Gravitational Wave Signatures of Baryonic Dark Matter

Bartosz Fornal

Barry University

AstroDark-2021

Axions, Neutrinos, Black Holes and Gravitational Waves

Kavli IPMU, Japan, December 7, 2021

In collaboration with: ***Barmak Shams***

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 symmetry

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

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**

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

➡ **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 $U(1)_B$

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

$$v_L \gg v_B \gg v$$

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

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

Dark matter

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

$$\boxed{\begin{array}{ll} \Psi_{L,R} \to e^{i\alpha}\,\Psi_{L,R} & \eta_{L,R} \to e^{i\alpha}\,\eta_{L,R} \\ \chi_{L,R} \to e^{i\alpha}\,\chi_{L,R} & \end{array}}$$

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

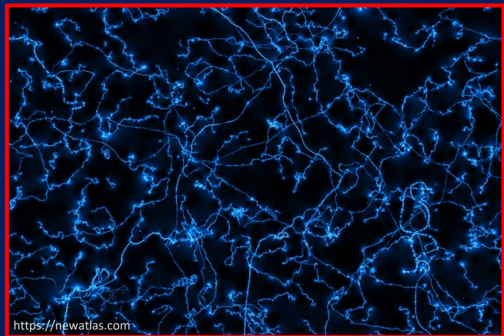
- Annihilation proceeds via $\boxed{\chi\,\bar{\chi} \to Z_B^* \to q\,\bar{q}}$

- Observed dark matter relic density implies

$$\boxed{g_B v_B \lesssim 20 \text{ TeV}}$$

Gravitational waves

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



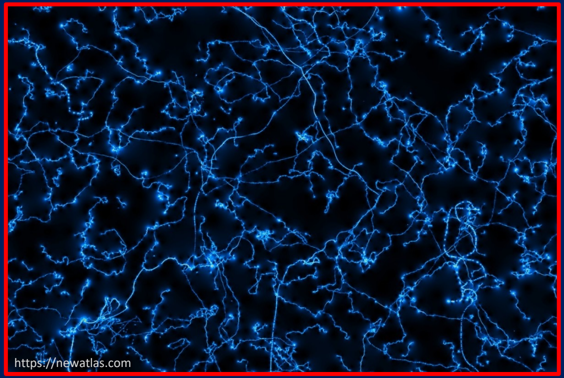
- **In a long-term process resulting from the dynamics of produced cosmic strings**

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

Cosmic strings

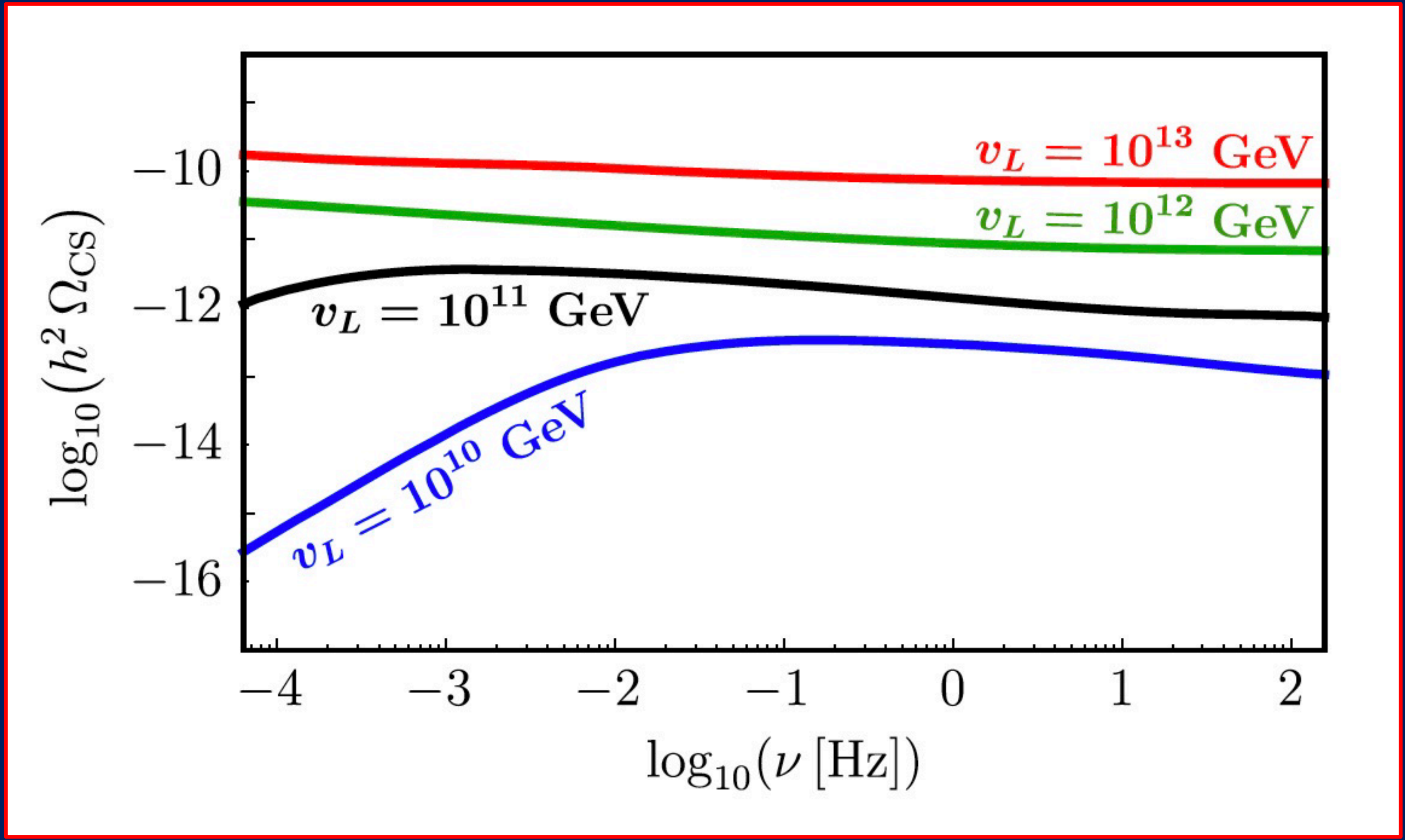
- **Topological defects: 1D field configurations with unbroken symmetry**
- **Characterized by the string tension μ**

$$G\mu = 2\pi \left(\frac{v_L}{M_P}\right)^2$$



- **Two competing contributions to the string network dynamics:**
  - **stretching (due to the universe's expansion)**
  - **formation of string loops (which decay via gravitational radiation)**
- **This leads to the *scaling regime***

Gravitational waves from cosmic strings

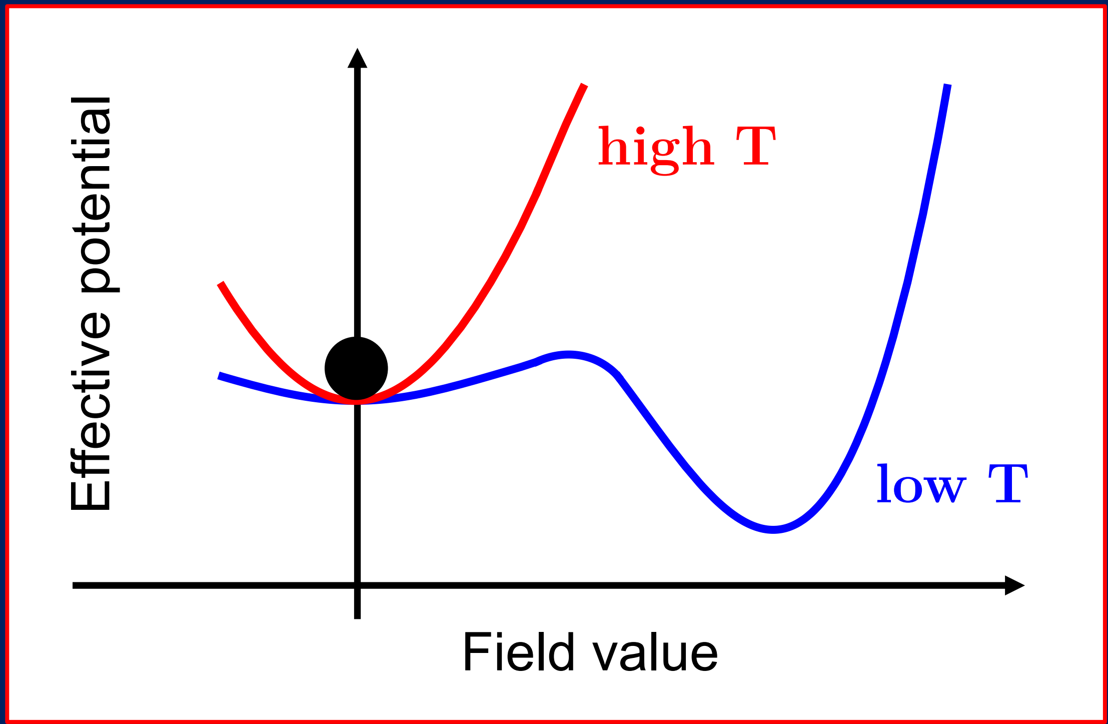


B.F. , B. Shams, PRD 102, 115037 (2020)

First order phase transition

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

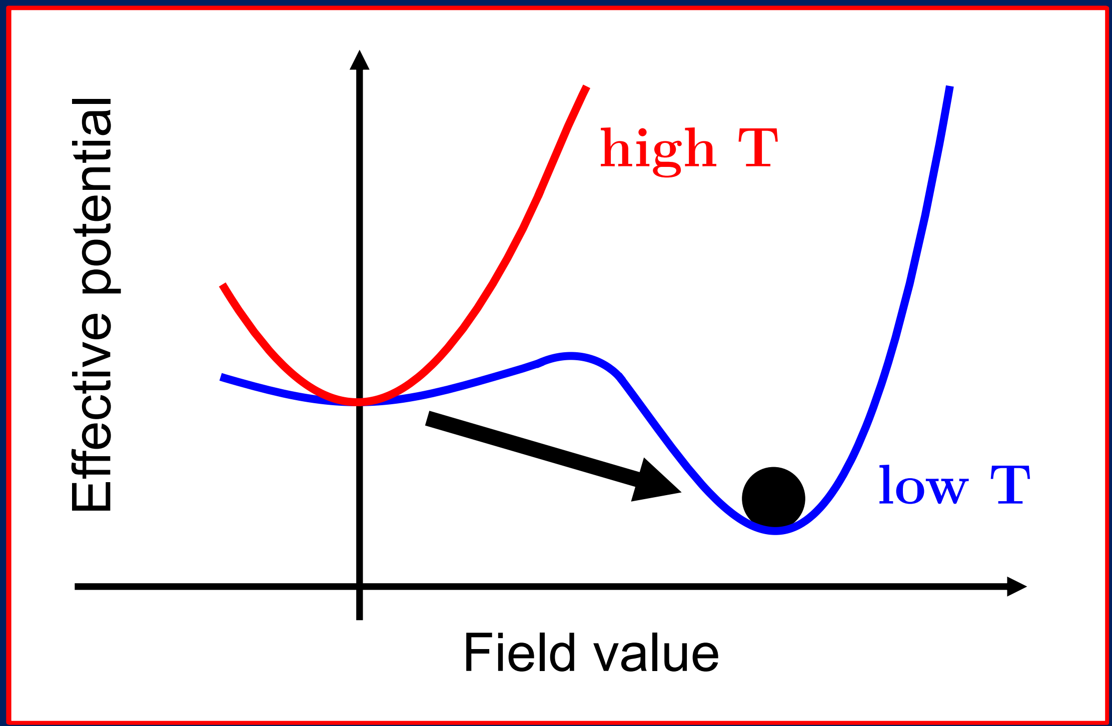
$$V_{\text{eff}}(\phi_B, T) = V_{\text{tree}}(\phi_B) + V_{\text{1-loop}}(\phi_B) + V_{\text{temp}}(\phi_B, T)$$



First order phase transition

→ **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

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

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

Relevant parameters

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

Gravitational waves from phase transition

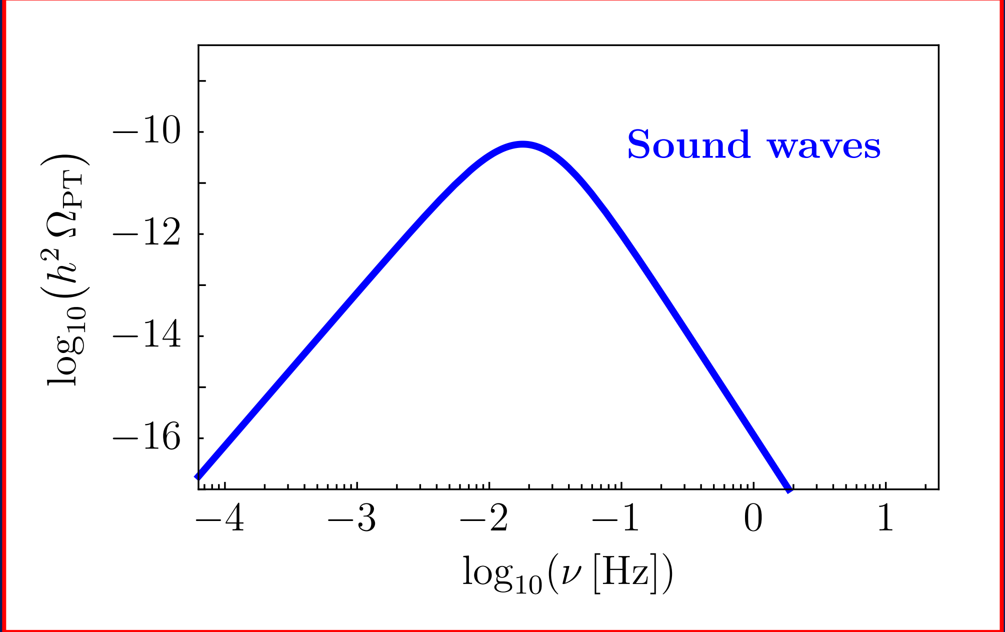
⟶ **Sound waves provide the leading contribution**

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

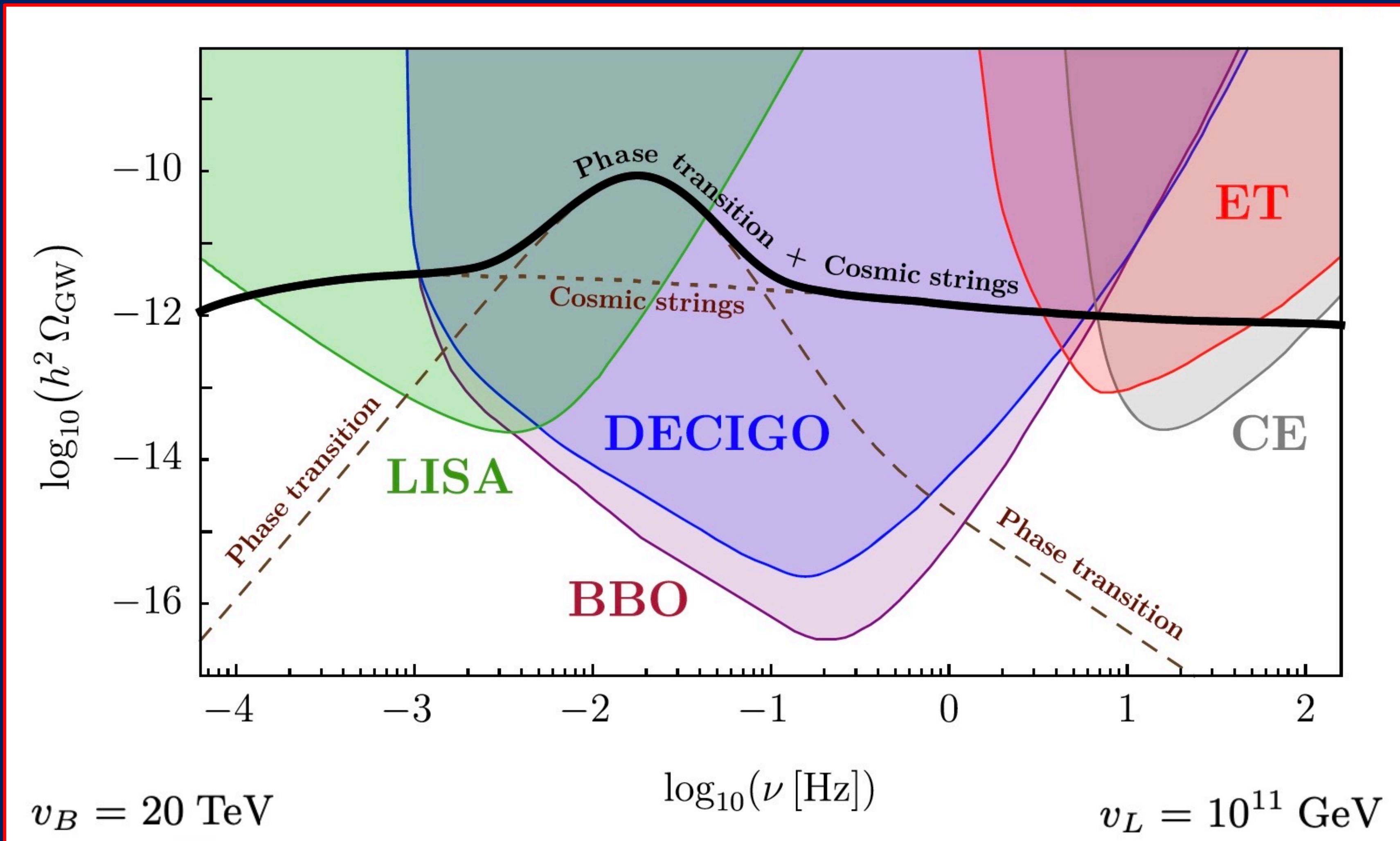
where

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

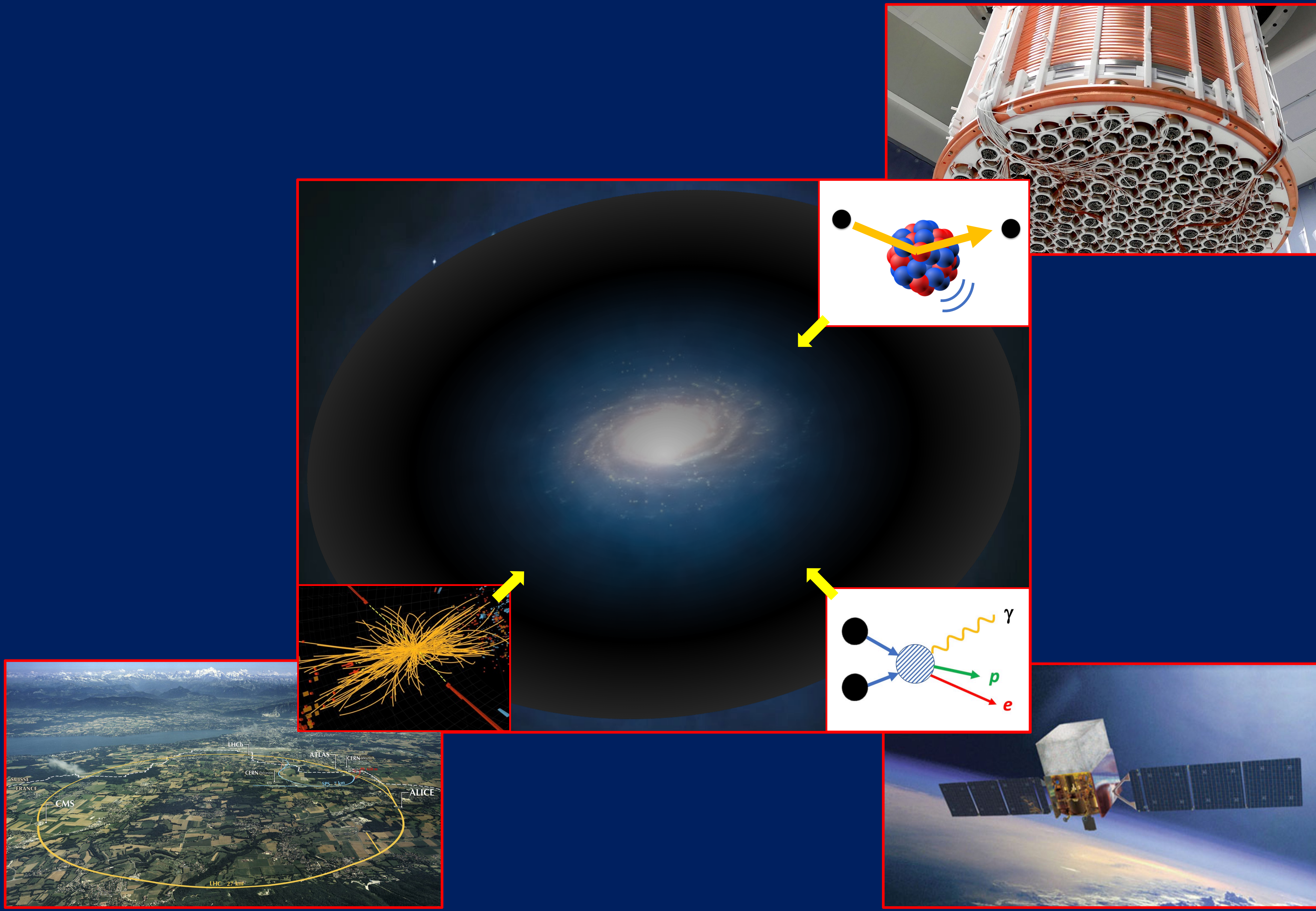
$$\nu_s \approx (1.9\times 10^{-4}\ \mathrm{Hz})\left(\frac{g_*}{100}\right)^{\frac{1}{6}}\frac{\tilde{\beta}}{v_w}\left(\frac{T_*}{1\ \mathrm{TeV}}\right)$$

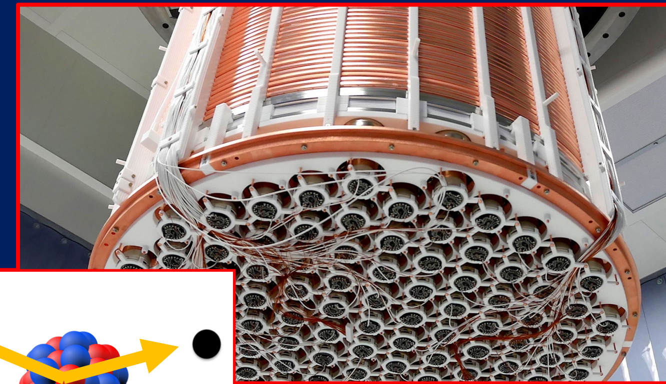


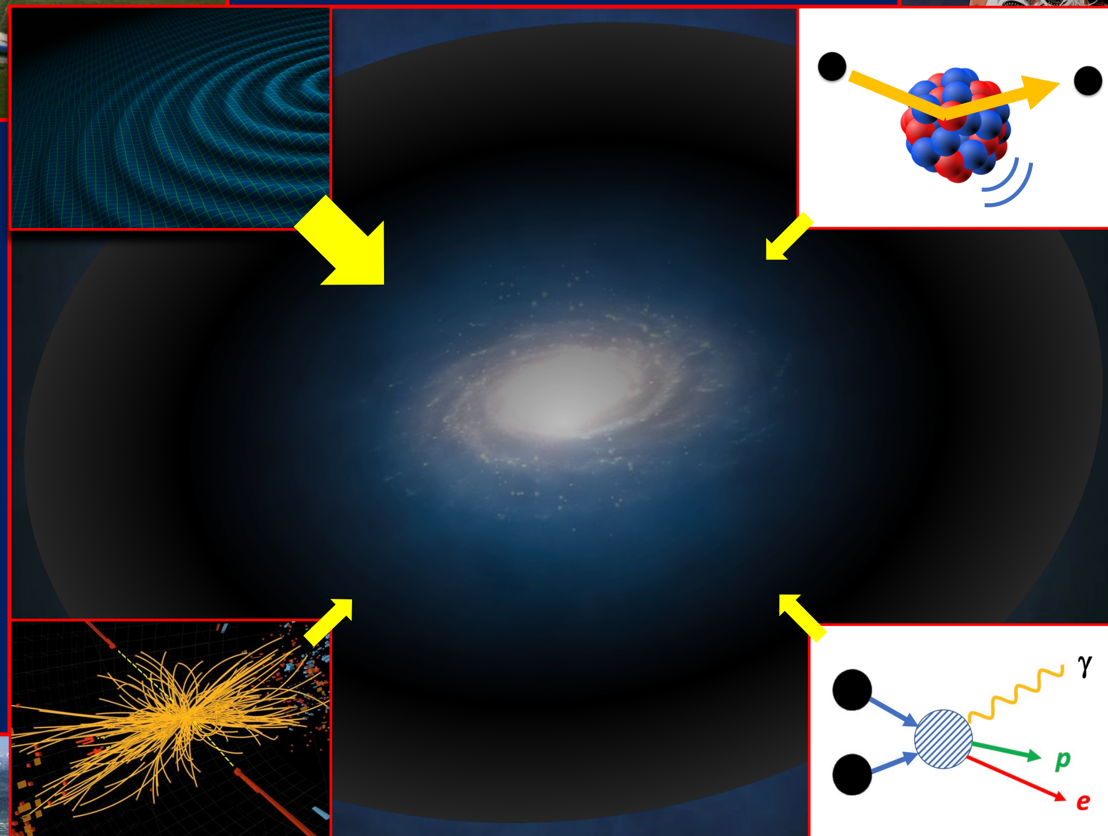
Gravitational wave signature

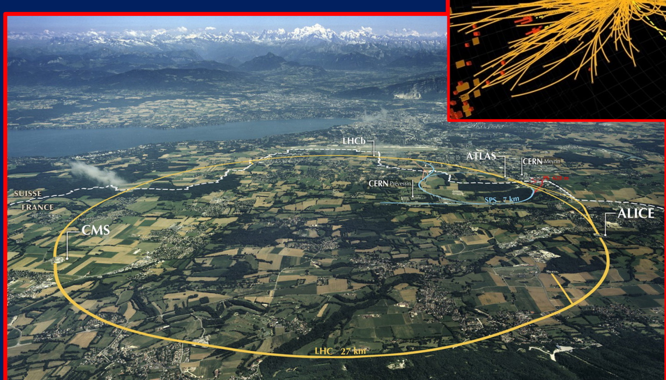


B.F. , B. Shams, PRD 102, 115037 (2020)


γ
p
e
LHCb
ATLAS
CMS
ALICE
SUISSE
FRANCE
LHC 27 km







Thank you!