The Cosmic Microwave Background Radiation

B. Winstein, U of Chicago

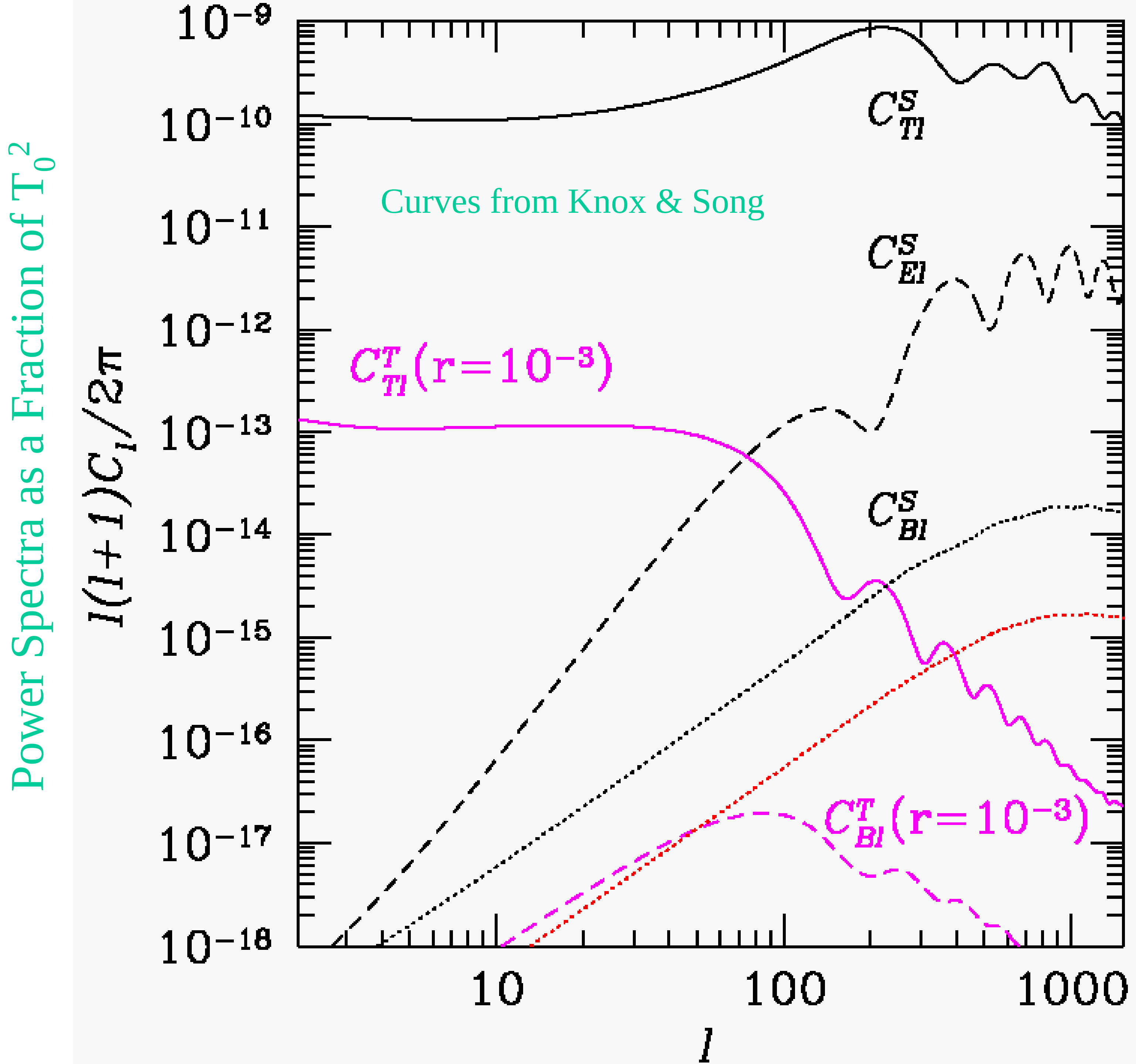
Lecture #1	What is it? How its anisotropies are generated? What Physics does it reveal?
Lecture #2	How it is measured.
Lecture #3	Main thrusts for the next decade.

New CMB Efforts

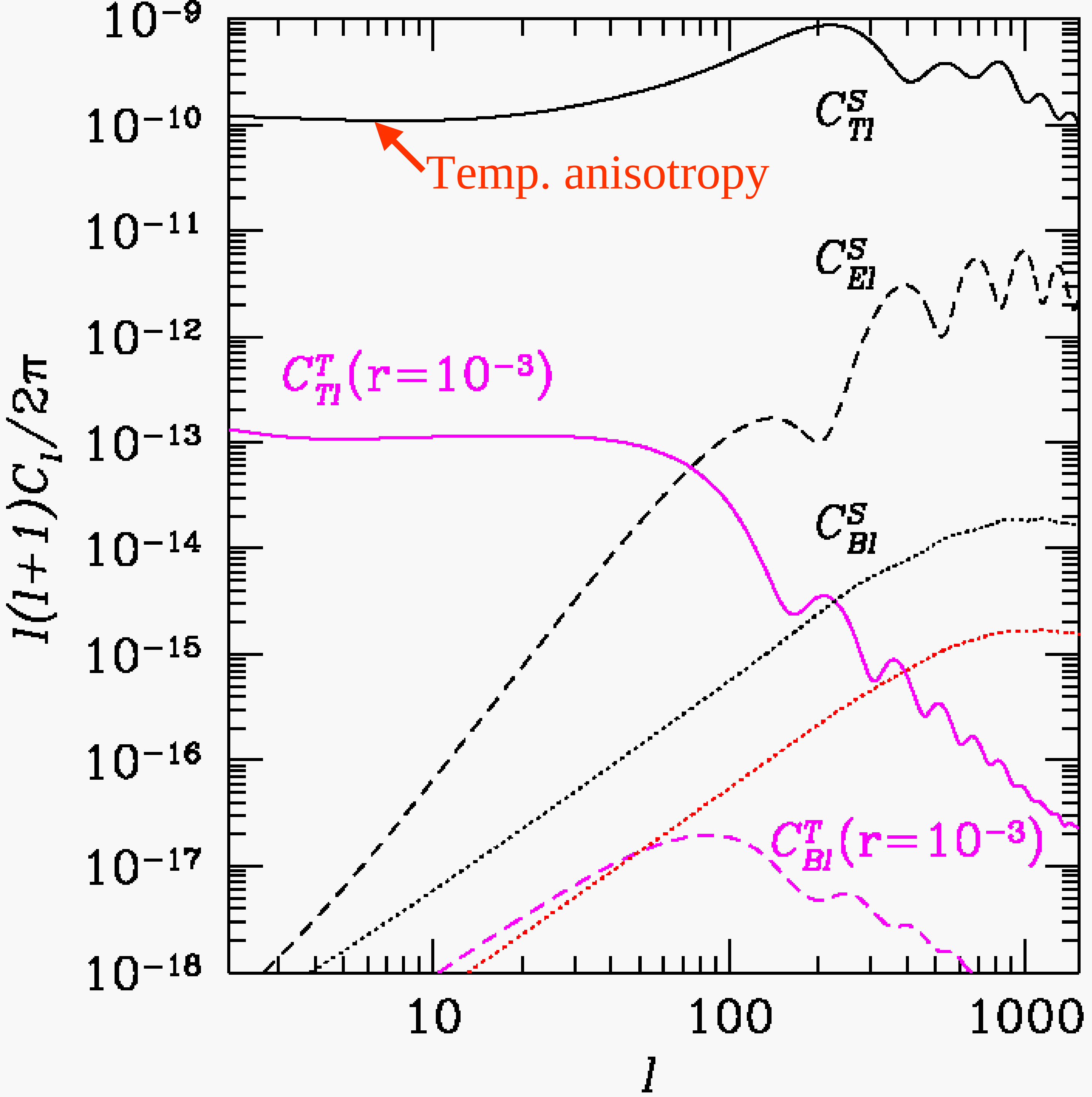
- An inflation probe?
  – Primordial gravity waves
- Polarization
  – Why it is there
  – How it can be detected
- Other topics
  – Neutrino mass
  – SUSY
  – Extra Dimensions/Trans Planckian physics

Primordial Gravity Waves

- Tensor perturbations generated during (slow roll) inflation
  - Just like density/scaler modes
- Strength depends upon: r = T/S
  - Tensor to scaler ratio unknown
  - r depends on the energy scale of inflation
    - $V^{0.25} = 0.003 M_{pl} r^{0.25}$
    - r = 0.001 corresponds to $E_{inflation} = 6.4 \times 10^{15}$ GeV
- r can be limited studying ΔT
- Best information from CMB polarization



Power Spectra as a Fraction of T_0^2
$l(l+1)C_l/2\pi$
Curves from Knox & Song
C^S_{Tl}
C^S_{El}
C^S_{Bl}
$C^T_{Tl}(r=10^{-3})$
$C^T_{Bl}(r=10^{-3})$
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10
100
1000
l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C^S_{Tl}
Temp. anisotropy
C^S_{El}
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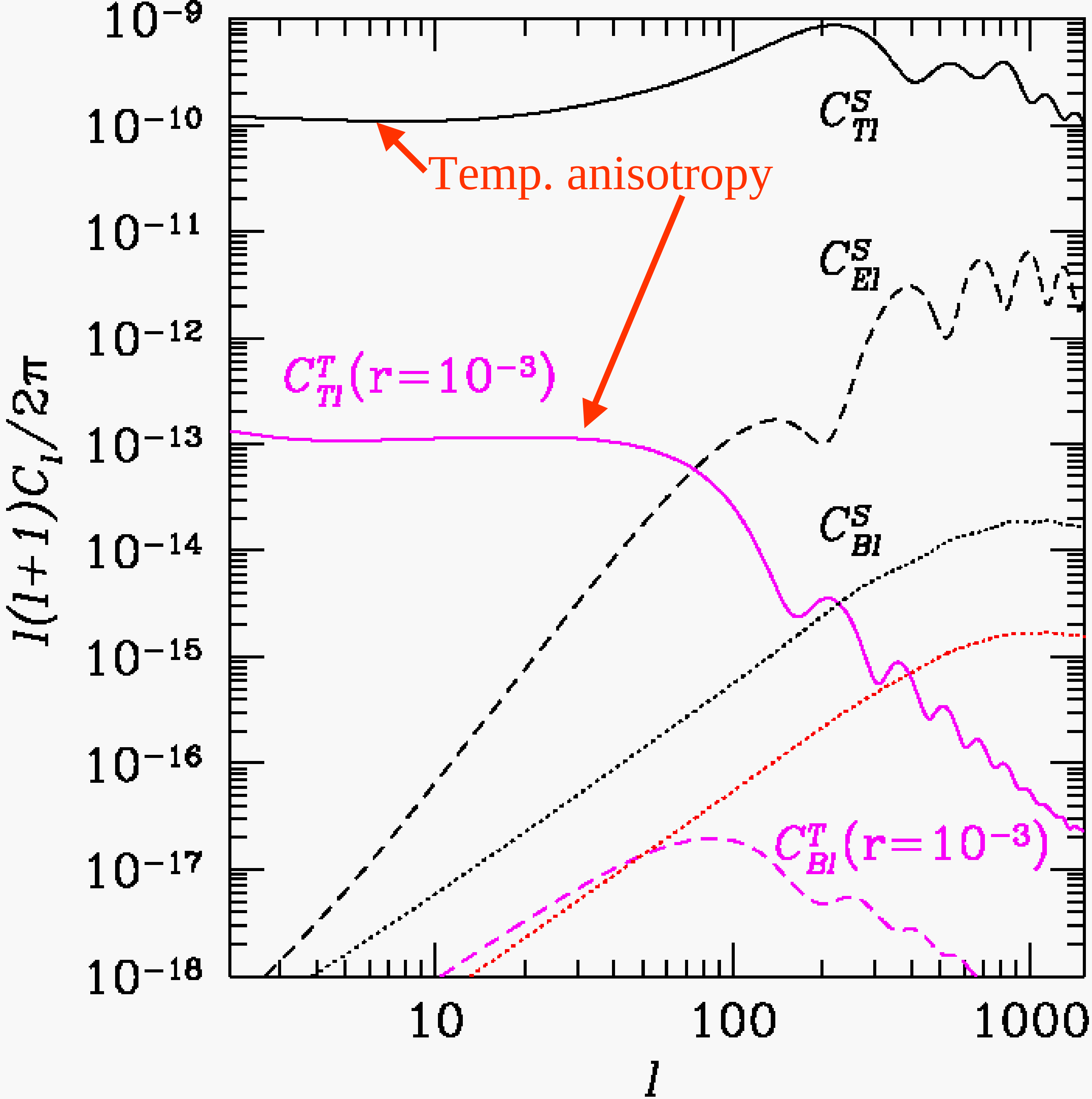

10^{-9}
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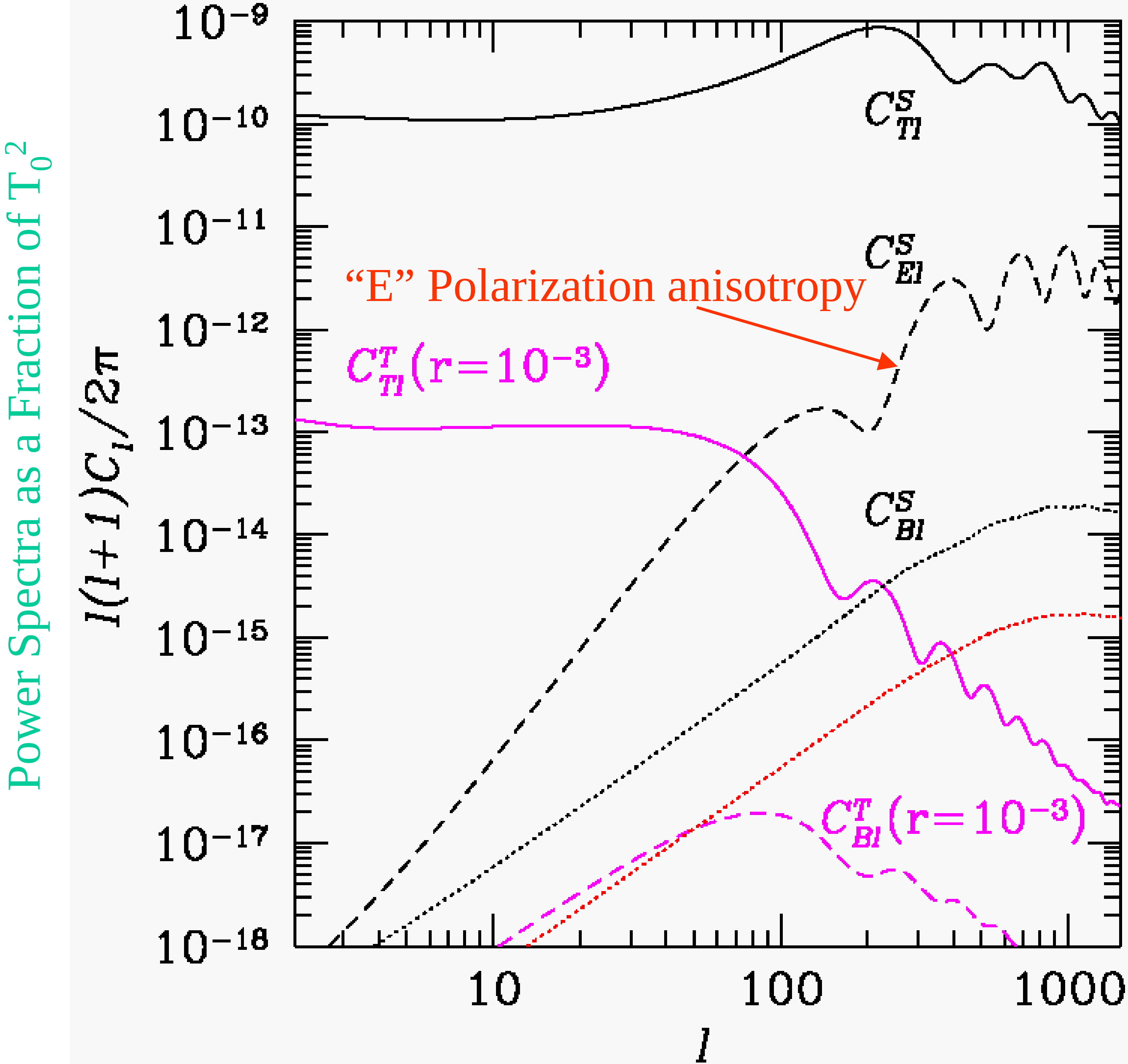

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10^{-10}
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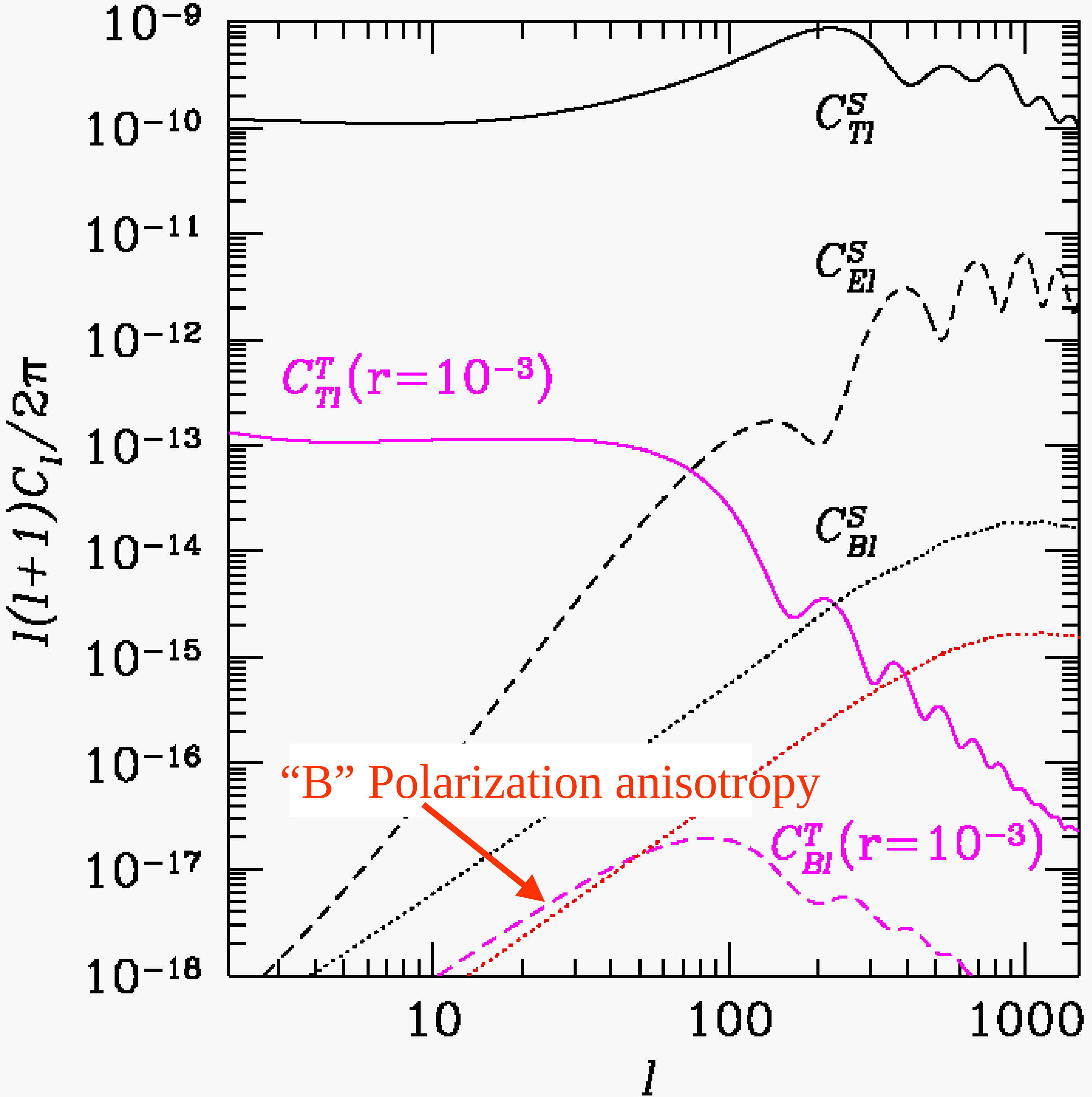
10^{-15}
10^{-16}
10^{-17}
10^{-18}
C^S_{Tl}
C^S_{El}
"E" Polarization anisotropy
$C^T_{Tl}(r=10^{-3})$
C^S_{Bl}
$C^T_{Bl}(r=10^{-3})$
10
100
1000
l

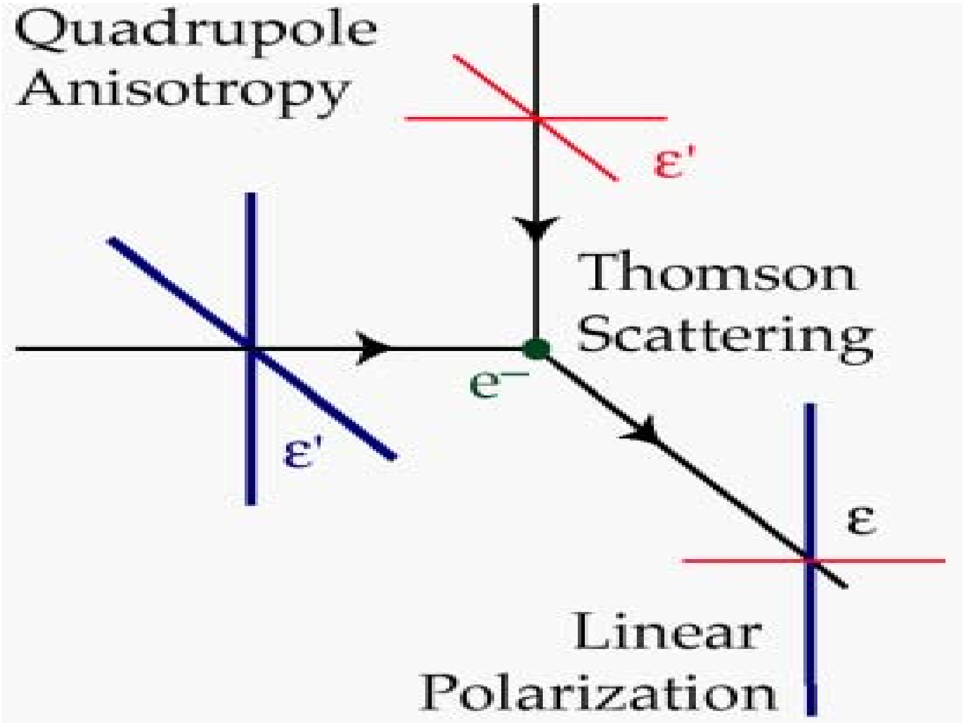


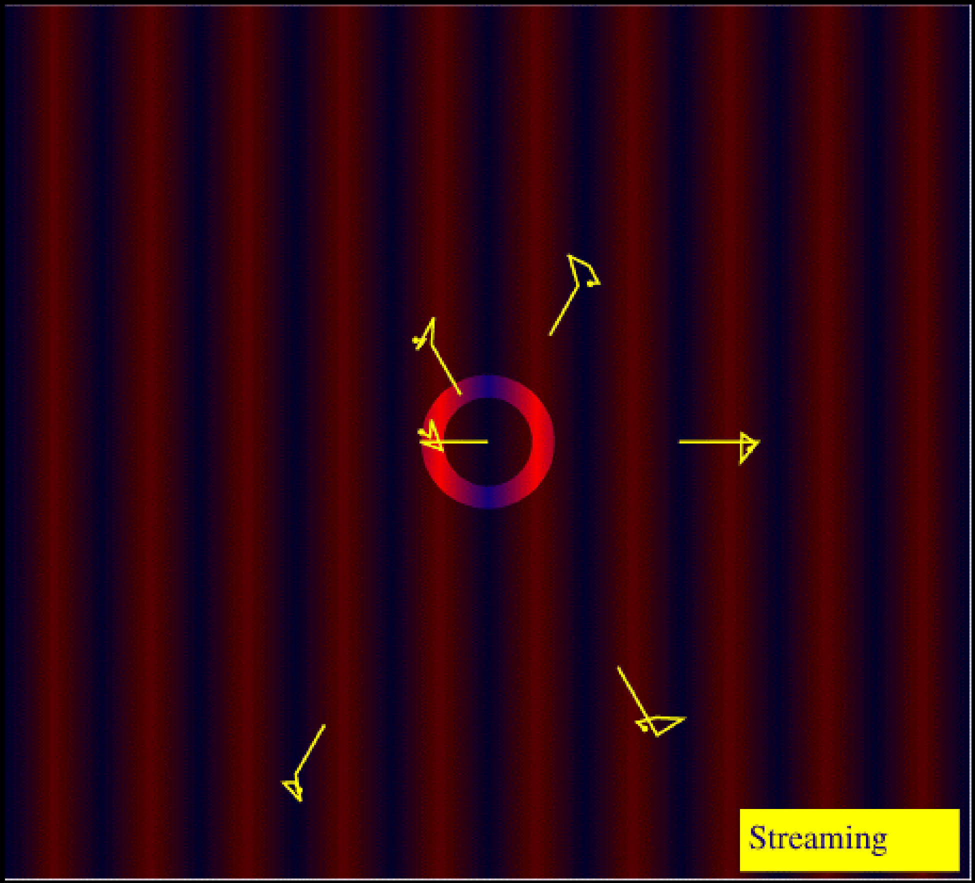
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$l(l+1)C_l/2\pi$
C^S_{Tl}
C^S_{El}
C^S_{Bl}
$C^T_{Tl}(r=10^{-3})$
$C^T_{Bl}(r=10^{-3})$
"B" Polarization anisotropy
10
100
1000
l

- From low l ΔT, r only weakly limited
  - r < 0.13 (at best: depends on assumptions)
    - $E_{infl.} < 2 \times 10^{16}$ GeV
- Best bet is (very weak) polarization
- Let's look at:
  - Sensitivities required
  - Why there will be polarization
  - Means of detecting polarization
  - A critical but interesting foreground
    - Provides an "ultimate limit" on the reach

CMB Polarization

- Arises from a non-zero Quadrupole moment in the radiation incident on scattering centers



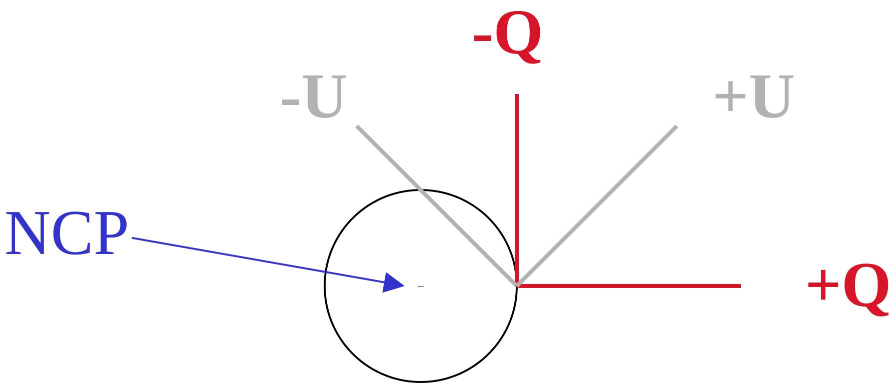

Streaming

CMB Polarization

- Need scattering for polarization; but…
- Scattering washes out the quadrupole
- ➢ Polarization peaks at higher l-values
- ➢ Polarization anisotropy is weak ≈ 0.05 T

CMB Polarization

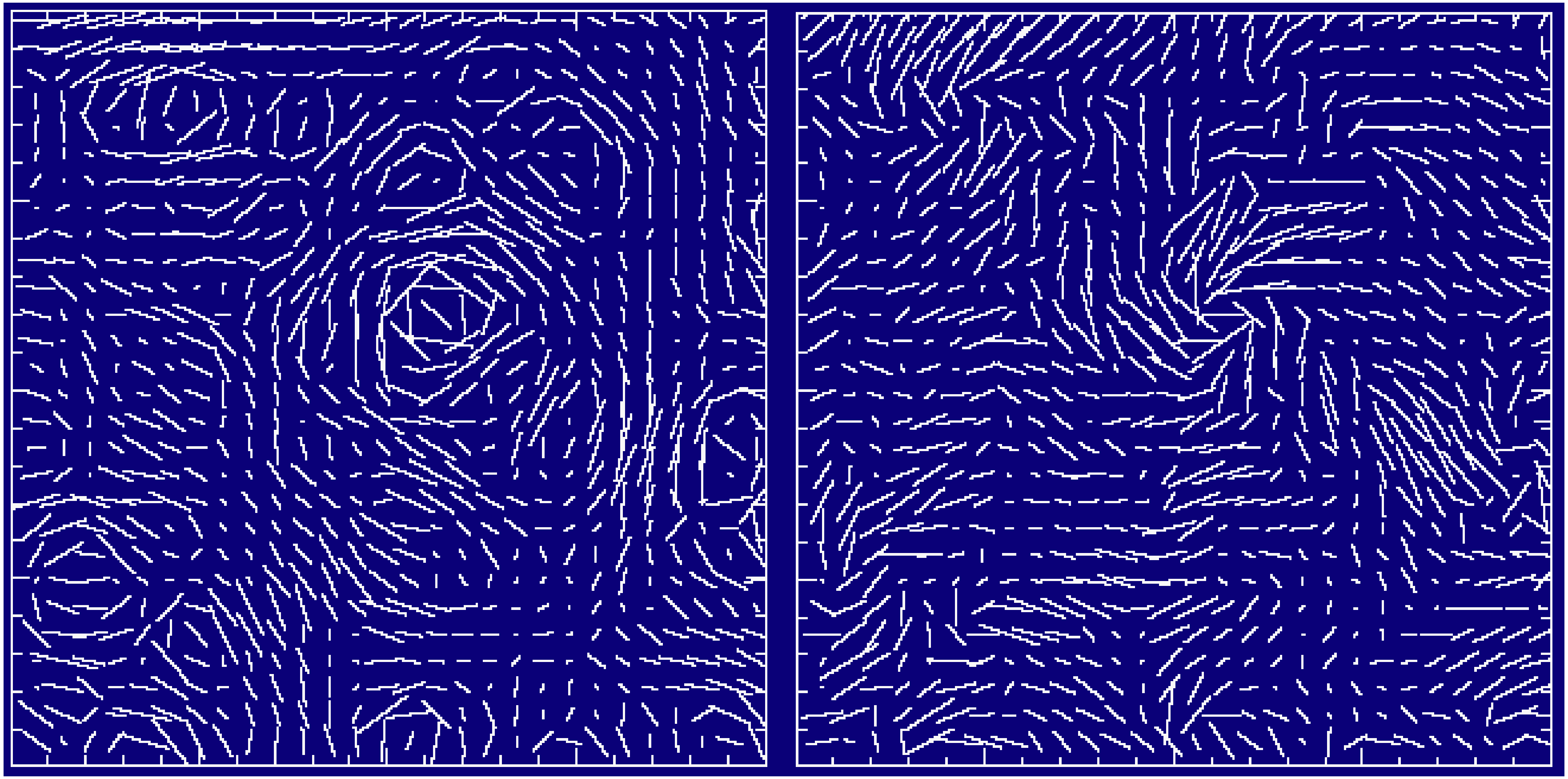
- A Direct look at the Surface of last scattering unlike T anisotropies
- Quantified by Stokes parameters **Q** and **U** at each pixel: orientation of Electric Field



- Can be expressed in terms of E and B fields

coordinate system independent closely linked to physical processes

E/B Modes

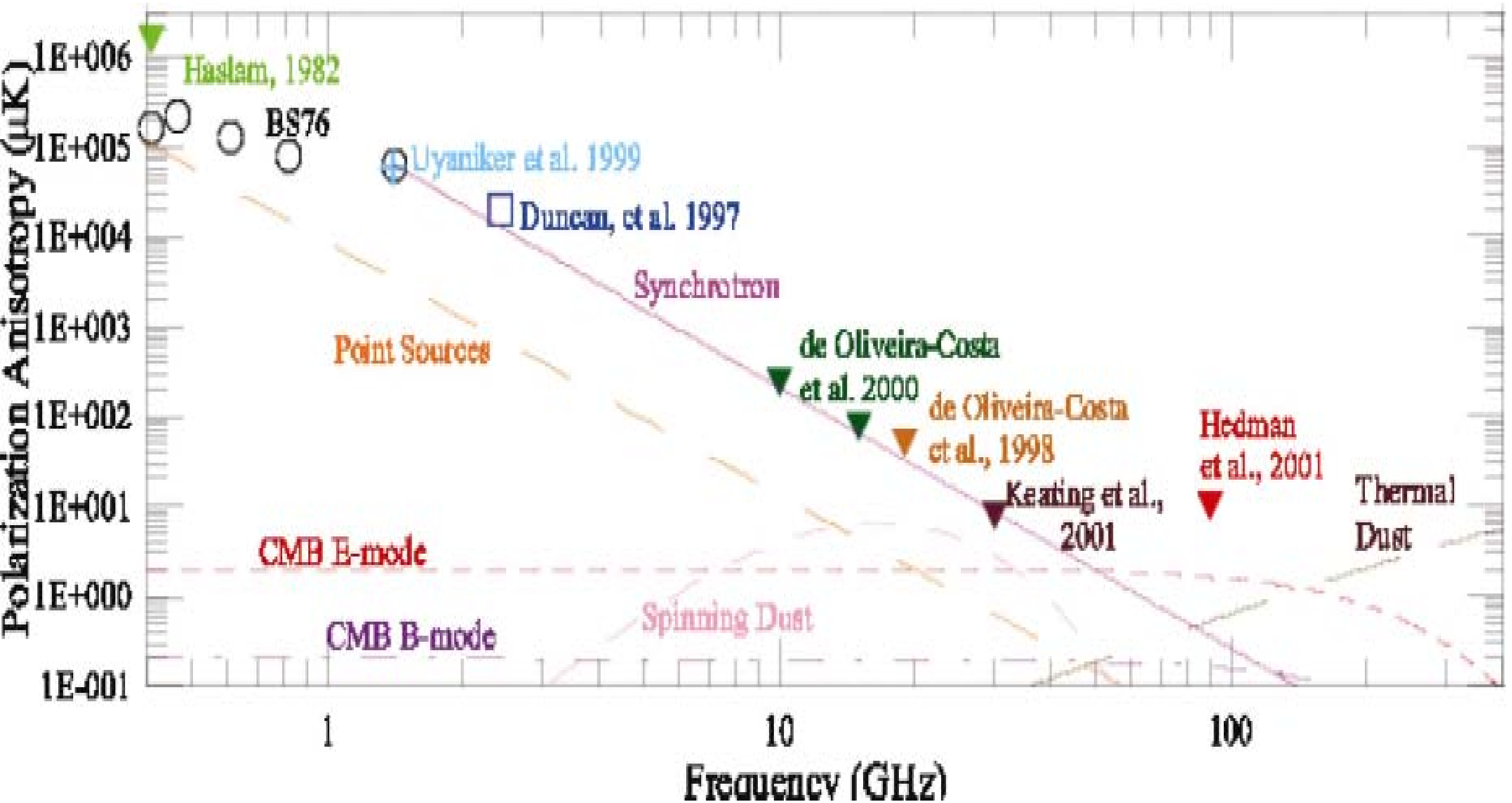


Key Points:

- Density perturbations produce only E modes
  - No handedness
- Gravity waves produce both E and B modes

What about Galactic Foregrounds for Polarization?

Poorly Studied but indicate ≈ 100 GHz is best.



Detector Technology

- Bolometer
  - Incoherent
  - Very high sensitivity
  - Stable
  - Systematics
    - Promising schemes
  - THE way to the B-modes(?)

–Boomerang 2001
–Maxipol
–Planck

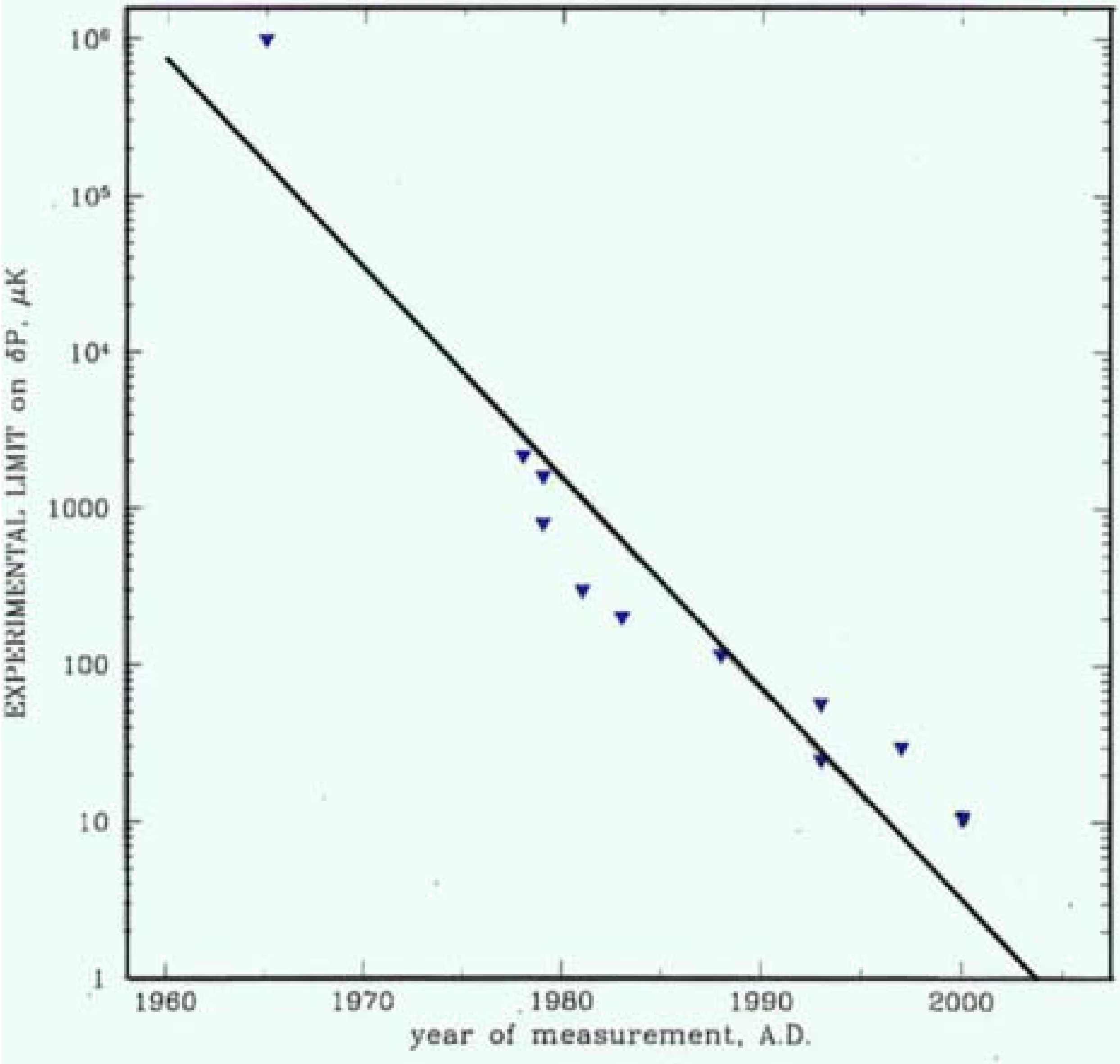
- HEMT
  - Coherent
  - High system temp.
  - Systematics
    - Most (all) limits today come from HEMT systems
  - Allows Interferometry

–PIQUE/CAPMAP
–Polar/Compass
–DASIPOL
–MAP

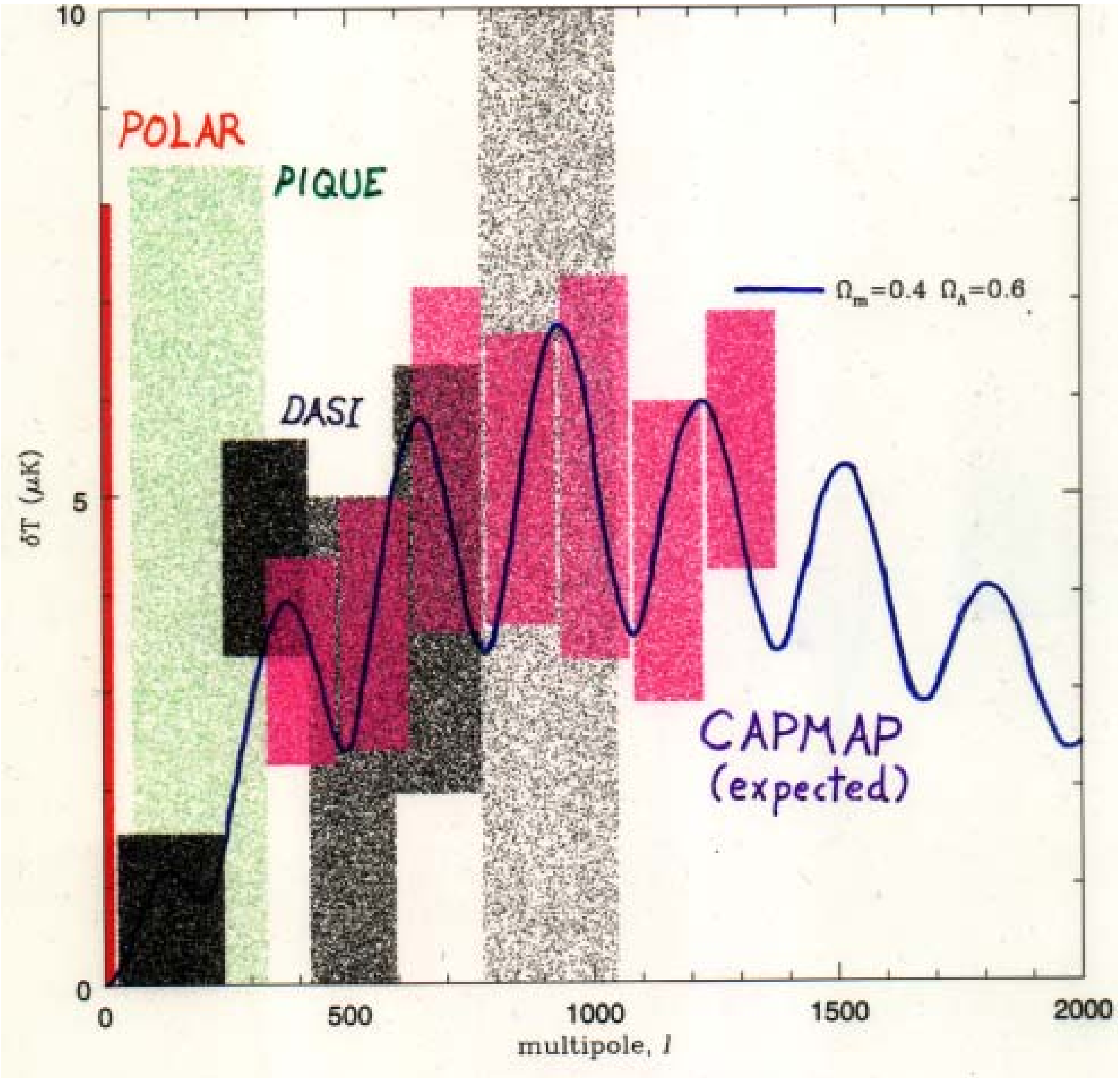
	Frequencies (#)	Beam	Site	Technique
POLAR	30 (1)	7°	WI	Correl. Rad., axial spin
COMPASS	30 (1), 90 (1)	20', 7'	WI	Correl. Rad., NCP scan
PIQUE	40 (1), 90 (1)	30', 15'	NJ	Correl. Rad., NCP chop
CAPMAP	40 , 90	13', 6'	NJ?	Correl. Rad. Array
DASI	30 (13)	20', 7'	S. Pole	Interferometer
CBI	30 (13), 90 (13)?	3'	Atacama	Interferometer
VLA	8.4	6"	Socorro	Interferometer
Polatron	90 (1)	2'	OVRO	Bolo,1/2 λ plate
QUEST	150 , 225 (~30)	4', 3'	Chile?	Bolo Array, 1/2 λ plate
POLARBEAR	150 … (3000 dt'rs)	10'	S. Pole or M. Kea	Bolo Array
BOOM2K	150 (4), 240 (4), 340 (4)	10'	Antarctic LDB	Bolo Array
MAXIPOL	150 (12), 420 (4)	10'	US-Balloon	Bolo Array,cold 1/2 λ plate
BaR-SPOrt	32, 90	30', 12'	Antarctic LDB	Correl. Rad. Array
MAP	22, 30, 40(2), 60(2), 90(4)	13'	L2, full-sky	Correl. Rad. Array*
SPOrt	22, 32, 60, 90	7°	ISS, full-sky	Correl. Rad. Array
PLANCK-LFI	30(4), 44(6), 70(12),100(34)	33',23',13', 10'	L2, full-sky	Correl. Rad. Array
PLANCK-HFI	100(4), 143(12), 217(12), 353(6), 545(8), 857(6)	11', 8', 6', 5', 5', 5'		Bolo Array

Compilation by Peter Timbie

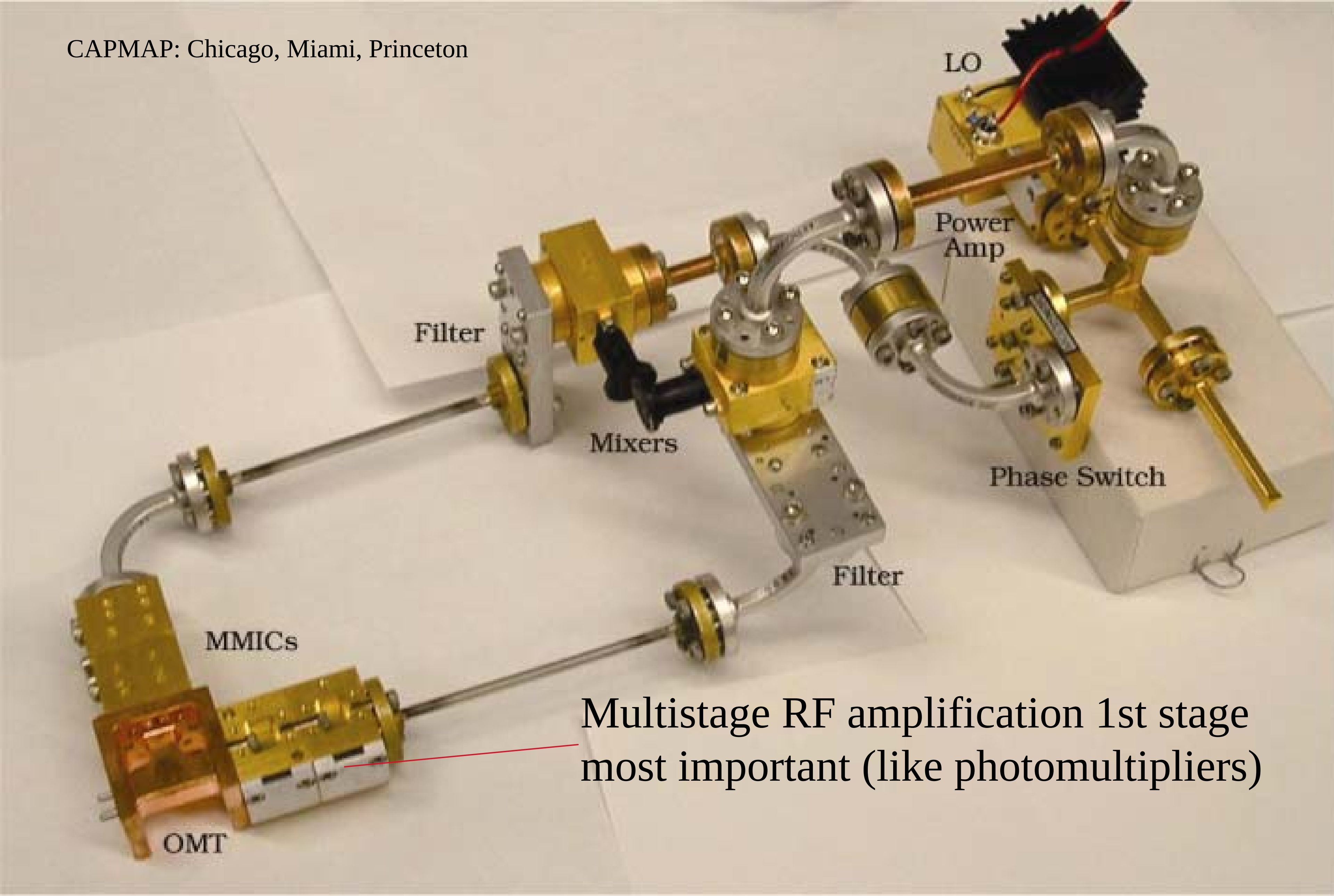
HISTORY OF POLARIZATION LIMITS



CAPMAP Expected Sensitivity

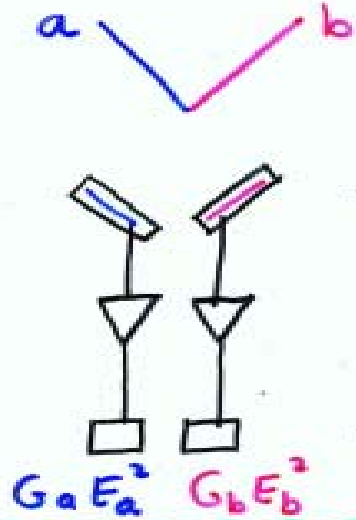


CAPMAP: Chicago, Miami, Princeton



Multistage RF amplification 1st stage most important (like photomultipliers)

How to Measure Polarization

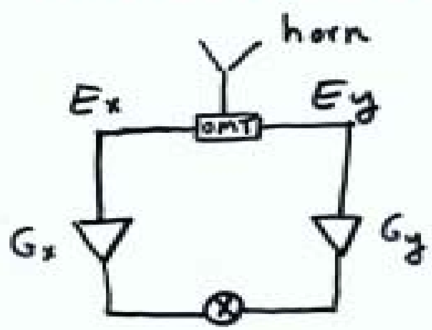


← Polarization sensitive

← amplifiers

← Total Power Detectors

"Brute Force"



$E_x \sim E_b - E_a$

$E_y \sim E_b + E_a$

$G_x G_y [E_b^2 - E_a^2]$

"Correlation Receiver"

⇒ signal will not be faked by gain changes

We move DC signal to 4kHz :

guards against slow drifts, multiplier imperfections

Detecting Tensor Perturbations with Polarization (r=0.001)

- Need to concentrate on 50 < l < 120
  - Horizon scale at decoupling
  - Finer-scale modes were red-shifted away
    - G-waves shear but do not make over-densities
- Need 7 orders of magnitude more sensitivity (than for density fluctuations) !

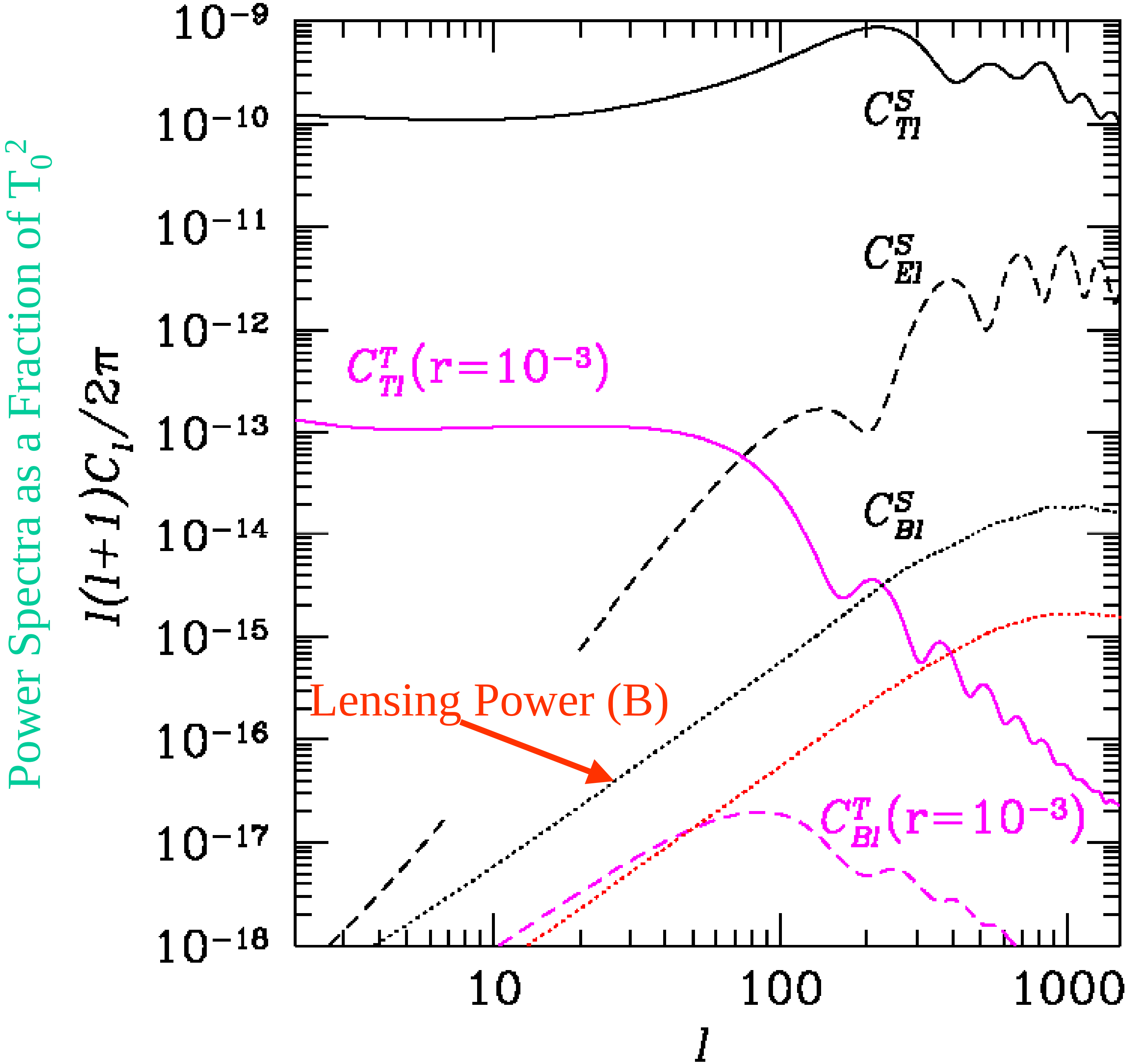
Sensitivity Calculation

- $\delta C_l / C_l = (2/(2l+1))^{0.5} [1 + C_N/C_l]$
- PS at peak is 2 x 10^{-17}
  - C_l is 0.12 nk^2
- Take Δl=70; then for a 3-σ detection:
  - $(1/(90x70))^{0.5} [1+C_N/0.12] = 1/3$
  - $C_N = 3\ nk^2$
  - SENFAC = 500 pk
- This would require 6400 WMAPs!

Contaminants to a B-mode signal

Gravitational Lensing of the CMB

- Most studied foreground
- Measures properties of the matter distribution from z = 1000 to today
  - Sensitive to growth of structure
- Deflection angles of order few arc-min.
- Coherence over few degree scales
- Leads to false power in the B-modes
  - Few x 10^{-3} of E-mode power (≈ observed galaxy shears)
  - Can be “cleaned” by reconstructing the (projected) deflecting potential



Power Spectra as a Fraction of T_0^2
l(l+1)C_l/2π
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
10
100
1000
l
C^S_Tl
C^S_El
C^S_Bl
C^T_Tl(r=10^-3)
C^T_Bl(r=10^-3)
Lensing Power (B)

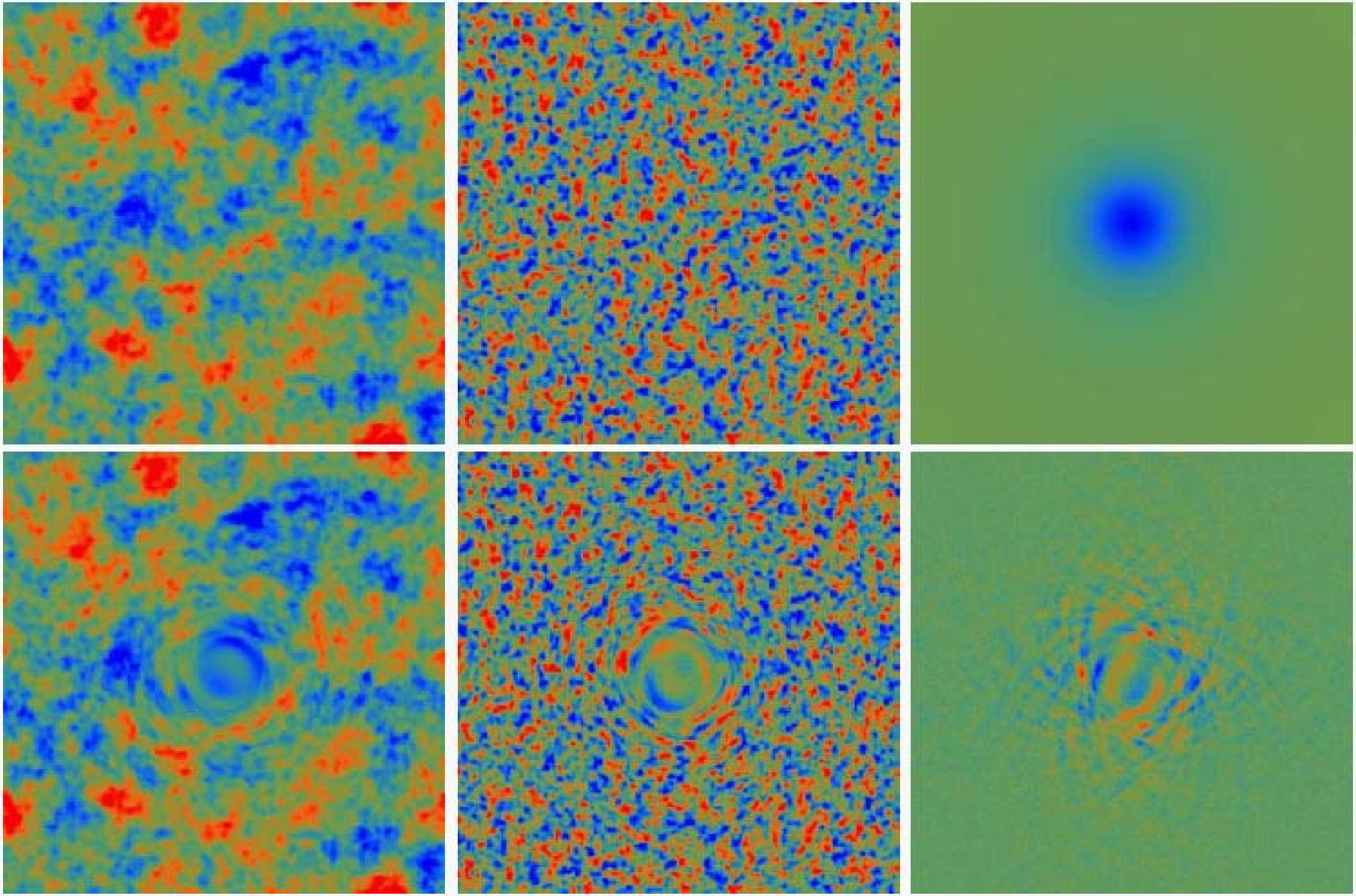


FIG. 1.— An exaggerated example of the lensing effect on a $10^\circ \times 10^\circ$ field. Top: (left-to-right) unlensed temperature field, unlensed E-polarization field, spherically symmetric deflection field $d(\mathrm{n})$. Bottom: (left-to-right) lensed temperature field, lensed E-polarization field, lensed B-polarization field. The scale for the polarization and temperature fields differ by a factor of 10.

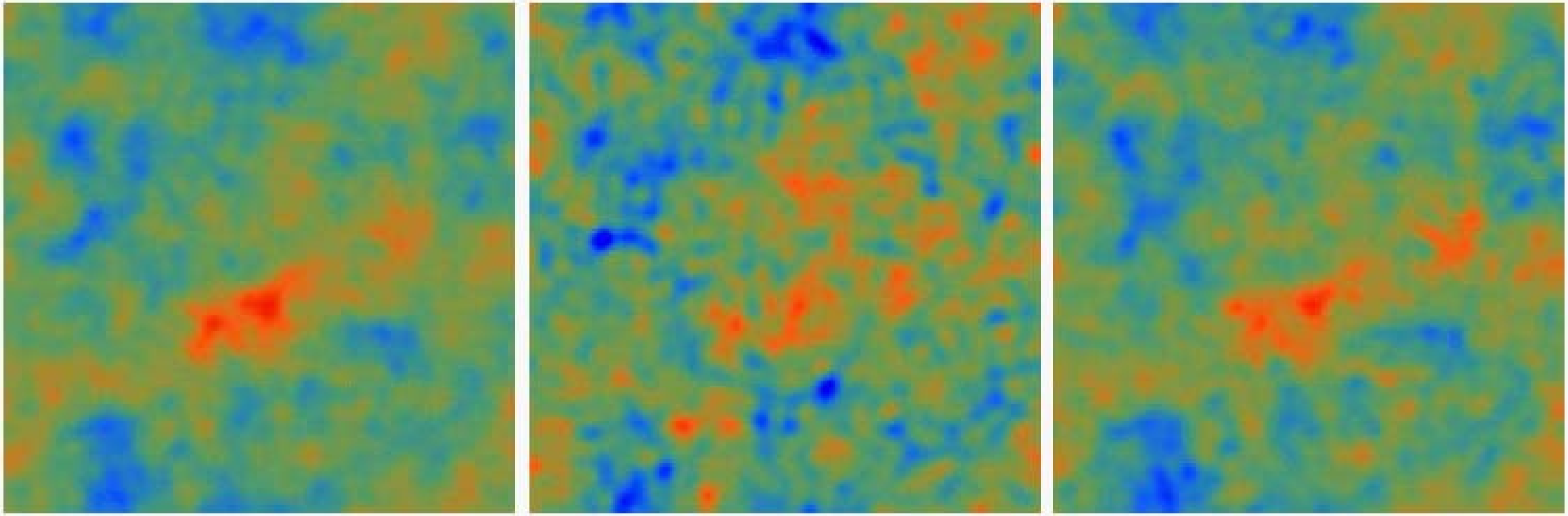


Fig. 5.— Mass reconstruction on a $10° \times 10°$ field with the reference experiment ($\Delta_T = \Delta_P/\sqrt{2} = 1\mu$K-arcmin and $\sigma = 4'$): (a) deflection field, (b) $\Theta\Theta$-reconstruction, (c) EB-reconstruction.

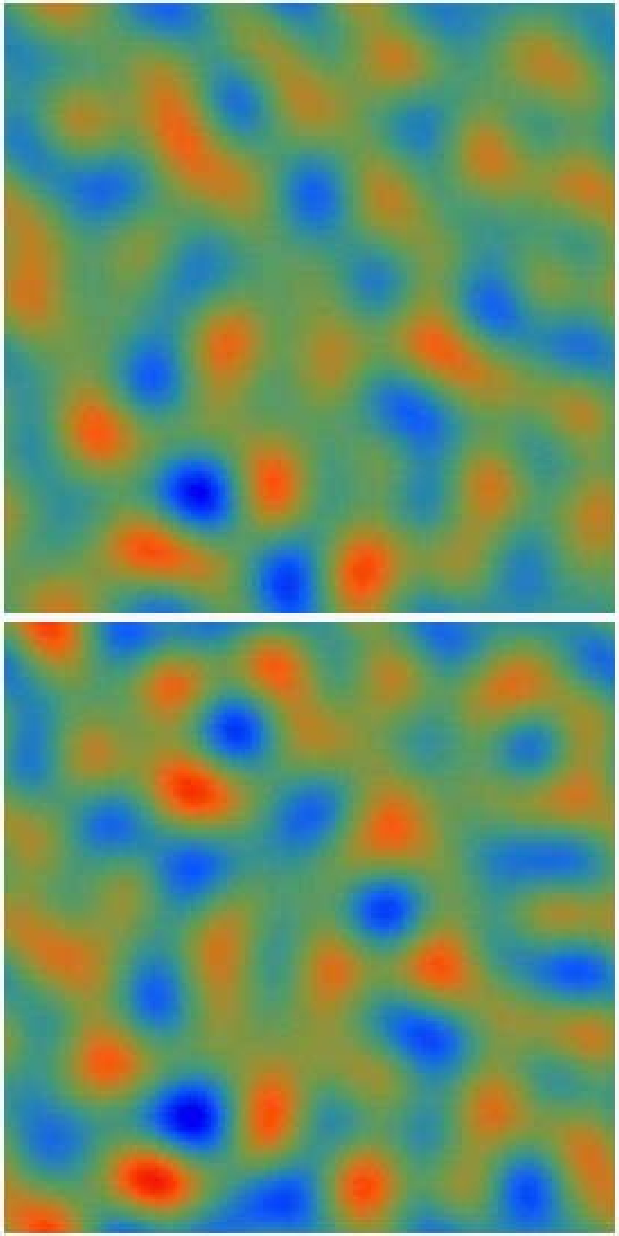
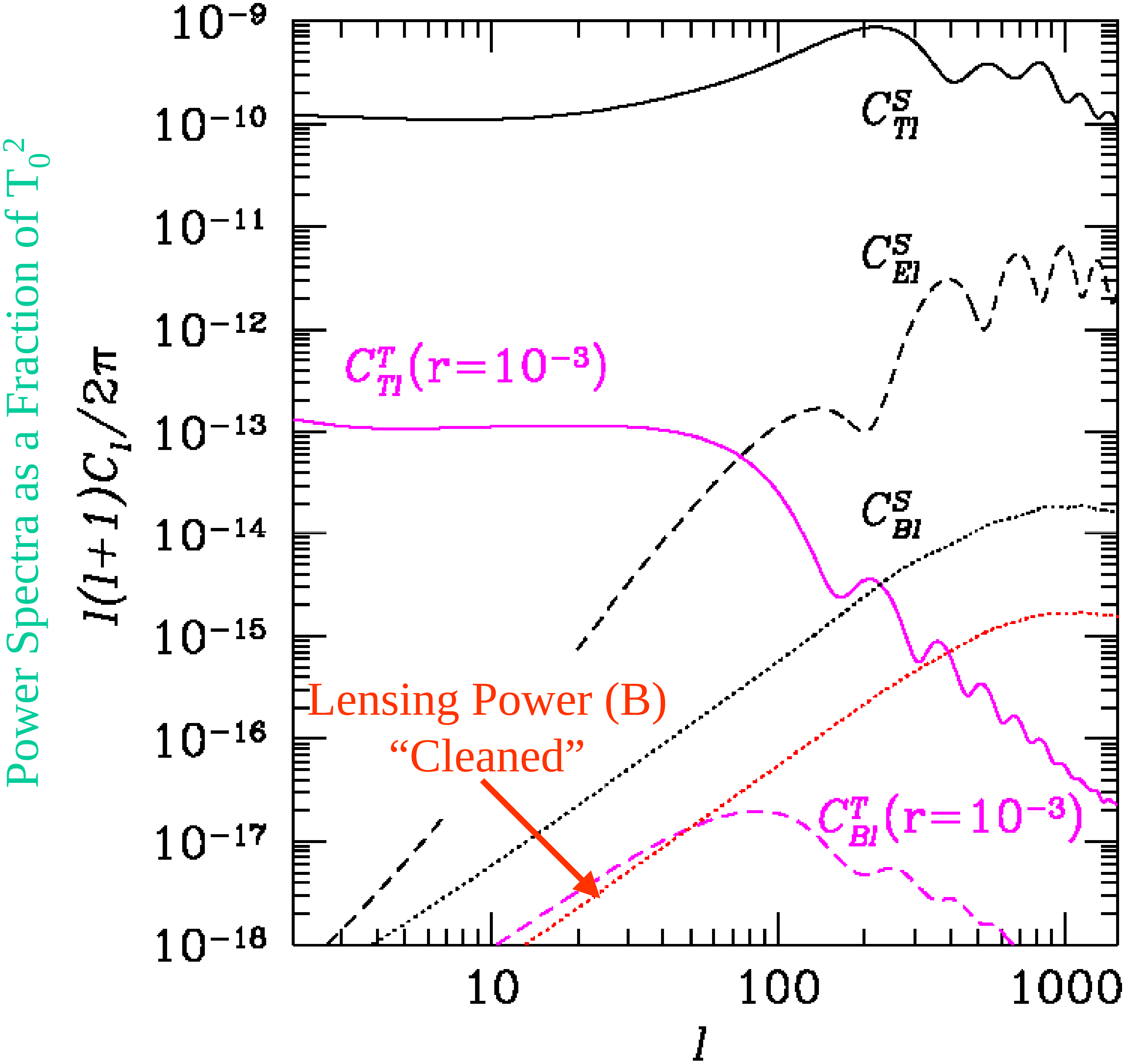


FIG. 9.— Large-angle ($l < 100$) lensing B-polarization field (top) and the reconstructed B-polarization field from the small angle EB deflection estimator and the observed E-field. Detector noise appropriate for the reference experiment has been added to this $25° \times 25°$ patch. Reconstruction techniques can help separate the gravitational wave and lensing B-modes.



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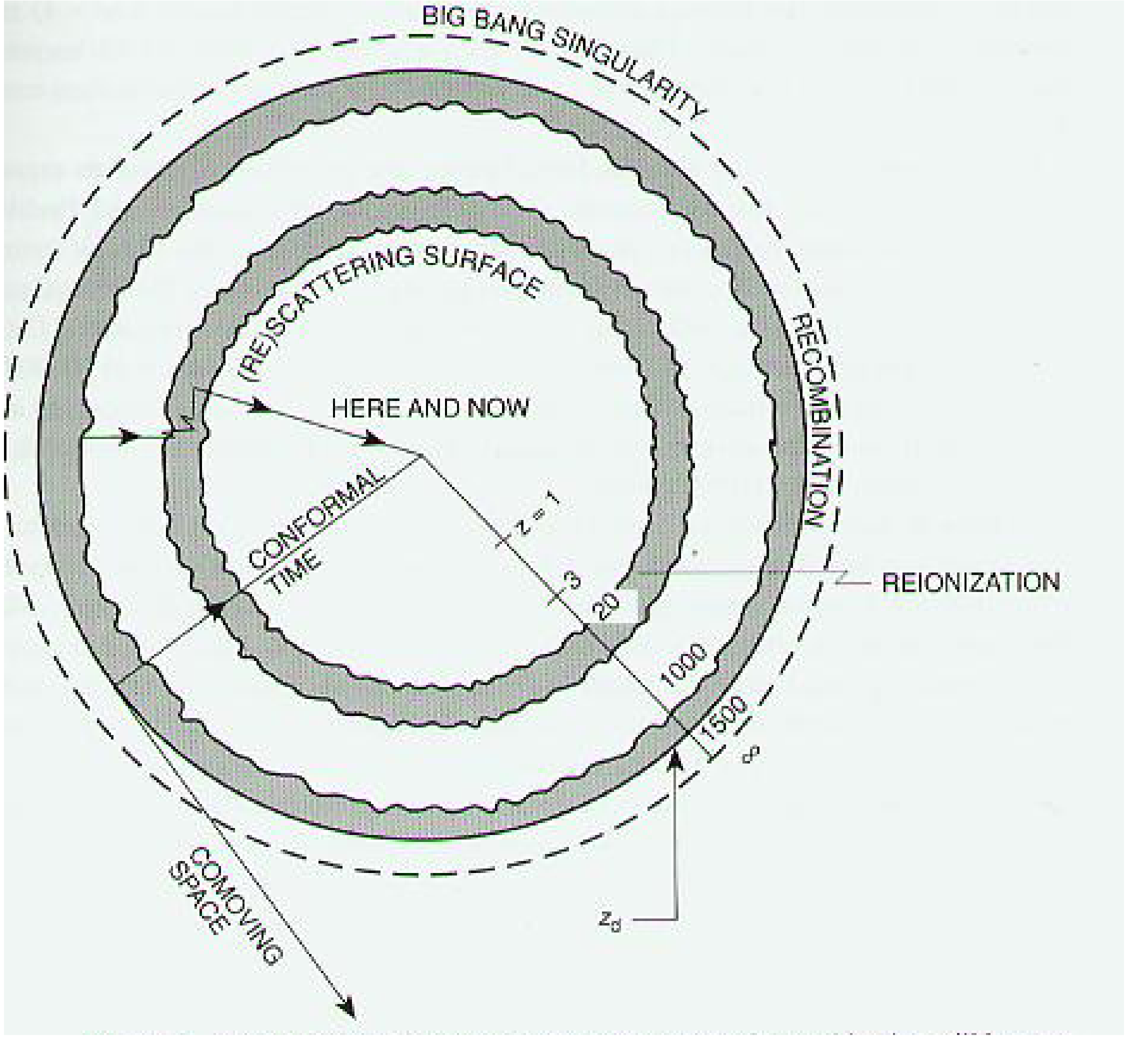
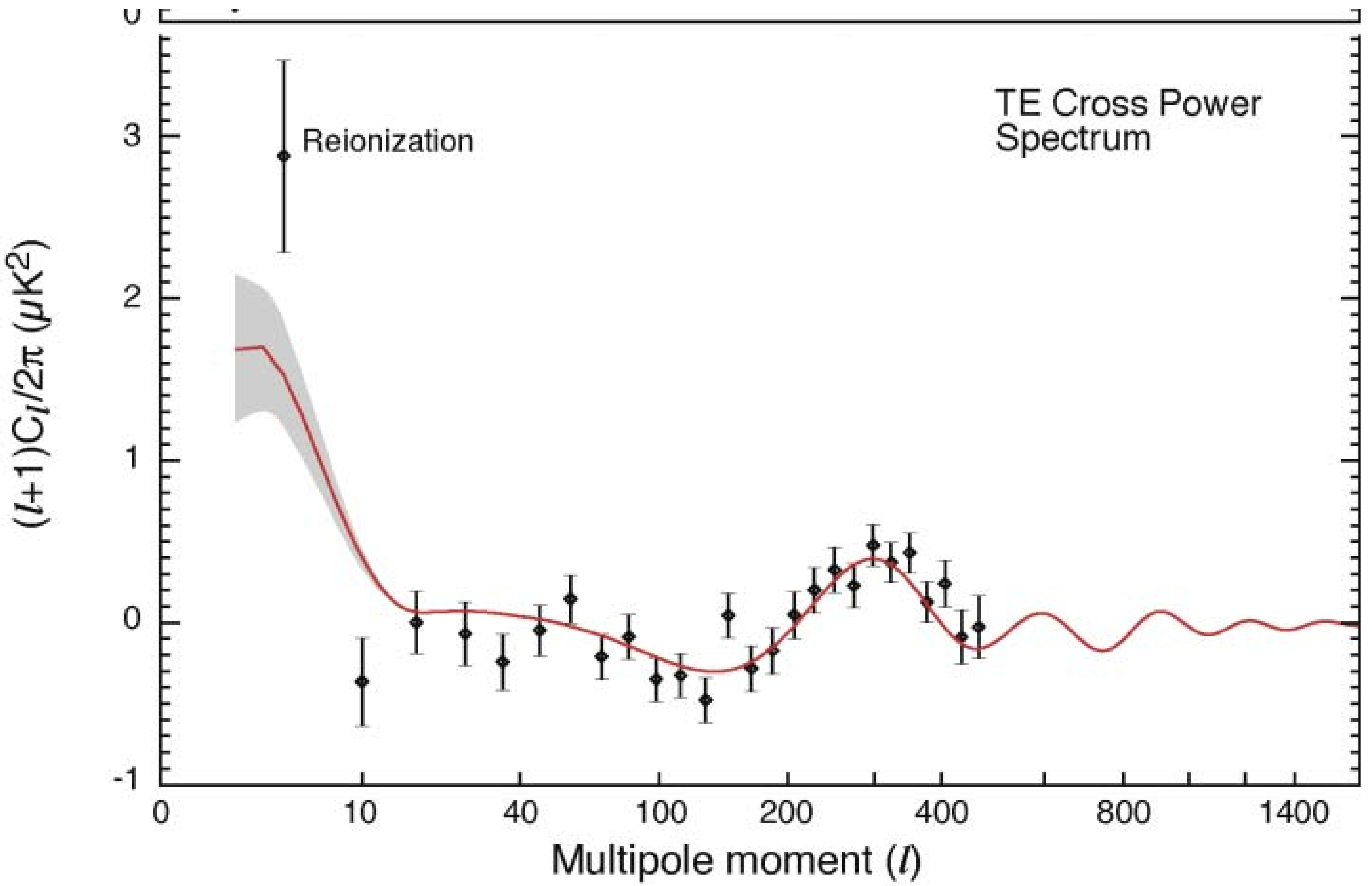
10^{-16}
10^{-17}
10^{-18}
C^S_{Tl}
C^S_{El}
C^S_{Bl}
$C^T_{Tl}(r=10^{-3})$
$C^T_{Bl}(r=10^{-3})$
Lensing Power (B)
"Cleaned"
10
100
1000
l

Table of Sensitivities

Signal	SENFAC (for 3σ)	# of WMAPS
E-modes @ l=1000	300 nk	0.02
Lensing @ l=1000	15 nk	8
B-modes, $r=10^{-3}$ (no lensing)	500 pk	6,400
B-modes, $r=10^{-4}$ (no lensing)	170 pk	64,000
B-modes, $r=10^{-4}$ (with lensing) $E_{infl} = 6.4 \times 10^{15}$ GeV	100 pk	150,000

But we can perhaps do even better …..

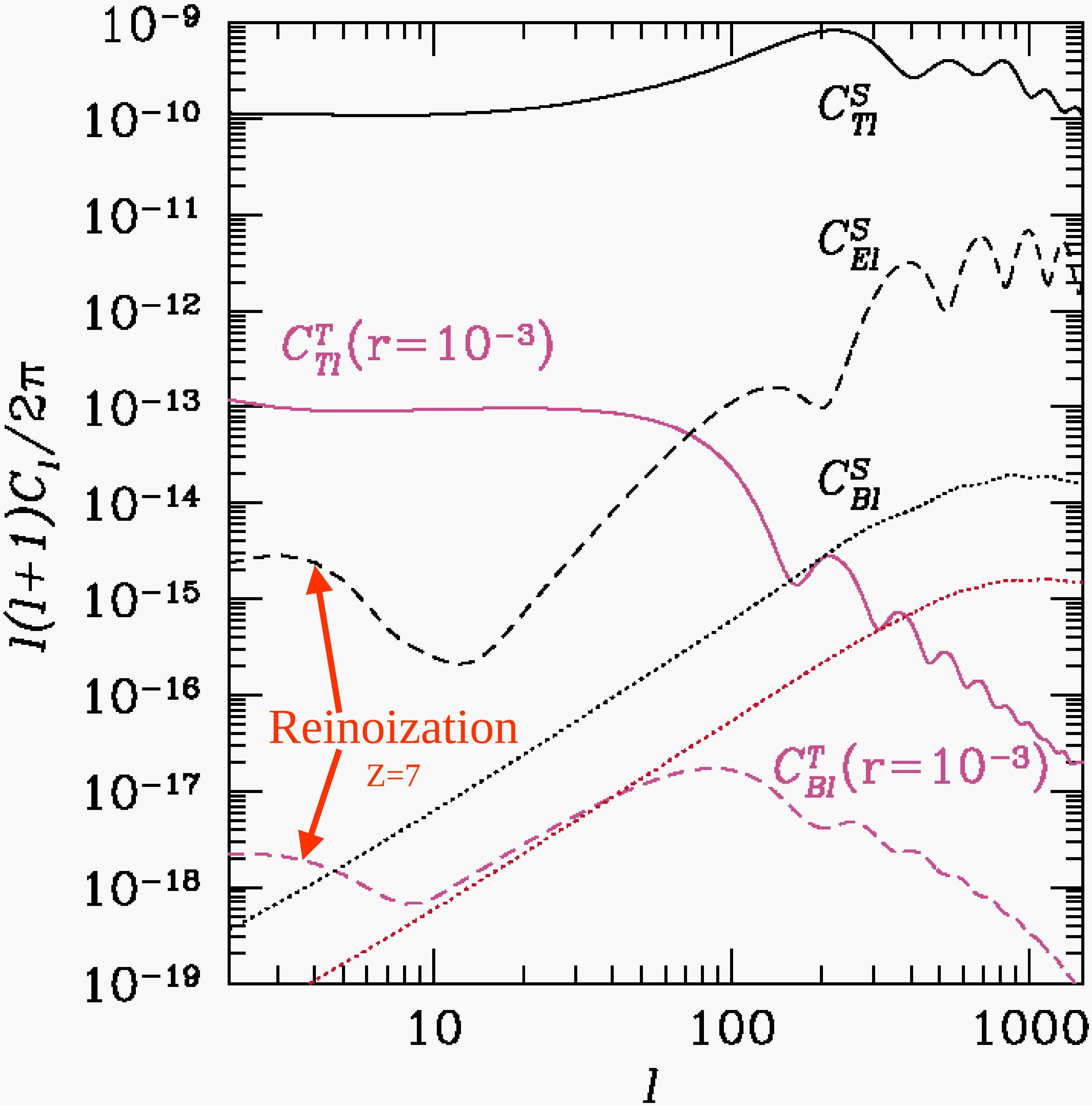

BIG BANG SINGULARITY
(RE)SCATTERING SURFACE
RECOMBINATION
HERE AND NOW
CONFORMAL
TIME
z = 1
3
20
1000
1500
∞
REIONIZATION
COMOVING
SPACE
z_d



TE Cross Power
Spectrum
Reionization
$(l+1)C_l/2\pi\ (\mu K^2)$
Multipole moment (l)
0
10
40
100
200
400
800
1400
-1
0
1
2
3

But we can perhaps do even better .....

- Reionization, at MAP level, provides another scattering surface for GWs
- Fewer modes but less contaminated with lensing
  - Comparable sensitivity
- Likely will be important to see both manifestations
  - Space mission



C^S_{Tl}
C^S_{El}
C^S_{Bl}
$C^T_{Tl}(r=10^{-3})$
$C^T_{Bl}(r=10^{-3})$
Reinoization
Z=7
$l(l+1)C_l/2\pi$
l

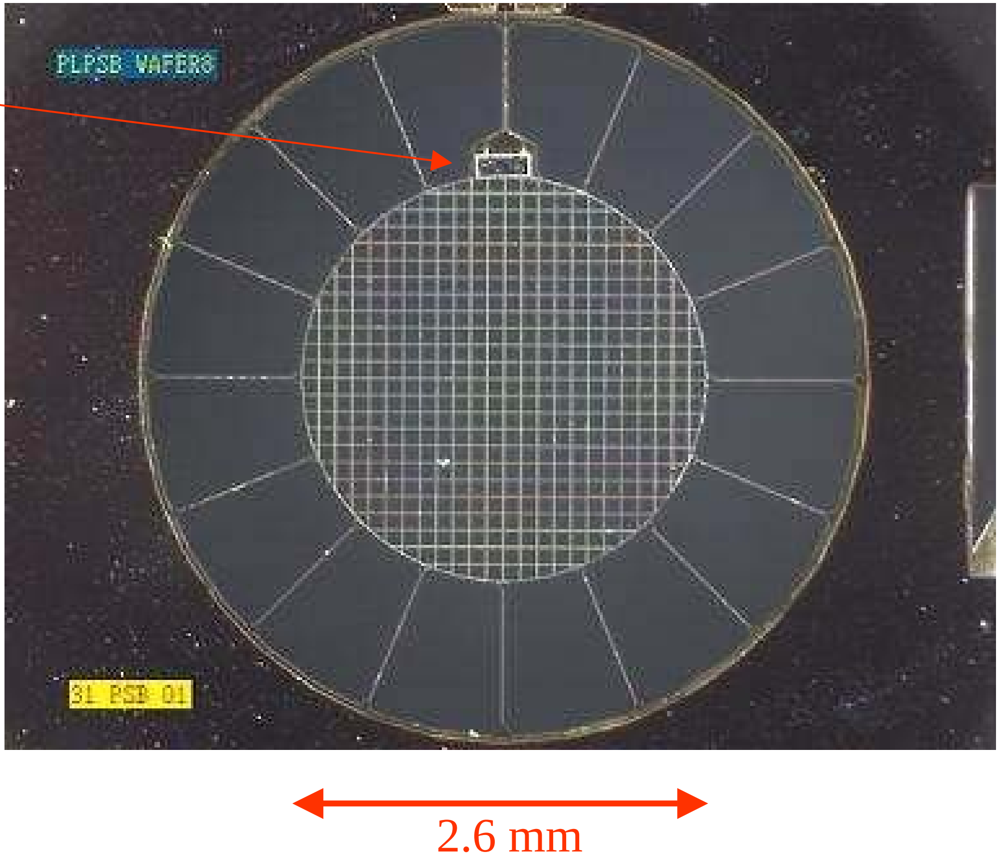
Detectors for the Future

- Large-format Bolometric arrays
- Integrated circuit “radiometers on a chip” coherent detectors

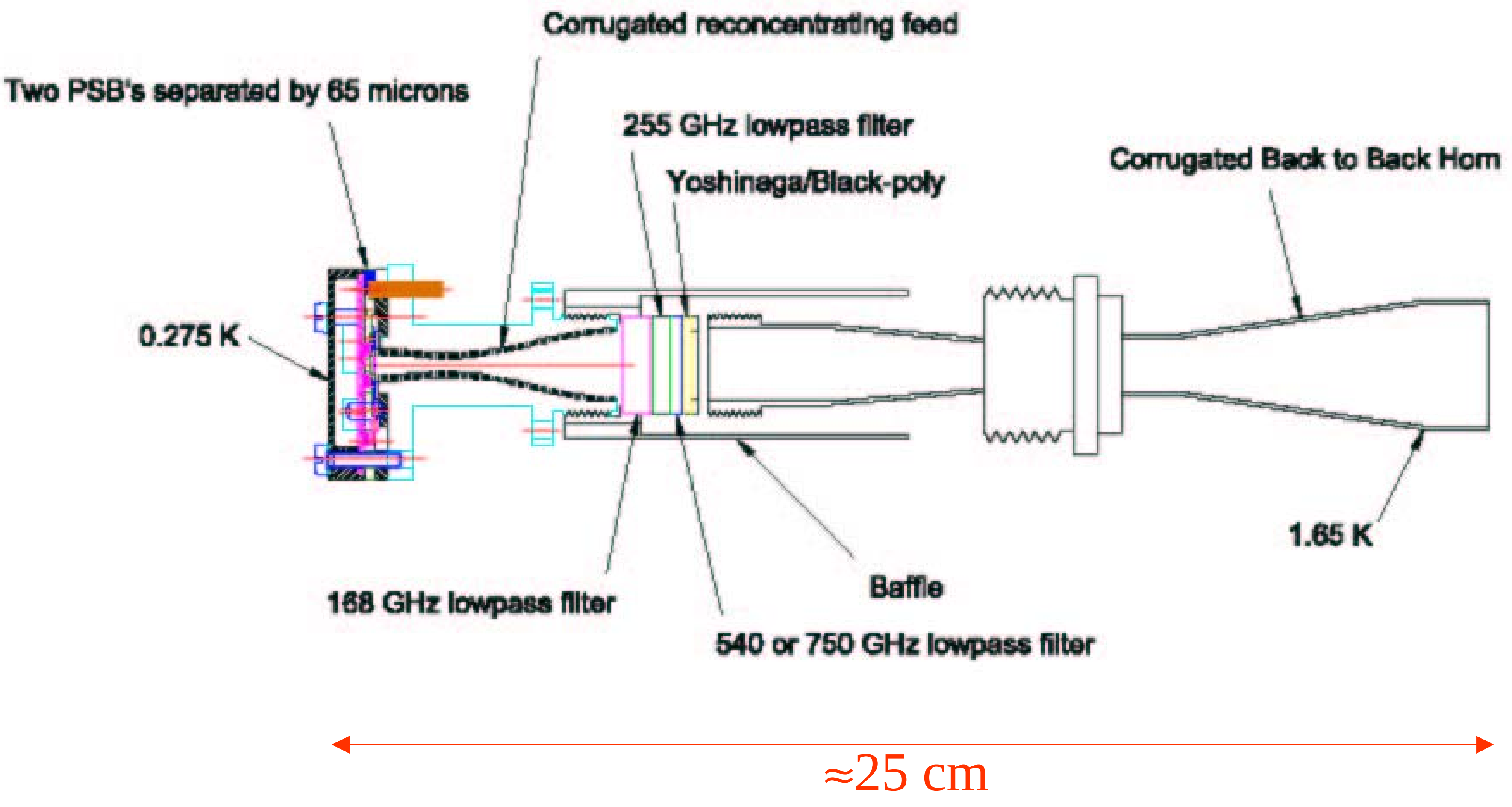
- JPL plays a major role in both
  - Also Goddard and NIST

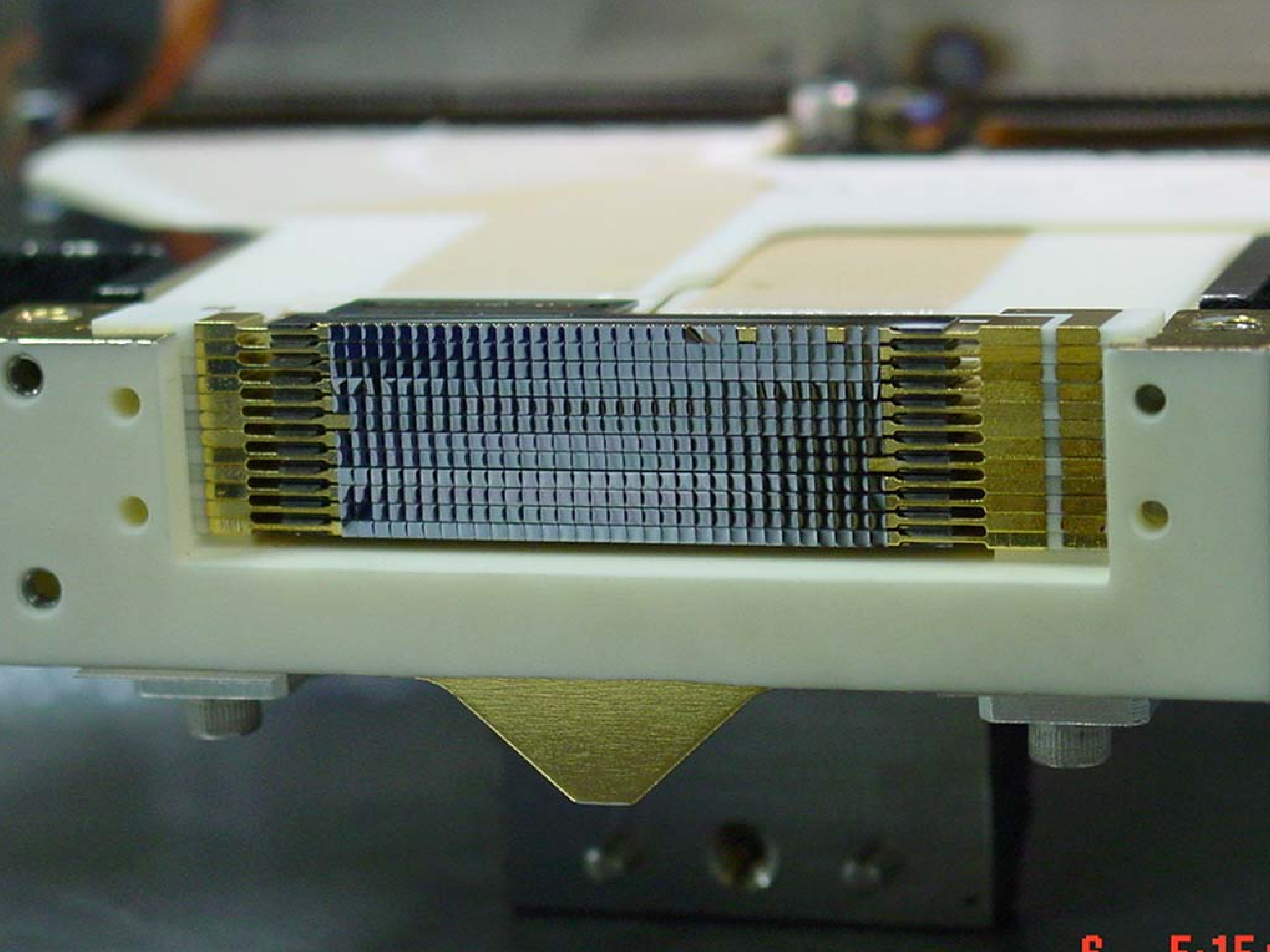
Bolometric Detectors

- Plastic with Au Coating
  - Coupled to termistor
- Few msec time constant
  - Influences scan rates
- Sensitivity can be dominated by photon noise itself!
  - comparable to HEMTs @10^{11} Hz
  - need big arrays for improvement
- Very stable
  - need control of load and bath
- Cosmic Ray rejection
- Polarization sensitive: PSBs

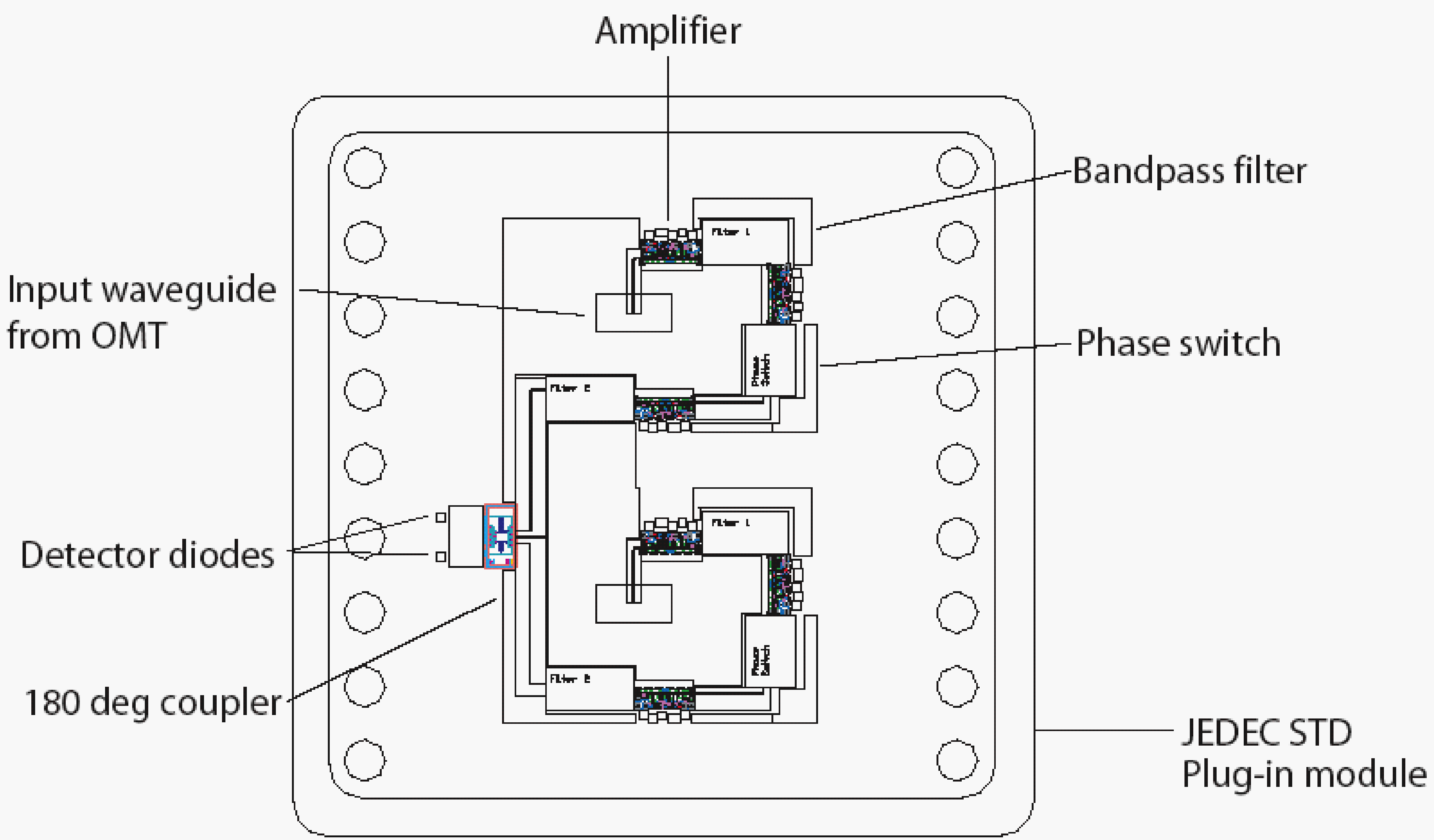


Boomerang Optics

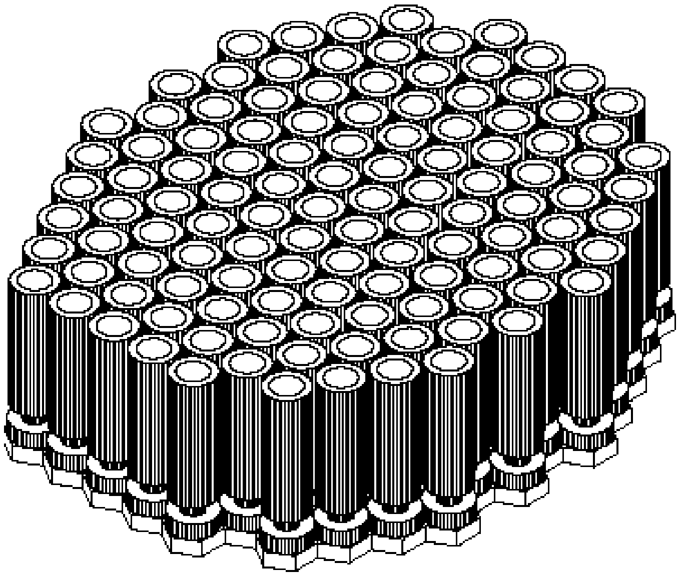




Radiometer on a Chip



Q/U Imaging ExperimenT (QUIET) Array Development Schedule



Functional 90 GHz “Q” Element Prototype: 10/03 ~500 μK√s/Q

91 Element Array: 9/04 ~50 μK√s/Q

1000 Element Q/UArrays: 2005 ~10 μK√s/Q

ν Masses and the CMB

- Non-zero mass changes time (z) of decoupling
- Relevant scale is $T_{dec} \cong 0.30$ ev
  - 0.26 ev limit
- Non-zero mass affects (delays) structure formation
  - Effect on lensing of the CMB
  - Claimed possible to get to 0.03 ev
    - Range suggested by atmospheric neutrinos

Two Additional Topics

- SUSY

  Ω_{cdm} limits imply tighter limits on the mass of the LSP

- Sensitivity to trans-Plancking physics?
  - modes we detect started with wavelengths smaller than the Planck length!
    - Models of such physics can be limited by precise cmb measurements

Final Thoughts on the Future

- What is the scale of Inflation?
  - Anything to do with GU?
- Does slow-roll make sense?
- Analogies to proton decay
  - Is CMB lensing like ν physics?
- Three NASA "Inflation Probe" studies are underway; MANY other experiments
- No sign yet of the curve rolling over!