# 4 lectures:

- 1. CMB back to basics
- 2. Cosmological parameters (a skeptical guide)
- (a skeptical guide) 3. Leftover stuff about neutrinos

(There are 3 types of people in the world, those who can count and those who cant)





# CMB Sky

- CMB "predicted" in 1940s
- Discovered by Penzias & Wilson 1965
- Spectrum measured 1970s
- Precisely blackbody by 1990
- Dipole measured 1970s
- Anisotropies predicted 1970s & 1980s
- Anistropies detected early 1990s
- Then lots of precision!





# CMB Spectrum

# CMB Spectrum

 $\begin{aligned} T_{\gamma} &= 2.728 \pm 0.002 \text{ K} \quad \text{(now } 2.7255 \pm 0.0006\text{K}\text{)} \\ n_{\gamma} &= (2\zeta(3)/\pi^2)T_{\gamma}^3 \simeq 413 \,\mathrm{cm}^{-3} \\ \rho_{\gamma} &= (\pi^2/15)T_{\gamma}^4 \simeq 4.68 \times 10^{-34} \,\mathrm{g} \,\mathrm{cm}^{-3} \simeq 0.262 \,\mathrm{eV} \,\mathrm{cm}^{-3} \\ |y| &< 1.2 \times 10^{-5} \quad (95\% \text{ CL}) \\ |\mu_0| &< 9 \times 10^{-5} \quad (95\% \text{ CL}) \\ |Y_{ff}| &< 1.9 \times 10^{-5} \, (95\% \text{ CL}) \end{aligned}$ 

tight constraints on distortions but expected distortions smaller still

# Spectral distorions

- •y-distortion from average amount of inverse-Compton scattering
- Dissipation of primordial adiabatic modes
- Structure formation and feedback effects
- Possible effects from decaying or annihilating particles •Other effects of reionization

# CMB history (eh)



CN measurements at DAO (1940, 1941)  $\Rightarrow$  rotational temp ≈ 2.3K



Herzberg (1950): "...only a very restricted meaning"

100

# THE ASTROPHYSICAL JOURNAL

MARGINE 1

JULY L 1961 to the last

> IPECTRAL IND PROTOMETRIC MEASUREMENTS OF SOLAR X-RAY EXTREME MELOW OF \$

R. L. SLARS,<sup>4</sup> T. A. CHONE, H. FERTMERS, 2007 A. K. UNIVERSE R. H. Mallari, Vision In: Specific Structure, VI: A Specific System in System (Neurosci), 2007. Biology 5 (2007).

# 10075-017

The second comparison of the Lagrangian structure of the second structure of

# -----

Normal Hammarch Ladoraneum: Tearn hard new Antohem readors on April 1 and 41, on almost the approximate of state 25 cars and their Magleman devolutions devolutions and the approximate of the approximate of the state of the Approximate of the state of the state of the state of the state of the devolution of the lase devices the high data of the state of t 4. Achiel is produces and its appendix flata bloc del provide belows device. We say the form the set of provide and the flat is an exception of the set of the set

# same catalog over the section.

In provide quantum-network provided of a member we call differ in particular, as single to distribution, and it is inclusively in the origin of the coupled distribution of the the inclusion of the coupled distribution of the couple distribution of the the second second. Second approaches of coupled distribution of the couple distribution of the distribution and the coupled quark of the coupled distribution of the coupled distribution of the order and coupled quark of the coupled quark of the coupled quark distribution of the distribution of the coupled quark of the distribution of the coupled quark distribution of the coupled quark distribution of the coupled quark of the coupled quark of the coupled quark distribution of the coupled quark dis

# the install of the University of University Resident I have been a supported to the Office of New Yorkshow and the Newson's Science Transmission

LETTERS TO THE ROOM \*\*\*

1 for her business, provided the build due to the solutions of safes gain. Man scalar galaxies ([96], whose optical properties as similar in these of (\$60°) that 7400. of the limit lines he

pand adding photon ([1015]) where spin-1d properties are mindre in these of QUES . These TWEST is the transmission of the state of the transmission of the transmissi

Assen formation Features Tillatore

104.142

L'an aller

# COMMENTARIAN MUSIC MADANTERY.

One of the basic gooldsteen of correcting in the singularity choice levels of the basility mentioping inductions of Eleventry's built reparities. Also possible if the presence of way is the distance areas consistentian in the controls. For Encourse and Spitom and Houghli is the assessed. Thus, is the Francessell of inductional distance we control tradition for the of encourse areas and the anisotropy of an advected and the state correspond-ted on encourse on the anisotropy. The one fieldingful the state corresponds to the of 90 with a state of the state of

perfolium. The summaries of continuous casesion (Band and fault First, Banks 1968), which is the singularity to possible range of the same casesing the of the same is continuous and controlline of our same in the same transmission of any matters in internation on an experime (Manuse FFR), then the contains of any matters in internation was to the contentue of the singularity, can be described and their hypothesis of the possible of the singularity, and is a sprayer matters introlucial of transmission of themselves build spatiation. The samespine for the integration can be been been to the singularity and the singularity and the sprayer matters in the definition of the singularity of the singularity of the singularity of the singularity of the definition of the singularity of

"This means in equipment is part by the Reliant Asiana Providence and the Obio of Neural and the U.S. Neural

## LATTERS IN THE SOUTH 34.4,996

the sequences of exist larger as actionating and that it would not more in the test acquit (Wheeler 1988, United and Kinderschere 1987).

It this third prevalue is accepted were investigated as a working hyperbasis, it reacts with it a units in reactivities of the second periodes, for the scores were as about to now your state.

parents instantistic of the second particles, but its strength with strength theory that the second strength of th

binty of the non-resulting readings from Dicke from the second Dick is the Discretion of the second Dick is a second Dick in the second Dick is the second Dick is a second Dick is a second Dick is the second Dick is the second Dick is a second Dick in the second Dick is a second Dick is a second Dick is a second Dick is a distribution of the second Dick is a second Dick is a second Dick is a distribution of the second Dick is a second Dick is a second Dick is a distribution of the second Dick is a second Dick is a second Dick is a distribution of the second Dick is a second

Two disc (P. I) R. and D. T. R. Phys. operated a reducence and we These of the (1, 1, 1), is and (1), 2, T. W. These constrained a problematic and secological properties of an indexed secondary of the second

# LETTING TO THE ADDING.

100

109

of in \$7.5. The in has to the hard-ground that to the store

. The constrained to the background data is the atomic plane in particular data in the constraint of the statement of the statement of the statement of the statement data with the statement of the statement data with the statement data with the statement data with the statement of the statement data with the statement data w

<text><text><text><text><text><text>

With all the data are ten just in hand we propose to present here the provide reach-ment to be deven if we instantiately assesses that the measurement of Privata and Wilson 1981) do instantiate their distances of 1.1° K. We the measurement that the questiones to be considered to be family and andreasy, and that the present energy density to prov-



But the second s

Section Description of a motion official based. Locating based on the section of the description of the d

There says the detects of the



initiand collimits is a usual part of the whole. Whether (2000) has remarked that provide

<page-header><page-header><text><text><text><text><text><text><text>

Ro. 1, 1941

144.142

LETTERS TO THE RESTOR.

247 Add presents such as the second model spectra of spectra dispersion in the second model spectra of spectra dispersion of the spectra dispersion dispersi dispersion dispersion d

We dought approxime the brightleward Dre, Paralan and Witnes of the Boll Tringshote Laborationer, Constant BRI, Estimatel, New Jarrey, in thesauting with an the result of Drey transmissioners and in develop at 3 an invasional optime, We are the granulat be writted height suggestions at 2 (Paralameter, A. Wander,

F. S. E. Provinces F. C. Brits D. T. Witspamore

410

APPROXIMATION AND

(ing. 1, (inc) Personal Personal Longenceuror Report State, State Statest

102 11 mil A of J. Sin, Annuel, Mil 100 12 mil Annuel, Y. J. Wall, Annuel, Mil 100 13 V. W. of Adaptionize A in 1998, Adv. in Phys., 93, 103 13 W. Will, Le Dimanne of Hadawe & Francesco (His Marcy ) and (Brancel, Elizione, Scangel), 1 W. Will, Le Dimanne of Hadawe & Francesco (His Marcy ) and (Brancel, Elizione, Scangel), 1 W. Will, Le Dimanne of Hadawe & Francesco (His Marcy ) and (Brancel, Elizione, Scangel), 1 W. Will, Le Dimanne of Hadawe & Francesco (His Marcy ) and (Brancel, Elizione, Scangel), 1 W. Will, Le Dimanne (His Marc), Scangel (His Marc)

[1] S. (10), Phys. Rev. D (2019) representation in the second state of the physical distance of the second state of the sec

Har, C. V., and Marriel M. & Mersley & Advances in Property 1998. Molecular Conf. J. Math. Mol. 1, J. V. Barriel, S. Marriel, et al. Advances in Taxaban Math. Soc. Soc. Phys. Rev. D 55, 100 (1998), p. 103. Bernell, St. B. Med, State Phys. -- (1477) P., va. 1946

A MEAN REMEAT OF ENCENS ANTENNA TEMPERATURE AT 1000 Mars

Biomensumed of the officient activity active recordences of the 20-last barn office to entonion of variation. Henge, and Plane 1990; or the Venetation Hill Lasternary, Reimidel, New Jense, or will be the closer priods to value about 1.0" & Sights Barnery, Reimidel, one recordences is, while its first in the second second second priod. The

# LETTERS TO THE IDED.

141.142

107 LETTER IN THE LOCID IN 1. A LET THE DESTINATION OF THE LOCID IN 1. A Real Strain Statistical Statistics of the second accurate which responsible to the site spaces by DNAL. Building statistical second strain the second accurate which responsible the site site site. The second strain strai

where L and conserting up (1) the structure is the sensitive measurements of the schemester of the extension. The schemester is the sensitive measurements of the schemester of the schemester based in two schemesters in the scenarios measurements are been extended on the schemester based in two schemesters. This much, 1 ⊂ 1 ⊂  $T_{-}$  is a final schemester is the schemester is the schemester of the schemester of the schemester is the schemester is the schemester is the schemester of the schemester is the schemester is the schemester is the schemester of the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schemester is the schemester is the schemester is provided in the schemester is the schem

and ease of the attest with duration up a search to intervalse damps of the terms. The localizer experime to granule multilizer for inside its fits the fits of K-fits tree-manner (C). Monoscenses of the response of the accession is a weak of the subscripts of the N-fits before interval of the interval of the response of the accession is a second to be of the before interval of the interval of the response of the interval one of the accession is the N-fit before interval of the interval of the interval of the interval one of the accession is a particle, N. However, we can be a set of the interval of the interval one of the interval of the interval particle, N. However, we can be a set of the interval of the interval of the interval of the interval particle, N. However, one was a set of the interval of the interval of the interval of the interval particle, N. However, we can be a set of the interval of the interval of the interval of the interval particle, N. However, the interval of the interval of

errors have back hole. The second of the prime we propose the encoding sizes are which for exceeding the proposed on the form of the prime second of the prime second

We use granulat to R. H. Thilus and kin canadians for builded discussions of their te-radia gains to calification. We also made to schemelingly with thesits for world concernen-and advices of A. K. Coveford, D. C. Hang, and E. A. Ulter in concerning with the pathleres matching why this concernence.

LOTTERS TO THE SUPPORT

Are obtain its party.—The bighter frequency or which the background temperature of the dep has a measured preventy to a HM. Mol. 5 Analogs that and Hadahad (\$2, where a solution to supported of H K is a decreed C and indicate one the effect of the solution of the source of the background relation on the phases; equal to be encourse in \$27. The decreed of another the analysis the unique to the source of the two of the phases in the analysis of the solution of the two of the source of the phases. In the solution the unique to the source of the two of the phases in a solution in the solution of the two of the two of the source of the phases in a solution in the solution of the source of the two of the source of the phases in a solution in the solution of the solution of the two of the source of the source of the source of the solution of the source of the two of the source o

A. A. Passais

421

Mar 11, 1997 And the Party of the

No. 1, 1997

where  $\lambda \in \mathcal{M}_{2}$  and  $\lambda \in \mathcal$ 

3-1,000 Management Scenters EXAMPLE:

In the paper "Turker Research 1. The Approach to the Main Segment" (2.4)  $A_1$  (44, 76), the behaviory store cases on twice analy gaps "M. In  $A_1$  replace hyperbolic transmission of the store for the transmission of the store of the stor have been by



Where did the CMB $e$ Kelvin(= 2.718 K)	
temperature $\sqrt{15/2}$ Kelvin(= 2.739 K)	
<b>come trom?</b> $30/11 \text{ Kelvin} (= 2.727 \text{ K})$	
(Fixsen 2009) $-\ln(9\alpha)  \text{Kelvin}(= 2.723  \text{K})$	
Triple point of water $\div 100(=2.7315 \text{ K})$	
$(2\alpha/\pi)^4 m_e c^2/k \ (= 2.762 \mathrm{K})$	
$(2/5)(\alpha_{\rm G}m_e/2\pi m_p)^{1/4}m_pc^2/k \ (= 2.719{\rm K})$	
$[\alpha_{\rm G} \equiv G m_e^2 / c\hbar] = 16\sqrt{2}\pi \alpha_{\rm G}^{1/4} m_e c^2 / k \ (= 2.727 \rm{K})$	
$(hc/k) \ \mu \text{Leagues}^{-1} (= 2.98 \text{ K})$	
$[\pi e^{\pi} \simeq 73]$ $e^{-73}T_{\rm Pl} (= 2.805 \mathrm{K})$	1











3000K
Photosphere 10% thick
Thomson scattering
~billion photons per atom
CMBology
No special directions
Fundamental mode in time
Info from power spectra
Synchronized init. conds.
Variability ~Gy <u>rs</u>



Cosmological perturbations are like standing waves, with a node at t=0, and observed as a snapshot at recombination

Wayne Hu

# Origin of acoustic peaks



Simplified explanation of acoustics: Scott & White, "Echoes of Gravity" arXiv.org/abs/astro-ph/9505102

CMB mini-review in RPP/PDG by Scott & Smoot pdg.lbl.gov/2022/reviews/contents\_sports.html

> For more description see Wayne Hu's web-pages: background.uchicago.edu/~whu/

# Temperature effect plus sub-dominant out-of-phase Doppler effect



Multiplied by damping envelope



e.g. camb (now cobaya) or class

Statistical description of anisotropies Expand sky in spherical harmonics  $T(\theta, \phi) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\theta, \phi)$ Monopole is To (=aoo) Dipole is our "absolute motion"  $\ell \ge 2$  modes give info on perturbations  $C_{\ell} \equiv \langle |a_{\ell m}|^2 \rangle$  i.e. average over ms  $(2\ell + 1)C_{\ell}/4\pi$  is power at each  $\ell$ 

# Statistical description of anisotropies

- Remember: we are measuring variance
- Variance of variance is:  $\{2/(2\ell+1)\}C_{\ell}^2$
- 🛊 This is "Cosmic variance"
- $\mathbf{k}$  Gives "theory uncertainty" at low  $\ell$
- ("Precision" for our realization
  <u>vs "acc</u>uracy" for underlying theory)
- 😫 Enhanced for partial sky coverage



Acoustic peaks easy to see (8 or 9 here, ~40 peaks and troughs in all power spectra)











# Information in the CMB CMB partially polarized 2 numbers for each pixel (as well as T) → call these "E" and "B" 4 correlations to measure: TT, TE, EE, BB → 4 different power spectra (TB and EB are zero) plus "non-Gaussian" signatures

# All-sky Cosmic Polarization (from Planck)



# Polarization Observables

- Linear polarization expected only
- Measure x and y E-fields
- Convert to Q and U Stokes parameters
- Or use pseudo-vectors with P<sup>2</sup>=(Q<sup>2</sup>+U<sup>2</sup>) and tan20=U/Q
- Or use coordinate-free geometric pair, "E" and "B"



TE















# **B-modes**

- Require source with handedness
   ⇒ Gravity waves (not density perts.)
- Gravity waves generated during inflation Amplitude ∝ inflationary energy scale
   ⇒probe of 10<sup>16</sup> GeV physics!
- Lots of experiments planned Hard!



But... polarized foregrounds are complicated and MUCH brighter!

# Can precisely calculate 4 power spectra (given a set of parameters)



# Information in the CMB

- CMB partially polarized
- 2 numbers for each pixel (as well as T)
   call these "E" and "B"
- 4 correlations to measure: TT, TE, EE, BB
   4 different power spectra
- (TB and EB are zero)
- plus "non-Gaussian" signatures

# Polarization: why bother?

- Check CMB is polarized as expected for Thomson scattering at z=1100
- Out of phase with Temp., confirming adiabatic modes + signature of superhorizon fluctuations at large angles
- Reionization signature for lowest multipoles
- Breaks some parameter degeneracies
- Go to higher l because no foregrounds
- Can we detect inflationary B-modes?

# **B-modes**

Require source with handedness
 ⇒ Gravity waves (not density perts.)

 Gravity waves generated during inflation Amplitude ∝ inflationary energy scale
 ⇒ probe of 10<sup>16</sup> GeV physics!

- •Lots of experiments planned But HARD!
- •If  $V=m^2\phi^2$  and  $n\approx 0.95$ , then  $r=T/S\approx 0.15$  $\Rightarrow$  ruled out!
- •New target is "large field excursion models", where r>0.001 expected



LiteBIRD will provide the definitive map of CMB polarization on degree and larger angular scales to search for the 'smoking gun' of inflation.

# CMB future

- ACT-Pol, SPT-3G, BICEP, ...
- Simons Observatory
- Litebird
- CMB-S4
- Spectral distortions?

Prog. Theor. Exp. Phys. 2015, 00000 (156 pages) DOI: 10.1003/parg/000000000

# Probing Cosmic Inflation with the LiteBIRD Cosmic Microwave Background Polarization Survey

# LiteBIRD Collaboration"

2202.02773v3 [astro-ph.IM] 27 Mar 2023

and the second	
E. Allys <sup>1</sup> , K. Arnold <sup>2</sup> , J. Auxont <sup>3</sup> , R. Autisn <sup>3</sup> , S. Antoni <sup>5,8</sup> , C. Baccigalupi <sup>7,8,9</sup> ,	
A. J. Bauday <sup>3</sup> , R. Banerji <sup>4</sup> , R. S. Barreiro <sup>10</sup> , N. Bartolo <sup>13,3111</sup> , L. Bautisto <sup>3</sup> ,	
D. Beck <sup>13</sup> , S. Beckman <sup>15</sup> , M. Brewanelli <sup>10,17</sup> , F. Boulanger <sup>1</sup> , M. Brilenkov <sup>1</sup>	
M. Bacher <sup>10</sup> , E. Calabreac <sup>10</sup> , P. Campeti <sup>20</sup> , A. Canner <sup>21,22</sup> , F. J. Canad <sup>10</sup> ,	
A. Catalano <sup>23</sup> , V. Chan <sup>24</sup> , K. Cheung <sup>11,21,28</sup> , Y. Chinome <sup>4,37</sup> , S. E. Chark <sup>14,28</sup>	
F. Columbro <sup>20,30</sup> , G. D'Alessandro <sup>20,30</sup> , P. de Bernardis <sup>20,30</sup> , T. de Baan <sup>20</sup> ,	
E. de la Hor <sup>10,10</sup> M. De Petris <sup>20,30</sup> S. Della Torre <sup>31</sup> , P. Dients-Palameter <sup>10,10</sup>	
M Dobba <sup>20</sup> T Dynari <sup>25,80</sup> J M Dova <sup>20</sup> T Hielos <sup>20</sup> B K Frihms <sup>1</sup> J Frend <sup>10</sup>	
T. Eminane Hilsman <sup>30</sup> , F. Finelli <sup>40,41</sup> , R. Flasser <sup>2</sup> , C. Franceschet <sup>10,17</sup> , U. Finkeland <sup>4</sup> .	
M Colores <sup>4</sup> K Central <sup>8</sup> M Certaind <sup>12</sup> M Certain <sup>10,43</sup> B T Cincen Sector <sup>40,41</sup>	
T Chima <sup>1,0</sup> S Classicalle <sup>40</sup> E Classical <sup>4</sup> J Casin <sup>47</sup> E Council <sup>8</sup> A Councerel <sup>8,41</sup>	
1.8 Cadmandaren <sup>40</sup> N.W. Habarran <sup>40</sup> P.Hartmar <sup>10</sup> , T. Handa <sup>4</sup>	
V Daman [0,0,0] V Bernet (0,0,0,0) C Barry Vertility D Barder H	
L T Hearth D Harman P House B B & Blanch H & Harman B & Station H	
THE REPORT OF THE REPORT OF THE PARTY OF THE	
S Printed A Print A Dist in them in being in the second se	
A. Katayanak, A. Katar, K. Kenskinas, T. Katar, T. Katarana,	
A, Kogat", K. Koleri", E. Komatsu", K. Komatsu", K. Komatsu	
N. Krathmannoolf ", C. L. Kun ", L. Lamagna", M. Latland",	
A. T. Lestinian, C. Lolospin, F. Levrier, E. Linderson, G. Lamin,	
J. Machan-Pervan, T. Machanek <sup>an</sup> , B. Maffer <sup>an</sup> , D. Maino <sup>10</sup> , S. Maeshelli <sup>10,17</sup> ,	
E. Martinez-Gonaller <sup>10</sup> , S. Masi <sup>10,00</sup> , M. Massa <sup>41</sup> , S. Matarrose <sup>11,12,13,00</sup>	
F. T. Matsuda <sup>40</sup> , T. Matsuzuara <sup>6</sup> , L. Mele <sup>29,40</sup> , M. Migliaccuo <sup>21,22</sup> , Y. Mixami <sup>49</sup>	
A. Mogg <sup>ar</sup> , J. Montgomery <sup>44</sup> , L. Montier <sup>3</sup> , G. Morgante <sup>40</sup> , B. Mot <sup>4</sup> , Y. Nagano <sup>81</sup>	
T. Nagasaki <sup>21</sup> , R. Nagata <sup>20</sup> , R. Nakano <sup>21,71</sup> , T. Namikawa <sup>6</sup> , F. Nati <sup>11,10</sup> , P. Natoli <sup>42,10</sup> ,	
S. Nerval <sup>24</sup> , F. Novielle <sup>10</sup> , K. Odagin <sup>40</sup> , S. Ogari <sup>40</sup> , H. Olsaki <sup>42</sup> , L. Pagano <sup>41,10,17</sup>	
A. Paiella <sup>20,10</sup> , D. Paoletti <sup>40,41</sup> , A. Passerini <sup>31,11</sup> , G. Patanchen <sup>15</sup> , F. Piacentini <sup>20,10</sup>	
M. Piat <sup>10</sup> , G. Pisano <sup>10,00,00</sup> , G. Pulenta <sup>40</sup> , D. Poletti <sup>10,10</sup> , T. Prozvo <sup>10</sup> , G. Paglas <sup>21,30</sup> ,	
10 10 1 10 10 10 10 10 10 10 10 10 10 10	

# CMB-S4 Science Book, First Edition

CMB-54 Collaboration (Kevork N. Abazajian (J.C. Weys), Peter Adahead (News U. Unava Inset), Zasahan Ahmed (LLAC), Staven W. Alian martier (1), David Alonso (tales (1), Nam S. Arnold (U.: Iwa David), Carlo Baccigalish (cord), Award, Arnes G. Bartlett (V.C. Hveg, Nicholas Battaglia (threads), Stadford A. Berson (transac), Cain A. Becholf (Constraint U), Julian Bortill (toC: Sensey), Woth Buzz Personal U), Emmini Catabatele (tolesco), Robert Catabatel (tolesco), Julian E. Catabatere (tolesco), Cataros E. C. Chard, Mysone Helin, Thomas M. Crawford (charge U), Francis-Yan Cyr-Racine (terrestic U), Francesco De Bernardis (construct)), Tjimen de Hean (UC. Betweet, Spendlo & Serego Alghier (Invest Oserv), Joanna Dunkley (Investor U), Cota Divorkin (Henries U), Josquin Errard (Lin Pano), Gluto Fabbian (355A, Trues), Stephen Feenay (CIA, Prezen), Simone Femaro (UC, Bekeley), Jeffrey P. Föppini (Involu., Utarra (Inard), Raphael Flauger, George M. Fuller (JC. San Degr), Vera Glutcevic (no: Anwood Suny, Butapet), Daniel Green (JC. Swiwey), Daniel Gren prevenue cars), Evan Groha (elunger LL), Jason W. Henning (charge LL), J. Coln Hill (churres LL), Renée Hozek (class inst.), Gibert Holder (Sixon U., University and Milliam Holdspfel (UCLA), Wayne Huldowys U.), Kevin M. Huffenberger (Honor Sixon U.), Reijo Keskitalo (LIN, Berkeny), Lloyd Knox (UC, Deve), Arthur Kosowsky (Plasturgh U.), John Kovet (Navers U.), Ely D. Kovetz (Johns Hopsons U.), Chelo-Lin Kuo (kuAc), Akito Kusaka (J.K. Benerey), Maude Le Joune (APC, Pani), Adrian T, Loe (UC, Benerey), Marc Lilley (AP, Chenwo), Maritona Loverde (vitre taxes trous), Mathew S. Mathewacheril (hwooser u.), Adam Mantz (stantoni L.), David J.E. Marsh progs Col. Lover), Jeffrey McMahon peckeer U.L. Pieter Daniel Meerburg (Canadan Inst. Their Astrophys.), Joel Meyers (Canadan Inst. Theor Astrophys.), Amber D. Millor Southern California U.J., Julian B. Mundz (Johns Hopkins U.J., Ho Nam Nguyen (1177), Sony Book), Michael D. Niemack (Convell U.S., Marton Petidec (Ministra U), Julien Peloton (Jusses U), Levon Poposian (Junor Fraser U), Clement Phylie (Ministra U), Marco Raveri (Chicago U), Christian L. Reichardt (Network V.), Grace Rocha (Celver, JPL), Addya Rott (News See V.), Emmanuel Schaan (Network V.), Marcel M. Schmittlell (J.C. Senery), Douglas Scott (Inner Celverse V.), Neelma Sehgal (NTP. Bory Book), Sarah Shandera (New See V.), Bake D. Perwin (UC, Beneley), Tristan L. Smith (Inventione Col.), Lorenzo Sorbo plassectuaets U. Annerg, Glerin D. Starkman (Casa Western Pasery (u), Kyle T. Story (Service U), Alexander van Engelen (Caradan ive: Two Ameriys), Josquin D. Vietra (Invisit U, Usana (Inari)), Scott Watson (Symum U), Nathan Whitehom, WL, Kommy Wu (U), Jersey) (1998)

# Oct 9, 2016 - 204 pages

# FERMLAB-FN-1024-A-AE e-Print: arXiv:1810.02743 (astro-ph.CO) | PDF

# Abstract (arXiv)

This book lays out the scientific goals to be addressed by the next-generation ground-based coemic microwave background experiment, CMB-54, envisored to constal of dedicated telescopes at the South Pols, the high Chilese Alexanee plateau and possibly a northern tensinghore also, all equipped with new superconducting cameras. CMB-54 will dramatically advance cosmological studies by prossing ontical thresholds in the search for the 8-mode polarization signature of primordiar gravitational waves, in the determination of the number and masses of the reactinos, in the search for evidence of new light relice, in combining the nature of dark energy, and in testing general nativity on large scales.

Keywordje: NSPRE: psylatione.indetice.intendel insultins.mew | identic bediptioned reliation | peceral midtyte | superconductivity | coornil.bediptioned.reliation; poletization | det.energy | it medie







