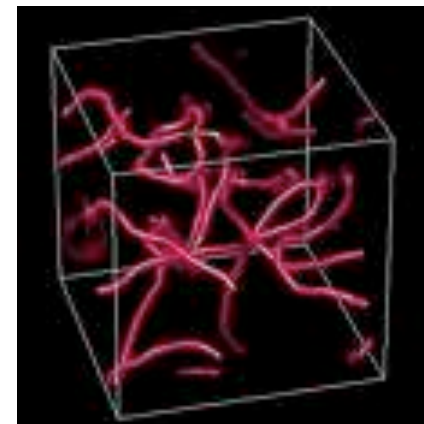
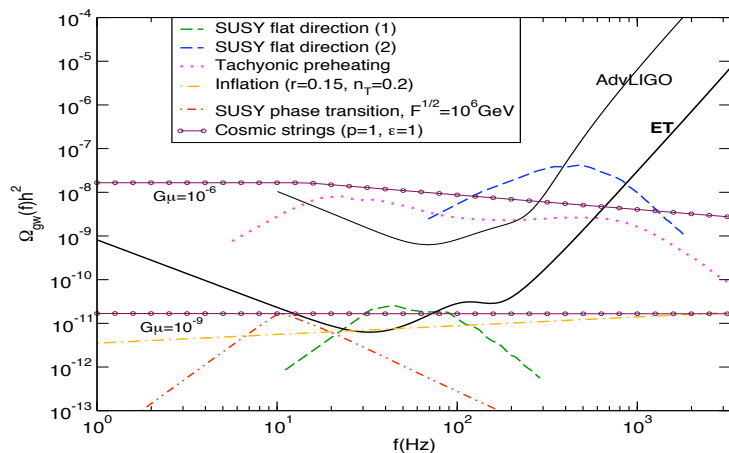


# Stochastic backgrounds and the Early Universe at ET

2<sup>nd</sup> 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

$$h_{\text{rms}}^2(f) \equiv f S_{\text{gw}}(f).$$

nb astrophysical sources need not be isotropic

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

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

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

$\alpha = 0$  : “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

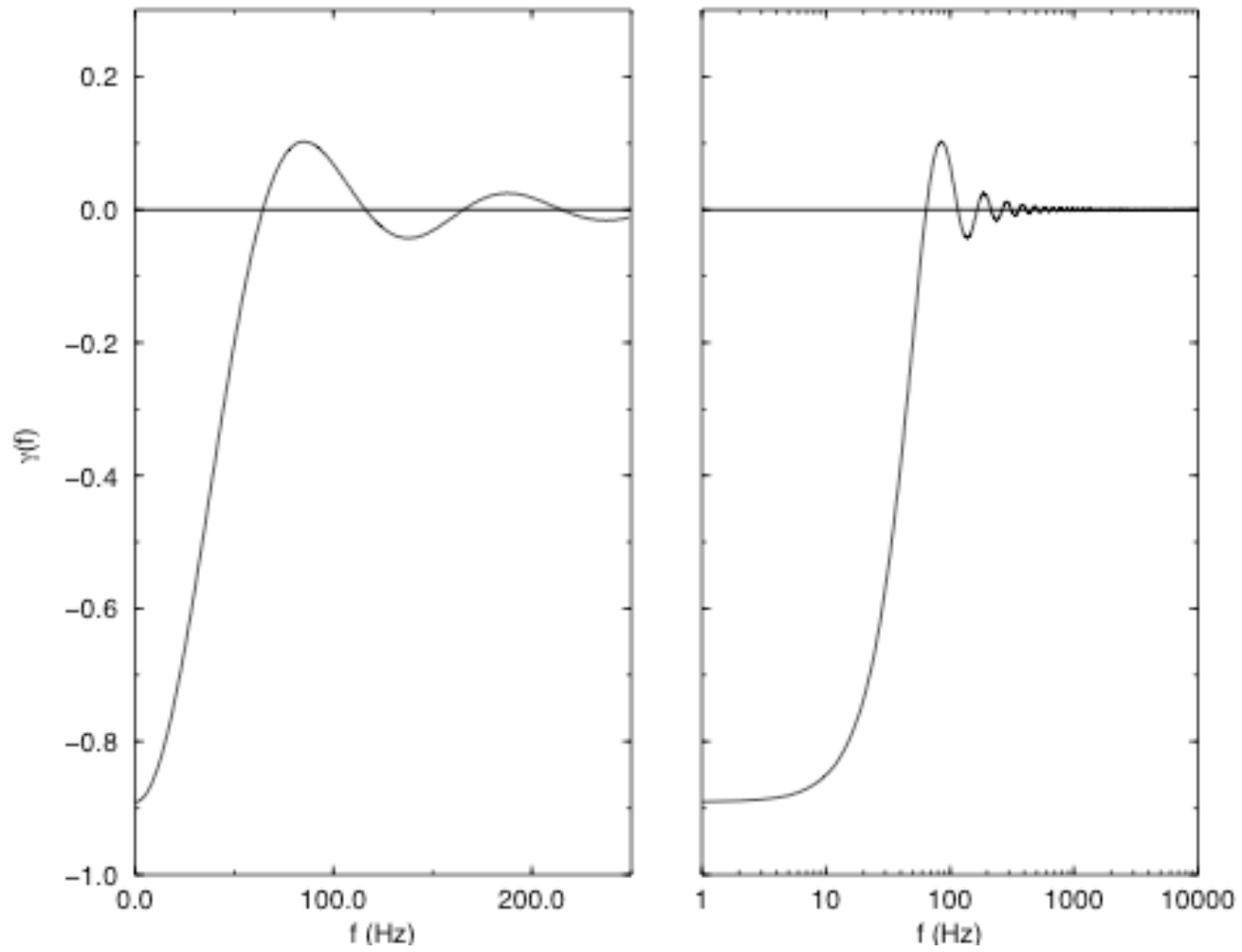
- Stochastic BG in a single ifo looks like extra Gaussian noise
- Strategy: Consider cross-correlation of two detector outputs

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

- If detector noises are uncorrelated  $S$  estimates the SGWB

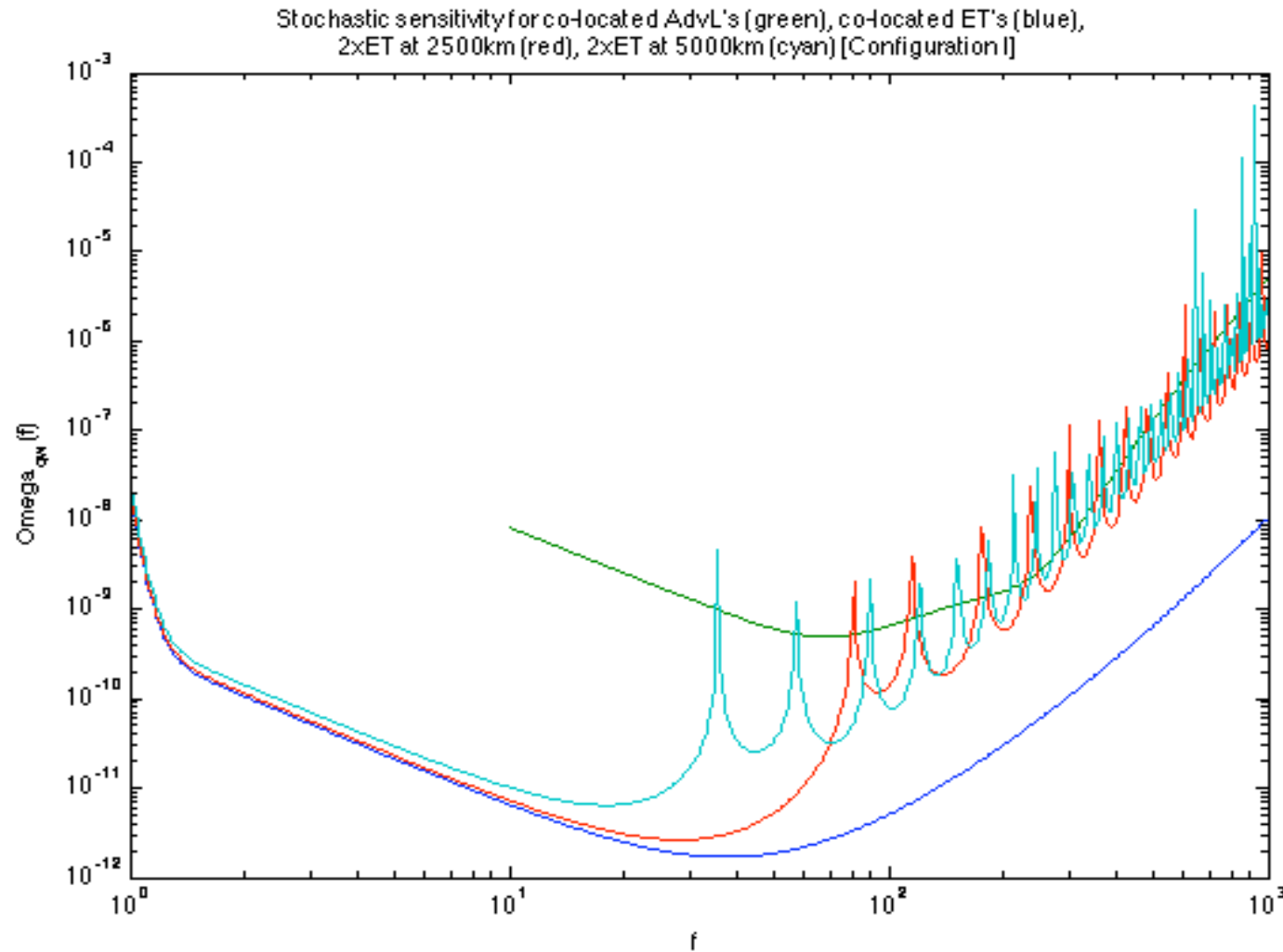
$$\frac{S}{N} \simeq \frac{3H_0^2}{4\pi^2} F_{12} \sqrt{2T\Delta f} \frac{\gamma(f)\Omega_{\text{gw}}(f)}{f^3 S_n(f)}$$

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



Hanford-Livingston overlap reduction function (Allen & Romano)

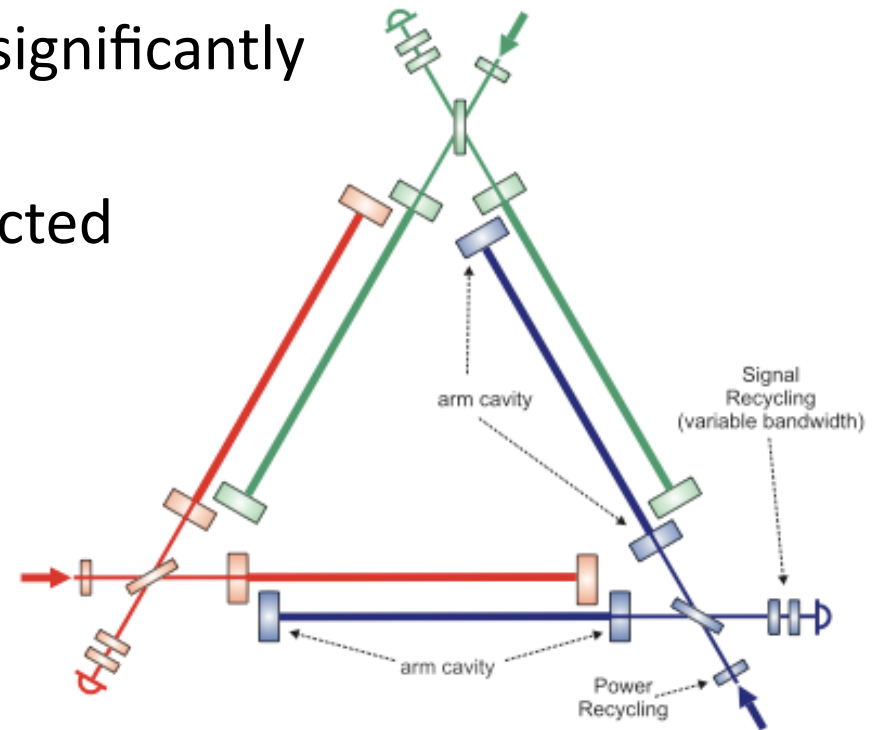
# ET ideal sensitivity in $\Omega$



Result considers optimally aligned  $90^\circ$  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?

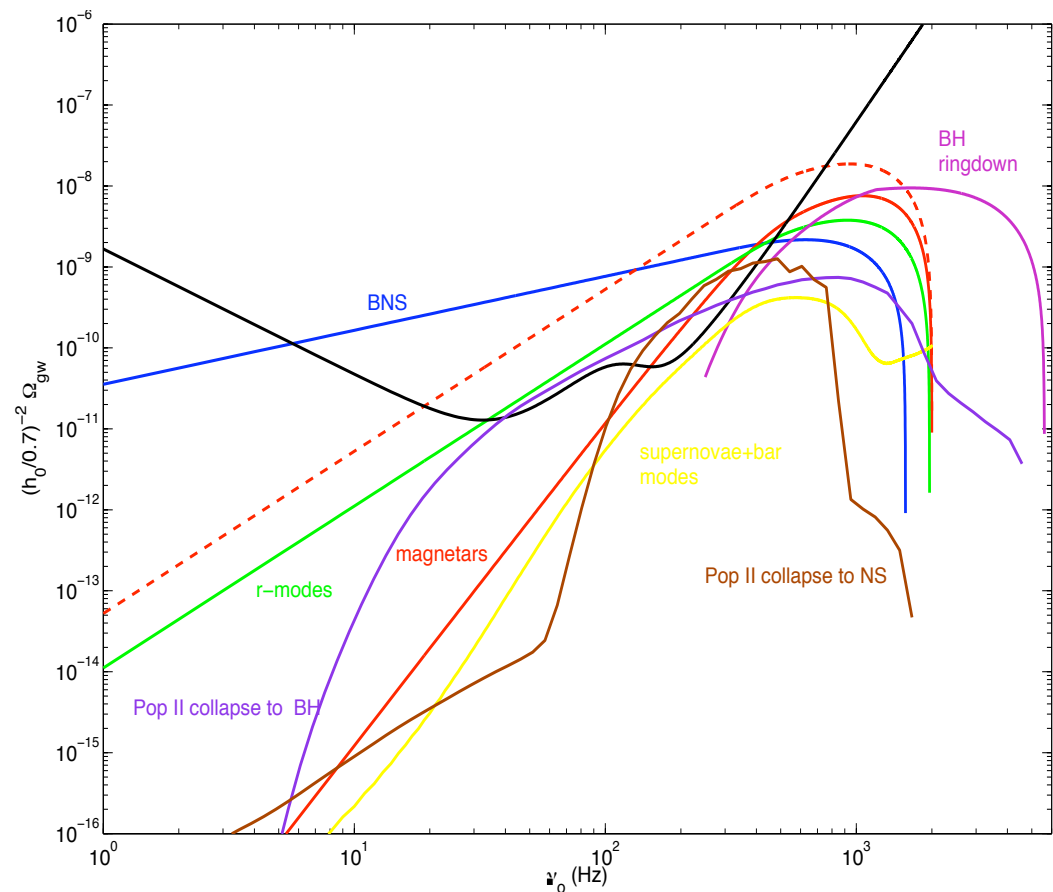


# Sources: Astrophysical

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





# Cosmological sources

- Broad-band: Processes that continue over range of  $\ln a(t)$ 
  - Inflation – fluctuations of quantum fields
  - Cosmic strings / superstrings – vibrate & kink
  - $\Omega(f) \sim \text{constant}$ , 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  $f_{\text{peak}}$  : needs to be in ET band, 10-1000Hz
  - Amplitude and  $f_{\text{peak}}$  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

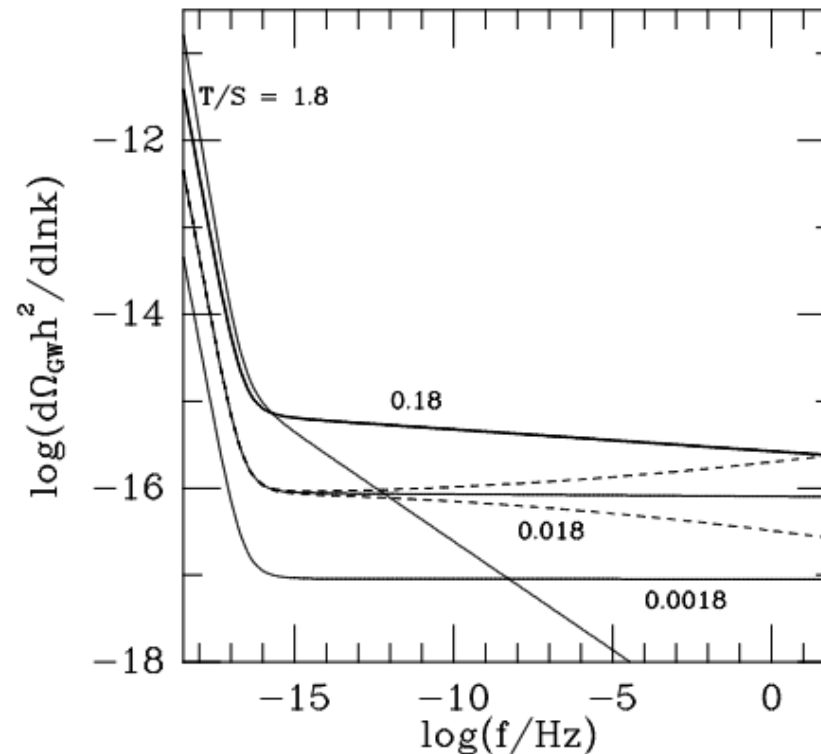
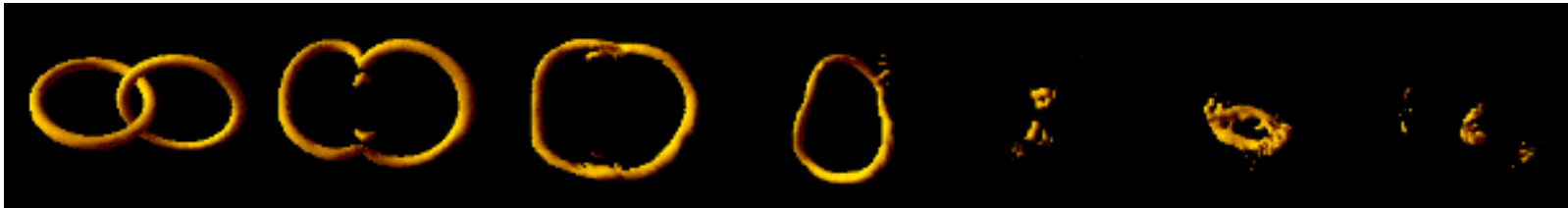


FIG. 3. Spectral energy density in gravity waves produced by inflation; for  $T/S = 0.018$ ,  $dn_T/d\ln k = -10^{-3}$ ,  $0$ ,  $10^{-3}$ .  $T/S = 0.18$  (heavy curve) maximizes the energy density at  $f = 10^{-4}$  Hz. Curves are from Eq. (6) using  $H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_0 = 1$ , 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  $\sim G\mu < 10^{-7}$
- 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

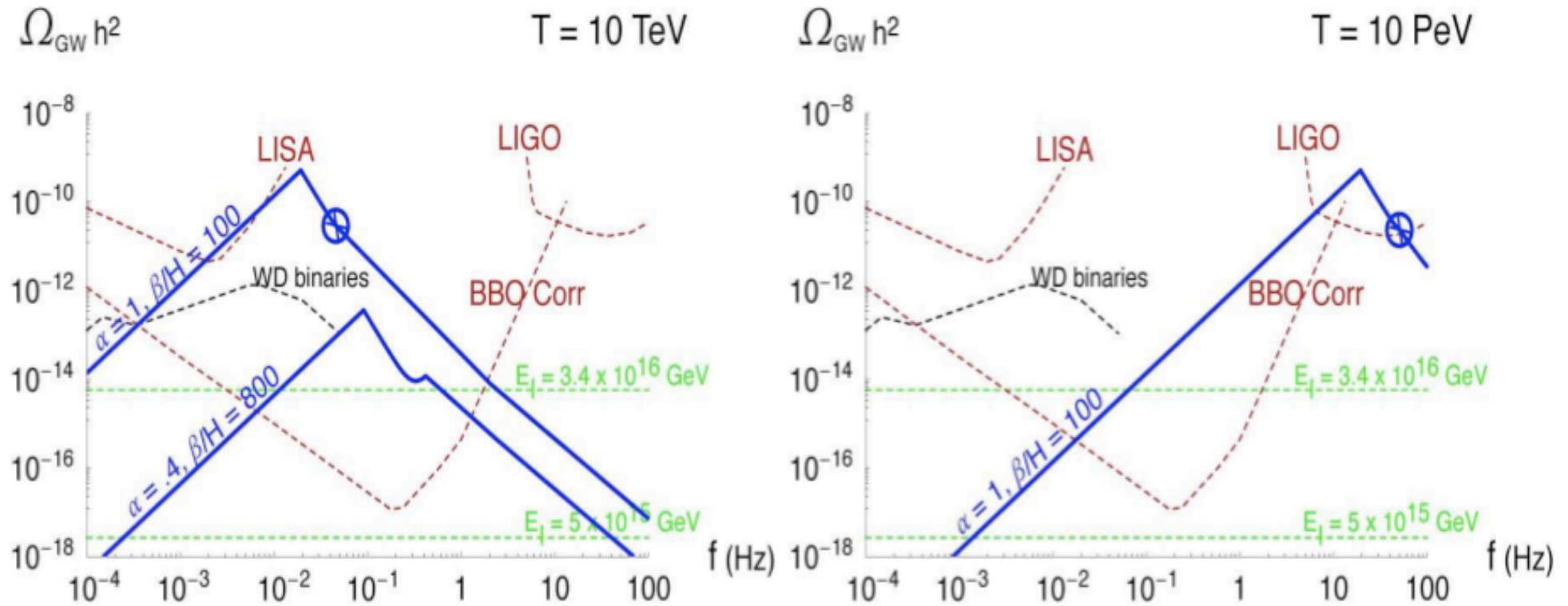
Relate present-day frequency to temperature at formation:

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

Generic value  $f_*/H_* \sim 10\text{-}100$

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  $\mu$  relative to  $M_{\text{Planck}}$

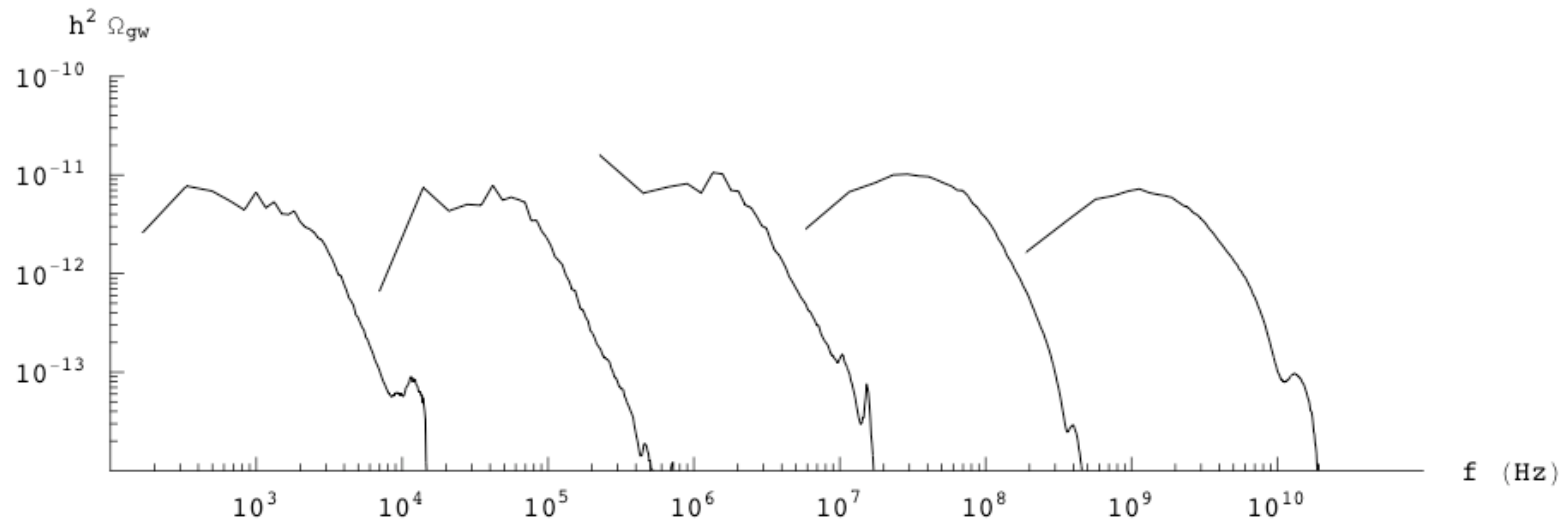
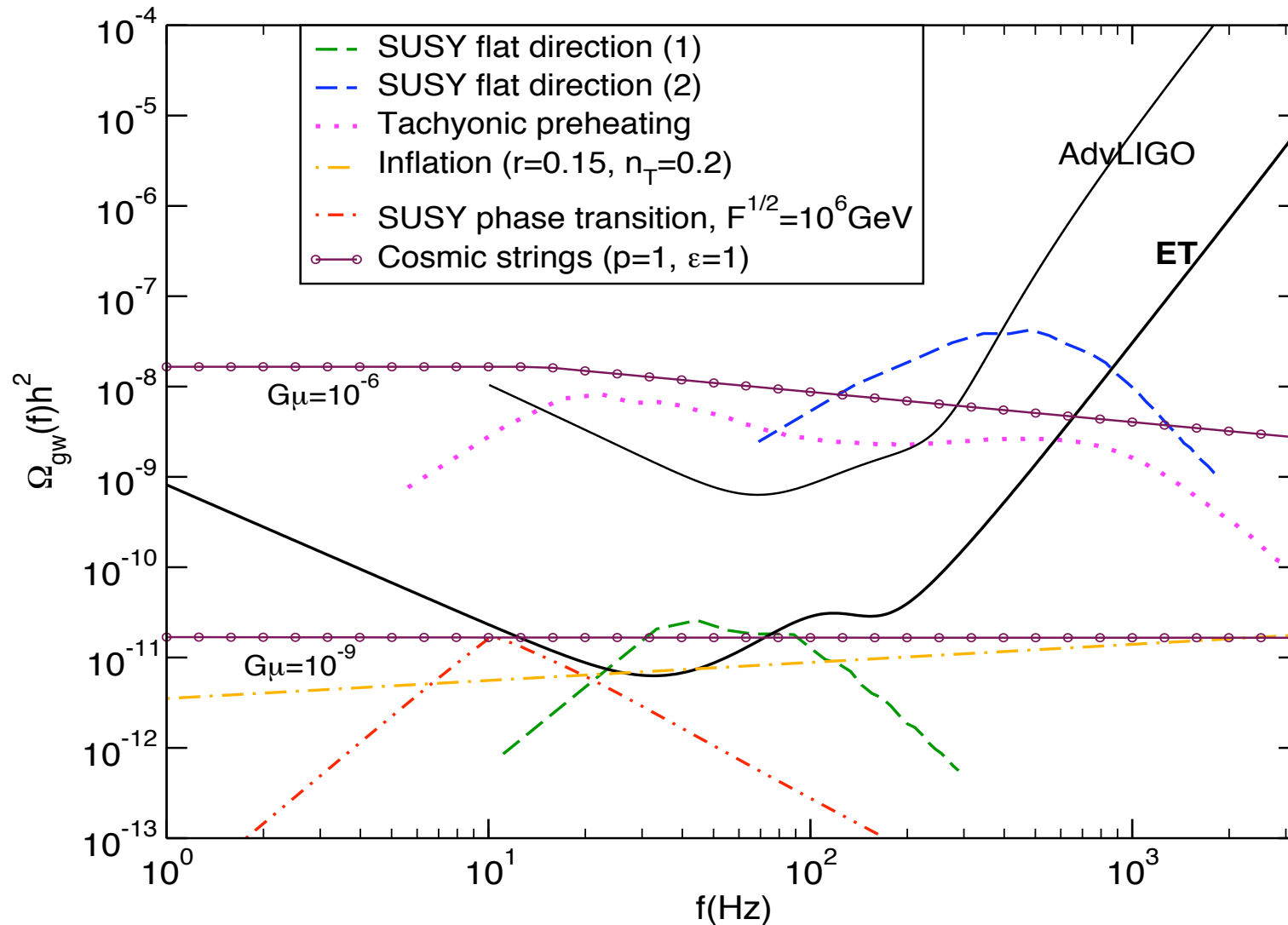


FIG. 1: We plot the spectrum of gravitational radiation produced during resonance with  $\mu = 10^{-18}$  (left) through to  $10^{-6}$  (right) in units where  $m_{Pl} \approx 10^{19} \text{ GeV} = 1$ , where each spectrum has a value of  $\mu$   $10^3$  times larger than the one immediately to the left. The corresponding initial energy densities run from from  $(4.5 \times 10^9 \text{ GeV})^4$  to  $(4.5 \times 10^{15} \text{ GeV})^4$  for our choice of  $\phi_0$ . The plots are made on  $128^3$  grids, and the “feature” at high frequency is a numerical artifact.

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

# The stochastic landscape at ET



ET curve for co-located  $60^\circ$  ifos rotated by  $120^\circ$ , 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  $\Omega_{\text{GW}}(f)$
- BUT: Design is crucial to detectability
- Correlated noises? One site or many?