Gravitational waves from first order phase transitions

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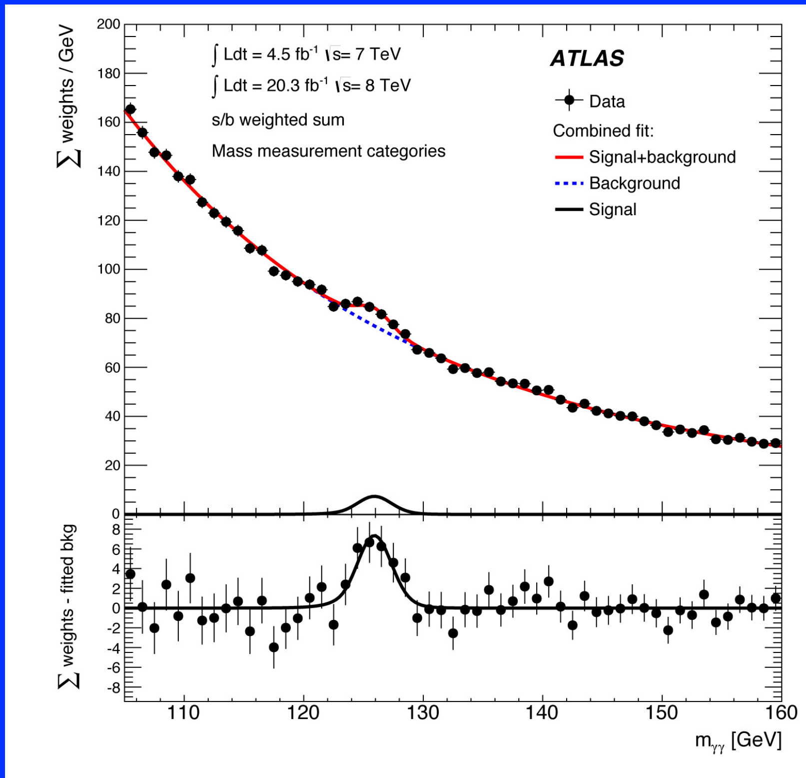
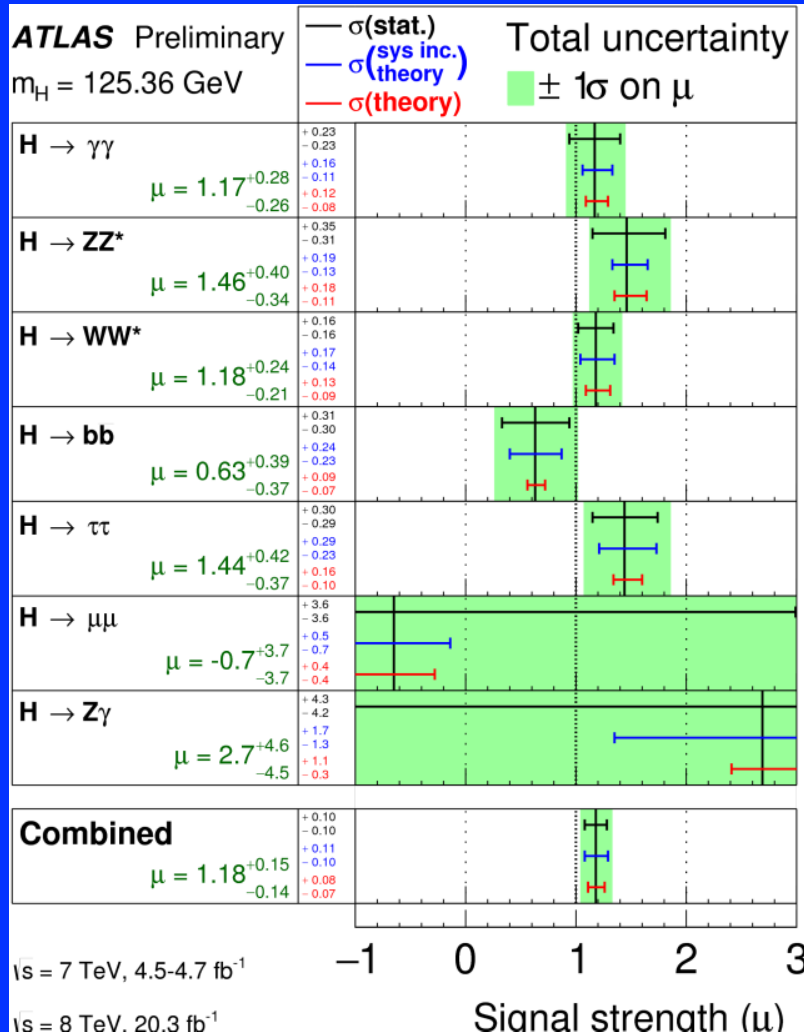
Two discoveries

The Higgs boson: 2012 (LHC)

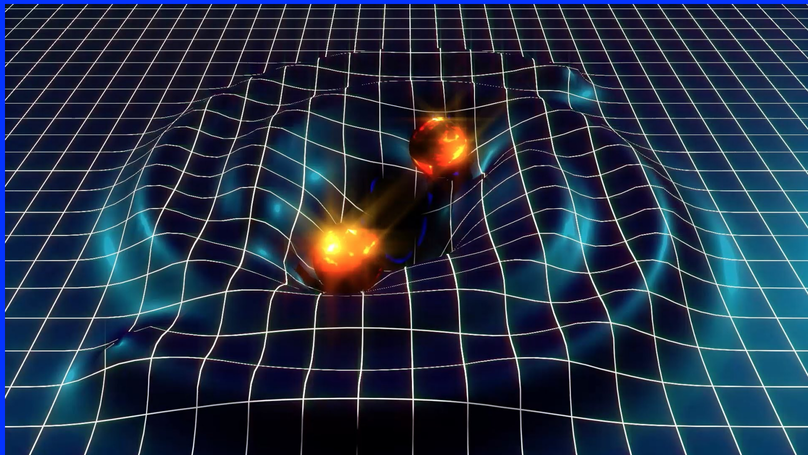


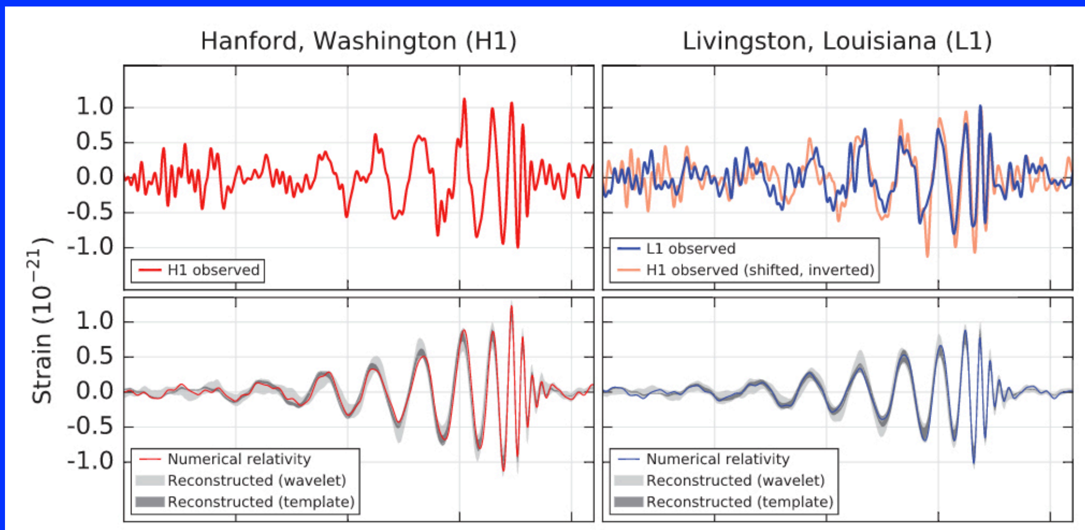


Prospects: LHC to collect

$3000\ \mathrm{fb}^{-1}$ of data by 2035

Gravitational waves: 2015 (LIGO)





Merger of two two black holes, having about 30 solar masses

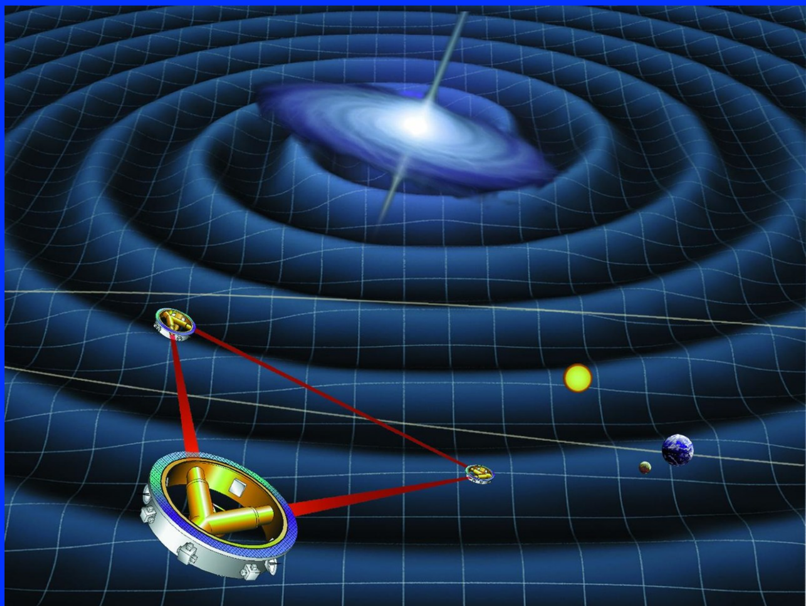
Frequency is in the kHz range

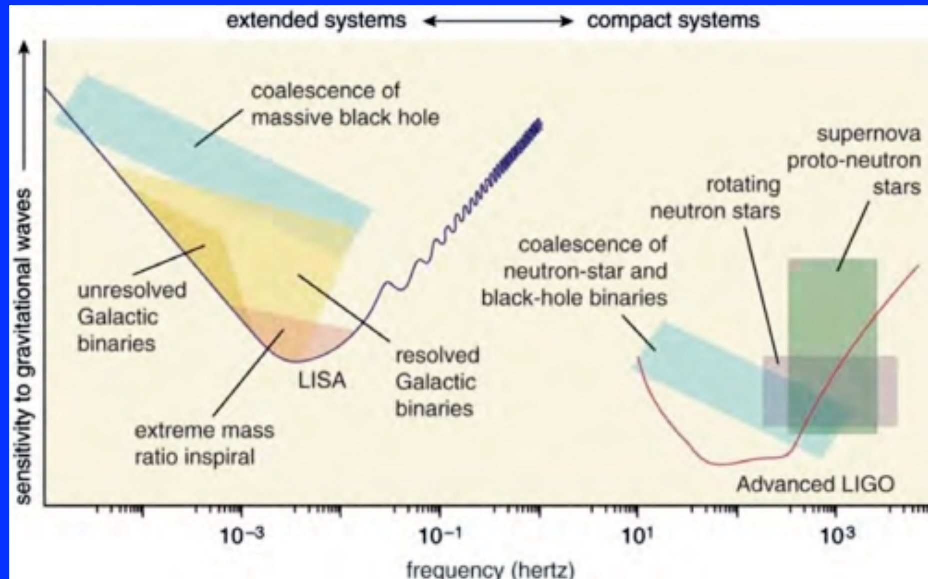
<u>New window to the early universe</u>

Future: LISA

Laser interferometer space antenna: launch ~2034

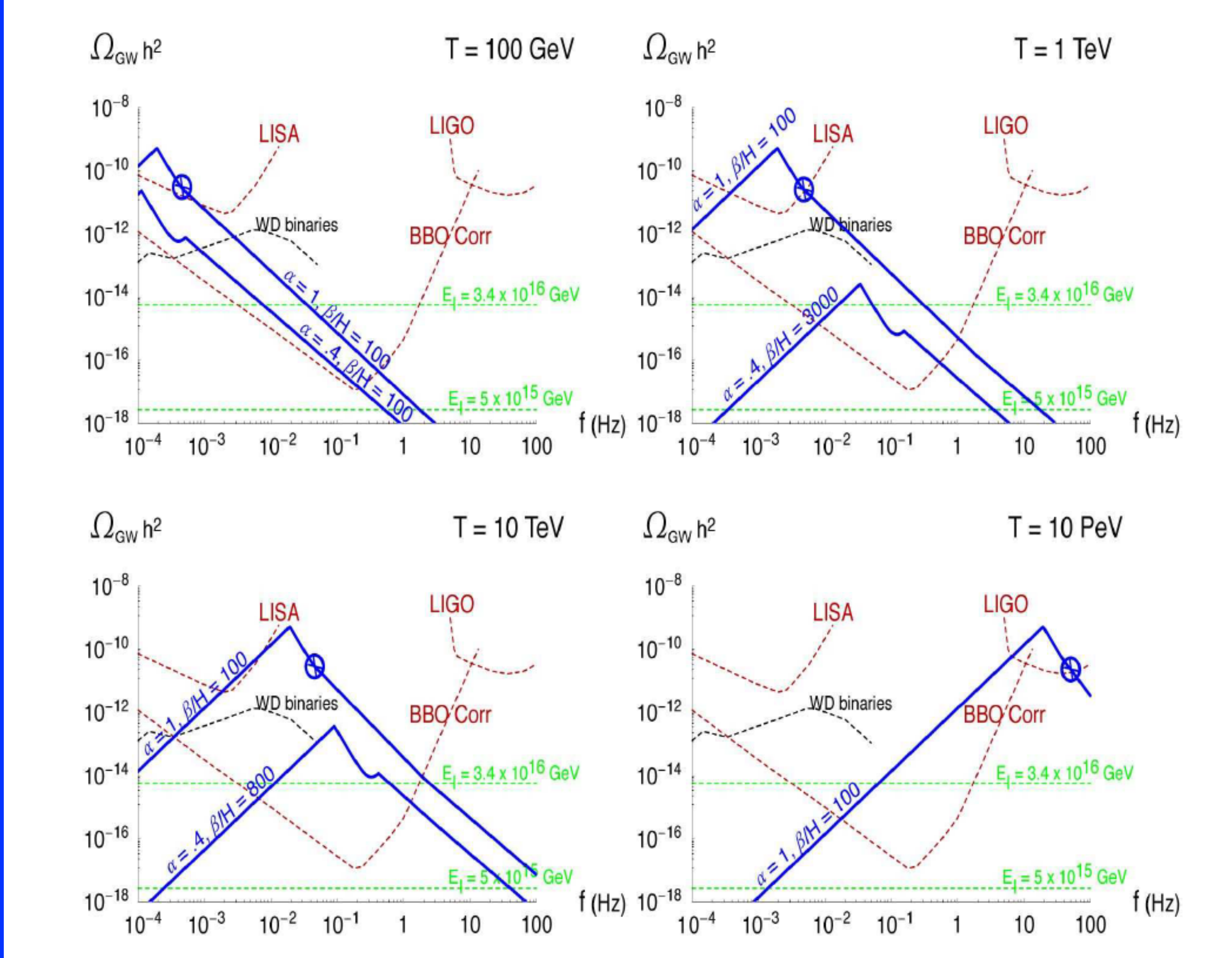
LISA pathfinder successfully demonstrated the concept in 2016





Maximal sensitivity in the milli-Hertz range

Corresponding to phase transitions around the EW scale



[Grojean, Servant '06]

Outline

Aim: link both discoveries by first order phase transitions

- brief review: cosmic first order phase transitions
- what we know about the GW signal from phase transitions
- possible connections to baryogenesis and collider physics
- Summary & outlook

First order phase transitions

Here for the electroweak phase transition, similar methods for PT's eg. in hidden sectors, or deconfinement transition in a new strong sector

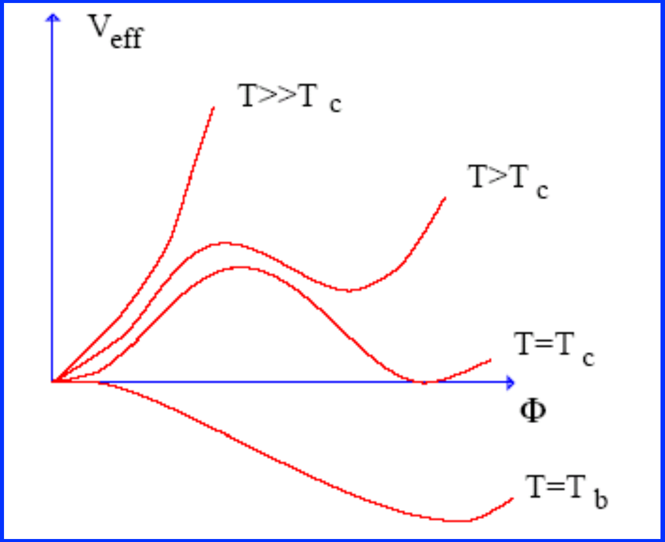
The strength of the PT

Thermal effective potential:

$$V_{\rm eff}(\phi,T) = (-m^2 + AT^2)\phi^2 - ET\phi^3 + \lambda\phi^4$$

Thermal mass:
symmetry restauration
at high temperature

Cubic term:
bosons only,
induces PT



Useful measure of the strength of the transition:

$$\xi = \frac{v_c}{T_c}$$

For strong transitions, ξ>~1: perturbation theory (1 or 2-loop)

Weak transitions: lattice methods [talk by Tranberg (Friday)]
eg. m_h>~80 GeV → the SM EW phase transition is a crossover

[Kajantie, Laine, Rummukainen, Shaposhnikov 1996; Csikor, Fodor, Heitger 1998]

How to make a strong transition?

1) Add new bosons, coupling sizably to the Higgs (increase E), eg.

- Light stops in the MSSM (now mostly excluded by Higgs properties)

[Carena, Nardini, Quiros,Wagner 2012]

- second Higgs doublet (2HDM)

[eg. Dorsch, SJH, Mimasu, No, 2017
Basler, Muehlleitner, Wittbrodt, 2017
Andersen et al. 2017,⋯]

- one can also build models relying on singlets, weak triplets, etc.

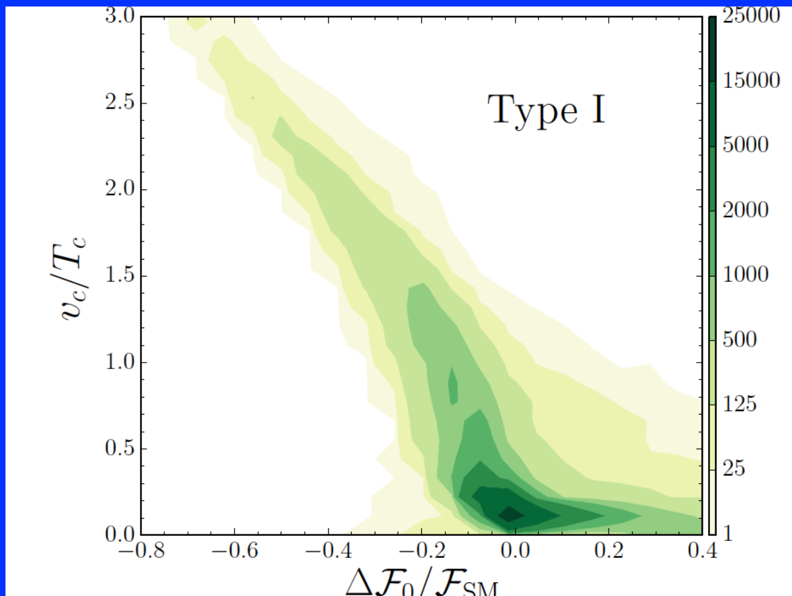
How to make a strong transition?

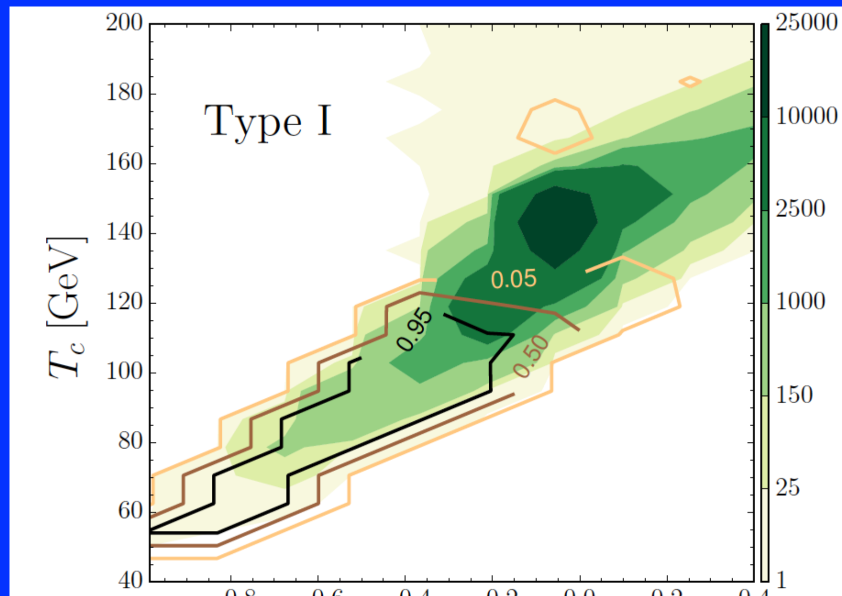
2) Make the EW minimum less deep (ie. lower T_c, larger v_c/T_c):

a) By bosonic Coleman-Weinberg logs, eg. 2HDM [Dorsch, SJH, Mimasu, No, 2017]

$$V_1 = \sum_\alpha n_\alpha \frac{m_\alpha^4(h_1,h_2)}{64\pi^2}\left(\log\frac{|m_\alpha^2(h_1,h_2)|}{Q^2} - C_\alpha\right)$$

Dominant effect for strong transitions





How to make a strong transition?

2b) make the EW minimum less deep at <u>tree-level</u>

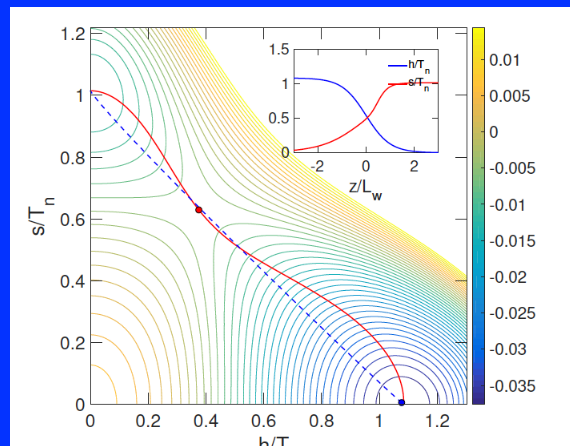
● include a Φ^6 term in the Higgs potential (a la EFT)

$$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{1}{8M^2}\phi^6$$

[eg. Chala, Krause, Nardini, 2018]

new term removes the link between the Higgs mass and vacuum depth

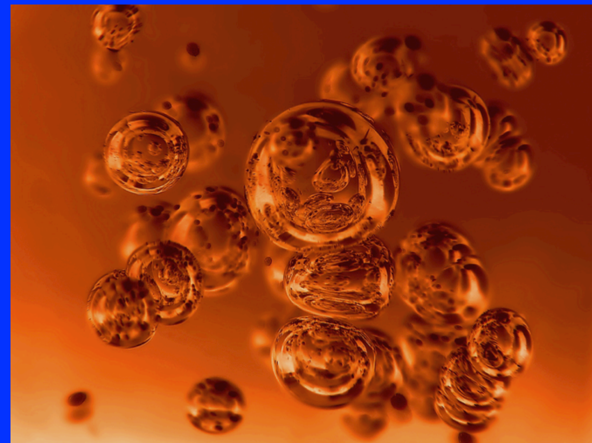
● use additional fields, in particular singlets to lower the <u>symmetric phase</u>
(“two step transition”)
ie. broken phase relatively less deep



[eg. Inoue, Ovanesyan, Ramsey-Musolf 2015;
Cline, Kainulainen, Tucker-Smith 2017]

The transition itself: bubbles

For $T<T_c$ bubbles of the new phase will nucleate and expand:

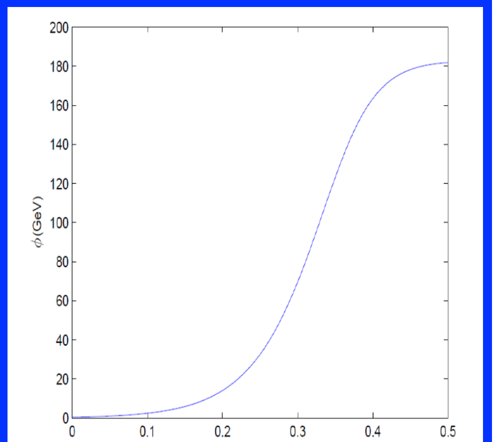


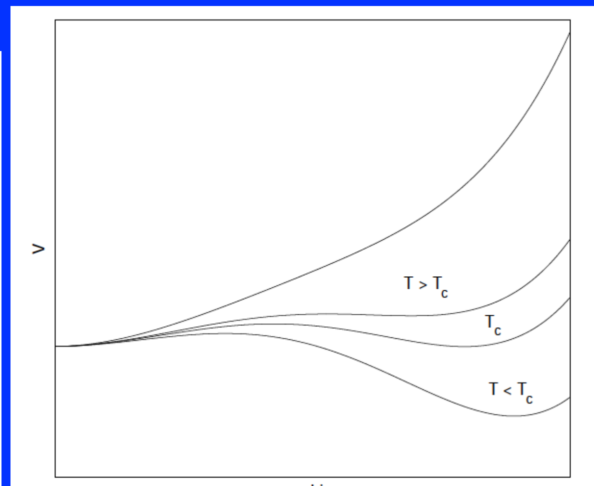
Nucleation rate governed by, S_3, the energy of the critical bubble

$$\Gamma \sim T^4 e^{-\frac{S_3}{T}}$$

Critical bubble (bounce): static, spherical solution to the field equations

At the nucleation temperature T_n the first first bubbles appear (S_3/T drops with T)





Key quantities for GW's

The gravitational wave signal will depend only on four global quantities:

1) Phase transition temperature T_n (Hubble length and red-shifting)

2) Available energy

typically α=0.01 to ~1

$$\alpha \sim \frac{\text{latent heat}}{\text{radiation energy}} \sim \frac{T\partial_T V(T)}{a g_* T^4}$$

3) Average bubble size at collision

$$\langle R \rangle \sim v_b \tau \sim \frac{v_b}{\beta}$$

$$\frac{\beta}{H_*} = T_* \frac{d}{dT}\left(\frac{S_3}{T}\right)\Big|_{T_*}$$

Typically β/H=10 to 10000, ie. transition fast compared to Hubble time

4) v_b bubble wall velocity   (eg. wall shape is irrelevant)

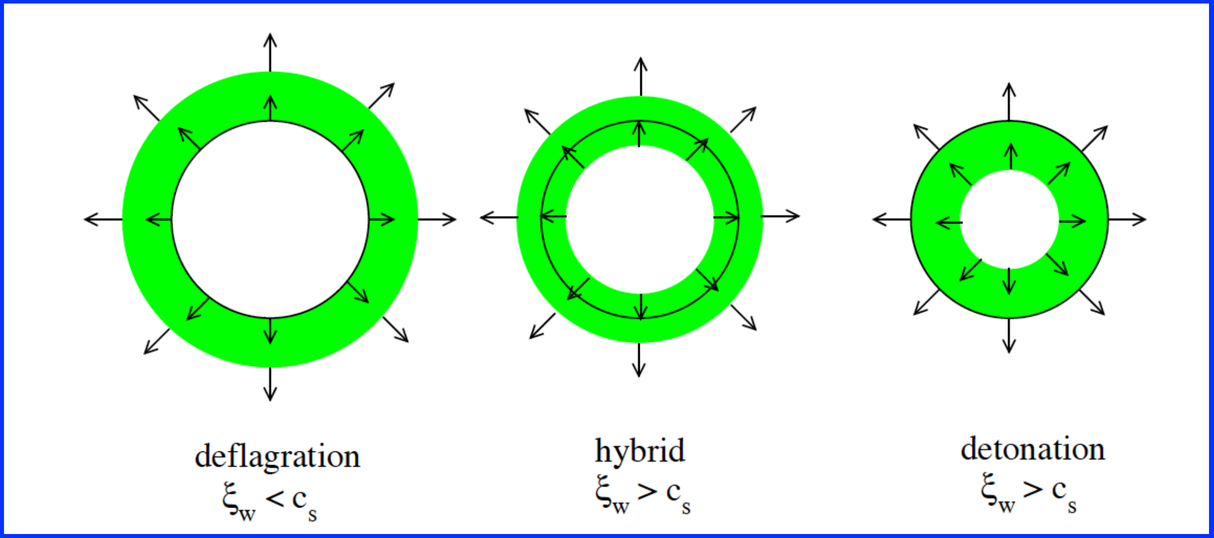
Wall velocity: resulting from pressure vs. plasma friction

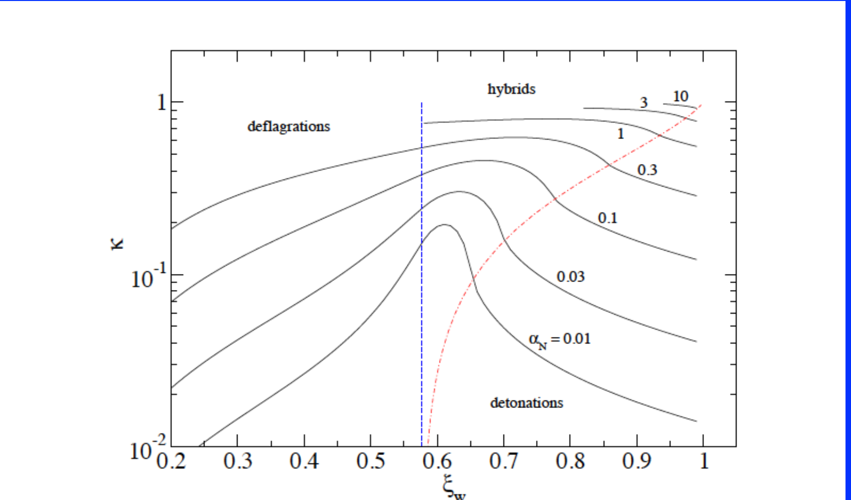
Generally very difficult QFT non-eq. problem (wall+plasma)

[eg. Konstandin et al., ’14
Moore, Prokopec, ’95
John, Schmidt, ‘ 00]

But simple criterion for ultra-relativistic walls

[Boedeker, Moore, ’09, ‘17]





[Espinosa, Konstandin, No, Servant, 2010]

Efficiency κ for turning latent heat into fluid motion

Gravitational waves

(In collaboration with M. Hindmarsh, K. Rummukainen, D. Weir)

Gravitational waves from phase transitions

Metric perturbations:

$$\ddot{u}_{ij} - \nabla^2 u_{ij} = 16\pi G(\tau^{\phi}_{ij} + \tau^{\mathrm{f}}_{ij}),$$

Difficult part: source (RHS)

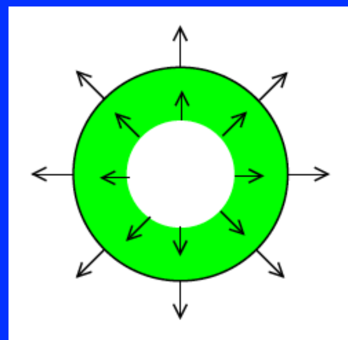
Possible contributions:

scalar bubble collisions

fluid excitations: turbulence

sound waves

(magnetic fields)



Science with the space-based interferometer eLISA. II: Gravitational waves from cosmological phase transitions

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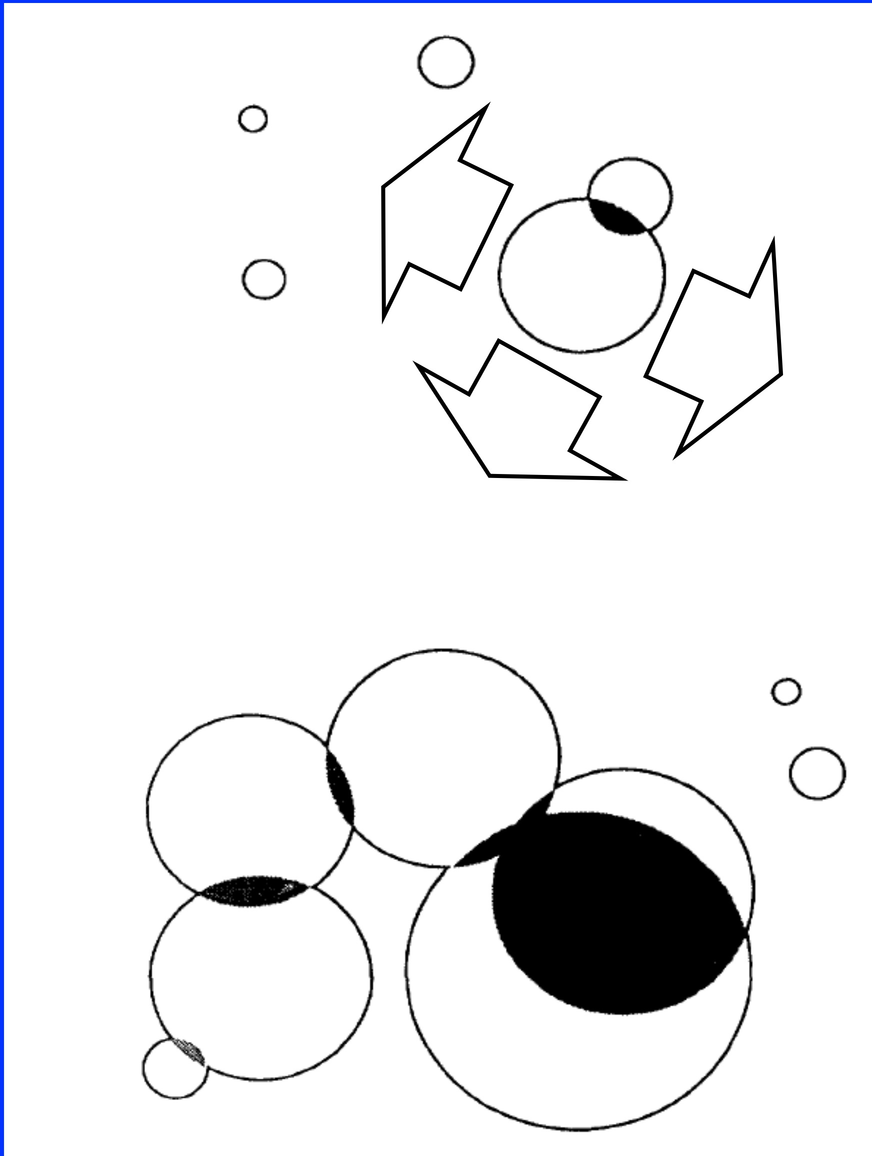
[see LISA Cosmo working group report '15, update this summer]

Scalar field only: The envelope approximation: [Kosowsky, Turner 1993, SJH, Konstandin 2008]



single bubble does not radiate (symmetry)!

energy momentum tensor of expanding bubbles modelled by expanding infinitely thin shells,

cutting out the overlap

➔ very non-linear!

Originally from colliding two scalar bubbles

Recent scalar field theory simulation:

Child, Giblin, 2012

Cutting, Hindmarsh, Weir, 2018

Comparison between envelope appr. and field theory simulation:

[Cutting, Hindmarsh, Weir, 2018]

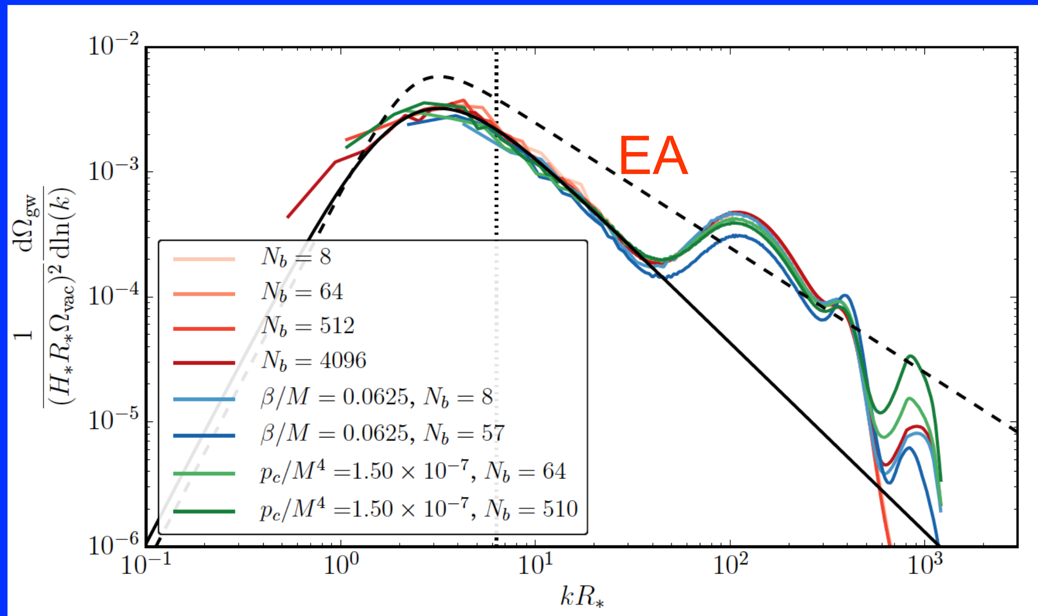
Energy momentum tensor from solving the KG eq. on a lattice:

$$\Box\phi - V'(\phi) = 0$$

$$V(\phi) = \frac{1}{2}M^2\phi^2 + \frac{1}{3}\delta\phi^3 + \frac{1}{4}\lambda\phi^4$$

Bubbles accelerate to the speed of light

$$\gamma \sim R_*/R_c \sim 10^{12}$$



Findings:

peak set by $k \sim 1/R_*$

slightly lower peak

UV power law $k^{-1.5}$ (not k^{-1})

BUT: with a plasma, the fraction of the energy in the scalar is ~1/gamma

ie. totally irrelevant and we need to understand the fluid!

We performed the first 3d simulation of a scalar + relativistic fluid system:

$$V(\phi, T) = \frac{1}{2}\gamma(T^2 - T_0^2)\phi^2 - \frac{1}{3}\alpha T\phi^3 + \frac{1}{4}\lambda\phi^4.$$

(thermal scalar potential)

phenom. friction parameter

$$-\ddot{\phi} + \nabla^2\phi - \frac{\partial V}{\partial \phi} = \eta W(\dot{\phi} + V^i\partial_i\phi)$$

(scalar eqn. of motion)

$$\dot{E} + \partial_i(EV^i) + P[\dot{W} + \partial_i(WV^i)] - \frac{\partial V}{\partial \phi}W(\dot{\phi} + V^i\partial_i\phi) = \eta W^2(\dot{\phi} + V^i\partial_i\phi)^2. \quad (7)$$

(eqn. for the energy density)

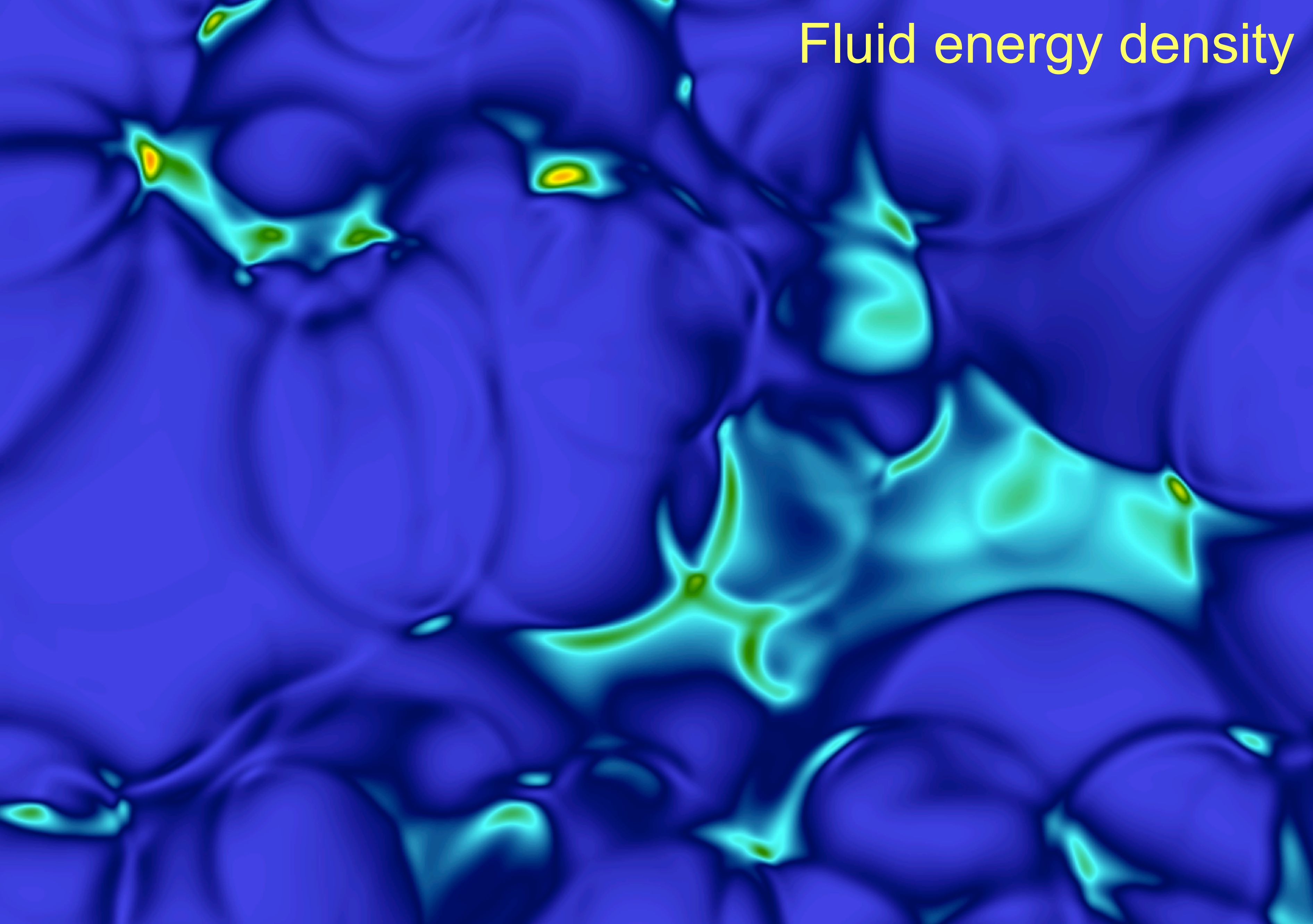
$$\dot{Z}_i + \partial_j(Z_iV^j) + \partial_iP + \frac{\partial V}{\partial \phi}\partial_i\phi = -\eta W(\dot{\phi} + V^j\partial_j\phi)\partial_i\phi.$$

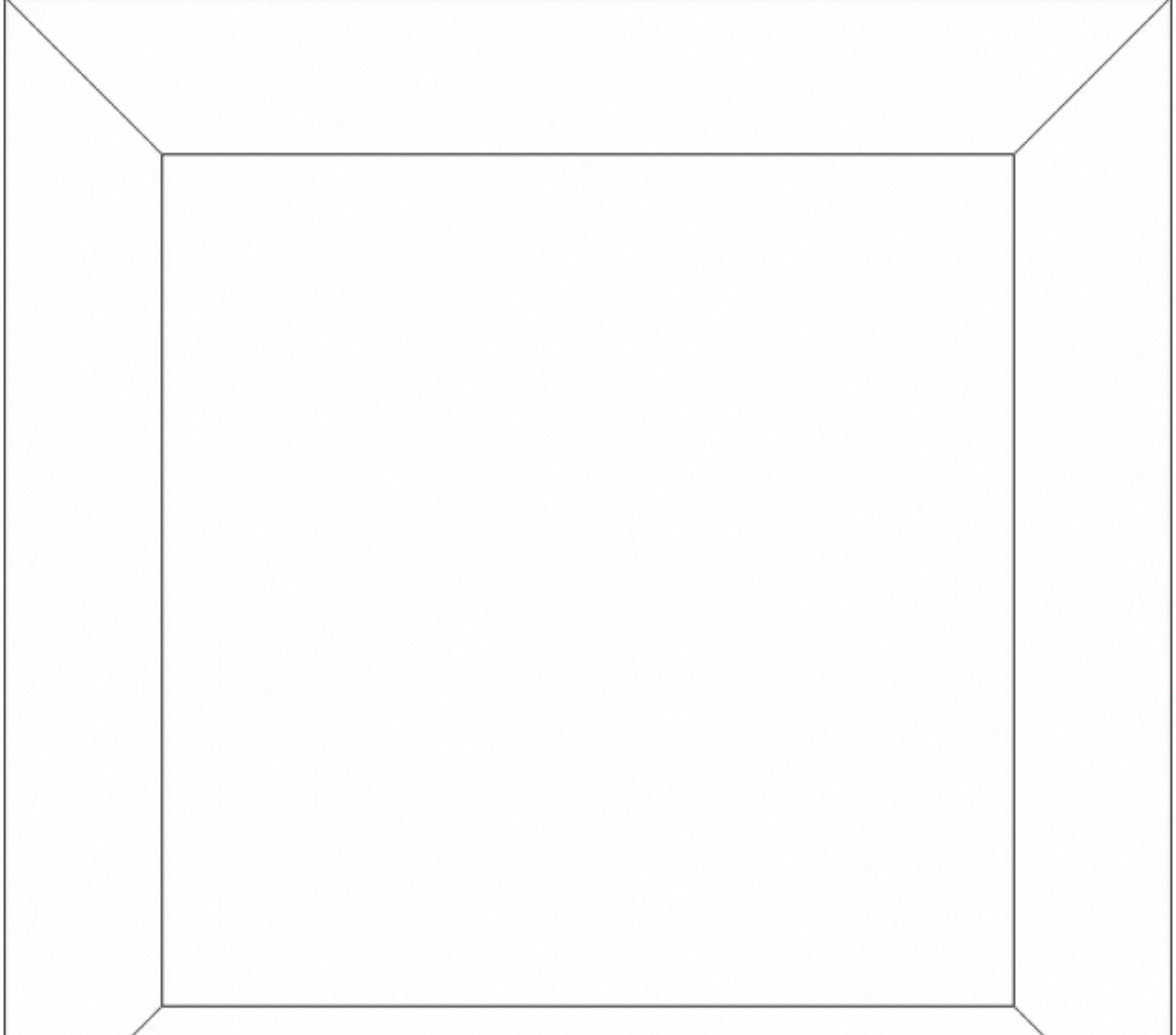
(eqn. for the momentum densities)

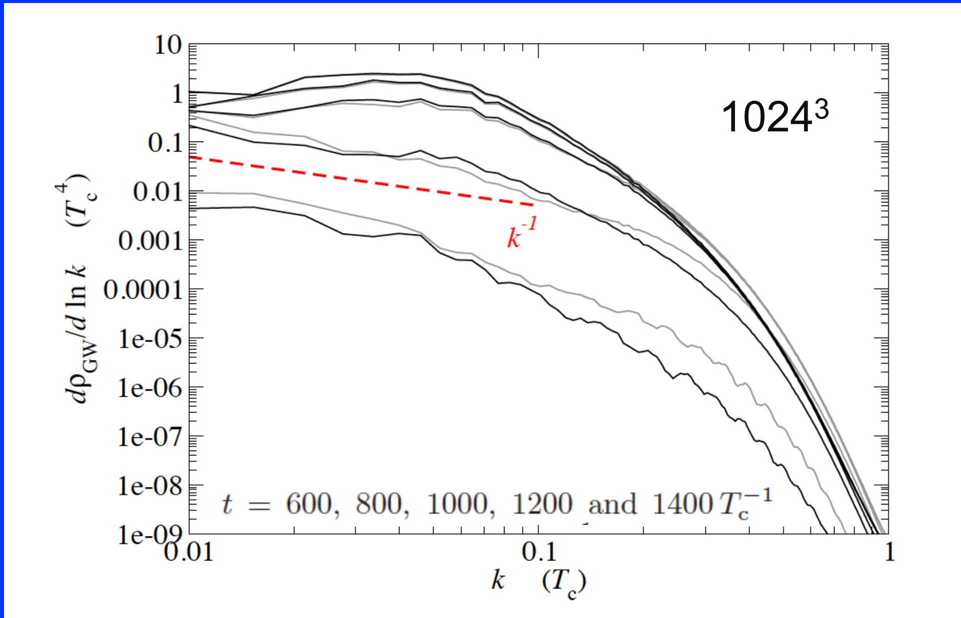
$$Z_i = W(\epsilon + p)U_i$$

$$\ddot{u}_{ij} - \nabla^2 u_{ij} = 16\pi G(\tau_{ij}^{\phi} + \tau_{ij}^{\mathrm{f}}),$$

(eqn. for the metric perturbations)

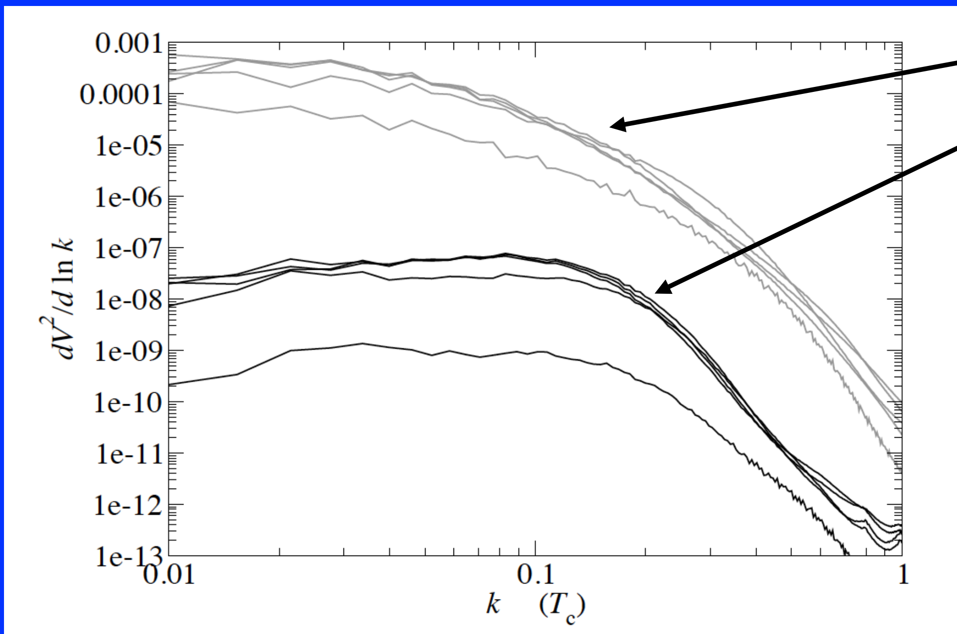

Fluid energy density





GW spectrum

Source keeps radiating until it is cut off at about a Hubble time



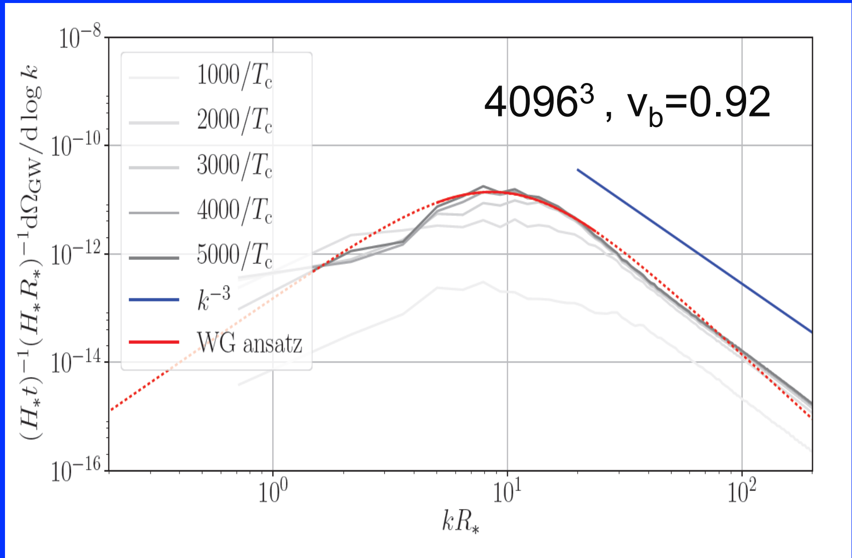
- longitudinal and
- transverse part of the fluid stress

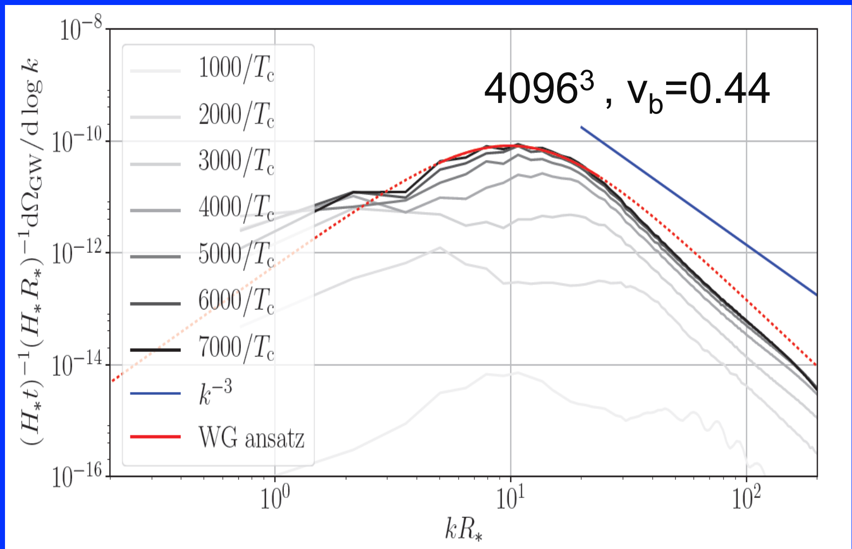
Logitudinal part dominates ➔ Basically <u>sound waves</u>

(suggested by Hogan 1986)

UV Power laws:

[Hindmarsh, SJH, Rummukainen, Weir '17]





Clear k^{-3} power law fall off in the UV

for the detonation (v_b=0.92)

and about k^{-4}

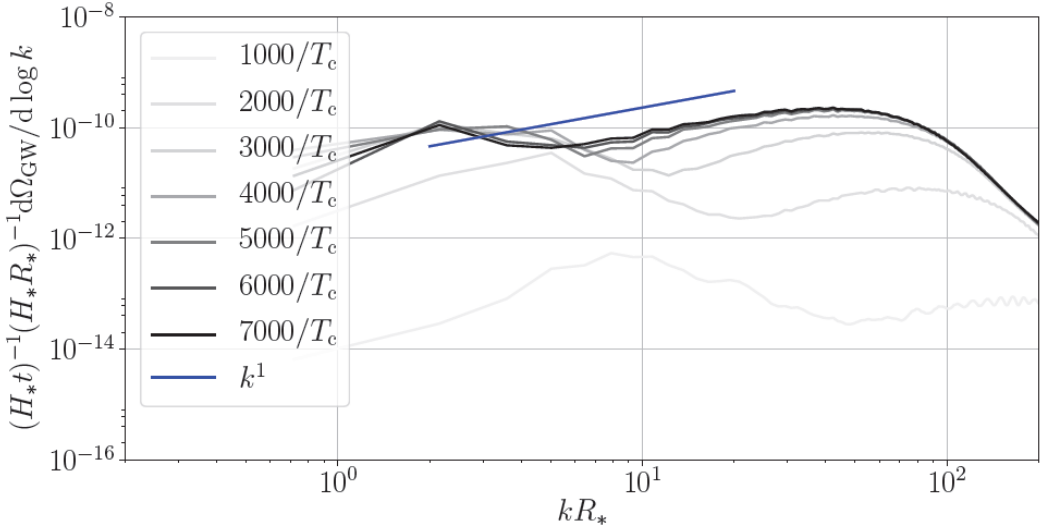
for the deflagration (v_b=0.44)

Both clearly <u>different from pure scalar</u>

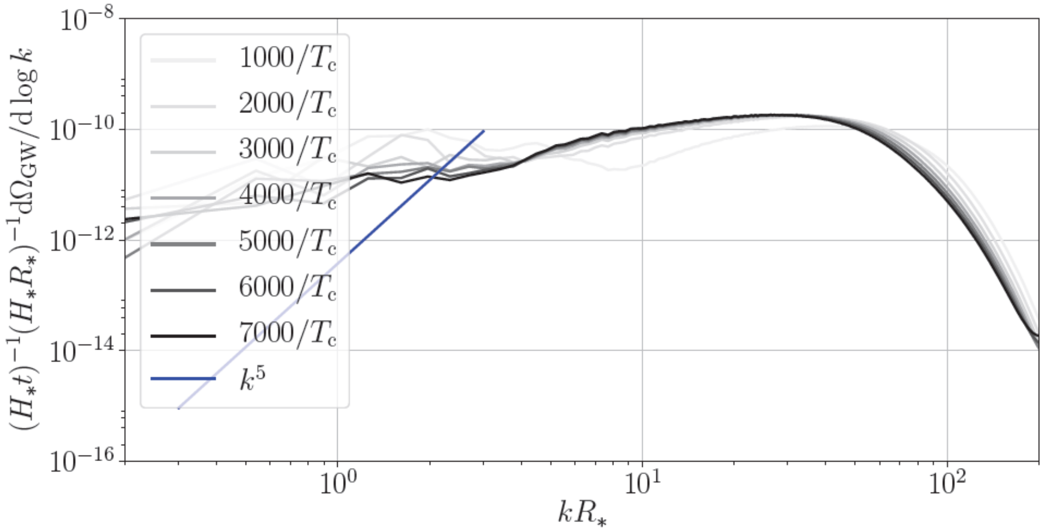
Observations will be able to <u>distinguish</u> between a thermal and a vacuum transition

Maybe also other information hidden in the spectrum, eg. on the wall speed?

hear-Jouguet deflagrations, $v_\mathrm{w} = 0.56$



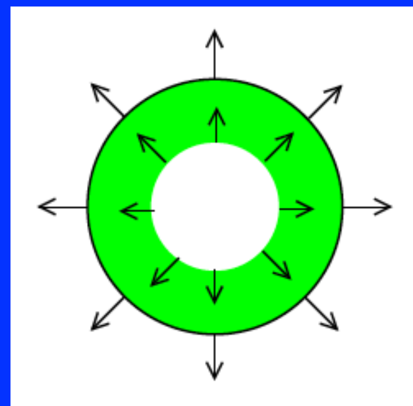
(d) $N_\mathrm{b} = 84$



(e) $N_\mathrm{b} = 5376$

Peak moves to higher frequencies because of <u>thinner fluid shell</u>

But this is a very tuned case



Strength of the GW signal:

$$\Omega_{\rm GW} \simeq \frac{3\bar{\Pi}^2}{4\pi^2}(H_*\tau_{\rm s})(H_*R_*)(1+w)^2\overline{U}_{\rm f}^4,$$

Simulation (sound)

$$\Omega_{\rm GW} \simeq \frac{0.11 v_{\rm w}^3}{0.42 + v_{\rm w}^2}\left(\frac{H_*}{\beta}\right)^2 \frac{\kappa^2\alpha_T^2}{(\alpha_T+1)^2}$$

env. appr. (scalar)

Enhancement by $\tau_{\rm s}/R_* v_{\rm w}$ up to a factor 100

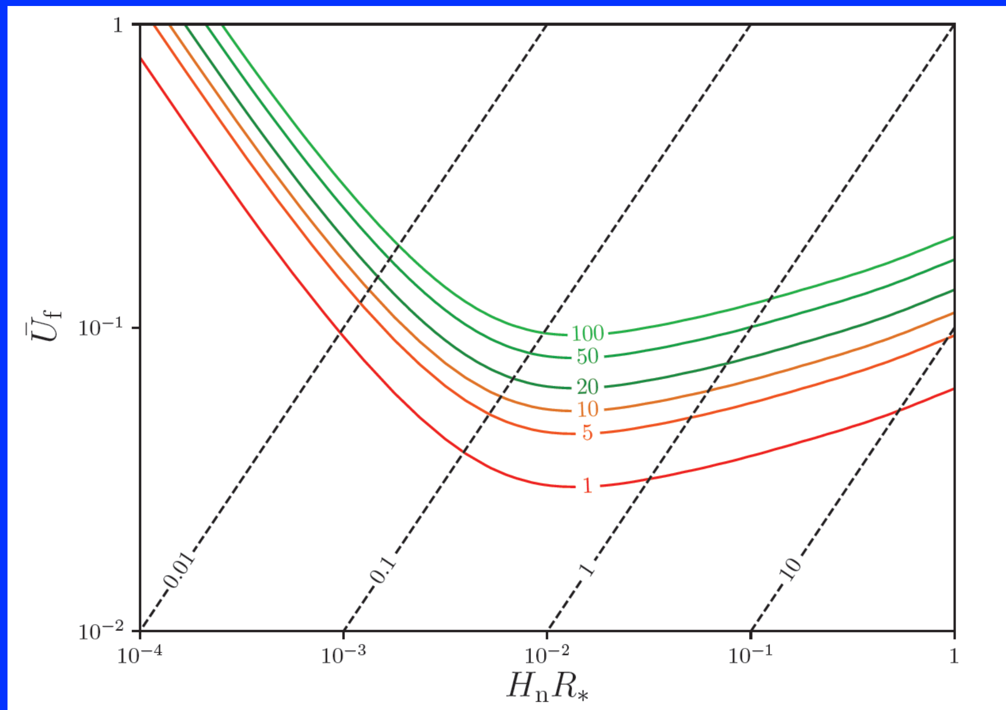
What sets τ_s? Normally the Hubble time!

Turbulence

The Reynold's number of this system is huge
We do not see turbulence because we do not run long enough
Turbulence will set in after about an eddy turnover time

For roughly $\frac{R_*}{\overline{U}_{\mathrm{f}}} < \frac{1}{H_{\mathrm{n}}}$

turbulence will develop before the source is cut off by Hubble expansion and the spectrum will be noticably modified



Examples

GW's in the SUSY with singlets

General Next-to-MSSM: no discrete symmetries

➔ no domain wall problem, rich Higgs phenomenology

$$W = L_1 \hat{S} + \mu \hat{H}_u \hat{H}_d + \frac{1}{2} M_S \hat{S}^2 + \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{1}{3} \kappa \hat{S}^3$$

[SH, Konstandin, Nardini, Rues '15]

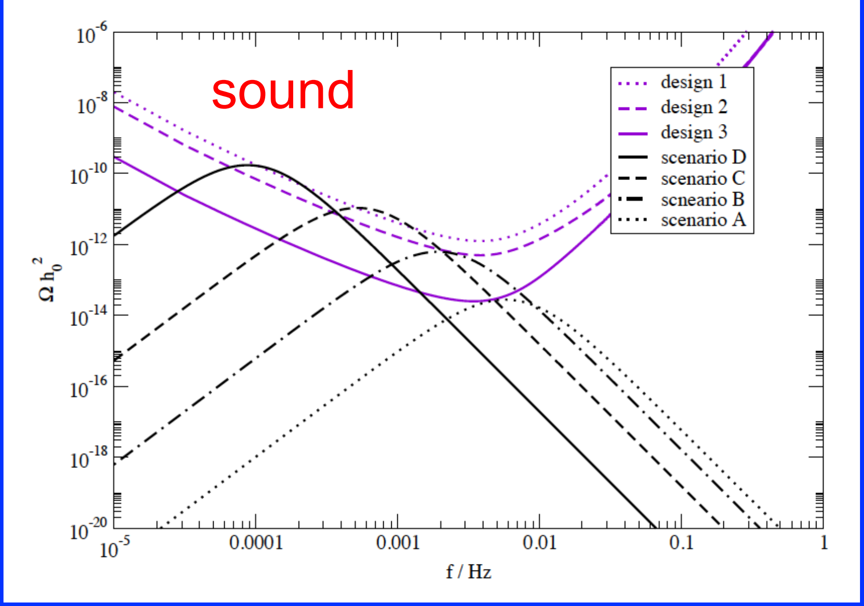
Look for parameter points with a <u>very strong phase transition</u> (substantially lifted electroweak vacuum): 4 benchmarks A-D

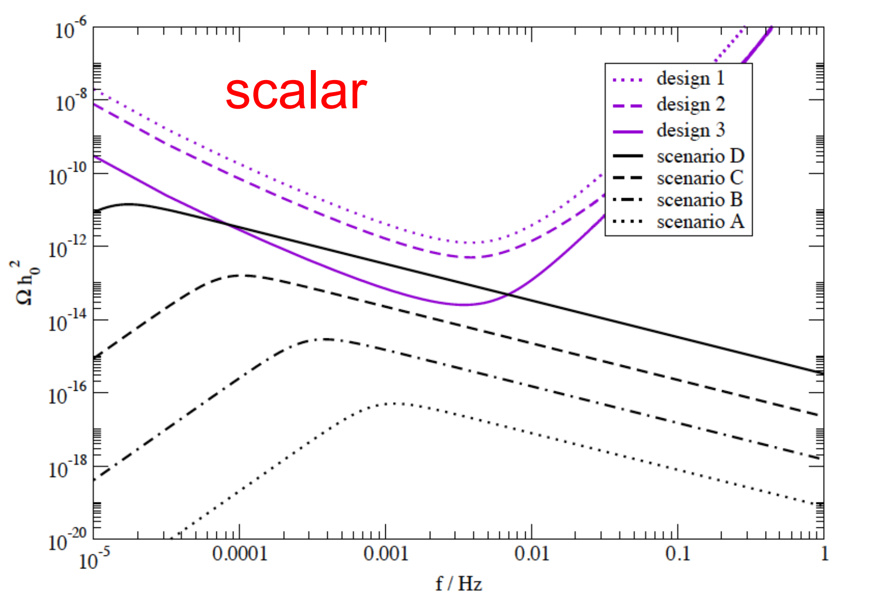
	A - D
$\tan\beta$	5
λ	0.7
κ	0.015
L_1	0
B_S [GeV^2]	-250^2
μ [GeV]	300

	A	B	C	D
T_n [GeV]	112.3	94.7	82.5	76.4
α	0.037	0.066	0.105	0.143
β/H	277	105.9	33.2	6.0
$v_h(T_n)/T_n$	1.89	2.40	2.83	3.12

1-loop	A - D
m_{h_1}	91
m_{h_2}	125.6
$\sin^2\gamma$	10^{-3}

Gravitational wave signal:





Very strong transitions in the GNMSSM lead to an observable GW signal in LISA

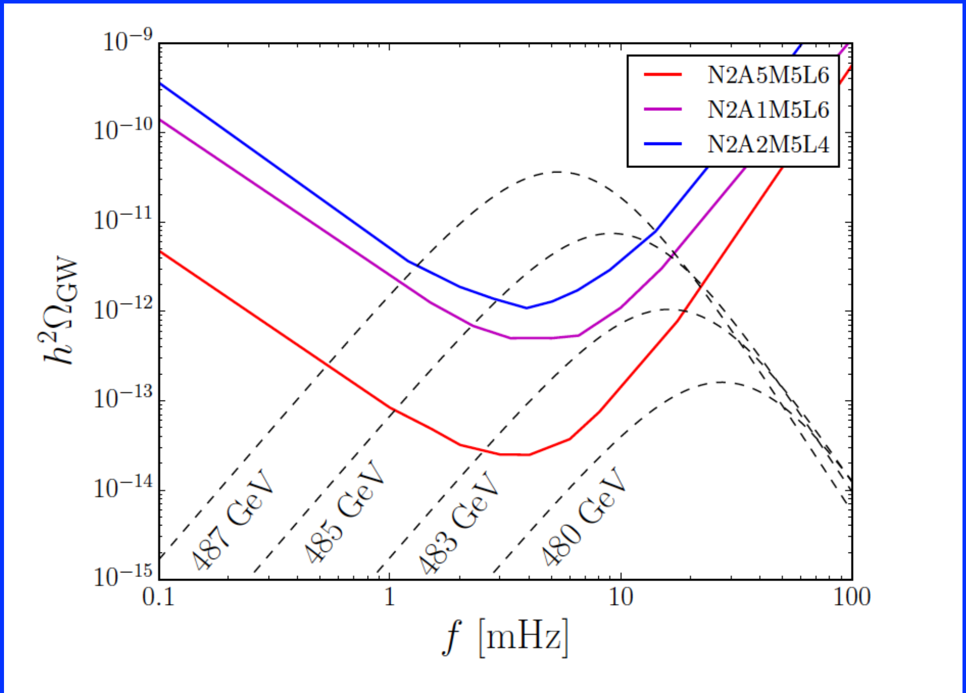
The spectrum from sound (fluid) clearly different from that of scalar only (vacuum transition)

GWs in the 2HDM

Consider the 2HDM from the first part:

[Dorsch, SH, Konstandin, No '16]

One can at the same time have successful baryogenesis and observational GWs:



m_{A^0} [GeV]	T_n	v_n/T_n	$L_w T_n$	$\Delta\Theta_t$	α_n	β/H_*	v_w
450	83.665	2.408	3.169	0.0126	0.024	3273.41	0.15
460	76.510	2.770	2.632	0.0083	0.035	2282.42	0.20
480	57.756	3.983	1.714	0.0037	0.104	755.62	0.30
483	53.549	4.349	1.556	0.0031	0.140	557.77	0.35
485	50.297	4.668	1.441	—	0.179	434.80	0.45
487	46.270	5.120	1.309	—	0.250	306.31	$\approx c_s$

In the 2HDM the GW frequency is one to two orders of magnitude larger (same α)

Deflagrations!

Turbulence?

2HDM baryogenesis

(with Dorsch, Konstandin, No 2016)

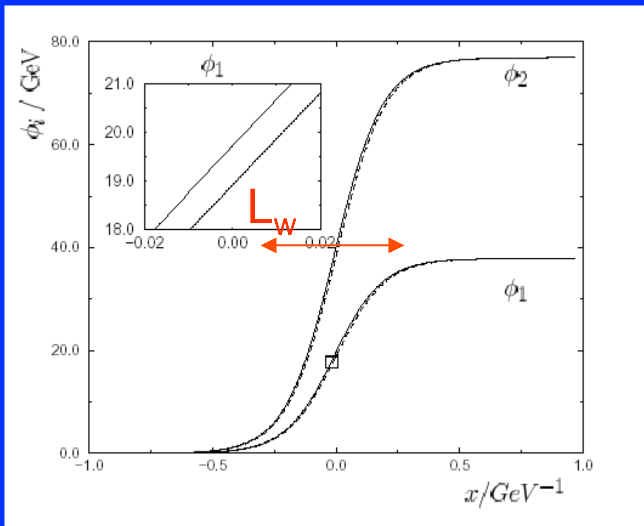
The bubble wall

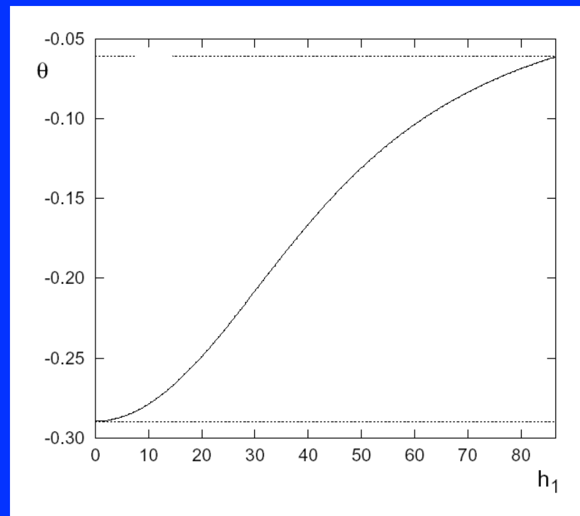
CP violating transport in a non-homogeneous background: top quark!

Solve the field equations with the thermal potential → wall profile $\Phi_i(r)$

kink-shaped with wall thickness L_w

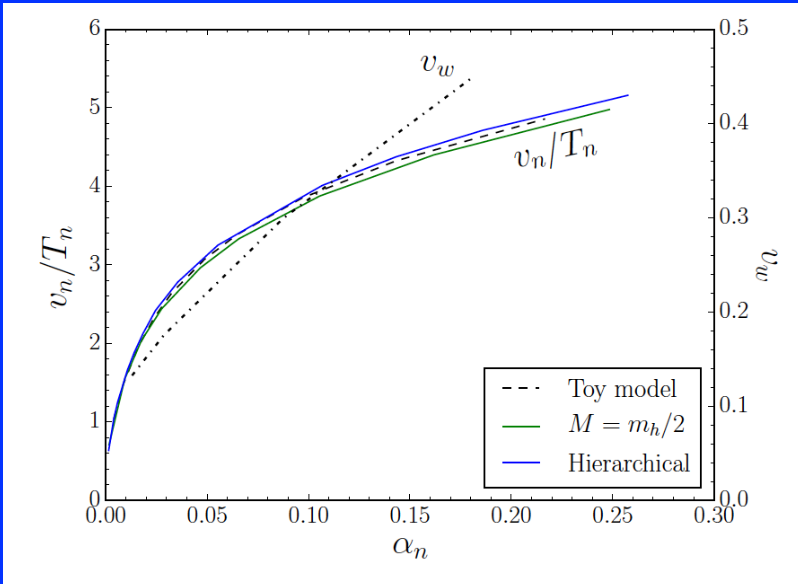
θ becomes dynamical





(numerical algorithm for multi-field profiles, T. Konstandin, S.H. ´06)

Status of baryogenesis in the 2HDM



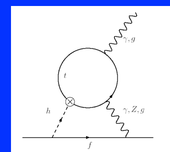
[Dorsch, SJH, Konstandin, No, 2016]

Key progress: computation of the bubble

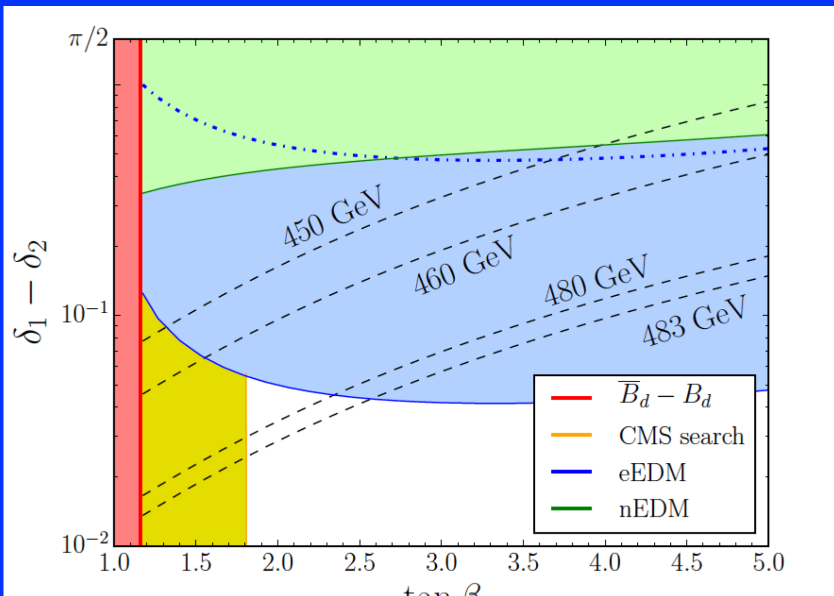
Velocity, which needs to be subsonic for

Successful baryogenesis via diffusion

True for even very strong transitions



Only one phase: baryon asymmetry makes a definite prediction for EDMs

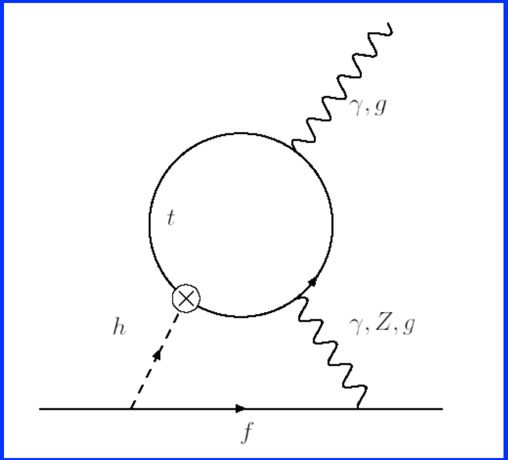


Improved bound on the electron EDM by ACME

$$|d_e^{\mathrm{ACME}}| < 8.7 \times 10^{-29}\ e \cdot \mathrm{cm}$$

Baryogenesis now tightly constrained but still possible (uncertainties?)

Remarks:



- The EDMs in 2HDMs are of Barr-Zee type
- The baryon asymmetry scales as

$$\eta \sim \frac{\delta}{L_w T_n} \left(\frac{v_n}{T_n} \right)^2 \frac{1}{1 + \tan^2 \beta}$$

so needs a strong transition with a thin wall and small tan β

- Even though the transition is very strong, v_n/T_n~4, the wall still moves subsonic (deflagration) because of strong Higgs self couplings

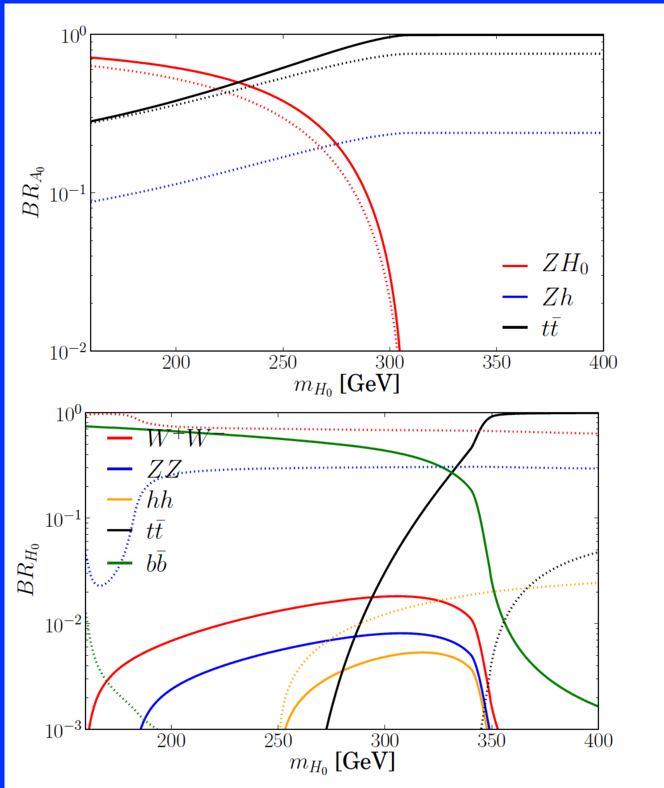
2HDM:

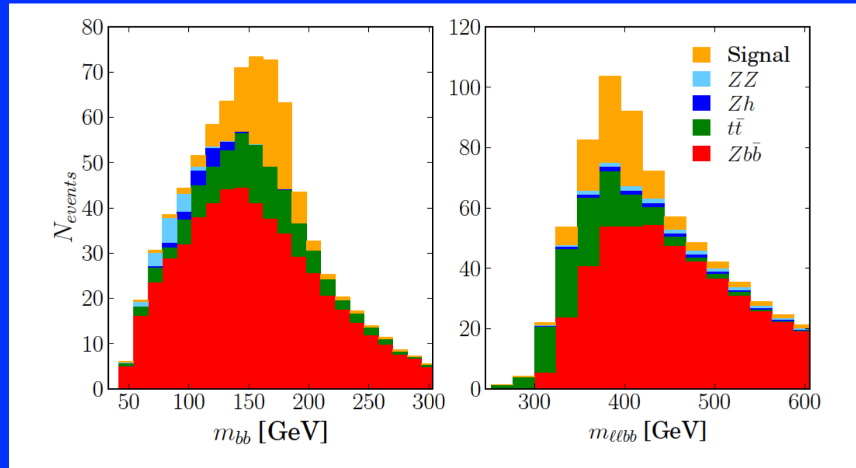
The strong phase transition at LHC

(with Dorsch, Mimasu, No)

Search for $A_0 \rightarrow H_0 Z \rightarrow ll\ bb$

[Dorsch, S.H., Mimasu, No '14]

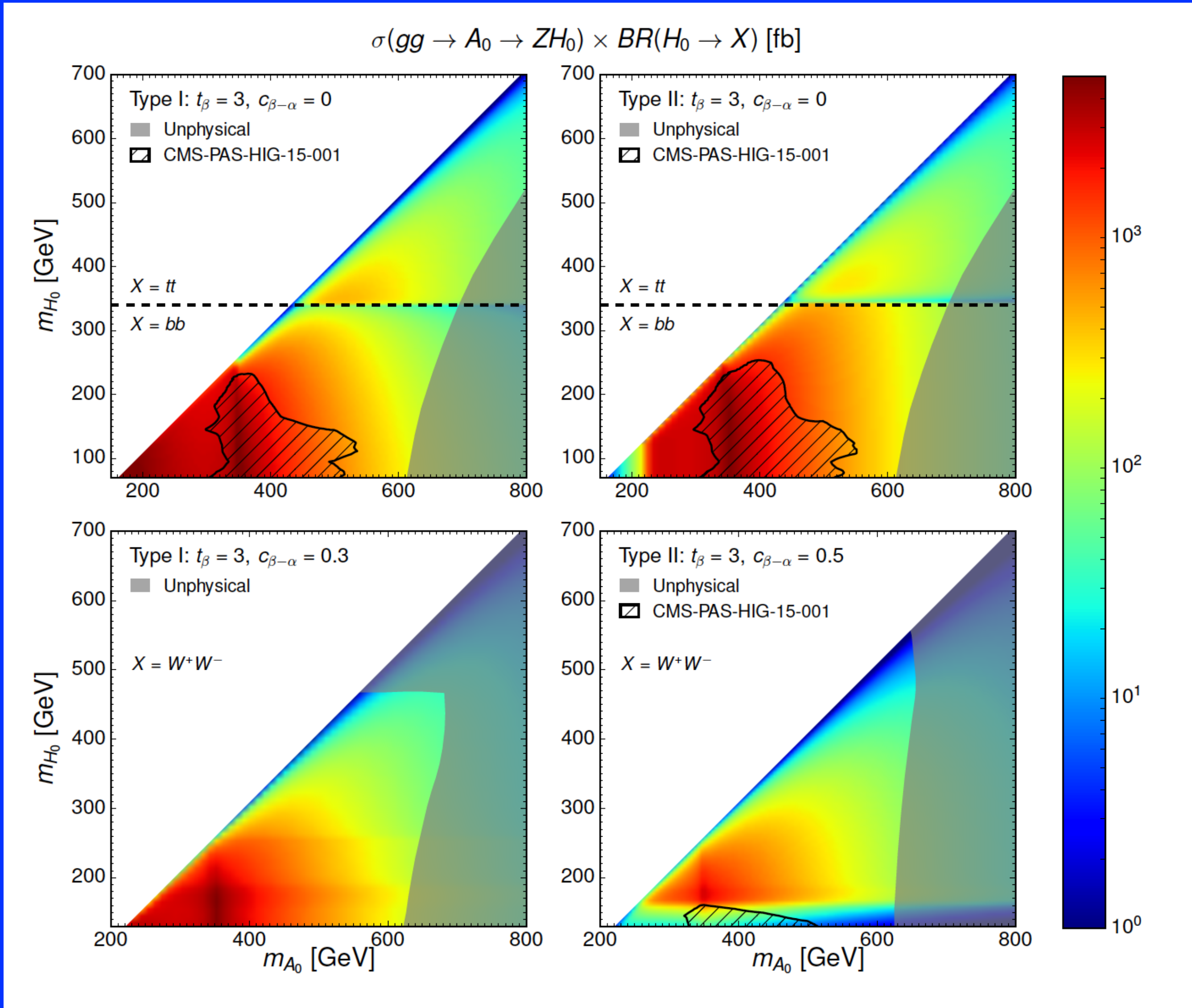




	Signal	$t\bar{t}$	$Z\,b\bar{b}$	ZZ	$Z\,h$
Event selection	14.6	1578	424	7.3	2.7
$80 < m_{\ell\ell} < 100$ GeV	13.1	240	388	6.6	2.5
$H_T^{\mathrm{bb}} > 150$ GeV, $H_T^{\ell\ell\mathrm{bb}} > 280$ GeV	8.2	57	83	0.8	0.74
$\Delta R_{bb} < 2.5,\ \Delta R_{\ell\ell} < 1.6$	5.3	5.4	28.3	0.75	0.68
$m_{bb},\ m_{\ell\ell bb}$ signal region	3.2	1.37	3.2	< 0.01	< 0.02

($m^{\pm}$=400 GeV, m_{H_0}=180 GeV)

Prospects for LHC run 2:



Summary

Many extension of the SM will have first order phase transitions (mostly will have new scalars)

Sound waves play a key role in generating the GW signal and are now well understood: peaked at the bubble scale with IR, UV power laws

Very strong transitions will be affected by turbulence (to be understood better)

Observed GW signal will contain valuable information on the transition

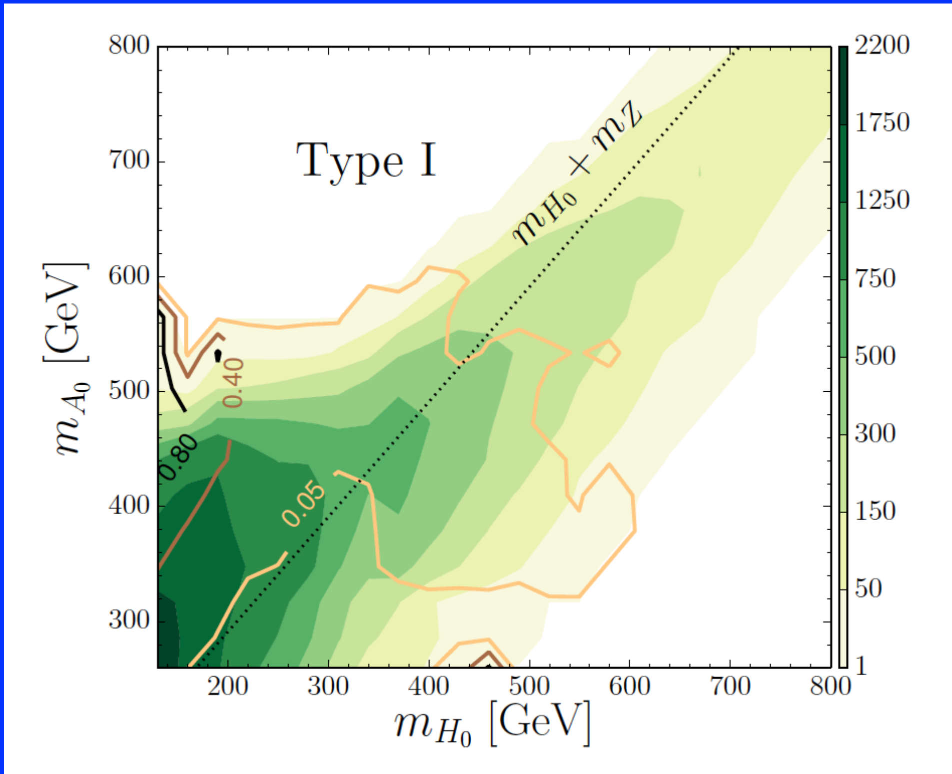
2HDM can have baryogenesis and GWs at the same time

Sometimes interesting LHC-GW interplay, but GW can also detect “hidden” transitions

The strong phase transition at LHC

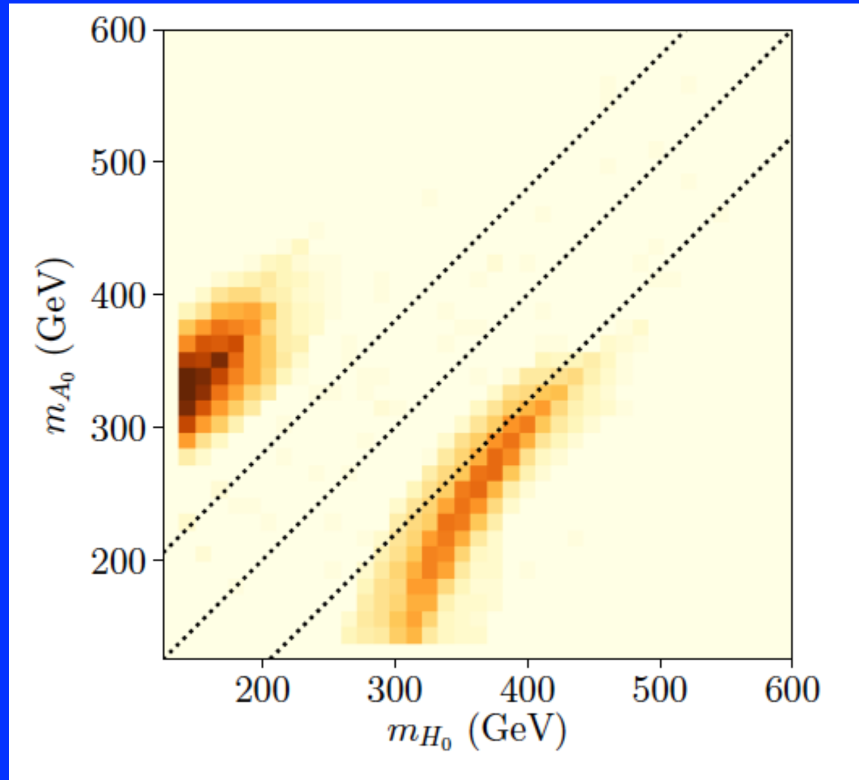
A strong phase transition prefers a hierarchical Higgs spectrum:

Prediction of a heavy pseudo scalar



(1-loop thermal potential)

[Dorsch, SJH, Mimasu, No, 2017]



(3d lattice simulation)

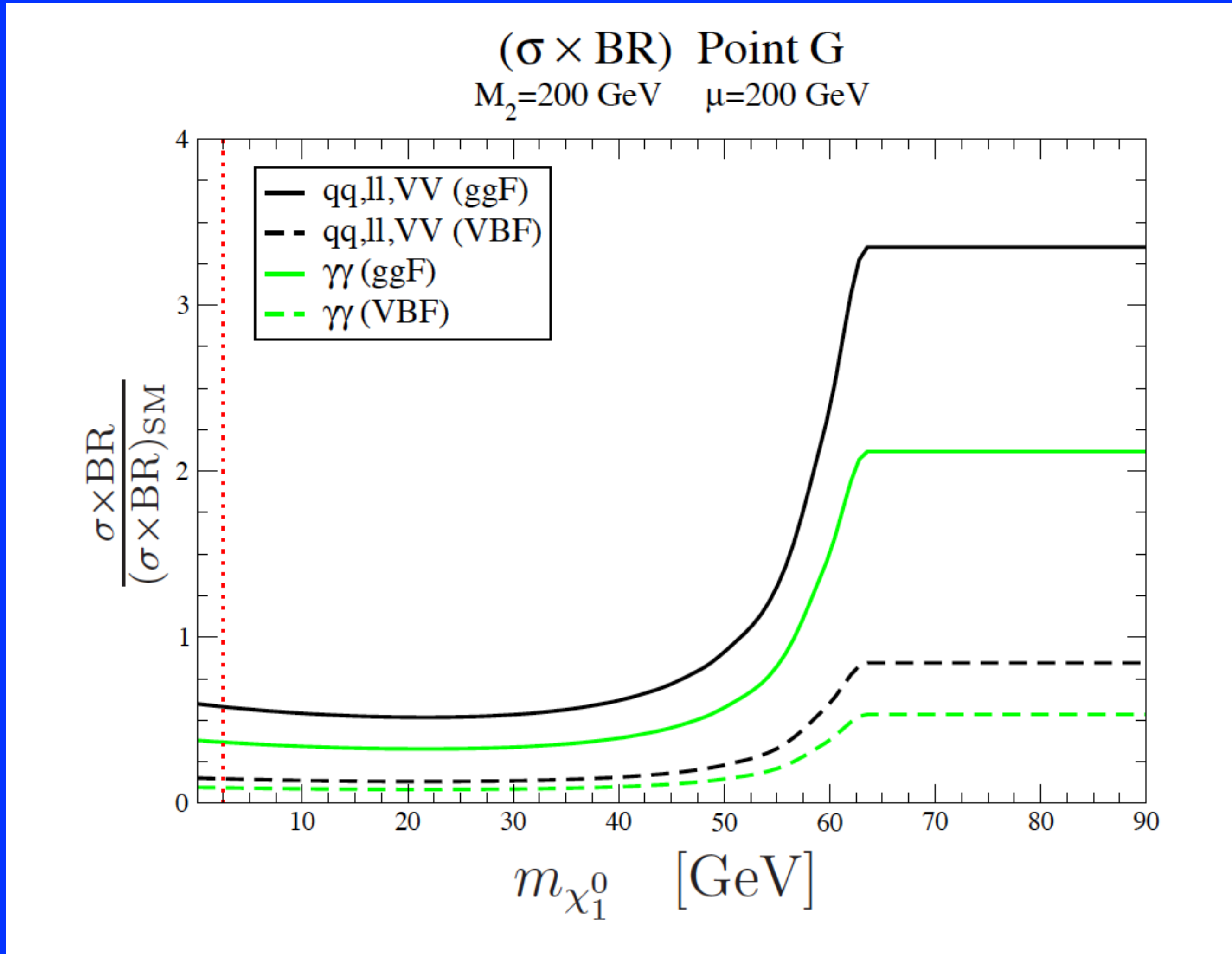
[Andersen et al., 2017]

a strong phase transition in the 2HDM is very much consistent with a SM-like light Higgs

specific prediction of a hierarchical Higgs mass spectrum

testable at LHC

Problem: modified Higgs branching ratios, e.g. into two photons:



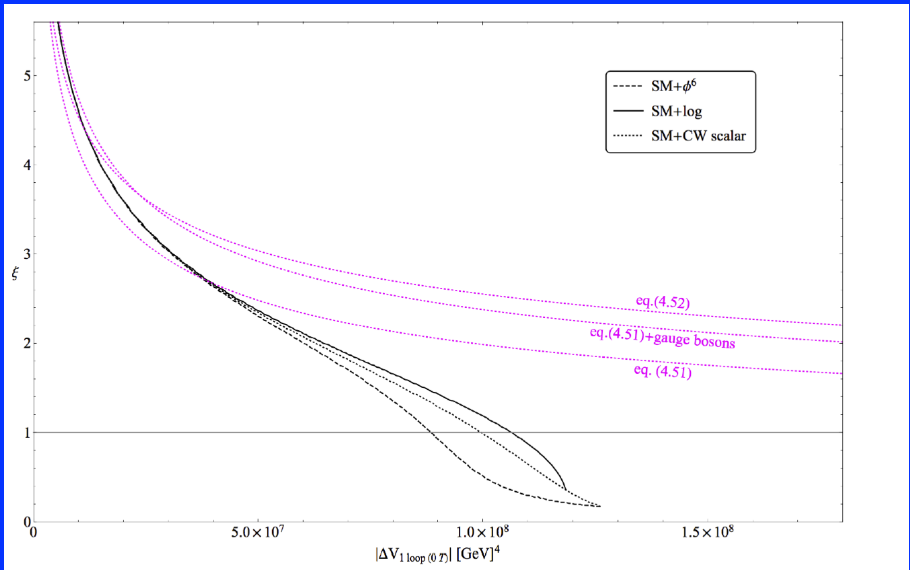
[Carena, Nardini, Quiros,Wagner 2012]

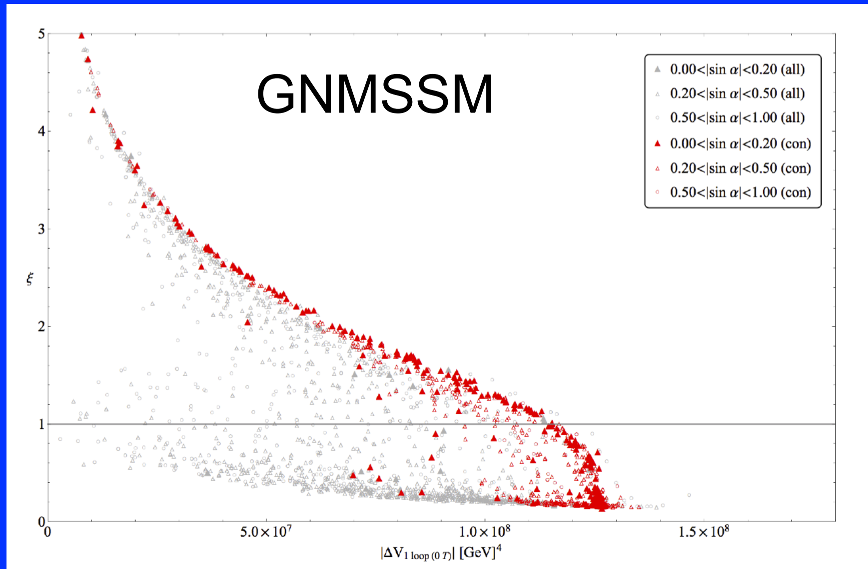
vacuum energy: general models

Consider the T=0 depth of the EM minimum: [Harman S.H. ‘15]

$$\Delta V_{1\ \text{loop}\ (0\text{T})} = V_{1\ \text{loop}\ (0\text{T})}\big|_{\text{broken}} - V_{1\ \text{loop}\ (0\text{T})}\big|_{\text{symmetric}}$$

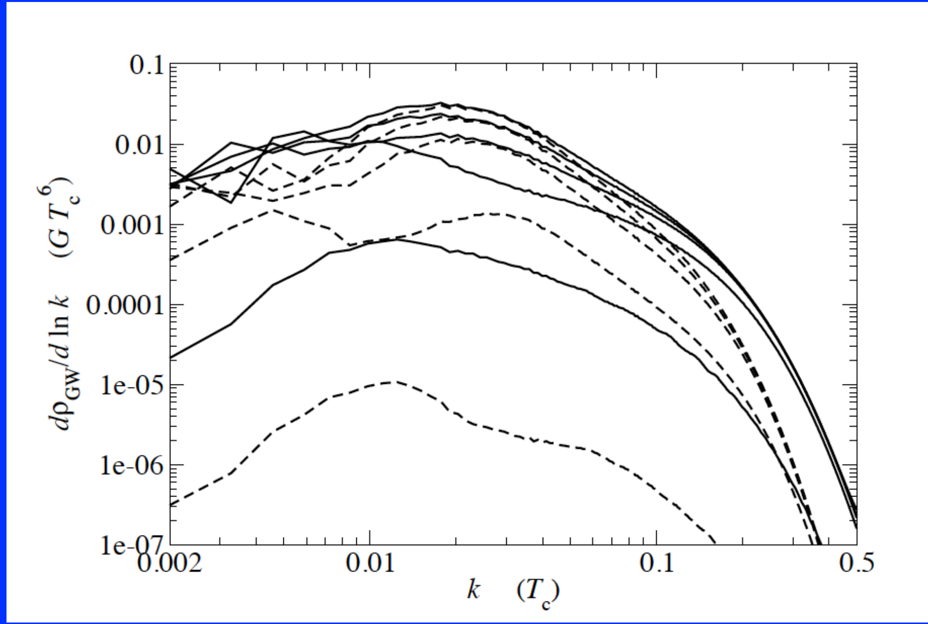
$$= V_{1\ \text{loop}\ (0\text{T})}(v, v_S) - V_{1\ \text{loop}\ (0\text{T})}(0, \tilde{v}_S)$$

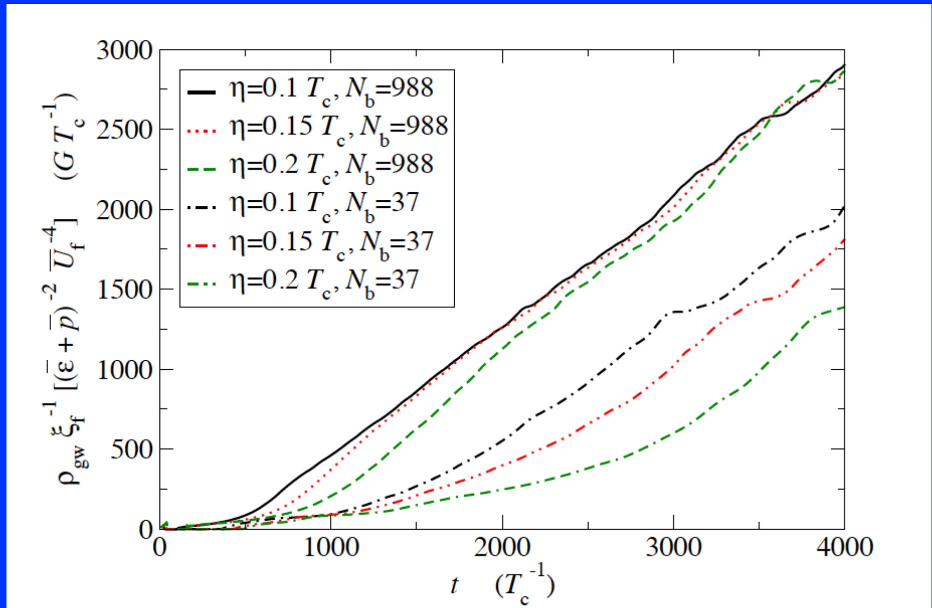


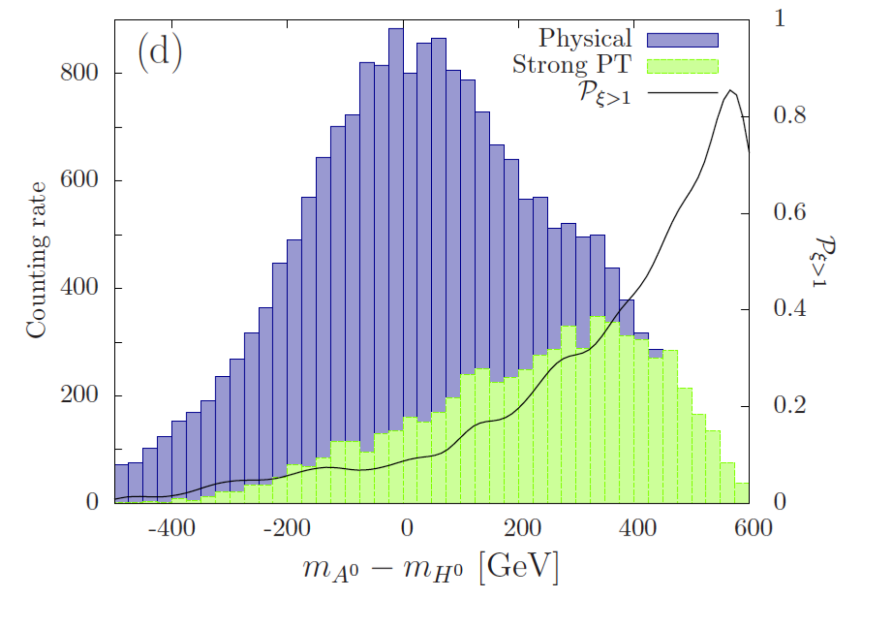


Strong transitions are entirely fixed by ΔV (once the Higgs SM-like)

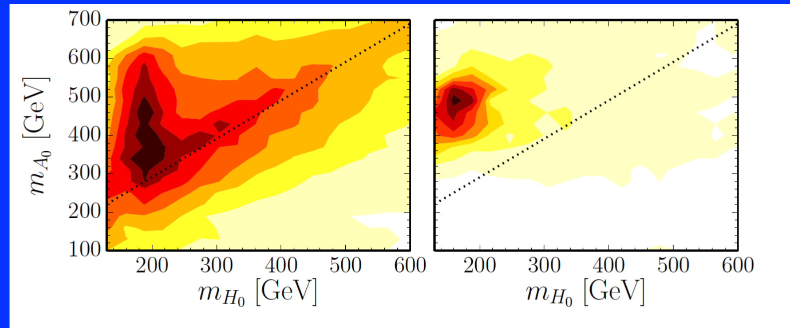
Time evolution:



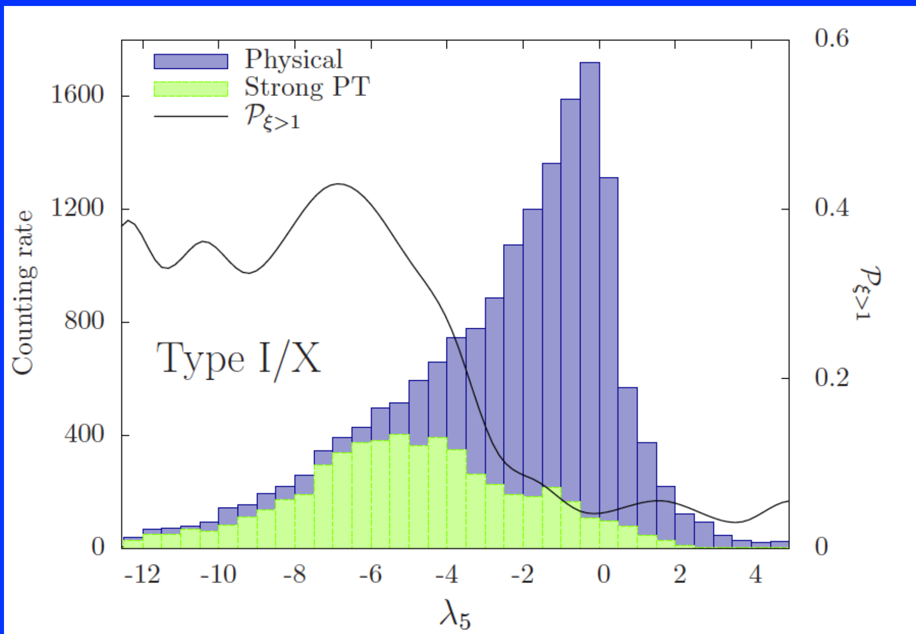




Preference for a <u>heavy pseudoscalar</u>



[Dorsch, S.H., Mimasu, No '14]



Preference for a large negative λ_5

$$\frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + H.c.\right]$$

Scale invariant Higgs

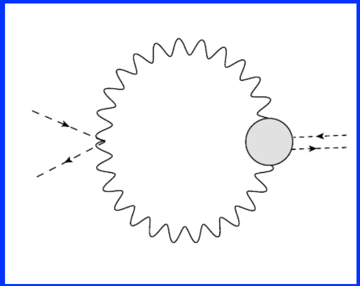
Higgs mass stabilized by conformal symmetry,

[Abel, Mariotti '13]

Broken in a hidden sector,

Transmitted to the SM by gauge mediation:

$$\delta V_{\rm eff} \equiv V_0 = -\frac{m_h^2}{4}\, h^2 \left(1 + X \log\left[\frac{h^2}{v^2}\right]\right) + \frac{\lambda}{4}\, h^4$$



[Dorsch, SH, No '14]