Observational and Theoretical Challenges:
I. Gravitational Waves from Inflation
II. Precision Dark Energy with Supernovae

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Cosmo-05

Inflation and Gravitational-waves

- **Inflation predicts tensor perturbations due to primordial gravity waves**

- **Hard to detect with temperature information alone (contribute to large angle anisotropies, dominated by cosmic variance)**

- **Distinct signature in polarization**

  (in terms of curl, or magnetic-like, modes)

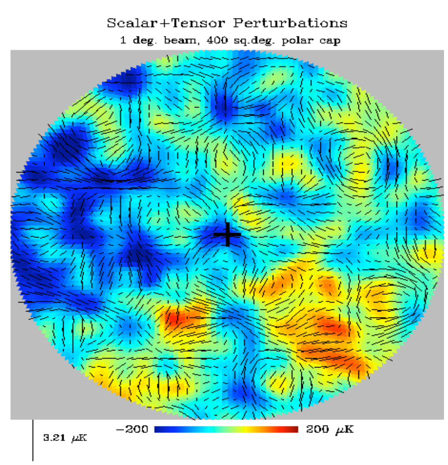
CMB Polarization

Grad (or E) modes

Curl (or B) modes

(density fluctuations have no handness, so no contribution to B-modes)

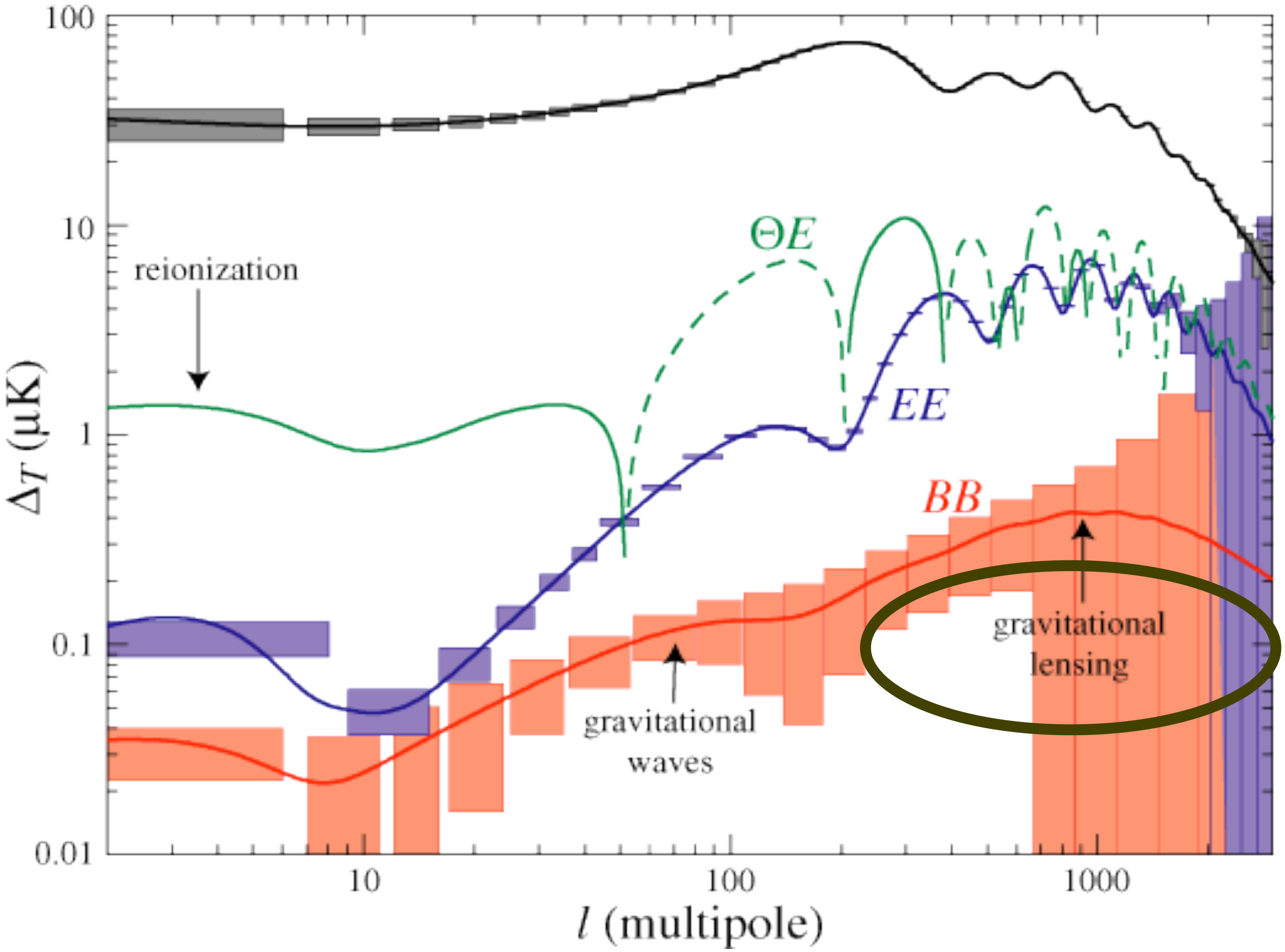
Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997



Temperature map : $T(\hat{n})$

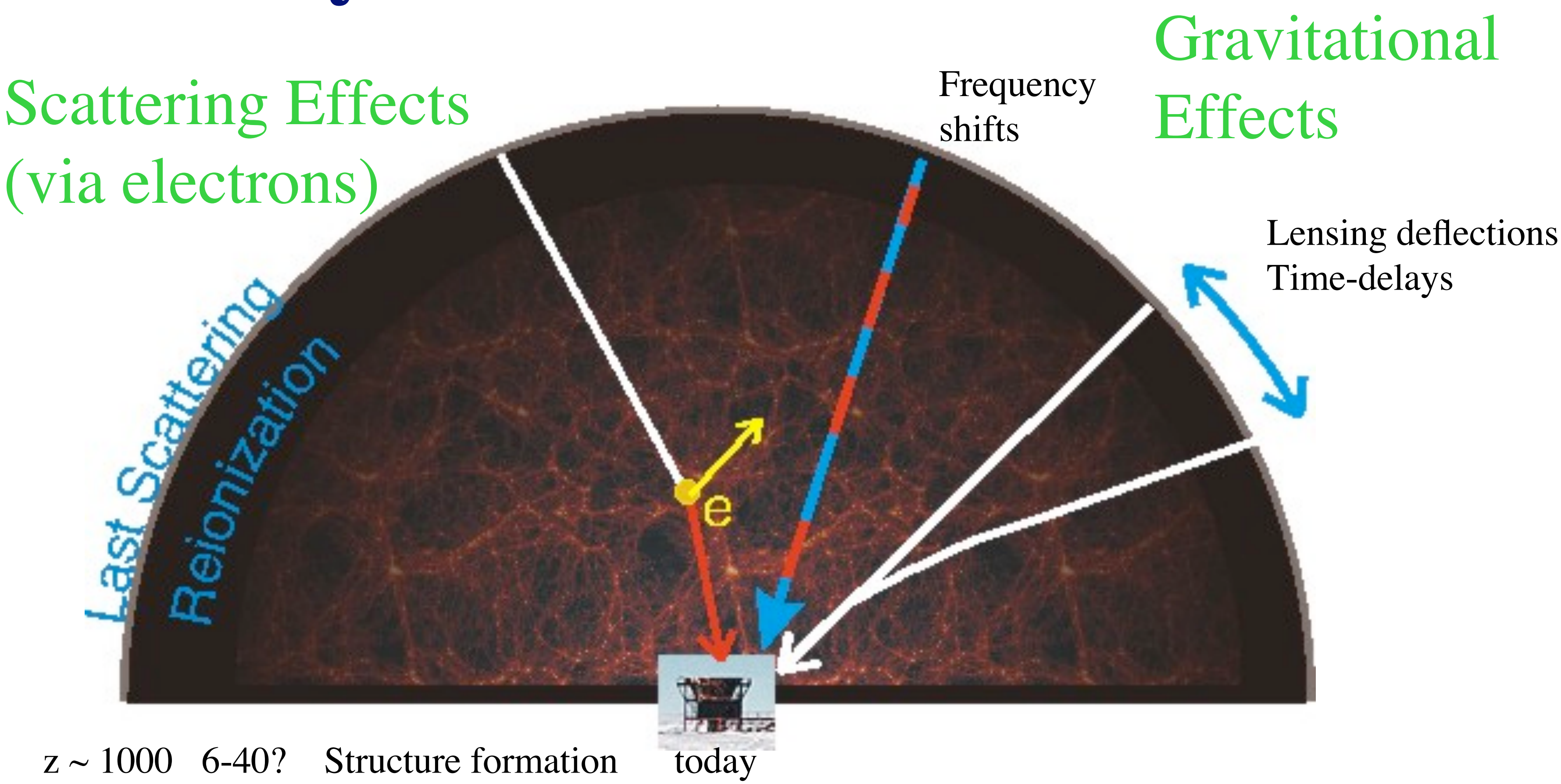
Polarization map : $P(\hat{n}) = \vec{\nabla} E + \vec{\nabla} \times \vec{B}$

Problem: IGWs in B-modes are not distinct



Hu & Dodelson (Annual Reviews 2002)

Why confusions?



• ***late-time universe: non-linear physics***. Large scale structure modifies CMB properties

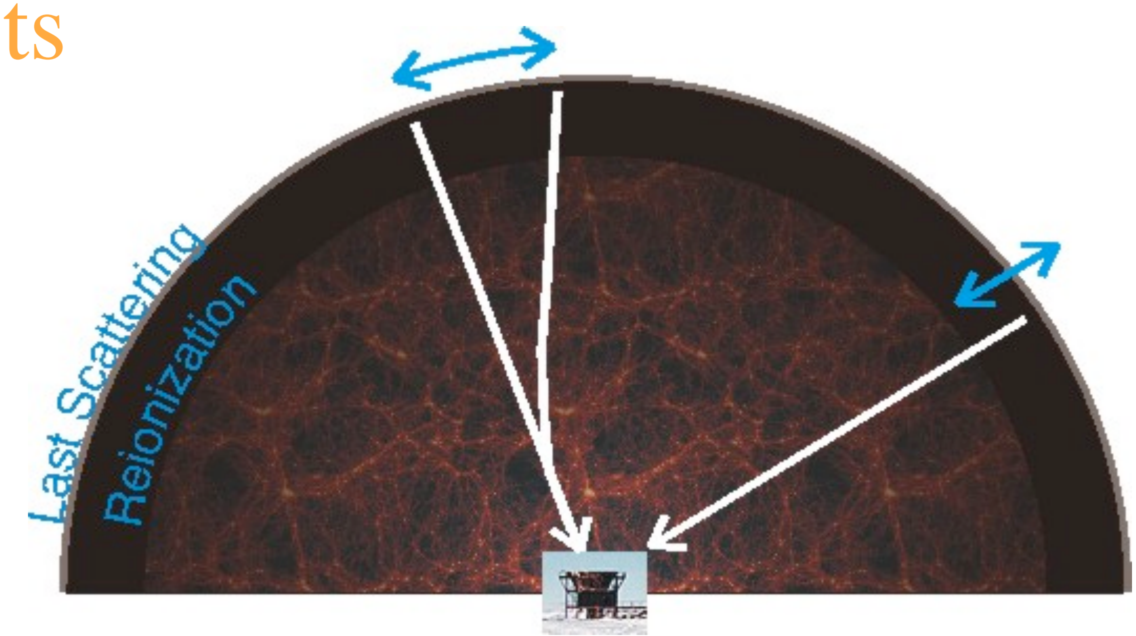
For B-modes, lensing effect is the main concern!!

Gravitational Effects

Lensing and time-delay

• Geometric effect

$\Rightarrow$ Angular deflection of Photons



• Potential effect

$\Rightarrow$ Time delay of photons

$$T(\bar{\theta}) \equiv T(\bar{\theta} + \delta\bar{\theta})$$

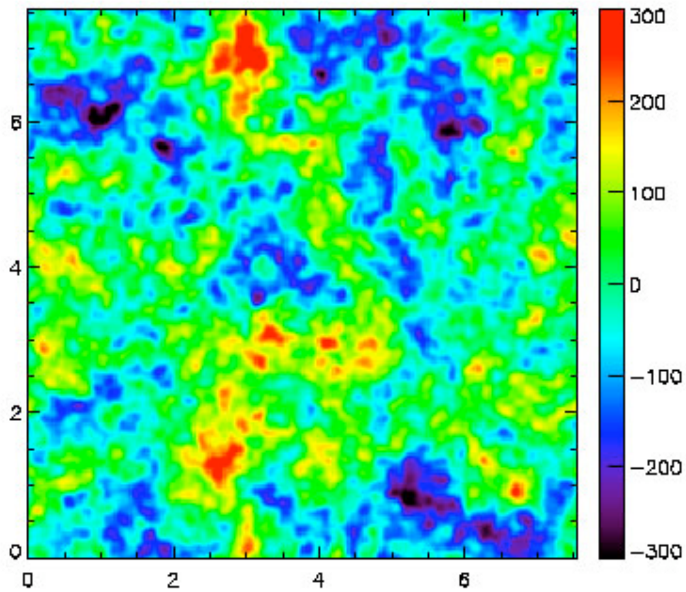
$$\approx T(\bar{\theta}) + \delta\bar{\theta} \bullet \nabla T(\bar{\theta}) + \ldots$$

$$\delta\bar{\theta} \equiv \nabla\phi \quad \text{(Deflection angle)}$$

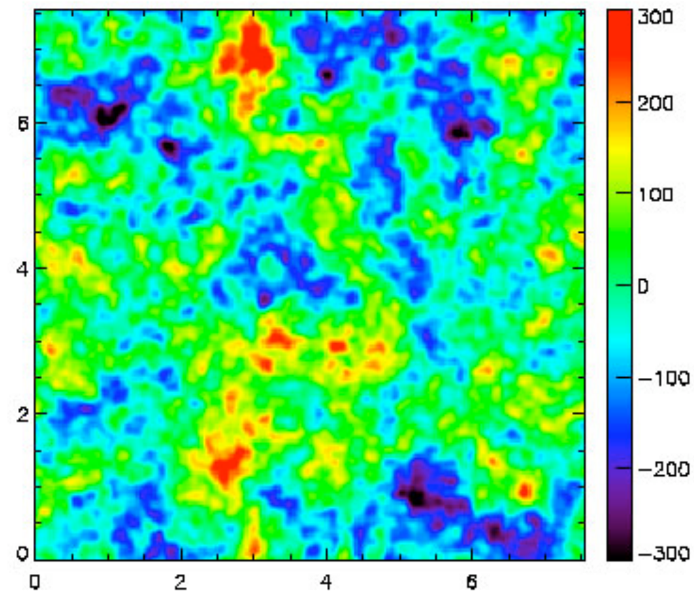
Two effects combined lead to the Fermat potential

(Hu & Cooray 2000)

Lensing in CMB - Very Weak!!!



Unlensed

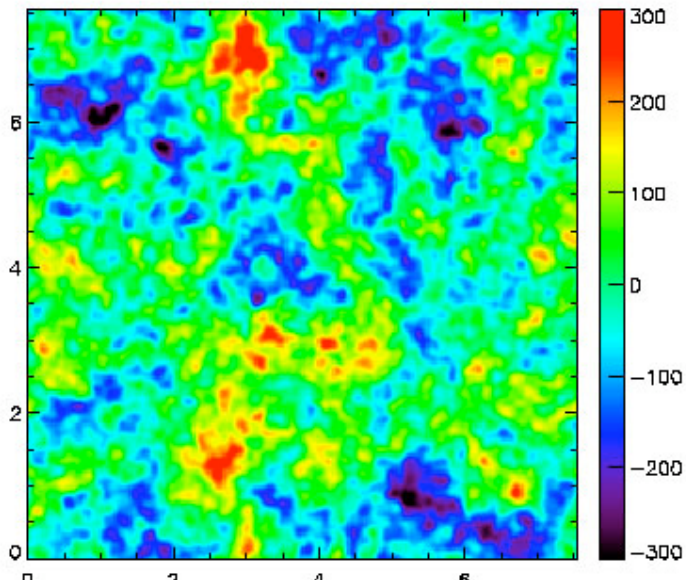


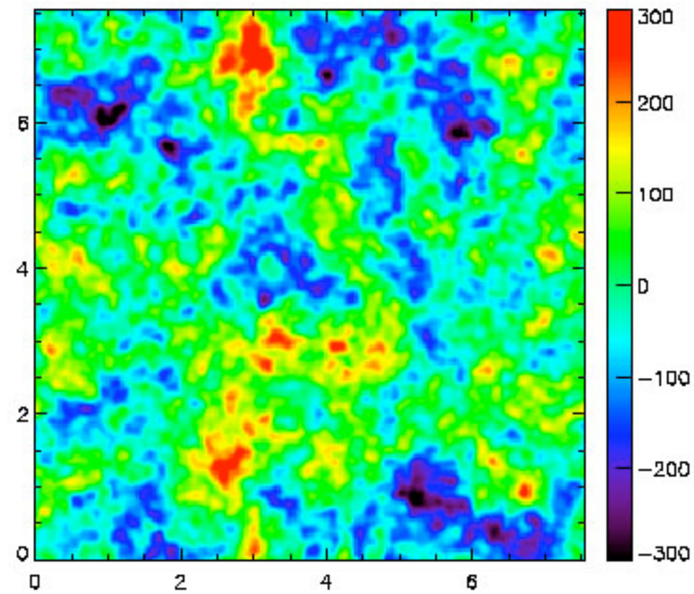
Lensed

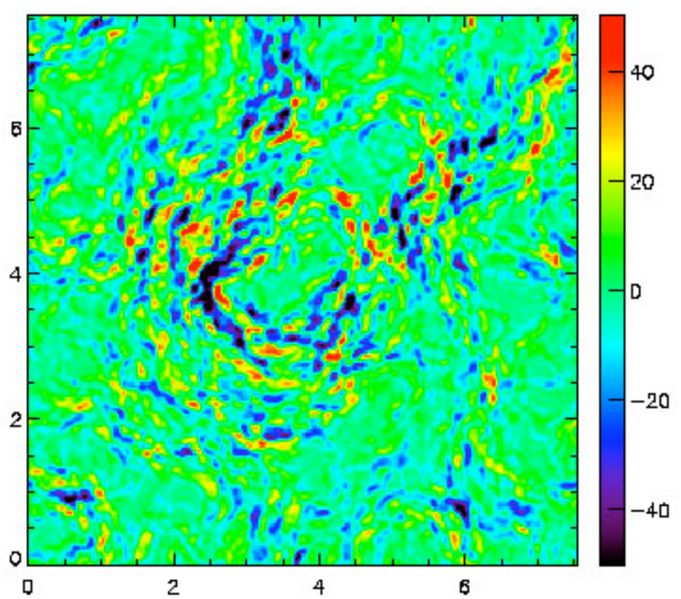
The real scenario: difference is very small!!!!

(Cooray & Kesden 2002; Vale et al. 2003)

Lensing in CMB - Very Weak!!!



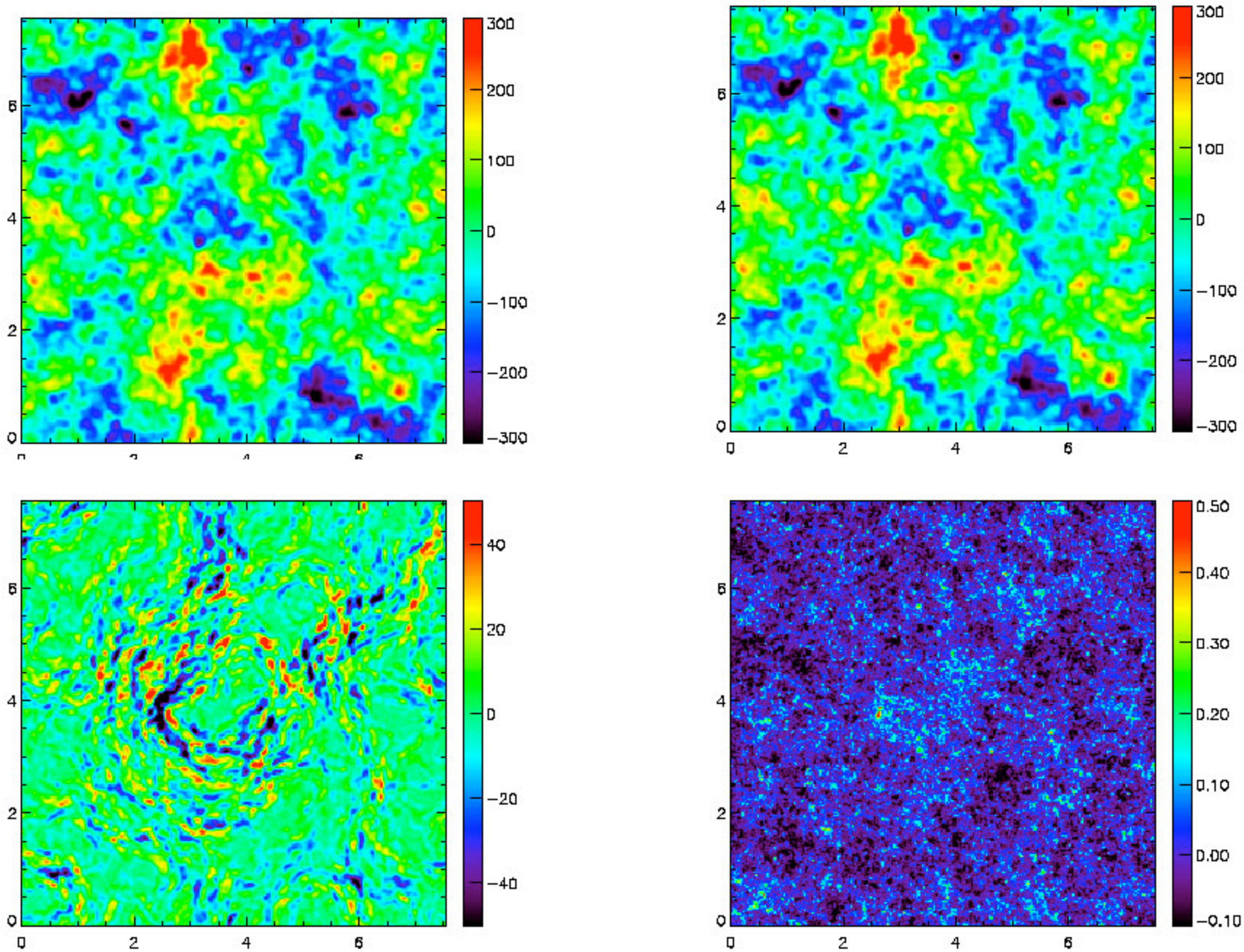




Difference between the two:
1) +/- dipolar structure
2) Color scale

(Vale et al. 2003)

Lensing in CMB - Very Weak!!!



Quadratic Statistics as a way to reconstruct lensing deflections

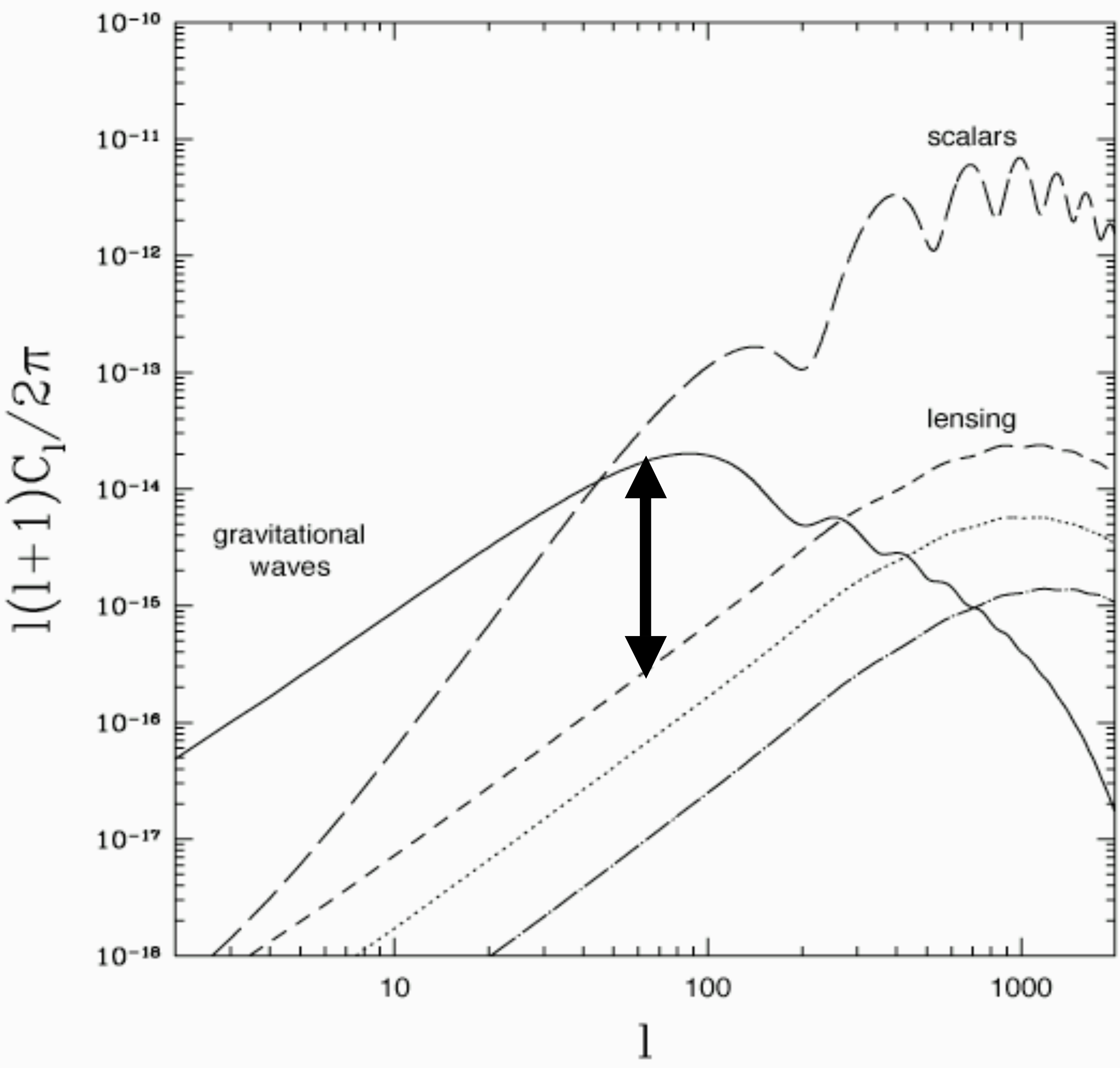
Reconstruction algorithm (basics)

Lensing effect is on the second order - has to be a quadratic statistic or higher order

CMB maps are noise dominated - has to be able to understand noise properties easily and be able to extract most information on lensing

(Algorithms in Hu & Okamoto 2002; Kesden, Cooray & Kamionkowski 2002; Seljak & Hirata 2003; among others)

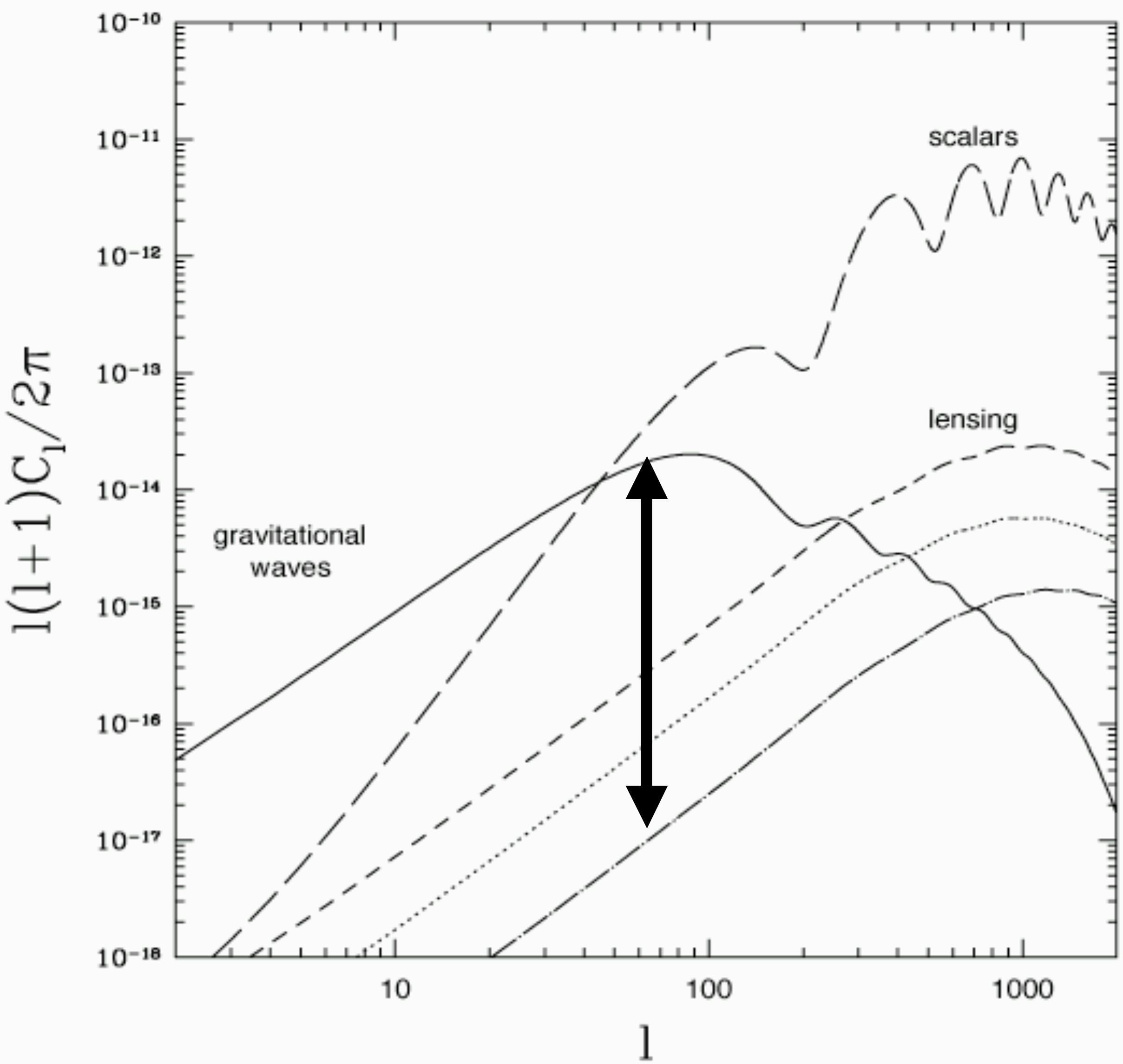
Removing the confusions



Extract with a noise contribution below an order of magnitude of the signal

(Kesden, AC, MK 2002; Knox & Song 2002; Hirata & Seljak 2003)

Removing the confusions



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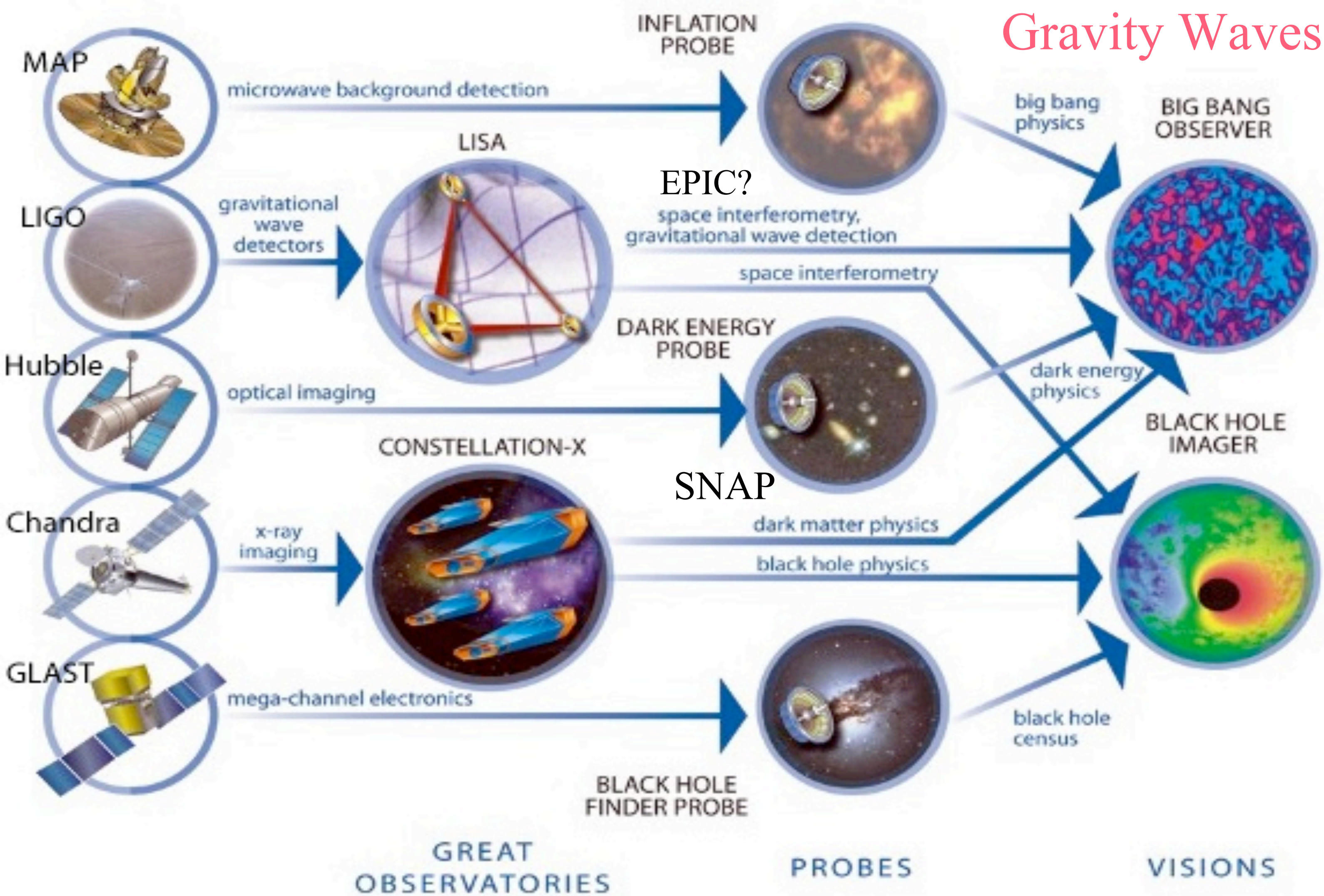
NASA's *Beyond Einstein* Program



Current Missions	Broad sciences/ Major resources Community-class	Focused/narrow sciences PI-class	After significant developments (both hardware/theory) > 25 year time-scales

EPIC: Exploration Probe of Inflationary Cosmology

Selected by NASA for pre-Phase A study and technology demonstration
Final selection/decision in about 3 years with launch ~ 2014 (?).

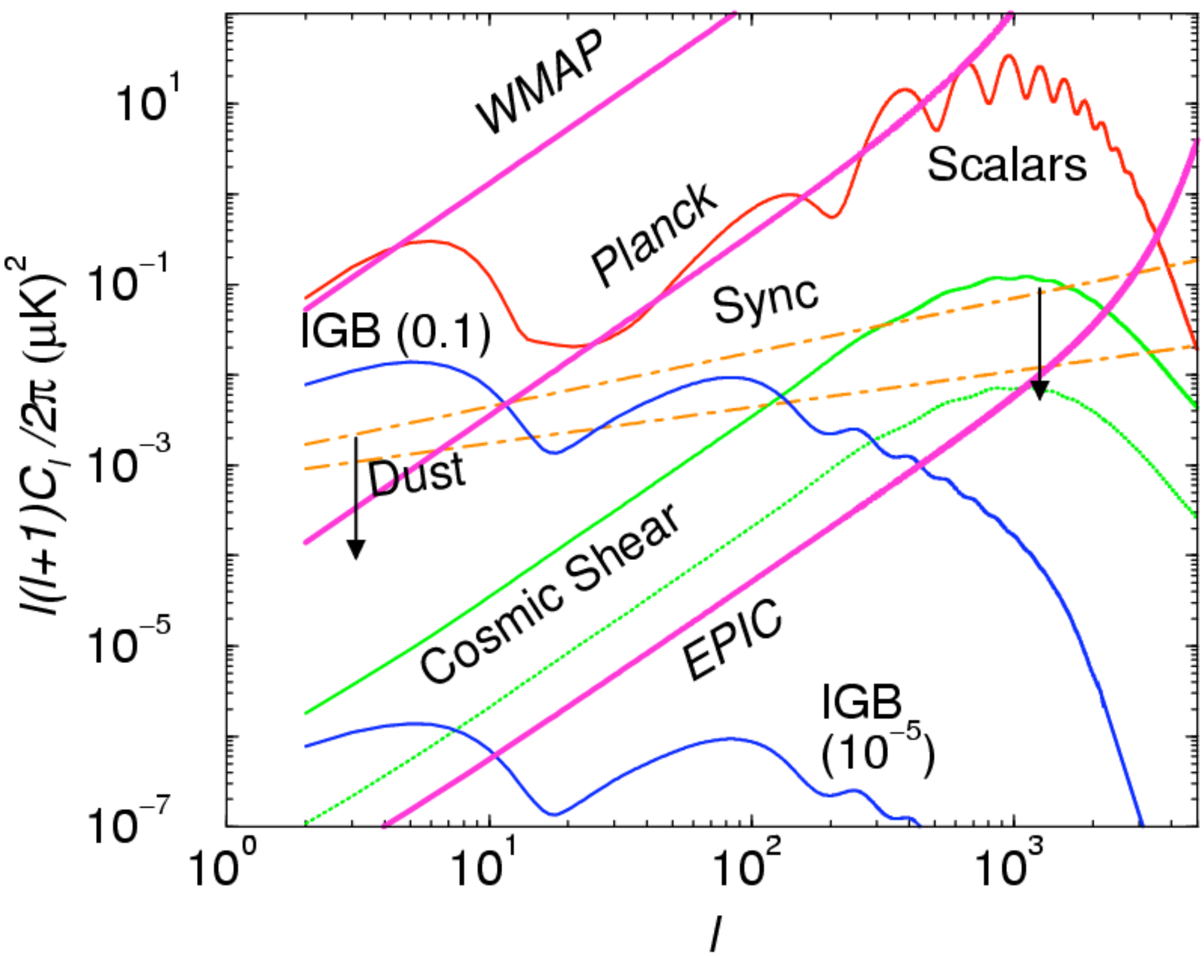
Consortium:

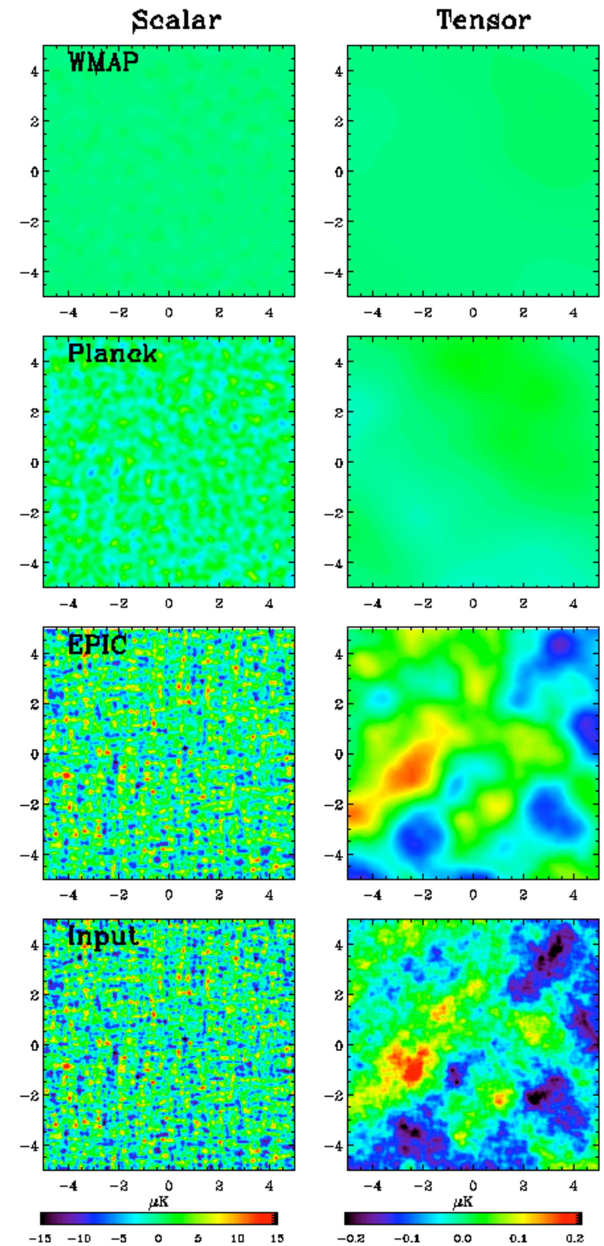
James Bock (PI; JPL)

Charles Beichman	Robert Caldwell	John Carlstrom	Sarah Church
Asantha Cooray	Peter Day	Scott Dodelson	Darren Dowell
Mark Dragovan	Todd Gear	Ken Ganga	Walter Gear
Jason Glenn	Alexey Goldin	Krzysztof Gorski	Shaul Hanany
Carl Heiles	Eric Hivon	William Holzapfel	Kent Irwin
Jeff Jewel	Marc Kamionkowski	Manoj Kaplinghat	Brian Keating
Lloyd Knox	Andrew Lange	Charles Lawrence	Rick LeDuc
Adrian Lee	Erik Leich	Steven Levin	Hien Nguyen
Gary Parks	Tim Pearson	Jeffrey Peterson	Clem Pryke
Jean-Loop Puget	Anthony Readhead	Paul Richards	Ron Ross
Mike Seiffert	Helmuth Spieler	Thomas Spilker	Martin White
Jonas Zmuidzinas			

*Co-Investigator

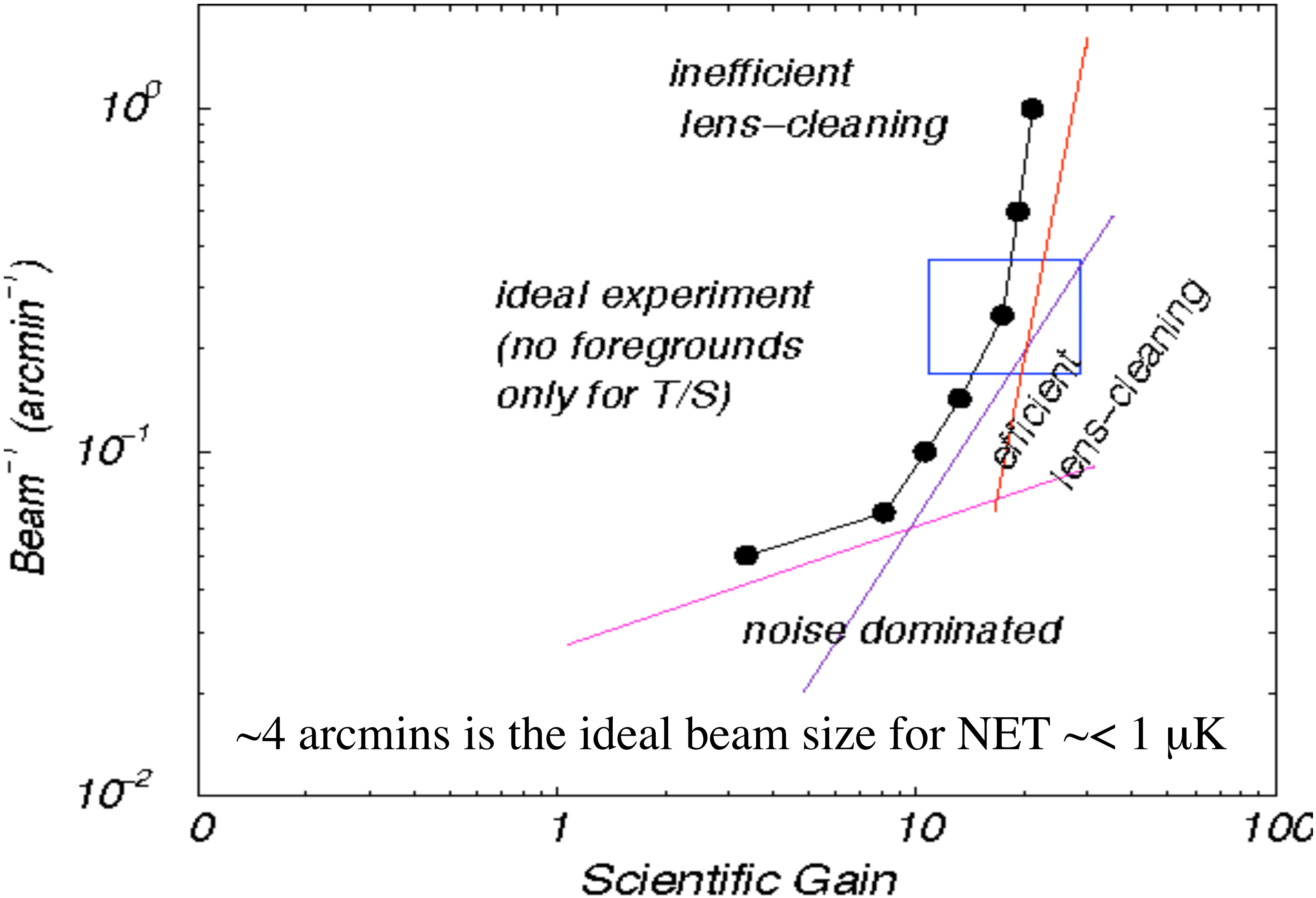
EPIC: CMB Polarization from Space



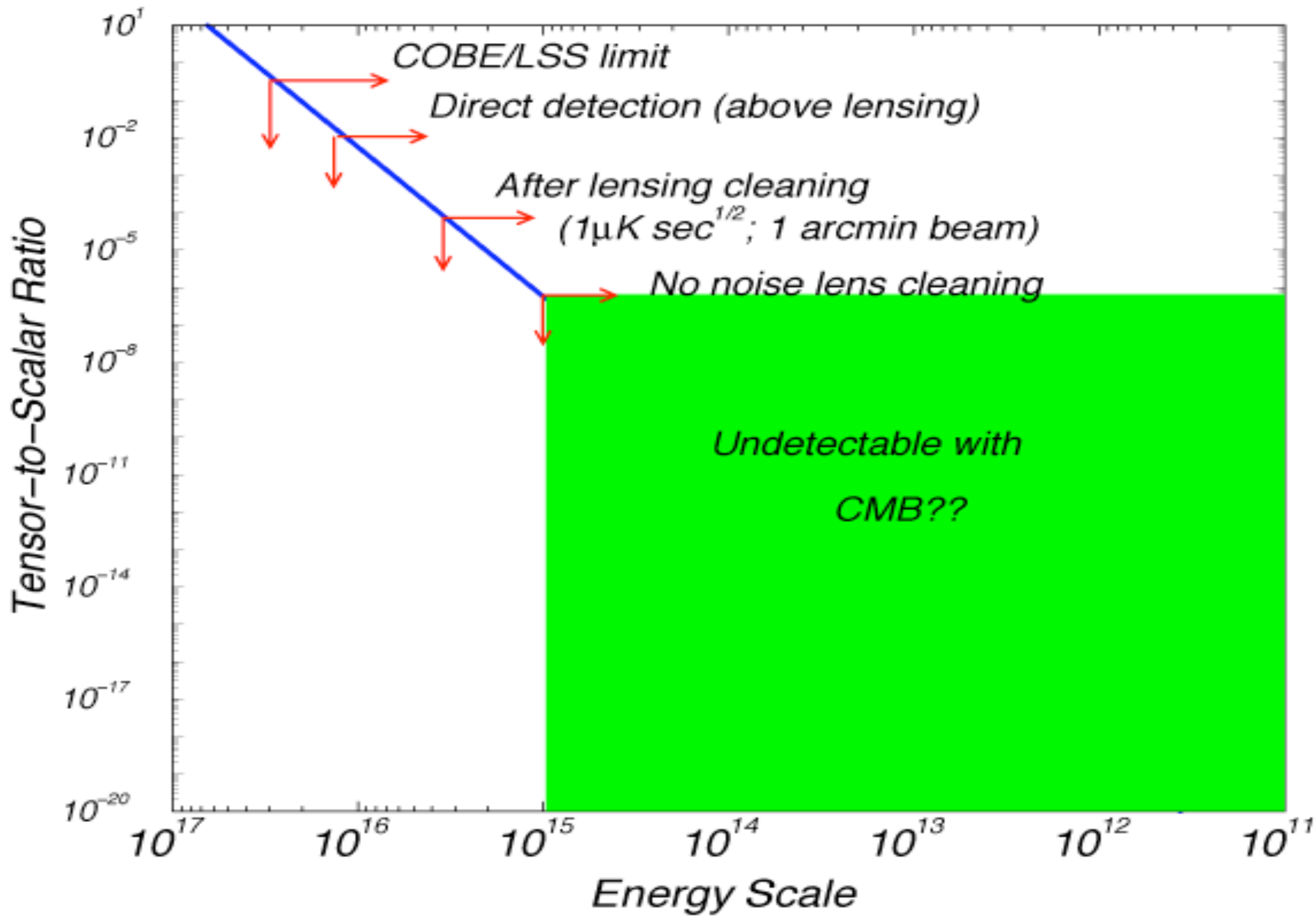


Scalars = Polarization from density fluctuations
Cosmic Shear = Gravitational lensing of CMB by matter
IGB = Signal from Inflationary Gravitational-Wave Bkgd.

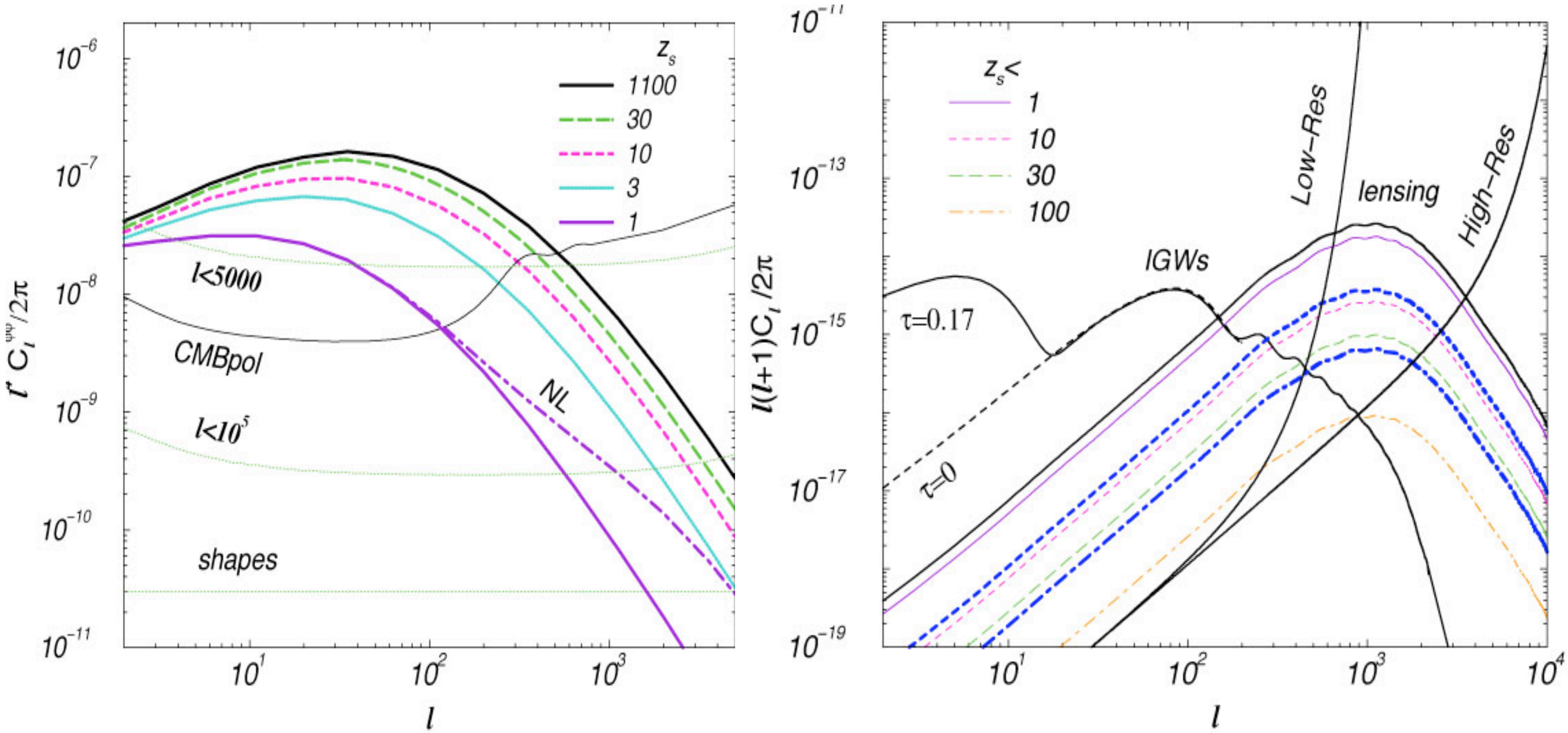
Optimal experiment for B-modes with lensing confusion alone?



How deep can we probe inflation? (with lensing as the confusion)



LSS information can help remove lensing

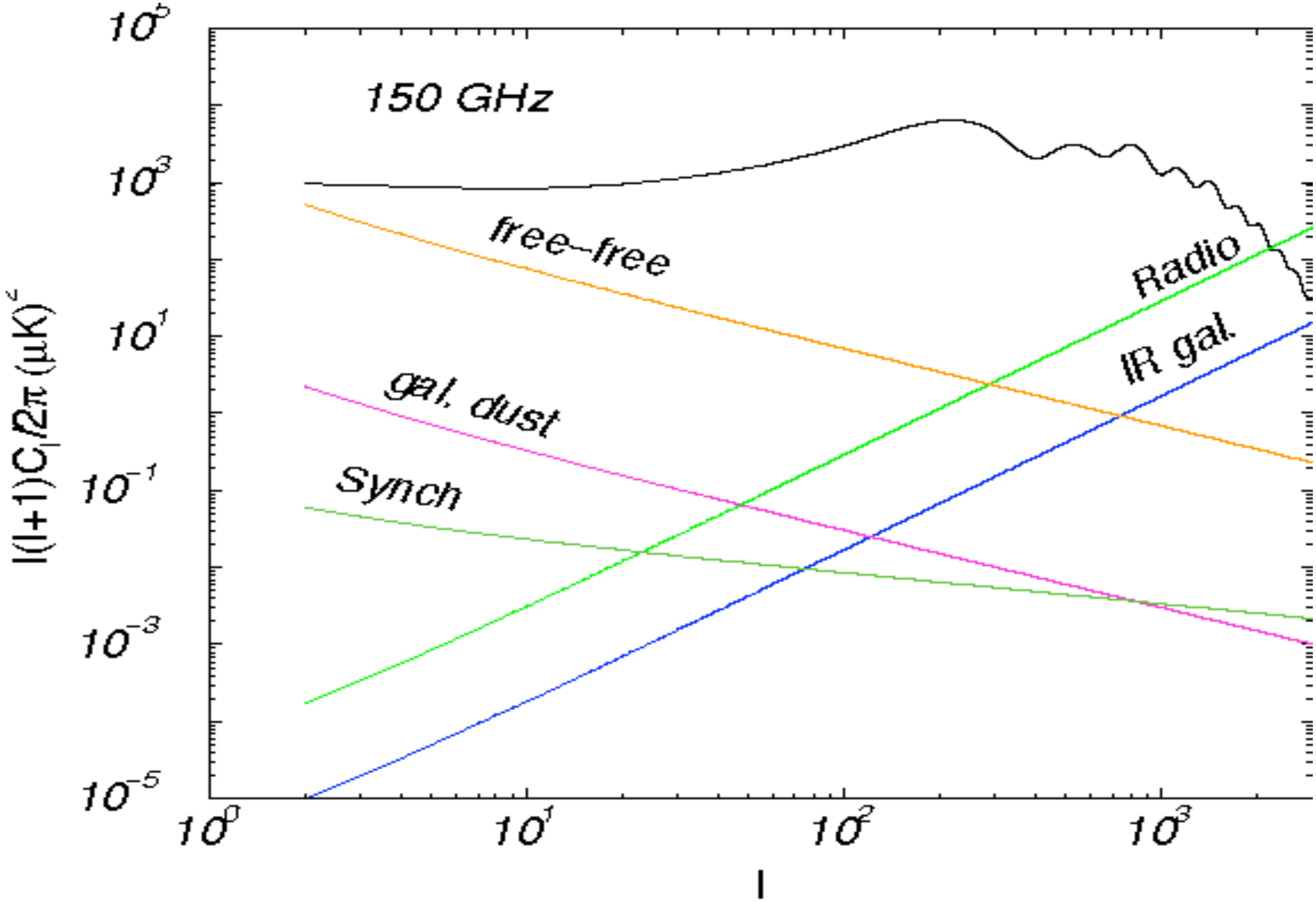


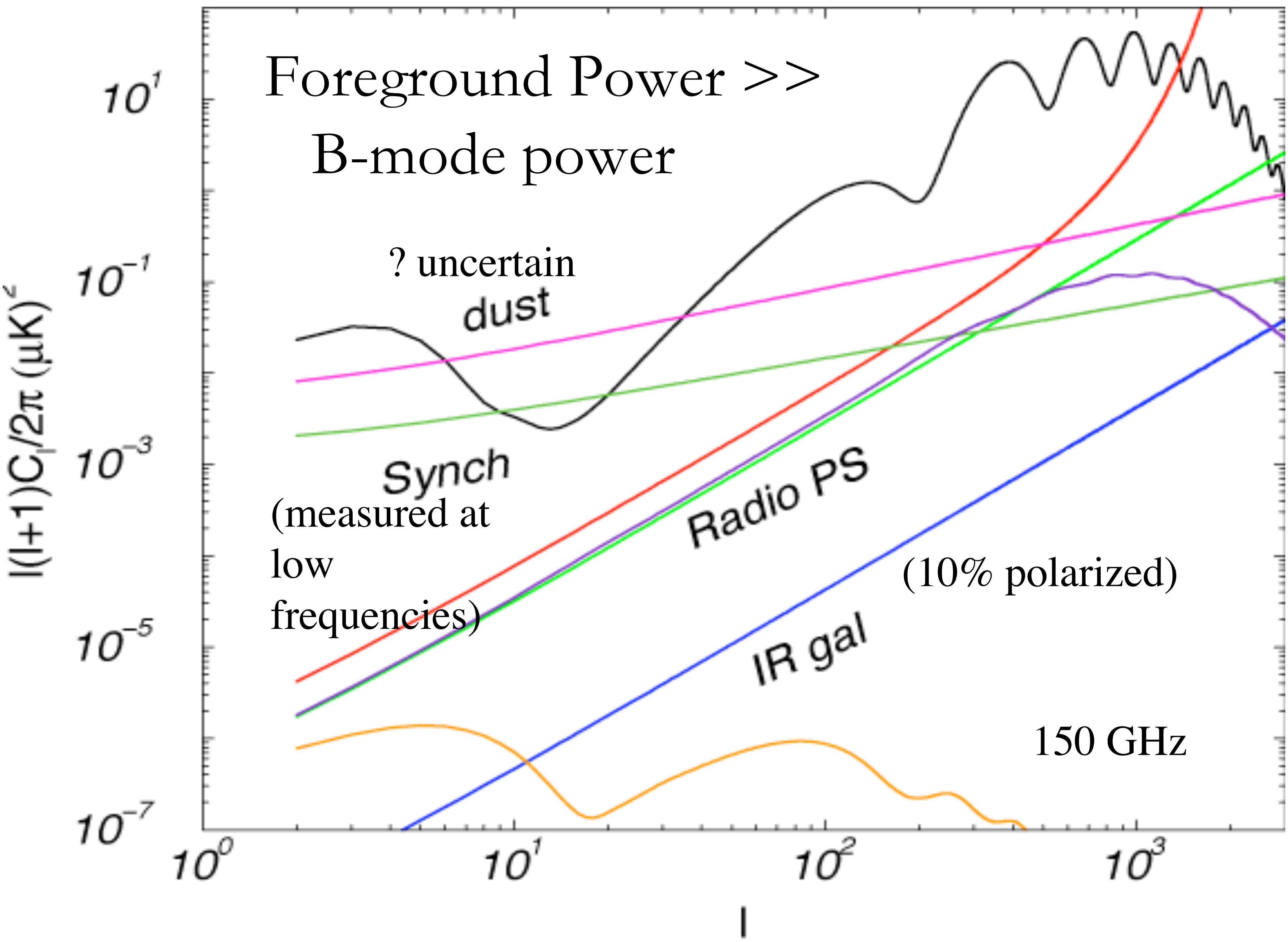
Galaxy lensing cannot be used to correct polarization, but 21 cm fluctuations at $z > 30$

Low-resolution CMB satellite + 21 cm array may be the way to dig deep

Sigurdson & Cooray, 2005, PRL, submitted

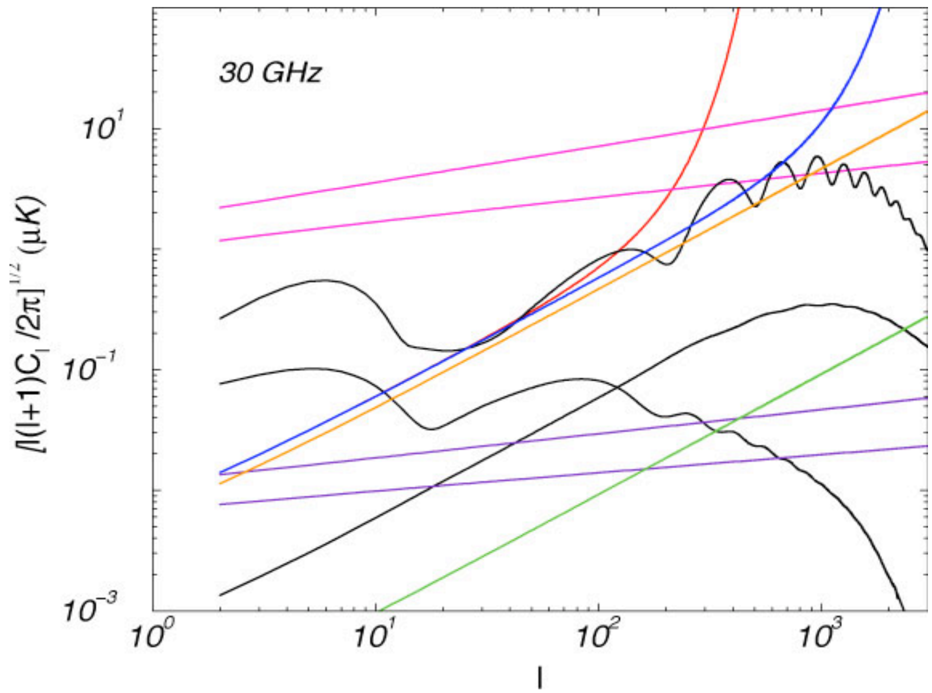
Reality for upcoming experiments:
Foregrounds dominated (not lensing)

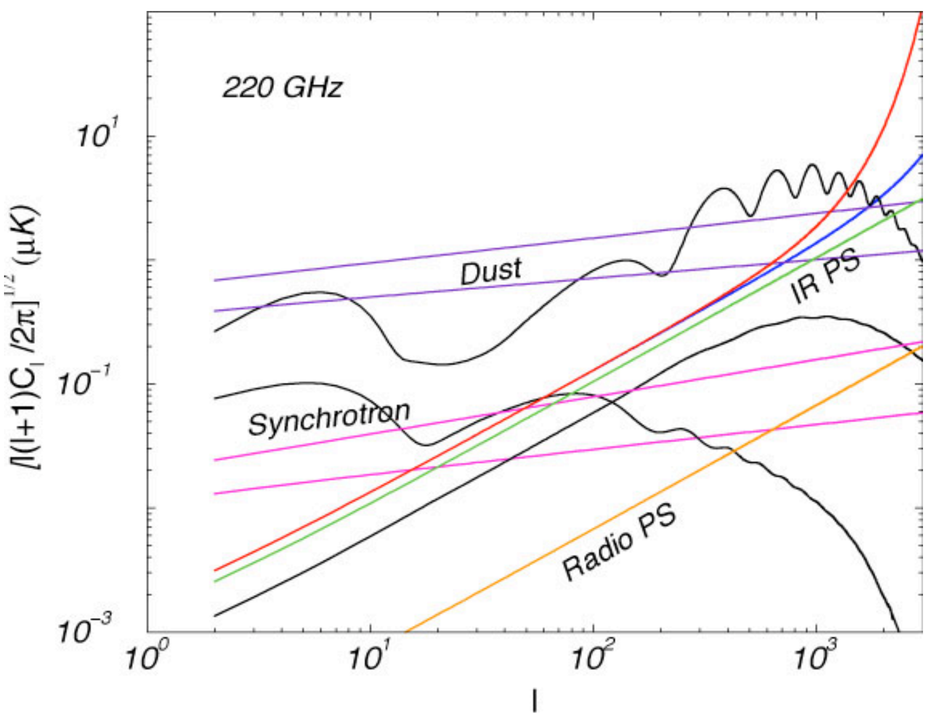


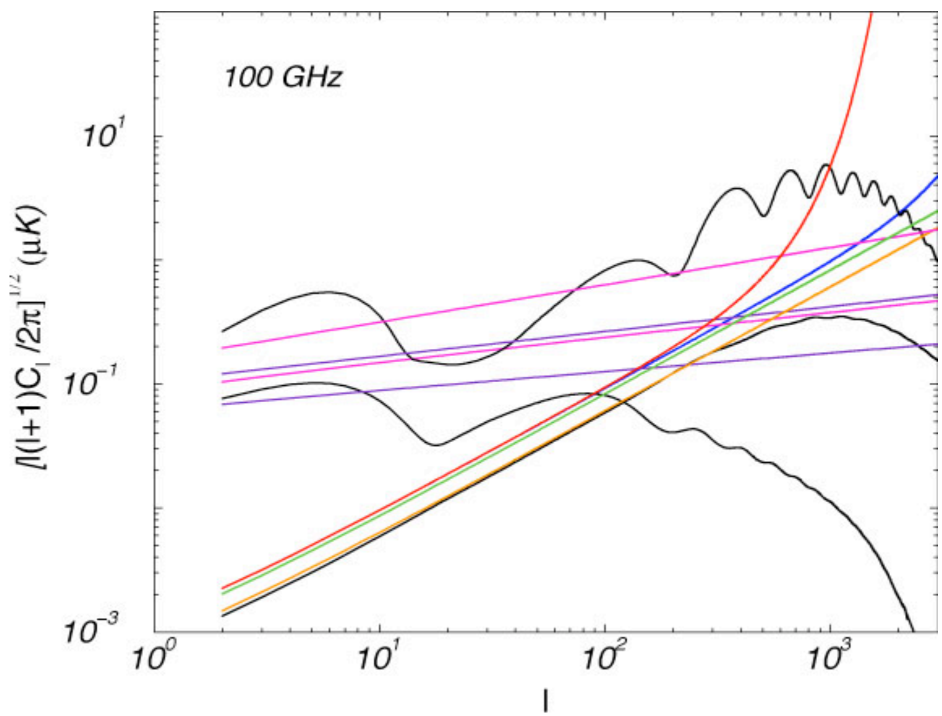


Foreground Power >>
B-mode power
? uncertain
dust
Synch
(measured at
low
frequencies)
Radio PS
(10% polarized)
IR gal
150 GHz
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{0}
10^{1}
10^{2}
10^{3}
$l(l+1)C_l/2\pi\ (\mu K)^2$
l

Multi-frequency allows some cleaning, but information on frequency and spatial variations are highly limited

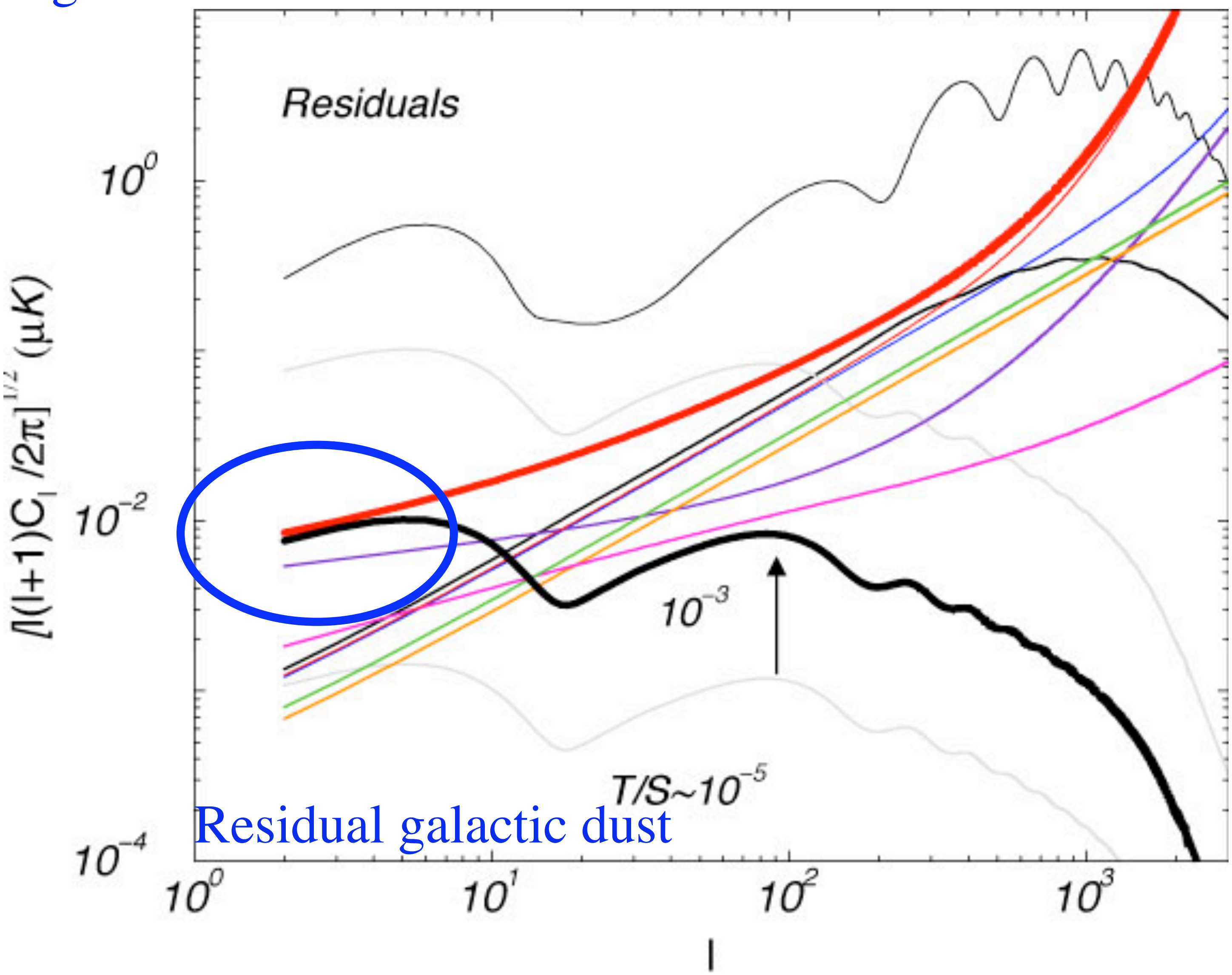






Reality:
Foreground-limited!!!!

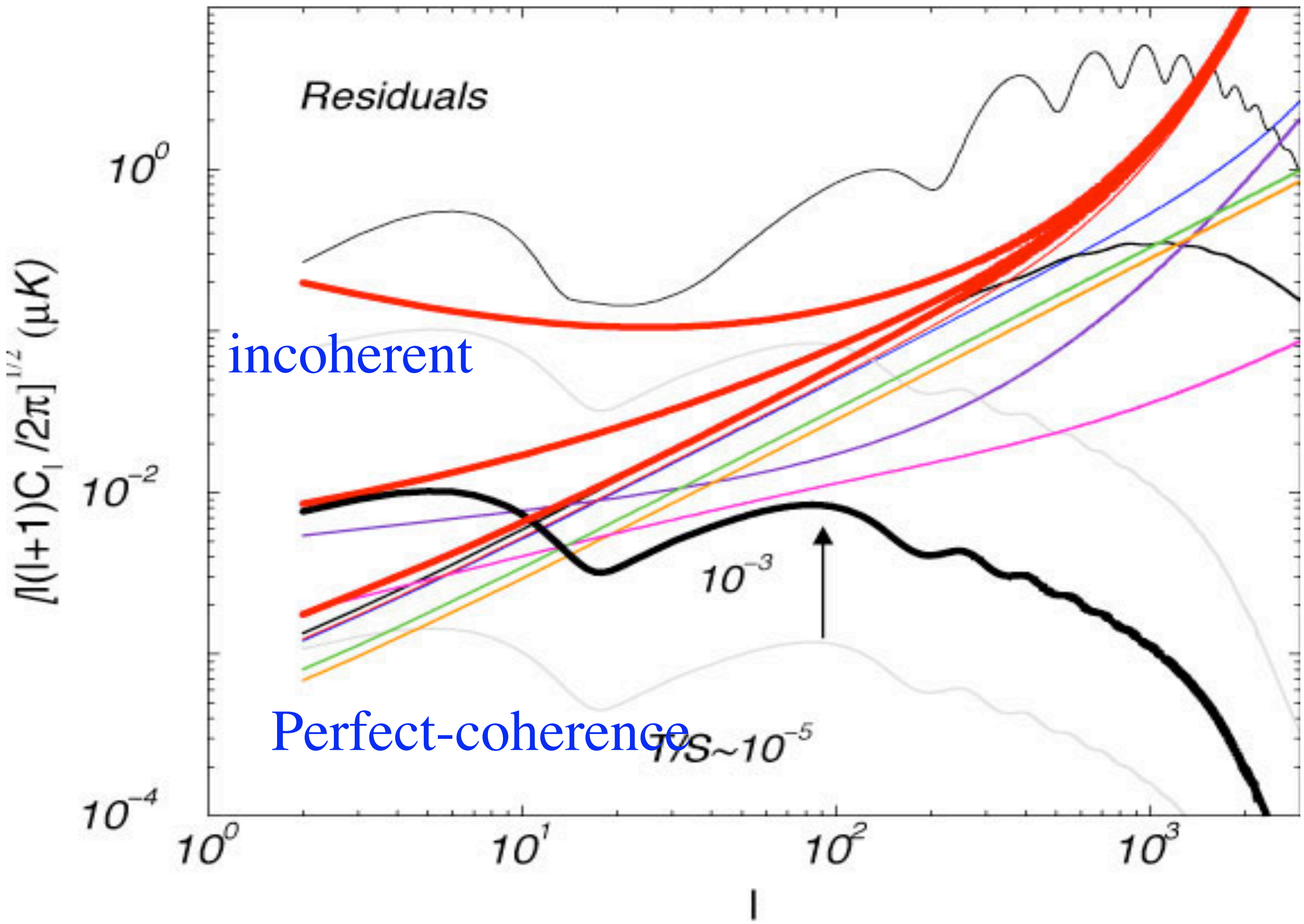
(After cleaning)



Reality:

Foreground-limited!!!!

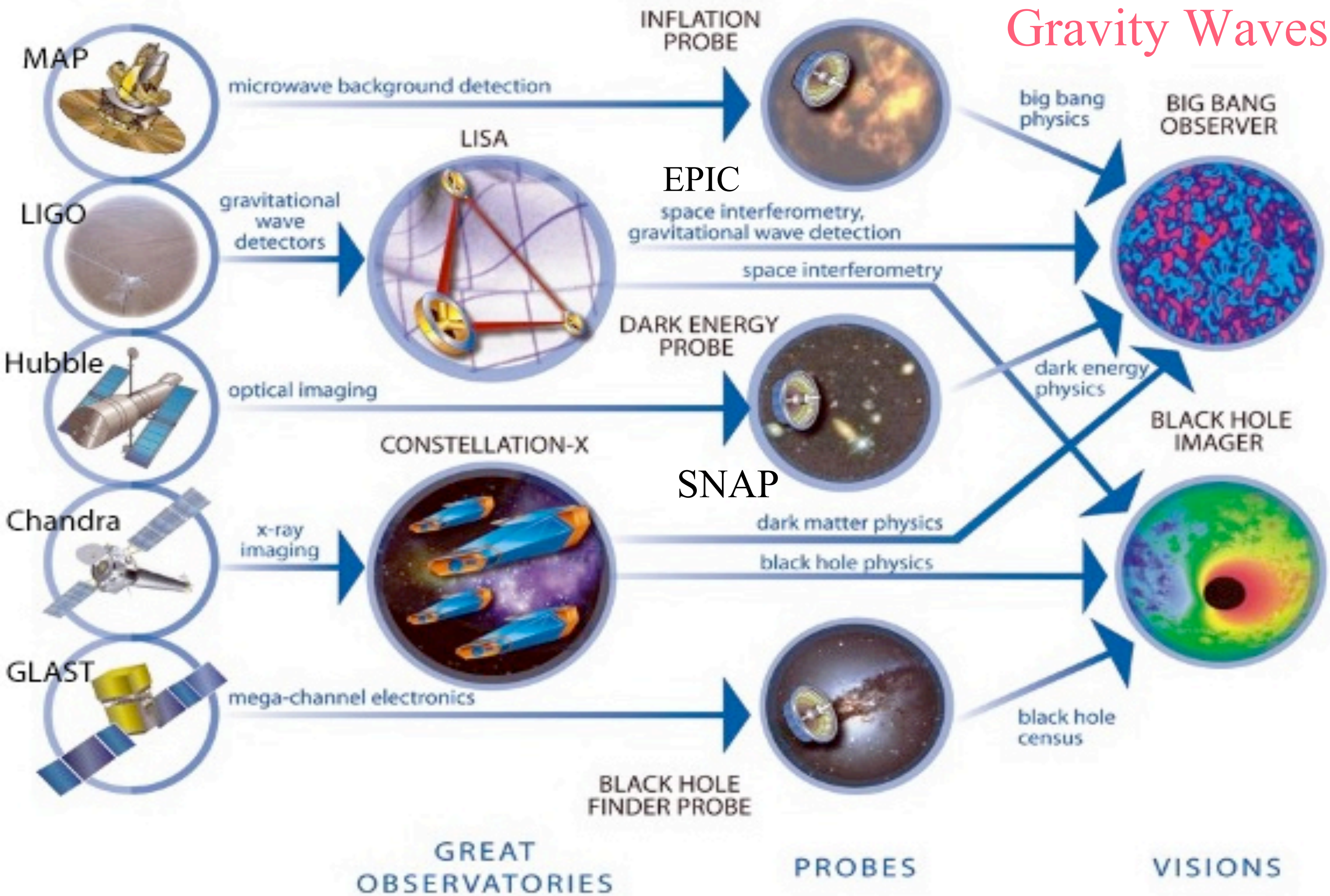
Coherence matters



Death by dust particles: can reach about 0.001 in T/S realistically!!!

(Cooray 05; also, Tucci et al.; Verde et al., Amarie et al.)

NASA's *Beyond Einstein* Program



Current Missions

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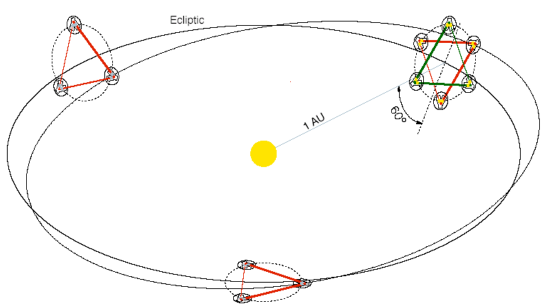
After significant developments (both hardware/theory) > 25 year time-scales

The Big Bang Observer (BBO)

- NASA Vision mission (~2030 launch)
- Primary goal: direct detection of GW from inflation by correlation analysis around 0.1-1Hz
- LISA's follow-on (also DECIGO in Japan)

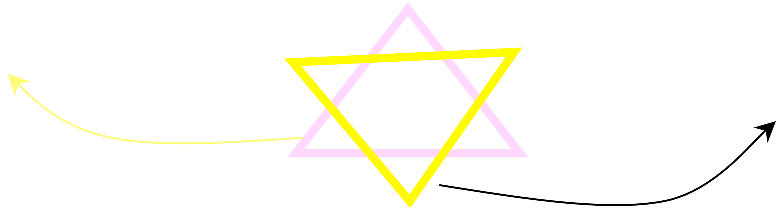


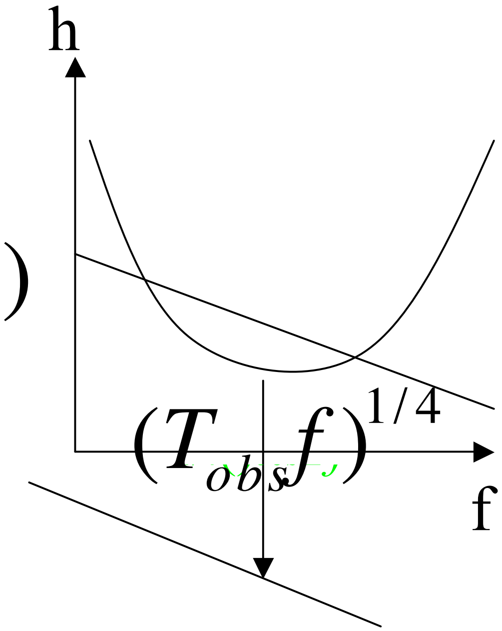
Example : a plan with 4 units

BBO: Digging deep with multiple detector correlations

$$s_1(t) = h(t) + n_1(t)$$

$$s_2(t) = h(t) + n_2(t)$$

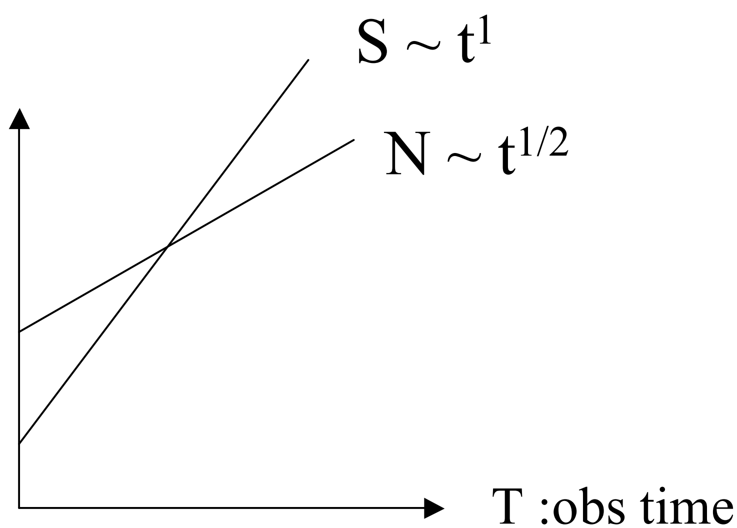




$$S = \int_0^T dt \int_0^T dt' s_1(t) s_2(t) Q(t - t')$$

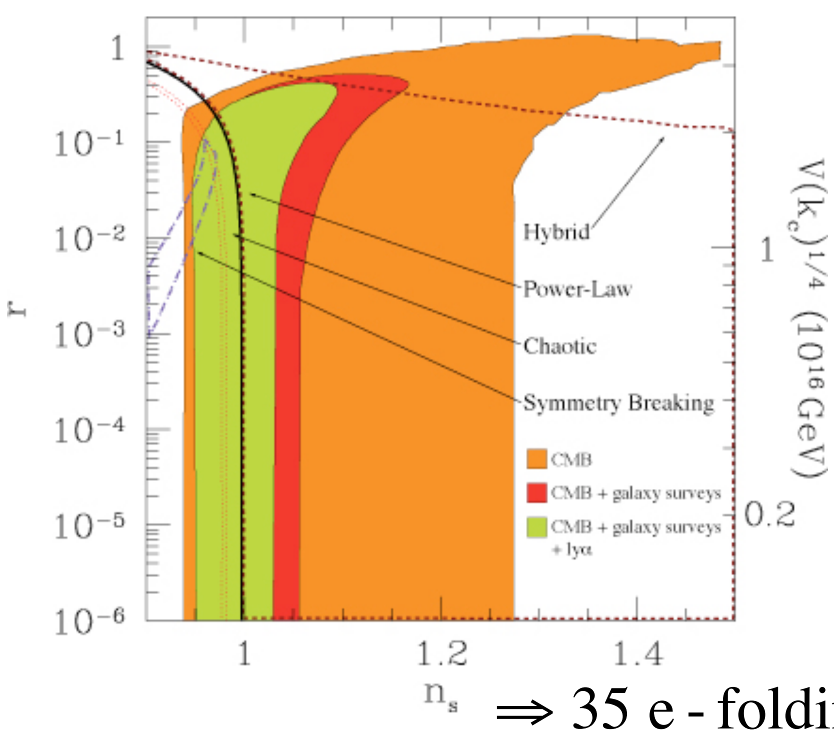
$$\Rightarrow (h \bullet h) + (n_1 \bullet n_2)$$

$$signal \propto T \qquad noise \propto T^{1/2}$$



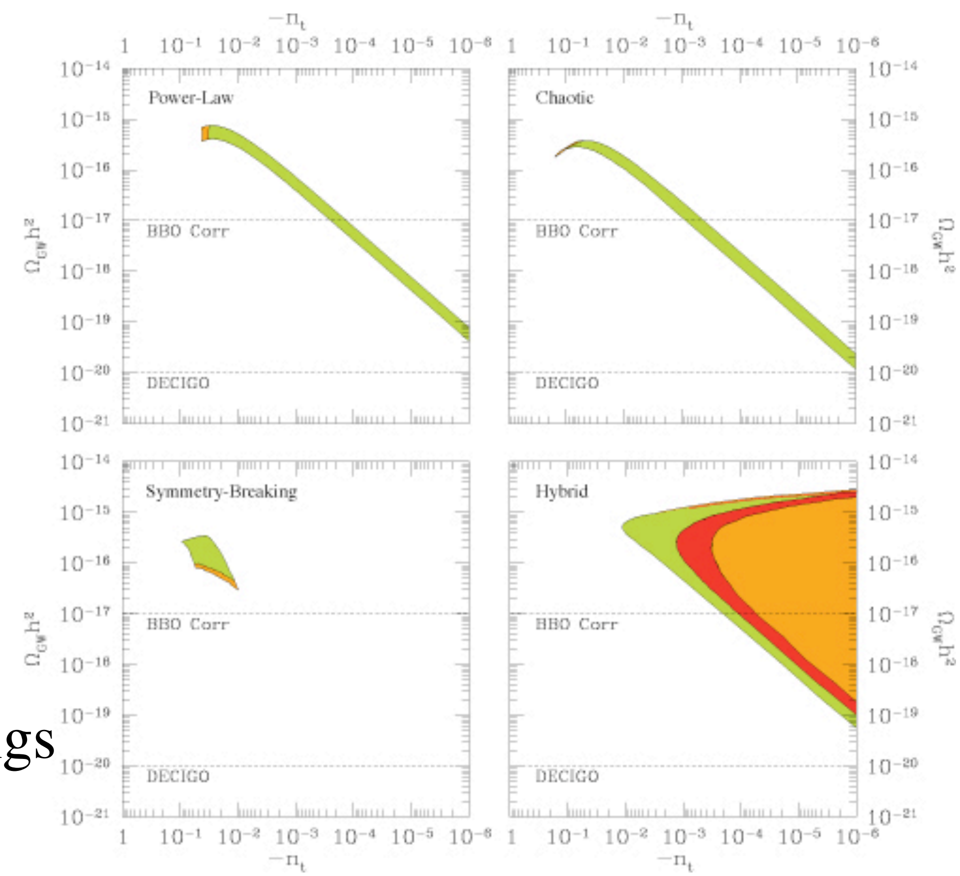
Reducing correlated noise is crucial for correlation analysis

Current constraints (at CMB scales)



$\Rightarrow$ 35 e - foldings

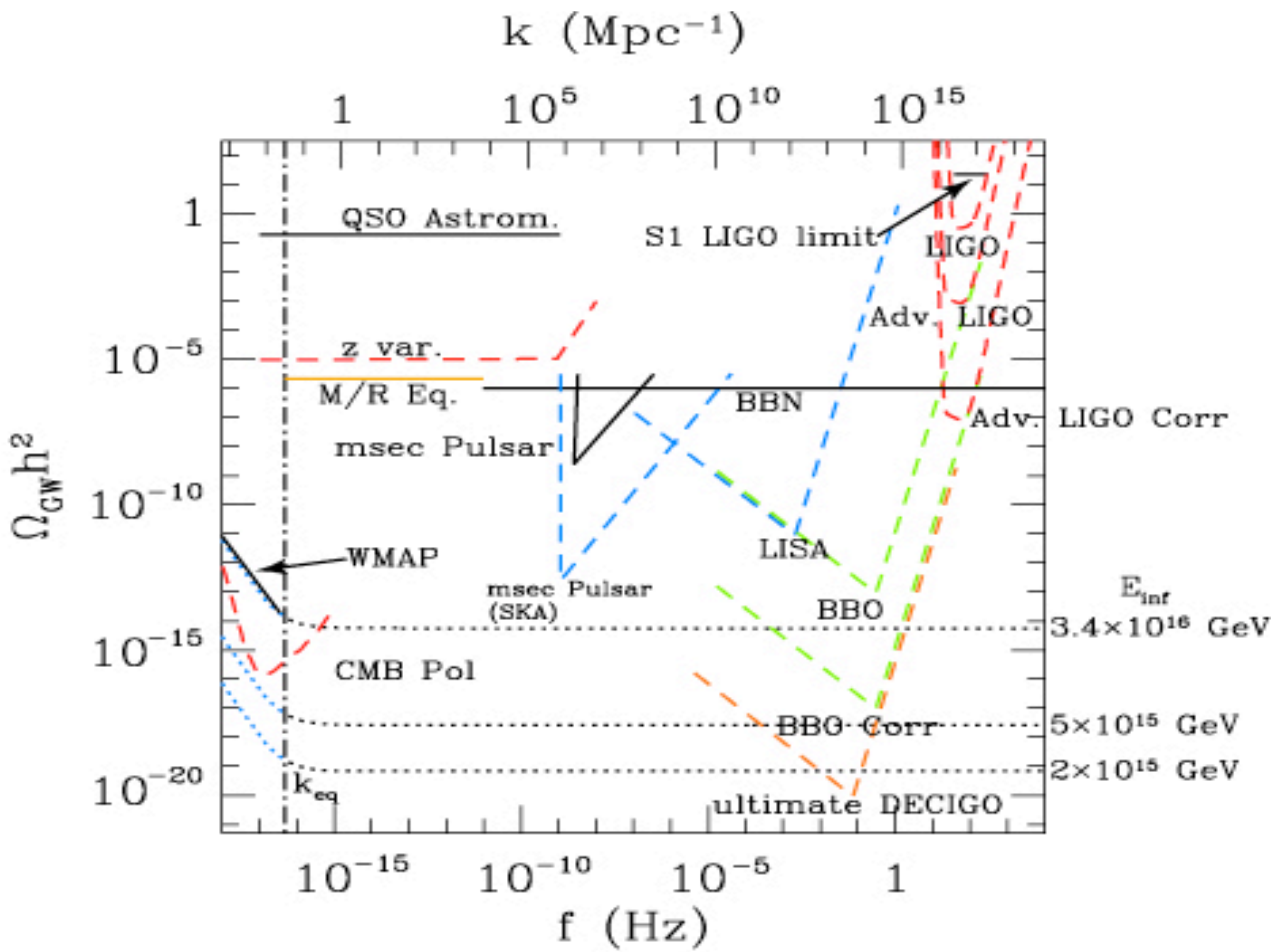
Expectation at BBO scales



(map n_s-r plane to model parameters of the potential.)

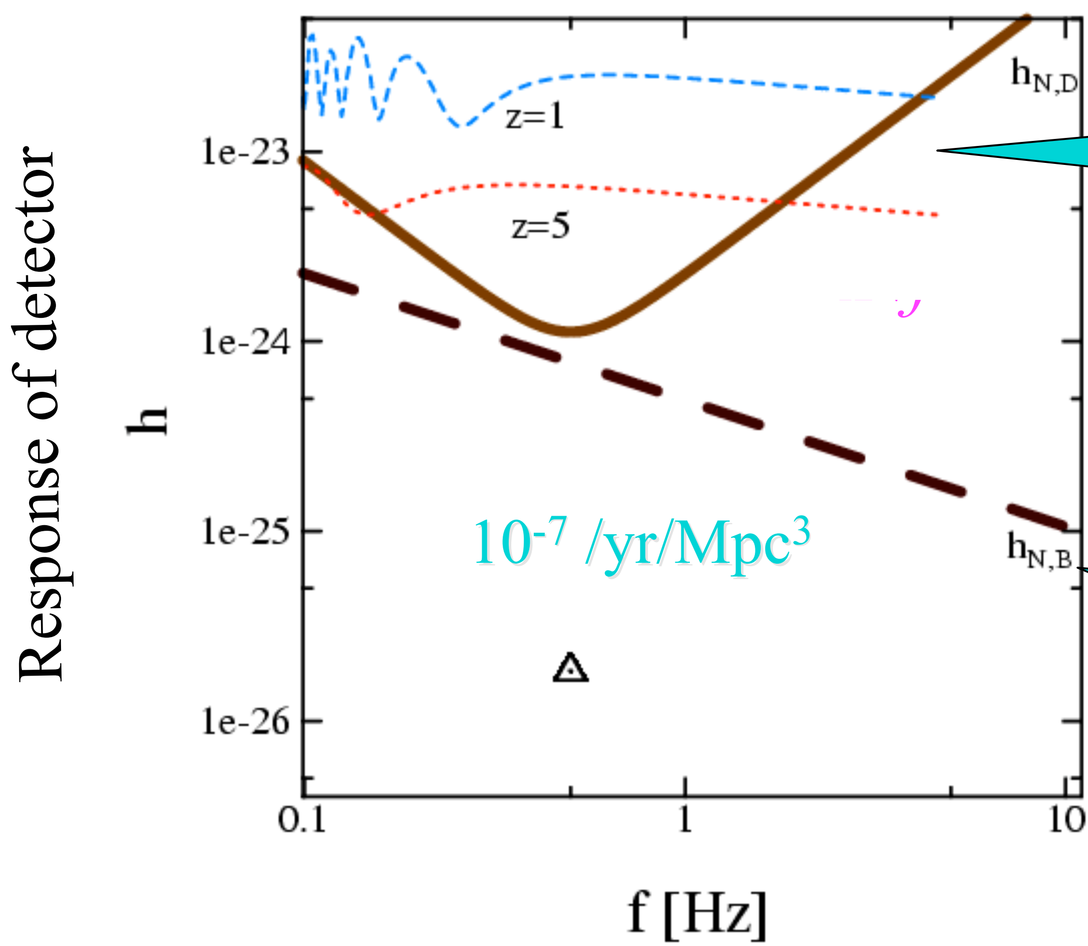
Extend to BBO scales and calculate tensor amplitude and index

Smith, Kamionkowski & Cooray 2005, astro-ph/0506422



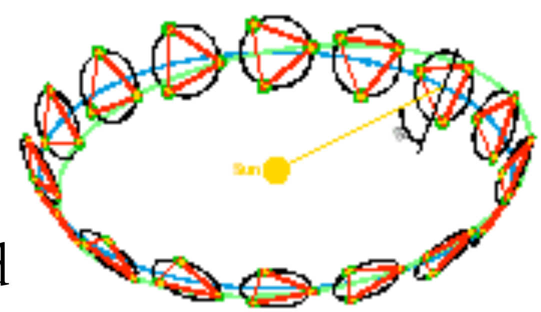
k (Mpc⁻¹)
1
10^5
10^10
10^15
QSO Astrom.
S1 LIGO limit
LIGO
Adv. LIGO
z var.
M/R Eq.
BBN
Adv. LIGO Corr
msec Pulsar
LISA
WMAP
msec Pulsar
(SKA)
BBO
E_inf
3.4×10^16 GeV
CMB Pol
BBO Corr
5×10^15 GeV
2×10^15 GeV
k_eq
ultimate DECIGO
1
10^-5
10^-10
10^-15
10^-20
Ω_GW h^2
10^-15
10^-10
10^-5
1
f (Hz)

Reality for BBO: Again foregrounds



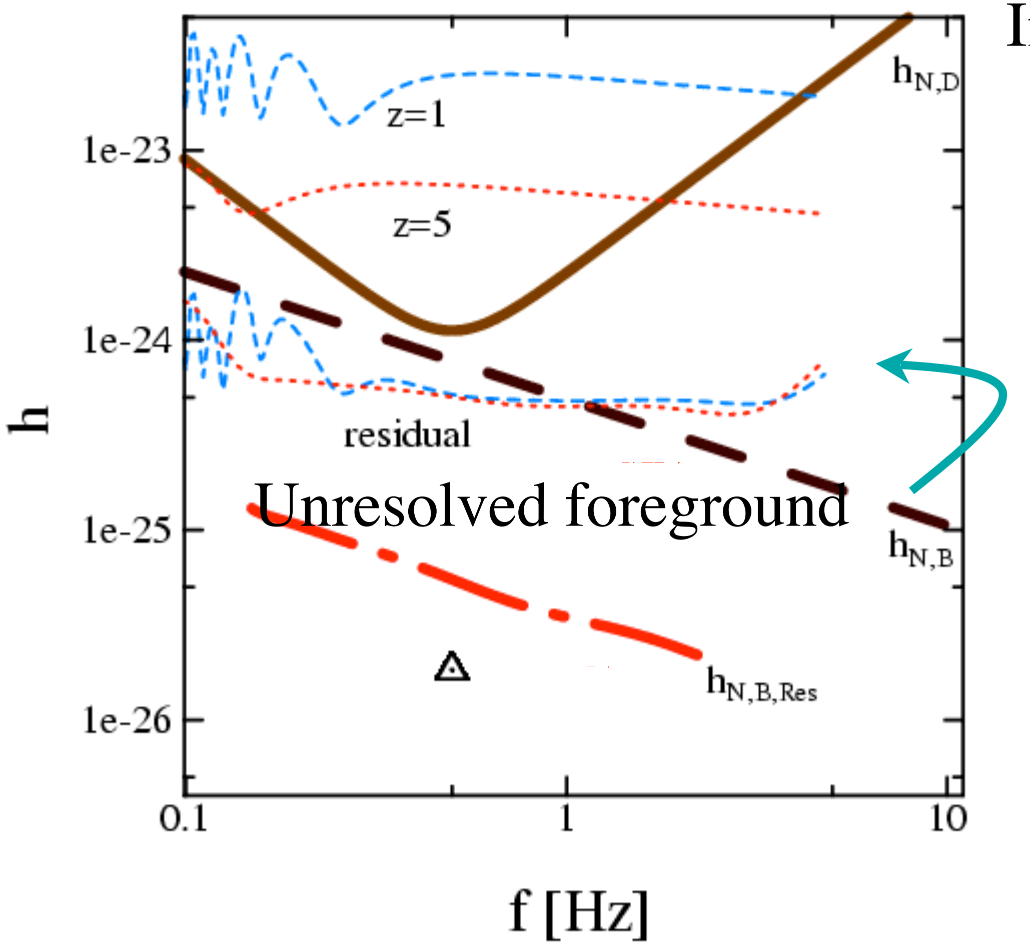
Chirp signals from binaries
transient

Total binary foreground
Stationary



Expectation: NS-NS binaries, move across the band in one month as they merge

Residual noise levels after cleaning



Individual resolved NS+NS binaries

Binary foreground is common to two detectors and makes correlated fitting residual

- Foreground reduced to 10% of original
- Critical coalescence rate around 1Hz 10^{-5} /yr/Mpc^3

Double NS merger rate: used to be low, but after PSRJ0737,
R~(0.01-1) x 10^{-5} /yr/Mpc^3 (Kalogera et al. 04)

Inflationary Gravitational Waves

- CMB polarization provides a measure of inflationary energy scale

- The measurement is hard and can easily be confused with effects due to the local universe (mainly gravitational lensing)

- CMB data can be used for a lensing reconstruction and to reduce the confusion

- Planning/technological studies for EPIC underway. Need to understand large-scale dust polarization!!!

- BBO may also be foreground limited.

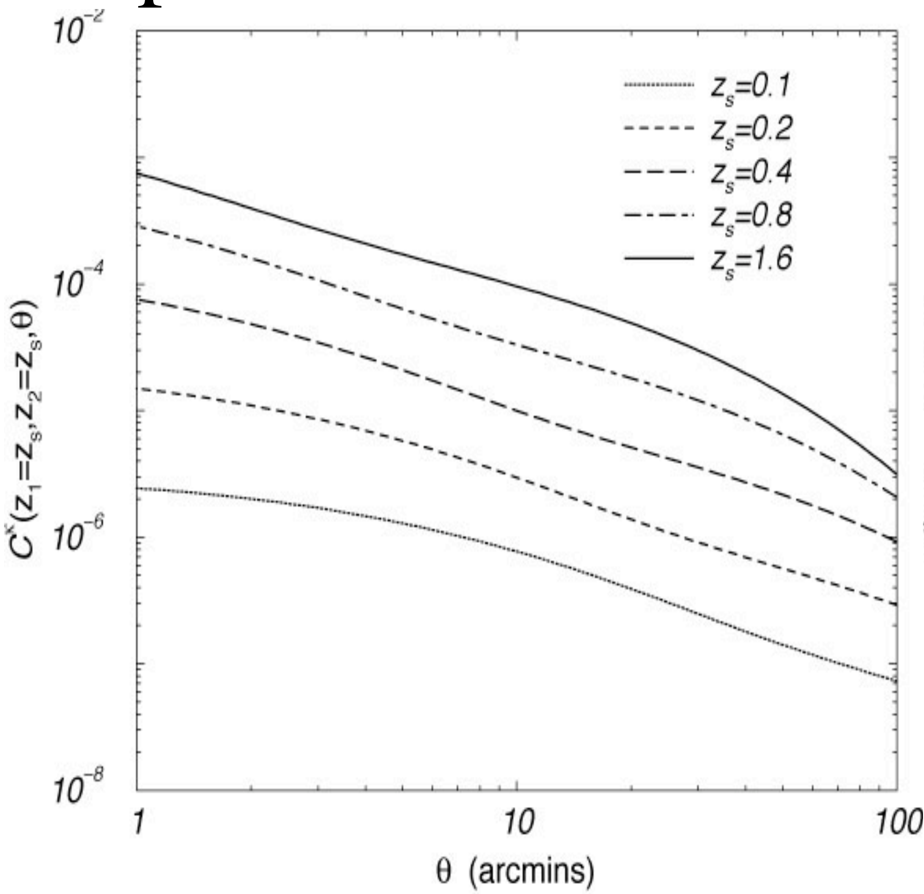
Supernovae and dark energy: Lensing matters

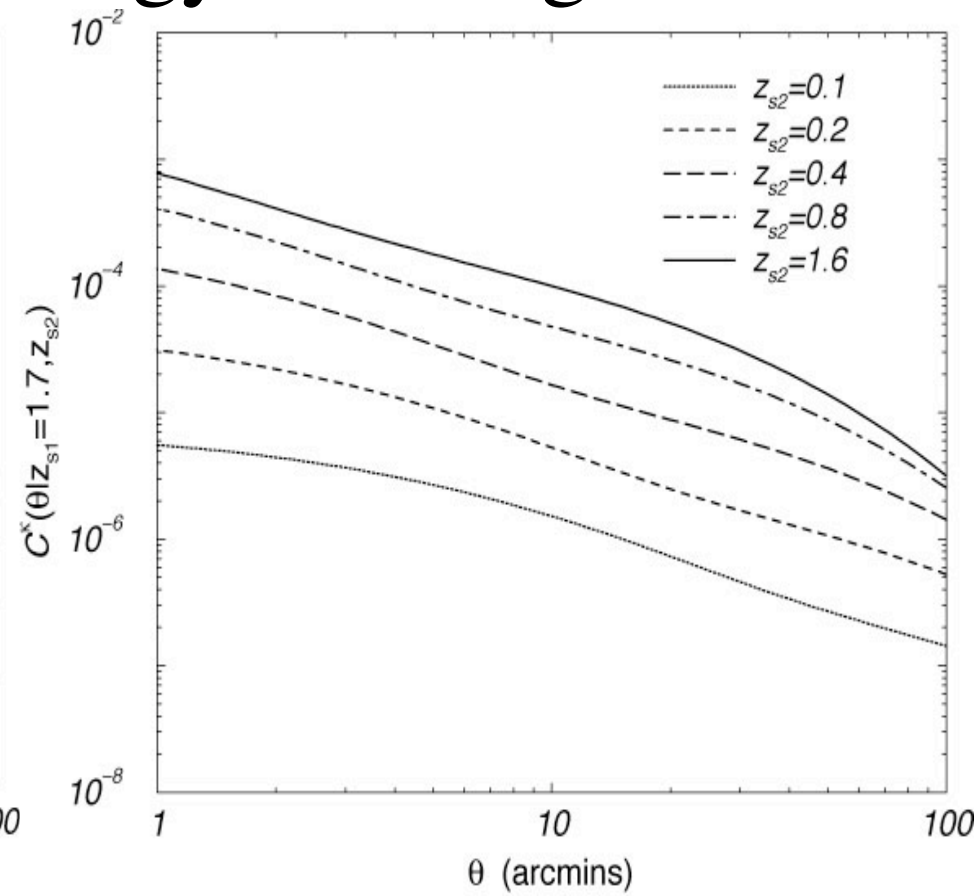
1. Lensing increases dispersion of standard candle calibration
(At $z >\sim 1$, lensing dominates over intrinsic calibration error
for a given supernova; Frieman 97)

2. It is not easy to correct for lensing effect on supernovae
(for example using galaxy shear due to small statistics of galaxies
over small surface area; Dalal et al. 03)

=> Increase in SNe sample size to reduce lensing dispersion
e.g., doubling sample size at $z > 1$ can get back at original precision of cosmology (Holz & Linder 03)

Supernovae and dark energy: Lensing matters



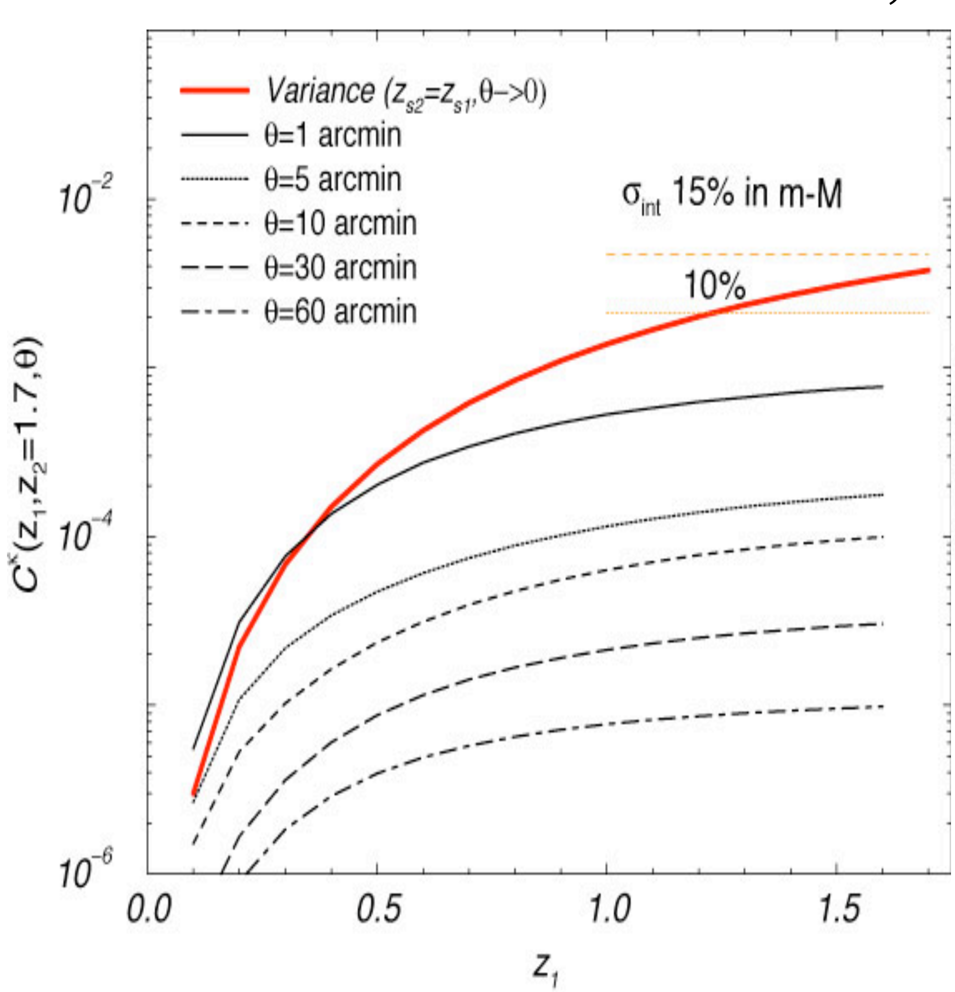


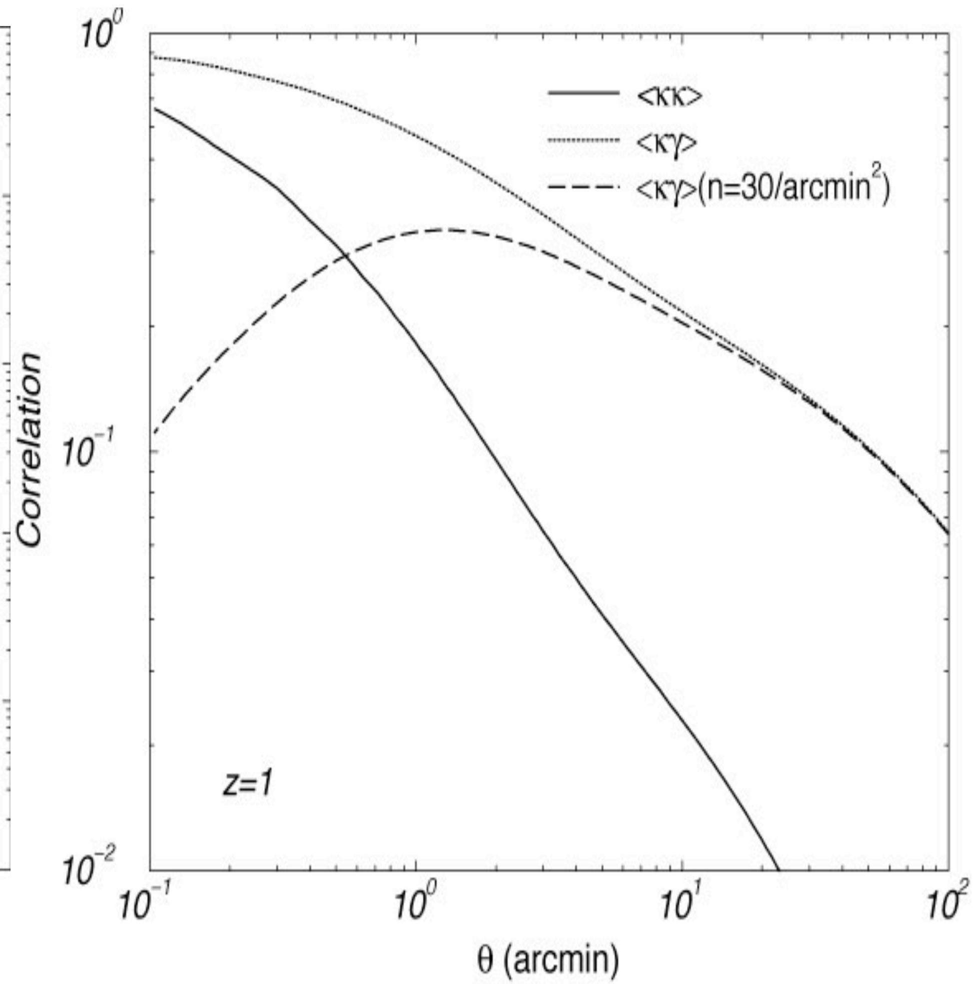
But, foreground mass fluctuations are correlared (previously ignored)

lensing effect of SNe-A (at reshift z_1) correlated with SNe-B (at z_2) and separated on the sky by angle (projected) θ

(to appear in Cooray, Huterer, Holz 05, astro-ph next week)

Not variance alone, covariance matters





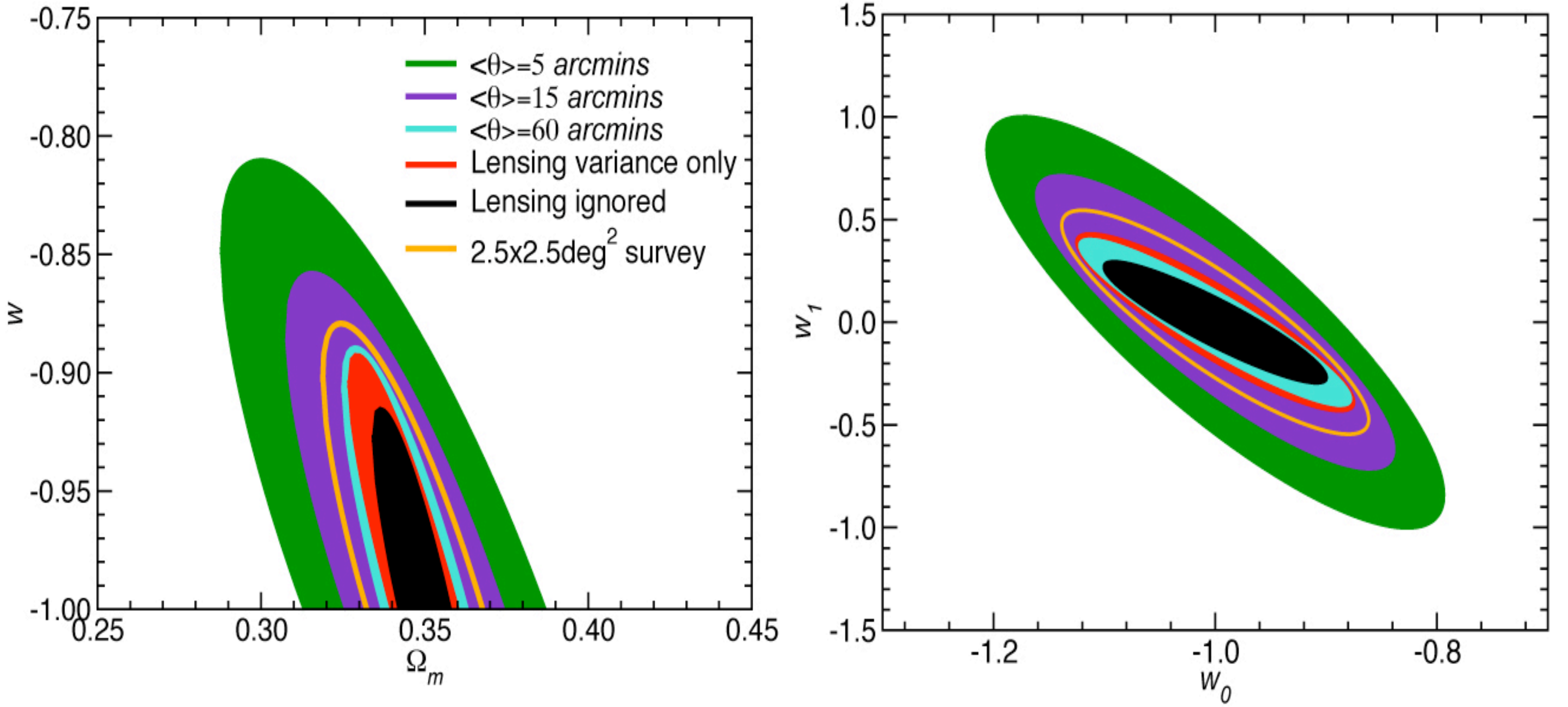
One cannot treat Sne Hubble diagram in terms of variances alone

=> *SNe distances are correlated due to lensing (covariance)*

Effect on parameter errors: **Increase error by Sqrt[1+(N-1)r^2]**

(in the limit of N supernovae, with equally correlated lensing "r")

Losing Precision: Further increase in sample?



Covariance large for small θ. Prefer wide-area sparse sampling.

For SNAP 2000 SNe over 2 fields of 2.5x2.5 sqr. degrees,

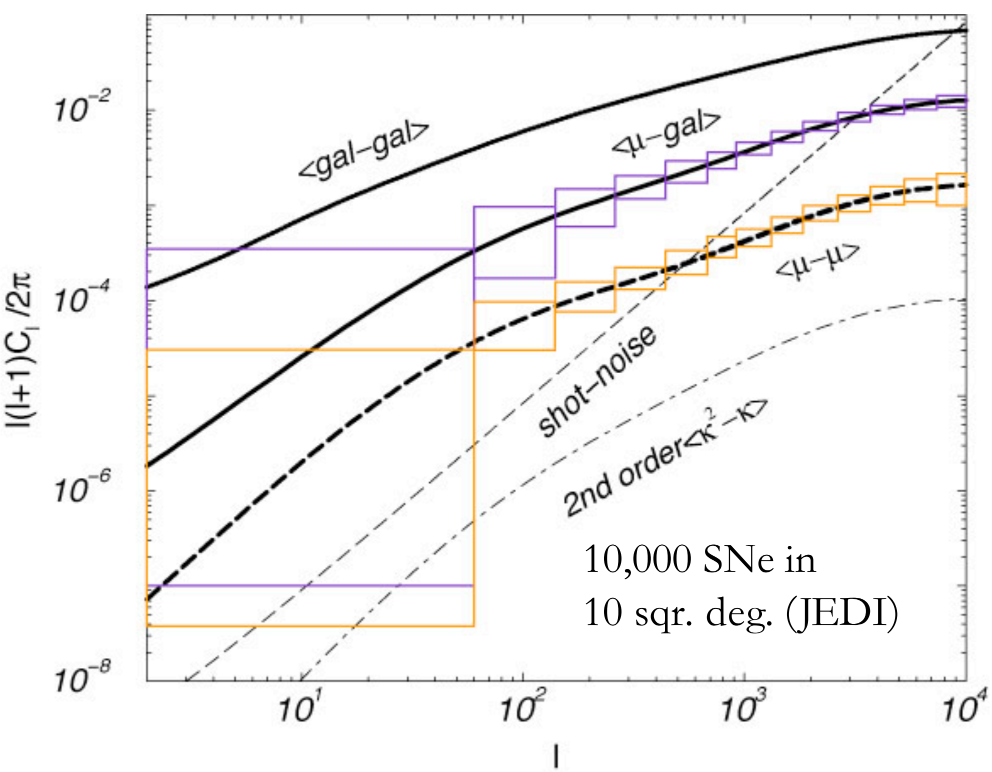
loss of precision by a factor of 1.4 to 1.7 in dark energy parameters

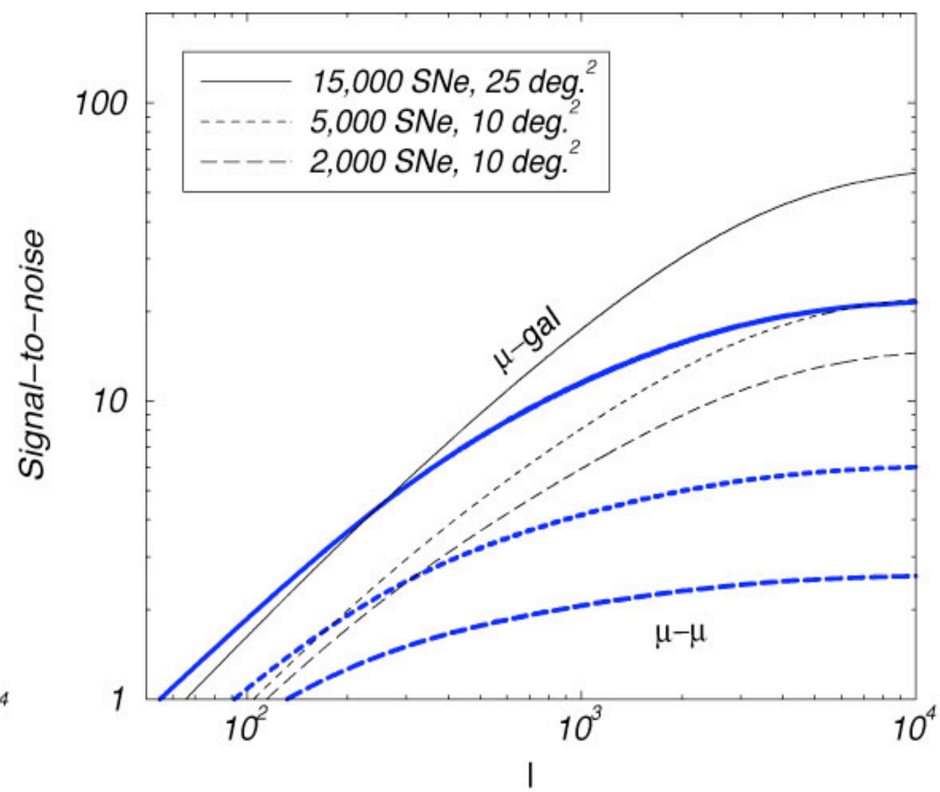
Bottom line: 2000x2000 Covariance matrix must be established!!!!

“One man’s noise is another man’s signal”

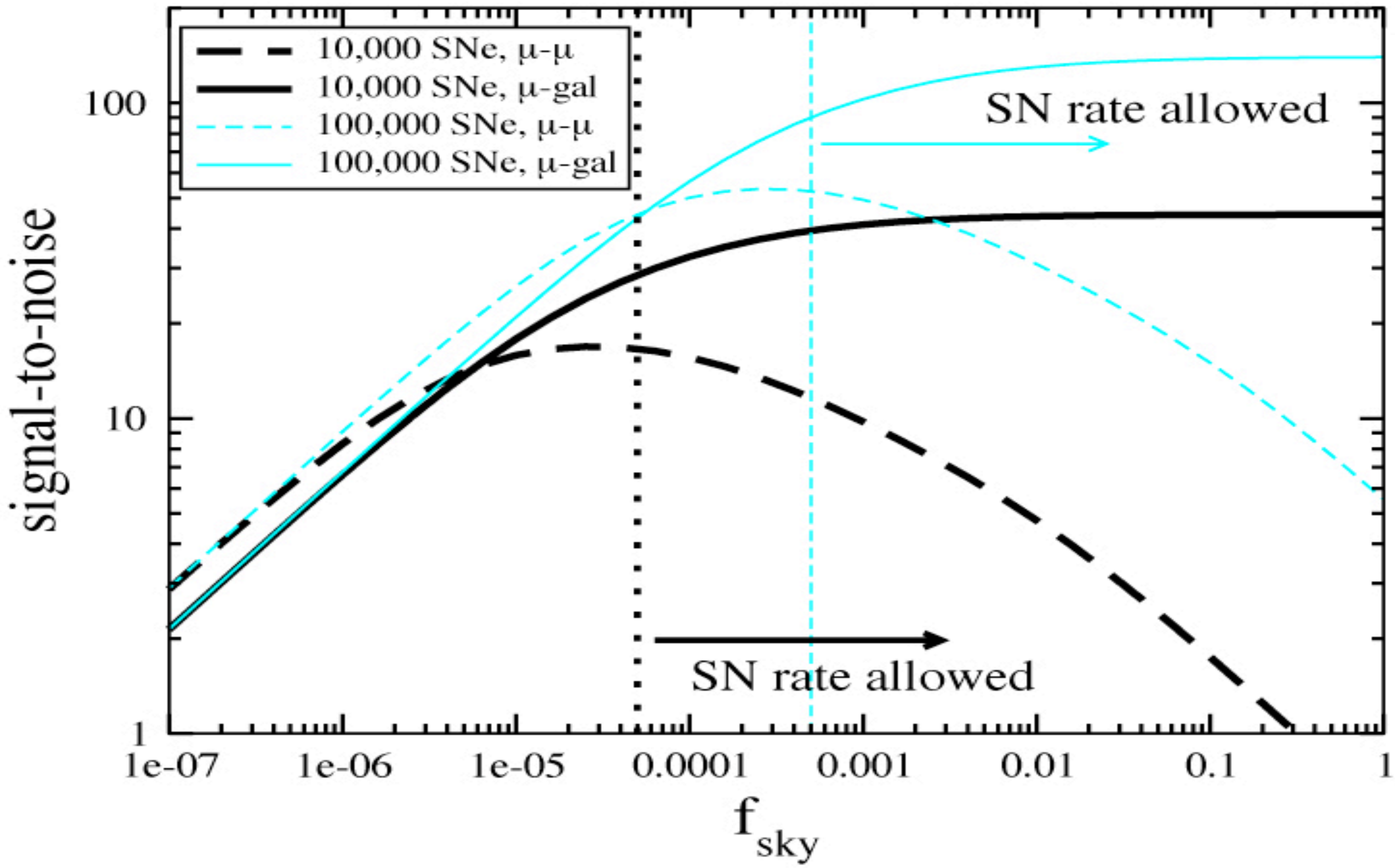
Covariance matrix captures fluctuations in lensing magnification (convergence in the weak lensing limit).

Correlations between distances in SNe can be used for a weak lensing anisotropy study (just as in galaxy shear using shapes).





"One man's noise is another man's signal"



Finite SNe rate (finite number of supernovae on the sky; < 1000/sqr. deg./year) limits the eventual signal-to-noise ratio

(to appear in Cooray, Holz, Huterer 05, also astro-ph next week)

Supernovae and Dark Energy

• Analysis of large sample of supernovae (with improved noise) may be more complicated than considered so far.

Example: gravitational lensing magnification requires a full understanding of the covariance matrix of the Hubble diagram. Establishing this (as a function of cosmology to be tested with data) will not be an easy task.

Large samples need to account for small correlations (~1000 SNe, few percent correlations)

These effects also decrease the precision of dark energy constraints.

Full talk and details at http://www.cooray.org