Listening to Dark Sectors with Pulsar Timing Arrays

(work with Y. Cui, Y.-D. Tsai and Y. Tsai)

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Chungbuk National University

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3$^{\text{rd}}$ Gordon Godfrey Workshop on Astroparticle Physics

10$^{\text{th}}$ December 2024

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- In particular: **connect** observed PTA spectrum to microphysics model parameters as opposed to macroscopic phase transition (PT) parameters
  T. Bringmann et al. (2023), A. Addazi et al (2023), M. Winkler & K. Freese (2024), ...

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- Can also consider a Yukawa term: $y_D\, \bar{\Psi} \Phi \chi$, with Dirac fermion Ψ and one singlet fermion χ.

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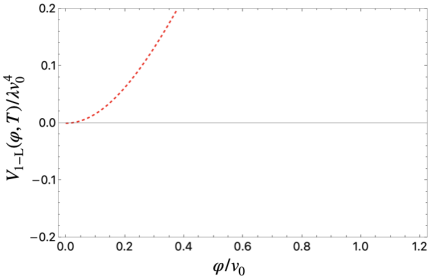

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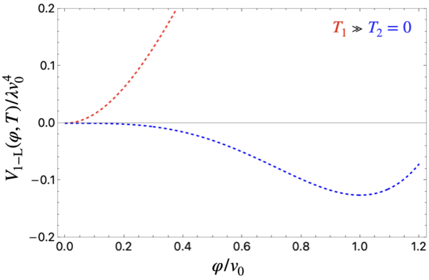

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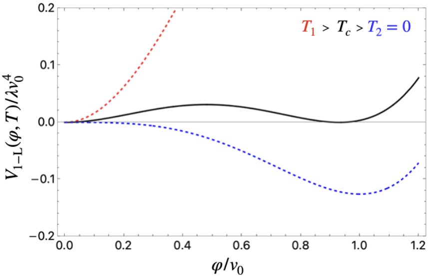
- As low T, φ ends up at the true vacuum $\varphi = v_0$ where the symmetry is broken.
- If a **barrier** forms (at critical temp. T_c) separating the two vacua, the PT is said to be **first-order (FOPT)**.



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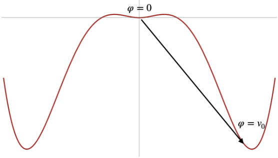

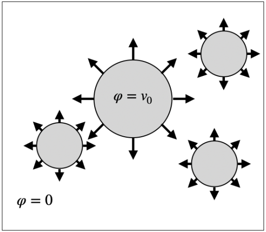

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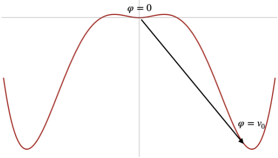

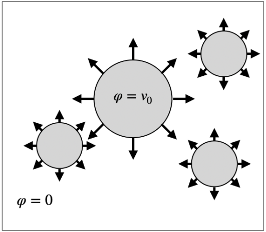

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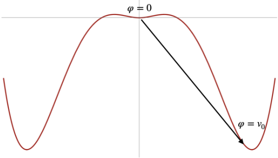

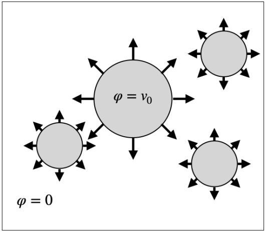

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Phase Transition Parameters

- Obtain

$$S_3 = 4\pi \int_0^\infty dr\, r^2 \left[\frac{1}{2} \left(\frac{d\varphi_b}{dr} \right)^2 + V_{1-\mathrm{L}}(\varphi_b, T) \right] ,$$

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- PT characterized by its inverse duration β and strength α_* ($\sim$ latent heat)

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- Model dependence comes from $V_{1-\mathrm{L}}(\varphi_b, T) \longrightarrow$ PT parameters end up depending on the model parameters $[\mu,\ \lambda,\ g_D, (\,y_D,\ N)]$

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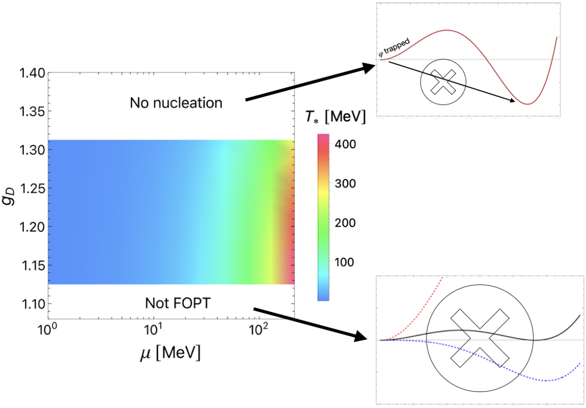

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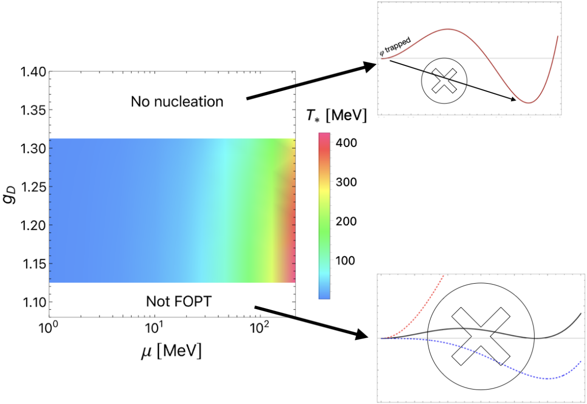

μ fixes the **relative scale** of T_*!

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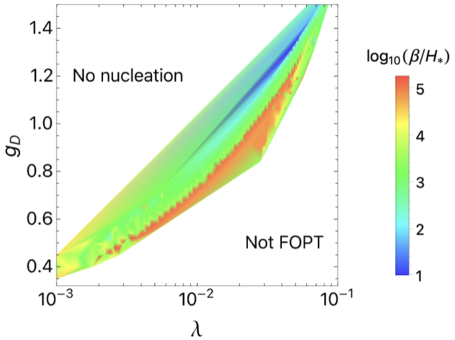

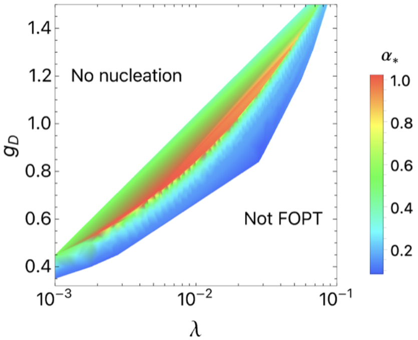

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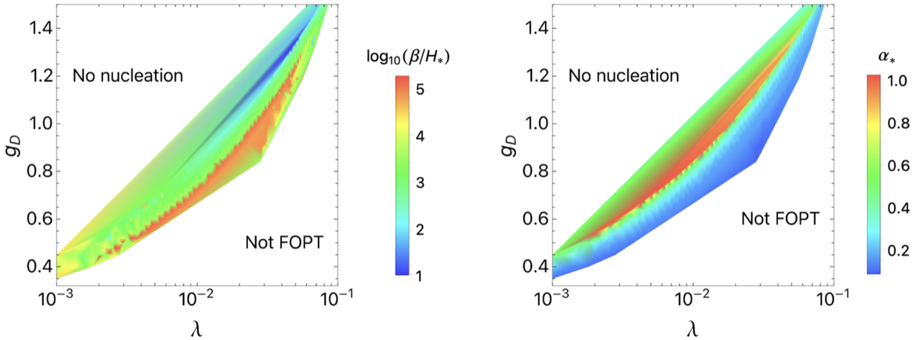

Larger couplings: PT lasts **longer**; increasing g_D (for fixed λ): PT is **stronger**.

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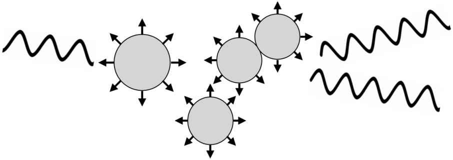
  [A. Kosowsky et al. (1992, 1993), S. J. Huber and T. Konstandin (2008), D. J. Weir (2016)], [Hindmarsh et al. (2013, 2015, 2017)], [Kosowsky et al. (2002), Dolgov et al. (2002), Caprini et al. (2009)]



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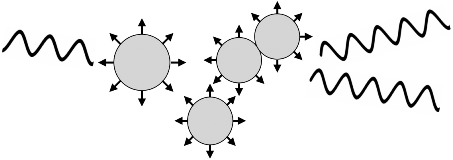

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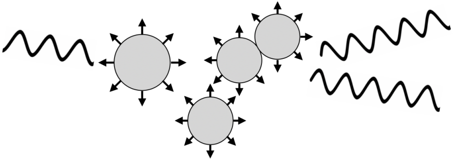

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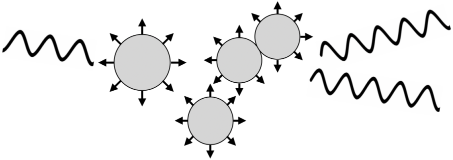

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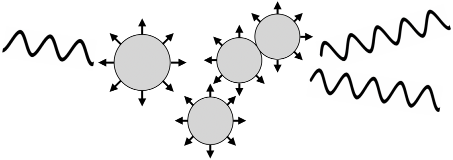

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Improvements: T. Ghosh et al. (2023); **H.-K. Guo** et al. (2024), also see **his plenary talk** tomorrow!

Model Parameters and the Spectrum

$$\Omega_{\rm GW}^{\rm sw,peak} h^2 = 5.71 \times 10^{-8}\, v_w \left(\frac{10}{g_{*,\rm tot}}\right)^{\frac{1}{3}} \left(\frac{\beta/H_*}{100}\right)^{-1} \left(\frac{\kappa_{\rm sw}\, \alpha_*}{1+\alpha_*}\right)^{2} \Upsilon$$

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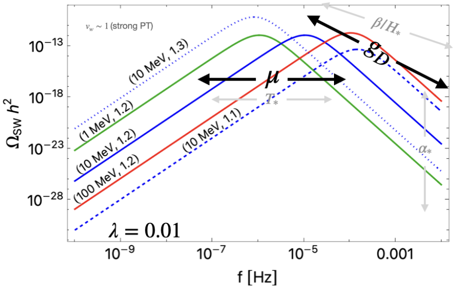

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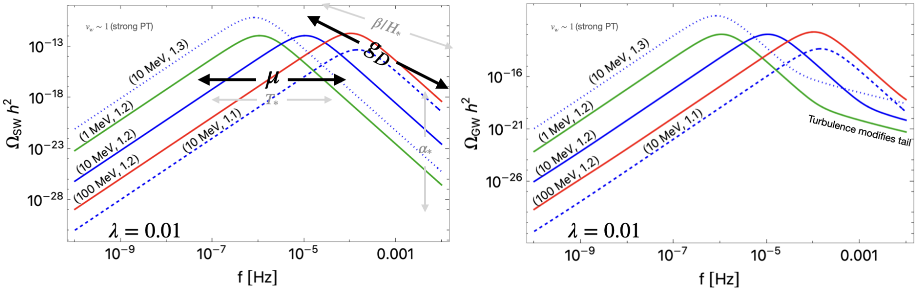

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- Test **compatibility** using

$$\chi^2 = \sum_{i=1}^{41} \left(\frac{\log \Omega_{\mathsf{GW},i}^{\mathrm{model}} - \log \Omega_{\mathsf{GW},i}^{\mathrm{data}}}{\Delta \log \Omega_{\mathsf{GW},i}^{\mathrm{data}}} \right)^2$$

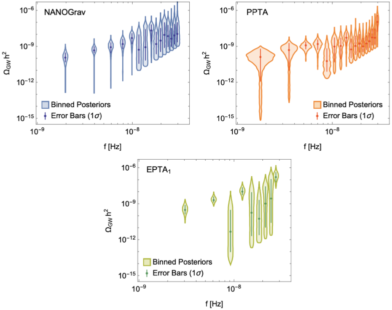
$\Omega_{\mathsf{GW},i}^{\mathrm{model}} \equiv$ model prediction,

$\Omega_{\mathsf{GW},i}^{\mathrm{data}} \equiv$ mean values of PTA data,

$\Delta \equiv$ error bars of PTA data.

- Need the degrees of freedom to determine confidence levels,

$$n_{\mathrm{d.o.f.}} = 41 - n_{\mathrm{params}}$$



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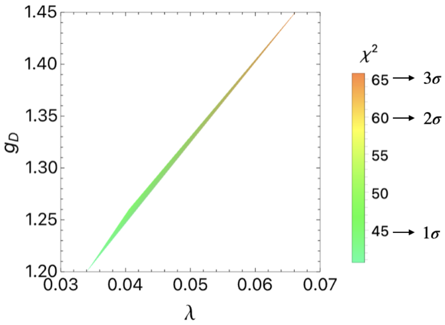

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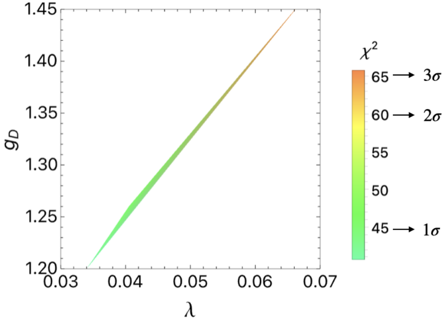

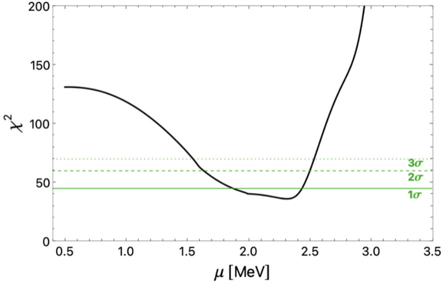

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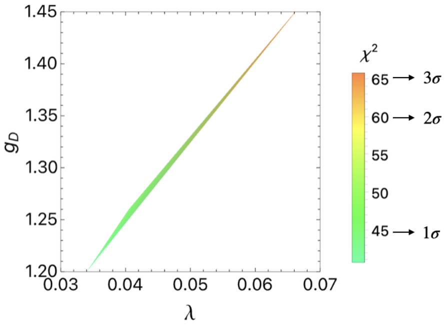

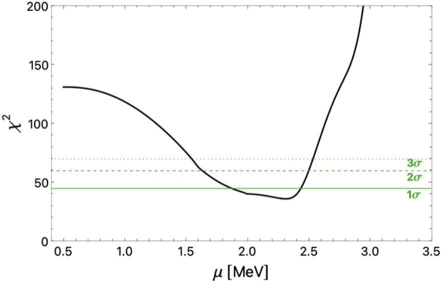

- Extremely narrow parameter space for which a DS PT can account for the PTA data.

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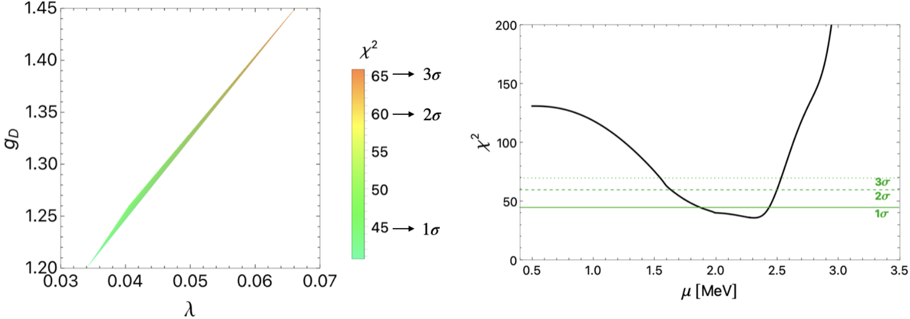
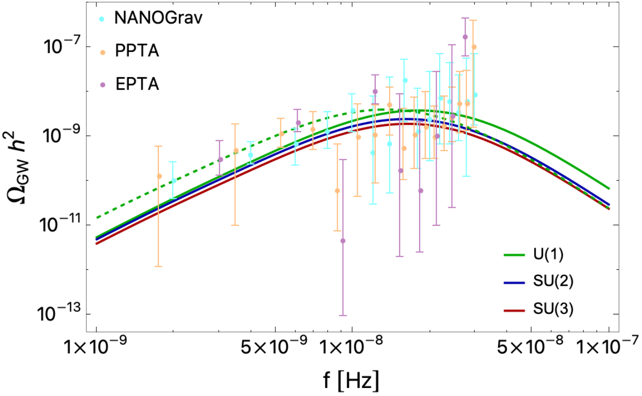


- Extremely narrow parameter space for which a DS PT can account for the PTA data.
- Expected to be a **generic problem** for most models.

Best Fit to the PTA Data

MODEL	$(\mu,\ \lambda,\ g_D,\ y_D)$	$(T_*,\ \alpha_*,\ \beta/H_*)$	χ^2
U(1)	(2.4 MeV, 0.034, 1.2, 0)	(2.35 MeV, 0.96, 47)	36
U(1) w/ Ψ and χ	(2.7 MeV, 0.0575, 1.5, 0.8)	(2.5 MeV, 0.76, 38)	29
SU(2)	(2.0 MeV, 0.052, 1.14, 0)	(1.9 MeV, 0.79, 58)	30
SU(3)	(1.8 MeV, 0.029, 0.68, 0)	(1.8 MeV, 1.06, 70)	40



Implications for Dark Sector Cosmology

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$$\Omega_\phi h^2 \sim 10^{-13} \left(\frac{m_\phi}{3\,\mathrm{MeV}}\right)^2 e^{x_f\,\Delta}, \quad \Delta \equiv \frac{2(m_{A'} - m_\phi)}{m_\phi}$$

Summary and Outlook

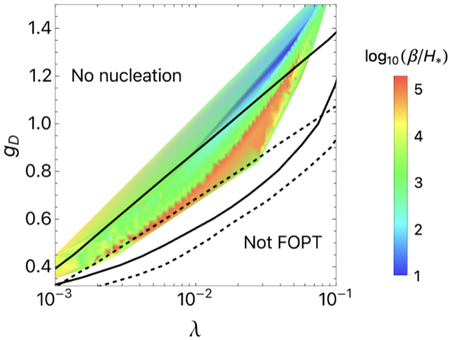
- A dark sector phase transition can account for the **whole PTA signal**, but parameter space is extremely constrained.
- Leads to predictive phenomenology for the underlying model.
- Interesting implications for the DS cosmology ("can" get right DM).

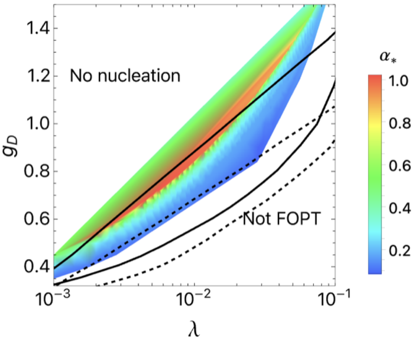
Thank you for your attention!

Backup

β/H_* and α_* for SU(N)

Set $\mu = 1$ MeV and $y_D = 0$. Study trend of β/H_* and α_* in (g_D, λ) plane.

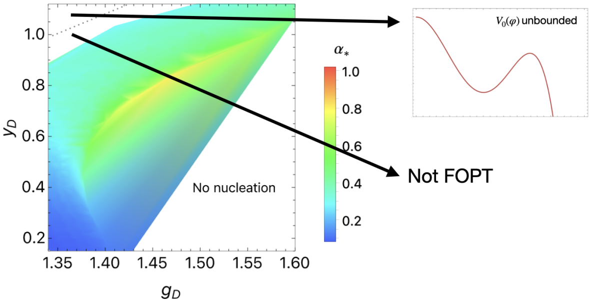




Enlarging the gauge group ($N = 2$: solid lines, $N = 3$: dashed lines) 'tilts' the parameter space!

Yukawa Coupling

Work with U(1) group with two fermions. Fix $\lambda = 0.05$ and $\mu = 1$ MeV to study trends in (g_D, y_D) plane.



Can increase g_D to compensate for negative fermionic contribution!