Probing the electroweak scale (and beyond) with gravity waves

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references:

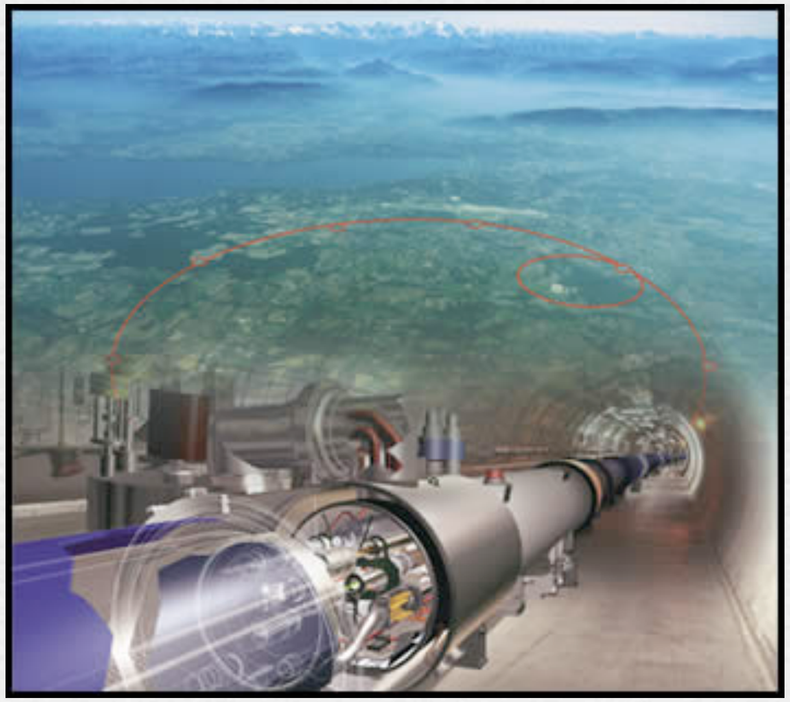
Grojean-Servant hep-ph/0607107, PRD
Randall-Servant hep-ph/0607158, JHEP
Caprini-Durrer-Servant 0711.2593, PRD & 0909.0622, JCAP
Caprini-Durrer-Konstandin-Servant 0901.1661, PRD
Espinosa-Konstandin-No-Servant 1004.4187, JCAP

2010: First collisions at the LHC

Direct exploration of the Fermi scale starts.

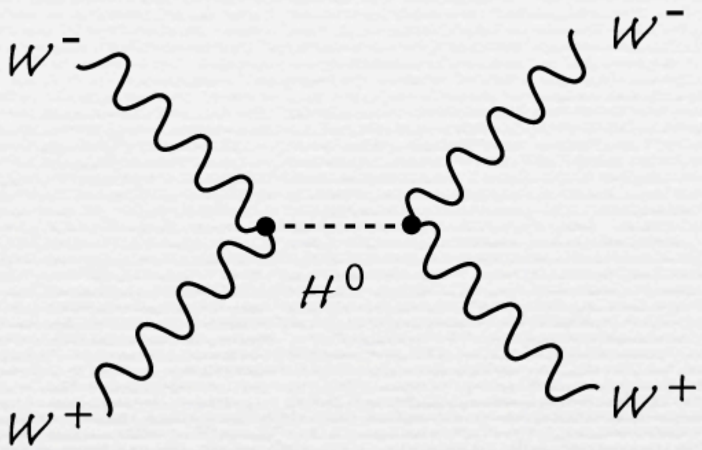
main physics goal:

What is the mechanism of Electroweak Symmetry breaking ?

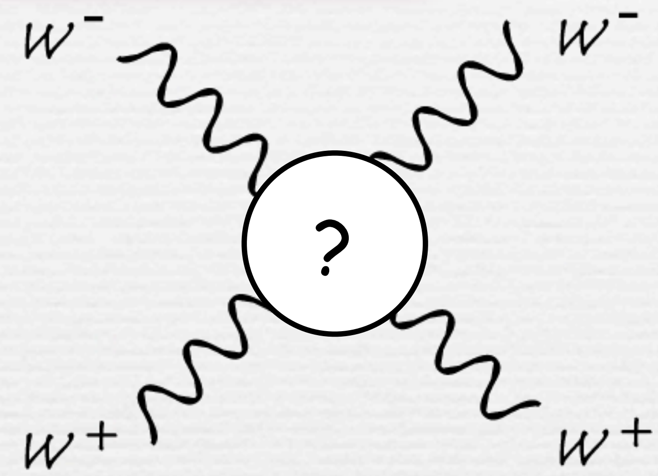


Electroweak symmetry breaking: 2 main questions

- ## What is unitarizing the $W_L W_L$ scattering amplitude?

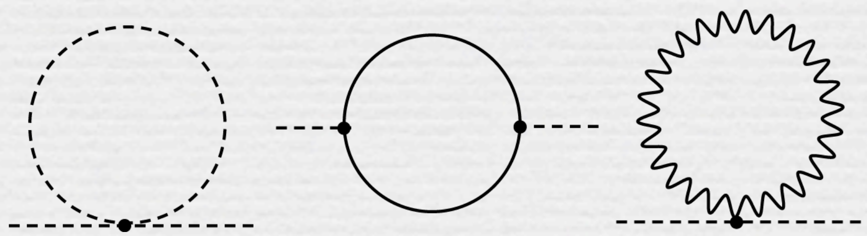


the Higgs or something else?



- ## What is cancelling the divergent diagrams?

(i.e what is keeping the Higgs light?)
: Hierarchy problem



$$\Rightarrow \delta M_H^2 \propto \Lambda^2$$

Λ , the maximum mass scale that the theory describes

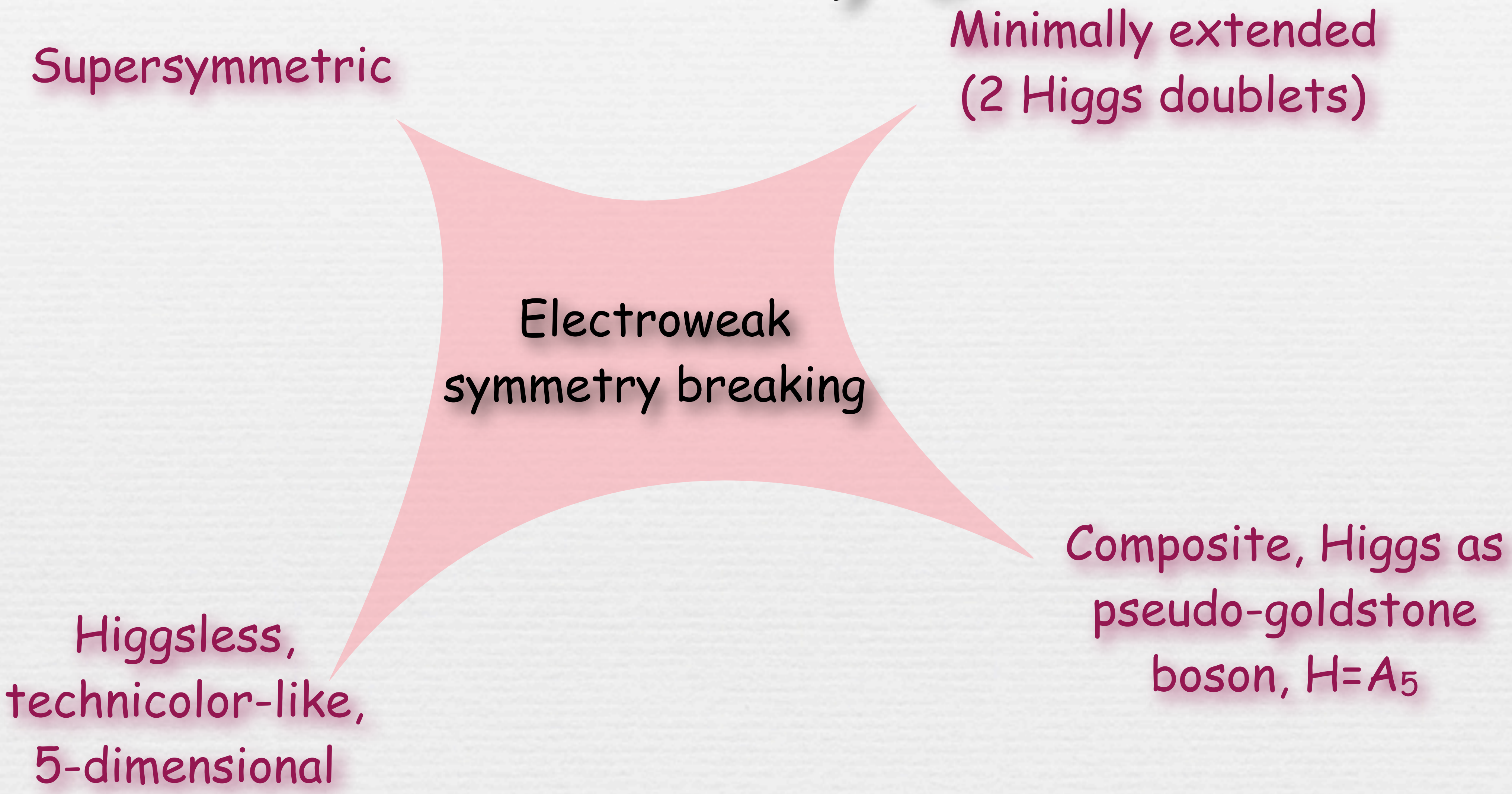
strong sensitivity on UV unknown physics

need new degrees of freedom & new symmetries to cancel the divergences

supersymmetry, gauge-Higgs unification, Higgs as a pseudo-goldstone boson...

→ theoretical need for new physics at the TeV scale

Which new physics?



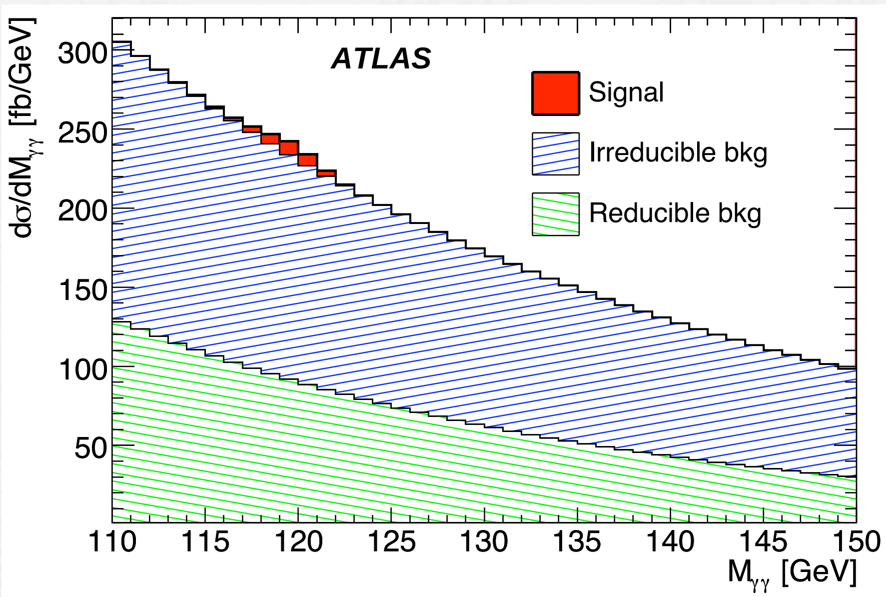
In all explicit examples, without unwarranted cancellations, new phenomena are required at a scale $\Lambda \sim [3-5] \times M_{Higgs}$

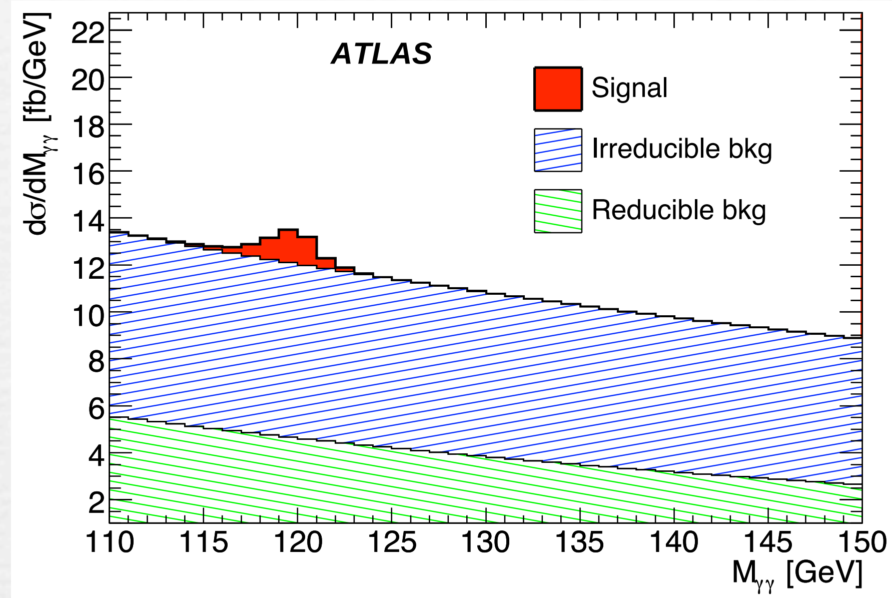
Which Higgs ?

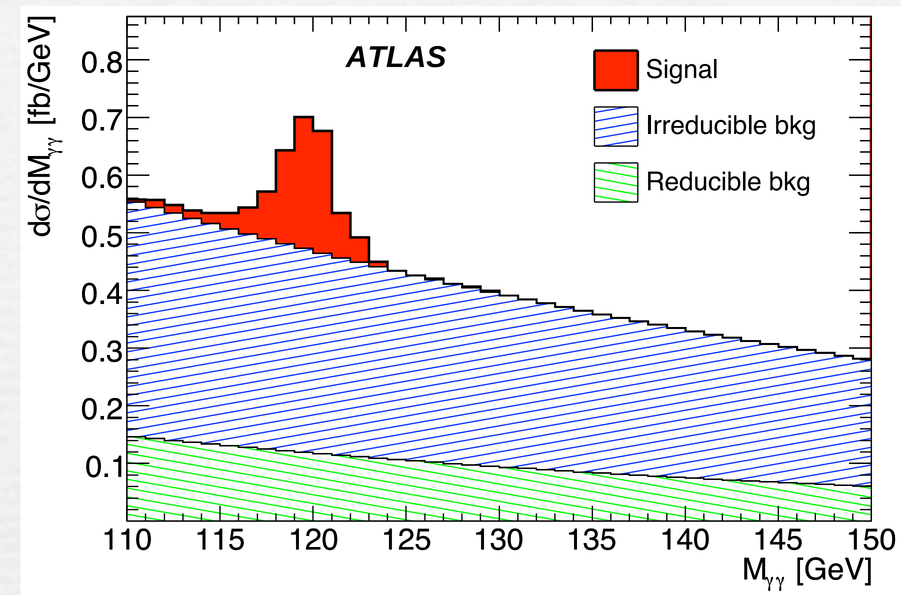
- Composite Higgs ?
- Little Higgs ?
- Littlest Higgs ?
- Intermediate Higgs ?
- Slim Higgs ?
- Fat Higgs ?
- Gauge-Higgs ?
- Holographic Higgs ?
- Gaugephobic Higgs ?
- Higgsless ?
- UnHiggs ?
- Portal Higgs ?
- Simplest Higgs ?
- Private Higgs ?
- Lone Higgs ?
- Phantom Higgs ?

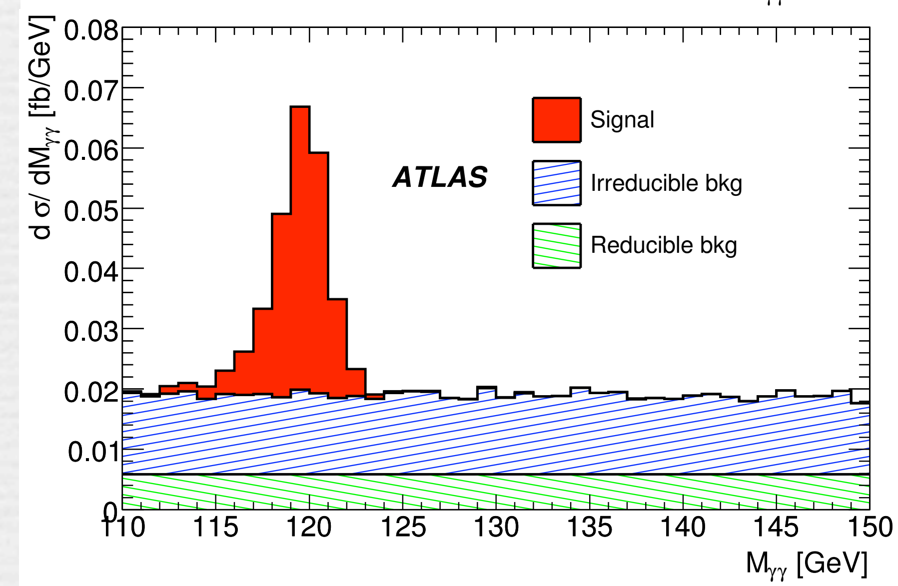
What questions the LHC experiments will try to answer :

Does a Higgs boson exist ?









If yes :

- is there only one ?
- what are its mass, width, quantum numbers ?
- does it generate EW symmetry breaking and give mass to fermions too as in the Standard Model or is something else needed ?
- what are its couplings to itself and other particles
- Spin determination
- CP properties

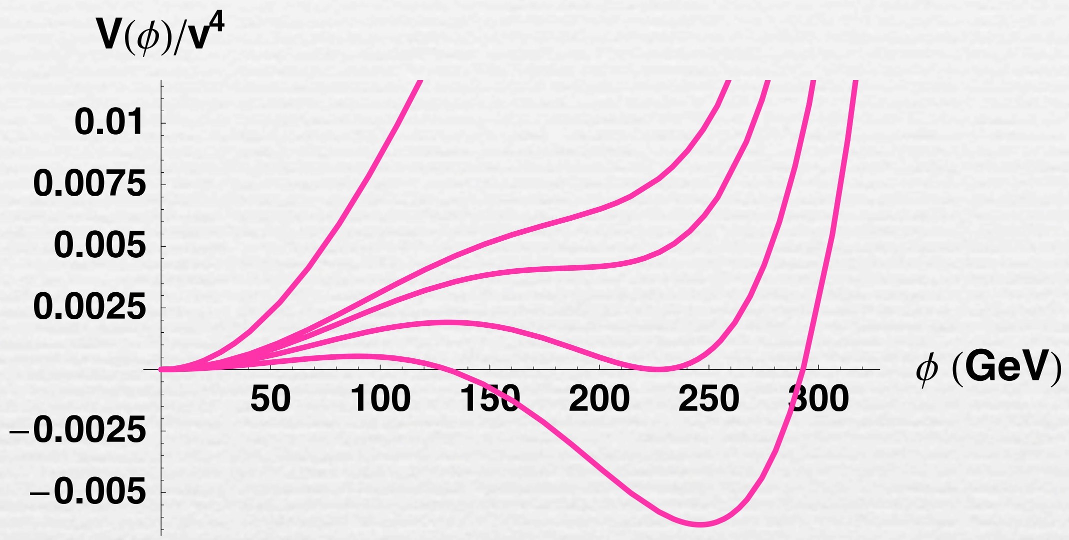
If no :

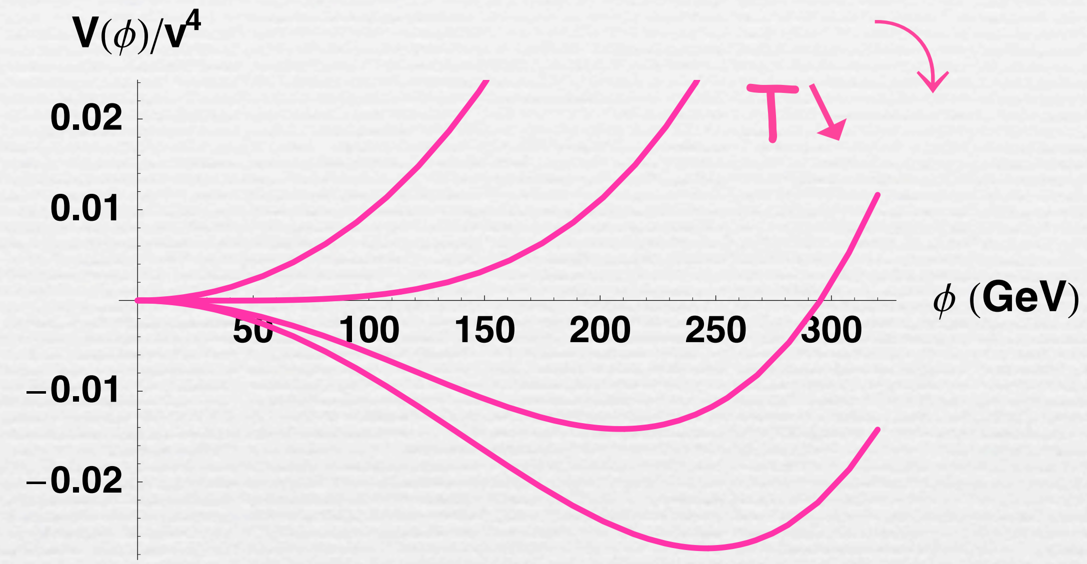
be ready for

- very tough searches at the (S)LHC (VLVL scattering, ...) or
- more spectacular phenomena such as W', Z' (KK) resonances, technicolor, etc...

What is the nature of the electroweak phase transition ?

first-order or second-order?





indispensable for reliable computations of electroweak baryogenesis

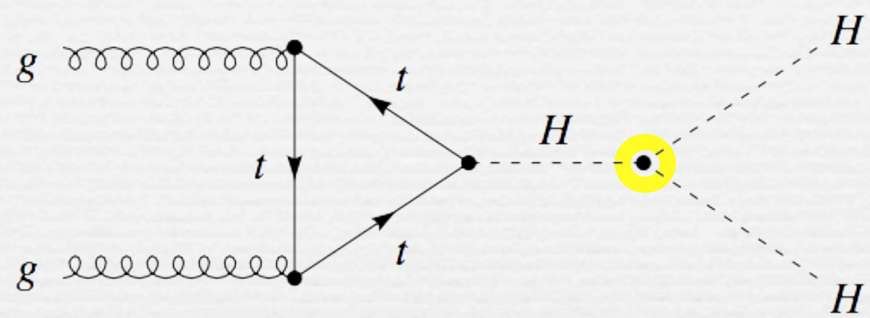
LHC will provide insight as it will shed light on the Higgs sector

Question intensively studied within the Minimal Supersymmetric Standard Model (MSSM). However, not so beyond the MSSM (gauge-higgs unification in extra dimensions, composite Higgs, Little Higgs, Higgsless...)

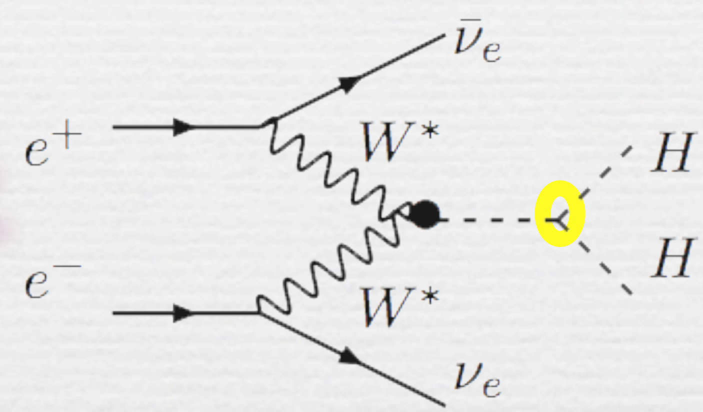
LHC will most likely not provide the final answer

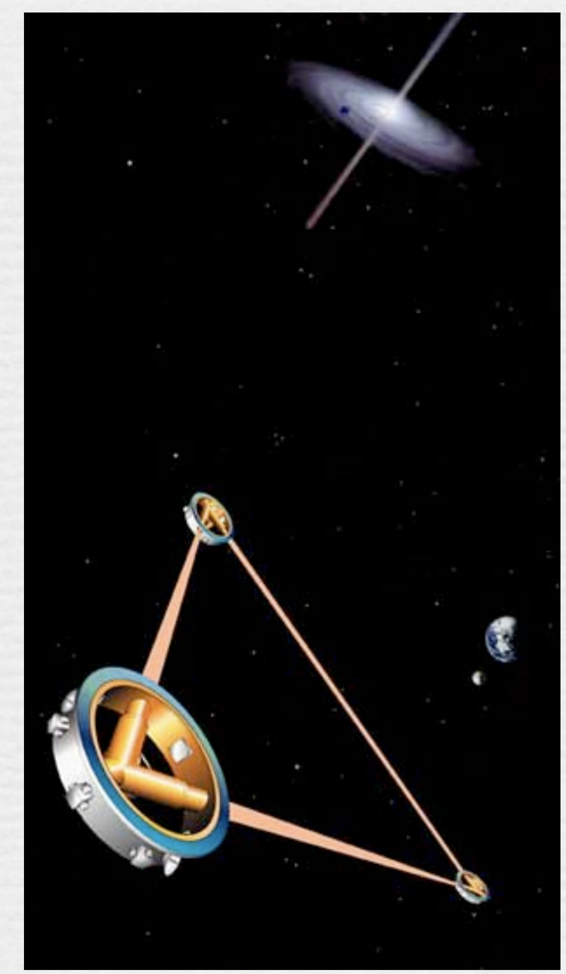
Experimental tests of the Higgs self-coupling

at a Hadron Collider

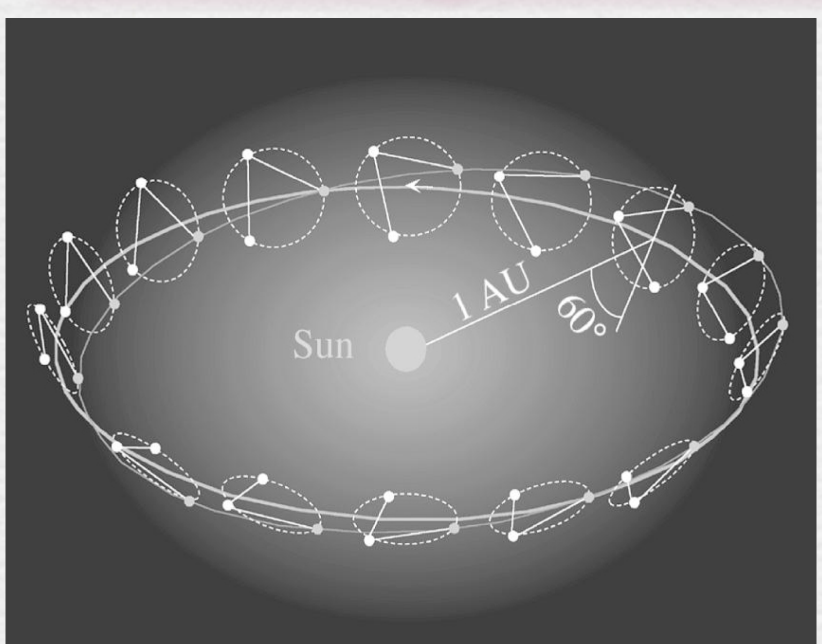


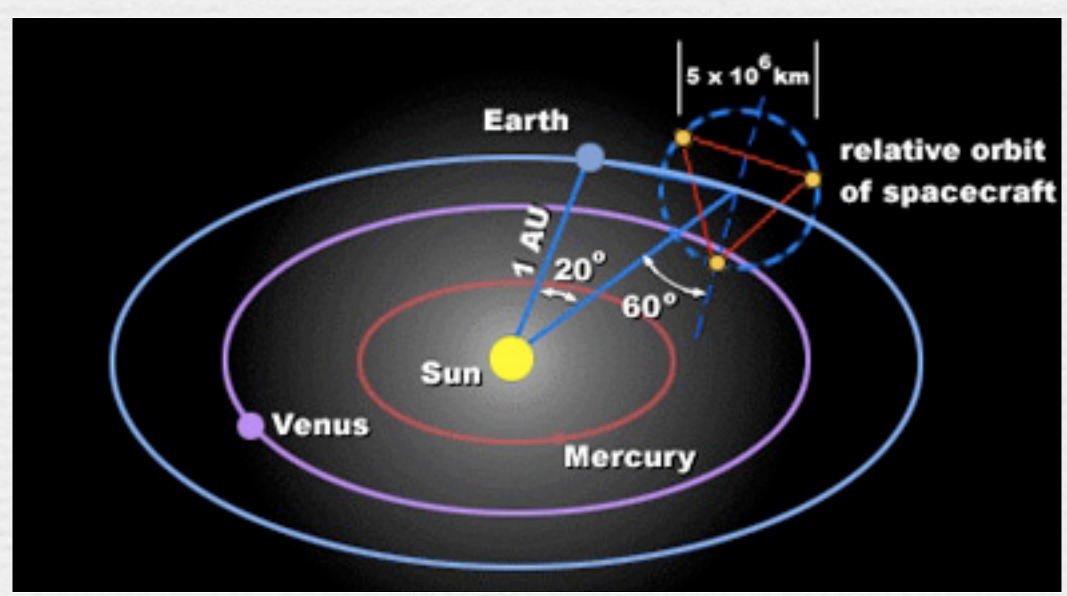
at an $e^+ e^-$ Linear Collider





... or at the gravitational wave detector LISA





Gravitational Waves: A way to probe astrophysics
... and high energy particle physics.

Gravitational Waves interact very weakly and are not absorbed

direct probe of physical process of the very early universe

Small perturbations in FRW metric:

$$ds^2 = a^2(\eta)(d\eta^2 - (\delta_{ij} + 2h_{ij})dx^i dx^j) \qquad G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\ddot{h}_{ij}(\mathbf{k},\eta) + \frac{2}{\eta}\dot{h}_{ij}(\mathbf{k},\eta) + k^2 h_{ij}(\mathbf{k},\eta) = 8\pi G a^2(\eta)\Pi_{ij}(\mathbf{k},\eta)$$

Source of GW: anisotropic stress

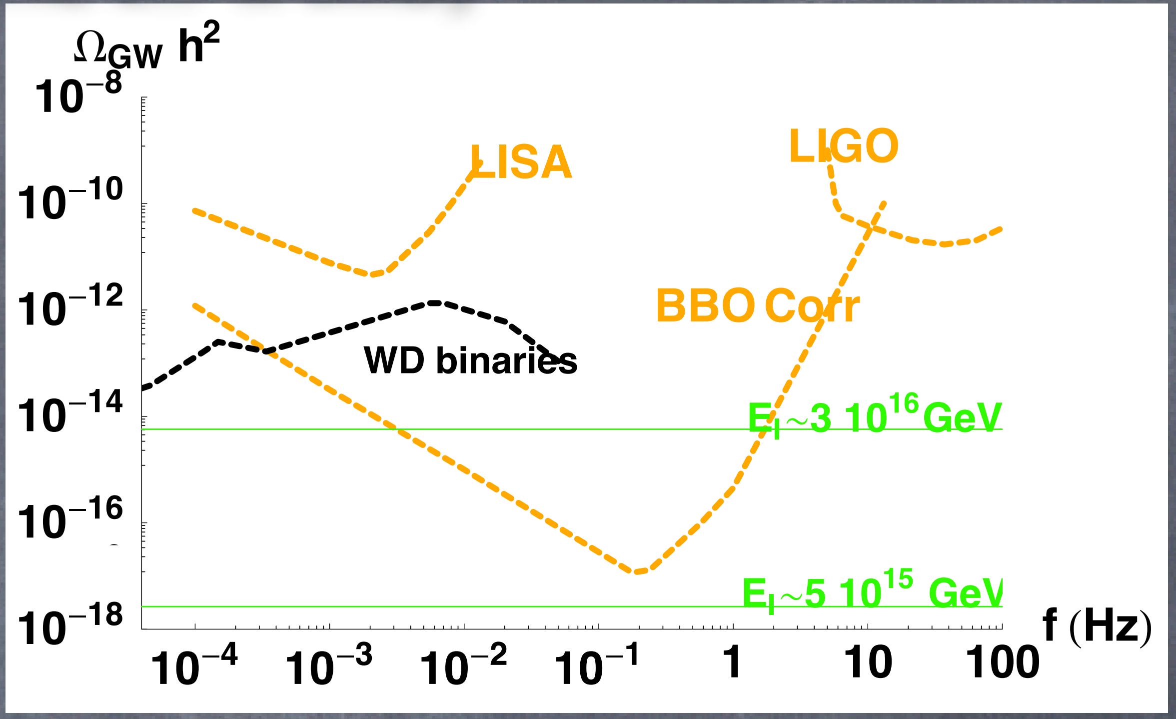
possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

frequency observed today:

$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6 \times 10^{-3}\text{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \text{GeV}} \frac{f_*}{H_*}$$

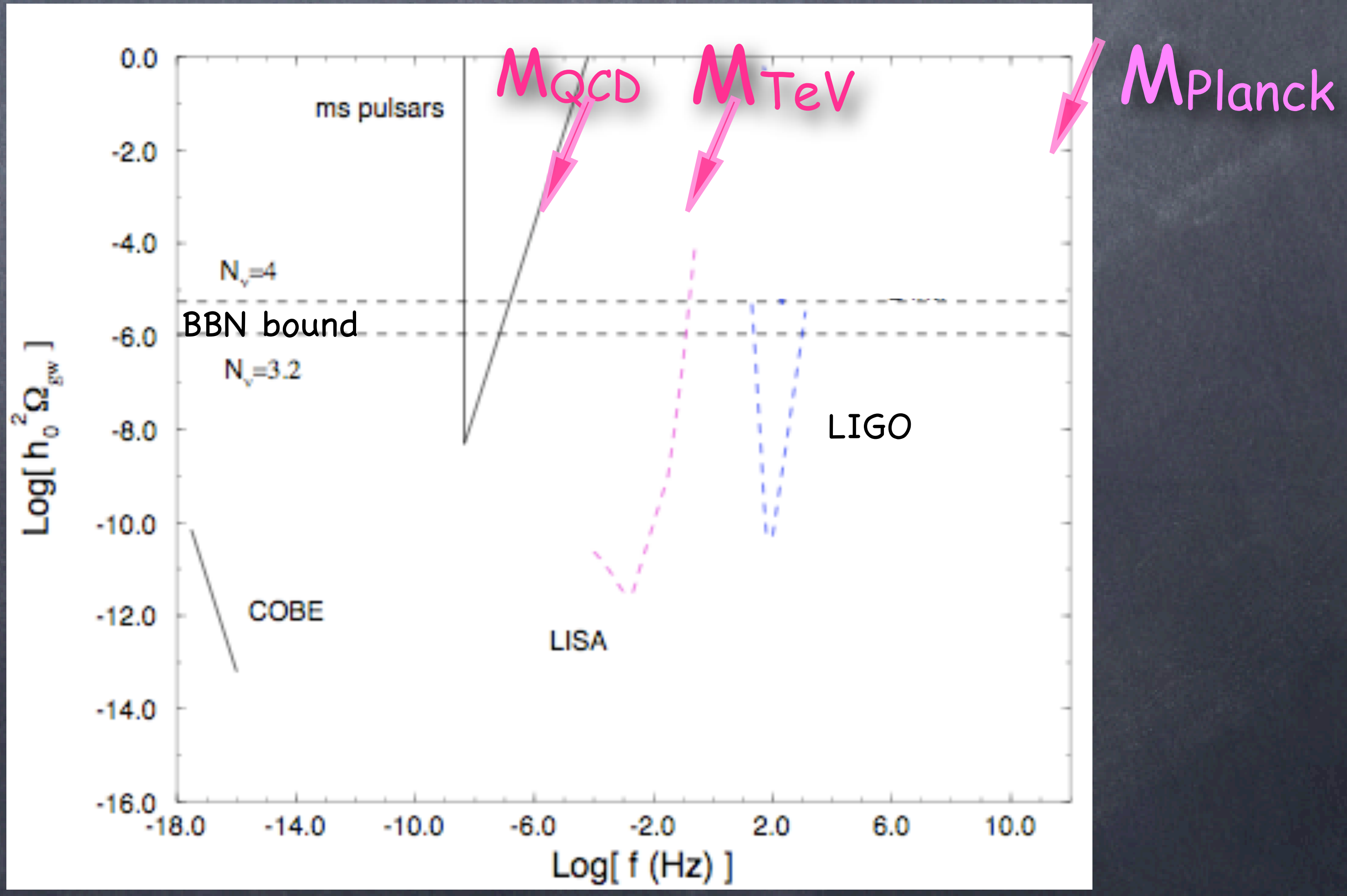
Beyond GW of astrophysical origin, another mission of GW astronomy will be to search for a stochastic background of gravitational waves of primordial origin (gravitational analog of the 2.7 K CMB)



Stochastic background: isotropic, unpolarized, stationary

GW energy density: $\Omega_G = \frac{\langle \dot{h}_{ij}\dot{h}^{ij}\rangle}{G\rho_c} = \int \frac{dk}{k}\frac{d\Omega_G(k)}{d\log(k)}$

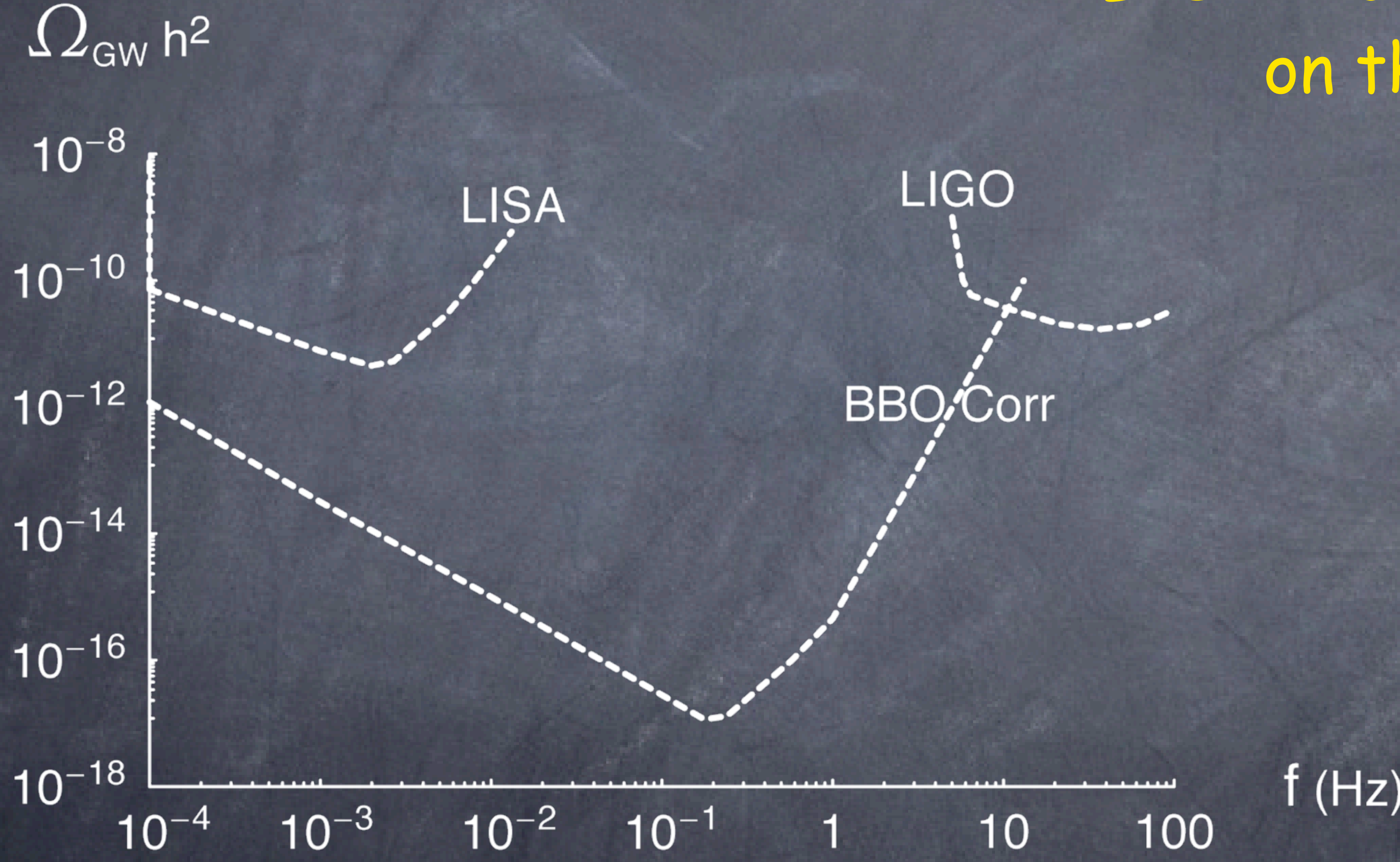
A huge range of frequencies



from Maggiore

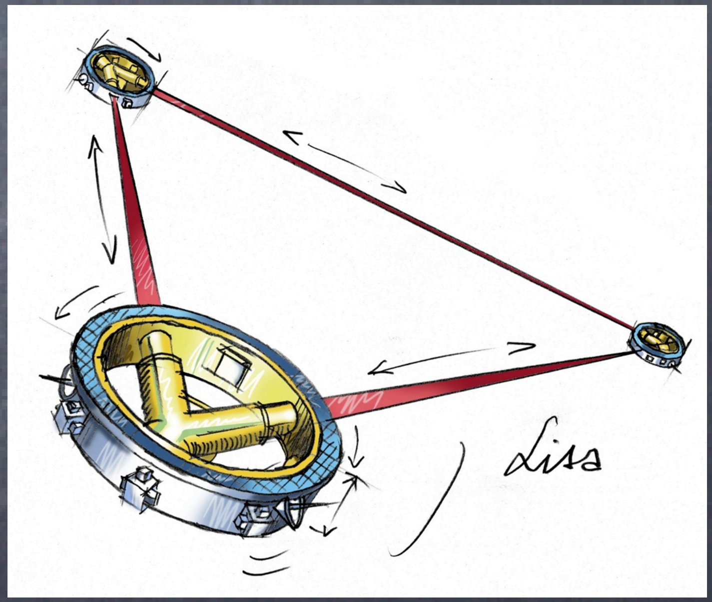
Why should we be excited about mHZ freq.?

$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6 \times 10^{-3} \mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \mathrm{GeV}} \frac{f_*}{H_*}$$



LISA: Could be a new window on the Weak Scale

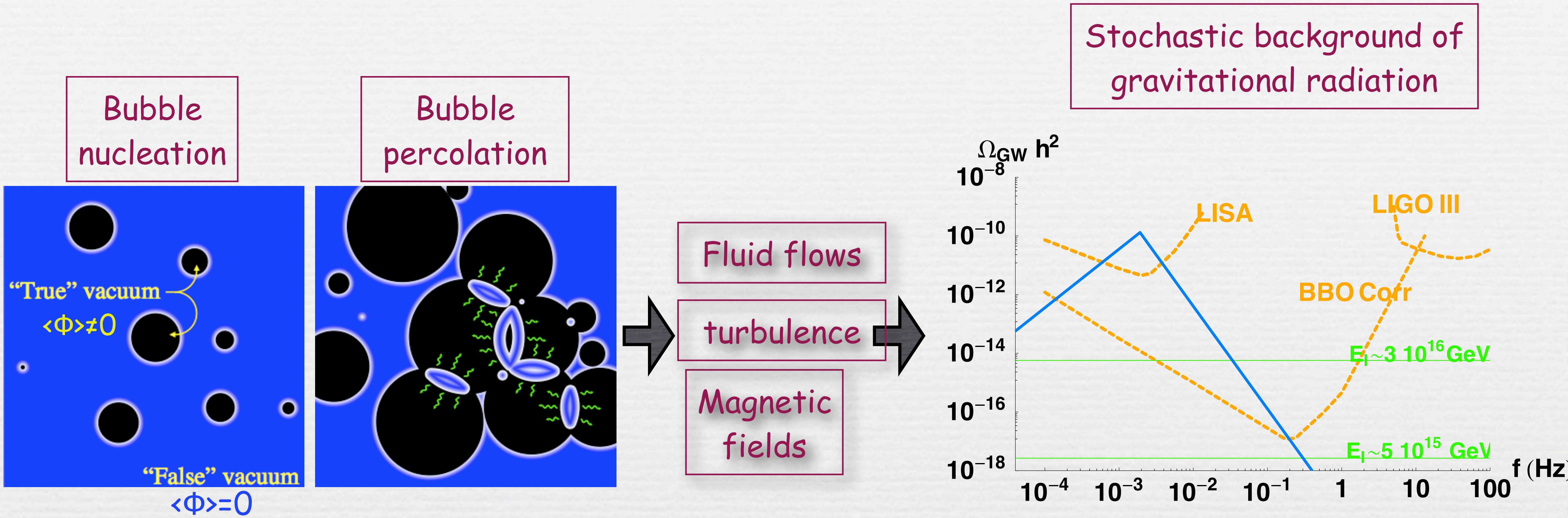
LISA band:
$10^{-4} - 10^{-2}$ Hz



complementary to collider informations

Which weak scale physics?

⇒ strong 1st order phase transition



violent process if v_b ~O(1)

- test of the dynamics of the phase transition
- relevant to models of EW baryogenesis
- reconstruction of the Higgs potential/study of new models of EW symmetry breaking (little higgs, gauge-higgs,composite higgs,higgsless...)

A not so new subject...

first suggestion: Witten'84

- Early 90's, M. Turner & al studied the production of GW produced by bubble collisions. Not much attention since the LEP data excluded a 1st order phase transition within the SM.

Kosowsky, Turner, Watkins'92
Kamionkowski, Kosowsky, Turner '94

- '01-'02: Kosowsky et al. and Dolgov et al. computed the production of GW from turbulence. Application to the (N)MSSM where a 1st order phase transition is still plausible.

Kosowsky, Mack, Kahniashvili'02
Dolgov, Grasso, Nicolis'02
Caprini, Durrer '06

Revival in 2006:

⇛ Model-independent analysis for detectability of GW from 1st order phase transitions

Grojean, Servant '06

⇛ Apply to Randall-Sundrum phase transition

Randall, Servant'06

⇛ Revisit the Turner et al original calculation

Caprini, Durrer, Servant'07'
Huber, Konstandin'08'

key quantities controlling the GW spectrum

$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 8\pi G a^2 T_{ij}^{(TT)}(k,t)$$

$$T_{ab}(\mathbf{x}) = (\rho + p)\frac{v_a(\mathbf{x})v_b(\mathbf{x})}{1 - v^2(\mathbf{x})}$$

Source of GW: anisotropic stress

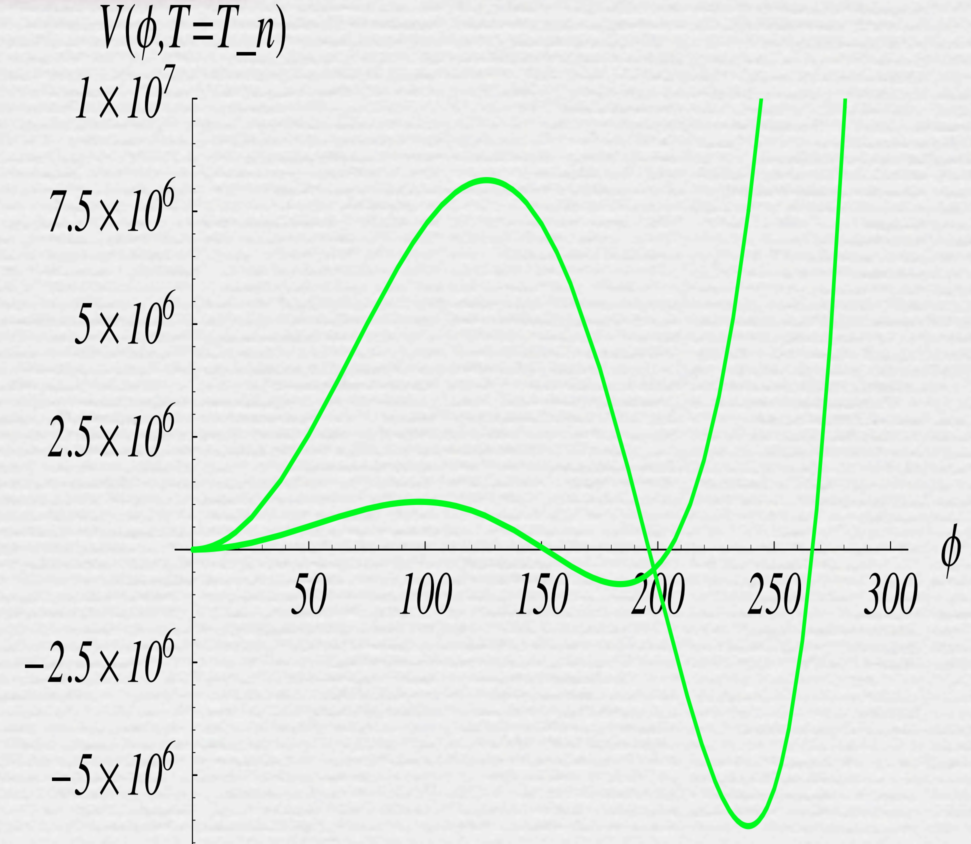
β : (duration of the phase transition)$^{-1}$

set by the tunneling probability $P \propto e^{\beta t} \propto \frac{T^4}{H^4} e^{-S_3/T} \sim 1$ ➔ $\frac{S_3}{T} \sim 140$

and typically $\frac{\beta}{H} \sim \mathcal{O}(10^2 - 10^3)$

α : vacuum energy density/radiation energy density

α and β : entirely determined by the effective scalar potential at high temperature



Estimate of the GW energy density at the emission time

$$\rho_{GW} \sim \dot{h}^2 / 16\pi G$$

$$\delta G_{\mu\nu} = 8\pi G T_{\mu\nu} \longrightarrow \beta^2 h \sim 8\pi G T \longrightarrow \dot{h} \sim 8\pi G T/\beta$$

where $T \sim \rho_{kin} \sim \rho_{rad}\, v^2$

$$\Omega_{GW_*} = \frac{H_*^2}{\beta^2} \frac{\rho_{kin}{}^2}{\rho_{tot}{}^2}$$

$\rho_{kin}{}^2 \to \kappa^2 \alpha^2 v^4$

$$\Omega_{GW_*} \propto \frac{H_*^2}{\beta^2} \kappa^2 \frac{\alpha^2}{(\alpha+1)^2} v^4$$

κ : fraction of vacuum energy transformed into bulk fluid motions

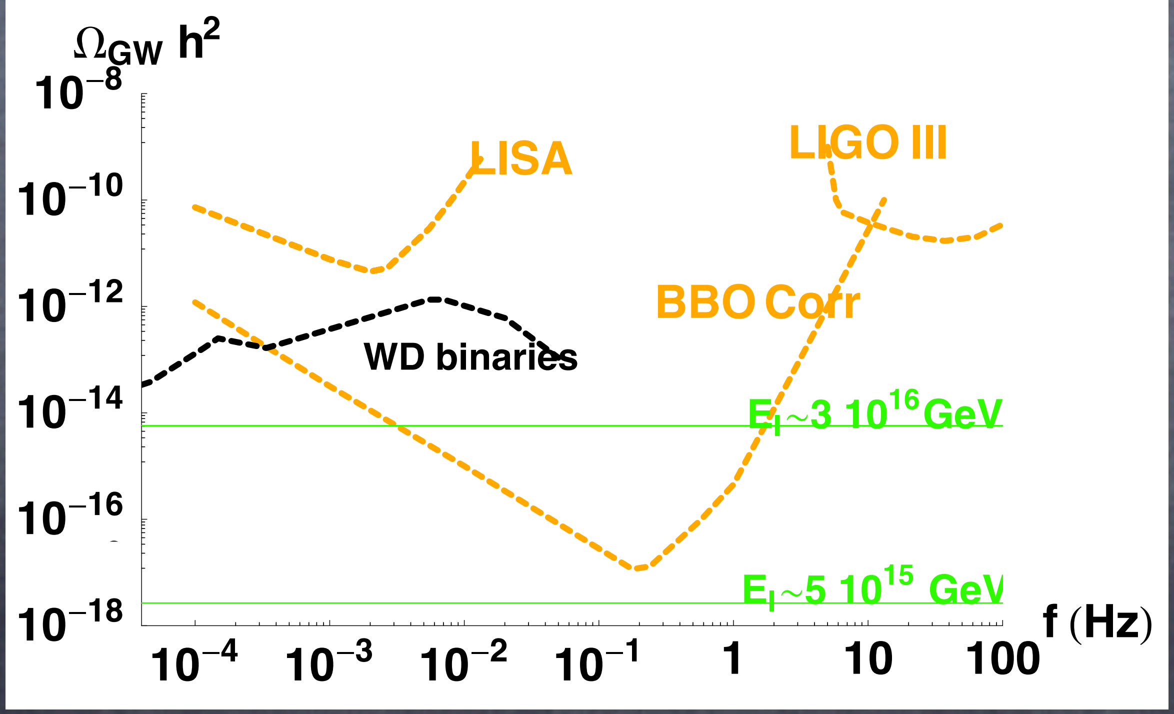
3 parameters: α, β, v

Fraction of the critical energy density in GW today

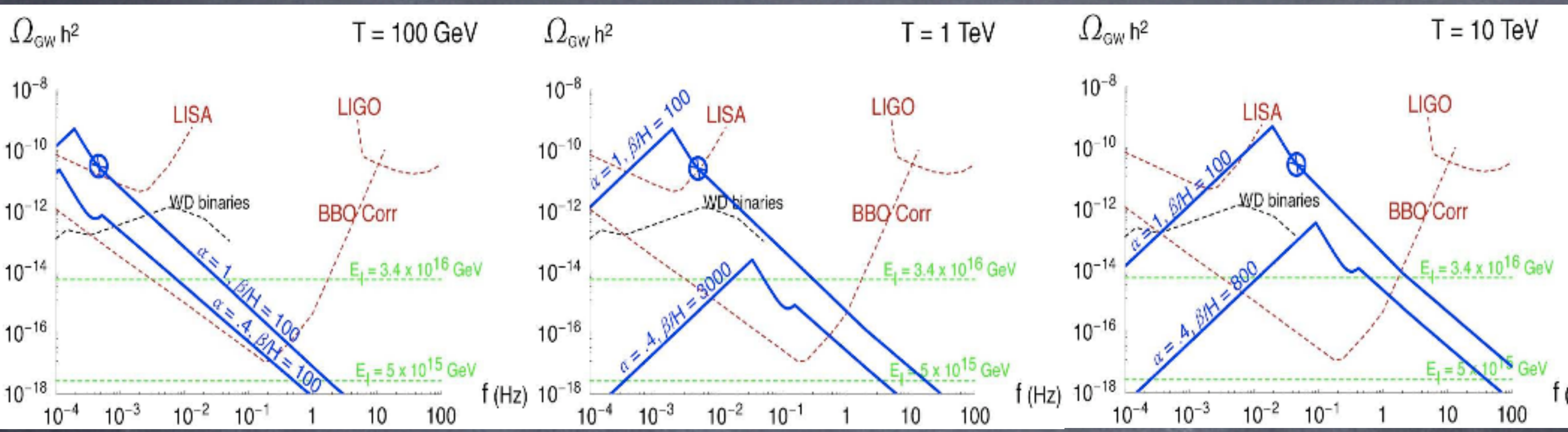
$$\Omega_{GW} = \frac{\rho_{GW}}{\rho_c} = \Omega_{GW*}\left(\frac{a_*}{a_0}\right)^4\left(\frac{H_*}{H_0}\right)^2 \simeq 1.67\times 10^{-5}h^{-2}\left(\frac{100}{g_*}\right)^{1/3}\Omega_{GW*}$$

Ω_{GW*} has to be big ($\gtrsim 10^{-6}$ for LIGO/LISA and $\gtrsim 10^{-12} - 10^{-9}$ for BBO)

where we used: $\rho_{GW} = \rho_{GW*}\left(\frac{a_*}{a_0}\right)^4$, $\rho_c = \rho_{c*}\frac{H_0^2}{H_*^2}$ and $H_0 = 2.1332\times h\times 10^{-42}\text{GeV}$

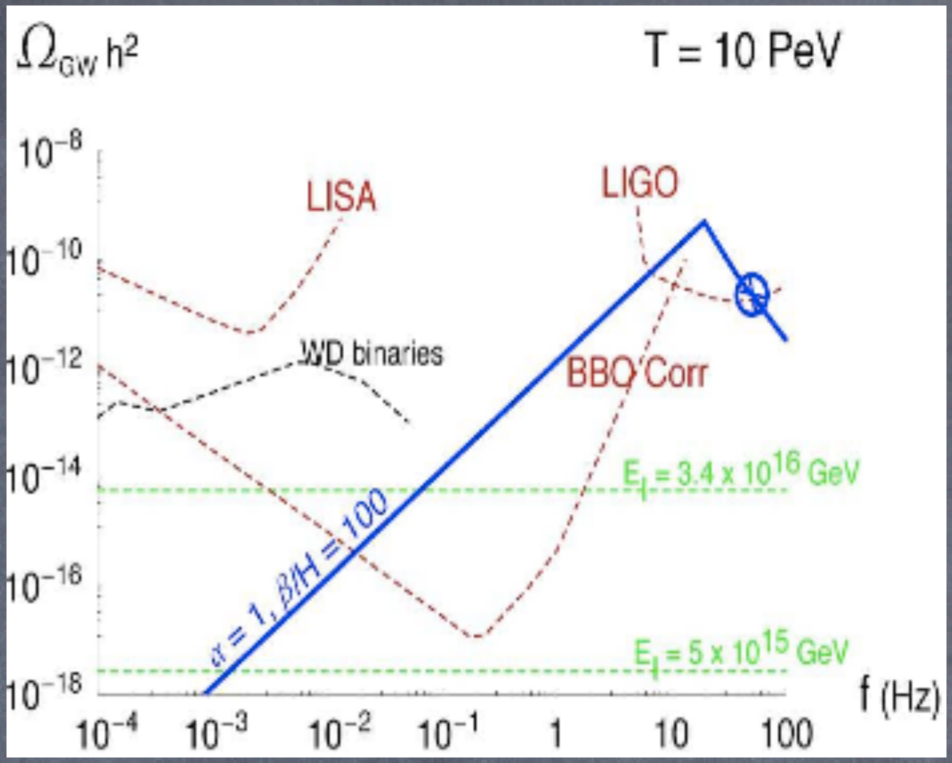


Spectrum of gravitational waves produced at 1rst order phase transitions

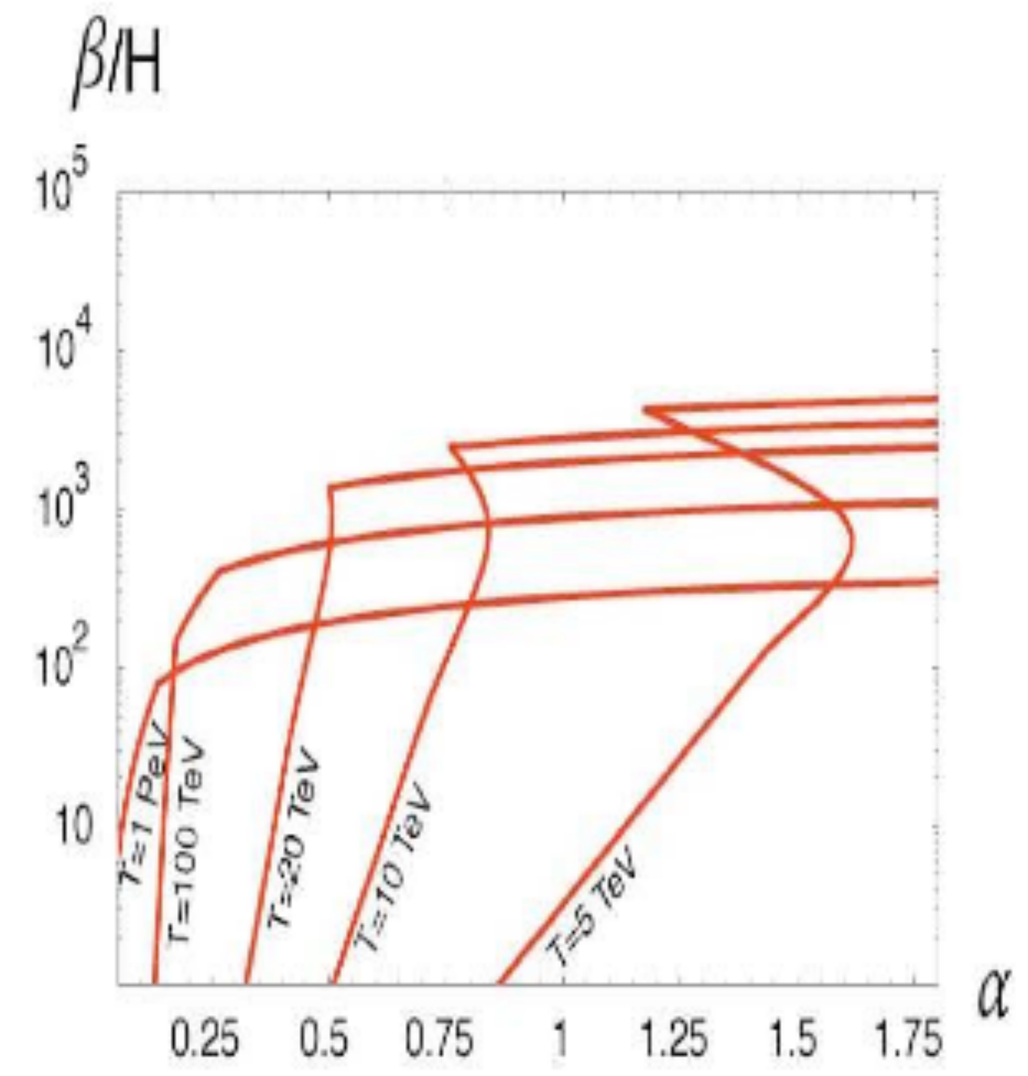


$$f_{\rm peak} \sim 10^{-2}\ {\rm mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ {\rm GeV}}\ \frac{\beta}{H_*}\ \frac{1}{v}$$

A phase transition at $T \sim 10^7$ GeV could be observed both at LIGO and BBO:



GW from phase transitions could entirely mask the GW signal expected from inflation:



What to expect for the EW phase transition

In the SM, a 1rst-order phase transition can occurr due to thermally generated cubic Higgs interactions:

$$V(\phi,T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - ET\phi^3$$

$$-ET\phi^3 \subset -\frac{T}{12\pi}\sum_i m_i^3(\phi)$$

Sum over all bosons which couple to the Higgs

In the SM: $\sum_i \simeq \sum_{W,Z}$ ⇒ not enough

mh<35 GeV would be needed to get Φ/T>1 and for mh >72 GeV, the phase transition is 2nd order

Strength of the transition in the SM:

$$\langle\phi(T_c)\rangle = \frac{2\ E\ T_c}{\lambda} \quad \Rrightarrow \quad \frac{\langle\phi(T_c)\rangle}{T_c} = \frac{2\ E\ v_0^2}{\lambda\ v_0^2} = \frac{4\ E\ v_0^2}{m_h^2}$$

$$v_0 \approx 246\ \text{GeV} \quad \text{and} \quad E = \frac{2}{3}\frac{2m_W^3 + m_Z^3}{4\pi v_0^3} \sim 6.3 \times 10^{-3}$$

$$\frac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1 \longrightarrow m_h \lesssim 47\ \text{GeV}$$

Effective field theory approach

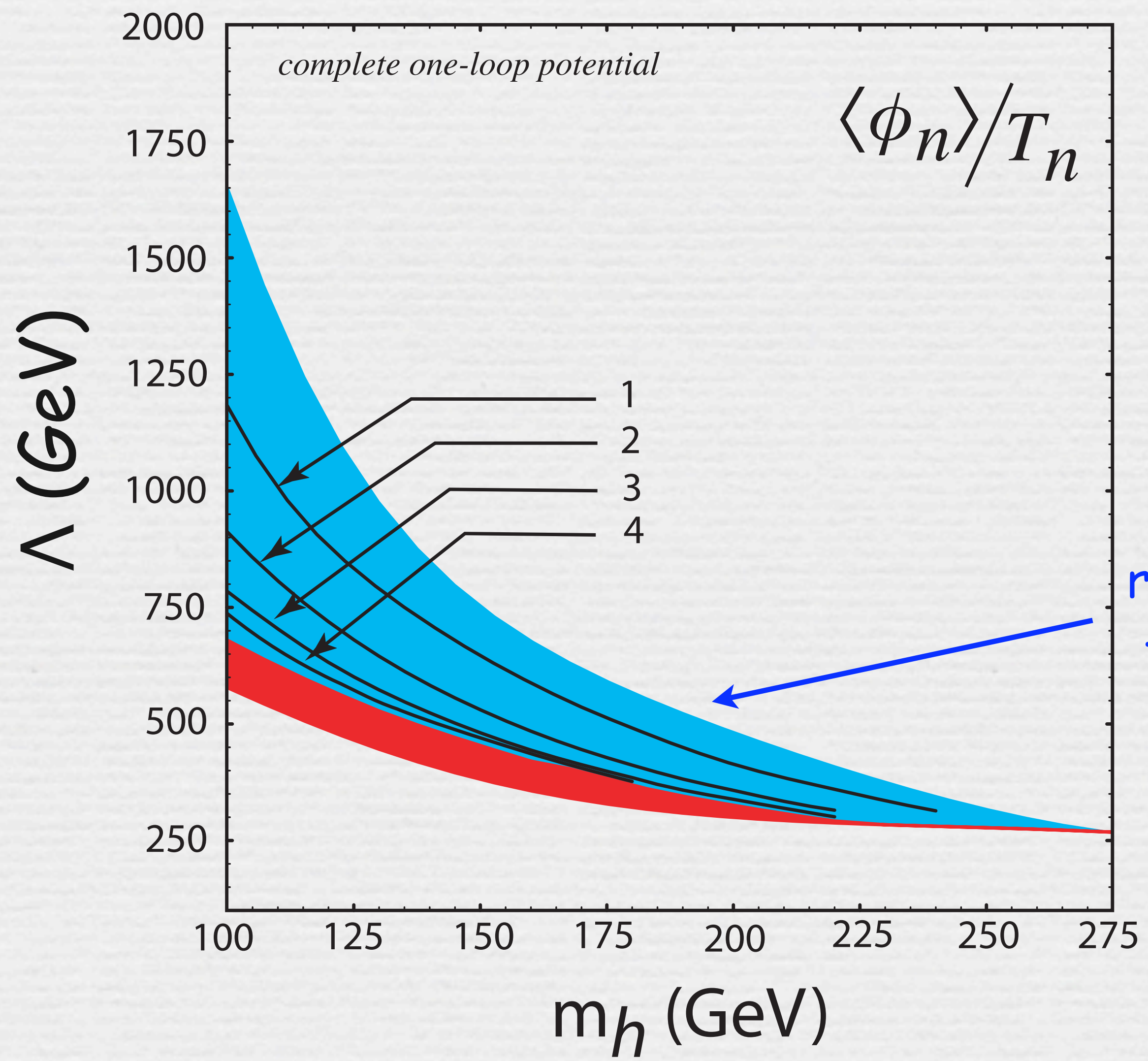
add a non-renormalizable Φ^6 term to the SM Higgs potential and allow a negative quartic coupling

$$V(\Phi) = \mu_h^2 |\Phi|^2 - \lambda |\Phi|^4 + \frac{|\Phi|^6}{\Lambda^2}$$

"strength" of the transition does not rely on the one-loop thermally generated negative self cubic Higgs coupling

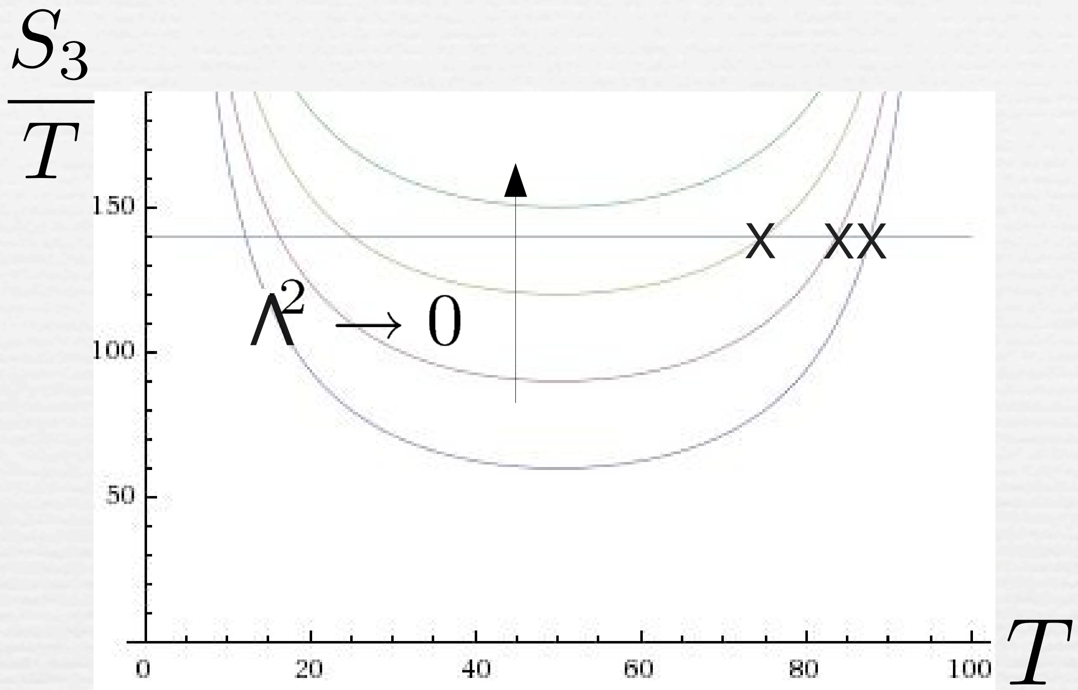
Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

strong enough for EW baryogenesis if $\Lambda \lesssim 1.3$ TeV

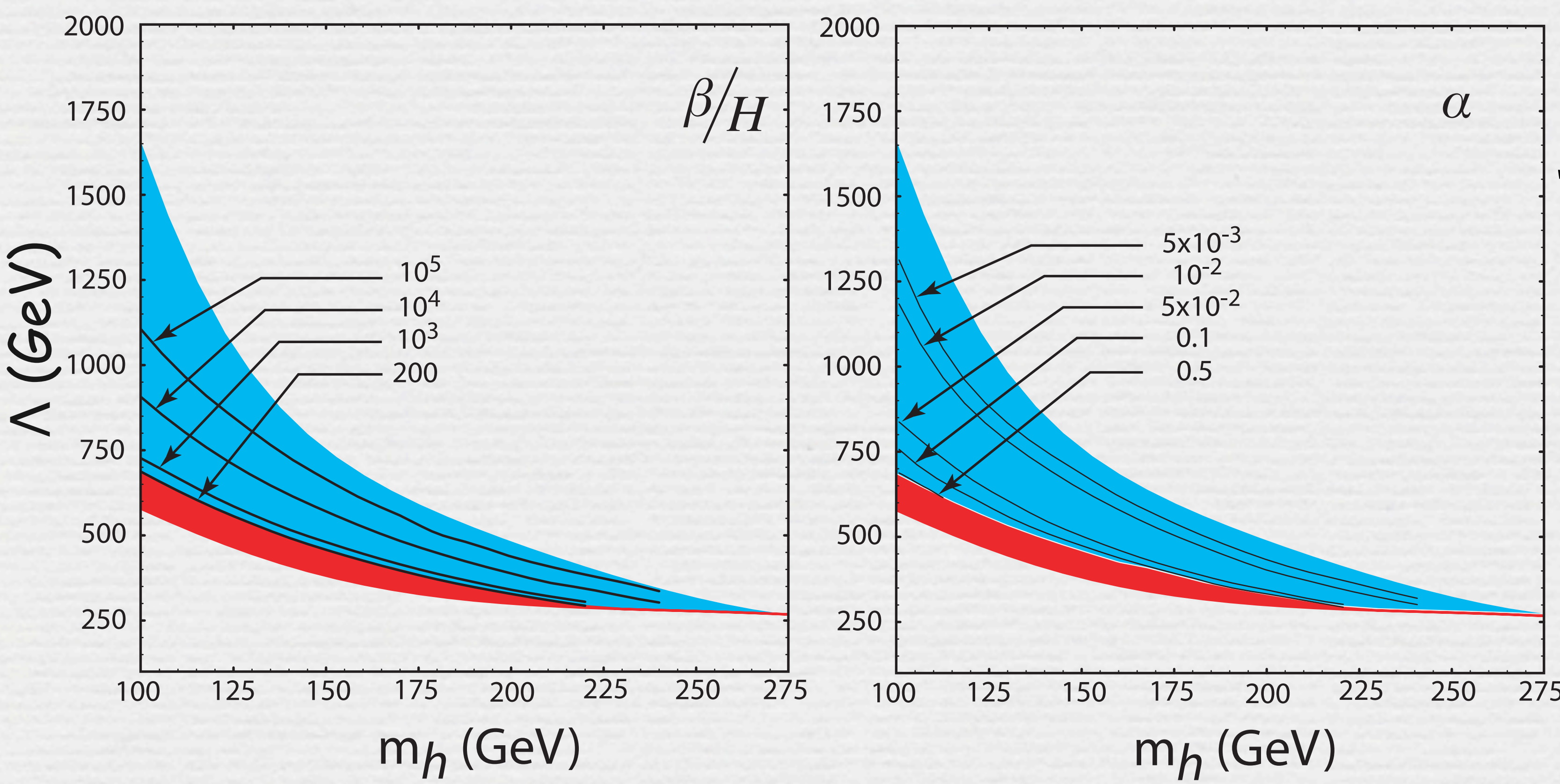


region where EW phase transition is 1st order

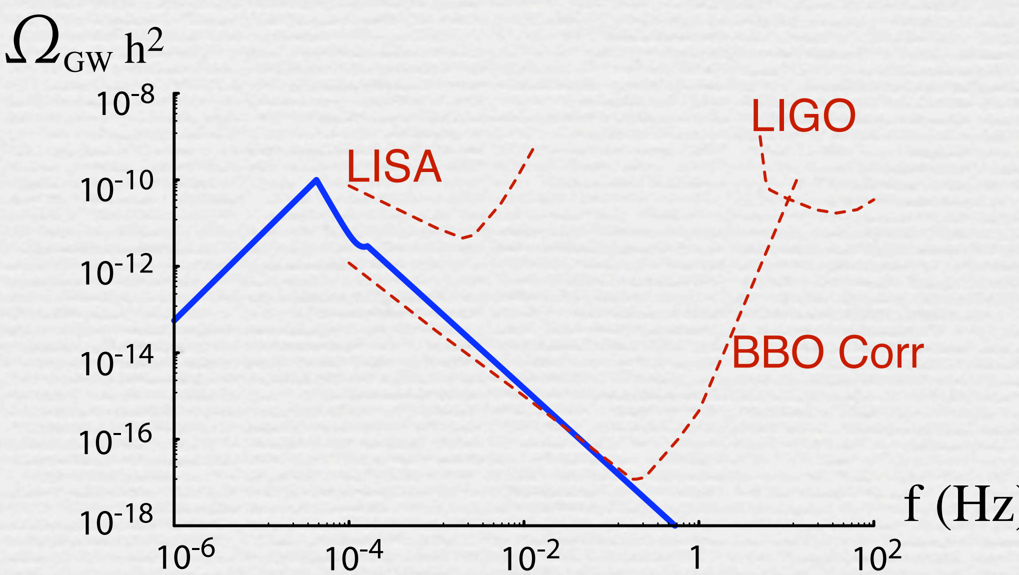
BUT...



as $\Lambda \searrow$, $T \searrow$, $\alpha \nearrow$ and $\frac{\beta}{H} \searrow$



peak is shifted out of the LISA range

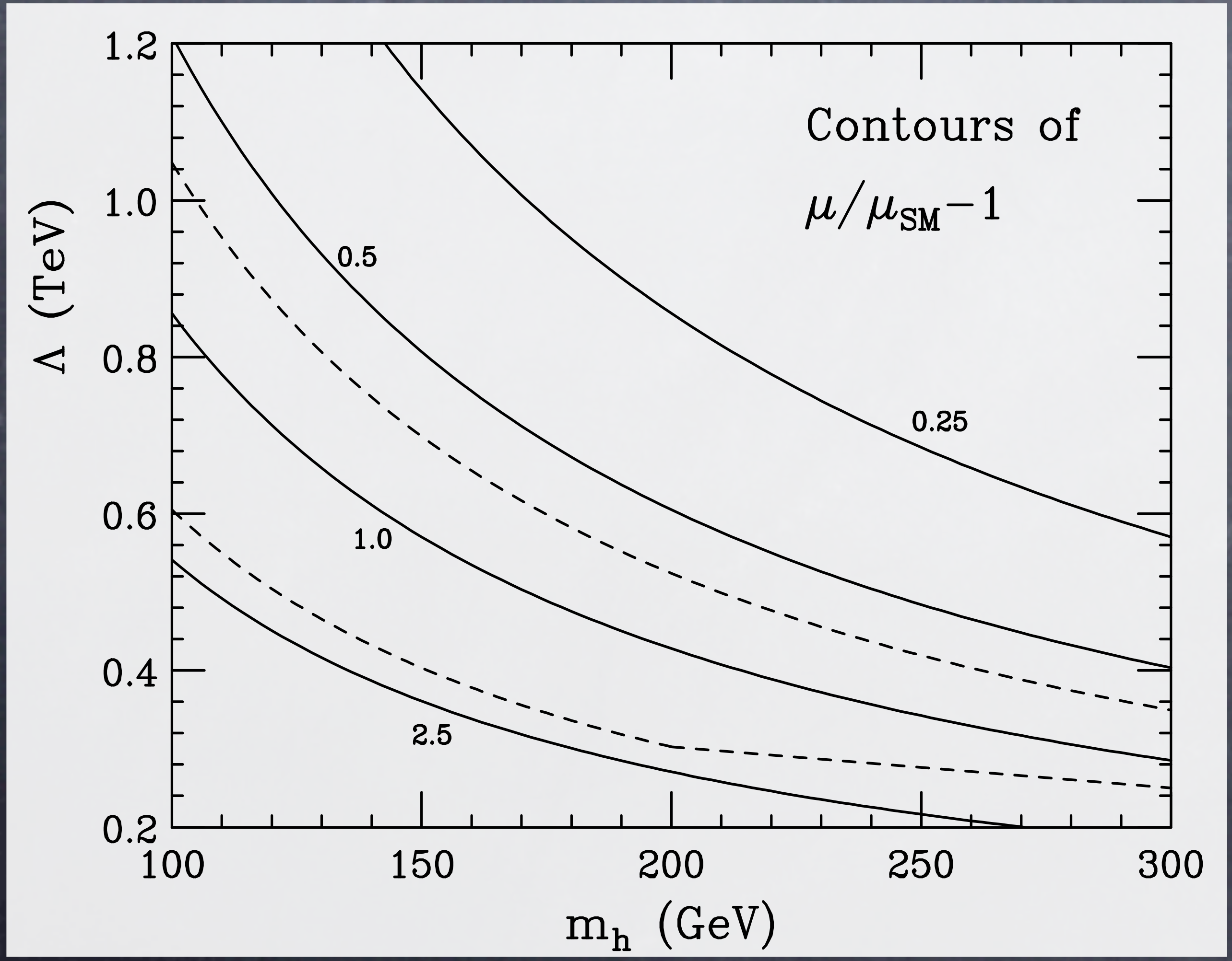


This scenario predicts large deviations to the Higgs self-couplings

$$\mathcal{L} = \frac{m_H^2}{2} H^2 + \frac{\mu}{3!} H^3 + \frac{\eta}{4!} H^4 + \ldots \quad \textit{where}$$

$$\mu = 3\frac{m_H^2}{v_0} + 6\ \frac{v_0^3}{\Lambda^2}$$

$$\eta = 3\frac{m_H^2}{v_0^2} + 36\ \frac{v_0^2}{\Lambda^2}$$



The dotted lines delimit the region for a strong 1rst order phase transition

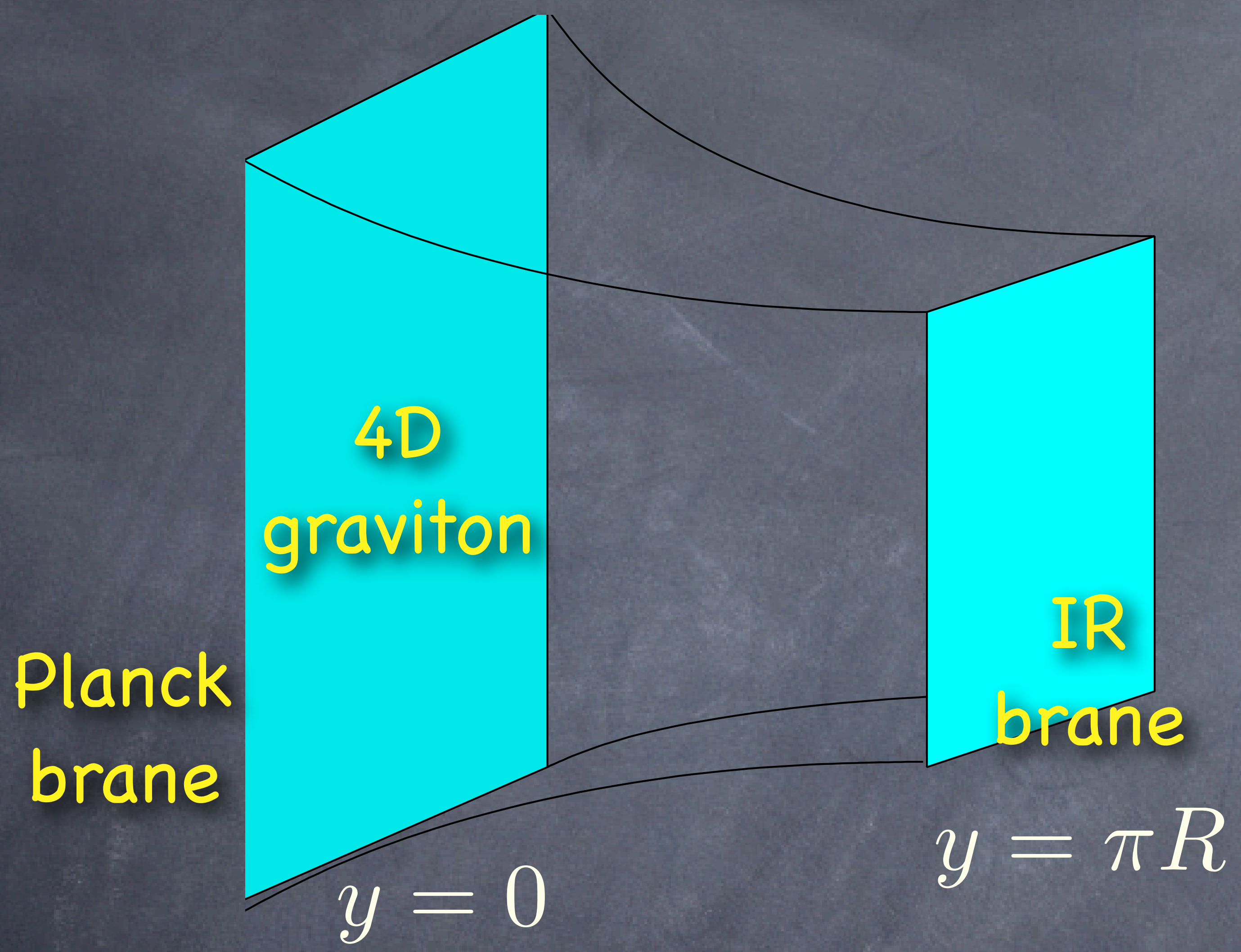
deviations between a factor 0.7 and 2

Gravitational Waves from Warped Extra-Dimensional Geometry

Randall-Servant '07

Space-time is a slice of AdS_5

[Randall, Sundrum '99]



$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

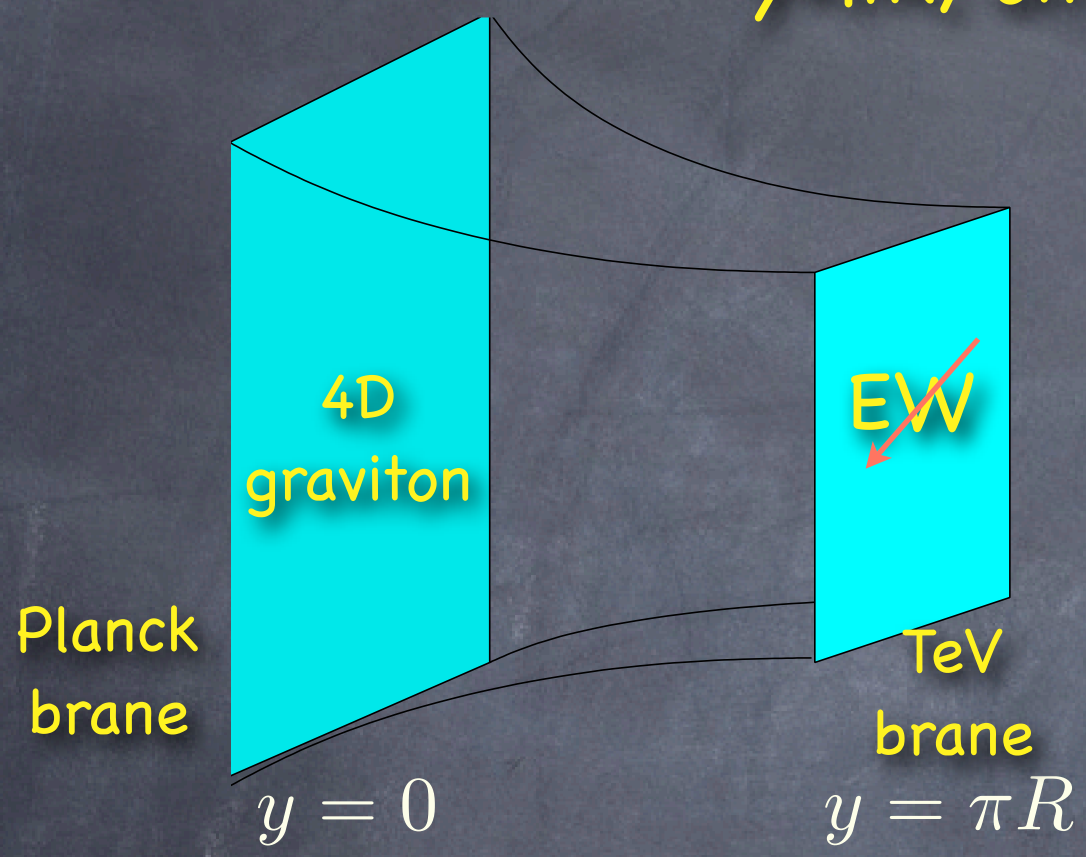
$$M_{Pl}^2 \sim \frac{M_5^3}{k}$$

The effective 4D energy scale varies with position along 5th dimension

RS1 (has two branes) versus RS2 (only Planck brane)

Solution to the Planck/Weak scale hierarchy

The Higgs (or any alternative EW breaking) is localized at y=πR, on the TeV (IR) brane



After canonical normalization of the Higgs:

$$v_{\rm eff} = v_0 e^{-k\pi R}$$

parameter in the 5D lagrangian

$$k\pi R \sim \log(\frac{M_{Pl}}{\rm TeV})$$

Exponential hierarchy from O(10) hierarchy in the 5D theory

One Fondamental scale : $M_5 \sim M_{Pl} \sim k \sim \Lambda_5/k \sim r^{-1}$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

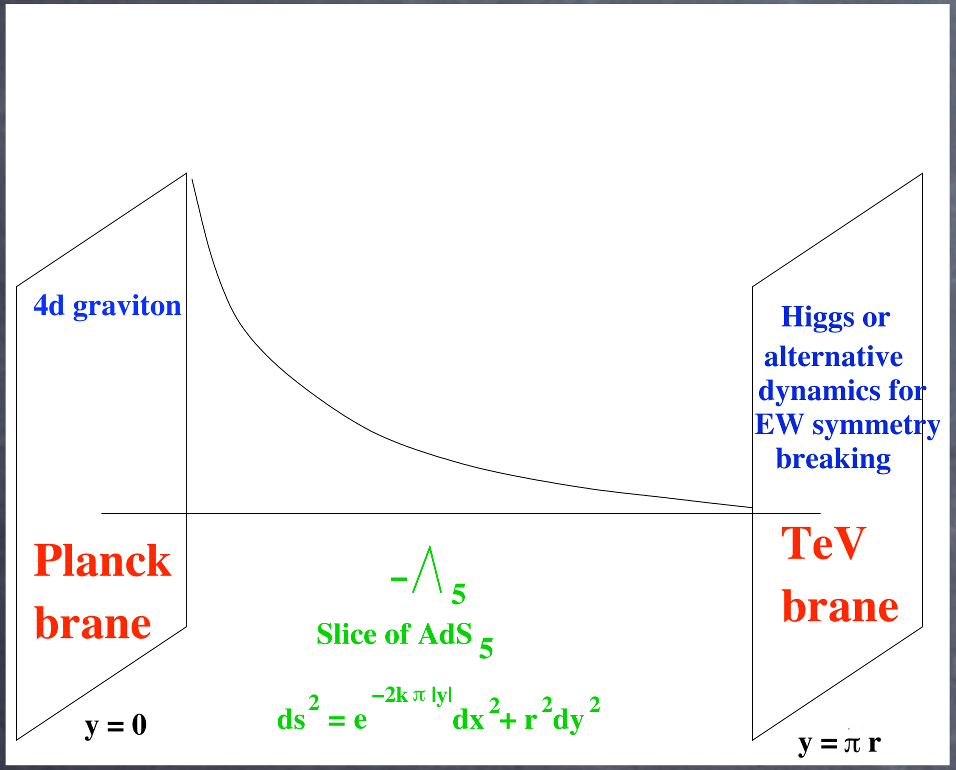
$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

Warped hierarchies are radiatively stable as cutoff scales get warped down near the IR brane

Cosmology of the Randall-Sundrum model

At high T: AdS-Schwarzchild BH solution with event horizon shielding the TeV brane

At low T: usual RS solution with stabilized radion and TeV brane



Natural stabilisation of radius à la Goldberger-Wise :

$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

Randall-Sundrum phase transition

Creminelli-Nicolis-Rattazzi '01

Assuming the universe started at T>> Tc, the PT has to take place if we want a RS set-up at low T.

Start with a black brane, nucleate "gaps" in the horizon which then grow until they take over the entire horizon.

Completion of the phase transition

a five-dimensional set-up
but we can treat this as bubble nucleation in four dimensions

Low energies: radion dominates potential

High energies: holography

$$(M/k)^3 \sim N^2/16\pi^2$$

Need N large

Goldberger-Wise mechanism

Start with the bulk 5d theory $\mathcal{L} = \int dx^4 dz \sqrt{-g}[2M^3\mathcal{R} - \Lambda_5]$ $\quad \Lambda_5 = -24M^3k^2$

The metric for RS1 is $ds^2 = (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2)$ where $k = L^{-1}$ is the AdS curvature

$$= e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2 \qquad z = k^{-1}e^{ky}$$

and the orbifold extends from $z=z_0=L$ (Planck brane) to $z=z_1$ (TeV brane)

Which mechanism naturally selects $z_1 \gg z_0$? simply a bulk scalar field φ can do the job:

$$\int d^4x dz \left(\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2] + \delta(z - z_0)\sqrt{g_0}L_0(\phi(z)) + \delta(z - z_1)\sqrt{g_1}L_1(\phi(z))\right)$$

φ has a bulk profile satisfying the 5d Klein-Gordon equation

$$\phi = Az^{4+\epsilon} + Bz^{-\epsilon} \qquad \text{where} \qquad \epsilon = \sqrt{4 + m^2L^2} - 2 \approx m^2L^2/4$$

Plug this solution into $V_{eff} = \int_{z_0}^{z_1} dz\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2]$

$$V_{\rm GW} = z_1^{-4}\left[(4 + 2\epsilon)\left(v_1 - v_0\left(\frac{z_0}{z_1}\right)^\epsilon\right)^2 - \epsilon v_1^2\right] + \mathcal{O}(z_0^4/z_1^8) = z_1^{-4}P(z_1^{-\epsilon})$$

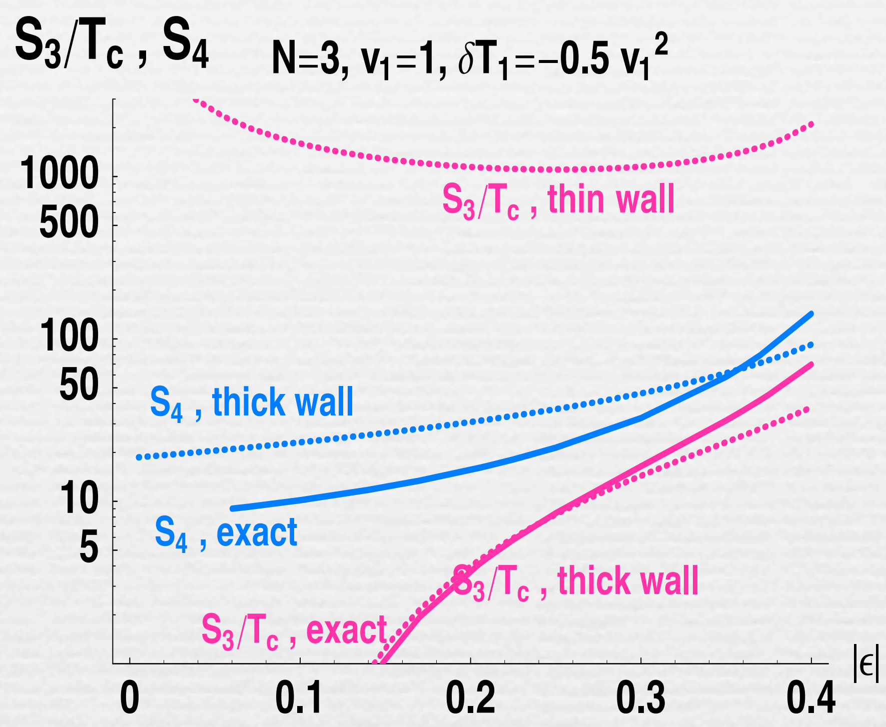
$$z_1 \approx z_0\left(\frac{v_0}{v_1}\right)^{1/\epsilon}$$

~ scale invariant fn modulated by a slow evolution through the $z^{-\epsilon}$ term

similar to Coleman-Weinberg mechanism

typically strong first-order PT, large supercooling

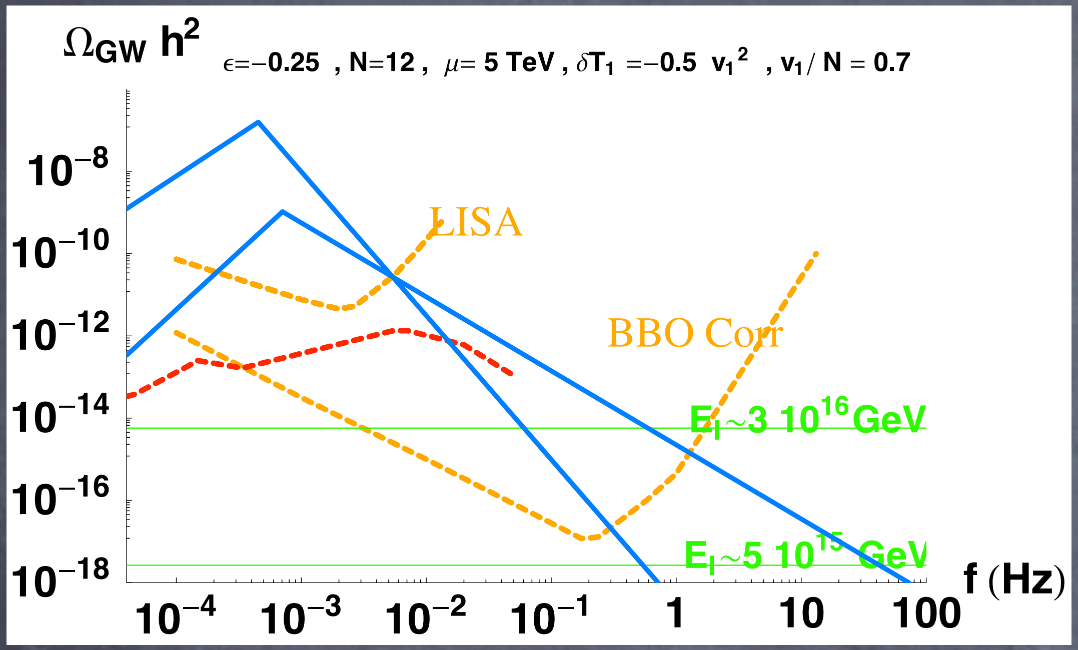
near conformal dynamics -> $T_n \ll \mu_{TeV}$, large α, small β/H

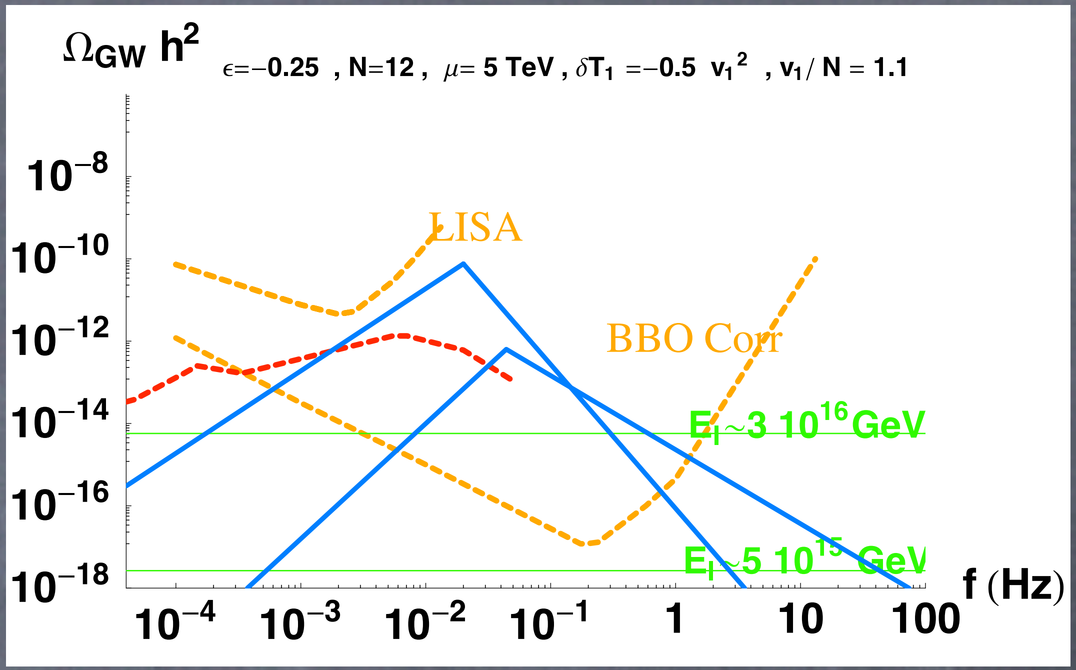


Randall-Servant'06

Gravitational Waves from "3-brane" nucleation:

Signal versus LISA's sensitivity





Randall-Servant'06

Signature in GW is generic,

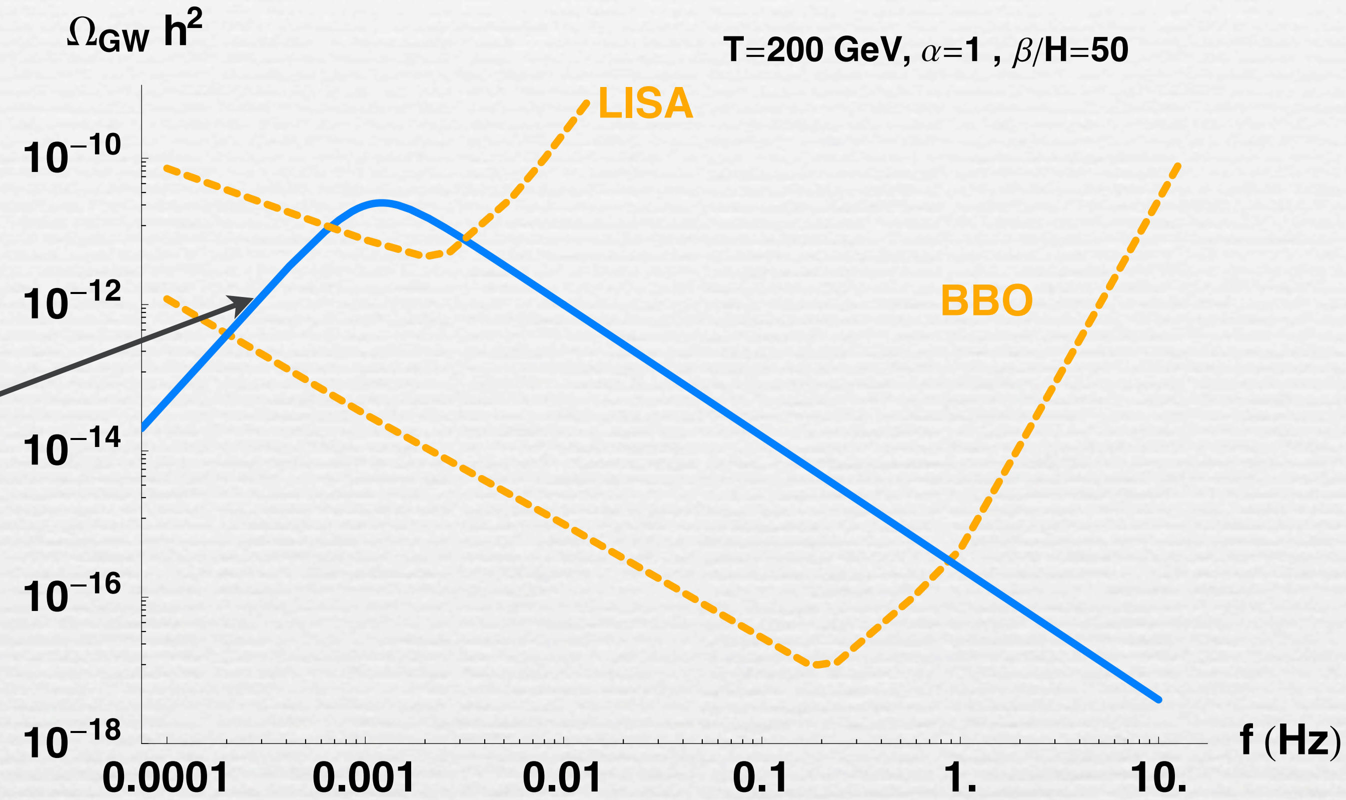
i.e. does not depend whether Standard Model is in bulk or on TeV brane

but crucially depends on the radion properties

Conclusion

We might be learning something about the Higgs/radion by looking at the sky

Expected shape of the GW spectrum



large scale part of the GW spectrum

~ f^3

$$\frac{d\Omega_G}{d\ln k} = \frac{k^3|\dot{h}|^2}{G\rho_c}$$

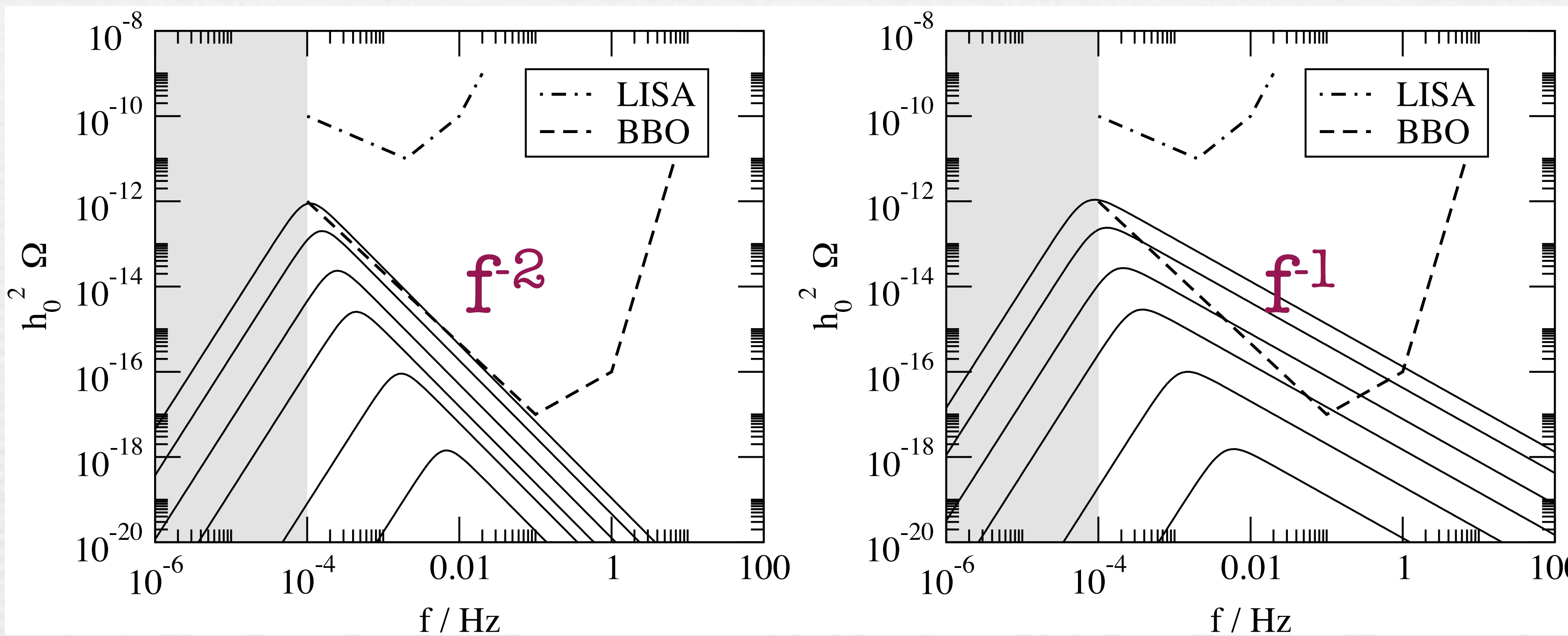
$$h_{ij}(\mathbf{k},\eta) = \int_{\eta_{\rm in}}^{\eta} d\tau \mathcal{G}(\tau,\eta)\Pi_{ij}(\mathbf{k},\tau)$$

white noise for the anisotropic stress -> k^3 for the energy density

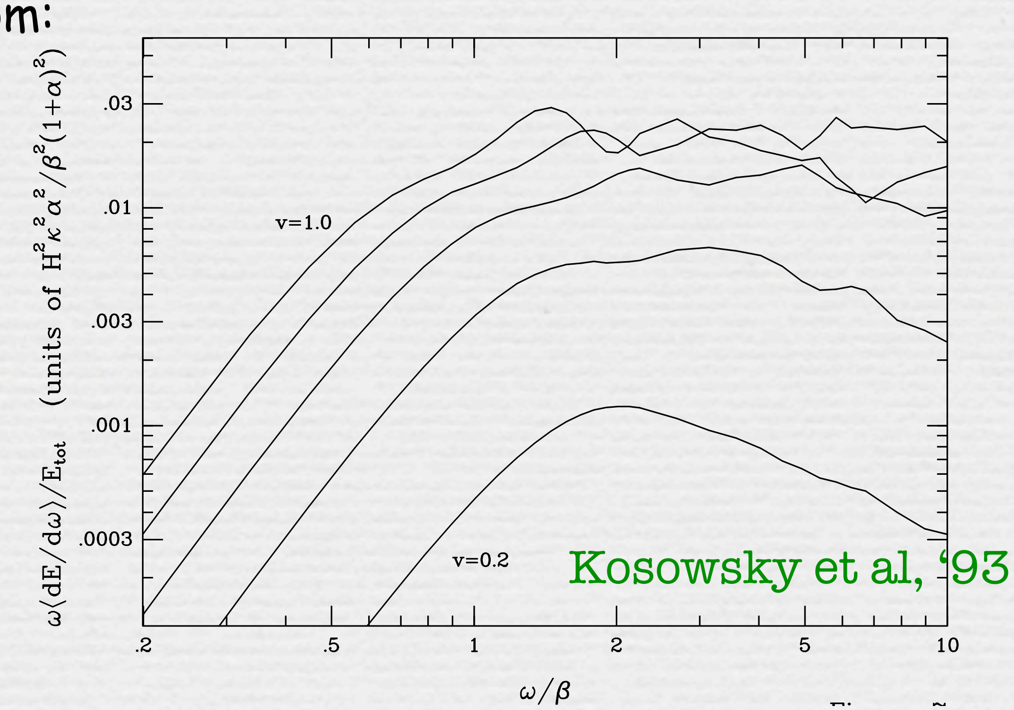
CAUSAL PROCESS: source is uncorrelated at scales larger than the peak scale

GW spectrum due to bubble collisions from numerical simulations: high frequency slope

Kosowsky et al, '93 $f^{-2} \rightarrow f^{-1}$ Huber-Konstandin,'08



derived from:

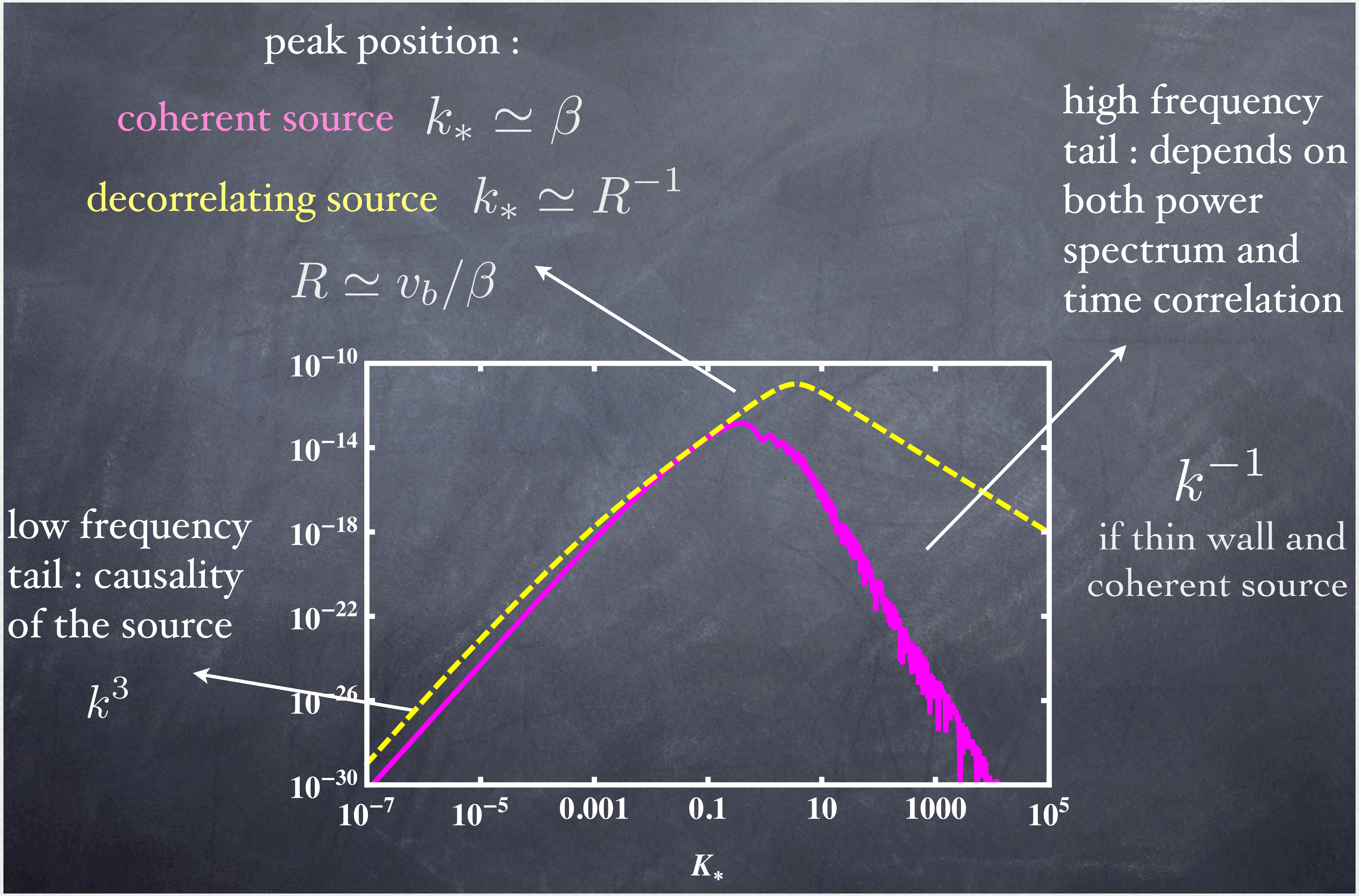


Kosowsky et al, '93

simulations with many bubbles and high accuracy too demanding in the 90ies

Expected shape of the GW spectrum from bubble collisions

Caprini-Durrer-Konstandin-Servant'09



Comparison between analytic results of Caprini-Durrer-Servant'07 and numerical simulations of Huber-Konstandin'08 discussed in Caprini-Durrer-Konstandin-Servant'09

Note: Slope of high-frequency tail is different for GW from **turbulence** (see Caprini-Durrer-Servant'09)

Bulk flow & hydrodynamics

higgs vaccuum energy is converted into :

- -kinetic energy of the higgs,
- -bulk motion
- - heating

$$\Omega_{GW} \sim \kappa^2(\alpha, v_b) \left(\frac{H}{\beta}\right)^2 \left(\frac{\alpha}{\alpha+1}\right)^2$$

fraction that goes into kinetic energy

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

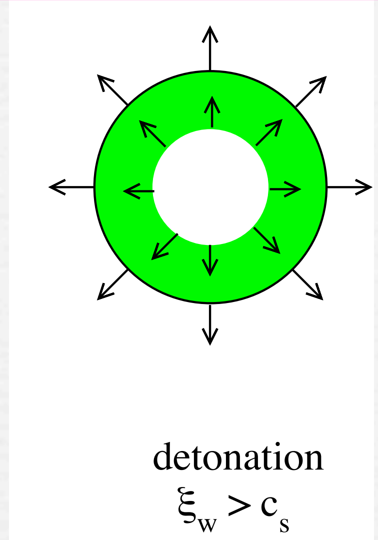
wall velocity

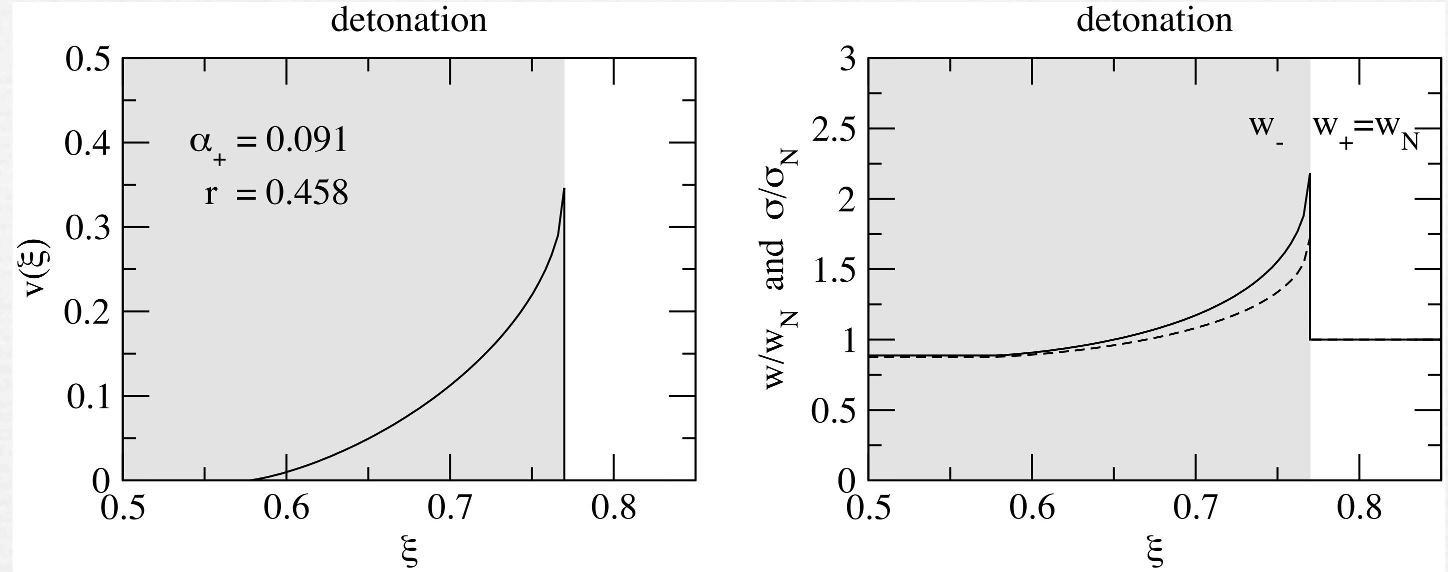
fluid velocity

-> all boils down to calculating the fluid velocity profile in the vicinity of the bubble wall

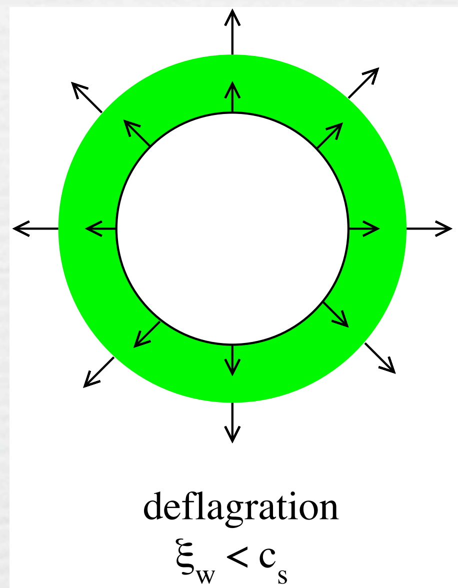
Depending on the boundary conditions at the bubble front, there are three possible solutions:

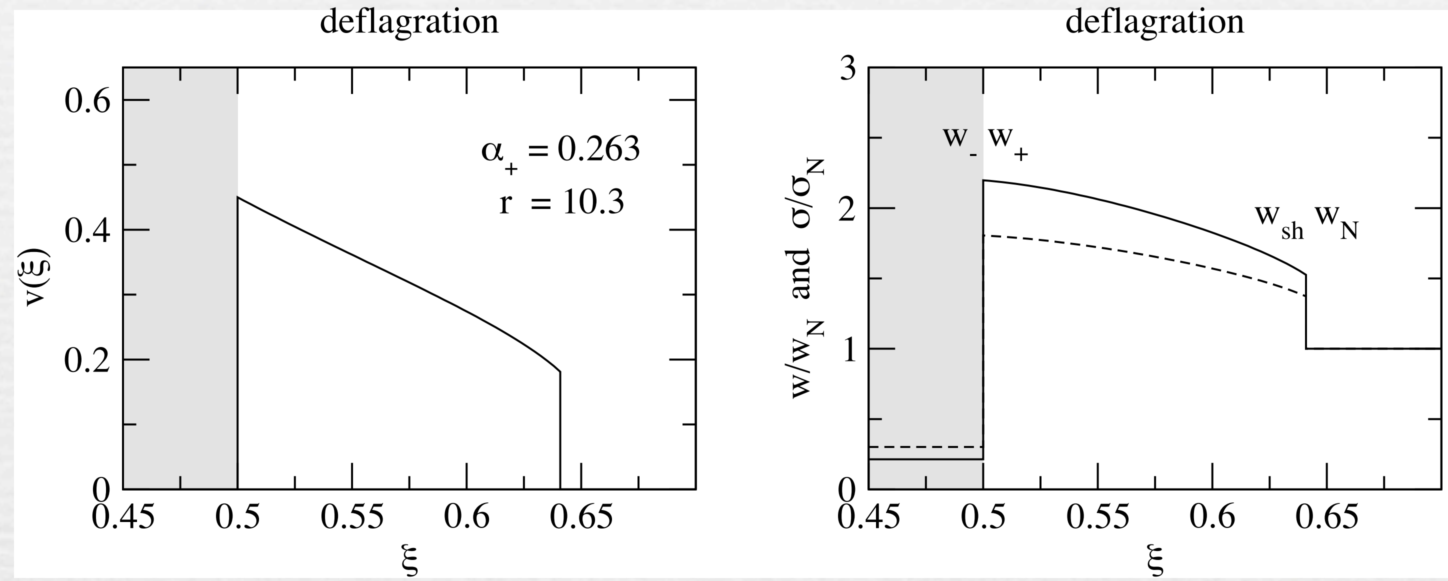
detonations -rarefaction wave



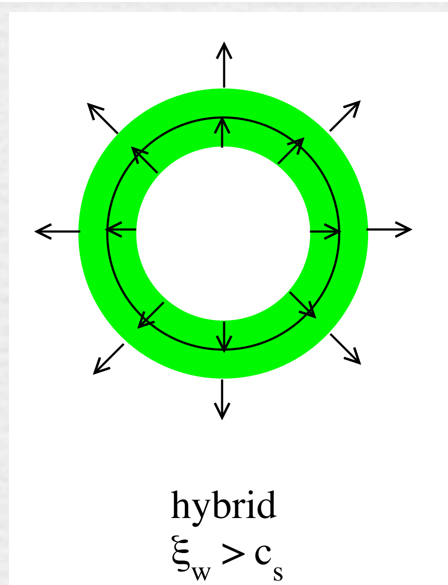


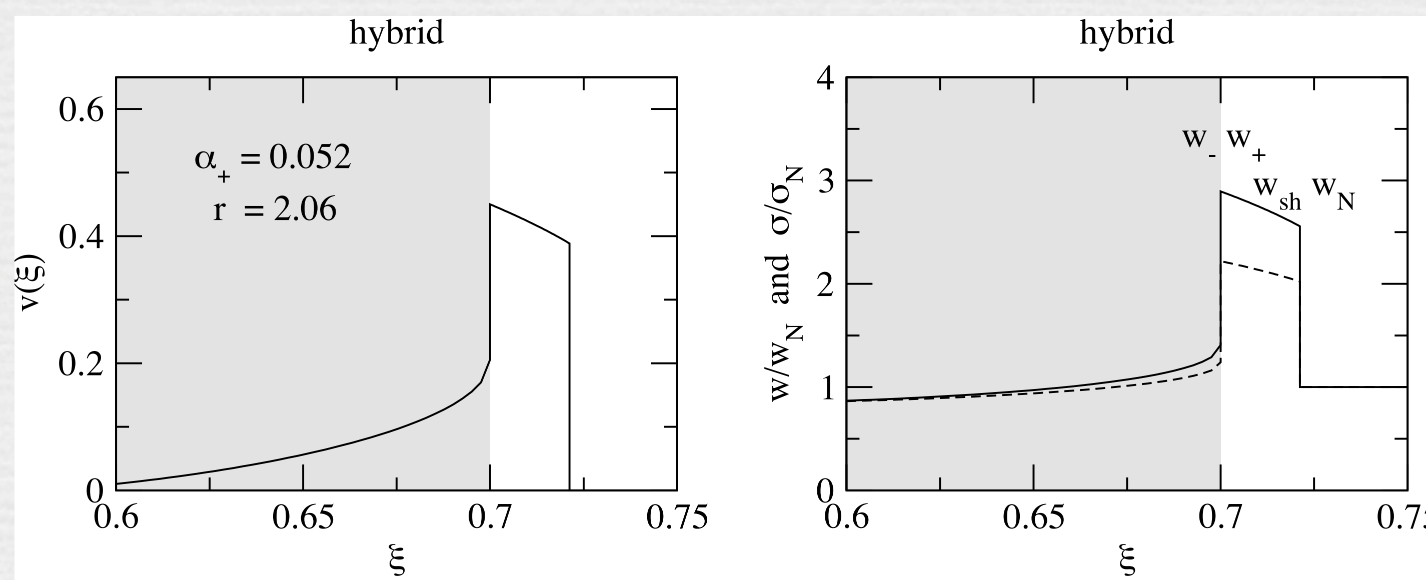
deflagrations -shock front





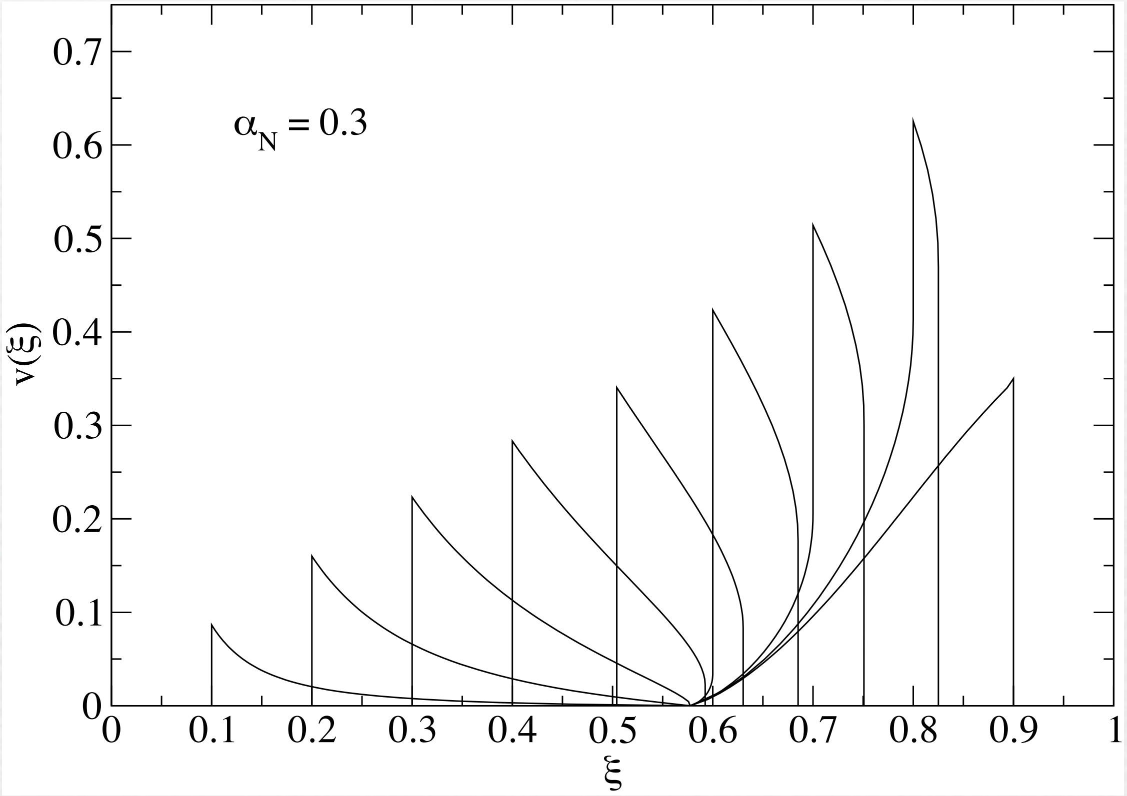
hybrids -both





Espinosa, Konstandin, No, Servant'10

fluid velocity profile for different wall velocities



v_{wall} increases

Espinosa, Konstandin, No, Servant'10

fraction κ of vacuum energy density ϵ converted into kinetic energy

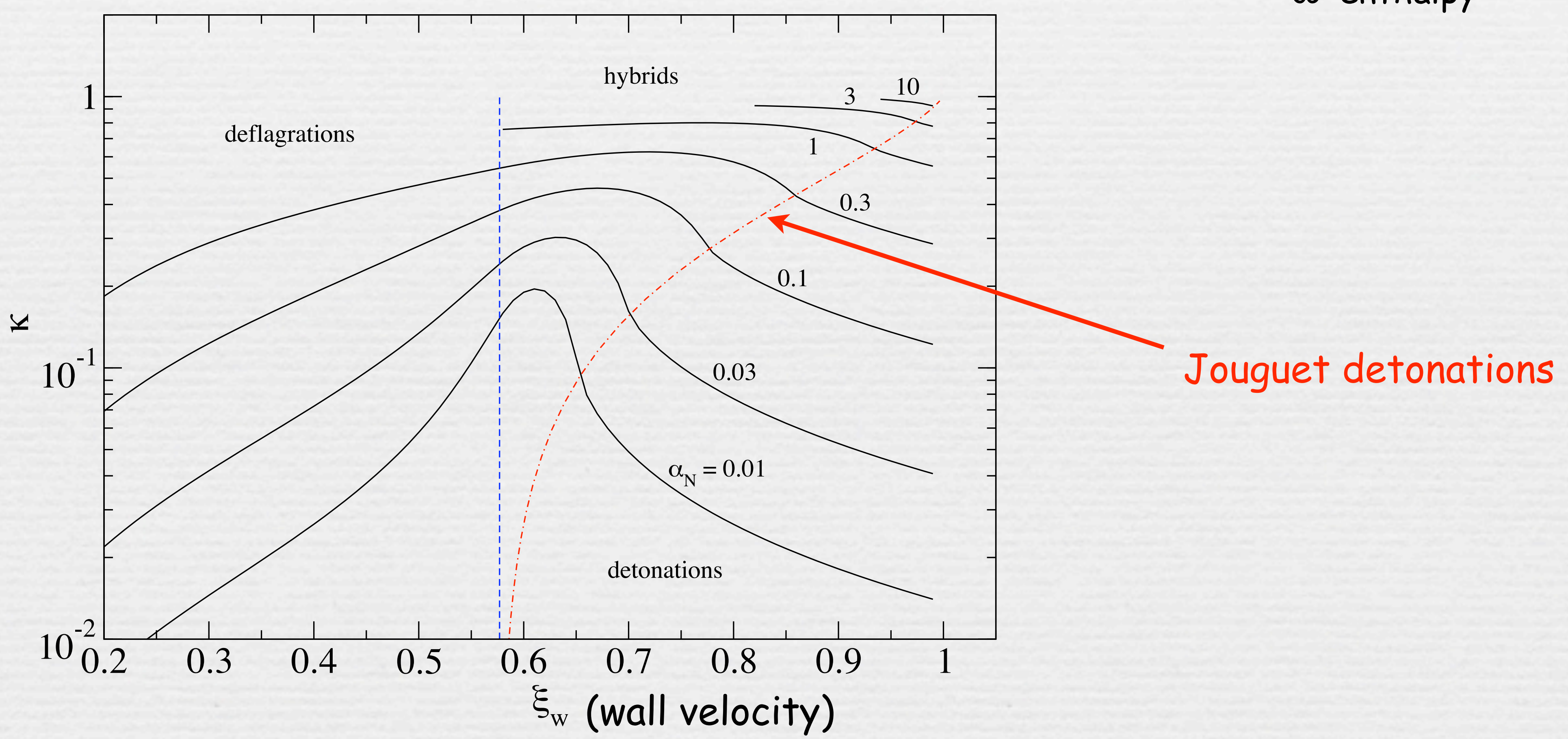
$$\kappa = \frac{3}{\epsilon \xi_w^3} \int w(\xi) v^2 \gamma^2 \xi^2 \, d\xi$$

v:fluid velocity

ξ_w=wall velocity

ξ =r/t where r is distance from the bubble center and t is time since nucleation

ω=enthalpy



Efficiency can be quite different than from the Jouguet detonations which were usually assumed

Espinosa, Konstandin, No, Servant'10

The velocity of the bubble wall can be determined by solving:

friction coefficient

$$\Box\phi + \frac{\partial \mathcal{F}}{\partial \phi} - \underbrace{T_N\ \tilde{\eta}\ u^\mu\partial_\mu}\phi = 0$$

=

$$-\sum_i \frac{dm_i^2}{d\phi}\int \frac{d^3p}{(2\pi)^3 2E_i}\delta f_i(p)$$

the wall velocity grows until the friction force equilibrates and a steady state is reached

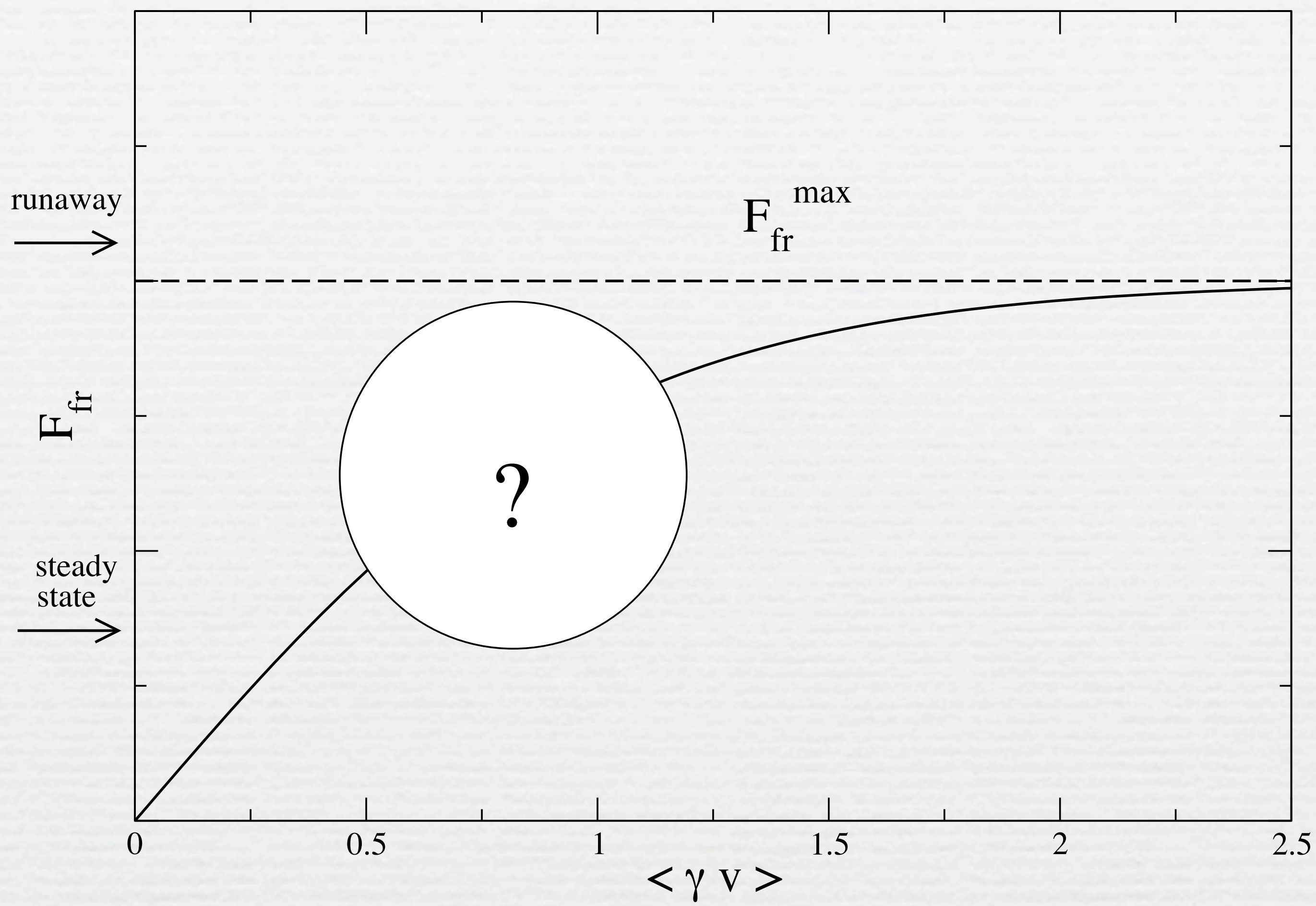
driving force: $$F_{dr} \equiv \int dz\,\partial_z\phi\,\frac{\partial \mathcal{F}}{\partial \phi}$$

$$F_{tot} = F_{dr} - F_{fr} = \Delta V_0 + \sum_i |N_i| \int dz \frac{dm_i^2}{dz}\int \frac{d^3p}{(2\pi)^3}\frac{f_i}{2E_i}$$

$\mathcal{F}_{tot} > 0$: runaway

[Bodecker-Moore '09]

Runaway regime



the friction force saturates at a finite value for v->1

runaway criterium

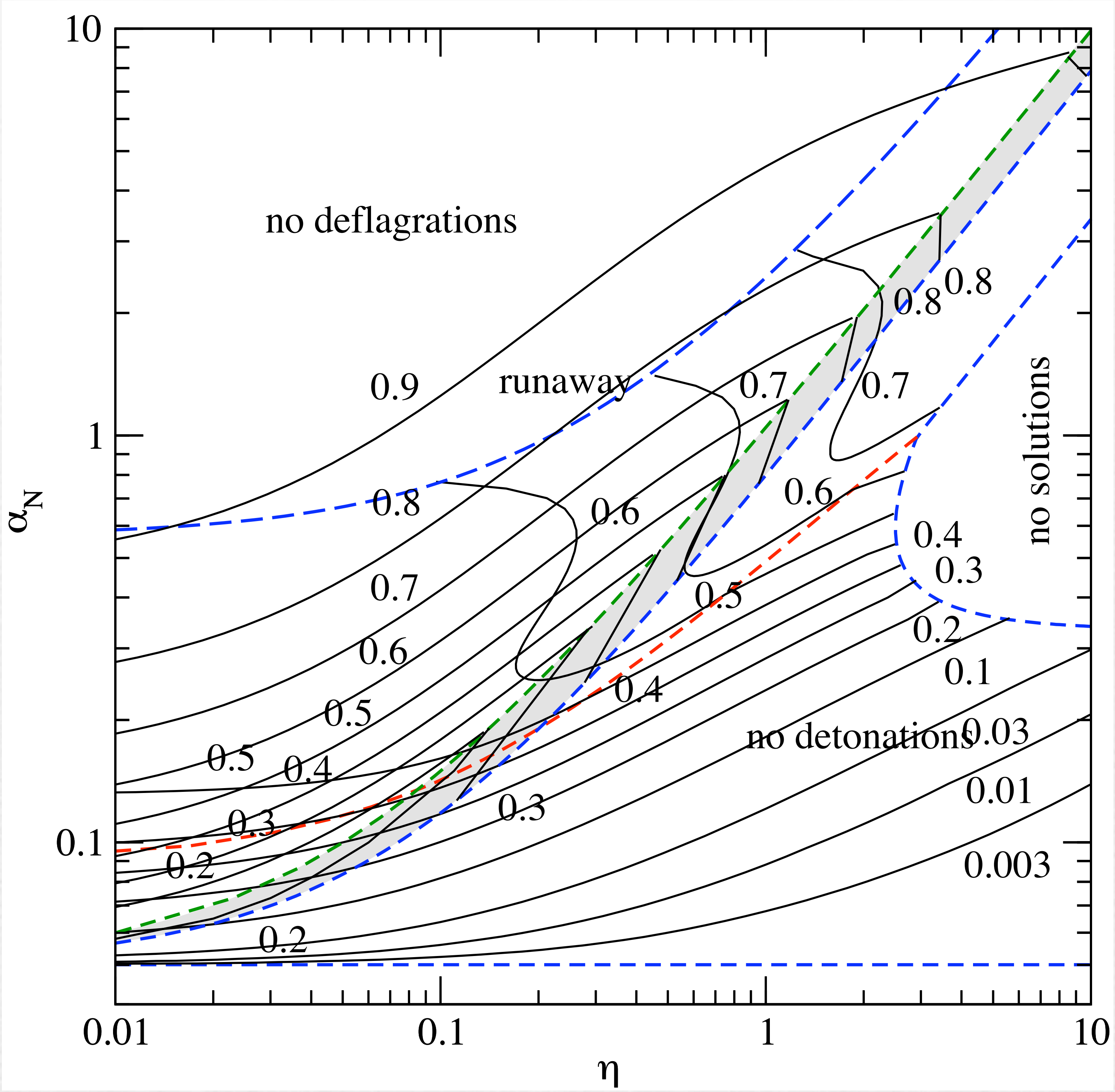
$$\alpha_N > \alpha_\infty \equiv \frac{30}{\pi^2}\left(\frac{\langle\phi\rangle}{T_N}\right)^2 \frac{\sum_{light\to heavy} c_i\,|N_i|\,y_i^2}{\sum_{light} c_i'\,|N_i|}$$

$$\alpha_N > 1.5\times 10^{-2}\left(\frac{\langle\phi\rangle}{T_N}\right)^2$$

For strong 1st order PT, the wall keeps accelerating

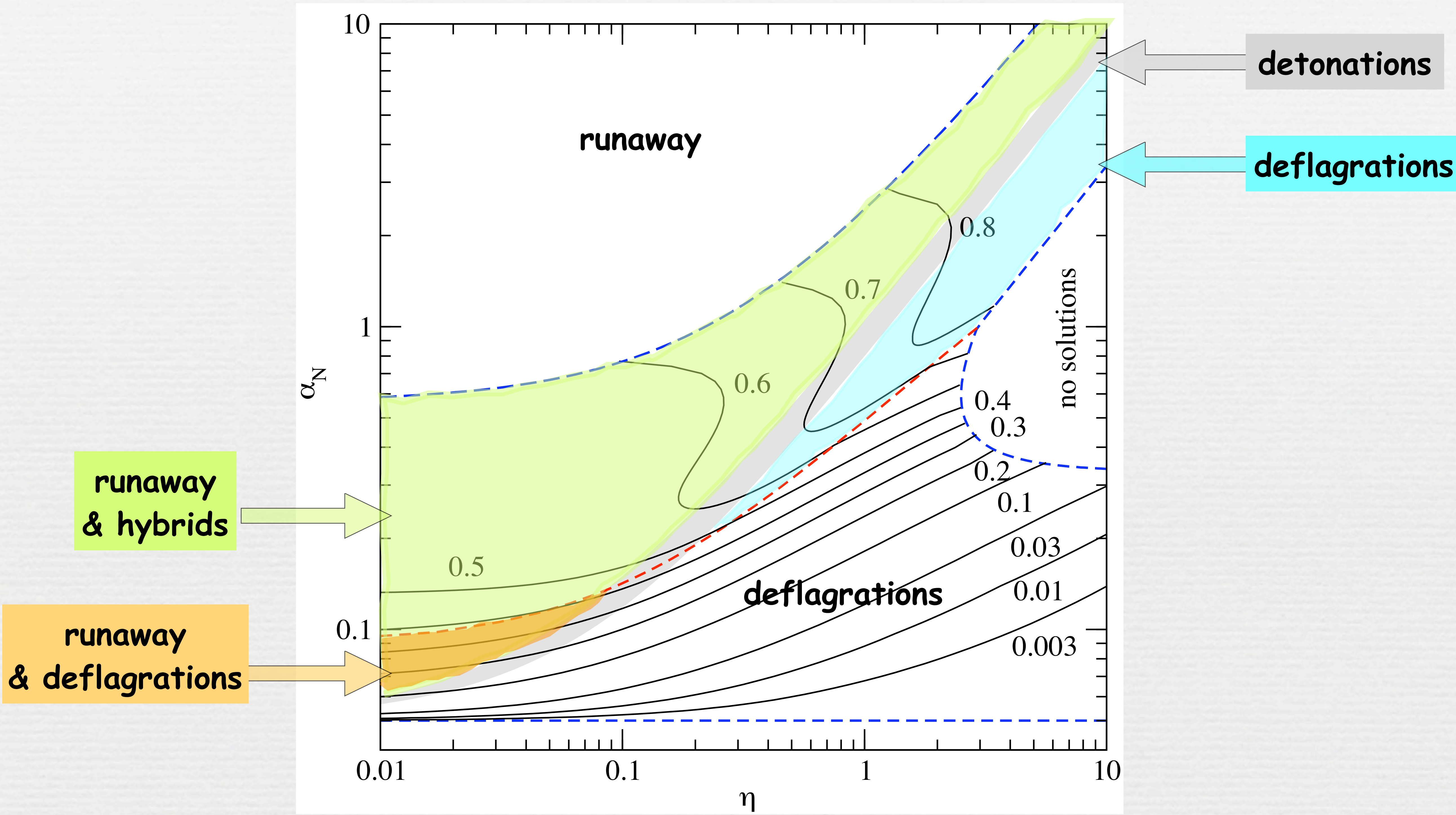
Model-independent κ contours

Espinosa, Konstandin, No, Servant'10

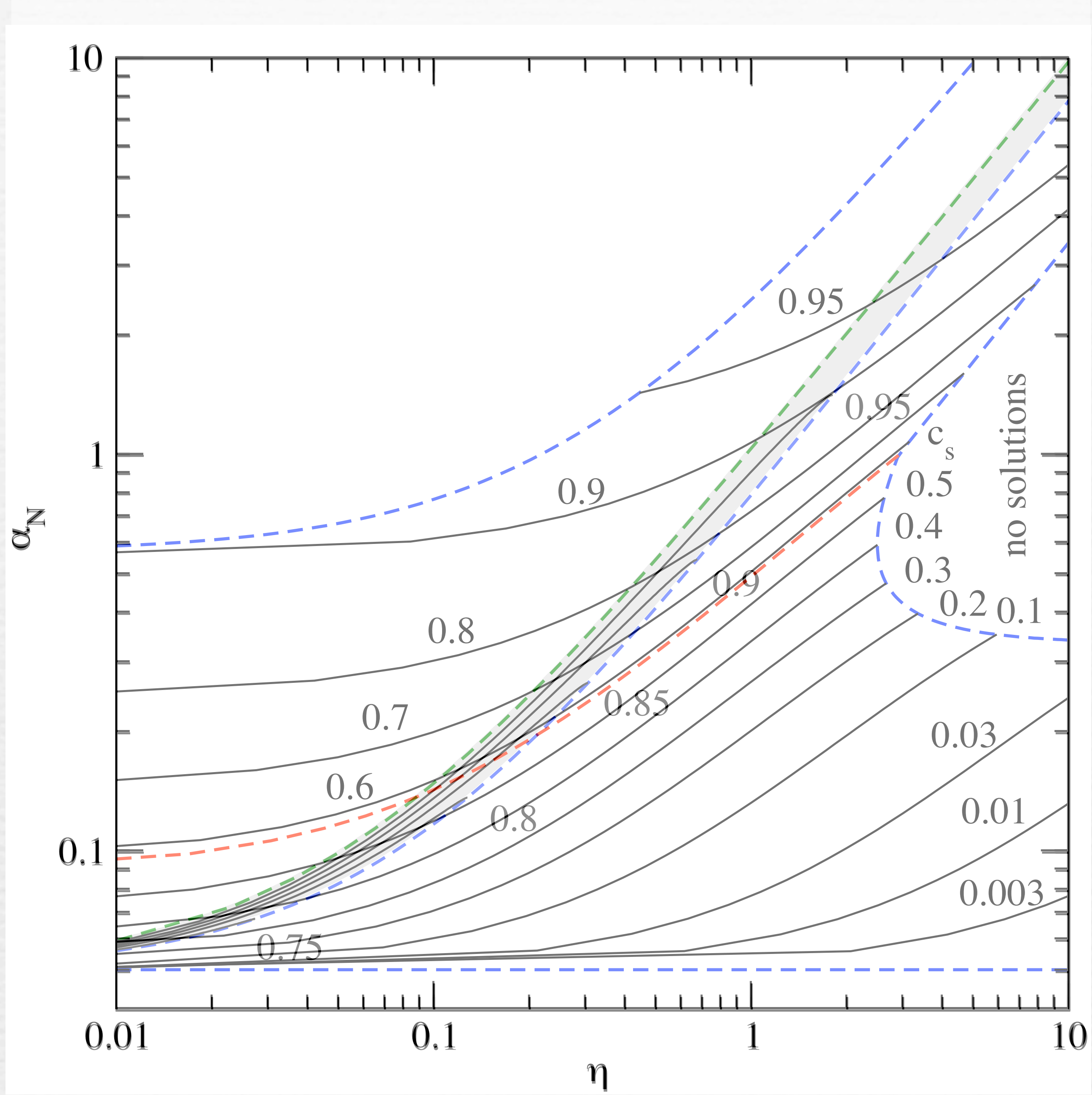


$$\frac{\tilde{\eta} T_N}{a_+ T_+^4} \int dz \; v \; (\partial_z \phi)^2 \equiv \eta \frac{\alpha_+}{\alpha_N} \langle v \rangle$$

More clearly:



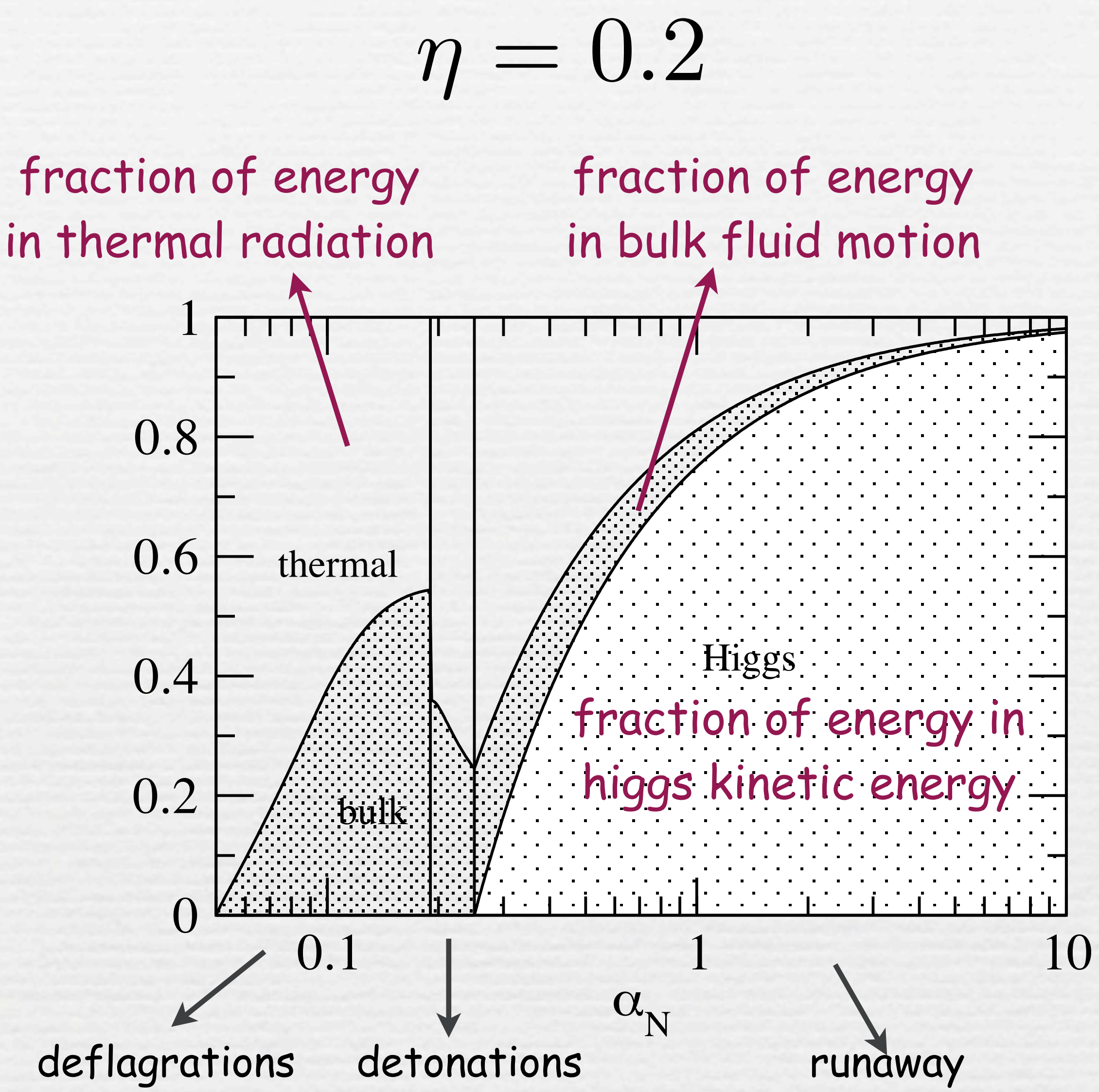
model-independent wall velocity contours

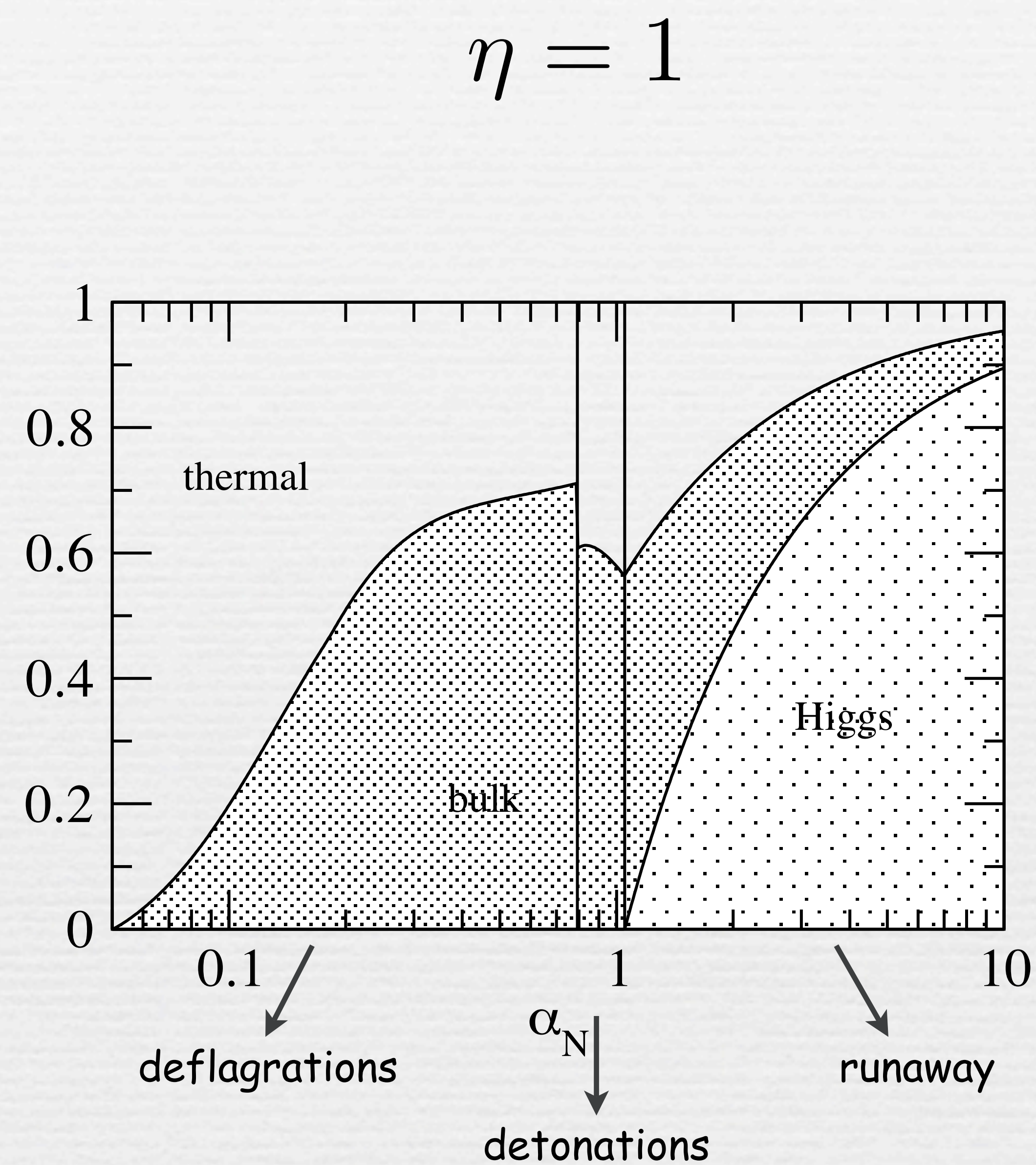


$$\eta_{\rm SM} \sim 10^{-3}$$

$$\eta_{\rm MSSM} \sim 10^{-2} \qquad v \sim 0.05 - 0.1$$

Energy budget of the phase transition





Determination of energy budget is important since gravity wave spectra from bubble collisions and turbulence are different

Summary

The nature of the EW phase transition is unknown & it will take time before we can determine whether EW symmetry breaking is purely SM-like or there are large deviations in the Higgs sector which could have led to a first-order PT

It is an interesting prospect that some TeV scale physics could potentially be probed by LISA

Discussion applies trivially to any other 1st order phase transition (only shift peak frequency, amplitude and shape of signal do not depend on the absolute energy scale of the transition)