LISA as a Probe for Particle Physics

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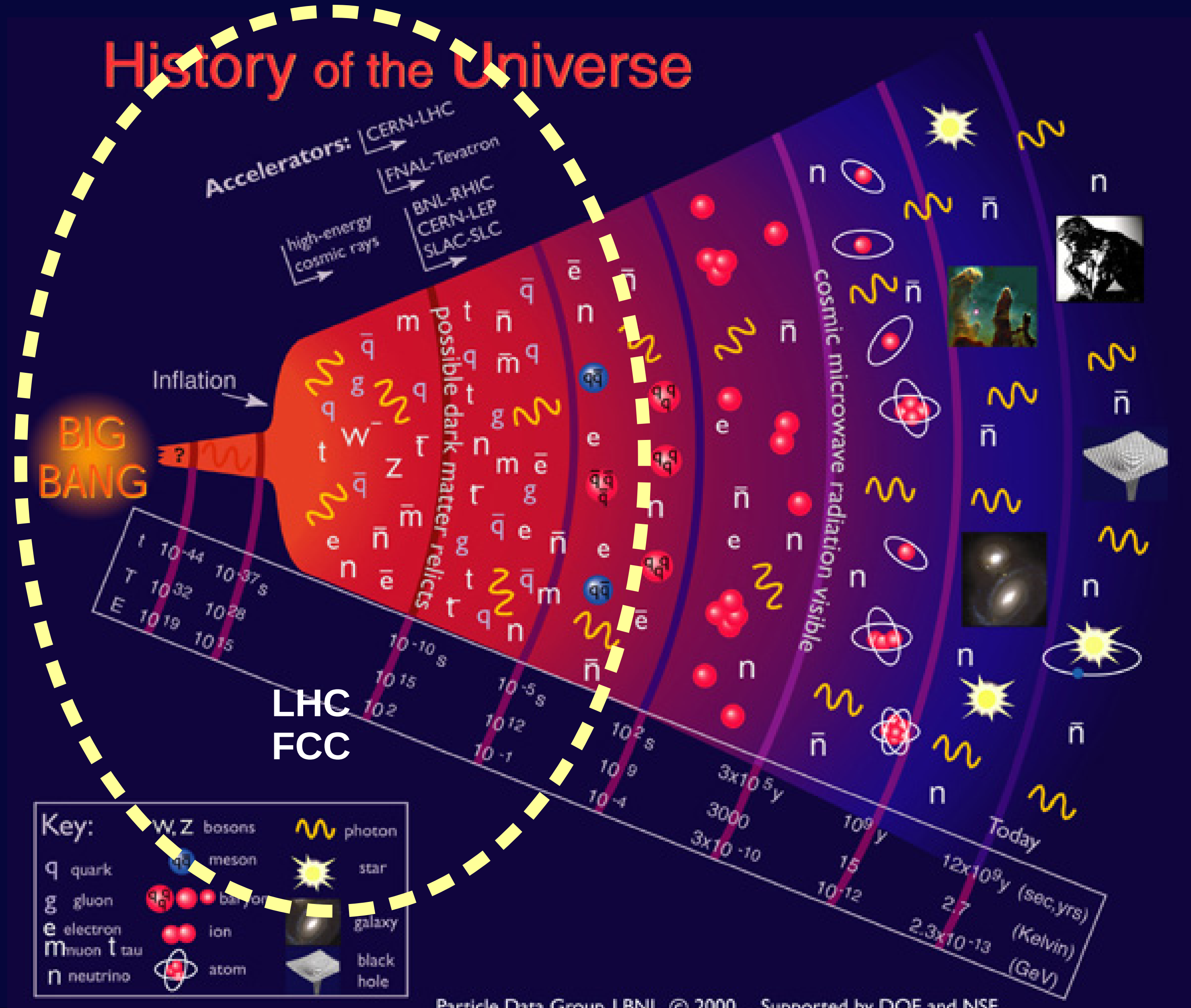
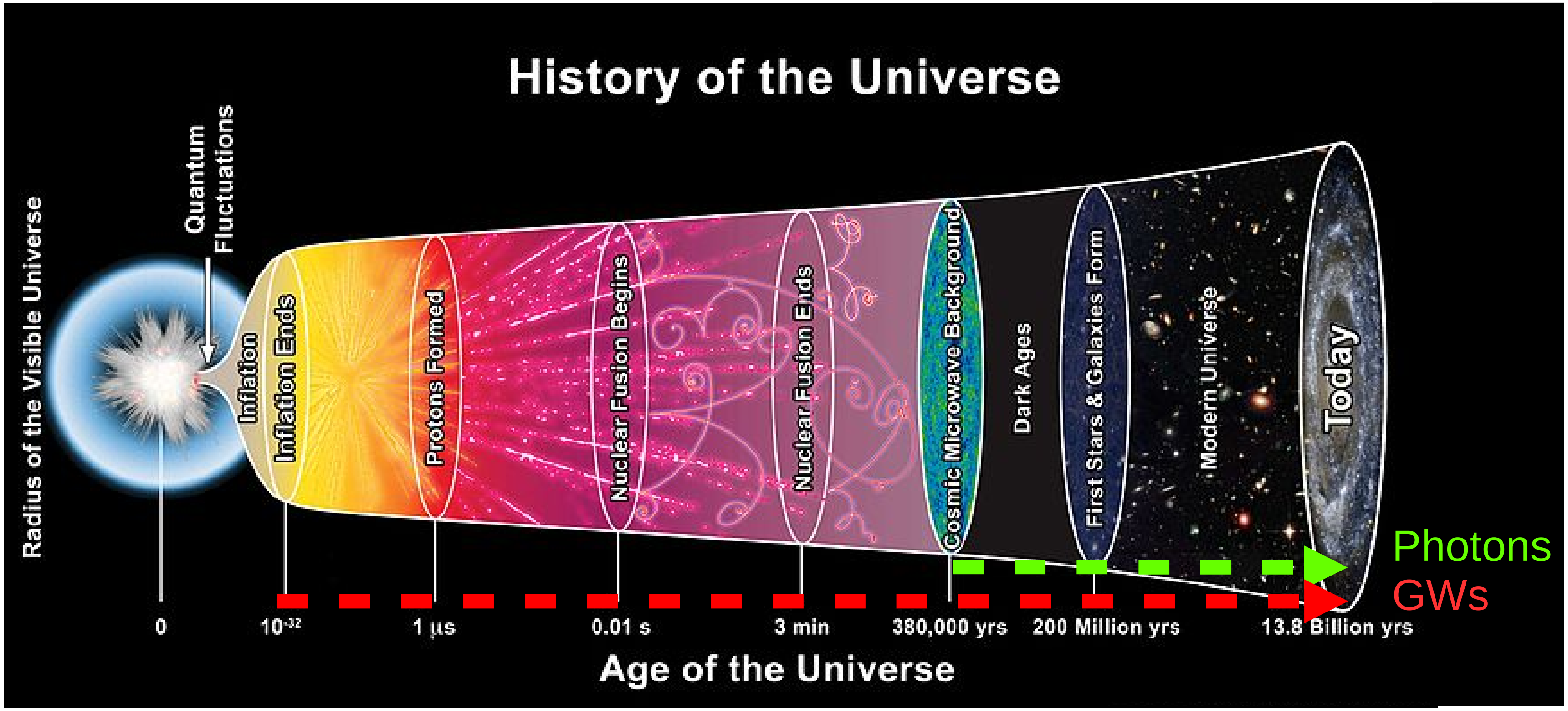
HISTORY OF THE EARLY UNIVERSE WITH GRAV. WAVES



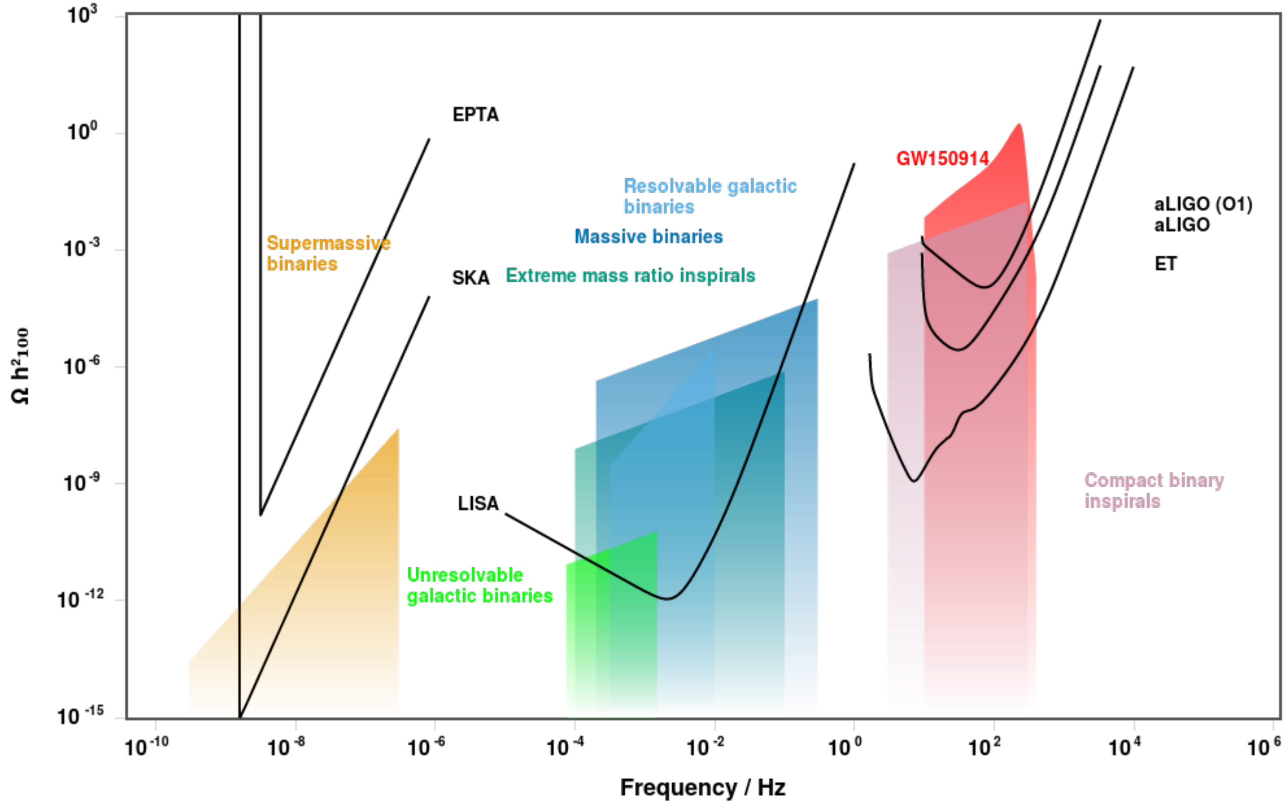
Early Universe: stochastic GW background

- By means of the GW messengers, we directly access the pre-CMB epoch for the first time!
- Early-universe GW sources (inflationary epoch, topological defects, phase transitions, ...) generate a stochastic GW background



Early Universe: stochastic GW background

- SGWB: the superposition of the sources that cannot be resolved individually
- SGWB components:
  - late-universe sources (when many but with small SNR)
  - signals from early universe (too small correlation scale)



Energy density power spectrum

$$\Omega_{GW} = \frac{\rho_{GW}}{\rho_c} = \frac{\langle \dot{h}_{ij} \dot{h}_{ij} \rangle}{32\pi G \rho_c} = \frac{df}{f}\frac{d\Omega_{GW}}{d\log f}$$

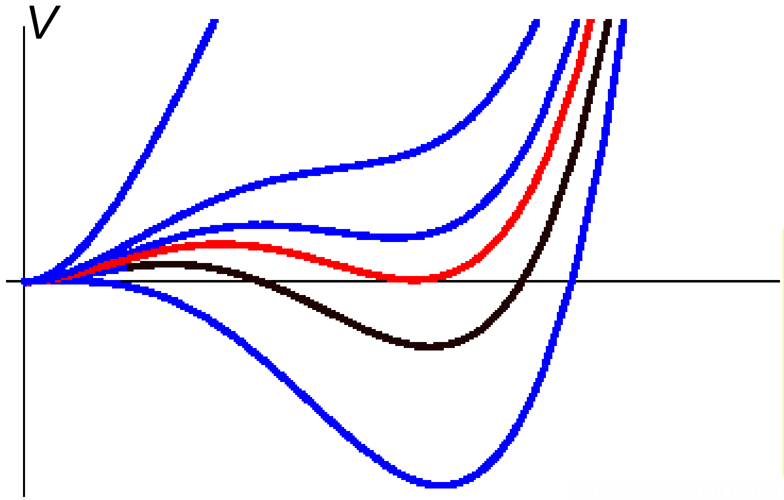
Cornish & Romano, '16
Caprini & Figueroa.'18

Early Universe: stochastic GW background

- SGWB: the superposition of the sources that cannot be resolved individually
- SGWB components:
  - late-universe sources (when many but with small SNR)
  - signals from early universe (too small correlation scale)
- Astrophyisical examples in LISA:
  - Unresolvable galactic binaries (non-isotropic!)
  - “Stellar origin” black hole binaries
  - Maybe neutron stars binaries and EMRI
- Cosmological / particle physics examples in LISA:
  - Inflationary processes
  - Cosmic strings
  - Primordial black holes
  - Superradiance
  - Cosmological 1st-order phase transitions

Gravitational Waves from 1st-Order PT

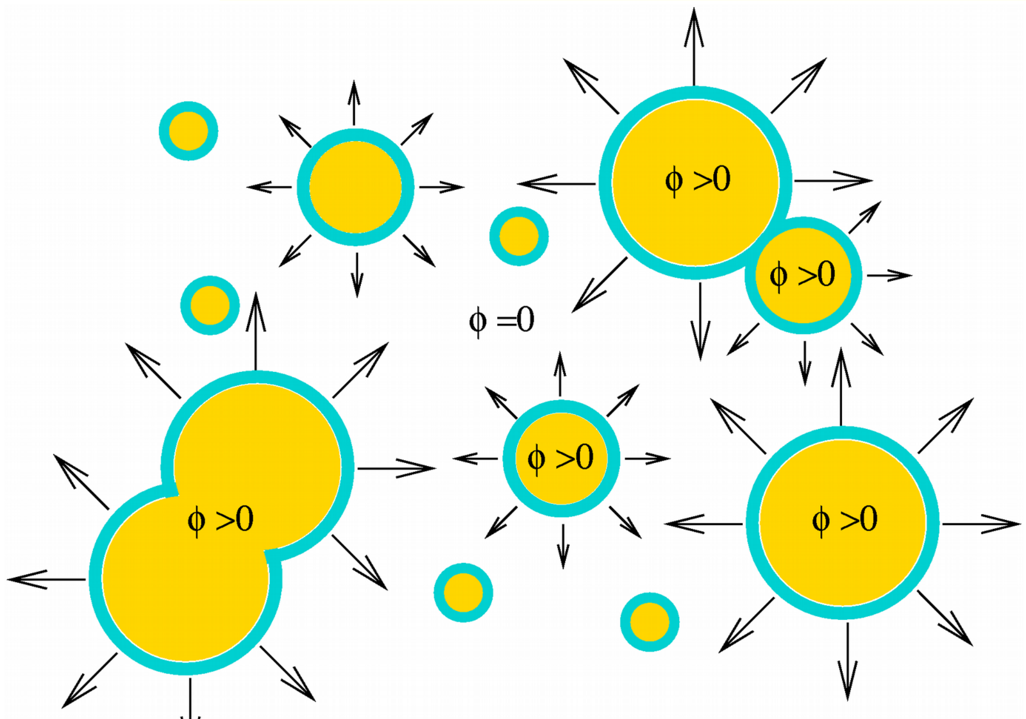
- When the transition is of first order...



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

$\alpha(T_n)$: ~normalized difference btw. the minima

$\beta(T_n)$: ~how fast the minimum goes down



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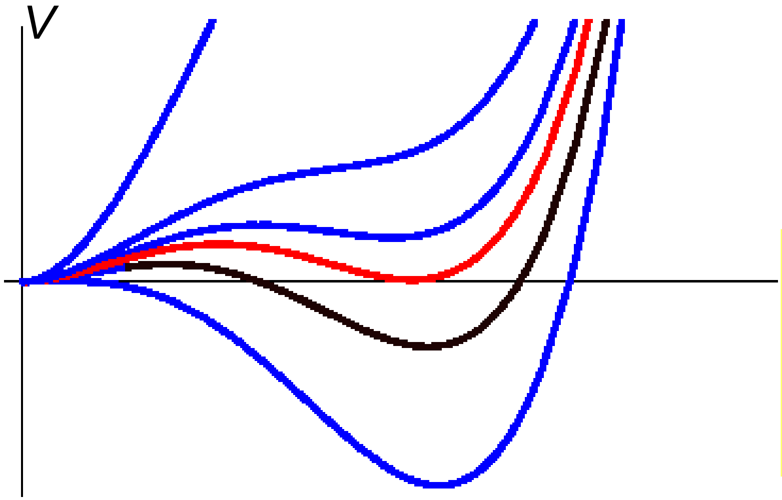

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> The phase transition occurs via tunneling. In the place where the tunneling happens, a bubble of EW broken phase ($\langle\phi\rangle = \phi_{brok}$) nucleates.

> Conventionally, the EWPT starts in the Universe when statistically we have 1 nucleated bubble per Hubble volume. 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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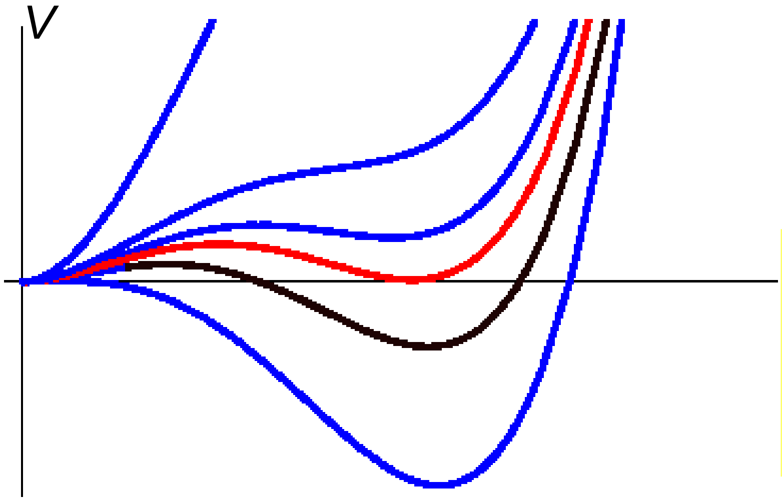

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> When bubbles collide, they convert part of their kinetic energy (of the expanding wall + turbulent fluid) into gravitational waves (GWs)!

M. Kamionkowski et al., '94

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

> This available energy is related to

$$\epsilon(T_n) \simeq V(\phi_{sym}, T_n) - V(\phi_{brok}, T_n)$$

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

Spectrum from 1st-Order PT

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

$$f_\phi = 16.5 \times 10^{-3}\,\mathrm{mHz}\left(\frac{0.062}{1.8 - 0.1 v_w + v_w^2}\right)\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,\mathrm{GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

$$h^2\Omega_\phi(f) = 1.67 \times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa_\phi \alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11\, v_w^3}{0.42 + v_w^2}\right) S_\phi(f)$$

$$S_\phi(f) = \frac{3.8\,(f/f_\phi)^{2.8}}{1 + 2.8\,(f/f_\phi)^{3.8}}$$

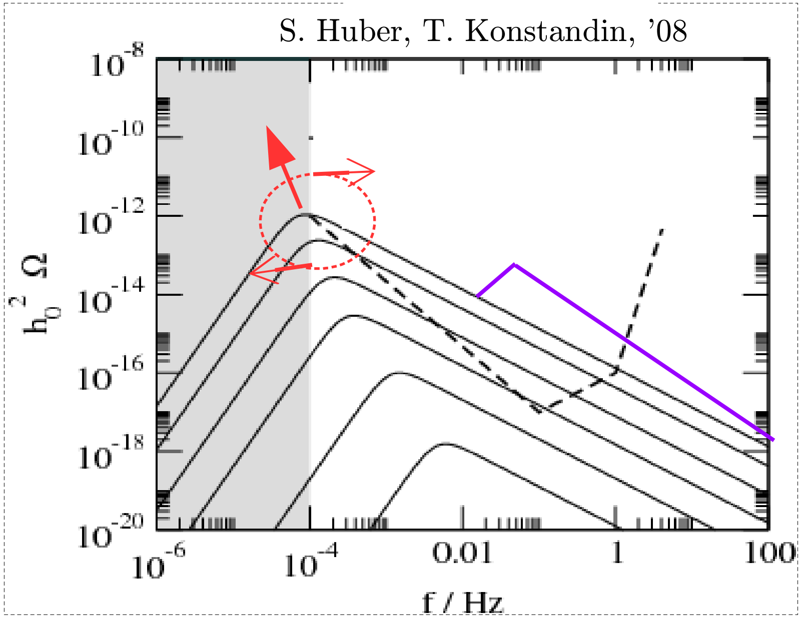
- On the top of the "envelope" result:

Sound Waves

M.Hindmarh,S.Huber,K.Rummukainen,D.Weir,'13,'15

Magnetic HD

P.Binetruy,A.Bohe,C.Caprini,J.Dufaux,'12
C.Caprini,R.Durrer,G.Servant, '09



1st-Order PT vs. Detectors (Peak Frequency)

> Using the "envelope approx" results (i.e. underestimating the spectrum)

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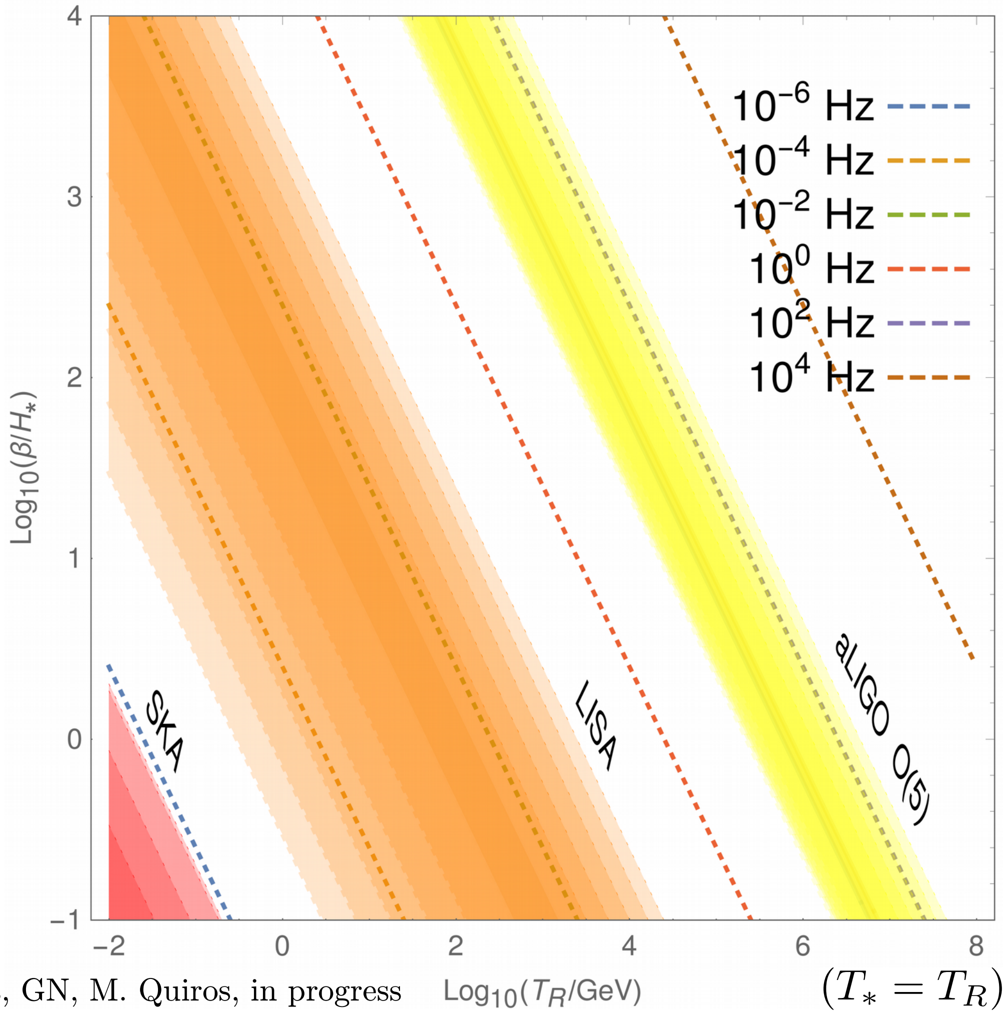
$$g_* = 100$$
$$v_w = 0.95$$



E. Megias, GN, M. Quiros, in progress

$(T_* = T_R)$

1^{st}-Order PT vs. Detectors (Full Spectrum)

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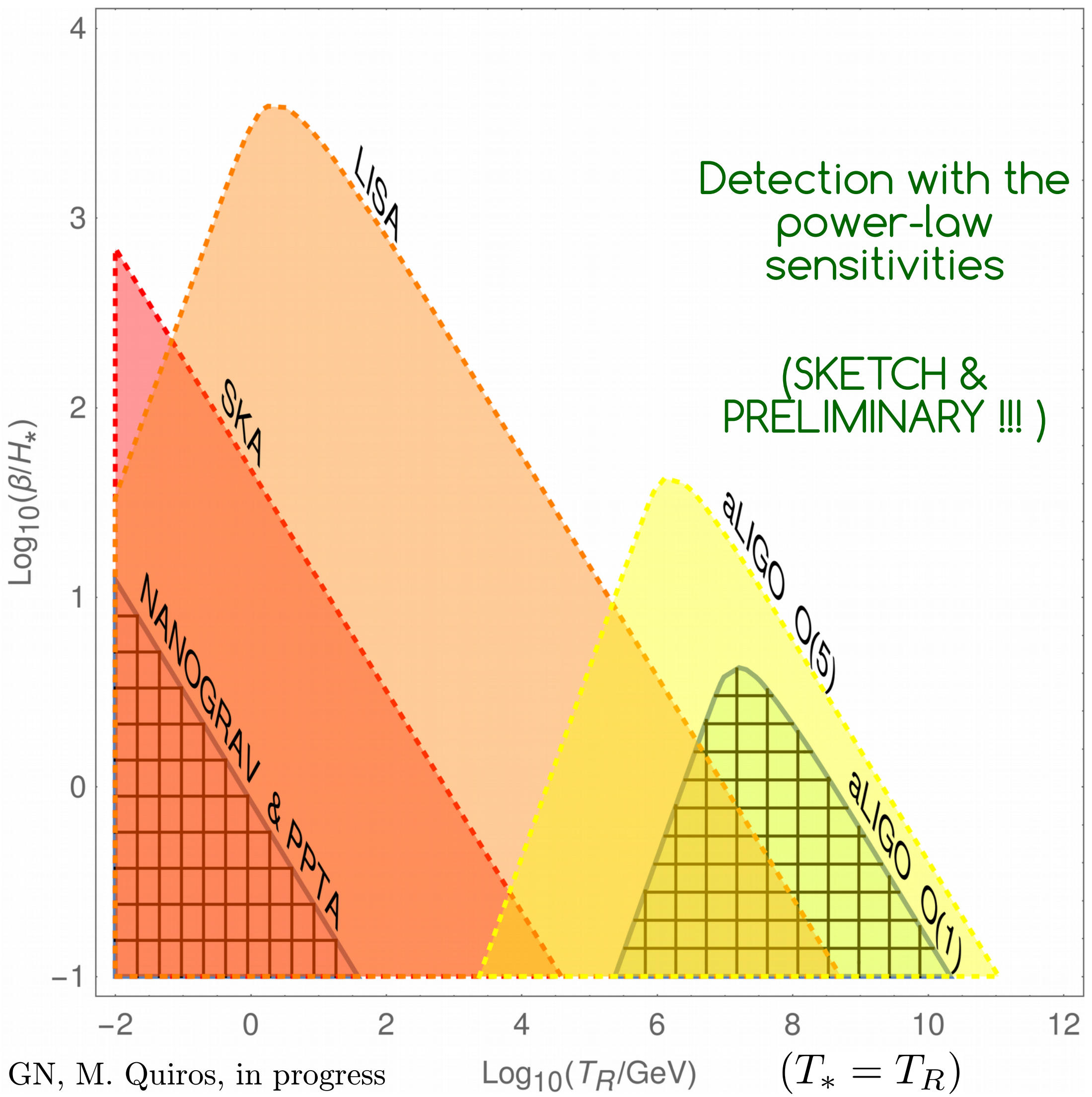

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ELECTROWEAK PHASE TRANSITION

(Higgs mechanism dynamics)

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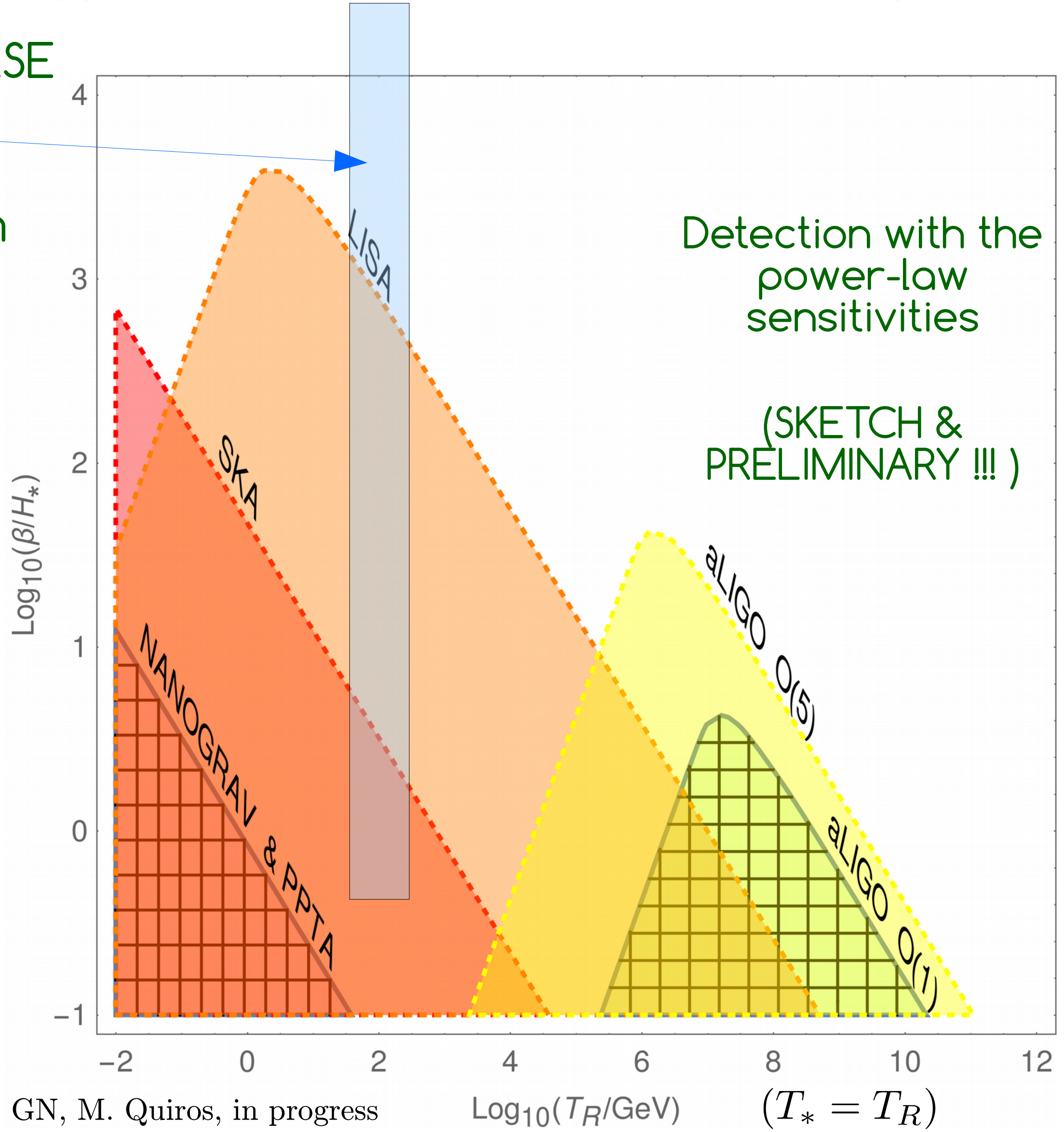
$$v_w = 0.95$$



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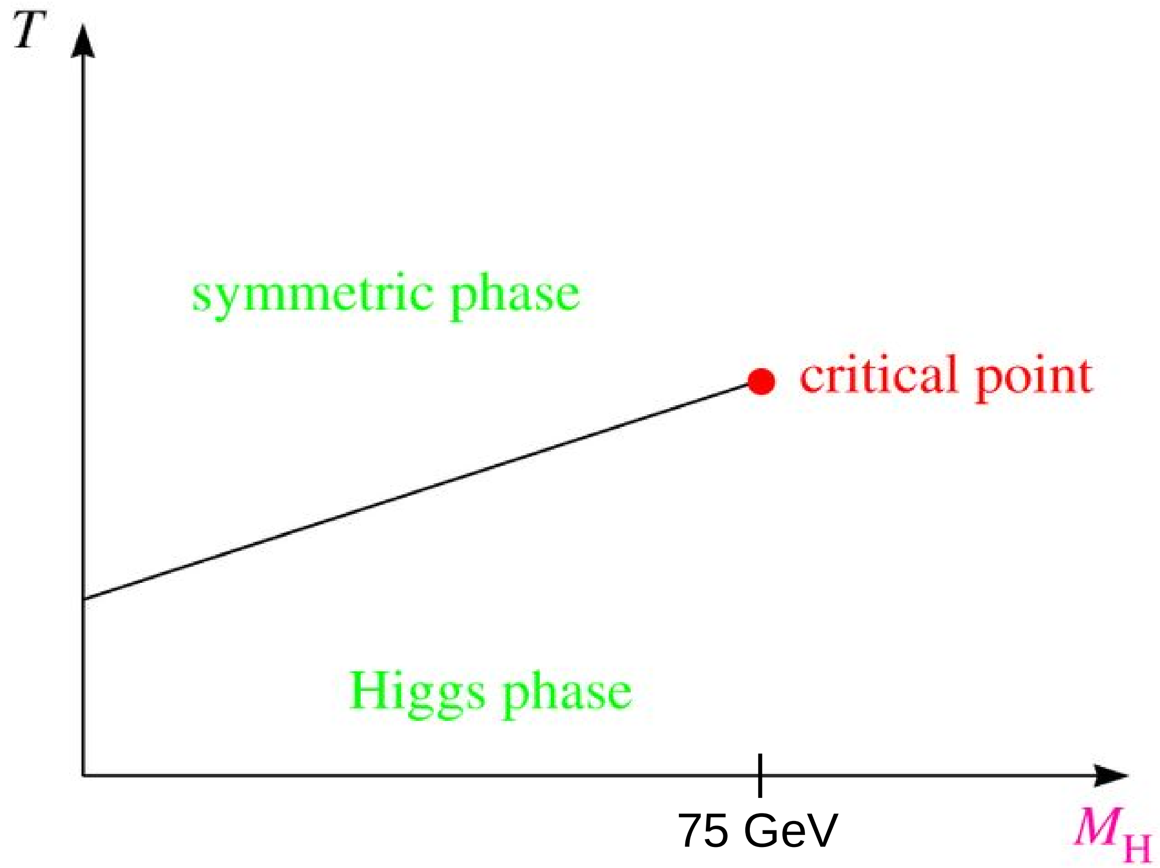
Electroweak Phase Transition in the SM

- In the SM the EWPT is not of first-order, i.e. no bubbles



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

Electroweak Phase Transition in BEYOND the SM

- In the SM the EWPT is not of first-order, i.e. no bubbles

- This feature can be different if the EW sector is modified by BSM physics introducing new finite-temperature radiative corrections or/and new Higgs fields. In practice BSM physics at the ~TeV scale

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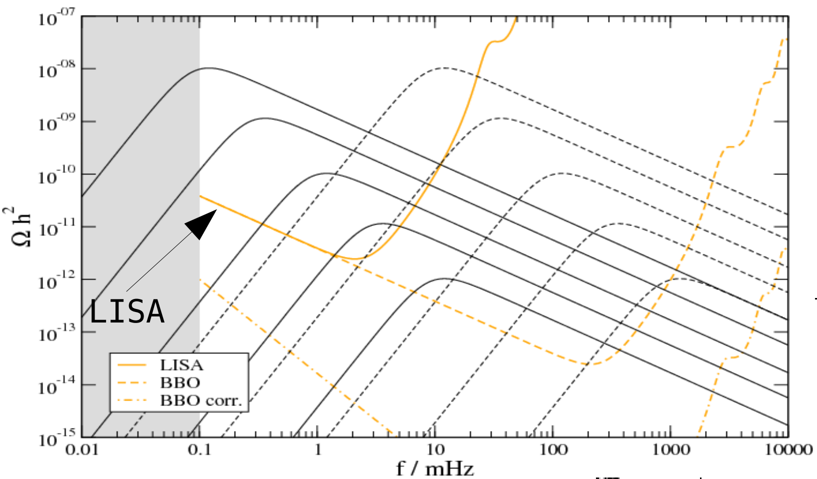
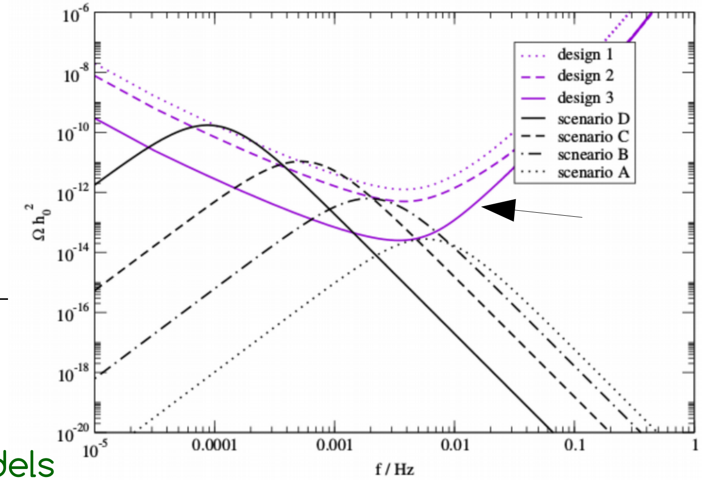
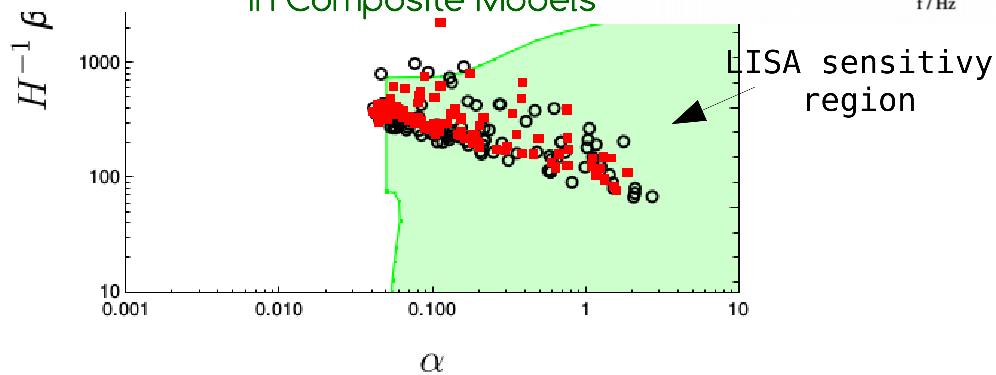
First order in Randall Sundrum



First order in SUSY



First order in Composite Models



Complementarity with the LHC

Nardini et al.'07
Konstandin et al.'10
Huber et al.'15
Chala et al.'16
(CosWG)Caprini et al.'16

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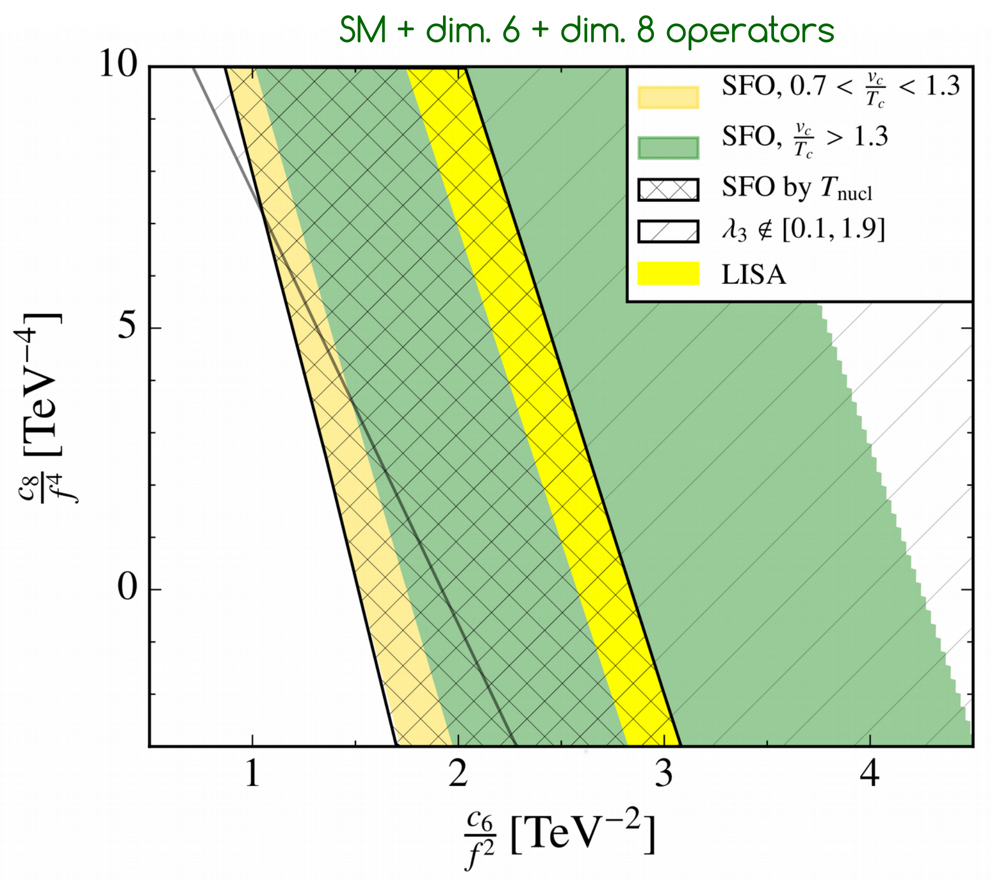
LISA can discover BSM physics in blind LHC regions.

Complementarity with FCC-ee



Signal reconstruction ?

- In LISA you can reconstruct the amplitude and power index of a SGWB with frequency dependence Adams and Cornish, '10, '13

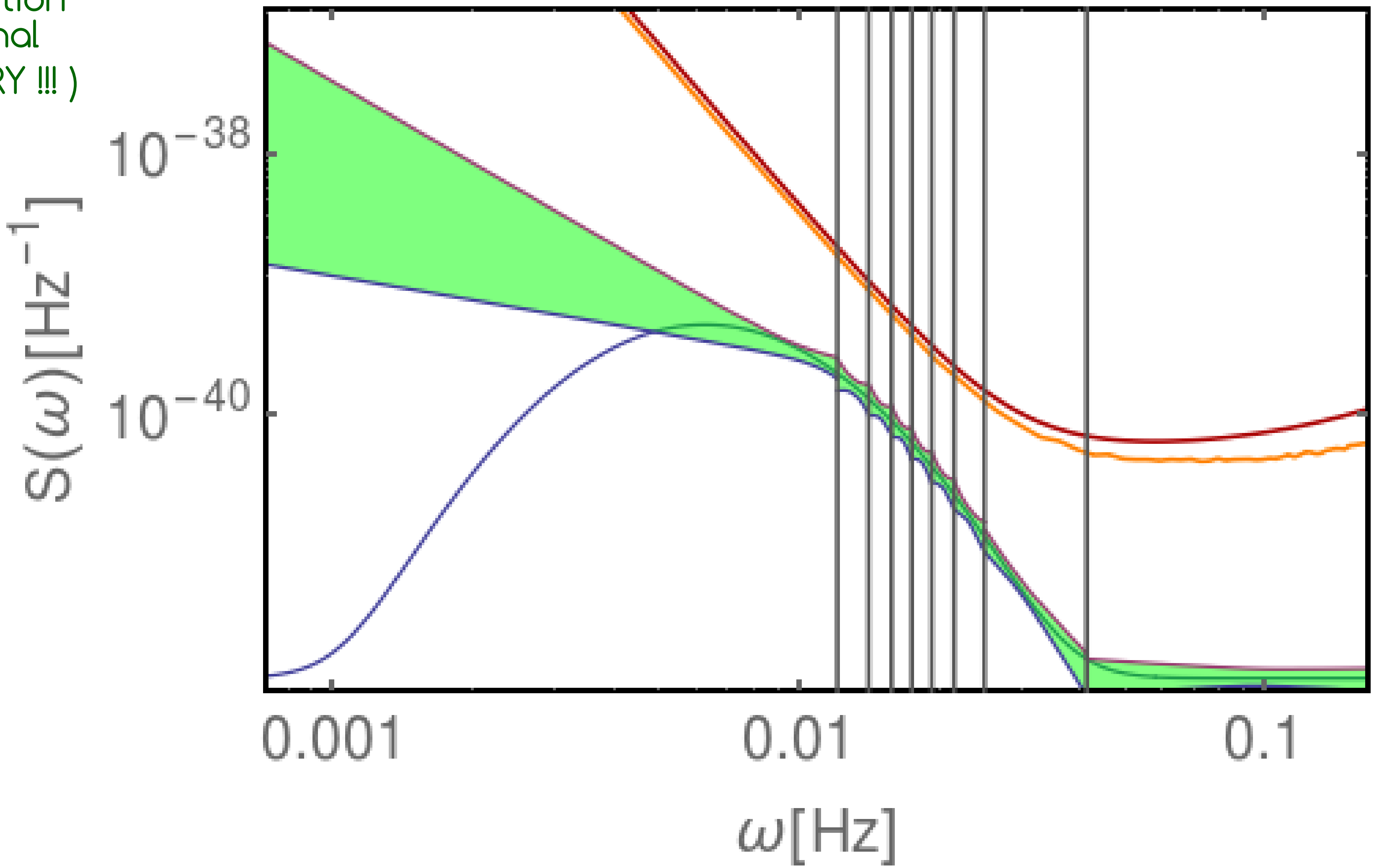
$$h^2\Omega_{GW} = \Omega_\alpha \left(\frac{f}{f_*}\right)^\alpha$$

- Thus, a signal with large enough SNR can be reconstructed in sub-regions of the LISA frequency band

- The signal is reconstructed as a series of power laws, for which of them the amplitude and power index are measured LISA CosWG, in progress

Signal reconstruction ? YES, EVEN IN WEIRED CASES!

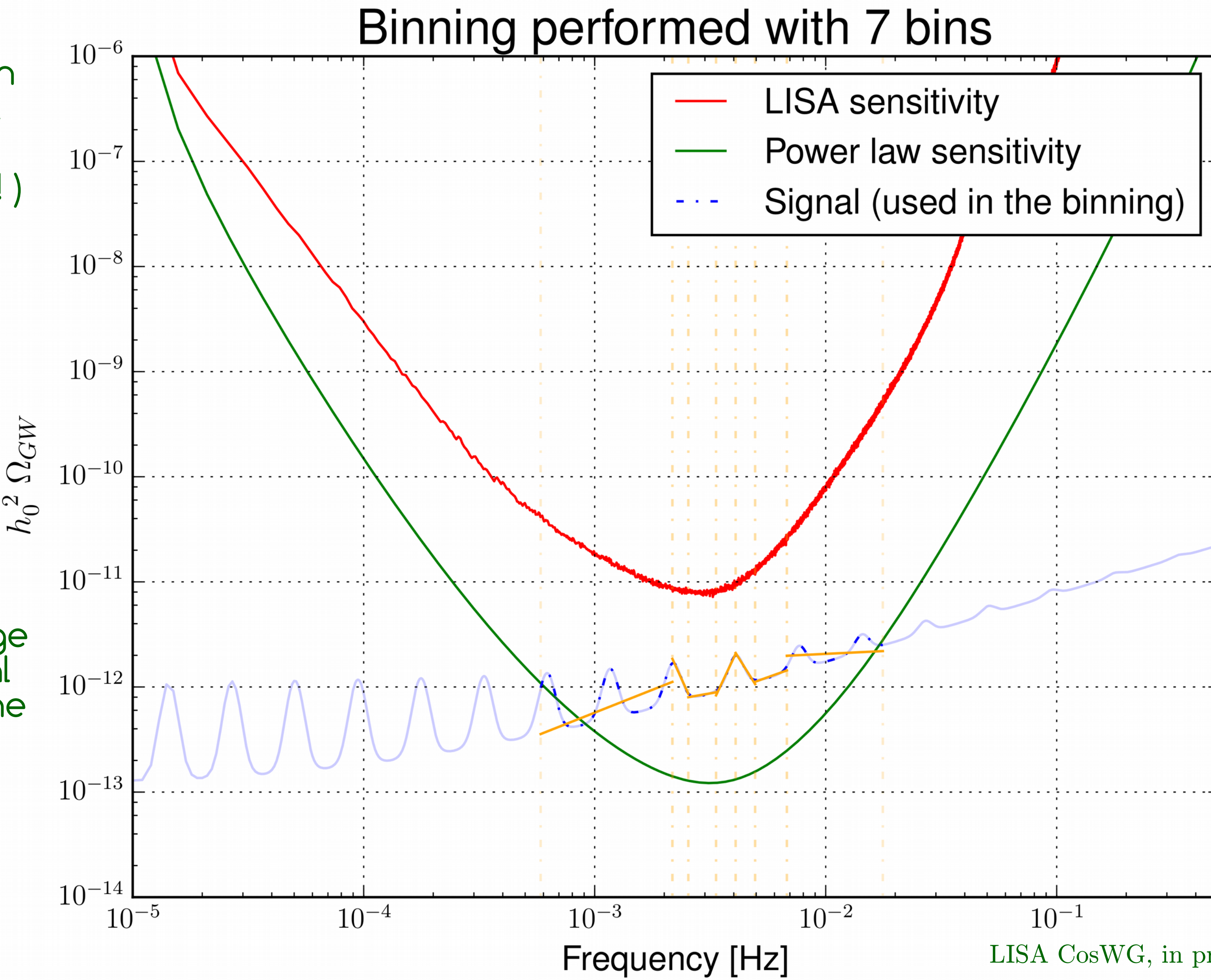
Reconstruction
bump signal
(PRELIMINARY !!!)



LISA CosWG, in progress

Signal reconstruction ? YES, EVEN IN WEIRED CASES!

Reconstruction weired signal (SKETCH & PRELIMINARY !!!)



Error bars large in the external bins, small in the internal ones

LISA CosWG, in progress

Conclusions

> GW experiments are starting detecting physics never tested before

> GW observatories have a big potential to test cosmology and 1st-order PTs

> LISA is particularly sensitive to the EW scale

> There are well-motivated models exhibiting 1st – order PTs involving new physics at roughly 10 GeV – 1 TeV with GW signatures in the LISA sensitivity region

> In some scenarios the 1st – order PT spectrum allows multi-experiment detection

> LISA can be complementary to the LHC or future colliders

> LISA can reconstruct the frequency shape of the signal and, in turn, essential features of the particle physics model sourcing it.