# **COSMIC COLLIDERS**

### **HIGH ENERGY PHYSICS WITH FIRST ORDER PHASE TRANSITIONS**

### **DECEMBER 9, 2024**



**Particle Physics and Cosmology in the Himalayas** 





Image Credit: betibup33/Shutterstock.com

### **HIGH ENERGY COLLIDERS (SIMPLIFIED)**

#### 1. Dig a tunnel

- 2. Pump a lot of energy into some object (and make sure it does not lose that energy), making it far more energetic<br>than the ambient temperature
- 3. Collide these objects: unravel the nature of physics/the Universe at high energies





#### **First order phase transition (FOPT)**





#### **The Universe quantum tunnels from one vacuum state to another**





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Releases significant latent energy stored in<br>the false vacuum

Energy pushed to the surface of<br>the expanding bubbles:<br>kinetic+gradient energy in the<br>bubble walls

Ο

## If there are multiple bubbles within a Hubble sized region, these bubbles collide with each other



**Collisions of runaway vacuum bubbles = epic, cosmic scale supercolliders!**

#### **ENERGY SCALE OF COSMIC COLLIDERS** *<sup>P</sup>*NLO ⇠ *<sup>g</sup>*<sup>2</sup> *<sup>w</sup> <sup>m</sup><sup>V</sup> <sup>T</sup>*<sup>3</sup> *,* (3) where *g* is the gauge coupling and *m<sup>V</sup>* is now the mass of the gauge boson, and we have dropped

Energy scale at bubble nucleation: phase transition sc *w*  $\sim$  *v V V C C temperature of plasma* if the *gy*  $\sim$  *g* Energy scale at bubble nucleation: phase transition scale (~ temperature of plasma)

If the frictional energy loss remains subdominant to  $\overline{V}$  , energy conservation distances that  $\overline{V}$ From energy conservation arguments, Lorentz boost factor of the runaway bubble wall grows linearly with<br>bubble size

$$
\gamma \approx \frac{2R}{3R_0}
$$

Bubble wall energy per unit area at point of collision (independent *MP l* of the energy scale of the FOPT!)

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

*v*

Viable scenarios that can realize such 1 runaway behavior needed for producing ultraheavy

where we have used the relations in Sec. 2.1 and assumed the energy density in the energy density in the bubble Physical scale over which bubble collision occurs

 $\begin{array}{rcl} \hline \textbf{P} & = \text{Boosted } \text{bubl} \\ \hline \textbf{P} & & \textbf{P} \end{array}$ = Boosted bubble wall thickness

particles up to this scale. Remarkable,  $E_{\text{wall}} = \gamma_{\text{ma}}$ 

scale *v*, where the bubble walls have lower the bubble scale, which is contributed by a lower Hubble scale, which is contributed by a lower Hubble scale, which is contributed by a lower Hubble scale, which is contributed allows the bubbles to expand for longer before collisions of the bubbles of the bubbles of the bubble walls can get The collision process is sensitive to physics that couples to the background field at this scale!

## **UNDERSTANDING THE PHYSICS OF BUBBLE COLLISIONS**

SHAKYA, 2308.16224; MANSOUR, SHAKYA, 2308.13070; GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252



#### $\overline{380}$ , and recently refined with numerical studies of more realistic second with numerical studies of more realistic se-Use the **effective action formalism:**  $\mathbf{u}$ *<u>fective action form</u>* Z *d*4*p*  $\lim$

interested readers is reader in the Probability of particle production: **Probability of particle production:** 

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

$$
\mathcal{P}=2\,\text{Im}\left(\,\Gamma[\phi\,]\,\right)
$$

 $\ddot{\cdot}$ 

. . . .

Using these and the above expressions, the number of particles produced per unit area of colliding

*Watkins+Widrow Nucl.Phys.B* 374 (1992)

Also

 $\mathcal{P} = 2 \, \mathrm{Im} \, (\, \Gamma[\phi \, ] \, )$  **(8)** Konstandin+Servant *1104.4793 [hep-ph] Falkowski+No 1211.5615 [hep-ph]*  $\mathcal{D} = 2 \operatorname{Im} \left( \left. \Gamma[\phi] \right] \right)$  Konstandin+Servant 1104 4793 [hen-nh]  $\mathcal{F} = 2 \ln \left( \frac{1}{\varphi} \right)$ <br>Falkowski+No 1211.5615 [hep-ph]

Number of of parti Number of particles produced per unit area of bubble wall collision:  $\mathbf{N} = \mathbf{1} \quad \mathbf{C} \quad \mathbf{A} \cdot \mathbf{1}$ 

$$
\frac{N}{A} = 2 \int \frac{dp_z d\omega}{(2\pi)^2} |\tilde{\phi}(p_z, \omega)|^2 \operatorname{Im}[\tilde{\Gamma}^{(2)}(\omega^2 - p_z^2)]
$$
  
2 point 1PI Green function.

Decompos 2 *d*<sub>2</sub> background field exci tation  $\sum_{n=1}^{\infty}$ **Decompose** background field excitation<br> **Decompose** background field excitation momentum *<sup>p</sup>*<sup>2</sup> <sup>=</sup> !<sup>2</sup> *<sup>p</sup>*<sup>2</sup> **2000 are to be interpreted as (o**  $\frac{1}{2}$  **properties** into **Fourier modes**

ary part gives **uecay probabilit**<sub>,</sub> Imaginary part gives **decay probability**

Each mode can be interpreted as off-shell field excitation with a fixed four-momentum ("mass") that can decay

## **UNDERSTANDING THE PHYSICS OF BUBBLE COLLISIONS**

Occupation number of modes with energy >> scale of phase

transition, or temperature of plasma

### $\sim$ **1/E<sub>4</sub>**

#### **UNIVERSAL to all ultrarelativistic collisions**

Numerical studies of bubble collisions: W/ HENDA MANSOUR 2308.13070 Analytic arguments: SHAKYA, 2403.03252



## **UNDERSTANDING THE PHYSICS OF BUBBLE COLLISIONS**

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CAUTION: off-shell excitations are **not manifestly physical configurations**; calculations may be **gauge-dependent**!

W/ GIAN GIUDICE, HYUN-MIN LEE, ALEX POMAROL







## **APPLICATION: HEAVY DARK MATTER**

#### W/ GIAN GIUDICE, HYUN MIN LEE, ALEX POMAROL, 2403.03252



#### **DARK MATTER: SETUP** as well as shape of the GW signal. The GW signal as shape of the GW signal. The GW signal as shape of the GW s<br>The GW signal. The GW signal as the GW sig

**Scalar DM**  $\chi_s$ , with mass  $m_{\chi_s}$  and interaction  $\frac{\lambda_s}{4} \phi^2 \chi_s^2$ .

 $N_{\rm eff}$  renormalizable operator that this is a renormalizable operator that can be valid to arbitrarily high scales. Since  $\alpha$ 

be produced from bubble collisions even if extremely heavy, via Can be produced from bubble collisions even if extremely heavy, via

$$
\phi_p^* \to \chi_s^2, \ \phi \chi_s^2
$$

 $\sigma$  being contributions, such as freeze in from the thermal bath, or other<br>interactions between expanding bubbles and the surrounding plasma, can be important, but become irrelevant if dark matter is extremely heavy Other contributions, such as freeze in from the thermal bath, or other interactions between expanding bubbles and the surrounding plasma, can

 $\alpha$  will be qualitatively similar for fermion or vector dark matter) the SM; however, in this case *m<sup>f</sup>* = *y<sup>f</sup> v* . *v*. Alternately, the e↵ective *yff*¯*<sup>f</sup>* interaction (Story will be qualitatively similar for fermion or vector dark matter)

## **SCALAR DARK MATTER PARAMETER SPACE**

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Contours:

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

Viable over many orders of magnitude in parameter space.

Can be of relevance for current and upcoming GW detectors

## **APPLICATION II: MATTER-ANTIMATTER ASYMMETRY**

#### W/ MARTINA CATALDI, 2407.16747



## **LEPTOGENESIS**

One of the most attractive realizations: produce lepton asymmetry from **out of equilibrium**  One of the most attractive realizations: produce lepton asymmetry from **out of equilibrium**<br>decays of heavy right-handed (sterile) neutrinos, sphalerons convert lepton asymmetry to baryon asymmetry In this setup, the RHNs *N* act as the portal between the dark sector undergoing the FOPT baryon asymmetry broken by the symmetry baryon asymmetry

Can also generate neutrino masses; e.g. type-I seesaw:

 $y_{\nu} L H N + M_N N N$ 

 $T_{\text{HINS}}$  tend to be fieavy: e.g.  $O(1)$  coupling needs  $N_{\text{N}} \sim 10^{14}$  GeV subsequently vasilout close Thermal leptogenesis works for M<sub>N</sub> ~10<sup>7</sup> - 10<sup>14</sup> GeV RHNs tend to be heavy: e.g.  $O(1)$  coupling needs  $M_N \sim 10^{14}$  GeV Strong washout close to this limit

(but no experimental signals, and requires large reheating temperatures above (but no experimental signals, and requires large reheating temperatures above the RHN masses)

### **LEPTOGENESIS VIA BUBBLE COLLISIONS** is a gauge singlet under the symmetry broken by the symmetry broken by the symmetry broken by the symmetry bro<br>In this enables us to write the symmetry broken by the symmetry broken by the symmetry broken by the symmetry

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

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

The first term gives the coupling of *N* to the dark sector, whereas the second term gives its

Dark sector fermion charged under the symmetry broken at the FOPT Dank sector reminon charged under the symmetry broken at the FOFT<br>Gets mass from type-I seesaw (analogous to SM neutrinos). Is like a light sterile neutrino, has a small mixing with SM neutrinos. via this novel mechanism in the neutrino portal setup specified in Sect.2, and later identifying

3 Idea: **Produce heavy RHNs from bubble collisions**

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

Their decays produce the lepton asymmetry. **Since T~v** $\phi$  **<< M<sub>N</sub>, washout effects exponentially suppressed**, easily achieving the **out-of-equilibrium** requirement.

> (Other variations, e.g. involving a l (Other variations, e.g. involving a heavy lepton-number-breaking scalar as the portal, also work ) *,* (20) **,** (2

### **LEPTOGENESIS: PARAMETER SPACE**



Contours: amount of baryon asymmetry

## **PHENOMENOLOGY: GRAVITATIONAL WAVES**

#### W/ KEISUKE INOMATA, MARC KAMIONKOWSKI, KENTARO KASAI, 241X.XXXXX



## **GRAVITATIONAL WAVES FROM FOPTS**

**FOPTs are one of the most promising and well studied cosmological sources of GWs from the early Universe**



W/ Ryusuke Jinno, Jorinde van de Vis 2211.06405

## **GRAVITATIONAL WAVES**

If particle production is efficient, the energy from the phase transition is now primarily stored in a nontrivial dynamic distribution of particles (that can survive long after all the bubbles have disappeared)



**A new source of gravitational waves from phase transitions?**

## **GRAVITATIONAL WAVES**



## **SUMMARY: COSMIC COLLIDERS**

• **Collisions of runaway vacuum bubbles act as high energy colliders**, leading to **particle production with ultrahigh mass, energy** close to the Planck scale

• Recent work: **Improved conceptual understanding and numerical results,**  which show a universal power law scaling of high energy excitations, and that naive calculations are **gauge dependent**

• Many possibilities and applications: **ultraheavy dark matter, high scale leptogenesis, gravitational waves**

