

The Condensing Universe

M.J. Ramsey-Musolf

- *T.D. Lee Institute/Shanghai Jiao Tong Univ.*
- *UMass Amherst (on leave)*
- *Caltech*

About MJRM:



Science



Family



Friends

My pronouns: he/him/his
MeToo

IHEP High Energy Theory Forum
Beijing March 25, 2026

Scientific Question

Was there cosmic condensation ?



Scientific Question

Was there cosmic condensation ?



Cosmic expansion $\overset{?}{\longleftrightarrow}$ *cosmic condensation*

Outline

I. Cosmic context

II. Cosmic condensation

III. Theoretical challenges & progress

IV. Electroweak condensation: results

V. Outlook

I. Cosmic Context

Einstein → Expansion & Condensation

Einstein

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Einstein → Expansion & Condensation

Einstein

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Einstein Tensor:
curvature of spacetime

Energy-Momentum Tensor:
energy density & pressure
→ *particle thermodynamics*

Einstein → Expansion & Condensation

Einstein

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Einstein Tensor:
curvature of spacetime

Energy-Momentum Tensor:
energy density & pressure
→ *particle thermodynamics*

Dependence on time

Dependence on temperature

Expanding, Isotropic, Flat Universe

Metric tensor: Friedmann-Robertson-Walker

$$g_{\mu\nu} = \text{diag} (1, -a^2, -a^2, -a^2)$$

- *Isotropic*
- *Expanding: $a = a(t)$*
- *Flat: $k = 0$*

Expanding, Isotropic, Flat Universe

Metric tensor: Friedmann-Robertson-Walker

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*Einstein tensor
ingredient*

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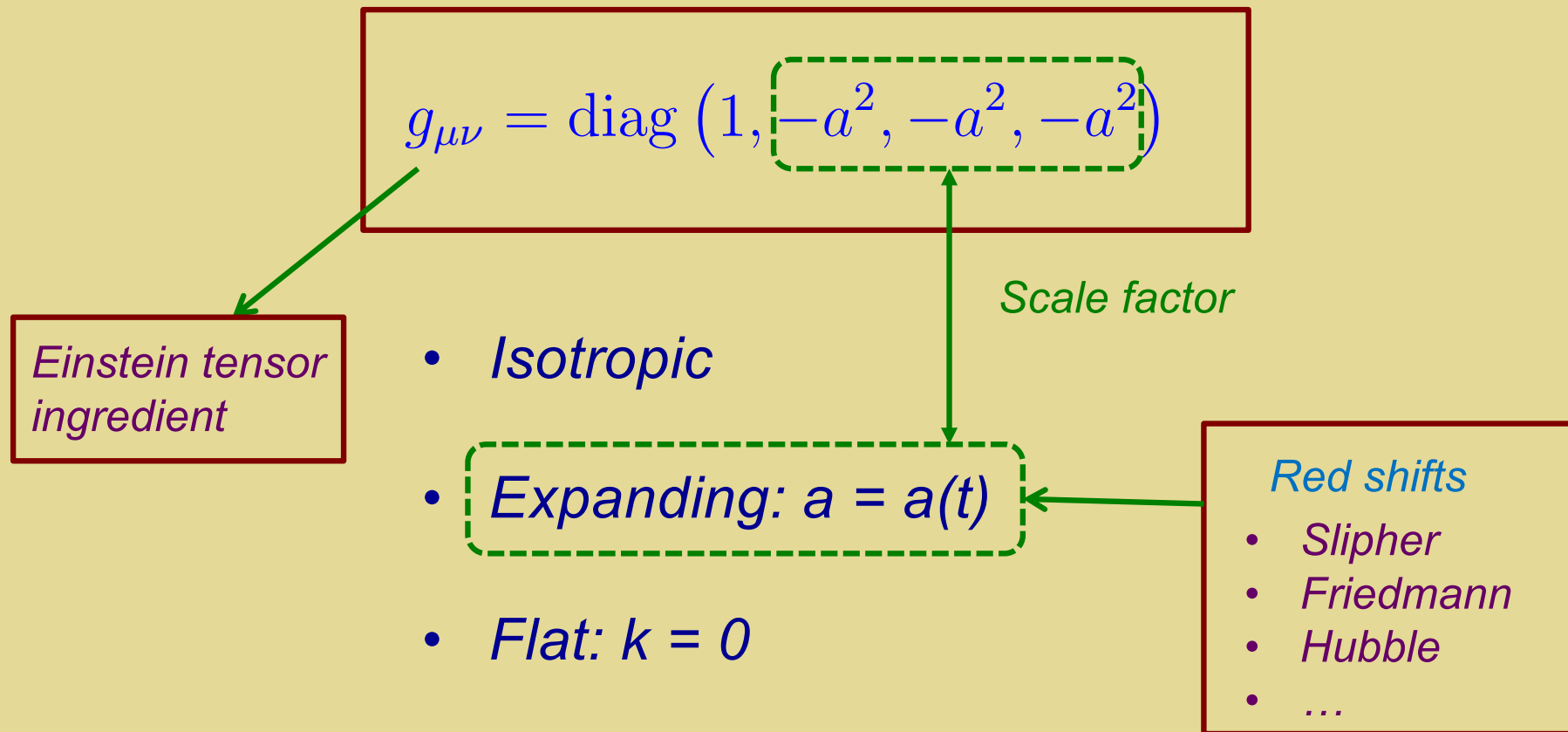
Einstein tensor
ingredient

Scale factor

- *Isotropic*
- *Expanding: $a = a(t)$*
- *Flat: $k = 0$*

Expanding, Isotropic, Flat Universe

Metric tensor: Friedmann-Robertson-Walker



Expanding, Isotropic, Flat Universe

“Friedmann Equation”

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G\rho$$

Hubble Rate

$$H(t) = \left(\frac{\dot{a}}{a}\right)$$

Expanding, Isotropic, Flat Universe

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$$H(t) = \left(\frac{\dot{a}}{a}\right)$$

$$H(t) = \left[\left(\frac{\pi^2}{90}\right) g_* \right]^{1/2} \frac{T^2}{M_P}$$

Expanding, Isotropic, Flat Universe

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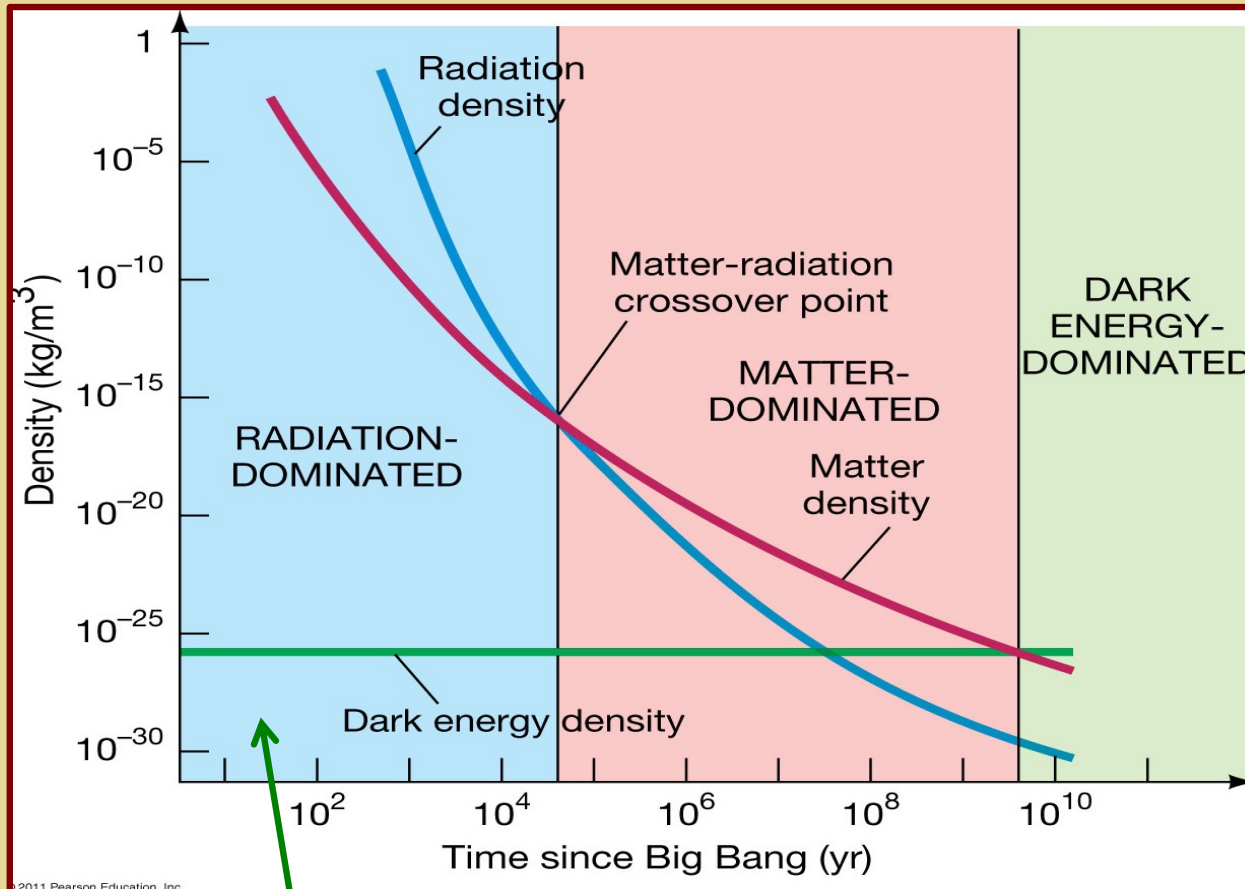
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Radiation, Matter, & Vacuum Epochs



Particle physics

J. Brau, U. Oregon

Expanding, Isotropic, Flat Universe

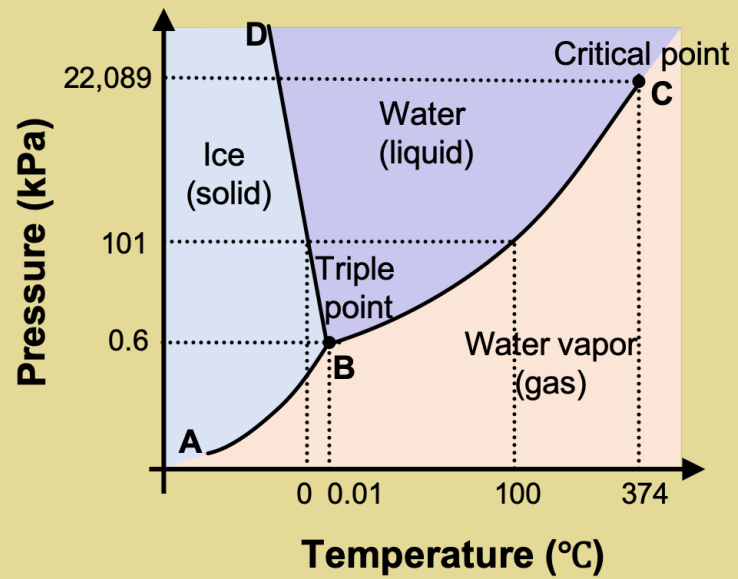
Radiation & matter eras

$$t = \frac{1}{2H}$$

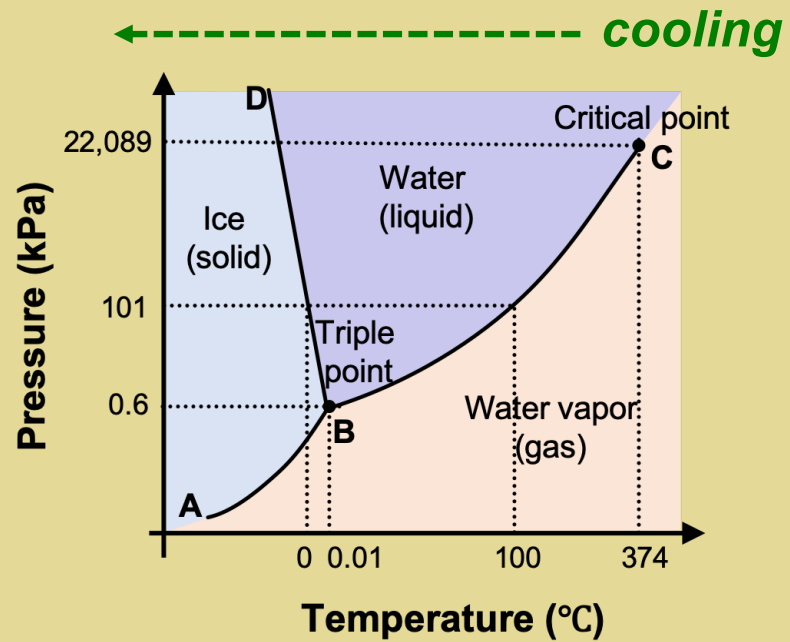
$$\frac{t_2}{t_1} = \left(\frac{T_1}{T_2} \right)^2$$

The Universe cools as it ages & expands

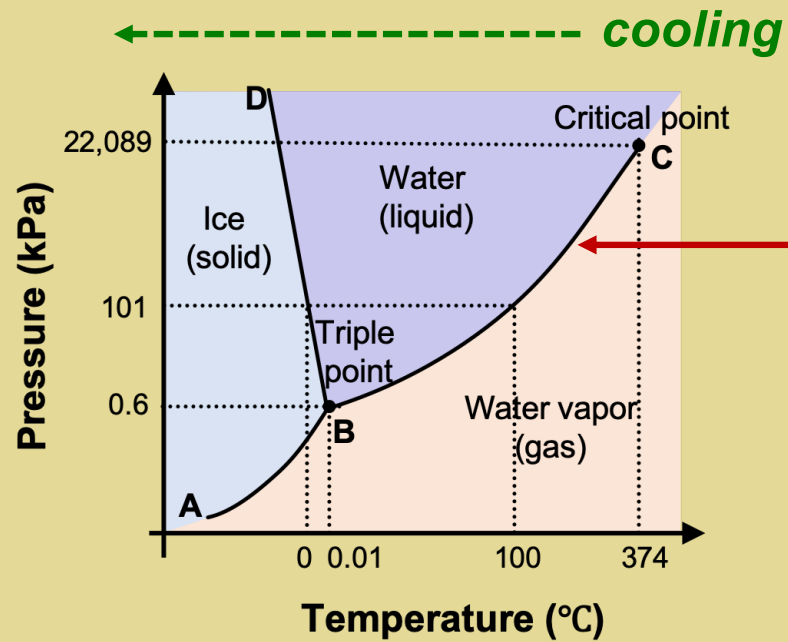
Ordinary Matter : Condensation ?



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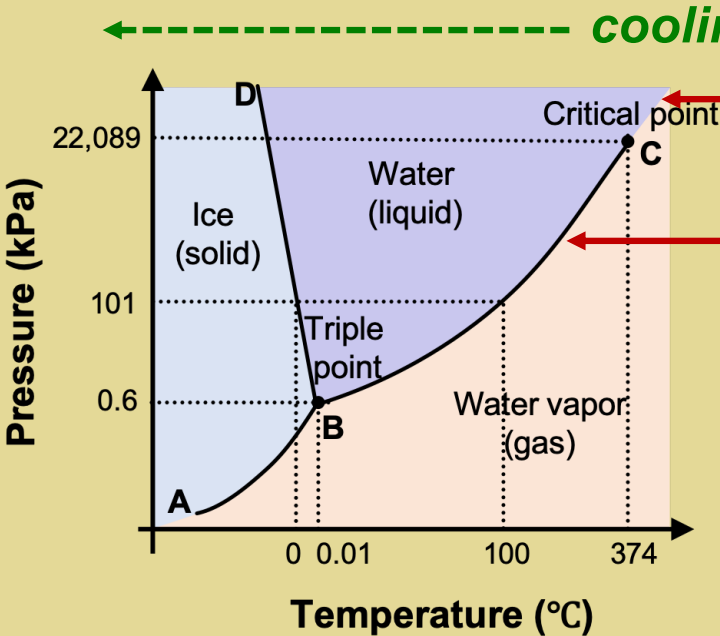
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**1st order phase transition
→ condensation**



Ordinary Matter : Condensation ?



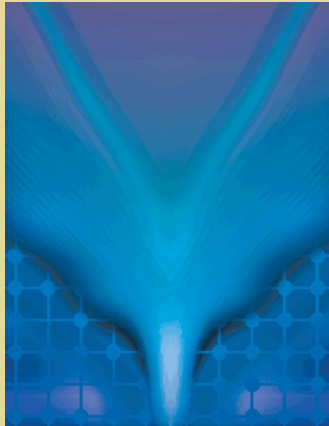
Crossover: no condensation

**1st order phase transition
→ condensation**



Particle Physics Condensation : Spontaneous Symmetry Breaking

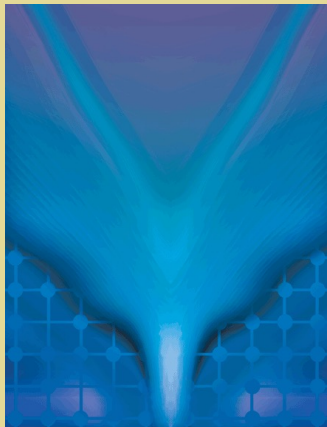
Spontaneous Symmetry Breaking



*Cooling
cosmos:
more order,
less symmetry*

Particle Physics Condensation : Spontaneous Symmetry Breaking

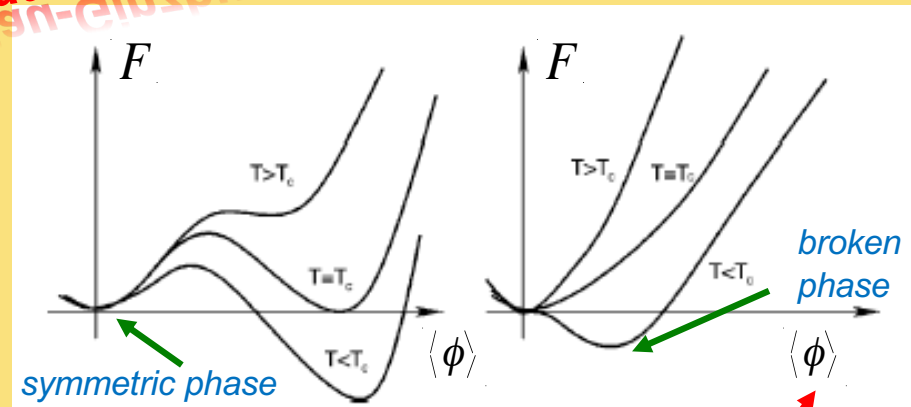
Spontaneous Symmetry Breaking



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Effective potential

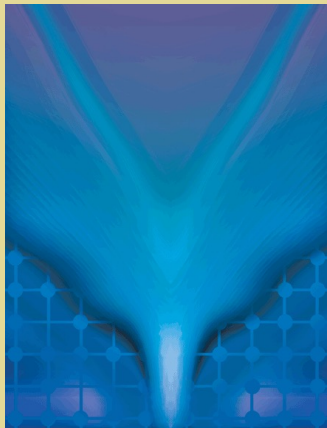
Landau-Ginzburg



“order parameter” : value of
classical field \rightarrow vacuum expect
value (VEV) of quantum field (v)

Particle Physics Condensation : Spontaneous Symmetry Breaking

Spontaneous Symmetry Breaking



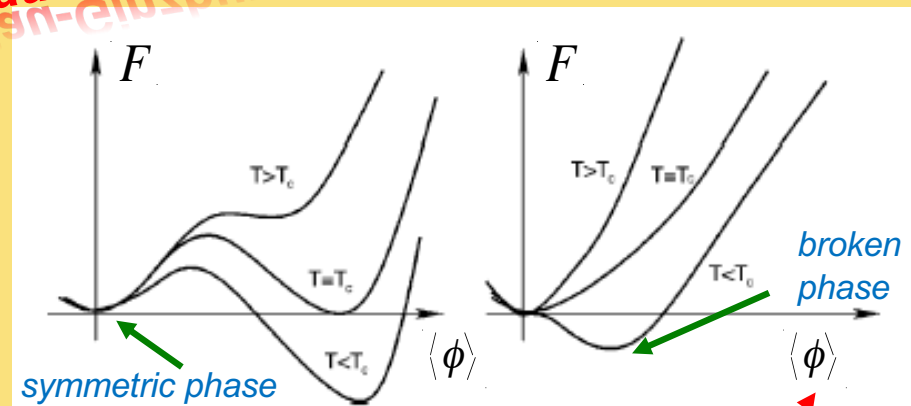
Cooling
cosmos:
more order,
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Symmetry encoded in group
theoretic structure of
underlying particle physics
model

Standard Model:
 $SU(3)_C \times SU(2)_L \times U(1)_Y$

Effective potential

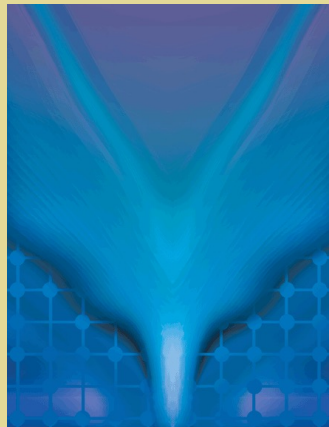
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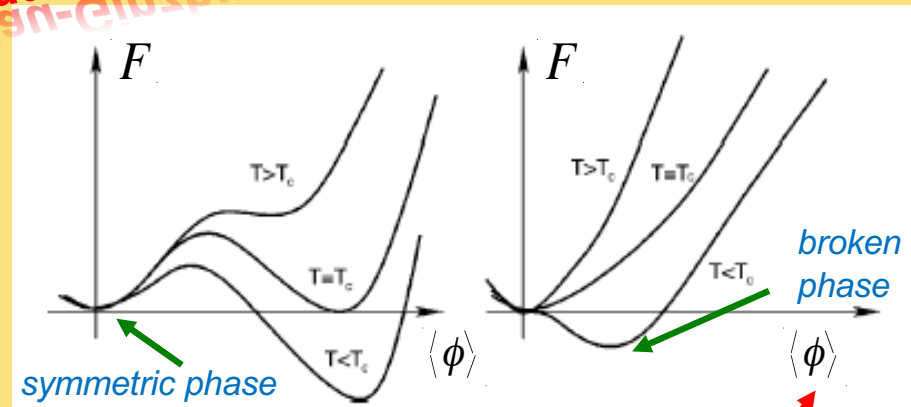
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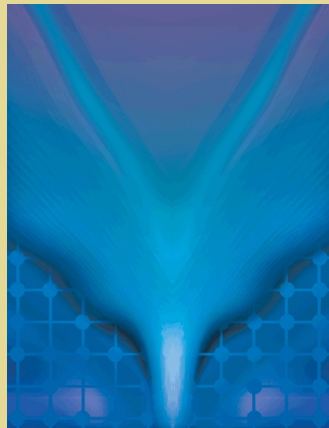
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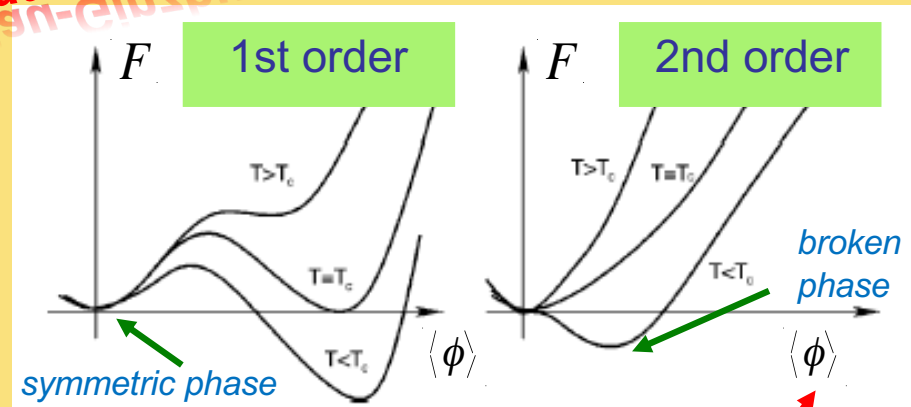
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Effective potential \rightarrow Phase transitions

Landau-Ginzburg



“order parameter” : value of
classical field \rightarrow vacuum expect
value (VEV) of quantum field (v)

Phase Transitions

Ehrenfest classification:

1st order PT: discontinuous first derivative of free energy

$$\left(\frac{\partial F}{\partial T}\right)_V = -S \qquad \left(\frac{\partial G}{\partial T}\right)_P = -S$$

Phase Transitions

Ehrenfest classification:

1st order PT: discontinuous first derivative of free energy

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1st order: entropy change

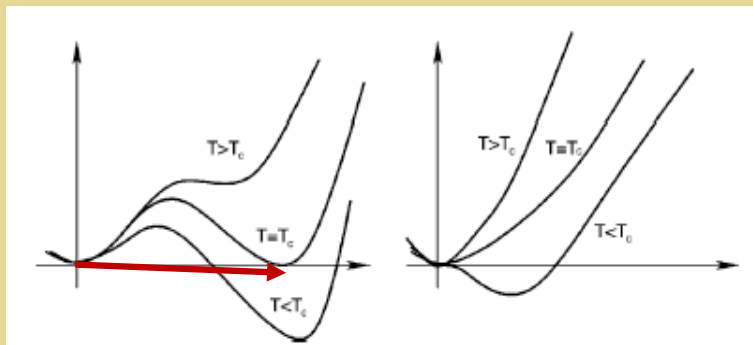
Phase Transitions

Ehrenfest classification:

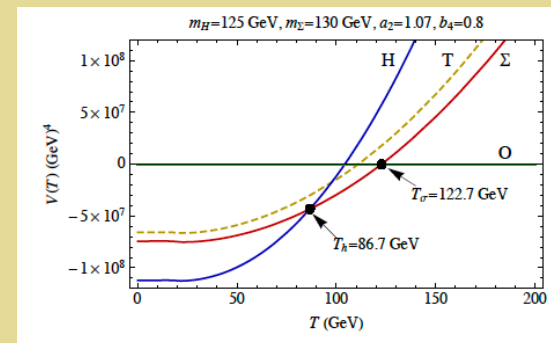
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Jump in entropy (i.e., entropy injection)



Real triplet model



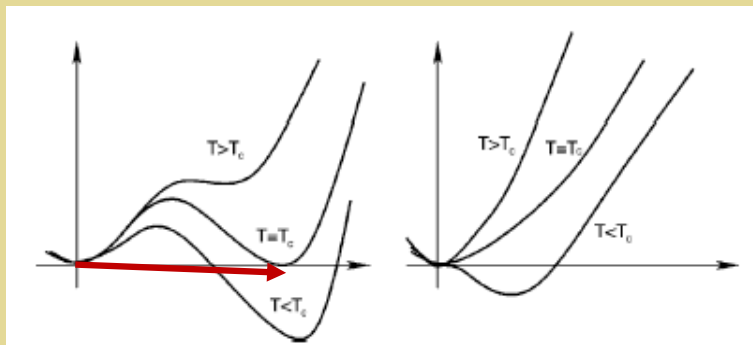
Phase Transitions

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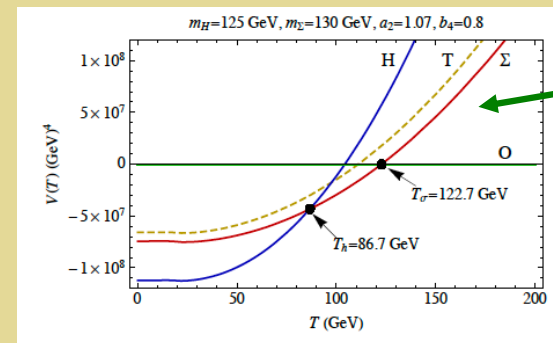
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Real triplet model



Broken phase

Sym phase

Phase Transitions

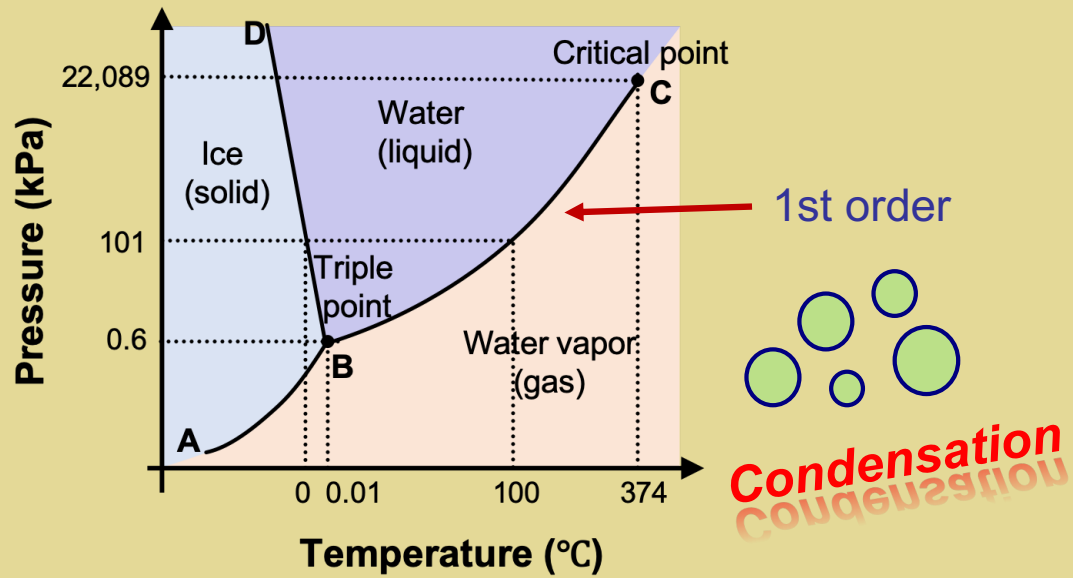
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1st order PT: discontinuous first derivative of free energy

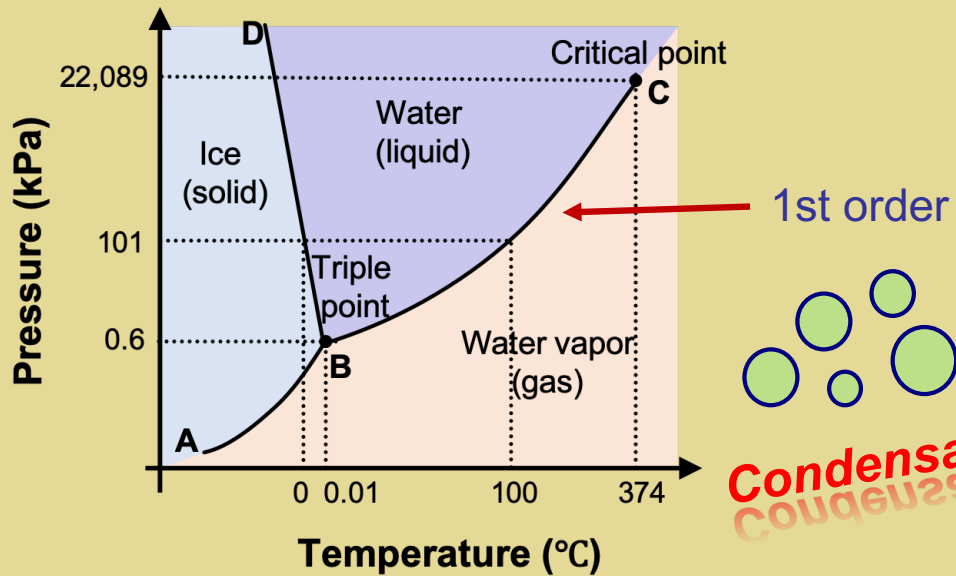
$$\left(\frac{\partial F}{\partial T}\right)_V = -S \qquad \left(\frac{\partial G}{\partial T}\right)_P = -S$$

- *nth order PT: discontinuous nth derivative of free energy*
- *smooth “crossover” transition: no discontinuities in derivatives of the free energy*

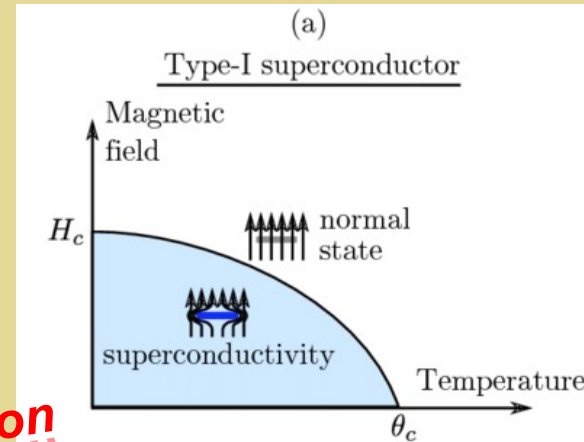
Phase Transitions



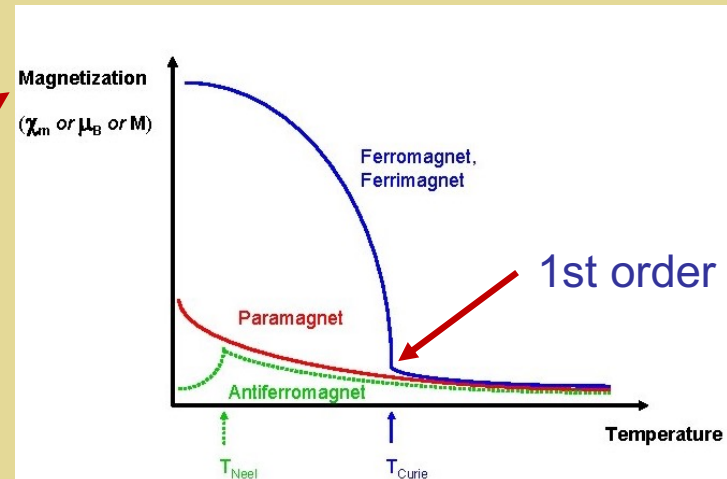
Phase Transitions



Condensation



Order parameter

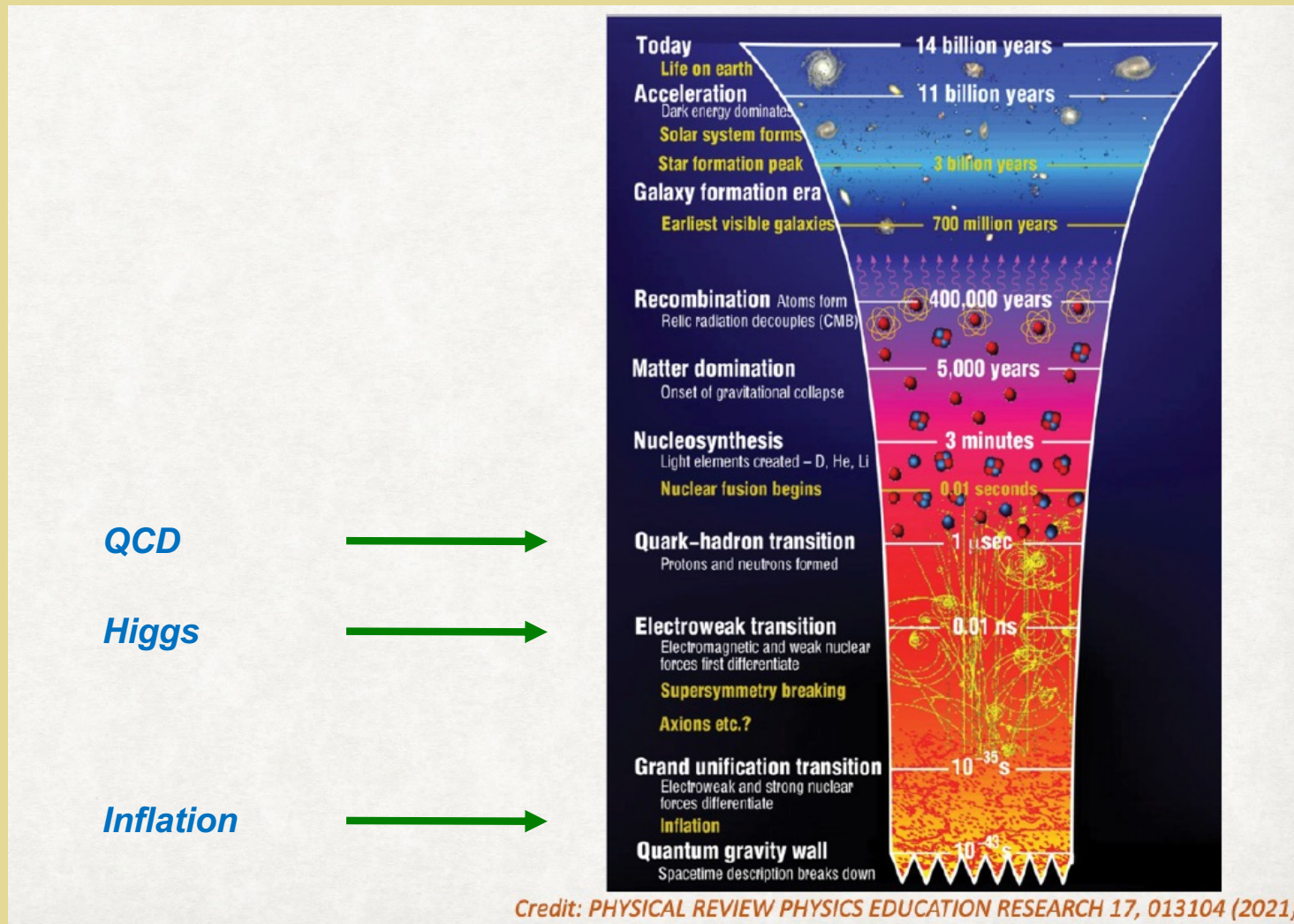


Questions

- *Did the early universe undergo symmetry breaking through condensation ?*
- *What are the experimental signatures of this process ?*
- *What theoretical challenges must be met to address this question ?*

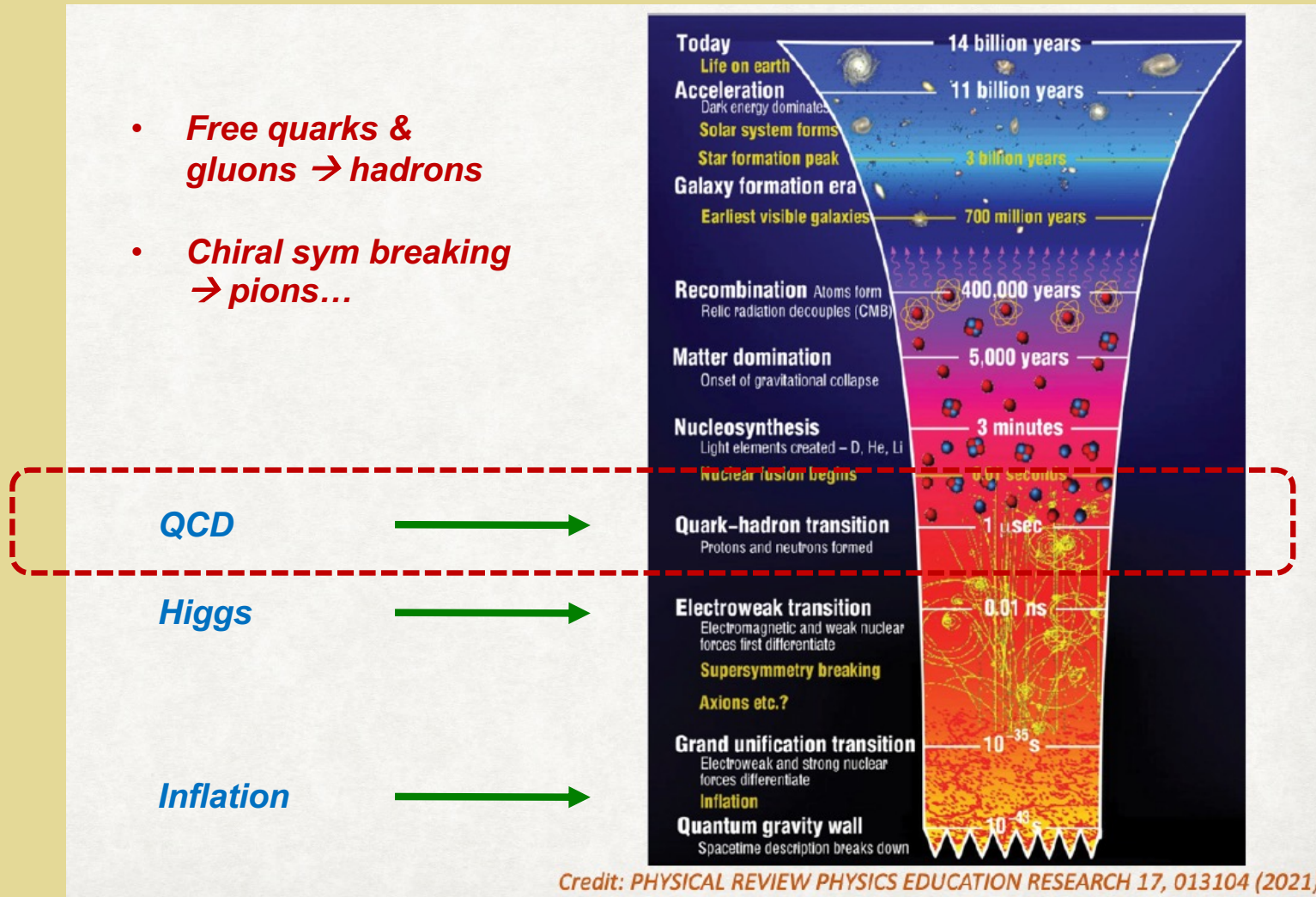
II. Cosmic Condensation

Thermal History of Symmetry Breaking

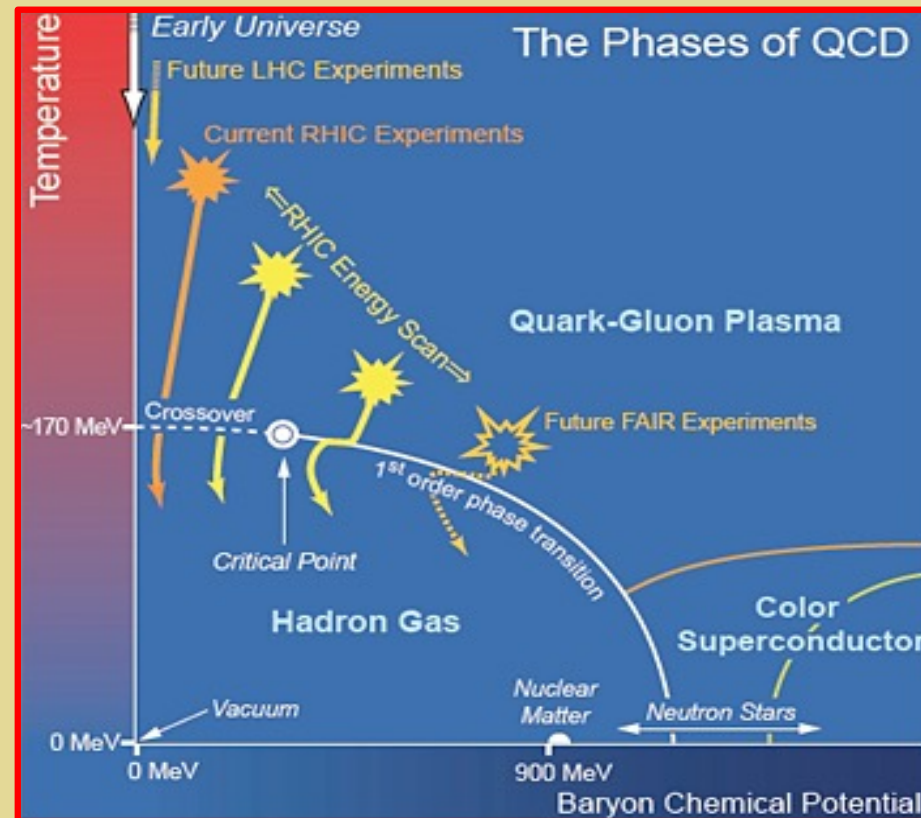


Thermal History of Symmetry Breaking

- **Free quarks & gluons \rightarrow hadrons**
- **Chiral sym breaking \rightarrow pions...**



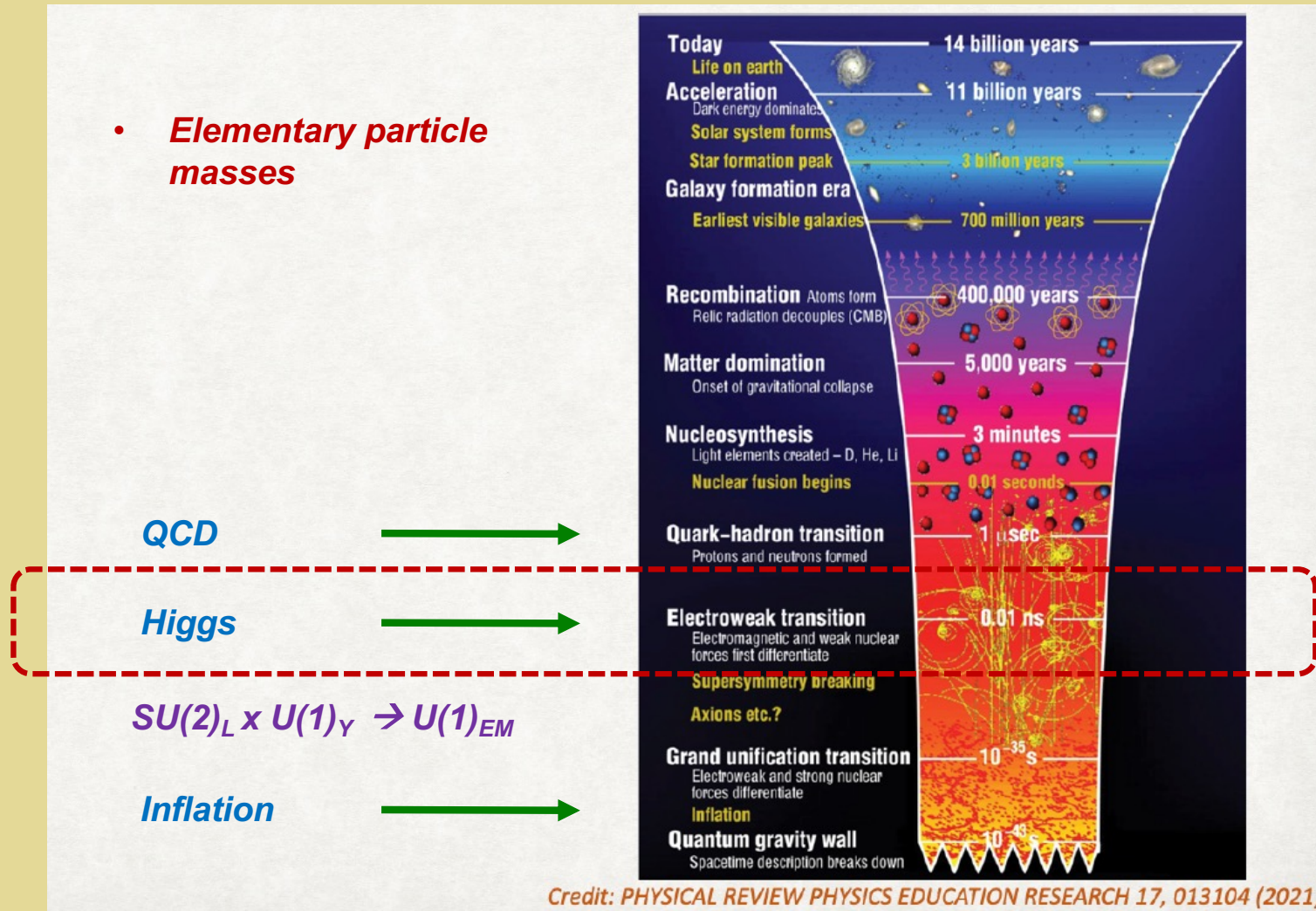
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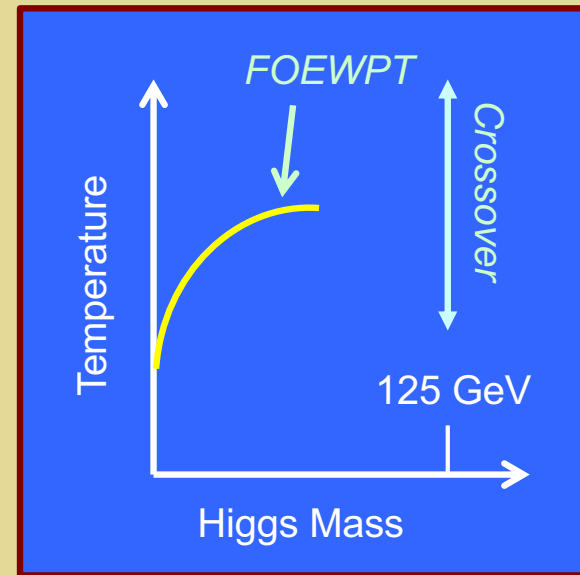
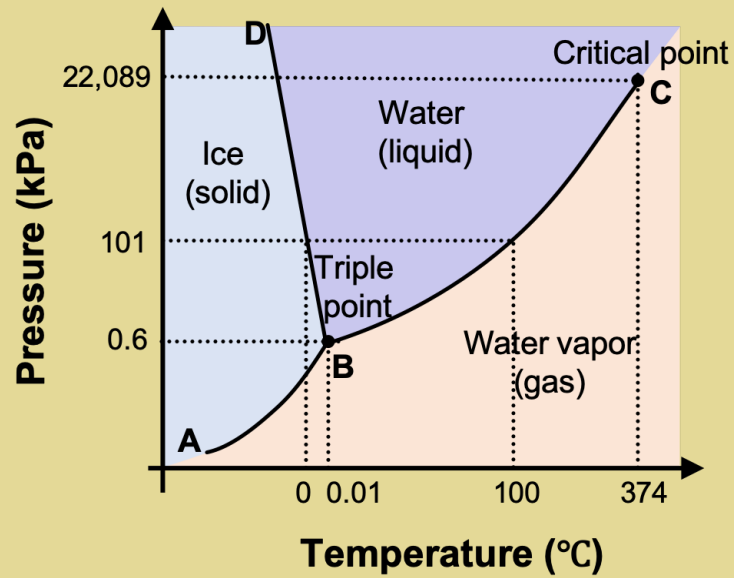
QCD Phase Diagram → EW Theory Analog ?
“Dark Sector” ? Cosmological consequences ?

Thermal History of Symmetry Breaking

- **Elementary particle masses**

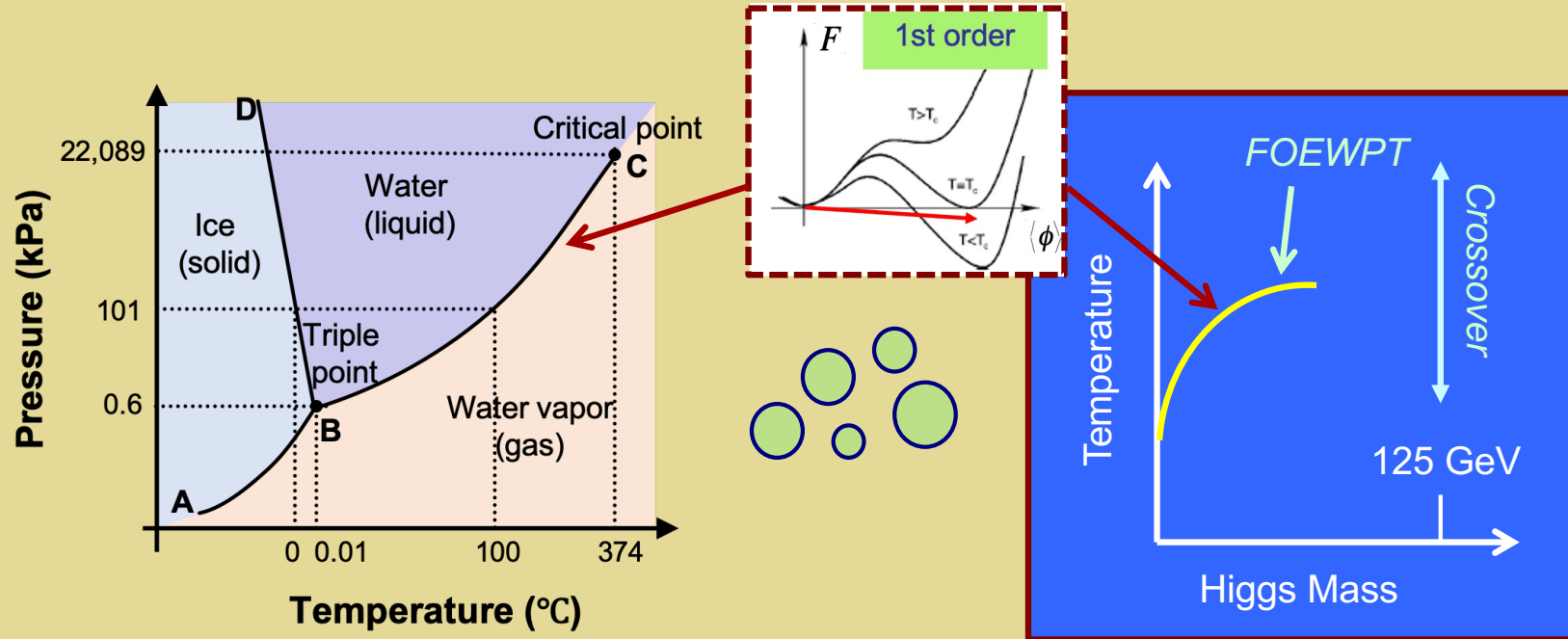


Electroweak Condensation ?



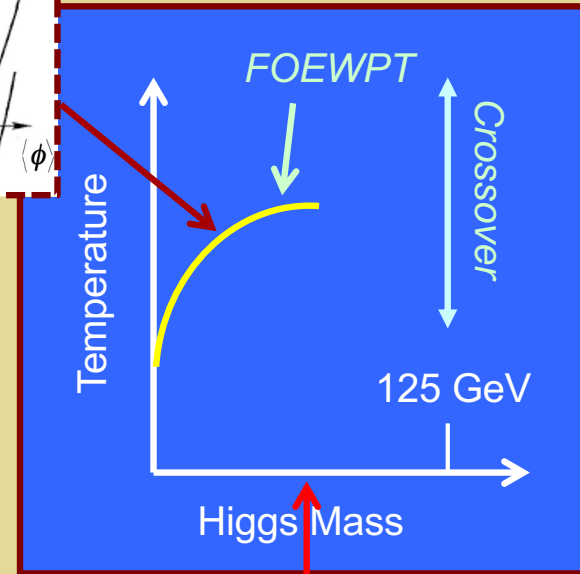
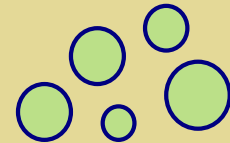
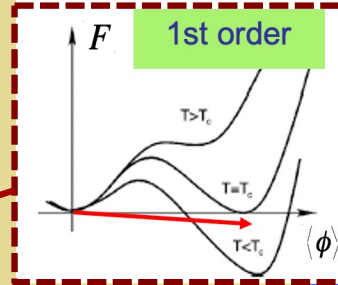
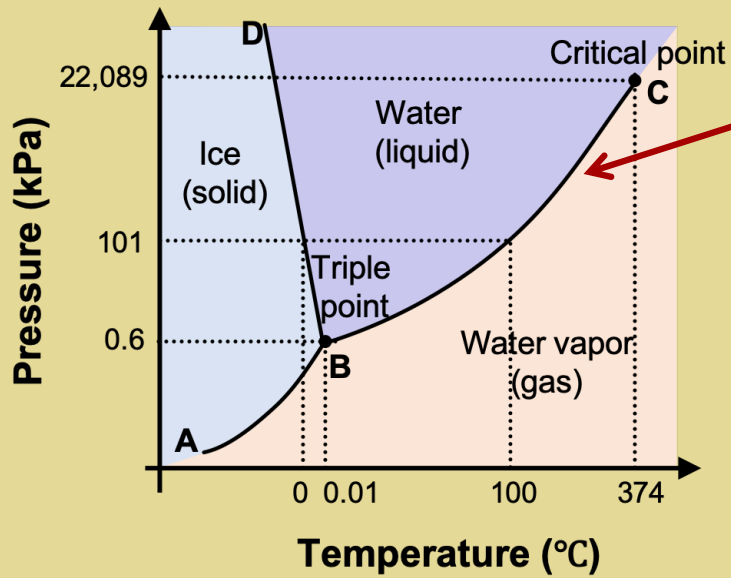
EW Phase Diagram

Electroweak Condensation ?



EW Phase Diagram

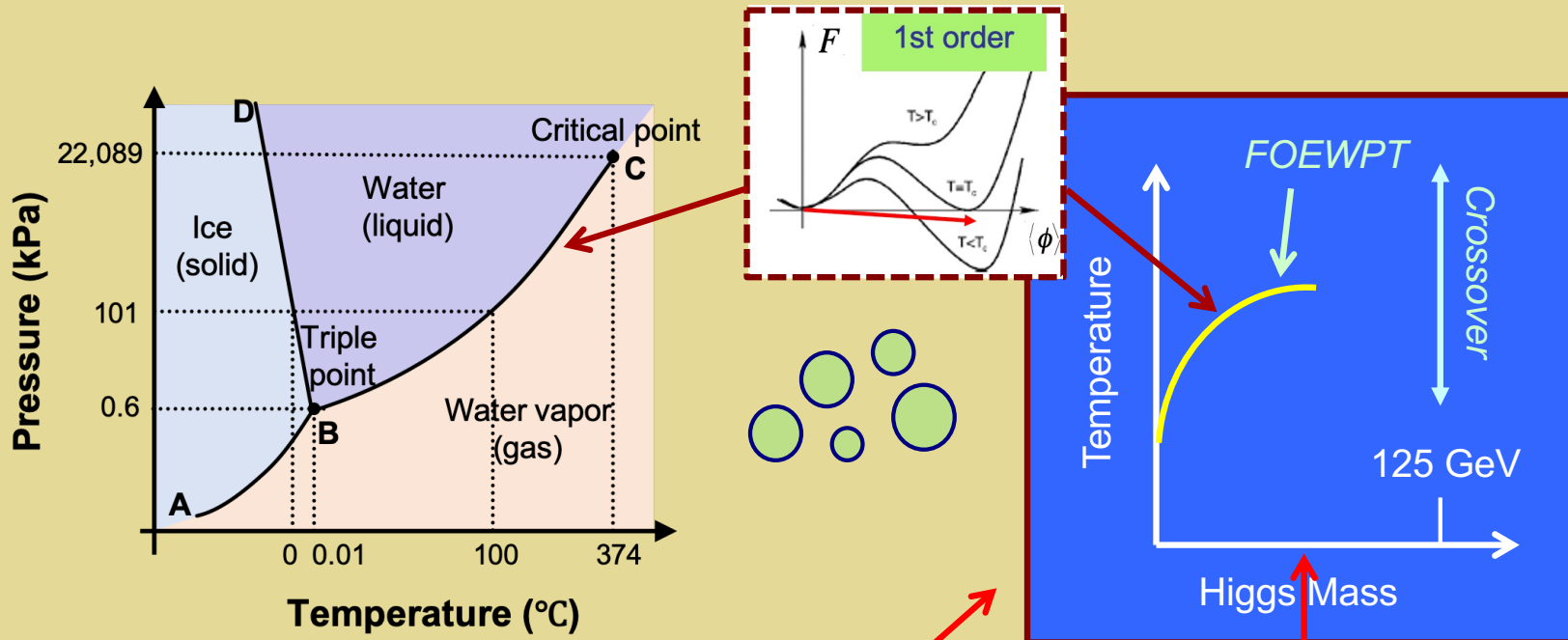
Electroweak Condensation ?



EW Phase Diagram

| Lattice | Authors | M_h^C (GeV) |
|----------------|---------|----------------|
| 4D Isotropic | [76] | 80 ± 7 |
| 4D Anisotropic | [74] | 72.4 ± 1.7 |
| 3D Isotropic | [72] | 72.3 ± 0.7 |
| 3D Isotropic | [70] | 72.4 ± 0.9 |

Electroweak Condensation ?

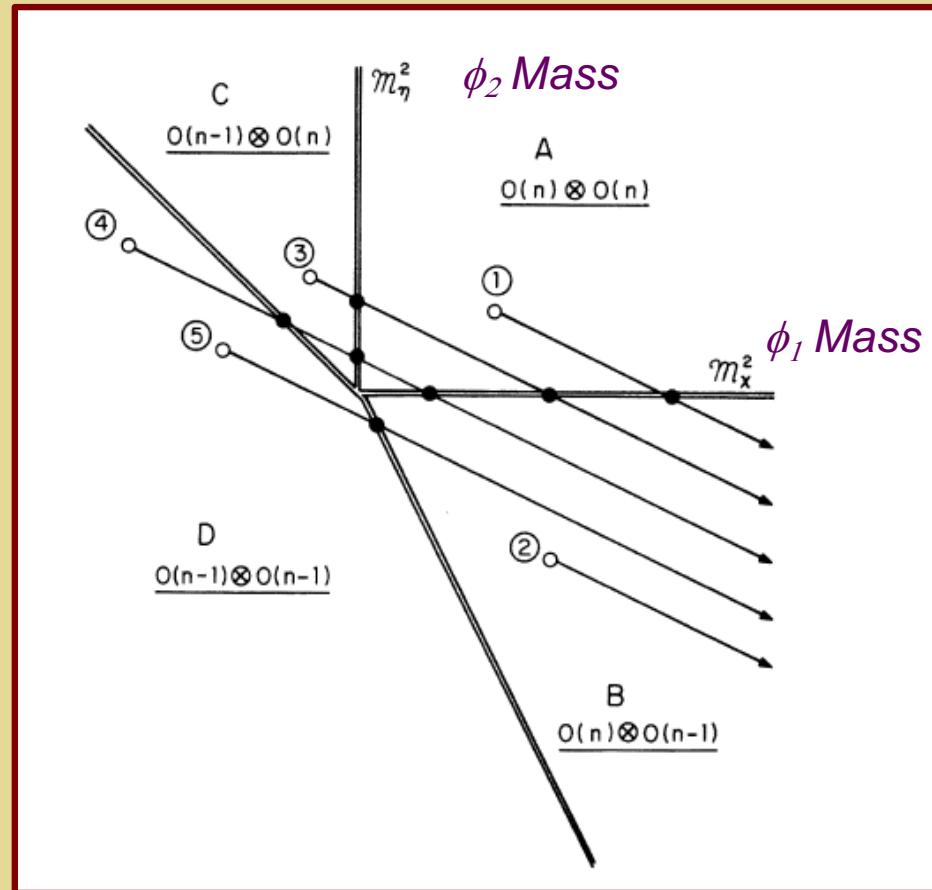


EW Phase Diagram

How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

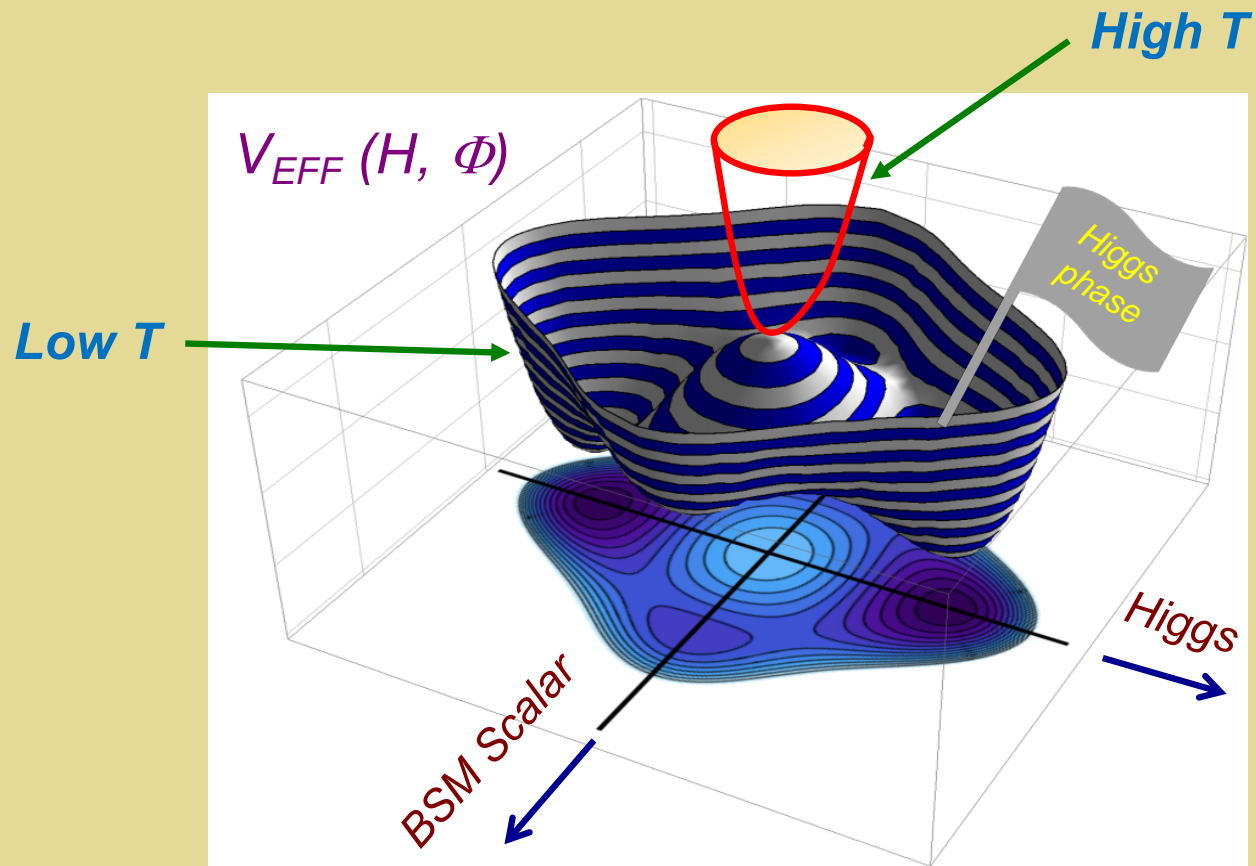
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Patterns of Symmetry Breaking



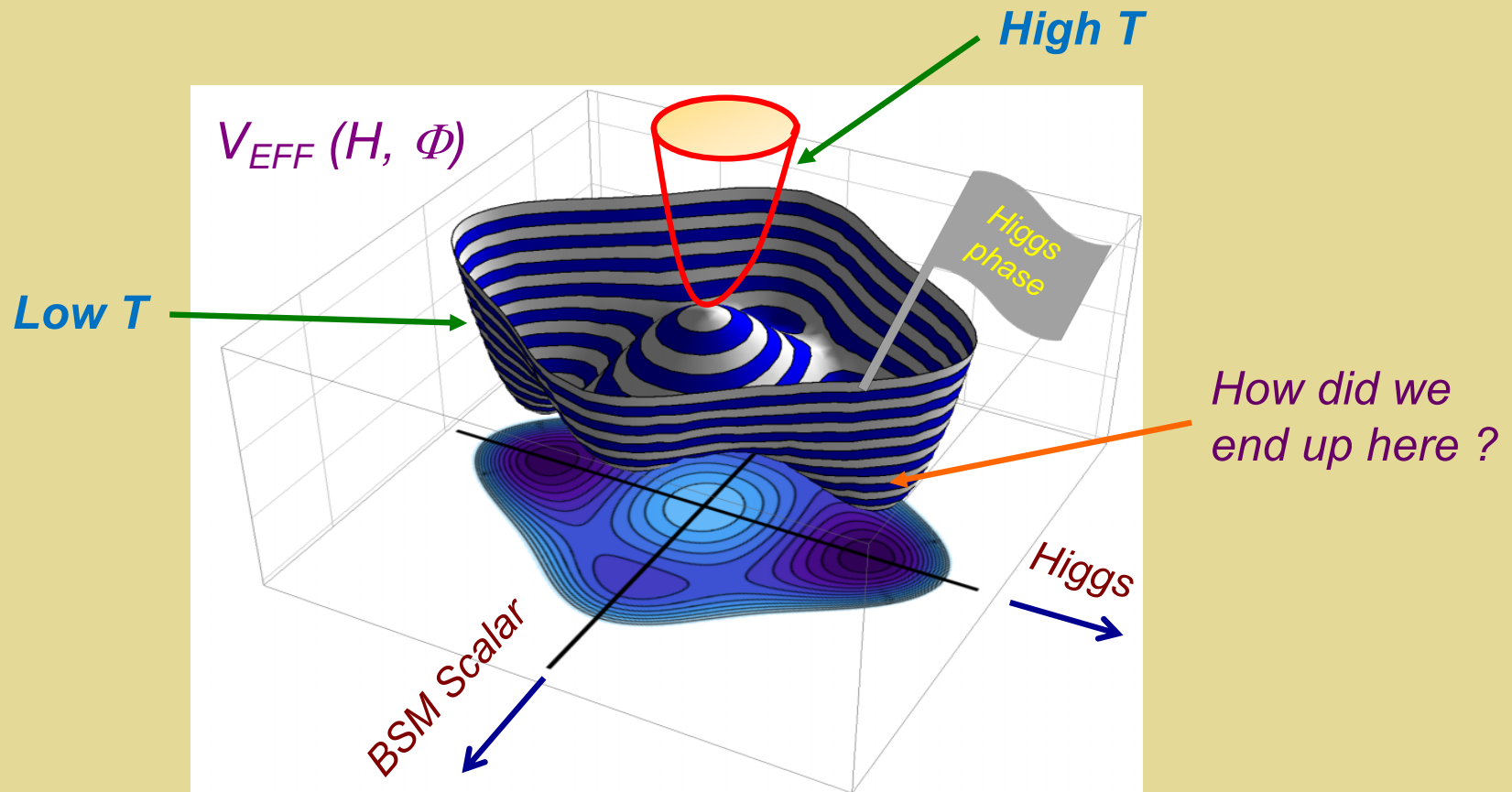
S. Weinberg, PRD 9 (1974) 3357

What Was the *EWSB* Thermal History ?



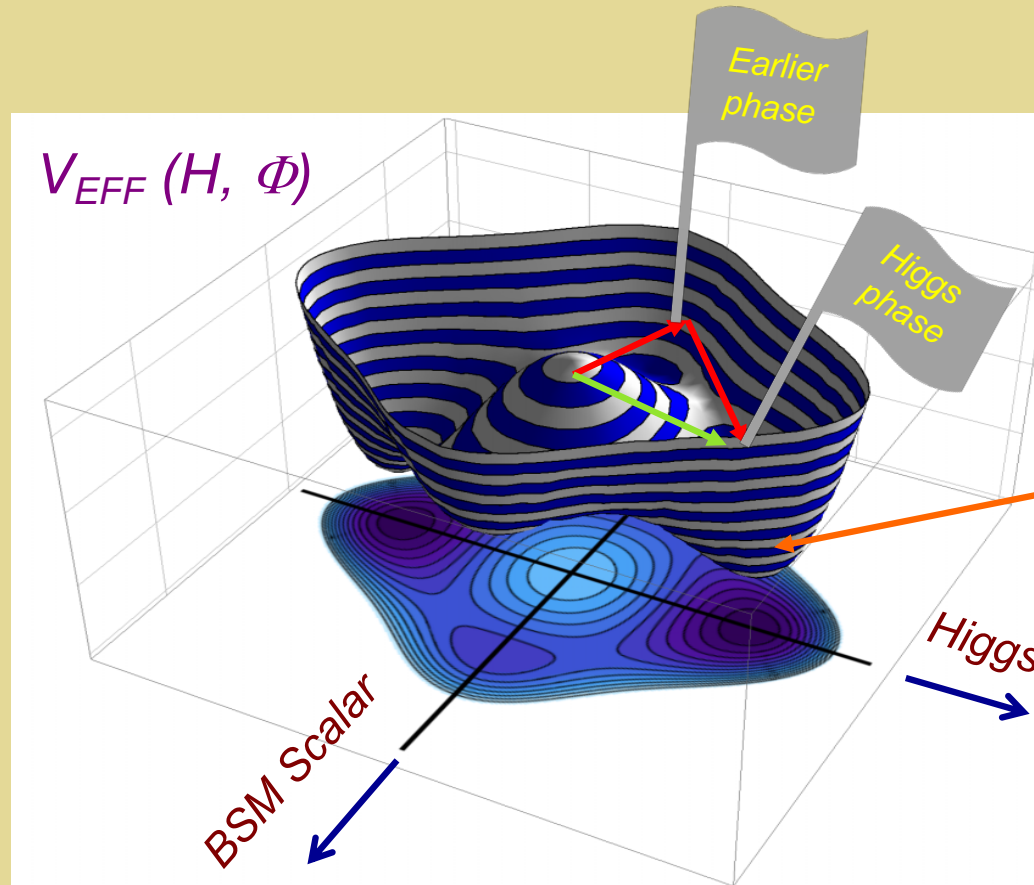
**Extrema can evolve differently as T evolves \rightarrow
rich possibilities for symmetry breaking**

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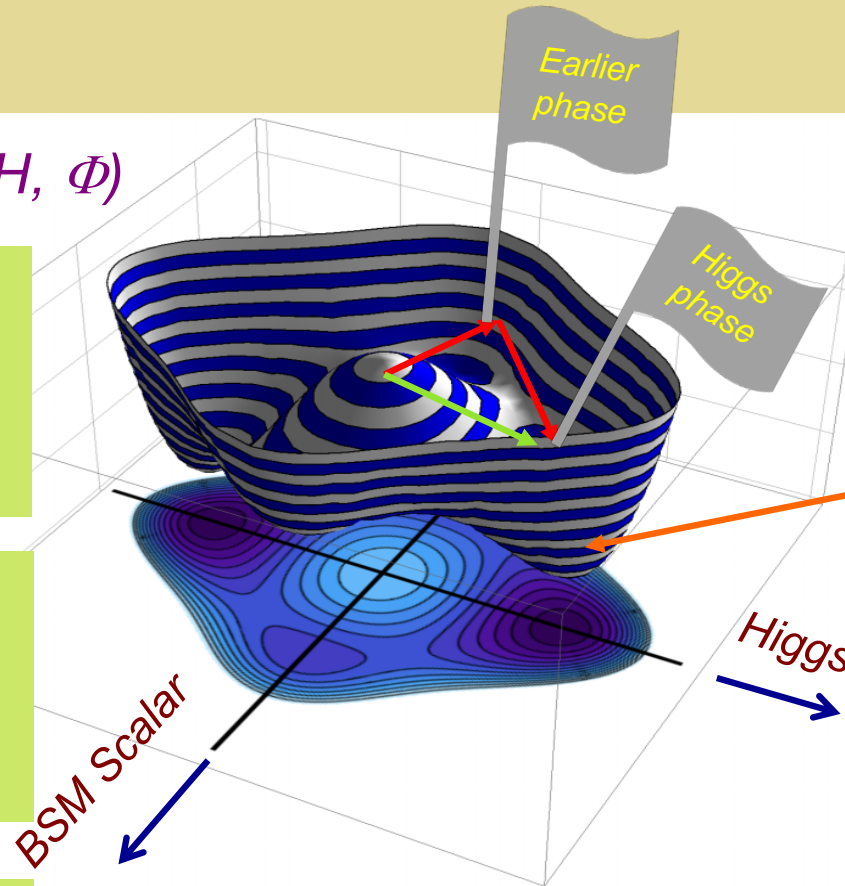


How did we end up here ?

Extrema can evolve differently as T evolves \rightarrow rich possibilities for symmetry breaking

What Was the EWSB Thermal History ?

$$V_{\text{EFF}}(H, \Phi)$$



• What is the landscape of potentials and their thermal histories?

• How can we probe this $T > 0$ landscape experimentally?

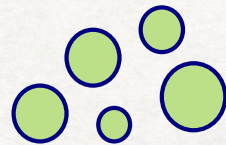
• How reliably can we compute the thermodynamics?

How did we end up here ?

**n evolve differently as T evolves \rightarrow
abilities for symmetry breaking**

Thermal History of Symmetry Breaking

- **Elementary particle masses**
- **Matter-antimatter asym?**



QCD

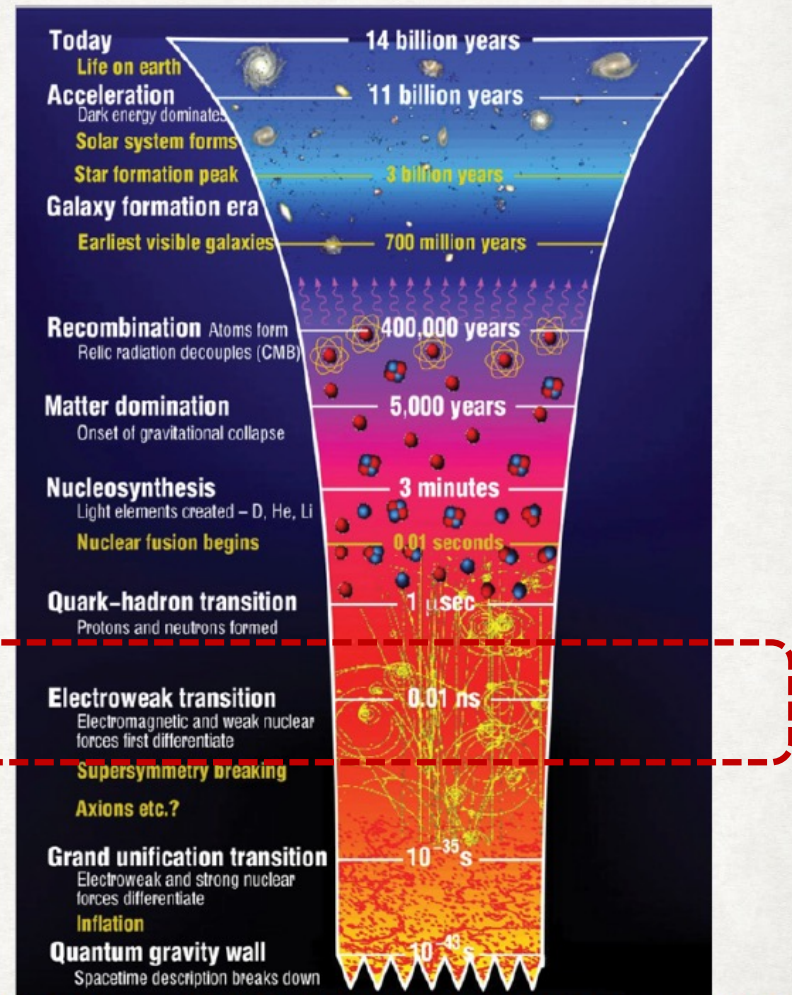


Higgs



$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

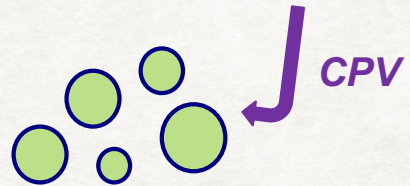
Inflation



Credit: PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH 17, 013104 (2021)

Thermal History of Symmetry Breaking

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QCD

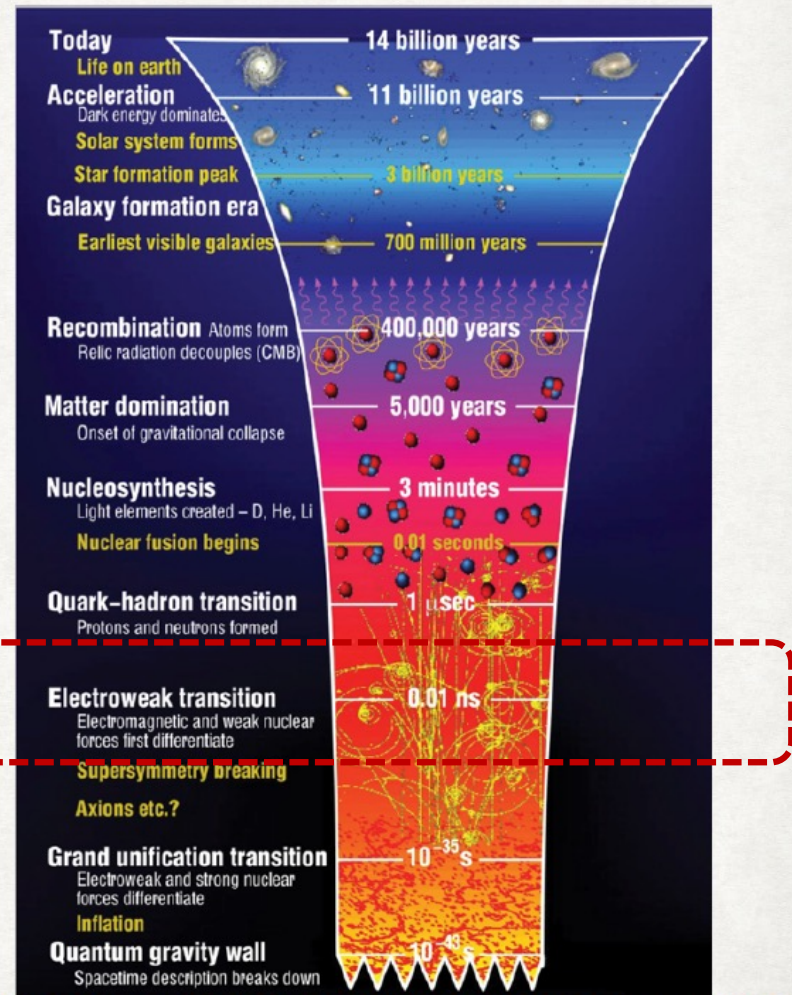


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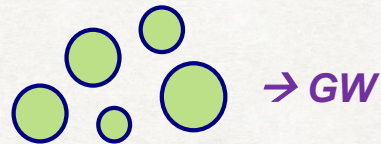
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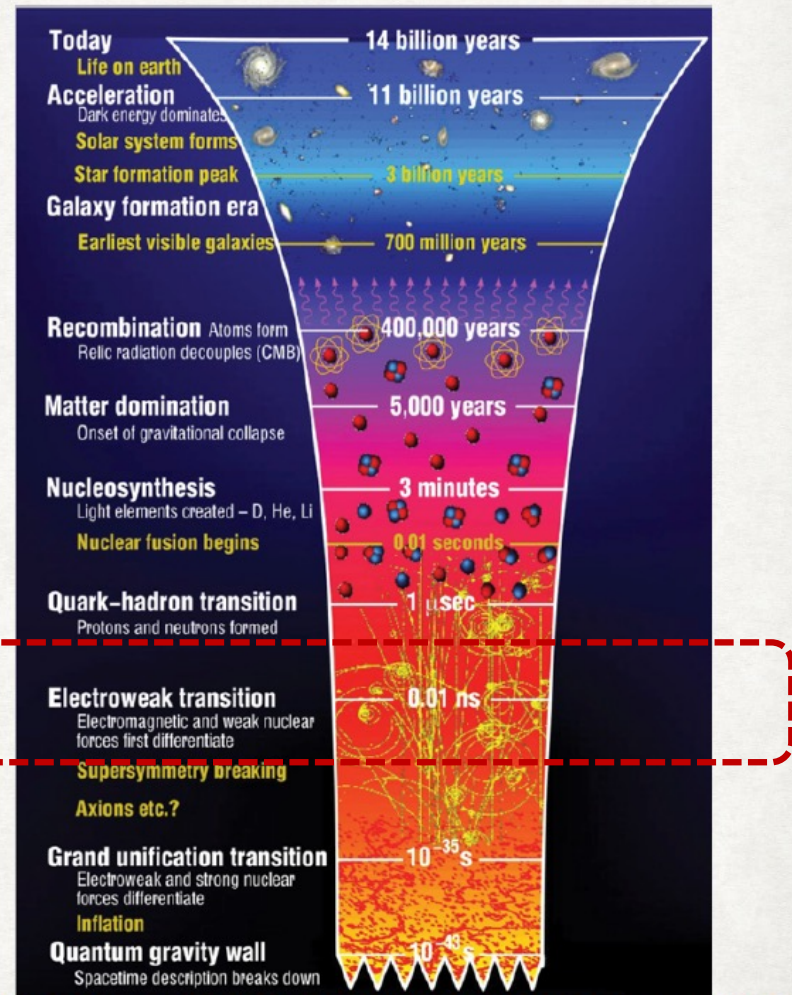


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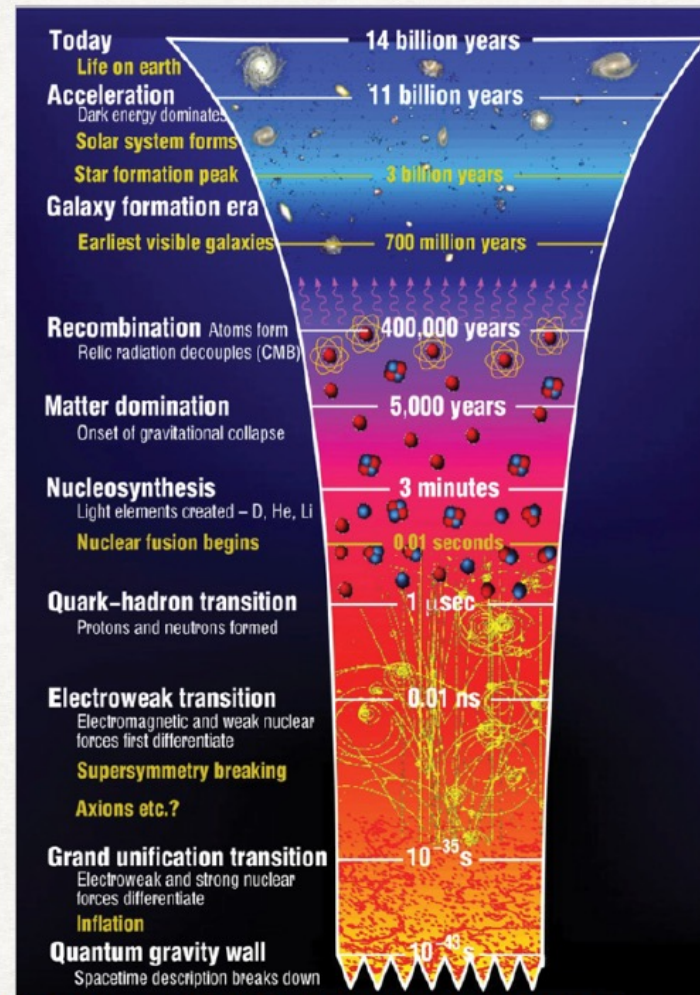
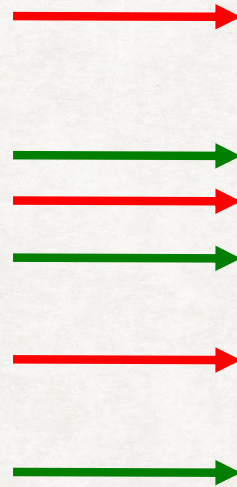
- **Neutrino masses ?**
- **Cosmic strings ?**
- **Dark matter ?**
- **Primordial black holes ?**
- **Hubble tension ?**
- ...

Other ?

QCD

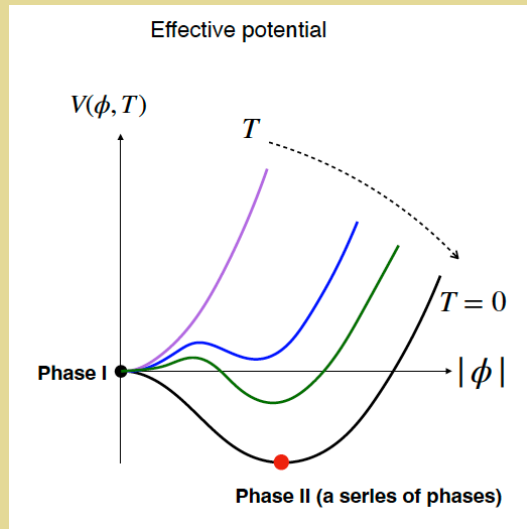
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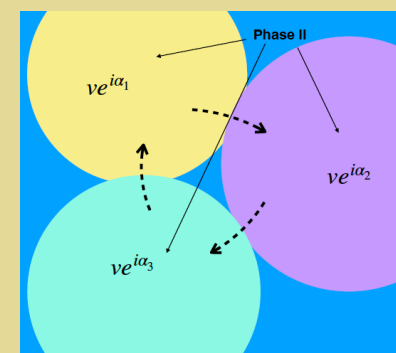
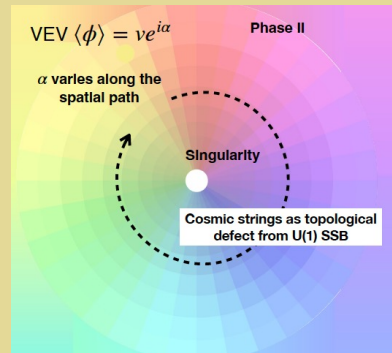
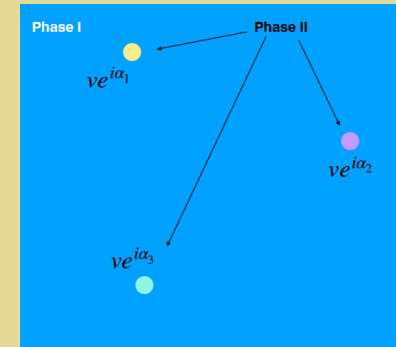
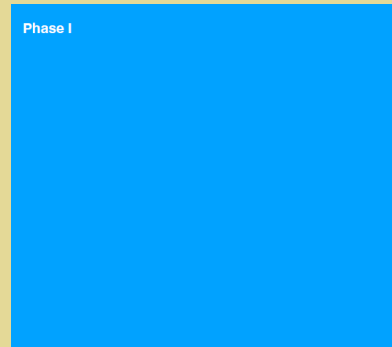


Credit: PHYSICAL REVIEW PHYSICS EDUCATION RESEARCH 17, 013104 (2021)

Particle Physics & GW: Spontaneous Symmetry Breaking



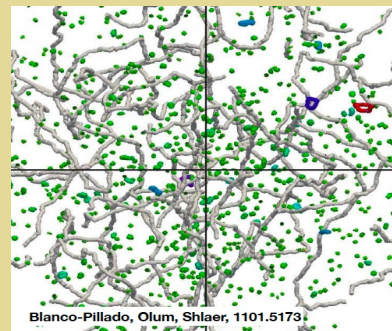
Thanks: Ye-Ling Zhou CPCS '24



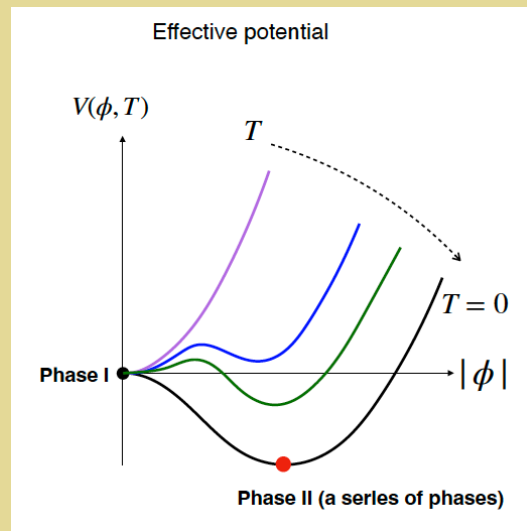
Spontaneous breaking of global $U(1)_X$

→ Cosmic strings:

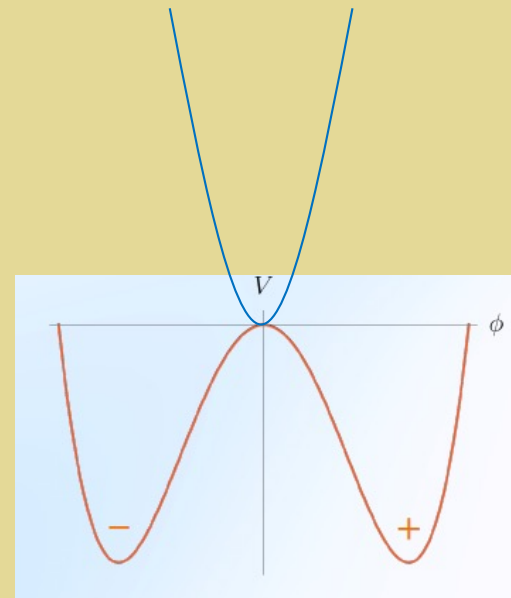
Dynamics can generate GW sources



Particle Physics & GW: Spontaneous Symmetry Breaking



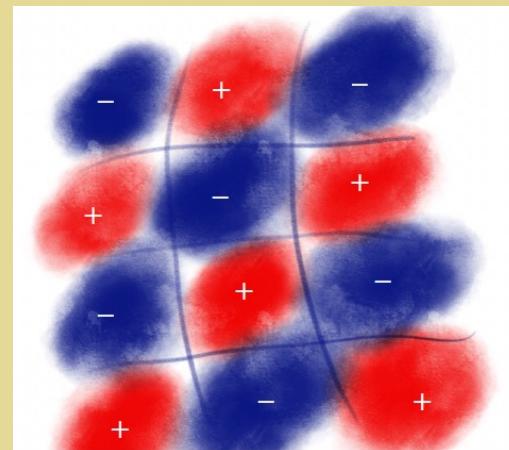
Thanks: Ye-Ling Zhou CPCS '24



Spontaneous breaking of discrete sym: e.g., Z_2

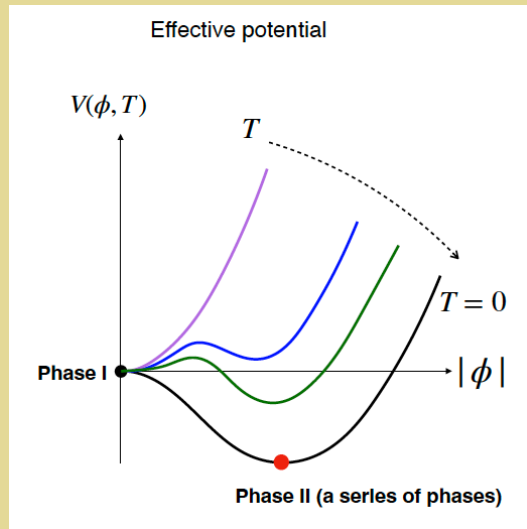
→ Domain walls:

Dynamics can generate GW sources



Thanks: Bowen Fu CPCS '24

Condensation & Dark Matter

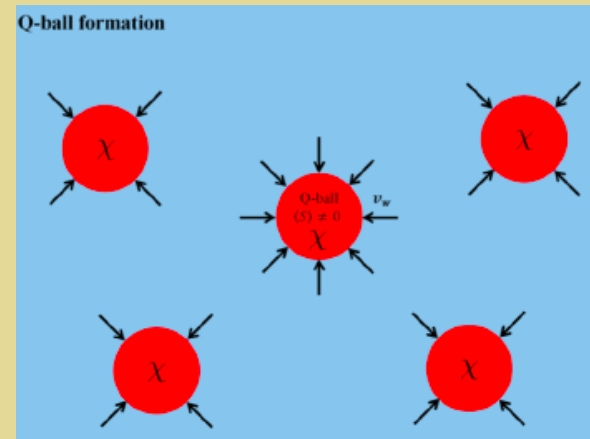
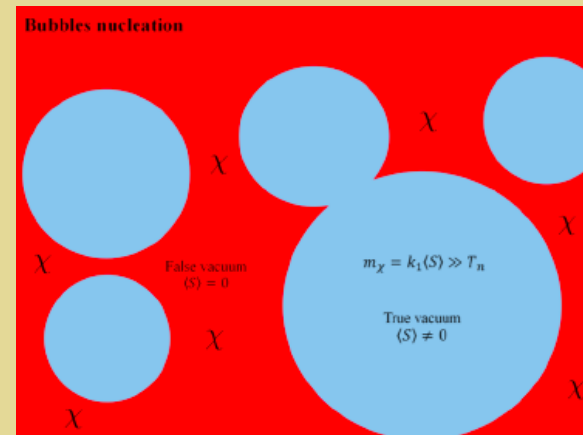


Thanks: Ye-Ling Zhou CPCS '24

Trapping of heavy particles outside bubbles

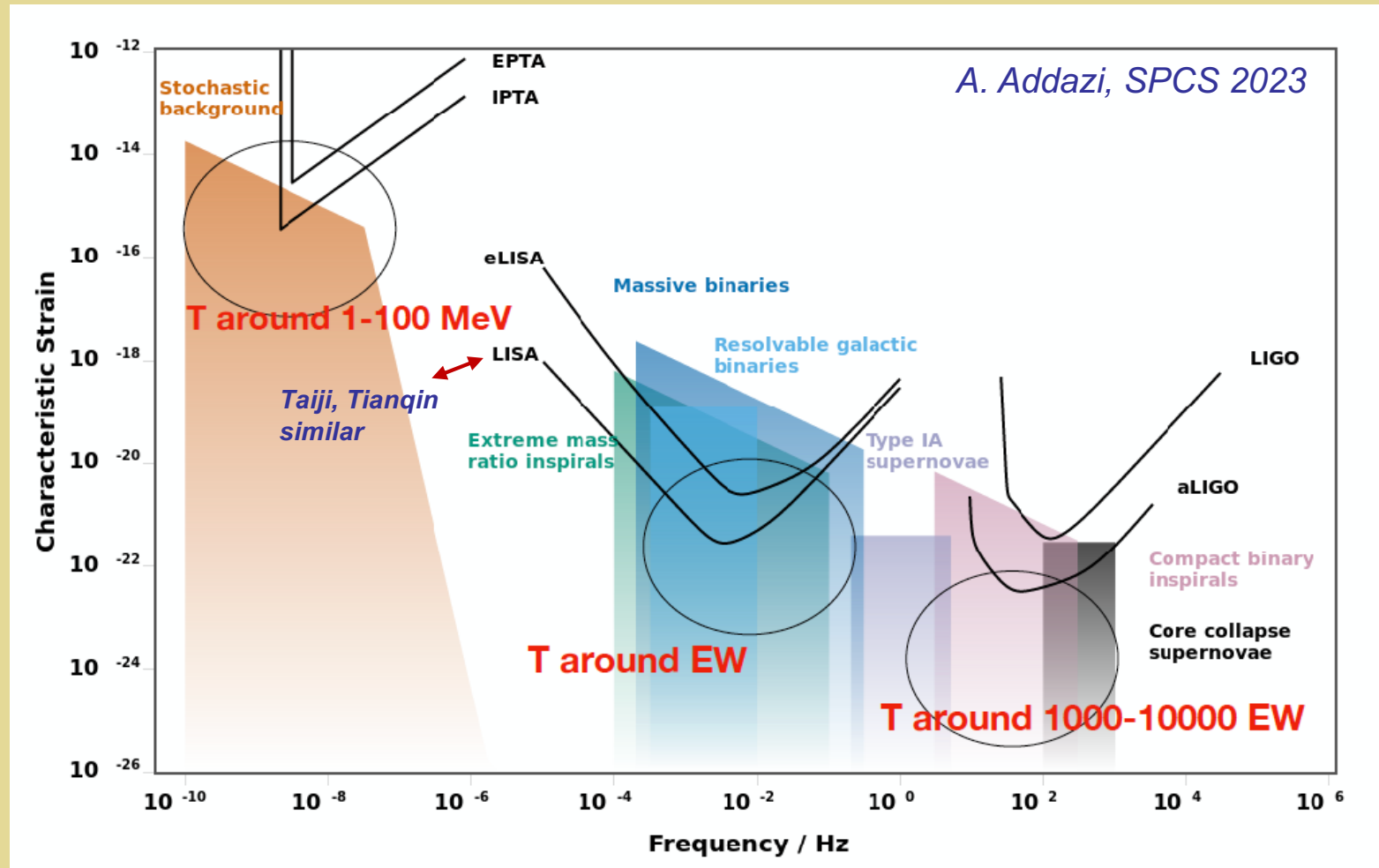
→ **Q-Ball dark matter**

GW from bubble collisions

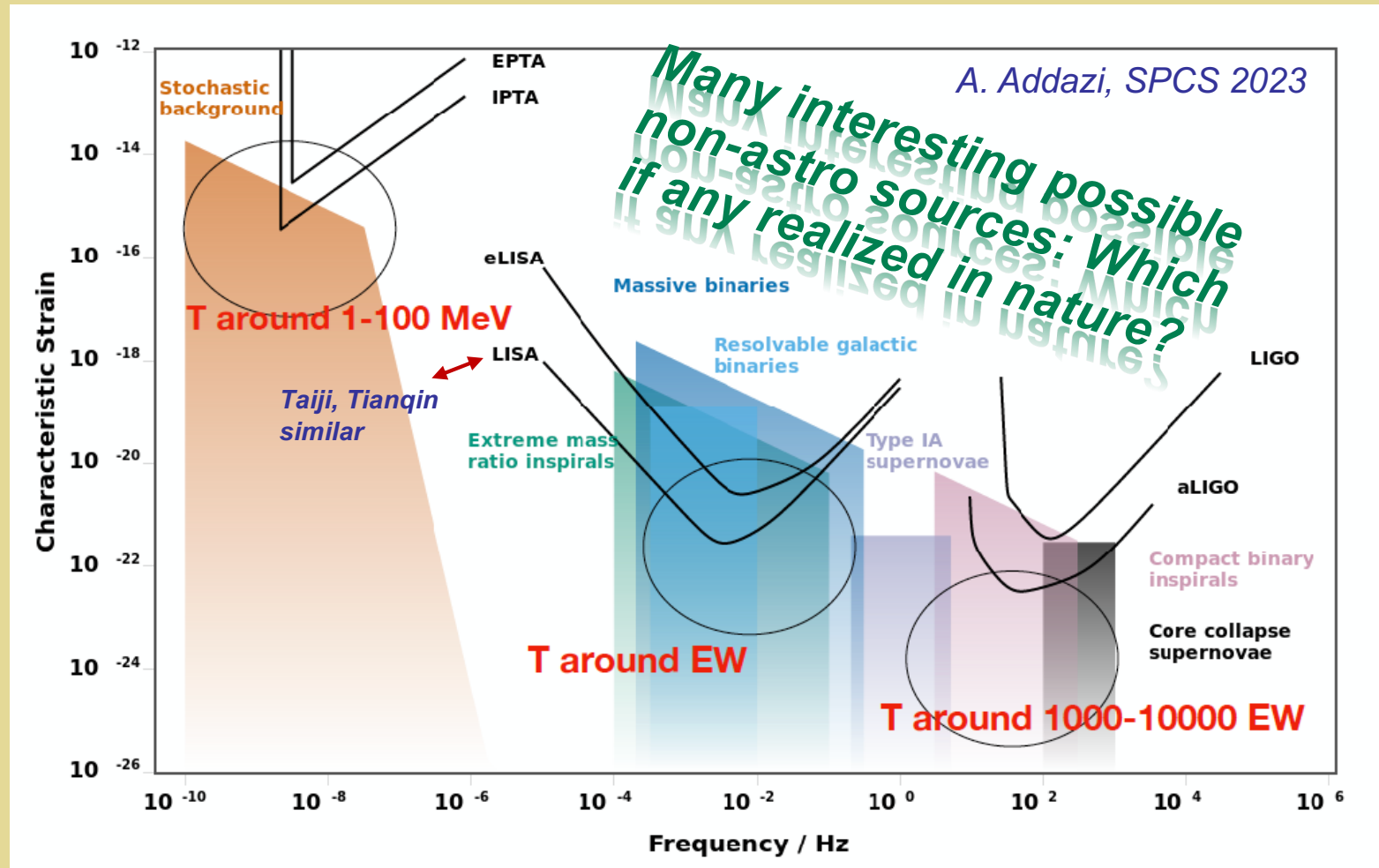


Thanks: Fa Peng Huang CPCS '24

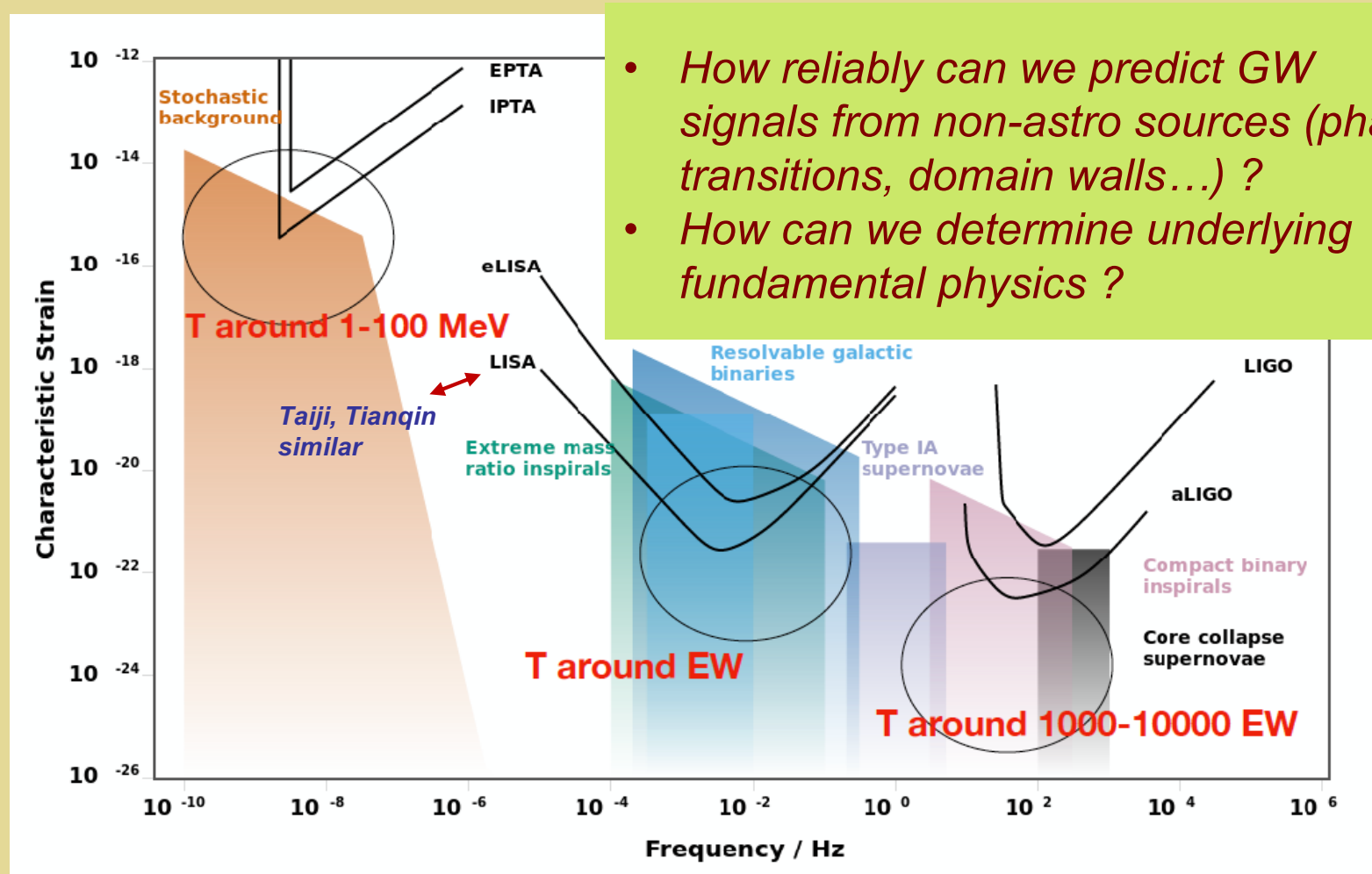
Condensation & Gravitational Waves



Condensation & Gravitational Waves

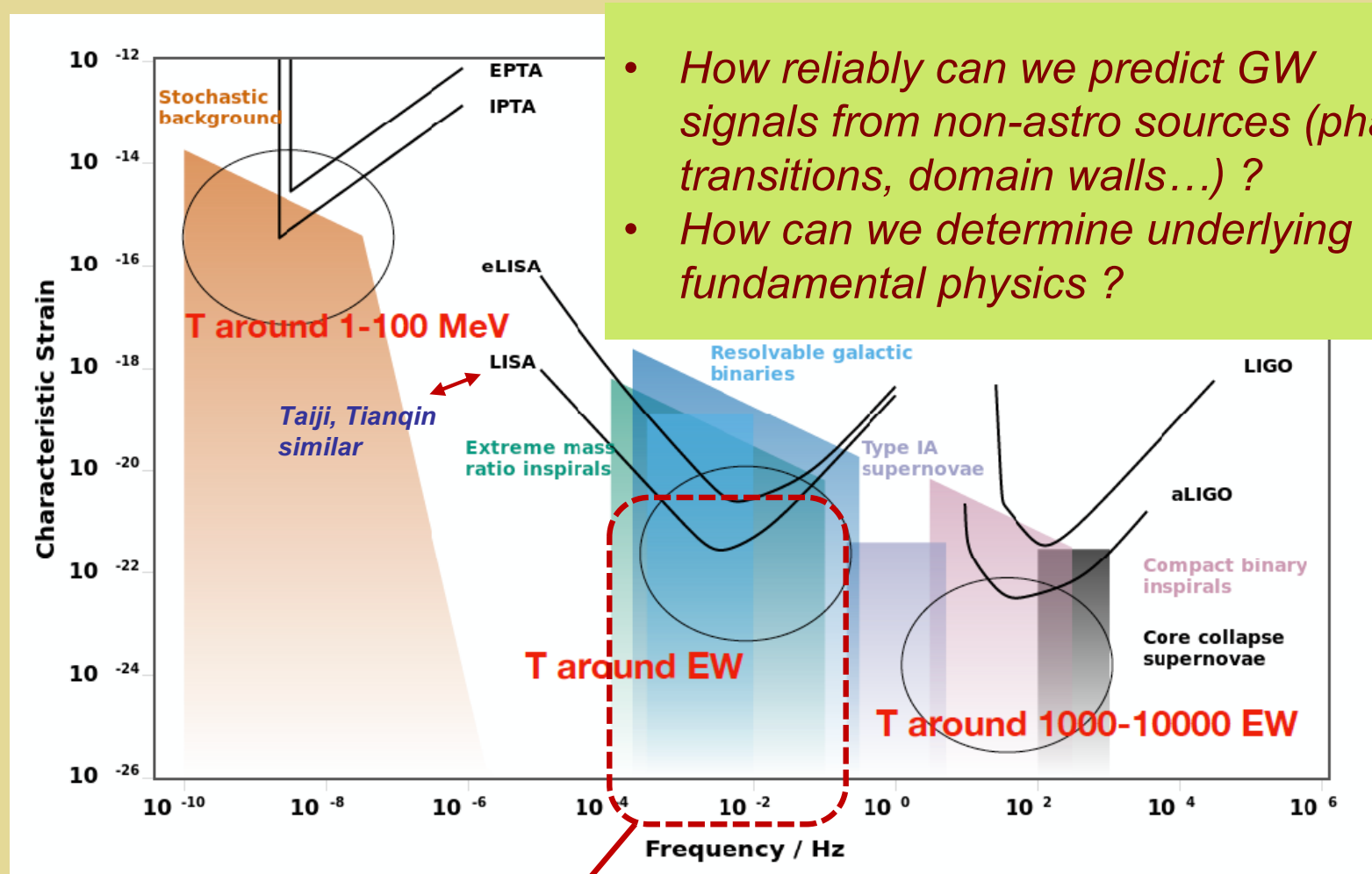


Electroweak Condensation ?



- How reliably can we predict GW signals from non-astro sources (phase transitions, domain walls...)?
- How can we determine underlying fundamental physics?

Electroweak Condensation ?



- How reliably can we predict GW signals from non-astro sources (phase transitions, domain walls...)?
- How can we determine underlying fundamental physics?

EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales

TDLI/SJTU Early Universe QFT

*Model building &
cosmological scenarios*

*Pheno: Collider, EDM,
Gravitational Radiation*

*EW Phase Transition &
EW Baryogenesis*

*Robust theory computations:
formal “machinery”, analytic,
non-perturbative*

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Model building & cosmological scenarios

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This talk

Robust theory computations: formal “machinery”, analytic, non-perturbative

TDLI/SJTU Early Universe QFT

Shanghai: Science City
张江科学城



TDLI/SJTU Early Universe QFT

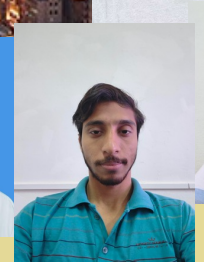
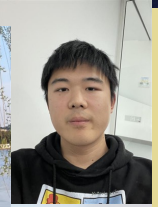
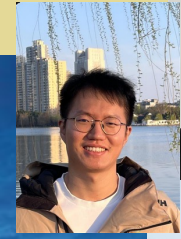
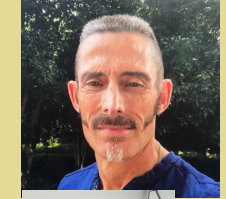
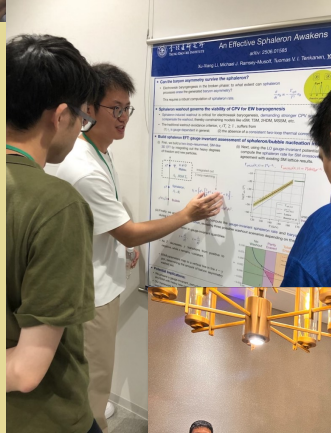


TDLI/SJTU Early Universe QFT

Shanghai: Science City
张江科学城

Team QFT

Cosmic
condensation



EW Phase Transition: IHEP Connections

Pioneering work: *Xinmin Zhang*

PHYSICAL REVIEW D

VOLUME 47, NUMBER 7

1 APRIL 1993

Operator analysis for the Higgs potential and cosmological bound on the Higgs-boson mass

Xinmin Zhang

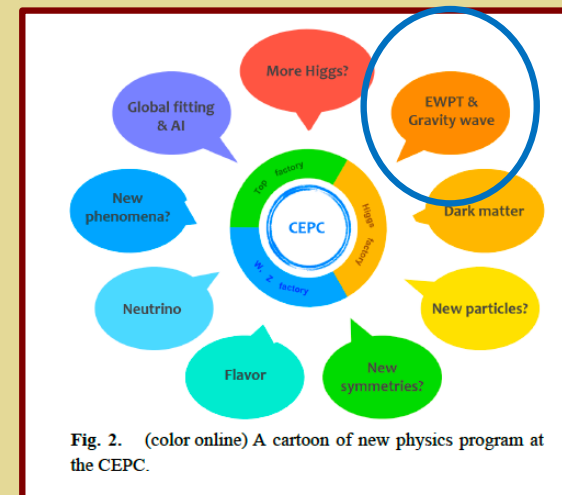
Center for Theoretical Physics, Department of Physics, University of Maryland, College Park, Maryland 20742
(Received 2 November 1992)

Using effective-field theory at finite temperature, we examine the impact of new physics on the electroweak phase transition. By analyzing the high-dimensional operators relevant to the Higgs potential we point out that the Higgs-boson mass bound obtained by avoiding the washout of the baryon asymmetry can be relaxed to the region allowed by experiments, provided that new physics appears at the TeV scale.

PACS number(s): 12.15.Cc, 11.15.Ex, 14.80.Gt, 98.80.Cq

CEPC BSM WP '25

CEPC physics: BSM target



III. Theoretical Challenges & Progress

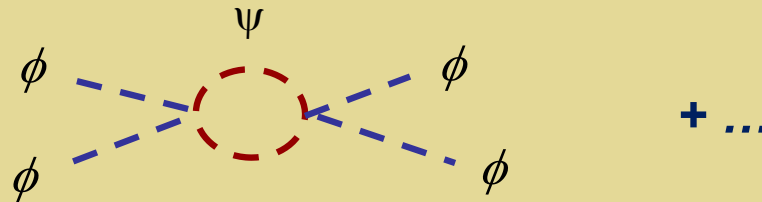
Robust assessment of early universe symmetry-breaking thermodynamics and confrontation between theory and experiment faces significant quantum field theory challenges

QFT Robustness

- ***IR Problem: limits of perturbation theory***
- ***Nucleation @ finite T : gauge invariance***
- ***Wall velocity: microphysics & fluid dynamics***

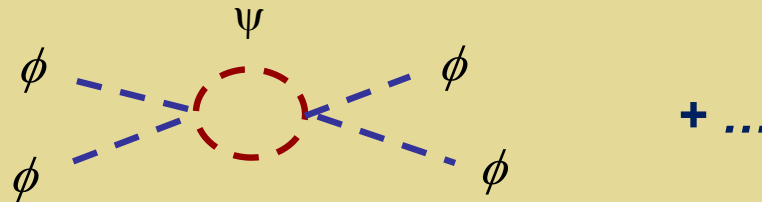
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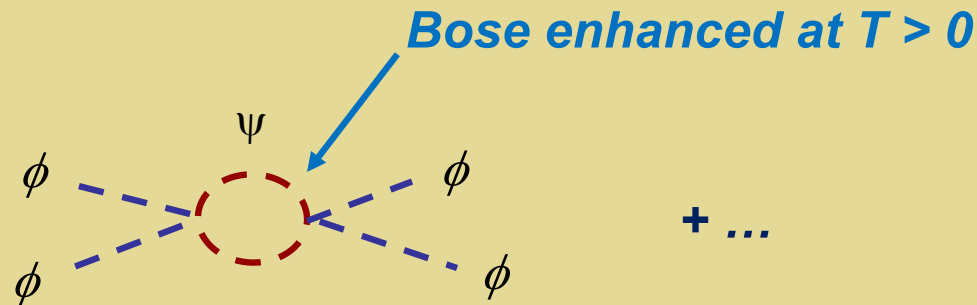
$$I(T) = g^2 \int \frac{d^3p}{(2\pi)^3} f_B(E, T) \frac{1}{(p^2 + m^2)^n}$$

Bose dist fn

An arrow points from the text "Bose dist fn" to the $f_B(E, T)$ term in the equation.

QFT Robustness

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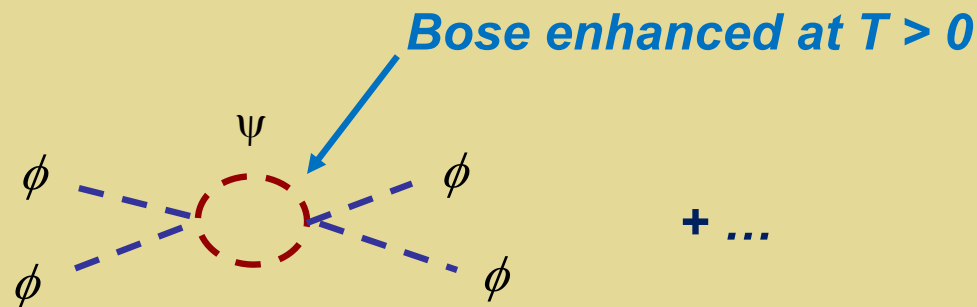


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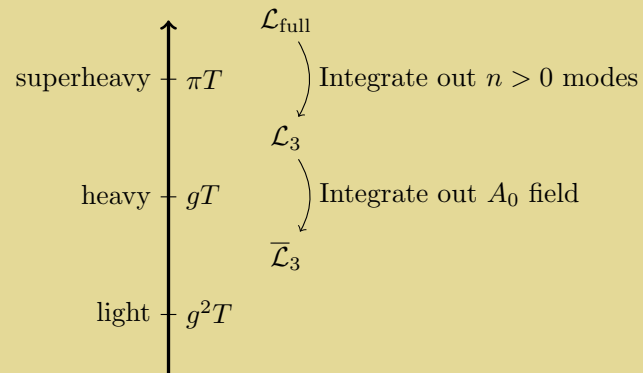


Progress @ TDLI

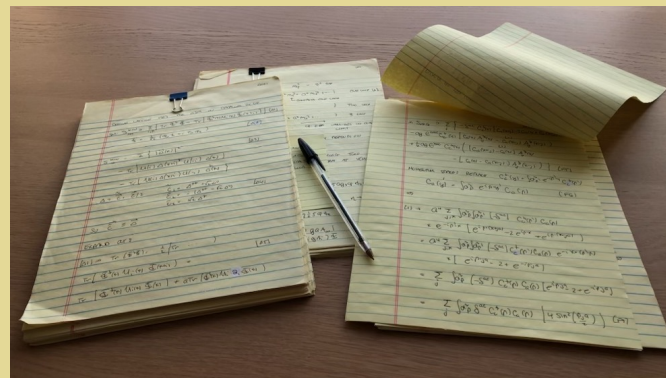
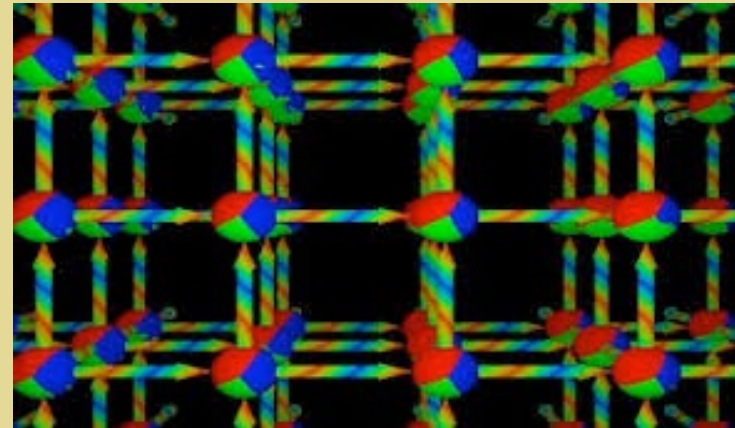
- **Combination of lattice computations & thermal EFT essential** \rightarrow 2005.11332, 2203.05889, 2405.01191, 2409.17554

Lattice + Thermal EFT

3-D high- T effective theory



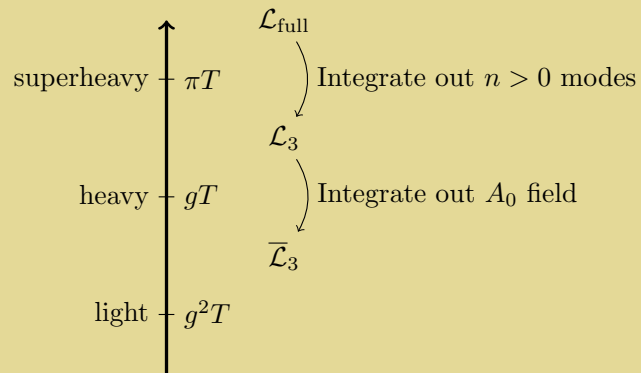
Lattice Monte Carlo: IR physics



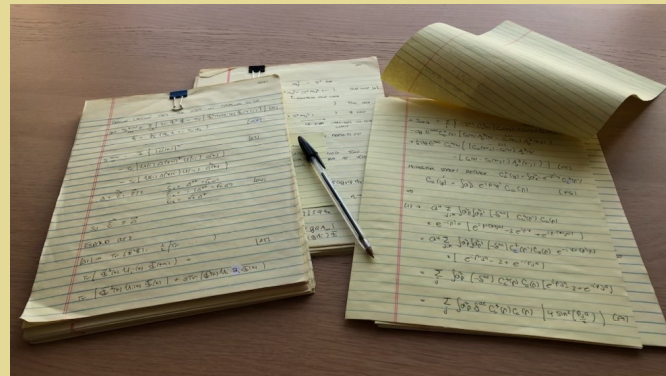
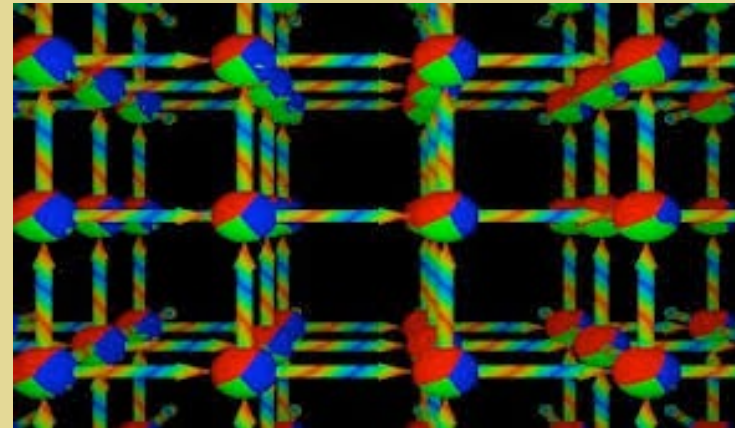
Analytic work

Lattice + Thermal EFT

3-D high- T effective theory



Lattice Monte Carlo: IR physics



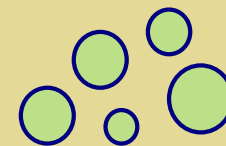
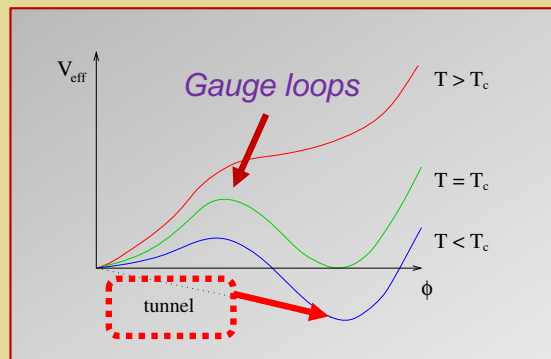
Analytic work



Sums low- p contributions to all orders

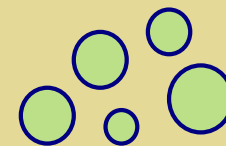
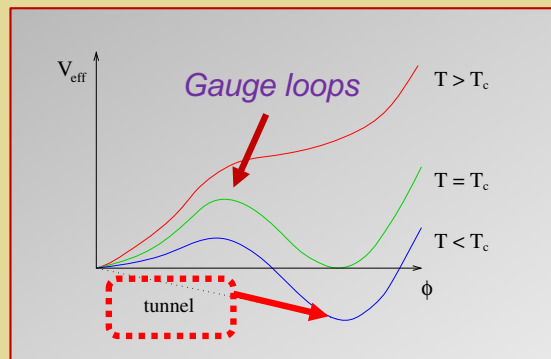
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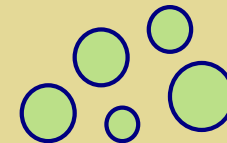
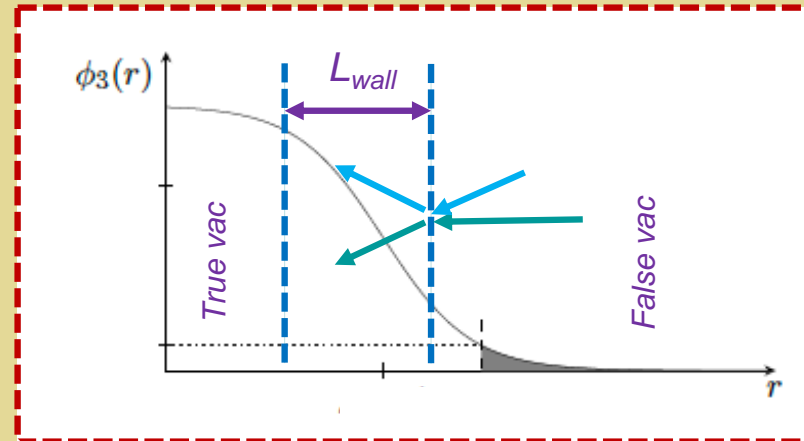


Progress @ TDLI

- **Reorganization of perturbative expansion yields a gauge-invariant computation \rightarrow 2112.05472, 2112.08912**

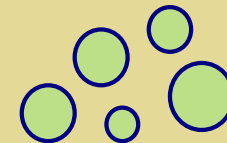
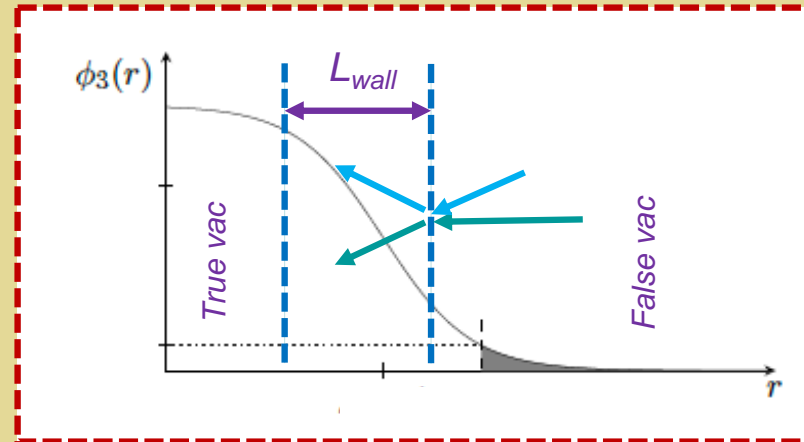
QFT Robustness

- **Wall velocity: microphysics & fluid dynamics**
 - Interplay between **driving force** (vacuum energy difference) and **friction pressure** (particle-wall interactions) decisive for obtaining $v_w \rightarrow$ decisive for GW probe sensitivity



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Progress @ TDLI
blou622 @ TDLI

- Rigorous treatment of p_{NORMAL} non-conservation in particle-wall interactions via Kadanoff-Baym equations \rightarrow 2504.13724

IV. Electroweak Condensation: Results

BSM EWPT: GW-Collider Interface

*Robust theory:
EFT + lattice*



Mapping



*Observables:
model specific*

Combination



*Bubble
dynamics:
 $\alpha, \beta / H^*, v_w$*

GW-Collider Inverse Problem

How can a combination of collider and GW measurements identify a given model and determine the Lagrangian parameters ?















- ***O. Gould, J. Kozaczuk, L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 1903.11604***
- ***L. Friedrich, MJRM, T.V.I. Tenkanen, V.Q. Tran: 2203.05889***
- ***+ Several collider-focused studies***

First Order EWPT: Collider Probes

Higgs property

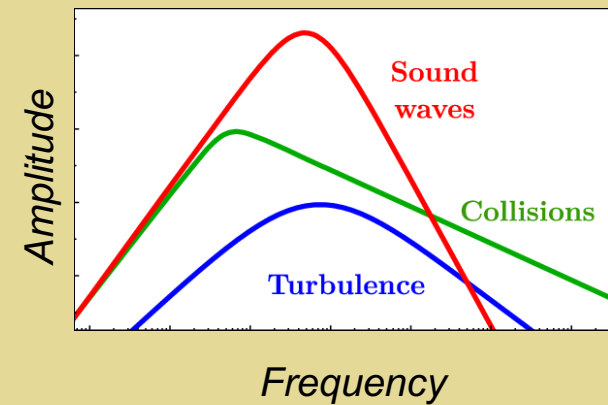
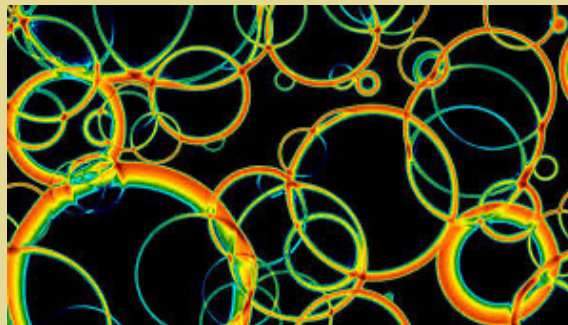
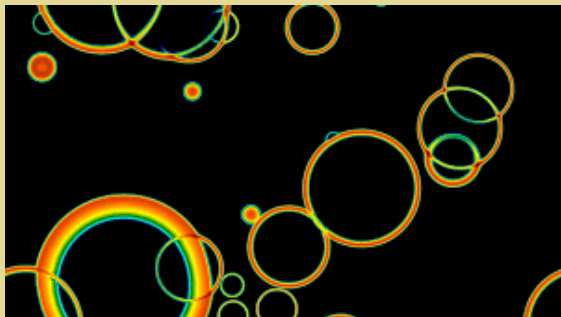
hadron

lepton

- $\Gamma(h \rightarrow \gamma\gamma)$  
- **Exotic Higgs Decays**  
- **Higgs signal strengths**  
- **Higgs self-coupling**  
- **Resonant di-Higgs production**  
- **Heavy Higgs $\rightarrow VV$**  
- **Associated production (Zh)**  

Gravitational Radiation

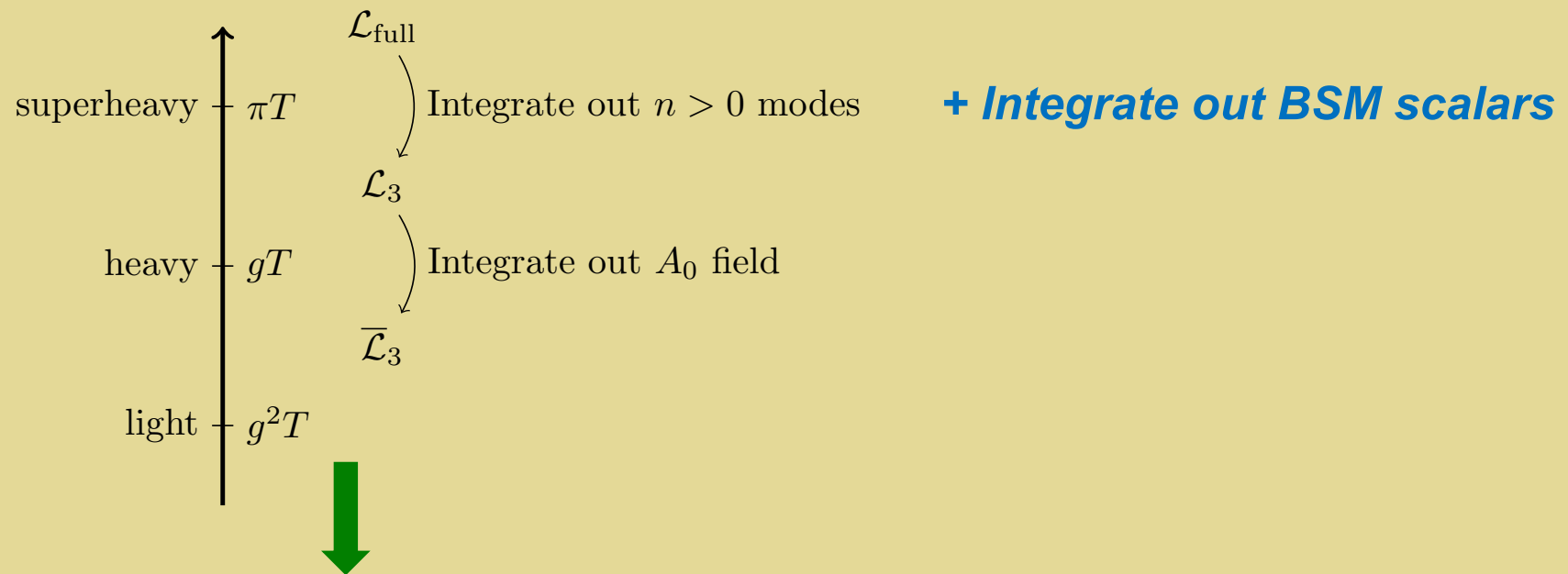
$$\Omega_{\text{GW}} = \Omega_{\text{coll}} + \Omega_{\text{sw}} + \Omega_{\text{turb}}$$



$\alpha, \beta / H_*, v_w, \dots \rightarrow$ inputs for GW sources: **collisions, sound waves, hydrodynamic turbulence**

Particle Physics Ingredients @ $T > 0$

Framework: 3-D high- T effective theory



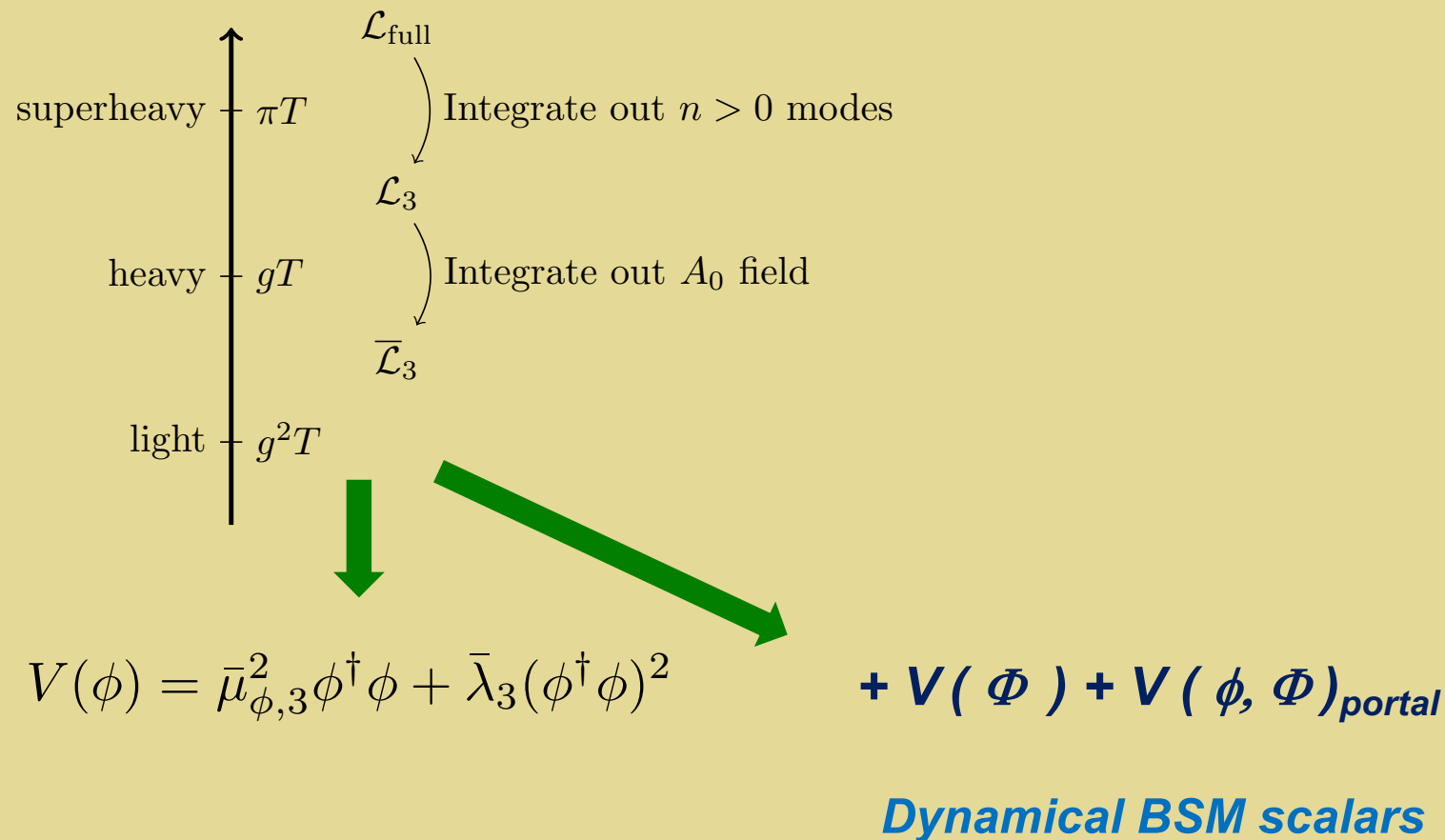
$$V(\phi) = \bar{\mu}_{\phi,3}^2 \phi^\dagger \phi + \bar{\lambda}_3 (\phi^\dagger \phi)^2$$

Non-dynamical BSM scalars

"Standard Model-like"

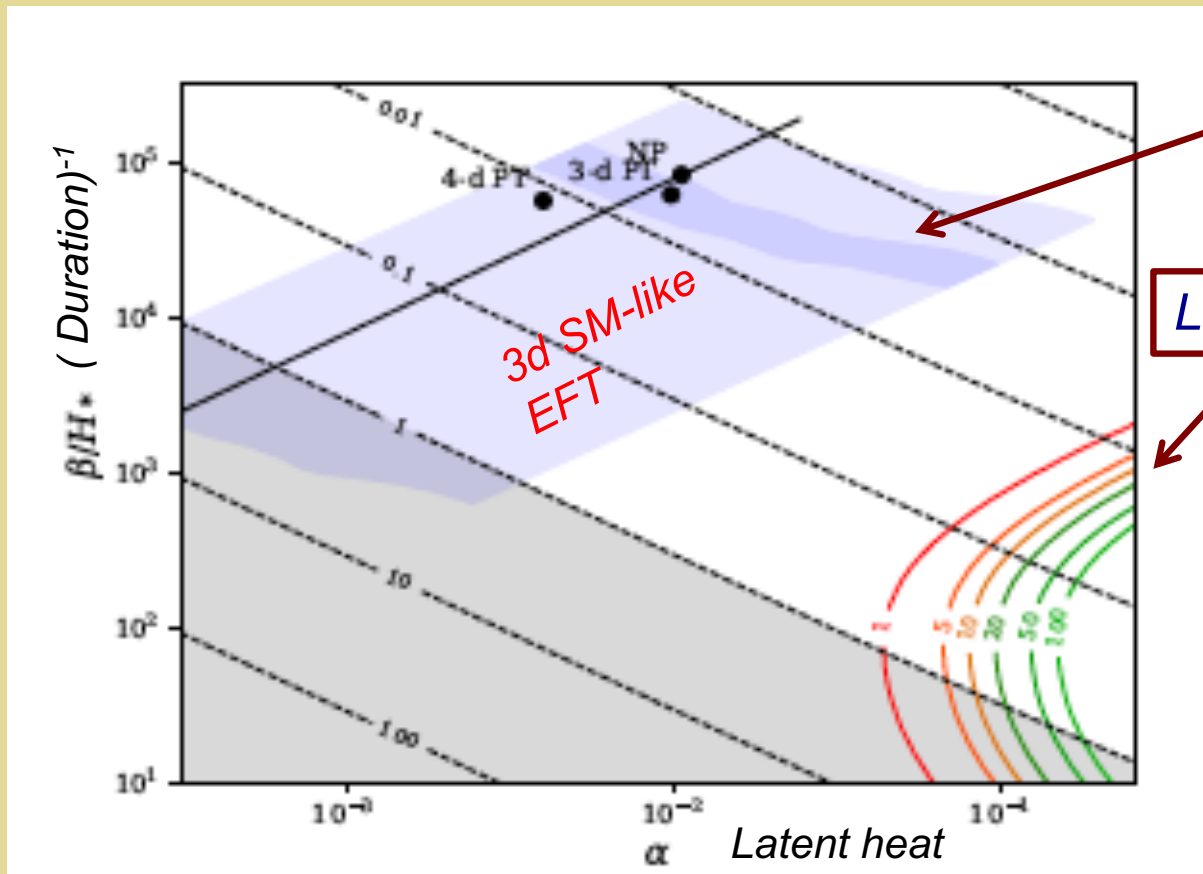
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BSM Scalar: EWPT & GW

High- T dimensional reduction: DR 3d EFT

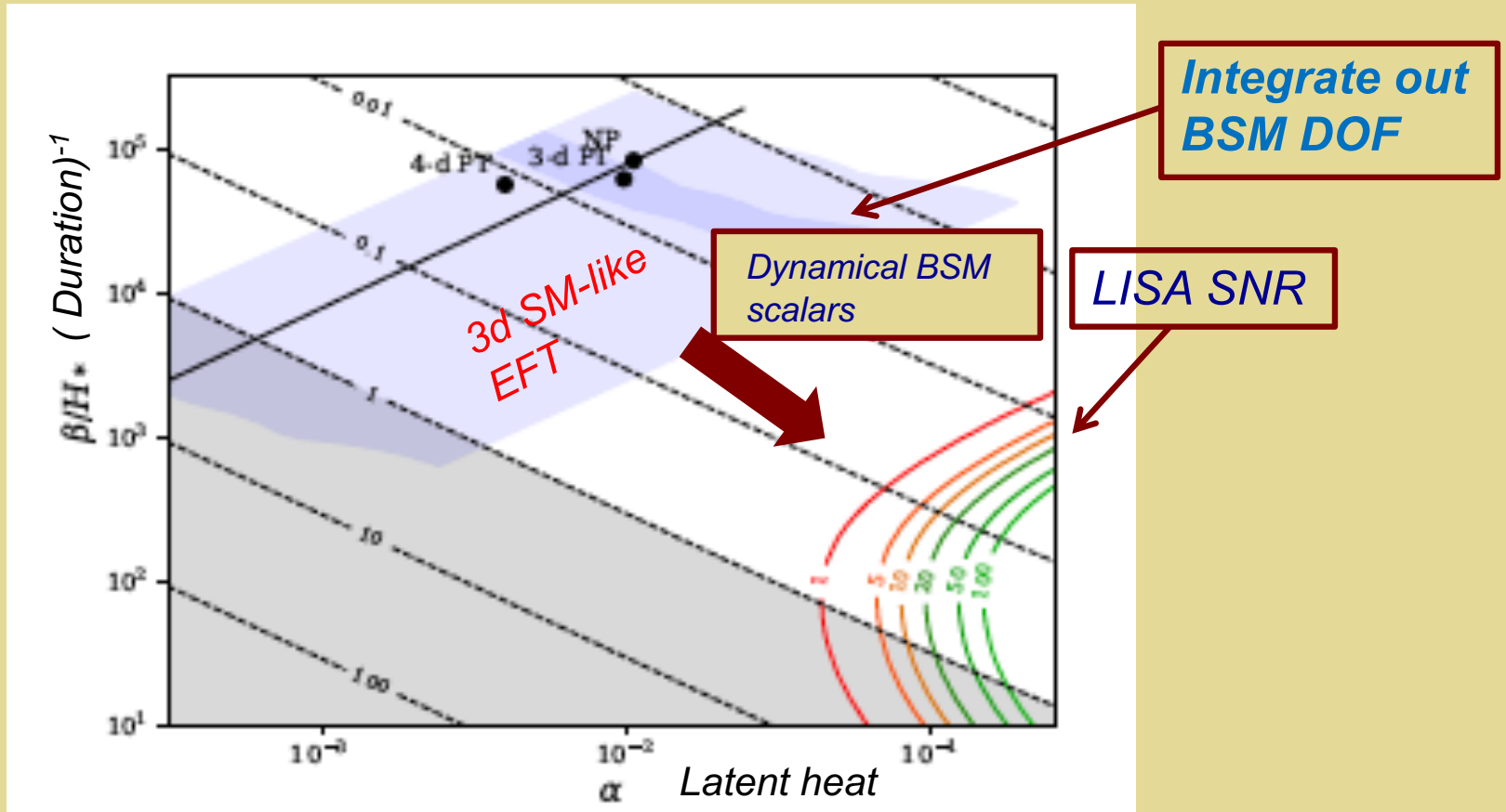


Integrate out BSM DOF

LISA SNR

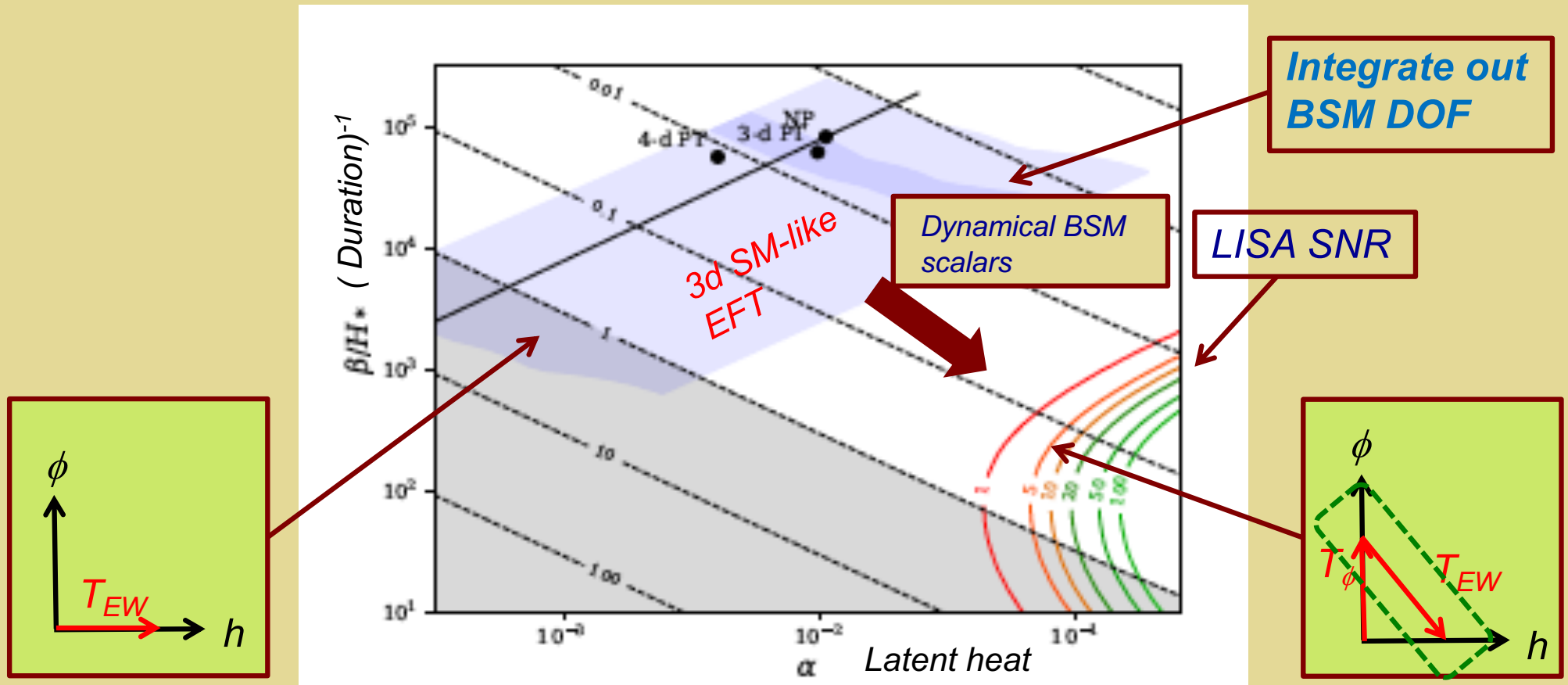
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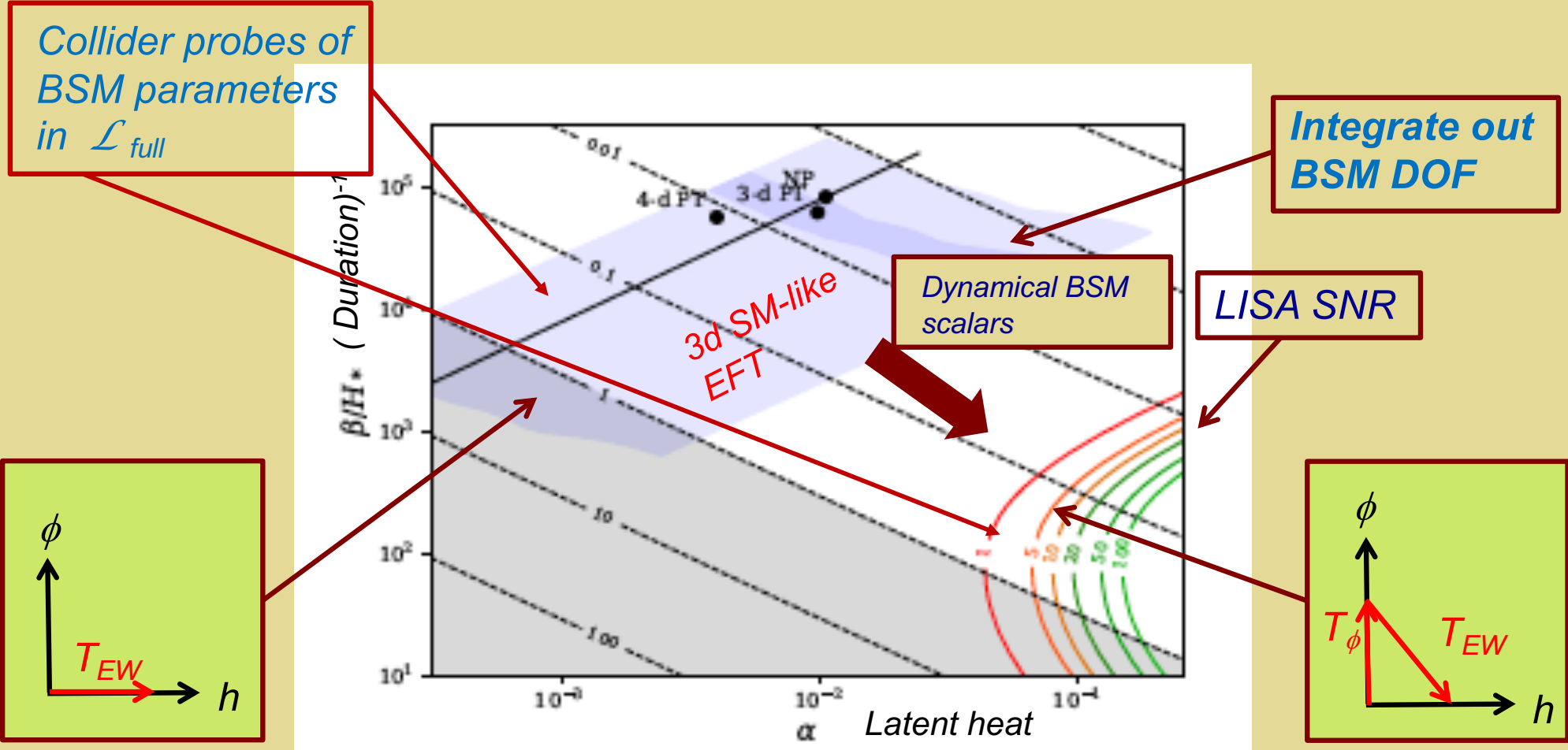


BSM Scalar: EWPT & GW

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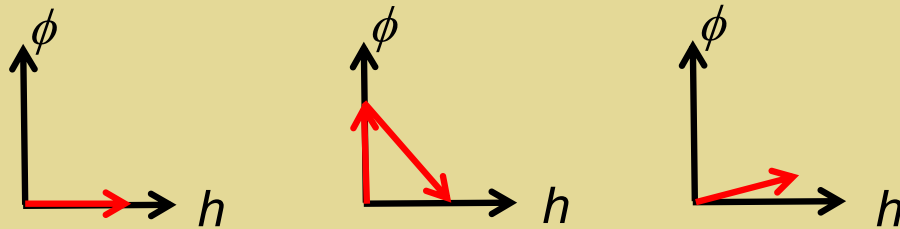
EW Condensation: Simplified Models



Simple Higgs portal models:

- *Real gauge singlet (SM + 1)*
- *Real EW triplet (SM + 3)*

$$V \subset a_1 H^2 \phi + a_2 H^2 \phi^2$$



EW Condensation: Simplified Models

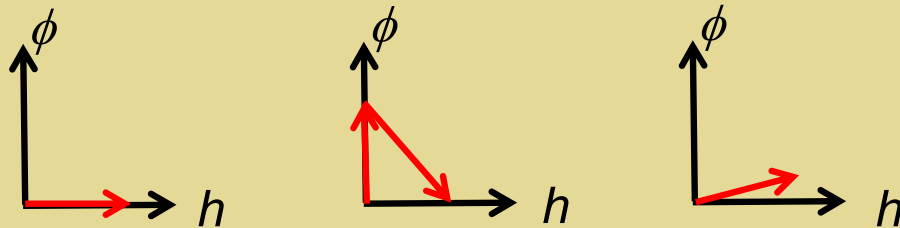


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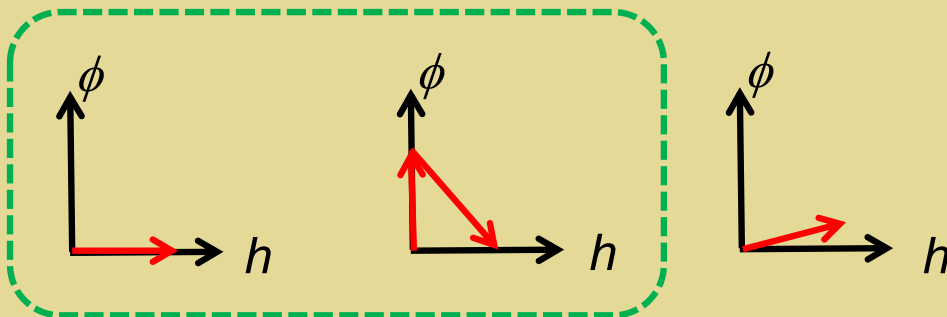
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small

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Thermal histories

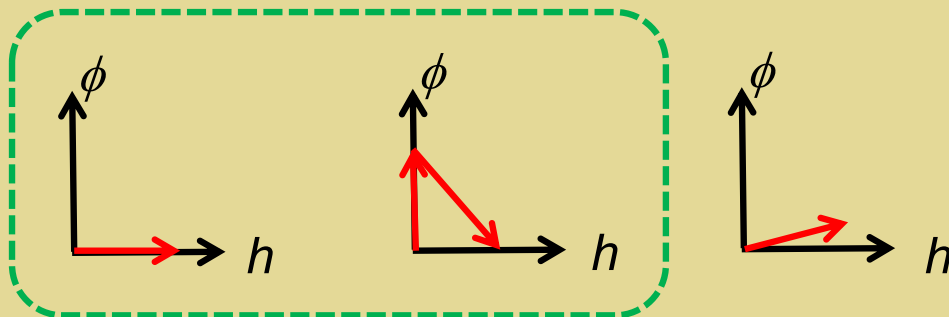
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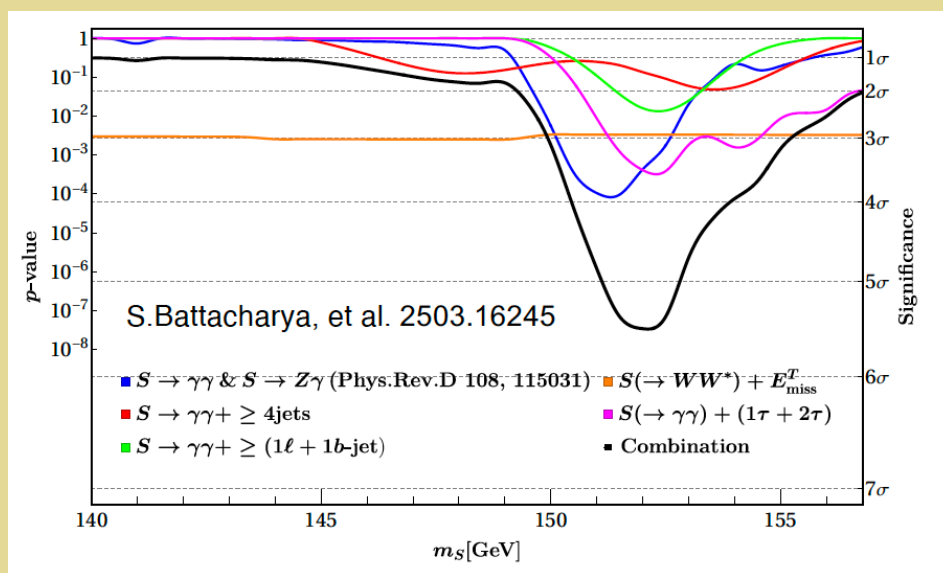


Thermal histories

Phenomenology

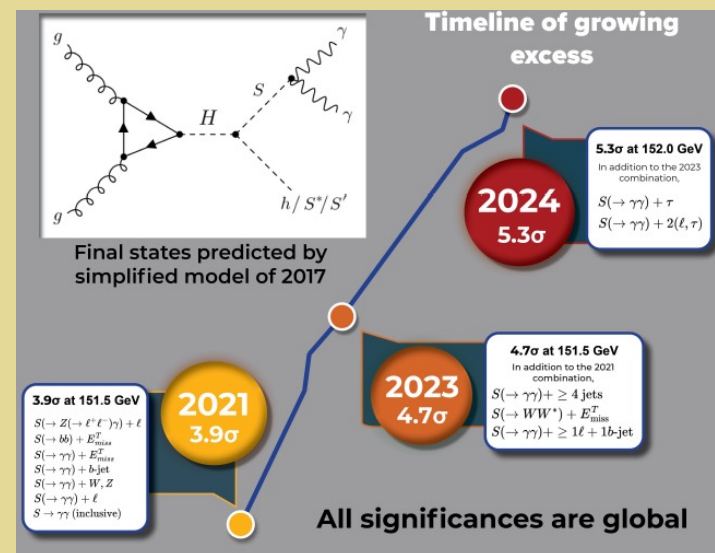
- Gravitational waves
- Collider: $h \rightarrow \gamma\gamma$, dis charged track, NLO $e^+e^- \rightarrow Zh...$

LHC Evidence

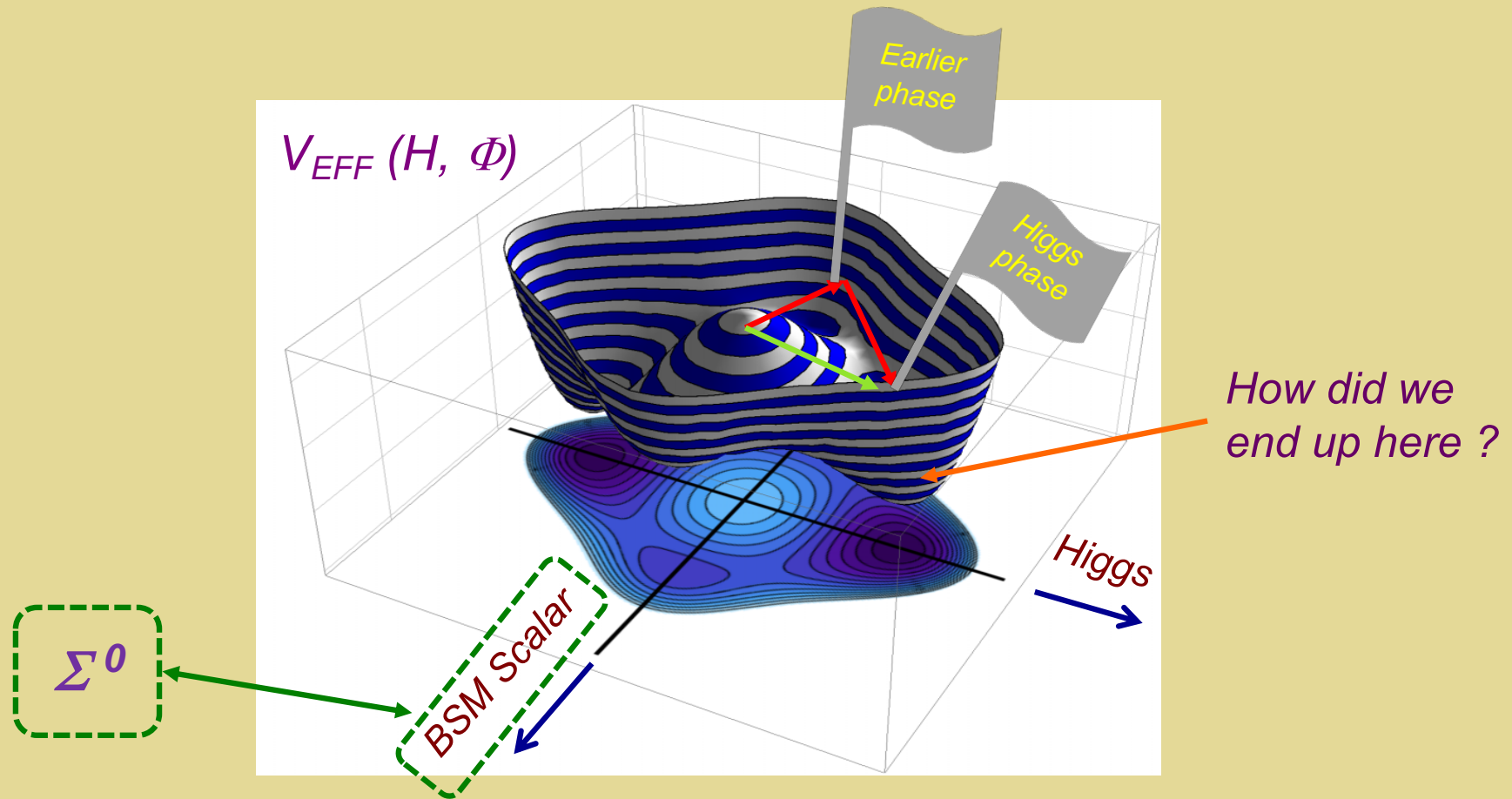


$$M_{\Sigma} = 152 \pm 1 \text{ GeV}$$

- Bruce Mellado talk, CEPC workshop November '25
- See also Andreas Crivellin talk, CEPC workshop November '25

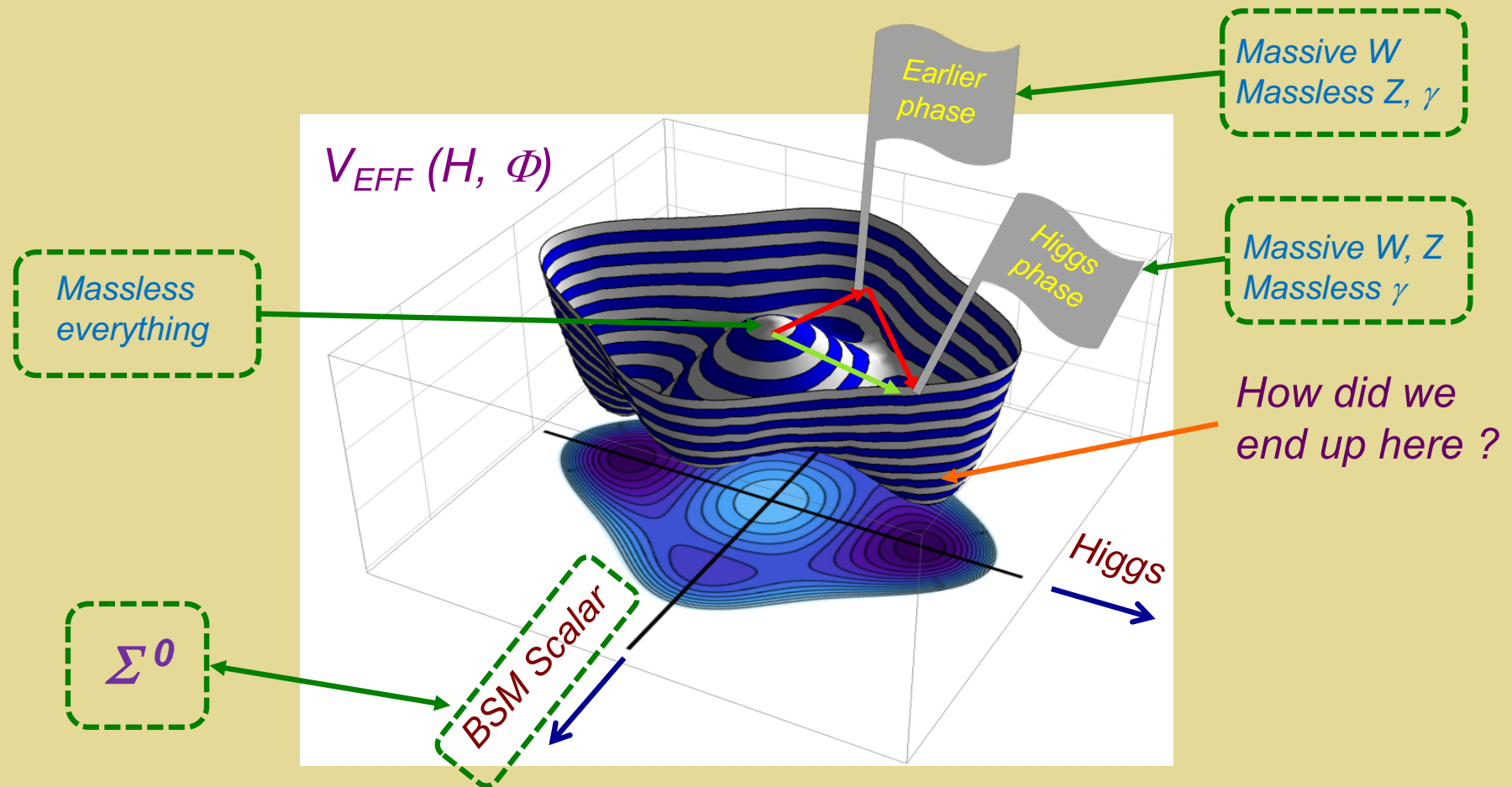


EW Condensation: Real Triplet



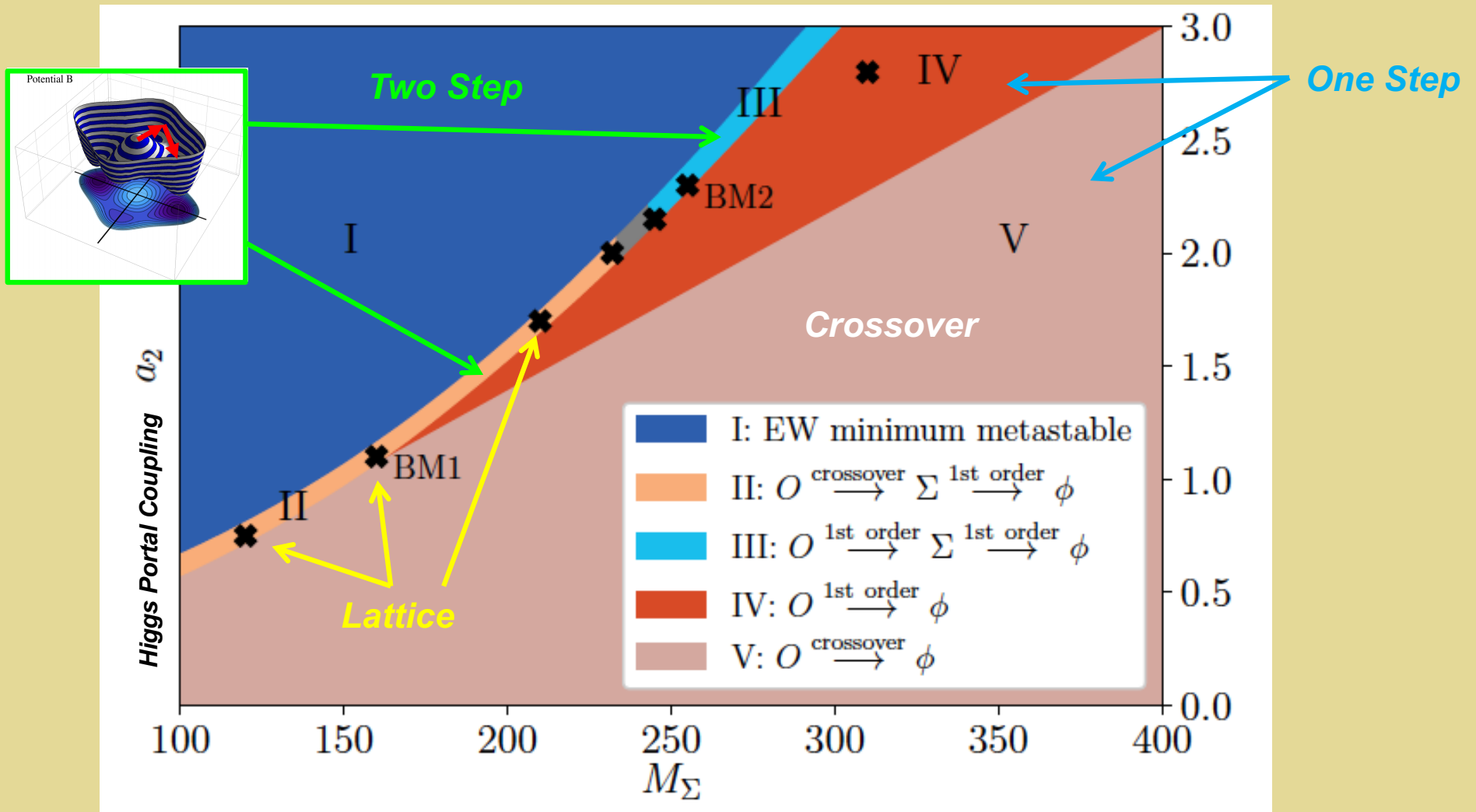
***Extrema can evolve differently as T evolves \rightarrow
rich possibilities for symmetry breaking***

EW Condensation: Real Triplet



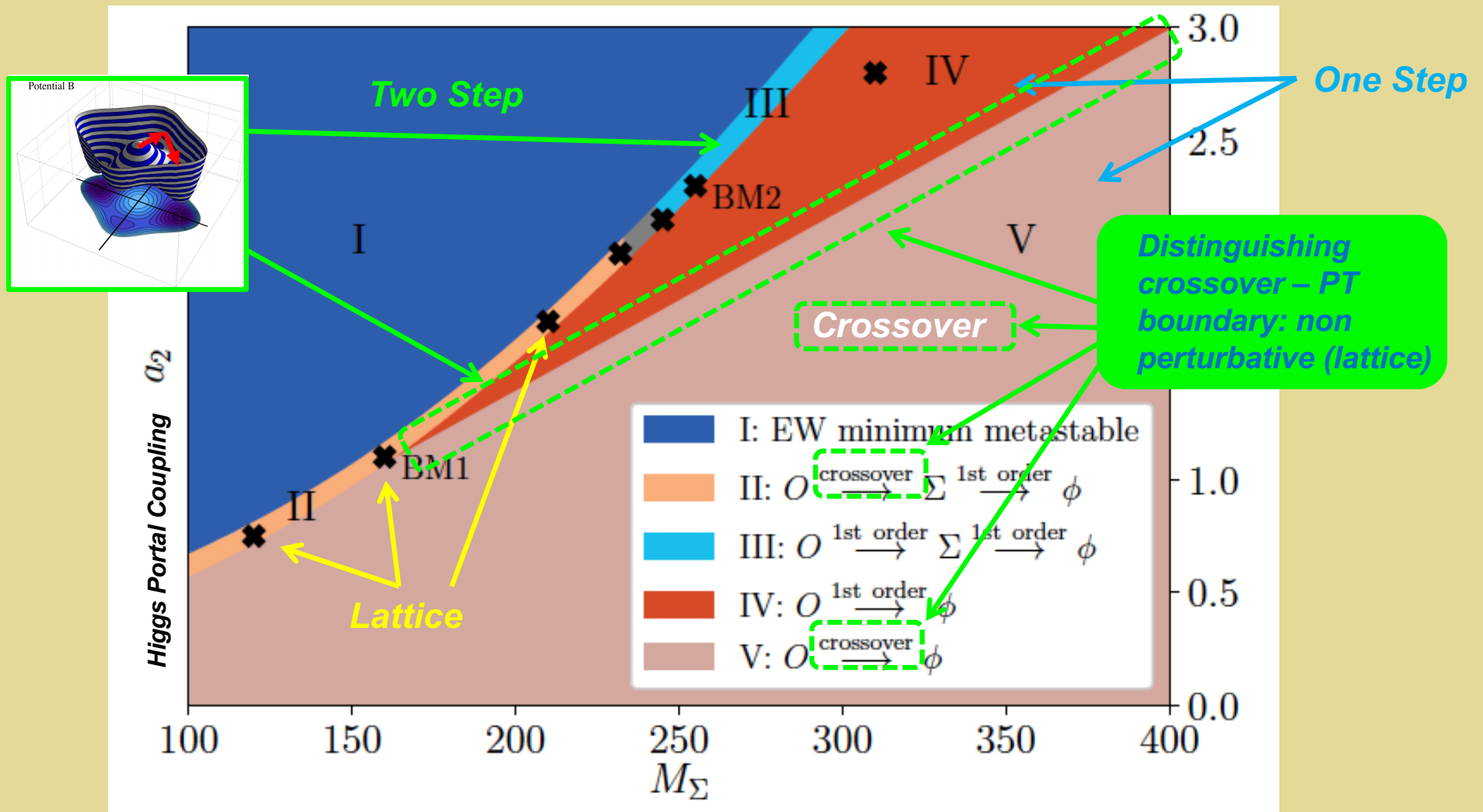
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Real Triplet: Novel EWSB



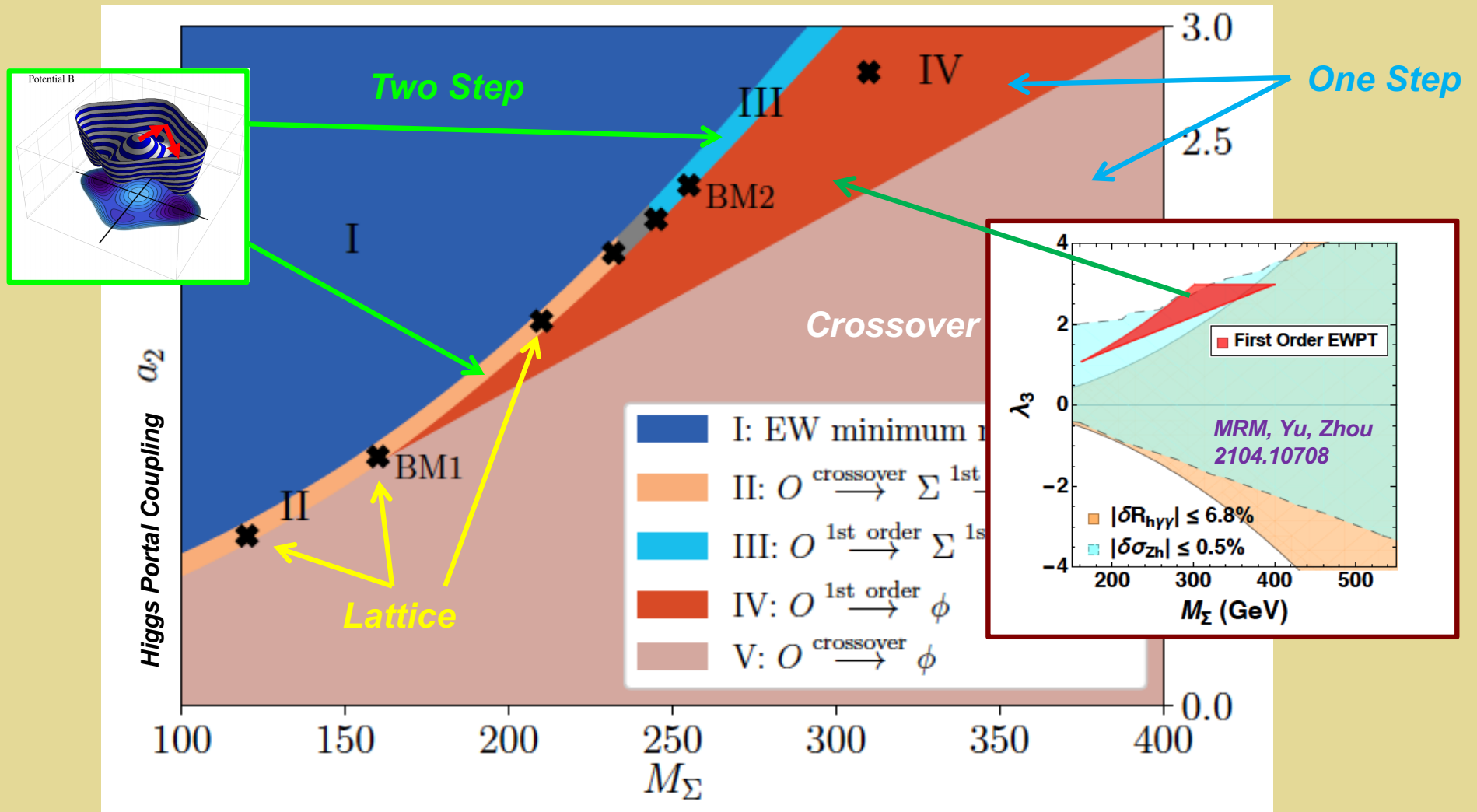
- 1 or 2 step
- Non-perturbative

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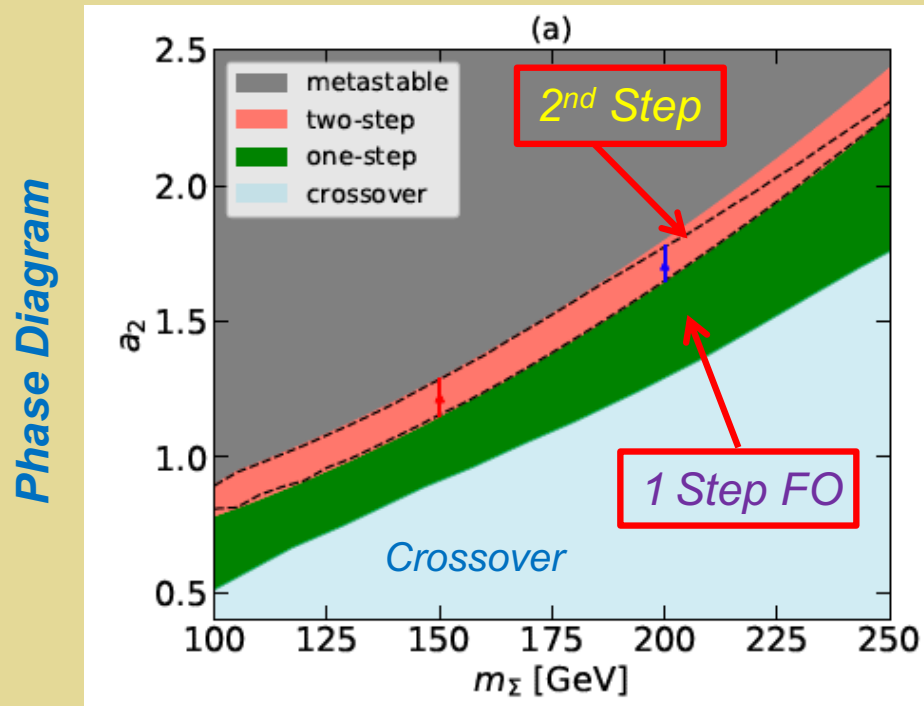
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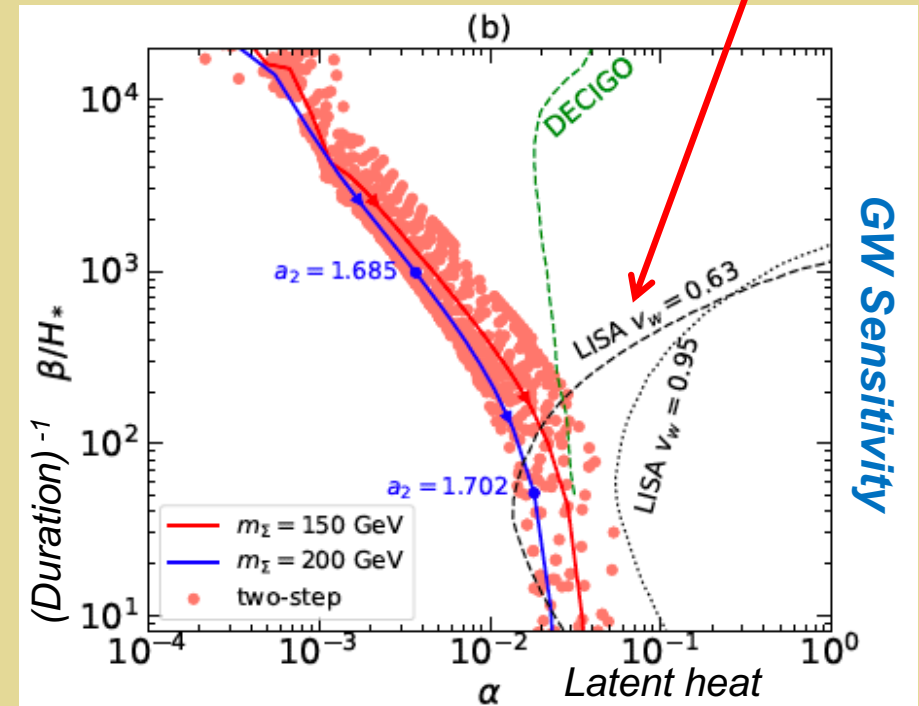
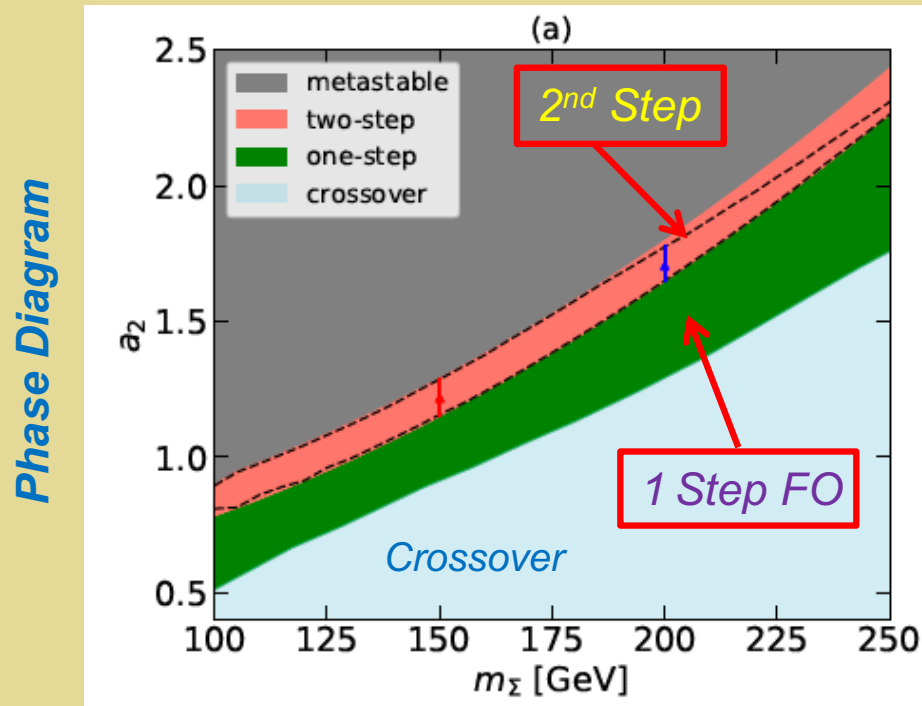
Exp't Probes: GW & Collider

Real triplet extension



Exp't Probes: GW & Collider

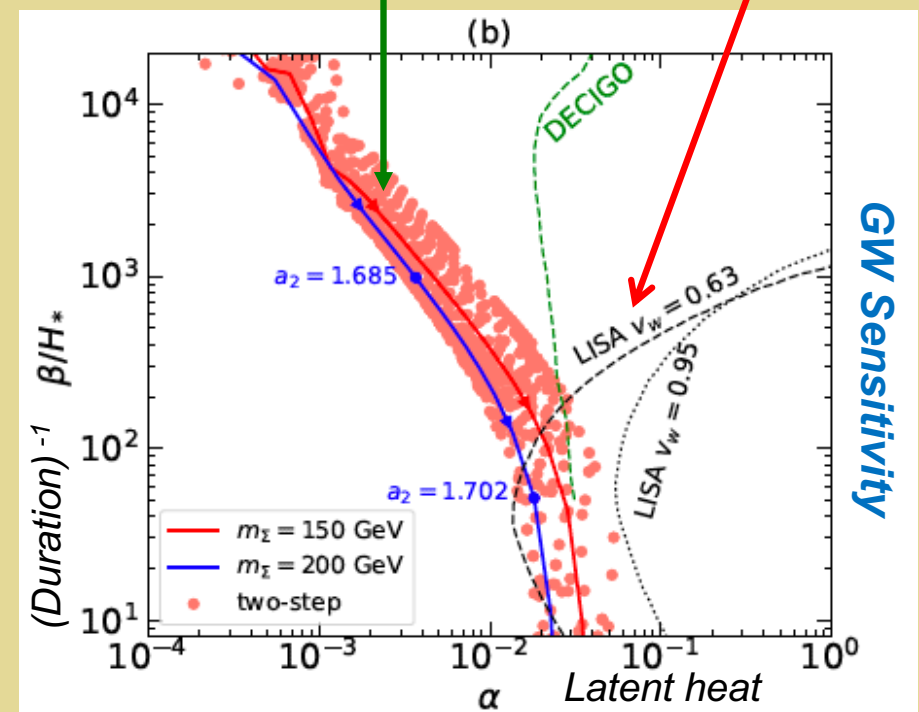
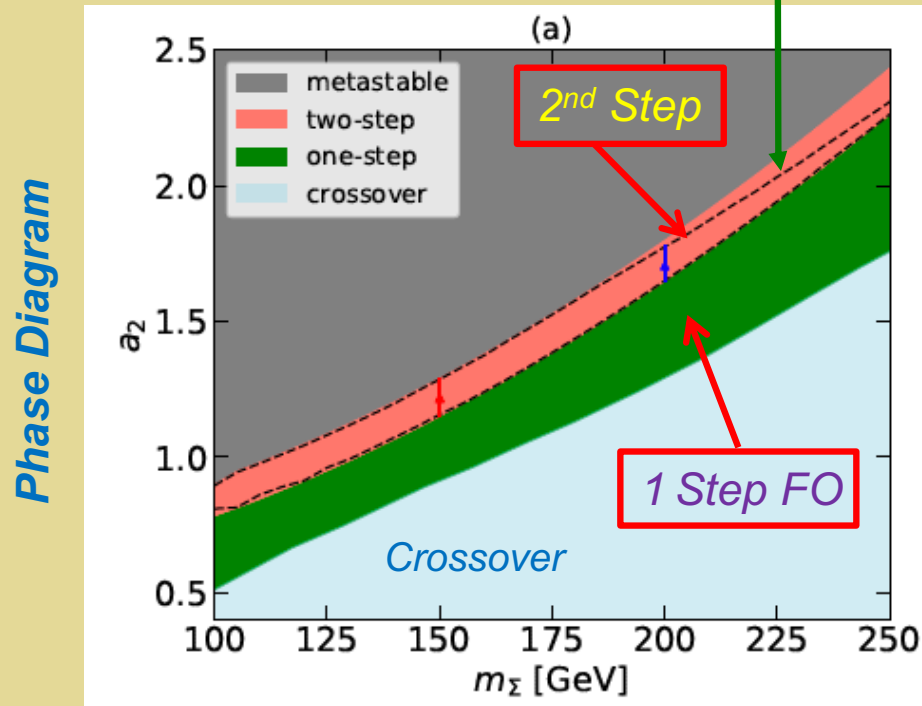
Real triplet extension



GW parameters: α , β/H^* , v_w

Exp't Probes: GW & Collider

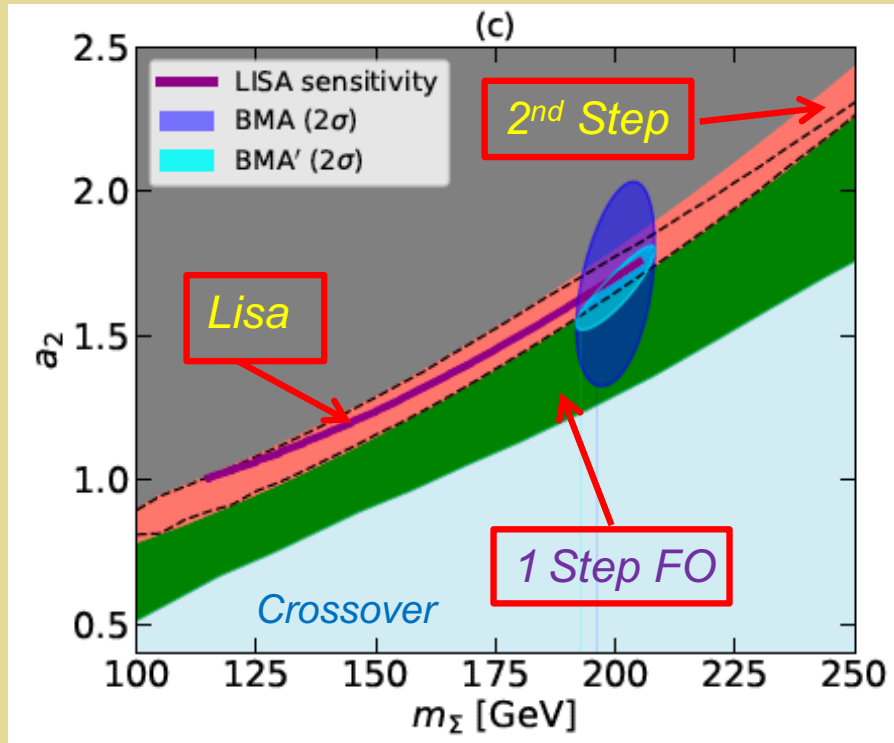
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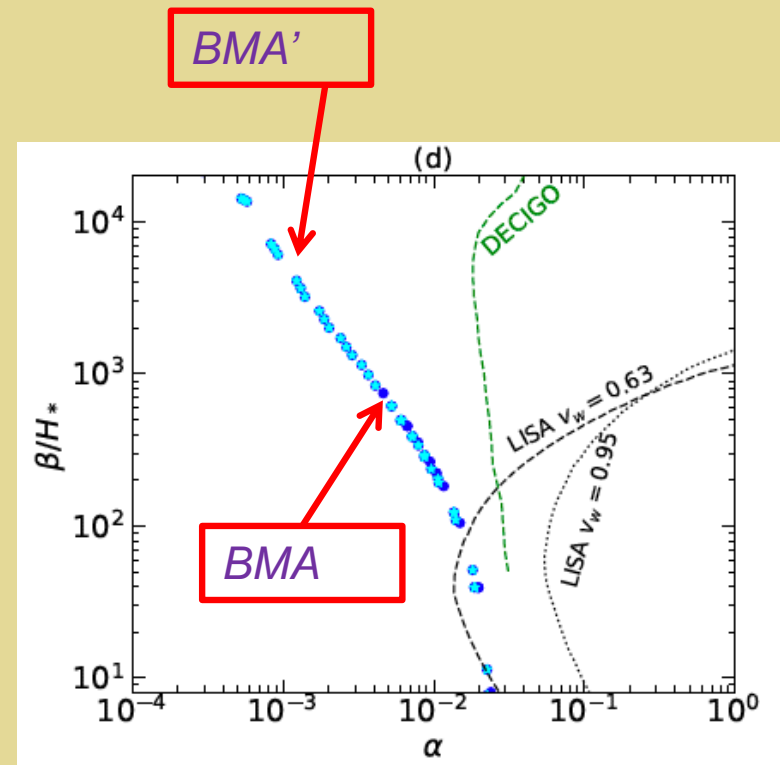
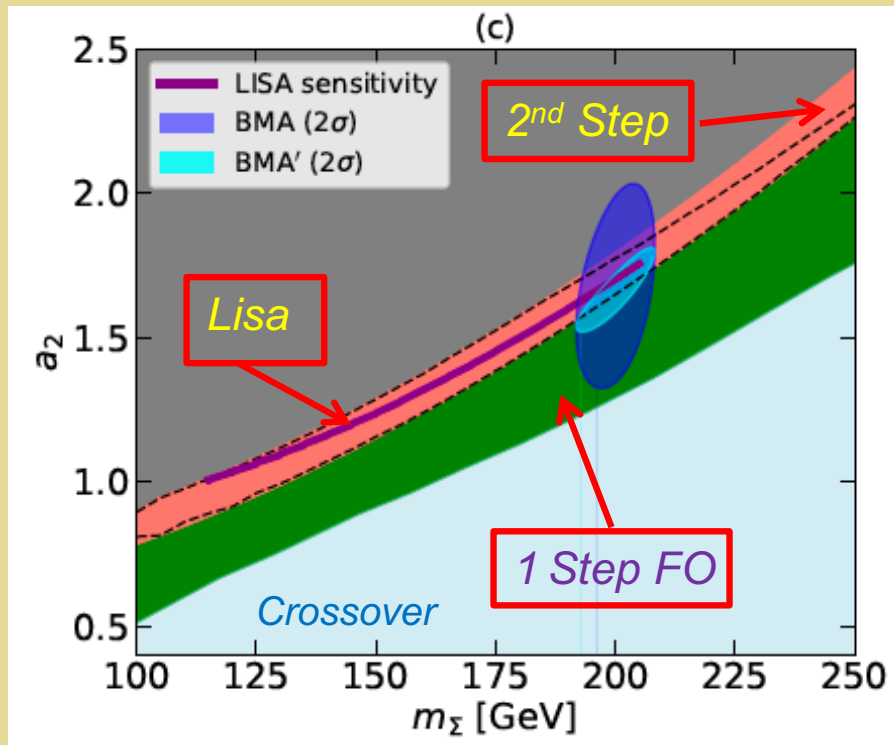
$$\text{BMA: } m_\Sigma + h \rightarrow \gamma\gamma$$

$$\text{BMA': } \text{BMA} + \Sigma^0 \rightarrow ZZ$$

Hypothetical
collider results

Exp't Probes: GW & Collider

Real triplet extension



$$\text{BMA: } m_\Sigma + h \rightarrow \gamma\gamma$$

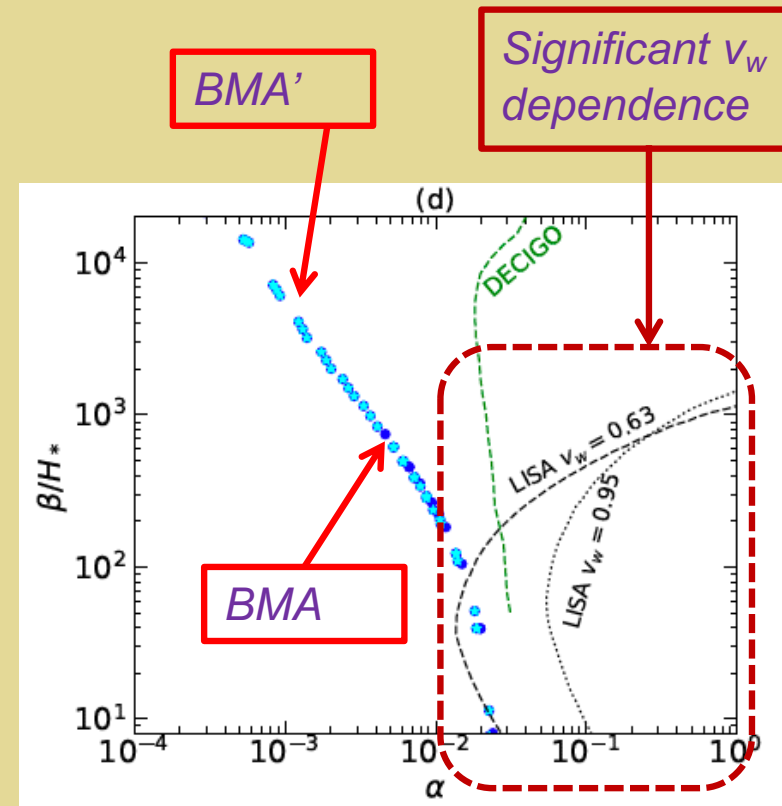
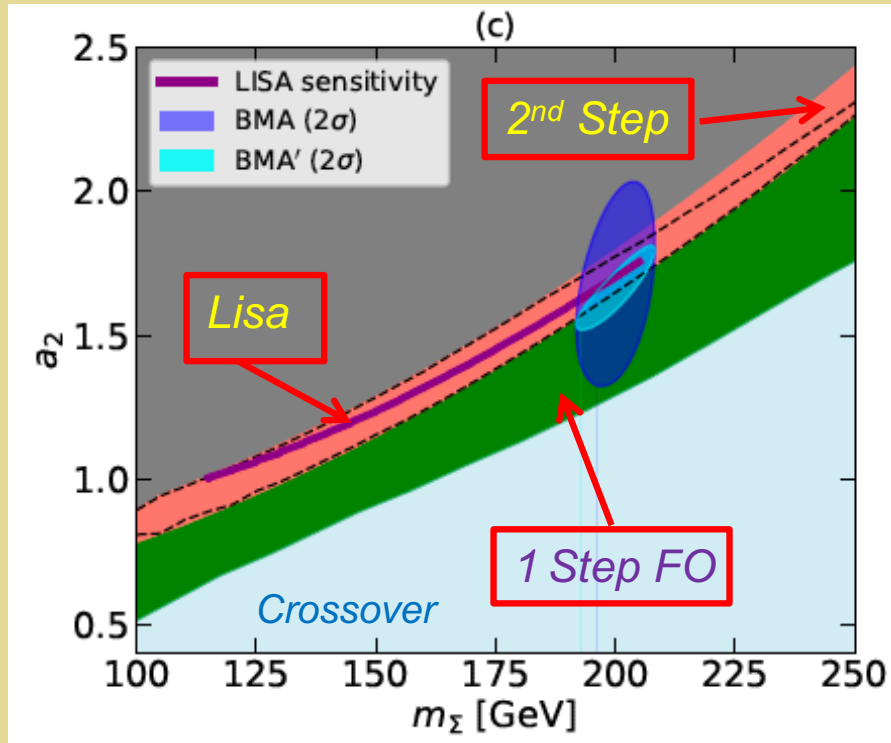
$$\text{BMA': } \text{BMA} + \Sigma^0 \rightarrow ZZ$$

Hypothetical
collider results

- Two-step
- EFT+ Non-perturbative

Exp't Probes: GW & Collider

Real triplet extension



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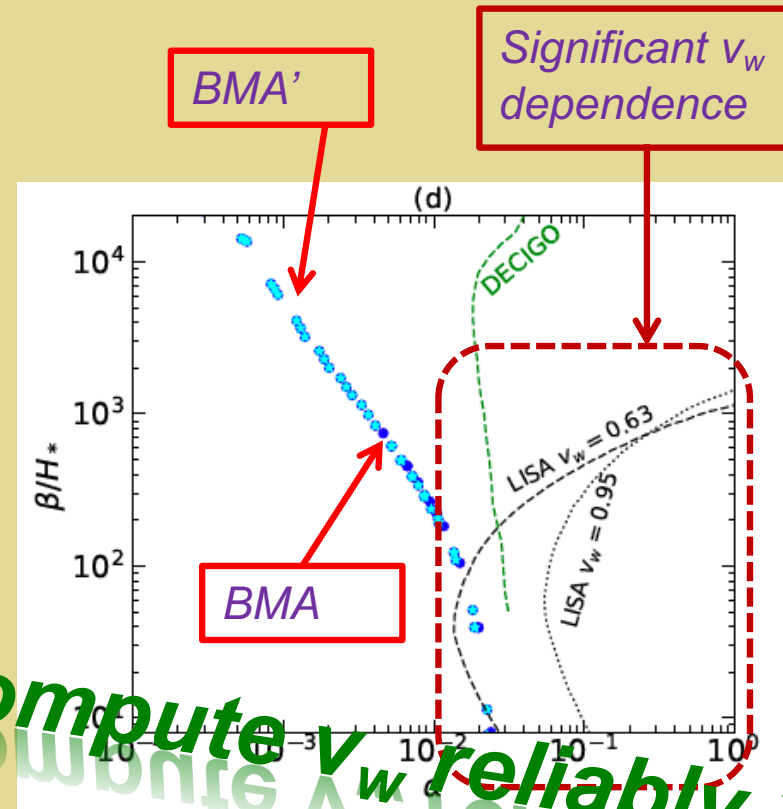
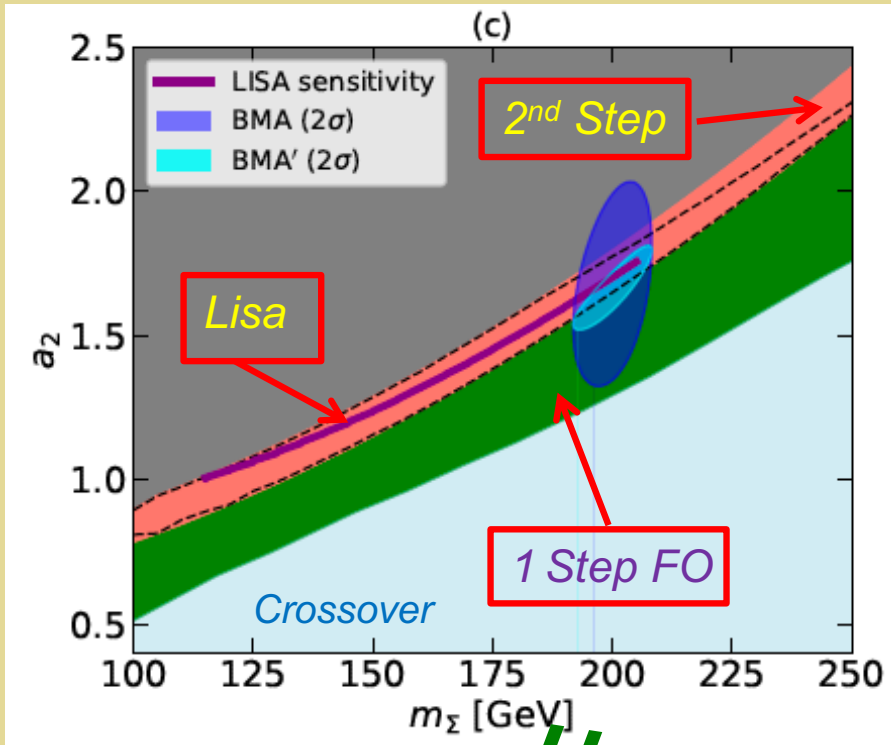
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BMA: $m_\Sigma + h \rightarrow \gamma\gamma$
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How to compute v_w reliably?

Hypothetical
collider results

- Two-step
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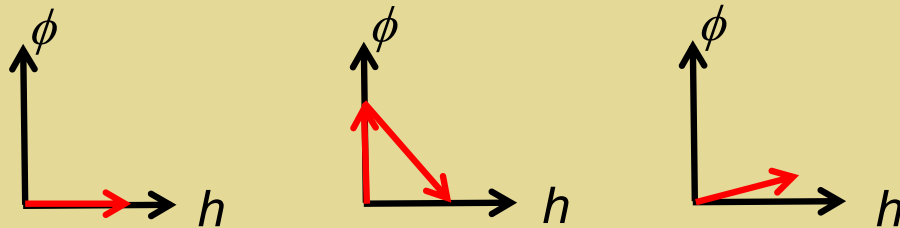
EW Condensation: Simplified Models



Simple Higgs portal models:

- *Real gauge singlet (SM + 1)*
- *Real EW triplet (SM + 3)*

$$V \subset a_1 H^2 \phi + a_2 H^2 \phi^2$$



EW Condensation: Simplified Models

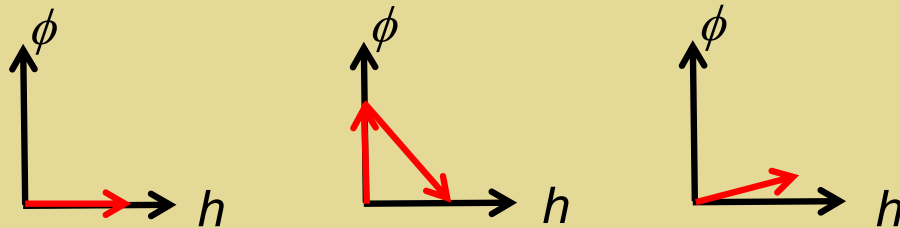


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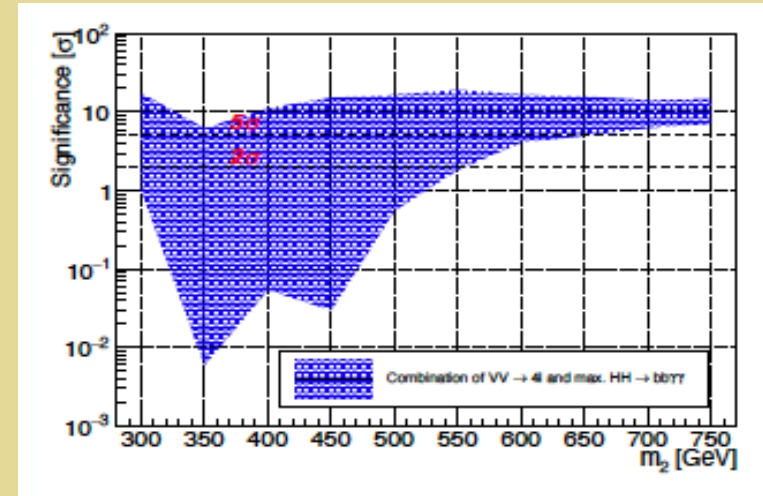
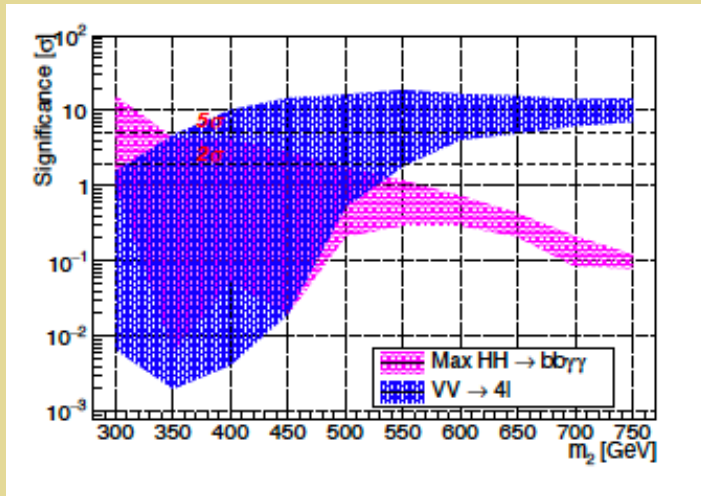
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H- ϕ mixing

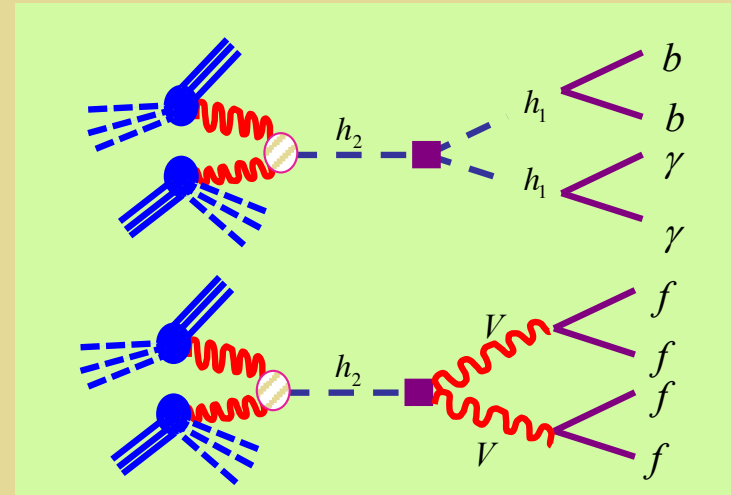
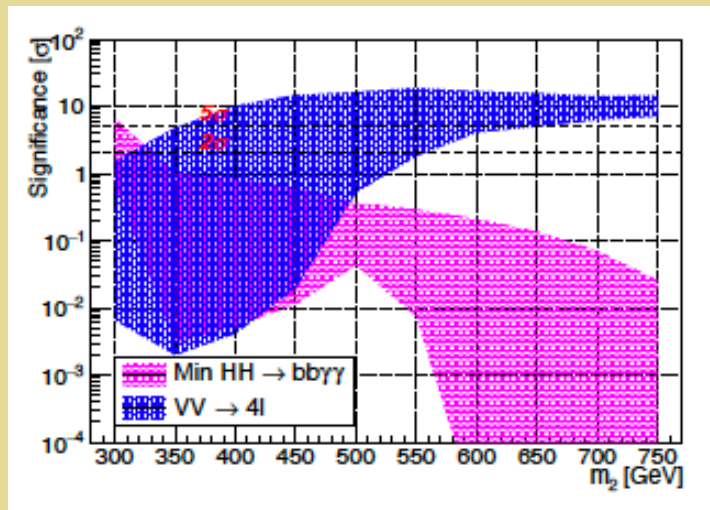


Singlets: Resonant Di-Higgs & $H_2 \rightarrow VV$

SFOEWPT Max Benchmarks: HL LHC Combination $bb\gamma\gamma$ & 4 lepton

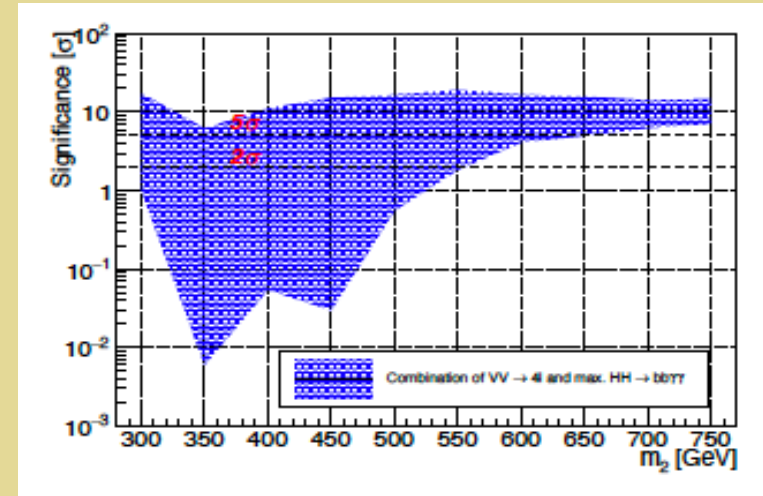
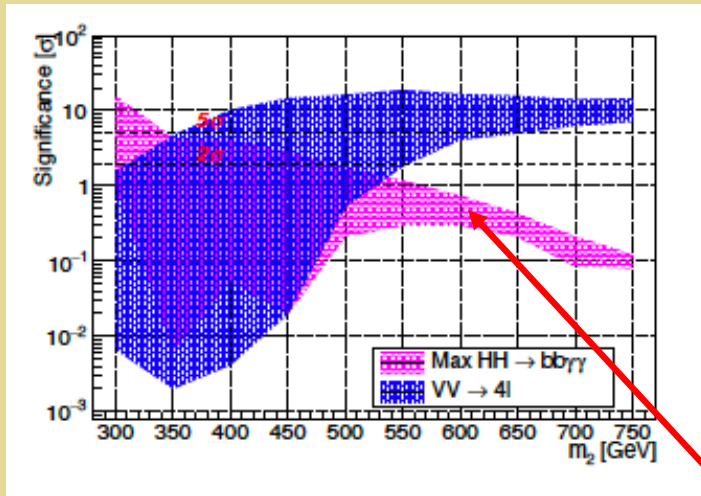


SFOEWPT Min Benchmarks:



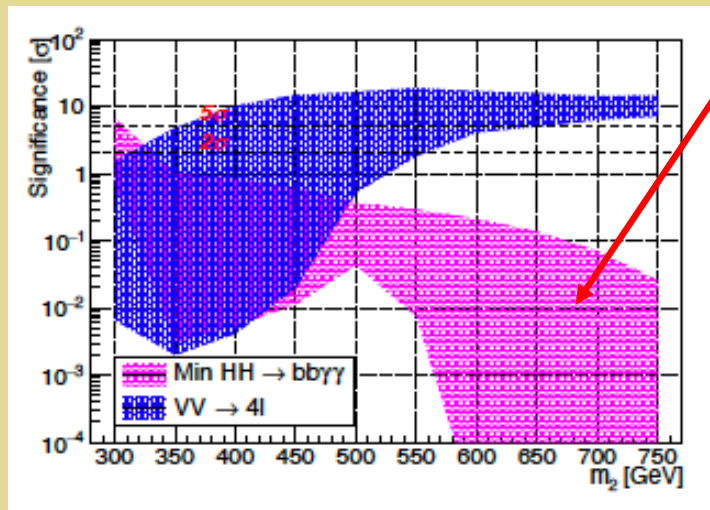
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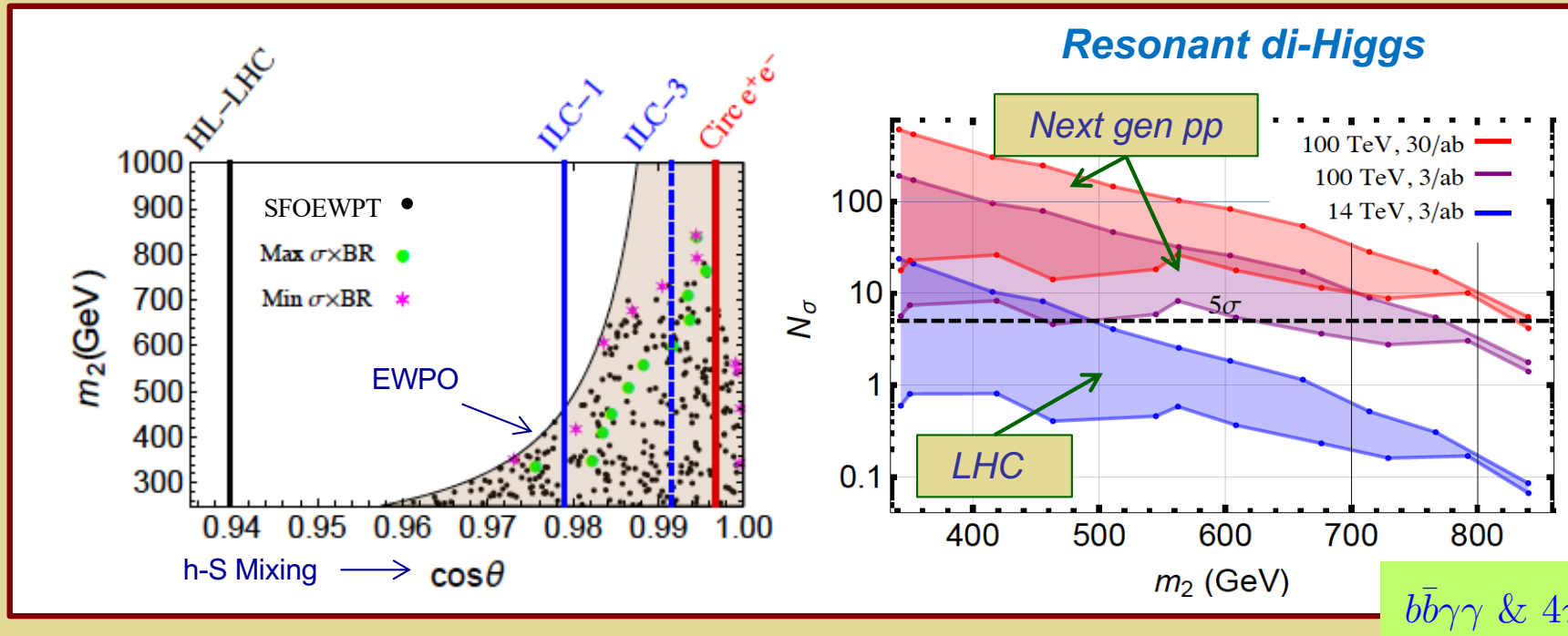
100 TeV accessible

SFOEWPT Min Benchmarks:



Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

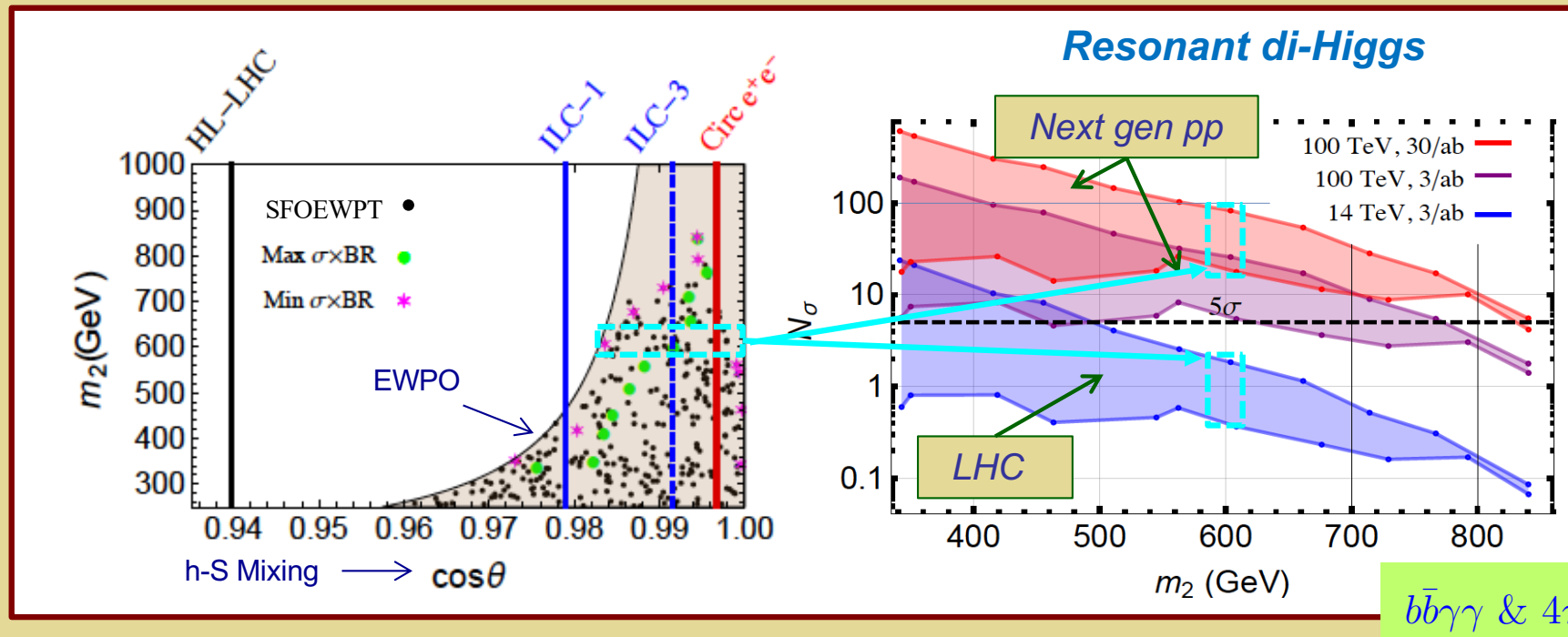


Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442;
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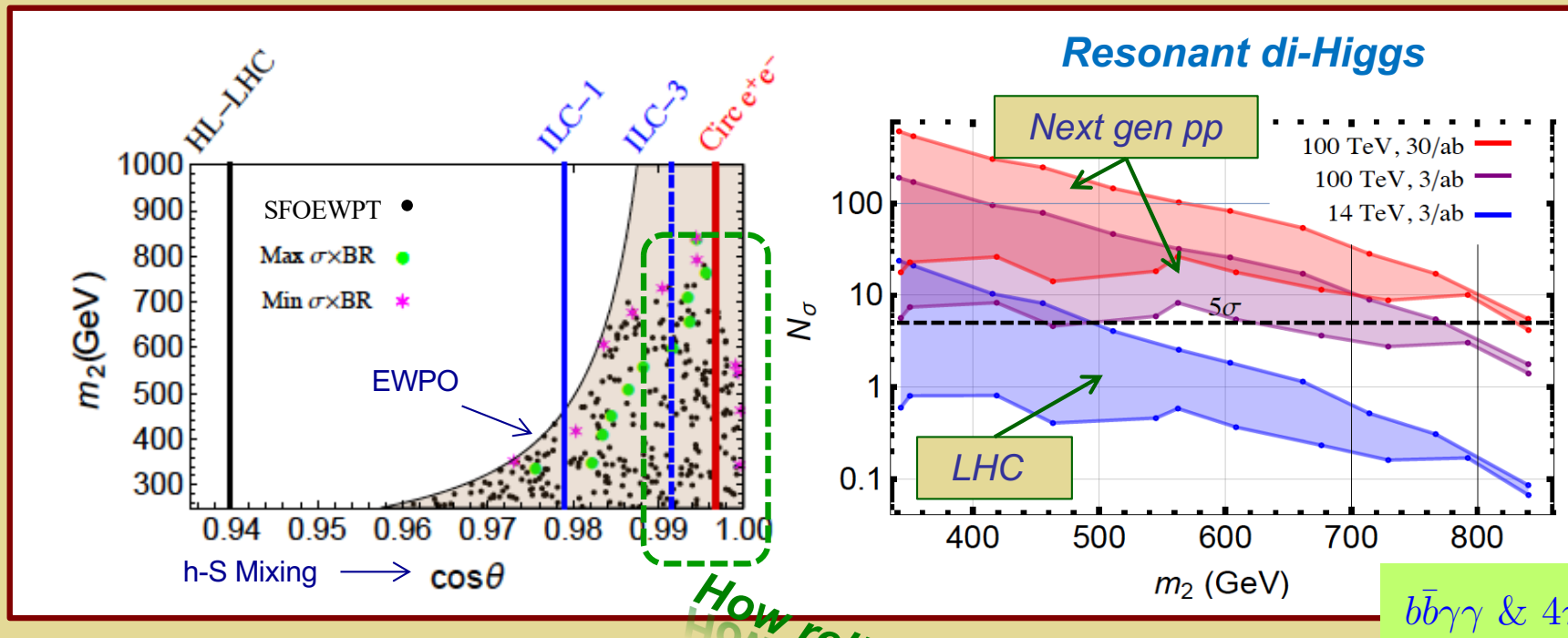


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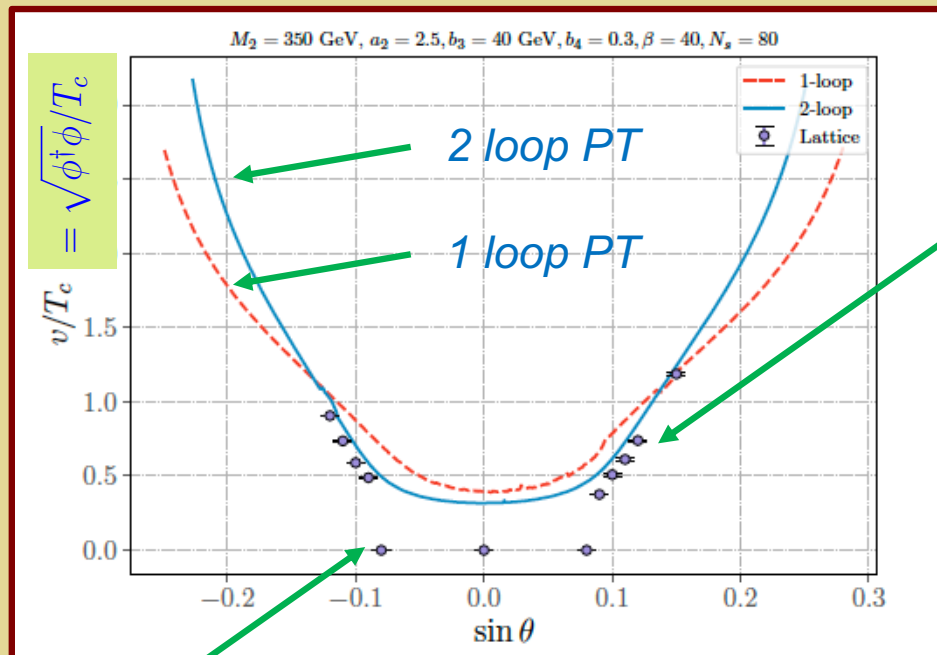
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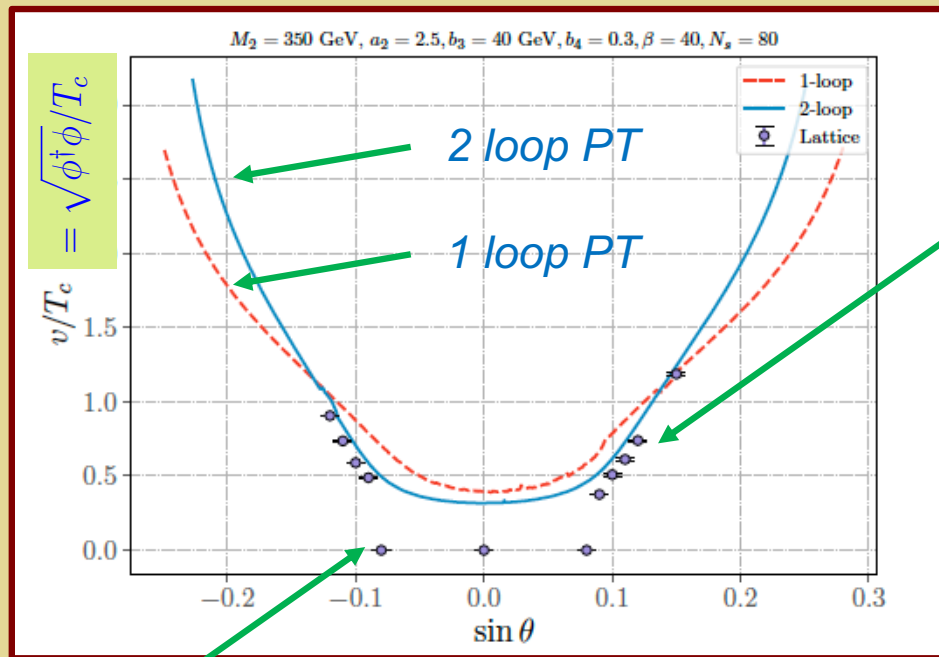
Singlets: Lattice vs. Pert Theory



Lattice:
FOEWPT

Lattice:
Crossover

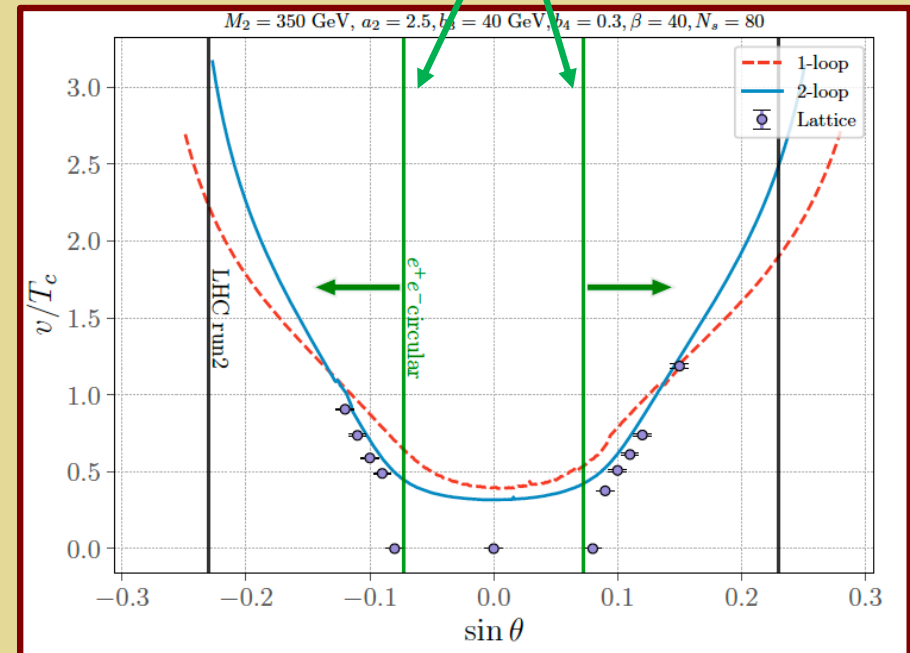
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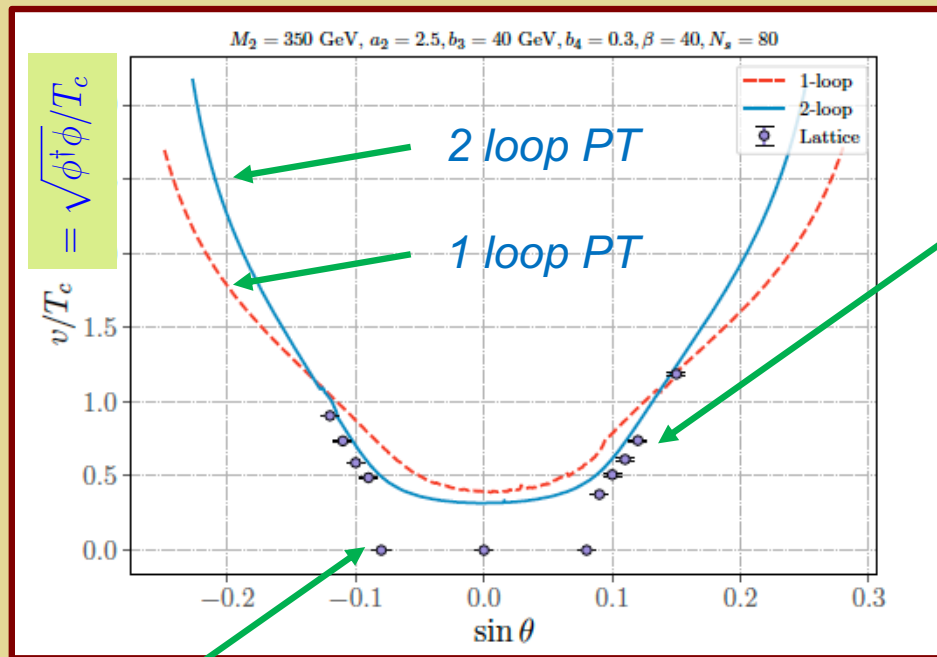
Lattice:
Crossover

Lattice:
FOEWPT

Future e^+e^-



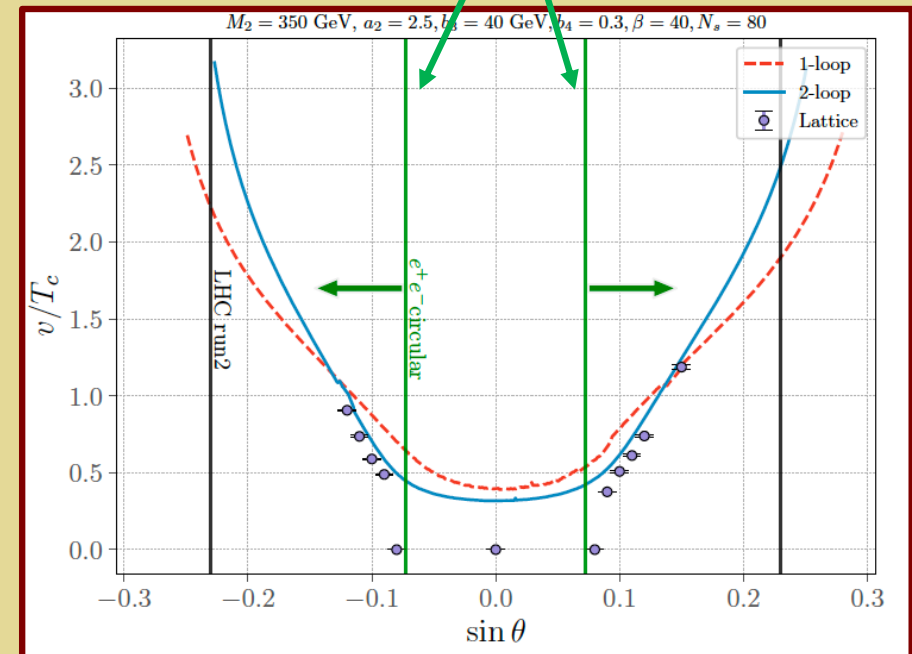
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Lattice:
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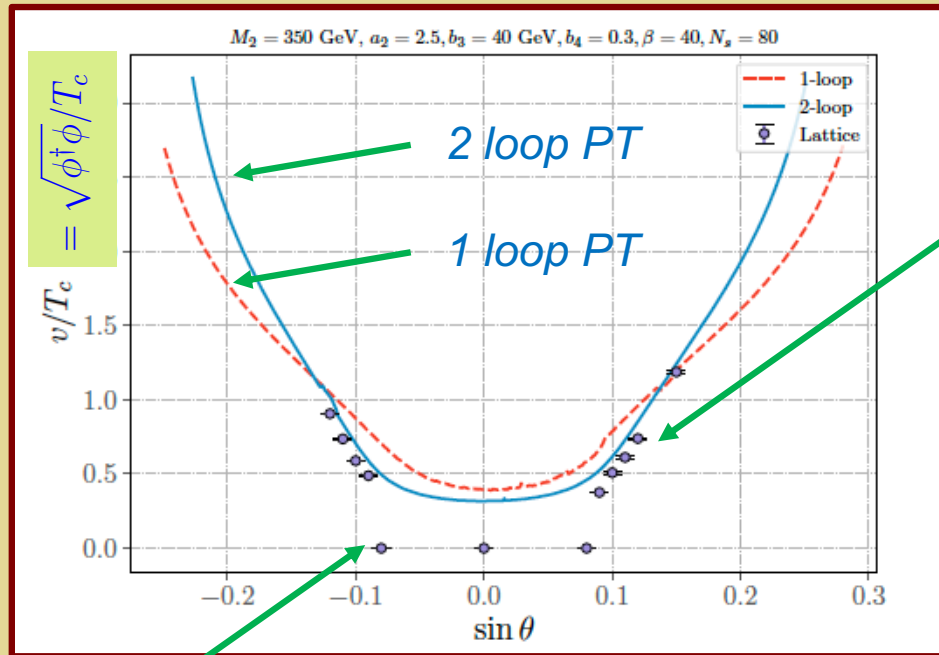
Lattice:
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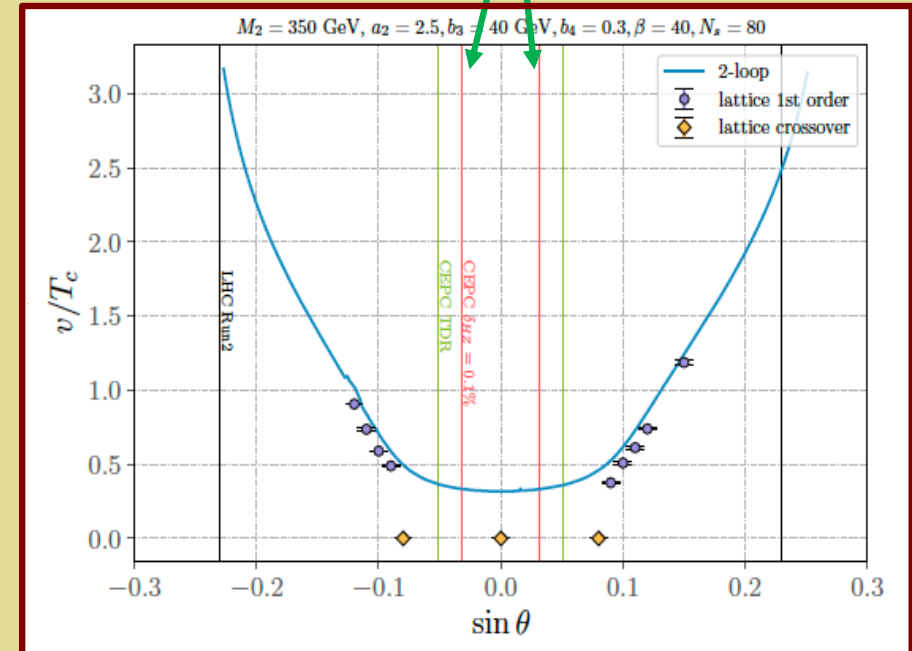
- Lattice: crossover-FOEWPT boundary
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- Pheno: precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized

Singlets: Lattice vs. Pert Theory



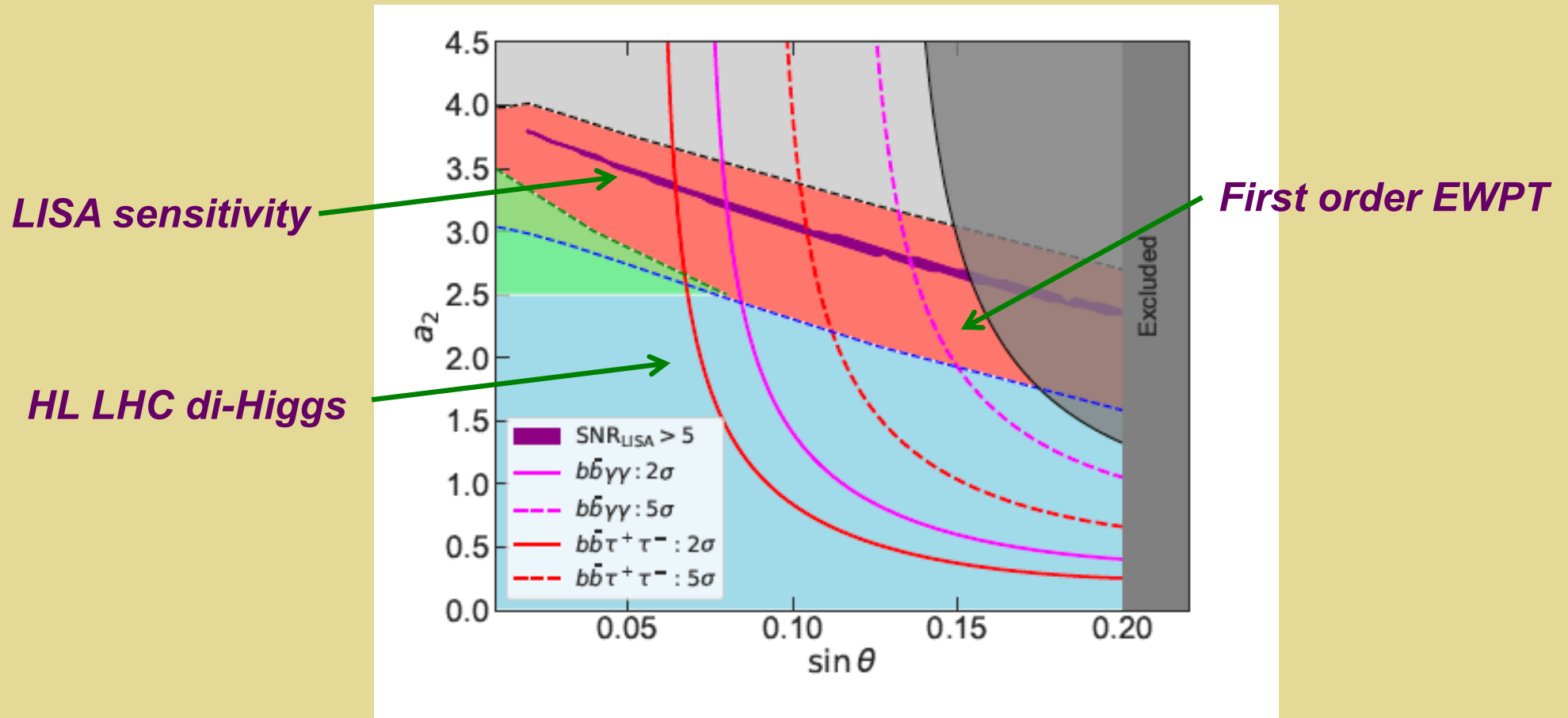
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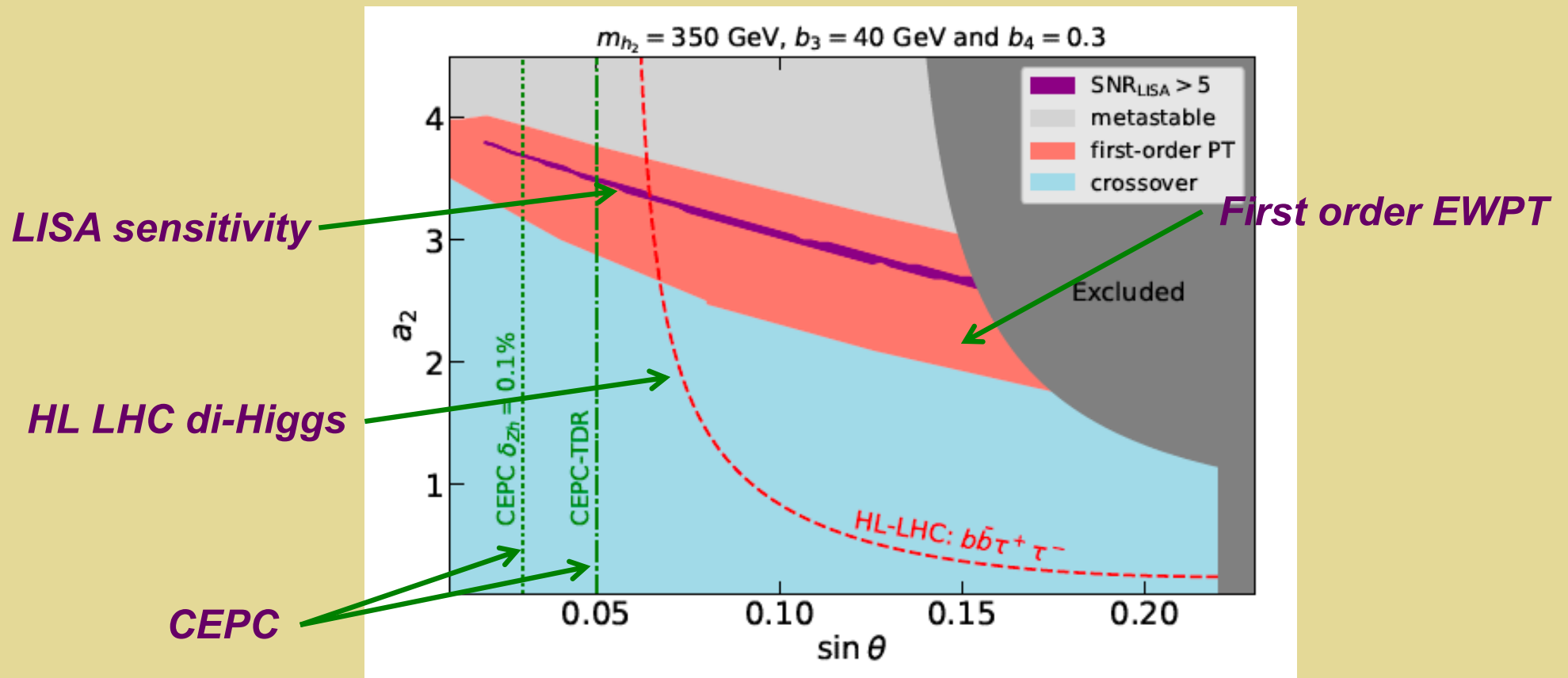


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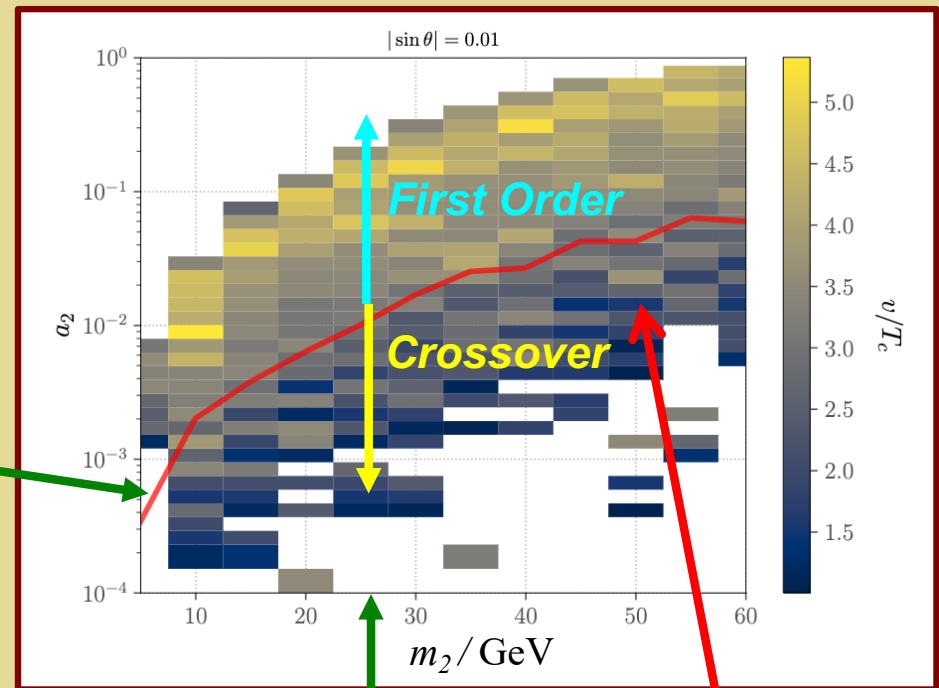
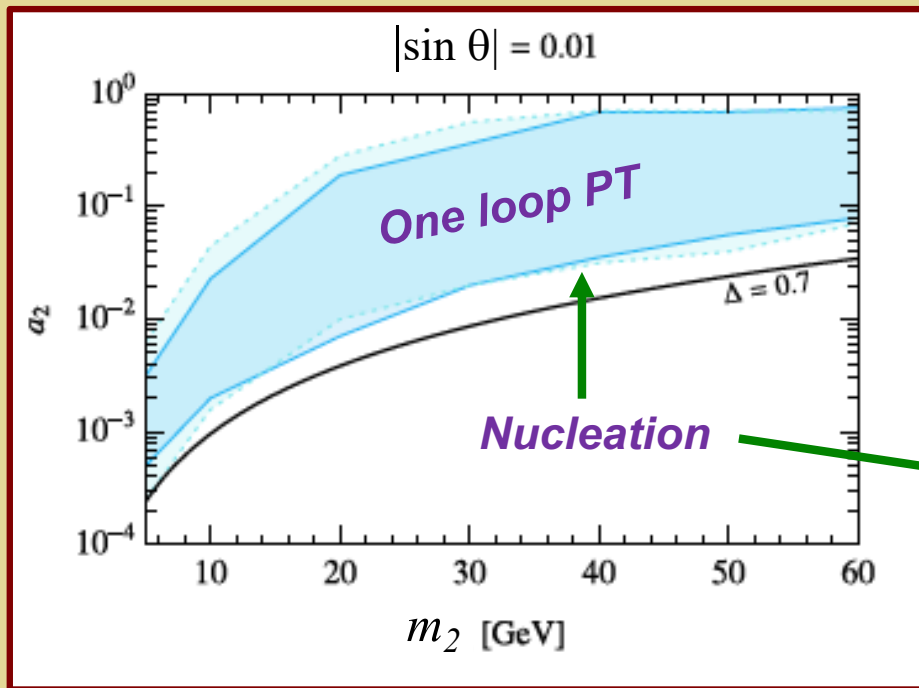
Singlets: GW & Colliders



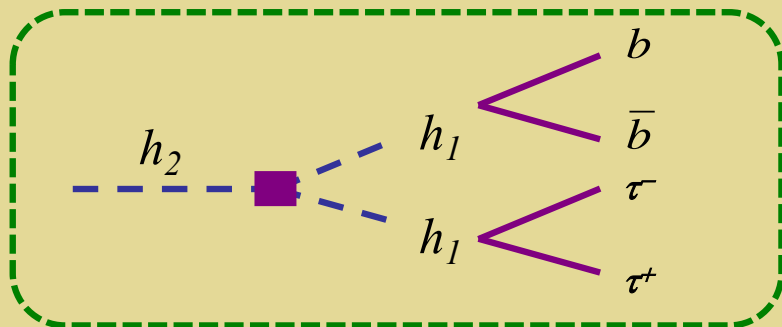
Singlets: GW & Colliders



Light Singlets: Exotic Higgs Decays



J. Kozaczuk, MR-M, J. Shelton 1911.10210



Lattice study

Two-loop PT:
3d EFT

L. Niemi, MJRM, G. Xia 2405.01191

V. Outlook

Was there cosmic condensation ?



Exciting possibility
Exciting possibility

Cosmic expansion $\overset{?}{\longleftrightarrow}$ ***cosmic condensation***

Cosmic Condensation ?

- *Particle physics of the early universe could have catalyzed a process of cosmic condensation → possible origin of as-yet unexplained phenomena: matter-antimatter asymmetry, dark matter, neutrino mass, ...*
- *Observable signatures could appear in next generation gravitational wave probes and collider searches*
- *Study of symmetry-breaking in condensed matter systems → great intuition for analogous possibilities in the early universe*
- *The electroweak phase transition provides a unique “laboratory” for testing our theoretical methods and ideas, with gravitational wave probes + LHC & future collider searches providing key input*

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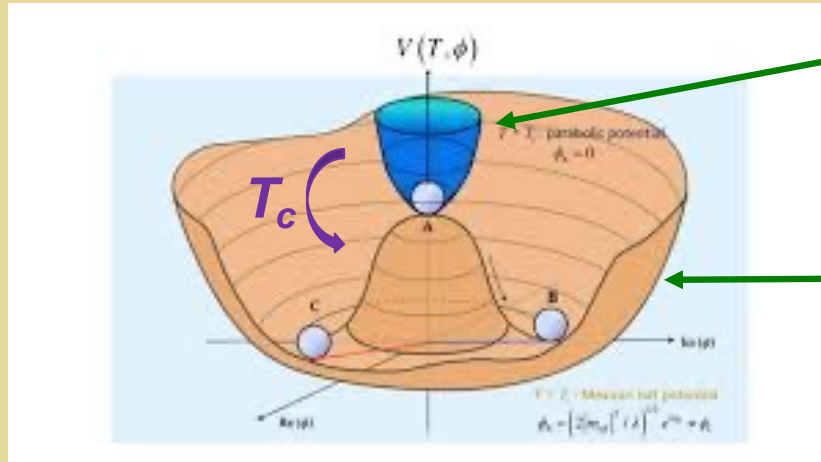
Recent progress with EFT, lattice, rigorous QFT... more challenges remain

谢谢!

Back Up Slides

Spontaneous Symmetry Breaking

Higgs Boson potential energy



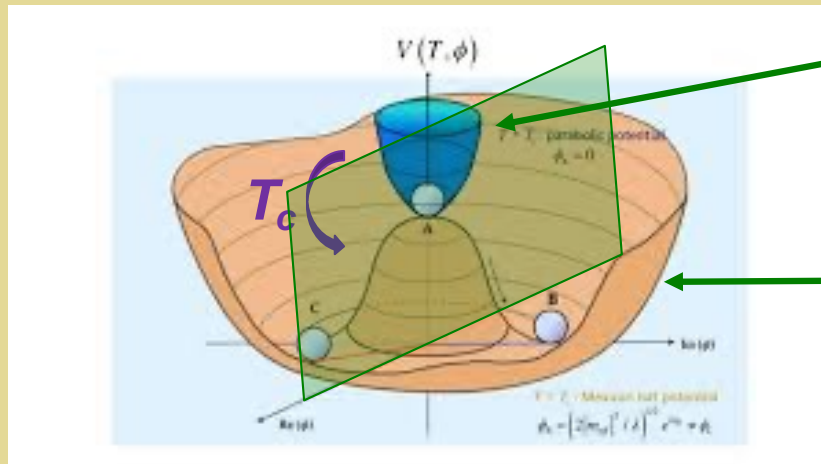
High T

Low T

How did this transition occur ?

Spontaneous Symmetry Breaking

Higgs Boson potential energy



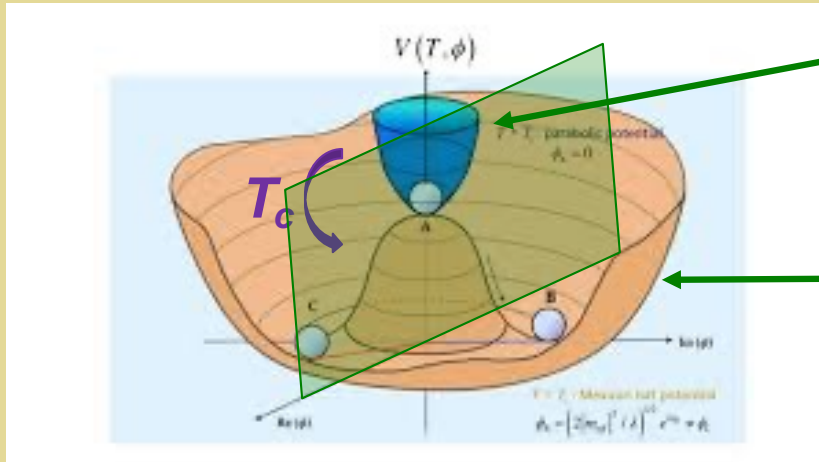
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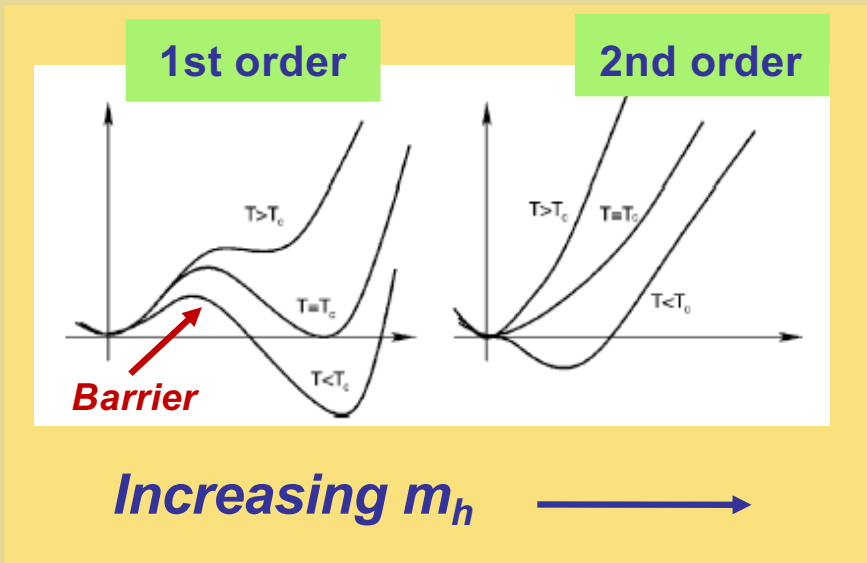
Higgs Boson potential energy



High T

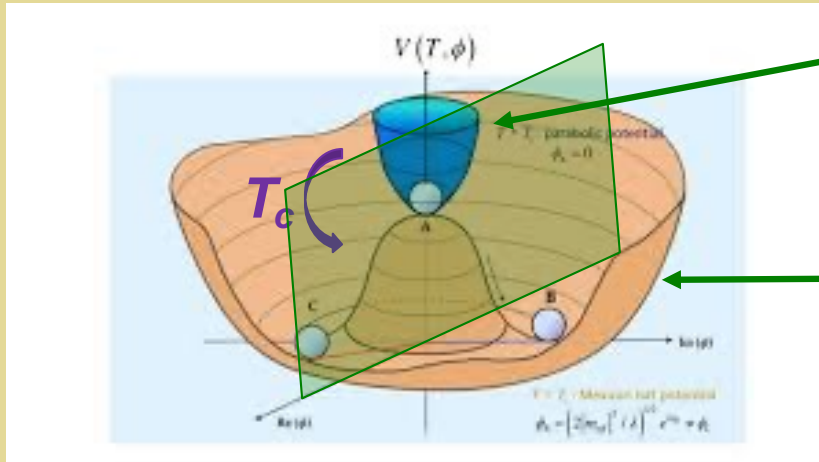
How did this transition occur ?

Low T



Spontaneous Symmetry Breaking

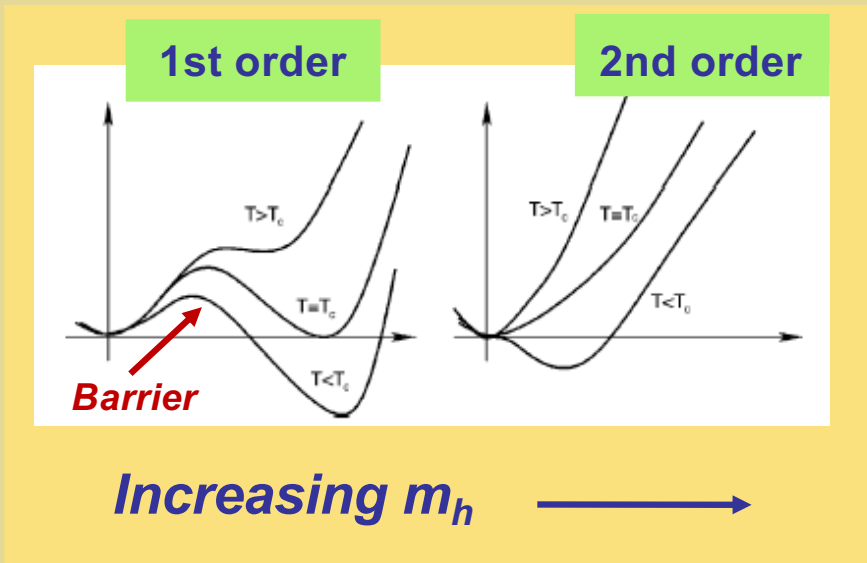
Higgs Boson potential energy



High T

Low T

How did this transition occur ?



• Was there an EW phase transition ?

• Was it 1st order ?

Cosmic condensation ?

$T_{EW} \rightarrow$ Scale for Colliders & GW probes

High- T SM Effective Potential

$$V(h, T)_{\text{SM}} = D(T^2 - T_0^2) h^2 + \lambda h^4 + \dots$$

$$T_0 \sim 140 \text{ GeV}$$

$$\equiv T_{EW}$$

$T_{EW} \rightarrow$ Scale for Colliders & GW probes

High- T SM Effective Potential

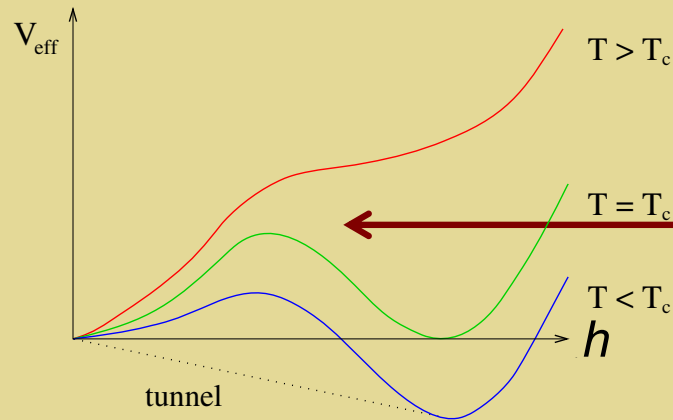
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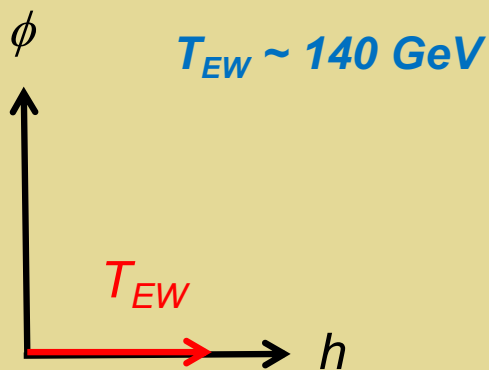
$$\equiv T_{EW}$$

Collider target
Collider target

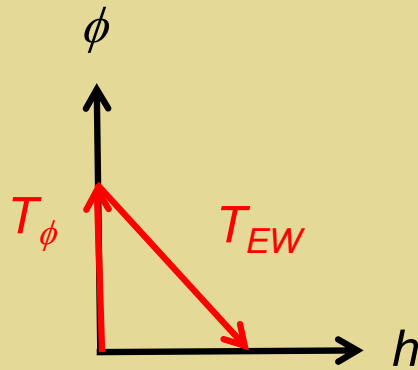
First Order EWPT from BSM Physics



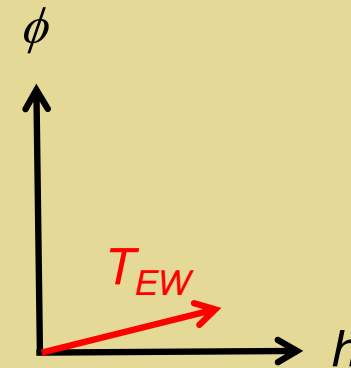
Representative thermal histories \rightarrow barrier for SFOEWPT



$a_2 H^2 \phi^2 : T > 0$
loop effect



$a_2 H^2 \phi^2 : T = 0$
tree-level effect



$a_1 H^2 \phi : T = 0$
tree-level effect

Nucleation @ $T > 0$: Gravitational Waves

Amplitude & frequency: latent heat & intrinsic time scale

Normalized latent heat

$$\Delta Q = \Delta F + T\Delta S$$

$$S = -\partial F / \partial T$$

$$F \approx V$$

Time scale

$$\frac{\beta}{H_*} = T \frac{d}{dT} \frac{S_3}{T}$$

$$\Delta Q \approx \Delta V - T \partial \Delta V / \partial T$$

$$\alpha = \frac{30 \Delta q}{\pi^2 g_* T^4}$$