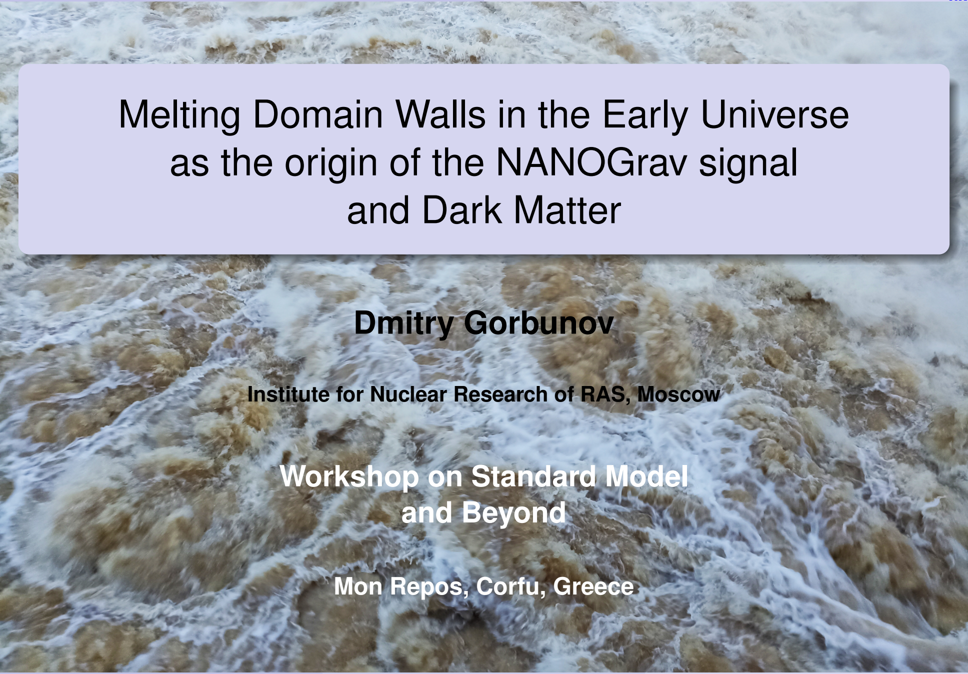

Melting Domain Walls in the Early Universe as the origin of the NANOGrav signal and Dark Matter

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Workshop on Standard Model and Beyond

Mon Repos, Corfu, Greece

Dark Matter Properties $p = 0$

(If) particles:

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

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

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

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

Freeze-out of nonrelativistic Dark Matter

Assumptions:

1. no $X - \bar{X}$ asymmetry — either $X = \bar{X}$ or $n_X = n_{\bar{X}}$
2. @ $T \lesssim M_X$ in thermal equilibrium with plasma — (e.g. neutrons)

$$n_X = n_{\bar{X}} = g_X \left(\frac{M_X T}{2\pi} \right)^{3/2} \mathrm{e}^{-M_X/T}$$

$$X\bar{X} \longrightarrow \text{light particles}$$

freeze-out temperature T_f $\qquad H \equiv T^2/M_{Pl}^*, \quad M_{Pl}^* = M_{Pl}/1.66\sqrt{g_*}$

$$n_X \langle \sigma_{ann} v \rangle = H(T_f) \longrightarrow T_f = \frac{M_X}{\ln\left(\frac{g_X M_X M_{Pl}^* \sigma_0}{(2\pi)^{3/2}} \right)} \,.$$

Bethe formula: $\qquad$ s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

Weakly Interacting Massive Particles

density after freeze-out: $$n_X(T_f) = \frac{T_f^2}{M_{Pl}^* \sigma_0}$$

present density: $$n_X(T_0) = \left(\frac{a(T_f)}{a(T_0)}\right)^3 n_X(T_f) = \left(\frac{s_0}{s(T_f)}\right) n_X(T_f) \propto \frac{1}{T_f}$$

$X + \bar{X}$ contribution to critical density:

$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} = 7.6\frac{s_0 \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl}\sqrt{g_*(T_f)}}$$

$$= 0.1 \cdot \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0}\right) \frac{10}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

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

$$v\sigma_{XX\to hh}\times n_h \sim H \;\to\; \Omega_X \propto \frac{1}{\sigma_0},\;\text{with}\; \frac{g^4}{(4\pi\ldots)^2M^2} = \sigma_0 \equiv \sigma v$$

- 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...

Freeze in via gravitational scatterings..?

any particles A in plasma

$$\sigma_{AA\to XX} \propto \frac{T^2}{M_{Pl}^4} \;\to\; \Omega_X \propto M_X \frac{T_i^3}{M_{Pl}^3}\dots$$

assuming $m \ll T_i$

called “unnatural” being dependent on the initial conditions

Free massive scalar field $g^2 = 0$

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m_\phi^2 \phi^2$$

Homogeneous scalar field in the expanding Universe

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

Two-stage evolution:

$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$

$$m_\phi > H(t) \quad \Longrightarrow \quad p = \langle E_k \rangle - \langle E_p \rangle = 0\,, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

- dust-like substance in the late Universe, $\Omega \propto m_\phi^{1/2} \phi_i^2$

depends on initial conditions

fuzzy DM

DM from oscillating scalar

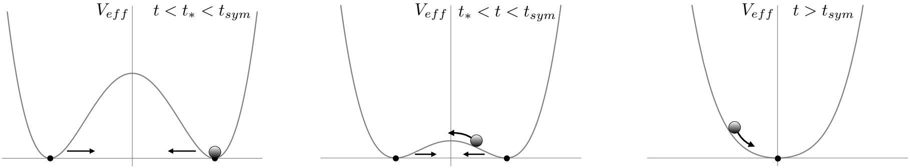
$0 \neq g^2 < 10^{-11}$ Z_2-invariant Higgs (Φ) portal

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

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

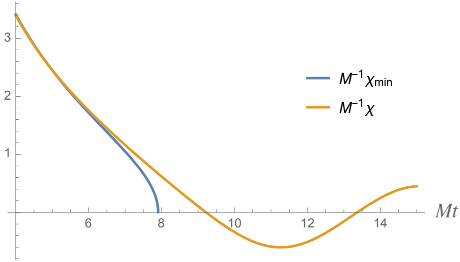


Temperature decrease restores Z_2

2004.03410

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu X\partial_\nu X - \frac{1}{2}M^2X^2 + g^2X^2T^2/3 - \frac{\lambda}{4}X^4$$

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

$$p = \langle E_{kin}\rangle - \langle E_p\rangle = 0$$

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

Dark Matter

with general setup:

white area

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

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

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

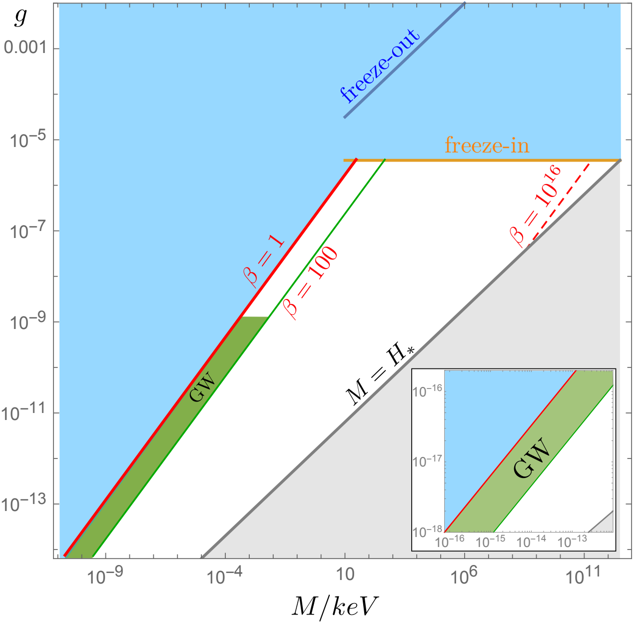
strong enough to be

detected by the present or

next genertation

experiments

2104.13722



GW signals from dissipating DWs ...

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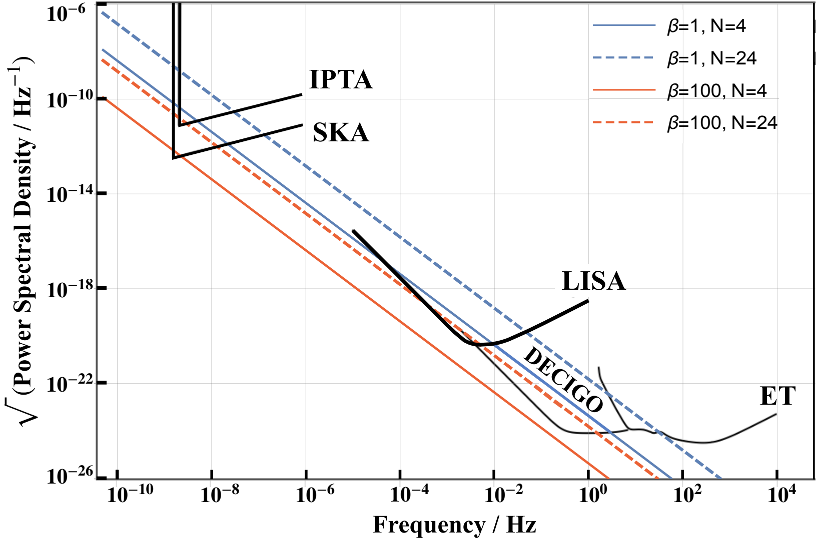
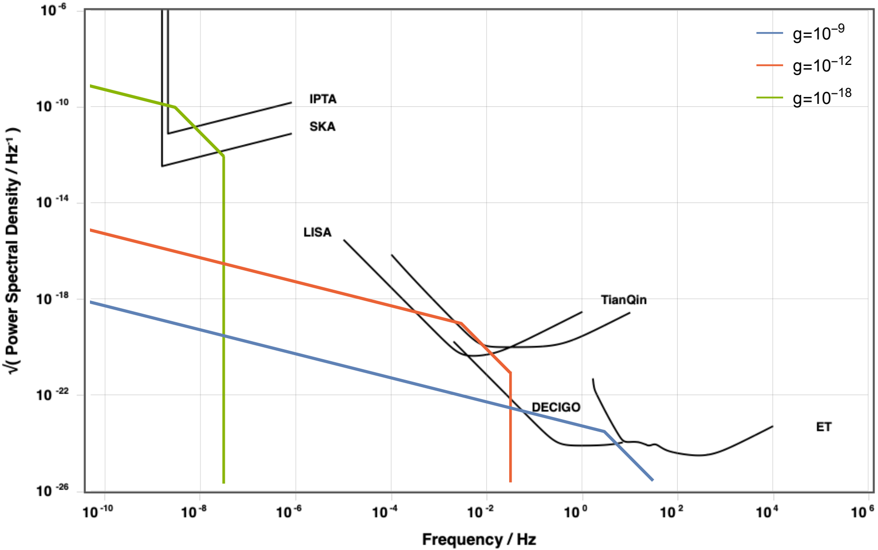




strain: $\Omega_{GW} H_0^2 \equiv 2\pi^2 f^3 S/3$

2104.13722

Analog of a well-known effect in CMB: by Rubakov, Sazhin and Veryaskin

From linear approximation to the geodesic equation. . .

for tensor perturbations

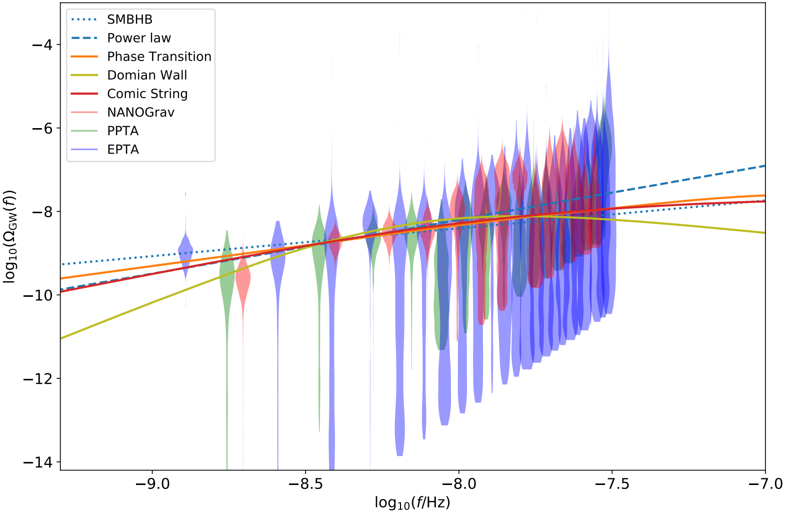
$$\frac{\delta T}{T}(\mathbf{n},\eta_0) = \frac{1}{2}\int_{\eta_r}^{\eta_0} d\eta\, n_i h_{ij}^{TT\,\prime} n_j\,,$$

strongest limit on primordial GW and Inflation scale:

$$h_{init} \sim H_{inf}/M_{Pl} \propto \sqrt{\rho_{infl}}$$

Pulsar frequencies are different but stable, and we observe its' time variantion

NANOGrav, T. Klein

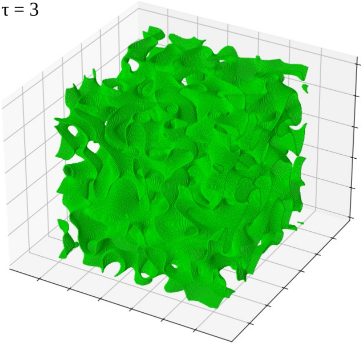


$$\Omega_{GW}h^2 = 6.3\cdot 10^{-10}\,A^2\left(\frac{f}{\mathrm{yr}^{-1}}\right)^d,\quad A=\{6.4^{+4.2}_{-2.7},\,2.9^{+2.6}_{-1.8},\,3.1^{+1.3}_{-0.9}\},\quad d=\{1.8\pm 0.6,\,0.81^{+0.63}_{-0.73},\,1.1\pm 0.4\}$$

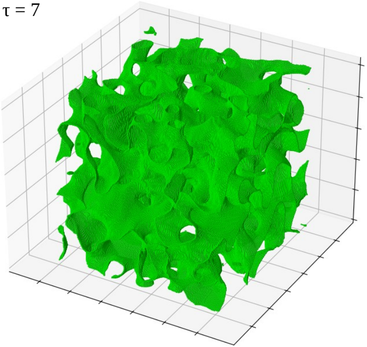
2307.03141, 2406.02288

2406.17053

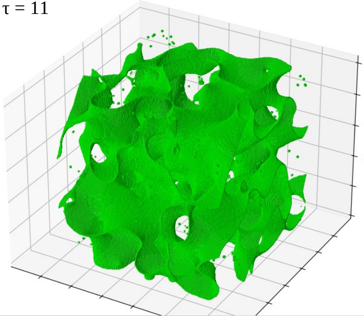
τ = 3



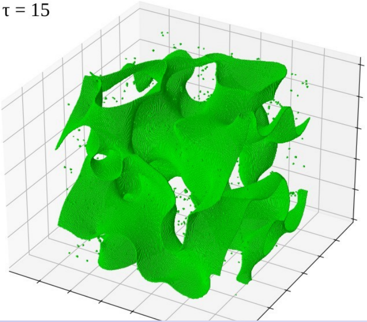
τ = 7



τ = 11

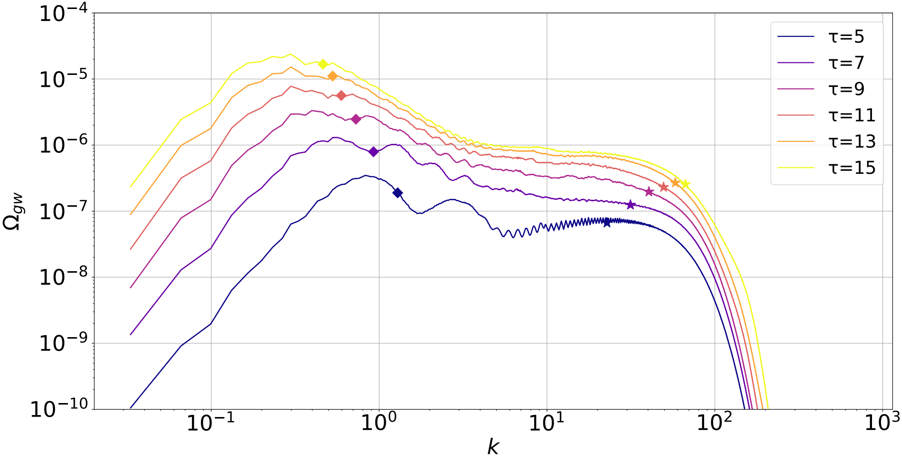


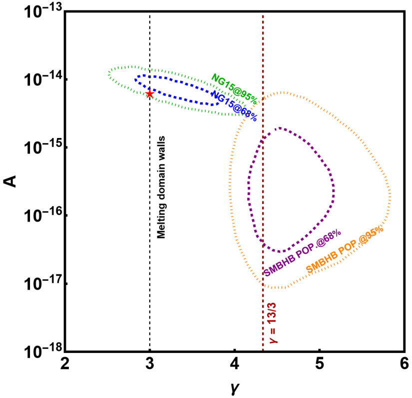
τ = 15

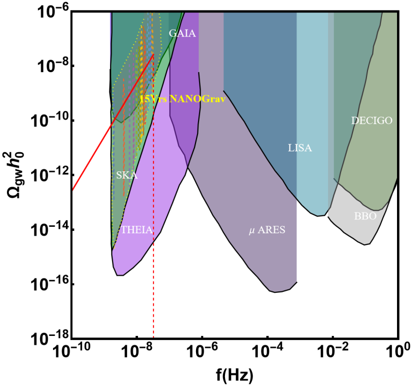


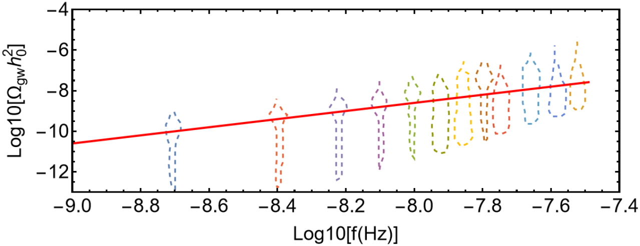
GW spectra: simulation with CosmoLattice

2406.17053



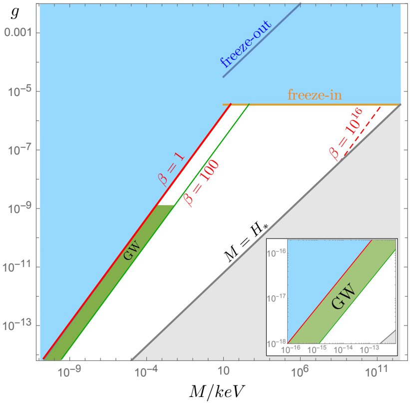


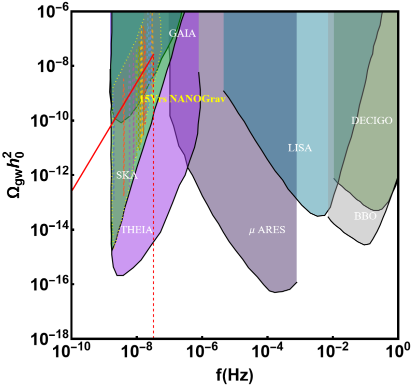




$$\gamma \equiv d+1$$

2307.04582



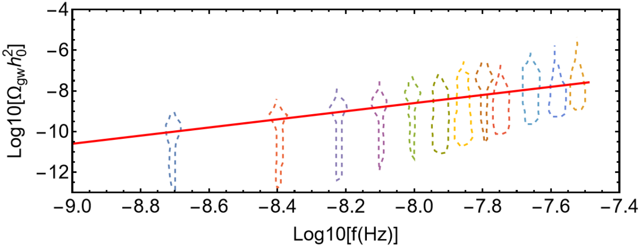


2104.13722

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

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

2307.04582



Conclusion

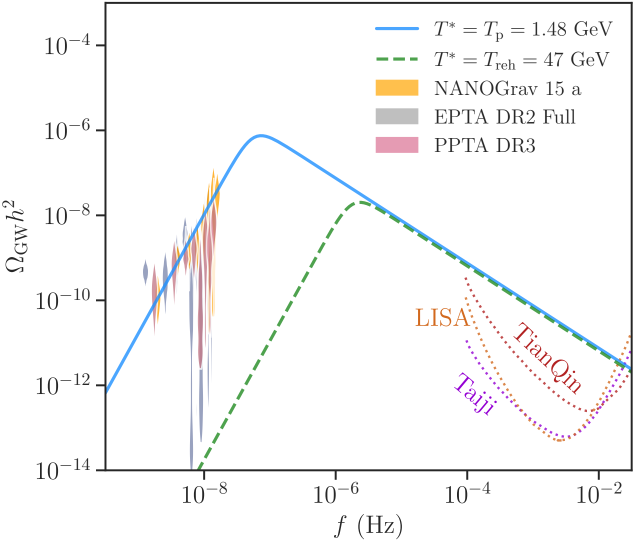
- What NANOGrav and others observe might be explained by the GW from melting domain walls
- they are expected in models with inverse phase transition
- which may induce light scalar dark matter production
- In realistic models its mass is of order 10^{-15}-10^{-11} eV
- That predicts super-radiance instability of rotating black holes with astrophysical masses 10-$10^5\,M_\odot$ see e.g. 0905.4720
  Might explain why the BH in binary system are not with $J \approx 1$

Large based on the results from
2004.03410, 2104.13722, 2112.12608, 2307.04582, 2406.17053

with Evgeny Babichev, Ivan Dankovsky, Sabir Ramazanov, Rome Samanta and Alex Vikman

Example: EW Ist order Phase Transition

2307.01072



Free massive scalar field $g^2 = 0$

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - \frac{1}{2} m_\phi^2 \phi^2$$

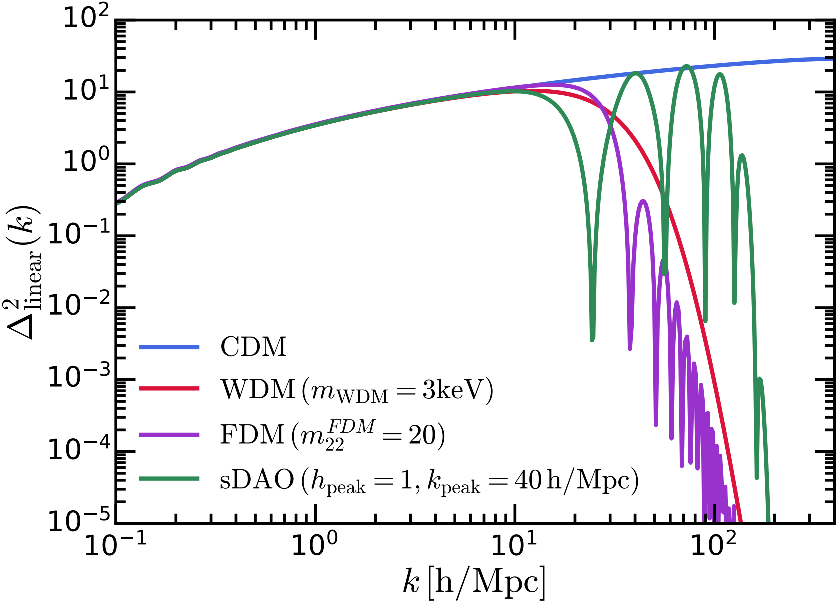
Homogeneous scalar field in the expanding Universe

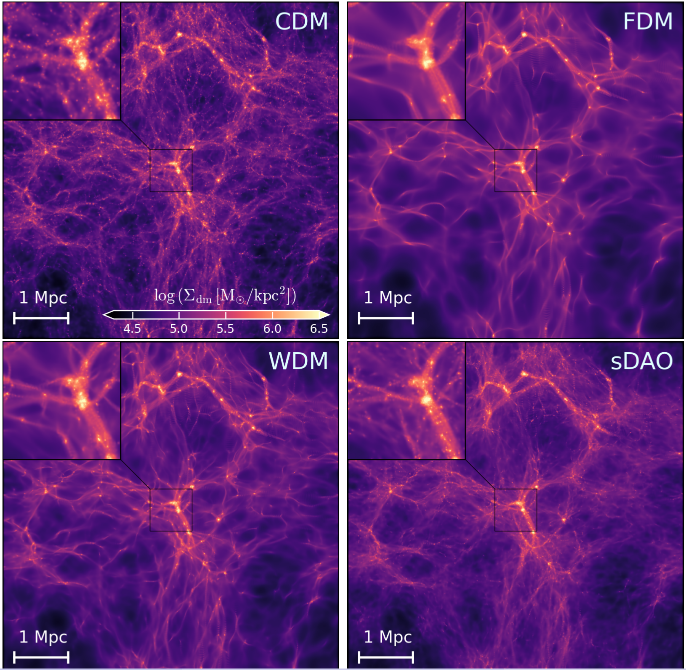
$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

Two-stage evolution:

$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$
$$m_\phi > H(t) \quad \Longrightarrow \quad p = \langle E_k \rangle - \langle E_p \rangle = 0\,, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

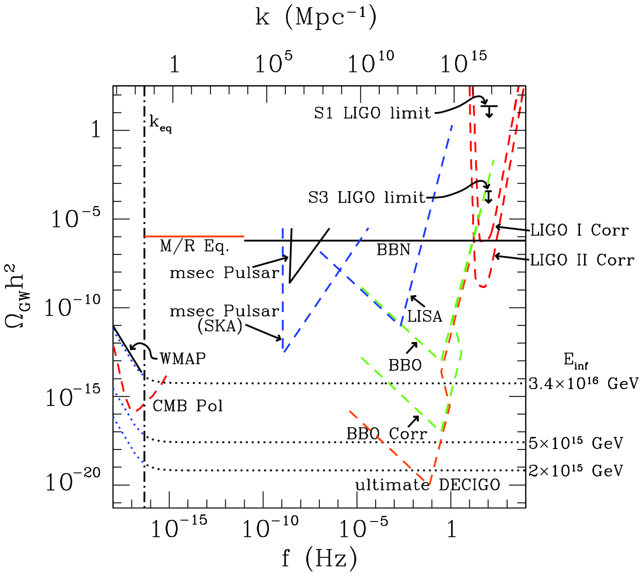
- dust-like substance in the late Universe, $\Omega \propto m_\phi^{1/2} \phi_i^2$
  at scales $l > 2\pi/m_\phi$ depends on initial conditions
  perturbations are suppressed at $l > M_{Pl}^{1/2}/(m_\phi^{1/2} \rho^{1/4})$ fuzzy DM


10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\Delta^2_{\rm linear}(k)$
10^{-1}
10^0
10^1
10^2
$k\,[\rm h/Mpc]$
CDM
WDM $(m_{\rm WDM} = 3\rm keV)$
FDM $(m_{22}^{FDM} = 20)$
sDAO $(h_{\rm peak} = 1, k_{\rm peak} = 40\,\rm h/Mpc)$


CDM
FDM
WDM
sDAO
1 Mpc
1 Mpc
1 Mpc
1 Mpc
$\log\left(\Sigma_{\rm dm}\,[{\rm M}_\odot/{\rm kpc}^2]\right)$
4.5
5.0
5.5
6.0
6.5

2304.06742

Prospects in 2014



Conclusion

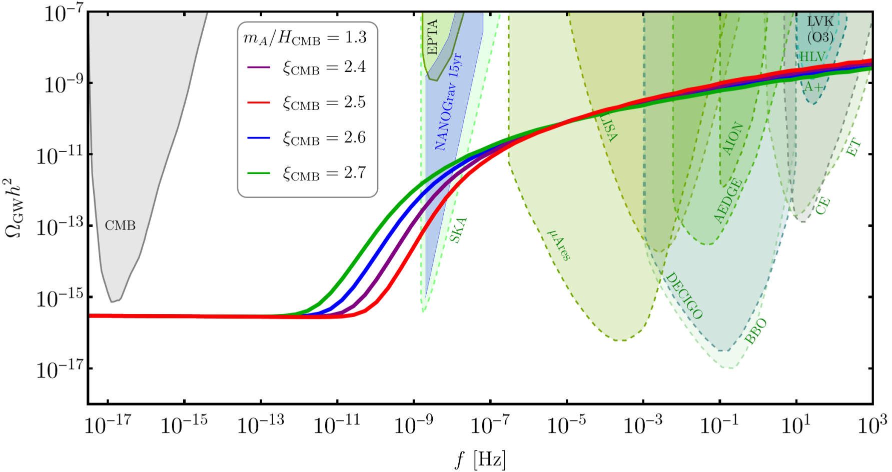
- What NANOGrav and others observe might be explained by the GW from melting domain walls
- they are expected in models with inverse phase transition
- which may induce light scalar dark matter production
- In realistic models it's mass is of order 10^{-16}-10^{-12} eV
- That predicts super-radiance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

see e.g. 0905.4720

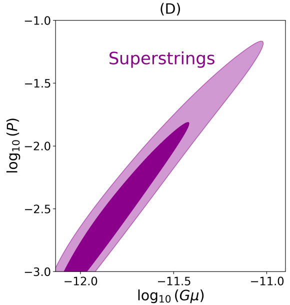
Other possible sources:
– scalar perturbations (but BH overproduction!)
– cosmic strings
– super heavy BH binaries (does not fit...)
– phase transitions
– violent reheating

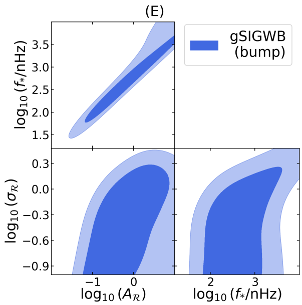
$$\Omega_{GW} h^2 = 6.5^{+4.1}_{-2.8} \times 10^{-9} \quad \text{at} \quad \nu \approx 1\,\text{yr}^{-1}$$

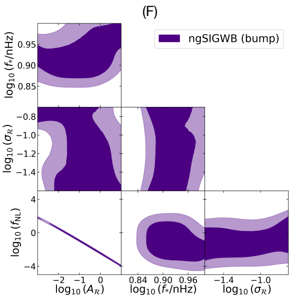
2306.17841



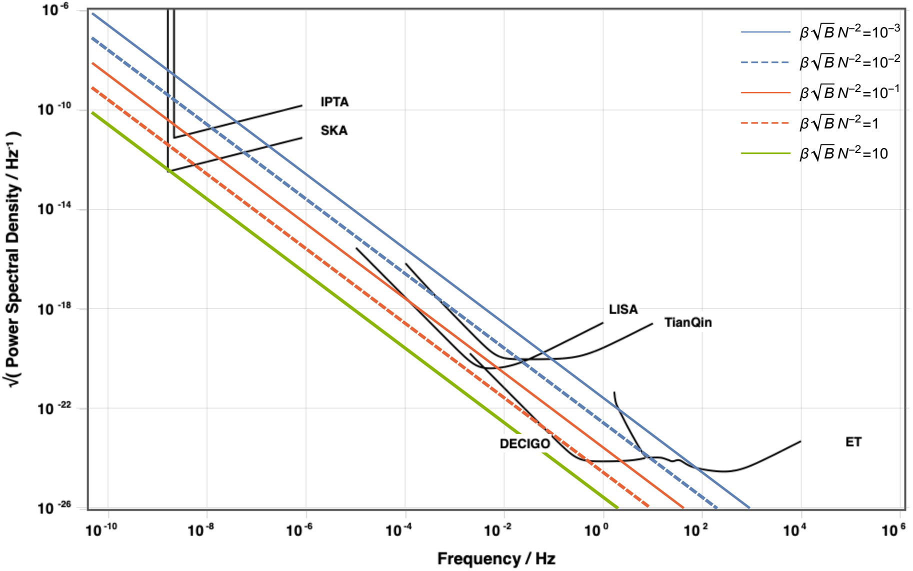
2307.01192







Template	$\mathrm{BF}_{\mathrm{NANO}}$	$\mathrm{BF}_{\mathrm{EPTA}}$	$\mathrm{BF}_{\mathrm{comb}}$	$\Delta\mathrm{AIC}_{\mathrm{comb}}$
PL($n_t = 0$)	0.02	0.62	0.0014	10.24
PL($n_t = 2/3$)	2.6	3.1	1.9	-5.20
PL($n_t, \mathscr{A}_*$)	16	4.1	180	-12.25
field th. CS	0.18	1.3	0.019	5.22
super CS	29	3.3	58	-11.11
gSIGWB	110	14	1200	-13.53
ngSIGWB	0.00017	0.001	$5\cdot10^{-6}$	4.34
AA	36	2.7	130	-12.36
BPL	17	1.6	120	-0.19
PhTNR	8.5	8.1	150	-12.85
PhTRV	37	13	110	-12.34
MHD	26	3.9	210	-8.77



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

2104.13722