COSMIC "COLLIDERS": HIGH ENERGY PHYSICS WITH FIRST ORDER PHASE TRANSITIONS

FUNDAMENTAL PHYSICS AND GRAVITATIONAL WAVE DETECTORS WORKSHOP

POLLICA PHYSICS CENTRE

SEPTEMBER 9, 2024 BIBHUSHAN SHAKYA

ABOUT ME

Currently: Junior Staff Scientist in Theory (Cosmo) group at DESY

Previously: Undergraduate @ Stanford University Ph.D. @ Cornell University Postdocs at U. Michigan, U.Cincinnati/UC Santa Cruz, CERN

Research Background / Interests:

Broadly high energy phenomenology: dark matter, hidden sectors, connections with neutrinos, Higgs dynamics in the early Universe, gravitational wave phenomena from the early Universe

FIRST ORDER PHASE TRANSITIONS

One of the most promising+widely studied cosmological source of gravitational waves

In the runaway case, bubble collisions also act as high energy colliders that reach energy scales possibly far higher than any temperature or energy ever reached in our cosmic history

 $E_{\text{wall}} = \gamma_{\text{max}}/l_{w0} \sim M_{Pl}/(\beta/H)$

3

ground field is a complicated phenomenon due to the highly inhomogeneous nature of the process. UNDERSTANDING THE PHYSICS OF BUBBLE COLLISIONS was first studied in $[50]$ in $[50]$ in $[50]$, and the formalism in $[50]$, and $[50]$ **PRODUCE COLLISIONS**

The probability of particle production from the dynamics of the field is given by the imaginary

$\overline{380}$, and recently refined with numerical studies of more realistic second with numerical studies of more realistic se-Use the **effective action formalism:** *Watkins+Widrow Nucl.Phys.B* 374 (1992) 1

 $\frac{1}{2}$ = 10 $\frac{1}{2}$ = 10 $\frac{1}{2}$ = 10 $\frac{1}{2}$

interested readers is reader in the Probability of particle production: **Probability of particle production:** $\overline{ }$ $\overline{$ *n*=2 *n*! *d*4*x*1*...d*4*xn*(*n*)

imeginery next of the effective ection of the heelzeround field part of its evening of \mathbf{p}_i **imaginary part** of the effective action of the background field

………

 $\mathcal{P} = 2 \operatorname{Im} \left(\left. \Gamma[\phi] \right. \right)$ Z *d*4*p*

Konstandin+Servant *1104.4793 [hep-ph]* (*x*1*, ..., xn*)(*x*1)*...*(*xn*)*.* (9) *Falkowski+No 1211.5615 [hep-ph]*

Im(˜(2)(*p*2))*,* (10)

where ϵ is the e ϵ -ction, is the generating function, is the generating function, is the generating function ϵ $\frac{1}{2}$ into to **Four** re *cc* Each mode can be interpreted as **off-shell field probability** *d*4*x*1*...d*4*xn*(*n*) muo **Fourier modes**

Fech meda een he intermeted es eff shell field The leading with given four momentum that can accay Im ([]) = ¹ *d*_{$f(x)$} $\frac{1}{2}$ ¹⁷ $(p_z, \omega)|^2 \ln$ (2⇡)⁴ *^eip*(*x*1*x*2) Im(˜(2)(*p*2))*,* (10) 2 *d*4*x*1*d*4*x*2(*x*1)(*x*2) (2⇡)⁴ *^eip*(*x*1*x*2) **Executives** Cackground neid CA ble with aiven four-momentum that can decay
Each mode can be interpreted as our-shell lield
 \boldsymbol{p} quanta with given four-momentum that can decay bubble walls can be written as \mathcal{S} $\frac{N}{A}=2\int\frac{dp_z\,d\omega}{(2\pi)^2}\,|\tilde{\phi}(p_z,\omega)|^2\,\mathrm{Im}[\tilde{\Gamma}^{(2)}(\omega^2-p_z^2)]$ *^z*)] *.* (11) **Decompose** background field excitation into **Fourier modes** 2 point 1PI Green function. **quanta with given four-momentum** that can decay

2 Efficiency **at high p falls as** $\sim 1/p^4$ **power law,** independent of the details of the collision

 D $C\cup\Lambda$ V V Λ Q Q Q Q Q I L Q Q Λ *z b i b* interpreted as (o⊥-shell) proposed as (o</u> the theory of the the B. SHAKYA, 2308.16224

H. MANSOUR, B. SHAKYA, 2308.13070 ble walls are planar and collisions occur in the *^z*direction, so that ˜(*p*) = (2⇡)2(*px*)(*py*)˜(*pz,* !).

NONTHERMAL DARK MATTER PRODUCTION

G. GIUDICE, H.M.LEE, A.POMAROL, B.SHAKYA, 2403.03252

$$
\tfrac{\lambda_s}{4}\phi^2\chi_s^2
$$

Contours:

Size of coupling needed to produce the correct dark matter relic density

Vertical dashed lines:

sensitivity of various GW experiments

\blacksquare via particle production from bubble collisions. We estimate the baryon asymmetry generated

en issentsis
Cataldi, Shakya, 2407.16747

The simplest extension: couple N to FOPT field, mirroring the same interaction The simplest extension: couple N to FOPT field, mirroring the same interaction

 $\mathcal{L} \supset y_D \phi \chi N + y_\nu L H N + M_N N N$

$$
\phi^* \to \chi N
$$

Inverse "decays" absent/ inefficient: no washout!

Contours:

amount of baryon asymmetry

NEXT STEPS

• Efficient production of (heavy) particles from bubble collisions provide **a new source of gravitation waves**, possibly with distinct features

Work in progress w/ Kentaro Kasai, Marc Kamionkowski, Keisuke Inamoto

- Production of heavy particles in **specific BSM setups**, with **interesting phenomenological consequences**
- **Improvements to the formalism** for calculating particle production from bubble collisions