HIGGS AND COSMOLOGY

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Higgs Hunting 2024
Results and prospects in the electroweak symmetry breaking sector

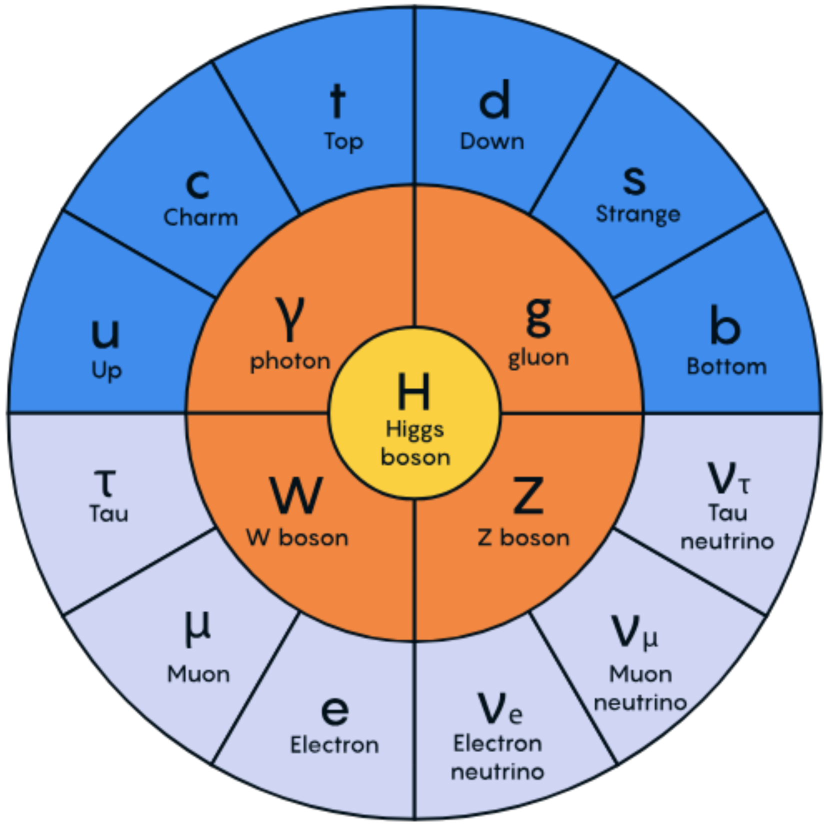
Sept 23, 2024

Image Credit: Orbiter

MAIN TAKEAWAY MESSAGES

- Extensions/modifications of the Higgs sector remain **as motivated as ever**
- The Higgs boson: possibly as **crucial for cosmology** as it is for particle physics
- Could play a role in **solving some of the main problems in cosmology**
- Even the **Standard Model Higgs, without any modifications, can play an important role** in the early Universe
- Could give rise to **distinct observable cosmological phenomena**
- **High energy colliders can play a crucial role** in unraveling Higgs cosmology

THE HIGGS: AT THE HEART OF EVERYTHING



THE HIGGS: AT THE HEART OF EVERYTHING

Cosmology

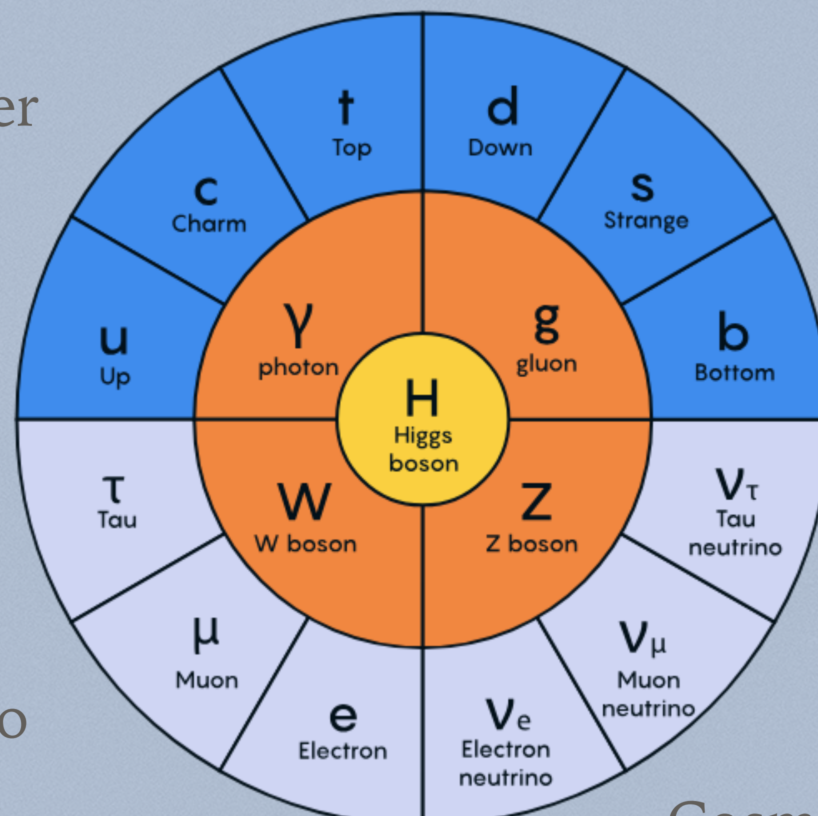
[Incomplete, biased list]

Dark Matter

Cosmological Phenomena

Baryon Asymmetry

Gravitational Waves



Primordial Black Holes

Neutrino Masses

Cosmic Microwave Background

Inflation

HIGGS AND DARK MATTER

Consider a **generic dark matter candidate in a dark sector**,
with no direct couplings to the SM

Massive and stable: most likely involves a dark Higgs mechanism

A **portal mixing between dark and SM Higgs always allowed;**
provides a link between the SM and dark sectors

Higgs Portal Dark Matter

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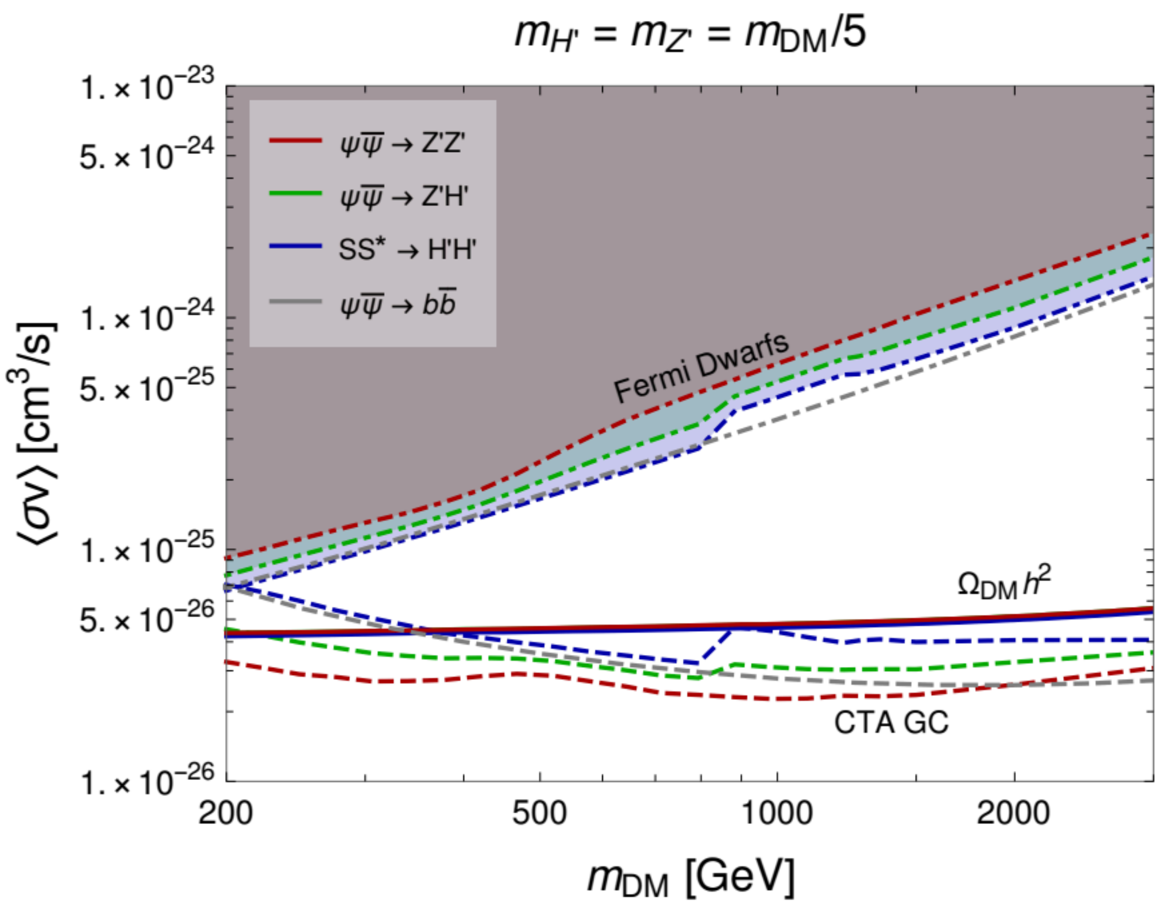
Strength of indirect detection signals suppressed by the cascade decay nature (hidden WIMPs essentially unconstrained)

Thermal target largely within reach of future experiments (Cherenkov Telescope Array)



P. Barnes, Z. Johnson, A. Pierce, B. Shakya, 2106.09740

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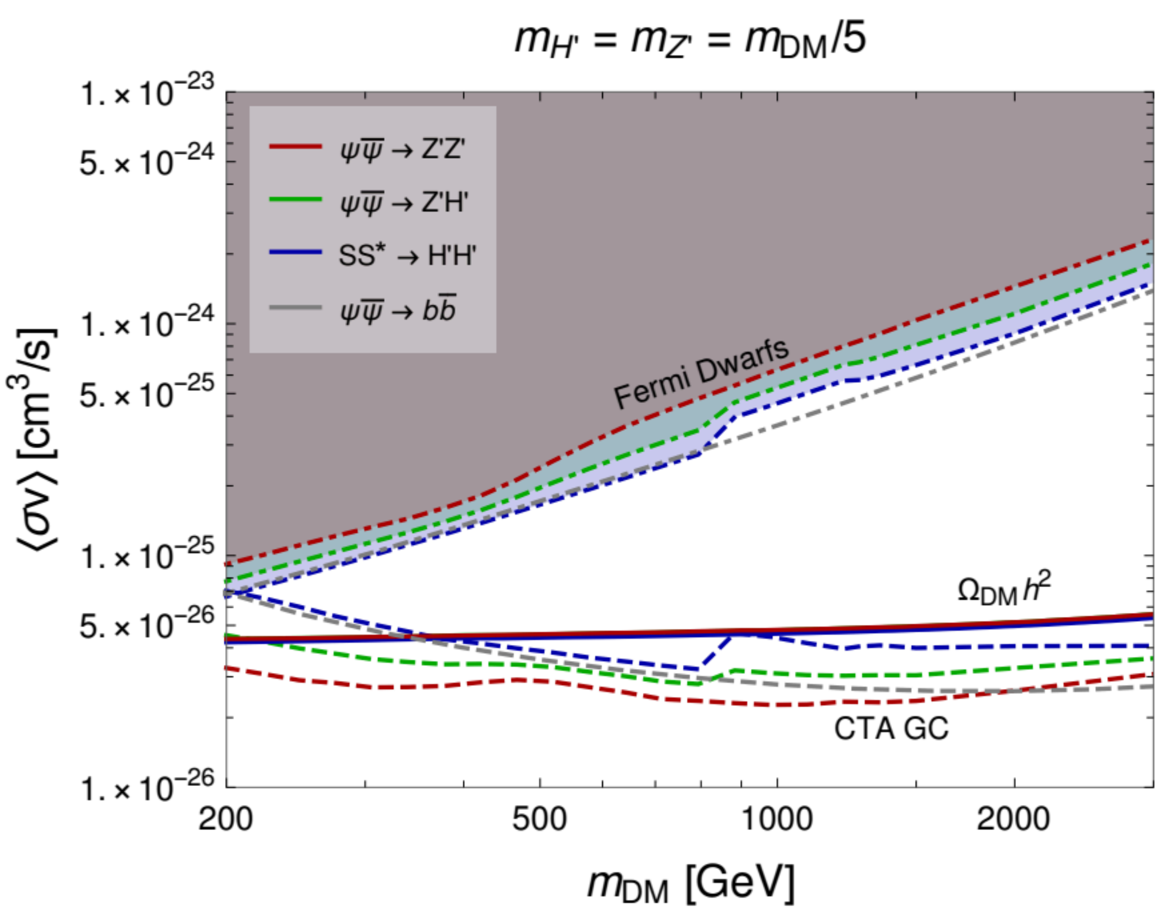
WIMP miracle provides an energy scale at which to expect new states coupled to the Higgs, **within reach of HE colliders!**



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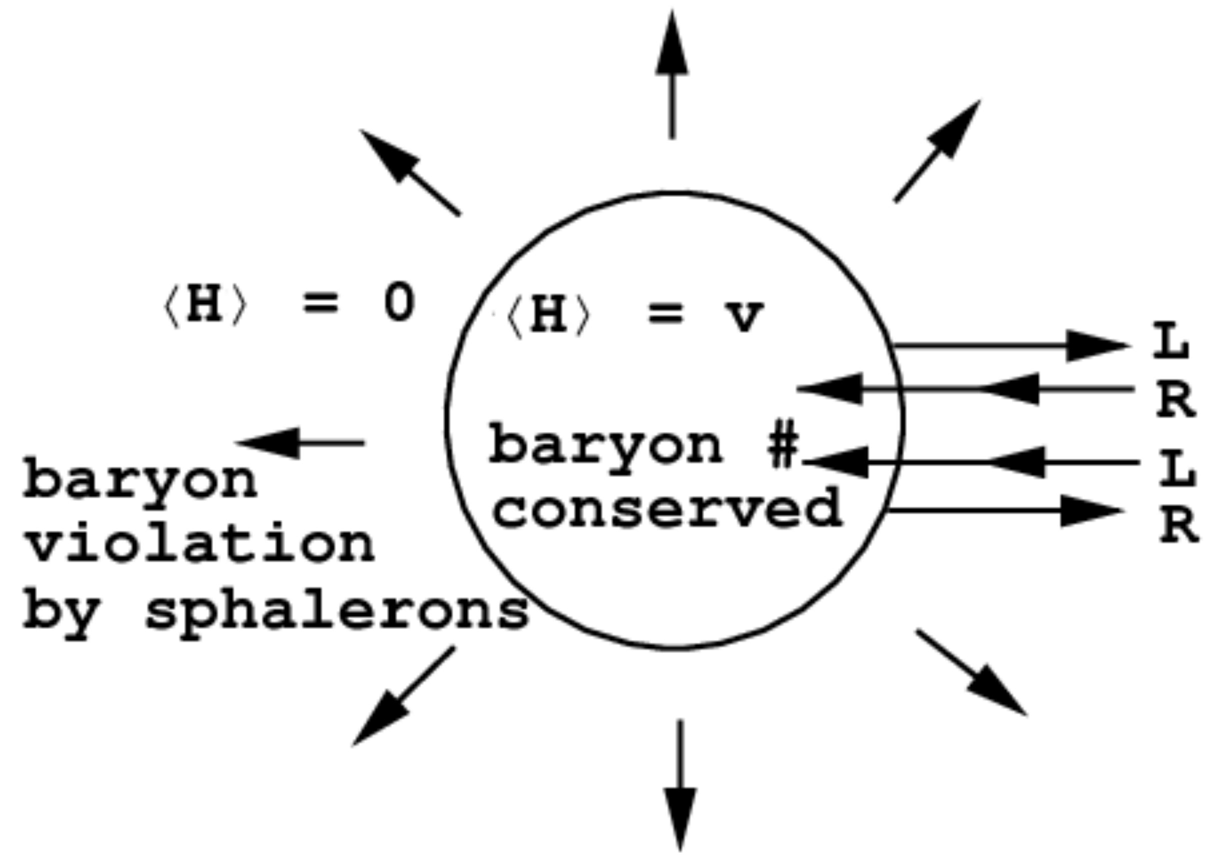
HIGGS AND THE BARYON ASYMMETRY

Electroweak Baryogenesis

If the electroweak phase transition is first order (occurs through nucleation, expansion, and percolation of bubbles of electroweak vacuum), **a baryon asymmetry can be produced across the bubble walls** separating the two phases



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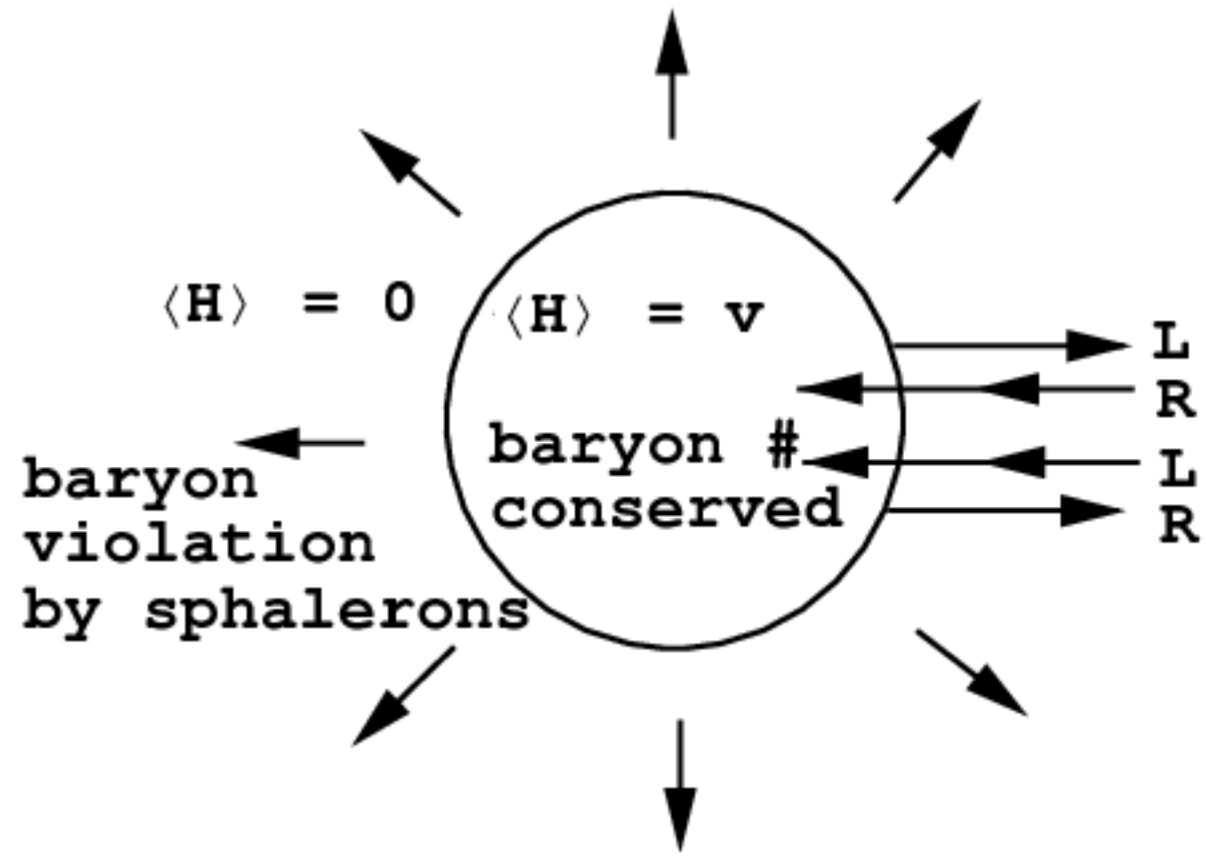


Recent research in this direction has focused on:

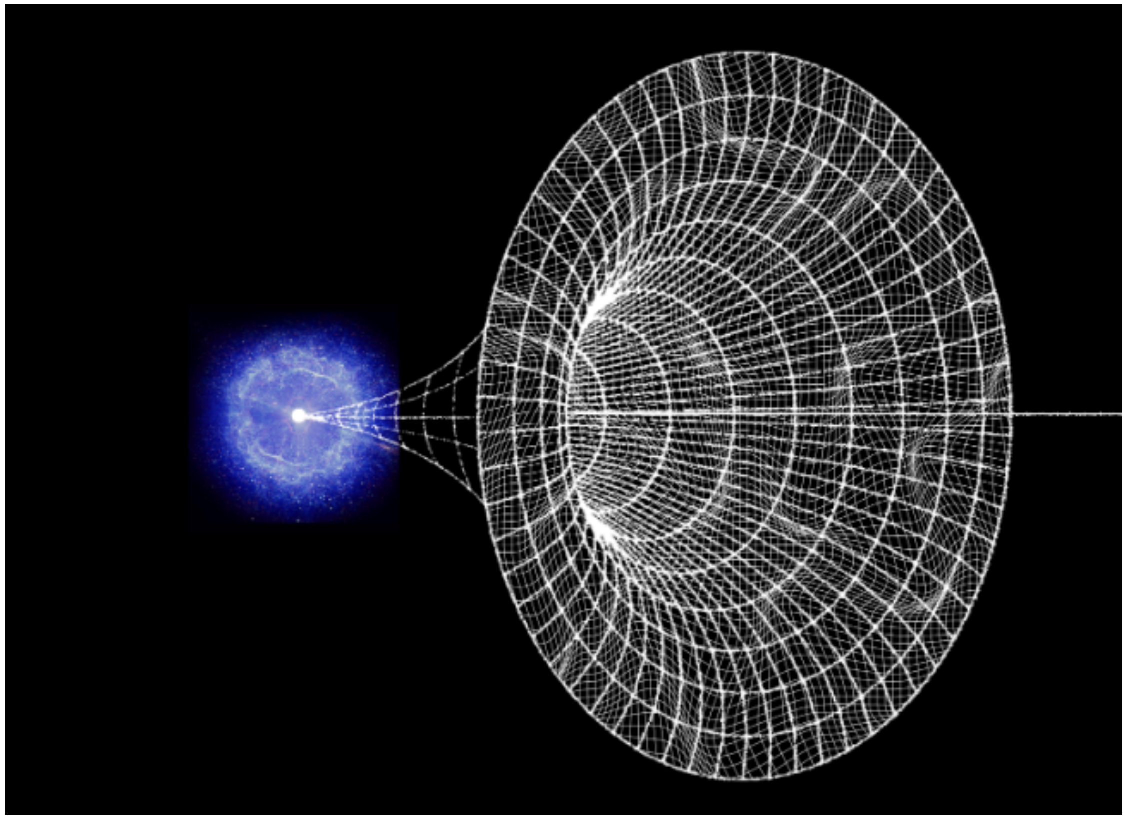
- Model building efforts to generate a first order phase transition (in the SM, the transition is a smooth crossover)
- Better calculation of bubble wall velocity (important for calculating the amount of asymmetry)
- Improving the calculation of scattering rates by including higher order corrections

Predicts new physics coupling to the Higgs at the EW scale, gravitational waves from the phase transition

HIGGS AND INFLATION

Inflation can be realized through vacuum domination with a scalar field - **the inflaton** - that undergoes "slow roll"

The Higgs can couple to the inflaton field (higgs portal)



The Higgs itself can be the inflaton:

Higgs Inflation

Requires modification of the Higgs potential: non minimal coupling to gravity

Possible tension with curvature power spectrum (requires large nonminimal couplings, possible unitarity violation)

HIGGS AND NEUTRINOS

The Higgs can couple left- and **right- handed neutrinos (RHN)**, analogous to other SM fermions

$$y_\nu \, L \, H \, N + M_N N N$$

Type-I seesaw mechanism

- Explains the small neutrino masses
- RHN can be dark matter (generally considered at keV scale)
- RHN decays can produce a lepton asymmetry, later converted to a baryon asymmetry: leptogenesis

Recent research directions:

- keV RHN production mechanism through mixing no longer viable; new production mechanisms needed
- With new production mechanisms for sterile neutrino DM, keV scale no longer needed; broader mass range possible
- No observable signals of high scale leptogenesis; embed leptogenesis in scenarios, e.g. first order phase transitions, that can yield gravitational wave signals

THE STANDARD MODEL HIGGS AND COSMOLOGY

One of the most striking implications of current measurements of the Higgs properties:

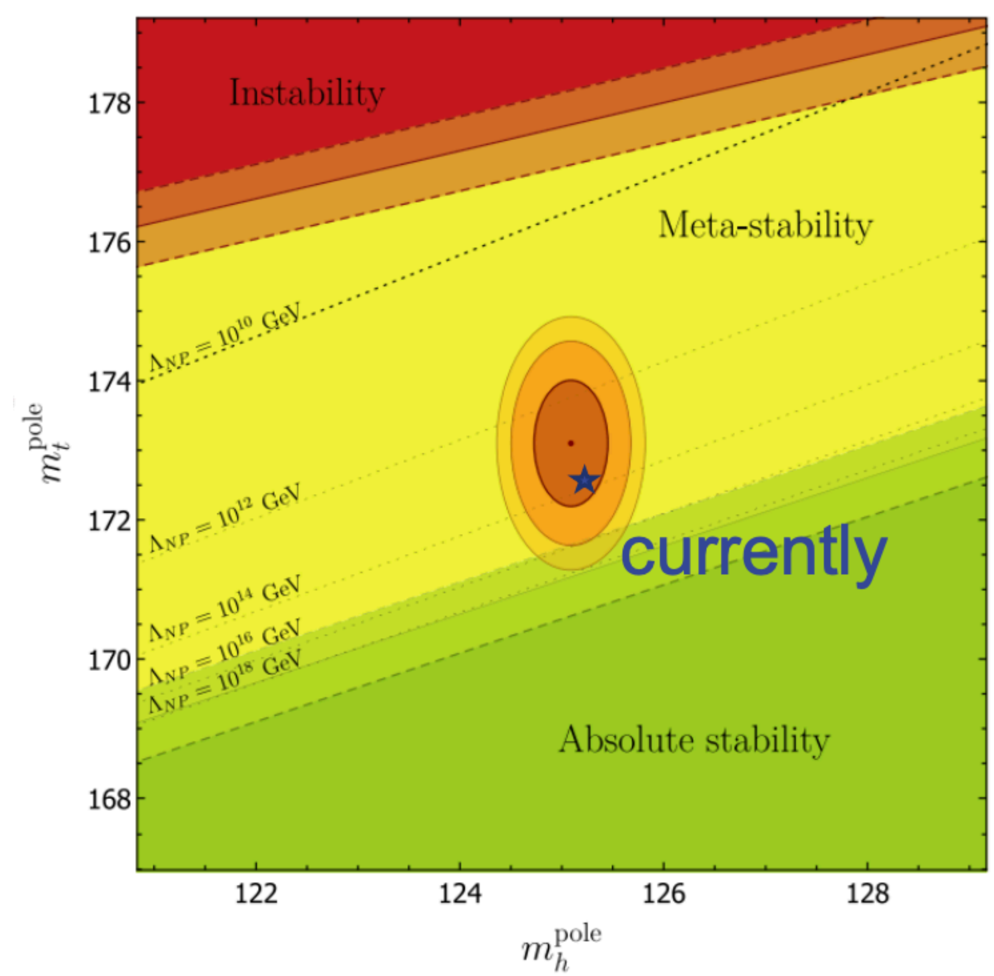
the electroweak vacuum of the Standard Model, in its current form, is likely **metastable**

Important cosmological implications+signatures!

→ Currently (PDG):

$m_H = (125.20 \pm 0.11)$ GeV

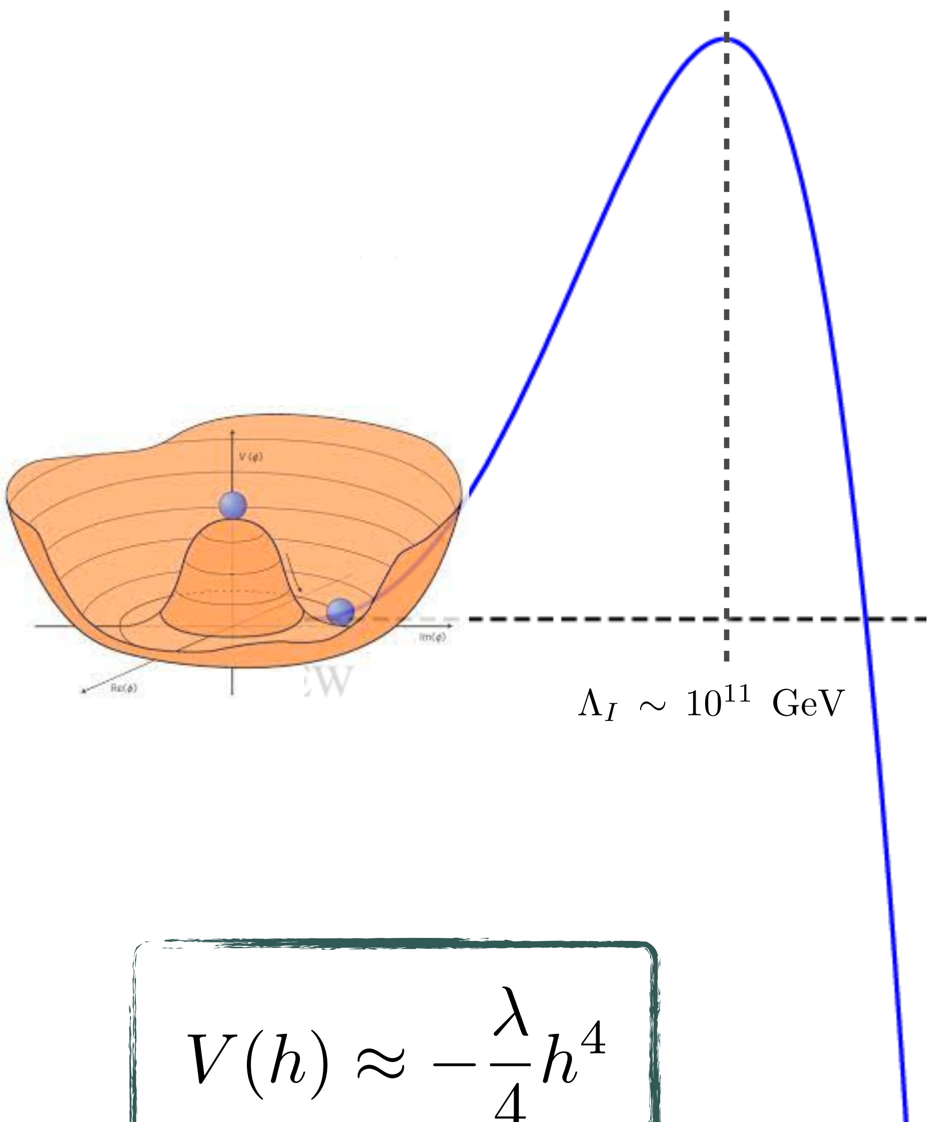
$m_t = (172.57 \pm 0.29)$ GeV



Modified from Andreassen, Frost, Schwartz, PhysRev D 97 056006 (2018)

From Valerie Lang's talk this morning

THE STANDARD MODEL HIGGS POTENTIAL EXTENDED TO HIGHER ENERGIES:



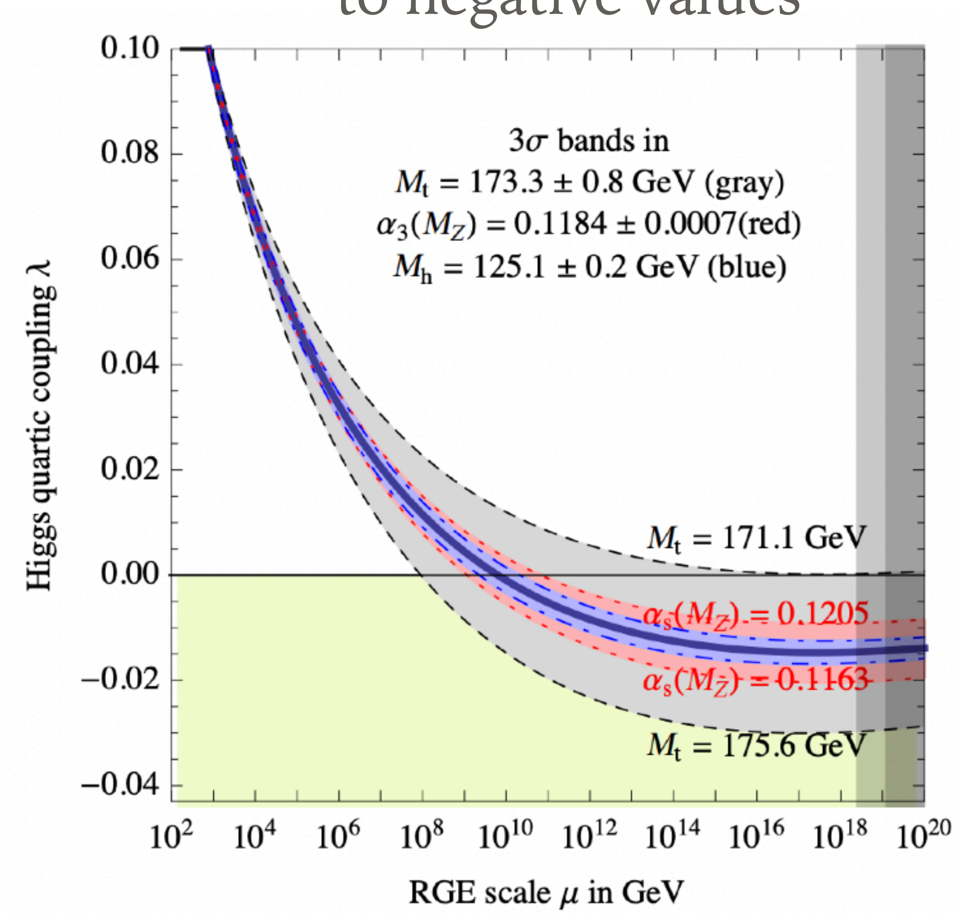
$$V(h) \approx -\frac{\lambda}{4} h^4$$

$$\lambda \approx 0.01$$

at high scales

A deeper true minimum somewhere

Higgs quartic coupling runs to negative values



1307.3536 [hep-ph]

HIGGS DURING INFLATION

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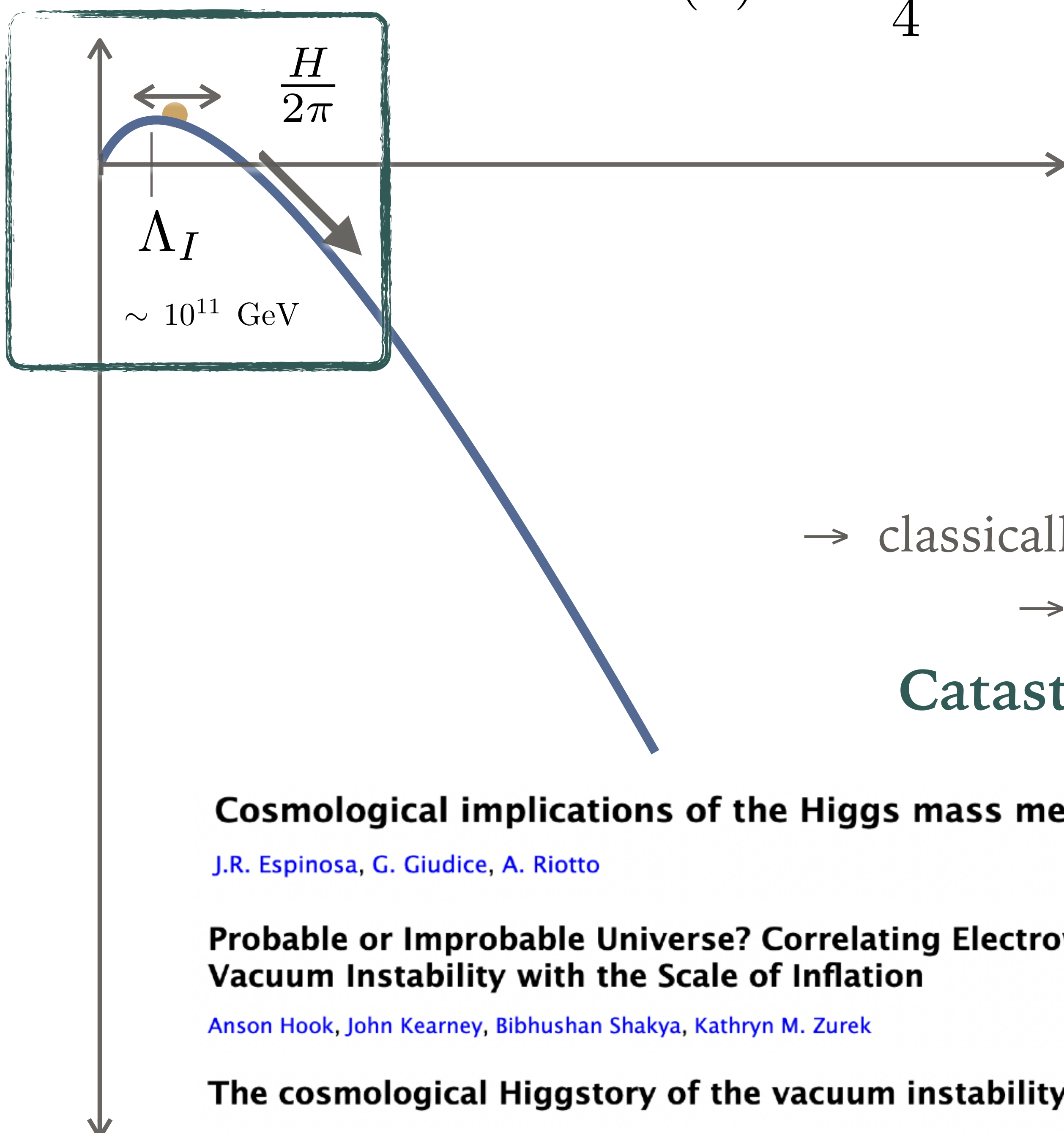


Metastable; however … **inflation**

An early inflationary epoch creates **fluctuations** $\sim \frac{H}{2\pi}$

Higgs field can fluctuate over barrier, destabilising the electroweak vacuum if Hubble scale H comparable to or larger than Λ_I

$\rightarrow$ classically rolls down to some negative energy minimum

$\rightarrow$ crunching anti-de Sitter (AdS) space

Catastrophic consequences for our Universe!

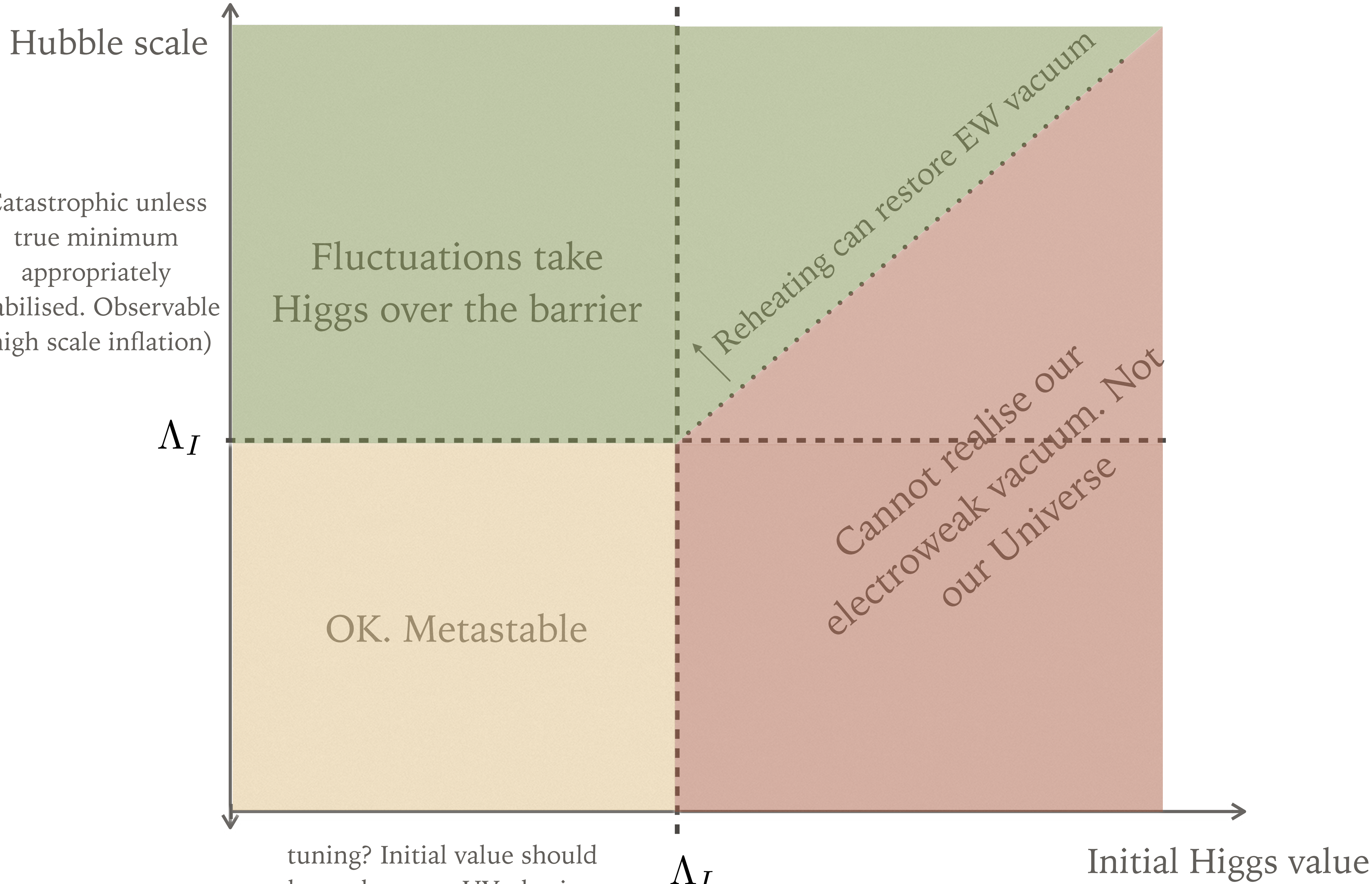
Cosmological implications of the Higgs mass measurement 0710.2484
J.R. Espinosa, G. Giudice, A. Riotto

Probable or Improbable Universe? Correlating Electroweak Vacuum Instability with the Scale of Inflation 1404.5953
Anson Hook, John Kearney, Bibhushan Shakya, Kathryn M. Zurek

The cosmological Higgstory of the vacuum instability 1505.04825
Jose R. Espinosa, Gian F. Giudice, Enrico Morgante, Antonio Riotto, Leonardo Senatore, Alessandro Strumia, Nikolaos Tetradis

Spacetime Dynamics of a Higgs Vacuum Instability During Inflation 1607.00381
William E. East, John Kearney, Bibhushan Shakya, Hojin Yoo, Kathryn M. Zurek

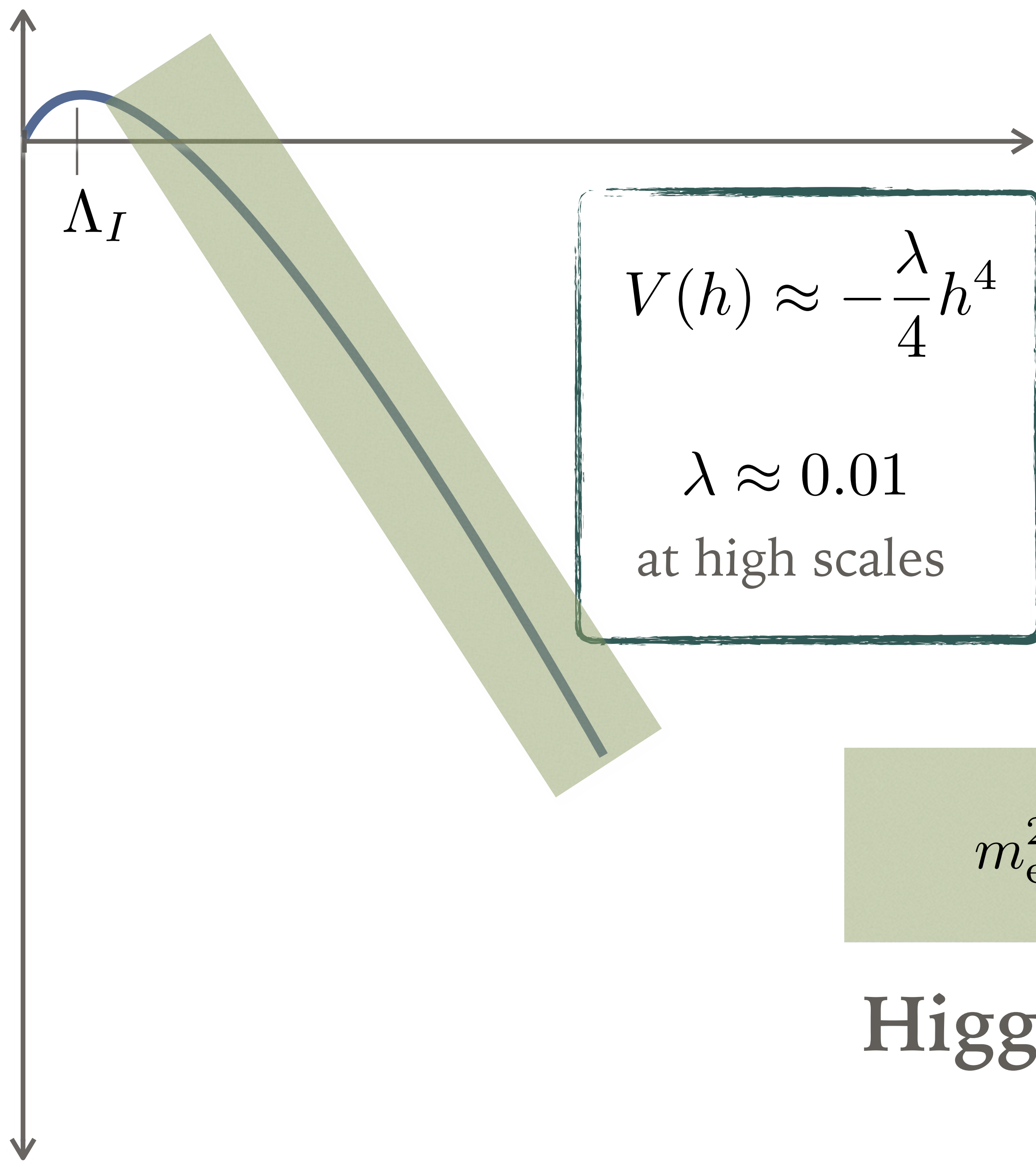
HIGGS DURING INFLATION



Catastrophic unless true minimum appropriately stabilised. Observable (high scale inflation)

tuning? Initial value should be set by some UV physics; why so small?

THE STANDARD MODEL HIGGS POTENTIAL EXTENDED TO HIGHER ENERGIES:



$$V(h) \approx -\frac{\lambda}{4} h^4$$

$$\lambda \approx 0.01$$

at high scales

Higgs quartic coupling runs to negative values

$$m^2_{\text{eff}}(h) = V_{hh} = -3\lambda h^2 \approx -(0.17\, h)^2 < 0$$

Higgs mass becomes tachyonic!

WIKIPEDIA

A **tachyon** (/ˈtækiɒn/) or **tachyonic particle** is a hypothetical particle that always travels faster than light. Physicists believe that faster-than-light particles cannot exist because they are not consistent with the known laws of physics.[1][a] If such particles did exist they could be used to send signals faster than light. According to the theory of relativity this would violate causality, leading to logical paradoxes such as the grandfather paradox.[1] Tachyons would exhibit the unusual property of increasing in speed as their energy decreases, and would require infinite energy to slow down to the speed of light. No verifiable experimental evidence for the existence of such particles has been found.

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WAS THE (UNSTABLE) TACHYONIC PHASE OF THE HIGGS PART OF OUR EARLY UNIVERSE HISTORY?

WHAT OBSERVABLE IMPRINTS DOES IT LEAVE?

The Tachyonic Higgs and the Inflationary Universe, B. Shakya [2301.08754]

TACHYONIC INSTABILITY

Consider the mode expansion of a field:

$$\hat{\psi}_{\mathbf{k}} = \frac{1}{\sqrt{2\omega_k}}(\hat{a_{\mathbf{k}}}^{-} e^{-i\omega_k t} + \hat{a}_{\mathbf{k}}^{\dagger} e^{i\omega_k t})$$

If $\omega_k = \sqrt{|\mathbf{k}|^2 + m^2}$ is imaginary,

$$e^{-i\omega t} = e^{|\omega| t}$$

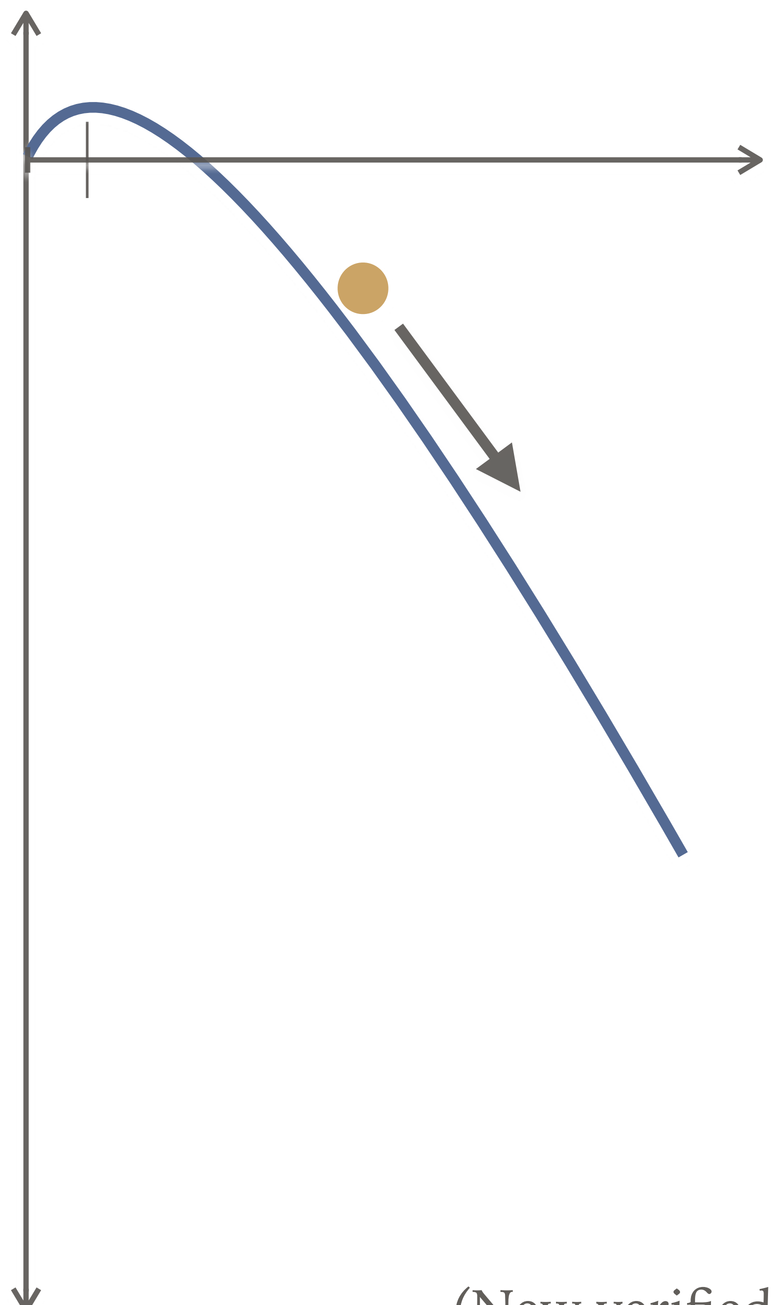
grows exponentially instead of oscillating

Tachyonic instability leads to explosive growth of inhomogeneities / particle densities!

G. N. Felder, J. Garcia-Bellido, P. B. Greene, L. Kofman, A. D. Linde, and I. Tkachev, Phys. Rev. Lett. **87**, 011601 (2001), hep-ph/0012142.

G. N. Felder, L. Kofman, and A. D. Linde, Phys. Rev. D **64**, 123517 (2001), hep-th/0106179.

TACHYONIC INSTABILITY



The homogeneous Higgs field becomes extremely inhomogeneous very quickly as it rolls down its potential

$$e^{-i\omega t} = e^{|\omega| t} \qquad\qquad \omega_k = \sqrt{|\mathbf{k}|^2 + m^2}$$

Two kinds of inhomogeneities:

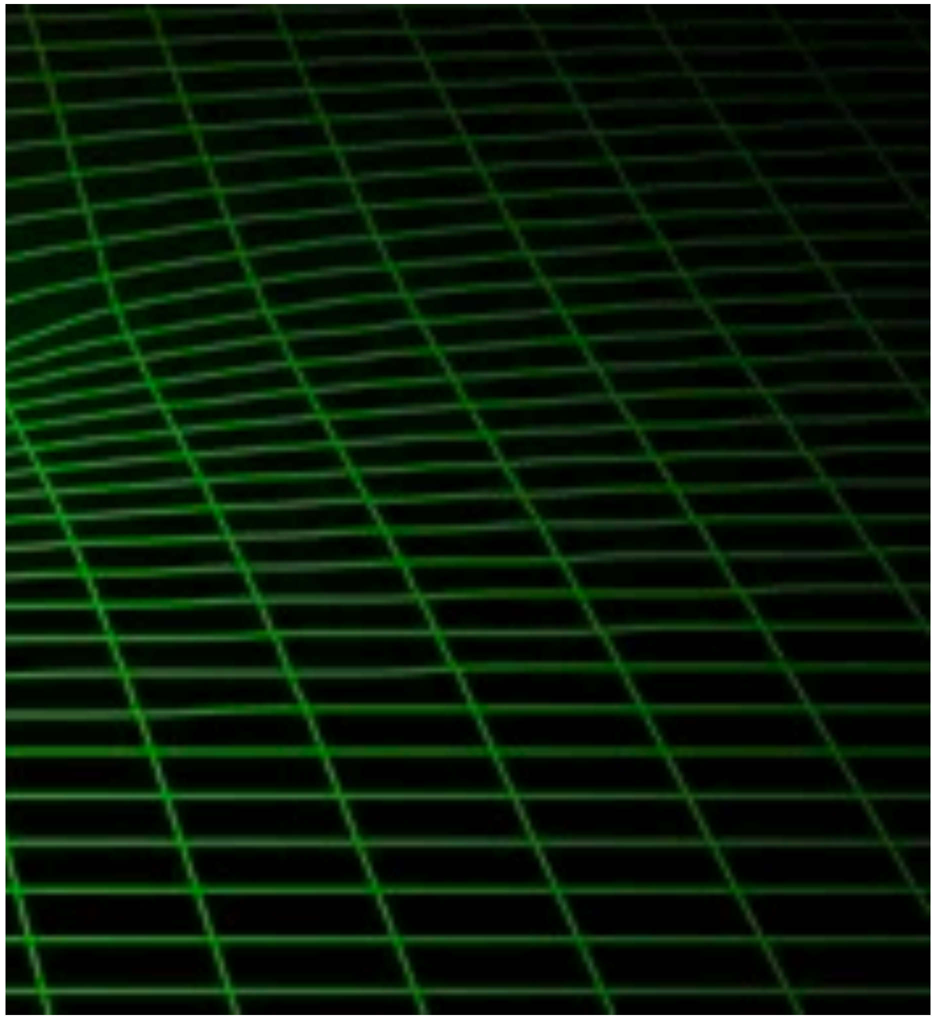
1. Earlier inhomogeneities are exponentially stretched by inflation, become super horizon scale
2. Late inhomogeneities remain subhorizon, grow the fastest

(New verified with lattice simulations: A. Chatrchyan, B. Shakya, in preparation)

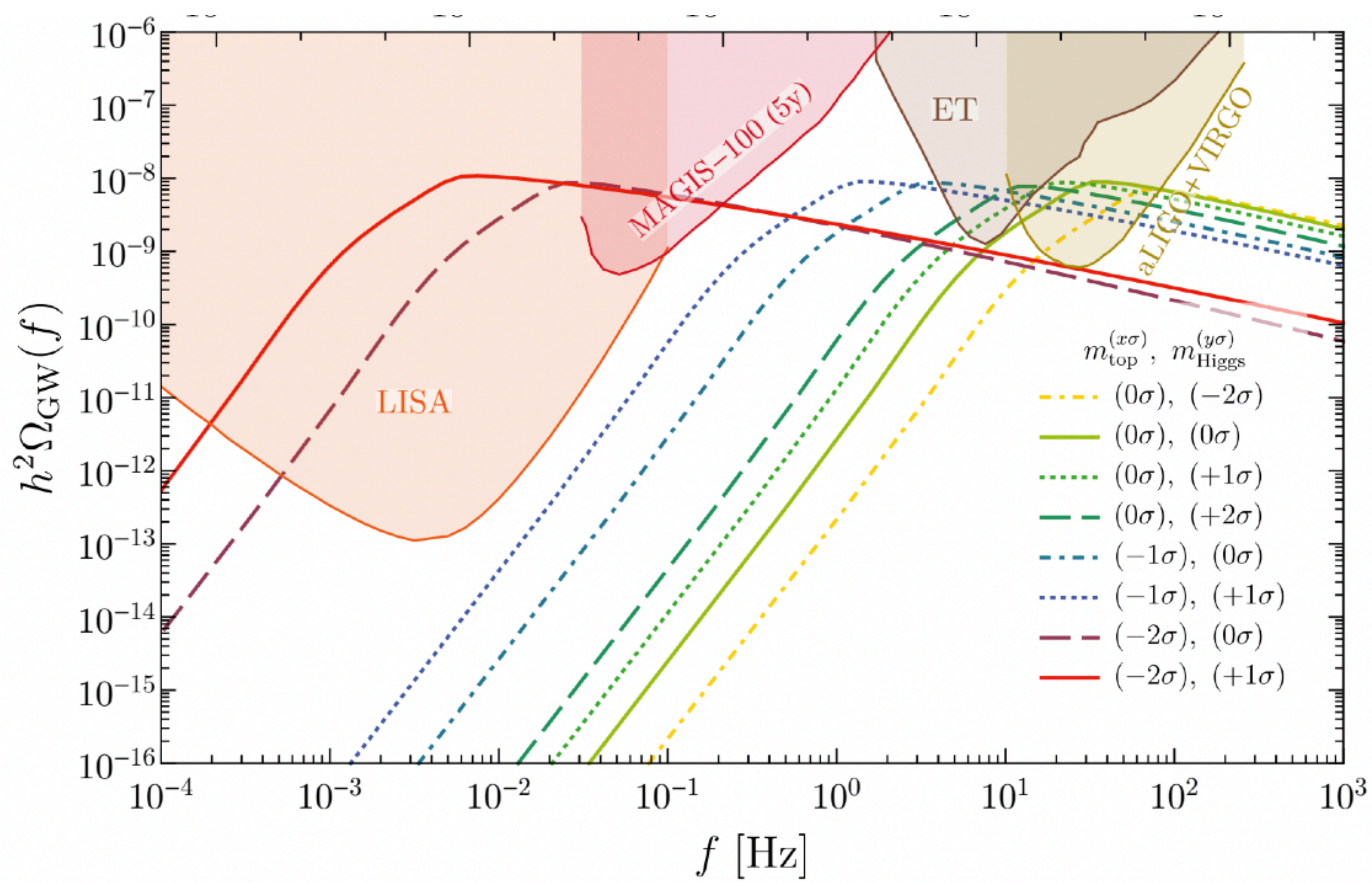
OBSERVATIONAL SIGNALS?

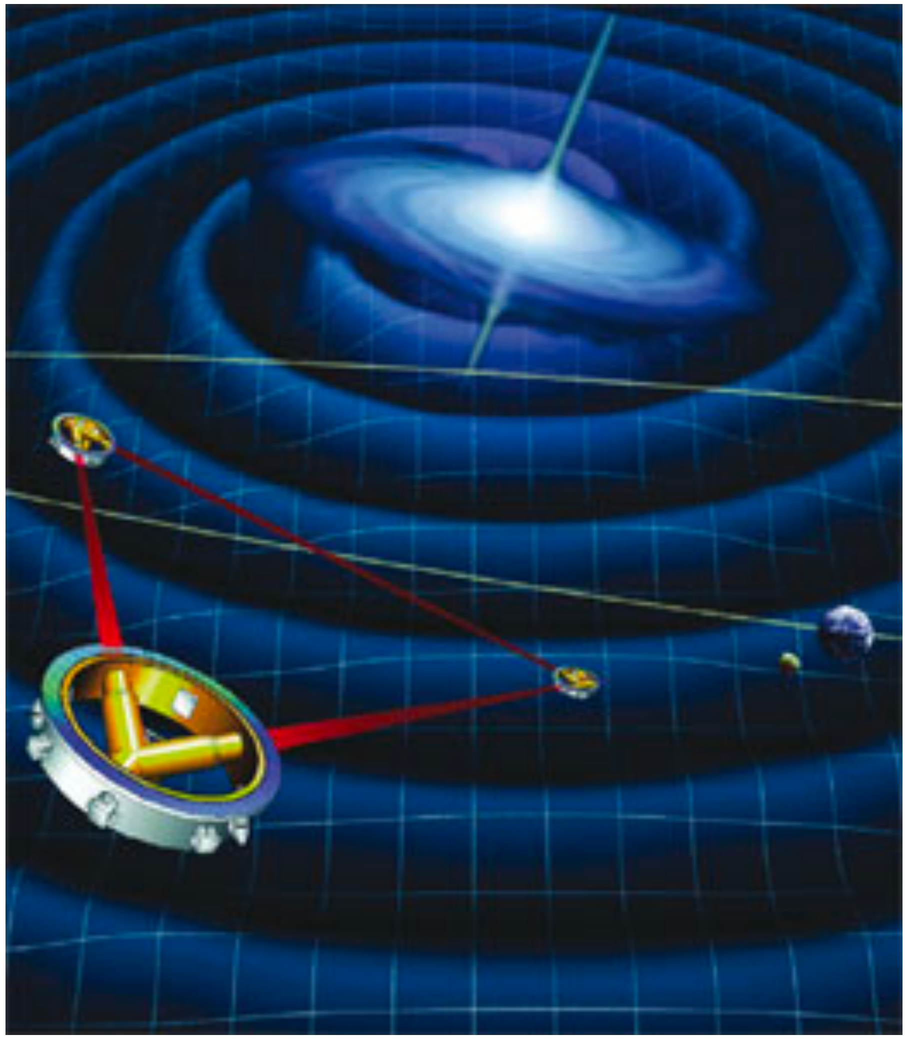
If the Higgs did indeed foray into its high energy tachyonic regime during/after inflation (without destroying the Universe as we know it), how would we know?

- Imagine that the Higgs evolves to such large values in **a small fraction of the Hubble patches during inflation**; most of spacetime remains within the stable part of the Higgs potential
- **Large Higgs inhomogeneities/particle densities in a small fraction of the post-inflationary Universe**



GRAVITATIONAL WAVES



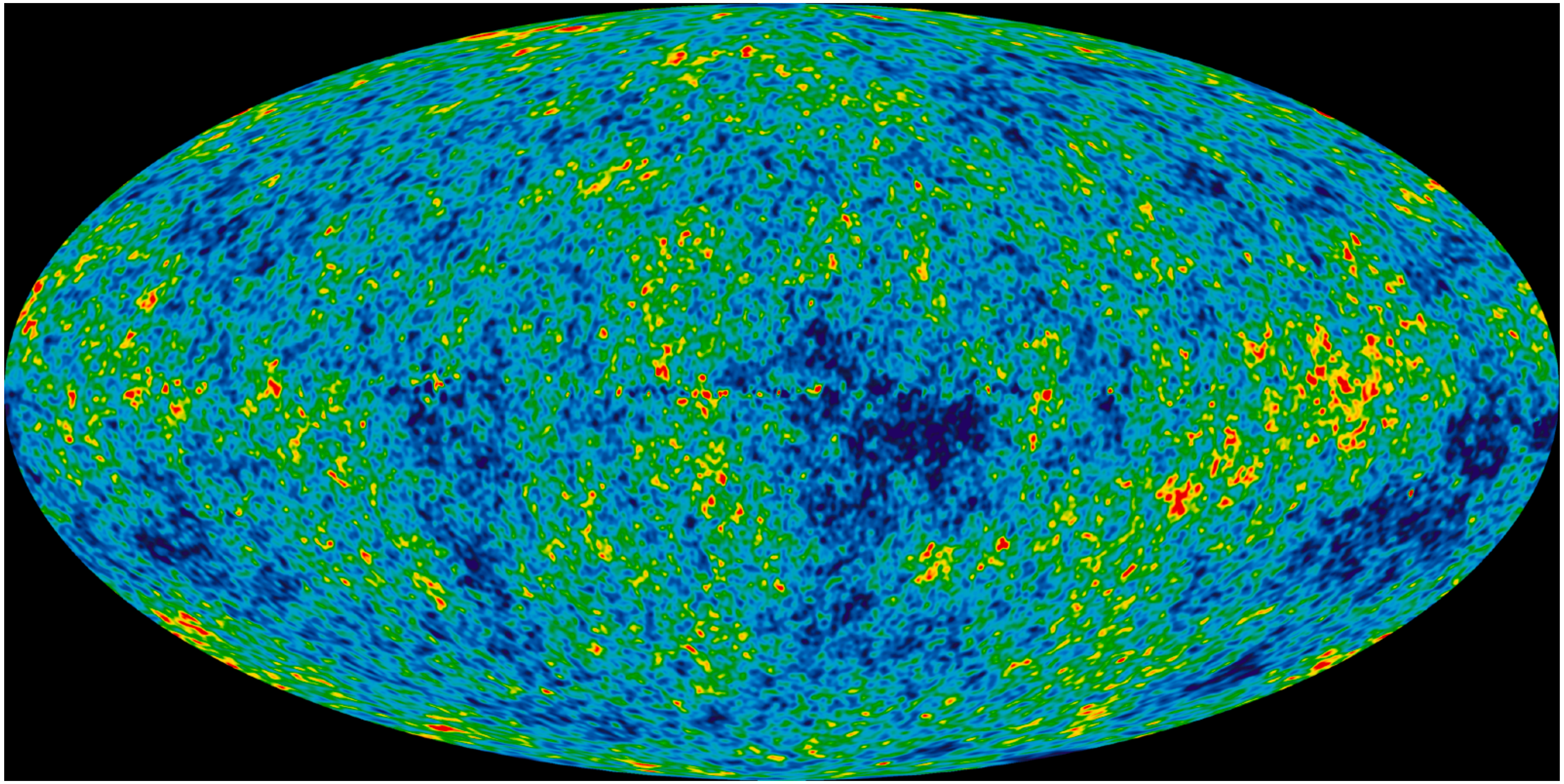


A Cosmological Signature of the SM Higgs Instability: Gravitational Waves

José Ramón Espinosa, Davide Racco, Antonio Riotto

hep-ph 1804.07732

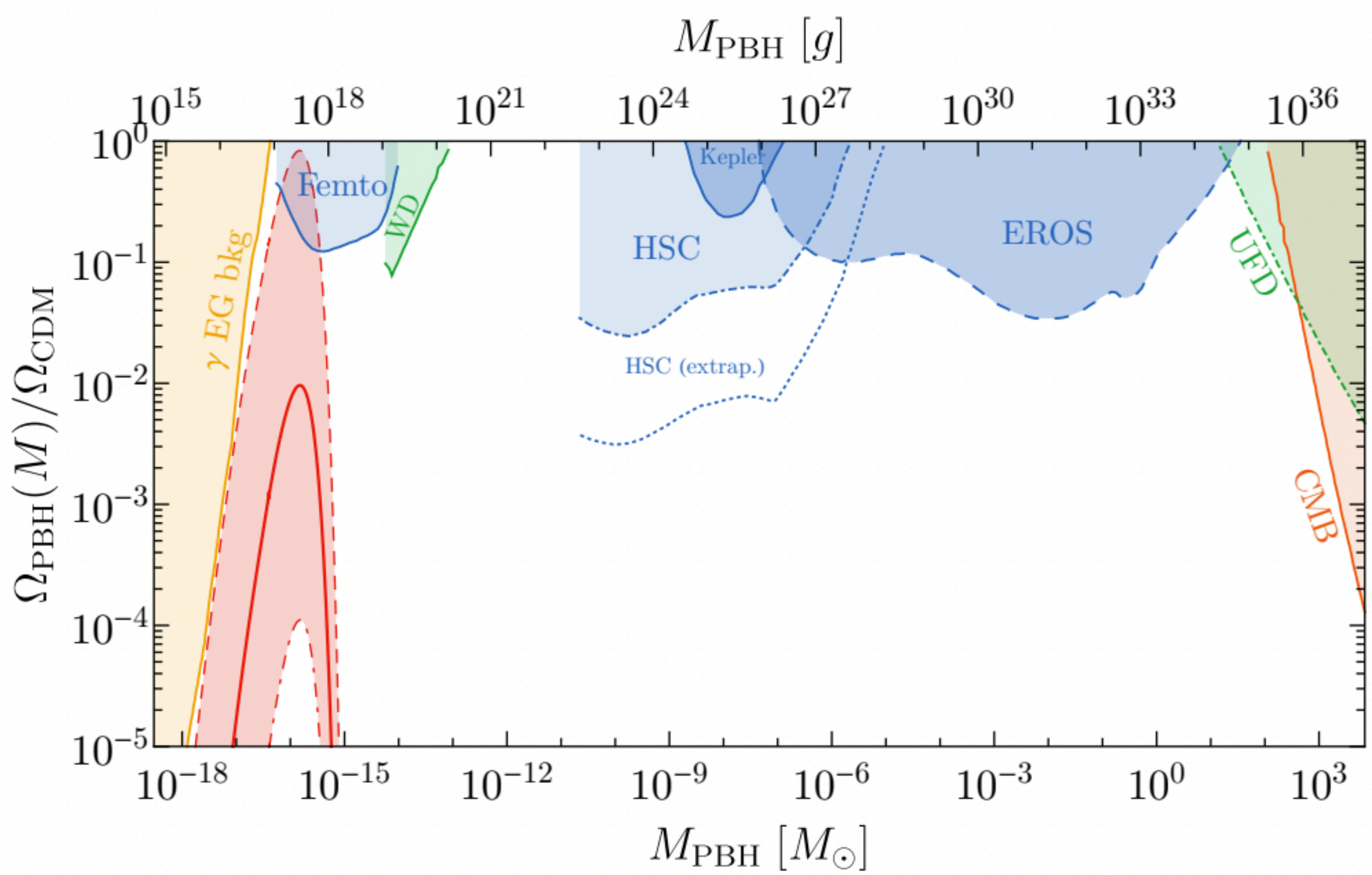
CMB IMPRINTS

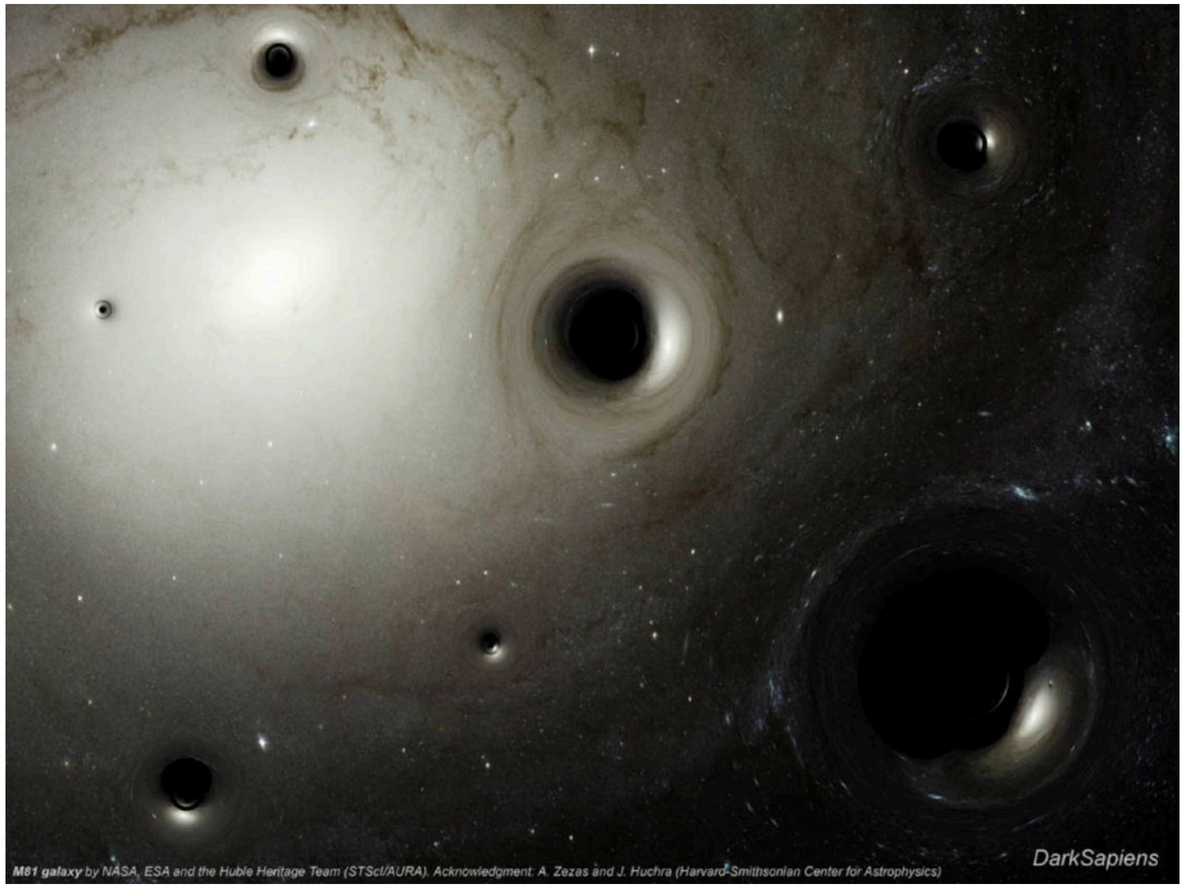


- Modification of power spectrum
- “Hotspots” in CMB

PRIMORDIAL BLACK HOLES

These high energy density fluctuations eventually collapse into black holes





A Cosmological Signature of the Standard Model Higgs Vacuum Instability: Primordial Black Holes as Dark Matter

J. R. Espinosa, D. Racco, A. Riotto

hep-ph 1710.1196

SUMMARY

- Extensions/modifications of the Higgs sector remain **as motivated as ever**
- The Higgs boson: possibly as **crucial for cosmology** as it is for particle physics
- Could play a role in **solving some of the main problems in cosmology** (dark matter, baryon asymmetry, inflation…)
- Even the **Standard Model Higgs, without any modifications, can be an important** player in the early Universe
- Could give rise to **distinct observable cosmological phenomena** (gravitational waves, black holes, CMB effects…)
- **High energy colliders can play a crucial role** in unraveling Higgs cosmology