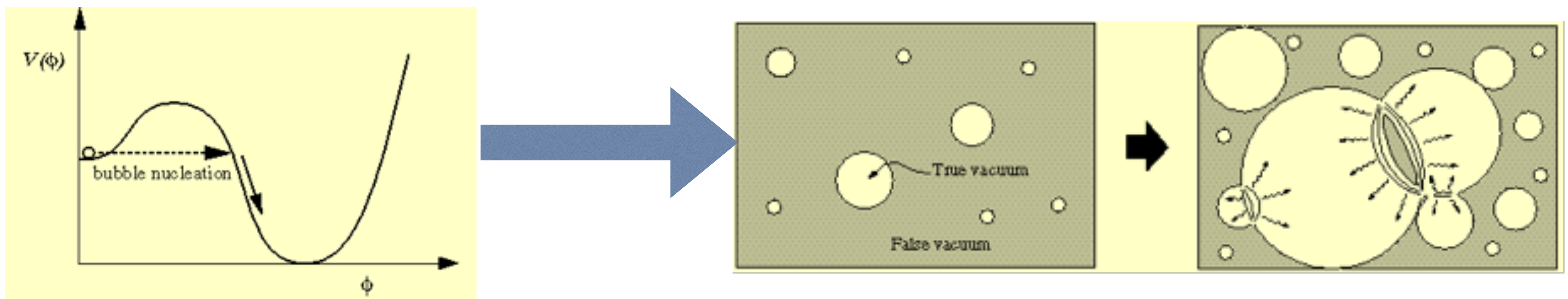
BSM PHYSICS FROM BUBBLE COLLISIONS

JANUARY 28, 2026

BIBHUSHAN SHAKYA

JOHNS HOPKINS UNIVERSITY

A FIRST ORDER PHASE TRANSITION (FOPT)



Scalar field **tunnels from a metastable (false) to stable (true) vacuum configuration; bubbles** of true vacuum nucleate, expand, merge

Since neither the EW nor the QCD phase transition in the SM is first order, an FOPT in the early Universe already involves BSM physics

The goal of this talk is to explore BSM possibilities from bubble collisions **BEYOND** the BSM setting that enables the FOPT

THE APPEAL OF BSM PHYSICS

Related to issues within the Standard Model

e.g.
supersymmetry
extra dimensions
seesaw mechanism
QCD axion
grand unification

Issues related to the observed Universe

e.g.
dark matter
dark energy
baryon asymmetry

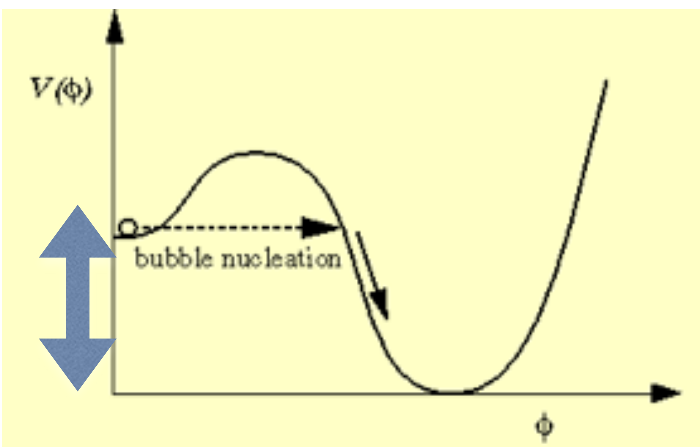
Higher Energy

Out of equilibrium

Bubble collisions can help achieve these

THE FATE OF VACUUM ENERGY

FOPT involves the release of (significant) latent energy stored in the false vacuum



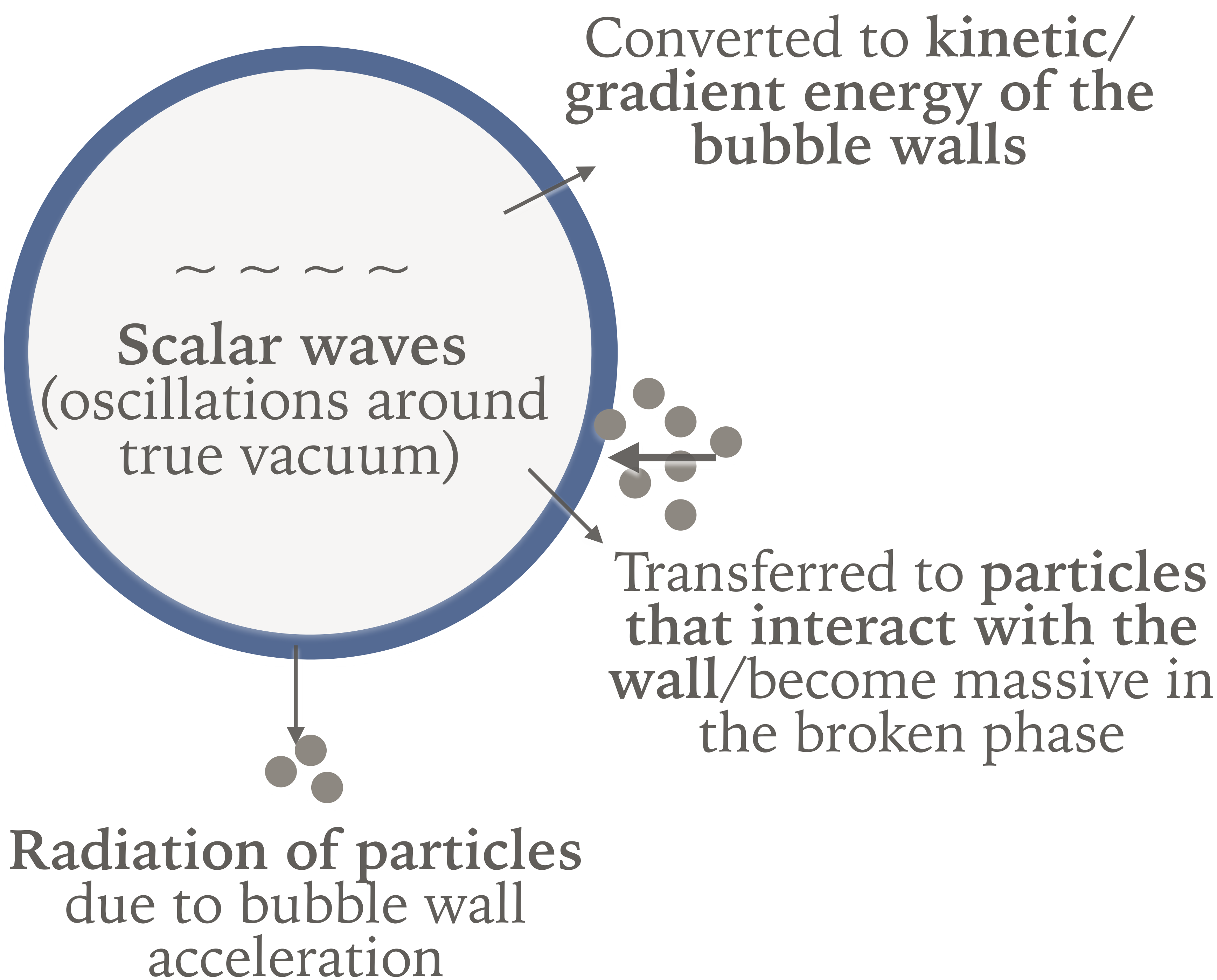
(could be the dominant energy component of the Universe)

$$\alpha = \frac{\Delta V}{\rho_{\rm rad}}$$

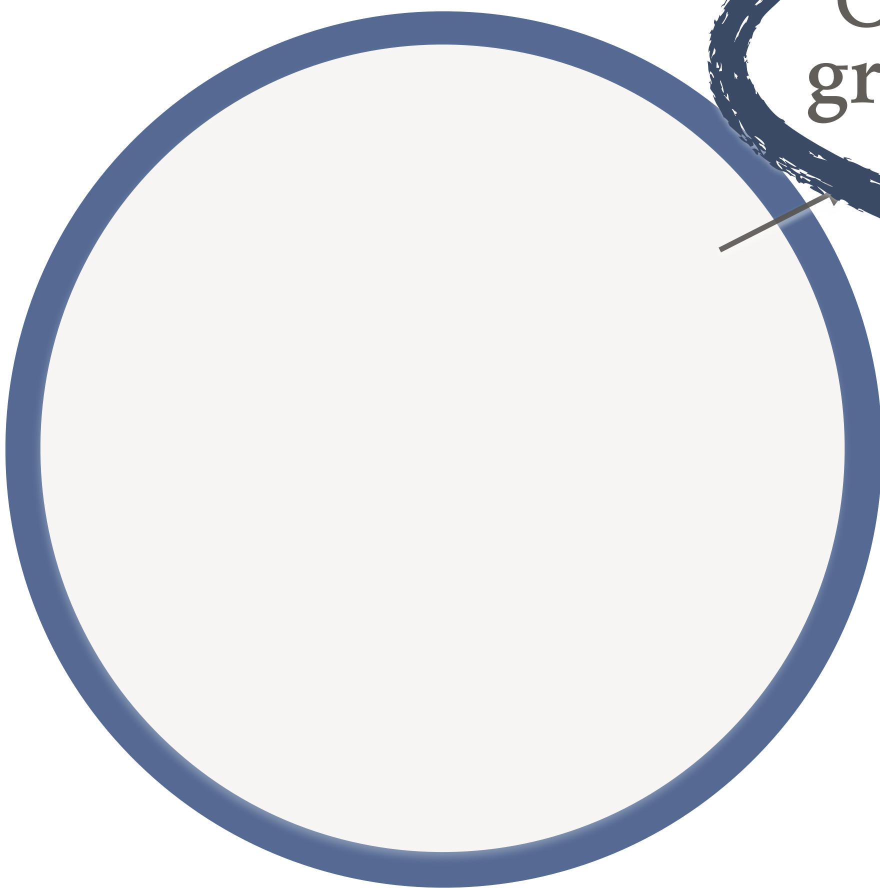
(~0.01 or larger for observable gravitational waves)

Where does all this energy go?

THE FATE OF VACUUM ENERGY



THE FATE OF VACUUM ENERGY



Converted to **kinetic/ gradient energy of the bubble walls**

We will focus on this runaway configuration

bubble walls accumulate the released latent energy from the false vacuum, and accelerate to higher boost factors

can occur in many scenarios: supercooled transitions, transition with light /no gauge bosons, quantum tunnelling in vacuum

2403.03252

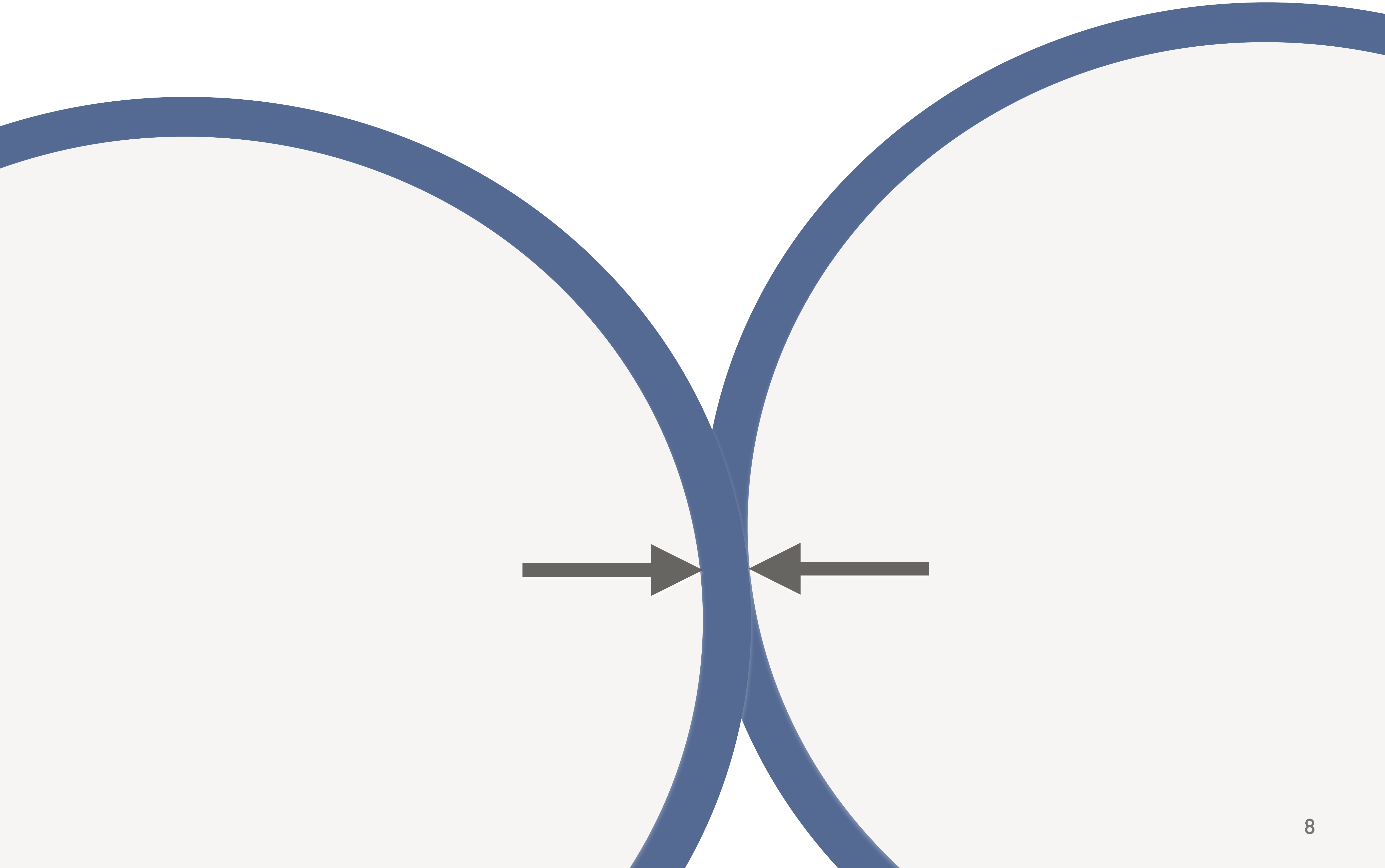
THE FATE OF VACUUM ENERGY

When such bubbles collide:
a (super) high energy collider!

- energy scale?
- efficiency?
- how to calculate particle production?
- BSM applications?

bosons, quantum tunnelling in vacuum

ENERGY OF COLLIDING BUBBLES



ENERGY OF COLLIDING BUBBLES

From energy conservation arguments,
Lorentz boost factor of the runaway bubble wall grows linearly with bubble size

$$\gamma \sim R/R_0$$

Initial energy scale: inverse of wall thickness at nucleation

$$l_{w0} \sim v_\phi^{-1}$$

Energy of collision

$$2\gamma_w/l_{w0} = \frac{2R_*}{R_0} v_\phi$$

$$R_* \sim H^{-1} \sim (T^2/M_P)^{-1} \sim (v_\phi^2/M_P)^{-1}$$

$$R_0 \sim v_\phi^{-1}$$

ENERGY OF COLLIDING BUBBLES

From energy conservation arguments,
Lorentz boost factor of the runaway bubble wall grows linearly with bubble size

$$\gamma \sim R/R_0$$

Initial energy scale: inverse of wall thickness at nucleation

$$l_{w0} \sim v_\phi^{-1}$$

Energy of collision

$$2\gamma_w/l_{w0} = \frac{2R_*}{R_0} v_\phi \sim M_P$$

Realistically, typical bubble size is $\beta^{-1} < H$, with $\beta/H \sim \mathcal{O}(10 - 10,000)$

Thus energy of collision $\lesssim M_P/(\beta/H)$

independent of the initial energy scale of the FOPT!

Bubbles from lower energy transitions have more time to grow because of larger Hubble radius!

RUNAWAY BUBBLE CONFIGURATIONS

Energy of collision $\lesssim M_P/(\beta/H)$

An intuitive understanding:

Particle production arises from scalar field dynamics at physical (length or time) scale over which bubble collision occurs

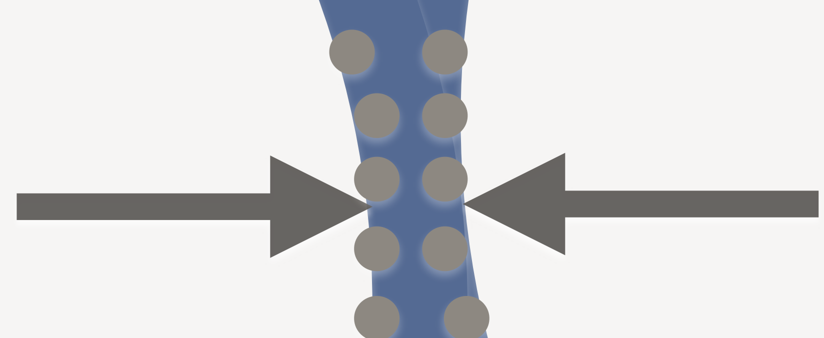
= Boosted bubble wall thickness (Lorentz contracted!)

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

CALCULATING PARTICLE PRODUCTION

The naive approach:

Treat the bubble wall as a condensate of quanta of background field traveling with the energy of the bubble wall



$$\sigma_{\rm coll} \sim \frac{1}{E^2} \sim \frac{1}{M_P^2}$$

Cross section is tiny; interaction unlikely, they should simply pass through each other

CALCULATING PARTICLE PRODUCTION

However, vacuum bubbles are classical objects, obeying classical laws (Klein-Gordon equation), which dictate that nontrivial dynamics occurs when bubbles collide

Moment of collision: scalar field gets a sharp "kick" to higher field value.

Two qualitatively different possibilities for subsequent evolution:

CALCULATING PARTICLE PRODUCTION

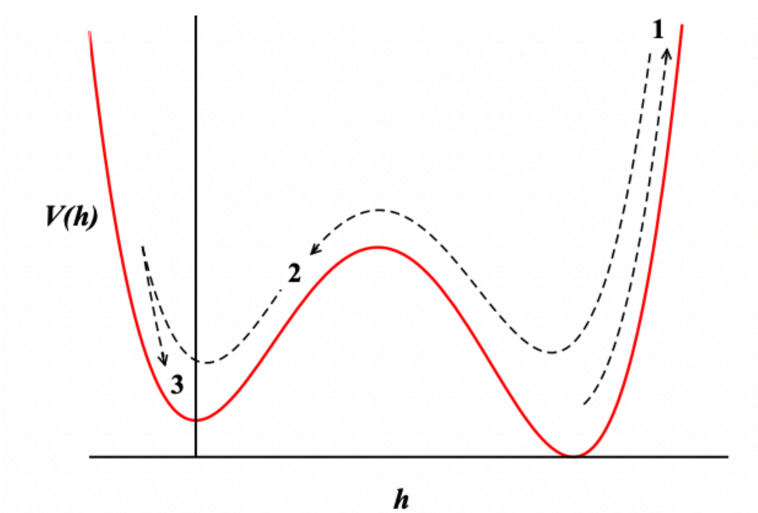
However, vacuum bubbles are classical objects, obeying classical laws (Klein-Gordon equation), which dictate that nontrivial dynamics occurs when bubbles collide

Moment of collision: scalar field gets a sharp "kick" to higher field value.

Two qualitatively different possibilities for subsequent evolution:

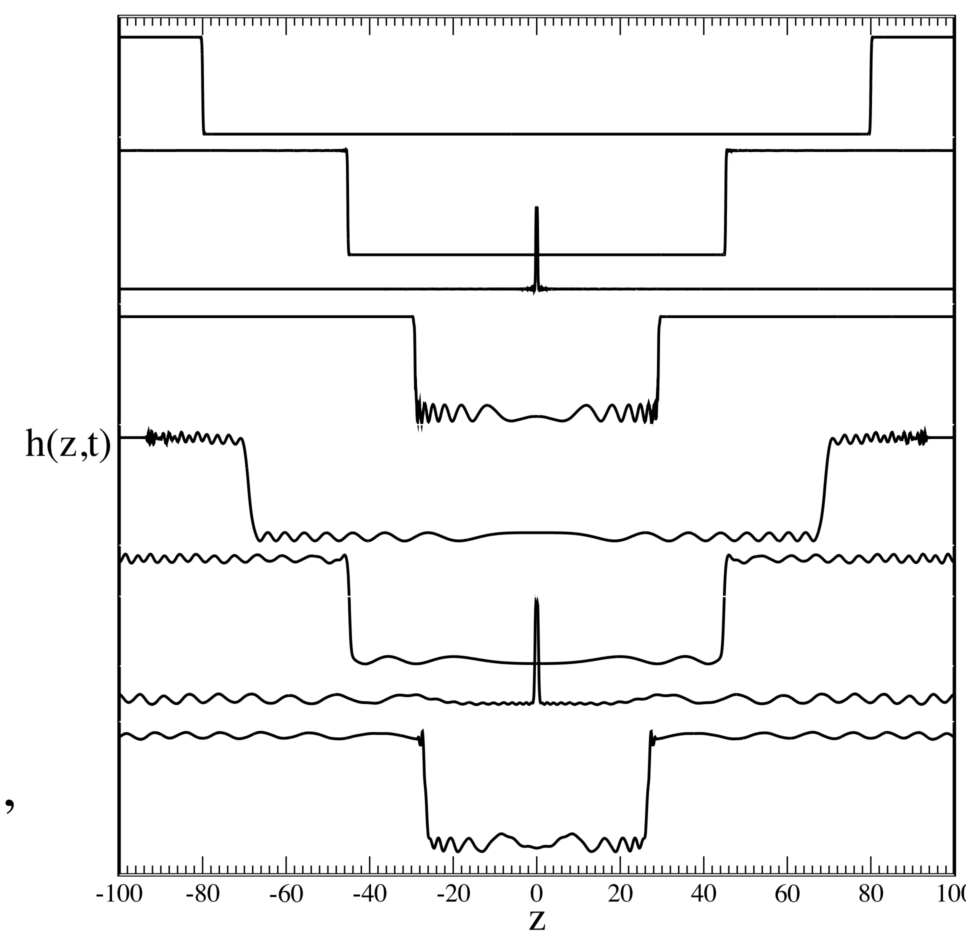
Elastic Collision

Field jumps back to false vacuum



Bubble walls reflect perfectly (get pulled back again, undergo multiple collisions)

1211.5615



CALCULATING PARTICLE PRODUCTION

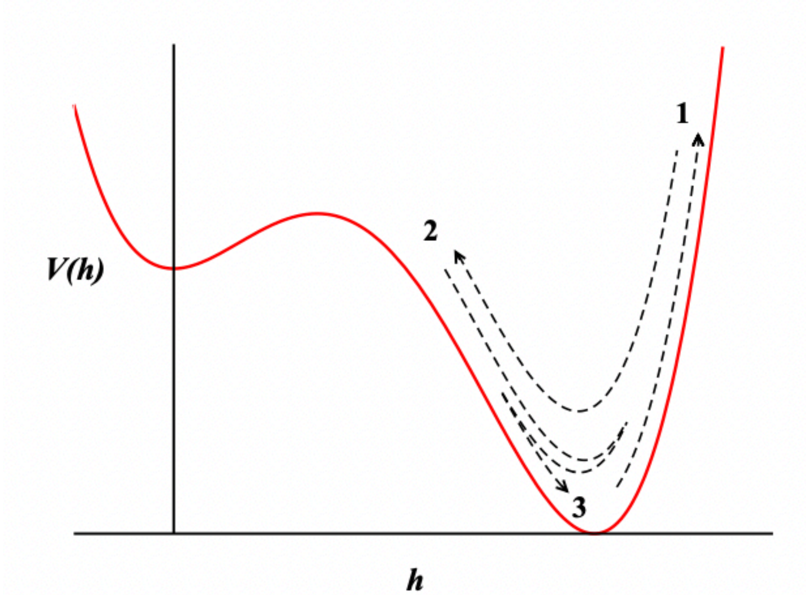
However, vacuum bubbles are classical objects, obeying classical laws (Klein-Gordon equation), which dictate that nontrivial dynamics occurs when bubbles collide

Moment of collision: scalar field gets a sharp “kick” to higher field value.

Two qualitatively different possibilities for subsequent evolution:

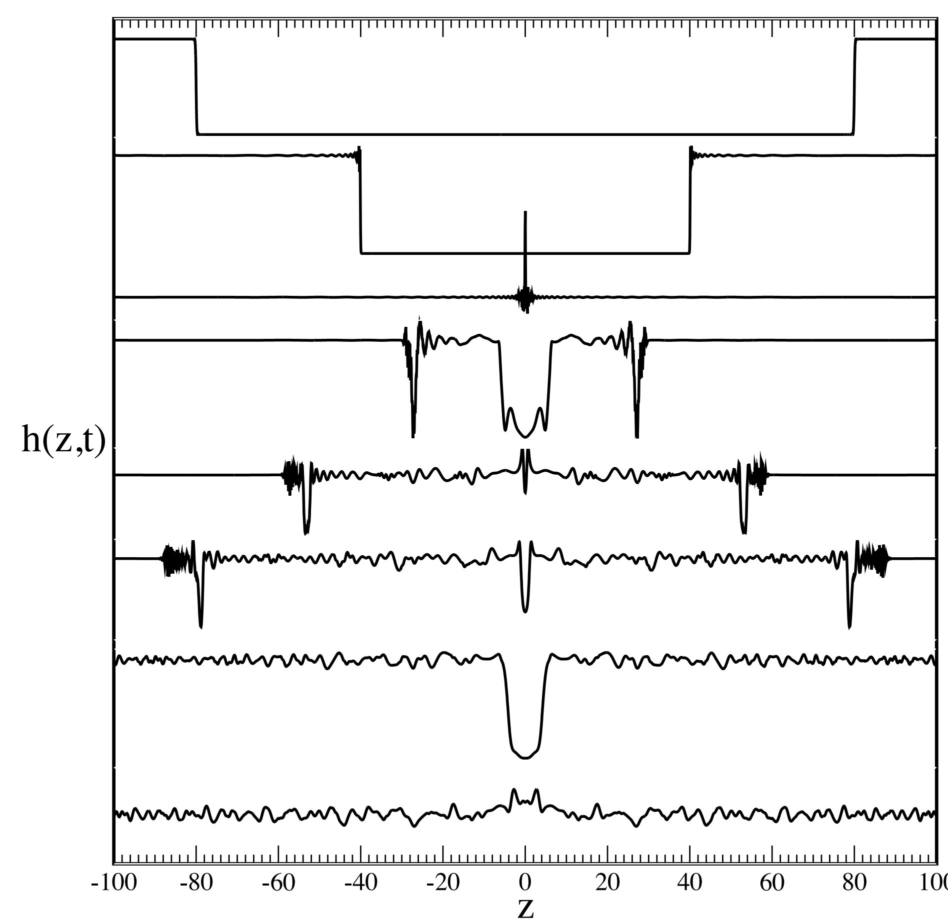
Inelastic Collision

Field oscillates around true vacuum



Bubble walls stick together; energy dissipated as scalar waves

1211.5615

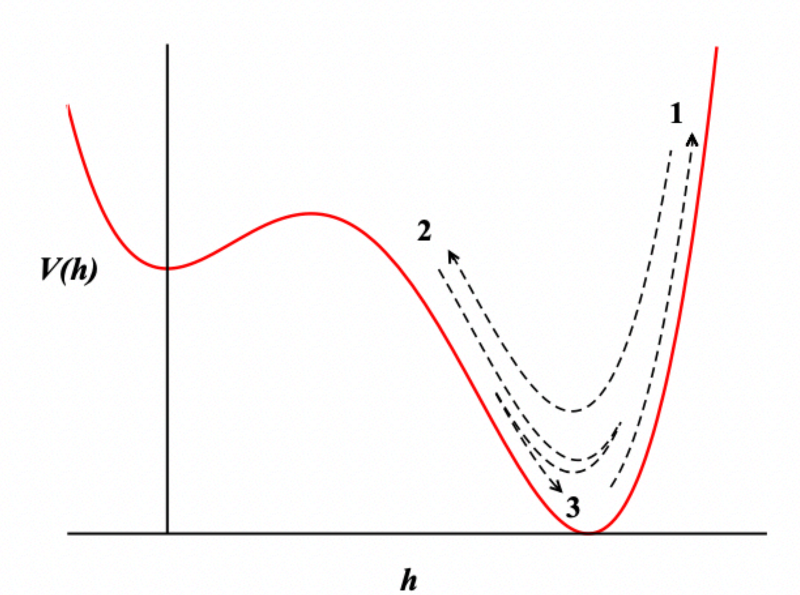


CALCULATING PARTICLE PRODUCTION

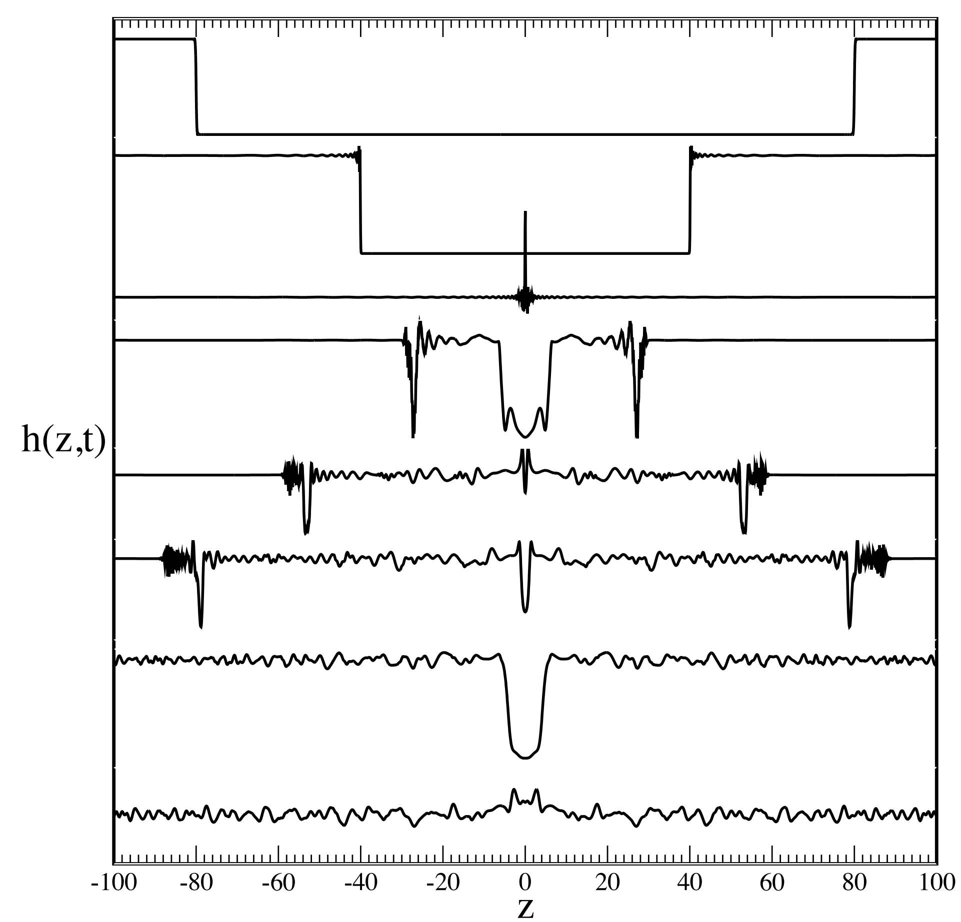
However, vacuum bubbles are classical objects, obeying classical

- In either case, the field jumps very sharply when the walls first collide
- During this, it can radiate very high energy (or high mass) particles

Field oscillates around true vacuum



Bubble walls stick together; energy dissipated as scalar waves



CALCULATING PARTICLE PRODUCTION

Use the **effective action formalism**:

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

Probability of particle production:

imaginary part of the effective action of the background field

Also

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

1104.4793, 1211.5615, 2403.03252

Effective action: generating functional of 1PI Green functions

$$\Gamma[\phi\,] = \sum_{n=2}^{\infty} \frac{1}{n!} \int d^4x_1...d^4x_n \Gamma^{(n)}(x_1, ..., x_n)\phi(x_1)...\phi(x_n).$$

Take leading (n=2) term, take Fourier transform

$$\mathrm{Im}\,(\Gamma[\phi]) = \frac{1}{2} \int d^4x_1 d^4x_2 \phi(x_1)\phi(x_2) \int \frac{d^4p}{(2\pi)^4} e^{ip(x_1-x_2)} \mathrm{Im}(\tilde{\Gamma}^{(2)}(p^2))$$

Assume planar symmetry at collision, plug in Fourier transform of the classical field configuration to get particle number density:

$$\frac{N}{A} = 2 \int \frac{dp_z\, d\omega}{(2\pi)^2}\, |\tilde{\phi}(p_z,\omega)|^2\, \mathrm{Im}[\tilde{\Gamma}^{(2)}(\omega^2 - p_z^2)]$$

CALCULATING PARTICLE PRODUCTION

Number of particles produced per unit area of bubble wall collision:

$$\frac{N}{A} = 2 \int \frac{dp_z \, d\omega}{(2\pi)^2} \, |\tilde{\phi}(p_z, \omega)|^2 \, \mathrm{Im}[\tilde{\Gamma}^{(2)}(\omega^2 - p_z^2)]$$

2 point 1PI Green function.

Imaginary part gives **decay probability**

Decompose background field excitation into **Fourier modes**

Each mode can be interpreted as **off-shell field quanta with given four-momentum** that can decay

CALCULATING PARTICLE PRODUCTION

Number of particles produced per unit area of bubble wall collision:

$$\frac{N}{A} = 2\int \frac{dp_z\, d\omega}{(2\pi)^2}\, |\tilde{\phi}(p_z,\omega)|^2\, \mathrm{Im}[\tilde{\Gamma}^{(2)}(\omega^2 - p_z^2)]$$

Decompose background field excitation into **Fourier modes**

2 point 1PI Green function.

Imaginary part gives **decay probability**

Rewrite as

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

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

(four-momentum, effective mass of the excitation)

Particle production efficiency factor

(encodes details of background field configuration)

(encodes particle physics details)

CALCULATING PARTICLE PRODUCTION

$$\frac{N}{A} = \frac{1}{2\pi^2} \int_{p_{\min}^2}^{p_{\max}^2} dp^2 \, f(p^2) \, \mathrm{Im}[\tilde{\Gamma}^{(2)}(p^2)]$$

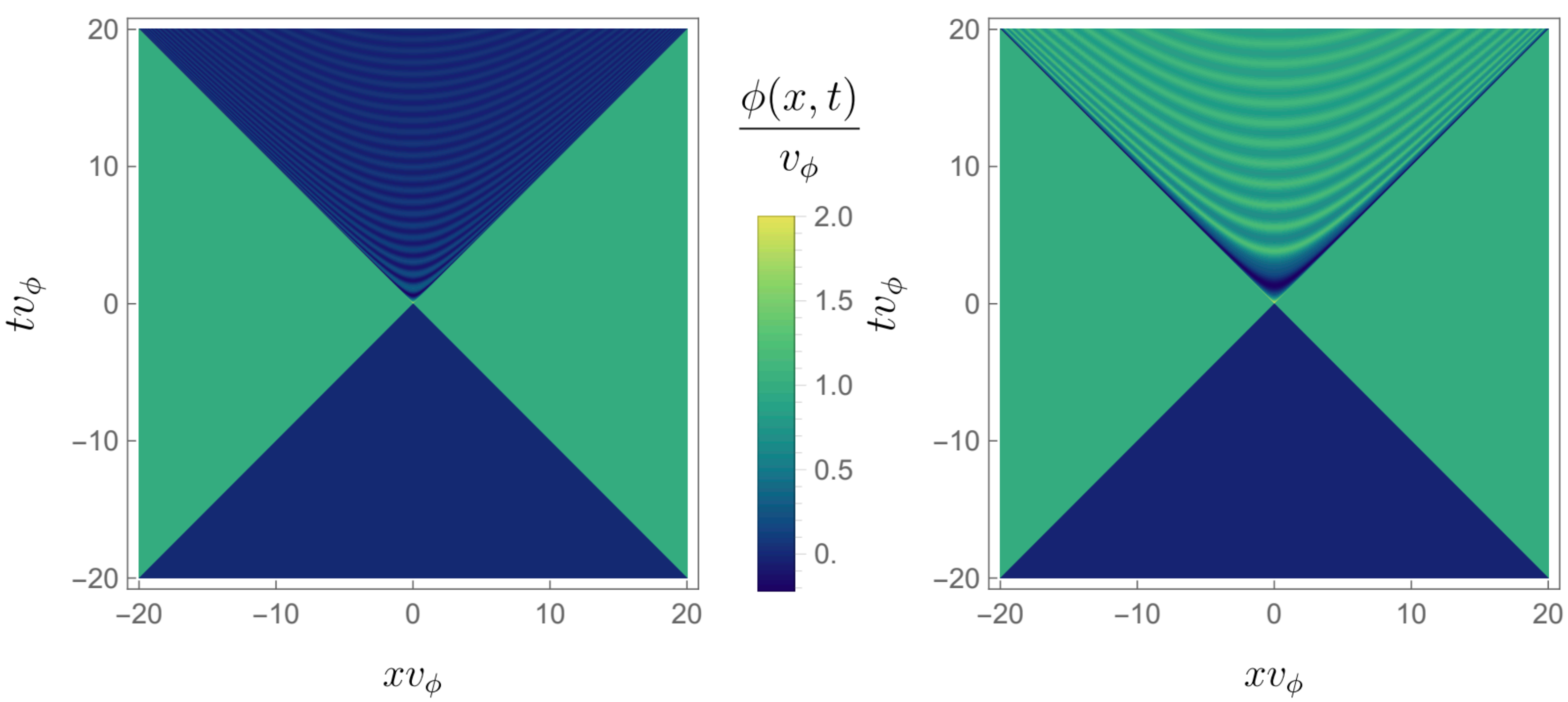
(Note: independent variable relabelled as p)

CALCULATING PARTICLE PRODUCTION

$$\frac{N}{A} = \frac{1}{2\pi^2}\int_{p^2_{\rm min}}^{p^2_{\rm max}} dp^2\, f(p^2)\, {\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]$$

encodes details of background field configuration

Calculate (analytically or numerically)



Elastic collision

Inelastic collision

~1/p⁴ falloff at high energies UNIVERSALLY for all collisions (elastic or inelastic)

2308.13070, 2308.16224

Green: true vacuum, blue: false vacuum

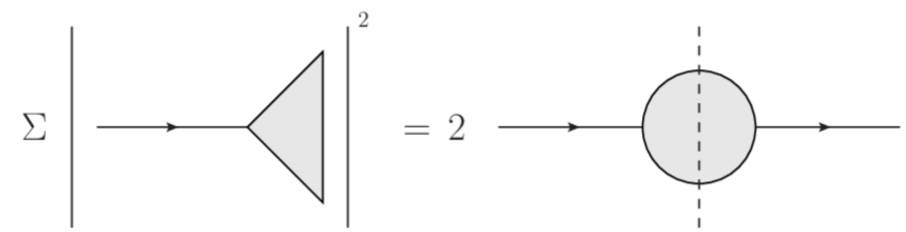
CALCULATING PARTICLE PRODUCTION

$$\frac{N}{A} = \frac{1}{2\pi^2} \int_{p^2_{\rm min}}^{p^2_{\rm max}} dp^2 \, f(p^2) \, {\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]$$

OPTICAL THEOREM

$$= \frac{1}{2} \sum_{\alpha} \int d\Pi_\alpha |\mathcal{M}(\phi \to \alpha)|^2$$

$|\mathcal{M}(\phi \to \alpha)|^2$ is the spin-averaged squared amplitude



Scalar self-interaction $\frac{\lambda_\phi}{4!}\phi^4$

$${\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi^*_p \to \phi\phi} = \frac{\lambda_\phi^2 v_\phi^2}{8\pi}$$

$${\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi^*_p \to 3\phi} = \frac{\lambda_\phi^2 p^2}{3072\,\pi^3}$$

Yukawa interaction with a fermion:

$${\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi^*_p \to \chi_f \bar{\chi}_f} = \frac{y_f^2}{8\pi} p^2$$

Gauge boson:

$$|\bar{\mathcal{M}}(\phi^*_p \to VV)|^2 \xrightarrow{p^2 > m_V^2} (2g^2 + \frac{\lambda_\phi^2}{g^2})\, m_V^2\, (1 + \mathcal{O}(m_V^2/p^2))$$

CALCULATING PARTICLE PRODUCTION

$$\frac{N}{A} = \frac{1}{2\pi^2}\int_{p^2_{\rm min}}^{p^2_{\rm max}} dp^2\, f(p^2)\, {\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]$$

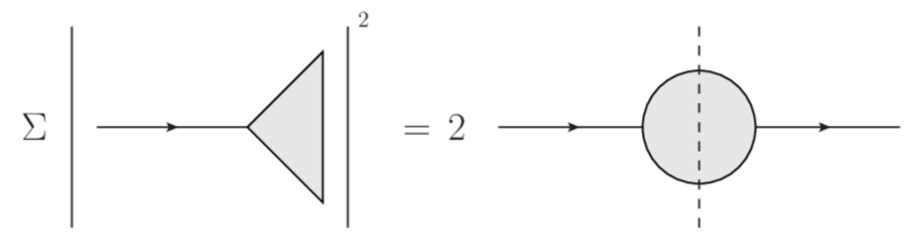
possible to efficiently produce very heavy/ energetic particles!

~1/p⁴

OPTICAL THEOREM

$$= \frac{1}{2}\sum_\alpha \int d\Pi_\alpha |\mathcal{M}(\phi\to\alpha)|^2$$

$|\mathcal{M}(\phi\to\alpha)|^2$ is the spin-averaged squared amplitude



Scalar self-interaction $\frac{\lambda_\phi}{4!}\phi^4$

$${\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi_p^*\to\phi\phi} = \frac{\lambda_\phi^2\, v_\phi^2}{8\pi}$$

$${\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi_p^*\to 3\phi} = \frac{\lambda_\phi^2\, p^2}{3072\,\pi^3}$$

Yukawa interaction with a fermion:

$${\rm Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi_p^*\to\chi_f\bar{\chi}_f} = \frac{y_f^2}{8\pi}p^2$$

Gauge boson:

$$|\bar{\mathcal{M}}(\phi_p^*\to VV)|^2 \xrightarrow{p^2>m_V^2} (2g^2 + \frac{\lambda_\phi^2}{g^2})\, m_V^2\, (1+\mathcal{O}(m_V^2/p^2))$$

BSM APPLICATION I: HEAVY DARK MATTER

DARK MATTER: SETUP

2403.03252

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

Produced from bubble collisions via $\phi_p^* \to \chi_s^2,\ \phi\chi_s^2$

$$\Omega_\chi h^2 \approx 0.1\,\frac{\beta/H}{10}\left(\frac{\alpha}{(1+\alpha)g_* c_V}\right)^{1/4}\frac{\lambda_s^2\, m_{\chi_s}\, v_\phi}{(24\ \mathrm{TeV})^2}\left[\frac{v_\phi^2}{m_{\chi_s}^2}+\frac{1}{16\pi^2}\ln\left(\frac{2\,\gamma_w/l_{w0}}{(2m_{\chi_s}+m_\phi)}\right)\right]$$

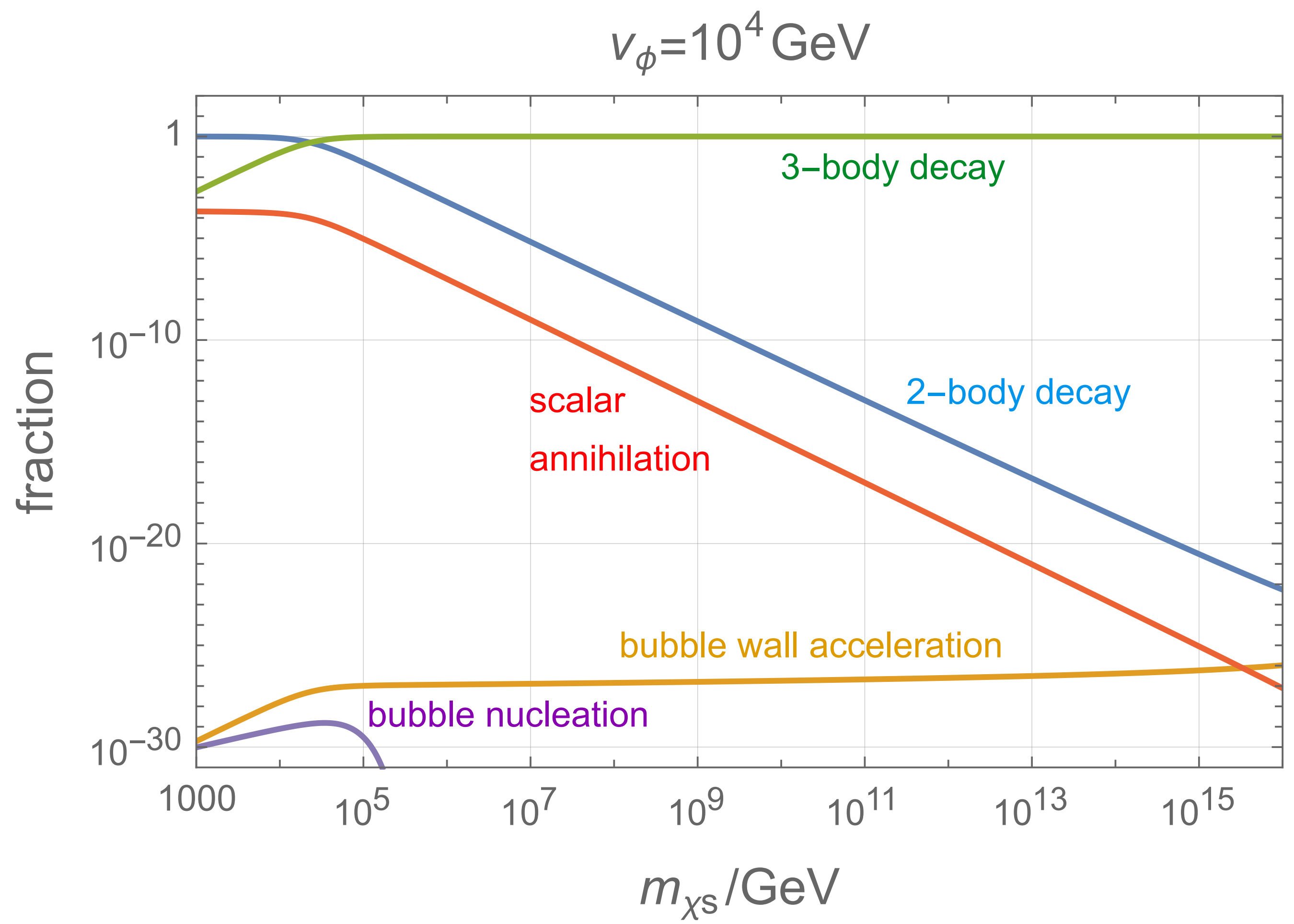
- v_ϕ: vev of scalar field ϕ in true vacuum
- Energy difference between vacua: $\Delta V \equiv V_{\langle\phi\rangle=0} - V_{\langle\phi\rangle=v_\phi} = c_V\, v_\phi^4$
- Energy fraction in false vacuum $\alpha = \dfrac{\Delta V}{\rho_{\mathrm{rad}}}$
- Bubbles formed with wall thickness l_{w0} ($\sim 1/v_\phi$)
- Bubble wall velocity v_w, boost factor γ_w
- β/H: number of bubbles per Hubble volume (~10-10,000)

DARK MATTER PRODUCTION

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

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

Relative importance of various processes (in the absence of a thermal bath)



DARK MATTER PRODUCTION WITH A THERMAL PLASMA

If dark sector particles are part of the thermal bath, additional production mechanisms exist:

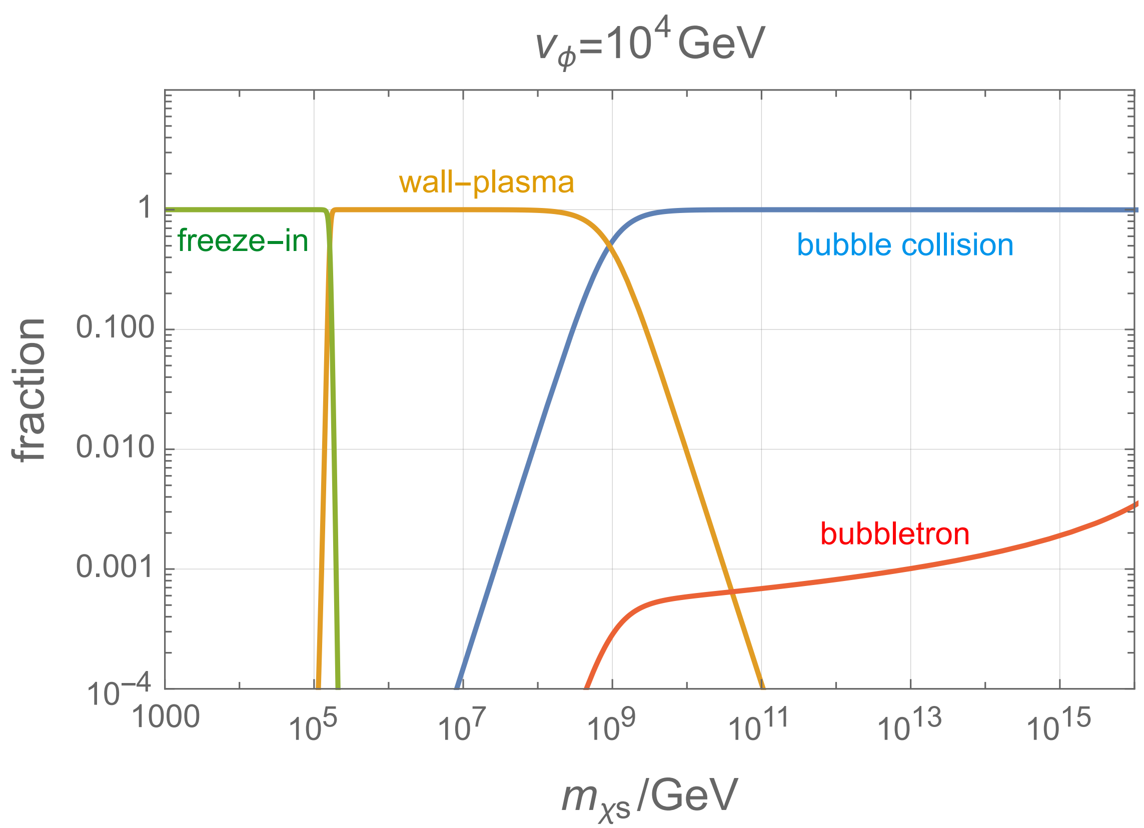
FREEZE-IN: Direct annihilation of scalar particles in the bath into DM

WALL-PLASMA INTERACTIONS: Scalar particles interacting with the boosted bubble walls can upscatter into DM

2101.05721

BUBBLETRON: Walls can boost scalar particles in the plasma to high energies, their collisions can efficiently produce DM

2306.15555



OTHER THINGS TO WORRY ABOUT

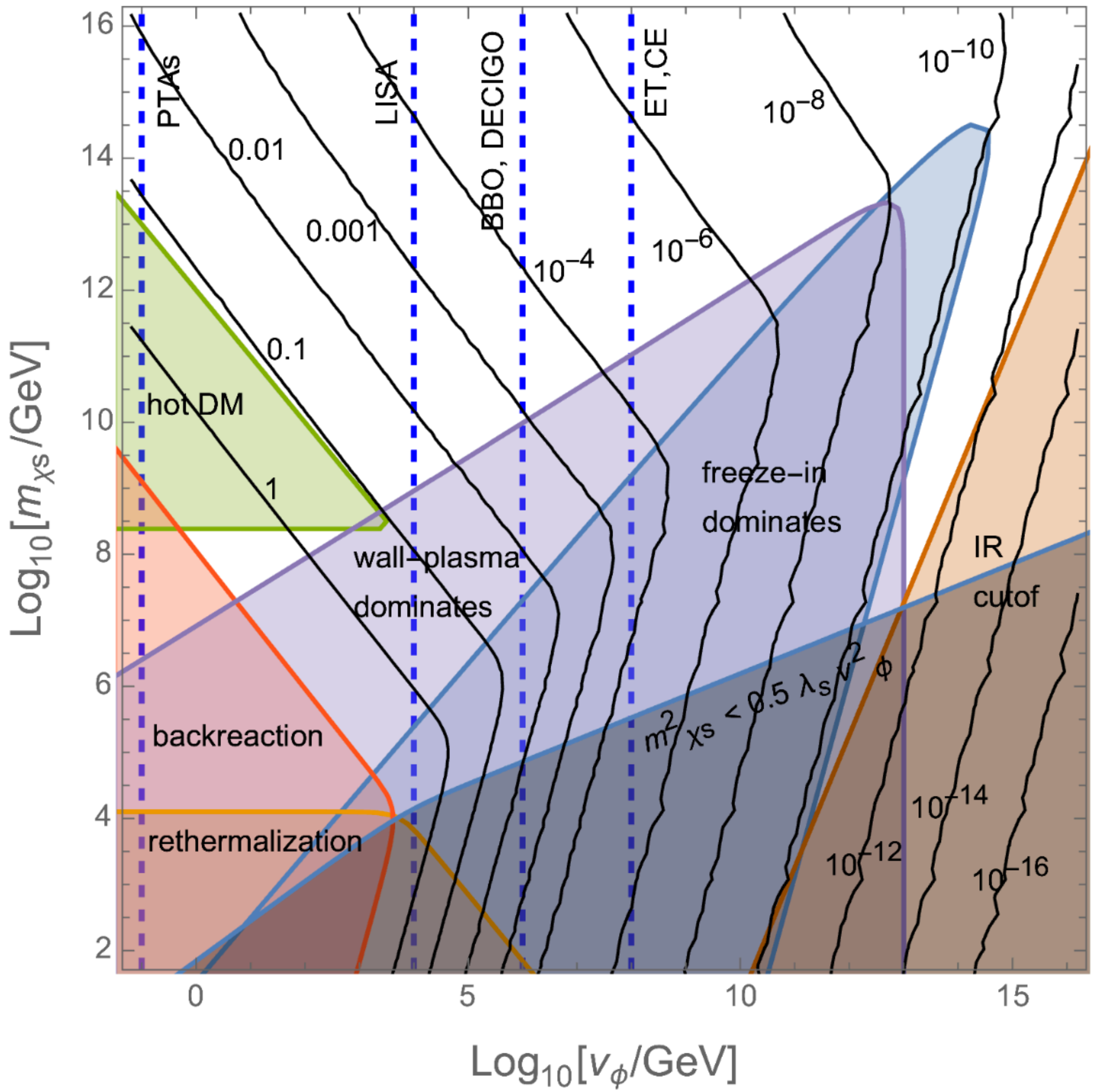
- **Isocurvature perturbations** and **perturbations from bubble collisions** must be negligibly small
- Dark matter should be **cold by the time of structure formation (~keV temp)**
- Dark matter fluid picks up and retains the **adiabatic perturbations necessary to support successful structure formation**

Generally OK as long as phase transition occurs before T~keV

2302.11579

SCALAR DARK MATTER PARAMETER SPACE

2403.03252



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

BSM APPLICATION II: LEPTOGENESIS

2407.16747

LEPTOGENESIS

produce lepton (consequently baryon) asymmetry from **out of equilibrium decays of heavy right-handed (sterile) neutrinos (RHNs)**

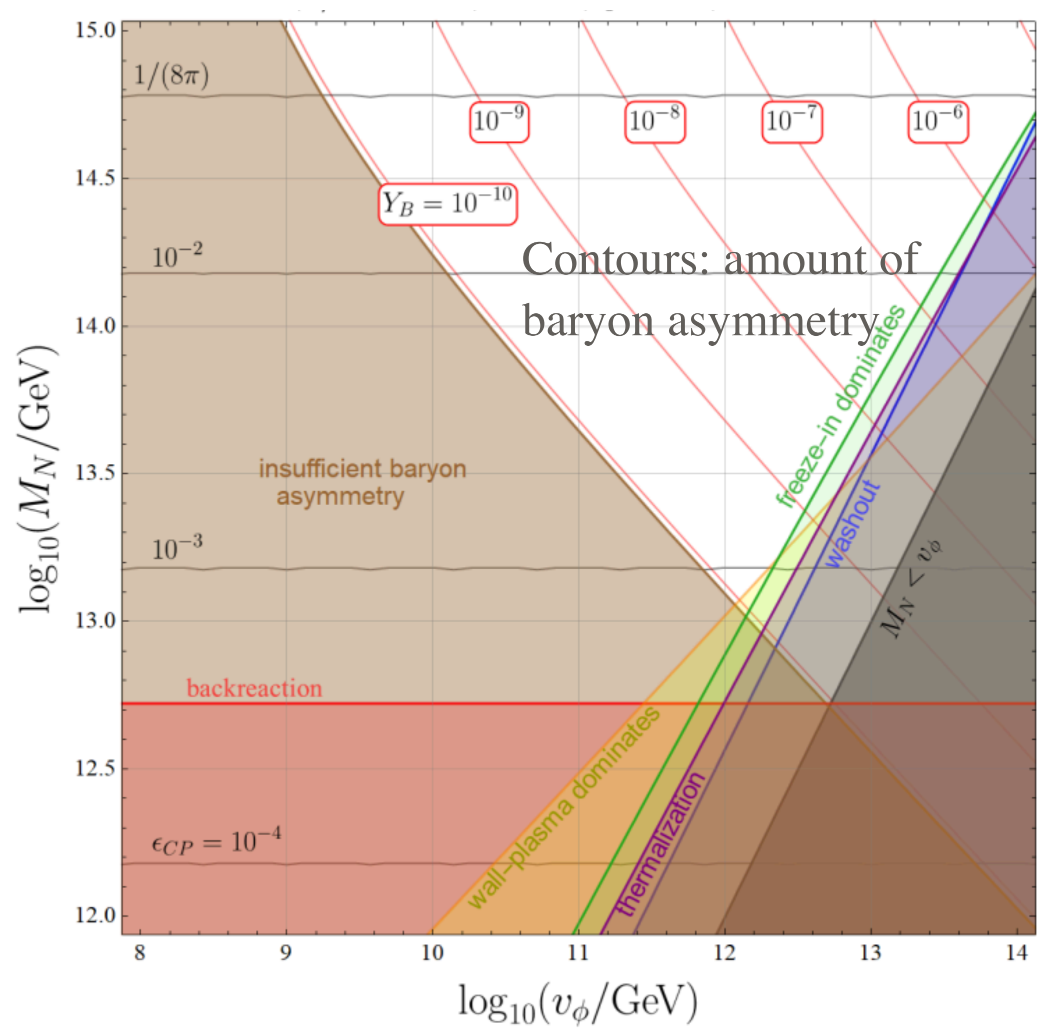
RHNs tend to be heavy (recall seesaw mechanism); the Universe needs to reheat above this scale

LEPTOGENESIS VIA BUBBLE COLLISIONS

Produce heavy RHNs from ultrarelativistic bubble collisions: **works with T << M_N**

washout effects exponentially suppressed

complementary gravitational wave signal

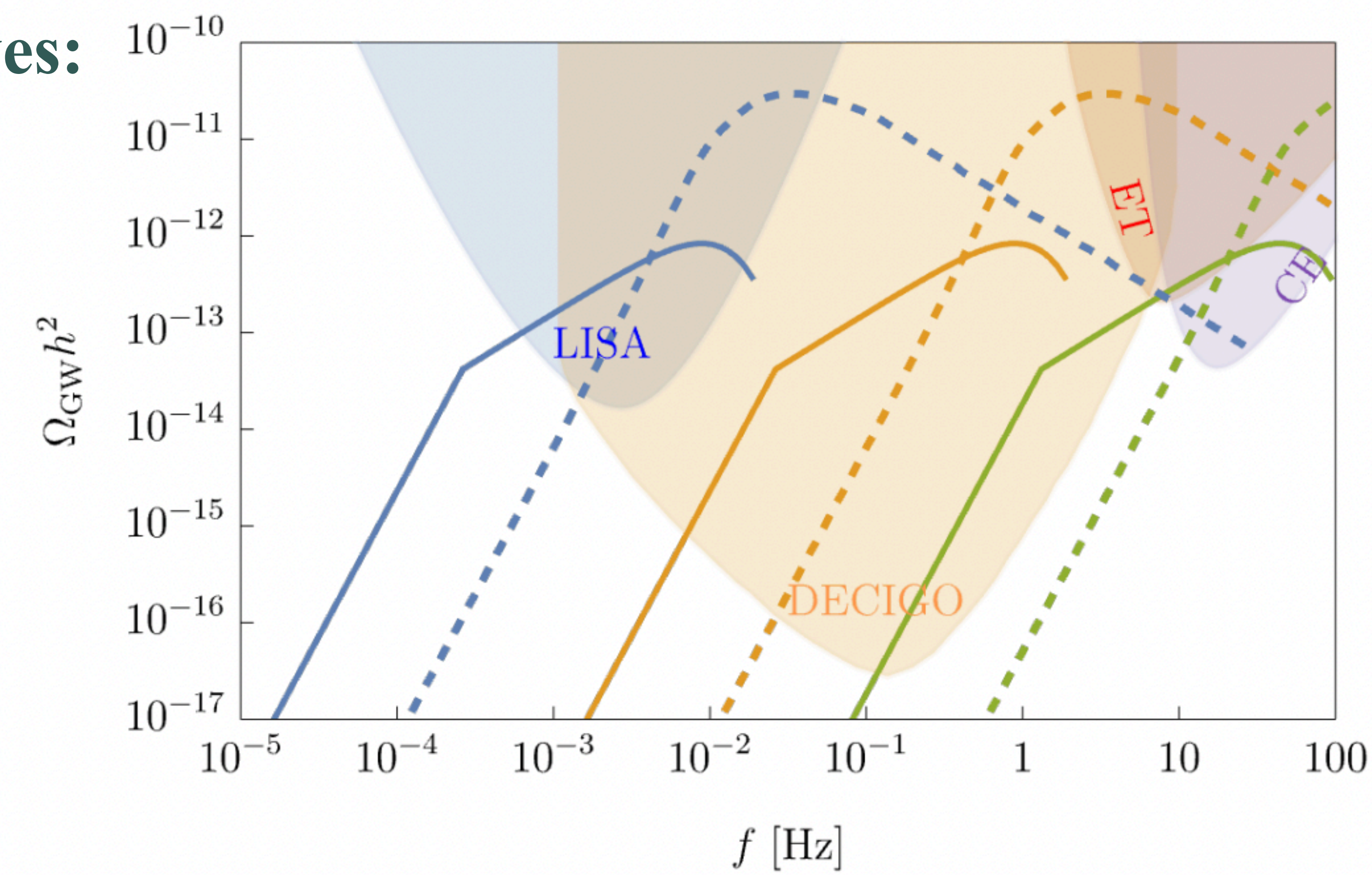


BSM (?) APPLICATION III: GRAVITATIONAL WAVES

2412.17912

A new source of gravitational waves:

If bubble collisions efficient at producing ultrahigh energy/mass particles, **a significant fraction of the energy** released during the phase transition is **converted into an inhomogeneous, dynamic particle population**



Qualitatively modifies the overall GW signal from such phase transitions, creating a **distinct shift in the spectral slope at low frequencies** that could be **observed by future GW experiments**

Dashed: standard GW signal

Solid: new component from particles from bubble collisions

SUMMARY

BSM PHYSICS FROM BUBBLE COLLISIONS

- Collisions of runaway bubbles at a first order phase transition opens **many avenues for BSM applications**
- Possible to produce **(out of equilibrium) heavy BSM states far higher than the temperature of the plasma or the energy scale of the transition**
- Can probe high scale BSM in the **same way as high energy colliders**
- Novel pathways for **standard (and non-standard!) BSM applications like dark matter and baryogenesis**
- Full of possibilities: **go explore!**