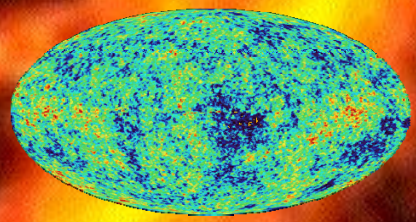
Polarization of the Cosmic Microwave Background:

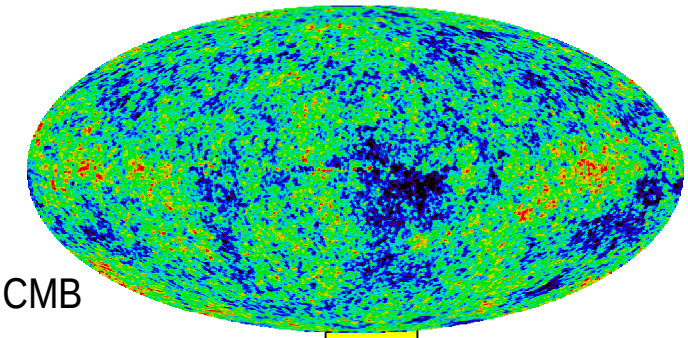
Are Those Guys Serious?



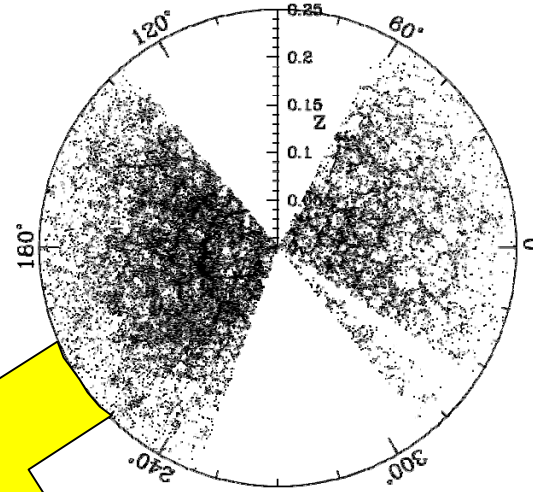
Al Kogut
Goddard Space Flight Center

Precision Cosmology

Lensing



CMB



Galaxy Surveys

ΛCDM

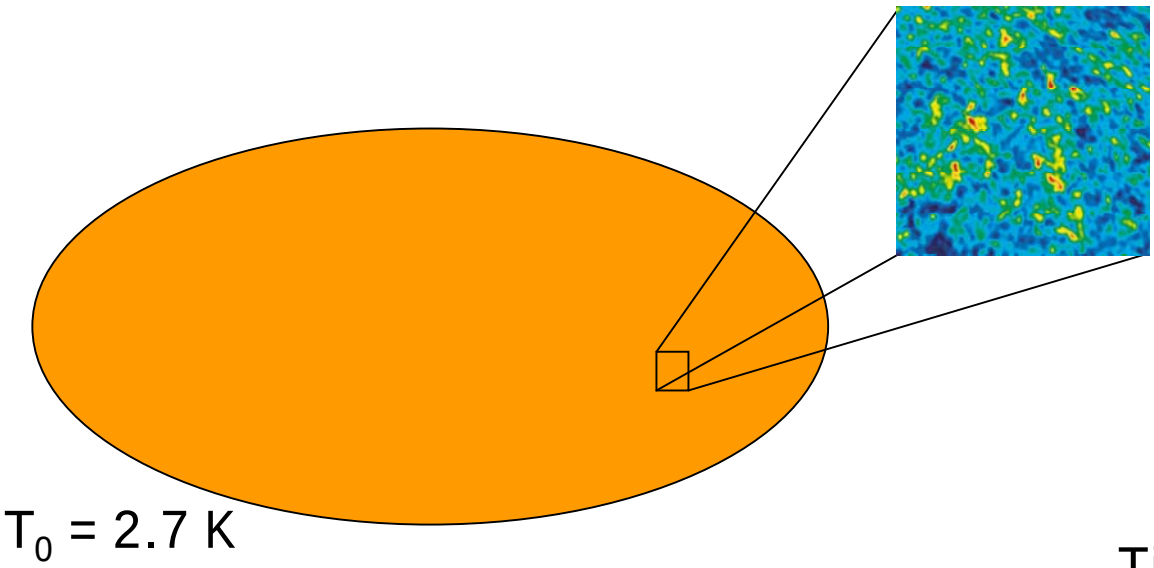
Structure formation seeded by adiabatic scale-invariant perturbations

6 Parameters get you all this!

The End Of Cosmology?

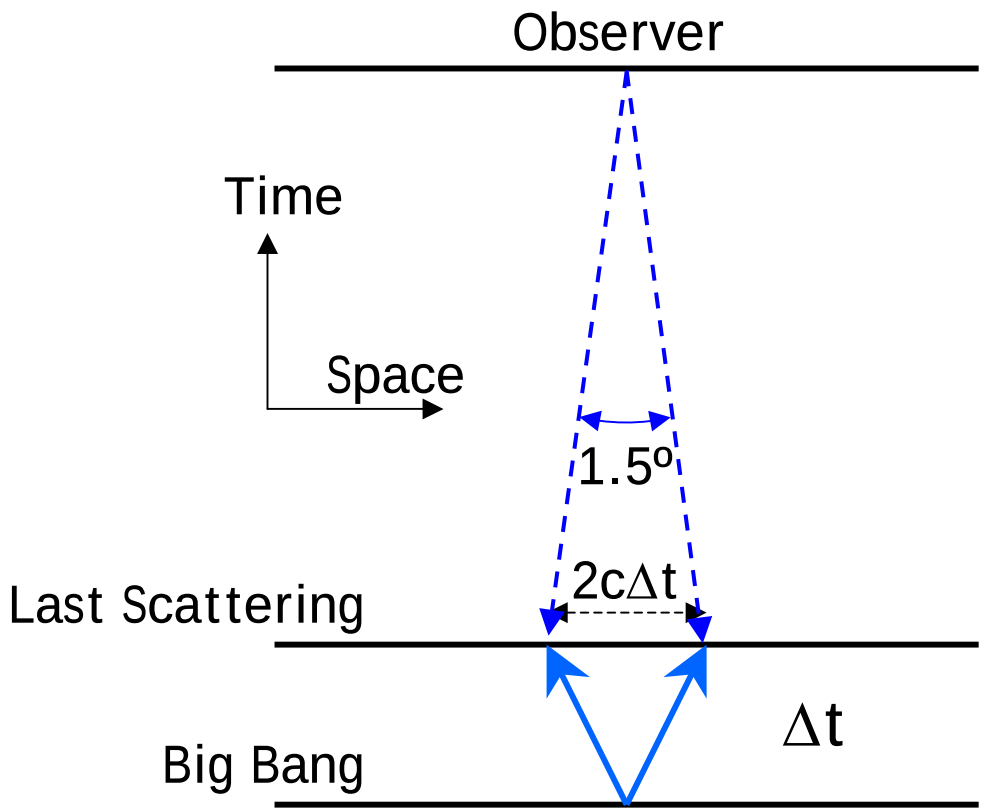
Breakfast of Theorists

Horizon Problem



10,000 Causally disconnected regions:

Why is the CMB so uniform?



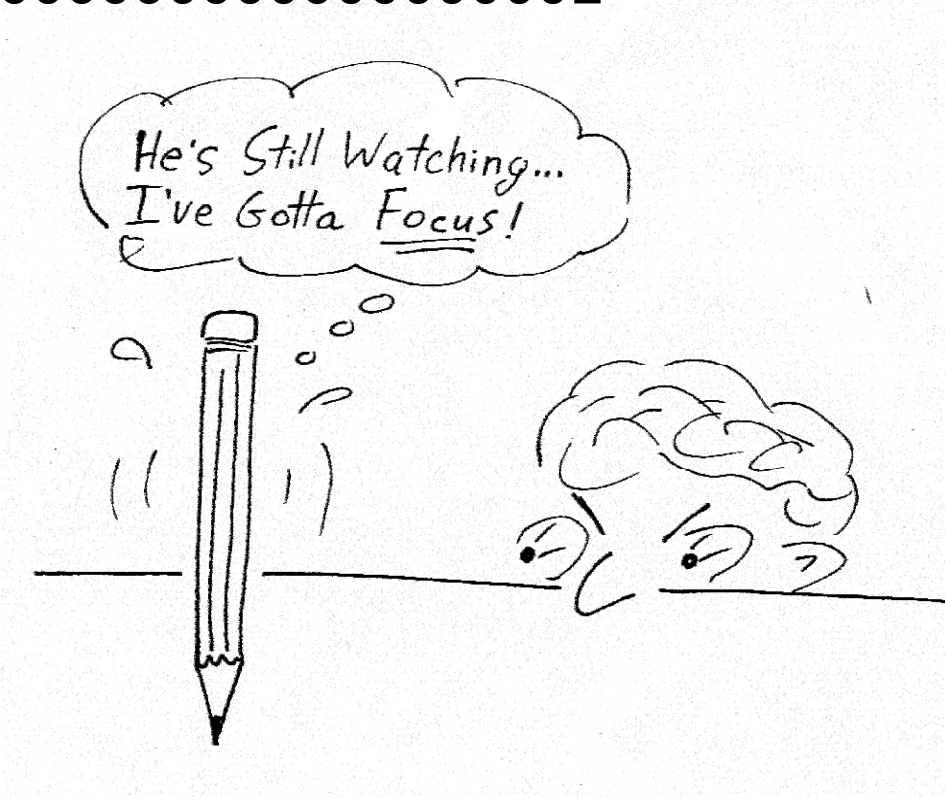
Flatness Problem

$\Omega = 1$ Is Unstable!

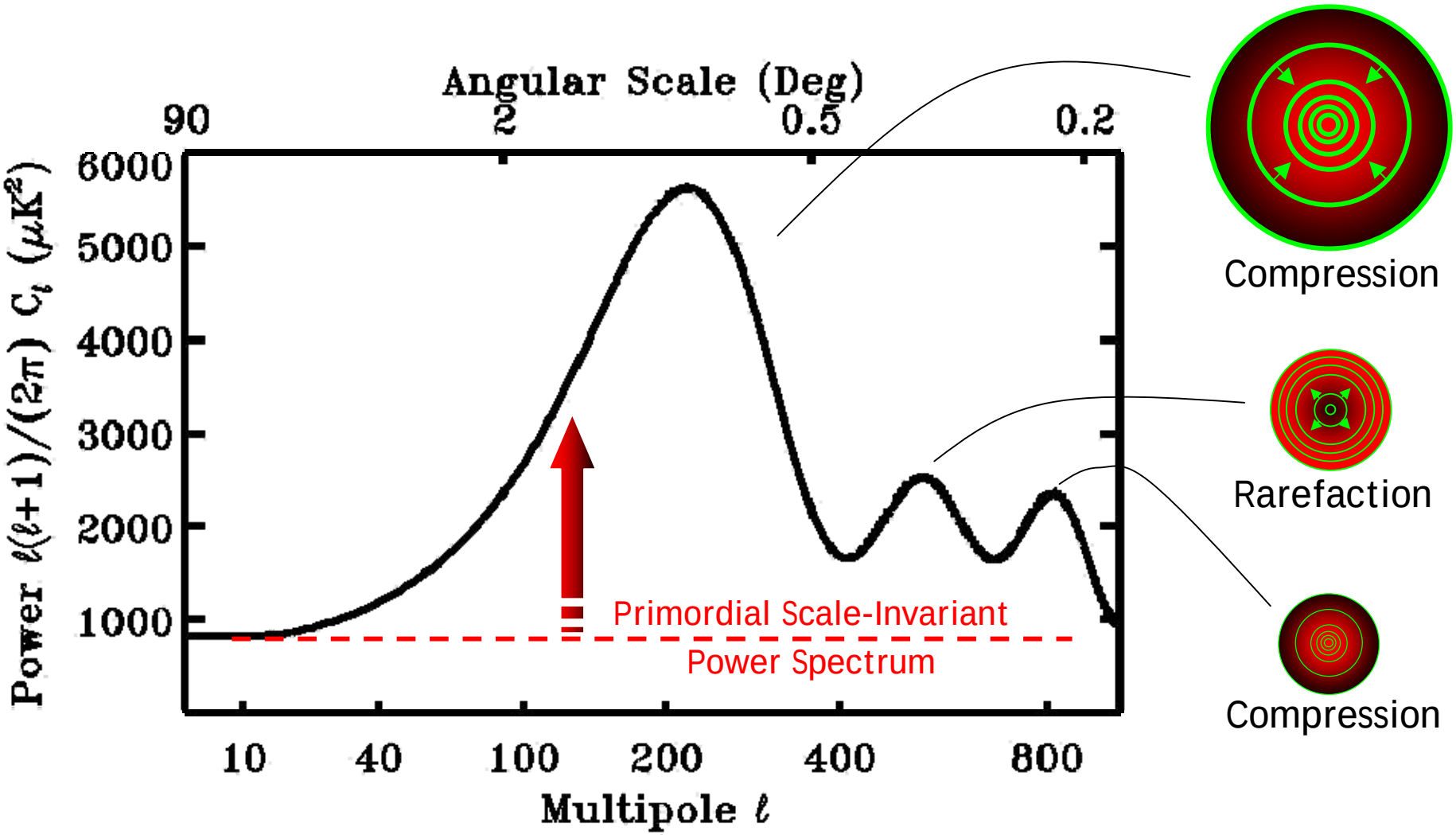
Now: $0.98 < \Omega < 1.02$

Then: $0.99999999999999999999999999999999999999$
$9999999999999999 < \Omega < 1.00000000000000000000$
$00000000000000000000000000000000000001$

Why is the universe so flat?

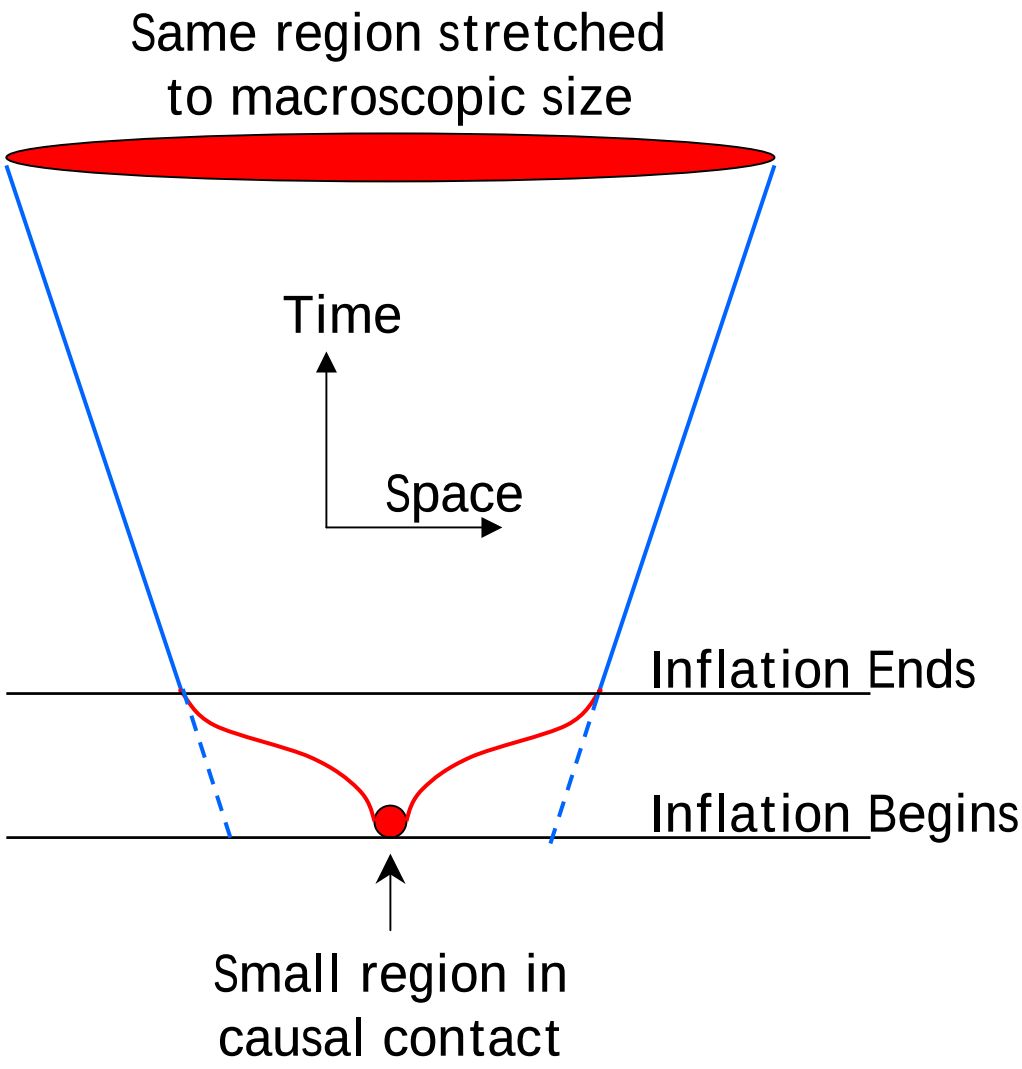


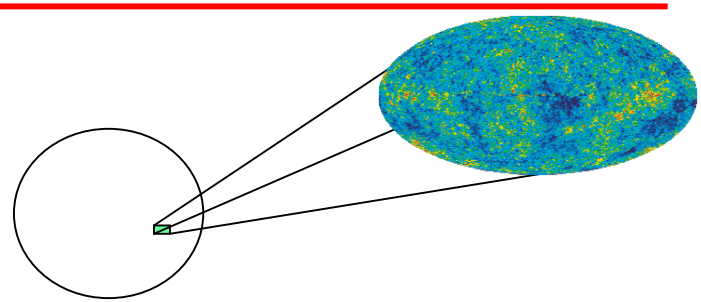
Initial Conditions Problem



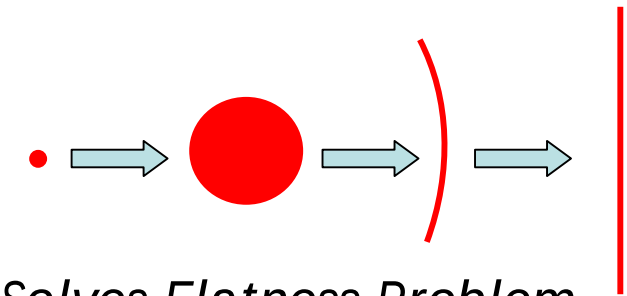
What generated primordial density fluctuations?

Solution: Inflation

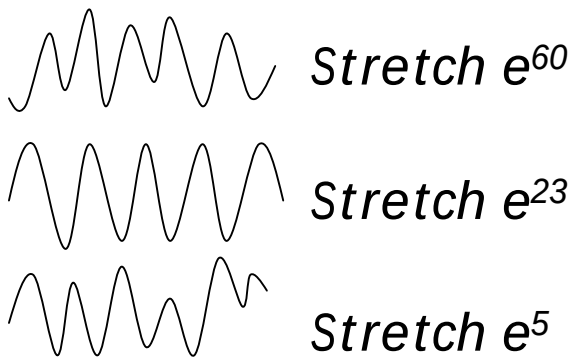




Solves Horizon Problem



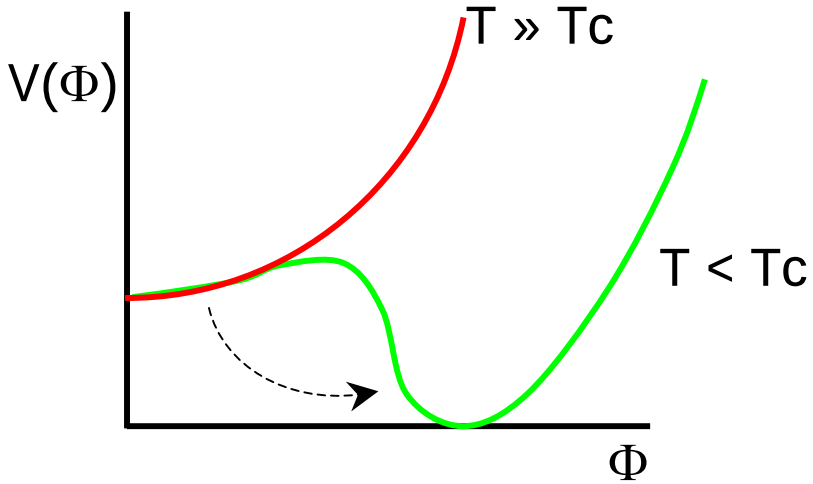
Solves Flatness Problem



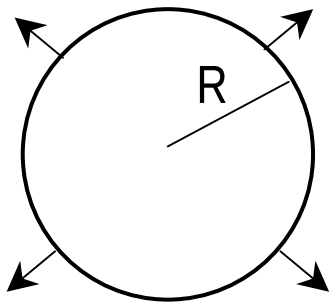
Scale-Invariant Fluctuations

Guth 1981, Linde 1982, Albrecht & Steinhardt 1982

Inflation 101



Phase transition at T=Tc drives exponential expansion



$$\frac{d^2R}{dt^2} = -\frac{GM}{R^2}$$

Case 1: Matter-Dominated

$$M = \text{Const}, \quad \frac{d^2R}{dt^2} < 0$$

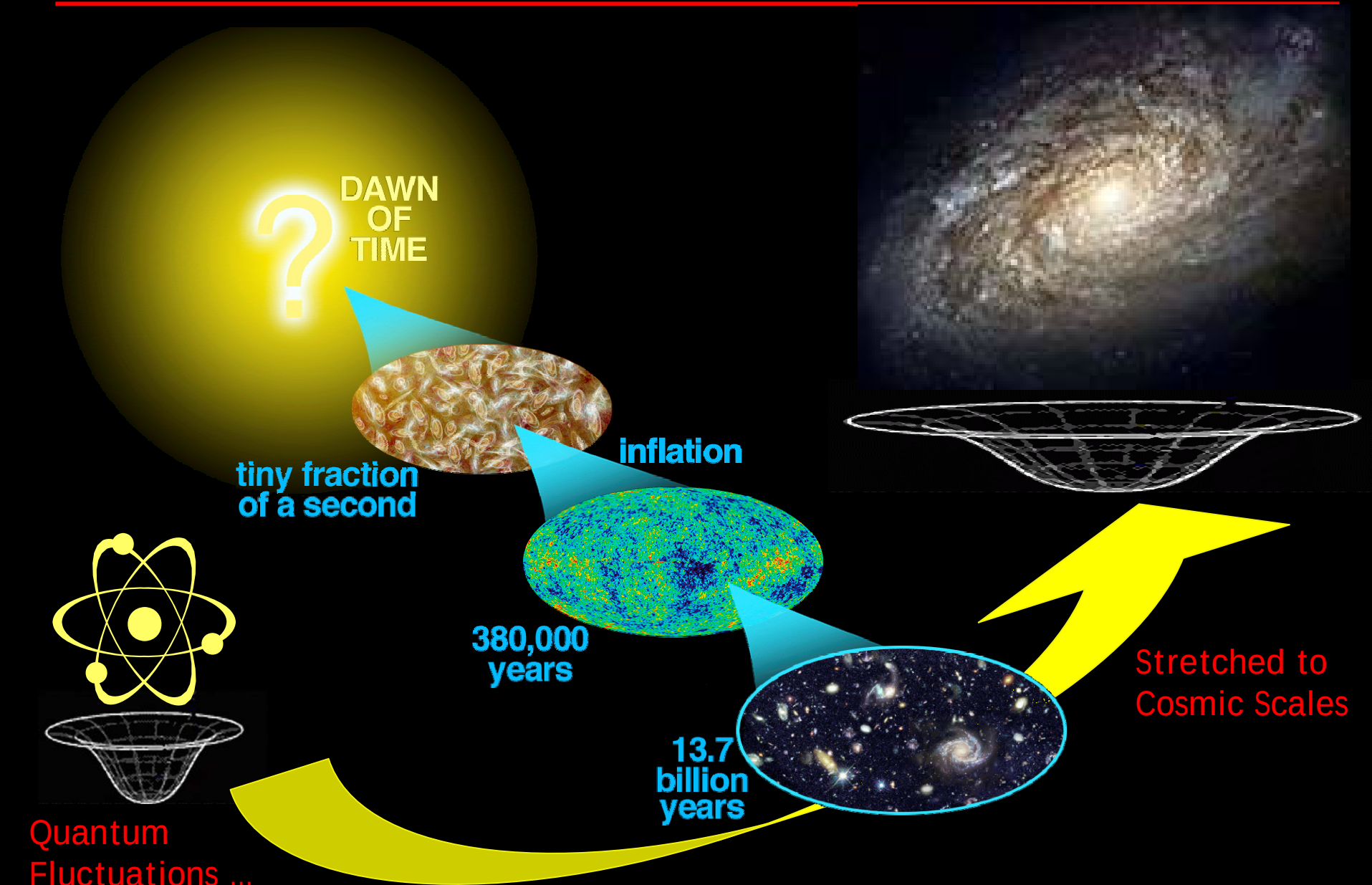
Case 2: Vacuum Energy Density

$$M = -V_0R^3, \quad \frac{d^2R}{dt^2} = R$$

$$R(t) = R_0 \exp(t)$$

Need ~60 e-foldings before inflation ends

Quantum Physics on a Cosmic Scale!

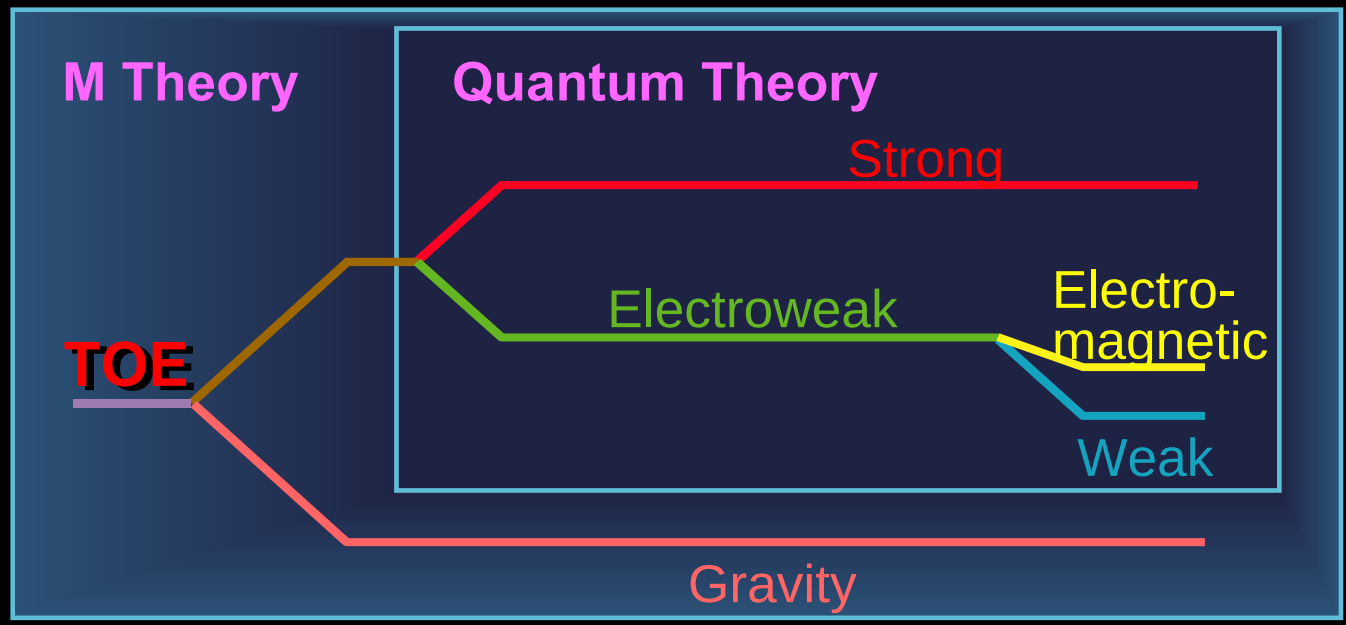


Is Inflation a Testable Theory?

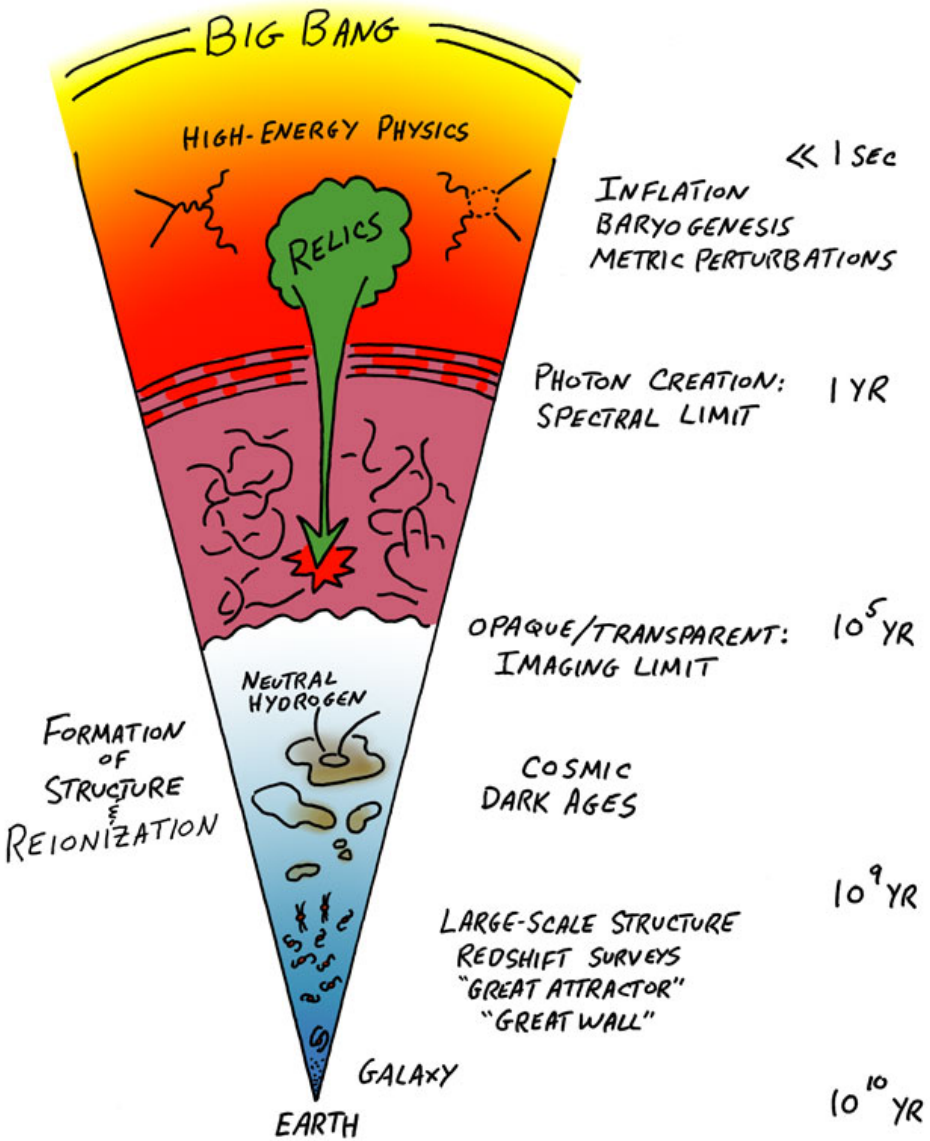
Prediction	Inflation	Ekpyrotic
Flat ($\Omega = 1$)	Yes	Yes
No Monopoles	Yes	Yes
Gaussian Fluations	Yes	Yes
Scale-Invariant (ns ~ 1)	Yes	Yes
Superhorizon Modes	Yes	Yes
Gravity Waves	Exist	Don't Exist

Search for Primordial Gravity Waves via CMB Polarization!

Towards a "Theory of Everything"



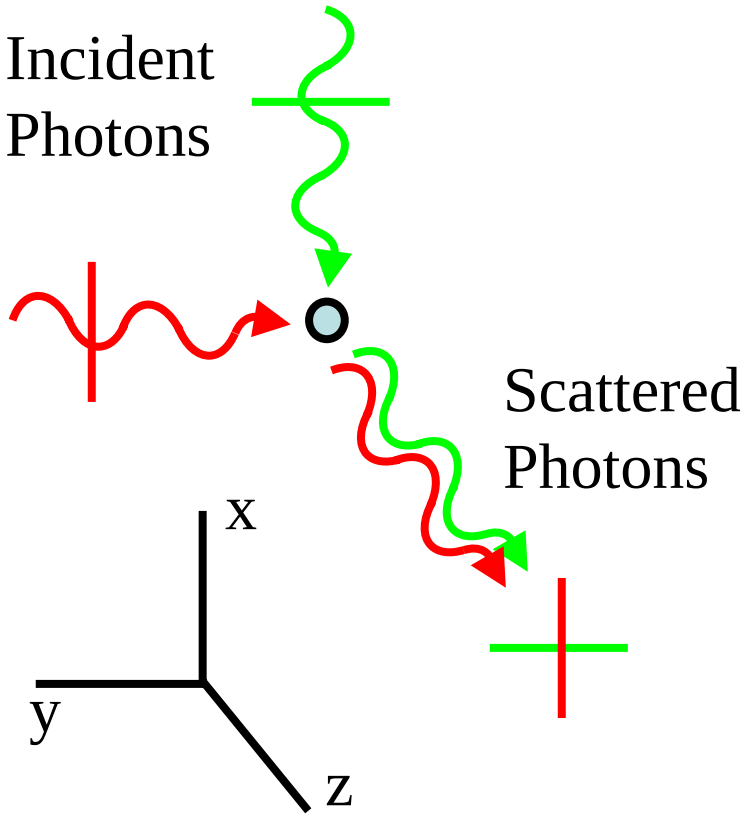
The Oldest Light In The Universe



Fossil Relic of Early Universe

- GUT Physics at 10^{16} GeV
- Inflation/Phase Transitions
- Geometry of Space-Time
- Contents of Universe
- Gravity & Structure Formation

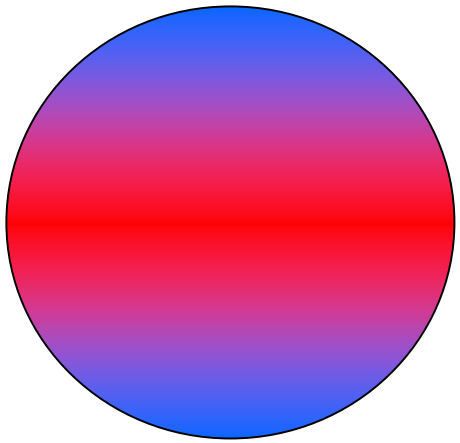
Physics of CMB Polarization



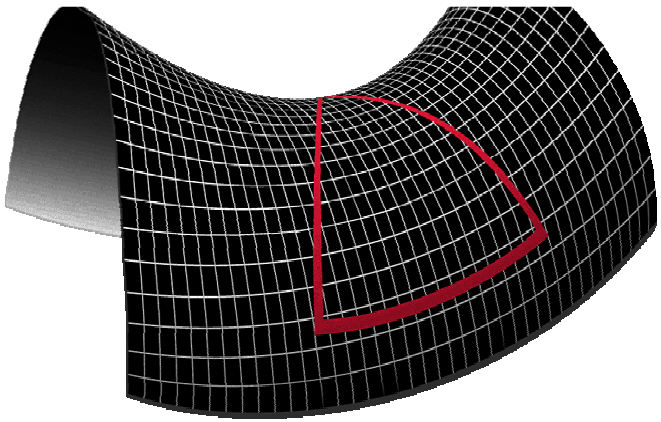
- Thomson scattering of anisotropic photon distribution by free electrons
- Quadropolar temperature anisotropy produces net linear polarization
- Expect few percent linear polarization

Whole New Look at Early Universe

Source Terms for Polarization



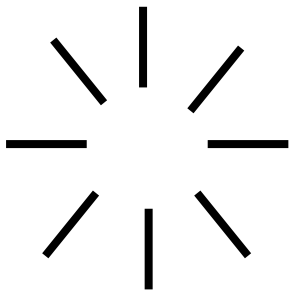
Temperature Quadrupole
Scalar Source
Gradient (“E mode”) Pattern

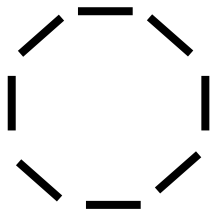


Gravity Wave
Tensor Source
Gradient (“E mode”) Pattern
Curl (“B mode”) Pattern

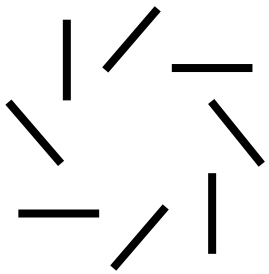
B-Mode Polarization "Smoking Gun" For Inflation!

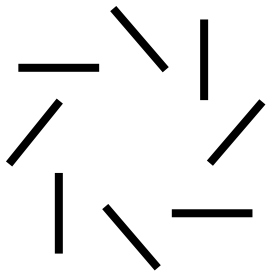
Polarization Patterns



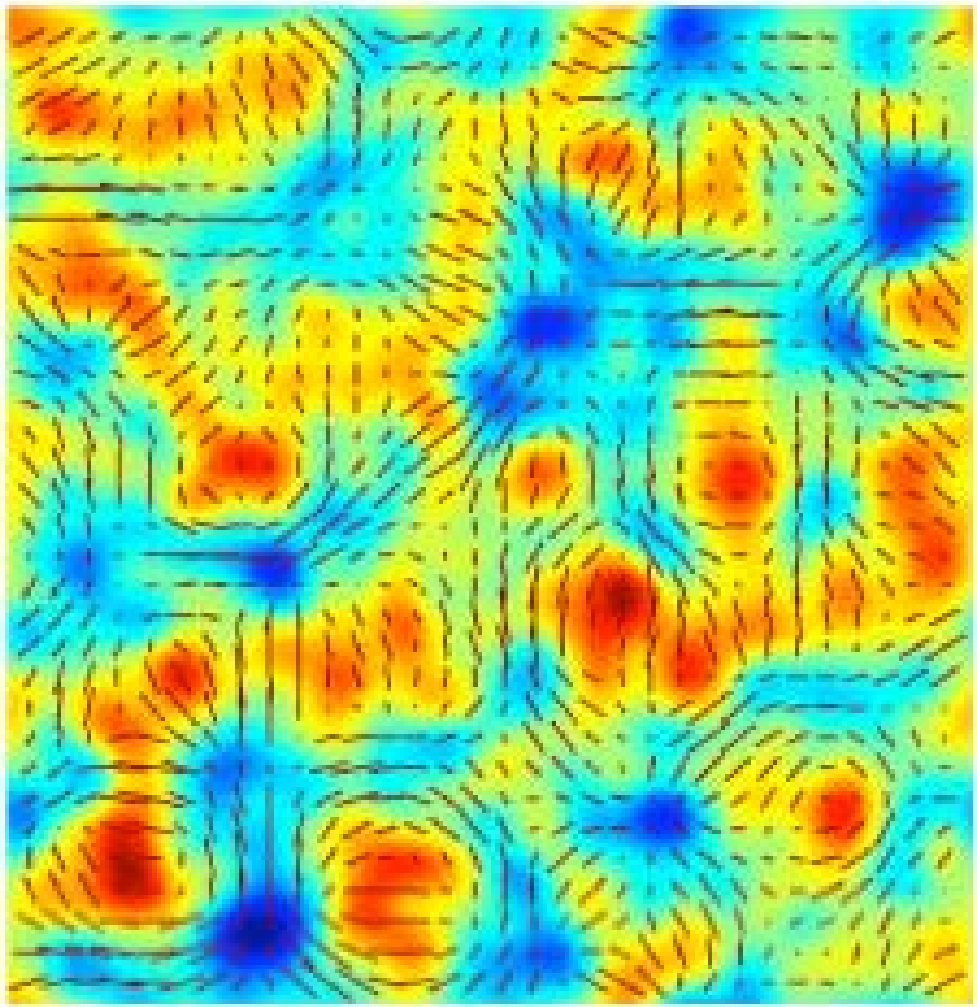


E Modes
Even Parity

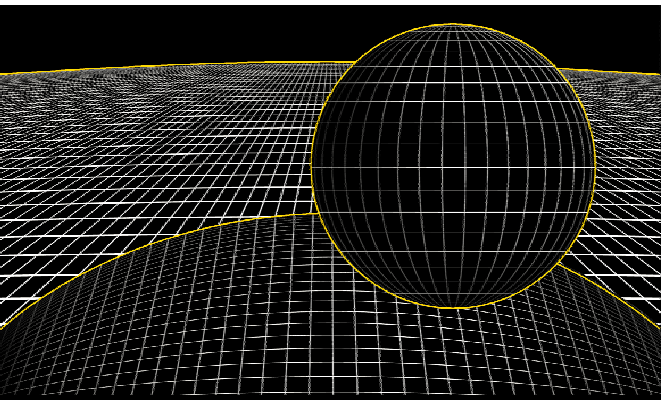




B Modes
Odd Parity



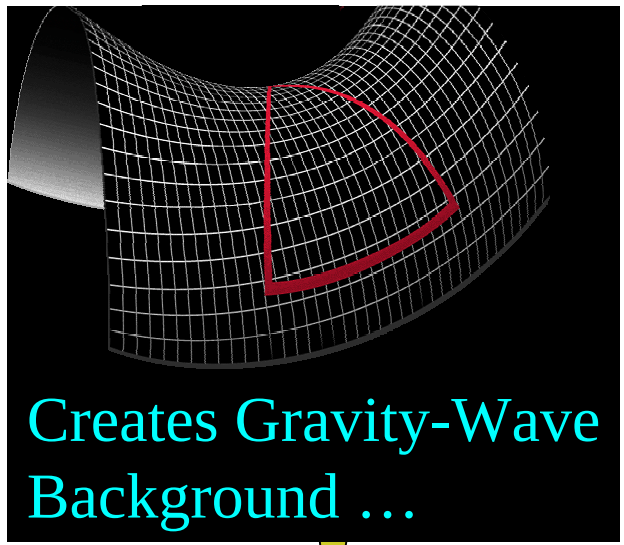
Polarization and Inflation



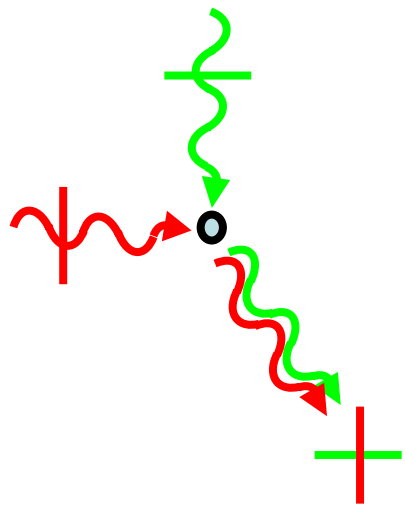
Inflating Space-Time …

Model-Independent Result:

Polarization ~ [Inflaton Potential]$^{1/4}$

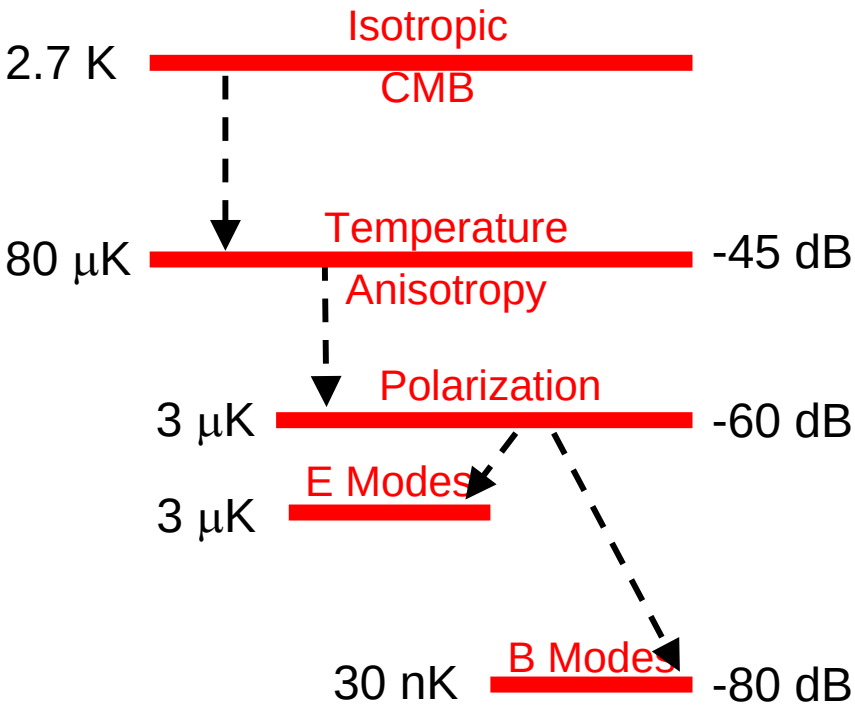


Creates Gravity-Wave Background …



Which Sources CMB Polarization

Show Me The … Polarization?



Hierarchy for CMB Signals

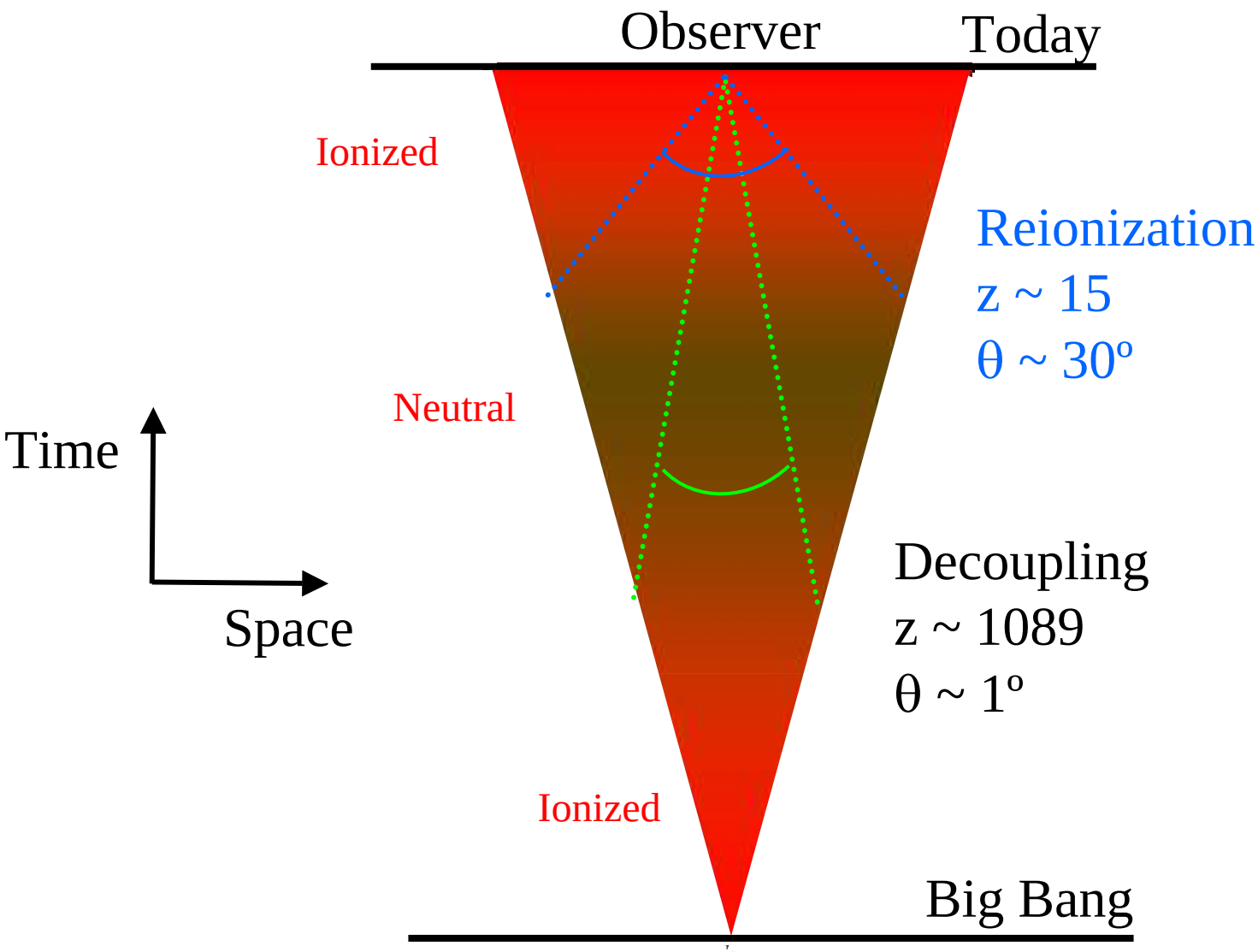
B-Mode Detection:

- Inflation is real
- Determine energy scale

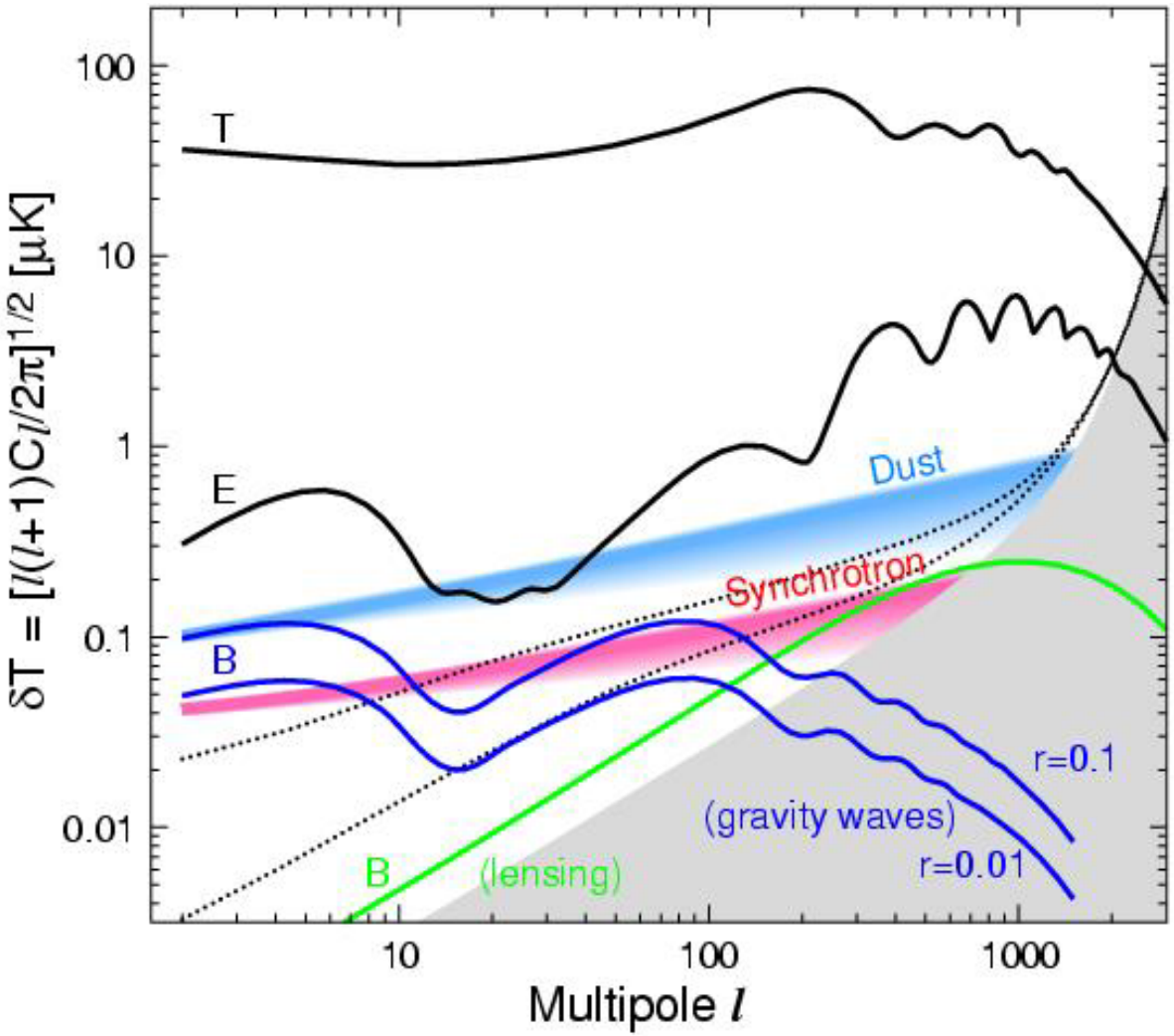
Parameterize using
Tensor/Scalar ratio r

WMAP Prediction: Signal should exist at 30--100 nK!

Angular Scale For Polarization

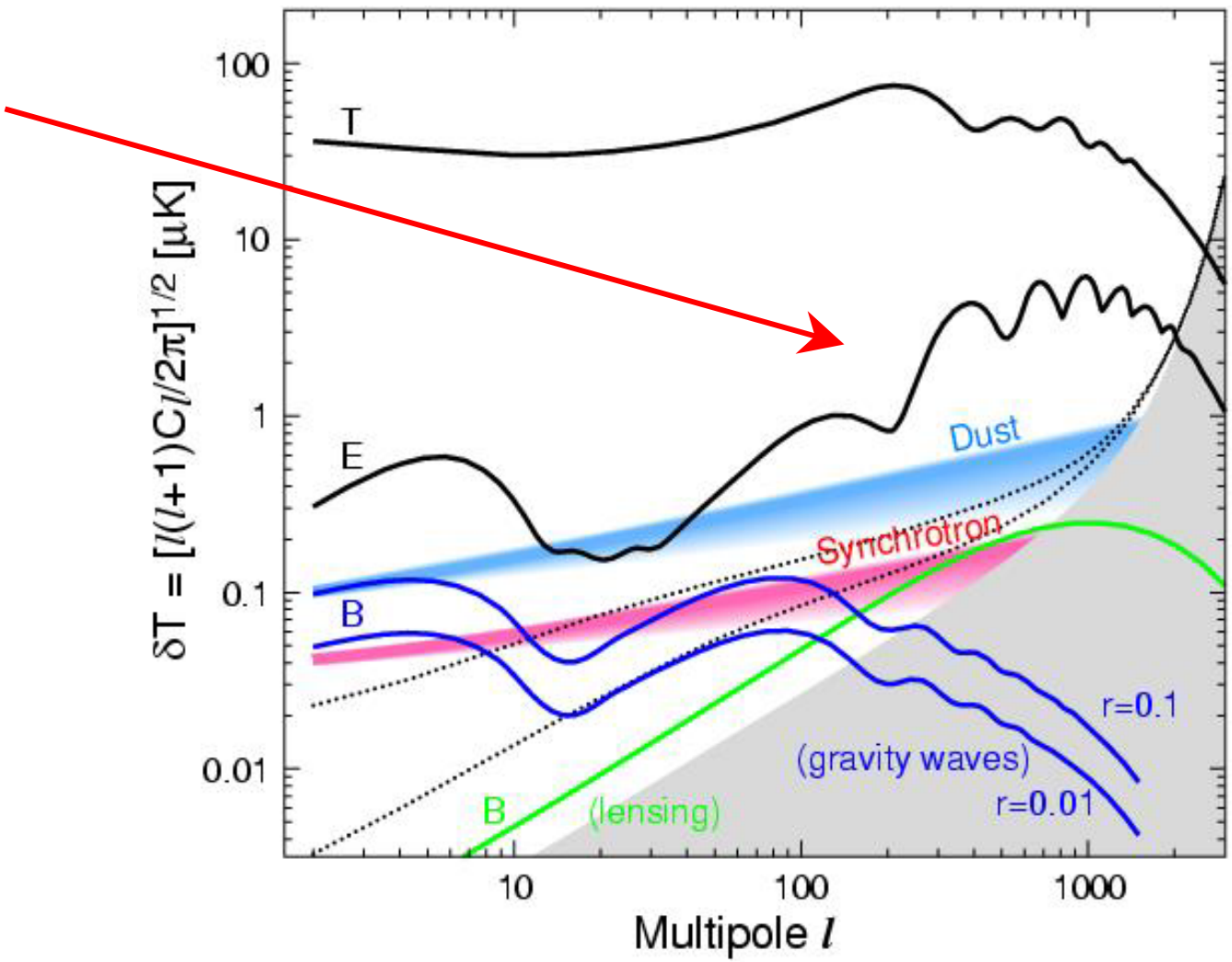


A Polarized Gold Mine for Cosmology



A Polarized Gold Mine for Cosmology

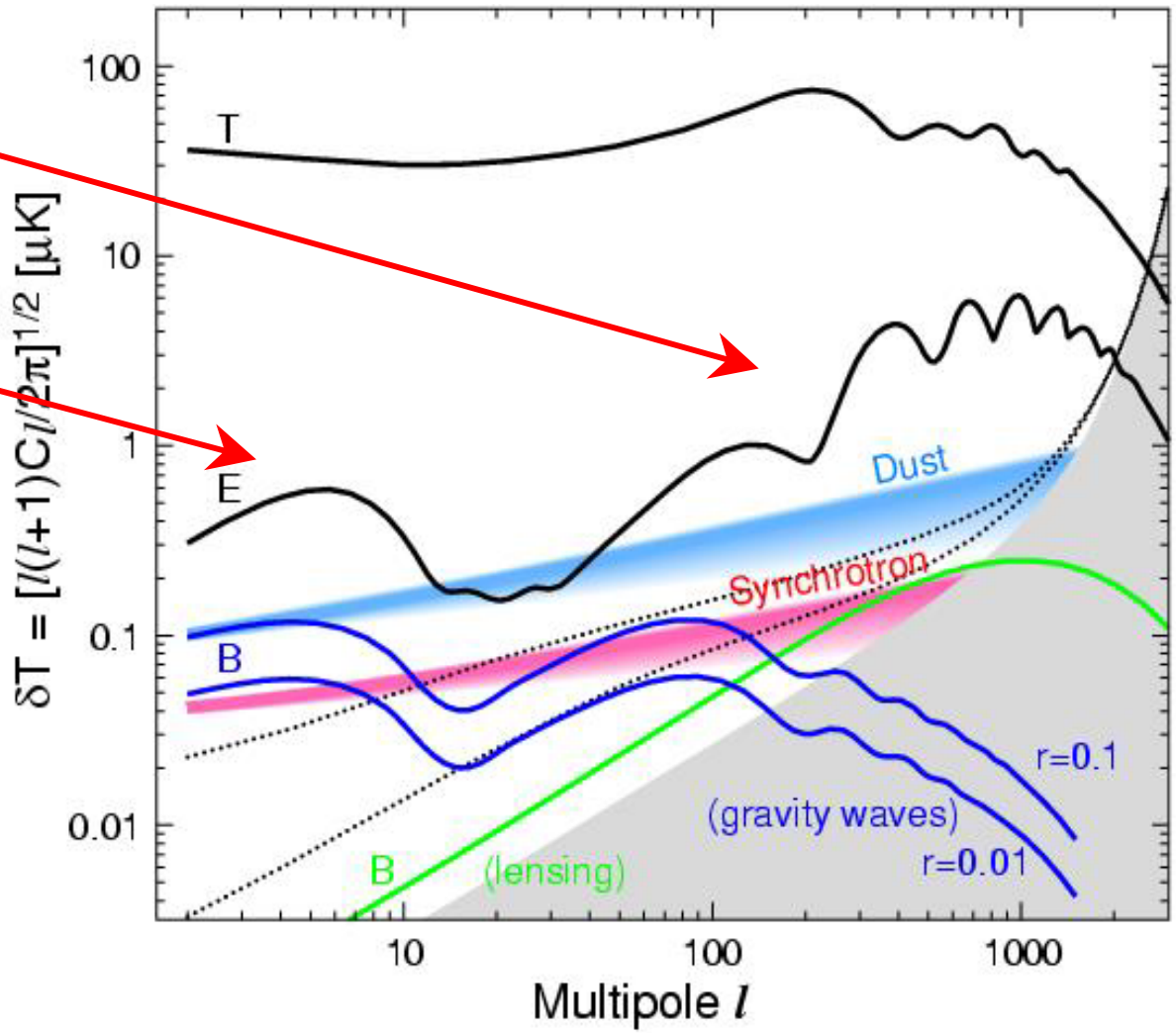
Physics at Decoupling



A Polarized Gold Mine for Cosmology

Physics at Decoupling

Reionization & First Stars

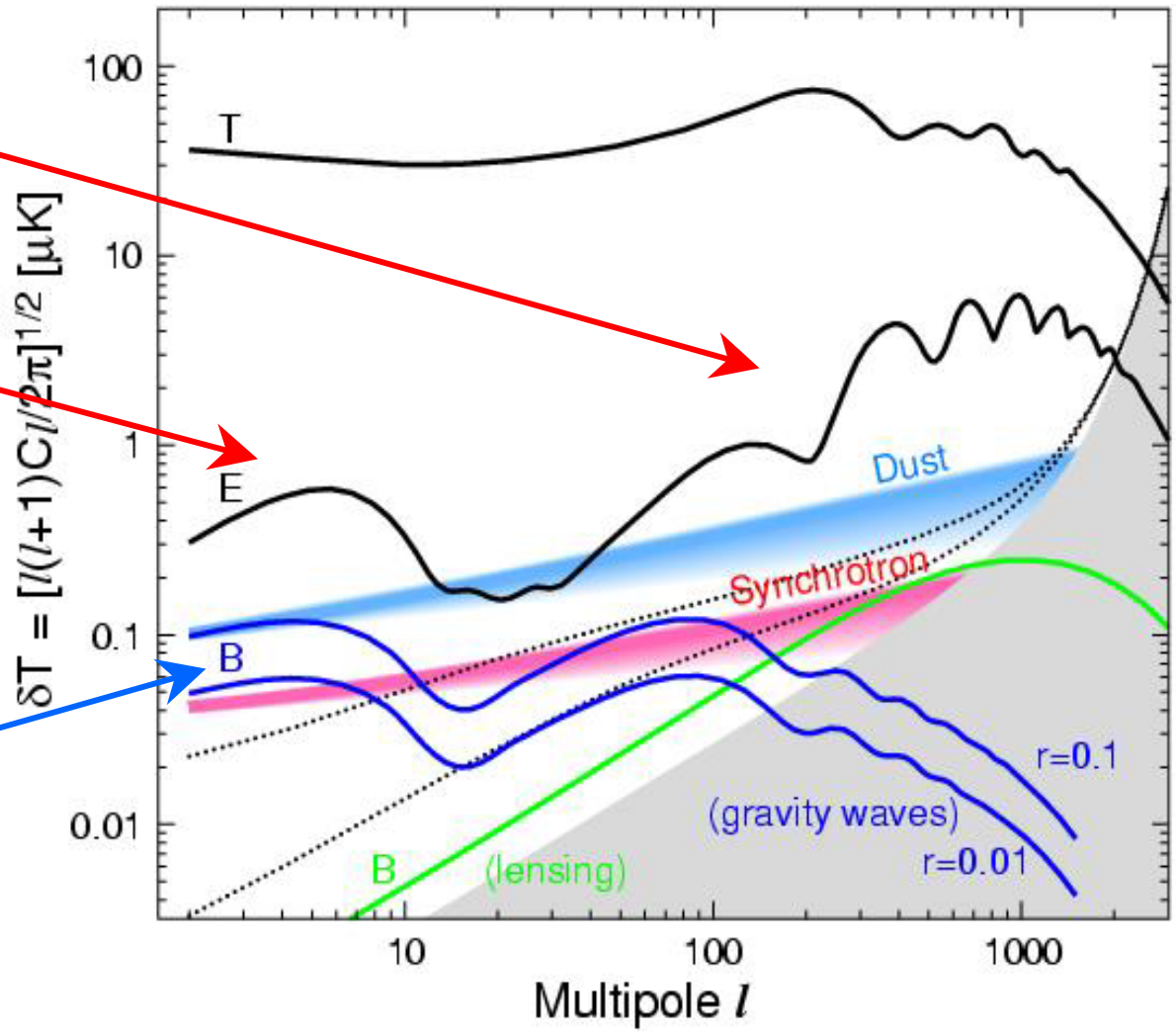


A Polarized Gold Mine for Cosmology

Physics at Decoupling

Reionization & First Stars

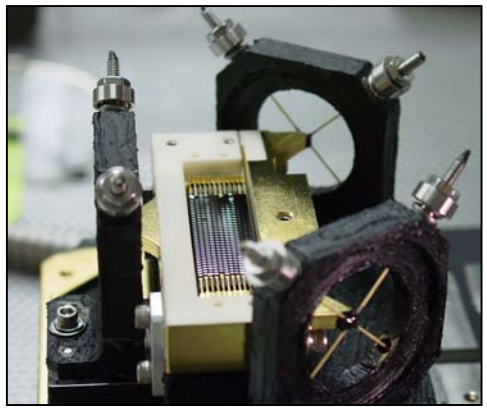
Gravity Waves GUT Physics



Experimental Challenges

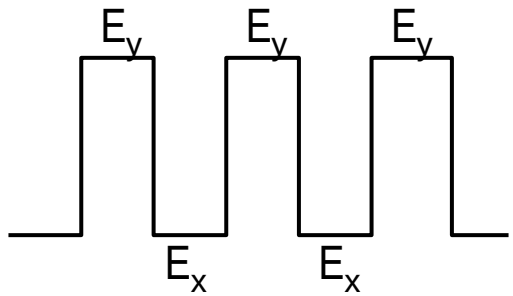
Faint Signal

- Photon Statistics Limit
- Large Arrays of Detectors



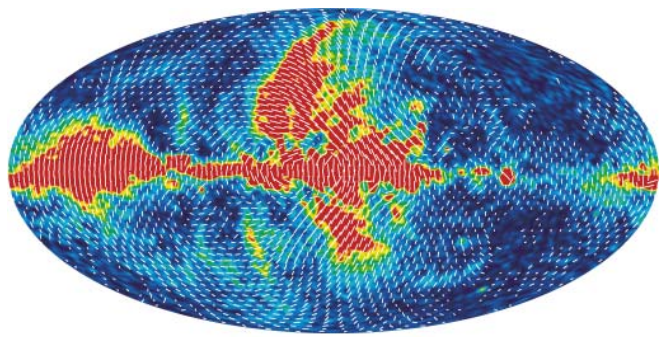
Avoid Aliasing Unpolarized Light

- Control Stray Light
- Modulation/Chopping



Polarized Galactic Foregrounds

- Multiple Frequency Bands

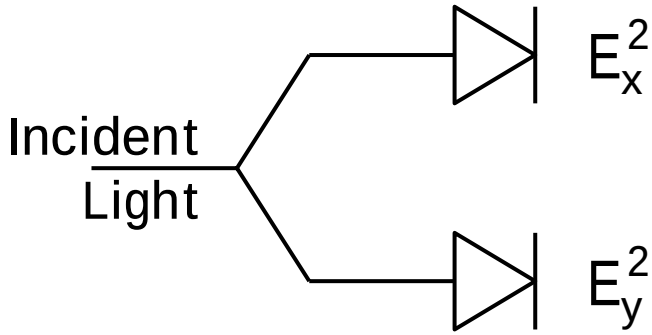


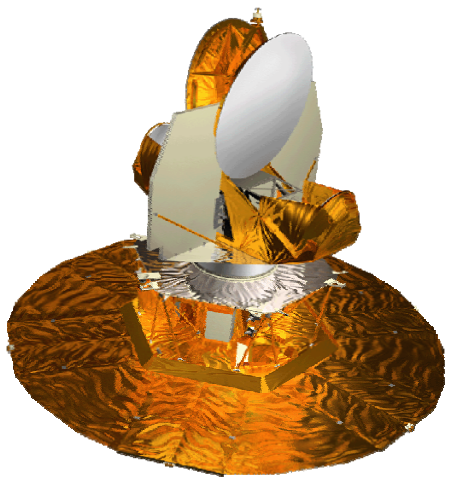
First Generation Measurements

Each detector measures single linear polarization

Difference detectors to get Stokes Q = $E_x^2 - E_y^2$

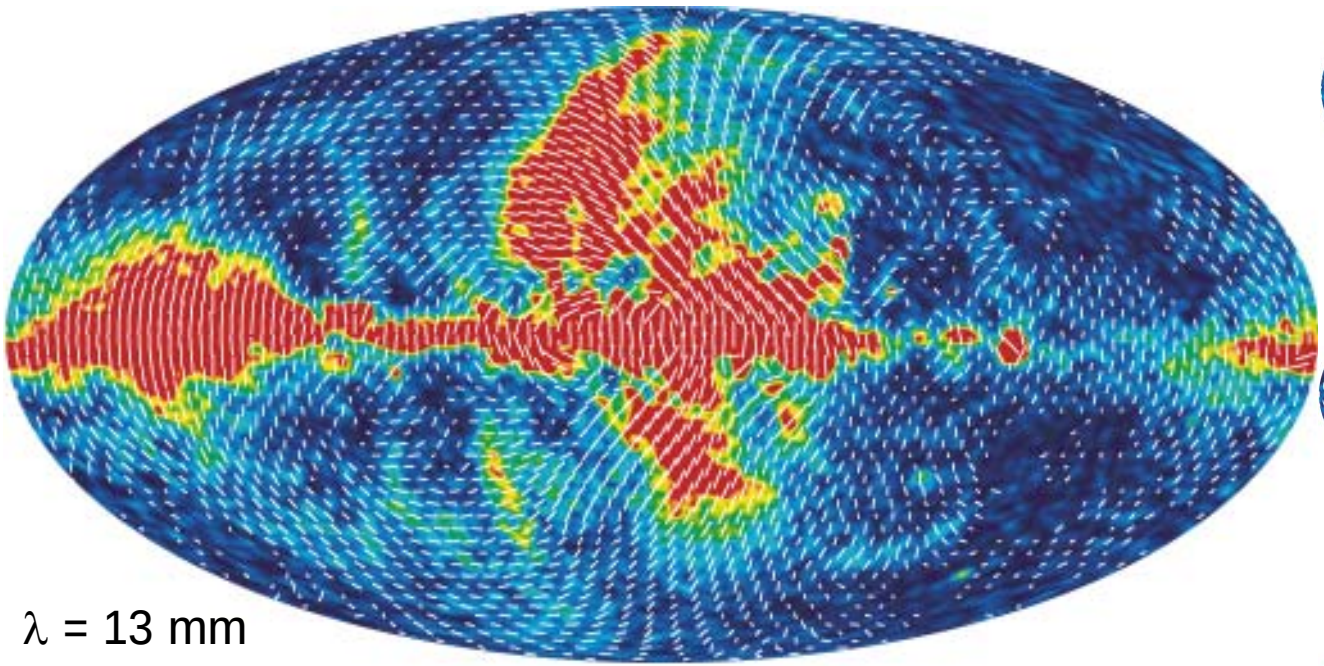
Sky rotation maps Q and U

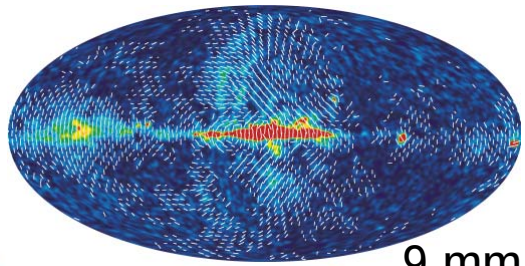


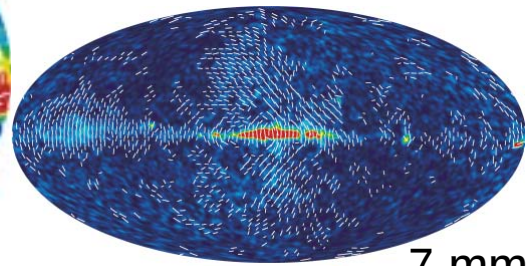


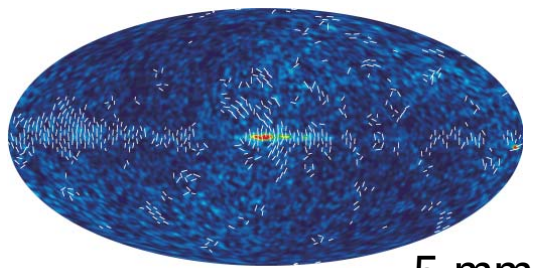
WMAP, BOOMERanG, QUaD, Planck, ...

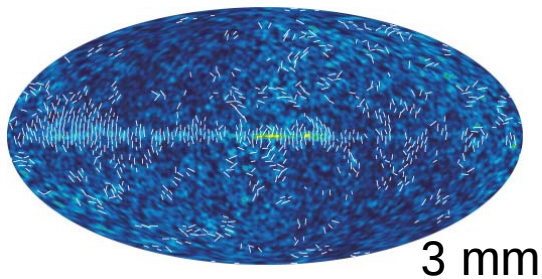
WMAP Full-Sky Polarization







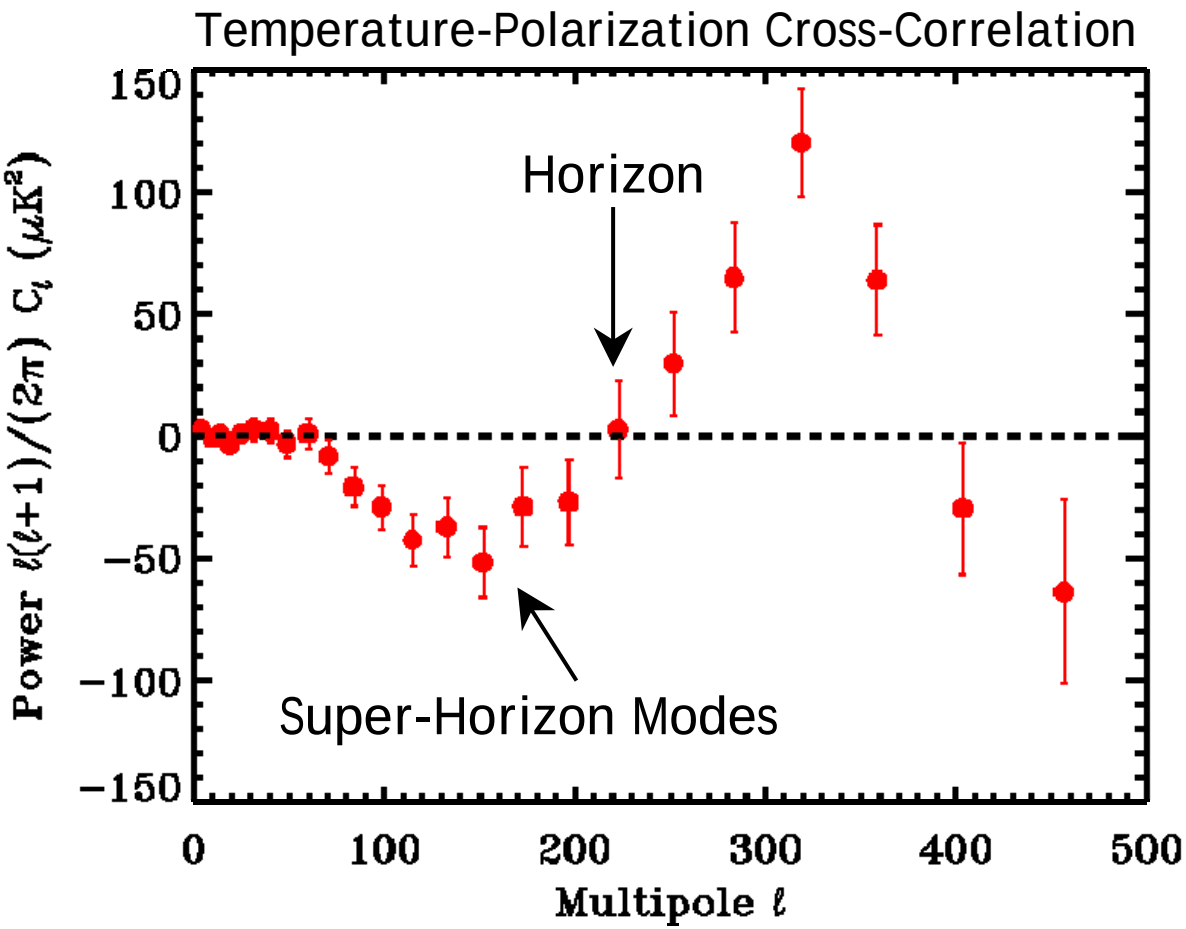




Foregrounds brighter than CMB
E-mode comparable to B-mode

Page et al. 2006, ApJ in press, astro-ph/0603450

WMAP and Inflation



Continuity:

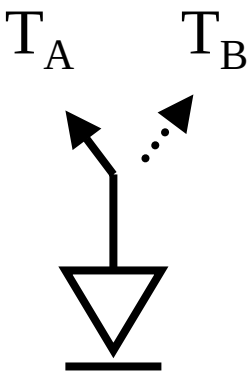
$\partial\rho/\partial t + \nabla\bullet(\rho v) = 0$

Observe beating between ρ and v

$v \neq 0$ on super-horizon scales requires super-horizon potential: Inflation!

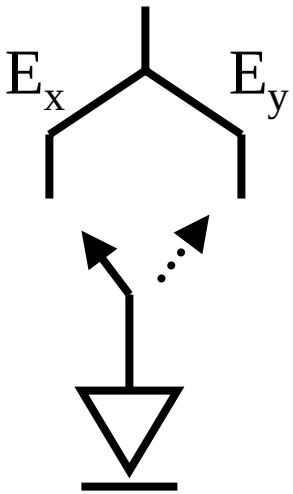
Peiris et al. 2003, ApJS, 148, 213

2nd Generation: Add Modulation



Temperature Anisotropy: $\Delta T/T \sim 10^{-5}$

Difference 2 beam spots on single detector

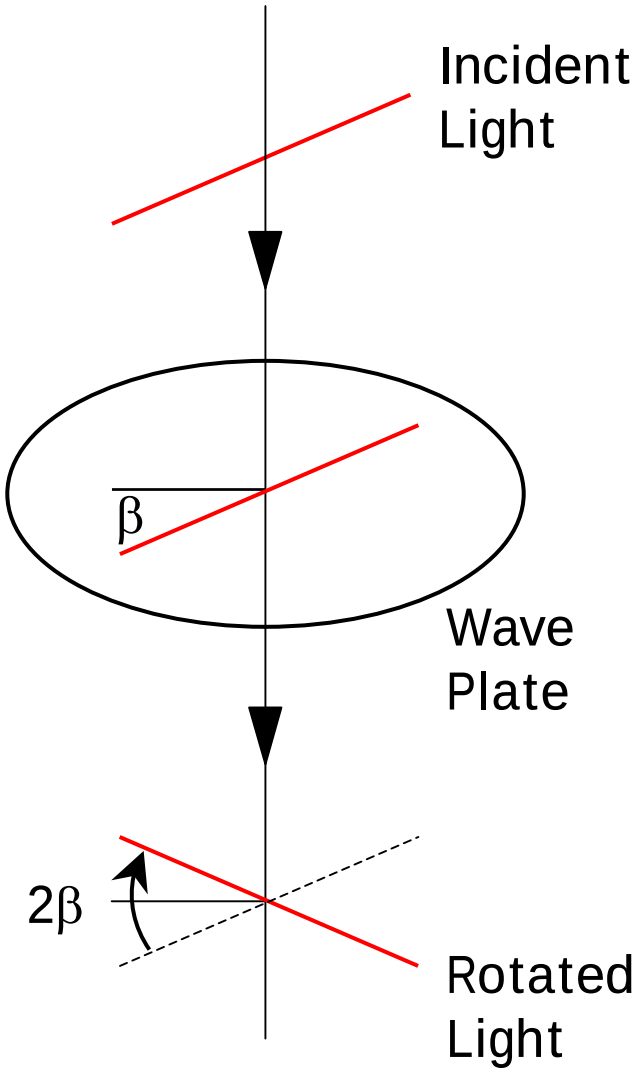


Polarization: $\Delta P/T < 10^{-6}$

Difference 2 polarizations on single detector

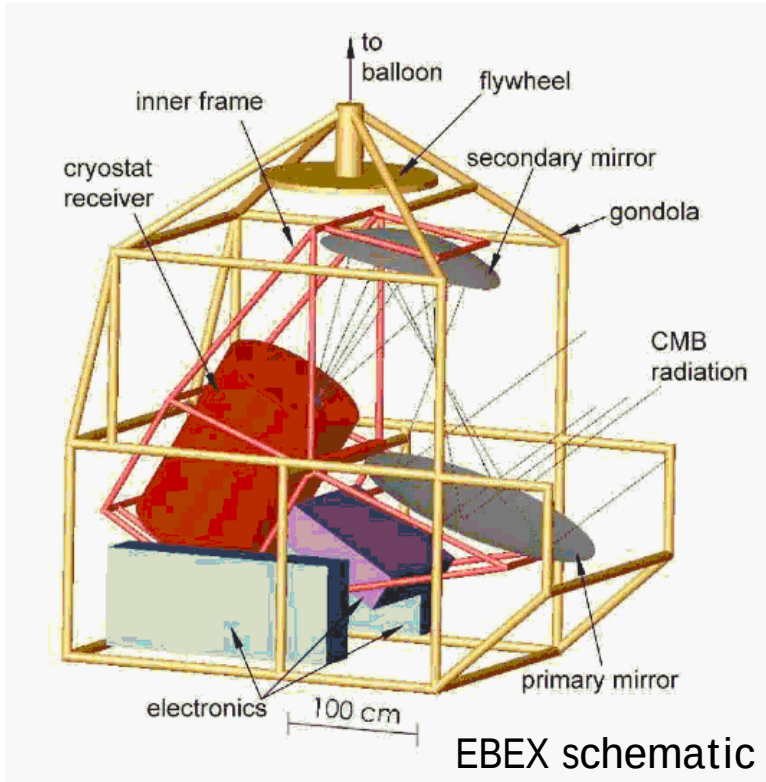
Many Approaches In Development!

Rotating Quarter-Wave Plate



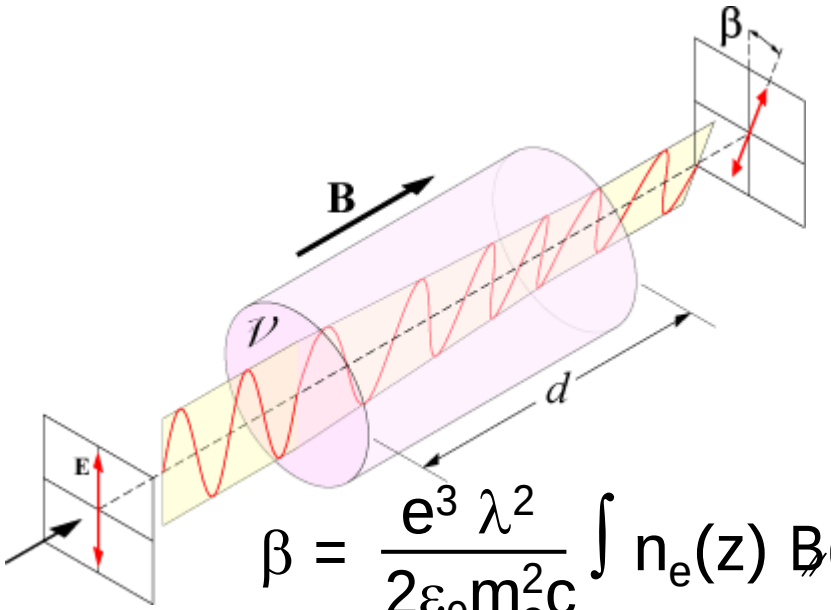
Rotate polarization on each detector

- Macroscopic moving parts
- Achromatic plate possible but hard
- MAXIPOL, EBEX, SPIDER balloon instruments



EBEX schematic

Faraday Rotation



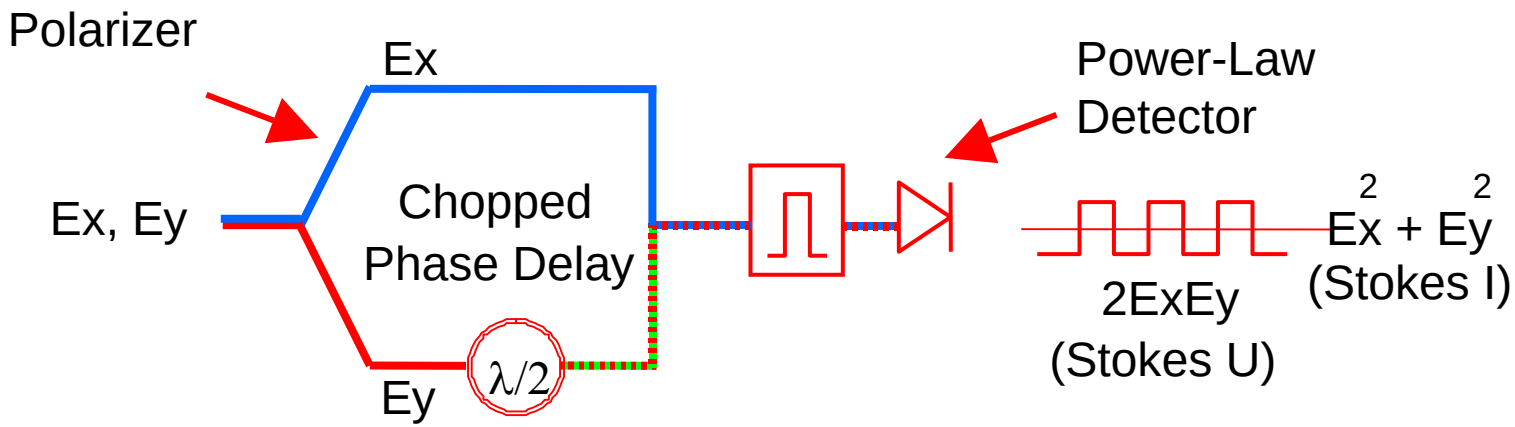
$$\beta = \frac{e^3 \lambda^2}{2\varepsilon_0 m_e^2 c} \int n_e(z)\, B_{\parallel}(z)\, dz$$

Rotate polarization in magnetic medium

- No moving parts
- Hand fabrication, high power
- BICEP ground-based instrument

BICEP at South Pole

Phase-Sensitive Detection



Switch Up $P_u = \langle (E_x + E_y)^2 \rangle = E_x^2 + E_y^2 + 2\,E_xE_y$

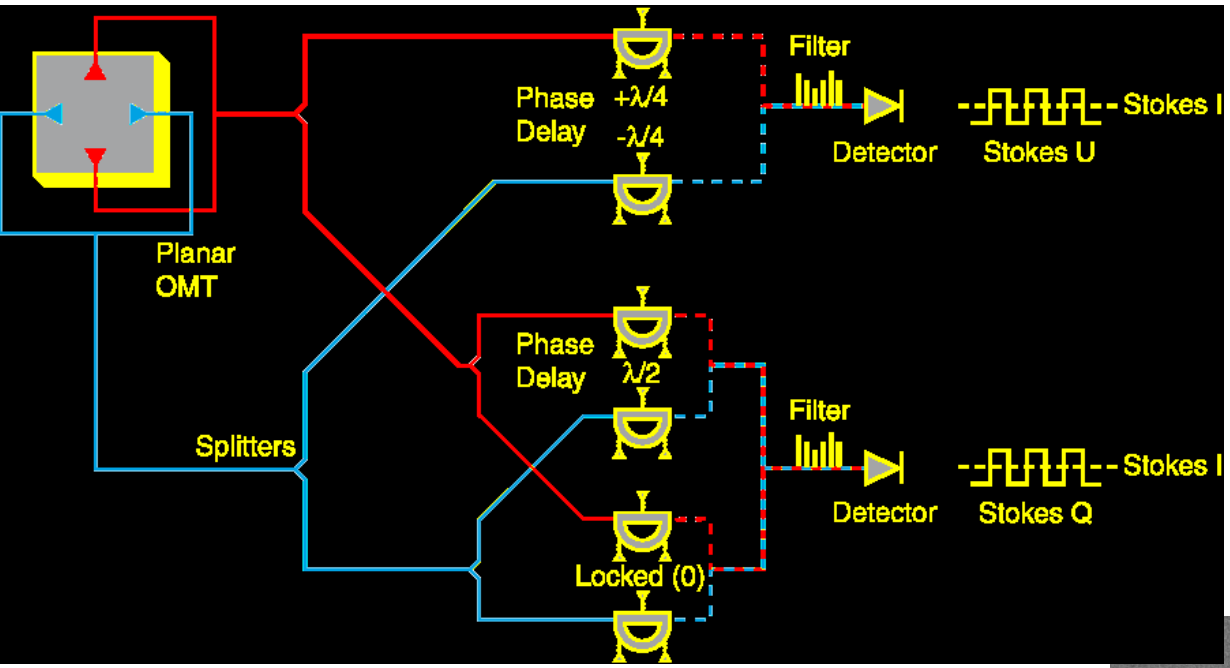
Switch Down $P_d = \langle (E_x - E_y)^2 \rangle = E_x^2 + E_y^2 - 2\,E_xE_y$

Output $P_{dc} = 1/2 \langle P_u + P_d \rangle = E_x^2 + E_y^2$

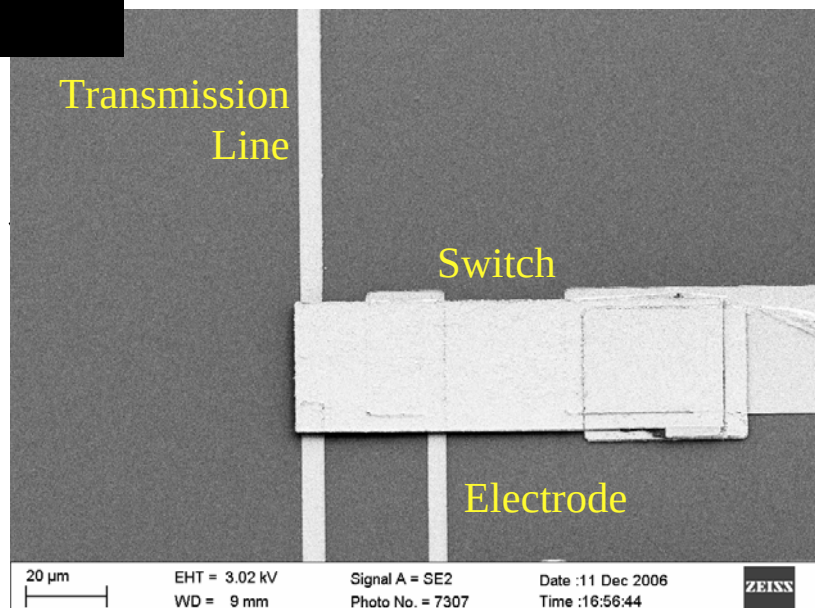
$P_{ac} = 1/2 \langle P_u - P_d \rangle = 2\,E_xE_y$

Demodulated Output ~ Linear Polarization

Polarimeter On A Chip



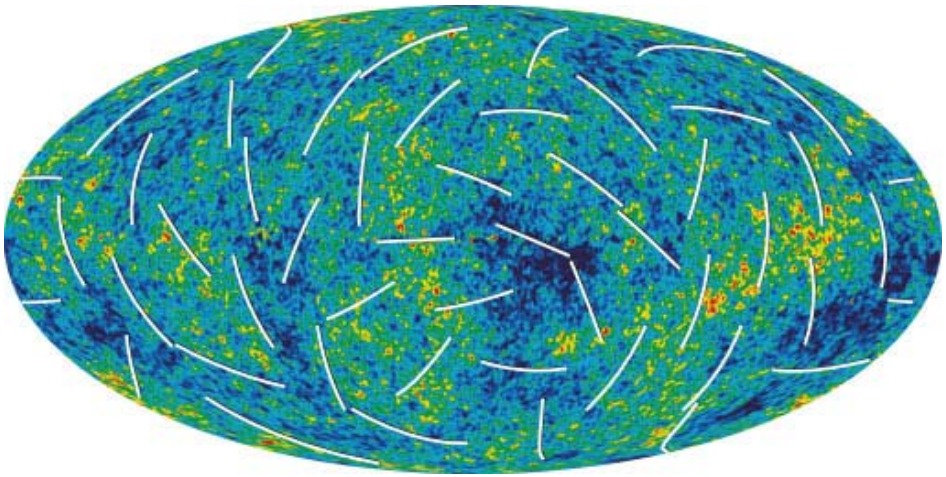
PAPPA Phase Switch



Photolithography for large arrays

- MEMS phase switches
- No macroscopic moving parts
- PAPPA balloon instrument

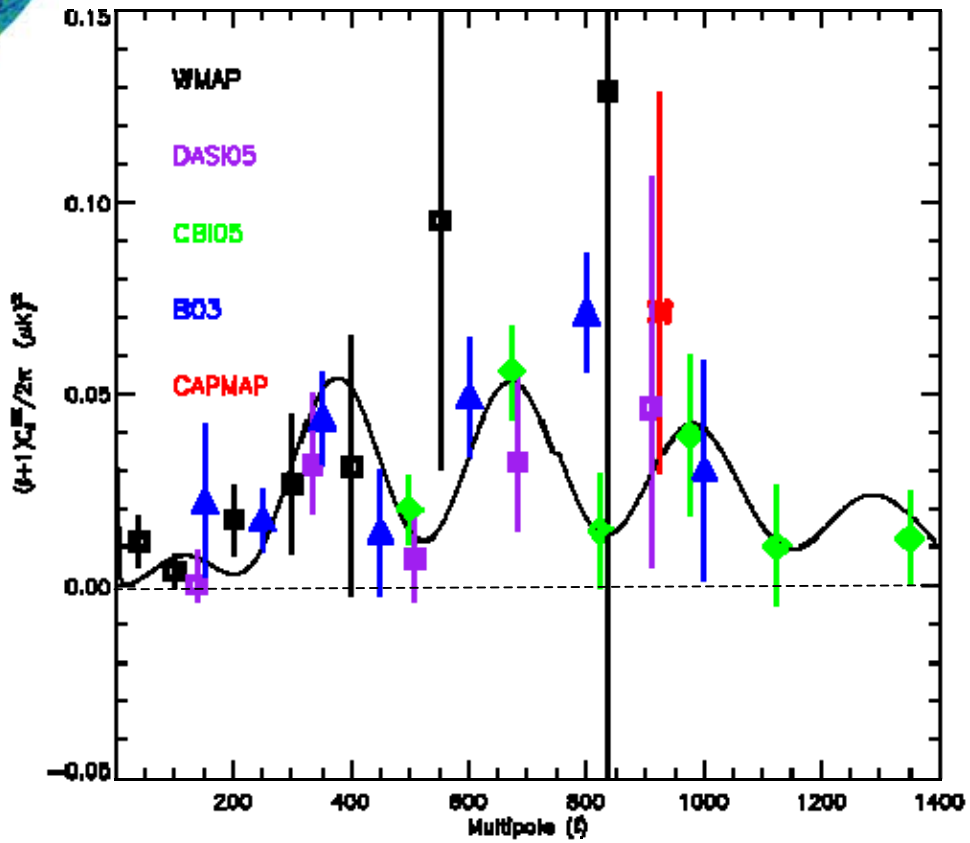
State Of The Art 2007

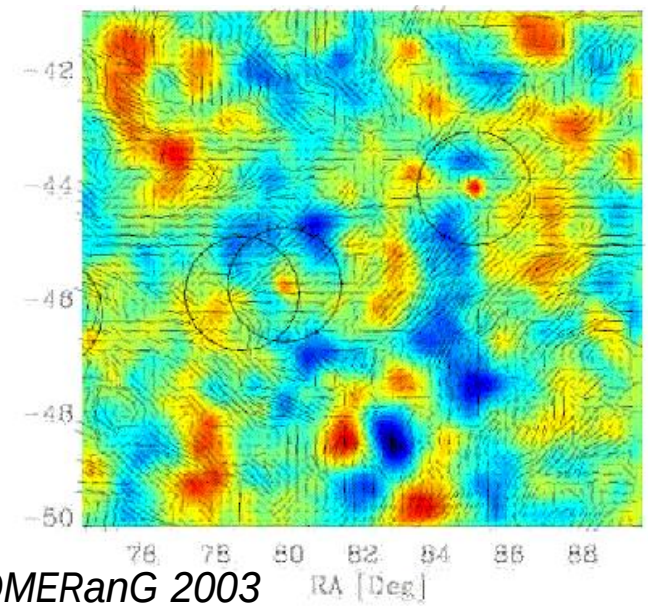


WMAP 3-year full-sky T + E-modes

Beginning to map E-mode

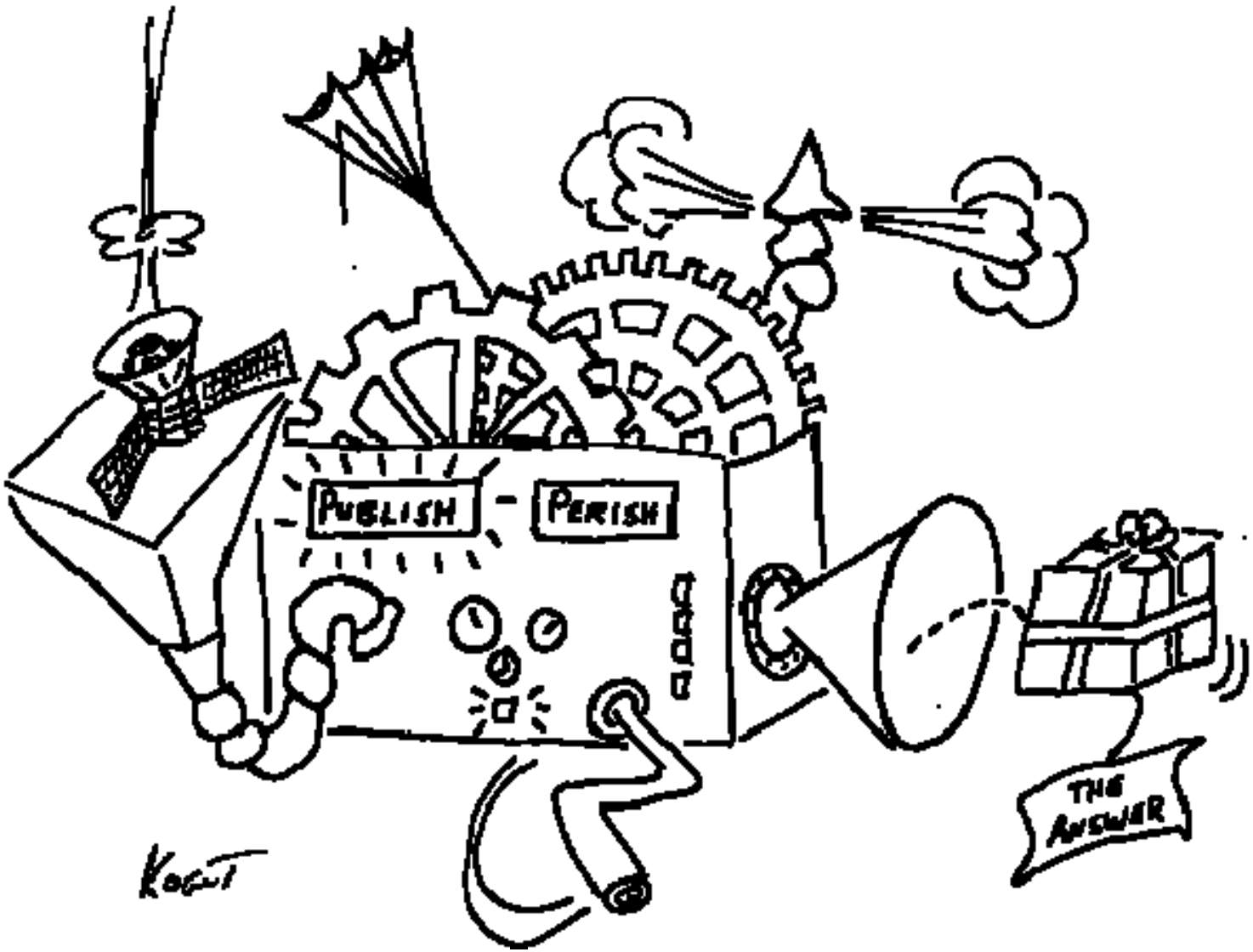
Upper limits to B-mode r < 0.28



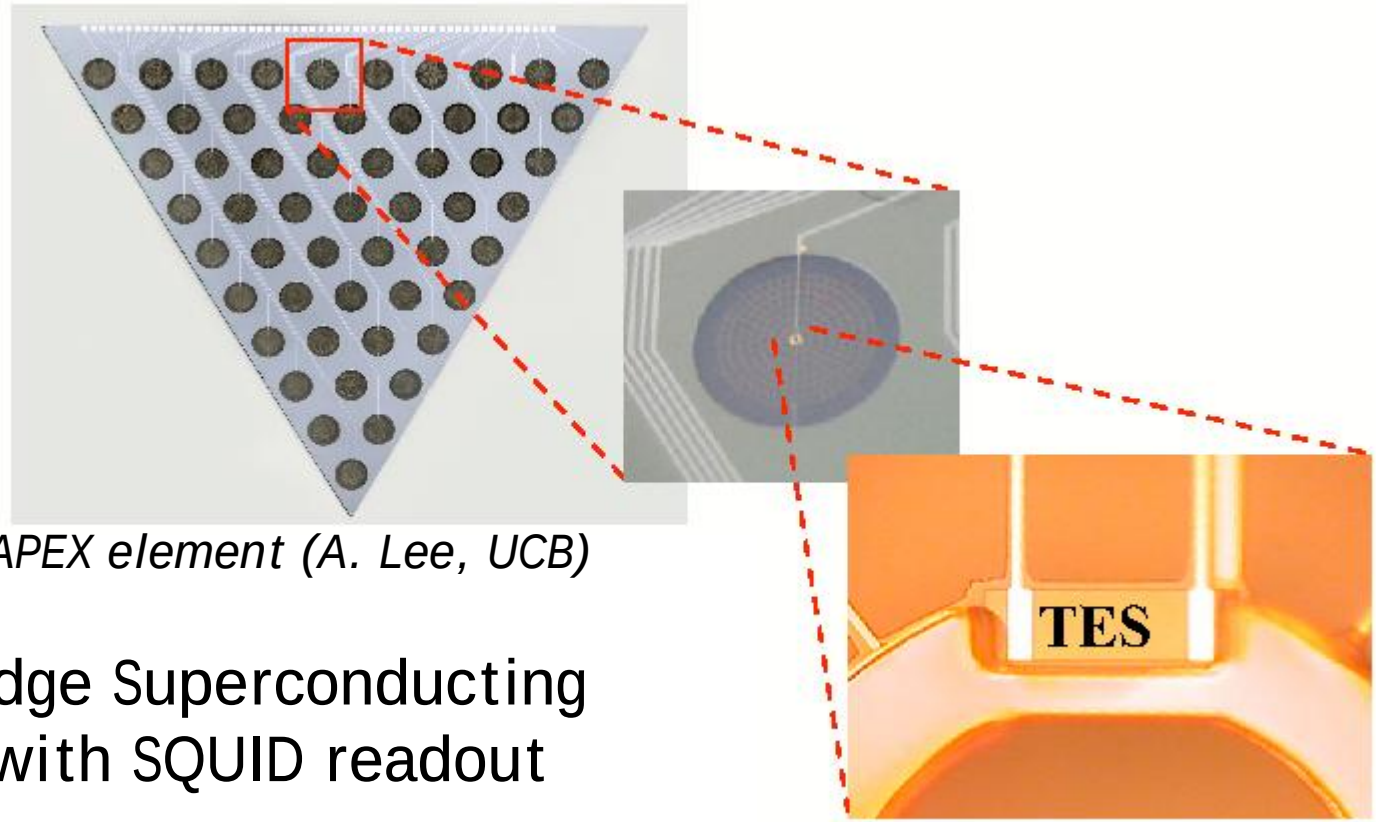


BOOMERanG 2003

Towards a B-Mode Machine



Kilo-Pixel Detector Arrays



APEX element (A. Lee, UCB)

Transition-Edge Superconducting bolometers with SQUID readout

10^2 to 10^3 element arrays now coming on line!

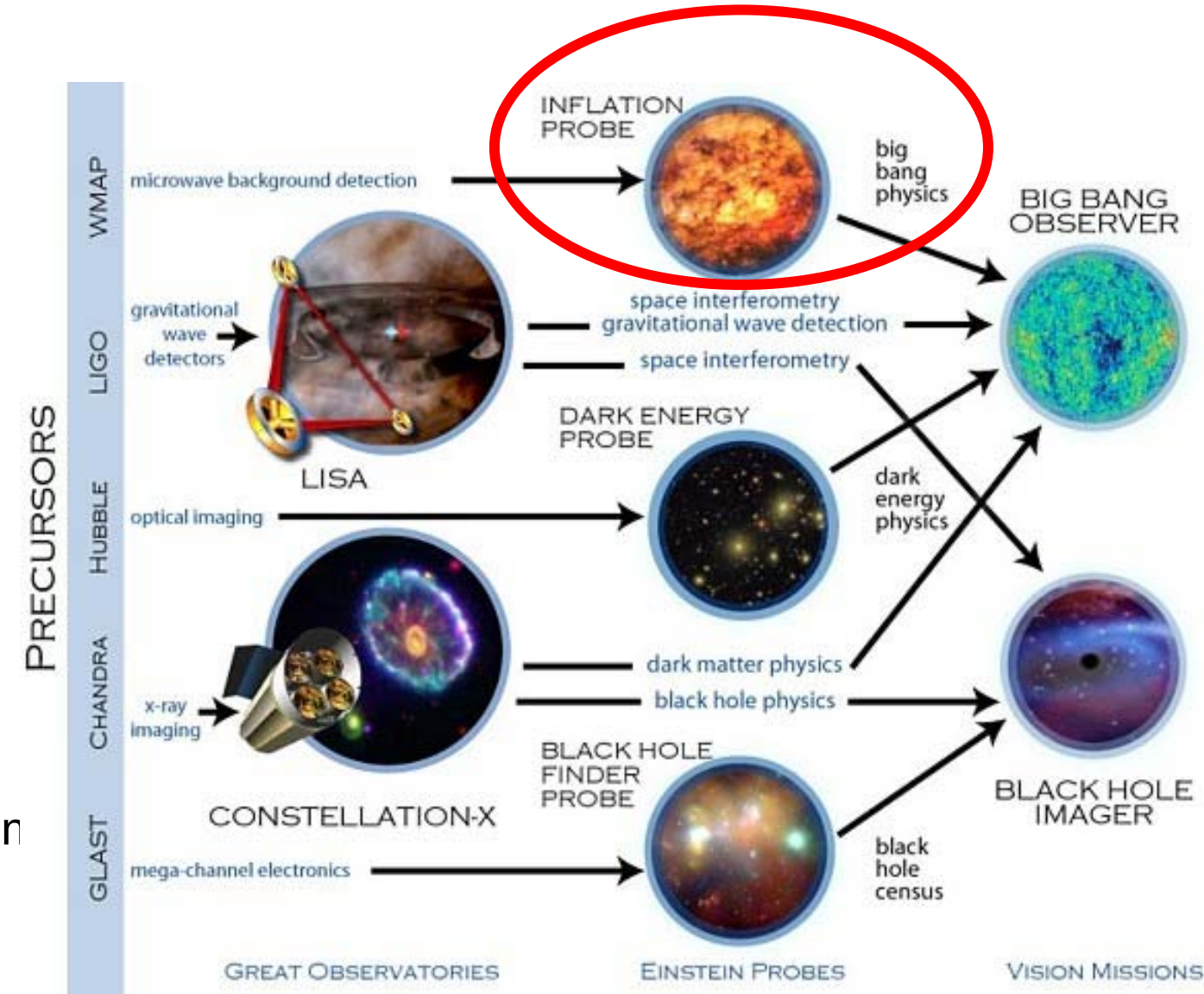
Beat photon noise by using multiple independent detectors

Future Missions

Open Opportunity:
NASA Explorer
Program (2013?)

Open Opportunity:
ESA "Cosmic Vision"
Program (2017)

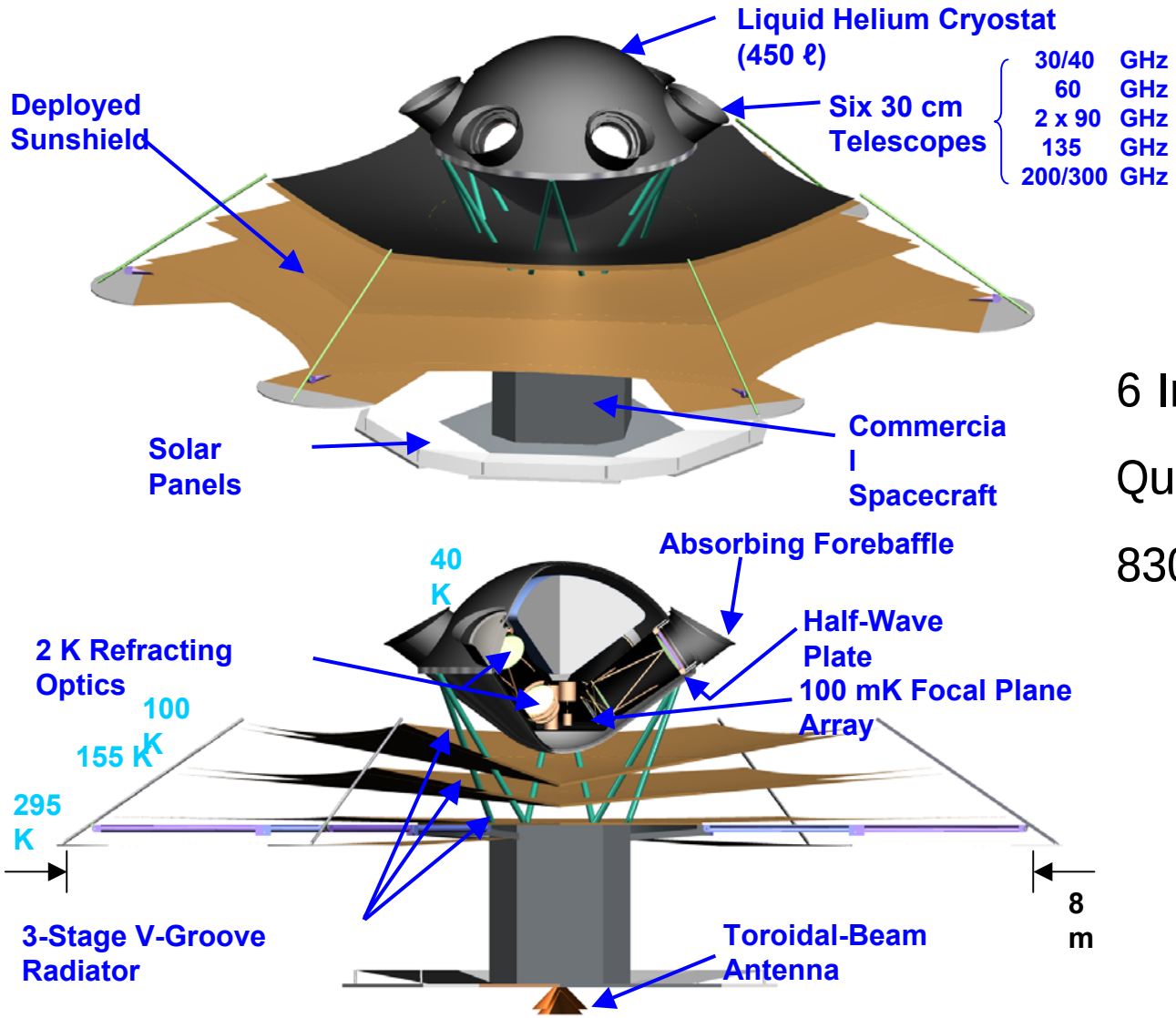
Dedicated Mission:
NASA "Beyond Einstein"
Program (2019?)



NASA "Beyond Einstein" Program

Experimental Probe of Inflationary Cosmology (EPIC)

J. Bock et al. (JPL)



6 Independent Telescopes

Quarter-Wave Plates

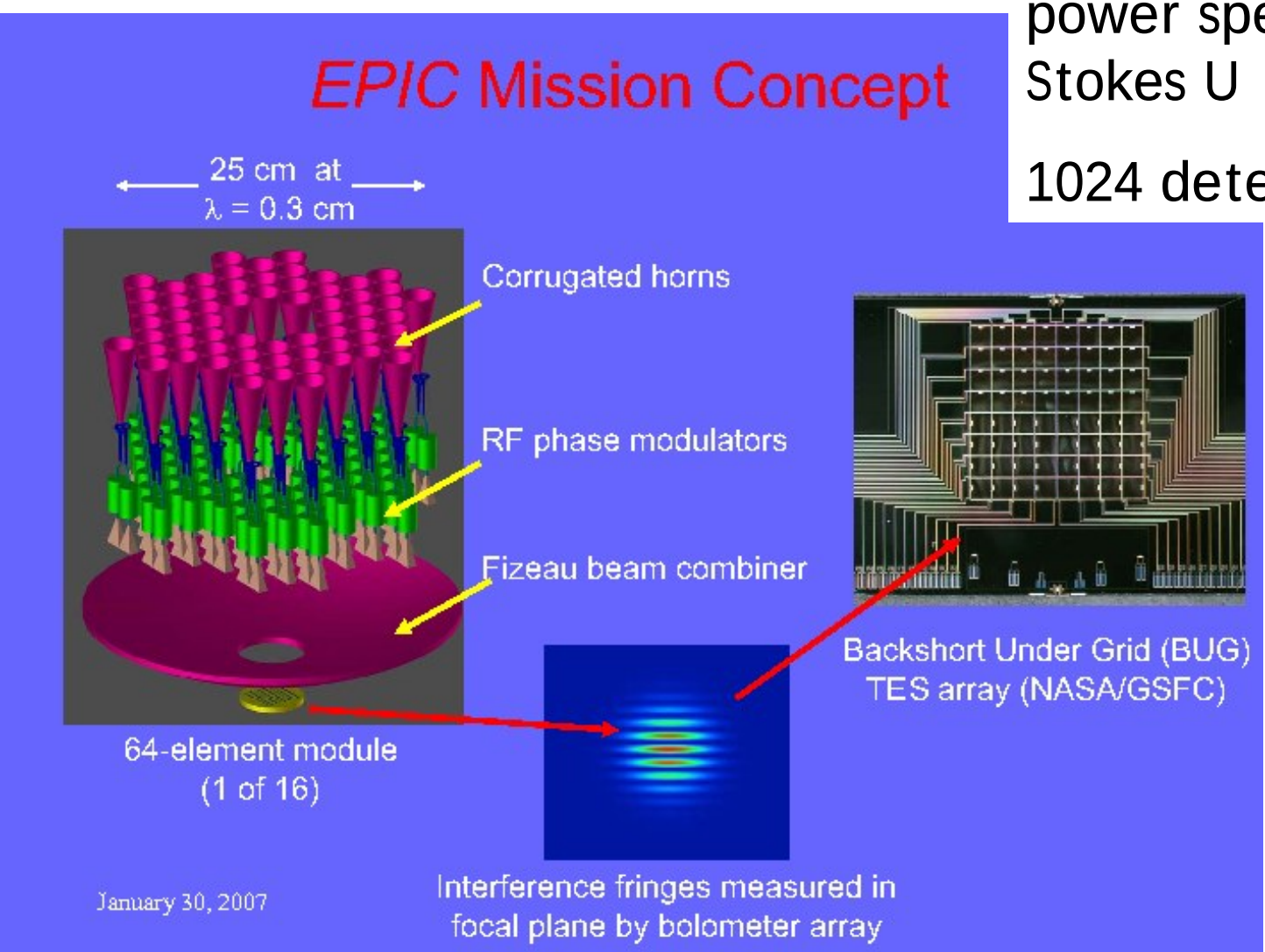
830 or 2366 detectors

Einstein Polarization Interferometer for Cosmology (EPIC)

P. Timbie et al. (U Wisc)

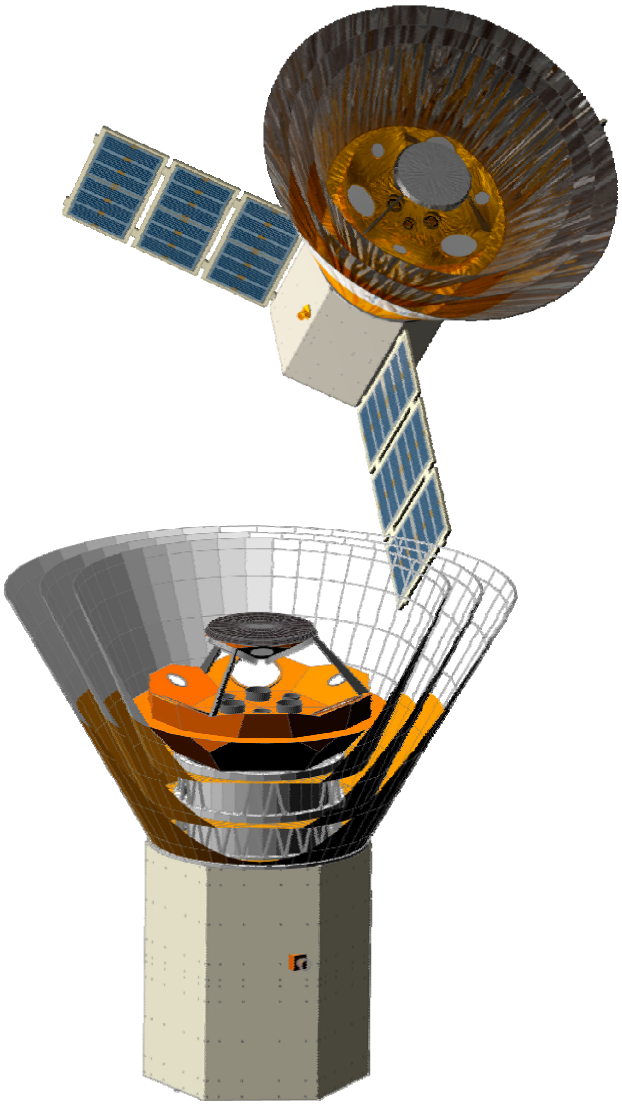
Interferometer measures power spectrum of Stokes U

1024 detectors



CMB Polarimeter (CPMPol)

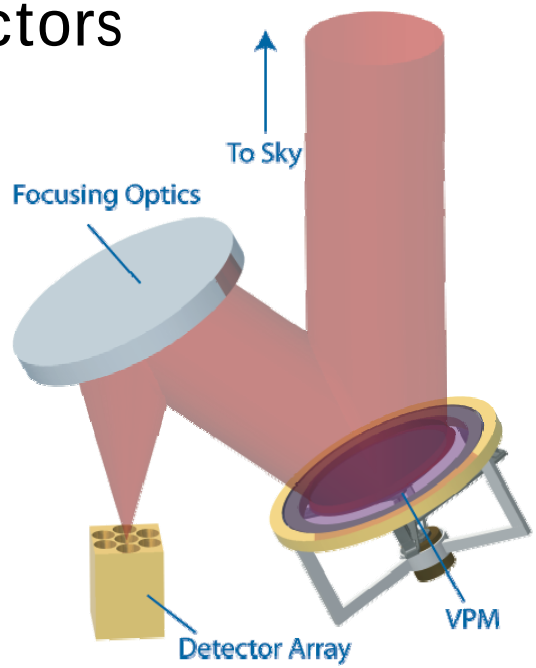
G. Hinshaw et al. (GSFC)



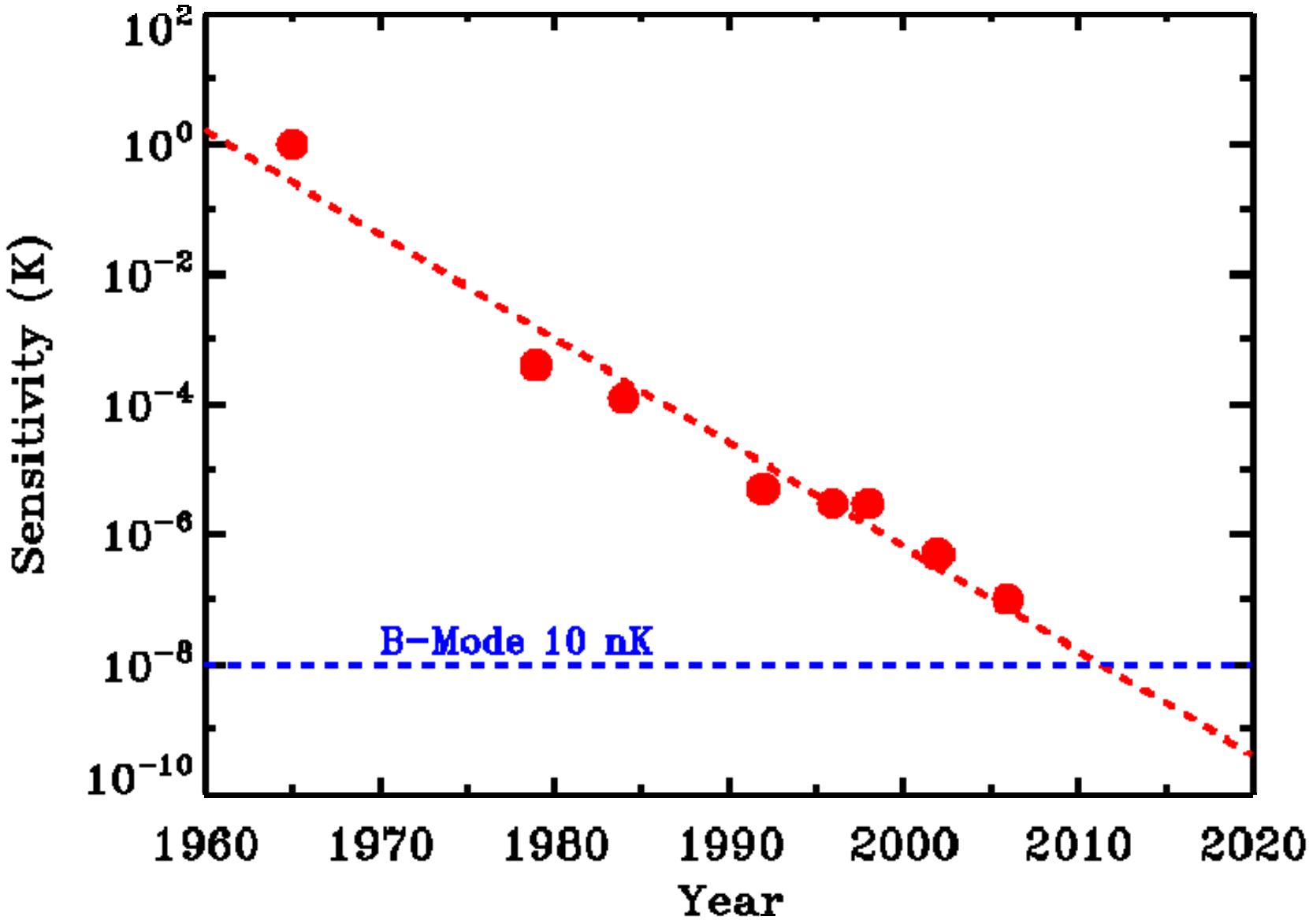
Optical phase delay as first element

- Modulates sky signal, not instrument
- Fast compared to 1/f knee

1024 TES detectors



Plausible Achievability



Coming Soon From a Spacecraft Near You:

Inflation,
Quantum Gravity,
And the
Theory of Everything!