Cosmological Backgrounds of Gravitational Waves

Jean-François Dufaux, APC

LISA Symposium 2012

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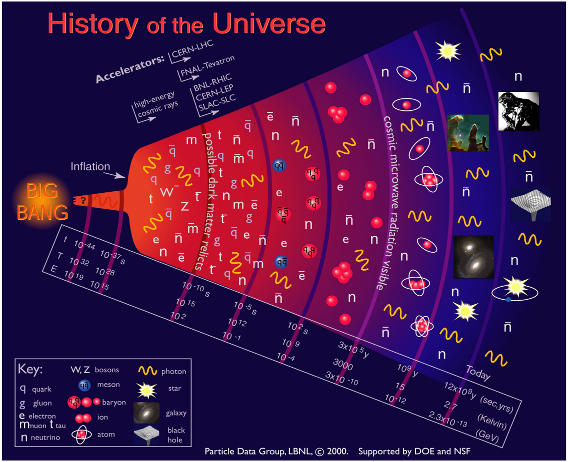
Content:

- GW from the Early Universe: Detectors and Sources
- First-Order Phase Transitions
- Cosmic Strings
- Detection Prospects for eLISA/NGO

Gravitational waves (GW): a unique probe of the early universe



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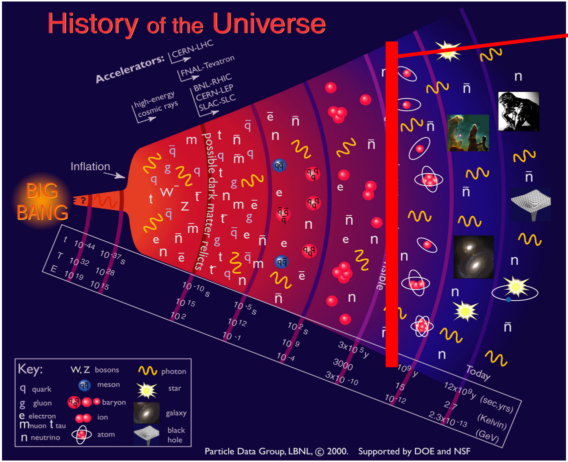
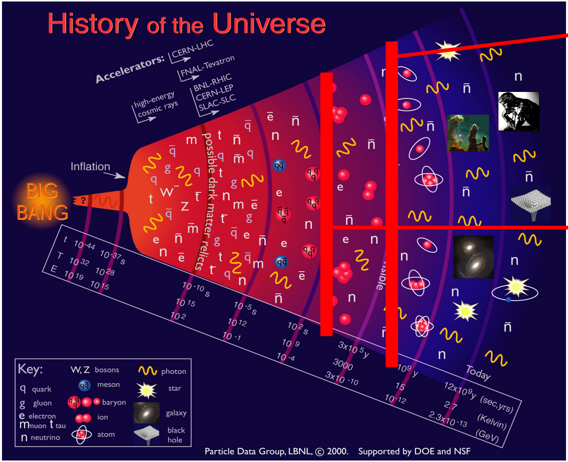


T = 0.3 eV:
Photons decouple
(CMB)

Gravitational waves (GW): a unique probe of the early universe



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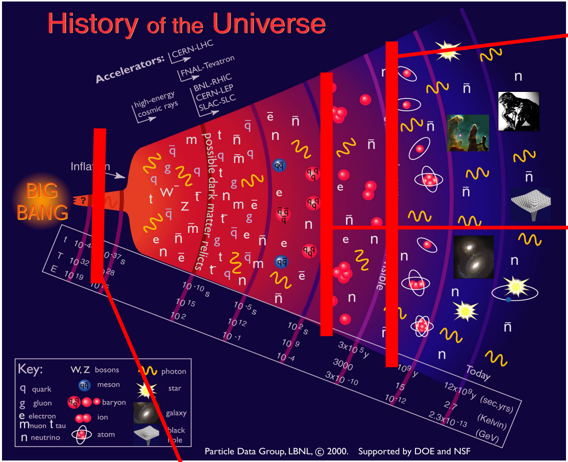
T = 1 MeV:
Neutrinos decouple

Gravitational waves (GW): a unique probe of the early universe



T = 0.3 eV:
Photons decouple (CMB)

T = 1 MeV:
Neutrinos decouple

T = 10^{19} Gev: Gravitons decouple

GW propagate freely during all the cosmic history

Characteristic Frequency of GW

Wavelength at the time of production (t_*):

$$\lambda_* = \epsilon_* \, H_*^{-1} \qquad \text{where} \;\; H_* = \frac{\dot{a}_*}{a_*}$$

$$\epsilon_* \leq 1 \;\; \text{depends on the source}$$

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Present-day frequency f of GW produced at temperature $\mathbf{T}_*$:
(during radiation era and with standard thermal history)

$$\mathbf{f} \sim \frac{10^{-4}\,\mathrm{Hz}}{\epsilon_*} \, \frac{\mathbf{T}_*}{1\,\mathrm{TeV}}$$

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Examples:

First-order phase transition ($\epsilon_* \sim 10^{-3} - 1$) at $T_* \sim$ TeV $\Rightarrow$ mHz range

Cosmic strings ($\epsilon_* \ll 1$): wide range of T_* $\Rightarrow$ very broad spectrum

Stochastic GW Backgrounds and Detectors

$$\Omega_{gw}(f) = \frac{1}{\rho_{\mathbf{c}}} \frac{d\rho_{gw}}{d\log f} \qquad \left[\propto \frac{f^3\, S_h(f)}{H_0^2} \ \text{ where } \ \langle h^2(t)\rangle = \int df\, S_h(f) \right]$$

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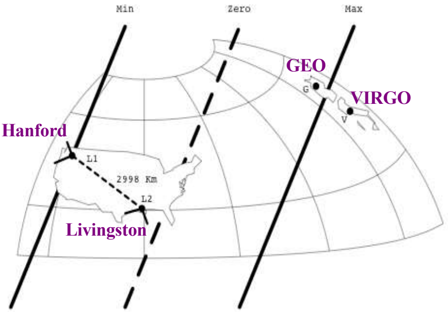
1) Ground-based detectors, $f \sim 10 - 10^3$ Hz

Cross-correlate different detectors



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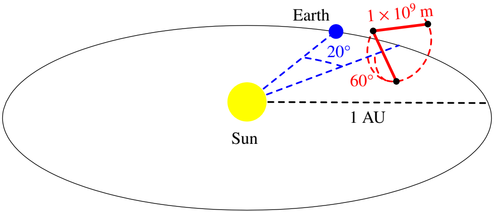
2) Space-based detectors: eLISA, $f \sim 10^{-4} - 10^{-1}$ Hz

Single detector, but lower frequencies



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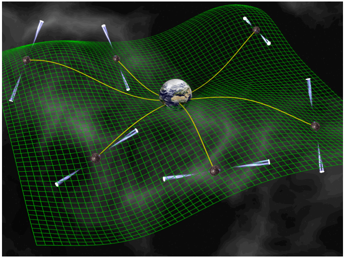
3) Pulsar timing arrays, $f \sim 10^{-9} - 10^{-7}$ Hz

GW perturb very accurate timing of msec pulsars



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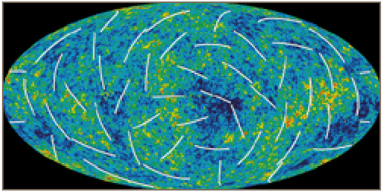
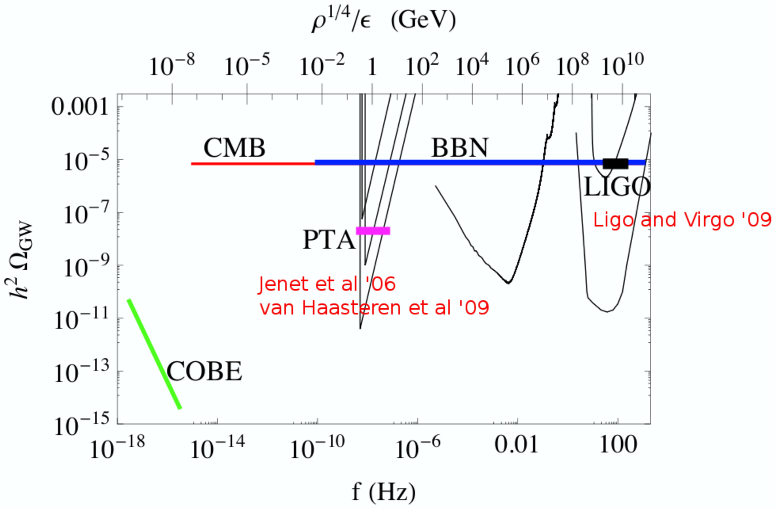
4) CMB experiments, $f \gtrsim 10^{-18}$ Hz

In particular CMB polarization



Current limits on a stochastic background



Cosmological Sources of GW

Leading to GW spectrum peaked at characteristic frequency:

- First-order phase transitions
- End of inflation, preheating
- Decay of supersymmetric scalar fields
- Formation of primordial black holes
- ...

Leading to GW spectrum over very wide frequency range:

- Cosmic strings and other topological defects
- Inflation, in particular with:
  - $\hookrightarrow$ equation of state $w > 1/3$ after inflation
  - $\hookrightarrow$ particle production during inflation
- Alternatives to inflation (pre-big-bang, cyclic models)
- Scalar field self-ordering after global phase transitions
- ...

In the Following:

Leading to GW spectrum peaked at characteristic frequency:

- **First-order phase transitions (at electroweak scale $\Rightarrow$ eLISA)**
- End of inflation, preheating
- Decay of supersymmetric scalar fields
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Leading to GW spectrum over very wide frequency range:

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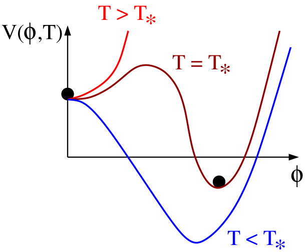
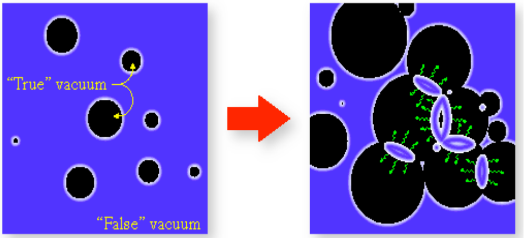
GW from First-Order Phase Transitions

Phase transitions as early universe cools down

If first-order (depends on particle physics model): violent process $\Rightarrow$ GW

Witten '84, Hogan '86, ...
Turner et al '92, Kosowsky et al '92, Kamionkowski et al '94, Kosowsky et al '02, ...





Tunneling across potential barrier $\Rightarrow$ Bubbles nucleate, grow and collide

Beyond the Standard Model (cf LHC and baryogenesis)

Apreda et al '01, Nicolis '04, Grojean et al '05, Randall and Servant '07,

Huber and Konstandin '08, ...

GW from First-Order Phase Transitions

Two processes emit GW:

- Bubble collision
  (Recent study: Huber and Konstandin '08)
- Turbulence
  (Recent study: Caprini et al '09)

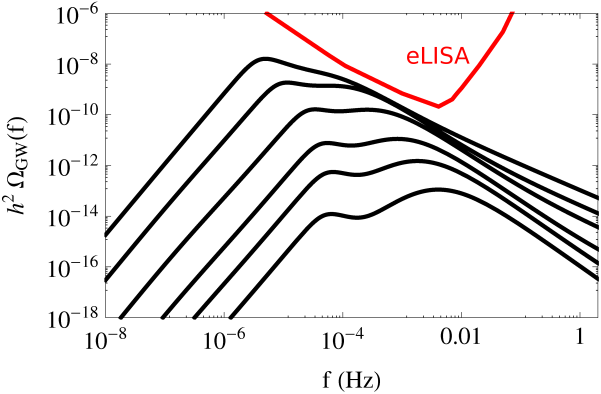
The GW signal depends on

- Scalar field potential at finite temperature
  $\Rightarrow$ temperature, strength and duration of the phase transition
- Bubble propagation in surrounding plasma
  $\Rightarrow$ bubble wall velocity and kinetic energy Vs thermal energy
  (Recent study: Espinosa et al '10)

See talk by J.-M. No on Thursday

Examples of GW spectrum from electroweak phase transition

Higgs potential with H^6 term   Huber and Konstandin '08



Binétruy, Bohé, Caprini and JFD '12

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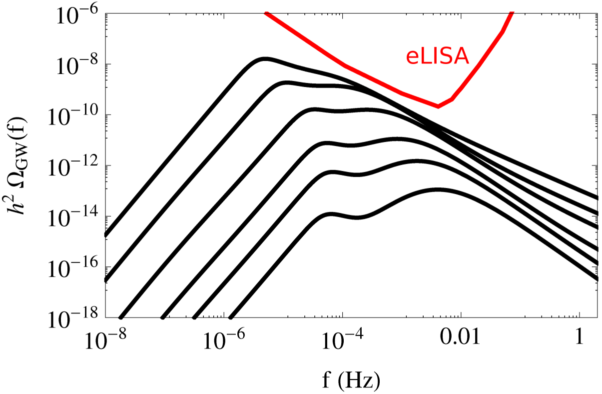

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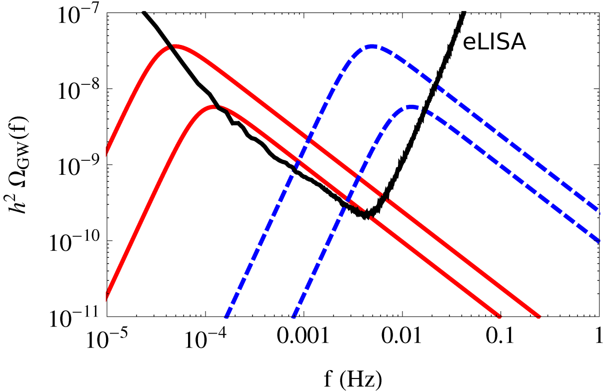
Sagnac calibration with third arm ? Hogan and Bender '01

Data analysis ? Adams and Cornish '10

Examples of GW spectrum from electroweak phase transition

Phase transition in Randall-Sundrum model Randall and Servant '07



T = 100 GeV T = 10^4 GeV

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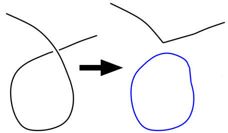
GW Background from Cosmic Strings

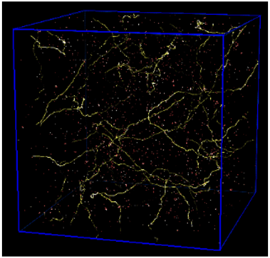
Cosmic strings: Relics from inflation and phase transitions in

- Field theory models (grand unification, supersymmetry, ...)
- String theory models (fundamental strings and branes)

Stable strings form a **cosmological network** that evolves in a scaling regime

Long strings intercommute and form smaller **loops** that oscillate relativistically and emit **GW**





Continuous GW production via the continuous production of loops

$\Rightarrow$ **Very broad GW spectrum**

Vilenkin '81, Hogan and Rees '84, Vachaspati and Vilenkin '85, Caldwell and Allen '92, ...

Hogan '06, Siemens et al '06, DePies and Hogan '07, Olmez et al '10, ...

GW Background from Cosmic Strings

<u>Note:</u> the GW signal includes strong infrequent bursts that can be looked for individually should not be included in stationary and nearly Gaussian background   Damour and Vilenkin '00 '01 '05

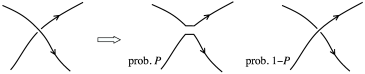
The GW background depends on three main parameters:

1) String tension $\mu =$ energy per unit length

Current constraint (CMB, gravitational lensing, pulsar timing):

$$G\mu < \text{few} \times 10^{-7} \qquad \left(\Leftrightarrow \ \mu \lesssim 10^{18}\,\text{kg/cm}\,!!\right)$$

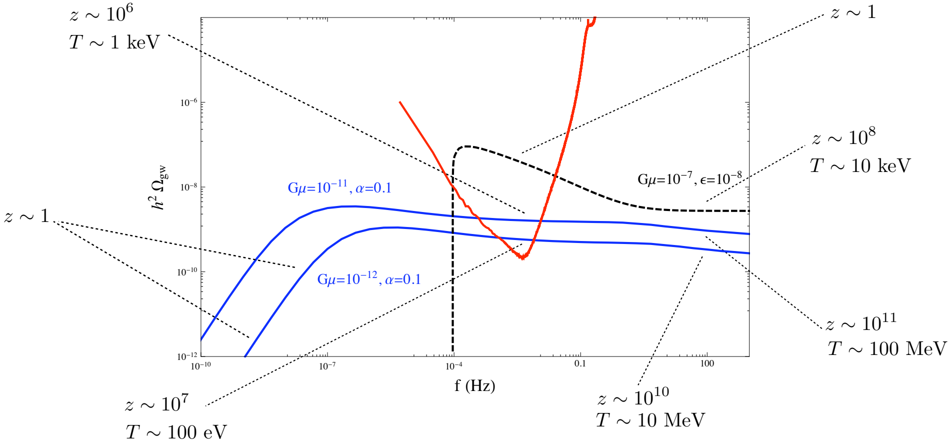
2) Reconnection probability p



3) Characteristic loop size $l = \alpha\, t$

- Small loops: $\alpha = \epsilon\,\Gamma\, G\mu$ with $\epsilon \leq 1$
- large loops: $\alpha \sim 0.1$

Typical Shape of the GW Spectrum



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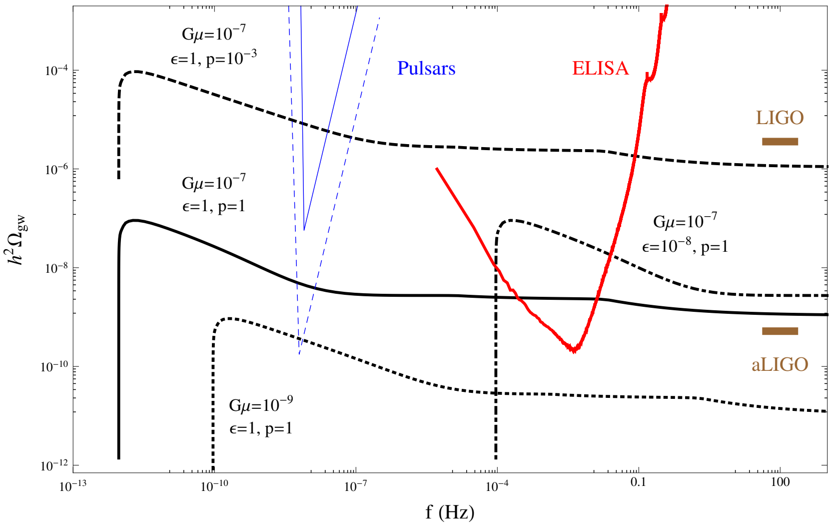
Comparison with Observations for Small Loops



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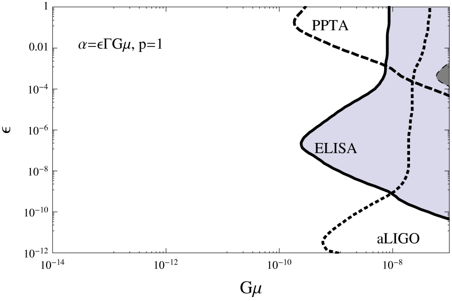
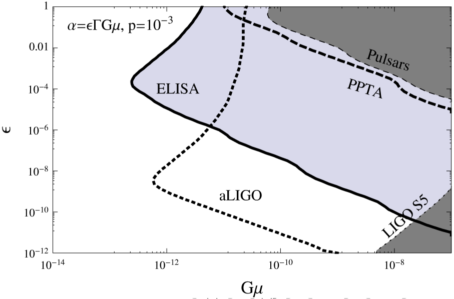
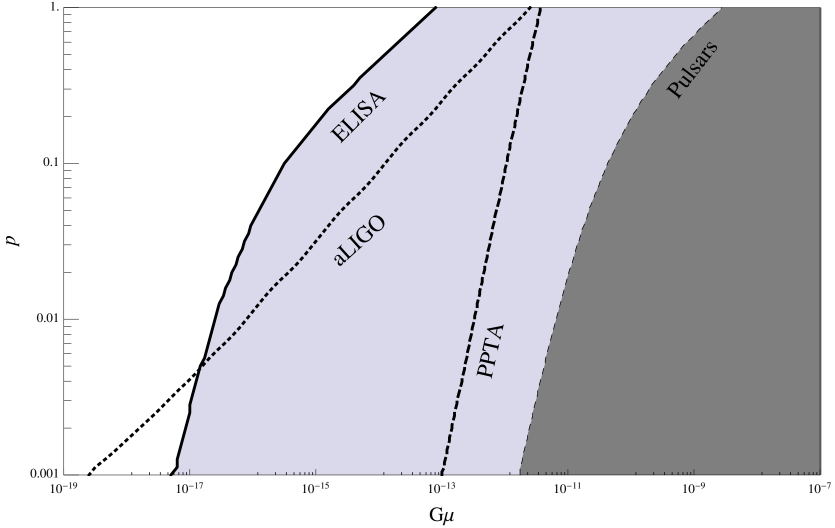
Accessible Regions in Parameter Space for Short-Lived Loops





Accessible Regions in Parameter Space for Large Loops



CONLUSIONS

- Cosmological GW backgrounds detectable by eLISA may be produced
- eLISA would be sensitive to very strong phase transitions occurring around 10 TeV and which last long: physics beyond the Standard Model, complementarity with the LHC
- For cosmic strings, significant regions of the parameter space are accessible simultaneously by different experiments, and eLISA would also be able to probe new regions of the parameter space
- GW are a powerful mean to learn about the early universe and high energy physics: detection may be difficult but great payoff