ULTRA-HIGH-ENERGY PARTICLES FROM VACUUM DECAY

DESY Particle Theory Seminar

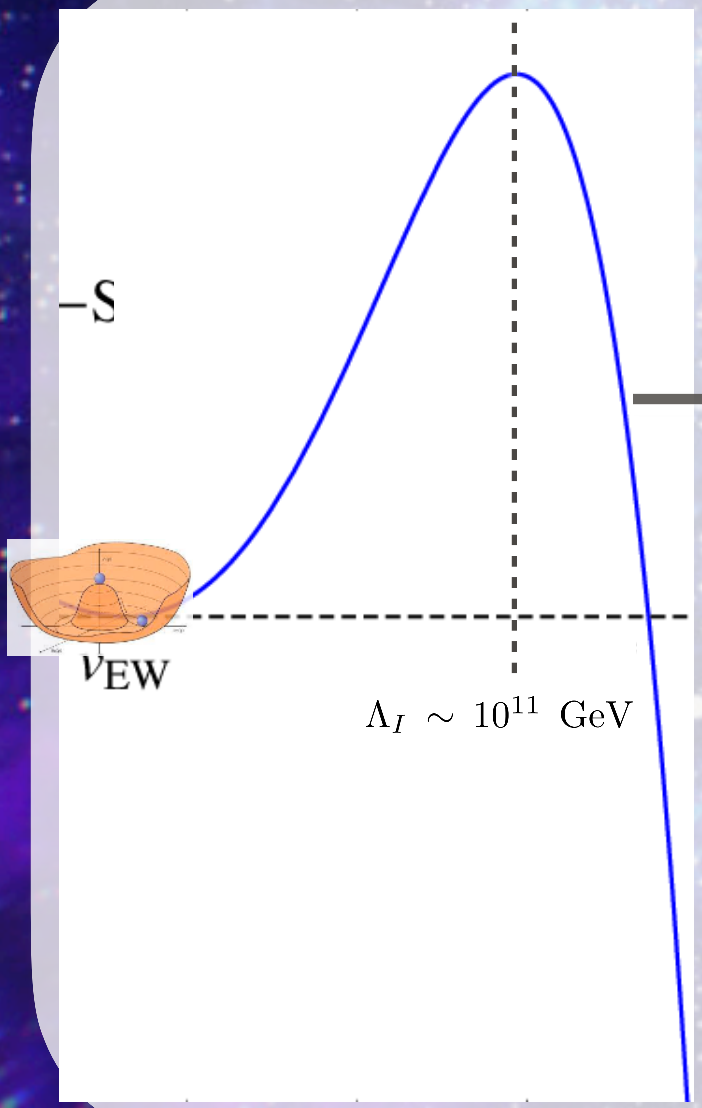
June 3, 2024

BIBHUSHAN SHAKYA


KANG-LA PASS
(5320 M)

(LAST YEAR)

THE TACHYONIC HIGGS
AND THE INFLATIONARY UNIVERSE



The Tachyonic Higgs and the Inflationary Universe

Bibhushan Shakya 2301.08754 [HEP-PH]

Higgs is tachyonic on this side of the potential

Exponential growth of particle number / fluctuations / inhomogeneities

Many phenomenological aspects: ultra high frequency gravitational waves, primordial micro-black holes, non-gaussianities/CMB “hotspots”…

[work in progress with Aleksandr Chatrychan, Gudrid Moortgat-Pick, Geraldine Servant , Julia Ziegler, Sven Ha…]

TODAY

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

2308.16224 [HEP-PH]

Bibhushan Shakya

On Particle Production from Phase Transition Bubbles

Henda Mansour[1,2,3] and Bibhushan Shakya[1]

2308.13070 [HEP-PH]

Nonthermal Heavy Dark Matter from a First-Order Phase Transition

Gian F. Giudice[1], Hyun Min Lee[2], Alex Pomarol[3,4], Bibhushan Shakya[5]

2403.03252 [HEP-PH]

Leptogenesis via Bubble Collisions

Martina Cataldi[1,2] and Bibhushan Shakya[2]

2406.XXXXX [HEP-PH]

On Particle Production from Phase Transition Bubbles

Henda Mansour[1,2,3] and Bibhushan Shakya[1]

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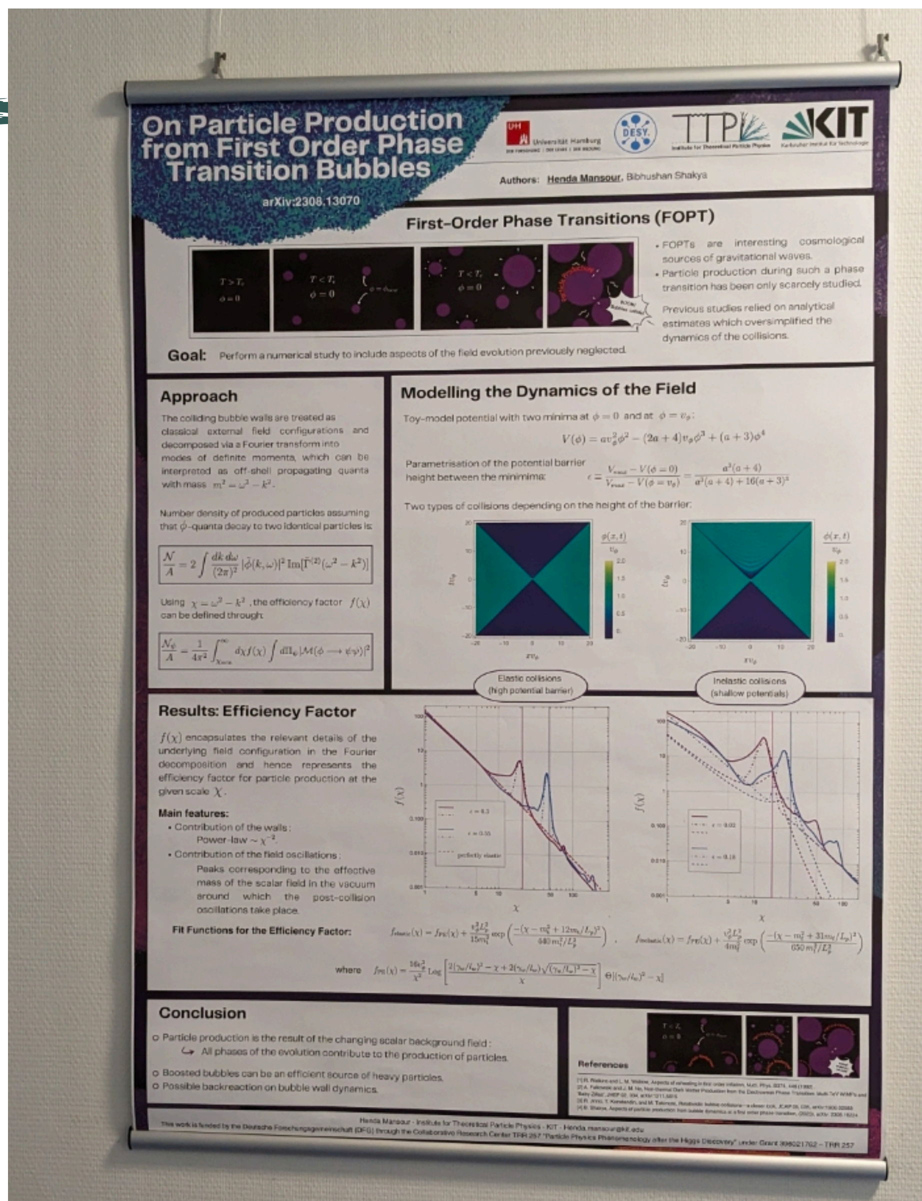

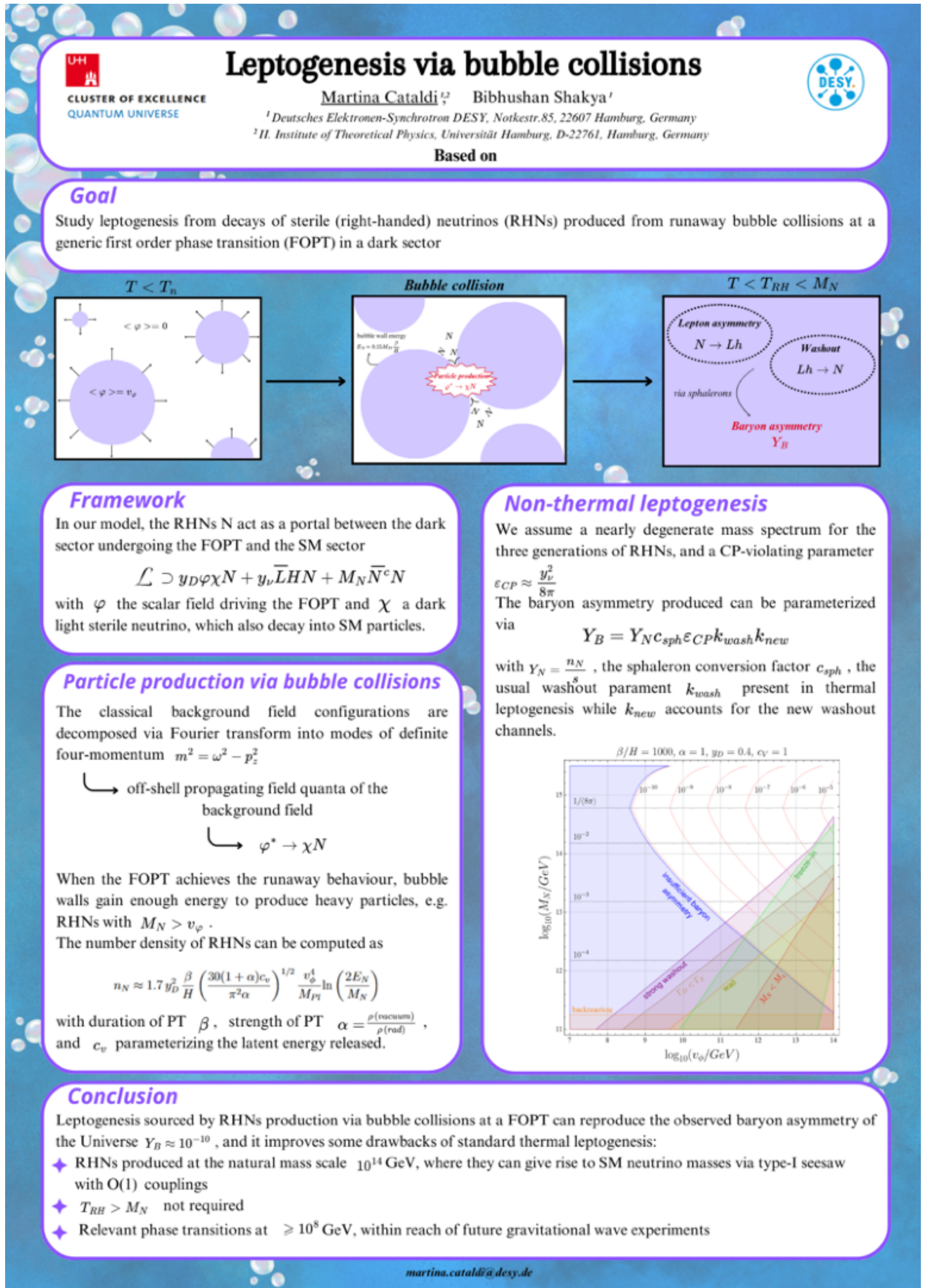

See Martina's talk tomorrow at QU day

	13:00 - 14:00
Leptogenesis via Bubble Collisions	*Martina Cataldi*
DESY Auditorium, Bahrenfeld	14:00 - 14:20
Early vs late string networks from a minimal QCD Axion *Marco Gorghetto*	
Signatures of ultralight bosons in the orbital eccentricity of binary black holes *Matthias Koschnitzke*	
DESY Auditorium, Bahrenfeld	14:40 - 15:00
TBD	*Pia Jakobus*
DESY Auditorium, Bahrenfeld	15:00 - 15:20
The Unique Potential of Detecting High Frequency Gravitational Waves with RF Cavities *Tom Krokotsch*	

Leptogenesis via Bubble Collisions

Martina Cataldi[1,2] and Bibhushan Shakya[2]

2406.XXXXX [HEP-PH]

MOTIVATION

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THEORY: The history of the Universe is, essentially, an evolution from a highly symmetric state to what we see today: a series of symmetry breaking steps, some likely involving first order phase transitions (FOPT)

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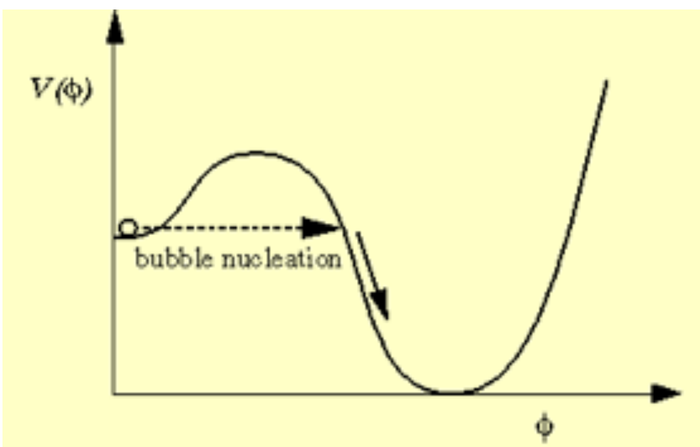
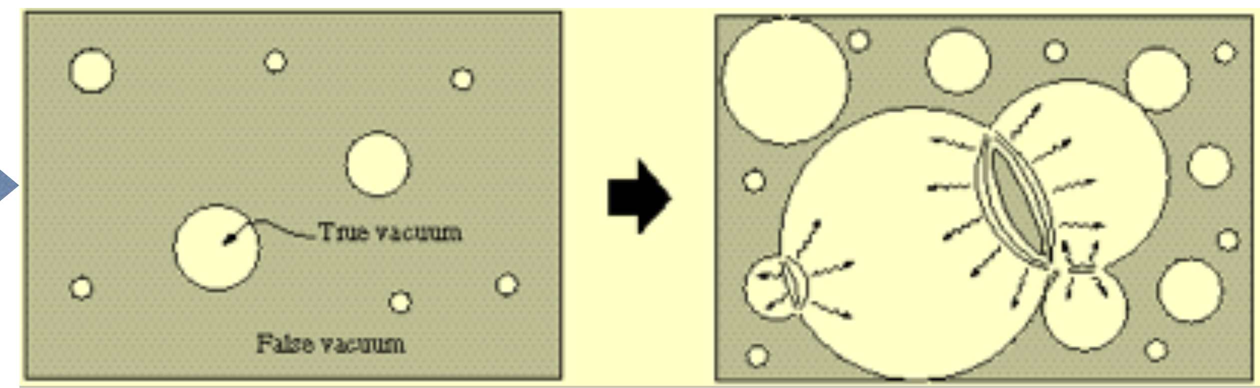
UNIQUENESS: A unique configuration that allows us to probe energies far higher than any energy reached in our cosmic history

FIRST ORDER PHASE TRANSITION (FOPT)



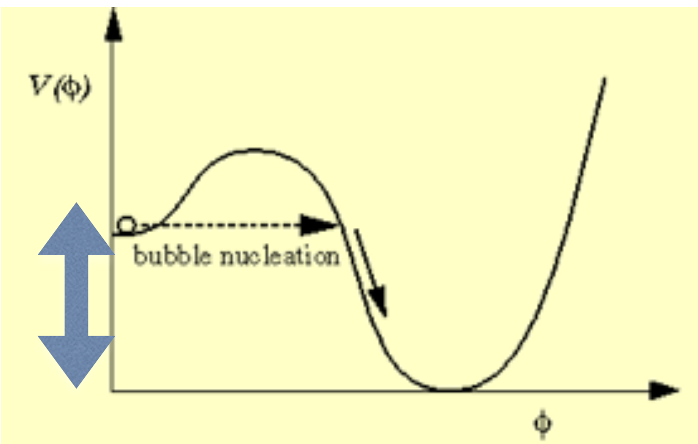


Transition of a **background scalar field** from its **false** (metastable, unbroken) vacuum to its **true** (stable, broken) vacuum state

Bubbles of true vacuum nucleate in the background of the false vacuum, **expand and percolate**, converting all space into the true vacuum configuration

ENERGY DISSIPATION

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

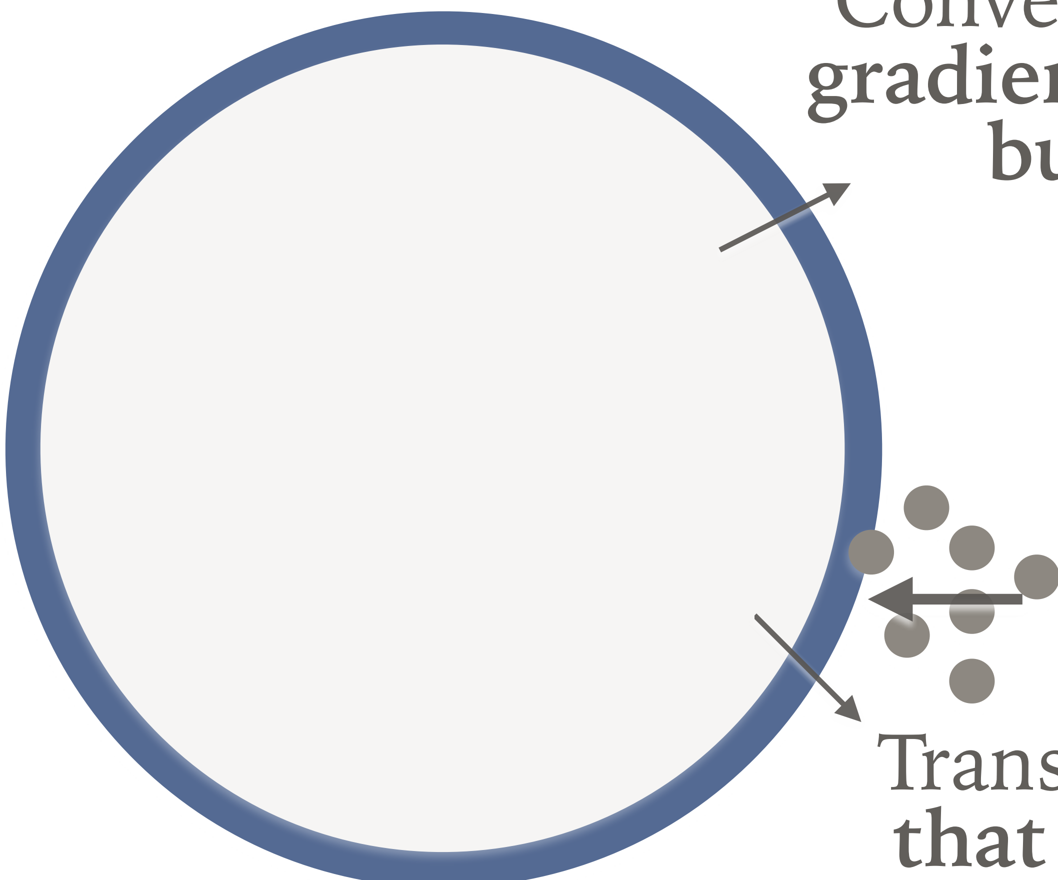


(could be the dominant energy component of the Universe)

Where does this energy go?

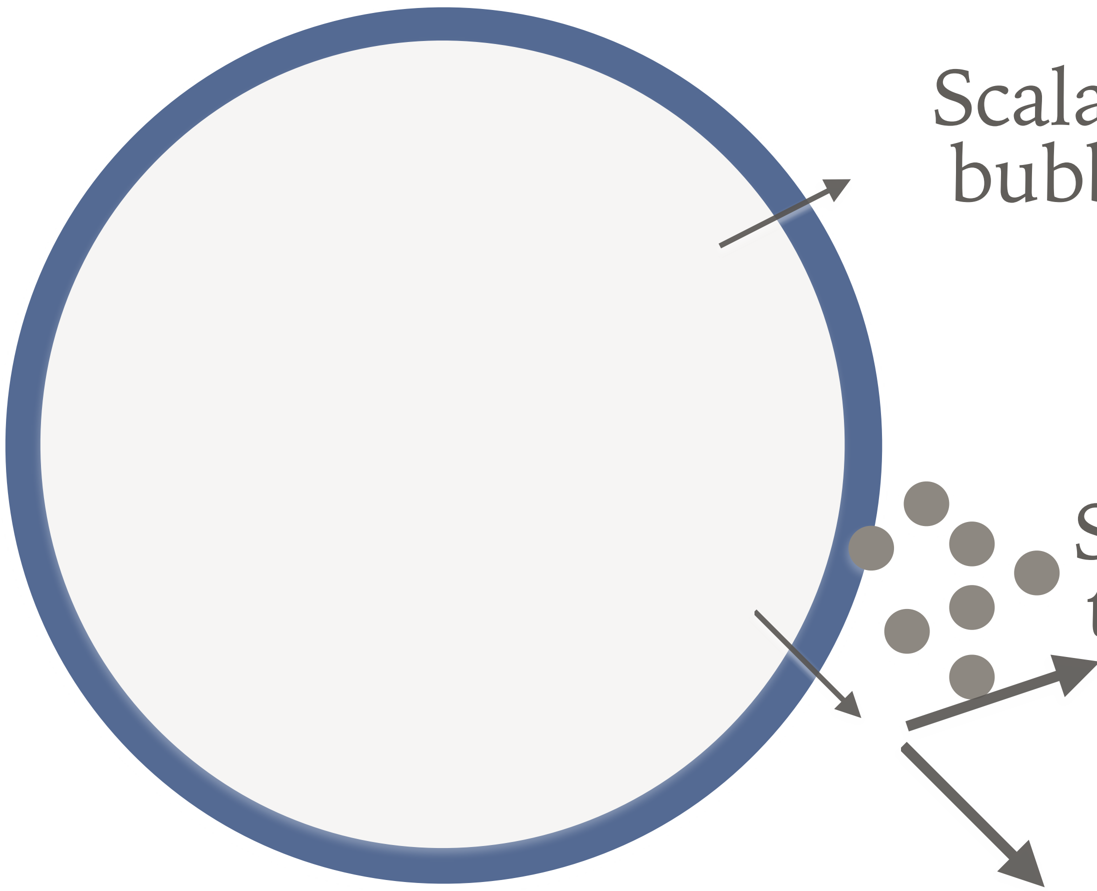
ENERGY DISSIPATION

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



Transferred to **particles that interact with the wall**/become massive in the broken phase

ENERGY DISSIPATION



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

RUNAWAY BUBBLE CONFIGURATIONS

If there is **no efficient energy dissipation*** into the plasma, **bubble walls continue to accumulate the released latent energy** from the false vacuum, and **accelerate to higher boost factors**.

*can occur in several cases: supercooled transitions, transition with a light /no gauge bosons, quantum tunnelling in vacuum)

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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 scale at point of collision
(independent of the energy scale of the FOPT!)

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

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

MANY orders of magnitude higher than the scale of the phase transition, and **possibly any temperature/energy even reached in our cosmic history!!!**

Is it possible to efficiently produce particles with such energies from these bubble walls?

PARTICLE PRODUCTION AT FOPTS

- **Significant effect:** compared to gravitational wave production (particle couplings are much larger than the gravitational coupling)
- **Highly inhomogeneous process:** Cannot be calculated in the same way as particle production from homogeneous phase transitions / changing backgrounds
- **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]

FIRST ORDER PHASE TRANSITION

TERMINOLOGY

- FOPT: scalar field ϕ obtains a nonzero vev v_ϕ
- 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 $\alpha = \dfrac{\Delta V}{\rho_{\rm rad}}$
- T_n , T_*: Temperature of thermal bath at beginning, end of phase transition
- Bubbles formed with wall thickness l_w($\sim 1/v_\phi$) and initial radius R_0($\sim 1/T_n$)
- Bubble wall velocity v_w, boost factor γ_w
- H: Universe expansion rate; $H \sim T^2_*/M_{Pl}$ (radiation dominated Universe)
- β : (inverse) timescale for completion of phase transition: expressed as a fraction of Hubble scale β/H (~10-10,000)
- R_*: typical size of bubbles at collision; $R_* \approx 1/\beta$

PARTICLE PRODUCTION FROM BACKGROUND FIELD DYNAMICS

An inevitable phenomenon

A changing background can produce particles out of vacuum

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

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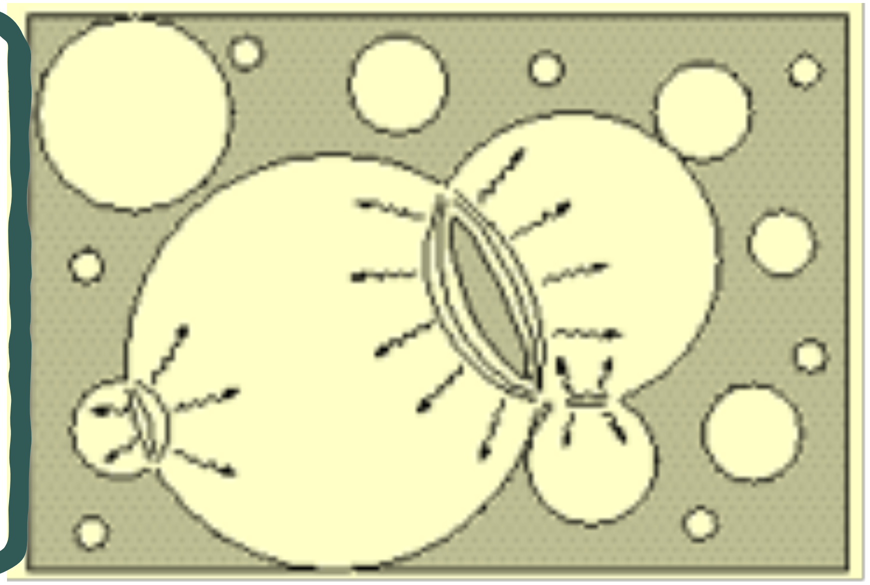
FOPTs involve nontrivial dynamics of the background field:

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



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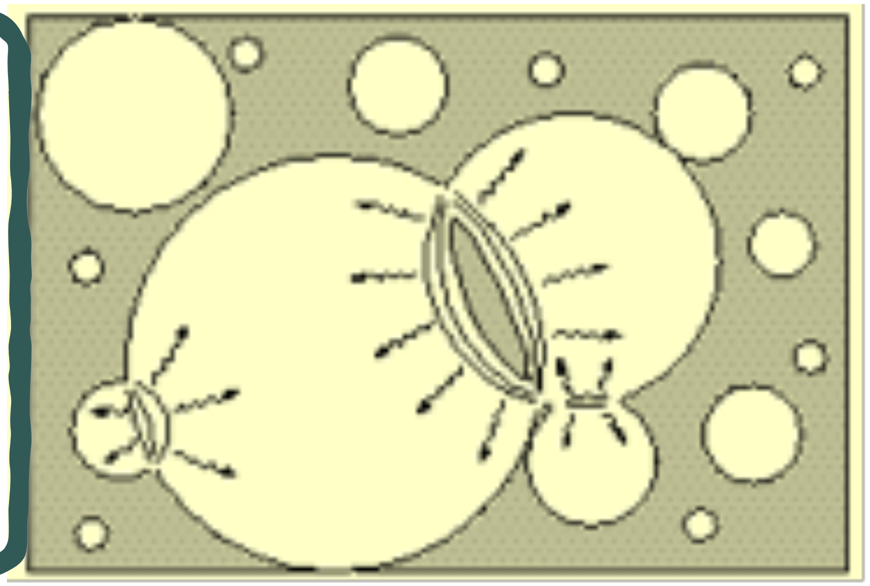

"Irreducible" form of particle production: does not depend on nature/existence of a particle bath

(Additional production mechanisms possible due to interactions with a thermal bath; will discuss these later)

PARTICLE PRODUCTION THROUGH THE STAGES

I. BUBBLE NUCLEATION

SHAKYA, 2308.16224

Consider a nucleated bubble with critical radius in the thin-wall approximation.

For $k \gg R_c^{-1}$ can use the homogeneous approximation, calculate particle number densities using standard homogeneous approach (Bogoliubov transform)

Number density of particles from bubble nucleation (accounting for diffusion into rest of volume)

$$\boxed{n_Y \approx \frac{g_Y}{4\pi^5}\, l_w^{-3} \left(\frac{R_0}{R_*}\right)^3 \mathcal{I}\left(l_{w0}\, m_Y\right) e^{-m_Y/(\lambda_Y v_\phi)}}$$

$$\mathcal{I}(a) \equiv \int_0^\infty dx\, x^2 \times \frac{\sinh^2\left[\frac{1}{4}\left(\sqrt{a^2+x^2}-x\right)\right]}{\sinh\left(\frac{1}{2}\sqrt{a^2+x^2}\right)\sinh\left(\frac{1}{2}x\right)} \qquad \text{(bosons)}$$

$$\mathcal{I}(a) \equiv \int_0^\infty dx\, x^2 \times \frac{\cosh\left(\frac{1}{2}a\right) - \cosh\left[\frac{1}{2}\left(\sqrt{a^2+x^2}-x\right)\right]}{2\sinh\left(\frac{1}{2}\sqrt{a^2+x^2}\right)\sinh\left(\frac{1}{2}x\right)} \qquad \text{(fermions)}$$

- **Negligible effect due to volume dilution**
- **No access to energies >> inverse wall thickness**

PARTICLE PRODUCTION THROUGH THE STAGES

II. BUBBLE EXPANSION

SHAKYA, 2308.16224

A PROPER CALCULATION: SINGLE PROPAGATING BUBBLE WALL

Consider a particle that becomes massive through the phase transition

Klein Gordon equation $$\left(-\frac{\partial^2}{\partial t^2}+\frac{\partial^2}{\partial x^2}\right)\psi(t,x)=\frac{m_\psi^2}{4}\left(1-\tanh\left(\frac{v_w t-x}{l_\mathrm{w}}\right)\right)^2\psi(t,x)$$

Mass term changes over both space and time; cannot perform a mode decomposition and solve for Bogoliubov coefficients analytically

Resolution: perform change of variables $$x_1=\frac{1}{\sqrt{1+v_w^2}}(v_w t-x),\quad x_2=\frac{1}{\sqrt{1+v_w^2}}(t+v_w x)$$

$$\left[\left(\frac{1-v_w^2}{1+v_w^2}\right)\left(-\frac{\partial^2}{\partial x_2^2}+\frac{\partial^2}{\partial x_1^2}\right)-\frac{4v_w}{1+v_w^2}\frac{\partial}{\partial x_1}\frac{\partial}{\partial x_1}\right]\phi(t,x)=m_\psi^2(x_1)\phi(t,x)$$

Condition for particle production out of vacuum:

$$\boxed{p_2^2(v_w^4-1)>m_\psi^2(1-v_w^2)}$$

Cannot be satisfied for v<1!

PARTICLE PRODUCTION THROUGH THE STAGES

II. BUBBLE EXPANSION

SHAKYA, 2308.16224

- Bubble wall moving at constant velocity in vacuum cannot produce particles (checked with an explicit Bogoliubov transformation calculation, but also obvious in rest frame)
- Runaway bubbles accelerate, accelerating system can produce particles! Using the equivalence principle, produced particle number density from accelerating bubble walls:

$$\boxed{n_Y \sim y_\chi^2 \, R_*^{-3}}$$

Bubble radius (at collision)

coupling between particle and background field

- **Can produce particles that are very energetic (in the plasma frame); however**
- **Since bubble radius is of order (inverse) Hubble, this contribution also tends to be subdominant to other stages**

III. BUBBLE COLLISION

The most energetic stage of the phase transition

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

Two qualitatively different possibilities for subsequent evolution:

PARTICLE PRODUCTION THROUGH THE STAGES

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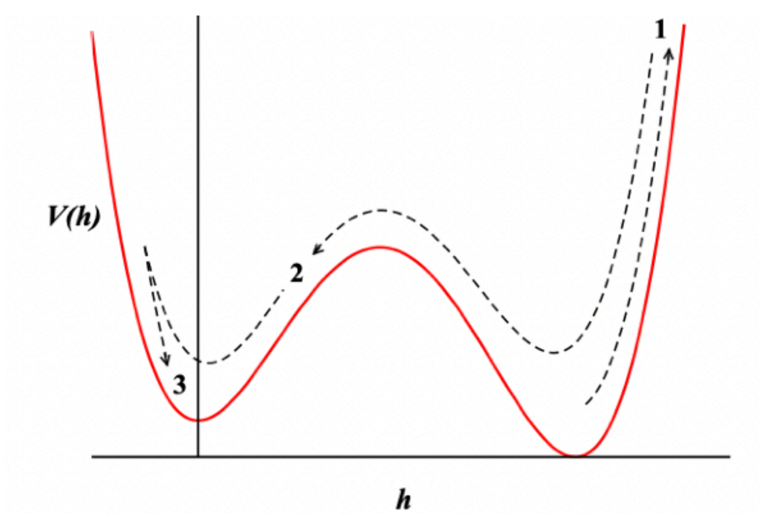
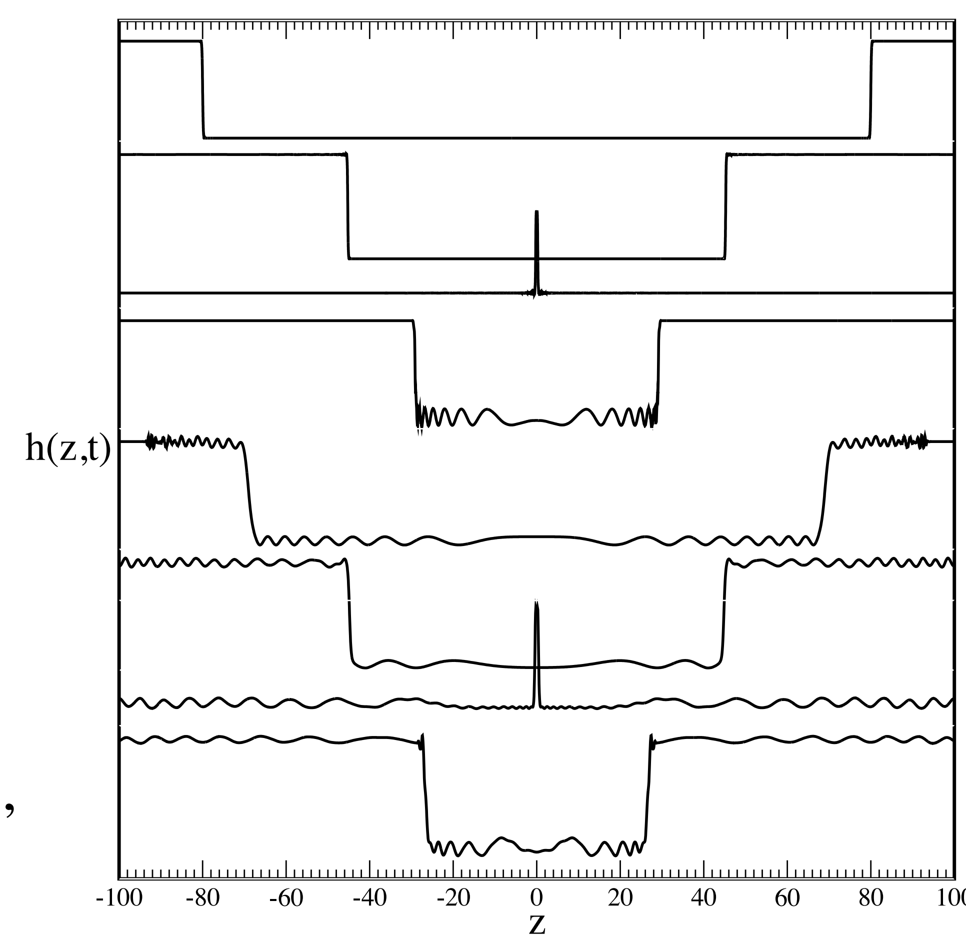
Elastic Collision

Falkowski+No 1211.5615 [hep-ph]

Field jumps back to false vacuum





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

PARTICLE PRODUCTION THROUGH THE STAGES

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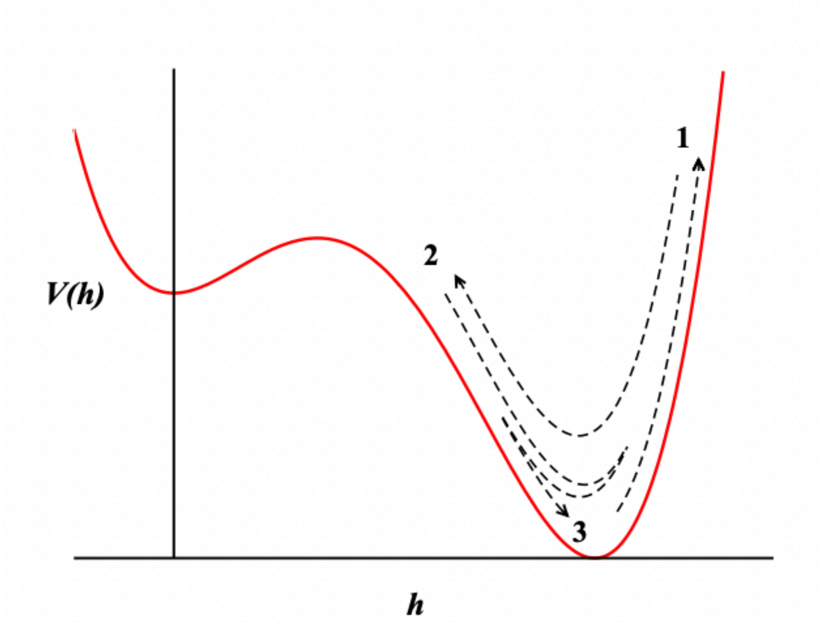
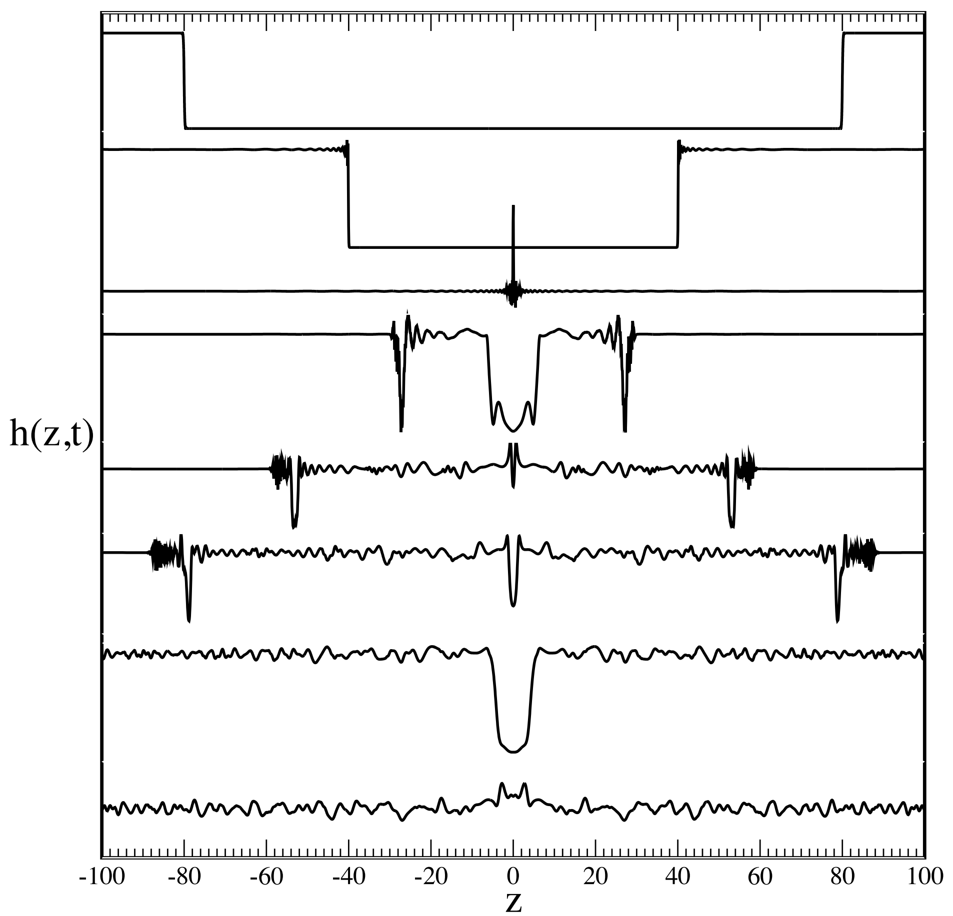
Inelastic Collision

Falkowski+No 1211.5615 [hep-ph]

Field oscillates around true vacuum



Bubble walls stick together; energy dissipated as scalar waves



PARTICLE PRODUCTION THROUGH THE STAGES

III. BUBBLE COLLISION

The most energetic stage of the phase transition

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

Two qualitatively different possibilities for subsequent evolution:

In both cases (elastic and inelastic collisions), eventually:

walls disappear, scalar field oscillations around the true vacuum,
which slowly radiates into light quanta that the field couples to

Watkins+Widrow Nucl.Phys.B 374 (1992)
Konstandin+Servant *1104.4793 [hep-ph]*
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CALCULATING PARTICLE PRODUCTION
BUBBLE COLLISION AND BEYOND

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

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

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
BUBBLE COLLISION AND BEYOND

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

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BUBBLE COLLISION AND BEYOND

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Decompose background field excitation into **Fourier modes**

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)

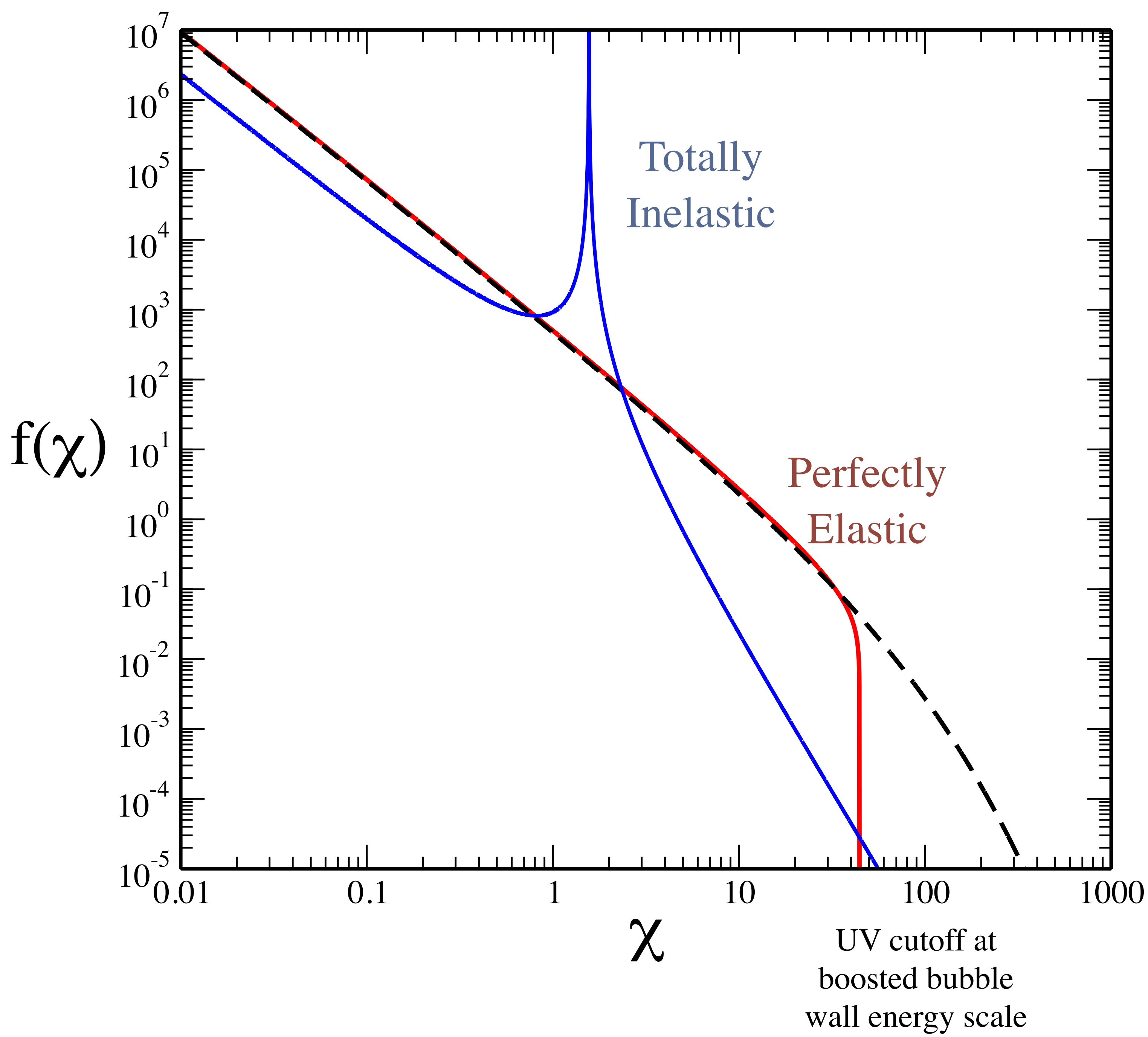
(encodes particle physics details)

CALCULATING PARTICLE PRODUCTION

BUBBLE COLLISION AND BEYOND

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

Semi-analytic solutions for idealized limits, Falkowski+No 1211.5615 [hep-ph]



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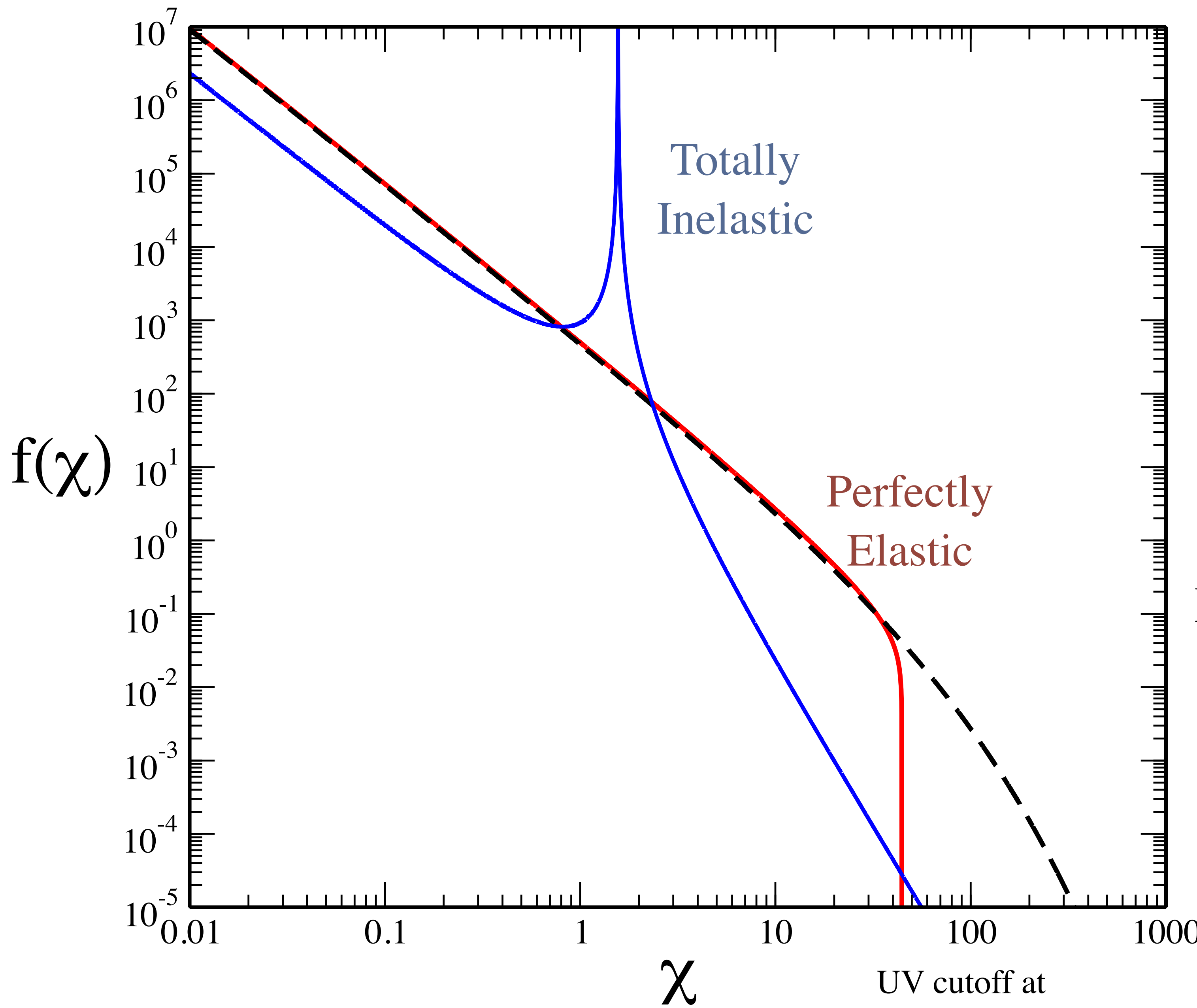


UV cutoff at boosted bubble wall energy scale

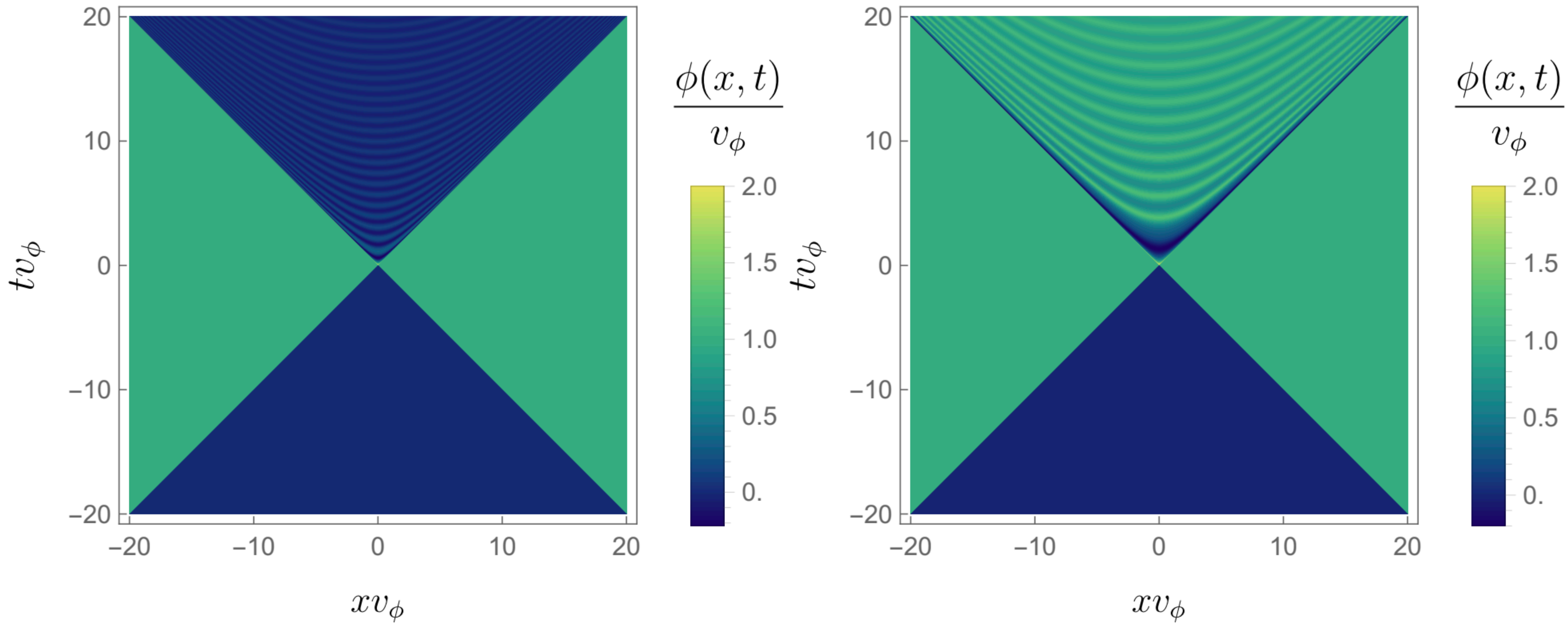
Falls off as power law at high energies
(no exponential suppression)

Elastic collisions more efficient than inelastic collisions

MORE REALISTIC CASES, NUMERICALLY

Result: field configuration both before and after collision

MANSOUR, SHAKYA, 2308.13070



Elastic collision

Inelastic collision

Green: true vacuum, blue: false vacuum

REALISTIC CASES, NUMERICALLY

Fourier transform of field configuration

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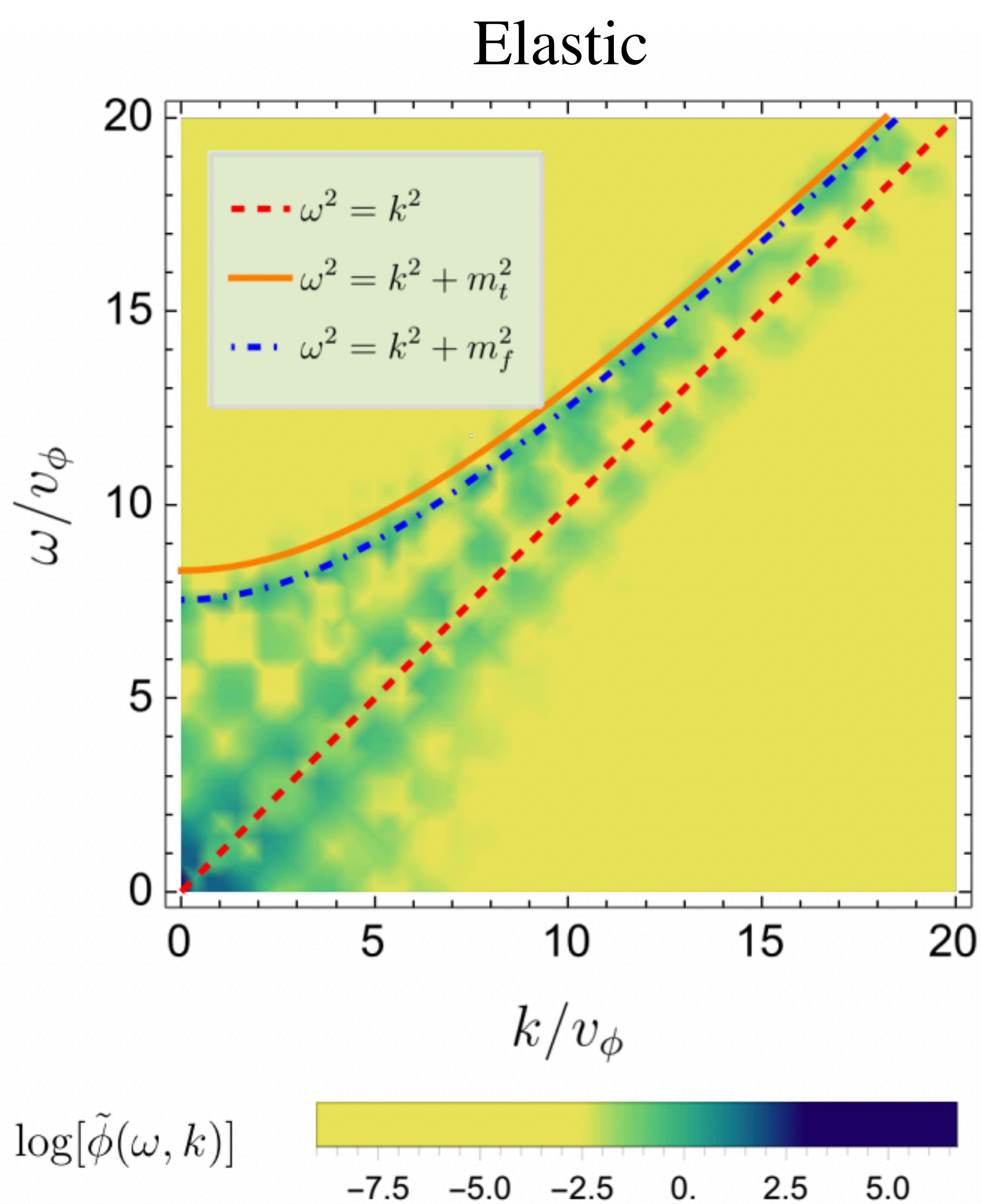
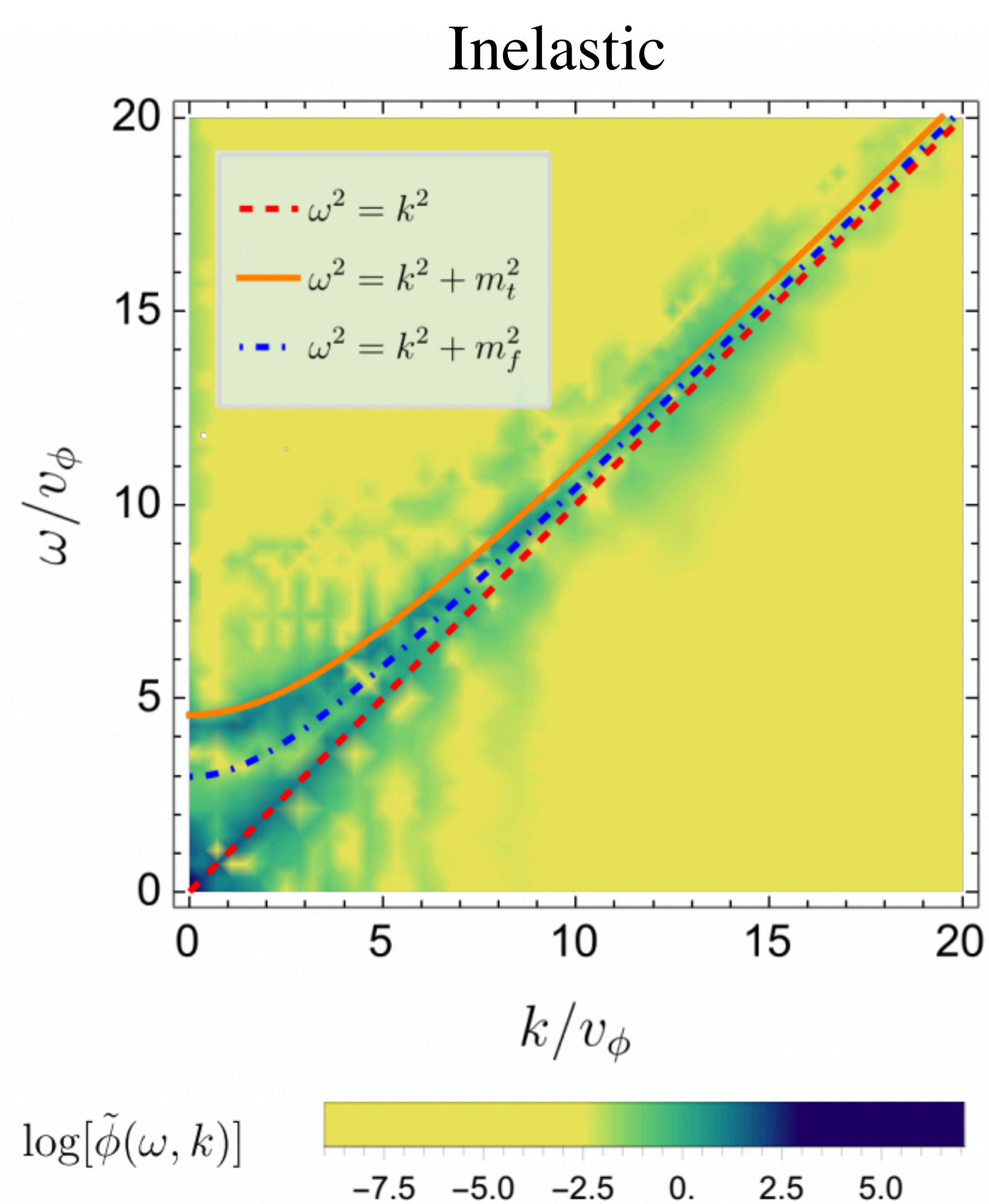


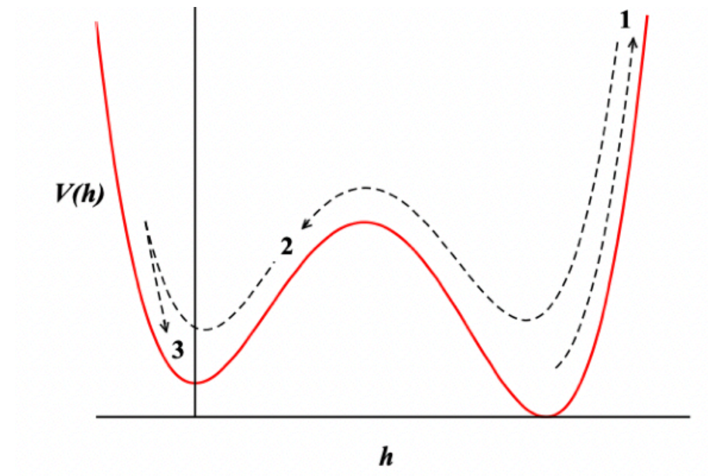


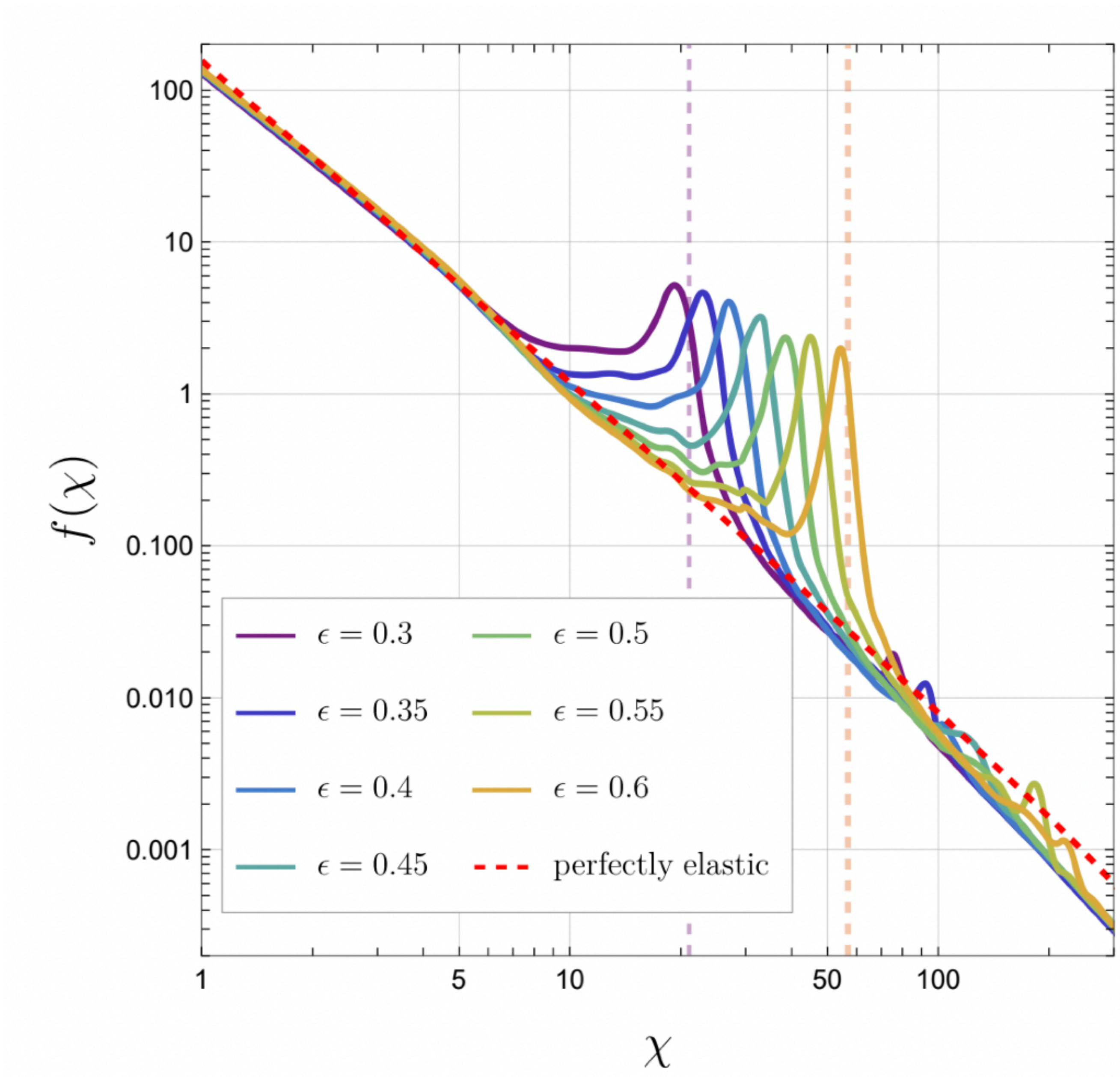
Mainly clustered around two regions

$$\omega^2 = k^2 \qquad\qquad \omega^2 = k^2 + m^2$$

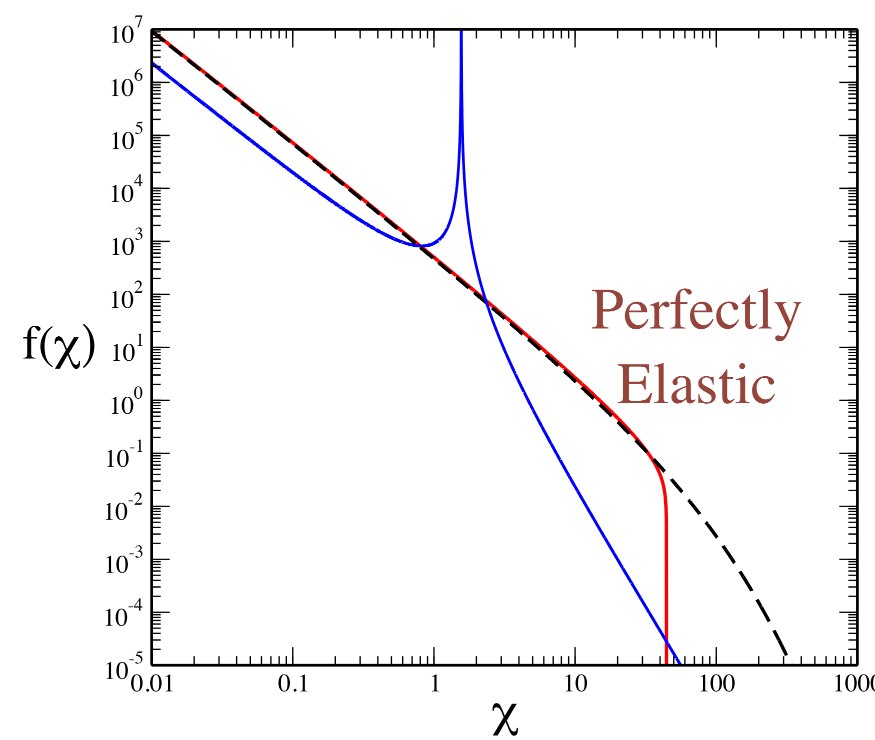
RESULTS: EFFICIENCY FACTOR

Elastic collisions





Different curves denote different shapes of the potential



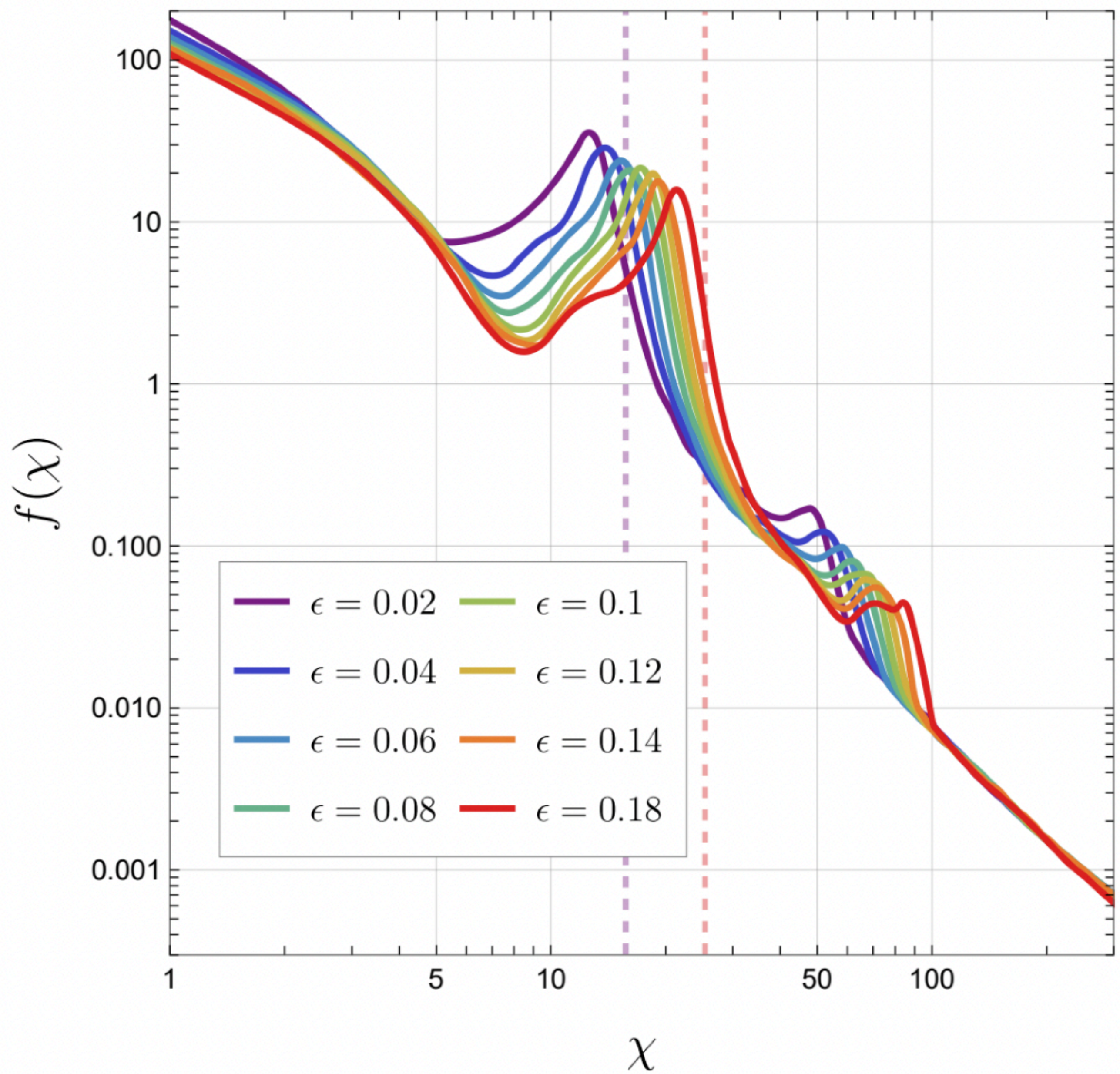
Compared to analytic result:

Same power law, get additional "peak" due to field oscillations around its minimum

MANSOUR, SHAKYA, 2308.13070

RESULTS: EFFICIENCY FACTOR

Inelastic collisions



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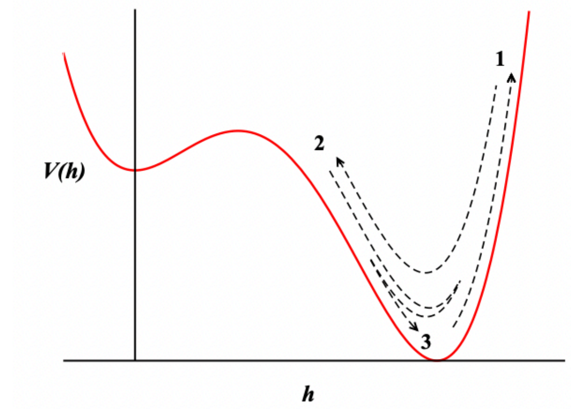

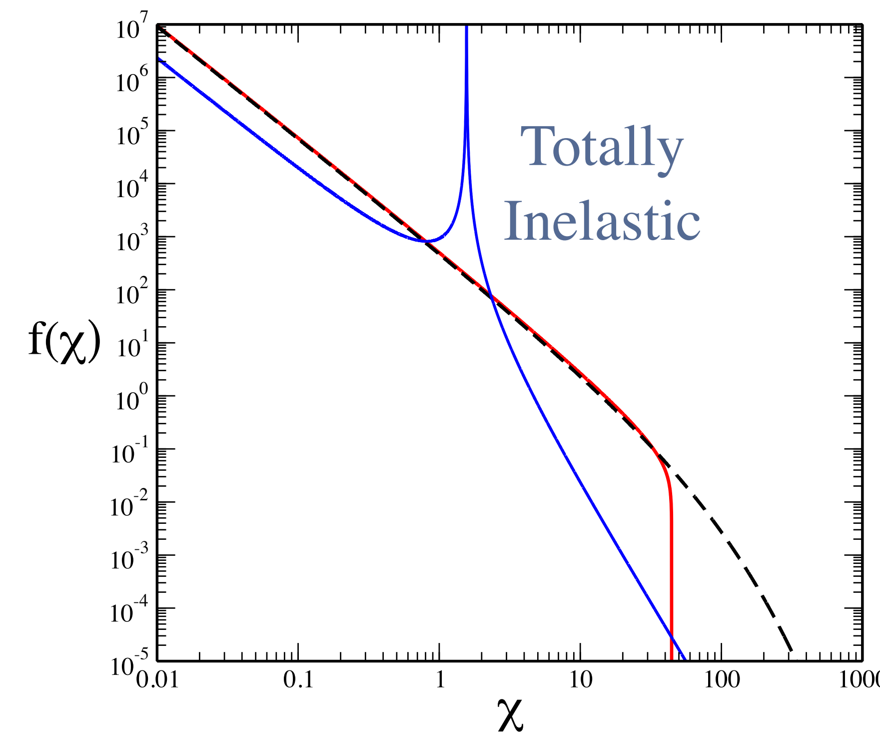

Compared to analytic result:

Peak+power law combination, power law matches below the peak but not above!

(Second peak: likely a numerical artifact)

RESULTS: EFFICIENCY FACTOR

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Simple fit functions:

$$f_{\text{elastic}}(p^2) = f_{\text{PE}}(p^2) + \frac{v_\phi^2 L_p^2}{15 m_{\text{t}}^2} \exp\left(\frac{-(p^2 - m_{\text{t}}^2 + 12 m_{\text{t}}/L_p)^2}{440\, m_{\text{t}}^2/L_p^2} \right) \qquad \text{(elastic collisions)}$$

$$f_{\text{inelastic}}(p^2) = f_{\text{PE}}(p^2) + \frac{v_\phi^2 L_p^2}{4 m_{\text{f}}^2} \exp\left(\frac{-(p^2 - m_{\text{f}}^2 + 31 m_{\text{f}}/L_p)^2}{650\, m_{\text{f}}^2/L_p^2} \right) \qquad \text{(inelastic collisions)}$$

Both cases well matched with the same power law

$$f_{\text{PE}}(p^2) = \frac{16 v_\phi^2}{p^4} \text{Log}\left[\frac{2(1/l_w)^2 - p^2 + 2(1/l_w)\sqrt{(1/l_w)^2 - p^2}}{p^2} \right]$$

Both elastic and inelastic collisions equally "efficient" at high energies

PARTICLE PHYSICS ASPECTS

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

$$\mathrm{Im}[\tilde{\Gamma}^{(2)}(\chi)] = \frac{1}{2}\sum_{\alpha}\int d\Pi_\alpha |\mathcal{M}(\phi \to \alpha)|^2\, \Theta(\chi - \chi_{min\,(\alpha)}).$$

α sums over all final particle states that can be produced.

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

PARTICLE PHYSICS ASPECTS

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

$$\mathrm{Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi_p^* \to \phi\phi} = \frac{\lambda_\phi^2\, v_\phi^2}{8\pi}(1 - 4m_\phi^2/p^2)\,\Theta(p - 2m_\phi)$$

$$\mathrm{Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi_p^* \to 3\phi} = \frac{\lambda_\phi^2\, p^2}{3072\,\pi^3}(1 - 9m_\phi^2/p^2)\,\Theta(p - 3m_\phi)$$

Yukawa interaction with a fermion:

$$\mathrm{Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi_p^* \to \chi_f \bar{\chi}_f} = \frac{y_f^2}{8\pi} p^2 (1 - 4m_{\chi_f}^2/p^2)^{3/2}\,\Theta(p^2 - 4m_{\chi_f}^2)$$

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Gauge boson?? $\mathrm{Im}[\tilde{\Gamma}^{(2)}(p^2)]_{\phi_p^* \to 2V} \sim ??$

GAUGE INVARIANCE OF THE FORMALISM

GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252

$$|\bar{\mathcal{M}}(\phi_p^* \to VV)|^2 = g^2 m_V^2 \left(3 - \frac{p^2}{m_V^2} + \frac{p^4}{4m_V^4}\right) \qquad \text{(Unitary gauge)}$$

Blows up at large energies, becomes non-perturbative

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More generally,

$$|\bar{\mathcal{M}}(\phi_p^* \to VV)|^2 = g^2 m_V^2 \times \begin{cases} \frac{(\xi-3)p^2}{2m_V^2} + \frac{\lambda_\phi^2}{g^4} + 3 & \text{for } \frac{p^2}{m_V^2} \gg \xi, 1 \\ \frac{p^4}{4m_V^4} - \frac{p^2}{m_V^2} + 3 & \text{for } \xi \gg \frac{p^2}{m_V^2}, 1 \end{cases} \qquad (R_\xi \text{ gauge})$$

Calculation is not gauge independent!

GAUGE INVARIANCE OF THE FORMALISM

GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252

The problem: sum over gauge boson polarizations

$$\sum \epsilon^\mu \epsilon^\nu \to -g^{\mu\nu} + (1-\xi)\frac{p^\mu p^\nu}{p^2 - \xi m_V^2}$$

Includes both physical and unphysical degrees of freedom.

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In any physical calculation, the unphysical contributions cancel out.

However, a collection of off-shell background field excitations is not a physical state, so gauge invariance is not guaranteed!

(The effective action formalism is known to suffer from gauge invariance issues in general)

GAUGE INVARIANCE OF THE FORMALISM

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Includes both physical and unphysical degrees of freedom.

PRACTICAL SOLUTION:

Instead of doing the above sum, restrict explicitly to physical states, use Goldstone Equivalence Theorem to get high energy behavior of longitudinal modes

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

APPLICATION I: HEAVY DARK MATTER

GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252

DARK MATTER: SETUP

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

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

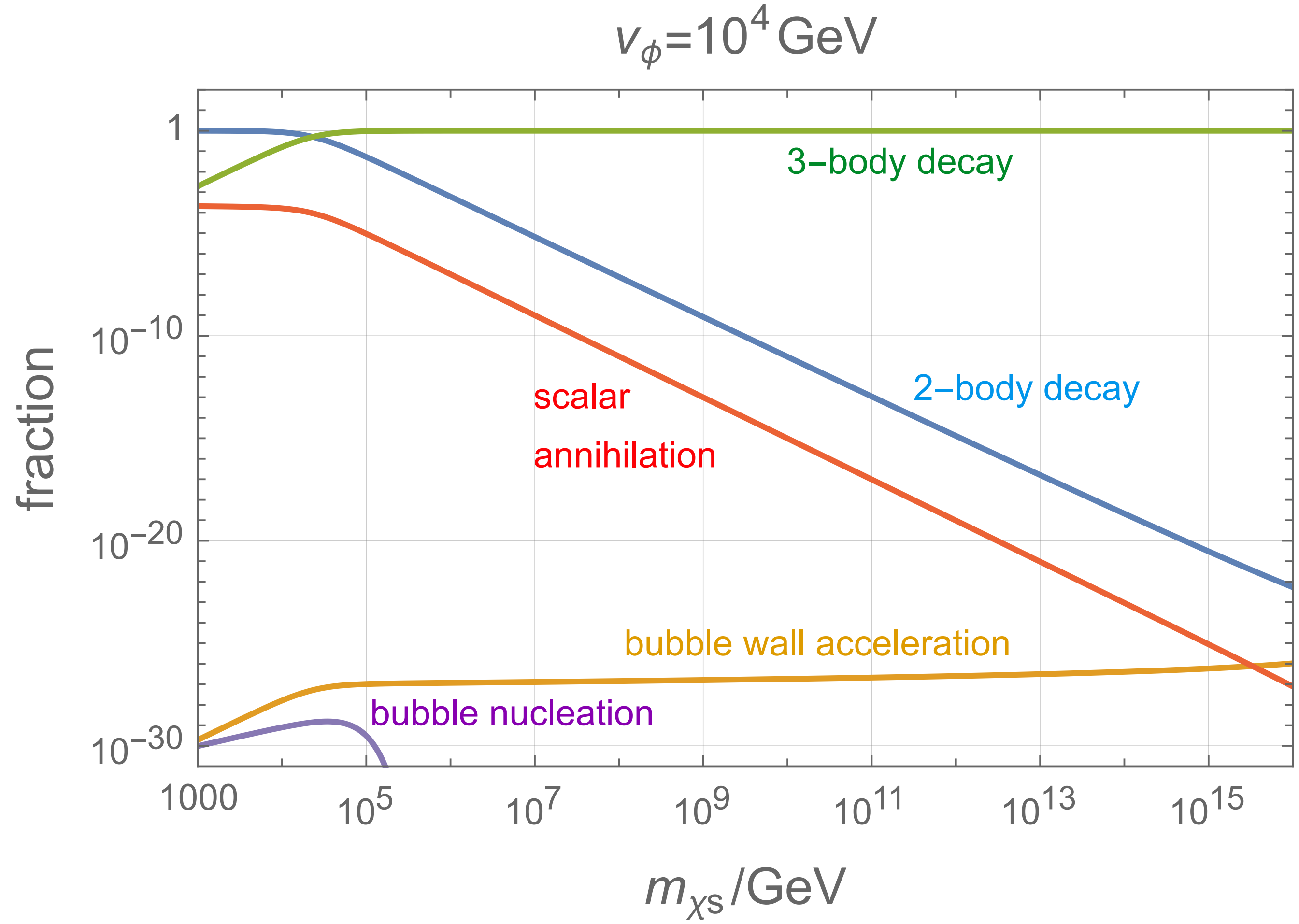
$$\Omega_\chi h^2 \approx 0.1\,\frac{\beta/H}{10}\left(\frac{\alpha}{(1+\alpha)g_* c_V}\right)^{1/4}\frac{\lambda_s^2\, m_{\chi_s}\, v_\phi}{(24\ \mathrm{TeV})^2}\left[\frac{v_\phi^2}{m_{\chi_s}^2}+\frac{1}{16\pi^2}\ln\left(\frac{2\,\gamma_w/l_{w0}}{(2m_{\chi_s}+m_\phi)}\right)\right]$$

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



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

A. Azatov, M. Vanvlasselaer, and W. Yin, arXiv:2101.05721 [hep-ph].

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

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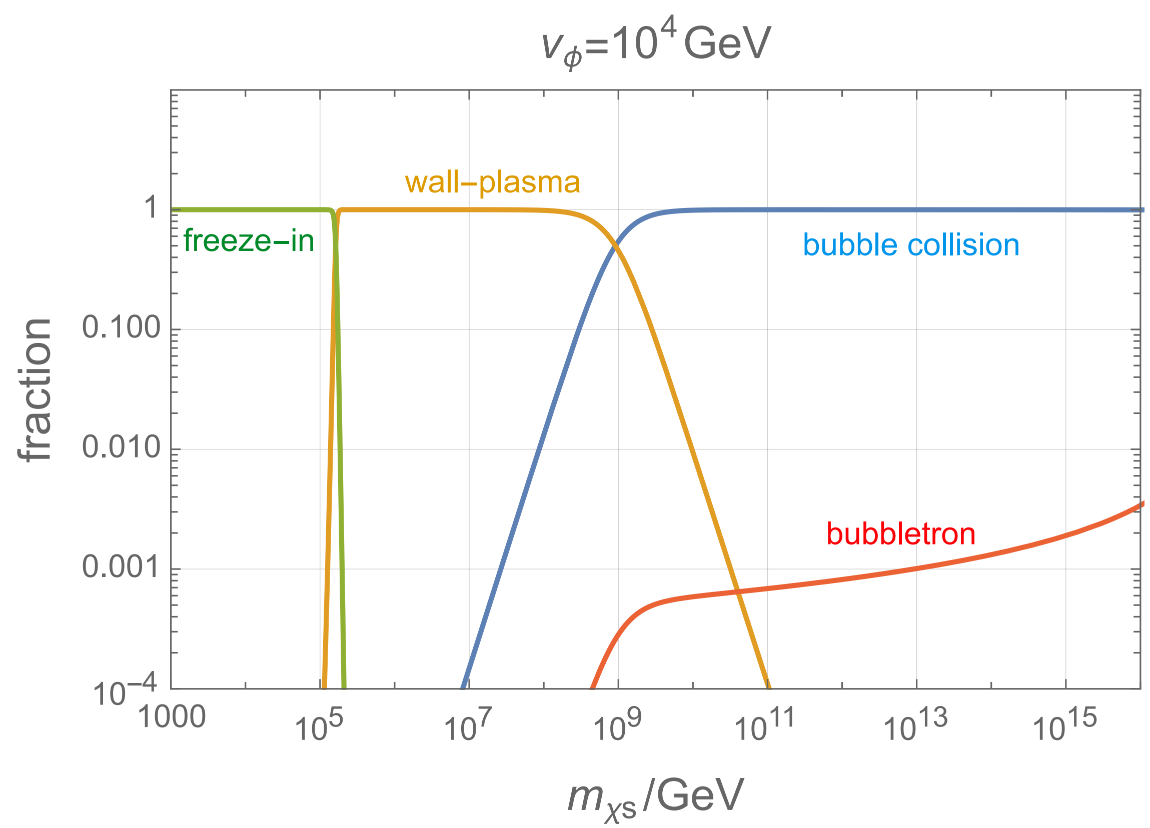
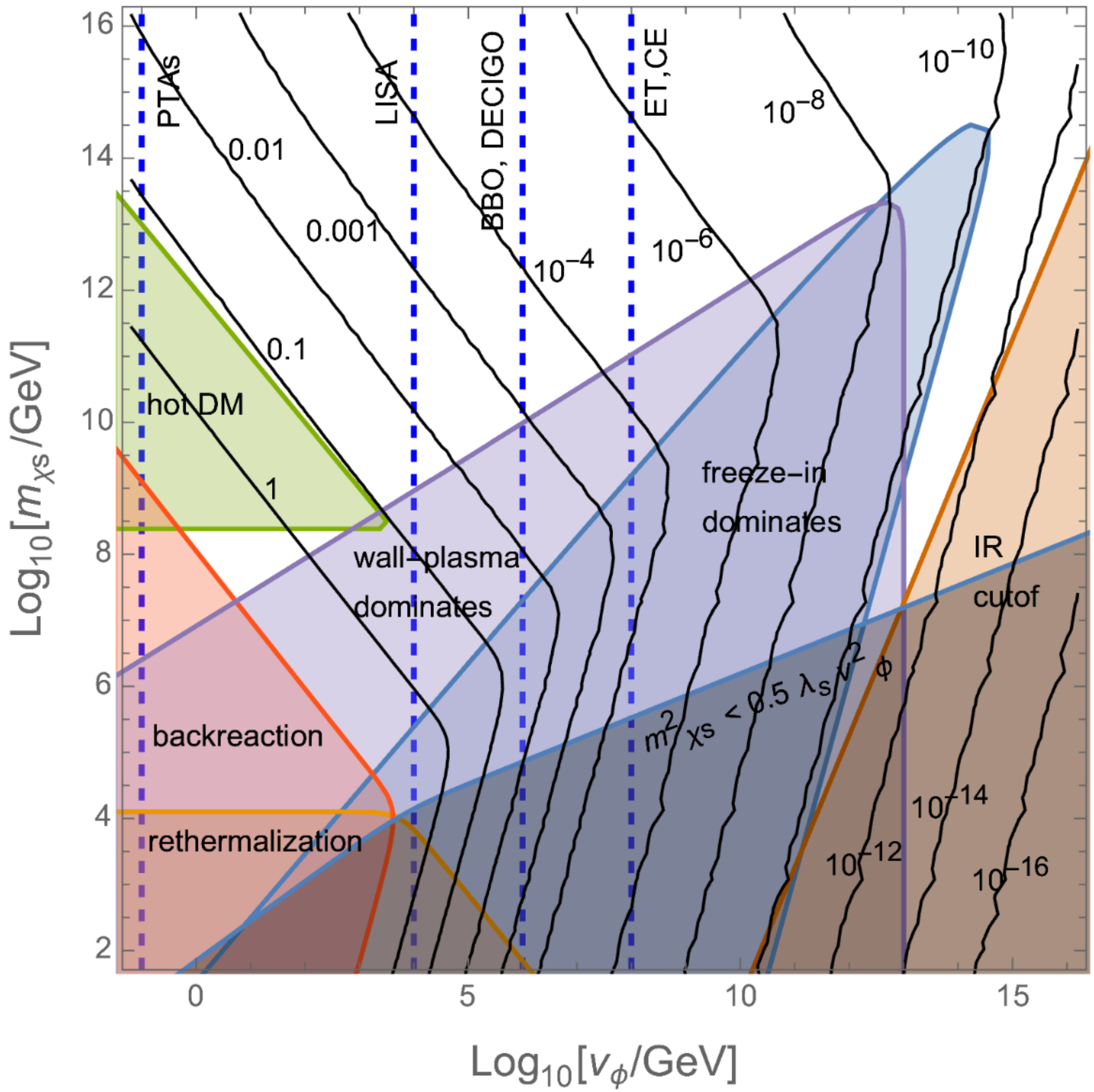


SCALAR DARK MATTER PARAMETER SPACE

GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252



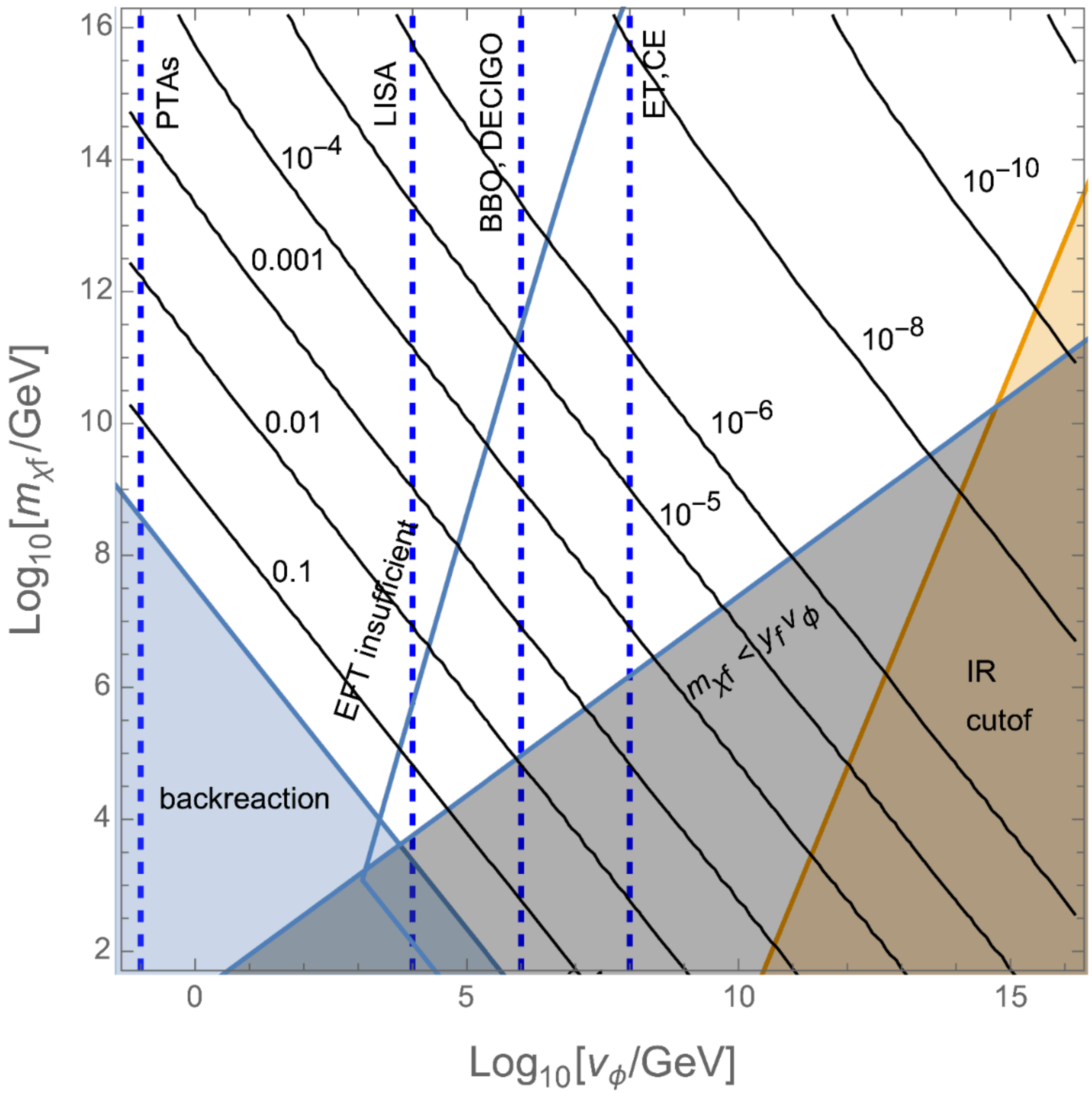
Contours:

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

FERMION DARK MATTER

GIUDICE, LEE, POMAROL, SHAKYA, 2403.03252

Fermion DM χ_f, with mass m_{χ_f} and effective interaction $y_f \phi \chi_f \bar{\chi}_f$



Contours:

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

PHENOMENOLOGY

Gravitational waves:

Experiment	$f_{optimal}/\mathbf{Hz}$	$v_\phi/\mathbf{GeV}$	$m_{\mathrm{DM}}/\mathrm{GeV}$
Pulsar Timing Arrays (PTAs) [107]	10^{-8}	0.1	$10^{13} - 10^{16}$
LISA [108]	0.001	10^4	$10^6 - 10^{15}$
BBO [109], DECIGO [110]	0.1	10^6	$10^5 - 10^{13}$
Einstein Telescope (ET) [111], Cosmic Explorer (CE) [112]	10	10^8	$10^6 - 10^{10}$

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Suppressed matter power spectrum:

Bubble collisions produce **DM with large boosts -> long free-streaming lengths**. **suppressed matter power spectrum** that could provide measurable effects for future cosmological observations?

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Bubble collisions produce **DM with large boosts -> long free-streaming lengths**. **suppressed matter power spectrum** that could provide measurable effects for future cosmological observations?

Gravitational interactions:

Possible to produce **ultraheavy DM** close to the Planck scale; for such massive particles, **individual gravitational interactions might be detectable** (e.g. Windchime project)

APPLICATION II: MATTER–ANTIMATTER ASYMMETRY

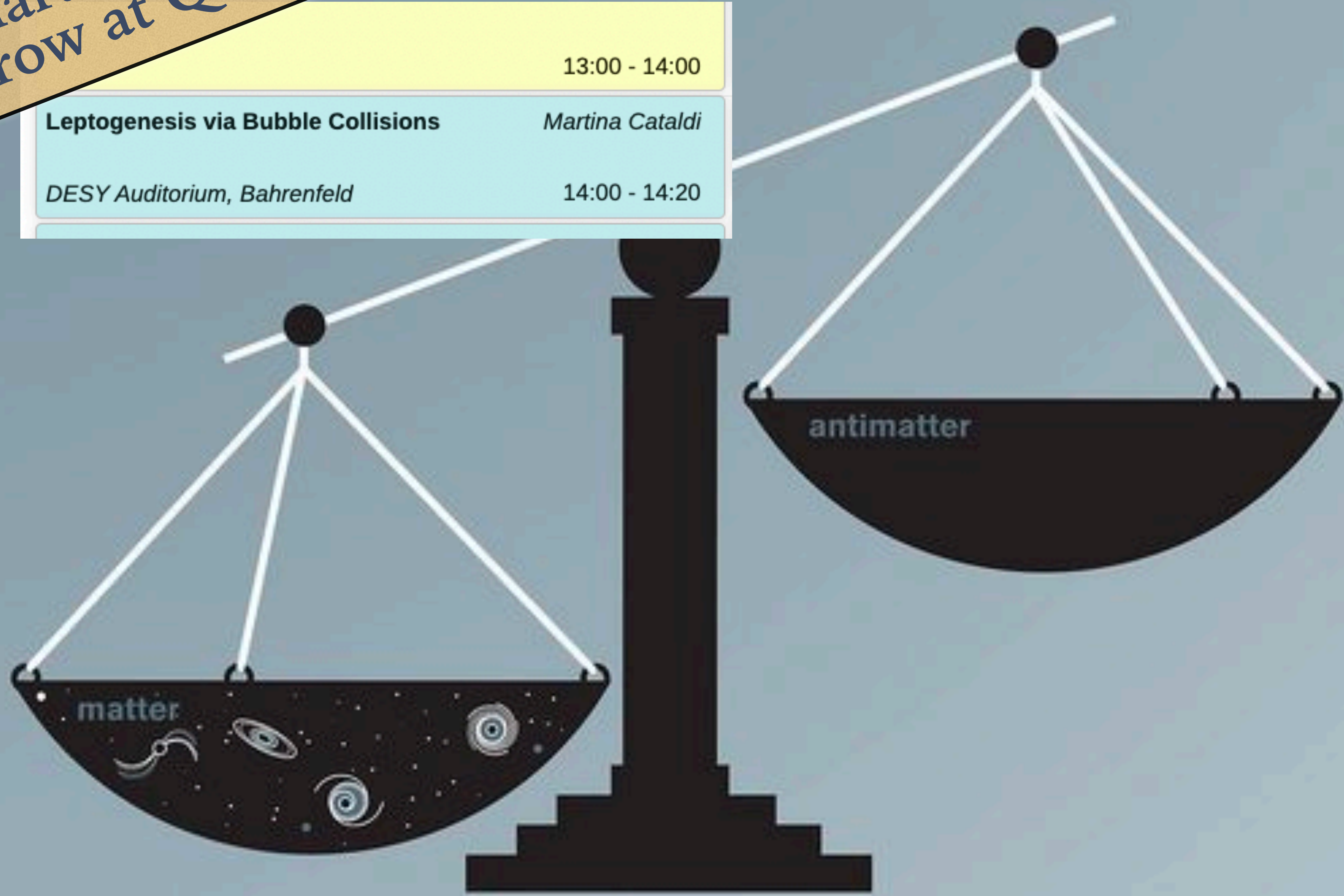
CATALDI, SHAKYA, 2406.XXXXX

See Martina's talk tomorrow at QU day

13:00 - 14:00

Leptogenesis via Bubble Collisions *Martina Cataldi*

DESY Auditorium, Bahrenfeld 14:00 - 14:20



FUTURE DIRECTIONS

- **Can such particle production affect GW signals from bubble collisions?**
  (work in progress w/ Keisuke Inomata, Marc Kamionkowski, Kentaro Kasai)
- Study cosmological/ astrophysical properties of dark matter produced from bubble collisions
- **Improved numerical studies of the collision process**
- How to make the formalism gauge invariant?
- **Applications to BSM setups (probe GUT physics?)**
- **…**

SUMMARY

ULTRA-HIGH-ENERGY PARTICLES FROM VACUUM DECAY

- **First order vacuum decay** with **runaway bubbles** can produce the **most energetic configuration to ever exist in our cosmic history**, within a few orders of magnitude of the Planck scale
- Collisions of such bubbles leads to **particle production with ultrahigh mass, energy:** an unavoidable phenomenon.
- Recent work: **Improved conceptual understanding and numerical results,** which show that such ultrahigh processes are only power law suppressed.
- Possible to produce **ultraheavy dark matter** up to 10^{16} GeV from phase transitions at scales as low as sub-GeV
- **Leptogenesis** with heavy right-handed neutrinos $M_N \sim 10^{14}$ GeV

THANK YOU FOR YOUR ATTENTION!