Detecting Electroweak Phase Transitions at eLISA

Germano Nardini
(Bern Univ. & DESY)

Particle Physics at the Dawn of the LHC13

Based on *arXiv:1512.xxxx* in collaboration with
Huber, Stephan (Sussex Univ.)
Konstandin, Thomas (DESY)
Rues, Ingo (DESY)
+
arXiv:1512.xxxx
(subset of the eLISA cosmology working group)

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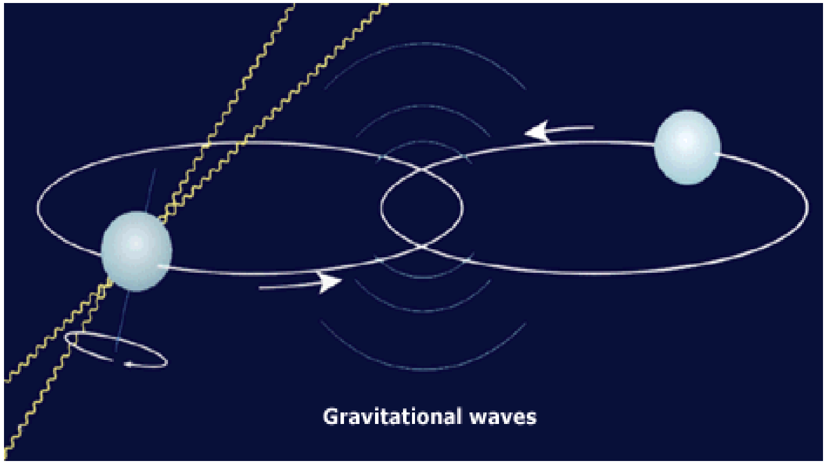
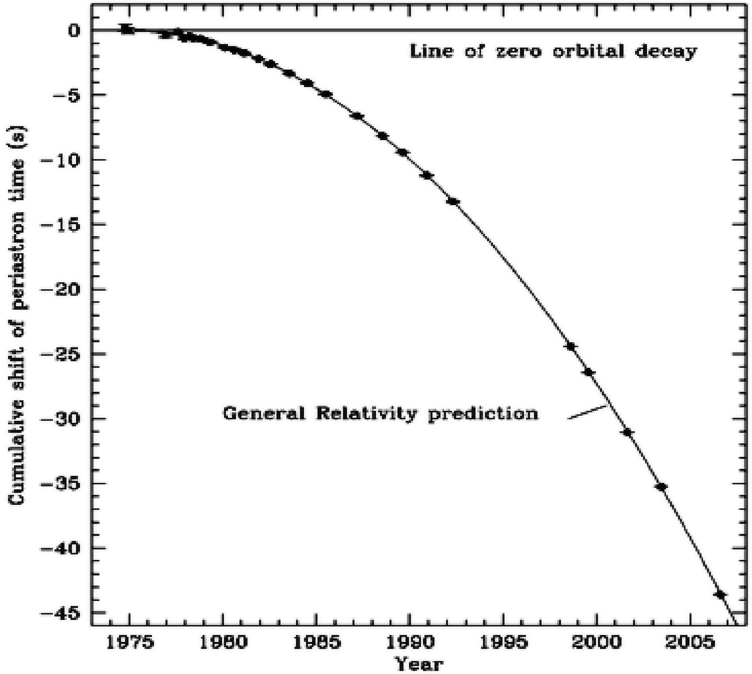
DESY

Gravitational Waves

- Gravitational Waves (GWs) are a prediction of General Relativity: accelerating masses produce a spacetime perturbation that propagates ("ripples in spacetime").

- The Hulse-Taylor binary system provided the first *indirect* evidence that GW exist.

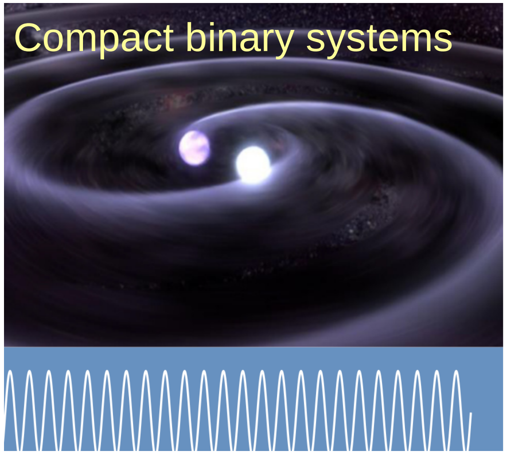


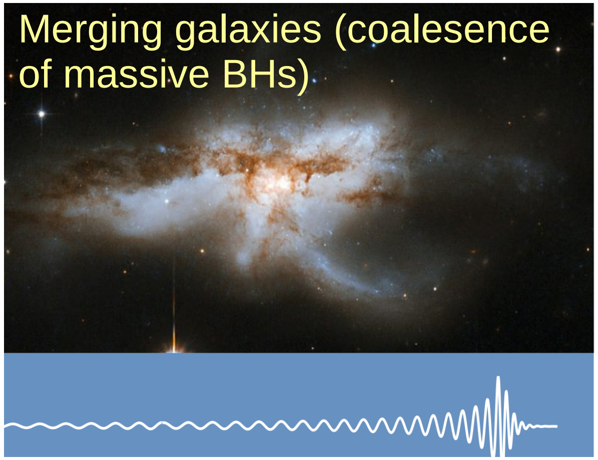


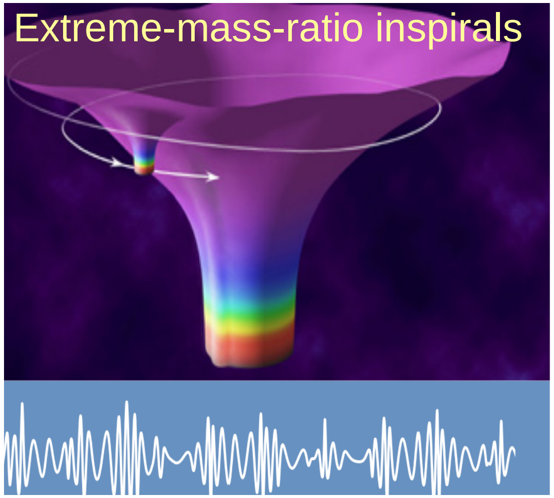
Gravitational Waves

> Nevertheless, we would feel more comfortable after a *direct* proof

> Many potential **localized** sources are expected there waiting for us...

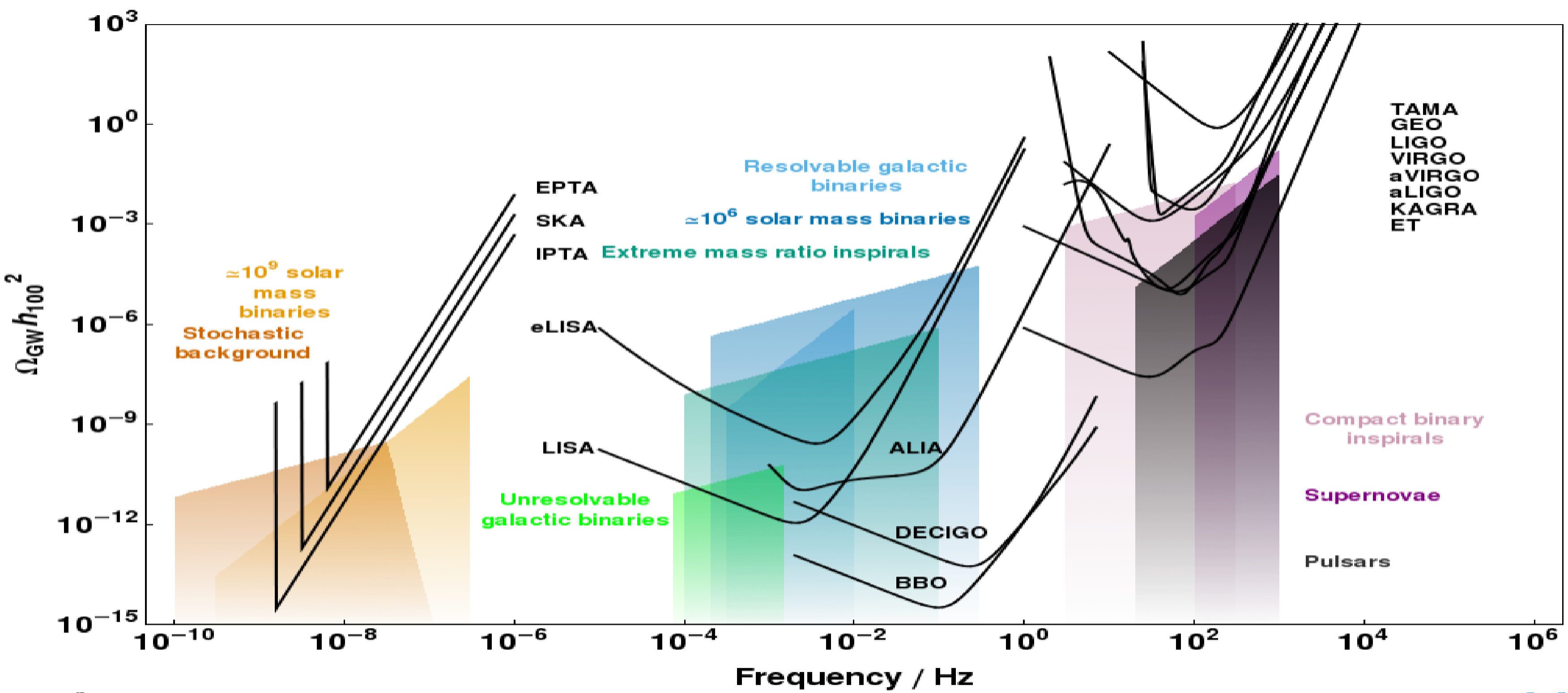






Gravitational Waves

- Nevertheless, we would feel more comfortable after a *direct* proof
- Many potential **localized** sources are expected there waiting for us...
- … and we are attempting to detect them (...and if you listen to rumours, maybe ...)



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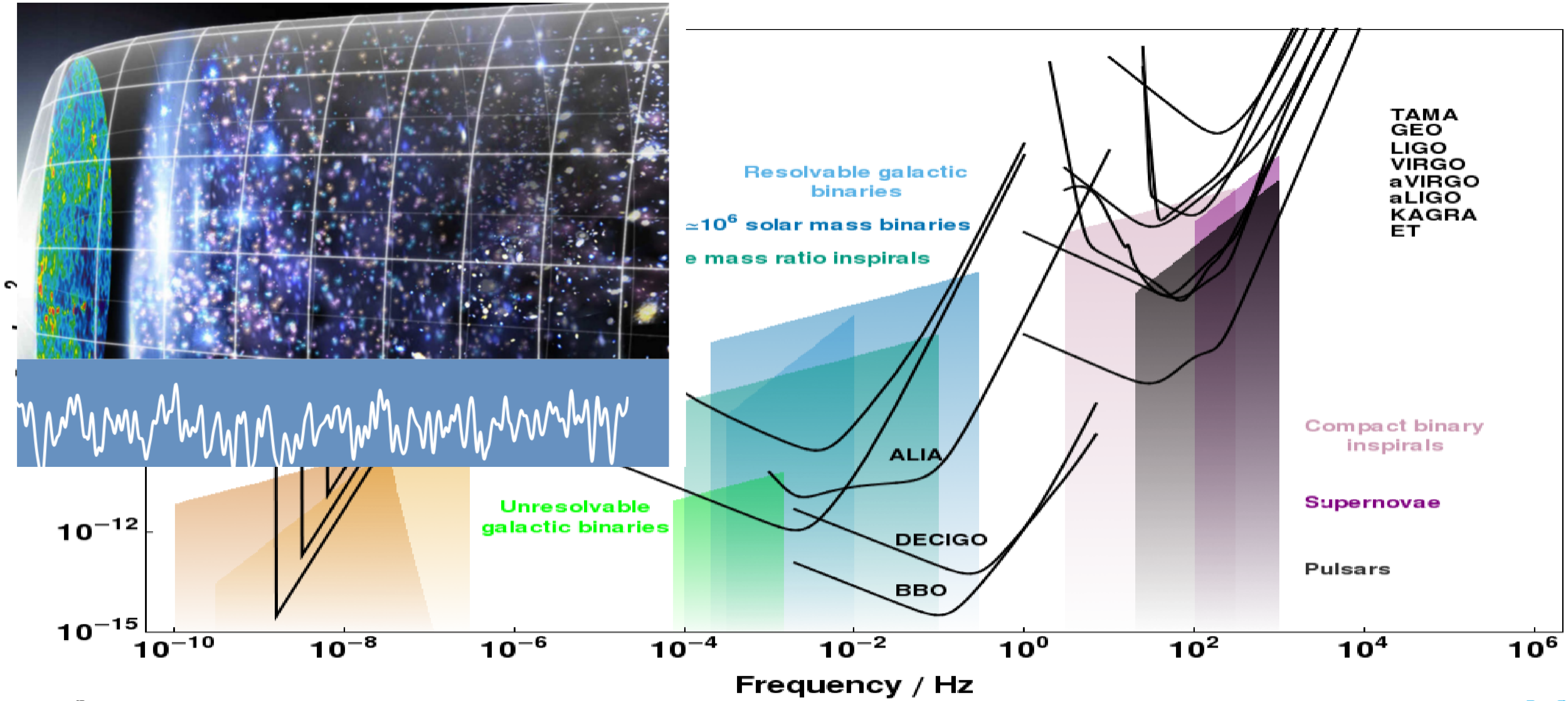
Gravitational Waves

- Besides astrophysical sources, we also expect pre-BBN cosmological sources (inflation, topological defects, phase tansitions, ...)
- These generate a stochastic (i.e. **non localized**) GW background



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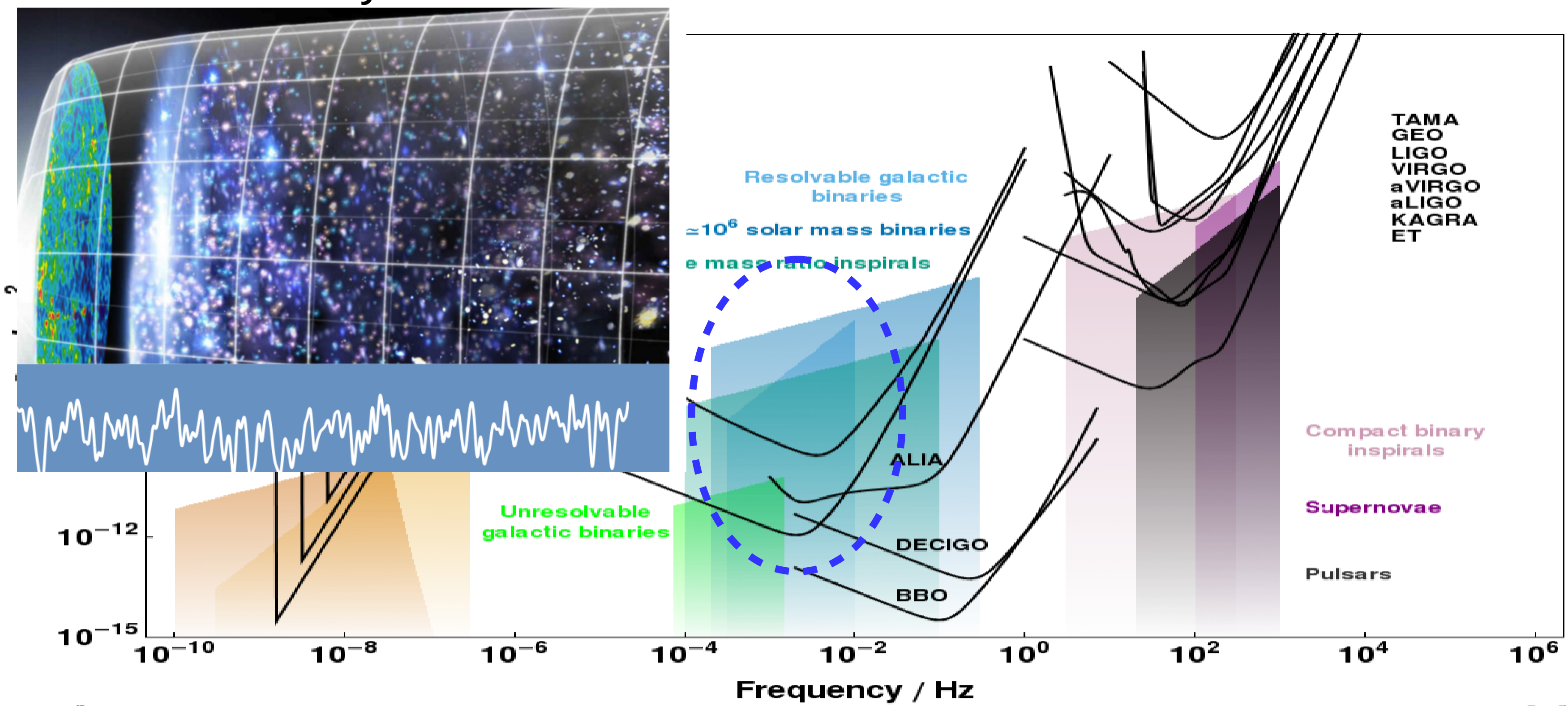
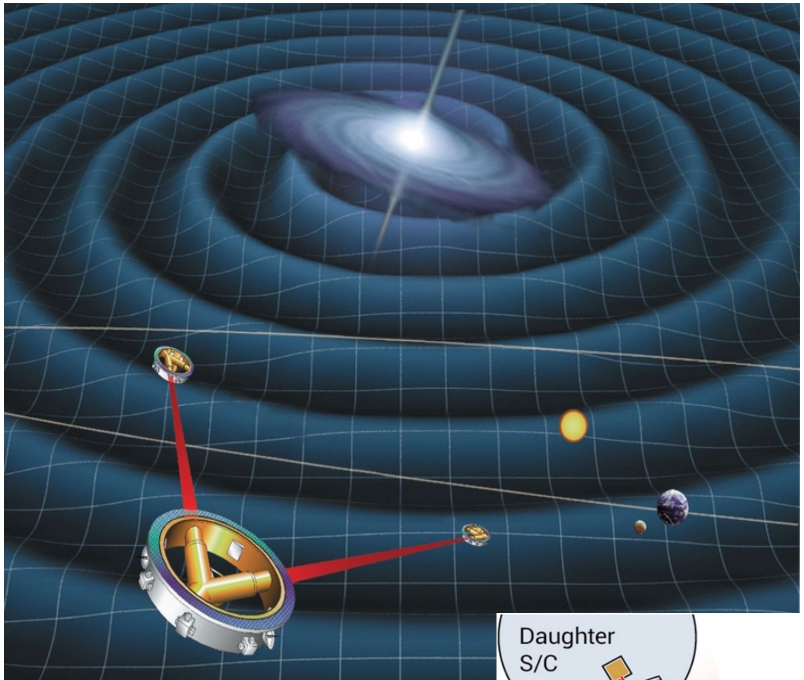
DESY

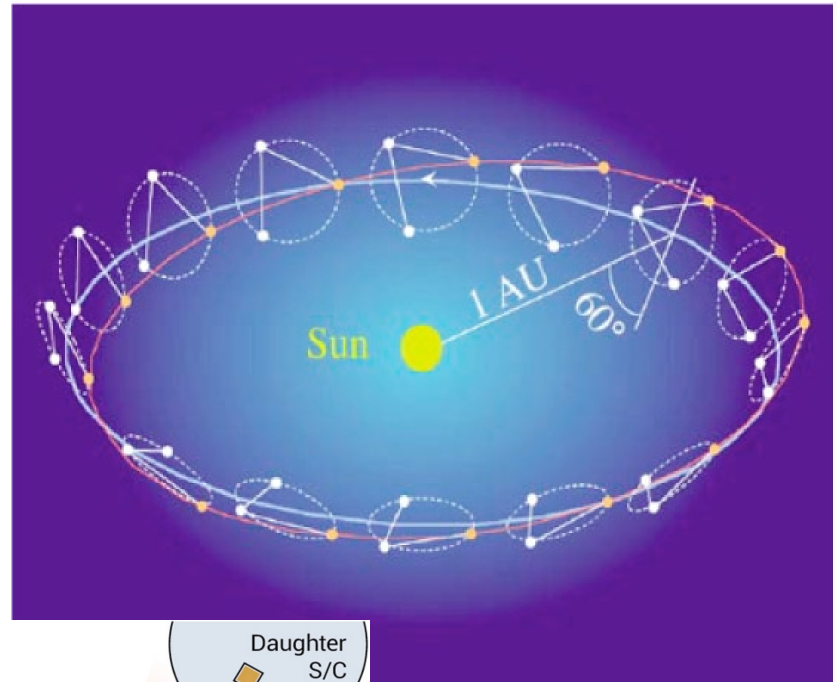
Gravitational Waves

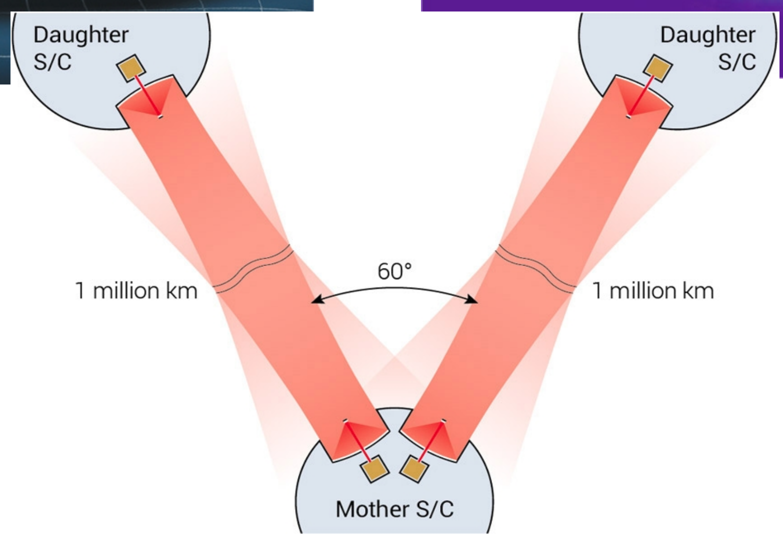
- The ELECTROWEAK phase transition (EWPT) is particularly interesting: energy scale of pp collision at LHC and “a bit” beyond heavy-ion collisions at RHIC and LHC
- Moreover it may be testable at eLISA!



The eLISA interferometer (open issues)

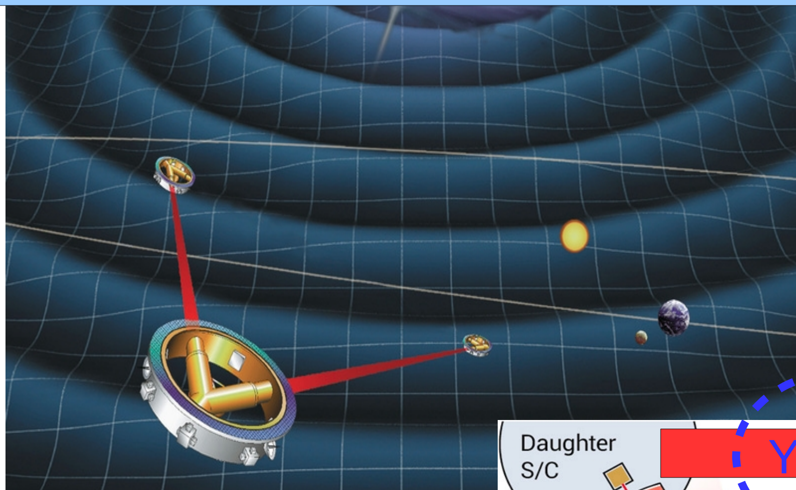


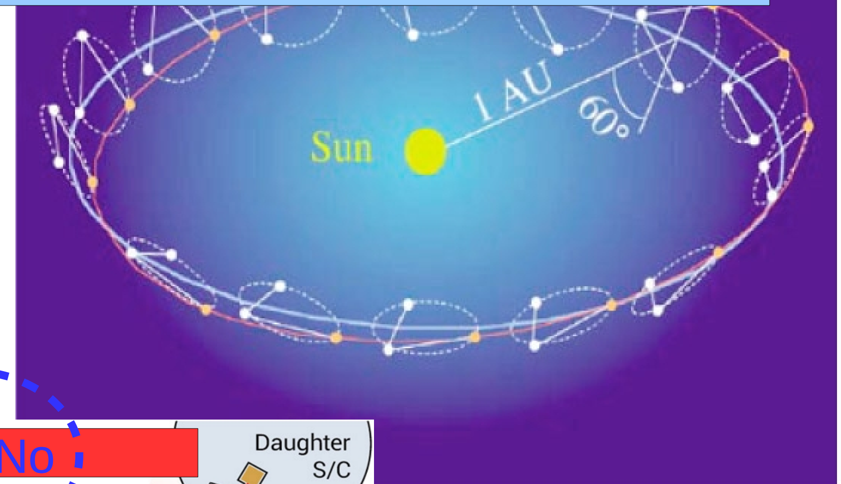


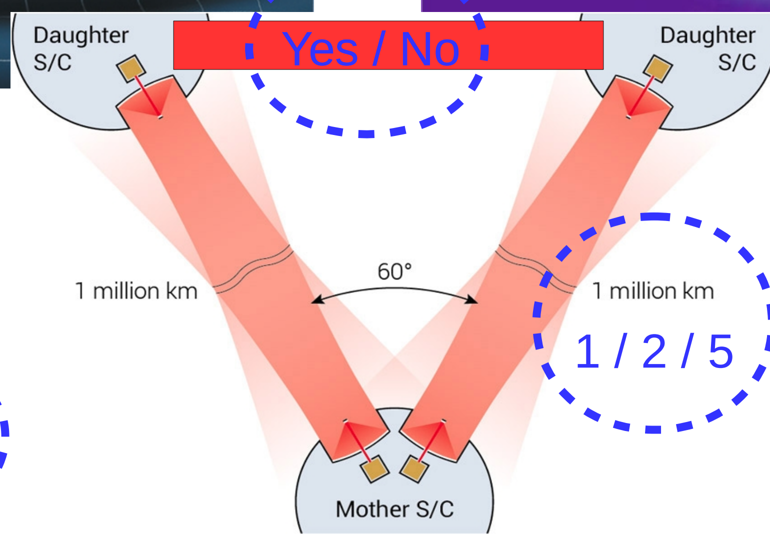


The eLISA interferometer (open issues)

Extra budget: partially because of reanalyses of costs, partially because of NASA+Japan, ...







Yes / No

1 / 2 / 5

2 / 5 years of data taking

The eLISA interferometer (agenda)

- Crucial period: from 2/12/2015 (Pathfinder launch; Kourou) –
  to 1/5/2016 (Pathfinder results)

- eLISA design vs. physics capability (e.g. this talk): < 15/12/2015

- eLISA design decided: ~March. 2016

- ESA decision: ~2017

- eLISA launch: 2028 – 2032

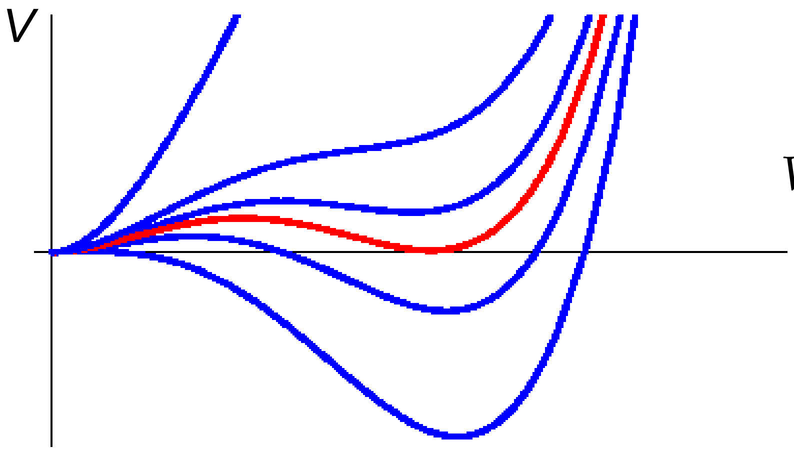
https://www.elisascience.org/

Outline

- Gravitational Waves from 1st-Order Electroweak Phase Transitions
- Mapping the EWPT of your model into the eLISA detection curves
- (Q1) Do well-motivated models overcoming the LHC bounds and producing strong GW signals exist?
- (Q2) Can eLISA probe these signals? Any preferable eLISA design?

Gravitational Waves from 1st-Order EWPT

- Let us assume that the EWPT is of first order, i.e.



$$V(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \lambda(T)\phi^4$$

- The phase transition occurs via tunneling. In the place where the tunneling happens, a bubble of EW broken phase ($\langle\phi\rangle = \phi_{brok}$) nucleates.

- Conventionally, the EWPT starts in the Universe when statistically we have 1 nucleated bubble per Hubble volume and time. The temperature of the Universe at this time is called T_n

- The tunneling rate is $\Gamma(t) = \Gamma_0 \exp[-S(t)]$. If $\beta = -dS/dt|_{t=t_n}$ is large (small), many (a few) bubbles have nucleated by the time the first bubbles have expanded, i.e. the phase transition ends with many little (a few large) bubbles.

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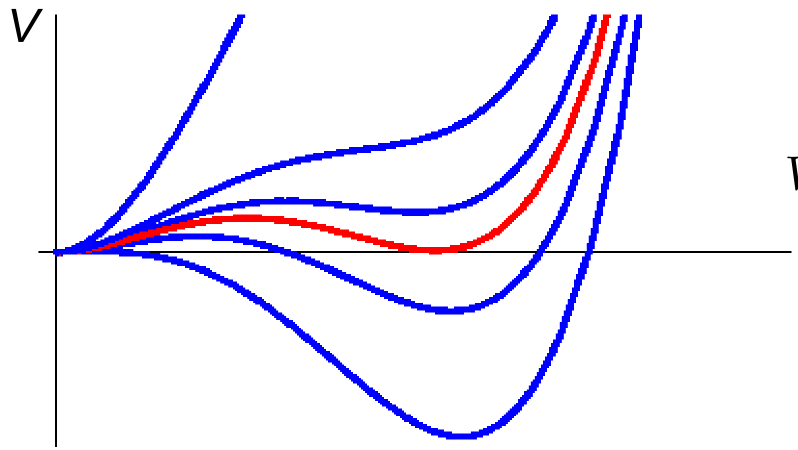


$$V(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \lambda(T)\phi^4$$

- When bubbles collide, they convert part of their kinetic energy (of the expanding wall + turbulent fluid) into gravitational waves (GWs)! M. Kamionkowski et al., '94

- So, the more energy is available (→ supercooling), the stronger the GW signal

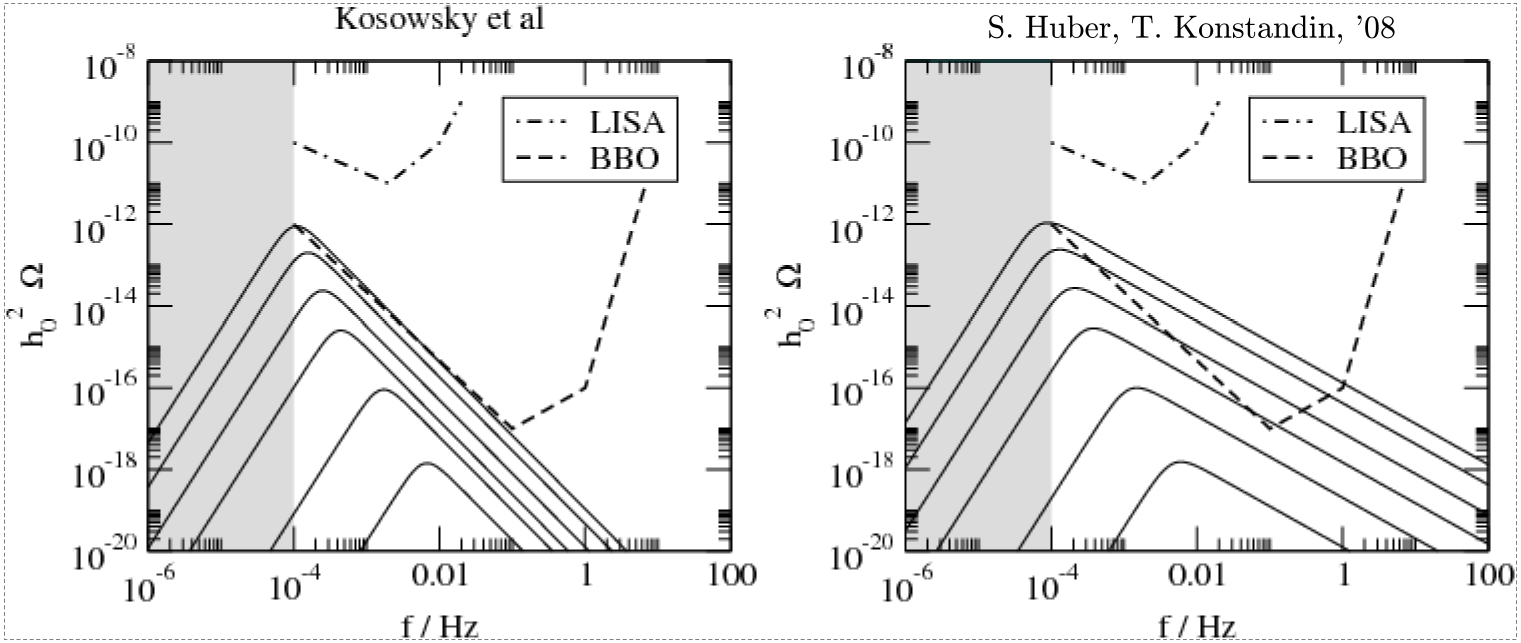
- This available energy is the latent heat

$$\epsilon(T_n) = \Delta V(T_n) - T\frac{\partial \Delta V(T_n)}{\partial T} \quad , \qquad \Delta V(T_n) = V(\phi_{sym}, T_n) - V(\phi_{brok}, T_n)$$

which we normalize to the radiation energy: $\alpha = \epsilon(T_n) / \left(\frac{\pi^2}{30} g_* T_n^4\right)$

Gravitational Waves from 1st-Order EWPT

> Simulations on bubble collisions (based on the "envelope approx") show



where (for $v_w \simeq 1$)

$$h_0^2\Omega_{GW} \approx 10^{-10}\kappa^2(\alpha)\left(\frac{100}{\beta/H}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2$$

$$f_{peak} \approx \mathrm{mHz}\left(\frac{\beta/H}{100}\right)\left(\frac{T_n}{100\mathrm{GeV}}\right)$$

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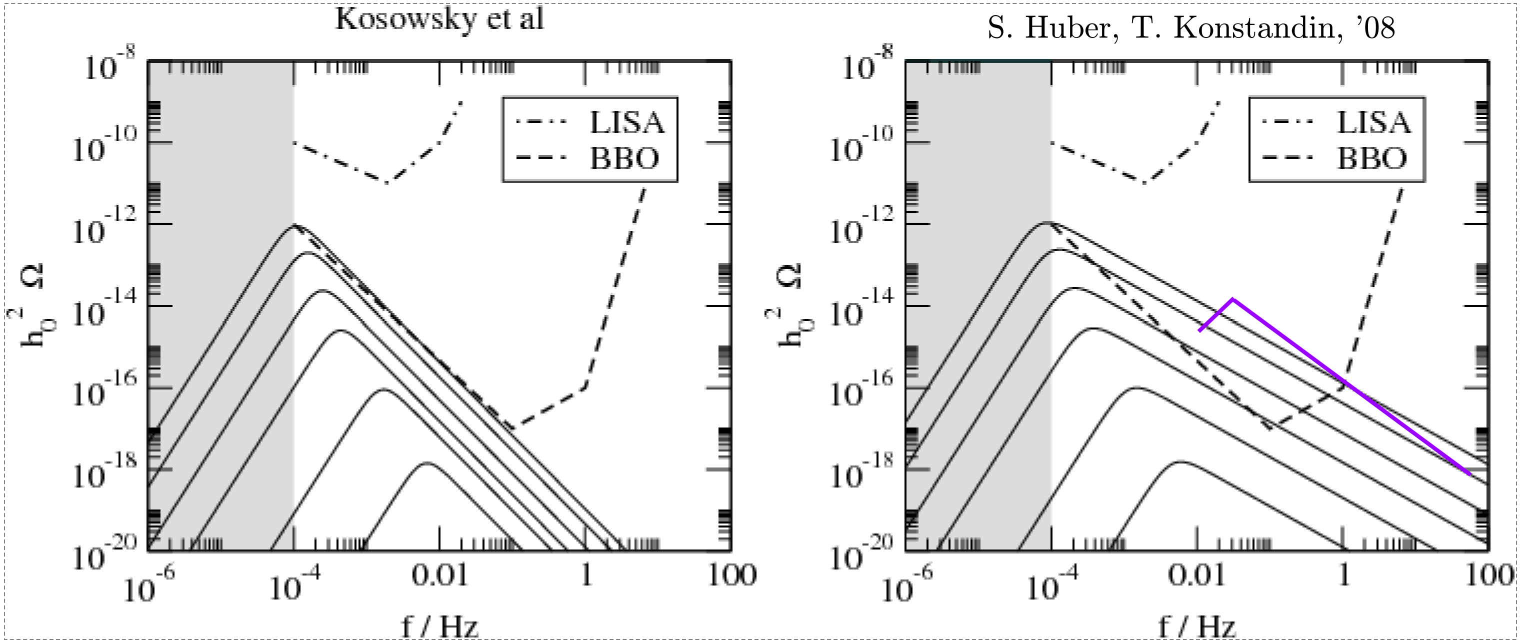

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> On the top of the "envelope" source, there might be contributions coming from the plasma dynamics: MHD turbulence

P.Binetruy,A.Bohe,C.Caprini,J.Dufaux,'12

Gravitational Waves from 1st-Order EWPT

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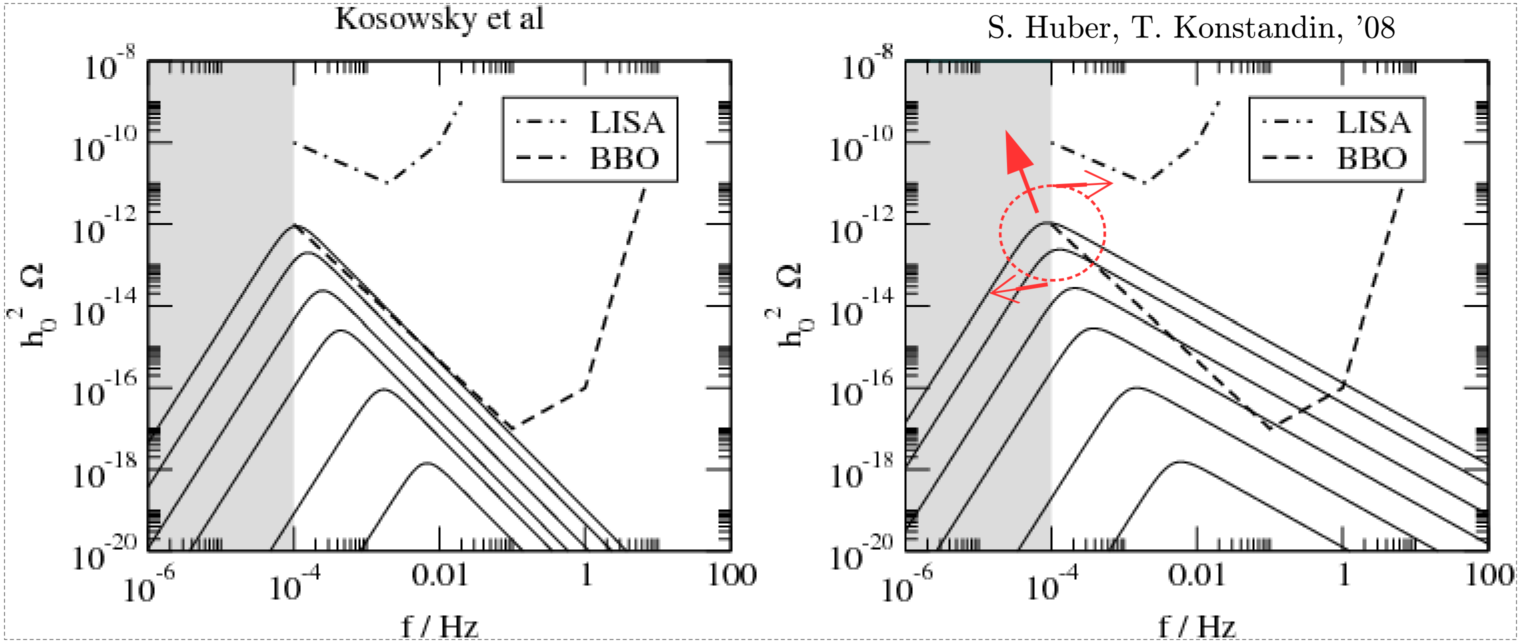

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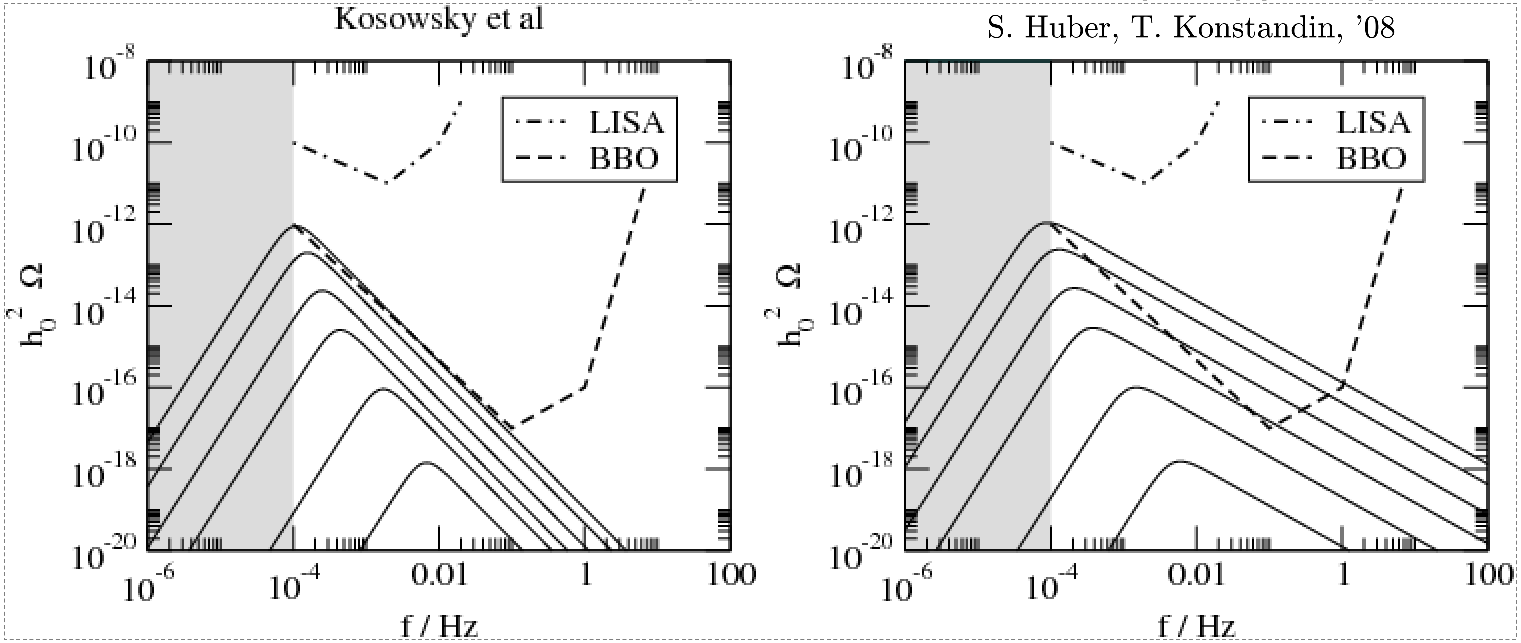
> On the top of the "envelope" source, there might be contributions coming from the plasma dynamics: sound waves M.Hindmarh,S.Huber,K.Rummukainen,D.Weir,'13,'15

Gravitational Waves from 1st-Order EWPT

> Simulations on bubble collisions (based on the "envelope approx") show



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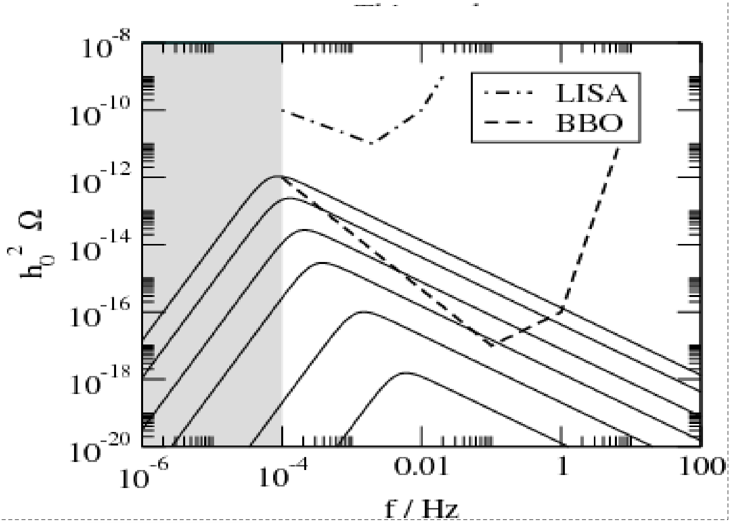
$$f_{peak} \approx \mathrm{mHz} \left(\frac{\beta/H}{100}\right) \left(\frac{T_n}{100\mathrm{GeV}}\right)$$

> Thus the actual GW spectrum is sensitive to the interactions of the field of the tunneling with the plasma (non-runaway/runaway/vacuum cases). For simplicity in this talk we restrict ourselves to the non-runaway case.

Mapping your model into the eLISA detection curves

- The eLISA sensitivity curves for a stochastic background are much better than what one could naively think.
- The dominant enhancement is that the signal has a continuous frequency spectrum over which you can integrate (the astrophysical sources are monochromatic). Thrane,Romano, '13
- Moreover the signal has to be enough above the sensitivity curve to have a discovery ($SNR > SNR_{thresh}$).
- The stochastic-background sensitivity source will be public soon A.Peteteau, 1512.xxx



Mapping your model into the eLISA detection curves

- The procedure to determine "SNR > SNR_{thresh}" for a given eLISA sensitivity curve is quite involved.
- The procedure can be absorbed into a detection map: you determine $(\alpha, \beta/H_*, case)$ in your model, and then...

Subset of eLISA cosmology working group, 1512.xxx

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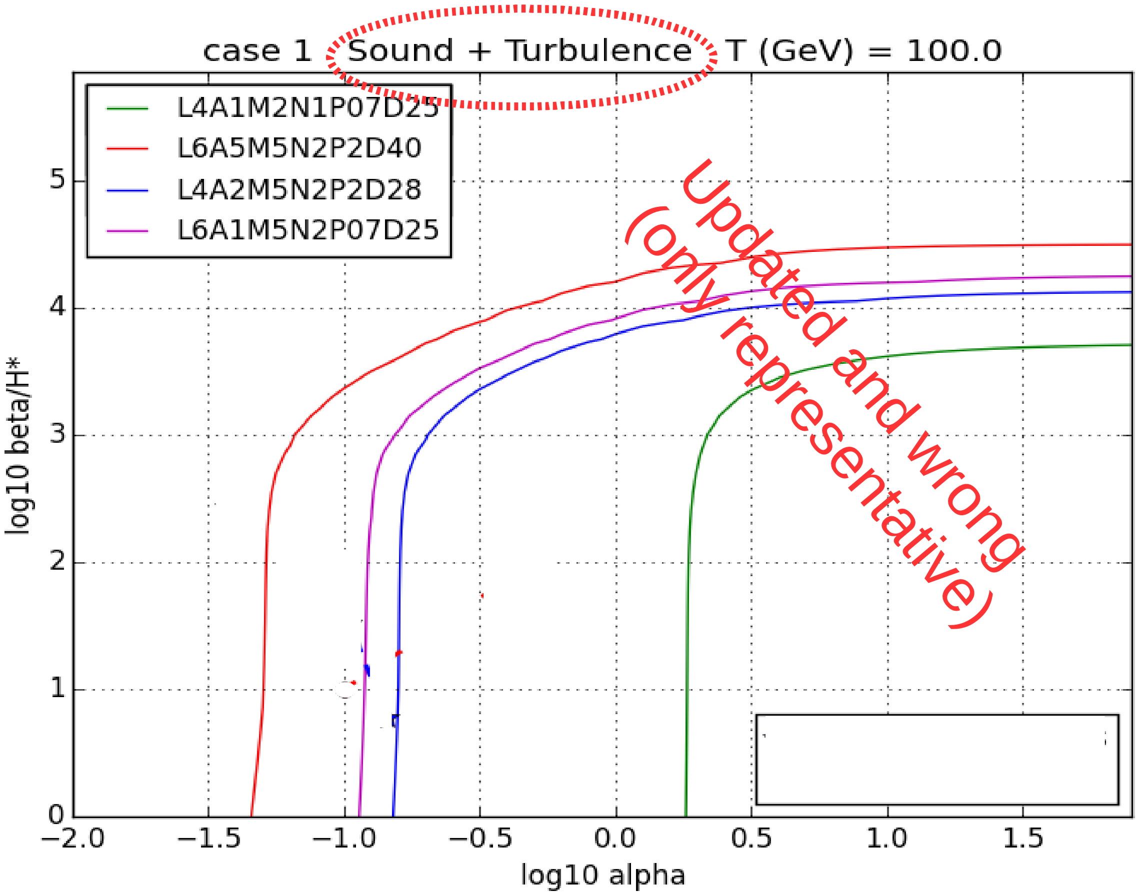


Question 1

- These bubble simulations show that a sizable GW spectrum from EWPTs is possible for some values of α and β/H taken as inputs
- A wide region of α and β/H, which correspond to a supercooled EWPTs, can be probed at eLISA
- But α and β/H are features of the potential that strongly depend on the particle physics model !!!

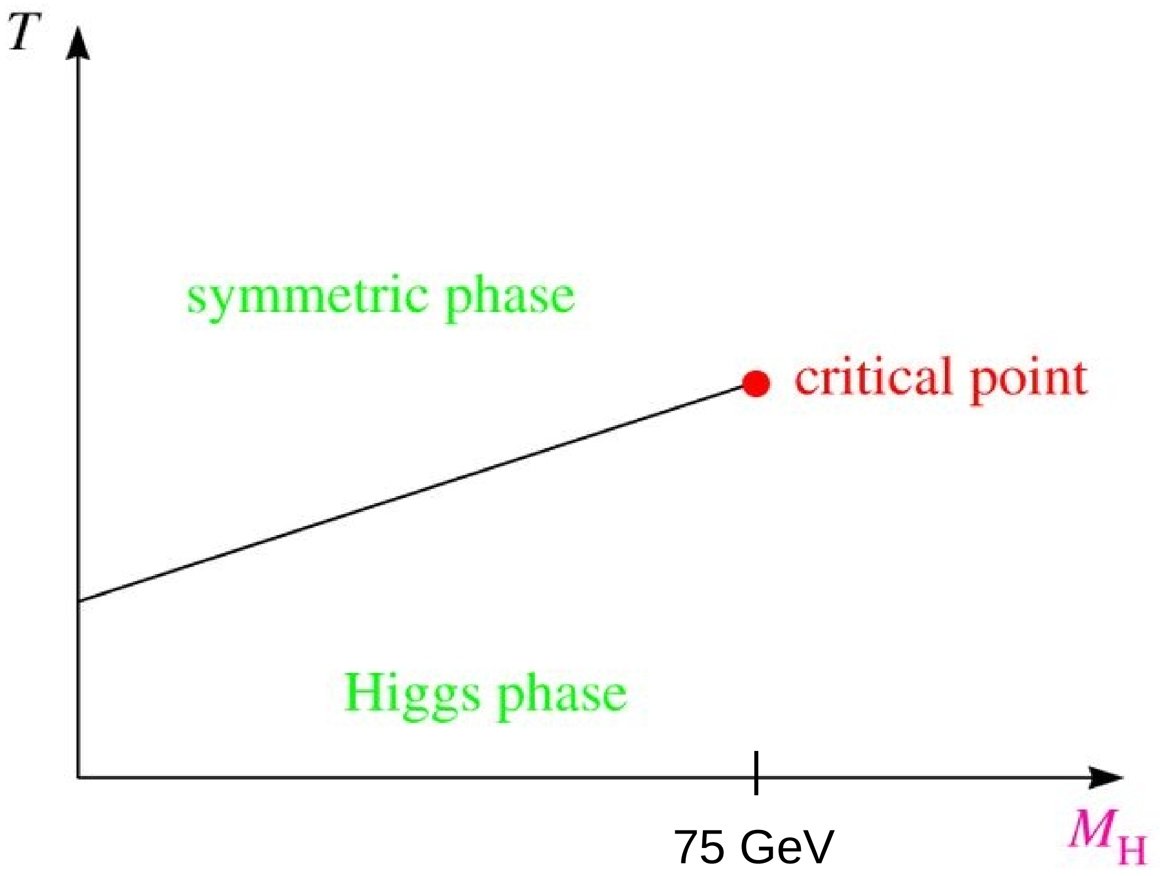
Are this region of α and β feasible in well-motivated UV theories?

- Remark: some low-energy extensions of the SM seem to be able to reproduce such values (but not much has been done, maybe because people focused on EWBG; see e.g. G.Dorsh, S.Huber, J.M.No, '14)

Answer 1

- In the SM the EWPT is not of first-order

Kajantie,Laine,Rummukainen,Shaposhnikov, '96; Karsh,Neuhaus,Patkos '96; Csikor,Fodor,Hietger '98.



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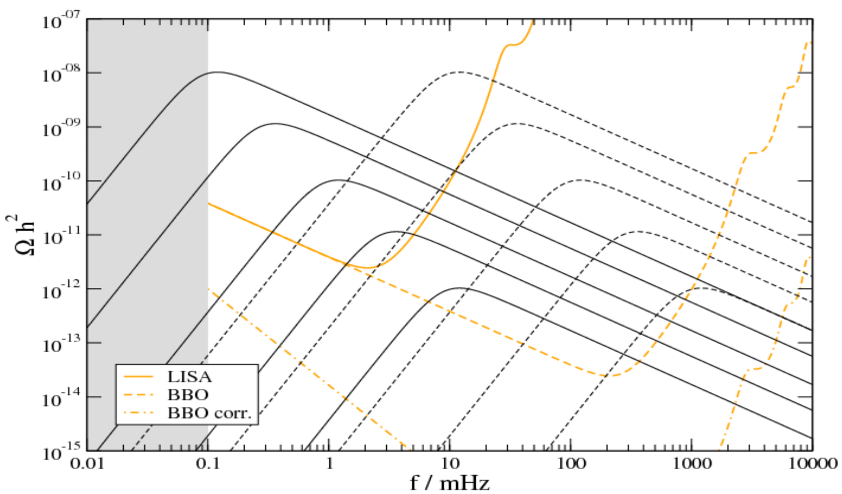
- To change this feature we need to modify the EW sector by means of either finite-temperature radiative corrections or/and new Higgs fields. In practice both options imply new scalar fields below the ~TeV scale (therefore testable)

- (Reminder) Exceptions to this criterion exist: RS models. If the Higgs start "existing" only at low temperature, its phase transition is strongly distorted although the Higgs potential is SM-like (in fact the EWPT can be linked to the transition of the radion).

Creminelli,Nicolis,Rattazzi, '02; Randall,Servant, '07; GN,Quiros,Wulzer, '07; Konstandin,GN,Quiros, '10

- YES in RS models



Answer 1bis (in supersymmetry)

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- SUSY models naturally satisfy both features.

- Let us start with the minimal supersymmetric extension...

Answer 1bis (in supersymmetry)

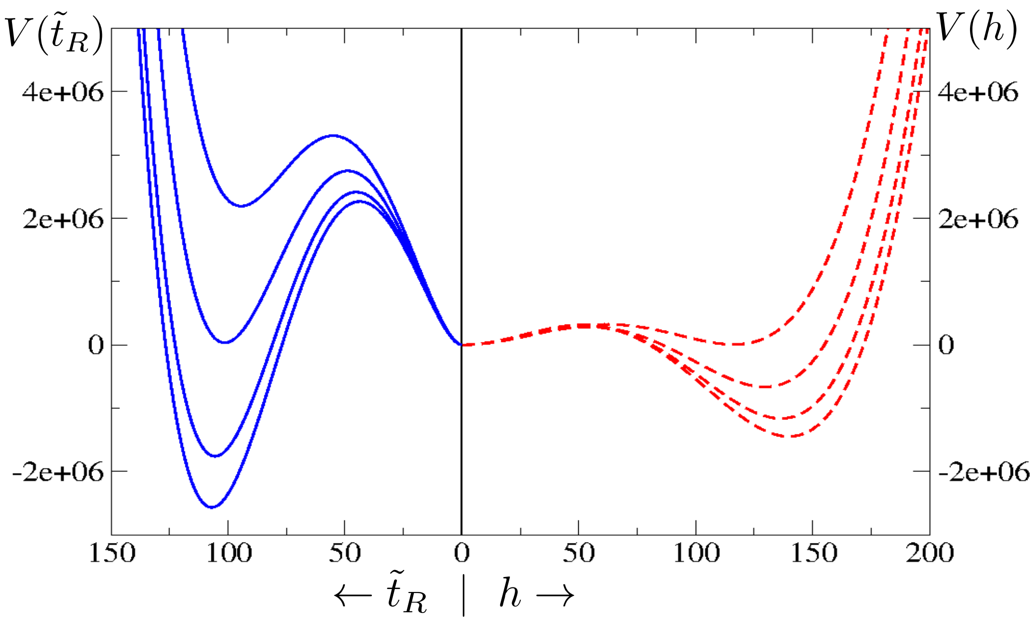
MSSM

Minimal option: MSSM

- To modify the T~100 GeV effective potential of the SM-like Higgs, we need a particle in the thermal bath (m/T<3) with large couplings to the Higgs. This particle is a light right-hand stop.

  Carena,Quiros,Wagner, '96; Delepine,Gerard,Gonzalez Felipe, Weyers, '96; Cline,Kainulainen '96.

- In the MSSM case the tunneling involves only the SM-like Higgs (no other directions but V(h) are relevant; m_A is typically large)



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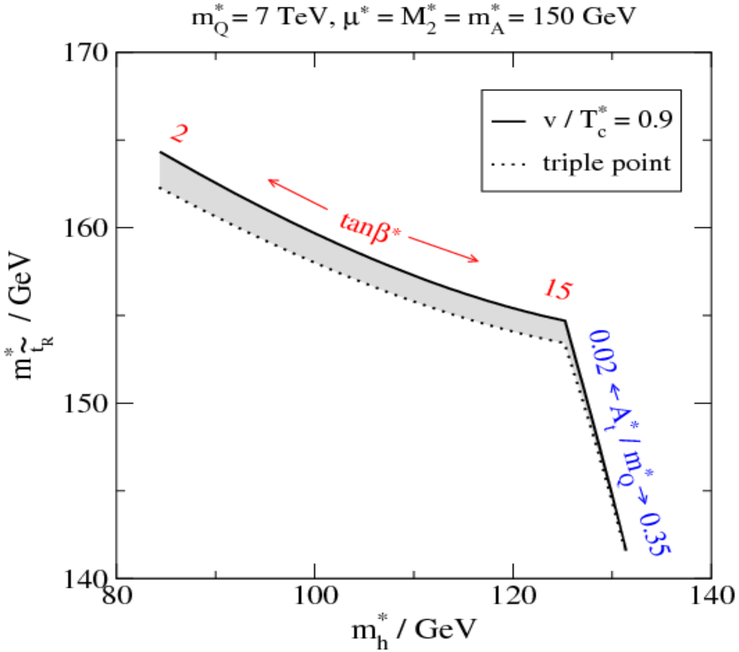
- Tension with stop searches and Higgs signal strengths.
Cohen,Morrissey,Pierce '12; Curtin,Jaiswal,Meade '12; Carena, GN, Quiros,Wagner,'13.



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GENERAL LESSON (but not a theorem!)

If the tunneling involves only the SM-like Higgs direction, a large barrier is possible only by means of new large radiative corrections to the Higgs. These tend to spoil the Higgs signal strenghts.

Beyond the minimal option

Is it possible to avoid this issue in extensions of the MSSM ?

OUR AIM IS TO PROVE

Despite the parameter constraints due to supersymmetry
and the LHC bounds, in principle, in extensions of the MSSM
we can have striking GW signals from the EWPT

Since our aim is a "proof of principle":

- We do not try to find the most minimal scenario exhibiting large GW
- We do not perform an exhaustive analysis of the full parameter space
- We choose a sensible model; we focus on a parameter region that is promising for GW and safe from collider constraints; we calculate the GW prediction

Beyond the minimal option

General NMSSM

(MSSM + singlet)

Beyond the minimal option

- We consider the general singlet extension of the MSSM (general NMSSM) with superpotential

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

- As usual, the tree-level Higgs mass is boosted at small $\tan\beta$; this alleviates the little hierarchy problem

Scalar potential

> The tree-level potential of the Higgs sector is

$$V_0 = \frac{1}{2} m_{H_d}^2 h_d^2 + \frac{1}{2} m_{H_u}^2 h_u^2 + \frac{1}{2}(B_S + m_S^2) s^2 + \frac{1}{3\sqrt{2}} T_\kappa s^3 - B_\mu h_d h_u - \frac{1}{\sqrt{2}} T_\lambda h_d h_u s$$
$$+ \frac{1}{32}(g_1^2 + g_2^2)(h_d^2 - h_u^2)^2 + \frac{2}{\sqrt{2}} \xi_1 \, s + \left(L_1 + \frac{1}{\sqrt{2}} M_S s + \frac{\kappa}{2} s^2 - \frac{\lambda}{2} h_d h_u \right)^2$$
$$+ \frac{1}{2}(h_d^2 + h_u^2) \left(\frac{1}{\sqrt{2}} \lambda s + \mu \right)^2$$

> We reparametrize $\{m_{H_d}^2, m_{H_u}^2, T_\lambda\}$ by imposing

$$\langle \{h_d, h_u, s\} \rangle_{brok} = \{v_h \cos\beta, v_h \sin\beta, 0\}$$

> We assume B_μ very large such that $m_{A^2}^2 \gg \mu v_h$ ($A_2, h_3, H^\pm$ are at the TeV)

We remain with only two light CP-even scalars

$$h = h_d \cos\beta + h_u \sin\beta \qquad\qquad S$$

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> The LHC bounds prefer small singlet-higgs mixing: $\sin^2\gamma < 0.23$ Giardino,Kannike, Masina,Raidal,Strumia, '14; Falkowsi,Riva,Urbano, '13.

The Z_2 symmetry guarantees this, but it cannot be imposed now due to gaugino constraints. We do it at least in the symmetric phase ($T_\kappa = -3M_S\kappa\ ,\quad \xi_1 = -L_1 M_S$)

> We replace m_S^2 by imposing

$$\langle\{h_u, h_d, s\}\rangle_{sym} = \{0, 0, \pm\bar{v}_s\}$$

Scalar potential

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$$+ \frac{1}{32}(g_1^2 + g_2^2)(h_d^2 - h_u^2)^2 + \frac{2}{\sqrt{2}} \xi_1 \, s + \left(L_1 + \frac{1}{\sqrt{2}} M_S s + \frac{\kappa}{2} s^2 - \frac{\lambda}{2} h_d h_u \right)^2$$
$$+ \frac{1}{2}(h_d^2 + h_u^2) \left(\frac{1}{\sqrt{2}} \lambda s + \mu \right)^2$$

> For this parameter choice, for $B_\mu \to \infty$ the tree-level potential has the minima

$$\langle \{h, s\} \rangle_{brok} = \{v_h, 0\} \qquad\qquad \langle \{h, s\} \rangle_{sym} = \{0, \pm \bar{v}_s\}$$

separated by a tree-level barrier. By modulated this barrier we might achieve very strong EWPT. Let us see... (similar idea used for EWBG, but not pushed to the regime useful for GW signals)

J.M.No,Ramsey-Musolf, '14;
Profumo,Ramsey-Musolf,Wainwright,Winslow, '15;
M.Jiang,L.Bian,W. Huang,J.Shu, '15;
Kozaczuk,Profumo,Haskin,Wainwright, '15.

Spectrum

> The light degrees of freedom:

- Higgsino-like chargino and neutralinos
- SM-like Higgs
- singlet-like scalar

Scalars are OK with LHC, LEP, … because of the tiny mixing

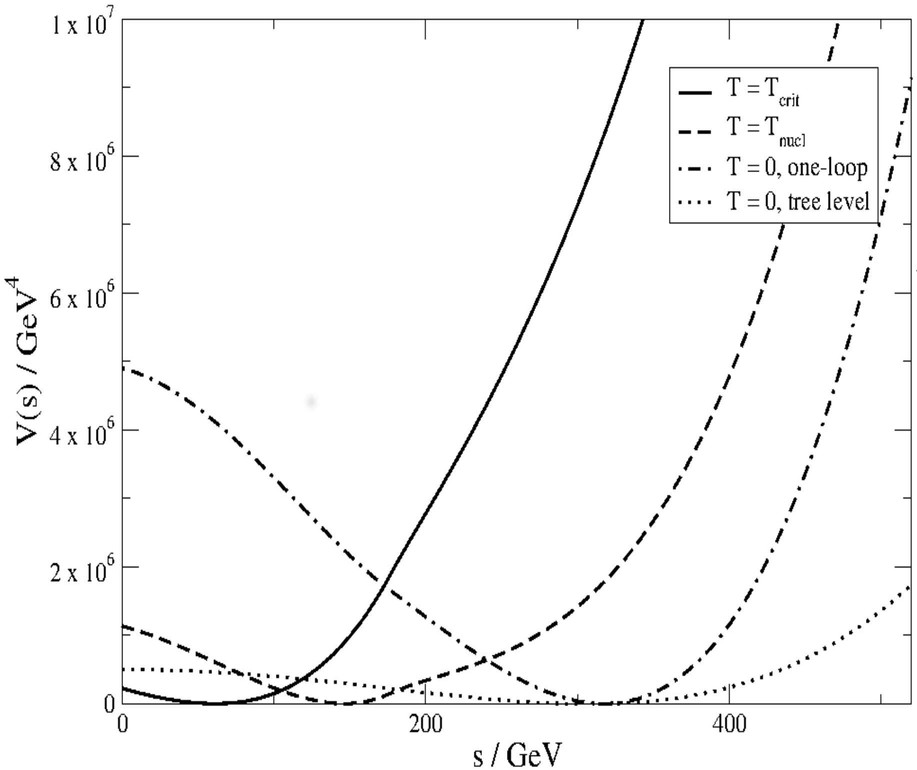
Higgsino-like states are compressed, so decays are too soft for the LHC

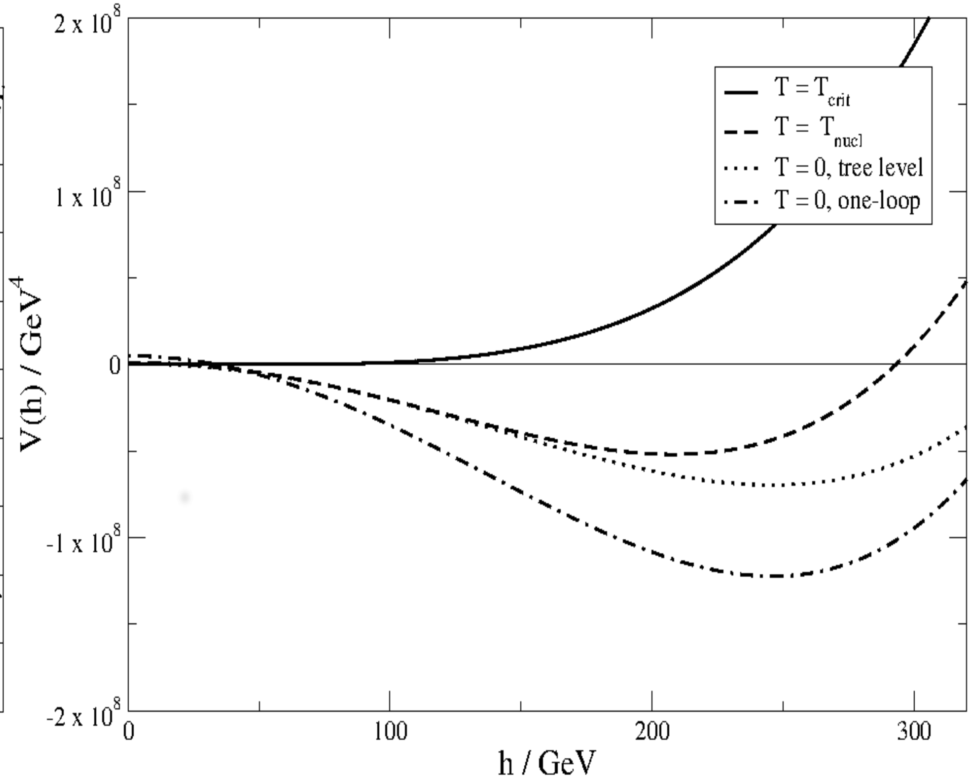
> The rest of the particles (squarks, sleptons, gauginos, singlino, …) are assumed heavy to easily overcome the LHC bounds

Heavy fields and the transition

- The heavy fields induce large radiative corrections to the Higgs potential.
- The modulation of the barrier that was transparent at tree level, now becomes obscure as depends on many inputs.
- Indeed the parameter region that was leading to the strong EWPT is now reshuffled.
- The usual solution is *brute-force*: the interesting parameter region is found by means of cumbersome and time-consuming parameter scans. *Scans likely miss small regions.*
- Here we propose a different approach. We adopt renormalization scheme that seems to suit for EWPT analyses.

Heavy fields and the transition

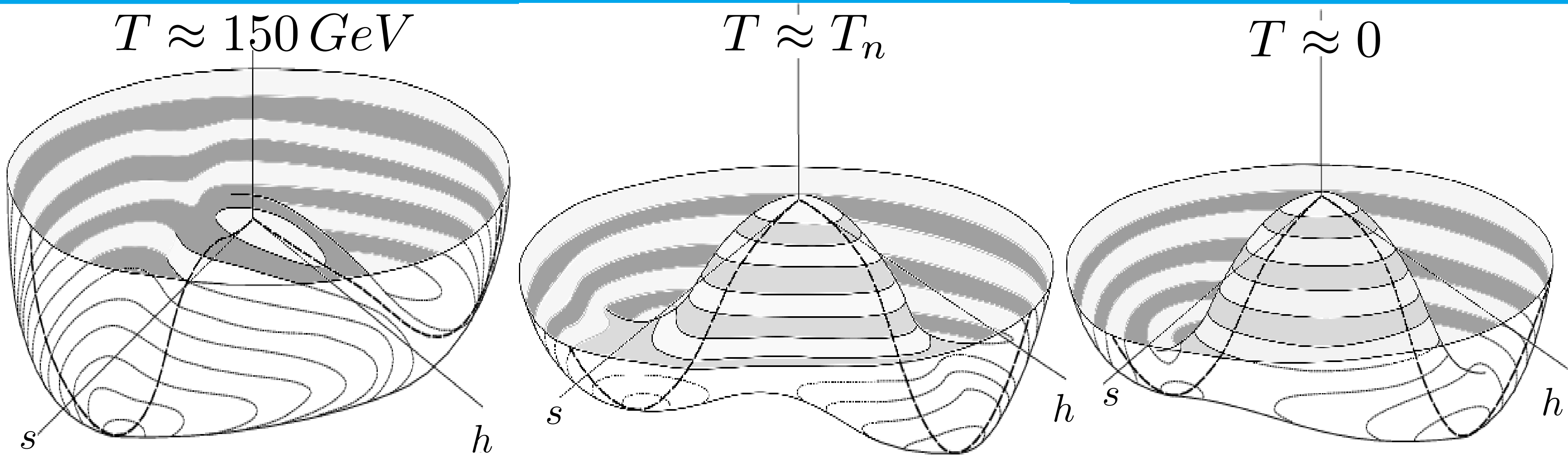




- On the top of the counterterms of the DR scheme, we add a counterterm to each soft-term interaction: $V_{1-loop} = V_0 + V_{CW} + V_{cnt}$

- Renormalize choice: we fix V_{cnt} such that the position of the minima of V_{1-loop} and V_0 are the same (at T=0).

Heavy fields and the transition



Graphics from: N.Blinov,J.Kozaczuk, D.Morrissey, C.Tamarit,'15

- At high T (but not too high), there is only the minimum along the singlet direction
- Nearby the critical T and below, there are minima in the singlet and Higgs orthogonal directions. They are separated by a barrier.
- The tunnelling involves more than one field: **2-step phase transition**
(it circumvents the LHC issues of the MSSM)

Benchmark points

	A	B	C	D
$\tan\beta$	5	-	-	-
$\bar{v}_s$ [GeV]	307.5	319.8	323.5	324.0
λ	0.7	-	-	-
κ	0.015	-	-	-
L_1	0	-	-	-
B_S [GeV^2]	-250^2	-	-	-
μ [GeV]	300	-	-	-

tree	A	B	C	D
m_{h_1}	93	-	-	-
m_{h_2}	96	-	-	-
m_{A_1}	373	-	-	-
$m_{\chi_1^0}$	286	-	-	-
$m_{\chi_2^0}$	310	-	-	-
$m_{\chi_1^\pm}$	296	-	-	-

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

> We choose a parameter point where the symmetric and broken EW minima are separated by a sizeable tree-level barrier

> We modulate the size of the barrier (mostly the width) by keeping all parameters constant but the singlet VEV

> We employ the usual bounce method to determine the tunneling action

> From the action we have β/H and α (via T_n) which can be plugged into the GW formulas

S. Huber, T. Konstandin, '08

Benchmark points

	A	B	C	D
$\tan\beta$	5	-	-	-
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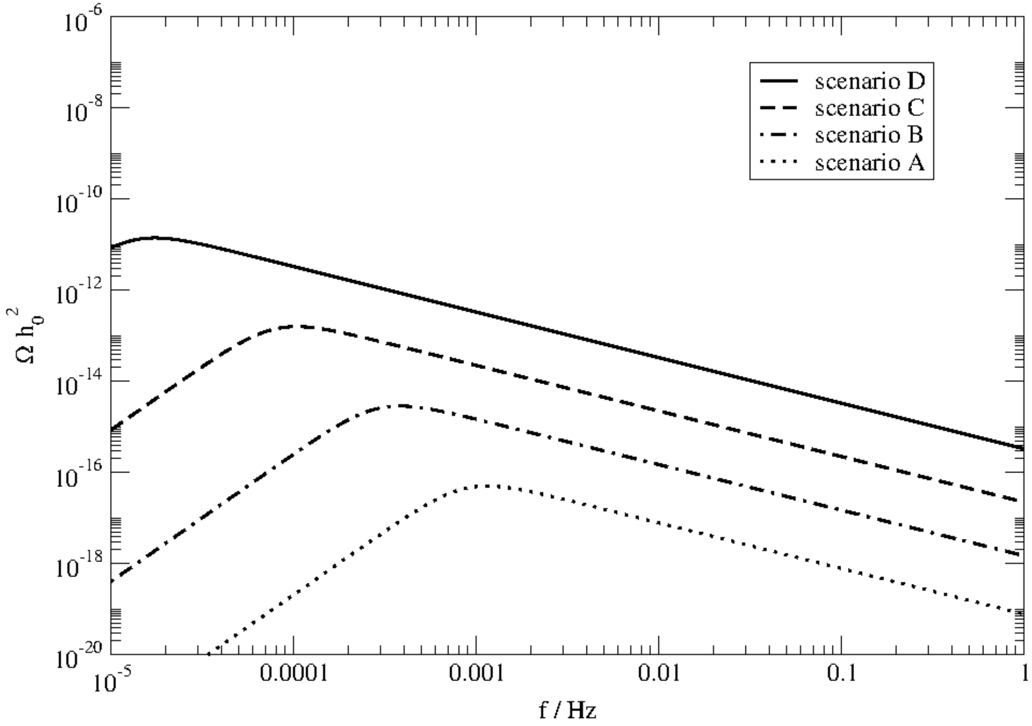
μ [GeV]	300	-	-	-

	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



UNIVERSITÄT BERN

DESY

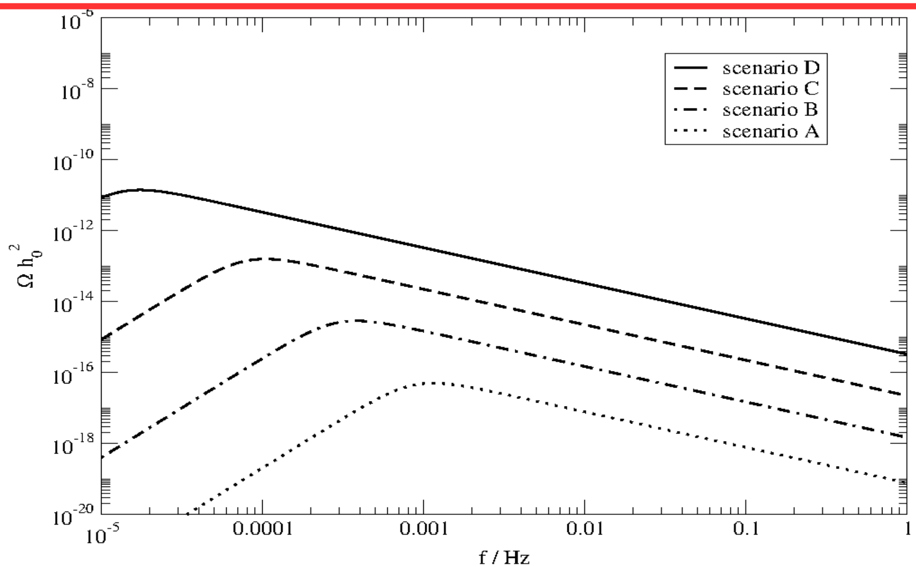
Answer to the Q1bis

Good news !!!

In principle we can have sizable GW spectrum from supersymmetric extensions of the SM.

Within supersymmetry, the most promising scenarios seem those where a 2-step EWPT is possible.

Likely, the presented results are quite generic and cover other susy models (if they do not depart too much from minimality).



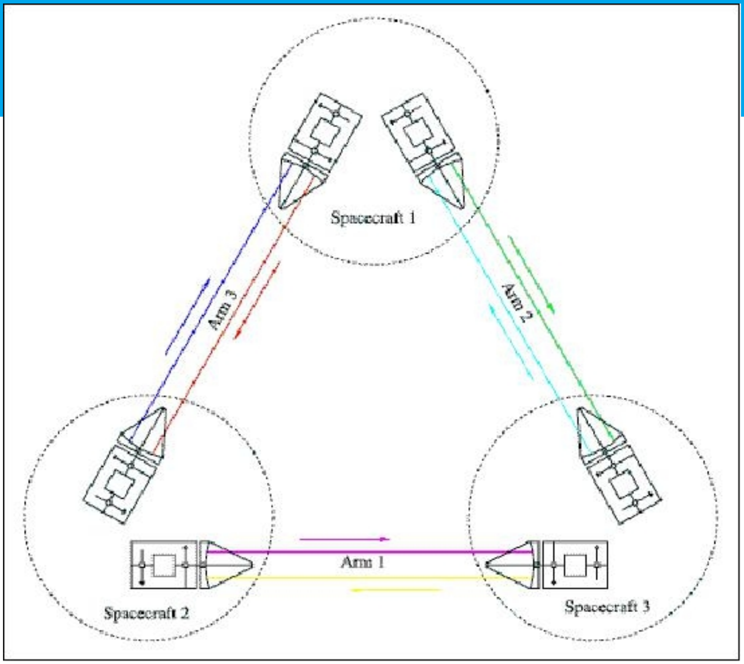
Question 2

- Part of the parameter region interesting for GWs is very hard to probe at the LHC-14TeV or at hadron FCC.
  If built, these machines will not take data before ~2028.
- These GW spectra have their peaks at ~0.1 mHz and have sizeable amplitudes.

Are these (SUSY) GW signals probed by eLISA?

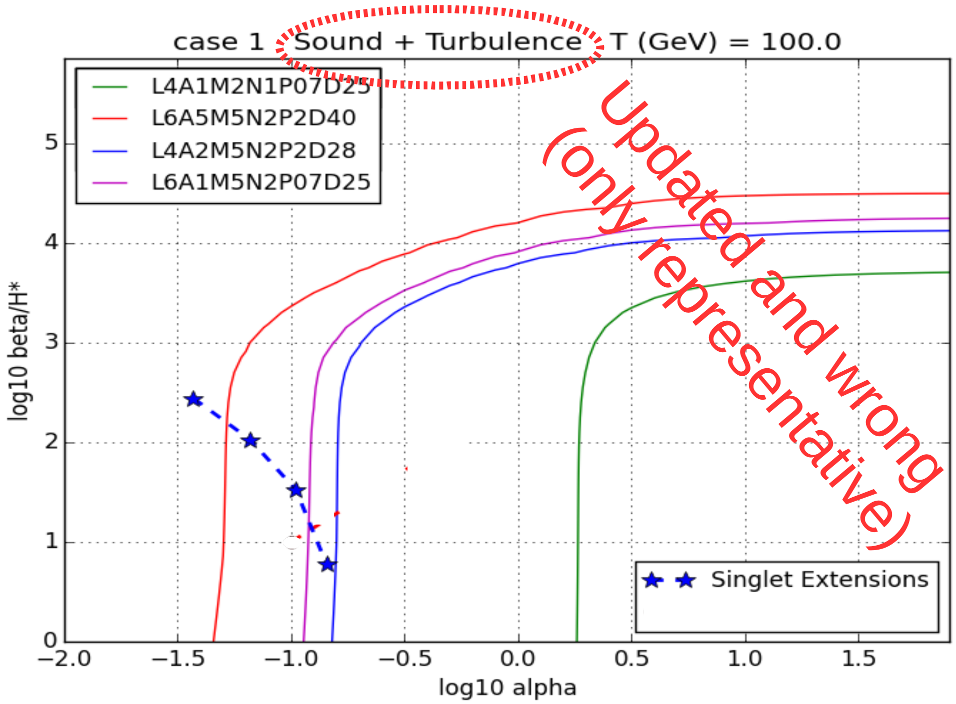
If yes, there will be complementarity between future colliders and eLISA

Answer 2



- To answer, we need to know the sensitivity curves of eLISA, which depend on options that are still under discussion:
  - # of arms: 2 or 3 ?
  - Length of the arms: 1, 2 or 5 Gm ?
  - # of years of data taking: 2 or 5 ?
  - Noise: pathfinder success or expected ?
- Reminder: the sensitivity curves for our spectra (i.e. stochastic GW background) are more sensitive than those for isolated sources Thrane,Romano, '13
- We consider 4 possible configurations:
  1) 2 arms of 1 Gm, 2 years, noise pathfinder success (Design 1)
  2) 2 arms of 2 Gm, 5 years, noise expected (Design 2)
  3) 3 arms of 1 Gm and 5 years, noise expected (Design 3)
  4) 3 arms of 5 Gm and 5 years, noise expected (Design 4)

Answer 2 (straightforward using the cosmology WG map)



Non-runaway case

The third arm is very beneficial for allowing eLISA to detect SUSY GW signals

1) 2 arms of 1 Gm, 2 years, noise of pathfinder success (Design 1)
2) 2 arms of 2 Gm, 5 years, noise expected (Design 2)
3) 3 arms of 1 Gm and 5 years, noise expected (Design 3)
4) 3 arms of 5 Gm and 5 years, noise expected (Design 4)

Conclusions

> GW measurements can be a way to probe the EWPT and, in turn, the Higgs sector

> However, in the forthcoming experiments only supercooled EWPT might be probed

> Detectable GWs are possible within warped models

> In supersymmetry:

- in the MSSM the LHC bounds make the EWPT too weak; it seems difficult to modify these results in extensions where only the SM-like Higgs plays a role in the tunneling
- in the general NMSSM a very strong EWPT is viable. Similar result should be possible in other extensions where the tunneling involves more fields
- The GW signal is border line with the preliminary sensitivity curves.

  .

- The third arm is very useful

IF OF YOUR INTEREST:

The eLISA collaboration is still expanding. Many things need to be done. If you are interested in any of the working groups below, contact the corresponding coordinators