{C,0}$
2. dark energy $\Omega_\Lambda = 0.7$
3. zero of deceleration parameter q_0 at $z_q \sim 0.7$

- 3 fits to local cosmological data (parameters $\Omega_{\mathrm{DM},e,0}, \kappa, \phi_{\mathrm{in}}$)
- q_0 out of supernovae Ia, luminosity distance redshift relation, standard ruler
- spatially homogeneous PSA model falsified by $z_q > 1$

PSA vortices: perculation/deperculation model

Definition: Ansatz

$$\frac{H(z)}{H_0} = \sqrt{\Omega_{\mathrm{DS}}(z) + \Omega_{b,0}(z+1)^3 + \Omega_{\mathrm{r},0}(z+1)^4} \tag{27}$$

- $\Omega_{\mathrm{r},0}$ is the radiation part in $\mathrm{SU}(2)_{\mathrm{CMB}}$
- Ω_{DS} represents dark sector composed of perculated/deperculated PSA vortices
- presumably PSA vortices abundantly generated across Hagedorn phase transitions in early universe due to Yang Mills theories going confining
- perculation of these PSA vortices in the sense of Kosterlitz-Thouless transition
- $\Omega_{\mathrm{DM},0} + \Omega_{\Lambda,0} = \Omega_{\mathrm{DS},0}$ equals the ΛCDM
- deperculation at $0 < z_p < z_*$

Fitting of z_p

Definition: instantanous phase transition

$$\Omega_{\mathrm{DS}}(z) = \Omega_{\Lambda,0} + \Omega_{\mathrm{DM},0}\left[(z+1)^3\,\theta(z_p - z) + (z_p+1)^3\,\theta(z - z_p)\right] \tag{28}$$

Definition: angular size of sound horizon

$$\theta_* = \frac{r_s(z_{\mathrm{lf},*})}{\int_0^{z_{\mathrm{lf},*}} \frac{\mathrm{d}z}{H(z)}} \tag{29}$$

- angle of first acoustic peak in TT angular power spectrum

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Fitting of z_p

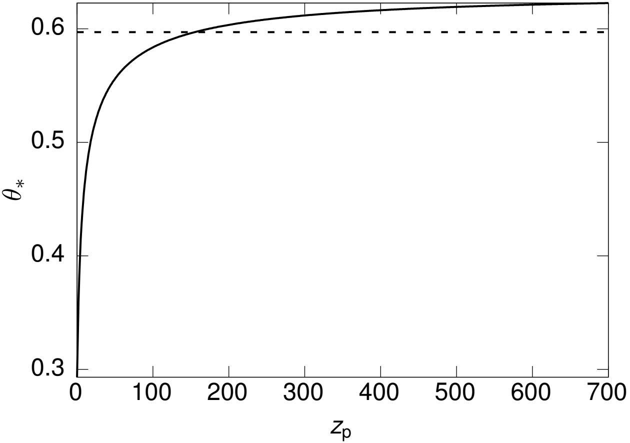

Figure 17 : Angle of first peak for different peculation redshifts (solid). Horizontal line (dashed) represents real value.

Selfconsistency of $\mathrm{SU}(2)_{\mathbf{CMB}}$ high-z model

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?

$$1 \gg \frac{\Omega_{\mathrm{DM},0}}{\Omega_{b,0}} \frac{(z_p + 1)^3}{(z_{\mathrm{lf},*} + 1)^3} \tag{30}$$

Yes.

$$\frac{\Omega_{\mathrm{DM},0}}{\Omega_{b,0}} \frac{(z_p + 1)^3}{(z_{\mathrm{lf},*} + 1)^3} \sim 0.6\% \ll 1 \tag{31}$$

Summary and outlook

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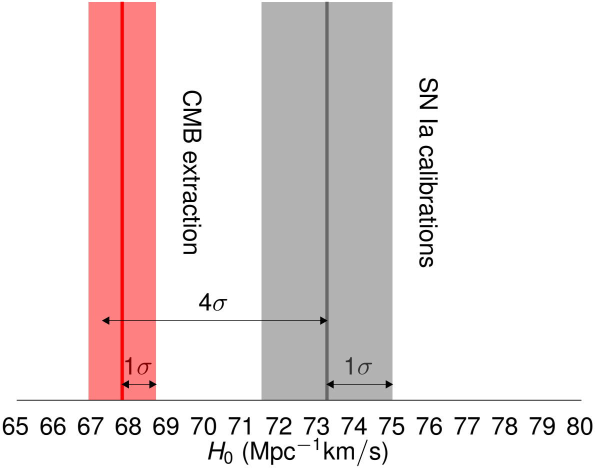
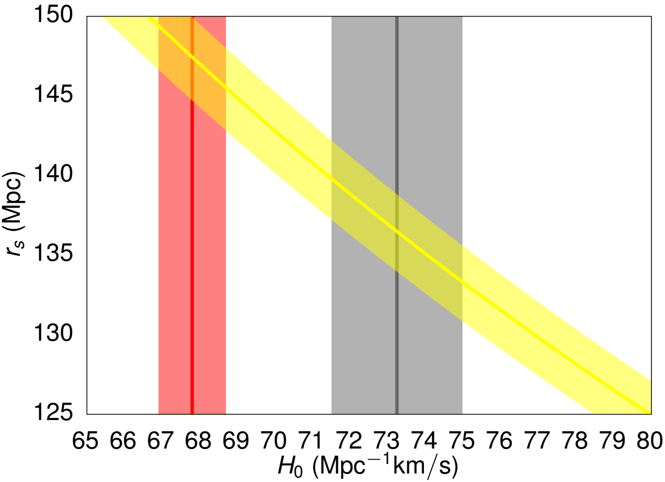
Summary and outlook



Summary and outlook



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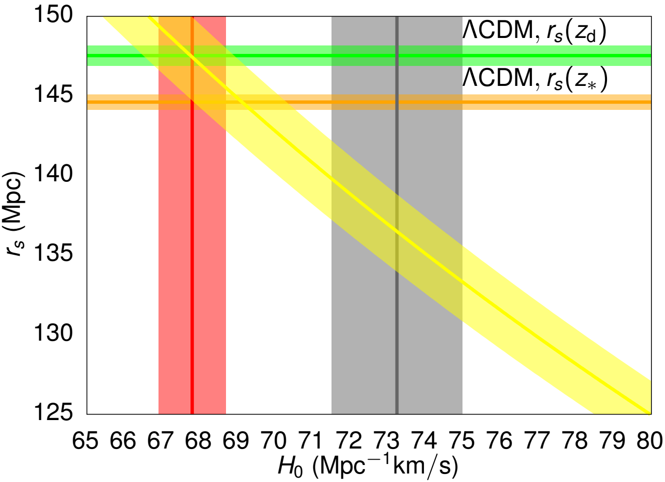
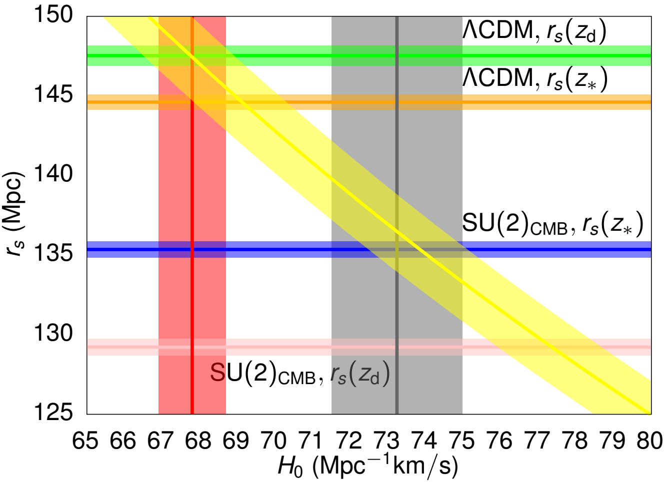
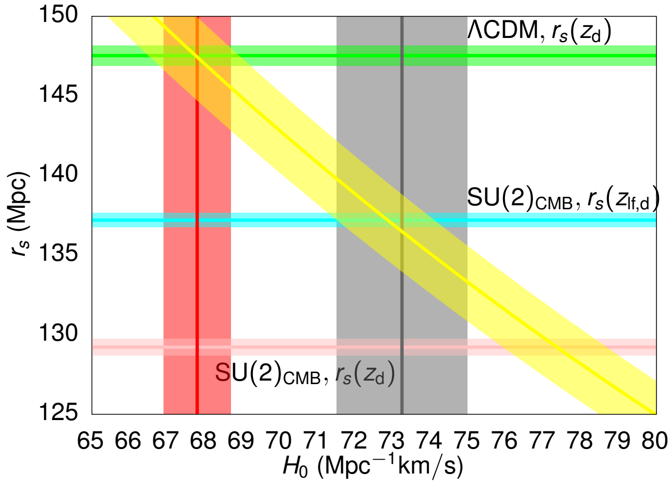


Summary and outlook



Summary and outlook



Summary and outlook

Interpolating model: high-z $SU(2)_{CMB}$ with low-z ΛCDM

- slow-roll dynamics of Planck-scale axion field falsified (z_q too high)
- however perculation/deperculation model for PSA vortices is promising: self consistent computation of angular size of sound horizon

Outlook

- Can such a model reproduce TT angular power spectrum?
- Can PSA interpolating model be made responsible for anomalous rotation curves in spiral galaxies (Tully-Fisher relation, elliptical galaxies, etc. ...)?
- Can radiative effects in $SU(2)_{CMB}$ explain large angle anomalies?

Bibliography I

[AAA+16] Ade, PAR ; Aghanim, N ; Arnaud, M ; Ashdown, M ; Aumont, J ; Baccigalupi, C ; Banday, AJ ; Barreiro, RB ; Bartlett, JG ; Bartolo, N u. a.:
Planck 2015 results-XIII. Cosmological parameters.
In: *Astronomy & Astrophysics* 594 (2016), S. A13

[AAAC+14] Ade, Peter A. ; Aghanim, N ; Armitage-Caplan, C ; Arnaud, M ; Ashdown, M ; Atrio-Barandela, F ; Aumont, J ; Baccigalupi, C ; Banday, Anthony J. ; Barreiro, RB u. a.:
Planck 2013 results. XVI. Cosmological parameters.
In: *Astronomy & Astrophysics* 571 (2014), S. A16

[BCS+16] Bonvin, V ; Courbin, F ; Suyu, SH ; Marshall, PJ ; Rusu, CE ; Sluse, D ; Tewes, M ; Wong, KC ; Collett, T ; Fassnacht, CD u. a.:
H0LiCOW V. New COSMOGRAIL time delays of HE 0435- 1223: H0 to 3.8% precision from strong lensing in a flat ΛCDM model.
In: *Monthly Notices of the Royal Astronomical Society* (2016), S. stw3006

[BFW+01] Becker, Robert H. ; Fan, Xiaohui ; White, Richard L. ; Strauss, Michael A. ; Narayanan, Vijay K. ; Lupton, Robert H. ; Gunn, James E. ; Annis, James ; Bahcall, Neta A. ; Brinkmann, J u. a.:
Evidence for Reionization at z 6: Detection of a Gunn-Peterson Trough in az= 6.28 Quasar.
In: *The Astronomical Journal* 122 (2001), Nr. 6, S. 2850

[BVR16] Bernal, José Luis ; Verde, Licia ; Riess, Adam G.:
The trouble with H0.
In: *Journal of Cosmology and Astroparticle Physics* 2016 (2016), Nr. 10, S. 019

[CHSS06] Copi, Craig J. ; Huterer, Dragan ; Schwarz, Dominik J. ; Starkman, Glenn D.:
On the large-angle anomalies of the microwave sky.
In: *Monthly Notices of the Royal Astronomical Society* 367 (2006), Nr. 1, S. 79–102

Bibliography II

[CHSS10] COPI, Craig J. ; HUTERER, Dragan ; SCHWARZ, Dominik J. ; STARKMAN, Glenn D.:
Large-angle anomalies in the CMB.
In: *Advances in Astronomy* 2010 (2010)

[FHSW95] FRIEMAN, Joshua A. ; HILL, Christopher T. ; STEBBINS, Albert ; WAGA, Ioav:
Cosmology with ultralight pseudo Nambu-Goldstone bosons.
In: *Physical Review Letters* 75 (1995), Nr. 11, S. 2077

[FKL+11] FIXSEN, DJ ; KOGUT, A ; LEVIN, S ; LIMON, M ; LUBIN, P ; MIREL, P ; SEIFFERT, M ; SINGAL, Jack ; WOLLACK, E ; VILLELA, T u. a.:
ARCADE 2 measurement of the absolute sky brightness at 3-90 GHz.
In: *The Astrophysical Journal* 734 (2011), Nr. 1, S. 5

[GH07] GIACOSA, Francesco ; HOFMANN, Ralf:
A Planck-scale axion and SU(2) Yang-Mills dynamics: Present acceleration and the fate of the photon.
In: *Eur. Phys. J.* C50 (2007), S. 635–646.
http://dx.doi.org/10.1140/epjc/s10052-007-0214-x. –
DOI 10.1140/epjc/s10052–007–0214–x

[GHN08] GIACOSA, Francesco ; HOFMANN, Ralf ; NEUBERT, Matthias:
A model for the very early Universe.
In: *JHEP* 02 (2008), S. 077.
http://dx.doi.org/10.1088/1126-6708/2008/02/077. –
DOI 10.1088/1126–6708/2008/02/077

[Hof15] HOFMANN, Ralf:
Relic photon temperature versus redshift and the cosmic neutrino background.
In: *Annalen der Physik* 527 (2015), Nr. 3-4, S. 254–264

Bibliography III

[HS96] HU, Wayne ; SUGIYAMA, Naoshi:
Small-Scale Cosmological Perturbations: An Analytic Approach.
In: *The Astrophysical Journal* 471 (1996), Nr. 2, 542.
http://stacks.iop.org/0004-637X/471/i=2/a=542

[LGSM+15] LUZZI, G ; GÉNOVA-SANTOS, RT ; MARTINS, CJAP ; DE PETRIS, M ; LAMAGNA, Luca:
Constraining the evolution of the CMB temperature with SZ measurements from Planck data.
In: *Journal of Cosmology and Astroparticle Physics* 2015 (2015), Nr. 09, S. 011

[MBB+13] MULLER, Sebastien ; BEELEN, A ; BLACK, John H. ; CURRAN, SJ ; HORELLOU, Cathy ; AALTO, Susanne ; COMBES, F ; GUÉLIN, M ; HENKEL, C:
A precise and accurate determination of the cosmic microwave background temperature at z= 0.89.
In: *Astronomy & Astrophysics* 551 (2013), S. A109

[OCTZH04] OLIVEIRA-COSTA, Angelica de ; TEGMARK, Max ; ZALDARRIAGA, Matias ; HAMILTON, Andrew:
Significance of the largest scale CMB fluctuations in WMAP.
In: *Physical Review D* 69 (2004), Nr. 6, S. 063516

[PW68] PEEBLES, PJE ; WILKINSON, David T.:
Comment on the anisotropy of the primeval fireball.
In: *Physical Review* 174 (1968), Nr. 5, S. 2168

[RMH+16] RIESS, Adam G. ; MACRI, Lucas M. ; HOFFMANN, Samantha L. ; SCOLNIC, Dan ; CASERTANO, Stefano ; FILIPPENKO, Alexei V. ; TUCKER, Brad E. ; REID, Mark J. ; JONES, David O. ; SILVERMAN, Jeffrey M. u. a.:
A 2.4% DETERMINATION OF THE LOCAL VALUE OF THE HUBBLE CONSTANT Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.
In: *The Astrophysical Journal* 826 (2016), Nr. 1, S. 56

Bibliography IV

[Sco] SCOTT, Douglas:
recfast.
http://www.astro.ubc.ca/people/scott/recfast.html. – accessed: November 17, 2016

[SH08] SZOPA, Michal ; HOFMANN, Ralf:
A model for CMB anisotropies on large angular scales.
In: *Journal of Cosmology and Astroparticle Physics* 2008 (2008), Nr. 03, S. 001

[TOCH03] TEGMARK, Max ; OLIVEIRA-COSTA, Angelica de ; HAMILTON, Andrew J.:
High resolution foreground cleaned CMB map from WMAP.
In: *Physical Review D* 68 (2003), Nr. 12, S. 123523

[Vie10] VIELVA, Patricio:
A comprehensive overview of the cold spot.
In: *Advances in Astronomy* 2010 (2010)