

The Complementarity of Colliders and Gravitational Waves for Probing the Electroweak Phase Transition



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Based on

... work in progress w/ Peisi Huang & Lian-Tao Wang [1608.XXXX].

... see also Barger, Chung, AL, Wang [1112.5460]
 and Chung, AL, Wang [1209.1819].

The Higgs “question” will not be answered by the LHC



‘The discovery of the Higgs boson
... determines the last free parameter of the Standard Model (it’s mass)’

Don’t misinterpret! The SM is flawed:

- SM fails to describe neutrino mass & dark matter
- Theoretical shortcomings: gauge hierarchy problem ($m_h \ll M_{pl}$) & strong CP prob.

The quote does not mean

‘The discovery of the Higgs boson
... leads to a complete understanding of SM degrees of freedom in nature’

E.g.,

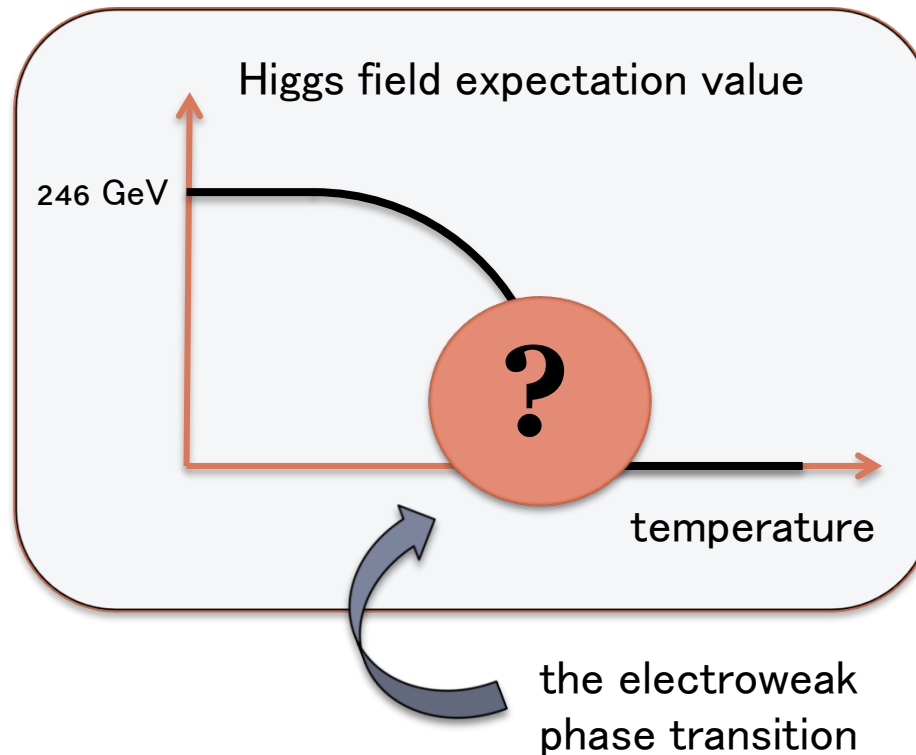
We know: that the Higgs is responsible for EW symmetry breaking (W & Z masses), and it has a vacuum expectation value $v = 246$ GeV.

We don’t know: what is nature of the dynamical process that led to $v = 246$ GeV?

The Electroweak Phase Transition



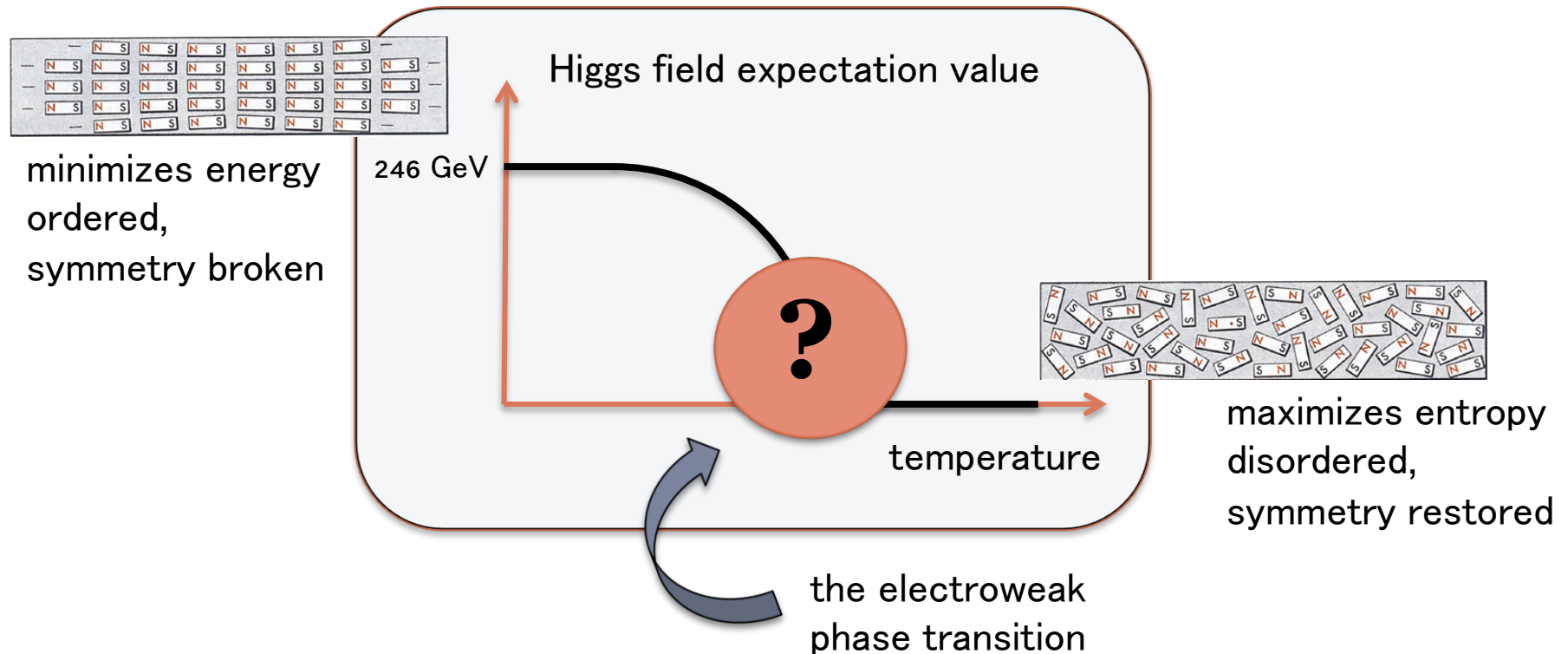
What happens if you heat a box of (neutral) SM stuff to $T \sim m_h$?



The Electroweak Phase Transition



What happens if you heat a box of (neutral) SM stuff to $T \sim m_h$?



What do we *want to know* about EWPT?

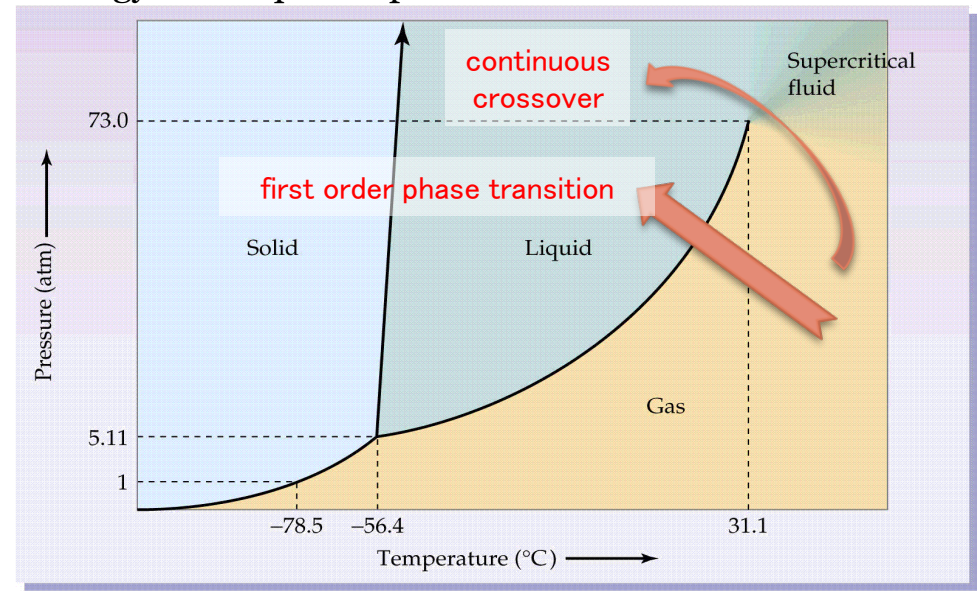
You can ask ...

- ... how much energy is stored? (latent heat)
- ... how quickly is energy released? (duration)
- ... what are the dynamics? (bubble wall profile & velocity)
- ... how are plasma properties affected? (dispersion relations, transport coefficients, electroweak sphalerons)

Most basic question:

Was the EWPT:
smooth (a *continuous crossover*) or
discontinuous (a *first order phase transition*)?

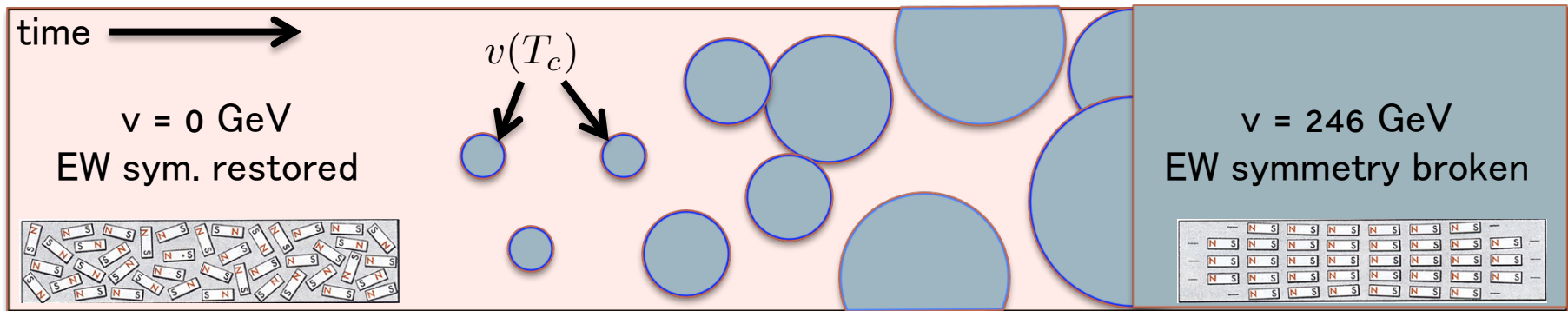
Analogy with liquid-vapor transition in CO₂:



Implications for Cosmology



Dynamics of the 1st Order Phase Transition



Origin of the Matter / Anti-Matter Asymmetry (baryogenesis)

... SM processes called EW sphalerons violate B-number outside of the bubbles

... To avoid *washout* these processes must be suppressed inside the bubbles Kuzmin, Rubakov, Shaposhnikov (1984)

$$v(T_c)/T_c \gtrsim 1.3 \quad (\text{“strongly first order”})$$

Cosmological Relics

... When the bubbles collide some of their energy is transferred to gravitational radiation

... Persists today as stochastic GW background

... Could be detected by space-based GW interferometer, like eLISA

Hogan (1986); Kamionkowski, Kosowsky, & Turner (1994)

The nature of the electroweak phase transition is an open question.

We want to know: first order or crossover?

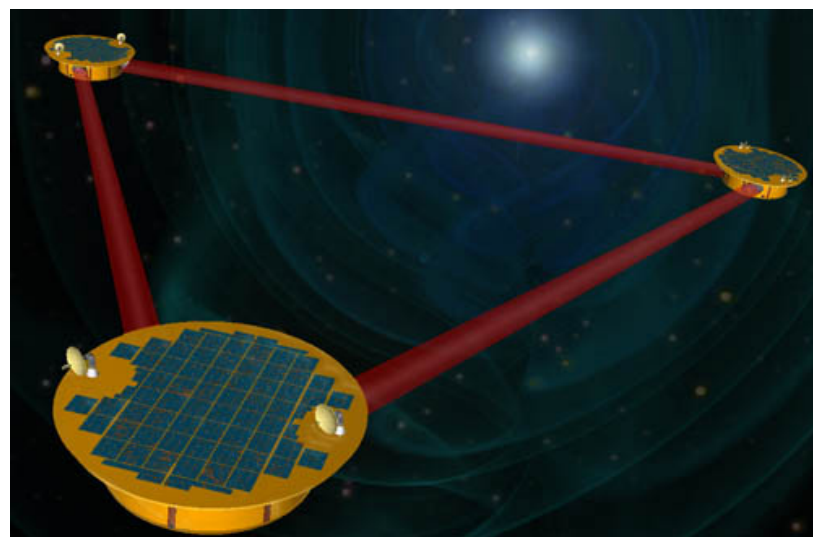
Relevant for baryogenesis & grav. waves (also magnetogenesis)

... how can we probe the EW phase transition?

How can we probe the EW phase transition?



Circles!

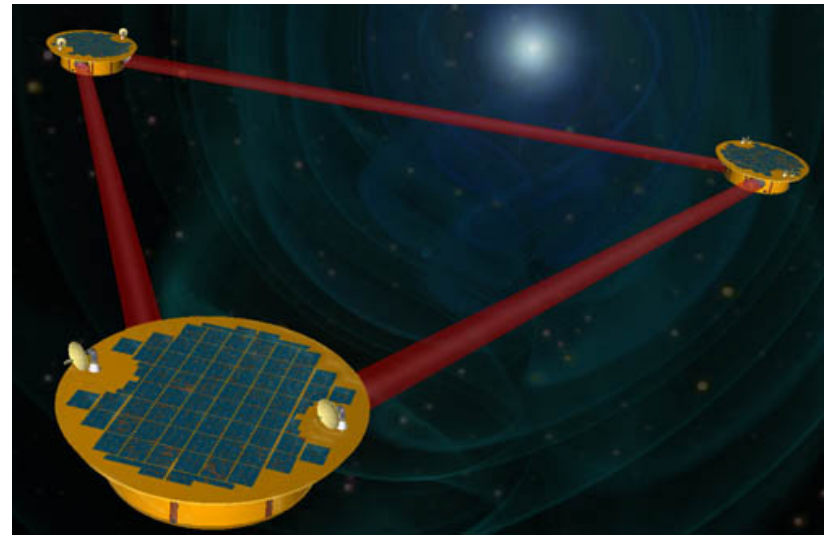


Triangles!

How can we probe the EW phase transition?



*Future
Colliders!*



*Space-Based
Interferometers!*

How do **future colliders** probe the EWPT?



In the Standard Model, the EWPT is not first order.

If the EWPT is first order *in nature*, there must be a new particle (or particles) with significant coupling to the Higgs boson.

The new particle masses should not be much higher than $m \sim \mathcal{O}(\text{few } 100 \text{ GeV})$ otherwise their effect on the EWPT is Boltzmann suppressed $\sim \text{Exp}[-m/T] \ll 1$.

So, either:

... we discover these particles at the LHC or a future collider

... or these particles evade discovery, but are still detected because they affect the way that the Higgs couples to other SM particles

... or these particles evade detection all together (“nightmare scenario”)

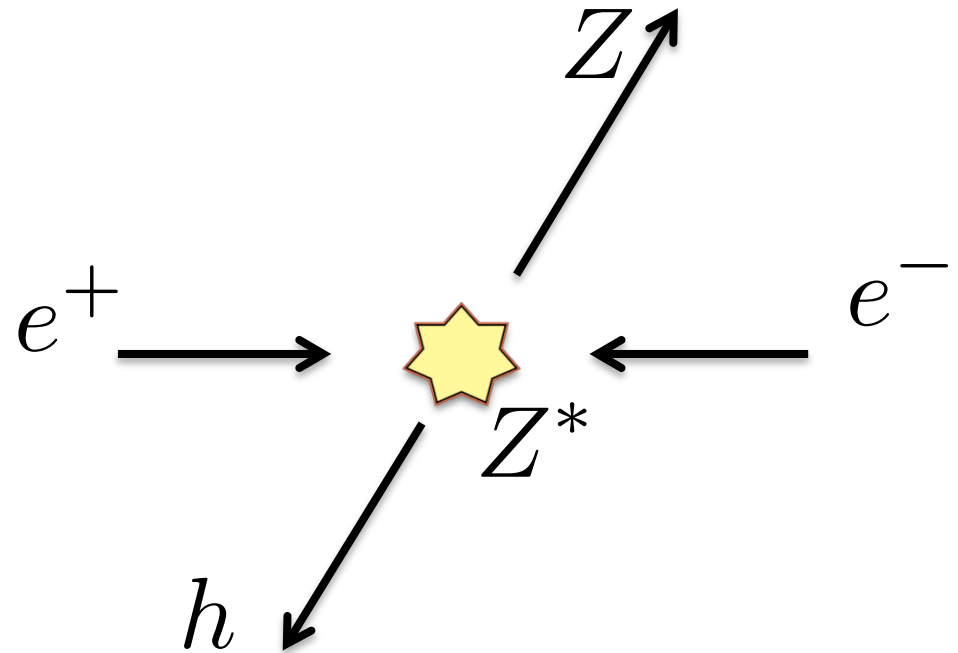
Will the projected sensitivity of **future colliders** be good enough to uncover evidence of the new particles that are responsible for a **first order EWPT**?

Higgs Factory

Lepton colliders provide “clean” environment for studying Higgs physics.

At $E \sim 250$ GeV, the production of Higgs + Z-boson is optimized.

E.g., the proposed Chinese circular collider (CEPC) will push precision Higgs measurements to the sub-percent level!



Projected Sensitivities to various Higgs couplings at different future colliders:

	current	HL-LHC	CEPC-250	ILC-500	FCC-ee	FCC-hh
hZZ	27%	7%	0.25%	0.25%	0.15%	-
$\Gamma(h \rightarrow \gamma\gamma)$	20%	8%	4%	-	1.5%	-
hhh	N/A	-	-	27%	-	10%

How do **interferometers** probe the EWPT?

A first order phase transition is a mess!

- “Bubbles” of Higgs phase nucleate
- They expand ... pushing their way through the plasma
- Eventually, the bubbles collide

Gravitational waves arise from bubble **collisions**, as well as **turbulence** and **sound waves** in the plasma.



$$f_{\text{gw}} \simeq (0.3 \text{ mHz}) \left(\frac{d_H(a_{\text{PT}})}{\lambda_{\text{gw}}(a_{\text{PT}})} \right) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{*,\text{PT}}}{106.75} \right)^{1/6}$$

GW frequency controlled by size of horizon at time of PT
→ fairly model-independent

$$\Omega_{\text{gw}} h^2 \simeq (1.6 \times 10^{-5}) \left(\frac{g_{*,\text{PT}}}{106.75} \right)^{-1/3} \Omega_{\text{gw}}(a_{\text{PT}})$$

GW energy depends on latent heat & efficiency of energy transfer to plasma
→ very model-dependent

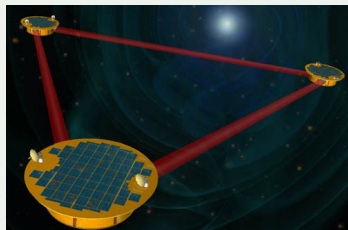
Space-Based GW Interferometer (e.g., eLISA)

On the ground, interferometers lose sensitivity at low frequency (< 10 Hz) due to seismic noise

Interferometers in space (eLISA, BBO, ALIA, DECIGO, etc) can reach the mHz frequencies where EWPT gravitational waves may reside

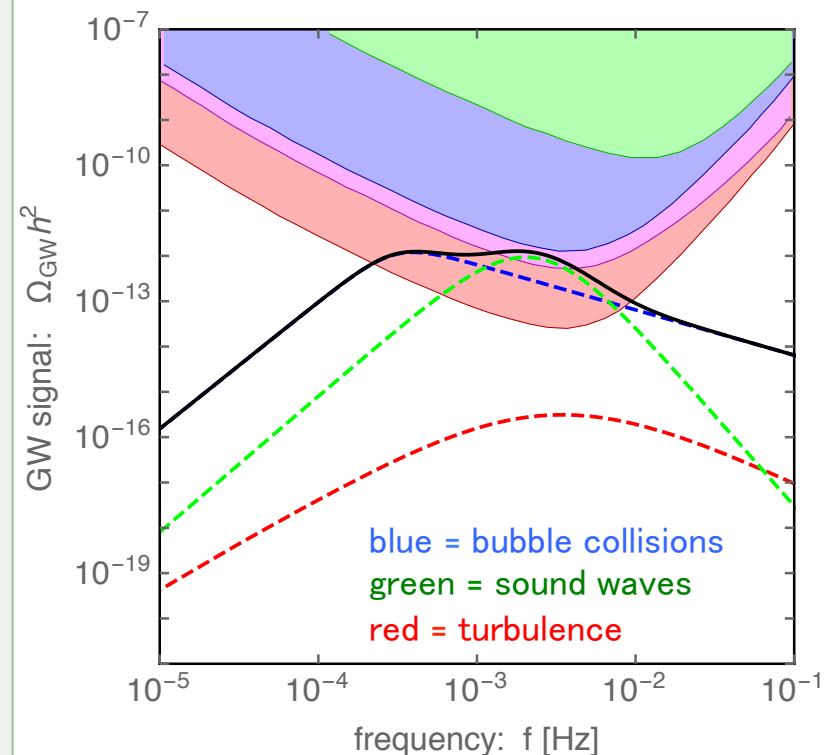
The eLISA project is studying four possible configurations [see Caprini et al, 1512.06293]

Name	C1	C2	C3	C4
Full name	N2A5M5L6	N2A1M5L6	N2A2M5L4	N1A1M2L4
# links	6	6	4	4
Arm length [km]	5M	1M	2M	1M
Duration [years]	5	5	5	2
Noise level	N2	N2	N2	N1



Three contributions to EWPT gravitational waves:

$T_{PT} = 100$ GeV, $\alpha = 0.2$, $\beta/H = 100$, $v/T = 4$ (run away)



How does it all work together?



SM + NEW PARTICLES



ALLOWS THE EWPT TO BE FIRST ORDER!



AND AS A BY PRODUCT LEADS TO:

**... DEVIATIONS IN HIGGS COUPLINGS (HZZ)
THAT CAN BE DETECTED AT FUTURE COLLIDERS**

**... AND STOCHASTIC GW BACKGROUND
THAT CAN BE DETECTED AT SPACE INTERFEROMETERS**

What Kinds of Models?



Model	References
SM + Scalar Singlet	Espinosa & Quiros, 1993; Benson, 1993; Choi & Volkas, 1993; McDonald, 1994; Vergara, 1996; Branco, Delepine, Emmanuel-Costa, & Gonzalez, 1998; Ham, Jeong, & Oh, 2004; Ahriche, 2007; Espinosa & Quiros, 2007; Profumo, Ramsey-Musolf, & Shaughnessy, 2007; Noble & Perelstein, 2007; Espinosa, Konstandin, No, & Quiros, 2008; Ashoorioon & Konstandin, 2009; Das, Fox, Kumar, & Weiner, 2009; Espinosa, Konstandin, & Riva, 2011; Chung & AL, 2011; Wainwright, Profumo, & Ramsey-Musolf, 2012; Barger, Chung, AL, & Wang, 2012; Huang, Shu, Zhang, 2012; Jiang, Bian, Huang, Shu, 2015
SM + Scalar Doublet	Davies, Froggatt, Jenkins, & Moorhouse, 1994; Huber, 2006; Fromme, Huber, & Seniuch, 2006; Cline, Kainulainen, & Trott, 2011; Kozhushko & Skalozub, 2011;
SM + Scalar Triplet	Patel, Ramsey-Musolf, 2012; Patel, Ramsey-Musolf, Wise, 2013
SM + Chiral Fermions	Carena, Megevand, Quiros, Wagner, 2005
MSSM	Carena, Quiros, & Wagner, 1996; Delepine, Gerard, Gonzales Felipe, & Weyers, 1996; Cline & Kainulainen, 1996; Laine & Rummukainen, 1998; Cohen, Morrissey, & Pierce,; Carena, Nardini, Quiros, & Wagner, 2012;
NMSSM / nMSSM / $\mu\nu$ SSM	Pietroni, 1993; Davies, Froggatt, & Moorhouse, 1995; Huber & Schmidt, 2001; Ham, Oh, Kim, Yoo, & Son, 2004; Menon, Morrissey, & Wagner, 2004; Funakubo, Tao, & Toyoda, 2005; Huber, Konstandin, Prokopec, & Schmidt, 2006; Chung, AL, 2010, Huang, Kang, Shu, Wu, Yang, 2014
EFT-like Approach (H^6 operator)	Grojean, Servant, Wells, 2005; Huang, Gu, Yin, Yu, Zhang 2015; Huang, Joglekar, Li, Wagner, 2015; Huang, Wan, Wang, Cai, Zhang (2016)

SM + Real Scalar Singlet



Consider

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial\phi_s)^2 - \frac{m_s^2}{2}\phi_s^2 - \frac{a_s}{3}\phi_s^3 - \frac{\lambda_s}{4}\phi_s^4 - \underbrace{\lambda_{hs}H^\dagger H\phi_s^2 - 2a_{hs}H^\dagger H\phi_s}_{\text{Higgs portal}}$$

Diagram annotations: Red arrows point from the text "five model parameters" to the parameters m_s^2 , a_s , λ_s , λ_{hs} , and a_{hs} . A red arrow points from "real scalar singlet" to ϕ_s in the kinetic term.

In the vacuum

$$\langle H \rangle = (0, v/\sqrt{2}) \quad \text{and} \quad \langle \phi_s \rangle = v_s$$

$$\sin 2\theta = \frac{4v(a_{hs} + \lambda_{hs}v_s)}{M_h^2 - M_s^2} \quad (\text{mixing})$$

Effective hhh coupling

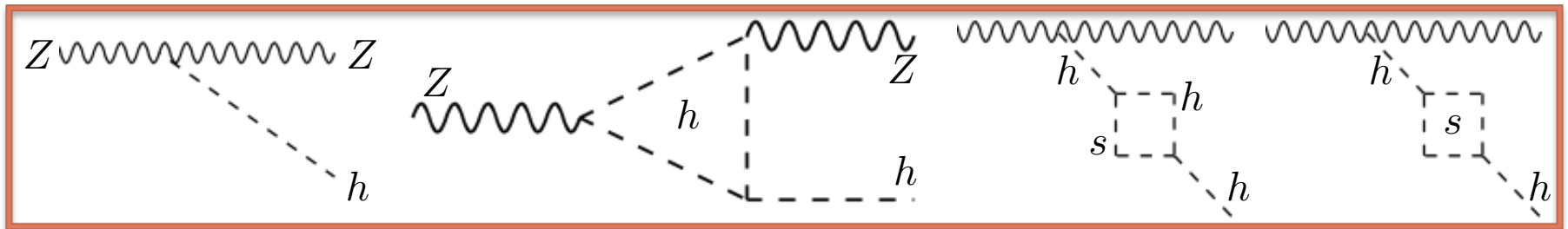
(adapted from: McCullough, 2014; Curtin, Meade, Yu, 2014)

$$\lambda_3 = (6\lambda_h v) \cos^3 \theta + (6a_{hs} + 6\lambda_{hs} v_s) \sin \theta \cos^2 \theta + (6\lambda_{hs} v) \sin^2 \theta \cos \theta \\ + (2a_s + 6\lambda_s v_s) \sin^3 \theta + 4 \frac{|\lambda_{hs}|^3 v^3}{16\pi^2 M_s^2}$$

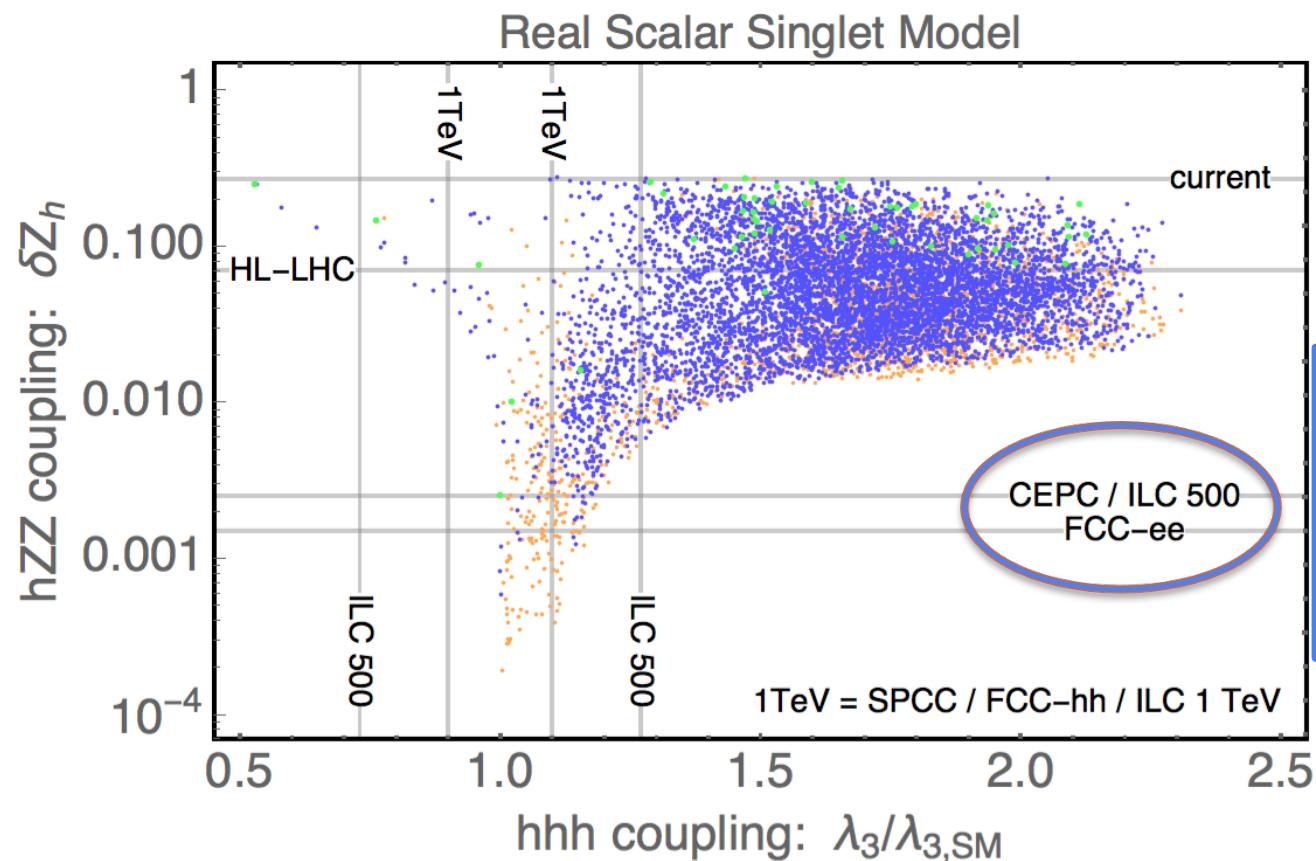
Effective hZZ coupling

$$\delta Z_h \approx (1 - \cos \theta) - 0.006 \left(\frac{\lambda_3}{\lambda_{3,\text{SM}}} - 1 \right) \\ - \frac{1}{2} \frac{|\lambda_{hs} v_s + a_{hs}|^2}{16\pi^2} I(M_h^2; M_h^2, M_s^2) - \frac{1}{2} \frac{|\lambda_{hs}|^2 v^2}{16\pi^2} I(M_h^2; M_s^2, M_s^2)$$

(leading effect is from mixing)

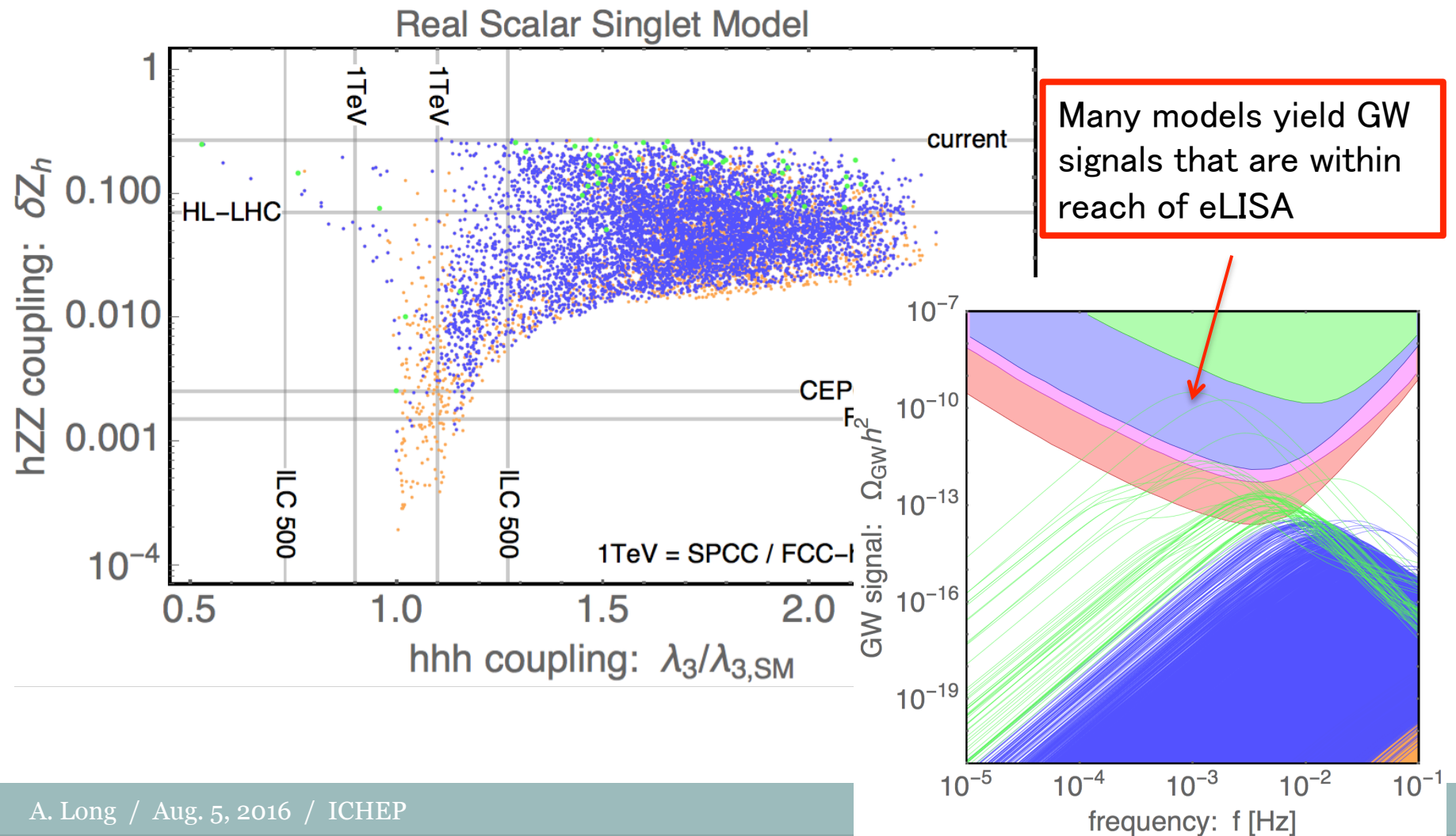


Orange = first order phase transition, $v(T_c)/T_c > 0$
 Blue = “strongly” first order phase transition, $v(T_c)/T_c > 1.3$
 Green = very strongly 1PT, could detect GWs at eLISA



Most models with a
 strongly 1st order PT,
 can be probed by hZZ
 coupling measurements
 at future Higgs factory

Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = “strongly” first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA



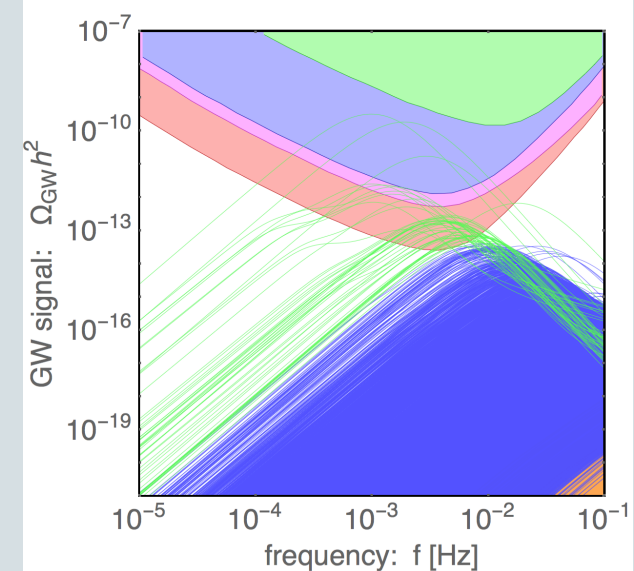
Cosmologists & Particle Physicists – in a race to the EWPT

Cosmologists Approach

... direct: uses GW interferometry
... with the sensitivity of eLISA, only models with
VERY strongly first order transitions can be probed

HEP Approach

... indirect: looks for modifications to hZZ couplings
... with the sensitivity of CEPC, most models with
strong first order phase transitions can be probed



green = can probe GW with eLISA
green & blue = can probe hZZ with colliders

Exceptions (nightmare scenarios)



Models with first order phase transitions *generically* have large deviations in hhh & hZZ. This is largely due to the tree-level mixing:

$$\sin 2\theta = \frac{4v(a_{hs} + \lambda_{hs}v_s)}{M_h^2 - M_s^2}$$

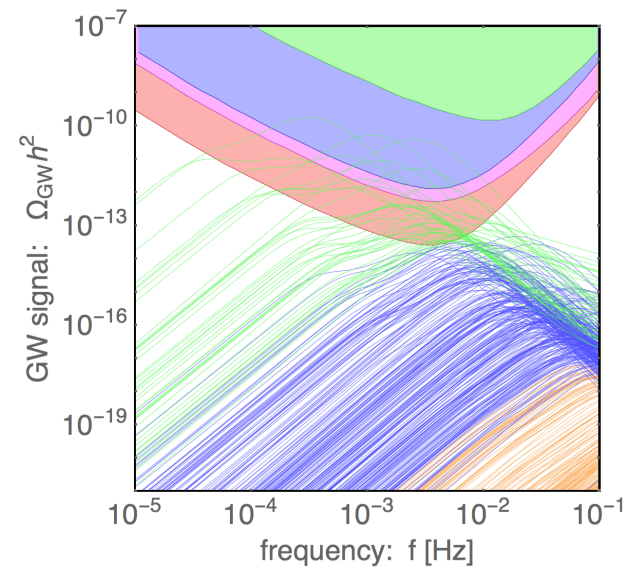
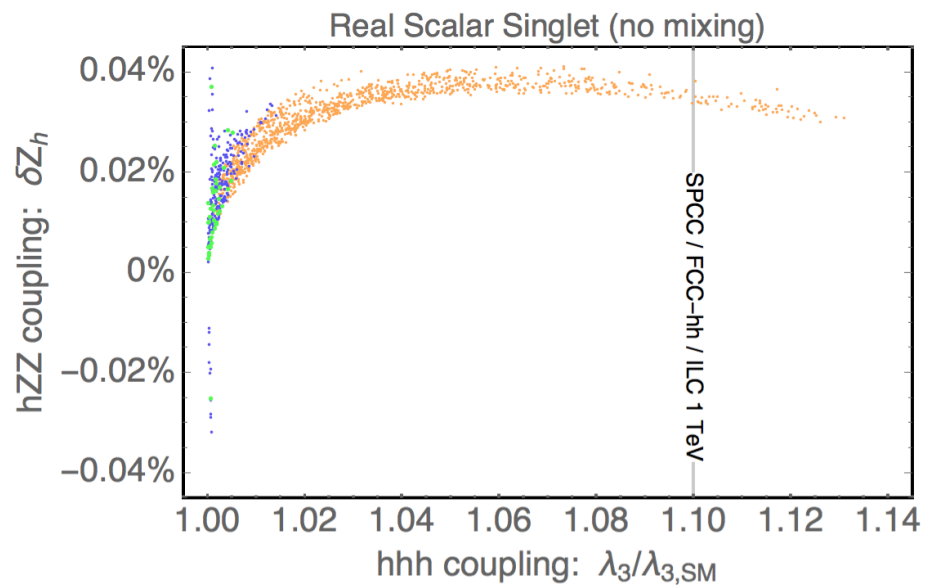
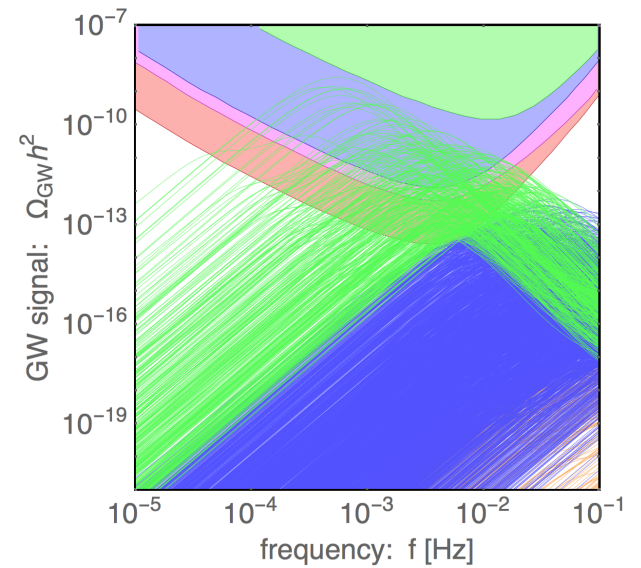
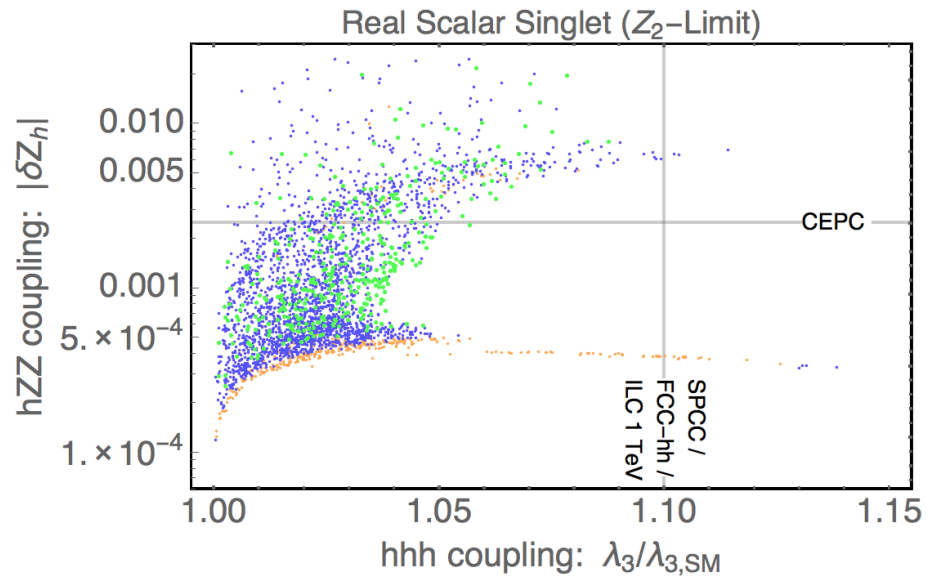
Without the mixing, it becomes difficult to probe the models at colliders.

Nightmare Scenario #1 – impose Z_2 to forbid mixing (Curtin, Meade, Yu, 2014)

$$a_s = 0 \quad , \quad a_{hs} = 0 \quad , \quad \text{and} \quad v_s = 0$$

Nightmare Scenario #2 – tune the mixing to zero

$$a_{hs} + \lambda_{hs}v_s = 0$$



Complementarity of Colliders & GW



Nature of the EW phase transition remains an outstanding question in high energy particle physics ... and the answer has direct bearing on early universe cosmology

- Explain origin of matter / anti-matter asymmetry
- Production of primordial magnetic field to seed galactic dynamo

Why should a cosmologist be excited about the future colliders?

- By measuring the Higgs couplings better, we are indirectly probing the EWPT

Large deviations in hZZ are generic in models with first order EWPT

The collider approach is complimentary to space-based GW interferometry

- eLISA's sensitivity peaks at the best frequency to probe EWPT

Interferometry: Robust, GWs are model-independent prediction of 1PT
Colliders: Powerful, can probe larger parameter space (weaker 1PTs)

Backup

Gravitational Wave Spectrum



Bubble nucleation temperature

See Caprini et. al.
eLISA study [1512.06293]

$$\left. \frac{S_3(T)}{T} \right|_{T=T_n} \simeq 142$$

Energy liberation

$$\alpha = \left. \frac{\rho_{\text{vac},u} - \rho_{\text{vac},b}}{\rho_{\text{rad},b}} \right|_{T=T_n}$$

Phase transition duration

$$\frac{\beta}{H} \equiv - \left. \frac{dS_3}{dt} \right|_{t=t_n} \approx T \left. \frac{d(S_3/T)}{dT} \right|_{T=T_n}$$

Gravitational Wave Spectrum



Gravitational Waves are produced by three sources

(1) Bubble collisions

$$\Omega_\phi h^2 = (1.67 \times 10^{-5}) \left(\frac{\beta}{H_{\text{PT}}} \right)^{-2} \left(\frac{\kappa_\phi \alpha}{1 + \alpha} \right)^2 \left(\frac{g_{*,\text{PT}}}{100} \right)^{-1/3} \left(\frac{0.11 v_w^3}{0.42 + v_w^2} \right) \frac{3.8(f/f_\phi)^{2.8}}{1 + 2.8(f/f_\phi)^{3.8}}$$

$$f_\phi = (1.65 \times 10^{-5} \text{ Hz}) \left(\frac{0.62}{1.8 - 0.1 v_w + v_w^2} \right) \left(\frac{\beta}{H_{\text{PT}}} \right) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{*,\text{PT}}}{100} \right)^{1/6}$$

(2) decaying turbulence

$$\Omega_{\text{turb}} h^2 = (3.35 \times 10^{-4}) \left(\frac{\beta}{H_{\text{PT}}} \right)^{-1} \left(\frac{\kappa_{\text{turb}} \alpha}{1 + \alpha} \right)^{3/2} \left(\frac{g_*}{100} \right)^{-1/3} v_w \frac{(f/f_{\text{turb}})^3}{(1 + f/f_{\text{turb}})^{11/3} (1 + 8\pi f/h_*)}$$

$$f_{\text{turb}} = (2.7 \times 10^{-5} \text{ Hz}) \frac{1}{v_w} \left(\frac{\beta}{H_{\text{PT}}} \right) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{*,\text{PT}}}{100} \right)^{1/6}$$

(3) and sound waves

$$\Omega_{\text{sw}} h^2 = (2.65 \times 10^{-6}) \left(\frac{\beta}{H_{\text{PT}}} \right)^{-1} \left(\frac{\kappa_v \alpha}{1 + \alpha} \right)^2 \left(\frac{g_*}{100} \right)^{-1/3} v_w \frac{7^{7/2} (f/f_{\text{sw}})^3}{[4 + 3(f/f_{\text{sw}})^2]^{7/2}}$$

$$f_{\text{sw}} = (1.9 \times 10^{-5} \text{ Hz}) \frac{1}{v_w} \left(\frac{\beta}{H_{\text{PT}}} \right) \left(\frac{T_{\text{PT}}}{100 \text{ GeV}} \right) \left(\frac{g_{*,\text{PT}}}{100} \right)^{1/6}$$

Gravitational Wave Spectrum



The efficiency factors (kappa's) depend on the strength of the phase transition.

For a strongly first order transition, the pressure gradient drives the bubble wall to expand and “run away” with $v_w \rightarrow 1$.

In this regime, the amount of energy transferred to the plasma saturates, and the surplus energy causes the bubble wall to accelerate.

$$\kappa_\phi = 1 - \frac{\alpha_\infty}{\alpha}, \quad \kappa_v = \frac{\alpha_\infty}{\alpha} \kappa_\infty, \quad \kappa_{\text{therm}} = 1 - \kappa_\phi - \kappa_v$$

$$\kappa_\infty = \frac{\alpha_\infty}{0.73 + 0.083\alpha_\infty^{1/2} + \alpha_\infty}$$

$$\alpha_\infty \simeq (4.9 \times 10^{-3}) \left(\frac{v(T_{\text{PT}})}{T_{\text{PT}}} \right)^2$$

$$\kappa_{\text{turb}} = (5\%) \times \kappa_v$$

(summarized in eLISA study: Caprini, et. al. 1512.06239)