

# The Status and Outlook of Cosmic Microwave Background Polarization Measurements

Dr. Kyle Helson  
University of Maryland Baltimore County  
Goddard Space Flight Center

UMD Astro Colloquium

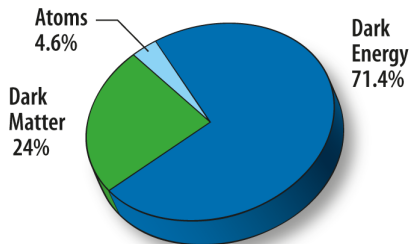
October 20, 2021

- 1 The Cosmic Microwave Background
- 2 Cosmic Inflation
- 3 CMB Polarization
- 4 Measuring the CMB Polarization

# The Cosmic Microwave Background

# $\Lambda$ CDM Cosmology

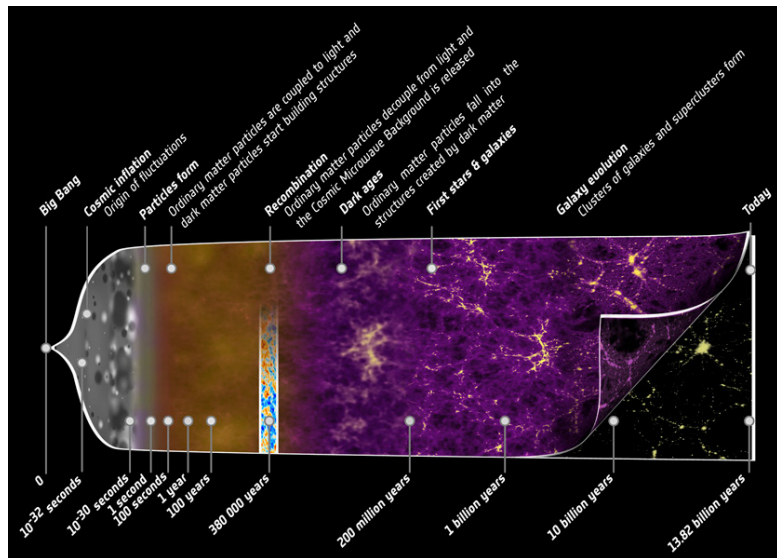
- Universe is homogenous and isotropic on  $\sim 100$  Mpc scales
- Intrinsic curvature/geometry:  $k, \Omega_k$
- Three primary constituents
  - Baryonic Matter
  - Dark Matter
  - Dark Energy



TODAY

- Unique observables:
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis (BBN)
  - (Accelerating) Expansion
    - Type Ia supernovae data
  - Large Scale-Structure of Matter
    - BAO, Weak Lensing surveys, etc.

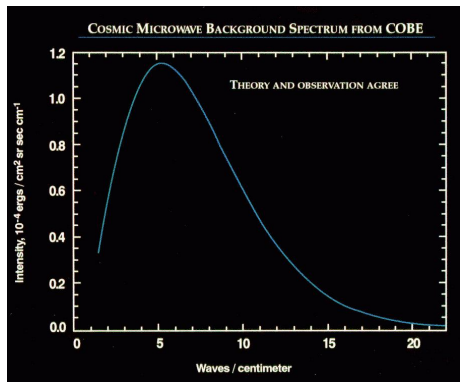
# Thermal History of the Universe



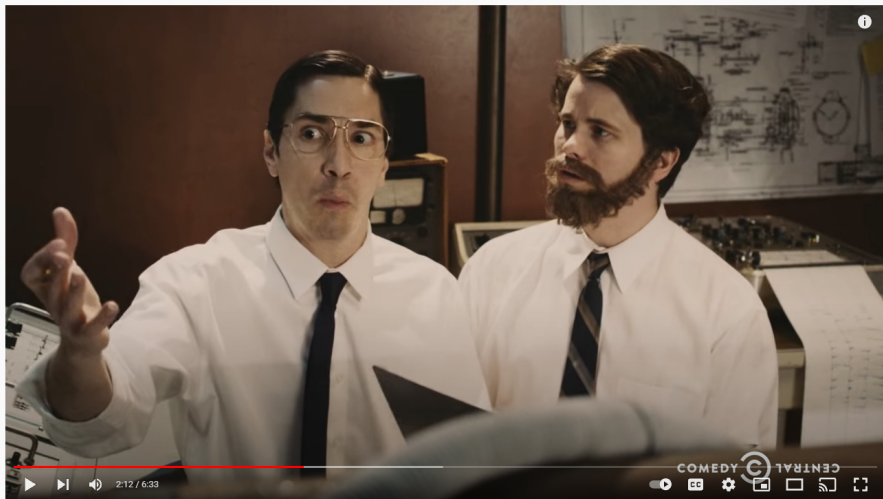
From the Planck Collaboration

# CMB Basics

- Discovered in 1965 by Robert Wilson and Arno Penzias at Bell Labs
- Near perfect blackbody at  $2.725 \pm 0.001$  K
- Highly isotropic;  $\sim 10^{-5}$
- Light released during Recombination
  - Primordial plasma cools with expansion of the Universe
  - Universe reaches  $\sim 3000$  K
  - Formation of neutral hydrogen
  - Photo-baryon decoupling
  - Last-scattering at  $z \simeq 1100$



# CMB Basics

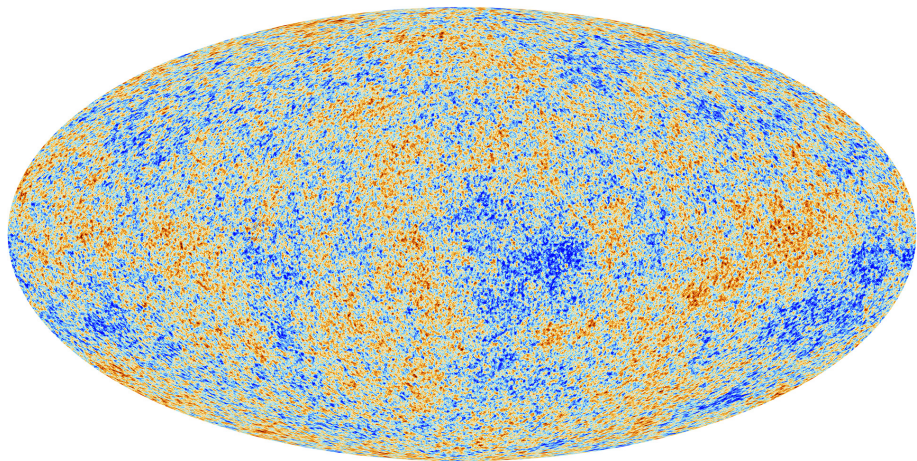


Drunk History - A Sound in Space (ft. Jenny Slate and Justin Long)

1,736,153 views · Sep 2, 2015

21K 459 SHARE SAVE ...

# The Cosmic Microwave Background as Seen by Planck



# CMB Anisotropies

- CMB anisotropies arise from phenomena in the early and recent Universe.
- Primordial anisotropies:
  - Primordial temperature/density fluctuations
  - Sachs-Wolfe Effect
  - Doppler effect of plasma vortices (negligible)
  - Gravitational wave distortion of particle density
- Recent anisotropies:
  - Integrated Sachs-Wolfe Effect
  - Sunyaev Zel'Dovich (SZ) Effect
  - Weak Gravitational Lensing

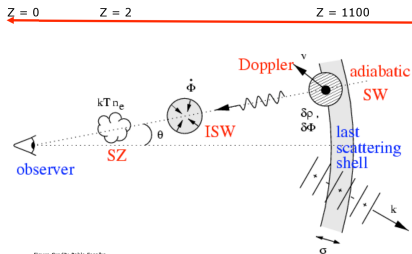
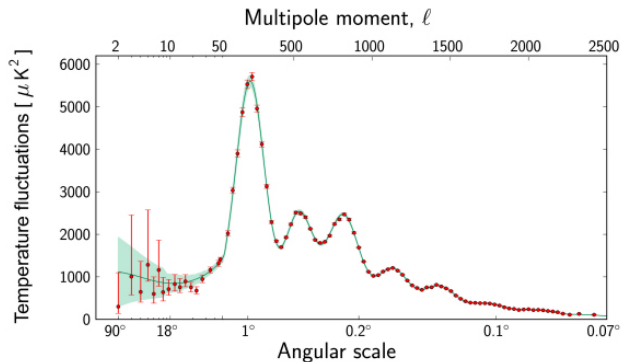


Figure Credit: Pablo Posa

- The SZ effect has been used to find thousands of high redshift galaxy clusters
- Cosmic neutrino background impacts anisotropies; constraint on  $\nu$  mass

# A Look at the CMB Power Spectrum

- The CMB sky maps can be converted into an angular power spectra
- Cosmological parameters determine the shape and location of the peaks in the CMB power spectrum, e.g. geometry of the Universe determines the location of the first acoustic peak



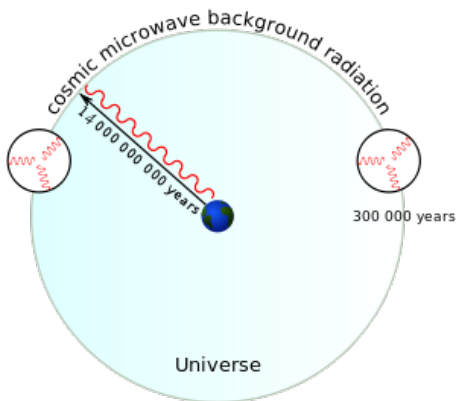
From the Planck Collaboration



# Cosmic Inflation

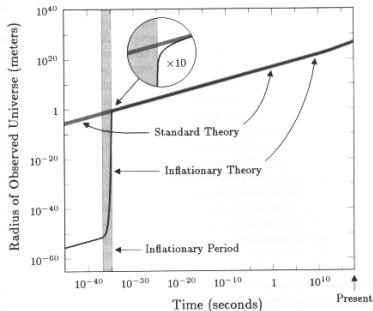
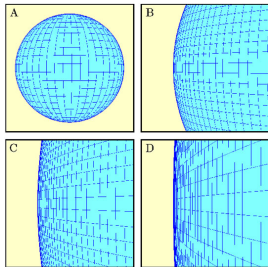
# Cosmological Problems

- Big Bang Cosmology has several “open” problems
- Exotic particle problem
  - High energies in the early Universe are favorable conditions for the creation of exotic particles like magnetic monopoles, yet we observe none.
- Flatness problem
  - Universe is flat to  $\sim 10^{-2}$  today; fine-tuning problem
- Horizon problem
  - Ordinary, linear expansion does not give the CMB time to be one causally connected region



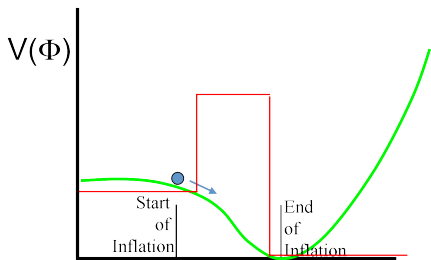
# Inflation Solution

- In the 80s, Albrecht, Guth, Linde, and Steinhardt proposed “Cosmic Inflation” as a solution to these three problems
  - $\sim 60$  e-folds of growth causally connects CMB, flattens out curvature, and dilutes exotic particle density
  - Inflation turns quantum density perturbations into macroscopic ones



# Inflation Details

- Inflation requires at least the introduction of a new scalar field
- Dynamics of the scalar field drive inflation
  - The Universe sits at false vacuum and rolls into “true” vacuum.
  - The Universe exists in a higher energy state and quantum tunnels to a lower one
- Simplest models have
  - $E \sim 10^{15} - 10^{16} \text{ GeV}$
  - $t \sim 10^{-33} \text{ s}$
  - Near the GUT scale

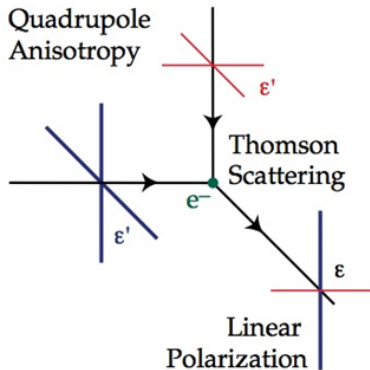


- So called “slow-roll” Inflation is the preferred model today

# CMB Polarization

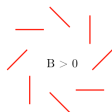
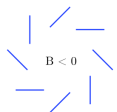
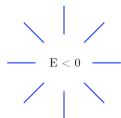
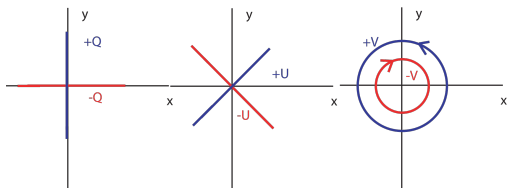
# From Anisotropy to Polarization

- Primordial CMB anisotropies perturb the local metric
- Quadrupolar anisotropy yields slight linear polarization from Thomson scattering
- Under local spherical harmonic decomposition ( $Y_\ell^m(\phi, \theta)$ ) scalar, vector, and tensor perturbations represent  $\ell = 2$ ,  $m = \pm 0, 1, 2$  modes respectively



<http://background.uchicago.edu/~whu/polar/webversion/node3.html>

# Stokes Parameters and Linear Polarization

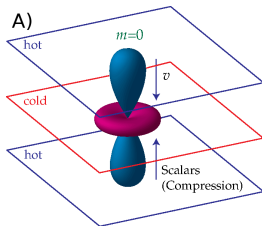


- Polarization can also be broken down into Stokes' Parameters,  $I, Q, U, V$ , so as not to be coordinate system dependent
- Only linear components  $Q$  and  $U$  are of interest for the CMB; circular polarization is expected to be zero
- Linear polarization can be decomposed into two modes
  - Curl-free or E-mode (positive parity)
  - Divergence-free or B-mode (negative parity)

# Polarization from Scalar, Vector and Tensor Perturbations

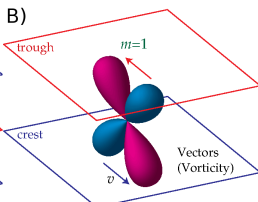
## Scalar Perturbations (Pure E)

- Slight increases or decreases in temperature/density of the primordial plasma



## Vector Perturbations (Pure B)

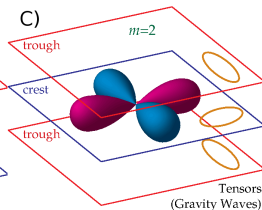
- Vortices or eddies in the plasma
- Decay away as  $\sim 1/a$ .



Source: <http://background.uchicago.edu/~whu/polar/webversion/polar.html>

## Tensor Perturbations (Mix of E and B)

- Inflationary gravity waves
- Weak Gravitational lensing



# Primordial B-modes from Inflation

- Inflation predicts gravitational wave amplitude
- $V_{\text{Inf}}^{\frac{1}{4}} \simeq \left(\frac{r}{0.1}\right)^{\frac{1}{4}} \times 10^{16} \text{ GeV}$

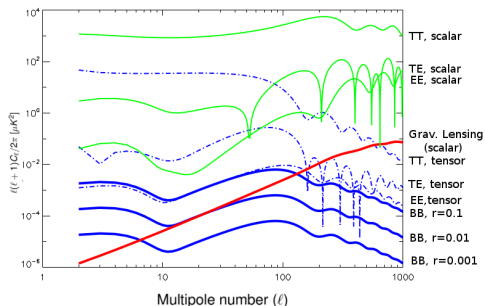


Figure credit: M. Bucher

- Gravitational wave amplitude is parameterized by  $r$ , the tensor-to-scalar ratio.
- As a power spectrum, BB amplitude constrains  $r$  and the energy scale of Inflation.
- Measuring B-mode polarization is the goal of many current CMB experiments

# Measuring the CMB Polarization

# CMB Polarization Measurements

- First detection of E-mode polarization by the Degree Angular Scale Interferometer (DASI) from the South Pole 2001
- Wilkinson Microwave Anisotropy Probe (WMAP) releases TE spectrum results 2003, EE in '06, final data release in '12.
- BOOMERanG (Balloon Observations Of Millimetric Extragalactic Radiation AND Geophysics) measures the EE power spectrum in 2003.
- Cosmic Background Imager (CBI) makes EE measurements from the Atacama Desert, 2004.
- The South Pole Telescope (SPT) makes the first gravitational lensing B-mode measurements, Sept. 2013.
- POLARBEAR makes the first lensing BB power spectrum measurements, March 2014
- The Atacama Cosmology Telescope (ACT) measures lensing B-modes, Dec. 2014.
- Planck releases polarization data, 2015

# BICEP2 B-mode Measurements

- March 2014, BICEP2 (Background Imaging of Cosmic Extragalactic Polarization) announced the first detection of degree angular-scale B-mode polarization in the CMB
  - Very high amplitude,  $r \simeq 0.2$ , which had been long ruled out by WMAP, others
  - BICEP2 made their observations at only 150 GHz
- Announcement was met with mixed reactions from the community
- It was determined that BICEP2's signal was due to polarized foreground galactic dust
  - BICEP2 made their observations in a "low dust" region of the sky
  - They made an estimate of their foreground contamination from data available at the time
- BICEP2 and Planck collaborated to release a joint analysis in early 2015

# CMB Polarization Status

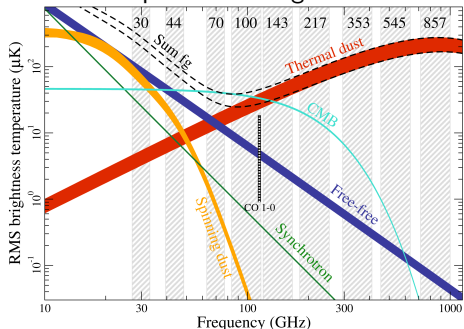
- E-mode polarization has been measured by many experiments.
- Small angular scale, gravitational lensing B-mode polarization has been measured by SPT, ACT, and Polarbear
- *October 2021 KECK/BICEP, Planck, WMAP, and BAO analysis suggests  $r < 0.036$  @ 95% CL*
- BICEP2 analysis highlights the importance of polarized galactic foreground measurements
- Many current experiments trying to measure B-modes
  - Ground: ACT, SPT, POLARBEAR/Simons Array, BICEP3/Keck Array, CLASS, Simons Observatory\*, CMB-S4\*
  - Balloon: SPIDER, PIPER, TAURUS\*
  - Satellite: LiteBIRD\* (JAXA 2028), PIXIE\* (proposed), PICO/CMB-pol\* (Decadal?)

# Experimental Challenges

- Measuring small signals is hard:  $\text{CMB}_T \simeq 3 \text{ K}$ ;  $\Delta_T \simeq 3 \times 10^{-4} \text{ K}$ ;  $\Delta_E \simeq 1 \times 10^{-6} \text{ K}$ ;  $\Delta_B \leq 10^{-7} \text{ K}$
- Increase number of detectors to beat down systematics; detectors are photon noise limited
- Limit background loading (balloon or space, use cold optics)
- Reduce  $1/f$  noise through polarization modulation
- Limit death by a thousand cuts from “small” systematics, e.g. knowledge of pointing, beam shape, bandpass, instrumental polarization, detector non-linearity, gain calibration, telescope cross-polarization, polarization calibration, detector time constants
- Measurements must be made at many frequencies to reject foreground signals

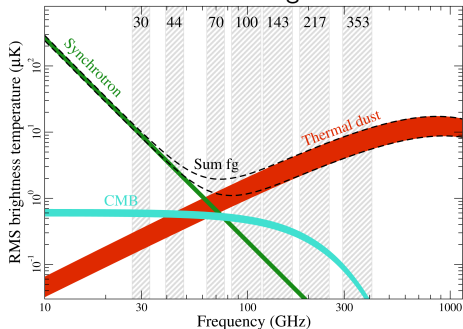
# Need to Fight Foregrounds

## Temperature Foregrounds



Figures from the Planck Collaboration

## Polarization Foregrounds



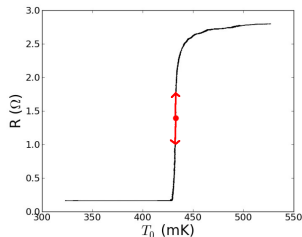
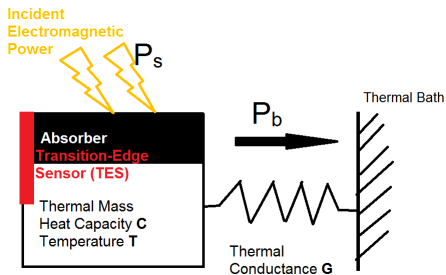
## Modern CMB Experiments

- Experiments have grown substantially in a short period of time
- Collaborations growing from  $\sim 20$  people to hundreds

Experiment	Mode	Year	N detectors
MAXIMA	balloon	1998	16 bolometers
WMAP	satellite	2002	20 radiometers
ACT	ground	2007	1,000 bolometers
PLANCK	satellite	2009	22 radiometers, 54 bolometers
EBEX	balloon	2013	1,000 bolometers
SPT-3G	ground	2017	15,000 TESes
Simons Observatory	ground	2020s	100,000
LiteBIRD	satellite	2020s	2000
CMB Stage 4 (S4)	ground	2030?	1,000,000???

# How Do We Do It?

- Most experiments have been “imagers”
  - Major results have come from interferometers, e.g. COBE, DASI, CBI
- Early experiments used High-electron-mobility transistor (HEMT) detectors, e.g. WMAP
- Today’s experiments use bolometers, often superconducting Transition-edge Sensor (TES) bolometers
  - Kinetic Inductance Detectors (KIDs) are also being pioneered in some experiments



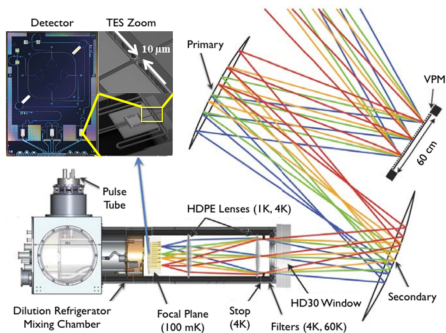
# CLASS

- I am a member of the Cosmology Large Angular Scale Surveyor (CLASS) collaboration.
- This work would not be possible without a whole host of people:

# CLASS Collaboration



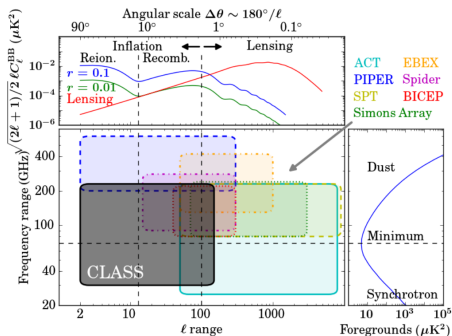
# CLASS Telescopes



- CLASS is a series of four receivers on two telescopes in the Atacama Desert in Northern Chile.
- One 40 GHz, two 90 GHz, and one 150/200 GHz receivers
- Unique Variable-delay Polarization Modulator (VPM) is first optical element, to ease removal of instrumental systematics

# CLASS Science Goals

- CLASS targets three primary science goals
  - B-mode polarization from gravitational waves produced during inflation
  - Make a cosmic-variance limited measurement of the optical depth to reionization through precision E-mode measurements
  - Constrain large scale structure and neutrino physics through grav-lensing induced structure correlations within and between the CMB temperature fluctuations, E-modes, and B-modes.



## CLASS Science Goals

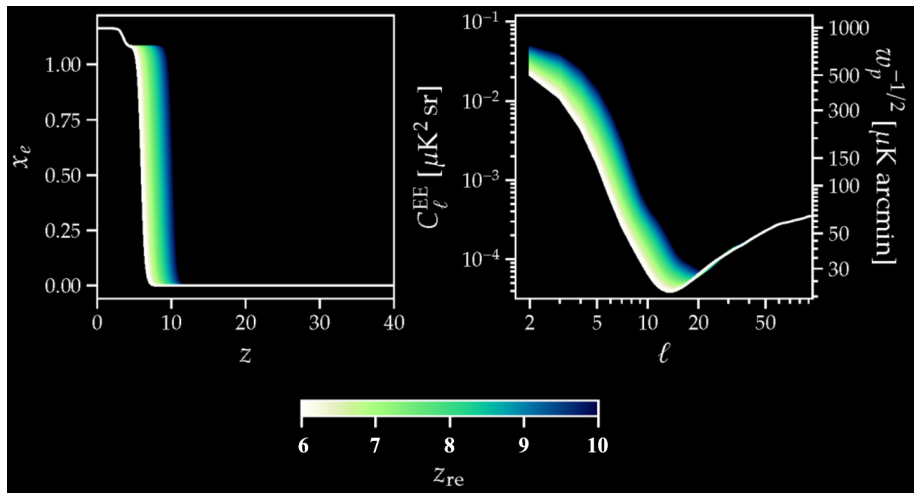
Parameter	Physical meaning	<i>Planck</i> Constraint	Precision
$\Omega_b h^2$	Baryonic mass fraction	$0.02233 \pm 0.00015$	0.07%
$\Omega_c h^2$	Cold dark matter mass fraction	$0.1198 \pm 0.0012$	1.00%
$100\theta_{MC}$	Angular size of acoustic oscillation	$1.04089 \pm 0.00031$	0.03%
$10^9 A_s$	Amplitude of primordial fluctuations	$2.100 \pm 0.030$	1.43%
$n_s$	Primordial spectral index	$0.9652 \pm 0.0042$	0.43%
$\tau$	Optical depth due to reionization	$0.0540 \pm 0.0074$	<b>13.70%</b>
$z_{re}$	Instantaneous reionization redshift	$7.64 \pm 0.74$	9.69%

The least constrained parameter

$$\tau \equiv \int_{t_{ISS}}^{t_0} \sigma_T n_e(t) c dt$$

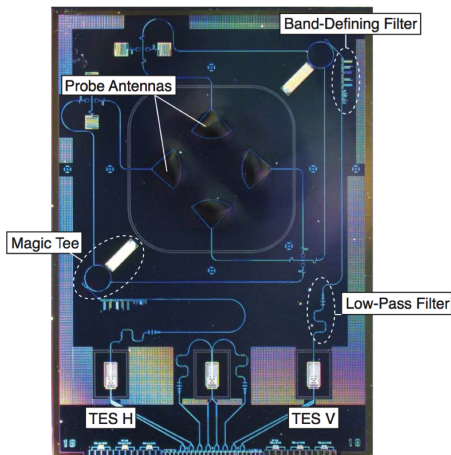
Planck 2018 Cosmological Parameters arXiv: 1807.06209

## CLASS Science Goals



D.Watts, et. al. 2020: arXiv: 1910.00590

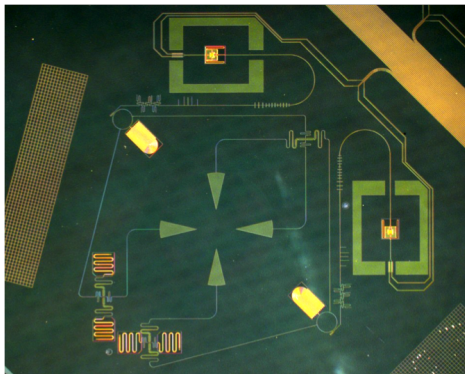
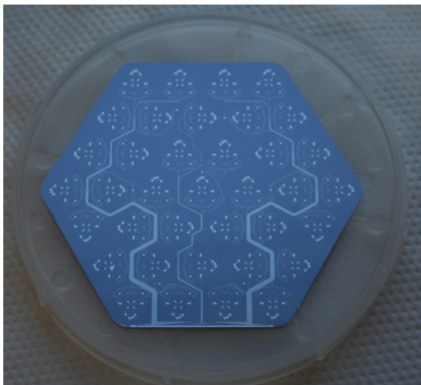
# What Do We Do at Goddard?



40GHz pixel

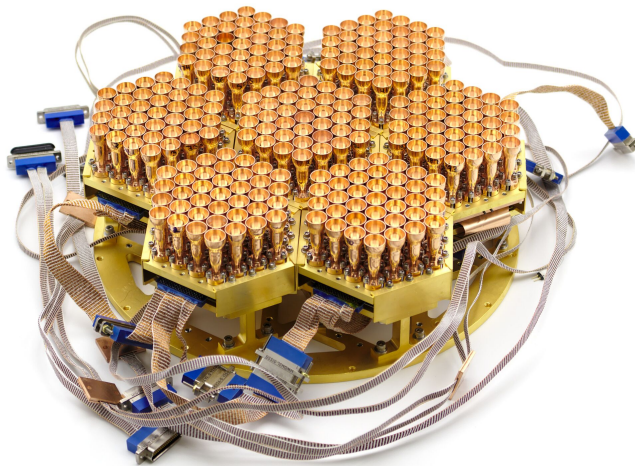
- Goddard has a history of developing state-of-the-art detectors and instrumentation for CMB experiments
- Each pixel in CLASS measures both orthogonal linear polarizations
- Goddard also developed the VPM technology.

# 90 GHz Sensor Details



- Space-flight optimized versions of these detectors are under development
- Microwave MUXing designs under test and development now

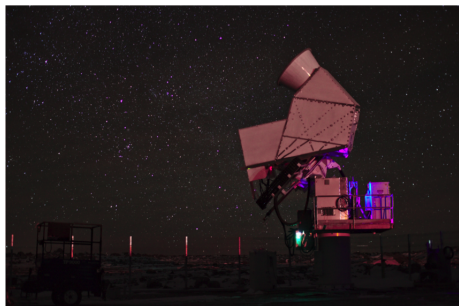
# Sensor Deployment



90 GHz Detector Focal Plane

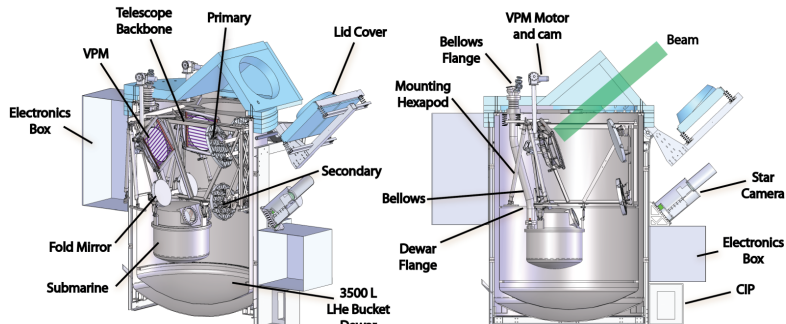
# Sensor Deployment

- Sensors are deployed now!
- 40, 90, and 150/220 GHz receivers all on sky.
- Dahal, Sumit, et al., “Four-year Cosmology Large Angular Scale Surveyor (CLASS) Observations: On-sky Receiver Performance at 40, 90, 150, and 220 GHz Frequency Bands”, arXiv:2107.08022



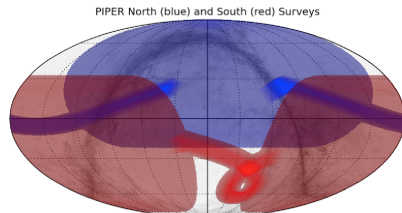
# PIPER Experiment

- I am also a member of the PIPER collaboration.
- PIPER is a GSFC-led CMB balloon-borne telescope to measure large-angular scale (low  $\ell$ ) polarization ( $\sim 90 - 1$  deg)
- PIPER TES detectors are made in the same foundry as CLASS
- PIPER is designed around shorter 12-36 hour North American or Australian high-altitude balloon flights



# PIPER Experiment

- PIPER is designed to measure the CMB and related foregrounds at frequencies only accessible by sub-orbital or satellite platforms - 200, 270, 350, and 600 GHz
- PIPER also features a VPM
- PIPER two telescopes inside one receiver, each with 32x40 arrays of Backshort Under Grid (BUG) bolometers.
- Each PIPER flight uses the same detectors with band-defining filters



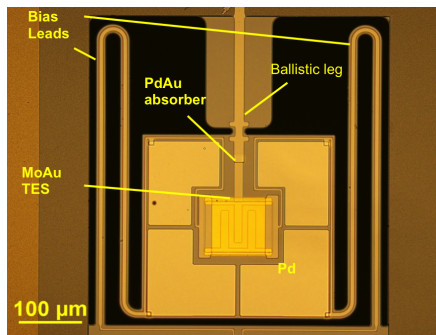
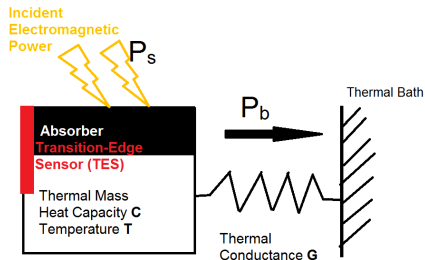
# Summary

- 50+ years of CMB measurements have yielded a wealth of knowledge about the Universe
- A whole host of on-going experimental efforts on the ground, balloons, and from space
- Small angular scale B-modes from gravitational lensing have been measured and confirmed
- Detection of large angular scale B-mode polarization consistent with Inflation remain elusive
- Experiments now address polarized foregrounds with the same importance as the CMB signal
- At Goddard we're working on several different experiments to measure the CMB polarization with several different science goals

## Extra Slides

# Sensor Details

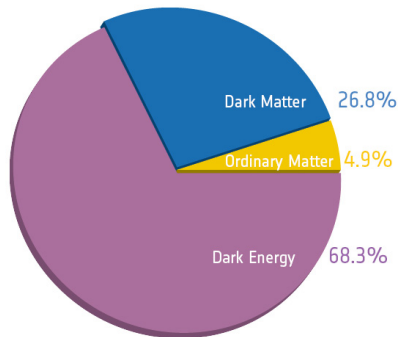
- The TES is deposited on a silicon membrane that is thermally isolated
- Ballistic phonon propagation through a short silicon leg



- Pd layer to control heat capacity
- PdAu absorber is electrically coupled to the TES.

# $\Lambda$ CDM Cosmology

- Three primary constituents
- Isotropic and homogenous on largest scales  $\sim 100$  Mpc.
- Dynamics driven by gravity
  - General relativity:  
 $ds^2 = a(t)^2 ds_3^2 - c^2 dt^2$
  - (Accelerated)  
Expansion/Cosmological constant



<http://planck.cf.ac.uk/results/cosmic-microwave-background>

# $\Lambda$ CDM Cosmology

- GR  $\rightarrow$  Curvature



## FriedmannLemaitreRobertsonWalker Metric

- $ds_3^2 = \frac{dr^2}{1-kr^2} + r^2 d\Omega^2$
- $d\Omega^2 = d\theta^2 + \sin^2 \theta d\phi^2$
- Exact solution to the Einstein Field Equations for a homogenous, isotropic, expanding (or contracting) Universe.
- $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi GT_{\mu\nu}$

## • Friedmann Equations

- $\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} - \frac{\Lambda}{3} = \frac{8\pi G}{3}\rho$
- $2\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} - \Lambda = -\frac{8\pi G}{3}p$

# $\Lambda$ CDM Cosmology

- Perfect fluid approximation

- $w = \frac{p}{\rho}$
- $\rho \propto a^{-3(1+w)}$ ;  $a \propto t^{\frac{2}{3(1+w)}}$ ;  $t$  is proper time

- Dark Energy

- $w = -1$

- Matter

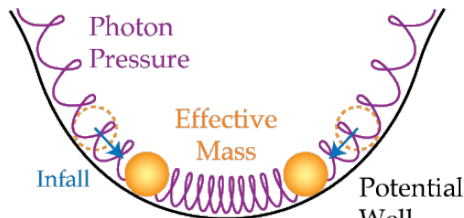
- $w = 0$

- Radiation

- $w = +\frac{1}{3}$

# Primordial Plasma Physics

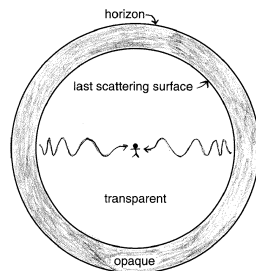
- Slight under/over densities in the distribution of matter.
- Over densities gravitationally attract more matter, releasing energy as heat.
- Increasing heat creates more photon pressure.
- Photon pressure eventually overcomes gravitational force.
- Photons push a pressure wave of baryons outward.
- These oscillations manifest themselves in the CMB power spectrum.



# CMB Physics

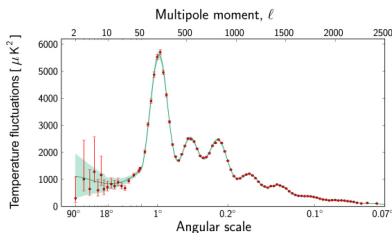
- The CMB and its properties are the result of several processes in the early Universe
  - Recombination
    - Formation of neutral hydrogen
  - Photon-baryon decoupling
    - Mean-free path of photons increases  $\rightarrow L_{obsUni}$
  - Last-scattering
    - Information about the Universe encoded; photons stream free

- Last-scattering occurs around  $z \simeq 1100$ .
  - Universe is  $T \sim 3000$  K
  - $t \simeq 380,000$  yr
- 3000 K is redshifted down to today's value of 2.7 K



Introduction to Cosmology, B. Ryden

# CMB Power Spectra



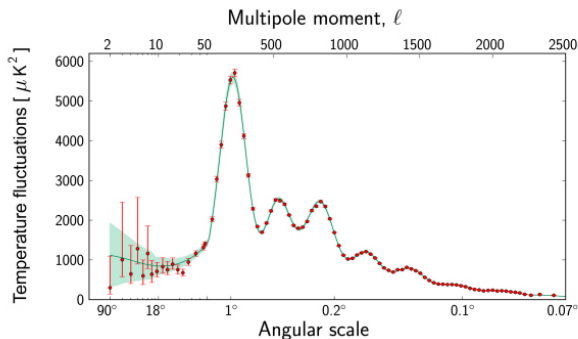
<http://sci.esa.int/multimedia-gallery/30913-multimedia-archiv/>

- Temperature anisotropy information in the “Fourier” domain
- $\Delta_T^2 = \frac{2\ell+1}{2\pi} C_\ell T^2$
- Power spectrum is normalized by the  $2\ell + 1$  factor; would be much harder to see high  $\ell$  tail.

- CMB measurements can be decomposed into spherical harmonic components on the sky,  $Y_\ell^m$ .
  - Two-point angular correlation function.
- $a_\ell^m = \int \int d\hat{\Omega} \frac{\Delta T}{T}(\hat{n}) \star Y_\ell^m(\hat{n})$
- The value of  $a_\ell^m$  is orientation dependent (like in QM)
- $C_{\ell\ell'} \delta_{\ell\ell'} \delta_{mm'} = \langle a_{\ell'}^{*m'} a_\ell^m \rangle$
- $C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} \langle |a_{\ell m}|^2 \rangle$

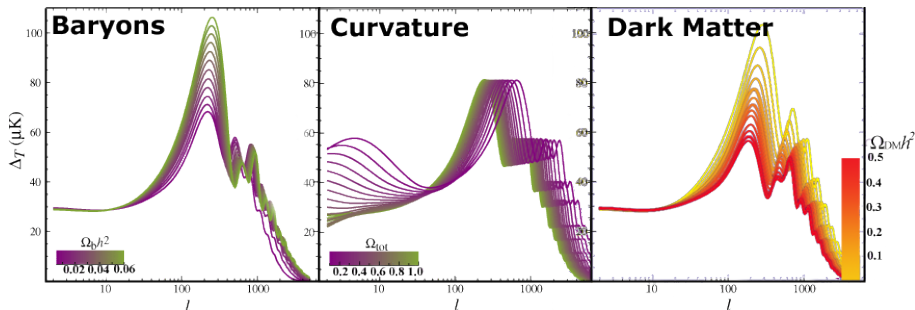
# A Look at the CMB Power Spectrum

- CMB power spectrum is a direct result of the primordial matter power spectrum and acoustic oscillations in the primordial plasma
- Quantum fluctuations in the primordial Universe turn into macroscopic fluctuations
- Perturbations are scale-invariant and adiabatic

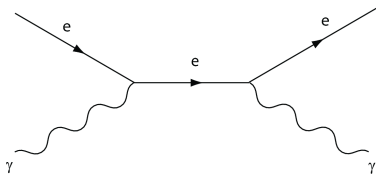


# A closer look at the CMB Power Spectrum

- Shape and location of CMB peaks  $\rightarrow$  cosmological parameters
  - First acoustic peak: BAO signature; flatness; degeneracy:  $H_0$ ,  $\Omega_M$ ,  $\Omega_\Lambda$
  - Second peak: Baryon density
  - Third peak: DM density
  - Damping tail: non-instantaneous recombination



# Thomson Scattering



- Photons and baryons interact via Thomson scattering

- $\sigma_t = \frac{8\pi}{3} \frac{\alpha \lambda_c^2}{2\pi} = 6.65 \times 10^{-29} \text{ m}^2$
- $\lambda_e = \frac{1}{n_e \sigma_e}$
- $\Gamma = \frac{1}{\lambda_e}$

# Recombination

- Formation of neutral hydrogen
- Recombination time depends on:
  - Baryon-to-photon ratio  $\eta$
  - Ionization energy of Hydrogen, 13.6 eV
- $H + \gamma \leftrightarrow p + e^-$
- Formation of Hydrogen follows Maxwell-Boltzmann statistics
  - $n_x = g_x \left( \frac{m_x k_b T}{2\pi \hbar^2} \right)^{3/2} \exp\left(-\frac{m_x}{k_b T}\right)$

- Saha Equation governs equilibrium

$$\bullet \frac{n_H}{n_e n_p} = \left( \frac{m_e k_b T}{2\pi \hbar^2} \right)^{-3/2} \exp\left(\frac{Q}{k_b T}\right)$$

$$\bullet \frac{1-X}{X} = \frac{n_p}{n_H}; \eta = \frac{n_p}{X n_\gamma}$$

$$\bullet n_\gamma = \frac{16\zeta(3)}{\pi^2} \left( \frac{k_B T}{\hbar} \right)^3$$

- Recombination temp

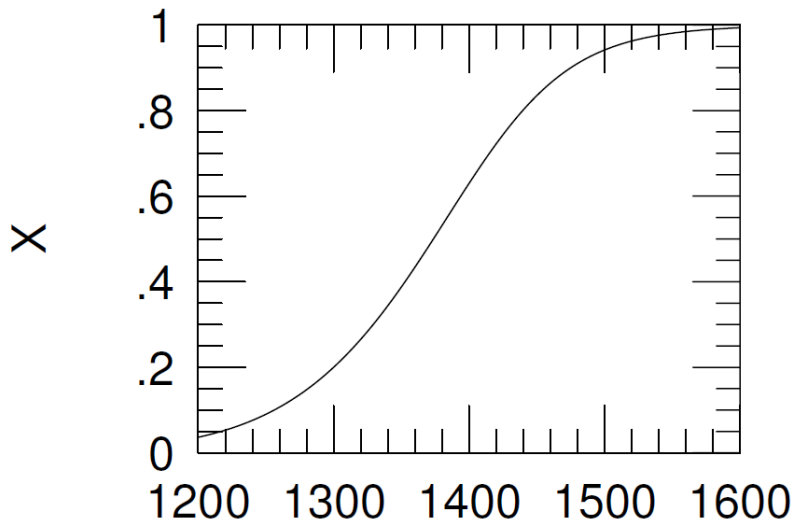
$$T_{rec} \simeq \frac{Q}{42} \simeq 0.323 \text{ eV} = 3740 \text{ K}$$

- $z_{rec} = 1370$

- $t_{rec} = 240,000 \text{ yr}$

- Quickly gives rise to photo-baryon decoupling.

# Ionization Fraction vs Redshift



# Photo-baryon Decoupling

- Before recombination, the entire Universe is ionized
  - $n_e = n_p = n_b$
- The number density  $\sim \frac{n_{b,0}}{a^3}$
- The current baryon density is  $n_{b,0} = 0.22 \text{ m}^{-3}$
- The scattering rate for photons
$$\Gamma = \frac{n_{b,0}\sigma_e}{a^3}$$
$$= \frac{4.4 \times 10^{-21} \text{ s}^{-1}}{a^3}$$
- Photons and baryons remain coupled while  $\Gamma > H$ .
- Photon mean-free path  $< \frac{1}{H}$
- Once  $\Gamma \leq H$ , electrons are diluted faster than photons scatter off them
- $\gamma$  decouple from the baryons and the Universe becomes transparent
  - Mean-free path of  $\gamma \sim$  observable Universe
- Decoupling occurs quickly due to the abrupt drop off in free-electron density during Recombination

# Last Scattering

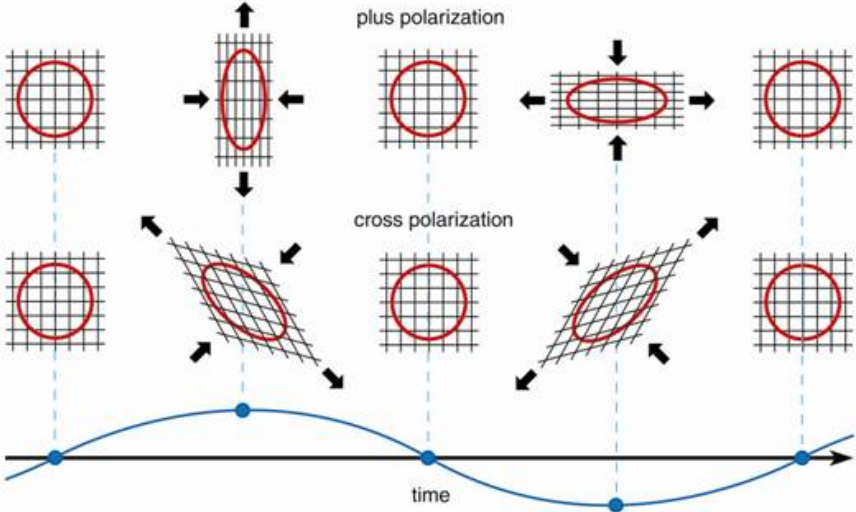
- The photons in the Universe experience one last interaction with the ionized matter before streaming freely and decoupling.
- CMB appears to radiate from the “Surface of Last Scattering” towards observers today.
- Photon temperature distribution remains a black-body, redshifted down to 2.7 K today.

Events in the early universe

event	redshift	temperature (K)	time (megayears)
radiation-matter equality	3570	9730	0.047
recombination	1370	3740	0.24
photon decoupling	1100	3000	0.35
last scattering	1100	3000	0.35

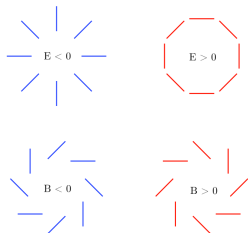
Introduction to Cosmology, B. Ryden

# Gravity Wave distortions



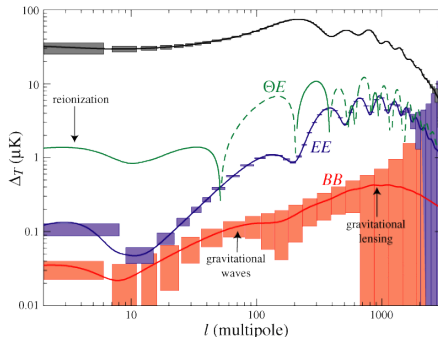
# E and B mode Spectra

- Linear polarization can also be decomposed into two modes
  - Curl-free or E-mode (positive parity)
  - Divergence-free or B-mode (negative parity)



arXiv:1004.2504

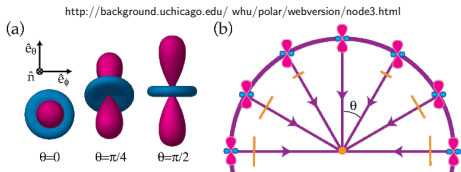
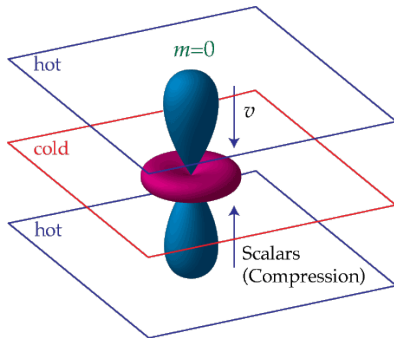
- Cross spectra, TT, TE, EE, and BB



<http://background.uchicago.edu/~whu/araa/node4.html>

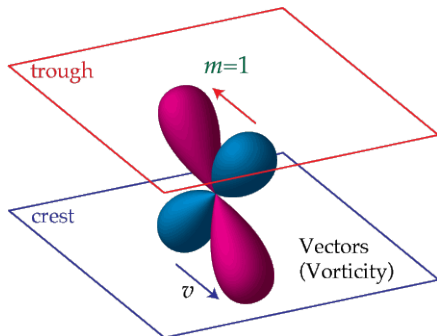
# Polarization from Scalar Perturbations

- Slight increases or decreases in the energy of the primordial plasma above the mean blackbody temperature.
  - Scalar perturbations also have associated density increases or decreases.
  - Orientation of the quadrupolar anisotropy relative to the observer determines the degree of linear polarity.
  - Density perturbations, and thus scalar, produce only E-modes.



# Polarization from Vector Perturbations

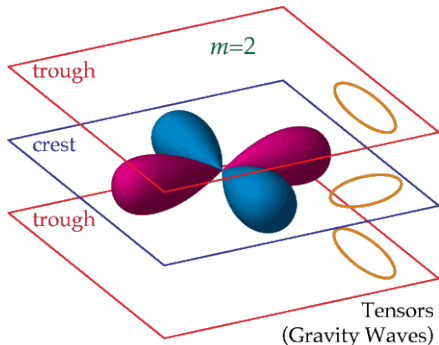
- Vortices or eddies in the plasma produce vector perturbations.
  - Relativistic effects of accelerating mass perturbs the metric.
  - Unlike Scalar perturbations, vector perturbations have no associated density perturbations.
  - Vortices decay away as  $\sim \frac{1}{a}$ .
  - Like scalar, polarization is maximal around the equator and goes to zero near the poles as the pattern changes the plane relative to the observer.



<http://background.uchicago.edu/~whu/polar/webversion/node5.html>

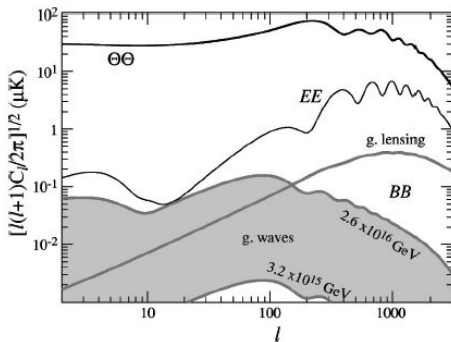
# Polarization from Tensor Perturbations

- Gravity waves distort space in the plane of the perturbation, changing a circle into an ellipse.
- The ellipse gives rise to  $m = 2$  quadrupolar perturbations
- At the pole, the tensor pattern is completely in the plane, maximizing the polarization.
- Primordial tensor perturbations are generated by Inflationary gravity waves in the early Universe.
- Weak Gravitational lensing can mix scalar perturbations into tensor perturbations in the recent Universe.



<http://background.uchicago.edu/~whu/polar/webversion/node6.html>

# Primordial B-modes from Inflation



- Residual levels of B-modes from gravitational lensing limits the detection of primordial B-modes to  $E_{\text{Inf}} \sim 2.0 \times 10^{15}$  GeV;  $r > 10^{-5}$ .
- The WMAP convention is:  $r = 4 \frac{\Delta_+^2}{\Delta_R^2} = 16\epsilon$
- $\Delta_+^2$  is the scale-invariant gravitational wave amplitude
- $\Delta_R^2$  is the comoving curvature power spectrum.

# Primordial B-modes from Inflation

- Modern Slow-roll Inflation is characterized by two parameters

- $\epsilon = \frac{m_p^2}{2} \left( \frac{V'}{V} \right)^2$

- $\eta = m_p^2 \frac{V''}{V}$

- These two parameters determine  $n_s$ , the scalar spectral index.

- $n_s - 1 = -6\epsilon + 2\eta$

- Planck data:

$$n_s = 0.960 \pm 0.0073$$

- The tensor to scalar ratio  $r$  determines the number of e-folds of expansion.

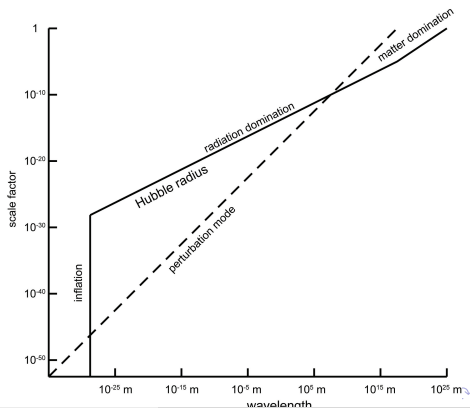
- $N_e = \int H dt = \int \frac{H}{\dot{\phi}} d\phi$

- For single-field, slow-roll Inflation

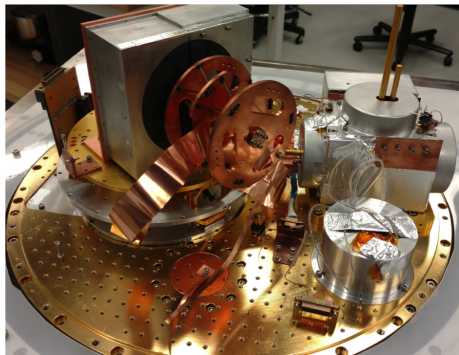
- $N_e = \sqrt{8} r^{-\frac{1}{2}} \frac{\Delta\phi}{m_p}$

# Inflation Details

- Inflation generates macroscopic density fluctuations in the primordial Universe by magnifying pre-inflationary quantum perturbations.
- Inflation ends; perturbations are macroscopic
- Perturbations are constantly generated (at all scales) throughout inflation
- Perturbations grow faster than horizon, leave horizon and stall.
- As horizon expansion catches up the perturbation re-enters the horizon.



# Sensor Characterization



- 90 GHz detector characterization includes, I-V curves, responsivity, heat capacity, thermal conductance, and detector efficiency
- We've developed several novel thermal sources, e.g the device pictured to the left.

Rostem et. al. A Waveguide-Coupled Thermally-Isolated Radiometric Source, 2013, Review of Scientific Instruments, Vol. 84, No. 4, p. 044701; doi: 10.1063/1.4795556.