# Prospects of Higgs Physics as a window to the electroweak phase transition

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University of Chicago

电弱相变与希格斯物理专题研讨会，July 31. 2020

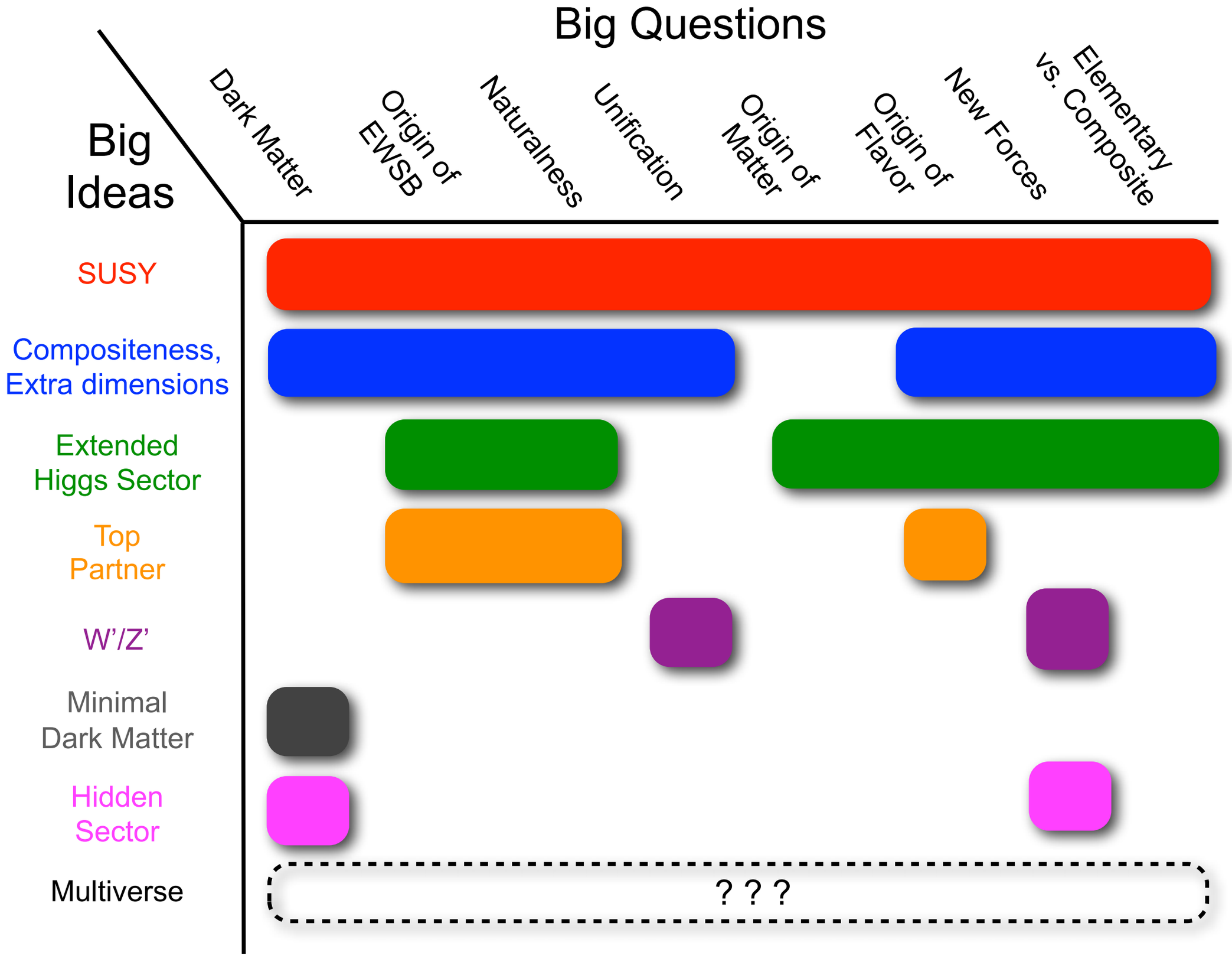
# Higgs is the focus of particle physics

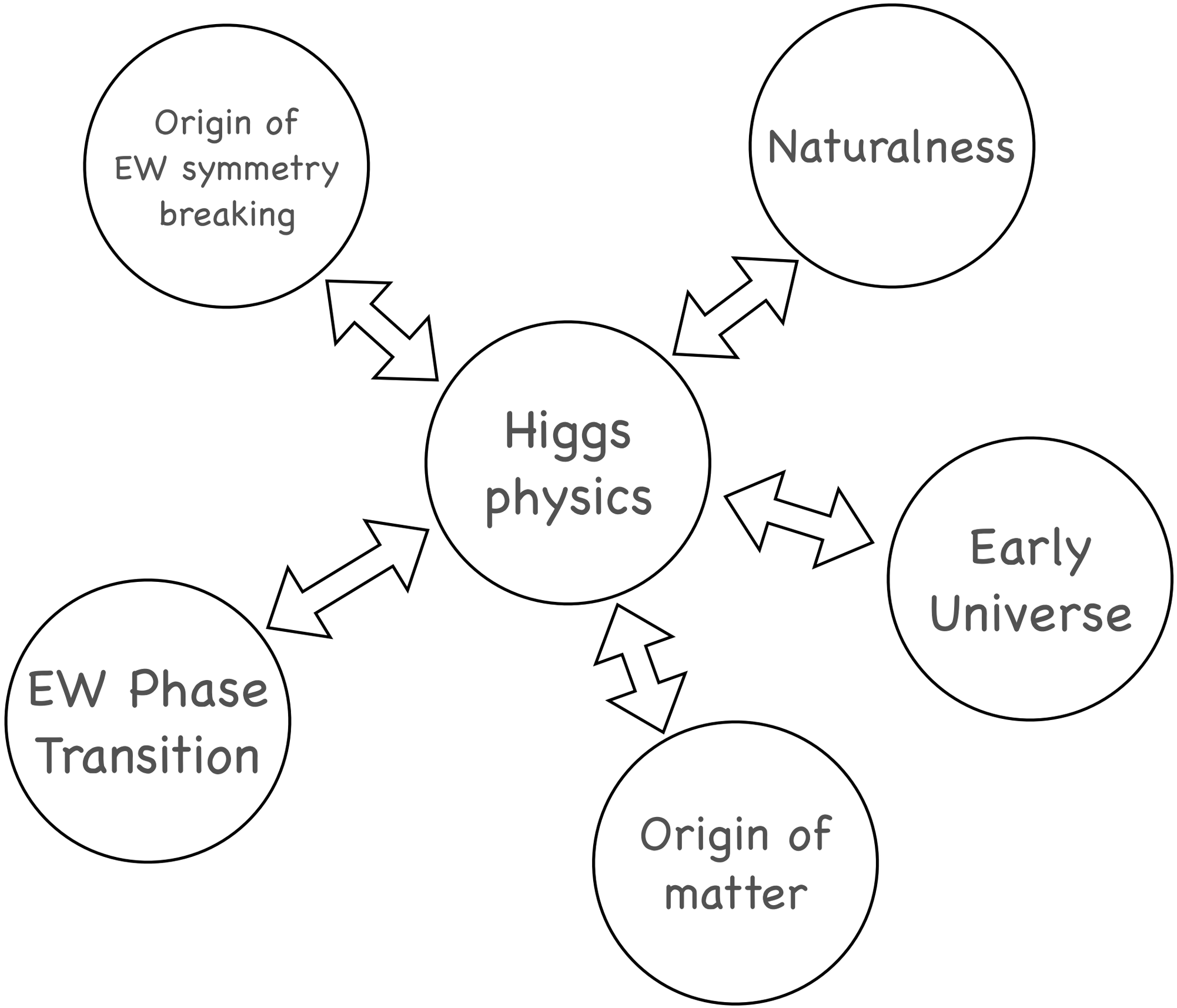
European strategy for particle physics:

- The Higgs (discovered at the LHC) is a unique particle that raises profound questions about the fundamental laws of nature.
- Higgs properties study in itself a powerful experimental tool to look for answers.
  - Electron-positron collider as Higgs factory
- Higgs boson pair production is key to understanding the fabric of the universe.

# Why is Higgs important?

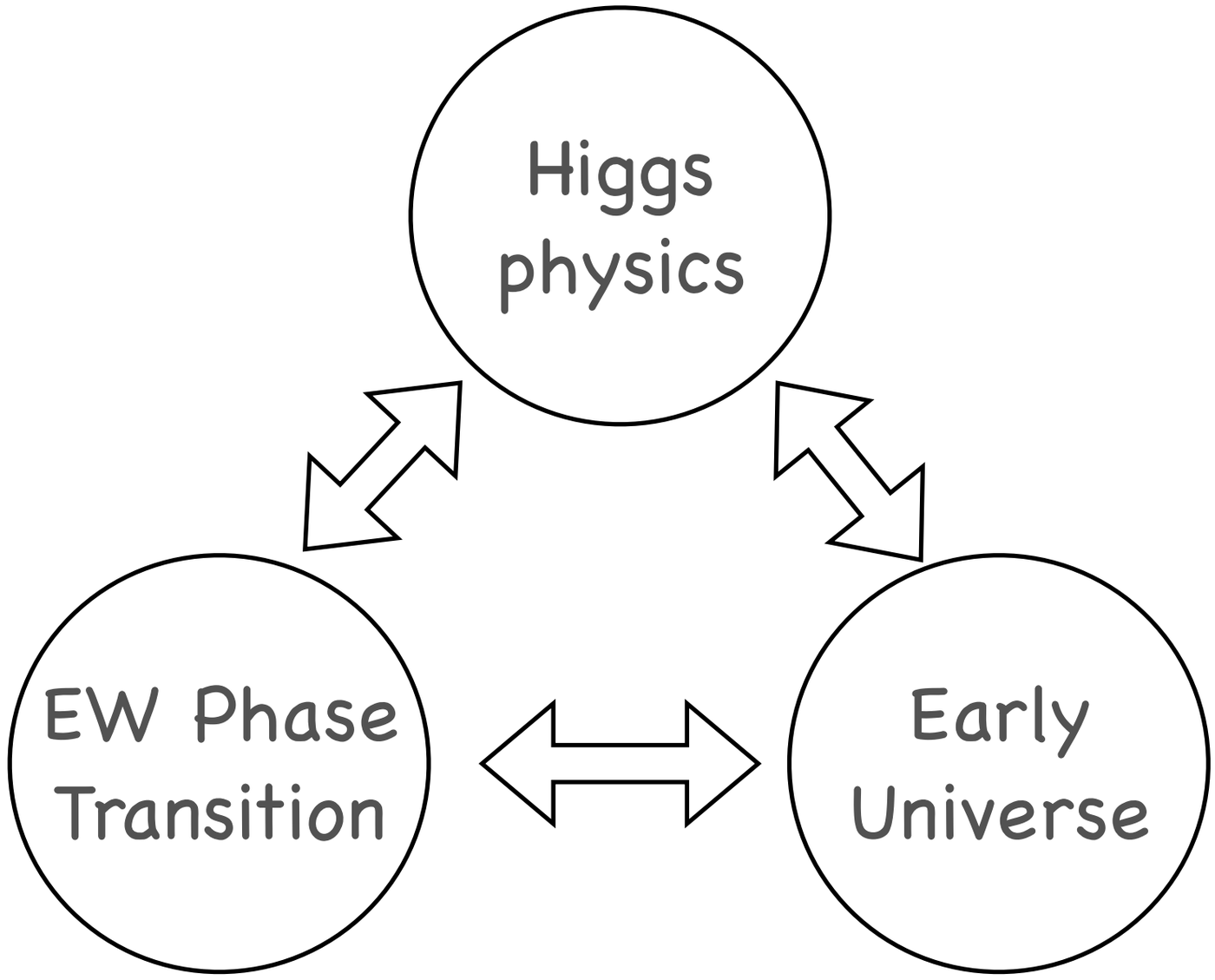
- It gives mass to all the elementary particles.
- True. But more importantly:
- It is at the center of intriguing mysteries/puzzles
- Holds the key to new discoveries!


Big Questions
Big Ideas
Dark Matter
Origin of EWSB
Naturalness
Unification
Origin of Matter
Origin of Flavor
New Forces
Elementary vs. Composite
SUSY
Compositeness, Extra dimensions
Extended Higgs Sector
Top Partner
W'/Z'
Minimal Dark Matter
Hidden Sector
Multiverse
? ? ?




Possible links with inflation, dark energy, ...

# My talk




- Overview.
- A lot of work in the area.
  - Highlight several interesting directions.

More details, the rest of the workshop

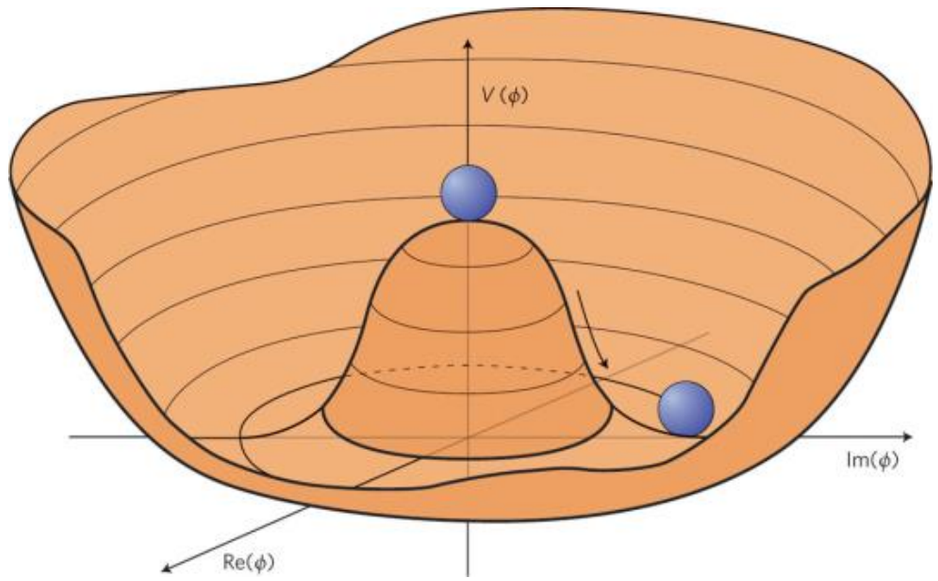
# Why is Higgs puzzling?

| particle | spin |
|---|---|
| quark: u, d,... | 1/2 |
| lepton: e... | 1/2 |
| photon | 1 |
| W,Z | 1 |
| gluon | 1 |
| Higgs | 0 |

h: a new kind of elementary particle

The "simplest" particle? Far from it!

# "Simple" = puzzling




Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

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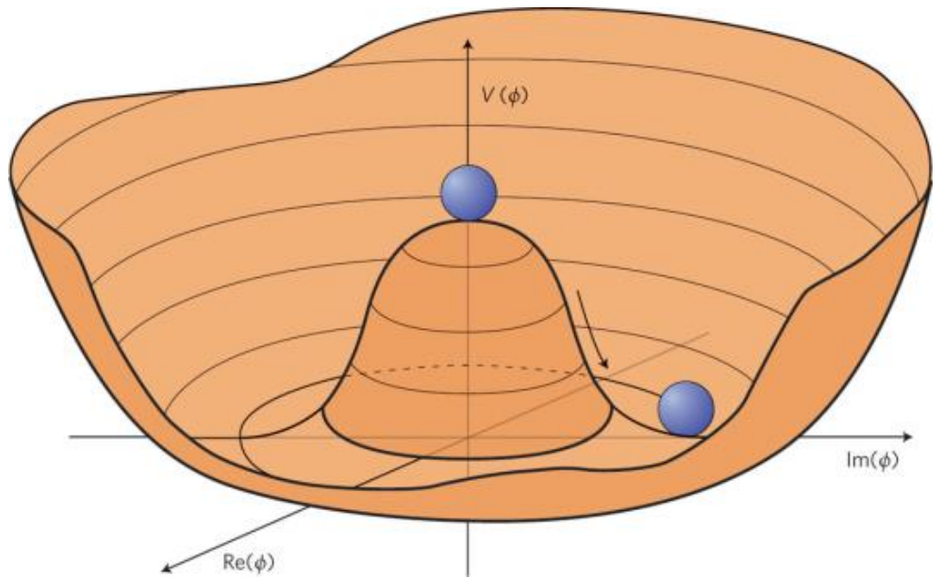


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Parameters not predicted by theory.
Can not be the complete picture.

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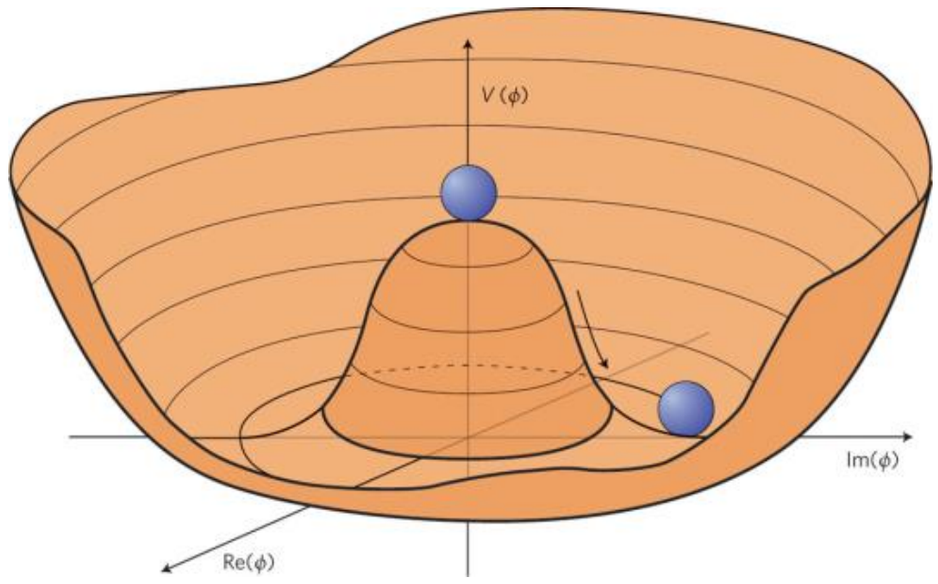


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simplicity = lack of tools
No symmetry,
no additional information!

In contrast, spin-1/2, spin-1, and spin-2, additional
tools (symmetries) available to understand their couplings.

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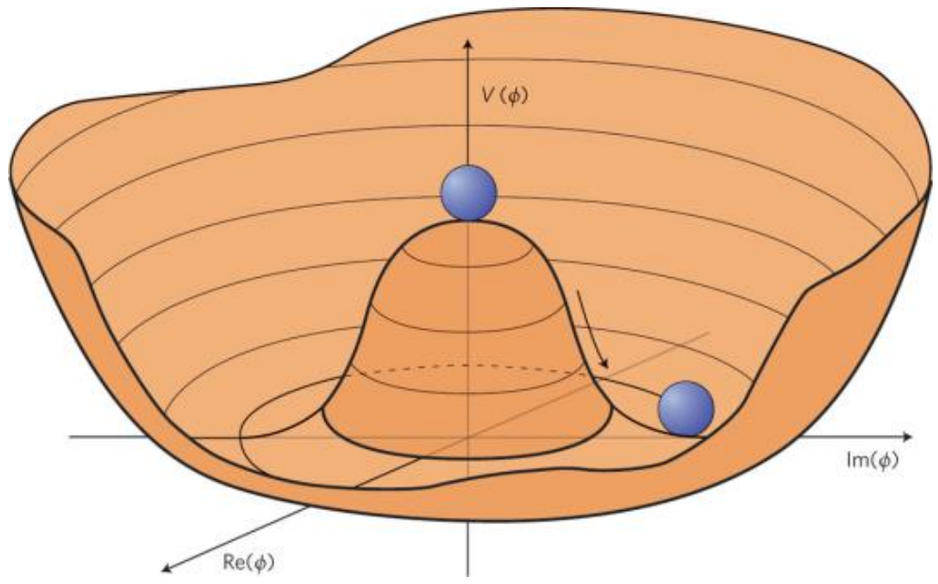


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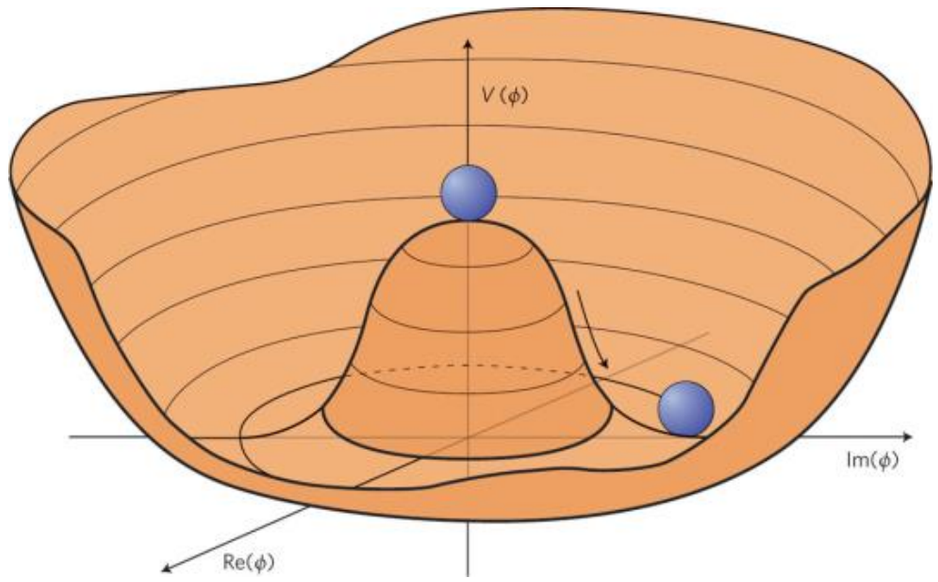


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Central question of particle physics:

What determines these parameters?

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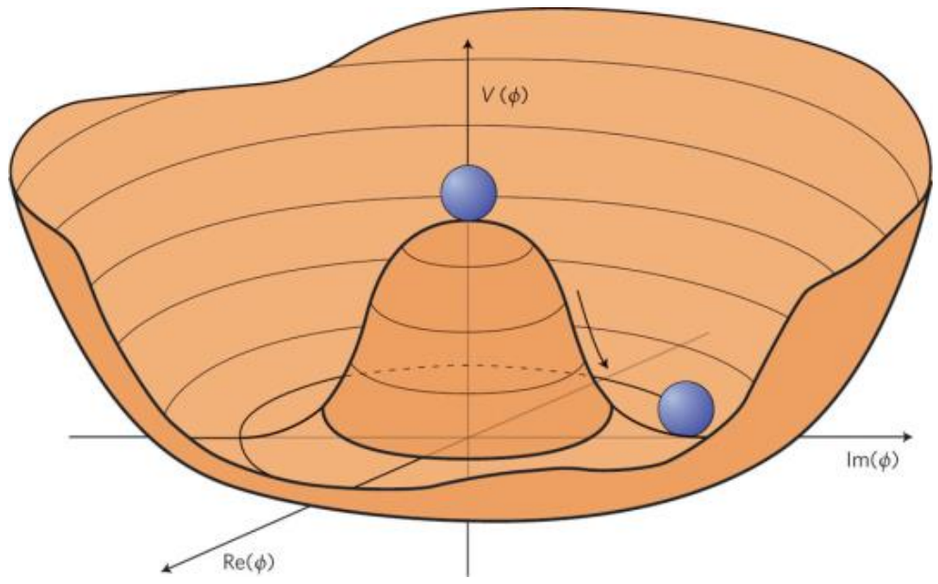


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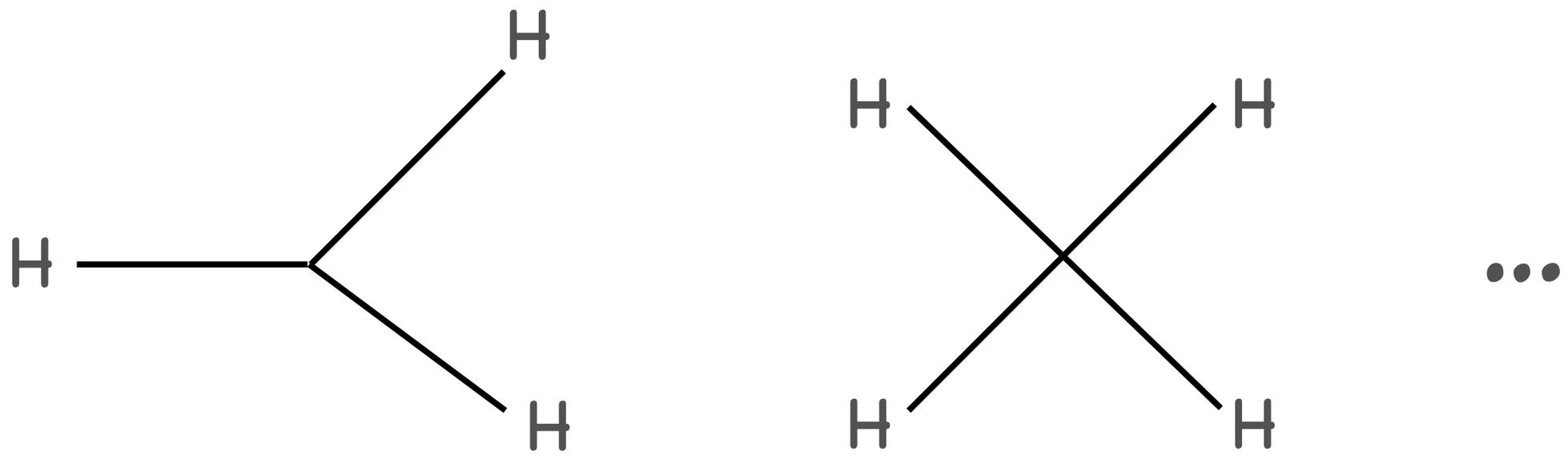
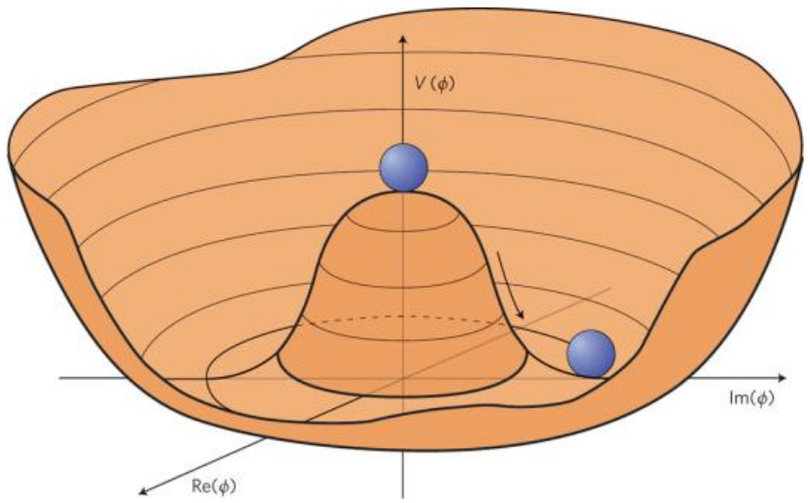
# Unique feature: Self coupling

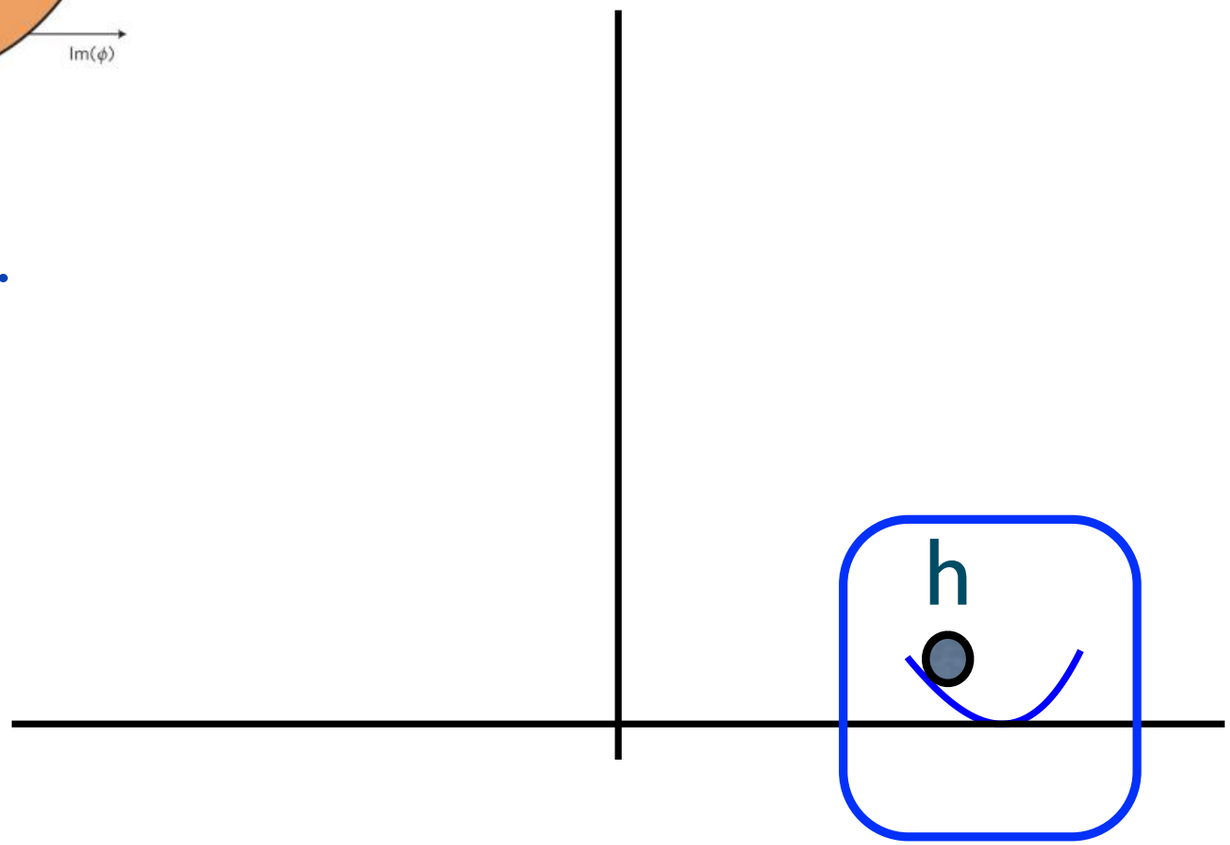



Not seen before in nature!

# We know very little about the Higgs.




What model says.

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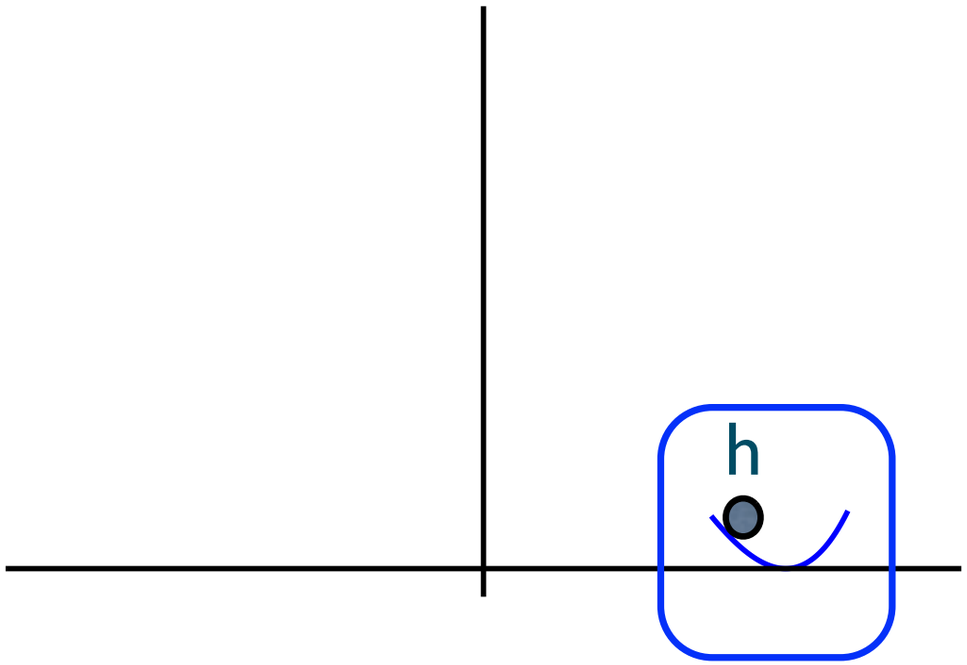


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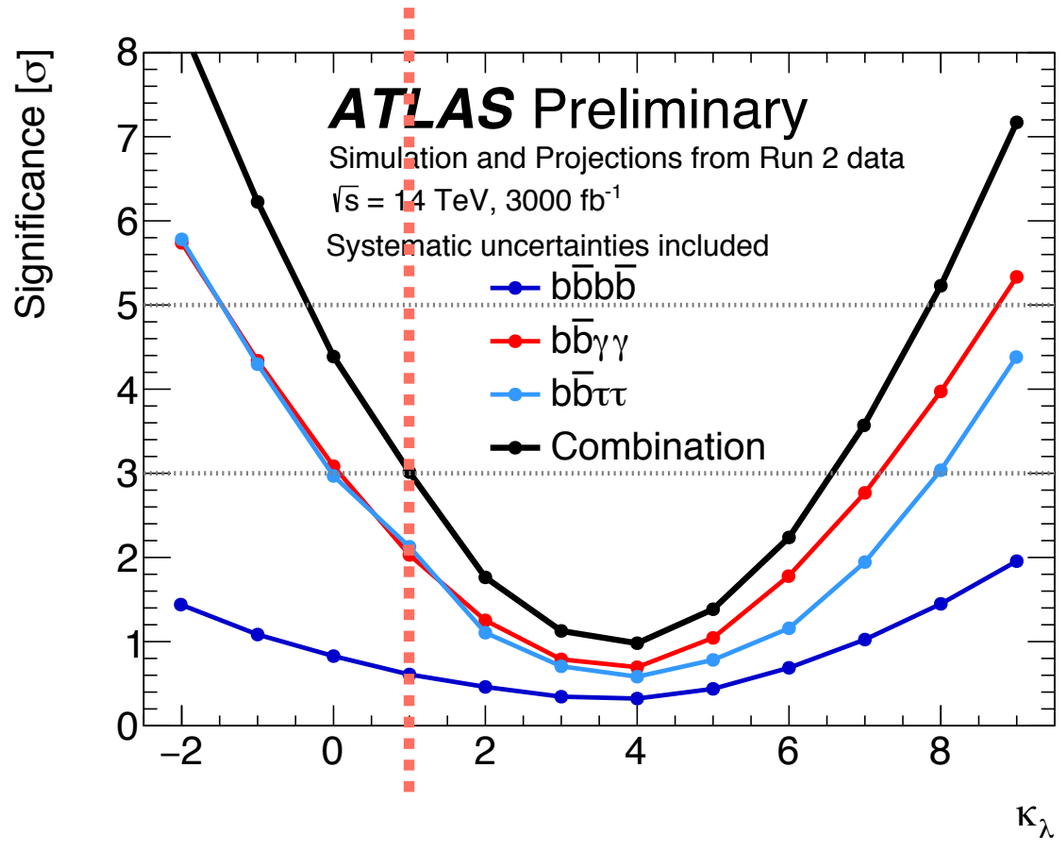
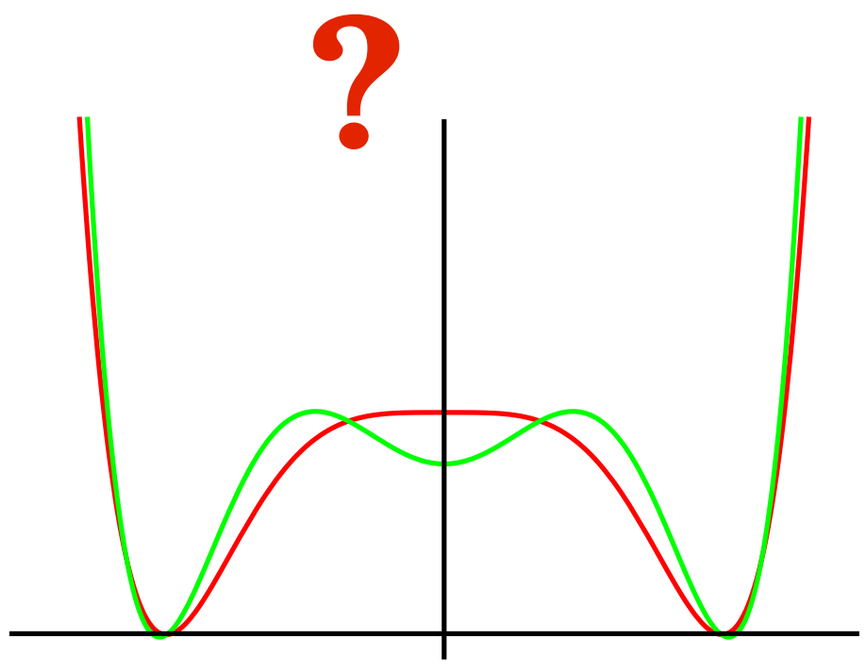



- LHC may not be able to tell us too much beyond this.

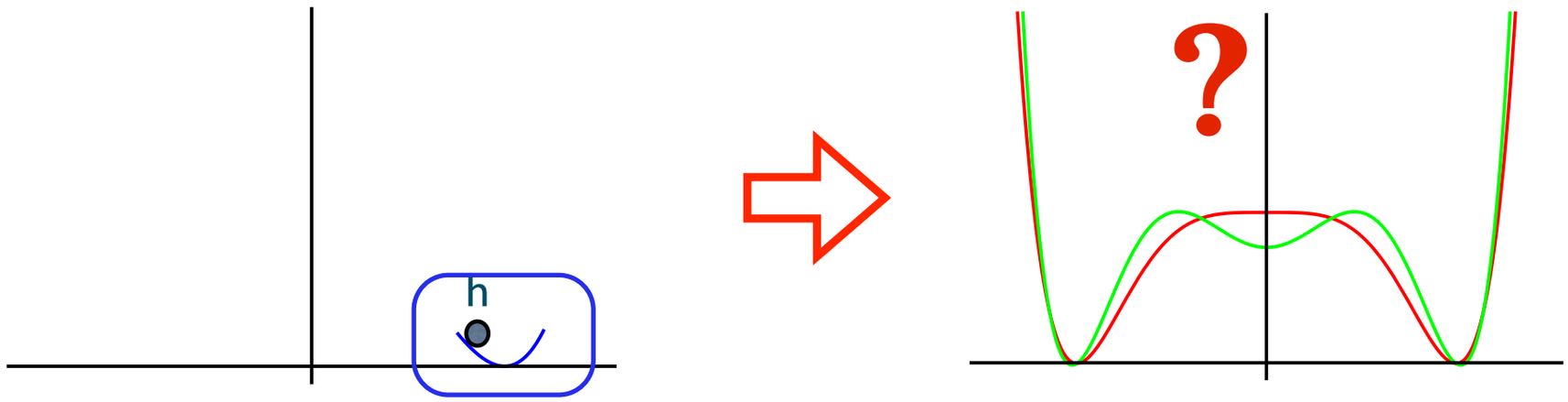
# Simplicity ⇨ greater unknown.

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \dots$$



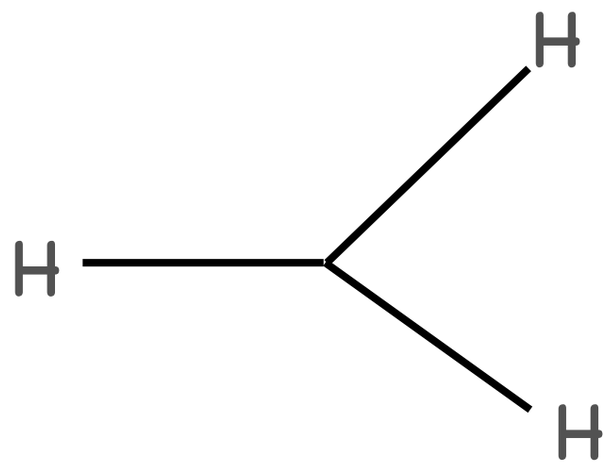

– Which one is the right picture?

# How do we find out?




"wiggles" in Higgs potential

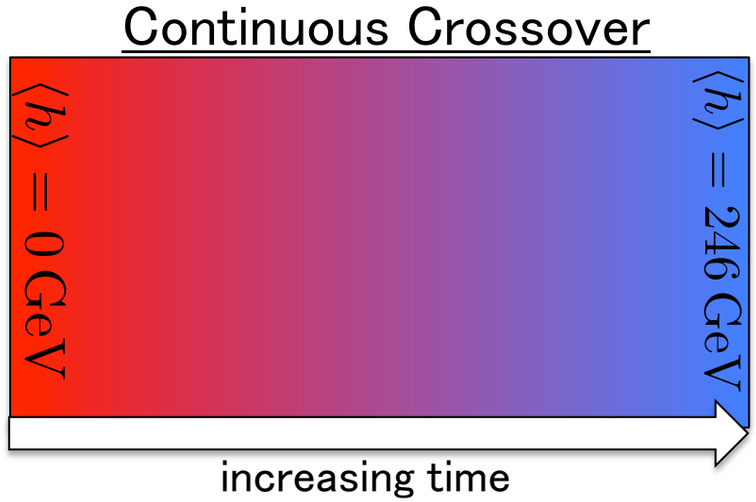
Big difference in triple Higgs coupling

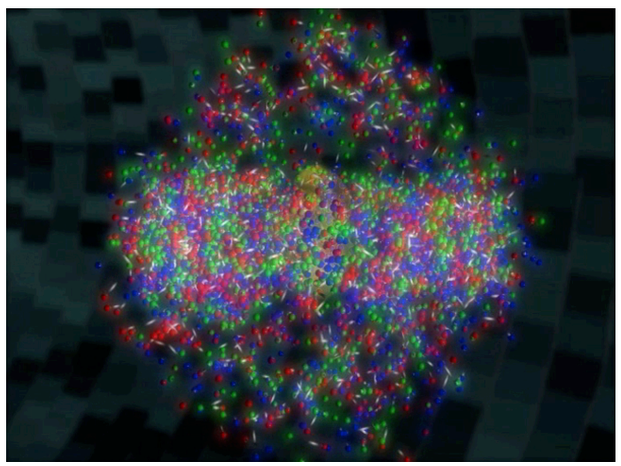


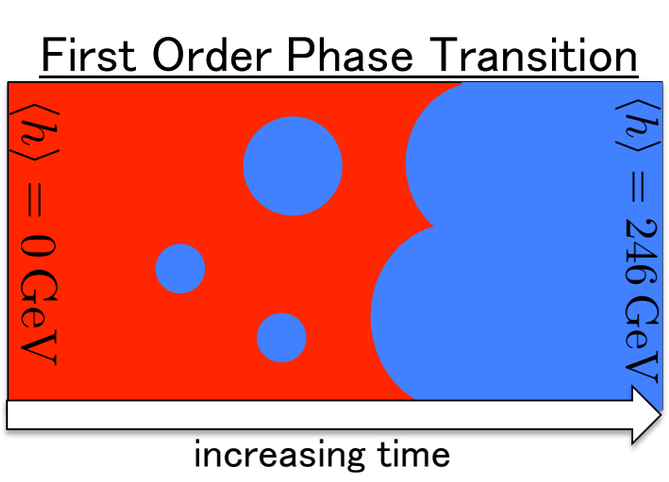

And more, later in this talk

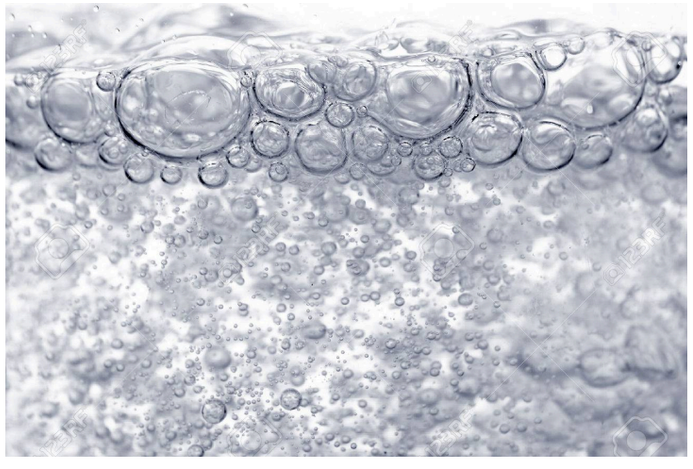
# What are the physics consequences?

## Nature of electroweak phase transition



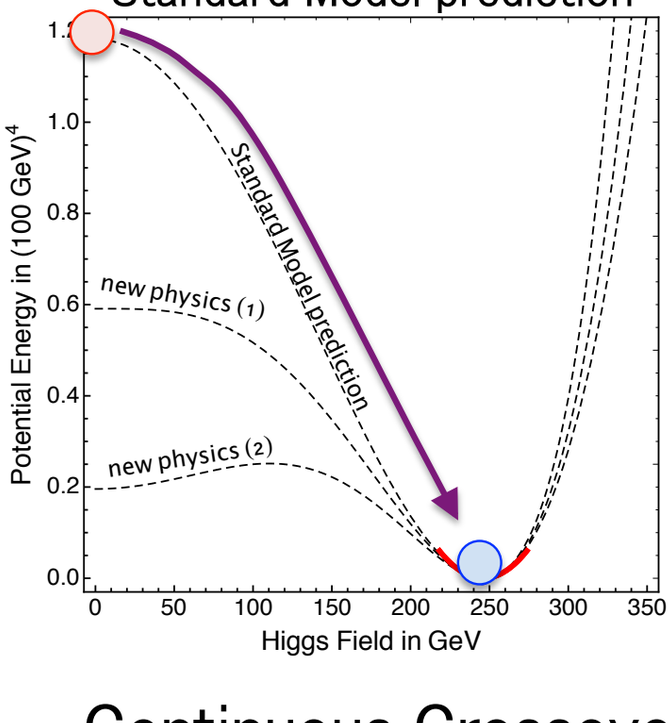


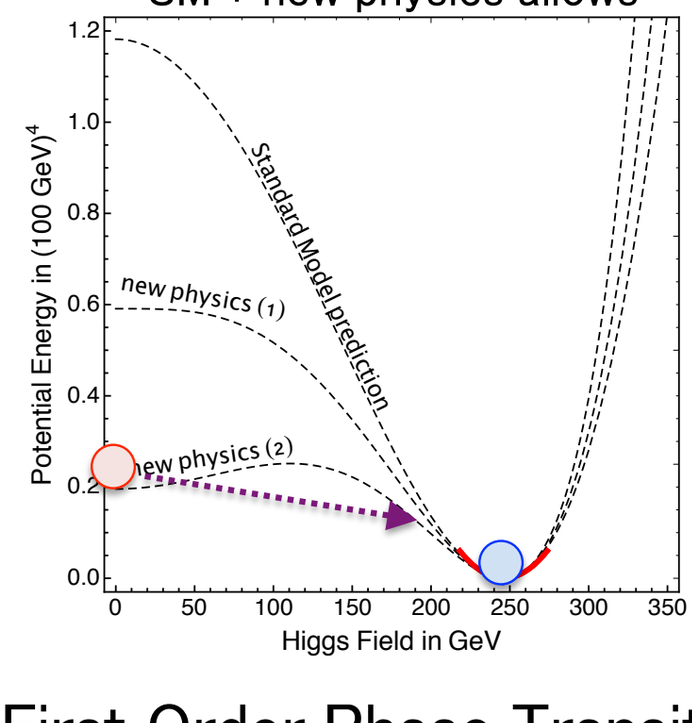
which one?

# Very different answers possible.

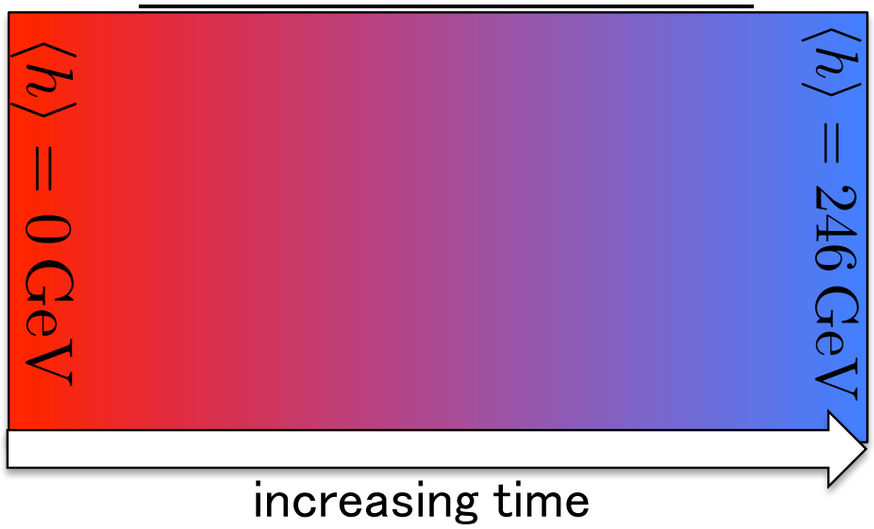
Standard Model prediction



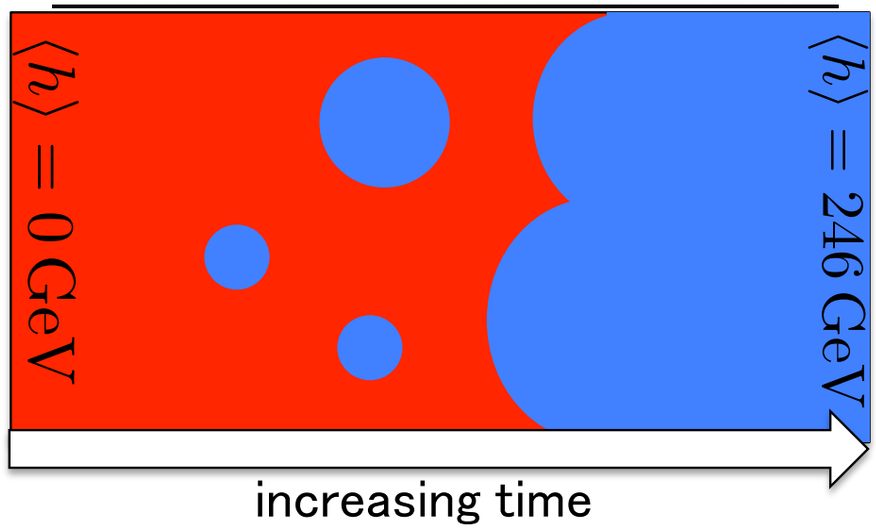

SM + new physics allows




Continuous Crossover




First Order Phase Transition

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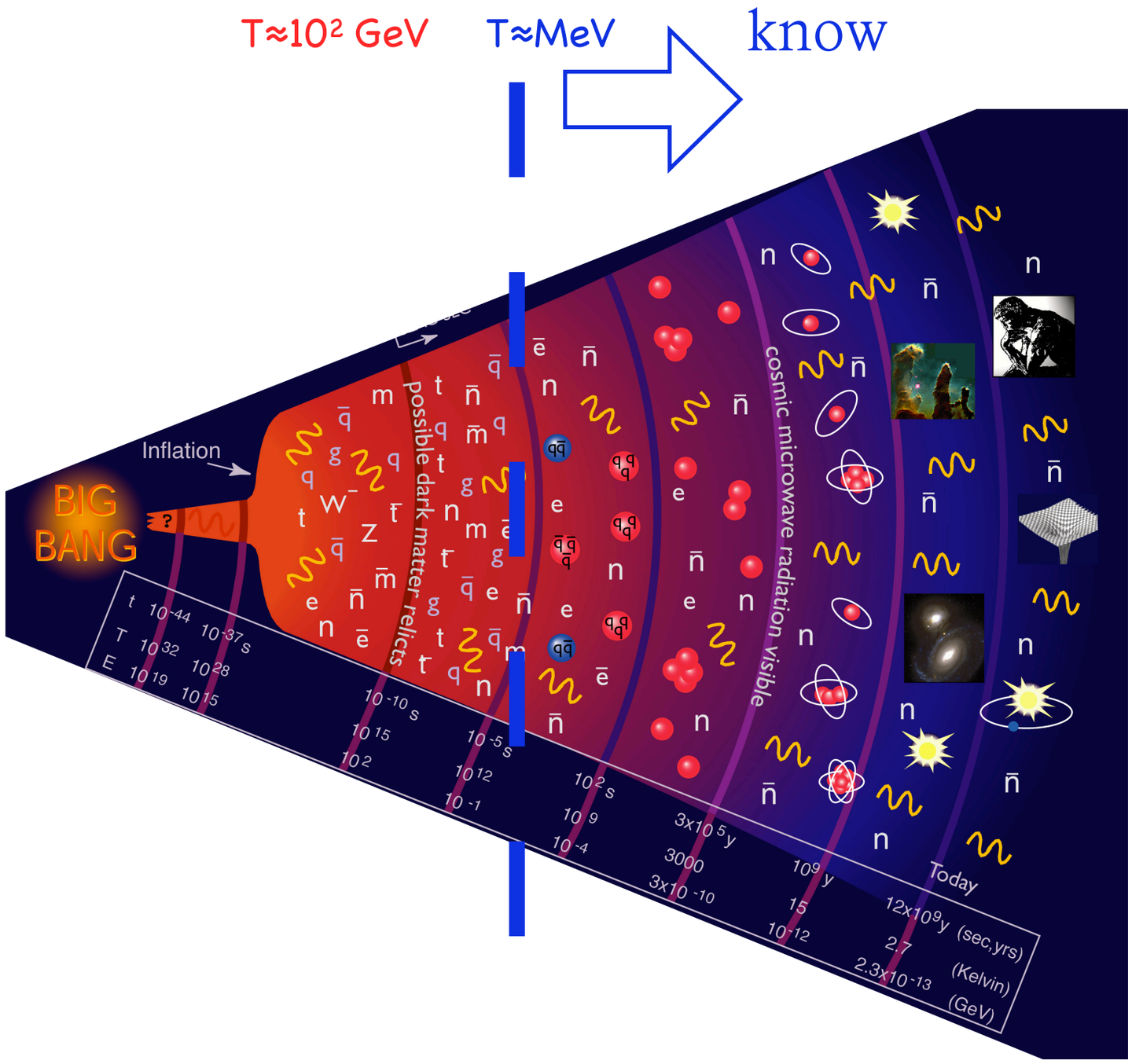
Wide open, likely place for new physics

# When did it happen?



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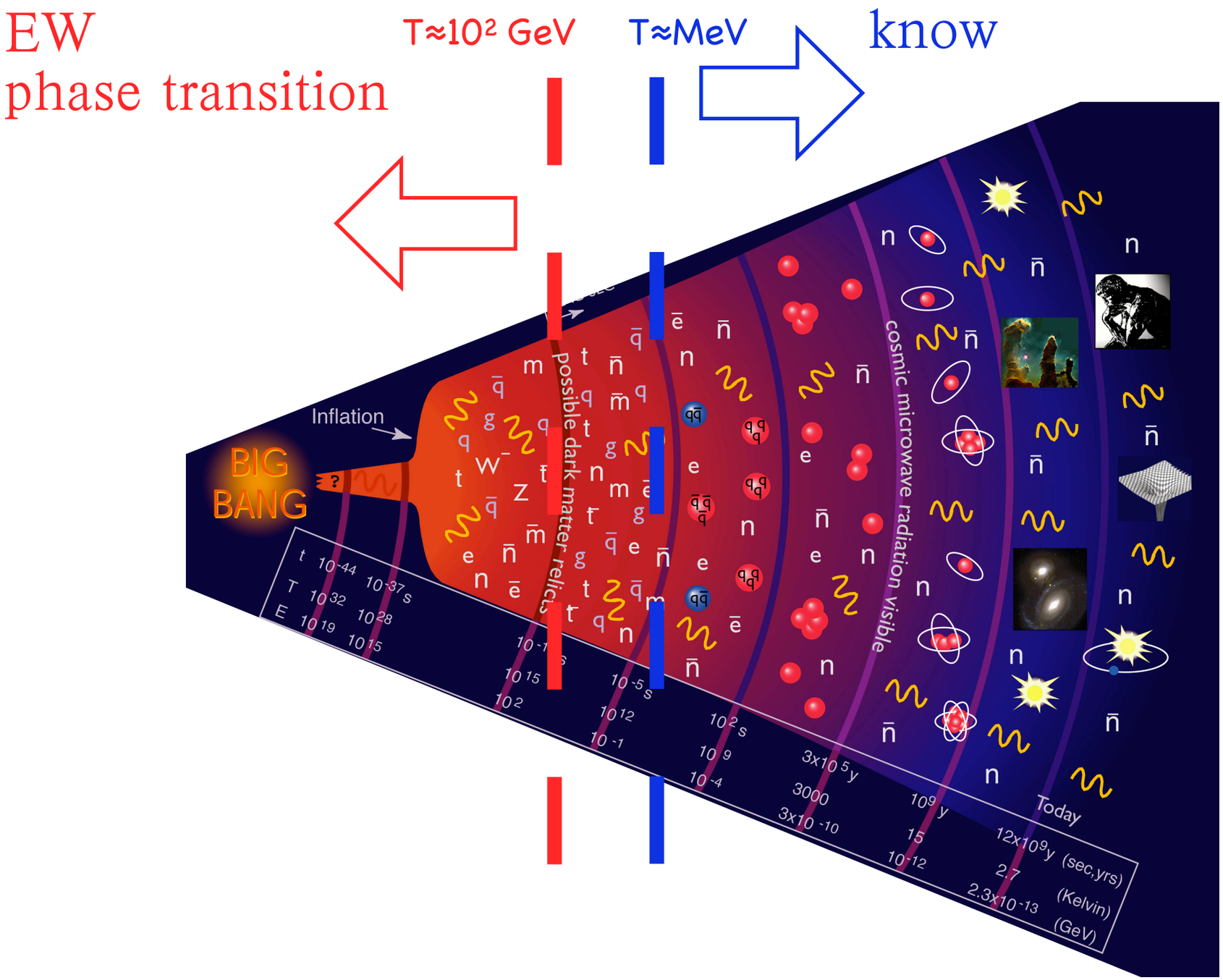


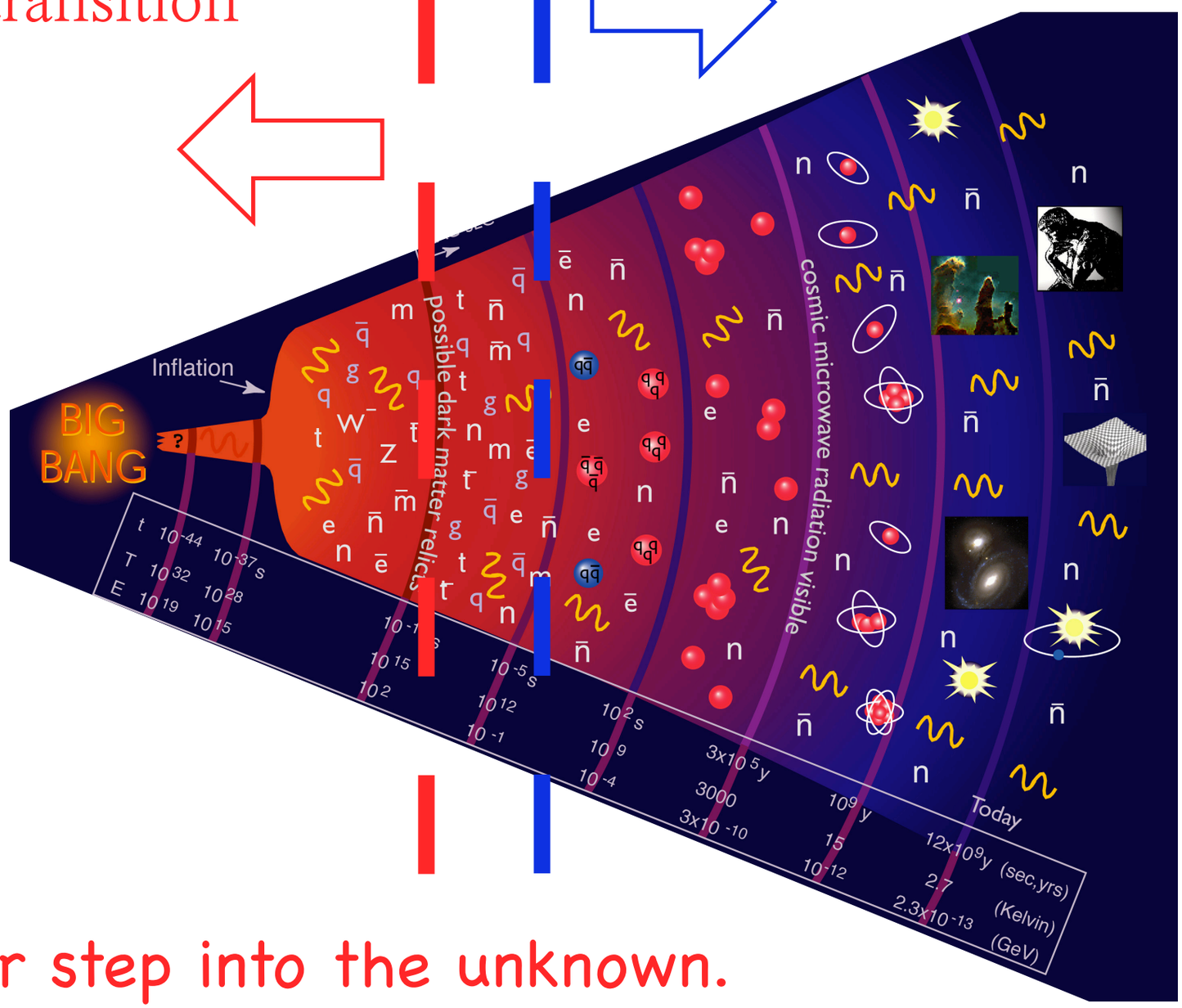
# When did it happen?

EW
phase transition

T≈10² GeV

T≈MeV

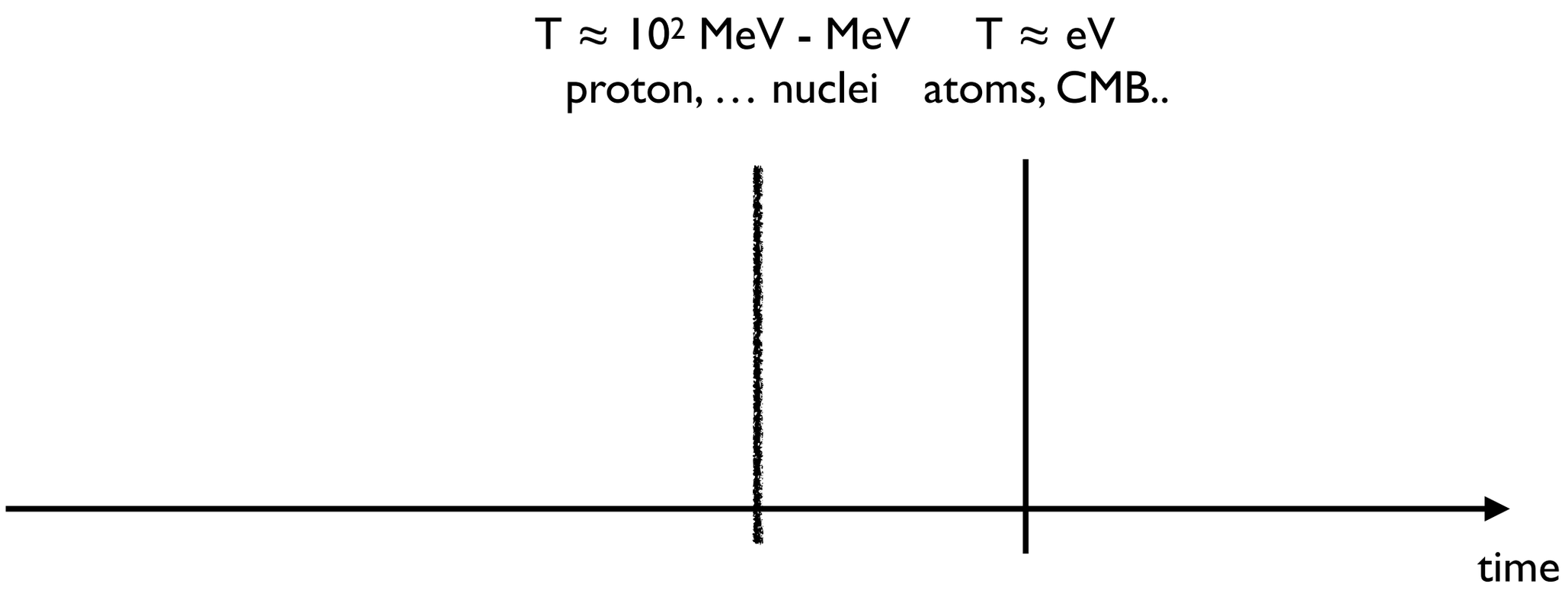
know




A major step into the unknown.

A big opportunity.

# The corner stone of modern cosmology



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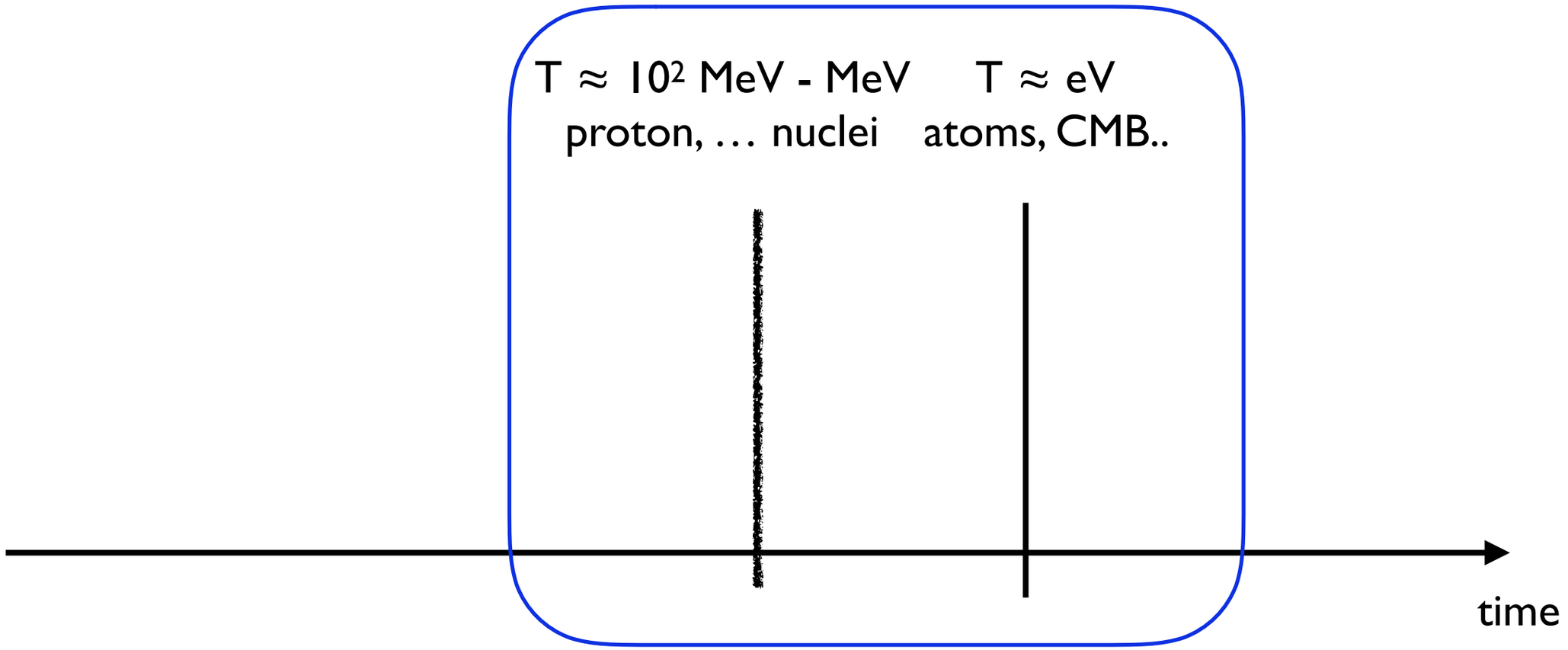
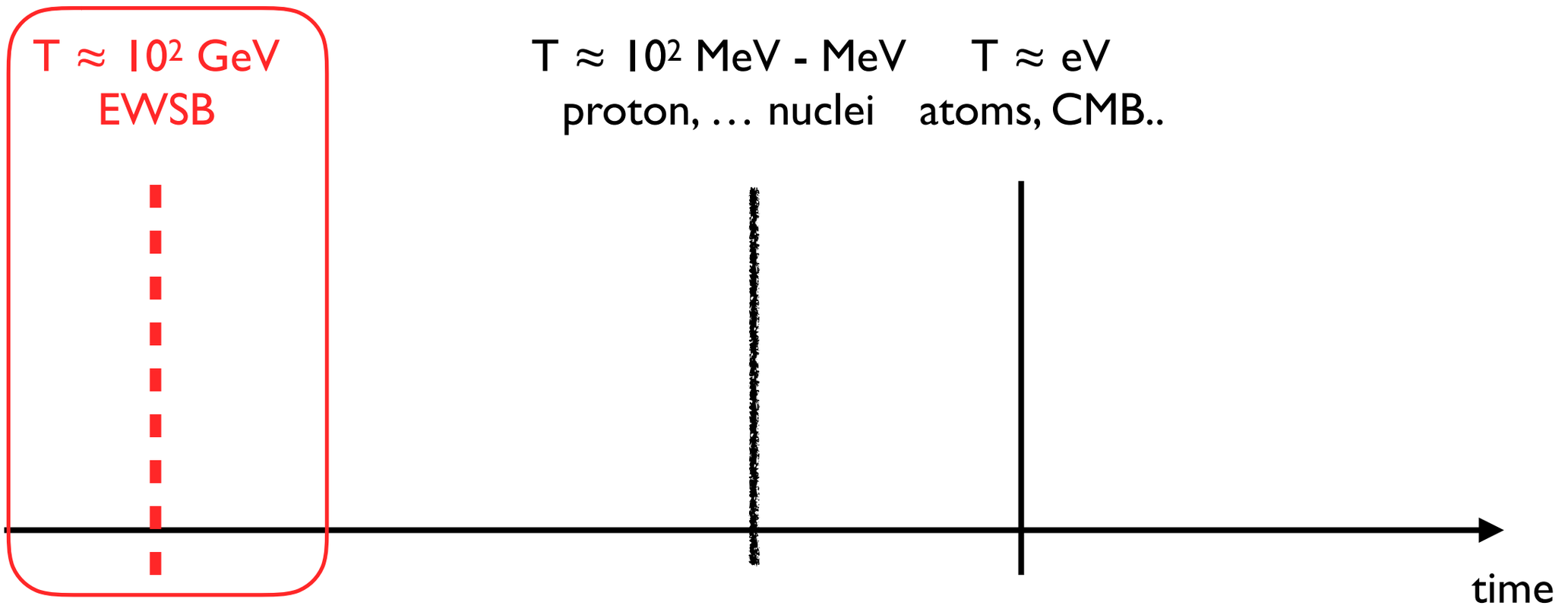



Well understood,  comso/astrophysical observation
+ laboratory measurements.

Lead to the establishment of modern cosmology

# EW phase transition, a new milestone




An important early universe event.

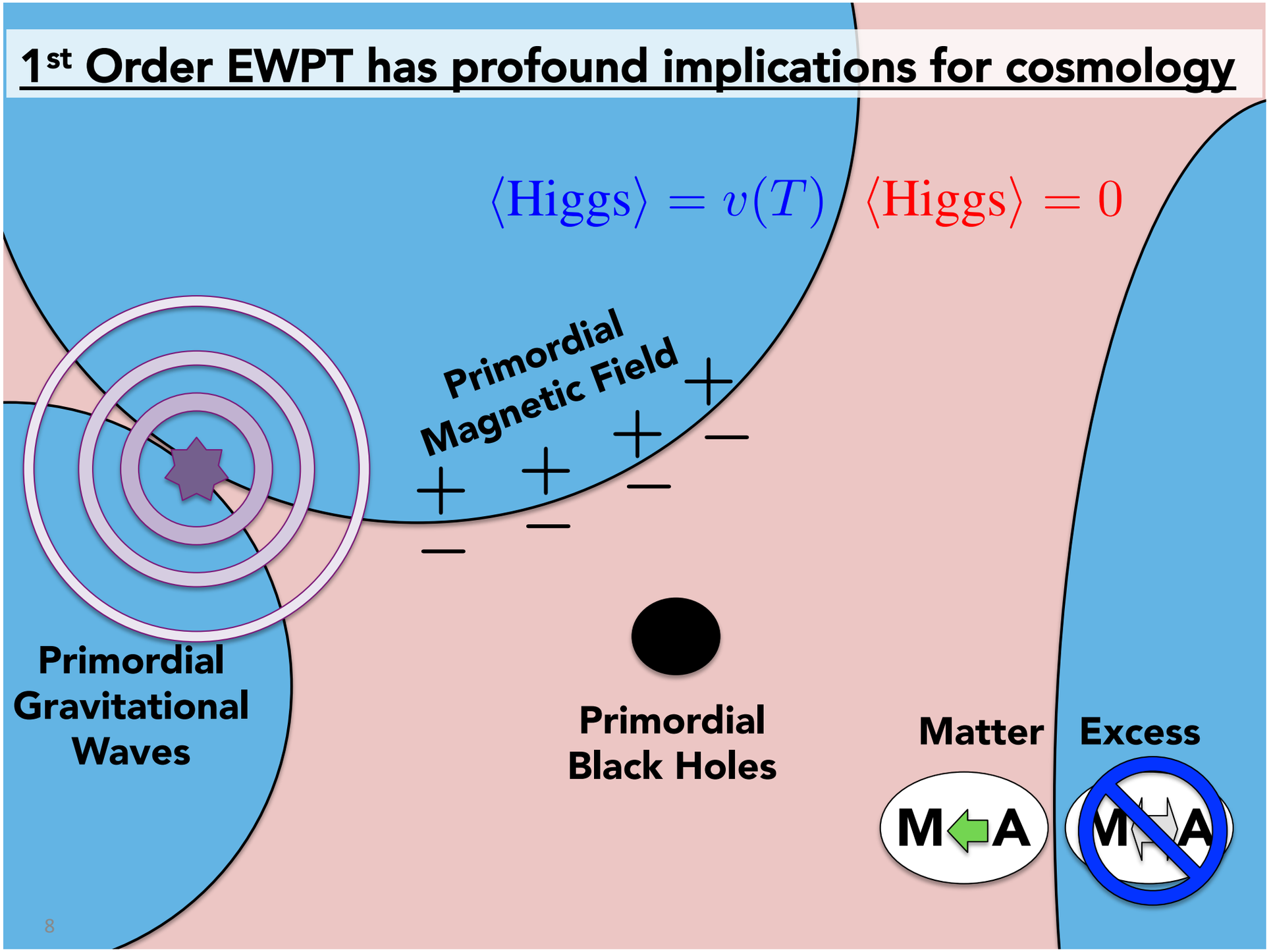
→ Cosmological observations

+

Lab measurement of Higgs properties

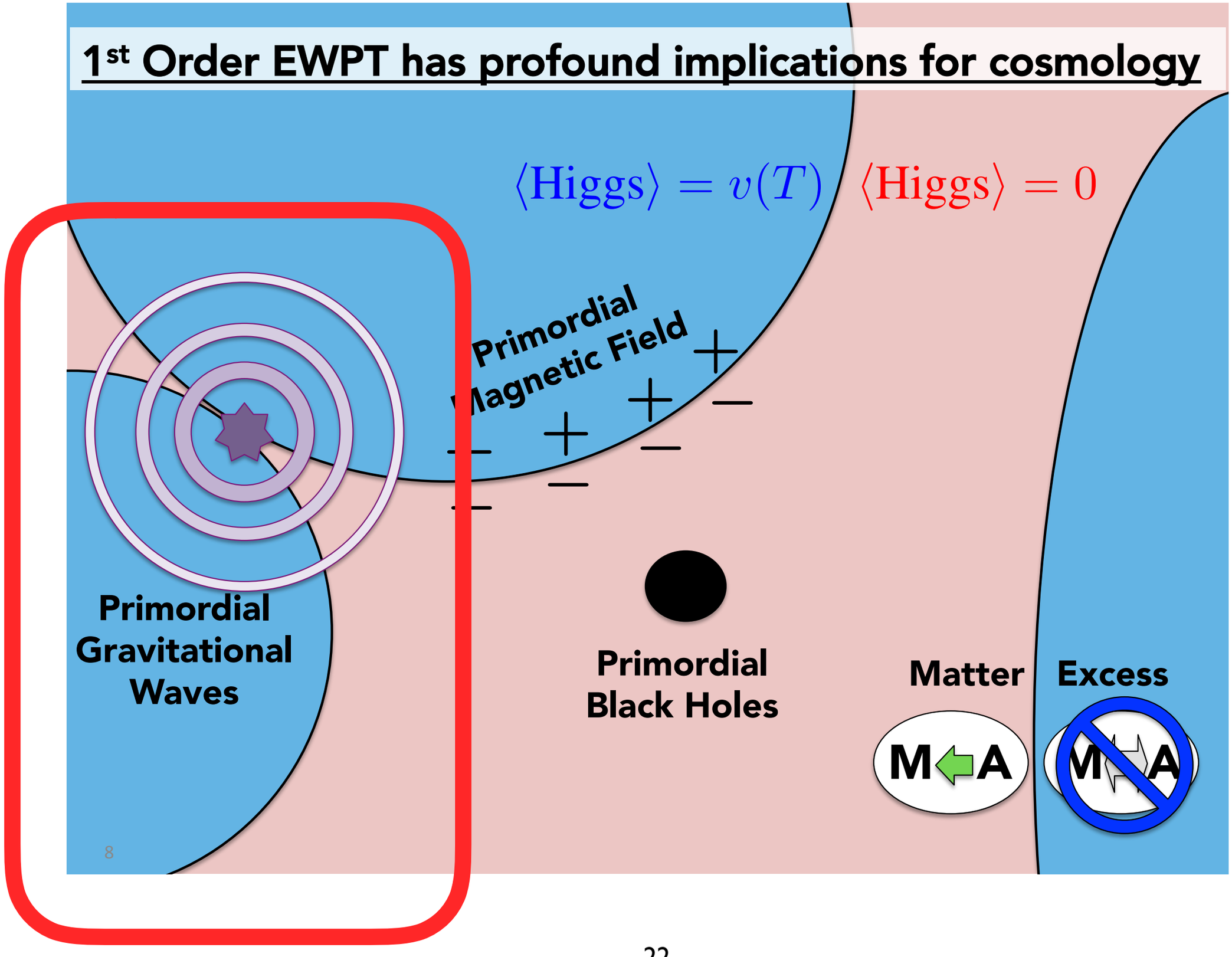
Another big step in cosmology!

# Cosmological observations



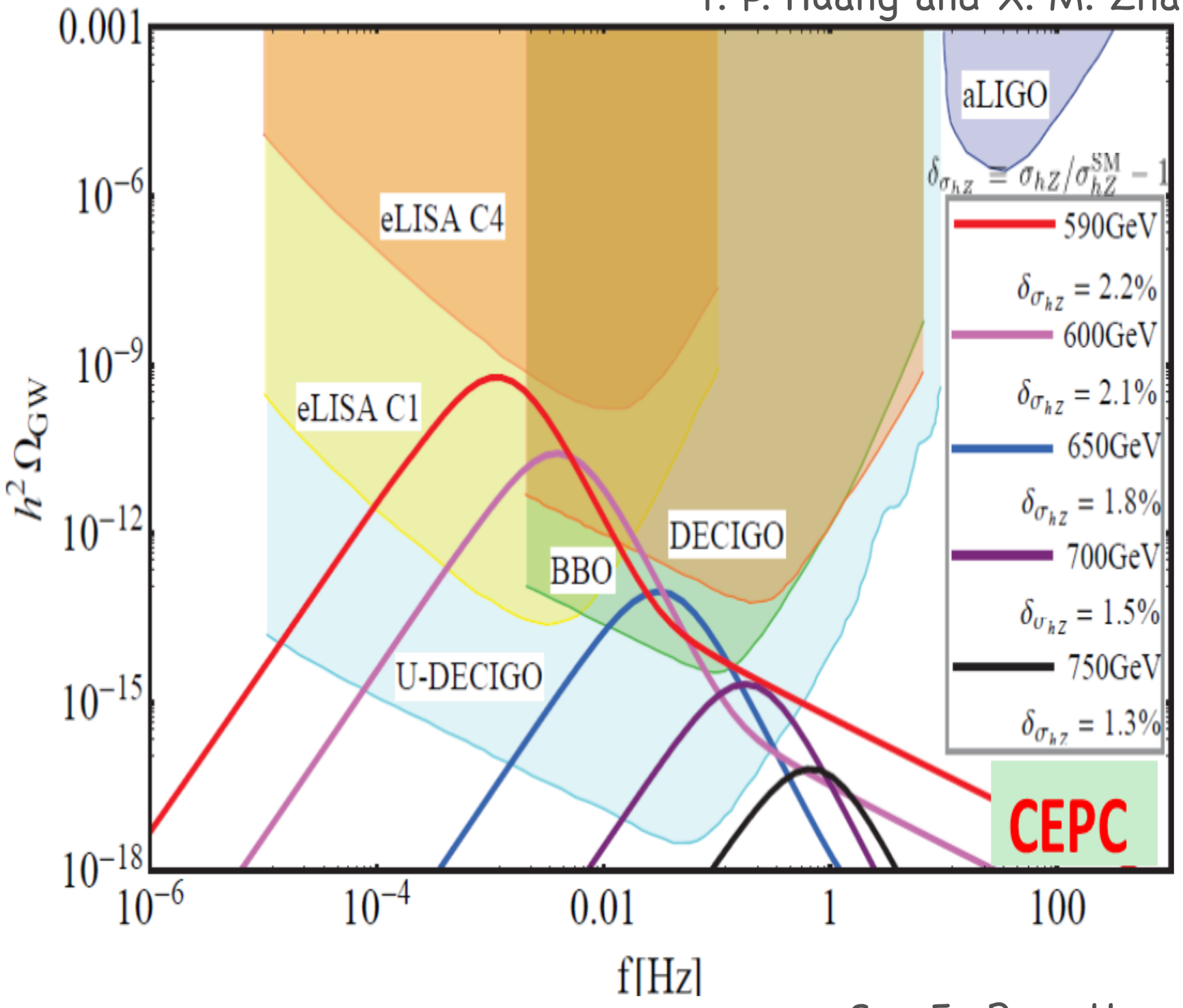

See also Tao Liu's talk for CMB signal

# Cosmological observations



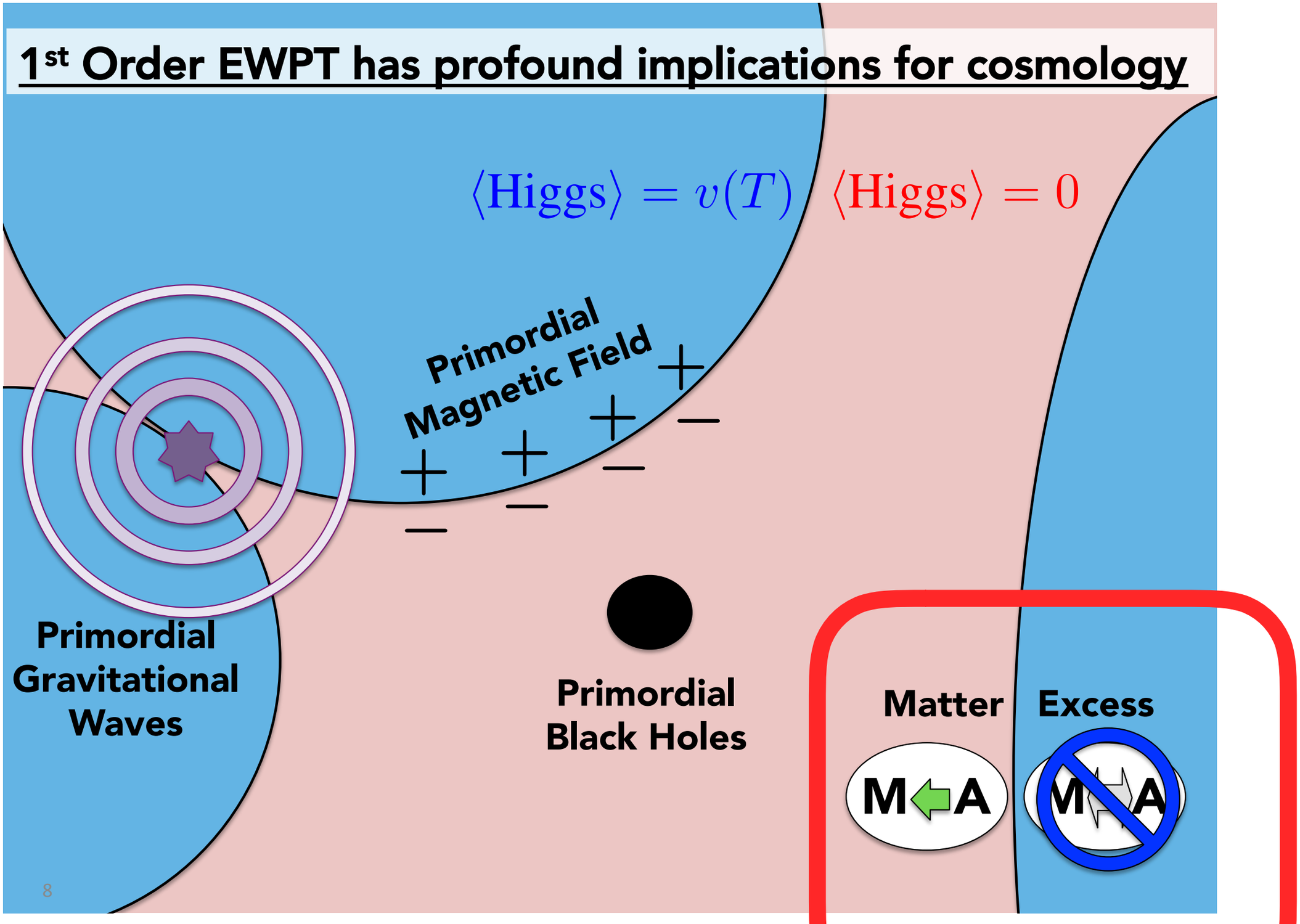
# Probes from gravitational waves.

F. P. Huang and X. M. Zhang

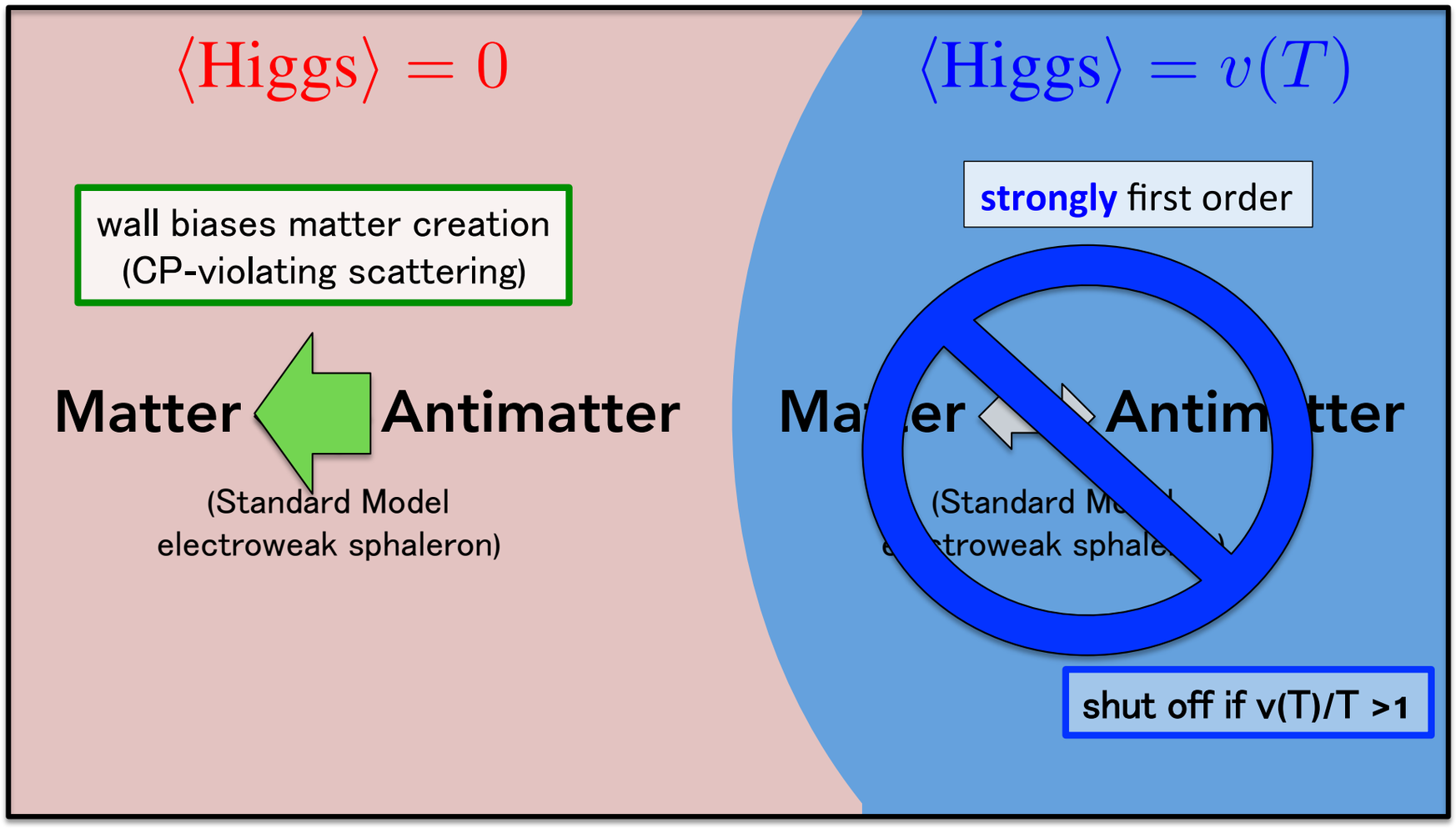



See Fa Peng Huang's talk.

# Cosmological observations



# Why is matter > anti-matter?



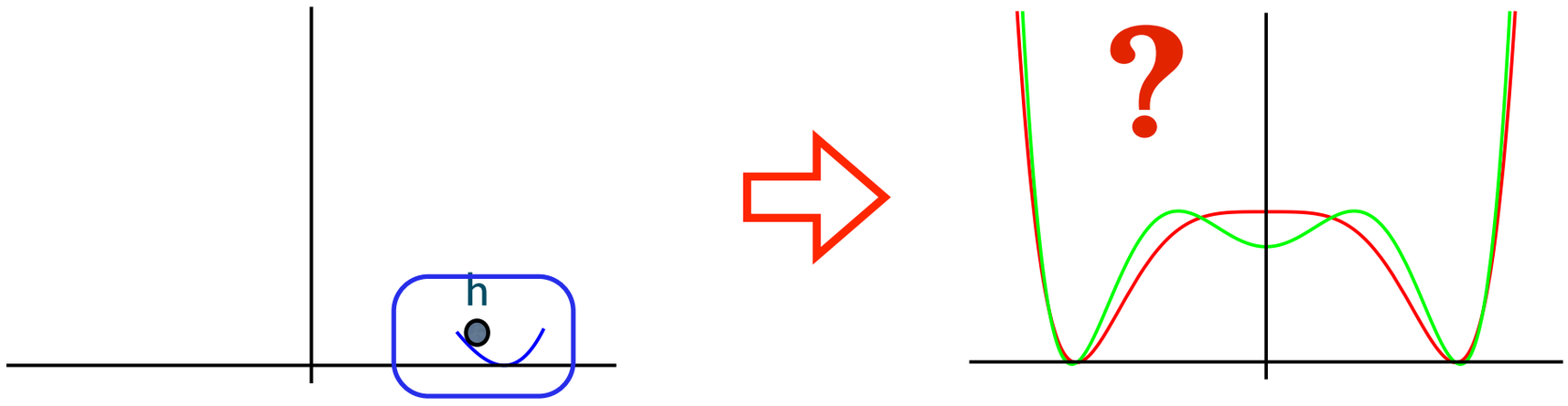

1st order EW phase transition is
a natural stage for generating the baryonic asymmetry

Michael Ramsey-Musolf, Ke-pan Xie's talk

# Higgs physics as a window

See also Jiang-Hao Yu's talk

# Nature of the Higgs field

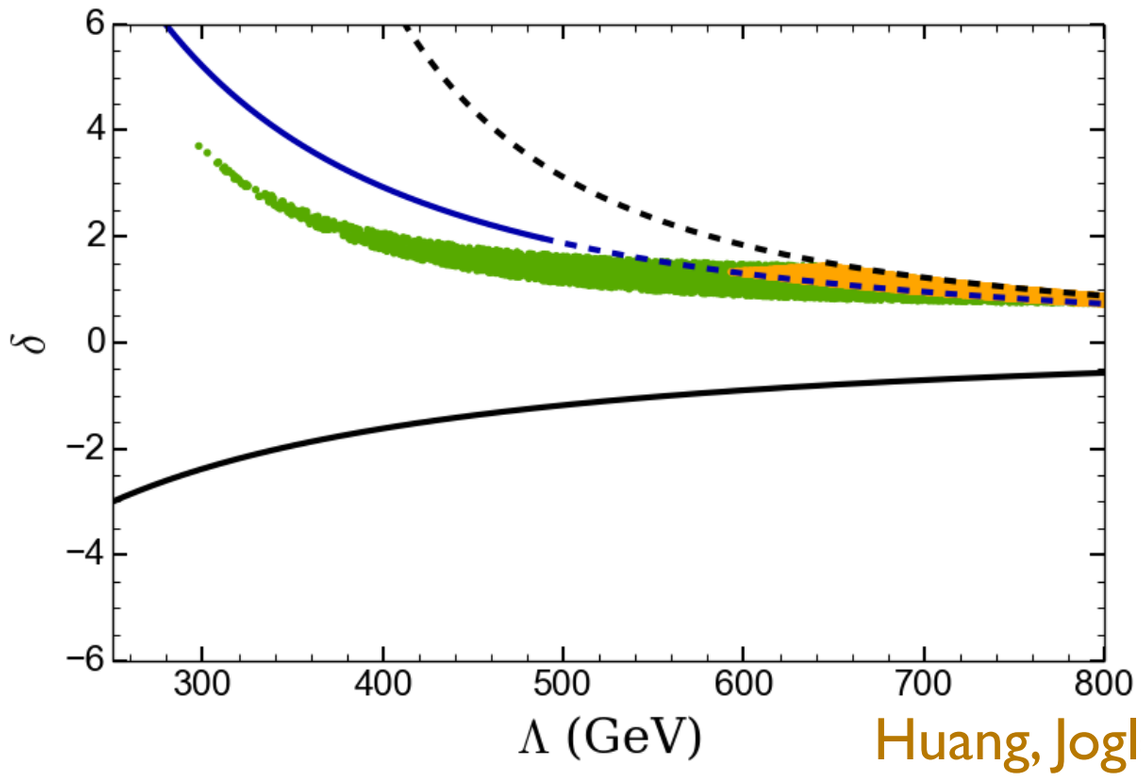



What we know from LHC
LHC upgrades won't go much further

"wiggles" in Higgs potential

Big difference in triple Higgs coupling

# 1st order phase transition
# ⇒ large modification of trilinear coupling




Huang, Joglekar, Li, Wagner, 1512.00068

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \dots$$

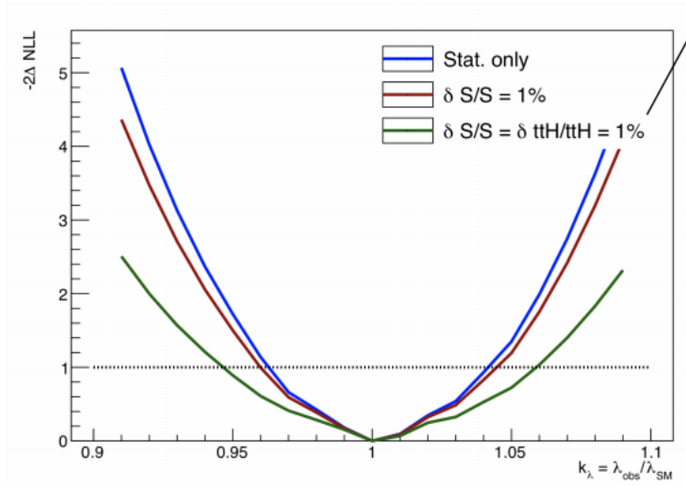
1st order phase transition → larger triple Higgs coupling

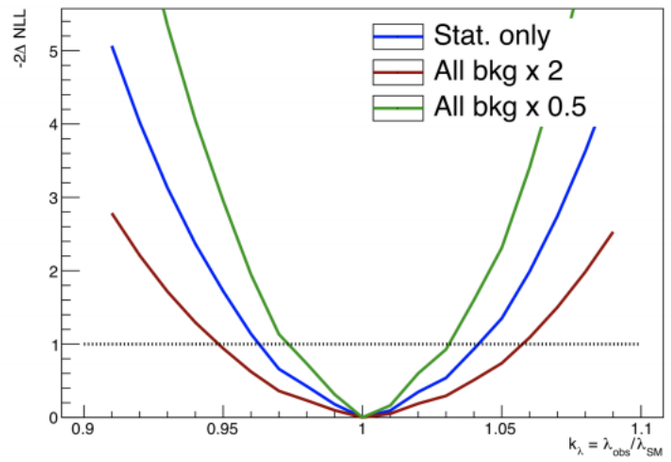
# Triple Higgs coupling at 100 TeV collider

## At FCC-hh or SppC

## Precision on the self-coupling

assuming QCD can be measured from sidebands




nominal background yields:

$\delta\kappa_\lambda(\text{stat}) \approx 3.5\ \%$
$\delta\kappa_\lambda(\text{stat + syst}) \approx 6\ \%$

varying (0.5x-2x) background yields:

$\delta\kappa_\lambda(\text{stat}) \approx 3 - 5\ \%$

Talk by Michele Selvaggi at 2nd FCC physics workshop

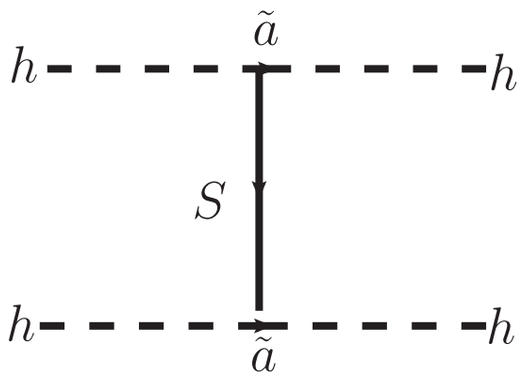
# But, there should be more

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \dots$$

- 1st order EW phase transition means there is new physics close to the weak scale.
- Can be difficult to discover at the LHC.
  - Maybe only couple weakly to the Higgs.
- Will leave more signature in Higgs coupling.

# For example

$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$




$$\frac{c}{m_S^2}\left(h^\dagger \partial h\right)^2$$

shift in h-Z coupling

$$\delta_{Zh} \sim c\frac{v^2}{m_S^2}$$

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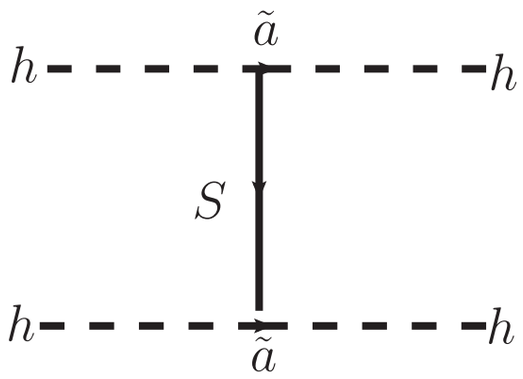


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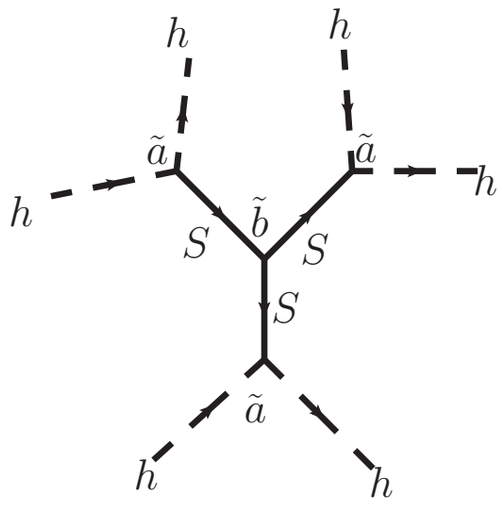
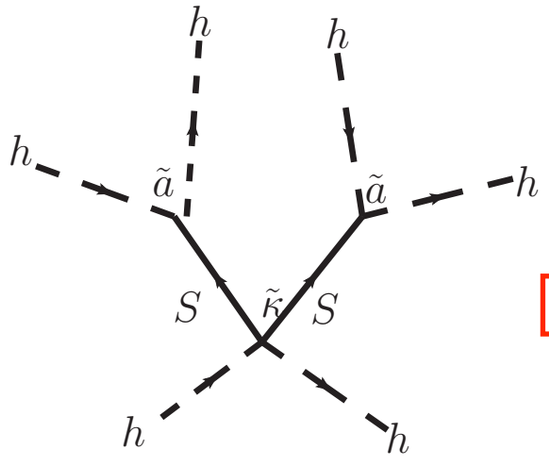
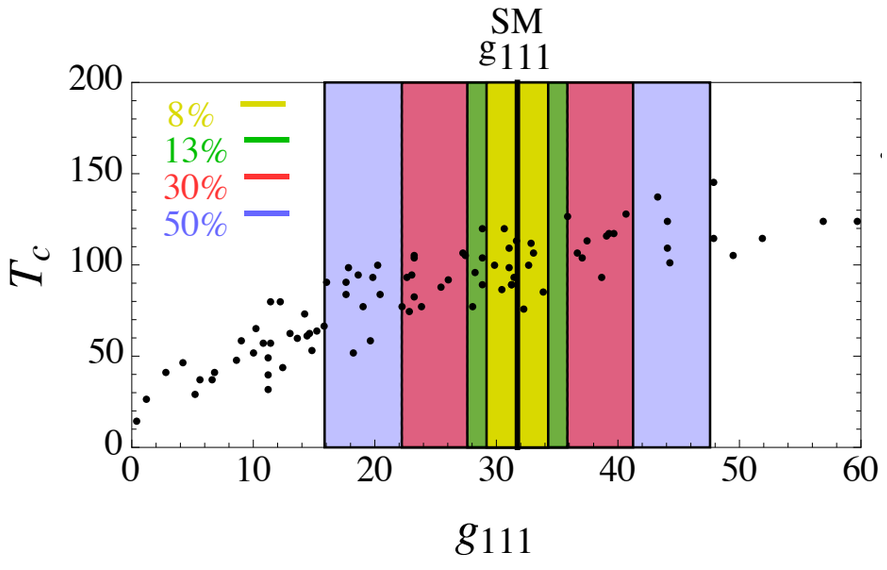
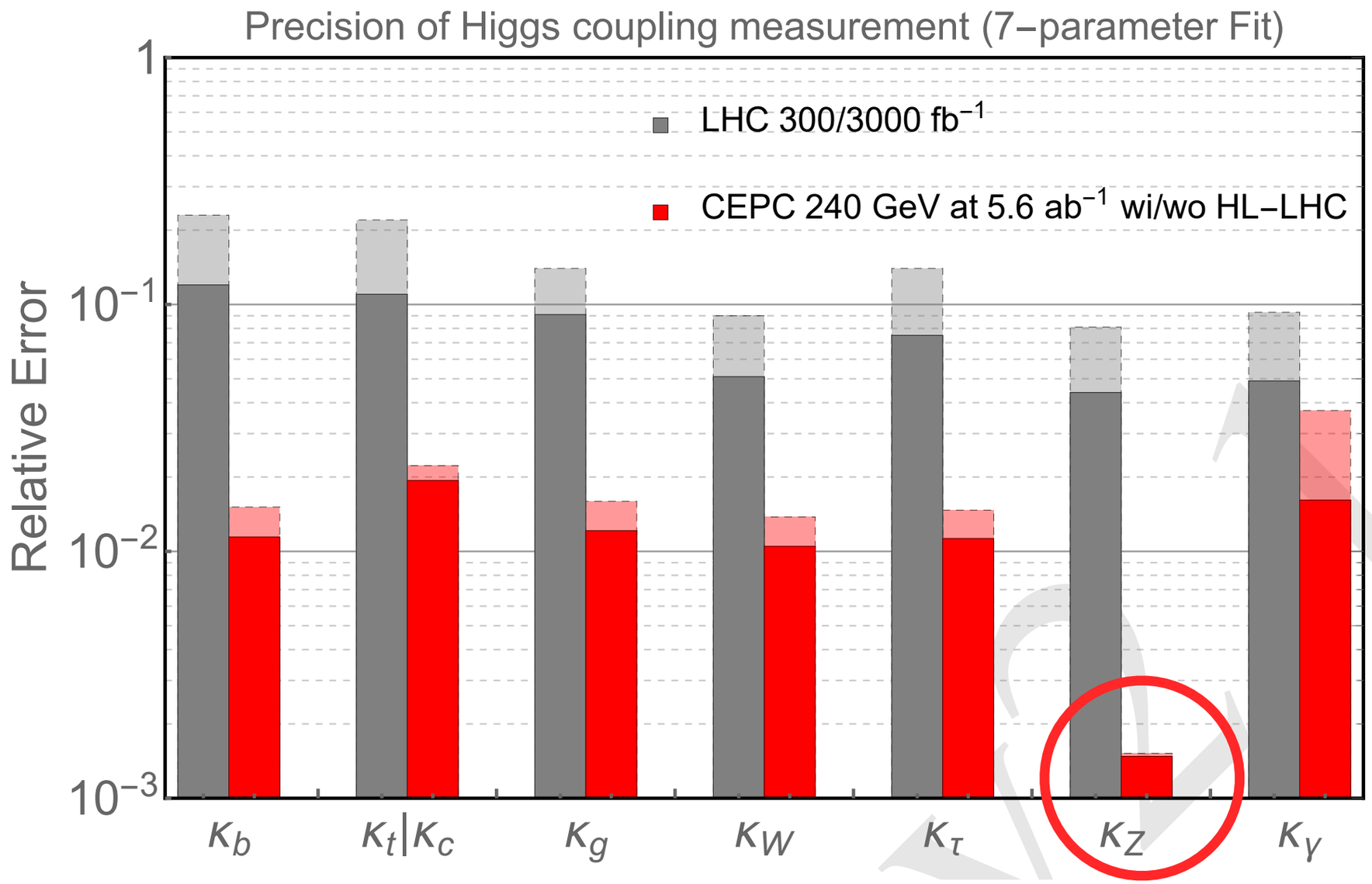


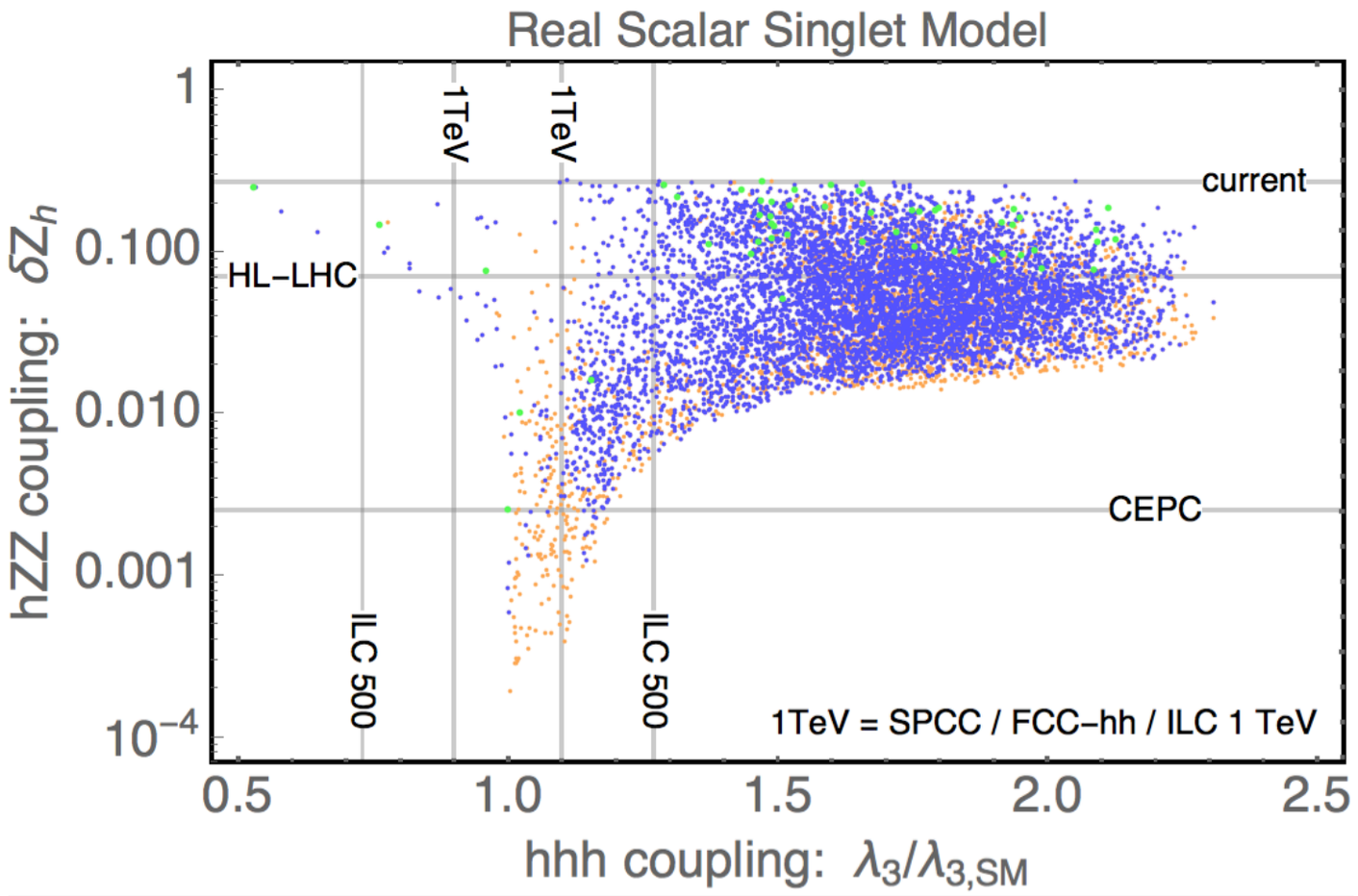

triple Higgs coupling

# Higgs coupling at the CEPC




- A large step beyond the HL-LHC.
  - Can achieve per-mil level measurement.
  - Determination of the Higgs width.

# Probing EWSB at higgs factories




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

Huang, Long, LTW, 1608.06619

Good coverage in model space

# Interesting limit of singlet model

J. Kozaczuk, M. Ramsey-Musolf, J. Shelton

small mixing limit

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

$h \to ss \to b\bar{b}b\bar{b}$

$Z_2$ limit

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

$h \to ss \to$ invisible

# Interesting limit of singlet model

J. Kozaczuk, M. Ramsey-Musolf, J. Shelton

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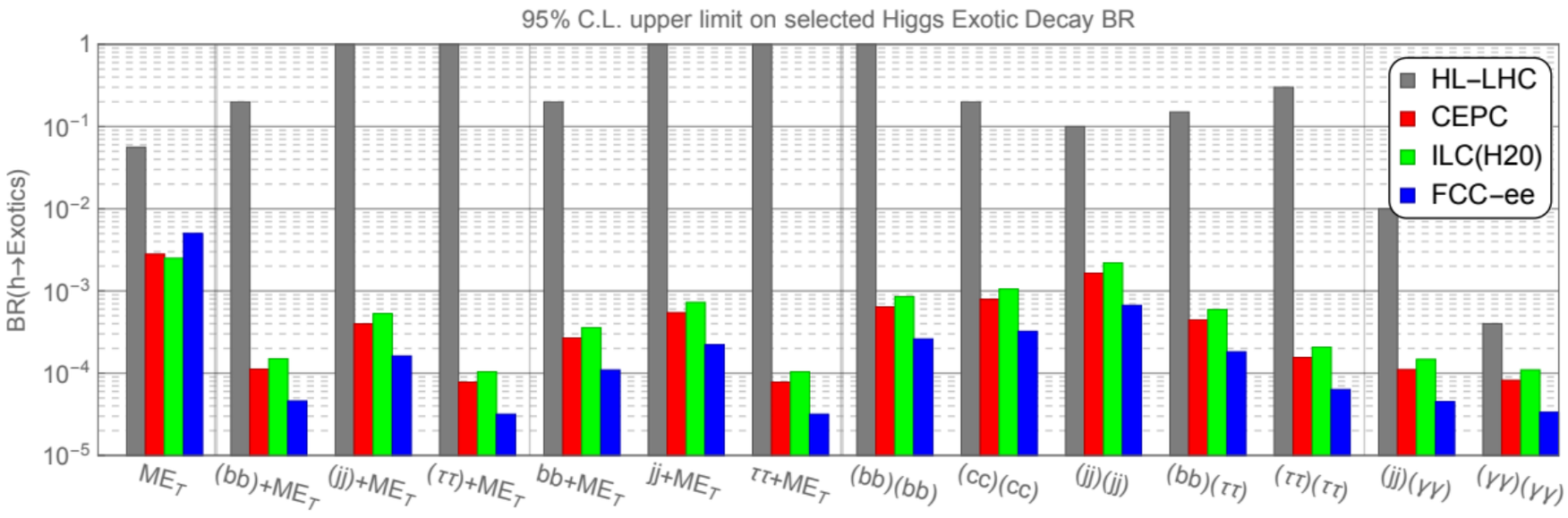
$h \to ss \to b\bar{b}b\bar{b}$

$Z_2$ limit

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

$h \to ss \to$ invisible

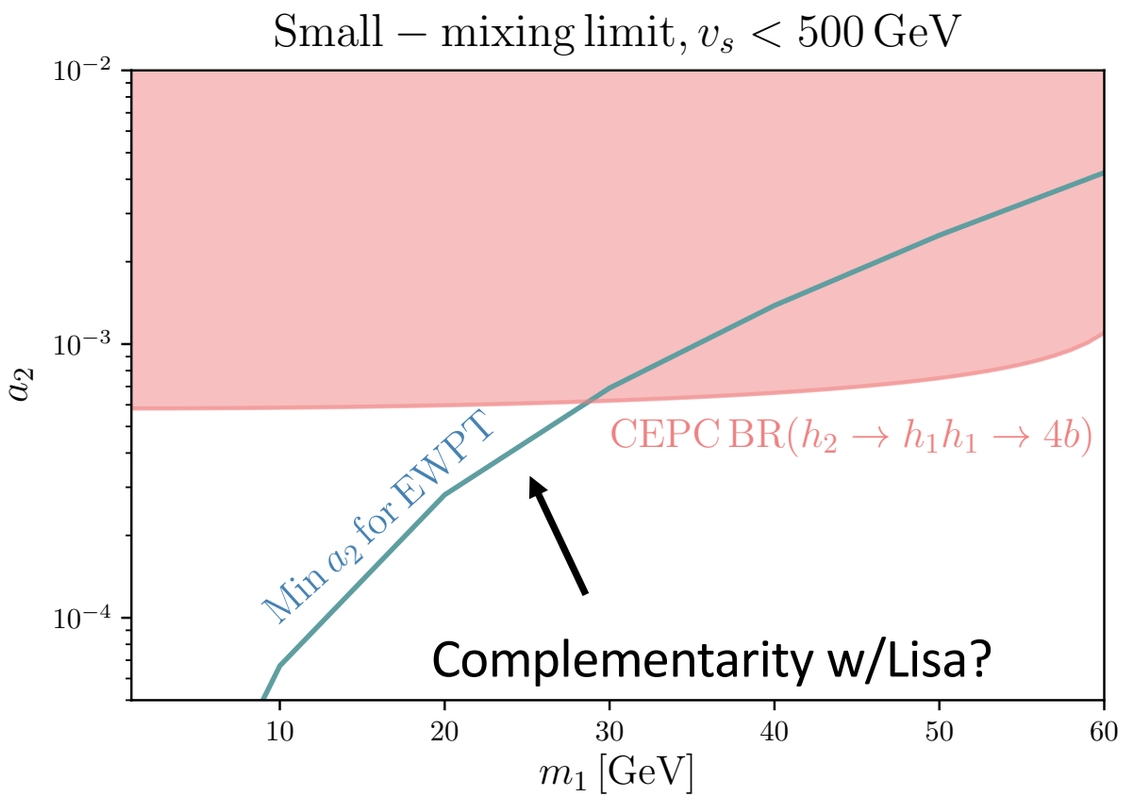


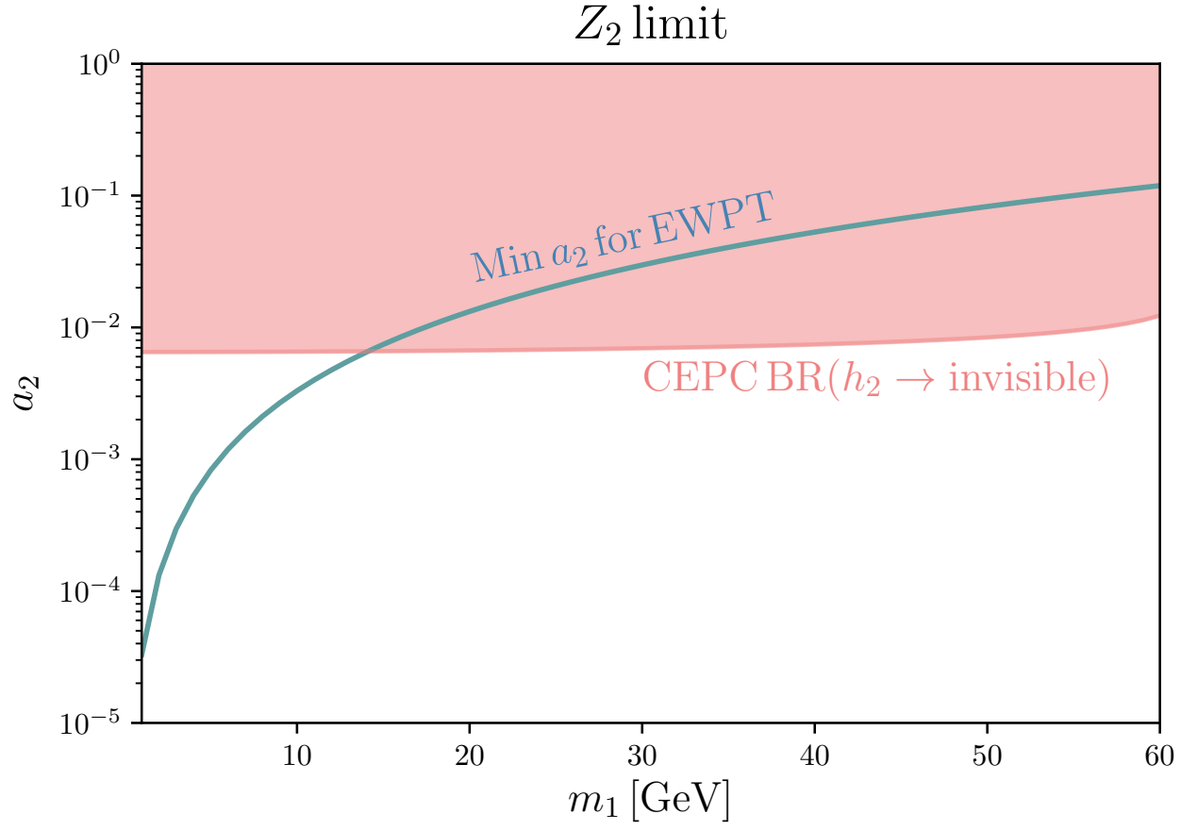

both can be probed well at CEPC

# Interesting limit of singlet model

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

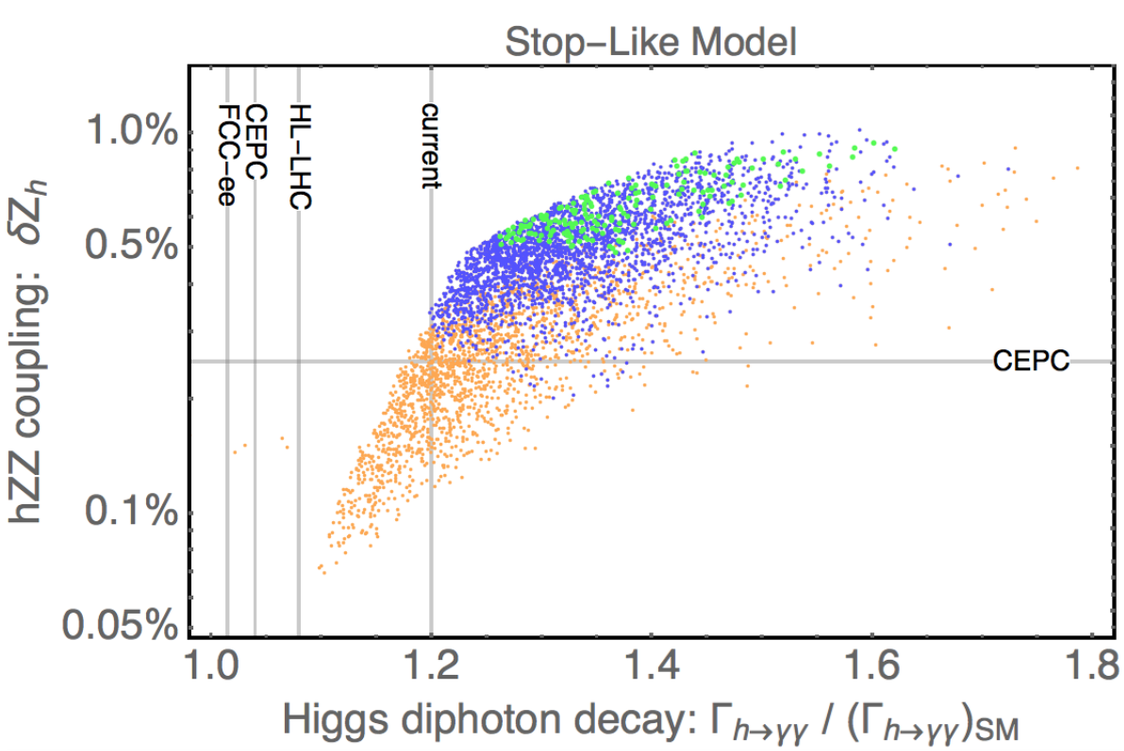
$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2}a_1 |H|^2 S + \frac{1}{2}a_2 |H|^2 S^2 + b_1 S + \frac{1}{2}b_2 S^2 + \frac{1}{3}b_3 S^3 + \frac{1}{4}b_4 S^4$$

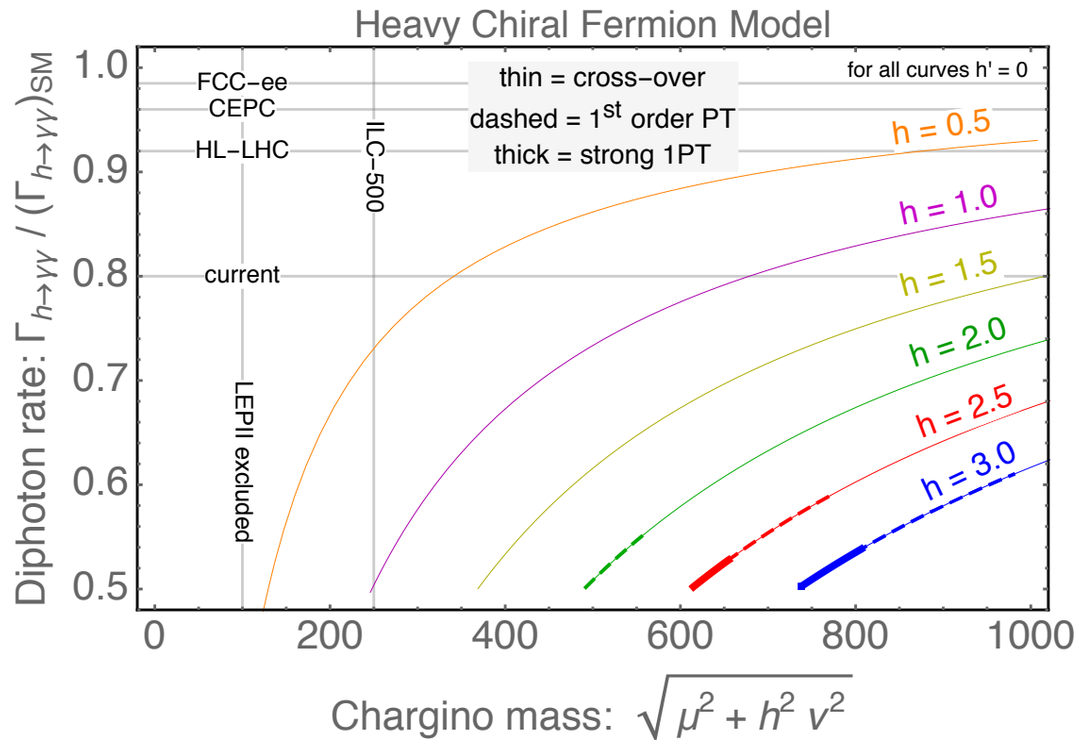


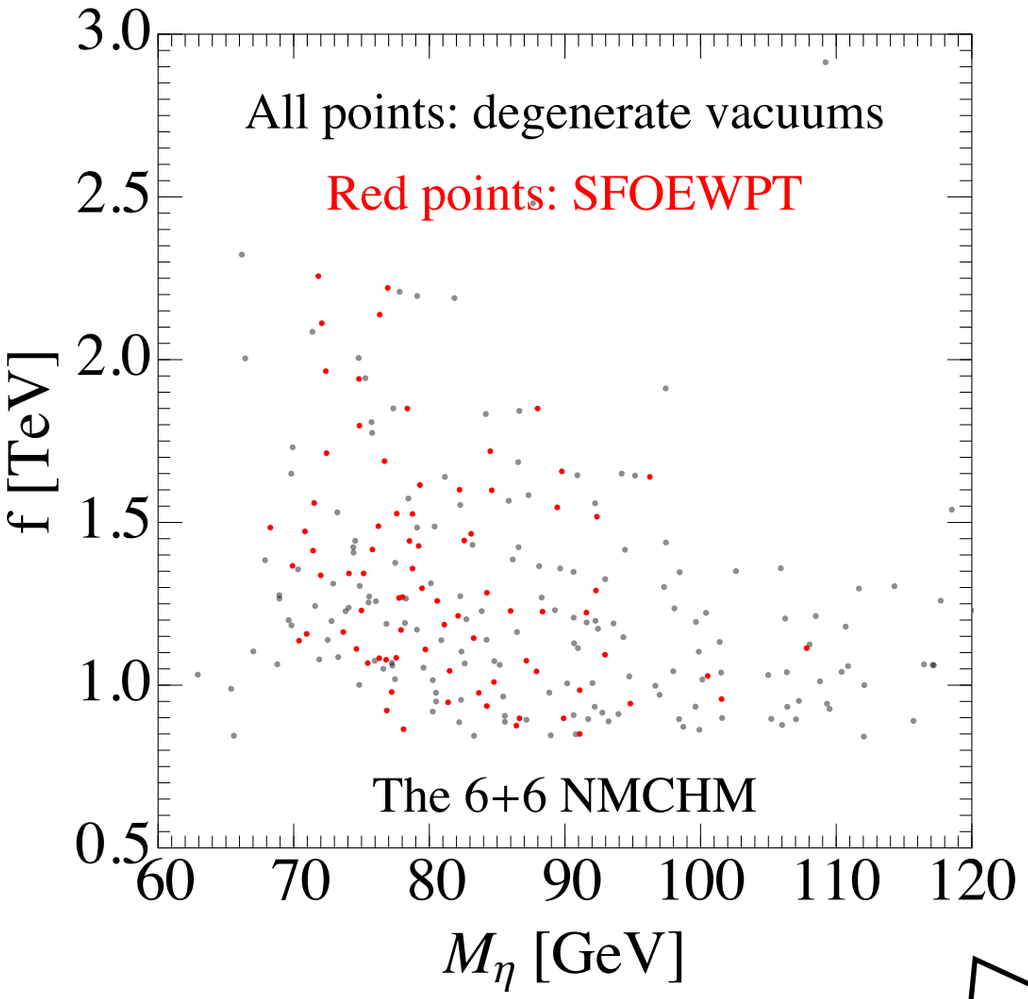

J. Kozaczuk, M. Ramsey-Musolf, J. Shelton

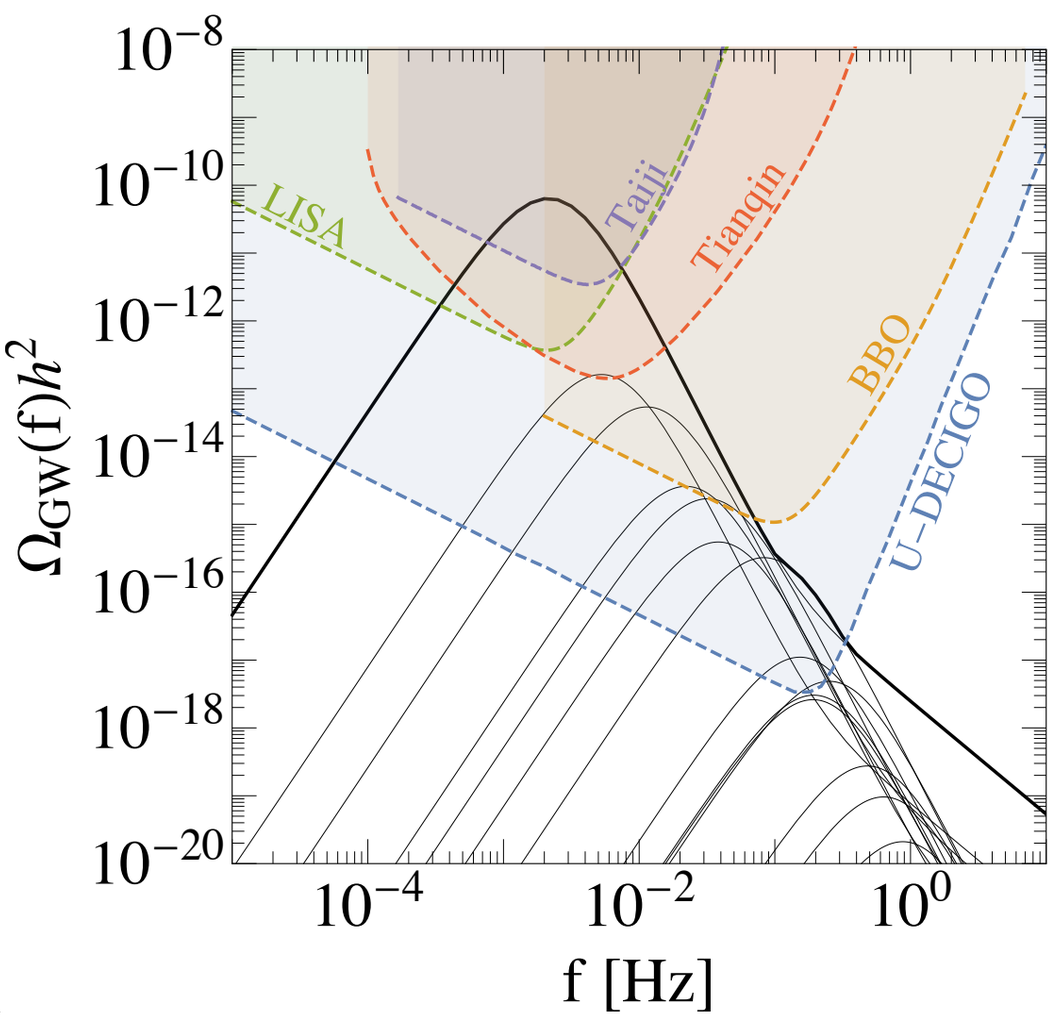
# More elaborated model
# ⇒ more signal in Higgs physics



# Within composite Higgs models




Should be able to probe at both the Higgs factories and hadron colliders.

Ligong Bian and Ke-pan Xie's talks

# Conclusions

- Electroweak phase transition is a key aspect of the electroweak symmetry breaking.

- Will be our next goal post for understanding early universe.
  - Can set the stage for baryogenesis
  - Rich signals: gravitational wave, PBH, etc.

- Study the Higgs boson will give an indispensable window into EW phase transition.

- Huge potential for the synergy of future colliders and cosmological observations!