Gravitational Waves from Dark Phase Transitions at Strong Coupling

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New Perspectives in Conformal Field Theories and Gravity

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Why bother with SU(N) Yang-Mills

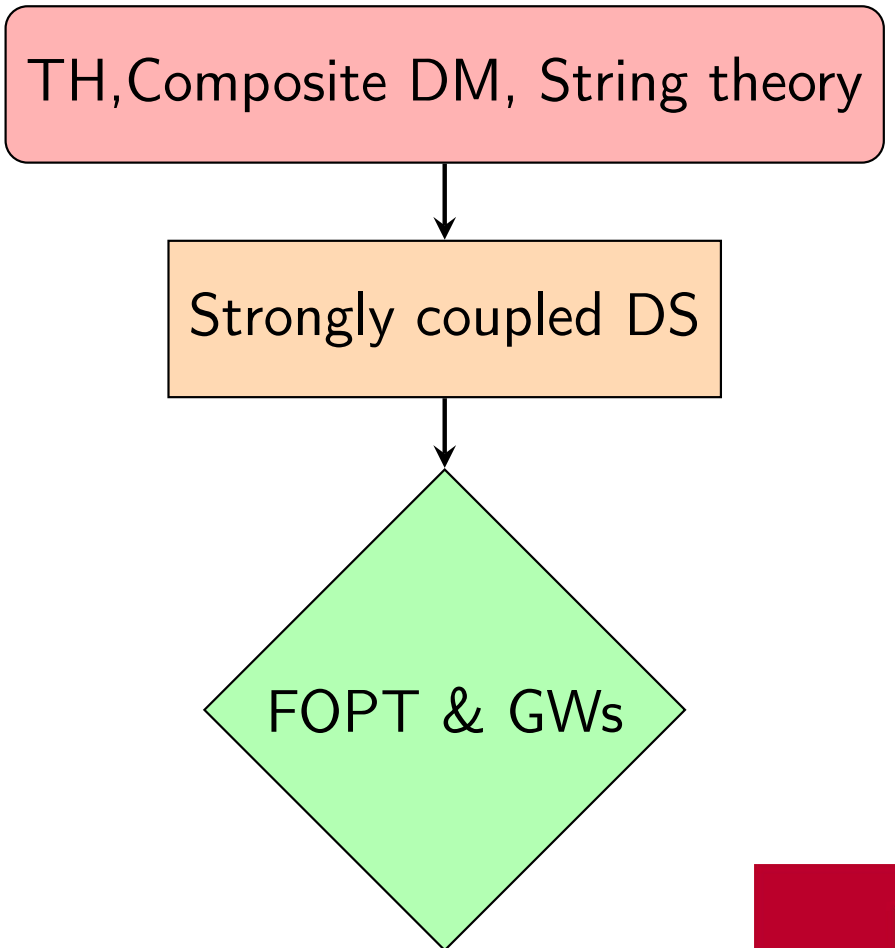
Consider SU(N_c) with n_f massless flavors

Benchmark point $N_c = 3$, $n_f = 0$ only parameter Λ_d

PT is First Order for

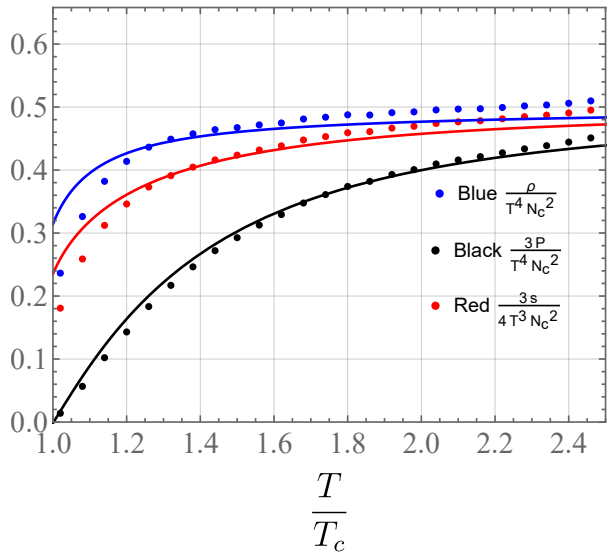
$N_c \geq 3$, $n_f = 0$.

$N_c \geq 3$, $3 \leq n_f \leq 4N_c$.



Strategy: Use Holography and Lattice Data for theoretical control and QCD-Like Theory resemblence

CFT-QFT	String/Gravity
$\mathcal{Z}_{CFT}$	$\mathcal{Z}_G$
W_{CFT}	$-\mathcal{S}_{OS}$
Temperature T	T_h
Entropy S	S_{BH}
Large-N ("QCD")	GR in AdS_{d+1}



$$\mathcal{S}_5 = -M_p^3 N_c^2 \int d^5x\sqrt{g}(R - \frac{4}{3}(\partial\Phi)^2 + V(\Phi)) + 2M_p^3 \int_{\partial\mathcal{M}} d^4x\sqrt{h}\mathcal{K}$$

Finite T Solutions

Regular BH Solution

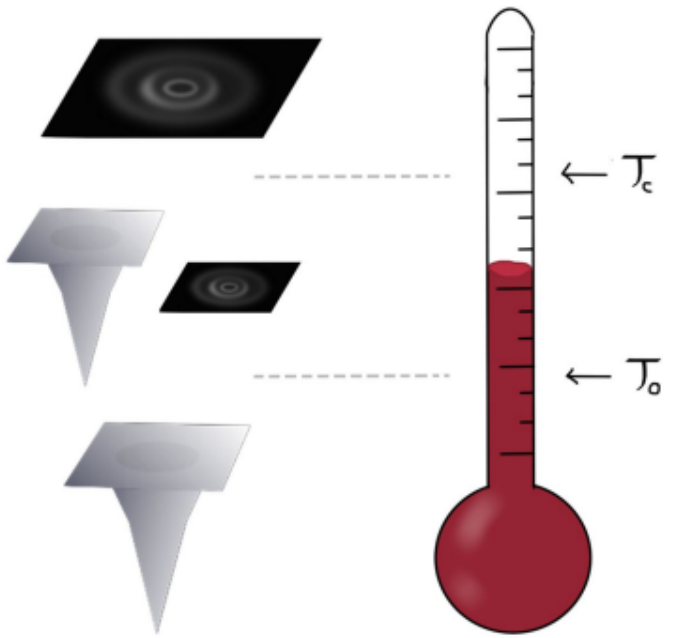
$$T_h = \frac{|\dot{f}(\lambda_h)|}{4\pi} = T_{AdS}$$

BH Area Law

$$S = 4\pi M_p^3 N_c^2 V_3 b(\lambda_h)^3$$

Free energy

$$\beta\Delta\mathcal{F} = (\mathcal{S}^{\epsilon}_{BH} - \mathcal{S}^{\epsilon}_{TG})/V_3$$



Dewolfe 2013

Confinement (HP) Phase Transition & Effective Action I

Big BH	Small BH	TG
Deconfined	Saddle Point	Confined

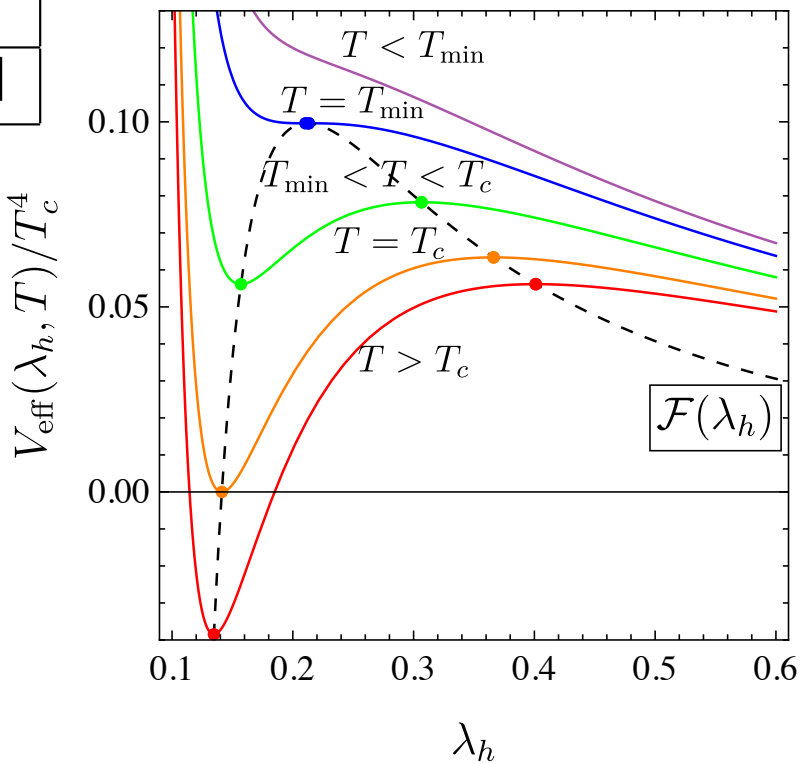
Free energy Landscape approach

Field/Metric Configurations

T$\neq$T$_h$

Conical singularity

Regularize with Spherical Cap



$$V_{\rm eff}(\lambda_h, T) = \mathcal{F}(\lambda_h) - 4\pi M_p^3 N_c^2 b(\lambda_h)^3 \left(1 - \frac{T_h}{T}\right) .$$

Confinement (HP) Phase Transition & Effective Action II

Kinetic Term Normalization

$$c\frac{N_c^2}{16\pi^2}$$

We vary $c \to \frac{1}{3} - 3$, Moderate dependence on GW spectrum

Thermal Tunneling effective action $\mathcal{O}(3)$ symmetric bounce

$$\mathcal{S}_{eff} = \frac{4\pi}{T}\int d\rho\,\rho^2\left[c\frac{N_c^2}{16\pi^2}(\partial_\rho\lambda_h(\rho))^2 + V_{\rm eff}(\lambda_h(\rho),T)\right]$$

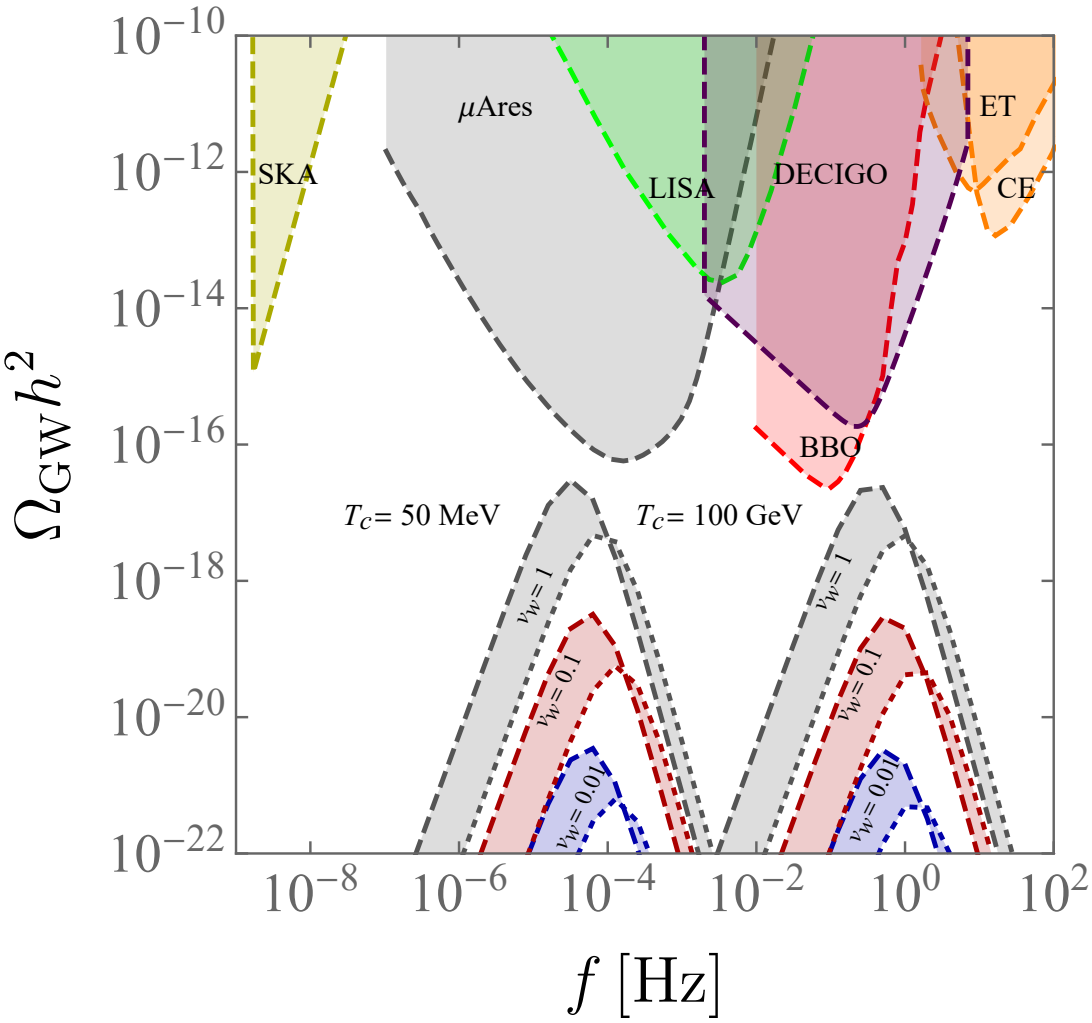
Nucleation Rate for Thermal Tunneling

$$\Gamma = T^4\left(\frac{\mathcal{S}_B}{2\pi}\right)^{3/2} e^{-\mathcal{S}_B}\,.$$

Percolation: $\mathcal{P}(true) \simeq \mathcal{P}(false)$ (End of PT! GW Emission)

	α	$\beta/H\,(v_w = 1)$	$\beta/H\,(0.1)$	$\beta/H\,(0.01)$
$T_c = 50\,\mathrm{MeV}$	0.343	9.0×10^4	8.6×10^4	8.2×10^4
$100\,\mathrm{GeV}$	0.343	6.8×10^4	6.4×10^4	6.1×10^4

Gravitational Wave Spectra SU(3) "The Money Plot"



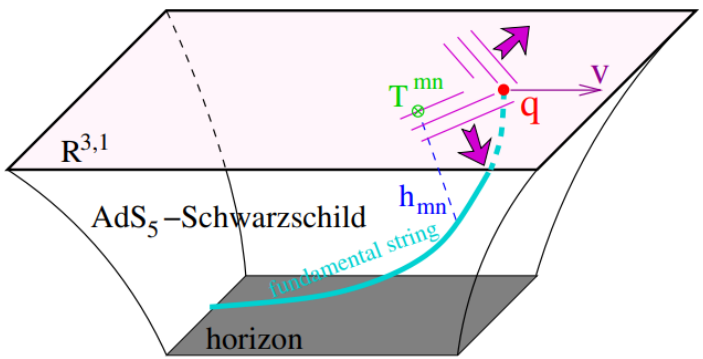
GW spectra for SU(3) at different critical temperatures

Bubble wall velocity at Strong Coupling

Employ steady state approach like Bigazzi 2104.12817

$$\Delta P^{tot}_{fric} = 0 = \frac{F_{fric}}{A} + \Delta P_{bubble}$$

$F_{fric} \sim F_{drag}$, F_{drag} is the drag force of an external probe quark traversing stationary in the plasma. Calculabel with AdS/CFT



From Dewolfe 2013

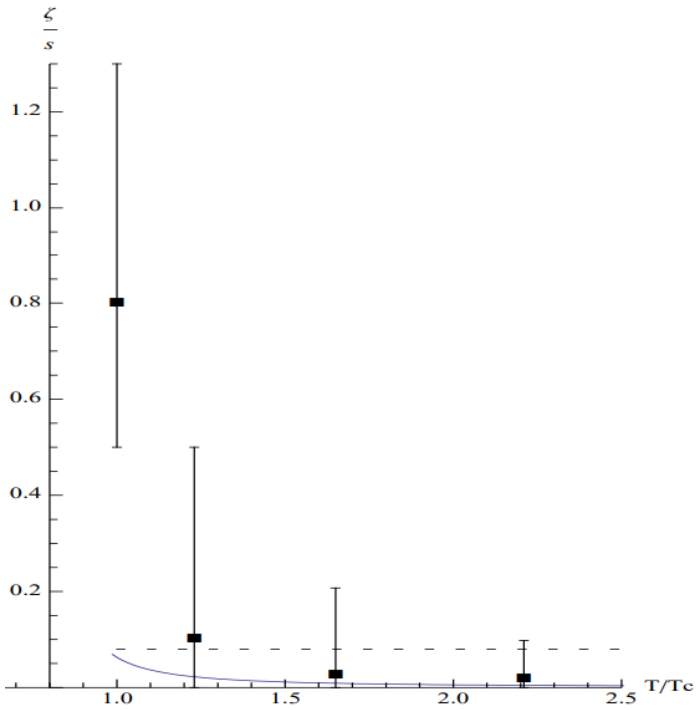
Access to the pressures in deconfined phase from the lattice fit.

Finally for the wall velocity we obtain so far

$$v_w = 0.07 \pm 0.03$$

Kinetic Term Computation

Bulk Viscosity $\zeta \sim$ (Breaking of scale symmetry) $\times$ (mean free path) $\times$ (energy momentum density).



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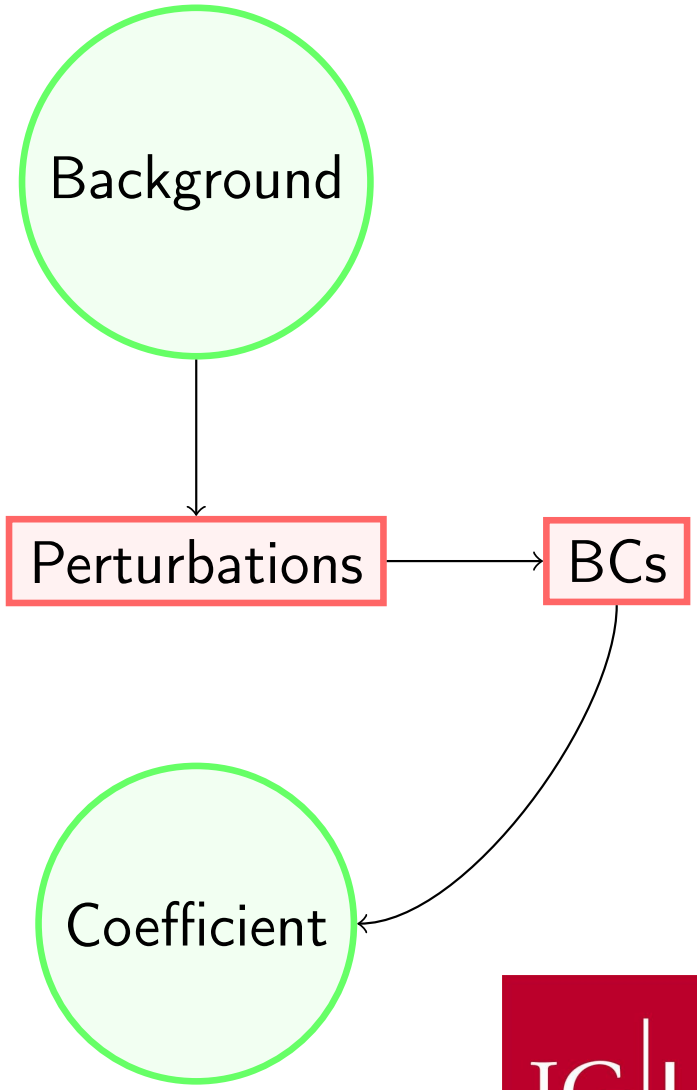
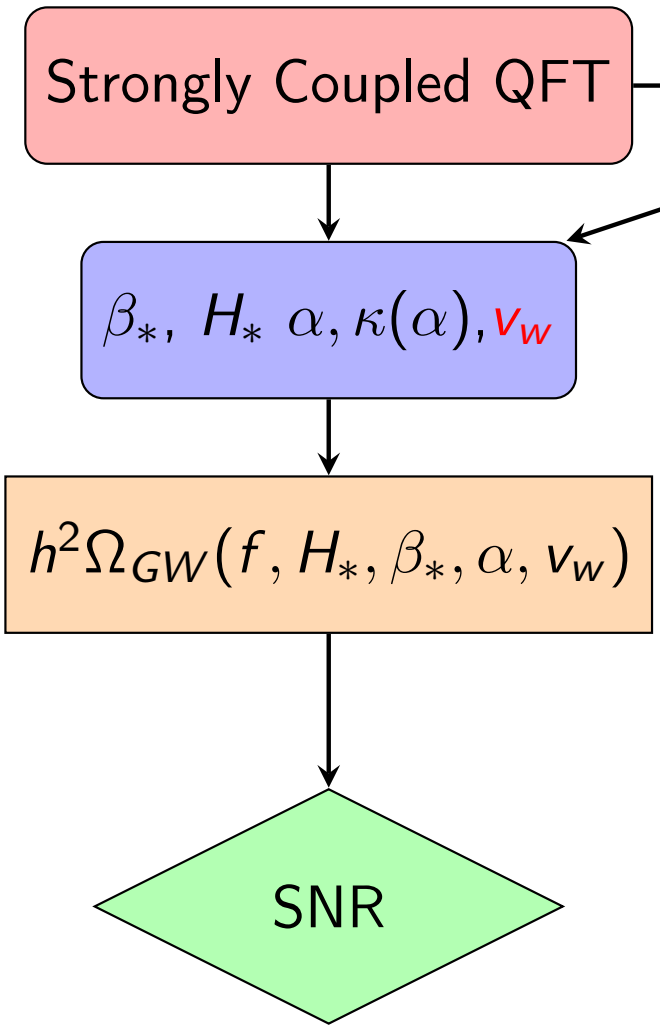


Take Home Messages



GWs from SU(3) YM not detectable

AdS/CFT powerful tool even for not CFTs

$V_w << 1$ for SU(3) YM

Kinetic Term very important sharp rise around PT

GW signal enhanced at larger N_c