Gravitational Waves from the Early Universe.

Géraldine SERVANT
DESY/U.Hamburg

SLAC Summer Institute 2020, August 13 2020
Key question:

What can we learn on particle physics from Gravitational-Wave (GW) observations?
Recent GW detections by LIGO/Virgo have opened a new era of GW astronomy but also of (late time) cosmology as compact binaries can be used to probe cosmological parameters and modified gravity theories.

E.g. GW170817 NS binary merger: first coincident detection of GW and electromagnetic signals

→ measure of Hubble factor, constraints on modified gravity theories
2 types:

- From astrophysical sources (in the late universe)
  ✔ detected

- Cosmological background filling the whole universe
  (relic from the early universe)
  ✗ not yet detected
Primordial probes: “Fossil radiation”.

As the universe expands, particles can get out of thermal equilibrium. The weaker the interaction, the earlier in the history of the universe the particles decouple.

\[ \Gamma(T) : \text{rate of the interaction maintaining thermal equilibrium} \]
\[ H(T) : \text{rate of expansion of the universe} \]

Decoupling happens when \[ \Gamma(T) < H(T) \]

- Before decoupling, their interactions obliterate information.
- After decoupling, they propagate freely, carrying direct information about the early universe.

Particles that decouple at temperature \( T_{\text{dec}} \) give a snapshot of the universe at \( T_{\text{dec}} \).
As photons decouple from the electron/proton plasma when the universe is 380 000 yrs old, we cannot use the electromagnetic probe to learn about earlier times. On the other hand, gravity is weak, and GW decouple from the hot plasma much earlier:

\[
\frac{\Gamma_{GW}(T)}{H(T)} \sim \frac{G^2 T^5}{T^2 / M_{pl}} = \left( \frac{T}{M_{pl}} \right)^3
\]

Therefore, GW produced below the Planck scale are decoupled: They propagate freely in the universe until today.

They do not loose memory of conditions when produced.

They retain spectral shape, typical frequency and intensity characteristic of production mechanism, encoding information about particle physics at high-energy scales that will never be probed by colliders.

\[
\rho_{GW}^{\text{today}} = \rho_{GW}^{\text{prod}} \left( \frac{a_{\text{prod}}}{a_{\text{today}}} \right)^4 \quad \text{red-shift factor (cosmic evolution)} \quad \Rightarrow \text{BSM of cosmology}
\]

\[
\text{its production mechanism} \quad \Rightarrow \text{BSM of particle physics}
\]
Gravitons:

\[
G^{\mu\nu} N^\mu N^\nu = T^\mu N^\mu = M^2_{\text{Pl}}
\]

✓

Graviton

✓

\[T^\mu M^\mu = 3\]

– gravitons decoupled below Planck scale:
– do not lose memory of conditions when produced
– retain spectrum/shape/typical frequency & intensity of physics at corresponding high energy scales.

QCD
EW
MeV
eV

10^{16}\text{ GeV}
M_{\text{Pl}} \leq


Primordial Inflation


BBN


ν
γ


Cosmological dark ages: Reheating, Phase transitions, Baryogenesis, Dark Matter...

Current and future GW experiments constitute a new avenue of investigation in particle physics and cosmology.
Tensor perturbations of FRW metric:

\[ ds^2 = -dt^2 + a^2(t)[(\delta_{ij} + h_{ij})dx^i dx^j] \]

Wave equation:

\[ \ddot{h}_{ij} + 3H \dot{h}_{ij} + k^2 h_{ij} = 16\pi G \Pi_{ij}^{TT} \]

Source:

Tensor anisotropic stress

\[ = \text{Transverse Traceless component of the energy-momentum tensor of the source} \]

\[ \Pi_{ij} = (P_{ij}P_{jm} - \frac{1}{2}P_{ij}P_{lm})T_{lm} \]

\[ P_{ij} = \delta_{ij} - \hat{k}_i \hat{k}_j \]
Well-known cosmological sources.

- Cosmological Phase Transitions
- Cosmic Strings
- Inflation
- Reheating of the universe

See review 1801.04268.
A GW signal of primordial origin can only be observed today as a superposition of GW generated by an enormous number of causally independent sources, arriving at random times and from random directions.

Individual waves are not detectable, sources can not be resolved but instead we can only observe a Stochastic GW Background. For most of the cosmological sources, it is homogeneous, isotropic, gaussian and unpolarized and appears as a noise in the detector.

It is characterised by the energy density in GW in frequency range:

\[
\Omega_G = \frac{\langle \dot{h}_{ij} \dot{h}^{ij} \rangle}{G \rho_c} = \int \frac{dk}{k} \frac{d\Omega_G(k)}{d \log(k)}
\]
Characteristic Frequencies for causal (and short-lasting) sources.

\[ T_* \quad \text{temperature of the universe at time of emission} \]
\[ f_* \quad \text{frequency at time of emission} \]

**Observed frequency:**
\[ f \sim f_* \frac{T_0}{T_*} \sim \mathcal{O}(H_*) \frac{T_0}{T_*} \sim \frac{T_*}{M_{Pl}} T_0 \sim T_* \times 10^{-18} 10^{-12} \text{ GeV} \]

**If** \( T_* \sim 100 \text{ GeV} \): 
\[ f \sim 10^{-28} \text{ GeV} \sim 10^{-28} \times 10^{25} \text{ Hz} \sim \text{mHz} \]

LISA!
Integrated Power-law sensitivity curves.

$f$ (Hz)

$\Omega_{GW} h^2$

$\mathcal{M}_{QCD}$

$\mathcal{M}_{TeV}$

$\mathcal{M}_{PeV}$

pulsar-timing arrays

space-based interferometers

ground-based interferometers

EPTA

NANOGrav

SKA

5 yrs

10 yrs

20 yrs

LISA

LIGO O2

O4

O5

DECIGO

BBO

CE

M_{QCD}$

$M_{TeV}$

$M_{PeV}$
Gravitational waves as probe into the early Universe

Energy density of GW today

GW propagates freely in the early universe:

Energy density of GW today

GW

1st order phase transition

Primordial Inflation

Cosmic strings

\[ V^{1/4} \approx 10^{16} \text{ GeV} \]
My single slide on GW from inflation.
Irreducible GW background from inflation

\[
\ddot{h}_{ij} + 3H \dot{h}_{ij} + k^2 h_{ij} = 0
\]

Source: amplification of initial quantum fluctuations of the gravitational field during inflation

Scale invariant spectrum well beyond the reach of direct detection

Observational signal only when going beyond the simple single-field slow-roll inflation model (with extra fields beyond the inflaton)

see e.g. 1610.06481

However, GWs leave an imprint on CMB through polarisation pattern of B-modes which is a primary probe for its detection today.
Gravitational Waves from cosmological phase transitions.
1st-order phase transition described by temperature evolution of scalar potential.

Nucleation, expansion and collision of Higgs bubbles

Barrier separates 2 degenerate minima
2 phases can coexist
GWs from a 1st-order phase transition.

\[ \ddot{h}_{ij} + 3H \dot{h}_{ij} + k^2 h_{ij} = 16\pi G \Pi^{TT}_{ij} \]

Source of GW, anisotropic stress

- Generated mainly from fluid velocities in the vicinity of colliding bubble walls

**Bubble nucleation**

**Bubble percolation**

- Fluid flows
- Magnetic fields
- Turbulence

Stochastic bgd of gravitational radiation
Sources of GWs during a 1st-order phase transition.

\[ \ddot{h}_{ij} + 3H \dot{h}_{ij} + k^2 h_{ij} = 16\pi G \Pi_{ij}^{TT} \]

Fluid (sound waves and turbulence)

\[ \Pi_{ij} \sim \gamma^2 (\rho + p) v_i v_j \]

Electromagnetic field (primordial magnetic fields MHD turbulence)

\[ \Pi_{ij} \sim (E^2 + B^2) \frac{\delta_{ij}}{3} - E_i E_j - B_i B_j \]

Scalar field (collision of bubble walls)

\[ \Pi_{ij} \sim \partial_i \phi \partial_j \phi \]
• \( \beta \): inverse duration of the phase transition set by the tunneling probability

\[
P \propto e^{\beta t} \propto \frac{T^4}{H^4} e^{-S_3/T} \sim 1 \quad \Rightarrow \quad \frac{S_3}{T} \sim 140
\]

typically

\[
\frac{\beta}{H} \sim O(10^2 - 10^3)
\]

corresponds to the characteristic inverse size of bubbles at time of collisions

\[
R_* = \frac{v_w}{\beta}
\]

sets the characteristic frequency

\[
f_* \propto \frac{\beta}{v_w}
\]

\[
f_0 = \frac{a_* f_*}{a_0} \approx 20 \frac{1}{v_w} \frac{H_* T_*}{100 GeV} \left( \frac{g_*}{100} \right)^{1/6} \mu Hz
\]

• \( \alpha \): vacuum energy/radiation energy density

\( \alpha \) and \( \beta \): entirely determined by the effective scalar potential at high temperature
Estimate of the GW energy density at the emission time.

\[
\Omega_{GW,*} = \frac{\rho_{GW,*}}{\rho_{tot,*}} \sim \frac{G}{\beta^2} \Pi_{source}^2 \times \frac{1}{\rho_{tot,*}} \sim \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\Pi_{source}}{\rho_{tot,*}}\right)^2
\]

\[
\Pi_{source} \sim \kappa \rho_{vac}
\]

\[
\kappa_\phi = \frac{\rho_\phi}{\rho_{vac}} \quad \kappa_v = \frac{\rho_v}{\rho_{vac}} \quad \kappa_t = \epsilon \kappa_v
\]

fractions of vacuum energy that goes into either gradient energy in bubble kinetic energy in the fluid o into turbulent motion.

\[
\left(\frac{\Pi_{source}}{\rho_{tot,*}}\right)^2 \sim \frac{\kappa^2 \alpha^2}{(1 + \alpha)^2}
\]

\[
\Omega_{GW,*} \sim \left(\frac{H_*}{\beta}\right)^2 \times \frac{\kappa^2 \alpha^2}{(1 + \alpha)^2}
\]
Bulk flow & hydrodynamics

The Higgs vacuum energy is converted into:
- kinetic energy of the Higgs,
- bulk motion
- heating

\[ \Omega_{GW} \sim \kappa^2 (\alpha, v_b) \left( \frac{H}{\beta} \right)^2 \left( \frac{\alpha}{\alpha + 1} \right)^2 \]

\[ \alpha = \frac{\epsilon}{\rho_{\text{rad}}} \]
\[ \beta = \frac{1}{T} \frac{dS}{dT} \]

\[ \kappa = \frac{3}{\epsilon \xi^3 w} \int w(\xi) v^2 \gamma^2 \xi^2 d\xi \]

Fraction \( \kappa \) of vacuum energy density \( \epsilon \) converted into kinetic energy

\( \rightarrow \) All boils down to calculating the fluid velocity profile in the vicinity of the bubble wall

Much development from powerful simulations in the last years

[Mark Hindmarsh, Stephan Huber, Kari Rummukainen, David Weir ...]
Electroweak Phase Transition
-> milli-Hertz  -> LISA!

LISA: a new window on the Weak Scale

complementary to collider informations

Grojean-Servant hep-ph/0607107

GWs from a 1st-order phase transition
The Einstein Telescope: A window on the PeV scale!

\[ \Omega_{GW} h^2 \]

- LISA
- T=200 GeV
- T=2TeV
- T=500 TeV
- BBO
- LIGO
- ET

From 1910.08068
Figure 1: Blueprint for analyzing cosmological PTs in the context of LISA. See text for details.

Each step of the analysis described above carries with it a set of technical challenges and open questions. A primary aim of this work is to elucidate these issues and propose a conservative approach to obtaining state-of-the-art sensitivity estimates for LISA in detecting stochastic GW from cosmic PTs. In what follows, we will attempt to clear up common misconceptions that arise in the literature, discuss the state-of-the-art in the various steps of Fig. 1, and, in cases where there remains some ambiguity or lack of concrete results, suggest as explained in Sec. 2, \( \alpha \) can be expressed as a function of \( \beta \) and \( v_w \), so it is not an independent parameter.
What about the electroweak phase transition?
THE HIGGS POTENTIAL.

TODAY, $T=0$

How did we end up here?

$V(\phi, T)$

$\phi$ (GeV)

$V(\phi, T)$

We’re here.

Tested part of the potential

> How did we end up here?
HEATING UP THE STANDARD MODEL

Electroweak sym. restored at $T \gtrsim 160$ GeV*** through a smooth crossover

No departure from thermal equilibrium
It would have been different if $m_H \lesssim 70$ GeV

***1404.3565
Electroweak baryogenesis during a first-order Electroweak phase transition.

Baryon asymmetry created at vicinity of CP-violating bubble wall.

\[ \langle \Phi \rangle \neq 0 \]

Strength of Electroweak phase transition

\[ \equiv \frac{\langle \Phi(T_n) \rangle}{T_n} > 1 \]

\[ T_n \equiv \text{nucleation temperature} \]
The Electroweak baryogenesis miracle.

\[ \eta_B = \frac{n_B(\infty)}{s} = \frac{135 N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{\infty} dz \Gamma_{ws} \mu_L \exp \left[ -\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} dz_0 \Gamma_{ws} \right] \]

\[ \Gamma_{ws} = 10^{-6} T e^{-\frac{E_{sph} \phi(T)}{v}} \]

\[ \phi \]

\[ \Gamma_{ws} \]

\[ \mu_L \]

\[ \mu \]

\[ z/L_w \]

\[ v_w \]

\[ L_w \]

\[ \text{broken} \]

\[ \text{symmetric} \]

bubble wall velocity

CP-violating source

sphaleron rate
The Electroweak baryogenesis miracle.

\[ \eta_B = \frac{n_B(-\infty)}{s} = \frac{135 N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} dz \Gamma_{ws} \mu_L \text{Exp} \left[ -\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} dz_0 \Gamma_{ws} \right] \]

\[ \Gamma_{ws} = 10^{-6} T e^{-\frac{E_{spho} \phi(T)}{v}} \]

\[ \eta_B \sim \frac{\Gamma_{ws} \mu_L L_w}{g_* T} \]

\[ \mu_L \sim M'' M \sim \frac{\delta_{CP}}{L_w^2 T} \quad L_w \sim \frac{1}{T} \]

All parameters fixed by EW physics. If new CP violating source of order 1 then we get just the right baryon asymmetry.
Electric dipole moments (EDM) provide one of the best indirect probes for new-physics. Since a non-zero EDM requires a violation of the CP symmetry, and the Standard Model (SM) contributions are accidentally highly suppressed, the EDM is an exceptionally clean observable to uncover beyond the SM (BSM) physics. Indeed, if BSM physics lies at the TeV scale, we expect new interactions and therefore new sources of CP violation to be present, inducing sizable EDM to be observed in the near future. For this reason, experimental bounds on the electron and neutron EDM have provided the most substantial constraints on the best motivated BSM scenarios, such as supersymmetry or composite Higgs models.

As in the SM, we can expect that any parameter of the BSM that can be complex will be complex, providing unavoidably large new sources of CP violation.

The most shaking news of the last years for Electroweak baryogenesis practitioners!

\[ |d_e| < 1.1 \cdot 10^{-29} \text{ e} \cdot \text{cm} \]


The most shaking news of the last years for Electroweak baryogenesis practitioners!
What makes the EW phase transition 1st-order?

> O(1) modifications to the Higgs potential

> Extra **EW-scale** scalar(s) coupled to the Higgs
What makes the EW phase transition 1st-order?

> Extra **EW-scale** scalar(s) coupled to the Higgs

**2 main classes of models**

1- Standard polynomial potentials, e.g. extra singlet S, 2HDM… under specific choices of parameters.

   - Effect of cross-quartic $\lambda_{\phi S} \phi^2 S^2$
   - Moderate strength of EW phase transition, $\alpha$, $\frac{\phi}{T} \approx O(1)$

2- Higgs emerging after confinement phase transition of strongly interacting new sector.

   - Higgs potential is trigonometric function
   - Fate of the Higgs ruled by the dilaton
   - Unbounded strength, $\alpha$, $\frac{\phi}{T}$ can naturally be $>>1$
EW Phase transition in Composite Higgs Models:

Naturally strongly first-order.
EW phase transition in Composite Higgs models.

> Higgs potential emerges at $E \approx f$.

For PNGB:

$$V_h \sim f^4 \left[ \alpha \sin^2 \left( \frac{h}{f} \right) + \beta \sin^4 \left( \frac{h}{f} \right) \right]$$

$f \sim O(\text{TeV})$: confinement scale of new strongly interacting sector, described by VEV of dilaton field $<\chi>$, Pseudo-Nambu-Goldstone Boson of spontaneously broken conformal symmetry of the strong sector.

$$V = V_\chi(\chi) + V_h(\chi, h)$$

$\chi$ dominates the dynamics

$$V(\chi) = \chi^4 \times f(\chi^\varepsilon)$$

$|\varepsilon| \ll 1$

Nearly conformal potential: $T_n \ll f$, SUPERCOOLING
Higgs-dilaton intertwined dynamics.

Which path?

global minimum at $T \gg f$

decofined strong sector
unbroken EW symmetry

1803.08546, 1804.07314
Strongly 1st order TeV scale confinement phase transition.

- Large number of massless dof in deconfined phase
- Shallow (nearly conformal) potential at $T=0$ with TeV minimum

Large thermal barrier

Supercooled confinement phase transition
Nearly-conformal potential with TeV minimum + large number of CFT states → supercooled confinement phase transition

Strongly 1st order TeV scale confinement phase transition.

Creminelli, Nicolis, Rattazzi’01
Randall, Servant’06
Hassanain, March-Russell, Schwellinger’07
Nardini, Quiros, Wulzer’07
Konstandin, Servant’11
Konstandin, Nardini, Quiros’10
Bunk, Hubisz, Jain’17
Dillon, El-Menoufi, Huber, Manuel’17
VonHarling, Servant’17
Megias, Nardini, Quiros’18
Bruggisser, VonHarling, Matsedonskyi, Servant’18
Baratella, Pomarol, Rompineve’18
Impact on EW phase transition in Composite Higgs.

(1) SM-like EW phase transition (crossover)

(2)-(3) Joint confinement-EW phase transitions: very rich pheno for EW baryogenesis (strongly 1st-order)

global minimum at $T \gg f$

deconfined strong sector
unbroken EW symmetry

global minimum at $T \ll f$

confinement and EWSB
1st-order EW phase transition.

Potential along the straight line trajectory:

\[ V_{\text{Tot}}(\chi) - V_{\text{Tot}}(0) \text{ [GeV}^4] \]

-1 \times 10^{10}

0

2 \times 10^{10}

3 \times 10^{10}

\chi \text{ [GeV]}

0

200

400

600

800

\begin{align*}
T &= 210 \text{ GeV}, \\
T_c &\approx 169.3 \text{ GeV}, \\
T_n &\approx 95.8 \text{ GeV}
\end{align*}
N: number of exact tunneling paths (cf. Fig. 1). In the central panel of Fig. 2, action of leads to a valley in the Higgs-dilaton potential which can at experimental sensitivities. Center: Average Higgs strength of EW phase transition <h>/T during the EWPT before decreasing, and since transitions studied so far, our Higgs dicative given order one uncertainties) are typically close to baryon asymmetry values (which should only be taken as in-

\[ m_\ast = g_\ast f \]

\[ g_\ast = 4\pi/\sqrt{N} \]
After confining phase transition: universe may be reheated above the sphaleron freeze out temperature

To preserve baryon asymmetry from washout:

$$\frac{h(T_{\text{reheat}})}{T_{\text{reheat}}} \gtrsim 1$$

LIGHT DILATON WINDOW $\sim 700$ GeV

Unavoidable? (see next...)
Constraints from reheating.

To preserve baryon asymmetry from washout: $h(T_{\text{reheat}})/T_{\text{reheat}} > \sim 1$

**LIGHT DILATON**

**WINDOW $\sim 700$ GeV**

$\rightarrow$ direct searches + Higgs physics
Collider bounds on dilaton.

Higgs-like couplings suppressed by $v/f$

Other signatures: $\delta g_{hhh}$, $\delta g_{Vhh}$, $\delta g_{htt}$, $\delta g_{Xtt}$
from Higgs-dilaton mixing

[Mikael Chala, using HiggsBounds]
Amount of supercooling.

\( m_\chi \) (N) 

\( h/T \) 

Critical

Nevertheless

Lower

F

Discussed in more detail in the next section.

Much less likely than in the direction with shallow. This means that tunneling in directions with somewhat di

Figure 11: 

\( N = 8 \) 0 0 GeV 

\( 10^{12} \) 

4

6

8

0.1

0.2

0.3

0.4

0.5

0.6

0.7

0.8

0.9

1.0

\( m_\star \) (TeV)

\( \frac{T_c}{T_n} \)

\( \hat{m} \)

Meson

Glueball

\( T \)

\( \hat{c} \)

Avg

N

\( m_\chi \) (TeV)

\( \hat{m} \) (TeV)

\( T_c/T_n \)

\( \hat{m} \)

Meson

Glueball

100

10

3

\( \hat{m} \)

\( T_c/T_n \)

\( \hat{m} \)

Meson

Glueball

1804.07314

\( \rightarrow \) Large GW signal.  

\( \rightarrow \) Large GW signal.

46
An interesting question:

Can we push up the temperature of the EW phase transition?
Why pushing up the temperature of the EW phase transition?

> Motivation: EW baryogenesis using high-scale sources of CP violation, allowed by data!

> Major implications even if pushed by only a few hundreds of GeV!

> Early baryon asymmetry safe from sphaleron wash-out even in models with B-L=0!

> opens large new windows of theory space for successful EW baryogenesis!
Pushing up the temperature of the EW phase transition?

In 3rd case, the baryon asymmetry produced during higher T phase transition is never washed out!

Observable consequence: a GW peak frequency shifted to higher frequencies
It remains very open how EW symmetry got broken in early universe

- **First-order EW phase transition: well alive and still likely**
  - supercooled EW phase transition: generic in Composite Higgs with light dilaton, rich pheno and cosmo.
  - *Testable through light dilaton signatures & GW signatures at LISA*

- **EW baryogenesis: under threat by EDM bounds**
  - Top transport may remain open only in composite Higgs.
  - CP in hidden sector, e.g. new leptons
  - EW phase transition occurring at high temperatures $\gg 100$ GeV, via additional singlet scalars or singlet fermions.
Gravitational Waves from Cosmic Strings.

> Key difference with respect to GWs from phase transitions: Long-lasting source! probe the entire cosmic history

> Probes of heavy, up to EeV mass, unstable particles
Cosmic Strings.

Topological defects generated during a spontaneous symmetry-breaking phase transition with $\pi_1(G/H) \neq 1$ [Kibble1976]

Network of cosmic strings

[Allen & Shellard, 1990]

String’s core $\ll$ horizon size $\Rightarrow$ 1D classical object with tension $\mu \sim \eta^2$ (Nambu-Goto string)

Network of cosmic strings

[Allen & Shellard, 1990]
Gravitational Waves from Cosmic Strings.

String inter-commuting: crossing, loop formation

Loops from the string network continuously produced

Scaling regime: \( \rho_{\text{network}} \sim t^{-2} \sim \rho_{bg} \)

if local strings: they decay via emission of gravitational waves
if global strings: they decay mainly by emission of Goldstone particles

We assume local strings from now.

\( \rightarrow \) string network acts as a long-lasting
GW source

Power of GW radiation per loop
estimated by quadrupole formula

\[
P_{GW} = - \frac{dE_{\text{loop}}}{dt} = \Gamma G \mu^2
\]

\( \Gamma \approx 50 \) dim.less constant [Vachaspati & Vilenkin, 1985]

GW from cosmic strings can probe the entire cosmic
history due to a continuous GW production
Gravitational Wave spectrum.

Evolution of the Universe

Higher $f \Leftrightarrow$ Earlier emission

smaller loop $\Leftrightarrow$ higher oscillation $f$

@ earlier $t_i$

more GW from more loops but more red-shift

$\Rightarrow$ Flat during radiation

$G\mu = 10^{-11}, \Gamma = 50, \alpha = 0.1$

[1912.02569]
**Spectra for different string tensions**

\[
\log_{10}(G\mu)
\]

\[
\Omega_{GW} h^2
\]

- **EPTA**
- **LIGO O5**
- **NANOGrav**
- **LISA**
- **SKA 5 yrs**
- **SKA 10 yrs**
- **SKA 20 yrs**
- **DECIGO**
- **BBO**
- **CE**

- **(cusp)**
- **(kink)**

\[ \eta \sim 10^{13} \text{ GeV} \]

\[ \eta \sim 10^9 \text{ GeV} \]

**Turning-point**

\[ f(G\mu, \eta) \]

**References**

[1912.02569]
⇒ Effect of change of number of degrees of freedom

**Injected entropy** in thermal bath

⇒ **Dilution** of the GWs existing before DOF decay
Probing non-standard cosmological histories.
Effect of additional DOFs.

Probing equation of state of the early universe

Figure 6. Left panel: illustration of our parametrization of the change in the number of DOFs for $T = 200$ GeV and $g^\ast = 10^{1}, 10^{2}, 10^{3}$. Right panel: modification of the GW spectrum from a cosmic string network with $G\mu = 10^{-11}$ and $\Delta g^\ast = 0, 1$. The colored regions in this panel show the expected sensitivities of SKA, LISA, DECIGO, ET, and CE. This agrees well with a similar calculation in Ref. [67]. This implies that the amplitude of the RD plateau depends on the number of DOFs via $\Omega$, and thus $\Omega GW (f) \sim \Omega SM GW (f) \Delta g^\ast g^\ast SM + \Delta g^\ast 1/3$, (3.9)

where $\Omega SM GW$ is the amplitude with only SM DOFs, and we have assumed $g^\ast = g^\ast S$ at high $T$. Therefore an increase of number of DOFs at $T$ leads to a drop in the amplitude at frequencies above $f$. In fact, similar changes in the GW amplitude from the RD era from changes in the number of $e$-effective SM degrees of freedom at the QCD phase transition and electron-positron decoupling are visible in Figs. 2 and 3. We also find that the magnitude of the amplitude decrease in Eq. (3.9) agrees well with the full numerical result shown in the right panel of Fig. 6.

3.3 Probing new phases of cosmological evolution

The second type of cosmological modification we consider is an early period in which the expansion of the universe is driven by a new source of energy density prior to the most recent radiation era, leading to a non-standard equation of state in the early universe. For example, an early epoch of matter domination with $\rho / a^3$ can arise from a large density of a long-lived massive particle or oscillations of a scalar moduli field in a quadratic potential [10]. Such a period of matter domination ends when the long-lived species decays to the SM. A more exotic class of deviations can arise from the energy density of a scalar field oscillating in a potential of the form $V(\phi) / N$, which gives $n = 6N / (N + 2)$. In the extreme limit of $N \rightarrow 1$ we have $n \rightarrow 6$, corresponding to the oscillation energy being dominated by the kinetic energy of the scalar. This behavior arises in models of inflation, quintessence, dark energy, and axions, and is called kination [11, 12, 16]. For all
Intermediate Matter era inside Radiation era induced by heavy unstable particle.

**Early stage of matter domination:**
- **faster expansion**→ **suppression of GW**

**temperature at decay:**
\[ T_{\text{dec}} = 1 \, \text{GeV} \left( \frac{80}{g_{\text{SM}}} \right)^{1/4} \left( \frac{2.7 \times 10^{-7} \, \text{s}}{\tau_X} \right)^{1/2} \]

\[ \begin{align*}
\rho_{\text{start}} & = \rho_{\text{tot}}(a) \\
\rho_{\text{end}} & = \rho_{\Delta} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{inflation} \\
\rho_{\text{end}} & \rightarrow \text{kinflation} \\
\rho_0 & \rightarrow \text{standard} \\
\rho_{\text{start}} & \rightarrow \text{radiation} \\
\rho_{\text{end}} & \rightarrow \text{radiation} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{modified cosmology} \\
\rho_{\text{end}} & \rightarrow \text{modified cosmology} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{kinflation} \\
\rho_{\text{end}} & \rightarrow \text{kinflation} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{standard} \\
\rho_{\text{end}} & \rightarrow \text{standard} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{radiation} \\
\rho_{\text{end}} & \rightarrow \text{radiation} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{modified cosmology} \\
\rho_{\text{end}} & \rightarrow \text{modified cosmology} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{kinflation} \\
\rho_{\text{end}} & \rightarrow \text{kinflation} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{standard} \\
\rho_{\text{end}} & \rightarrow \text{standard} \\
\rho_0 & \\
\rho_{\text{start}} & \rightarrow \text{radiation} \\
\rho_{\text{end}} & \rightarrow \text{radiation} \\
\rho_0 & \]
Extracting the temperature of the universe at the time of the particle decay.

**Turning-point frequency & Changing cosmology**

**Example:** 1st order phase transition

\[ f \approx H_* \left( \frac{a_*}{a_0} \right) \quad \text{standard cosmo.} \quad f \approx (19 \text{ mHz}) \left( \frac{T_*}{100 \text{ TeV}} \right) \]

**Cosmic string**

Loop production @ \( t_i \)

\[ f \approx H_* \left( \frac{a_*}{a_0} \right) \left( \frac{1}{G\mu} \right)^{1/2} \]

Loop emission @ \( t_* \)

\[ f \approx (19 \text{ mHz}) \left( \frac{T_i}{0.1 \text{ GeV}} \right) \left( \frac{10^{-11}}{G\mu} \right)^{1/2} \]

LISA probes TeV physics.

LISA probes MeV scale & ET probes TeV physics.
Probing large new regions of theory space.

\[ T_{\text{dec}} = T_{\Delta} \]

\[ T_{\Delta} \text{ [GeV]} \]

Figure 3: Constraints on the lifetime \( \tau_X \) and would-be abundance \( m_{X \gamma} \) of a heavy unstable particle inducing an early-matter era, assuming the observation of a SGWB from CS by a GW interferometer, c.f. sec. 3.3. We compare the new prospects with the current limits inferred from BBN \[2-4\]. We assume the detectability of the turning point in the GW spectrum at the frequency \( f \), induced by the decay of the particle at \( T_{\text{dec}} = T_{\Delta} \), c.f. turning-point description \( r_1 \) in sec. 3.2. Limitation due to particle production in the cusp-domination case \[5\] are shown in purple.

Probing large new regions of theory space.

\[ G \mu = 10^{-13} \]

\( \tau_X \) [s]

\( m_{X \gamma} \) [GeV]

[1912.03245]
Reach of future GW interferometers.

\[ \Gamma_X \propto m_X^3 / M_{pl}^2, \]

Heavy particle decaying through a Planck suppressed operator, supposing it is sufficiently produced to induce a matter era before the decay.

[1912.03245]
Short late stage of inflation era inside Radiation era.

\[ N_e = \log \left( \frac{a_{\text{end}}}{a_{\text{start}}} \right) \]

“Duration of inflation”

\[ \rho_{\text{inf}} = E_{\text{inf}}^4 \]

\[ \rho_{\text{total}} \]

Inflation

Cosmic-string network formation

Intermediate Inflation

radiation

standard

rad. Inflation

\( a_{\text{start}} \)

\( e^{N_e,1} a_{\text{start}} \)

\( e^{N_e,2} a_{\text{start}} \)

\( a \)

rad.

inflation

rad.

another \( N_e \)

string re-enter

frozen

Intermediate matter: \( r_{\text{cusp}} \)

Turning-point frequency

10 MeV

Scaling

VOS

Standard

CE

ET

LISA

BBO

CE

DECIGO

100,000 Hz

\( T \)

10 TeV

\( f \)

9

6

10,w11

50,000

10 GW

0.1
Late inflation induced by e.g. a supercooled phase transition.

Intermediate Inflation: $E_{\text{inf}} = 100$ TeV

$\left(G\mu = 10^{-11}, \Gamma = 50, \alpha = 0.1\right)$
Sensitivity to the energy scale of the intermediate inflationary stage.

Intermediate inflation

through measurement of turning-point frequency

\[ E_{\text{inf}} \text{ [GeV]} \]
Conclusion 2.

GW from cosmic strings:

- Very rich array of possible spectra encoding physics happening at very different energy scales.

- Huge laboratory of exploration.

- Complementarity between space-based, ground-based interferometers & radio telescopes
If detected, a cosmic relic GW background can bring unique information on the very early universe and high energy particle physics complementary to particle colliders.

In particular, LISA is on the path to launch in 2034. Has huge potential to probe early and late-time cosmology (non-standard inflationary models, EW symmetry breaking and beyond, cosmic strings... )

And other exciting proposals on the table to probe higher energy scales: ET, CE ...
From future observations of primordial GW we can learn about:

- 1st-order phase transitions and symmetry breaking events from hidden sectors at low energies (EPTA) to the PeV scale at the ET & CE

- Cosmic Strings

- Non-standard cosmology, modified equation of state of the universe with respect to radiation domination (early matter or kination eras, secondary short intermediate inflation era)

  but also (which I had no time to cover)

- Particle Production during/after Inflation

- Scalar field dynamics
Annexes.
HIGGS EFFECTIVE POTENTIAL AT HIGH TEMPERATURE.

At one-loop:

\[
V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_T^1(\phi, T) + V_{\text{Daisy}}(\phi, T).
\]

Tree level \quad l\text{-loop} \quad l\text{-loop} \quad \text{Daisy resummation}

\[
T=0 \quad T \neq 0
\]

For high-\( T \), \( m/T \ll 1 \):

\[
\Delta V_{b,i}^T \simeq \frac{\pi^2 T^4}{90} + \frac{T^2 m_i^2(\phi)}{24}
\]

\[
\Delta V_{f,i}^T \simeq \frac{7\pi^2 T^4}{180} + \frac{T^2 m_i^2(\phi)}{12}
\]

\[
\delta m_H^2(T) \simeq +T^2 \left[ \frac{y_t^2}{4} + \frac{\lambda}{2} + \frac{3g^2}{16} + \frac{g'^2}{16} \right]
\]

Depth of negative correction to \( V_{\text{eff}} \) at \( m=0 \) \quad Sets the thermal mass

\( \infty \int_0^\infty dk \ k^2 \left( 1 \mp e^{k^2+m_i^2(\phi)/T^2} \right) \)
At one-loop:

\[ V_{\text{eff}} = V_{\text{tree}}(\phi) + V_1^0(\phi) + V_1^T(\phi, T) + V_{\text{Daisy}}(\phi, T). \]

Tree level \hspace{1cm} \text{l-loop } T=0 \hspace{1cm} \text{l-loop } T \neq 0 \hspace{1cm} \text{Daisy resummation}

At high T:

\[ V_T \neq 0 + \delta m_H^2(T) T^2 + V_T = 0 \]

\[ \rightarrow \text{Symmetry restoration at } T_c \]
Add n new fermions N with Higgs-dependent mass contribution. Mass vanishes at \( \langle h \rangle \neq 0 \)

\[
m_N(h) = m_N^{(0)} - \lambda_N h^2 / \Lambda = 0 \quad \longrightarrow \quad h^2 = m_N^{(0)} \Lambda / \lambda_N,
\]

\[
\delta m_h^2[T] \simeq n \frac{T^2}{12} (m_N^2(h))'' = n \lambda_N \frac{m_N^{(0)}}{3 \Lambda} T^2.
\]

Negative thermal mass

Enables to push Tc to \( \sim 500 \) GeV while keeping \( \langle h \rangle / T > 1 \) for \( T < T_c \).
SUMMARY OF PRINCIPLE: Massless or sufficiently light \((m<T)\) particles coupled to the Higgs produce a dip in the Higgs potential of the size \(\sim -T^4\)!
GW spectrum from Cosmic Strings.

\[
\Omega_{GW}^{(k)}(f) = \frac{1}{\rho_c} \cdot \frac{2k}{f} \cdot \frac{(0.1)\Gamma^{(k)} G\mu^2}{\alpha(\alpha + \Gamma G\mu)} \int_{t_F}^{t_0} dt \frac{C_{eff}(t_i)}{t_i^4} \left[ \frac{a(t)}{a(t_0)} \right]^5 \left[ \frac{a(t_i)}{a(t)} \right]^3 \Theta(t_i - t_F)
\]

- **k-mode of loop-oscillation**
- **string’s nature**
- **loop number**
- **red-shift**

\[ t_i \equiv \text{loop production, } \tilde{t} \equiv \text{loop emission} \]
Beyond Nambu-Goto

- **Nambu-Goto approximation**
  - 1D classical objects with tension: $\mu \sim \langle \phi \rangle^2$
  - Valid when curvature radius $\gg$ string thickness

$\mu \sim \langle \phi \rangle^2$

- **NG approx. violated by small-scale structure**
  - Massive Particle production

Cosmological $\gg$ Microscopic

loop
kink
cusp