Prospects for Gravitational Wave Signals from Higgs Inflation

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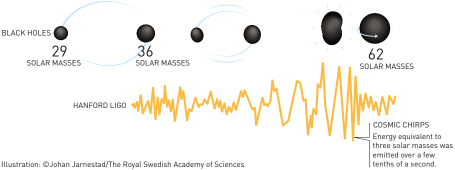
Based on R.I.P. by the Sinchon GW Group:
Injun Cheon, JK, Seong Chan Park, Yeji Park, Stefano Scopel, Juhoon Son,
Liliana Velasco Sevilla

A New Window to the Universe

Virgo collaboration/CCO 1.0



COSMIC CHIRPS
Energy equivalent to three solar masses was emitted over a few tenths of a second.

Illustration: ©Johan Jarnestad/The Royal Swedish Academy of Sciences

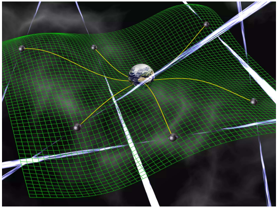
Caltech/MIT/LIGO Lab

- Discovery of gravitational waves (GW) by LIGO & Virgo
  LIGO/Virgo, PRL **116** (2016), PRL **118** (2017)
- Source: mergers of black holes and neutron stars

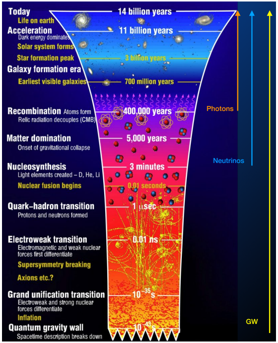
$\rightsquigarrow$ GW astronomy and cosmology

A Window to the Very Early Universe?

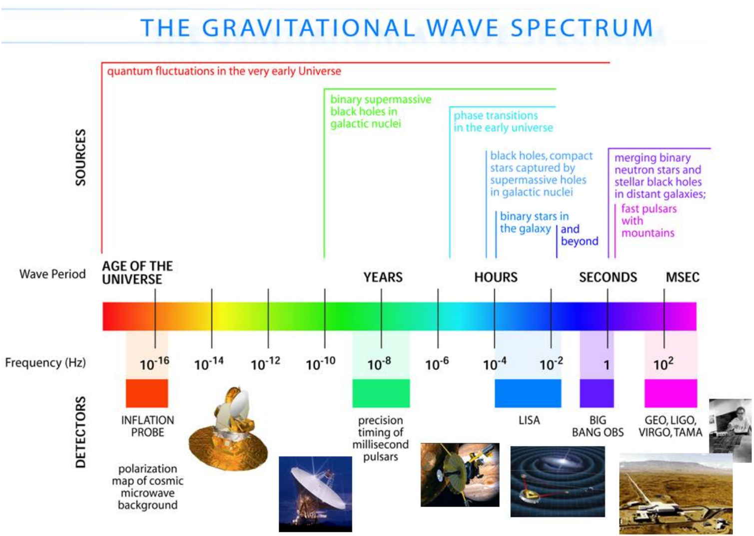
- Pulsar Timing Arrays
  $\rightsquigarrow$ Evidence for Stochastic GW Background
  NANOGrav, ApJL **951** (2023)
  EPTA, InPTA, A&A **678** (2023)
  Parkes PTA, ApJL **951** (2023)
  CPTA, RAA **23** (2023)
- Lower frequency than LIGO/Virgo events
  $\rightsquigarrow$ Mergers of supermassive black holes?
- More interesting: particle physics origin
  - First-Order Phase Transition (FOPT)
  - Cosmic strings



D. Champion/MPI for Radio Astronomy



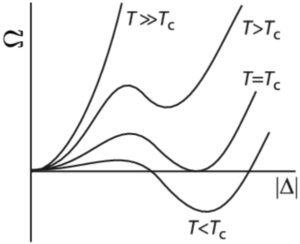
Looking Forward to More Discoveries



https://www.astro.gla.ac.uk/users/martin/powersof60/images/gwspectrum.jpg

First-Order Phase Transitions

See talks by Merchand, Kowalska

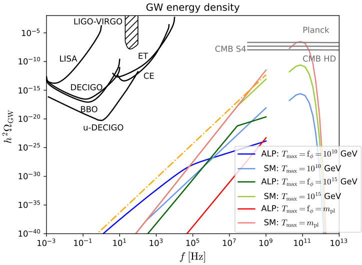


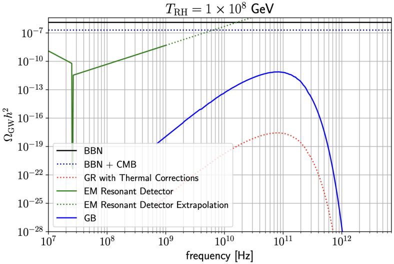
Kinnunen et al., Rep. Prog. Phys. **81** (2018)

1. High temperature: potential minimum at $\phi = 0$
2. $T < T_c$: deeper mimimum at $\phi = v$, separated by barrier
3. Tunneling $\rightsquigarrow$ bubbles of true vacuum
4. GW from bubble collisions and turbulence

Gravitational Waves from Particle Physics

- SM: no FO electroweak PT for Higgs mass $\gtrsim$ 70 GeV
  Kajantie et al., PRL **77** (1996); Karsch et al., NP Proc. Suppl. **53** (1997)
  Csikor et al., PRL **82** (1999)
- GW from thermal fluctuations in plasma Ghiglieri & Laine, JCAP **07** (2015)
- Peak at frequency ~ GHz
- Amplitude enhanced for
  - Very weakly interacting new particles Drewes et al., JCAP **06** (2024)
  - Gauss-Bonnet Cosmology Biswas, . . . , Scopel, Velasco Sevilla, 2405.15998





SM Extensions with First-Order Phase Transitions

- Most famous: SUSY with light stop
  Carena et al., PLB **380** (1996); Espinosa, NPB **475** (1996)
  Delepine et al., PLB **386** (1996); Cline & Kainulainen, NPB **482** (1996); . . .
- Minimal from model building perspective: 2HDM
  Dorsch et al., JHEP **10** (2013); Basler et al., JHEP **02** (2017)
  Andersen et al., PRL **121** (2018); . . .
- Minimal from EFT perspective: higher-dimensional operators
  Zhang, PRD **47** (1993); Grojean et al., PRD **71** (2005)
  Bödeker et al., JHEP **02** (2005); Chala et al., JHEP **07** (2018); . . .
- Many recent works Review: Roshan & White, arXiv:2401.04388
  See talks by Rubio, Merchand, Koutroulis, Gorbunov, Kowalska, Wang, King

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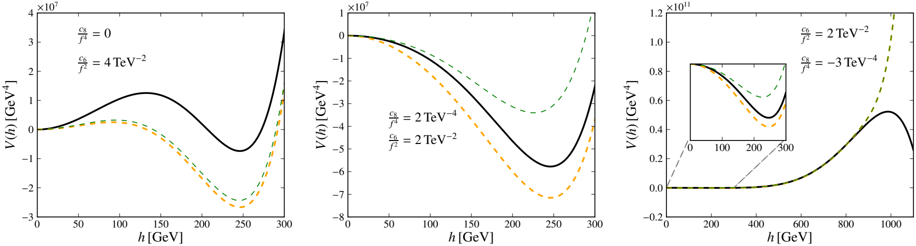

Higgs Inflation

Bezrukov & Shaposhnikov, PLB **659** (2008)

$$\mathcal{L}_J = \sqrt{-g_J}\left[\frac{M_\mathrm{P}^2}{2}R_J + \xi\phi^\dagger\phi\, R_J - g_J^{\mu\nu}(D_\mu\phi)^\dagger(D_\nu\phi) - V_J(\phi) + \ldots\right]$$

- J: Jordan frame
- R: Ricci scalar
- V_J: SM Higgs potential
- ξ: non-minimal coupling to gravity
  - Consistent with all symmetries
  - Required for renormalization in curved spacetime See talk by Rubio
  - Not necessarily small

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- Def.: conformal factor $\Omega^2(\phi) \equiv 1 + 2\xi\frac{\phi^\dagger\phi}{M_P^2}$

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Higgs Inflation

- Unitary gauge: $\phi = \begin{pmatrix} 0 \\ (\varphi + v)/\sqrt{2} \end{pmatrix}$
- Weyl transformation to Einstein frame: $g_J \to g_E \equiv \Omega^2(\varphi)\, g_J$
- Canonical normalization: $\chi = \int_0^\varphi \mathrm{d}\varphi \sqrt{\frac{3}{2} \frac{(\Omega^2{}_{,\varphi})^2}{\Omega^4} + \frac{1}{\Omega^2}}$

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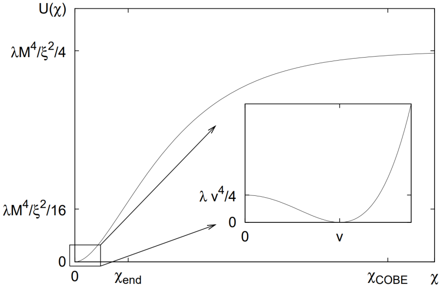
- Gravity remains weak below cutoff $\sim M_\mathrm{P}\,\Omega$
- Potential flat for large field values $\rightsquigarrow$ slow-roll

Higgs Inflation



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FOPT and Inflation from the Higgs?

- SM + higher-dimensional operators ⇝ FO EWPT

$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 + \frac{c_6}{f^2}(\phi^\dagger\phi)^3 + \frac{c_8}{f^4}(\phi^\dagger\phi)^4$$

  - f: cutoff
  - c_6, c_8: dimensionless couplings
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Can we have both?

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CMB measurements

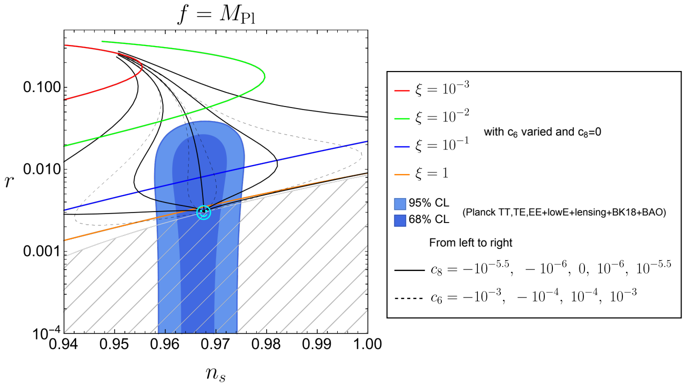
Scalar power spectrum amplitude	$\ln(10^{10} A_s) = 3.044 \pm 0.014$
Scalar spectral index	$n_s = 0.9649 \pm 0.0042$
Tensor-to-scalar power ratio	$r < 0.036$ (95% CL)

Planck, A&A **641** (2020); BICEP/Keck, PRL **127** (2021)

⇝ Strong contraints on inflationary parameters

⇝ Strong bounds on higher-dimensional operators

Effects of Higher-Dimensional Operators

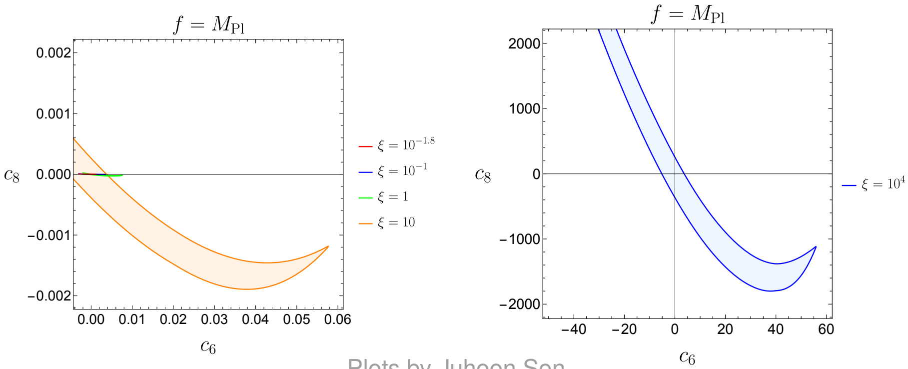


Plot by Juhoon Son

See also Jinno, . . . , Park, JCAP **03** (2020)

Attractor point for $\xi \gg 1 \rightsquigarrow$ effects of c_6 and c_8 reduced

CMB Constraints



Plots by Juhoon Son

- Very strong constraints for $\xi \lesssim 1$
- Room for new physics at high scales ($f \lesssim M_P$) for $\xi \gg 1$
- No way to affect EWPT (requires $f \sim$ TeV)

Higgs Inflation in a Dark Sector

- $U(1)_X$ gauge symmetry
- SM singlet scalar with $U(1)_X$ charge
  - Spontaneously breaks $U(1)_X$ $\rightsquigarrow$ FOPT $\rightsquigarrow$ GW
  - Non-minimal coupling to gravity $\rightsquigarrow$ Higgs-inflation-like inflation
- Optional: fermion(s) with mass from Yukawa coupling
- Very weak coupling to SM (details t.b.d.) $\rightsquigarrow$ reheating

Effective Scalar Potential at Finite Temperature

$$\begin{aligned}
V(h_c, T) &= V_{\text{tree}}(h_c) + V_{\text{1-loop}}(h_c) + V_{\text{th}}(h_c, T) \\
V_{\text{tree}}(h_c) &= -\frac{\mu^2}{2} h_c^2 + \frac{\lambda}{4} h_c^4 \\
V_{\text{1-loop}}(h_c) &= \sum_{i=h,\chi,g,f} \frac{n_i}{64\pi^2} m_i^4(h_c) \left[\ln \frac{|m_i^2(h_c)|}{v^2} - C_i \right] \\
V_{\text{th}}(h_c, T) &= \sum_{i=h,\chi,g} \frac{n_i}{2\pi^2} T^4 J_b\!\left(\frac{m_i^2(h_c)}{T^2} \right) + \frac{n_f}{2\pi^2} T^4 J_f\!\left(\frac{m_f^2(h_c)}{T^2} \right) \\
m_h^2(h_c) &= -\mu^2 + 3\lambda h_c^2 \\
m_\chi^2(h_c) &= -\mu^2 + \lambda h_c^2 \\
m_g^2(h_c) &= \frac{g^2}{4} h_c^2 \\
m_f^2(h_c) &= \frac{y^2}{2} h_c^2
\end{aligned}$$

Scalar Potential with Barrier

2 options for generating potential barrier around $T \sim v$ (so far)

- No fermions, $\lambda \ll 1$ See talk by Kowalska
- 1 (Dirac) fermion, $\lambda \sim 0.1$

$\rightsquigarrow$ FOPT possible

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GW spectrum determined by

- Nucleation temperature T_n
- $\alpha \leftrightsquigarrow$ strength of PT
- $\beta \leftrightsquigarrow$ duration

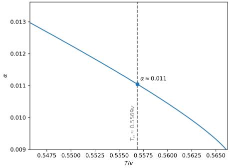
See talks by Merchand, Wang

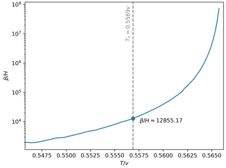
Calculated with help from `CosmoTransitions`
Wainwright, Comput. Phys. Commun. **183** (2012)

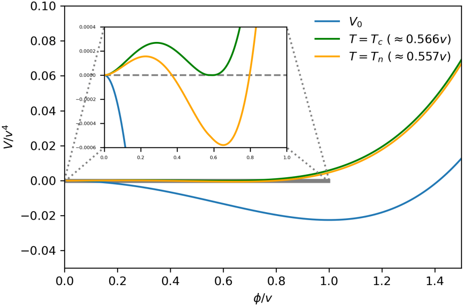
Example: 1 Fermion

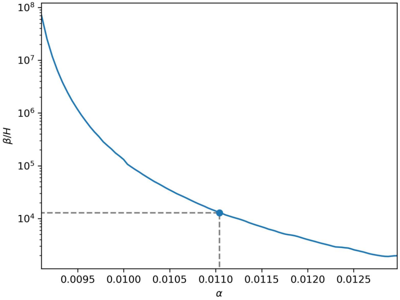
Case 3. U(1) model

- VEV: $\Lambda = 10^{15}$ GeV
- D.O.F of particles: (scalar, gauge boson, fermion) =(1+1, 3, 4)
- coupling constants
  - scalar self-coupling: λ = 0.09
  - gauge coupling: $g = 1$
  - Yukawa coupling: $y = 1$



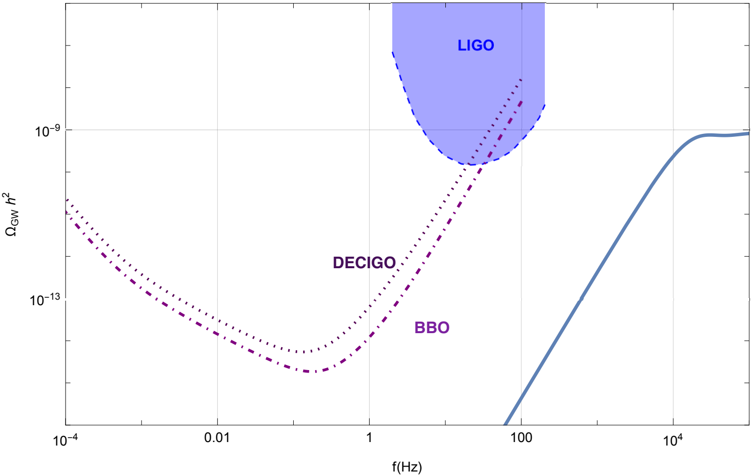






Slide by Yeji Park

Resulting Gravitational Wave Spectrum



Plot by Liliana Velasco Sevilla

Conclusions and Outlook

- Higgs inflation doesn't like higher-dimension operators in potential
- Dark $U(1)_X \rightsquigarrow$ gravitational waves and inflation from same scalar
- Ongoing work
  - Constraints on and from inflation
  - Map parameter space
  - Calculation of GW predictions
- Future directions
  - Inflaton coupling to SM $\rightsquigarrow$ reheating
  - Lower scale of symmetry breaking
  - Different gauge groups
  - Dark Matter