Pulsar timing signals from an innverse phase transition in the early Universe

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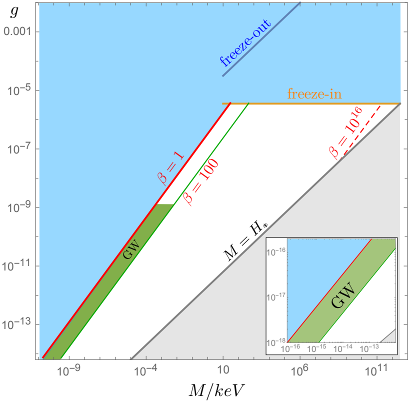

Based on the papers
2004.03410, 2104.13722, 2112.12608, 2307.04582
with Evgeny Babichev, Sabir Ramazanov, Rome Samanta and Alex Vikman

2105.05208

$$\beta \equiv \lambda/g^4$$

$$V = \frac{1}{2}M^2X^2 + \frac{\lambda}{4}X^4 - \frac{g^2T^2}{12}X^2$$

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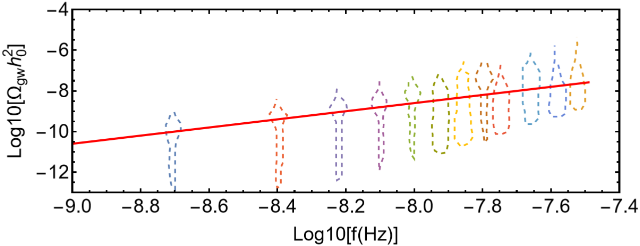
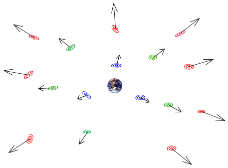
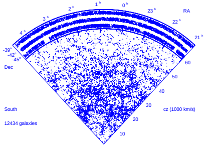


Conclusions from observations

The Universe is homogeneous, isotropic, hot and expanding...





Conclusions

- interval between events gets modified

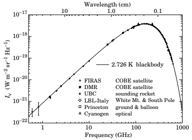
$$\Delta s^2 = c^2 \Delta t^2 - a^2(t)\,\Delta \mathbf{x}^2$$

in GR expansion is described by the Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \dots$$

- in the past the matter density was higher, our Universe was “hotter” filled with electromagnetic plasma



$$\rho_{\text{matter}} \propto 1/a^3(t), \quad \rho_{\text{radiation}} \propto 1/a^4(t), \quad \rho_{\text{curvature}} \propto 1/a^2(t)$$

certainly known up to $T \sim 1\,\text{MeV} \sim 10^{10}$ K

Microscopic processes in the expanding Universe

A competition between scattering, decays, etc and expansion

for general processes one should solve kinetic equations

$$\frac{dn_{X_i}}{dt} + 3Hn_{X_i} = \sum(production - destruction)$$

Boltzmann equation in a comoving volume: $\frac{d}{dt}\left(n\,a^3\right) = a^3 \int \dots$

production:

$$\sigma(A+B \to X+C)n_A n_B, \quad \Gamma(D \to E+X)n_D \cdot M_D/E_D, \quad \text{etc}$$

desrtuction:

$$\sigma(A+X \to C+B)n_A n_X, \quad \Gamma(X \to F+G)n_X \cdot M_X/E_X, \quad \text{etc}$$

Fast direct and inverse processes, $\Gamma \gtrsim H$, are in equilibrium,

$\sum(\ \ ) = 0$ and thermalize particles

Known decoupled components

- relic photons froom recombination, CMB

  (before reionisation)
- primnordial elements from BBN

  (far from stellar nucleosyntesis)
- relic neutrinos

  (only indirect emasurements)
- Dark Matter

  (no registration so far)
- relic Gravitational waves

  (never in equilibrium)

Dark Matter Properties $p = 0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

If were in thermal equilibrium: $M_X \gtrsim 1$ keV

If not: for bosons

$\lambda = 2\pi/(M_X v_X)$, in a galaxy $v_X \sim 0.5 \cdot 10^{-3} \longrightarrow M_X \gtrsim 3 \cdot 10^{-22}$ eV

for fermions

Pauli blocking: $M_X \gtrsim 750$ eV

$$f(\mathbf{p}, \mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}} \Bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

Dark Matter: many well-motivated candidates

WIMPs	related to EW scale, SUSY
sterile neutrinos	active neutrino oscillations
light scalar field	string theory
axion	strong CP-problem
gravitino	local SUSY
Heavy relics	GUTs
(Topological) defects	GUTs
Massive Astrophysical Compact Heavy Objects	
Primordial black hole (remnants)	Phase transitions exotic inflation, reheating

Multicomponent Dark Matter ?

γ, ν, H, He

A simple example of scalar DM

most general renormalizable coupled to SM:

Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu X\partial_\nu X - \frac{1}{2}M^2X^2 + g^2X^2\Phi^\dagger\Phi - \frac{\lambda}{4}X^4$$

Options:

- freeze-out: sufficiently large g^2

$$\sigma_{hh\to XX}\times n_h \gtrsim H \;\; \to \;\; \sigma_{XX\to\dots} = \sigma_0, \;\; \text{e.g.} \;\; \frac{g^4}{(4\pi\dots)^2M^2} = \sigma_0$$

- freeze-in: intermediate g^2

$$\dot{n}_X + 3Hn_X = \sigma_{hh\to XX}n_h^2 \;\; \to \;\; \frac{n_X}{s} = \#\int dT\frac{n_h^2}{sHT}\times\frac{g^4}{T^2} \sim g^4\frac{M_{Pl}}{M} \;\; \to$$

$\Omega_X \propto g^4 \;\; \to \;\; g^2 \approx 10^{-11}$ still natural...

DM from oscillating scalar

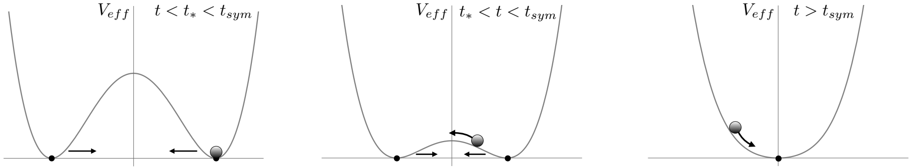
$0 \neq g^2 < 10^{-11}$ $\quad$ Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu X \partial_\nu X - \frac{1}{2}M^2X^2 + g^2X^2\Phi^\dagger\Phi - \frac{\lambda}{4}X^4$$

Higgs particles in plasma change the potential:

$$g^2X^2\Phi^\dagger\Phi \;\rightarrow\; g^2X^2T^2/3$$

Z_2 symmerty is broken after reheating by the plasma contribution



2004.03410

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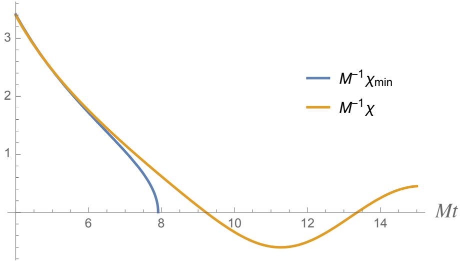
X starts from the false vacuum



at $g^2T_*^2 \simeq M^2$ sign changes
and X starts to oscillate
gravitational misalignment

$$\rho_{DM}(t_*) = \frac{M^2\cdot S_*^2}{2} \simeq \frac{\left(M^5H_*\right)^{2/3}}{4\lambda}$$

And the correct amount of DM by classical oscillating field $\quad p = \langle E_{kin}\rangle - \langle E_p\rangle = 0$

$$g^2 \simeq 10^{-12}\times\left(\frac{\lambda}{10^{-6}}\right)^{6/5}\times\left(\frac{10^6\,\text{GeV}}{M}\right)^2$$

Dark Matter

with general setup:

white area

$$\beta \equiv \lambda / g^4 < 1$$

$$V = \frac{1}{2} M^2 X^2 + \frac{\lambda}{4} X^4 - \frac{g^2 T^2}{12} X^2$$

The inverse phase transition may be accompanied by the production of GW

strong enough to be

detected by the present or

next genertation

experiments

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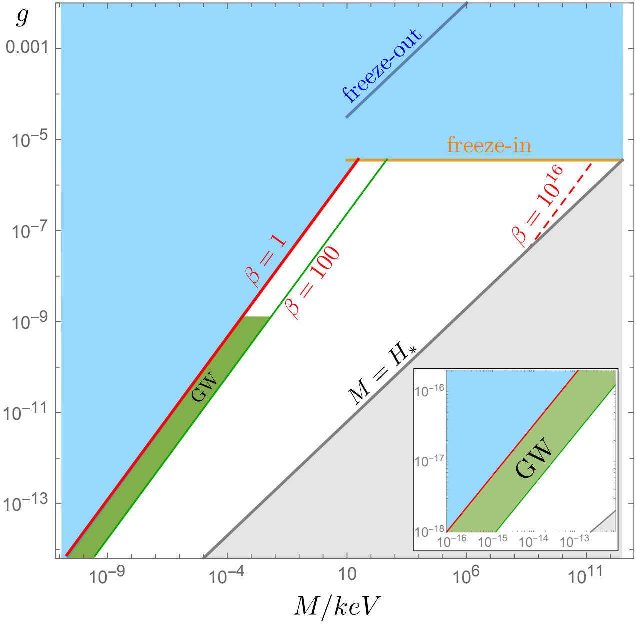

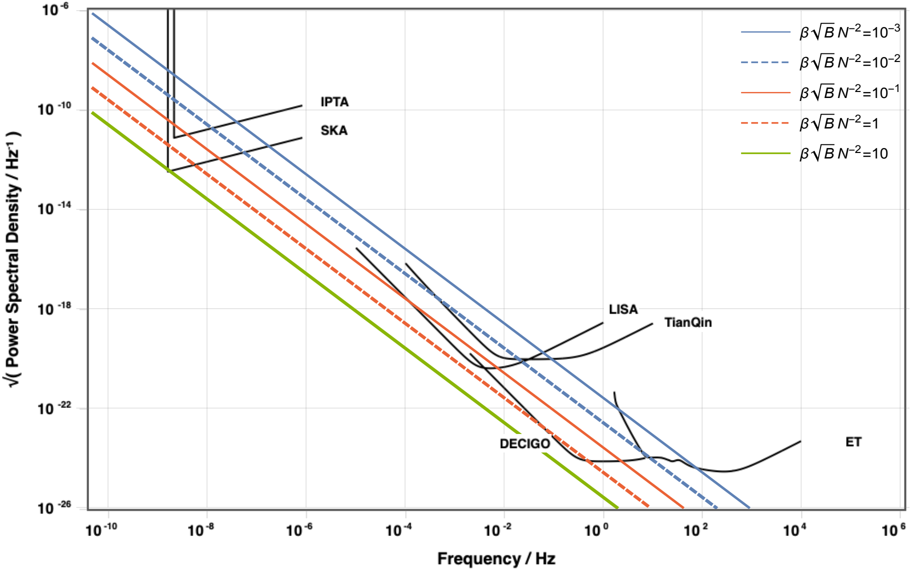

strain: $\Omega_{GW} H_0^2 \equiv 2\pi^2 f^3 S/3$

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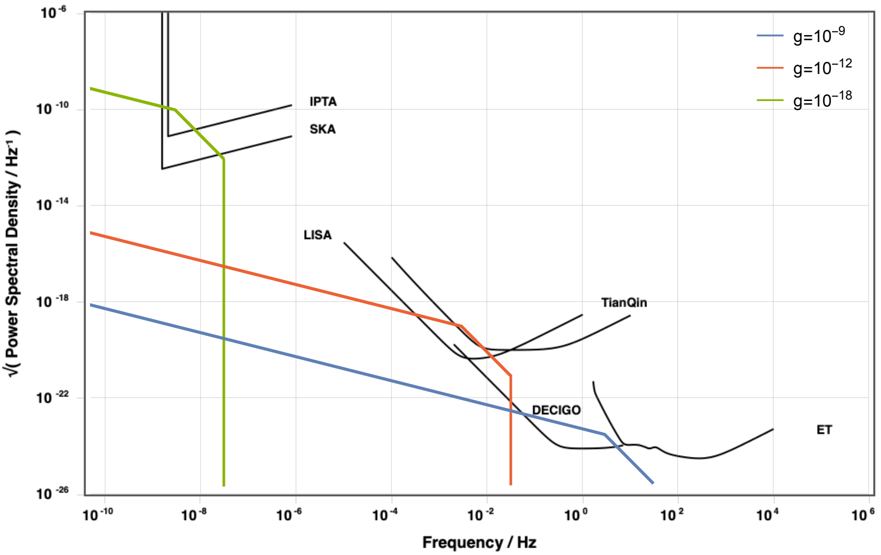

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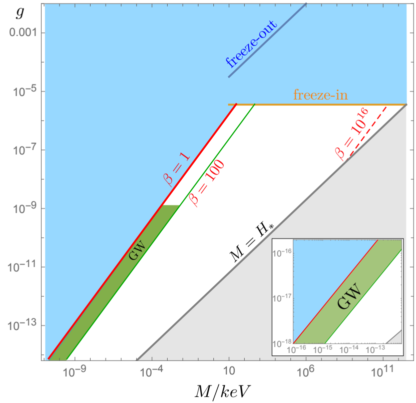

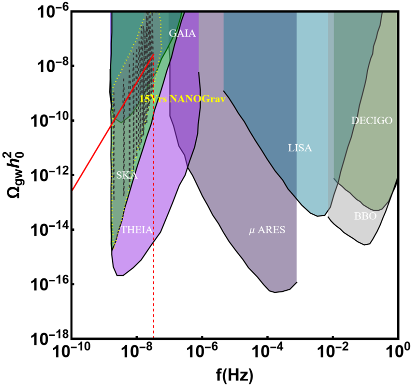

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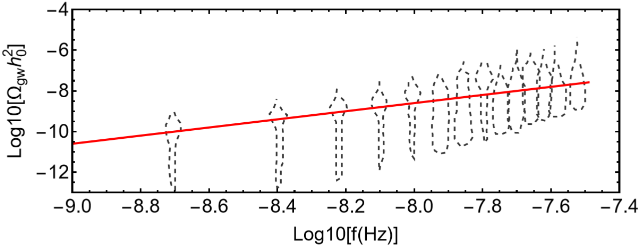

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Conclusion

- What NANOGrav and others observe might be explained by the GW from melting domain walls
- they are expected in models with inverse phase transition
- which may induce light scalar dark matter production
- In realistic models it's mass is of order 10^{-16}-10^{-12} eV
- That predicts super-radiance instability of rotating black holes with astrophysical masses

see e.g. 0905.4720