Cosmic phase transitions at the TEV scale

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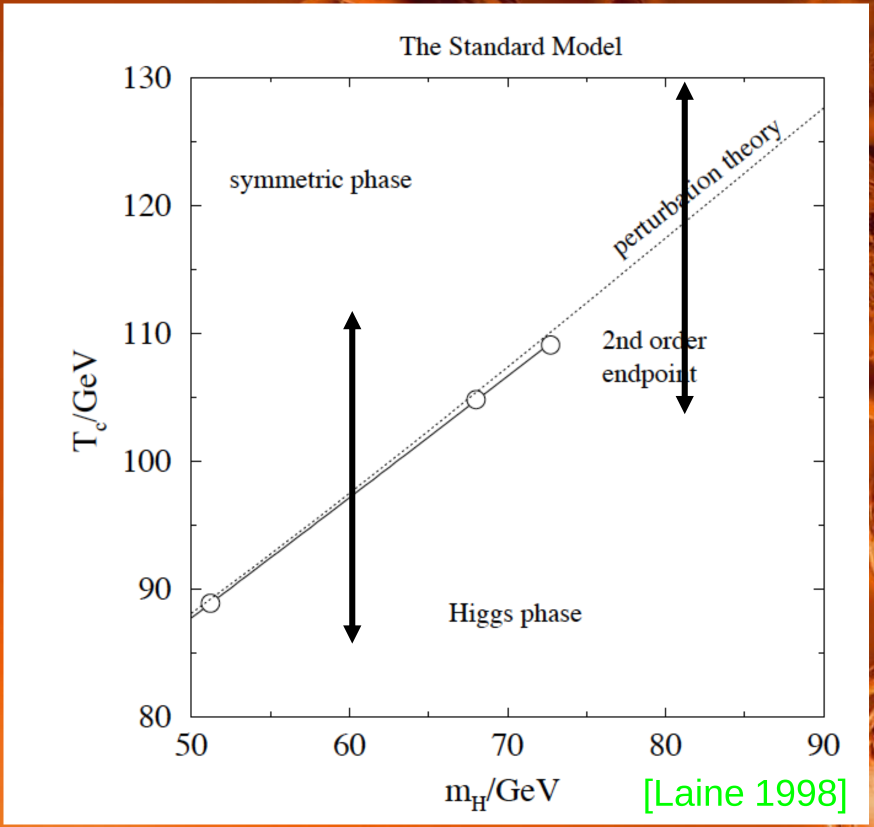
April 2019

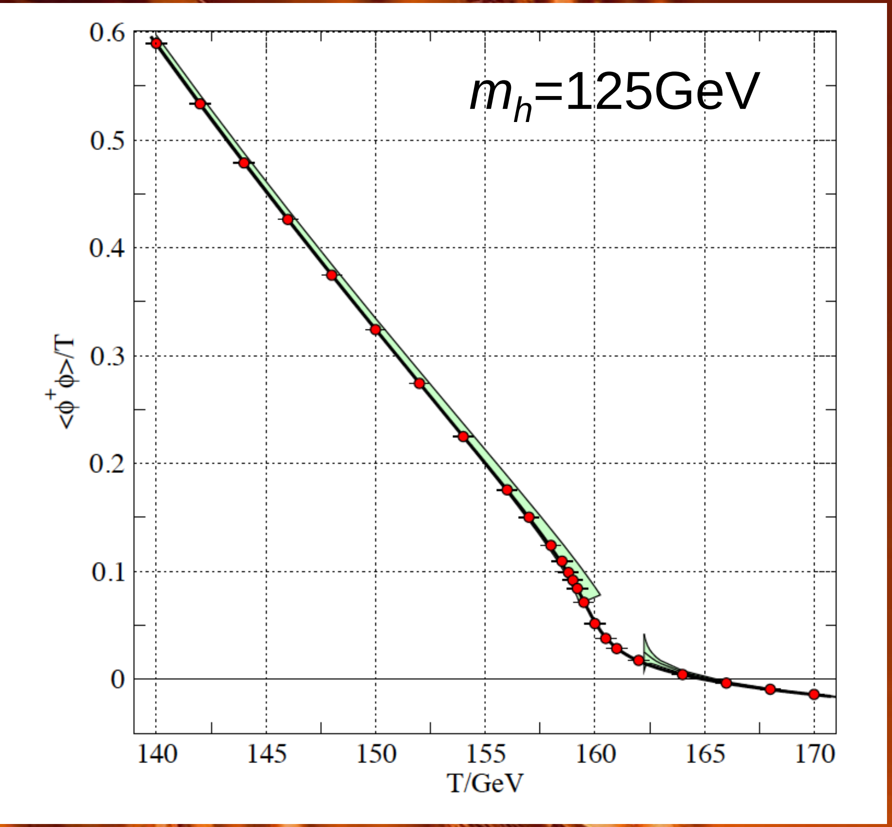
Cosmic electroweak symmetry breaking in the Standard Model

$m_h \lesssim m_W$: first order phase transition



[Kajantie, Laine, Rummukainen, Shaposhnikov 1995]

$m_h \gtrsim m_W$: crossover



[D`Onofrio, Rummukainen, 2015]

Eg. relevant for freeze out of EW processes

Outline

- brief review: cosmic first order phase transitions
- collider links
- connections to baryogenesis
- what we know about the gravitational wave signal from phase transitions
- 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

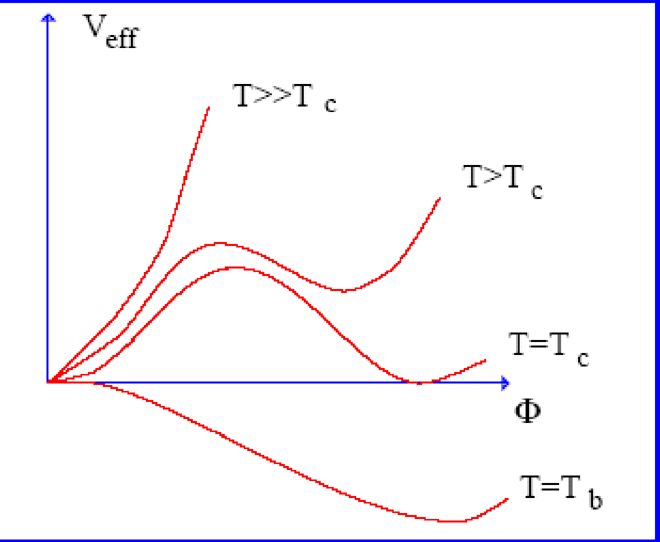
The strength of the PT

Thermal effective potential:

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

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, $\xi \gtrsim 1$: thermal perturbation theory (1 or 2-loop)

Weak transitions: lattice methods (often 3D), eg. for SM crossover

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.

[eg. Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 2018]

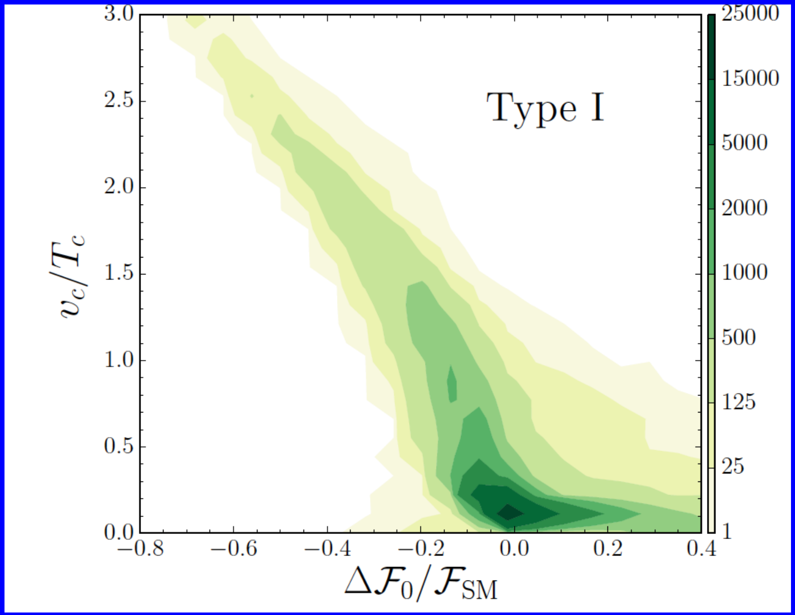
How to make a strong transition?

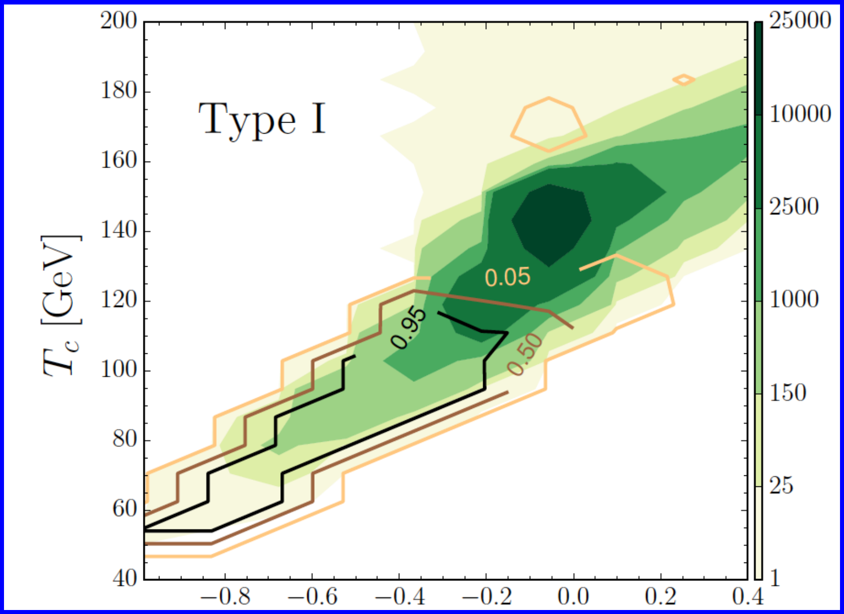
2) Make the EW minimum less deep (ie. lower T_c, larger v_c/T_c):

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 less deep at <u>tree-level</u>

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

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

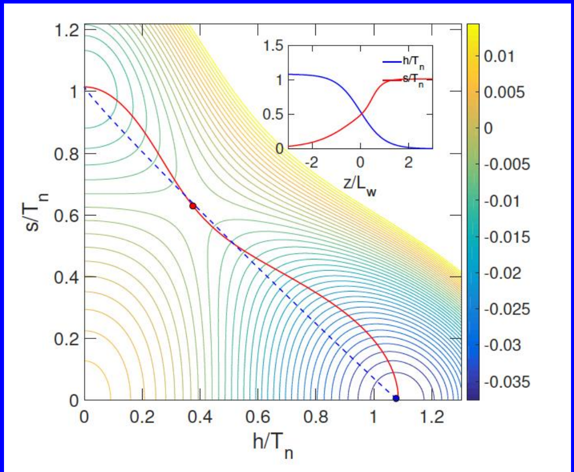
[eg. Chala, Krause, Nardini, 2018]

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]



Applications

1) Collider links

2) Baryogenesis

3) Gravitational waves

2HDM phase transition at LHC

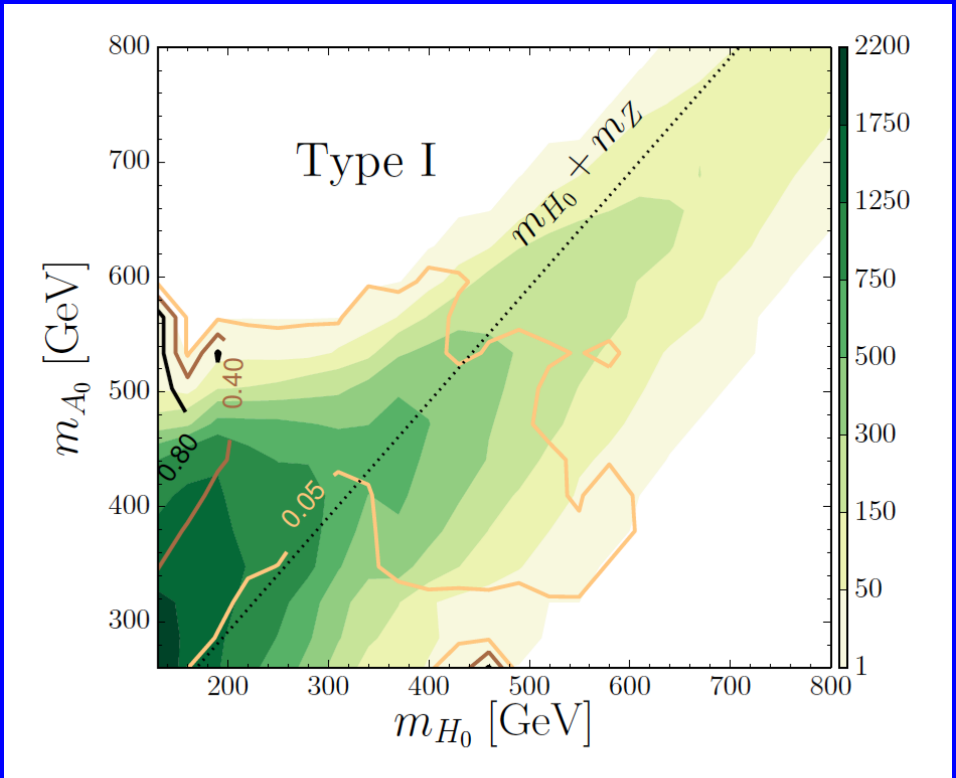
(with Dorsch, Mimasu, No)

$$V_{\rm tree}(\Phi_1,\Phi_2) = \mu_1^2\left|\Phi_1\right|^2 + \mu_2^2\left|\Phi_2\right|^2 - \mu^2\left[\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}\left|\Phi_1\right|^4 + \frac{\lambda_2}{2}\left|\Phi_2\right|^4 + \lambda_3\left|\Phi_1\right|^2\left|\Phi_2\right|^2 + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right],$$

(with softly broken Z_2 symmetry)

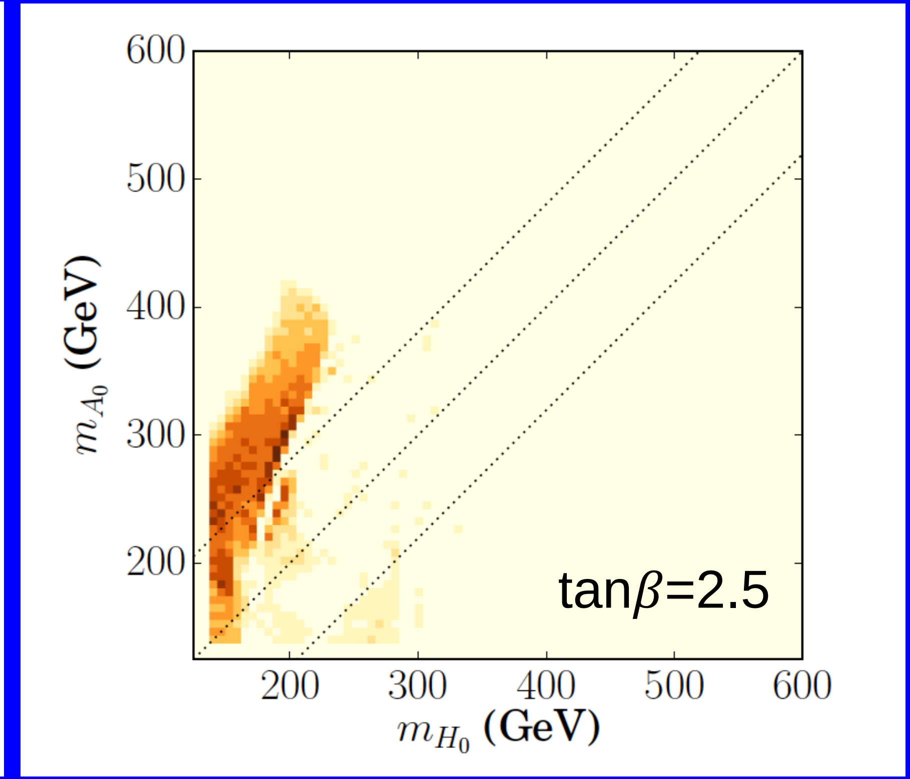
A strong phase transition prefers a hierarchical Higgs spectrum:

Prediction of a heavy pseudo scalar



(1-loop thermal potential)

[Dorsch, SJH, Mimasu, No, 2017]

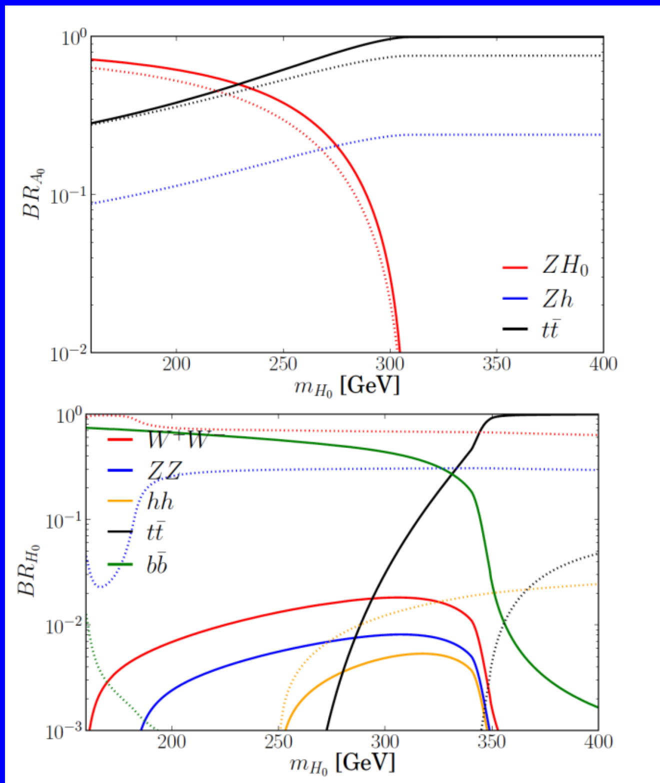


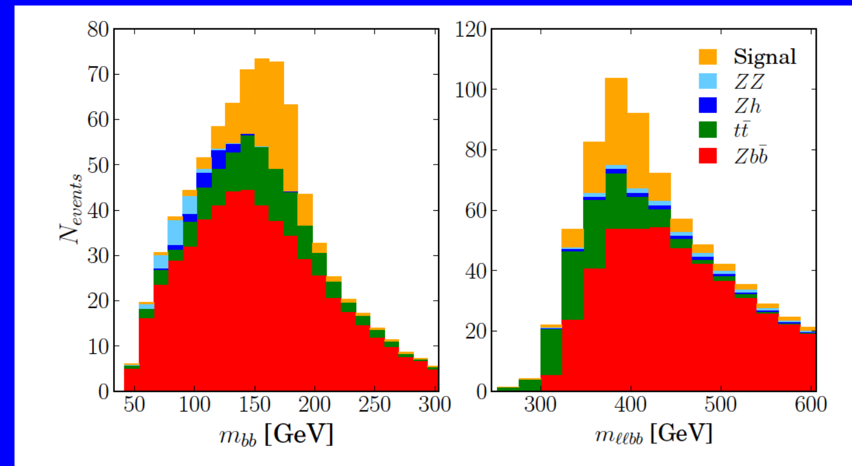
(3d lattice simulation)

[Andersen et al., 2017]

Search for $A_0 \to H_0 Z \to ll\, bb$

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

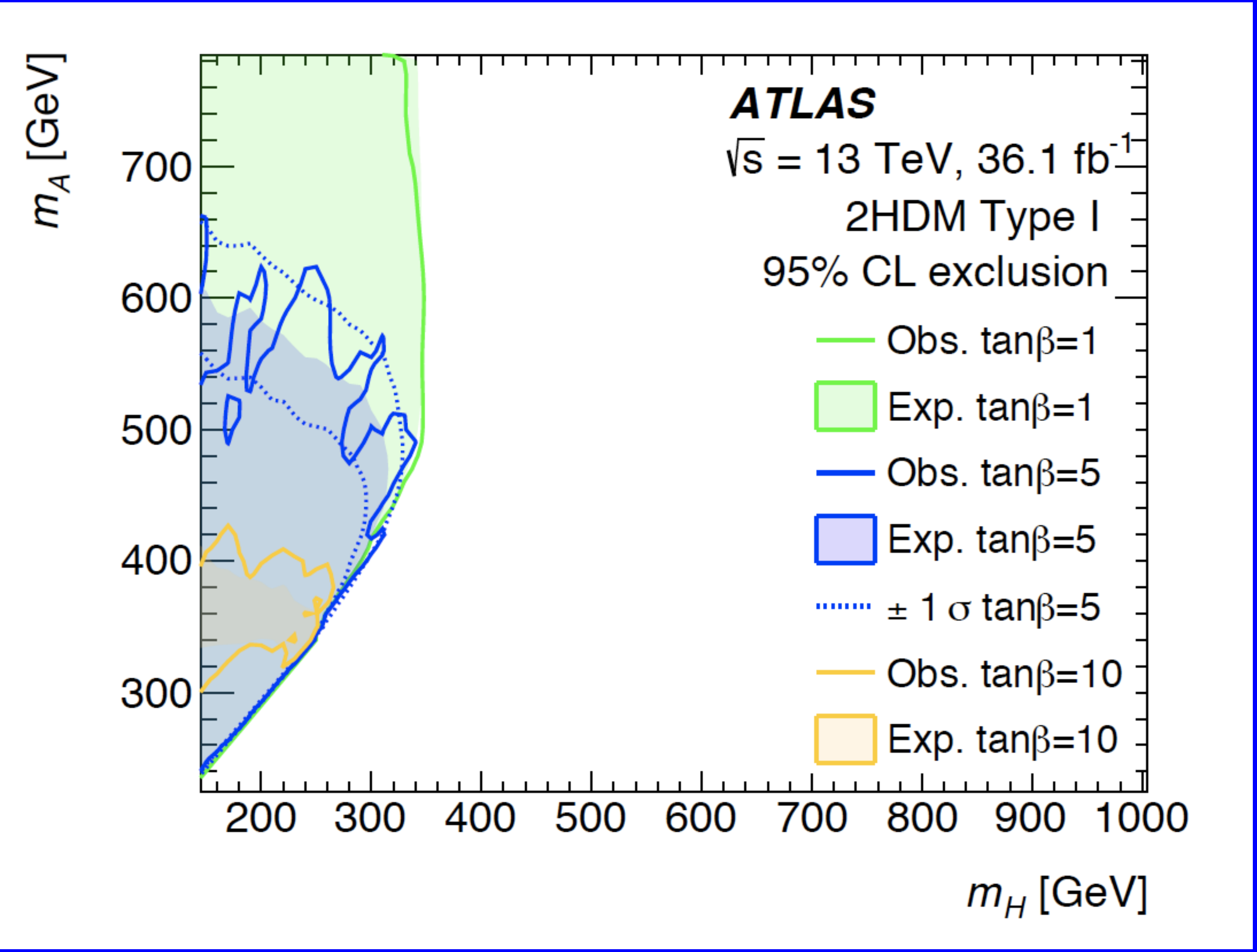




	Signal	$t\bar{t}$	$Z\,b\bar{b}$	$Z\,Z$	$Z\,h$
Event selection	14.6	1578	424	7.3	2.7
$80 < m_{\ell\ell} < 100$ GeV	13.1	240	388	6.6	2.5
$H_T^{bb} > 150$ GeV $H_T^{\ell\ell bb} > 280$ GeV	8.2	57	83	0.8	0.74
$\Delta R_{bb} < 2.5,\ \Delta R_{\ell\ell} < 1.6$	5.3	5.4	28.3	0.75	0.68
$m_{bb},\ m_{\ell\ell bb}$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

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

ATLAS search: (2018)



(Charged Higgs and pseudoscalar degenerate, alignment limit)

2HDM baryogenesis

(with Dorsch, Konstandin, No)

Electroweak baryogenesis: Non-equilibrium via EWPT

observed (PLANCK): $$\eta_B = \frac{n_B}{n_\gamma} = (6.047 \pm 0.074) \times 10^{-10}$$

semiclassical force:

(CP-violating source,

derivative expansion)

$$M(z) = m(z) e^{i\theta(z)}$$

$$\begin{aligned} E_\pm &= E_0 \pm \Delta E_0 \\ &= \sqrt{p^2 + m^2} \pm \theta' \frac{m^2}{2(p^2 + m^2)} \end{aligned}$$

$$\dot{p}_z = -\partial_z E(z, p_z)$$

Boltzmann equations: $$(\partial_t + \dot{z}\partial_z + \dot{p}_z \partial_{p_z}) f = \mathcal{C}[f]$$

(diffusion, needs $v_w < v_c$)

B violation by EW sphalerons

The bubble wall

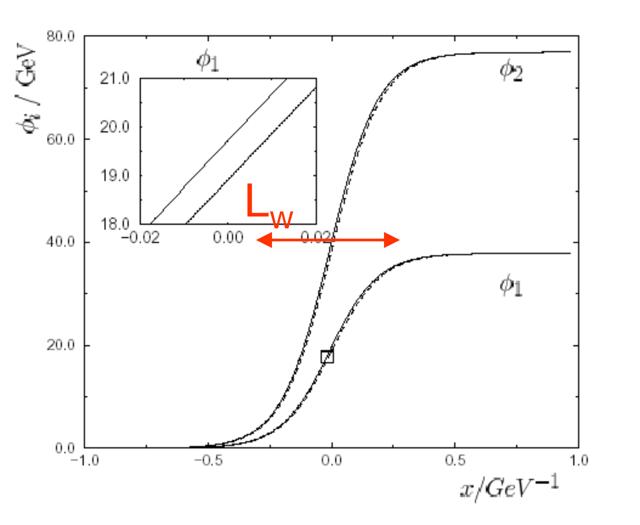
CP violating transport in a non-homogeneous background: top quark!

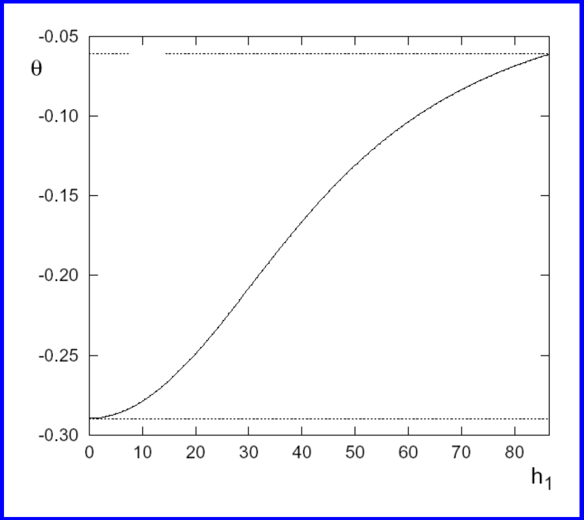
Solve the field equations with the thermal potential → wall profile $\Phi_i(r)$

kink-shaped with wall thickness L_w

θ becomes dynamical

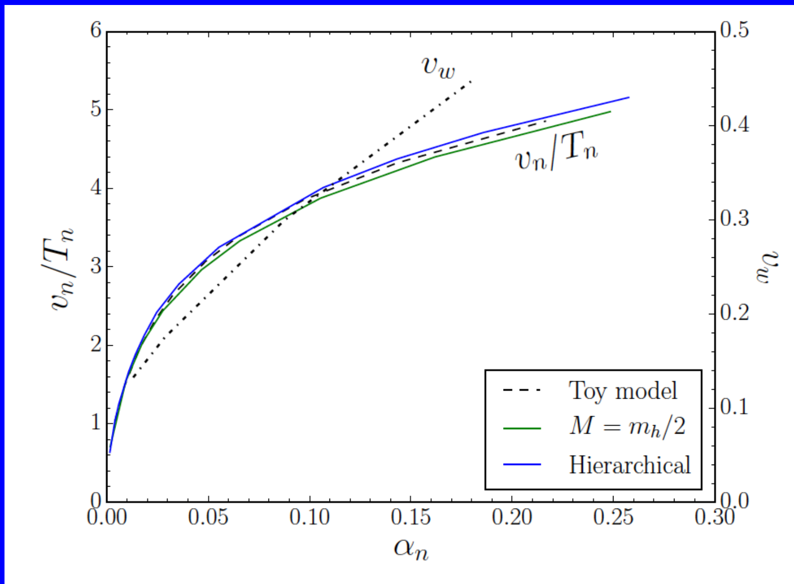
(phase between both vevs)





(for a novel algorithm for multi-field profiles, see poster by Victor Guada)

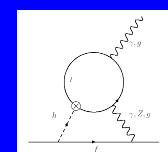
Status of baryogenesis in the 2HDM

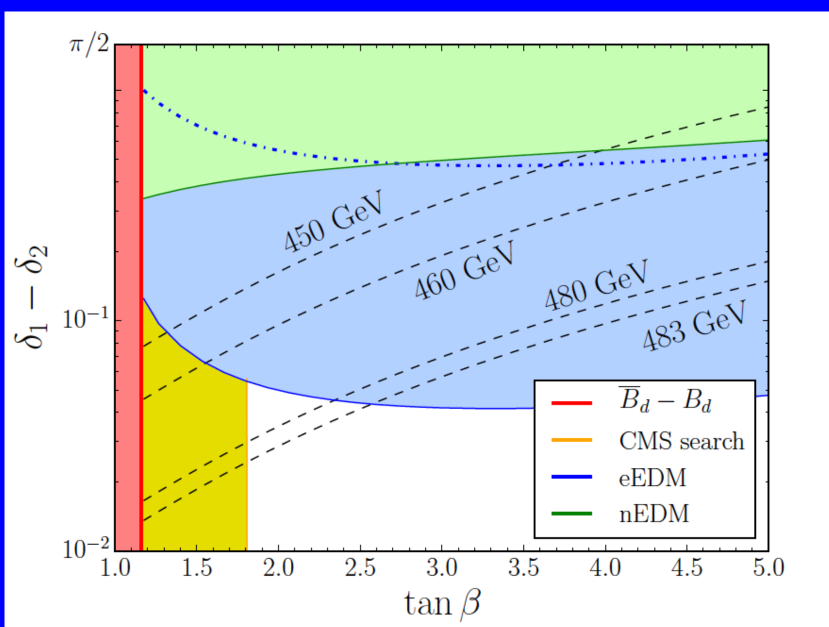


[Dorsch, SJH, Konstandin, No, 2016]

Key progress: computation of the bubble velocity, which needs to be subsonic for successful baryogenesis via diffusion

True for even very strong transitions





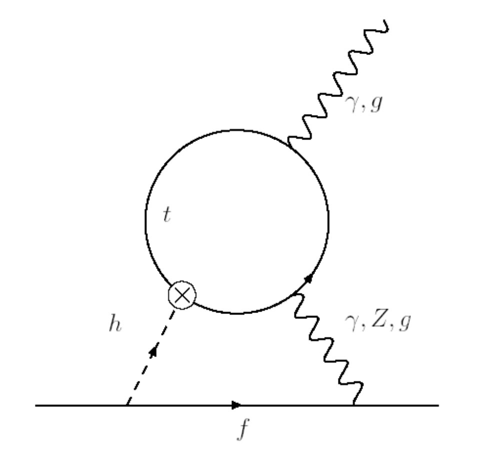
Only one phase: baryon asymmetry makes a definite prediction for EDMs

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

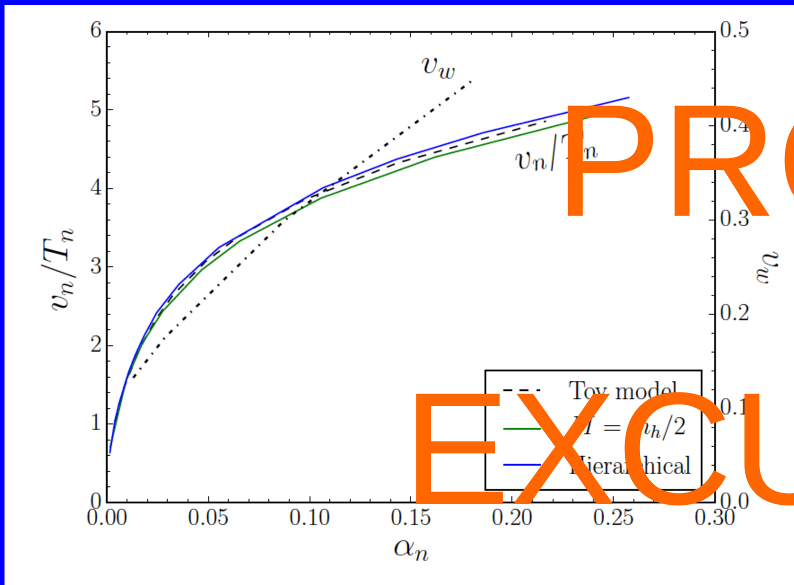
$$\eta \sim \frac{\delta}{L_w T_n} \left(\frac{v_n}{T_n} \right)^2 \frac{1}{1 + \tan^2 \beta}$$

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

Status of baryogenesis in the 2HDM

PROBABLY EXCULDED bY NEW ACME RESULT And also LHC



[Dorsch, SJH, Konstandin, No, 2016]

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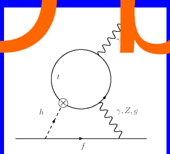

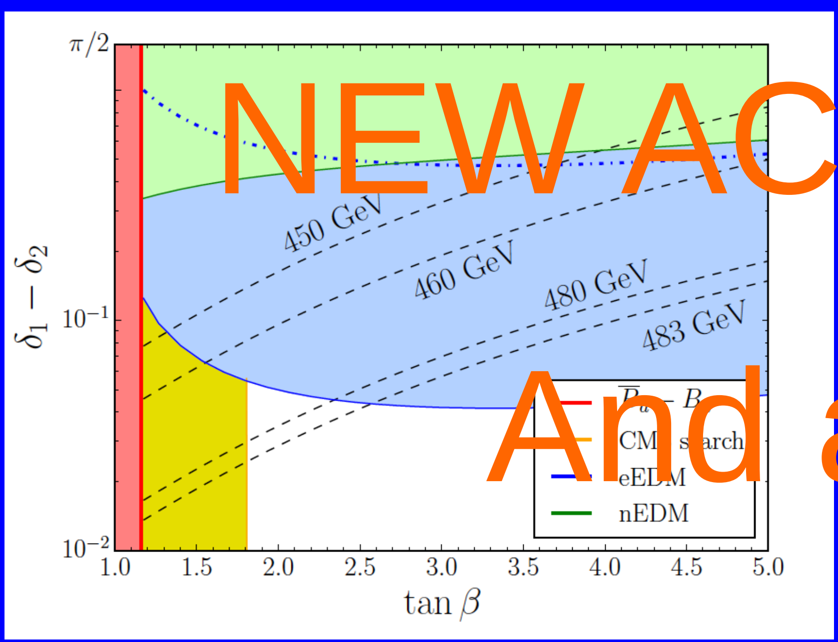

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Can it be saved?

Strong constraints from EDMs are generic (eg also when adding a singlet or in SUSY)

Models with “transitional” CP violation (needs an additional singlet)

Uncertainties due to thin bubble wall

Impact of leptons in transport has been underestimated?

Approximation	FR(q)	N(q,t,h)	N(q,t,h,u)	N(q,t,h,u,l)	A(q,t,h,u,l)
Y_B	1.6×10^{-12}	3.5×10^{-13}	3.4×10^{-13}	1.5×10^{-12}	1.1×10^{-12}

[de Fries, Postma, van de Vis ‘18]

Here roughly a factor of five enhancement for a EFT benchmark point:

Reasons: leptons efficiently diffuse (compared to quarks)

leptons do not suffer from strong sphaleron suppression

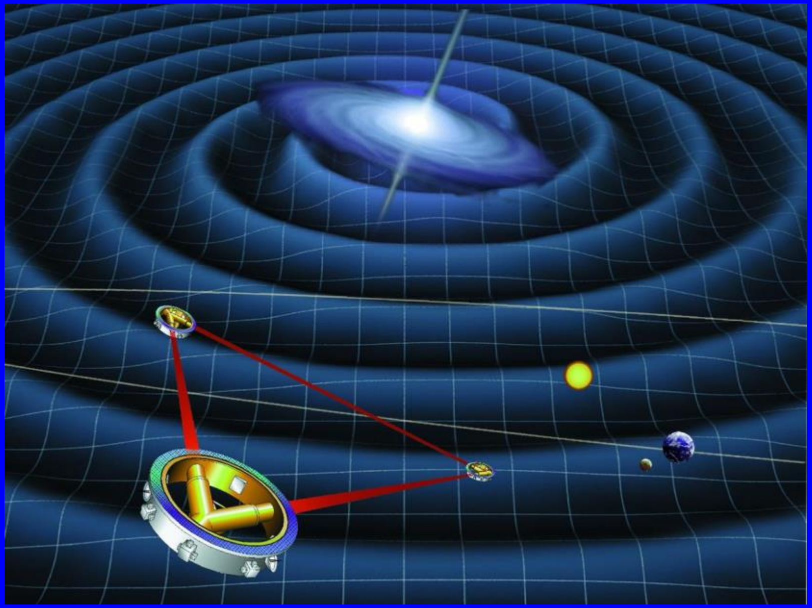
Gravitational waves

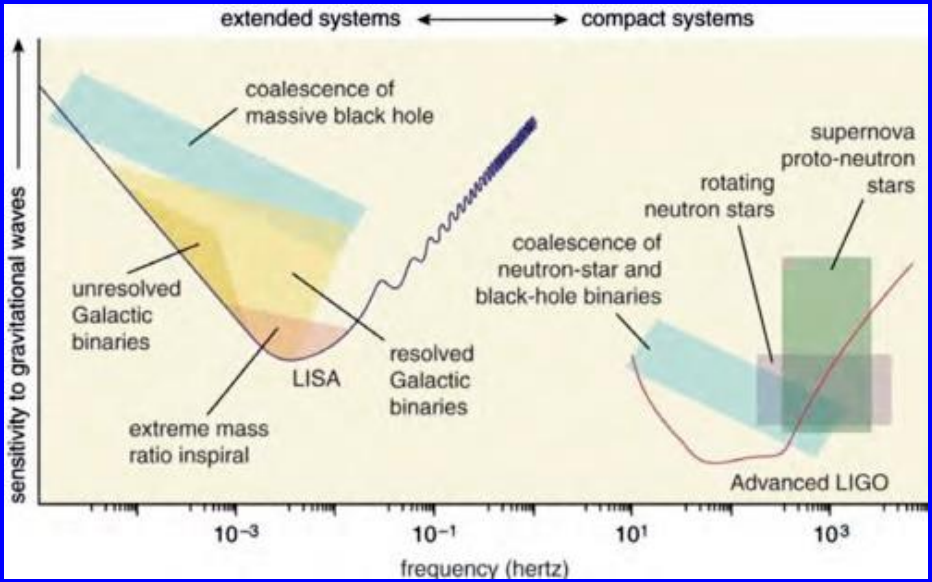
(In collaboration with M. Hindmarsh, K. Rummukainen, D. Weir)

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

Key quantities for GW's

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

1) Phase transition temperature T_n (via subsequent 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

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

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

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

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

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

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)

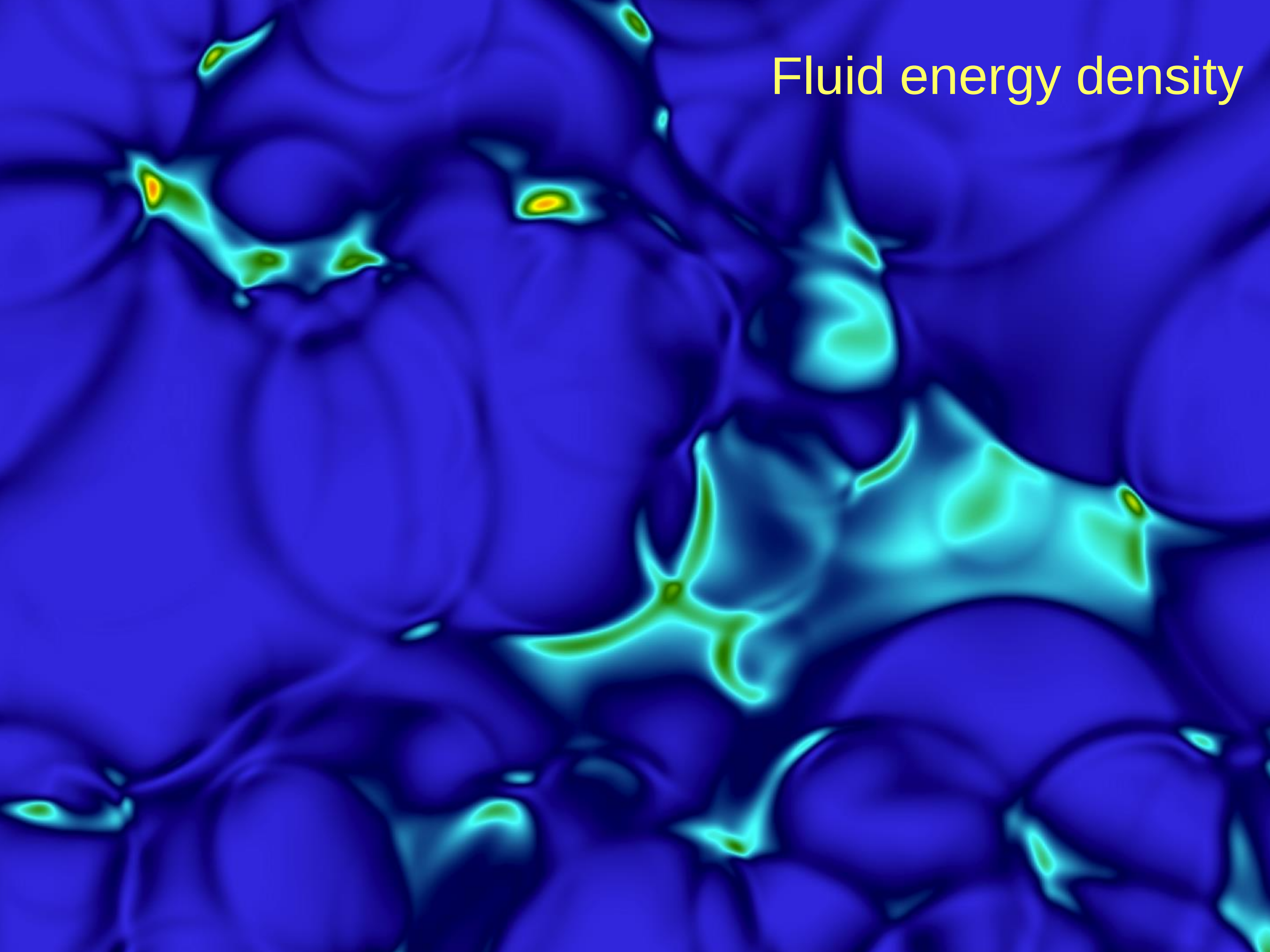
$$\dot{Z}_i+\partial_j(Z_iV^j)+\partial_iP+\frac{\partial V}{\partial\phi}\partial_i\phi=-\eta W(\dot{\phi}+V^j\partial_j\phi)\partial_i\phi.$$

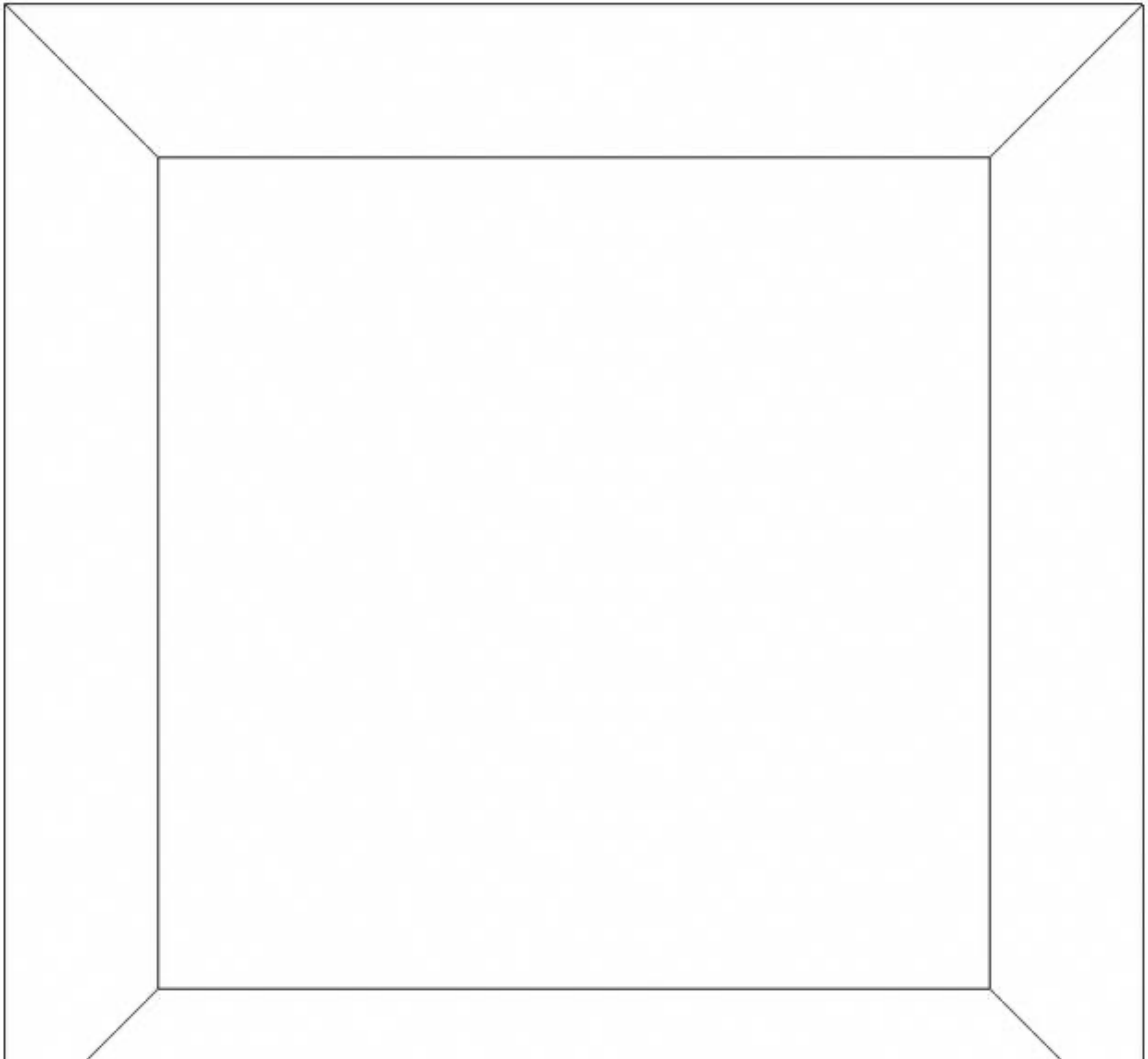
(eqn. for the momentum densities)

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

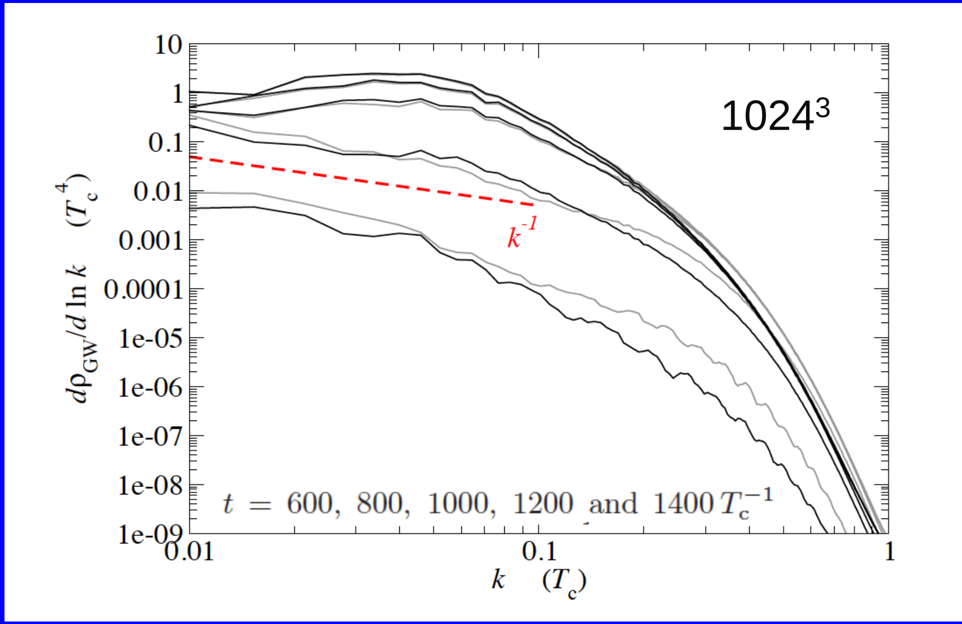
$$\ddot{u}_{ij}-\nabla^2u_{ij}=16\pi G(\tau_{ij}^{\phi}+\tau_{ij}^{\mathrm{f}}),$$

(eqn. for the metric perturbations)


Fluid energy density

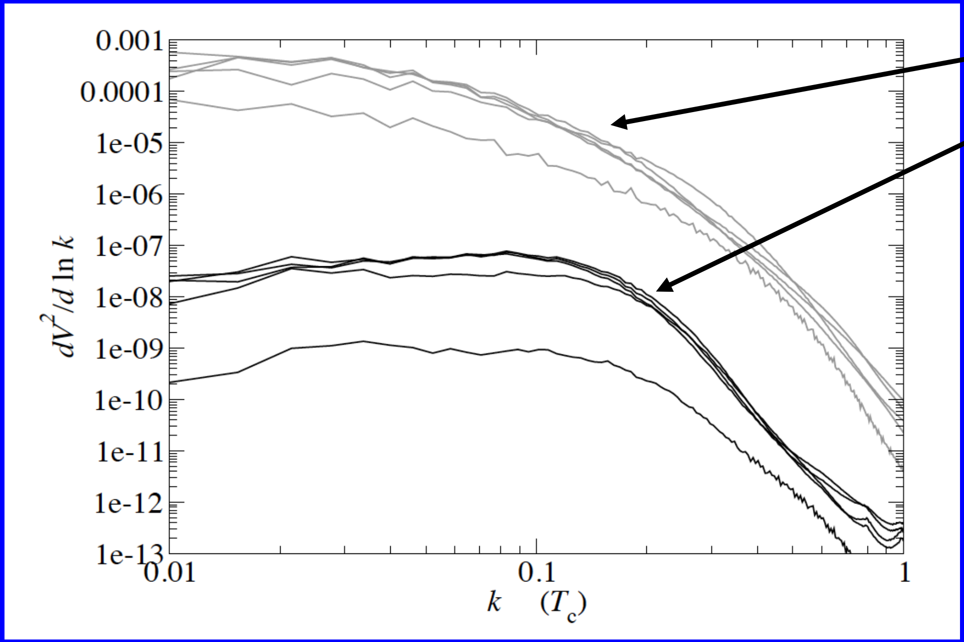


[Hindmarsh, SH, Rummukainen, Weir ’13]



GW spectrum

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



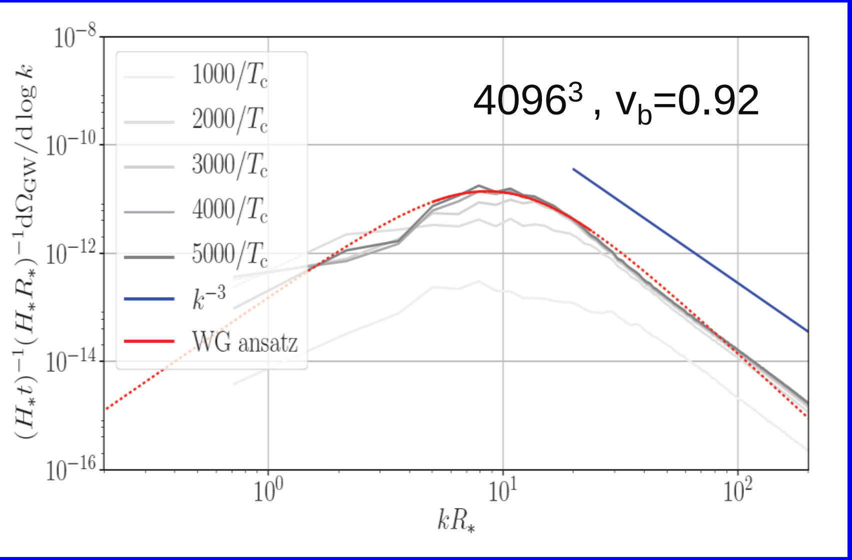
longitudinal and transverse part of the fluid stress

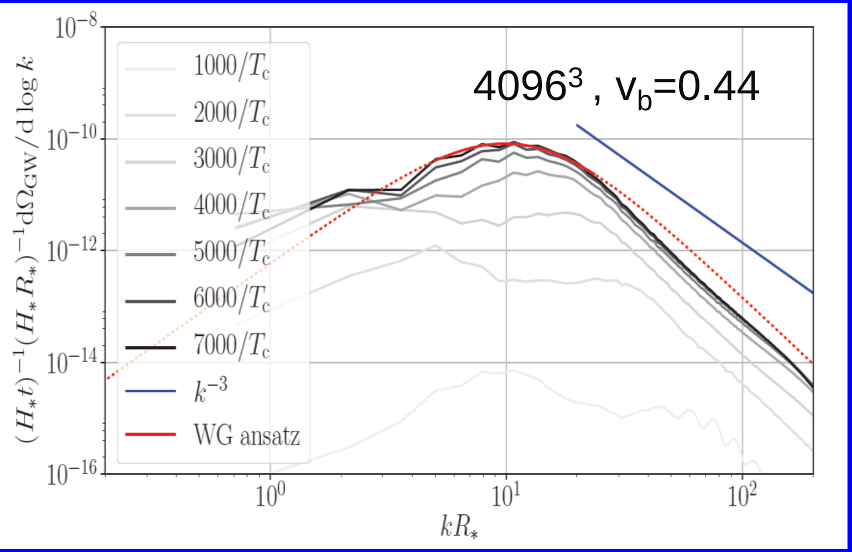
Longitudinal part dominates
➔ Basically sound waves

(suggested by Hogan 1986)

UV Power laws:

[Hindmarsh, SJH, Rummukainen, Weir '17]





Peak frequency set by R_*

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 different from pure scalar

Observations will be able to distinguish between a thermal and a vacuum transition

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

Strength of the GW signal (peak amplitude):

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

Simulation (sound)

What sets τ_s ?

Time scale for generating turbulence

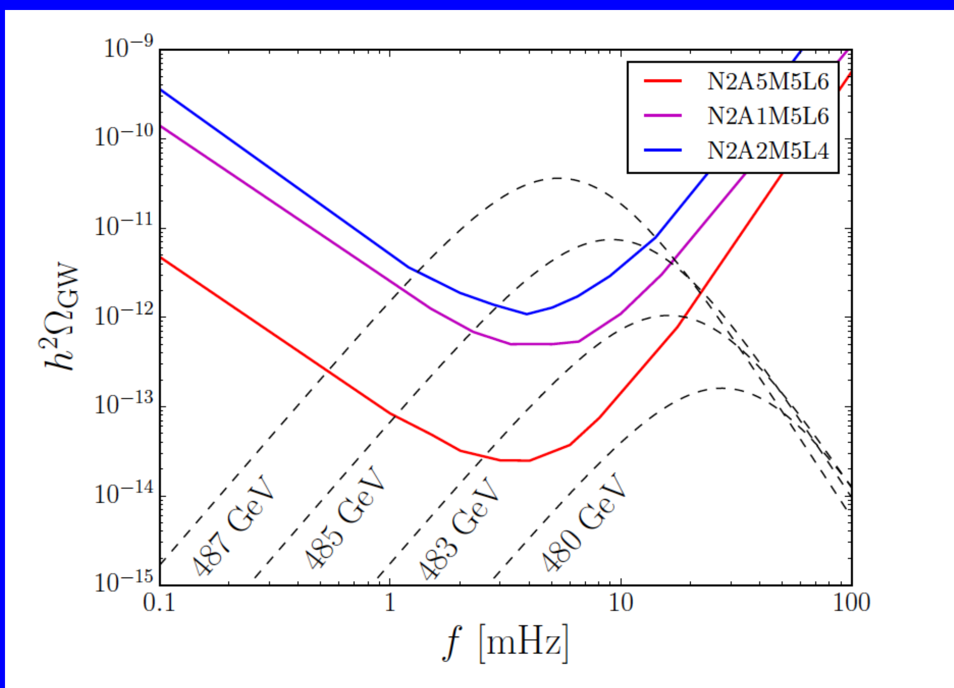
(eddy turn over time $\frac{R_*}{\overline{U}_{\mathrm{f}}} < \frac{1}{H_{\mathrm{n}}}$)

Can be up to the Hubble time

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_wT_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?

Summary

Many extensions of the SM will have first order phase transitions (most of these will have new scalars)

1) In some models (eg 2HDM) the phase transition can be probed at LHC

2) Electroweak baryogenesis (2HDM and beyond) is strongly constrained by EDMs (also sometimes by LHC)

but: still quite some uncertainties in the transport equations

3) Gravitational waves are a direct probe to phase transitions

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)

but GWs can also signal "hidden" transitions

Turbulence

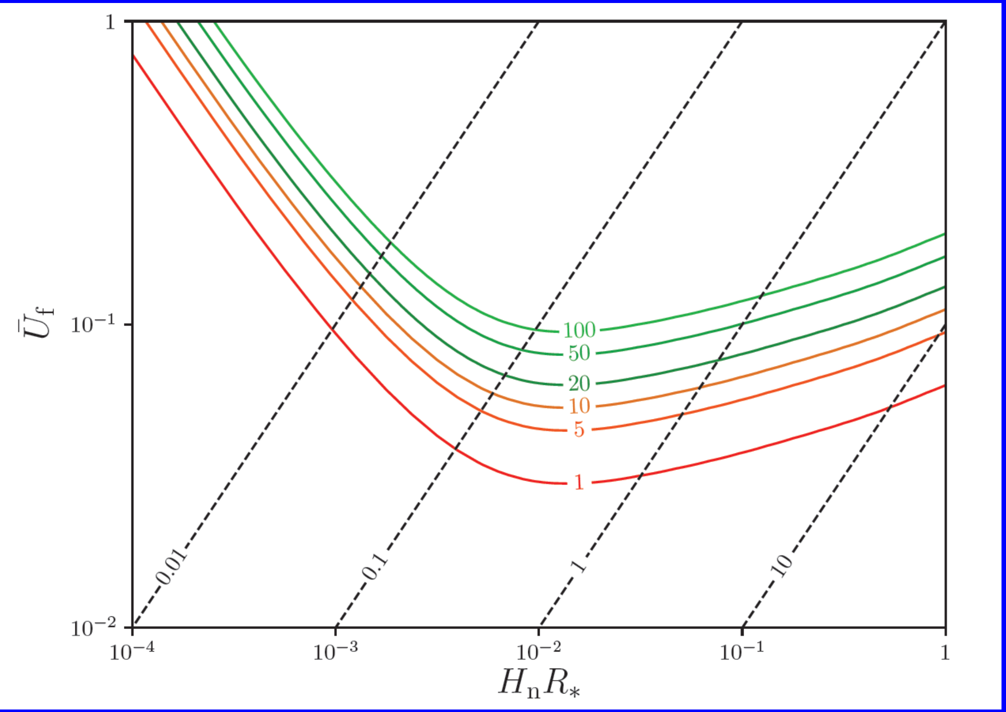
The Reynold's number of this system is huge

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



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]

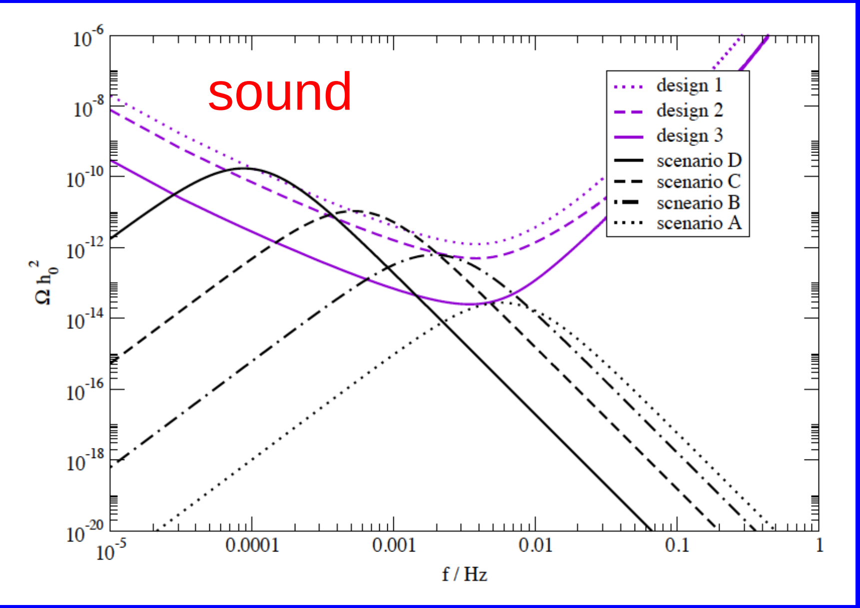
Look for parameter points with a <u>very strong phase transition</u> (substantially lifted electroweak vacuum): 4 benchmarks A-D

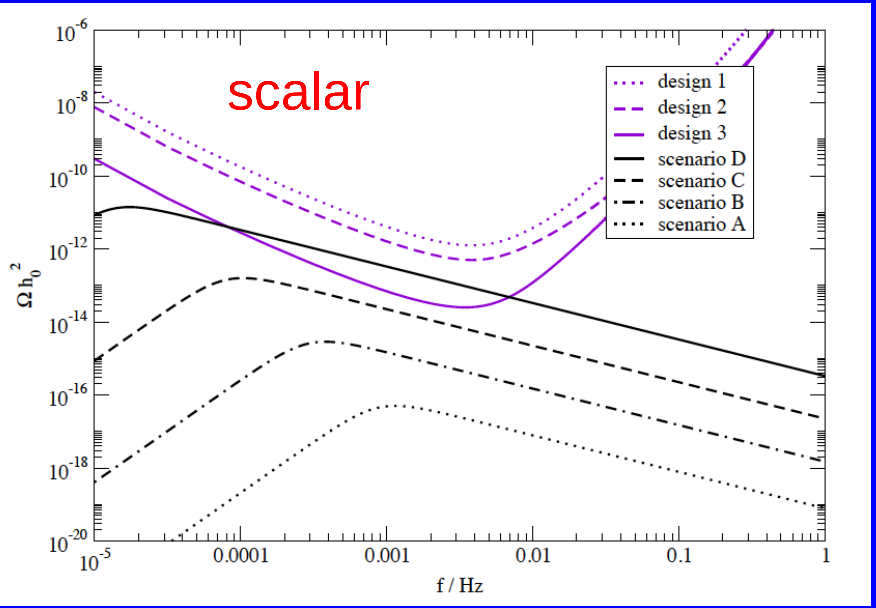
	A - D
$\tan\beta$	5
λ	0.7
κ	0.015
L_1	0
B_S [GeV^2]	-250^2
μ [GeV]	300

	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:





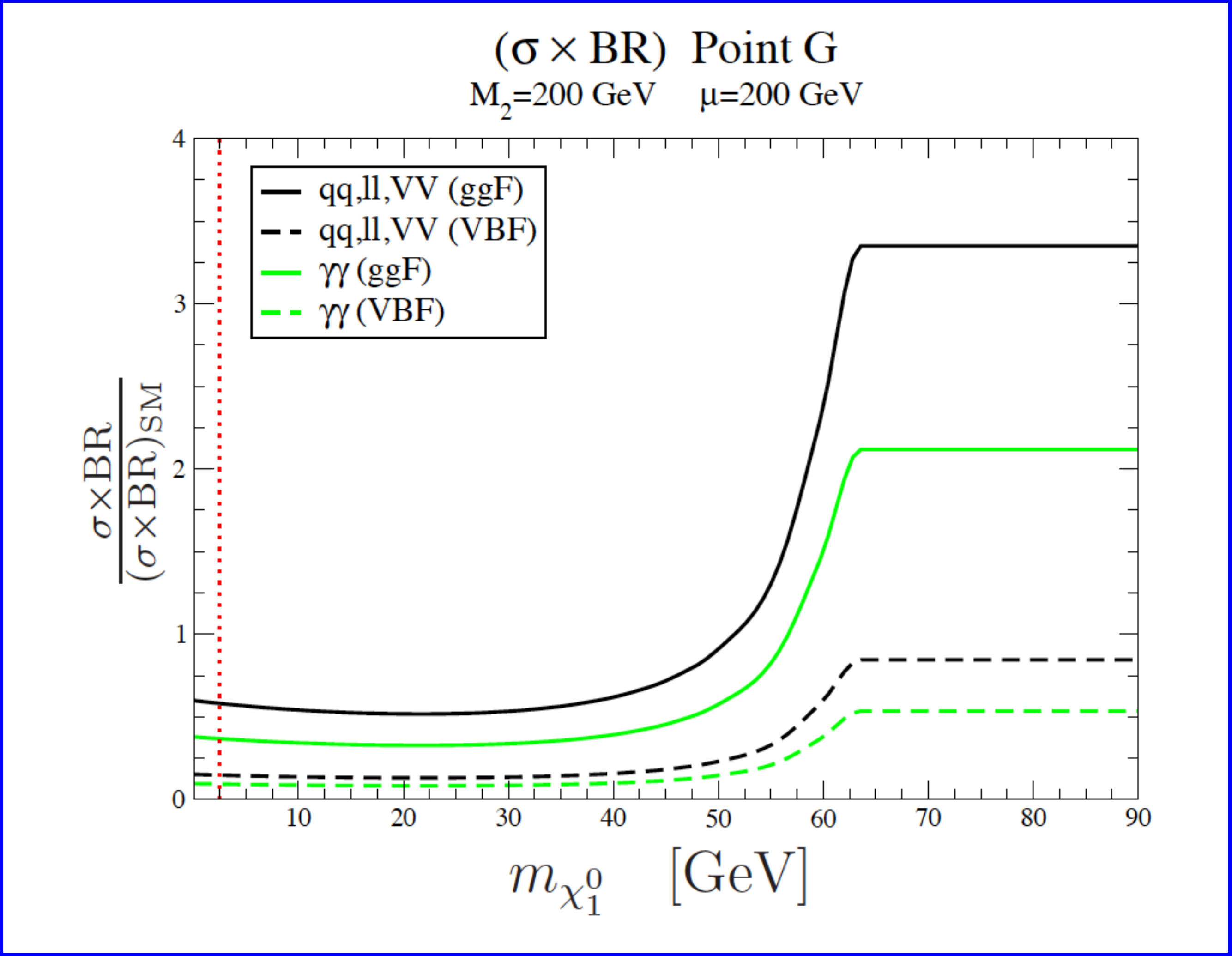
Very strong transitions in the GNMSSM lead to an observable GW signal in eLISA

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

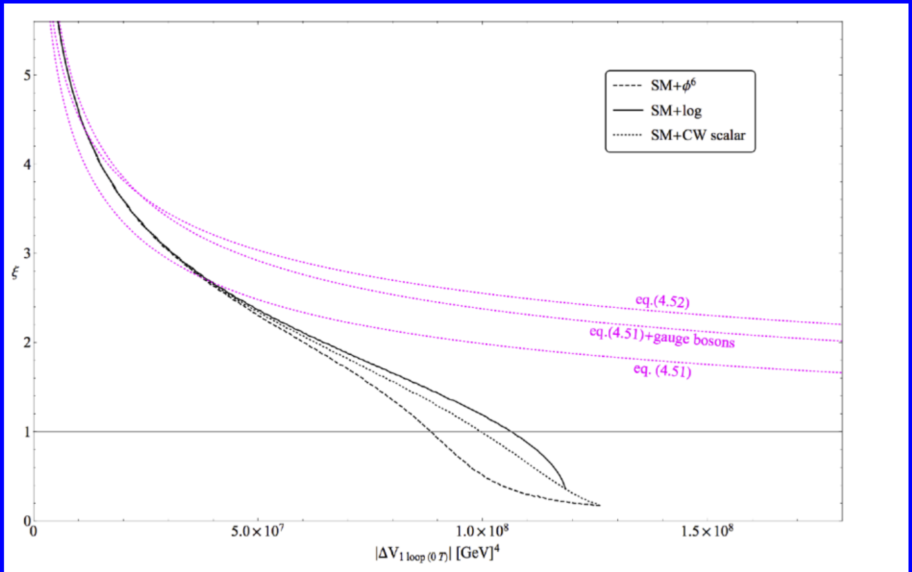


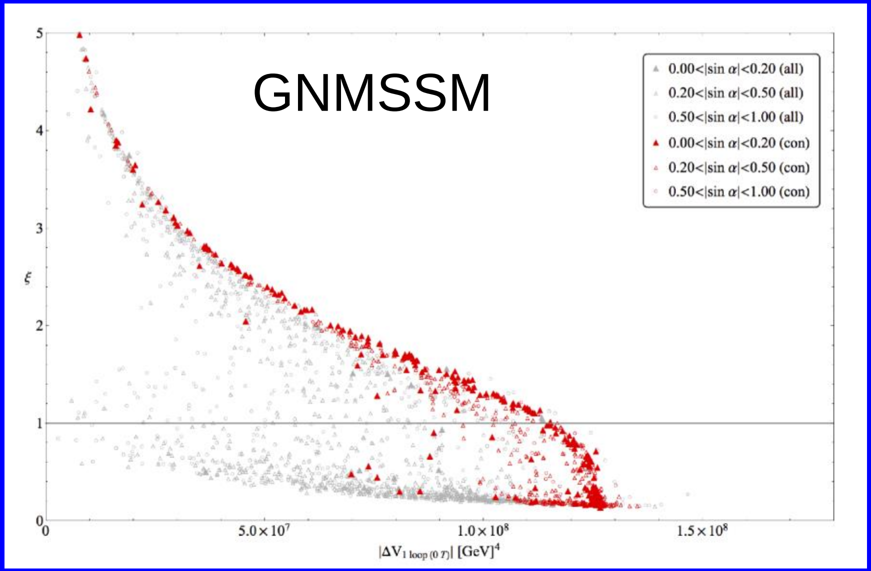
[Carena, Nardini, Quiros,Wagner 2012]

vacuum energy: general models

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

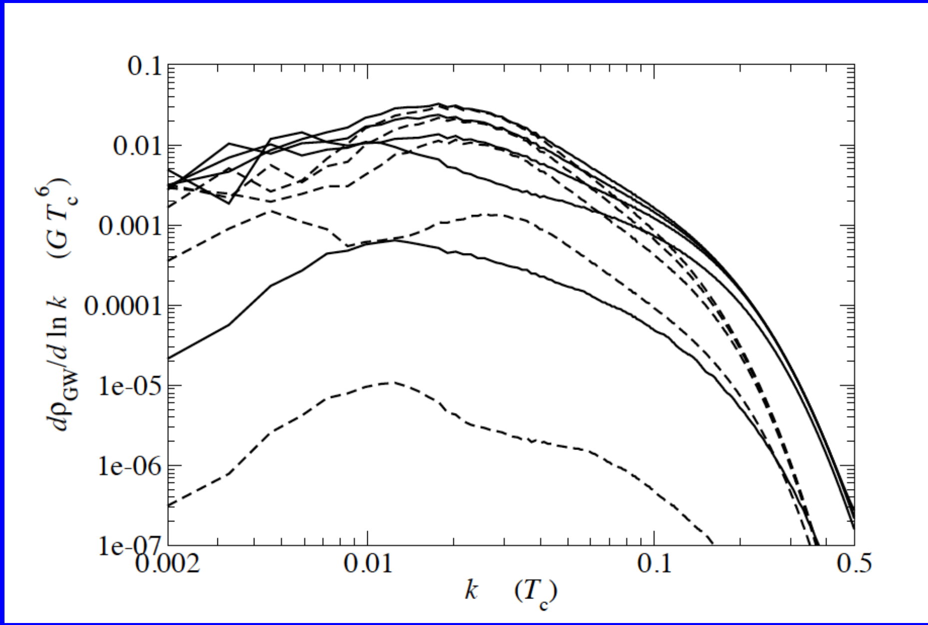
$$
\begin{aligned}
\Delta V_{1\ \mathrm{loop}\ (0\mathrm{T})} &= V_{1\ \mathrm{loop}\ (0\mathrm{T})}\big|_{\mathrm{broken}} - V_{1\ \mathrm{loop}\ (0\mathrm{T})}\big|_{\mathrm{symmetric}} \\
&= V_{1\ \mathrm{loop}\ (0\mathrm{T})}(v, v_S) - V_{1\ \mathrm{loop}\ (0\mathrm{T})}(0, \tilde{v}_S)
\end{aligned}
$$

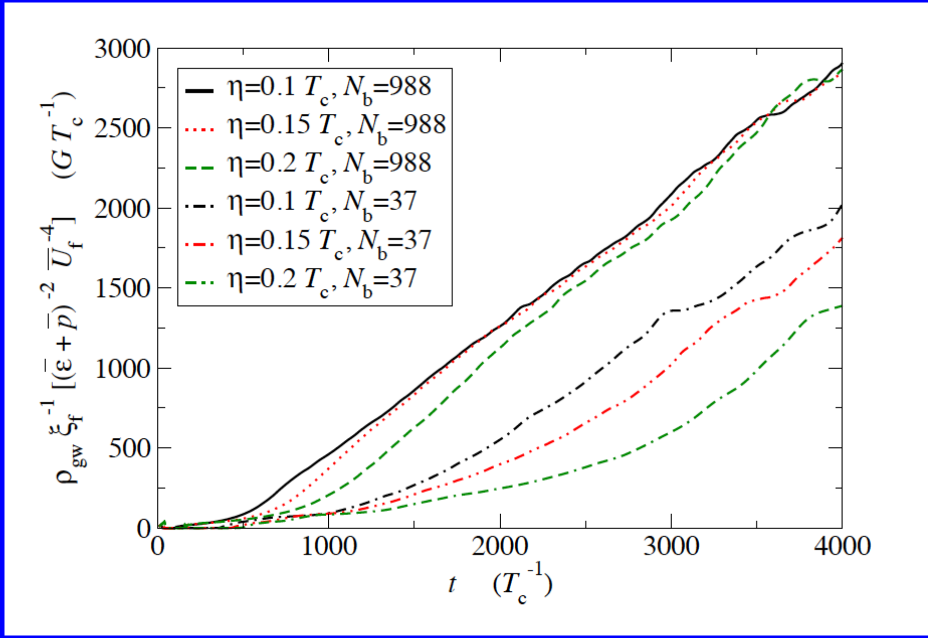


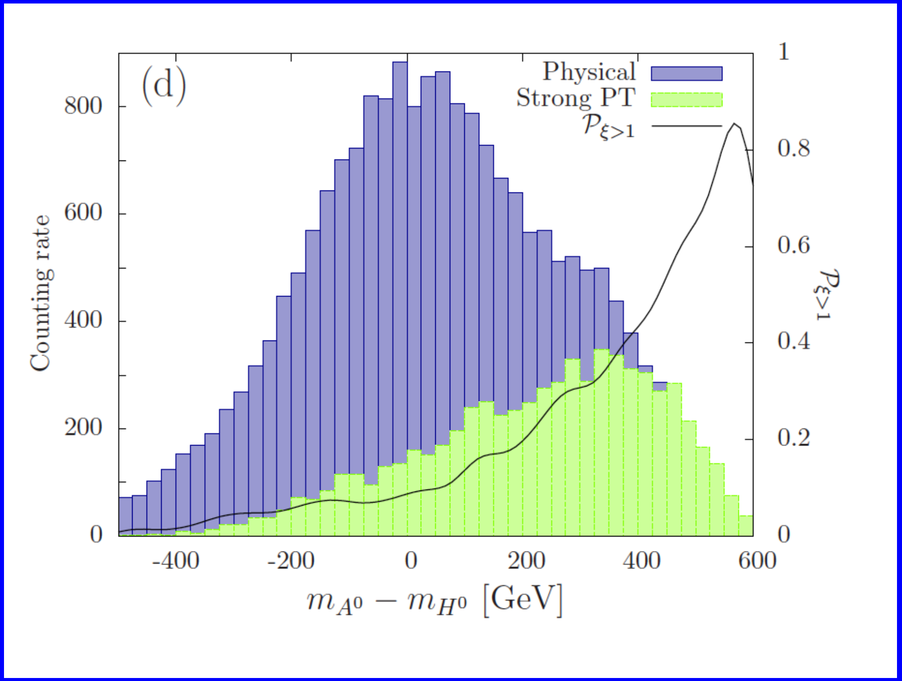


Strong transitions are entirely fixed by ΔV (once the Higgs SM-like)

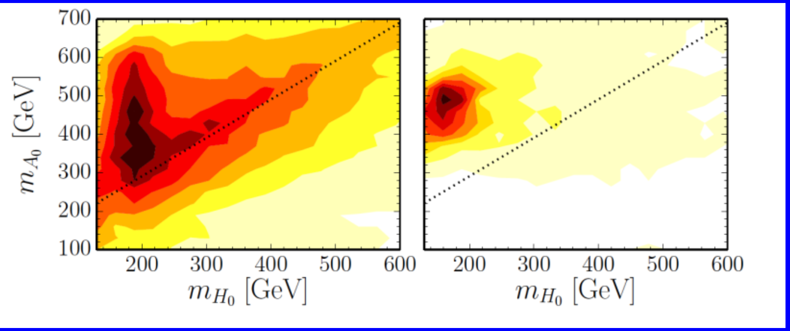
Time evolution:



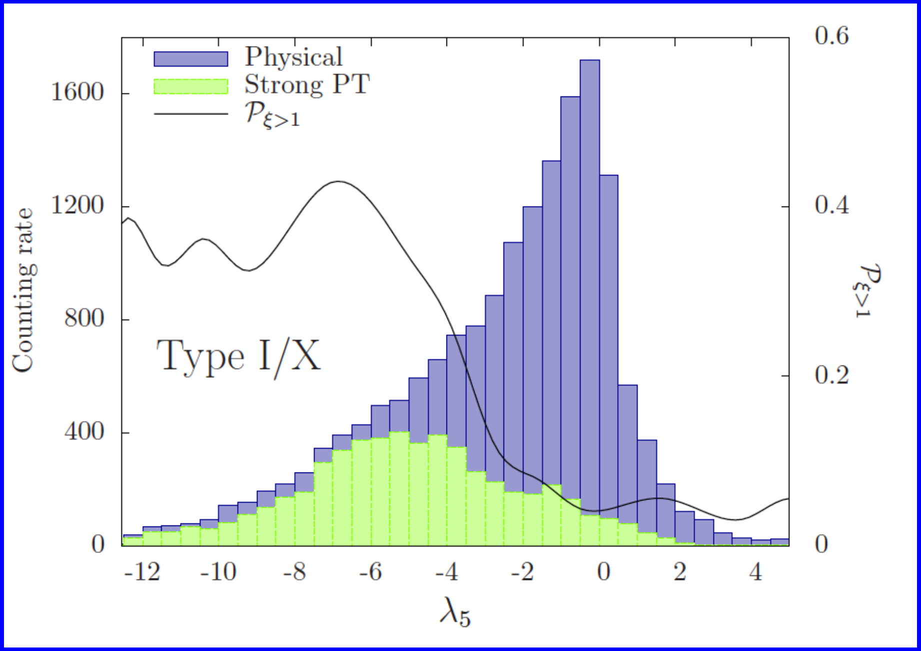




Preference for a heavy pseudoscalar



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

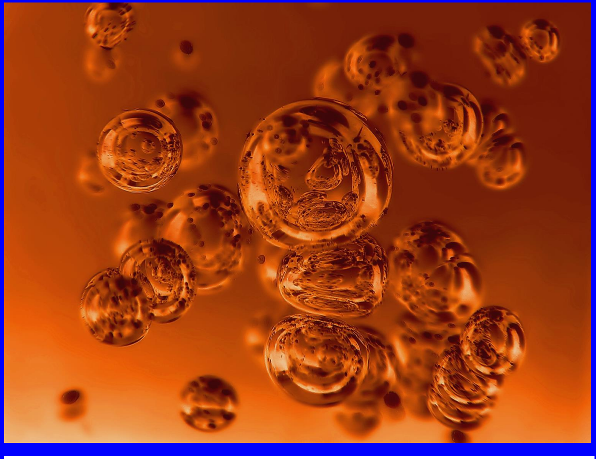


Preference for a large negative λ_5

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

The transition itsself: bubbles

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

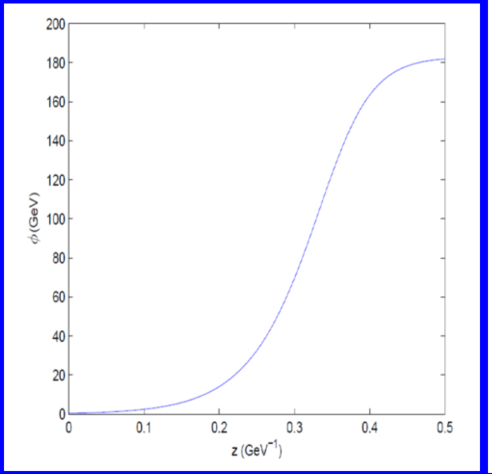


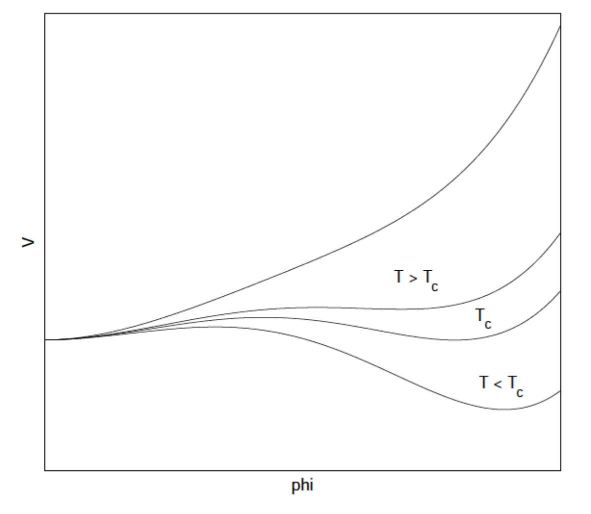
Nucleation rate governed by, S_3, the energy of the critical bubble

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

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)

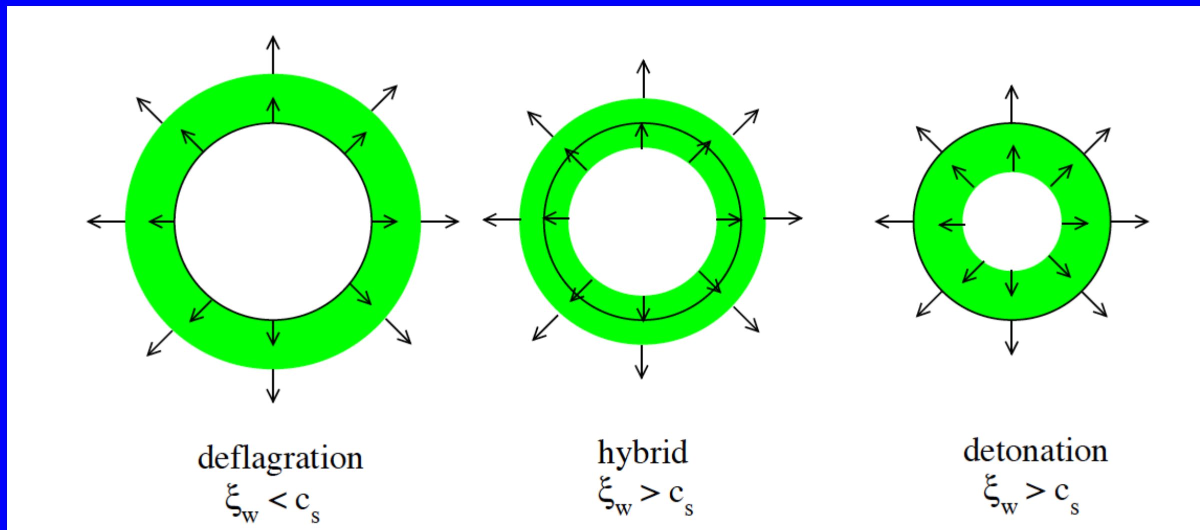


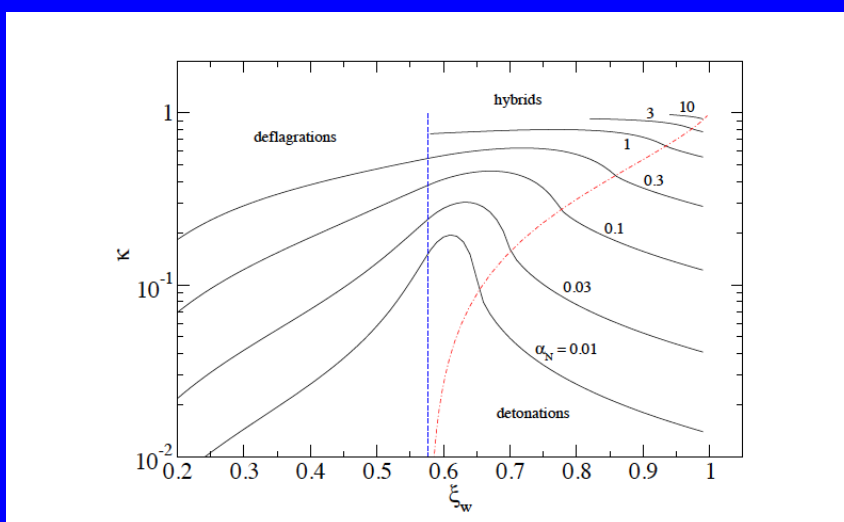


Wall velocity: resulting from pressure vs. plasma friction

Generally very difficult QFT non-eq. problem (wall+plasma) [eg. Konstandin et al., '14]

But simple criterion for ultra-relativistic walls [Boedeker, Moore, '09]





[Espinosa, Konstandin, No, Servant, 2010]

Efficiency κ for turning latent heat into fluid motion

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)

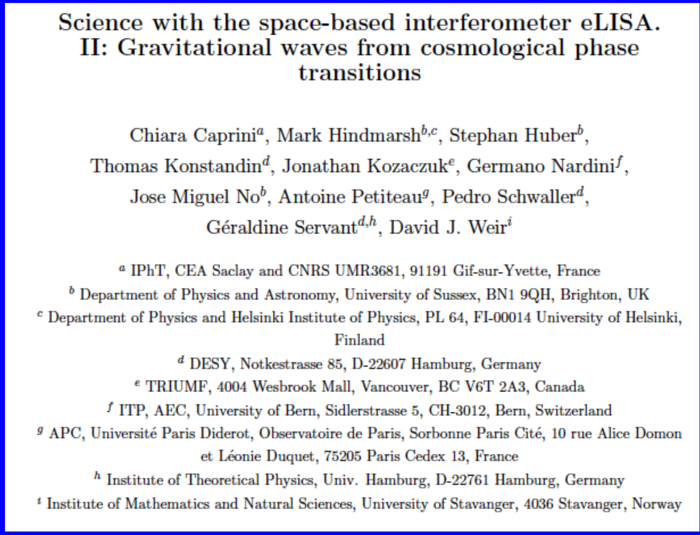
Possible contributions:

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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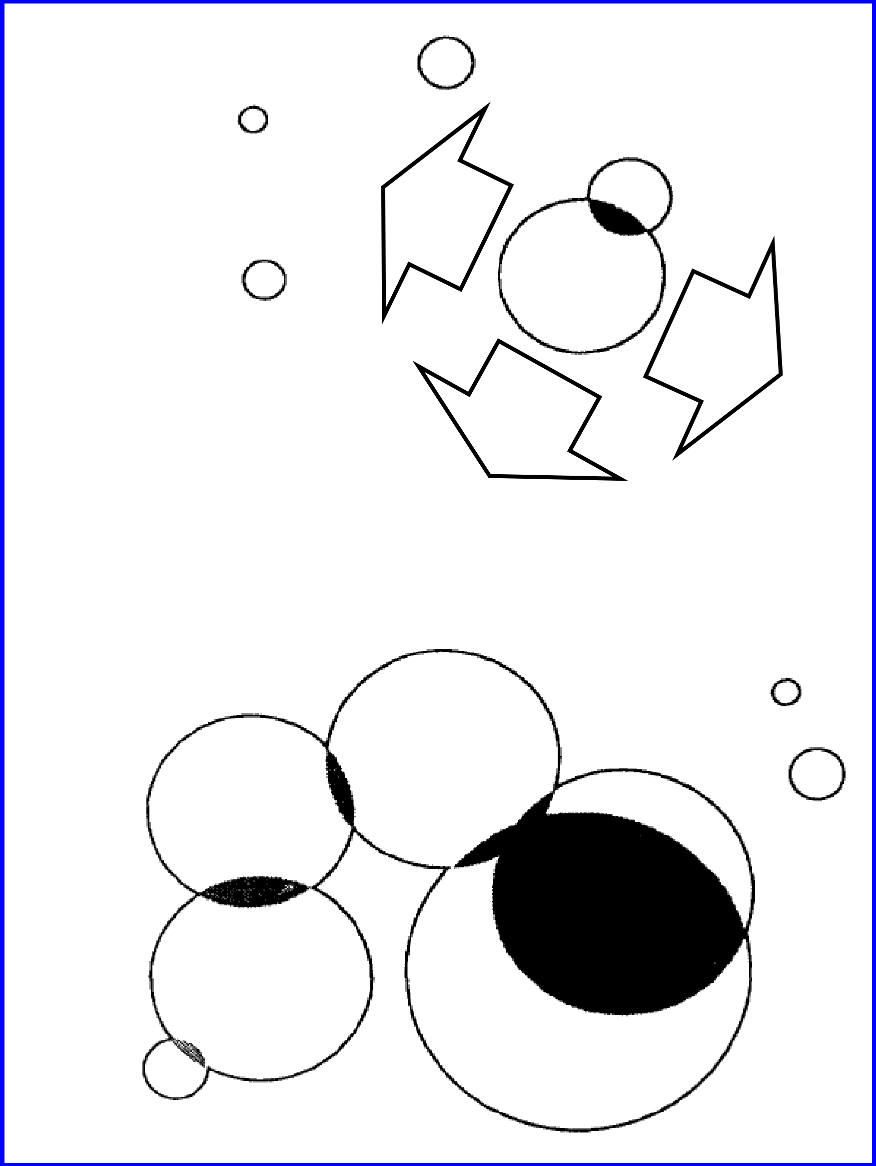
[see LISA Cosmo working group report '15,

update this summer]

Scalar field only: The envelope approximation: Kosowsky, Turner 1993



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

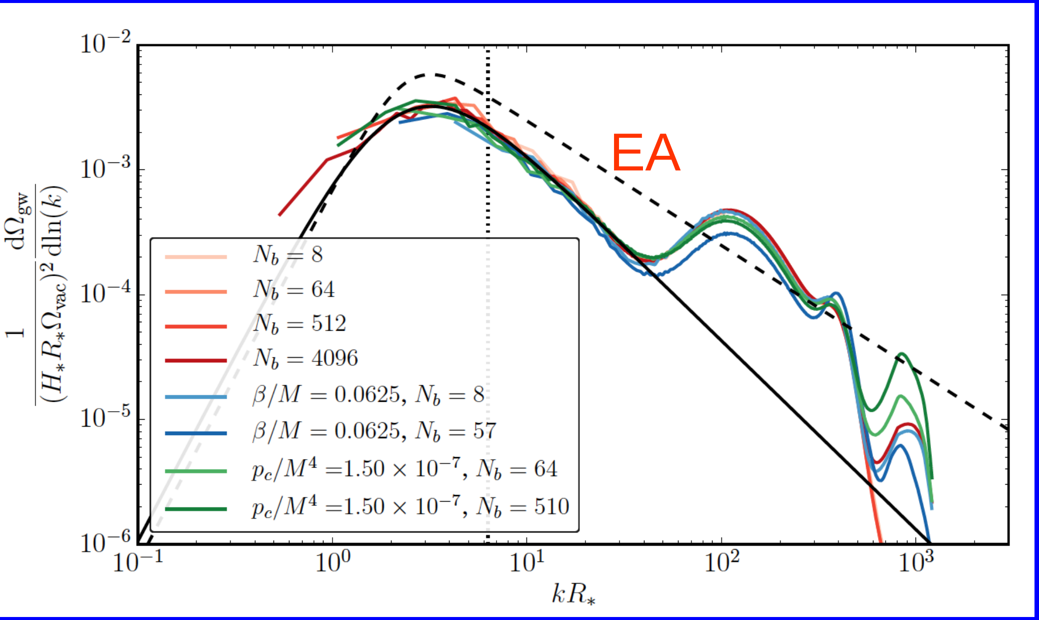
Comparison between envelope appr. and field theory simulation:

[Cutting, Hindmarsh, Weir, 2018]

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

$$\Box\phi - V'(\phi) = 0 \qquad V(\phi) = \frac{1}{2}M^2\phi^2 + \frac{1}{3}\delta\phi^3 + \frac{1}{4}\lambda\phi^4$$

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!

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!