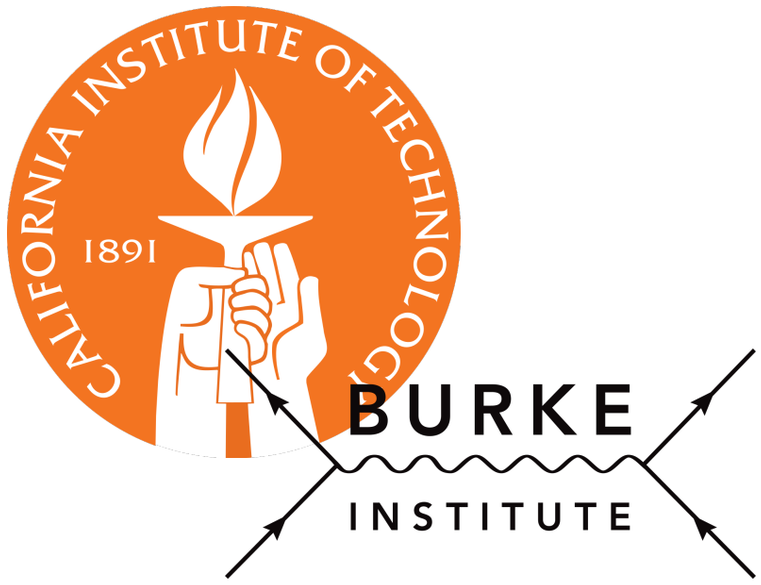
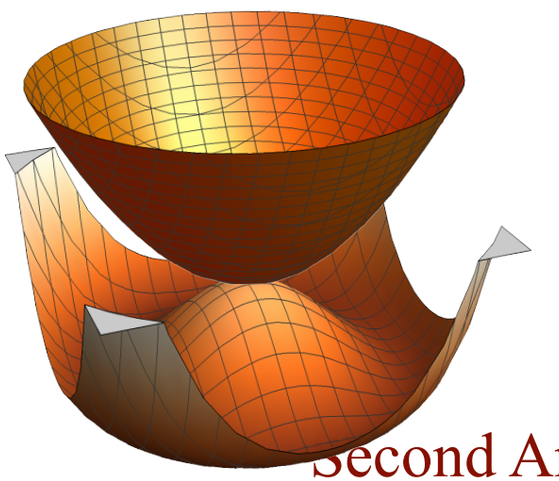
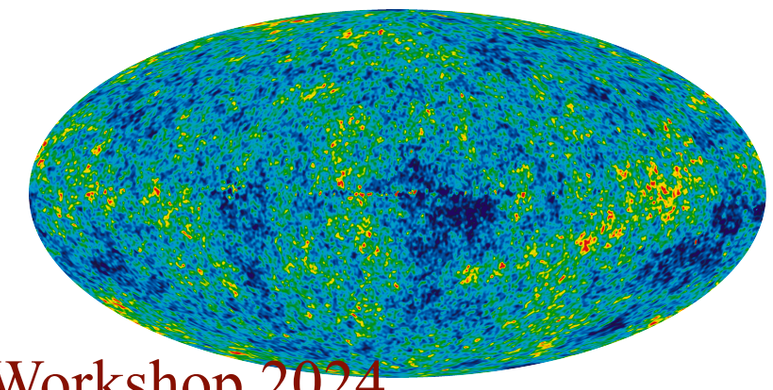


Electroweak Phase Transition and Higgs Exotic Decays



Yikun Wang

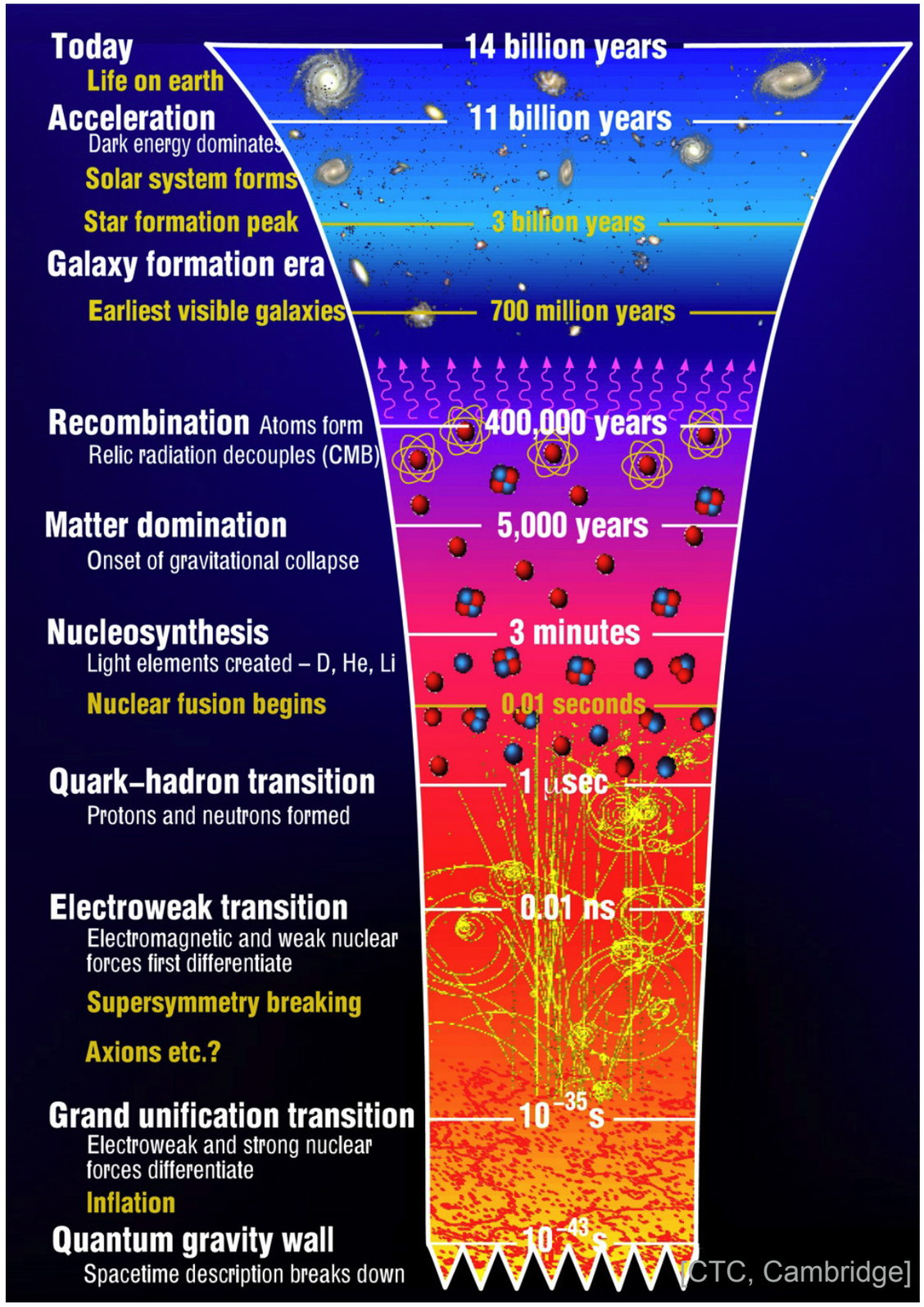
California Institute of Technology

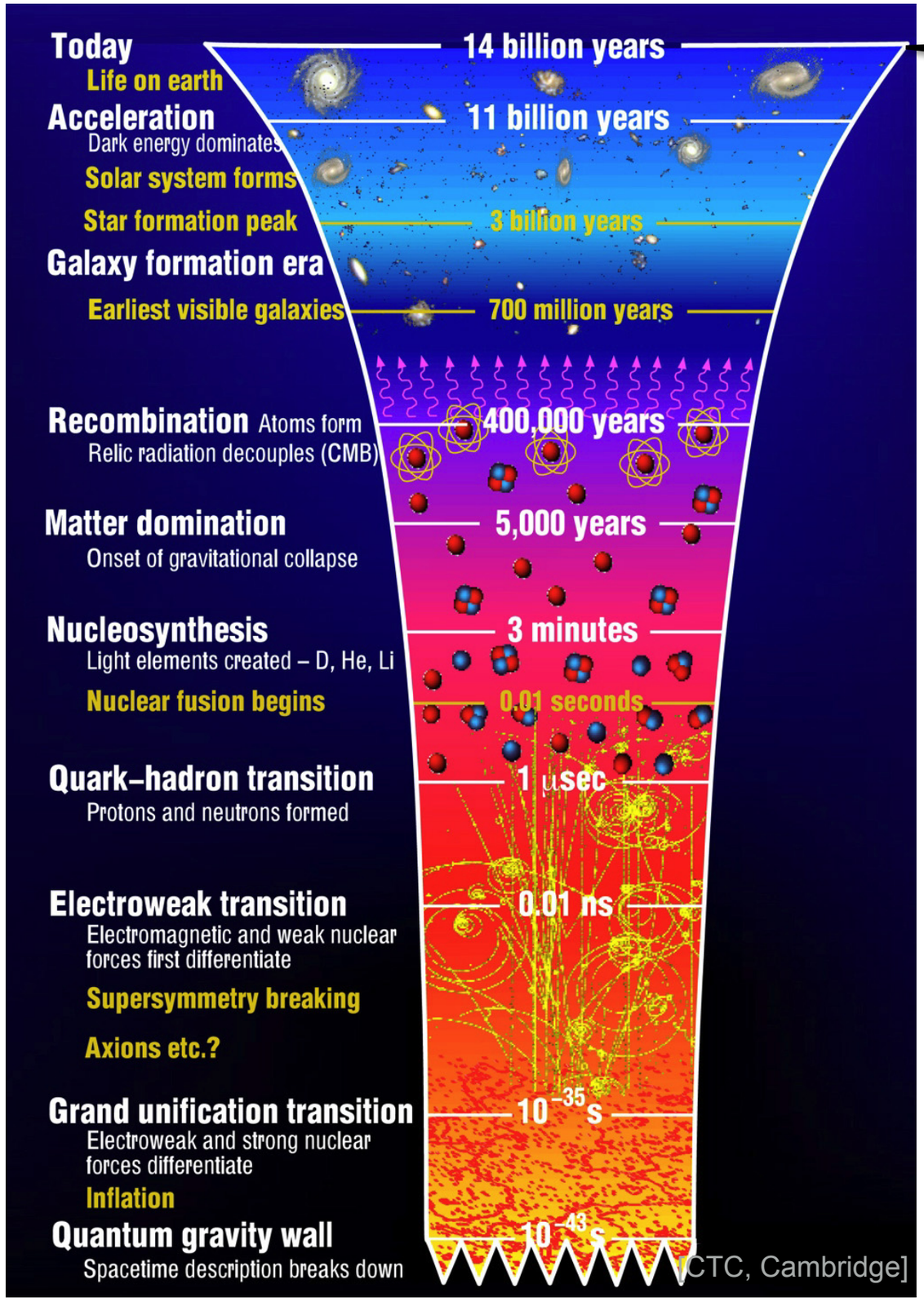


Second Annual U.S. Future Circular Collider (FCC) Workshop 2024

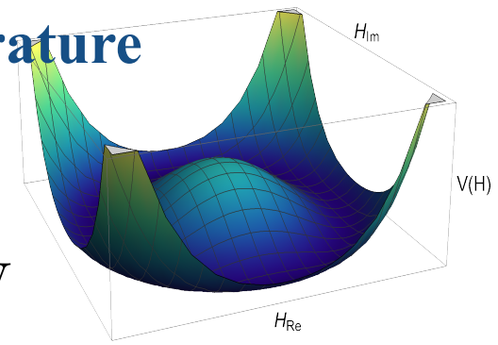
March 26th, 2024, MIT, Boston

with Marcela Carena, Zhen Liu based on arXiv:1911.10206;
with Marcela Carena, Jonathan Kozaczuk, Zhen Liu, Tong Ou, Michael J. Ramsey-Musolf, Jessie Shelton, and Ke-Pan Xie based on arXiv:2203.08206.


Today
14 billion years
Life on earth
Acceleration
11 billion years
Dark energy dominates
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation decouples (CMB)
400,000 years
Matter domination
Onset of gravitational collapse
5,000 years
Nucleosynthesis
Light elements created – D, He, Li
3 minutes
Nuclear fusion begins
0.01 seconds
Quark–hadron transition
Protons and neutrons formed
1 μsec
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
0.01 ns
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
10 −35 s
Inflation
Quantum gravity wall
Spacetime description breaks down
10 −43 s
CTC, Cambridge]



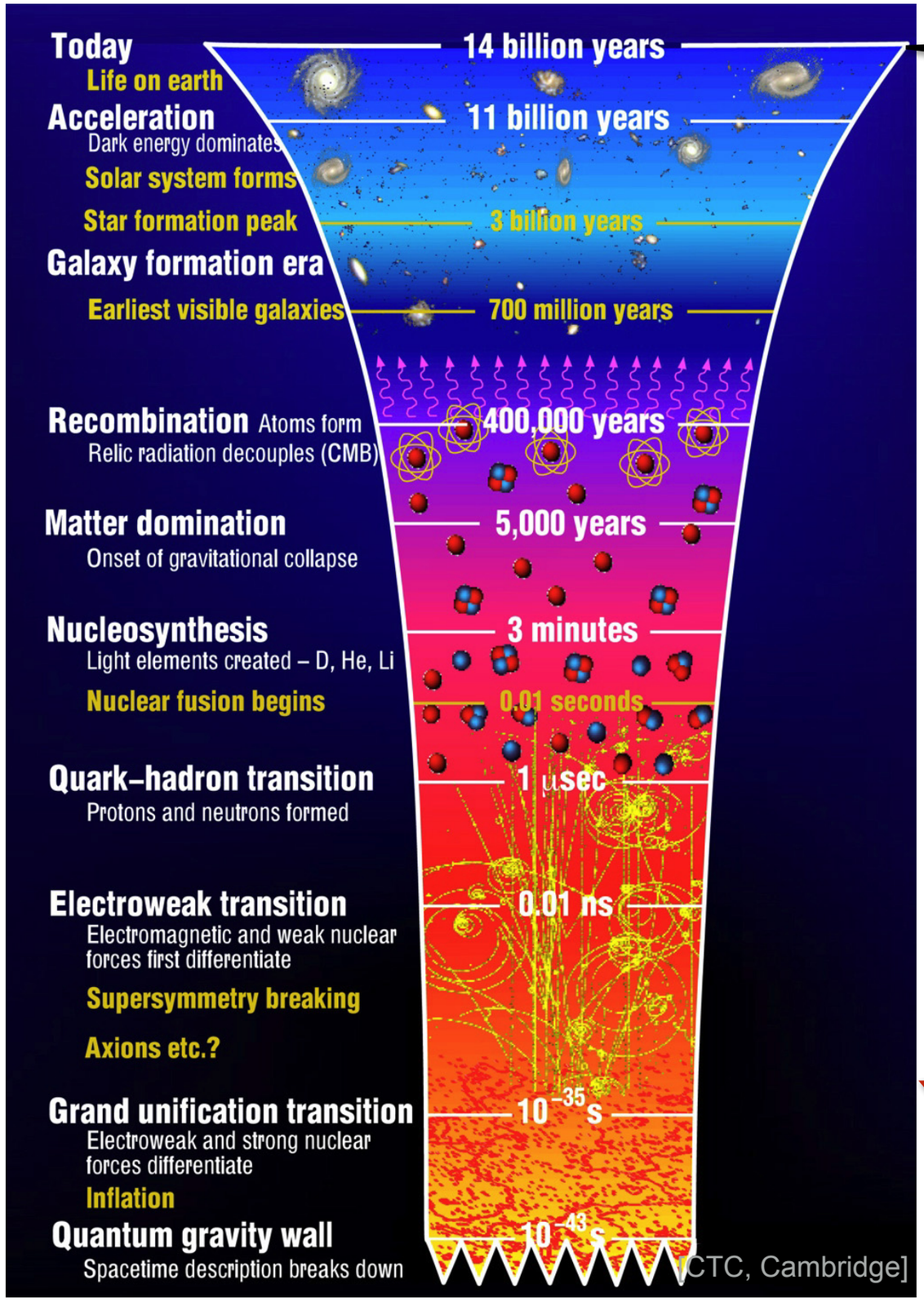
Zero Temperature



$$\langle h \rangle = 246\,\mathrm{GeV}$$

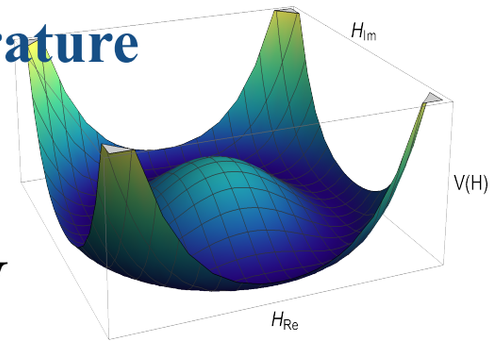
$$V(H) = -\mu_H^2 |H|^2 + \lambda_H |H|^4$$

Electroweak Symmetry Breaking



Temperature increases

Zero Temperature



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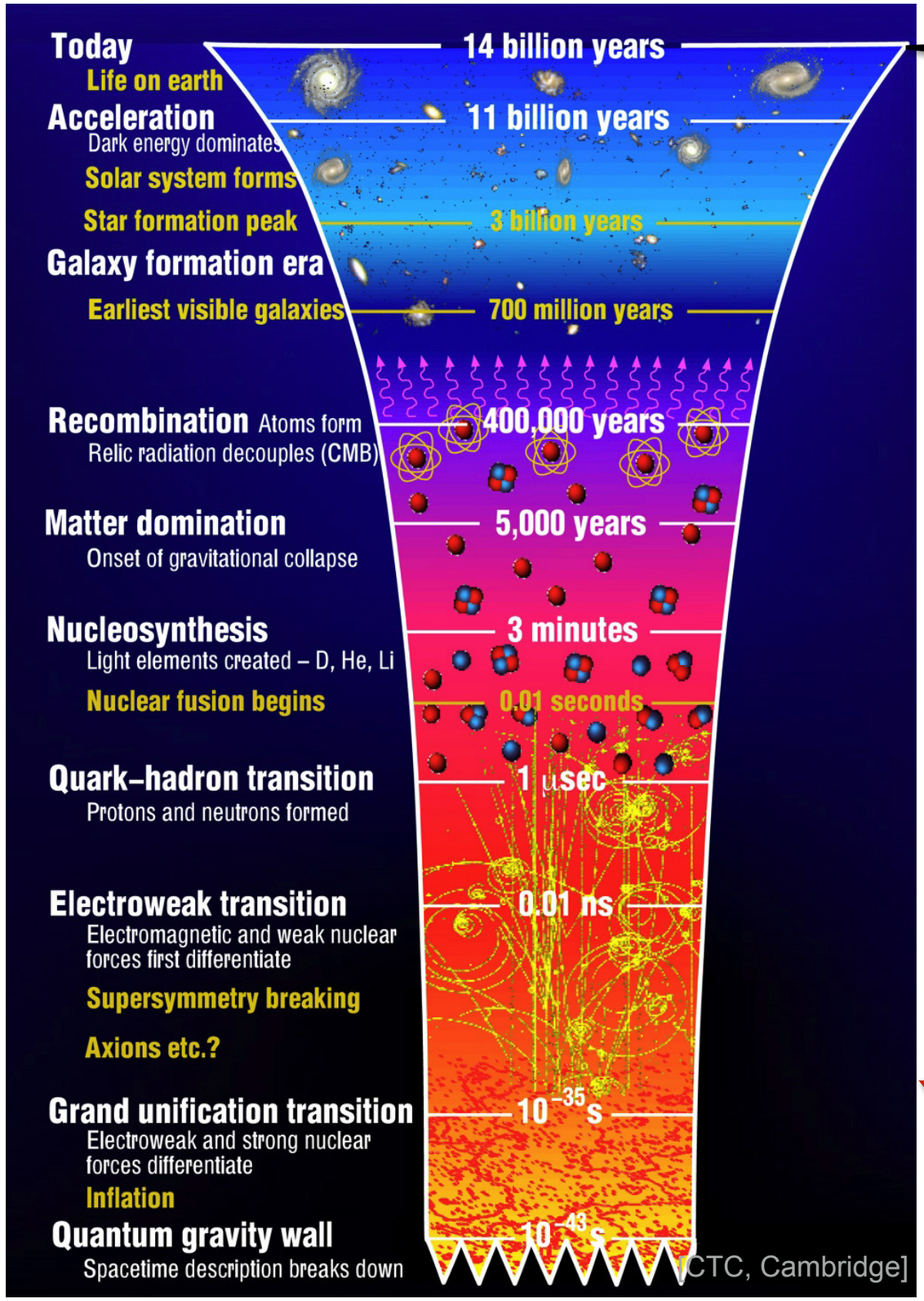
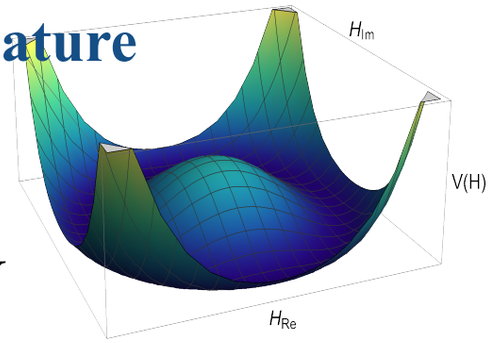


Temperature increases

Zero Temperature



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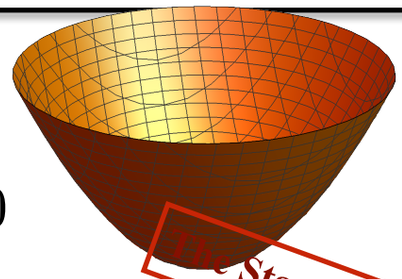
High Temperature



$$\langle h \rangle = 0$$

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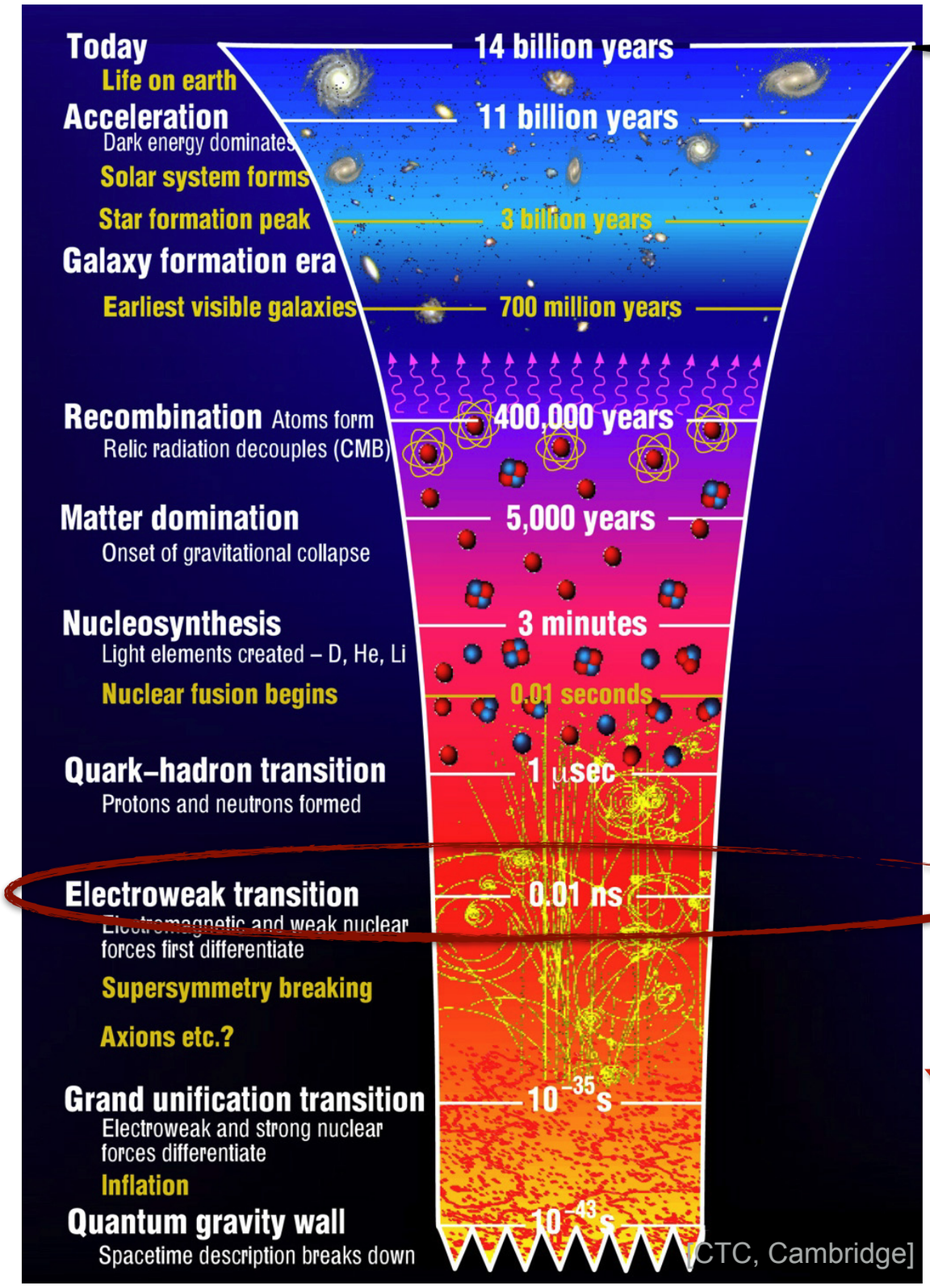
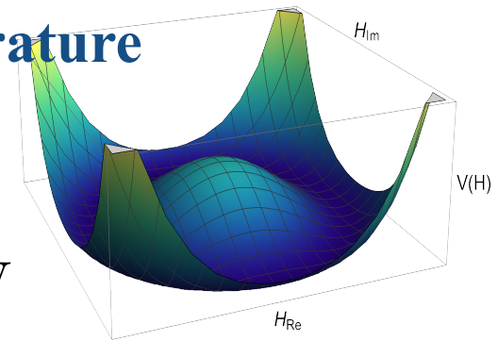
The Standard Model

Electroweak Symmetry Preserved



Temperature increases

Zero Temperature



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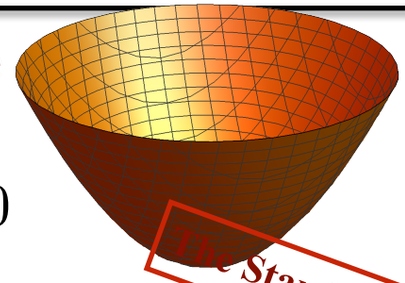
Electroweak Symmetry Breaking

Electroweak Phase Transition

High Temperature



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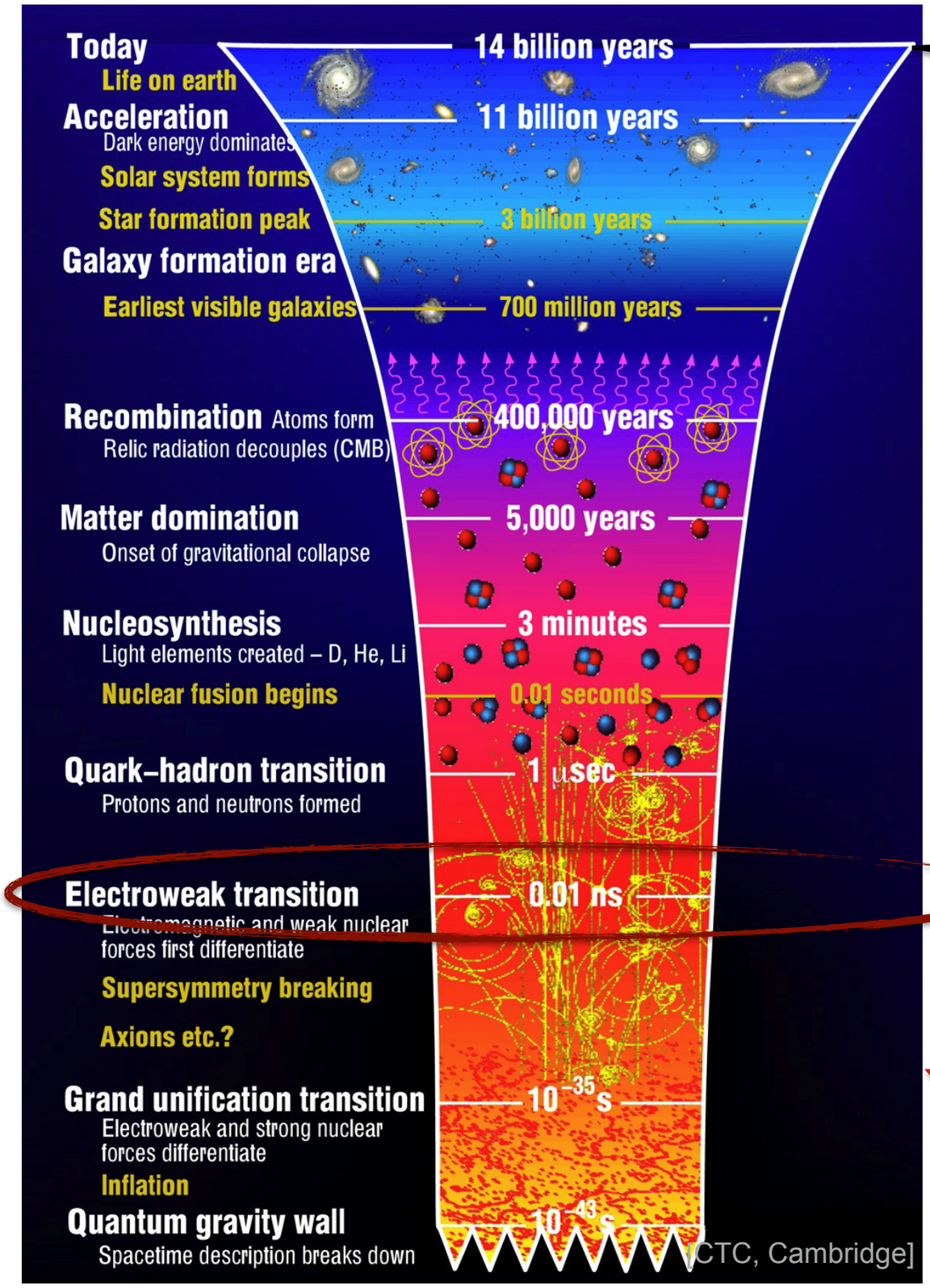
The Standard Model

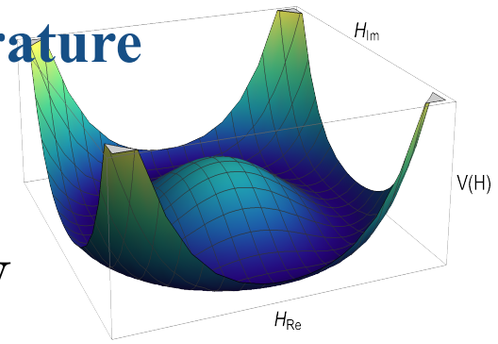
Electroweak Symmetry Preserved

Nature of the phase transition



Temperature increases

Zero Temperature



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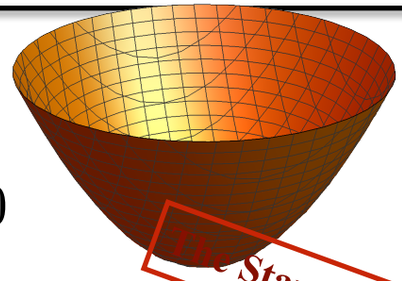
Electroweak Symmetry Breaking

Electroweak Phase Transition

?

High Temperature



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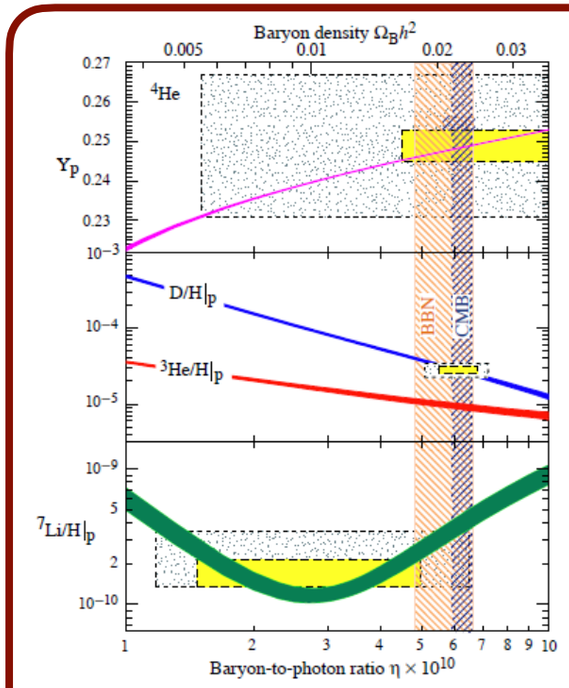
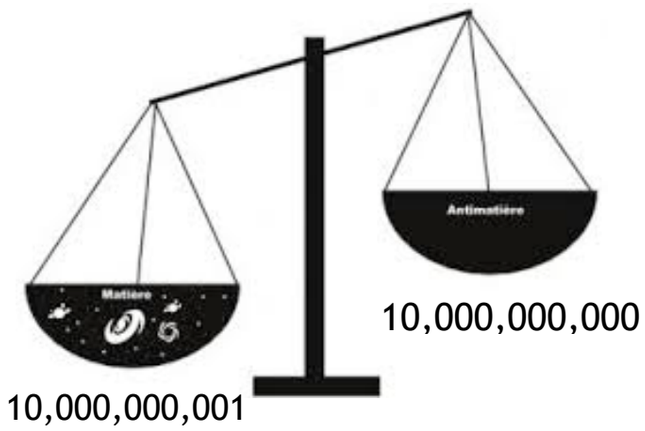
The Standard Model

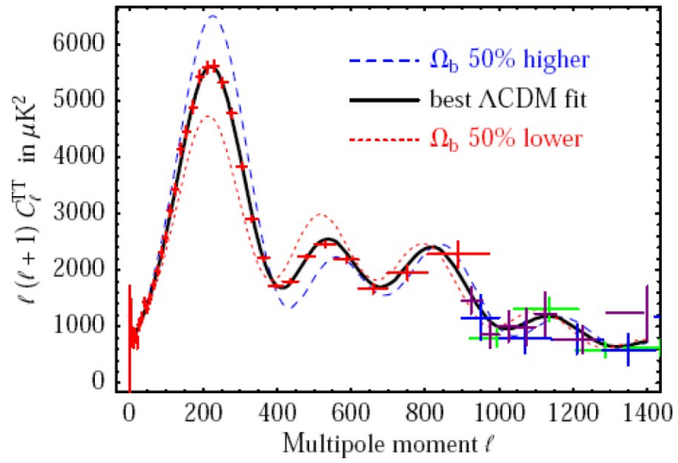
Electroweak Symmetry Preserved

A bonus for answering the question



Big Bang Nucleosynthesis

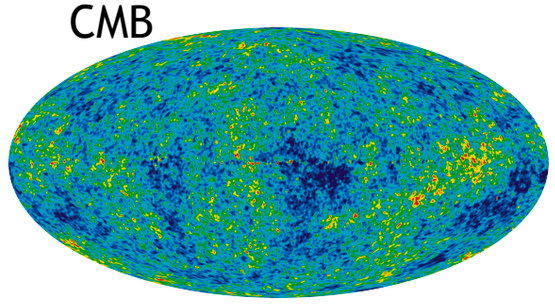




Baryon Asymmetry of the Universe

$$\eta = \frac{n_B}{n_\gamma} = (6.11 \pm 0.19) \times 10^{-10}$$

CMB



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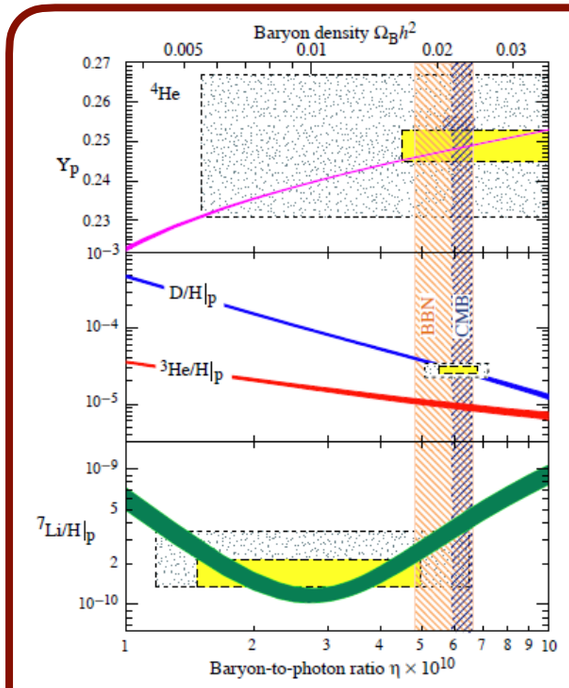

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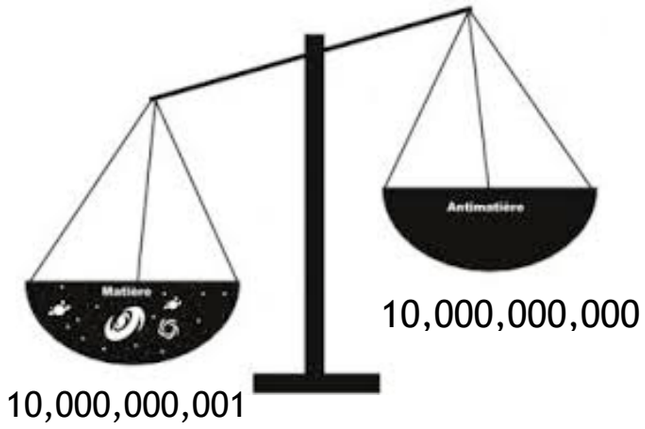

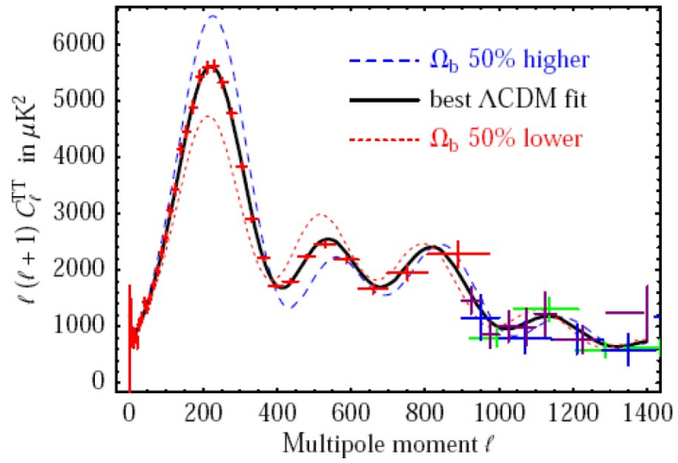

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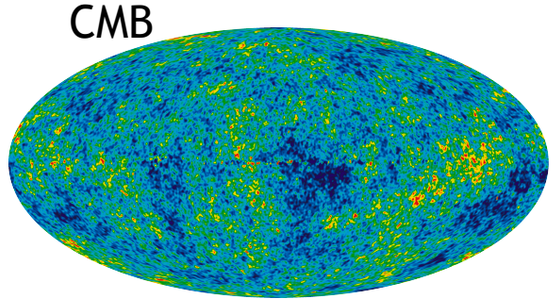
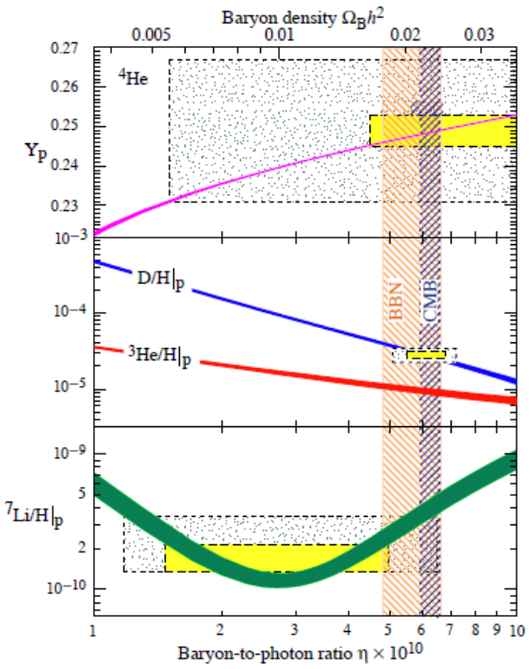


The Standard Model of particle physics could not explain the generation of BAU

A bonus for answering the question



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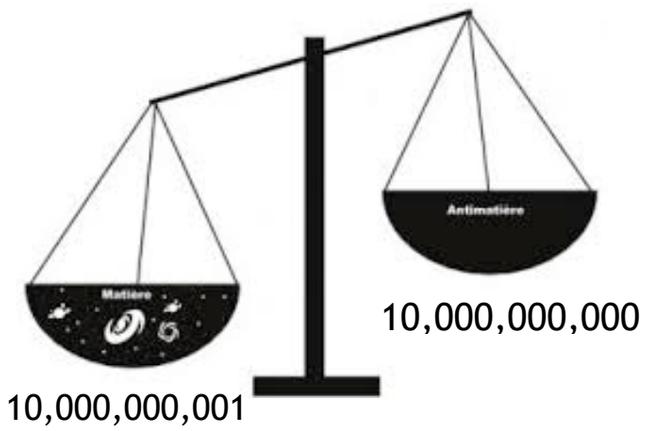

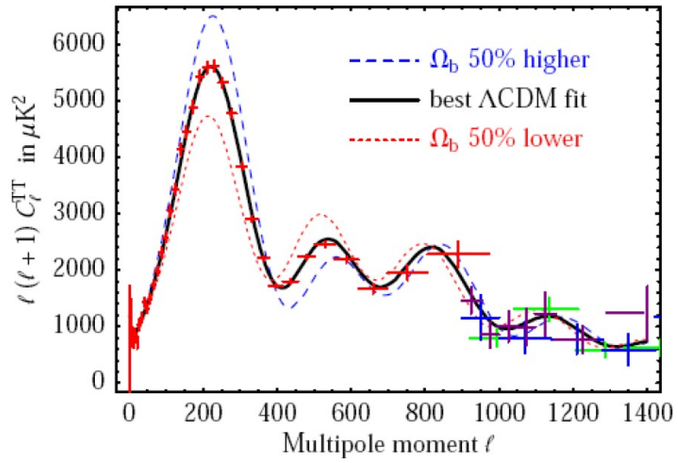

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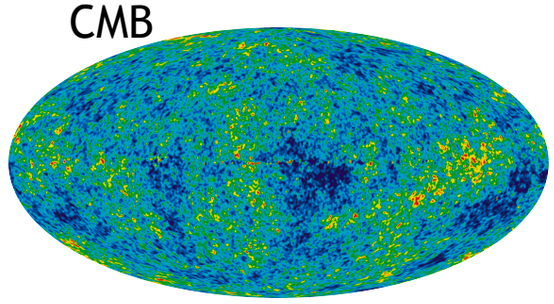

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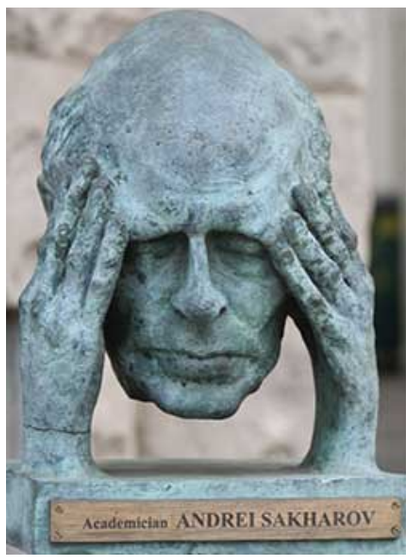
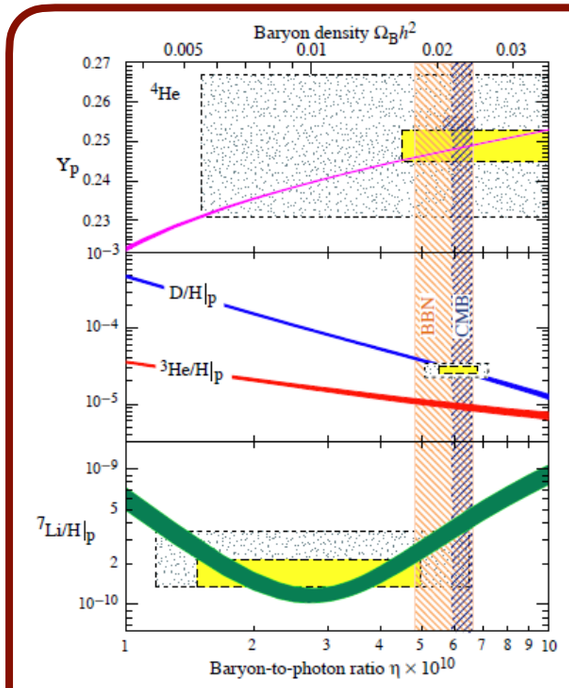
Sakharov's conditions for BAU creation



- **Baryon number violation**
- **C and CP violation**
- **Out-of-equilibrium**

A bonus for answering the question



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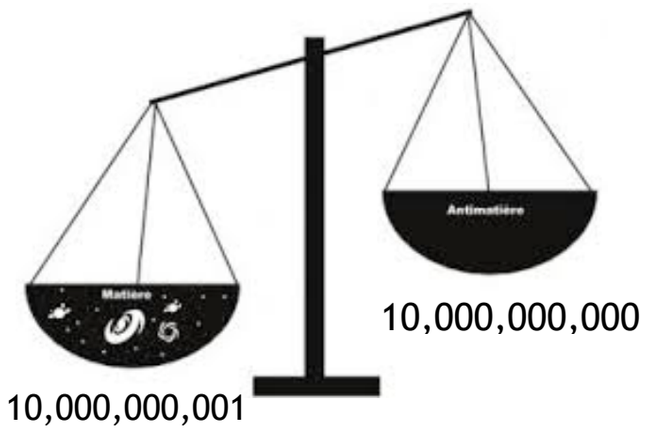

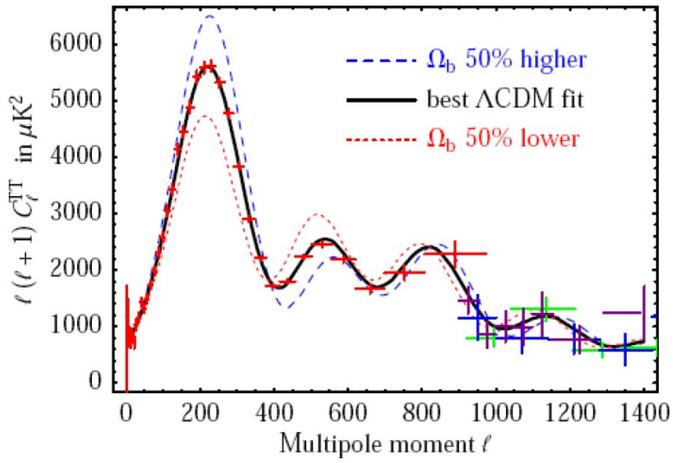

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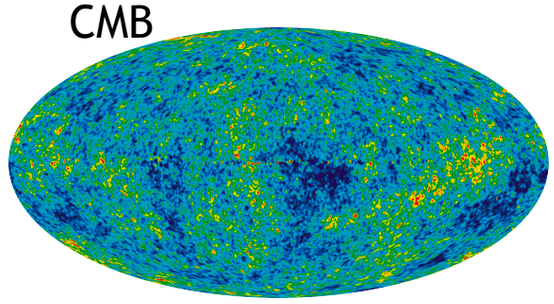

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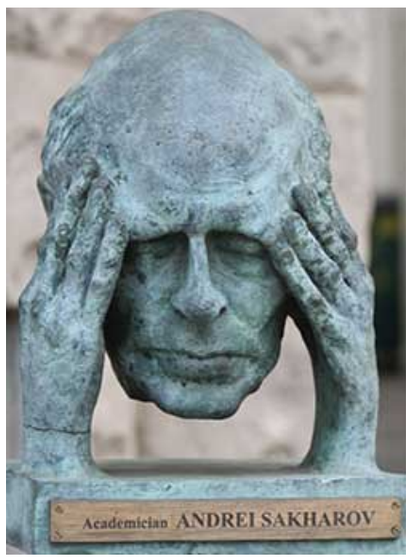

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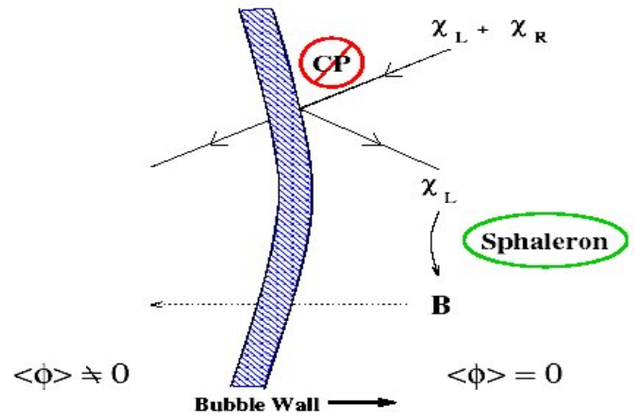
Electroweak Baryogenesis



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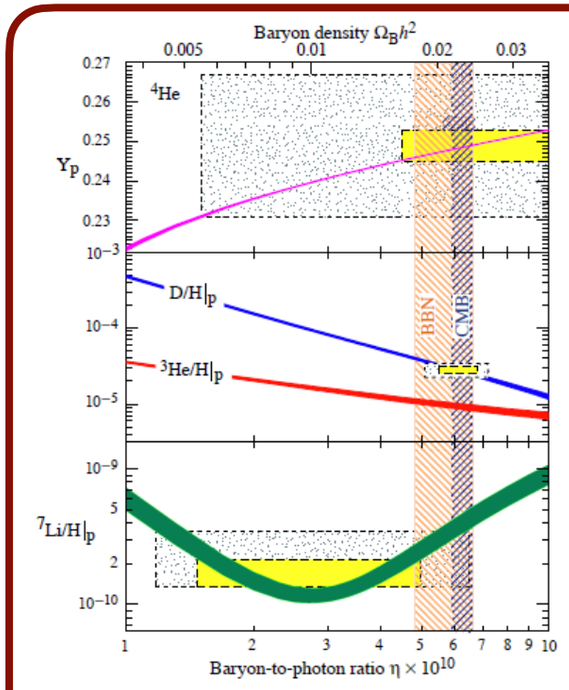

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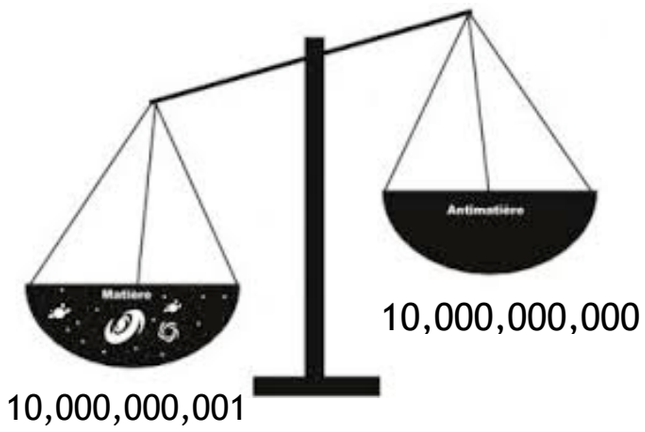

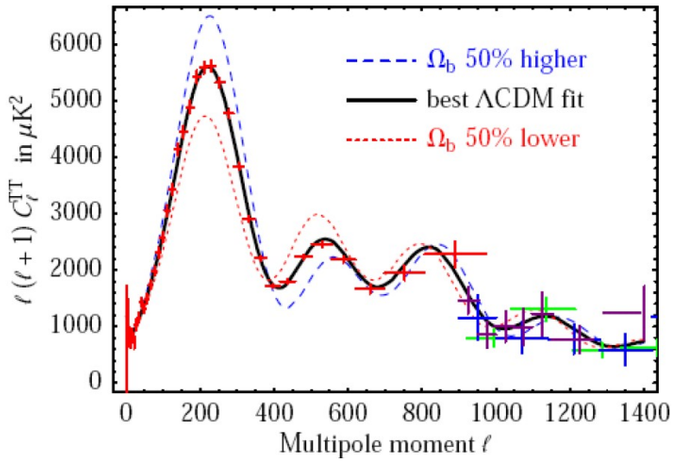

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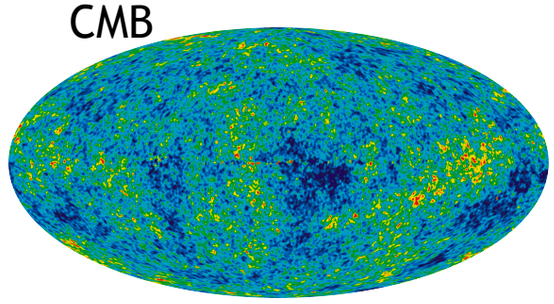

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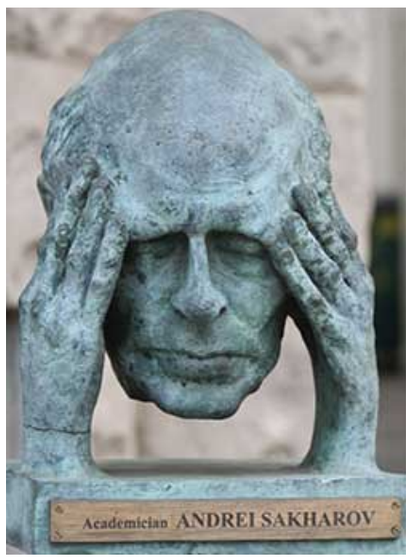

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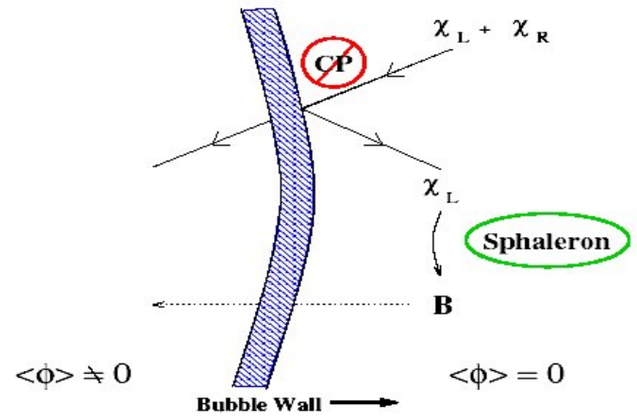

Strongly First Order
Electroweak Phase Transition

Electroweak phase transition and Higgs properties (at zero T)

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$

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$$\widetilde{\lambda_H} \sim \lambda_H \left(1 + \alpha \log \frac{h^2}{M^2}\right)$$

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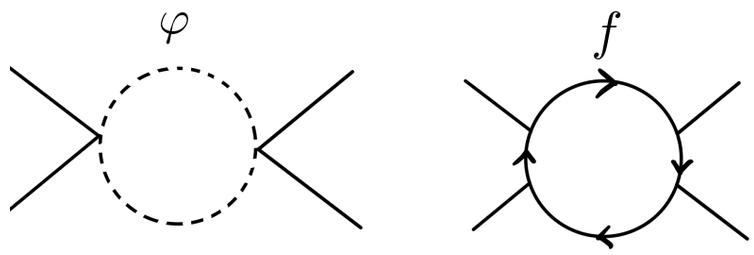
- **Zero Temperature loop effects**

$$\widetilde{\lambda_H} \sim \lambda_H \left(1 + \alpha \log \frac{h^2}{M^2}\right)$$



E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …

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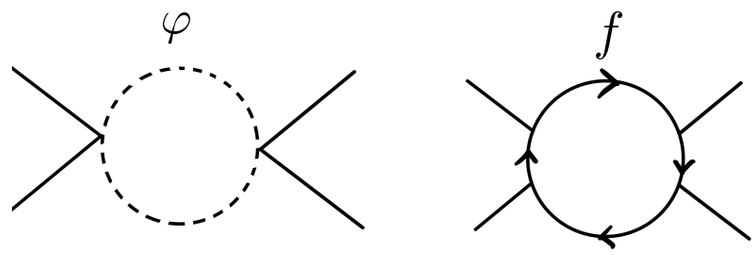

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$$Eh^3 \sim \left(m_{\rm eff}(h, T_c)\right)^{3/2} \sim \lambda^{3/2} h^3$$

Electroweak phase transition and Higgs properties (at zero T)

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$

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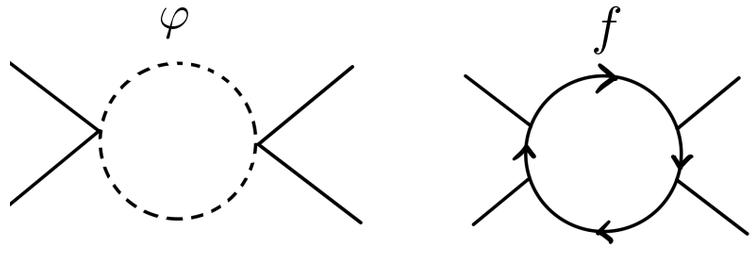

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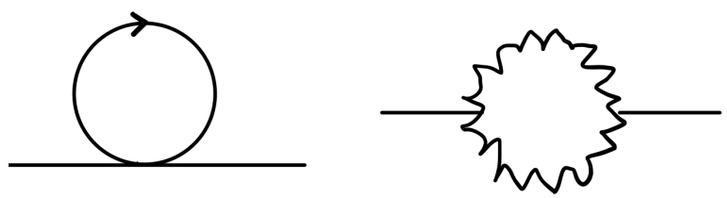
- **Thermal effects**

$$Eh^3 \sim \left(m_{\rm eff}(h, T_c)\right)^{3/2} \sim \lambda^{3/2} h^3$$



E.g. [Anderson, Hall '92], [Cohen, Morrissey, Pierce '12], [Chowdhury et al '12]
[Carena, Quiros, Wagner, '96], [Delepine, et al '96]

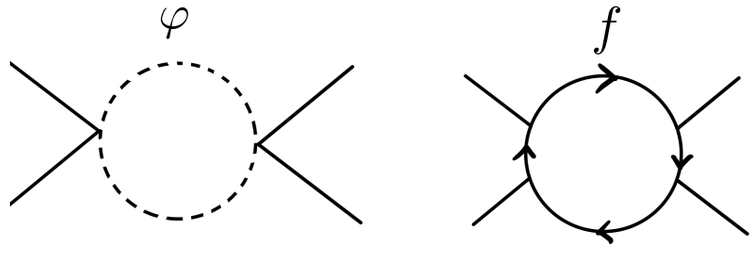
Electroweak phase transition and Higgs properties (at zero T)

$$V_{\rm EFF}(h,T) = c_H(T^2 - T_0^2)h^2 - (ET + e)h^3 + \frac{\widetilde{\lambda_H}}{2}h^4 + \cdots$$

Order of the Phase Transition $\propto \dfrac{E + e/T}{\widetilde{\lambda_H}} \gtrsim 1$

- **Zero Temperature loop effects**

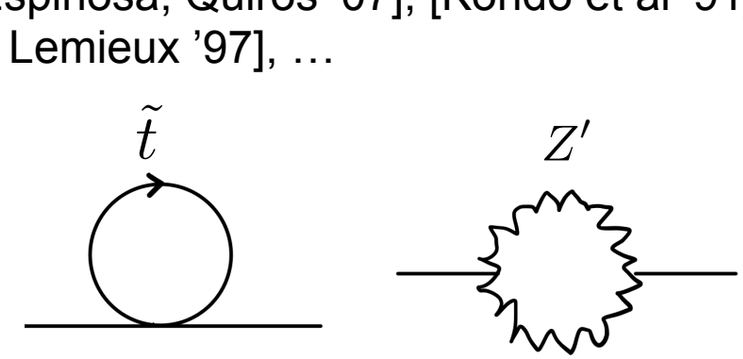
$$\widetilde{\lambda_H} \sim \lambda_H \left(1 + \alpha \log \frac{h^2}{M^2}\right)$$



E.g. [Espinosa, Quiros '07], [Kondo et al '91], [Cline, Lemieux '97], …

- **Thermal effects**

$$Eh^3 \sim \left(m_{\rm eff}(h,T_c)\right)^{3/2} \sim \lambda^{3/2}h^3$$



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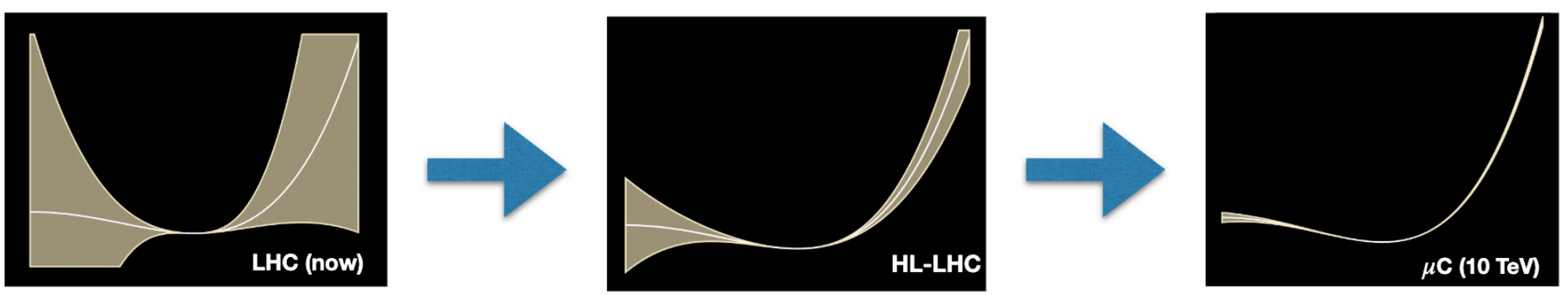

Courtesy of N. Craig

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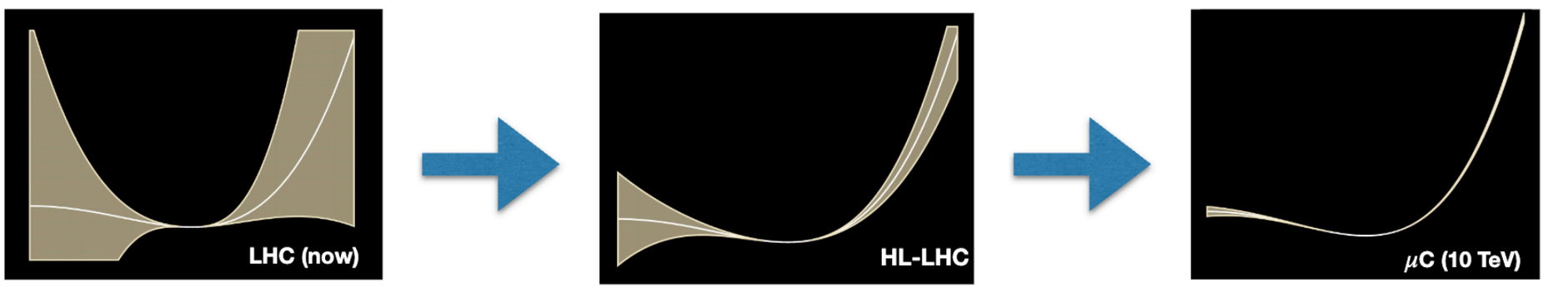

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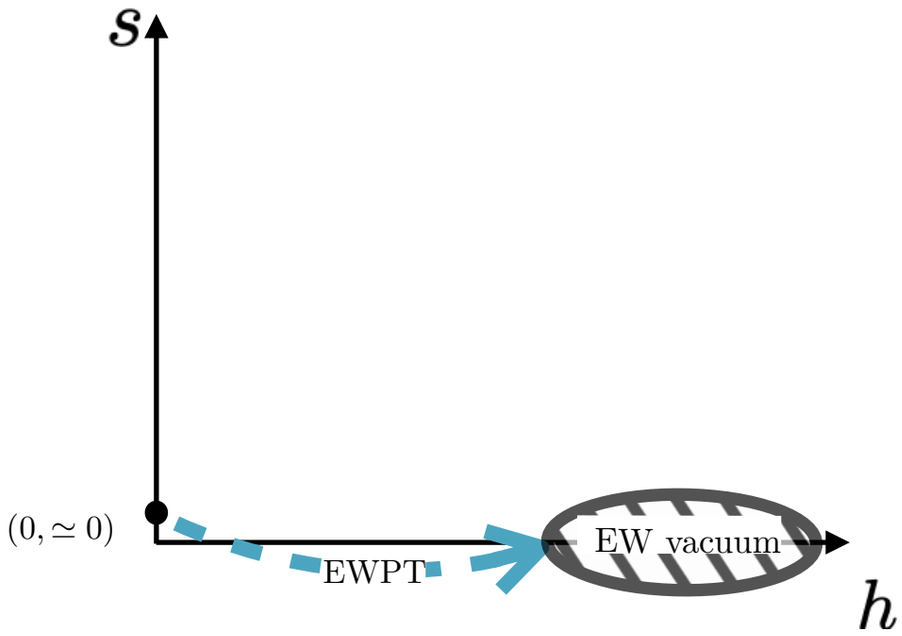

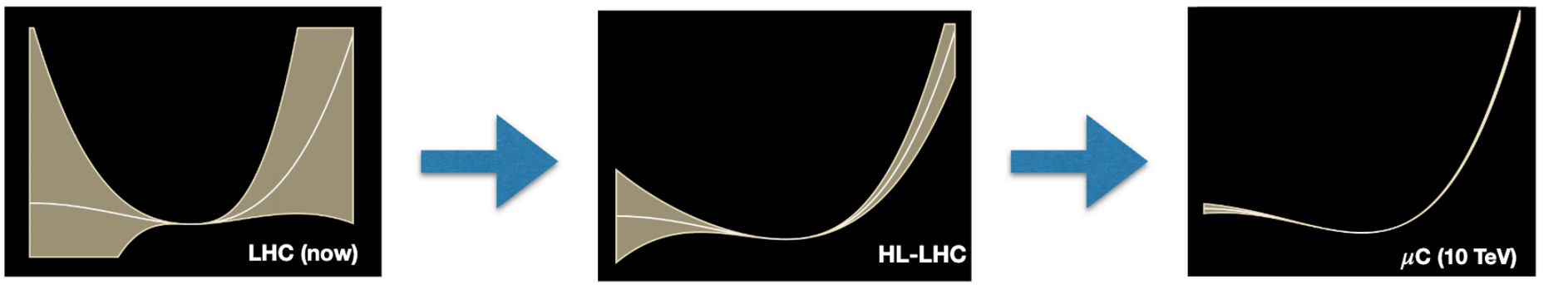

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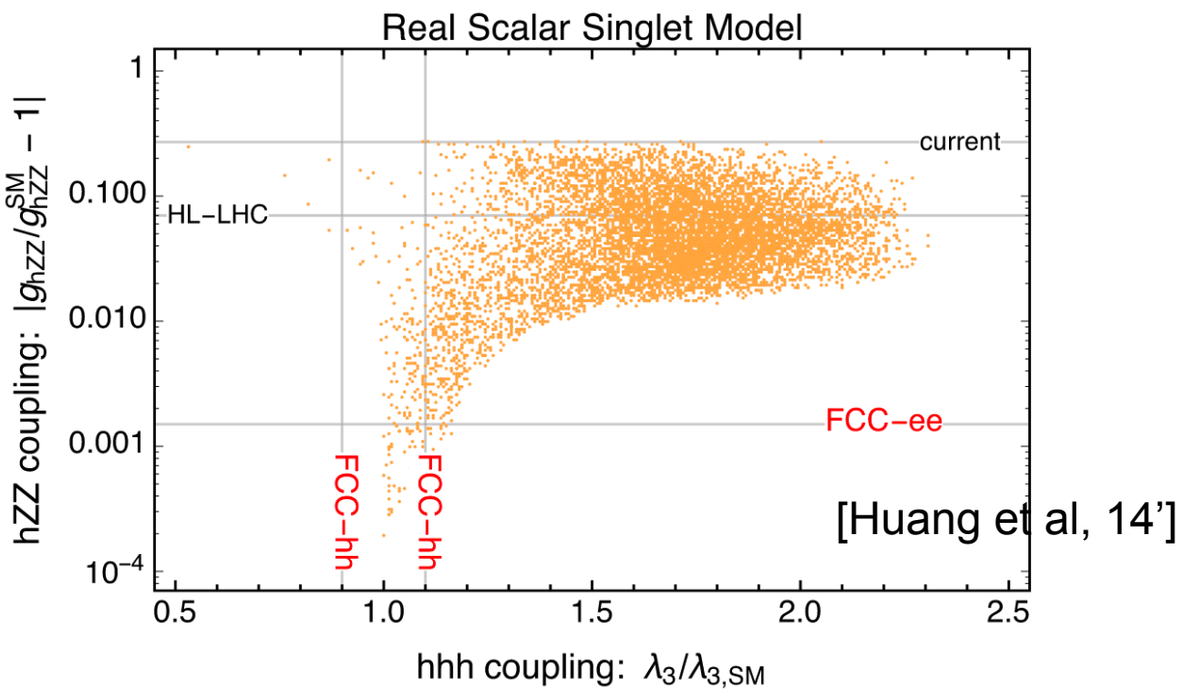
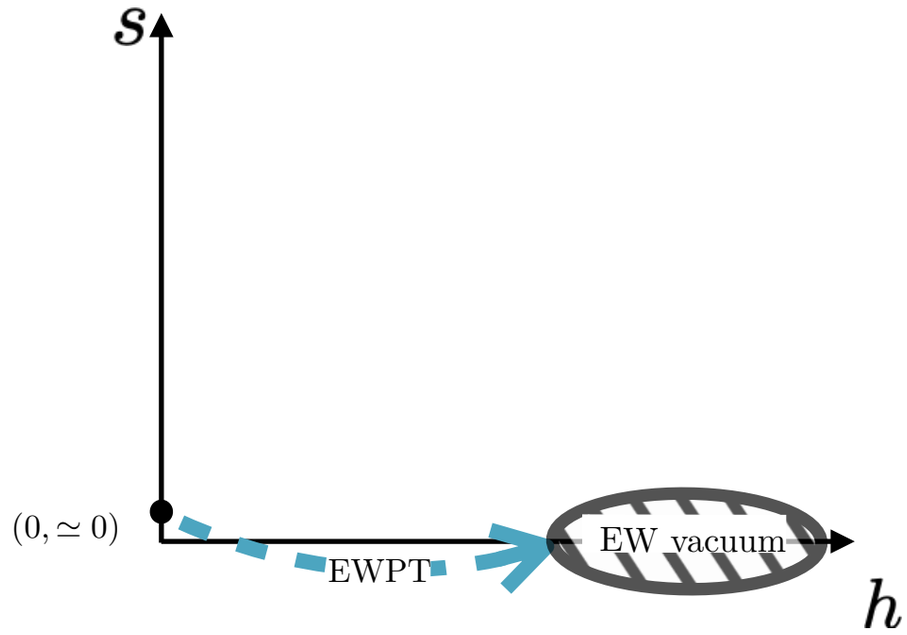
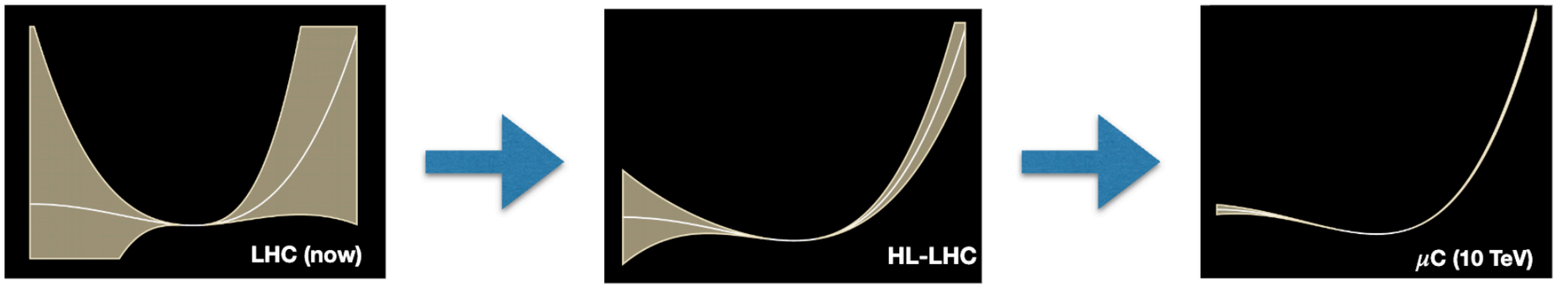


[Huang et al, 14']





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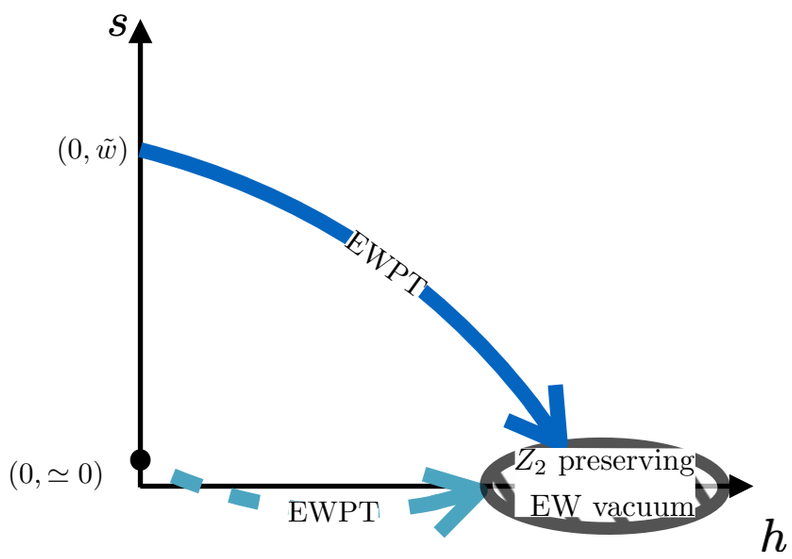
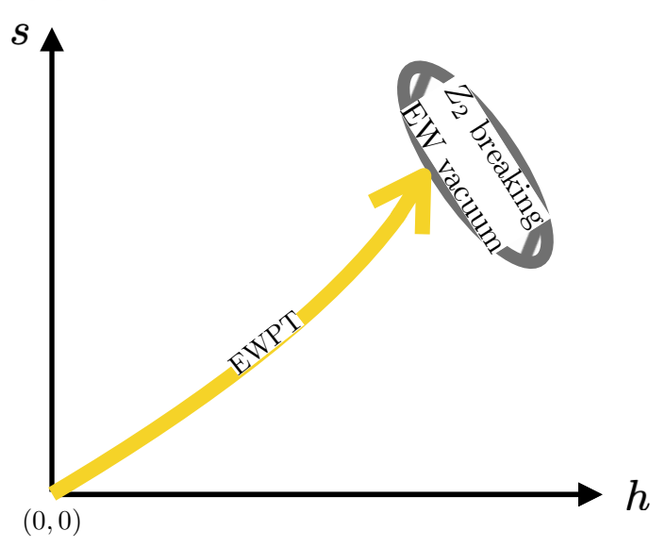
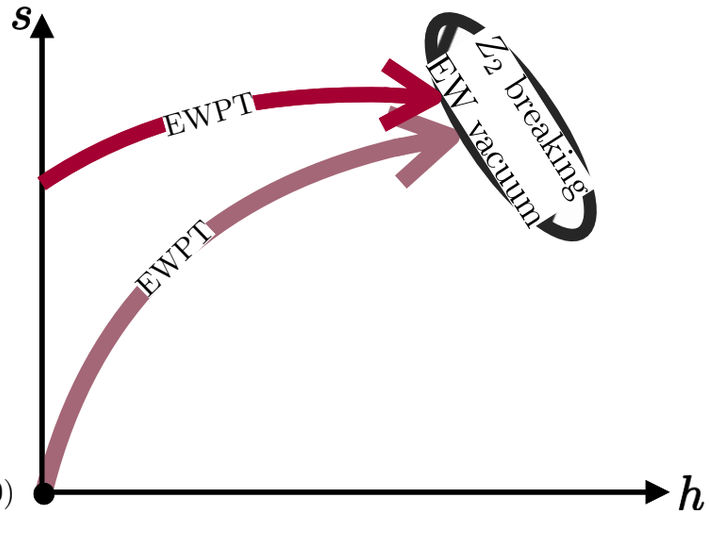


Z_2 preserving



Z_2 breaking (explicit)



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Electroweak phase transition and Higgs properties (at zero T)

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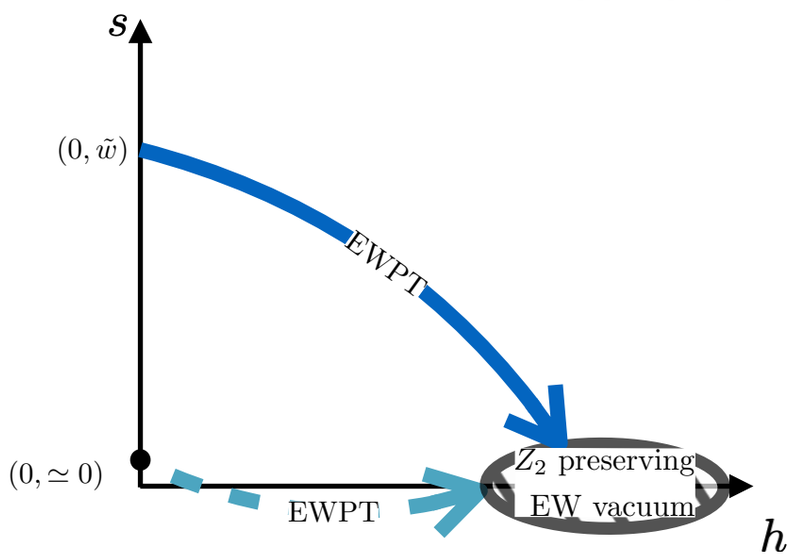

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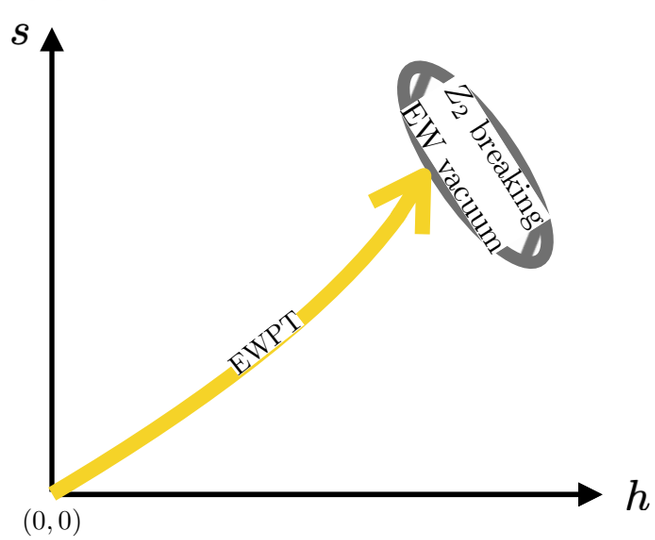

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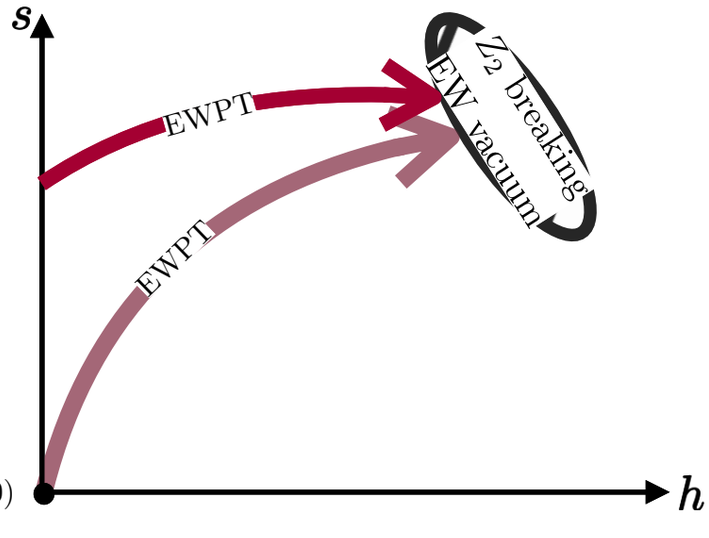

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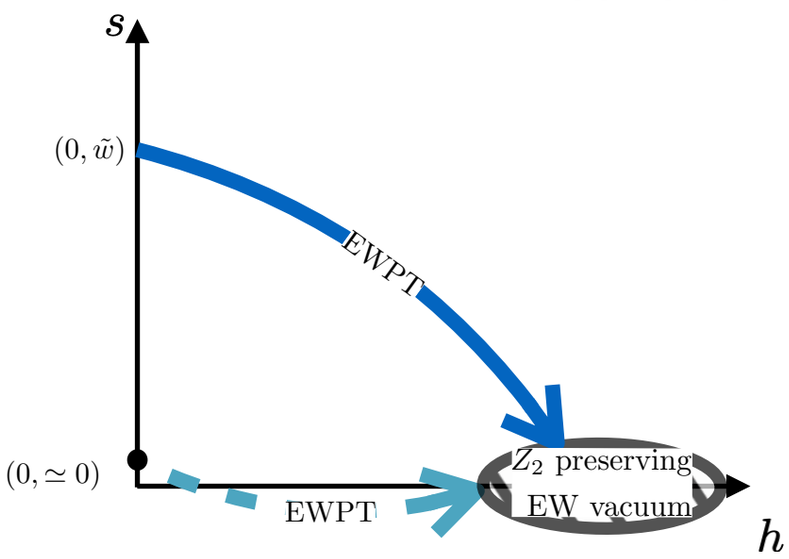

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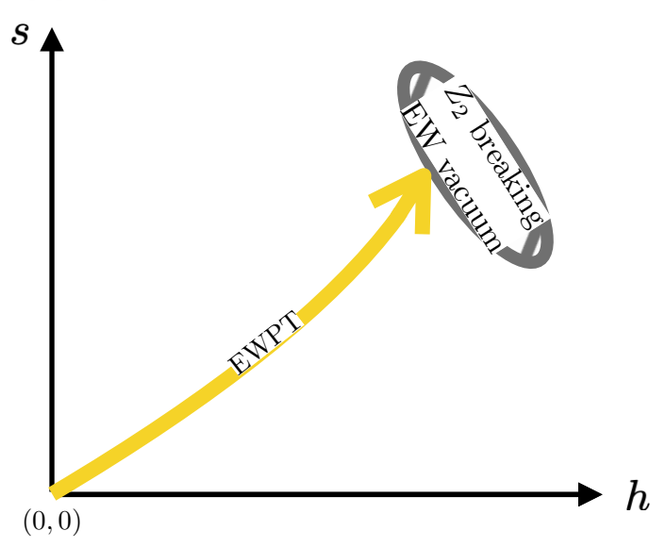

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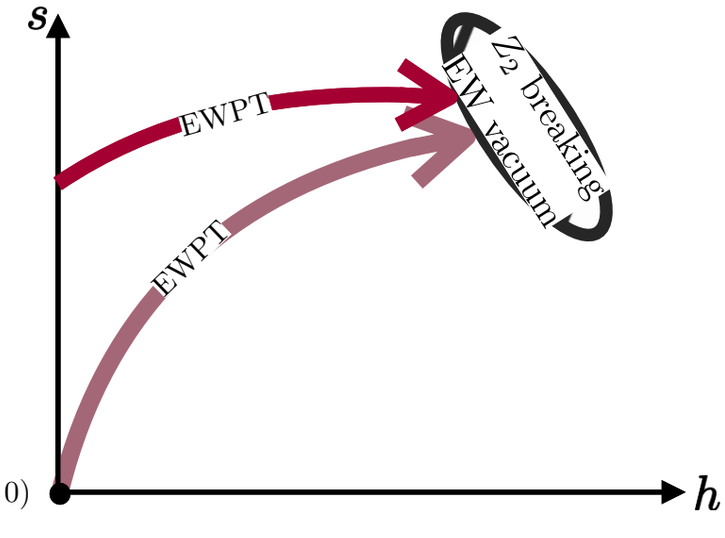

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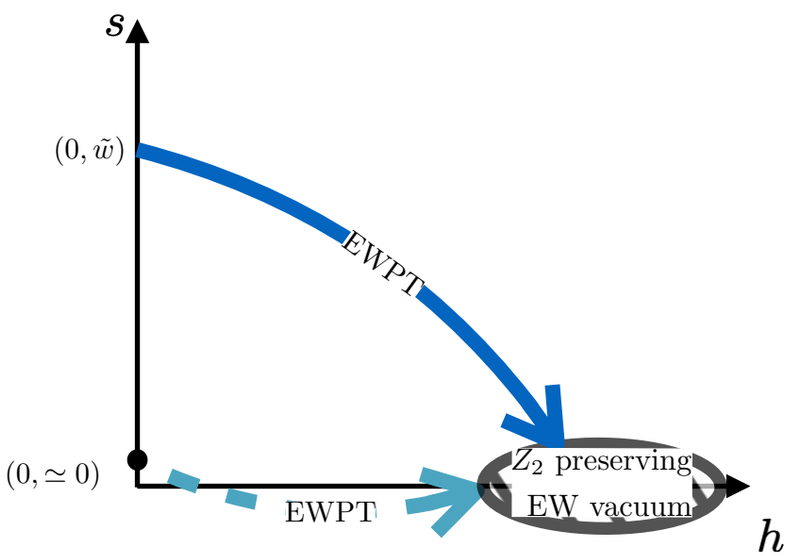

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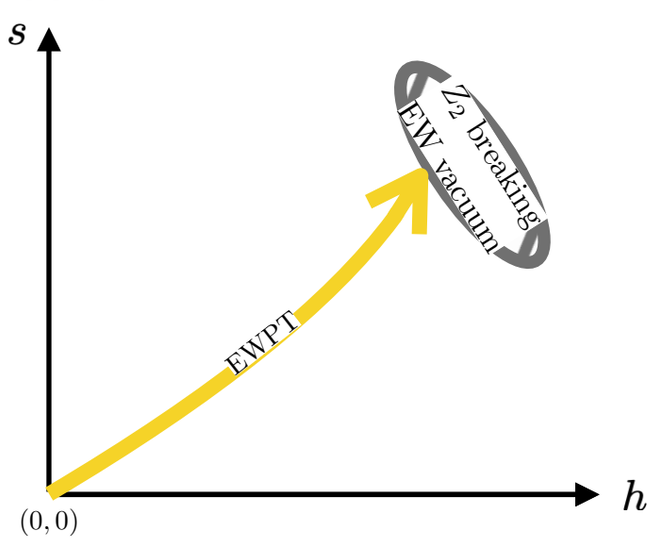

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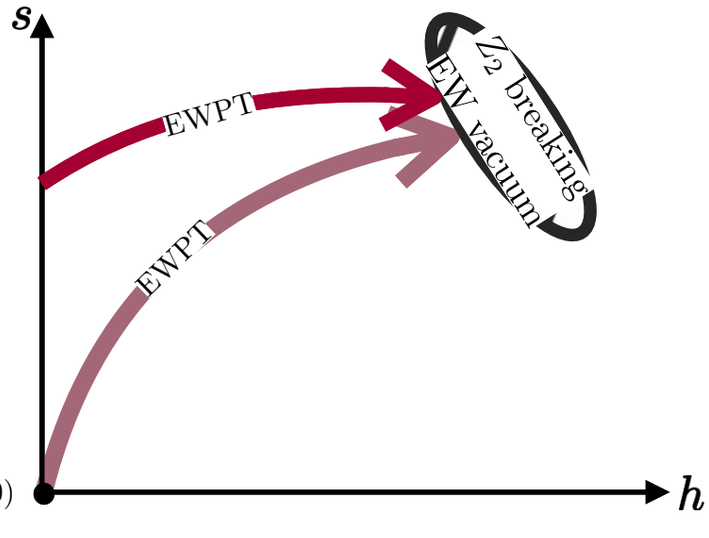

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[Carena, et al, 22']

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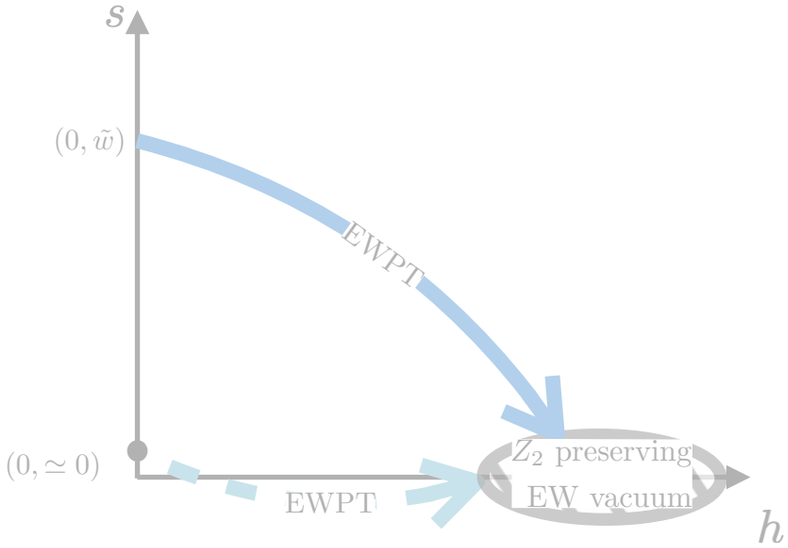

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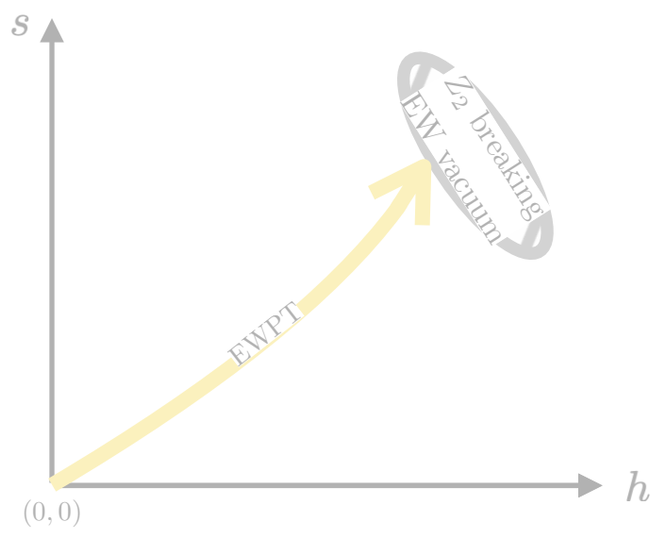

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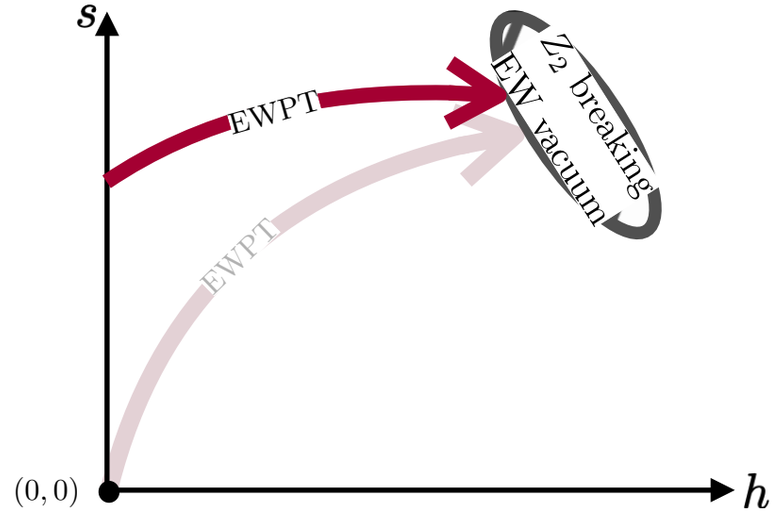

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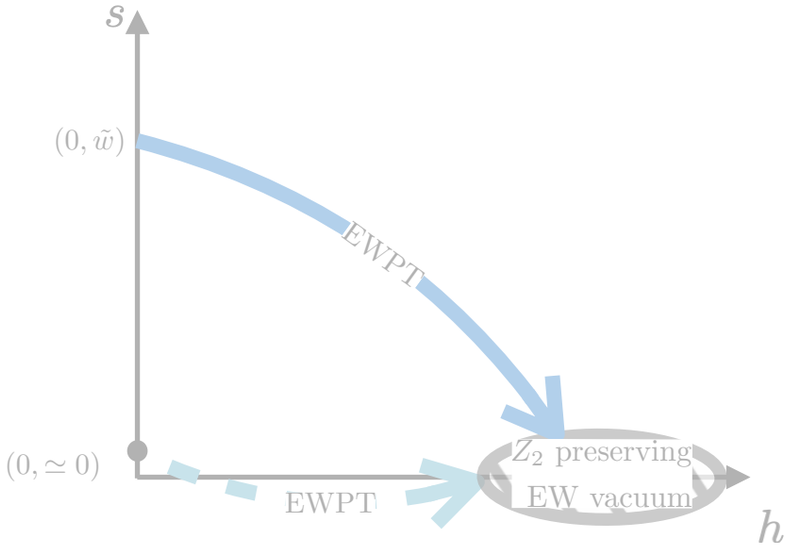

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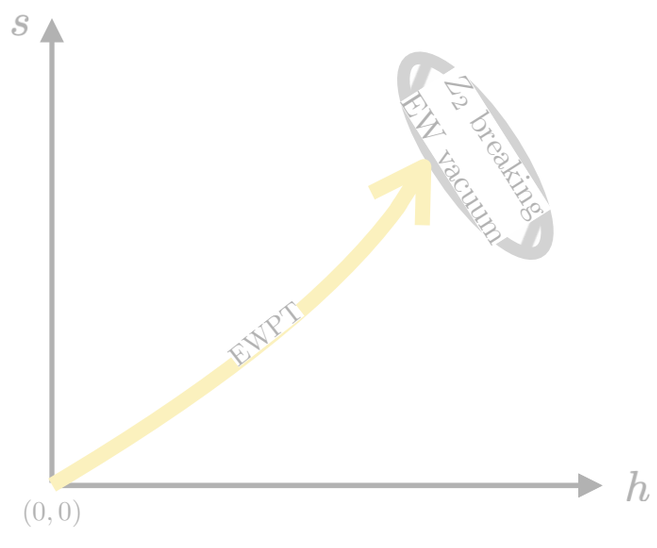

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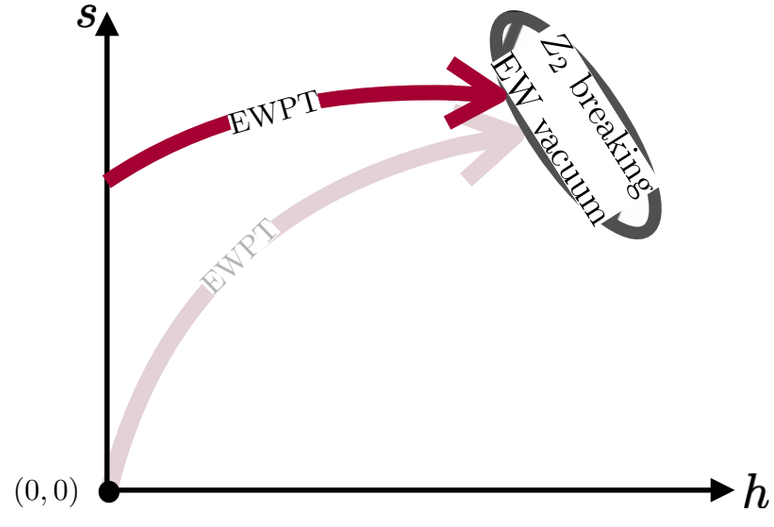

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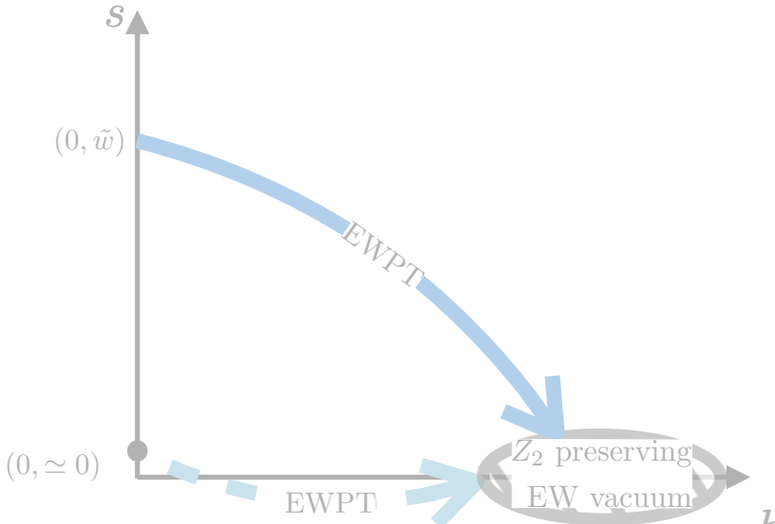

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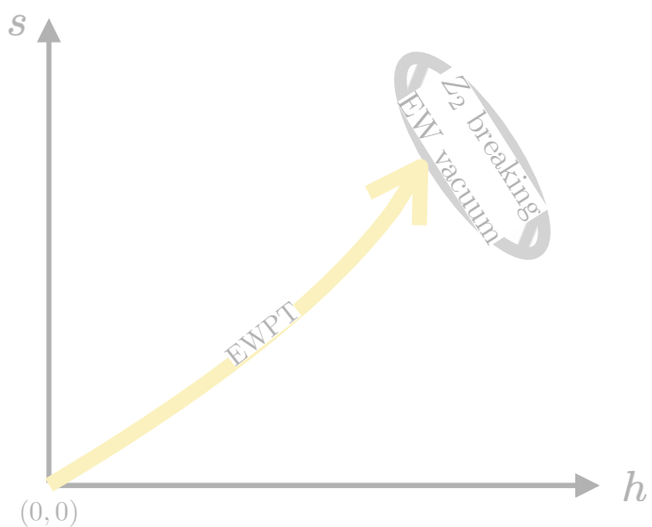

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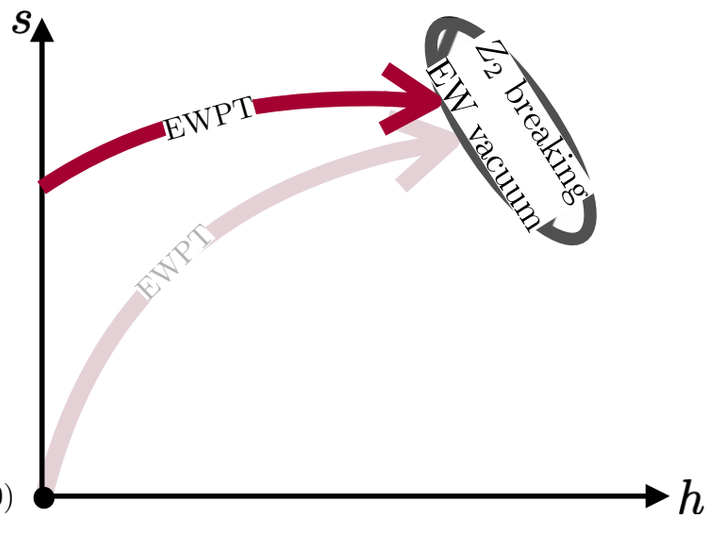

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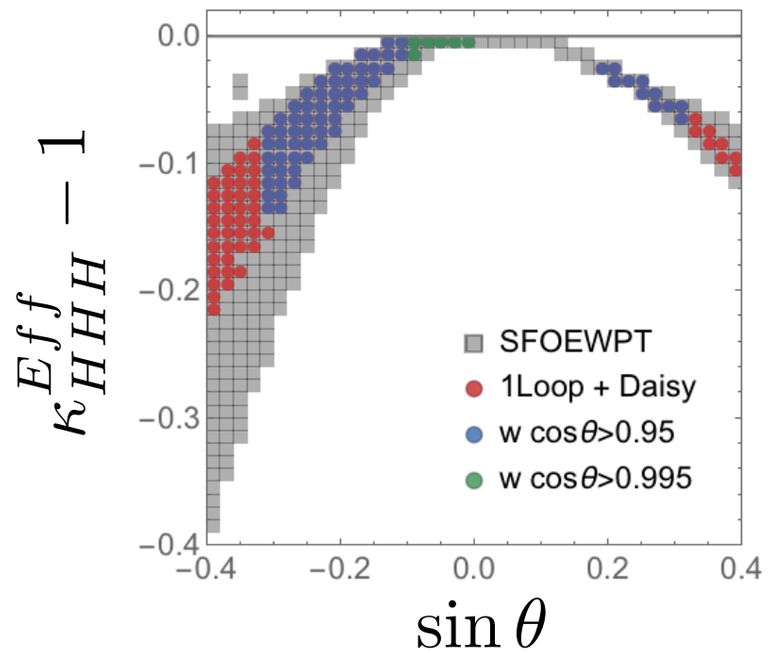
$$\Lambda_{HHH} = \frac{m_H^2\left(-\sin^3\theta + \tan\beta\cos^3\theta\right)}{2\tan\beta\ v}$$

$$\Lambda_{SHH} = \frac{(2m_H^2 + m_S^2)(\sin\theta + \tan\beta\cos\theta)\sin 2\theta}{4\tan\beta\ v}$$

$$\kappa_{HHH}^{Eff} \equiv \frac{\Lambda_{HHH}^{Eff}}{\Lambda_{HHH}^{SM}}$$



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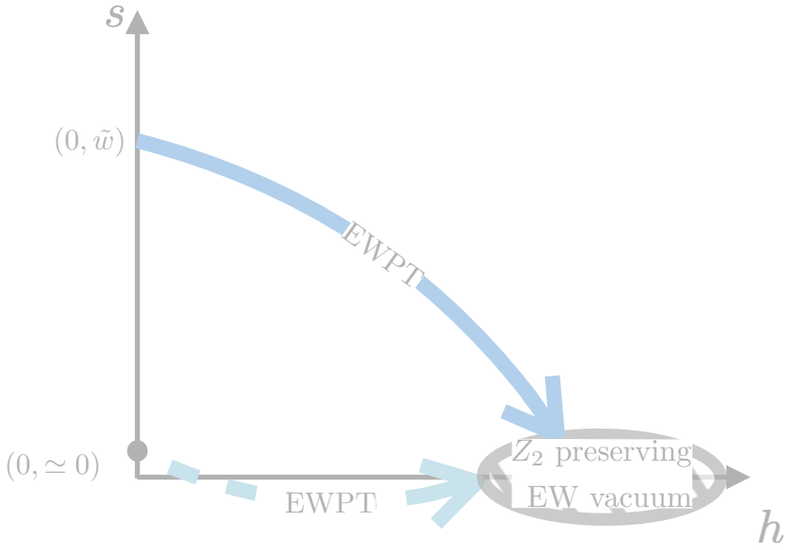

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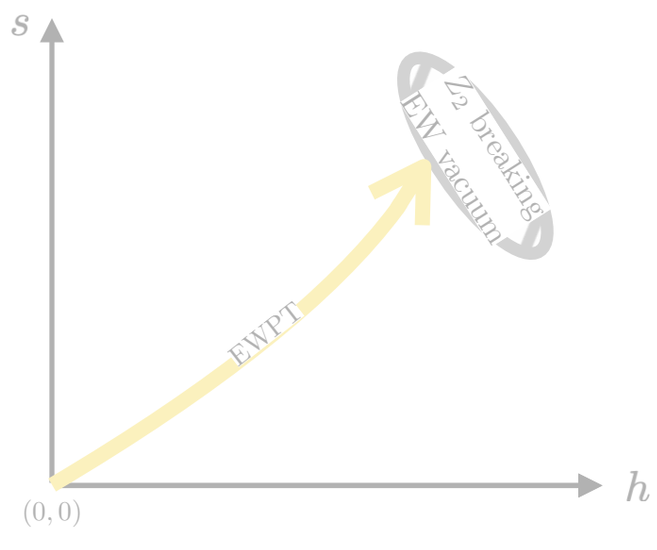

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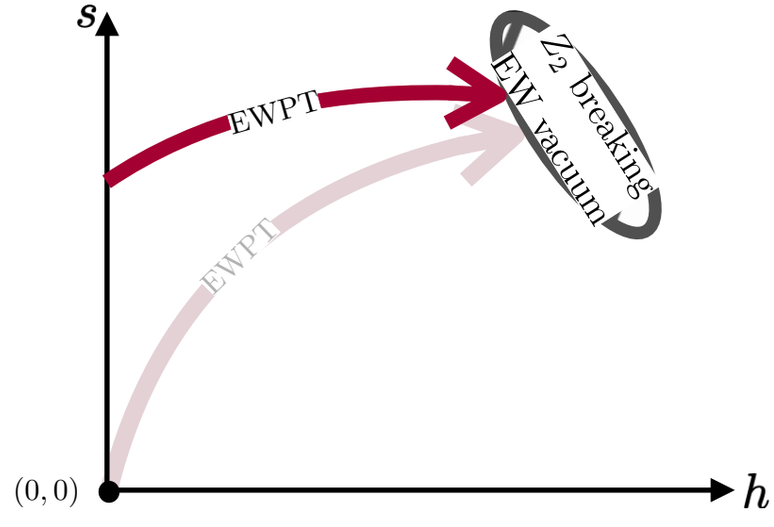

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- $\sin\theta \lesssim 0.4$ bounded by **Higgs precision measurements**
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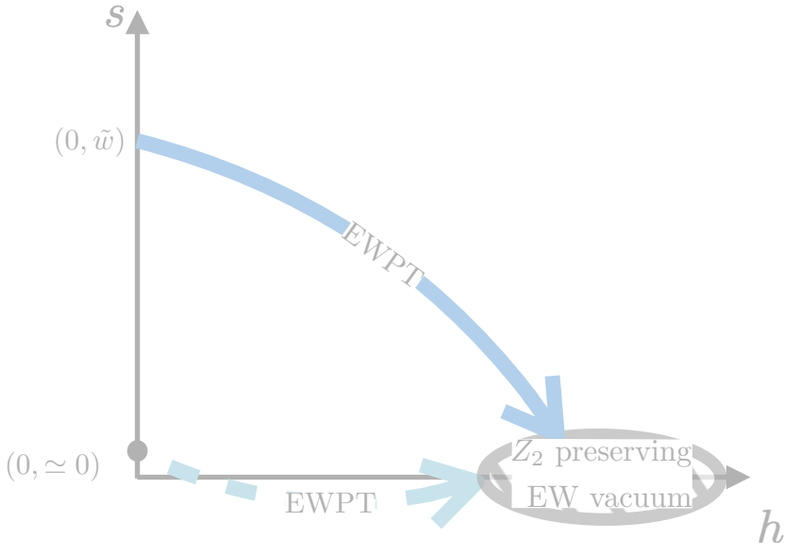

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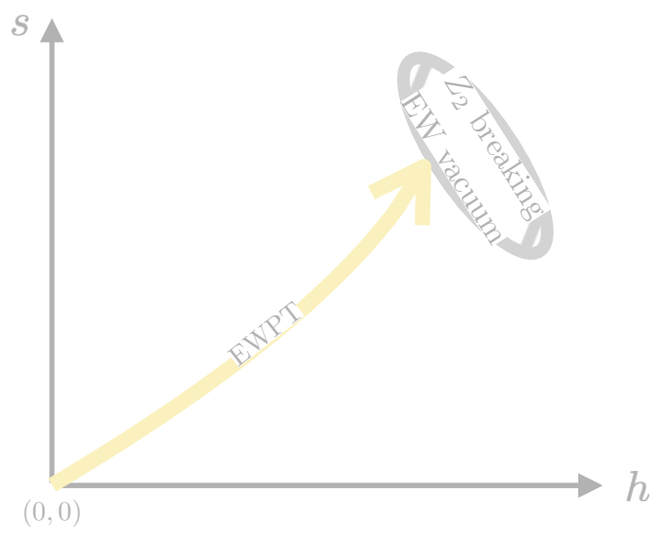

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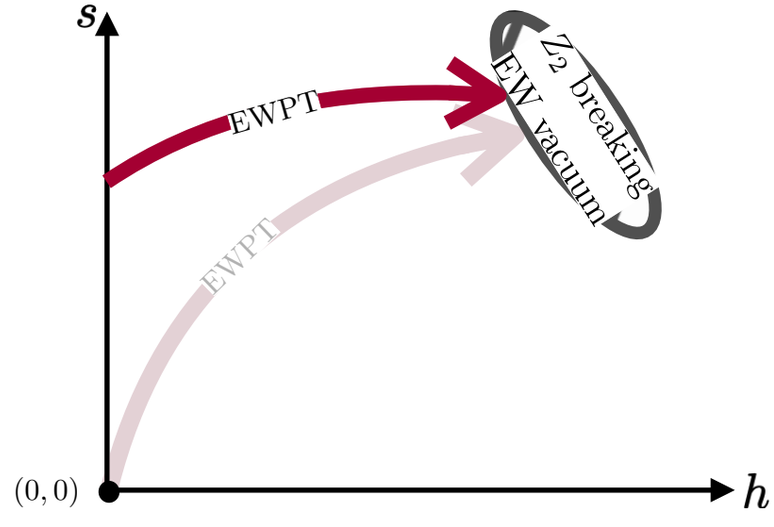

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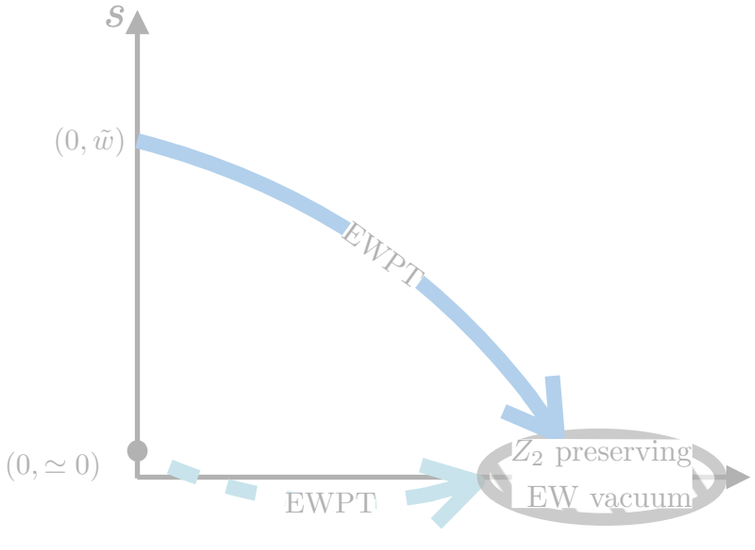

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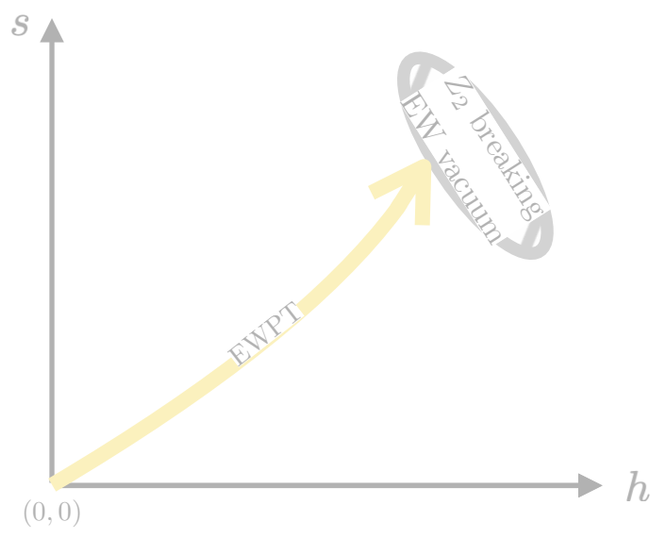

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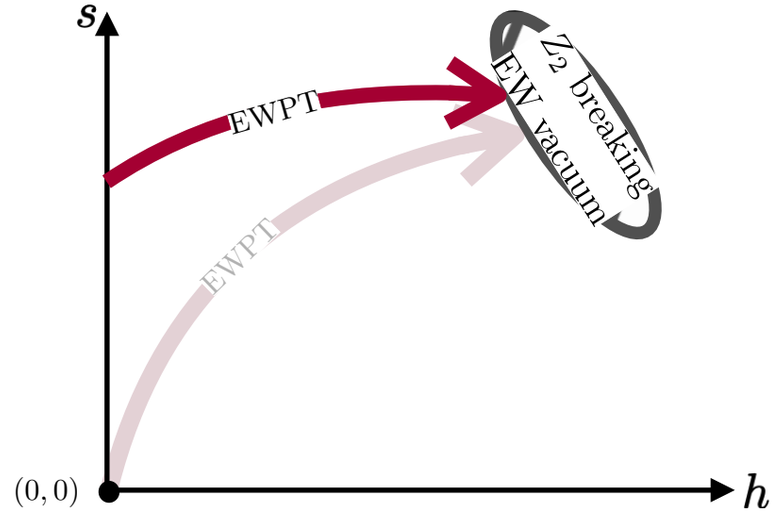

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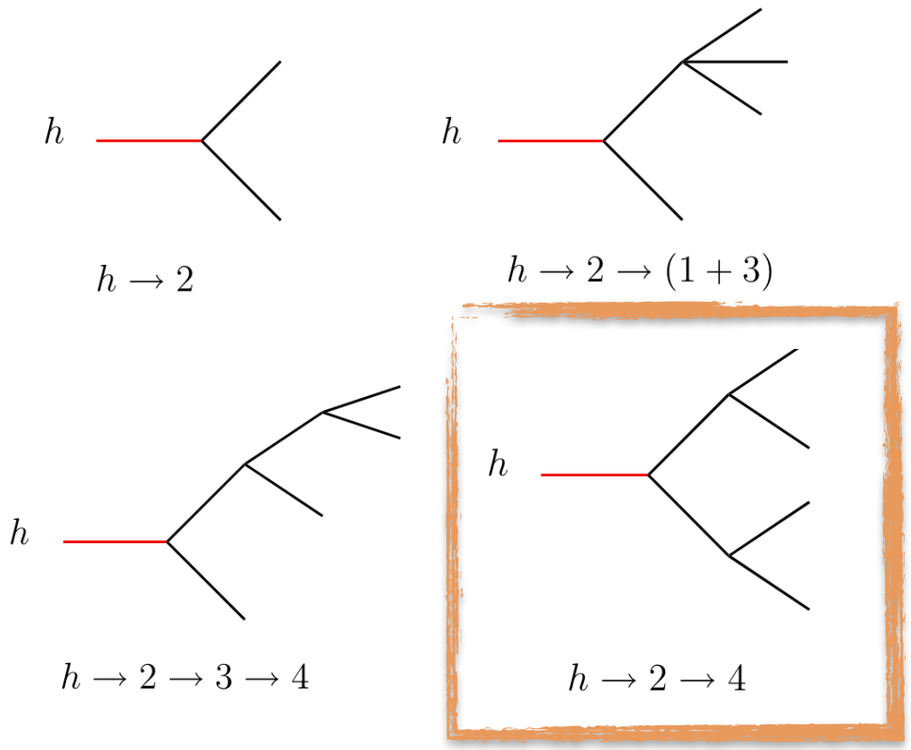
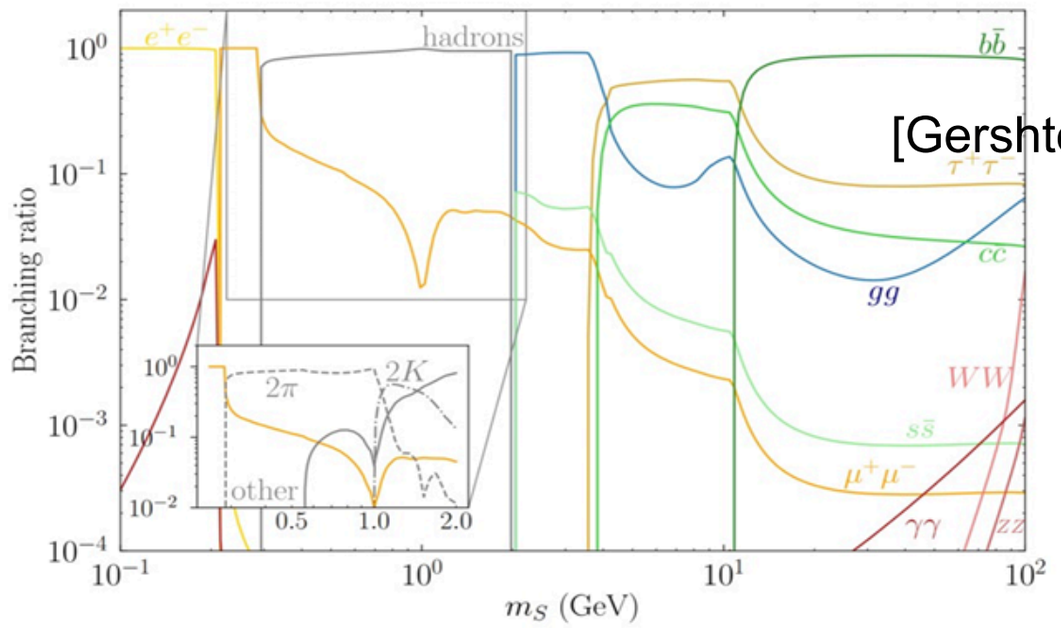
Example: Order of the Phase Transition $\propto \left(\lambda_h - \frac{\lambda_m^2}{4\lambda_s}\right)^{-1} \propto 1 + \sin^2\theta \left(\frac{(125\text{GeV})^2}{m_S^2} - 1\right)$

- $\sin\theta \lesssim 0.4$ bounded by **Higgs precision measurements**
- A firm prediction of a **light scalar**
- $\text{BR}(H \rightarrow SS)$ **bounded from below**

Observation window: Higgs exotic decay

Electroweak phase transition and Higgs Exotic Decays

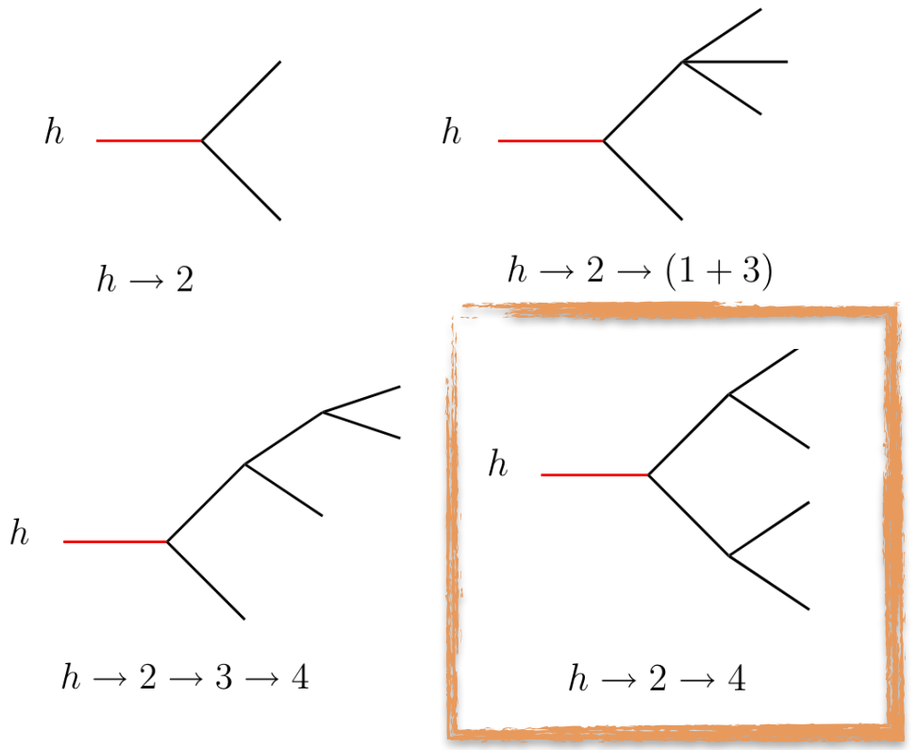


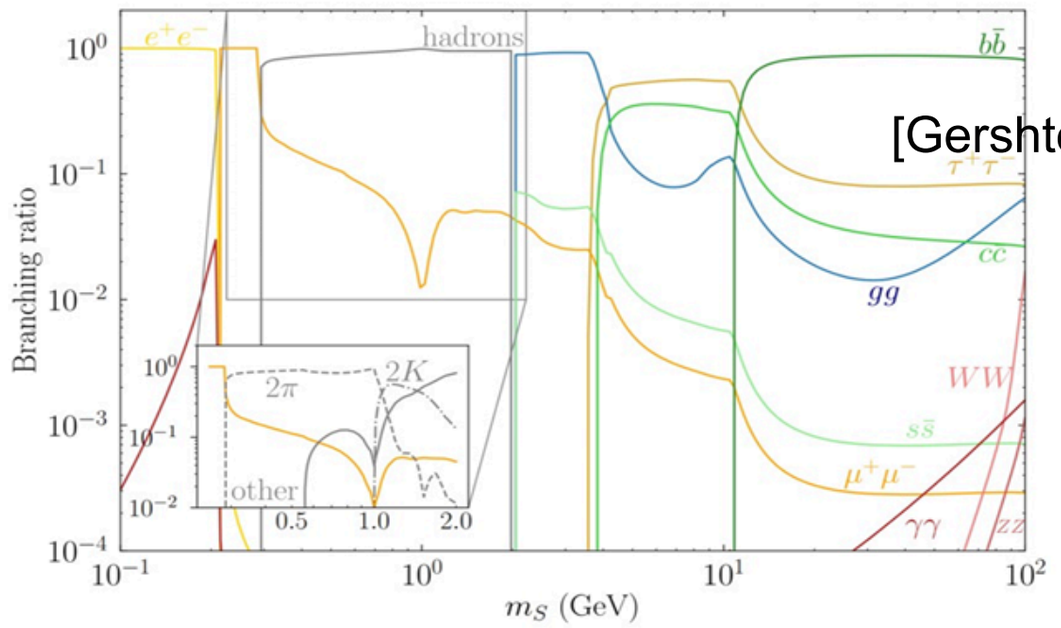


[Gershtein, et al, 21']

Higgs exotic decay $H \to SS$ and S branching fraction into $XXYY$ final states mediated through mixing.

Electroweak phase transition and Higgs Exotic Decays





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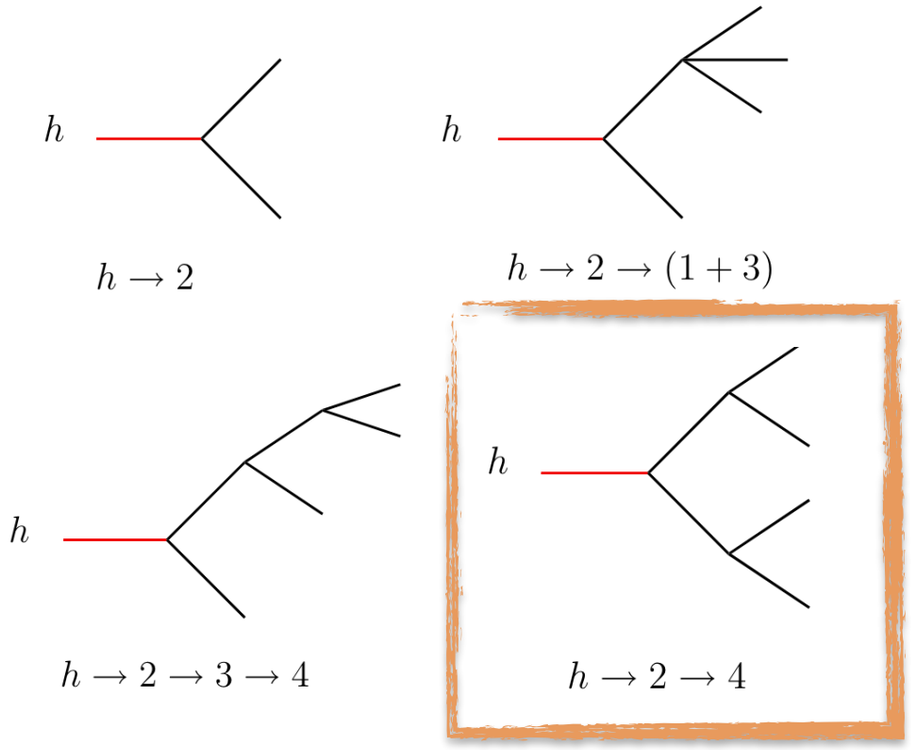

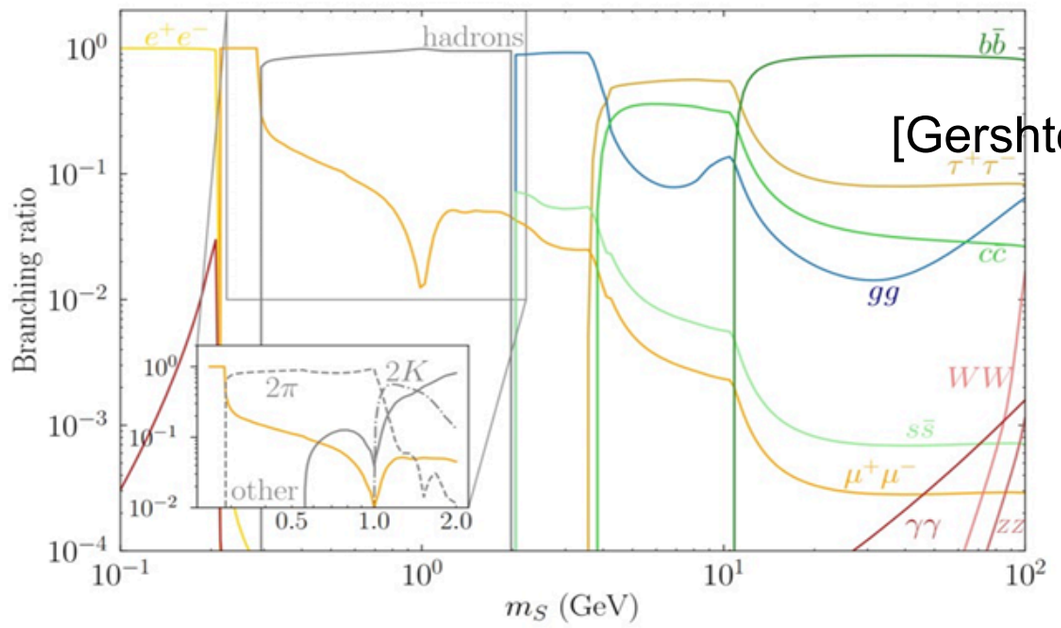

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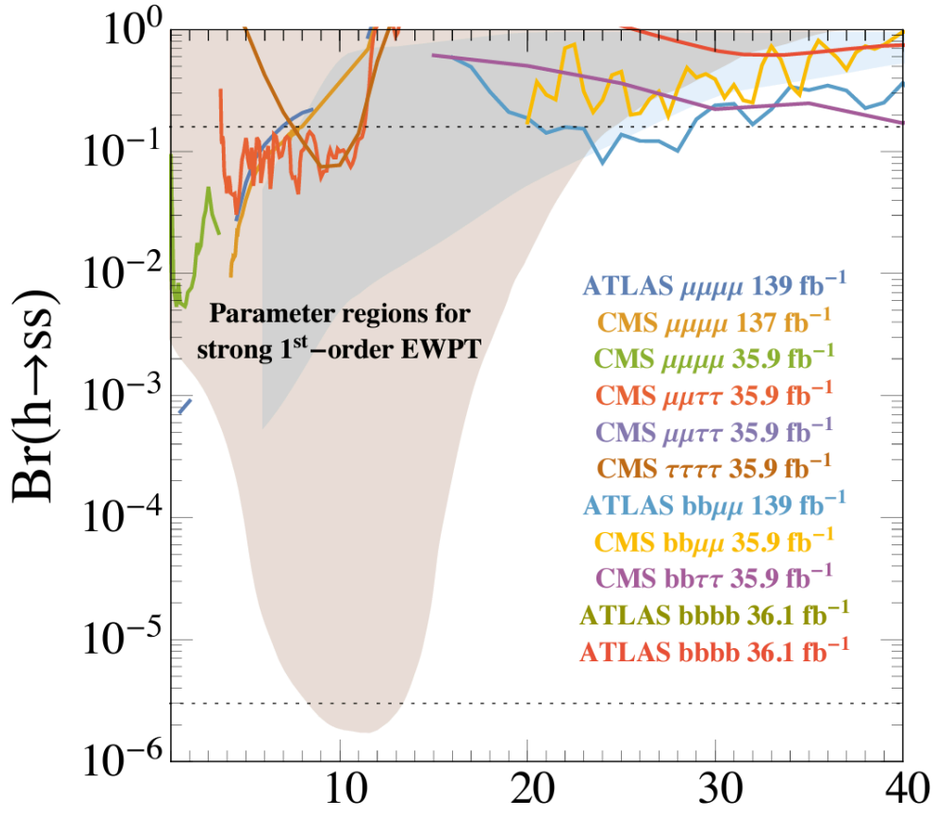
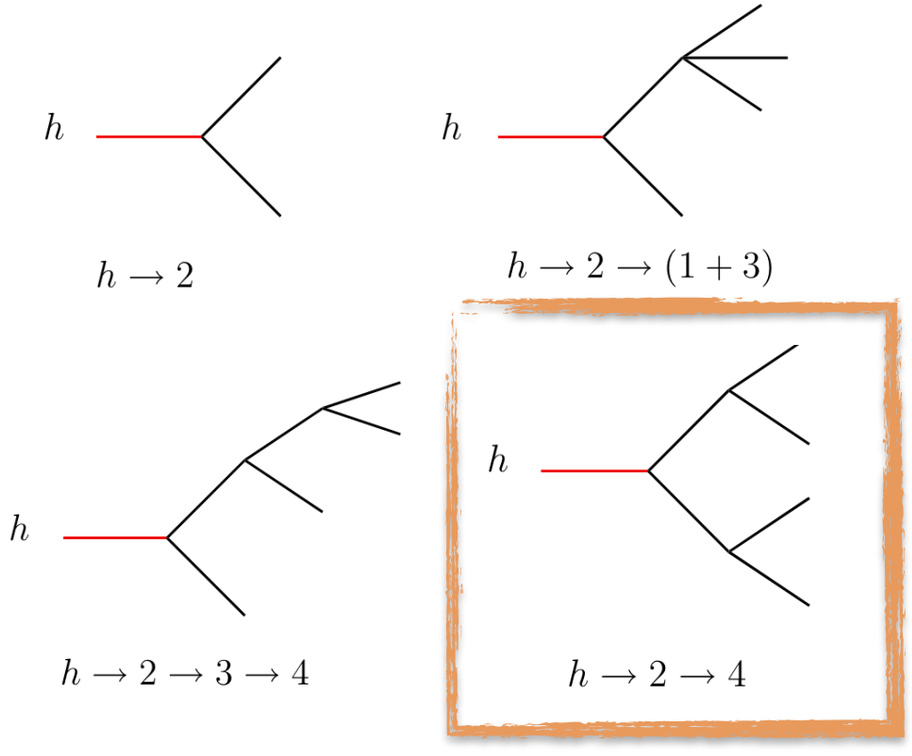
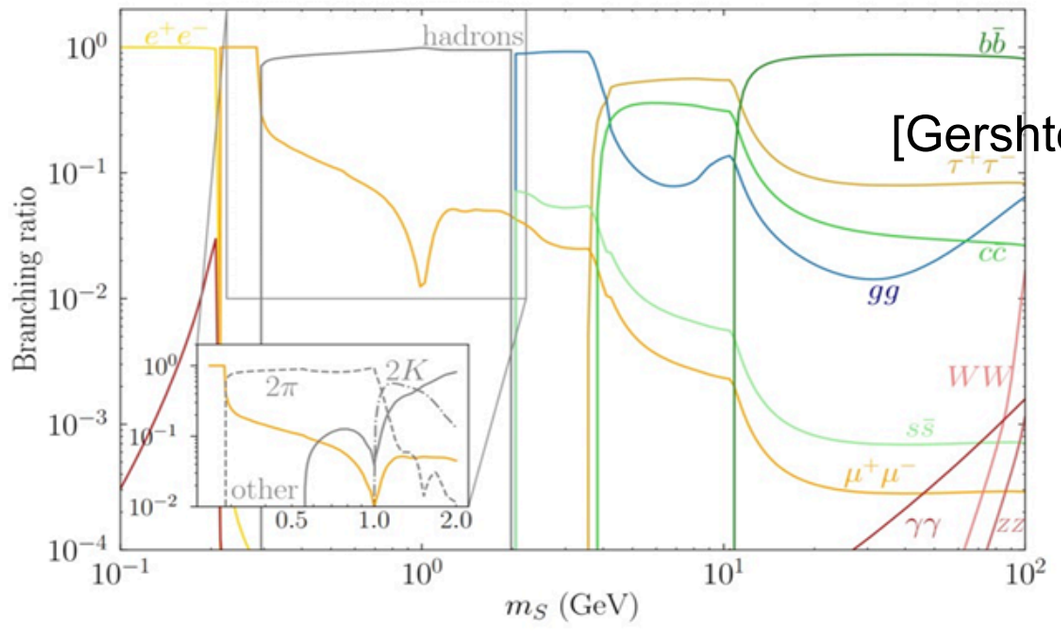


[Kozaczuk, et al, 19']

Current bounds on Higgs exotic decay $H \to SS$

Electroweak phase transition and Higgs Exotic Decays





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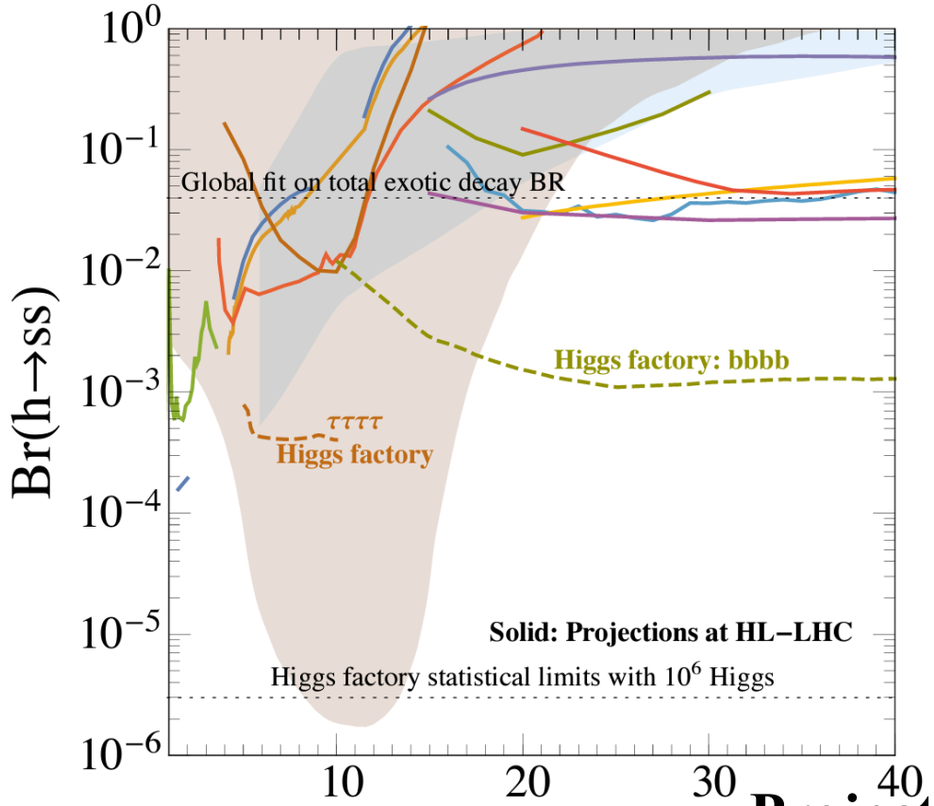
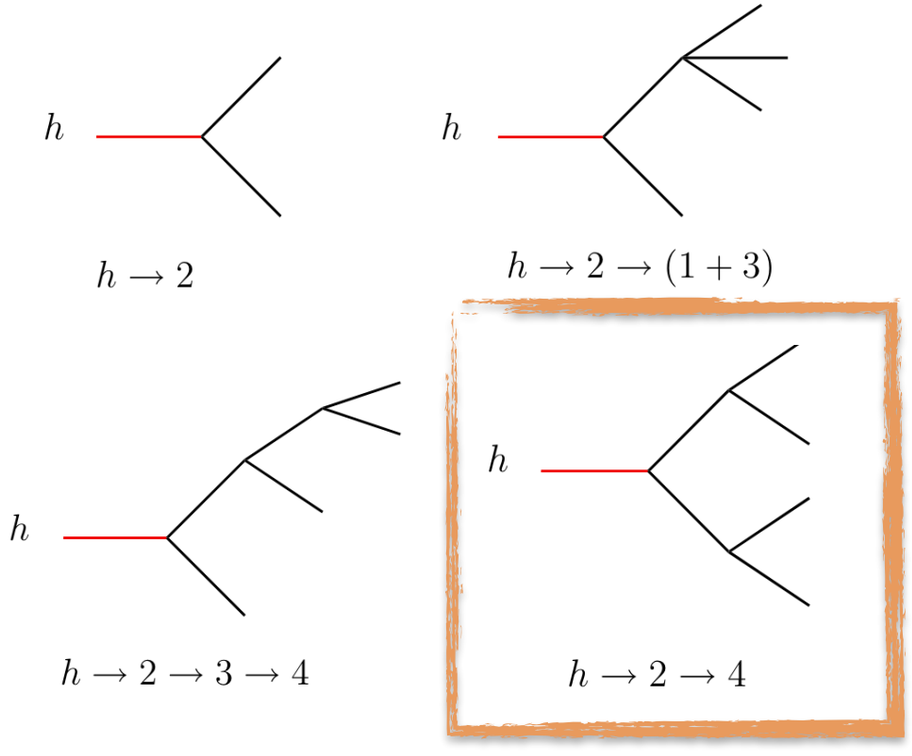
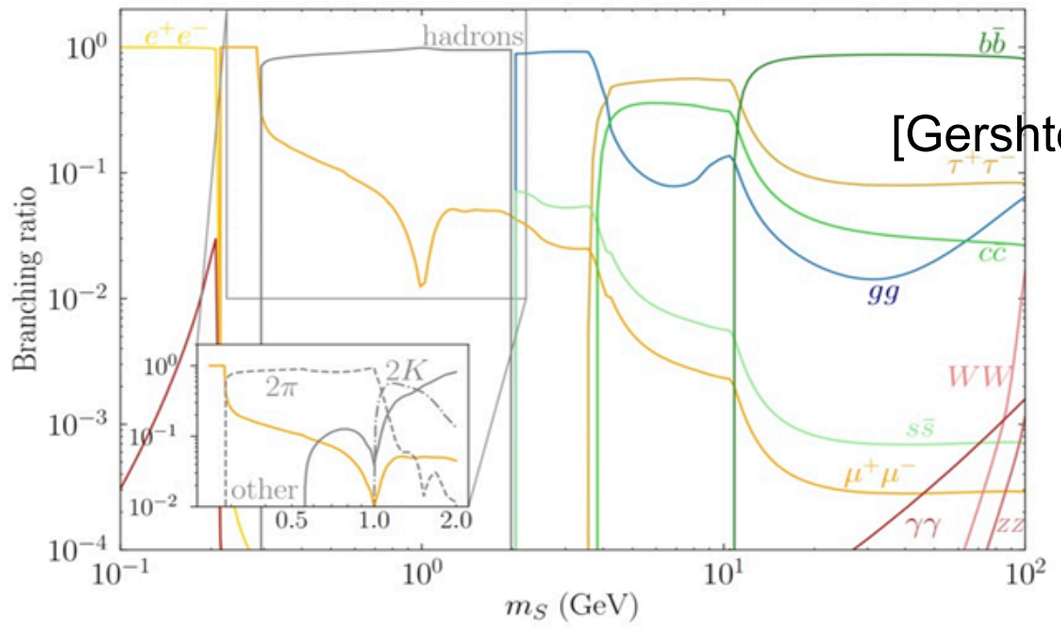


[Kozaczuk, et al, 19']

Projections at HL-LHC and Higgs factories on Higgs exotic decay $H \to SS$

Electroweak phase transition and Higgs Exotic Decays





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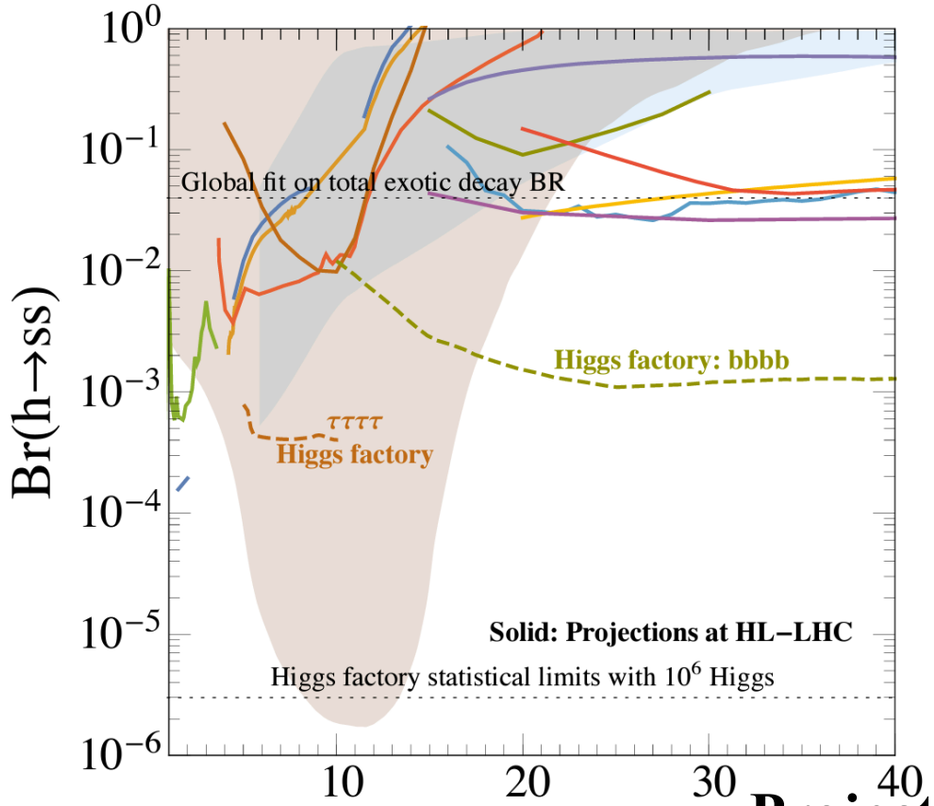

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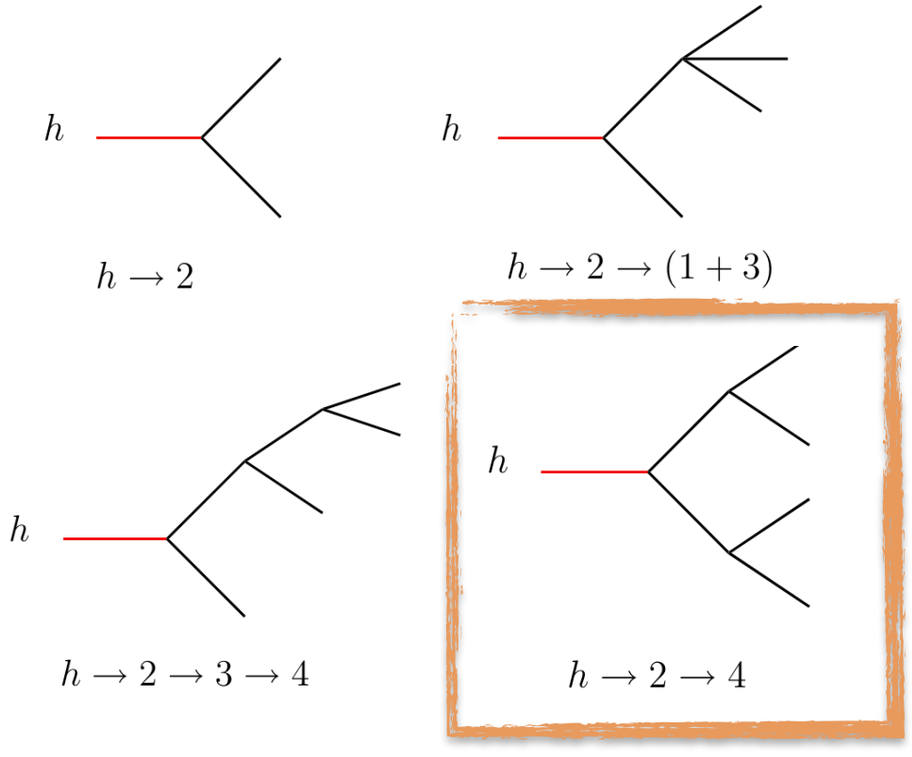

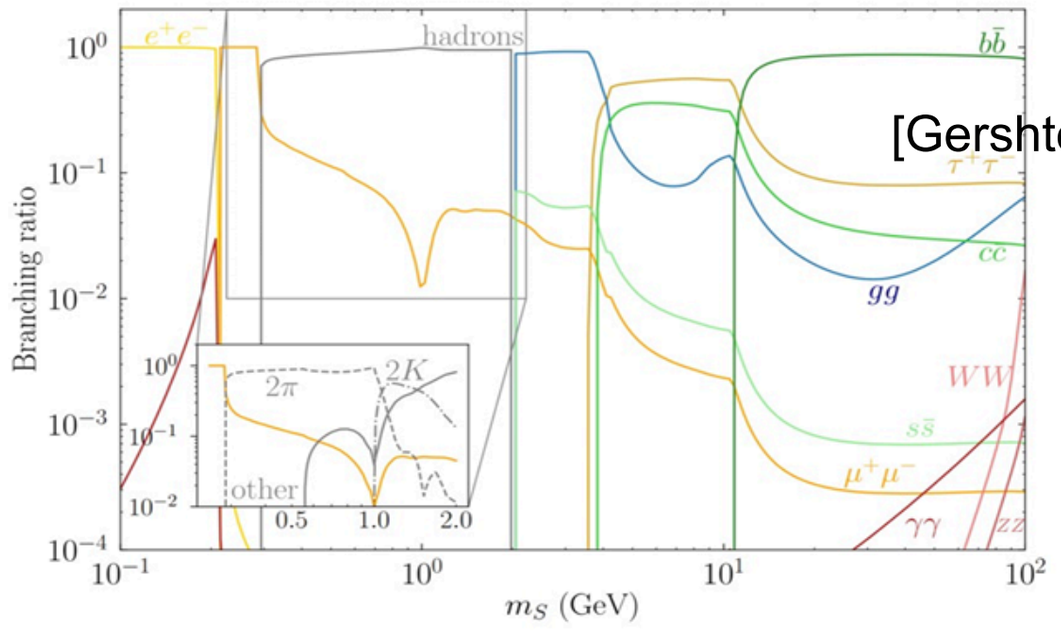

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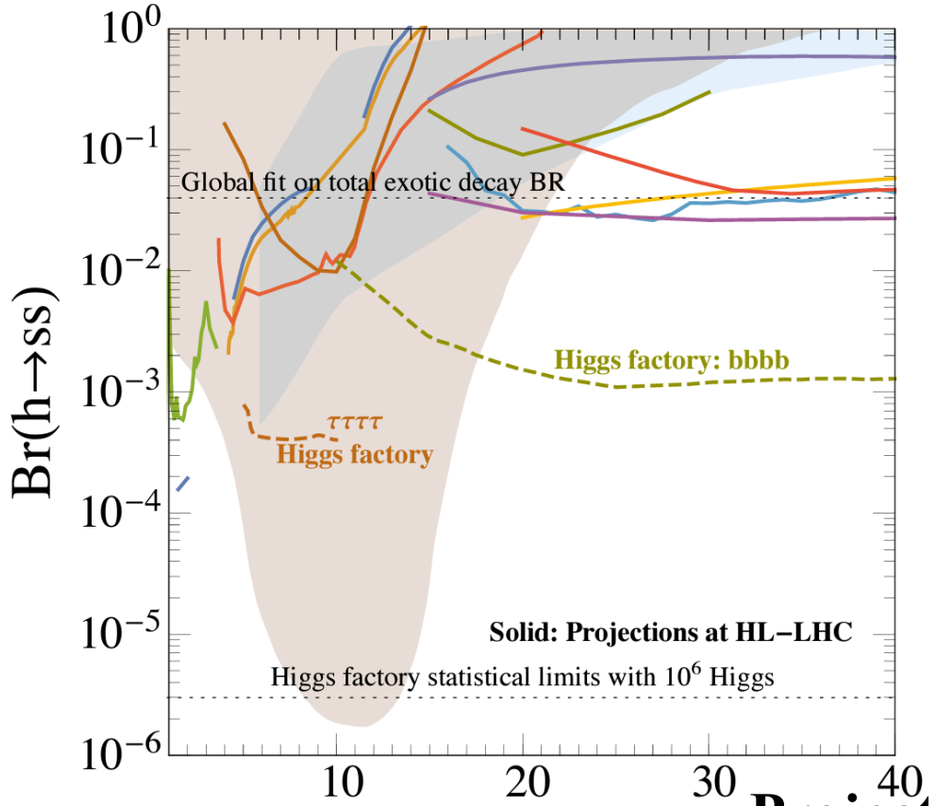
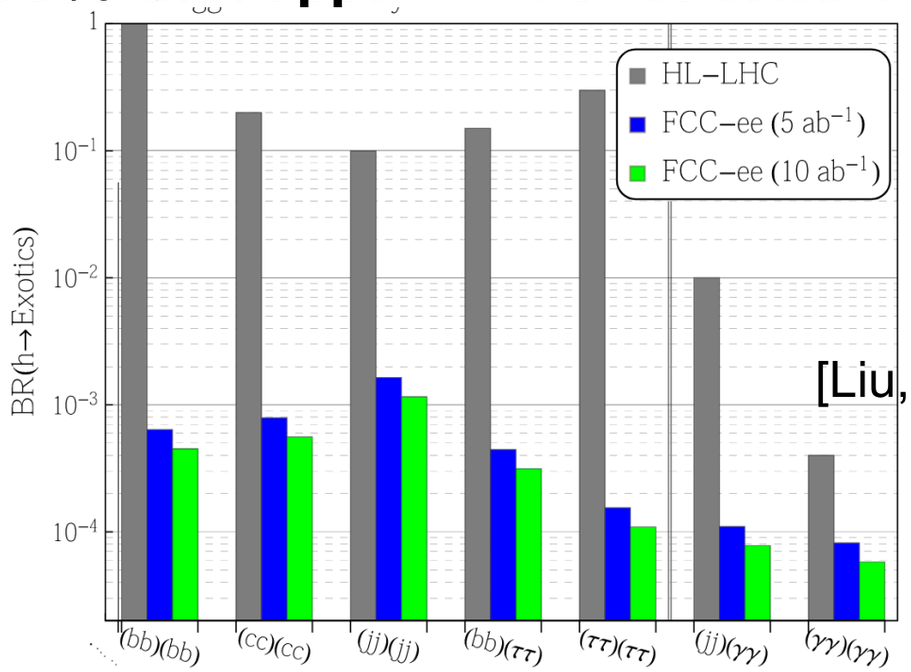


[Kozaczuk, et al, 19']

95% C.L. upper limit on selected BRs



[Liu, et al, 16']

Projections at HL-LHC and Higgs factories on Higgs exotic decay $H \to SS$

Summary and Outlook

- An important goal of the Higgs physics is to explore the nature of the Electroweak Phase Transition, and its potential role in BAU generation;
- Higgs exotic decay is a powerful channel to probe scenarios involving rendering strongly first order Electroweak Phase Transition otherwise inaccessible by other channels;
- FCC-ee and other Higgs factors can improve the bounds on Higgs exotic decay branching ratios by many orders of magnitude and have the potential to make discovers in or excluding phenomenological interesting parameter space;
- Further theoretical and collider studies are needed: extensions beyond real singlet (complex scalar, doublet, triplet, etc); perturbative convergence for very light scalars; room for improvement; more final states for lighter masses…