First order phase transitions in the SMEFT: A new perspective

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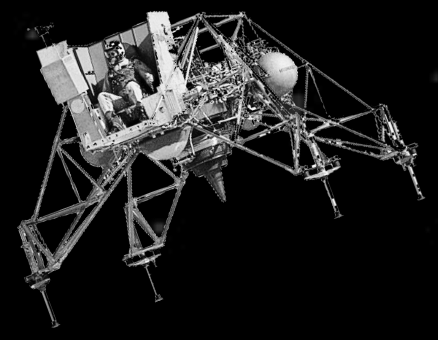
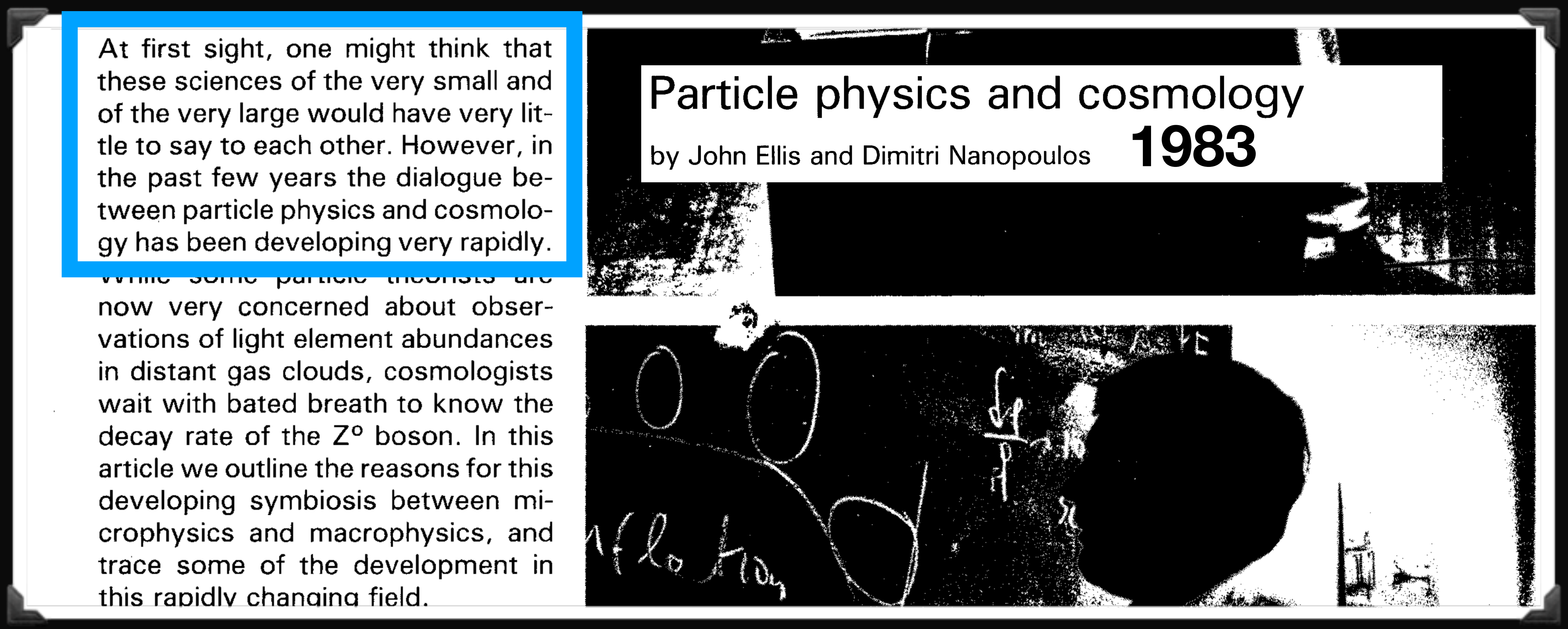


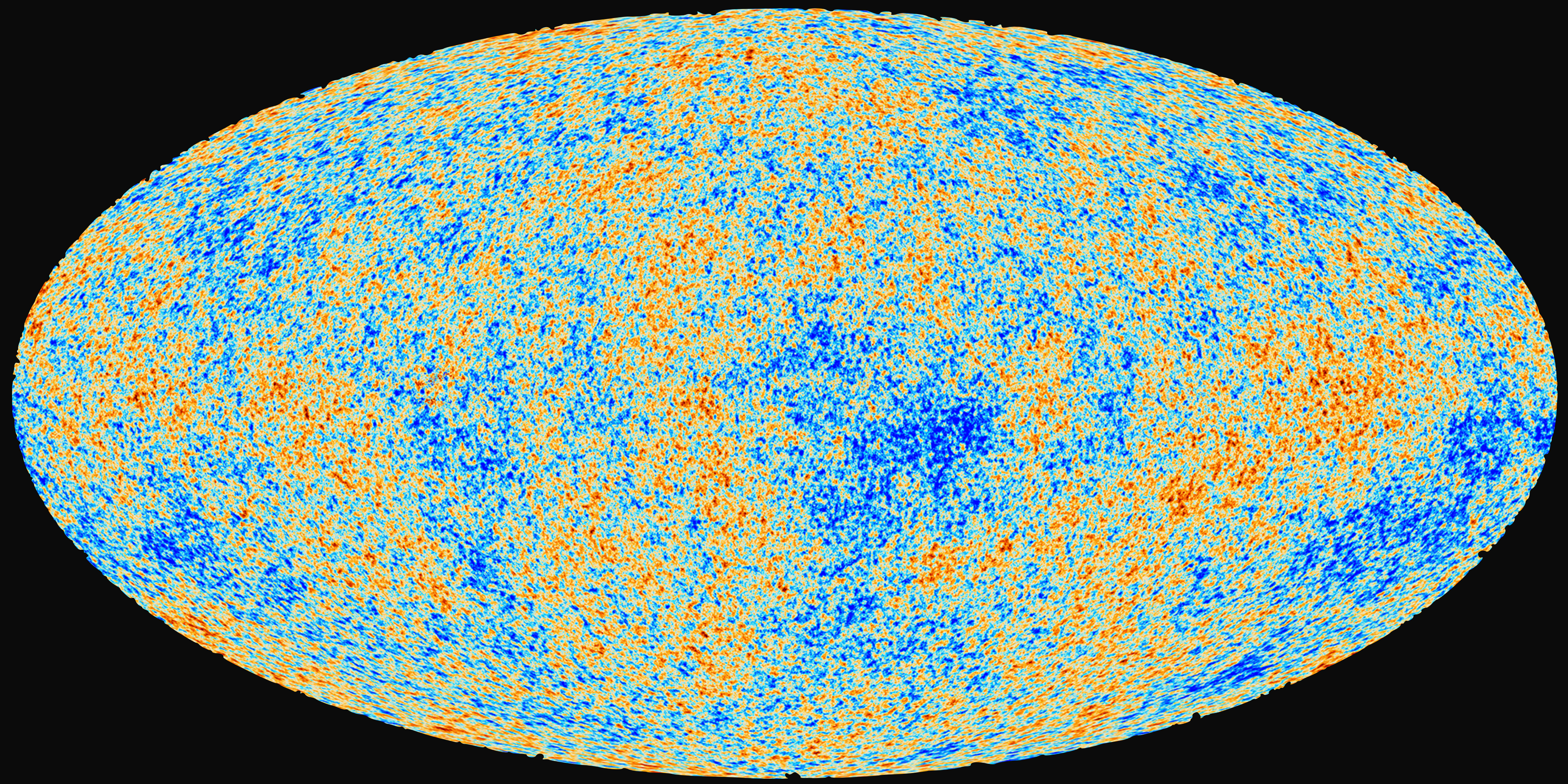
Beyond the Standard Models: Probing the intersection of cosmology and particle physics



At first sight, one might think that these sciences of the very small and of the very large would have very little to say to each other. However, in the past few years the dialogue between particle physics and cosmology has been developing very rapidly. While some particle theorists are now very concerned about observations of light element abundances in distant gas clouds, cosmologists wait with bated breath to know the decay rate of the Z^o boson. In this article we outline the reasons for this developing symbiosis between microphysics and macrophysics, and trace some of the development in this rapidly changing field.

Particle physics and cosmology

by John Ellis and Dimitri Nanopoulos 1983

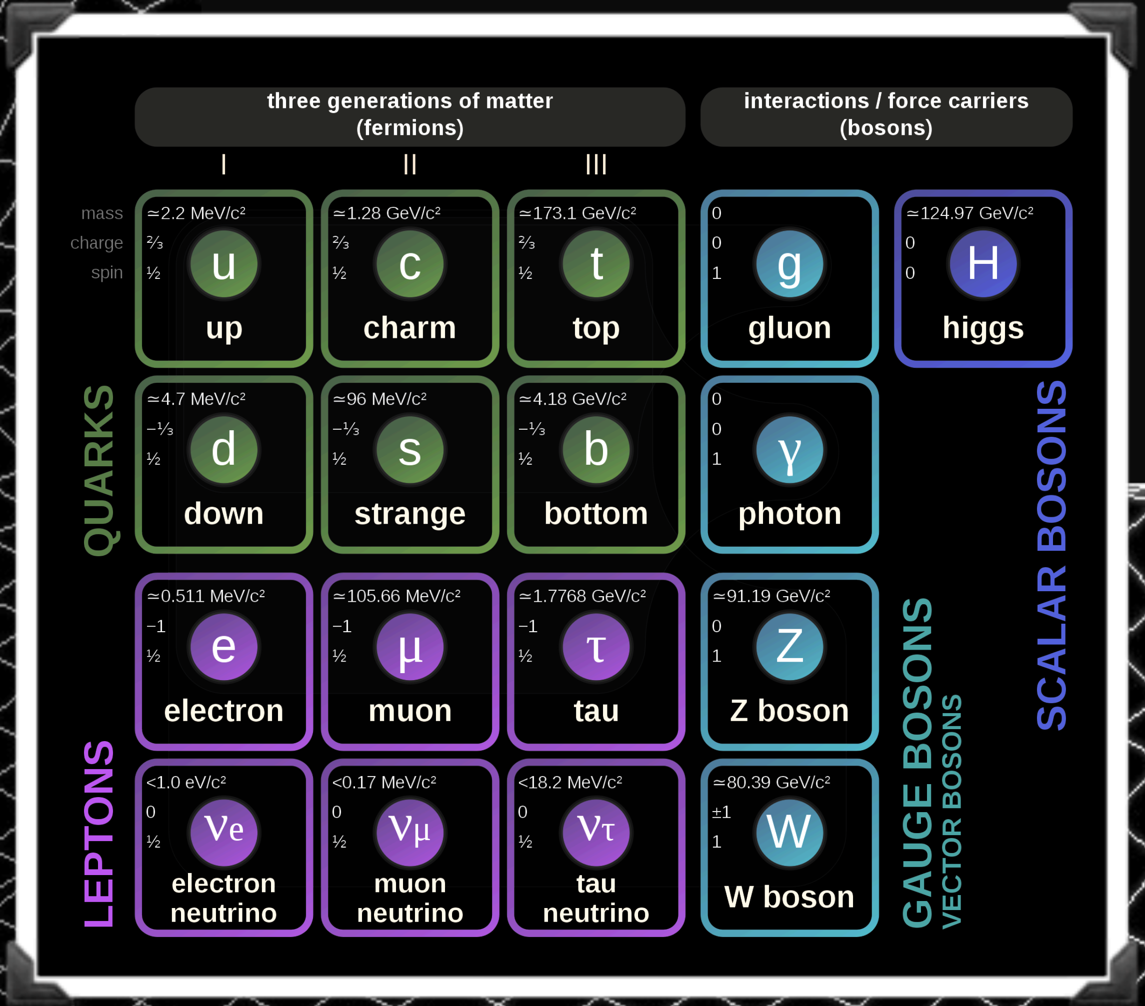


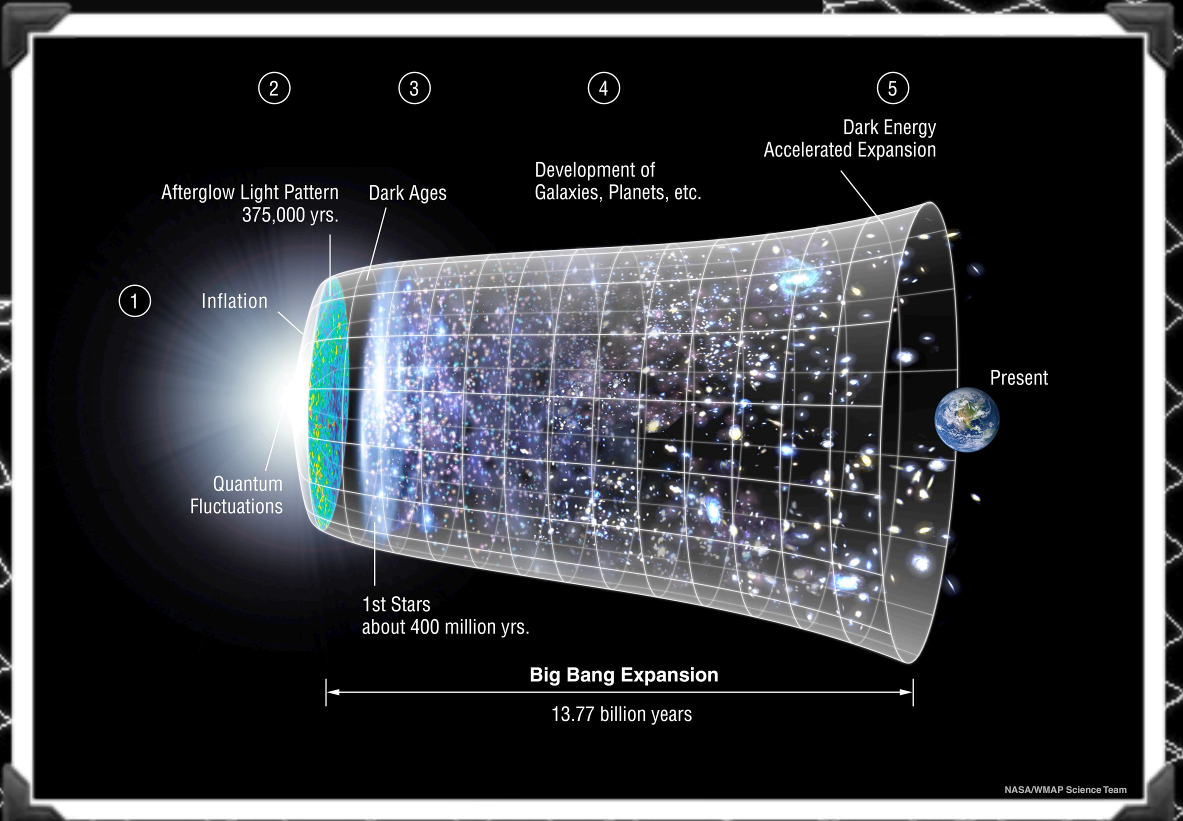
- Connecting the very small and the very large has been in the sight of physicists for a while. GUTs started paving the road
- We knew first from Cosmology that there were ~ 3 Neutrinos. Still only have an upper bound on neutrinos’ masses from Cosmology
- Nuclear physics is crucial for star formation, abundances

THE STANDARD MODEL
Of Particle Physics

THE STANDARD MODEL
Of Cosmology

Of Particle Physics	Of Cosmology
No Dark Matter	What is Dark Matter?
No Inflation	Flatness problem: Initial conditions for a present-day flat universe are < $O(10^{-60})$
Predicted vacuum energy is huge!	Inflation?
No reason for so much more matter than anti-matter	Vacuum energy is tiny!
Origin of its very special parameter values	CC, is it constant?
No gravity	Missing Baryon problem (maybe solved)
Why is the Higgs so light?	Hubble constant disagreement
Vacuum Stability	6 free parameters, too much?





Phase transitions

Transition from one vacuum (+symmetries) to another broken phase (+other symmetries).

First order > STRONG

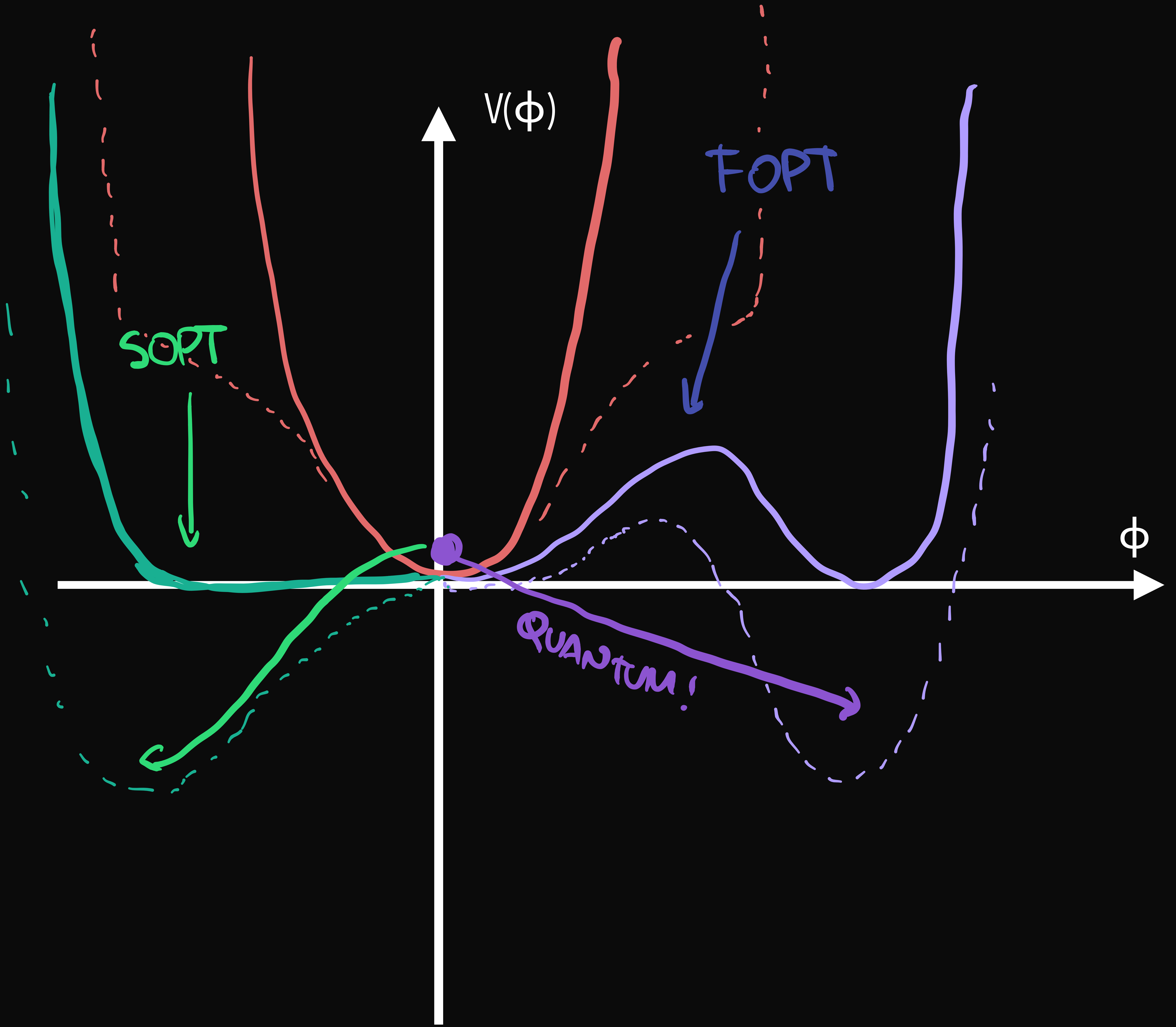
Second order > SOFT

Necessary for generating baryon asymmetry:

1) Baryon number violation

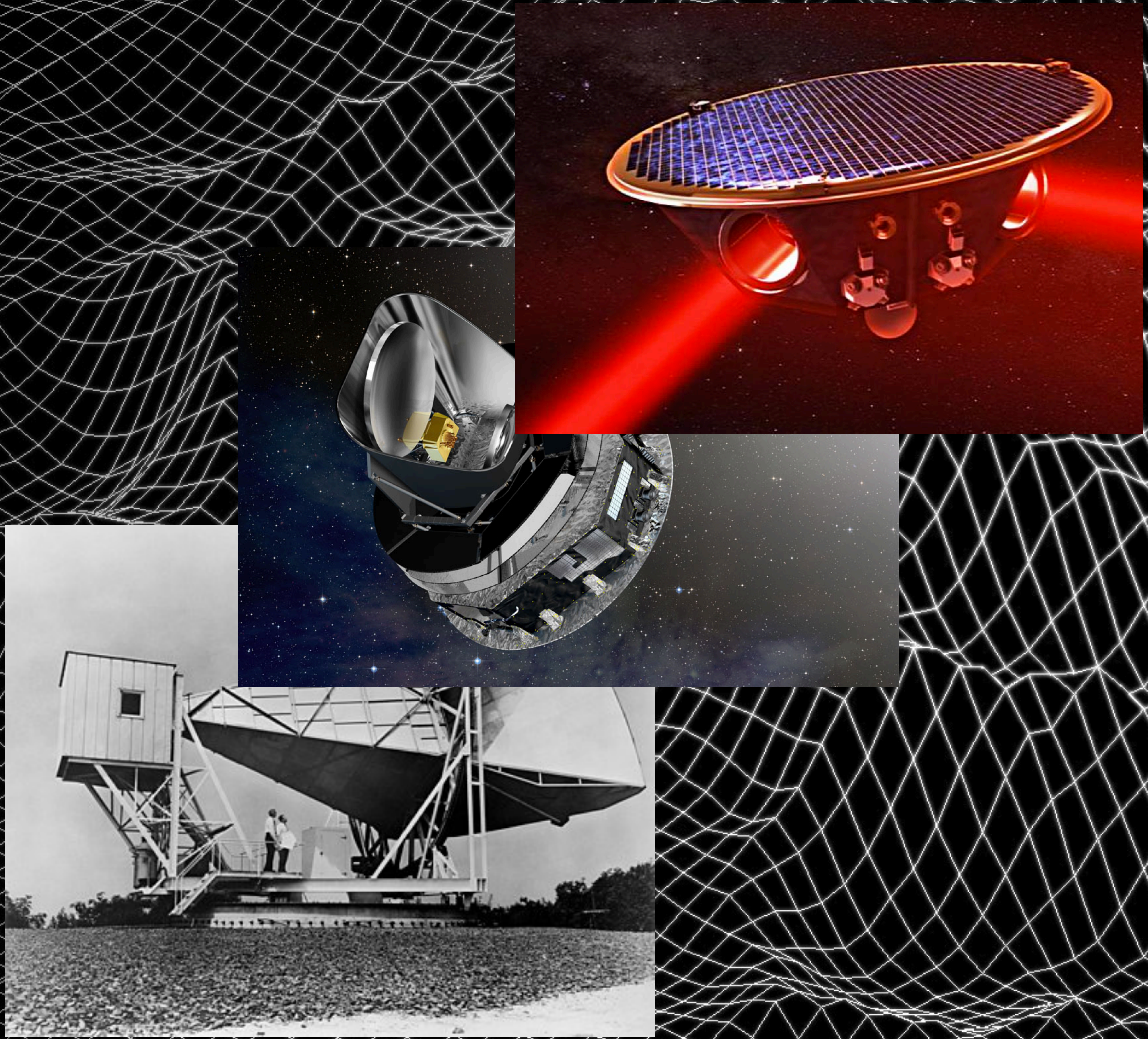
2) Charge and Charge-Parity violation

3) Departure from thermal equilibrium




Can we measure that?

Gravitational Waves and Vacuum Decay



The early universe was transparent to GWs!

A first-order PT means bubbles. Bubbles collide and disturb spacetime massively.

But, the SM (of particle physics) has no first order phase transitions.

First order phase transitions from EW to TeV Scales predict stochastic GW backgrounds accessible by the Laser Interferometer Space Antenna (LISA).

Prospects for measurements, Part I

Particle Physics model

↓

PT parameters
- Effective action → β, H_*
- Energy budget → α, $\kappa(\alpha, v_w)$
- Bubble wall dynamics → v_w

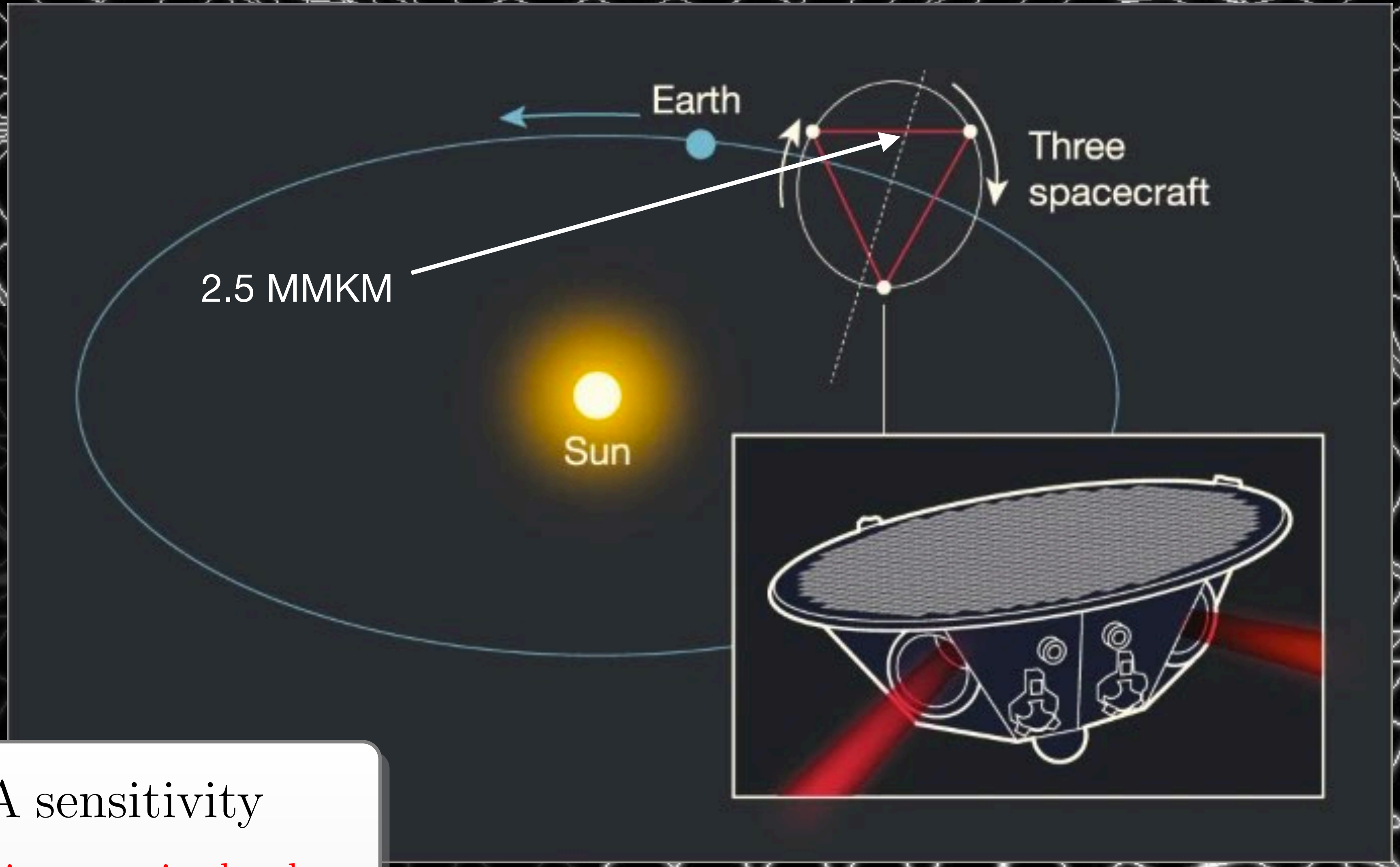
→ **GW power spectrum**
Numerical simulations → $h^2\Omega_{GW}(f; H_*, \alpha, \beta, v_w)$

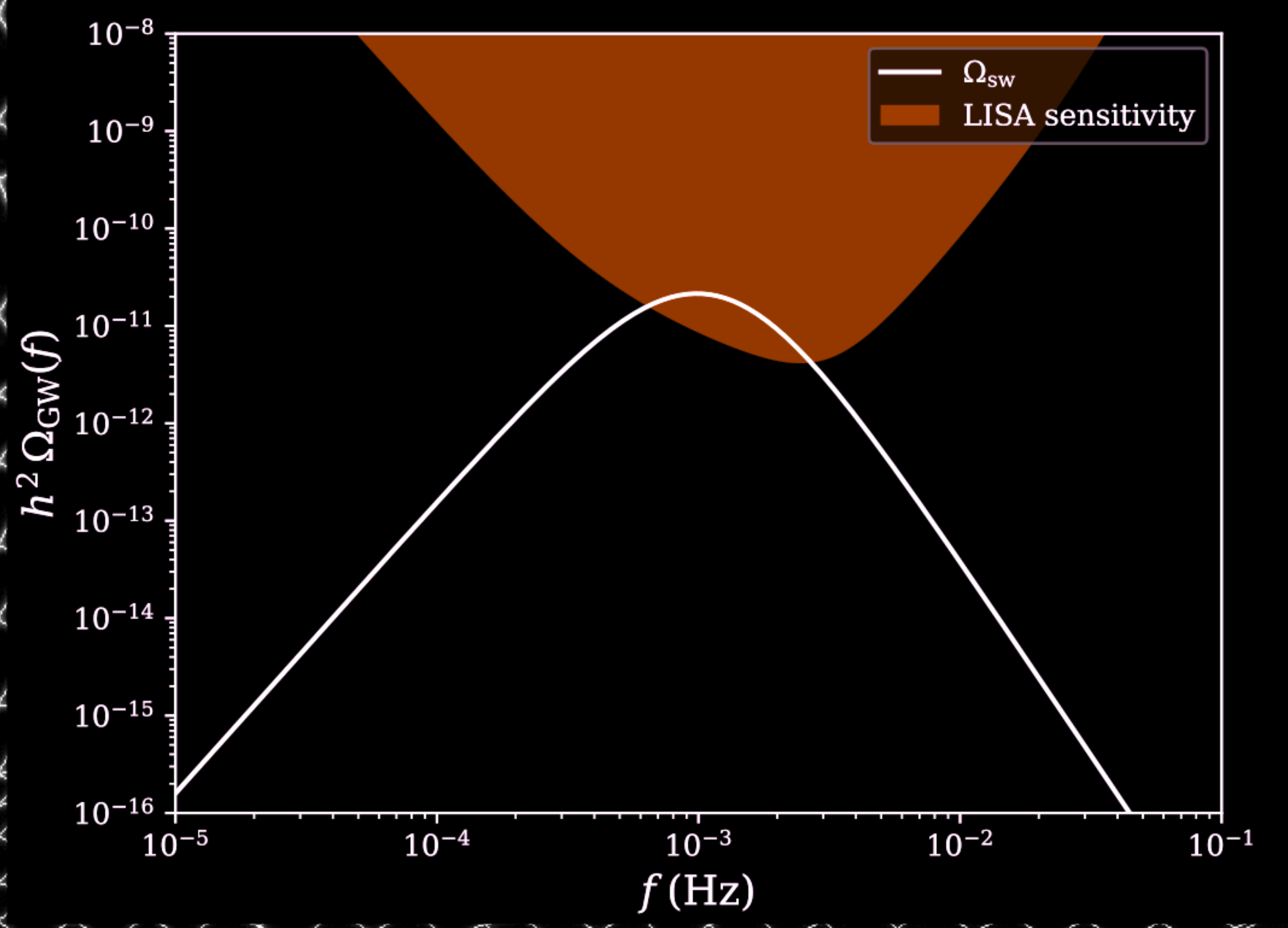
→ **LISA sensitivity**
Configuration + noise level → $h^2\Omega_{sens}(f)$

↓

Signal-to-noise ratio

From 1910.13125, Caprini et al.

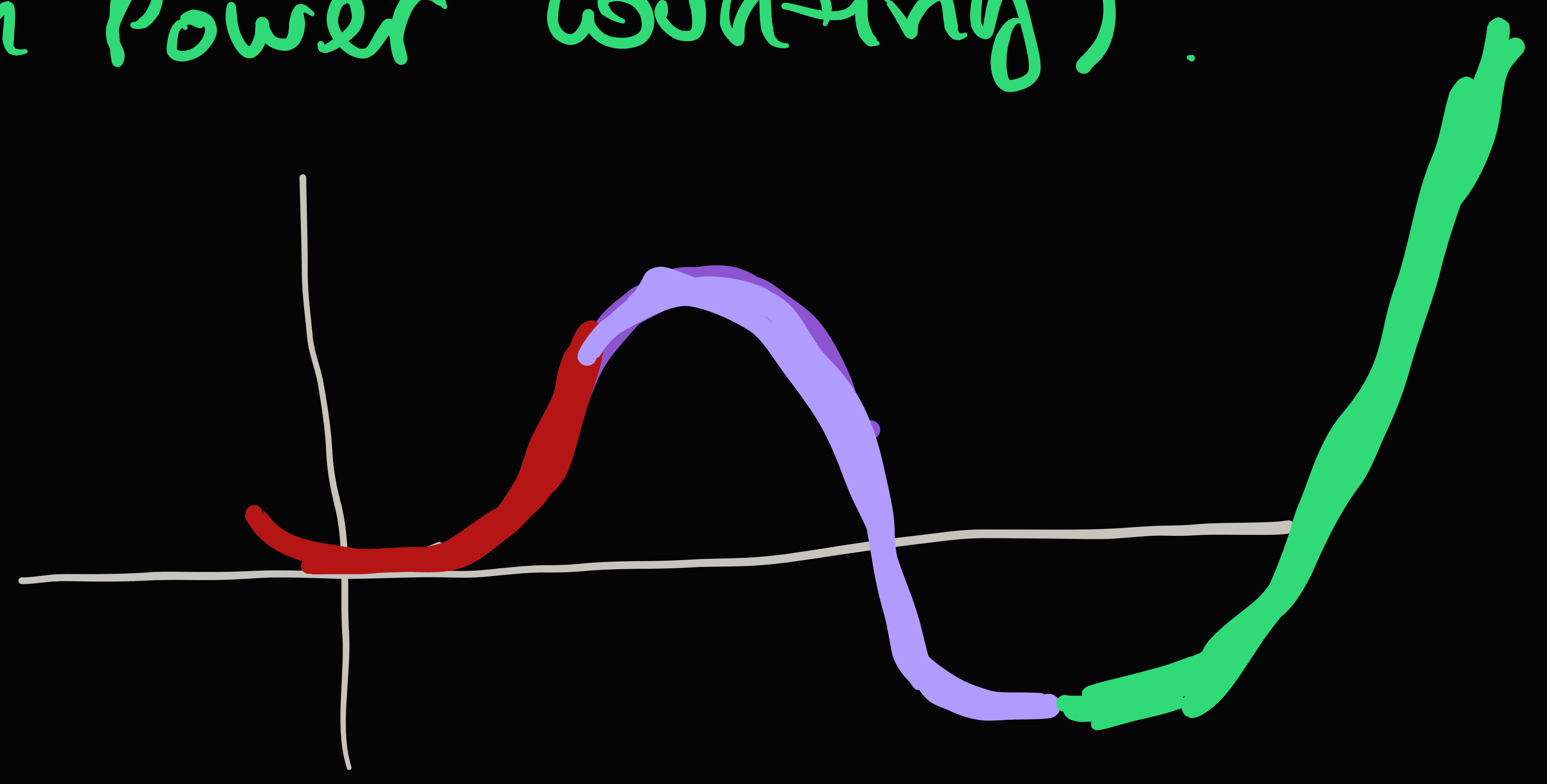




FOPT in the SM (schematically)

the LO potential (Being careful with Power counting).

$$V_{LO} = -m_{eff}(T)\frac{\varphi^2}{2} + \frac{\lambda}{8}\varphi^4 - \frac{Te^3}{12\pi}\varphi^3$$



for this to work out, we need a certain scaling of Lagrangian parameters (Arnold + Espinosa, 9212235)

FOPT $\rightarrow \lambda \sim e^3 \quad \phi \sim T \quad m_{eff}^2 \sim e^3 T^2 \quad T \sim \frac{\sqrt{m^2}}{e}$

$\hookrightarrow m_h \sim \lambda v^2 \Rightarrow$ If FOPT then $m_h \ll 125$ GeV

Want to know more?
Check Johan Löfgren talk
Session 8-C

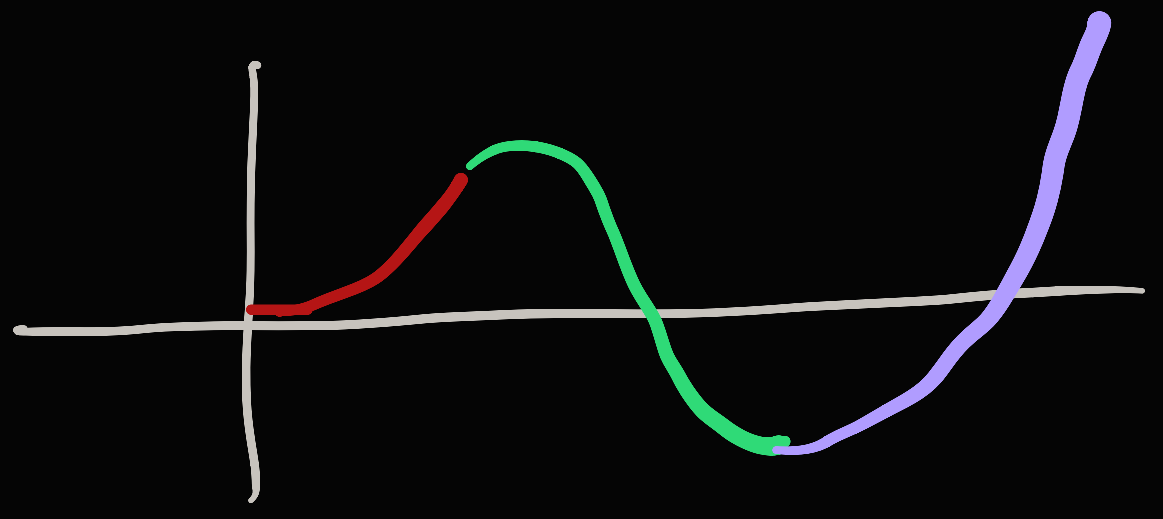
FOPT in the SMEFT

$$\mathcal{L}^{H}_{SMEFT} = \mathcal{L}_{SM} + C^{\varphi}(\phi\phi^{\dagger})^3 + C^{\varphi\Box}\phi\phi^{\dagger}\Box\phi\phi^{\dagger} + C^{\varphi D}(\phi D_\mu \phi^{\dagger})^{*}(\phi D^{\mu}\phi)$$

$\leftarrow$ GeV^{-2}

$$V(T=0) = -\frac{m^2}{2}\varphi^2 + \frac{\lambda}{8}\varphi^4 - \frac{C^{\varphi}}{8}\varphi^6$$

$\lambda < 0$



$\times$ Leads to small Λ_{NP} $\rightarrow$ EFT approach ?

$\lambda > 0$ $\longrightarrow$ Rely on ϕ^3 term for $T \neq 0$

✓ maybe? Needs to be checked

if $\lambda > 0$, then we can have $\underline{\lambda \sim e^3}$ AND $m_H \sim 125$ GeV
AND FOPT

how?

$$m_H^2 = \lambda v^2 - \left(3C^{\varphi} - 2\lambda C^{\varphi\Box} + \frac{\lambda}{2}C^{\varphi D}\right)v^2$$

$$C^{\varphi} \sim \frac{\lambda}{v^2} \qquad C^{\varphi D}, C^{\varphi\Box} \sim \frac{1}{v^2}$$

What about all other experiments?

Finding allowed regions with λ > 0 and FOPT

Pick a point within a reasonable slice of parameter space

$$C^{\varphi} \in [-1 \cdot 10^{-5}, 0]$$
$$C^{\varphi D} \in [-1 \cdot 10^{-7}, 0.5 \cdot 10^{-7}]$$
$$C^{\varphi \Box} \in [-1.5 \cdot 10^{-6}, 3 \cdot 10^{-6}],$$

~ Scaling for FOPT

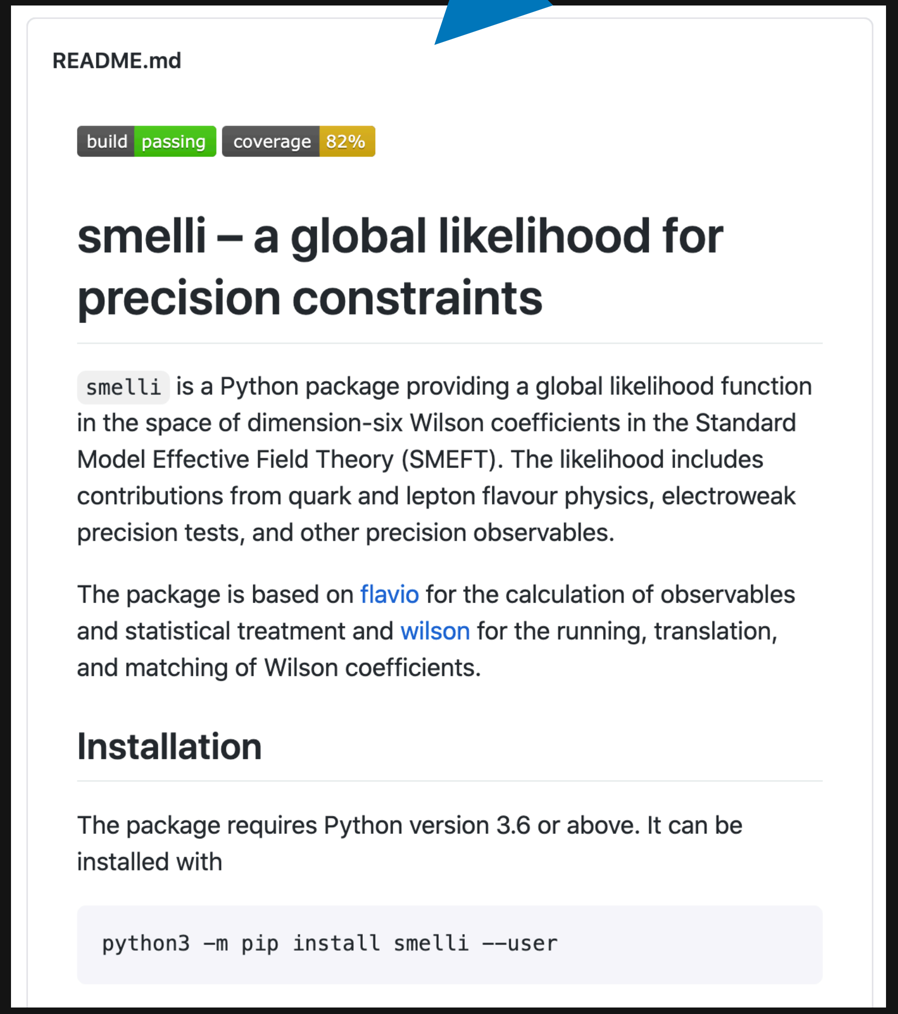
EWPT, rho par, …

EWPT …

NP ~ 0.5 - 3 TeV

Find λ and m^2

Calculate the Δ log likelihood given experimental data using smelli


README.md

build passing coverage 82%

smelli – a global likelihood for precision constraints

`smelli` is a Python package providing a global likelihood function in the space of dimension-six Wilson coefficients in the Standard Model Effective Field Theory (SMEFT). The likelihood includes contributions from quark and lepton flavour physics, electroweak precision tests, and other precision observables.

The package is based on flavio for the calculation of observables and statistical treatment and wilson for the running, translation, and matching of Wilson coefficients.

Installation

The package requires Python version 3.6 or above. It can be installed with

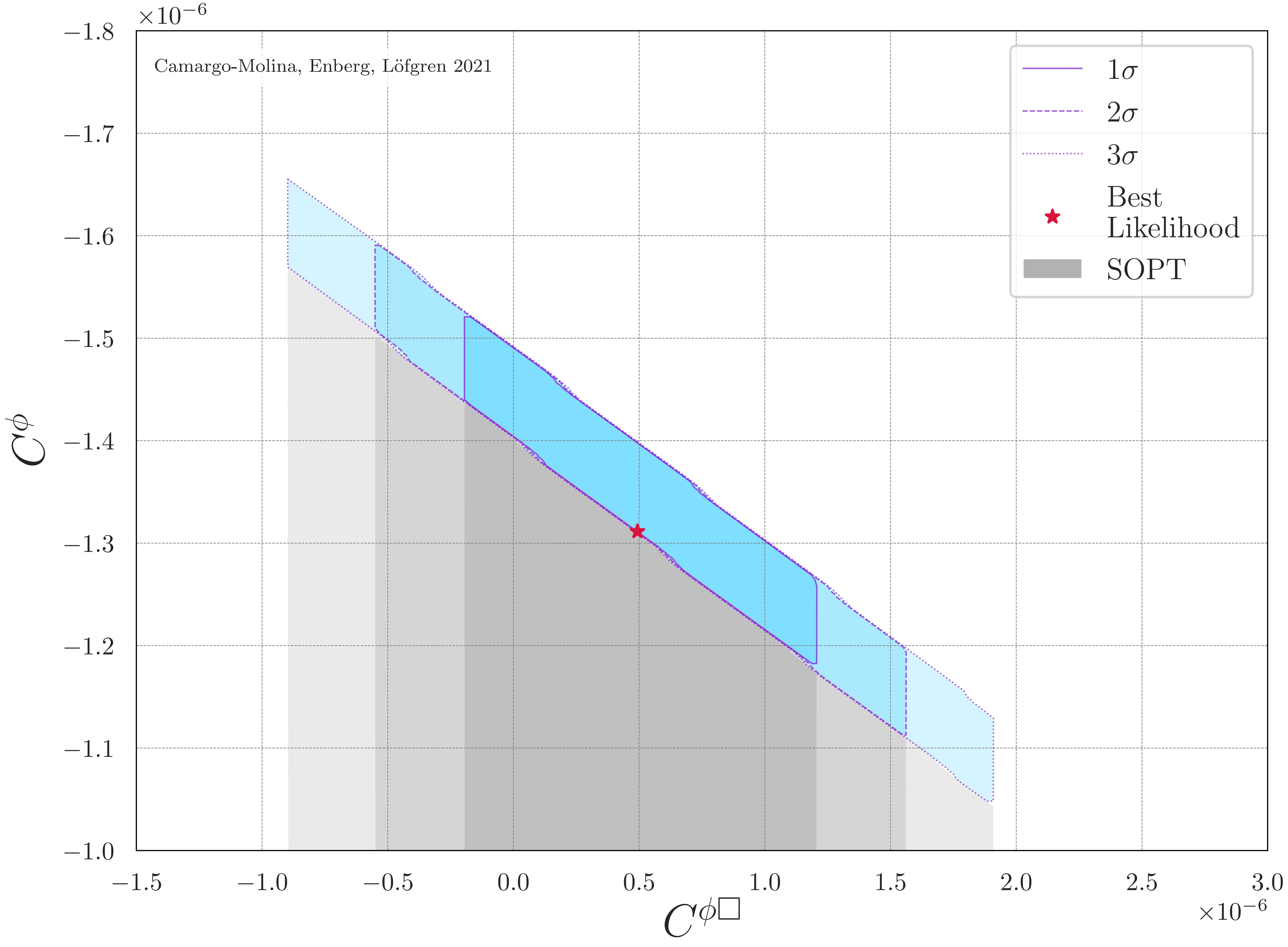
```
python3 -m pip install smelli --user
```

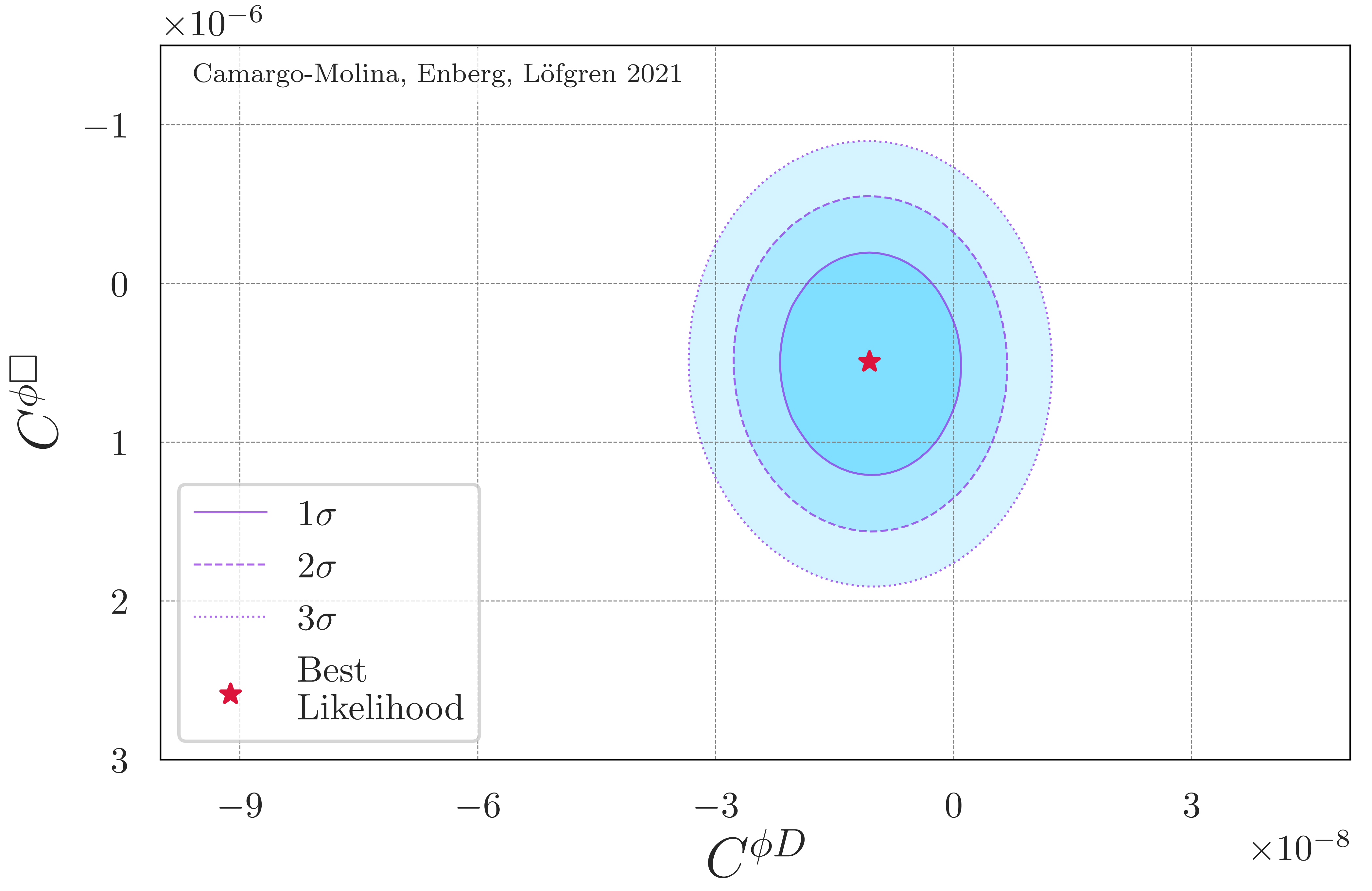
Check if it leads to a FOPT

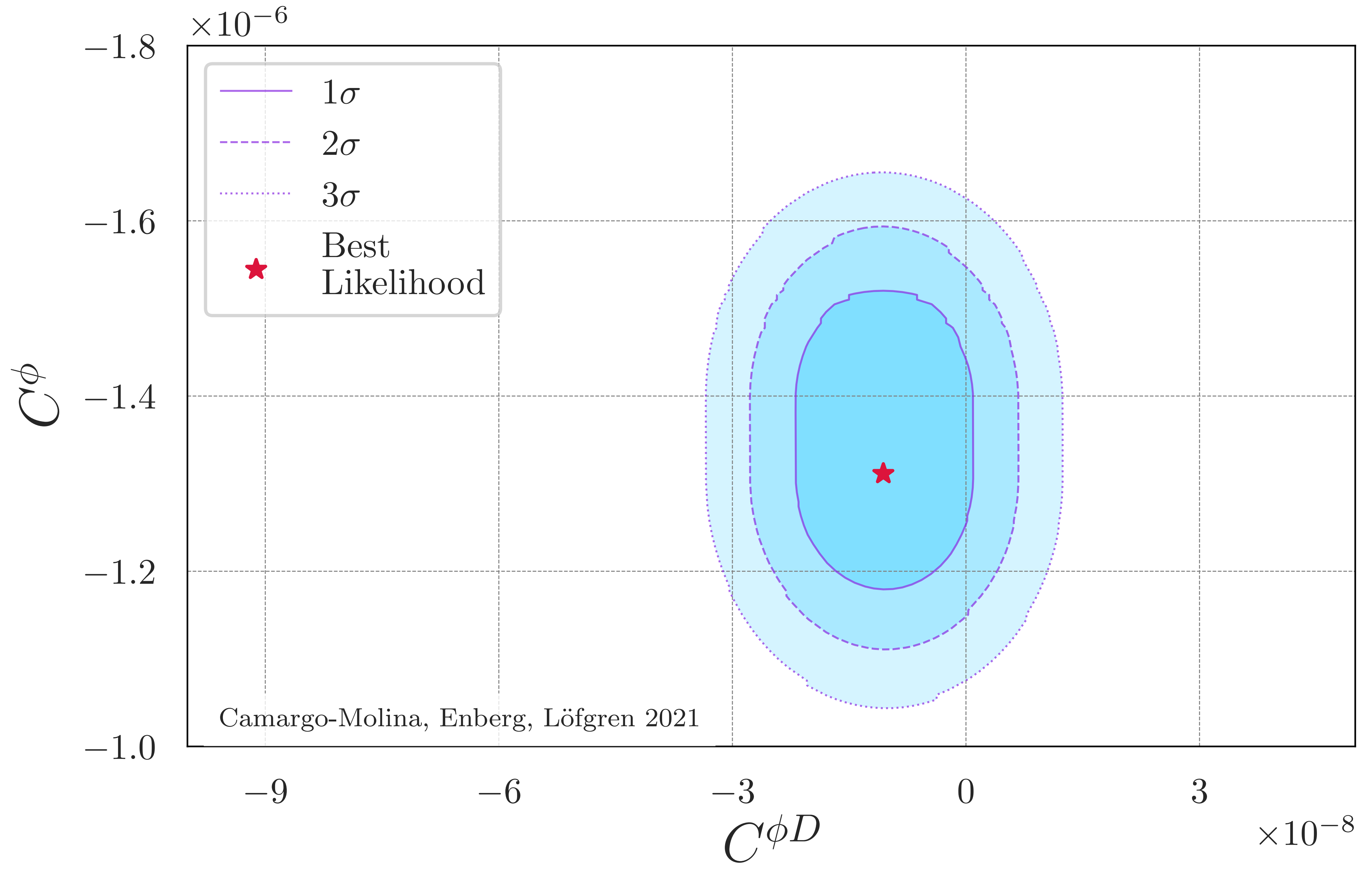
Finding v/Tc: Numerical implementation of a binary search by first placing lower and upper bound on the critical temperature and minimising the potential.

Find points in agreement with data and a FOPT

Allowed regions with λ > 0 and FOPT



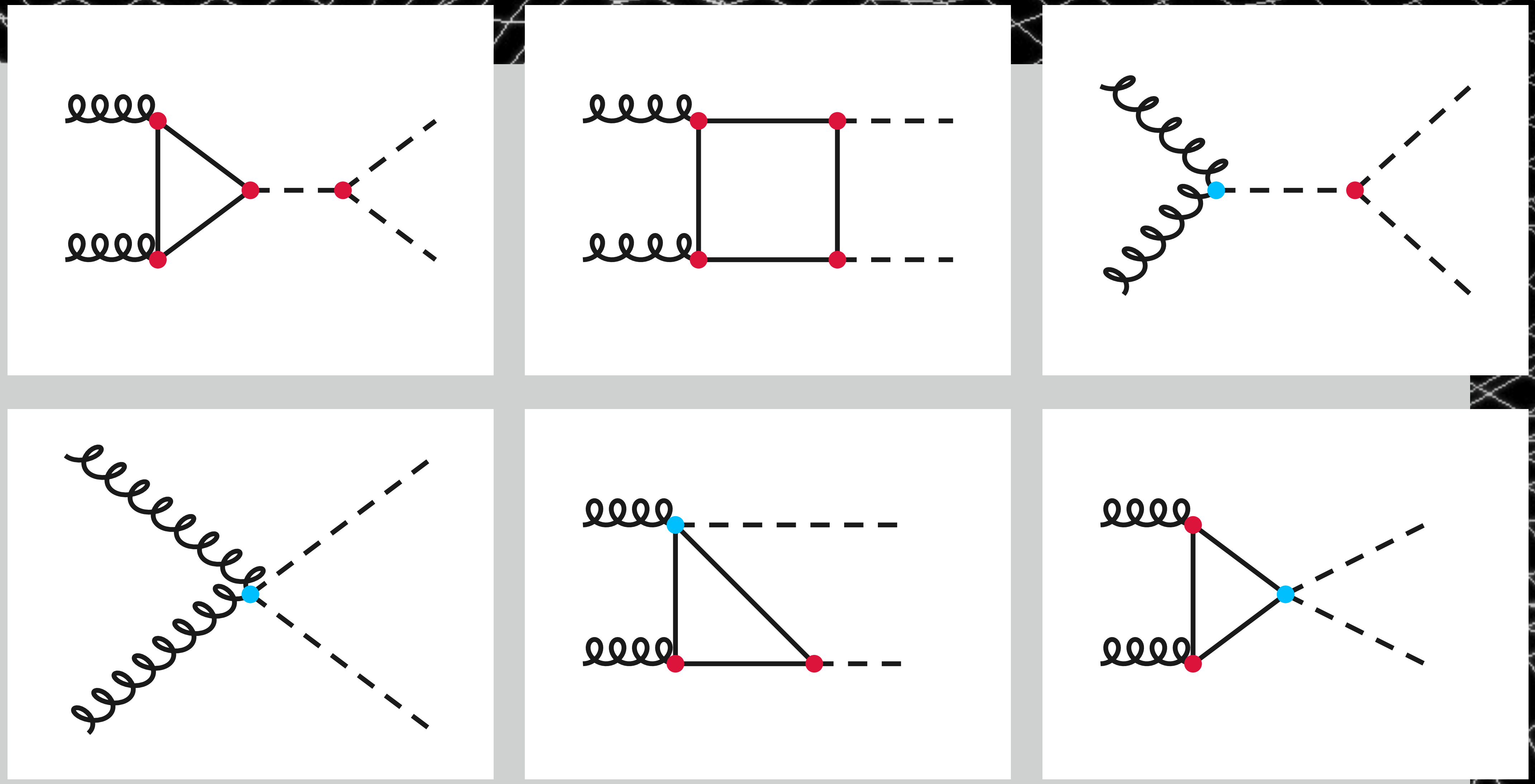




Prospects for measurements, Part II

The same WCs that affect the EWPT also impact Di-Higgs production

The ranges/size for the WCs is precisely in the range that could be probed with a dedicated analysis at LHC, HL-LHC



Modified vertex

New vertex

Constraints on the Higgs boson self-coupling from the combination of single-Higgs and double-Higgs production analyses performed with the ATLAS experiment

The ATLAS Collaboration

Constraints on the Higgs boson self-coupling are set by combining the single Higgs boson analyses targeting the $\gamma\gamma$, ZZ^*, WW^*, $\tau^+\tau^-$ and $b\bar{b}$ decay channels with the double Higgs boson analyses in the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}\gamma\gamma$ decay channels, using data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC. The data used in these analyses correspond to an integrated luminosity of up to 79.8 fb^{-1} for single Higgs boson analyses and up to 36.1 fb^{-1} for the double Higgs boson analyses. With the assumption that new physics affects only the Higgs boson self-coupling (λ_{HHH}), values outside the interval $-2.3 < \lambda_{HHH}/\lambda_{HHH}^{\rm SM} < 10.3$ are excluded at 95% confidence level. Results with less stringent assumptions are also provided, introducing additional coupling modifiers for the Higgs boson interactions with the other Standard Model particles.

ATLAS-CONF-2019-049
23/10/2019

$$\frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}} = \frac{\lambda_{EFT}}{\lambda_{SM}} - \frac{v^2}{\lambda_{SM}}\left(5C^{\varphi} - 3\lambda_{EFT}C^{\varphi\Box} + \frac{3}{4}\lambda_{EFT}C^{\varphi D}\right)$$

$$-1.9\cdot 10^{-5} < C^{\varphi}_{LHC} < 7.0\cdot 10^{-6}$$

ATLAS

$$-2.8\cdot 10^{-6} < C^{\varphi}_{HL-LHC} < 1.7\cdot 10^{-6}.$$

Kim, Sakaki, Son [1801.06093]

$$-1.65\cdot 10^{-6} \lesssim C^{\varphi}_{FOPT} \lesssim -1.05\cdot 10^{-6}$$

Conclusions

- First order phase transitions are the (most promising) link between observations, cosmology and particle physics.
- SMEFT a good “agnostic” proxy for interpreting measurements.
- So far, only $\lambda < 0$ has been seriously thought about.
- Proper power counting and care for gauge invariance surprisingly opens up $\lambda > 0$.
- It is also allowed by measurements so far!

TOMORROW, ON ARXIV:

A new perspective on the electroweak phase transition in the Standard Model Effective Field Theory

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A first-order Electroweak Phase Transition (EWPT) could explain the observed baryon-antibaryon asymmetry and have a detectable gravitational wave signature, but is not possible in the Standard Model. We therefore study the EWPT in the Standard Model Effective Field Theory (SMEFT) including dimension-six operators. A first-order EWPT has previously been shown to be possible in the SMEFT in scenarios with a tree-level barrier between minima, which requires a negative Higgs quartic coupling and a new physics scale low enough to raise questions about the validity of the EFT approach. In this work we show that a first-order EWPT is possible in a novel scenario where the barrier between minima is generated radiatively, the quartic coupling is positive, the scale of new physics is higher, and there is good agreement with experimental bounds. Our calculation is done in a consistent, gauge-invariant way, and we carefully analyze the scaling of parameters necessary to generate a barrier in the potential. We perform a global fit in the relevant parameter space and explicitly find the points with a first-order transition. We also briefly discuss the prospects for probing the allowed parameter space using di-Higgs production in colliders.

I. INTRODUCTION

According to standard cosmological models, the electroweak symmetry of the Standard Model (SM) was broken in the early Universe through a phase transition from a phase of unbroken symmetry with a vanishing Higgs field, to a phase of broken symmetry with a non-

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A roadmap for the future

The particle physics community refreshes the roadmap for the field in Europe, taking into account the worldwide context, in the so-called European Strategy for Particle Physics update, which happens every seven years.

Fabiola Gianotti and Gian Francesco Giudice

The focus of particle physics has thus evolved towards addressing structural questions about spacetime, fundamental interactions and the origin of the Universe. Some of these are as old as civilization itself and it is fascinating that we have today reached the maturity and developed the technologies to address them. The urge to seek answers to such questions is part of what defines us as humans. The ambitious task that lies ahead entails global collaboration on a courageous experimental venture, involving high-energy colliders, low-energy precision tests, observational cosmology, cosmic rays, dark-matter searches, gravitational waves, terrestrial and cosmic neutrinos, and much more.

ありがとうございます