Universität Hamburg
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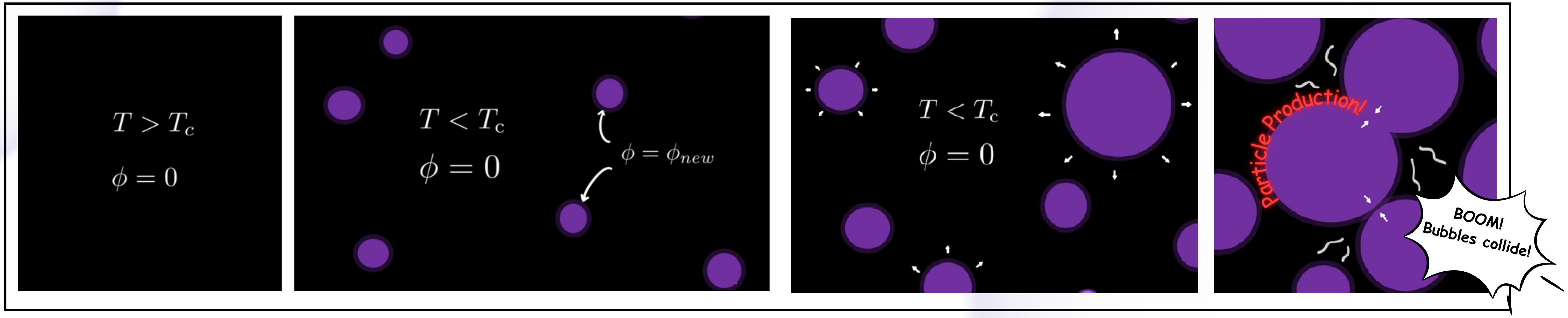
DESY.

KIT
Karlsruher Institut für Technologie

ON PARTICLE PRODUCTION FROM PHASE TRANSITION BUBBLES

HENDA MANSOUR - DESY THEORY WORKSHOP SEPTEMBER 2023

[Based on 2308.13070 in collaboration with Bibhushan Shakya]



MOTIVATION

- Particle production is an essential aspect of first-order phase transitions with interesting implications

- Previous research focuses on wall-plasma interactions or leaves out important details of the field dynamics

Fermi National Accelerator Laboratory

FERMILAB-Pub-91/164-A
June 1991

Aspects of Reheating in First-Order Inflation

Richard Watkins

Department of Astronomy and Astrophysics
Enrico Fermi Institute
The University of Chicago
Chicago, IL 60637 U.S.A.

NASA/Fermilab Astrophysics Center
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, IL 60510 U.S.A.

Lawrence M. Widrow

adian Institute for Theoretical Astrophysics
University of Toronto
60 St. George Street
Toronto, ON M5S 1A1 Canada

Evidently, we can produce particles up to energy γm. If the bubble walls are highly relativistic when they collide, there will be the possibility of producing particles well above the mass of the inflaton.

Non-thermal Dark Matter Production from the Electroweak Phase Transition: Multi-TeV WIMPs and "Baby-Zillas"

Adam Falkowski[a] and Jose M. No[b,c]

Goal:

Perform a numerical study to include aspects of the field evolution previously neglected.

APPROACH

Treat the expanding and colliding bubbles as a scalar background field $\phi(x,t)$ and the fields it is coupled to as quantum fields in the presence of a source.

NUMBER DENSITY PER AREA OF PRODUCED PARTICLES:

$$\frac{\mathcal{N}}{A} = 2\int \frac{dk_x\, dw}{(2\pi)^2} \underbrace{|\tilde{\phi}(k_x, w)|^2}_{\text{Fourier modes with } m^2 = w^2 - k_x^2} \underbrace{\text{Im}\left(\tilde{\Gamma}^{(2)}(w^2 - k_x^2)\right)}_{\text{Decay probability}}$$

[1] R. Watkins, L. Widrow. Aspects of reheating in first order inflation. Nucl. Phys. B, 374:446–468, 1992
[2] Adam Falkowski and Jose M. No., feb 2013.

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DETERMINED BY THE FIELD DYNAMICS

[1] R. Watkins, L. Widrow. Aspects of reheating in first order inflation. Nucl. Phys. B, 374:446–468, 1992
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DETERMINED BY THE FIELD DYNAMICS

DETERMINED BY THE INTERACTION LAGRANGIAN (PERTURBATIVE)

[1] R. Watkins, L. Widrow. Aspects of reheating in first order inflation. Nucl. Phys. B, 374:446–468, 1992

[2] Adam Falkowski and Jose M. No., feb 2013.

MODELLING THE DYNAMICS

TOY MODEL

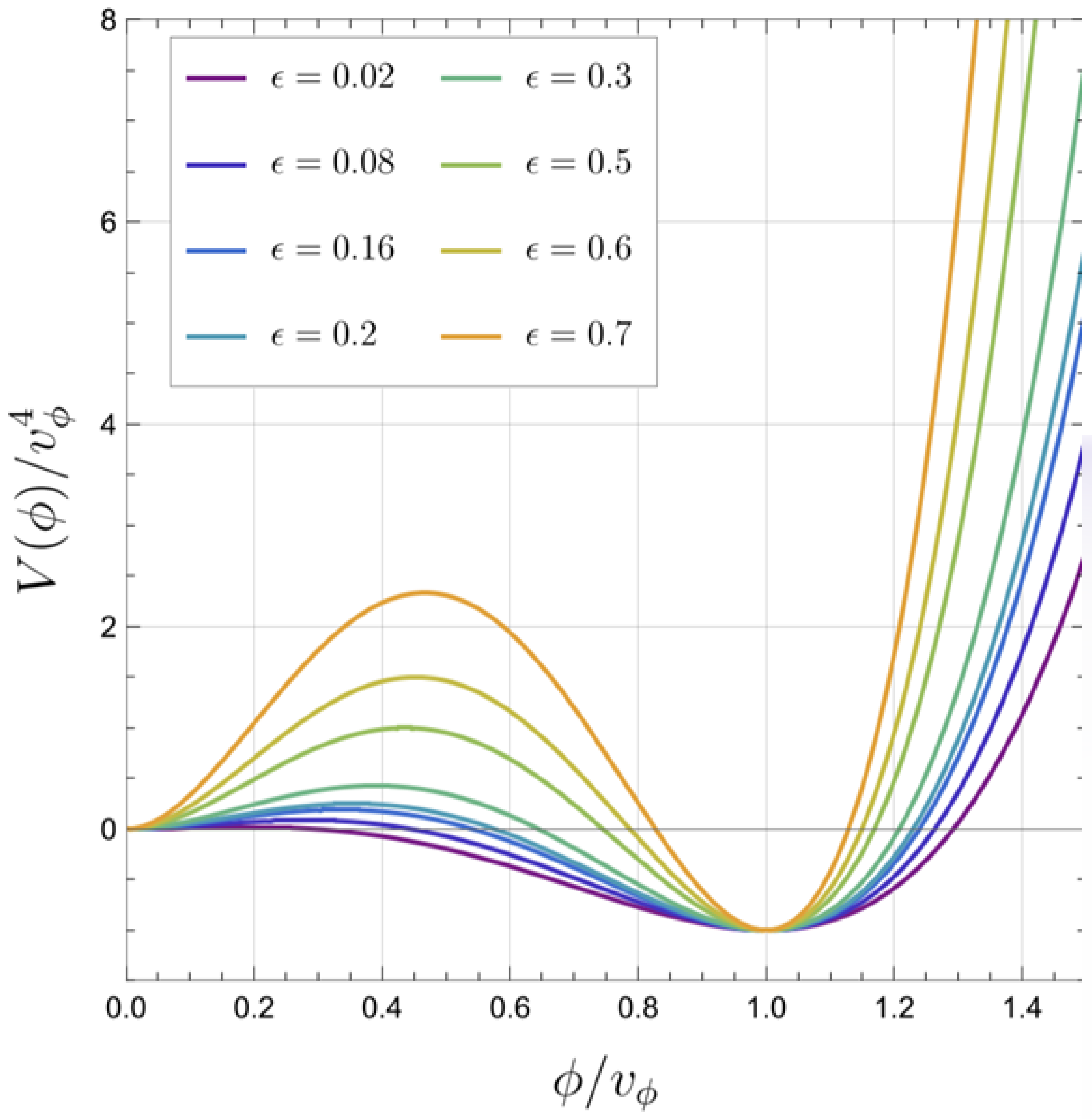
Real scalar potential with two non-degenerate minima:

$$V(\phi) = a v_\phi^2 \phi^2 - (2a+4) v_\phi \phi^3 + (a+3)\phi^4$$

The barrier height between the two minima is parameterised by:

$$\epsilon \equiv \frac{V_{max} - V(\phi = 0)}{V_{max} - V(\phi = v_\phi)} = \frac{a^3(a+4)}{a^3(a+4) + 16(a+3)^3}$$

We consider planar ultra-relativistic bubble walls.



[R.Jinno, T. Konstandin, and M.Takimoto. sep 2019 , ArXiv: 1906.02588]

FIELD DYNAMICS I

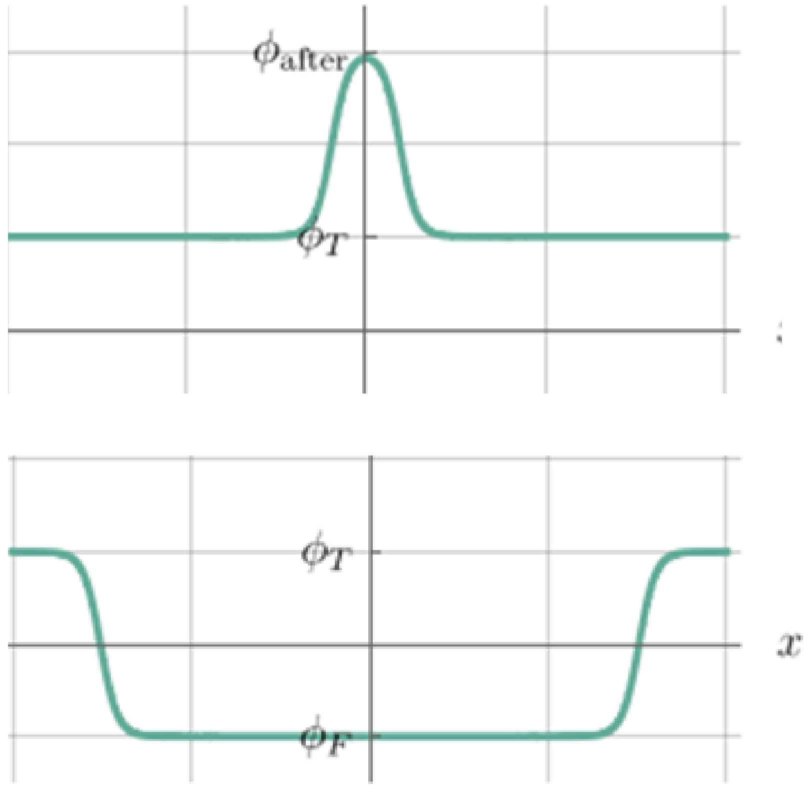
time

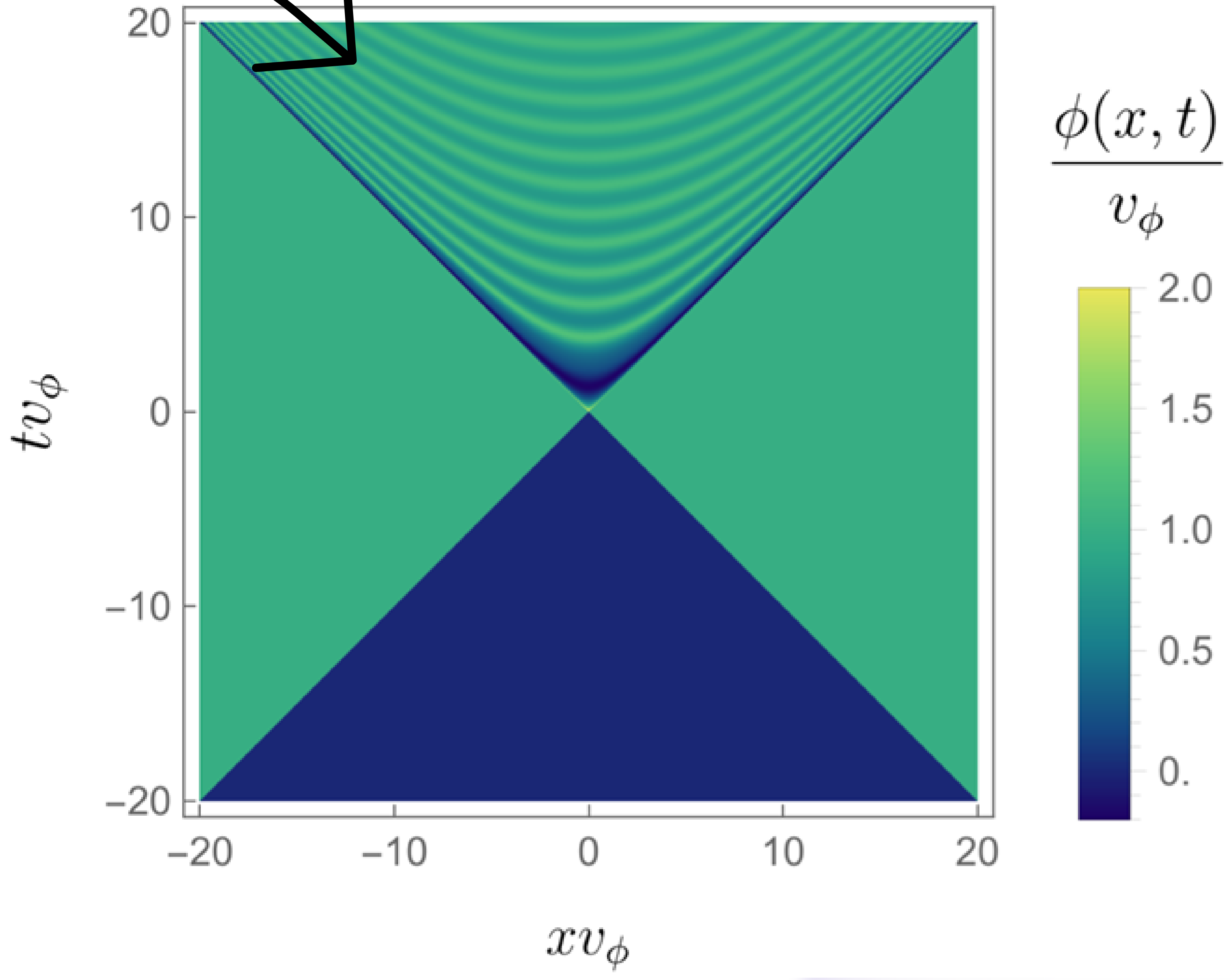
Numerically solve:

$$\partial_s^2\phi + \frac{1}{s}\partial_s\phi + \frac{dV}{d\phi} = 0$$

with $s = \sqrt{t^2 - x^2}$

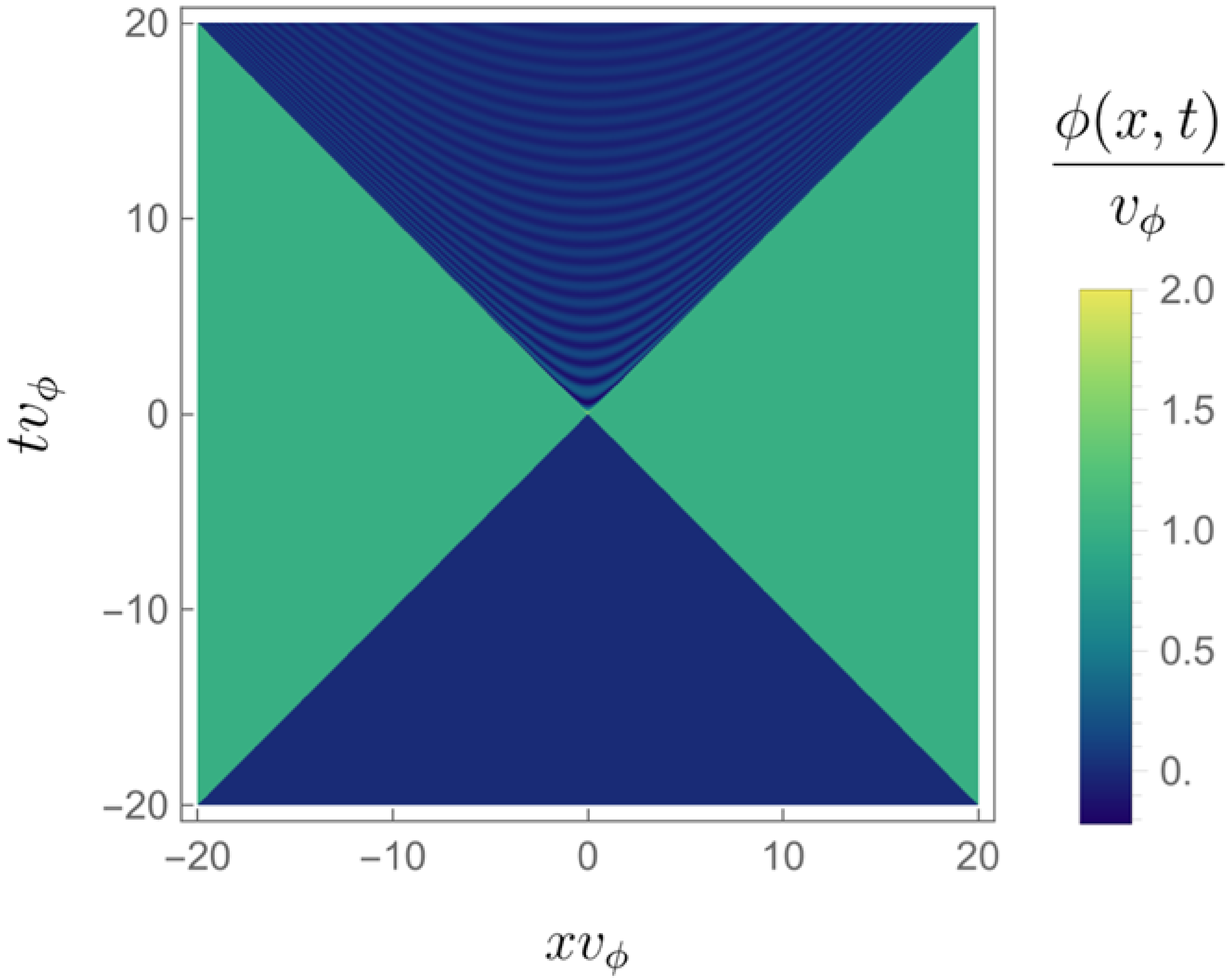
$t_{\mathrm{collision}}$





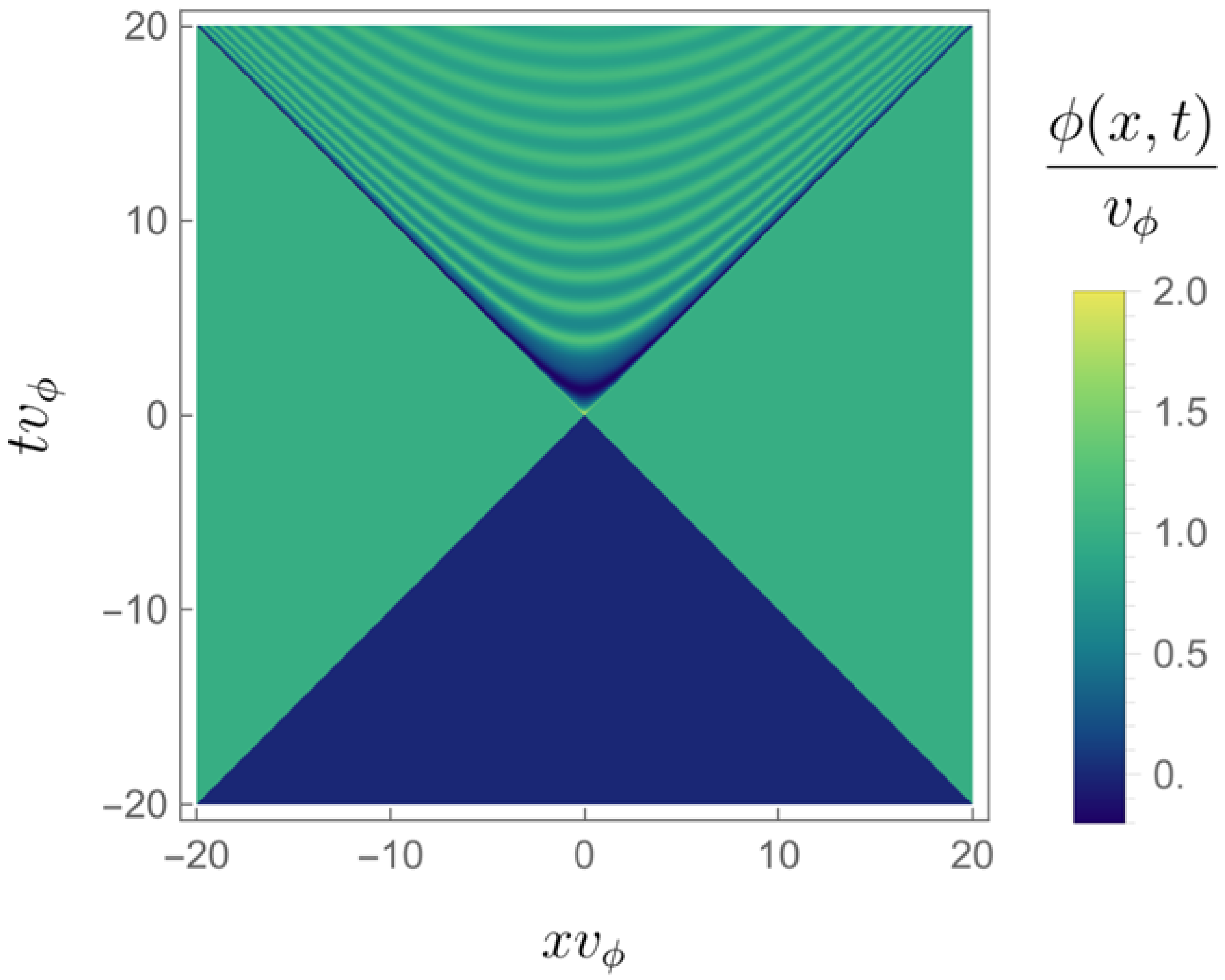
[R.Jinno, T. Konstandin, and M.Takimoto. sep 2019 , ArXiv: 1906.02588]

FIELD DYNAMICS II



ELASTIC COLLISIONS

The field oscillates around the false minimum



INELASTIC COLLISIONS

The field oscillates around the true minimum

PARTICLE PRODUCTION

EFFICIENCY FACTOR

NUMBER DENSITY OF PRODUCED PARTICLES PER AREA:

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

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$$\chi = \omega^2 - k^2 \quad \xi = \omega^2 + k^2$$

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$$\chi = \omega^2 - k^2 \quad \xi = \omega^2 + k^2$$

$$\frac{\mathcal{N}}{A} = \frac{1}{4\pi^2} \int_{\chi_{min}}^{\infty} d\chi\, f(\chi)\, \mathrm{Im}[\tilde{\Gamma}^{(2)}(\chi)]$$

$f(\chi)$ represents the efficiency factor for particle production at the given scale χ.

[1] R. Watkins, L. Widrow. Aspects of reheating in first order inflation. Nucl. Phys. B, 374:446–468, 1992
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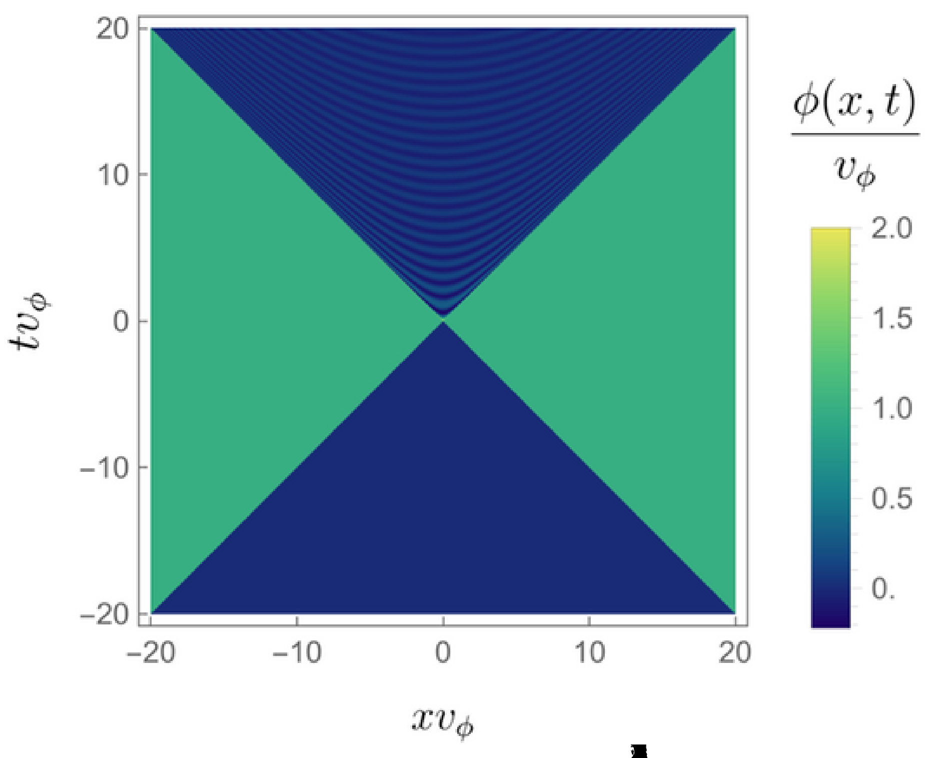
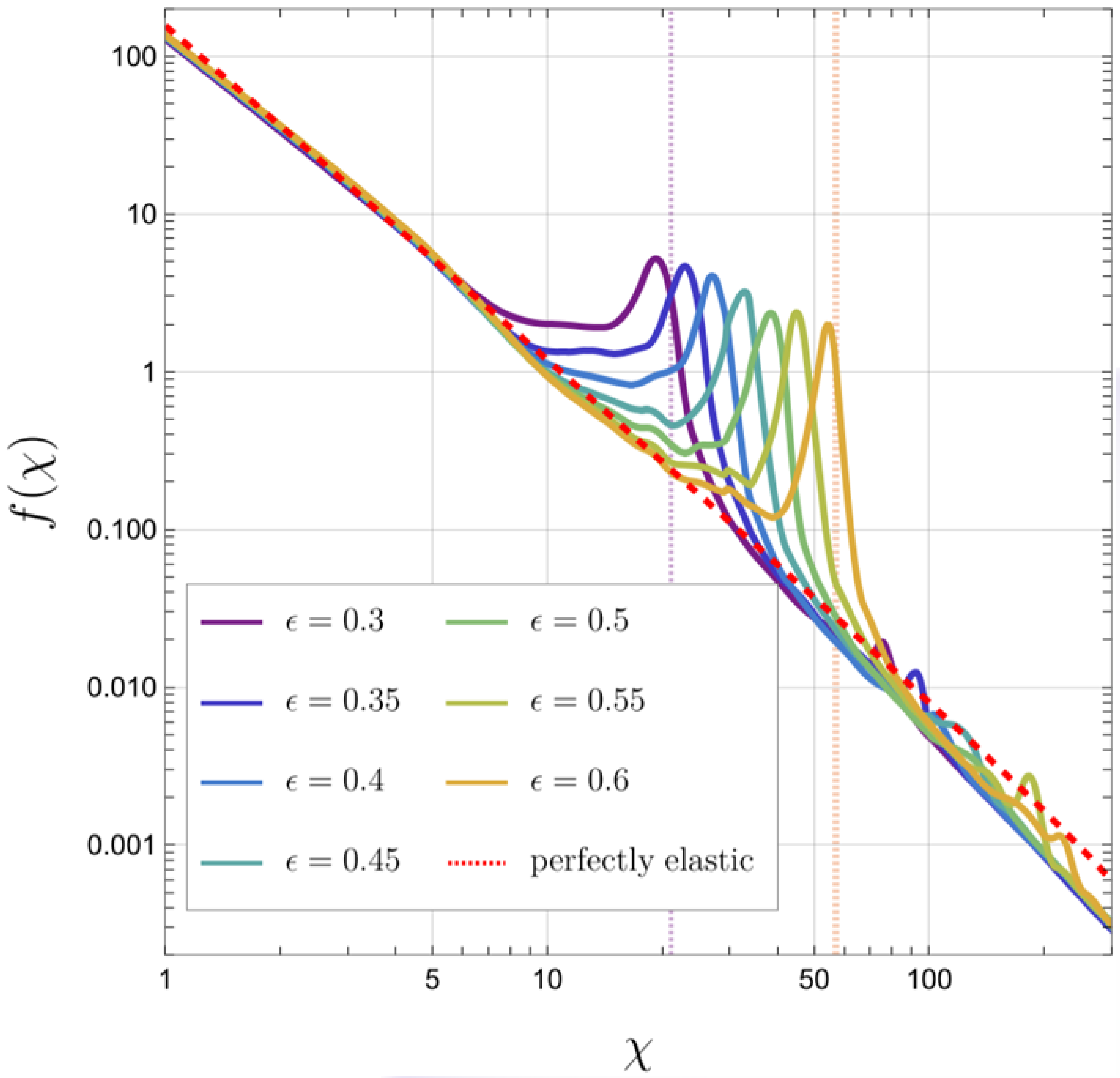
RESULTS: EFFICIENCY FACTOR

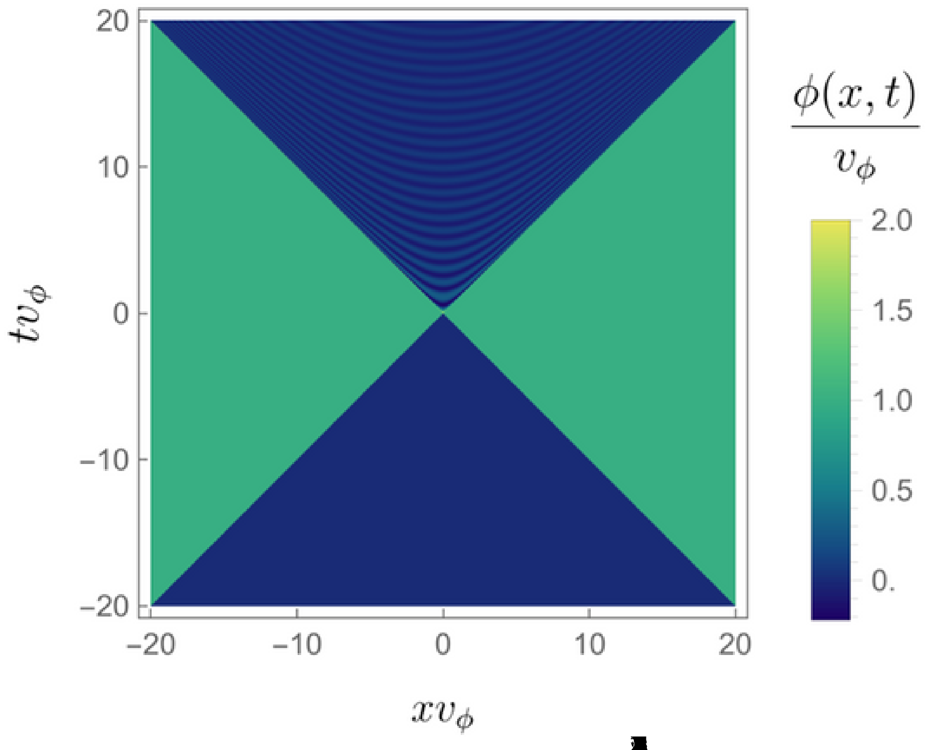
ELASTIC COLLISIONS

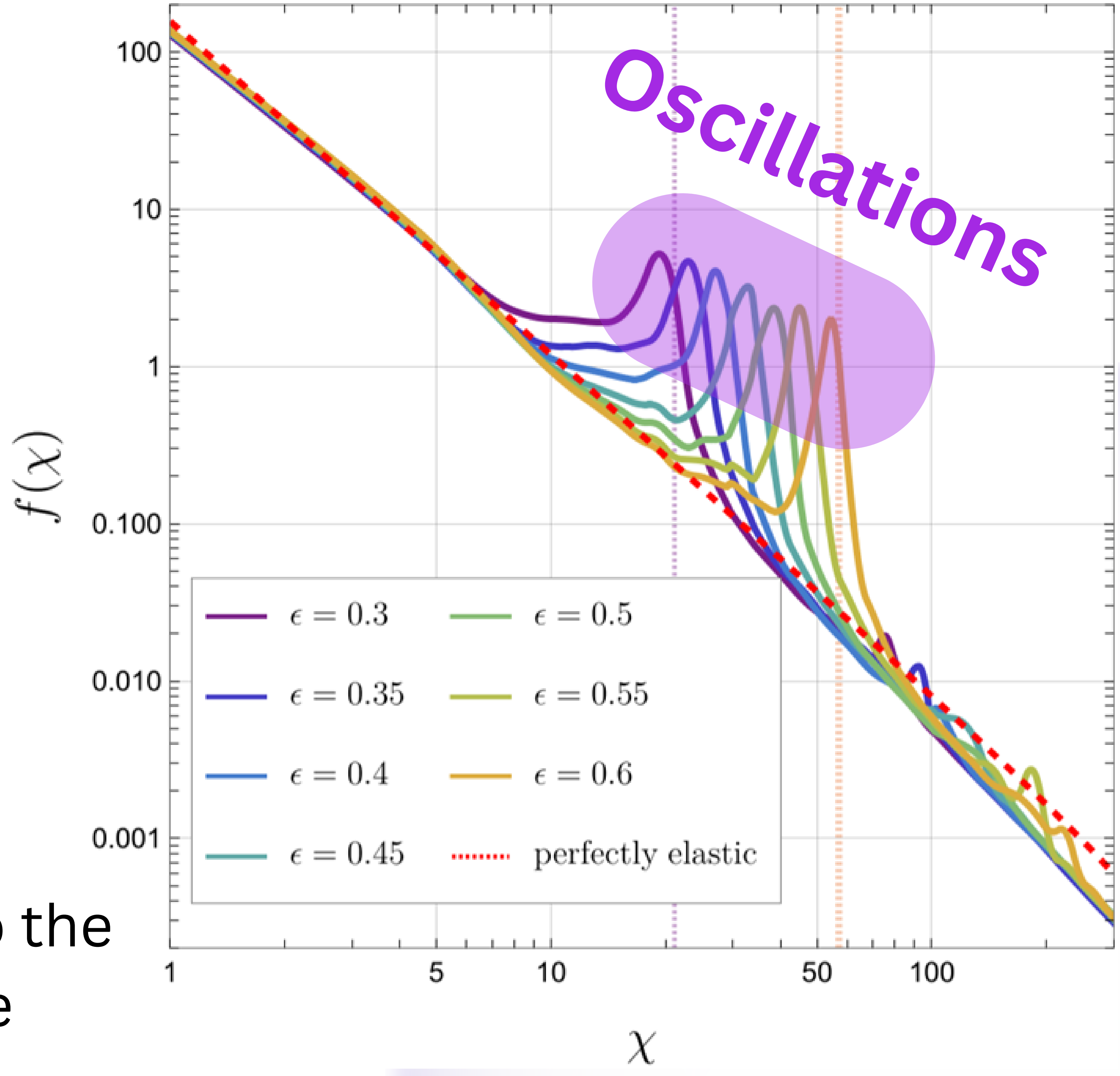




RESULTS: EFFICIENCY FACTOR

ELASTIC COLLISIONS

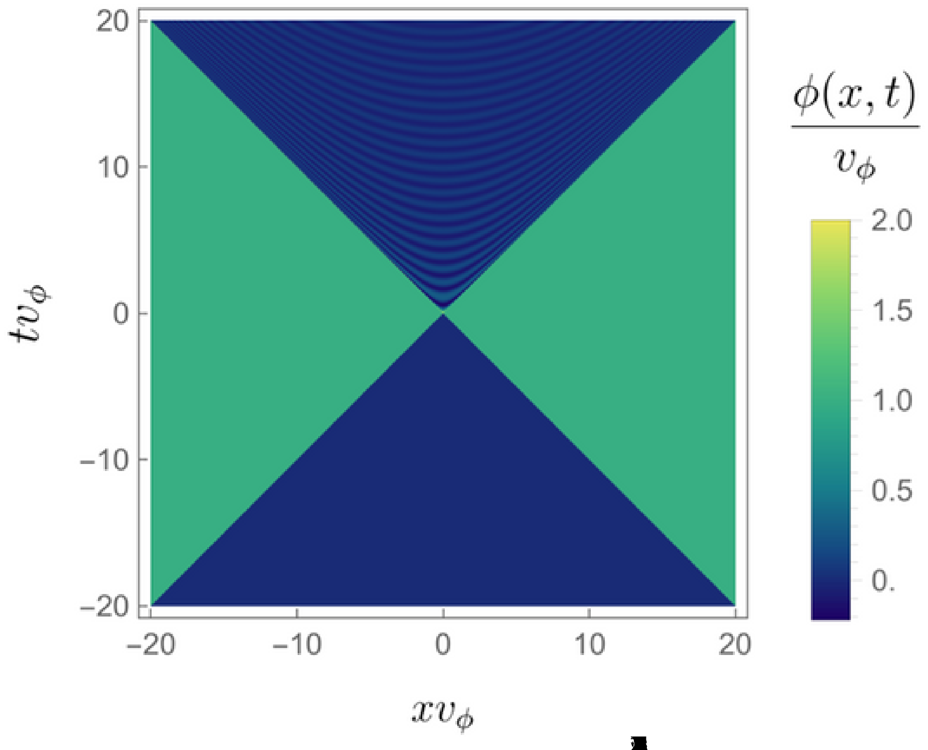




- Peaks at mass scales corresponding to the effective mass of the scalar field in the false vacuum

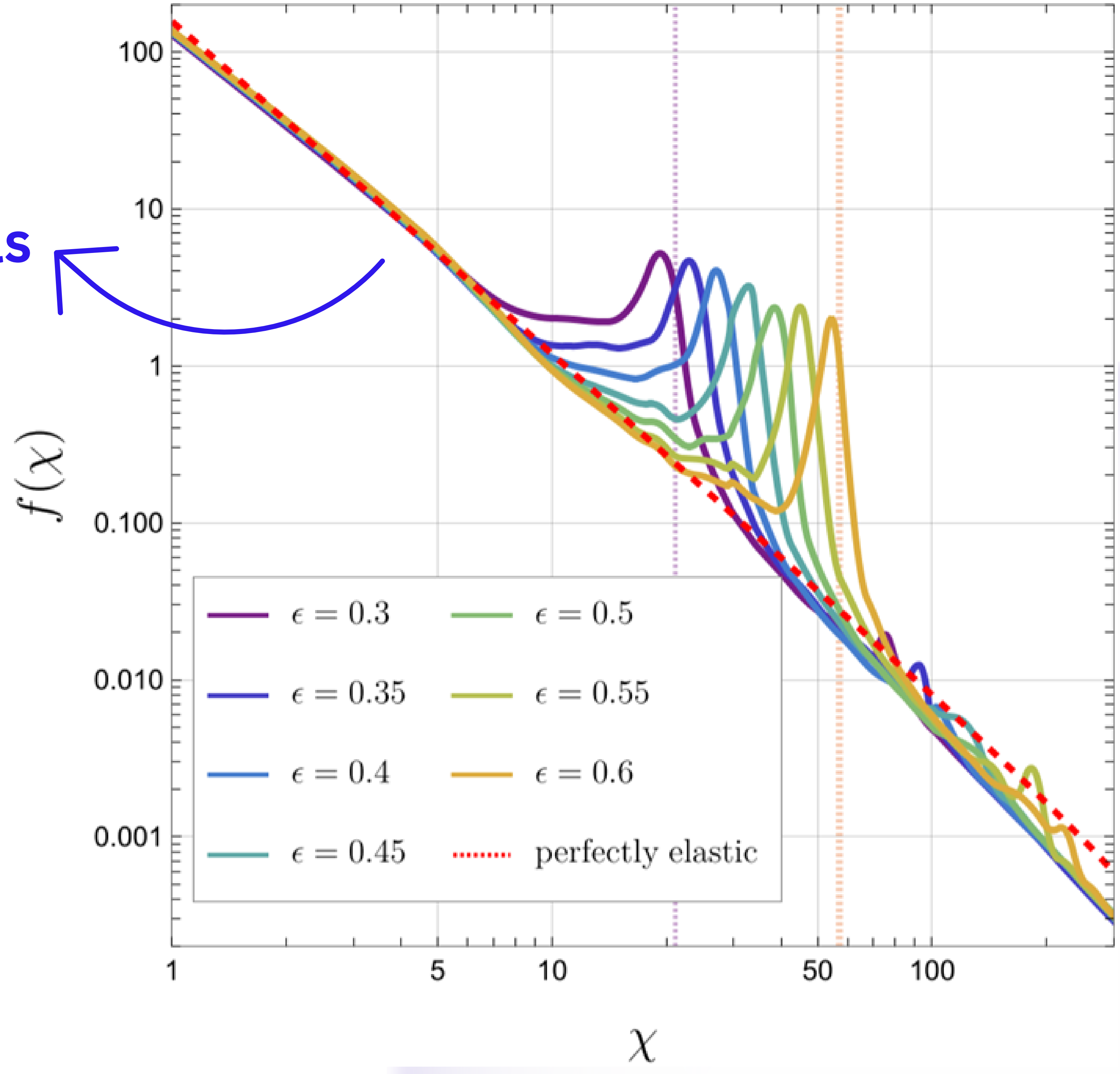
RESULTS: EFFICIENCY FACTOR

ELASTIC COLLISIONS



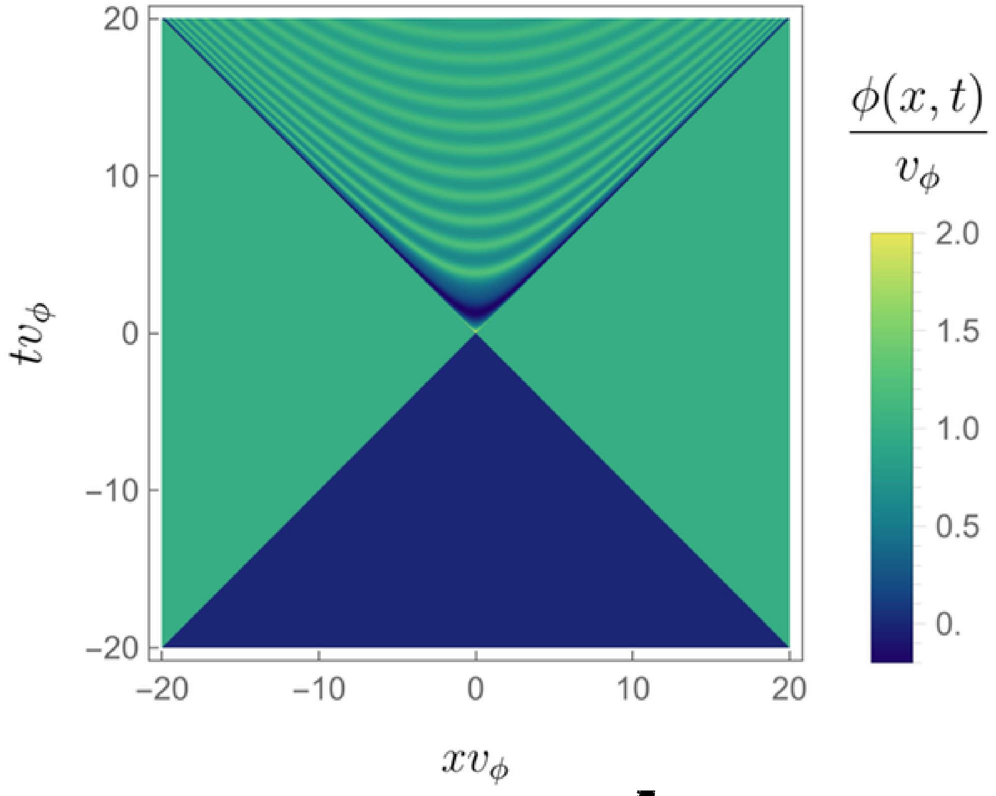
Power law

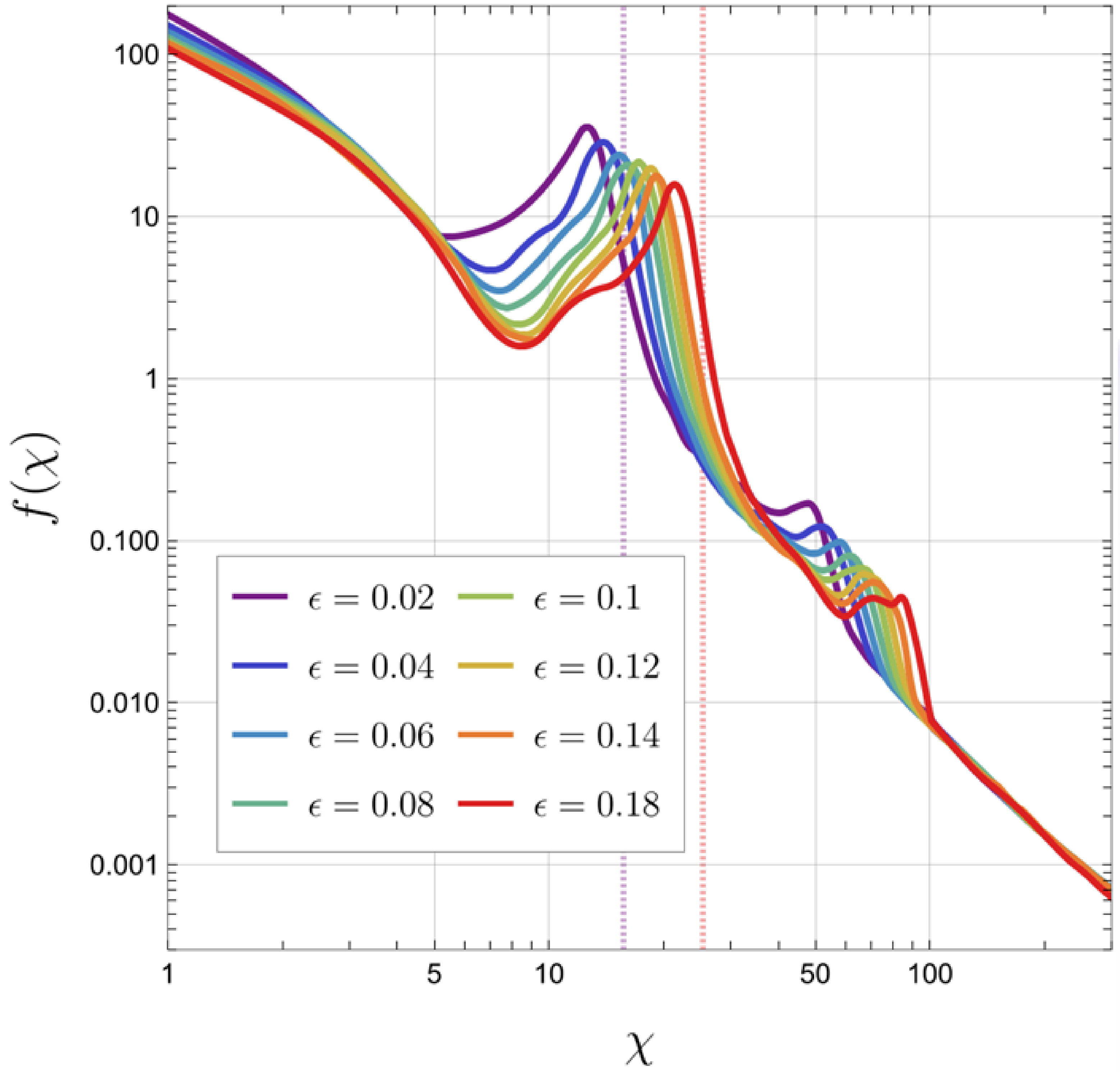
Propagating walls



RESULTS: EFFICIENCY FACTOR

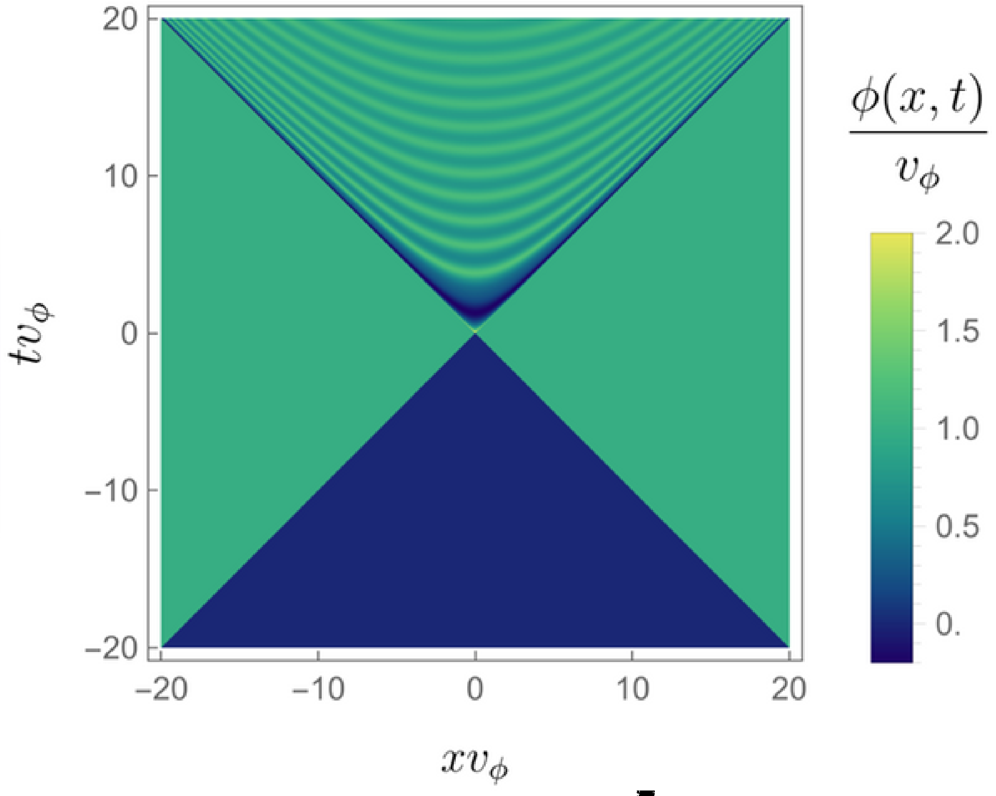
INELASTIC COLLISIONS





RESULTS: EFFICIENCY FACTOR

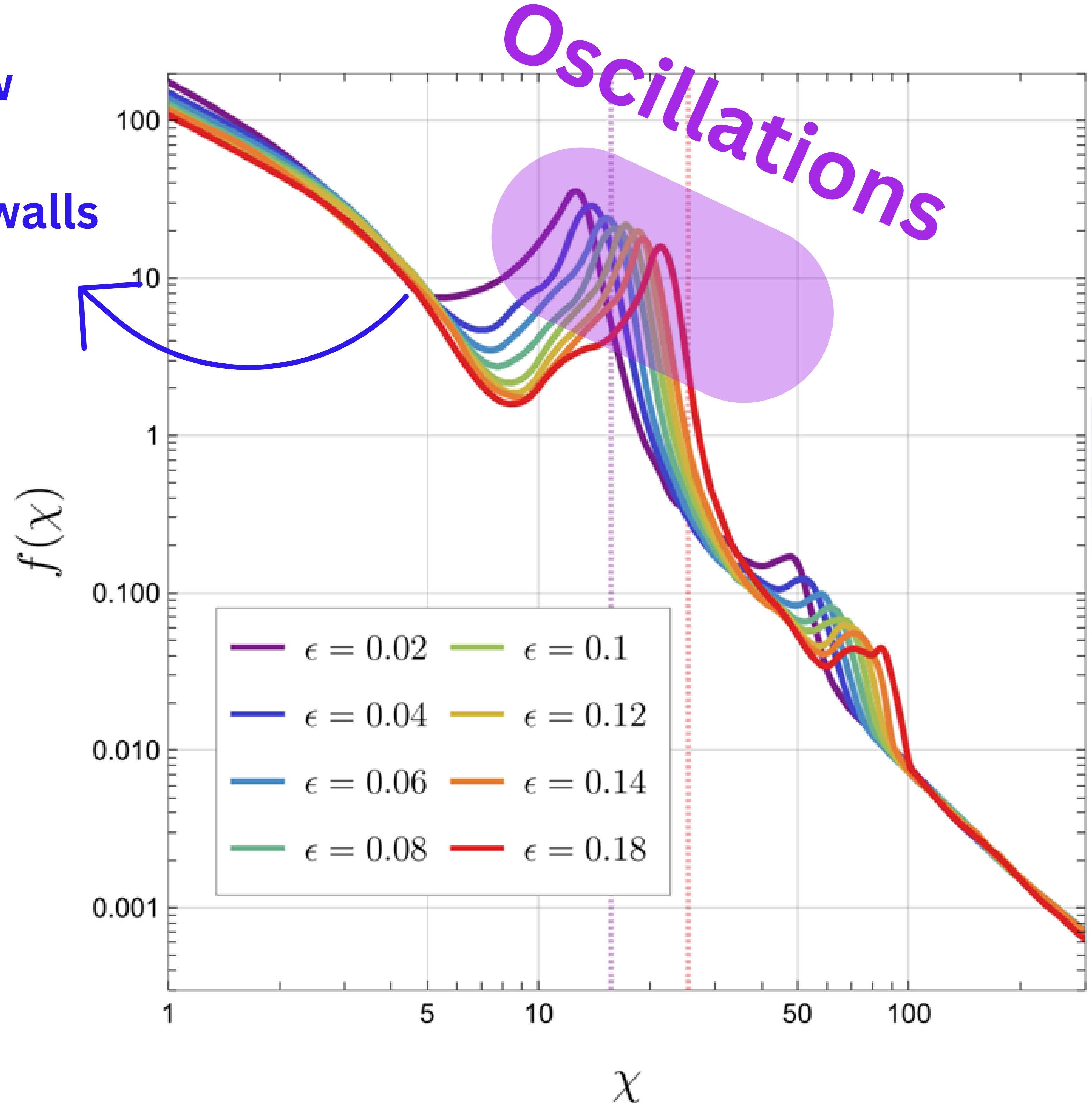
INELASTIC COLLISIONS



Power law

↕

Propagating walls



- Peaks at mass scales corresponding to the effective mass of the scalar field in the true vacuum.

RESULTS: FIT FUNCTIONS

The main features of $f(\chi)$ can be incapsulated in the following fit functions:

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

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

Power law

with $$f_{\text{PE}}(\chi) = \frac{16 v_\phi^2}{\chi^2} \text{Log}\left[\frac{2(\gamma_w/l_w)^2 - \chi + 2(\gamma_w/l_w)\sqrt{(\gamma_w/l_w)^2 - \chi}}{\chi}\right] \Theta[(\gamma_w/l_w)^2 - \chi]$$

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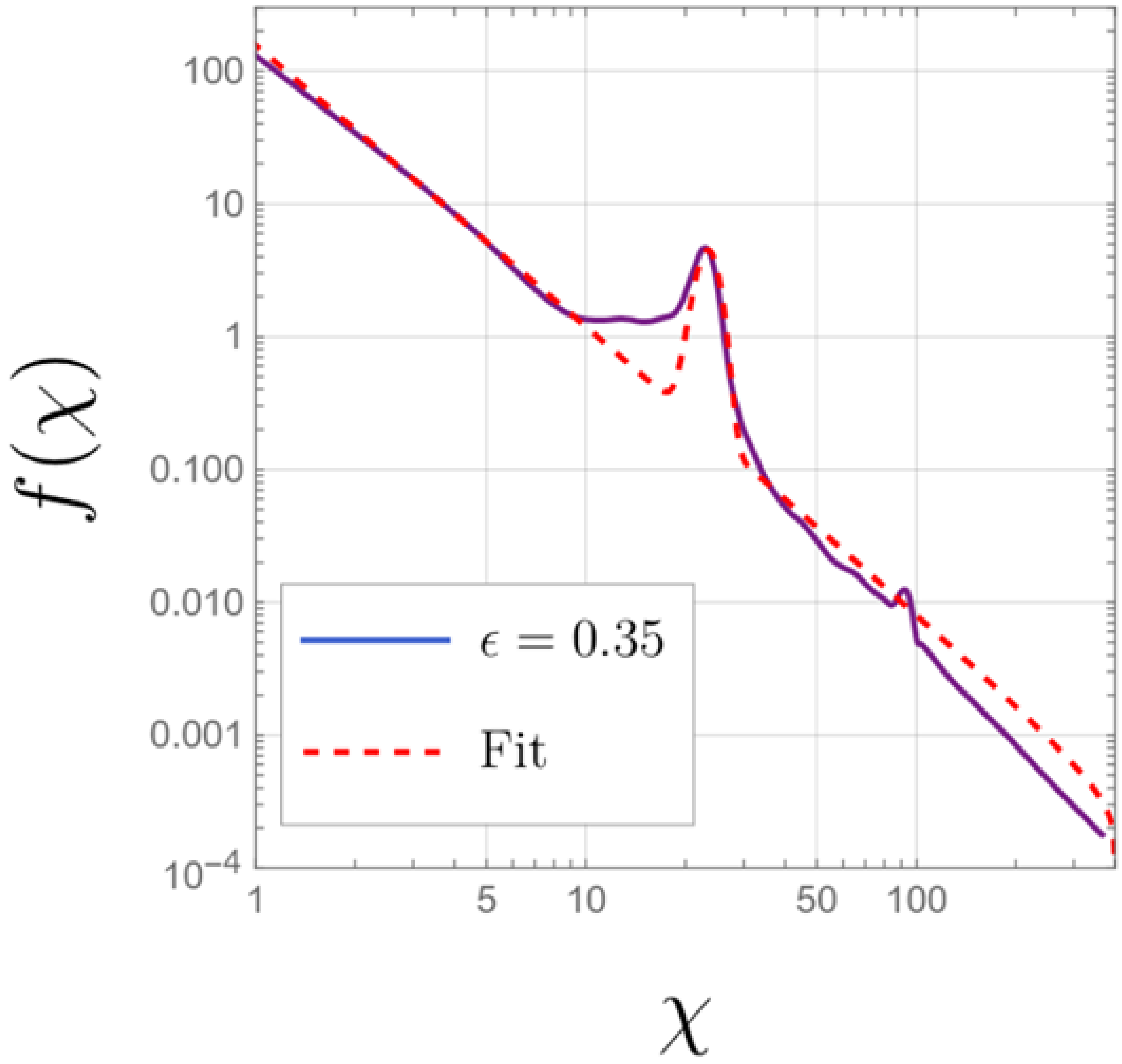
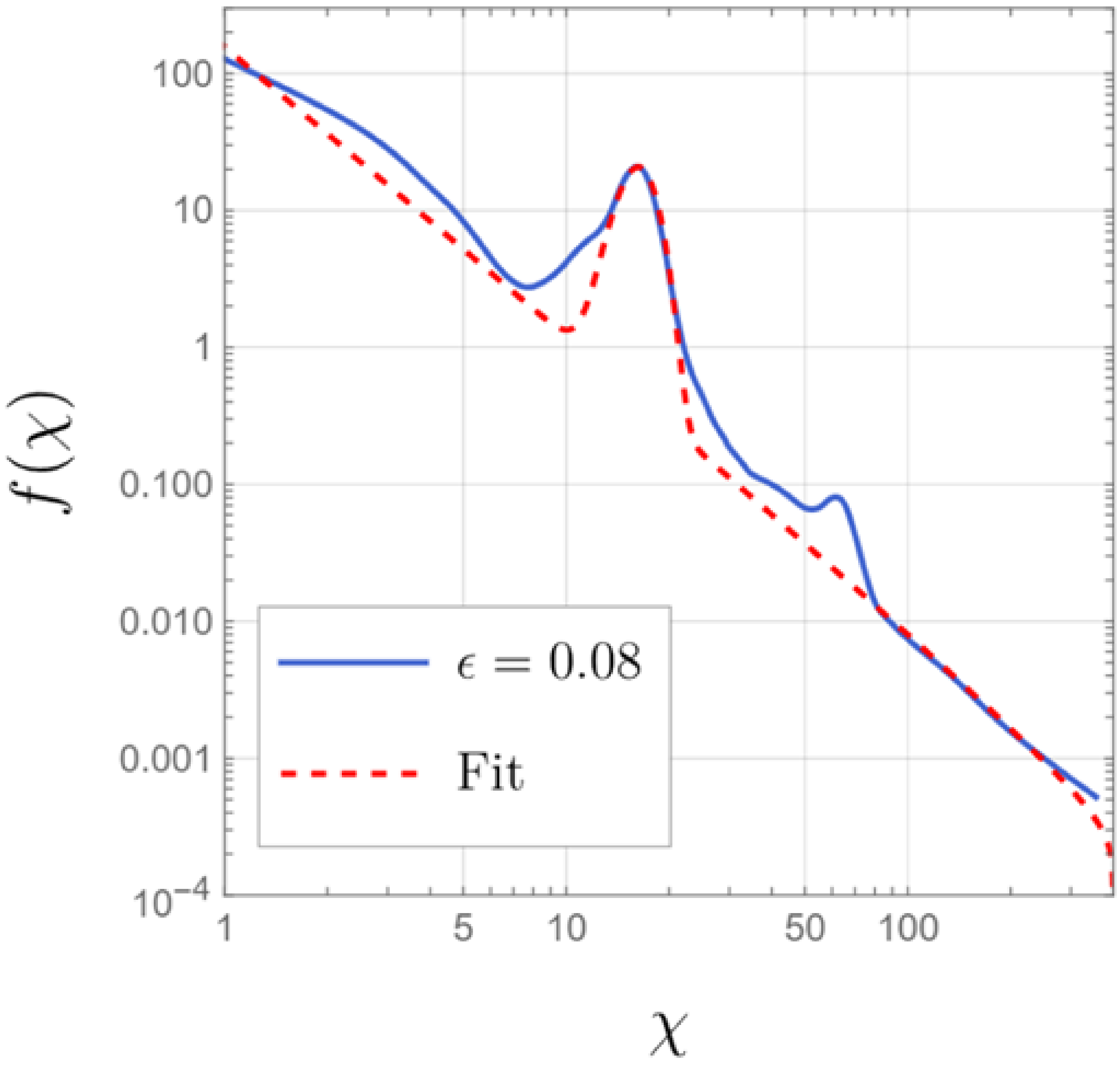
RESULTS: FIT FUNCTIONS

ELASTIC COLLISIONS



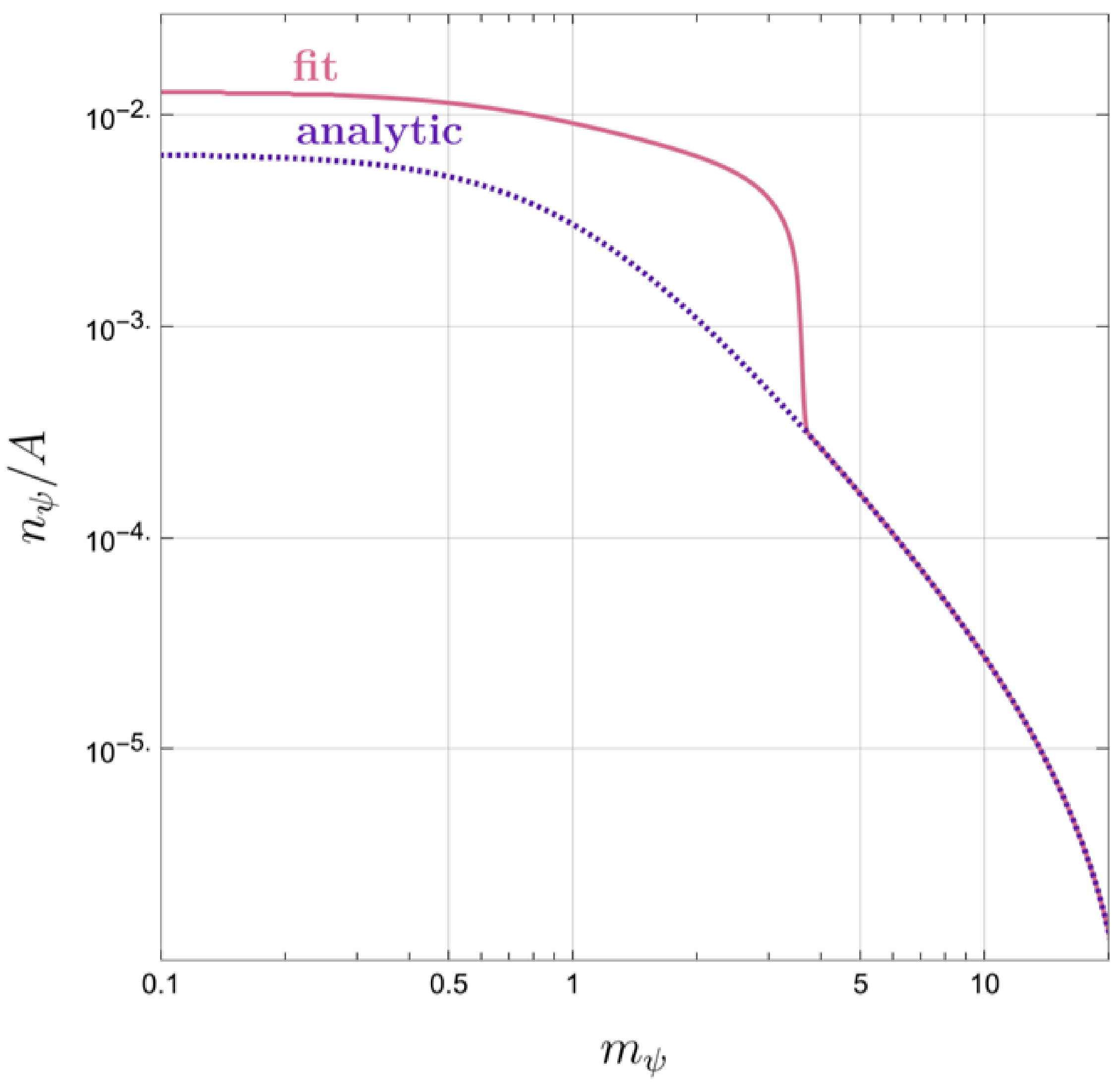
INELASTIC COLLISIONS



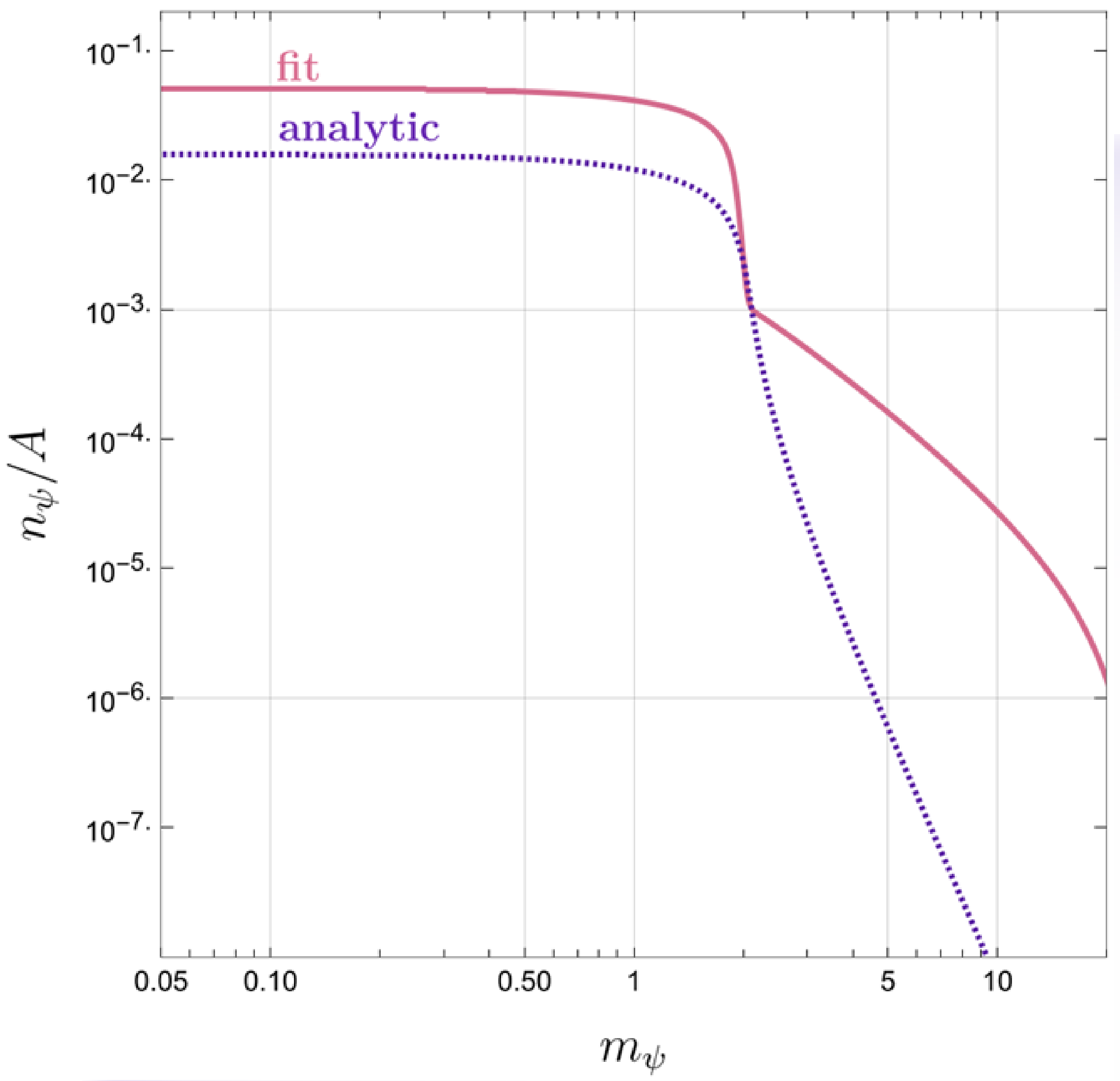
NUMBER DENSITIES

Simple example:
Interaction with
a scalar: $\frac{1}{2}\lambda v_\phi \phi \psi^2$

ELASTIC COLLISIONS



INELASTIC COLLISIONS



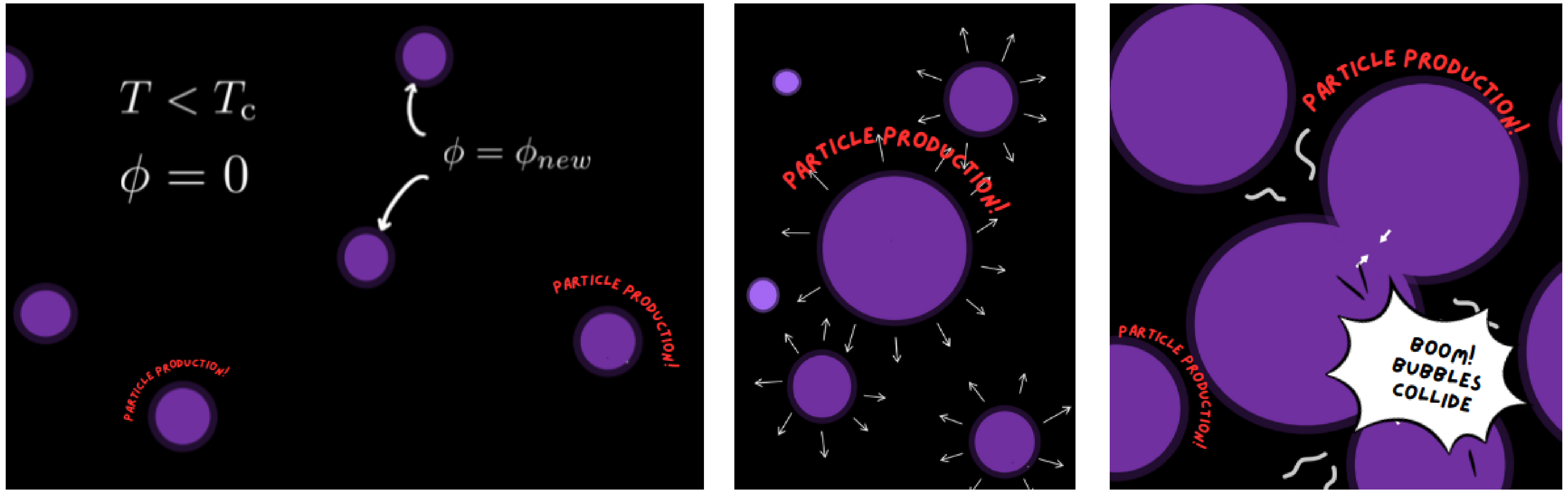
CONCLUSIONS

- Boosted bubbles can be an efficient source of heavy particles.
- Possible backreaction on bubble wall dynamics.

- Particle production is the result of the changing scalar background field

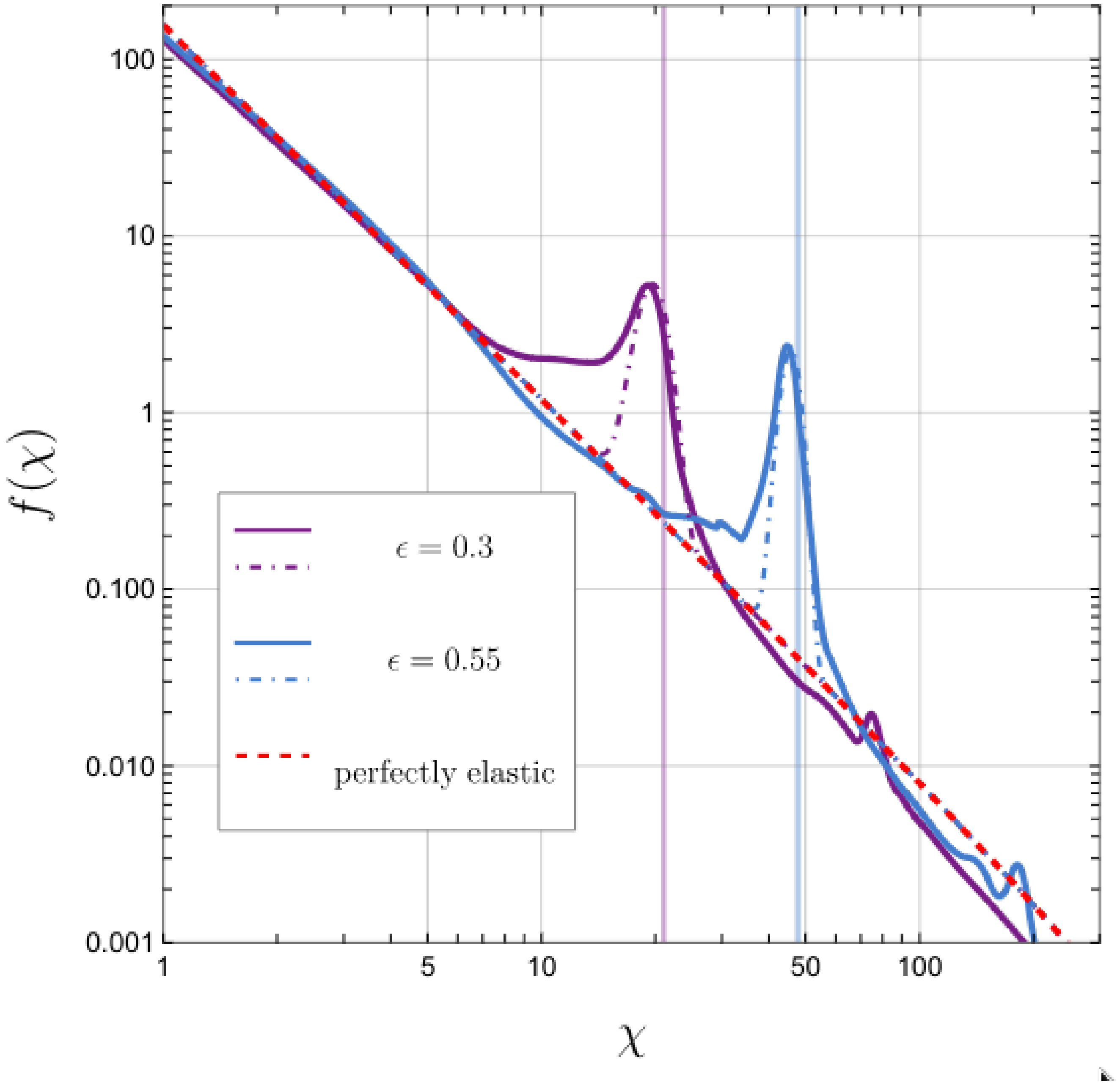
  All phases of the evolution contribute to the production of particles.

  (See Bibhushan’s paper for more details on this, arXiv:2308.16224)

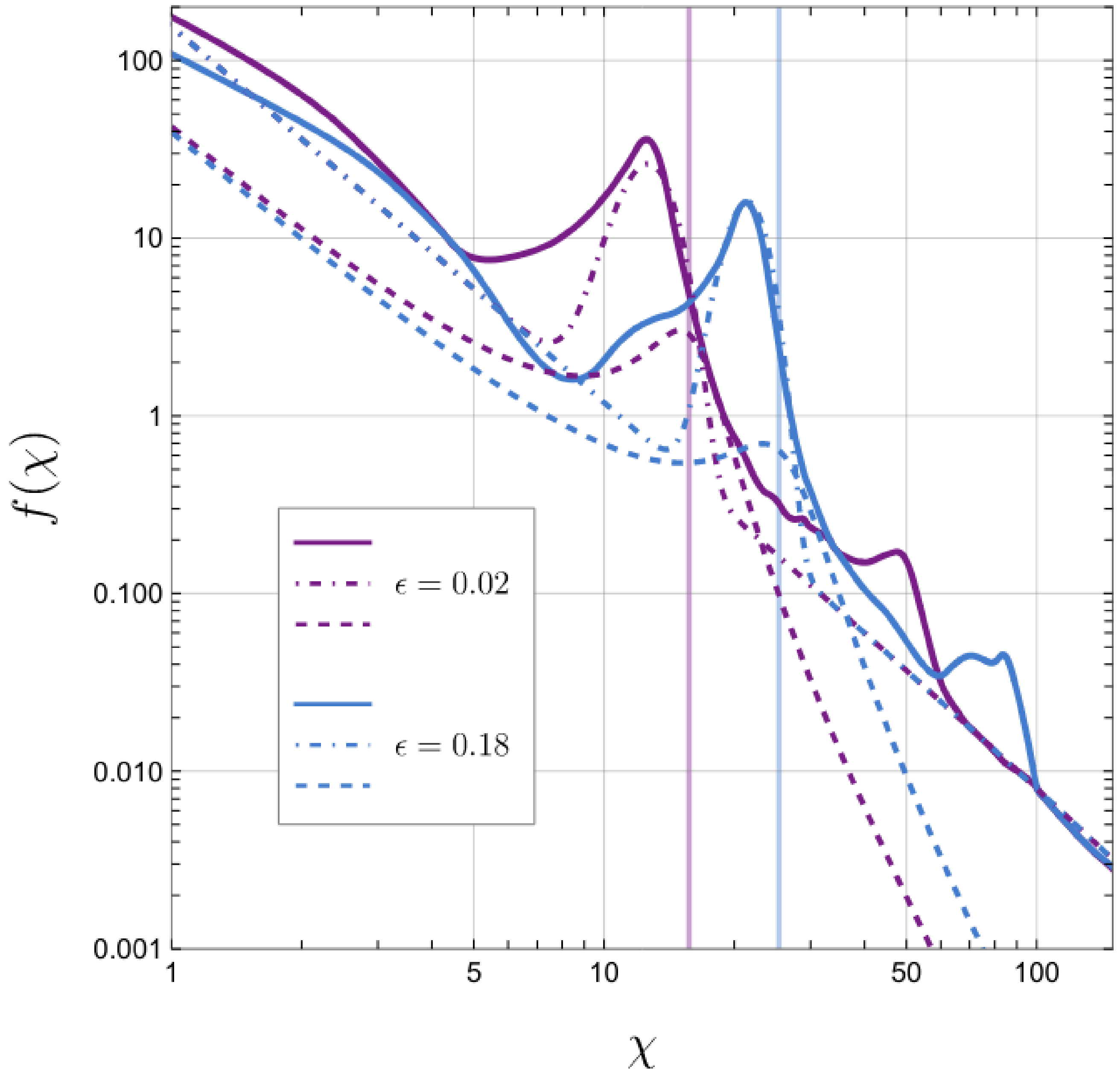


Thank you for your attention!
Questions?

BACK-UP

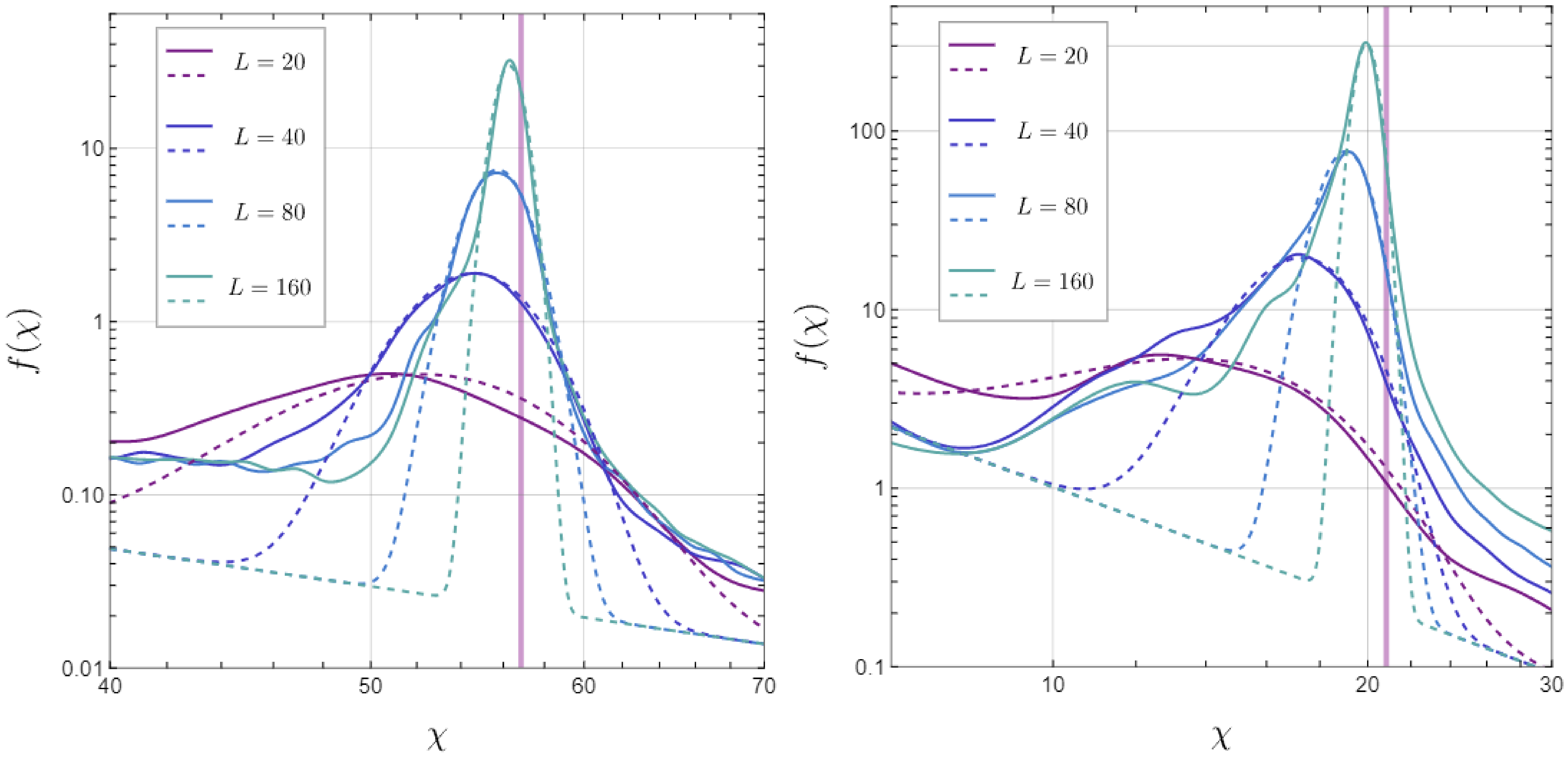


$\epsilon = 0.3$
$\epsilon = 0.55$
perfectly elastic
$f(\chi)$
χ



$\epsilon = 0.02$
$\epsilon = 0.18$
$f(\chi)$
χ

BACK-UP



(a) elastic cases ($\epsilon = 0.6$)

(b) inelastic cases ($\epsilon = 0.1$)