Beyond SM phase transitions in the early Universe and gravitational wave detection

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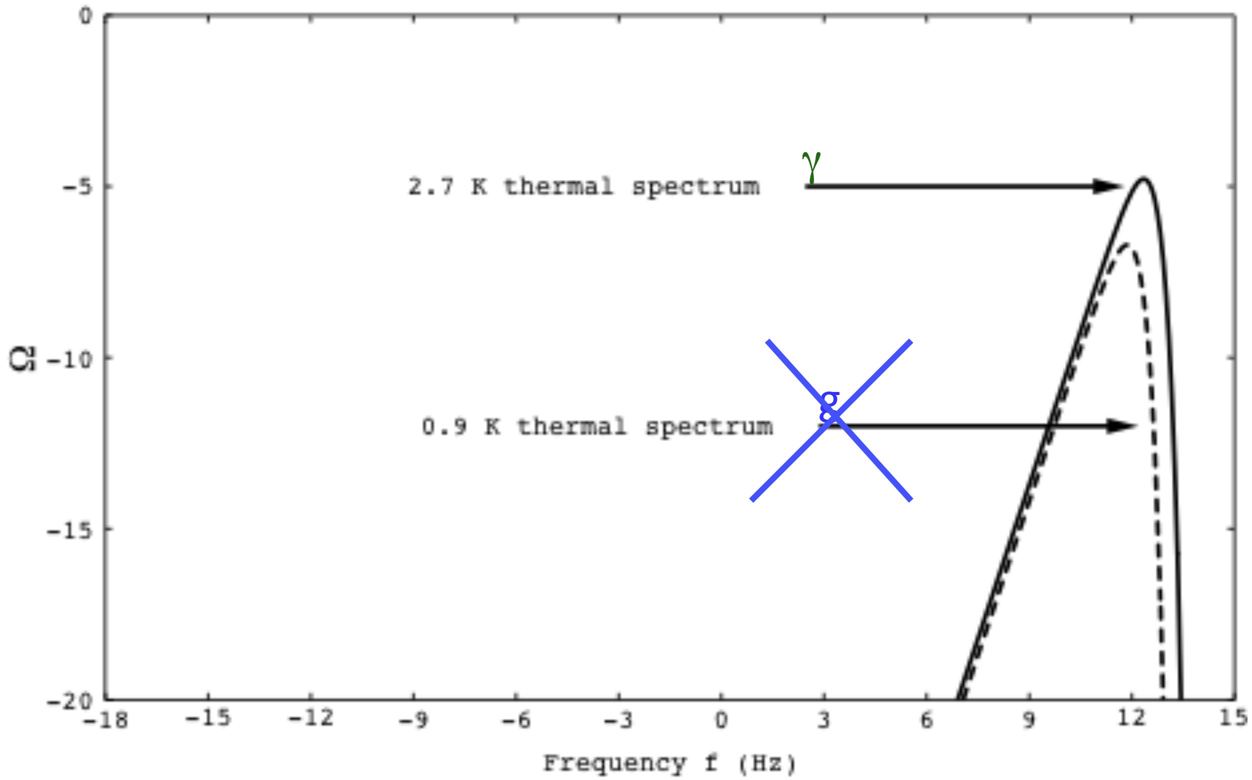
APPIC meeting
APC, 9 May 2014

If gravitons were in thermal equilibrium in the primordial universe

$\Omega = \rho^{-1}\, d\rho/d\log f$



When do gravitons decouple?

Interaction rate $\Gamma \sim G_N^2 T^5 \sim \frac{T^5}{M_{Pl}^4}$

Expansion rate $H \sim \frac{T^2}{M_{Pl}}$ (radiation dominated era)

$$\frac{\Gamma}{H} \sim \frac{T^3}{M_{Pl}^3}$$

Gravitons decouple at the Planck era : fossile radiation

Gravitons of frequency f_* produced at temperature T_* provide a background observed at a redshifted frequency

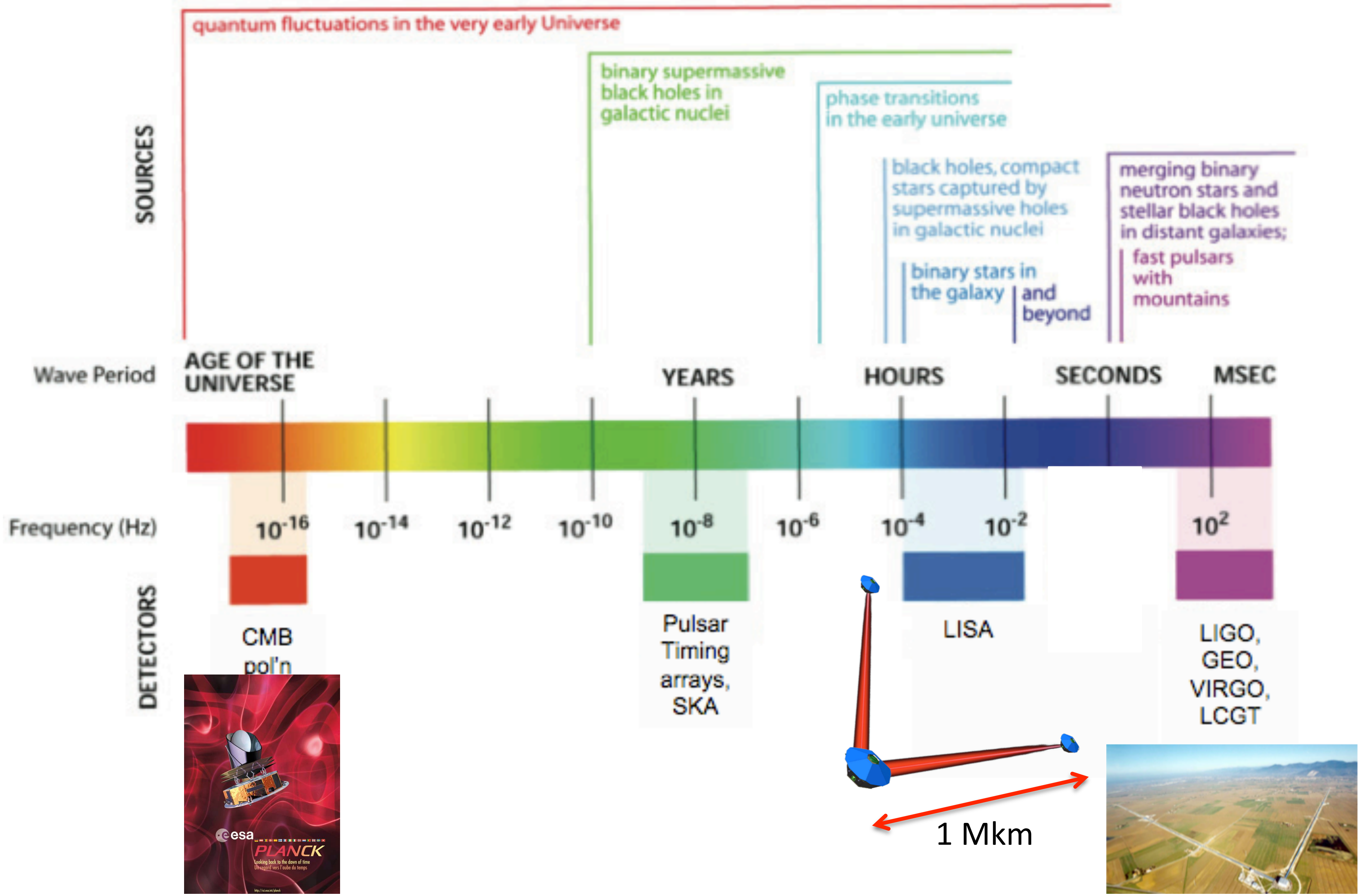
$$f = 1.65\ 10^{-7}\ \mathrm{Hz}\ \frac{1}{\varepsilon} \left(\frac{T_*}{1\mathrm{GeV}} \right) \left(\frac{g_*}{100} \right)^{1/6}$$

At production $\lambda_* = \varepsilon H_*^{-1}$ (or $f_* = H_*/\varepsilon$)

Wavelength

Horizon length

The frequency spectrum of gravitational waves

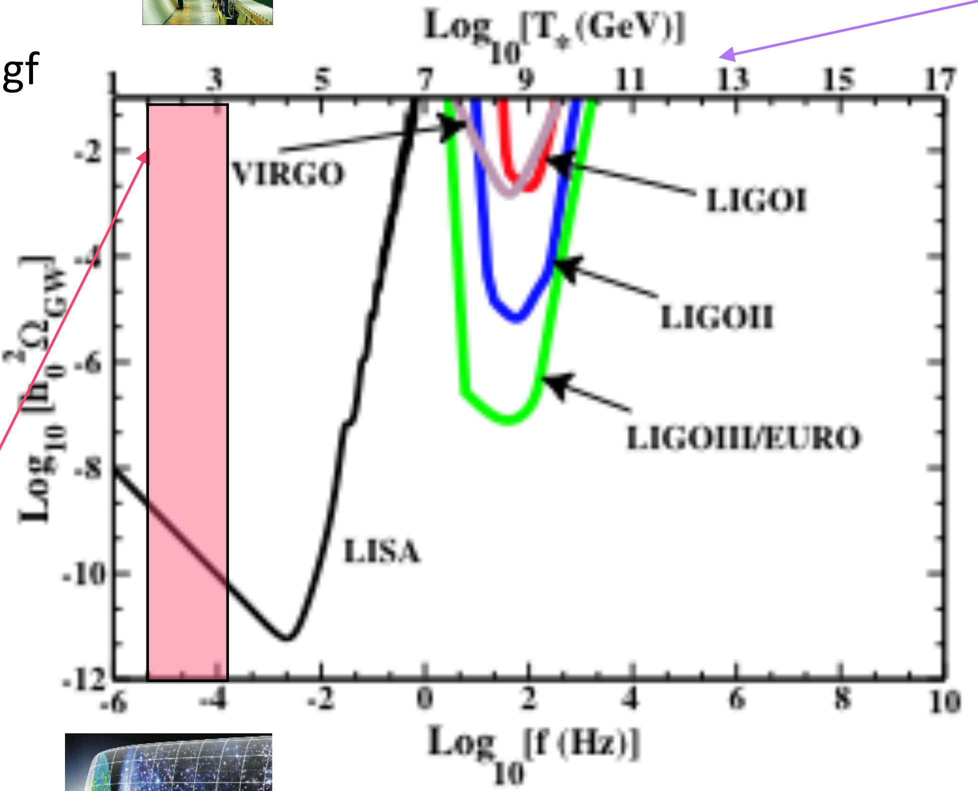


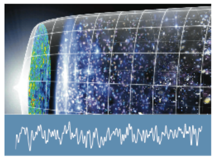
The electroweak phase transition

$$f = 1.65\ 10^{-7}\ \text{Hz}\ \frac{1}{\varepsilon}\ \left(\frac{T_*}{1\text{GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

for $\varepsilon=1$

$\Omega_{GW} = \rho_c^{-1}\, d\rho_{GW}/d\log f$

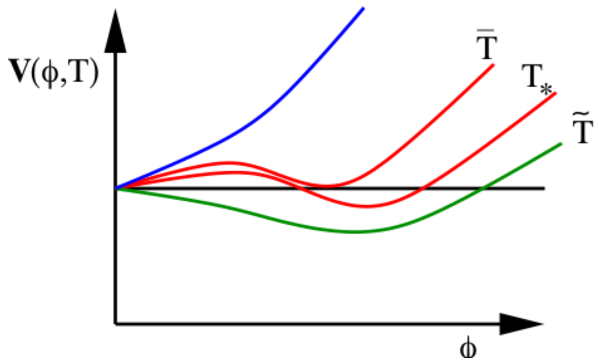


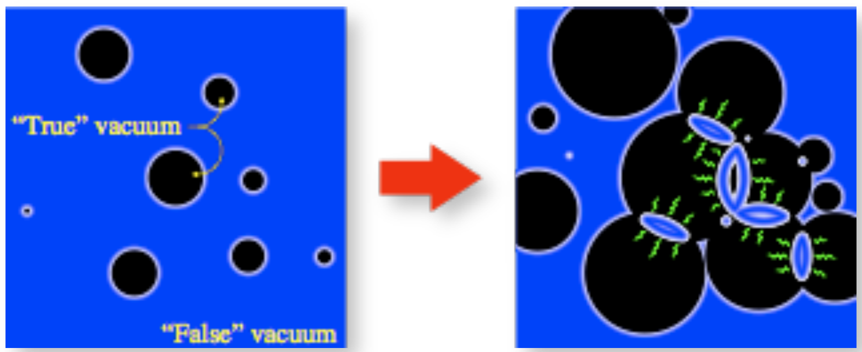


Gravitons produced at the electroweak phase transition would be observed in the LISA window.

But are gravitons produced in sufficient numbers at the electroweak phase transition?

If the transition is first order, nucleation of true vacuum bubbles inside the false vacuum





Collision of bubbles and (MHD) turbulence
→ production of gravitational waves

Pros and cons for a 1st order phase transition at the Terascale:

- in the Standard Model, requires $m_h < 72$ GeV (ruled out)
- MSSM requires too light a stop but generic in NMSSM
- possible to recover a strong 1st order transition by including H^6 terms in SM potential
- other symmetries than SU(2)xU(1) at the Terascale ($\rightarrow$ baryogenesis)

Two basic parameters :

$$\alpha = \frac{E_{false\ vac}}{aT_*^4}$$

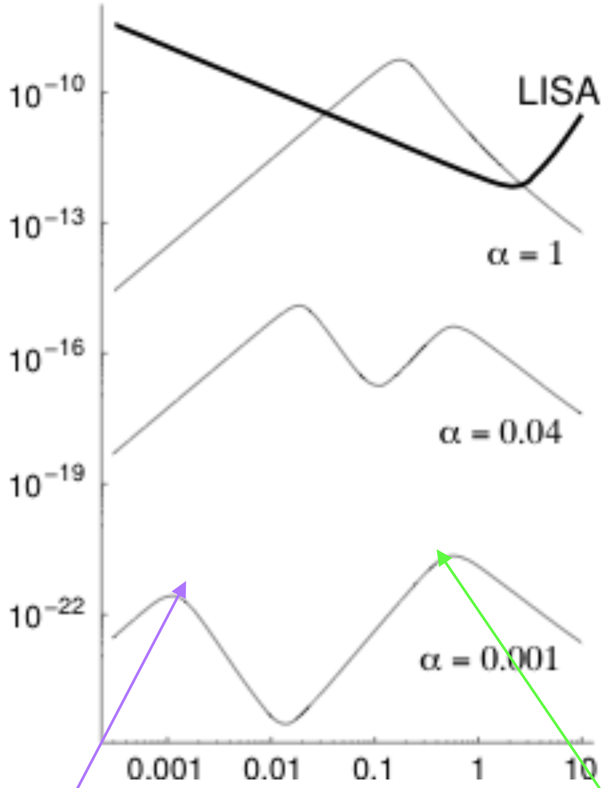
β= time variation of bubble nucleation rate

radiation energy at transition

$\beta^{-1} \sim 10^{-2}\ H^{-1}$

duration of phase transition

$h_0^2\,\Omega_{GW}$

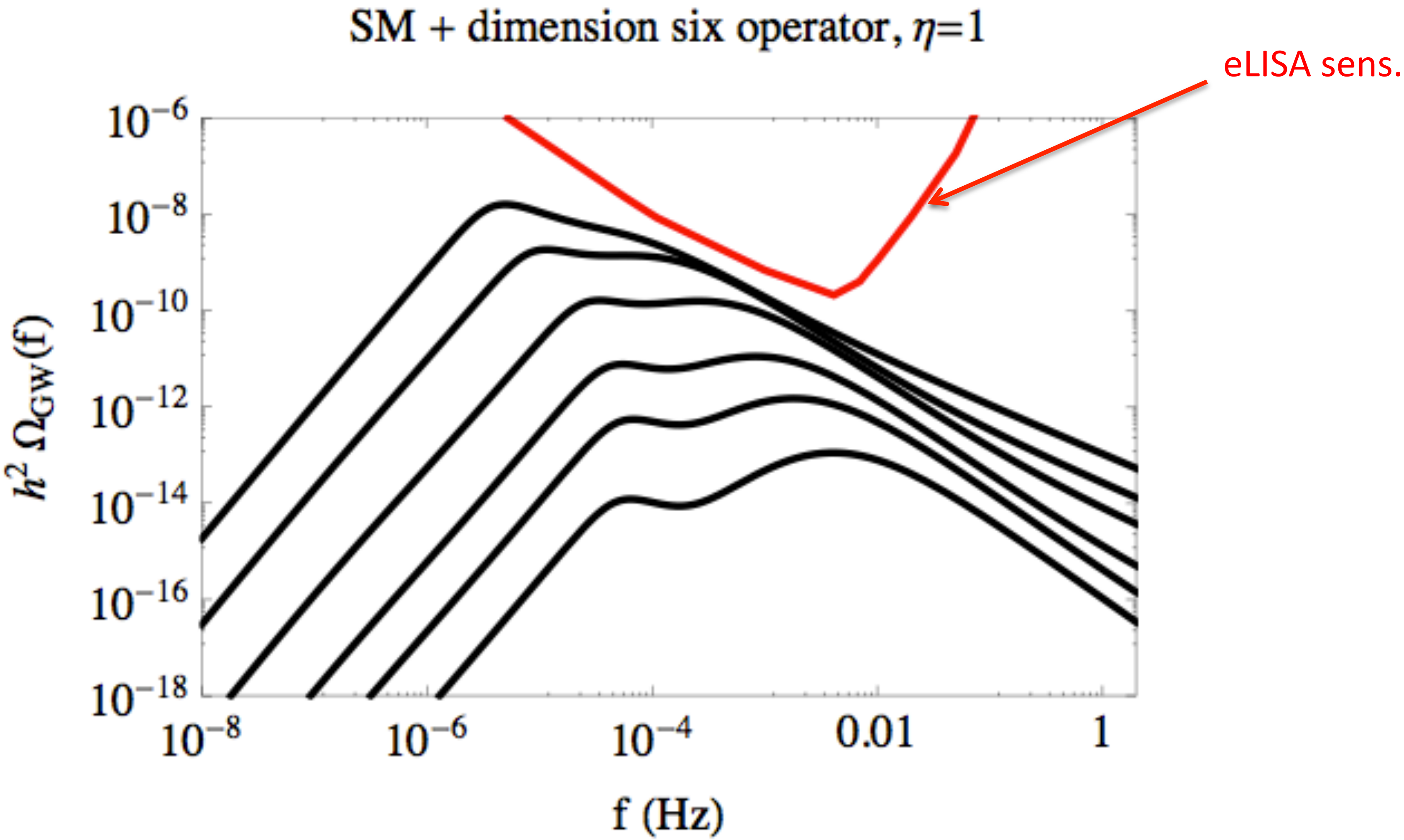


f in mHz

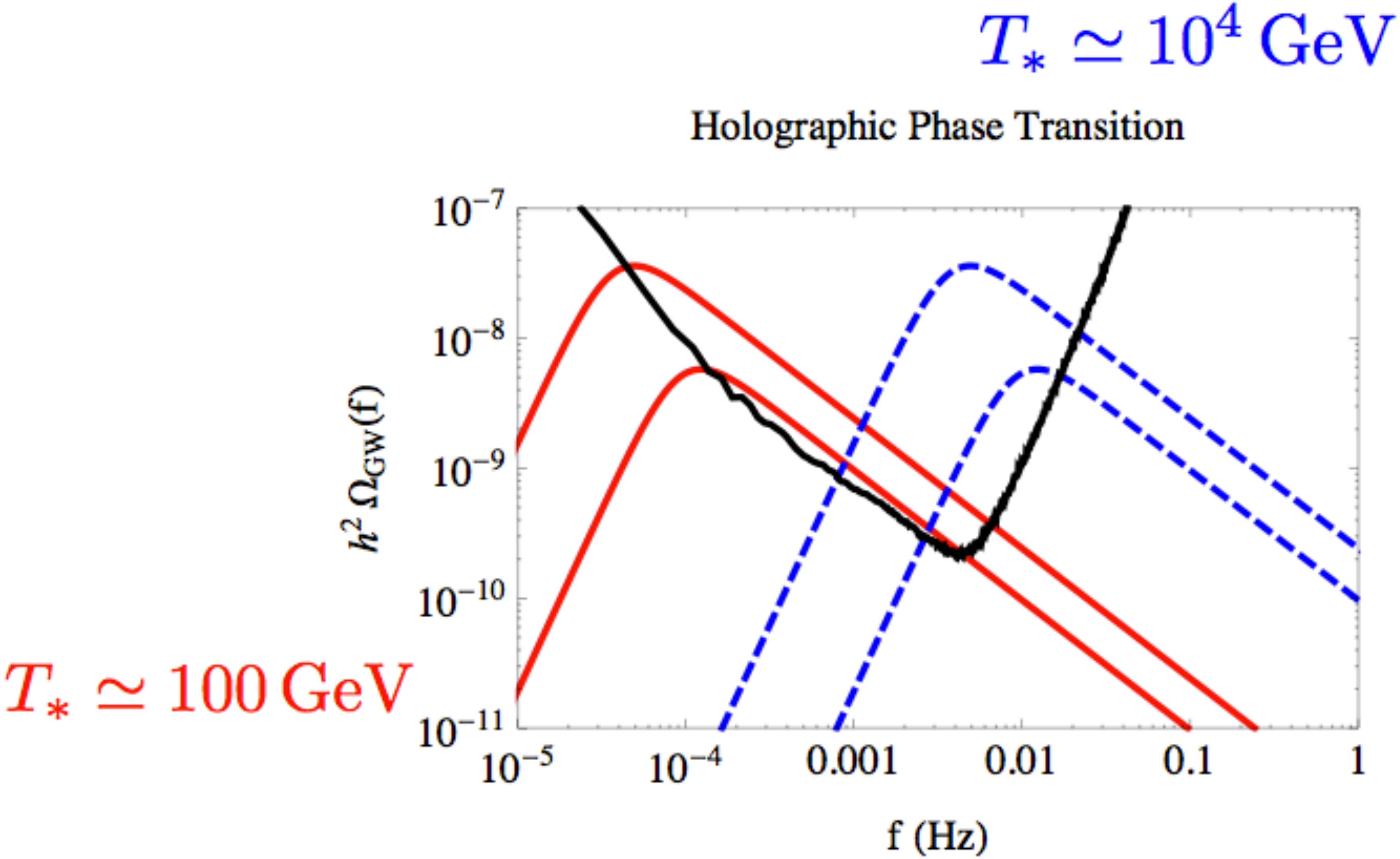
Nicolis gr-qc/0303084

turbulence

bubble collision

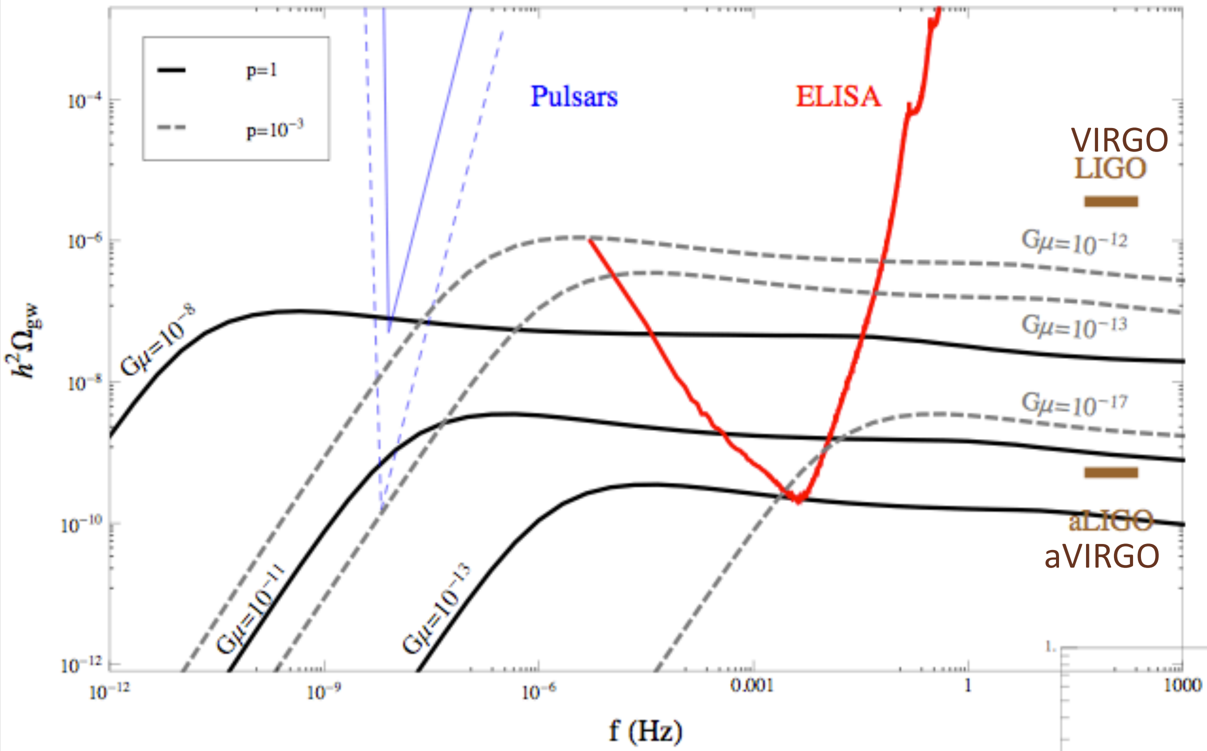


A. Bohé, P.B., C. Caprini, J.F. Dufaux 1201.0983



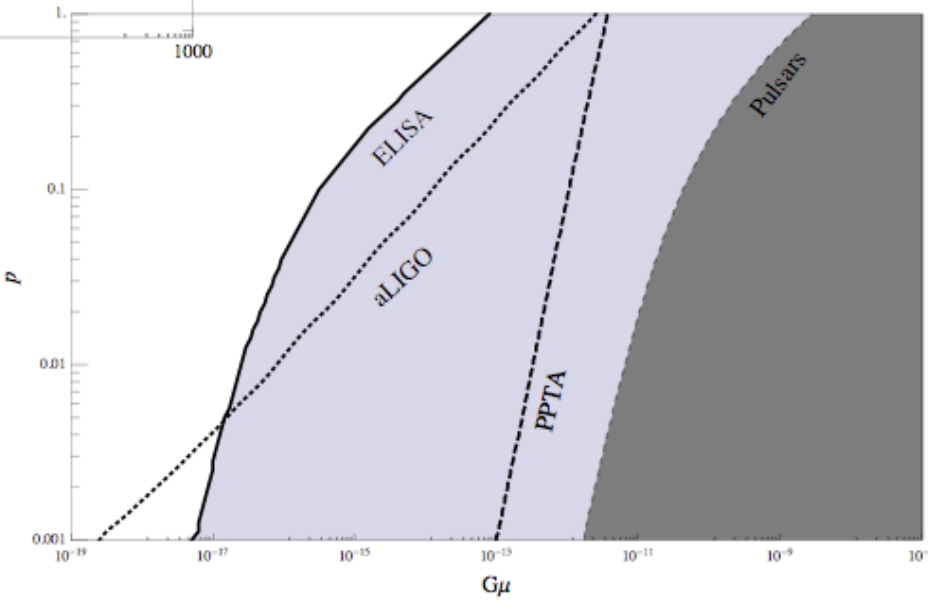
A. Bohé, P.B., C. Caprini, J.F. Dufaux 1201.0983

- **Cosmic strings and superstrings**



parameters:
tension, reconnection probability, loop size (?)

different detectors are complementary for some regions of the parameter space



Stochastic backgrounds from cosmological sources

other sources

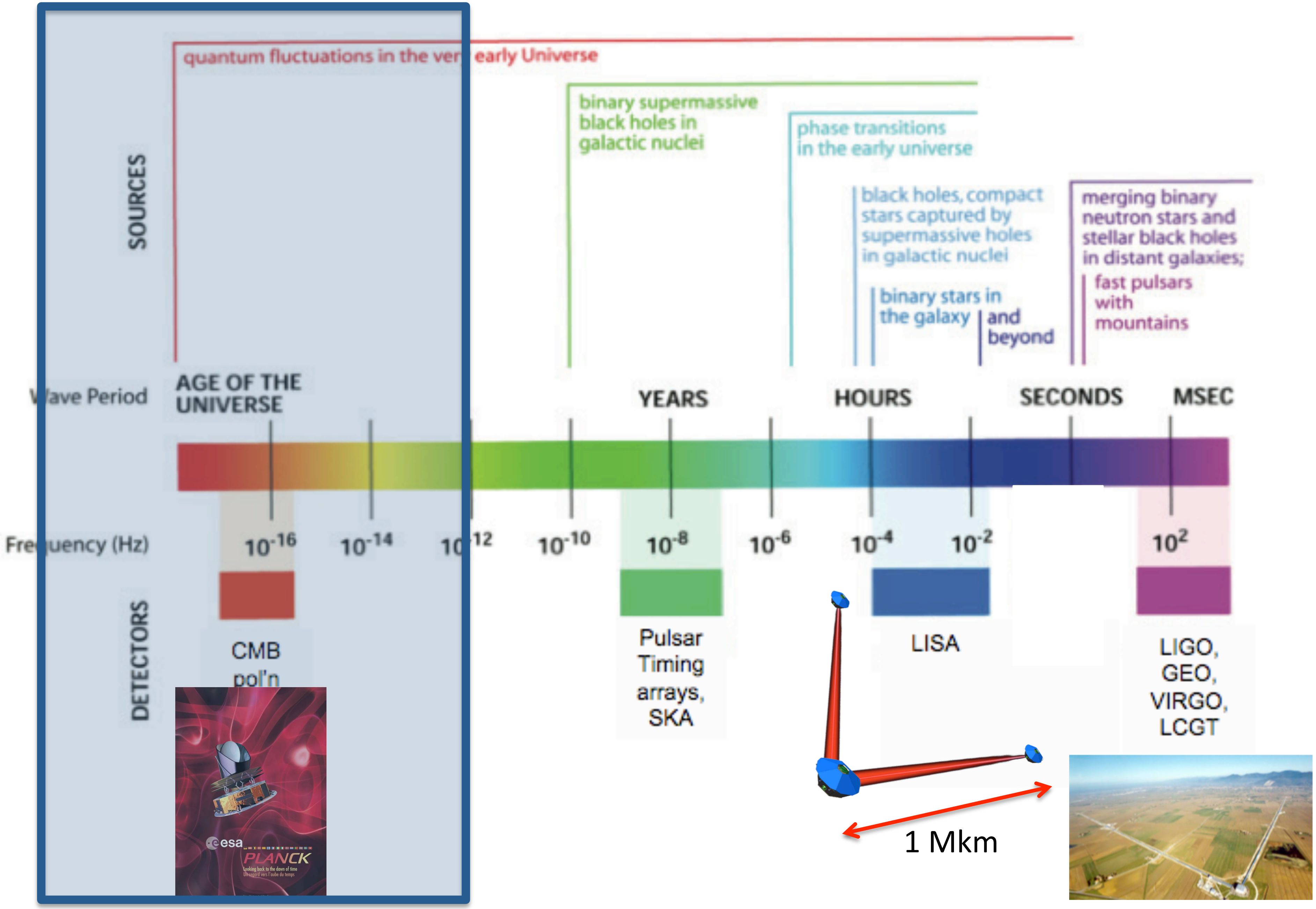
- fluid stiffer than radiation after inflation
- preheating after inflation
- phase transitions at the end or during inflation
- unstable domain walls
- primordial black holes
- scalar field relaxation
- SUSY flat directions ...

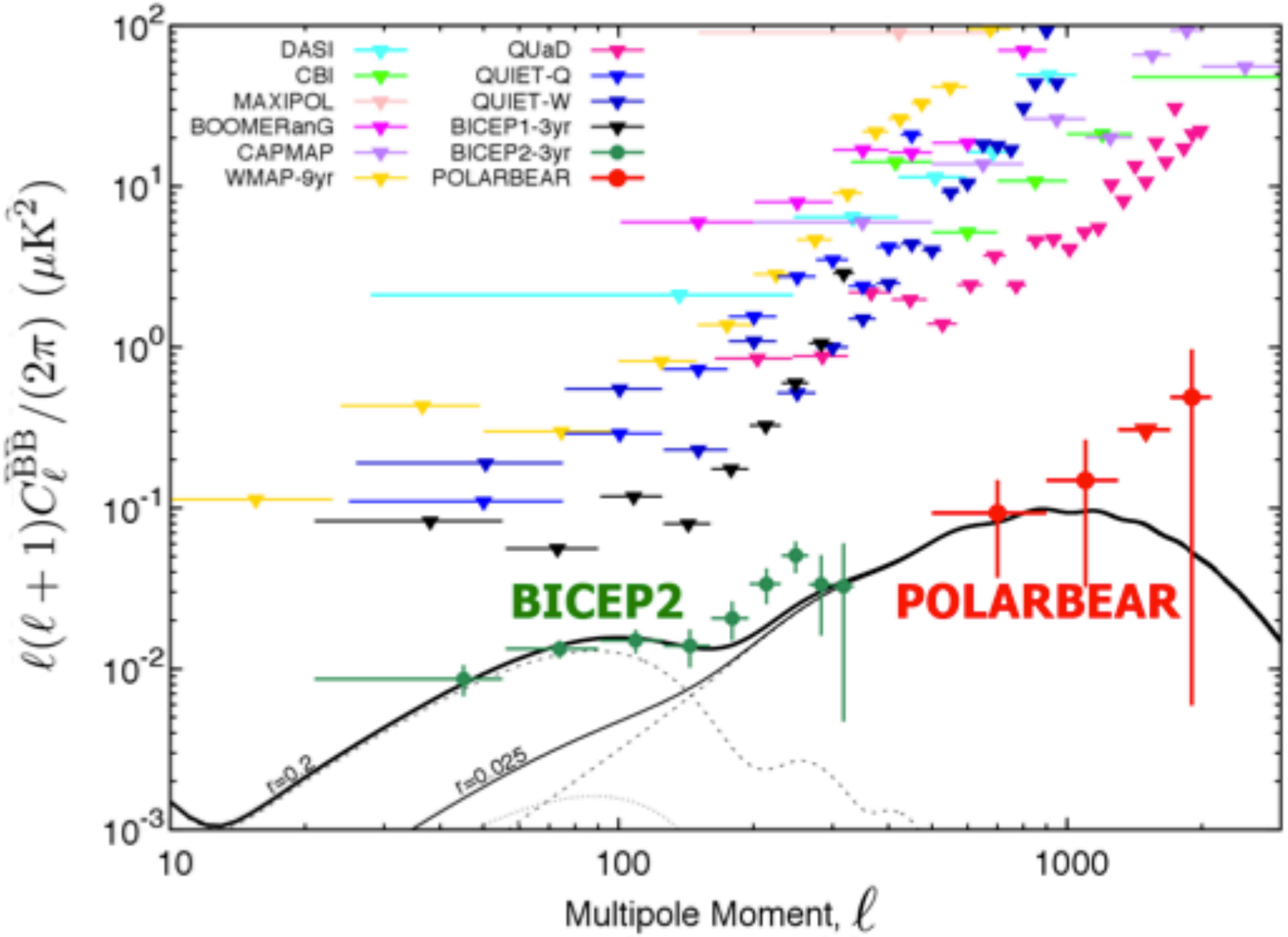
new proposals are constantly appearing in the literature
(even though the community working on this is small)

sound waves from PTs, GW from fermions, anisotropic preheating, Higgs decay after inflation, oscillons decay at preheating...

Hindmarsh 1304.2433, Enqvist 1203.4943, Bethke 1309.1148, Figueroa 1402.1345, Zhou et al 1304.6094 ...

The frequency spectrum of gravitational waves





5.2σ excess in the B-mode spectrum at low multipoles!

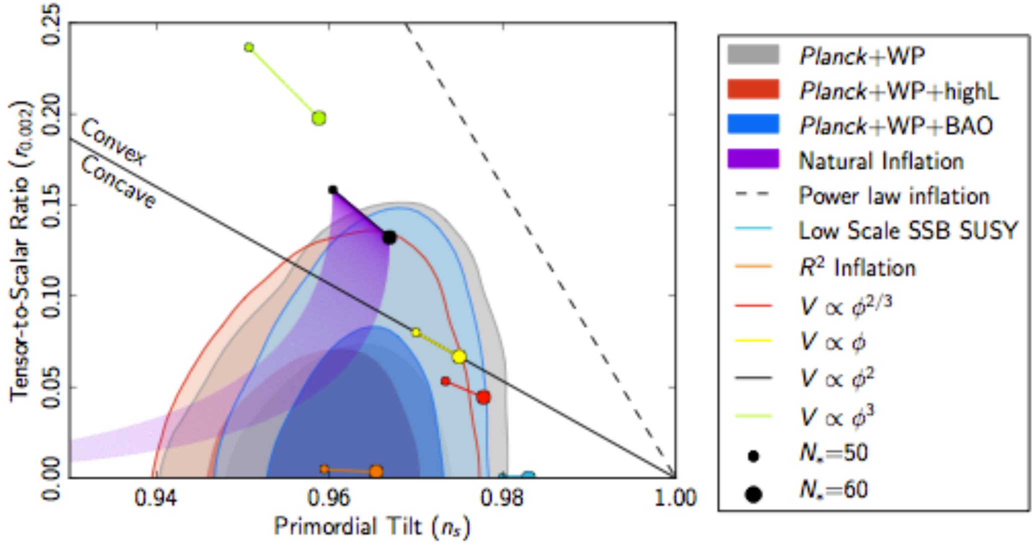
Constraint on tensor-to-scalar ratio r in simple inflationary gravitational wave model:

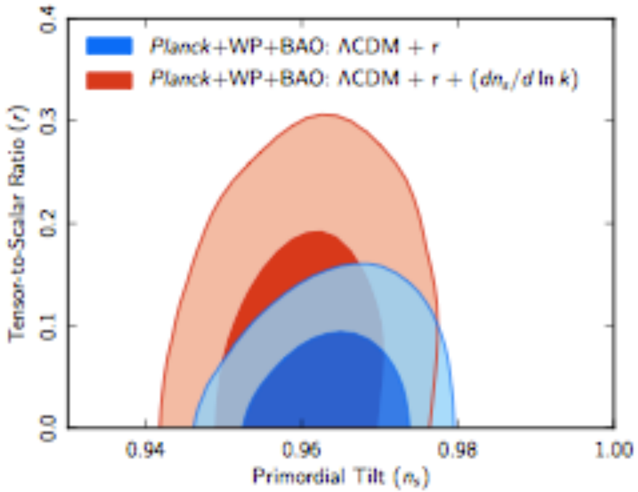
$$r = 0.20^{+0.07}_{-0.05}$$

arXiv:1403.3985

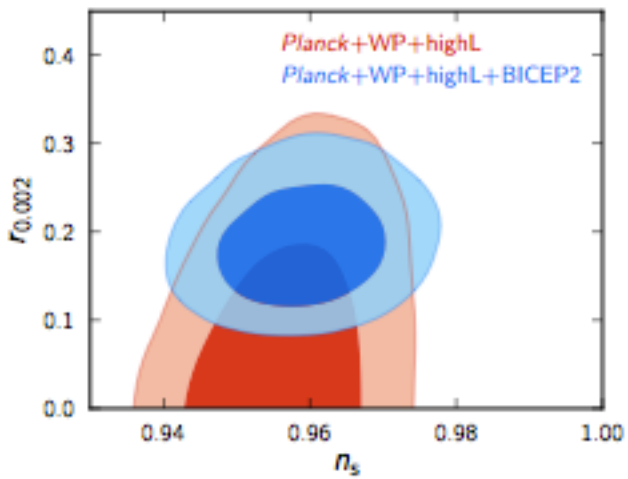
arXiv:1403.2369

Planck with no running of n_S





Planck with running of n_S allowed



Planck + BICEP2

But only one wavelength: is the estimate of the polarisation coming from dust adequate?

Planck will tell.

If r=0.2, Planck will confirm as well.

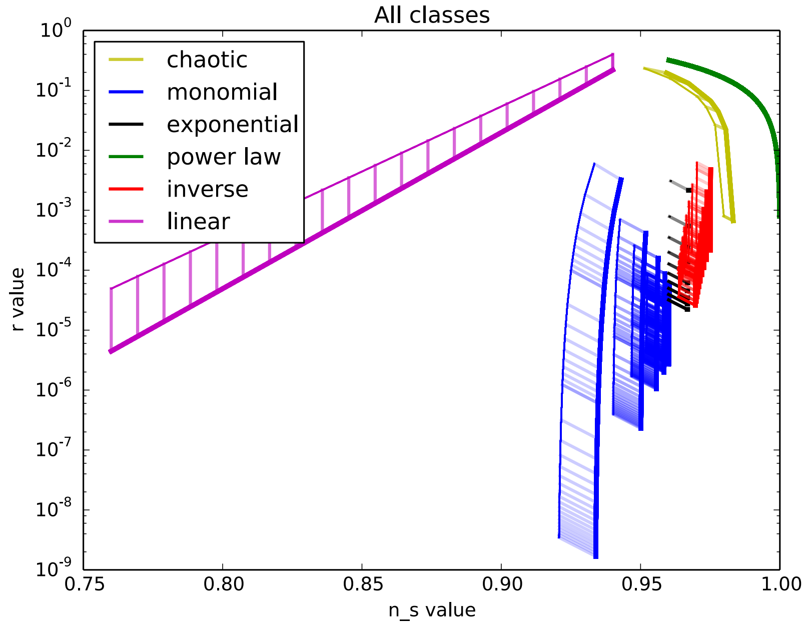
Are these primordial gravitational waves? Could be unexpected foreground.

See e.g. Liu, Mertsch, Sarkar 1404.1899

If it is the trace of primordial gravitational waves, what does it tell us about fundamental physics?

First both expected and not expected:

- Most theoretical models predicted values of r much lower



P.B., E. Kiritsis, J. Mabillard, M. Pieroni, C. Rosset

- The non-observation of non-gaussianities conflicts many « realistic » theoretical models

- For the simplest toy models, a generic prediction is

n_S-1 ~ O(1/N)

$dn_S/d\ln k$ ~ O(1/N^2)

r ~ O(1/N)

or

r ~ O(1/N^2)

N number of e-foldings

Is this an argument for grand unification?

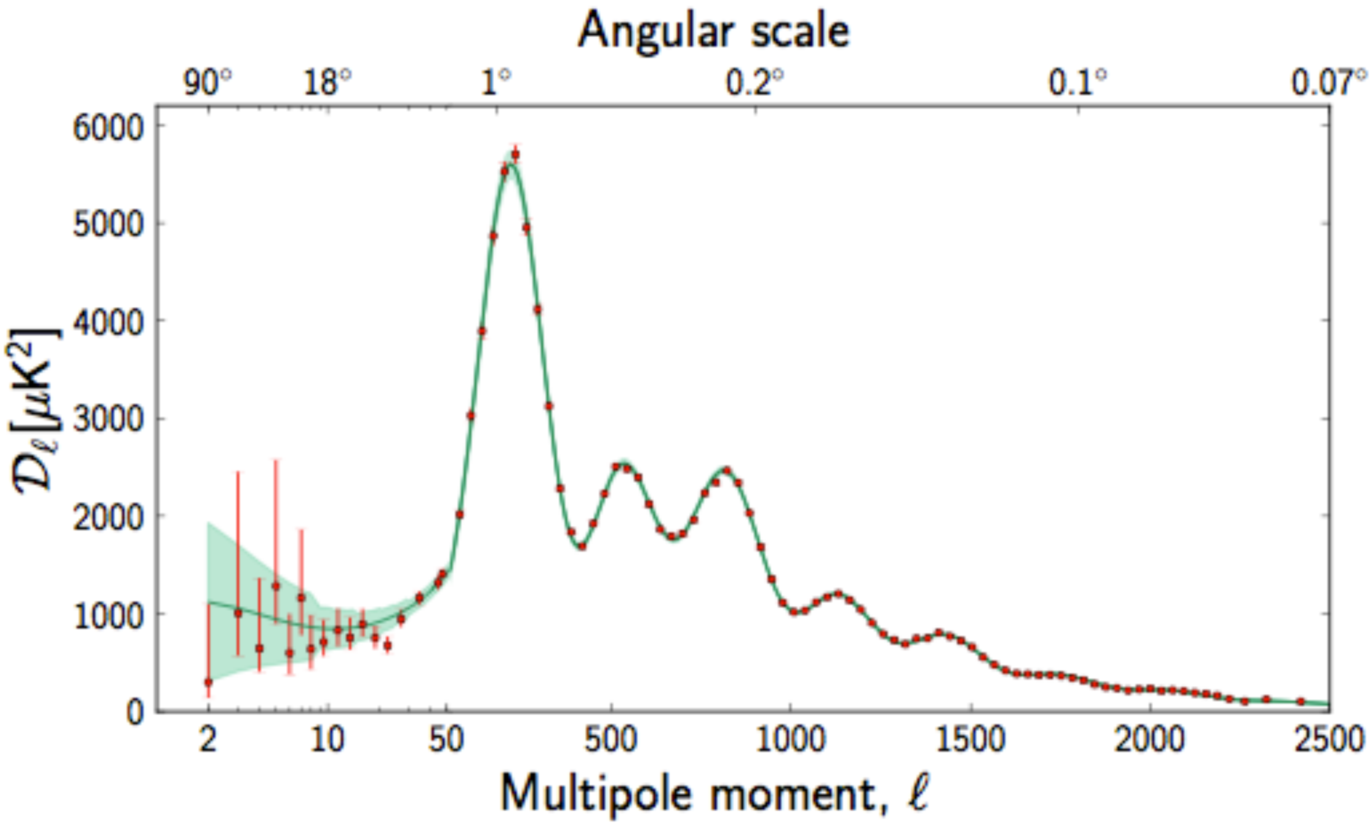
In the simplest models

$$H \sim 1.23\ (r/0.2)^{1/2}\ 10^{14}\ \text{GeV}$$

$$\rho^{1/4} \sim 2.26\ \ (r/0.2)^{1/4}\ 10^{16}\ \text{GeV}$$

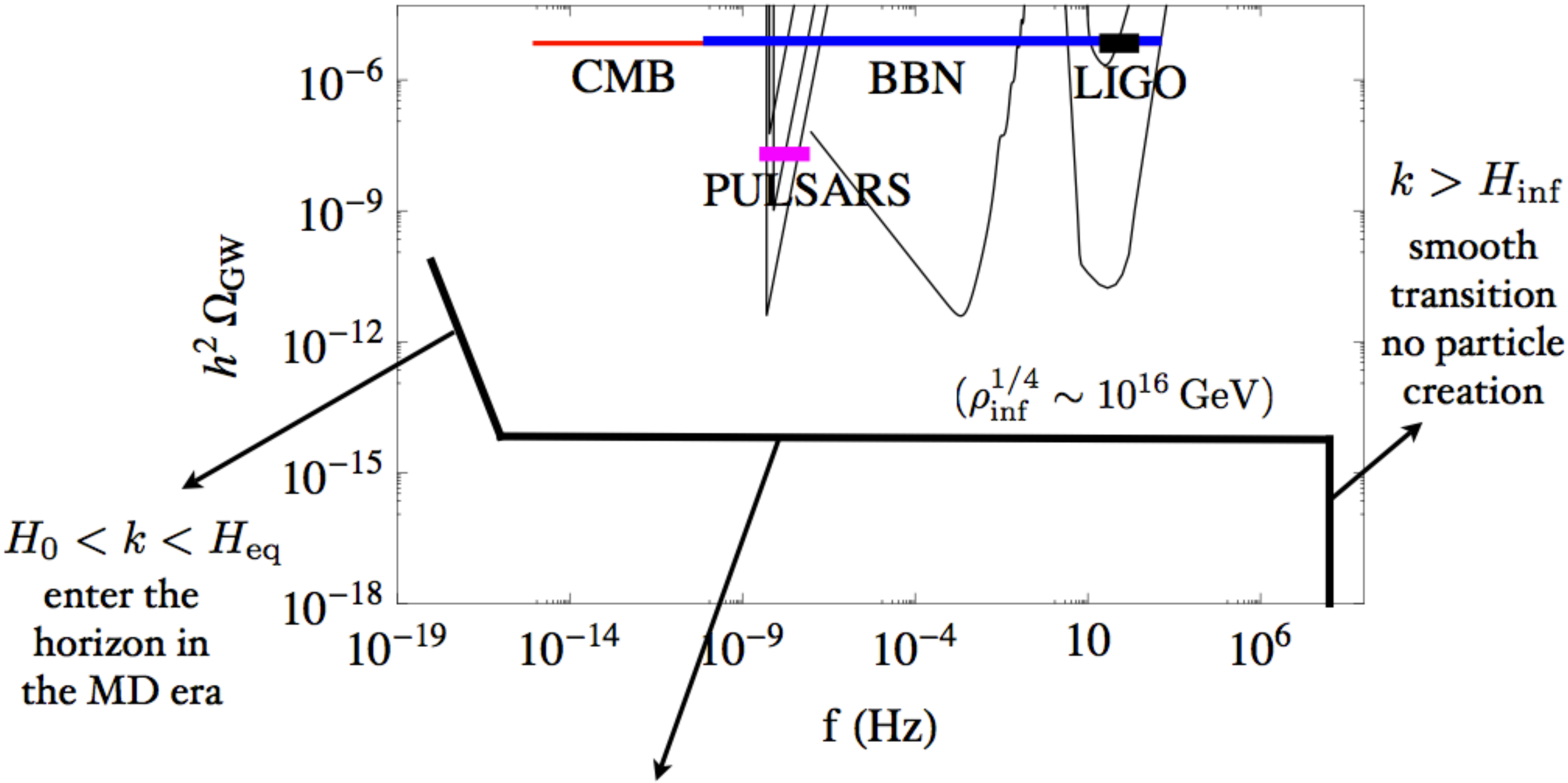
But:

- It remains to be seen whether the simplest modesl work (do they explain the missing power at low l ?).
- Is there a corresponding phase transition at 10^{16} GeV? The case of dark energy is not encouraging.



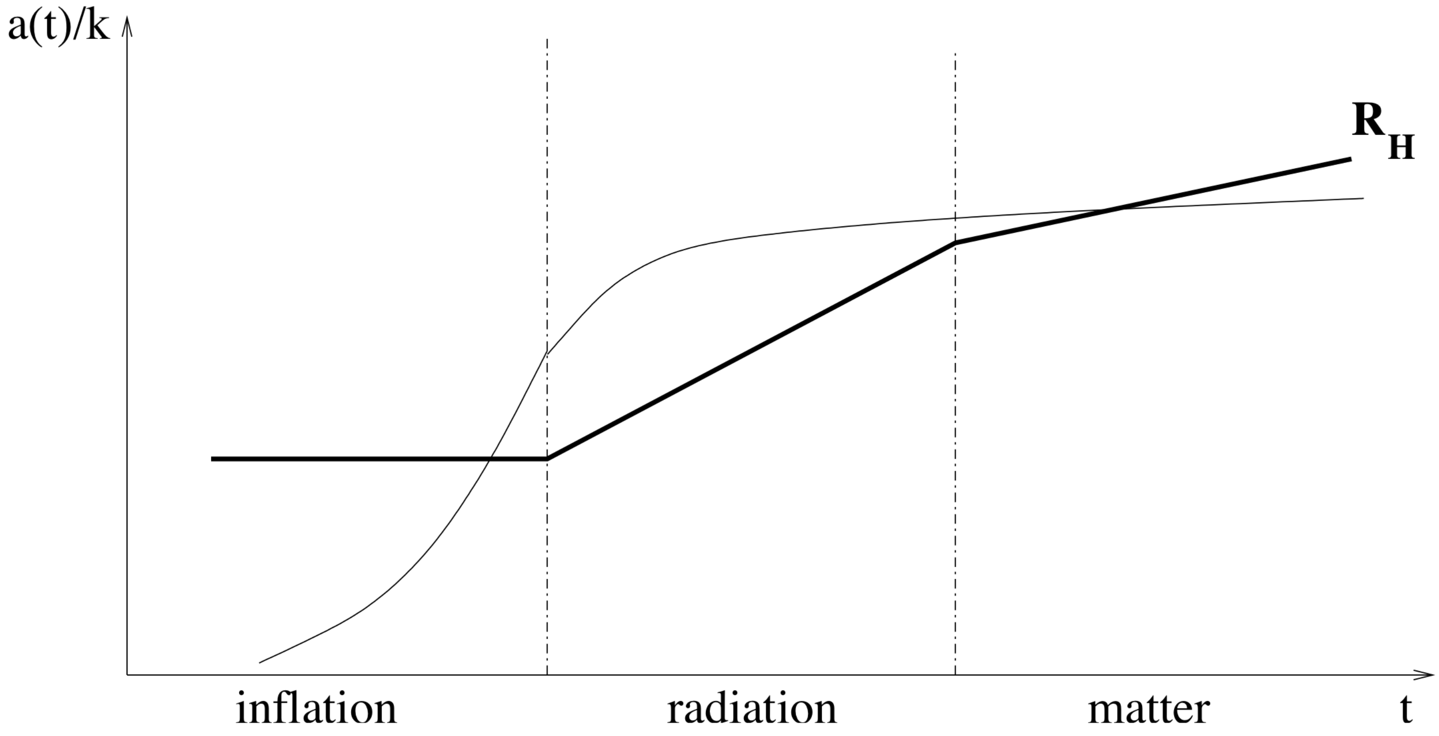
Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Can we expect direct detection at higher frequencies?



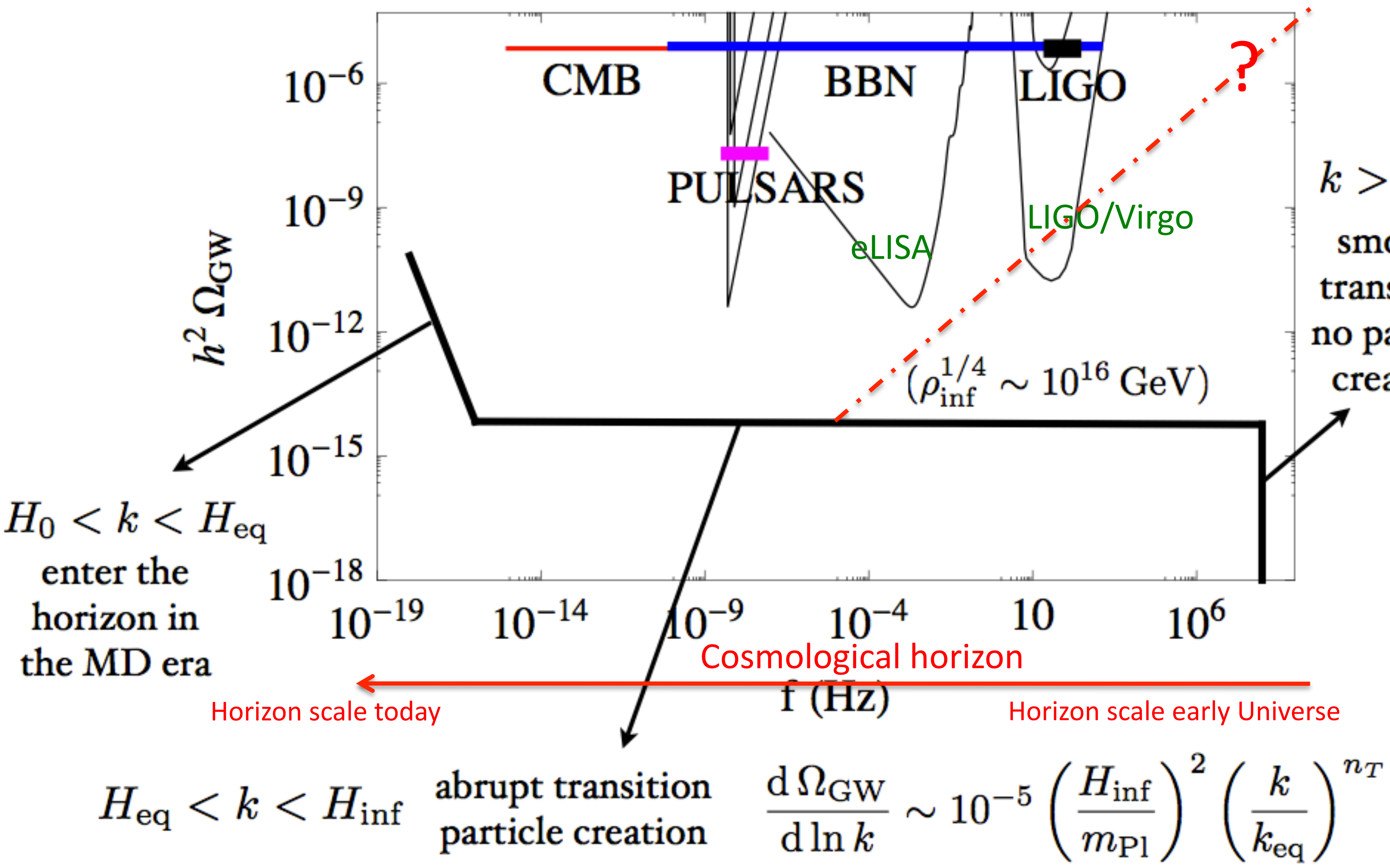
$H_{\rm eq} < k < H_{\rm inf}$ abrupt transition particle creation

$$\frac{{\rm d}\,\Omega_{\rm GW}}{{\rm d}\ln k} \sim 10^{-5}\left(\frac{H_{\rm inf}}{m_{\rm Pl}}\right)^2\left(\frac{k}{k_{\rm eq}}\right)^{n_T}$$



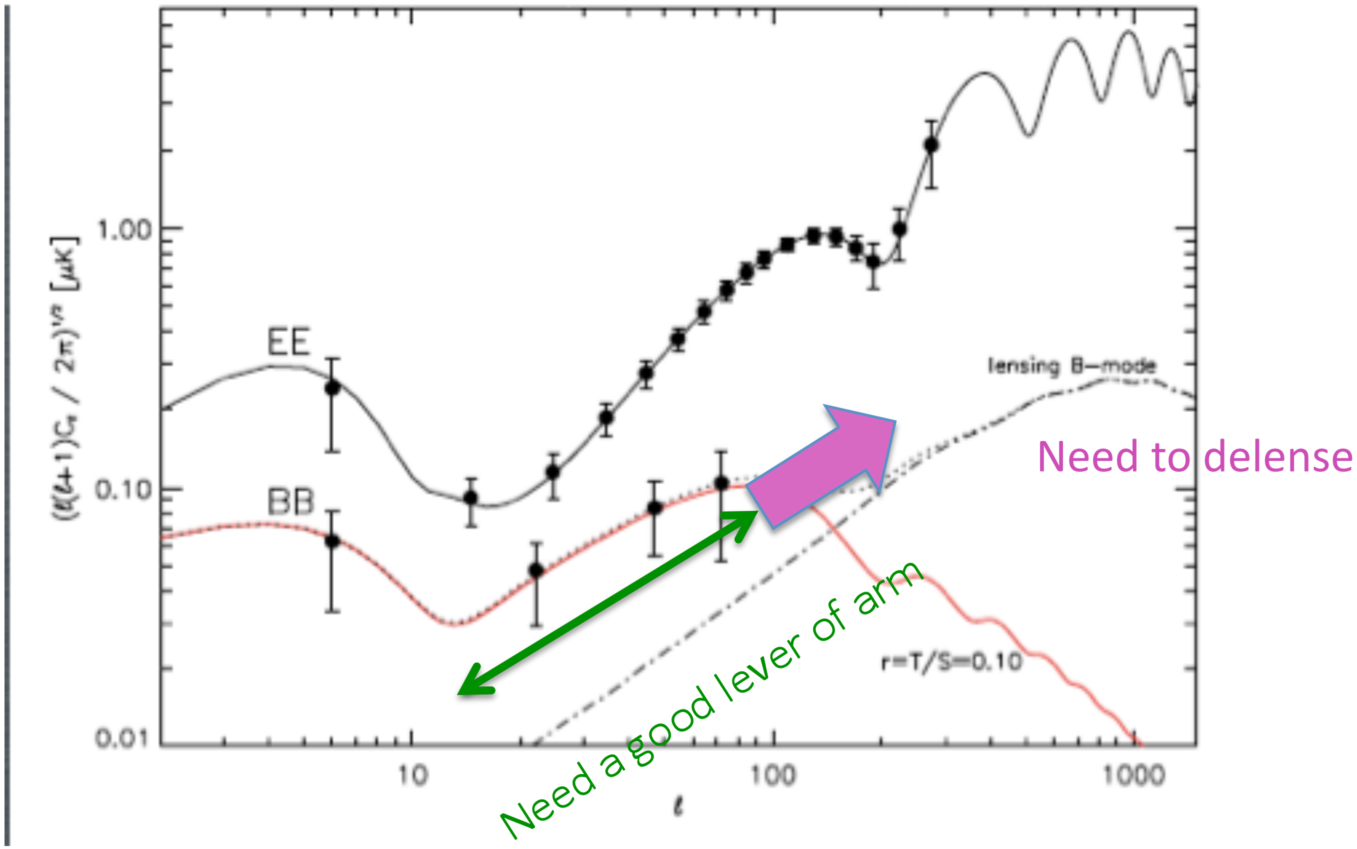
a(t)/k
R_H
inflation
radiation
matter
t

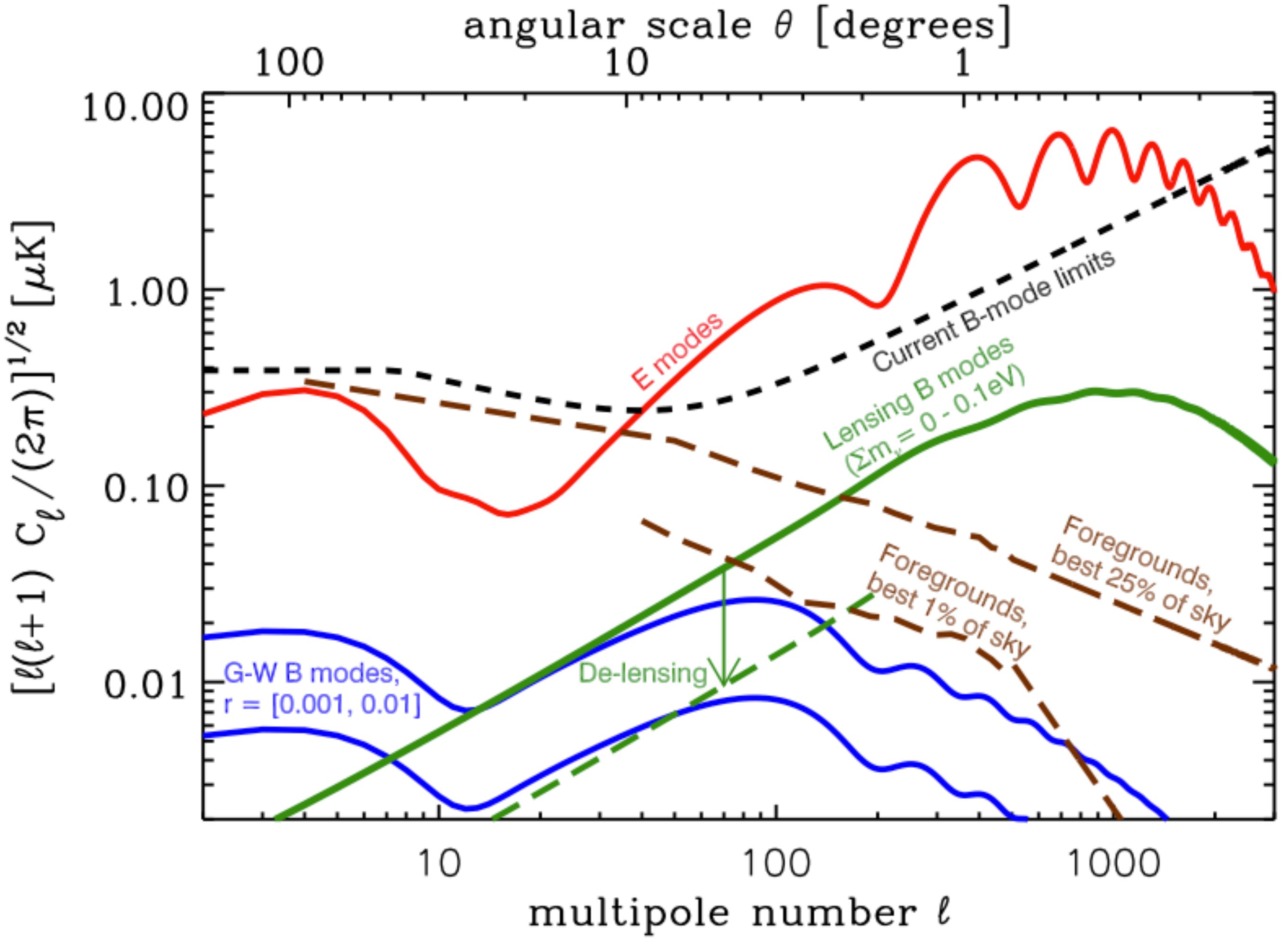
Can we expect direct detection at higher frequencies?



Future of CMB study: probe deeper into inflation scenarios (not easy!)

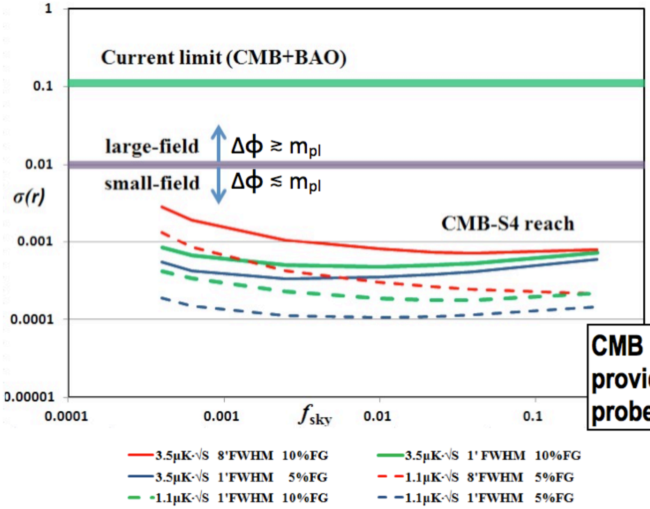
In order to check inflation and reconstruct the inflation potential, need to check the « consistency » relation $r = -8n_T$ and look at the scale dependence $dn_s/d\ln k$,…





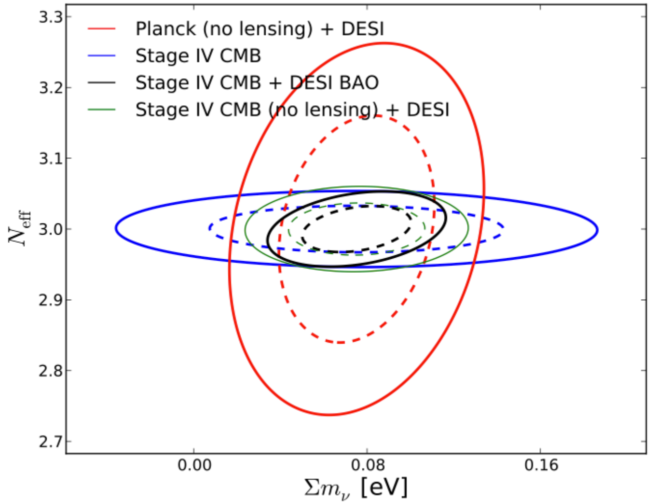
angular scale θ [degrees]
100
10
1
10.00
1.00
0.10
0.01
[ℓ(ℓ+1) C_ℓ /(2π)]^1/2 [μK]
E modes
Current B-mode limits
Lensing B modes
(Σm_ν = 0 - 0.1eV)
Foregrounds,
best 25% of sky
Foregrounds,
best 1% of sky
De-lensing
G-W B modes,
r = [0.001, 0.01]
10
100
1000
multipole number ℓ

Inflation projection for CMB-S4



CMB polarization provides the only probe for r < 0.1

Joint projections N_{eff} - Σm_ν



$\sigma(\Sigma m_\nu)$ = 16 meV
with two probes!

$\sigma(N_{eff})$ = 0.020
unique to CMB

J. Carlstrom, CMB Stage IV, Talk at P5 2nd meeting