Gravitational waves from pion dark matter?

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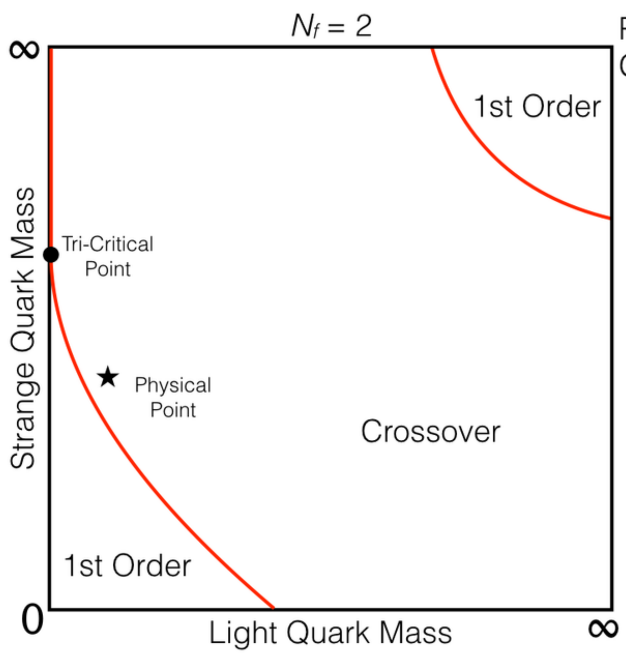
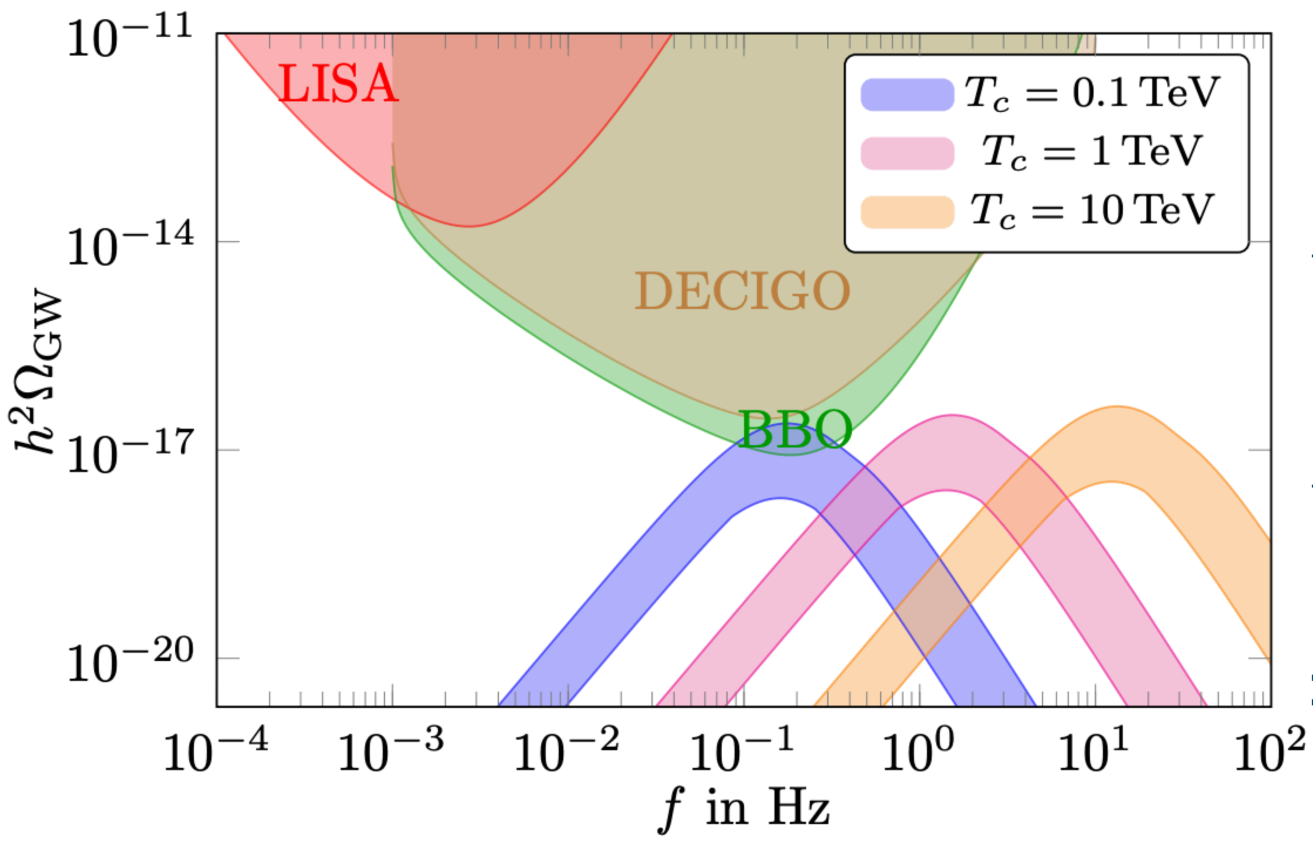
Chiral phase transition



[Sketch of the expected "Columbia Plot" from 1801.00358]

- In the Standard Model QCD, chiral phase transition is a smooth crossover. However, order of the chiral phase transition depends on the quark masses!
- First order phase transition in beyond-Standard-Model QCD-like theories?

- Lattice calculations for SU(3) gauge theory with $N_f = 3$ quark flavours were not able to find the critical pion mass up to now, for $N_f = 4$ Ref. [1] suggests that the phase transition is of first order for $m_\pi/T_c \sim m_\pi/f_\pi \lesssim 3$
- Gravitational wave signal from a chiral phase transition with massless quarks studied in [2] using PNJL model, sound waves assumed to be the main source, dark and visible sectors assumed to be thermalised



GW signal related to SU(3) gauge theory with $N_f = 3$ flavours of massless quarks in fundamental representation, reprinted from [2]

Gravitational waves from dark sectors

- For a (relatively weak) phase transition happening in a dark sector, gravitational wave signal suppressed if energy fraction in dark sector small [3]

$$\Omega_{\mathrm{GW}} h^2 \propto \left(\kappa_{\mathrm{sw}}[\alpha_{(\mathrm{tot})}]\frac{\alpha_{\mathrm{tot}}}{\alpha_{\mathrm{tot}}+1}\right)^2 \lesssim \kappa_{\mathrm{sw}}[\alpha_{(\mathrm{tot})}]^2\left(\frac{\rho_D}{\rho_{\mathrm{tot}}}\right)^2$$

where

$$\alpha = \frac{V_0}{\rho_D - V_0}, \qquad \alpha_{\mathrm{tot}} = \frac{V_0}{\rho_{\mathrm{tot}} - V_0}$$

and V_0 is the vacuum energy released in the phase transition

- The efficiency coefficient κ_{sw} determines what fraction of the vacuum energy is transferred to the fluid motion, e.g., $\kappa_{\mathrm{sw}} \propto \alpha_{(\mathrm{tot})}$ for relativistic bubble walls. It depends on α if the dark sector is decoupled or on α_{tot} if the dark sector forms single fluid with the Standard Model plasma.

NB: For correct prediction of the GW signal, it should be checked if the dark and visible sectors form a single fluid or not!

References

[1] H. Ohno, Y. Kuramashi, Y. Nakamura, and S. Takeda, "Continuum extrapolation of the critical endpoint in 4-flavor QCD with Wilson-Clover fermions", PoS **LATTICE2018** (2018) 174, arXiv:1812.01318 [hep-lat].

[2] M. Reichert, F. Sannino, Z.-W. Wang, and C. Zhang, "Dark confinement and chiral phase transitions: gravitational waves vs matter representations", JHEP **01** (2022) 003, arXiv:2109.11552 [hep-ph].

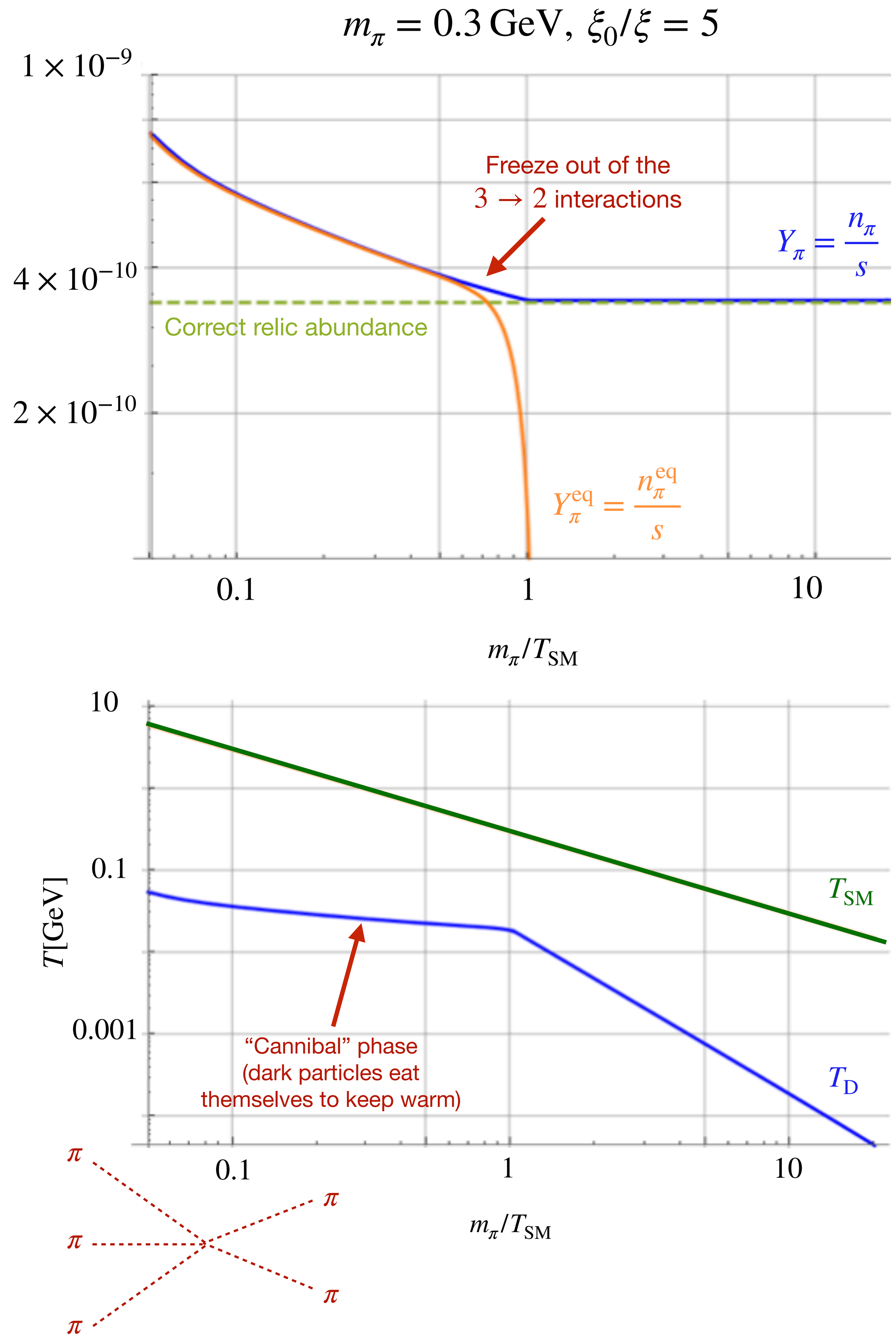
[3] M. Breitbach, J. Kopp, E. Madge, T. Opferkuch, and P. Schwaller, "Dark, Cold, and Noisy: Constraining Secluded Hidden Sectors with Gravitational Waves", JCAP **07** (2019) 007, arXiv:1811.11175 [hep-ph].

[4] Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, and J. G. Wacker, "Model for Thermal Relic Dark Matter of Strongly Interacting Massive Particles", Phys. Rev. Lett. **115** no. 2, (2015) 021301, arXiv:1411.3727 [hep-ph].

[5] M. Heikinheimo, K. Tuominen, and K. Langæble, "Hidden strongly interacting massive particles", Phys. Rev. D **97** no. 9, (2018) 095040, arXiv:1803.07518 [hep-ph].

Strongly interacting massive particles (SIMP)

- Dark matter abundance set by 3→2 interactions among pions (due to chiral anomaly ⇔ Wess-Zumino-Witten term in Chiral Perturbation Theory) [4]
- If dark sector and SM temperatures equal: $T_D = T_{\mathrm{SM}}$, large m_π/f_π needed for correct relic abundance ⇒ no first order phase transition. On the other hand, low m_π/f_π achievable for **secluded SIMP dark dark sector** [5]!
- Entropy ratio in the visible and dark sectors $\xi = S_{\mathrm{SM}}/S_D$, $\xi \propto (T_{\mathrm{SM}}/T_D)^3$ for relativistic particles. Convenient normalization: $\xi_0/\xi \sim (2\times 10^8/\xi) \times m_\pi/(0.3\,\mathrm{GeV})$. For $\xi_0/\xi \lesssim 2$, dark matter freezes out when still relativistic.
- Boltzmann equations solved to obtain the evolution of the dark matter density and the dark sector temperature. Non-relativistic dark sector with number-changing processes cools down much slower in the "secluded" case!



- Unfortunately, $T_D = T_c \sim f_\pi$ achieved when the dark pions are still relativistic ⇒ $T_D \ll T_{\mathrm{SM}}$ at the phase transition, $\rho_D/\rho_{\mathrm{tot}} \propto (T_D/T_{\mathrm{SM}})^4$ ⇒ very suppressed gravitational wave signal ☹