Gravity waves from 1st order PTs

Thomas Konstandin

in collaboration with

S. Huber (0806.1828, 0709.2091)
C. Caprini, R. Durrer, G. Servant (0901.0126)
G. Servant, J.M. No, J.R. Espinosa (xxxx.xxxx)

RPP Lyon, Jan. 25, 2010

GWs from bubble collisions

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Outline

- Introduction
- GW spectra for bubble collisions
- Efficiency factors from hydrodynamics

Introduction

- 1st order phase transitions proceed by bubble nucleations
- In case of the electroweak PT, the bubble wall separates the symmetric from the broken phase
- This is a violent process ($v_b = O(1)$) and the kinetic energy in the bulk fluid motion and Higgs field is sizable

GW production by
- bubble collisions (this talk)
- turbulence in the plasma
- magnetic fields (see talk by R. Durrer)

Weinberg's master formula

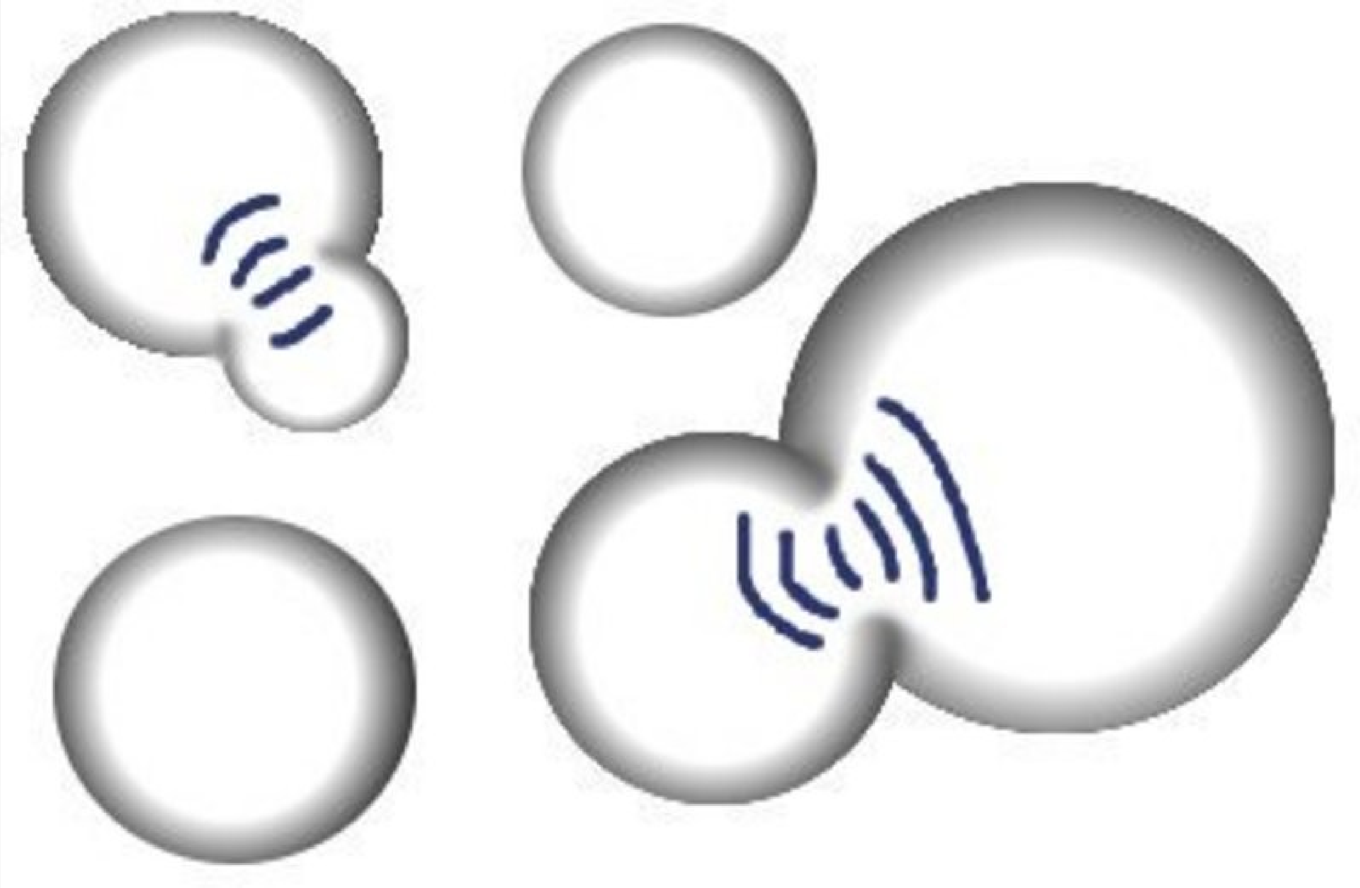
Using linearized GR and the wave zone approximation, the total energy radiated into a direction $\hat{\mathbf{k}}$ is given by

$$\frac{dE_{GW}}{d\omega d\Omega} = 2G\omega^2 \Lambda_{ij,lm}(\hat{\mathbf{k}}) T^*_{ij}(\hat{\mathbf{k}}, \omega) T_{lm}(\hat{\mathbf{k}}, \omega),$$

where $T_{ij}(\hat{\mathbf{k}}, \omega)$ denotes the stress-energy tensor in Fourier space and Λ is the projection tensor for the transverse-traceless part.

Spherical symmetric configurations do hence not contribute and the bubbles produce GWs only when they collide.

Colliding bubbles produce GWs



At the colliding bubble regions, spherical symmetry is lost and GWs are produced.

Back on the envelope

1) The tunnel probability usually increases exponentially

$$P \propto \exp(\beta\, t) \quad \text{and typically} \quad \beta/H = O(100).$$

β

2) The latent heat ρ_{vac} is with efficiency κ transformed into the bulk motion of the fluid

α

$$T_{\mu\nu} \propto \kappa\, \rho_{vac}, \quad G \propto H^2/(\rho_{vac} + \rho_{rad}).$$

v_b

For dimensional reasons we obtain for the energy fraction in GWs per frequency octave

$$\Omega_{GW} = \omega \frac{dE_{GW}}{d\omega} \frac{1}{E_{tot}} = \kappa^2(\alpha, v_b) \left(\frac{H}{\beta}\right)^2 \left(\frac{\alpha}{\alpha + 1}\right)^2 \Delta(\omega/\beta, v_b),$$

with Δ some dimensionless function and $\alpha = \rho_{vac}/\rho_{rad} \lesssim 1$

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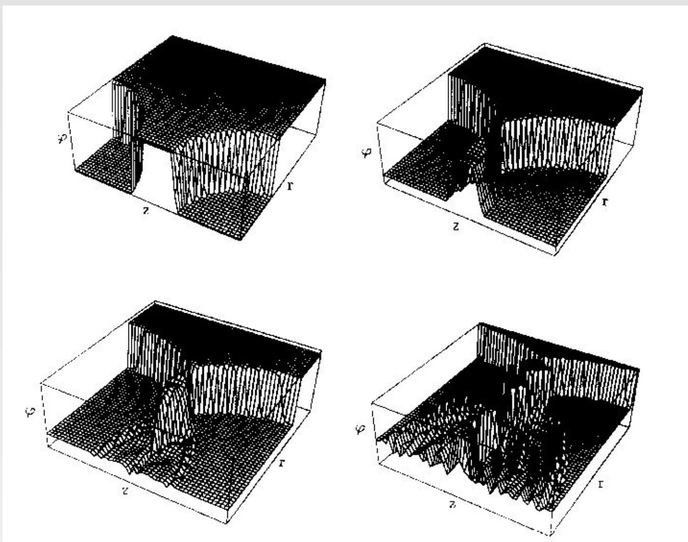
GW spectra

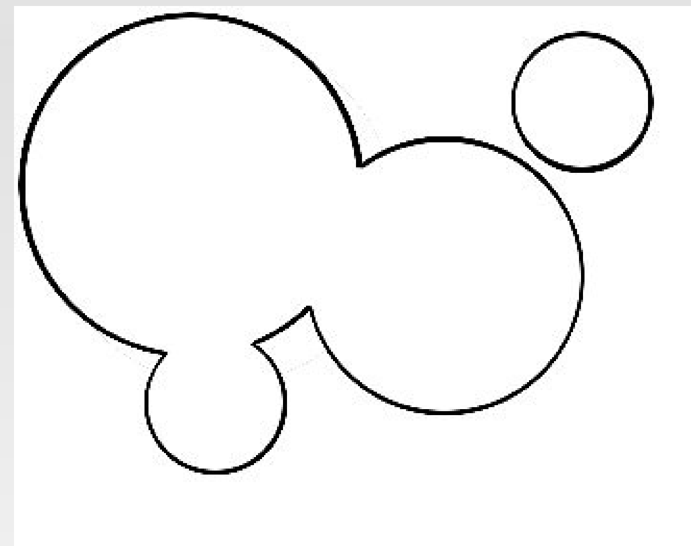
GWs specctra for bubble collisions

$$\kappa^2(\alpha, v_b)\left(\frac{H}{\beta}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2 \Delta(\omega/\beta, v_b)$$

Envelope approximation

Kosowski, Turner, Watkins '91



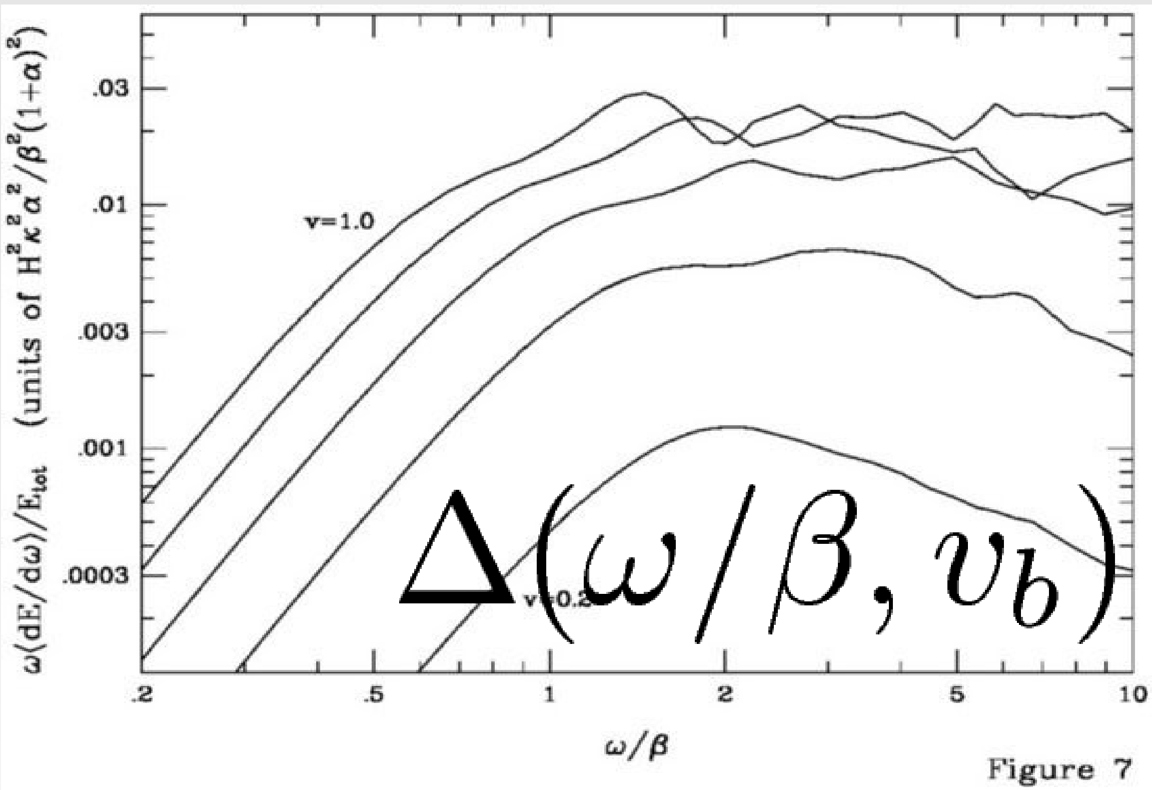


Simulations show that for the production of GWs the energy of the Higgs field can be approximated by its envelope.

Still, simulations with many bubbles and high accuracy have been too demanding in the 90s.

Simulation results

Kamionkowski, Kosowski, Turner '93



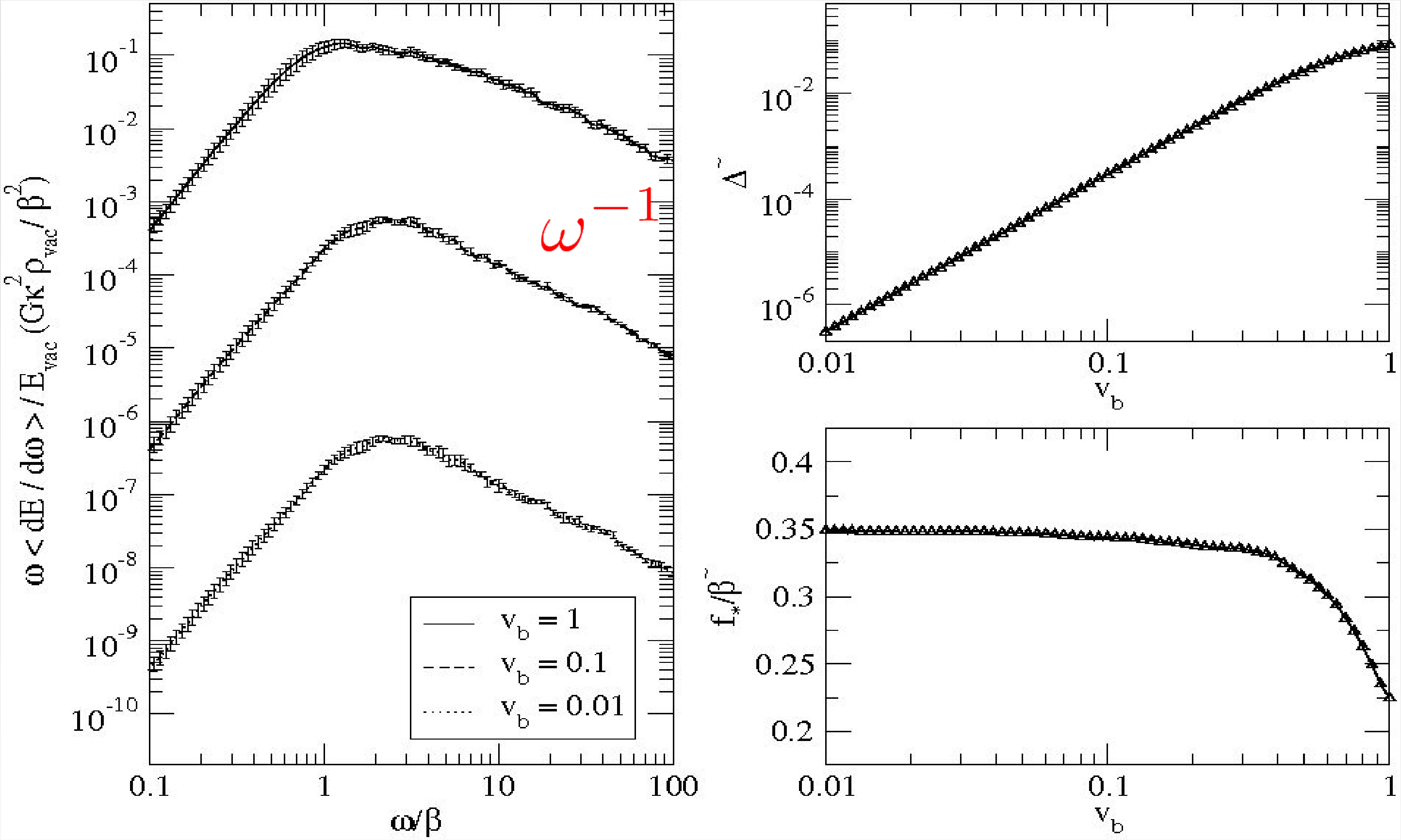
However, scaling at large frequencies could not conclusively be decided and the result for two bubbles is frequently used in the literature $\Delta \sim \omega^{-2}$

Simulations of bubblecollisions show that

- The energy fraction scales as ~ v_b^3
- The peak corresponds to the duration of the phase transition and not to the size of the bubbles $1/\beta \leftrightarrow v_b/\beta$

More bubble collisions

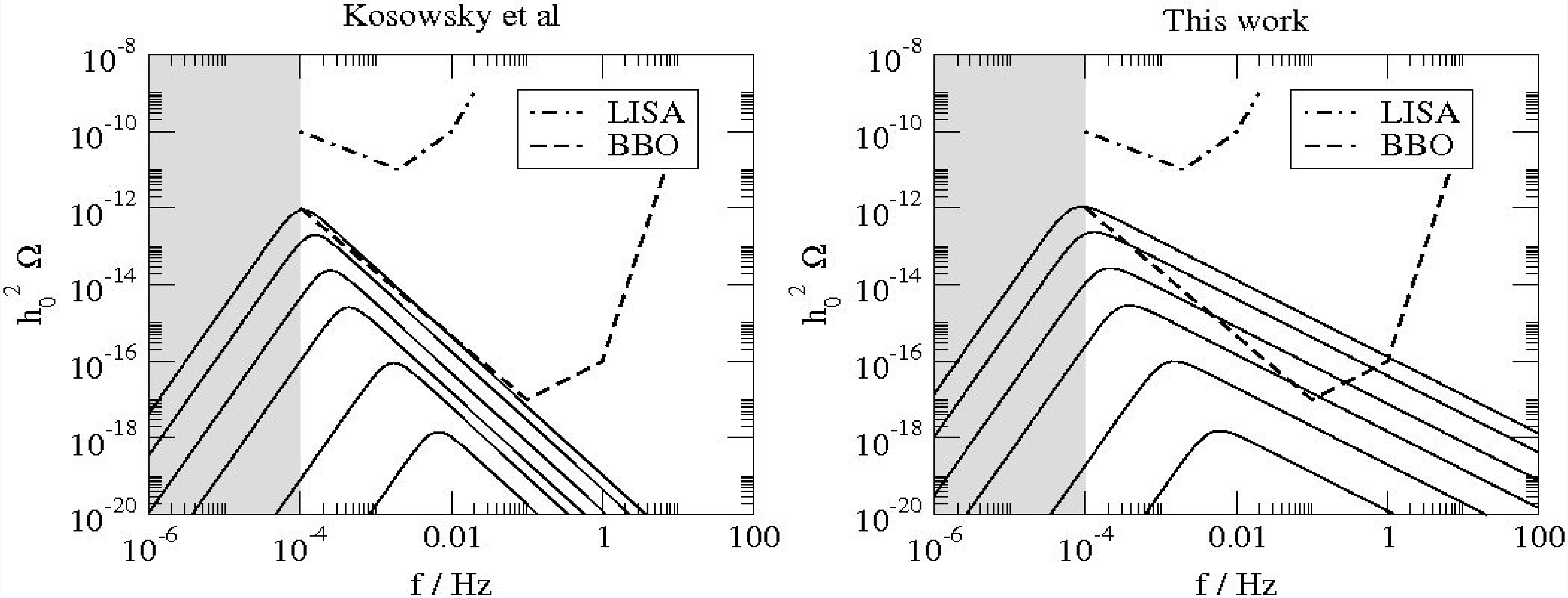
S.J. Huber and TK '08



High precision results with ~130 bubbles show that the spectrum scales as ω^{-1} for large frequencies unlike earlier results.

Bubble collisions

This is essential for the prospects of GW detection in many models



The flat spectrum is due to quite a peculiar time dependence of the anisotropic stress (Caprini, Durrer, TK, Servant '09).

Efficiency coefficient

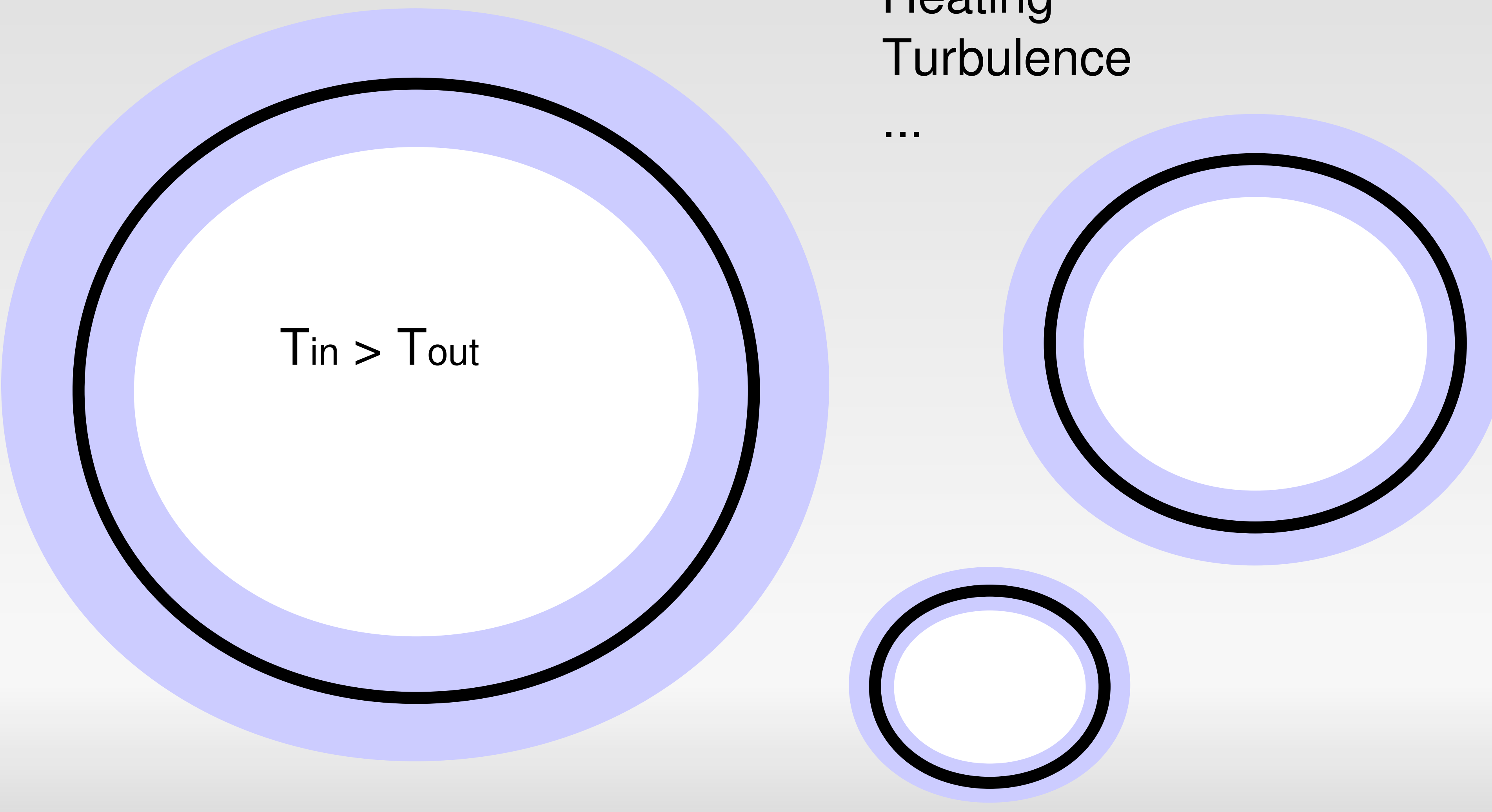
bulk flow and hydrodynamics

$$\kappa^2(\alpha, v_b) \left(\frac{H}{\beta}\right)^2 \left(\frac{\alpha}{\alpha+1}\right)^2 \Delta(\omega/\beta, v_b)$$

Energy budget

Vacuum energy of the Higgs

Kinetic energy of the Higgs
Bulk motion
Heating
Turbulence
...



Matching conditions at the wall

For a ideal relativistic fluid one has

$$T_{\mu\nu} = u_\mu u_\nu \omega - g_{\mu\nu} p, \quad u_\mu = \gamma(1, \vec{v})$$

Bag equation of state $\qquad \omega = 4p = aT^4/3$

Across the bubble wall, the plasma gains energy from the vacuum energy of the Higgs field.

Stationarity in the wall frame and energy-momentum conservation then implies

$$T_{0z}|_-^+ = 0 \quad T_{zz}|_-^+ = \rho_{vac}$$

Where ρ_{vac} denotes the vacuum energy of the Higgs.

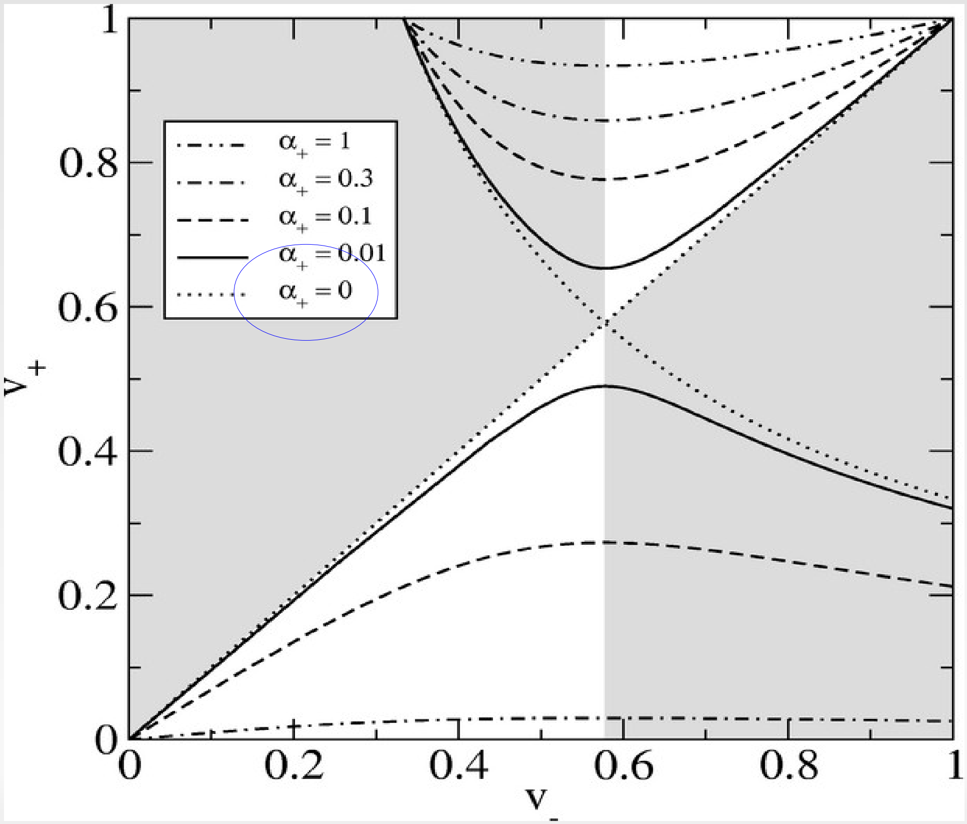
Matching conditions

Unknown parameters

$T_-,\ v_+,\ v_-$

known parameters

$T_+,\ a_-,\ a_+$



Steinhardt '81 $\alpha = \rho_{vac}/\rho_{rad}$

Two types of solutions

Detonations v+ > v-
Deflagrations v- > v+

In earlier work by Steinhardt, the missing constraint was replaced by the Chapman-Jouget condition

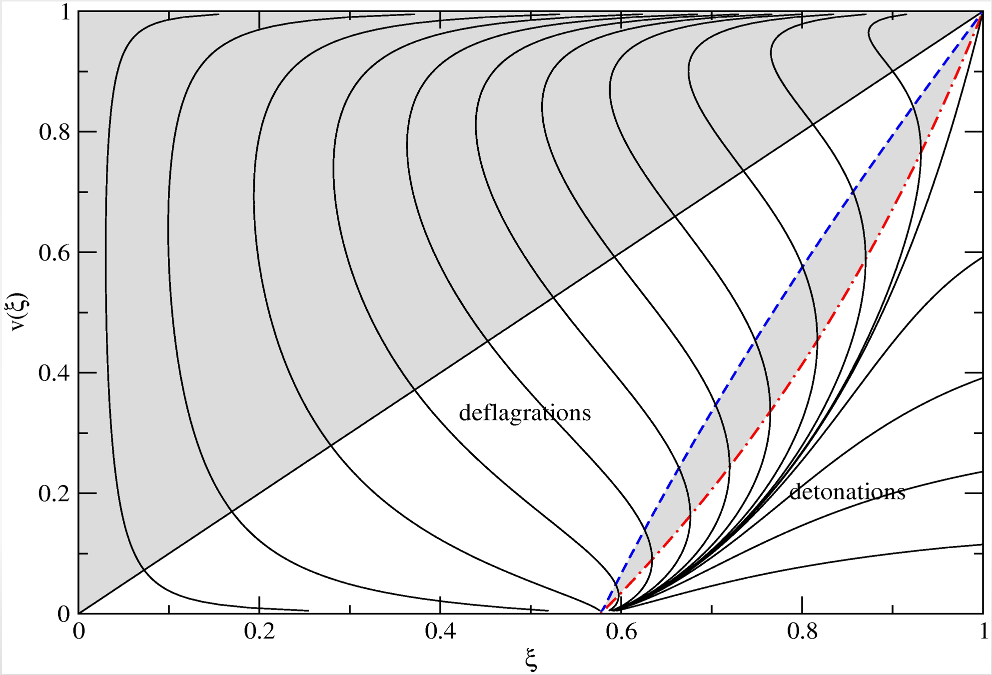
$$v_- = c_s = 1/\sqrt{3}$$

what is motivated by chemical combustions

Hydrodynamic equations

Away from the bubble wall, the plasma velocities are determined by hydrodynamics. Since there is no intrinsic scale available, solutions can only depend on $\xi = r/t$

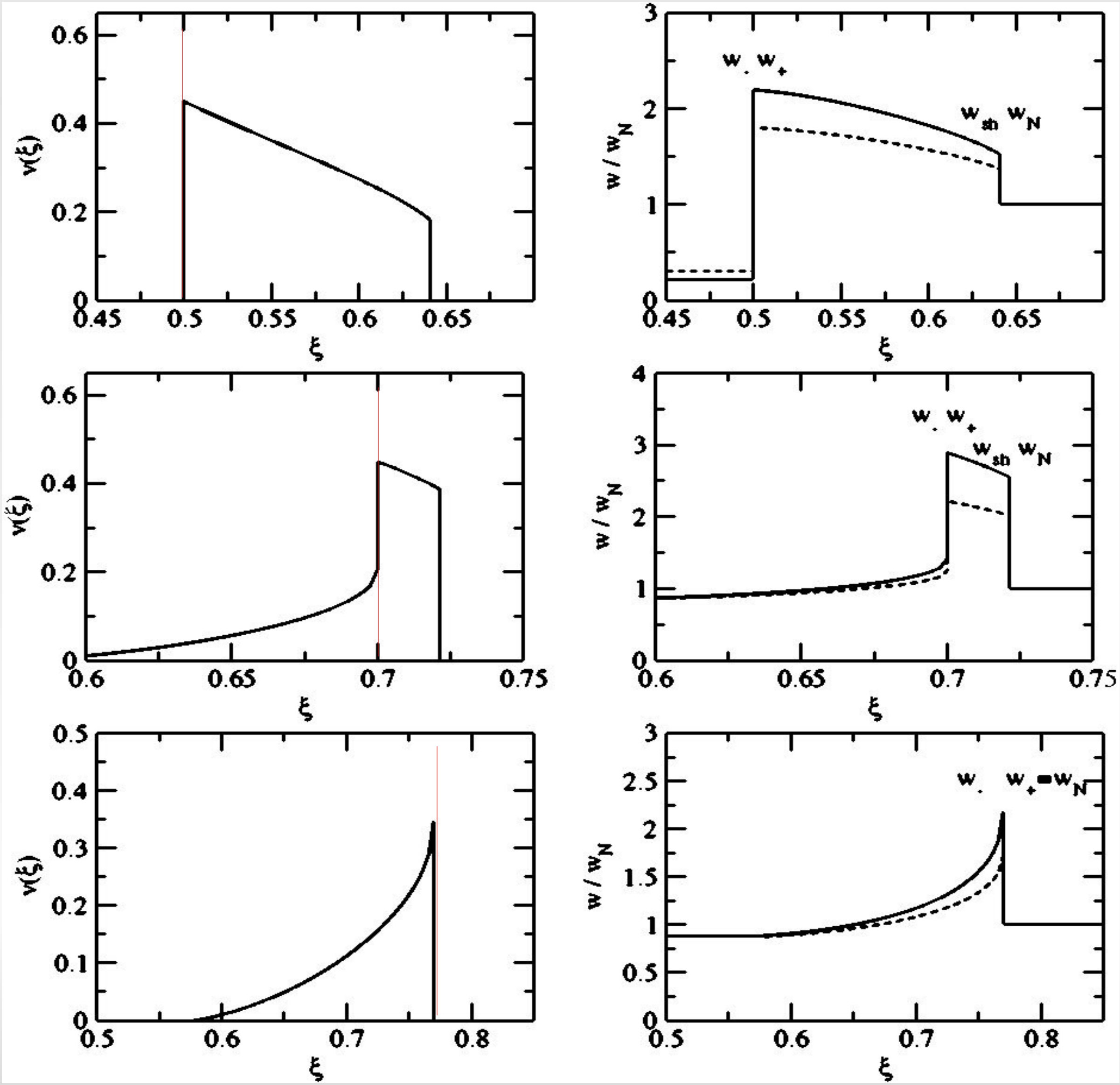
$$2\frac{v}{\xi} = \partial_\xi v \; \gamma^2 (\xi - v) \left(\frac{(\xi - v)^2}{c_s^2 (1 - \xi v)^2} - 1 \right)$$



At the blue line, the velocity can jump to 0 without any energy injection into the plasma

Efficiency coefficient

Espinosa, TK, No, Servant



Depending on the boundary conditions at the bubble wall front, there are three types of solutions possible

Detonations – rarefaction wave

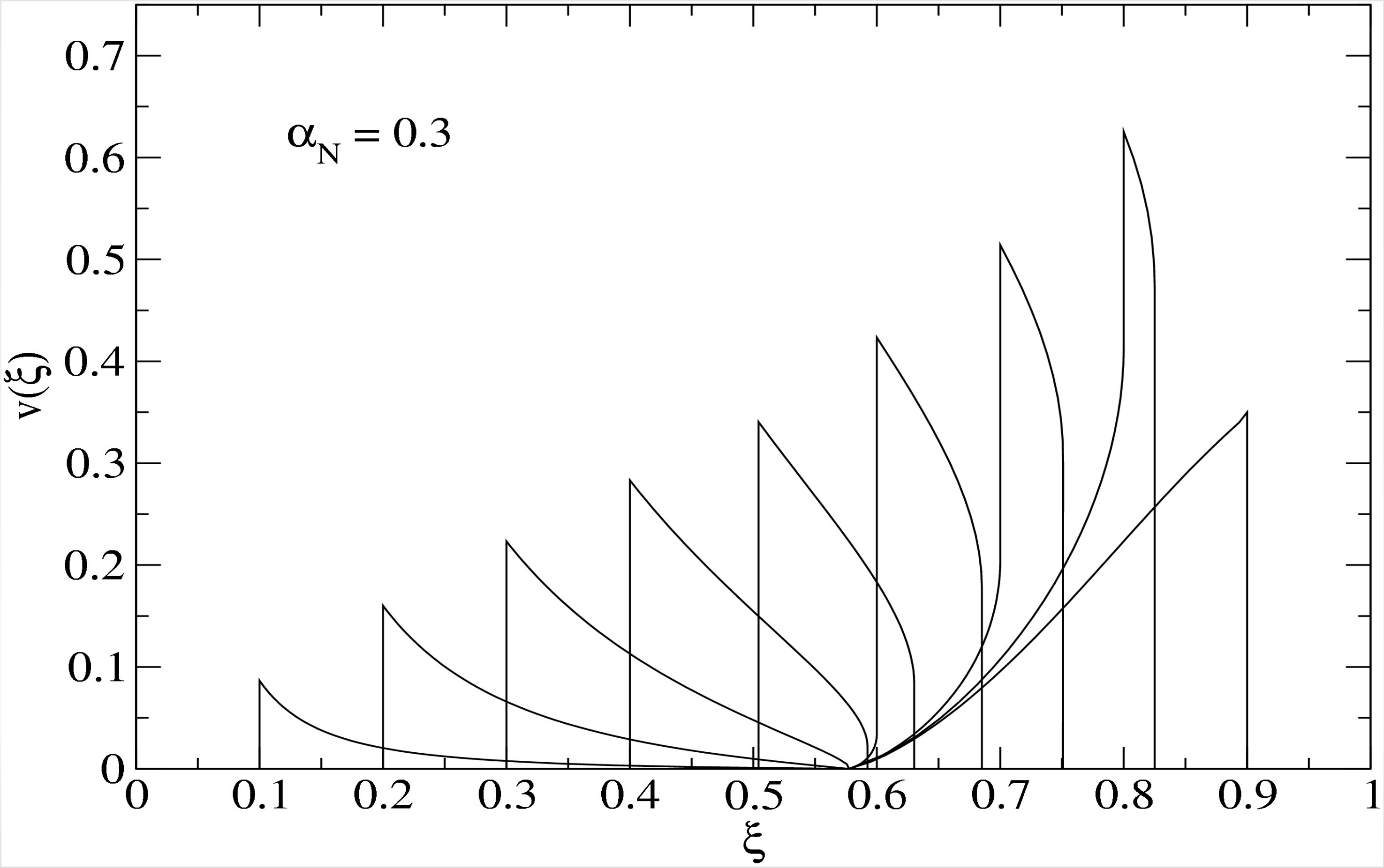
Deflagrations – shock front

Hybrids – both

Evolution

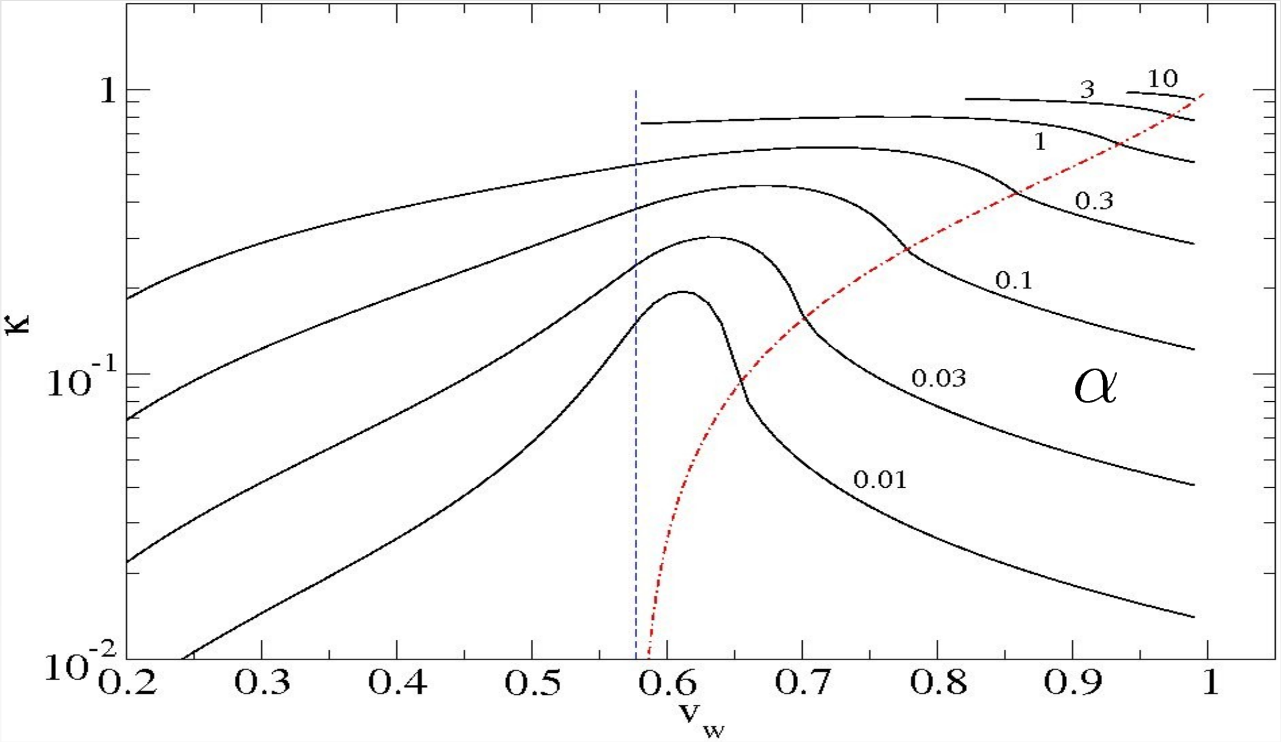
Espinosa, TK, No, Servant

For small fixed $\alpha = \rho_{vac}/\rho_{rad}$ the solutions pass all three stages depending on the wall velocity



Efficiency coefficient

$$\kappa = \frac{3}{\epsilon \xi_w^3} \int \omega(\xi) v^2(\xi) \gamma^2 \xi^2 d\xi$$



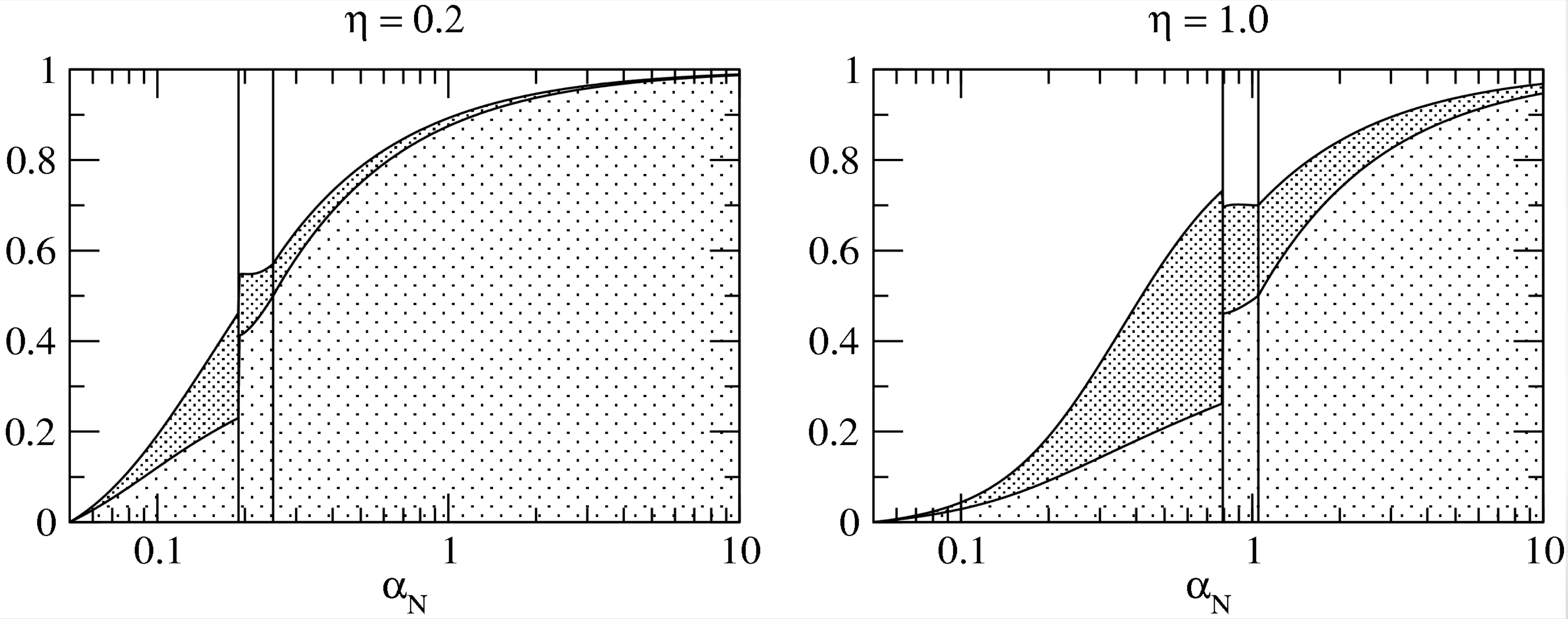
The efficiency in the general case can be quite different than for Jouget detonations.

Higgs equation

The velocity of the bubble wall can be determined by a phenomenological ansatz

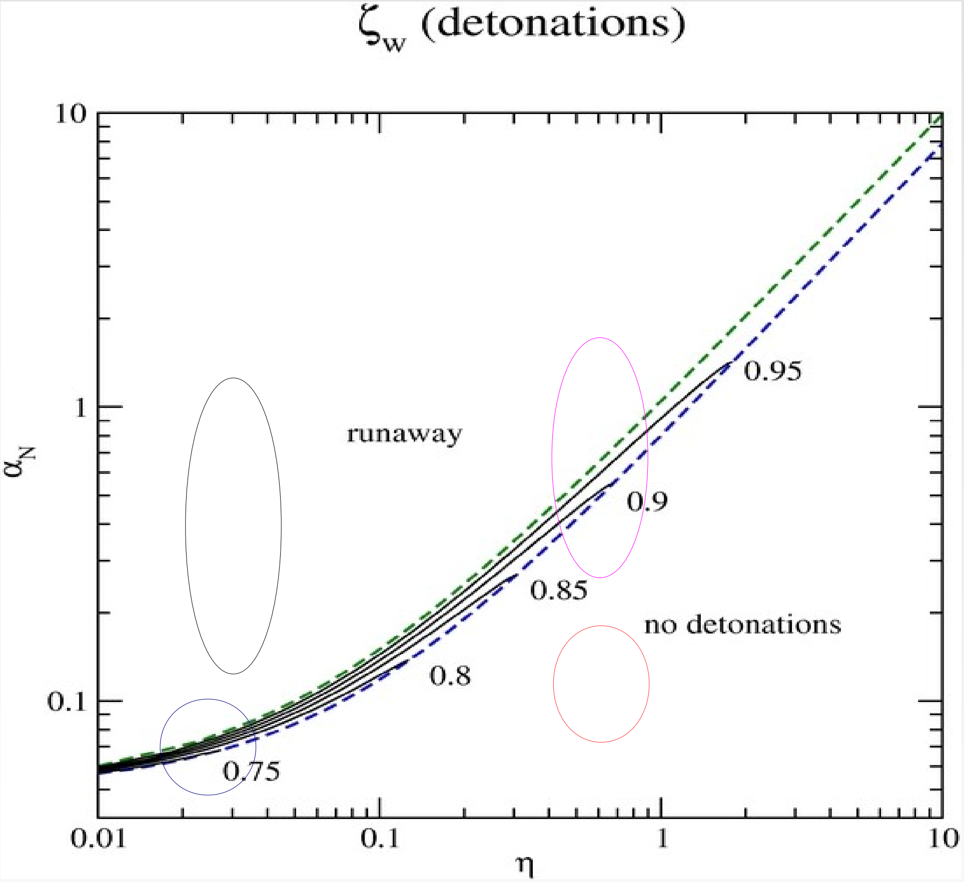
$$\Box\phi + \frac{\partial \mathcal{F}}{\partial \phi} + \eta\, u^{\mu}\partial_{\mu}\phi = 0$$

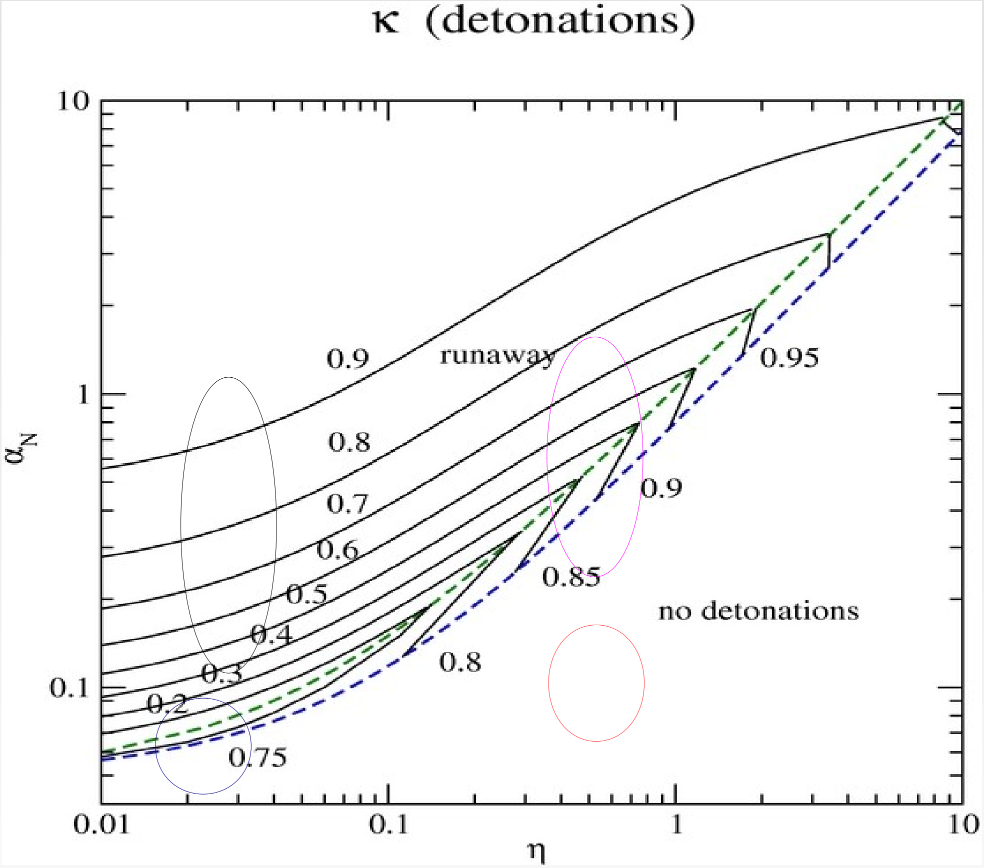
Where η denotes a friction coefficient.



Contour - detonations

Espinosa, TK, No, Servant

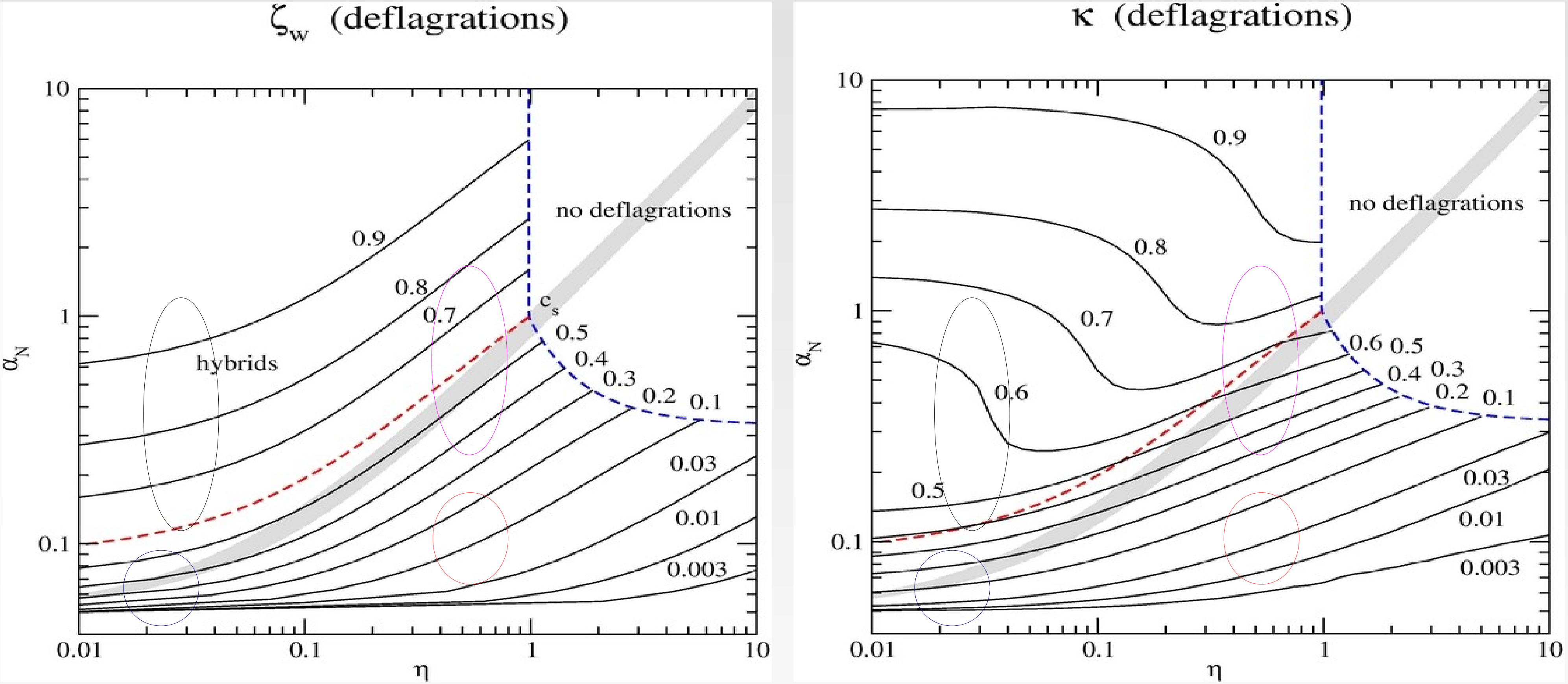




SM (mH = 40 GeV) nSM MSSM nMSSM

Contour – deflagrations

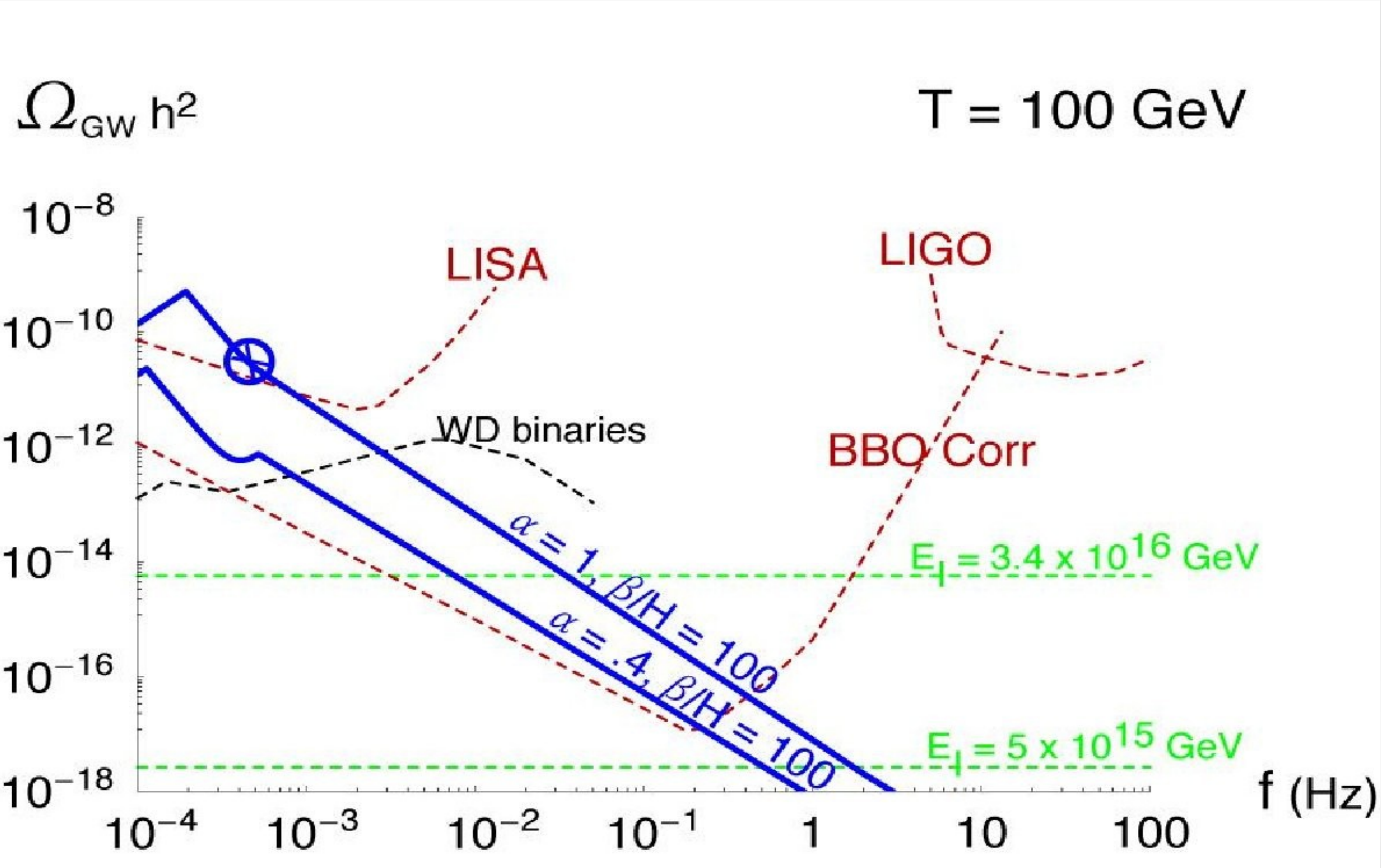
Espinosa, TK, No, Servant



SM (mH = 40 GeV) nSM MSSM nMSSM

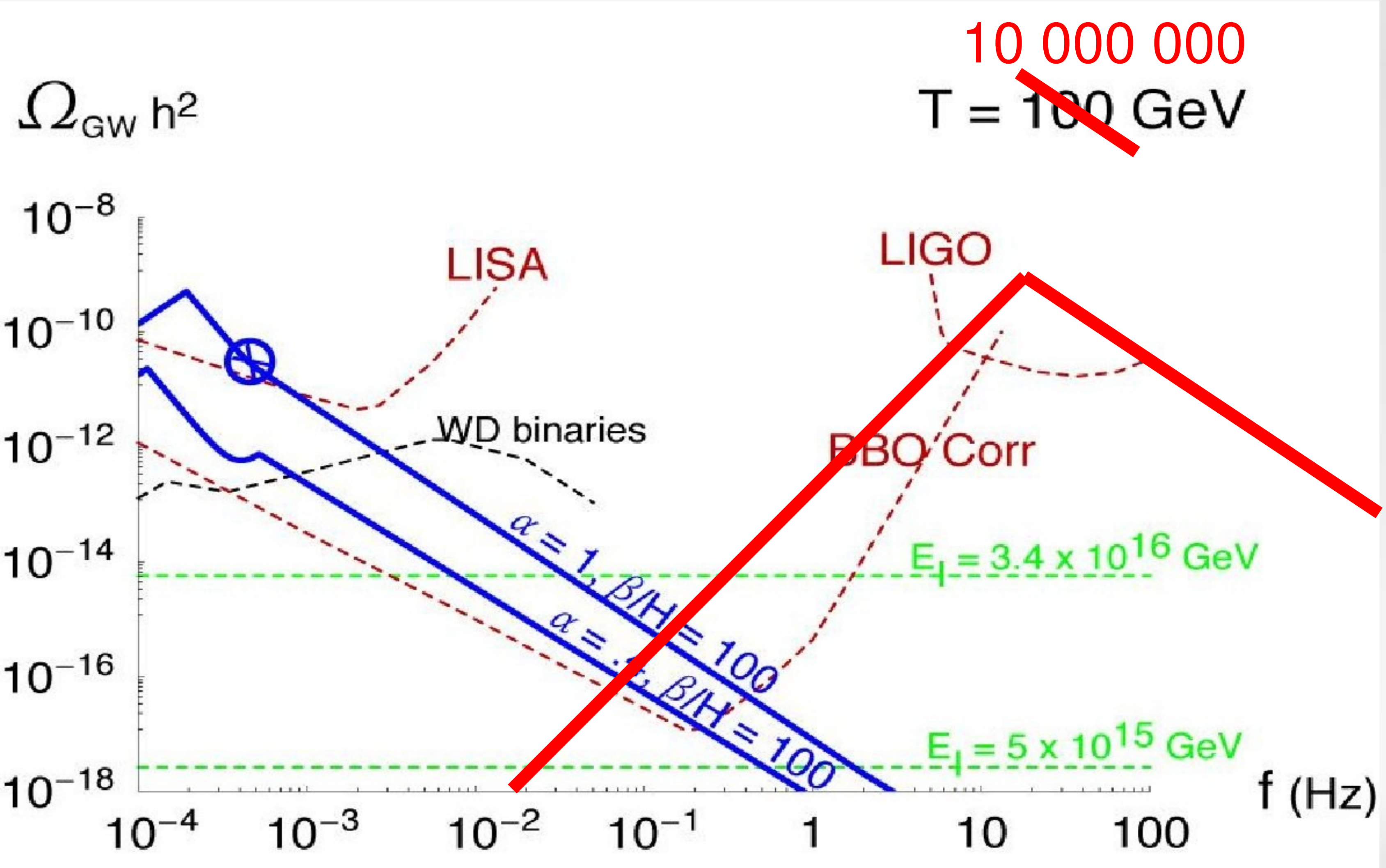
Conclusions

Grojean & Servant '06



High energies

Grojean & Servant '06



Conclusions

Observation of stochastic gravitational waves will (hopefully) start in this decade. They open up the unique possibility to complement collider experiments and probe

• the process of electroweak symmetry breaking in the early Universe

• particle physics at scales significantly higher than the electroweak scale

LISA