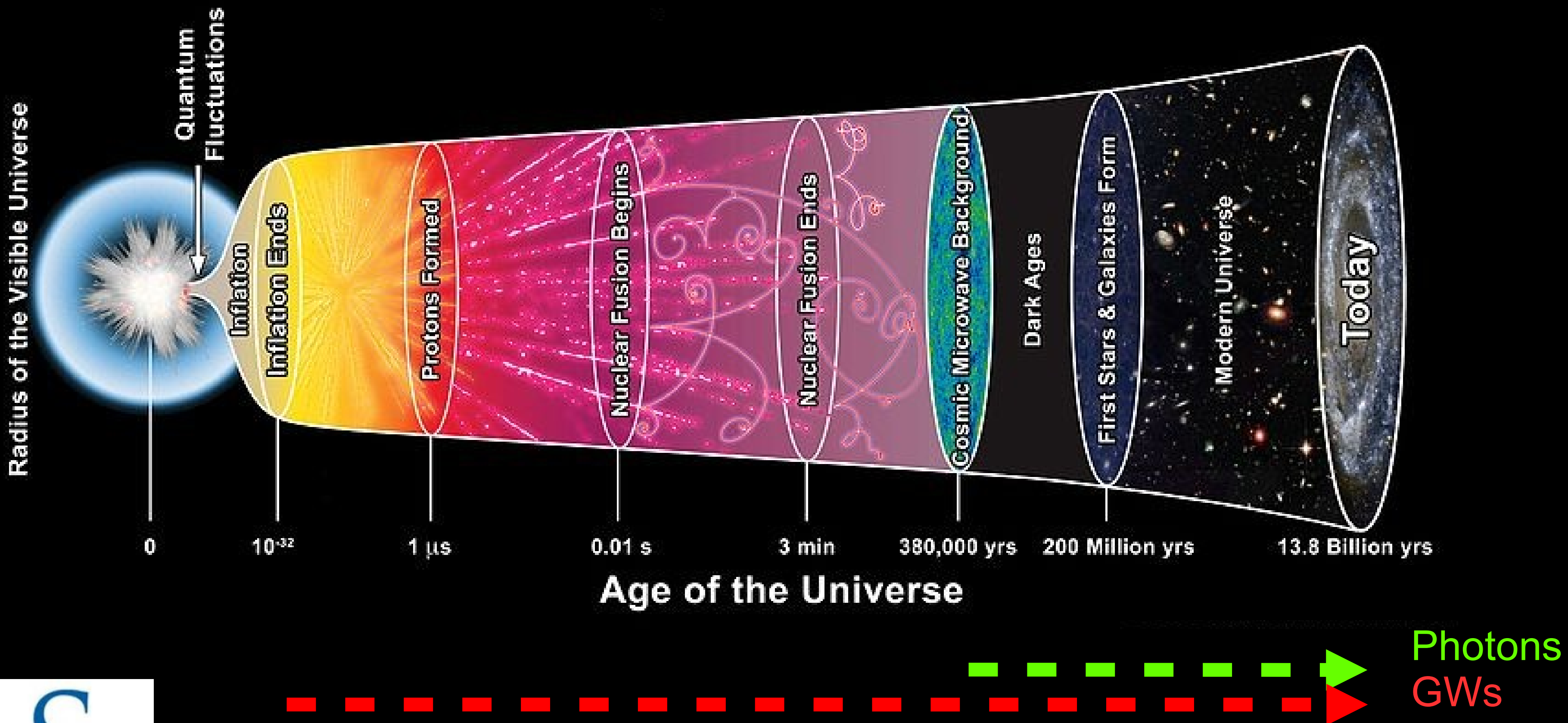
Stochastic GW Background: the need for a multifaceted approach

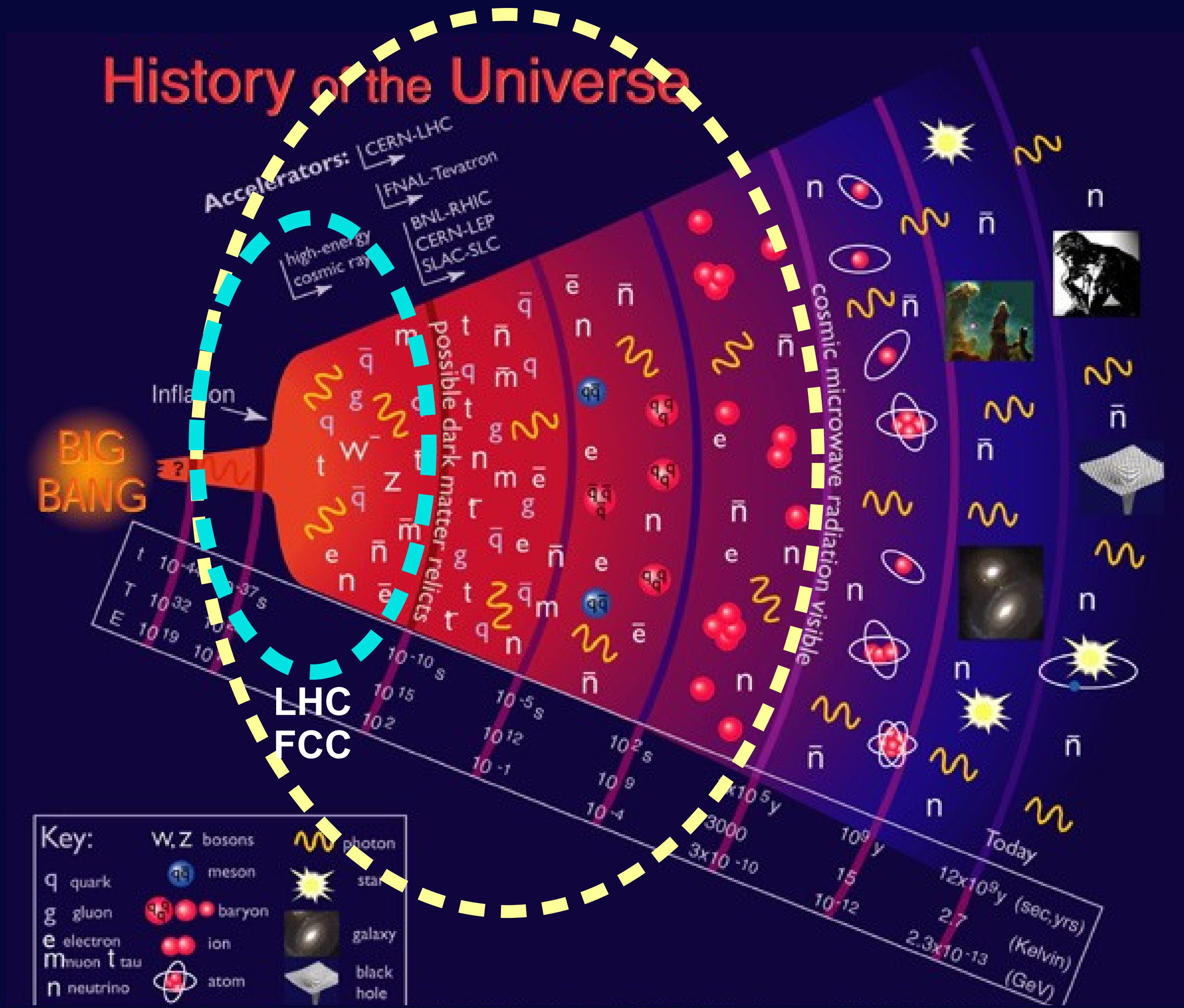
GWmess2021



Germano Nardini
(University of Stavanger)

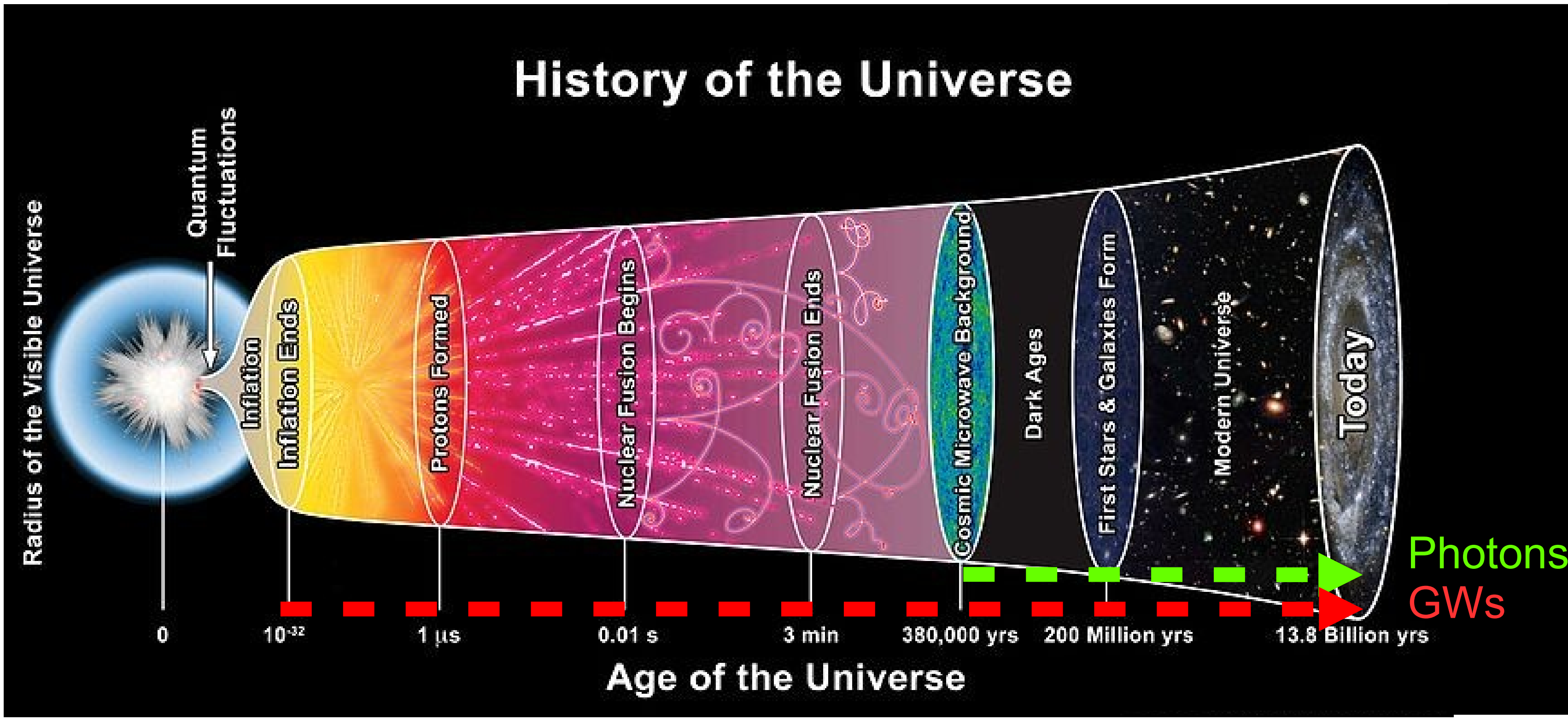
Universitetet i Stavanger

Early Universe: stochastic GW background



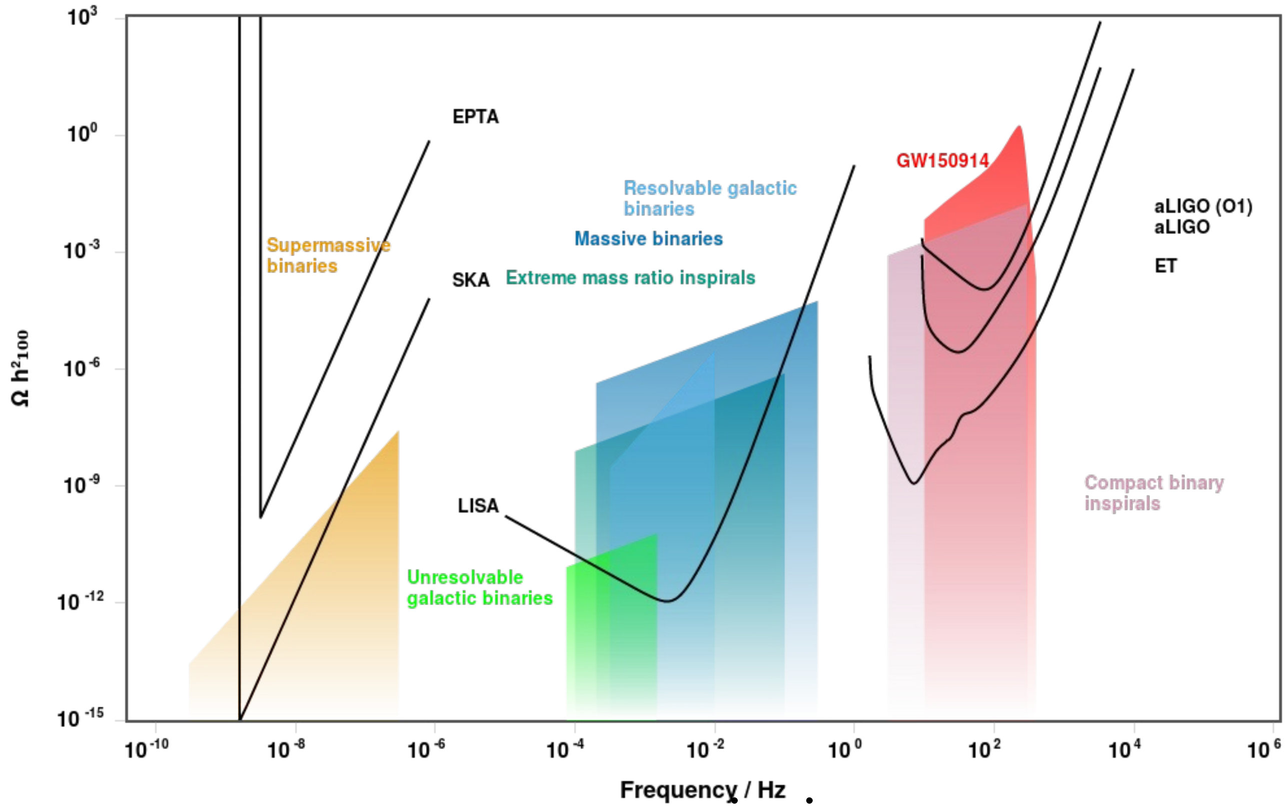
Early Universe: stochastic GW background

- 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



Stochastic GW Background

- SGWB: the superposition of the sources that cannot be resolved individually
- SGWB components:
  - late-universe sources
  - signals from early universe



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 too weak, or too close one each other to be resolved)
  - signals from early universe

- Astrophyisical examples in LISA:
  - Unresolvable galactic binaries (non-isotropic!)
  - "Stellar origin" black hole binaries
  - Maybe neutron stars binaries, EMRI, uncertain binary populations
- Cosmological / particle physics examples in LISA:
  - Inflationary processes
  - Cosmic strings
  - Primordial black holes
  - Superradiance
  - Cosmological 1st-order phase transitions

Outline

Why a first-order phase transition (FOPT) ?

FOPT GW signature

What is a FOPT ?

Collider signatures ?

Detection at LISA ?

Why and how this asymmetry ?

In the Universe there is more matter than antimatter.

Antiproton abundance compatible with secondary production.

BBN and CMB analyses yield an extreme number:

$$\boxed{Y_{\Delta B} \equiv \left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = (8.75 \pm 0.23) \times 10^{-11}}$$

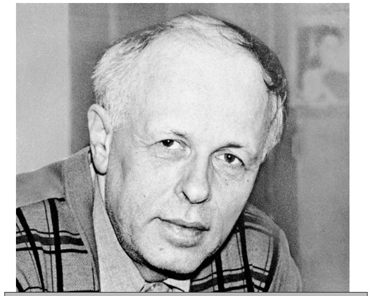
Why this number ???

Why and how this asymmetry ?

In general, it is possible to produce the baryon asymmetry by means of a mechanism providing the Sakharov conditions

A. Sakharov '67

- B violation
- C and CP violation
- Departure from thermal equilibrium



A. Sakarov
Nobel Prize '75…
… for Peace

The SM contains the Sakharov conditions:

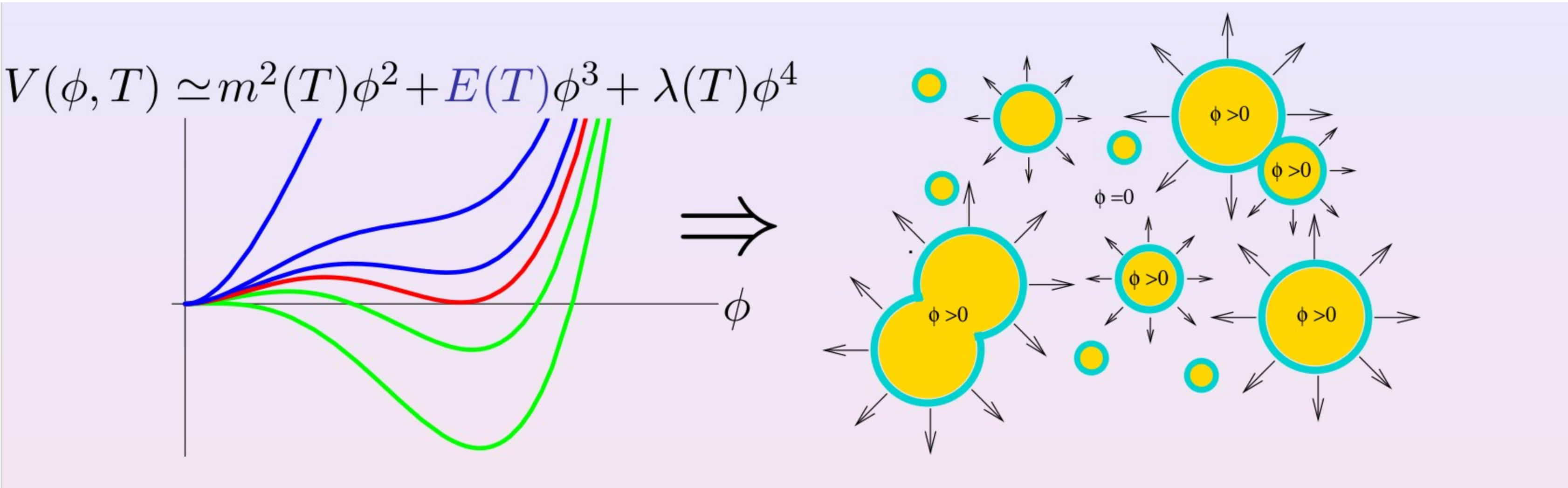
- B number is violated by non-perturbative processes at finite T (sphalerons)
- CKM matrix contains the CP violation phases
- **If the EW phase transition is of strongly first order**, it proceeds via bubble nucleations whose expansion break the thermal equilibrium

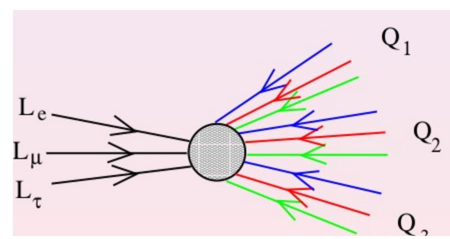
This mechanism is called ELECTROWEAK BARYOGENESIS
(other options: leptogenesis, ….)

Kuzmin, Rubakov and Shaposhinoov, '94

Quiros '99, Riotto '98, Cline '06, Morrissey,Ramsey-Musolf '12

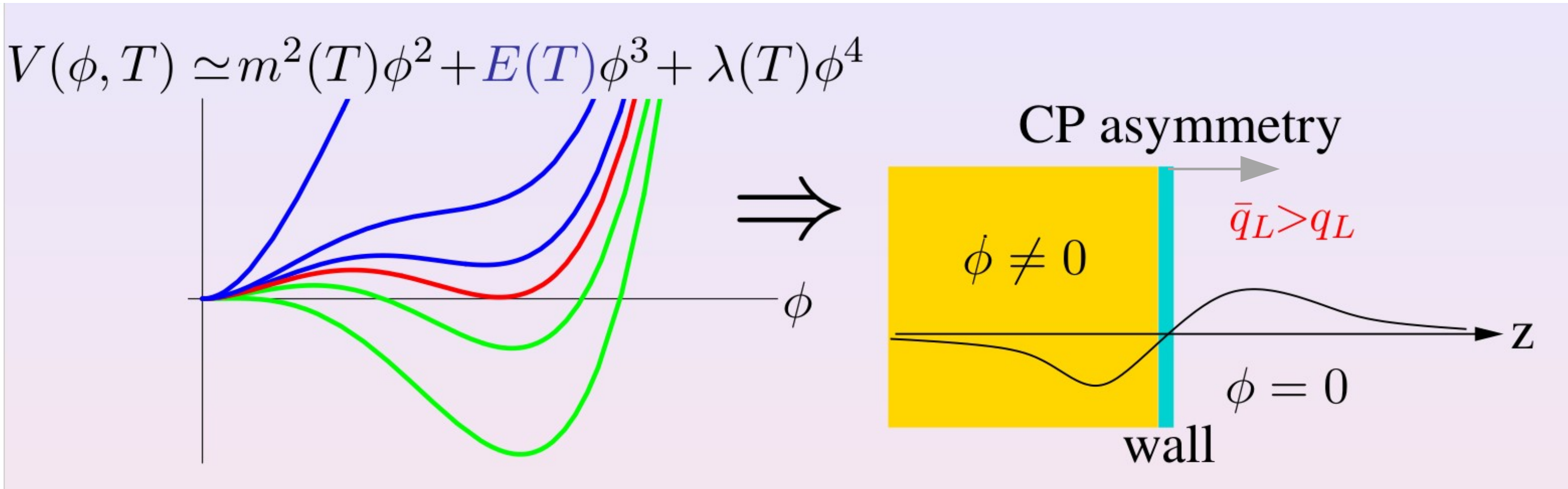
First-order EW phase transition and EW baryogenesis

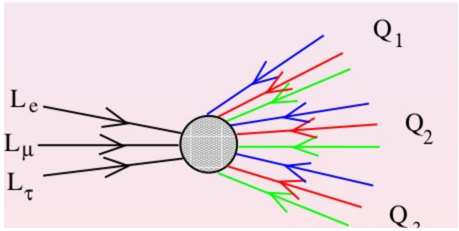




sphaleron

First-order EW phase transition and EW baryogenesis



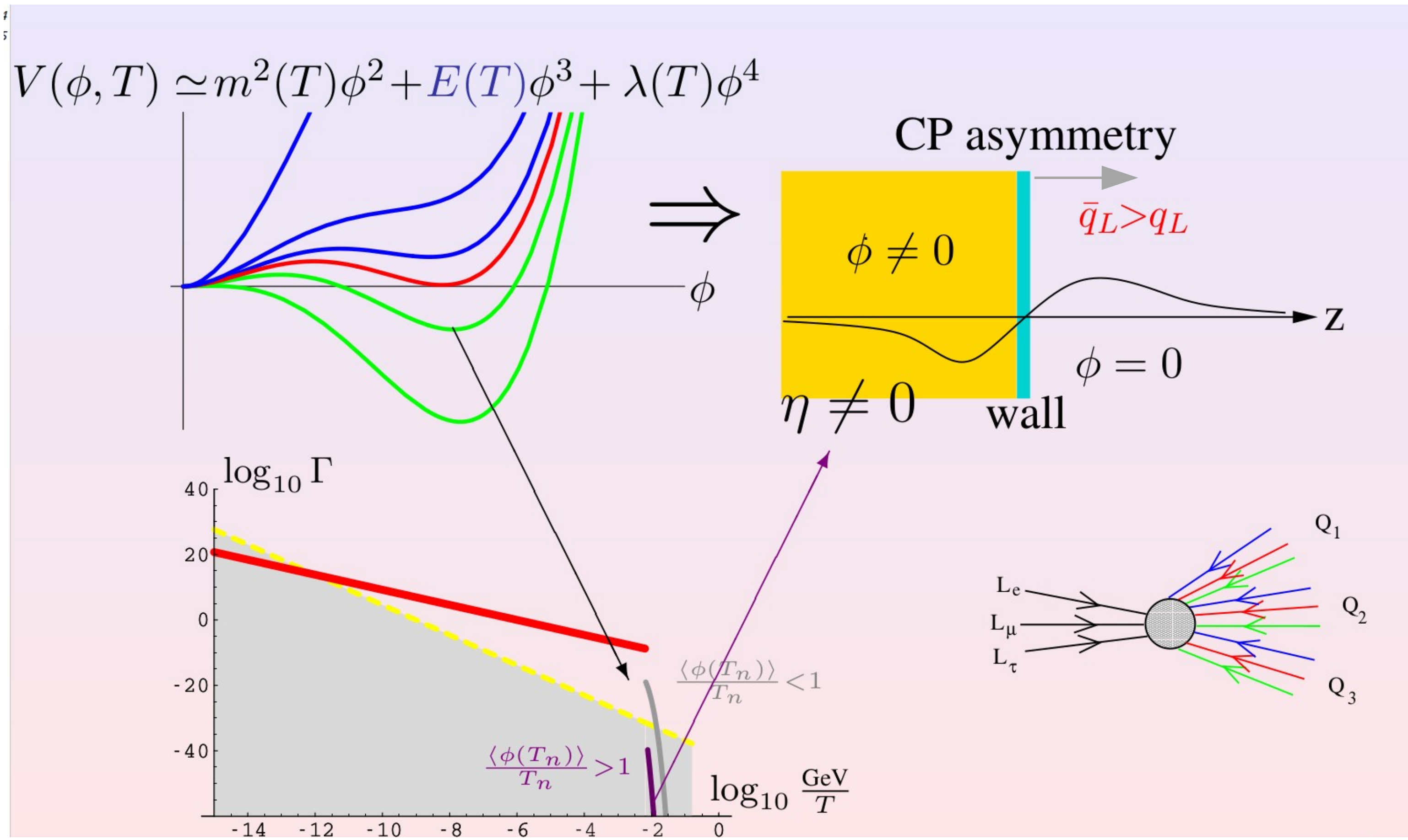


sphaleron

In front of the wall, the CP asymm. temporally induces $\bar{q}_L > q_L$

- There are more sphalerons killing $\bar{q}_L$ than killing q_L , converting CP asymm. into B asymm.
- Temporally, a B asymm. is present in front of the wall
- The expanding wall goes through it and incorporates it inside, where ...

First-order EW phase transition and EW baryogenesis



The sphalerons inside the bubbles do not wash out the accumulated B asymmetry if the ELECTROWEAK TRANSITION IS OF FIRST ORDER and STRONG

Remark: if the bubbles expand super fast, $v_w \simeq c$, the rates have no time to “feel” the CP-violating barrier

First-order EW phase transition and SGWB

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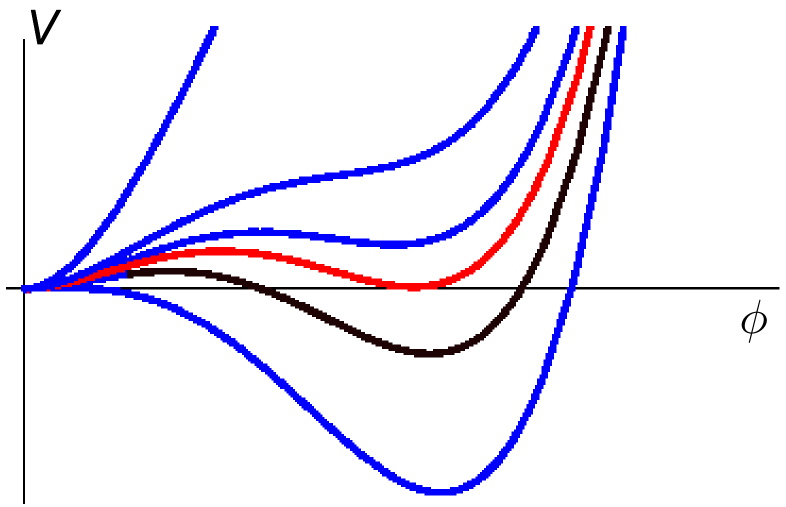
- Let us assume that the EWPT is of first order, i.e.



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

- 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. 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.

First-order EW phase transition and SGWB

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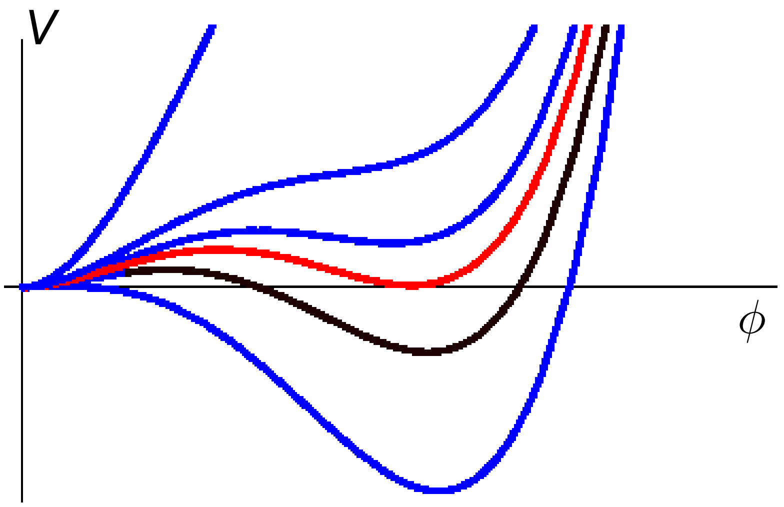


$$V(\phi,T) \approx D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \lambda(T)\phi^4$$

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

Witten '84
Kamionkowski et al., '94

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

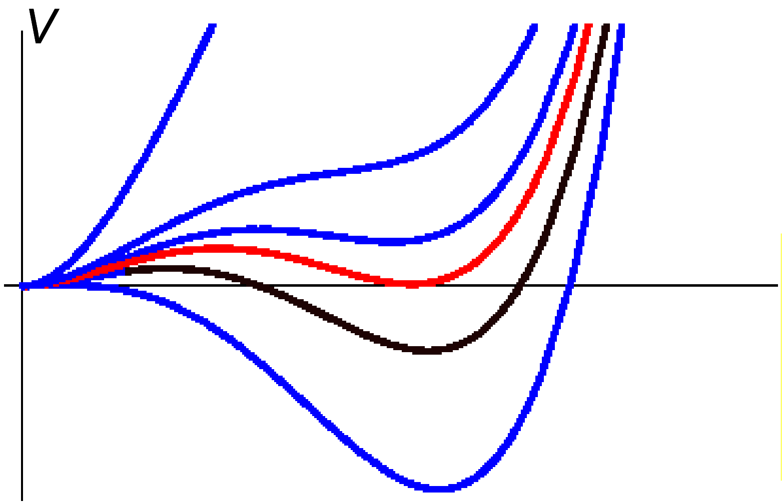
- This available energy is related to

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

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

First-order EW phase transition and SGWB

> When the transition is of first order...



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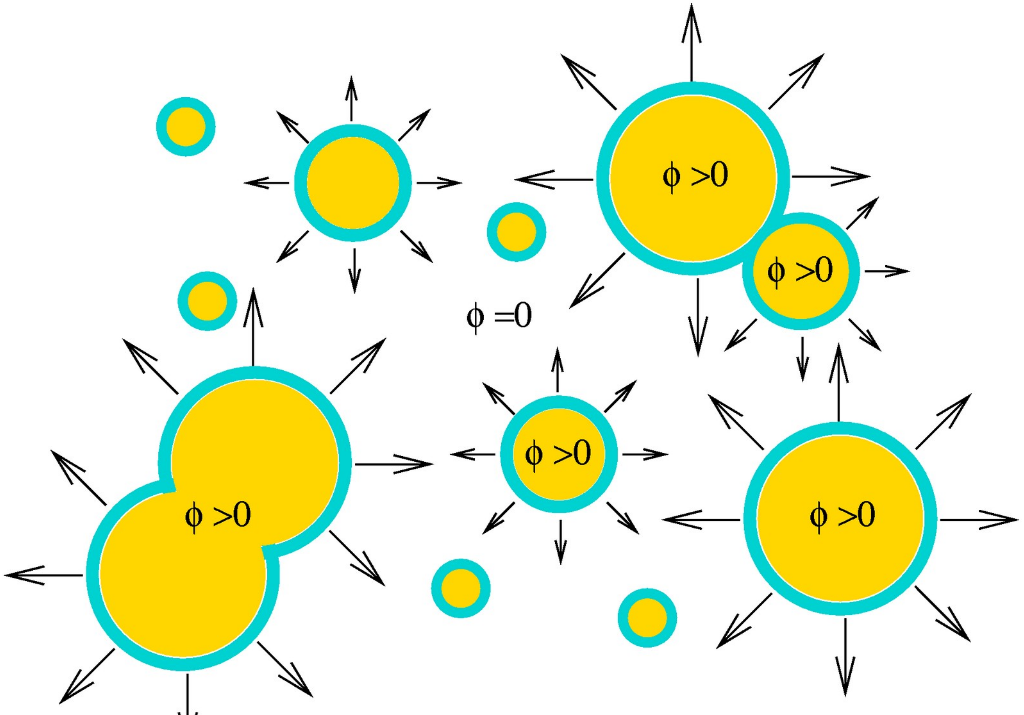
$\alpha(T_n)$: ~normalized difference btw. the minima

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



First-order EW phase transition and SGWB

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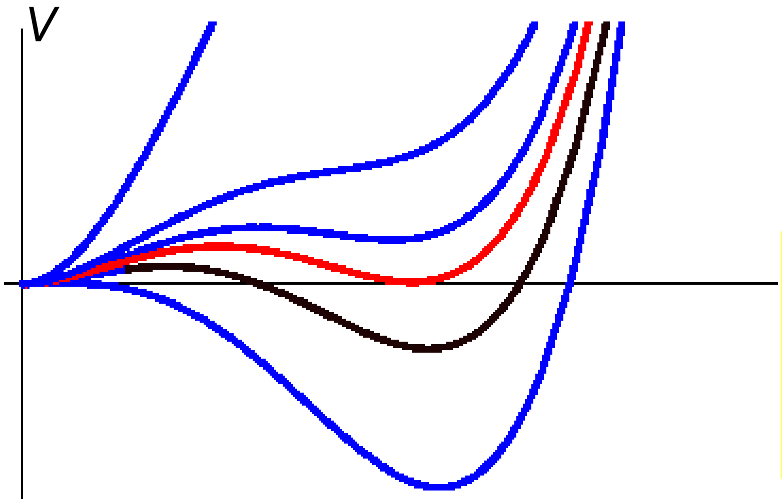

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$\alpha(T_n)$: ~normalized difference btw. the minima

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

$\alpha(T_n)\ large$: large supercooling, thus large amount of energy can go into GWs

$\beta(T_n)/H\ large$: many bubbles, thus high frequency of collisions

Gravitational Wave Signal

Approximate the spectrum as a linear combination of the sources

$$h^2\Omega_{\rm GW} \simeq h^2\Omega_\phi + h^2\Omega_{\rm sw} + h^2\Omega_{\rm turb}\ ,$$

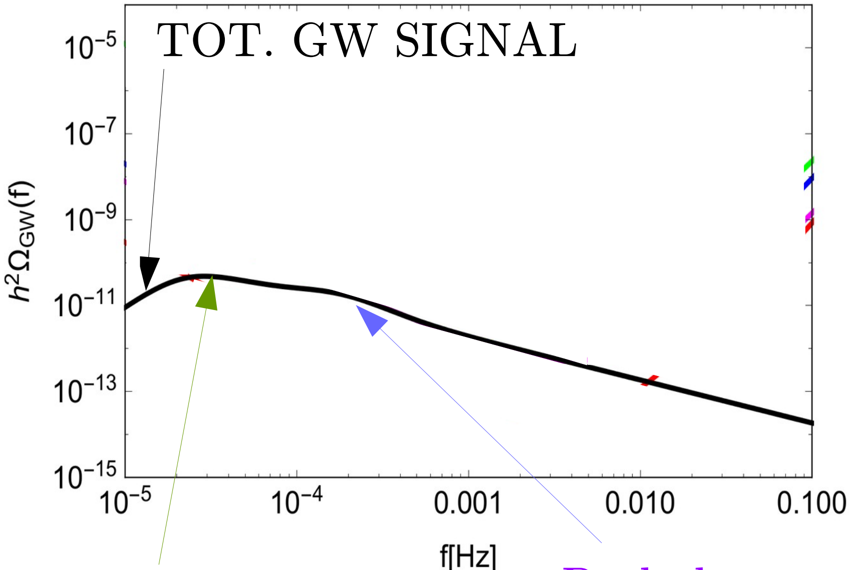
Ω_ϕ : from the motion of the Higgs profile

$\Omega_{\rm sw}$: from the coherent motion of the plasma

$\Omega_{\rm turb}$: from the turbulent motion of the plasma

Gravitational Wave Signal

C.Caprini, ... GN ... [LISA CosWG] '16, '20



Peak due to
SOUND WAVES
CONTRIBUTION

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

Peak due to
TURBULENCE
CONTRIBUTION

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

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

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

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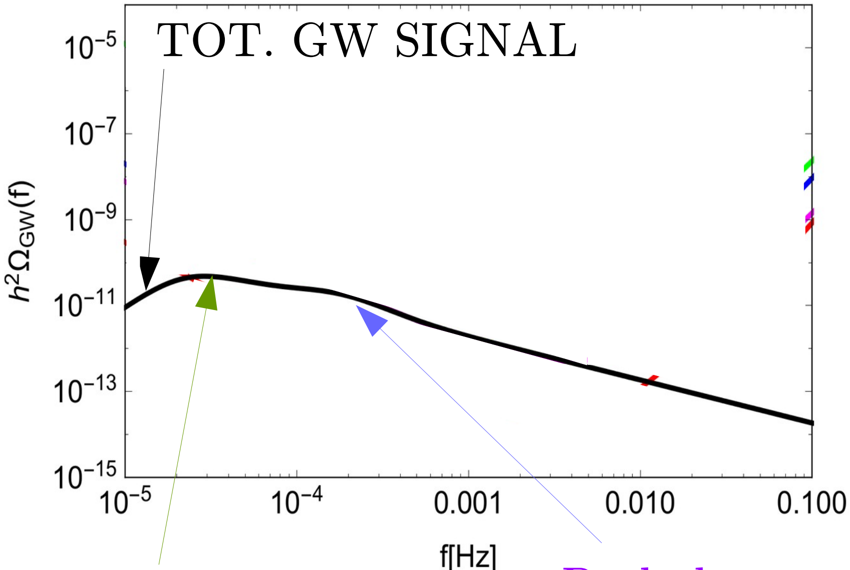

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Gravitational Wave Signal

Recipe for the standard model builder:

- Calculate $\alpha(T_n)$, $\beta/H(T_n)$, T_n (or T_{rh})
- Estimate/guess v_w

Reasonable guess in SM-like plasma:

Ultrarelativistic velocity is achieved when $\alpha > \frac{30}{24\pi^2} \frac{\sum_a c_a \Delta m_a^2(\phi_*)}{g_* T_*^2}$,

Bodeker, Moore ’08, ‘17

SGWB vs Baryogenesis

- Several studies to make the prediction more accurate are planned
- Usage of the predictions is becoming less and less straightforward
- Tool for the signal in LISA, assuming negligible turbulence:
  http://www.ptplot.org/ptplot/single (David Weir)

$v_\mathrm{w} = 1.0,\ \alpha_\theta = 0.5,\ \beta/H_* = 10.0,\ g_* = 100.0,\ T_* = 200.0\,\mathrm{GeV}.$

$v_\mathrm{w} = 0.1,\ \alpha_\theta = 0.5,\ \beta/H_* = 10.0,\ g_* = 100.0,\ T_* = 200.0\,\mathrm{GeV}.$

$v_\mathrm{w} = 0.01,\ \alpha_\theta = 0.5,\ \beta/H_* = 10.0,\ g_* = 100.0,\ T_* = 200.0\,\mathrm{GeV}.$

SNR = ??? SNR = ??? SNR = ???

Omega_peak = ??? Omega_peak = ??? Omega_peak = ???

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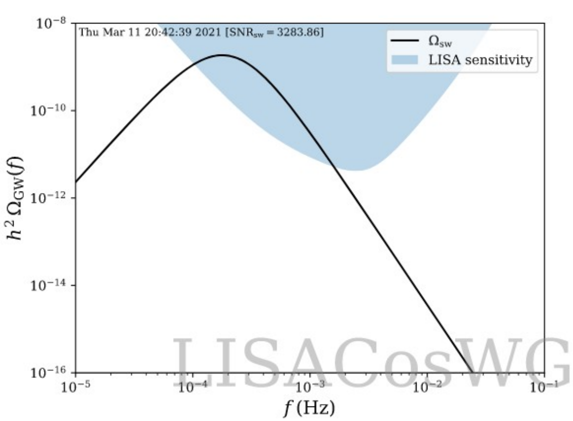

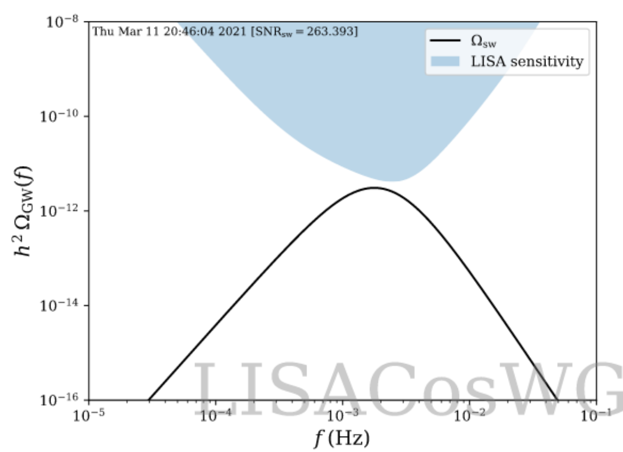

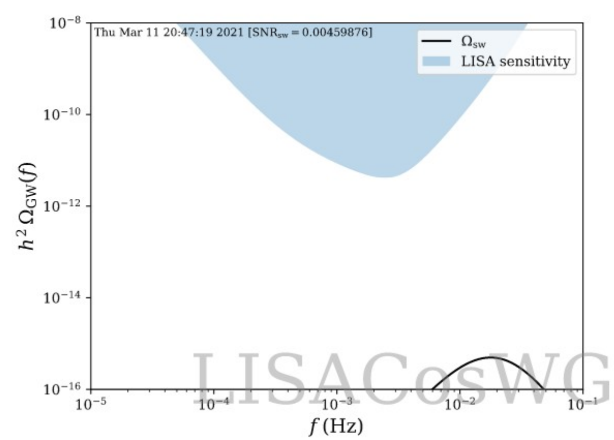

SGWB vs Baryogenesis

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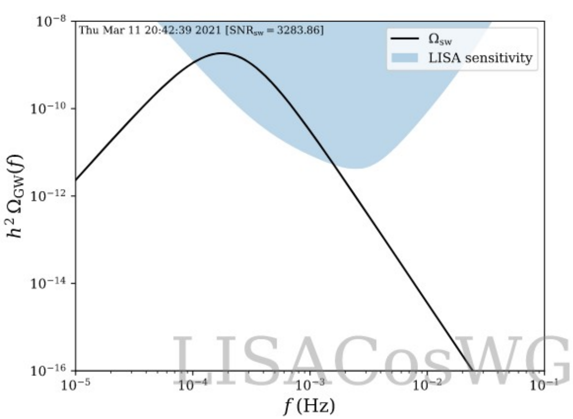
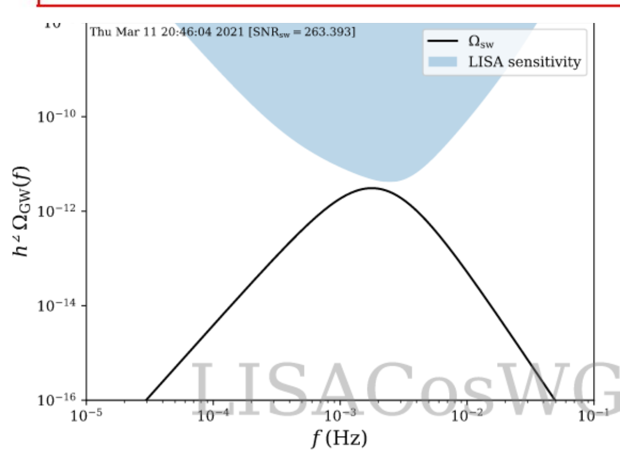
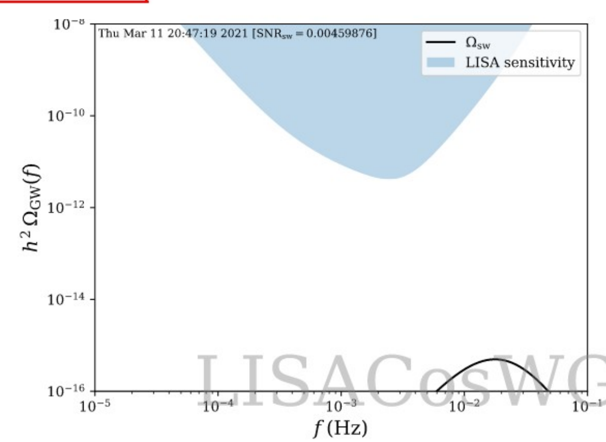
Good detection, high signal-to-noise ratio :

$$\boxed{\mathrm{SNR} = \sqrt{T \int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_n(f)} \right)^2}}$$







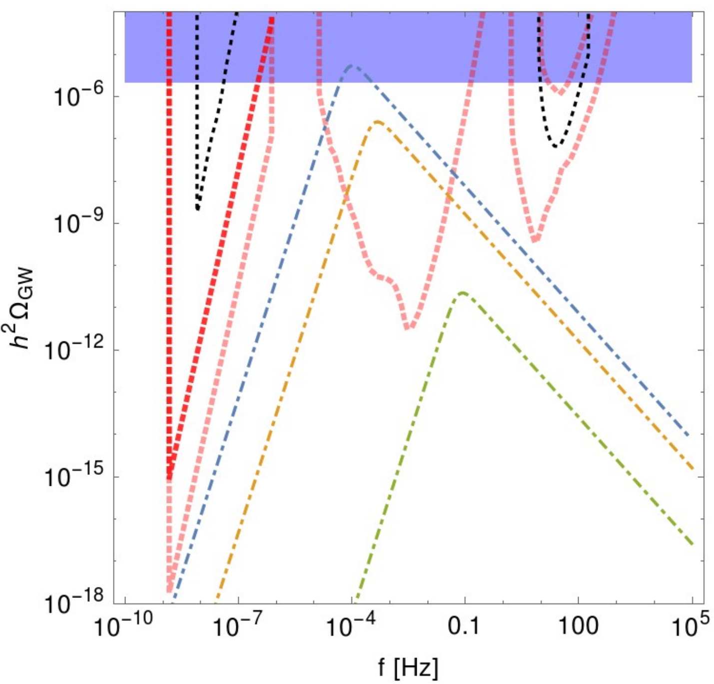
SGWB multiband

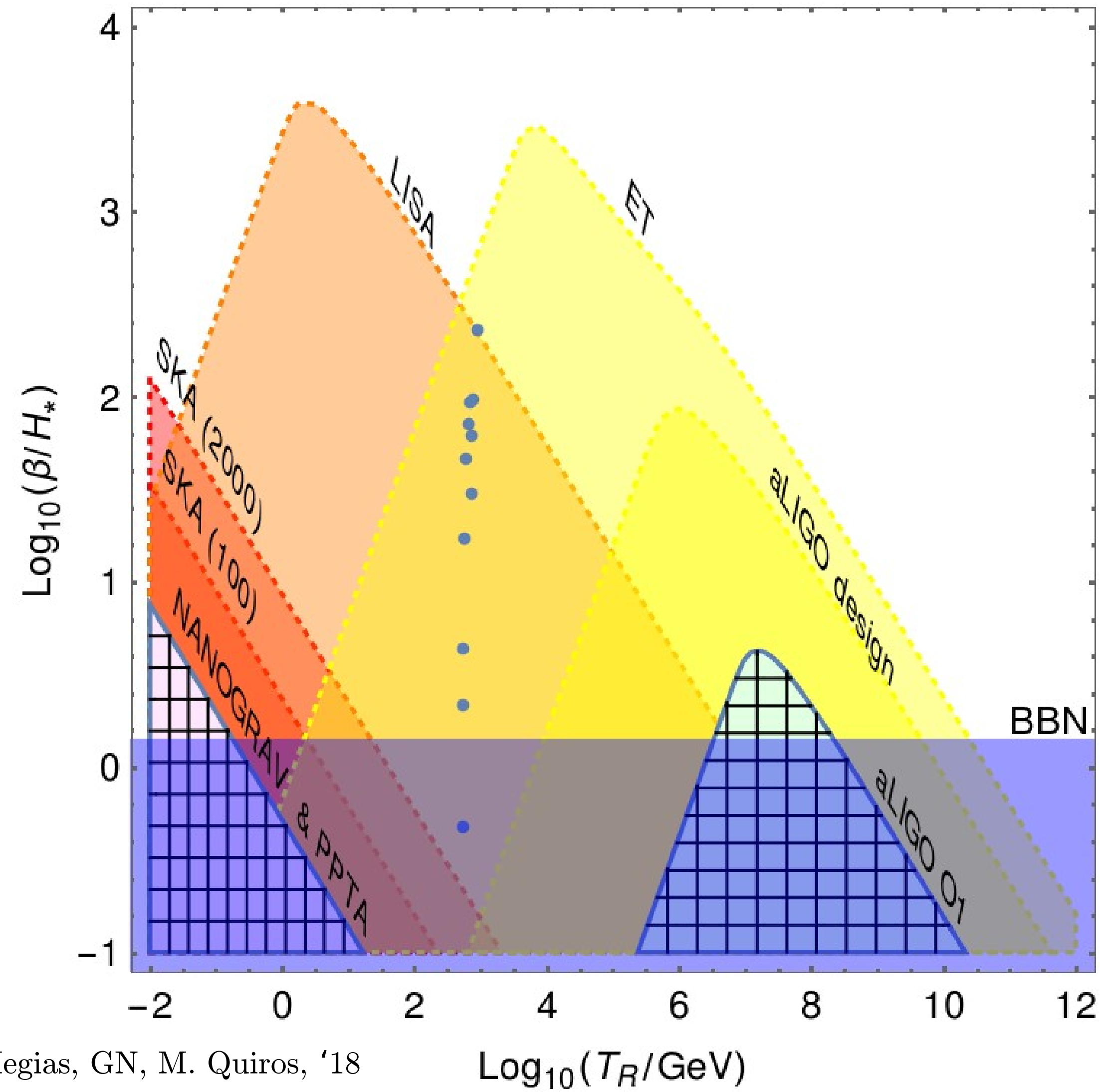
(w/o plasma;alpha >> 1)

Using the "without plasma" result (i.e. underestimating the spectrum typically)

$$\boxed{\mathrm{SNR} = \sqrt{T \int_{f_{\min}}^{f_{\max}} df \left(\frac{\Omega_{\mathrm{GW}}(f)}{\Omega_n(f)} \right)^2}}$$

$$\boxed{\begin{aligned} g_* &= 100 \\ v_w &= 0.95 \end{aligned}}$$





E. Megias, GN, M. Quiros, '18

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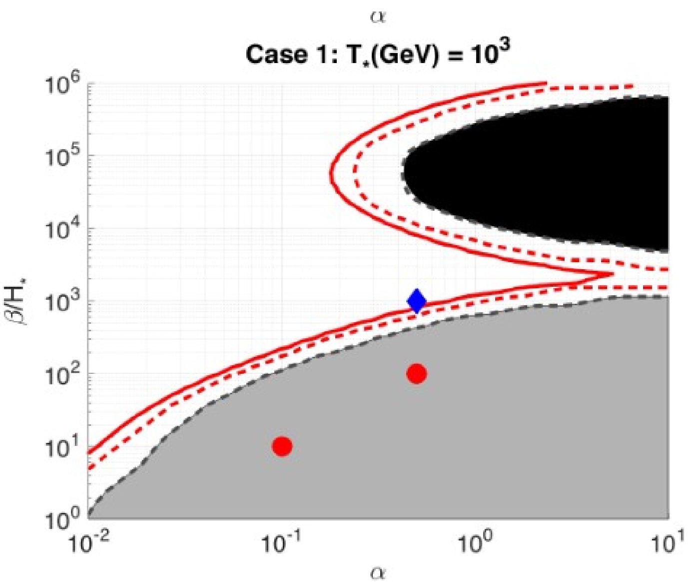
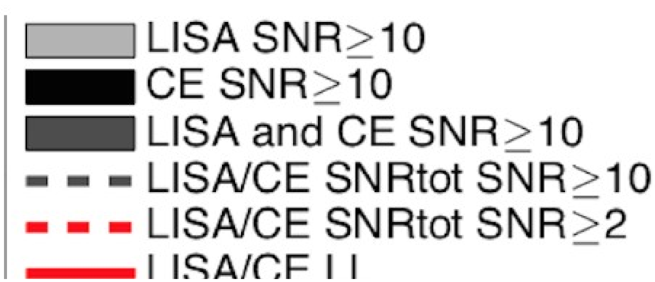
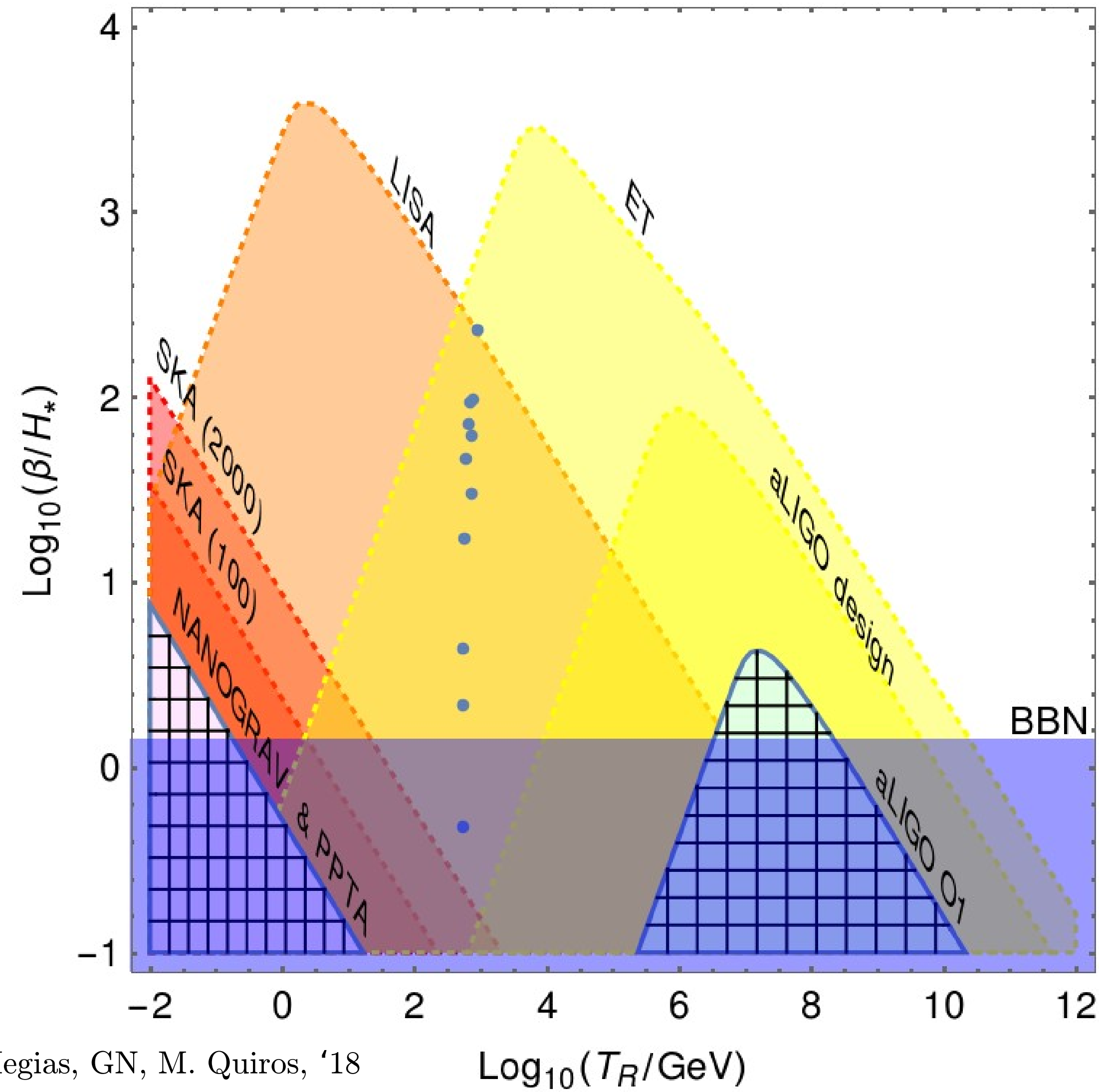


Axen, Banagiri, Matas, Caprini, Mandic ‘18





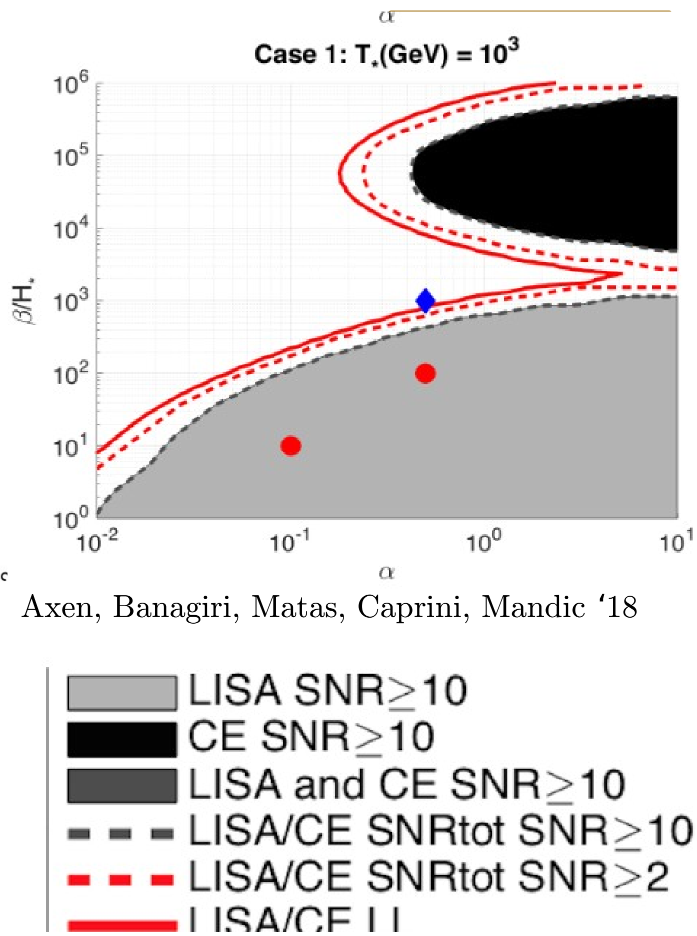
E. Megias, GN, M. Quiros, ‘18

1st-Order PT vs. GW detectors (w/o turb. or sound waves; alpha >> 1)

- Using the “without plasma” result (i.e. underestimating the spectrum typically)

ELECTROWEAK PHASE TRANSITION

OTHER PHASE TRANSITION



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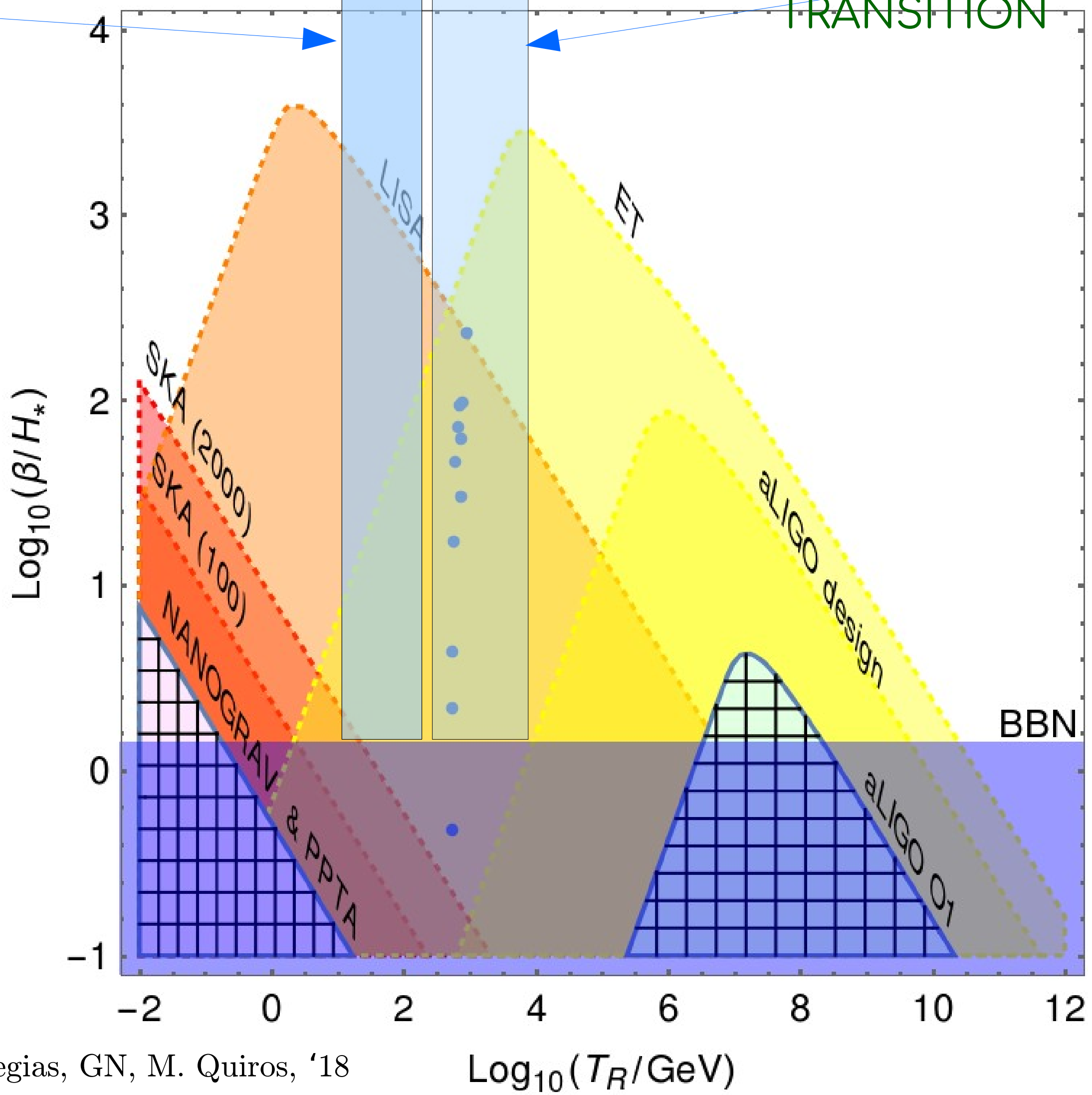
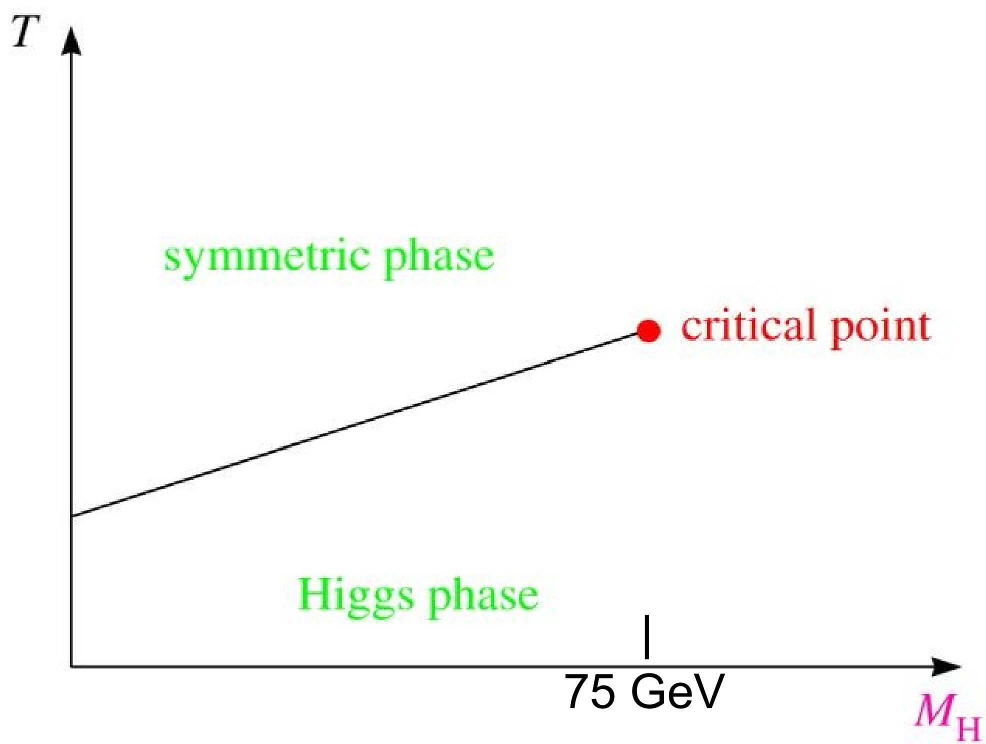


E. Megias, GN, M. Quiros, ‘18

From GWs to Particle Physics

- LISA sensitive to 1st order PTs of *1 GeV– 1000 TeV* scale physics
- SKA+LISA+ET sensitive to 1st order PTs of *1 MeV– 1000 PeV* scale physics
- The SM of particle physics predicts that no strong phase transitions ever occurred
- If we detect GWs from strong phase transitions, we have discovered BSM physics



Kajantie,Laine,Rummukainen,Shaposhnikov, ’96;
Karsh,Neuhaus,Patkos ’96; Csikor,Fodor,Hietger ’98;
D’Onofrio, Rummukainen, Tranberg, ‘14.

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- Synergy among LHC, FCC and GW observatories, in particular LISA !

Questions about LISA and LHC physics (focussing on the EWPT)

1) Any SM extension with signatures at LISA that overcomes the current LHC bounds?

2) Can LISA discover BSM physics earlier than colliders ?

Model building for SGWB

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

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

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

$$V_{tree}(h,\phi_1,\dots) = m_1^2 h^2 + m_2^2 \phi_1^2 + \dots$$

$$\Delta V_{1\ell}(h,\phi_1,\dots) = \Delta V_{1\ell,T=0}(h,\phi_1,\dots) + V_{1\ell,T\neq 0}(h,\phi_1,\dots)$$

$$\Delta V_{1\ell,T=0} = \sum_{i=h,G,W,Z,t,\dots} \frac{n_i\, m_i^4(h,\phi_1,\dots)}{64\pi^2}\left(\log\frac{m_i^2(h,\phi_1,\dots)}{v^2} - C_i\right) \;,$$

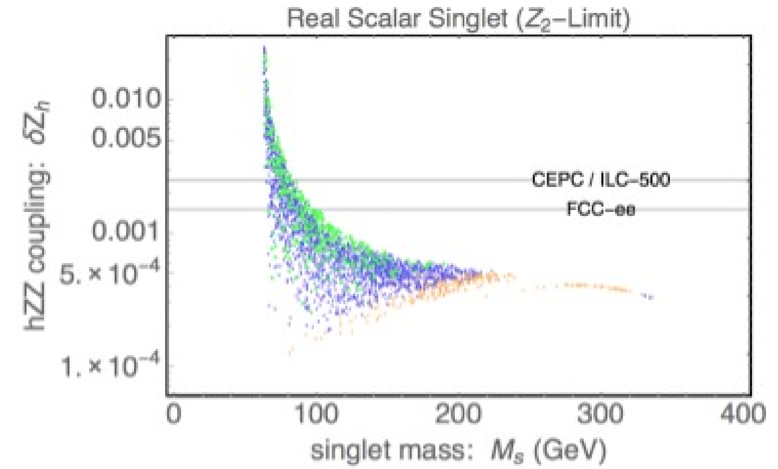
$$V_{1\ell,T\neq 0} = \sum_{i=t,b,\dots} \frac{n_t\, T^4}{2\pi^2} J_f\left(\frac{m_i^2(h,\phi_1,\dots)}{T^2}\right) + \sum_{i=h,W,Z,\dots} \frac{n_i\, T^4}{2\pi^2} J_b\left(\frac{m_i^2(h,\phi_1,\dots)}{T^2}\right)$$

Some rationales:

- New color fields → Large T effects but also Higgs gluon fusion changes
- New dynamical scalar fields → Mixing → Higgs signal strengths
- New fermions → no large T-effects (read: no barrier → no 1st order)
- Very heavy fields → Boltzmann suppressed and small low-energy effects

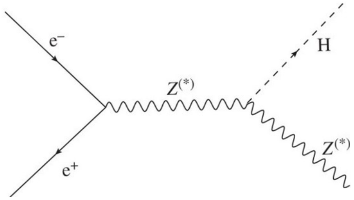
Model building for SGWB

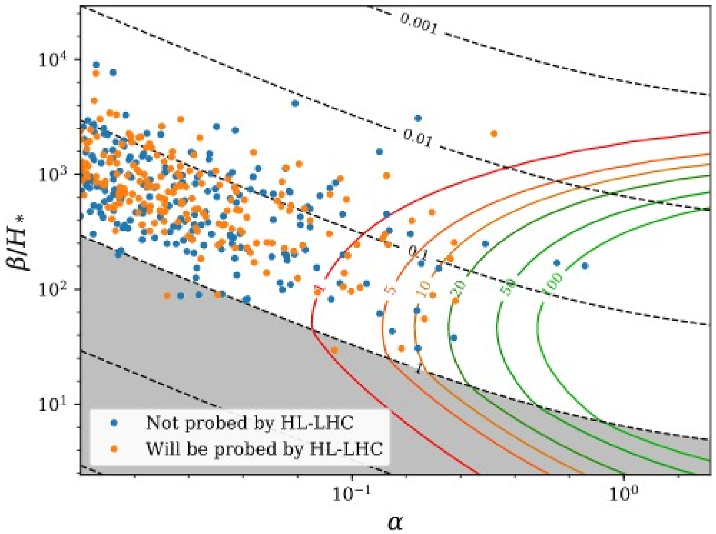
C.Caprini, … GN et al. [LISA CosWG] ’16, ’20

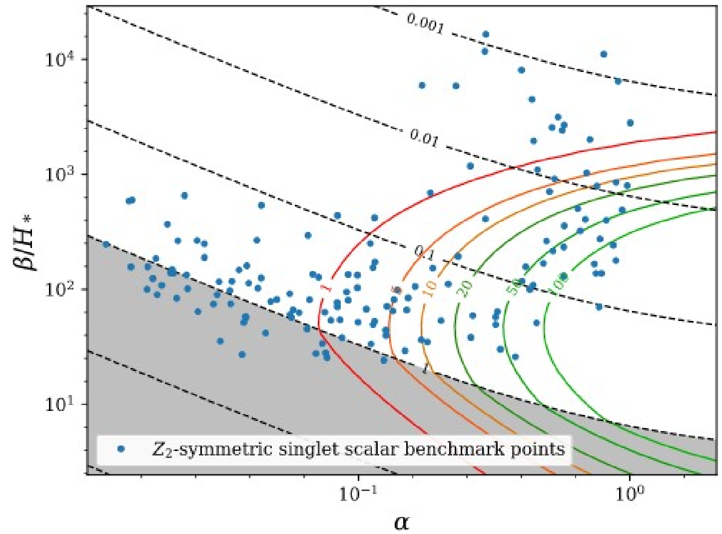


Singlet extension of the SM with

- small mixing 0.1 (orange, left)
- tiny mixing 0.01 (blue, left)
- zero mixing 0 (right)

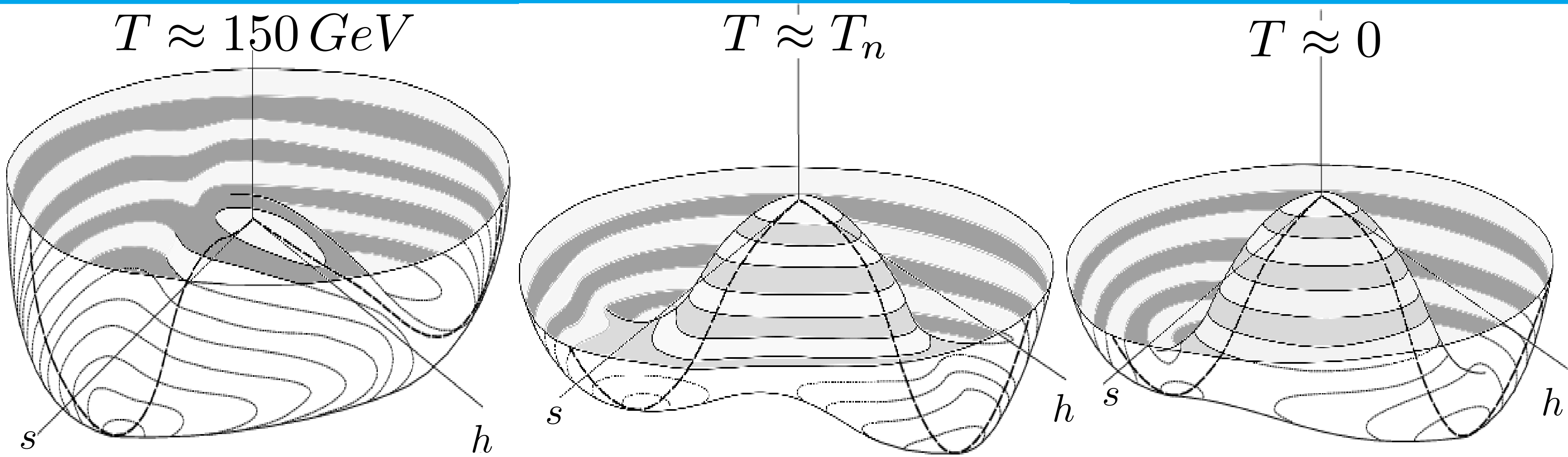






Scenario non-testable at the LHC

Model building for SGWB (Z$_2$ singlet idea)



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

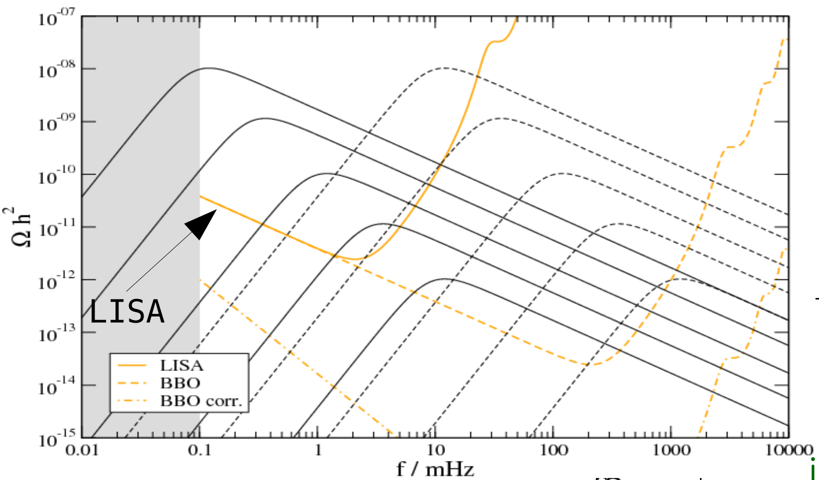
- Singlets as new dynamical scalars hard to detect
- Z_2 symmetry to avoid mixing.
- No extra Higgs invisible width if heavier than 63 GeV.

Model building for SGWB

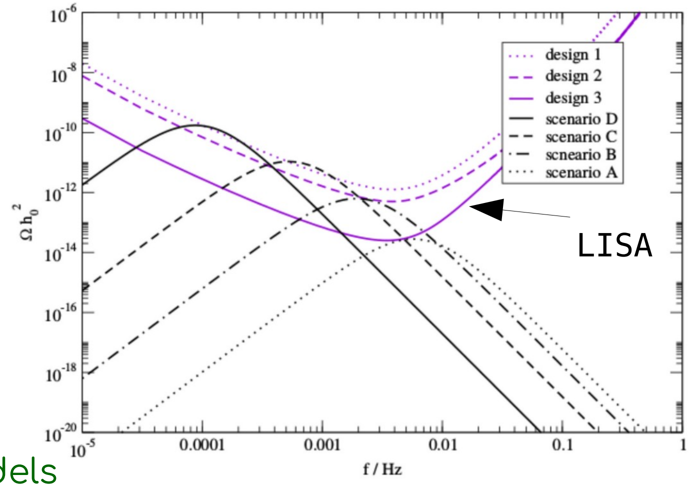
C.Caprini, ... GN et al. [LISA CosWG] '16, '20

- Examples of UV-motivated setups exhibiting a detectable first-order phase transition:

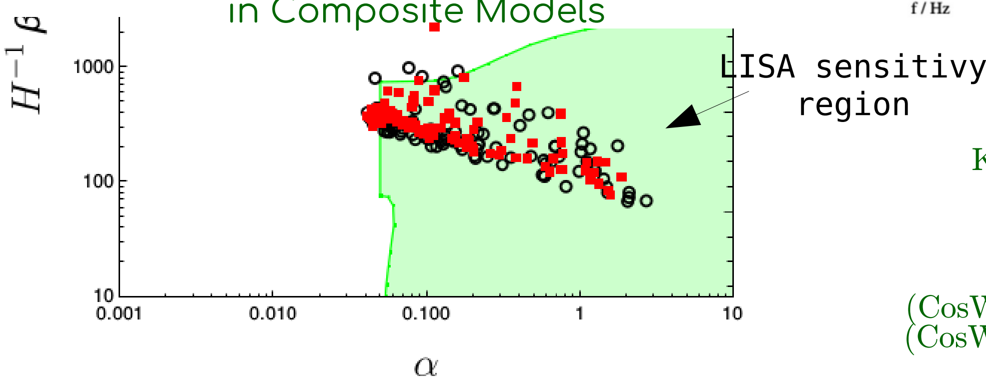
First order in Randall Sundrum



First order in SUSY



First order
in Composite Models



Complementarity with the LHC

Figs. from:
Konstandin, GN et al.'10
Huber, GN et al.'15
Chala, GN et al.'16

More examples in:
(CosWG)Caprini, GNet al.'16
(CosWG)Caprin, GN et al.'20

SGWB reconstruction prospects: PT and more (some considerations)

Some ideas in Rjusuke et al '17, Croon et al '18

- GW observables contain rich information about fundamental physics
- The freq. shape of the SGWB sourced by 1st order transitions depends on some "effective thermodynamics" parameters
- How well can we reconstruct these parameters in LISA ?
- 1st method: template search. Efficient but prone to theoretical biases
- 2nd method: agnostic search. Useful as sanity check and sensitive to the unknown. Parameter reconstr. not straightforward

Reconstruction prospects: PT and more (some considerations)

Caprini… GN .. et al '19
Flauger ..GN et al '20

- The LISA band can be split into small freq. intervals
- Any signal can be well approximated by a power law in each interval

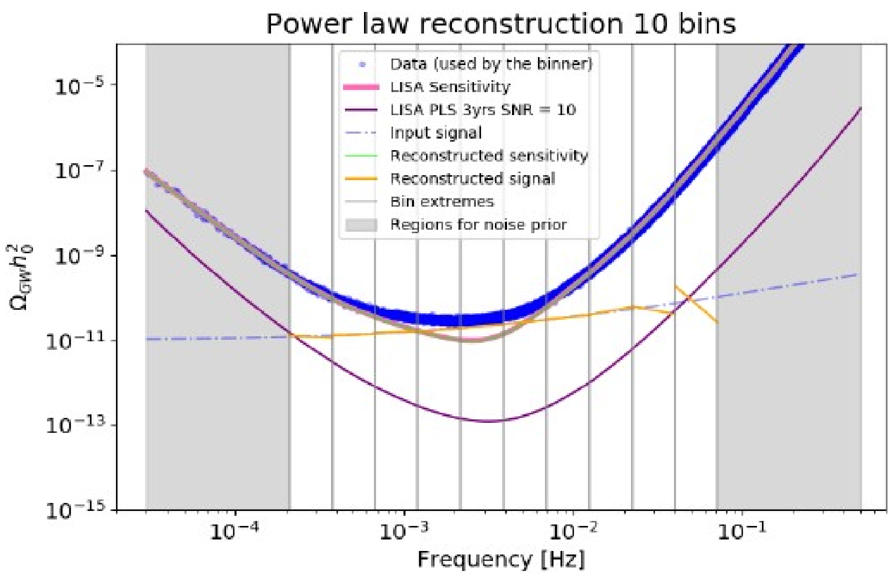
  (i.e. a power-law fit performed in an interval instead of the whole LISA freq. band [Adams and Cornish '13])

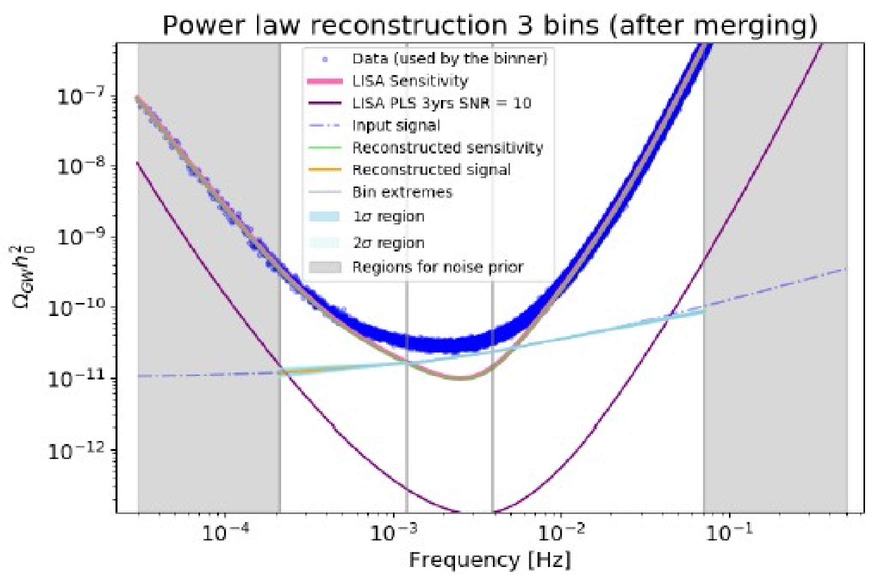
  - The larger the interval, the more data you have. Errors of the fit also depend on the amount of data you analyze.
  - The smaller the interval, the better you fit the signal.

Reconstruction prospects: PT and more (some considerations)

Caprini… GN .. et al '19
Flauger ..GN et al '20

- The LISA band can be split into small freq. intervals
- Any signal can be well approximated by a power law in each interval
- AIC merging method to optimize the size and number of the intervals

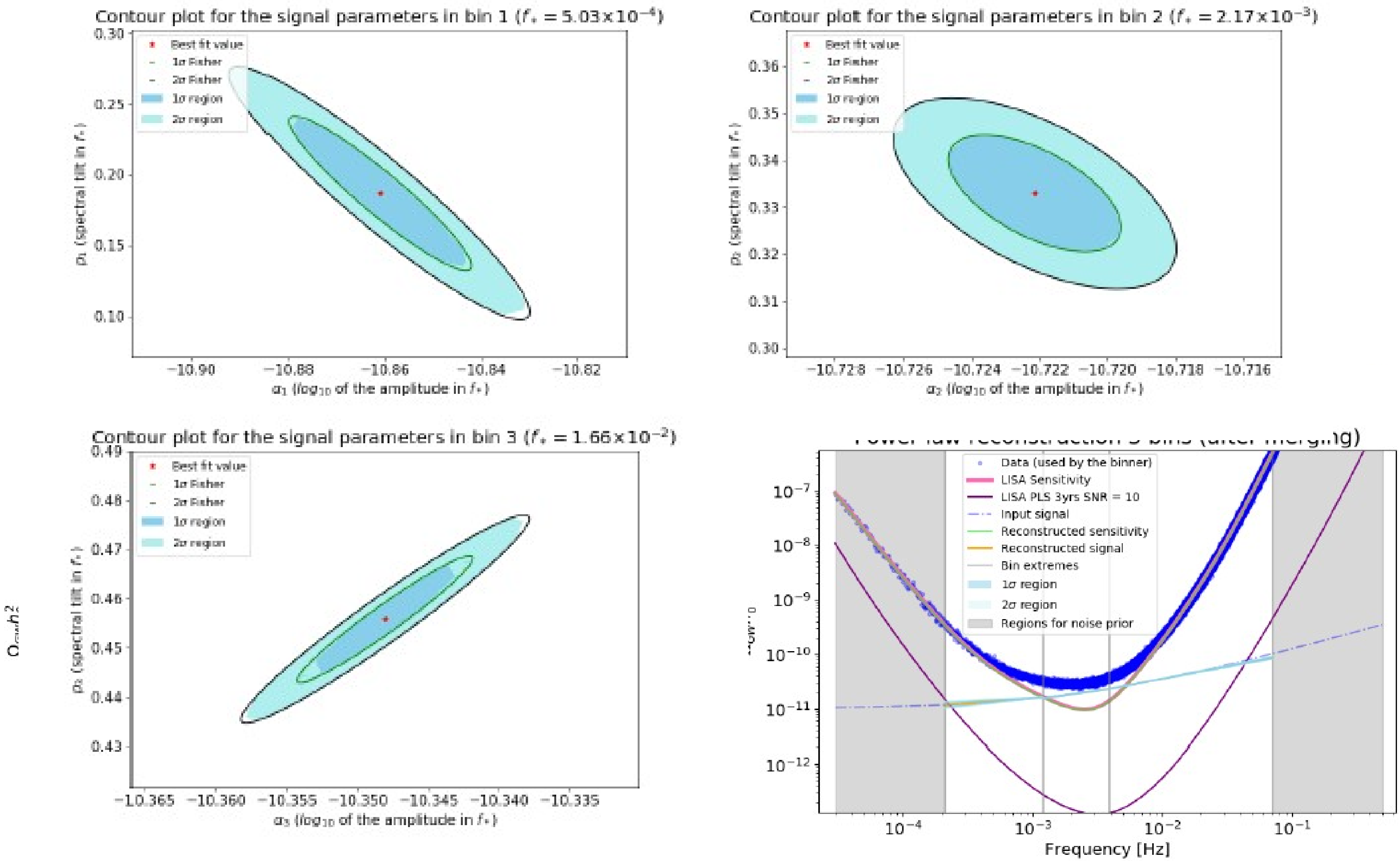




After the merging procedure only 3 bins with small error bands are left.

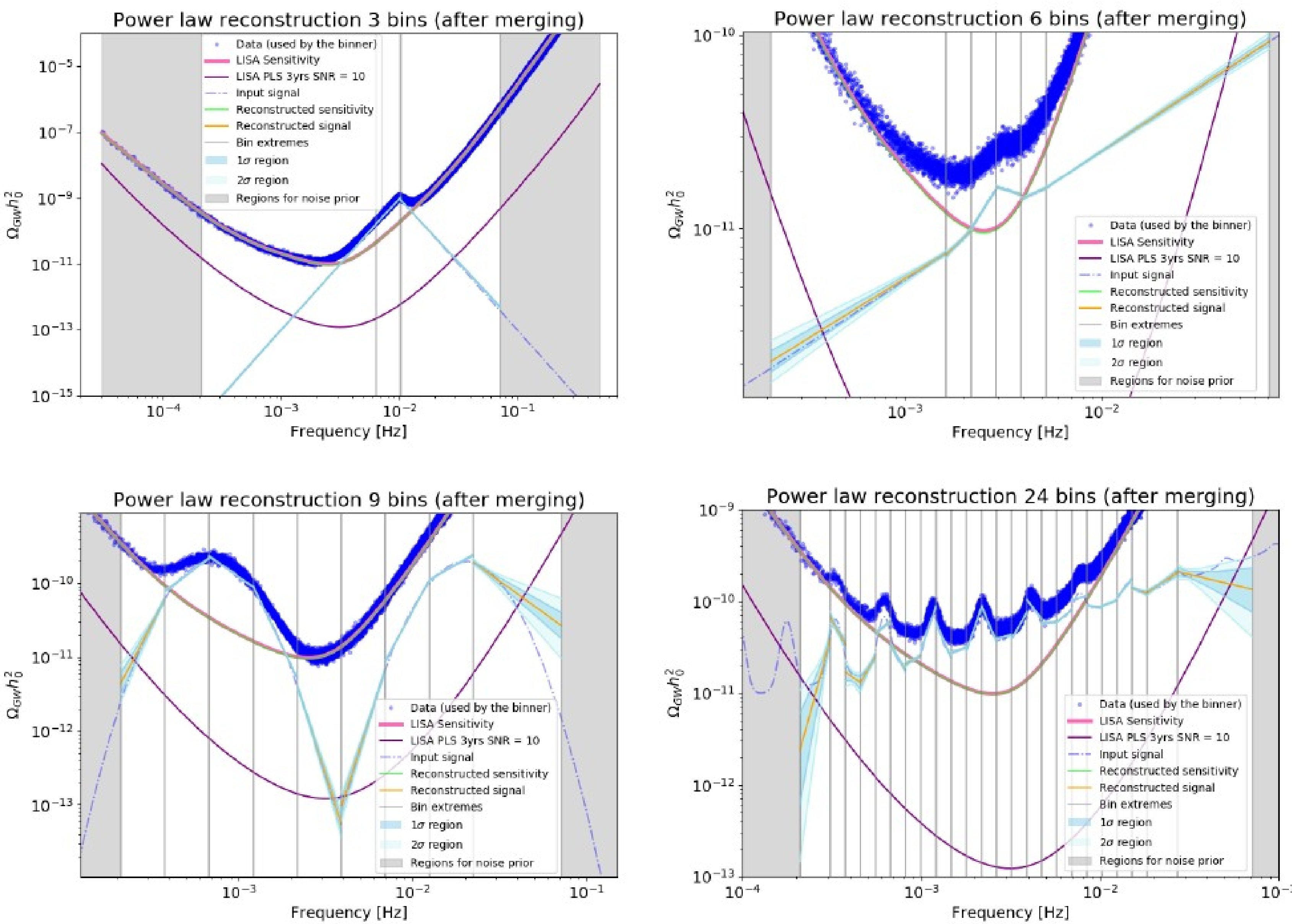
Reconstruction prospects: PT and more (some considerations)

Caprini... GN .. et al '19
Flauger ..GN et al '20



After the merging procedure only 3 bins with small error bands are left.

Reconstruction prospects: PT and more (some considerations)



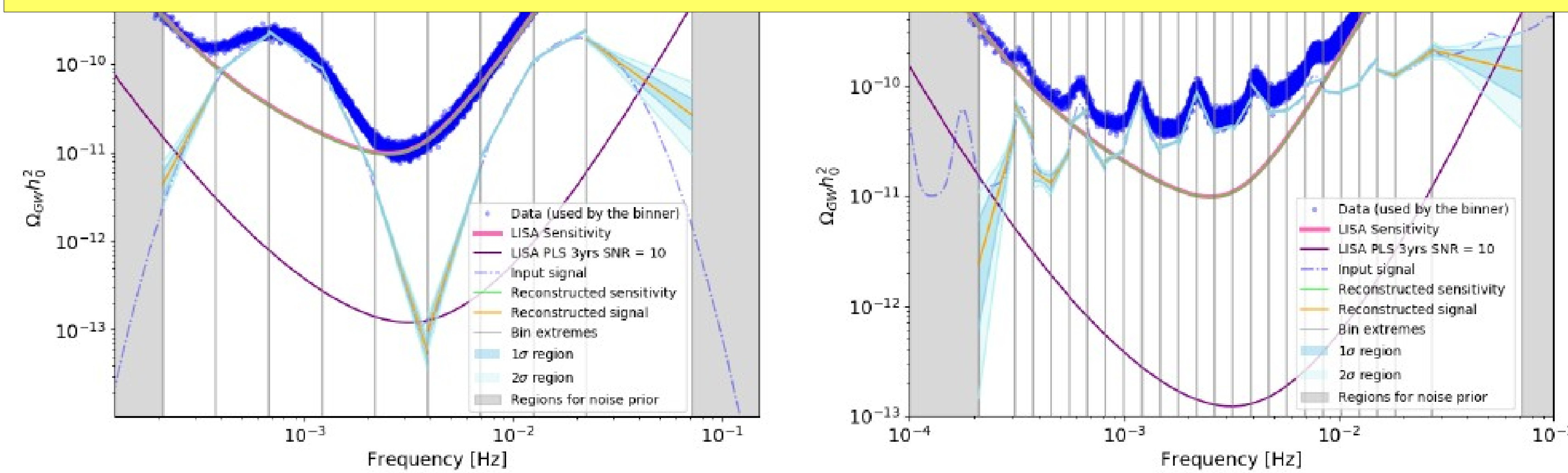
Reconstruction prospects: PT and more (some considerations)

Powerful signals can be well reconstructed even by using the agnostic approach

For weak signals, more care is required (foregrounds, noise mismodeling and instabilities, ...)

Non-agnostic approach would be even better (if the template is correct). The reconstruction of the "effective thermodynamic" parameters is expected to be very good, although with some degeneracies

This applies to many other primordial SGWBs



Conclusions

- From model building, there are reasonable expectations for 1st order Phase Transitions (1PTs) detectable at GW observatories
- A SGWB from 1PT may shed light on baryogenesis
- The prediction of the 1PT SGWB signal is becoming more and more precise
- It looks that LISA can reconstruct the freq. shape SGWB very precisely if signal powerful enough. For firm, quantitative conclusions you must solve the LISA global fit.
- Reasonable expectations for a good parameter estimation of the effective thermodynamic parameters with degeneracies that may or may not be broken by collider data
- A multiband analysis is an opportunity also for SGWBs
- Synergy between present and planned GW experiments and current and future colliders!