Cosmic Archaeology with Gravitational Wave Signals from Cosmic Strings

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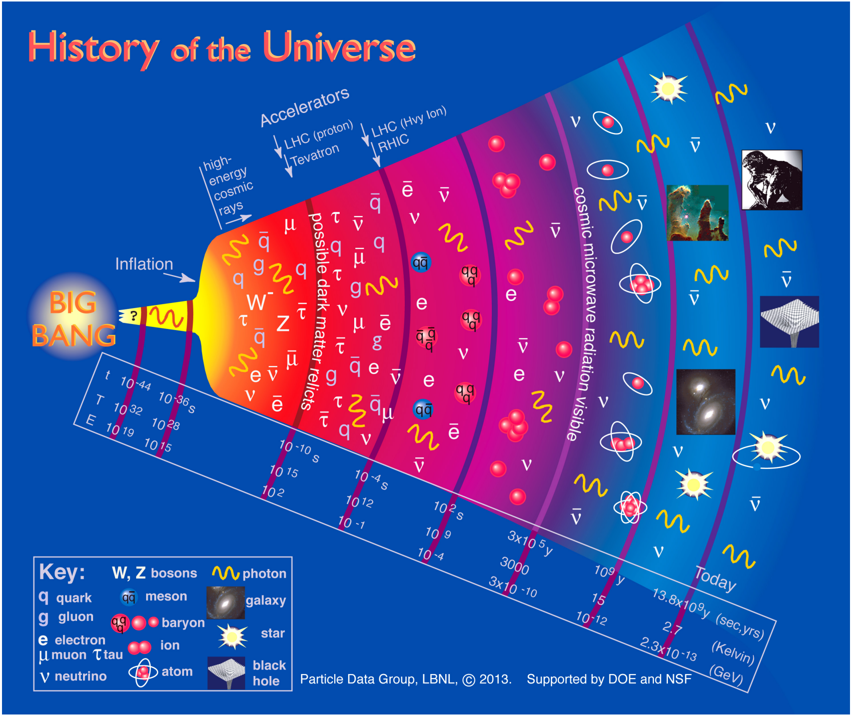
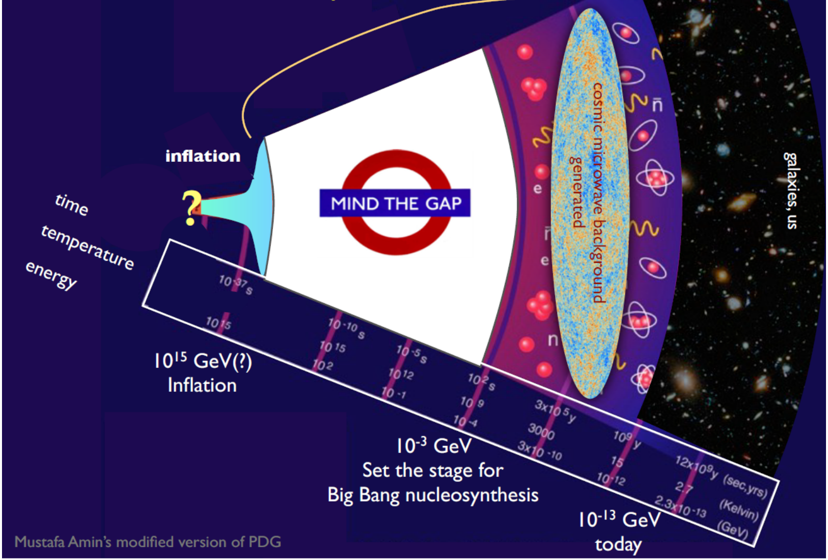
StringPheno18, 3 July 2018

Based on:

Y. Cui, D. Morrissey, ML and J. D. Wells. arXiv:1711.03104, arXiv:1807.XXXXX


History of the Universe
BIG BANG
?
Inflation
high-energy cosmic rays
Accelerators
LHC (proton)
Tevatron
LHC (Hvy Ion)
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t 10-44 10-36 s 10-10 s 10-4 s 102 s 3x105 y 109 y 13.8x109y (sec,yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

A Different View of the Gap



Mustafa Amin's modified version of PDG

Plan

- A brief review of cosmic strings
- Stochastic GW background from Cosmic Strings
- Cosmic Archaeology
  - GW frequency temperature relation
  - Detection capabilities
  - Non standard cosmologies
- Conclusions

Cosmic String

- **What are cosmic strings?**
  - → Stable one-dimensional topological defects
- **The origins of cosmic strings:**
  - → Prediction from Superstring theory:
    (F-) string, D-string
  - → Vortex-like solutions in field theory
    e.g. from spontaneously broken U(1) symmetry

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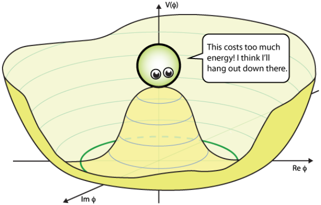
- Charged complex scalar field

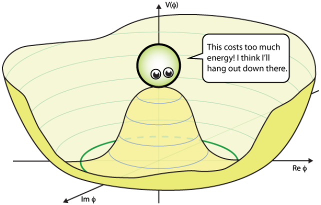
$$V = \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$



Cosmic String formation (Kibble mechanism)

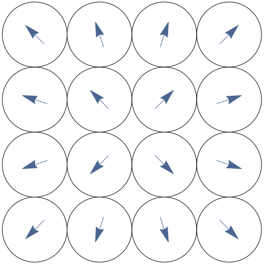
- Charged complex scalar field

$$V = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$



- Horizon size at early time (high temperature) $d_H \propto M_p/T^2$
- we need a solution:

$$\Phi \xrightarrow{r\to\infty} \frac{v}{\sqrt{2}}e^{i\theta}$$



Cosmic String solution

- In the Abelian Higgs model

$$\mathcal{L} = D_\mu \Phi D^\mu \Phi^\dagger - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2$$

- approximate solution

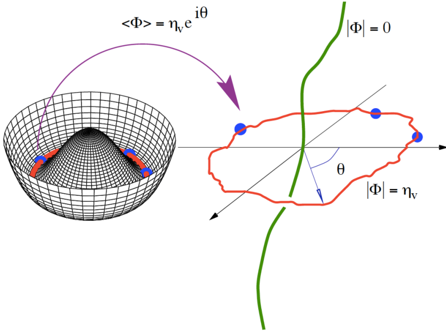
$$\Phi = \frac{v}{\sqrt{2}} \left(1 - \exp(-r/r_1)\right) \exp(-i\theta)$$

$$A_\theta = \frac{1}{er} \left(1 - \exp(-r/r_2)\right)^2$$

$\langle \Phi \rangle = 0$ at the origin

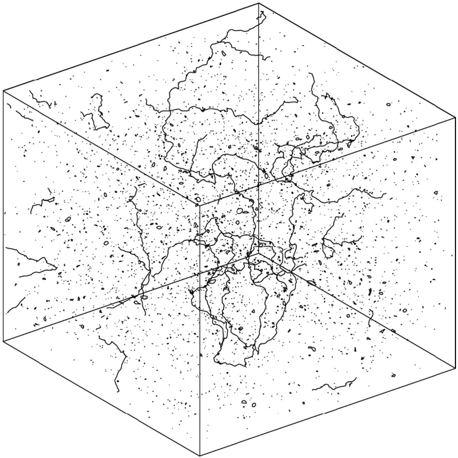
$r_1, r_2 \propto v^{-1}$

- tension of the string (energy per unit length) $\mu \propto v^2$



Christophe Ringeval (Adv.Astron. 2010)

Cosmic Strings



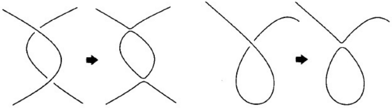
Vilenkin and Shellard 94'

Cosmic String network

- Static string network would red-shift as

$$\rho_\infty \propto a^{-2}$$

- strings intercommute on collision



- overall energy density of the network scales with total energy density

$$\frac{\rho_\infty}{\rho_{\text{tot}}} \propto G\mu$$

Cosmic String network

- We use a simplified loop distribution

$$l_i = \alpha t_i, \quad \alpha \approx 0.1$$

- After its creation each loop radiates energy at a constant rate

$$\frac{dE}{dt} = -\Gamma G\mu^2, \quad \Gamma \approx 50$$

- The loop size decreases as

$$l = \alpha t_i - \Gamma G\mu \, (t - t_i)$$

- The final loop density reads

$$n(l,t) = \frac{C_{\rm eff}(t_i)}{\alpha^2 t_i^4} \frac{a^3(t_i)}{a^3(t)}$$

where the factor $C_{\rm eff}$ depends on the background evolution.

Stochastic GW background from Cosmic Strings

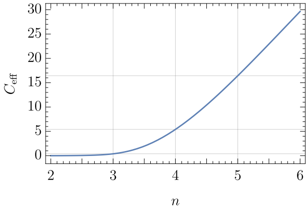
- the observed frequency f of GWs and time when emitting loop was created

$$f = \frac{2}{l}\frac{a(t_0)}{a(\tilde{t})} \qquad t_i = \frac{1}{\alpha + \Gamma G\mu}\left(\frac{2}{f}a(\tilde{t}) + \Gamma G\mu \tilde{t}\right)$$

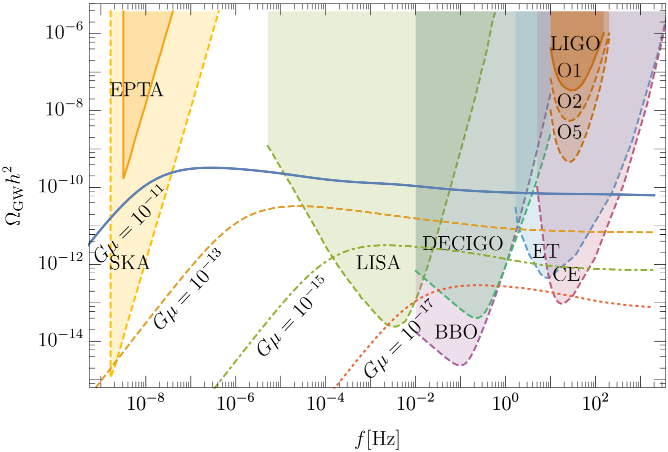
- The final estimate for GW density today, reads

$$\Omega_{\rm GW}(f)h^2 = h^2 \frac{16\pi}{3f}\frac{\Gamma(G\mu)^2}{H_0^2\alpha\left(\alpha + \Gamma G\mu\right)}\int_{t_F}^{t_0} d\tilde{t}\frac{C_{\rm eff}(t_i)}{t_i^4}\left(\frac{a(\tilde{t})}{a(t_0)}\right)^5\left(\frac{a(t_i)}{a(\tilde{t})}\right)^3\Theta\left(t_i - t_F\right)$$

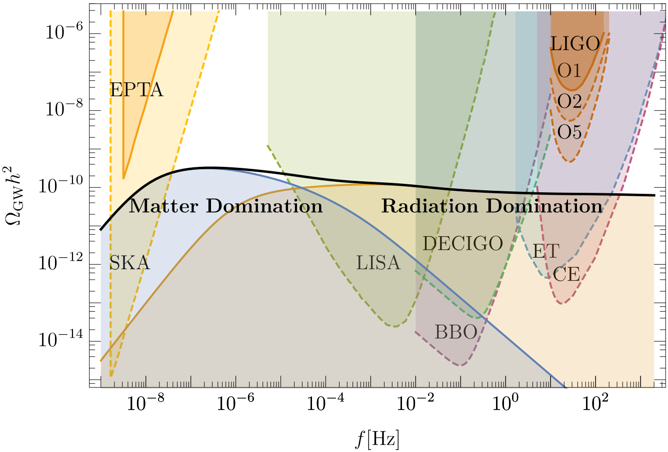
- where the factor $C_{\rm eff}$ depends on the background evolution $H^2 \propto a^{-n}$



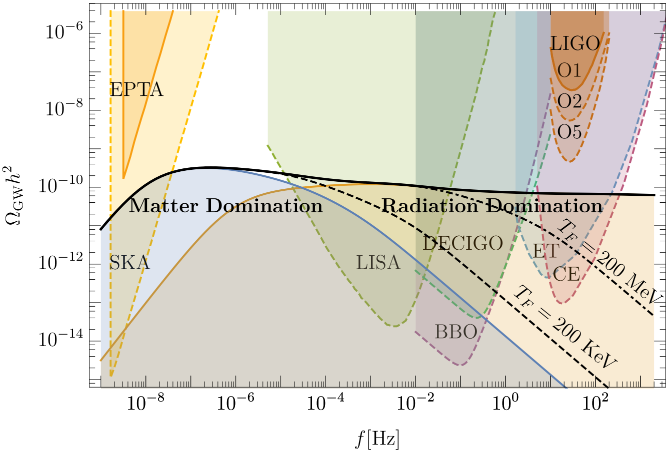
Stochastic GW background from Cosmic Strings



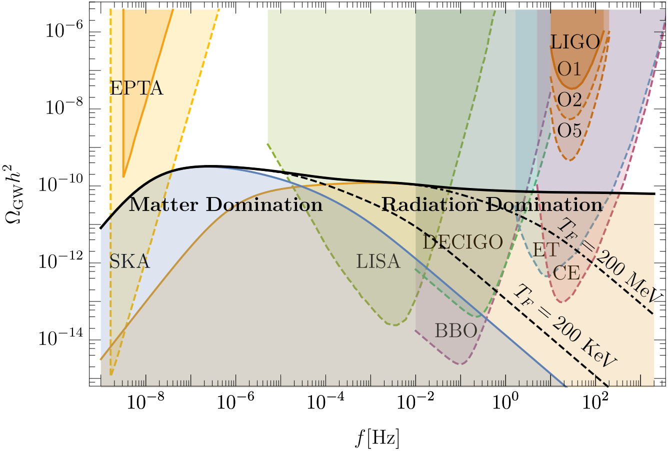
Stochastic GW background from Cosmic Strings



Stochastic GW background from Cosmic Strings



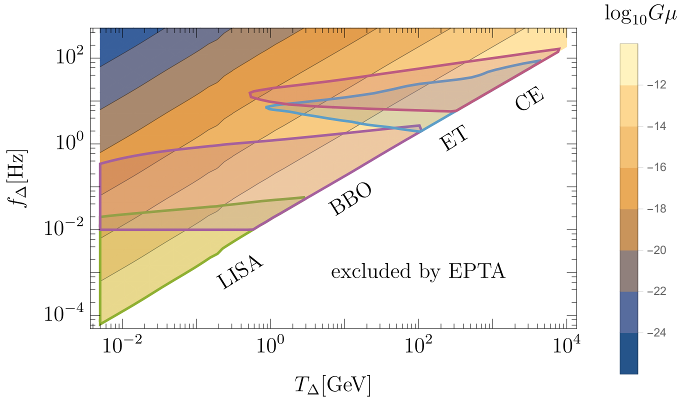
Stochastic GW background from Cosmic Strings



- GW frequency ↔ temperature

$$f_\Delta \propto \frac{T_\Delta}{\sqrt{G\mu\,\alpha}}$$

Detection capabilities



- slightly better numerical result

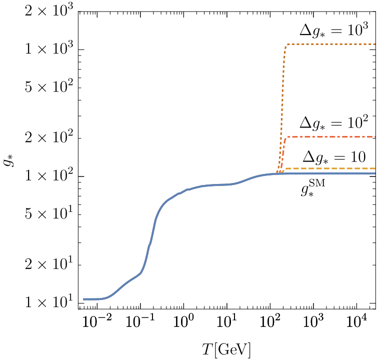
$$f_\Delta = (8.67 \times 10^{-9}\,\mathrm{Hz})\,\frac{T_\Delta/\mathrm{GeV}}{\sqrt{\alpha\, G\mu}} \left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}} \left(\frac{g_S(T_0)}{g_S(T_\Delta)}\right)^{-\frac{7}{6}}$$

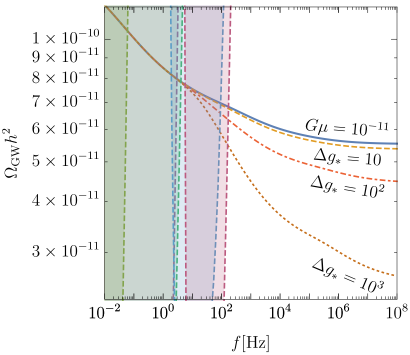
Extra DOF

- We add Δg_* new degrees of freedom at T_Δ

$$g_*(T) = \begin{cases} g_*^{\rm SM}(T) & \text{for} \quad T < T_\Delta \\ g_*^{\rm SM}(T) + \Delta g_* & \text{for} \quad T > T_\Delta \end{cases}$$

- An example with $T_\Delta = 200\,\text{GeV}$ and $G\mu = 10^{-11}$





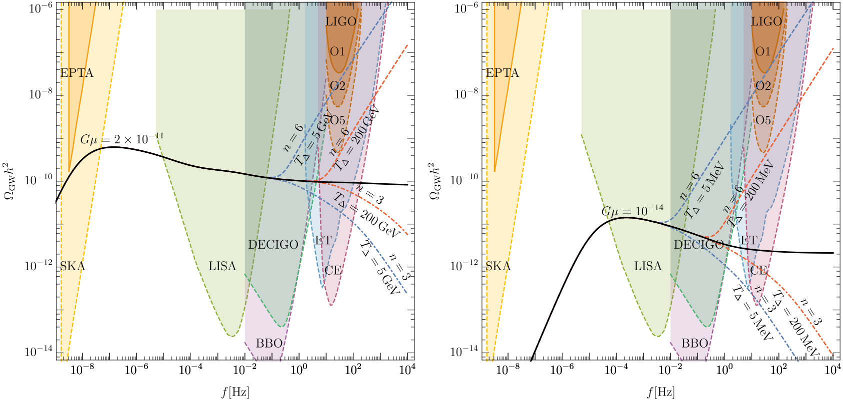
Non standard cosmologies

- We will model the energy budget of the universe as

$$\rho(t) = \begin{cases} \rho_{st}(t) & ;\, t \geq t_\Delta \\ \rho_{st}(t_\Delta) \left[\frac{a(t_\Delta)}{a(t)}\right]^n & ;\, t < t_\Delta \end{cases}$$

- examples:
  1. standard radiation domination ($n = 4$)
  2. early matter domination ($n = 3$)
  3. oscillating scalar field (for non-renormalisable potential $n \to 6$)
  4. ...
- experimental bounds: RD during BBN $\Rightarrow T_\Delta \gtrsim 5$ MeV

Non standard cosmologies



- at large frequencies

$$H^2 \propto a^{-n} \Longrightarrow \Omega_{GW}(f) \propto \begin{cases} f^{\frac{8-2n}{2-n}} & n > 10/3 \\ f^{-1} & n \leq 10/3 \end{cases}$$

Conclusions

1. Cosmic strings could provide a unique and powerful tool for probing the early history of the universe.
2. Any departure from a flat spectrum predicted by standard cosmological evolution can be traced to the respective temperature of cosmological modification.
3. This method could probe the cosmological evolution to time well before the currently available BBN data.