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BUBBLE WALL VELOCITY FROM
HYDRODYNAMICS

FEBRUARY 2025

PARTICLE ASTROPHYSICS IN POLAND

THE SPECTRUM OF GRAVITATIONAL WAVES

Observatories & experiments

Ground-based experiment



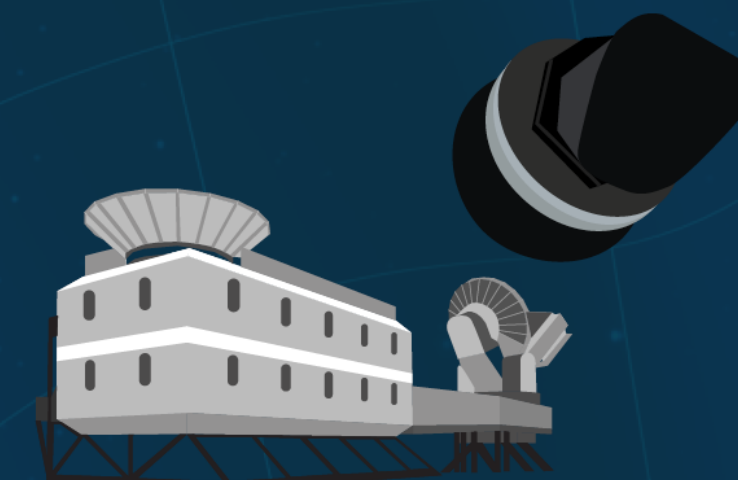
Space-based observatory



Pulsar timing array



Cosmic microwave background polarisation



Timescales

milliseconds

seconds

hours

years

billions of years

Frequency (Hz)

100

1

10^{-2}

10^{-4}

10^{-6}

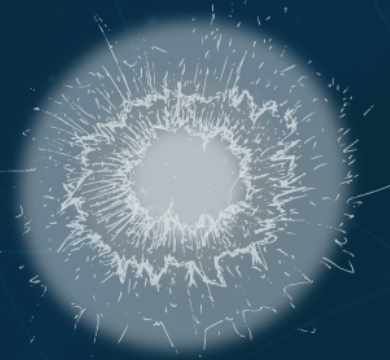
10^{-8}

10^{-16}

EW phase transition?

Cosmic fluctuations in the early Universe

Cosmic sources



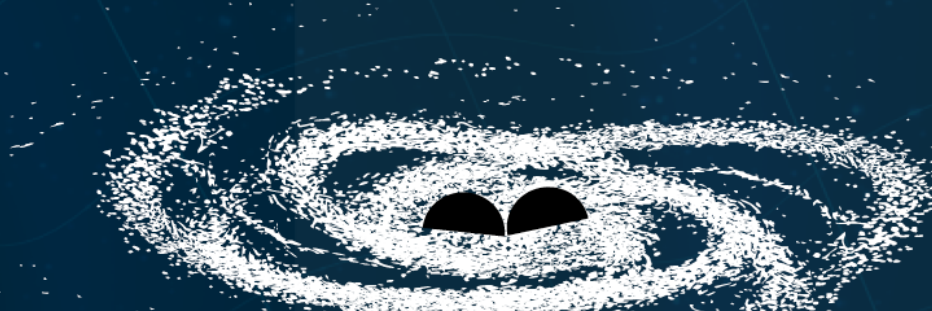
Supernova



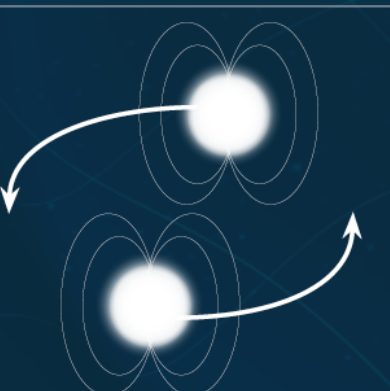
Pulsar



Compact object falling onto a supermassive black hole



Merging supermassive black holes



Merging neutron stars in other galaxies



Merging stellar-mass black holes in other galaxies



Merging white dwarfs in our Galaxy

PRODUCTION OF GRAVITATIONAL WAVES

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

Key parameters:
 v_w - bubble-wall velocity
 $\alpha \approx \frac{\Delta V}{\rho_r}$ - transition strength
 $\frac{\beta}{H}$ - characteristic timescale

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 \leftrightarrow stationary state

Hydrodynamic equations + Matching conditions

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

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

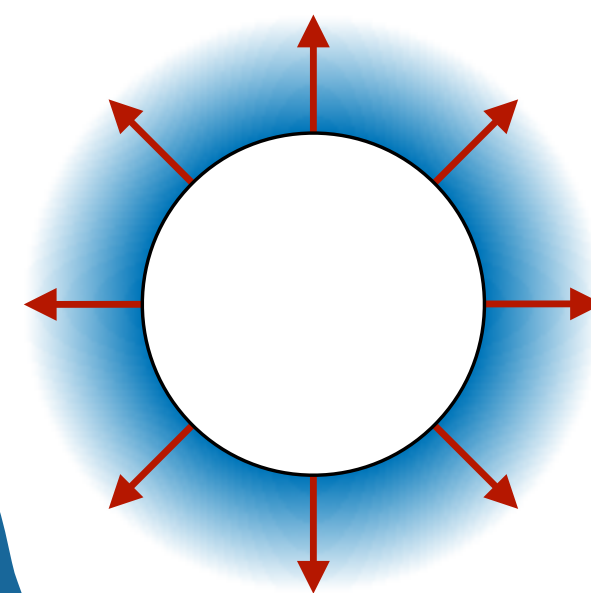
$$w_+ \gamma_+^2 v_+ = w_- \gamma_-^2 v_-$$

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

$$\xi = r/t$$

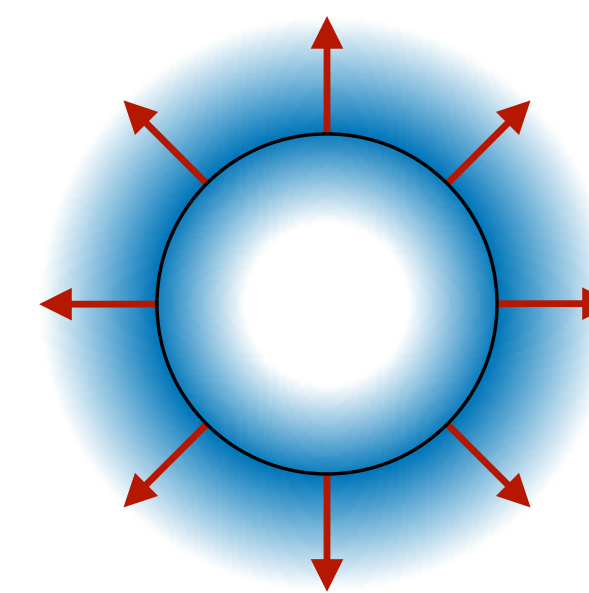
$$\langle \phi \rangle = v$$

Deflagrations



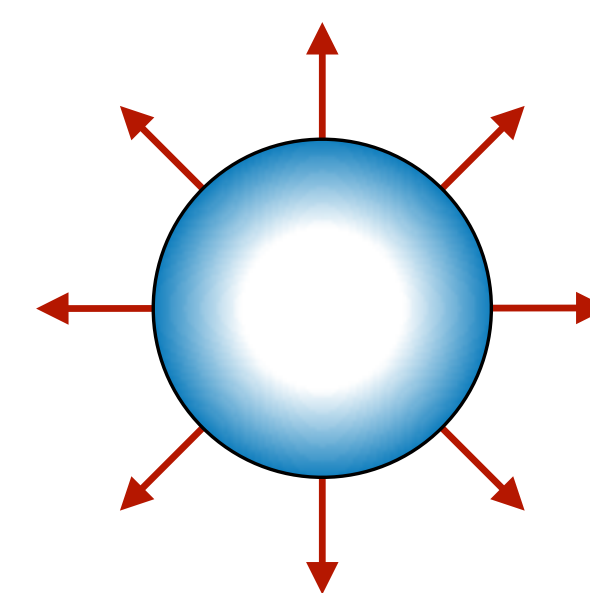
$$v_w < c_s$$

Hybrids



$$c_s < v_w < c_J$$

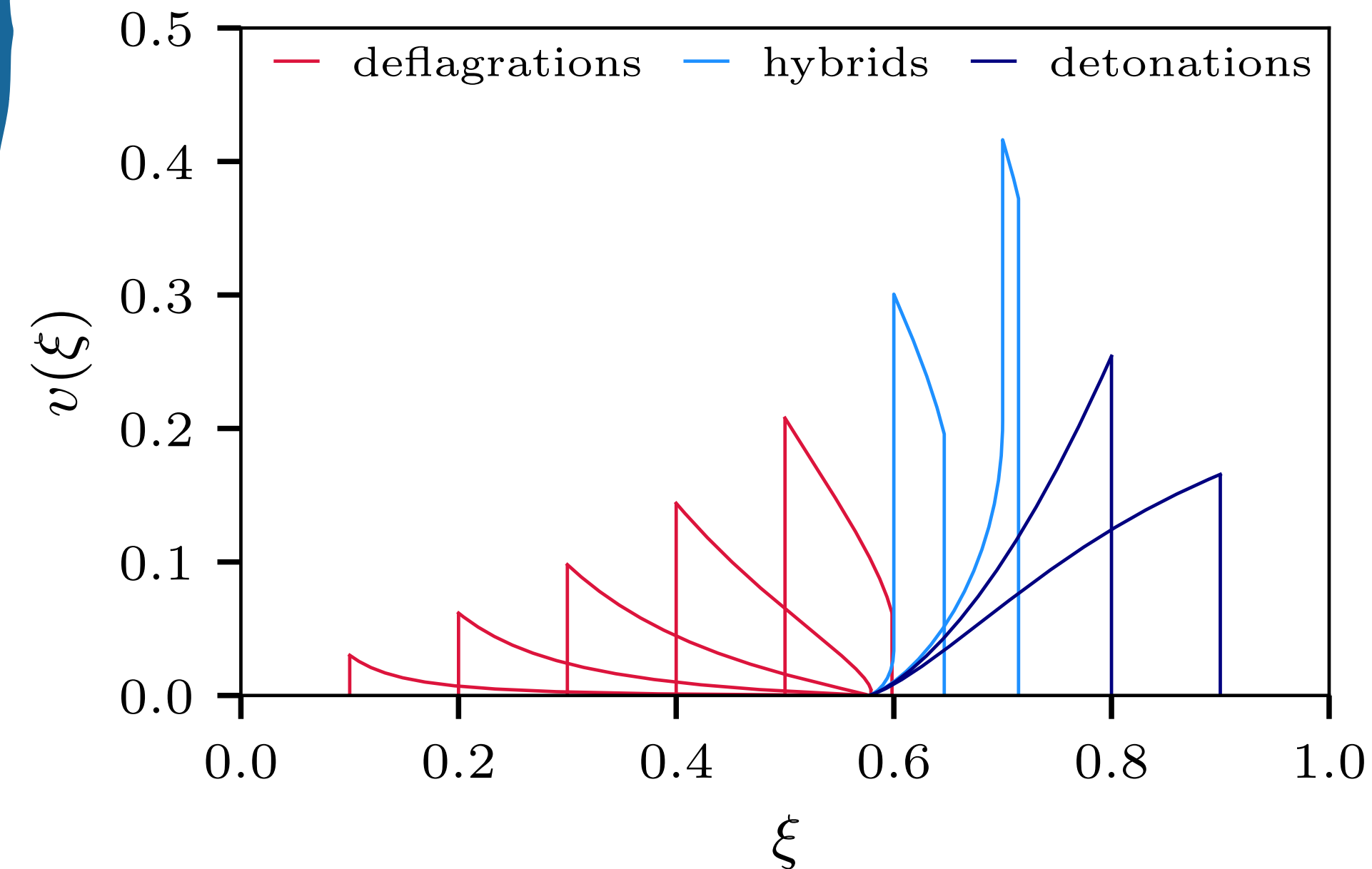
Detonations



$$c_J < v_w$$

Plasma velocity profiles

$$\alpha_\theta = 0.1$$



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

LOCAL THERMAL EQUILIBRIUM

2402.15408

Conservation of entropy \leftrightarrow only hydrodynamic backreaction

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

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

Hydrodynamic real-time simulations:

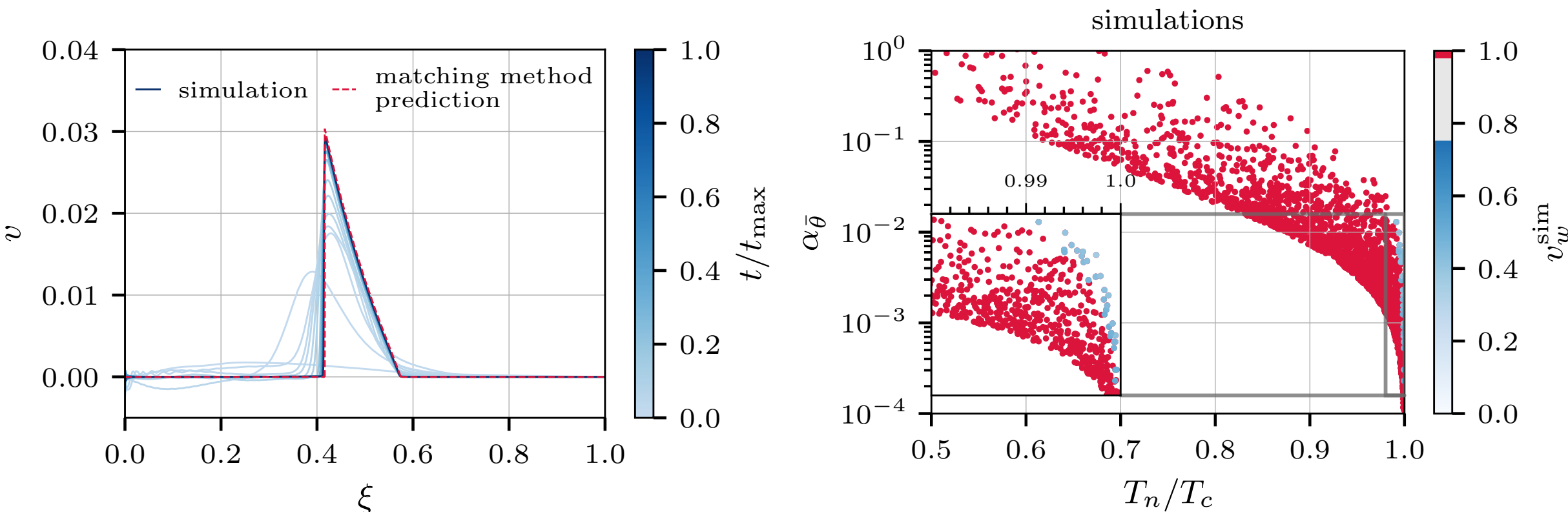
$$-\partial_t^2 \phi + \frac{1}{r^2} \partial_r (r^2 \partial_r \phi) = \frac{\partial V}{\partial \phi} \partial_t \phi + \eta \gamma (\partial_t \phi + v \partial_r \phi)$$

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

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

In LTE $\eta = 0$

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



BEYOND LOCAL THERMAL EQUILIBRIUM

2411.16580

Entropy production \leftrightarrow non-equilibrium friction

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

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

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

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

