Probing fundamental physics and the early Universe by detecting relic gravitational waves

Alessandra Buonanno

Department of Physics, University of Maryland

Content:

- Which unexplored physics the detection of relic GWs can probe
- Complementarity between different GW experiments
- Astrophysical foregrounds

XXIII Texas Symposium on Relativistic Astrophysics, Melbourne, Australia

LIGO-G060676-00-Z

Disclosing the *dark age* of the early Universe

- **What is currently measured?**

− $\rho_\gamma, \rho_{\rm m}, \rho_{\rm b}, (n_{\rm b} - n_{\bar{\rm b}})/s, \rho_\Lambda \cdots$

− $(\Delta^2_{\mathcal{R}})_{|k_\bullet}, n_s, (d\log\Delta^2_{\mathcal{R}}/d\log k)_{|k_\bullet}$

- **Particles as probes**

$\gamma \rightarrow$ **free-streaming at** $\sim 1{\rm eV}$

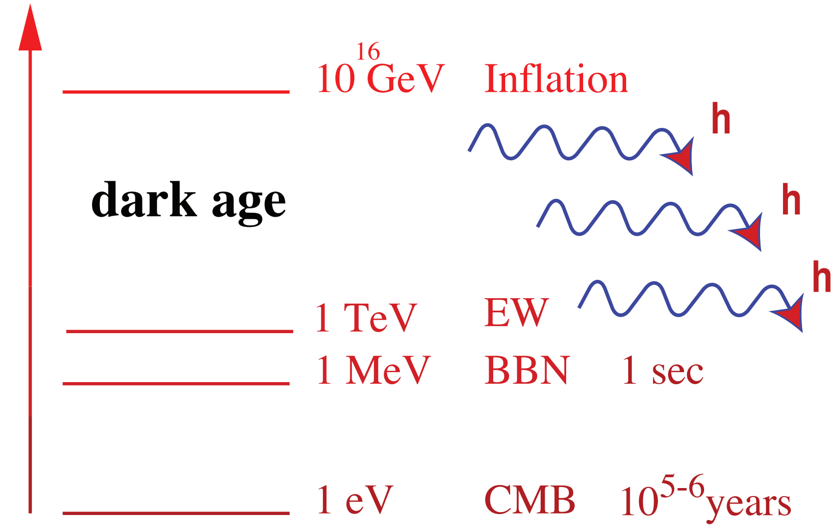
$\nu \rightarrow$ **streaming at** $\sim 1{\rm MeV}$

$h \rightarrow$ **streaming since end of inflation**

$\sim 10^{?}{\rm TeV}$

$$ds^2 = a^2\,[-d\tau^2 + (\delta_{ij} + h_{ij})\,dx^i\,dx^j]$$

Very *clean* cosmological probes



10^{16} GeV Inflation

dark age

1 TeV EW

1 MeV BBN 1 sec

1 eV CMB $10^{5\text{-}6}$years

- **What can we probe by detecting primordial GWs?**
  - **Universe equation of state**
  - **end of inflation**
  - **phase transitions**
  - **cosmic strings**

Characteristic intensity and frequency of relic gravitational waves

- **The intensity**

Tensor power spectrum: $\Delta_h^2(k\tau) \equiv \frac{d<0|h_{ij}^2|0>}{d\log k} \propto k^3\,|h_k(\tau)|^2$

GW energy spectrum: $\Omega_{\rm GW}(k,\tau) \equiv \frac{1}{\rho_c(\tau)}\,\frac{d<0|\rho_{\rm GW}(\tau)|0>}{d\log k} \propto \frac{k^2\,\Delta_h^2(k\tau)}{a^2(\tau)\,H^2(\tau)}$

- **The phenomenological bounds**
- **Features determining typical GW frequencies: the *dynamics* of production mechanism which is model dependent, and the *kinematics*, i.e. the redshift from the production era**

Suppose a graviton is produced at time t_* with frequency f_* during RD or MD era

$$f_0 = f_*\,a_*/a_0, \quad g\,a^3\,T^3 = \text{const.}, \quad 1/f_* = \lambda_* = \epsilon\,H_*^{-1}$$

$$f_0 \simeq 10^{-7}\,\frac{1}{\epsilon}\,\left(\frac{T_*}{1\,\text{GeV}}\right)\,\left(\frac{g_*}{100}\right)^{1/6}\,\text{Hz}$$

[Kamionkowski, Kosowski & Turner 94; Maggiore 00]

Phenomenological bounds

- BBN bound

$$\int h_0^2\,\Omega_{\rm GW}(f)\,d\log f \leq 5.6\times 10^{-6}\,(N_\nu - 3)$$

`[Copi, Schramm and Turner 97]`

- New CMB bound `[Smith et al. 06]`
- COBE bound

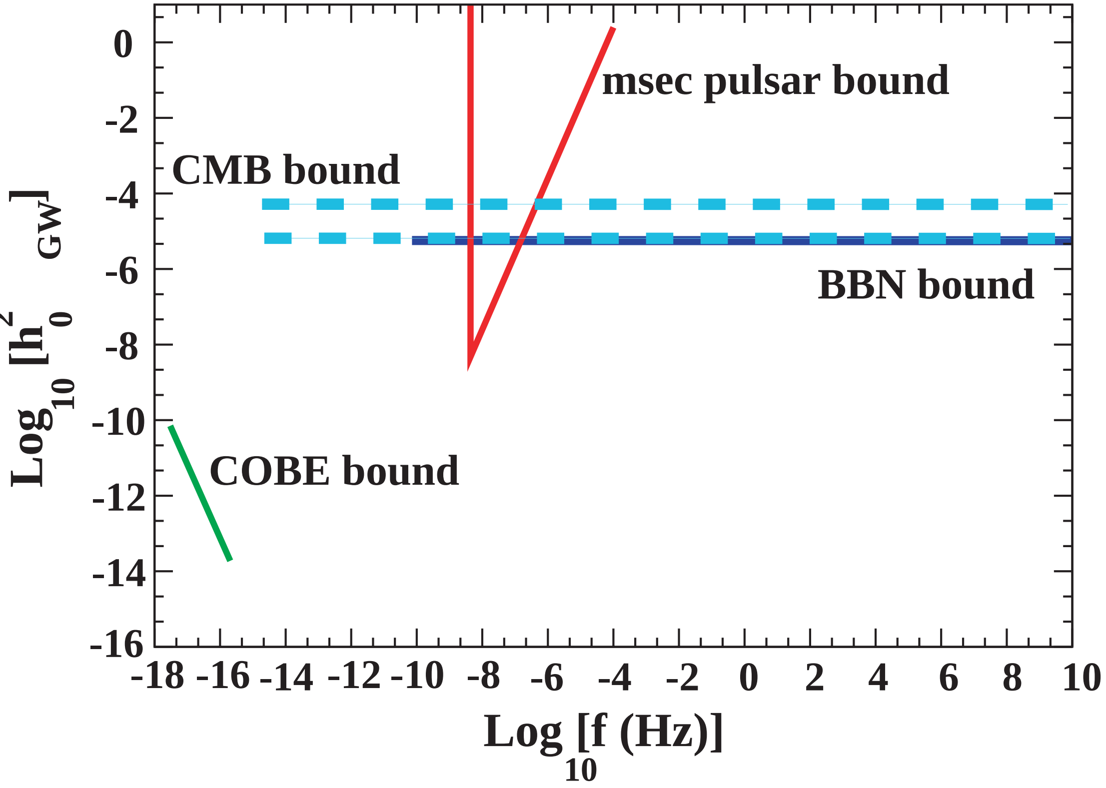
$$h_0^2\,\Omega_{\rm GW}(f) \leq 7\times 10^{-11}\,\left(\frac{H_0}{f}\right)^2 \quad H_0 \leq f \leq 10^{-16}\ \text{Hz}$$

`[Koranda & Turner 94]`

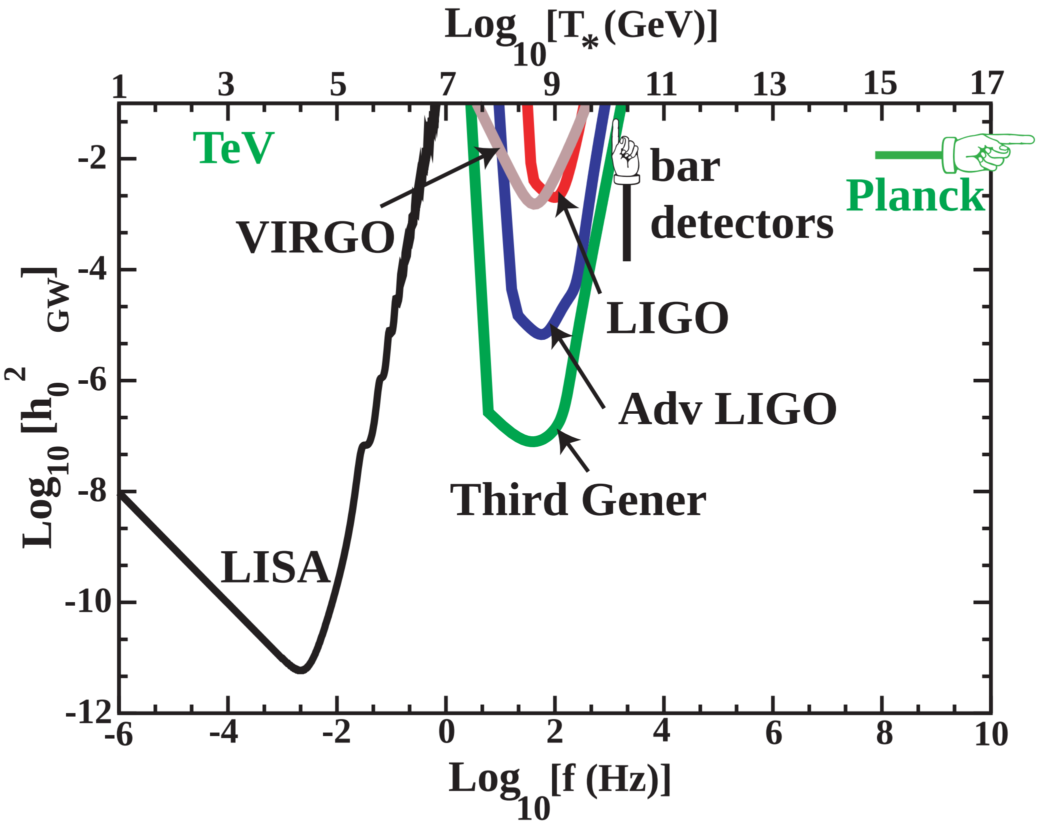
- msec pulsar bound

$$h_0^2\,\Omega_{\rm GW}(f) \leq 4.8\times 10^{-9}\,\left(\frac{f}{f_{\rm o}}\right)^2 \quad f > f_{\rm o} \equiv 4.4\times 10^{-9}\ \text{Hz}$$

`[Thorsett & Dewey 96]`



Typical temperatures probed by GWs produced by *causal* mechanisms



Production of GWs from inflation: leaving and re-entering the *horizon*

`[Grishchuk 74; Starobinsky 79]`

Introducing “canonical field” $\psi_k(\tau) = a\, h_k(\tau)$:

$$\psi_k'' + \left[k^2 - U(\tau)\right]\,\psi_k = 0 \qquad U(\tau) = \frac{a''}{a}$$

$$h_k = \frac{1}{\sqrt{2k}}\,\frac{1}{a}\,e^{-ik\,\tau}$$

- If $k^2 \gg |U(\tau)|$

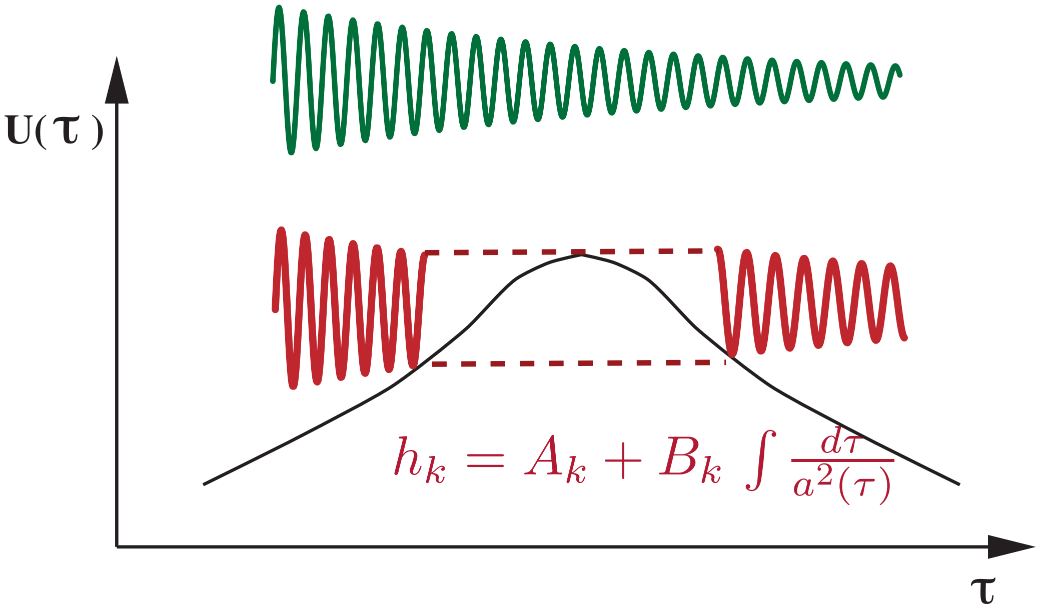
$k\tau \gg 1\,, k/a \gg H\,, \lambda_{\rm phys} \ll H^{-1}$

$\Rightarrow$ the mode is inside the Hubble radius

- If $k^2 \ll |U(\tau)|$:

$k\tau \ll 1\,, k/a \ll H\,, \lambda_{\rm phys} \gg H^{-1}$

$\Rightarrow$ the mode is outside the Hubble radius



$$h_k = A_k + B_k \int \frac{d\tau}{a^2(\tau)}$$

Stochastic GW background from *single-field slow-roll* inflation

[Grishchuk 74; Starobinsky 79; Turner 97]

In *slow-roll* inflation Hubble radius slightly increases in time

- $\Delta_h^2(k) \approx 8 \left(\frac{H_\bullet}{2\pi M_{\rm pl}}\right)^2 \quad \Delta_{\mathcal{R}}^2(k) \approx \frac{1}{\epsilon_\bullet} \left(\frac{H_\bullet}{2\pi M_{\rm pl}}\right)^2$

  $\Delta_h^2(k;\tau) = \underbrace{\mathcal{T}_h(k;\tau)}_{\text{transfer function}} \; \Delta_h^2(k;\tau_i)$

- $r(k) \equiv \Delta_h^2(k)/\Delta_{\mathcal{R}}^2(k) = 16\epsilon_\bullet$

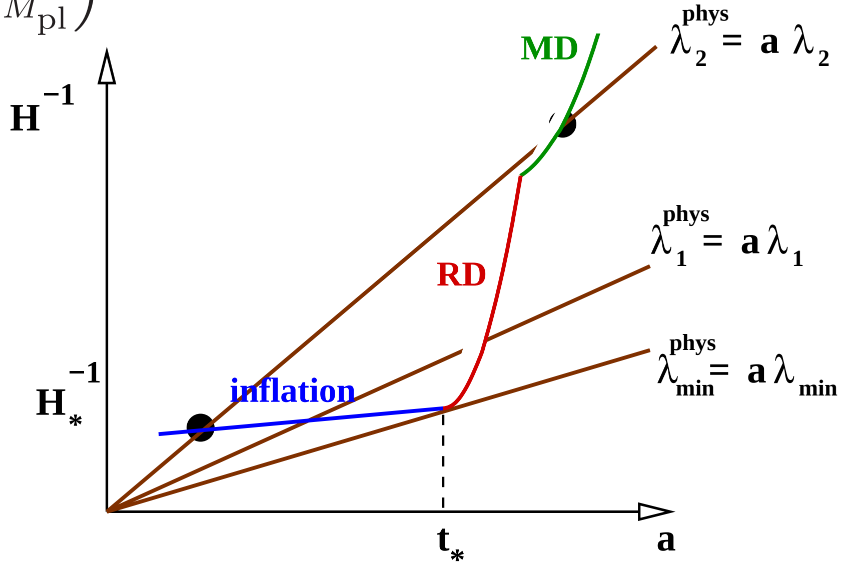
  $\epsilon \propto d\log V/d\log N$

  $\eta \propto d\log V'^2/d\log N$

  $\Omega_{\rm GW}(f) \sim H_\bullet^2\, f^{n_T} \quad n_T = -r/8$

  cutoff frequency $f_*^{\rm max} \sim H_*/2\pi$

- **GWB carries information on two moments of cosmic history: when k *left* the horizon and *re-entered* it**

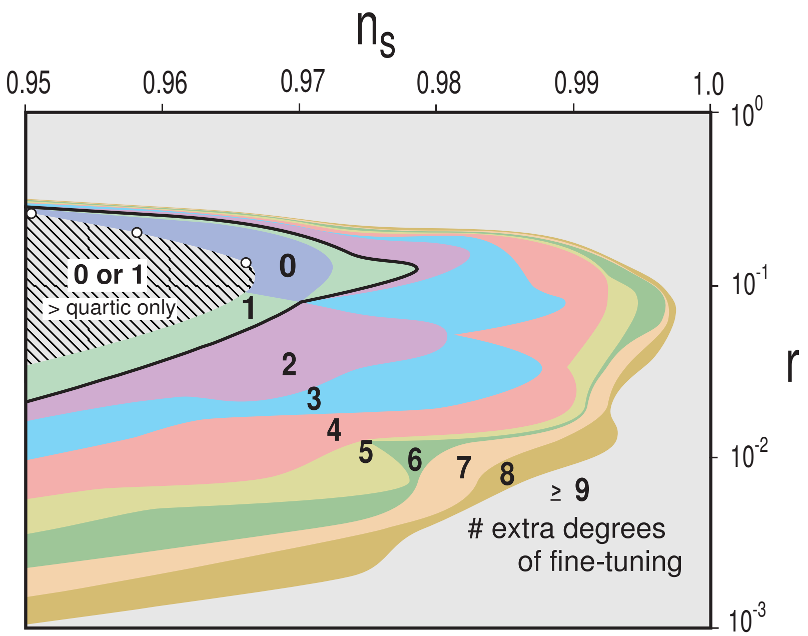


Inflation: $H^{-1} \simeq \text{const.}$

RD: $H^{-1} \propto a^2$

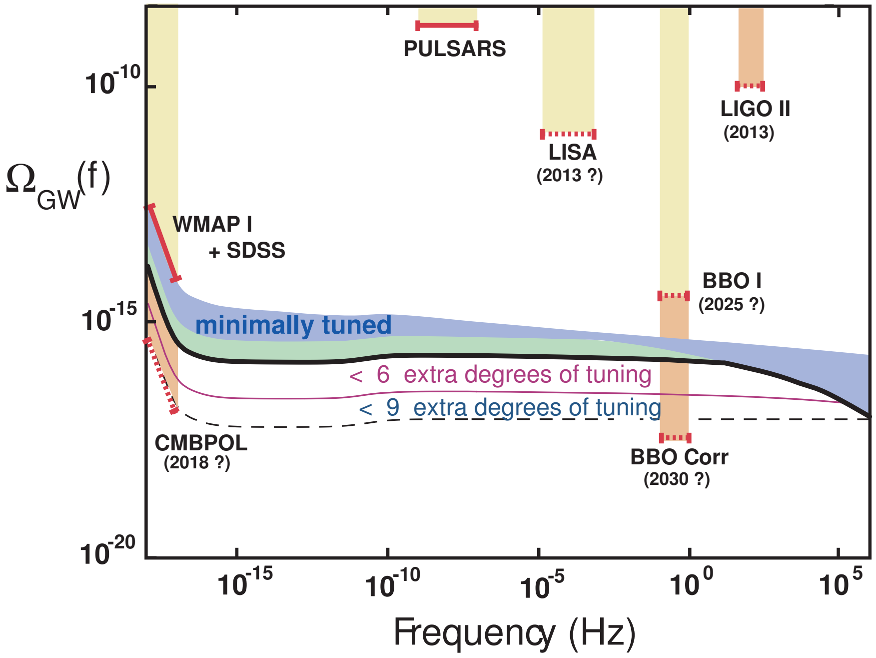
MD: $H^{-1} \propto a^{3/2}$

Predictions from slow-roll inflationary models



- In minimally tuned models, e.g., $V \sim \phi^n$, ϵ and η don't have zeros during the last 60 e folds
- Degree of fine-tuning: number of zeros in ϵ and η: number of extra accelerations, jerks, bumps when modes leave horizon during inflation

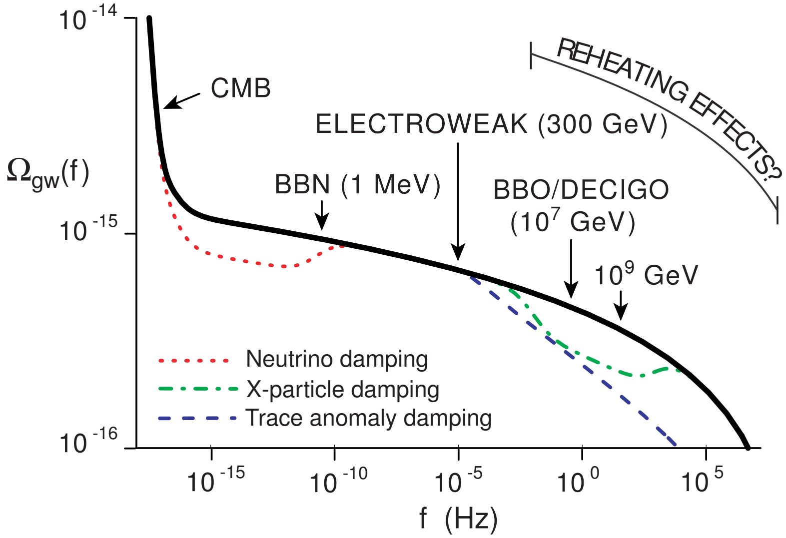
[Boyle, Steinhardt & Turok 05]



- CMB sensitive to long wavelengths that *re-entered* at low temperature (after BBN)
- GW IFOs sensitive to short wavelengths that *re-entered* at high temperature

Transfer function and sensitivity to inflationary models

`[Boyle & Steinhardt 06]`

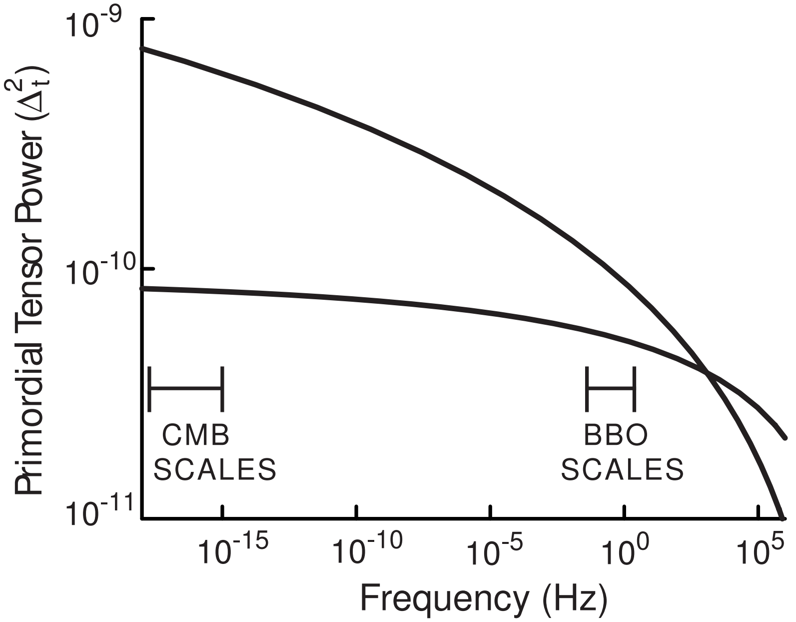


- Transfer function includes

— dark energy with time dependent eq of state

— tensor anisotropic stress due to free-streaming of relativistic particle in early Universe

`[Weinberg 03]`



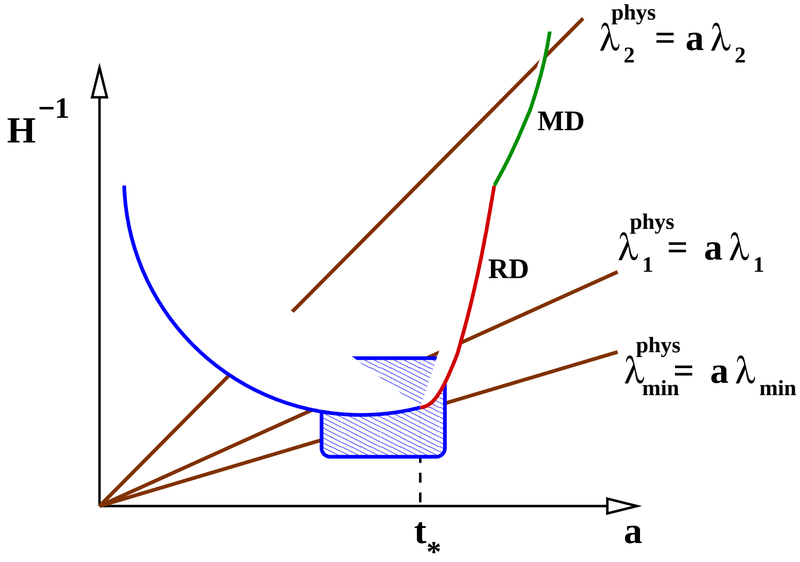
- *Convergence* effect if consistency relation, $n_T = -r/8$, holds

[see also Ungarelli et al. 05; Smith et al. 06]

[Efstathiou et al.; Kudoh et al.; Watanabe et al. 06]

Stochastic GW background in *bouncing-Universe* models

In some string-inspired inflationary models, such as pre-big bang [Gasperini & Veneziano 93] **and ekpyrotic scenarios** [Khoury et al. 00], **or in inflationary models violating the null energy condition, such as phantom inflation** [Brown et al. 04; Baldi et al. 05] **and ghost inflation** [Arkani-Hamed et al. 04] **the Hubble parameter grows toward the would-be big bang singularity**



GW spectrum is blue at low frequency

$$\Omega_{\rm GW}(f) \sim f^n \quad n > 0$$

cutoff frequency $f_*^{\rm max} \sim H_*/2\pi$

Warnings on pre-big bang models:

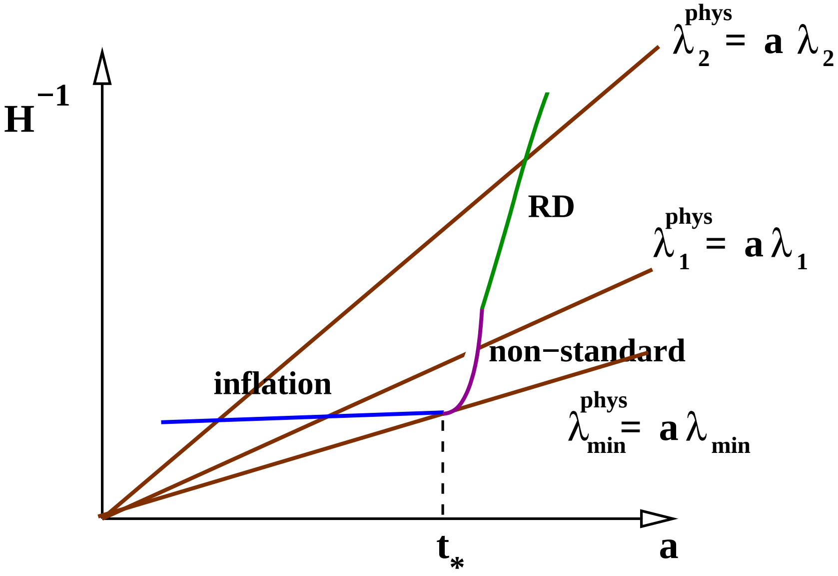
- *Full* **description of the transition pre-post big bang not available, yet**
- **GWB detectable by IFOs affected by** *details* **of pre-post big bang transition**

Stochastic GW background from *non standard* cosmological phases

In some models the inflationary era is not followed immediately by the radiation era but rather by an expanding phase whose equation of state is stiffer than radiation

`[Grishchuk 75]`

stiff era: $H^{-1} \propto a^3$



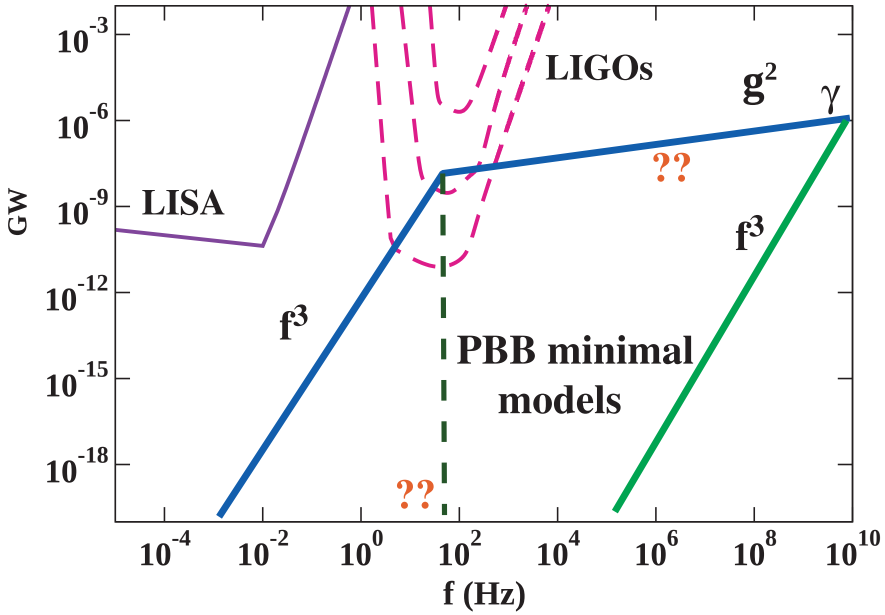
GW spectrum at high frequency can be blue

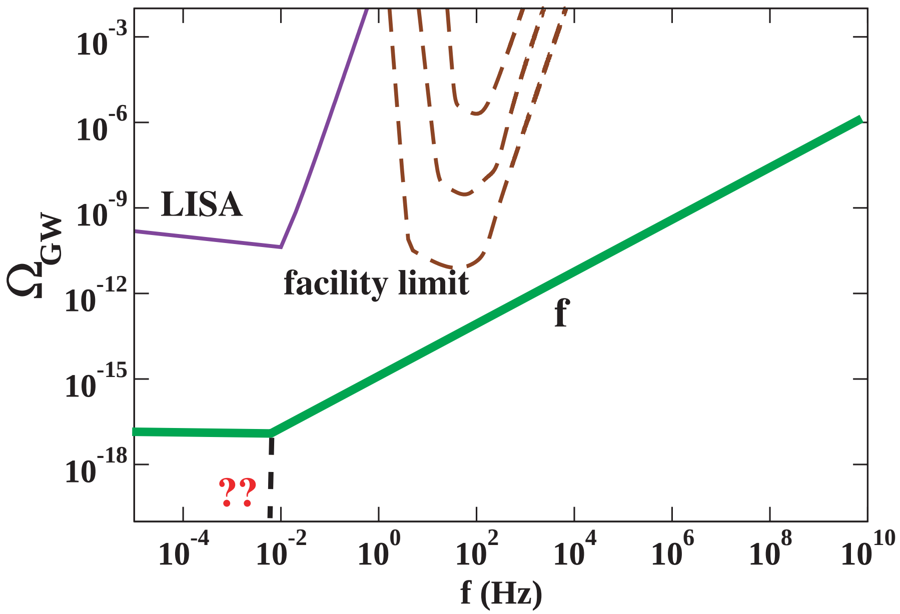
$$\Omega_{\rm GW}(f) \sim f$$

cutoff frequency $f_*^{\max} \sim H_*/2\pi$

- Quintessential inflation `[Peebles & Vilenkin 98; Giovannini 99]`
- Brane world inflation `[Sahni, Sami & Souradeep 99]`

Examples of GWB in presence of *non-standard* phases





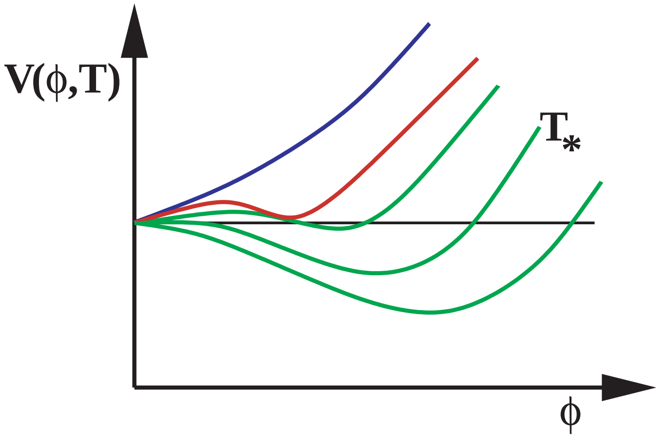
[Brustein, Gasperini, Giovannini & Veneziano 96]

[AB, Maggiore & Ungarelli 97; Mandic & AB 06]

[Peebles & Vilenkin 98; Giovannini 99]

[Babusci & Giovannini 99]

GWs from first-order phase transitions: bubble collisions and turbulence in the plasma



Via quantum tunnelling true vacuum bubbles nucleates

When bubbles collide $\Rightarrow$ emission of gravitational waves

$\beta \longrightarrow$ bubble nucleation rate per unit volume

$\alpha \longrightarrow$ jump in energy density experienced by order parameter

EW phase transition: $T_* \simeq 300\,\mathrm{GeV}$ and $\beta/H_* \simeq 10^2$–10^3

$\Rightarrow f_{\rm peak} \simeq 10^{-8}(\beta/H_*)\,(T_*/1\mathrm{GeV}) \simeq 10^{-4}$–$5 \times 10^{-3}$Hz

Intensity of GW spectrum: $h_0^2\,\Omega_{\rm GW} \simeq 10^{-6}\,(H_*/\beta)^2\,f(\alpha, v)$

– In SM there is *no* first-order EW phase transition for Higgs mass larger then $M_{\rm W}$

– In MSSM, for certain values of Higgs mass, there are possibilities but $h_0^2\,\Omega_{\rm GW} \leq 10^{-16}$

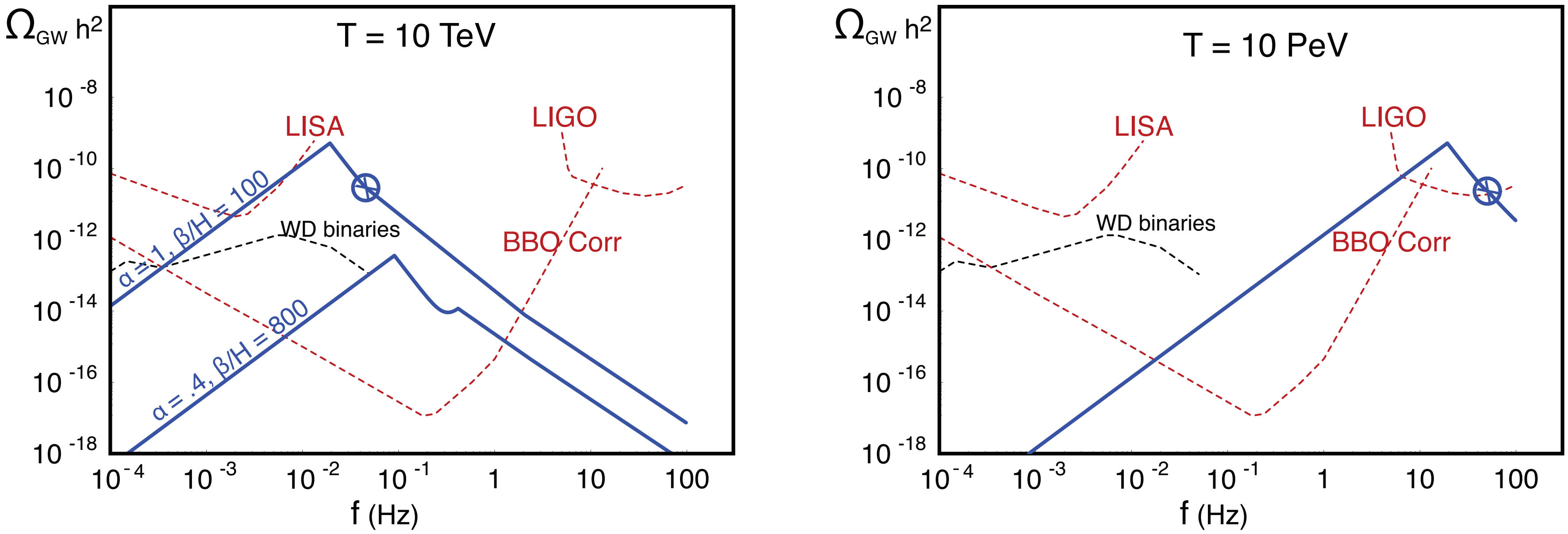
`[Kosowsky & Turner 94; Kosowsky, Turner & Kamionkowski 94]`

– In NMSSM: $h_0^2\,\Omega_{\rm GW} \leq 10^{-15}$–$10^{-10}$ with $f_{\rm peak} \simeq 10$mHz

`[Apreda, Maggiore, Nicolis & Riotto 01; Nicolis 03] [Caprini & Durrer 06]`

GW background from phase transitions at EW scale and beyond it

- EW phase transition will be probed at LHC. It depends on Higgs sector
- New models of EW symmetry-breaking recently proposed

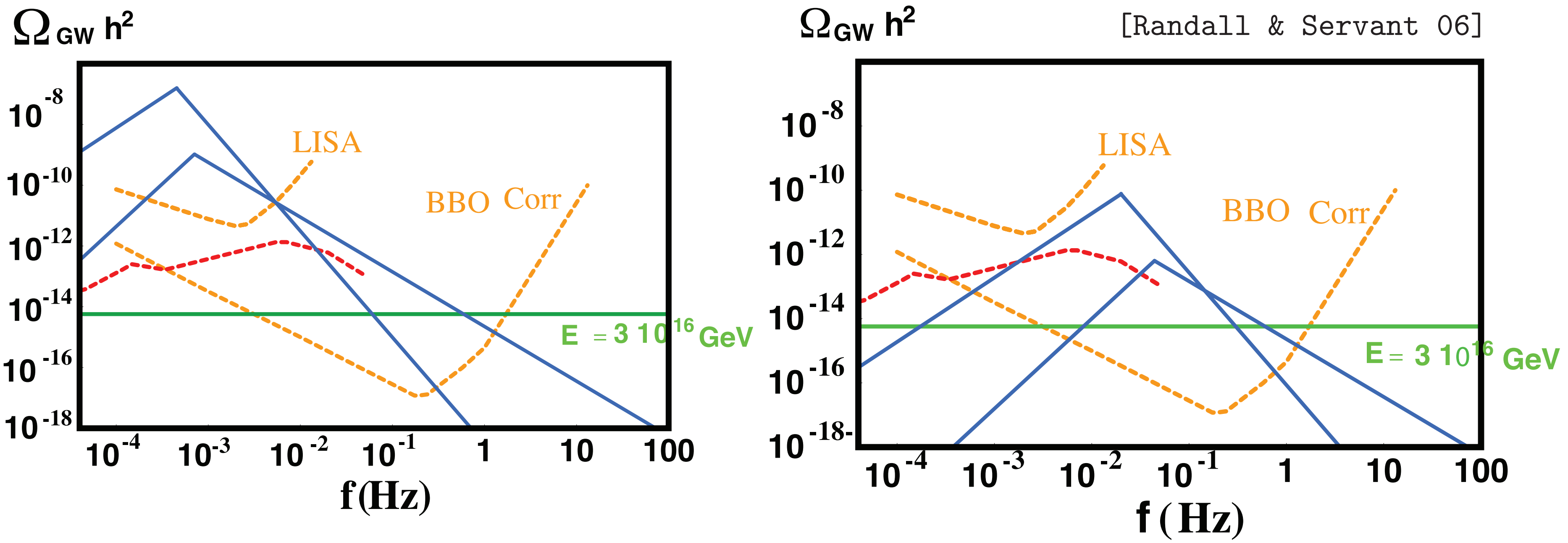


[Grojean & Servant 06]

- For low α: turbulence and collision peaks can be well separated
- For large α: only peak of turbulence is visible

GW background from phase transition in Randall-Sundrum model

- If strong cosmological phase transition to stabilize the distance (radion field) between the two branes occured at temperatures $\sim$ TeV



[Randall & Servant 06]

- Uncertainties from unknown temperature dependence of the potential, back reaction effects and proximity to the perturbative limits of the calculation

Probing how inflation ended

- **GWs from bubble collision in false vacuum (or first-order) inflation**

  [Turner & Wilczek 90]

  If phase transitions occurs well before end of inflation ⇒

  $f_{\rm GW} \sim 10$–10^3 Hz

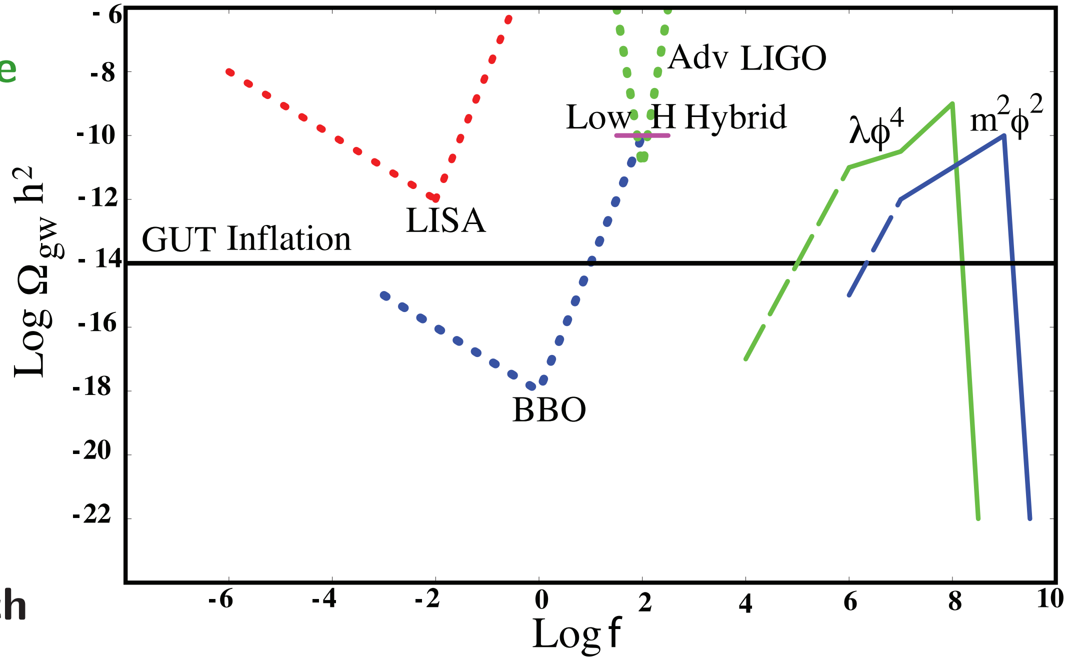
  [Baccigalupi et al. 97]

- **GWs produced during preheating**

  [Khlebnikov & Thachev 97]

— **Highly non-thermal phase during which inflaton pumps energy to coupled-field momentum modes**

— **Transient density inhomogeneities ⇒ GWs**



[Easther & Lim 06]

— **GWB's frequency peak fixed by energy scale at the end of inflation**

GWs from (vibrating) cosmic string

Topological defects formed at phase transitions

- **Contribution of topological defects to structure formation $< 10\%$**
- **Cosmic strings have large tension (mass-per-unit length) μ, e.g., if formed at GUT scale $\mu \sim 10^{22} \mathrm{g/cm}$; they oscillate relativistically and emit GWs** `[Vilenkin 81]`
- **Small loops (smaller than Hubble radius) oscillate, emit GWs and disappear, but are replaced by small loops broken off very long loops (longer than Hubble radius)**

$r \longrightarrow$ characteristic loop's radius $\tau \longrightarrow$ oscillation period $(\tau \sim r)$

Quadrupole moment $Q \sim \mu\, r^3$

Loop radiates with power: $dE/dt = P \sim G \dddot{Q}^2 \sim \Gamma\, G\, \mu^2$

$\Omega_{\mathrm{GW}} \sim P/\rho_c < 10^{-9}$–$10^{-8}$ for cosmic strings with $G\,\mu < 10^{-7}$ and $\Gamma \sim 50$

GWs from cusps and kinks of vibrating strings

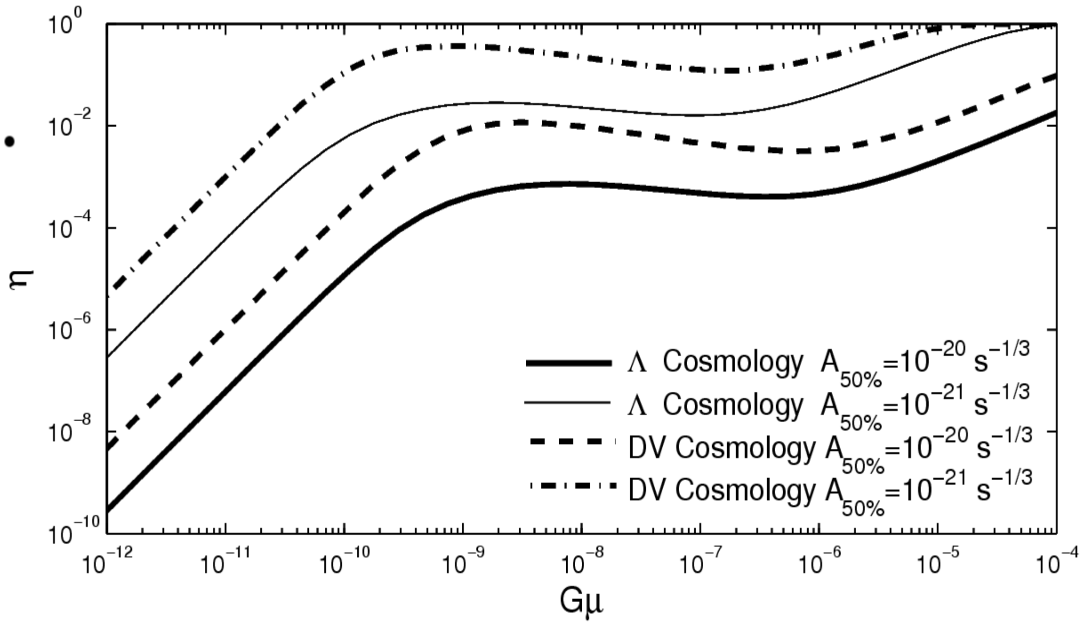
The stochastic ensemble of GWs from network of oscillating loops is strongly non Gaussian and include occasional, sharp GW bursts emanating from cusps and kinks

`[Berezinsky et al. 00; Damour & Vilenkin 00,01,04; Copeland et al. 04; Jackson et al. 05]`

Strongly non-Gaussian “burst” part

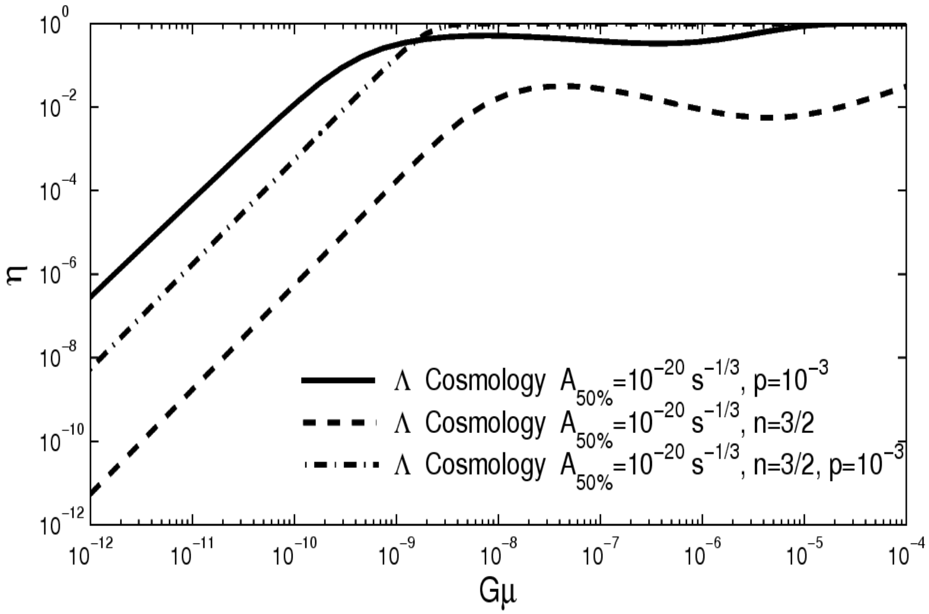
+ nearly Gaussian “background”

Individual bursts stand out above the background



at $f_{\rm GW} = 75$Hz, optimal oriented `[Siemens et al. 06]`

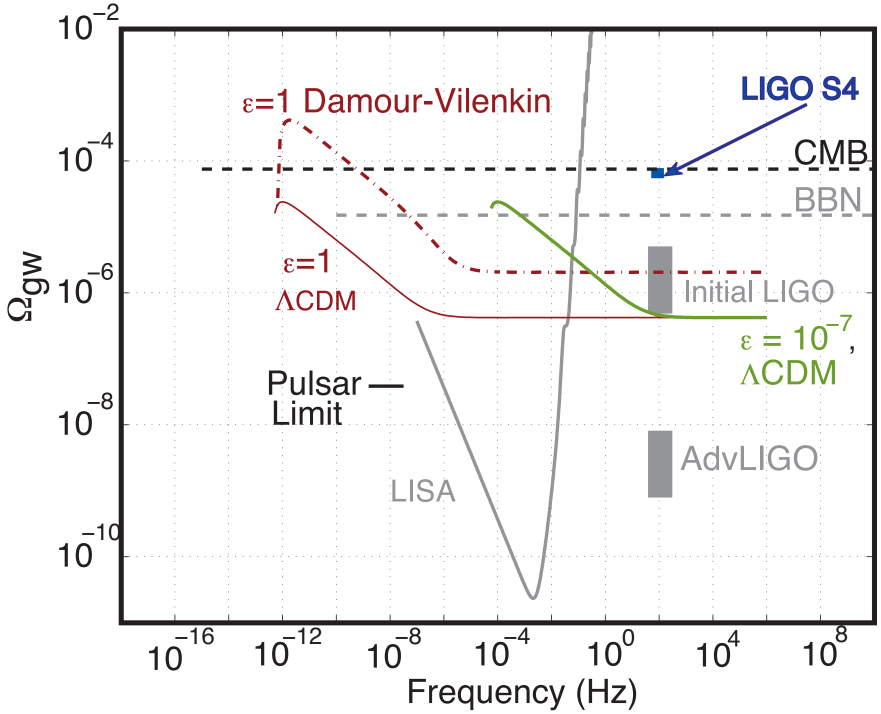
GW burst and GWB from incoherent superposition of bursts



[Siemens, Mandic & Creighton 06]

Signal detectable for a large range of values of the string tension μ reconnection probability p and loop size ϵ for cosmic (super)strings

$$p = 5 \times 10^{-3},\ G\mu = 10^{-7}$$

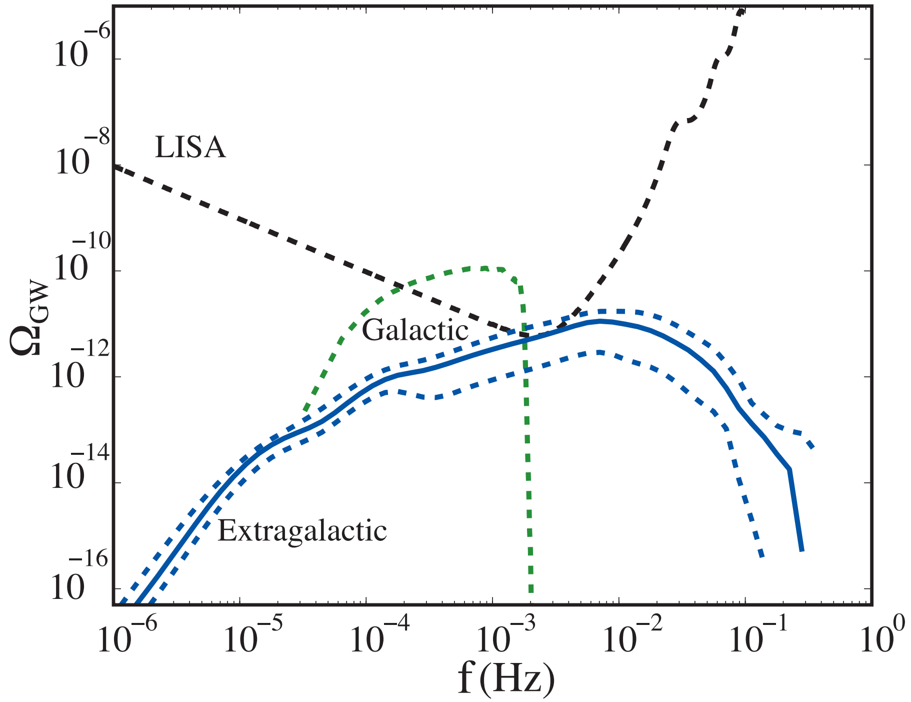


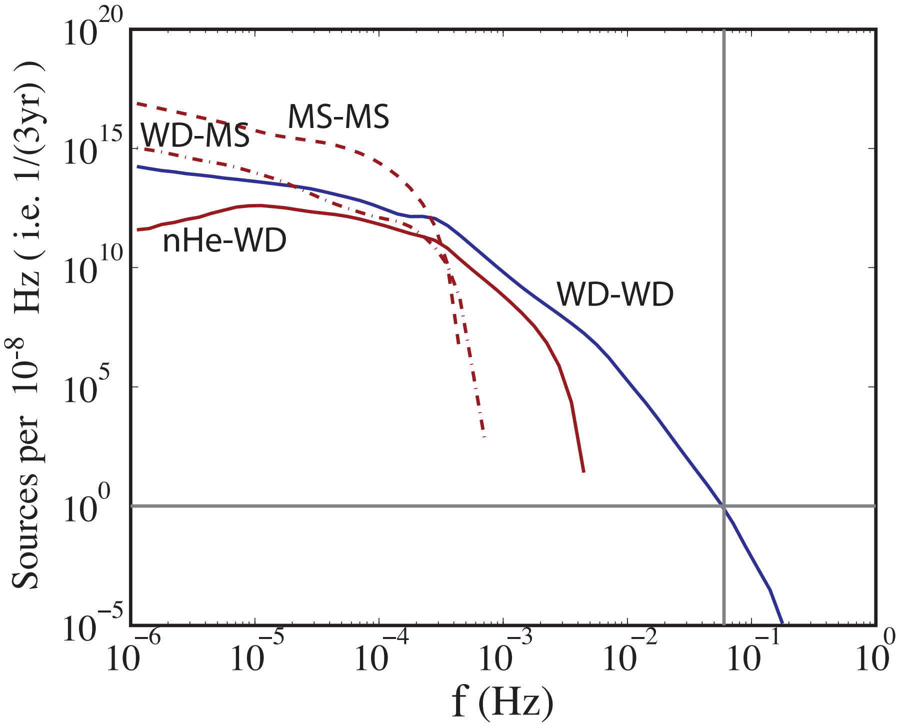
[Siemens, Mandic & Creighton 06]

see also [Hogan 06]

Astrophysical GWBs due to comparable-mass binaries

[Farmer & Phinney 03]

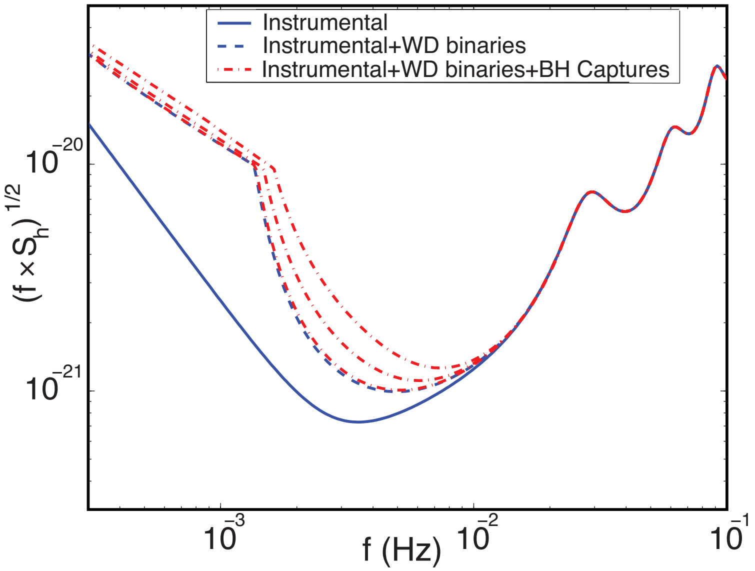




- **Galactic background in principle subtractable because anisotropic**
- **Extra-galactic background due to WD-WD could be subtracted if $f \gtrsim 50$ mHz**
- At high freq the dominant foreground sources are NS-NS, NS-BH and BH-BH [Cutler & Harms 06]

Astrophysical GWBs and GW bursts from extreme mass-ratio binaries

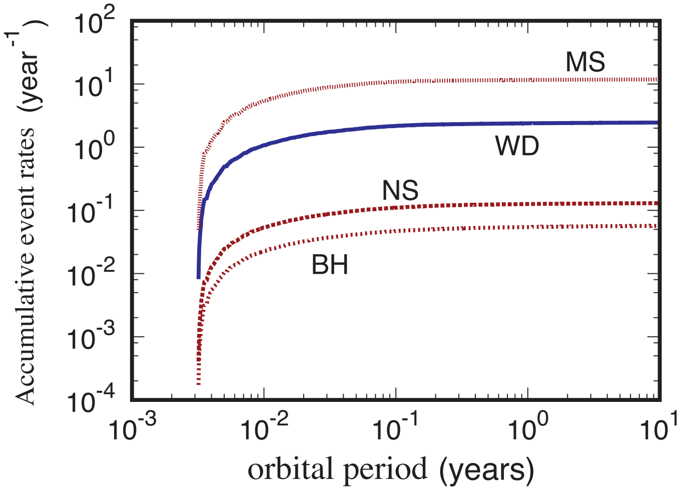
Capture of compact object by massive BH

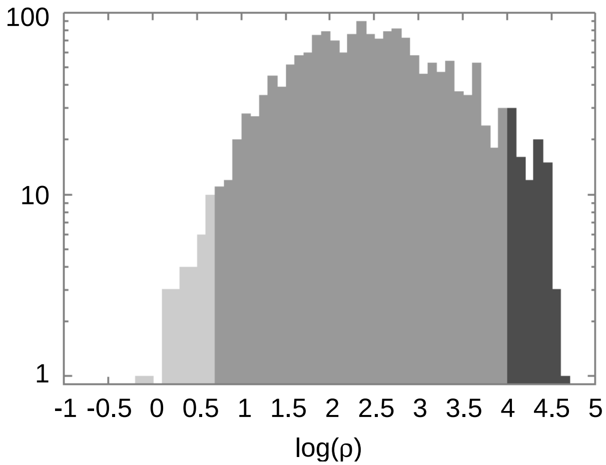


[Barack & Cutler 04]

event rates 6×10^{-7}–6×10^{-8}**/yr**

$$S_h^{\rm unsub} = 0.3 \times \mathcal{S}_h^{\rm BH\,capt}$$





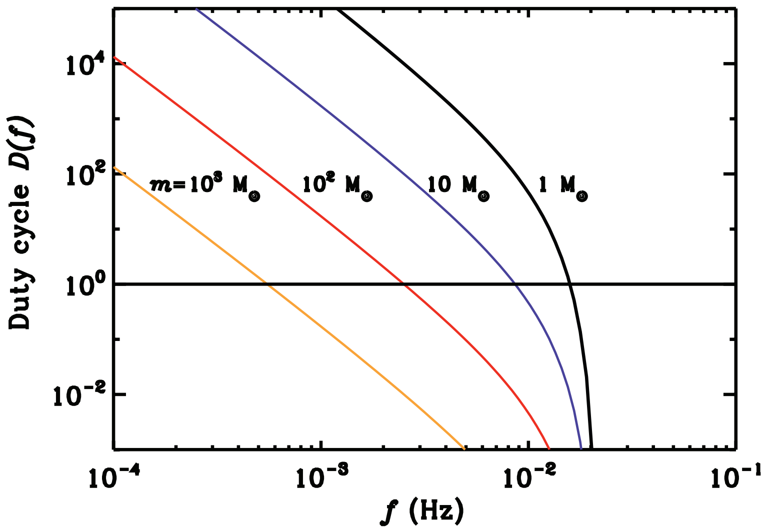
[Rubbo, Holley-Bockelmann & Finn 05]

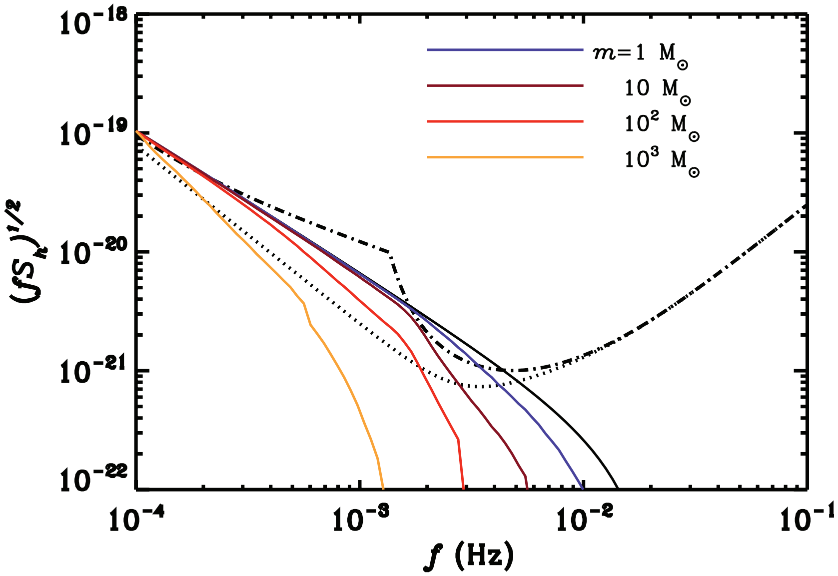
Astrophysical GWB from compact objects embedded in AGNs

- Assuming compact object formation $\propto$ steady-state gas accretion rate

$\Rightarrow$ event rates and signal strength estimated from hard X-ray AGN luminosity

`[Sigl, Schnittman & AB 06]`



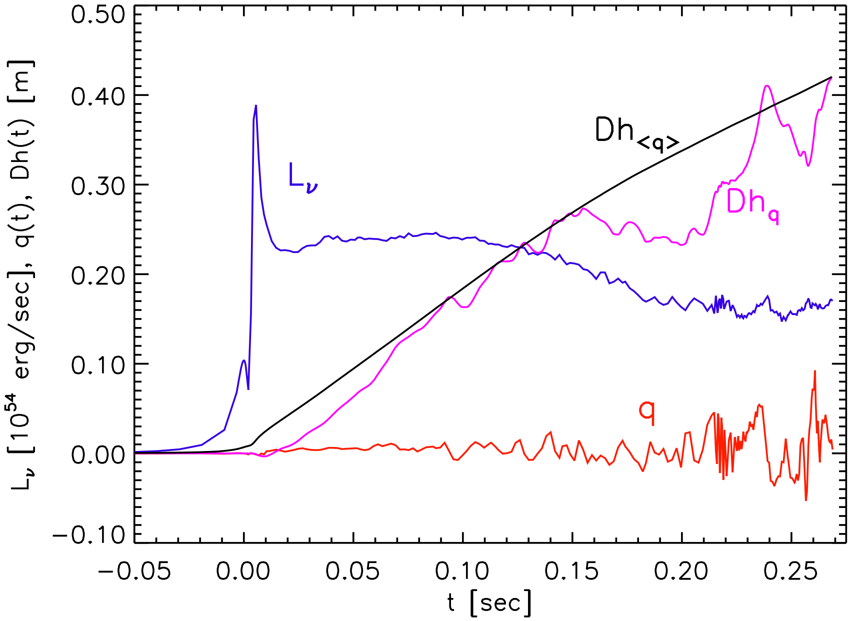


- Assuming $\sim 1\%$ of accreted matter is in compact objects `[Levin 04, 06]`
- Below a few mHz more than one event contributes at any given time $\Rightarrow$ "Gaussian"
- At higher frequencies, individual events with sufficient SNR $\Rightarrow$ subtractable

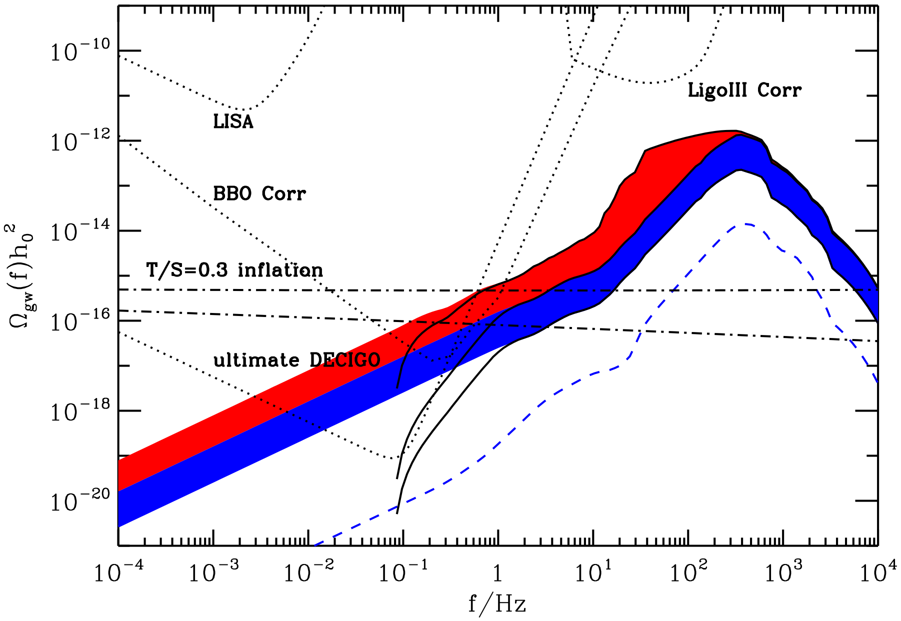
Astrophysical GWBs from cosmic supernovae

- **Anisotropic mass-motion and ν-emission in collapse of massive starts produce GWs**
- **At low frequencies anisotropic ν-emission with luminosity L_ν and anisotropy $q(t)$**

dominates $\Rightarrow h(t) = \frac{2G}{D} \int_{-\infty}^{t-D} dt' \, L_\nu(t') \, q(t'), \quad f|\tilde{h}(f)| \sim 10^{-19} < q > \frac{10\text{kpc}}{D} \frac{E_\nu}{3\times 10^{53}\text{erg}}$



$< q >= 0.45\%$; core collapse of rotating $15 M_\odot$ star



[AB, Sigl, Raffelt, Janka & Mueller 05]

Strong dependence on progenitor model!

Conclusions

- The search for primordial GWs is very challenging but the outcome is worth the affort
- Relic GWs at large and small wavelengths can carry information on otherwise unexplored physics between $\sim 10^2$ GeV and $\sim 10^{16}$ GeV
- Current direct-detection experiments, such as LIGOs, are close to BBN bound and soon start exploring interesting regions of parameter space
- Most promising predictions for current and near-future experiments from cosmic (super)strings and phase transitions
- If GWB produced during inflation has reddish spectral index, only post-LISA missions or radically vnew ground-based detectors could observe it.

  More optimistic, but less robust predictions if Universe underwent an accelerated contraction, as in bounce-Universe scenarios, or if non-standard post-inflationary eras were present
- In some frequency bands, astrophysical signals compete with cosmological ones