Probing Baryonic Dark Matter Models with Gravitational Waves

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Standard Model

Gauge symmetry

$$\boxed{\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}$$

Glashow (1961), Weinberg (1967), Salam (1968), Fritzsch and Gell-Mann (1972)

Accidental global symmetries

$$\boxed{\mathrm{U}(1)_B \times \mathrm{U}(1)_L}$$

Gauging baryon and lepton number

→ **Early attempts**

- *A. Pais (1973), S. Rajpoot (1988), R. Foot, G. Joshi, H. Lew (1989), C. Carone, H. Murayama (1995), H. Georgi, S. Glashow (1996)*

→ **Phenomenologically viable model**

- *P. Fileviez Perez, M. Wise, PRD 82, 011901 (2010)*

→ **Further investigations**

- ★ *M. Duerr, P. Fileviez Perez, M. Wise, PRL 110, 231801 (2013)*
- *J. Arnold, P. Fileviez Perez, B.F. , S. Spinner, PRD 88, 115009 (2013)*
- *P. Fileviez Perez, S. Ohmer, H. Patel, PLB 735, 283 (2014)*
- *B.F., A. Rajaraman, T. Tait, PRD 92, 055022 (2015)*
- *…*

Gauging baryon and lepton number

$$\boxed{\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_B \times \mathrm{U}(1)_L}$$

➡ **Possible choice of extra fermion fields**

$$\boxed{\begin{array}{ll} \Psi_L = \left(1, 2, \frac{1}{2}, B_1, L_1\right) & \Psi_R = \left(1, 2, \frac{1}{2}, B_2, L_2\right) \\ \eta_R \ = (1, 1, 1, B_1, L_1) & \eta_L \ = (1, 1, 1, B_2, L_2) \\ \chi_R = (1, 1, 0, B_1, L_1) & \chi_L = (1, 1, 0, B_2, L_2) \end{array}}$$

➡ **Anomaly cancellation requires**

$$\boxed{B_2 - B_1 = 3} \qquad \boxed{L_2 - L_1 = 3}$$

Gauging baryon and lepton number

→ Fields with vevs breaking U(1)$_L$ and U(1)$_B$

$$\boxed{\Phi_L = (1,1,0,0,-2) \qquad \Phi_B = (1,1,0,-3,-3)}$$

$$\boxed{v_L \gg v_B \gg v}$$

→ Type I seesaw for neutrinos $\boxed{v_L \approx 10^{11}\ \mathrm{GeV}}$

→ U(1)$_B$ breaking only by 3 units:
No proton decay!

Dark matter

- After U(1)$_L$ and U(1)$_B$ breaking a residual symmetry remains

$$\Psi_{L,R} \to e^{i\alpha}\,\Psi_{L,R} \qquad \eta_{L,R} \to e^{i\alpha}\,\eta_{L,R}$$
$$\chi_{L,R} \to e^{i\alpha}\,\chi_{L,R}$$

- The lightest leptobaryon χ is stable and can be the dark matter

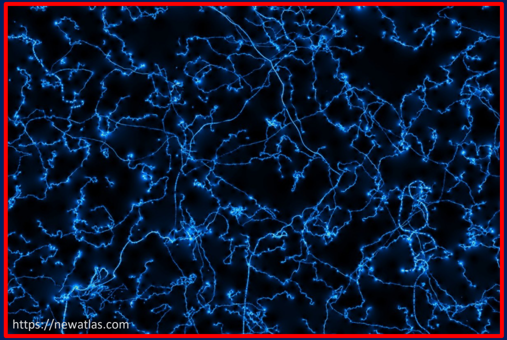
- Annihilation proceeds via $\chi\,\bar{\chi} \to Z_B^* \to q\,\bar{q}$

- Observed dark matter relic density implies

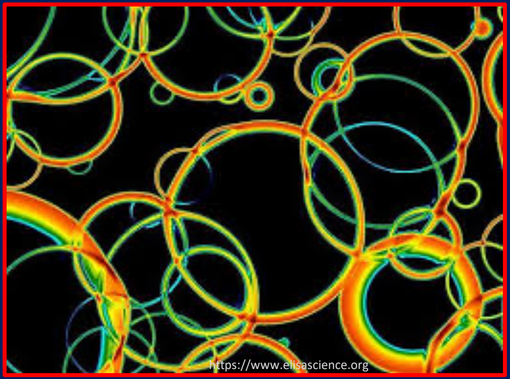
$$g_B v_B \lesssim 20\ \mathrm{TeV}$$

Gravitational waves

→ **Spontaneously broken U(1) can lead to gravitational wave production in two ways:**


https://newatlas.com

- **In a long-term process resulting from the dynamics of produced cosmic strings**

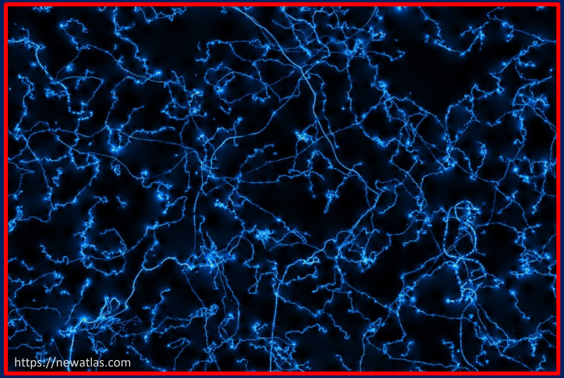

https://www.elisascience.org

- **Within a very short timescale during a phase transition**

Cosmic strings

- **Topological defects: 1-dim. field configurations with unbroken symmetry**
- **Characterized by the string tension μ**

$$G\mu = 2\pi \left(\frac{v_L}{M_P}\right)^2$$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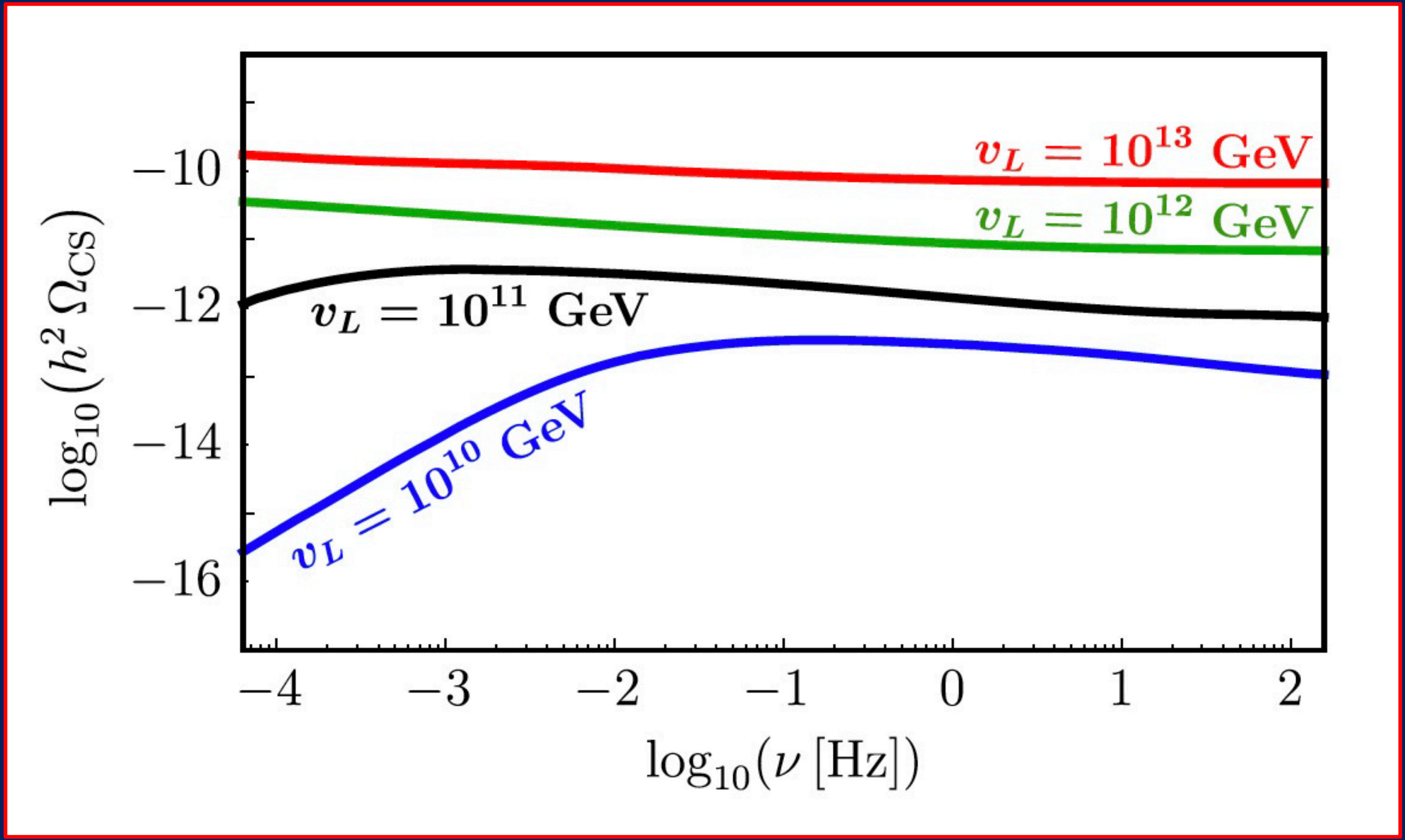
- **Two competing contributions to the string network dynamics:**
  - **stretching (due to the universe expansion)**
  - **formation of string loops (which decay via gravitational radiation)**
- **This leads to the *scaling regime***

Gravitational waves from cosmic strings

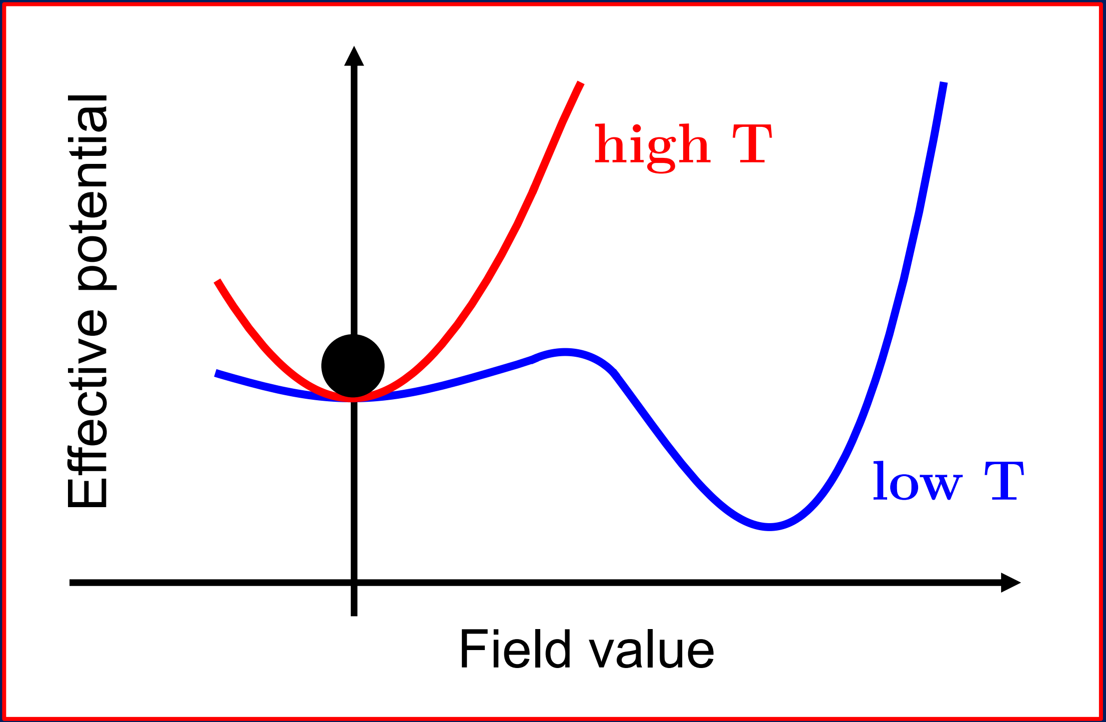


B.F. , B. Shams, PRD 102, 115037 (2020)

First order phase transition

→ **When the effective potential develops a barrier**

$$V_{\text{eff}}(\phi_B, T) = V_{\text{tree}}(\phi_B) + V_{\text{1-loop}}(\phi_B) + V_{\text{temp}}(\phi_B, T)$$



First order phase transition

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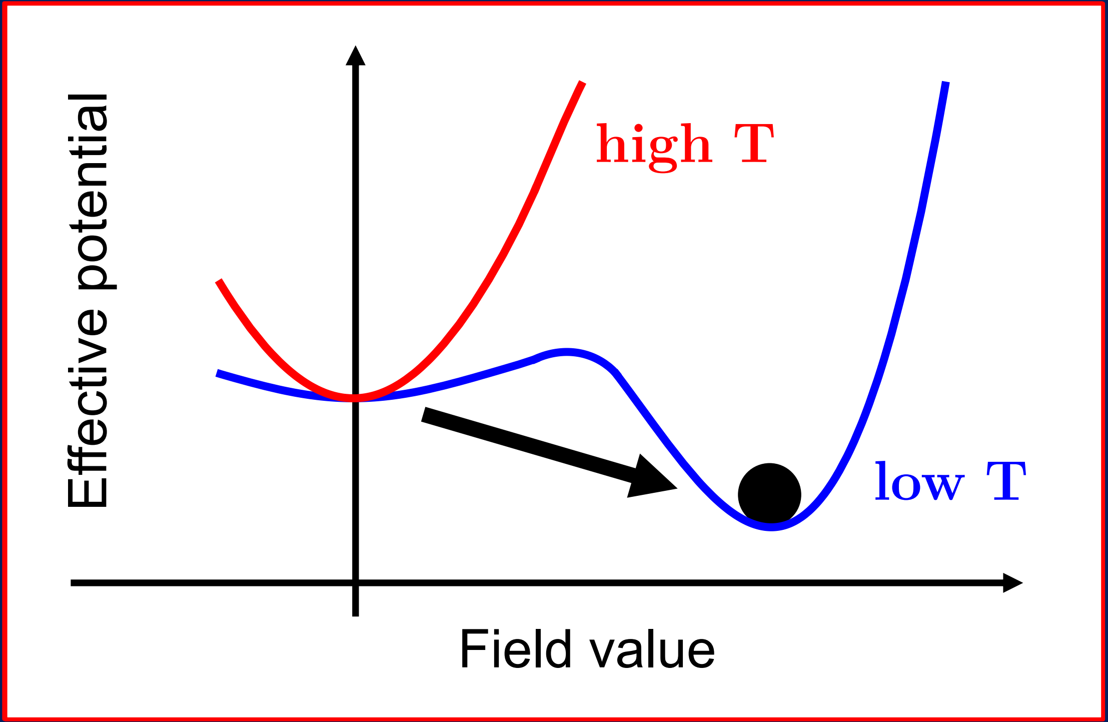
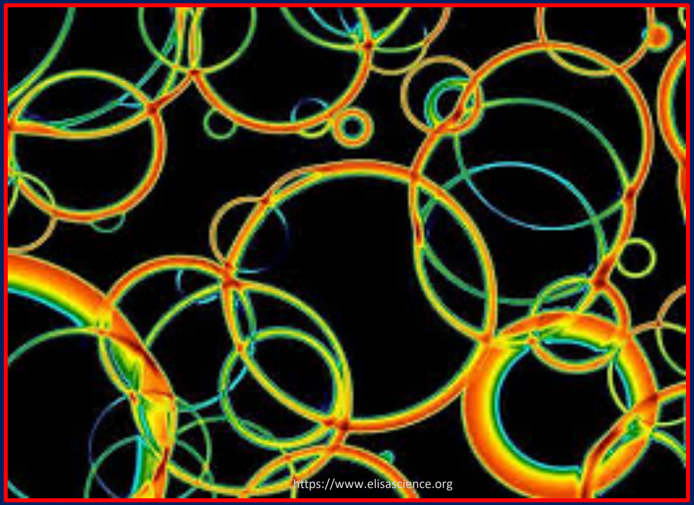


First order phase transition

- When a patch of the universe undergoes tunneling, a bubble is formed and expands

- The gravitational wave signal is produced via sound waves, bubble collisions and turbulence



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Relevant parameters

- Bubble wall velocity $\boxed{v_w}$
- Nucleation temperature $\boxed{T_*}$
- PT duration $\boxed{1/\tilde{\beta}}$ where $\boxed{\tilde{\beta} = T_* \frac{d}{dT}\left(\frac{S(T)}{T}\right)\Big|_{T=T_*}}$
- Strength of the transition $\boxed{\alpha = \frac{\rho_{\mathrm{vac}}(T_*)}{\rho_{\mathrm{rad}}(T_*)}}$

Gravitational waves from phase transition

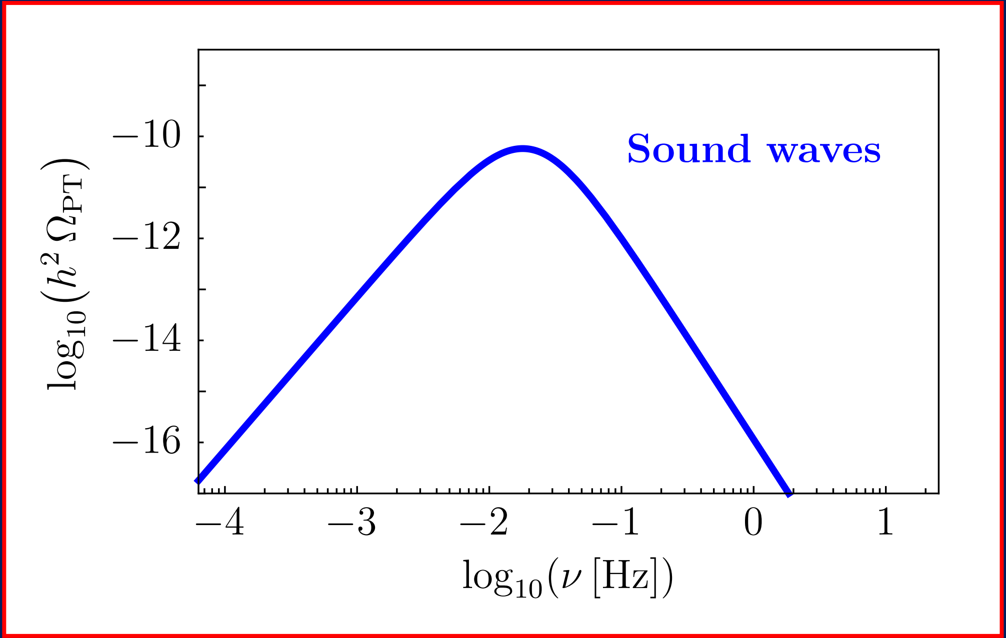
→ **Sound waves provide the leading contribution**

$$h^2\Omega_s(\nu) \approx \frac{(1.86\times 10^{-5})\left(\frac{\nu}{\nu_s}\right)^3}{\left[1+0.75\left(\frac{\nu}{\nu_s}\right)^2\right]^{\frac{7}{2}}}\,\frac{v_w}{\tilde{\beta}}\left(\frac{\kappa_s\,\alpha}{\alpha+1}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\Upsilon$$

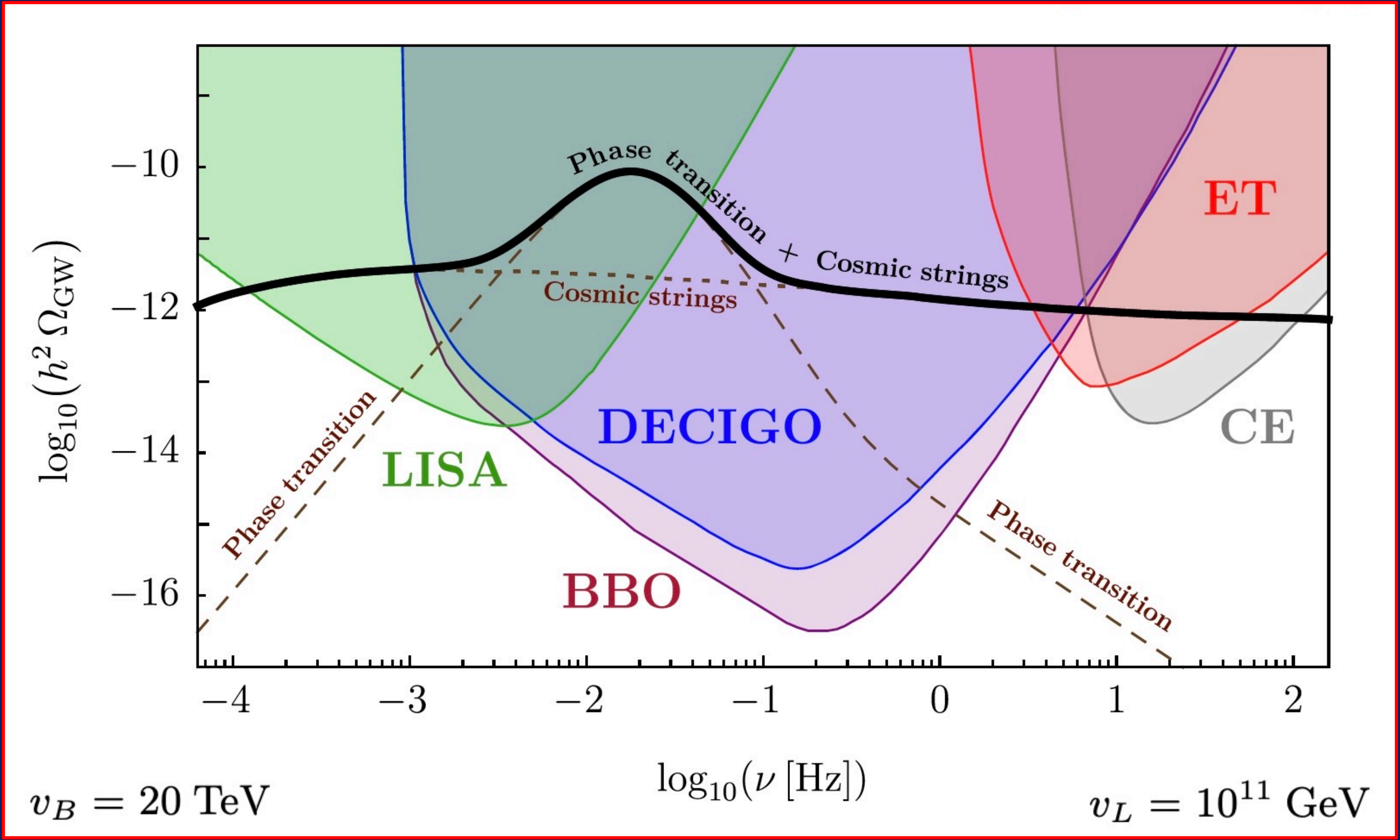
where

$$\kappa_s \approx \frac{\alpha}{0.73+0.083\sqrt{\alpha}+\alpha}$$

$$\nu_s \approx (1.9\times 10^{-4}\ \mathrm{Hz})\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\frac{\tilde{\beta}}{v_w}\left(\frac{T_*}{1\ \mathrm{TeV}}\right)$$



Gravitational wave signature



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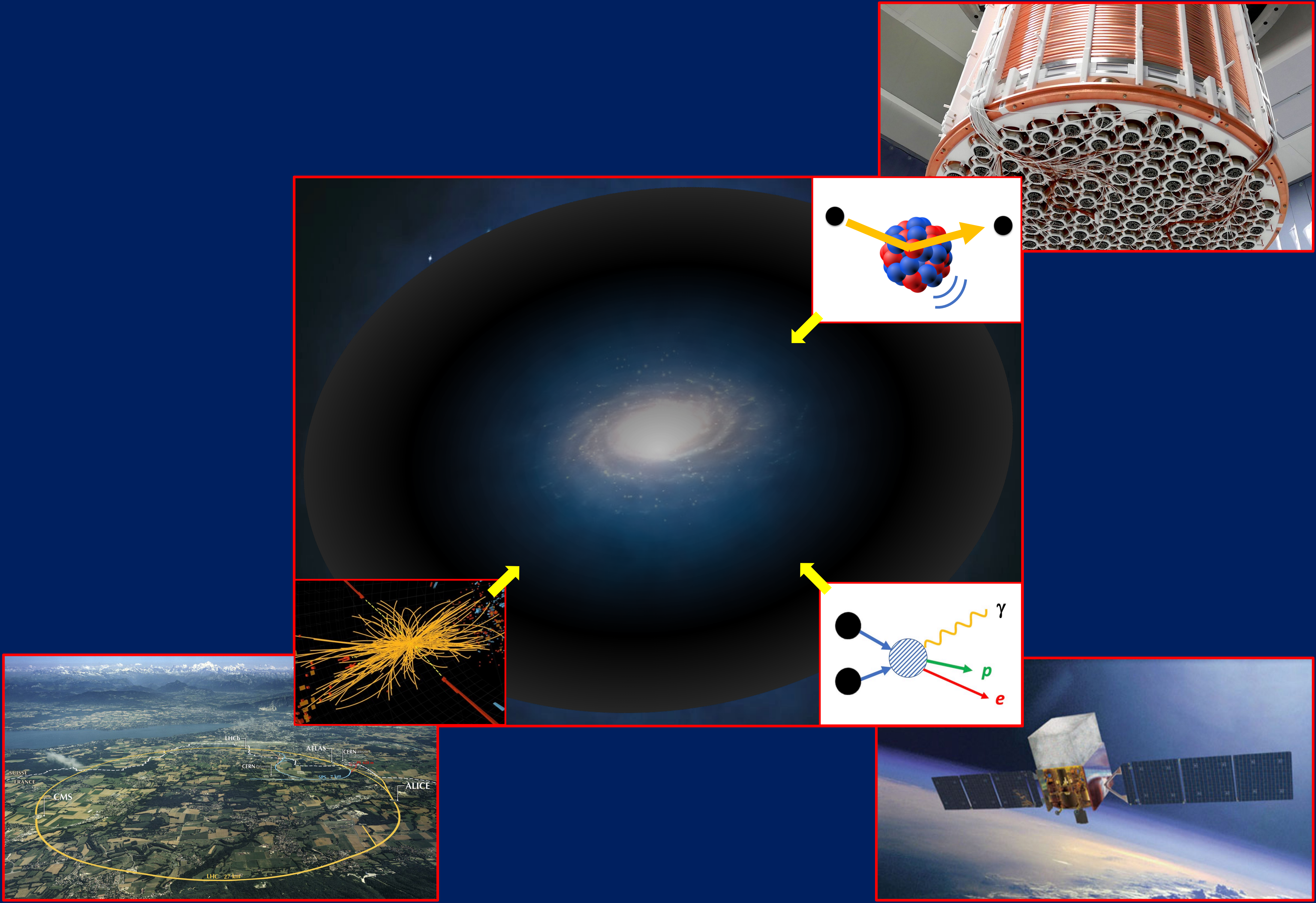
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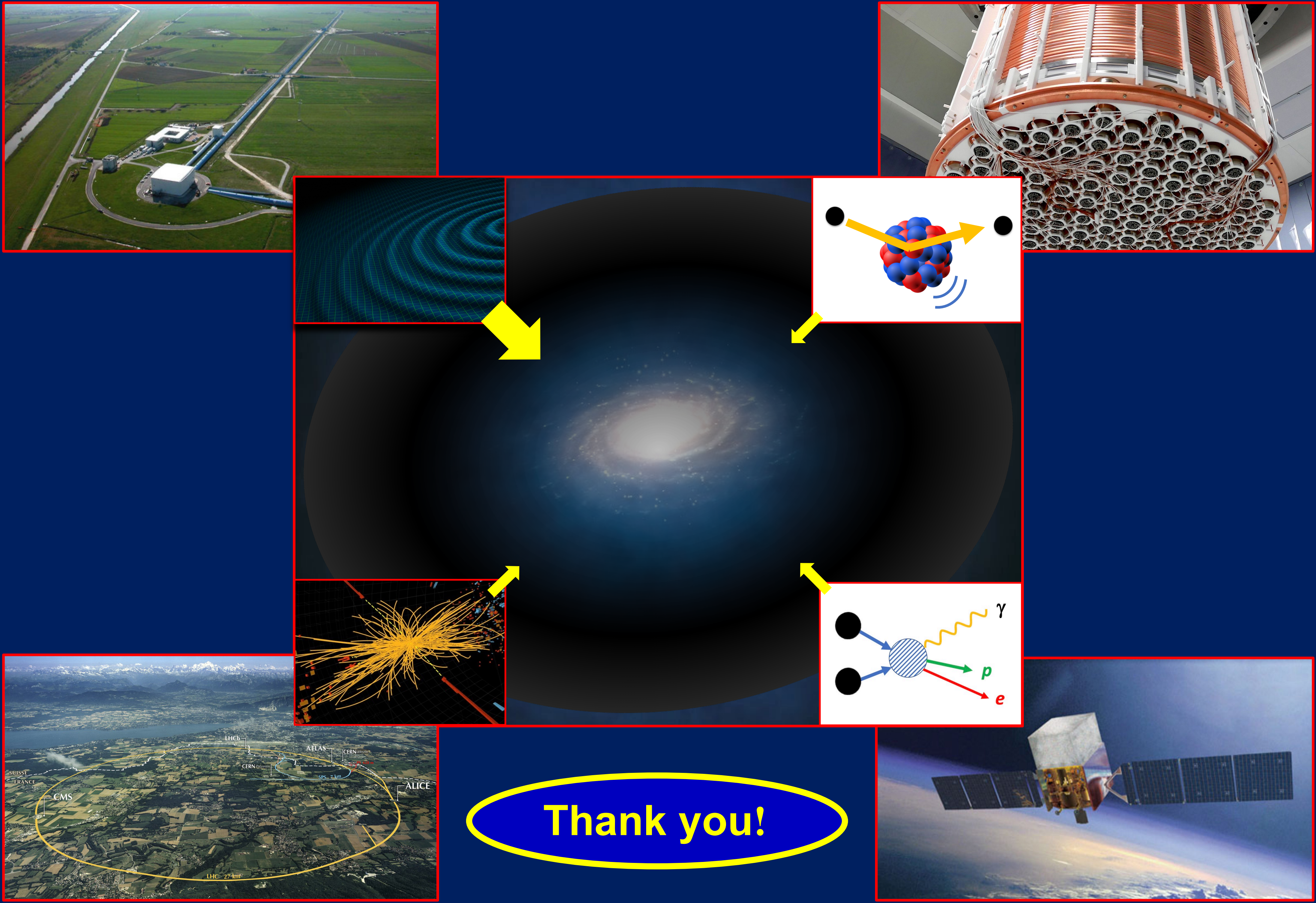
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km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Thank you!