Complementarity between collider and gravitational wave searches for new physics

Mikael Chala
(University of Granada)

based mostly on ***1910.13125***, *1802.02168*, *1905.00911*

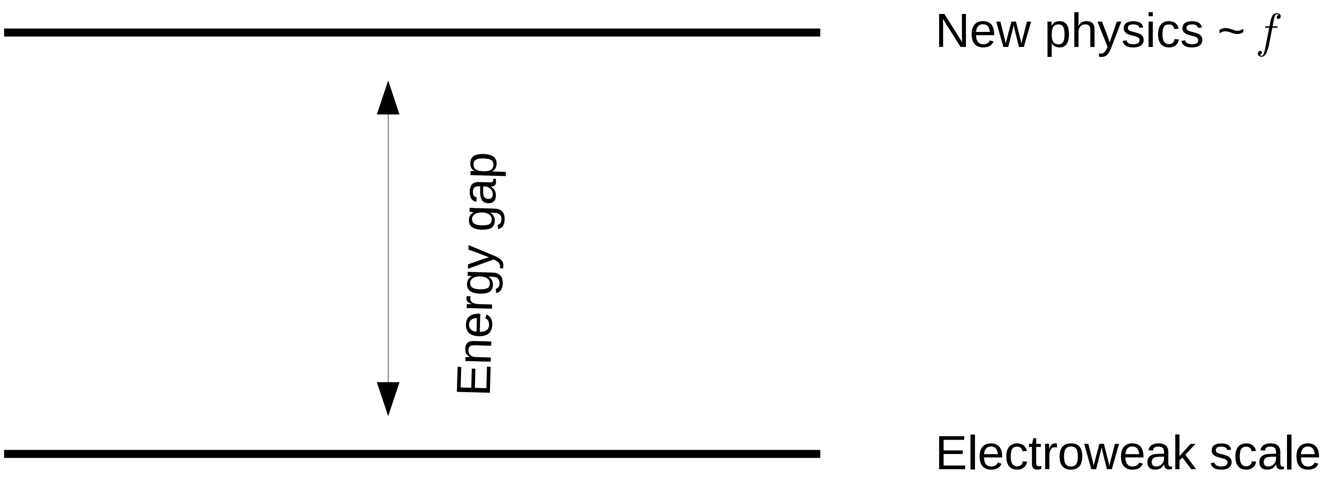
The 2021 International Workshop on the High Energy Circular Electron Positron Collider; November 11, 2021

Disclaimer:

(i) All models discussed here (and more!) can be found in the LISA Cosmology Working group paper 1910.13125

(ii) In some cases, I naively project results from FCC-ee to CEPC

The SM effective-field theory (SMEFT) is probably the best motivated new physics scenario (no light resonances anywhere, B-anomalies point to high scale, etc.)

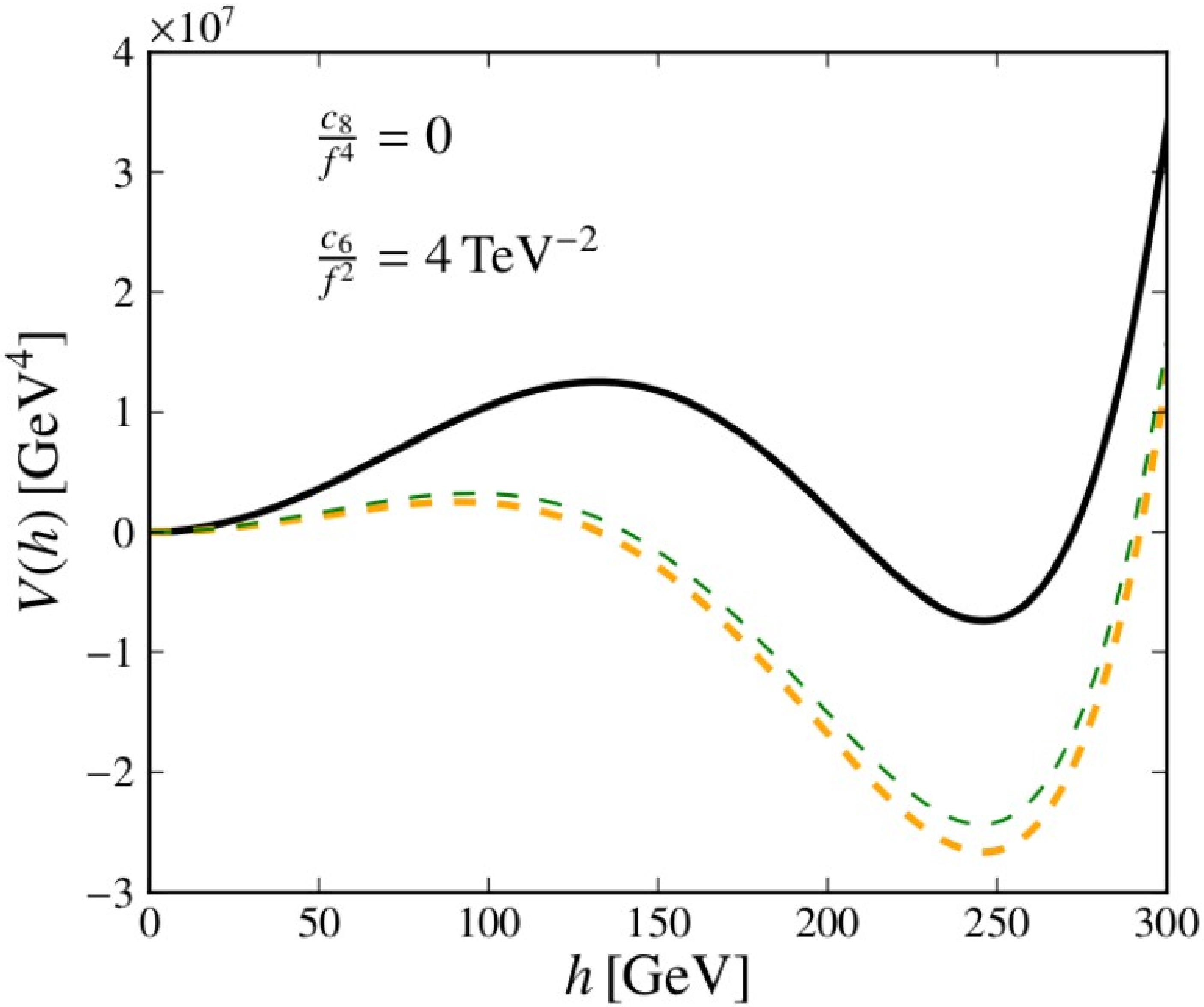


The SM Lagrangian must be extended with effective interactions. This implies in particular modifications of the Higgs potential

$$V_{\mathrm{tree}}(h) = -\mu_H^2|H|^2 + \lambda_h|H|^4 + \frac{c_6}{f^2}|H|^6 + \frac{c_8}{f^4}|H|^8$$
$$= -\frac{1}{2}\mu_H^2 h^2 + \frac{1}{4}\lambda_H h^4 + \frac{c_6}{8f^2}h^6 + \frac{c_8}{16f^4}h^8$$

T=0 one-loop

Finite-T potential at critical point

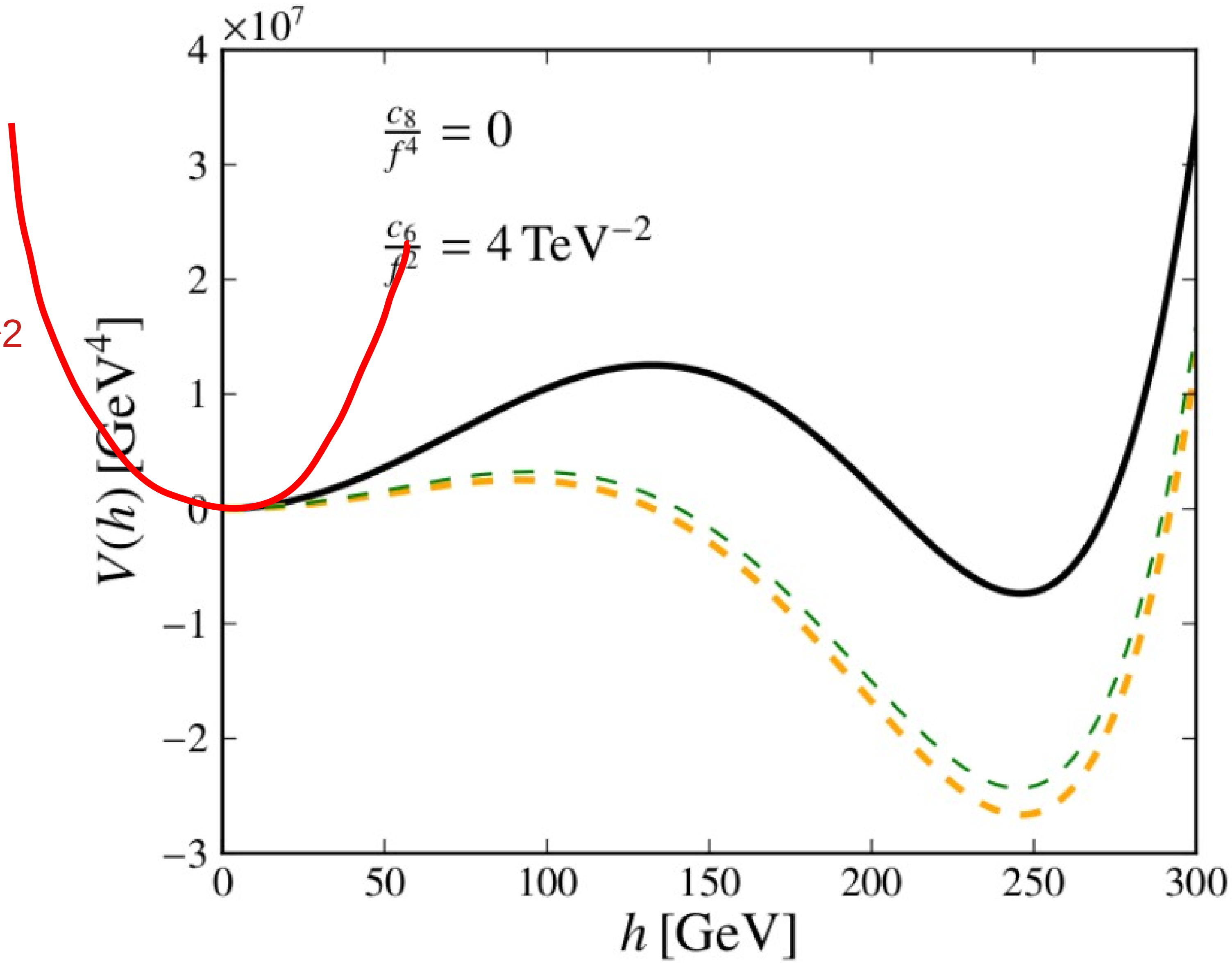


T=0 one-loop

Finite-T potential at critical point

Very high T

V(h)~T^2 h^2



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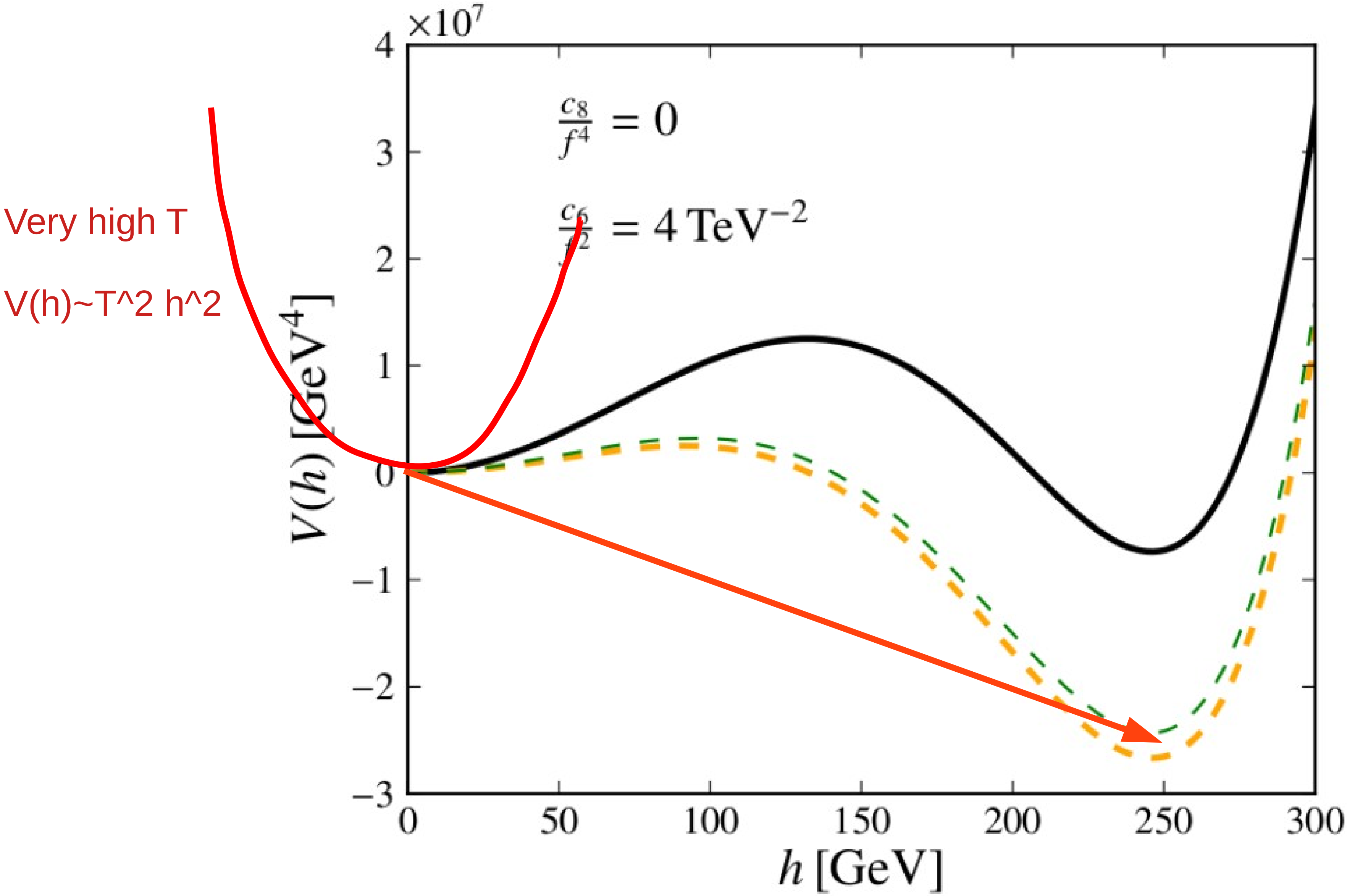
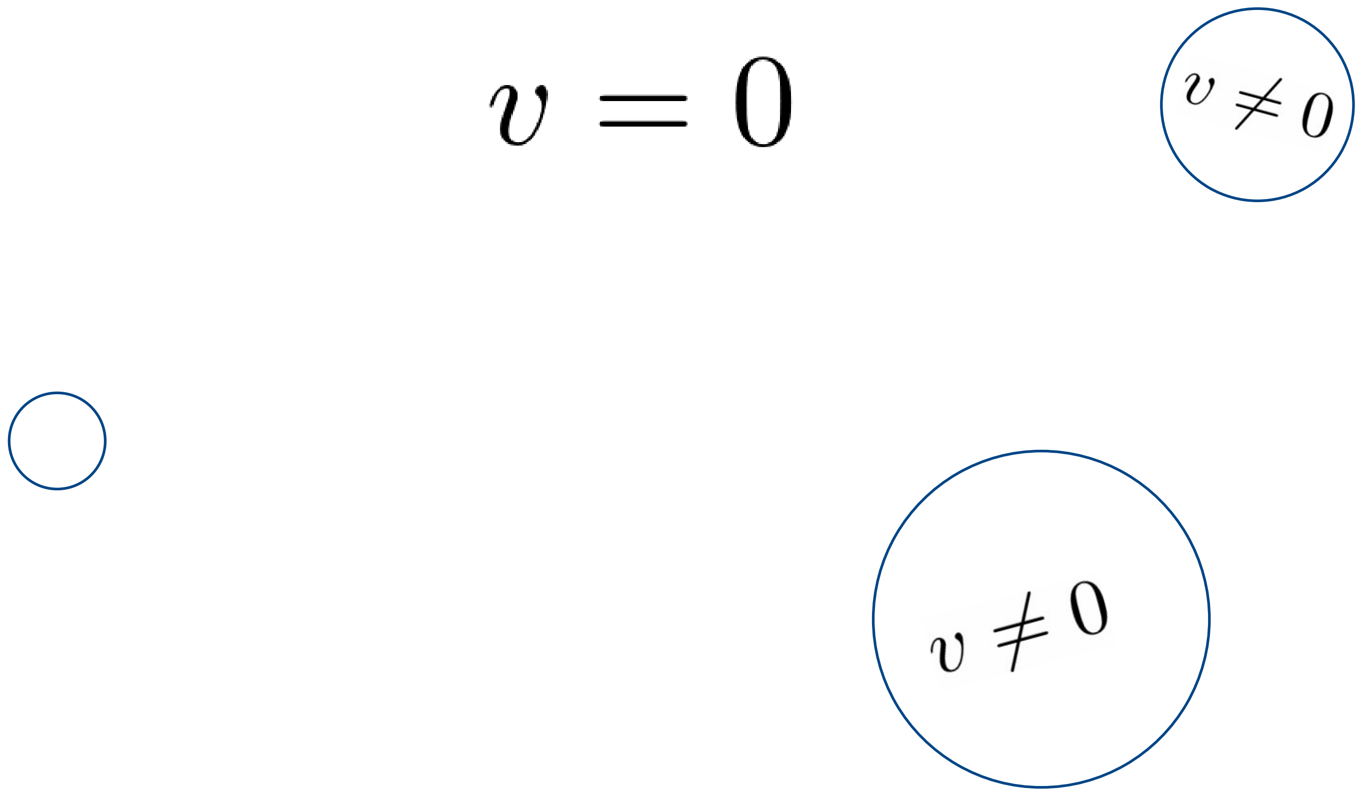


Contrary to what occurs within the SM, this phase transition is first-order and eventually strong: $v/T > 1$.

The phase transition occurs through nucleation of bubbles than can collide generating gravitational waves

$$v = 0$$

The phase transition occurs through nucleation of bubbles than can collide generating gravitational waves



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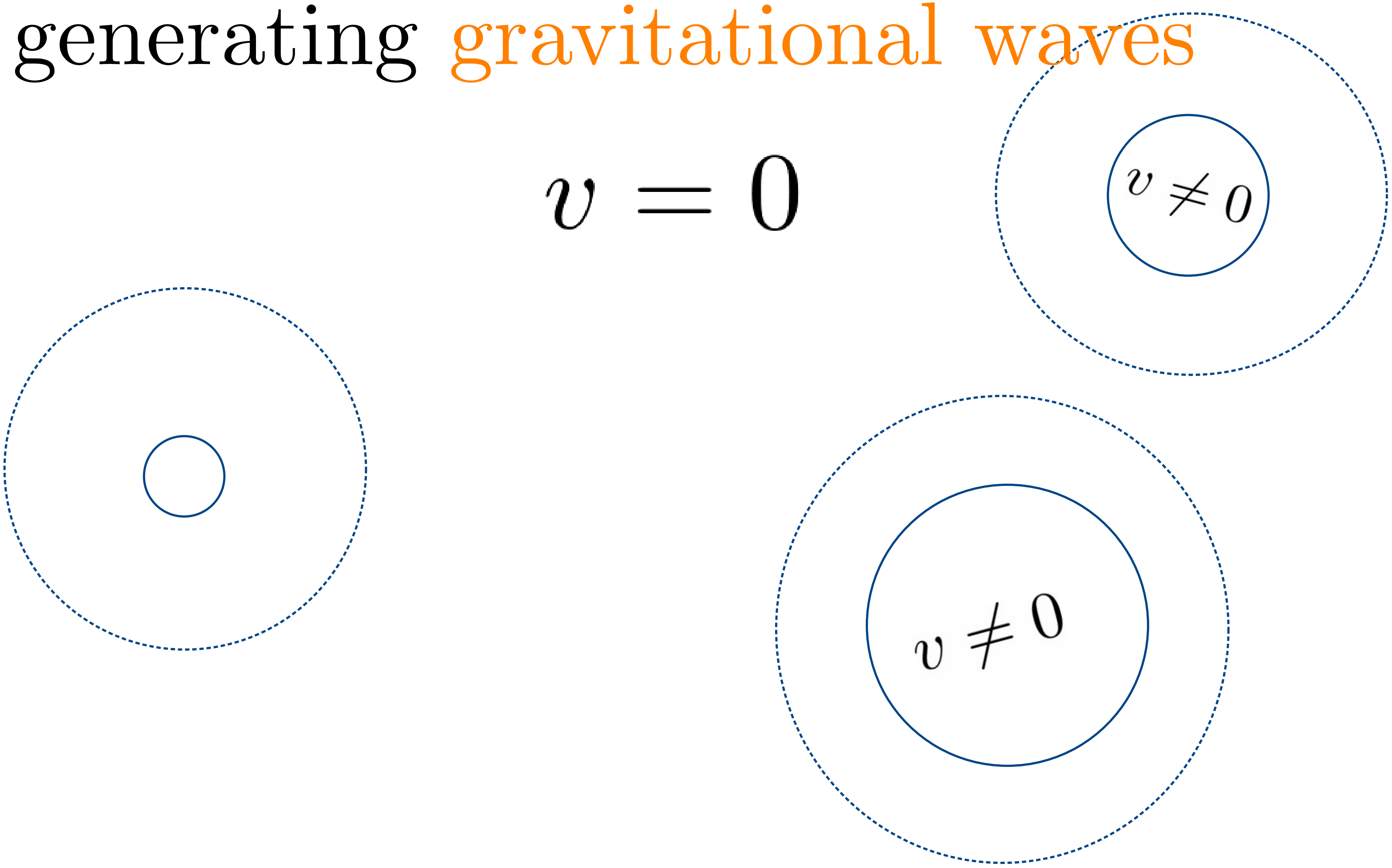

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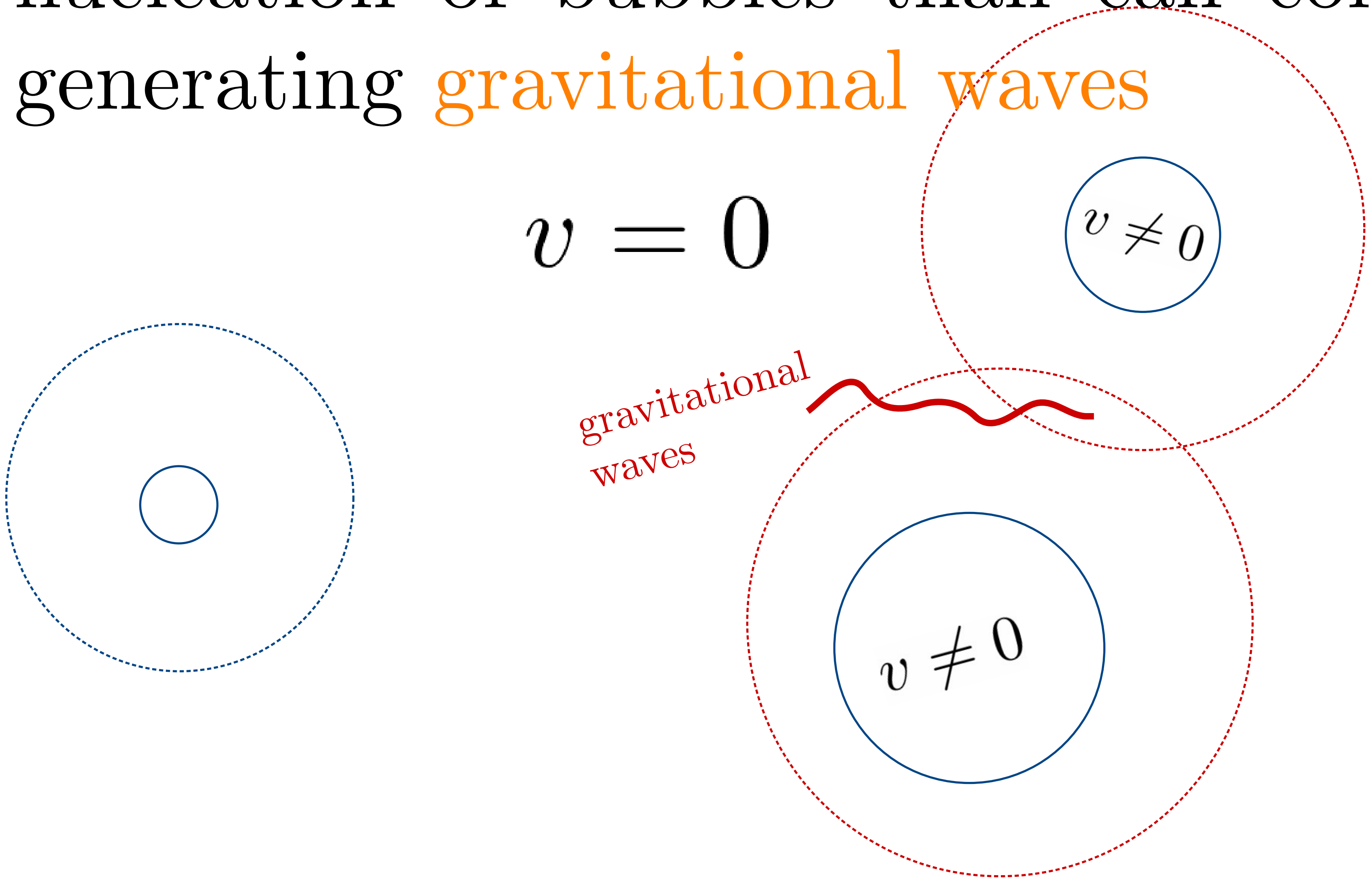
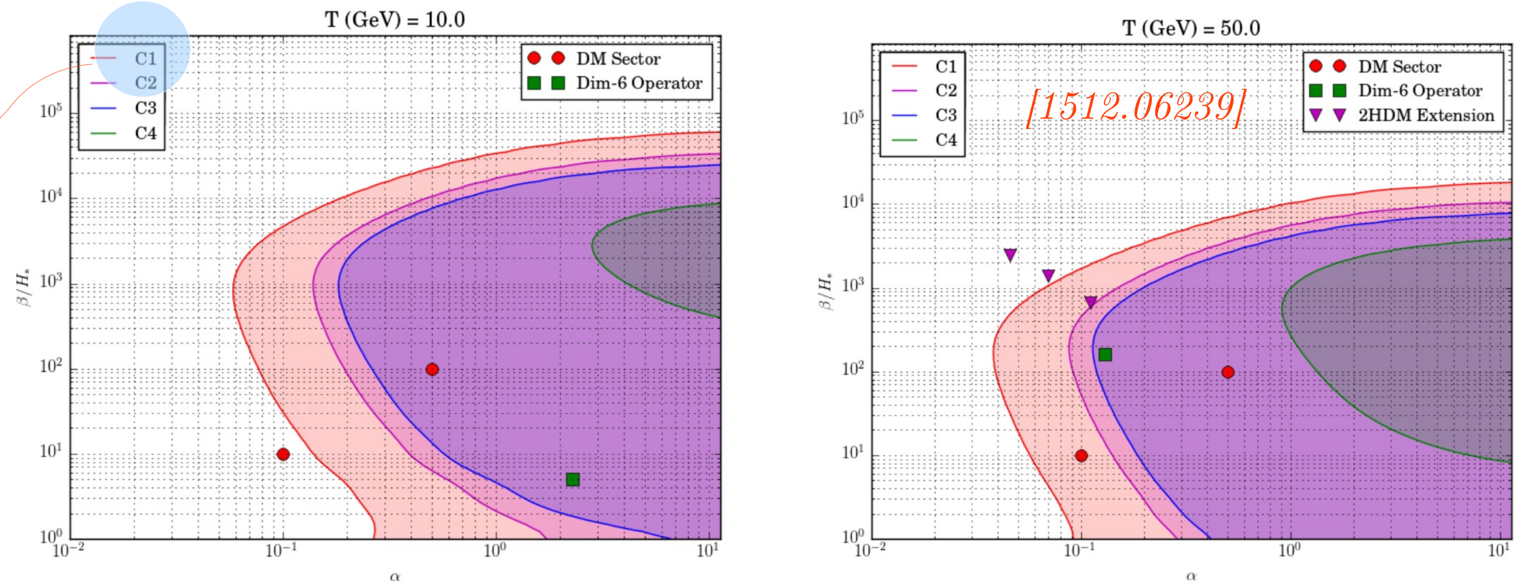


Parameters relevant for the gravitational waves

- Inverse duration time of the EWPT: $\beta/H = T_n \frac{d}{dT}(S_3/T)$
- Normalized latent heat: $\alpha = \epsilon(T_n)/(35T_n^4)$



current LISA
expectation

We need to included dimension-8 terms because the separation of scales is not very large: $v/f < 1$ is not super small

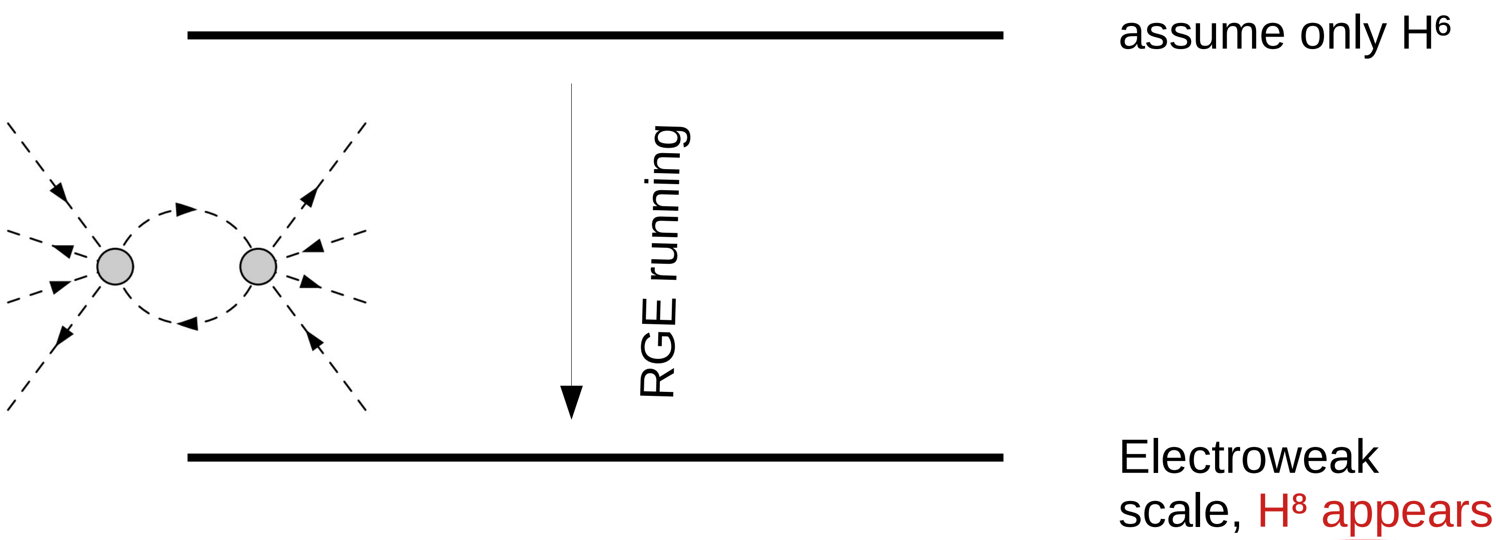
$$\frac{v_n}{T_n} \sim a_6 c_6 \frac{v^2}{f^2} + \mathcal{O}(c_8 \frac{v^4}{f^4}) \sim 1.5 + \mathcal{O}(c_8 \frac{v^4}{f^4}) \sim 1 - 2$$

for $c_6/f^2 \sim 2\ \mathrm{TeV}^{-2}$

for $c_8/f^4 \in [-3, 3]\ \mathrm{TeV}^{-4}$

$$\alpha \sim 2 \times 10^{-2} + \mathcal{O}(c_8 \frac{v^4}{f^4}) \sim (1-4) \times 10^{-2}$$

Even running effects can be important

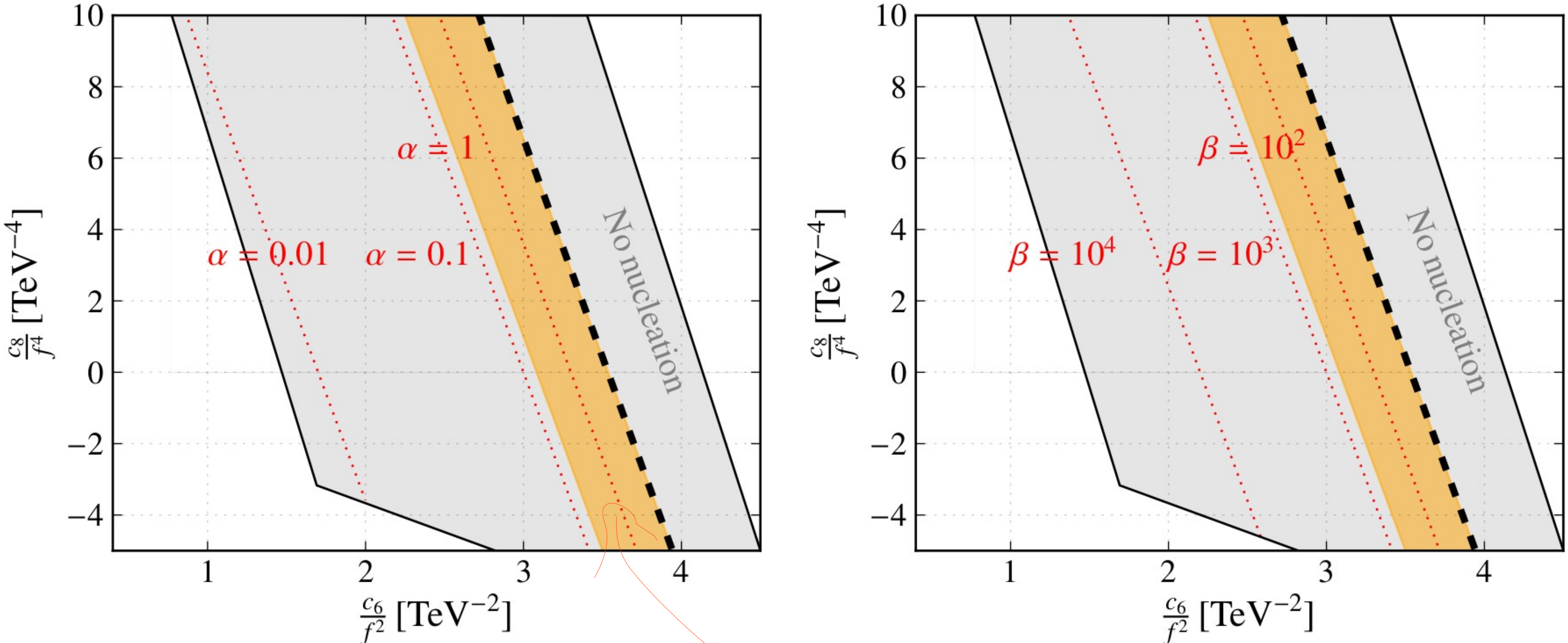


$$V \sim -\mu^2|\phi|^2 + \lambda|\phi|^4 + \frac{c_\phi}{\Lambda^2}\left(1 - \frac{108}{16\pi^2}\lambda \log\frac{\Lambda}{v}\right)|\phi|^6 + \frac{126}{16\pi^2\Lambda^4}\log\frac{\Lambda}{v}c_\phi^2\,|\phi|^8$$

30% differences if the running is neglected; see 2106.05291

Parameters relevant for the EWPT

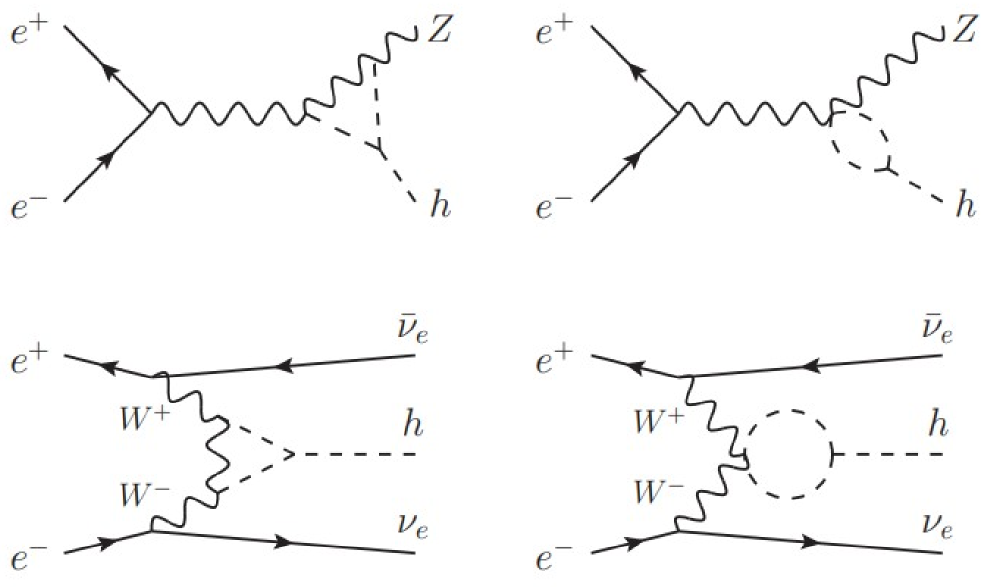
(and for gravitational waves)



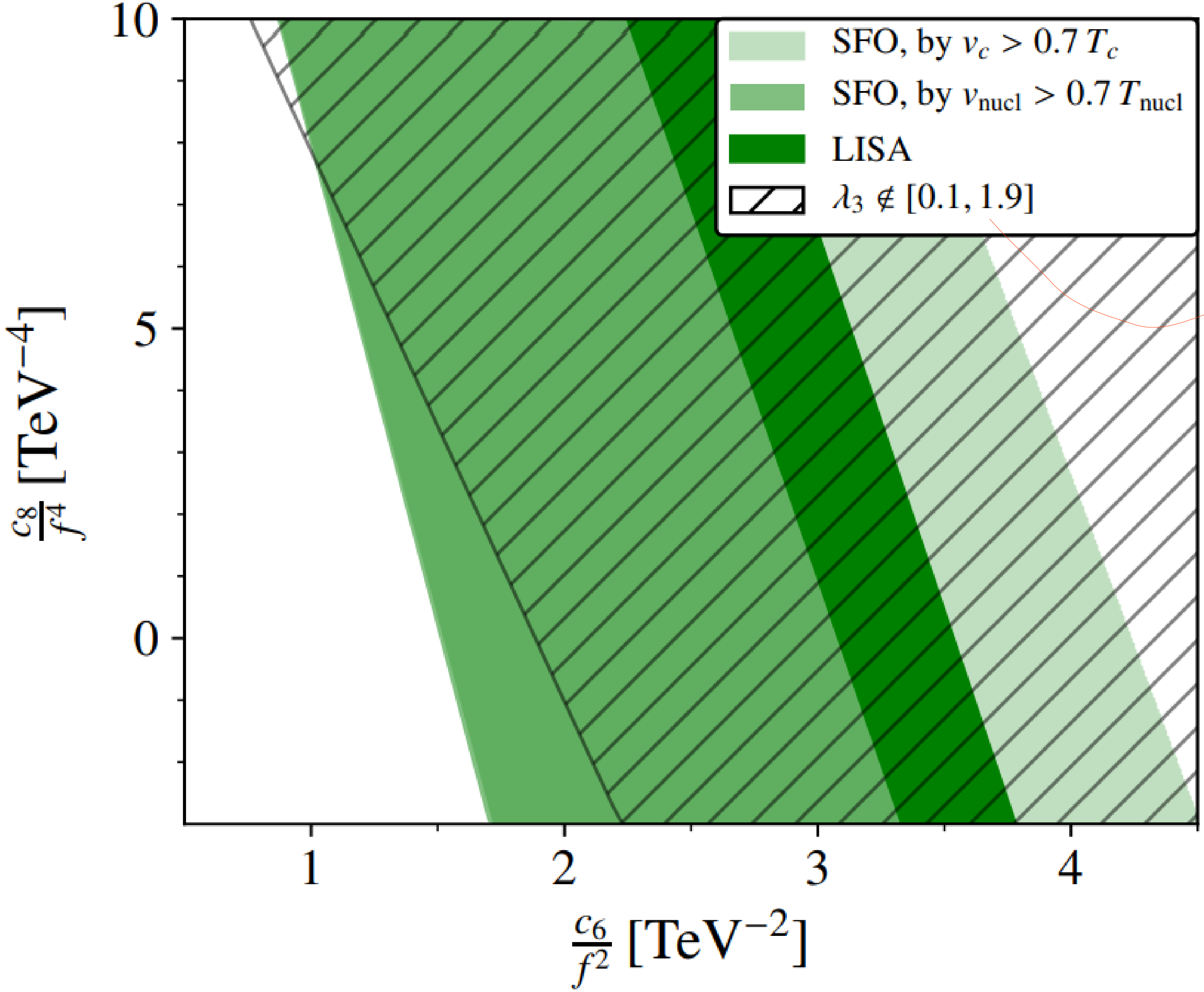
LISA
sensitivity

The Higgs self couplings are modified by the effective interactions too

$$\frac{\lambda_3}{\lambda_{3,\mathrm{SM}}} = 1 + \frac{v^2}{m_h^2}\left(2c_6\frac{v^2}{f^2} + 4c_8\frac{v^4}{f^4}\right) , \quad \frac{\lambda_4}{\lambda_{4,\mathrm{SM}}} = 1 + 4\frac{v^2}{m_h^2}\left(3c_6\frac{v^2}{f^2} + 8c_8\frac{v^4}{f^4}\right)$$



Di Vita et al, 1711.03978



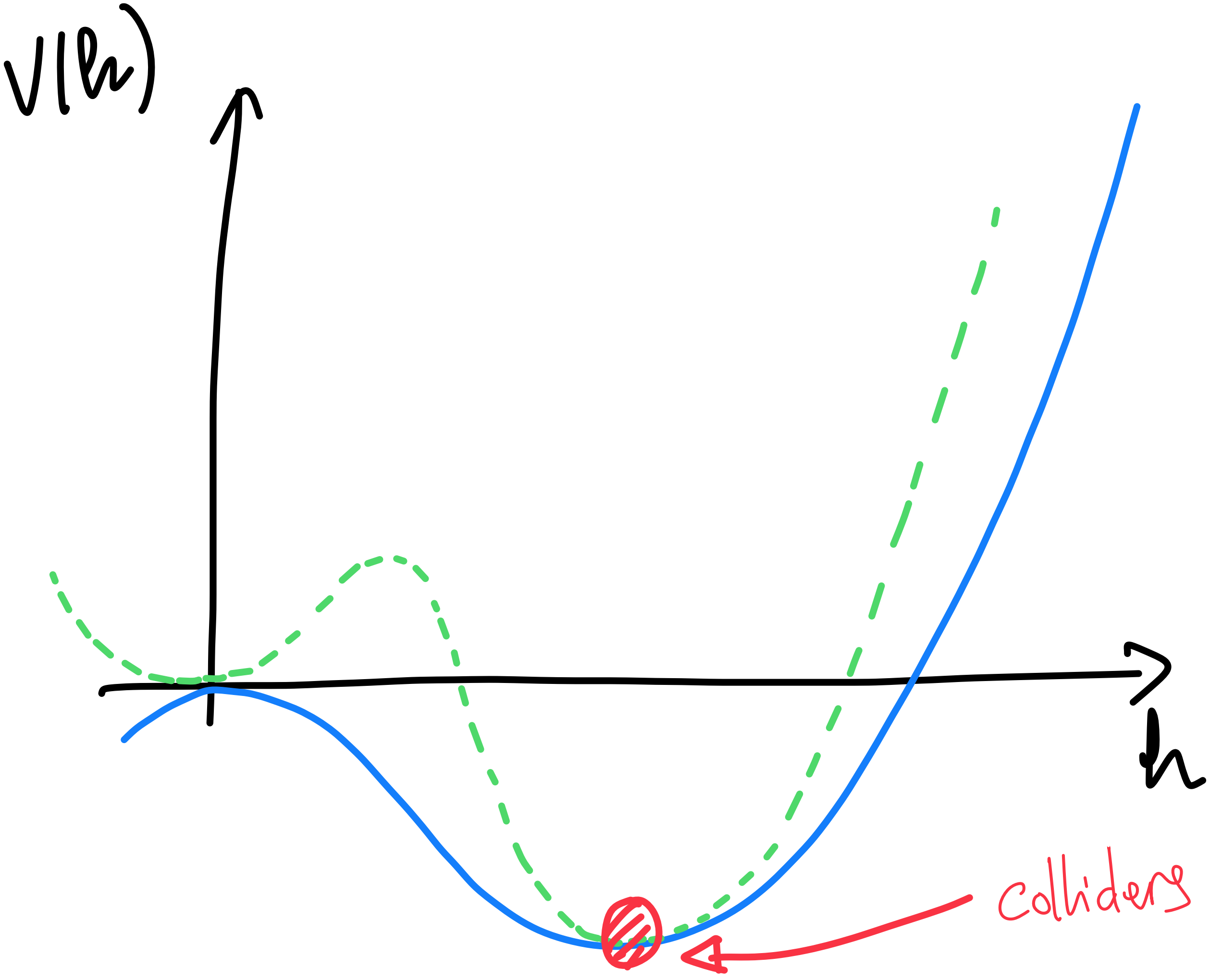
1711.03978

[it assumes runs at both ~240 GeV **and** 350 GeV]

Comparing gravitational wave detectors to colliders in sensitivity to modifications of the Higgs self coupling is an artifact of the model

CEPC could provide a very precise picture of the Higgs potential in a vecinity of its minimum

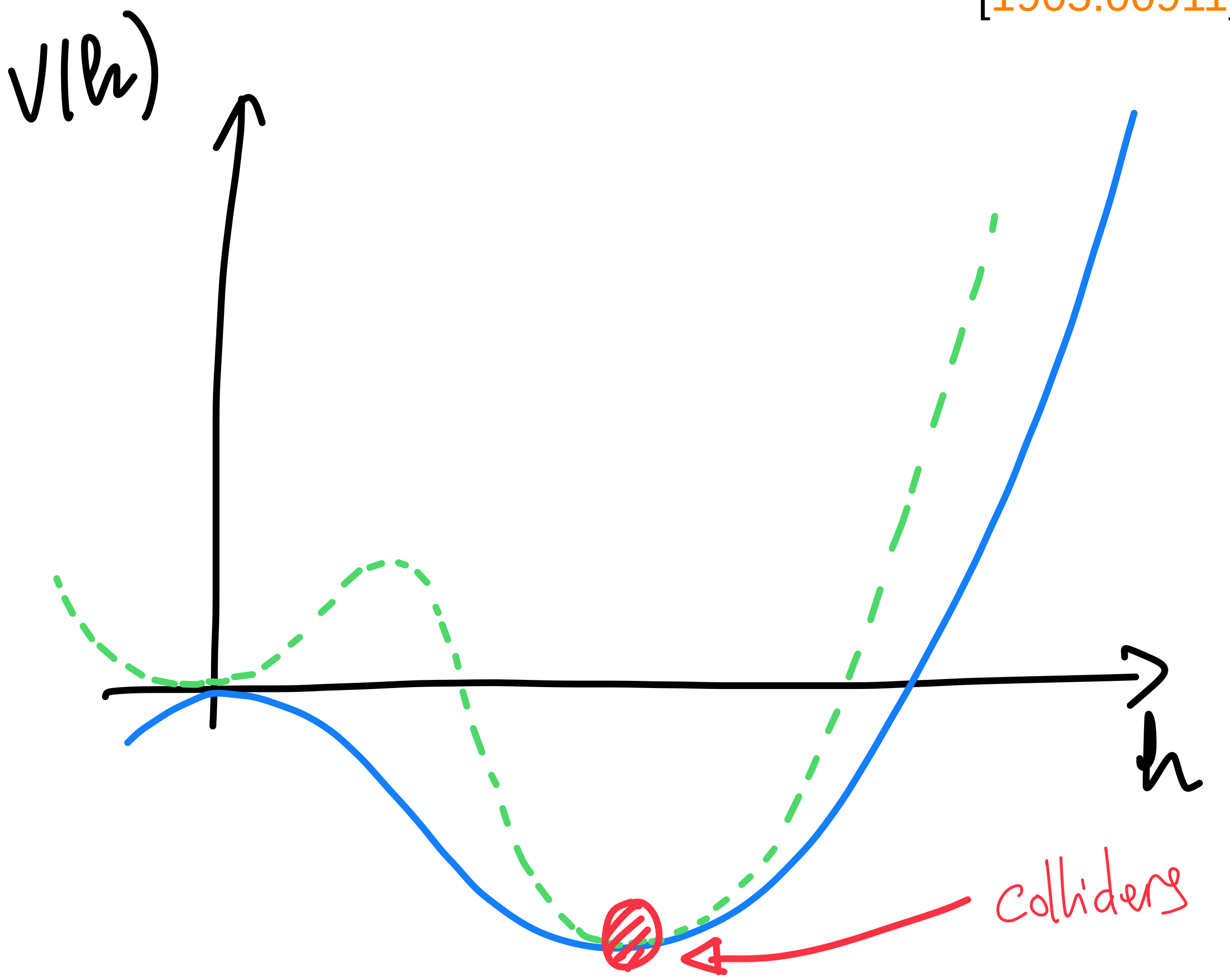
LISA could give a rough picture of the global Higgs potential



V(h)
h
colliders

$$V(h) = \frac{m_h^2}{2}(h-v)^2 + \frac{m_h^2}{2v}(h-v)^3 + a_4(h-v)^4$$

Same trilinear coupling as in the SM, but with a barrier for a_4~ 0.1!
[1905.00911]

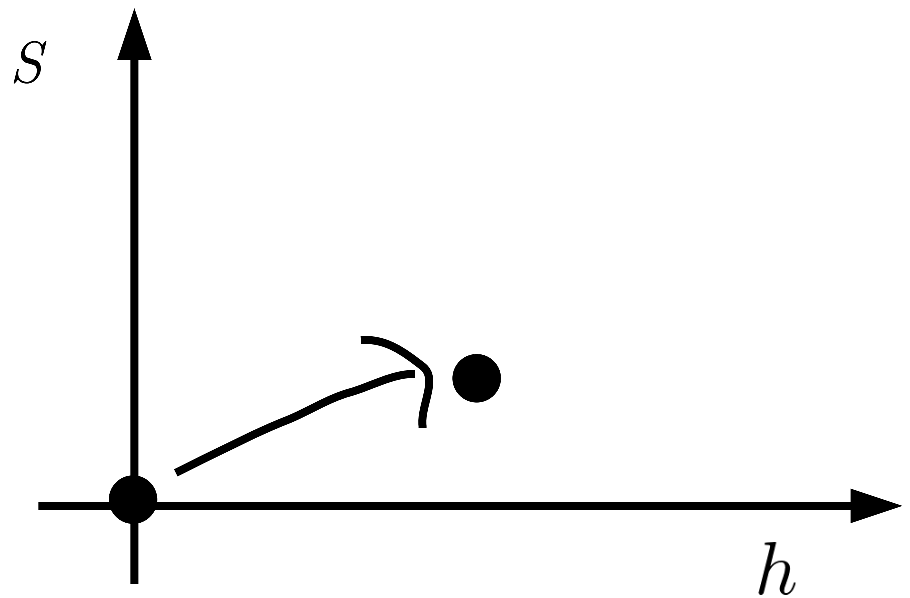


This is, in my opinion, the most important sense in which these two kind of facilities are complementary

The singlet extension of the SM is motivated by CHMs, DM, EW baryogenesis, etc.

$$V(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2$$
$$+ b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4.$$

Two types of phase transitions:



It implies S-h mixing → it can be probed at CEPC

(all Higgs couplings
are modified by S)

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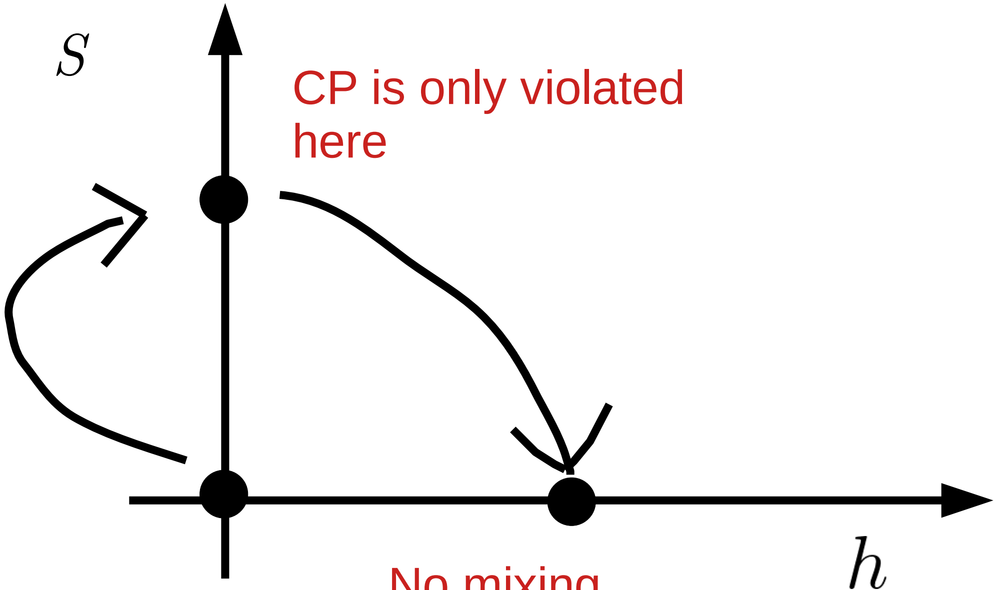
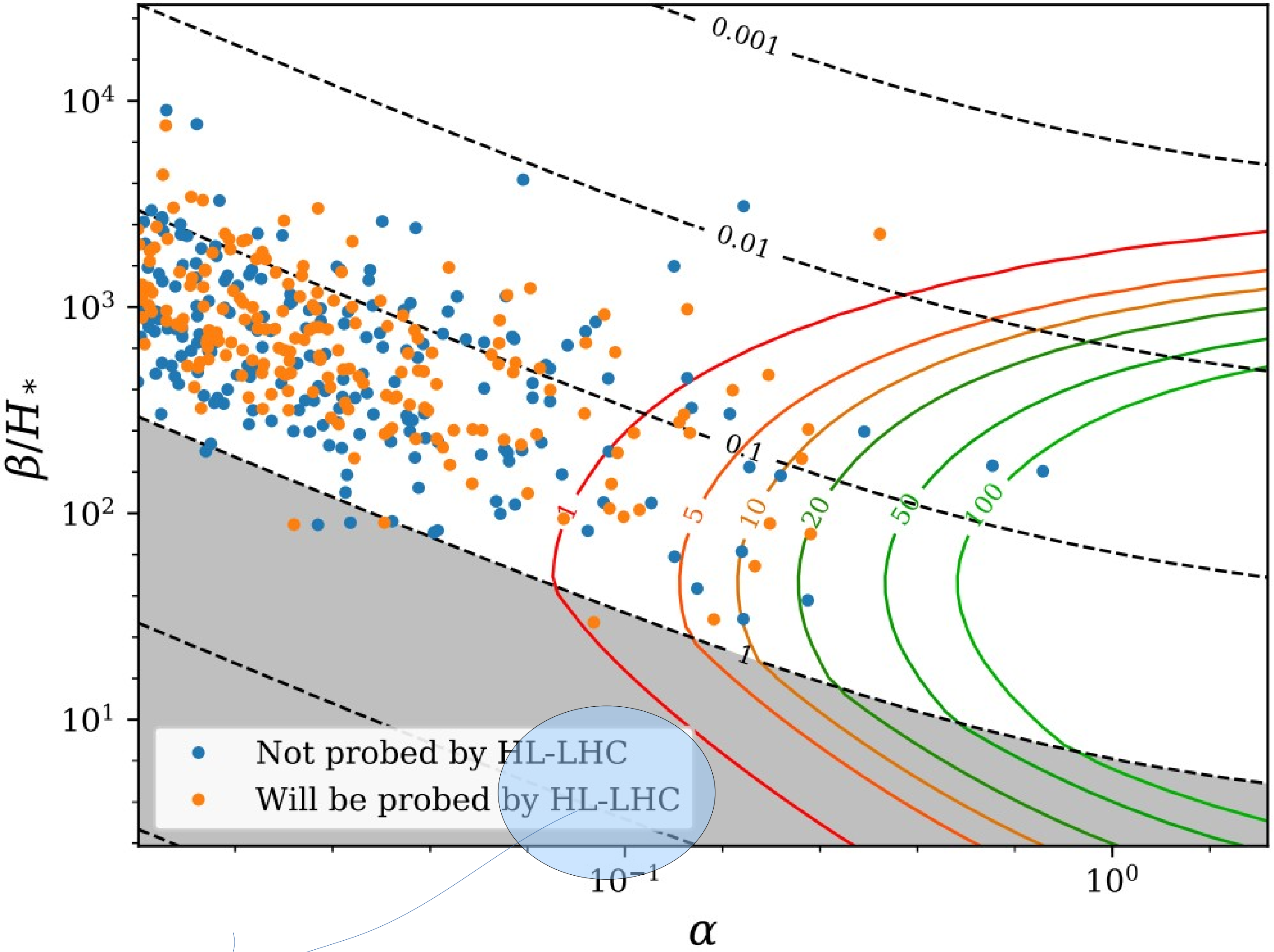


No constraints! Gravitational wave probes needed

$m_2 = 170$ GeV and 240 GeV

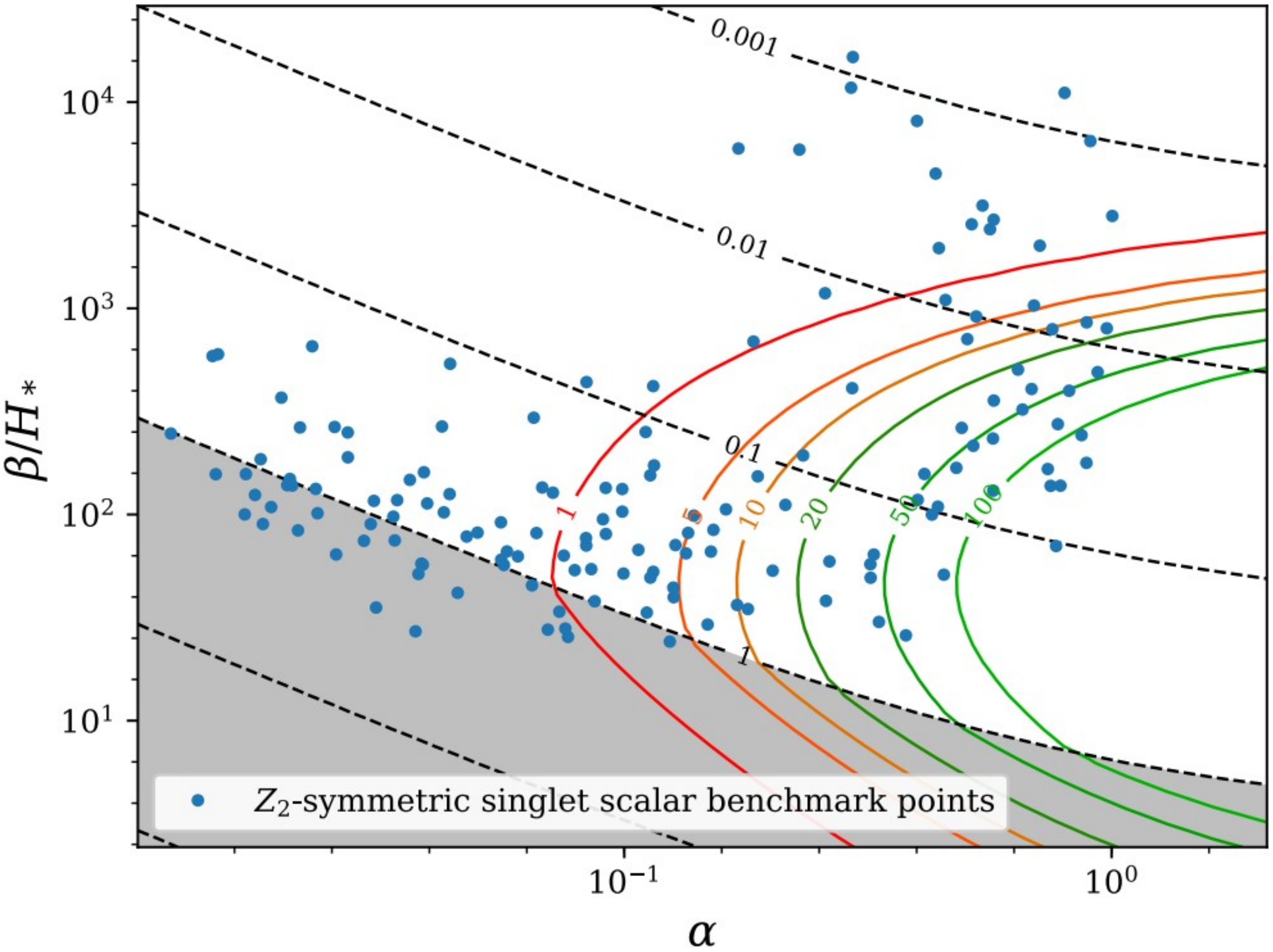
sinθ = 0.1

sinθ = 0.01



It applies to CEPC too!

$m_2 = 170$ GeV and 240 GeV



The 2HDM is another SM extension motivated by SUSY, CHMs, DM, EW baryogenesis, etc.

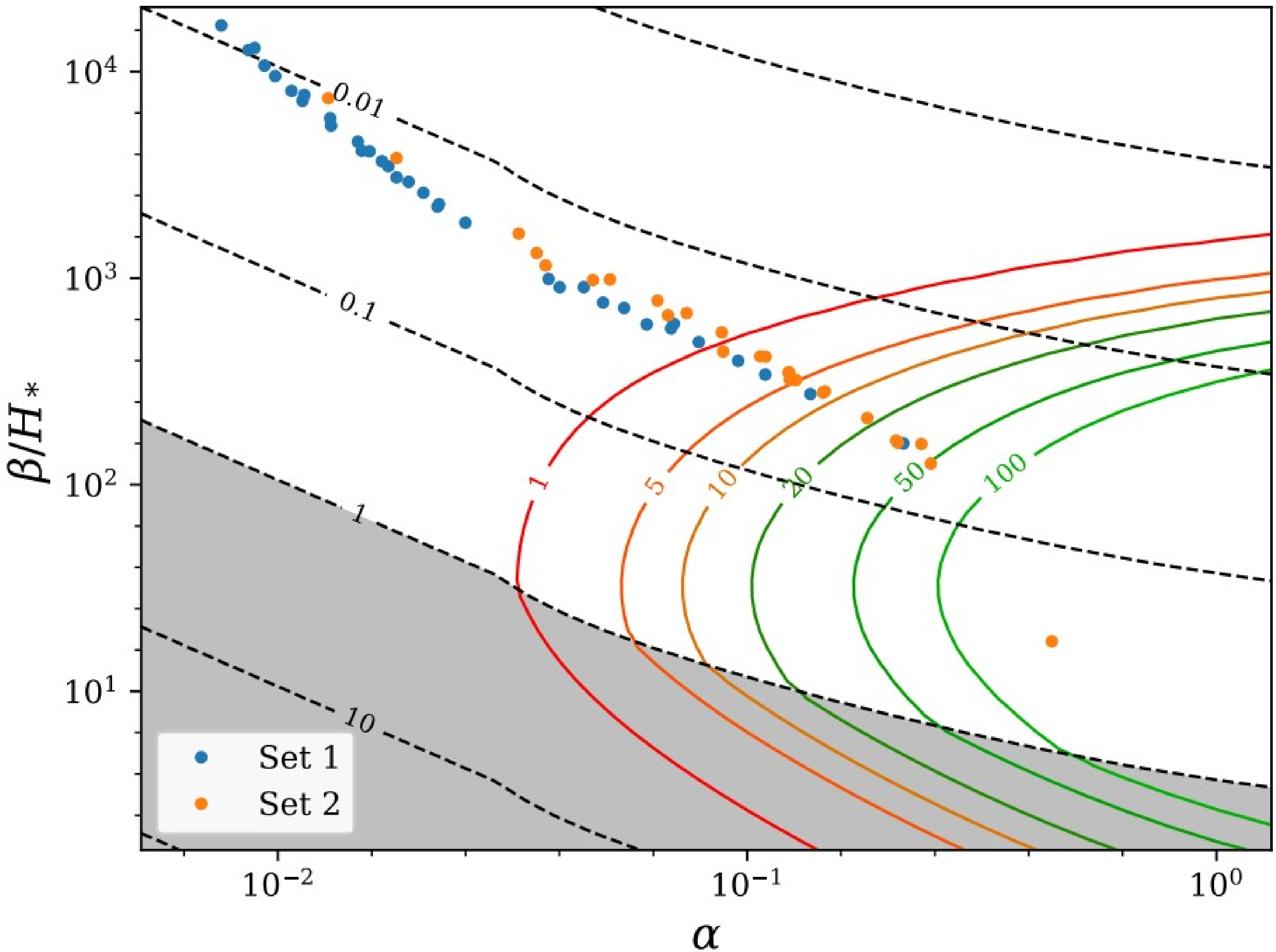
$$V(H_1, H_2) = \mu_1^2 \left|H_1\right|^2 + \mu_2^2 \left|H_2\right|^2 - \mu^2 \left[H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2} \left|H_1\right|^4 + \frac{\lambda_2}{2} \left|H_2\right|^4$$
$$+\lambda_3 \left|H_1\right|^2 \left|H_2\right|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{\lambda_5}{2} \left[\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right],$$

Strong first-order PT correlated with large H0-A0 splitting

We scan over m_{H0} in [180,450] GeV and m_{A0} in $[m_{H0}+100$ GeV, $m_{H0}+350$ GeV$]$

2HDM type (I or II) irrelevant for PT, but important for colliders

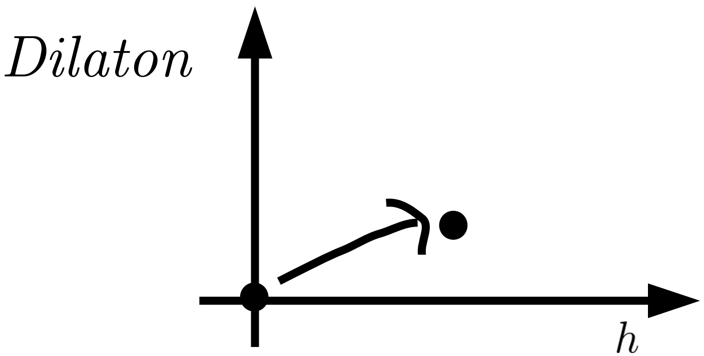
Excluded by LHC
Testable at CEPC depending on tanβ [in searches for A0 → Z H0; see 1405.5537 and talk by Wei Su on Monday]

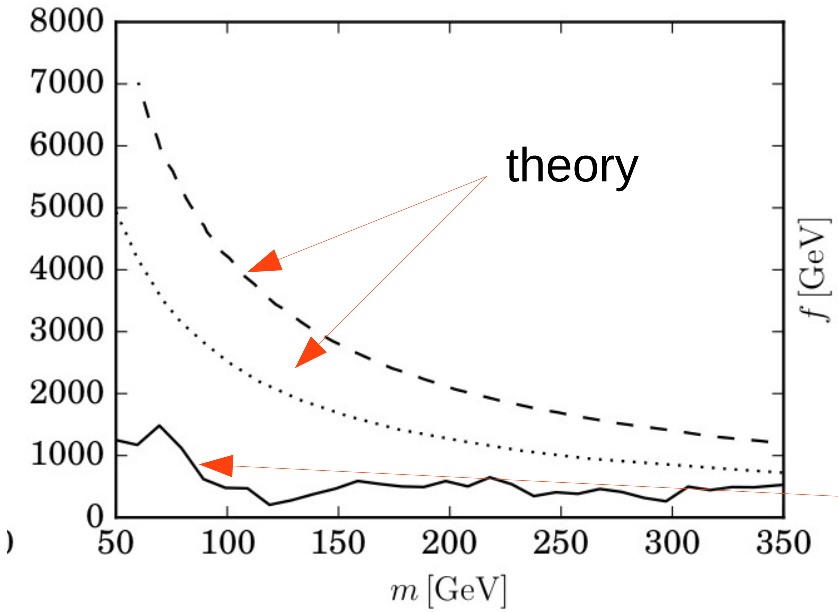


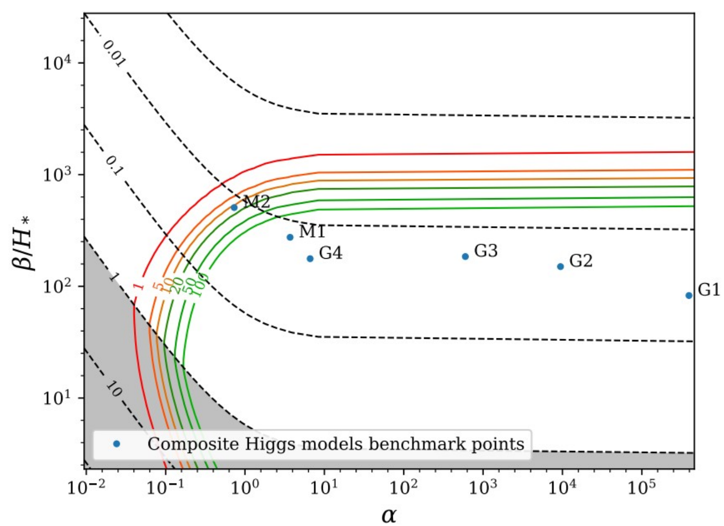
Other scenarios: **dilaton**, dark sector...

G→H symmetry breaking in CHMs [Bruggisser et al, 1804.07314]

Leptophilic, target for CEPC [Madge and Schwaller, 1809.09110]







CEPC could improve on these LHC+LEP bounds!

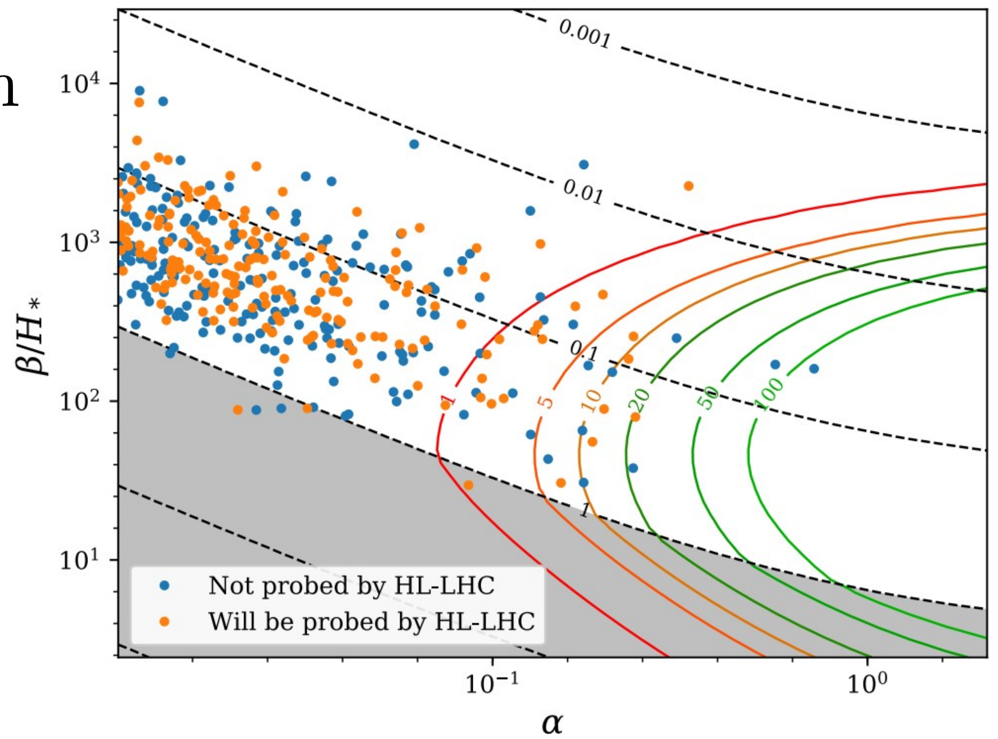
Conclusions

Gravitational wave observatories and CEPC are very complementary in probing models of new physics

Sometimes trivial: e.g. fermion (CEPC) versus scalar sector (LISA)

Others not so obvious: sensitivity to different regions of the scalar potential

Understanding this plot from EFT point of view



$m_2 = 170$ GeV and 240 GeV

sinθ = 0.1

sinθ = 0.01

$$\mathcal{S} \sim (1,1)_0$$

$$V_{\mathcal{S}} = \kappa_{\mathcal{S}}\, \mathcal{S}\phi^\dagger\phi + \lambda_{\mathcal{S}}\, \mathcal{S}^2\phi^\dagger\phi + \kappa_{\mathcal{S}^3}\, \mathcal{S}^3$$

Dimension-Four Operators

$$\alpha_{\phi 4} = \frac{\kappa_{\mathcal{S}}^2}{2M_{\mathcal{S}}^2}$$

Scalar Operators

$$\frac{\alpha_\phi}{\Lambda^2} = 3\frac{\kappa_{\mathcal{S}}^2}{M_{\mathcal{S}}^2}\left(-\frac{\lambda_{\mathcal{S}}}{M_{\mathcal{S}}^2} + \frac{\kappa_{\mathcal{S}^3}\kappa_{\mathcal{S}}}{M_{\mathcal{S}}^4}\right) \qquad \frac{\alpha_{\phi\Box}}{\Lambda^2} = -\frac{\kappa_{\mathcal{S}}^2}{2M_{\mathcal{S}}^4}$$

Relevant for GWs

Relevant for CEPC

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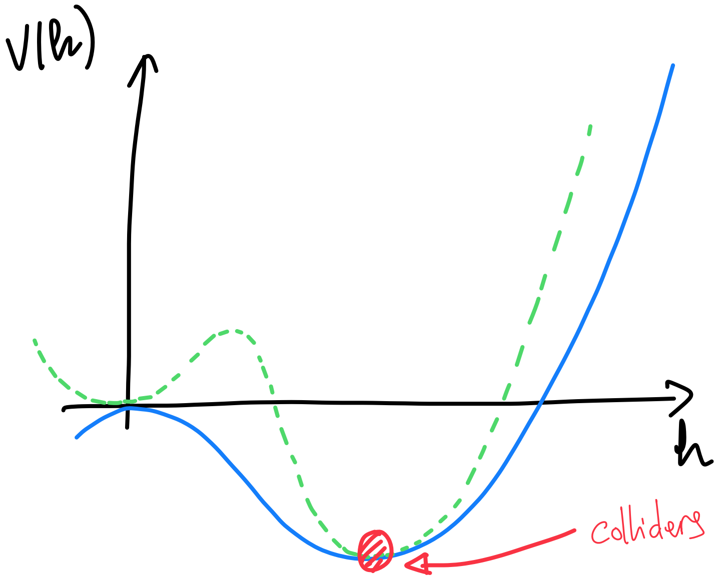
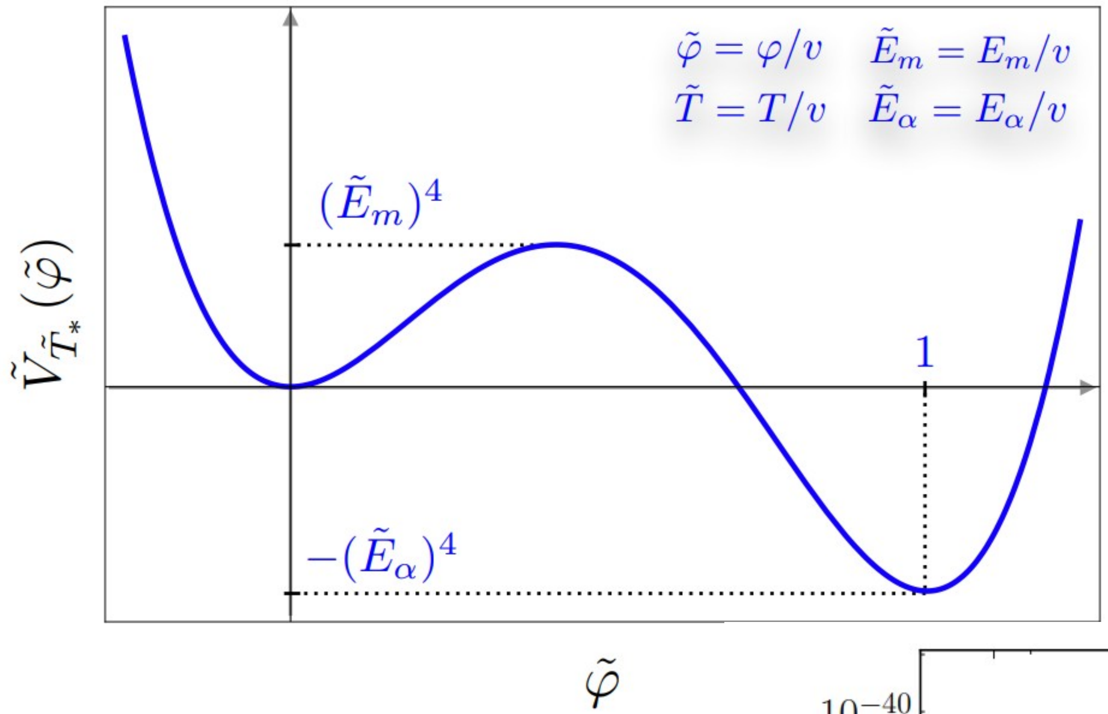
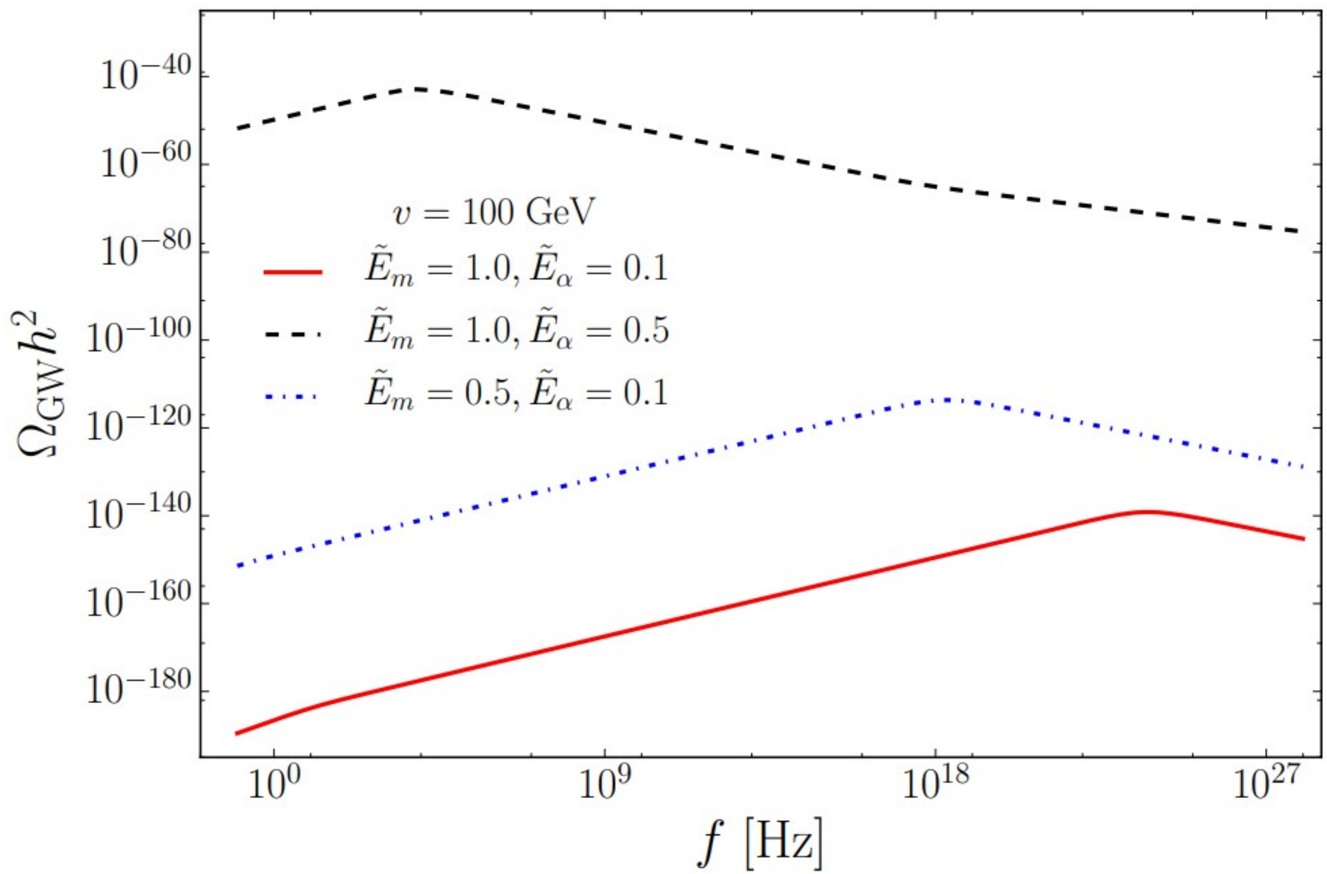




$\tilde{\varphi} = \varphi/v$ $\tilde{E}_m = E_m/v$
$\tilde{T} = T/v$ $\tilde{E}_\alpha = E_\alpha/v$
$(\tilde{E}_m)^4$
$-(\tilde{E}_\alpha)^4$
1
$\tilde{V}_{\tilde{T}_*}(\tilde{\varphi})$
$\tilde{\varphi}$

1905.00911



$v = 100$ GeV
$\tilde{E}_m = 1.0, \tilde{E}_\alpha = 0.1$
$\tilde{E}_m = 1.0, \tilde{E}_\alpha = 0.5$
$\tilde{E}_m = 0.5, \tilde{E}_\alpha = 0.1$
$\Omega_{\rm GW}h^2$
f [Hz]
10^{-40}
10^{-60}
10^{-80}
10^{-100}
10^{-120}
10^{-140}
10^{-160}
10^{-180}
10^{0}
10^{9}
10^{18}
10^{27}

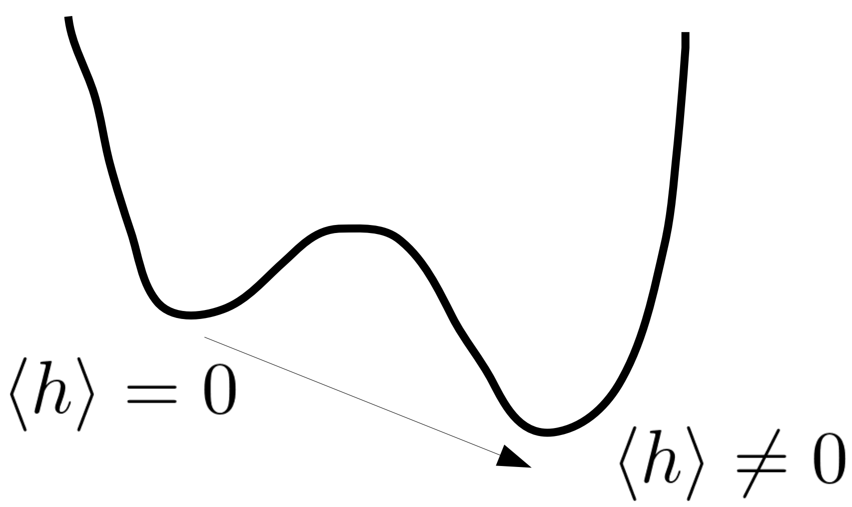
Thank you!

Backup

- Shakarov conditions: B and C and CP violated **during non-thermal equilibrium**

- Excess of LH over RH fermions transformed into excess of baryons over antibaryons by SM sphalerons. Baryon asymmetry eventually captured by growing bubble

- Necessary condition: strong first-order EWPT, namely $<\mathrm{h}>/T > 1$



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$$<h> = 0$$

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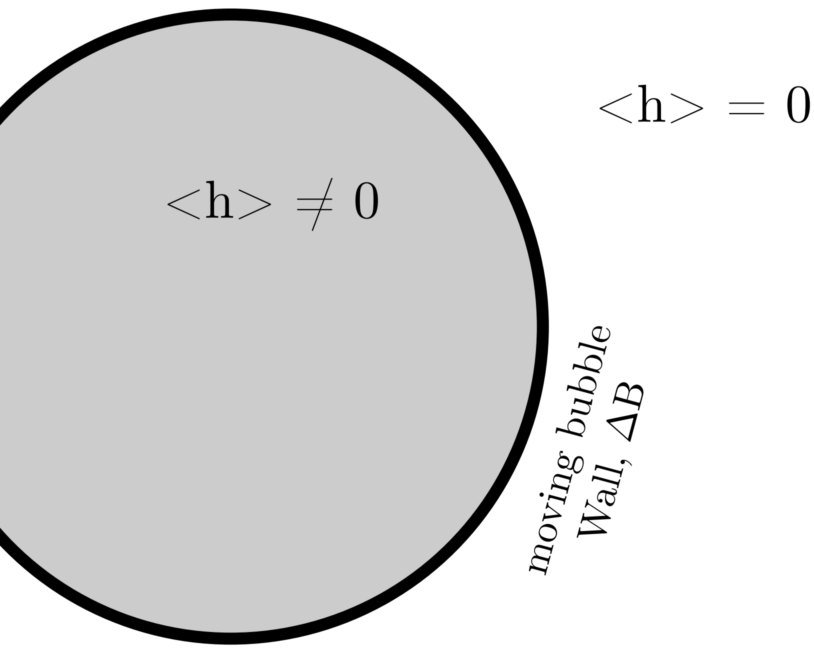

$$\Gamma_{ws} \sim T^4$$

[Mariano Quiros, 9901312, Sean Tulin ‘18]

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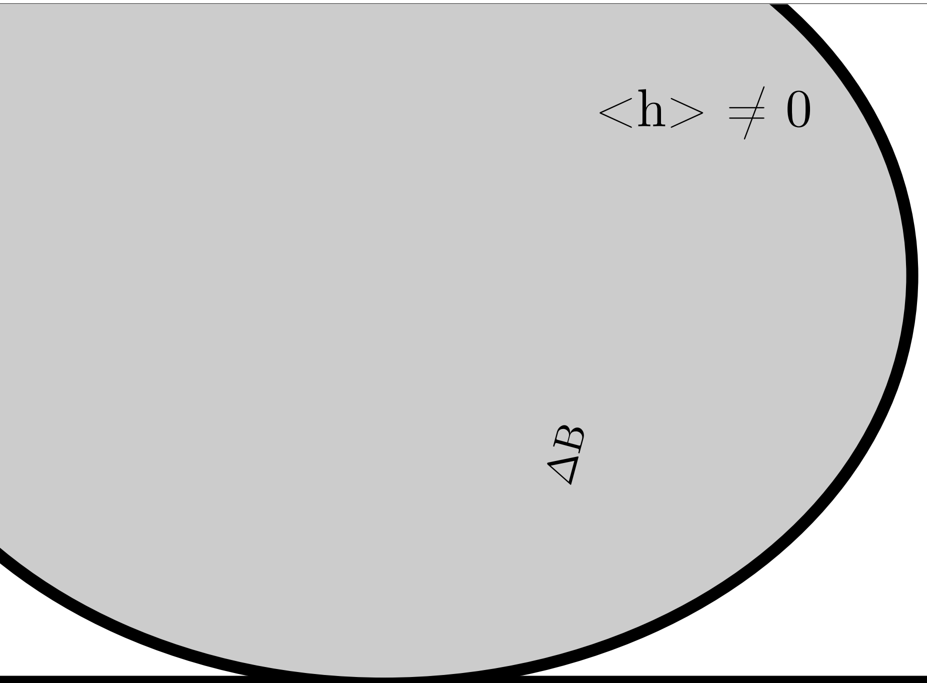


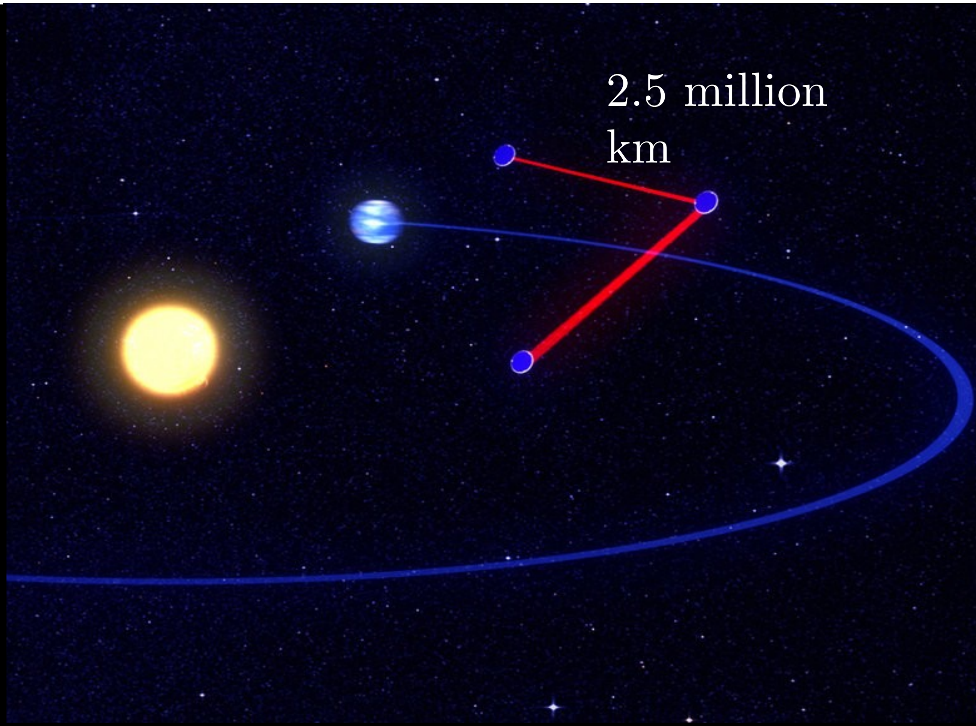
$$\Gamma_{ws} \sim T^4 \exp\left\{ -\frac{E_{sph}}{T} \right\}$$

[Mariano Quiros, 9901312, Sean Tulin ‘18]

- The eventual collision of bubbles (and secondary effects) produce gravitational waves

- Depending on the **energy released to the plasma**, its **temperature**, the change of the euclidean action with the temperature, the **bubble wall velocity**, etc., different spectra predicted; see *[1512.06239]*

- Potentially observable at LISA. **LISA Pathfinder** mission ended in 2017 with great success



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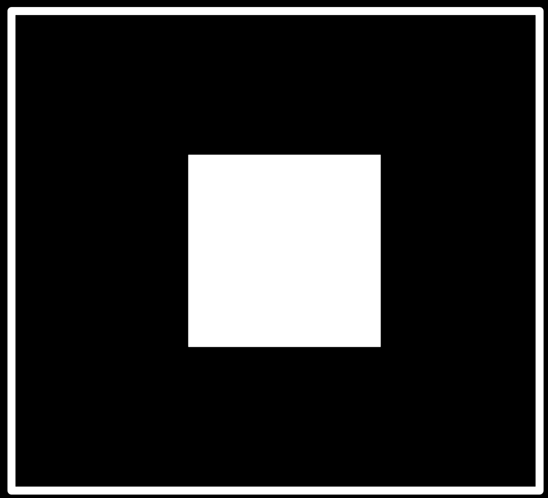
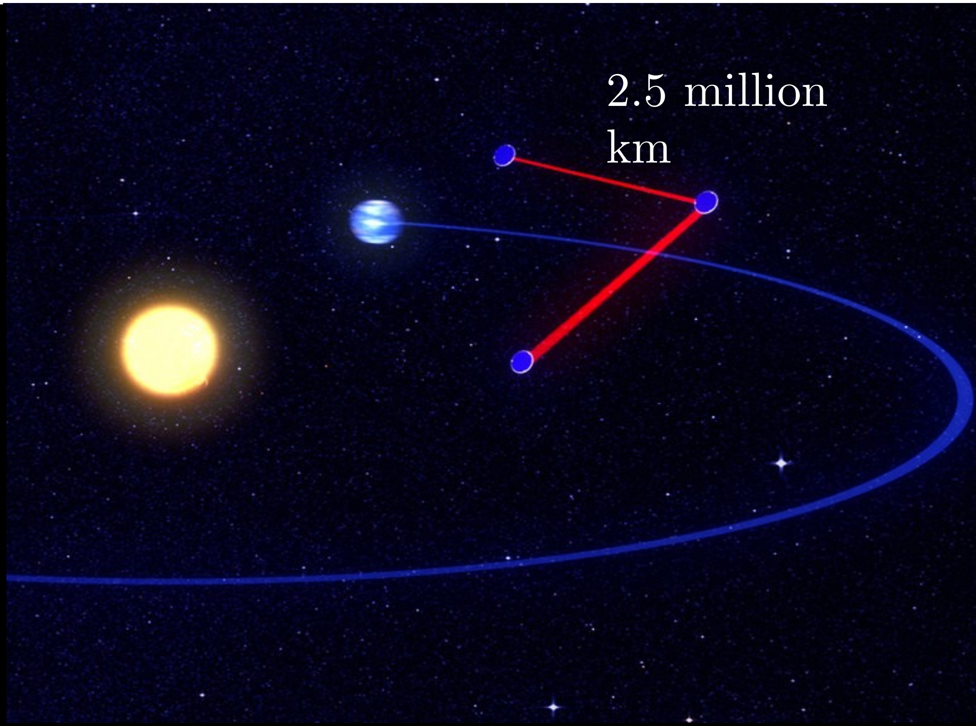


[Schleicher et al, '17]



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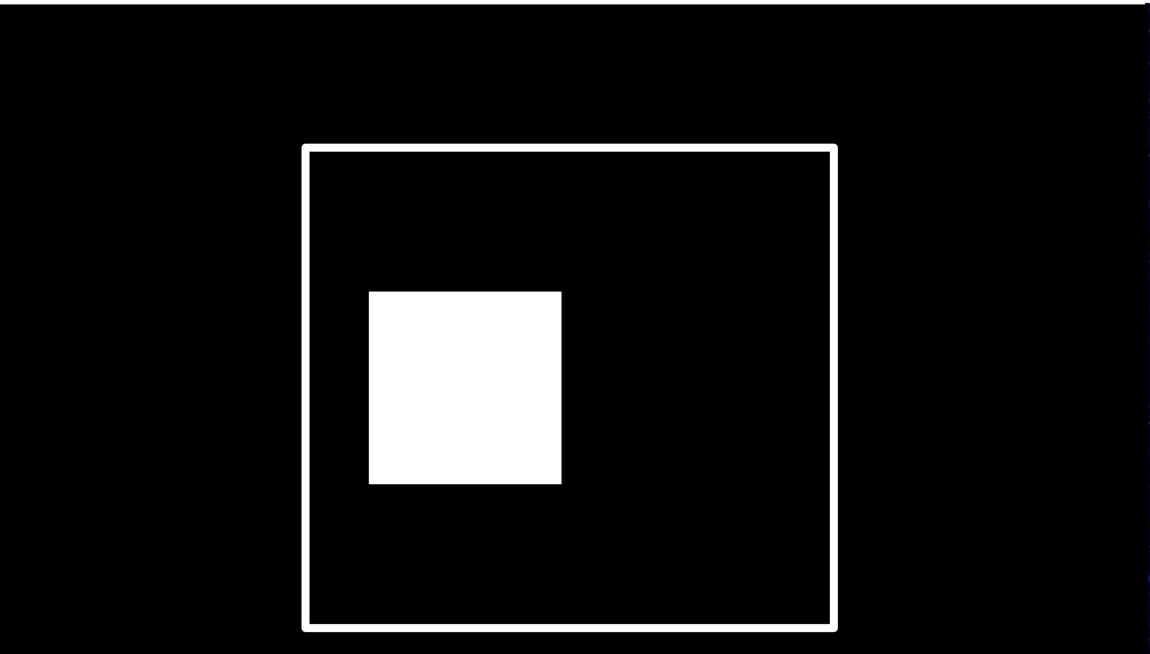

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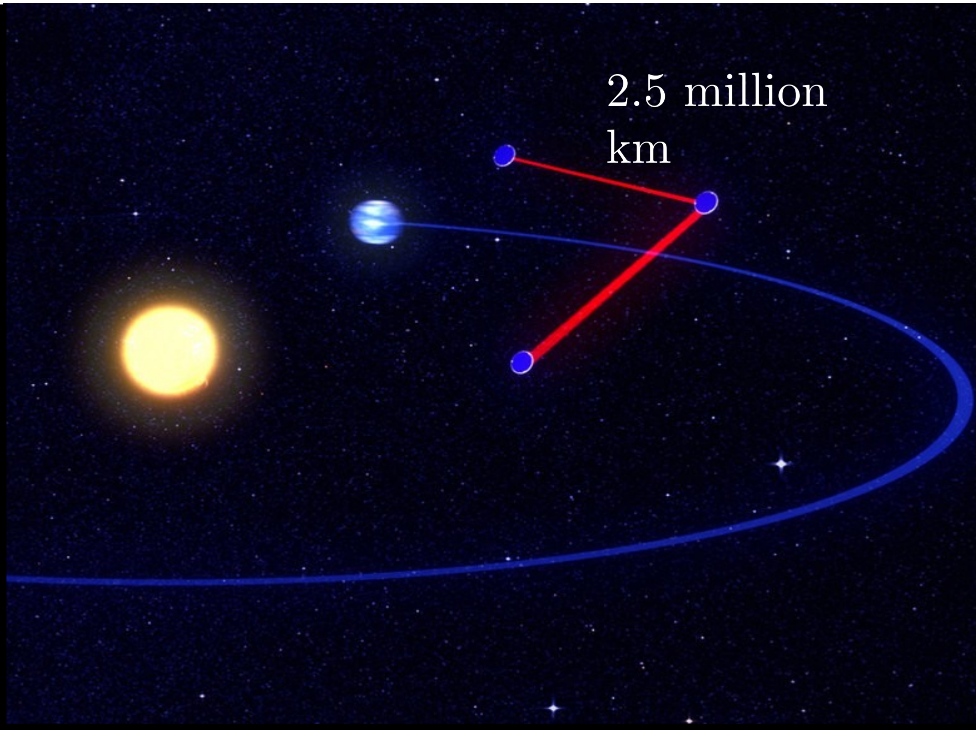

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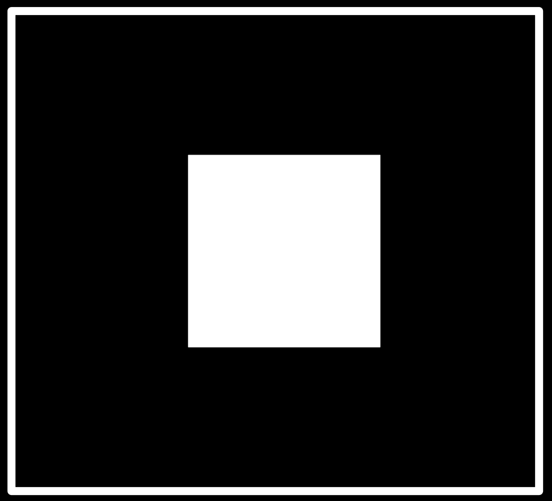

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