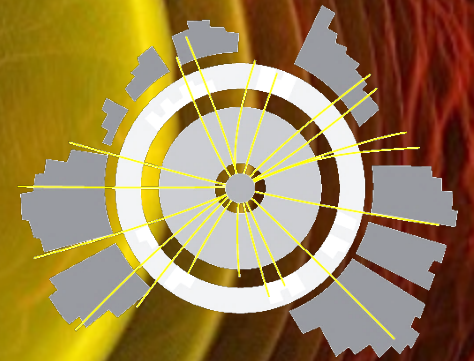


stochastic gravitational waves at aLIGO

Csaba Balázs
Andrew Fowlie
Anupam Mazumdar
Graham White
PRD 95 (2017) no.4 043505
arXiv:1611.01617

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

MONASH
University

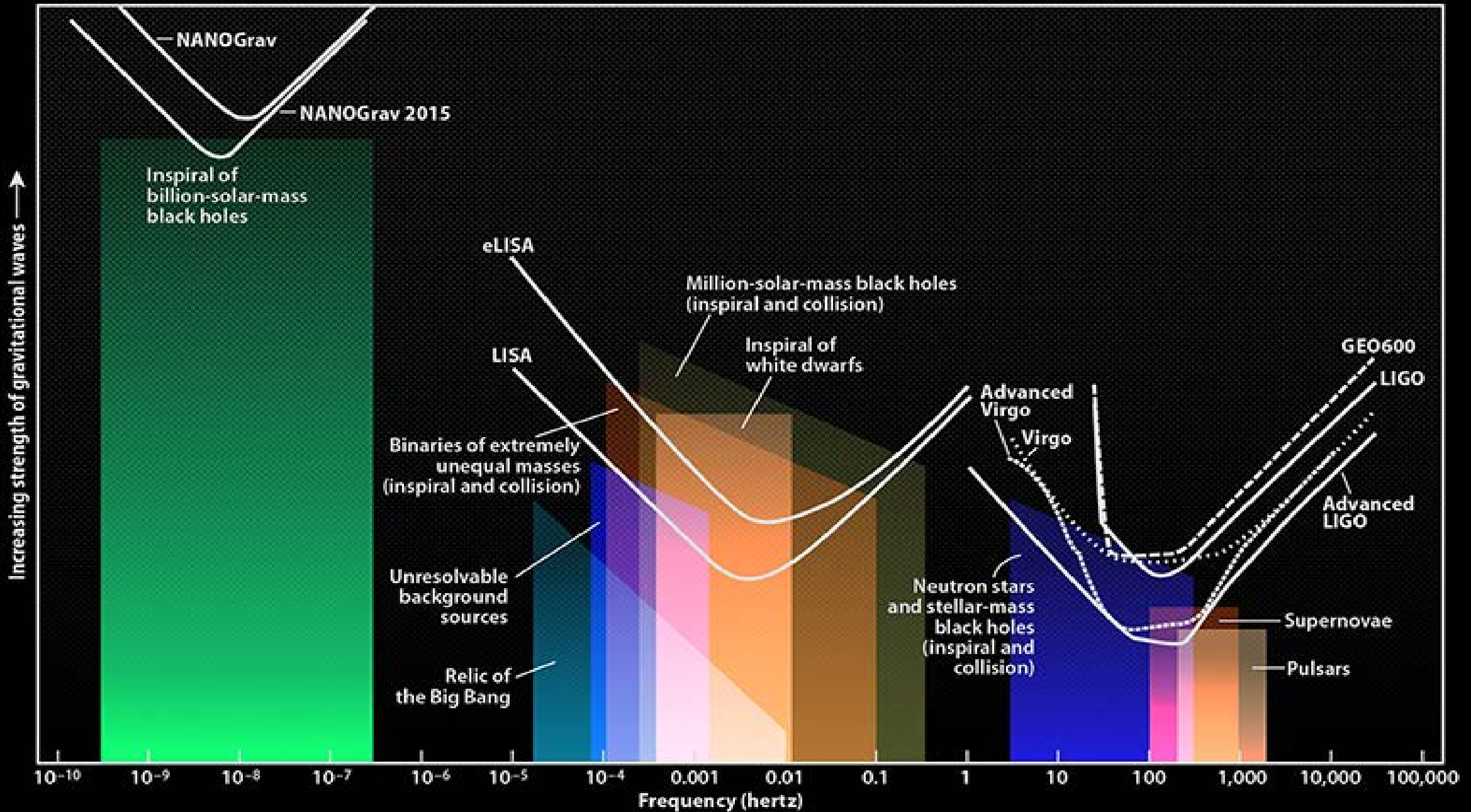


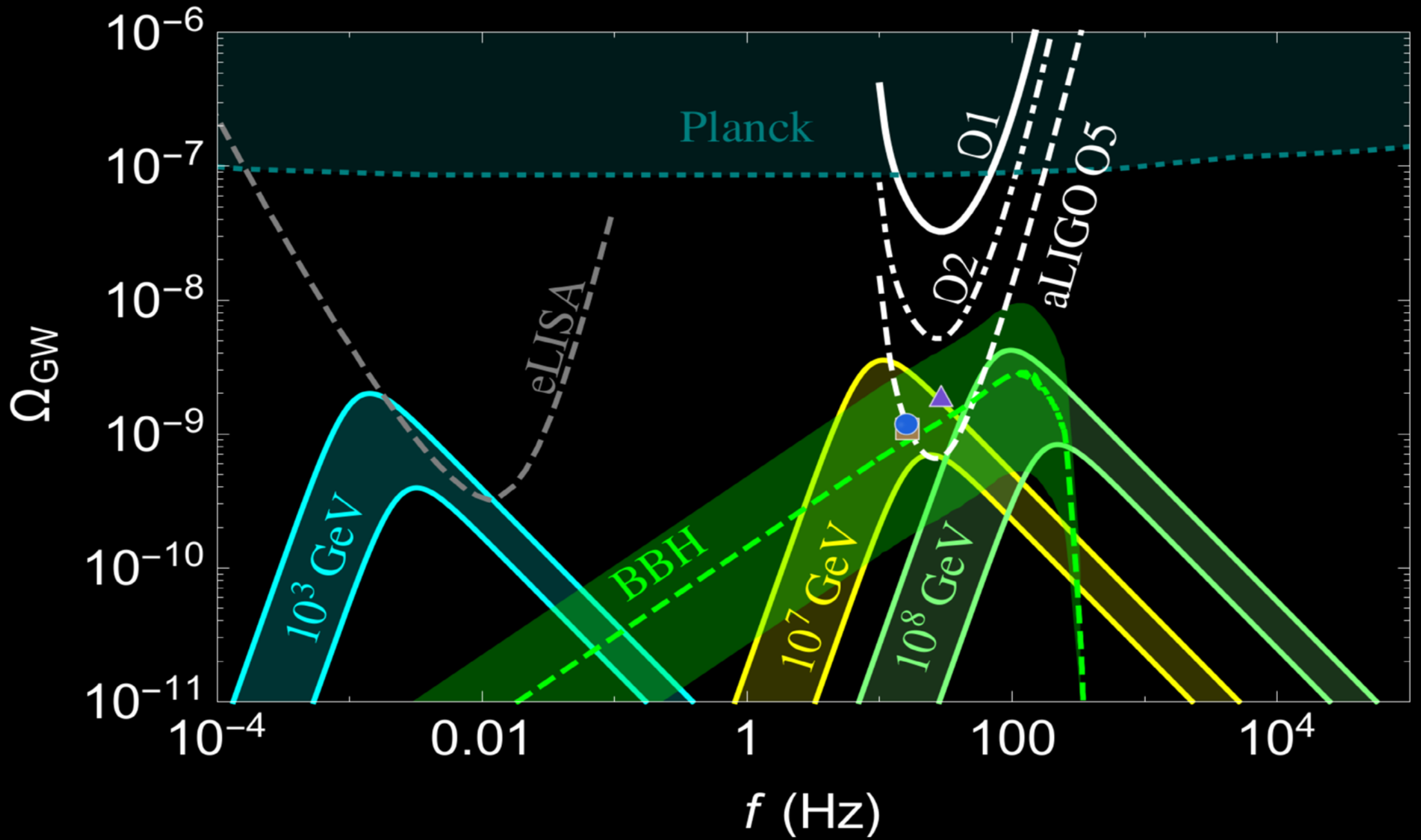
COEPP

ARC Centre of Excellence for
Particle Physics at the Terascale

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!





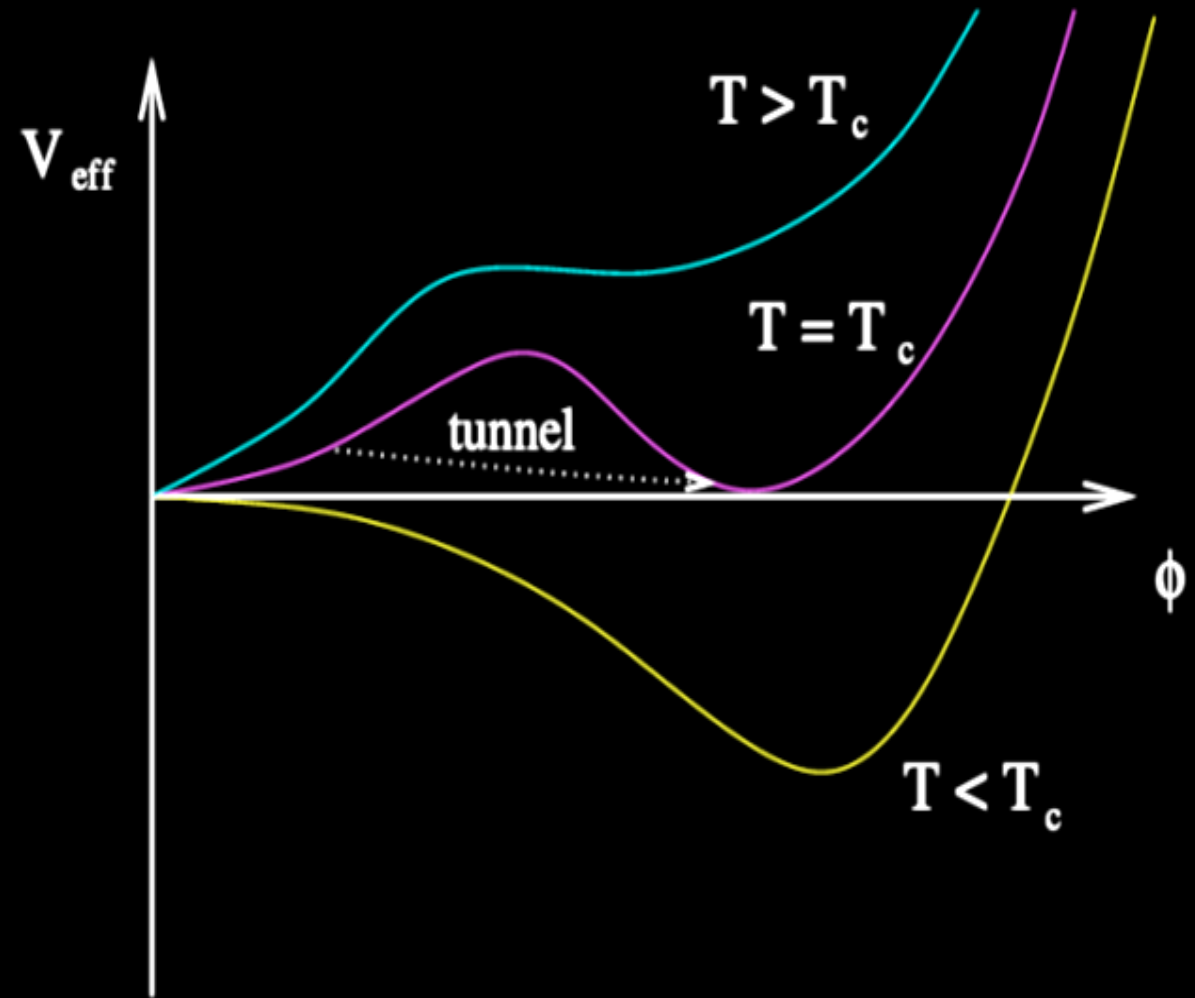
electroweak phase transition

- 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.

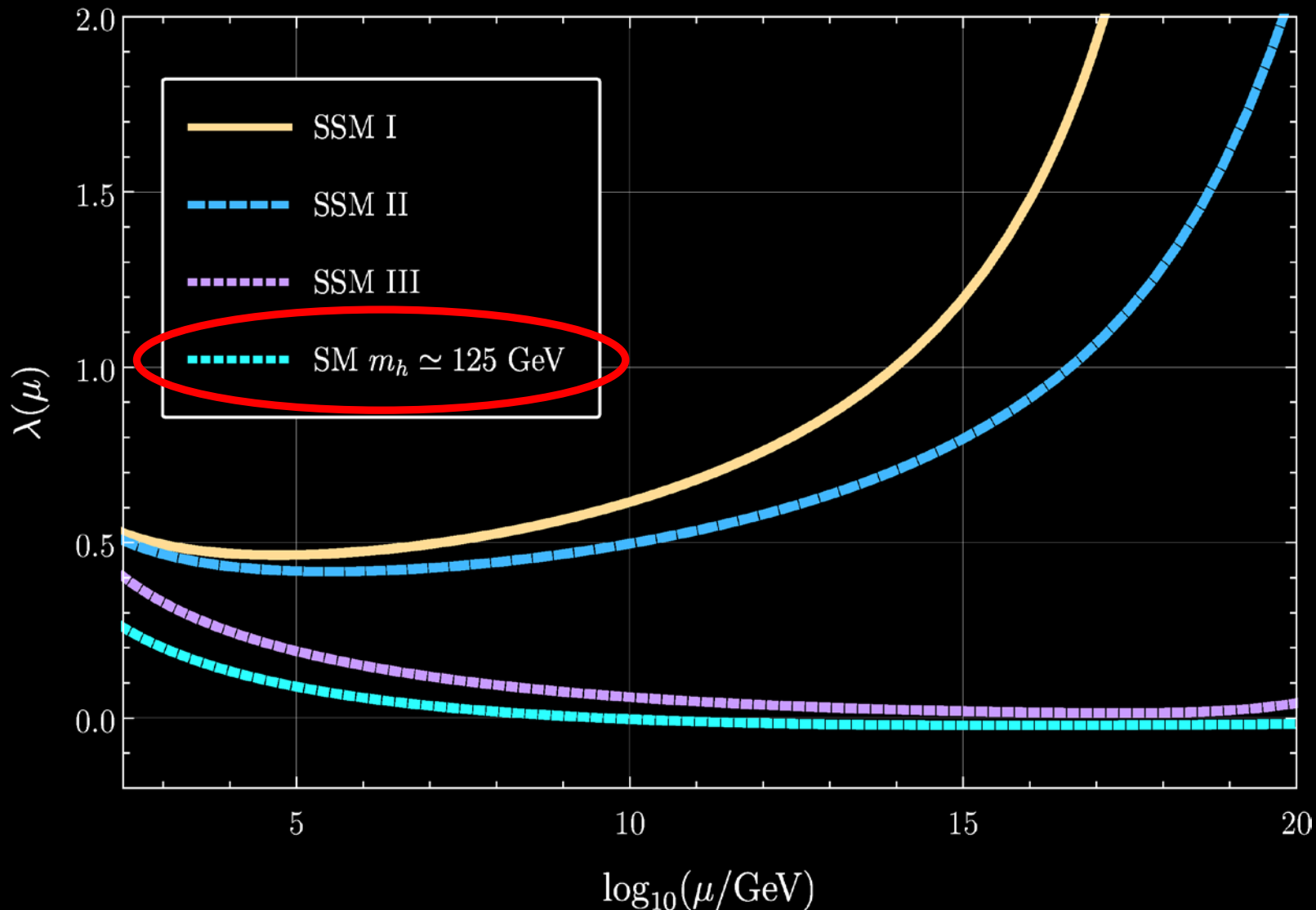


$E = T$ in the early Universe

electroweak vacuum stability

Balazs, Fowlie, Mazumdar & White (2016)

- λ changes sign
 $E \sim 10^9$ GeV
- unstable vacuum
- unless new physics
before $\sim 10^9$ GeV
Universe falls into
bottomless pit



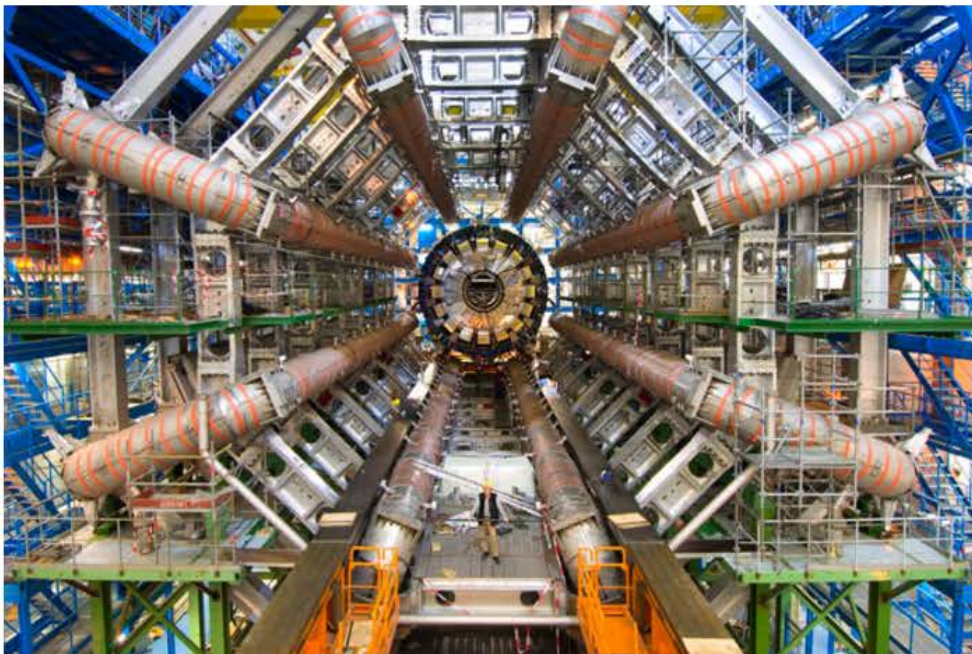
2014 God Particle Project: Opening A Bottomless Pit to Hell Now! (Disturbing Video)

Friday, January 3, 2014 21:35

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FLASH LIKE

(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
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2014 God Particle Project: Opening A Bottomless Pit to Hell Now! (Dist... ↗

gauge singlet scalar

➤ a gauge singlet scalar can stabilize the Higgs potential

➤ standard particles

➤ standard forces

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	≈4.8 MeV/c ²	≈95 MeV/c ²	≈4.18 GeV/c ²	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	d down	s strange	b bottom	γ photon	
	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	91.2 GeV/c ²	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	80.4 GeV/c ²	
	0	0	0	±1	
	1/2	1/2	1/2	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
				GAUGE BOSONS	

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

➤ a singlet doesn't couple to
g, γ, Z, W

chart on left by MissMJ, PBS NOVA, Fermilab, Office of Science, US Department of Energy, Particle Data Group, CC BY 3.0, <https://commons.wikimedia.org/w/index.php?curid=4286964>

gauge singlet scalar model

- scalar potential: masses and interactions at zero temperature

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

- + thermal contributions to the potential

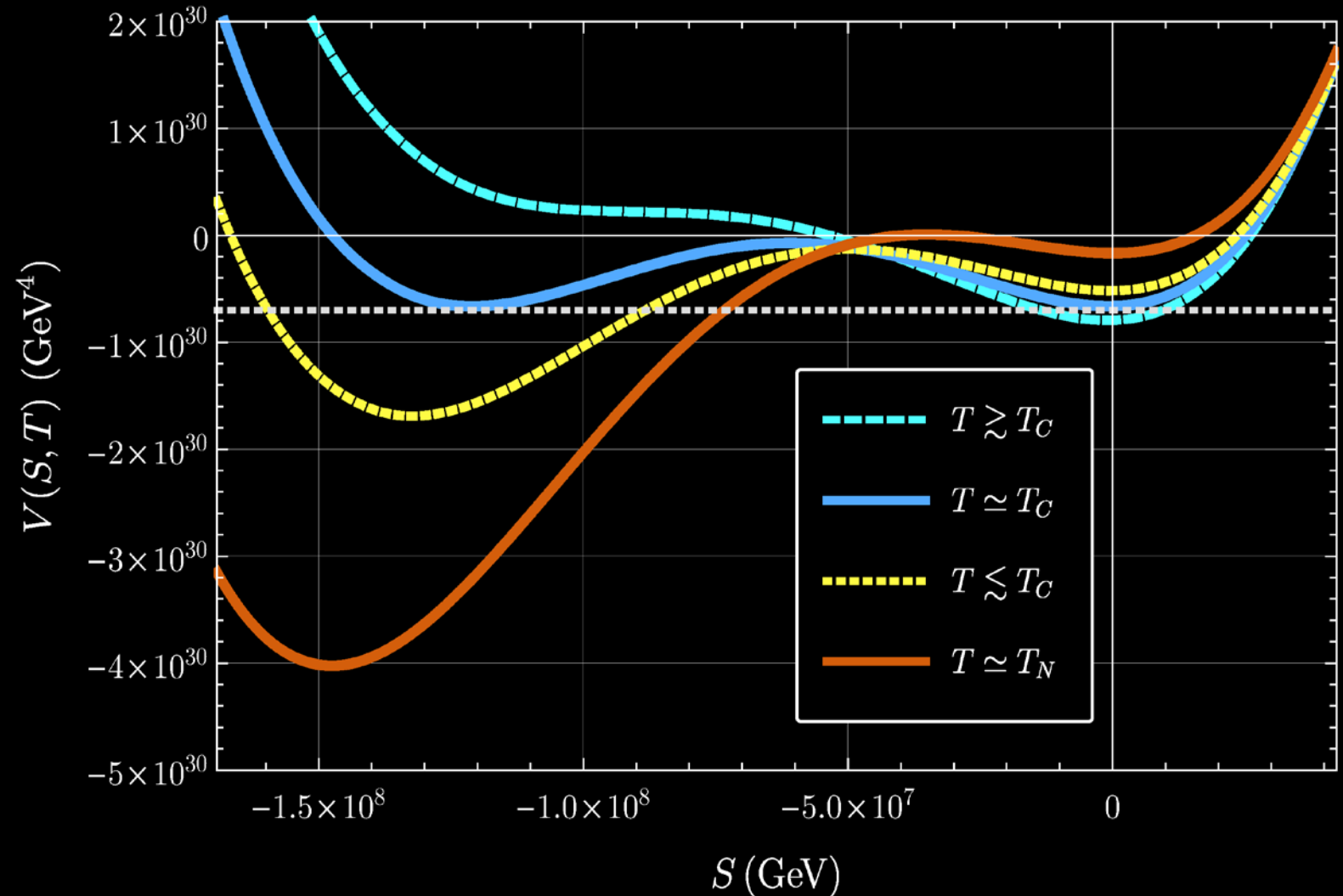
$$V = V_0 + \Delta V_D + \Delta V_T + \Delta V_{CW}$$

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

phase transition at $\sim 10^8$ GeV

Balazs, Fowlie, Mazumdar & White (2016)

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



phase transition at $\sim 10^8$ GeV

➤ regions in the para space

$$10^{-8} \text{ GeV} \leq |\kappa_1| \leq 10^8 \text{ GeV}$$

$$10^{-8} \leq \kappa_2 \leq 2$$

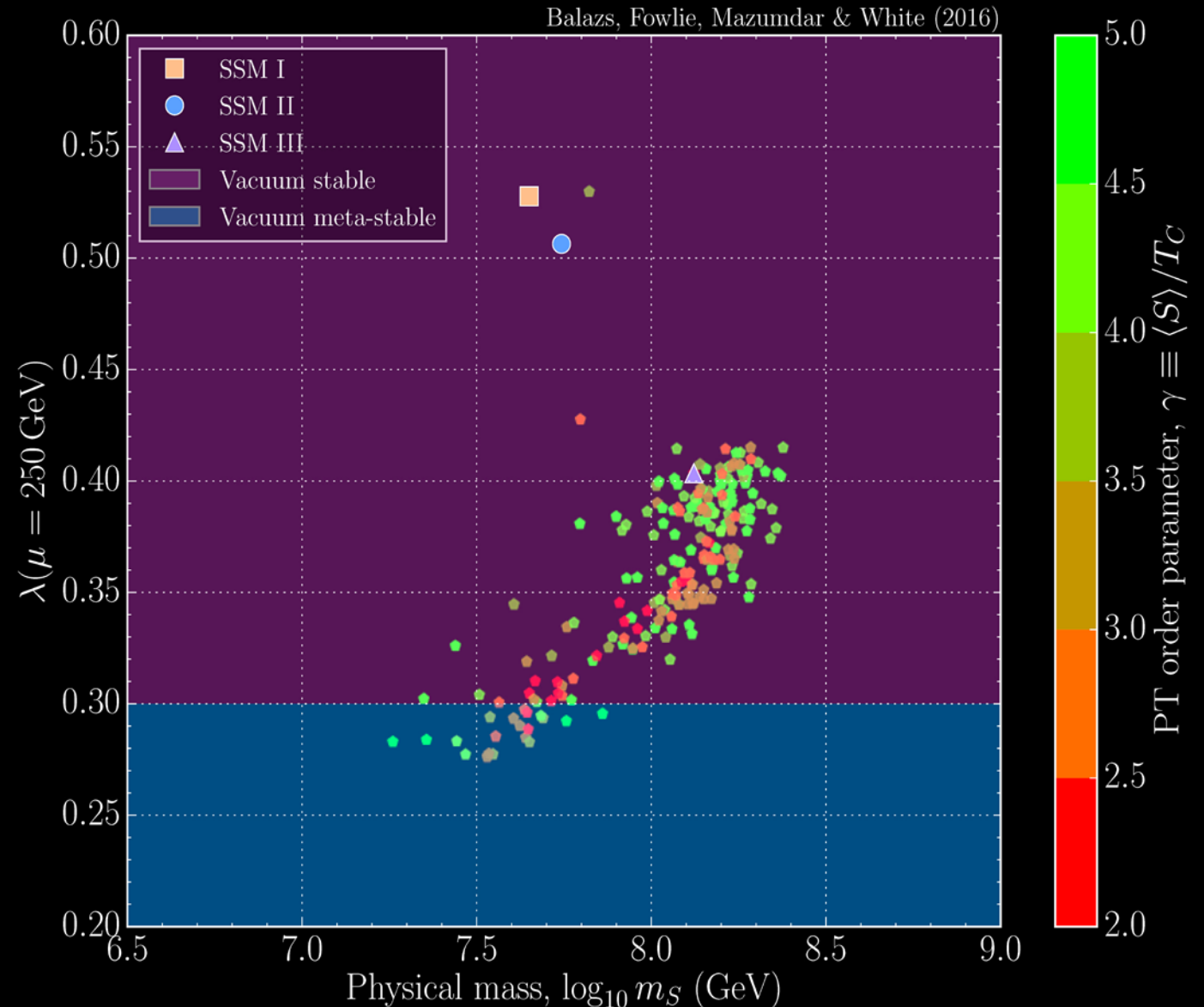
$$10^{12} \text{ GeV}^2 \leq M_S^2 \leq 10^{18} \text{ GeV}^2$$

exist with

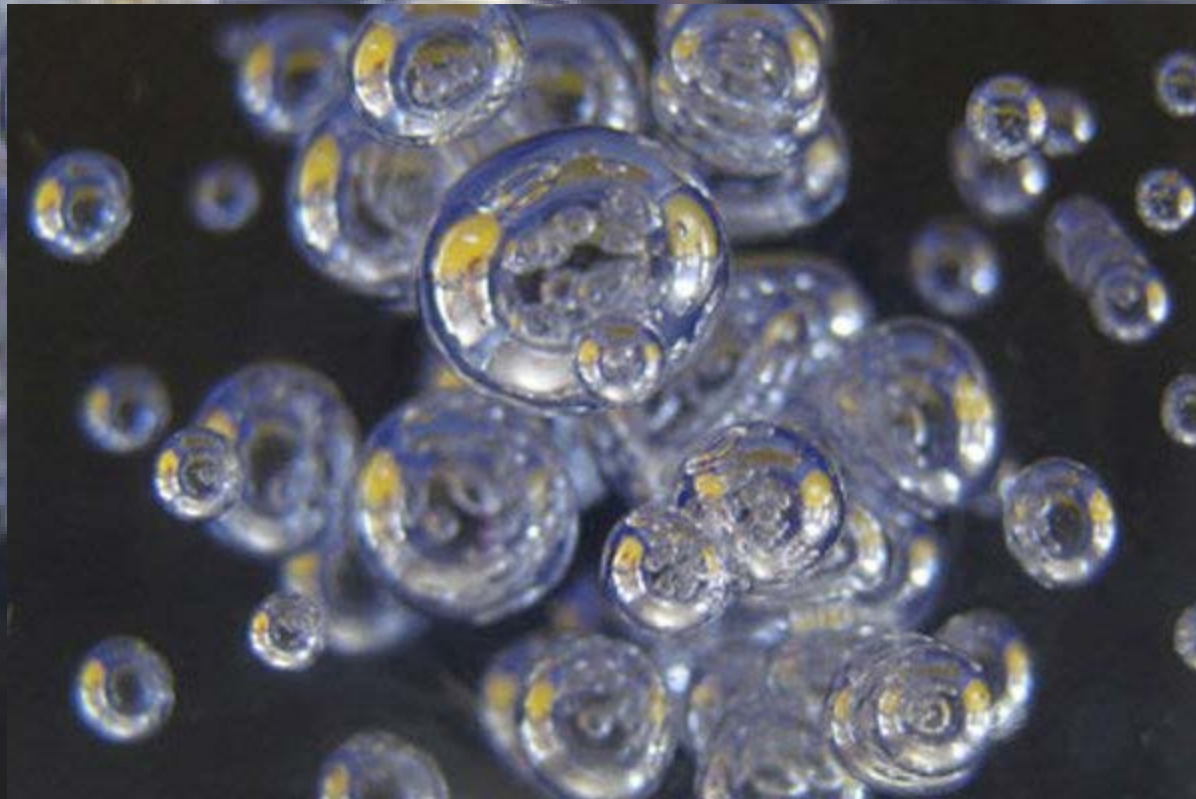
➤ stable vacuum

➤ acceptable pheno.

➤ strong 1st order phase transition at $\sim 10^8$ GeV



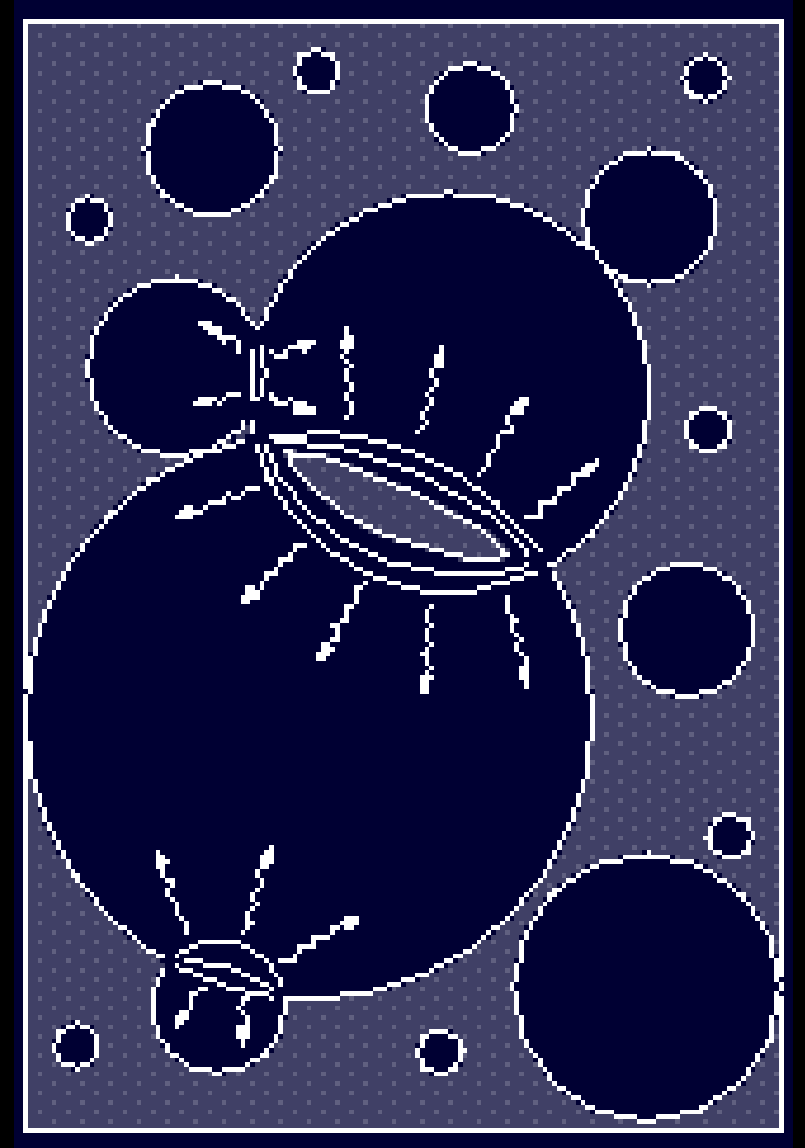
Bubble nucleation



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

($g_* = 107.75$)

$$\Omega_{\text{GW}} \simeq 10^{-9} \cdot \left(\frac{31.6 H_N}{\beta} \right)^2 \left(\frac{\alpha}{\alpha + 1} \right)^2 \epsilon^2 \left(\frac{4v_w^3}{0.43 + v_w^2} \right) \left(\frac{100}{g_*} \right)^{\frac{1}{3}}$$

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

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

phase transition properties

- β is calculated by numerical differentiation of the action

$$\beta \equiv - \left. \frac{d\mathcal{S}_4}{dt} \right|_{t_N} \approx H_N \left[\frac{d \ln \mathcal{S}_E / T}{d \ln T} \right] \left. \frac{\mathcal{S}_E}{T} \right|_{T_N}$$

a complete calculation 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

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

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

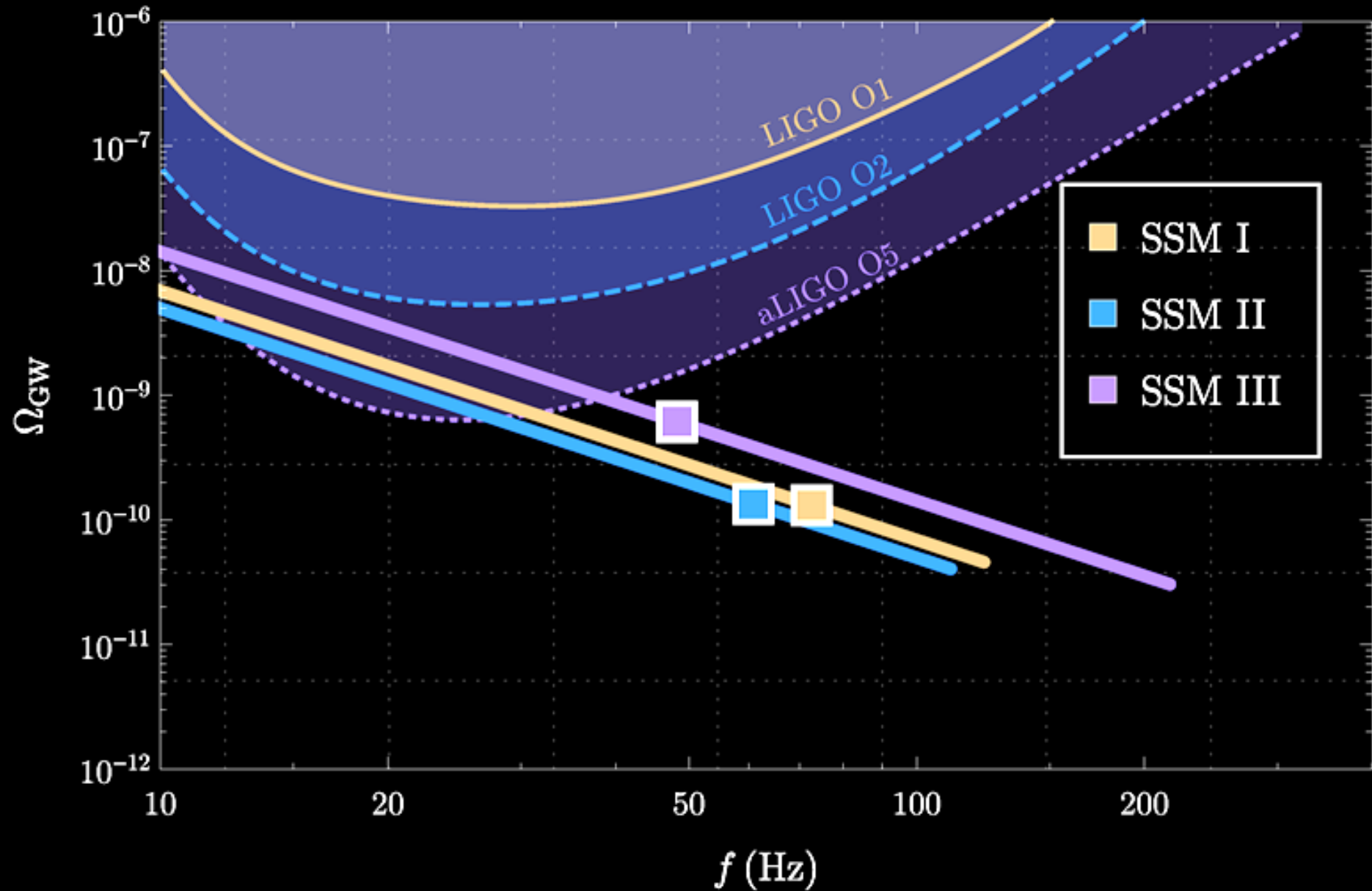
benchmark points

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)



conclusion

aLIGO might see gravitational wave relics from the early universe
(stochastic GW waves) in a few years