FACULTY OF PHYSICS

MATEUSZ ZYCH

UNIVERSITY OF WARSAW

Supervisor: dr hab. Marek Lewicki

BUBBLE WALL VELOCITY FROM HYDRODYNAMICS

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PARTICLE ASTROPHYSICS IN POLAND

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THE SPECTRUM OF GRAVITATIONAL WAVES

PRODUCTION OF GRAVITATIONAL WAVES

Key parameters:

v_w - bubble-wall velocity

$\alpha \approx \frac{\Delta V}{\rho_r}$ - transition strength

$\frac{\beta}{H}$ - characteristic timescale

Bubbles collisions

Ultrarelativistic, accelerating bubble-walls

$$v_w \approx 1$$

Energy stored in the scalar field

Acoustic waves in the plasma

Stationary bubble-walls, Different expansion modes

$$v_w \lesssim 1$$

Energy transferred to the plasma

Magnetohydrodynamic turbulences

Associated with acoustic waves

Typically subdominant?

DYNAMICS OF THE EXPANDING BUBBLE

$$\Delta V = \int dz \frac{\partial V}{\partial T}\frac{dT}{dz} - \sum_i \int d\phi \frac{dm_i^2(\phi)}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i}\delta f_i(p,x)$$

Driving force — Hydrodynamic backreaction — Non-equilibrium friction

balance of forces ↔ stationary state

Hydrodynamic equations + **Matching conditions**

$$2\frac{v}{\xi} = \gamma^2(1 - v\xi)\left[\mu^2/c_s^2 - 1\right]\partial_\xi v$$

$$\partial_\xi w = w\left(1 + c_s^{-2}\right)\gamma^2\mu\partial_\xi v$$

$$w_+\gamma_+^2 v_+ = w_-\gamma_-^2 v_-$$

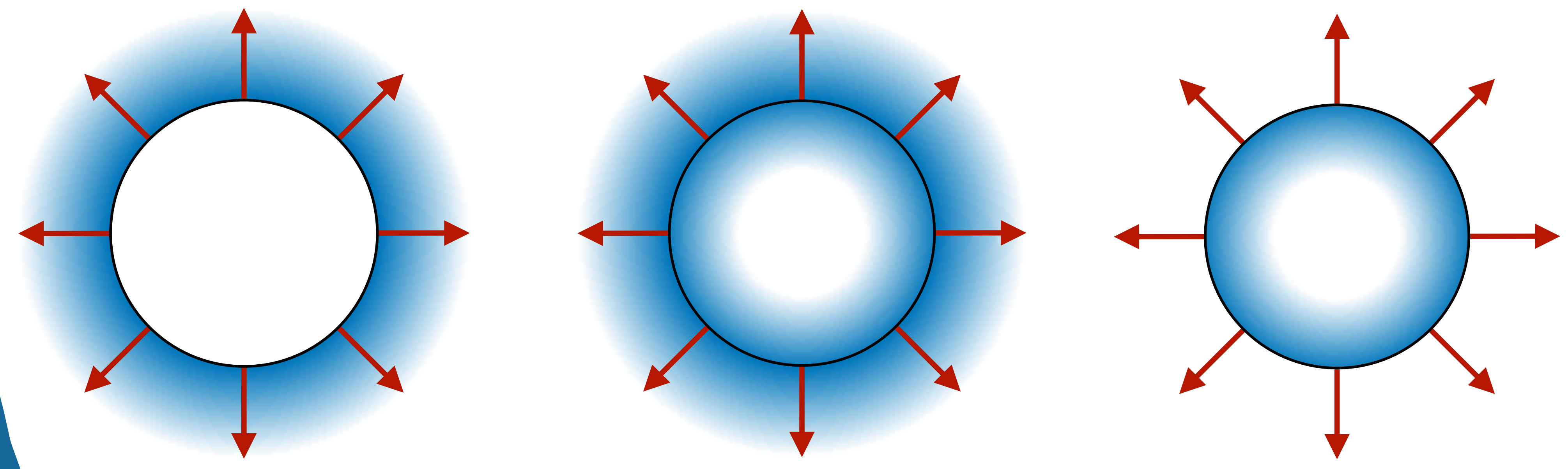
$$w_+\gamma_+^2 v_+^2 + p_+ = w_-\gamma_-^2 v_-^2 + p_-$$

$$\xi = r/t$$

$$\langle\phi\rangle = v$$

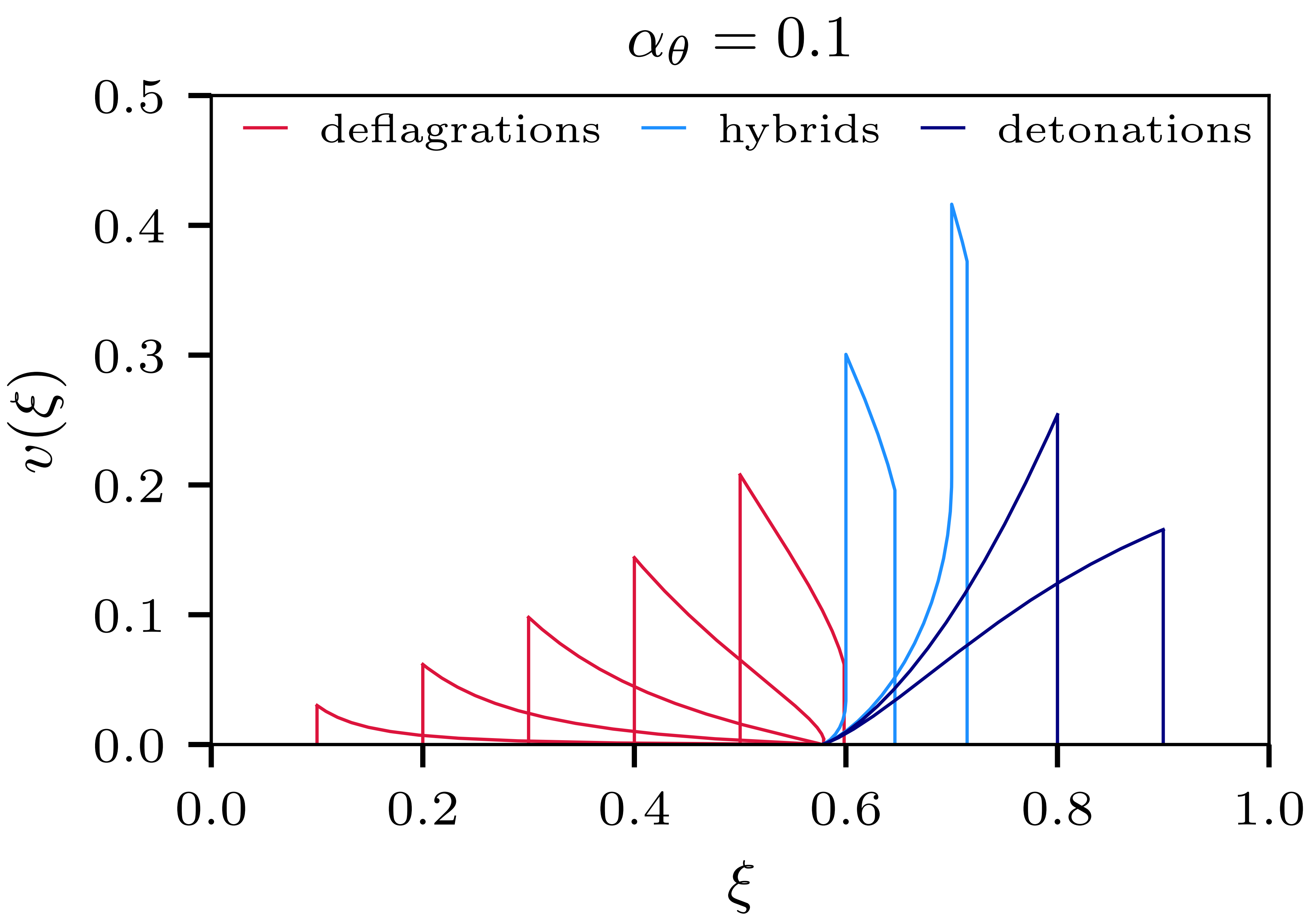
$$\langle\phi\rangle = 0$$

Deflagrations — Hybrids — Detonations



$v_w < c_s$ — $c_s < v_w < c_J$ — $c_J < v_w$

Plasma velocity profiles



LOCAL THERMAL EQUILIBRIUM

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Conservation of entropy ↔ only hydrodynamic backreation

$$s_-\gamma_-v_- = s_+\gamma_+v_+$$

Analytical prediction for $v_w(\alpha, \Psi)$

Hydrodynamic real-time simulations:

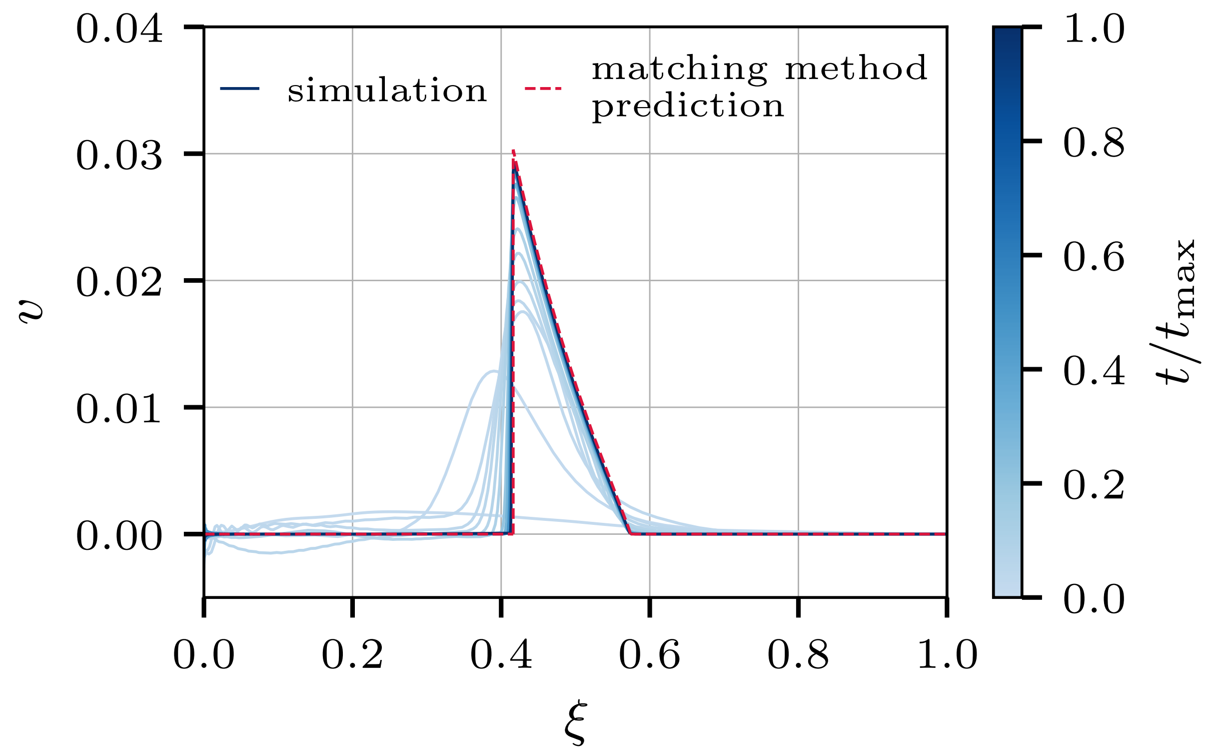
$$-\partial_t^2\phi + \frac{1}{r^2}\partial_r(r^2\partial_r\phi) = \frac{\partial V}{\partial\phi}\partial_t\phi + \eta\gamma(\partial_t\phi + v\partial_r\phi)$$

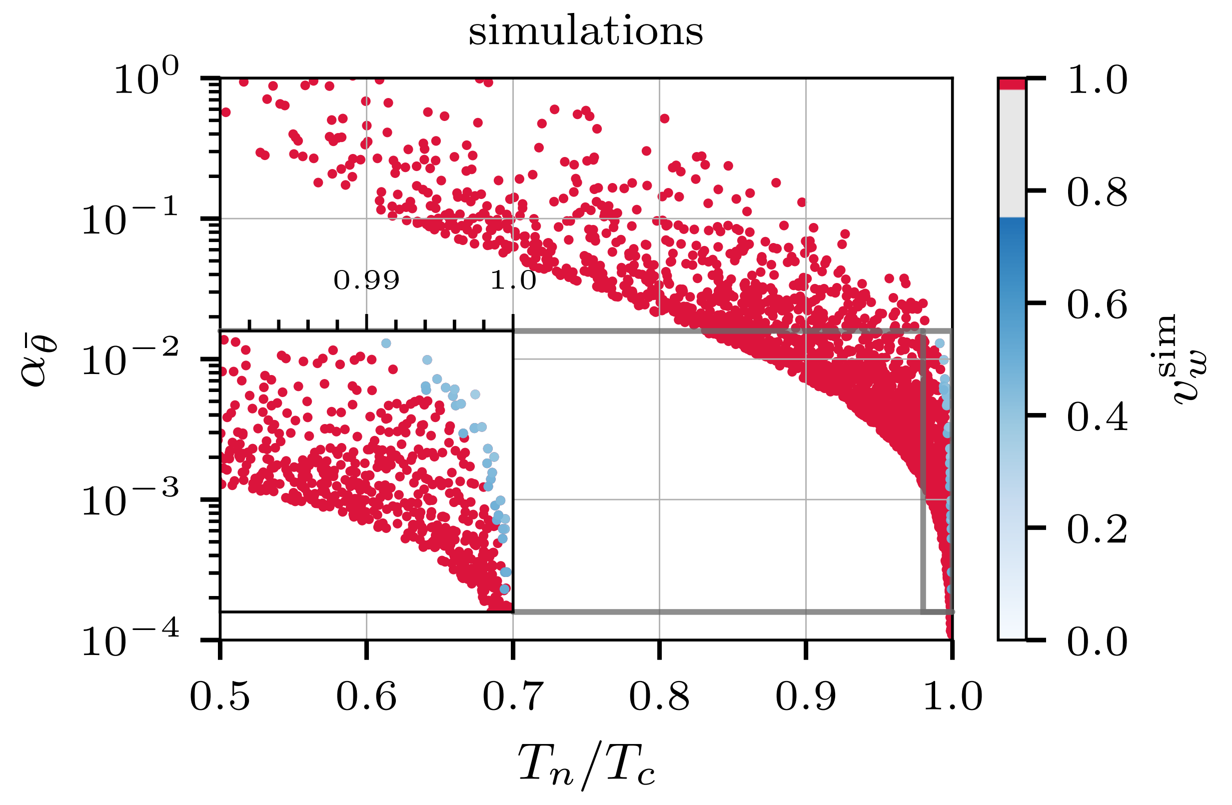
$$\partial_t\tau + \frac{1}{r^2}\partial_r(r^2(\tau+p)v) = \frac{\partial V}{\partial\phi} + \eta\gamma(\partial_t\phi + v\partial_r\phi)\partial_t\phi$$

$$\partial_t Z + \frac{1}{r^2}\partial_r\left(r^2 Z v\right) + \partial_r p = -\frac{\partial V}{\partial\phi}\partial_r\phi - \eta\gamma(\partial_t\phi + v\partial_r\phi)\partial_r\phi$$

In LTE $\eta = 0$

Stationery states from simulations agree very well with analytic predictions, however we observe much more runaways!





BEYOND LOCAL THERMAL EQUILIBRIUM

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Entropy production ↔ non-equilibrium friction

$$\partial_\mu(u^\mu s) = \frac{\eta}{T}\left(u^\mu\partial_\mu\phi\right)^2$$

New matching condition: $s_-\gamma_-v_- - s_+\gamma_+v_+ = \frac{\eta}{3}\frac{v_0^2}{L_w}\frac{\gamma_+^2v_+^2}{T_+}$

Analytical prediction for $v_w(\alpha, \Psi, \eta)$

We can calculate friction-dependent wall velocity and predict if the LTE result is physical!