COSMIC COLLIDERS

HIGH ENERGY PHYSICS WITH FIRST ORDER PHASE TRANSITIONS

PLANCK 2025

BIBHUSHAN SHAKYA

DESY.

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Image Credit: betibup33/Shutterstock.com

BASED ON

FORMALISM

2308.16224, B. Shakya
Conceptual/analytic arguments

2308.13070, w/ Henda Mansour
Numerical studies

2403.03252, w/ Gian Giudice, Hyun Min Lee,
Alex Pomarol
Gauge dependence of formalism

+ more work in progress

PHENOMENOLOGY

2403.03252, w/ Gian Giudice, Hyun Min Lee,
Alex Pomarol
Ultraheavy dark matter

2407.16747, w/ Martina Cataldi
Nonthermal high scale leptogenesis

2412.17912, w/ Keisuke Inomata,
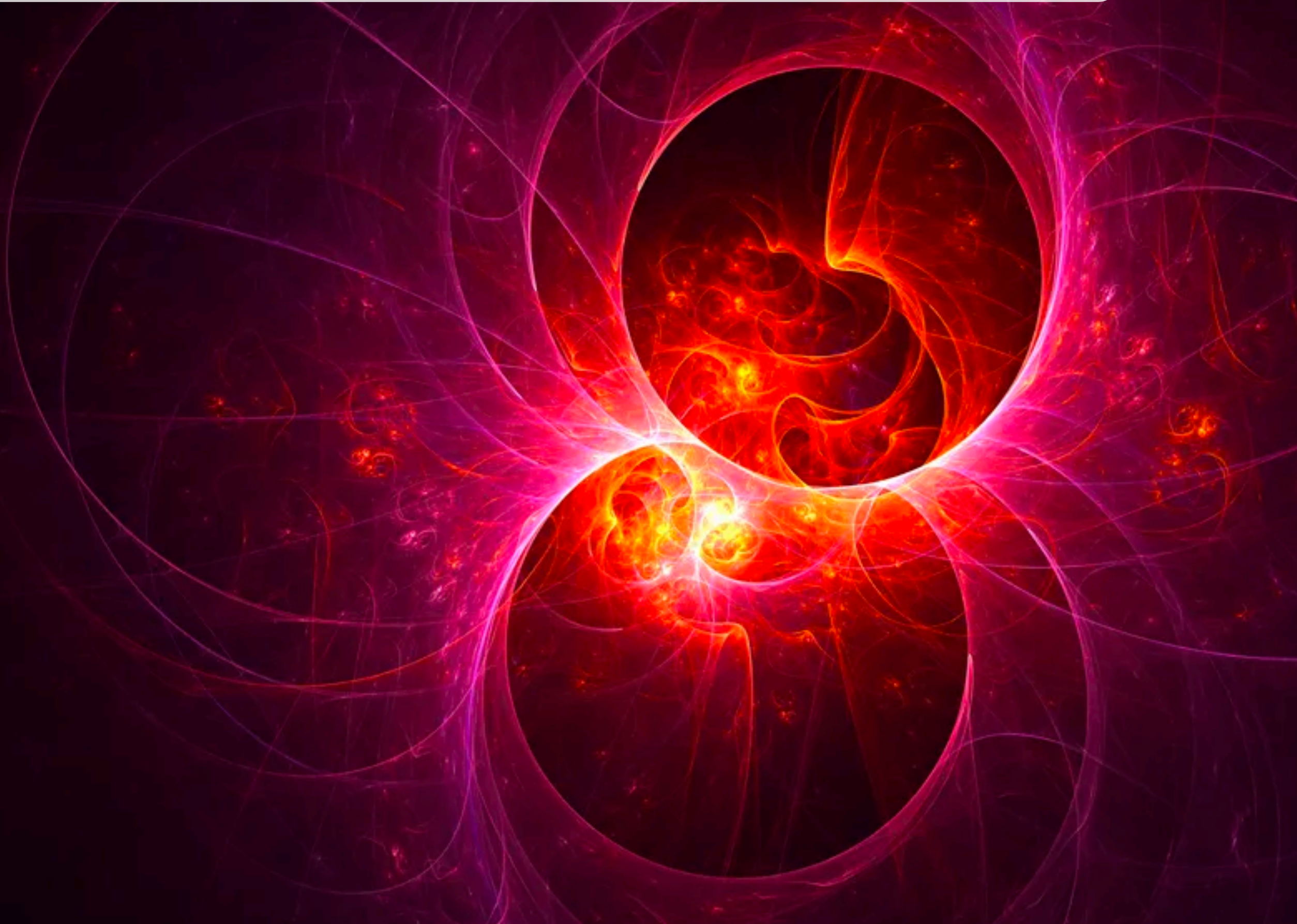Marc Kamionkowski, Kentaro Kasai
Gravitational Waves

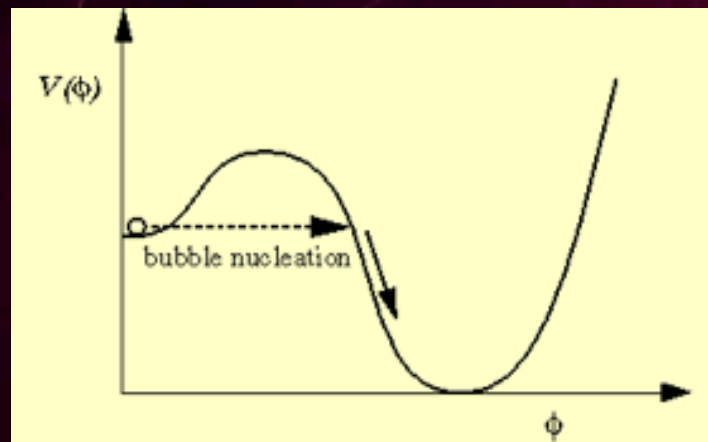+ more work in progress

2412.18752, B. Shakya
Conference proceeding summarising main ideas

WHAT IS A COSMIC COLLIDER?
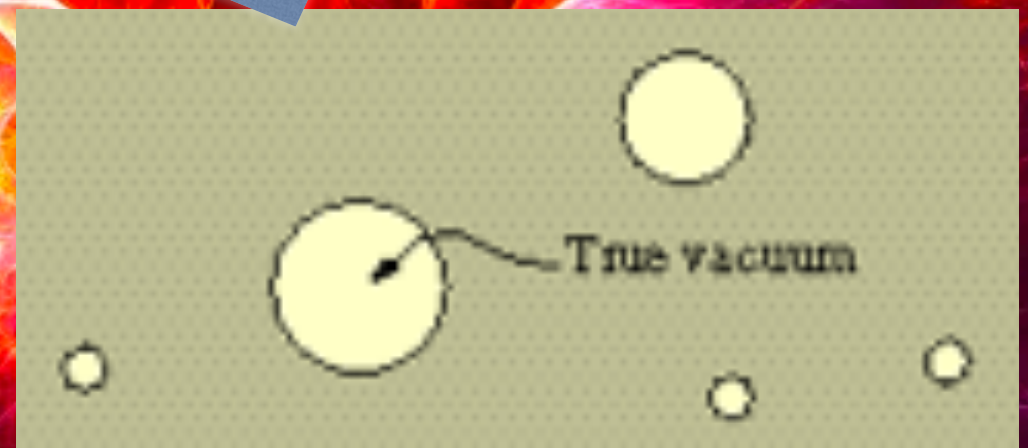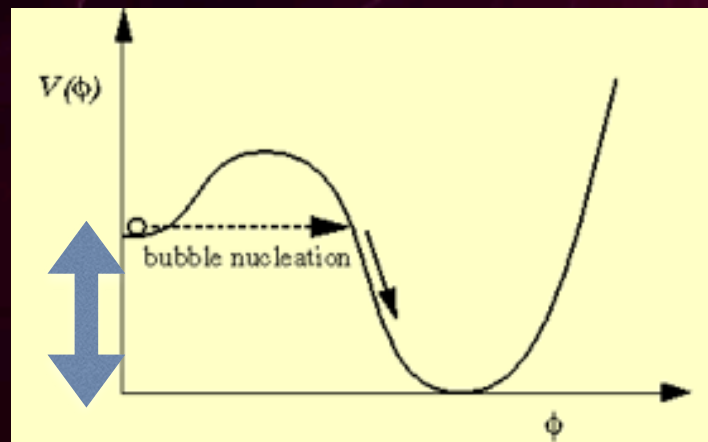
WHAT IS A COSMIC COLLIDER?

First order phase transition (FOPT)

The Universe quantum tunnels from one vacuum state to another

Nucleation of bubbles of true vacuum in a background of false vacuum
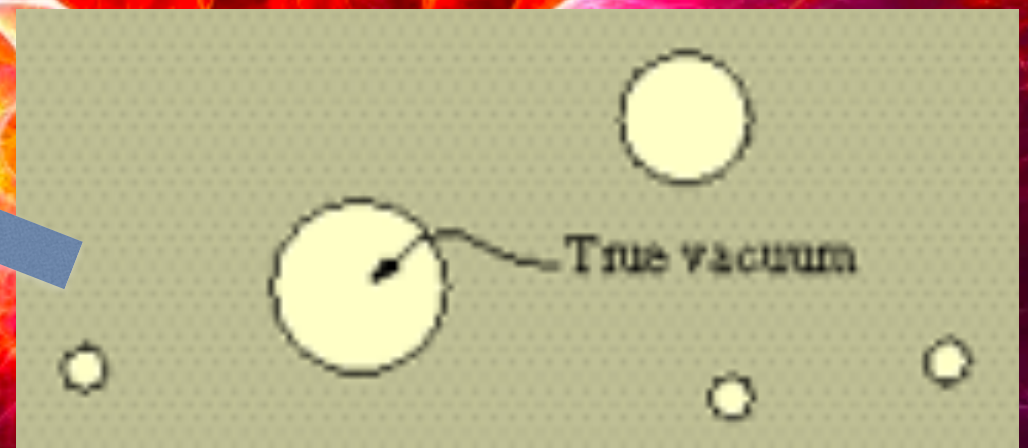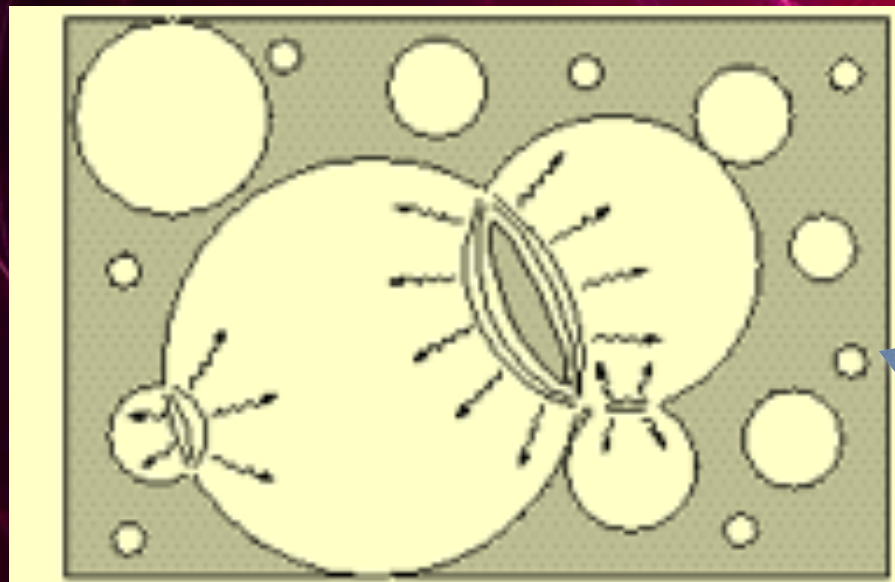
WHAT IS A COSMIC COLLIDER?

Releases significant latent energy stored in the false vacuum

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

WHAT IS A COSMIC COLLIDER?

The bubbles eventually collide with each other for the transition to complete

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

ENERGY SCALE OF COSMIC COLLIDERS

Energy scale at bubble nucleation: phase transition scale
($\sim$ temperature of plasma)

Energy conservation:
bubble wall boost factor grows linearly with bubble size

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

Energy per unit area at point of collision (independent of the
energy scale of the FOPT!)

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

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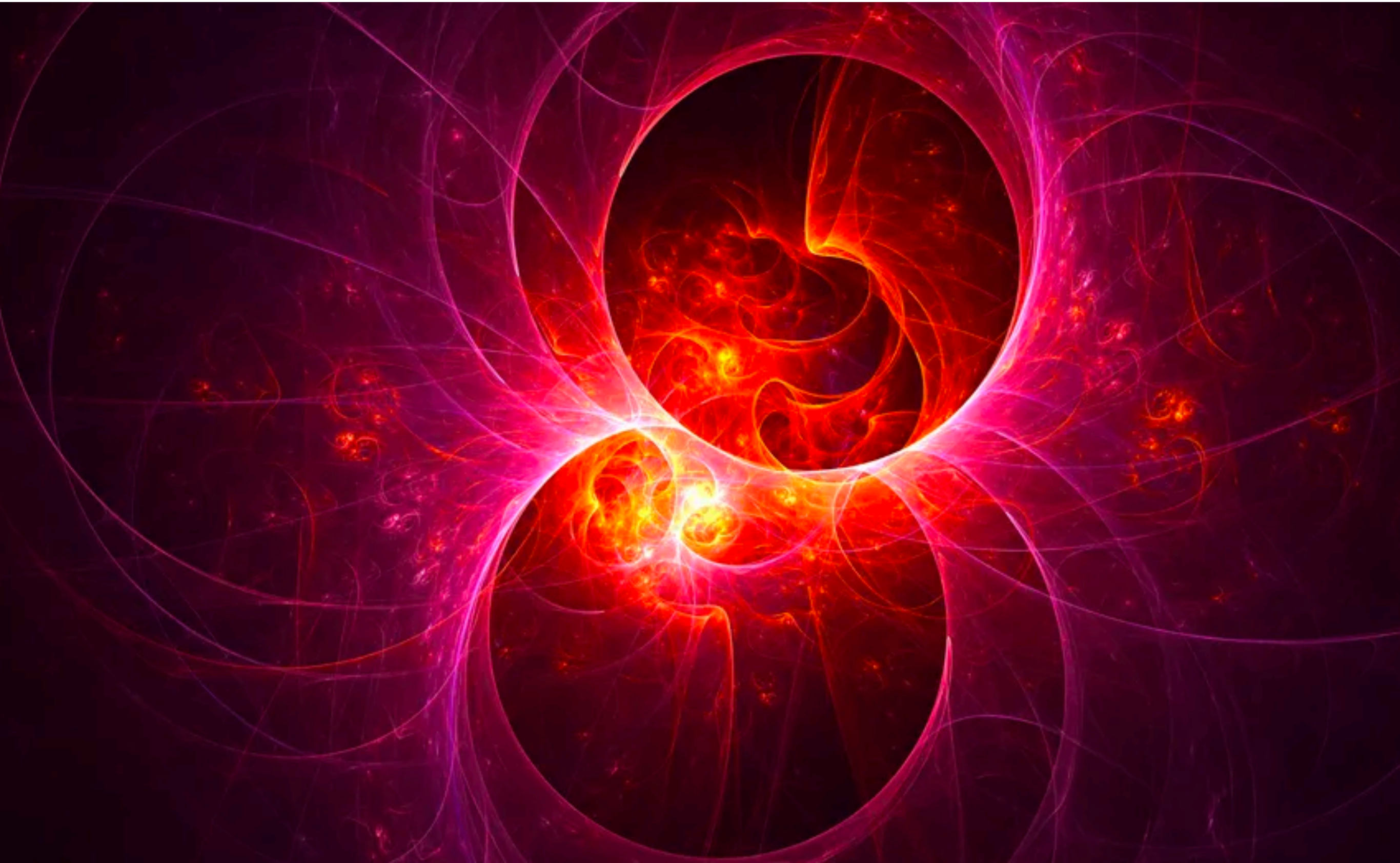Physical scale over which bubble
collision occurs

= Boosted bubble wall thickness

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

The collision process is sensitive to
any 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

Use the **effective action formalism**:

Probability of particle production:

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

imaginary part of the effective action of the background field

Also

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

Konstandin+Servant *1104.4793 [hep-ph]*

Falkowski+No *1211.5615 [hep-ph]*

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.

Decompose background field excitation into **Fourier modes**

Imaginary part gives **decay probability**

(optical theorem)

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

Occupation number of modes with energy >> scale of phase transition, or temperature of plasma

$$\sim 1/E^4$$

UNIVERSAL to all ultrarelativistic collisions

Analytic arguments: SHAKYA, 2403.03252

Numerical studies of bubble collisions: W/ HENDA MANSOUR 2308.13070

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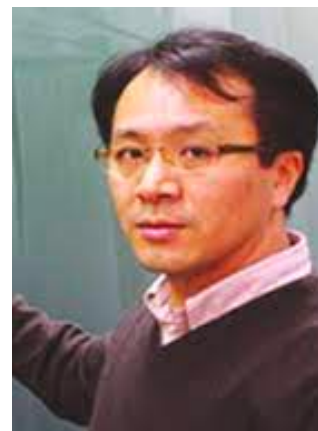
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SUBTLETIES: off-shell excitations are **not manifestly physical configurations**; calculations are **gauge-dependent** (but tractable)

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

APPLICATION: ULTRAHEAVY DARK MATTER

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

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

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

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

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

(Story will be qualitatively similar for fermion or vector dark matter)

SCALAR DARK MATTER PARAMETER SPACE
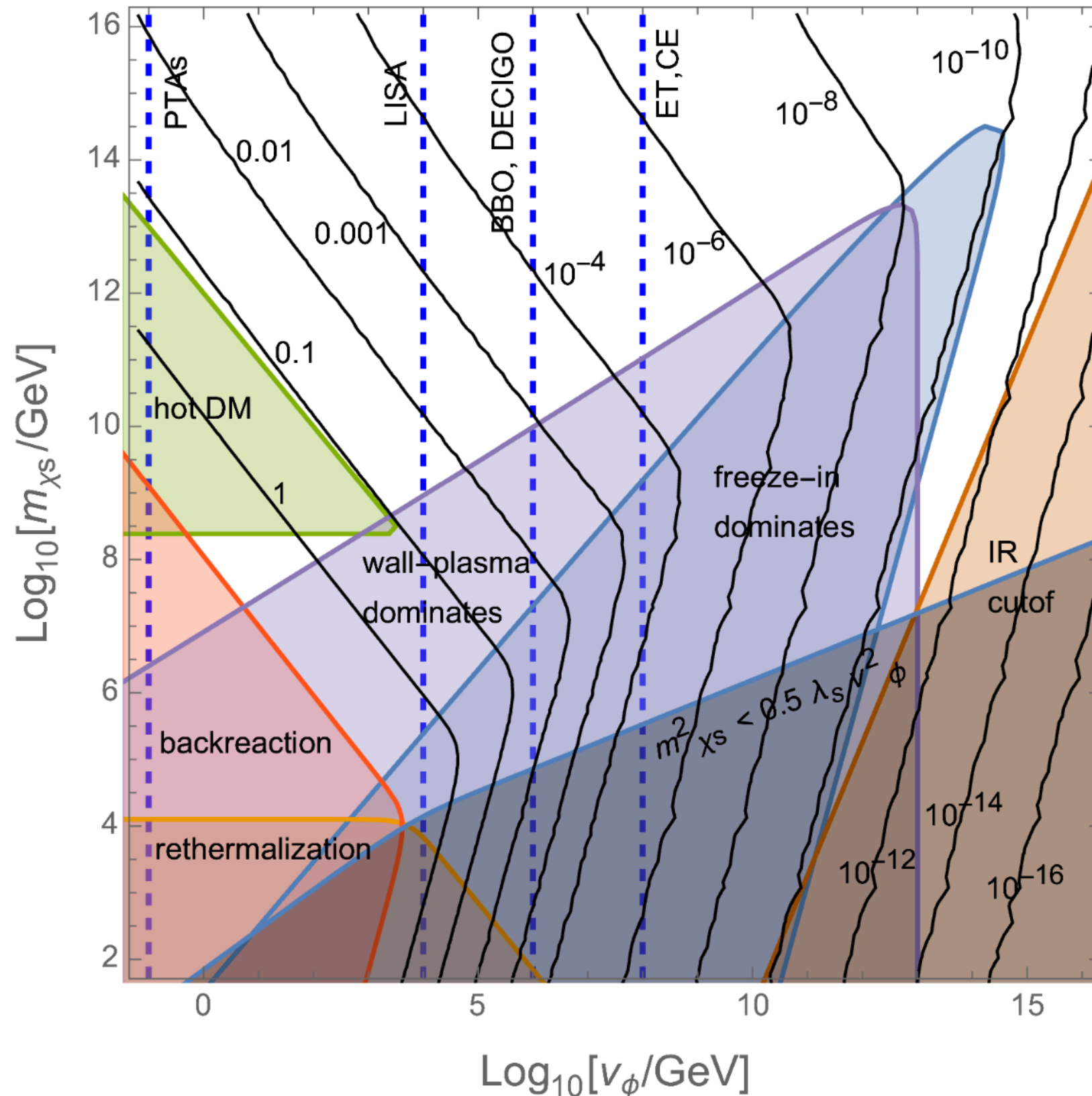
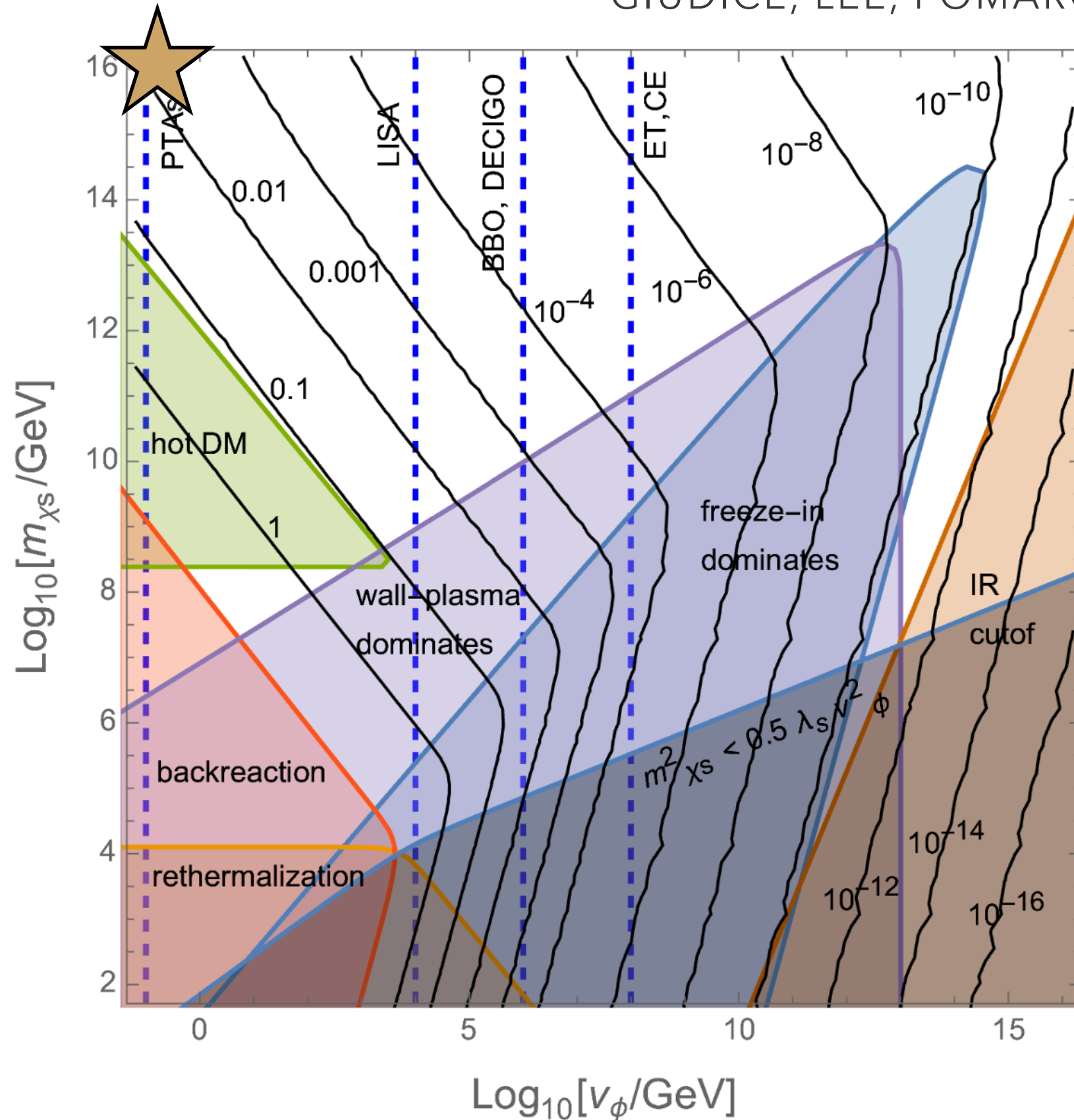GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252

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 (dashed vertical curves)

SCALAR DARK MATTER PARAMETER SPACE

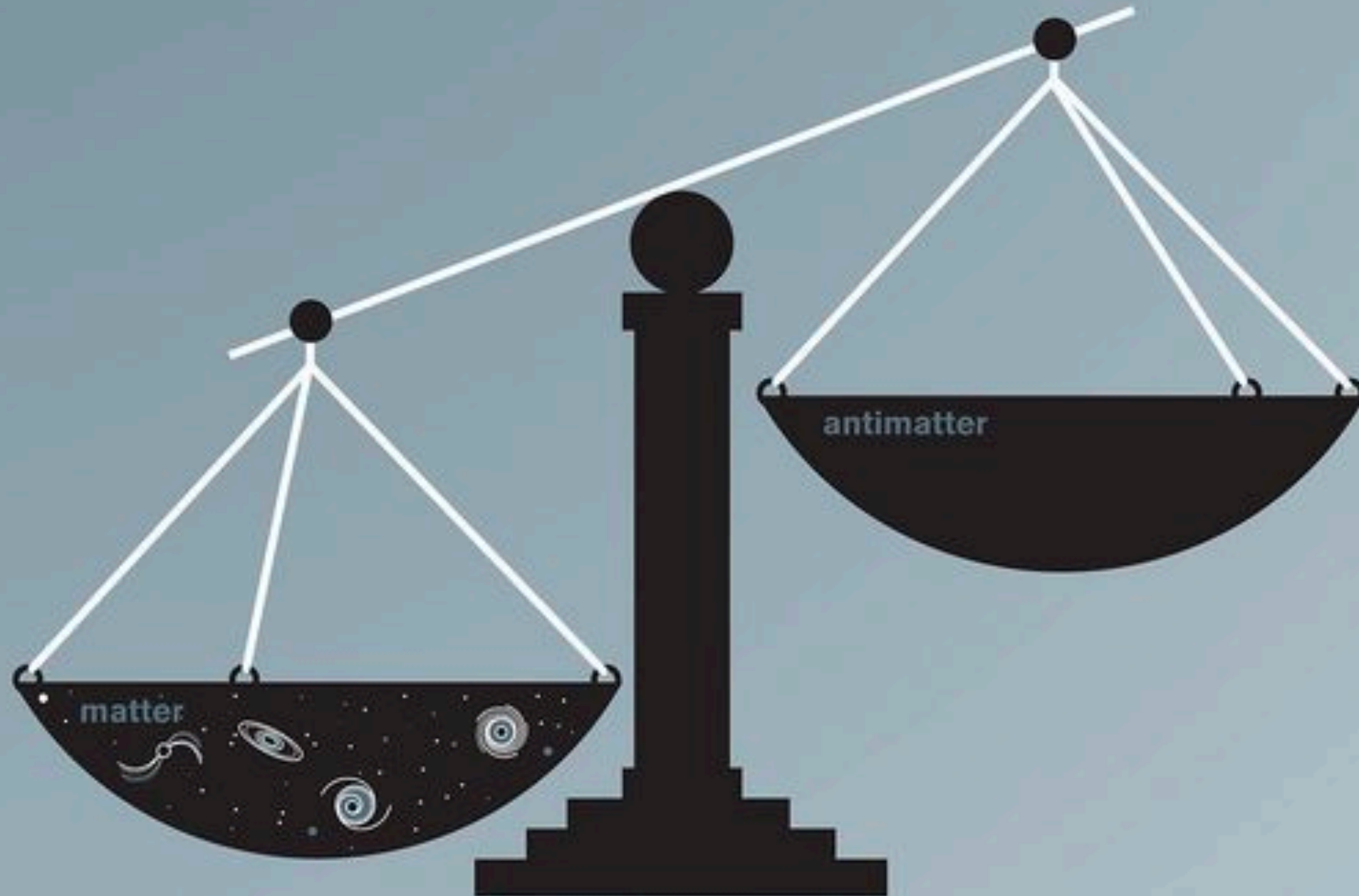GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252

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W/ MARTINA CATALDI, 2407.16747

LEPTOGENESIS

One of the most attractive realizations: produce lepton asymmetry from **out of equilibrium decays of heavy right-handed (sterile) neutrinos**, sphalerons convert lepton asymmetry to baryon asymmetry

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

$$y_\nu \, L \, H \, N + M_N N N$$

RHNs tend to be heavy: e.g. O(1) coupling needs $M_N \sim 10^{14}$ GeV   Strong washout close
to this limit

Thermal leptogenesis works for $M_N \sim 10^7 - 10^{14}$ GeV

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

LEPTOGENESIS VIA BUBBLE COLLISIONS

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

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

Dark sector fermion charged under the symmetry broken at the FOPT

Gets mass from type-I seesaw (analogous to SM neutrinos). Is like a light sterile neutrino, has a small mixing with SM neutrinos.

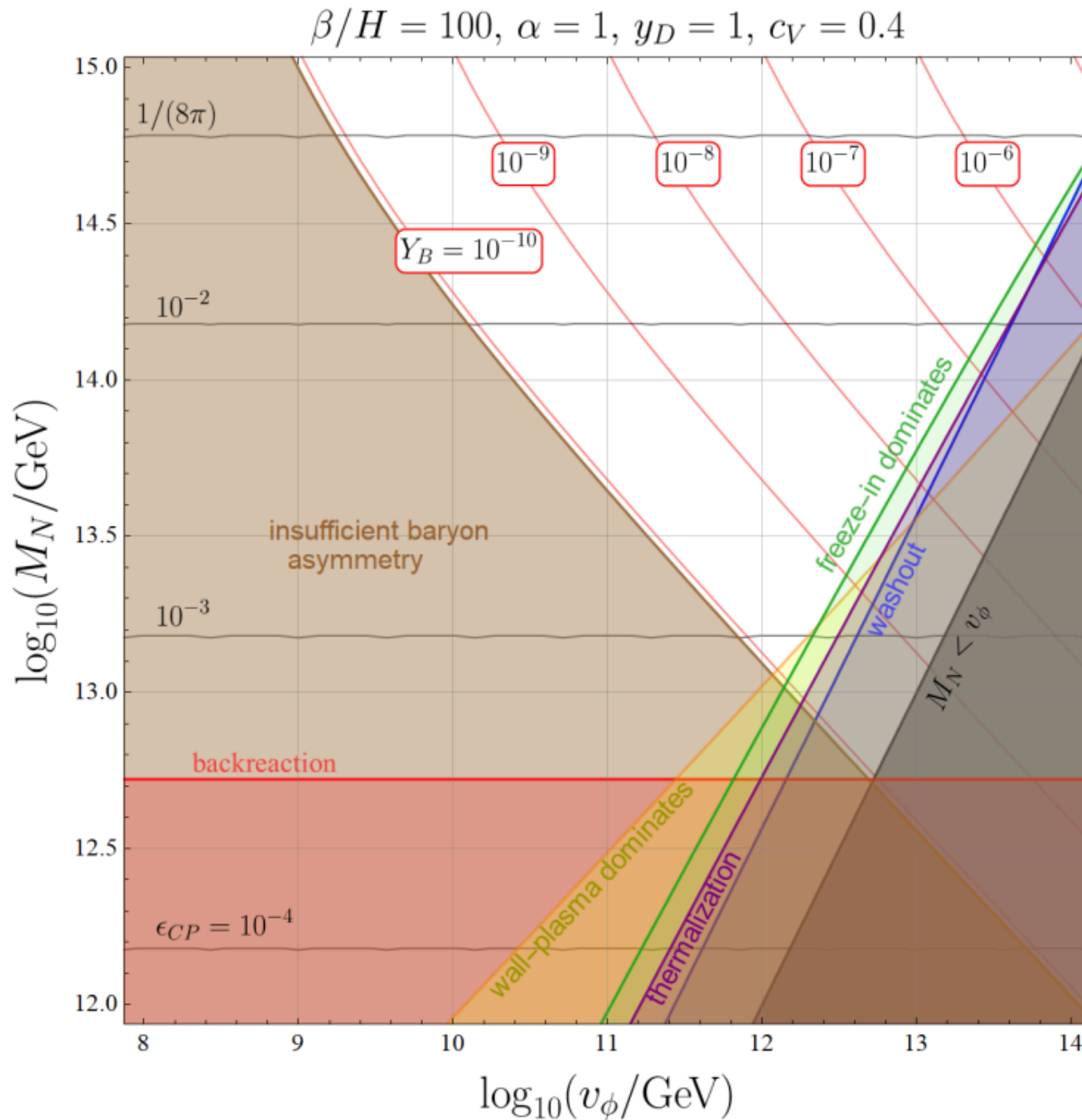Idea: **Produce heavy RHNs from bubble collisions**

$$\phi^* \rightarrow \chi N$$

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

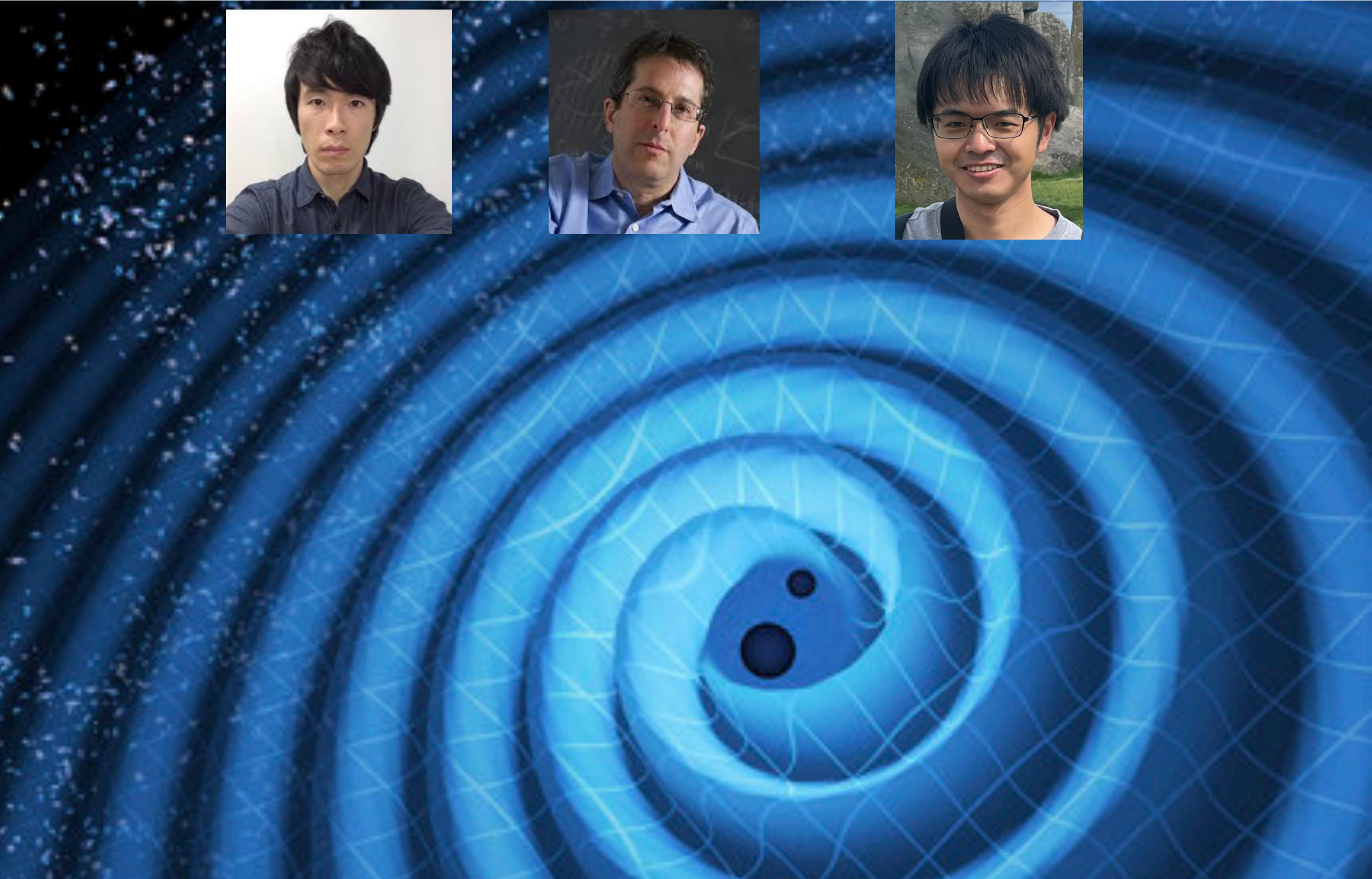(Other variations, e.g. involving a heavy lepton-number-breaking scalar as the portal, also work)

CATALDI, SHAKYA, 2407.16747

$\beta/H = 100,\ \alpha = 1,\ y_D = 1,\ c_V = 0.4$
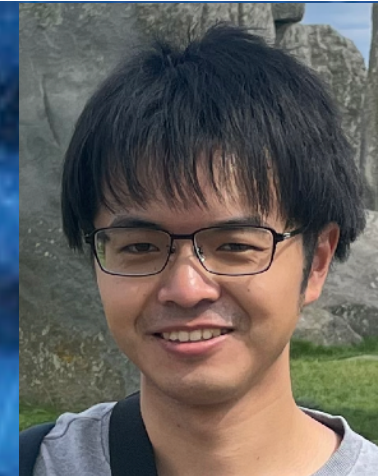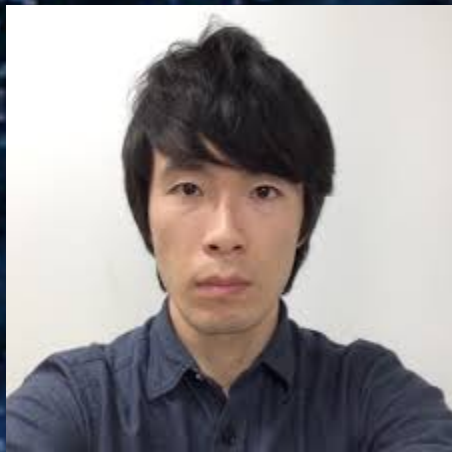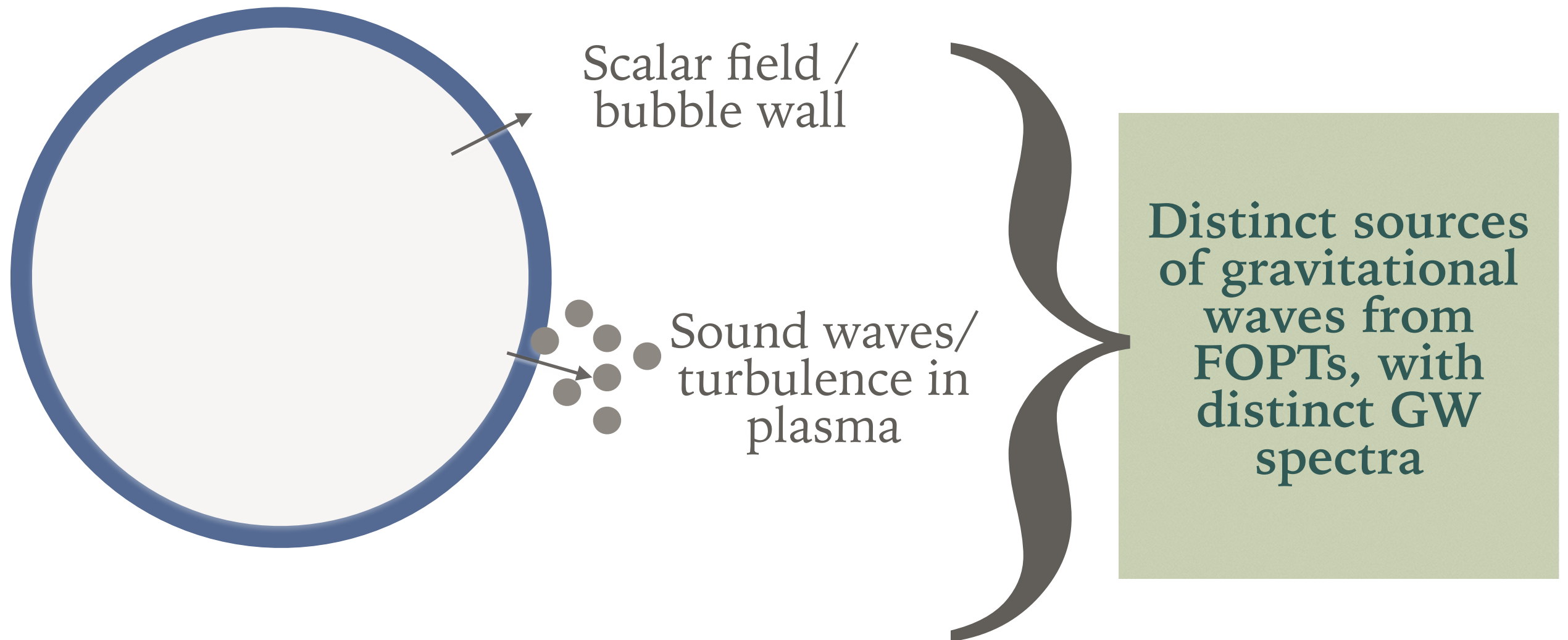
Contours:

amount of
baryon asymmetry

PHENOMENOLOGY: GRAVITATIONAL WAVES

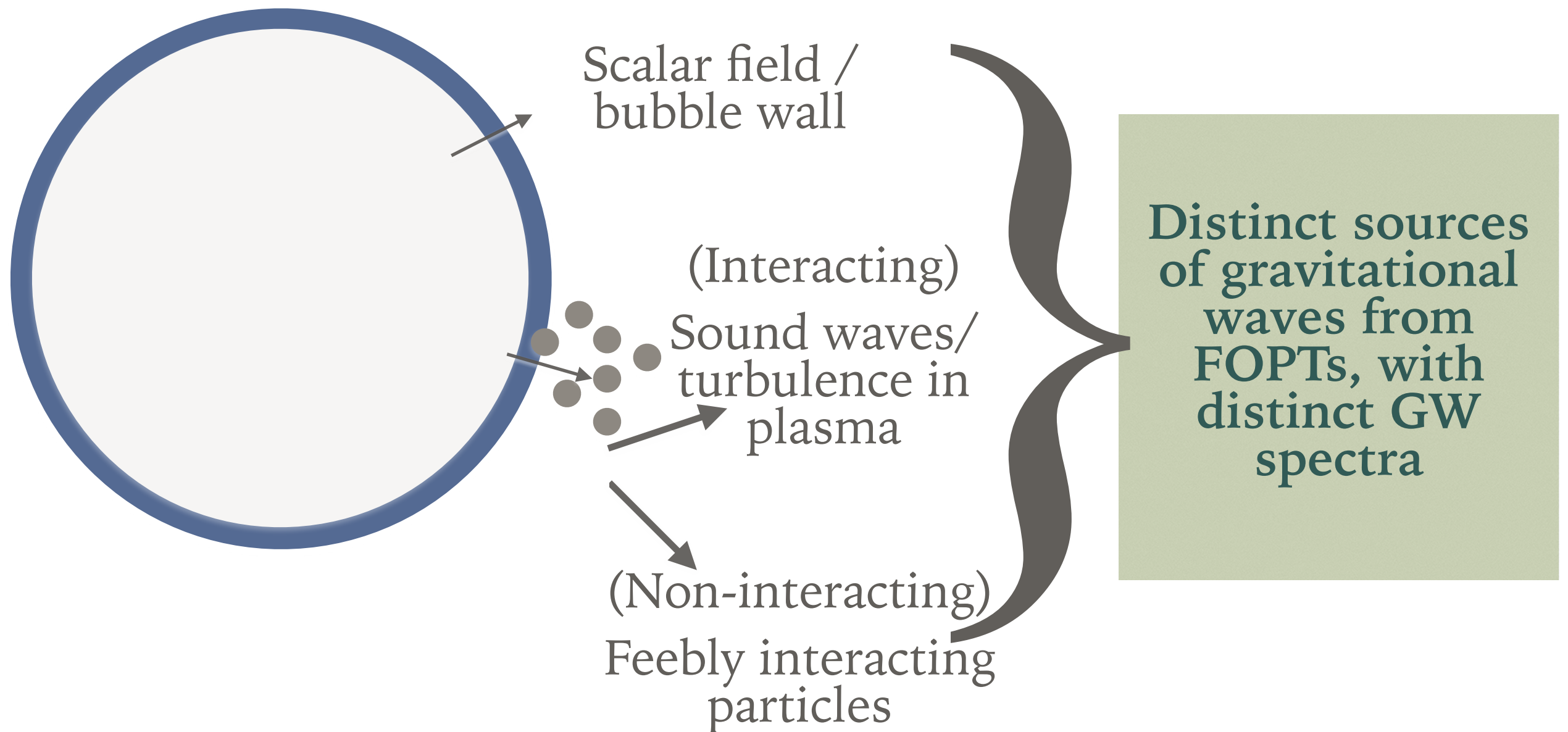W/ KEISUKE INOMATA, MARC KAMIONKOWSKI, KENTARO KASAI, 2412.17912

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

Scalar field / bubble wall

Sound waves/ turbulence in plasma

Distinct sources of gravitational waves from FOPTs, with distinct GW spectra

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

Scalar field / bubble wall

(Interacting)
Sound waves/ turbulence in plasma

(Non-interacting)
Feebly interacting particles

Distinct sources of gravitational waves from FOPTs, with distinct GW spectra

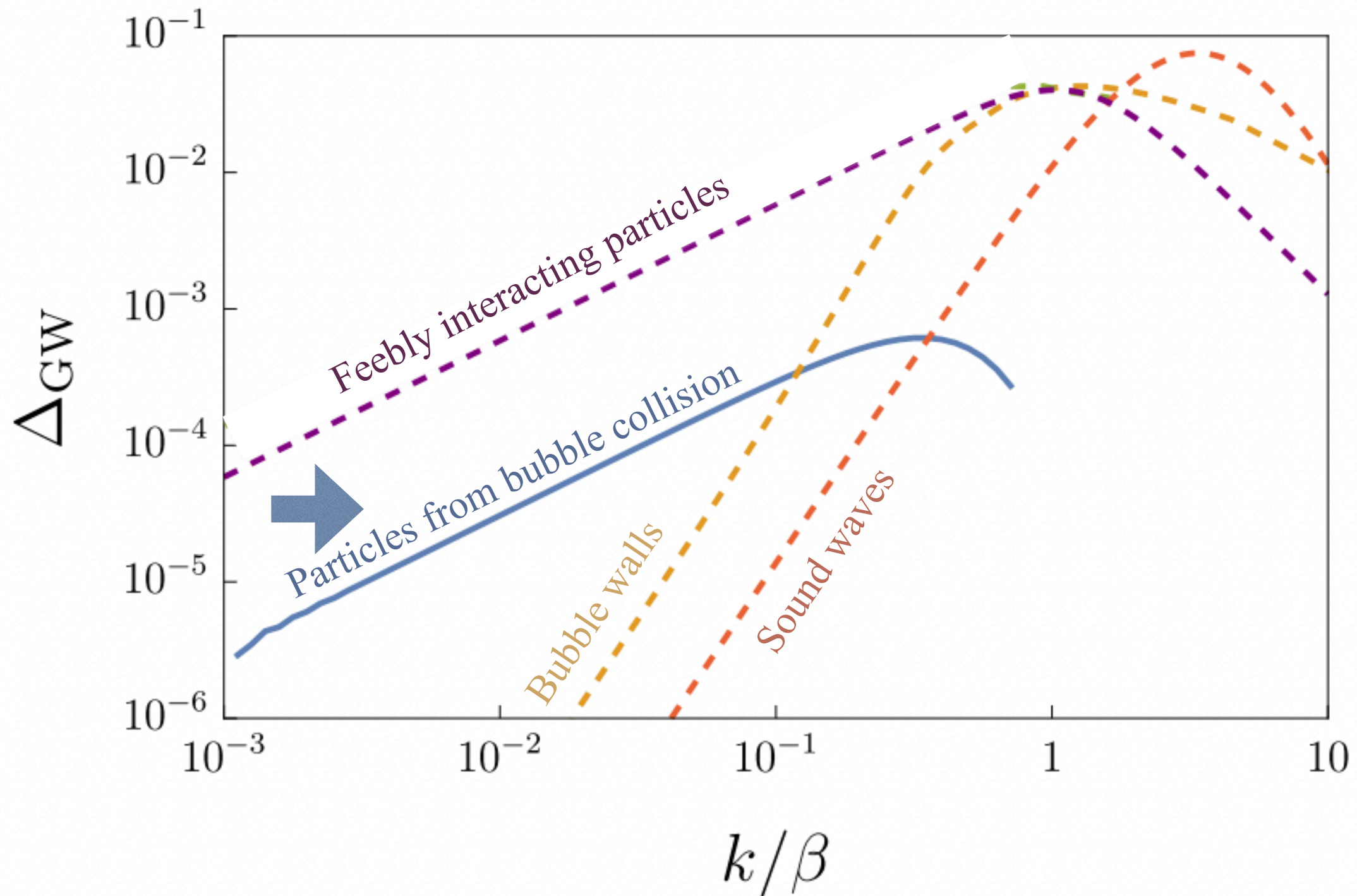w/ Ryusuke Jinno, Jorinde van de Vis   2211.06405

GRAVITATIONAL WAVES

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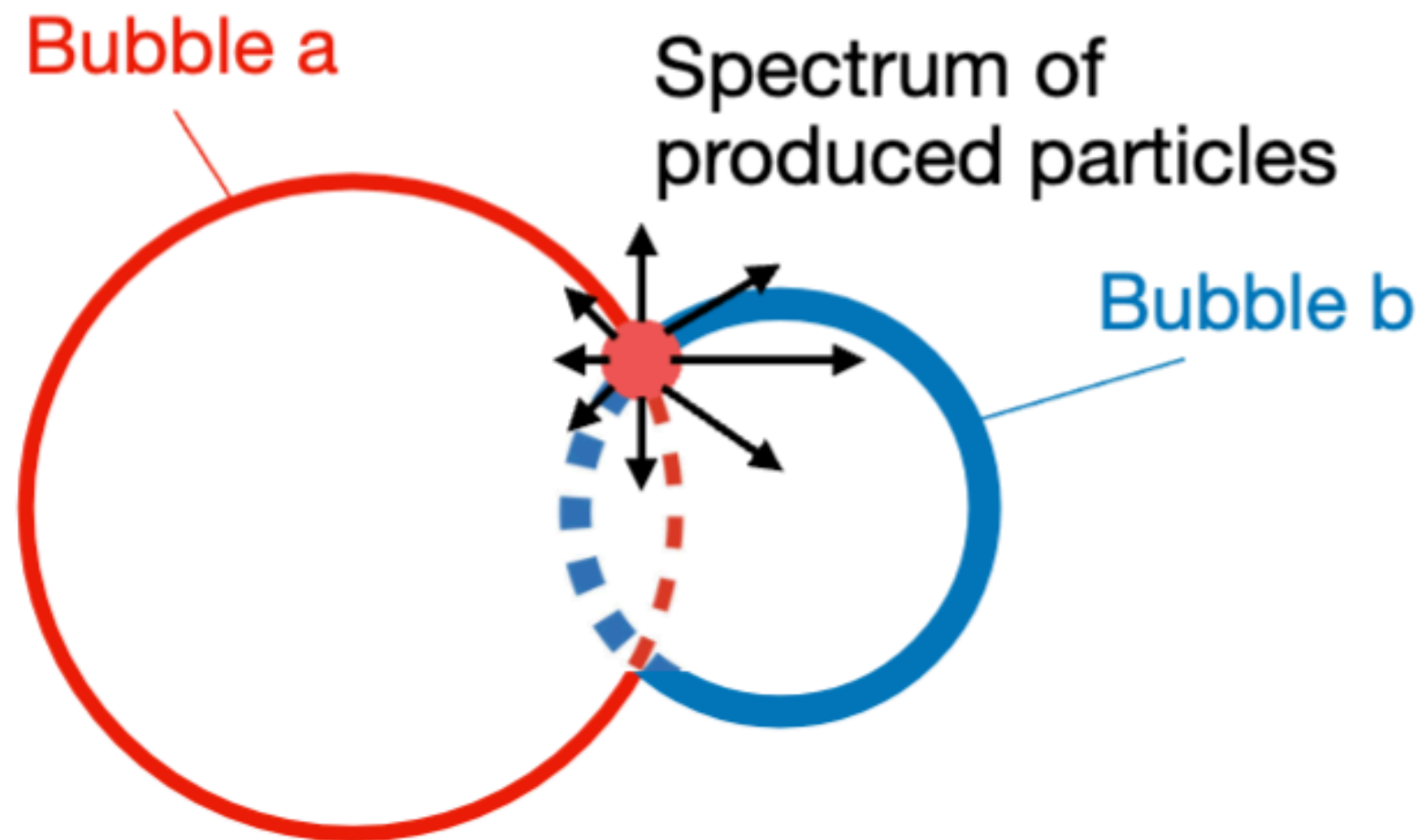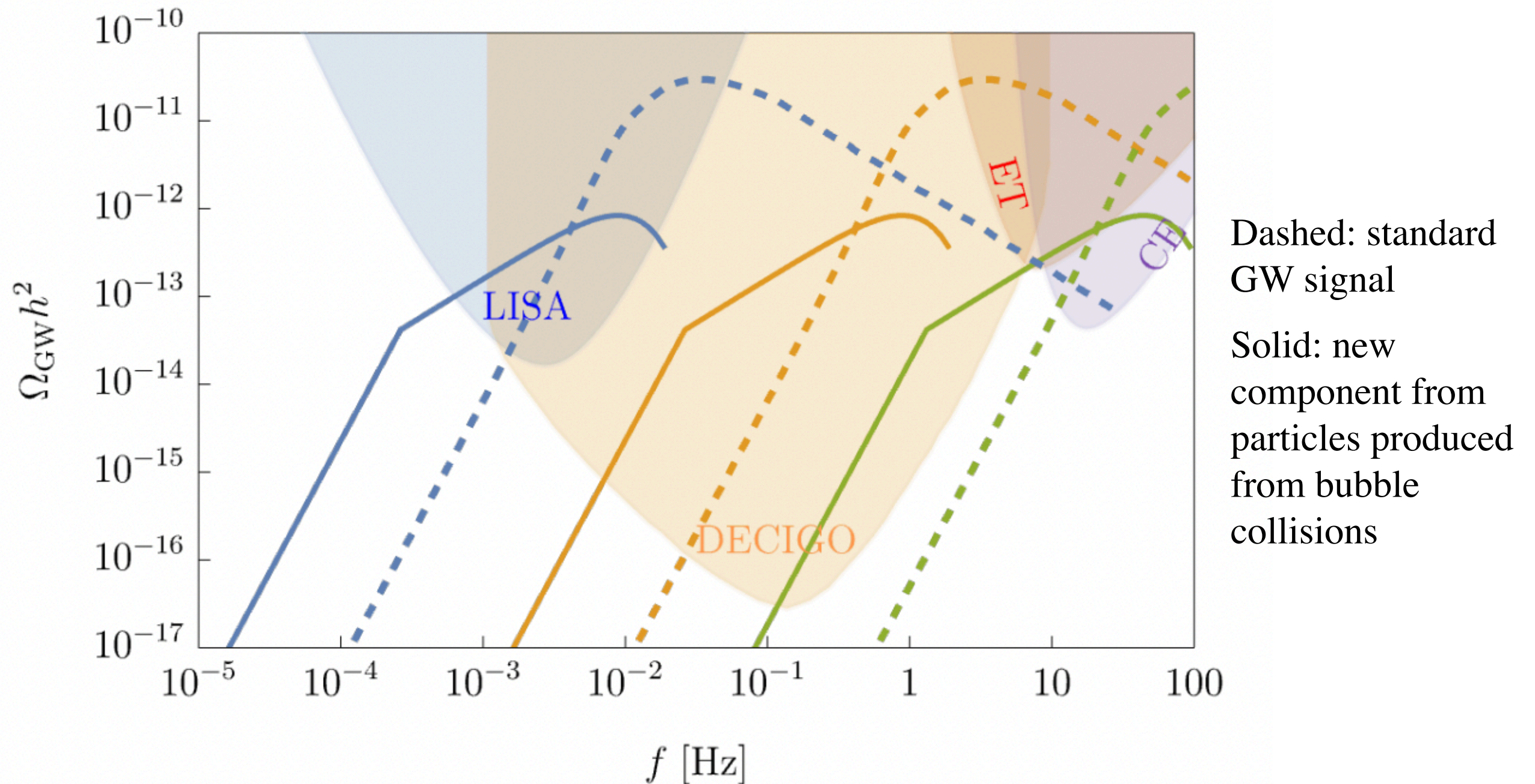

A new source of gravitational waves from phase transitions!

Gravitational waves signals from different FOPT sources

Dashed: standard GW signal

Solid: new component from particles produced from bubble collisions

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**

SUMMARY: COSMIC COLLIDERS

- **Collisions of runaway vacuum bubbles act as high energy colliders**, leading to particle production with **ultrahigh mass, energy up 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,…**