Quark-hadron phase transition in the early Universe: a hot or cold universe?

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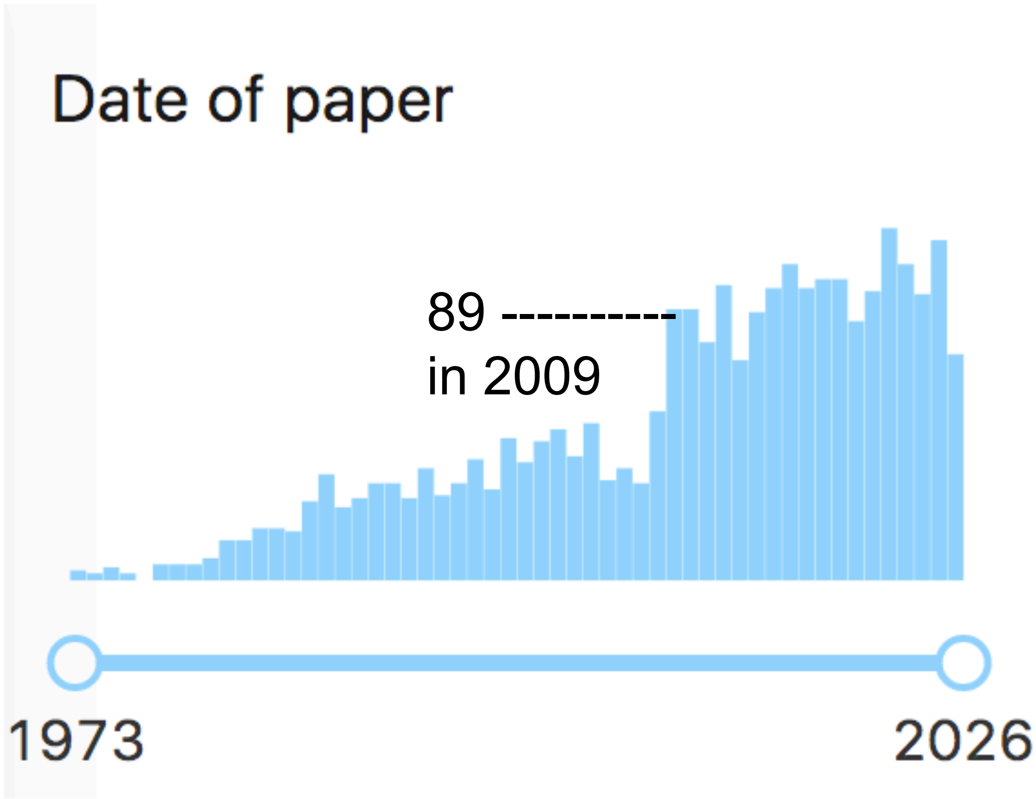
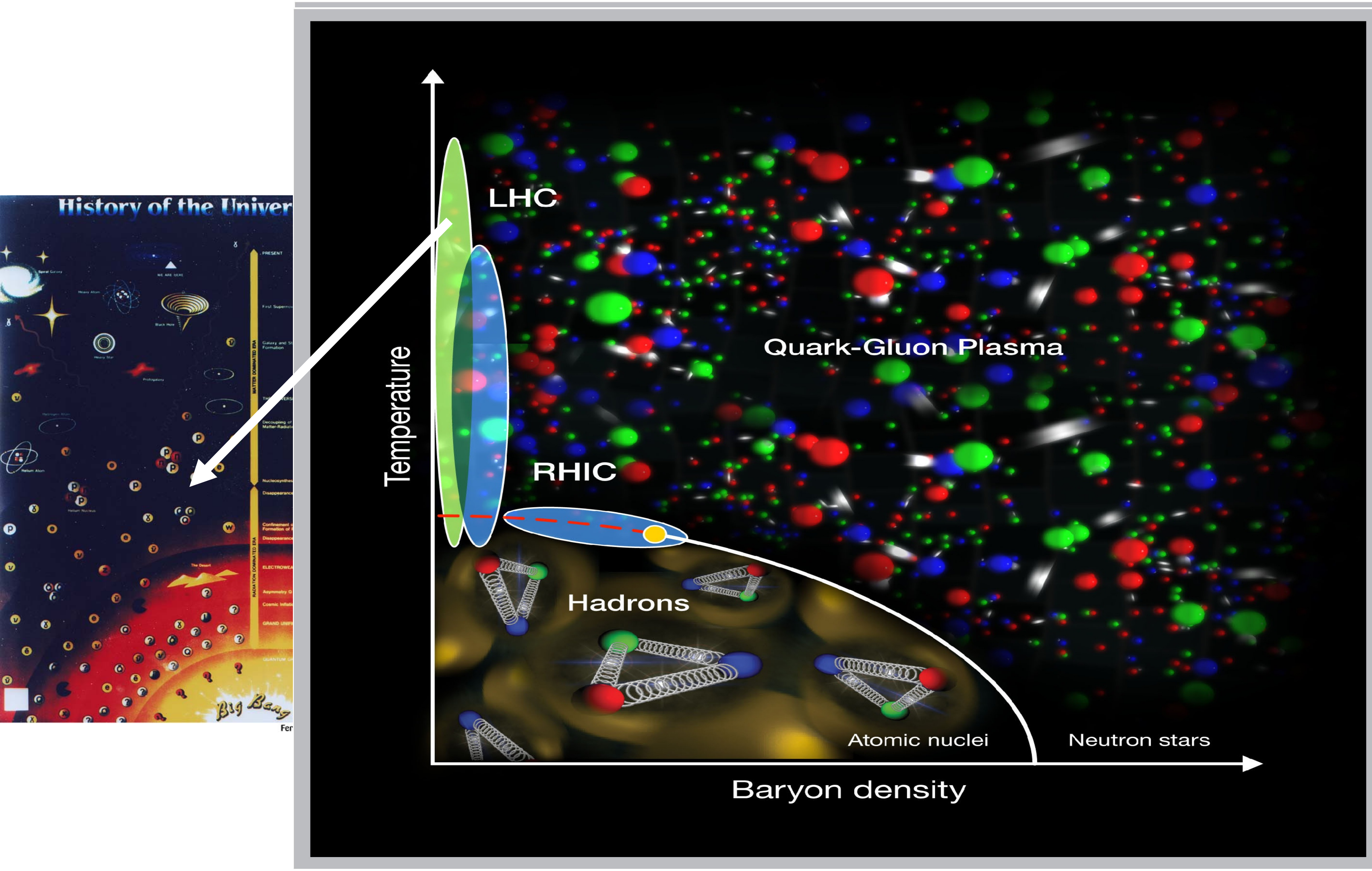
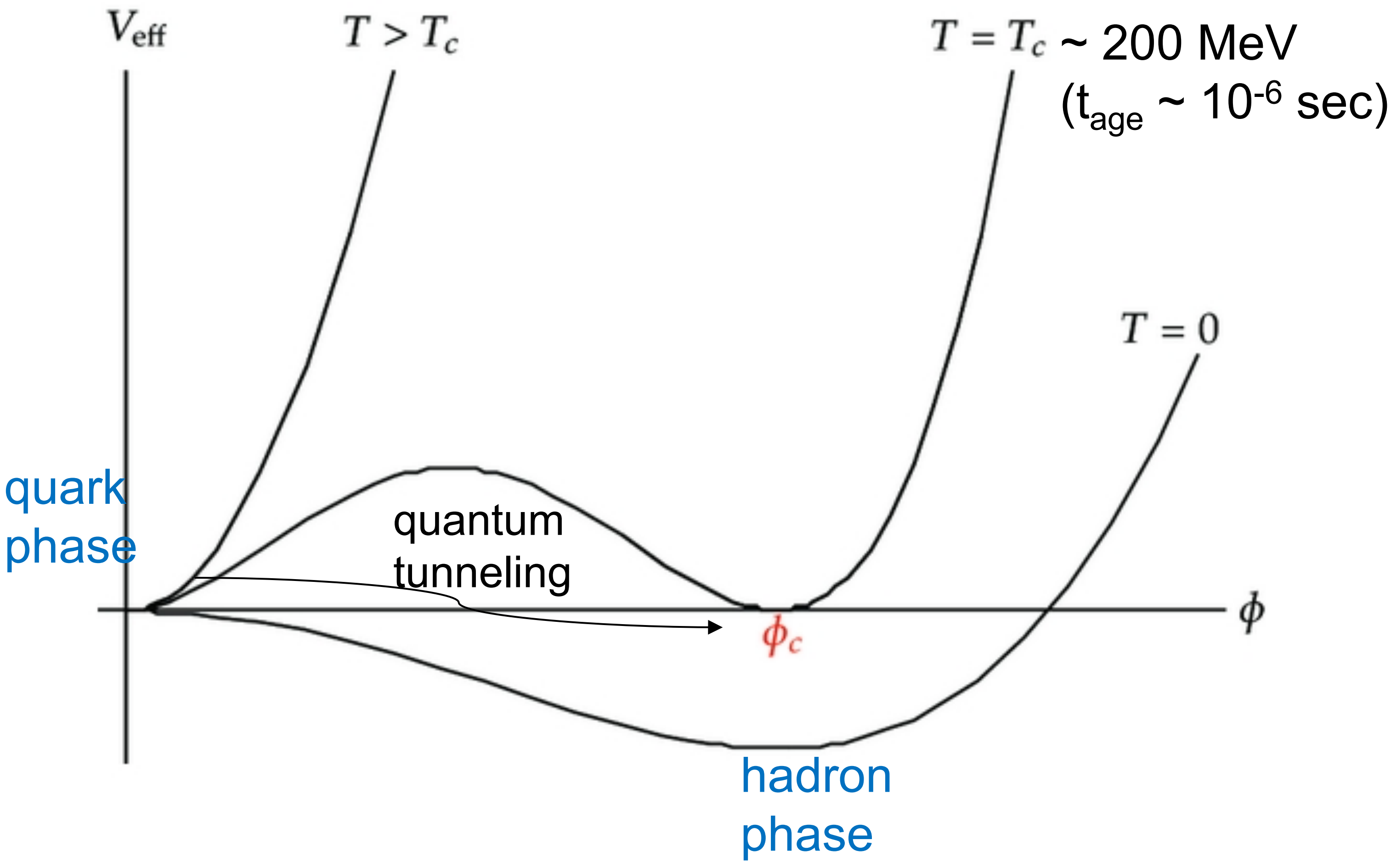


Quark-hadron phase diagram



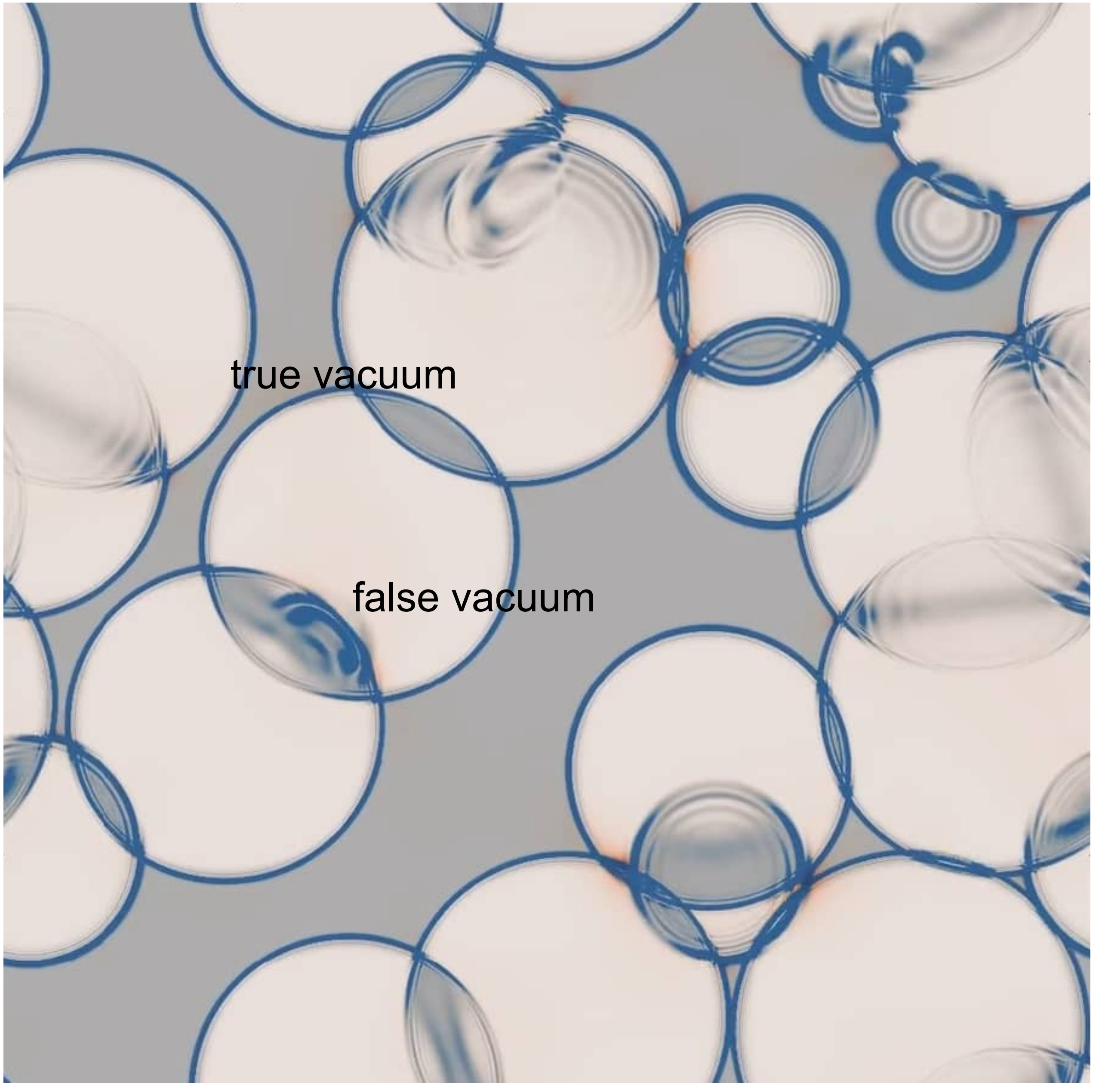
A cosmologist's wish for the quark-hadron phase transition of the early Universe

Supercooling down from very high temperature and very low baryon density, e.g. 1st order phase transition



Bubble nucleation

- Bubbles may collapse to form primordial black holes of masses about 1 $M_{\odot}$ (mass contained in a Hubble volume)
- Inhomogeneous nucleosynthesis
- Phase separation forms quark nuggets

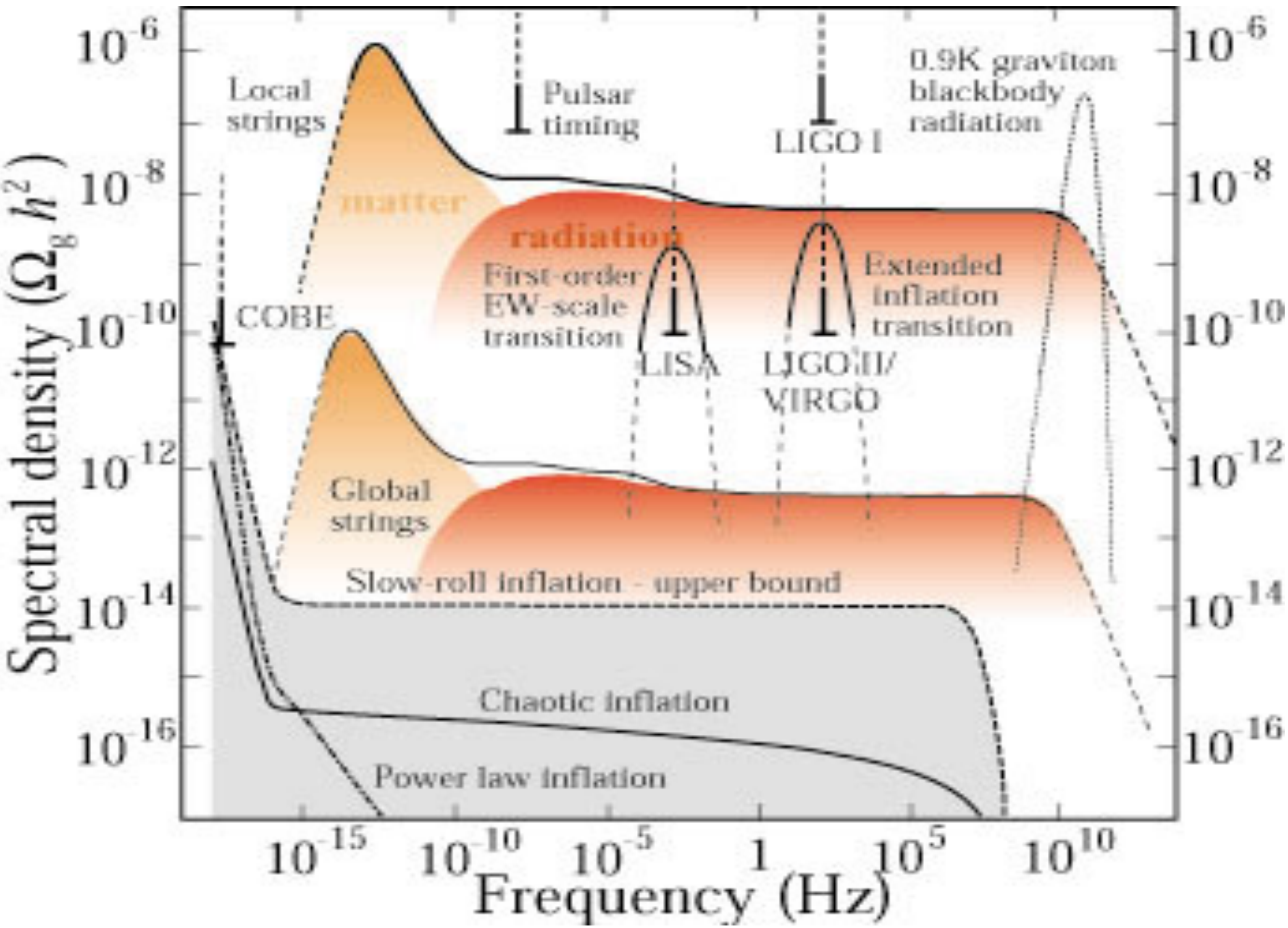


Contributions to the gravitational-wave energy spectrum

- Collisions of bubble walls and shocks in the plasma
- Sound waves in the plasma after the bubbles have collided
- Magneto-hydrodynamic (MHD) turbulence in the plasma forming after the bubbles have collided

$$h^2\Omega_{\text{GW}} \simeq h^2\Omega_\phi + h^2\Omega_{\text{sw}} + h^2\Omega_{\text{turb}}$$

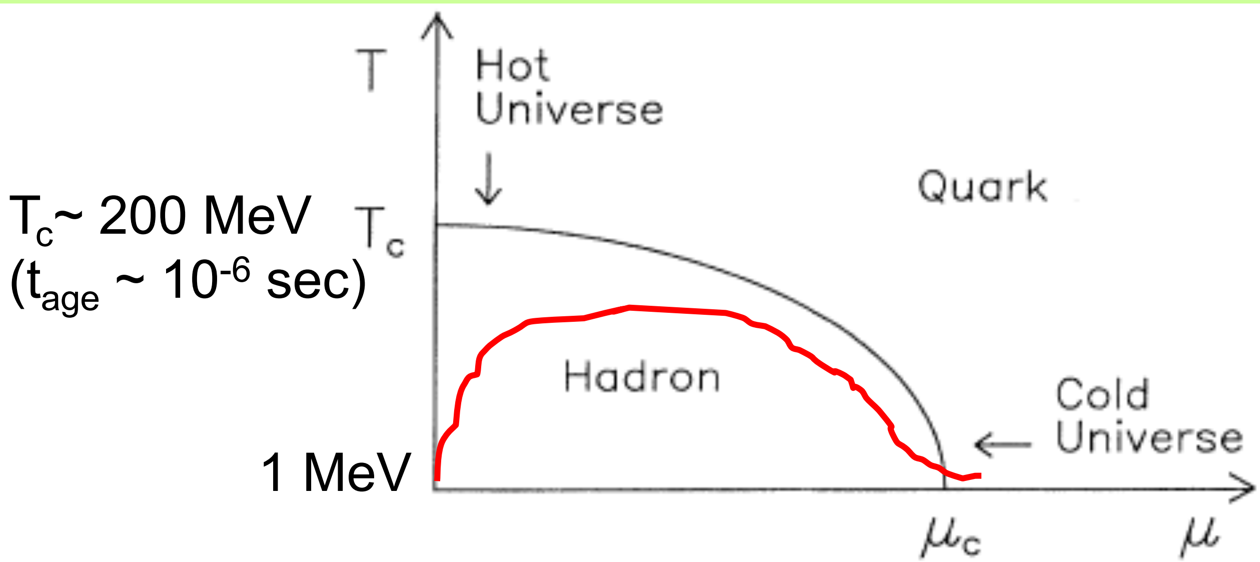
Cosmological sources for gravitational waves

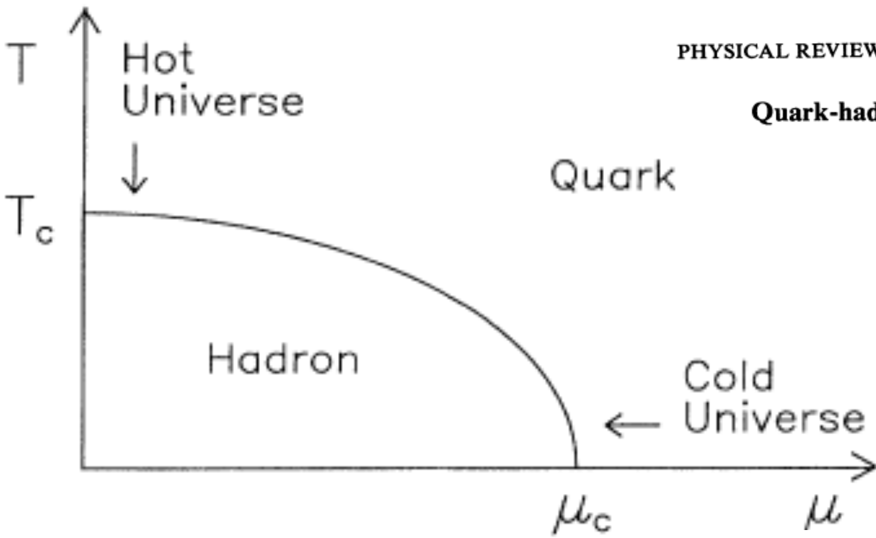


What we know about the thermal history of the early Universe

- 2.7K cosmic microwave background
- Big bang nucleosynthesis of light elements (H, He, Li) constrains $n_B/n_\gamma \sim 10^{-8}$ at about 1 MeV (10^{10} K)
- We know little at temperatures > 1 MeV

So cook up your favorite history of the early Universe >> 1 MeV !





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Quark-hadron phase transition of the early Universe in the nontopological soliton model

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Revisiting QCD-induced little inflation with chiral density wave state and its implications on pulsar timing array gravitational-wave signals

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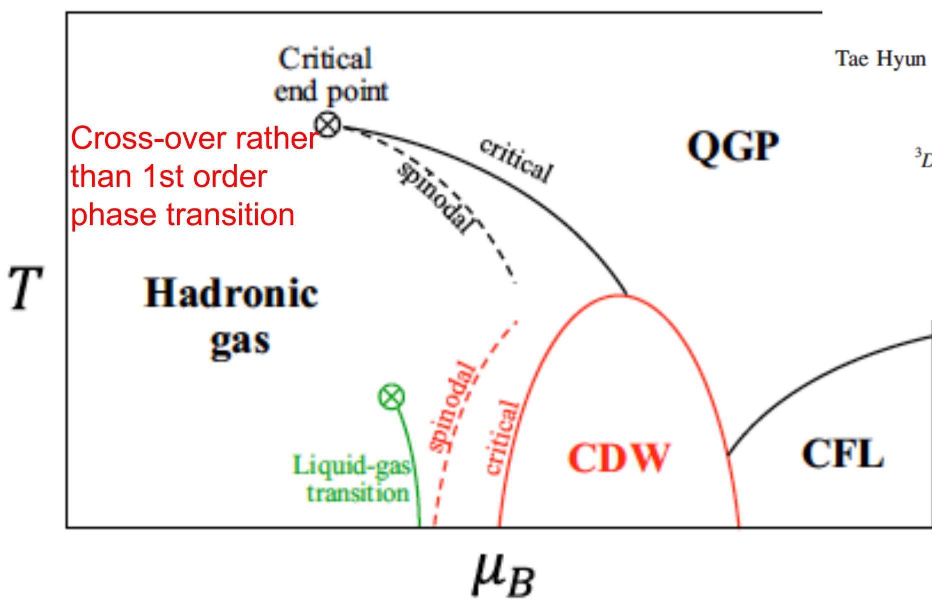

An alternative history to the early Universe?

Non-topological soliton model for quark-hadron transition

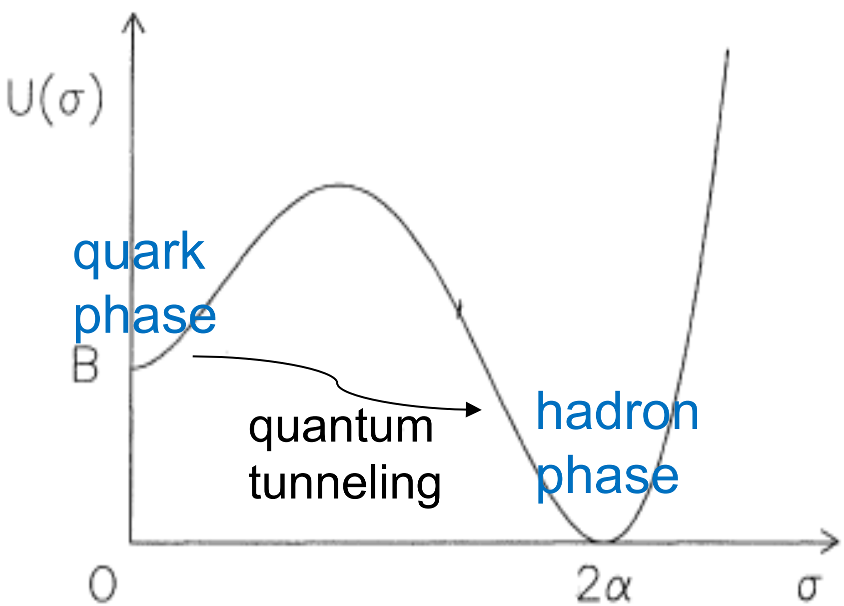

FIG. 1. Typical potential $U(\sigma)$ in the nontopological soliton model.

$$\mathcal{L} = i\sum_{i=1}^{n_F} \bar{\psi}_i \gamma^\mu \partial_\mu \psi_i + \tfrac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - U(\sigma) - \sum_{i=1}^{n_F} f\sigma \bar{\psi}_i \psi_i ,$$

$$U(\sigma) = \frac{a}{2!}\sigma^2 - \frac{b}{3!}\sigma^3 + \frac{c}{4!}\sigma^4 + B$$

B - bag constant

One-fermion-loop corrections

$$U(\sigma, T) = U(\sigma) + \frac{n_F}{12} f^2 T^2 \sigma^2$$

$$U(\sigma, \mu) = U(\sigma) + \frac{n_F}{4\pi^2} f^2 \mu^2 \sigma^2$$

A cold early universe

- Start with T~0, n_B/n_γ >> 1 (e.g. via Affleck-Dine baryogenesis in SUSY models)
- Undergo a 1st quark-hadron phase transition at high baryon density
- Reheat to T >> 1 MeV, with diluted $n_B/n_\gamma \sim 10^{-8}$ to facilitate big-bang nucleosynthesis
- Supercooling to allow the formation of primordial black holes of masses ~ 30 $M_\odot$
- Generate nanohertz gravitational waves probed by pulsar timing arrays
- Inhomogeneous nucleosynthesis
- Big quark nuggets easier to survive