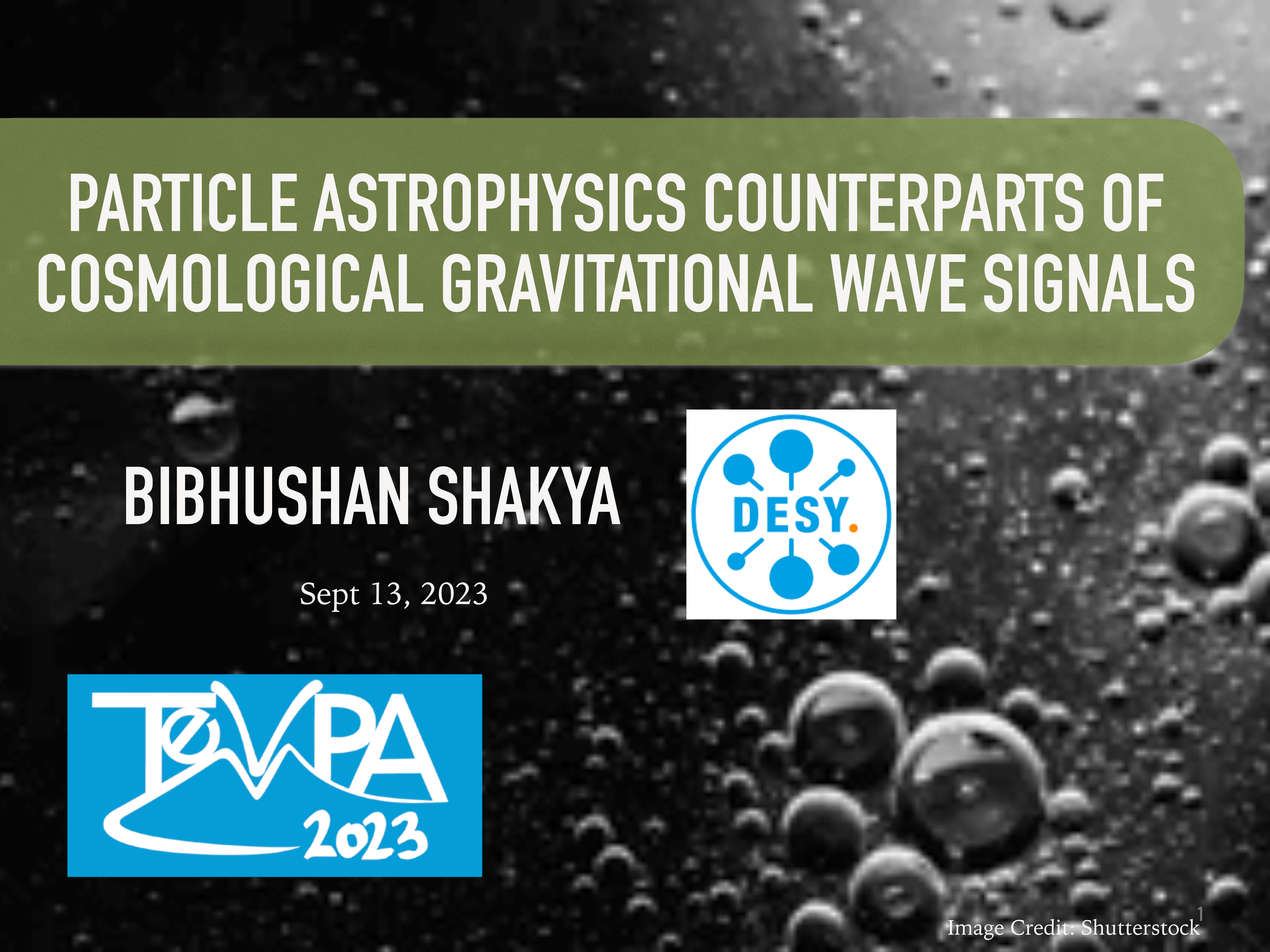


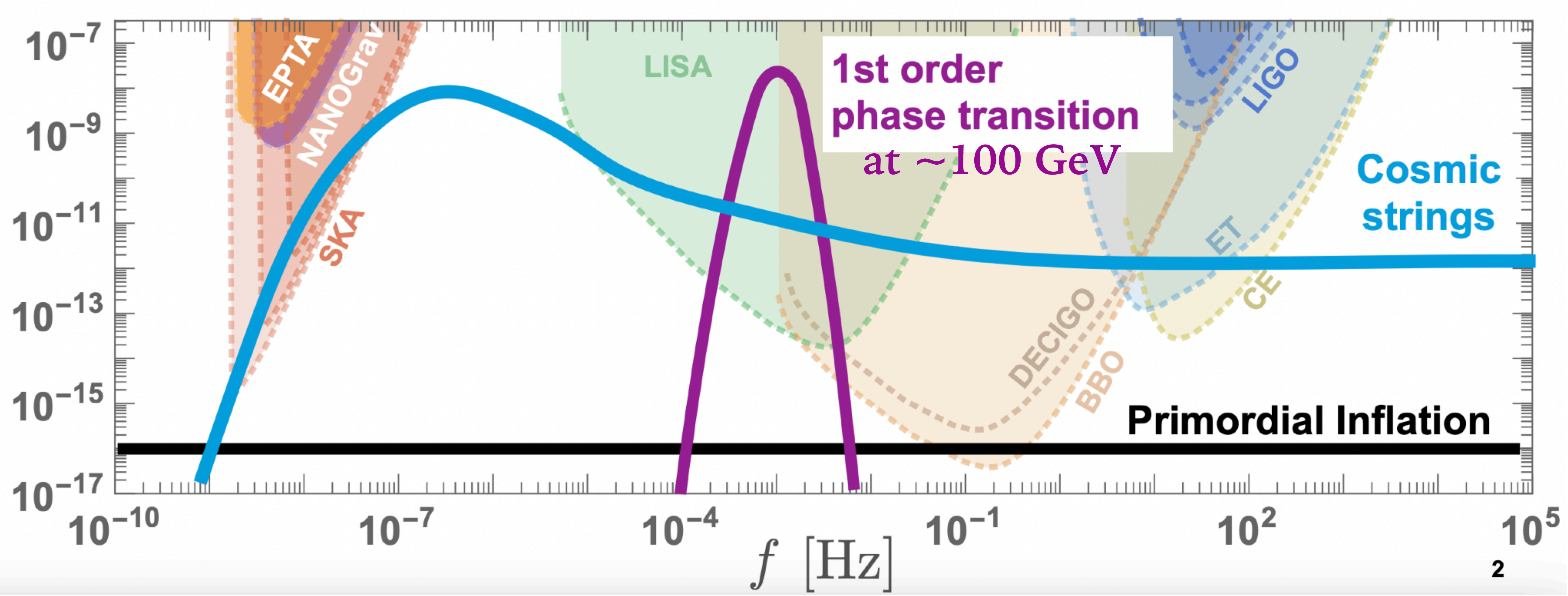
PARTICLE ASTROPHYSICS COUNTERPARTS OF COSMOLOGICAL GRAVITATIONAL WAVE SIGNALS

BIBHUSHAN SHAKYA

Sept 13, 2023

Image Credit: Shutterstock

GRAVITATIONAL WAVES:
A UNIQUE PROBE OF EARLY UNIVERSE PHENOMENA



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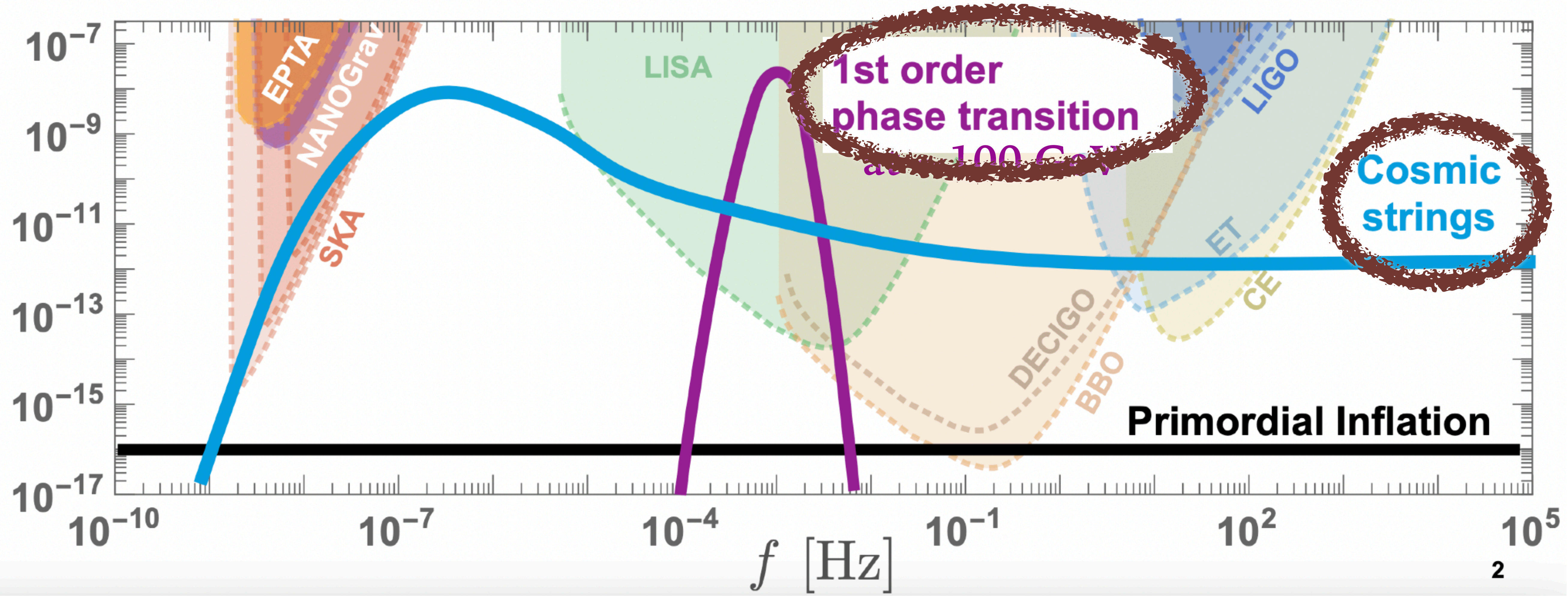


Also promising sources of high energy particle astrophysical phenomena!

THE INTERPLAY OF DIFFERENT ENERGY SCALES

FIRST ORDER PHASE TRANSITIONS

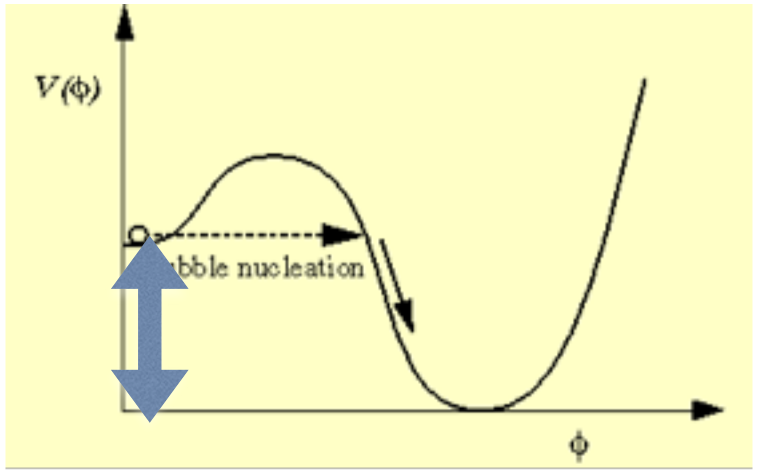
COSMIC STRING (LOOPS)

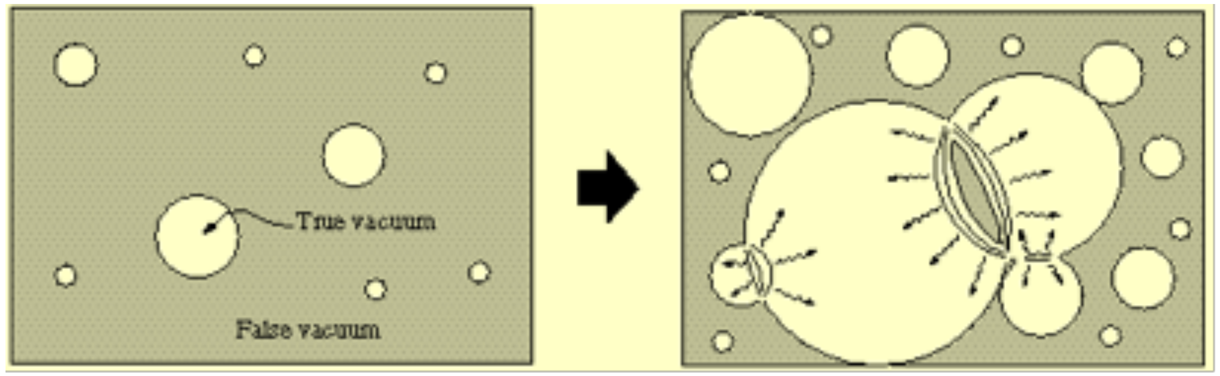
THE INTERPLAY OF DIFFERENT ENERGY SCALES

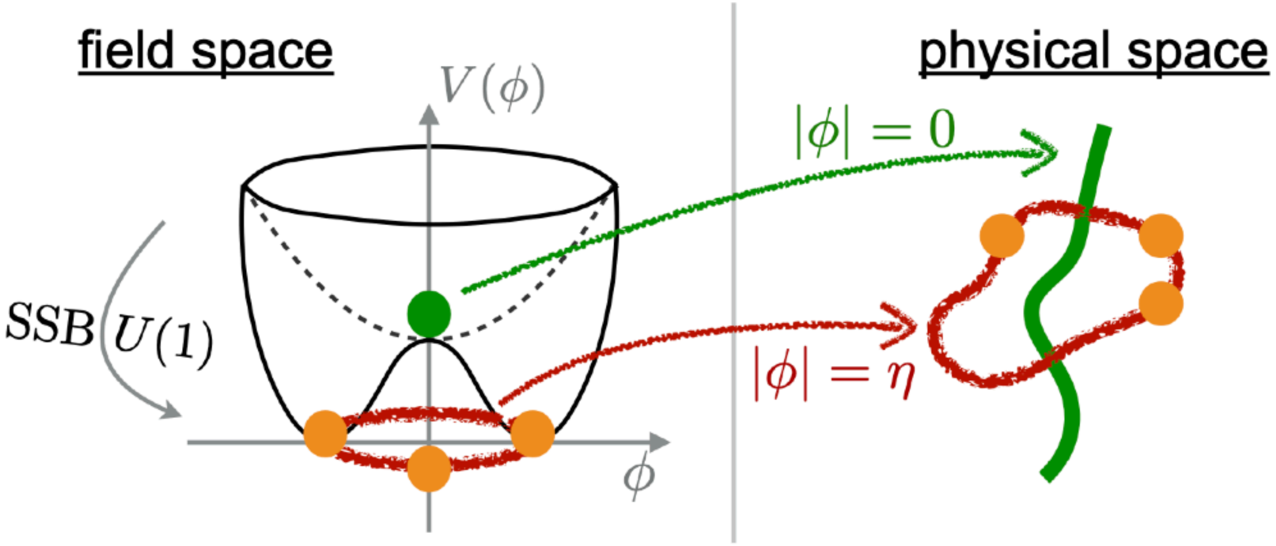
FIRST ORDER PHASE TRANSITIONS

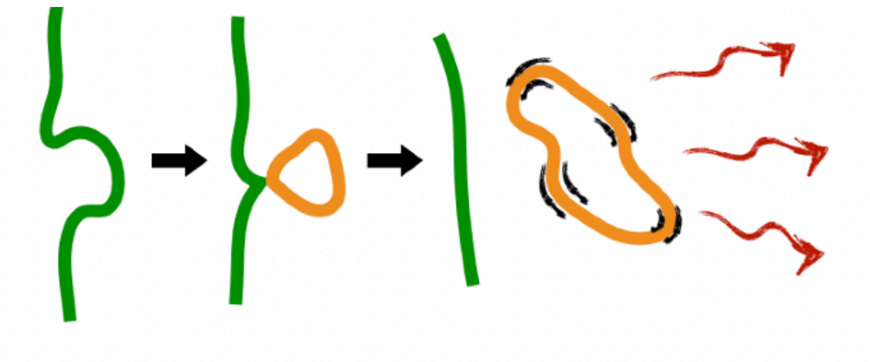
COSMIC STRING (LOOPS)

Topological defects formed due to symmetry breaking at some temperature **T** corresponding to some particle physics symmetry breaking scale









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COSMIC STRING (LOOPS)

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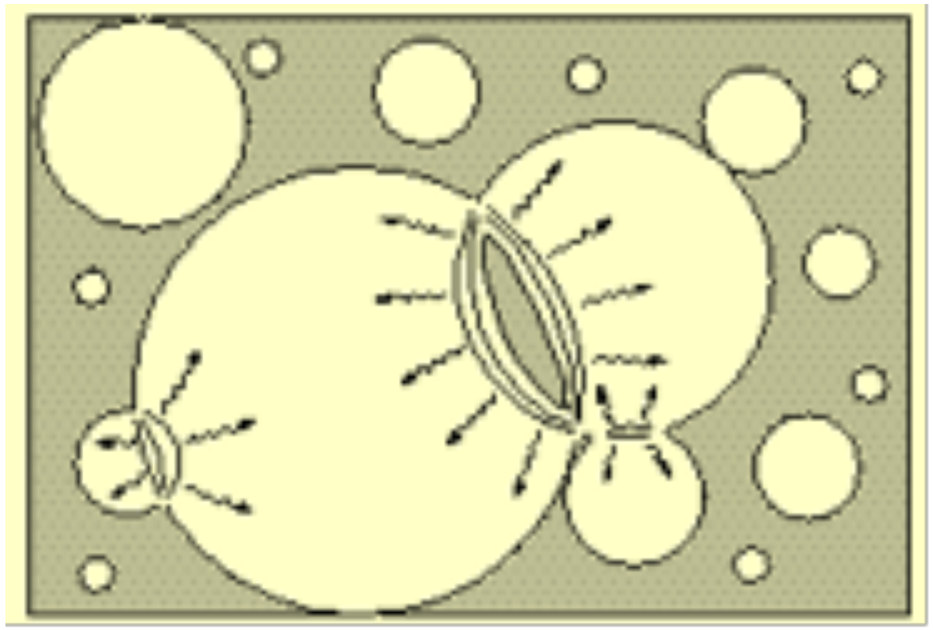
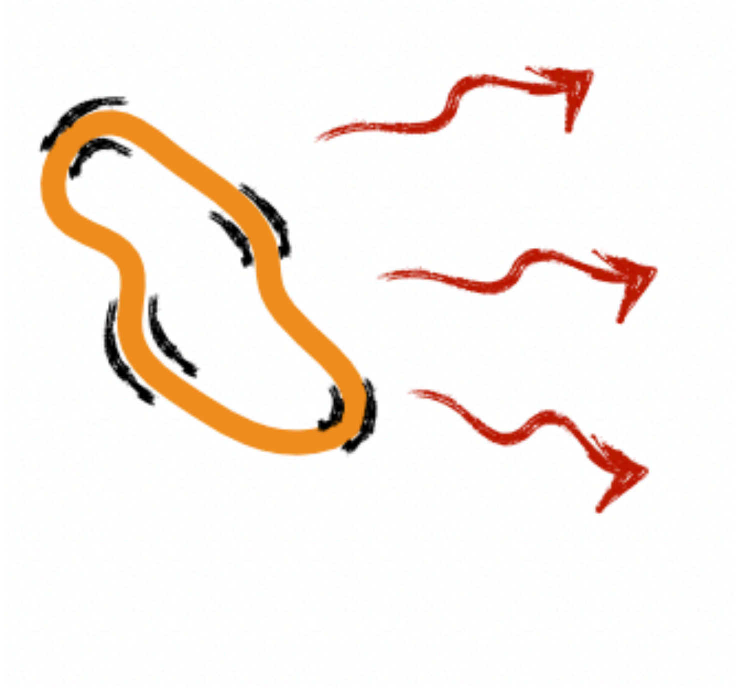
Gravitational wave production comes from dynamics associated with cosmic (Hubble) scale **H**

size of vacuum bubbles at collision

size of cosmic string loops at production





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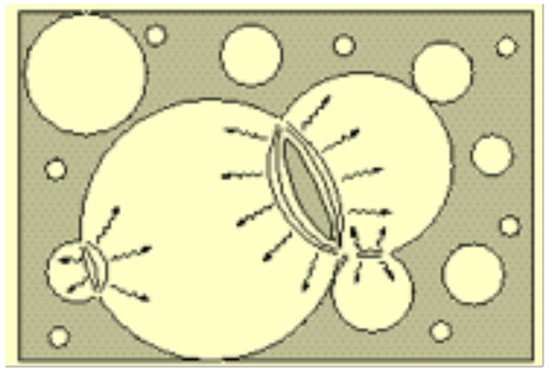
size of vacuum bubbles at collision

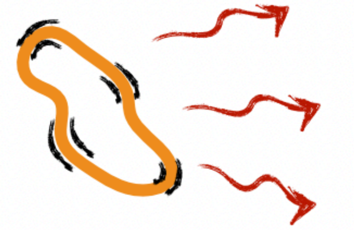
size of cosmic string loops at production

System has access to much higher energy scales **E >> T**

Boosted bubble walls are Lorentz contracted and have boosted energies γT



Loops are not smooth but have defects (cusps, kinks); correspond to higher oscillation modes. Also shrink as they radiate energy.



Can produce particles that are much heavier than the ambient temperature / scale of physics:

HIGH ENERGY ASTROPHYSICAL SIGNALS!

PARTICLE PRODUCTION FROM FIRST ORDER PHASE TRANSITIONS (FOPTS)

- **Significant effect** (particle couplings are much larger than the gravitational coupling)
- **Not very well studied in the literature** (only a handful of papers with semi-analytic estimates in idealized scenarios, underlying physics not well understood)

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

Konstandin+Servant *1104.4793 [hep-ph]*

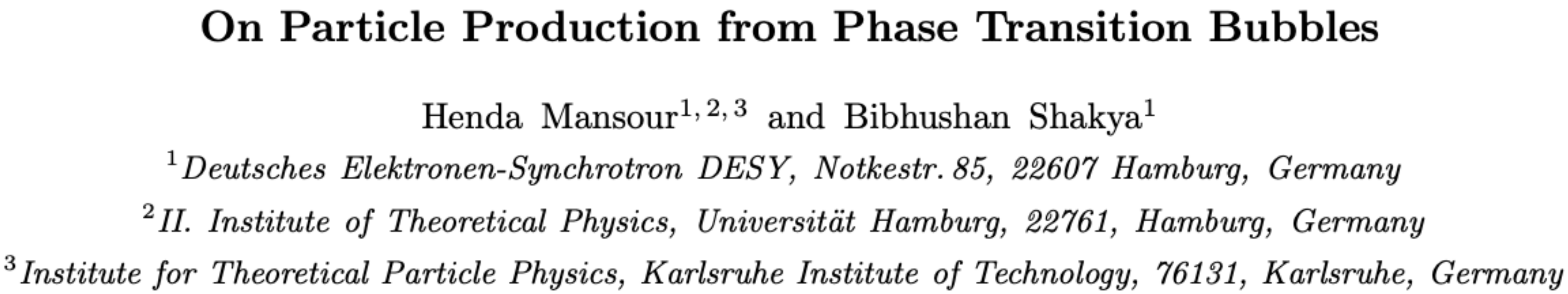
Falkowski+No 1211.5615 [hep-ph]

- **Cannot** be calculated in the same way as particle production from homogeneous phase transitions / changing backgrounds (**highly inhomogeneous process**)
- **Can** be calculated in the a manner **analogous to gravitational wave production** (but with **several crucial differences**)

PARTICLE PRODUCTION FROM FIRST ORDER PHASE TRANSITIONS (FOPTS)

Based on

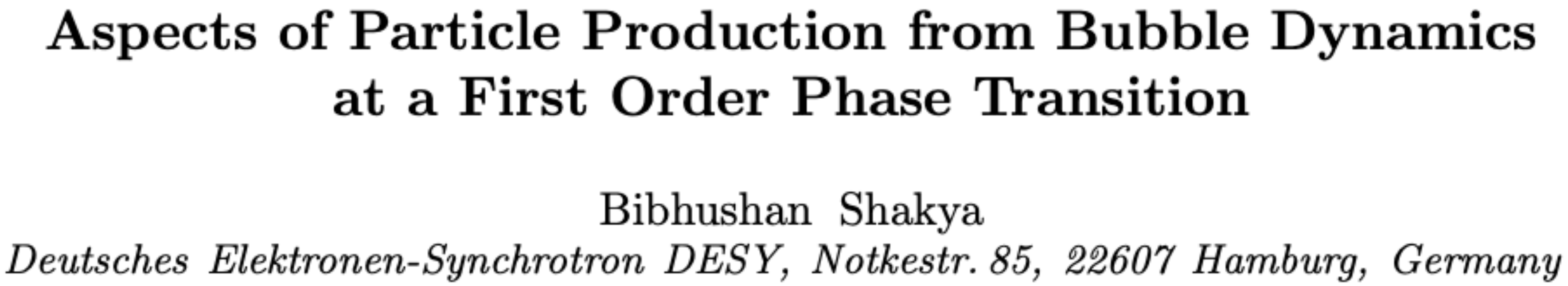
2308.13070 [HEP-PH]



On Particle Production from Phase Transition Bubbles

Henda Mansour[1, 2, 3] and Bibhushan Shakya[1]
[1] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[2] *II. Institute of Theoretical Physics, Universität Hamburg, 22761, Hamburg, Germany*
[3] *Institute for Theoretical Particle Physics, Karlsruhe Institute of Technology, 76131, Karlsruhe, Germany*

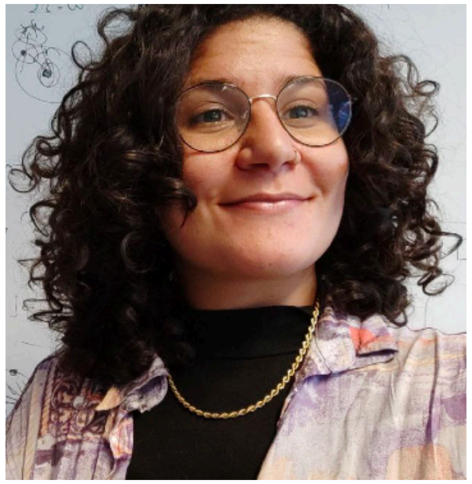
2308.16224 [HEP-PH]



Aspects of Particle Production from Bubble Dynamics at a First Order Phase Transition

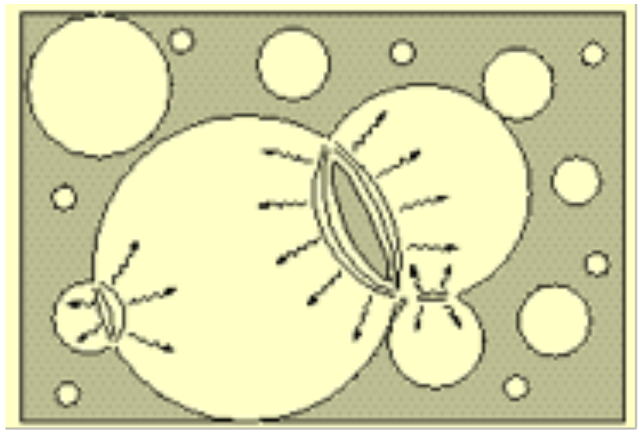
Bibhushan Shakya
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

HENDA MANSOUR



Hamburg/DESY (Master's)
→ Karlsruhe (PhD)

PARTICLE PRODUCTION FROM BACKGROUND FIELD DYNAMICS



A changing background can produce particles out of vacuum

(Gravitational particle production, Schwinger effect, Hawking radiation…)

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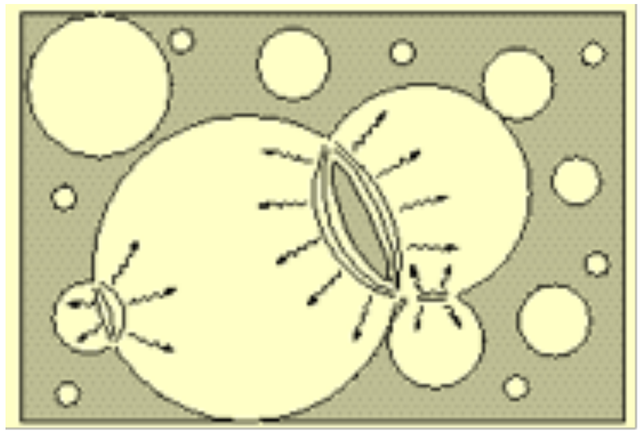


A changing background can produce particles out of vacuum

(Gravitational particle production, Schwinger effect, Hawking radiation…)

FOPTs involve nontrivial dynamics of the background field:

- Bubbles nucleate
- Bubble walls propagate in space
- Bubble walls collide
- Excitations/oscillation of the background field after collision

"Irreducible" form of particle production: does not depend on nature/existence of a particle bath

Complicated to calculate because of inhomogeneous nature of the process

SCALAR FIELD DYNAMICS AT BUBBLE COLLISION

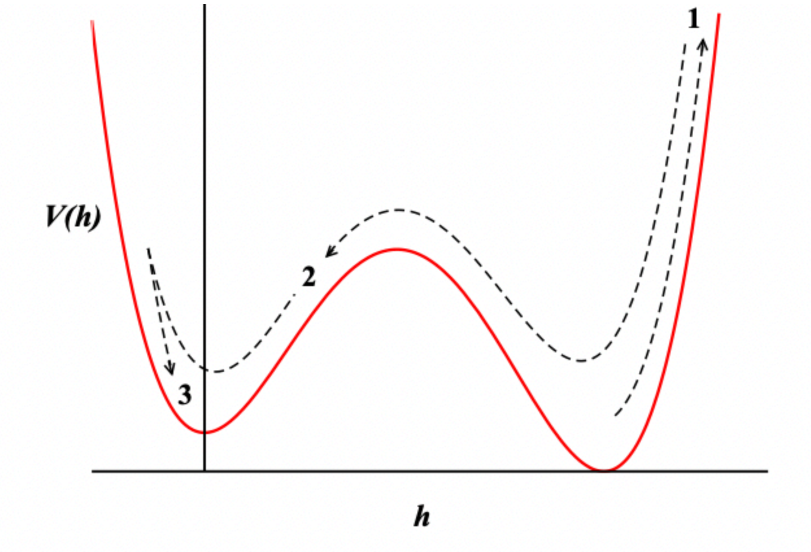
Configuration before collision is fairly simple: spherical propagating bubble walls

Moment of collision: scalar field gets a “kick”

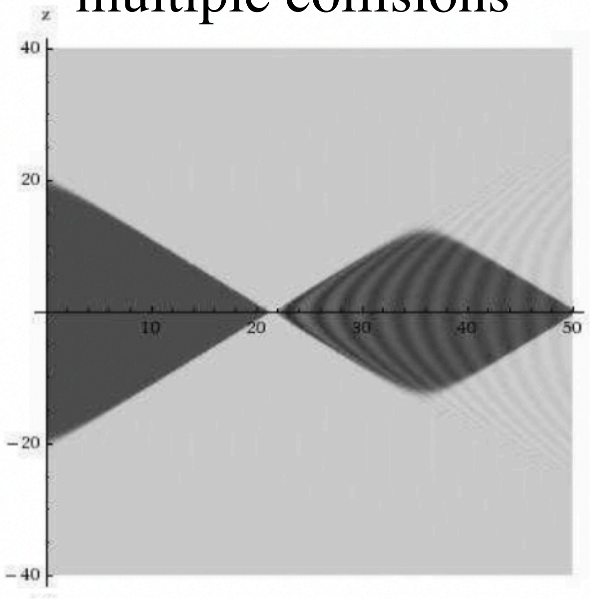
Two qualitatively different possibilities:

Field gets kicked back to false vacuum

Elastic Collision

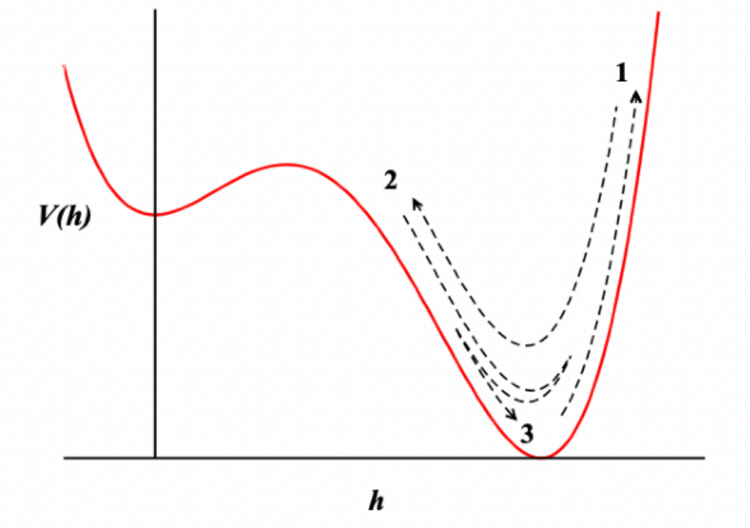


Bubble walls recede, get pulled back again, undergo multiple collisions



Field oscillates around true vacuum

Inelastic Collision



Bubble walls stick together; generates scalar waves

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

Konstandin+Servant *1104.4793 [hep-ph]*

Falkowski+No 1211.5615 [hep-ph]

PARTICLE PRODUCTION AT BUBBLE COLLISION

Particle production per unit bubble wall area

Watkins+Widrow Nucl.Phys.B 374 (1992)
Konstandin+Servant *1104.4793 [hep-ph]*
Falkowski+No 1211.5615 [hep-ph]

$$\frac{\mathcal{N}}{A} = 2\int \frac{dp_z\, d\omega}{(2\,\pi)^2} \left|\tilde{h}(p_z,\omega)\right|^2 \mathrm{Im}\left(\tilde{\Gamma}^{(2)}\left(\omega^2 - p_z^2\right)\right)$$

2 point 1PI Green function.

Imaginary part gives decay probability

Decompose excitation into Fourier modes

Each mode can be interpreted as field quanta with given energy that can decay

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2 point 1PI Green function.

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Rewrite as

$$\frac{\mathcal{N}}{A} = \frac{1}{2\,\pi^2}\int_0^\infty d\chi\, f(\chi)\,\mathrm{Im}\left(\tilde{\Gamma}^{(2)}\left(\chi\right)\right)$$

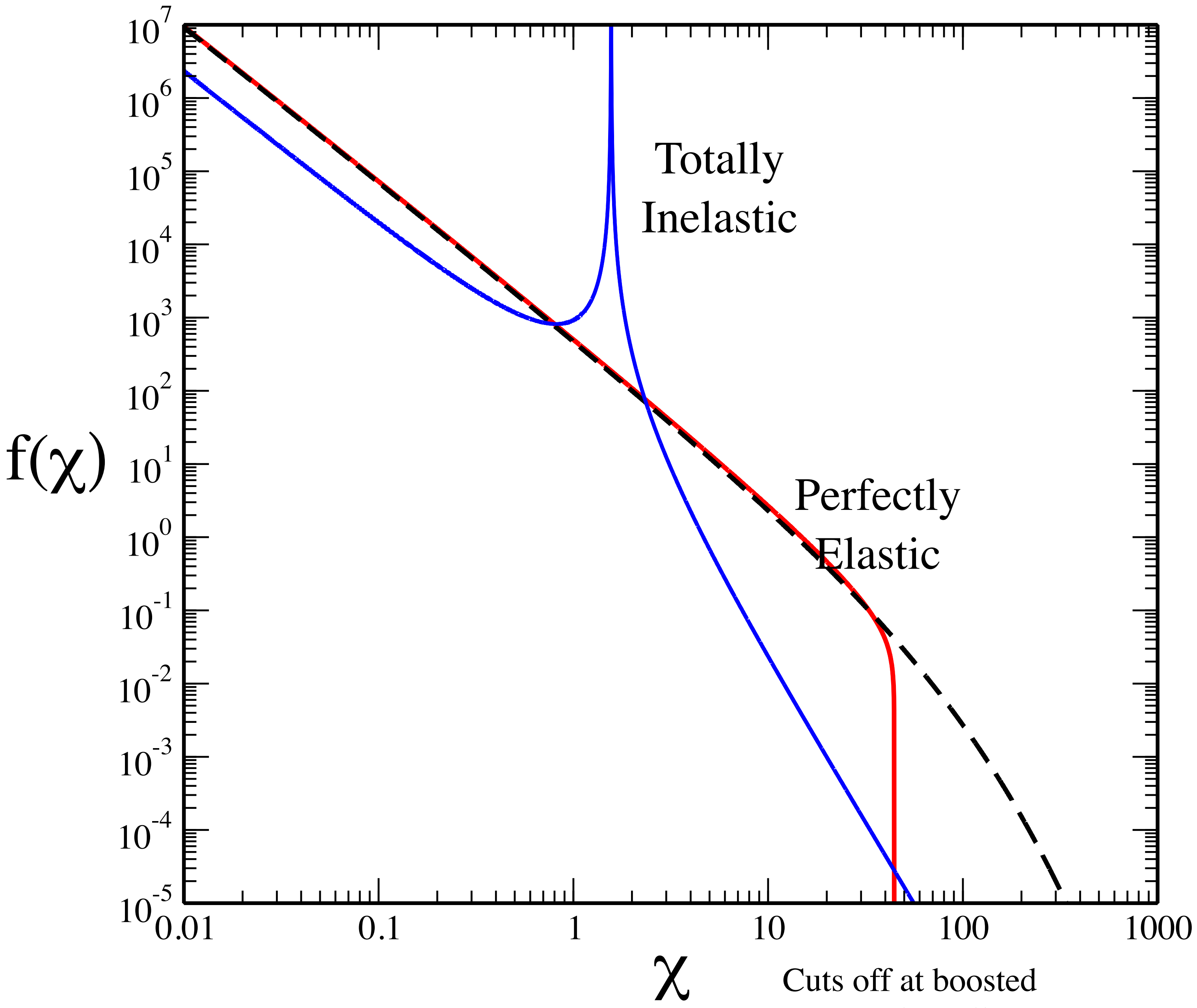
$\chi = \omega^2 - k^2$

Particle production efficiency factor

PARTICLE PRODUCTION AT BUBBLE COLLISION

$$\frac{\mathcal{N}}{A} = \frac{1}{2\,\pi^2}\int_0^\infty d\chi\, f(\chi)\,\mathrm{Im}\left(\tilde{\Gamma}^{(2)}(\chi)\right) \qquad \chi = \omega^2 - k^2$$

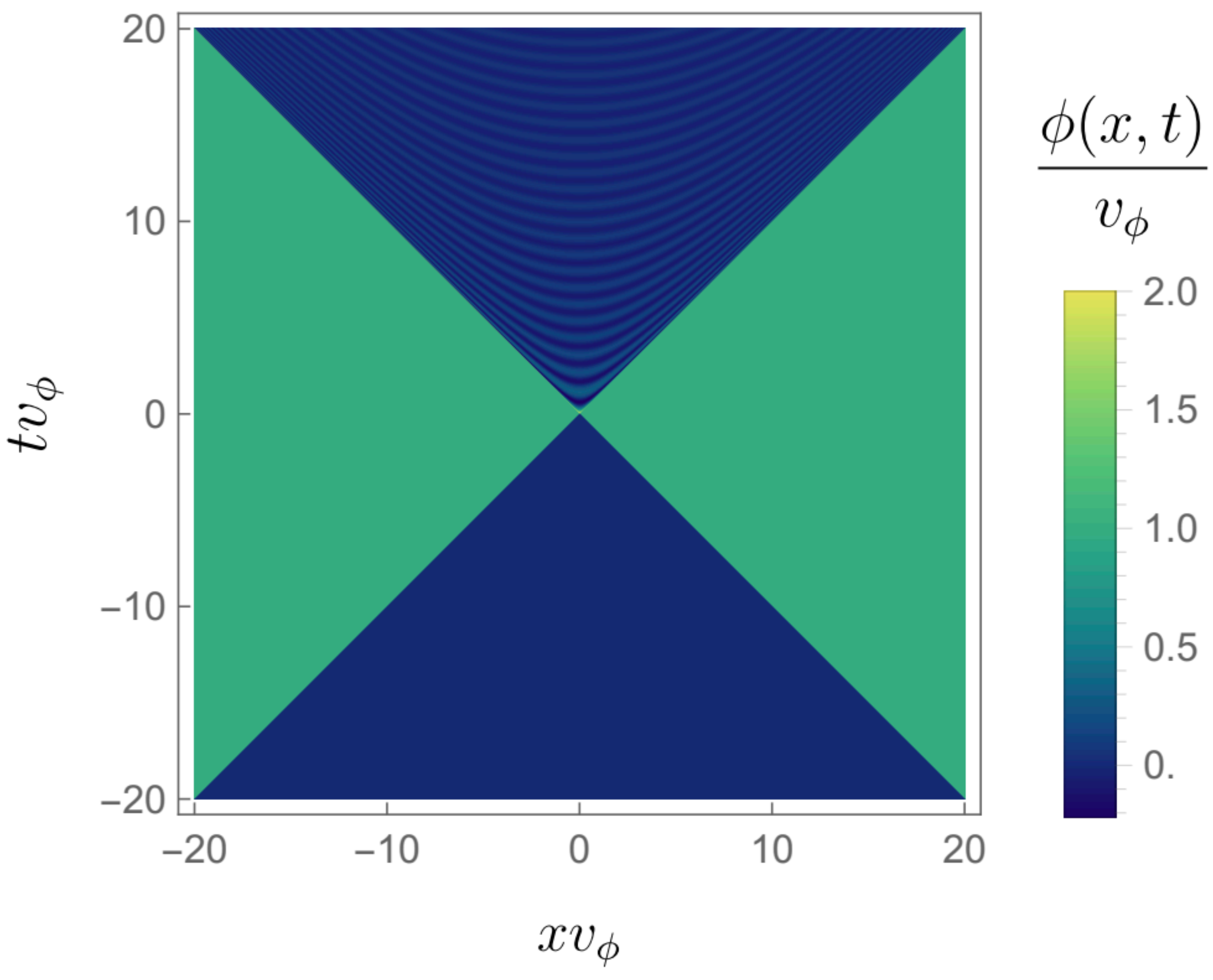
Semi-analytic solutions for idealized limits from 1211.5615



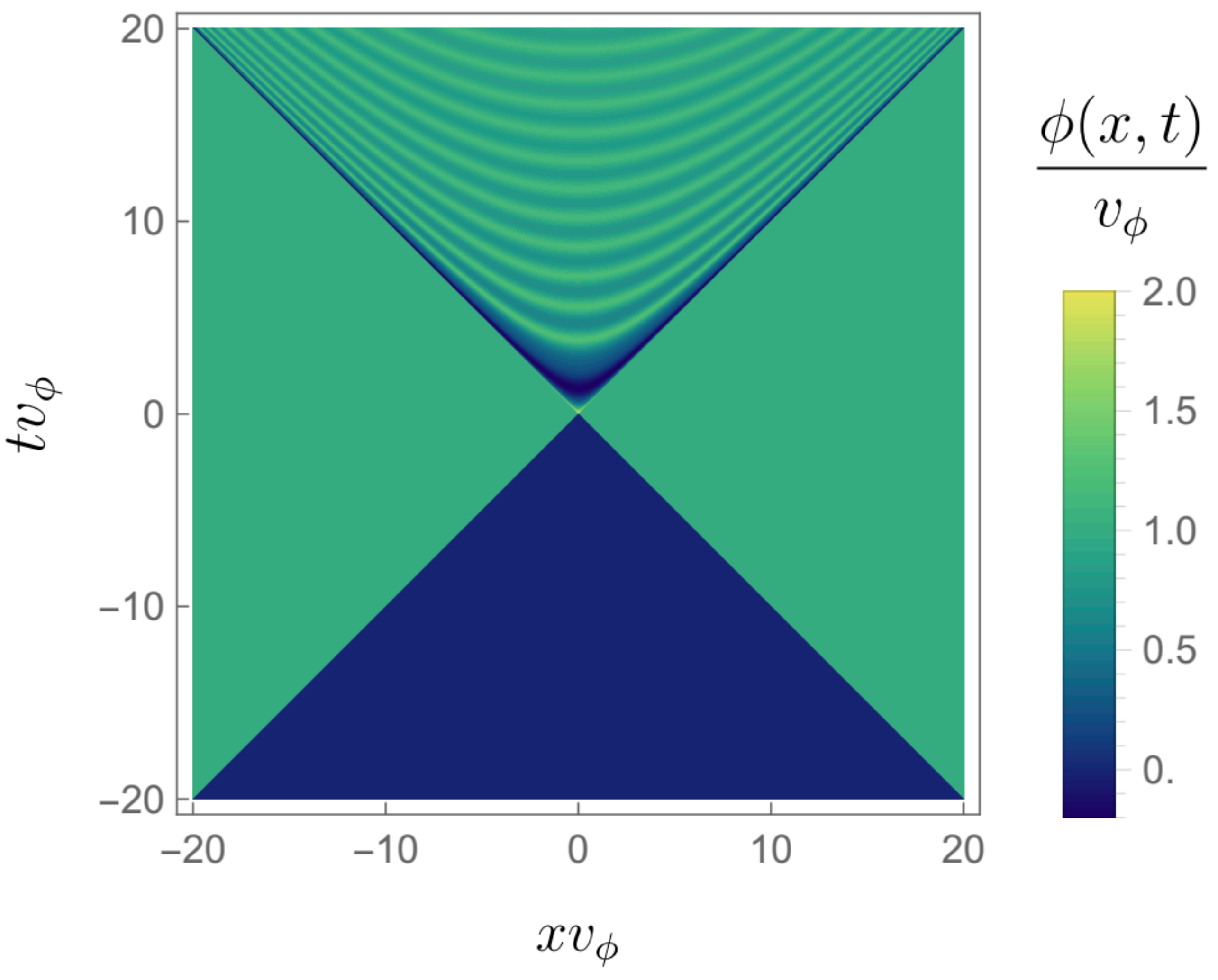
Cuts off at boosted
bubble wall
thickness scale

REALISTIC CASES, NUMERICALLY

We study numerical solutions of realistic cases away from these ideal limits



(a) Elastic collision ($\epsilon = 0.6,\ a = 28.4$)

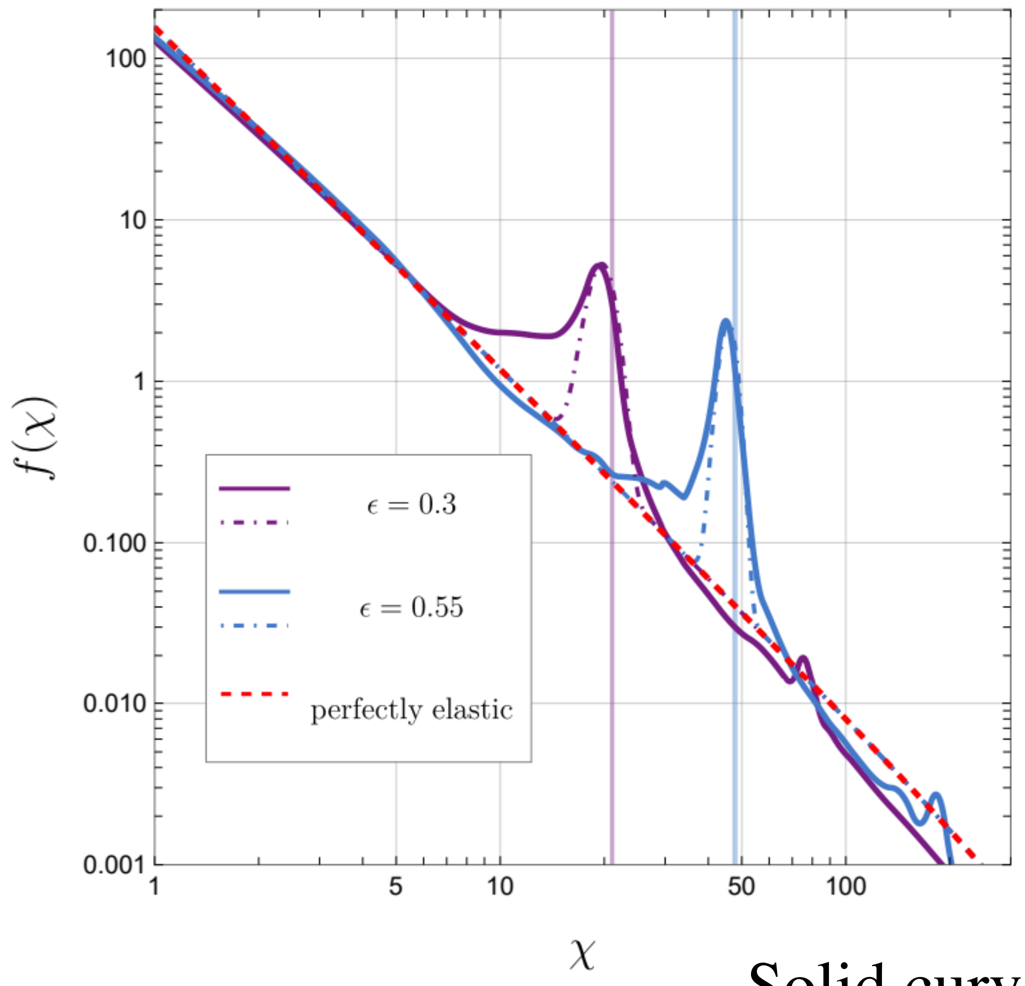


(b) inelastic collision ($\epsilon = 0.1,\ a = 4.4$)

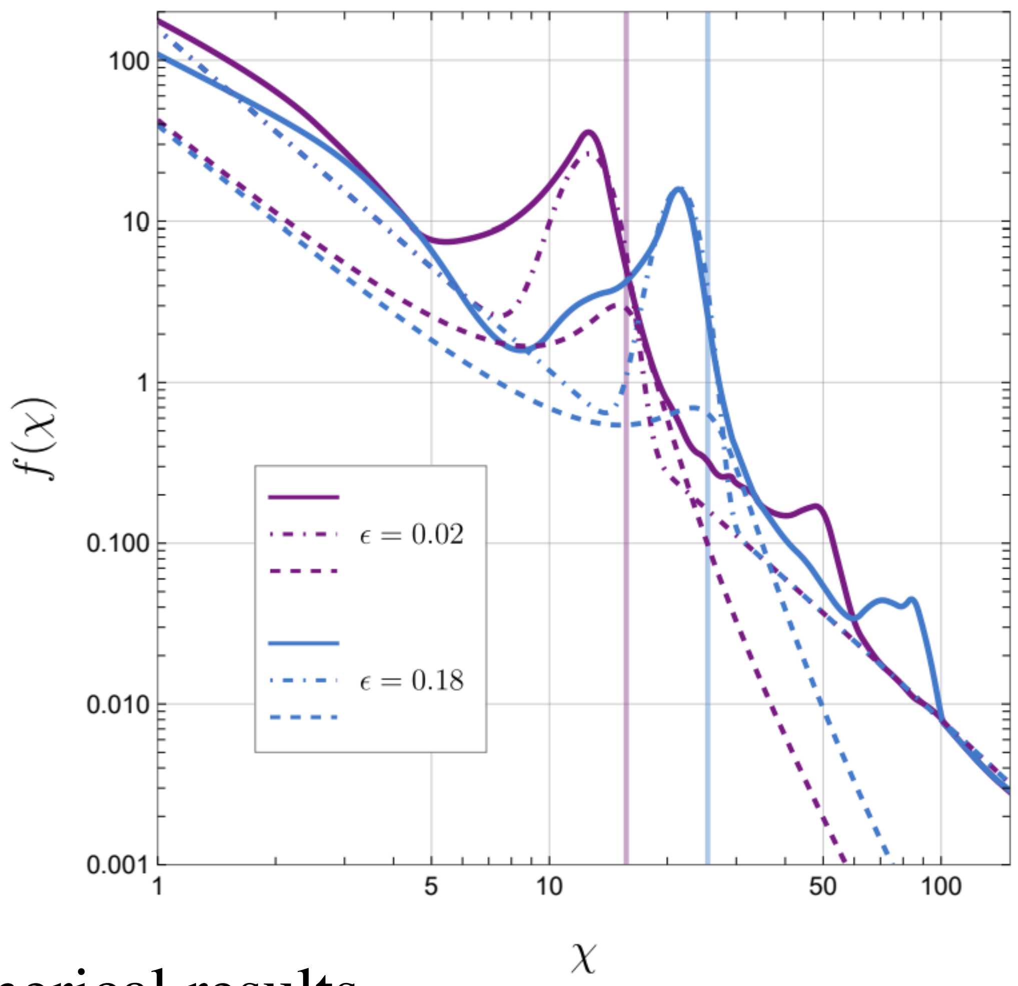
Green: true vacuum, blue: false vacuum

RESULTS: EFFICIENCY FACTOR

Elastic



Inelastic



Solid curves: numerical results

Dashed curves: analytic results in perfectly elastic/inelastic limits

Dot-dashed curves: fit functions to numerical results

(See paper for easy to use fit functions) 2308.13070 [hep-ph]

Reproduces the main features from analytic solutions of idealises cases

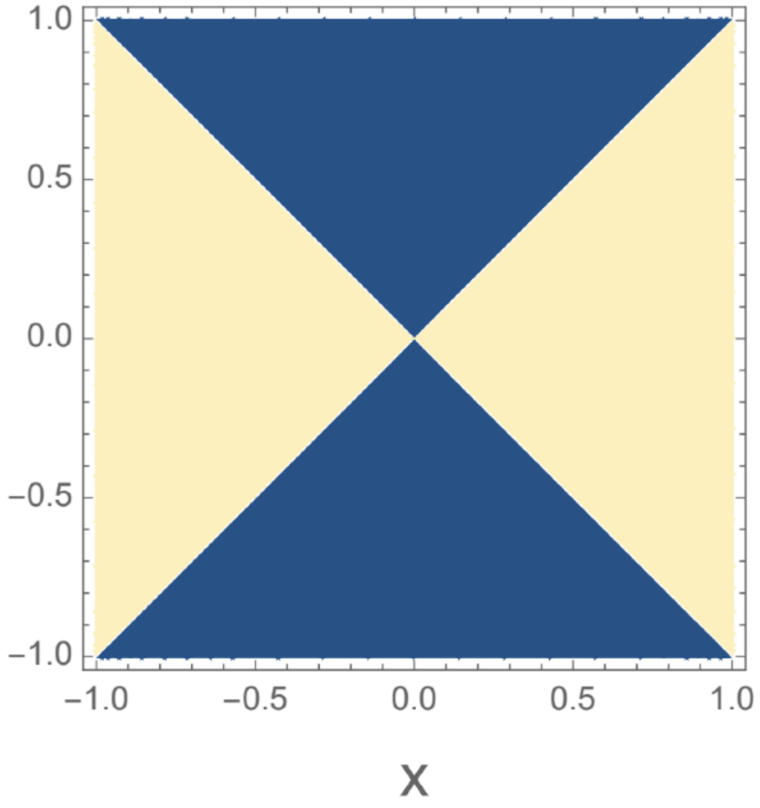
Reveals additional features not captured by analytic results

UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

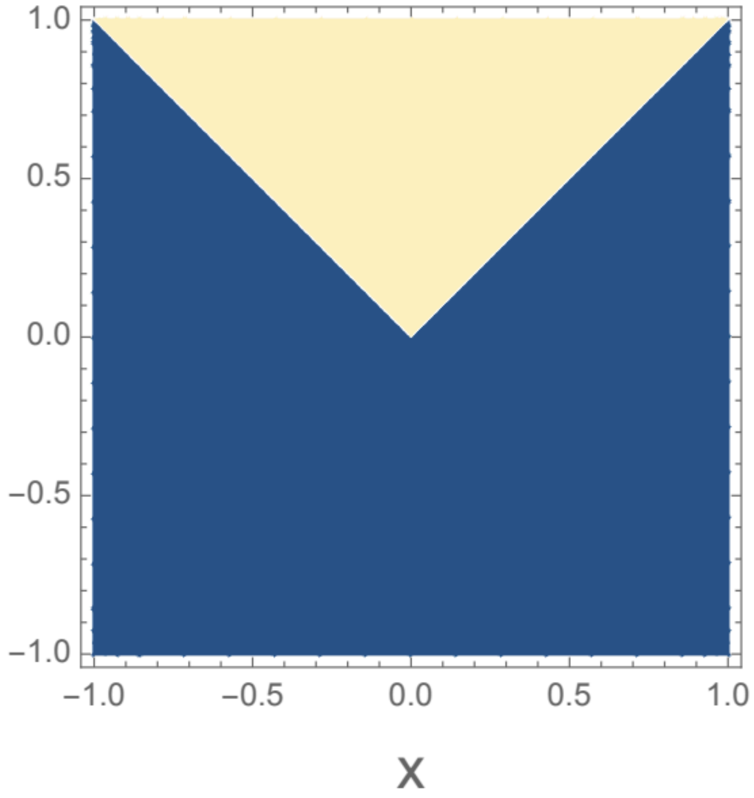
Naive interpretation: everything happens at the moment of collision+ gradual radiation from oscillations after collision

UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

Perfectly elastic case



Two bubble walls colliding at the origin



Single bubble expanding out from the origin

Yellow: true vacuum, blue: false vacuum

Fourier transform

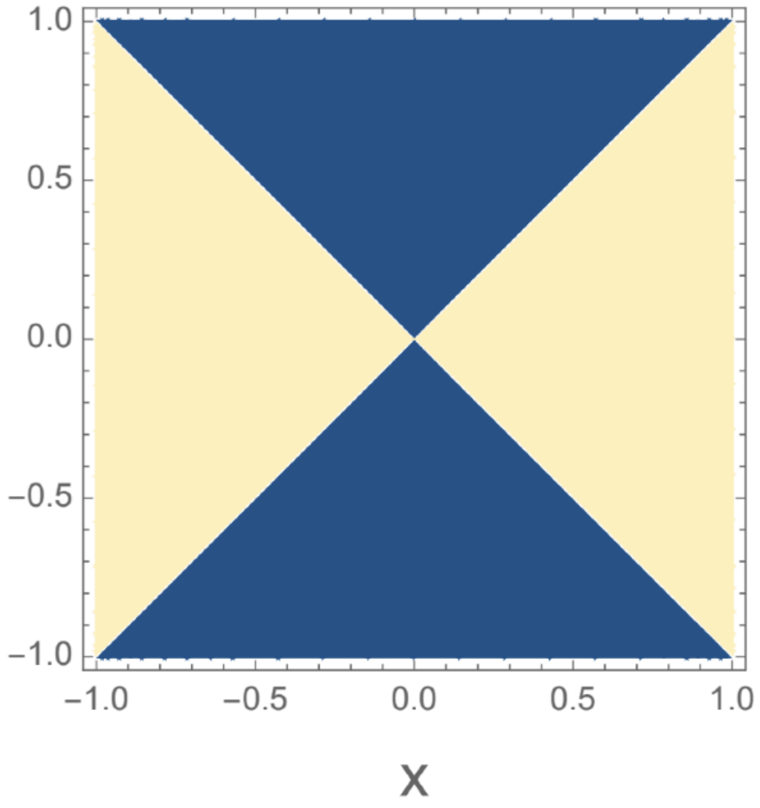
$$\tilde{\phi}(k,\omega) = \frac{4\,v_\phi}{\omega^2 - k^2\,v_{\rm w}^2}$$

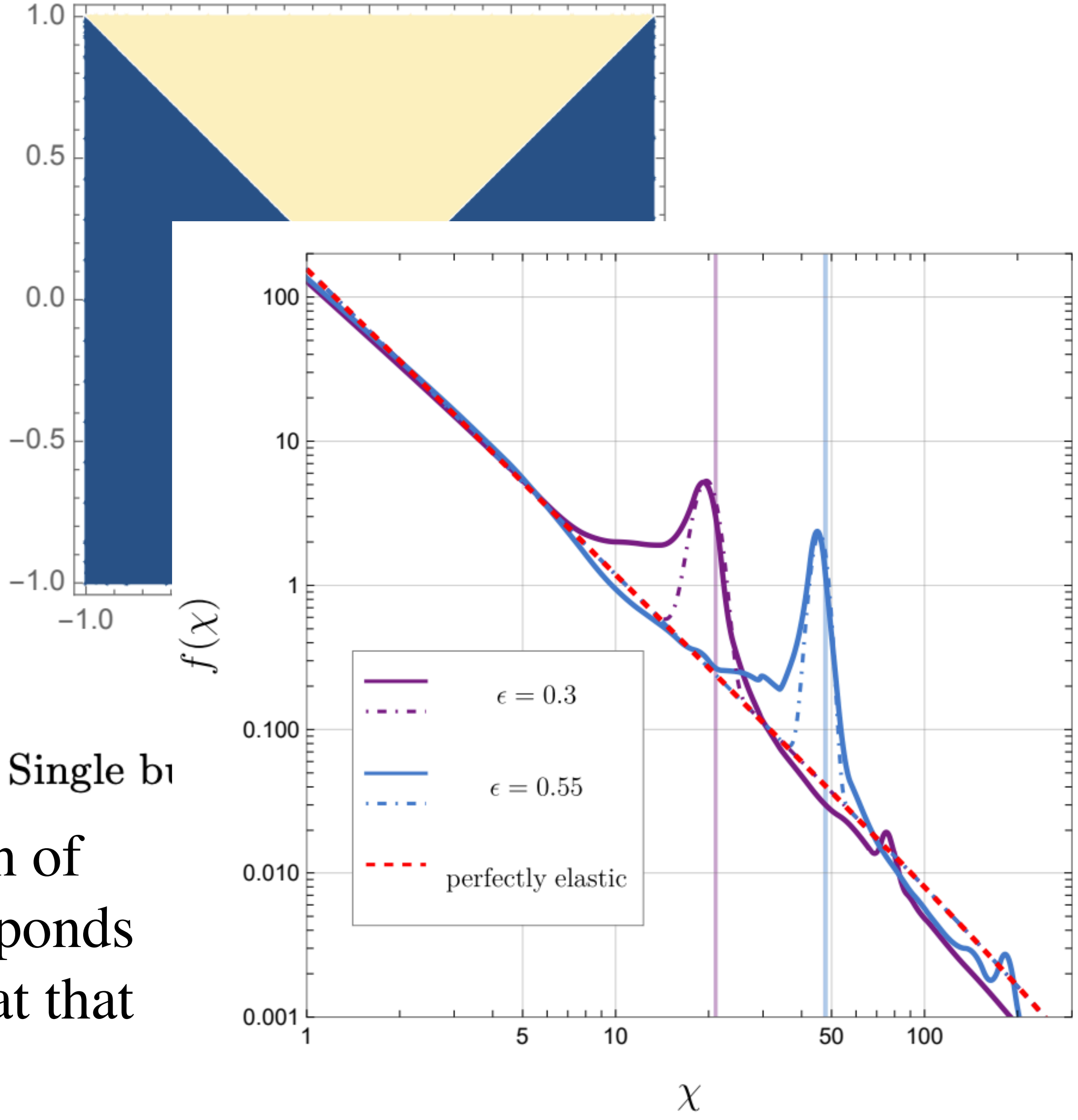
Fourier transform

$$\tilde{\phi}(k,\omega) = \frac{2\,v_\phi}{\omega^2 - k^2\,v_{\rm w}^2}$$

UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

Perfectly elastic case





Single b

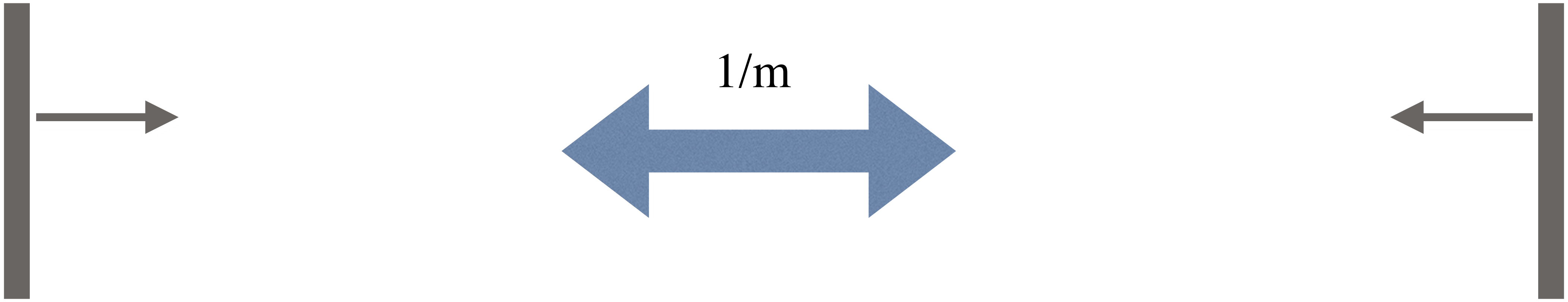
Everything comes from relative motion of bubble walls! Each χ contribution corresponds to a configuration with the bubble walls at that corresponding distance.

[Note crucial difference with GW production: no GWs produced before collision (spherically symmetric sources cannot excite transverse traceless excitations), hence no “power law” in GW spectra.]

UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

Particle production is a “local” process

Consider a particle of mass m. Has a length scale associated with it: its Compton wavelength 1/m



Relative wall motion at distances much farther away cannot lead to particle production.

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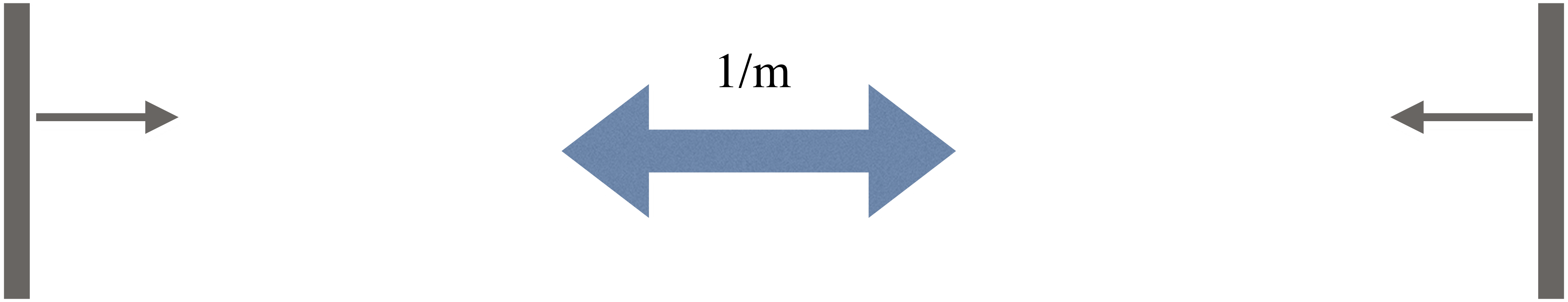
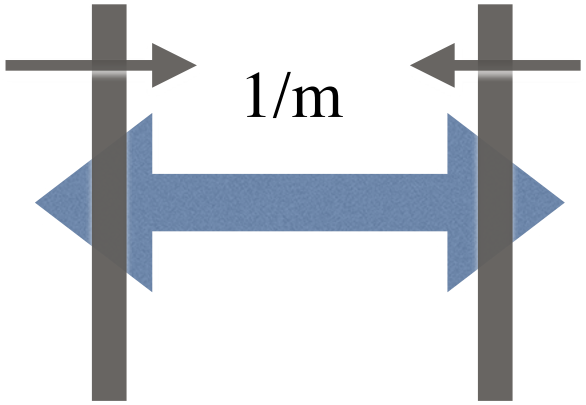
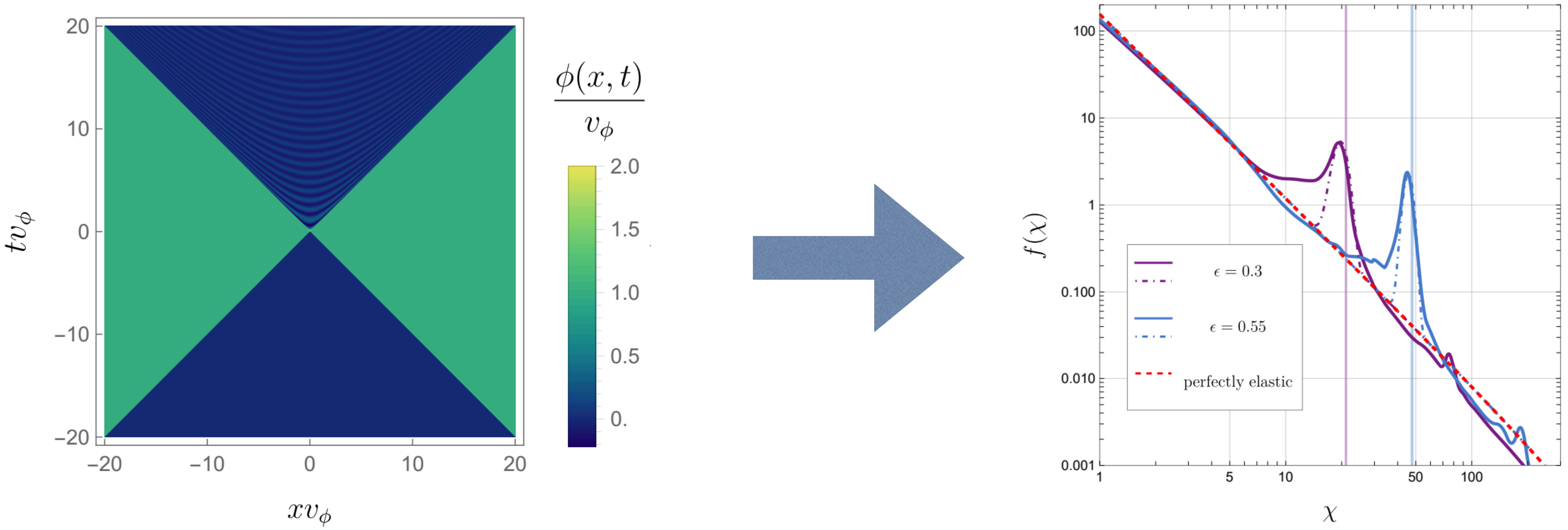


Relative wall motion at distances much farther away cannot lead to particle production.

Particles can only be produced when the dynamics occurs within a Compton wavelength distance



NON-UNIVERSALITY OF PARTICLE INTERACTIONS



The efficiency factor gives the mode decomposition of the excitations of the scalar field over all spacetime (in both true and false vacua, which exist simultaneously)

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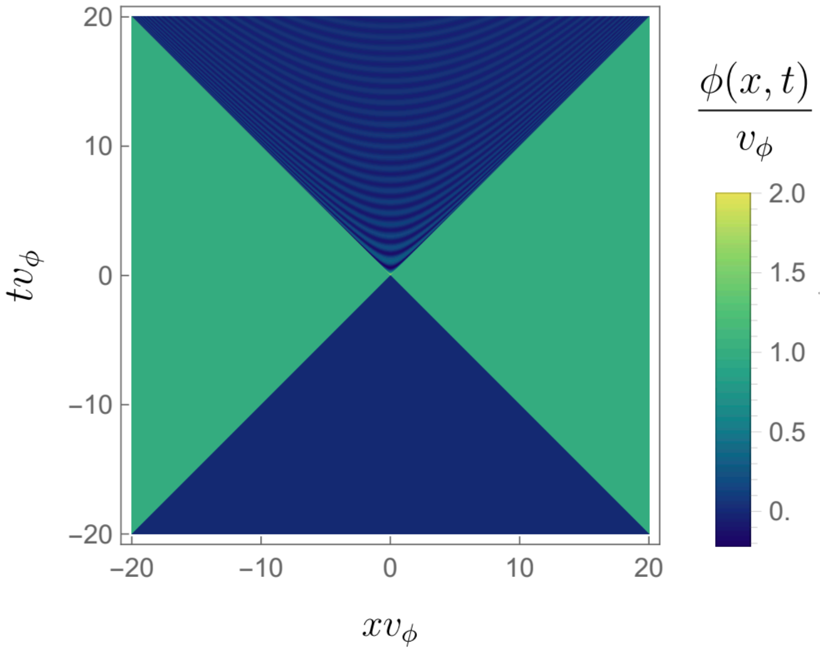

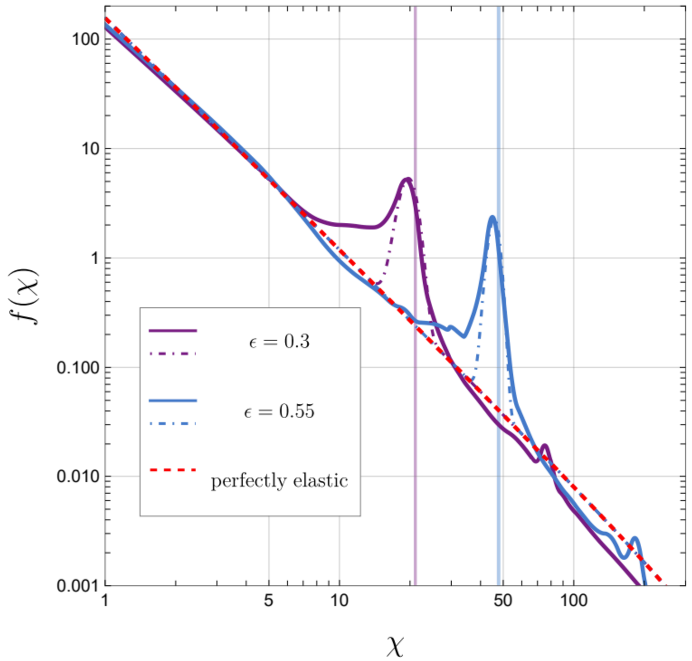

The efficiency factor gives the mode decomposition of the excitations of the scalar field over all spacetime (in both true and false vacua, which exist simultaneously)

Particle interactions and masses are different in different vacua!

E.g. consider $\frac{\lambda}{2}\phi^2\psi^2$

True vacuum $\phi^* \to \phi\psi\psi$ $\phi^* \to \psi\psi$

False vacuum $\phi^* \to \phi\psi\psi$ only

What is the correct vacuum to use for the calculation?

Need to be more careful, consider things case by case depending on where the excitations that create the particles occur

NONPERTURBATIVE RESONANT EFFECTS

In standard reheating scenarios, nonperturbative, resonant effects e.g. parametric resonance, tachyonic instability are important, and can lead to explosive particle production

FOPTs are inhomogeneous events; affects the efficacy of such phenomena

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FOPTs are inhomogeneous events; affects the efficacy of such phenomena

Consider tachyonic instability:

EOM for a field $(\partial_t^2 - \partial_x^2 + m^2_{\text{eff},\psi}(x,t))\,\psi(t,x) = 0$

If $m^2_{\text{eff},\psi}(t) < 0$, for $k < |m_{\text{eff},\psi}|$

Homogeneous case

$$\psi_k(t) \propto \exp\left[\sqrt{m^2_{\text{eff},\psi}(t) - k^2}\, t\right]$$

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Homogeneous case

$$\psi_k(t) \propto \exp\left[\sqrt{m^2_{\mathrm{eff},\psi}(t) - k^2}\; t\right]$$

However, at FOPT the background field is not coherent over length scales $m^2_{\mathrm{eff},\psi}(x,t)$

Spatial gradients important, suppress the coherent growth of the field

Particle production is also localized: diffuse out over space over timescales smaller than $m^2_{\mathrm{eff},\psi}(x,t)$

Resonant effects unlikely to be important at FOPTs

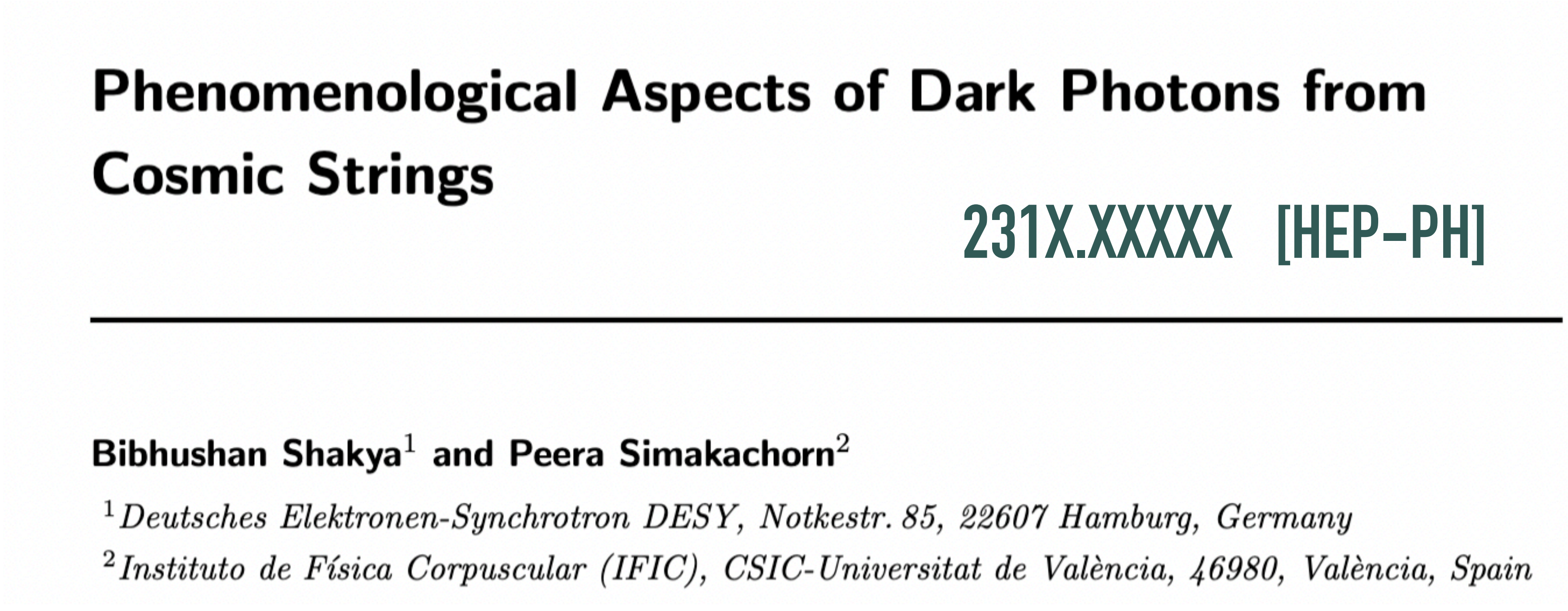
HIGH ENERGY PARTICLES FROM COSMIC STRINGS

Higher oscillation modes of cosmic string loops can efficiently radiate energetic particles

The radiation of e.g. dark photons from cosmic strings not understood in sufficient detail

Affects parameter space for dark photon dark matter

Spectra of dark photon decay products (e.g. neutrinos) carry distinct features that can be observed with experiments



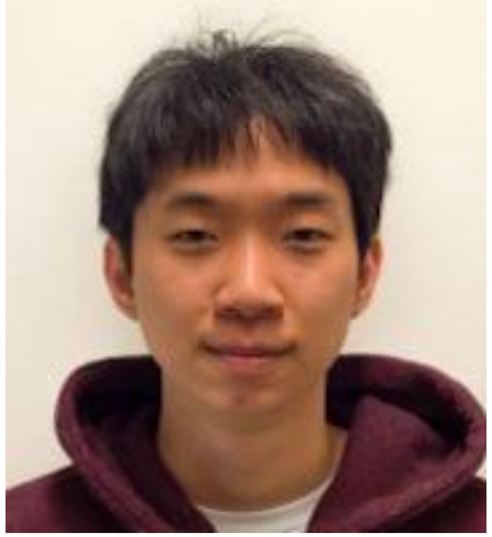
Phenomenological Aspects of Dark Photons from Cosmic Strings

231X.XXXXX [HEP-PH]

Bibhushan Shakya[1] **and Peera Simakachorn**[2]

[1] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[2] *Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València, 46980, València, Spain*

PEERA SIMAKACHORN



Hamburg/DESY (PhD)
→ Valencia (Postdoc)

SUMMARY

PARTICLE ASTROPHYSICS COUNTERPARTS OF COSMOLOGICAL GRAVITATIONAL WAVE SIGNALS

- Promising cosmological gravitational wave sources (first order phase transitions (FOPTs), cosmic strings) are also **promising sources of high energy astrophysical phenomena**

- Particle production at FOPTs is an **important effect**, but currently **very poorly understood**

- **Recent developments:** Numerical studies of realistic scenarios; provided simple fit functions for more general use. More careful treatment and understanding of various important aspects: nature and location of particle production, non-universality of particle interactions and masses across different vacua, suppression of resonant effects due to the inhomogeneous nature of the process