Karlsruhe Institute of Technology

Institute for Theoretical Particle Physics

Nano-Hertz gravitational waves and sub-GeV dark matter from a classically conformal phase transition

Jonas Matuszak

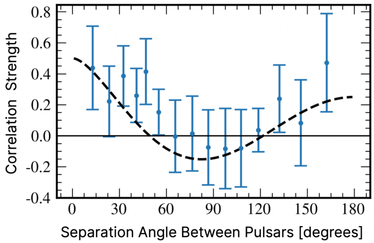
Based on arxiv:2502.19478

with Sowmiya Balan, Torsten Bringmann, Felix Kahlhöfer, Carlo Tasillo

24. September 2025

Pulsar Timing Arrays and the GW Background

NANOGrav 15 Year Data Release



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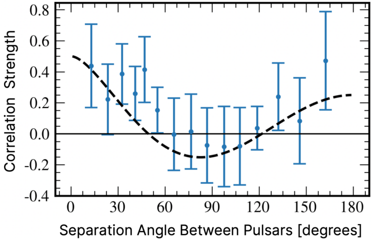
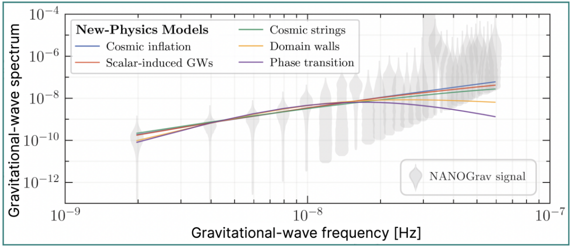


- Pulsar timing arrays found evidence of a stochastic GW background
- Astrophysical source: inspiralling black hole binaries
- Data allows for BSM sources of signal



Figures: arxiv:2306.16213, arxiv:2306.16219

Pulsar Timing Arrays and the GW Background

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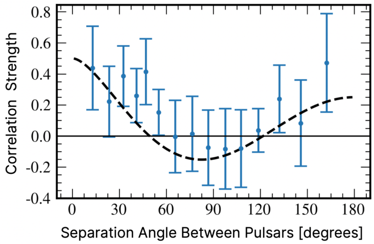

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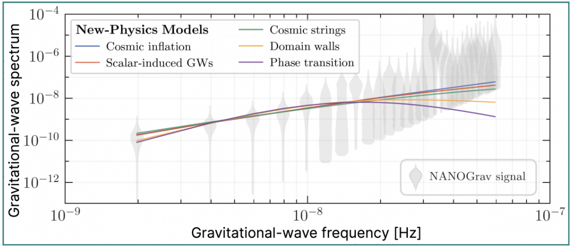
Question:

Can a new scalar field give us a GW signal *and* dark matter from a first-order phase transition?



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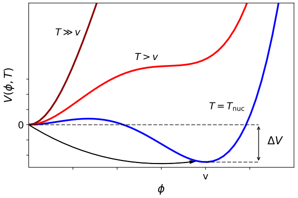
Dark Sector Phase Transition Recipe

$U(1)'$ dark sector

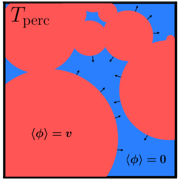
- Ingredients:
  - Dark Higgs: Φ
  - Dark photon: A'_μ
  - Dark matter (fermion): χ
  - Scalar potential: $V(\Phi, T)$
- Mix to get the Lagrangian

$$\mathcal{L}_{\text{DS}} = |D_\mu \Phi|^2 - \frac{1}{4} A'^2_{\mu\nu} + i\chi_L \not{D} \chi_L + i\chi_R \not{D} \chi_R - y\Phi\chi_L^\dagger \chi_R + \text{h.c.} - V(\Phi)$$

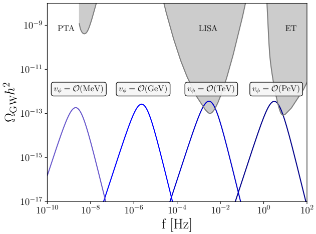
- Cook at high $T \gg v_\phi$
- Let cool until symmetry breaks $\langle\phi\rangle \neq 0$
  $\Rightarrow$ Mass generation + stochastic GW signal



Symmetry breaking



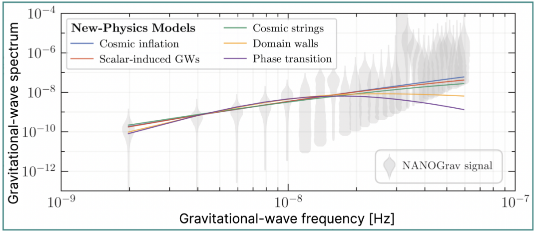
Bubble collision & Sound Waves



Fitting the PTA Gravitational Wave Signal
Nano Hertz Frequencies

PTA signal:

- Frequency at nHz
- Large amplitude: $h^2\Omega_{\text{PTA}} \sim 10^{-8}$



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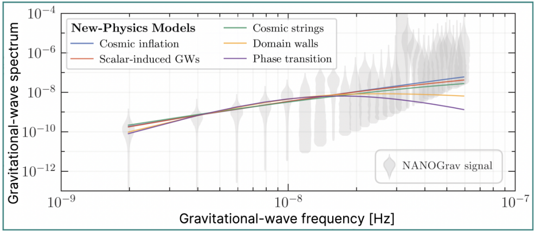
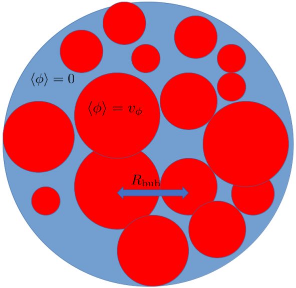
GW frequencies from a FOPT:

- Set by the characteristic length scale: R_*





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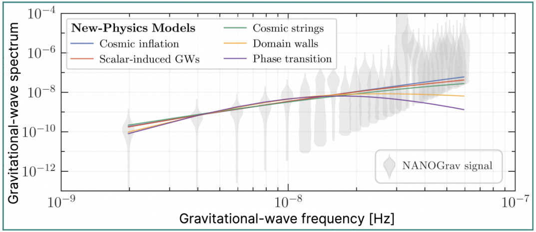

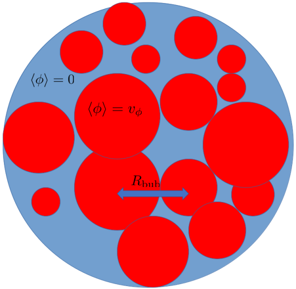

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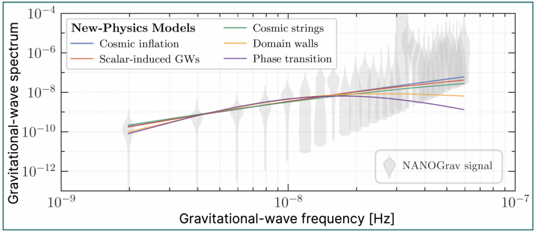

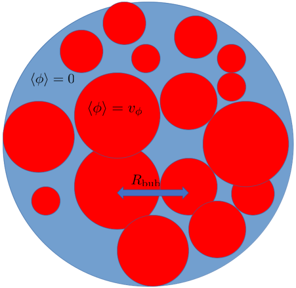

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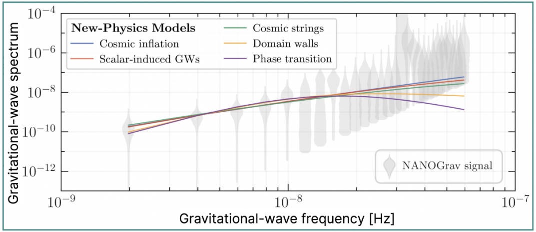

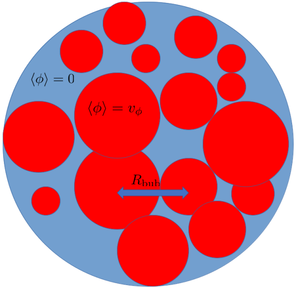

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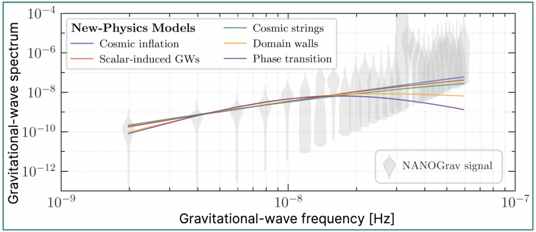
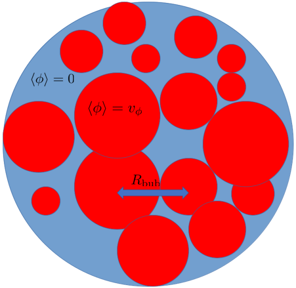




Sub-GeV dark matter

PT around $\mathcal{O}(\rm MeV)$ to fit the PTA data requires a DS mass scale $\mathcal{O}(\rm MeV)$

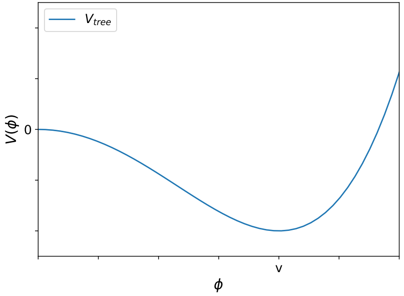
Fitting the PTA Gravitational Wave Signal
Amplitude

GW amplitude scaling

$$h^2\Omega_{\mathrm{GW}} \propto \underbrace{\left(\frac{\Delta V}{\Delta V + \rho_{\mathrm{rad}}}\right)^2}_{\equiv \text{kin. energy fraction}} \underbrace{(R_* H)^2}_{\equiv \text{mean bubble sep.}}$$

Potential:

$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$



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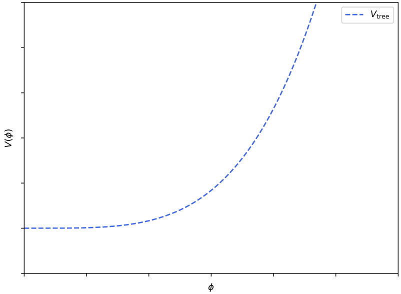

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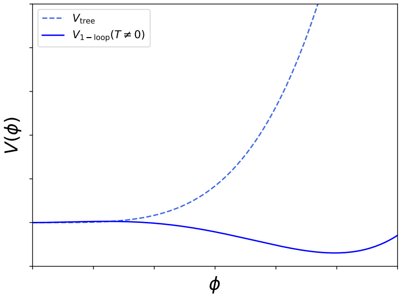
$$V_{\rm eff}(\Phi) = \lambda|\Phi|^4 + \sum_a \frac{g_a}{64\pi^2} m_a^4(\Phi)\left[\log\frac{\phi^2}{v^2} - \frac{6}{25}\right]$$



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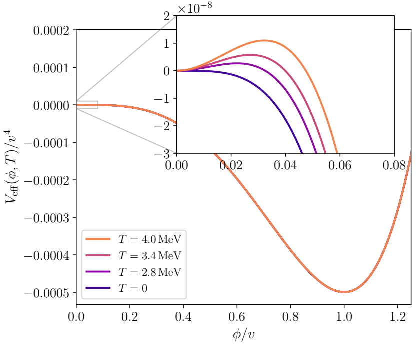

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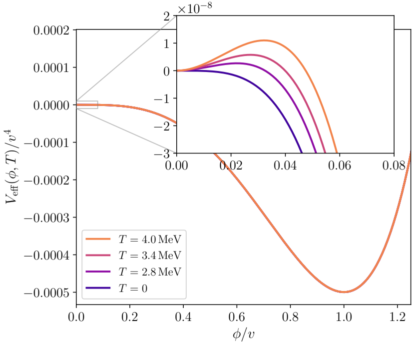

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Classically conformal symmetry

Classical conformal symmetry gives strong supercooling and large GW signal.

Relic Abundance

Freeze-out for Sub-GeV DM

BBN & CMB

How to get rid of DS the energy density after a PT around $\mathcal{O}(10)$ MeV and produce $h^2\Omega_{\mathrm{DM}} \simeq 0.12$?

What portal to the SM can we have?

- Couplings allowed by symmetry

$$\mathcal{L}_{\text{int}} = \lambda_{h\phi}|H|^2|\Phi|^2 + \frac{\kappa}{\cos 2\theta_{\mathrm{w}}} F'_{\mu\nu} B^{\mu\nu}$$

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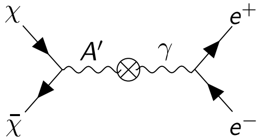
Effective coupling

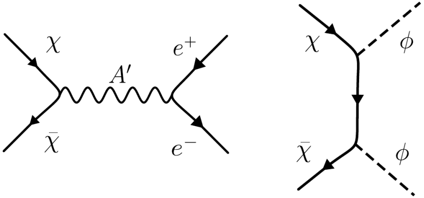


- Collider constraints $\kappa \lesssim 10^{-3}$
- First freeze-out of DS
- Then freeze-out of DM within DS

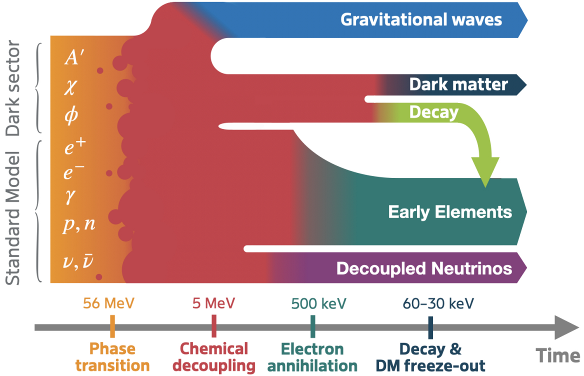
Thermal History

Thermal history of a benchmark point

$$\mu_\chi = \mu_\phi = 0$$



- After phase transition



Thermal History

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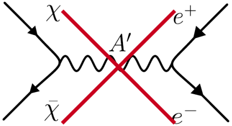
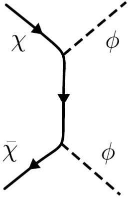
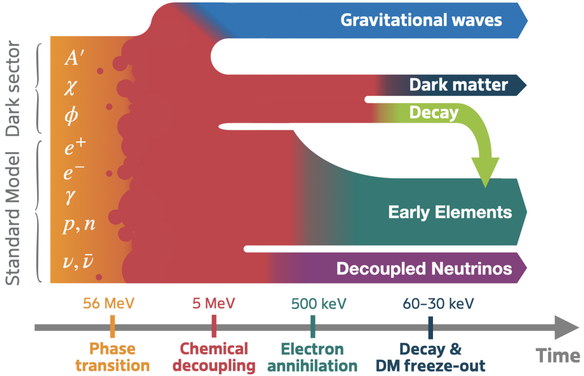
$$\mu_\chi = \mu_\phi \neq 0 \qquad 2Y_\chi + Y_\phi = \text{const}$$





- DS decoupling



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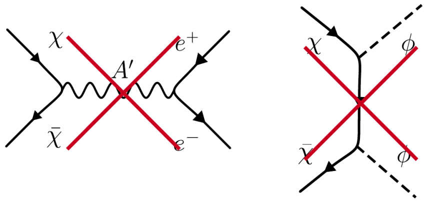
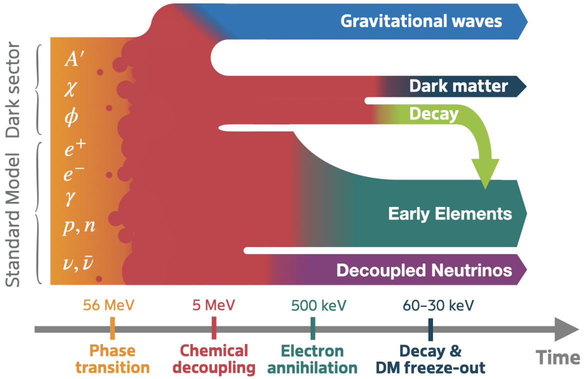


- DM freeze-out
- Decay of ϕ during/after BBN



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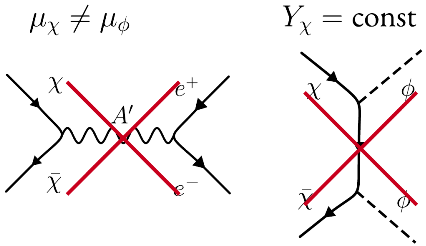

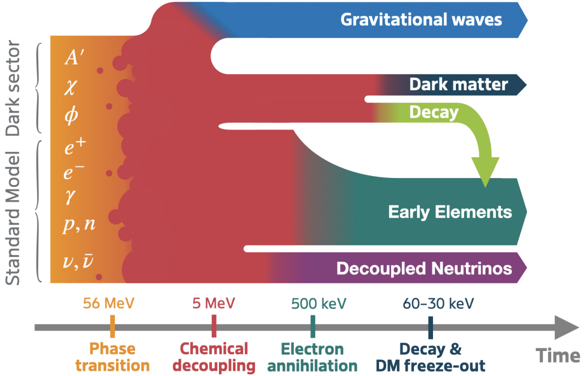

Cosmological constraints

Dark Higgs ϕ decays around BBN. Can we avoid the cosmological and collider constraints?

Cosmological, Astrophysical and Collider Constraints

Is this model consistent with data?

Cosmological constraints:

- NANOGrav 15 year dataset: likelihood for SMBHB + FOPT GW signal arxiv:2109.06208
  PTArcade (Ceffyl), TransitionListener (CosmoTransitions) arxiv:2306.16377
- Relic density calculation:
  DarkSUSY arxiv:1802.03399
- BBN: Light element abundances ^{4}He and D
  AlterBBN arxiv:1806.11095
- CMB constraints:
  - If semi-relativistic around neutrino decoupling increase N_{eff}
  - DM annihilation into e^+e^- raise T_γ and decrease N_{eff}

  Likelihood from Plank collaboration: $N_{\mathrm{eff}} = 2.99 \pm 0.17$ (BAO+lensing+TT,TE,EE+lowE)

Cosmological, Astrophysical and Collider Constraints

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Astrophysical constraints:

- Bullet cluster constraints: $\sigma_0/m_{\mathrm{DM}} < 1.25\,\mathrm{cm}^2\mathrm{g}^{-1}$
- X-Ray: $\chi\bar{\chi} \to A'$ p-wave suppressed $\Rightarrow$ no constraints

Accelerator constraints:

- Beam dump experiments: MiniBooNE, LSND
  Missing energy searches through $\pi^0, \eta \to \gamma + A', A' \to \chi\bar{\chi}$
- NA64: dark photon production through $e^- Z \to e^- Z A'$ and $A' \to \chi\bar{\chi}$
- BaBar: Single photon searches: $e^+ e^- \to \gamma A'$

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Global fit with GAMBIT

- Parameters: $m_{\mathrm{DM}}, m_{A'}, \mathrm{vev}, \kappa$ $(\gamma_{\mathrm{SMBHB}}, A_{\mathrm{SMBHB}})$
- Combined likelihood:

$$\mathcal{L}_{\mathrm{tot}} = \mathcal{L}_{\mathrm{PTA}} \times \mathcal{L}_{\Omega_{\mathrm{DM}} h^2} \times \mathcal{L}_{\mathrm{BBN,CMB}} \times \mathcal{L}_{\mathrm{BC}} \times \mathcal{L}_{\mathrm{Coll}}$$

arxiv:1705.07908

Calculation of the GW Spectrum

TransitionListener v2.0

Work on a new code based on
CosmoTransition arxiv:1109.4189

- Using best practices for computation of GW signal
  - Tracking of false vacuum fraction $P(T)$
  - Computation of T_{perc}, T_{reh}
  - Computation of v_{wall} (LTE)
  - Calculation of $R_* H$ from bubble density
  - Latest GW templates [arxiv:2403.03723]
- Interface to PTArcade for the PTA likelihoods
- Can handle strong supercooling

Phase transition temperature

- Typically:

$$\frac{S_3(T_{\mathrm{nuc}})}{T_{\mathrm{nuc}}} \approx 140$$

- Here track true vacuum fraction:

$$P(t) = \exp\left(-\frac{4\pi}{3}\int_{t_c}^{t} \mathrm{d}t' \Gamma(t') v_w^3 (t-t')^3\right)$$

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Bubble wall velocity

- Typically:

$$v_w = \text{const.}$$

- Here compute v_w in the LTE approximation

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Transition speed/characteristic length scale

- Typically:

$$\frac{\beta}{H} \approx T \frac{\mathrm{d}}{\mathrm{d}T}\left(\frac{S_3}{T}\right)$$

- Here compute

$$\frac{\beta}{H} = (8\pi)^{1/3} \frac{\max(c_s, v_w)}{P(T_*)^{1/3} R_* H}, \quad R_* = n_{\mathrm{bub.}*}^{-1/3}$$

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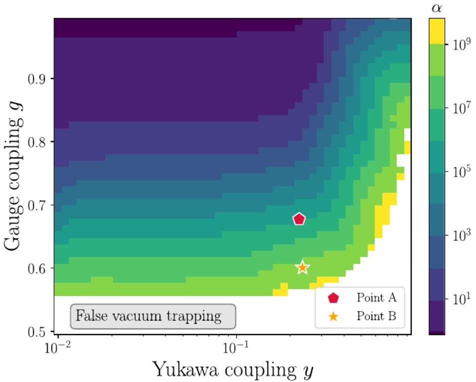


Calculation of the GW Spectrum

TransitionListener v2.0

Work on a new code based on
CosmoTransition arxiv:1109.4189

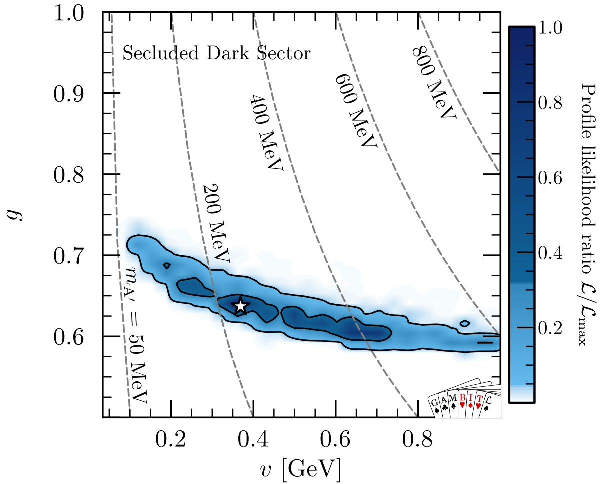
- Using best practices for computation of GW signal
  - Tracking of false vacuum fraction $P(T)$
  - Computation of T_{perc}, T_{reh}
  - Computation of v_{wall} (LTE)
  - Calculation of $R_* H$ from bubble density
  - Latest GW templates [arxiv:2403.03723]
- Interface to PTArcade for the PTA likelihoods
- Can handle strong supercooling

Upcoming code release [Ongoing work with Carlo Tasillo]

Implemented in a new version of TransitionListener (v2), which is based on CosmoTransition. Soon* to be released.

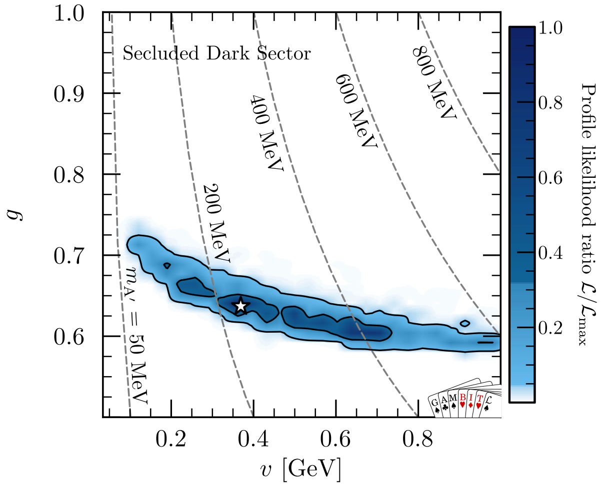
* Fall 2025

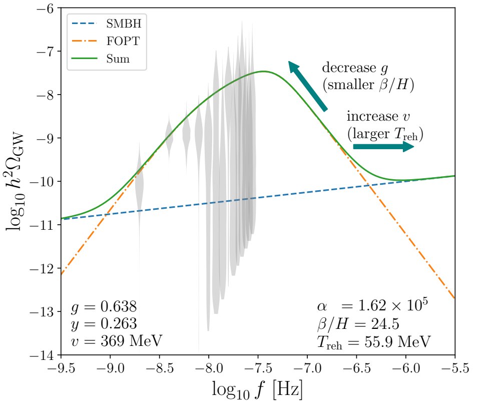
Global Scans
Gravitational Wave Signal



Global Scans

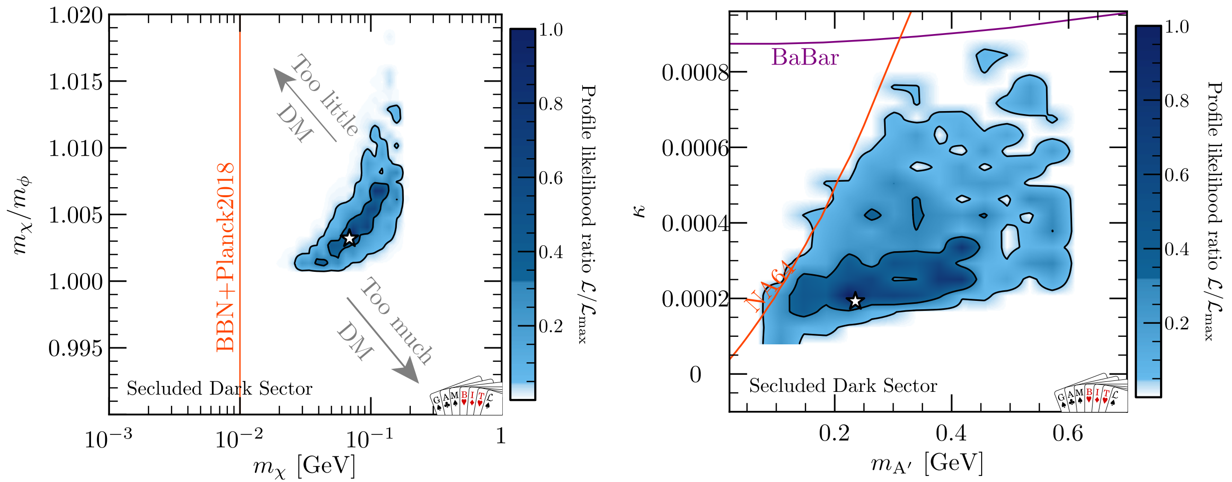
Gravitational Wave Signal





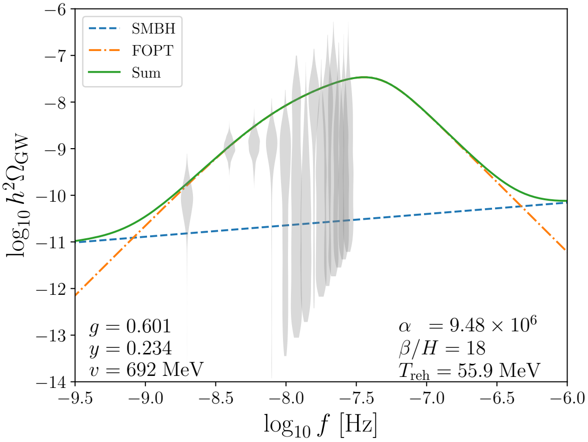
Global Scans

Relic Density and Collider Constraints



Conclusion

- Dark sector phase transition can fit NANOGrav data
- At the same time produce Sub-GeV dark matter, evading current constraints
- Model testable with future experiments (LDMX)
- Upcoming code release



Backup Slides

Coupled Dark Sector

Standard freeze-out

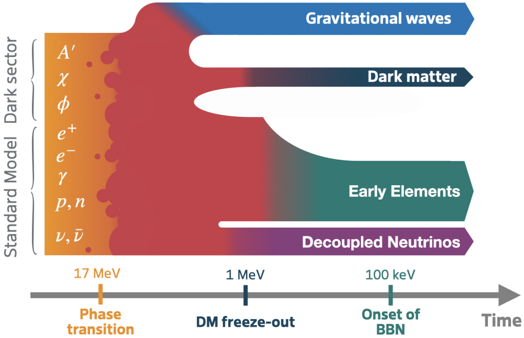
- Assume chemical equilibrium between SM and DS during freeze-out
- Generated through e.g. heavy vector like leptons, charged under SM and DS gauge groups
- Generates effective interaction

$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}\phi^\dagger \phi \bar{l}_L e_R H + \text{h.c.}$$

- After electroweak symmetry breaking

$$\mathcal{L}_{\rm eff.\,int} = \frac{v_h v_\phi}{2\Lambda^2}\phi \bar{e} e$$

- Standard freeze out of DM χ from SM-DS bath



GW spectrum

Template from arxiv:2403.03723

$$h^2\Omega_{\rm gw}^{\rm PT}(f) = \mathcal{R}h^2 A_{\rm sw} K^2 \mathcal{Y}_{\rm sw}\,(RH_*)\,\tilde{S}(f)\,,$$

Spectral shape: $S(f) = N\left(\frac{f}{f_1}\right)^3\left[1+\left(\frac{f}{f_1}\right)^2\right]^{-1}\left[1+\left(\frac{f}{f_2}\right)^4\right]^{-1}$, with the normalisation
$\tilde{S}(f) = \frac{1}{\pi}\left(\sqrt{2}+\frac{2\,f_2/f_1}{1+f_2^2/f_1^2}\right)\frac{S(f)}{S(f_2)}$.
Frequencies breaks $f_1 \simeq 0.2\left(\frac{H_{*,0}}{RH_*}\right)$, $\quad f_2 \simeq 0.5\,\Delta_w^{-1}\left(\frac{H_{*,0}}{RH_*}\right)$.
Sound shell thickness $\Delta_w = |v_w - c_s|\,/\max(v_w, c_s)$. Frequency redshift factor is given by
$H_{*,0} = \; 16.5\,\mathrm{nHz}\left(\frac{T_{\rm reh}}{100\,\mathrm{MeV}}\right)\left(\frac{g_{\rm reh}}{100}\right)^{1/2}\left(\frac{100}{h_{\rm reh}}\right)^{1/3}$.
Redshift of amplitude: $\mathcal{R}h^2 = \left(\frac{a_{\rm reh}}{a_0}\right)^4\left(\frac{H_{\rm reh}}{H_0}\right)^2 h^2 = \Omega_\gamma h^2\left(\frac{h_0}{h_{\rm reh}}\right)^{4/3}\frac{g_{\rm reh}}{g_\gamma}$,
$\mathcal{Y} = \min\,[1, \tau_{\rm sh} H] \simeq \min\left[1, \frac{3.38}{\beta/H}\sqrt{\frac{1+\alpha}{\kappa_{\rm SW}\,\alpha}}\right]$

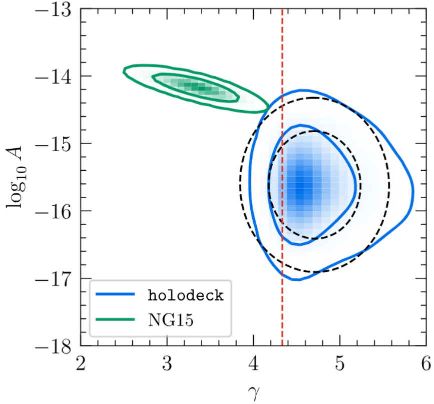
SMBHB Signal

- Spectral shape:

$$\Phi_{\rm SMBHB} = \frac{A^2_{\rm SMBHB}}{12\pi}\frac{1}{T_{\rm obs}}\left(\frac{f}{\rm yr^{-1}}\right)^{-\gamma_{\rm SMBHB}} \rm yr^3$$

- Amplitude

$$\Omega_{\rm GW}h^2 = 8\pi^4 f^5 \left(\frac{\rm Mpc}{100}\right)^2 \frac{\Phi_{\rm SMBHB}}{\Delta f}$$



Dimensional Transmutation

Renormalised 1-loop effective potential:

$$V_{1-\text{loop}} = \frac{\lambda}{4}\phi^4 + \sum_a \frac{\eta_a g_a}{64\pi^2} m_a^4(\phi)\left[\ln\frac{m_a^2(\phi)}{m_a^2(\Lambda)} - \frac{50}{12}\right].$$

Define λ at the vev of the theory $\Lambda = \langle\phi\rangle = v_\phi$

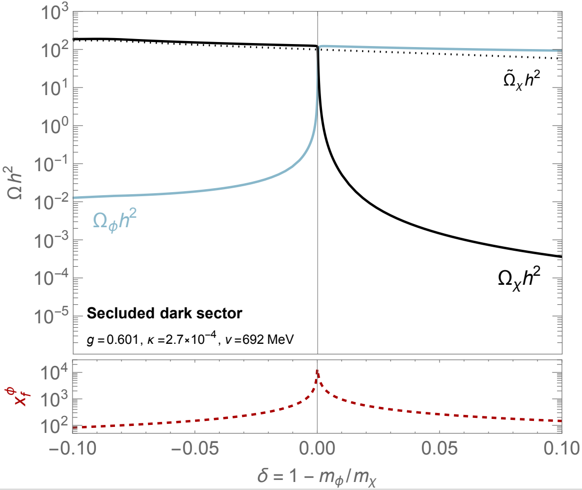
$$\frac{\partial V}{\partial\phi}\Big|_{\langle\phi\rangle} = \left(\lambda - \frac{32}{3}\sum_a \frac{\eta_a g_a}{64\pi^2}\lambda_a^4\right)\langle\phi\rangle^3 = 0$$

For $\lambda \ll g, y$:

$$\lambda \approx \frac{32}{3}\sum_a \frac{\eta_a g_a}{64\pi^2}\lambda_a^4$$

$\Rightarrow m_\phi = m_\phi(g, y) = \sqrt{3\lambda(g, y)}v_\phi$

Dark Matter Relic Density



Dark Higgs Decays