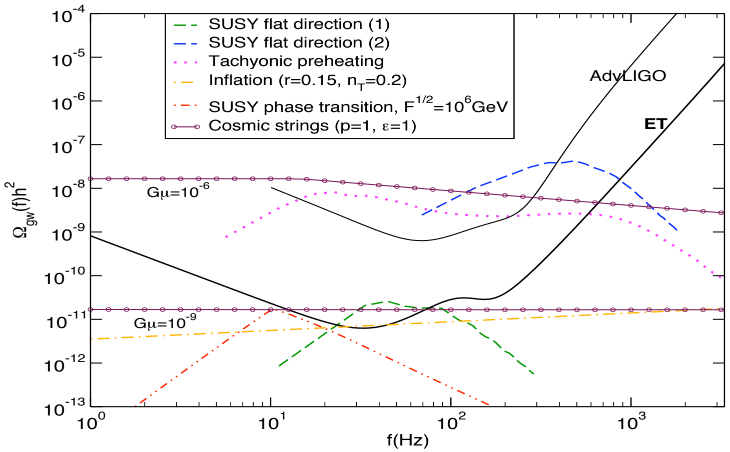
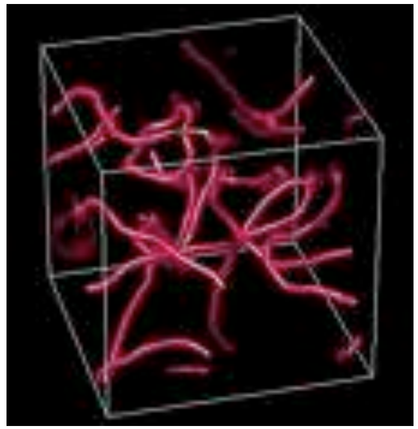
Stochastic backgrounds and the Early Universe at ET

2nd ET General Workshop, Erice 2009

Thomas Dent (Cardiff University)

WG4, ET Science Case





Outline

- Motivation: Detect & characterize stochastic GW sources
  - very numerous: cannot be individually distinguished
  - may be very far away
- Properties & detection methods
  - Recent LSC result
  - Challenge for ET if only one site: correlated noise
- Detectable sources
  - Astrophysical (will not consider in detail – see T. Regimbau/VisDoc)
  - Cosmological: early Universe, topological defects

Stochastic GW are unique probe of early Universe

Reach us from large redshift essentially unchanged

Discover new physics related to inflation / phase transitions?

Stochastic GW basics

Individual sources overlap strongly in time/frequency

Isotropic SGWB described by *spectrum* alone

$$h^2_{\rm rms}(f) \equiv f S_{\rm gw}(f).$$

nb astrophysical sources need not be isotropic

Energy density in stochastic GW per log frequency (relative to closure density)

$$\frac{d\rho_{\rm gw}}{d\ln f} = \frac{\pi c^2}{2G} f^3 S_{\rm gw}(f), \qquad \Omega_{\rm gw}(f) = \frac{4\pi^2}{3H_0^2} f^3 S_{\rm gw}(f).$$

Standard assumption for LSC search: $\Omega_{\rm GW}(f) = \Omega_\alpha (f/100\,{\rm Hz})^\alpha$

$\alpha = 0$: "flat spectrum"

$$\Omega_0 < 6.9 \times 10^{-6}.$$

S5 result, LSC&Virgo Collaborations, Nature 2009

Detection by cross-correlation

see Allen & Romano, Phys.Rev.D59:102001,1999

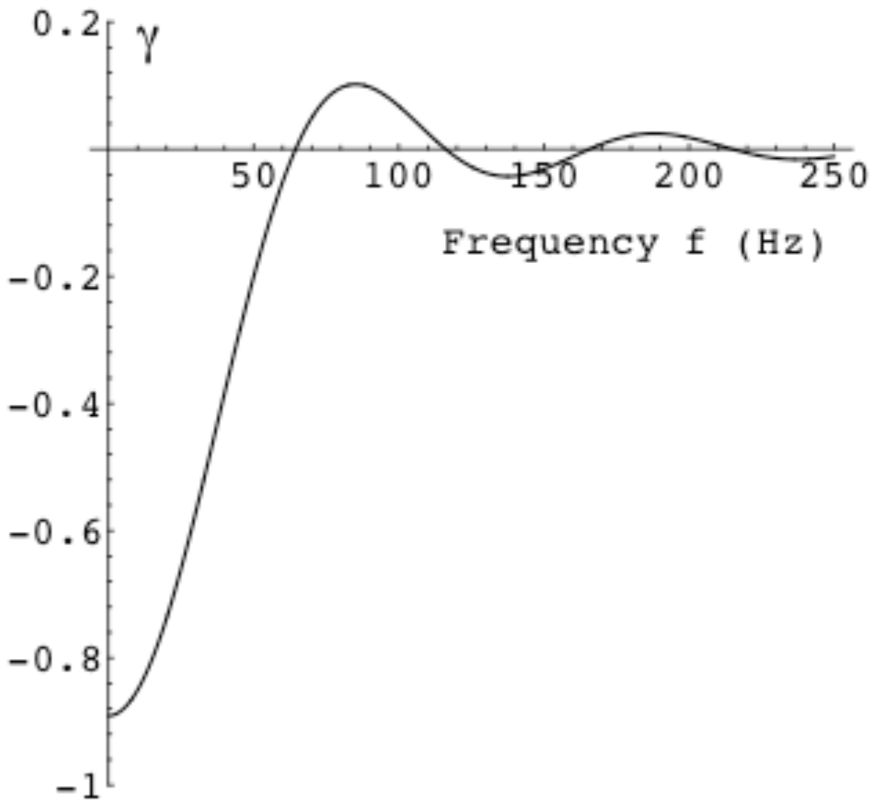
- Stochastic BG in a single ifo looks like extra Gaussian noise
- Strategy: Consider cross-correlation of two detector outputs

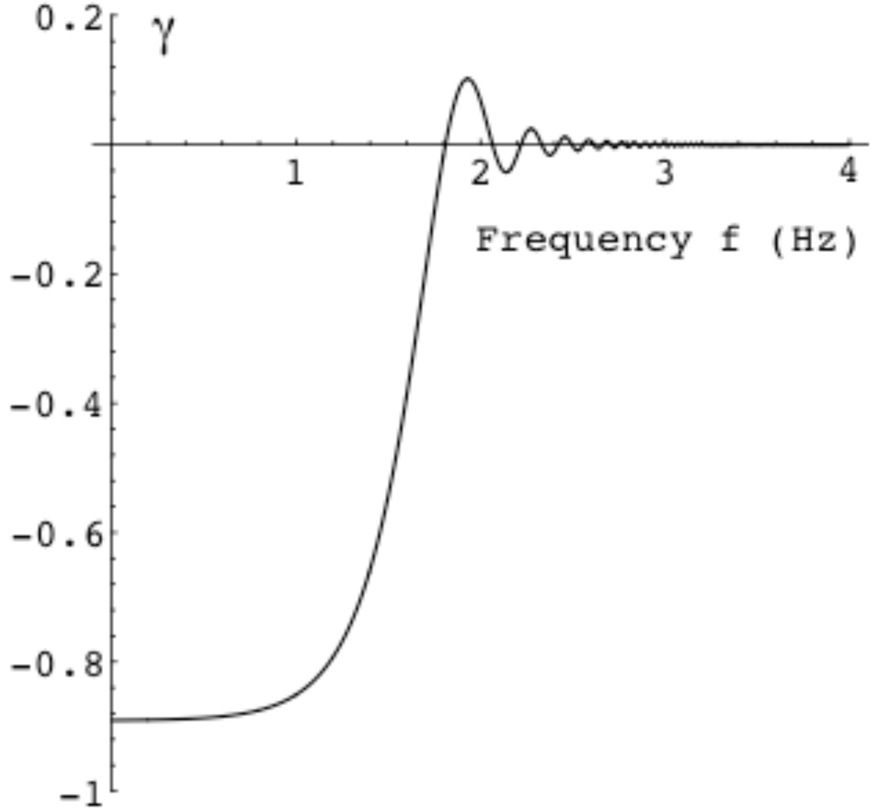
$$S := \int_{-T/2}^{T/2} dt\ s_1(t) s_2(t)$$

- If detector noises are uncorrelated S estimates the SGWB

$$\frac{S}{N} \simeq \frac{3H_0^2}{4\pi^2} F_{12} \sqrt{2T\Delta f} \frac{\gamma(f)\Omega_{\rm gw}(f)}{f^3 S_n(f)}$$

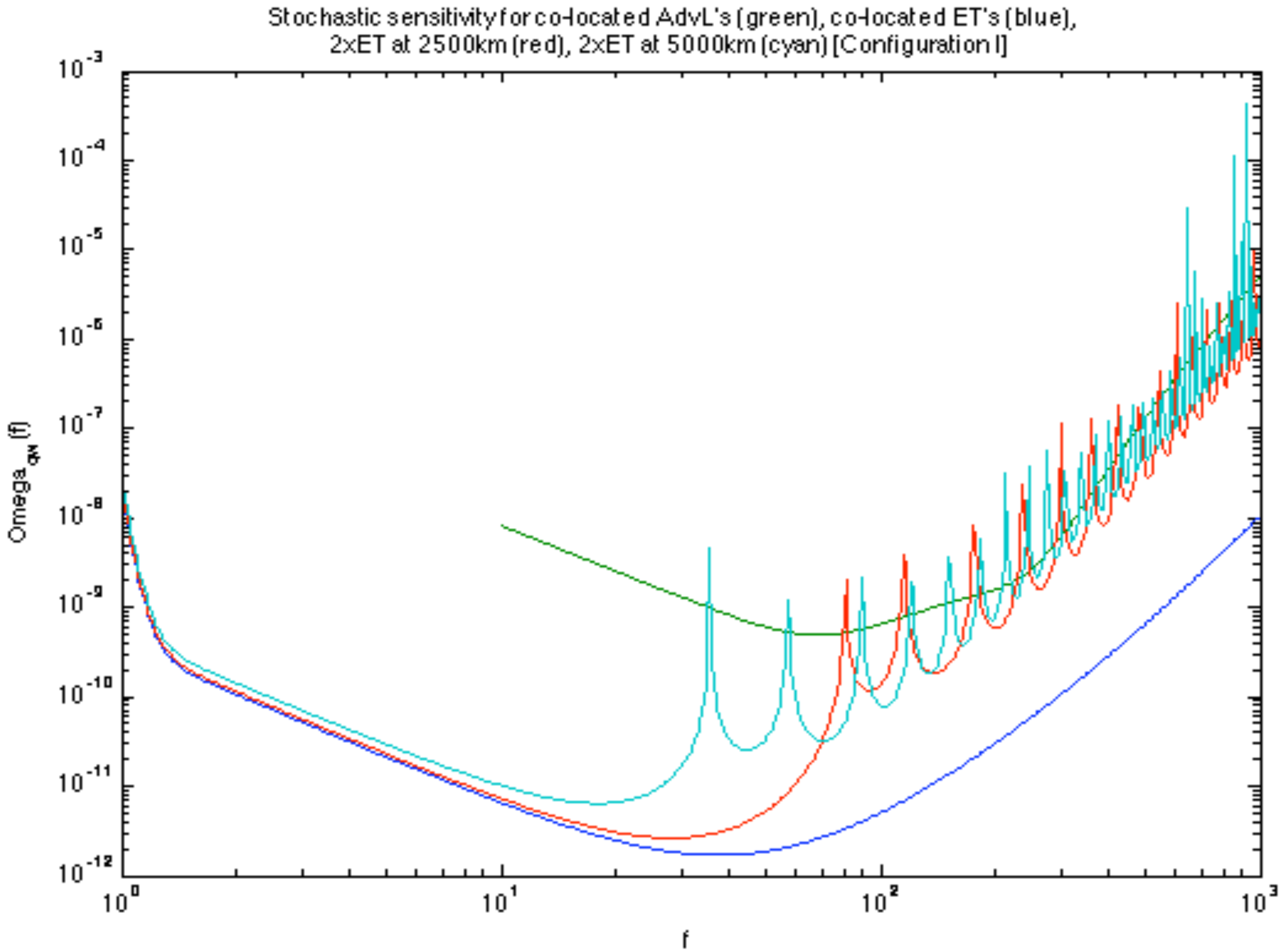
- $F_{12}\ \gamma(f)$ is "overlap reduction function"
  - – depends on orientation and separation of ifos
  - – eg co-located 60^o ifos rotated by 120^o : $\gamma = 3/8$





Hanford-Livingston overlap reduction function (B. Allen, Les Houches lectures (1996))

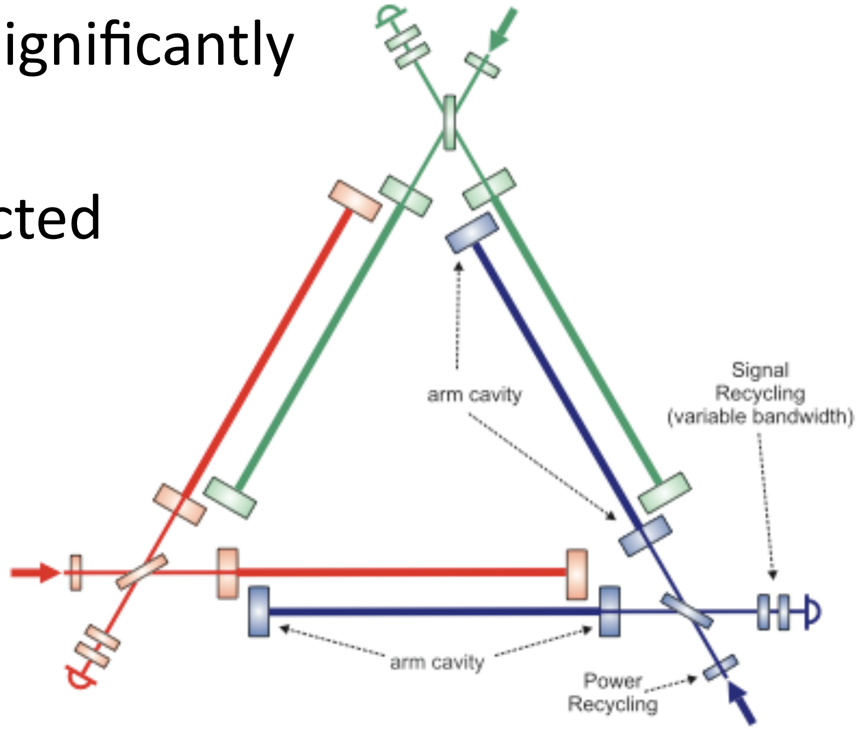
ET ideal sensitivity in Ω



Result considers optimally aligned 90º detectors with ET-B base sensitivity, observing time 3 years

Correlated noise at triple Michelsons

- First idea for ET design has three co-located ifos (A. Freise, 0804.1036)
- Environmental noise will be significantly correlated between outputs
- A null stream can be constructed
- Can this be used to control correlations?
- Do we need >1 site?

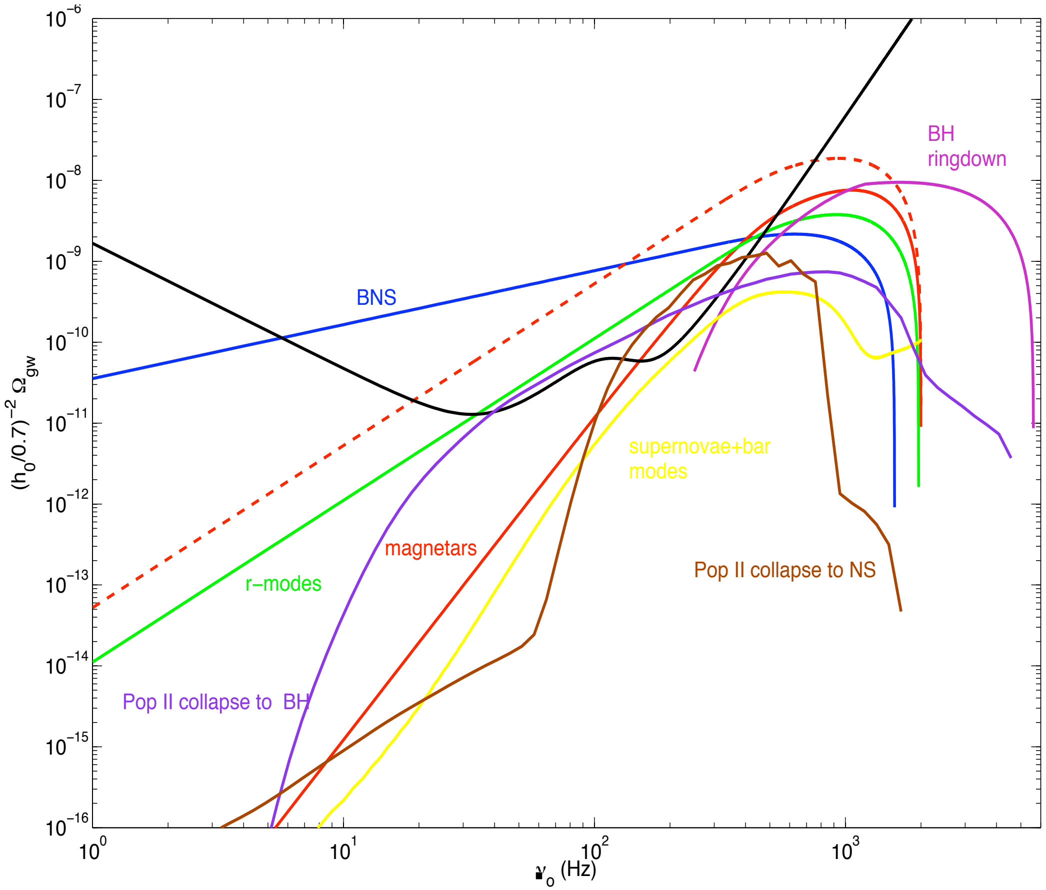


Sources: Astrophysical

Very many sources overlapping in time/frequency:

"confusion noise"

- Continuous eg pulsars, magnetars
- Burst-like eg Type II SN
- Inspiral-like eg BNS
- Observational and theoretical uncertainty



T.Regimbau, ET VisDoc

Cosmological sources

- Broad-band: Processes that continue over range of ln $a(t)$
  - Inflation – fluctuations of quantum fields
  - Cosmic strings / superstrings – vibrate & kink
  - $\Omega(f)$ ~ constant, detectable if > 10^{-11}-10^{-12}
- Narrow-band/peaked: Processes occurring at given time, scale factor a^*, temperature T^*
  - Reheating after inflation – classical field evolution
  - Phase transitions – bubbles nucleate, collide, turbulence, magnetic fields…
  - $\Omega(f)$ peaks at f_{peak} : needs to be in ET band, 10-1000Hz
  - Amplitude and f_{peak} value tell us about new physics (if we're lucky!)

Inflation

Standard inflation models cannot be seen at any planned ground-based detectors (or LISA!)

To stand any chance at ET you need large positive n_T (Grishchuk et al). – not realized in known models

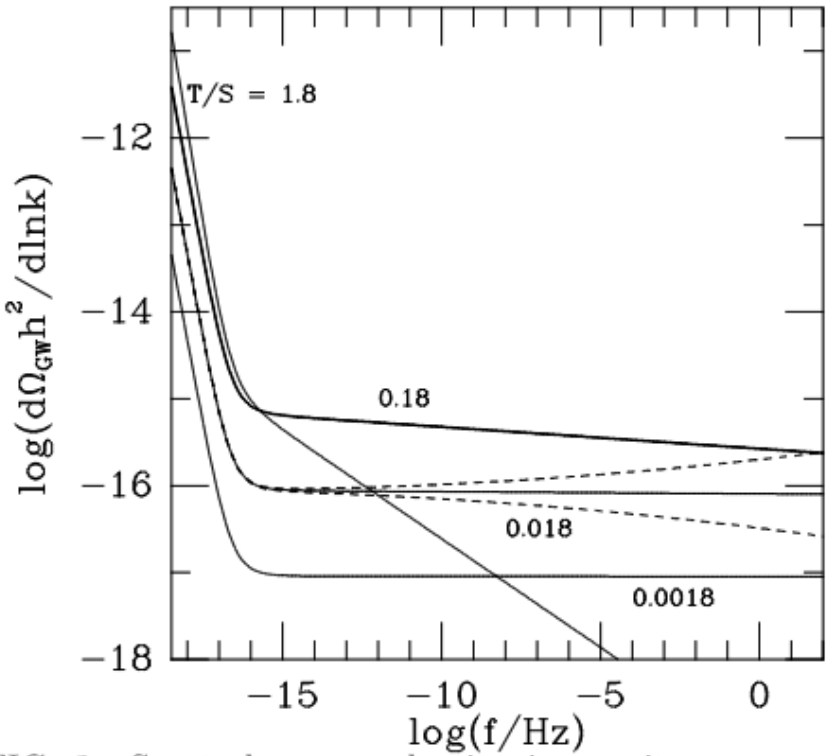
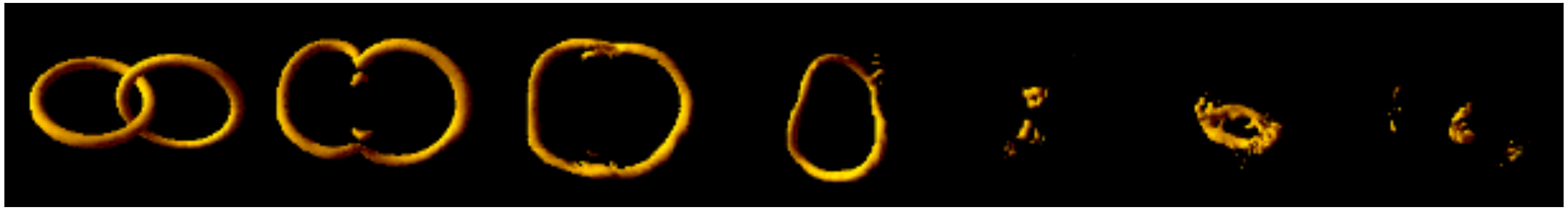


FIG. 3. Spectral energy density in gravity waves produced by inflation; for $T/S = 0.018$, $dn_T/d\ln k = -10^{-3}$, 0, 10^{-3}. $T/S = 0.18$ (heavy curve) maximizes the energy density at $f = 10^{-4}$ Hz. Curves are from Eq. (6) using $H_0 = 60\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_0 = 1$, and $g_* = 3.36$.

(Mike Turner, Phys.Rev. D (1997))

Cosmic strings

- Strings form at phase transitions (GUT or lower energy scale) or after brane inflation (superstring scale)
- Emit GW by vibrating, evolve via collisions (R.Battye & E.P.Shellard)



- Evolution and radiation properties under debate
- Main unknown parameter $G\mu$ – mass per length
  Cosmological bound now ~ $G\mu < 10^{-7}$
- ET could see strings with much smaller $G\mu$ – depending on evolution properties

Reheating & phase transitions

- Events occurring in early Universe with large energy density
- Relativistic velocities, strongly inhomogeneous:
  - Strong amplification of field fluctuations (preheating)
  - Bubble nucleations & collisions: first order phase transitions

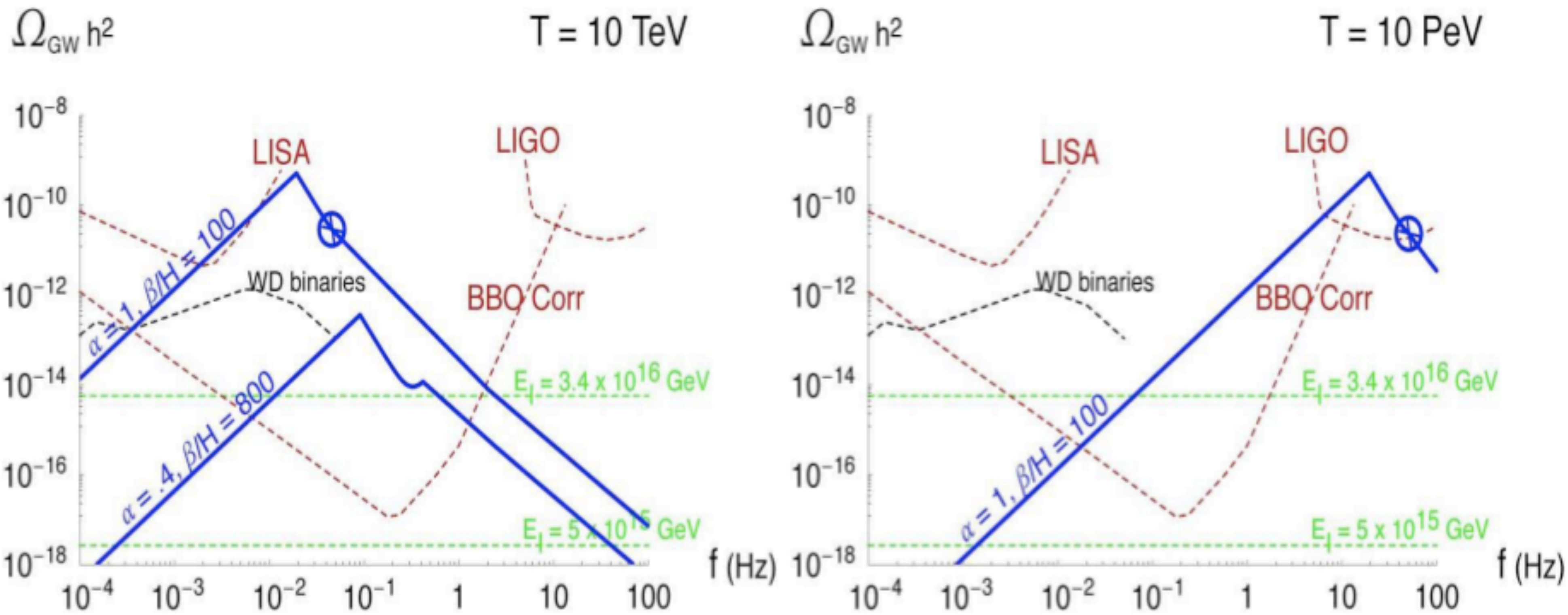
Relate present-day frequency to temperature at formation:

$$f = f_* \frac{a_*}{a_0} \approx (6 \times 10^{-8}\,\mathrm{Hz}) \frac{f_*}{H_*} \frac{T_*}{1\,\mathrm{GeV}} \left(\frac{g_*}{100}\right)$$

Generic value f_*/H_* ~ 10-100

ET frequencies correspond to huge energies: 10^6 – 10^{10} GeV!

Possible phase transition spectra



Grojean & Servant, Phys. Rev. D (2007)
NB ET sensitivity should be $< 10^{-11}$

N. Craig (0902.1990) : Transitions between SUSY-breaking vacua may have right energy scale…

Possible spectra from preheating

- Resonant decays of inflaton to other fields
- Main parameter is inflaton mass μ relative to M_{Planck}

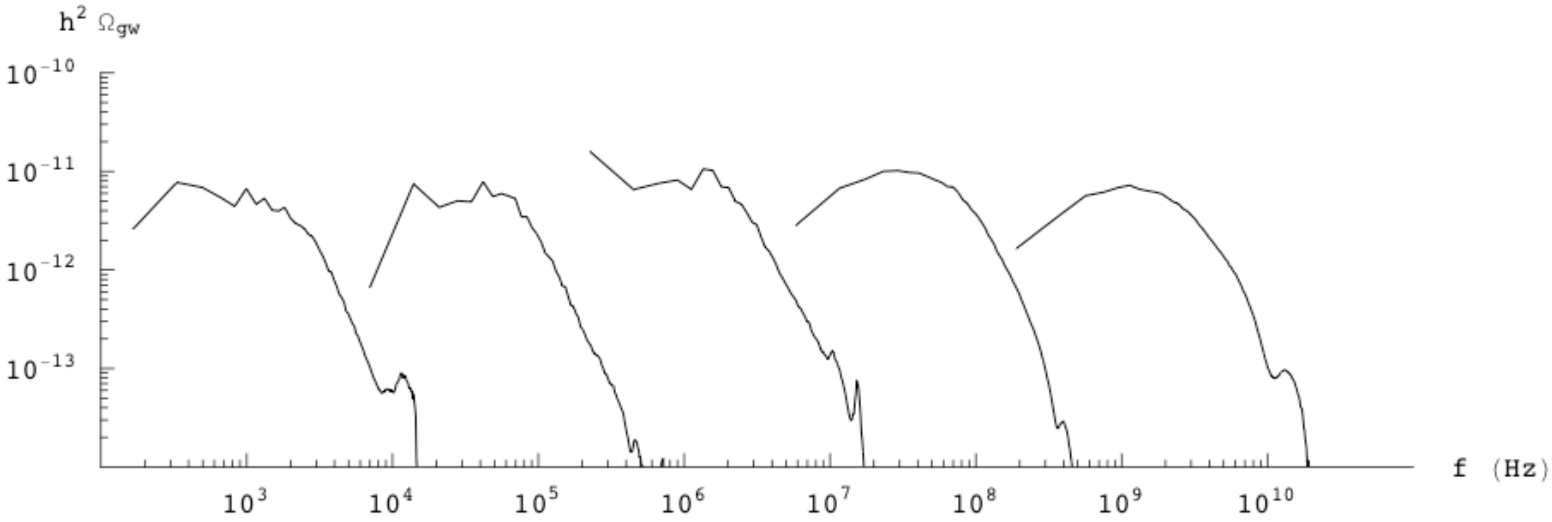
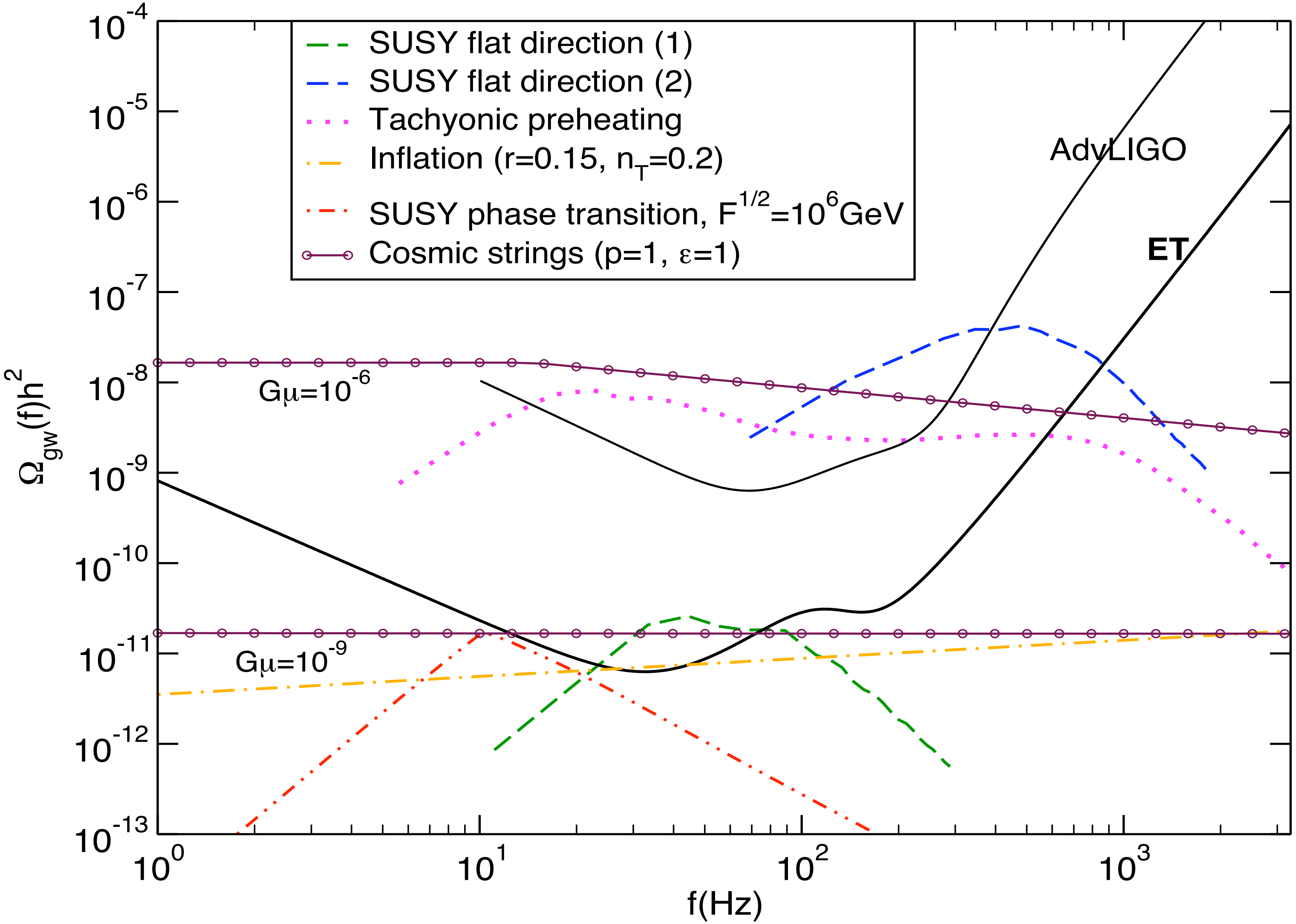


FIG. 1: We plot the spectrum of gravitational radiation produced during resonance with $\mu = 10^{-18}$ (left) through to 10^{-6} (right) in units where $m_{Pl} \approx 10^{19} GeV = 1$, where each spectrum has a value of μ 10^3 times large than the one immediately to the left. The corresponding initial energy densities run from from $(4.5 \times 10^9 \mathrm{GeV})^4$ to $(4.5 \times 10^{15} \mathrm{GeV})^4$ for our choice of ϕ_0. The plots are made on 128^3 grids, and the "feature" at high frequency is a numerical artifact.

Easther & Lim, Phys.Rev.Lett. (2007)

The stochastic landscape at ET



ET curve for co-located 60° ifos rotated by 120°, observing time 1 year
Curves from X. Siemens (cosmic strings,) N.Craig (SUSY ph.tr.),
J.-F. Dufaux (SUSY flat direction), J.-F. Dufaux et al. (tachyonic preheating)

Conclusions

- Stochastic BG is an important arm of the science case
- We would be extremely unlucky not to detect any astrophysical background
- Detectability of cosmological SGWB depends completely on unknown theoretical parameters
- If we are lucky new physics can be discovered beyond LHC energy reach

- ET base sensitivity should give impressive reach in $\Omega_{GW}(f)$
- BUT: Design is crucial to detectability
- Correlated noises? One site or many?