PHENOMENOLOGICAL ASPECTS OF DARK FIRST ORDER PHASE TRANSITIONS

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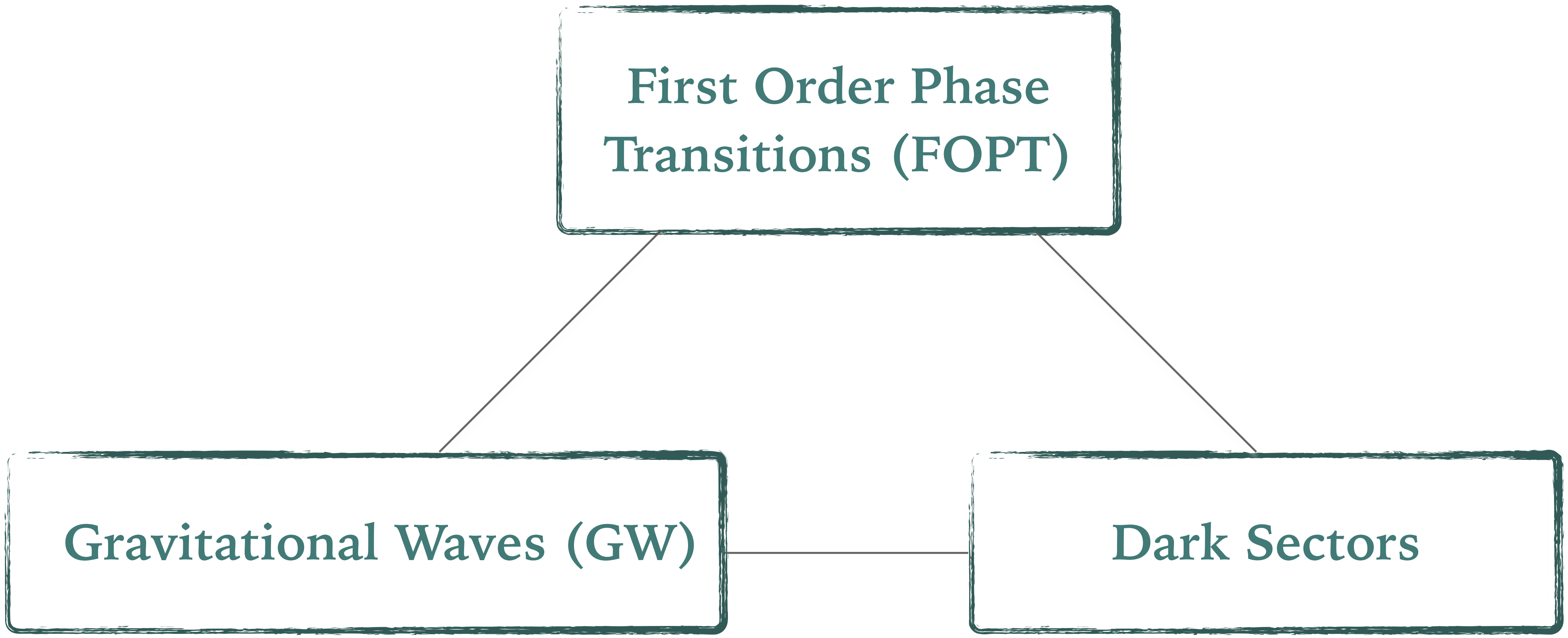
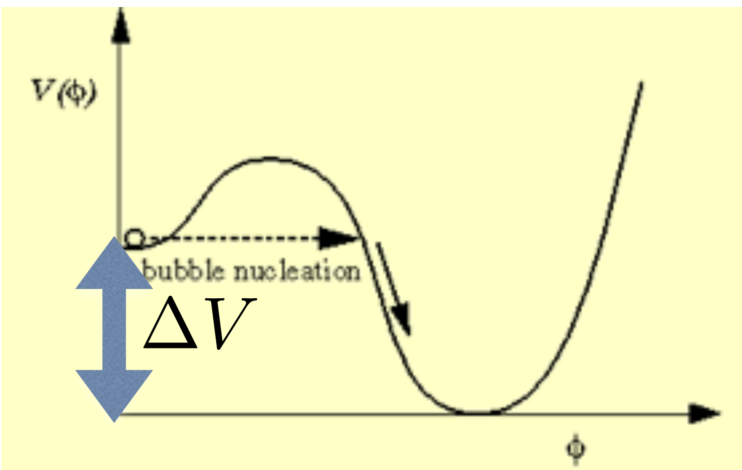
DESY.

Sept 8, 2023

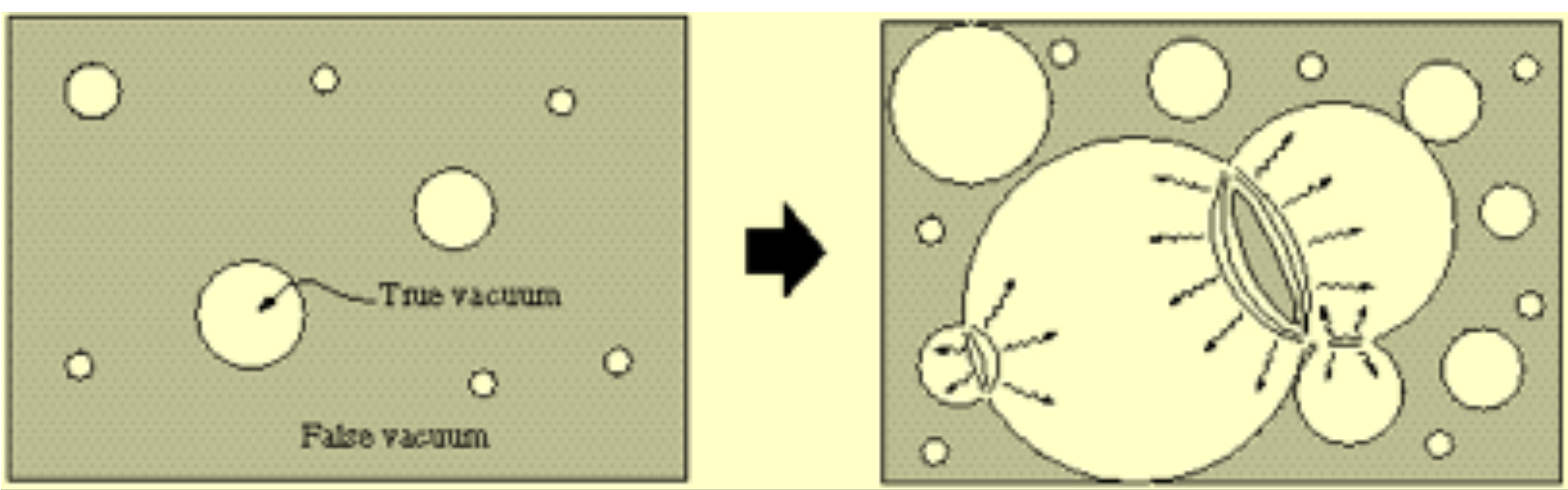
Image Credit: Shutterstock

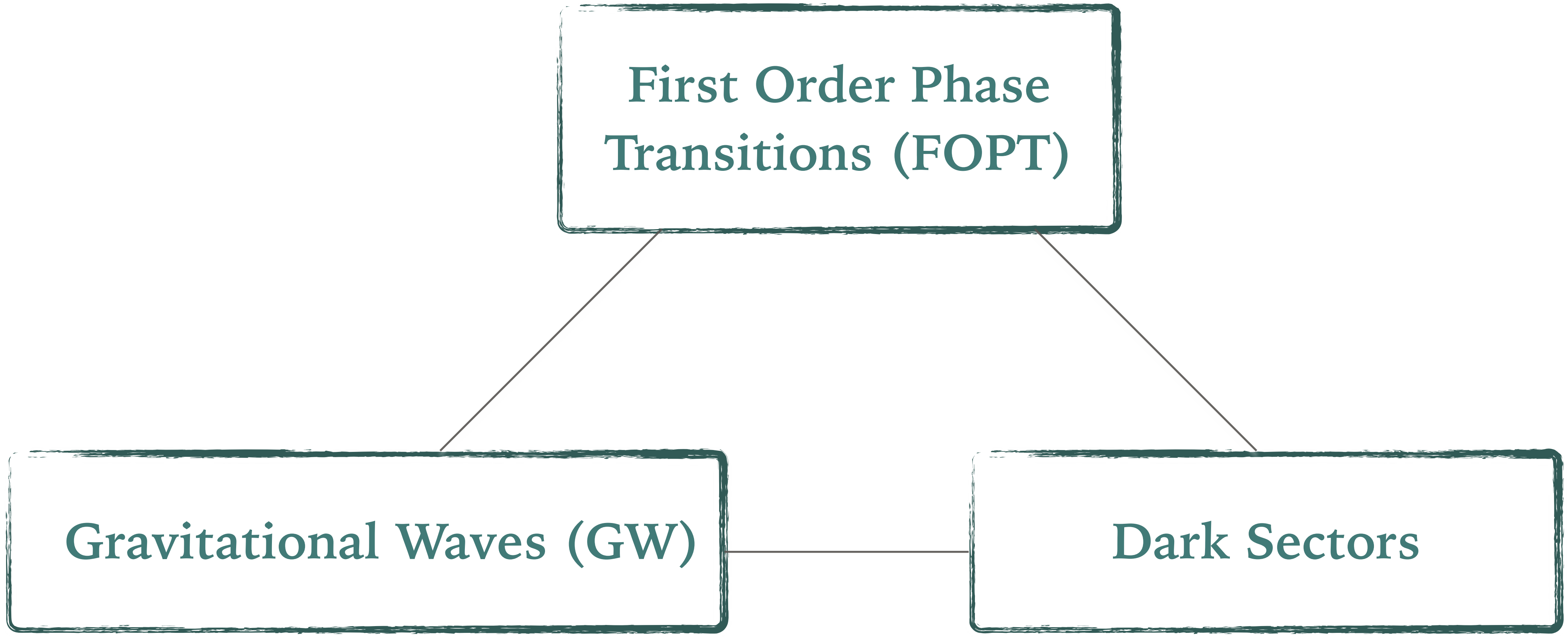

First Order Phase Transitions (FOPT)
Gravitational Waves (GW)
Dark Sectors

FIRST ORDER PHASE TRANSITION



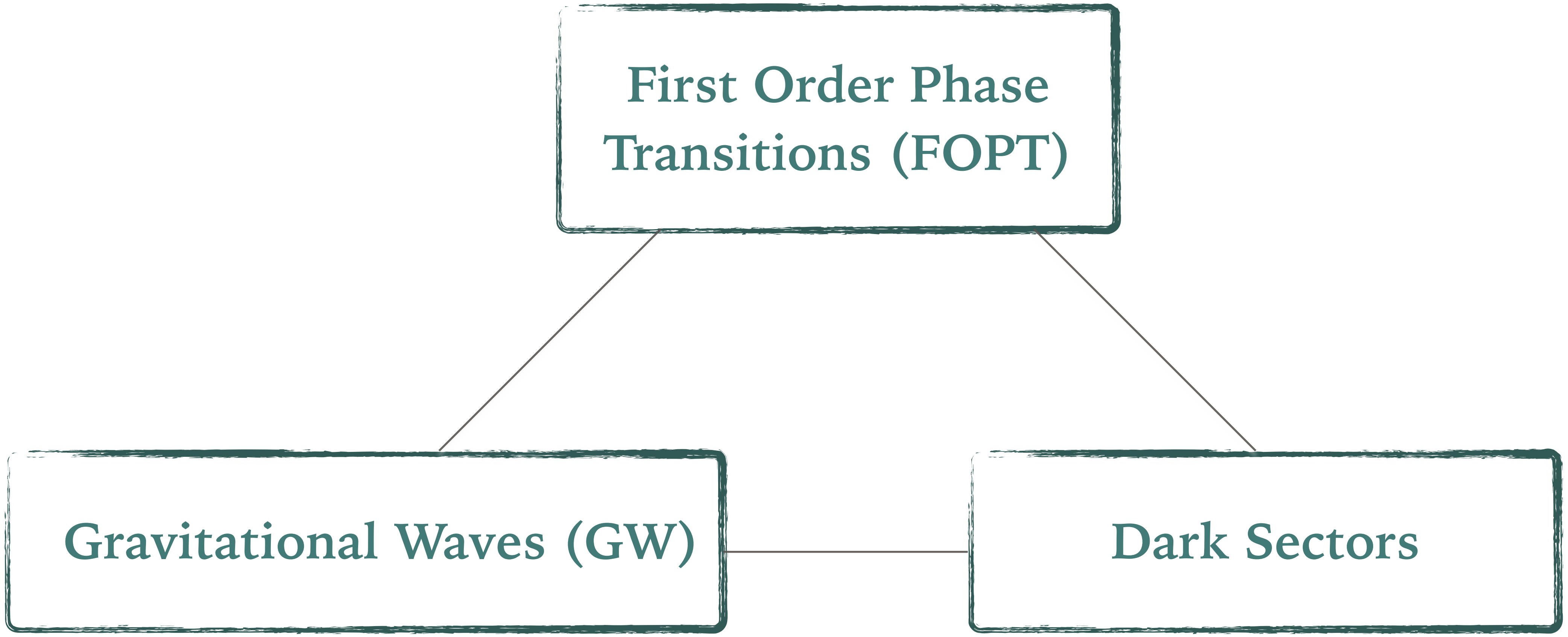
- **First order phase transition** (FOPT): the Universe transitions from **a metastable (false) vacuum to a more stable (true) vacuum** when the latter emerges/ becomes more favourable as the Universe cools
- **Bubbles** of **true vacuum nucleate and grow** in a **background of false vacuum**
- **Release** of **latent energy** scored in the false vacuum





PART I:

Can the existence of feebly interacting dark sectors give novel forms of GW signals from FOPTs?



PART II:

(How) can FOPTs provide new production mechanisms for (dark sector) particles?

PART I: NOVEL GW SIGNALS FROM FIPS+FOPTS

BASED ON 2211.06405

Gravitational Waves from Feebly Interacting Particles in a First Order Phase Transition

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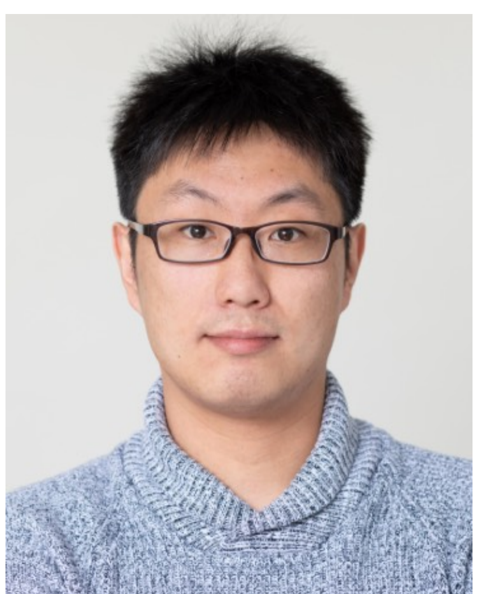

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WHERE DOES ENERGY RELEASED IN FOPT GO?

Two sources of GWs from FOPTs studied in the literature

A. Bubble walls (scalar field)

Energetic bubble walls with large boost factors, in the absence of significant sources of friction

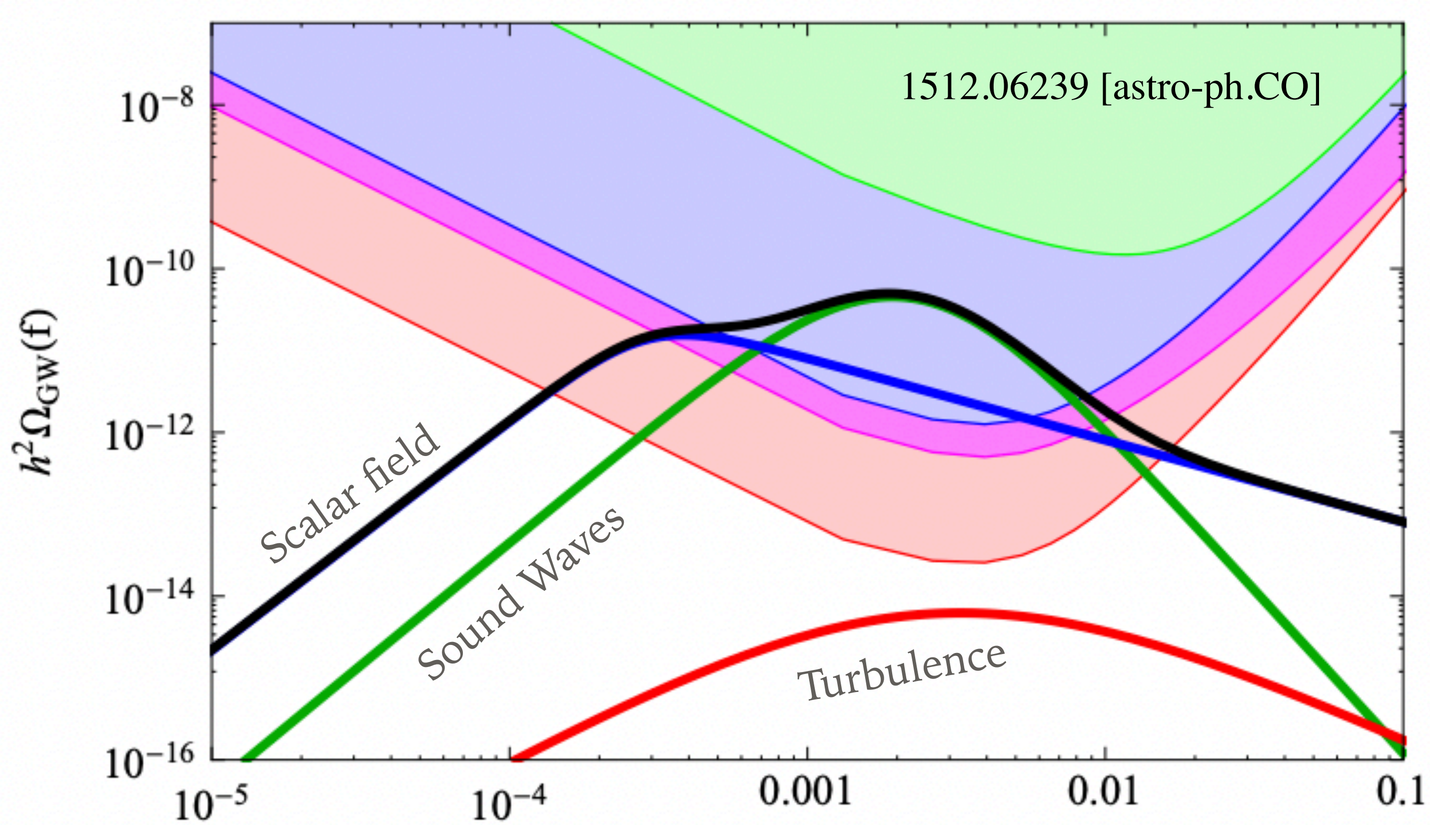
B. Fluid motion (sound waves, turbulence)

Arise from efficient interactions between the expanding bubble walls and plasma

Both can produce gravitational waves when the bubble walls/ sound shells collide

GWs have **distinct features and carry information** about the underlying physics

extensively studied, with analytic approaches as well as simulations



$T_* = 100$ GeV, $\alpha = 1$, $v_w = 1$ $\beta/H_* = 100$

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THIS TALK

C. Feebly Interacting Particles (FIPs)

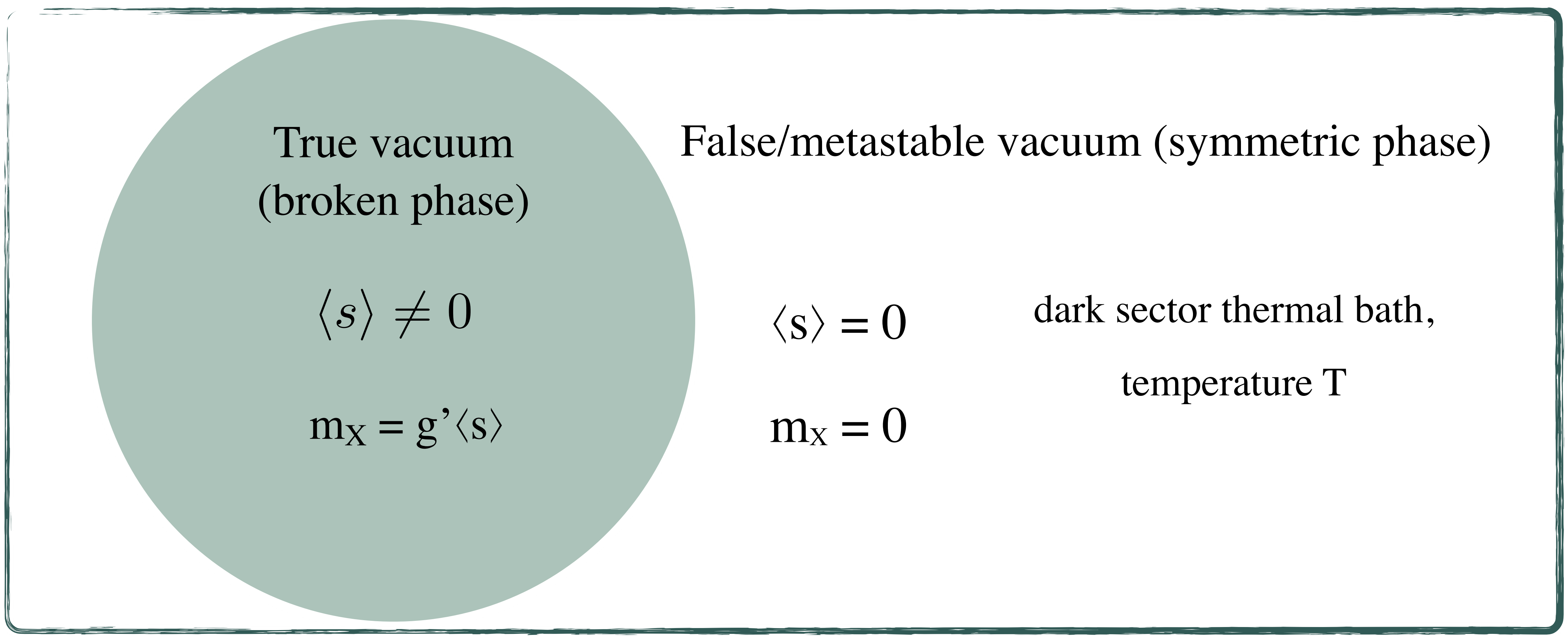
Particles with no significant ("feeble") interactions.

Do not mix with the plasma /generate sound waves

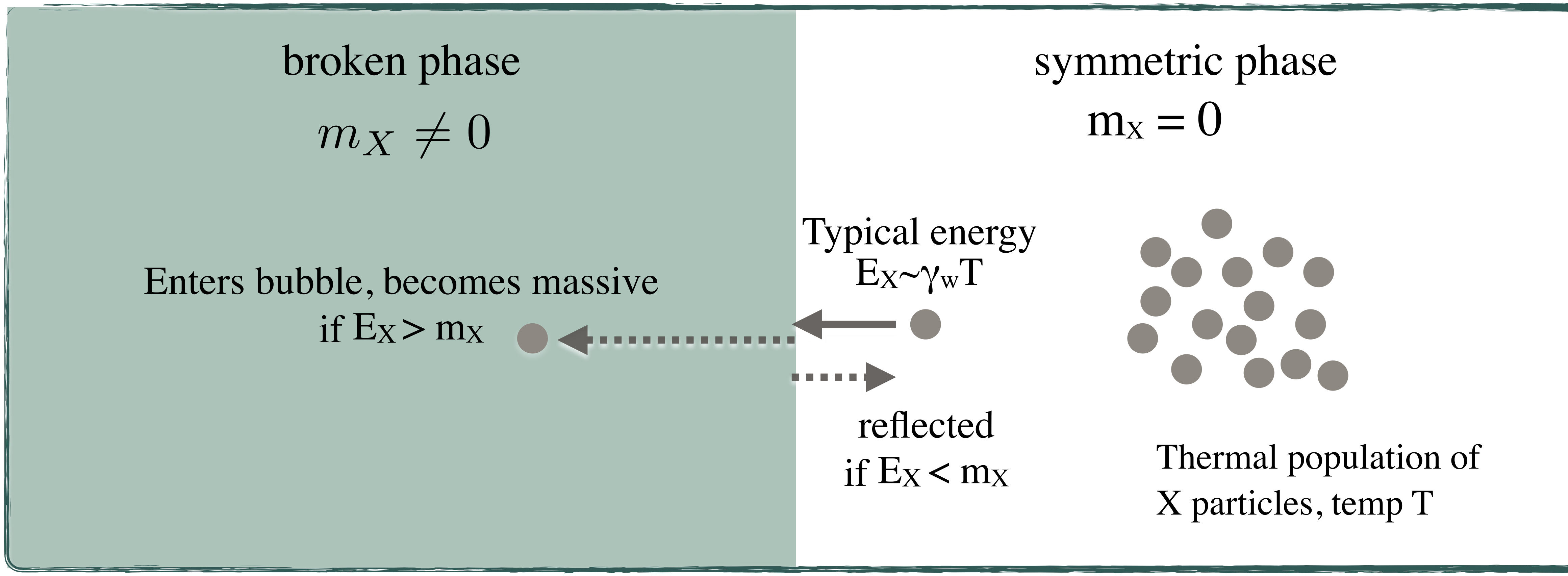
Individual d.o.f. that simply free-stream

TRANSFERRING ENERGY TO PARTICLES

Consider a particle X, present in the thermal bath, that becomes massive at phase transition (due to coupling with the background scalar s)



PARTICLES CROSSING BUBBLE WALLS



Momentum transfer from single particle crossing: $\sim \dfrac{m_X^2}{2E_X}$

[bubble wall frame]

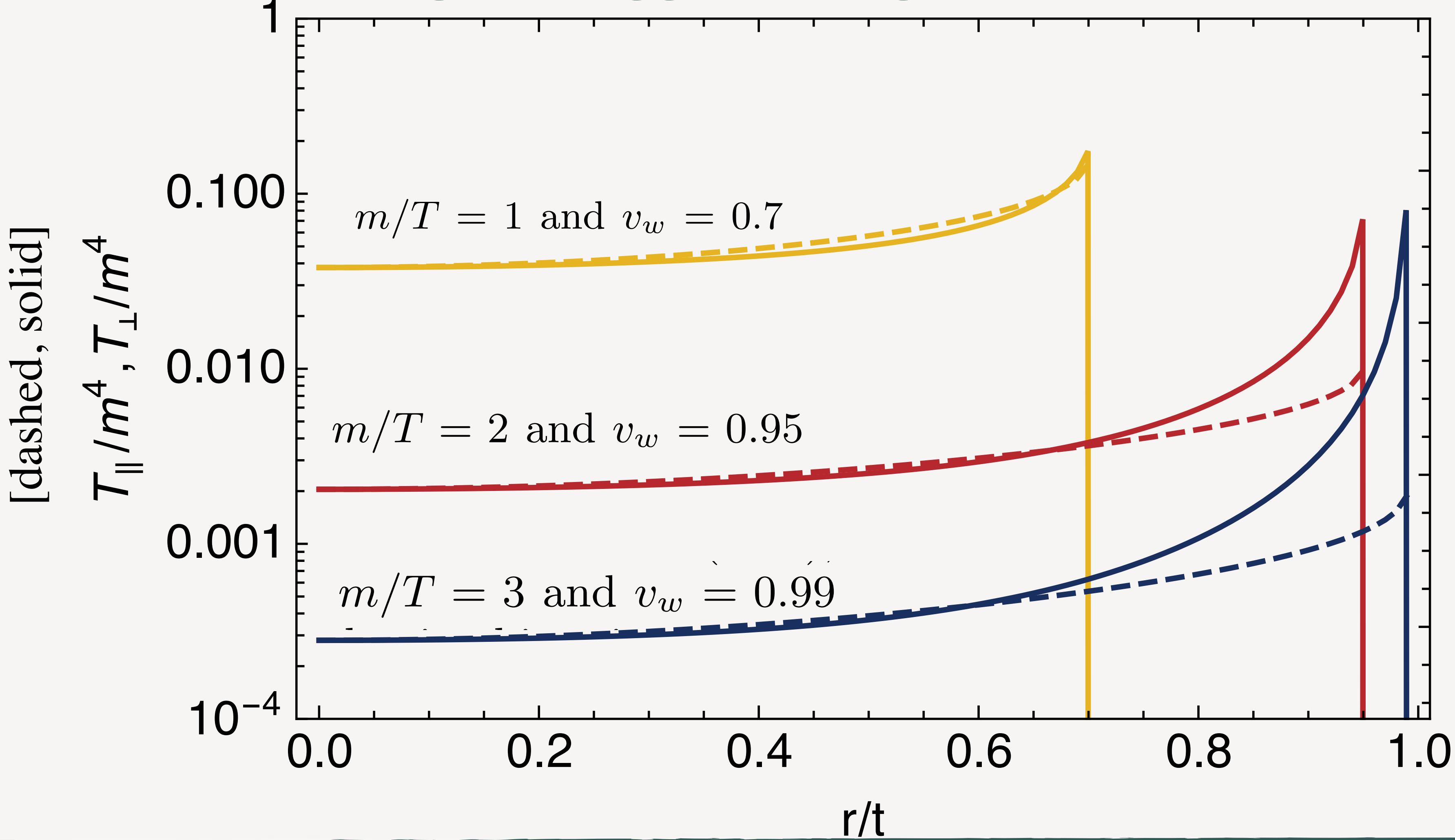
Particle slows down

[plasma frame]

Particle gains momentum along direction of bubble wall motion (gets dragged along with the bubble)!

PARTICLE DISTRIBUTION FROM BUBBLE WALL CROSSING

Particles get dragged along with the bubble



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...emp T

[bubble wall frame]

Particle slows down

[plasma frame]

Particle gains momentum along direction of bubble wall motion (gets dragged along with the bubble)!

DOMINANT EFFECT?

If **entire thermal ensemble passes through**, effective pressure on bubble wall

$$\mathcal{P}_{\max} \approx \frac{1}{24} m^2 T^2$$

If $\Delta V < \mathcal{P}_{\max}$ such **massive particles saturate the energy released in the phase transition**

This is the case for

$$m_X > \sqrt{g_*^D \alpha T}$$

No runaway behavior: the wall boost factor reaches a **terminal value $\gamma_w \sim O(1)$**

- Focus on such cases, with most of the particles passing through, only a small fraction getting reflected (only for simplicity of treatment; opposite scenario can still be consistent with the GW signals we will discuss)

PARTICLE INTERACTIONS

FEEBLY INTERACTING PARTICLES

We are interested in particles that do not interact over the timescale of the phase transition , ie $R_* \approx 1/\beta$

NONINTERACTING: $$T^3 \sigma R_* < 1$$

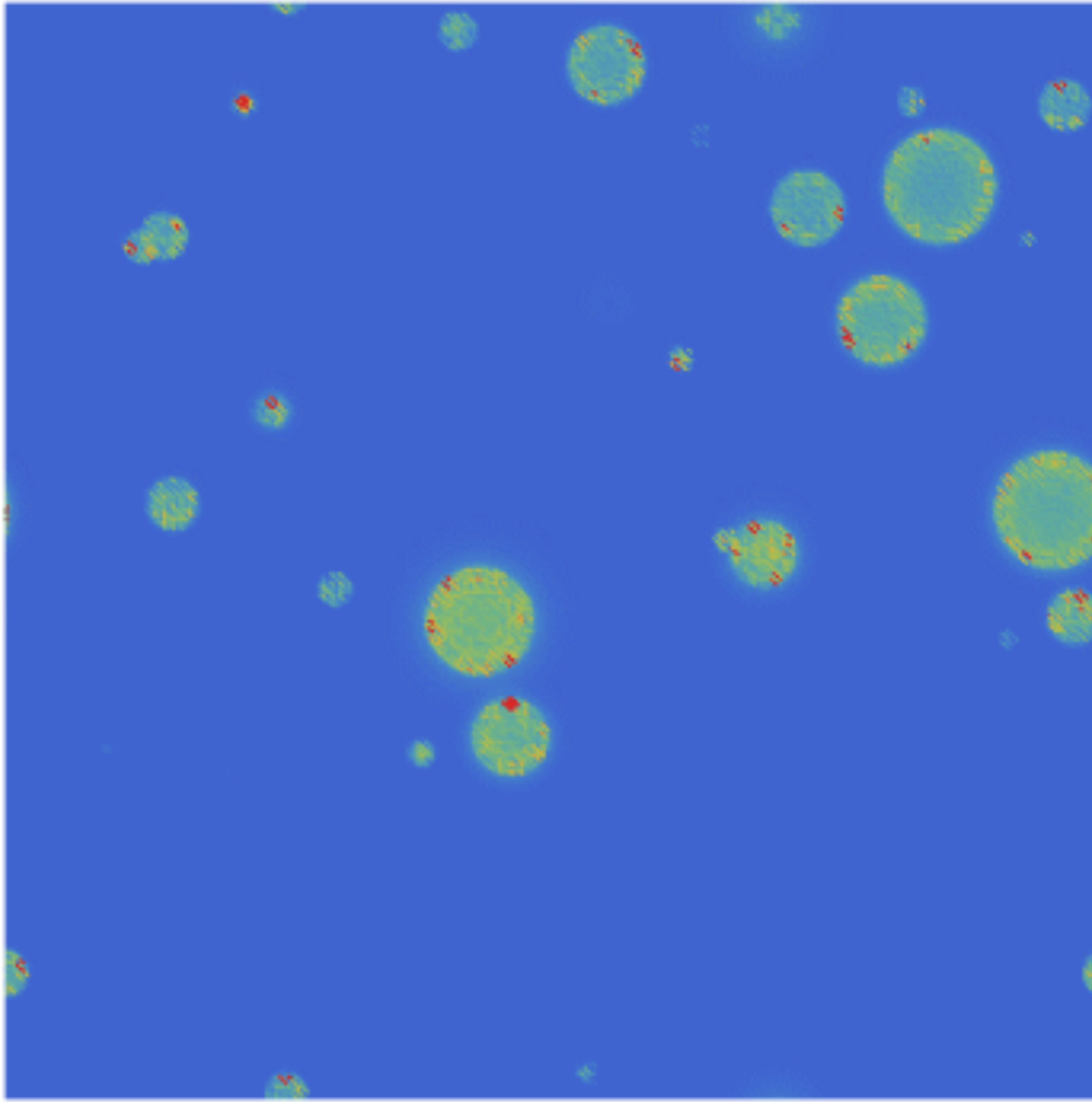
Can occur in many dark sectors models

Irreducible interaction mediated by the scalar: can be "noninteracting" if scalar is very heavy

The massive particles can also decay away rapidly into FIPs

SIMULATION:

FIPS FROM FOPT



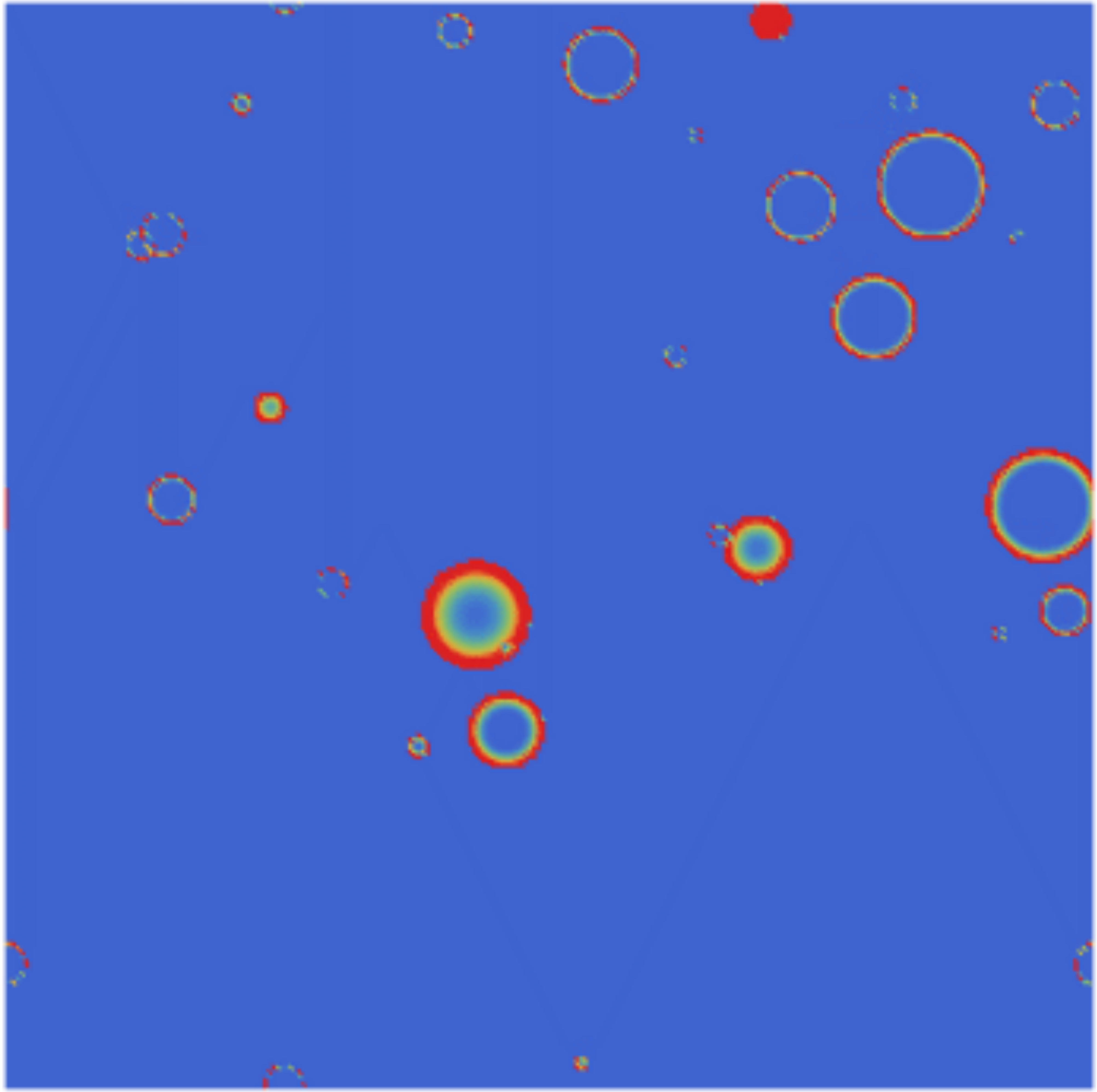
Blue→ yellow→red

Increasing energy density

(Ignore red dots: numerical artefacts)

SIMULATION COMPARISON:

SOUND WAVES



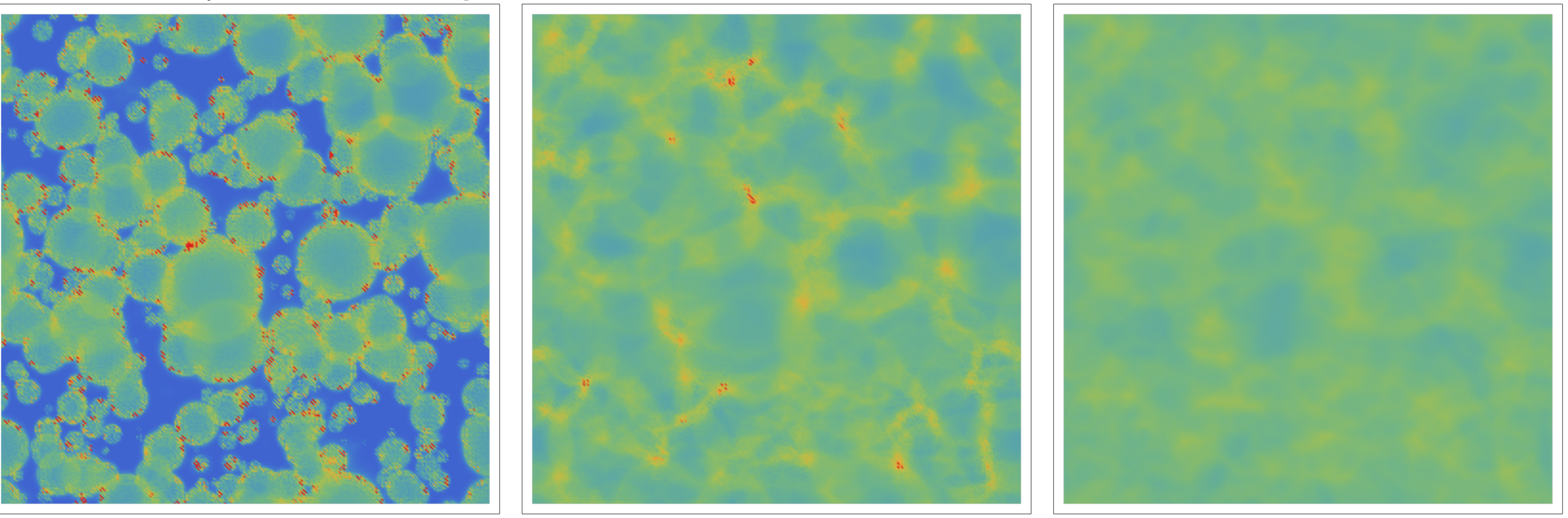
Blue→ yellow→red

Increasing energy density

(Different scaling from FIP simulation)

COMPARISONS

Feebly Interacting Particles (FIPs)

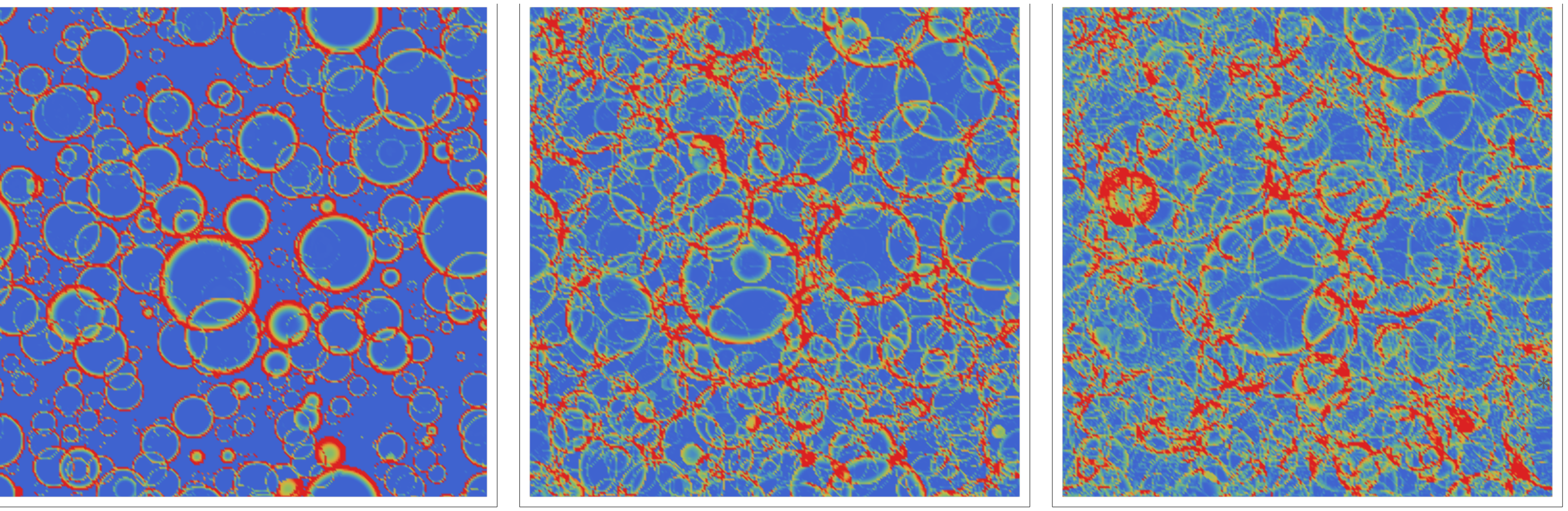


Bubbles contain thick noninteracting particle shells, pass through each other without interacting

$$T_{ij}(t,\vec{x}) = \sum_{I:\ \text{bubbles}} T_{ij}^{(I)}(t,\vec{x})$$

Particle shell thickness continues to grow after bubbles merge

Sound waves

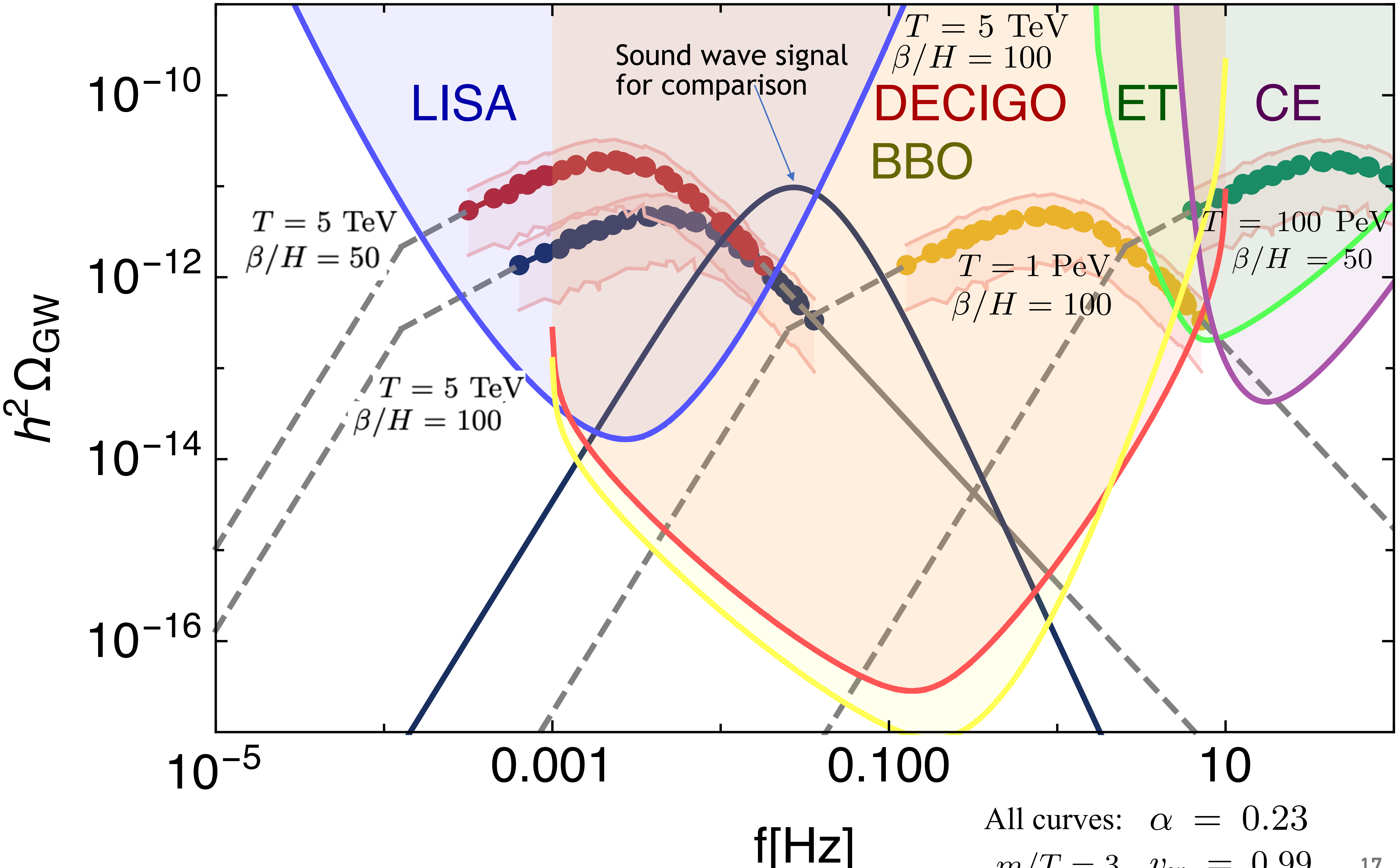


Sound shells interact when they meet

$$v_i^{(\text{fluid})}(t,\vec{x}) = \sum_{I:\ \text{bubbles}} v_i^{(\text{fluid})(I)}(t,\vec{x})$$

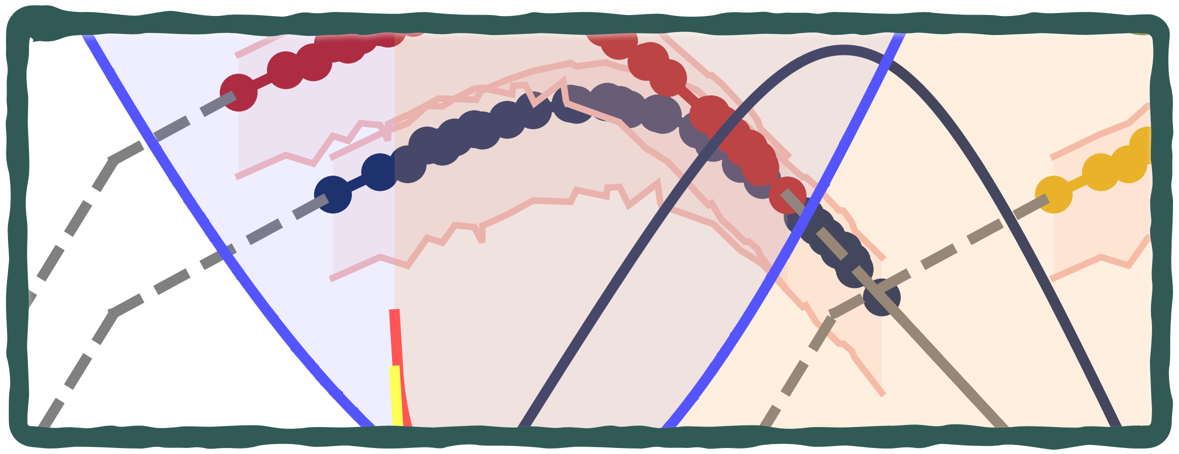
Sound shells thickness is characteristic, does not change after collision

GRAVITATIONAL WAVE SIGNALS



All curves: $\alpha = 0.23$
$m/T = 3, \; v_w = 0.99$

COMPARISON WITH SOUND WAVE SIGNAL



Can be fit with a simple formula (see paper)

- **Peaks at lower frequency**
  FIP particle shell thickness is of order bubble size, sounds shell thickness is an order of magnitude smaller
- **Broader peak with ~k plateau**
  sound wave signals get imprinted at the same scale, FIP signals accumulate across a range of wavenumbers
- **Comparable amplitude**
  FIP shells are noninteracting: no energy loss inefficiencies

PART I SUMMARY

NOVEL GRAVITATIONAL WAVE SIGNALS FROM DARK PHASE TRANSITIONS

- A new possibility for first order phase transitions, beyond bubble walls and sound waves (+turbulence): **feebly interacting particles**
- Can produce **observable gravitational wave signals**, with **distinct characteristics**
- We provide an easy to use **simple analytic fit formula**, to estimate this contribution in frameworks that contain noninteracting particles

PART II: PARTICLE PRODUCTION FROM FOPTS

2308.13070

On Particle Production from Phase Transition Bubbles

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[2] *II. Institute of Theoretical Physics, Universität Hamburg, 22761, Hamburg, Germany*
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2308.16224

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

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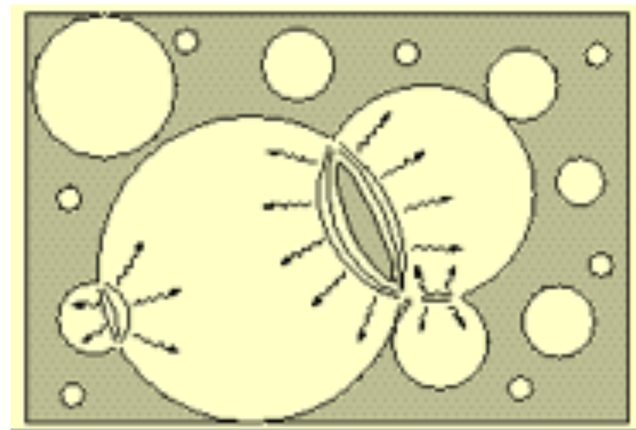
PARTICLE PRODUCTION FROM SCALAR FIELD DYNAMICS



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

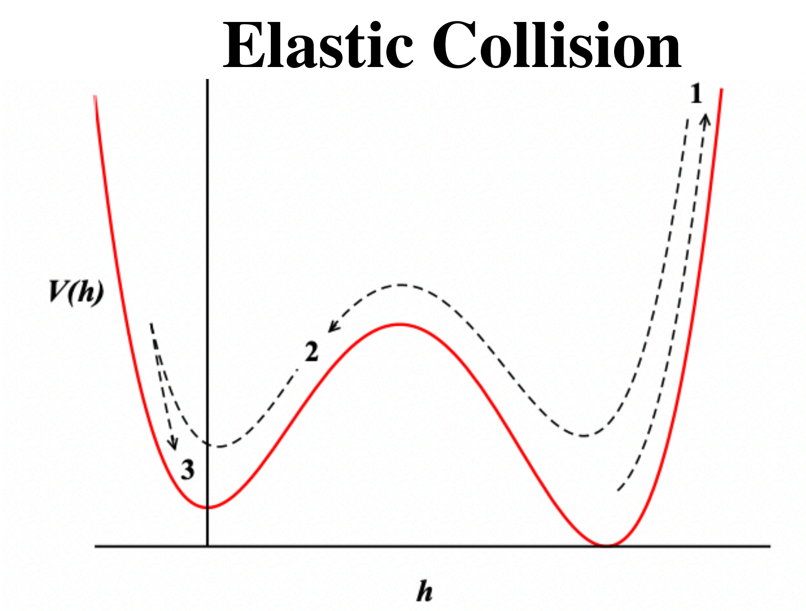
Complicated to calculate because of inhomogeneous nature of the process (e.g. cannot use Bogoliubov transformation)

SCALAR FIELD DYNAMICS AT BUBBLE COLLISION

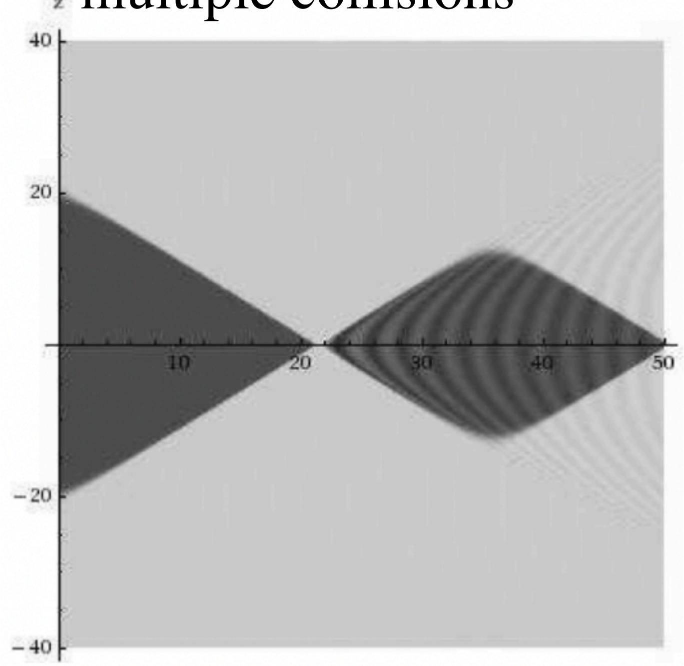
Moment of collision: scalar field gets a “kick”

Two qualitatively different possibilities:

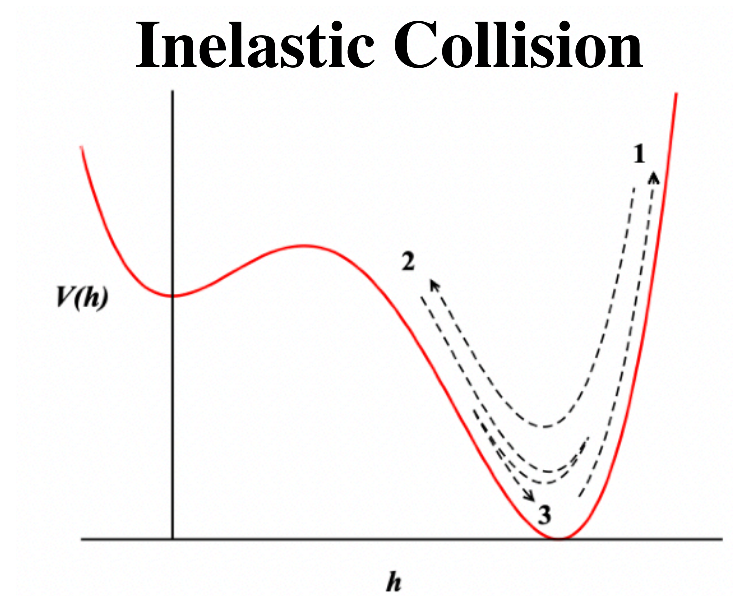
Field gets kicked back to false vacuum



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



Field oscillates around true vacuum



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

PARTICLE PRODUCTION AT BUBBLE COLLISION

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2 point 1PI Green function.

Imaginary part gives decay probability

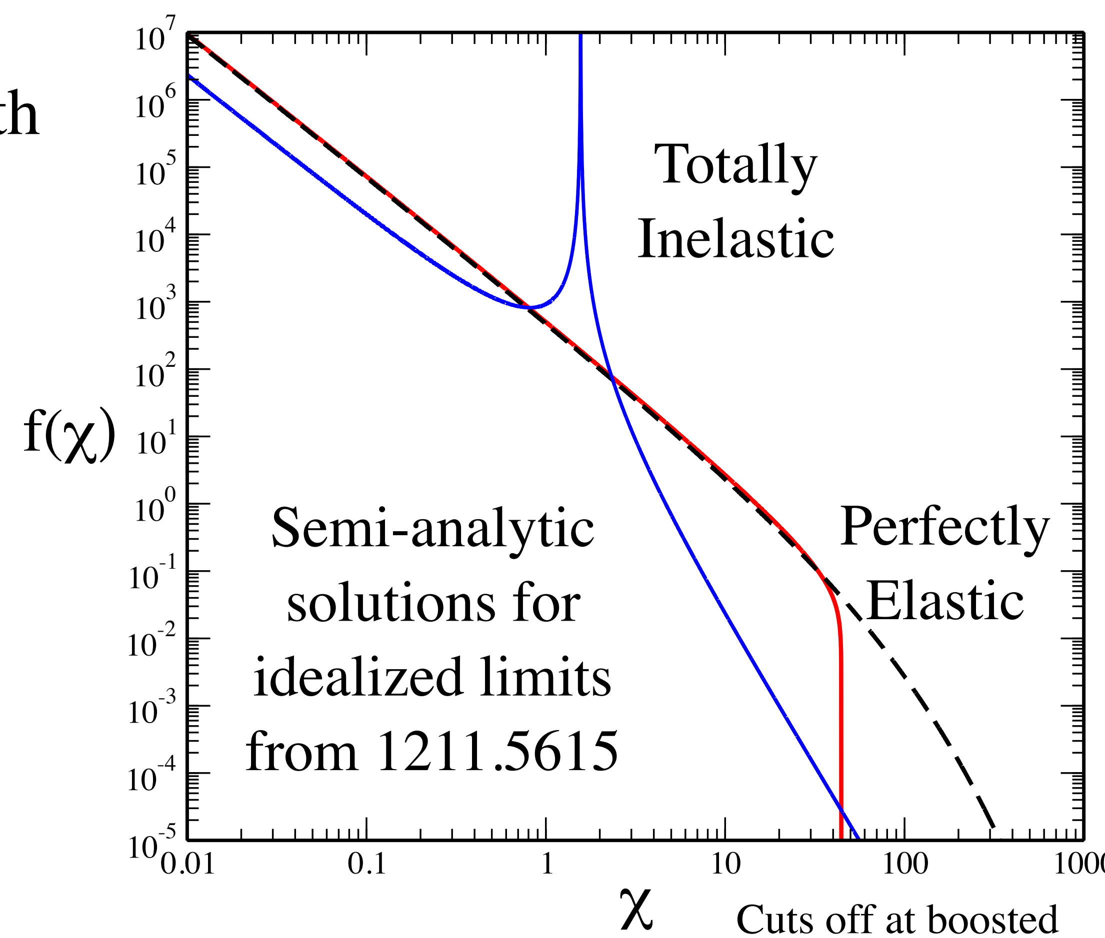
Decompose excitation into Fourier modes

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

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

Particle production efficiency factor

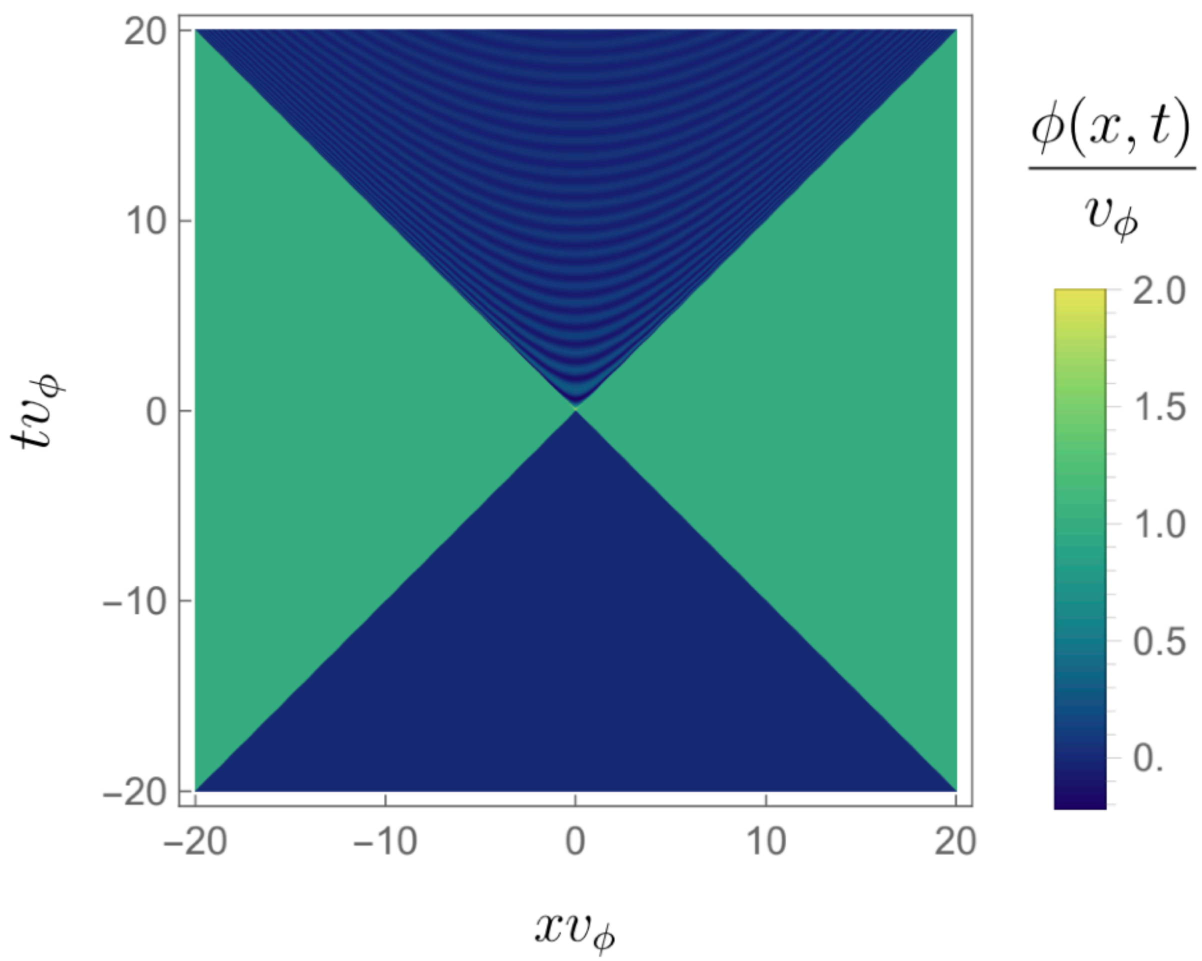
$\chi = \omega^2 - k^2$



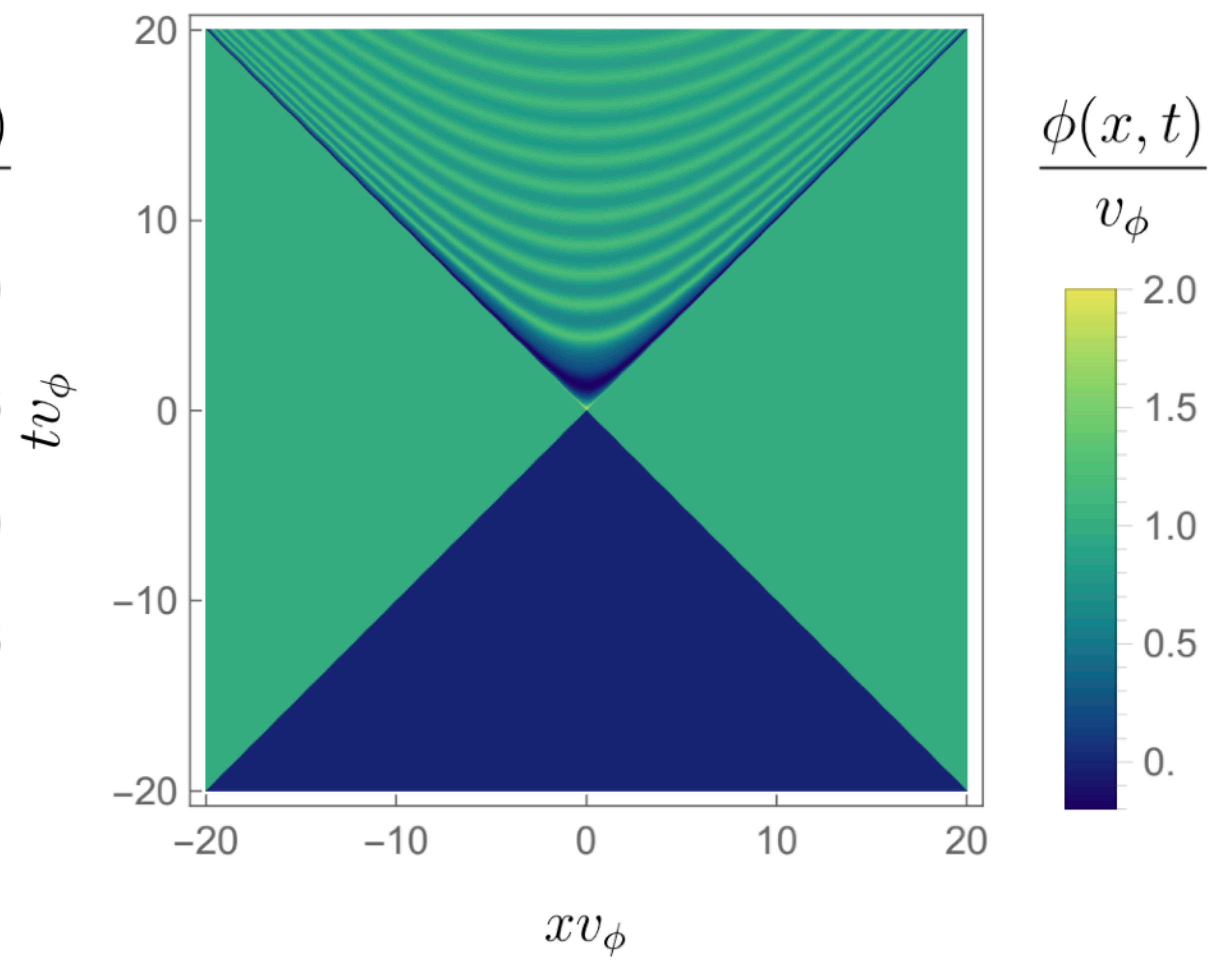
Cuts off at boosted bubble wall thickness scale

REALISTIC CASES

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



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

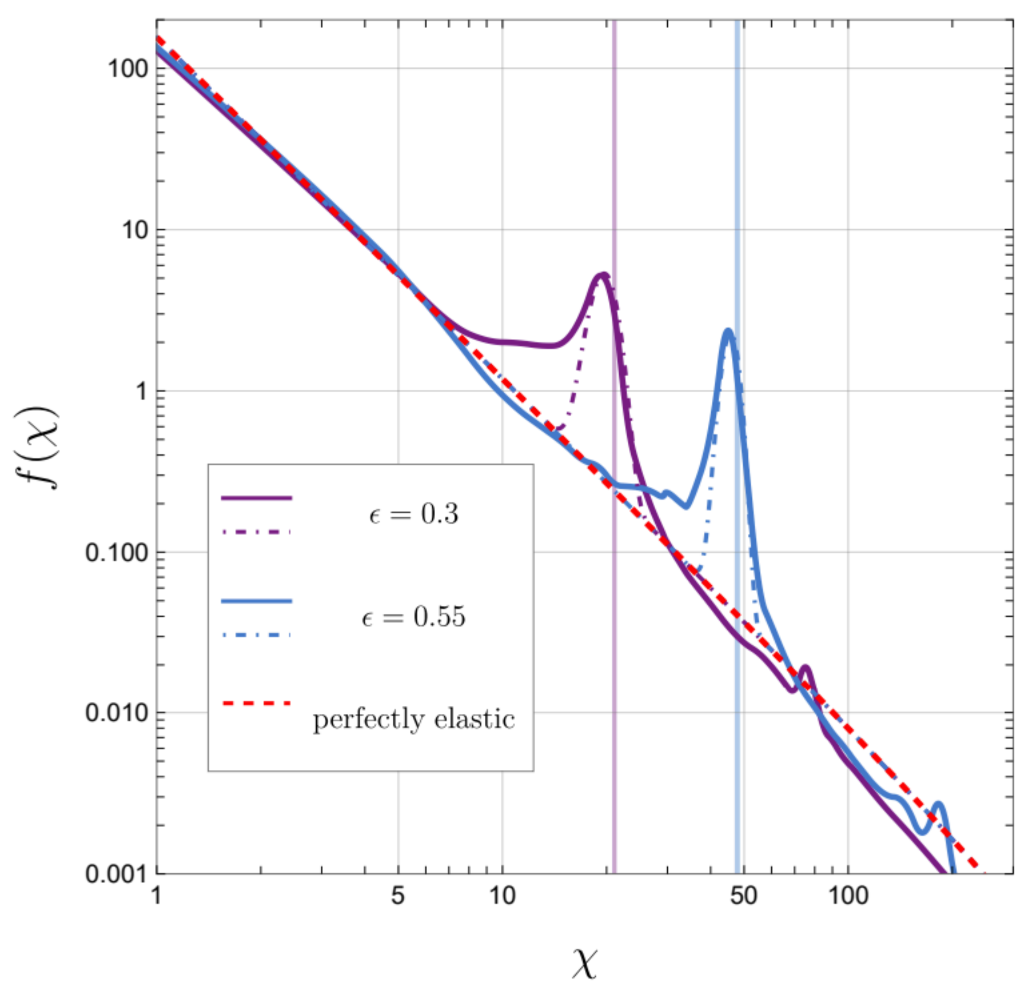


(b) inelastic collision ($\epsilon = 0.1,\ a = 4.4$)

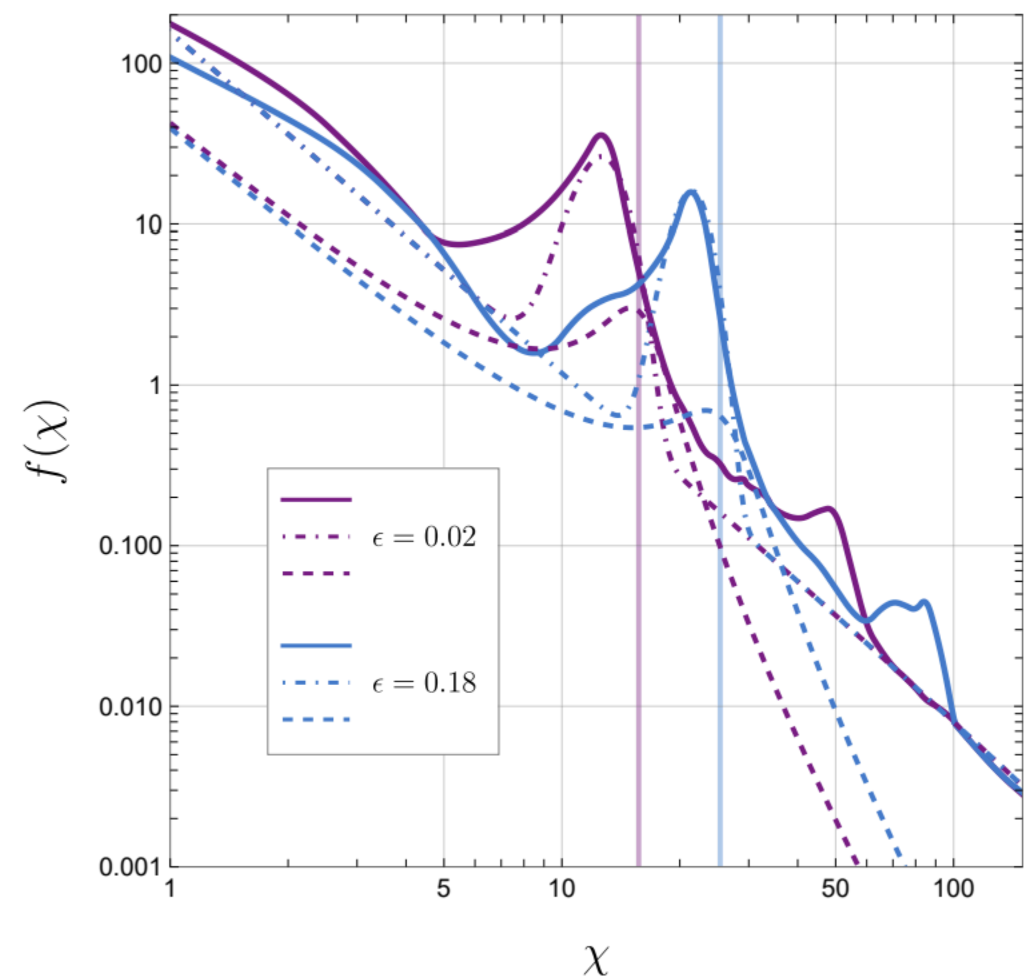
Green: true vacuum, blue: false vacuum

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

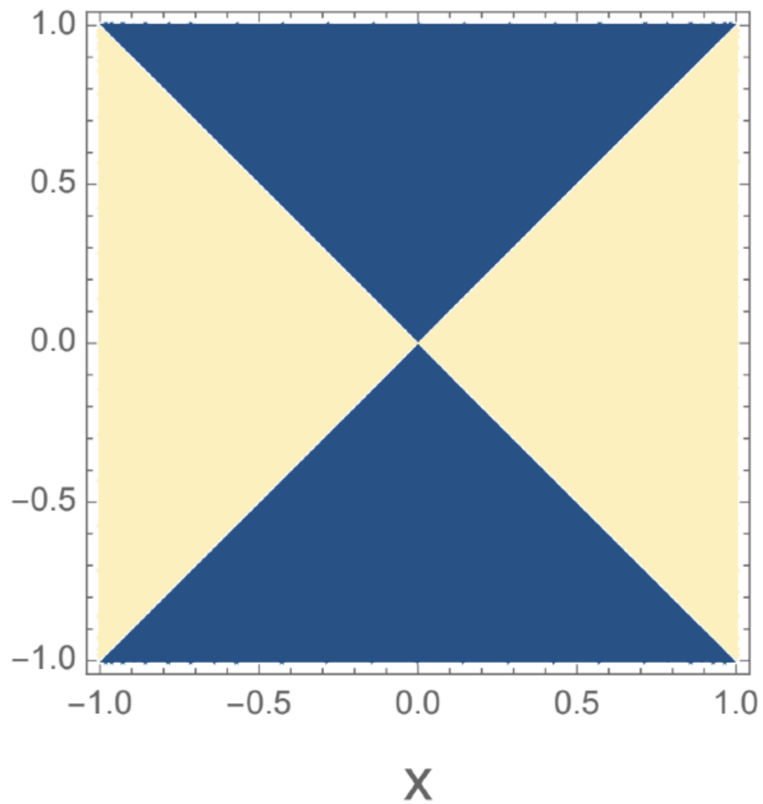
(See paper for easy to use fit functions)

UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

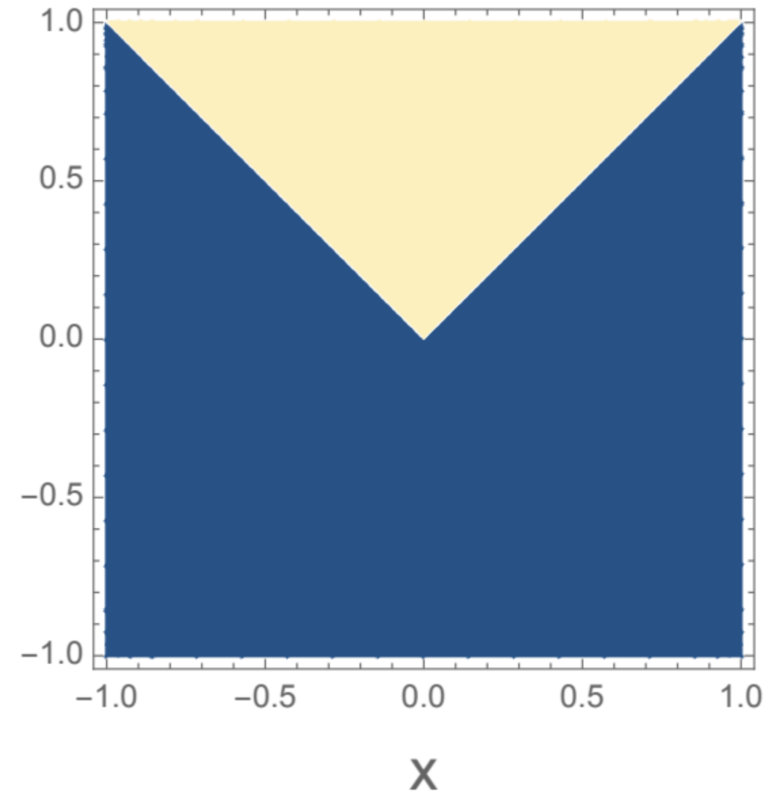
Naive interpretation: everything happens at the moment of collision+ gradual radiation from oscillations after collision

UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

Perfectly elastic case



Two bubble walls colliding at the origin



Single bubble expanding out from the origin

Fourier transform

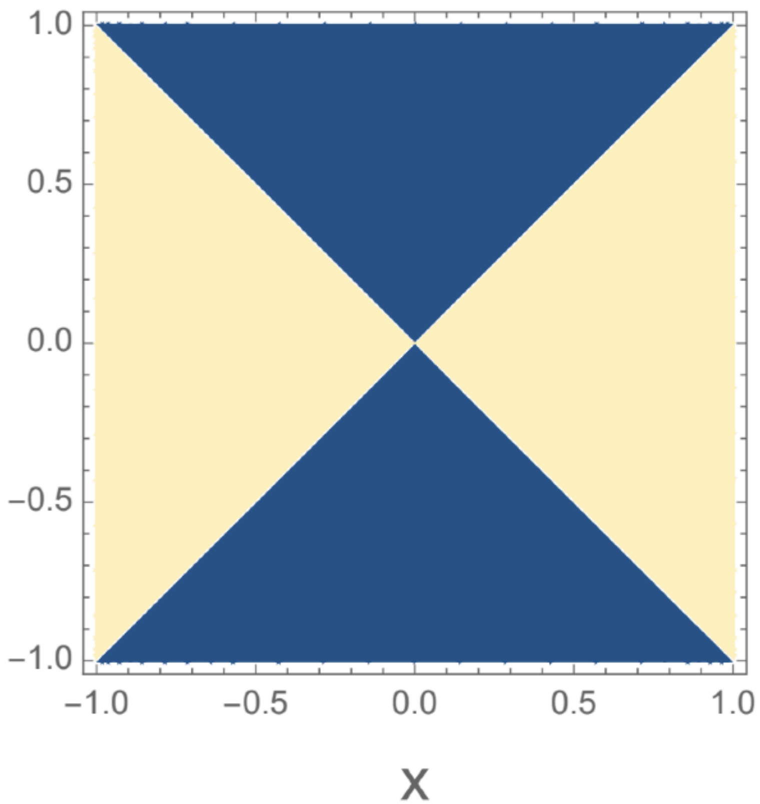
$$\tilde{\phi}(k,\omega) = \frac{4\,v_\phi}{\omega^2 - k^2\,v_{\rm w}^2}$$

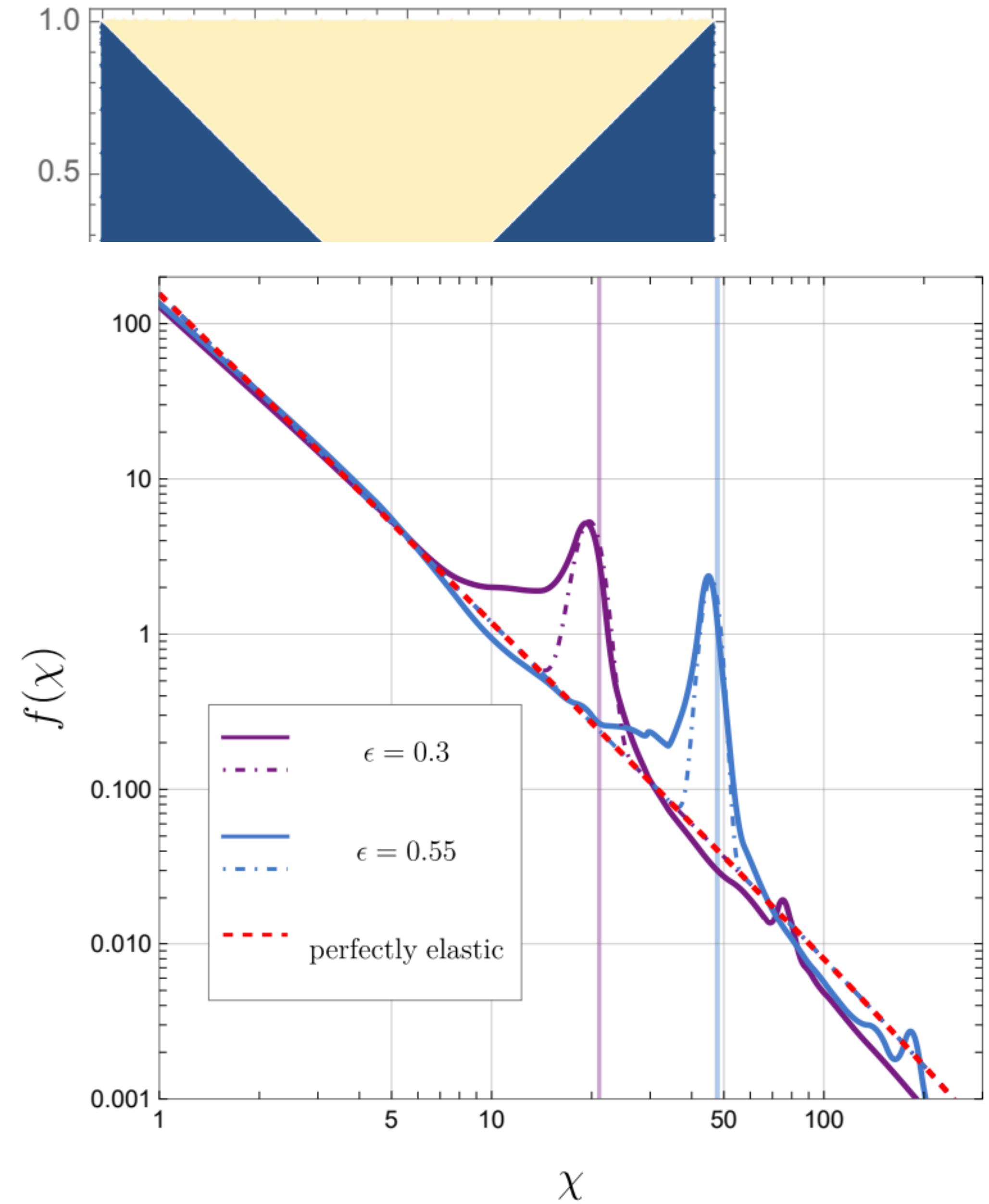
Fourier transform

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

UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

Perfectly elastic case





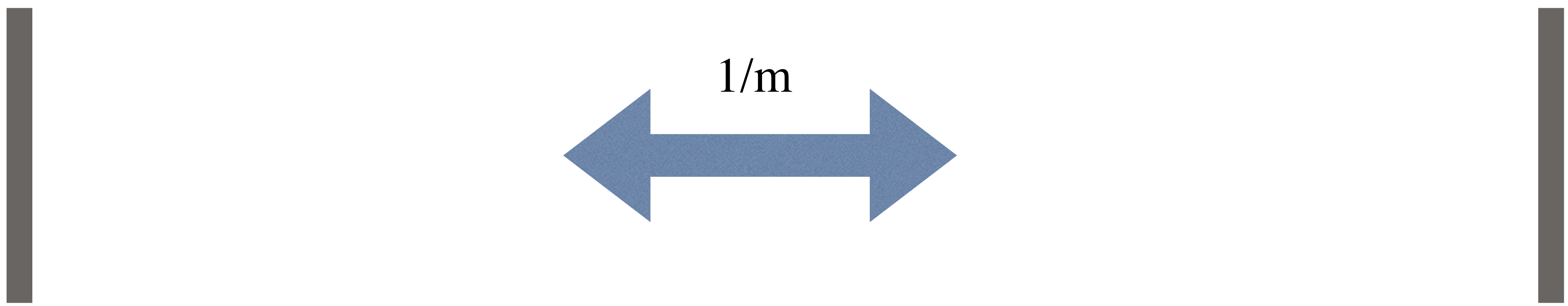
Everything comes from relative motion of bubble walls! Each \chi contribution corresponds to a configuration with the bubble walls at that corresponding distance!

[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!]

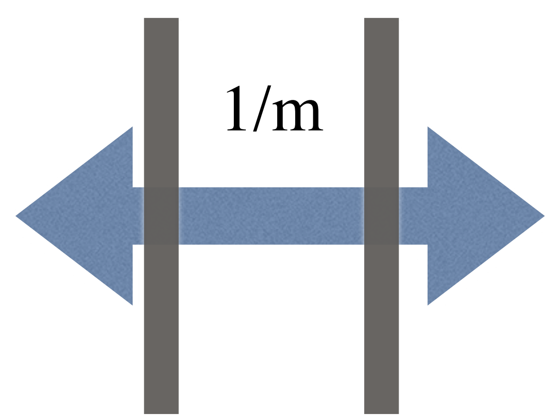
UNDERSTANDING HOW AND WHERE PARTICLE PRODUCTION OCCURS

Particle production is a "local" process

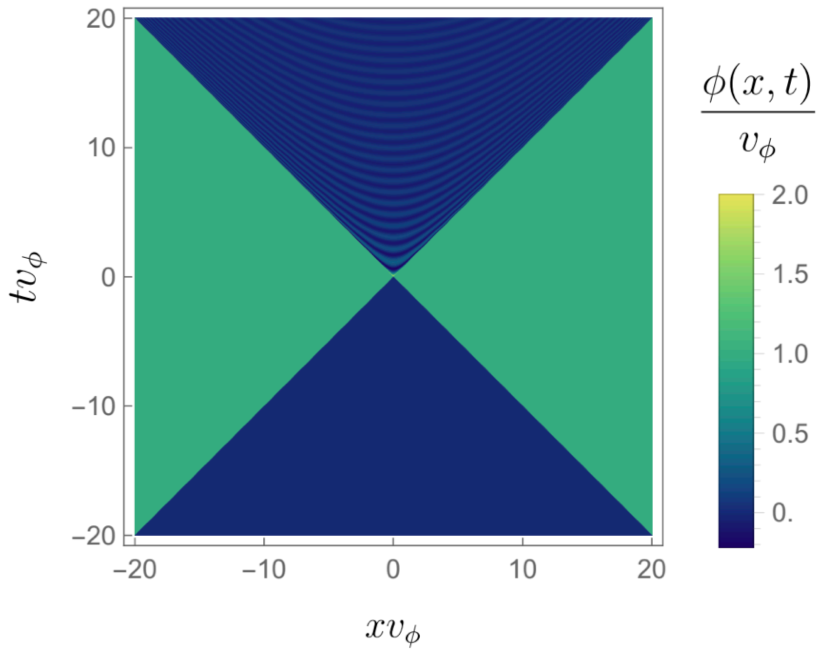
Consider a particle of mass m. Has a length scale associated with it: its Compton wavelength 1/m

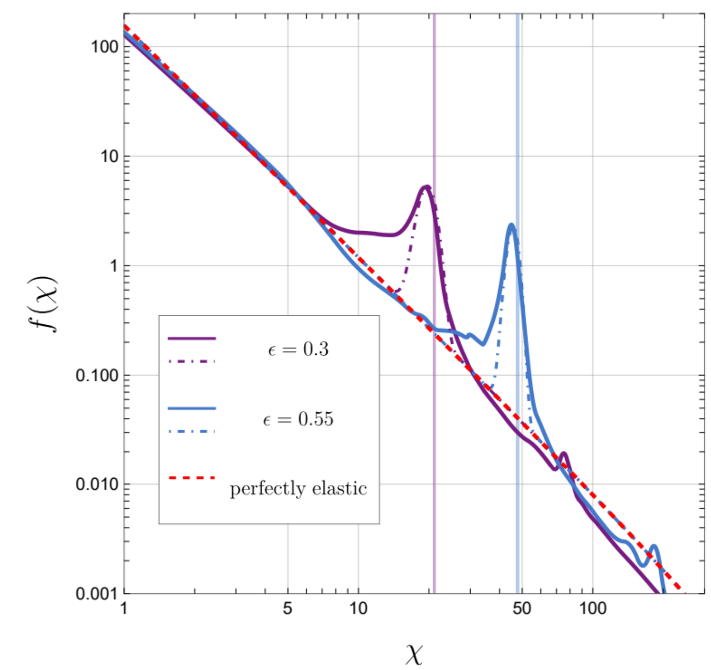


Walls moving relative each other at distances much farther away cannot lead to particle production. Can only be produced when the dynamics occurs within a Compton wavelength distance



NON-UNIVERSALITY OF PARTICLE INTERACTIONS





The efficiency factor gives a 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

Consider tachyonic instability:

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

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

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

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

Spatial gradients important, suppress the coherent growth of the field

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

PART II SUMMARY

PARTICLE PRODUCTION FROM FIRST ORDER PHASE TRANSITIONS

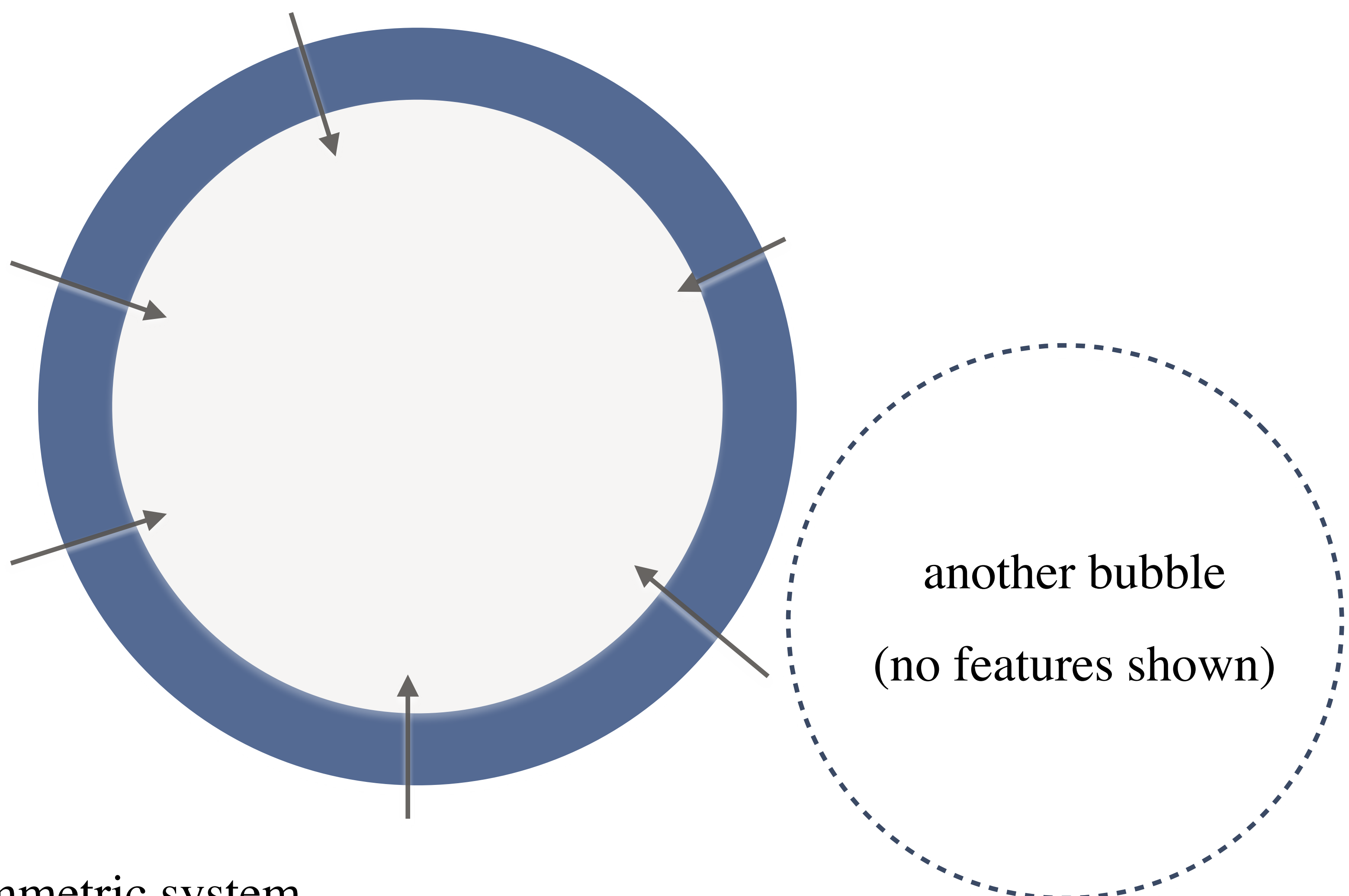
- Not studied very carefully in the literature, only semi-analytically in idealized limits
- Numerical studies of more realistic scenarios; provided **simple fit functions** for more general use
- More careful treatment of various aspects important: nature and location of particle production, non-universality of particle interactions and masses across different vacua, suppression of resonant effects due to the inhomogeneous nature of the process

BACKUP SLIDES

UNDERSTANDING THE PHYSICS

Consider accumulation of particles in a single expanding bubble

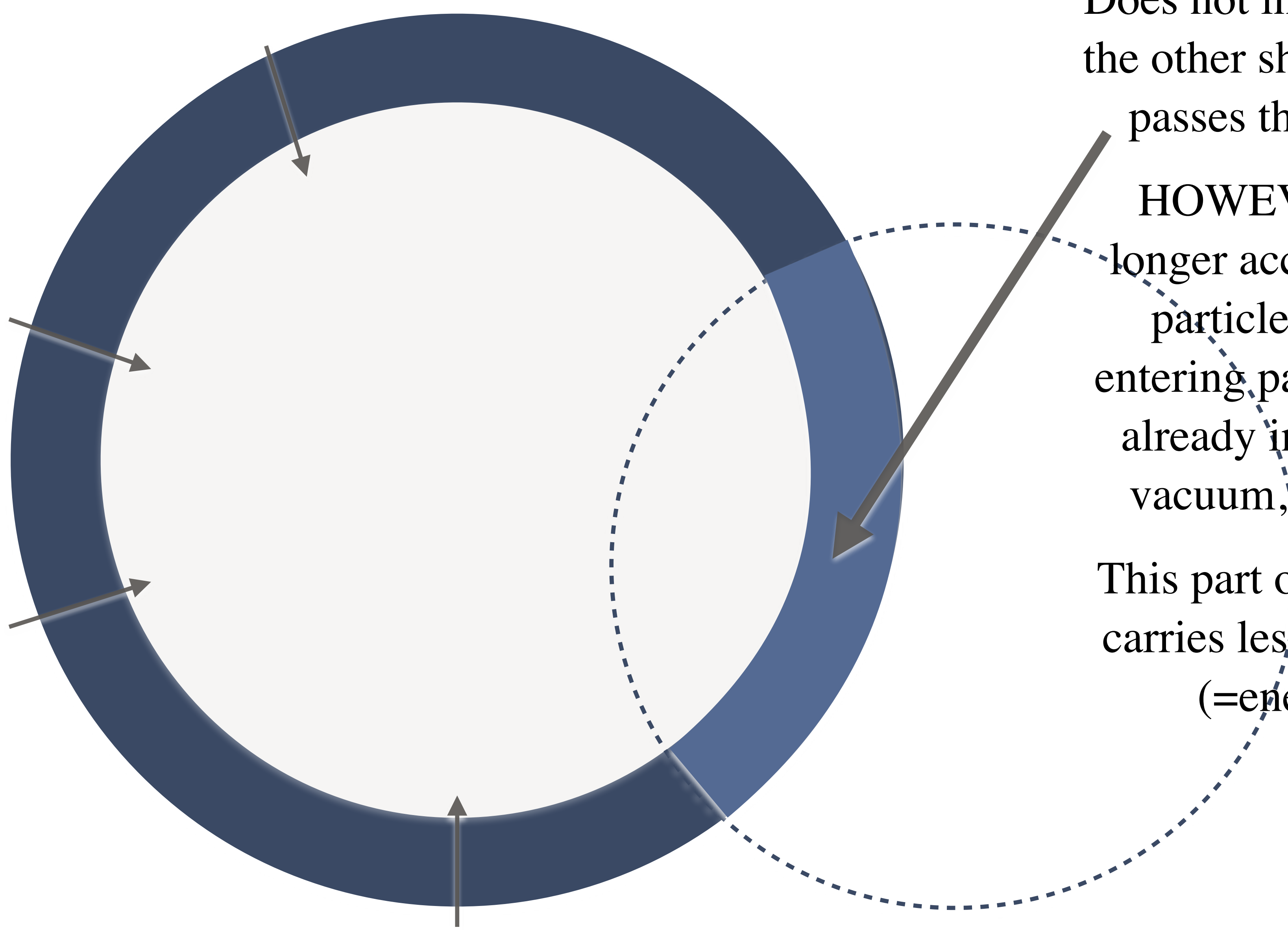
Particles continue to enter, become massive, and accumulate on the shell as bubble expands into false vacuum



Spherically symmetric system,
no gravitational waves

UNDERSTANDING THE PHYSICS

Consider accumulation of particles in a single expanding bubble



Particles continue to enter, become massive, and accumulate on the shell as bubble expands into false vacuum

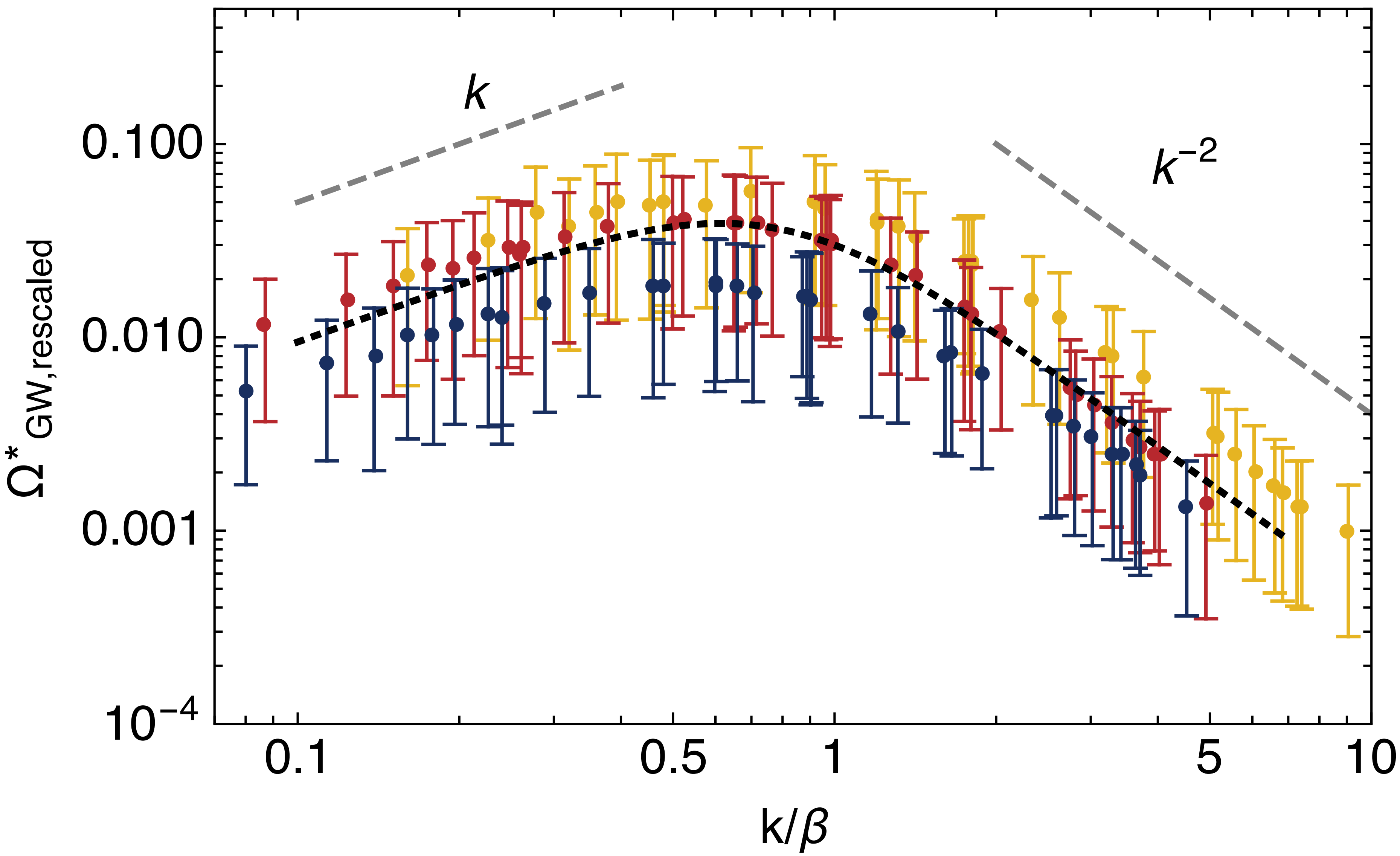
Does not interact with the other shell, simply passes through…

HOWEVER, no longer accumulates particles as the entering particles are already in the true vacuum, massive

This part of the shell carries less particles (=energy)

Spherically symmetry broken, system can generate gravitational waves!

UNIVERSALITY OF GW SIGNAL



$(m/T, v_w)$	
(1, 0.7)	yellow
(2, 0.95)	red
(3, 0.99)	blue

“FIT” FORMULA

$$\Omega^*_{\rm GW}(k) \sim \frac{3}{4\pi^2}\left(\frac{H}{\beta}\right)^2\left(\frac{\frac{1}{24}m^2T^2}{\rho_{\rm tot}}\right)^2\left[\left(\bar{K}^{(\rm GW)}\right)^2\frac{s}{1+s^3}\right]$$

$$s = 0.77\times k/\beta$$

“model dependent” piece

(Distribution function: carries information on the distribution of particles in the broken phase)