# **Gravitational waves from composite dark sectors**

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**RP, M. Reichert, F. Sannino and Z.W. Wang, JHEP 02 (2024) 159, 2309.16755**

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# Strongly coupled dynamics: outlook

- **O** Important physical examples of gauge fields are realised in Nature (QCD and electroweak interactions)
- Non porturbativ Non-perturbative QCD phenomena are far from being understood (e.g. quark confinement, mass gap, OCD phase t (e.g. quark confinement, mass gap, QCD phase transitions,<br>hot/dense OCD phenomena etc)  $\mathbf{s}$ . quant commentency mass  $\mathbf{s}$ ap,  $\mathbf{c}$ es phase cransic hot/dense QCD phenomena etc) what component component sectors the strongly control of the strongly control of the strongly control of the s<br>The strongly control of the strongly control of the strongly control of the strongly control of the strongly co (ii) Cosmic strings
	- $G$  background as a gravitational probe for  $\mathcal{G}$  as a gravitational probe for  $N$ of the Standard Model (e.g. GUTs, string/EDs compactifications etc) (iii) **Strong cosmological phase transitions (PTs)** !  $b$  - abelian gauge (Tang-Mills) news are present in mi **O** Non-abelian gauge (Yang-Mills) fields are present in most of UV completions <br>
	of the Standard Medel (e.g. GUTs, strips/EDs sempectifications ats)
		- Confining dark Yang-Mills sectors are often considered as a States of paintments. In the striverse (sign administration) source of Dark Matter in the Universe (e.g. dark glueballs) **Confining dark Yang-Mills sectors are often considered as a possible**<br>Course of Dark Matter in the Universe (e.g. dark glueballs)
		- Study a simple model with **multiple-step strongly 1**st**-order** EWPTs **GW background as a gravitation as a gravitation of New Physics**  $Dirac$  gluance Pure gluons Stockhause Gravitations **O** Pure gluons

 $A_{\rm{max}}$  and  $\sigma$  and  $\sigma$  and  $\sigma$  and  $\sigma$  multi-step electroweak phase transition  $\sigma$  and  $2$  /  $\rightarrow$  Commenter accommentation prided transition  $\alpha$ i are gravits<br>confinament-deconfinament phase transition  $\Rightarrow$  commentent-decording value phase transition (i) Inflation  $\Rightarrow$  confinement-decor  $\Rightarrow$  confinement-deconfinement phase transition

- $G(x) = \frac{1}{2} \int_{0}^{x} \frac{1}{x} e^{-x} dx$ Gluons + fermions Pure gluons ) confinement-deconfinement phase transition  $U$ a Gluons + fermions  $F$ Figures in fundamental representation  $\mathcal{F}$
- $\rightarrow$  a Ferminne in fundamental representation  $\rightarrow$  chiral phase transitions  $\Rightarrow$  • Fermions in fundamental representation  $\Rightarrow$  chiral phase transition
	- APM, RP, TV (AU, LU,NPI, UPS) Multi-peaked signatures of primordial gravitational gravitation July 2nd, 2018 4 / 26<br>Apple transition July 2nd, 2018 4 / 261 / 262 / 263 / 264 / 264 / 265 / 265 / 266 / 267 / 268 / 268 / 268 • Fermions in adjoint rep.  $\Rightarrow$  confinement & chiral phase transition  $\epsilon$  Fermions in adioint rep.  $\Rightarrow$  confinement & chiral phase transit
- $\blacksquare$  Studiente-strong processes and  $\blacksquare$  processes on Germions in 2-index symmetric rep  $\rightarrow$  confinement & c  $\bullet$  Fermons in Z-muck symmetric rep.  $\rightarrow$  commenien • Fermions in 2-index symmetric rep.  $\Rightarrow$  confinement & chiral phase transition Gluons + Fermions + Ferm

## **Polyakov Loop Model for pure gluons I Stockastic Gravitation Control Gravitation** Introduction

- Pisarski first proposed the Polyakov-loop Model as an effective field  $\bullet$ theory to describe the confiner theory to describe the confinement-deconfinement phase transition of  $SU(N)$  as  $SU(N)$  gauge theory (Pisarski, PRD 62 (2000) 111501).
- $\ln a \text{ local } S U(N)$  cauga theory a global In a local *SU*(*N*) gauge theory, a global center symmetry *Z*(*N*) is used to In a local  $SU($  . a local  $SU(1V)$  yauge theory, a global cent distinguish confinement phase distinguish confinement phase (unbroken phase) and deconfinement phase (broken phase) phase (broken phase)
- An order parameter for the  $Z(N)$  symmetry is constructed using the Polyakov Loop (thermal Wilson line) (Polyakov, PLB <sup>72</sup> (1978) 477) Polyakov Loop (thermal Wilson line) (Polyakov, PLB 7: An order narameter for the  $Z(N)$  symmetric biusi parameter ior the  $Z(Y)$  symmetry r An order parameter for the

$$
\mathbf{L}(\vec{x}) = \mathcal{P} \exp\left[i \int_0^{1/T} A_4(\vec{x}, \tau) d\tau\right]
$$

- The symbol  $P$  denotes path ordering and  $A_4$  is the Euclidean temporal component of the gauge field  $F_{\rm F}$  and  $F_{\rm F}$  is the EW phase transition (EWPT) relevant  $\frac{1}{4}$  relevant for EWPT) relevant for EW baryon for EWPT. component or the gauge held  $\bullet$  The symbol  $D$  denotes noth or
- The Polyakov Loon transforms like an adjoint field • The Polyakov Loop transforms like an adjoint field under local  $SU(N)$ The Polvakov (iii) **Strong cosmological phase transitions (PTs)** ! gauge transformations Study the impact of multiple-step strong PTs on GW spectra by expanding and colliding vacuum bubbles of new phase (i) Inflation

#### Polyakov Loop Model for pure gluons II Stochastic Gravitation and Gwelen Company of the Gwelen Company of t Polyakov Loop Model for pure gluons II

Convenient to define the trace of the Polyakov loop as an order parameter for the  $Z(N)$  symmetry only operation fluctuations that  $\blacksquare$  Definitive define the wave-order include its wave-function  $Z(N)$  symmetry

$$
\ell\left(\vec{x}\right)=\frac{1}{N}\text{Tr}_c[\mathbf{L}]\,,
$$

where  $\text{Tr}_c$  denotes the trace in the colour space. d**q**<sup>2</sup>  $\frac{1}{2}$ 

• Under a global  $Z(N)$  transformation, the Polyakov loop  $\ell$  transforms as a field with charge one **ICIU WILLI** 

$$
\ell \to e^{i\phi} \ell, \qquad \phi = \frac{2\pi j}{N}, \qquad j = 0, 1, \cdots, (N - 1)
$$

• The expectation value of  $\ell$  i.e.  $< \ell >$  has the important property: The expectation Stochastic Gravitational Wave (GW) background xpeciation value of  $\ell$  i.e.  $\lt \ell >$  rias the lift

 $\langle \ell \rangle = 0$  (*T* < *T<sub>c</sub>*, Confined);  $\langle \ell \rangle > 0$  (*T* > *T<sub>c</sub>*, Deconfined)  $\langle \ell \rangle = 0$  (1 < 1<sub>c</sub>, Confined);  $\langle \ell \rangle > 0$  (1 >  $\langle \rho \rangle$  $\langle v \rangle = 0$  (1 \ 1c, commonly,  $\langle 2 \rangle = 0$ <sup>2</sup> *r*  $\langle T_c, \text{Cor}$  $\begin{pmatrix} 1 \\ 2 \end{pmatrix}$ @¯ d*r*  $T > T_c$ @*V*eff  $\overline{D}$ 

At yery high temperature the vacua exh At very high temperature, the vacua exhibit a *N*-fold degeneracy: At very high te very inghitemperature, the vacua exilibit a

$$
\langle \ell \rangle = \exp\left(i\frac{2\pi j}{N}\right)\ell_0, \qquad j = 0, 1, \cdots, (N-1)
$$

where  $\ell_0$  is defined to be real and  $\ell_0 \to 1$  as  $T \to \infty$ Study a simple model with **multiple-step strongly 1**st**-order** EWPTs by expanding and colliding vacuum bubbles of new phase def  $\int$   $\rightarrow \infty$ 

### **Effective PLM potential example Frame PLM potential entital of the Polyakov Loop Model: Internative Model:** Stockastic Gravitation and Wave (Gw) background wave (Gw) background wave (Gw) background wave (Gw) background

The simplest effective potential preserving the  $Z_N$  symmetry in the polynomial form is given by (Pisarski, PRD **<sup>62</sup>** (2000) 111501) organomik

$$
V_{\text{PLM}}^{(\text{poly})} = T^4 \left( -\frac{b_2(T)}{2} |\ell|^2 + b_4 |\ell|^4 + \dots - b_3 (\ell^N + \ell^{*N}) \right)
$$
  
where  $b_2(T) = a_0 + a_1 \left( \frac{T_0}{T} \right) + a_2 \left( \frac{T_0}{T} \right)^2 + a_3 \left( \frac{T_0}{T} \right)^3 + a_4 \left( \frac{T_0}{T} \right)^4$ 

- " $\cdot \cdot \cdot$ " represent any required lower dimension operator than  $\ell^N$  i.e.  $(\ell\ell^*)^k = |\ell|^{2k}$  with  $2k < N$ .  $\mathcal{S}$   $\mathcal{S}$  we have  $\mathcal{S}$  and  $\mathcal{S}$  and  $\mathcal{S}$  and  $\mathcal{S}$  and  $\mathcal{S}$  and  $\mathcal{S}$ 
	- For the  $SU(3)$  case, there is also an alternative logarithmic form For the  $SU(3)$

$$
V_{\text{PLM}}^{(3\text{log})} = T^4 \left( -\frac{a(T)}{2} |\ell|^2 + b(T) \ln(1 - 6|\ell|^2 + 4(\ell^{*3} + \ell^3) - 3|\ell|^4) \right)
$$

$$
a(T) = a_0 + a_1 \left( \frac{T_0}{T} \right) + a_2 \left( \frac{T_0}{T} \right)^2 + a_3 \left( \frac{T_0}{T} \right)^3, \quad b(T) = b_3 \left( \frac{T_0}{T} \right)^3
$$

The  $a_i,\,b_i$  coefficients in  $V_{\sf PLM}^{\sf (poly)}$  and  $V_{\sf PLM}^{\sf (3log)}$  are determined by fitting the lattice results and multiple-step strongly 1st The  $\epsilon$  b coofficiente in  $L^{r(poly)}$  and  $L^{r(3log)}$  are determent The  $a_i, b_i$  coeff (i) Inflation

#### Fitting the PLM potential to the lattice data  $F = \frac{1}{2}$ Marco Panero, Phys.Rev.Lett. 103 (2009) 232001 1



#### **Lattice data**

**Best fit of the PLM potential**

Huang, Reichert, Sannino and Wang, PRD 104 (2021) 035005

Marco Panero, Phys.Rev.Lett. 103 (2009) 232001



## **Including fermions: the PQM model Including**

(B. Schaefer, J. Pawlowski, J. Wambach PRD **76** (2007) 074023; B. Schaefer, M. Wagner, PPNP **62** (2009) 391) Pasechnik, Reichert, Sannino and Z-W W,JHEP **02** (2024) 159. B. Schaefer, J. Pawlowski, J. Wambach PRD 76 (2007) 074023 B. Schaefer, M. Wagner, PPNP 62 (2009) 391 RP, Reichert, Sannino and Wang, JHEP 02 (2024) 159

 $\overline{I}$ 

- Stochastic Gravitational Wave (GW) background The Polyakov quark meson model (PQM) is widely used as an effective theory to study the first order chiral phase transition theory to study the first order chiral
- The Lagrangian of the PLSM where mesons couple to a spatially constant temporal background gauge field reads constant temporal background gauge field re

$$
\mathcal{L} = \bar{q} (i\rlap{\,/}D - g (\sigma + i\gamma_5 T^a \pi_a)) q + \frac{1}{2} (\partial_\mu \sigma)^2 + \frac{1}{2} (\partial_\mu \pi_a)^2
$$

$$
-V_{\rm PLM}^{\rm (poly)} + V_{\rm LSM} + V_{\rm medium}, \text{where } \rlap{\,/}D = \gamma_\mu \partial_\mu - i\gamma_0 A_0
$$

 $V_{\rm LSM}$  under symmetry  $SU(N_f)\times SU(N_f)$  with  $N_f$  flavours reads  $\frac{1}{\sqrt{2}}$  phase transition  $\frac{1}{\sqrt{2}}$  baryon  $\frac{1}{\sqrt{2}}$  baryon  $\frac{1}{\sqrt{2}}$  baryon  $\frac{1}{\sqrt{2}}$  $V_{\rm LSM}$  under s

$$
V_{\text{LSM}} = \frac{1}{2} (\lambda_{\sigma} - \lambda_{a}) \operatorname{Tr} [\Phi^{\dagger} \Phi]^{2} + \frac{N_{f}}{2} \lambda_{a} \operatorname{Tr} [\Phi^{\dagger} \Phi \Phi^{\dagger} \Phi] - m^{2} \operatorname{Tr} [\Phi^{\dagger} \Phi] - 2 (2N_{f})^{N_{f}/2 - 2} c (\det \Phi^{\dagger} + \det \Phi)
$$

where the meson field  $\Phi$  is a  $N_f \times N_f$  matrix defined as

$$
\Phi = \frac{1}{\sqrt{2N_f}} (\sigma + i\eta') I + (a_a + i\pi_a) T^a , I \equiv \text{identity matrix}
$$

## Thermatic or rections: the CJT Method **Thermal corrections: the CJT Method**

J. Cornwall, R. Jackiw, E. Tomboulis PRD 10 (1974) 2428<br>
J. Cornwall, R. Jackiw, E. Tomboulis PRD 10 (1974) 2428 Pasechnik, Reichert, Sannino and Z-W W, JHEP **02** (2024) 159. G. Amelino-Camelia, PRD 47 (1993) 2356 RP, Reichert, Sannino and Wang, JHEP 02 (2024) 159

- Cornwall, Jackiw and Tomboulis (CJT) first proposed a generalized  $\mathcal{L}$  statistic Gravitational Wave ( $\mathcal{L}$   $\mathcal{L}$ ) of equal  $\mathcal{L}$ Introduction effective action  $\Gamma$   $(\phi, G)$  of composite operators, where the effective enective<br>Cotion po action not only depends on  $\phi(x)$  but also on the propagator  $G(x,y)$
- The effective action becomes the general The effective action becomes the generating functional of the two-particle The effective  $\bullet$ by experience and colliding vacuum bubbling incorporation of new phase of new phase of new phase of  $n$ Stockhold Gravitation Cooperation irreducible (2PI) vacuum graphs rather than the conventional 1PI III BUUCIDI<br>Mindromo diagrams as a gravitation of unresolved as a gravitation of unresolved as a gravitation of unresolved astrophysics of unresolved astrophysics as a gravitation of unresolved astrophysics as a gravitation of unresolved astro
- The C<sub>ul</sub>T method is equivalent to summing The CJT method is equivalent to summing up the infinite class of "daisy" The CJT meth by expanding and colliding and colliding vacuum bubbles of new phase of new phase of new phase of new phase of n and "quinor doiou" aronho and i and "super daisy" graphs and is thus useful in studying such strongly coupled models beyond mean-field approximation
- The POM with the CJT method compare The PQM with the CJT method compared to other model computations The PQM with  $\blacksquare$ ic revivi with the OUT method compared to t such as holography and the PNJL model, can bridge perturbative and **JULIE UP** non-perturbative regimes of the effective theory

### **First-order phase transitions and bubble's nucleation** s of user primes afunctions untust

- In a first-order phase transition, the transition occurs via bubble nucleation and it is essential to compute the nucleation rate
- (i) Inflation The tunnelling rate due to thermal fluctuations from the metastable The tunnelling rate due to ther vacuum to the stable one is suppressed by the three-dimensional  $E<sub>II</sub>$ didoor Euclidean action  $S_3(T)$ Eddingodi i dolio

$$
\Gamma(T) = T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} e^{-S_3(T)/T}
$$

The generic three-dimensional Euclidean action reads Study a simple model with **multiple-step strongly 1**st**-order** EWPTs The generic thre Introduction **JULE SETTEM** 

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

where  $\rho$  denotes a generic scalar field with mass dimension one,  $[\rho]=1$  $\mathbf{C}$ WHELE  $\rho$  deficies a generic scalar field with mass difference from  $\rho_\parallel =$  $S_{\rm T}$  the impact of multiple-step strong PTs on  $P_{\rm T}$  strong PTs on  $G_{\rm T}$  strong PTs on  $G_{\rm T}$ where  $\rho$  denotes a generic scalar field with

- Thucleation per Hubble volume and time is order one:  $1/H^2 \sim U(1)$ The phase-transition temperature  $T_*$  is often identified with the nucleation temperature  $T_n$  defined as the temperature where the rate of bubble nucleation per Hubble volume and time is order one:  $\Gamma/H^4 \sim \mathcal{O}(1)$ GW Tho phase transition tomporature  $T$  is often • The phase-transition temperature  $T$ io importier inducation per i nucleation per Hubble volume and time is  $\overline{\phantom{a}}$  The nhase
	- More accurately, we can use percolation temperature  $T_p$ : the temperature at which  $34\%$  of false vacuum is converted
	- Ear cufficiantly fact phase transitions the decay re **For sufficiently fa** For sufficiently fast phase transitions, the decay rate is approximated by: **TOI SUITCITLITY**  $G_{\rm{M}}$  background as a gravitational probe for  $N$  as a gravitational probe for  $N$

$$
\Gamma(T) \approx \Gamma(t_*) e^{\beta (t - t_*)}
$$

# **Phase transition characteristics**

The inverse duration time then follows as 

$$
\beta = -\frac{\mathrm{d}}{\mathrm{d}t} \frac{S_3(T)}{T} \Big|_{t=t_*}
$$

Huang, Reichert, Sannino, Wang PRD 104 (2021) 035005

The dimensionless version  $\tilde{\beta}$  is defined relative to the Hubble parameter  $H_*$  at the characteristic time  $t_*$ (iii) **Strong cosmological phase transitions (PTs)** ! The dimensionless version  $\tilde{\beta}$  is defined relative to the  $G_{\rm{M}}$  background as a gravitational probe for  $N_{\rm{H}}$  as a gravitational probe for  $N_{\rm{H}}$  $H_*$  at the c

$$
\tilde{\beta} = \frac{\beta}{H_*} = T \frac{\mathrm{d}}{\mathrm{d}T} \frac{S_3(T)}{T} \bigg|_{T = T_*},
$$

where we used that  $dT/dt = -H(T)T$ .

• We define the strength parameter  $\alpha$  from the trace of the energy-momentum tensor  $\theta$  weighted by the enthalpy 3 *w*<sup>+</sup> ✓ • We define the strength parameter  $\alpha$  from the trace of the Study the impact of multiple-step strong PTs on GW spectra  $\mathbf{r}$  photon conduct tensor  $\theta$  weighted by the enthalpy We define the strength parameter  $\alpha$  from the trace of the  $\mathbf{r} \theta$  weighted by th

$$
\alpha = \frac{1}{3} \frac{\Delta \theta}{w_+} = \frac{1}{3} \frac{\Delta e - 3\Delta p}{w_+}
$$
,  $\Delta X = X^{(+)} - X^{(-)}$ , for  $X = (\theta, e, p)$ 

 $(+)$  denotes the meta-stable phase (outside of the bubble) while  $(-)$ denotes the stable phase (inside of the bubble). *w* = @*p* @ ln *<sup>T</sup> , <sup>e</sup>* <sup>=</sup>  $\mathcal{S}$  the impact of multiple-step strong PTs on  $\mathcal{S}$  on  $\mathcal{S}$  on  $\mathcal{S}$  on  $\mathcal{S}$  on  $\mathcal{S}$  on  $\mathcal{S}$  $\left( \begin{array}{c} \cdot & \cdot \\ \cdot & \cdot \end{array} \right)$  denotes the stable pheene (ineide of the bubb  $(1)$  denotes the stable phase (inside of the bubble). rioles trie m<br>re the stable s  $1$ -Sidi  $\lambda$ **le** phase oursiue)<br>tho bubb of the bu pole) wrille Introduction

The relations between enthalpy *w*, pressure *p*, and energy *e* are given by • The relations between enthalpy  $w$ , pressure  $p$ , and energy  $e$  are given by

$$
w = \frac{\partial p}{\partial \ln T} \,, \qquad \qquad e = \frac{\partial p}{\partial \ln T} - p \,, \qquad \qquad p^{(\pm)} = -V_{\rm eff}^{(\pm)}
$$

 $\tau_{\mathsf{sw}}$  is suppressed for large  $\beta$  occurring often in strong  $\overline{\mathsf{U}}$ Study the impact of multiple-step strong PTs on GW spectra (iii) **Strong cosmological phase transitions (PTs)** !  $\tau_{\mathsf{sw}}$  is suppressed for large  $\beta$  occurring often in strongly coupled sectors

# Gravitational wave spectrum: an outlook

**6. Caprini et al., JCAP 03, 024,<br>1910.13125** C. Caprini et al., JCAP 03, 024, 1910.13125

11 4

Contributions from bubble collision and turbulence are subleading The GW spectrum from sound waves is given by Contributions from bubble collision and turbulence are subleading<br>The CW spectrum from equipal usuan is sitten by: (i) Inflation **Contribution** 

$$
h^2 \Omega_{\rm GW}(f) = h^2 \Omega_{\rm GW}^{\rm peak} \left(\frac{f}{f_{\rm peak}}\right)^3 \left[\frac{4}{7} + \frac{3}{7} \left(\frac{f}{f_{\rm peak}}\right)^2\right]^{-\frac{7}{2}}
$$

The peak frequency 

$$
f_{\text{peak}} \simeq 1.9 \cdot 10^{-5} \,\text{Hz} \left(\frac{g_*}{100}\right)^{\frac{1}{6}} \left(\frac{T}{100 \,\text{GeV}}\right) \left(\frac{\tilde{\beta}}{v_w}\right)
$$

The peak amplitude Study a simple model with **multiple-step strongly 1**st**-order** EWPTs **by the peak amplitude vacuum bubbles of new phases** 

$$
h^{2}\Omega_{\text{GW}}^{\text{peak}} \simeq 2.65 \cdot 10^{-6} \left(\frac{v_{w}}{\tilde{\beta}}\right) \left(\frac{\kappa_{sw} \alpha}{1+\alpha}\right)^{2} \left(\frac{100}{g_{*}}\right)^{\frac{1}{3}} \Omega_{\text{dark}}^{2} \qquad \Omega_{\text{dark}} = \frac{\rho_{\text{rad},\text{dark}}}{\rho_{\text{rad},\text{tot}}}
$$

- The factor  $\Omega_{\text{dark}}^2$  accounts for the dilution of the GWs by the non-participating SM d.o.f.  $\bullet$  The factor  $\Omega_{\text{dark}}^2$  accounts for<br>non-narticipating SM d o f  $\begin{bmatrix} 1 \\ 2 \end{bmatrix}$ *f*  $GW$ *v w w w* The factor  $\Omega^2$  , accounts for the dilution of the GWs by the The ladior suppression and measured in the sound-wave period in the Hubble time radio  $\frac{1}{2}$  and  $\frac{1}{2}$ The factor  $\Omega_{\text{dark}}^2$  accounts for the dilution of the GWs by the The factor  $\Omega_{\rm dark}^2$  accounts for the dilution of the GWs by the phase of the phase of  $\Omega_{\rm dark}$ 
	- ior trie sound v additional suppression due to the length of the sound-wave period  $\tau_\mathsf{sw}$  $\mathsf{a}$  $_{\mathsf{sw}}$  cor • The efficiency factor for the sound waves  $\kappa_{\text{sw}}$  consist of  $\kappa_v$  as well as an  $\mathbf{s}$  is suppressed for large in strongly coupled sectors in strongly coupled sectors. *v* waves  $\kappa_{\text{SW}}$  consist of  $\kappa_v$  as well as an  $\alpha$  and  $\kappa_v$ non participating onitation<br>The efficiency factor for the sound wayes represented for the struggles and additional suppression due to the length of the sound-wave period  $\tau_{\mathsf{sw}}$  $\tau_{\textsf{sw}}$ ه د ..<br>۱۱۵ e length o d-wave p for *>>* 1 additional suppression due to the length of the sound-• The efficiency factor for the sound waves  $\kappa_{\textsf{sw}}$  c  $\mathsf{T}_{\mathsf{ho}}$  officion ITIU UIIIUIUIUJ IUI additional suppression due to the length of the sou The efficiency fac

$$
\kappa_{\text{sw}} = \sqrt{\tau_{\text{sw}}} \, \kappa_v \qquad \tau_{\text{sw}} \sim \frac{(8\pi)^{\frac{1}{3}} v_w}{\tilde{\beta} \, \bar{U}_f} \quad \text{for } \beta >> 1 \qquad \kappa_v (v_w = v_J) = \frac{\sqrt{\alpha}}{0.135 + \sqrt{0.98 + \alpha}}
$$
\n
$$
\text{where } \bar{U}_f \text{ is the root-mean-square fluid velocity} \qquad \bar{U}_f^2 \simeq \frac{3}{4} \frac{\alpha}{1 + \alpha} \kappa_v \qquad (11)
$$

## Phase diagram and gravitational waves in the PQM model

RP, Reichert, Sannino and Wang, JHEP 02 (2024) 159



## **Summary:**

- We developed a new approach based upon the well-established thermal EFT confining gauge theories incorporating confinement effects and nonperturbative self-interactions (iii) **Strong cosmological phase transitions (PTs)** ! **and the existing lattice results to explore phase structure and PTs in**  a *IN<sub>te</sub>* develop
- utilising the CJT method and computed the resulting primordial interactions and light sigma meson relevant for example,  $\epsilon$ **• We analysed the phase transitions in the Polyakov-loop extended LSM** gravitational wave spectra showcasing an enhancement for weak sigma selfinteractions and light sigma meson 11 and 11 an (iii) **Strong cosmological phase transitions (PTs)** !
- Studies of the impact to the chinamics<br>The strength of the chiral phase transition and  $\theta$  $\frac{1}{\sqrt{2}}$  compared to ESM phase transition (EWPT) relevant for  $\frac{1}{\sqrt{2}}$ Inclusion of the Polyakov loop enhances **the strength of the chiral phase transition Compared to LSM** (ii) Cosmic strings
- The DI SM represents an important framework of new phase  $\sim$ The PLSM represents an important framework for analysis of various cosmological implications For analysie of the tear coemicles. Can in probe her of strongly coupled dynamics in consistency with lattice simulations  $\frac{1}{2}$

