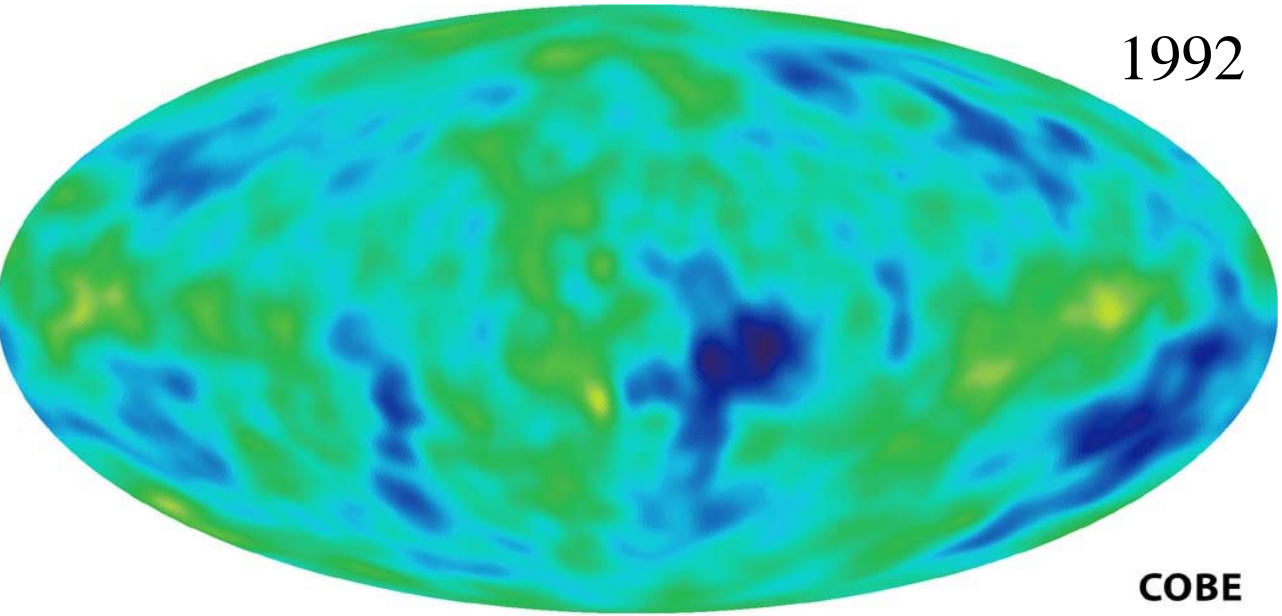
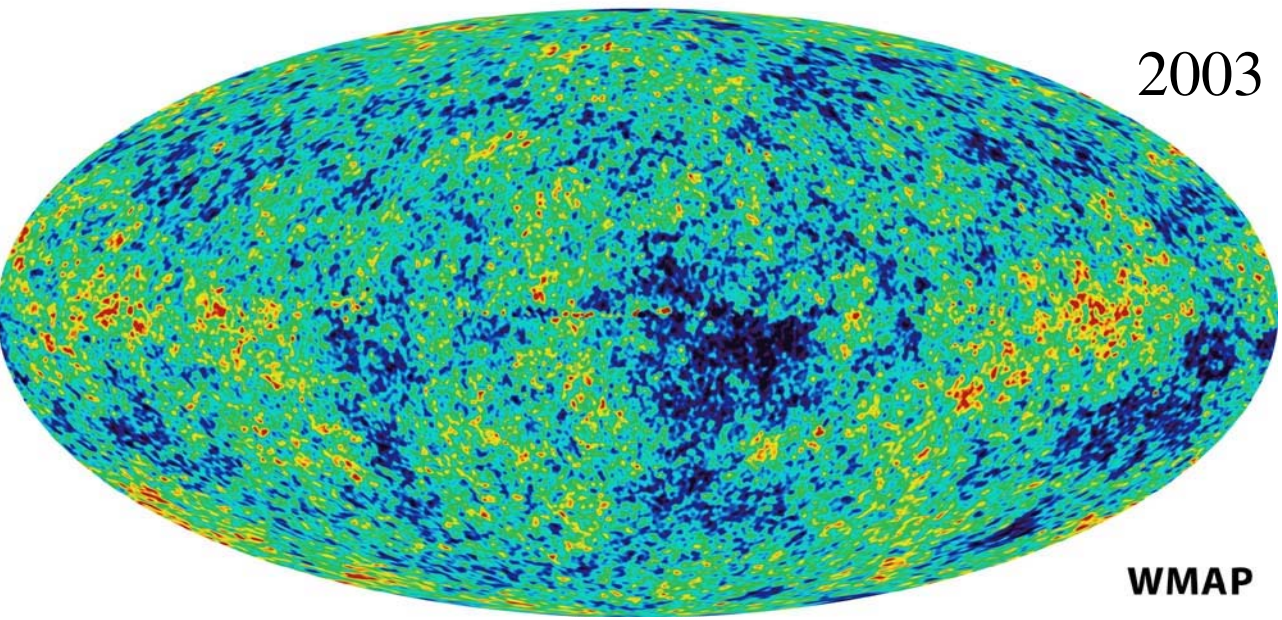
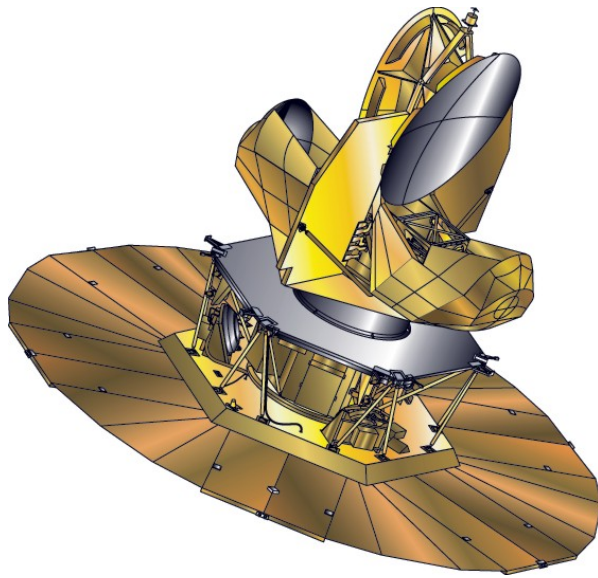
1992



COBE

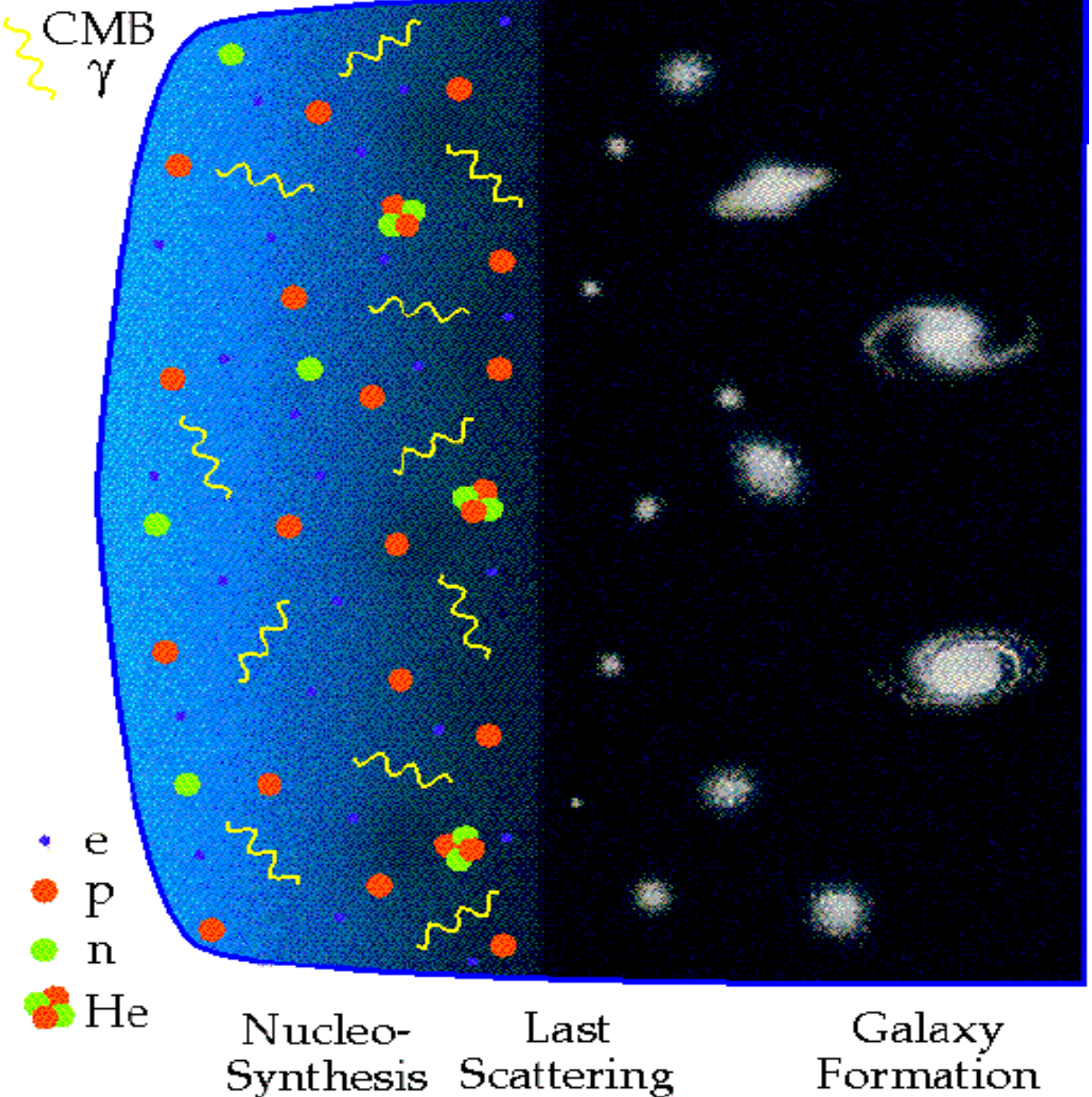
2003



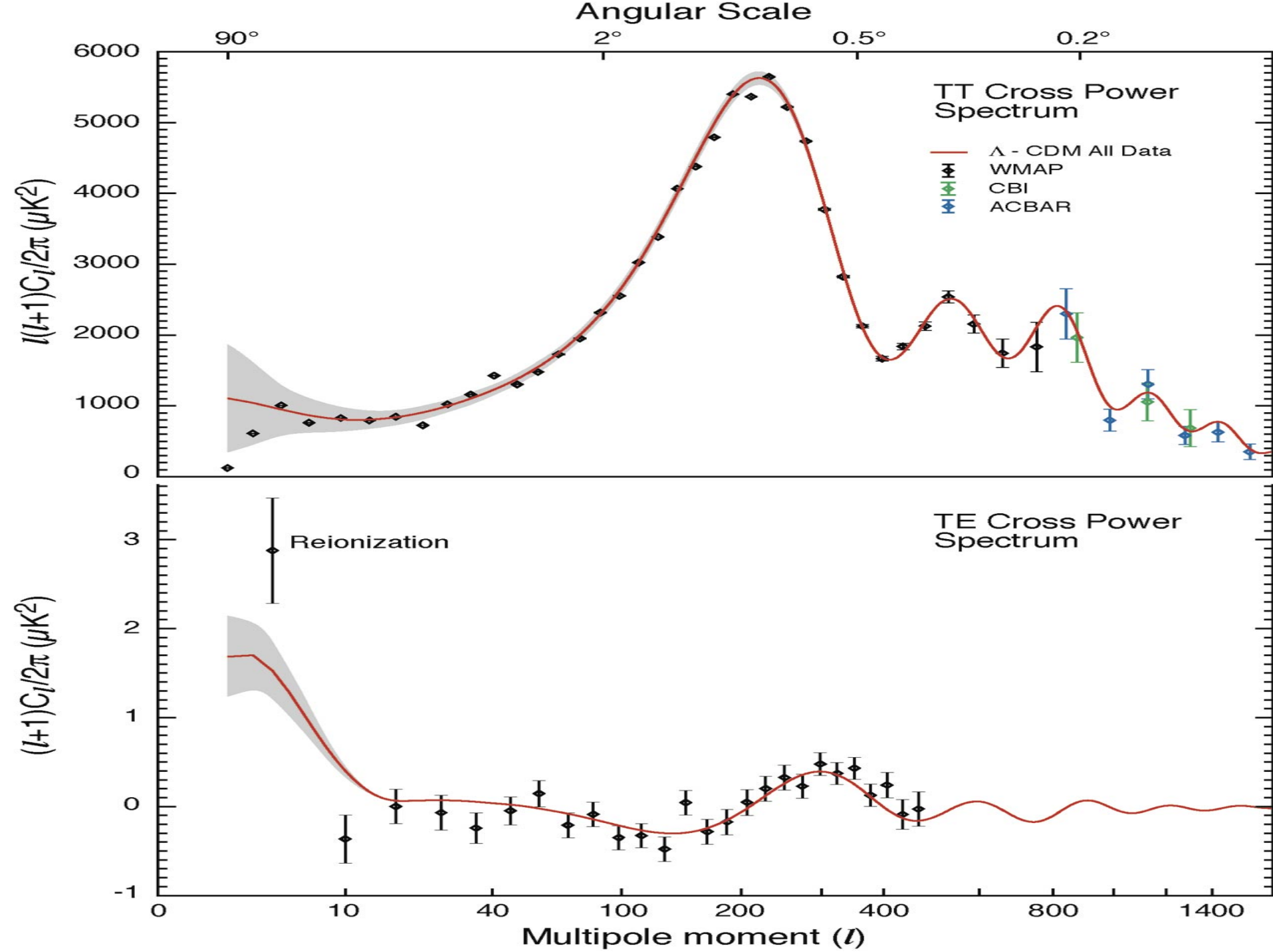


WMAP

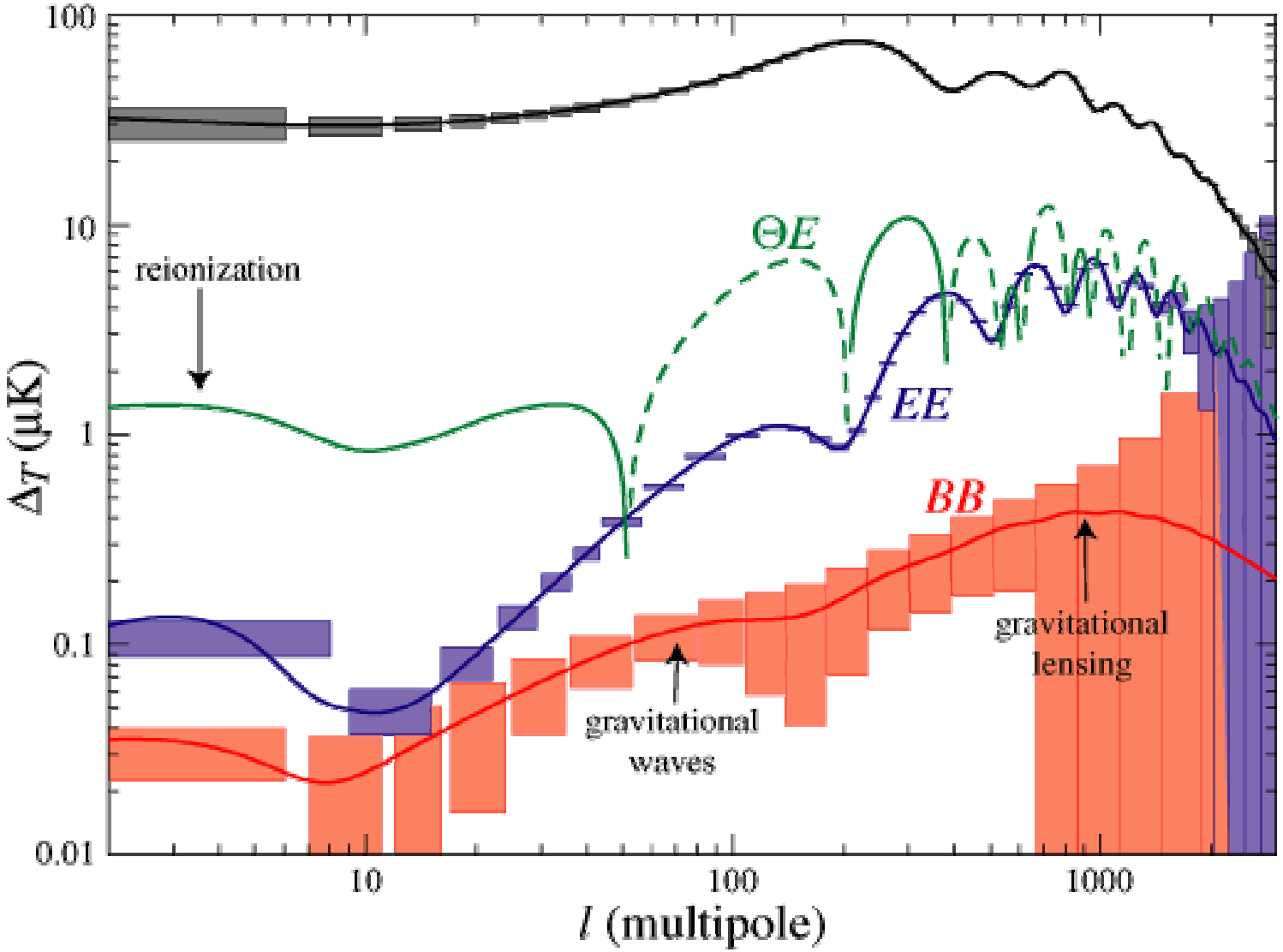
http://map.gsfc.nasa.gov


CMB
γ
e
p
n
He
Nucleo-
Synthesis
Last
Scattering
Galaxy
Formation

(Hu)


Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK^2)
6000
5000
4000
3000
2000
1000
0
TE Cross Power Spectrum
Reionization
(l+1)C_l/2π (μK^2)
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)

Around ~ 2009, with Planck (ESA mission)



Hu & Dodelson (Annual Reviews 2002)

The Quest for Inflationary Gravitational Waves

Asantha Cooray
Caltech

Daniel Chalonge 8th Paris Cosmology Colloquium

The Quest for Inflationary Gravitational Waves

Goal: Determine the energy scale of inflation and other inflationary physics

- CMB Polarization
- Space-Based Gravitational Wave Detectors

(foreground confusions, utlimate limits and where we are going experimentally)

Collaborators: Mark Kamionkowski, Mike Kesden, Naoki Seto, Tristan Smith (Caltech)

What do we already know?

Presence of harmonic oscillations: coherence of initial fluctuations

Strong evidence for inflation!!!

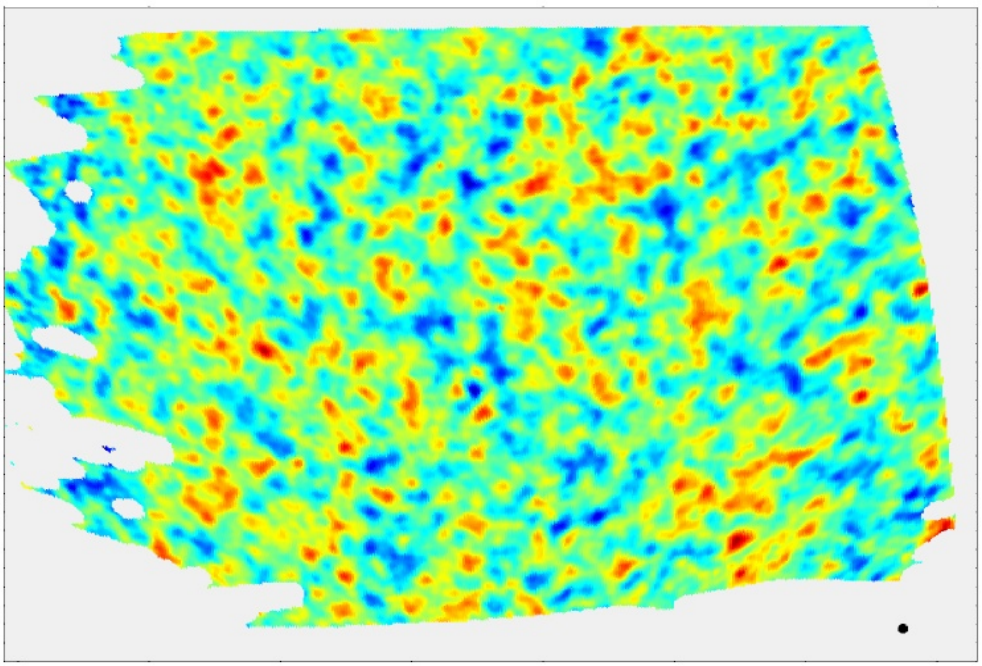
What do we already know?

Presence of harmonic oscillations: coherence of initial fluctuations

Strong evidence for inflation!!!

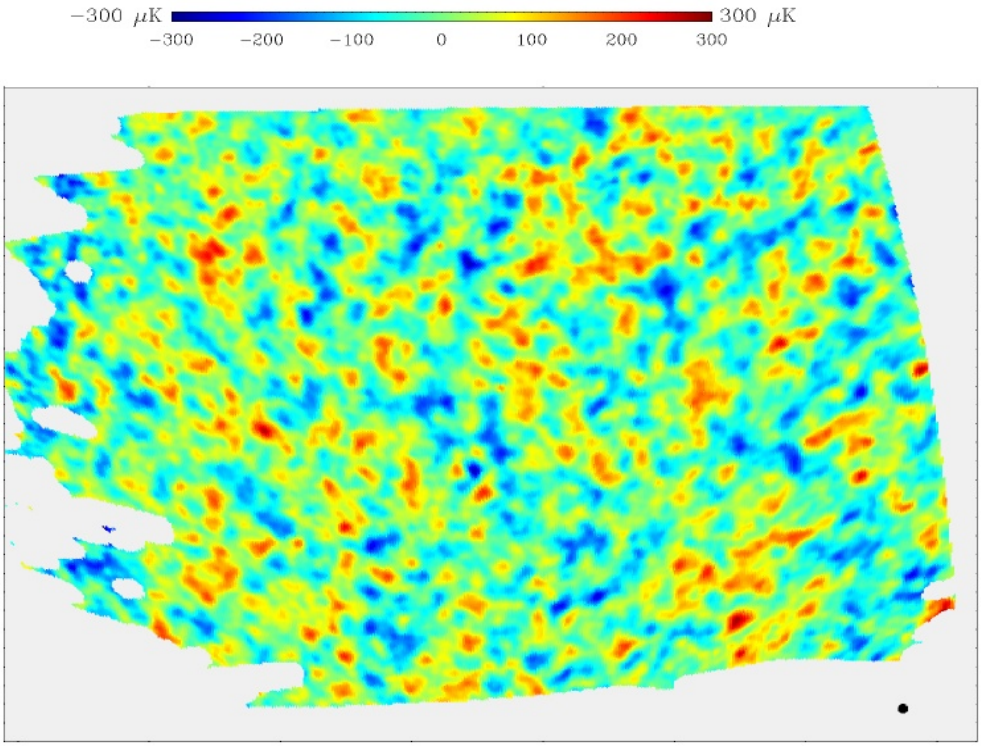
(initial fluctuations: "nearly" scale invariant, adiabatic, Gaussian)

Adiabaticity => fluctuations in pressure are proportional to the density (essentially, particles trace the density field).



Highly ***coherent*** fluctuations

-> preferred size scale
(fluctuations start at the same time)

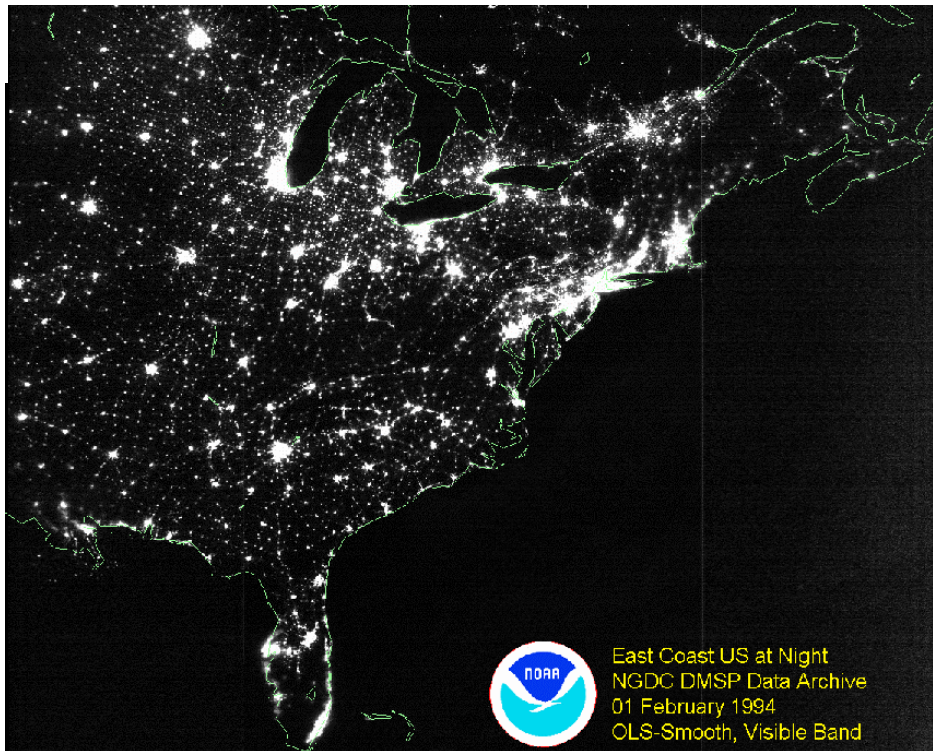


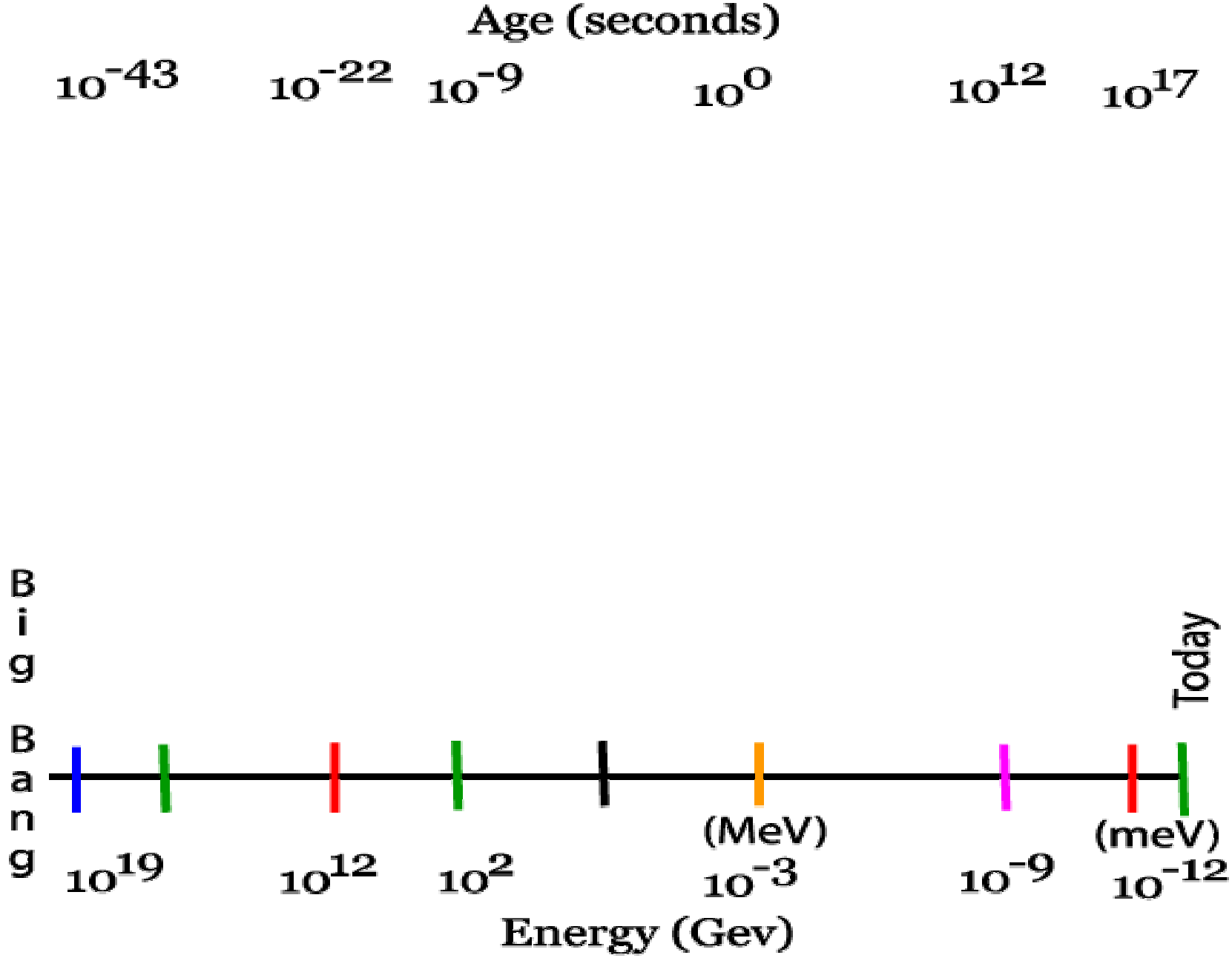
Highly ***coherent*** fluctuations

-> preferred size scale
(fluctuations start at the same time)

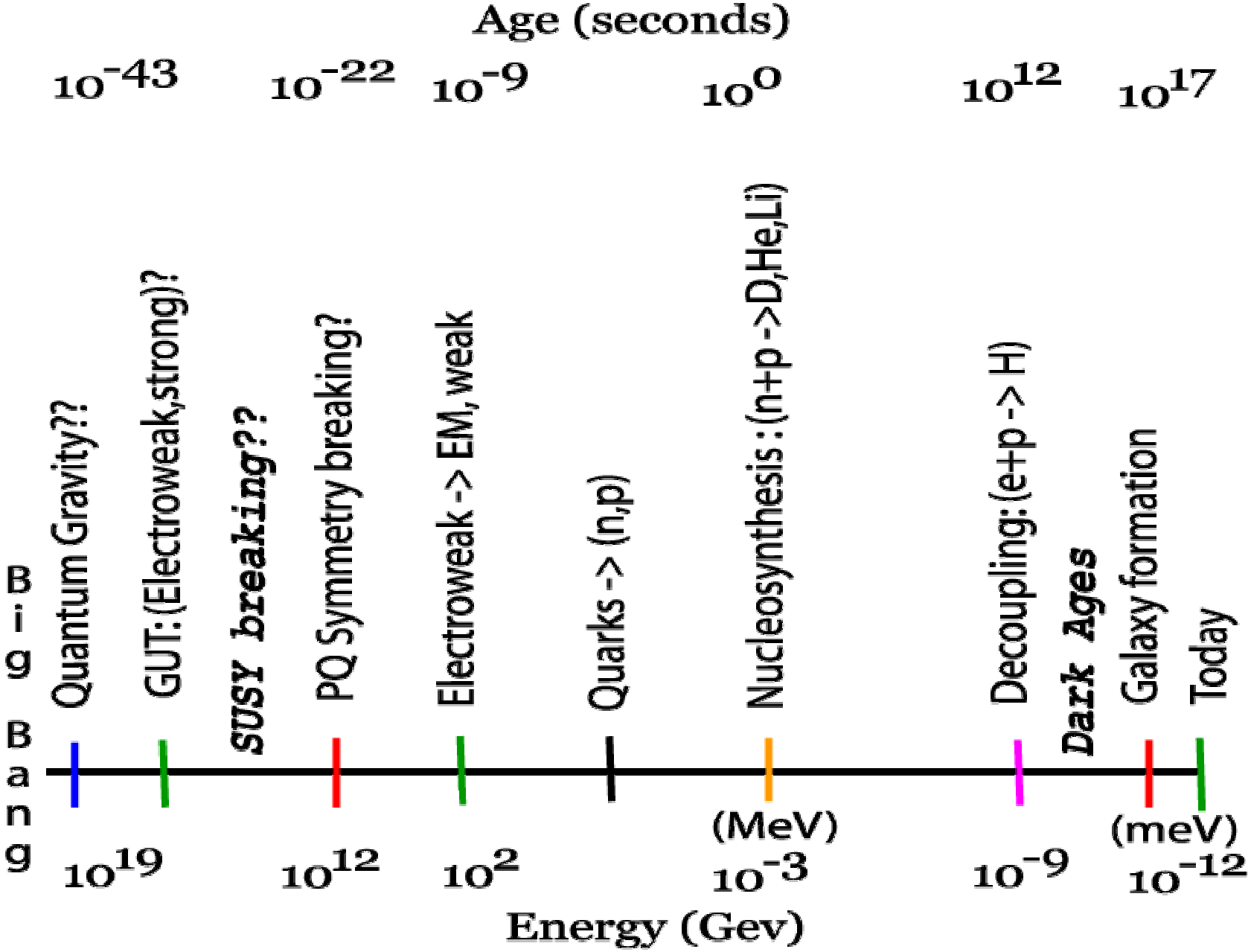
Highly ***incoherent*** fluctuations

-> fluctuations have varying sizes
(power-law: bigger things get bigger)
(fluctuations start at different times)

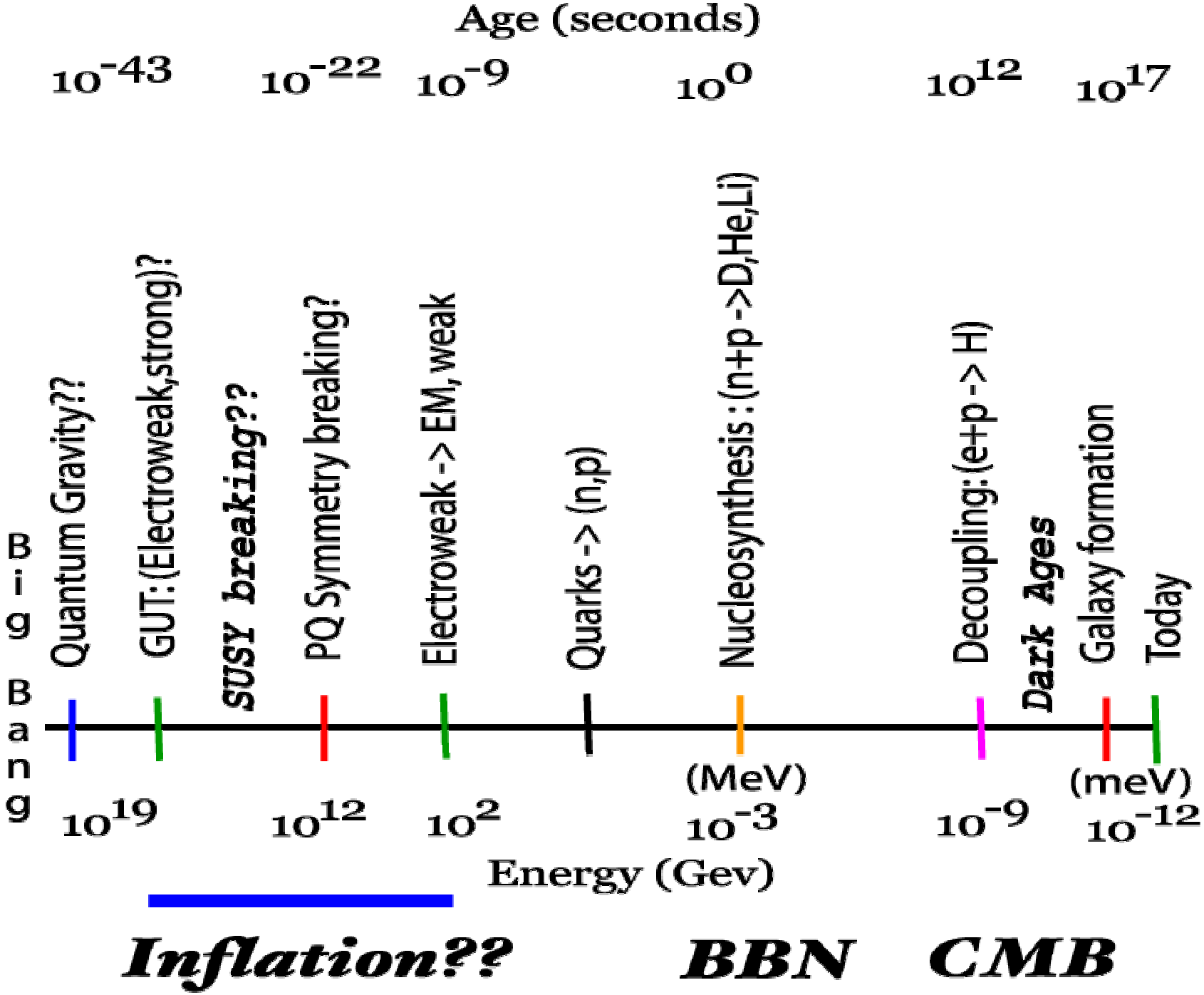




Cosmic Time Line



Cosmic Time Line


Age (seconds)
10^-43
10^-22
10^-9
10^0
10^12
10^17
Big Bang
Quantum Gravity??
GUT: (Electroweak,strong)?
SUSY breaking??
PQ Symmetry breaking?
Electroweak -> EM, weak
Quarks -> (n,p)
Nucleosynthesis: (n+p ->D,He,Li)
Decoupling: (e+p -> H)
Dark Ages
Galaxy formation
Today
10^19
10^12
10^2
(MeV)
10^-3
10^-9
(meV)
10^-12
Energy (Gev)
Inflation??
BBN
CMB

Evidence for Inflation

Geometry *Smoothness* *Structure Formation*

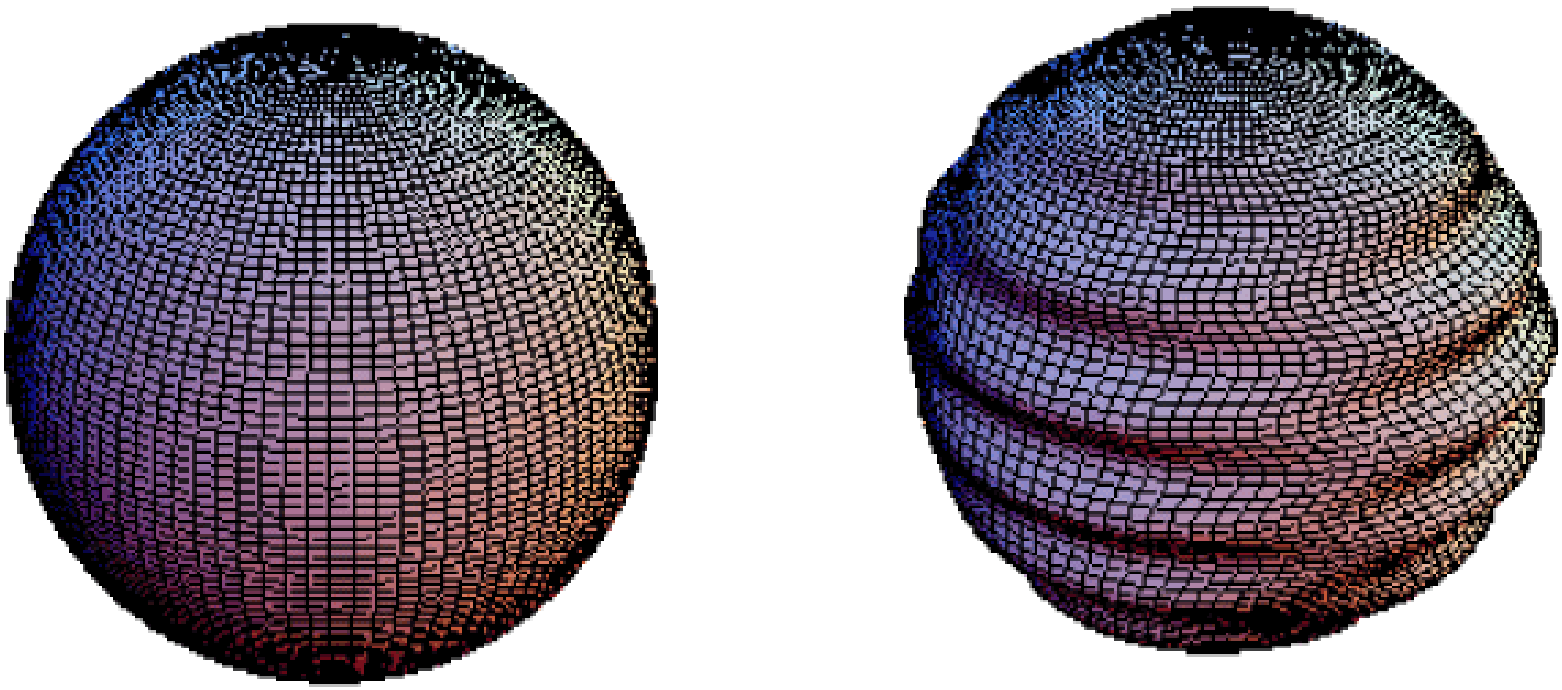
When did inflation happen?

A natural prediction:
A stochastic background of gravitational waves

$$A_{IGW} \propto E^2_{\text{inflation}}$$

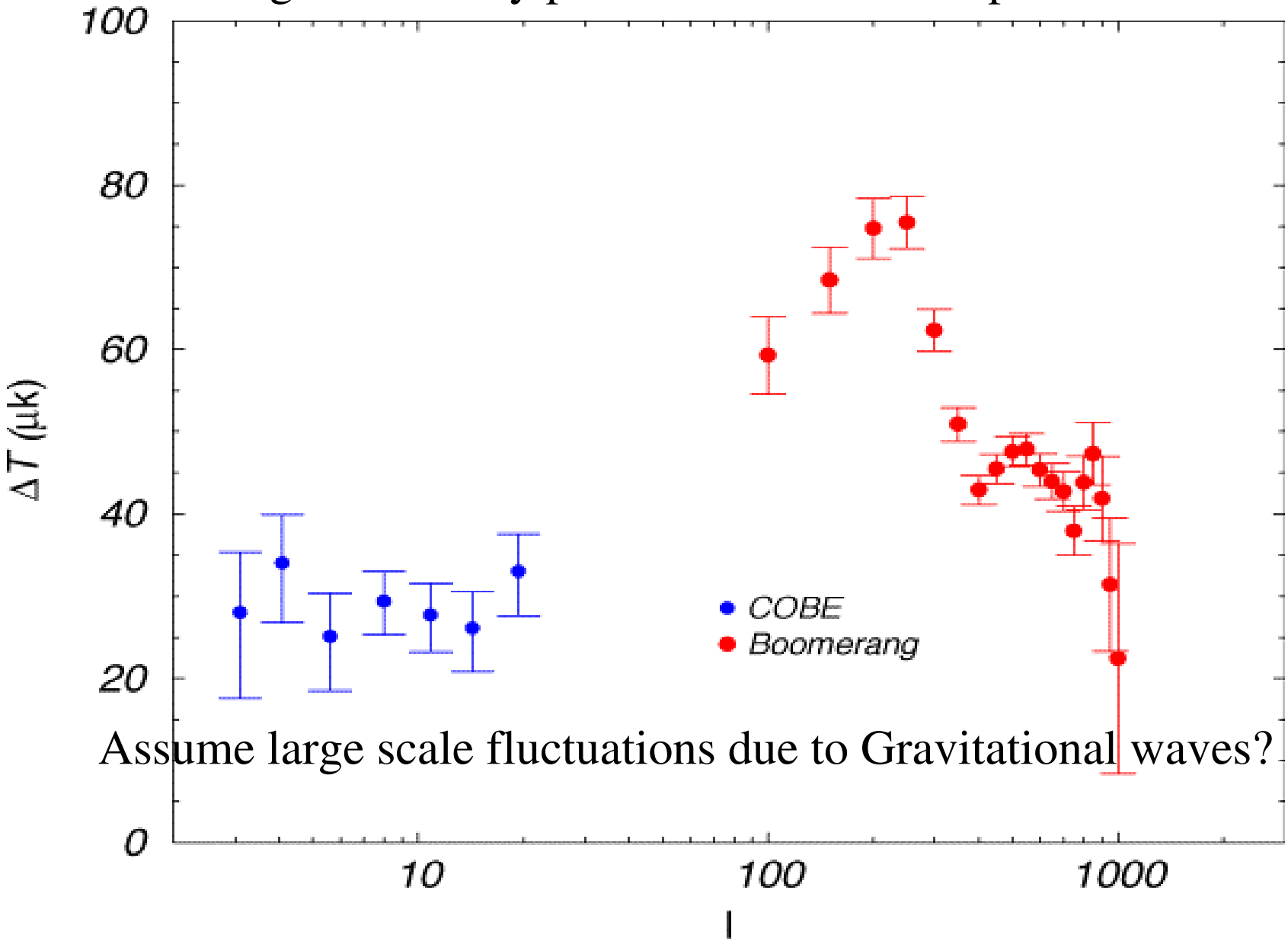
(This is in addition to dominant density perturbations)

Detection of ultralongwavelength GWs from inflation: use plasma at CMB surface of last scatter as sphere of test masses.

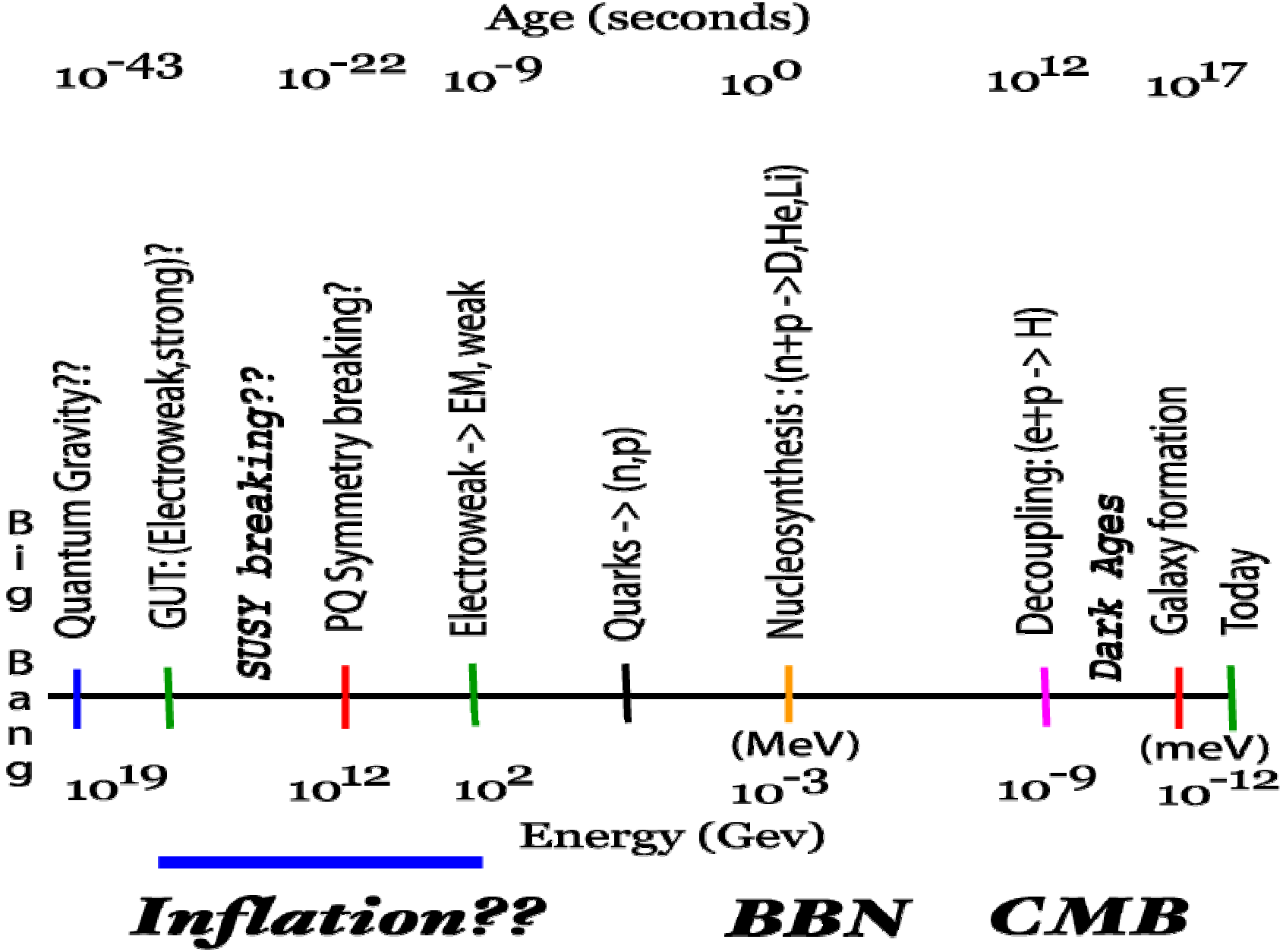


Kamionkowski & Caldwell; Scientific American 2000

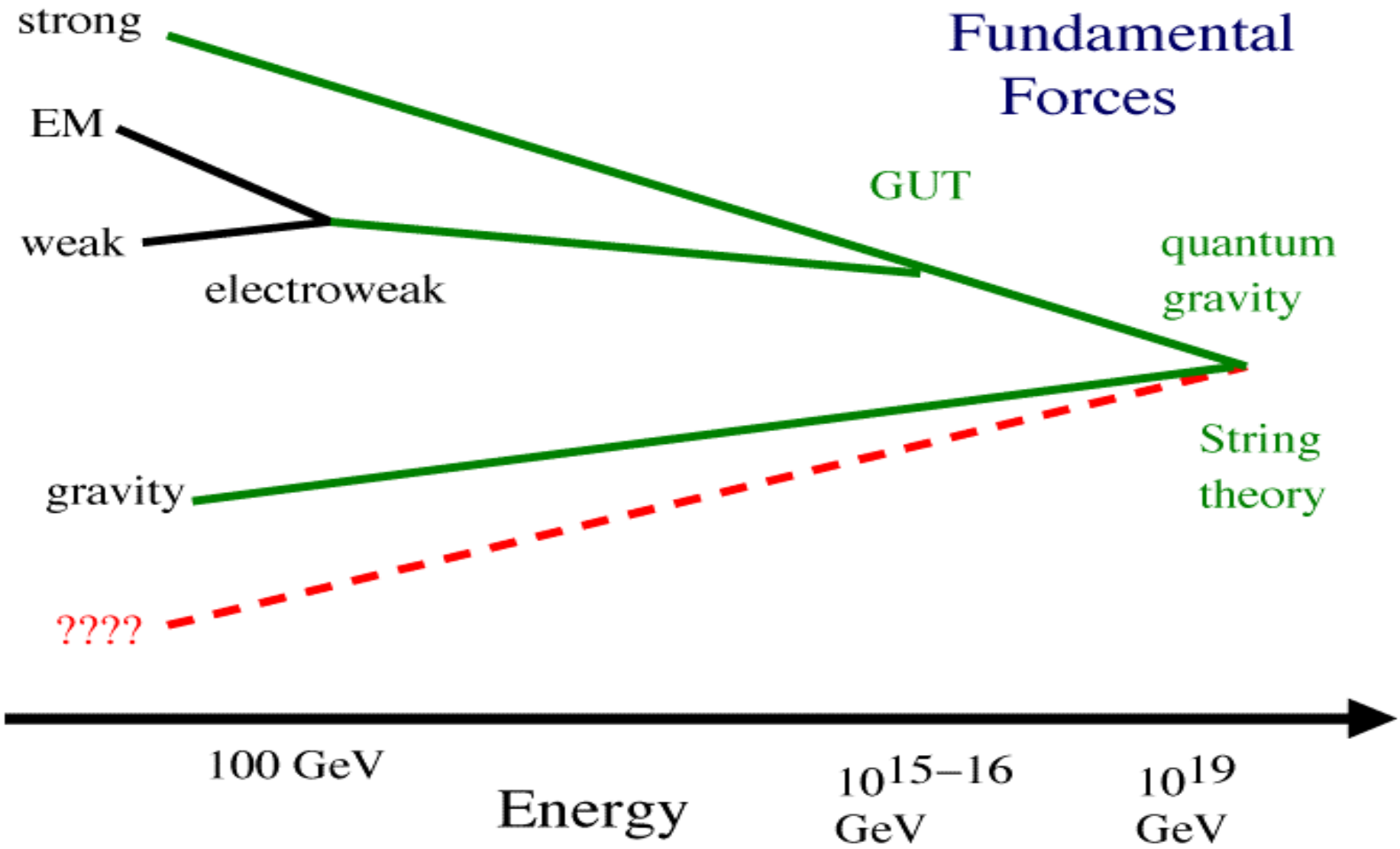
A limit on the GW contribution:
ignore density perturbations/acoustic peaks



Assume large scale fluctuations due to Gravitational waves?



Present limit: E(Inflation) < 3x 10^{16} GeV



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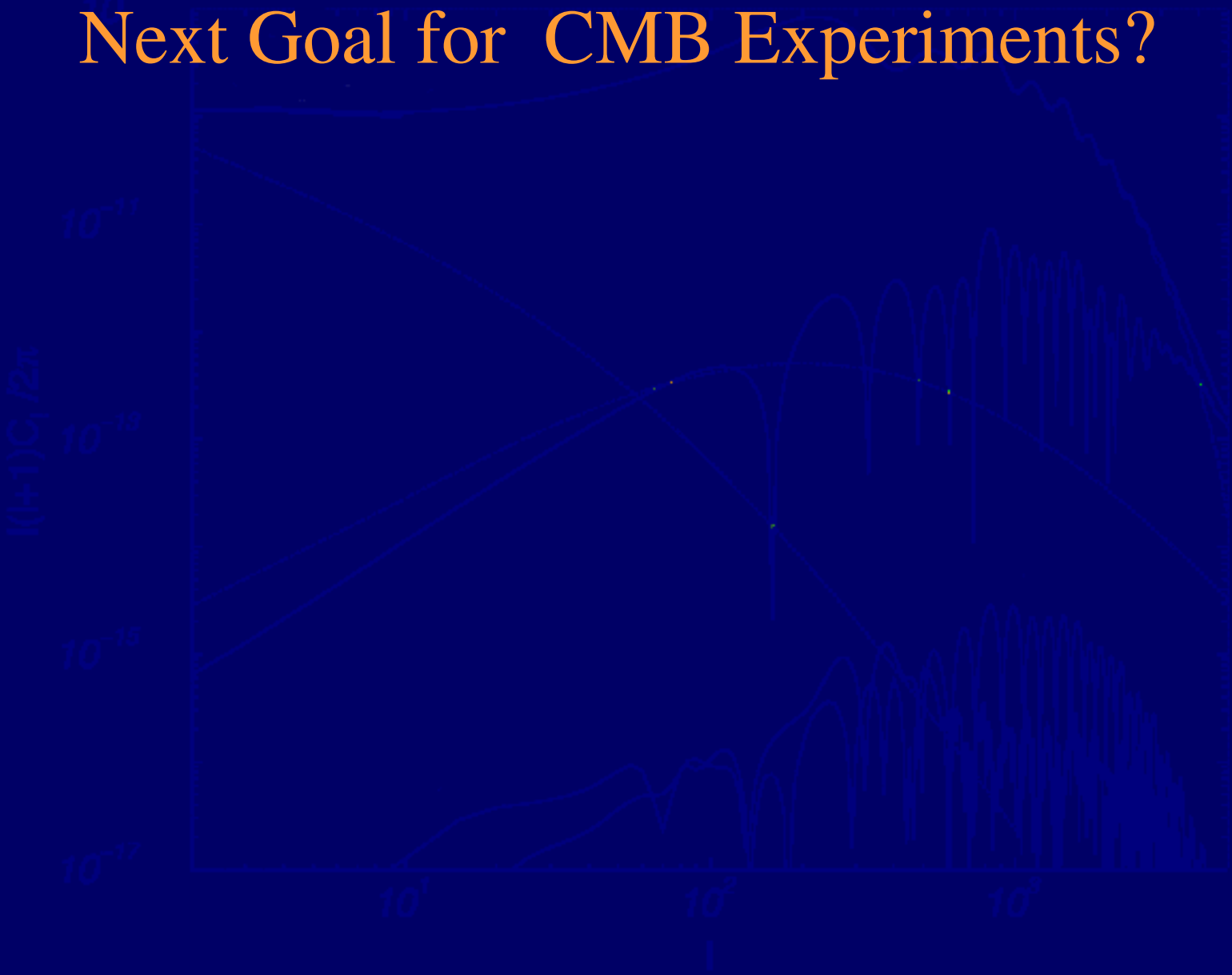
Next Goal for CMB Experiments?



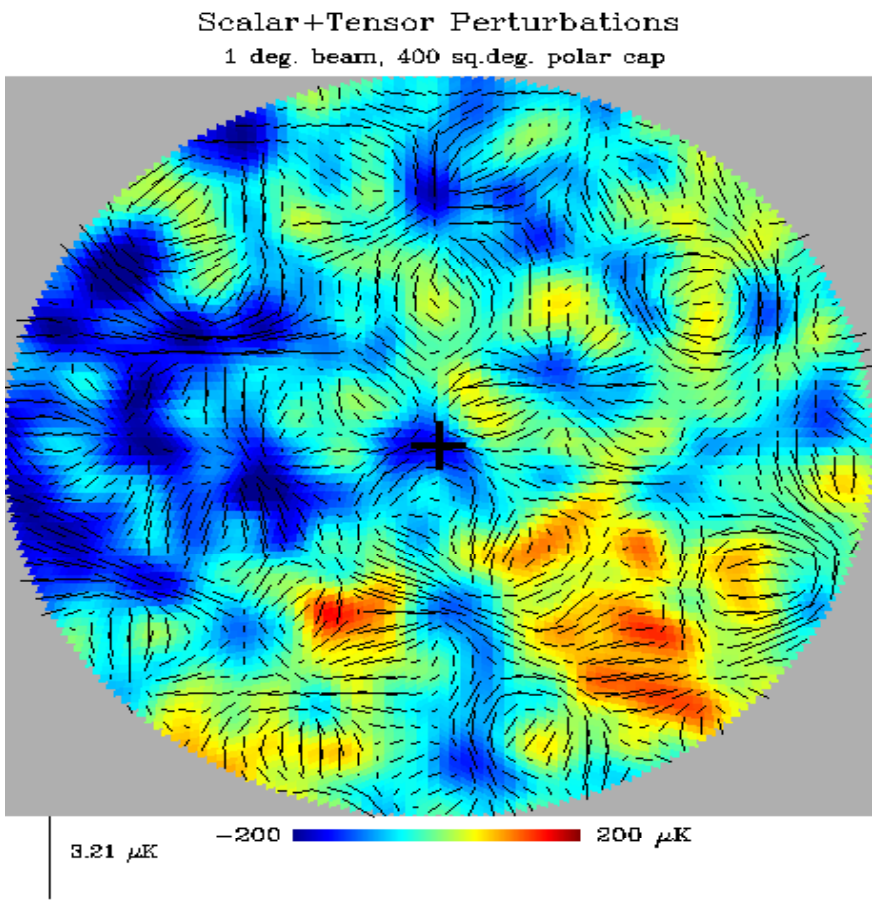
Next Goal for CMB Experiments?

I. Determine the energy scale of inflation

- CMB Polarization
- The role of confusions: weak lensing
- With confusions partly removed

CMB Polarization

- **Polarization is described by Stokes-Q and -U**
- **These are coordinate dependent**
- **The two dimensional field is described by a gradient of a scalar (E) or curl of a pseudo-scalar (B).**



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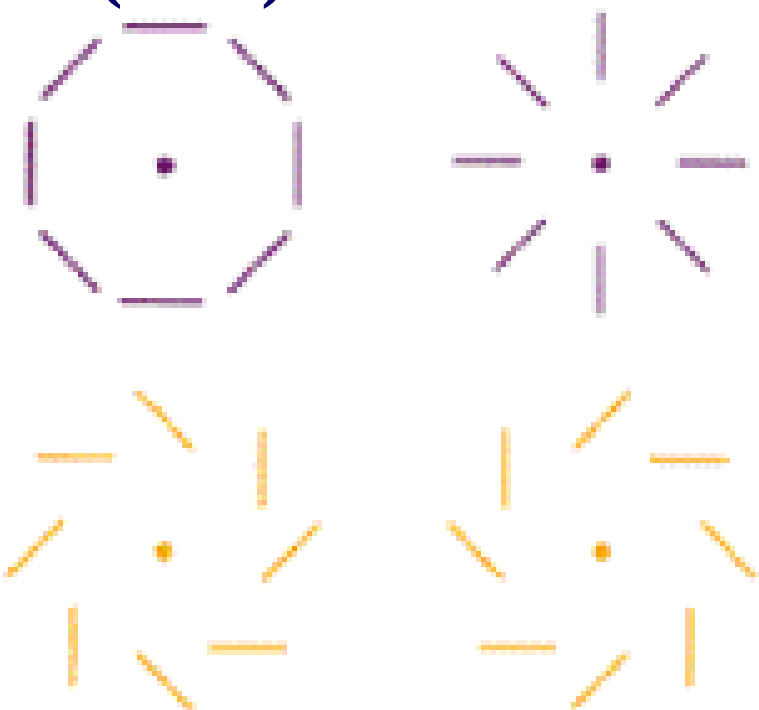
Grad (or E) modes



Curl (or B) modes

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

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

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

Kamionkowski et al. 1997;
Seljak & Zaldarriaga 1997

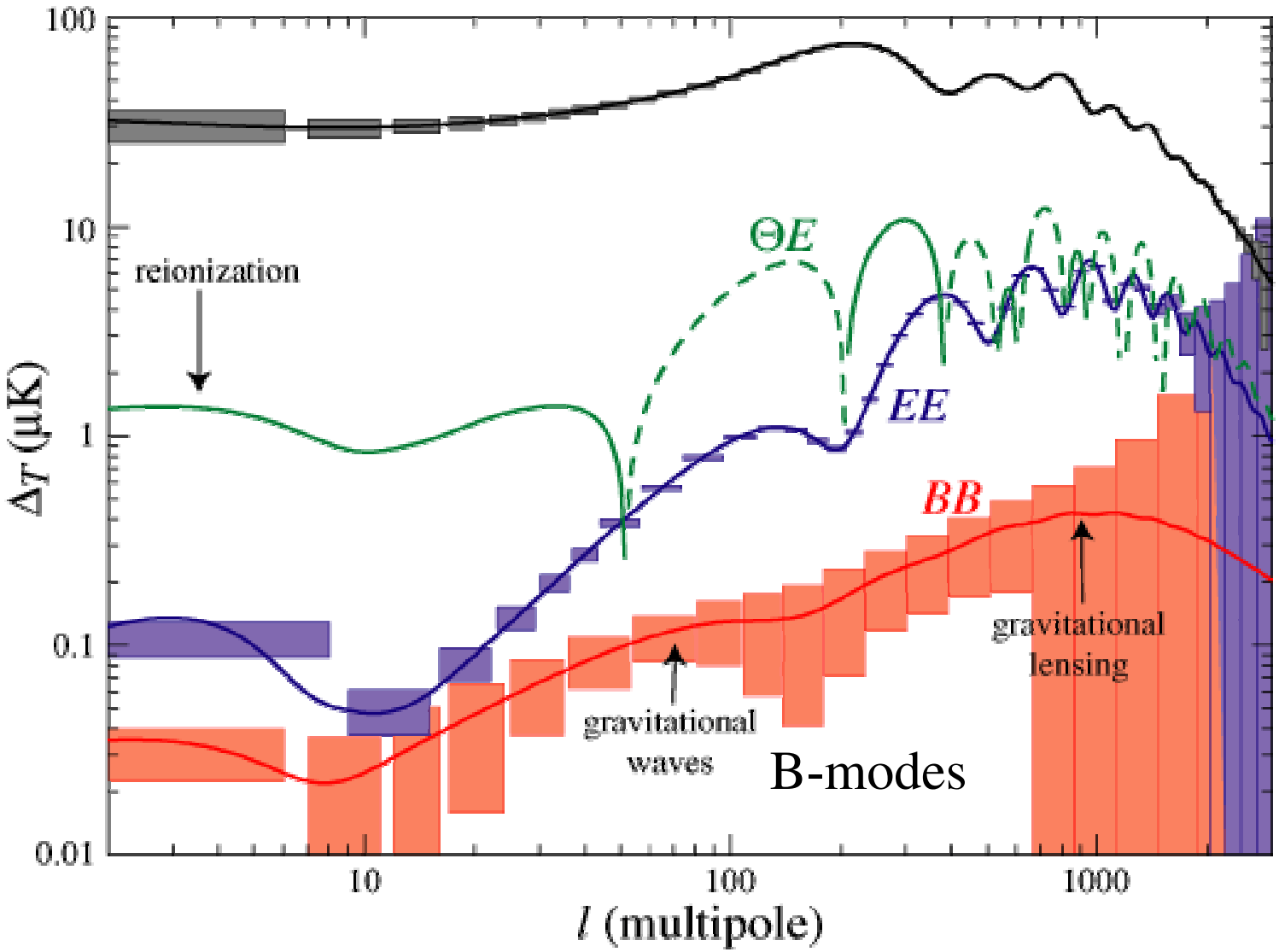
Gravitational-waves

- **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)

EE -> BB confusions



What else can we do with CMB?

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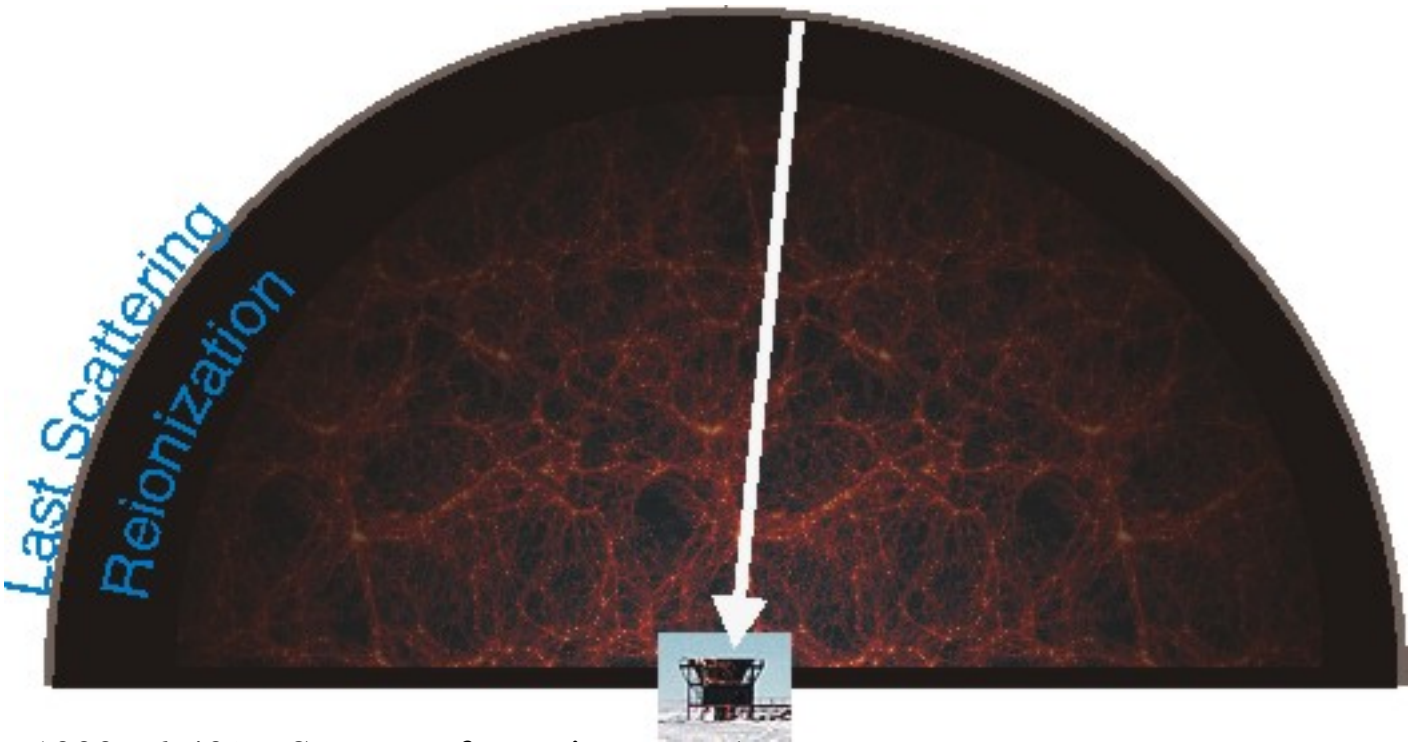
Why confusions?



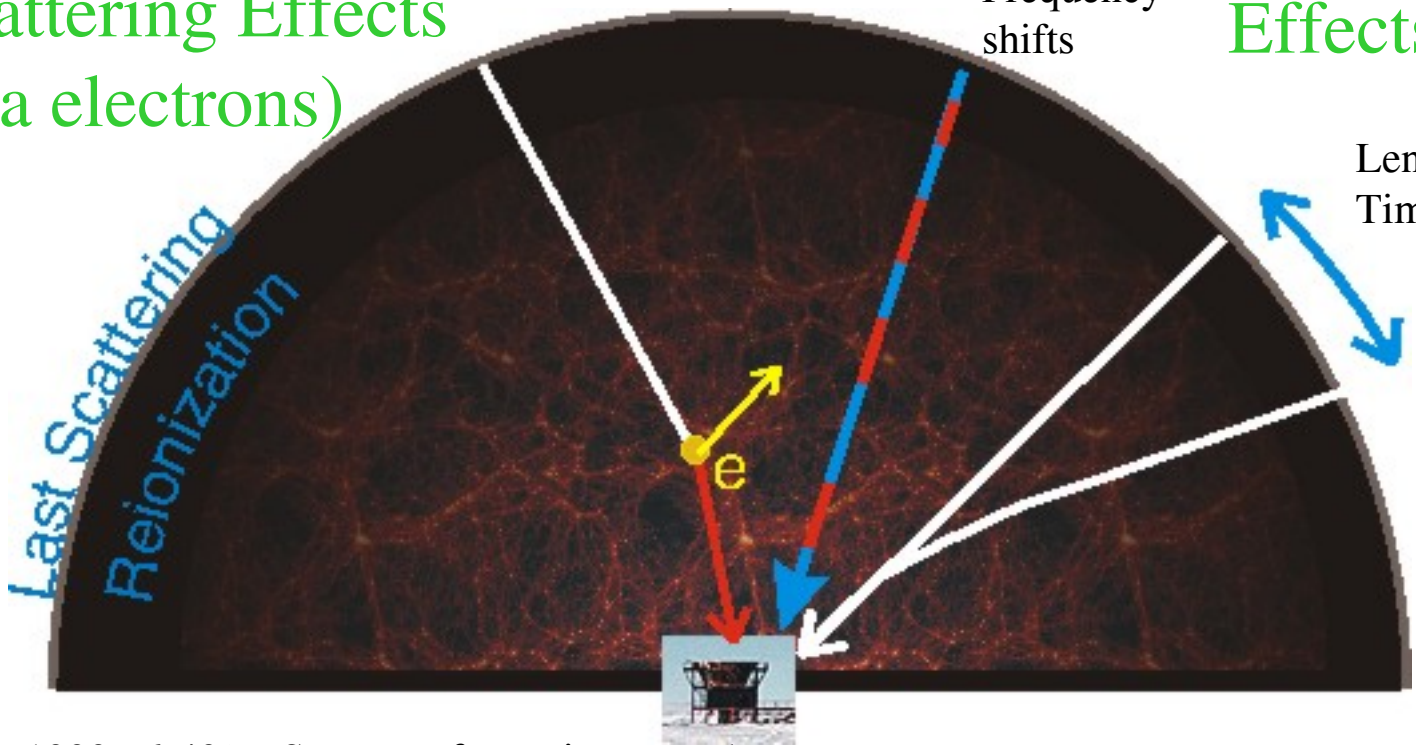
z ~ 1000 6-40? Structure formation today

- We are collecting photons from the last scattering surface

Why confusions?

Scattering Effects (via electrons)

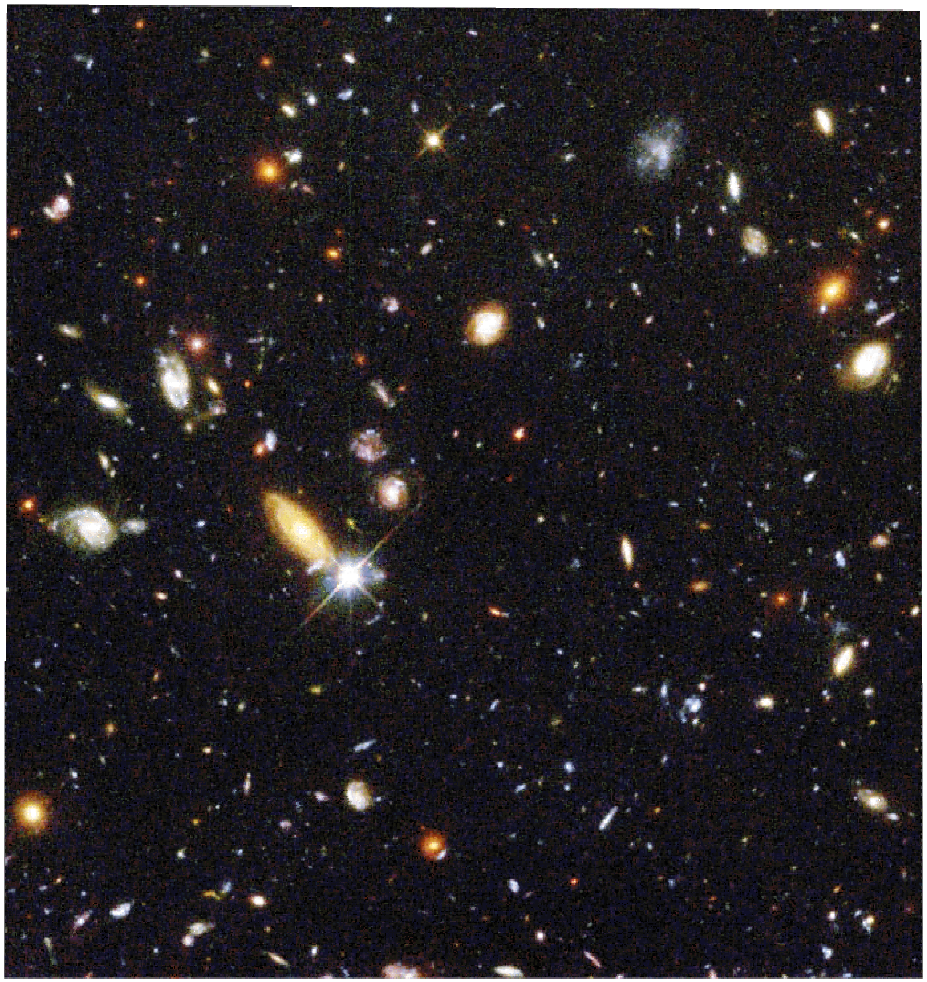
Gravitational Effects



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

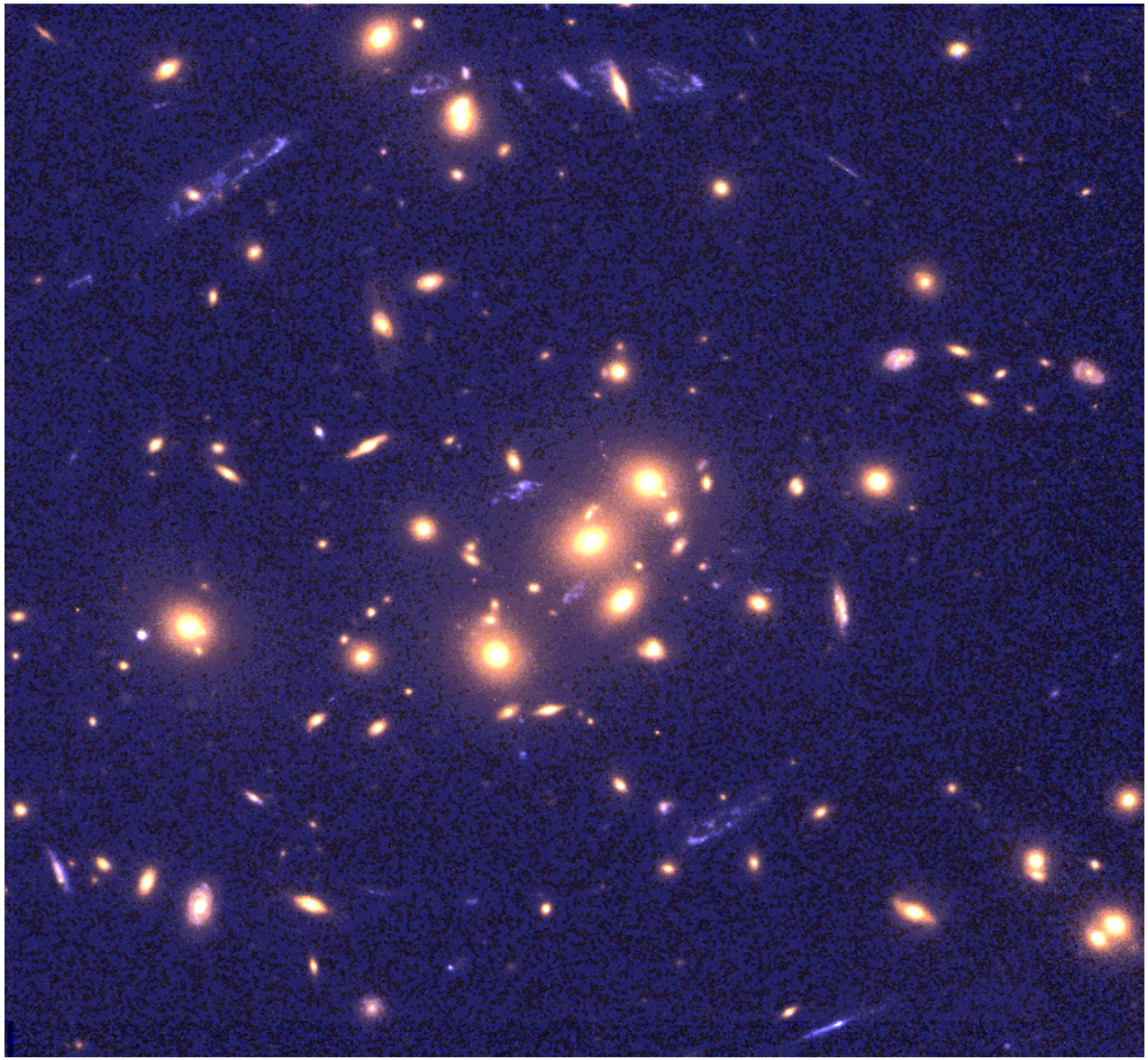
For B-modes, lensing effect is the main concern!!

Gravitational Lensing



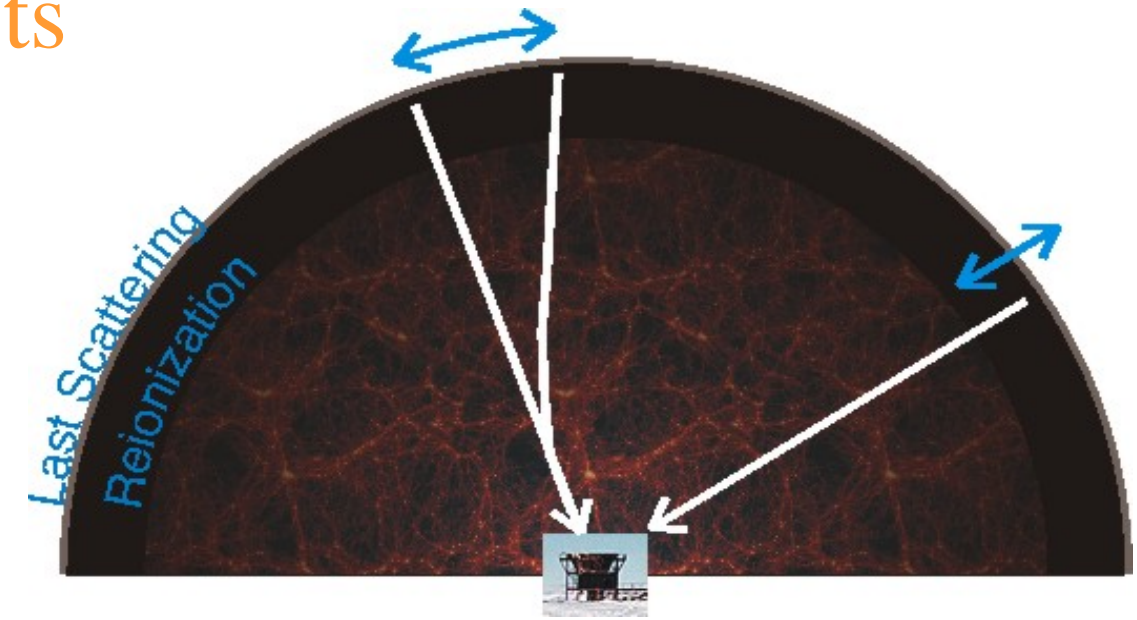
GIF decompressor
are needed to see this picture.

Gravitational Lensing



Gravitational Effects

Lensing and time-delay



- Geometric effect

⇒ Angular deflection of Photons

- Potential effect

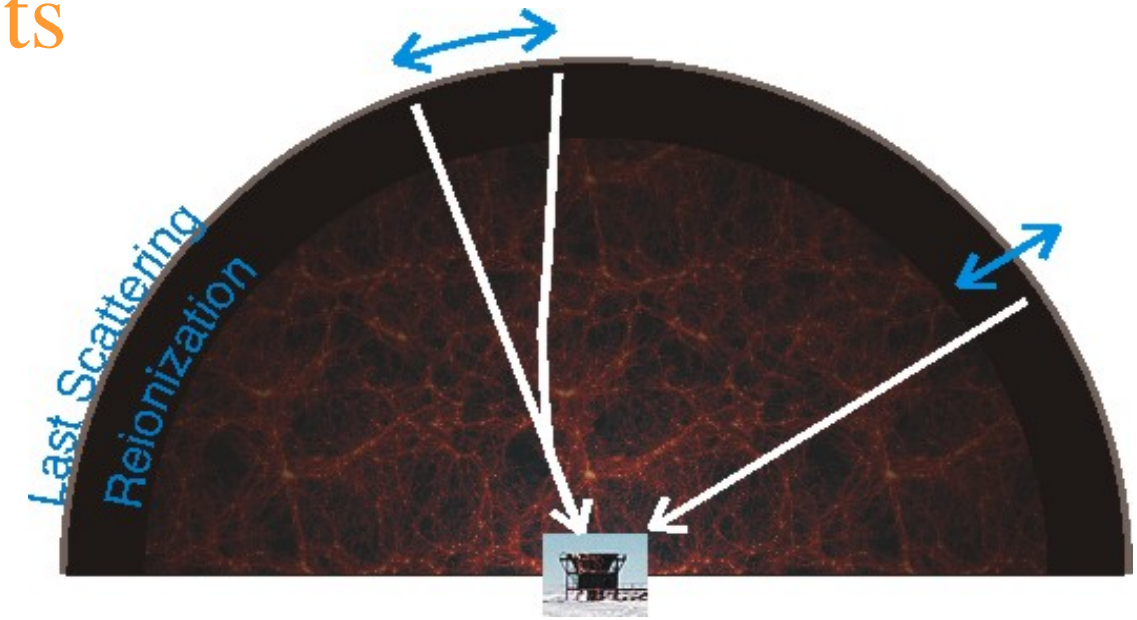
⇒ Time delay of photons

Two effects combined lead to the Fermat potential

(Hu & Cooray 2000)

Gravitational Effects

Lensing and time-delay



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

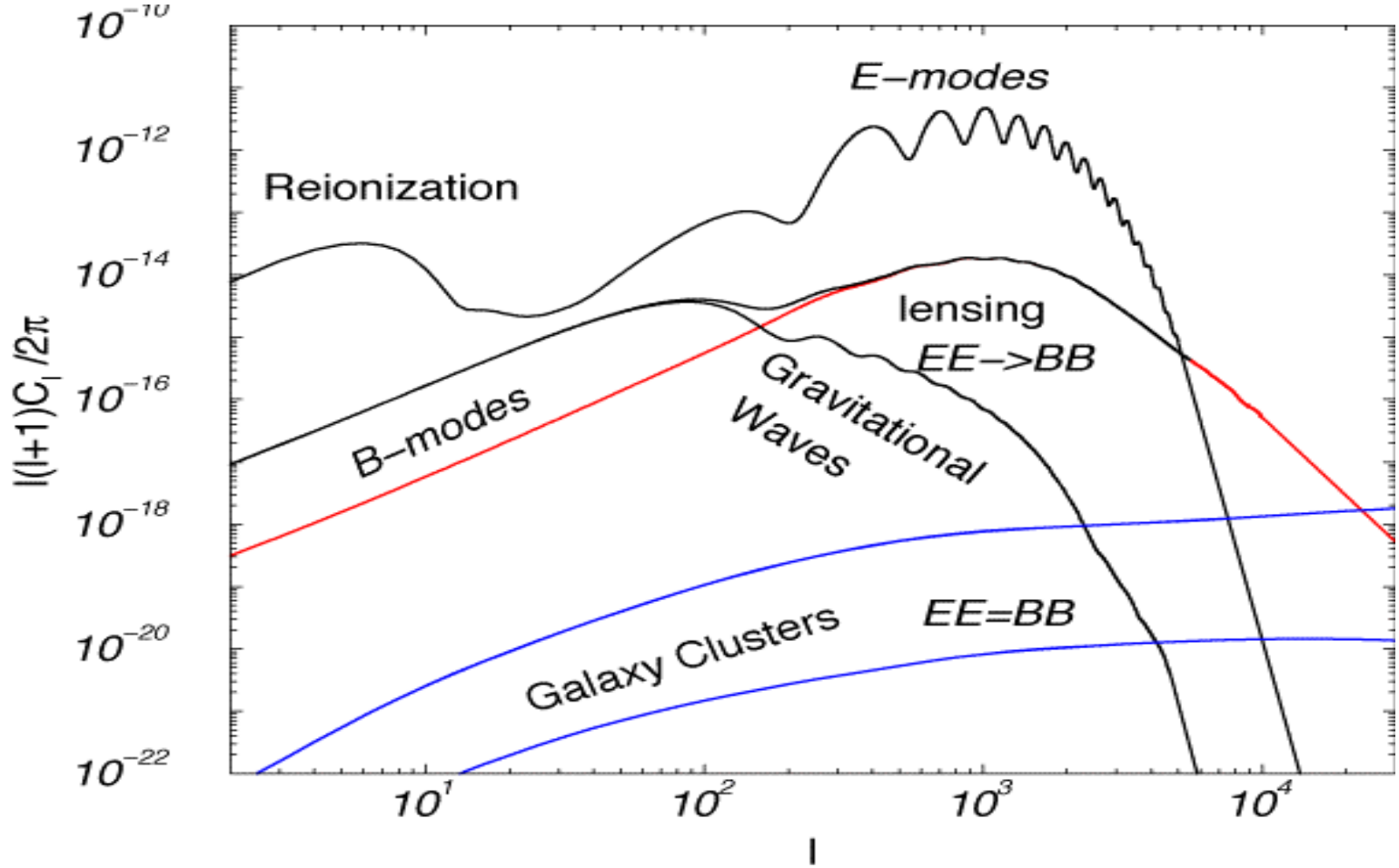
$$\approx T(\bar{\theta}) + \delta\bar{\theta} \bullet \nabla T(\bar{\theta}) + \ldots$$

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

Two effects combined lead to the Fermat potential

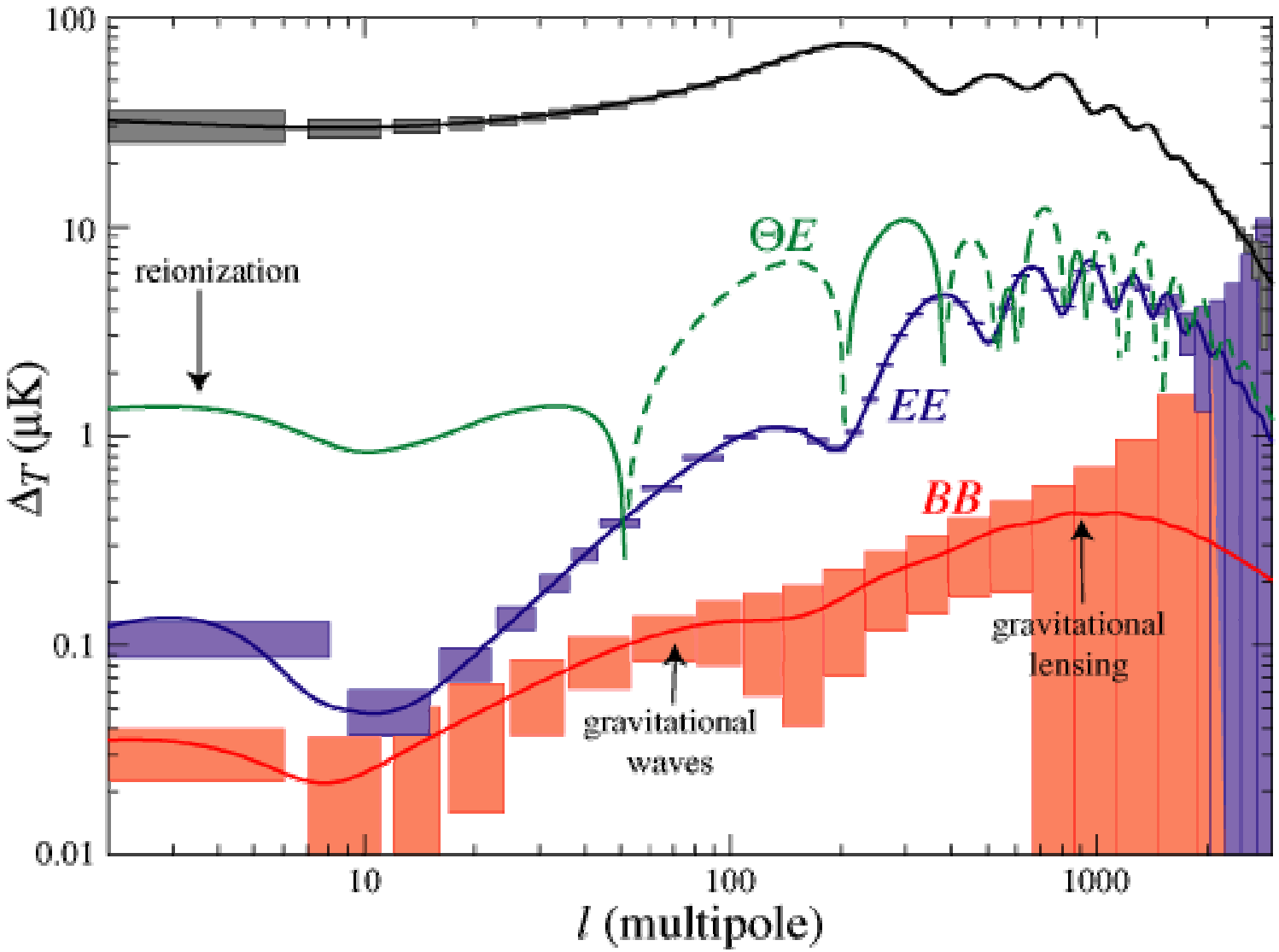
(Hu & Cooray 2000)

Also in Polarization…

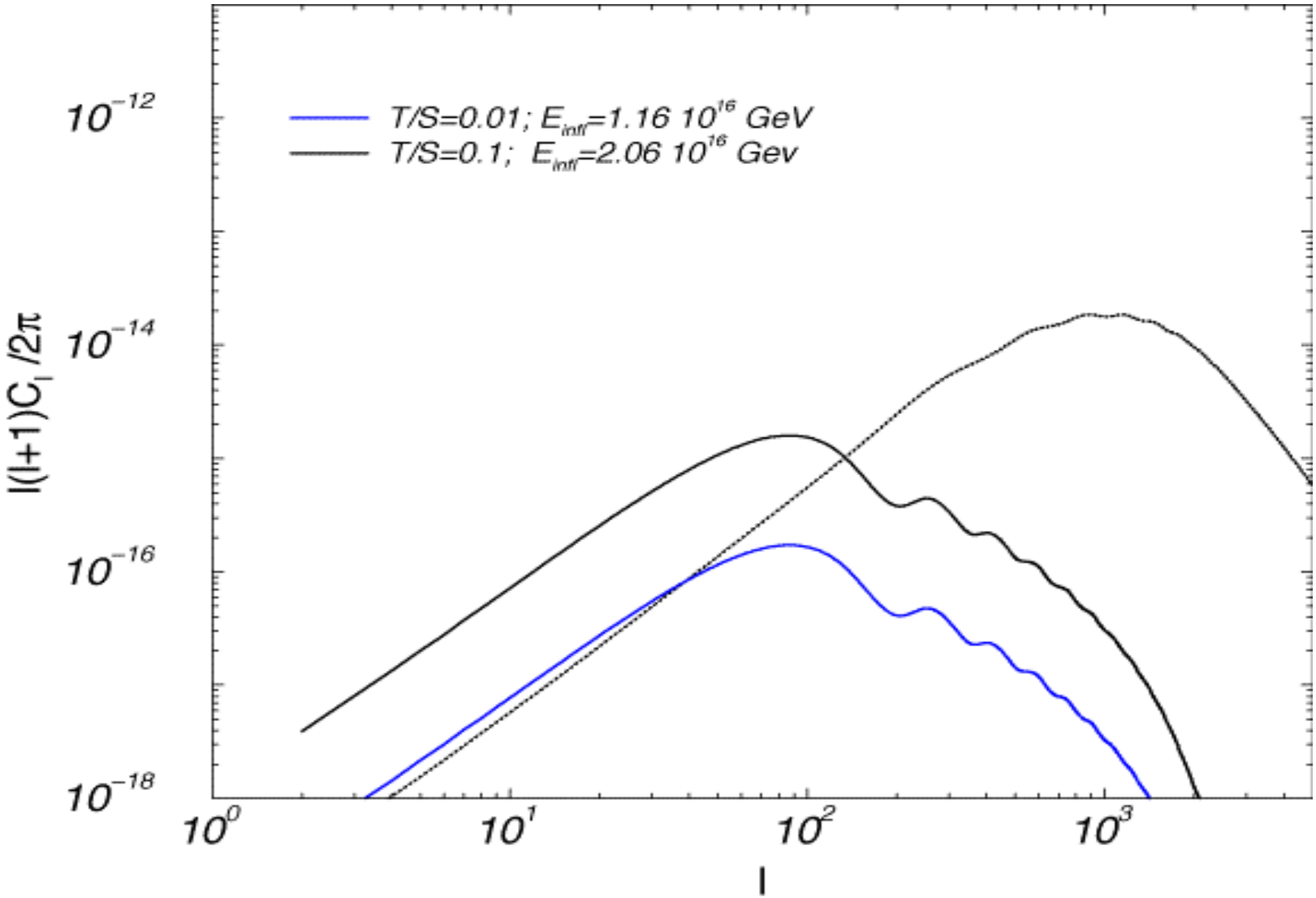


Lensing mixes Stokes-Q and U, or alternatively, between E and B.

Few percent of E-modes converted to B-modes via lensing



Lensing vs. Gravitational-Waves: Which dominates?



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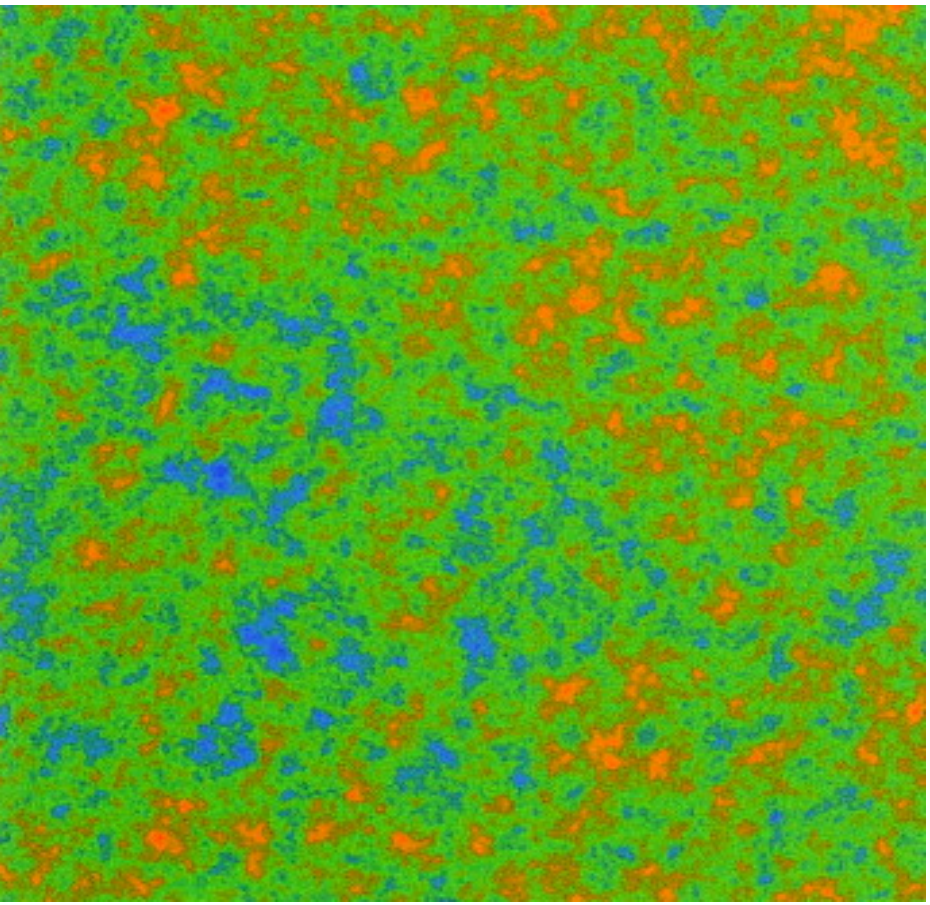
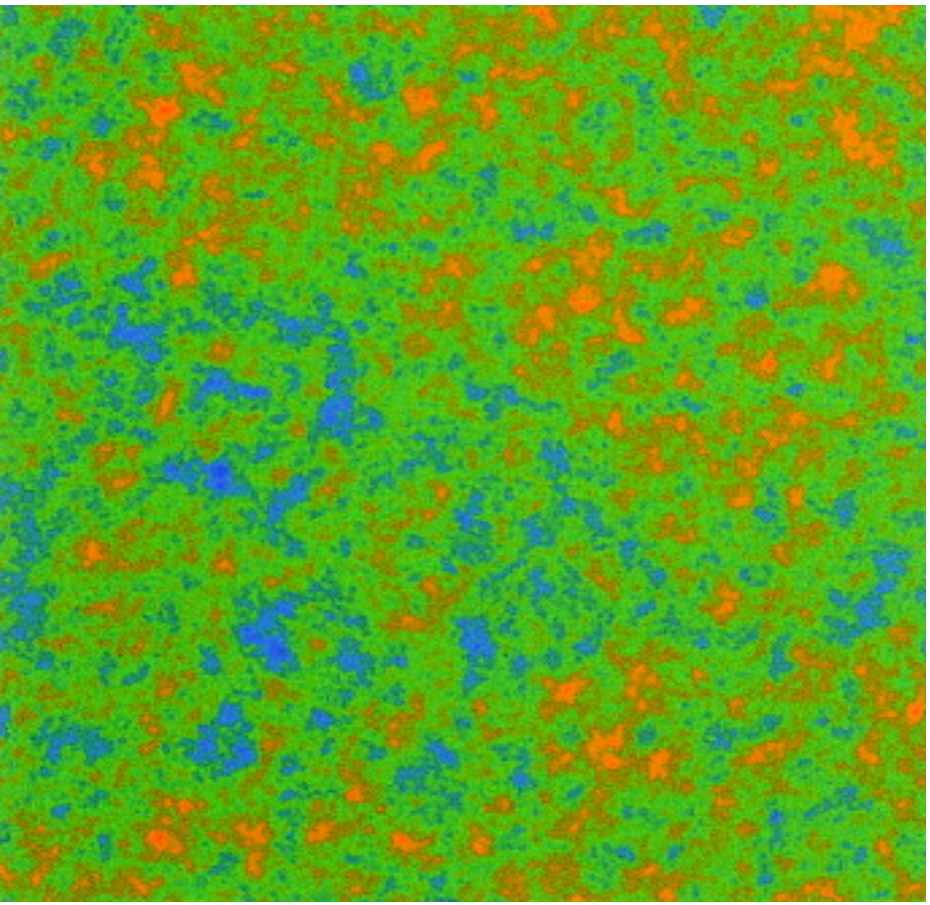
Weak Lensing in CMB



Temperature field

Hu 2002

Weak Lensing in CMB



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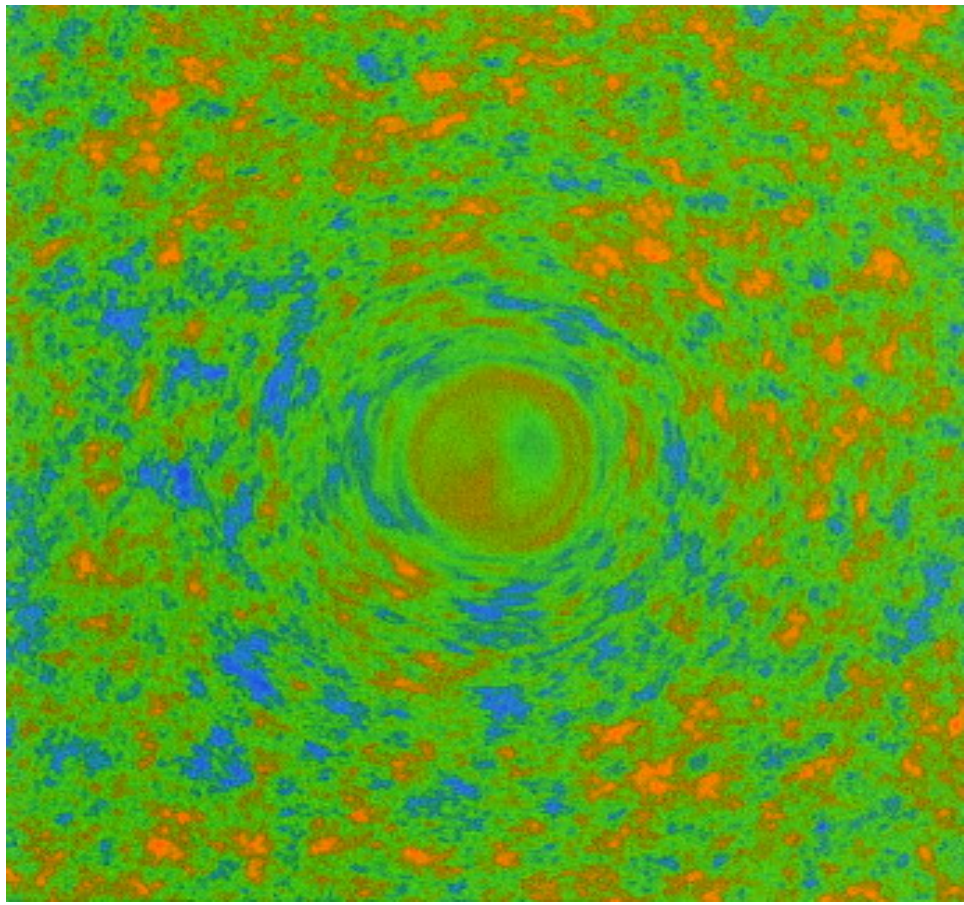
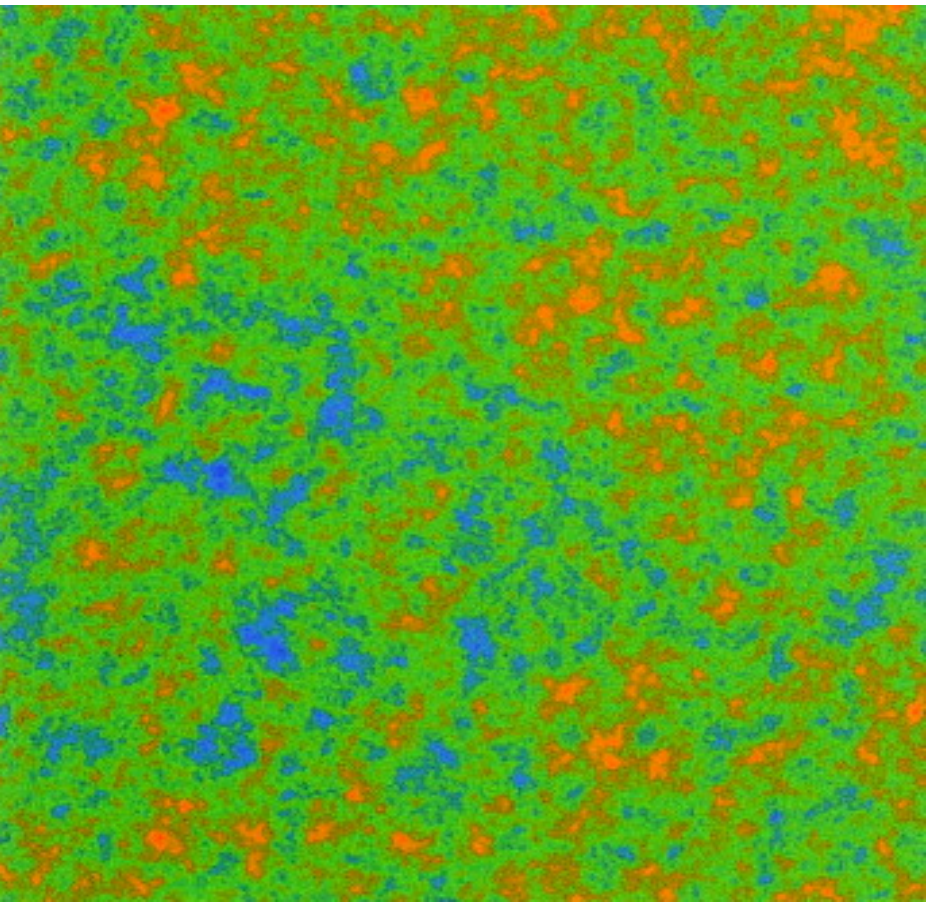


Lensed temperature field

Hu 2002

Weak Lensing in CMB

But, this is unrealistic… (requires a massive cluster)



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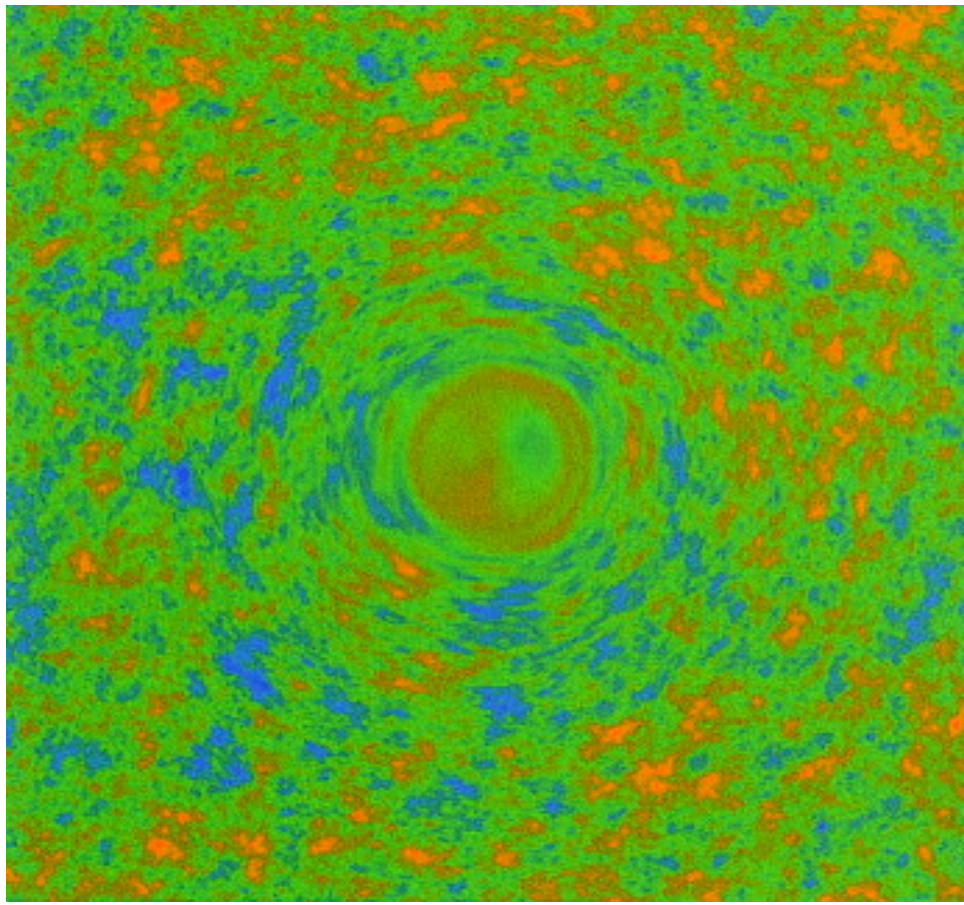

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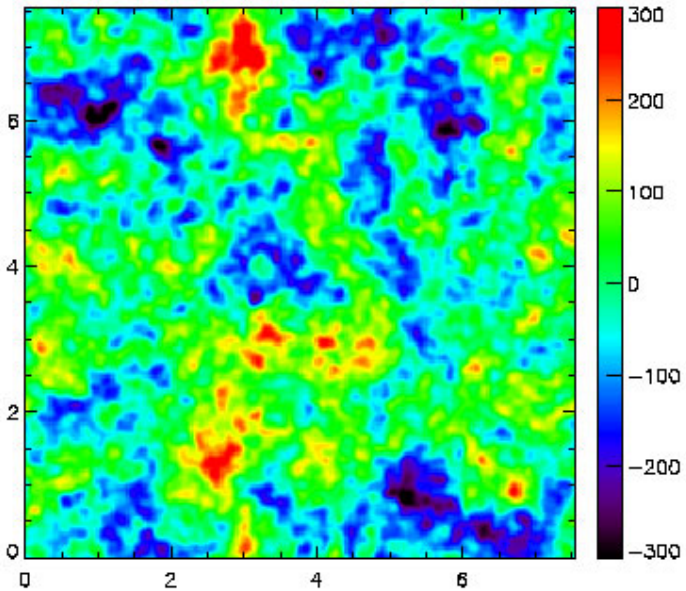
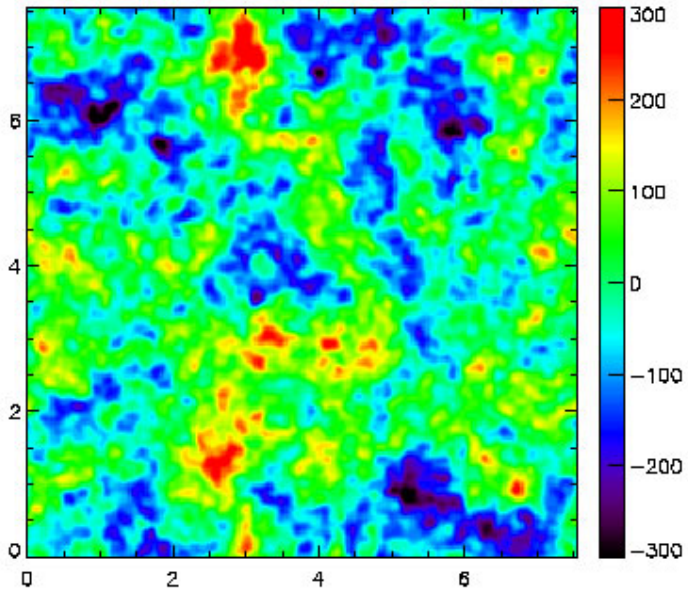


Unlensed

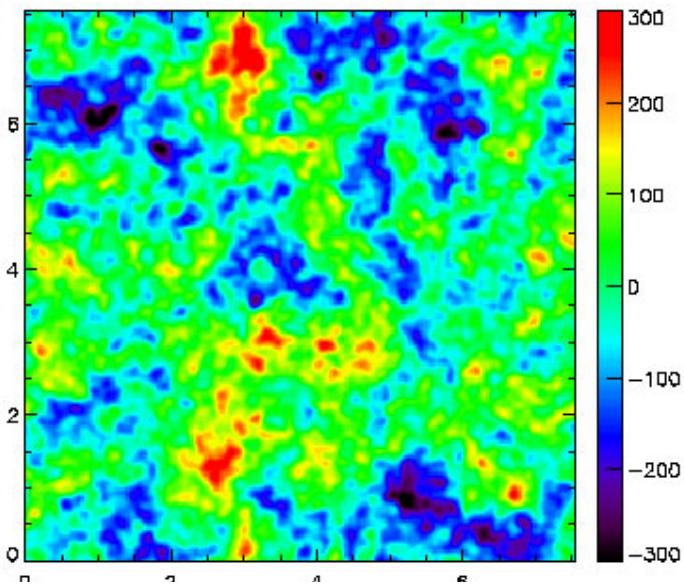


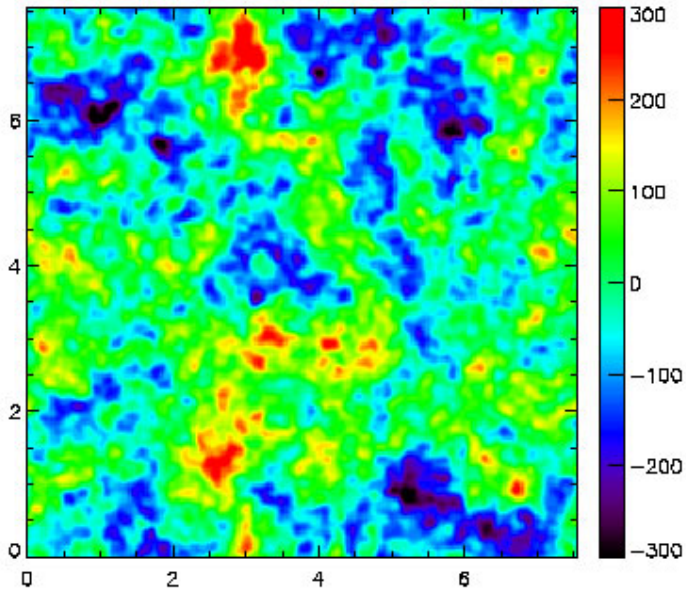
Lensed

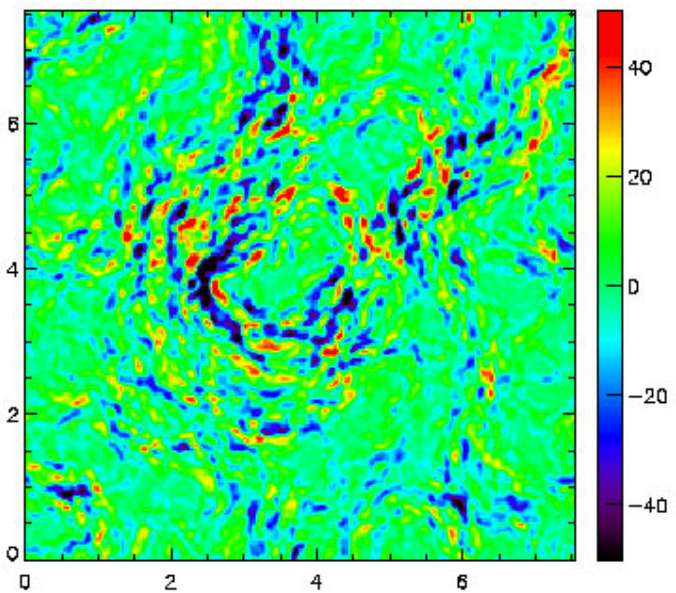
The real scenario: difference is very small!!!!

Vale et al.

Weak Lensing in CMB







Difference between the two:

1) +/- dipolar structure
2) Color scale

Vale et al.

Weak Lensing in CMB

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

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

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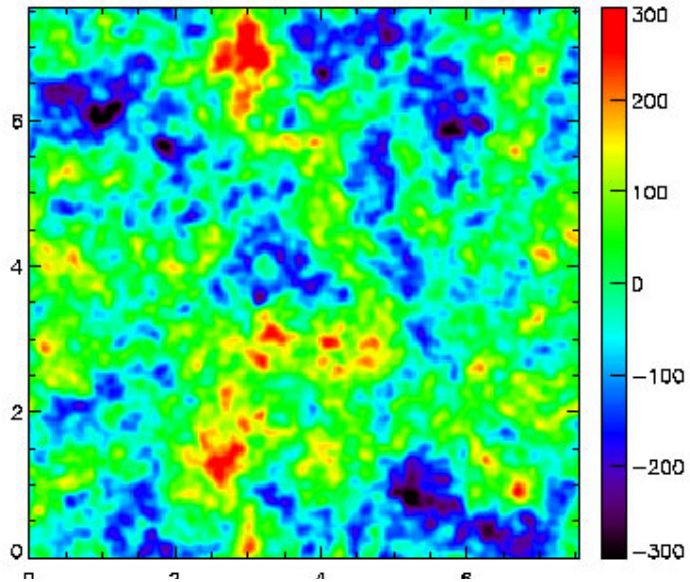
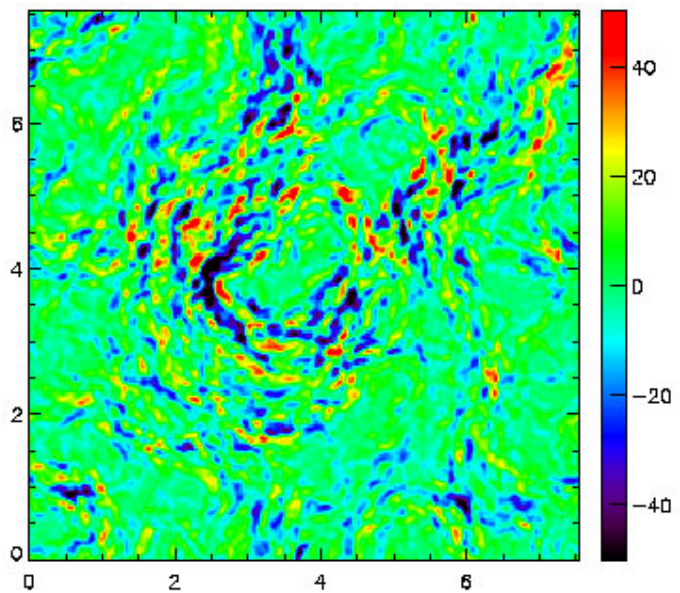
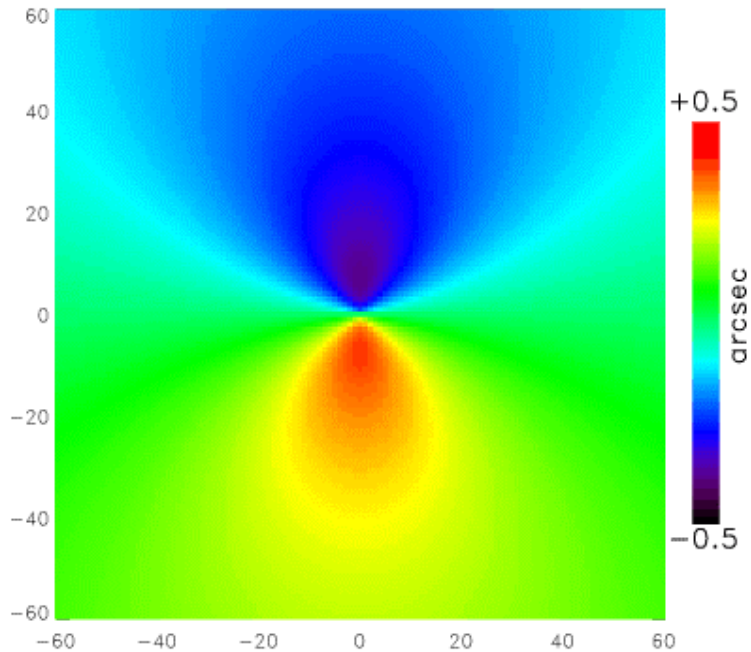
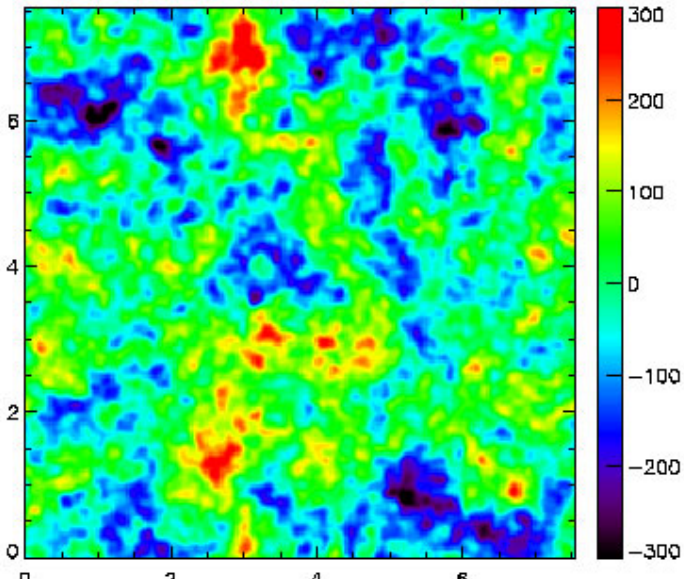


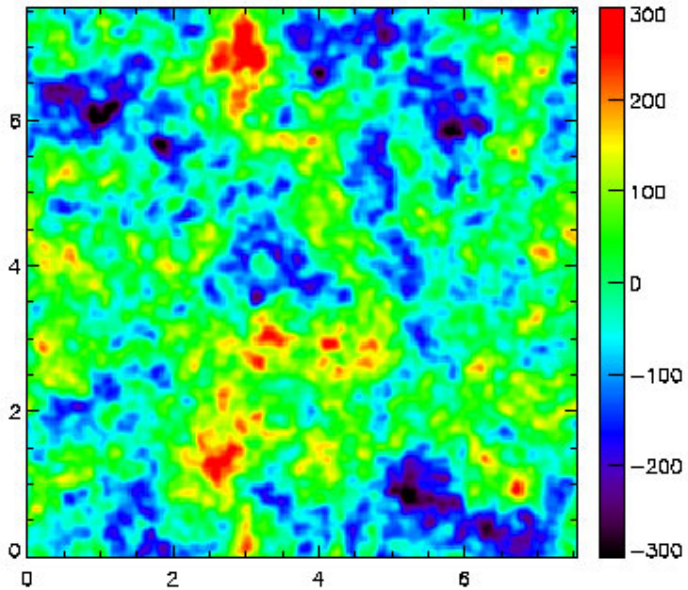
1. Modifies CMB gradient
2. Modification is highest when the gradient is highest

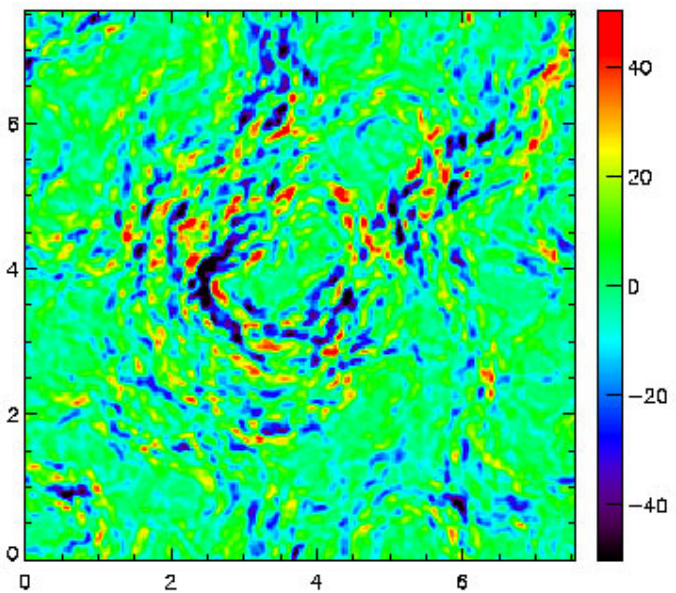


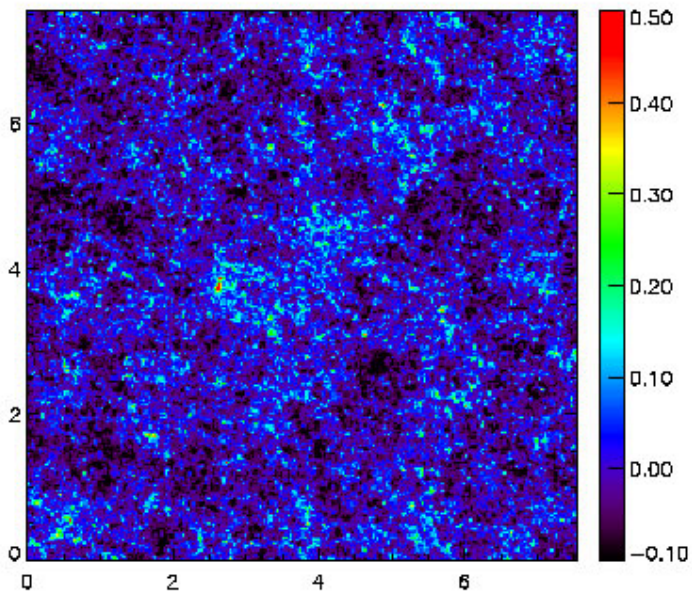


Weak Lensing in CMB









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

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

Quadratic Statistics as a way to reconstruct lensing deflections

Reconstruction algorithm (naïve description)

1. Take the temperature map and square it.

$$\tilde{T}^2(\bar{l}) = \int d\bar{\theta}\, T^2(\bar{\theta})\, e^{-i\bar{l}\bullet\bar{\theta}}$$

$$= \int \frac{d^2 l_1}{(2\pi)^2} \tilde{T}(\bar{l}_1)\tilde{T}(\bar{l} - \bar{l}_1)$$

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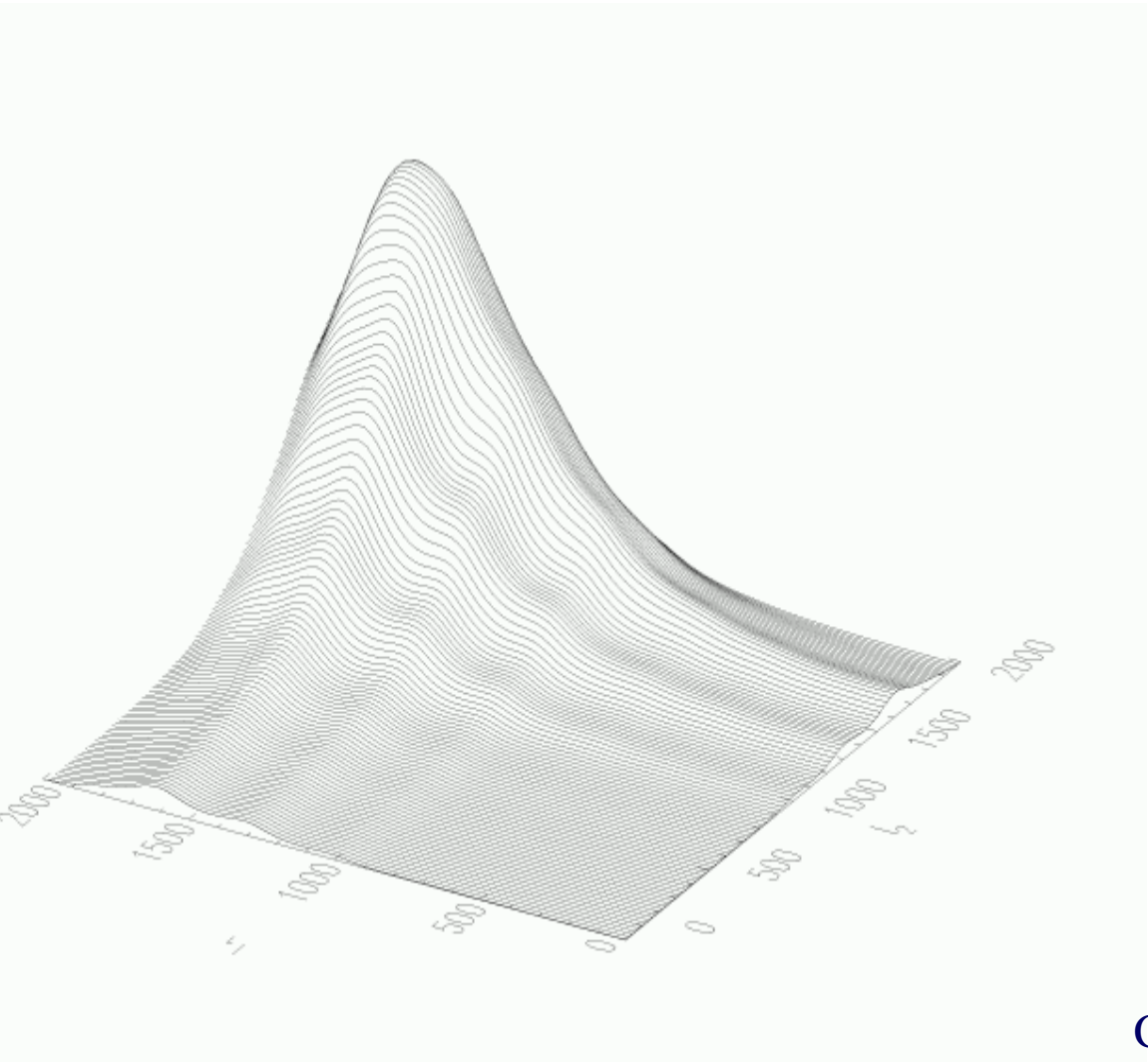
Homework: $\tilde{T}^2(\bar{l}) \propto \delta\theta(\bar{l})$

Cooray 2002; Cooray & Kesden 2002

Quadratic Statistics as a way to reconstruct lensing deflections

- Filter the CMB^2 map to get rid of the excess high frequency noise



- Optimal filter depends only on the primary CMB anisotropies and behavior of the lensing mode coupling

- Optimal filter returns all info from the trispectrum ***(CMB^2- CMB^2 statistic is not loseless to the extent Gaussian noise is the only noise source)***

Cooray 2001; Cooray & Kesden 2002

Quadratic Statistics as a way to reconstruct lensing deflections

What are we doing here?

Correlation function of the background is expected to be isotropic.

In the presence of lensing, the correlation function is, however, anisotropic.

The proposed statistic is optimized to measure this anisotropy, which can be inverted to reconstruct the deflection angle.

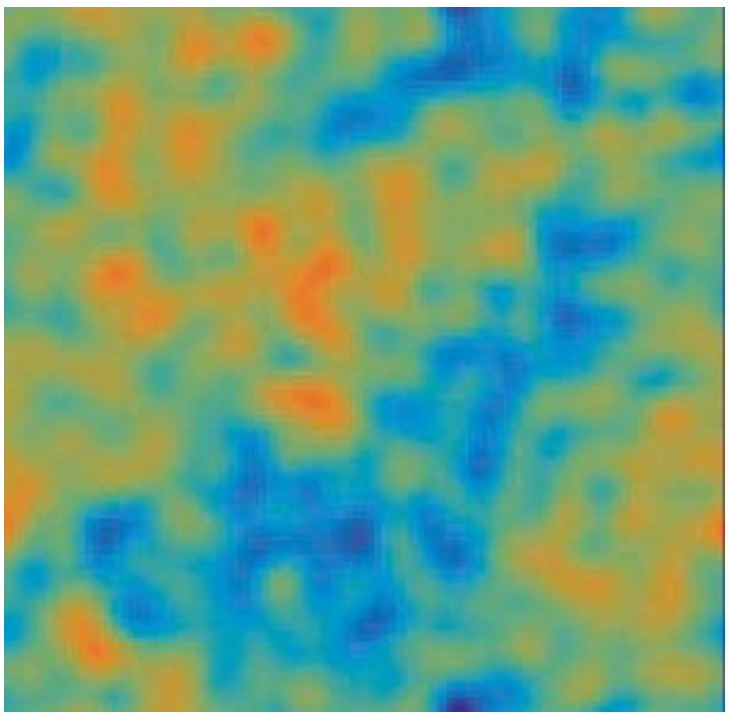
Cooray & Kesden 2002

CMB as a weak lensing experiment

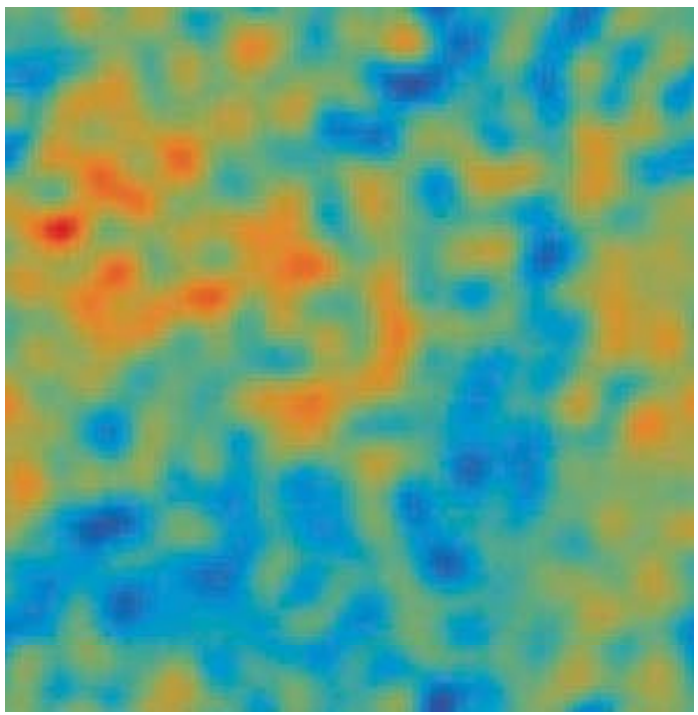
Squared Temperature-Squared Temperature Power Spectrum

(Other suggestions: temperature gradients
Seljak & Zaldarriaga; Bernardeau et al.)

Hu 2001
Cooray & Kesden 2002



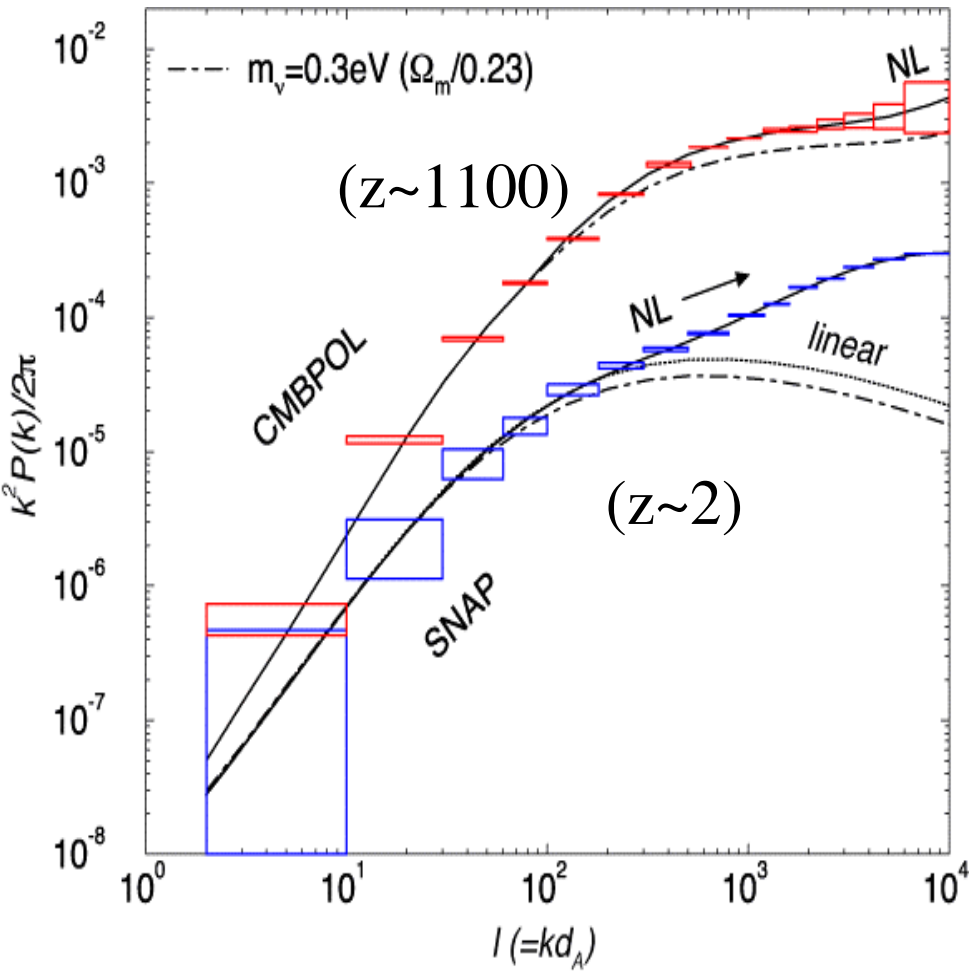
Input deflection (mass) field



Constructed deflection map with 1.5 arcmin beam and 27 μK arcmin noise

CMB as a weak lensing experiment

Lensing convergence

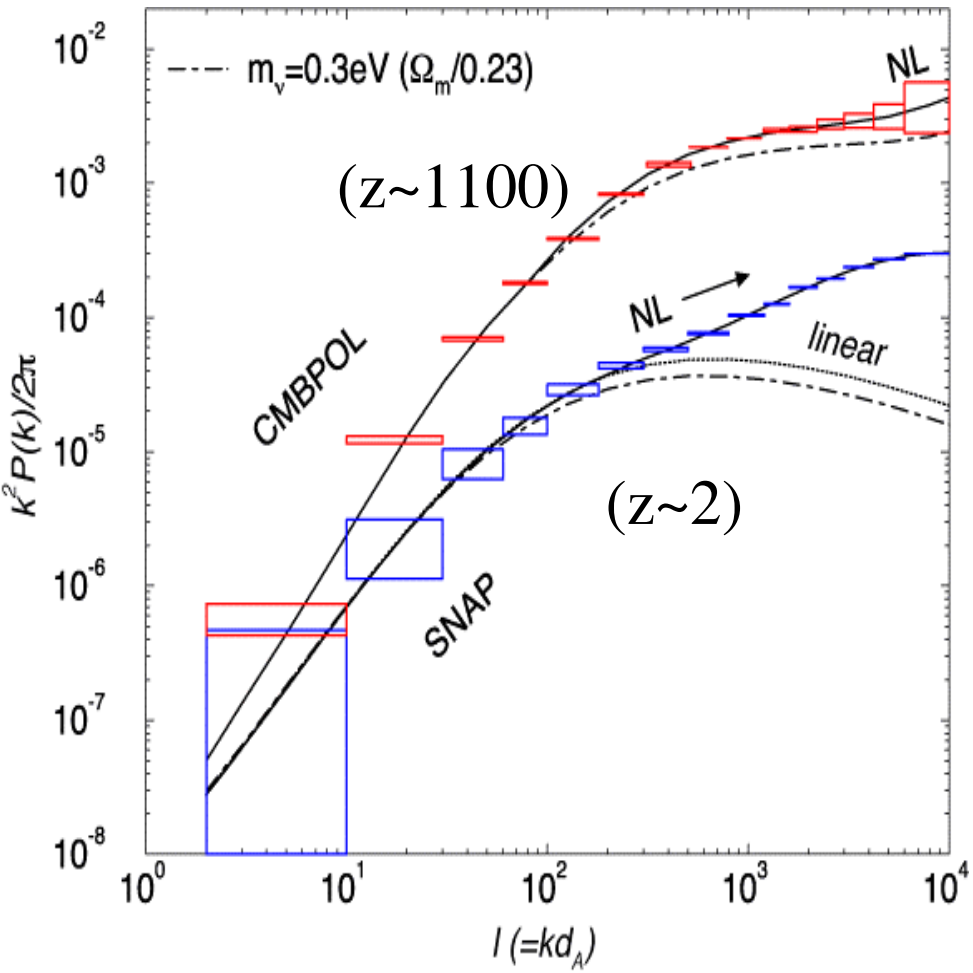


Expected Weak lensing results

(plotted is convergence power spectrum related to the integrated mass responsible for lensing)

CMB as a weak lensing experiment

Lensing convergence



Why do this?

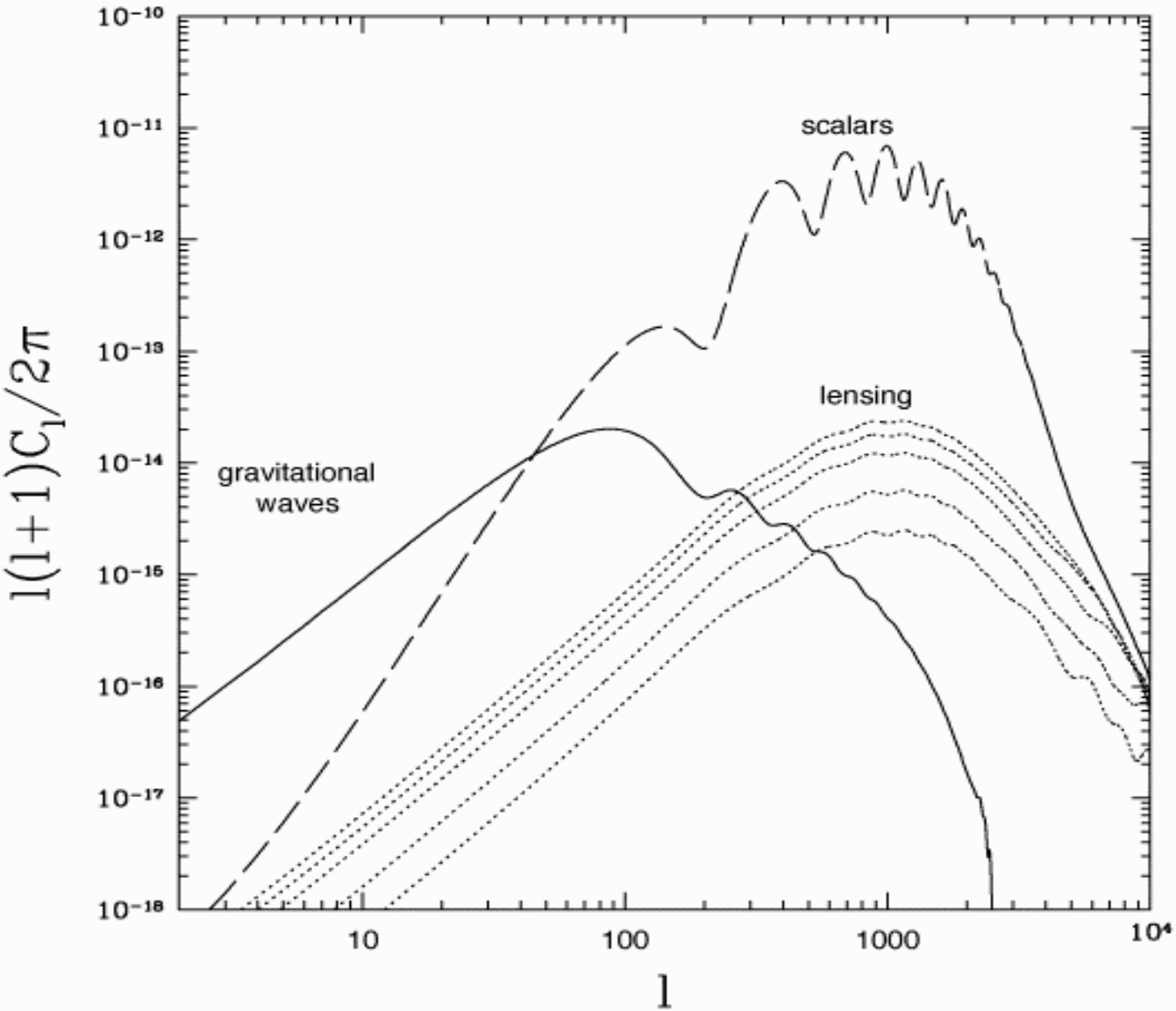
1. Source redshift is known (recombination)

2. Linear power spectrum - (cosmology)

3. Test evolution

4. Get this for free

Removing the confusions



As a function of z

z > 0

z > 1

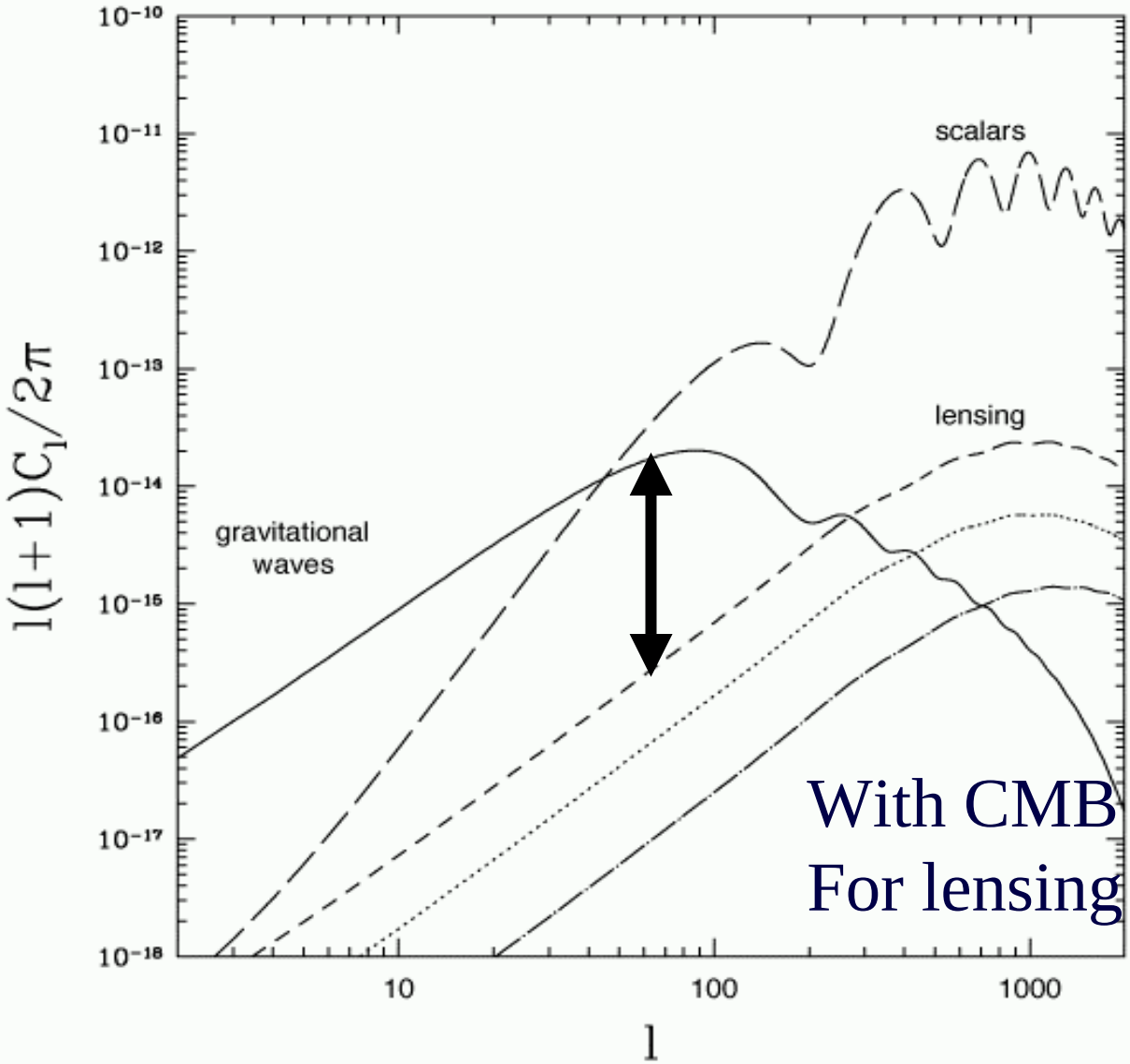
z > 2

z > 5

z > 10

Galaxy lensing cannot be used to correct Polarization

Removing the confusions

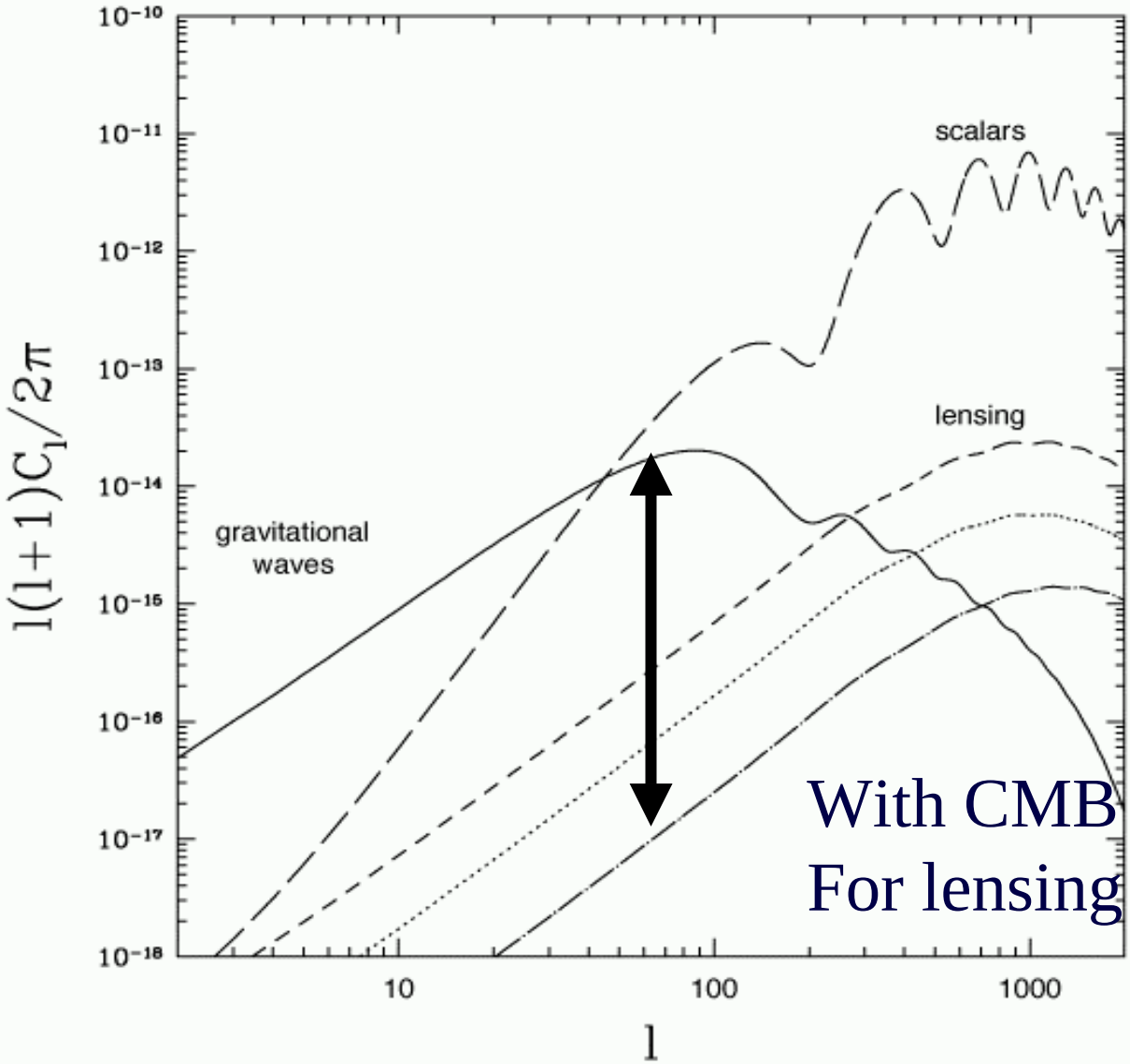


Extract with a noise contribution below an order of magnitude of the signal

(Kesden et al. 2002; Knox & Song 2002)

With CMB temp. data cleaned For lensing

Removing the confusions



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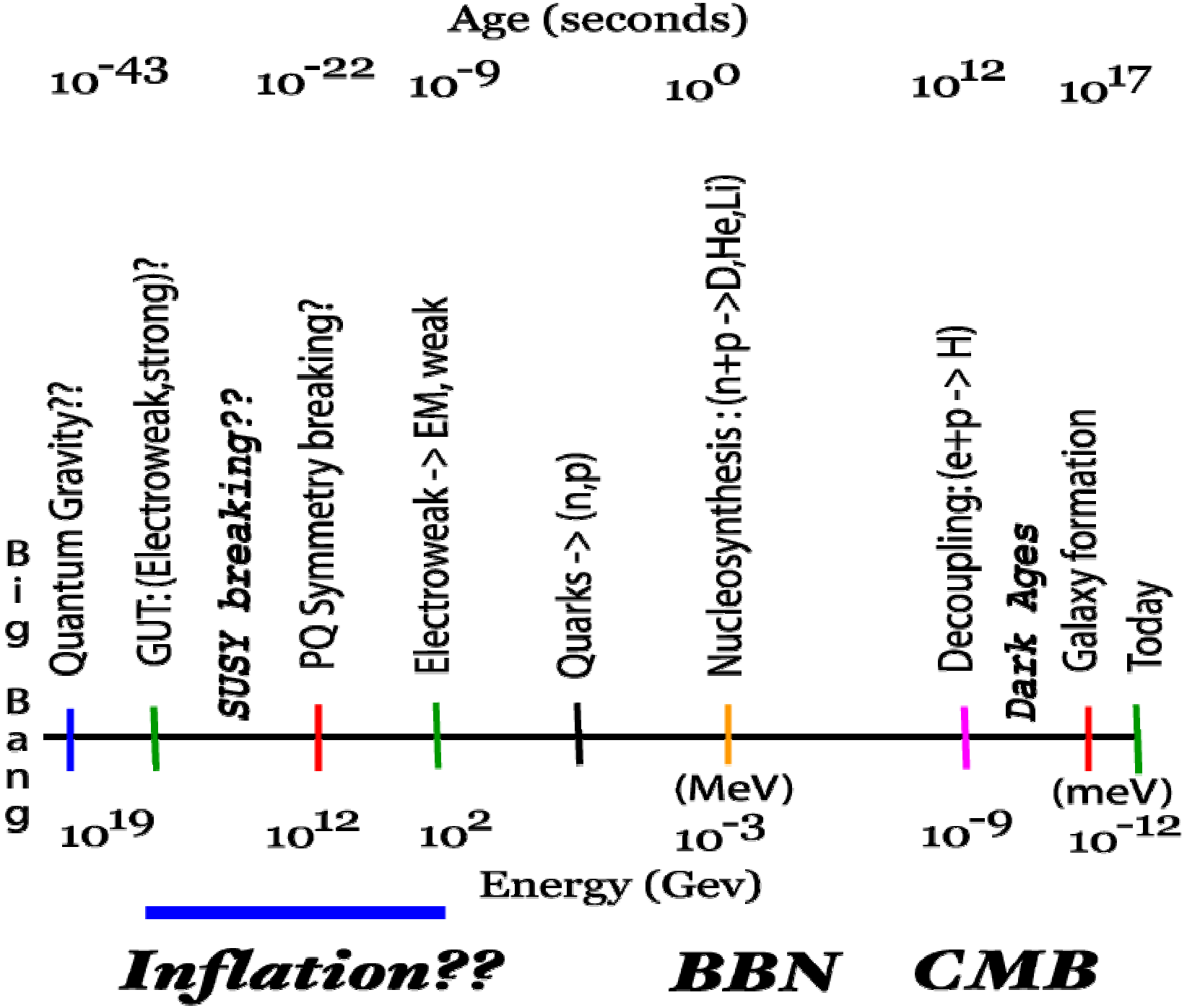
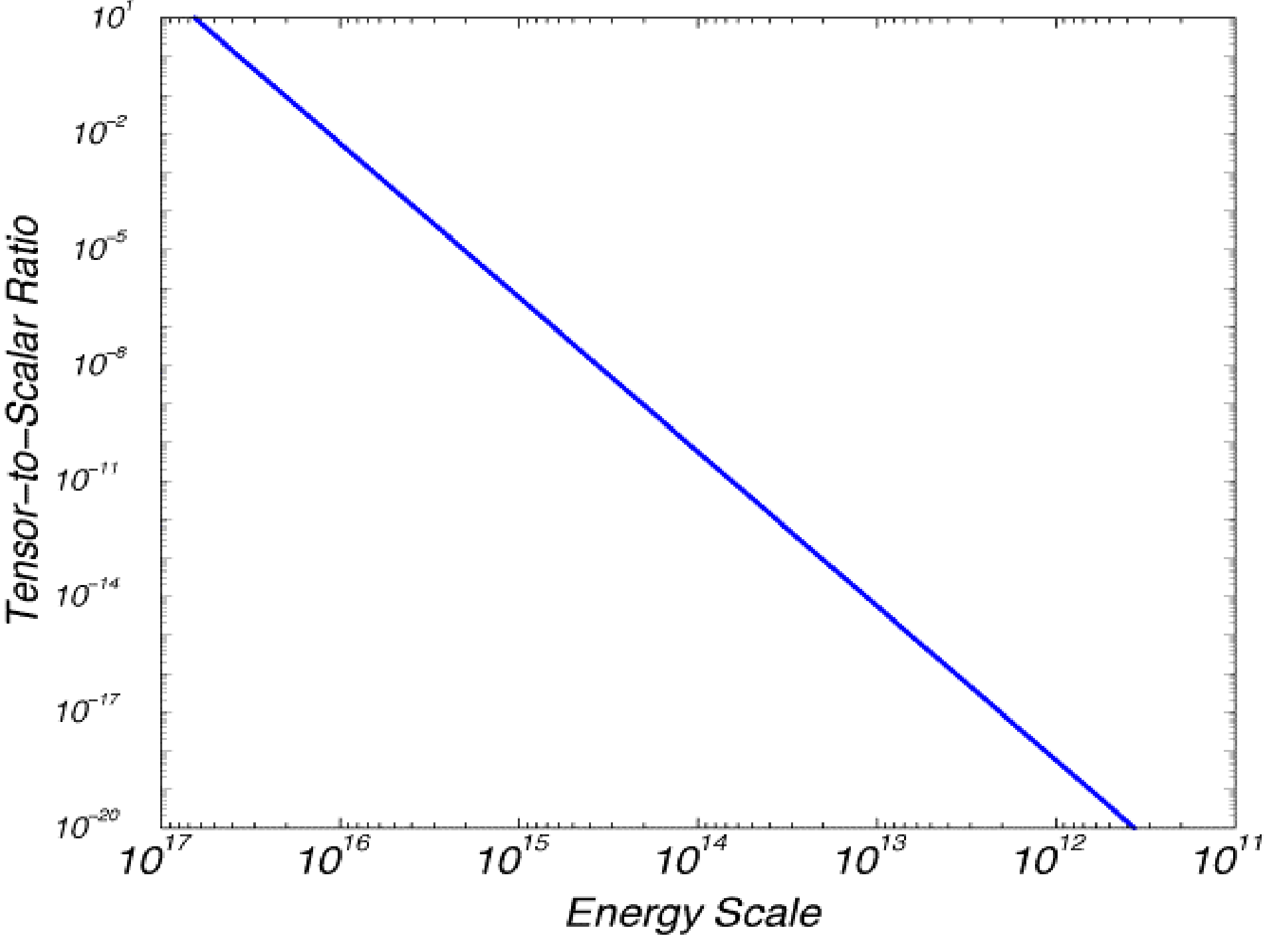
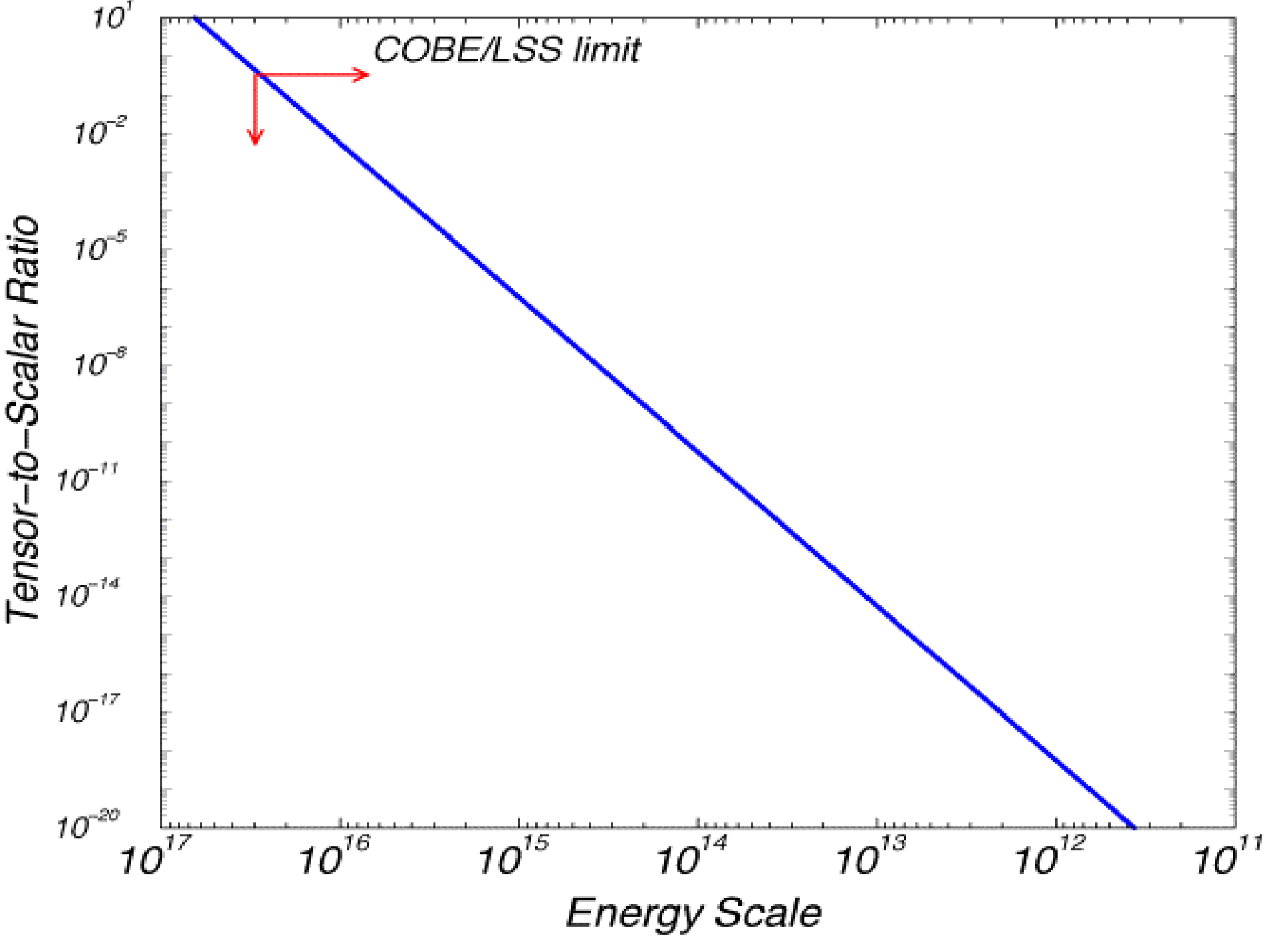
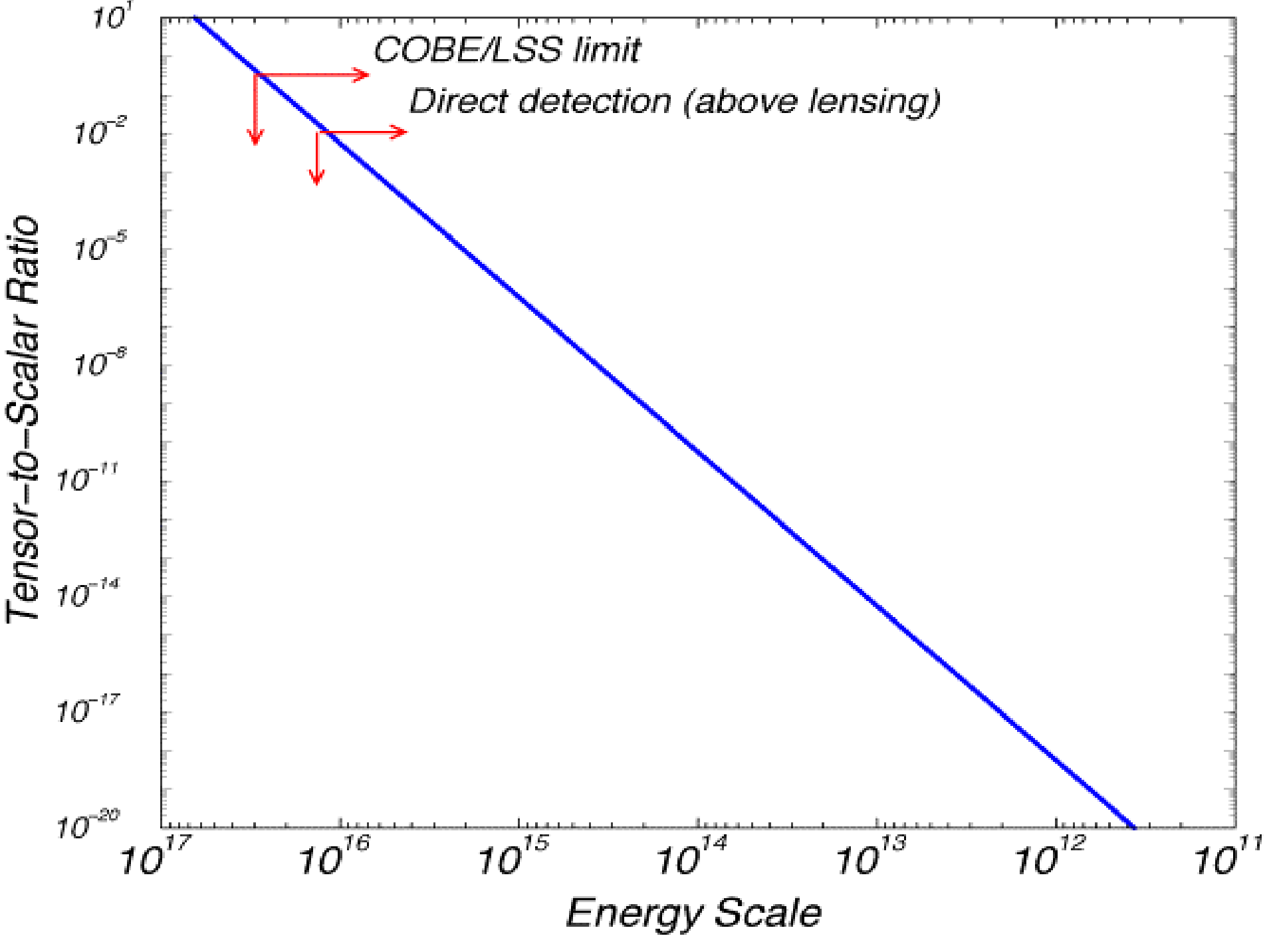
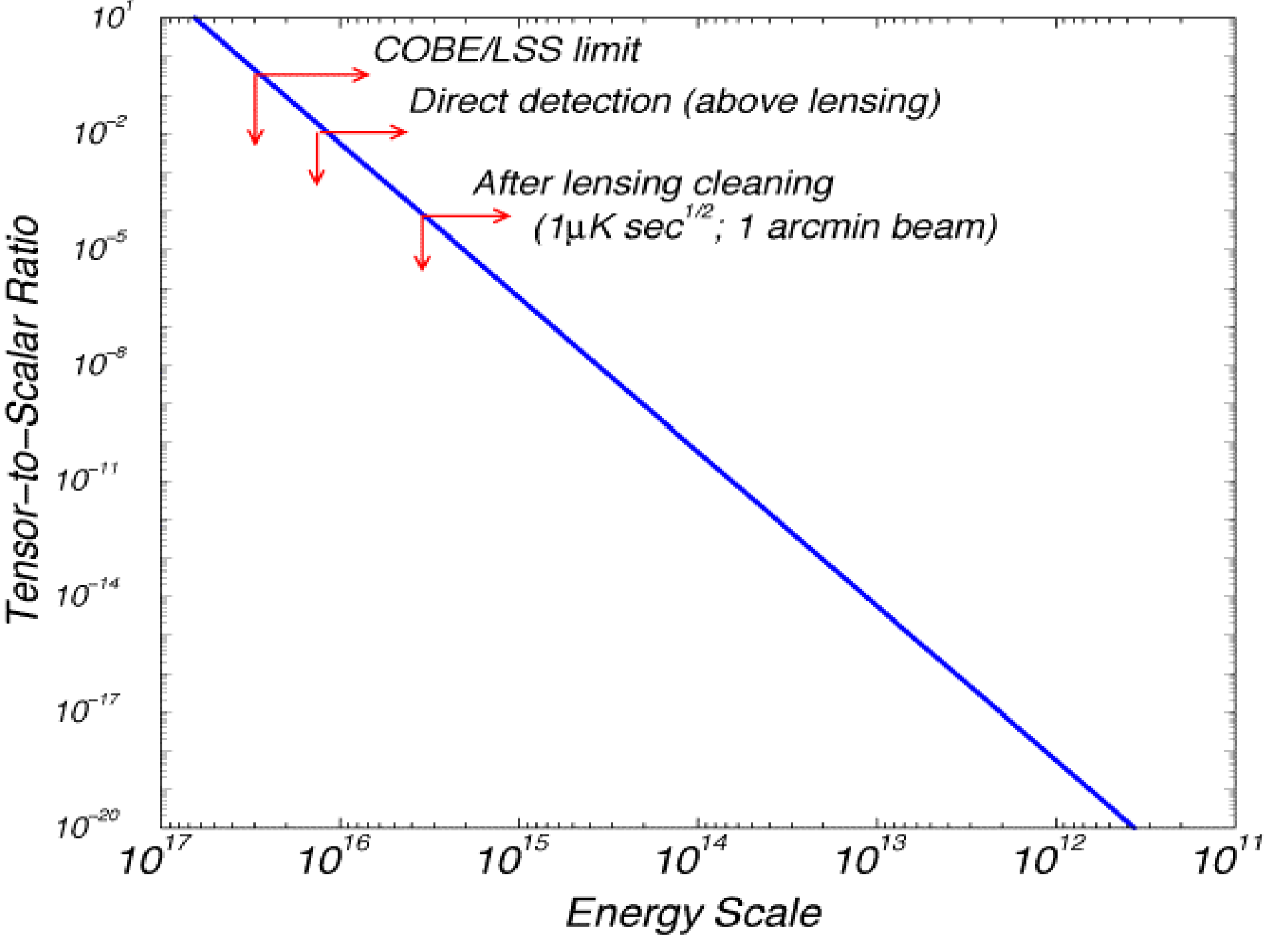
With CMB temp. data cleaned For lensing

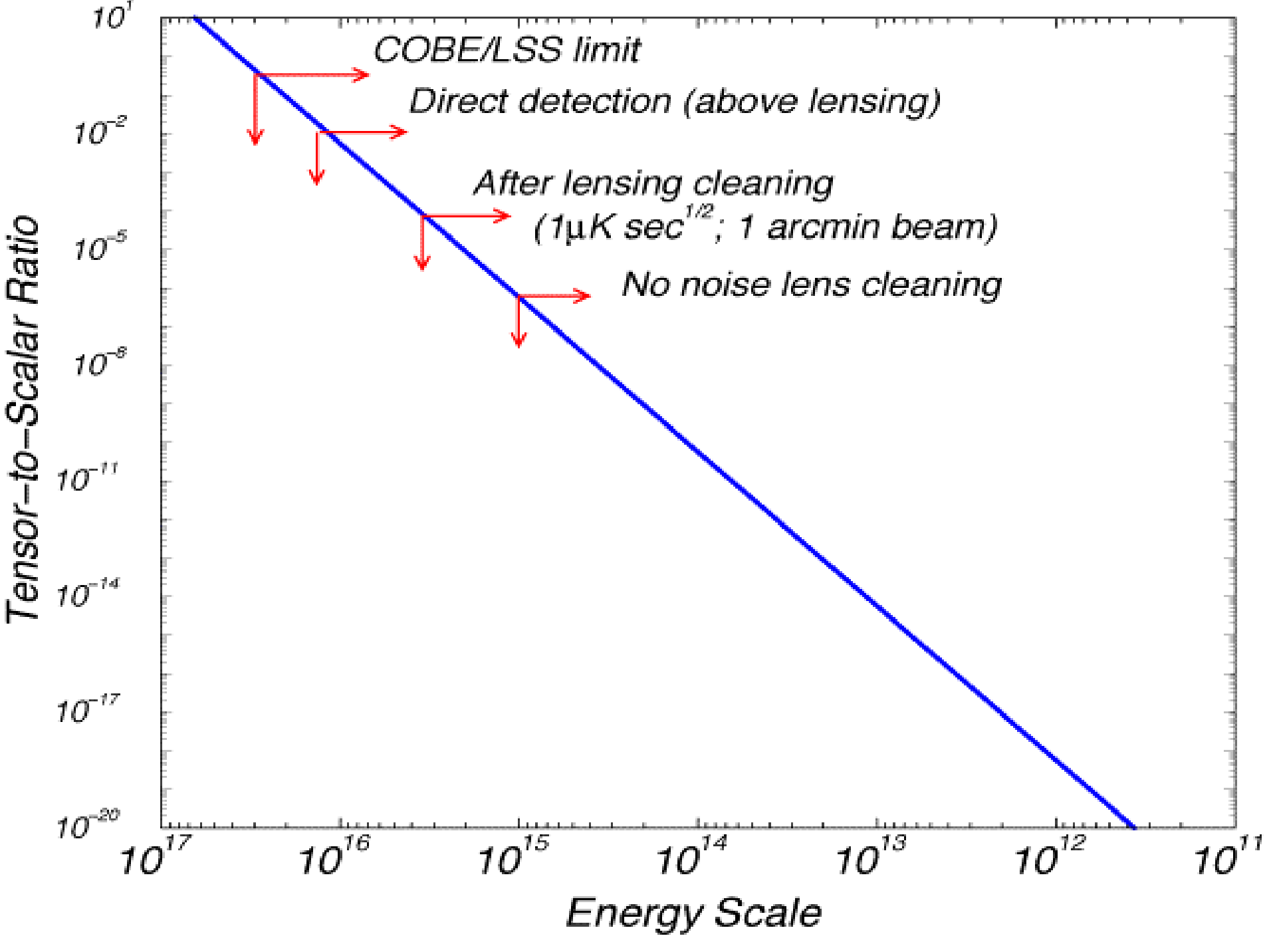

Age (seconds)
10^-43
10^-22
10^-9
10^0
10^12
10^17
Big Bang
Quantum Gravity??
GUT:(Electroweak,strong)?
susy breaking??
PQ Symmetry breaking?
Electroweak -> EM, weak
Quarks -> (n,p)
Nucleosynthesis:(n+p->D,He,Li)
Decoupling:(e+p -> H)
Dark Ages
Galaxy formation
Today
10^19
10^12
10^2
(MeV)
10^-3
10^-9
(meV)
10^-12
Energy (Gev)
Inflation??
BBN
CMB

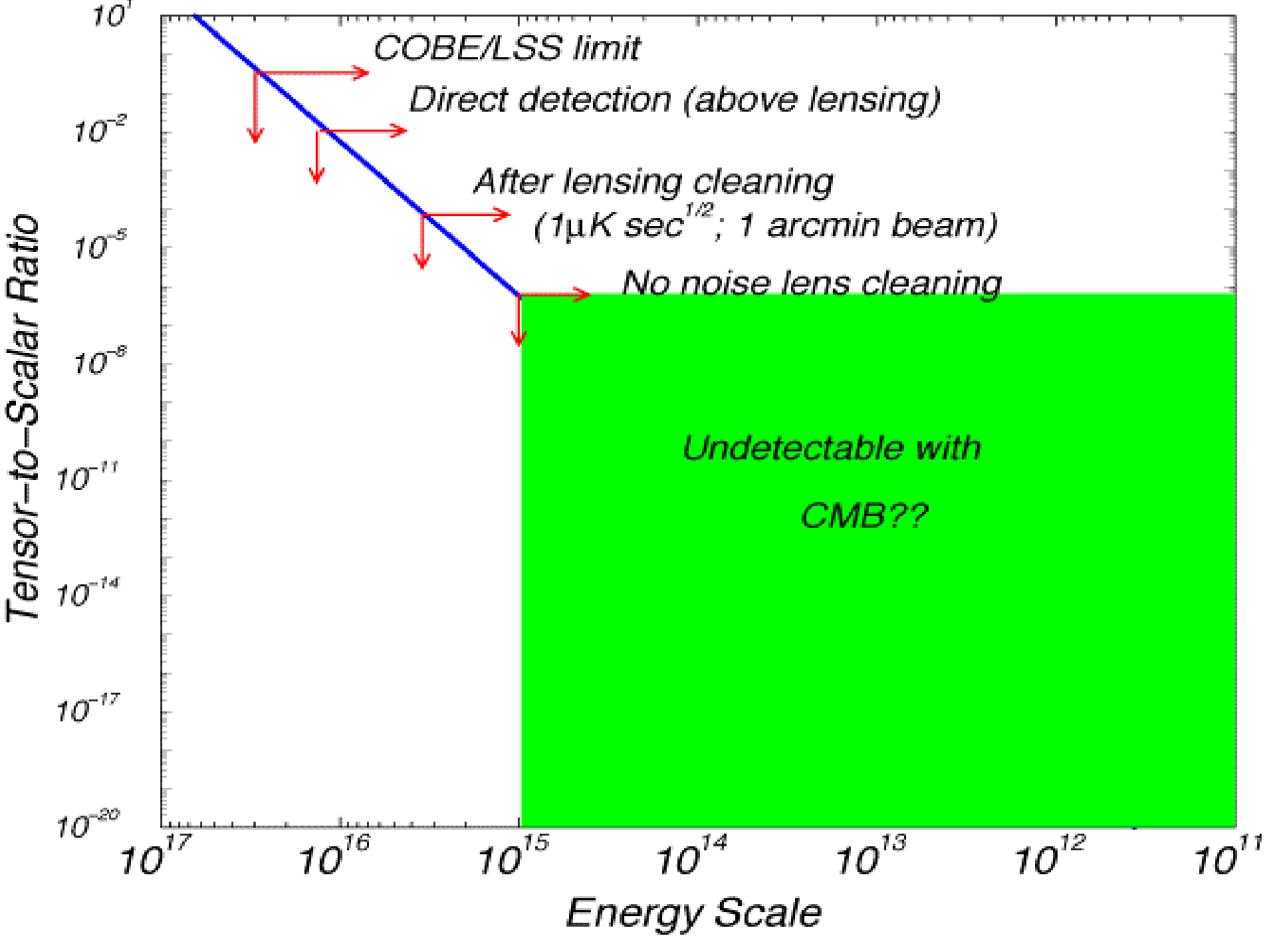

Tensor–to–Scalar Ratio
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-20}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
Energy Scale

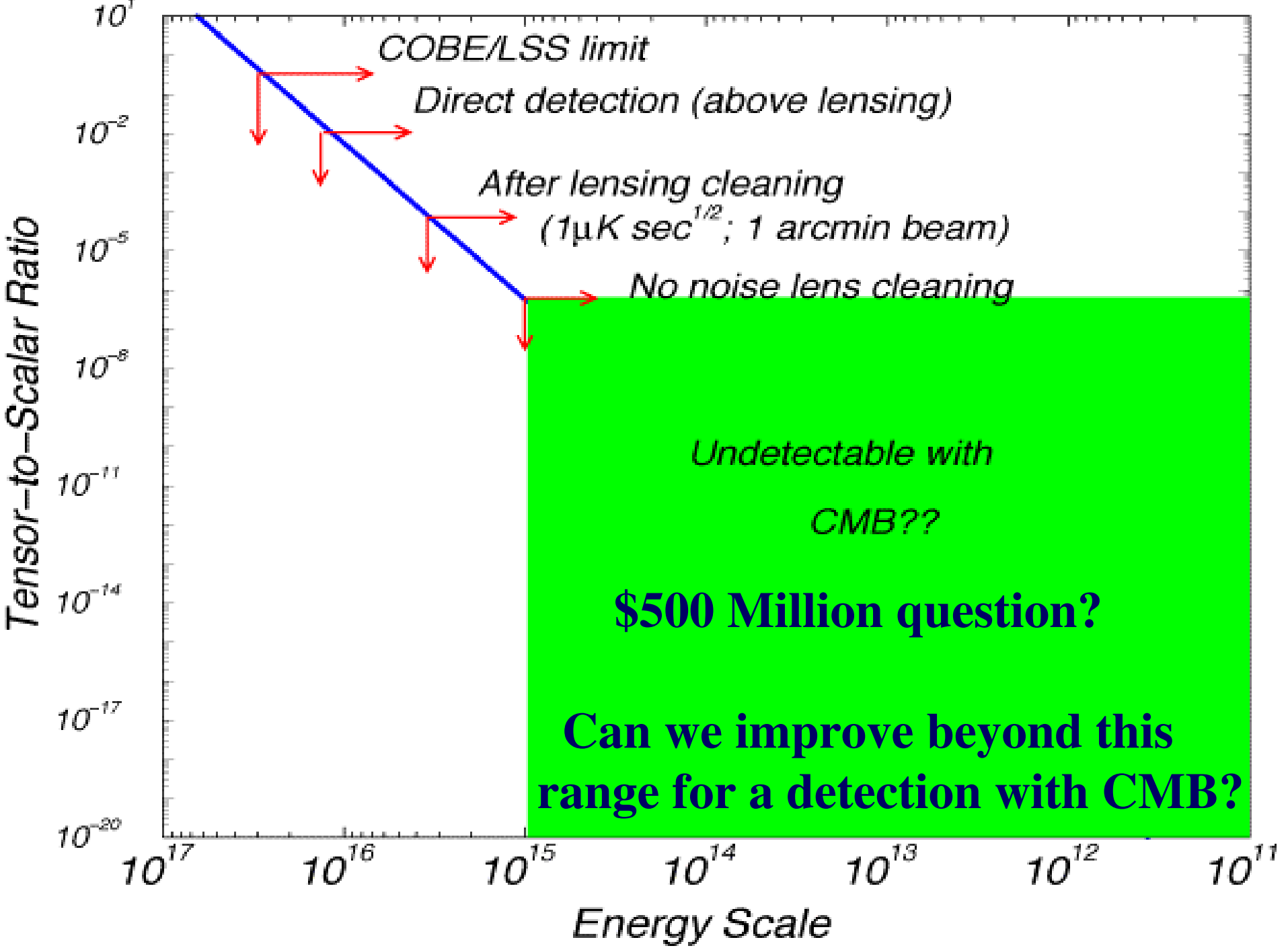

COBE/LSS limit
Tensor–to–Scalar Ratio
Energy Scale
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-20}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}

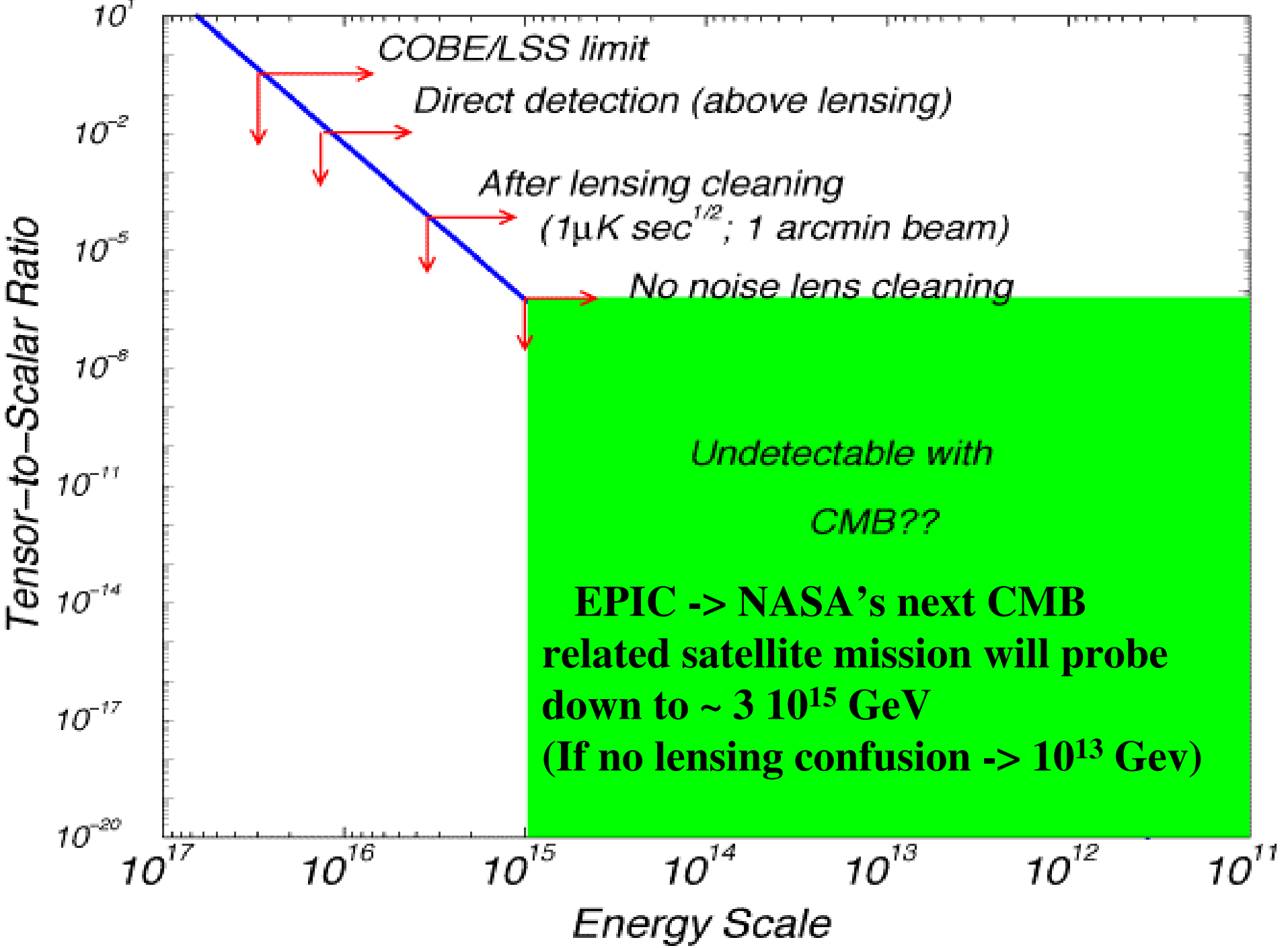

COBE/LSS limit
Direct detection (above lensing)
Tensor–to–Scalar Ratio
Energy Scale
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-20}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}


COBE/LSS limit
Direct detection (above lensing)
After lensing cleaning
(1μK sec^1/2; 1 arcmin beam)
Tensor–to–Scalar Ratio
Energy Scale
10^1
10^-2
10^-5
10^-8
10^-11
10^-14
10^-17
10^-20
10^17
10^16
10^15
10^14
10^13
10^12
10^11

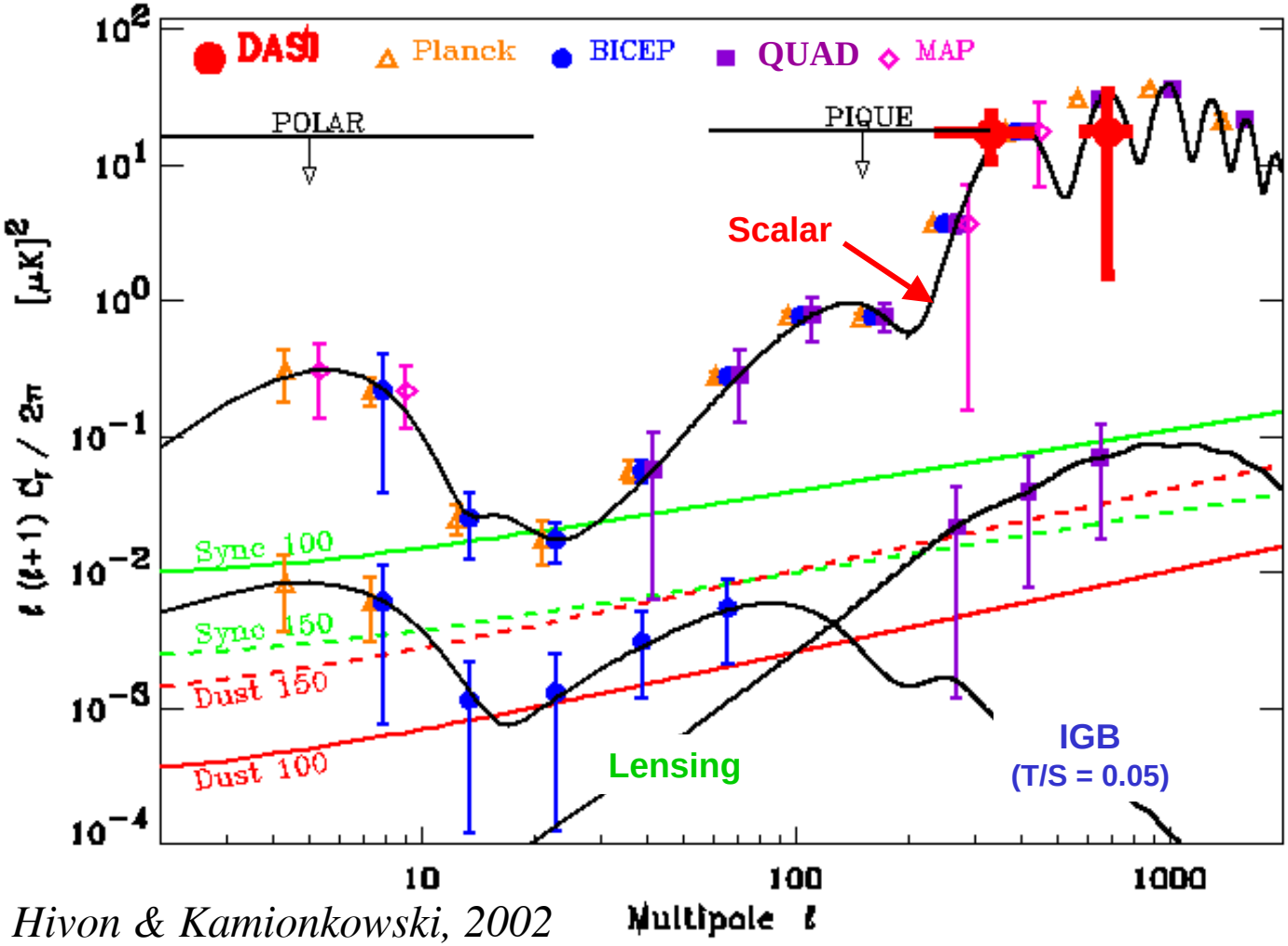

COBE/LSS limit
Direct detection (above lensing)
After lensing cleaning
(1μK sec^1/2; 1 arcmin beam)
No noise lens cleaning
Tensor–to–Scalar Ratio
Energy Scale
10^1
10^-2
10^-5
10^-8
10^-11
10^-14
10^-17
10^-20
10^17
10^16
10^15
10^14
10^13
10^12
10^11


COBE/LSS limit
Direct detection (above lensing)
After lensing cleaning
(1μK sec^1/2; 1 arcmin beam)
No noise lens cleaning
Undetectable with
CMB??
Tensor–to–Scalar Ratio
Energy Scale
10^1
10^-2
10^-5
10^-8
10^-11
10^-14
10^-17
10^-20
10^17
10^16
10^15
10^14
10^13
10^12
10^11

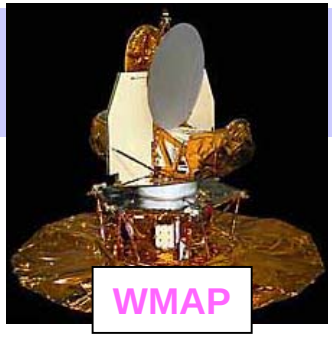

COBE/LSS limit
Direct detection (above lensing)
After lensing cleaning
(1μK sec^1/2; 1 arcmin beam)
No noise lens cleaning
Undetectable with
CMB??
$500 Million question?
Can we improve beyond this range for a detection with CMB?
Tensor–to–Scalar Ratio
Energy Scale
10^-1
10^-2
10^-5
10^-8
10^-11
10^-14
10^-17
10^-20
10^17
10^16
10^15
10^14
10^13
10^12
10^11

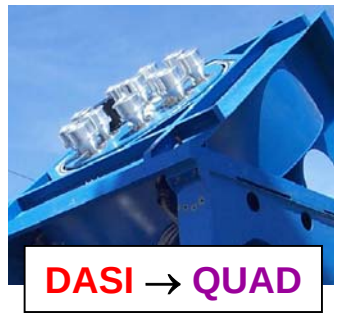

COBE/LSS limit
Direct detection (above lensing)
After lensing cleaning
(1μK sec^1/2; 1 arcmin beam)
No noise lens cleaning
Undetectable with
CMB??
EPIC -> NASA's next CMB related satellite mission will probe down to ~ 3 10^15 GeV
(If no lensing confusion -> 10^13 Gev)
Tensor-to-Scalar Ratio
Energy Scale
10^-1
10^-2
10^-5
10^-8
10^-11
10^-14
10^-17
10^-20
10^17
10^16
10^15
10^14
10^13
10^12
10^11

The Not-So Distant Future



Hivon & Kamionkowski, 2002

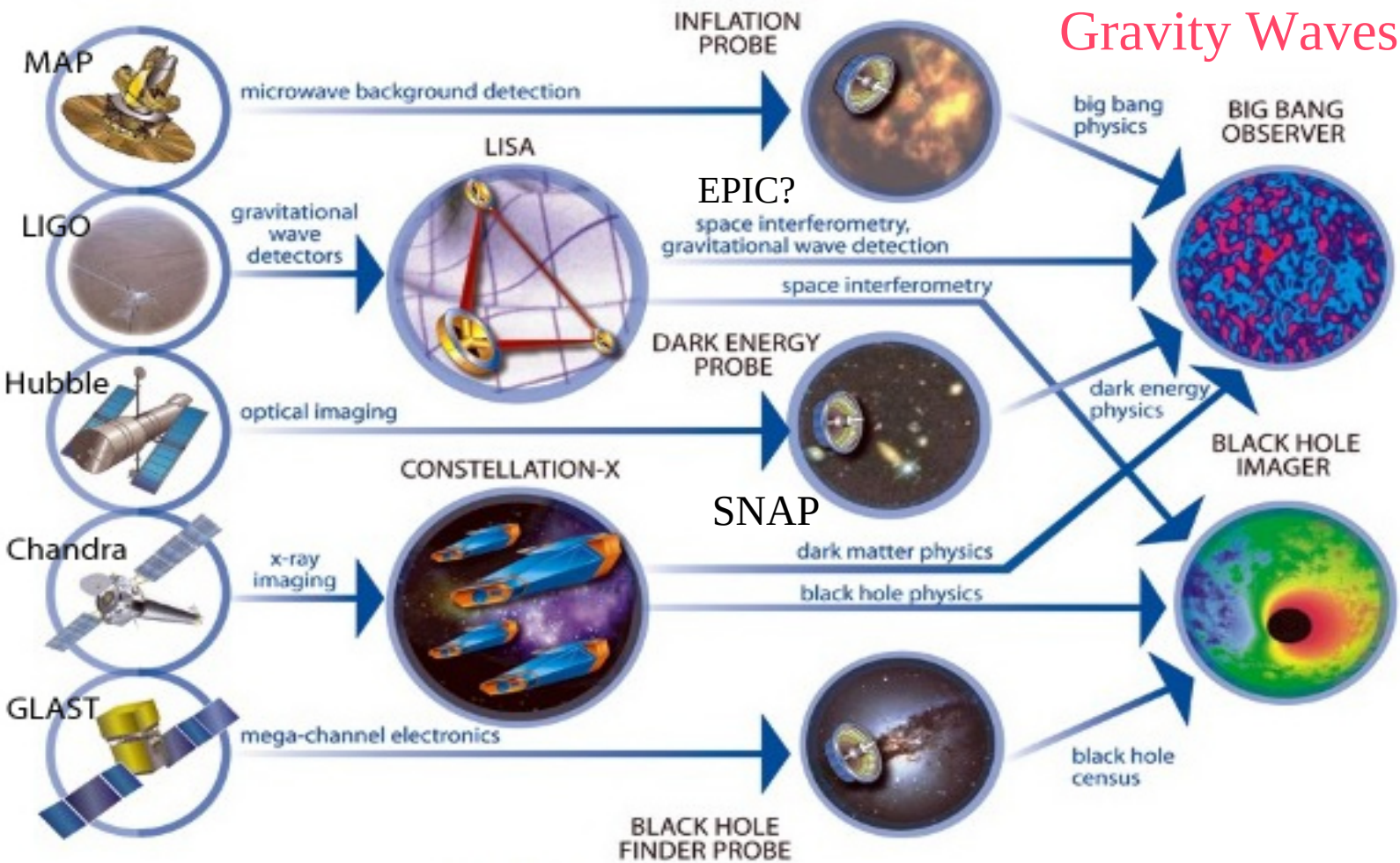




We're soon to learn a great deal more about:

- **Scalar and lensing signals**
- **Methodology**
- **Foregrounds**
- **Technology**

NASA's *Beyond Einstein* Program

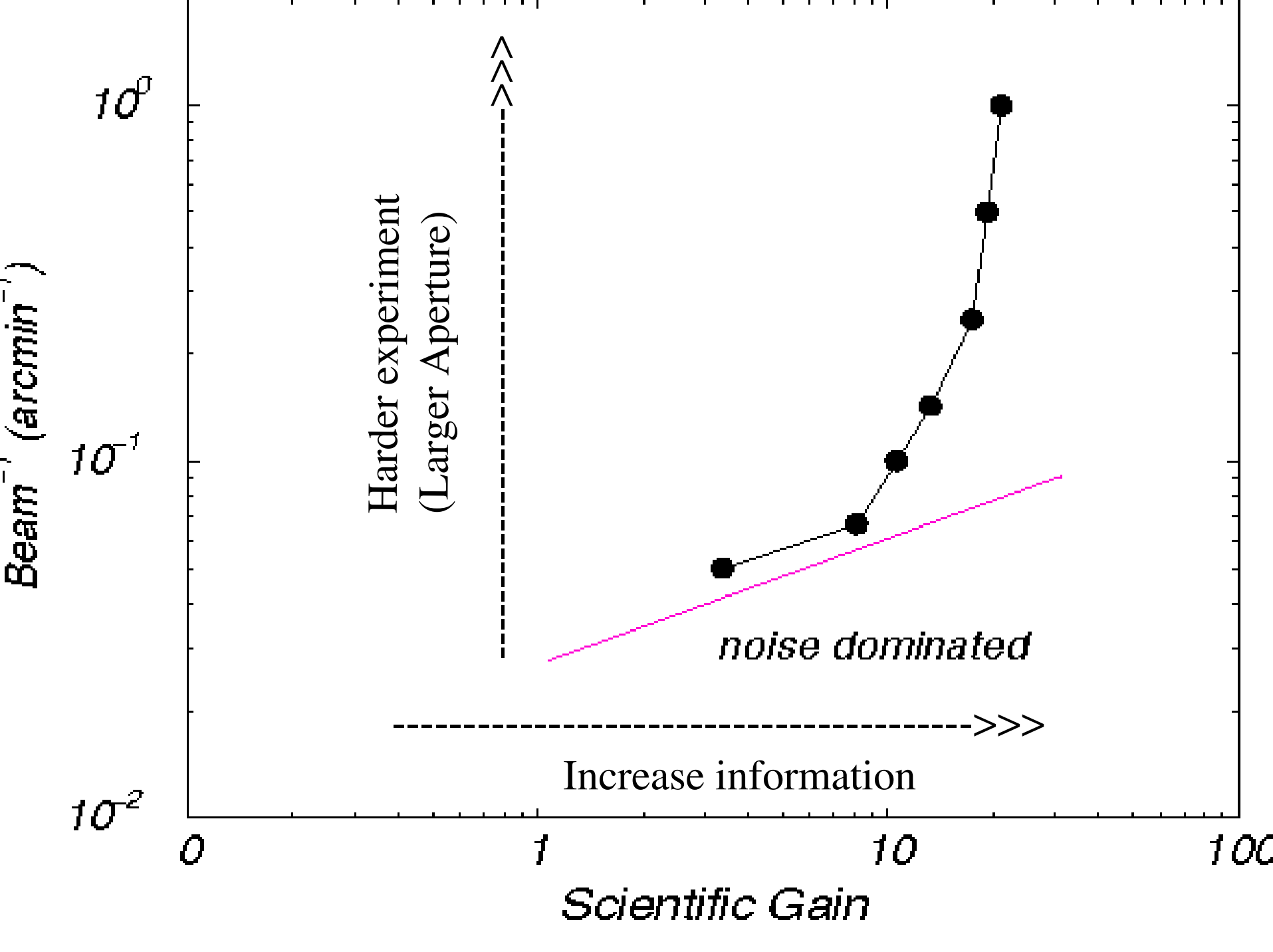


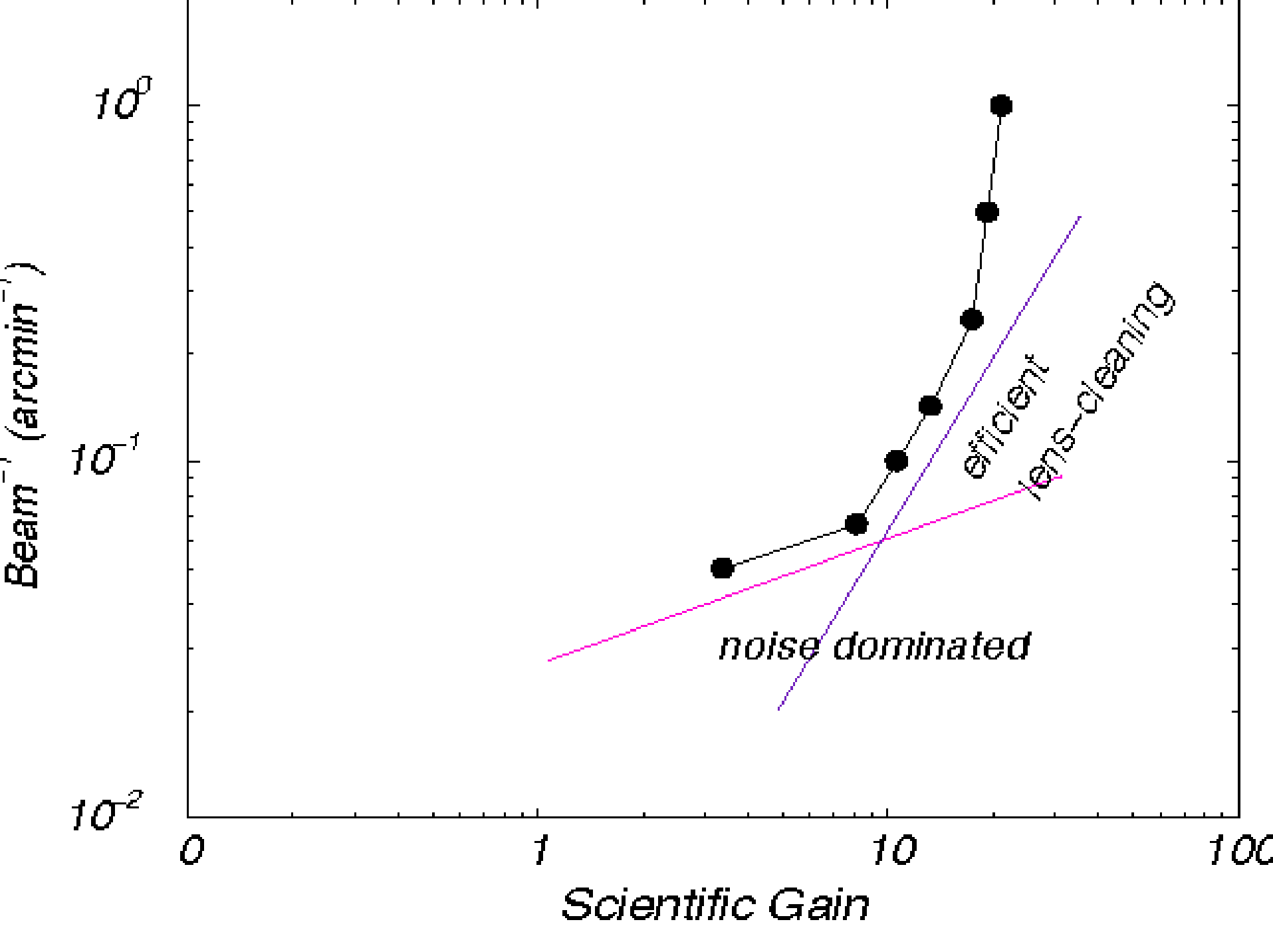
Current Missions

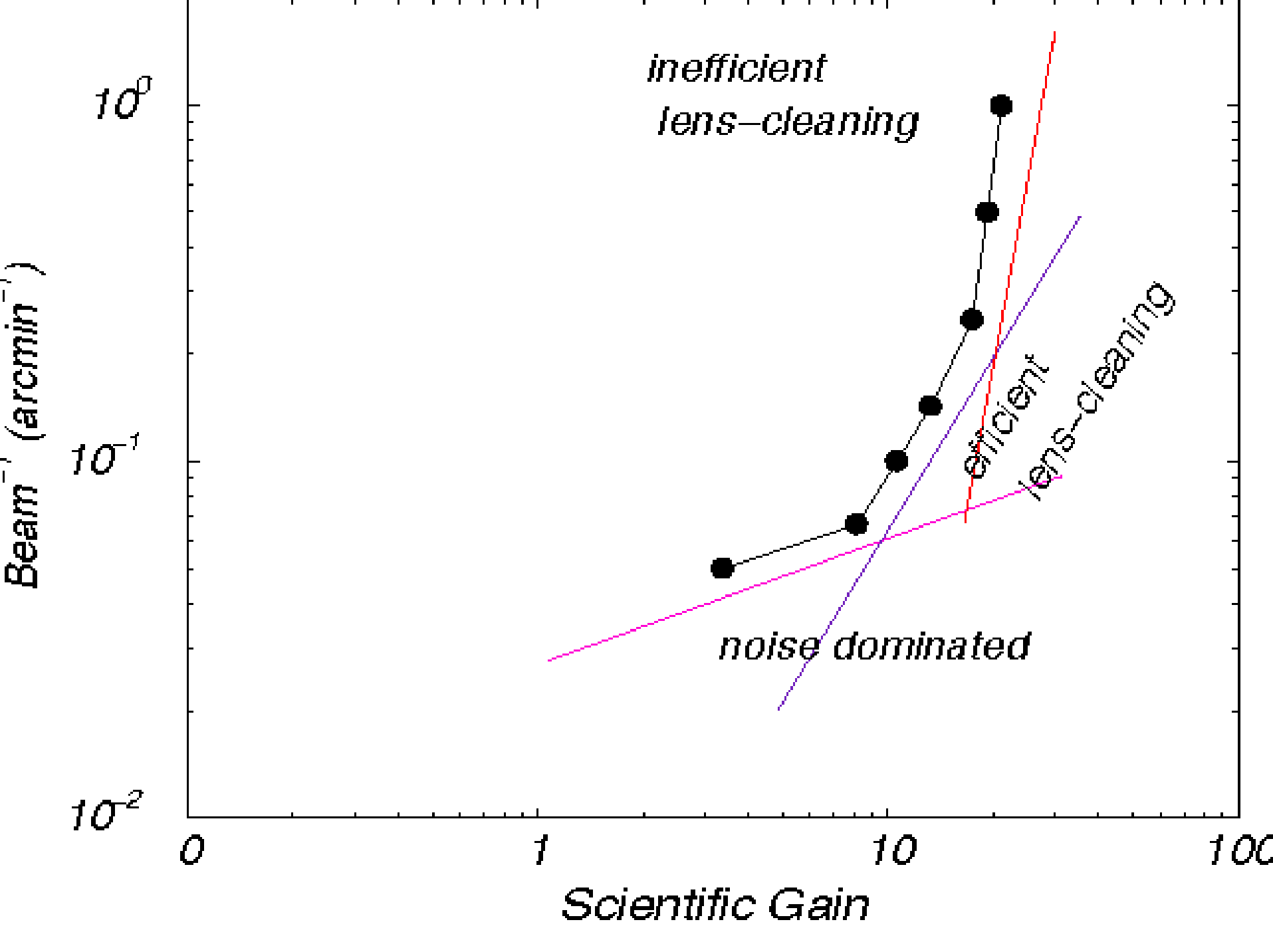
Broad sciences/ Major resources Community-class

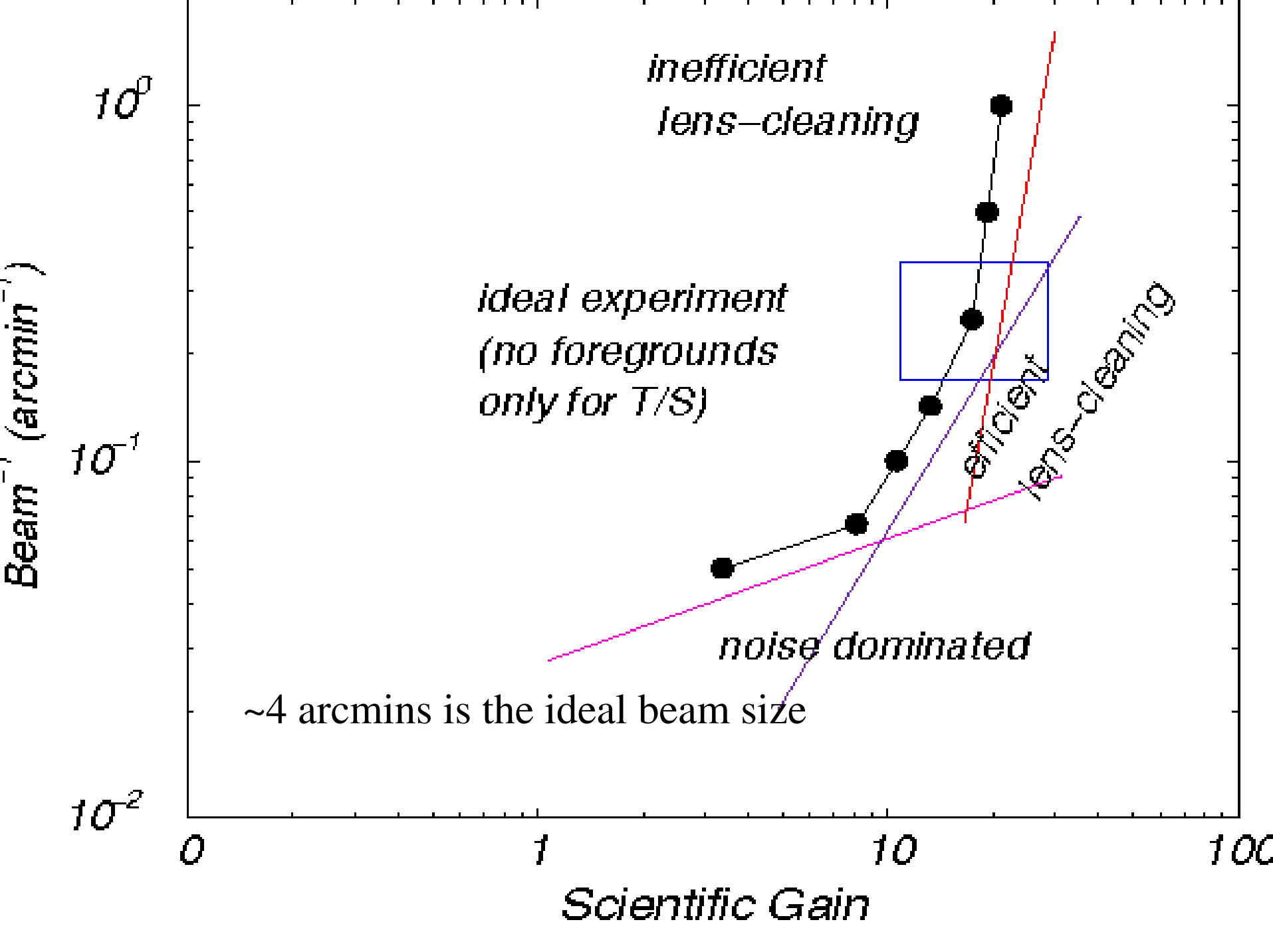
Focused/narrow sciences PI-class

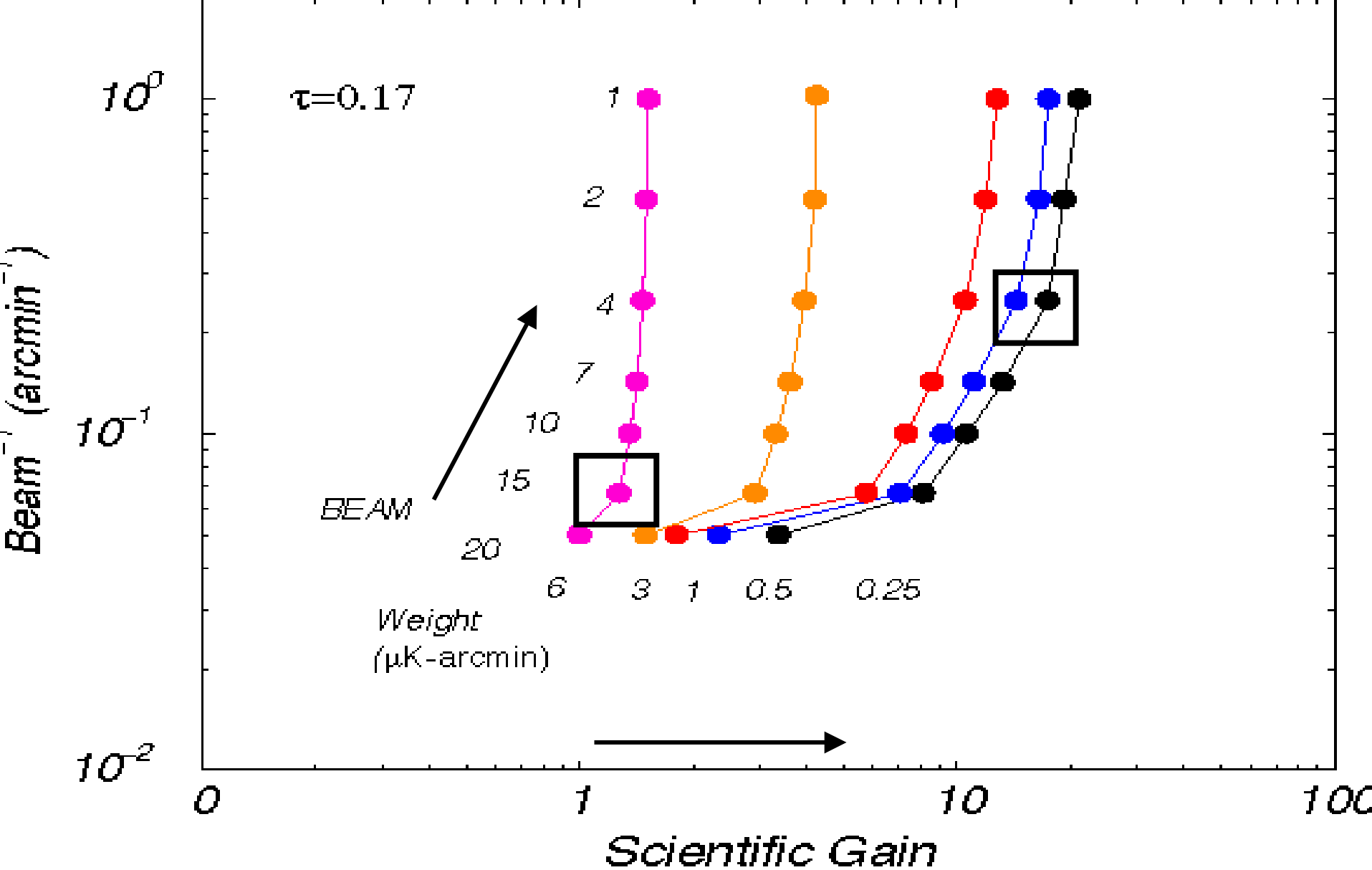
After significant developments (both hardware/theory) > 25 year time-scales


10^{0}
10^{-1}
10^{-2}
$Beam^{-1}$ $(arcmin^{-1})$
Harder experiment
(Larger Aperture)
>>>
noise dominated
Increase information
>>>
0
1
10
100
Scientific Gain


10^0
10^{-1}
10^{-2}
$Beam^{-1}$ $(arcmin^{-1})$
0
1
10
100
Scientific Gain
noise dominated
efficient
lens-cleaning


inefficient
lens–cleaning
efficient
lens–cleaning
noise dominated
10^0
10^{-1}
10^{-2}
$Beam^{-1}$ (arcmin^{-1})
0
1
10
100
Scientific Gain


inefficient
lens–cleaning
ideal experiment
(no foregrounds
only for T/S)
efficient
lens–cleaning
noise dominated
~4 arcmins is the ideal beam size
10^0
10^{-1}
10^{-2}
Beam^{-1} (arcmin^{-1})
0
1
10
100
Scientific Gain



Ideal beam size depends on noise. For weight < 1 muK-arcmins, 4 arcmins is adequate.

EPIC:
Exploration Probe of Inflationary Cosmology

Selected by NASA for Phase A study and technology demonstration

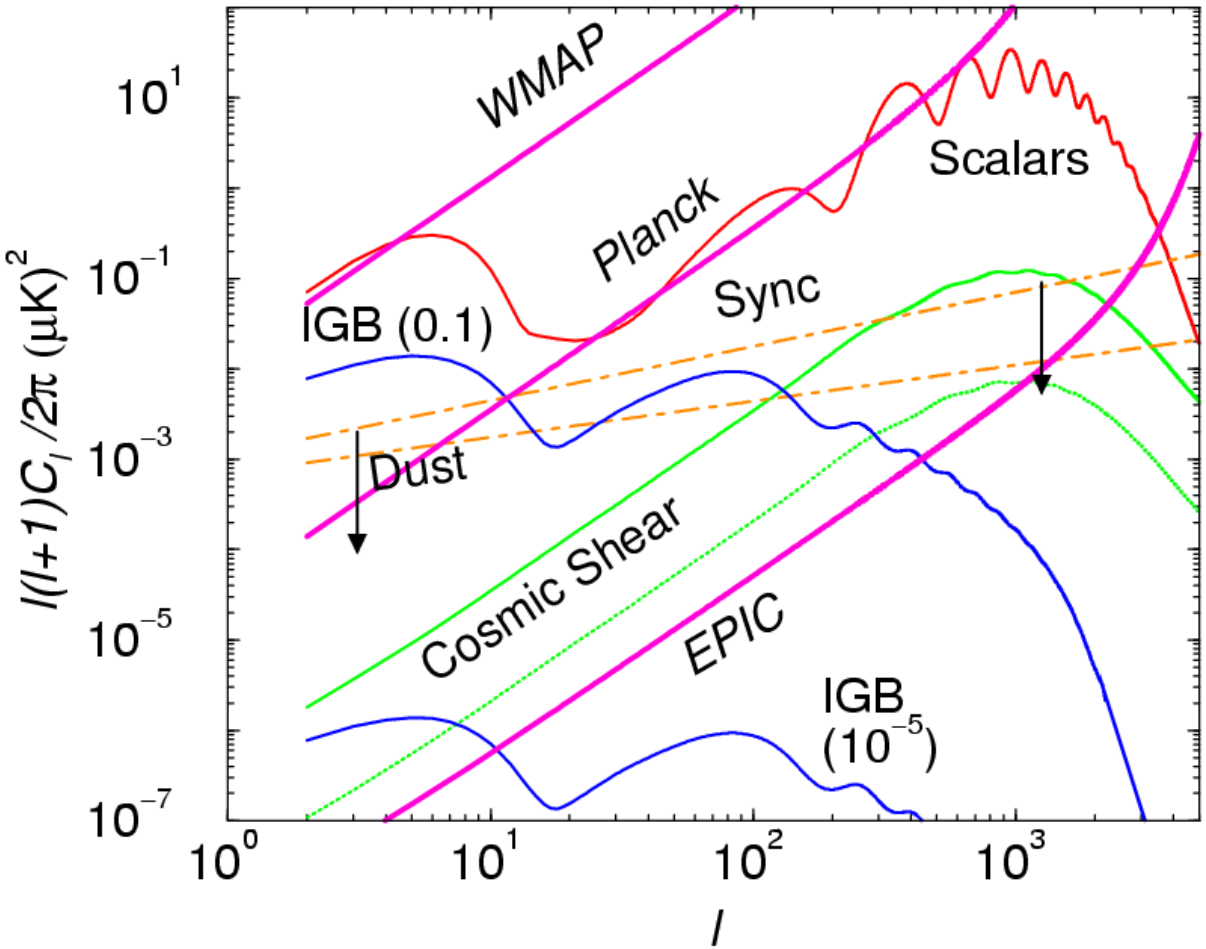
Final selection/decision in about 2-3 years with launch ~ 2014 (?).

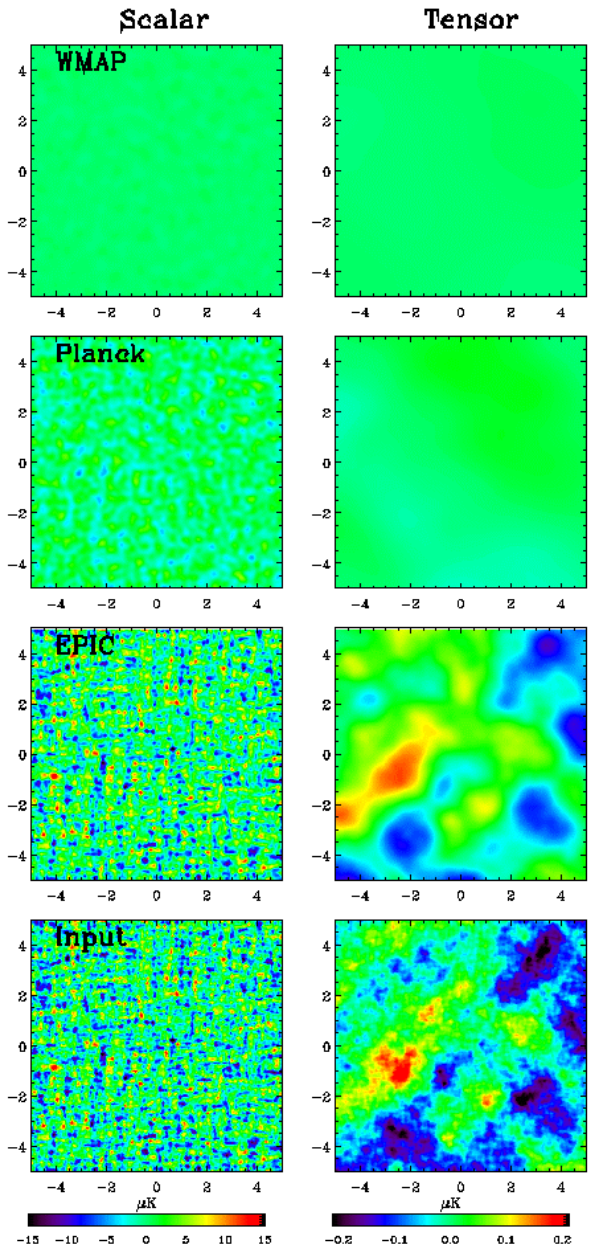
Collaboration of ~60 members.
(mostly west-coast institutions)

Primary working group:

James Bock (PI; JPL)
Asantha Cooray
Mark Dragovan
Kris Gorski
Shaul Hanany
Eric Hivon
Marc Kamionkowski
Brian Keating
Andrew Lange
Charles Lawrence
Adrian Lee
Mike Seiffert

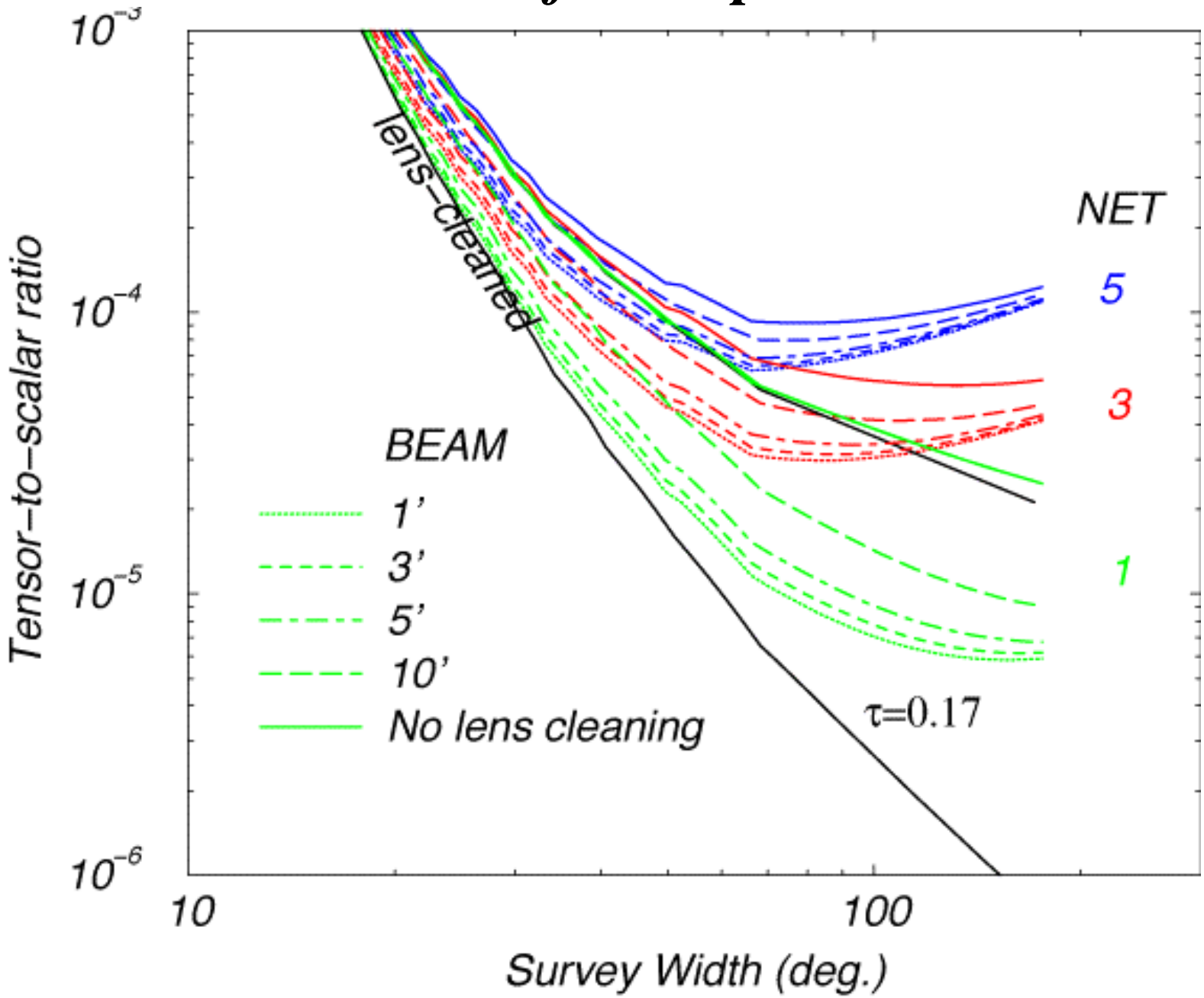
EPIC: CMB Polarization from Space





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

What kind of an experiment?



Future Focal Plane Sensitivities

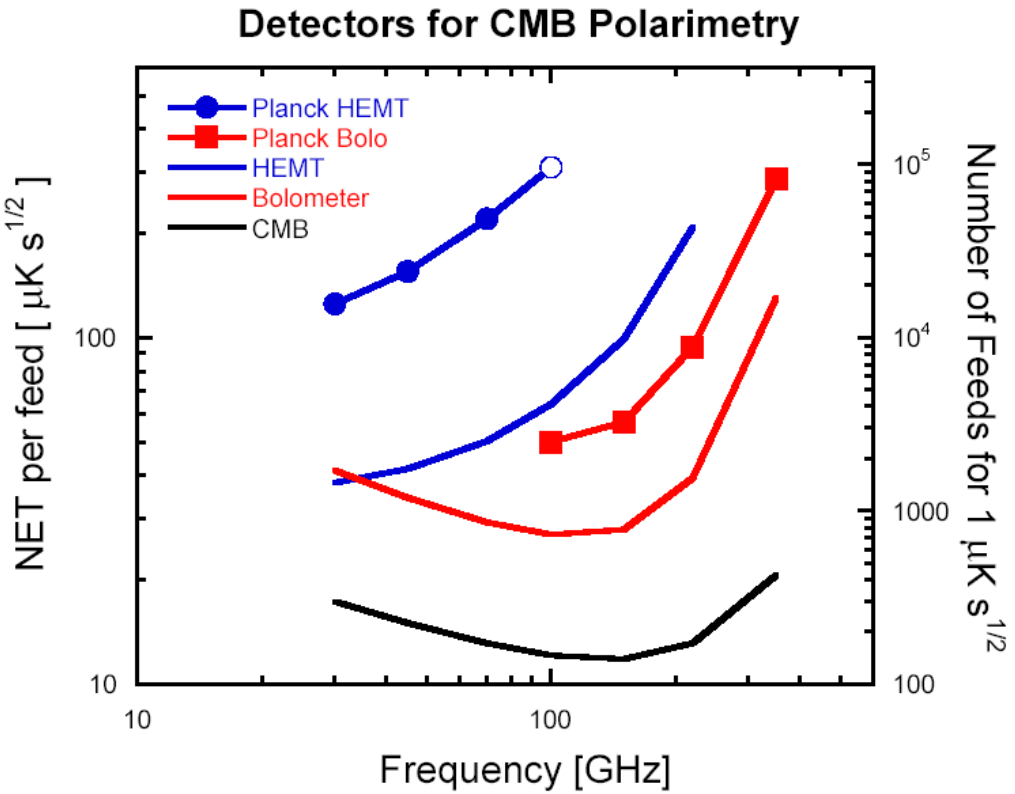
Planck bolos near photon noise limit

Need arrays for improved sensitivity

- ~10^4 detectors
- polarization sensitivity
- collimated beams
- physically large
- *no* mixed focal plane technology

Current and future focal planes

	Future		Planck	
Freq	NET (calc)	# feeds for 1 uK√ s	NET (goal)	# feeds
30	38	1500	125	2
45	42	1750	155	3
70	25	750	220	6
100	25	750	55	4
150	25	750	57	4
220	38	1500	95	4
350			290	4



HEMTs vs. **Bolometers**

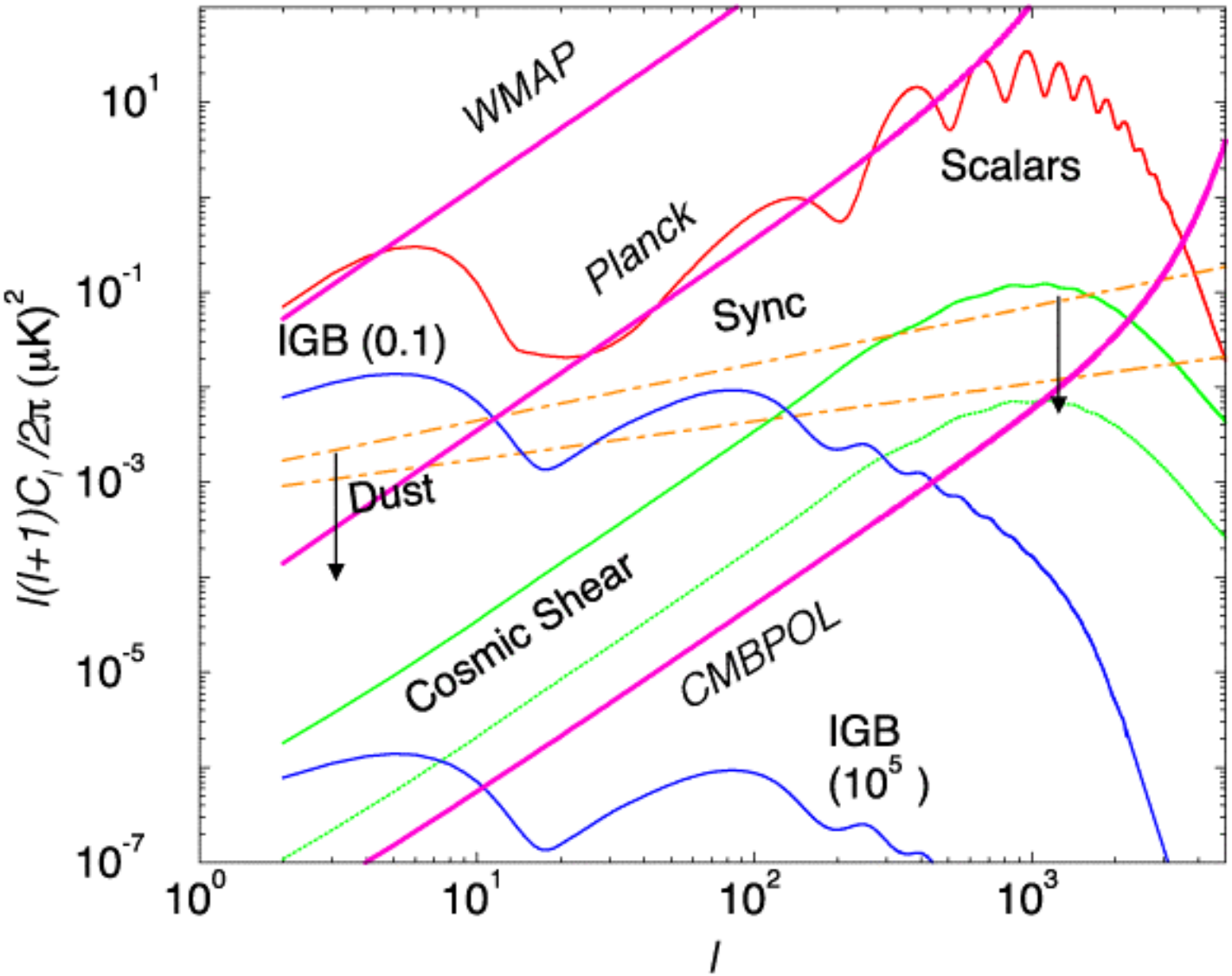
$T_A = 3h\nu/k$ — $\eta_{opt} = 50\ \%$

$\Delta\nu/\nu = 30\ \%$ — $\Delta\nu/\nu = 30\ \%$

Q&U / feed — $Q_{max}/Q_0 = 5$

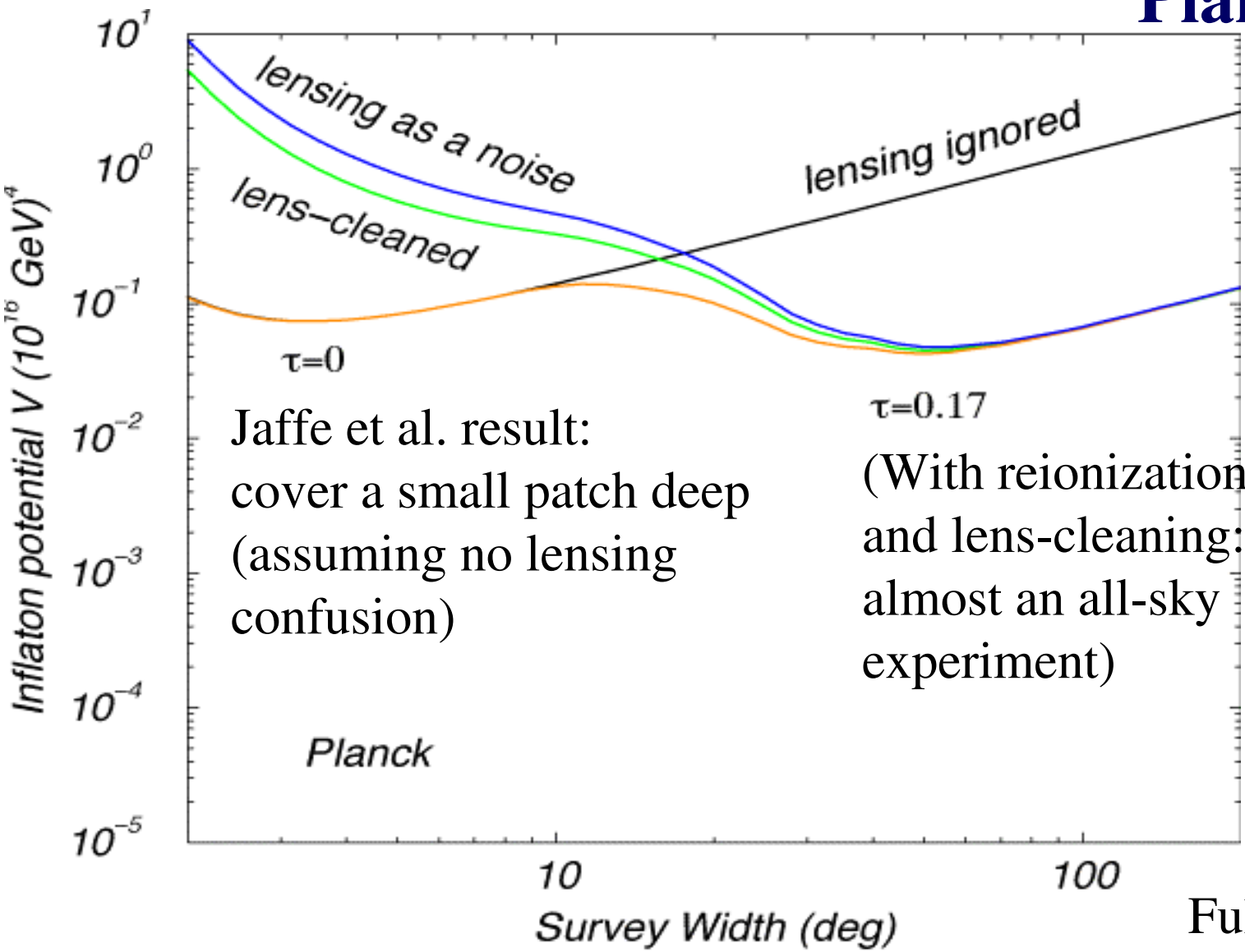
1 % emissive 60 K telescope

Lensing vs. Gravitational-Waves



Why we need EPIC

Planck

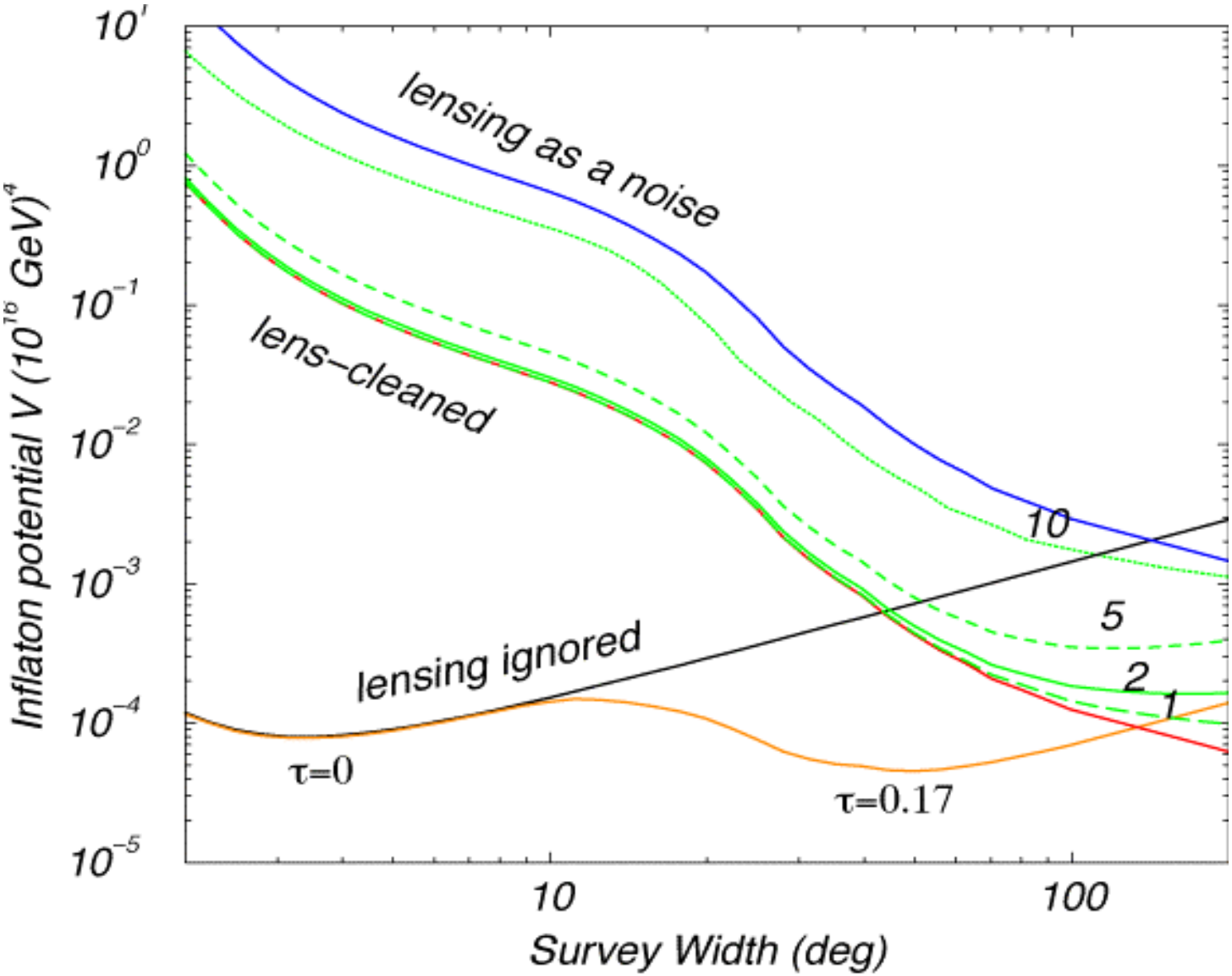


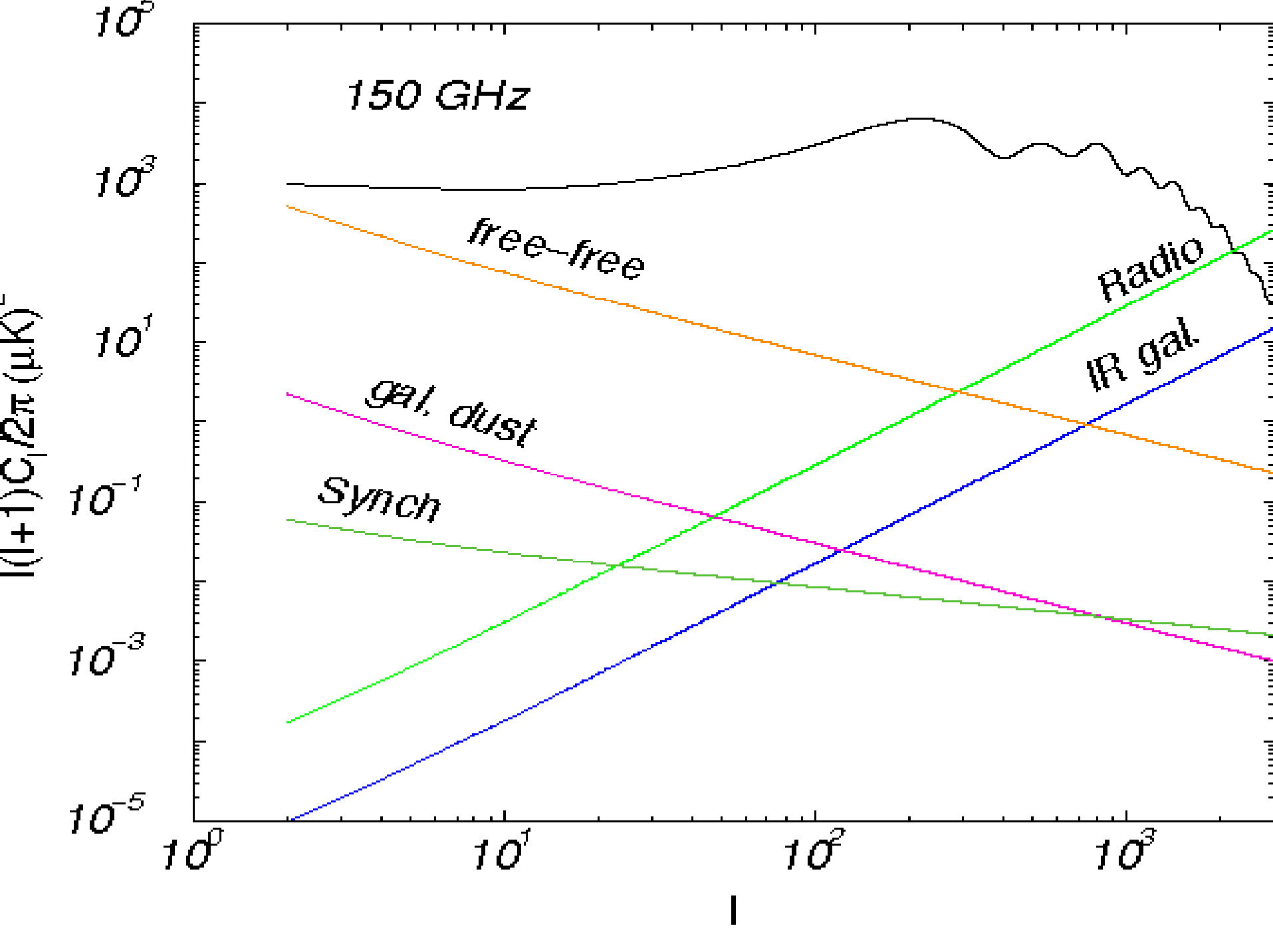
Jaffe et al. result:
cover a small patch deep
(assuming no lensing
confusion)

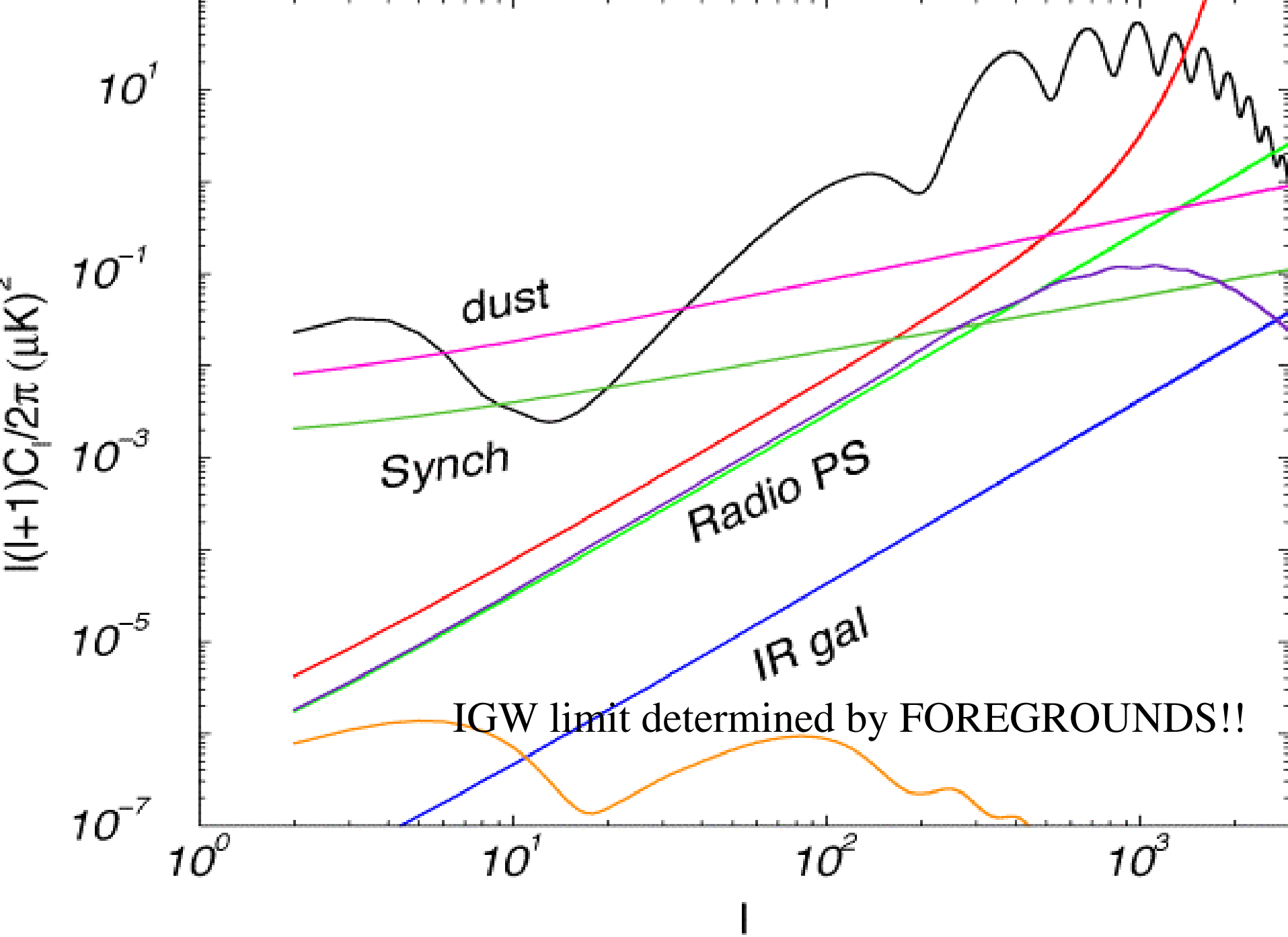
(With reionization
and lens-cleaning:
almost an all-sky
experiment)

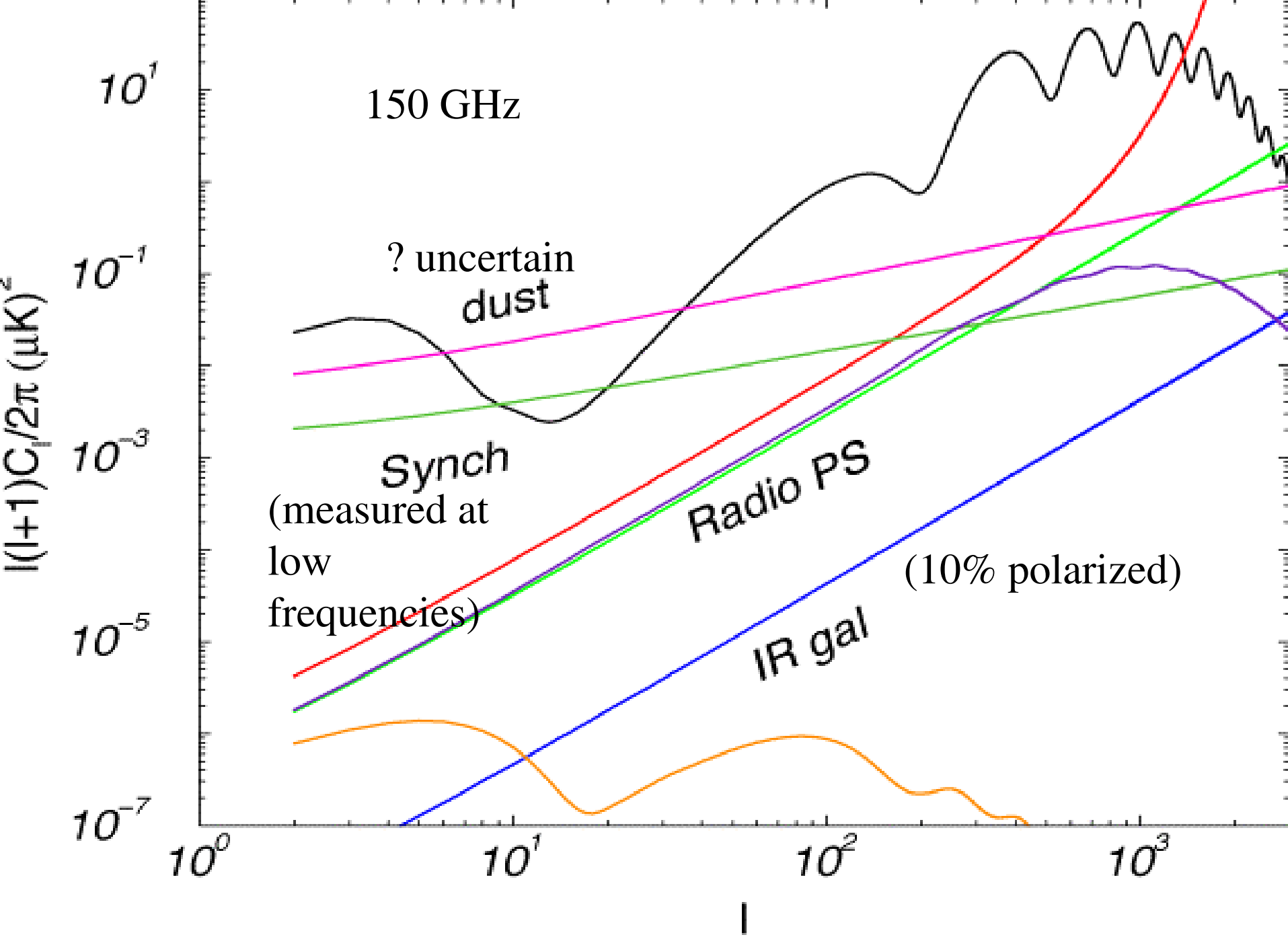
Full-sky

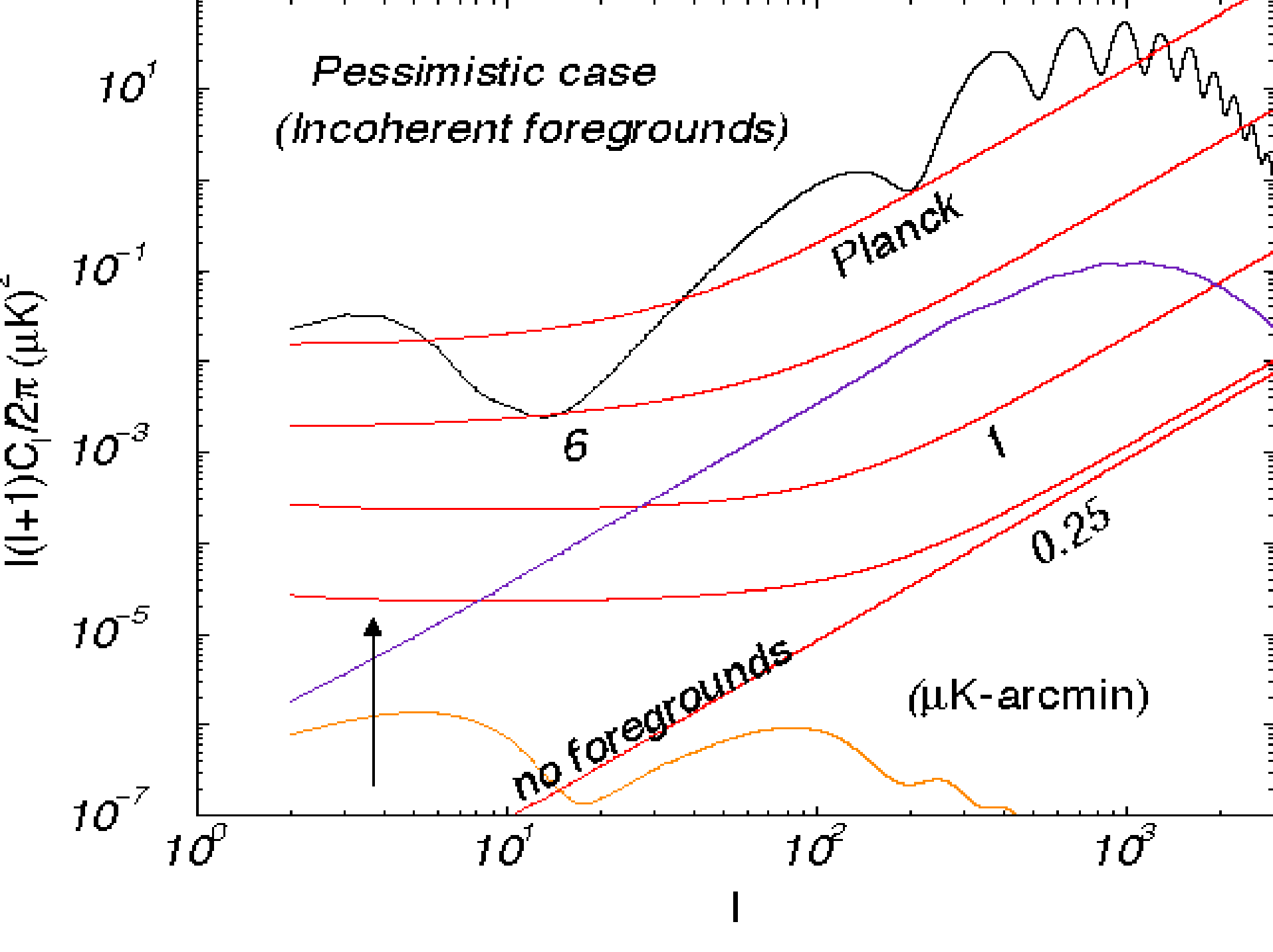
EPIC (Exploration Probe of Inflationary Cosmology)

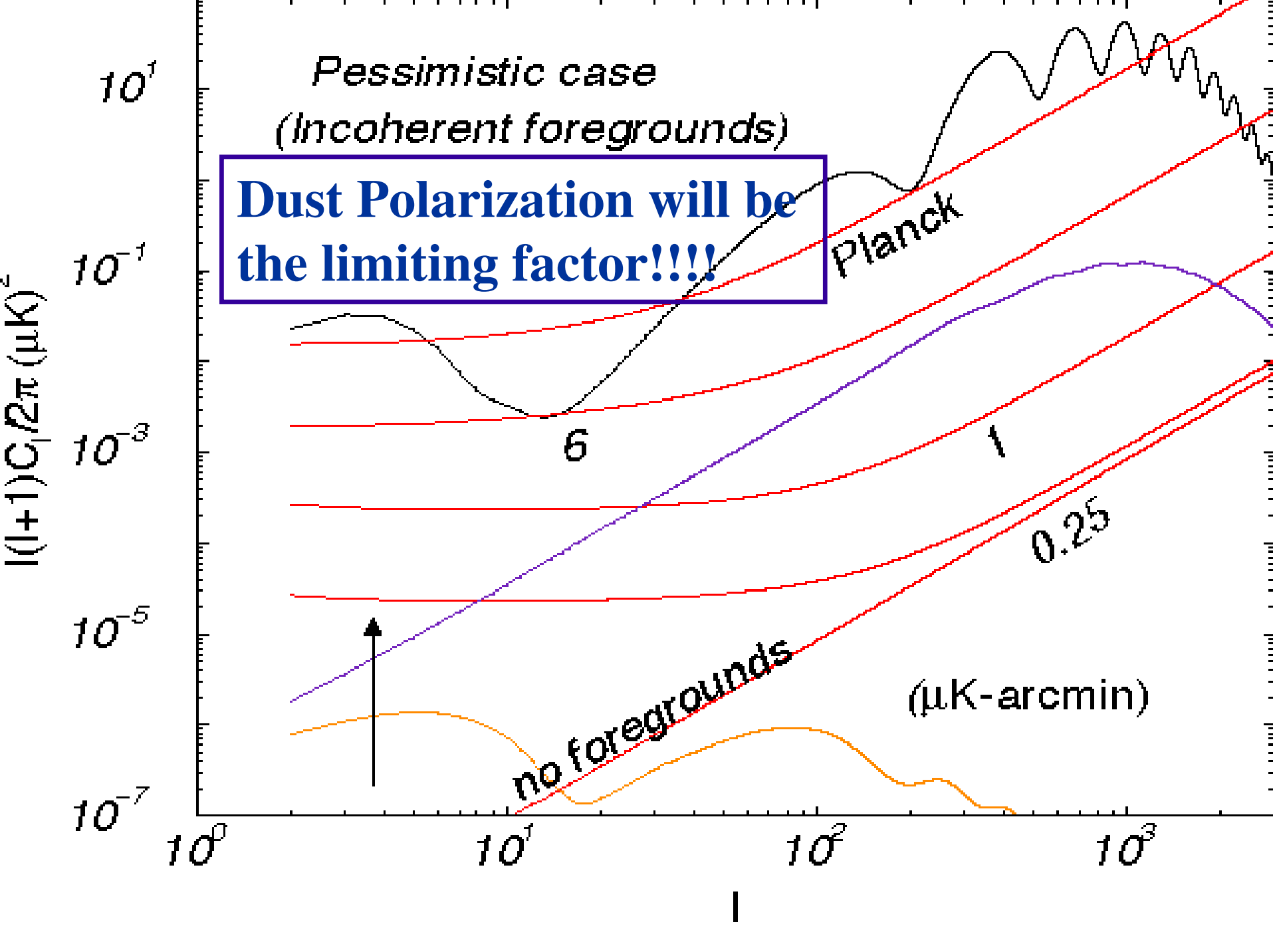



150 GHz
free–free
Radio
IR gal.
gal. dust
Synch
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
$l(l+1)C_l/2\pi\ (\mu K)^2$
10^0
10^1
10^2
10^3
l

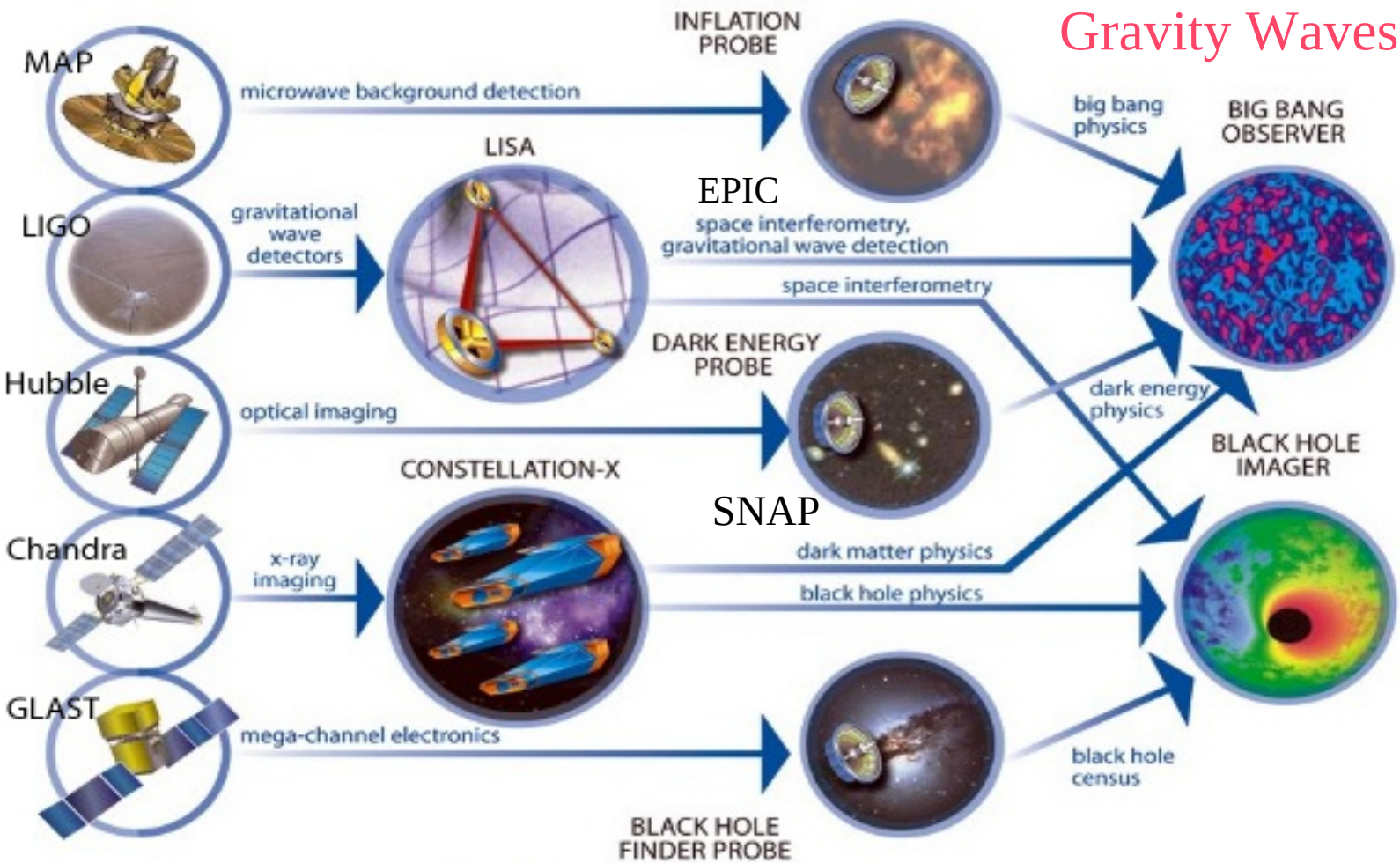

dust
Synch
Radio PS
IR gal
IGW limit determined by FOREGROUNDS!!
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{0}
10^{1}
10^{2}
10^{3}
l
$l(l+1)C_l/2\pi\ (\mu K)^2$


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


Pessimistic case
(Incoherent foregrounds)
Planck
6
1
0.25
no foregrounds
(μK-arcmin)
l(l+1)C_l/2π (μK)^2
l
10^1
10^-1
10^-3
10^-5
10^-7
10^0
10^1
10^2
10^3


Pessimistic case
(Incoherent foregrounds)
Dust Polarization will be the limiting factor!!!!
Planck
6
1
0.25
no foregrounds
(μK-arcmin)
l(l+1)C_l/2π (μK)^2
l
10^1
10^-1
10^-3
10^-5
10^-7
10^0
10^1
10^2
10^3

NASA's *Beyond Einstein* Program

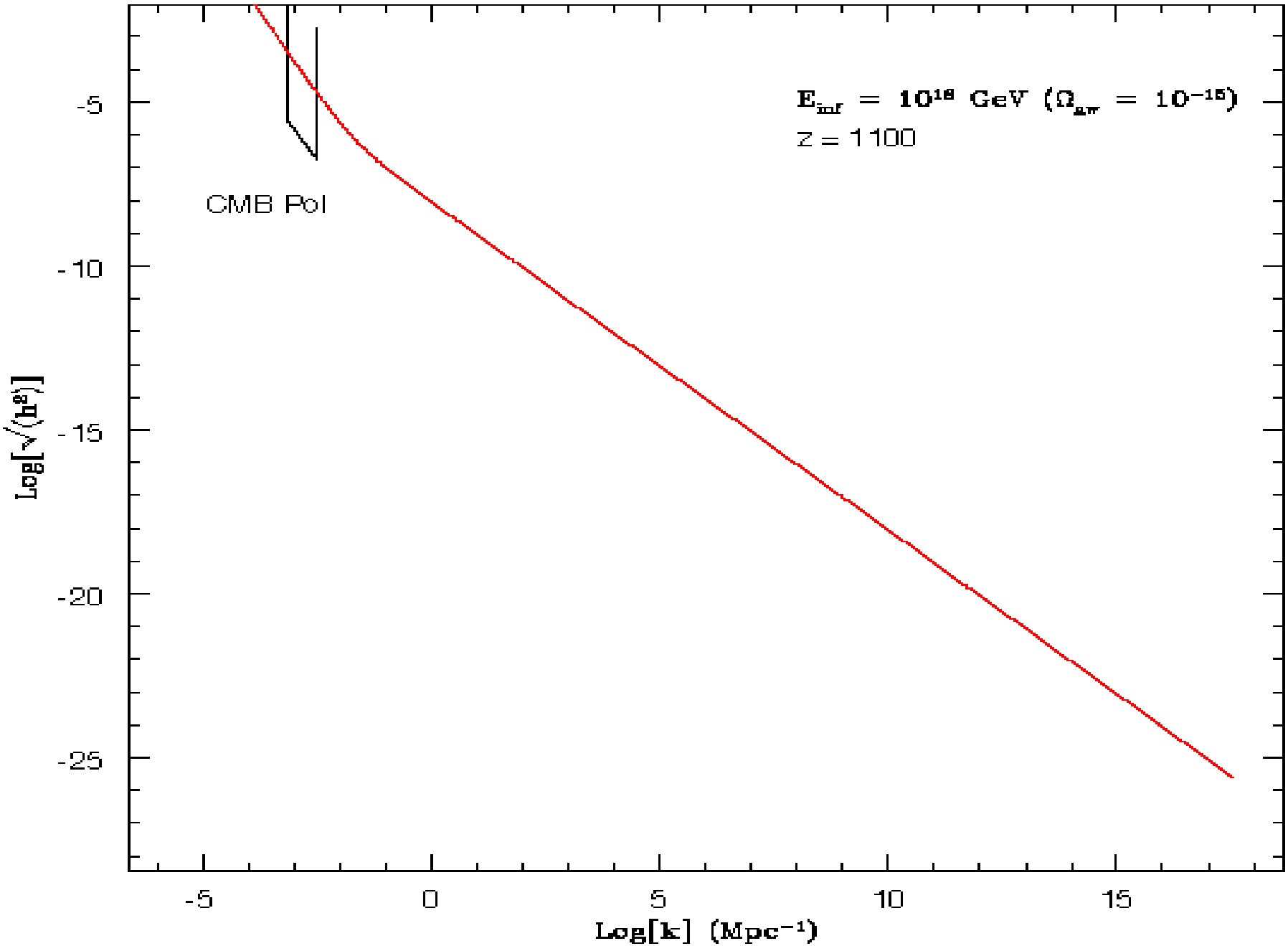


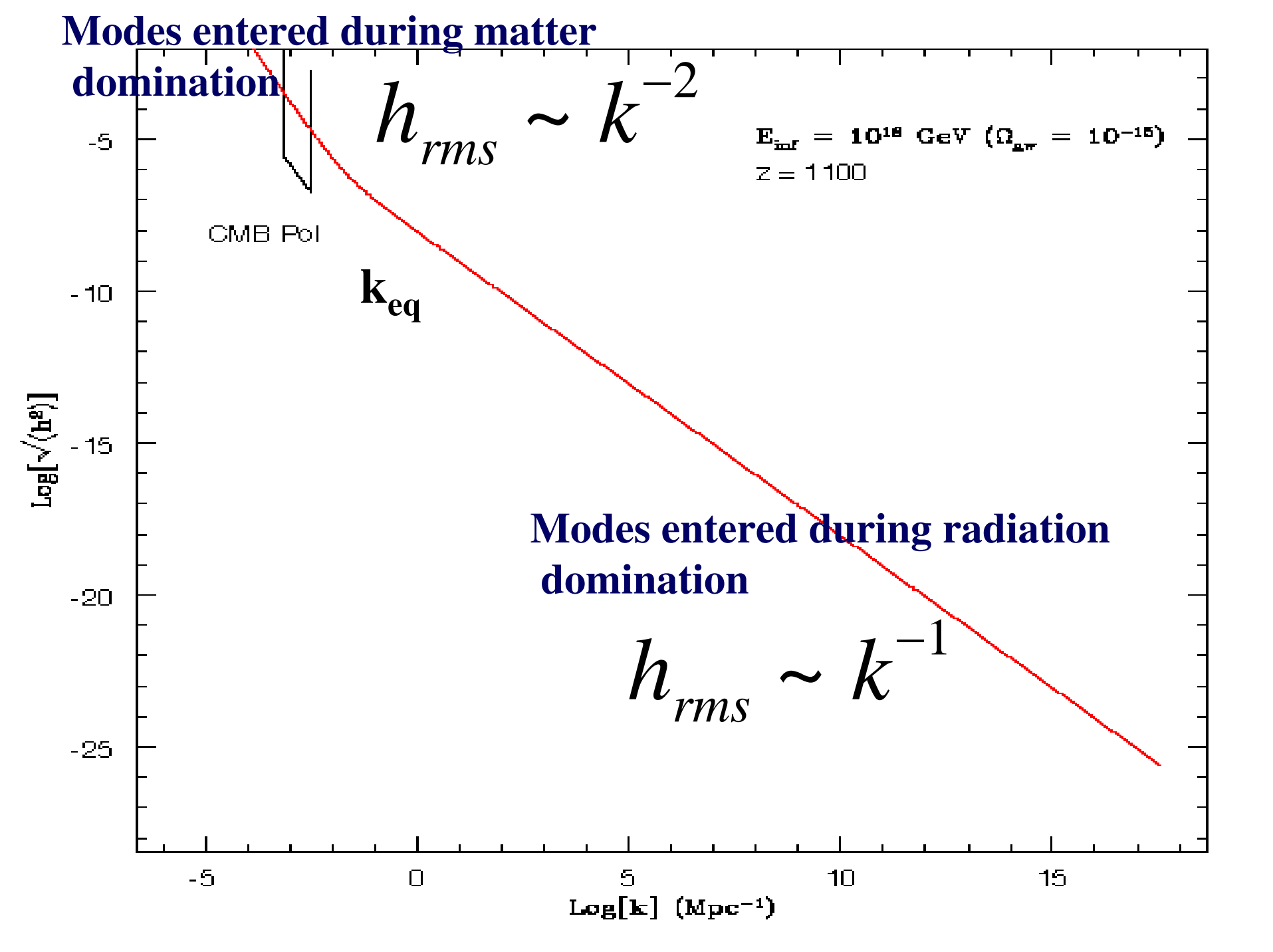
Current Missions

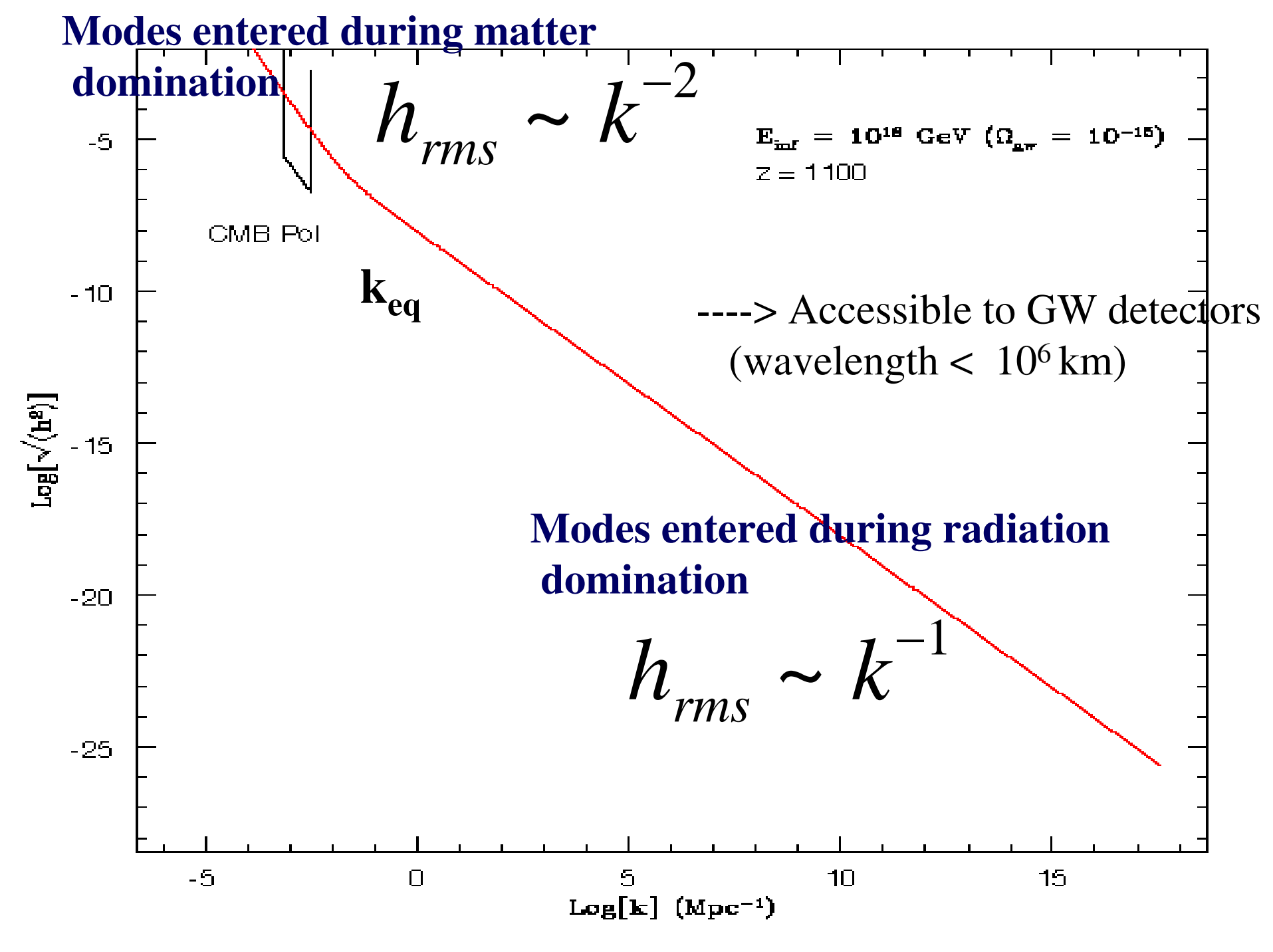
Broad sciences/ Major resources Community-class

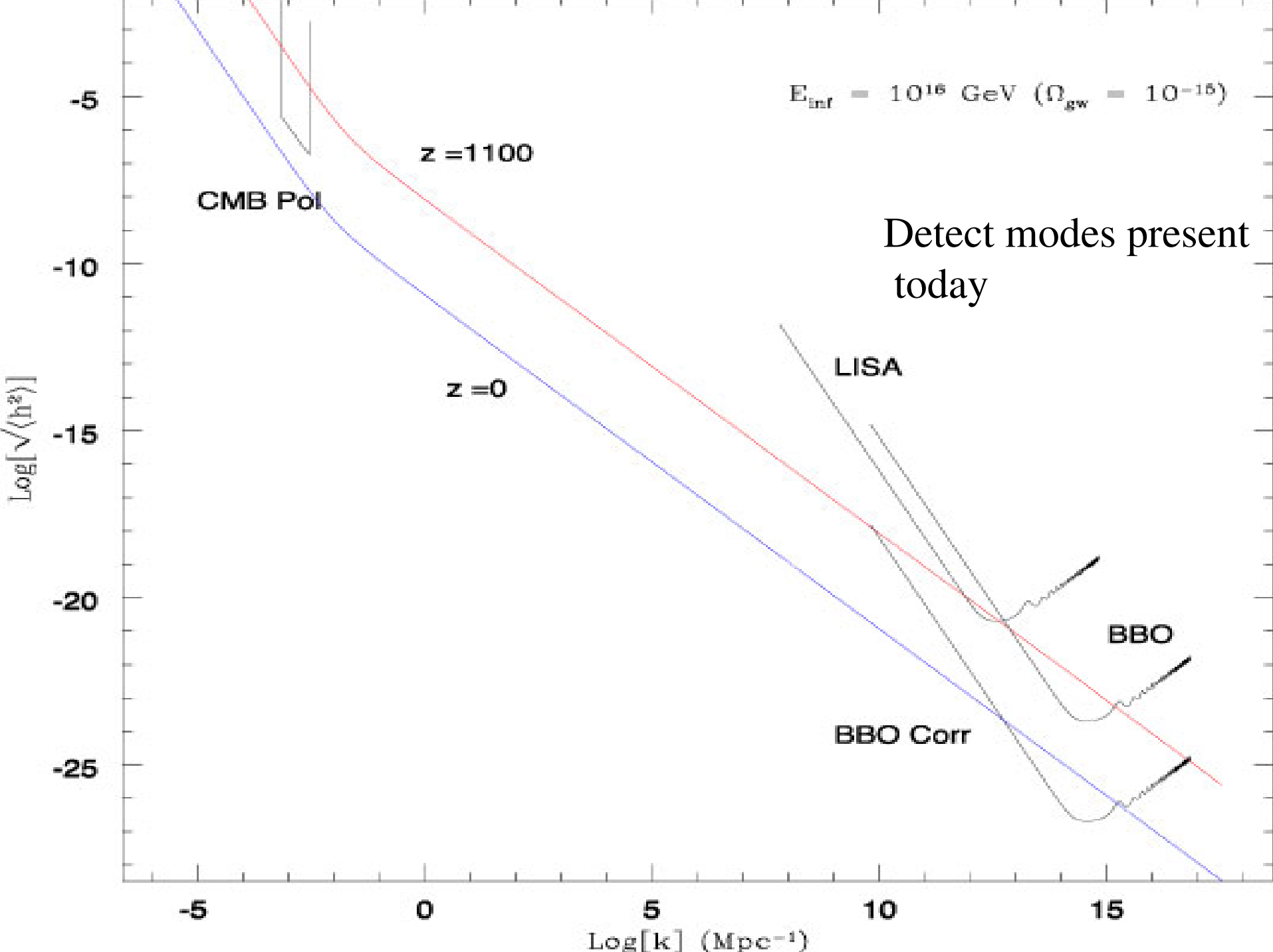
Focused/narrow sciences PI-class

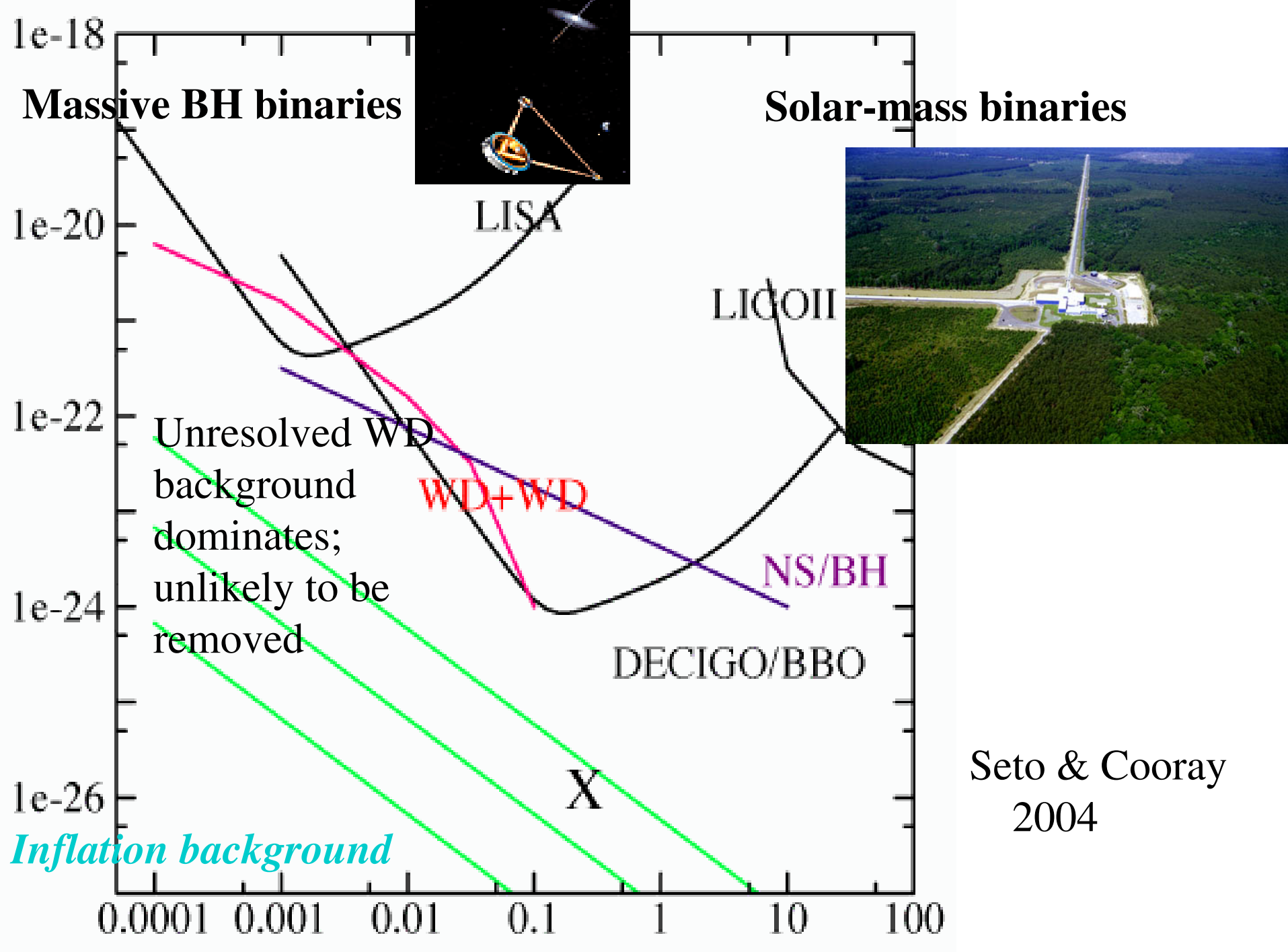
After significant developments (both hardware/theory) > 25 year time-scales


$E_{inf} = 10^{16}$ GeV ($\Omega_{gw} = 10^{-15}$)
z = 1100
CMB Pol
-5
-10
-15
-20
-25
Log[$\sqrt{(h^2)}$]
-5
0
5
10
15
Log[k] (Mpc^{-1})


Modes entered during matter domination
$h_{rms} \sim k^{-2}$
$E_{inf} = 10^{16}$ GeV ($\Omega_{gw} = 10^{-15}$)
z = 1100
CMB Pol
k_{eq}
Modes entered during radiation domination
$h_{rms} \sim k^{-1}$
Log[$\sqrt{\langle h^2 \rangle}$]
-5
-10
-15
-20
-25
-5
0
5
10
15
Log[k] (Mpc^{-1})


Modes entered during matter domination
$h_{rms} \sim k^{-2}$
$E_{inf} = 10^{16}$ GeV ($\Omega_{gw} = 10^{-15}$)
z = 1100
CMB Pol
k_{eq}
----> Accessible to GW detectors
(wavelength < 10^6 km)
Modes entered during radiation domination
$h_{rms} \sim k^{-1}$
Log[$\sqrt{\langle h^2 \rangle}$]
-5
-10
-15
-20
-25
-5
0
5
10
15
Log[k] (Mpc^{-1})


$E_{inf} = 10^{16}$ GeV ($\Omega_{gw} = 10^{-15}$)
z =1100
CMB Pol
z =0
LISA
BBO
BBO Corr
Detect modes present today
-5
-10
-15
-20
-25
Log[$\sqrt{\langle h^2 \rangle}$]
-5
0
5
10
15
Log[k] (Mpc^{-1})

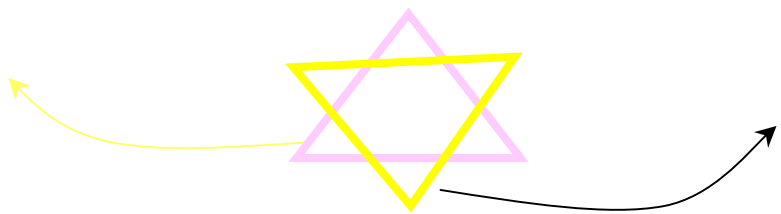


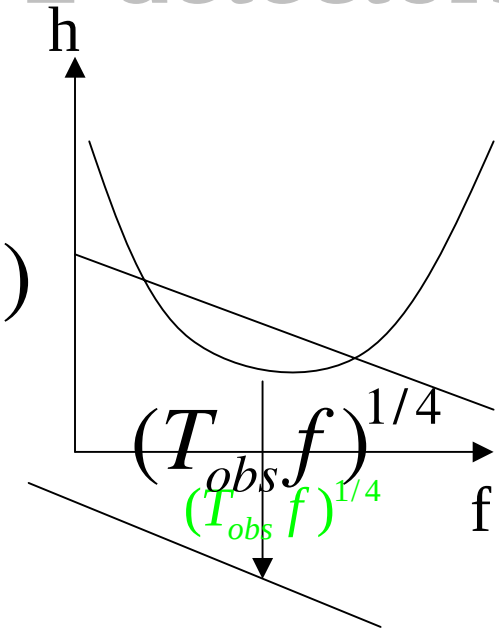
Seto & Cooray 2004

Correlation analysis (with 2 detectors)

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

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



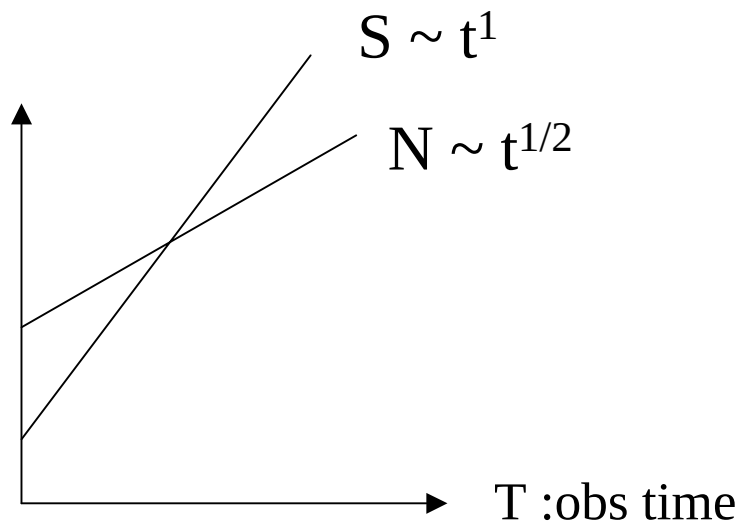


$$S = \int_0^T dt \int_0^T dt' s_1(t) s_2(t) Q(t - t')$$

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

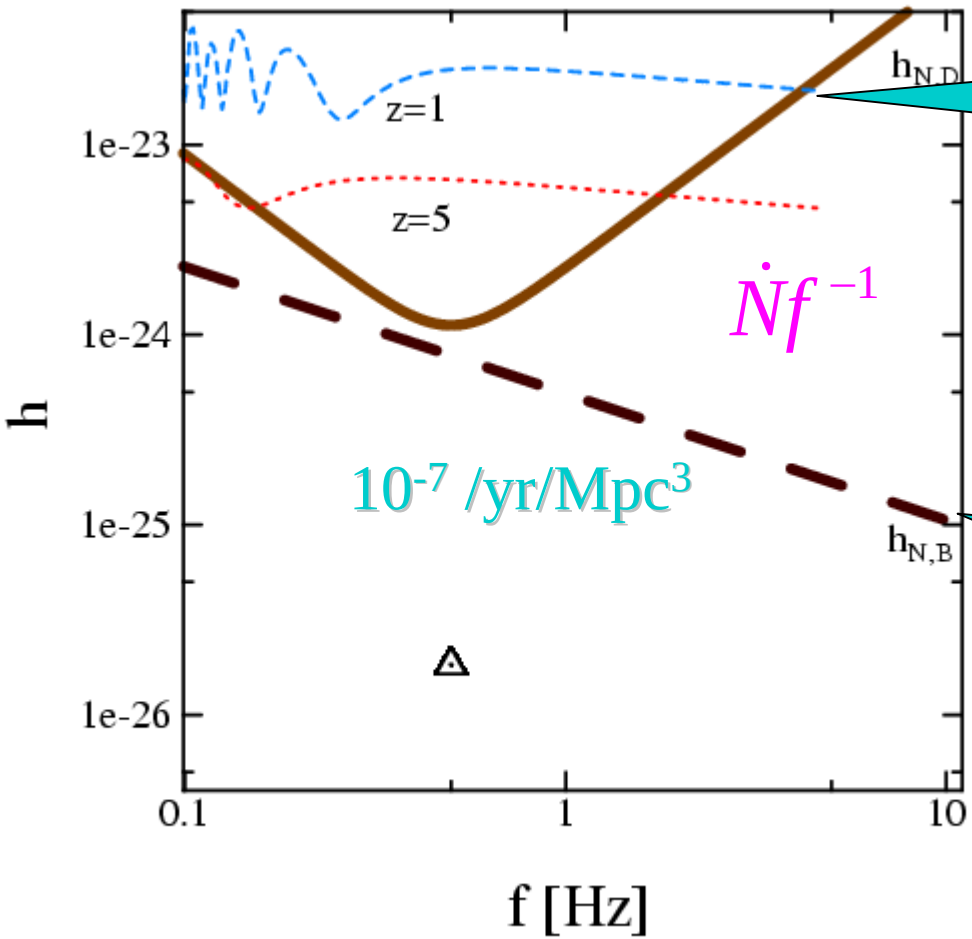
$noise \propto T^{1/2}$

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



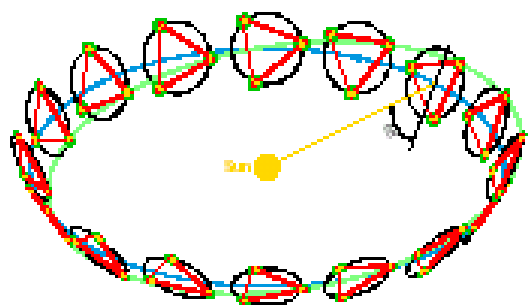
Reducing correlated noise is crucial for correlation analysis

Resolved binaries and their foreground

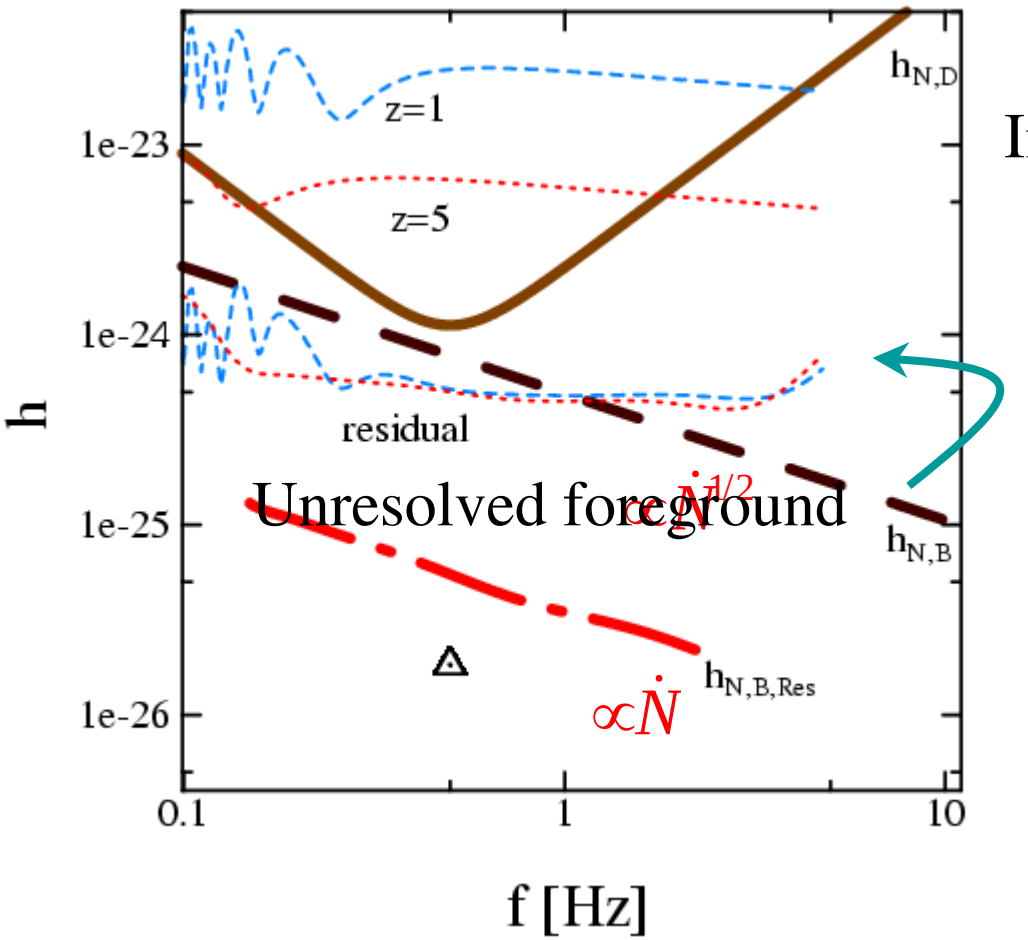


Chirp signals from binaries
transient

Total binary foreground
Stationary



Residual noise levels after cleaning



Individual resolved NS+NS binaries

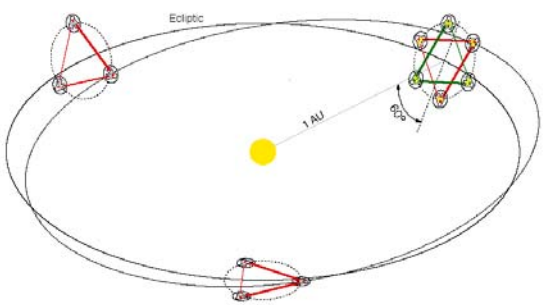
Binary foreground is common to two detectors and makes correlated fitting residual

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

$\dot{N}_{obs} f^{-1} \sim 1$

The Big Bang Observer (BBO)

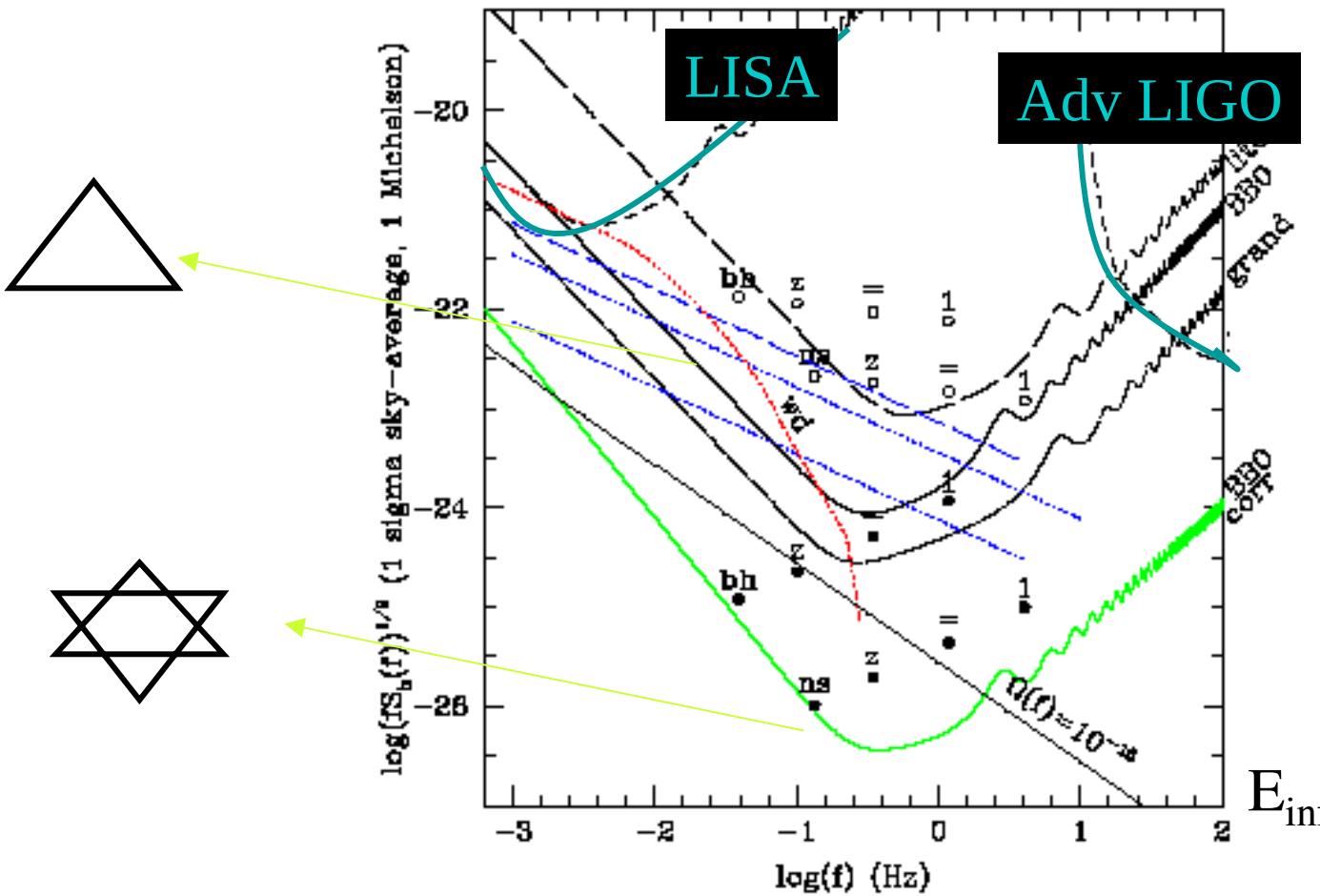
- NASA Vision mission (~2030 launch)
- Primary goal: direct detection of GW from inflation by correlation analysis around 0.1-1Hz
- LISA's follow-on



Example : a plan with 4 units

Phinney et al. 2003

The Big Bang Observer (BBO)

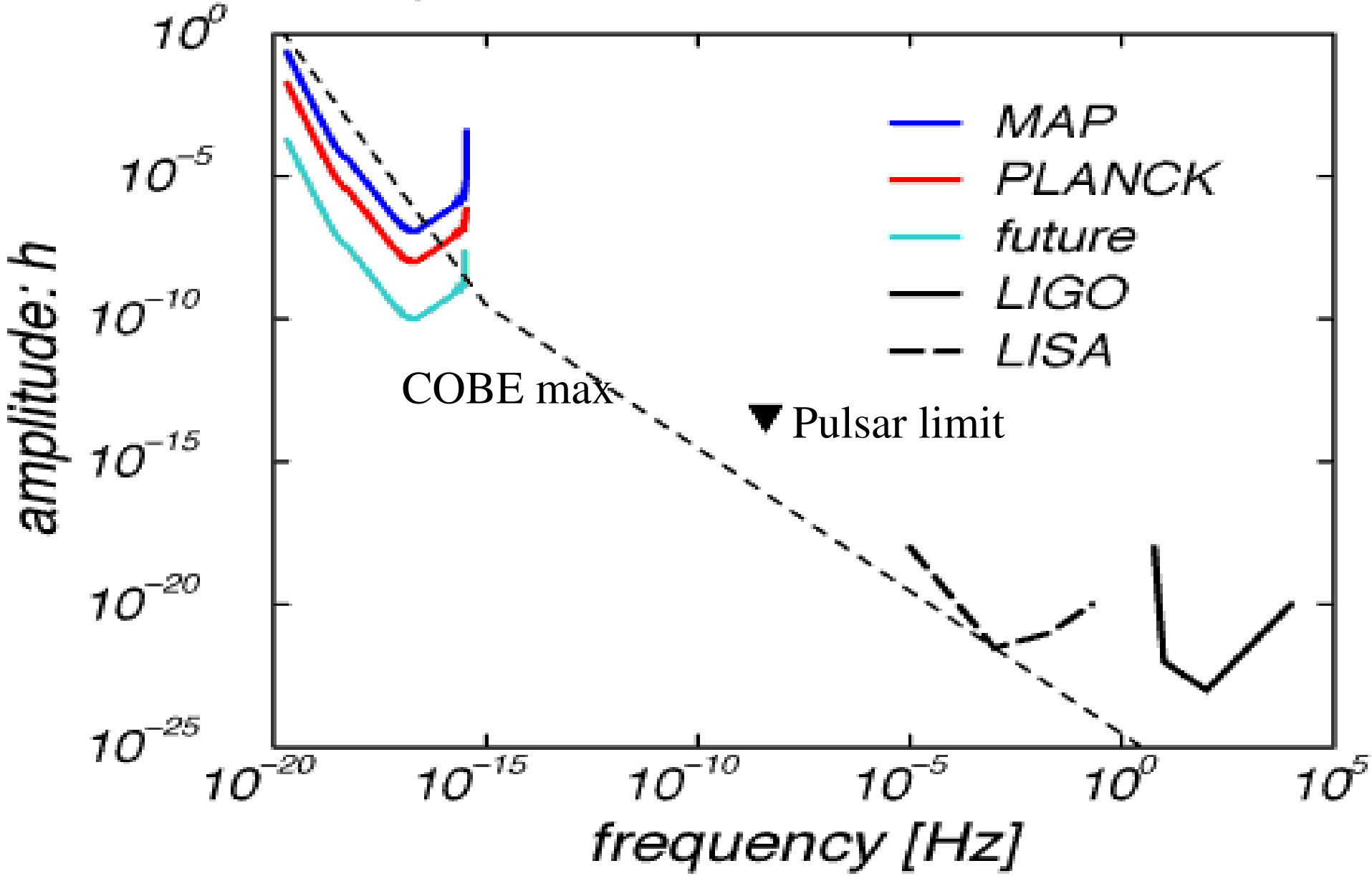


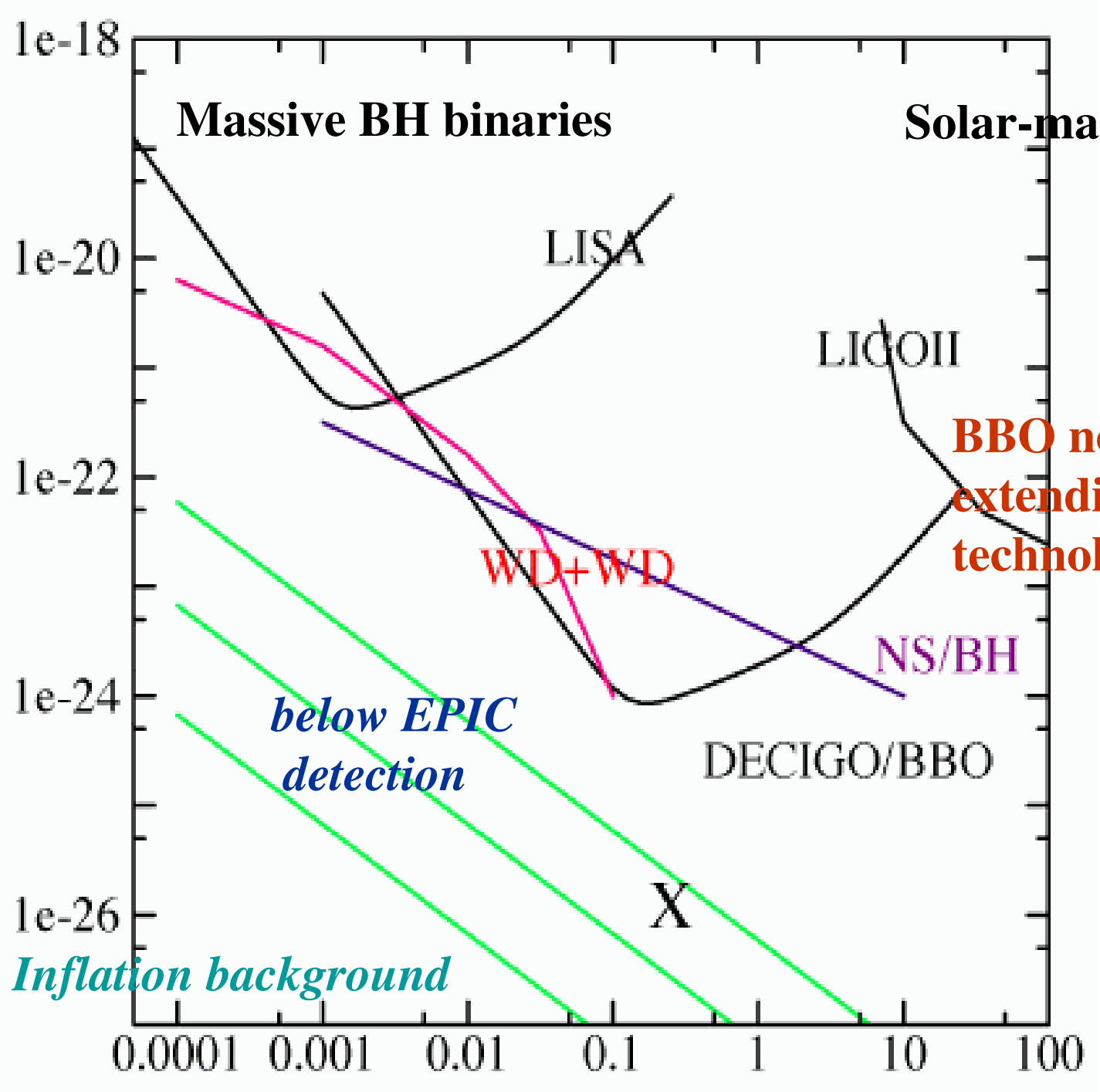
$E_{infl} \sim 10^{16}$ GeV

Phinney et al. 2003

Gravitational Wave Detectors

Space–Based and Terrestrial





below EPIC detection

Inflation background

BBO noise achievable by extending current technology

Seto & Cooray 2004

Future CMB

- 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!!!
- Brighter future in gravity-wave astronomy (LISA $\Rightarrow$ BBO)

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