COSMIC COLLIDERS

HIGH ENERGY PHYSICS WITH FIRST ORDER PHASE TRANSITIONS

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DESY.

DECEMBER 9, 2024

BCVSPIN CONFERENCE

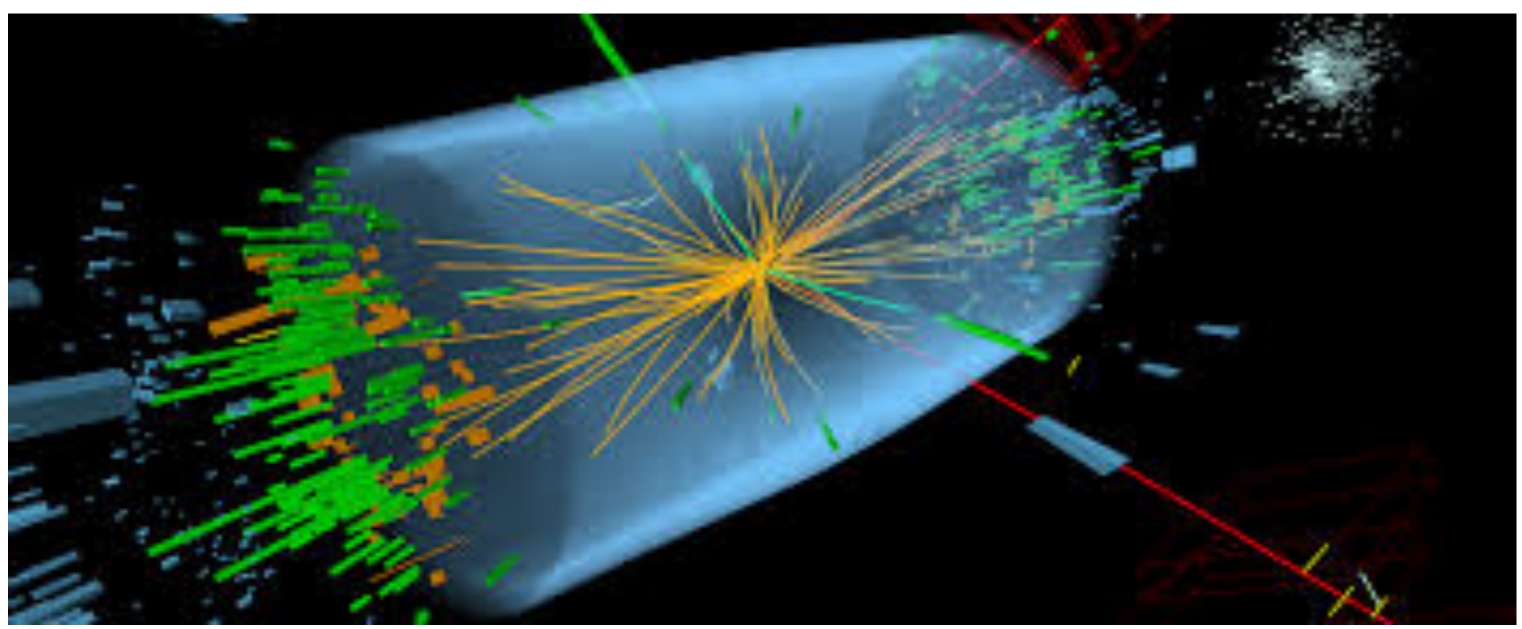
Particle Physics and Cosmology in the Himalayas

December 9-13, 2024

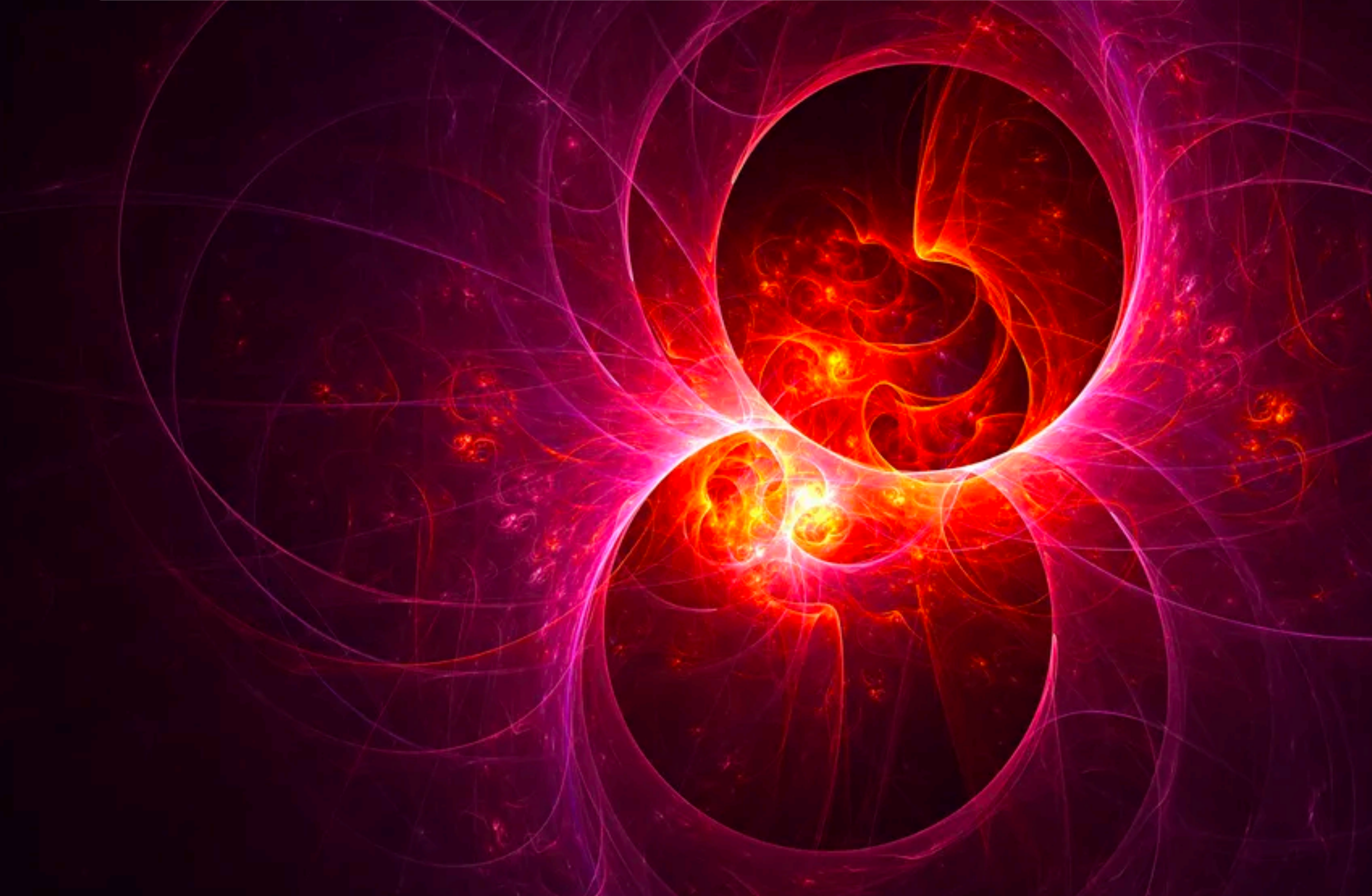
KATHMANDU, NEPAL

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 than the ambient temperature
3. Collide these objects: unravel the nature of physics/the Universe at high energies

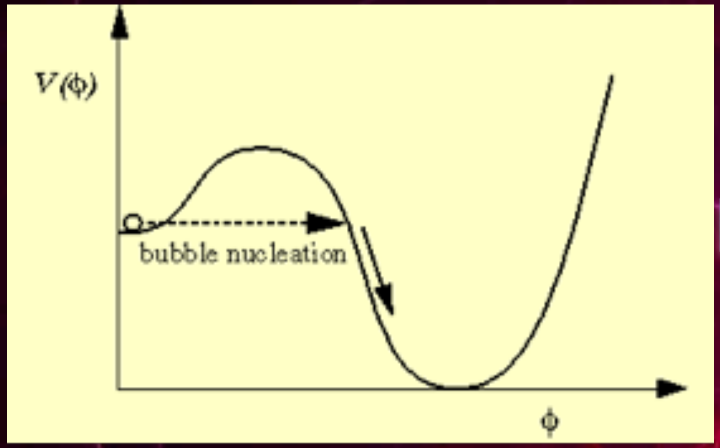


WHAT IS A COSMIC COLLIDER?



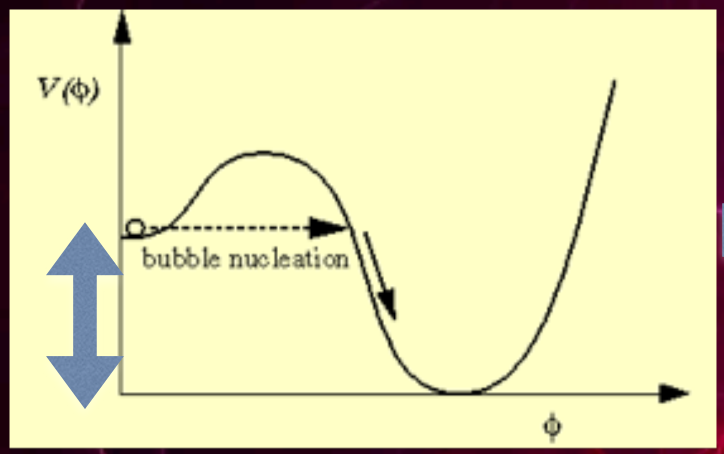
WHAT IS A COSMIC COLLIDER?

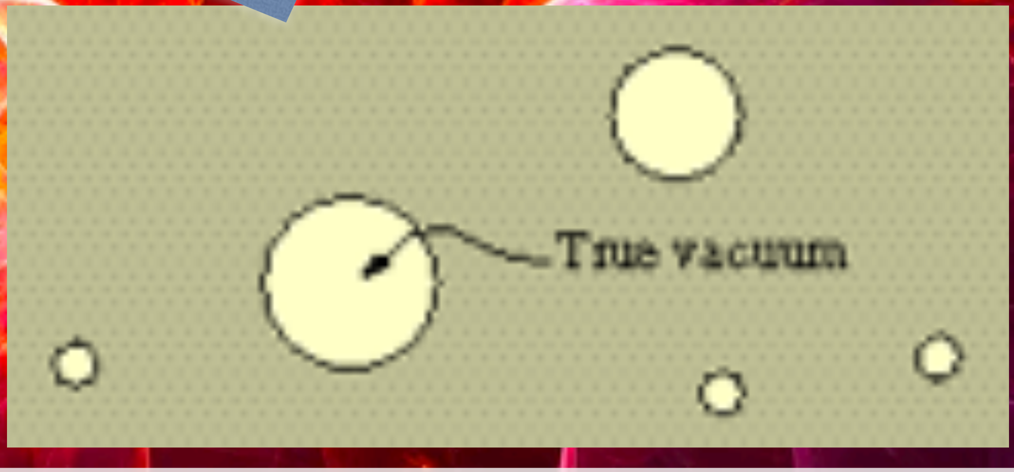
First order phase transition (FOPT)



The Universe quantum tunnels from one vacuum state to another

WHAT IS A COSMIC COLLIDER?



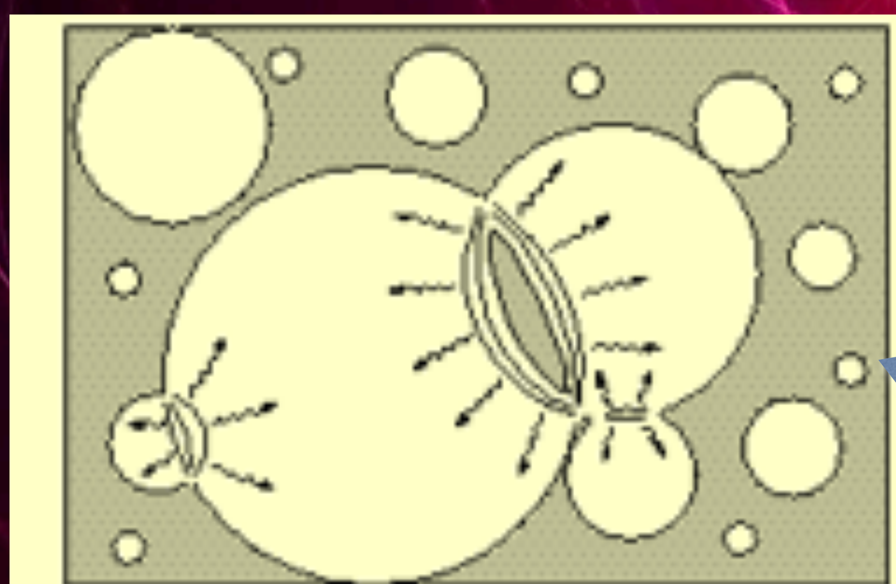


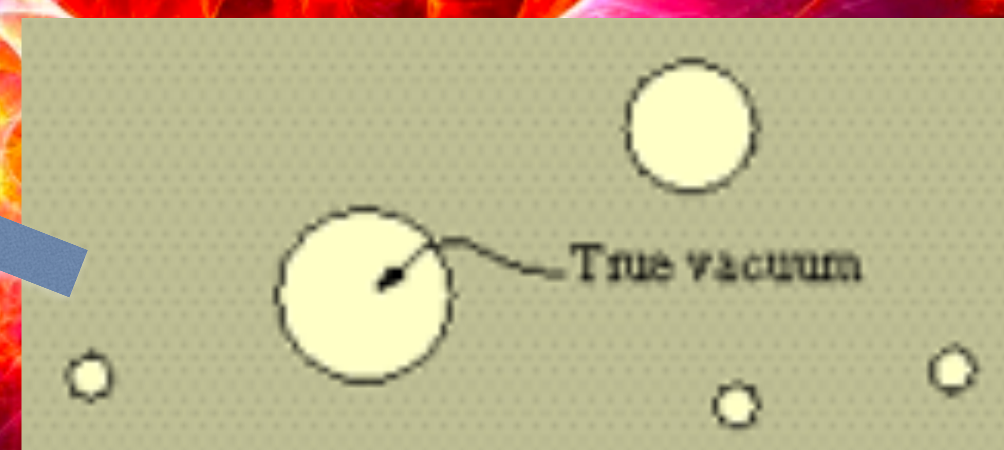
Releases significant latent energy stored in the false vacuum

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

WHAT IS A COSMIC COLLIDER?

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

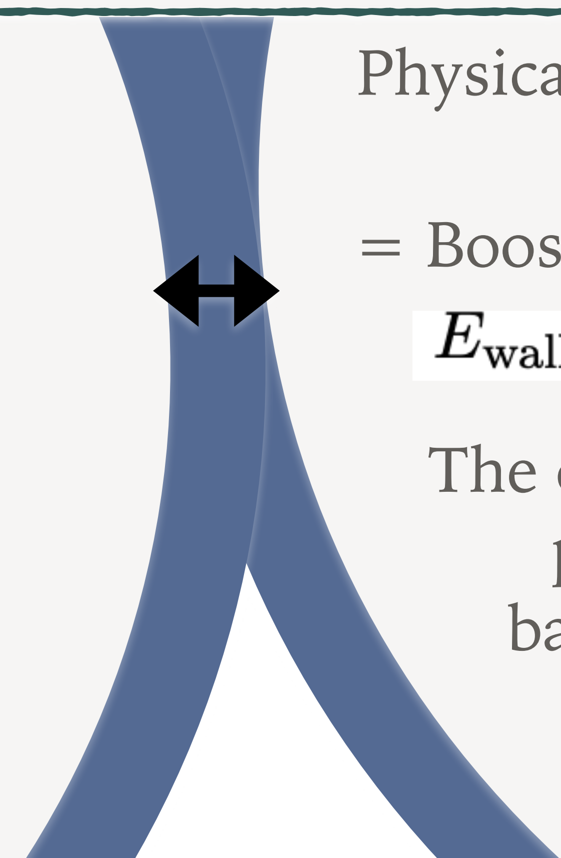
Energy scale at bubble nucleation: phase transition scale
($\sim$ temperature of plasma)

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

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

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

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



Physical scale over which bubble collision occurs

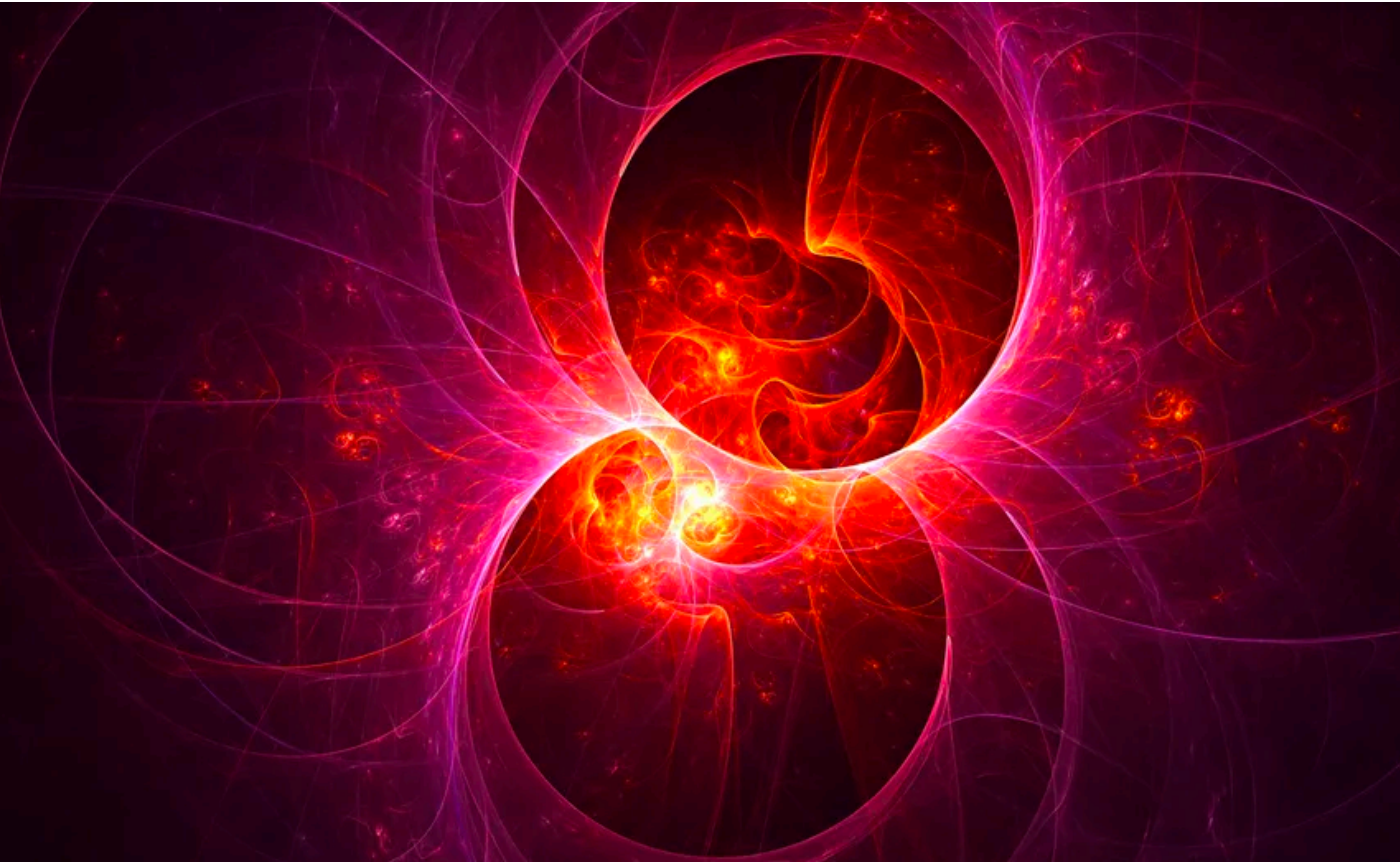
= Boosted bubble wall thickness

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

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



UNDERSTANDING THE PHYSICS OF BUBBLE COLLISIONS

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

Konstandin+Servant *1104.4793 [hep-ph]*
Falkowski+No 1211.5615 [hep-ph]

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

$$\vdots$$

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**

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

$$\sim 1/E^4$$

UNIVERSAL to all ultrarelativistic collisions

Analytic arguments: SHAKYA, 2403.03252

Numerical studies of bubble collisions: W/ HENDA MANSOUR 2308.13070

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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

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

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

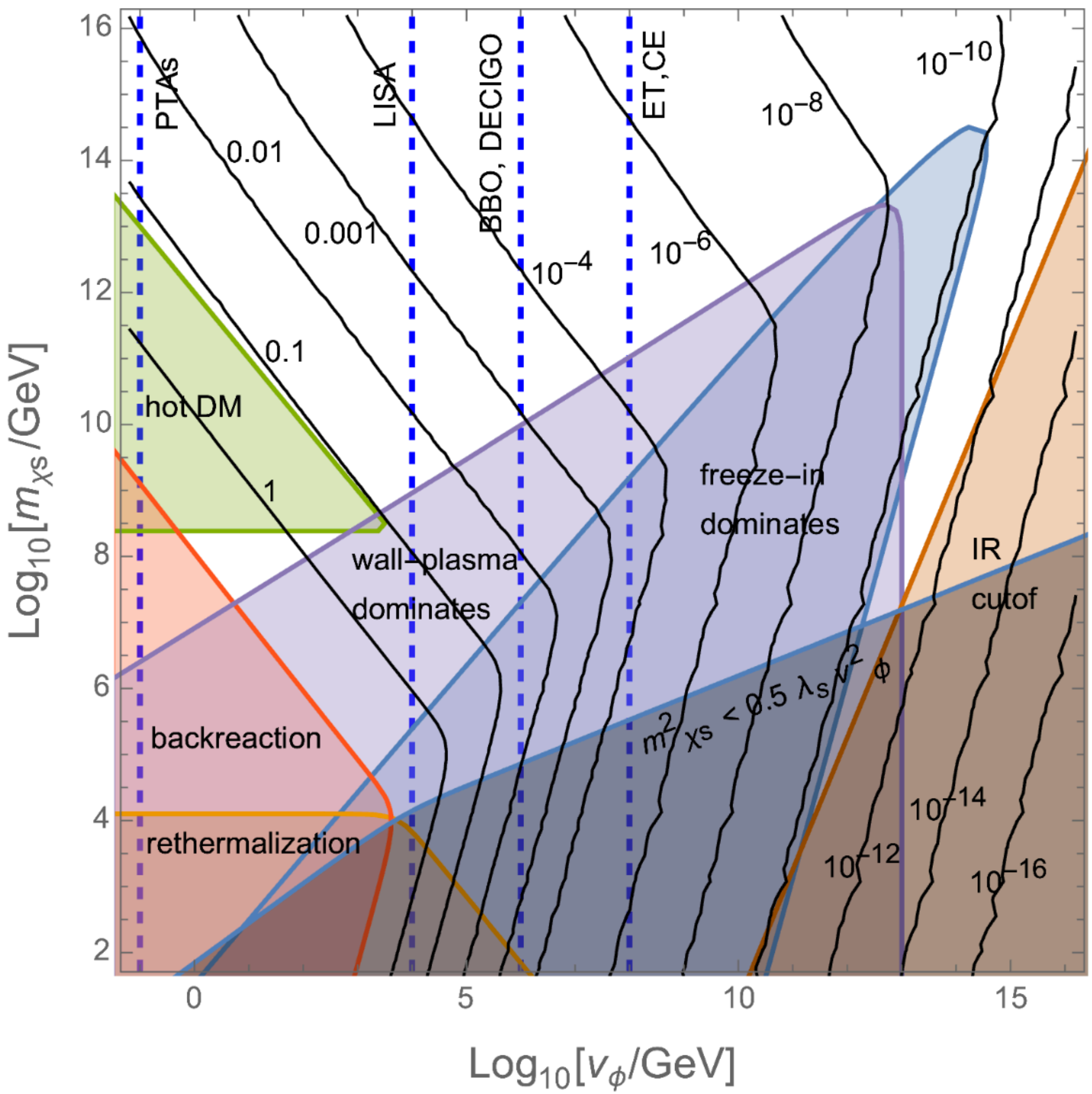
$$\phi_p^* \to \chi_s^2,\ \phi\chi_s^2$$

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:

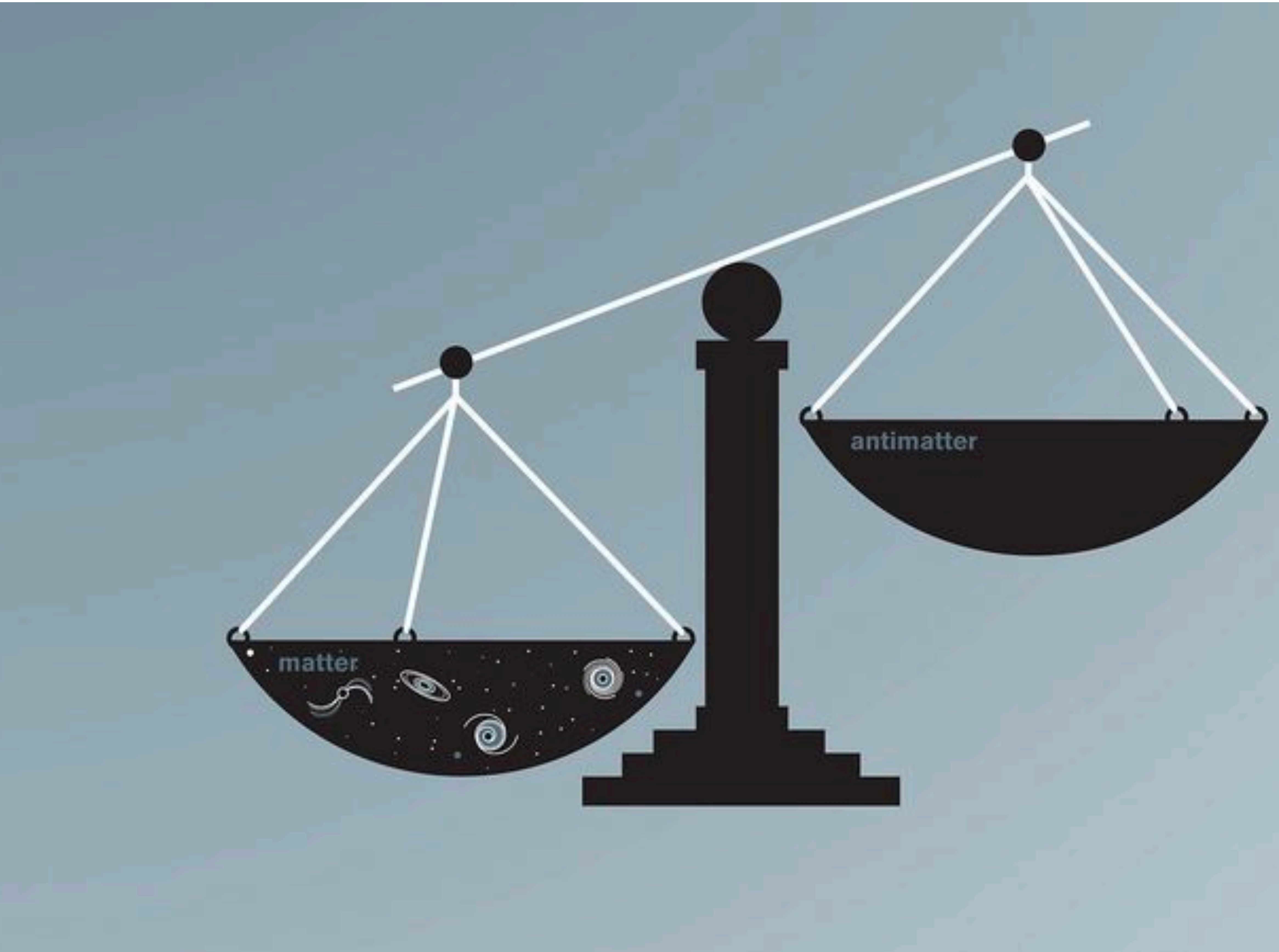
Size of coupling needed to produce the correct dark matter relic density

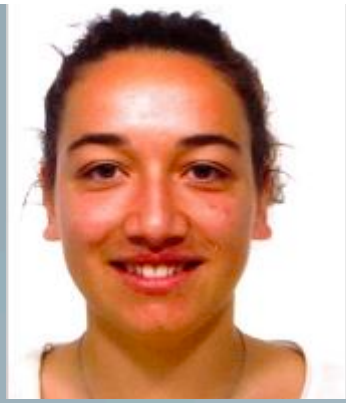
Viable over many orders of magnitude in parameter space.

Can be of relevance for current and upcoming GW detectors

APPLICATION II: MATTER-ANTIMATTER ASYMMETRY

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.

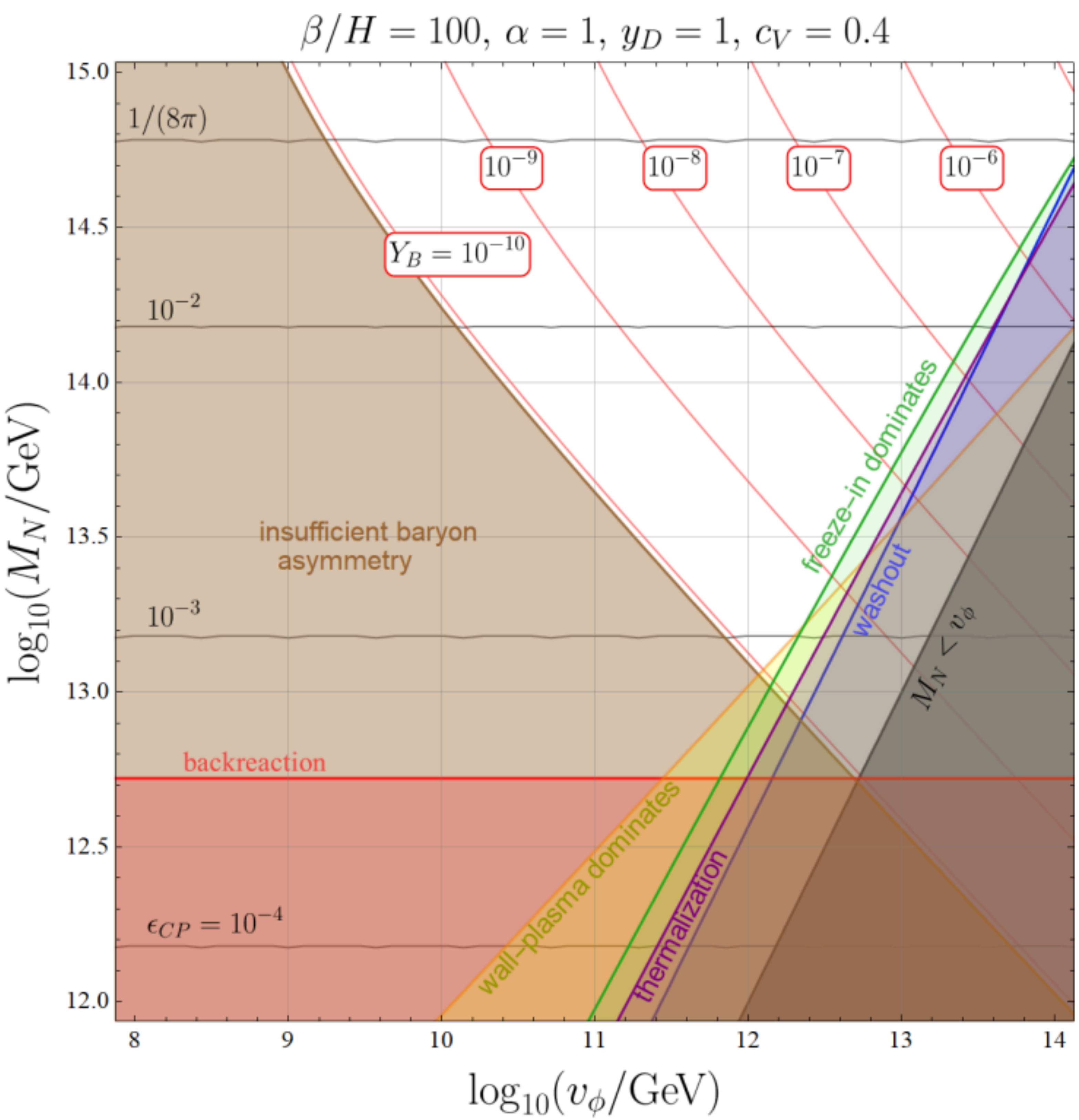
Idea: **Produce heavy RHNs from bubble collisions**

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

Their decays produce the lepton asymmetry. **Since $T \sim v_\phi \ll M_N$, 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)

LEPTOGENESIS: PARAMETER SPACE

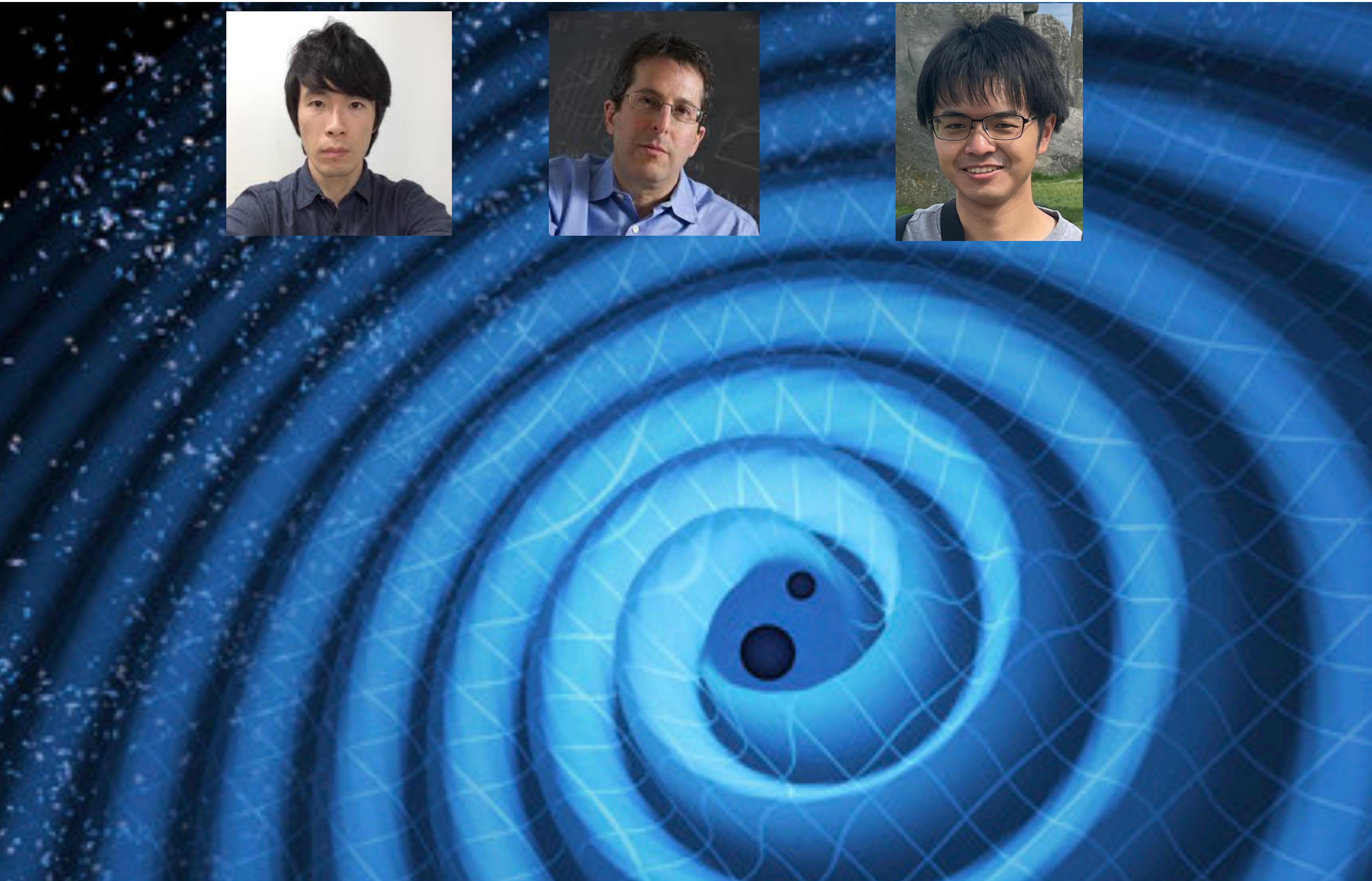


Contours:

amount of baryon asymmetry

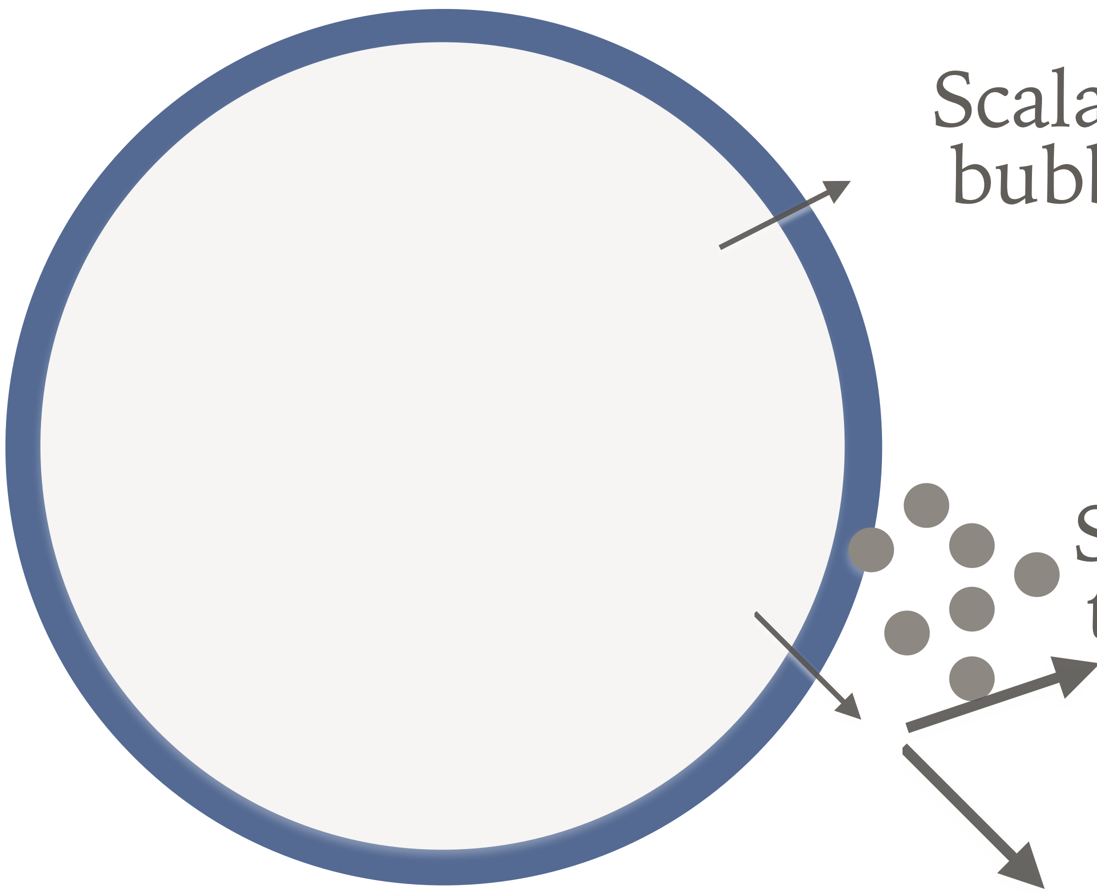
PHENOMENOLOGY: GRAVITATIONAL WAVES

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



Scalar field / bubble wall

(Interacting)
Sound waves/ turbulence in plasma

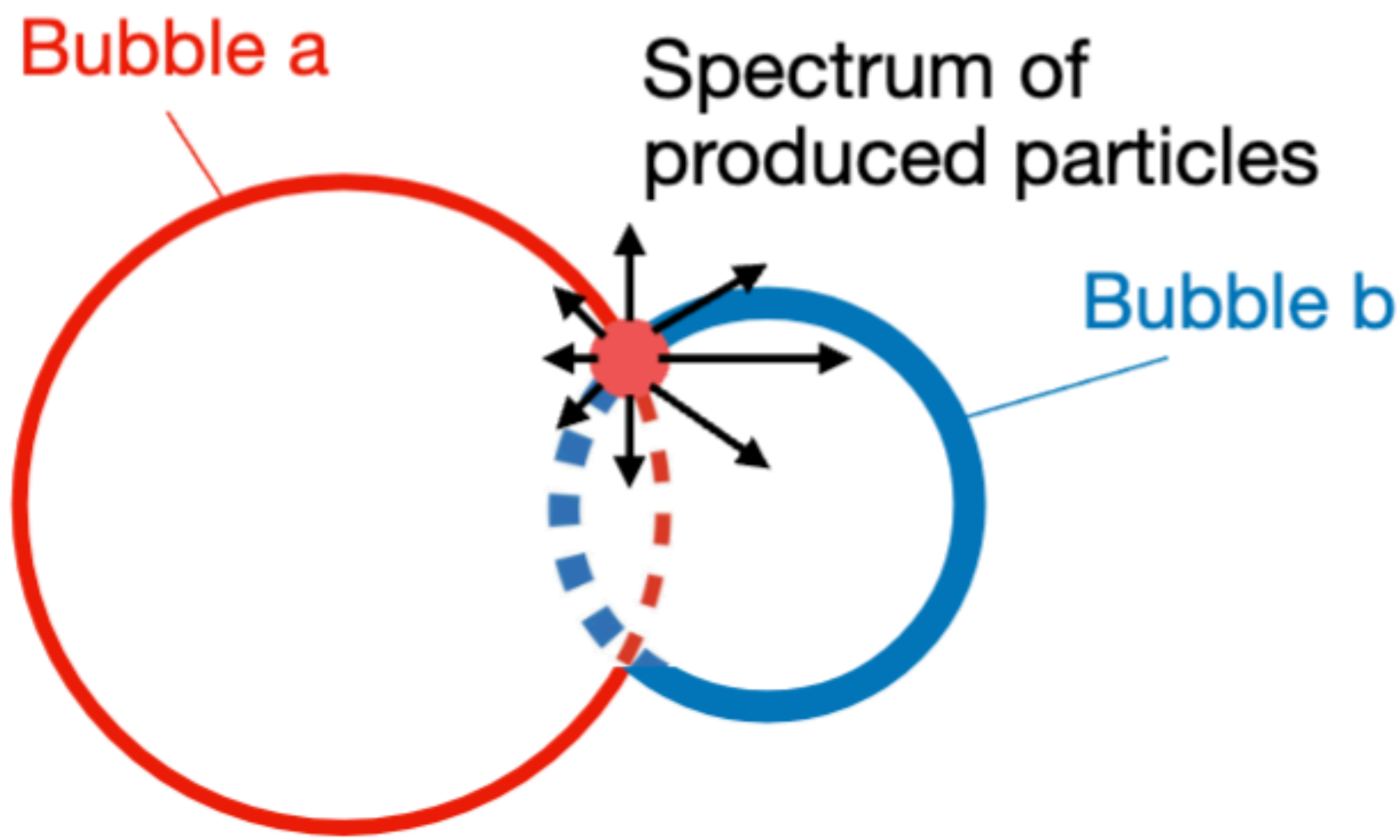
(Non-interacting)
Feebly interacting particles

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

W/ Ryusuke Jinno, Jorinde van de Vis 2211.06405

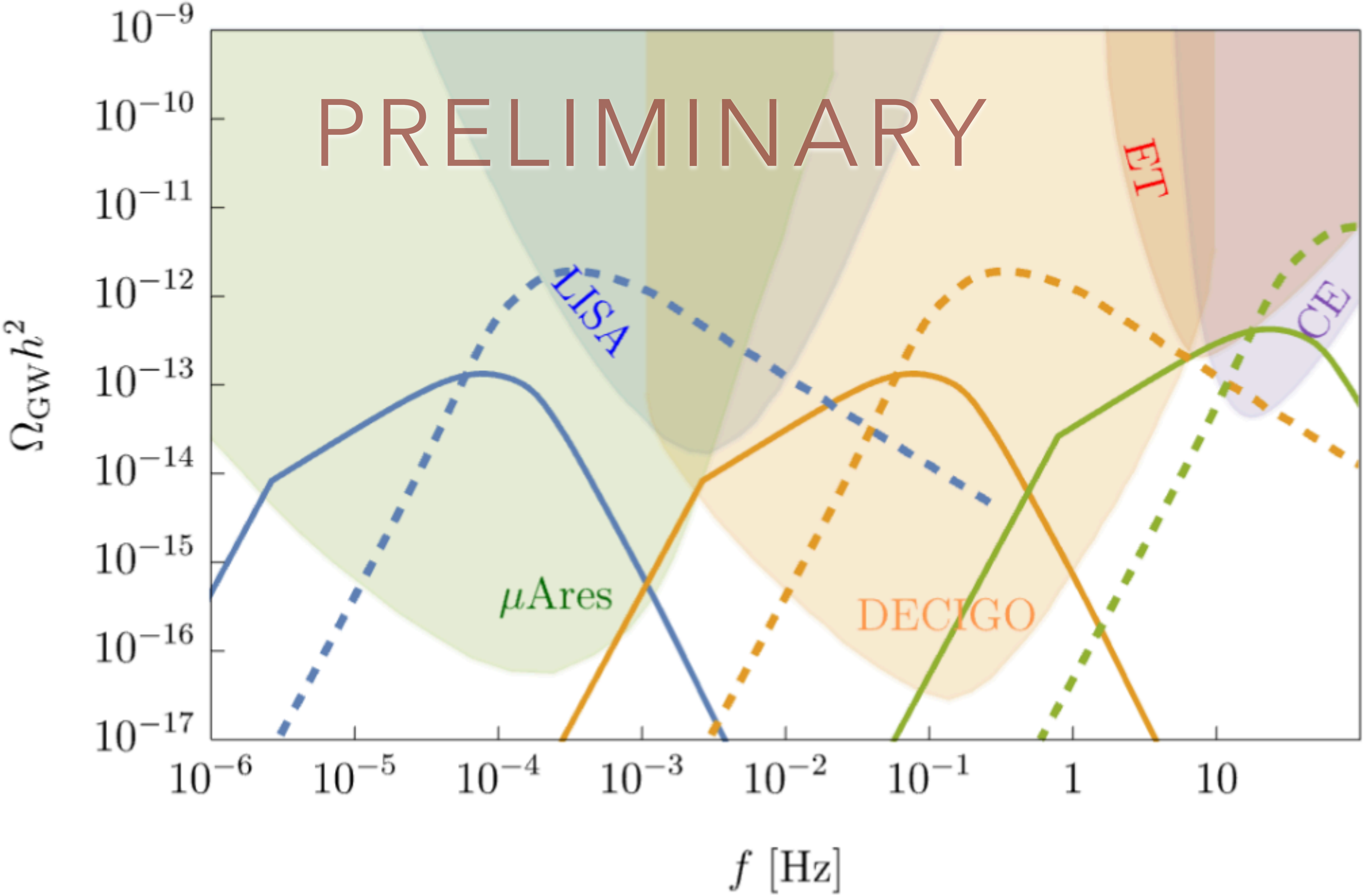
GRAVITATIONAL WAVES

If particle production is efficient, the energy from the phase transition is now primarily stored in 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**