Title: Searching for Tensor modes from Inflation

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Abstract:

B-Pol: A B-Polarization Satellite Mission for detecting primordial gravitational waves generated during inflation

Martin BUCHER, Laboratoire de Physique Théorique, Université Paris-Sud)

10 September 2007 / Frontiers in Cosmology Conference, Perimeter Institute

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B-Pol People and Institutions

ESA Cosmic Vision 2015-2025, Call for proposals Feb 2007, (Class M - $\leq$ 300 M € ESA contribution) 2017 target launch date.

B-Pol Countries : France, Germany, Italy, Spain, United Kingdom, Denmark, Ireland, Netherlands, Norway, Portugal, Romania, Sweden, Switzerland

Non-EU expression of interest from 3 US groups (Bock et al., Kogut et al., Timbie et al.) and from Canada (Halpern, Bond et al.)

National coordinators :
P de Bernardis (IT), F Bouchet (FR), E Kreysa (GE), L Piccirillo (UK), R Rebolo (SP)

Instrument working group :
P de Bernardis, L Piccirillo, P Ade, M Bersanelli, FX Desert, E Kreysa, L Kuzmin, B Maffei, N Mandolesi, S Masi, P Mauskopf, T Peacocke, F Piacentini, M Piat, G Pisano, R Rebolo, G Savini, R Tascone, F Villa, S Withington, G Yassin

Science working group :
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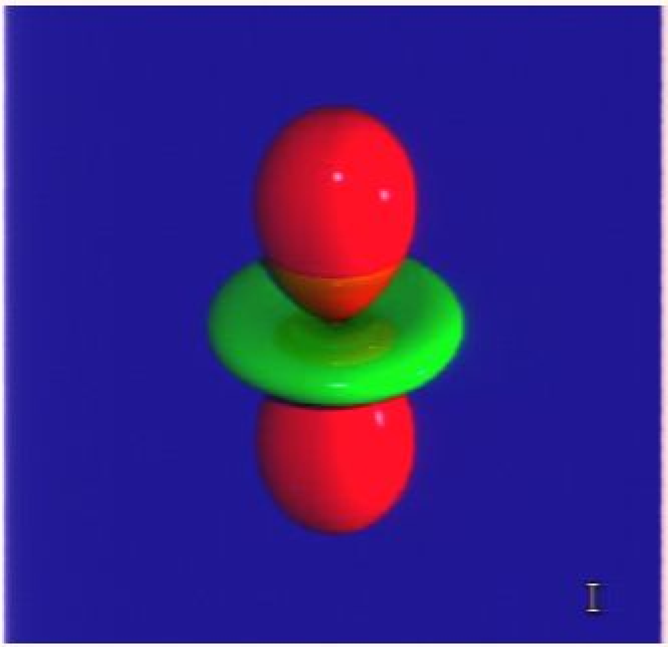
Foregrounds working group :
C Burigana, T Arshakian, C Baccigalupi, A Banday, D Barbosa, R Beck, JP Bernard, G Bernardi, A Bonaldi, E Carretti, D Clements, P Coles, G de Zotti, R Fabbri, P Fosalba Vela, J Gonzales-Nuevo, M Hobson, L La Porta, P Leahy, JF Macias-Perez, E Martinez-Gonzalez, M Massardi, P Naselsky, N Ponthieu, W Reich, S Ricciardi, F Stivoli, L Toffolatti, M Tucci, P Vielva

For more information,a full text of the proposal, and related documents and links, see www.b-pol.org

Origin of CMB Polarization

Polarized Thomson scattering ($\gamma + e^- \rightarrow \gamma + e^-$) is anisotropic.

$$\sigma_{Thomson} \propto (\epsilon_{in} \cdot \epsilon_{out})^2$$



When we look at the polarization of the CMB today, we measure (roughly speaking) the CMB quadrupole seen by the electron at last scattering, which may be due to (1) intrinsic temperature fluctuations, (2) gravitational redshift, or (3) Doppler shift from shear of the velocity field.

Sources of the CMB polarization (known and possible)

- E-mode polarization
  - Scalar modes (presumably from inflation) (already seen)
  - Tensor modes (presumably from inflation) (not yet seen)
  - Cosmic strings, more generally any non-linear late time source (speculative)
  - Polarized foreground emission (galactic dust, synchrotron, IR galaxies, spinning dust,.....) (seen but not well characterized)
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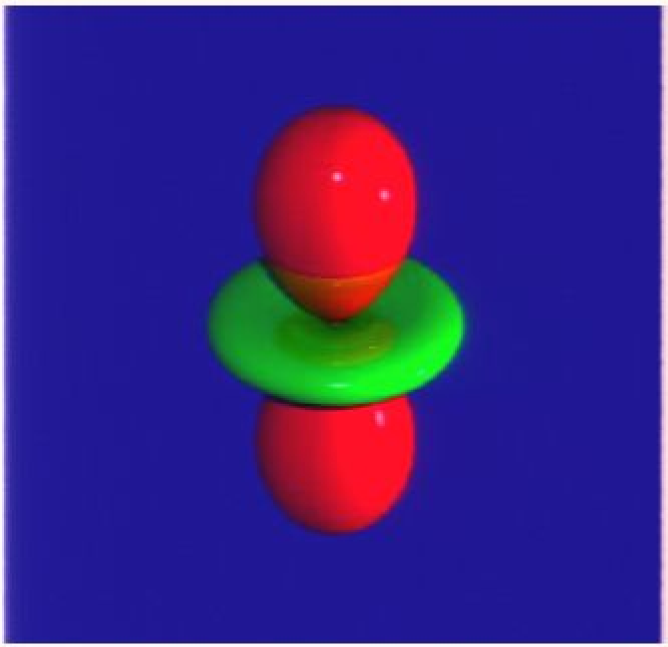

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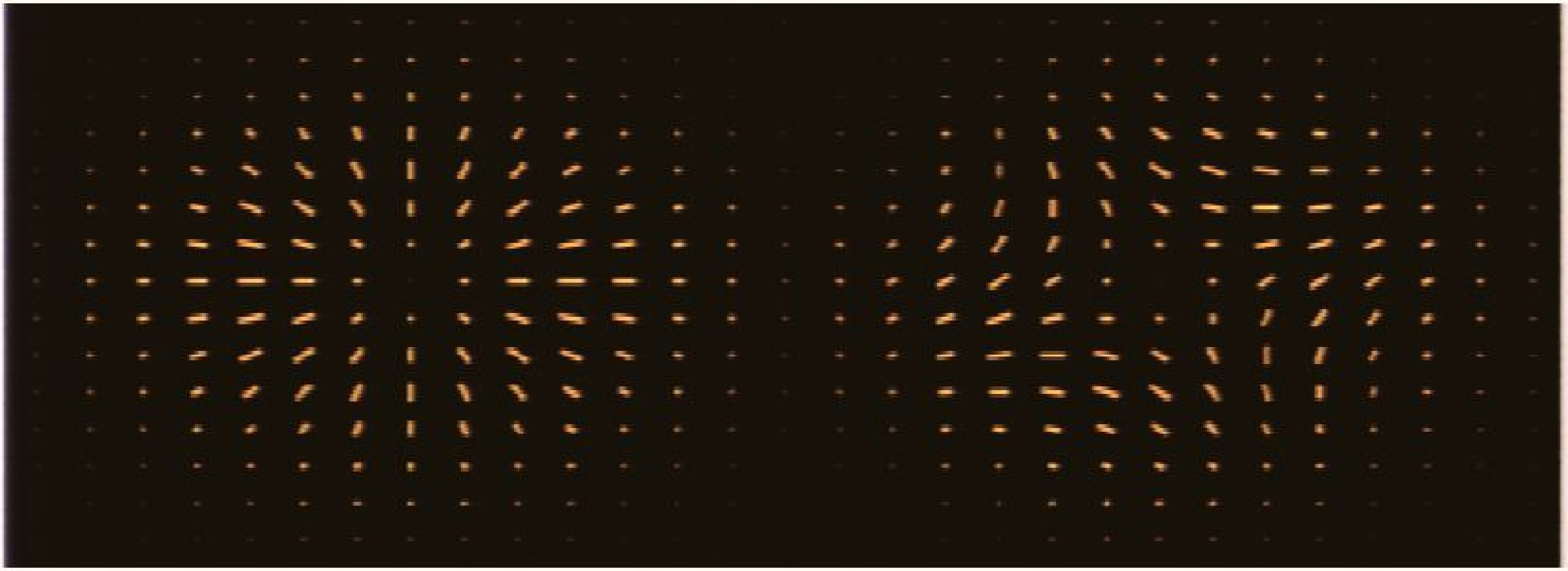
E and B Mode Polarization



E mode B mode

$$\mathbf{Y}^{(E)}_{\ell m,ab} = \sqrt{\frac{2}{(\ell-1)\ell(\ell+1)(\ell+2)}}\left[\nabla_a\nabla_b - \frac{1}{2}\delta_{ab}\right] Y_{\ell m}(\hat{\Omega})$$

$$\mathbf{Y}^{(B)}_{\ell m,ab} = \sqrt{\frac{2}{(\ell-1)\ell(\ell+1)(\ell+2)}}\frac{1}{2}\left[\epsilon_{ac}\nabla_c\nabla_b + \nabla_a\epsilon_{bc}\nabla_c\right] Y_{\ell m}(\hat{\Omega})$$

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Projection of « scalars, » « vectors » and « tensors » onto the celestial sphere

Under projection onto the celestial sphere :

$$(scalar)_3 \rightarrow (scalar)_2,$$

$$(vector)_3 \rightarrow (scalar)_2 + (vector)_2,$$

$$(tensor)_3 \rightarrow (scalar)_2 + (vector)_2.$$

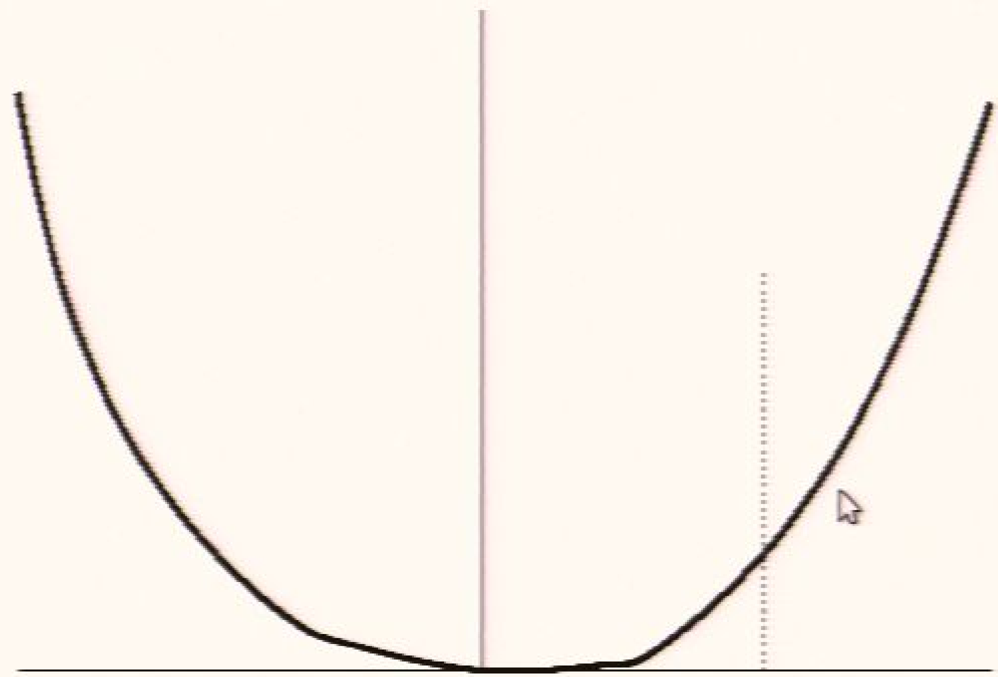
There is no $(tensor)_2$ component. The E mode polarization is scalar ; the B mode is vector.

It follows that at linear order the scalar modes cannot generate any B mode polarization.

Note crucial role of linearity assumption.

Single-Field Inflation

At the beginning there was a scalar field that dominated the universe. Everything came from this scalar field and there was nothing without the scalar field. The quantum fluctuations of this field (that is, those of the vacuum) generated small fluctuations that advanced or retarded the instant of re-heating. These were the seeds of the large-scale structure.



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Perturbations generated during inflation

$$\boxed{\hbar = c = 1, M_{pl}^{-2}} \qquad \delta\phi \approx H \qquad \frac{\delta\rho}{\bar{\rho}} \approx H \cdot \delta t, \quad \delta t \approx \frac{\delta\phi}{\dot{\phi}}$$

$$H\dot{\phi} \approx V_{,\phi}, \quad \dot{\phi} \approx V_{,\phi}/H, \quad H^2 \approx \frac{1}{M_{pl}^2} V, \frac{\delta\rho}{\bar{\rho}} \approx \frac{V^{3/2}[\phi(k)]}{M_{pl}^3 \, V_{,\phi}}$$

Scalar perturbations : $\boxed{\mathcal{P}_S^{1/2}(k) \approx O(1) \cdot \frac{V^{3/2}[\phi(k)]}{M_{pl}^3 \, V_{,\phi}[\phi(k)]}.}$

Tensor perturbations : $\boxed{\mathcal{P}_T^{1/2}(k) \approx O(1) \cdot \frac{H}{M_{pl}} \approx O(1) \cdot \frac{V^{1/2}}{M_{pl}^2}}$

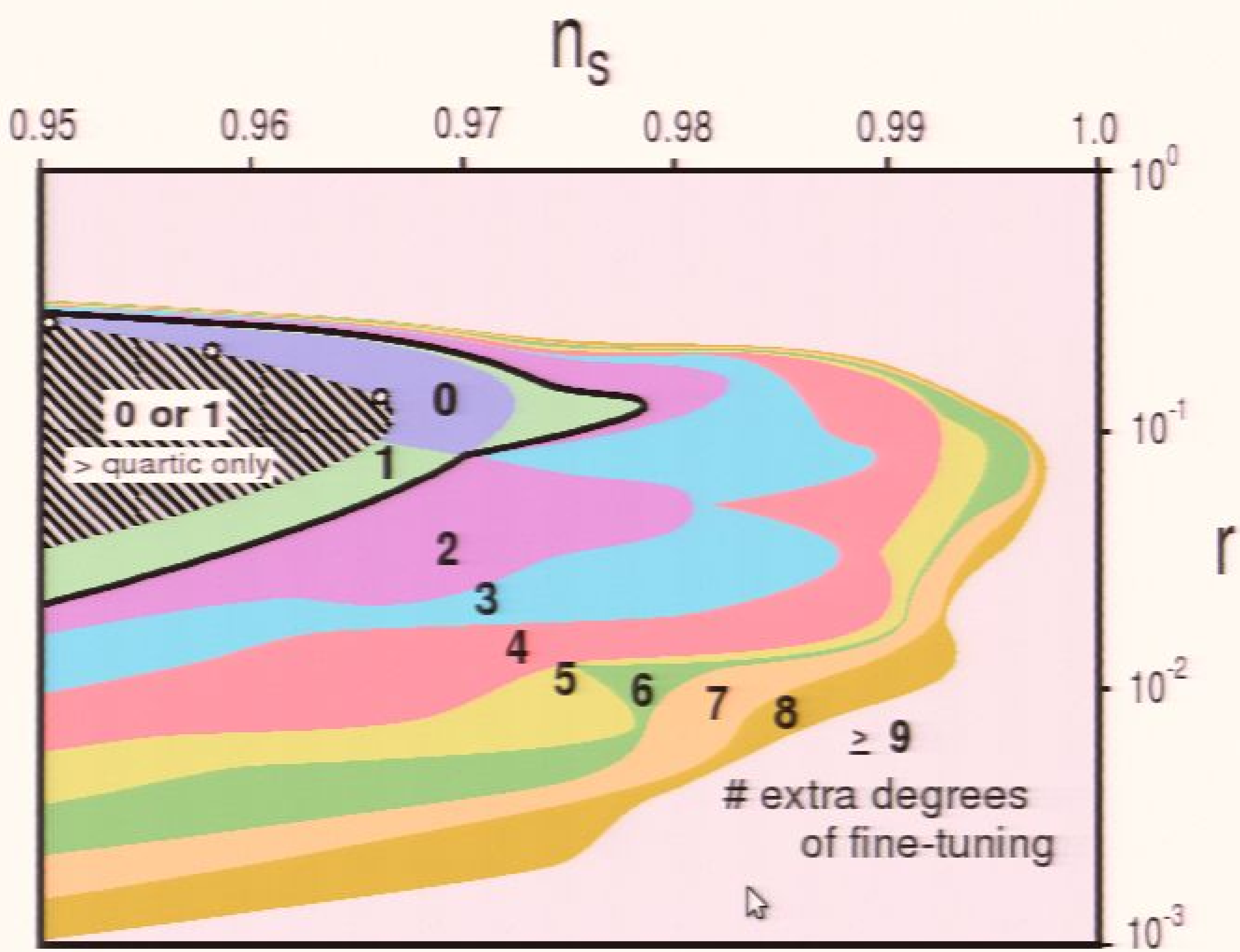
$\phi(k) \equiv$ value of ϕ at horizon crossing of the mode k

Reconstruction of the inflationary potential : the tensors measure the height of the potential, the scalars the slope.

Tests of inflation

- Order zero tests
  - Flatness, homogeneity, isotropy, no monopoles, entropy of observable universe
- Scalar perturbations
  - Scale invariance (approximate) (Harrison, Zeldovich, Peebles)
  - Gaussianity
  - Primordial character of comsological perturbations. No decaying modes observed.
- Tensor perturbations
  - Direct measure of the Hubble constant in the **very** early universe when a given mode left the horizon
  - New unique prediction of inflation

Expected (T/S) From Inflation ? (I)



From Boyle, Steinhardt and Turok.

Expected (T/S) From Inflation ? (II)

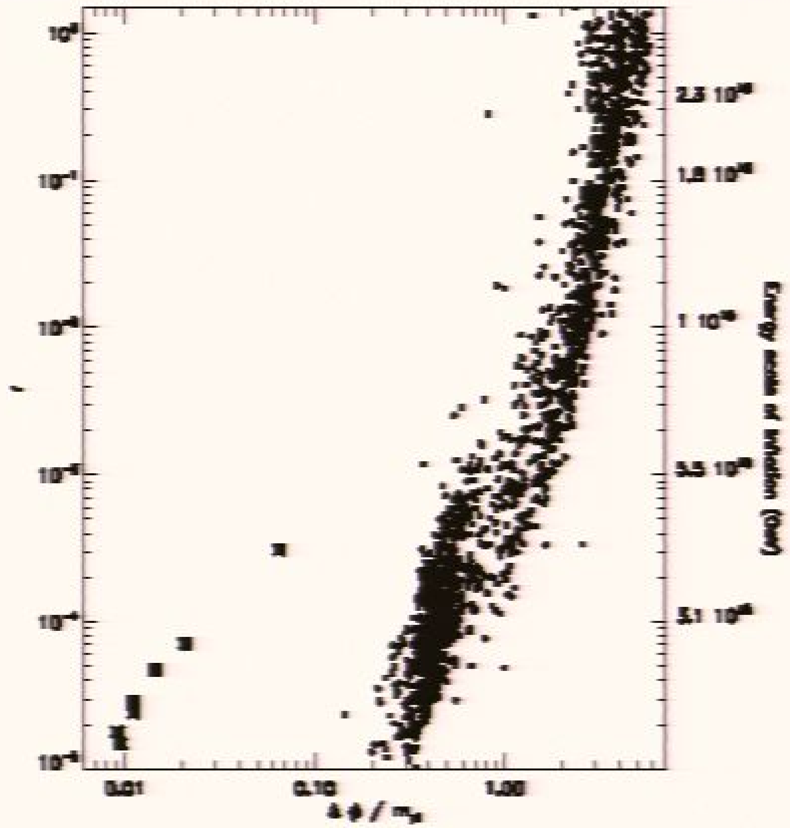
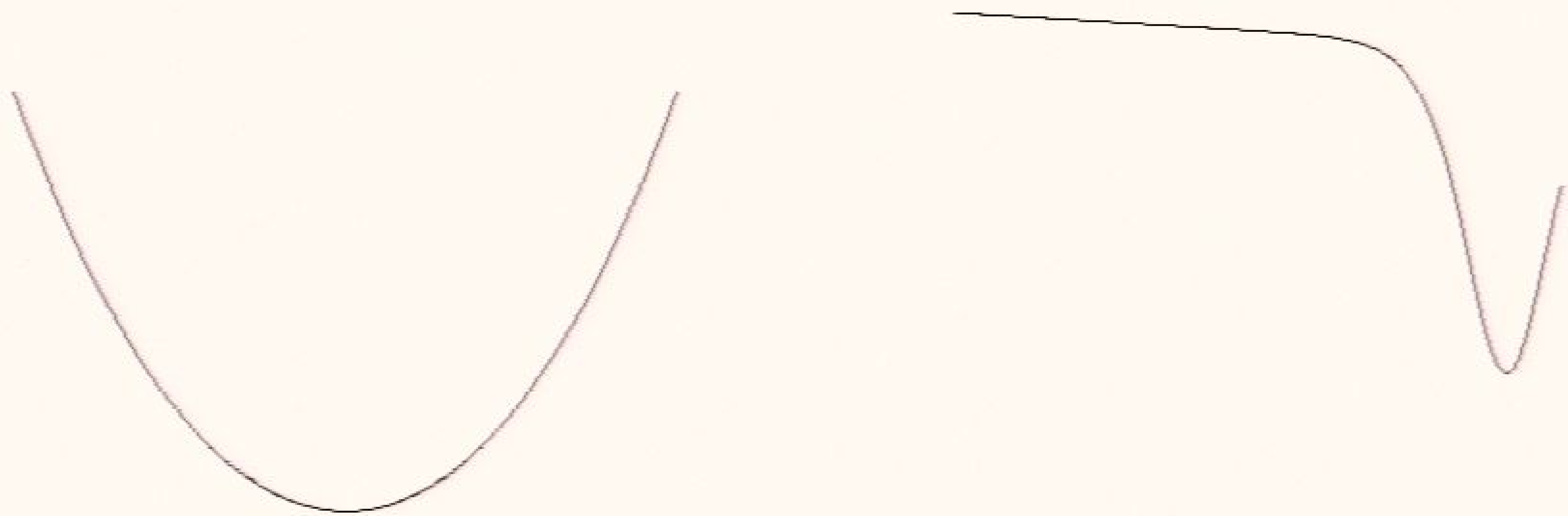


Figure produced by L. Verde, following closely the method of W. Kinney et al., Phys. Rev. D74, 023502 (2006) (astro-ph/0605338).

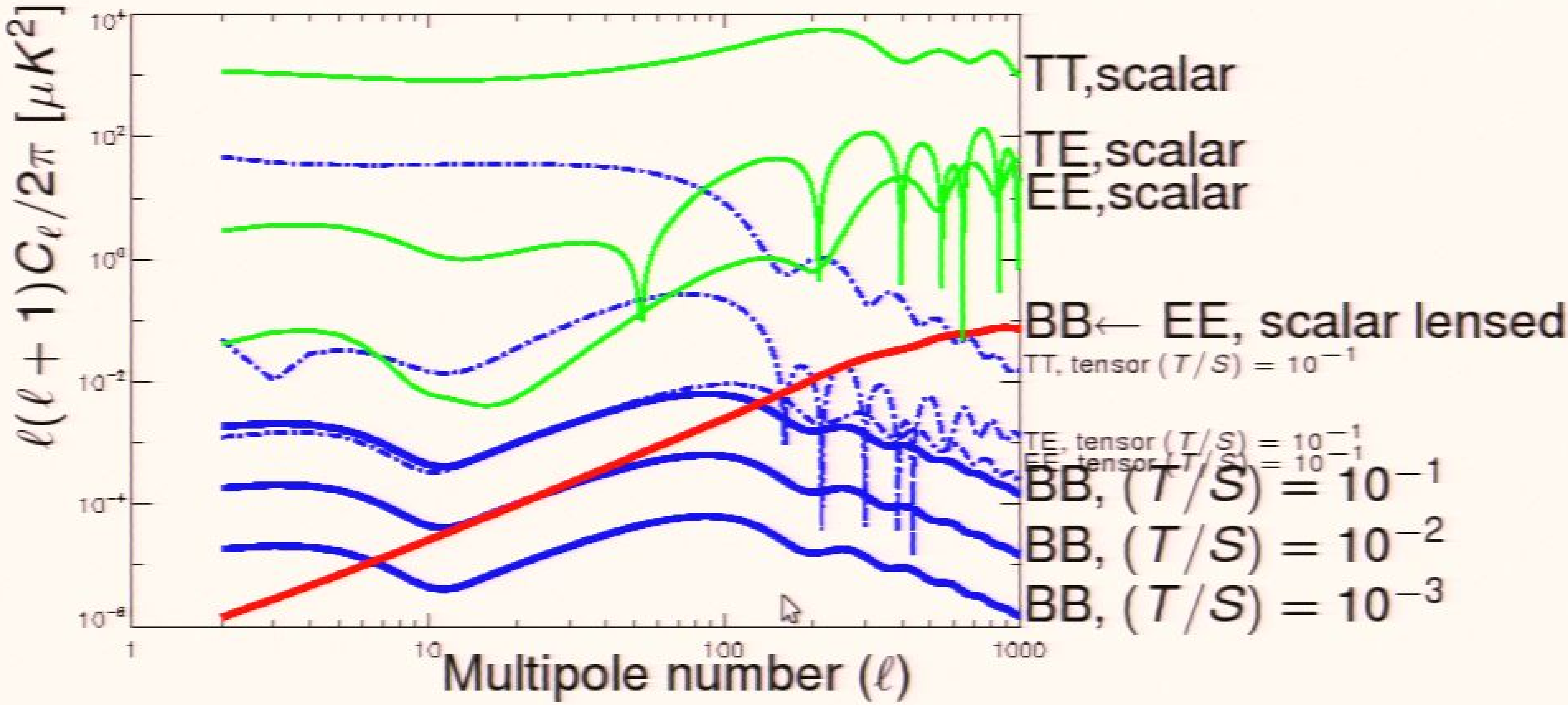
Scale of inflation depends on shape of potential



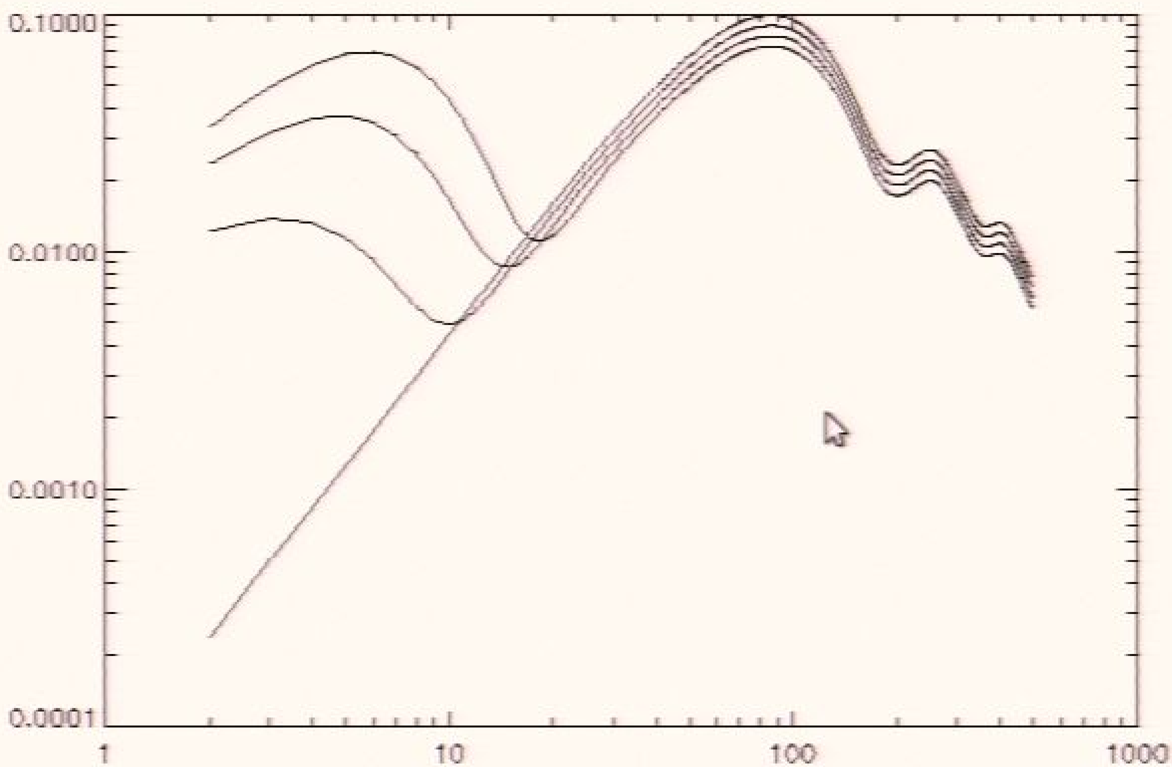
Large-field inflation
Significant GWs

Small-field inflation
Few GWs
Requires inflation to end abruptly

Inflationary Prediction for Scalar & Tensor Anisotropies

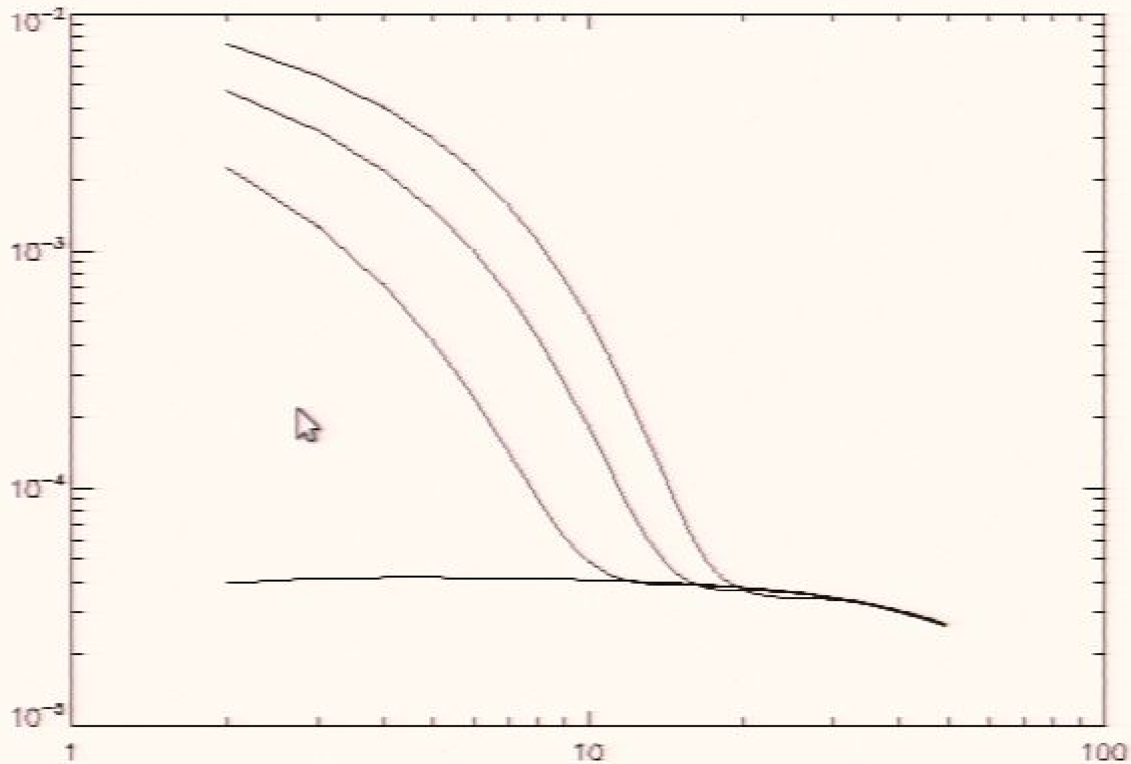


The Reionization Bump (I)



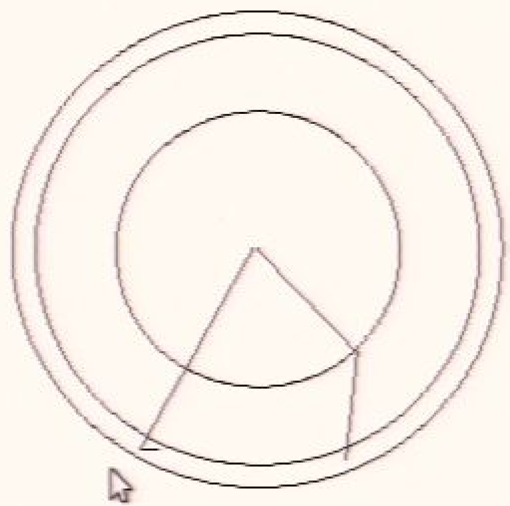
$\tau = 0.0, 0.5, 0.10, 0.15$ (bottom → top)

The Reionization Bump (II)



Amplification of the B mode signal relative to the non reionized case by a factor of about 50,100, and 150 at $\tau = 0.05$, $\tau = 0.10$, and $\tau = 0.15$, respectively.

The Reionization Bump (III)



It turns out that

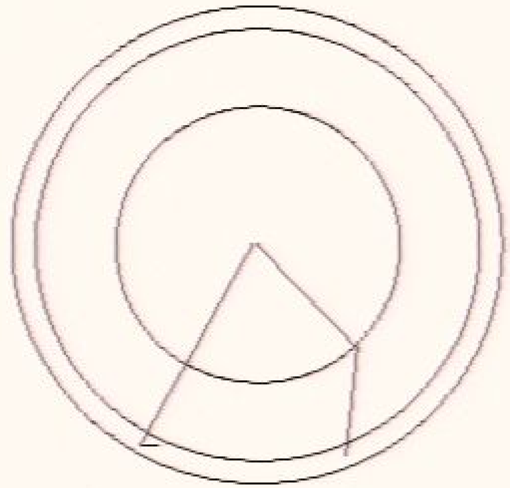
$$P \propto (1-\tau) d^2_{lastscatter} \frac{\partial^2 T}{\partial x^2}$$

is small compared to

$$P \propto \tau d^2_{reion} \frac{\partial^2 T}{\partial x^2}$$

even when τ is small.

The Reionization Bump (III)



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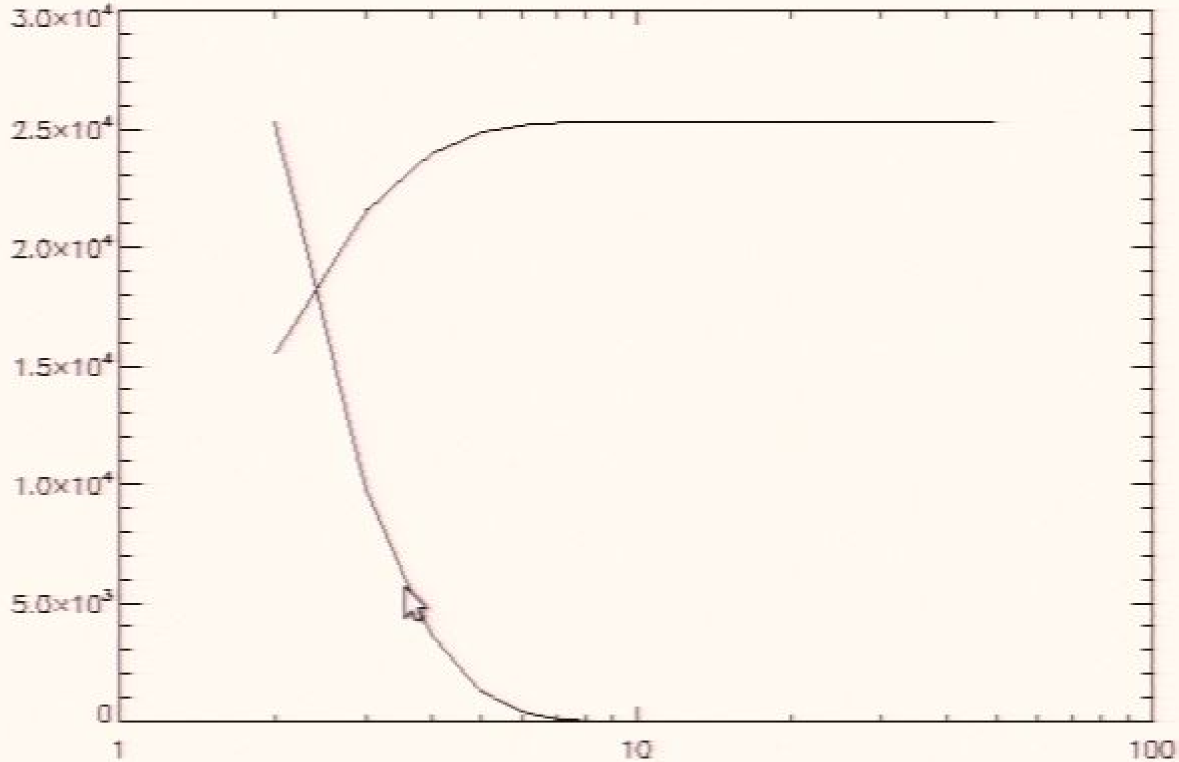
The Reionization Bump (IV)



Information is concentrated at the very lowest multipoles.

Pro : There is comparatively a very large signal.

Drawback : It may be very hard to rule out a galactic explanation given the large role of the lowest ℓ. No way to jacknife the data. (Cf. Controversy regarding the significance of the WMAP low quadrapole.)

Lensing of the E mode into the B mode — $(E^{scalar} + \Phi \to B^{scalar})$

(Flat sky approximation : $(\ell m) \to \boldsymbol{\ell}, \quad \boldsymbol{\theta}, \boldsymbol{\ell} \in \mathcal{R}^2$.)

$$\delta\boldsymbol{\theta} = (\nabla\Phi), \qquad \delta T(\boldsymbol{\theta}) = (\nabla\Phi)\cdot(\nabla T).$$

$$\delta T(\boldsymbol{\ell}_F) = \int \frac{d^2\boldsymbol{\ell}_L}{(2\pi)^2}\,(-\boldsymbol{\ell}_L)\cdot(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L)\,\Phi(\boldsymbol{\ell}_L)\,T(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L).$$

$$\langle T(\boldsymbol{\ell})\,T(\boldsymbol{\ell}')\rangle = (2\pi)^2\,\delta^2(\boldsymbol{\ell}+\boldsymbol{\ell}')\,C^{TT}(\ell)$$

$$C^{TT}(\boldsymbol{\ell}_F) = \int \frac{d^2\ell_L}{(2\pi)^2}\,[\boldsymbol{\ell}_L\cdot(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L)]^2\,C^{\Phi\Phi}(\boldsymbol{\ell}_L)\,C^{TT}(\ell_I = |\boldsymbol{\ell}_F - \boldsymbol{\ell}_L|)$$

$$C^{BB}(\boldsymbol{\ell}_B) = \int \frac{d^2\ell_L}{(2\pi)^2}\,[\boldsymbol{\ell}_L\cdot(\boldsymbol{\ell}_F - \boldsymbol{\ell}_L)]^2\,\sin^2[2\Theta(\boldsymbol{\ell}_B, \boldsymbol{\ell}_E)]C^{\Phi\Phi}(\boldsymbol{\ell}_L)\,C^{EE}(\boldsymbol{\ell}_E = |\boldsymbol{\ell}_B - \boldsymbol{\ell}_L|)$$

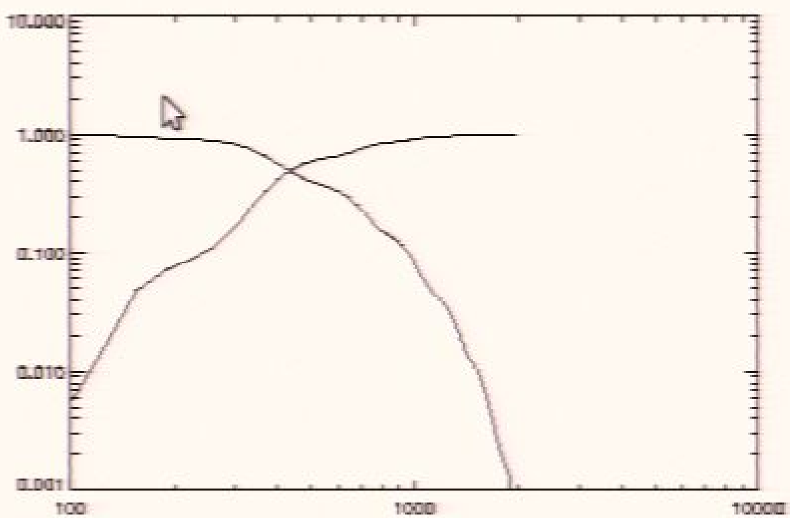
Lensing of the E mode into the B mode (II)

For small values of ℓ_B,

$$C^{BB}(\ell_B \approx 0) \sim \int_0^{\infty} \frac{d\ell}{\ell}\, \ell^6 C^{\Phi\Phi}(\ell)\, C^{EE}(\ell)$$

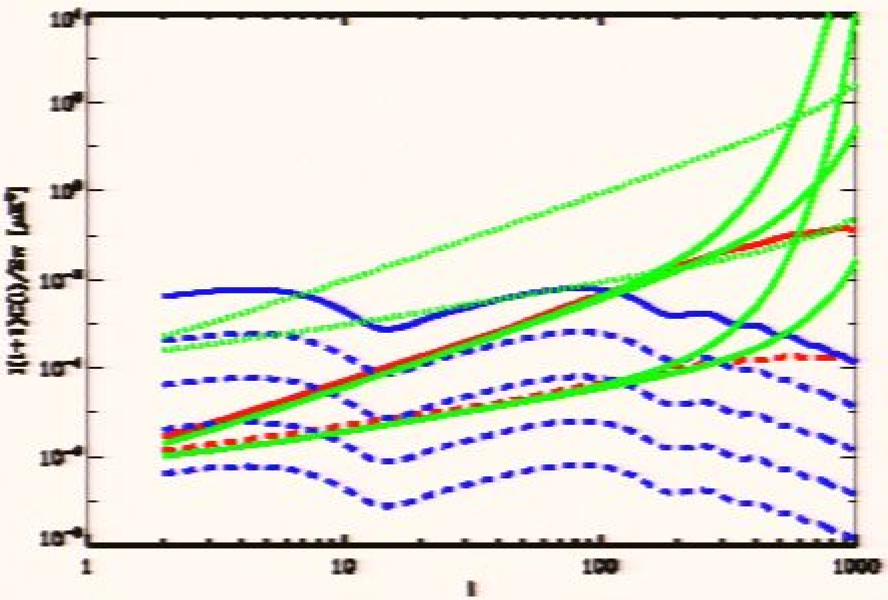
The bulk of the integral is concentrated around $\ell \approx 300$.
White noise spectrum up to $\ell \lesssim 300$

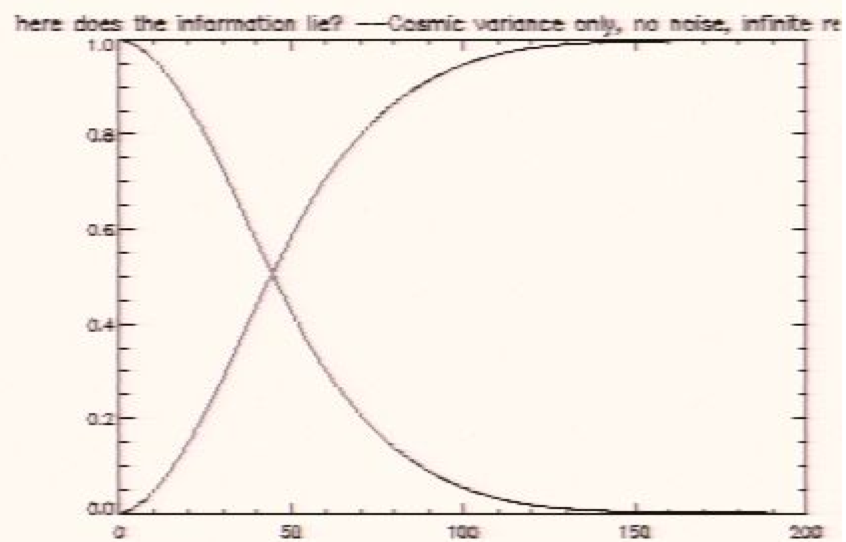
$$F(\ell_{max}) = \frac{\int_0^{\ell_{max}} \frac{d\ell}{\ell}\, \ell^6 C^{\Phi\Phi}(\ell)\, C^{EE}(\ell)}{\int_0^{\infty} \frac{d\ell}{\ell}\, \ell^6 C^{\Phi\Phi}(\ell)\, C^{EE}(\ell)}$$



Where does the information on (T/S) lie ?

$$\delta c_{\ell,measurable} \sim \frac{c_{\ell,parasite} + n_\ell}{\ell}$$

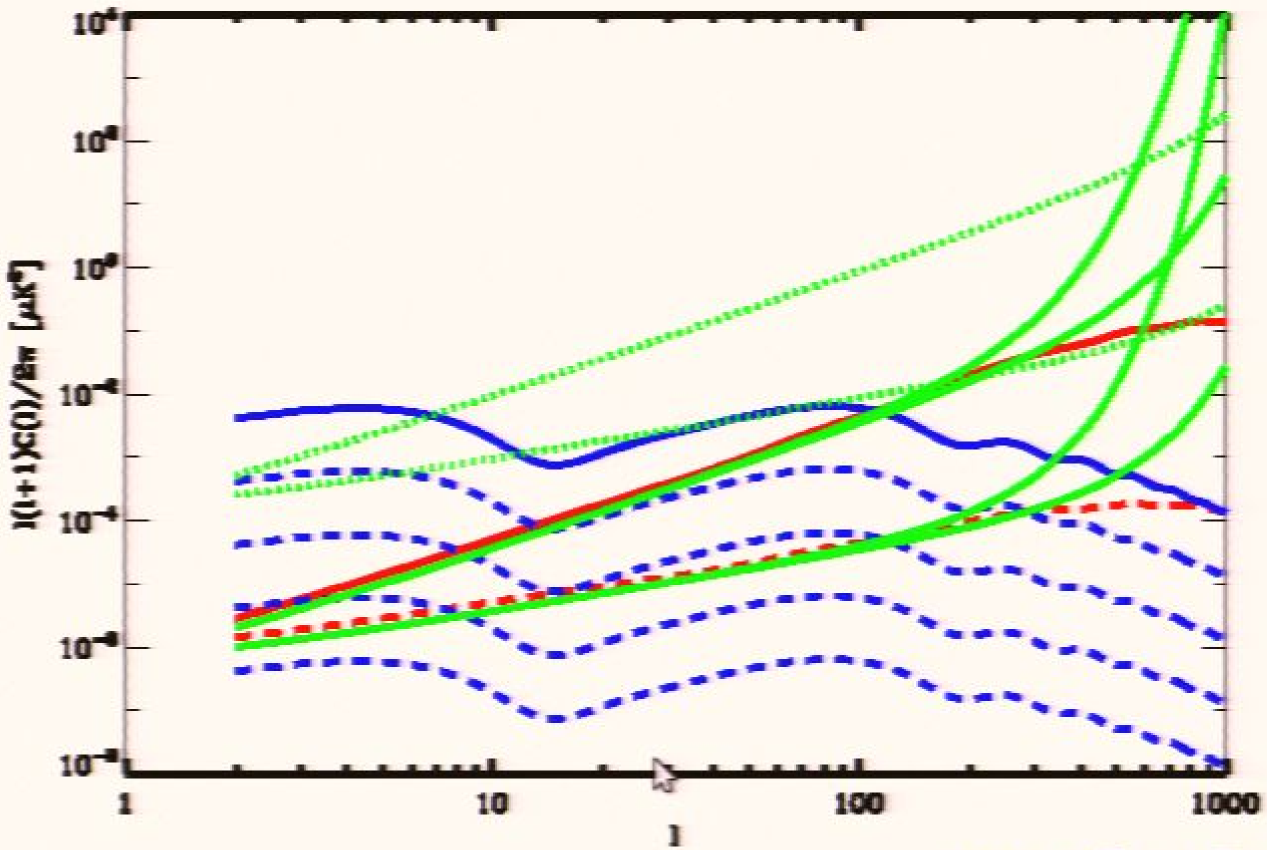




Conclusion : Approx. 80 % of the information (excluding the reionization bump) lies between $\ell = 20$ and $\ell = 80$.

The detection of B modes

The B mode is that component that cannot be represented as a double gradient on the celestial sphere. In the linear approximation there is no B mode component arising from scalar degrees of freedom. The presence of the B mode would unambiguously signal the presence of primordial gravitational waves.



BPol Capabilities : Fisher matrix analysis

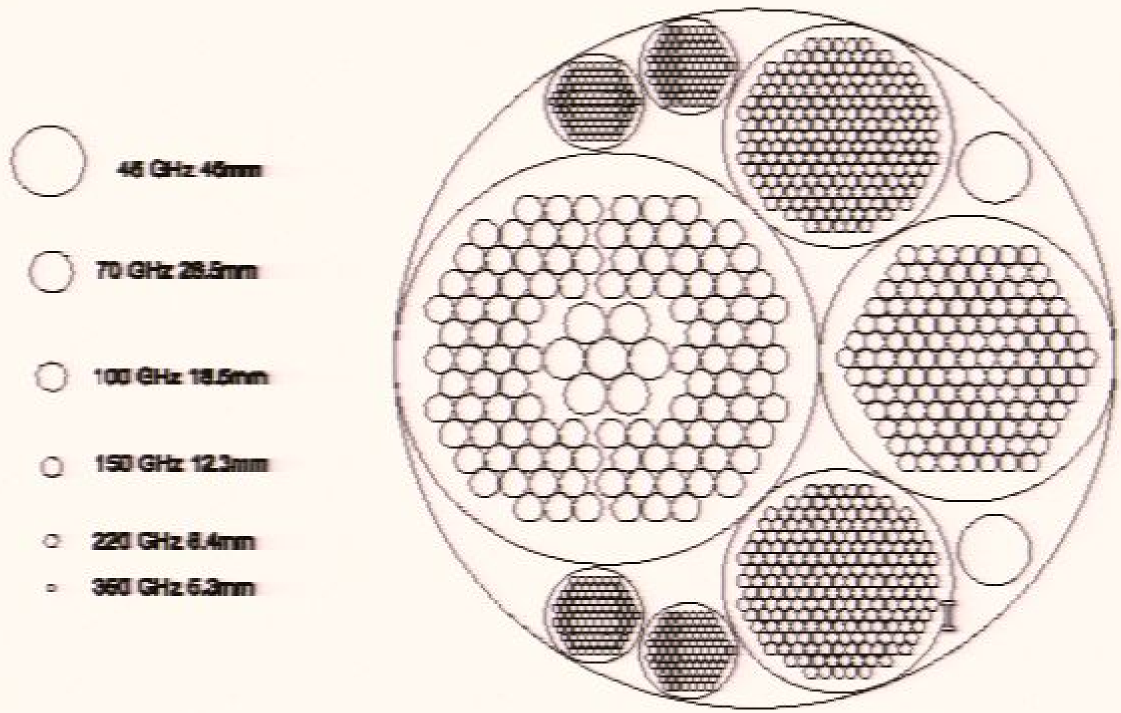
	Fiducial model	BPol 20′ fwhm, $(5\mu K \cdot \mathrm{arcmin})^2$ (No reionization)					
		TT	TE	EE	BB	BB+EE	All
r	0.0	1.57×10^{-1}	7.19×10^{-2}	1.32×10^{-2}	1.58×10^{-3}	6.71×10^{-4}	6.60×10^{-4}
$\delta A_S/A_S$	1.00×10^{0}	3.14×10^{-1}	6.15×10^{-3}	3.81×10^{-3}	2.70×10^{0}	3.57×10^{-3}	1.27×10^{-3}
H	7.20×10^{1}	9.96×10^{-2}	6.62×10^{-2}	9.91×10^{-2}	5.94×10^{0}	8.06×10^{-2}	3.93×10^{-2}
Ω_b	5.00×10^{-2}	3.43×10^{-4}	2.68×10^{-4}	6.01×10^{-4}	3.91×10^{-2}	4.88×10^{-4}	1.39×10^{-4}
Ω_c	2.50×10^{-1}	3.73×10^{-5}	5.03×10^{-5}	1.34×10^{-4}	3.45×10^{-2}	1.28×10^{-4}	2.68×10^{-5}
n_s	1.00×10^{0}	3.47×10^{-3}	6.69×10^{-3}	3.98×10^{-3}	1.49×10^{-1}	3.74×10^{-3}	1.84×10^{-3}
Ω_k	0.0	5.53×10^{-4}	4.37×10^{-4}	3.08×10^{-4}	3.04×10^{-2}	3.01×10^{-4}	1.87×10^{-4}
τ	0.0	1.73×10^{-1}	8.00×10^{-4}	1.19×10^{-5}	1.60×10^{0}	5.96×10^{-6}	5.96×10^{-6}

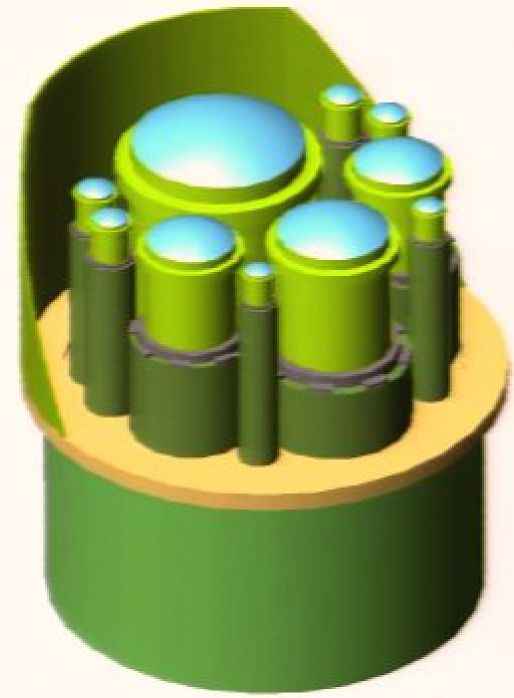
TAB.: 1σ errors resulting from the fit of an eight parameter family of cosmological models for a detector rms white noise amplitude of $5\mu K \cdot \mathrm{arcmin}$ and a resolution of 20 arc minute. (Note that $\delta A_S/A_S$ denotes the variation of the normalization of the scalar power spectrum as compared to that inferred from COBE data.) This table

Requirements for a B Mode Polarization Mission

- **Sensitivity in the neighborhood of** $5\mu K \cdot arcmin$. Chosen equal to contaminant lensing signal. Approximately 13 times more sensitive than PLANCK.
- **Angular resolution of** $\approx 30 - 60'$ Lower than PLANCK ; therefore, one does not necessarily need a large mirror deployed in space.
- **Excellent control of systematic errors.** (These should not exceed the intrinsic random detector noise.)
- **Full sky coverage.** In particular important for mapping the low-ℓ modes of the re-ionization bump.
- **Sufficiently broad frequency coverage to remove galactic foreground components (synchrotron radiation, spinning dust (?), polarized dust emission.**

The B-Pol Instrument





B-Pol Characteristics Summary

Freq. band (GHz)	45	70	100	143	217	353
$\Delta\nu$	30%	30%	30%	30%	30%	30%
ang. res.	15d	68'	47'	47'	40'	59'
# horns	2	7	108	127	398	364
det. noise ($\mu K \cdot \sqrt{s}$)	57	33	53	53	61	119
Q & U sens. ($\mu K \cdot$ arcmin)	33	23	8	7	5	10
Tel. diam. (mm)	45	265	265	185	143	60

$$c_{noise}^2 = 4 \times \frac{4\pi}{t_{miss} N_{det}} \times s_{det}^2 = (5 \mu K \cdot arcmin)^2 \times \left(\frac{2 \ years}{t_{miss}} \right) \times \left(\frac{s_{det}}{50 \mu K \sqrt{s}} \right)^2 \quad (1)$$

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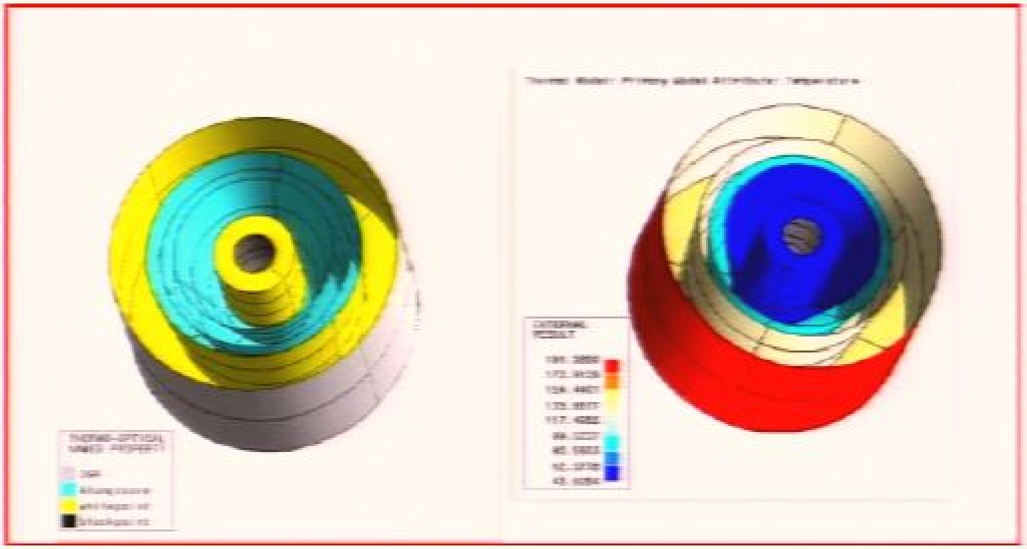
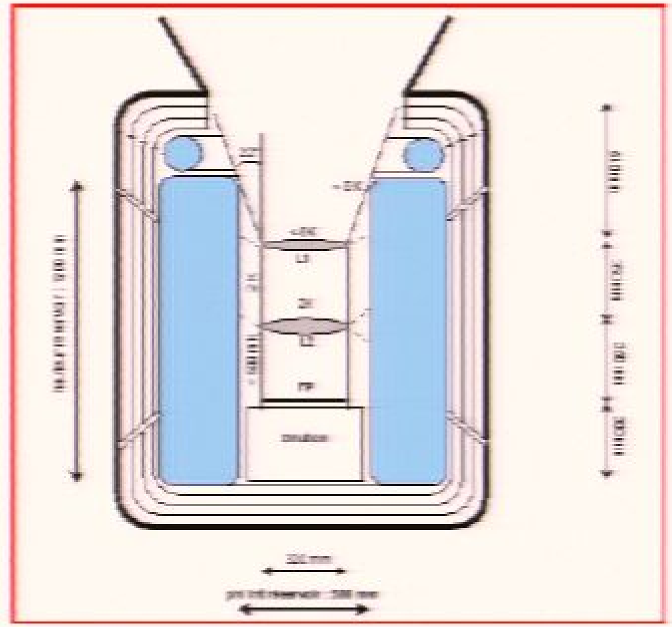
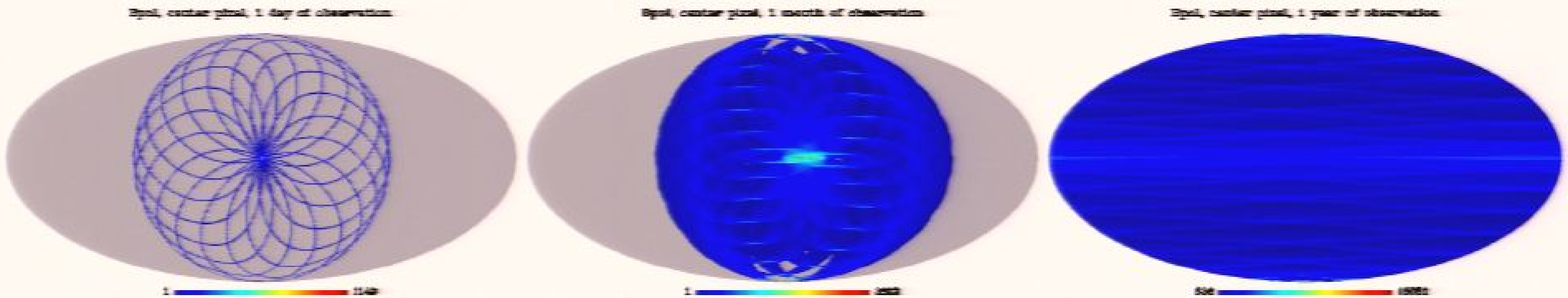




Example of a possible overall cryogenic architecture : shields (grey) and on-axis V-grooves (yellow) provide the first stages for a cryostat (blue) surrounding the optics and the detector assembly.

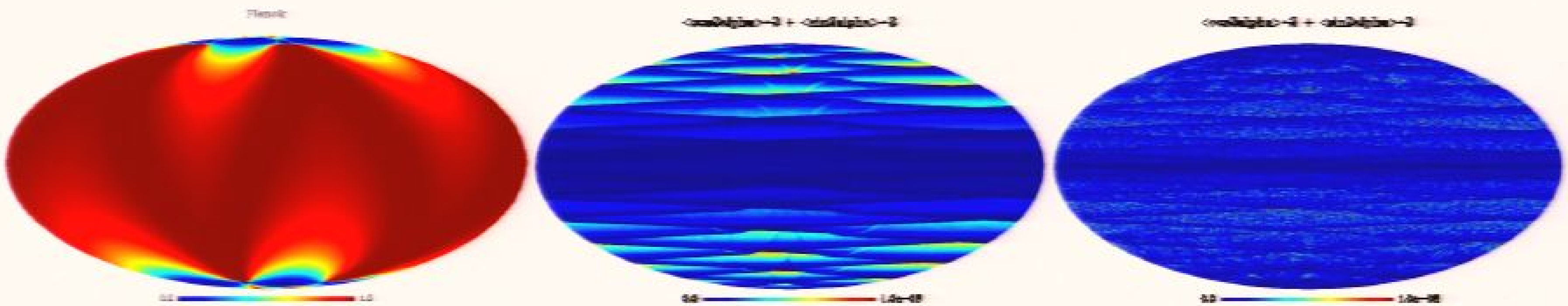
Example of a possible B-Pol cryostat

Scanning Strategy (I)



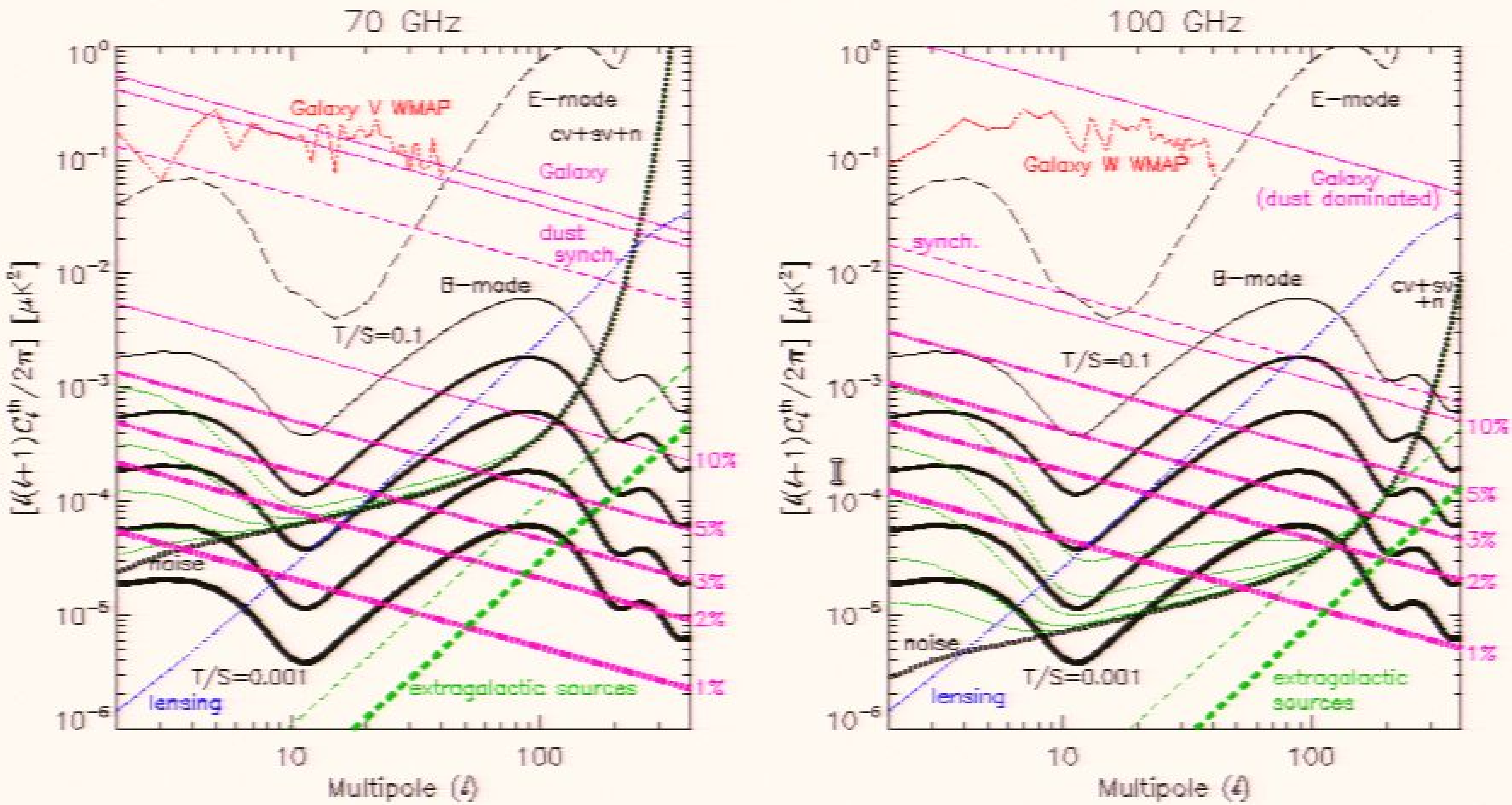
Hit count for a pixel at 1.6 degrees from the center of the B-pol focal plane for observation lasting 1 day (left), 1 month (center) and 1 year (right). The precession and nutation angles are 45 degrees, the precession period is 0.5 days, the nutation period is 40 min. Only one pixel at a fiducial frequency of 10Hz is represented.

Scanning Strategy (II)

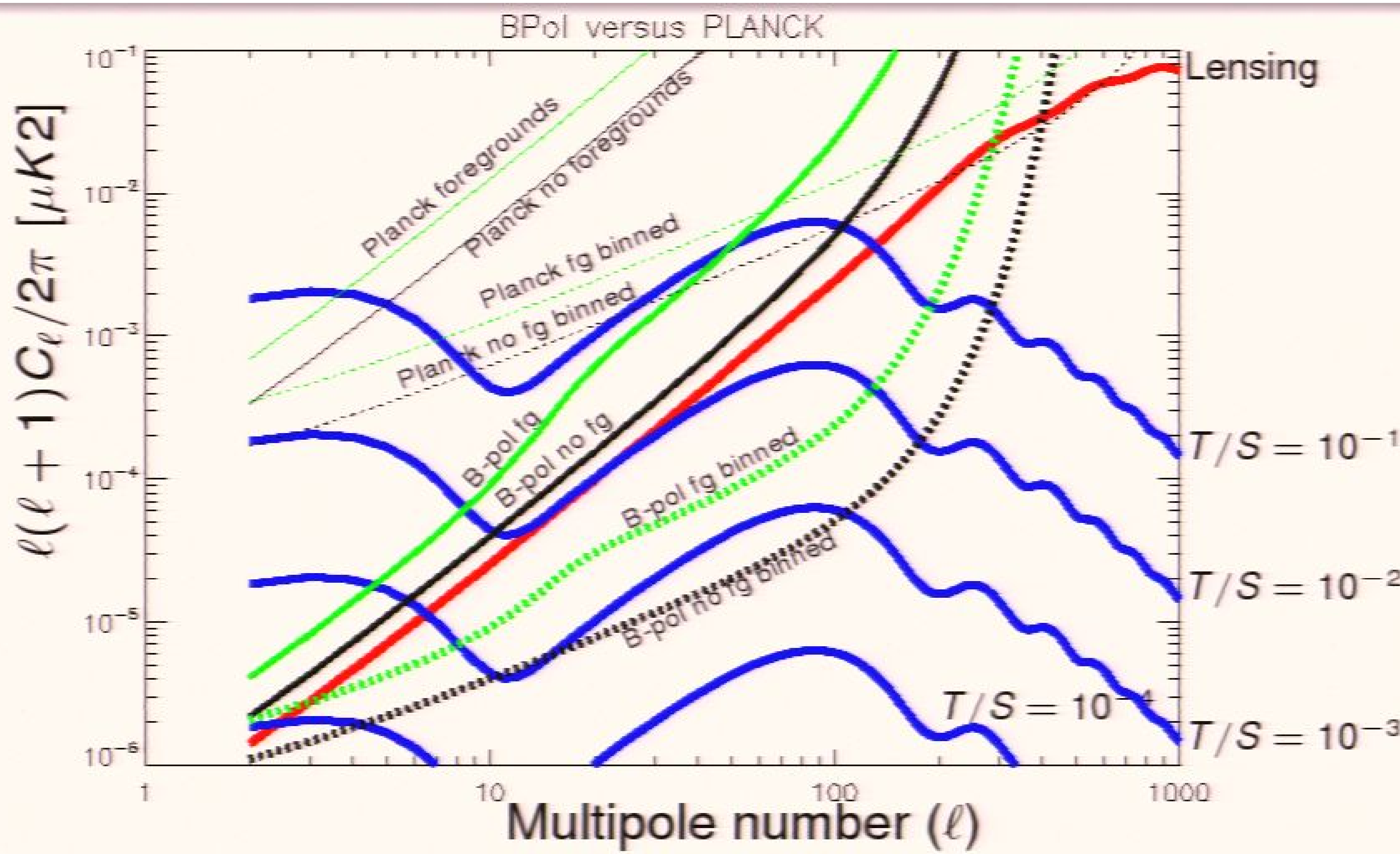


Maps of angular coverage relevant for polarization determination for one year of observation by a pixel at 1.6 degrees from the center of B-pol focal plane. The estimator we chose is $\langle \cos 2\alpha \rangle^2 + \langle \sin 2\alpha \rangle^2$, where α is the angle between the main axis of the polarimeter and a reference direction on the sky. The smaller the better (0=ideal, 1=worst). Compared to Planck, (left) B-pol's angular coverage is a factor 10^6 better without an internal modulator (center), and even 10^9 with a rotating Half Wave Plate (5Hz, right)

Foregrounds relative to signal



(Courtesy of Carlo Burigana)


BPol versus PLANCK
Lensing
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$T/S = 10^{-1}$
$T/S = 10^{-2}$
$T/S = 10^{-3}$
$T/S = 10^{-4}$
$\ell(\ell+1)C_\ell/2\pi$ [$\mu K2$]
Multipole number (ℓ)
1
10
100
1000

3σ detection thresholds for (T/S)

- Idealized experiment : No foregrounds, no instrument noise, just contamination from gravitational lensing. $(T/S) = 1.1 \times 10^{-4}$ (with the reionization bump) $(T/S) = 7.3 \times 10^{-4}$ (reionization bump excluded, $\ell > 15$ only.
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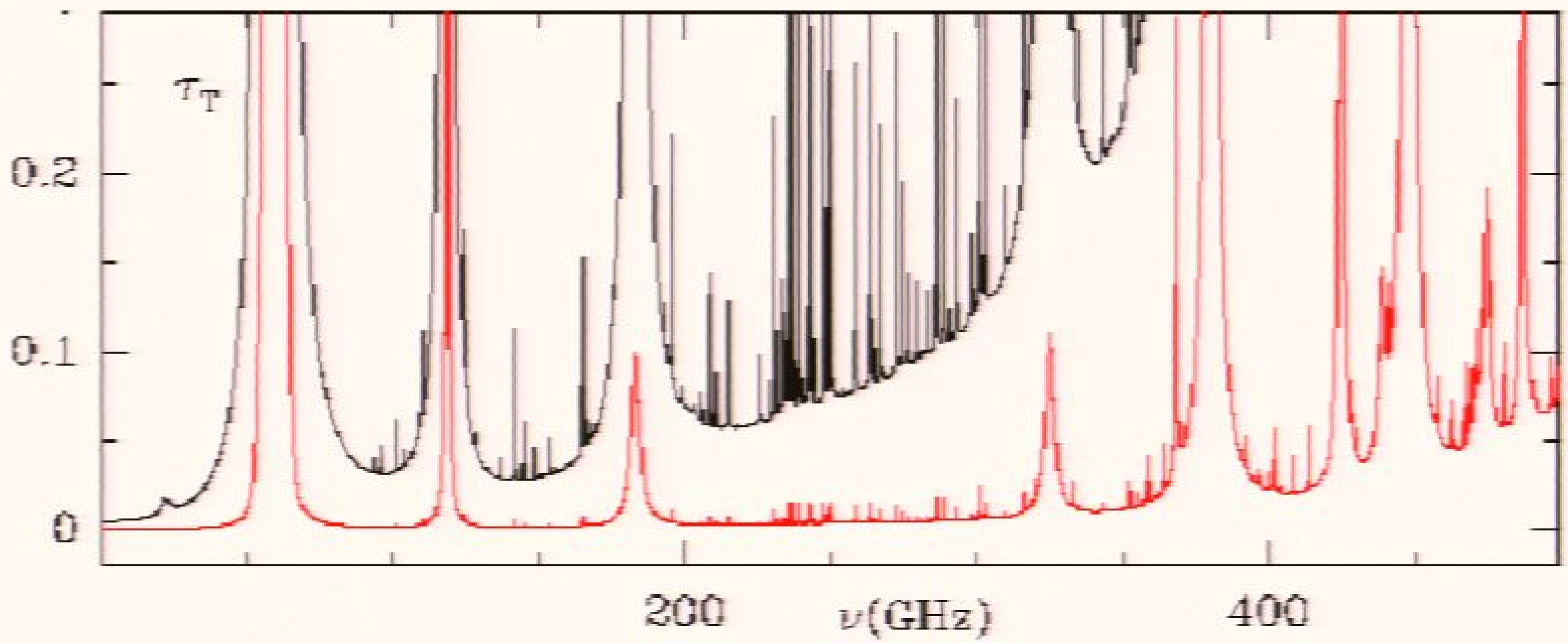
- For PLANCK one would obtain, $(T/S) = 2.6 \times 10^{-2}$ and $(T/S) = 0.17$ for the nominal sensitivity and $(T/S) = 5.3 \times 10^{-2}$ and $(T/S) = 0.36$ with foreground residuals.
- Most realistic projection, where (T/S), A_S, n_S, H_0, Ω_b, Ω_{cdm}, Ω_Λ, and τ are allowed to vary and are determined using only data internal to the experiment. We find that for B-Pol the resulting sensitivities are as follows. With and without the reionization bump, one has $(T/S) = 2.8 \times 10^{-4}$ and $(T/S) = 2.2 \times 10^{-3}$, respectively, for the nominal sensitivity, and $(T/S) = 4.3 \times 10^{-4}$ and $(T/S) = 6.1 \times 10^{-3}$ with foreground residuals included as described above.

Observations from the ground (I)



Atmospheric interference. Calculated optical depth through the atmosphere for a good ground-based site like the South Pole or Dome-C in Winter (black) and at balloon altitude (red). Frequency bands for sub-orbital experiments must be carefully chosen to avoid the emission by molecular lines. Moreover, emission from oxygen lines is circularly polarized and care must be taken to avoid a significant polarized signal from the tails of these lines.

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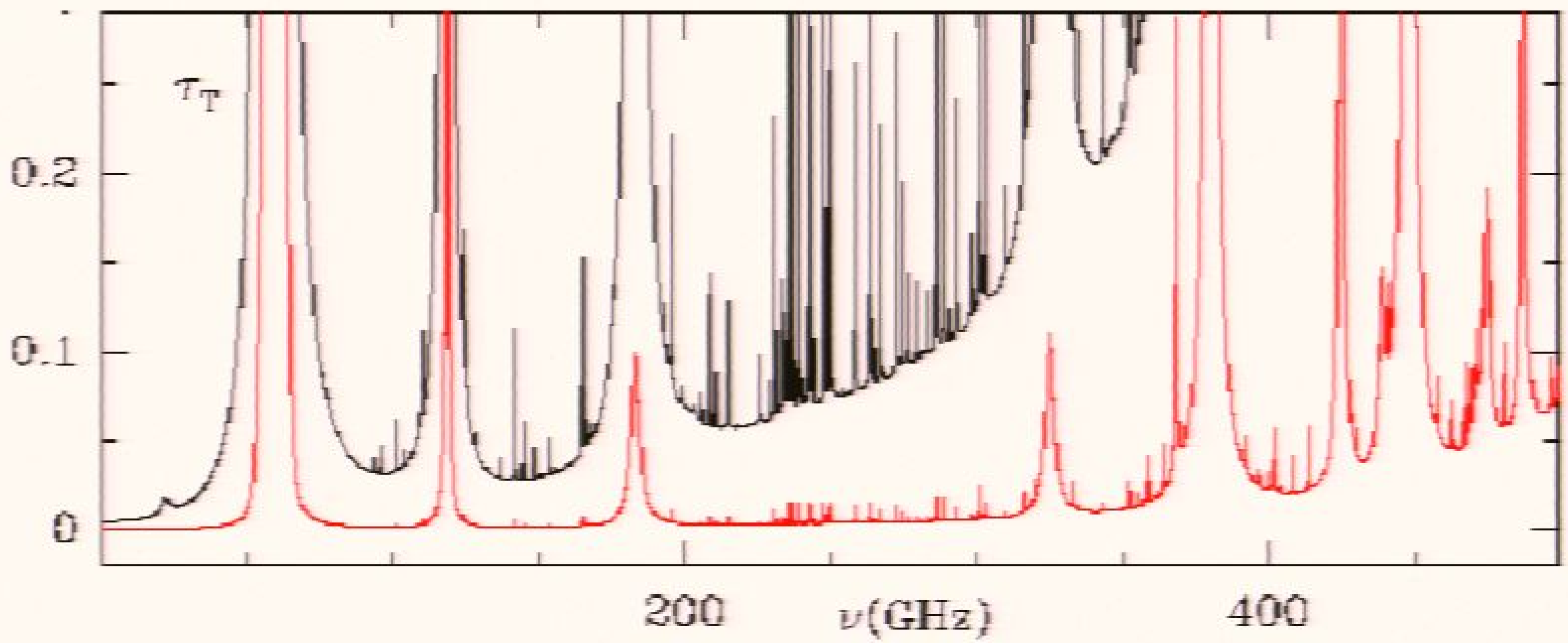

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Observations from the ground (II)

Numerous CMB polarization experiments from the ground and balloons at various stages : QUaD, BICEP ; BRAIN, CLOVER, EBEx, PAPPA, PolarBear, QUIET and Spider

- Far side lobes
- Scanning strategy (must scan at constant zenith angle)
- Polarization from interaction of Zeeman splitting by earth's magnetic field of oxgen lines. Atmospheric backscattering (very polarized) could be a serious problem. [See L. Pietranera et al., "Observing the CMB polarization through ice," MNRAS 346, 645 (2007)].
- Lack of stability and partial sky coverage

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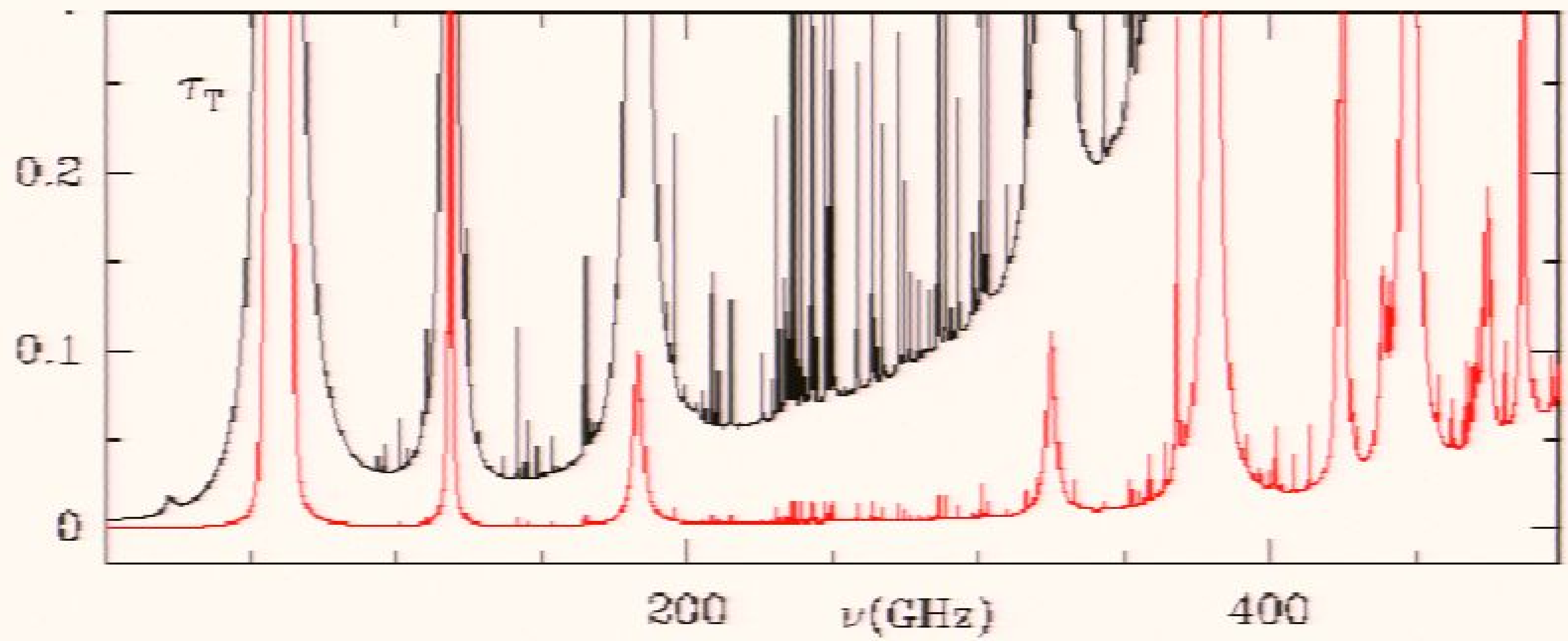

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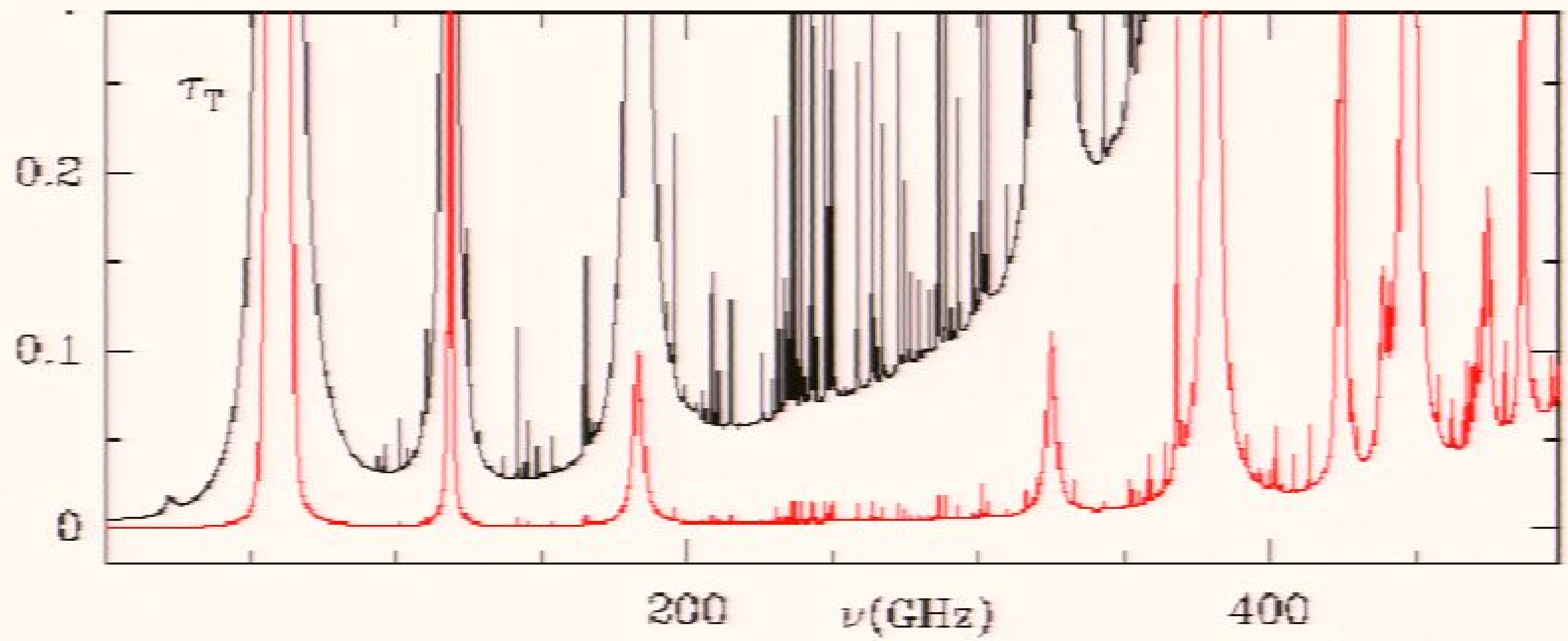

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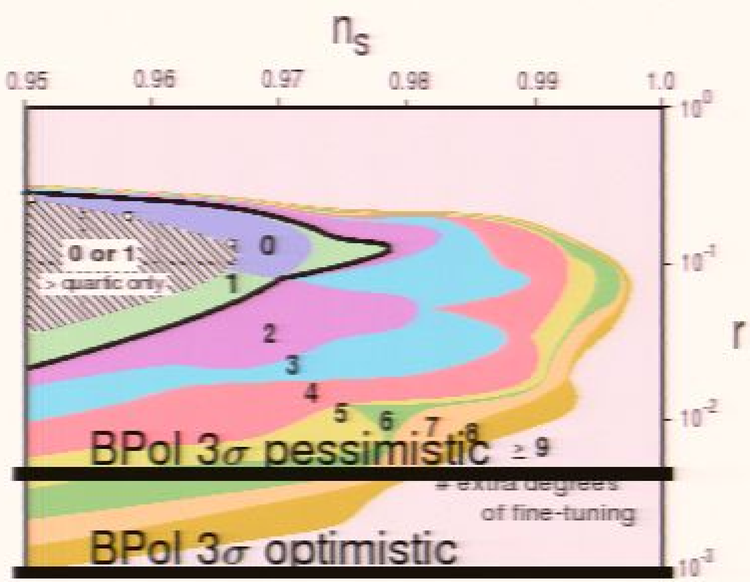
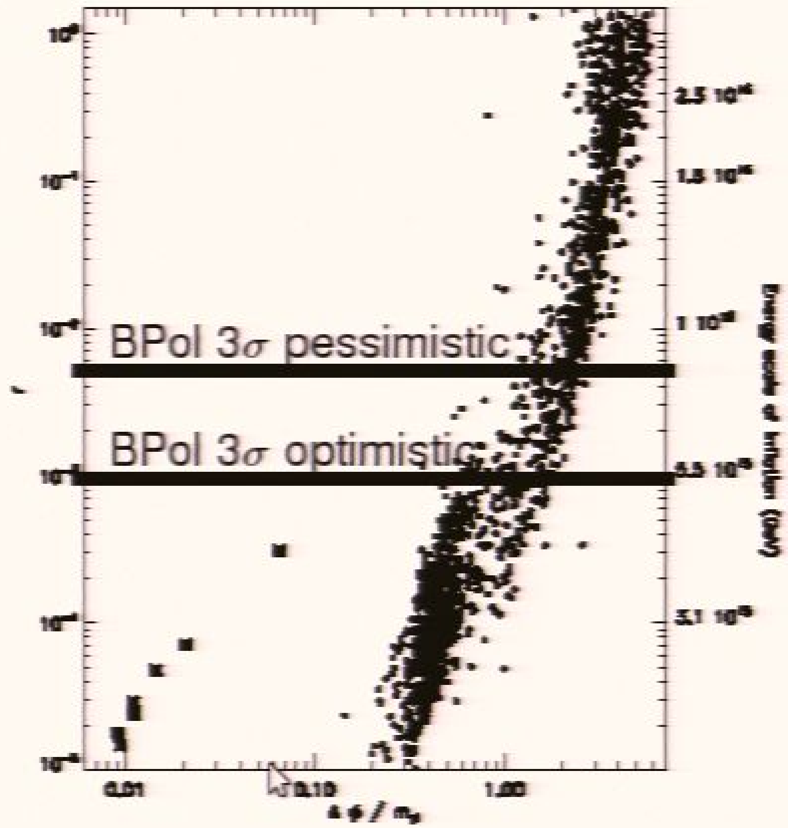
Projected B-Pol Constraints on Inflation

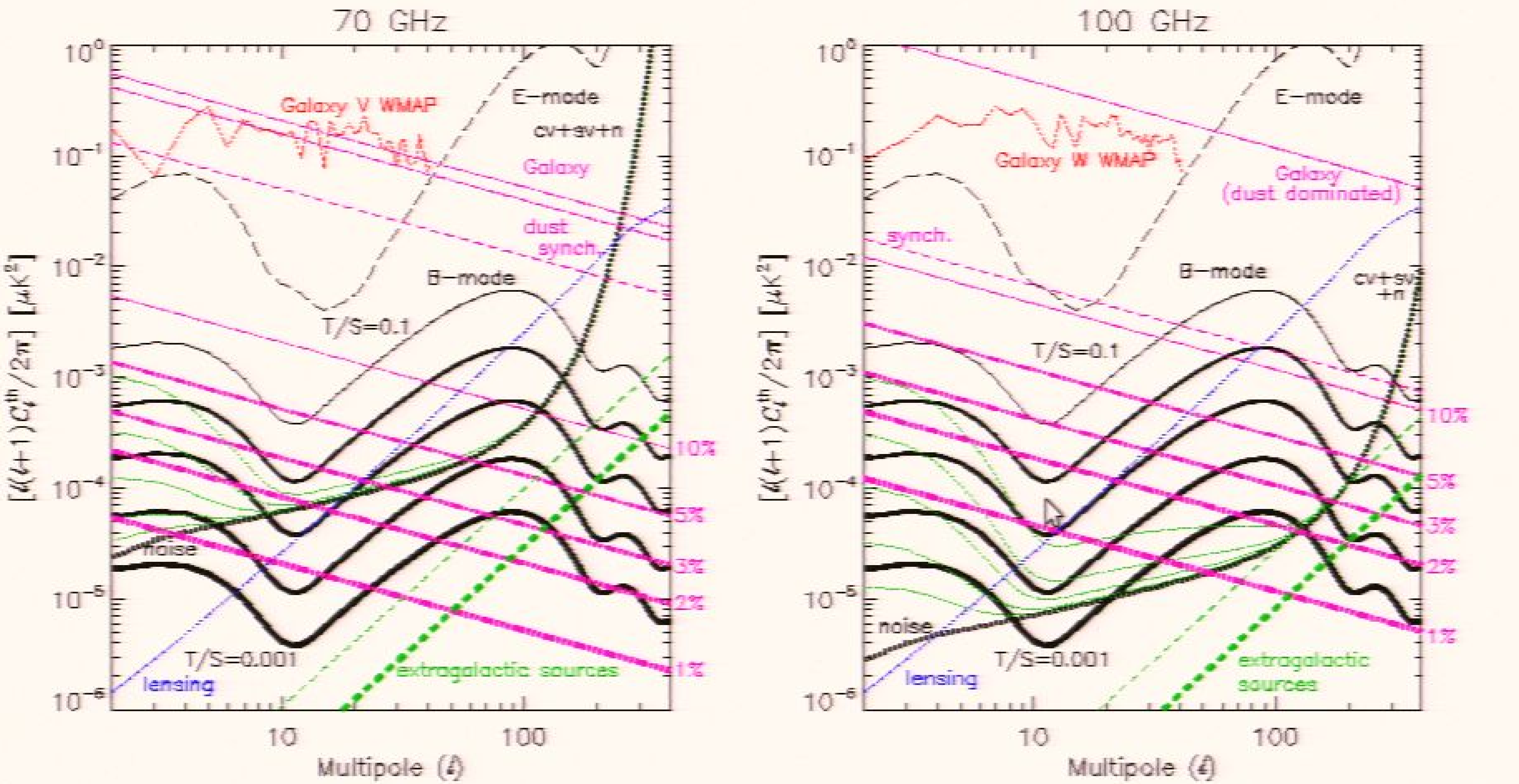


Boyle, Steinhardt & Turok

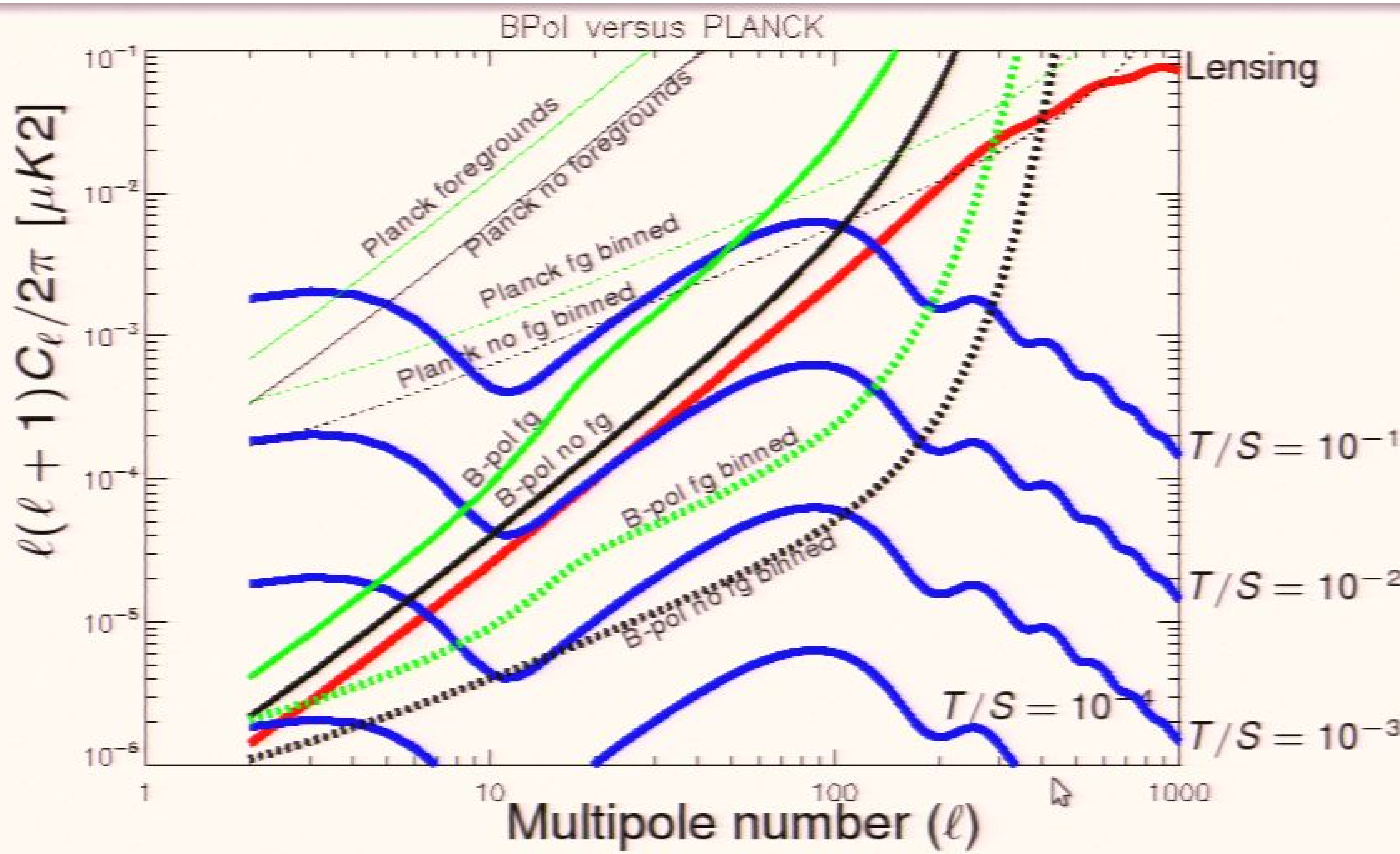


L. Verde et al.

Foregrounds relative to signal



(Courtesy of Carlo Burigana)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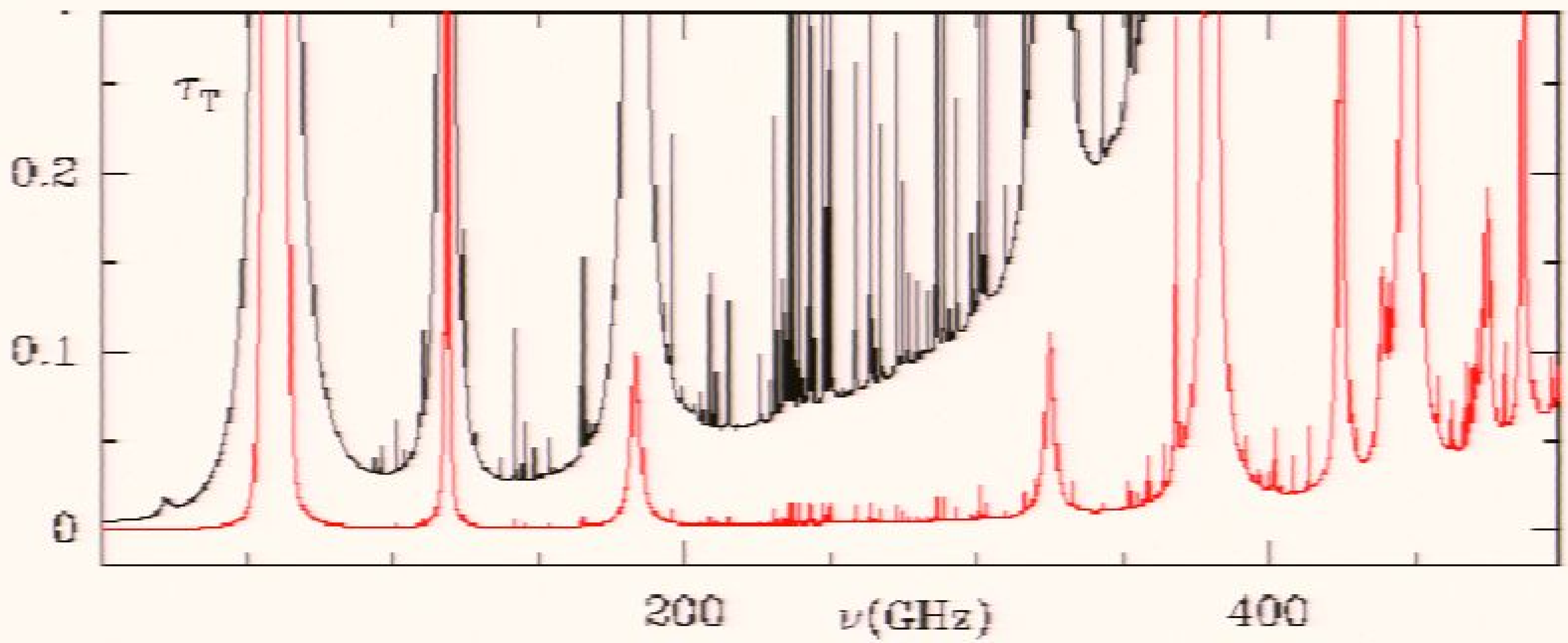

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Conclusions (I)

- The discovery of primordial tensor modes with a scale-invariant would :
  - Confirm the most remarkable prediction of inflation - that the scalar perturbations are accompanied by a very red spectrum of primordial gravitational waves
  - Fix the scale of inflation, and thus break the degeneracy in reconstruction of the inflationary potential, providing valuable clues concerning physics near the Planck scale for fundamental physics
- There are two windows for observations of tensor modes, one at very large scales at the reionization bump, and another centered around $\ell = 50$, with almost no useful information beyond $\ell = 100$. Ground based experiments may be able to access the second window if (T/S) is sufficiently large, but cannot access the first. Two non-zero detections would provide a consistency check between the tensor and scalar power spectra.

Conclusions (II)

- The level of the gravitational lensing contaminant ($\approx 5\mu K \cdot \mathrm{arcmin}$) sets a natural sensitivity goal for a B mode polarization experiment. The B-Pol design goal was to set the instrumental noise and systematic errors at this level. A coarse angular resolution ($\approx 30'$) is sufficient for searching for primordial tensors. Particular attention must be paid to eliminating errors on large scales given the white noise character of the signal.
- Ground based experiments will play an important testing ground for new detection technolgies and help better characterize foregrounds. If T/S is high enough, we may be able make a detection from the ground, but given the importance of such a discovery, we would in any case want a confirmation from space, where large angular scales can be reliably probed. Far-side lobes, atmosphere interference, and the limitations of scanning at constant zenith angle pose formidable challenges for observations from the ground.

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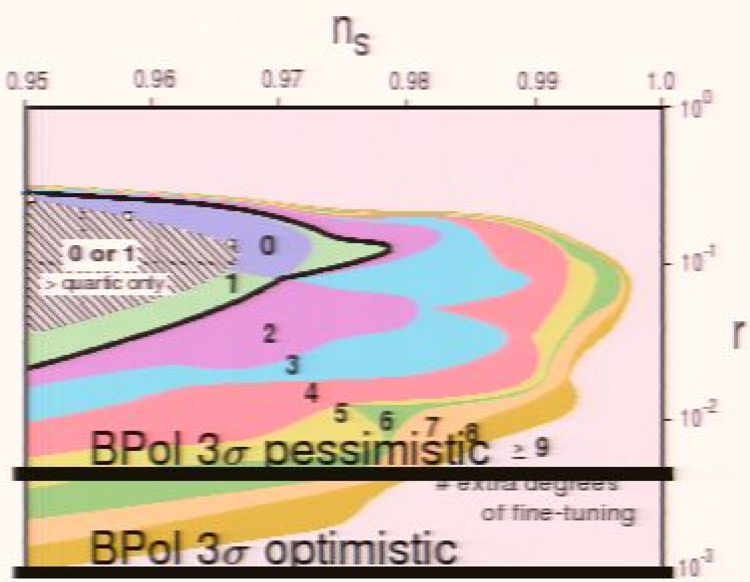

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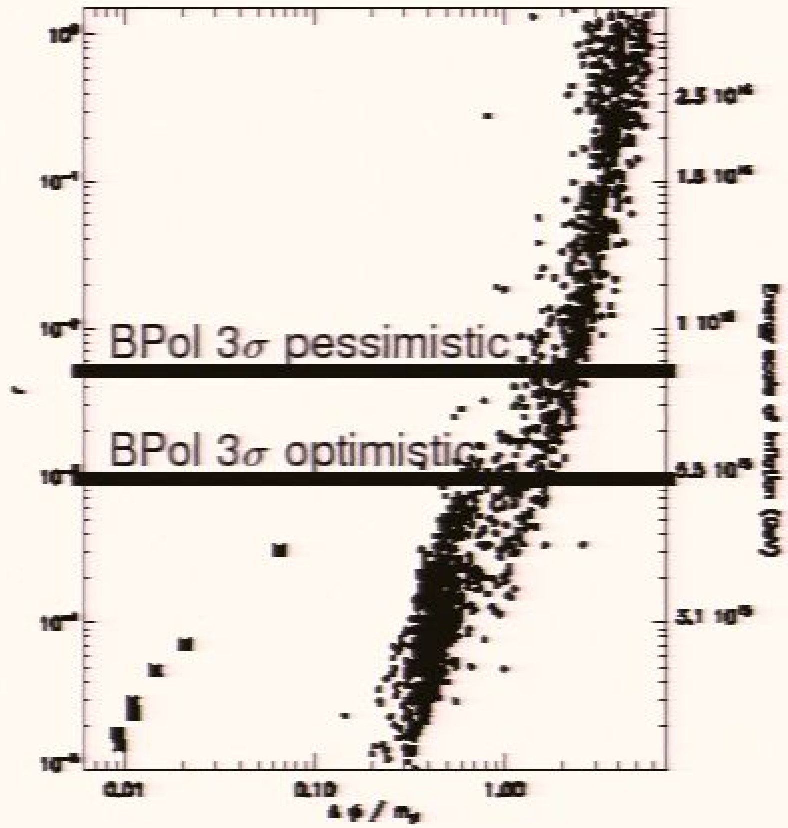
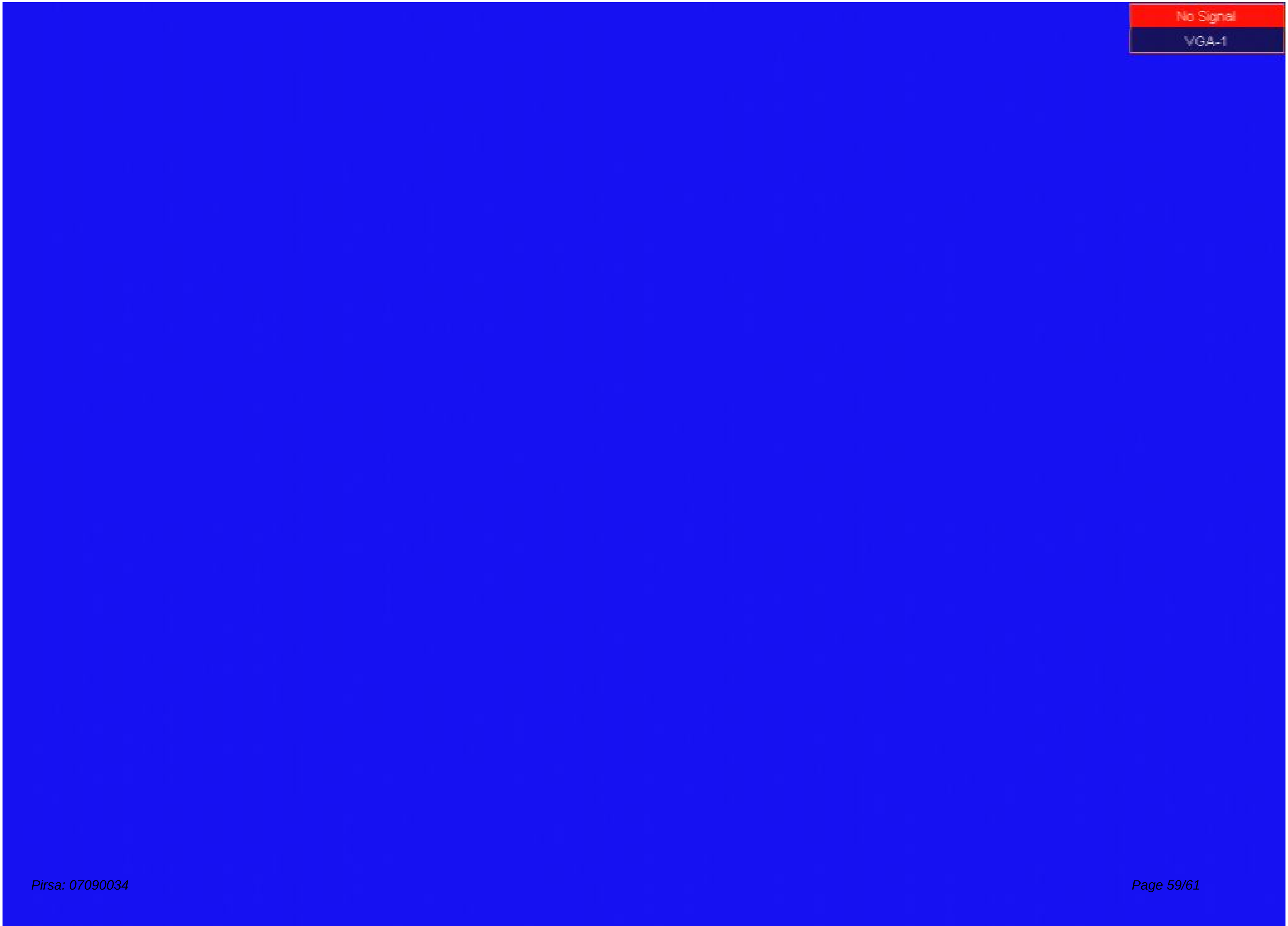


L. Verde et al.


No Signal
VGA-1

No Signal
VGA-1

No Signal
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