stochastic gravitational waves at aLIGO

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PRD 95 (2017) no.4 043505
arXiv:1611.01617

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

graphics: http://www.cbc.ca/news/technology/ligo-gravitational-wave-1.3440315

outline

a long-long time ago in a Universe far-far away

electroweak phase transition happened around 10^2 GeV

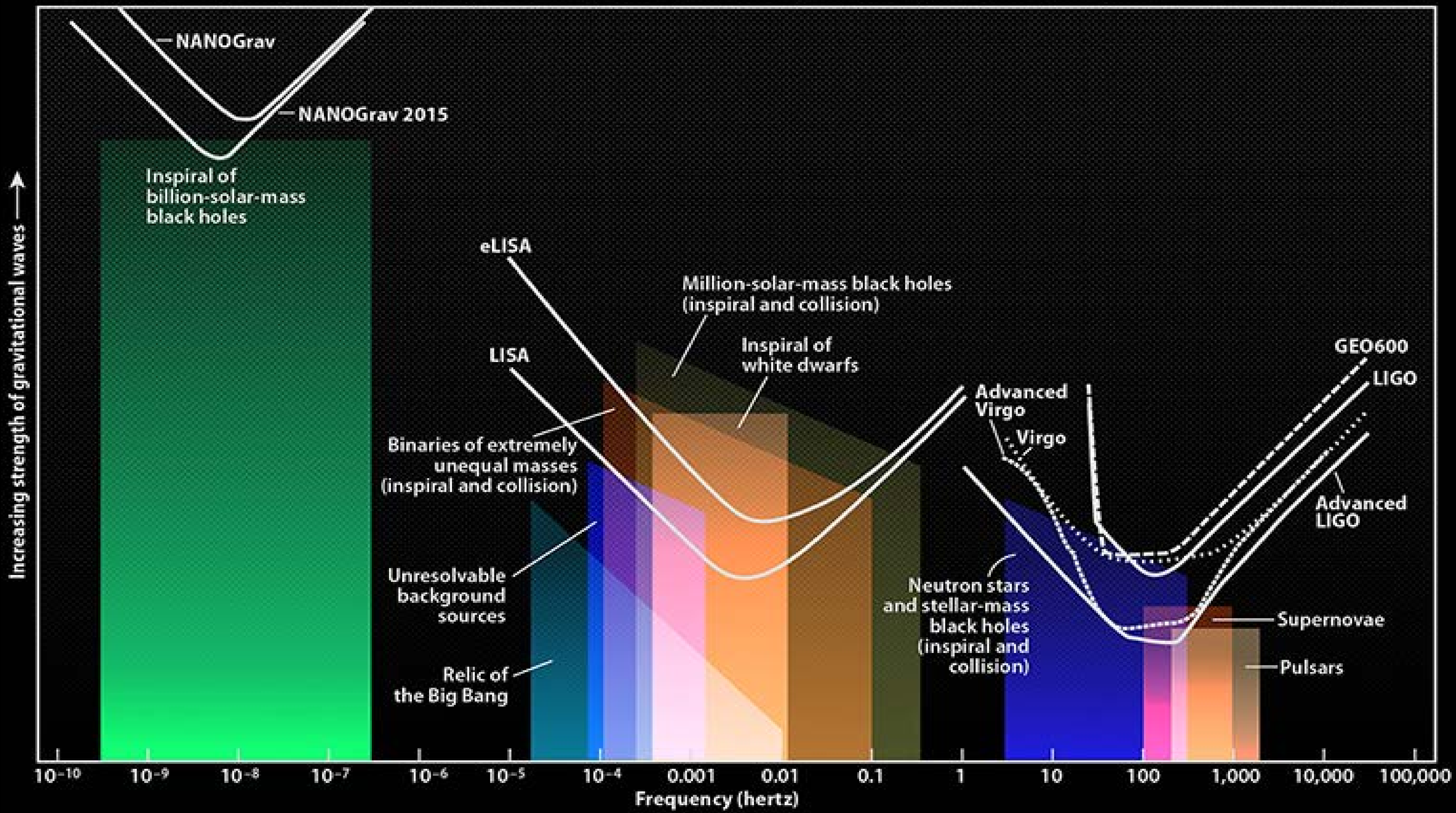
vacuum stability needed new physics below 10^9 GeV

a gauge singlet stabilized the vacuum and

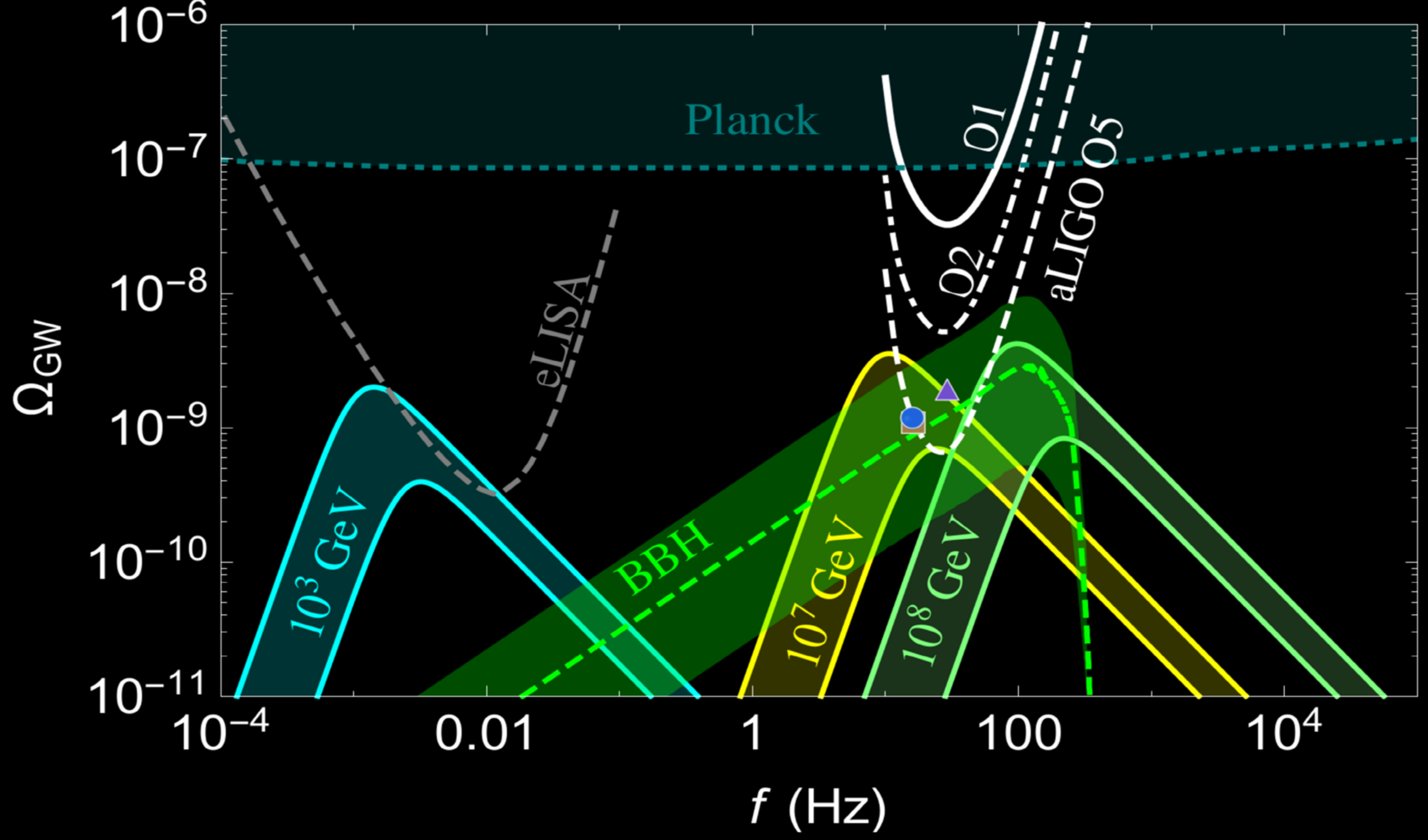
had a phase transition at 10^8 GeV leading to

gravitational waves from bubble collisions

potentially in the reach of aLIGO



http://cdn.media.astronomy.com/~/media/images/bonus/gravity/redshiftSpectrum.jpg



Dev, Mazumdar PRD93 (2016) no.10, 104001

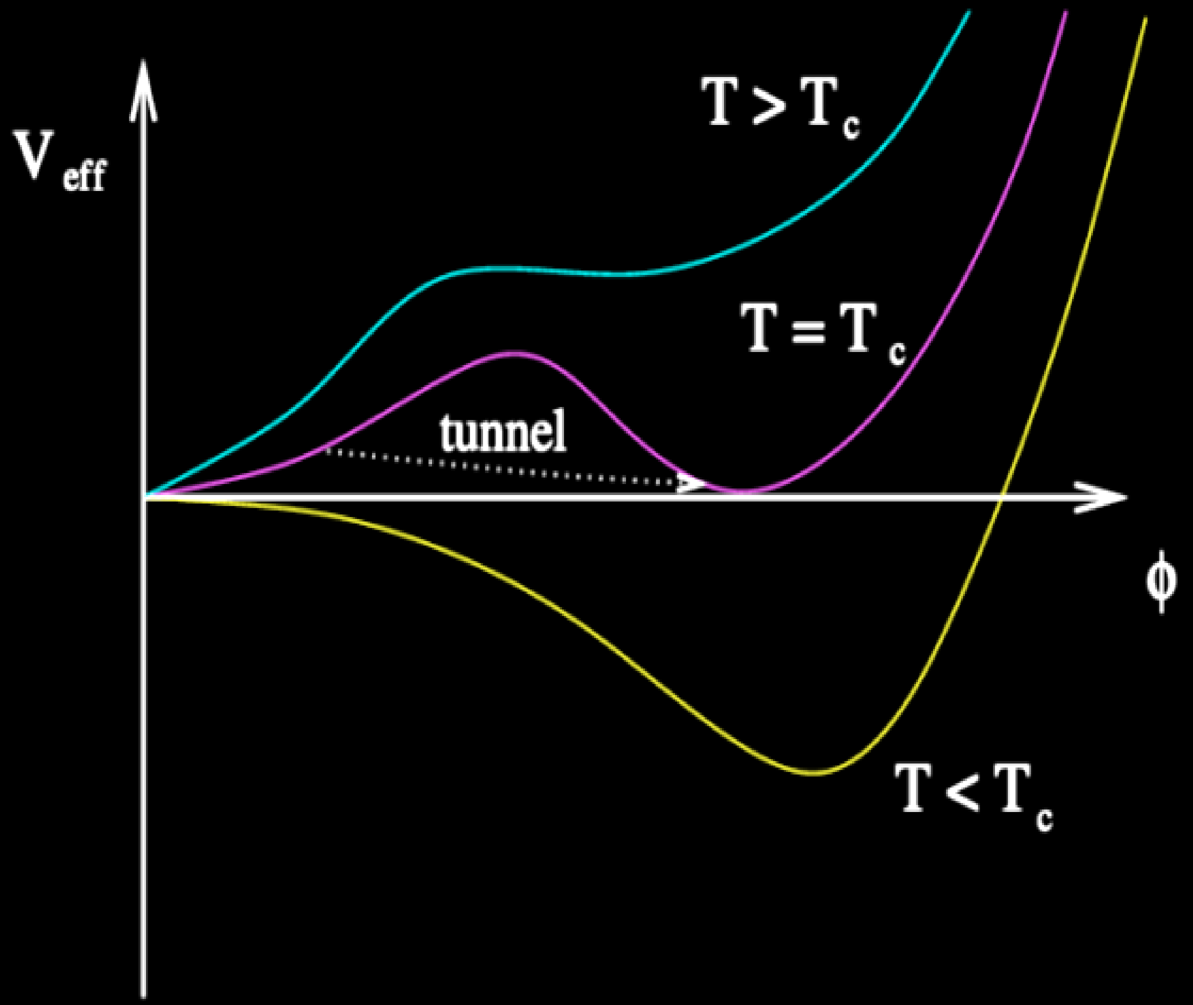
electroweak phase transition

- Higgs potential

$$V = \mu^2(E,T)|H|^2 + \lambda(E,T)|H|^4 + V(T)$$

evolves with E and T

- μ^2 changes sign $T \sim 300$ GeV
- the famous Mexican hat forms
- Higgs develops a vev.



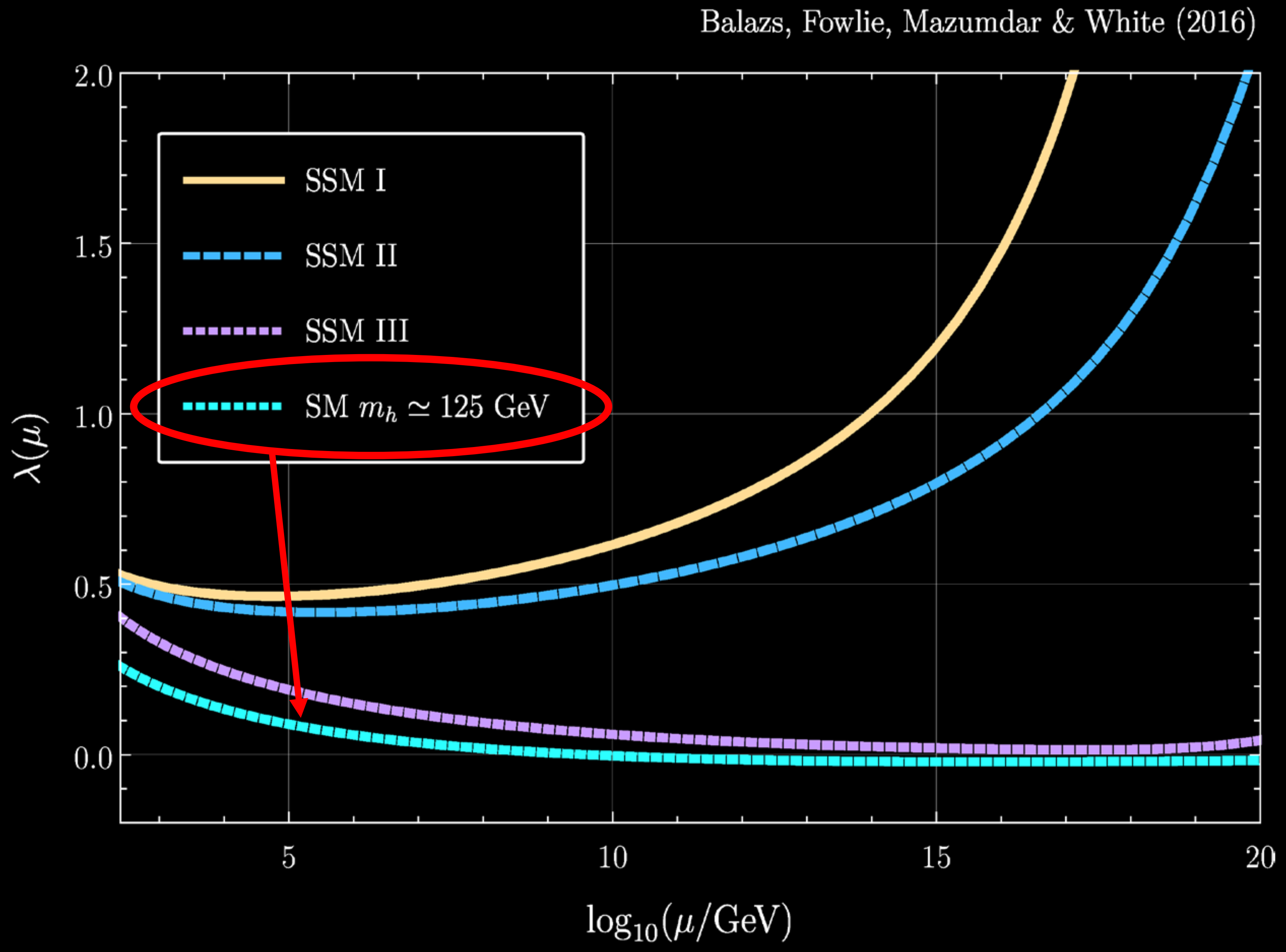
$E = T$ in the early Universe

electroweak vacuum stability

- λ changes sign
  $E \sim 10^9$ GeV

- unstable vacuum

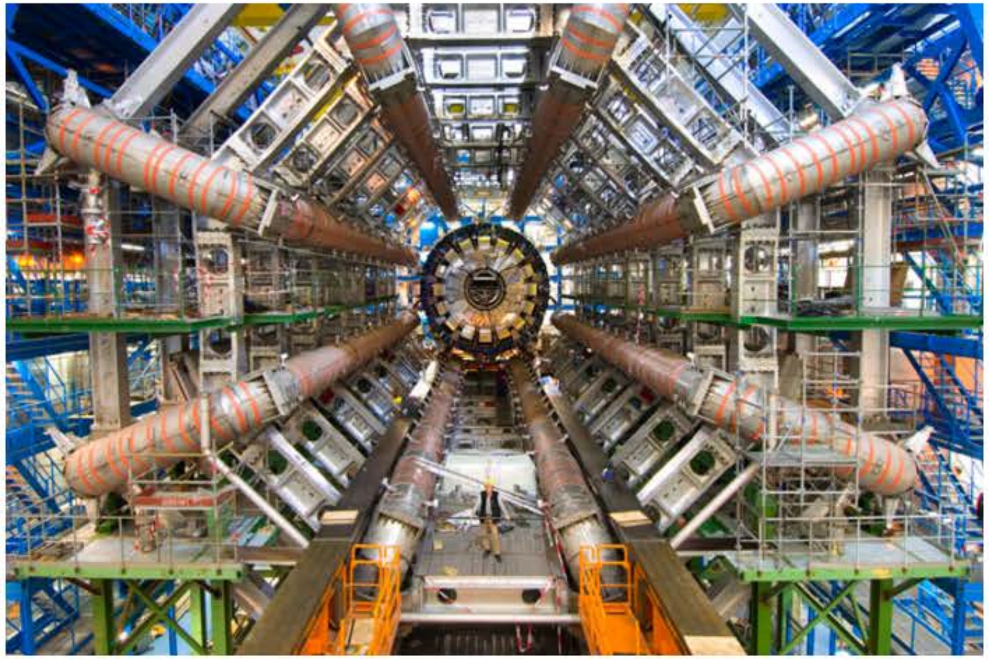
- unless new physics
  before $\sim 10^9$ GeV
  Universe falls into
  bottomless pit



2014 God Particle Project: Opening A Bottomless Pit to Hell Now! (Disturbing Video)

Friday, January 3, 2014 21:35

(Before It's News)



The Key to the Bottomless Pit, Top World Researchers are attempting to open other dimensions. http://www.BpearthWatch.com

(Video)
Whoa! Here's Why PizzaGate Was Really Blown Wide Open! And Who Blew the Whistle!
Drink Warm Turmeric Water Every Morning for 12 Months and This Will Happen
The Video That Could Destroy Washington's Pedo Ring - Very Disturbing!!
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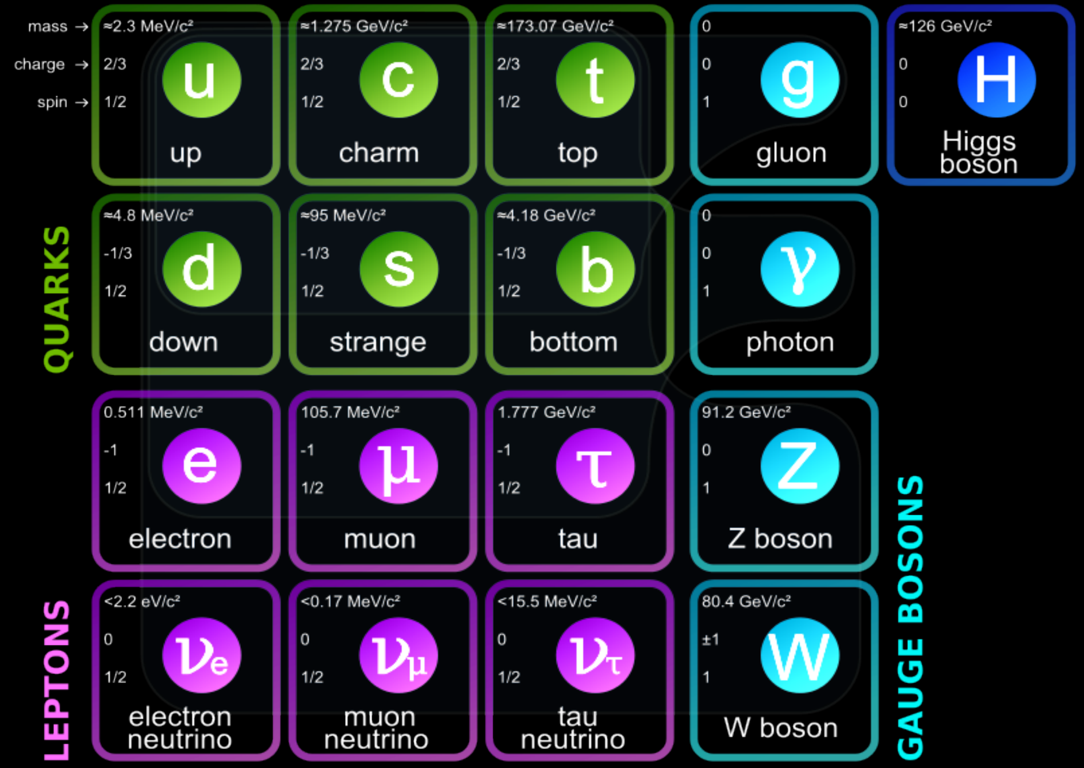
gauge singlet scalar

- a gauge singlet scalar can stabilize the Higgs potential
- standard particles



- standard forces

SU(3) x U(1) x SU(2)

strong electroweak

- a singlet doesn’t couple to g, γ, Z, W

gauge singlet scalar model

- scalar potential: masses and interactions at zero temperature

$$V_0(H,S) = \mu^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \frac{1}{2}M_S^2 S^2 + \frac{1}{3}\kappa S^3 + \frac{1}{2}\lambda_S S^4 + \kappa_1 S|H|^2 + \frac{1}{2}\kappa_2 S^2|H|^2,$$

- + thermal contributions to the potential

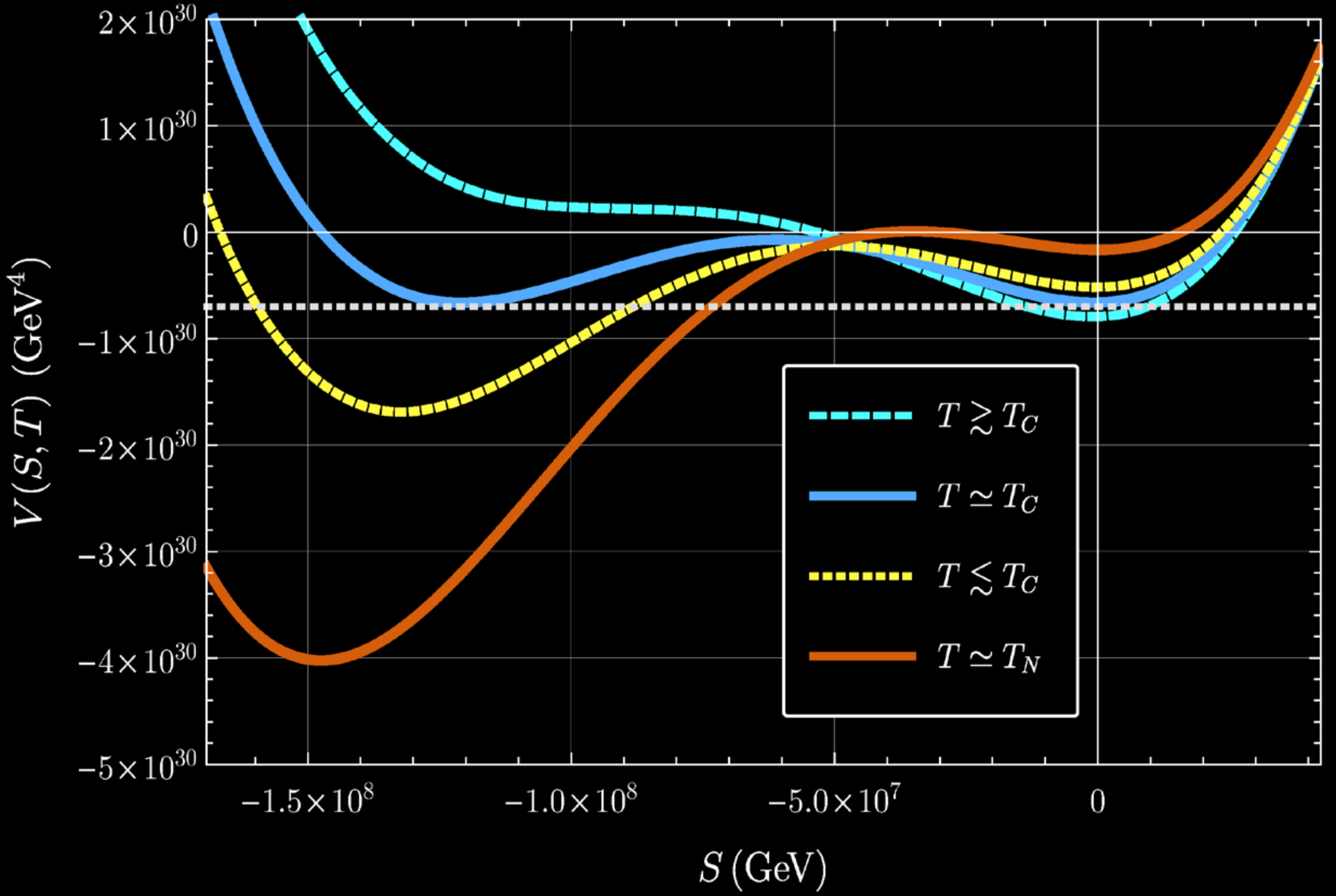
$$V = V_0 + \Delta V_D + \Delta V_T + \Delta V_{\text{CW}}$$

- free parameters: $M_S, \lambda_S, \kappa, \kappa_{1,2}$

phase transition at $\sim 10^8$ GeV

- S can develop a vev.
- its mass & vev. are set by vacuum stability to $\sim 10^8$ GeV arXiv:1203.0237
- accompanying cosmological phase transition can be 1st order

Balazs, Fowlie, Mazumdar & White (2016)



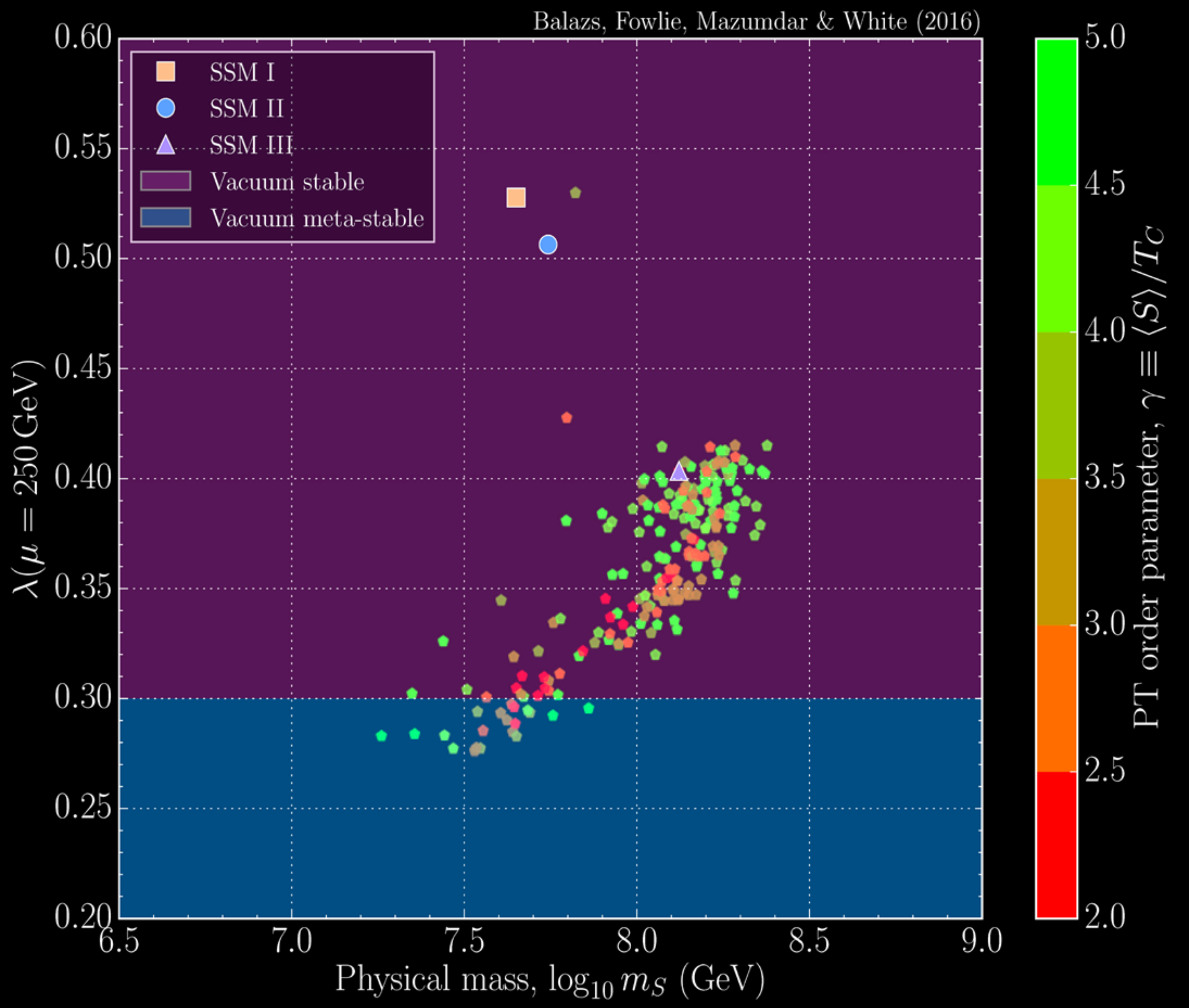
phase transition at ~ 10^8 GeV

- regions in the para space

$$10^{-8}\,\text{GeV} \leq |\kappa_1| \leq 10^8\,\text{GeV}$$
$$10^{-8} \leq \kappa_2 \leq 2$$
$$10^{12}\,\text{GeV}^2 \leq M_S^2 \leq 10^{18}\,\text{GeV}^2$$

exist with

- stable vacuum
- acceptable pheno.
- strong 1st order phase transition at ~ 10^8 GeV



Bubble nucleation

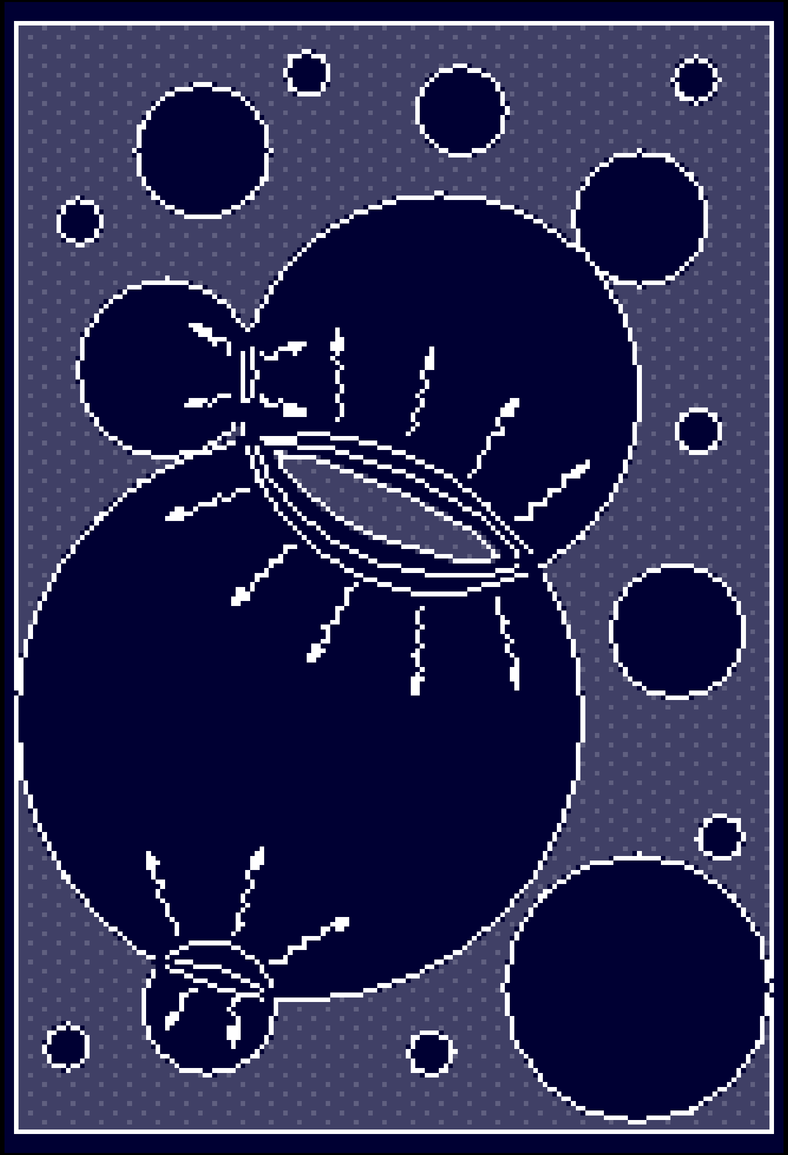
Hindmarsh, Huber, Rummukainen, Weir arXiv:1203.0237

animation: http://www.helsinki.fi/~weir/visualisation.html

gravitational wave production

during a 1st order phase transition gravitational waves are produced by

- collisions of bubble walls
- sound waves in the plasma
- magneto-hydrodynamics turbulence following bubble collisions



frequency and amplitude

for bubble collisions the amplitude and frequency of GWs is determined by the phase transition properties

- ➢ length of the PT: $1/\beta$
- ➢ "latent heat": α
- ➢ wall velocity: v_w
- ➢ nucleation temp: T_N
- ➢ $g_*(T_N) = 107.75$

$$\Omega_{\rm GW} \simeq 10^{-9} \cdot \left(\frac{31.6 H_N}{\beta} \right)^2 \left(\frac{\alpha}{\alpha+1} \right)^2$$

$$\epsilon^2 \left(\frac{4 v_w^3}{0.43 + v_w^2} \right) \left(\frac{100}{g_\star} \right)^{\frac{1}{3}}$$

$$f_0 \simeq 16.5\,{\rm Hz} \cdot \left(\frac{f_N}{H_N} \right) \left(\frac{T_N}{10^8\,{\rm GeV}} \right) \left(\frac{g_\star}{100} \right)^{1/6}$$

$$f_N = \frac{0.62\beta}{1.8 - 0.1 v_w + v_w^2}$$

arXiv:0806.1828

phase transition properties

- β is calculated by numerical differentiation of the action

$$\beta \equiv -\frac{\mathrm{d}\mathcal{S}_4}{\mathrm{d}t}\bigg|_{t_N} \approx H_N \left[\frac{\mathrm{d}\ln \mathcal{S}_\mathrm{E}/T}{\mathrm{d}\ln T}\right] \frac{\mathcal{S}_\mathrm{E}}{T}\bigg|_{T_N}$$

  a proper evaluation of $\beta(T)$ requires a lattice calculation

  we reflect uncertainties in our calculation by using a range for β

- α comes from the latent heat during the phase transition

$$\Delta\rho = \left[V - \frac{\mathrm{d}V}{\mathrm{d}T}T_N\right]_\mathcal{F} - \left[V - \frac{\mathrm{d}V}{\mathrm{d}T}T_N\right]_\mathcal{T}$$

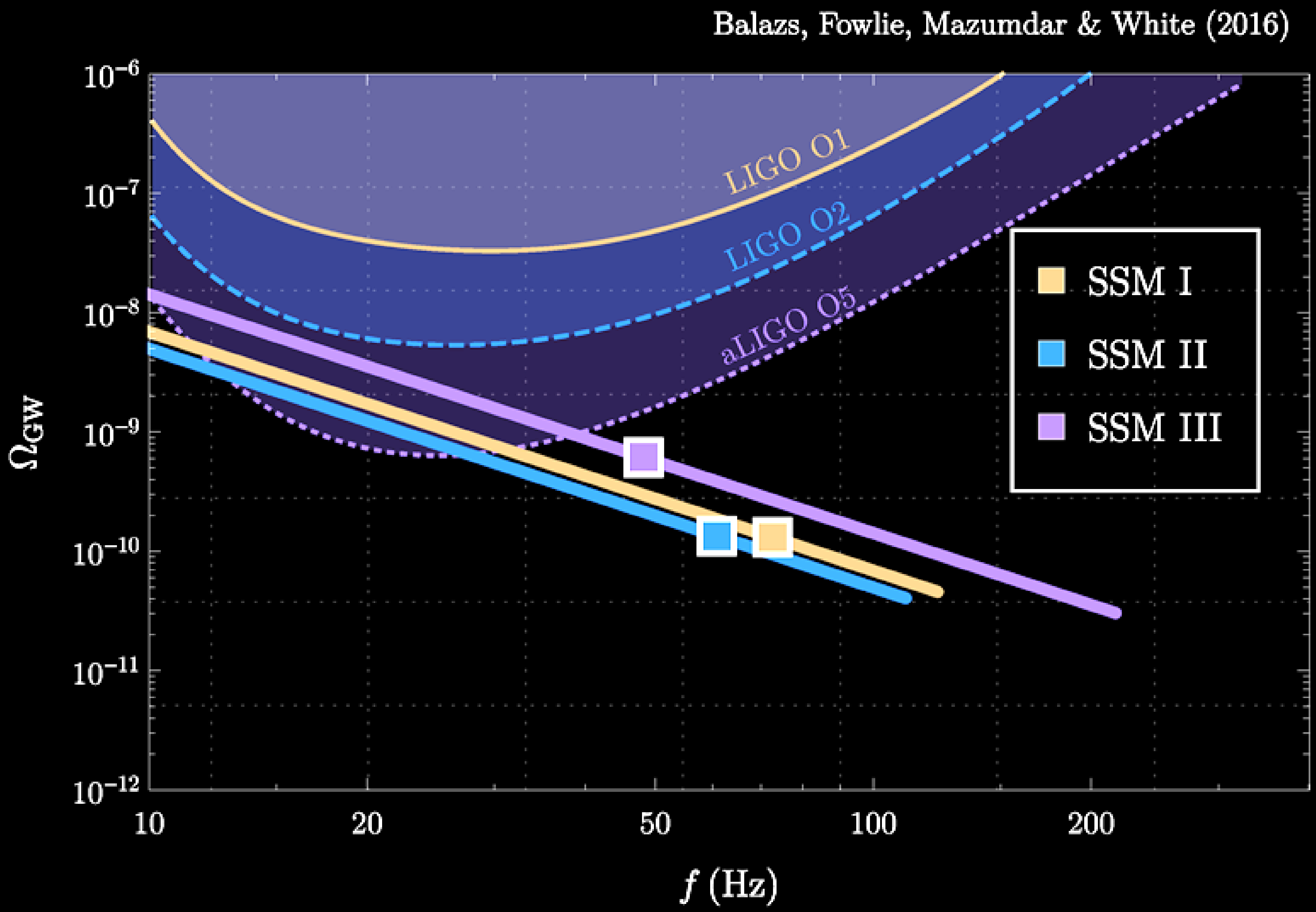
- v_w is approximated to be $O(1)$

benchmark points

Point	M_S^2/GeV^2	λ_S	κ/GeV	κ_1/GeV	κ_2	λ	m_S/GeV	γ	T_C/GeV	T_N/T_C	β/H_N	Ω_{GW}
SSM I	$4.2 \cdot 10^{14}$	0.064	$2.1 \cdot 10^7$	$-4.9 \cdot 10^5$	0.14	0.53	$4.5 \cdot 10^7$	2.8	$3.7 \cdot 10^7$	0.44	118	$1.3 \cdot 10^{-9}$
SSM II	$6.9 \cdot 10^{14}$	0.073	$2.8 \cdot 10^7$	$-7.3 \cdot 10^5$	0.15	0.51	$5.5 \cdot 10^7$	2.9	$4.2 \cdot 10^7$	0.45	110	$1.3 \cdot 10^{-9}$
SSM III	$1.3 \cdot 10^{15}$	0.13	$7.4 \cdot 10^7$	$-1.4 \cdot 10^6$	0.09	0.40	$1.3 \cdot 10^8$	2.3	$8.2 \cdot 10^7$	0.35	45	$6 \cdot 10^{-9}$

- calculated all relevant thermal quantities:
  nucleation temperature, order parameter, characteristic timescale
- and from those the peak amplitude and frequency
- checked vacuum stability
- checked TeV scale phenomenology (EWSB, Higgs properties, etc.)

results



Balazs, Fowlie, Mazumdar & White (2016)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Ω_{GW}
10
20
50
100
200
f (Hz)
LIGO O1
LIGO O2
aLIGO O5
SSM I
SSM II
SSM III

conclusion

aLIGO may see stochastic gravitational waves in a few years