DESY, 17 May 2022

Naturalness & Self-Organised Localisation

G. F. Giudice

The LHC has revolutionised our
views on the particle world.

LEP didn't discover any new particles,
but LEP had a profound impact on the
way we think about particle physics.

The LHC results have forced us to think
differently about BSM physics.

Idiotic statements

- Since LHC hasn't discovered supersymmetric particles, naturalness is wrong.
- Since there are no quadratic divergences in dimensional regularisation, naturalness is wrong.
- Since it depends on probability measures in theory space, naturalness is wrong.
- Since it depends on arbitrary aesthetic criteria, naturalness is wrong.
- Naturalness is no longer a motivation for future colliders.

- Naturalness is a powerful tool in QFT to signal the sensitivity of some low-energy parameters on heavy modes that are integrated out.

- We must question the hypotheses on which the naturalness principle rests and see what are the consequences.

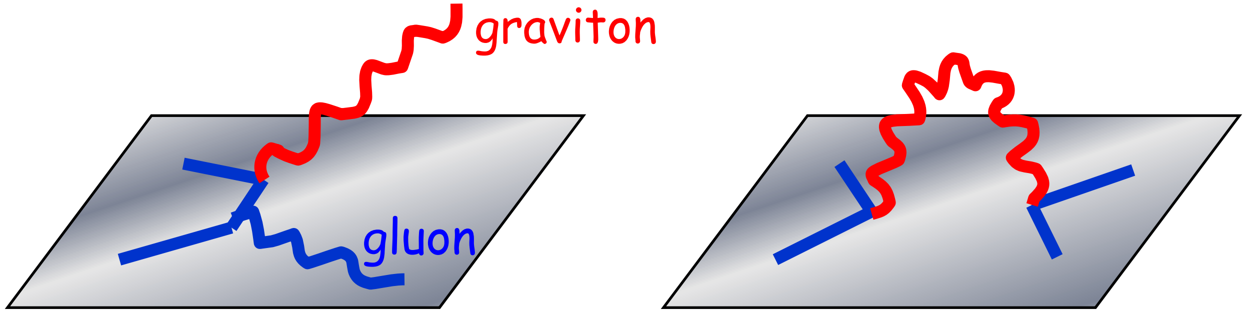
1) Scale separation

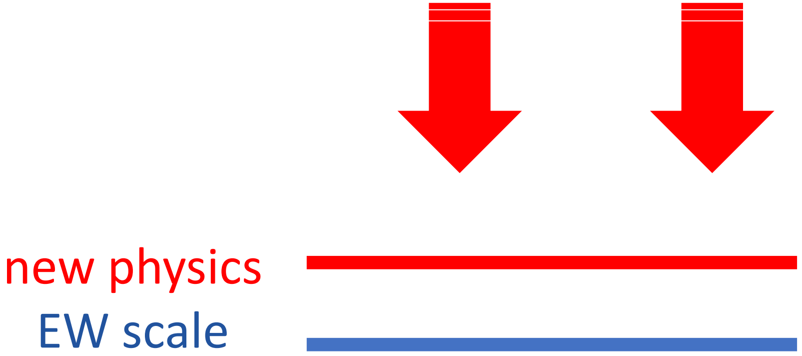
Are there any new mass scales above the weak scale?

Quantum gravity?

Neutrino masses, the strong CP problem, inflation, gauge coupling unification, flavour…?

Large Extra Dimensions





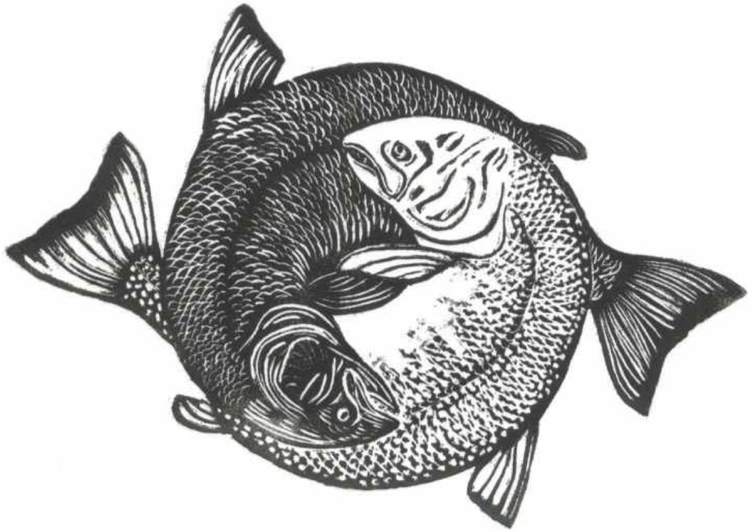
new physics

EW scale

2) EFT validity

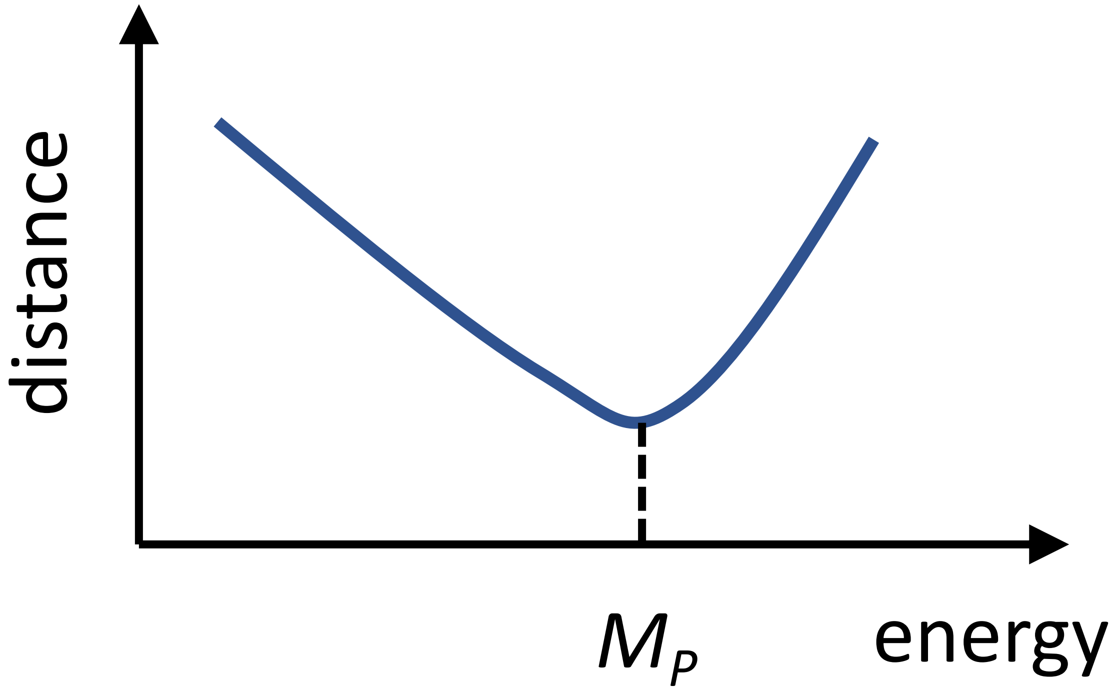
Naturalness: parameters being sensitive to heavy modes integrated out from the low-energy theory.

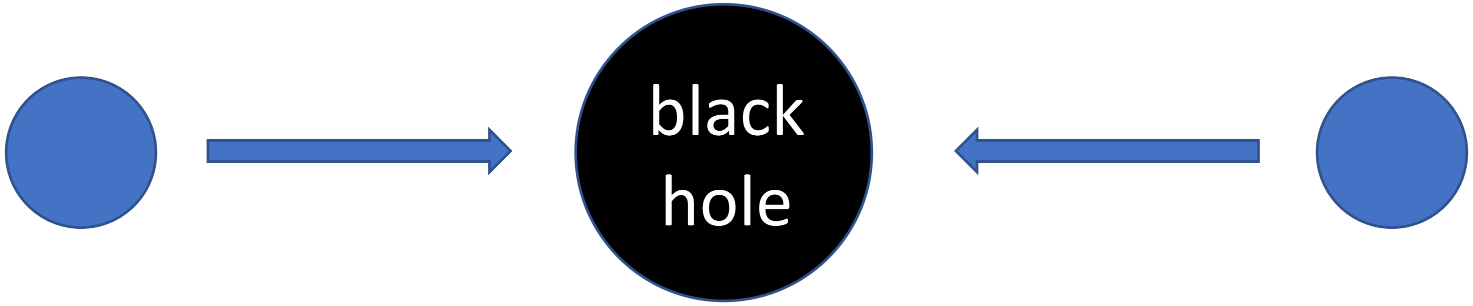
Could it be that the rules of EFT break down?



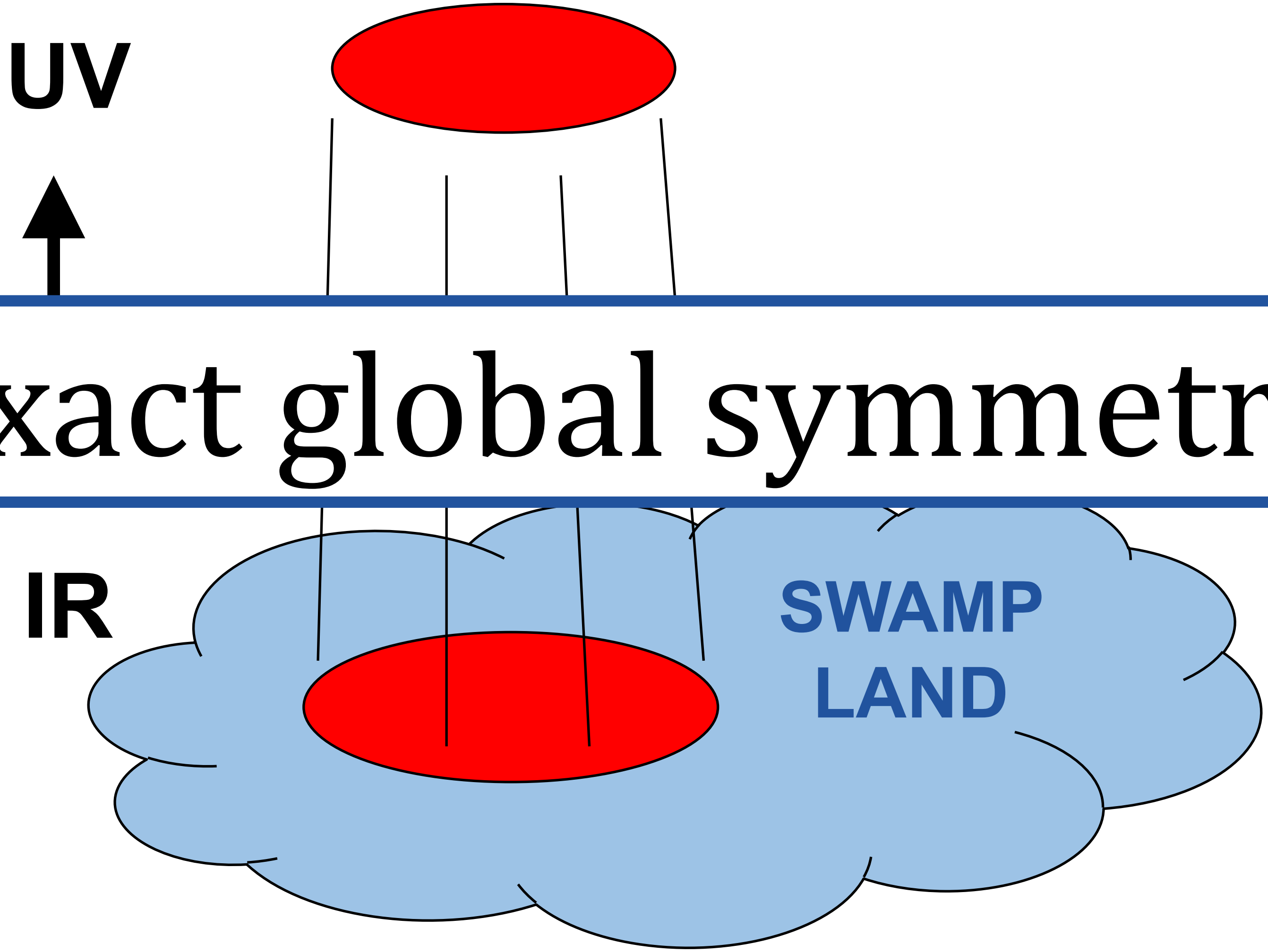
IR/UV correlation?

Breakdown of locality in QFT?


distance
M_P
energy


black hole

Some theories allowed by EFT symmetries live in the swampland

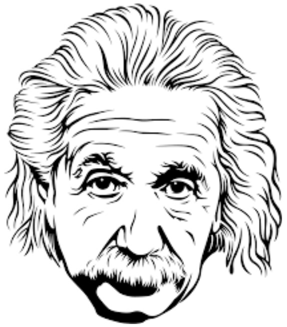


No exact global symmetries

It challenges EFT intuition
and naturalness is based on EFT intuition

3) IR free parameters are calculable quantities in the UV completion

Nature is comprehensible



IR parameters are functions of some fields whose value vary during the cosmological history or throughout a complex vacuum structure

- A r nge ctiv
- An evit que ation.
- It c pre ctio

Alexander Westphal

Christophe Grojean

Geraldine Servant

Relaxing some of the naturalness hypotheses is possible, but it often leads to consequences that are even more radical than those of conventional naturalness.

CERN-TH-2021-077

arXiv:2105.08617v1 [hep-ph] 18 May 2021

Self-Organised Localisation

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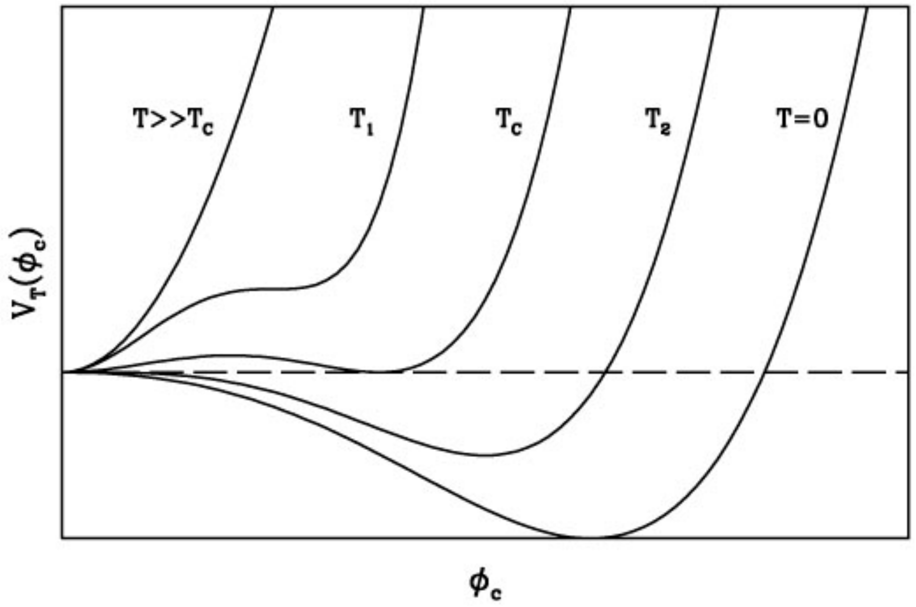
Abstract

We describe a new phenomenon in quantum cosmology: self-organised localisation. When the fundamental parameters of a theory are functions of a scalar field subject to large fluctuations during inflation, quantum phase transitions can act as dynamical attractors. As a result, the theory parameters are probabilistically localised around the critical value and the Universe finds itself at the edge of a phase transition. We illustrate how self-organised localisation could account for the observed near-criticality of the Higgs self-coupling, the naturalness of the Higgs mass, or the smallness of the cosmological constant.

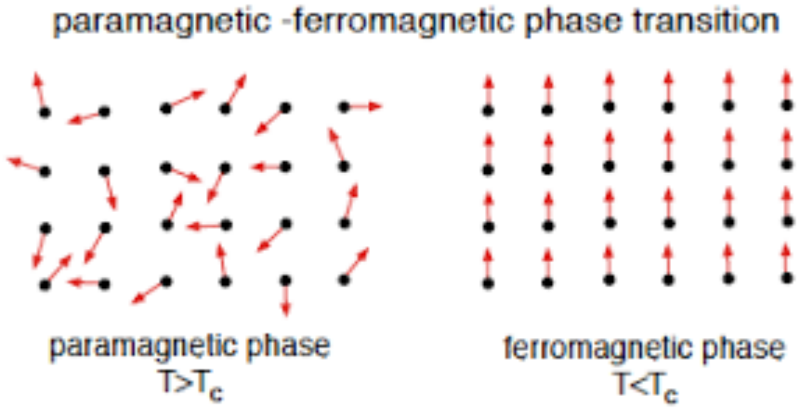
Critical phenomena

Phase transitions in the early universe
(QCD, EW, inflation?, baryogenesis?)



Classical phase transitions: the phase changes as the temperature is varied.

Ferromagnet:

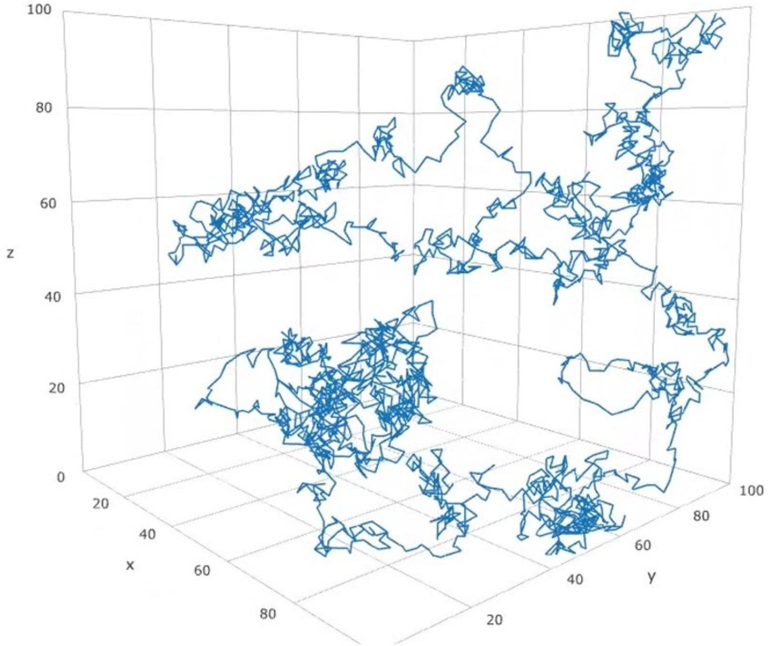


Quantum phase transitions: the phase changes as an external field is varied.

$$V(\phi) = V_\phi + (\phi - \phi_c)\,\mathcal{O} \qquad \begin{cases} \langle\mathcal{O}\rangle = 0 & \phi > \phi_c \\ \langle\mathcal{O}\rangle \neq 0 & \phi < \phi_c \end{cases} \qquad \Rightarrow \qquad \begin{array}{c} V'(\phi) = V'_\phi + \langle\mathcal{O}\rangle \\ \text{discontinuous at } \phi = \phi_c \end{array}$$

Ingredient 1:

Some parameters of the microscopic theory are promoted to functions of one or more scalar fields.



$$\mu \quad \longrightarrow \quad \mu(\phi)$$

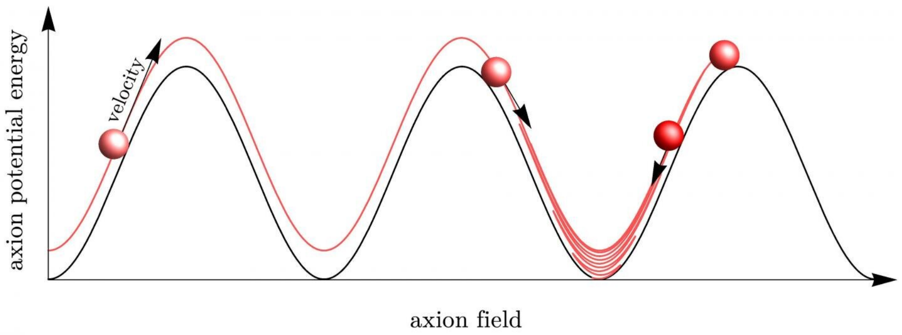
Axion: $\mathcal{L}_{\mathrm{dim}=4} = \frac{g_s^2}{32\pi^2}\,\bar{\theta} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$ $\qquad \bar{\theta} \longrightarrow a$

Cosmological constant: Abbott, Brown-Teitelboim, etc.

Higgs mass: relaxion, etc.

Ingredient 2:

Selection mechanism in the multiverse.



Axion: symmetry

Cosmological constant: anthropics (Weinberg)

Higgs mass: back-reaction from EW breaking (relaxion)

Self-Organised Criticality (SOL): criticality

Stochastic approach (Vilenkin, Starobinsky, Linde, ...)

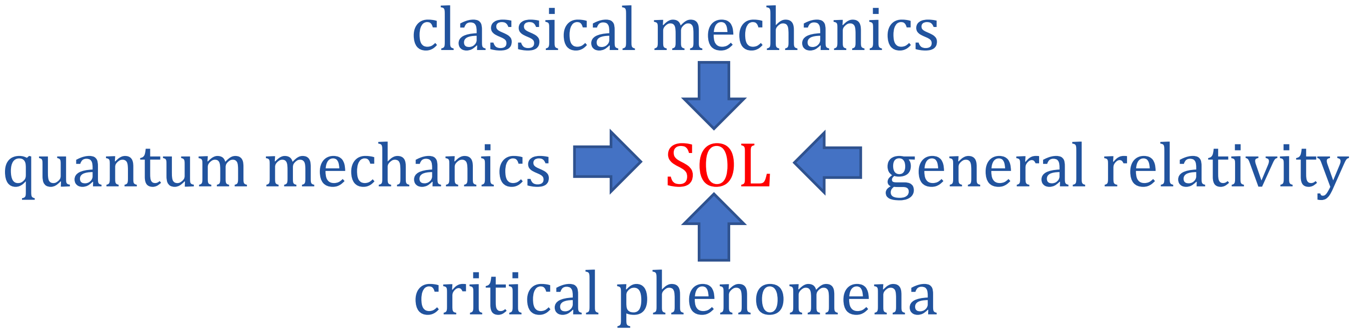
$P(\phi,t)$ distribution of volume occupied by ϕ at time t

$$\frac{\partial}{\partial\phi}\left[\frac{\hbar}{8\pi^2}\frac{\partial(H^3\,P)}{\partial\phi}+\frac{V'\,P}{3H}\right]+3HP=\frac{\partial P}{\partial t} \qquad \text{(FPV)}$$

quantum term
$\hbar$

classical term
1

volume term
$1/M_P^2$


classical mechanics

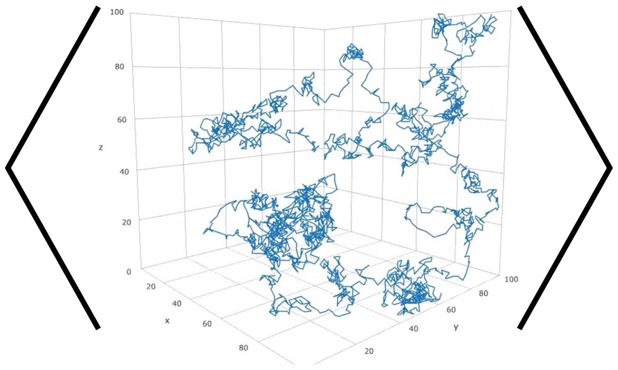
quantum mechanics

SOL

general relativity

critical phenomena

Fokker-Planck: $$\frac{\partial}{\partial\phi}\left[\frac{\hbar}{8\pi^2}\frac{\partial(H^3\,P_{\rm FP})}{\partial\phi}+\frac{V'\,P_{\rm FP}}{3H}\right]=\frac{\partial P_{\rm FP}}{\partial t}$$



Langevin: $$\frac{d\phi}{dt}+\frac{V'(\phi)}{3H}=\eta(t)\ ,\qquad \langle\eta(t)\eta(t')\rangle=\frac{H^3}{4\pi^2}\,\delta(t-t')$$

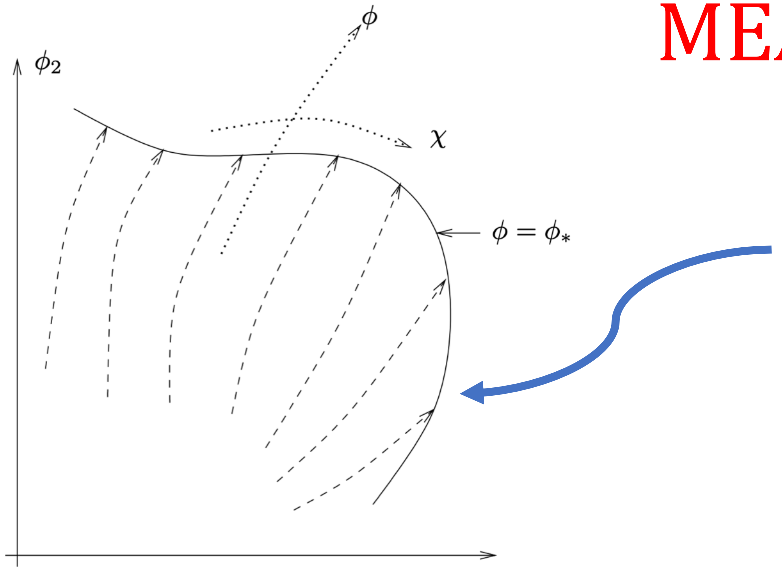
Volume-weighted Fokker-Planck (FPV): $$\frac{\partial}{\partial\phi}\left[\frac{\hbar}{8\pi^2}\frac{\partial(H^3\,P)}{\partial\phi}+\frac{V'\,P}{3H}\right]+3HP=\frac{\partial P}{\partial t}$$

each trajectory is weighed by e^{3Ht}

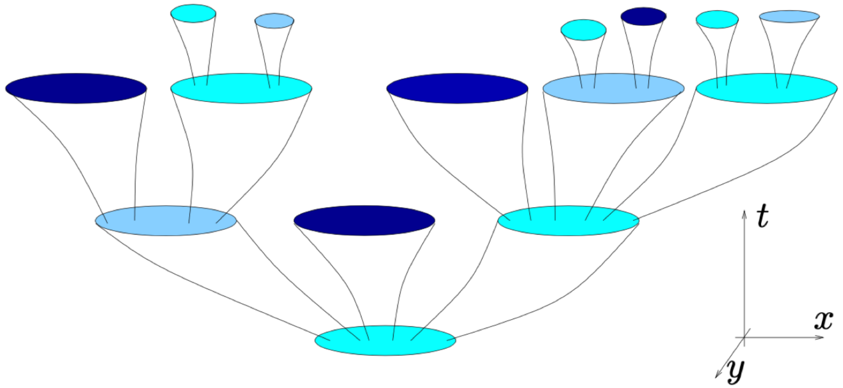
GAUGE DEPENDENCE

- The localisation of P at the critical point is gauge-independent.
- The degree of localisation (which is measured by the width of the distribution P) is gauge-dependent.

MEASURE PROBLEM



Reheating surface: 3-volume hypersurface of all reheating events in spacetime.



Eternal inflation: the reheating surface is infinite and non-compact.

Steady-state solutions: $P(\phi, t) \xrightarrow{t \gg t_R} e^{K(t)} p(\phi)$

VALIDITY OF THE SEMICLASSICAL APPROXIMATION

$$N < S_{\rm dS} = \frac{8\pi^2 M_P^2}{\hbar\, H^2}$$

Arkani-Hamed *et al*, 0704.1814
Creminelli *et al*, 0802.1067
Dubovsky *et al*, 0812.2246; 1111.1725

Does the semiclassical approach break down after this time?

Dvali *et al*, 1312.4795; 1701.08776

SWAMPLAND CONJECTURES

Do super-Planckian field excursions, slow-roll inflation and eternal inflation live in the swampland?

In spite of all these open issues, I will use the probabilistic interpretation of P as an exploratory tool for SOL.

$$\frac{\partial}{\partial\phi}\left[\frac{\hbar}{8\pi^2}\frac{\partial(H^3\,P)}{\partial\phi}+\frac{V'\,P}{3H}\right]+3HP=\frac{\partial P}{\partial t}\qquad \text{(FPV)}$$

EFT POTENTIALS

$$V=3H_0^2M_P^2+g_\epsilon^2f^4\omega(\varphi)\ ,\qquad \omega(\varphi)=\sum_{n=1}^{\infty}\frac{c_n}{n!}\varphi^n\ ,\qquad \varphi\equiv\frac{\phi}{f}$$

“inflaton” term

“apeiron” term

g_ϵ : shift-symmetry breaking coupling

f : field range

$$P(\varphi,T)=\sum_\lambda e^{\lambda T}p(\varphi,\lambda)$$

$$\boxed{\alpha=\frac{3\hbar H_0^4}{4\pi^2g_\epsilon^2f^4}\ ,\qquad \beta=\frac{3\xi f^2}{2M_P^2}}$$

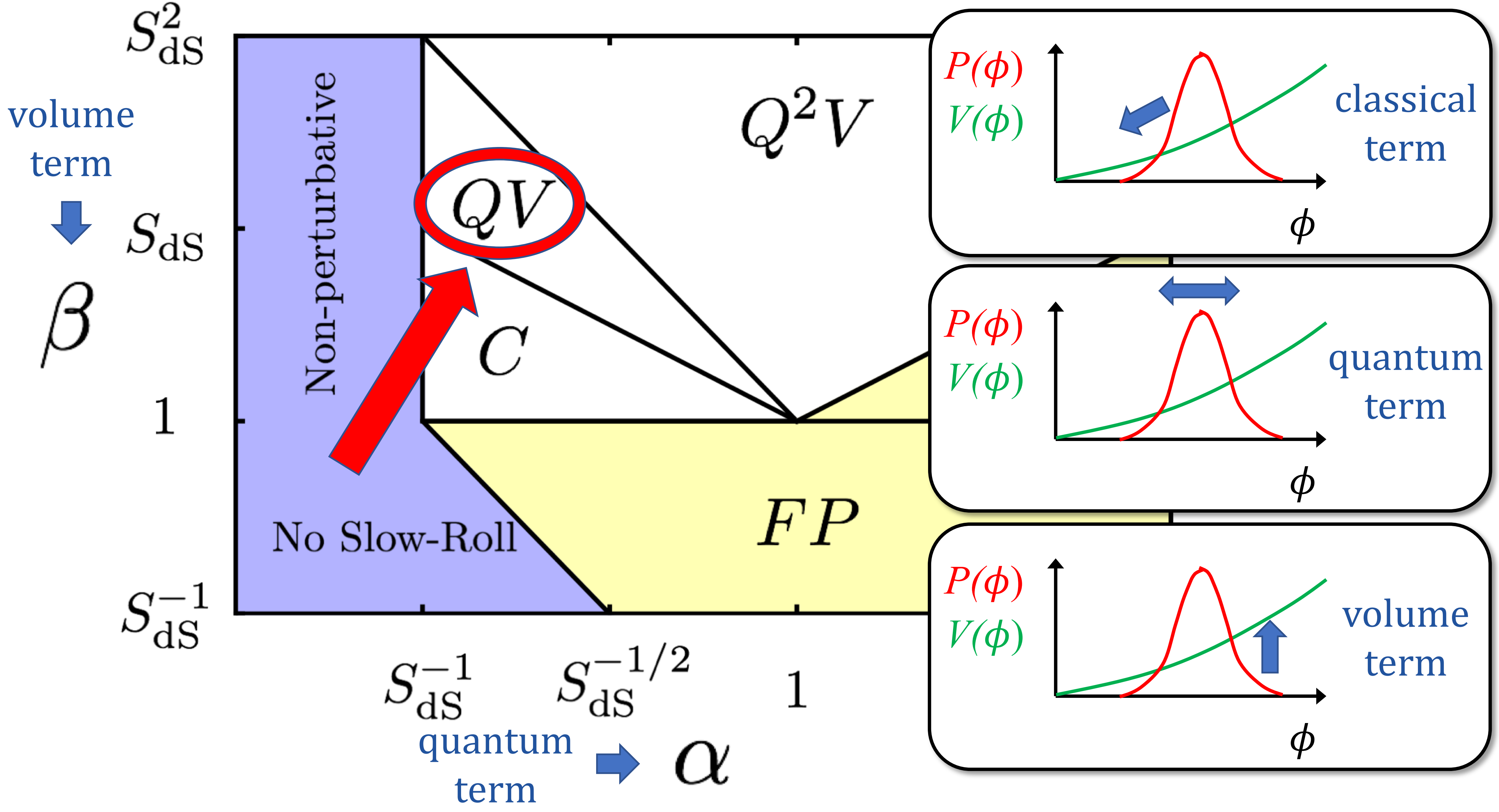
$$T=\frac{t}{t_R}\ ,\qquad t_R=\frac{3H_0}{g_\epsilon^2f^2}$$

$$\alpha\,\frac{\partial^2p}{2\partial\varphi^2}+\frac{\partial(\omega'p)}{\partial\varphi}+\beta\,\omega p=\lambda p$$

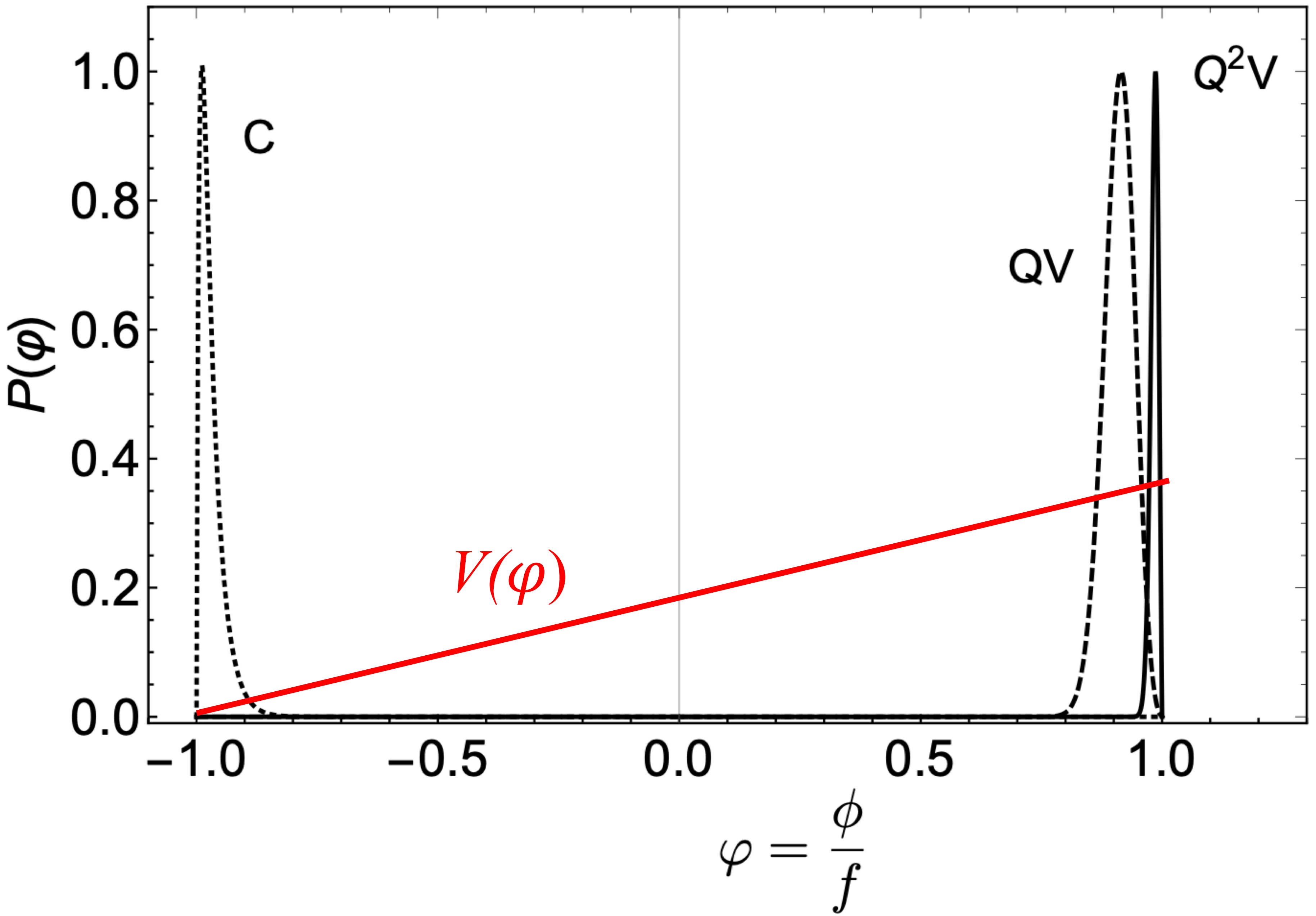
quantum term

classical term

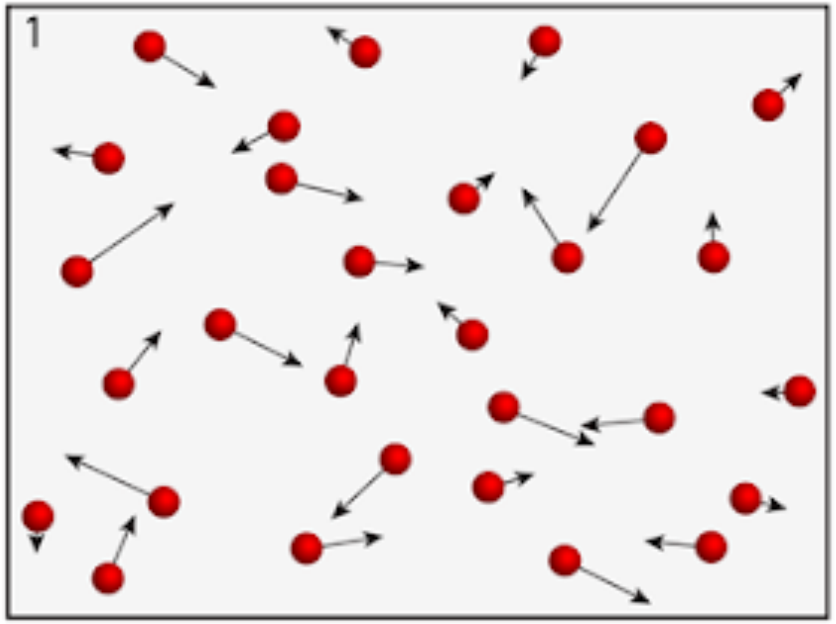
volume term


$S_{\rm dS}^2$
volume term
$S_{\rm dS}$
β
1
$S_{\rm dS}^{-1}$
Non-perturbative
QV
Q^2V
C
FP
No Slow-Roll
$S_{\rm dS}^{-1}$
$S_{\rm dS}^{-1/2}$
1
quantum term
α
$P(\phi)$
$V(\phi)$
classical term
ϕ
$P(\phi)$
$V(\phi)$
quantum term
ϕ
$P(\phi)$
$V(\phi)$
volume term
ϕ

LINEAR POTENTIAL



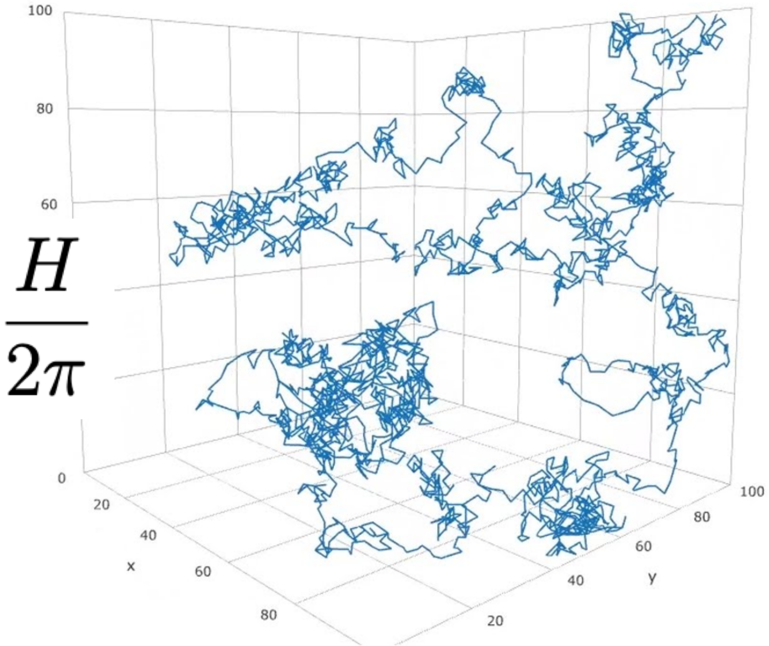
GAS



T = constant

MULTIVERSE

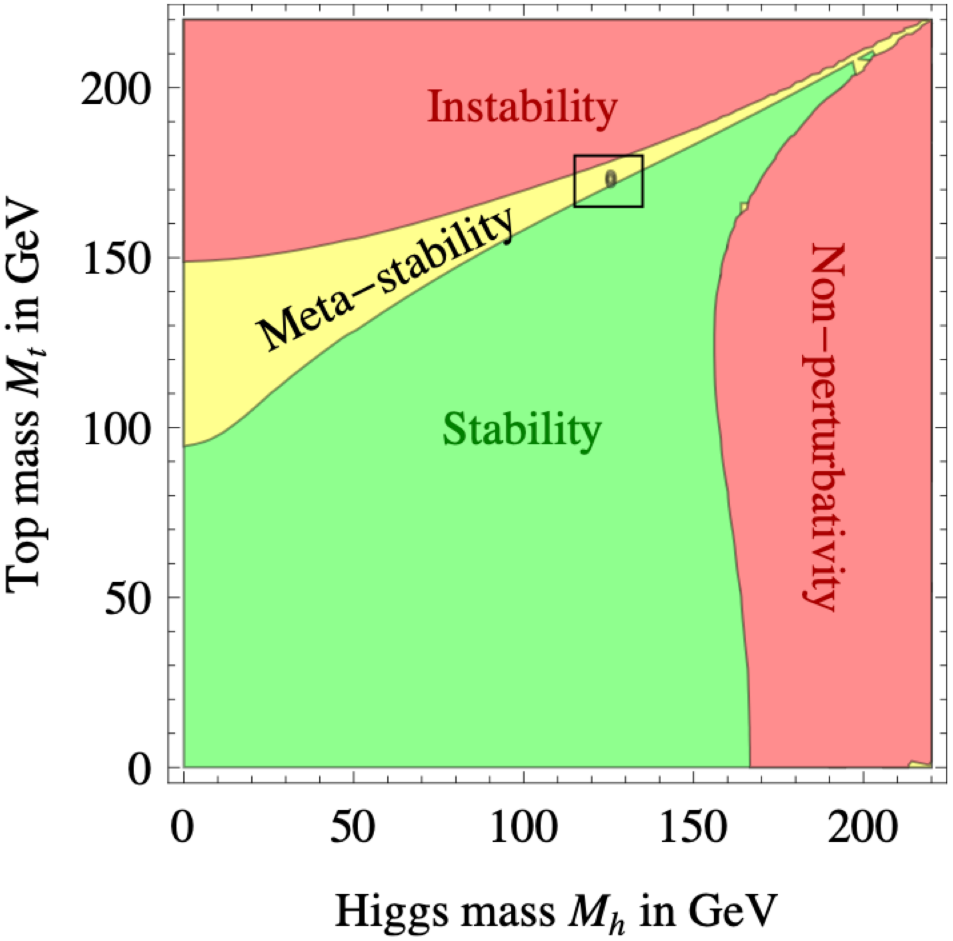
$$T_{\mathrm{dS}} = \frac{H}{2\pi}$$



Steady-state solutions:

$$P(\phi, t) \xrightarrow{t \gg t_R} e^{K(t)}\, p(\phi)$$

NEAR-CRITICALITY OF THE HIGGS SELF-COUPLING

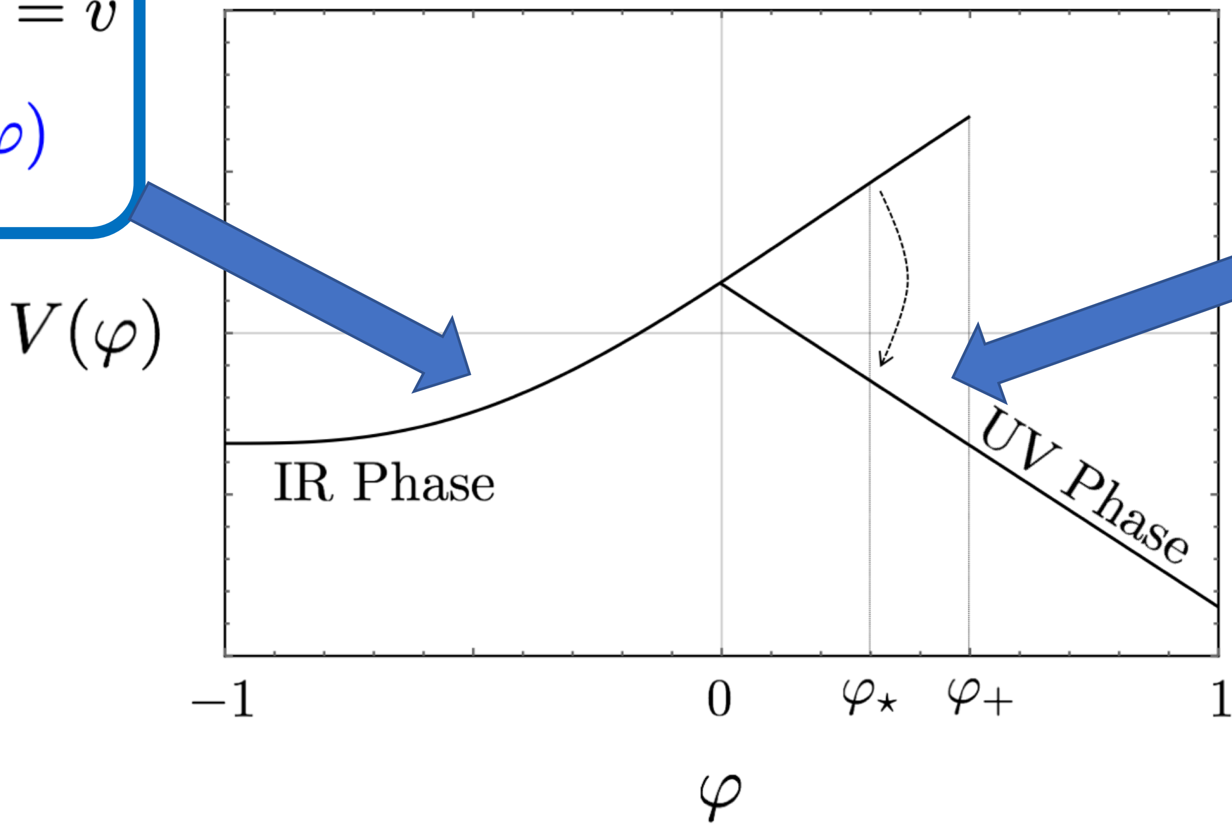


$$V(\varphi,h)=\frac{M^4}{g_*^2}\,\omega(\varphi)+\frac{\lambda(\varphi,h)}{4}\left(h^2-v^2\right)^2$$

$$\lambda(\varphi,M/g_*)=-g_*^2\,\varphi\ ,\qquad \frac{d\,\lambda(\varphi,h)}{d\ln h^2}=\beta_\lambda(h)$$

IR Phase: $\langle h\rangle = v$

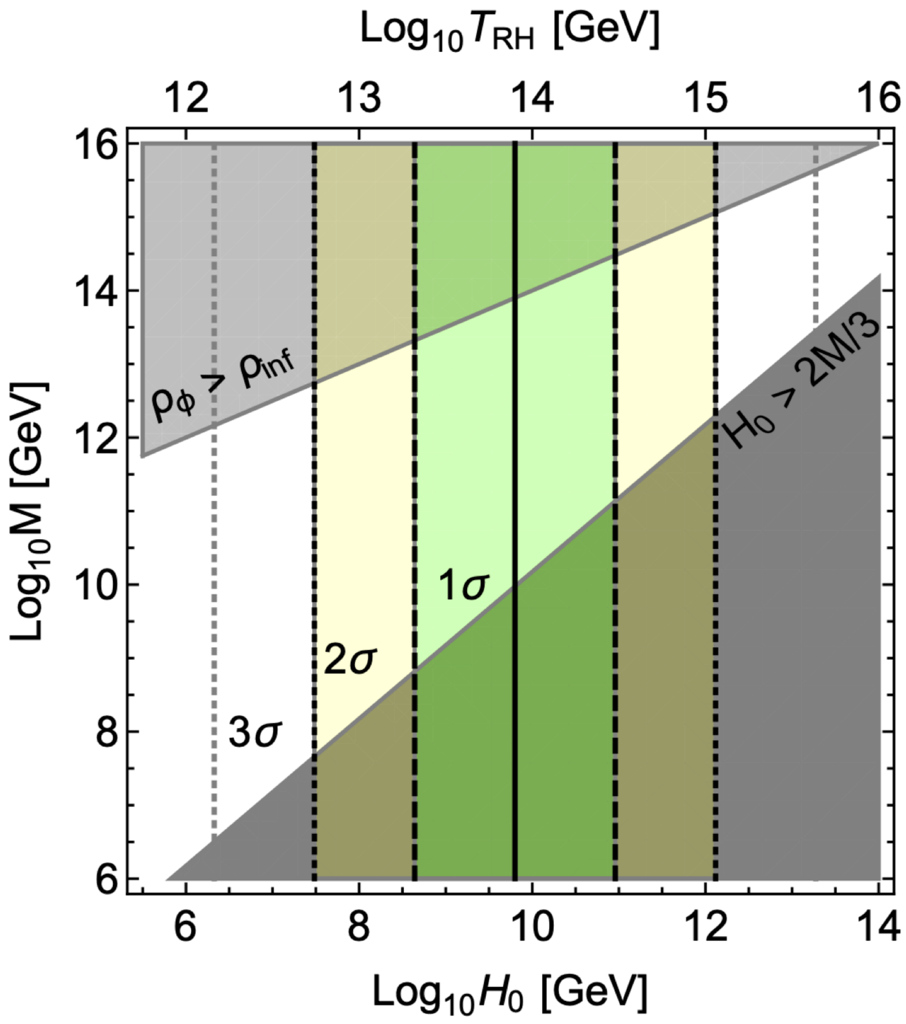
$$V=\frac{M^4}{g_*^2}\,\omega(\varphi)$$



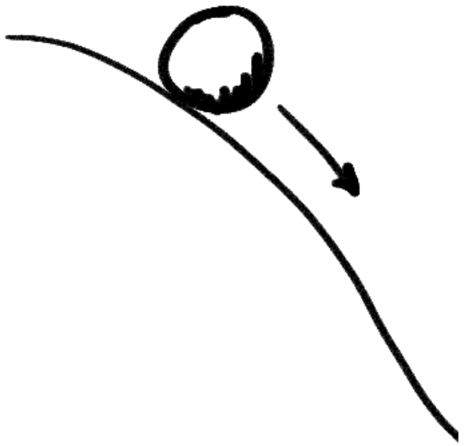
UV Phase: $\langle h\rangle = \frac{\sqrt{2}\,c}{g_*}\,M$

$$V=\frac{M^4}{g_*^2}\left[\omega(\varphi)-c^4\,\varphi\right]$$

SOL: at the end of inflation, there is a strong probabilistic preference for patches of the Universe where the Higgs self-coupling is near its critical value.



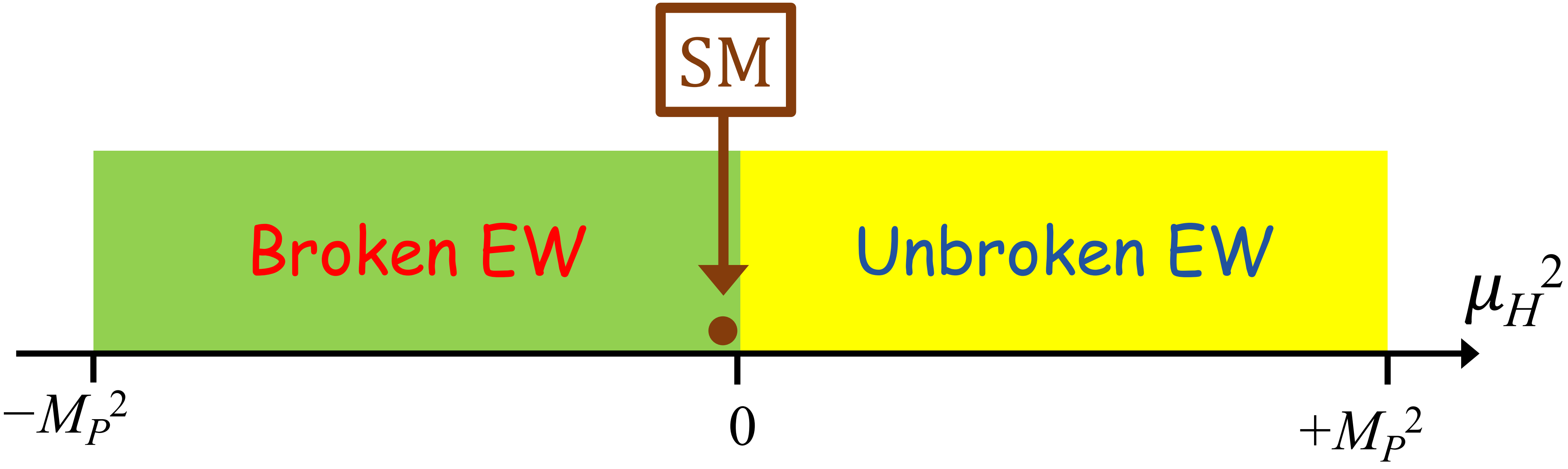
What happens to the SOL prediction during the thermal phase of the Universe?



$$\alpha^2\beta > \left(\frac{\hbar\, H_0^4}{M_P H_{\rm now}\Lambda^2}\right)^2 = \left(\frac{H_0}{2\times 10^{-3}\ {\rm eV}}\right)^8$$

$\Rightarrow$ Q^{2}V & eternal inflation

HIGGS NATURALNESS

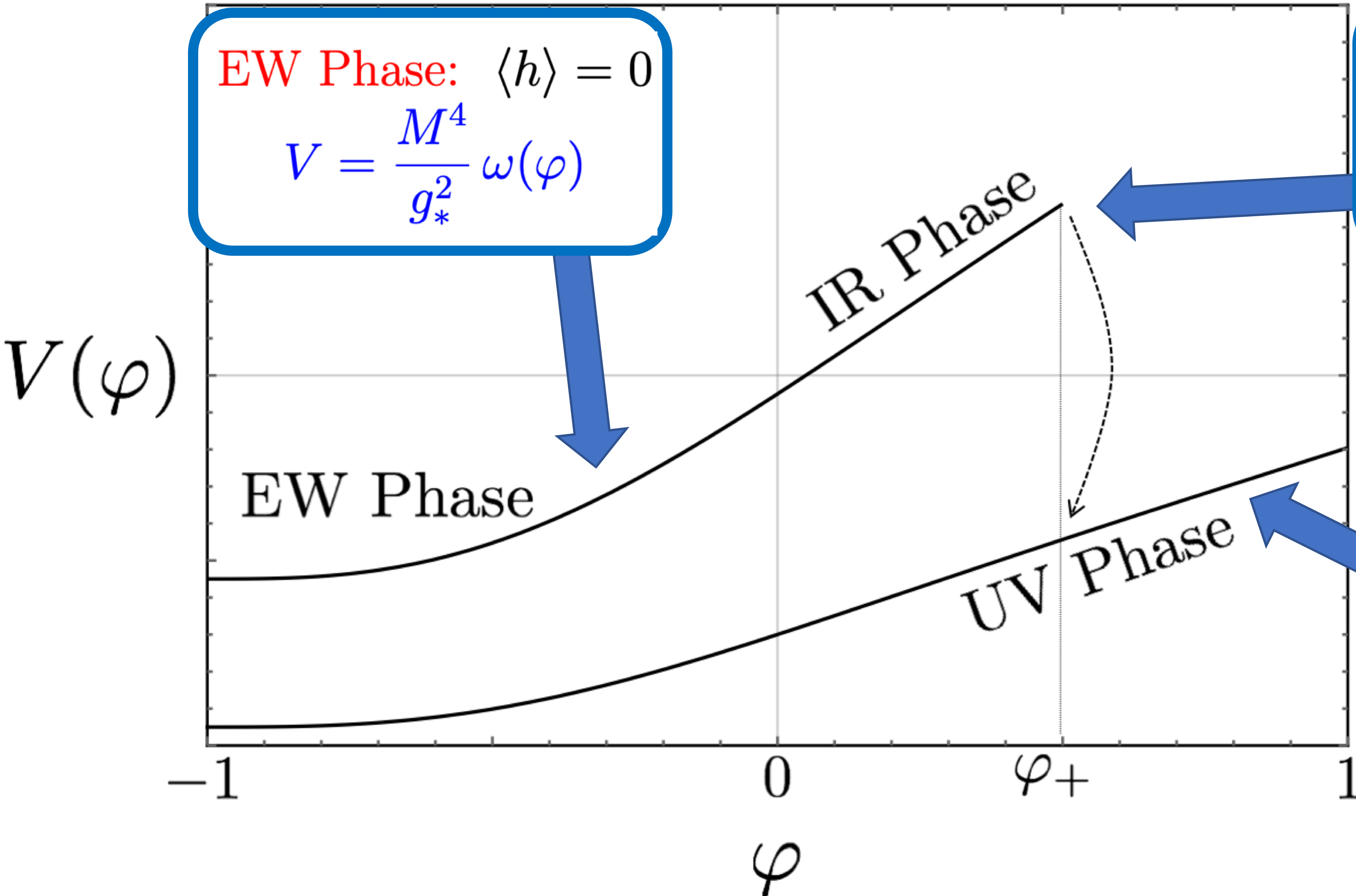


Higgs naturalness: why is nature so close to the critical point?

HIGGS NATURALNESS

$$V(\varphi,h)=\frac{M^4}{g_*^2}\,\omega(\varphi)-\frac{\varphi M^2h^2}{2}+\frac{\lambda(h)\,h^4}{4}$$

scanning mass term



EW Phase: $\langle h\rangle=0$

$$V=\frac{M^4}{g_*^2}\,\omega(\varphi)$$

IR Phase: $\langle h\rangle=v$

$$V=\frac{M^4}{g_*^2}\left[\omega(\varphi)-\frac{g_*^2}{4\lambda}\varphi^2\right]$$

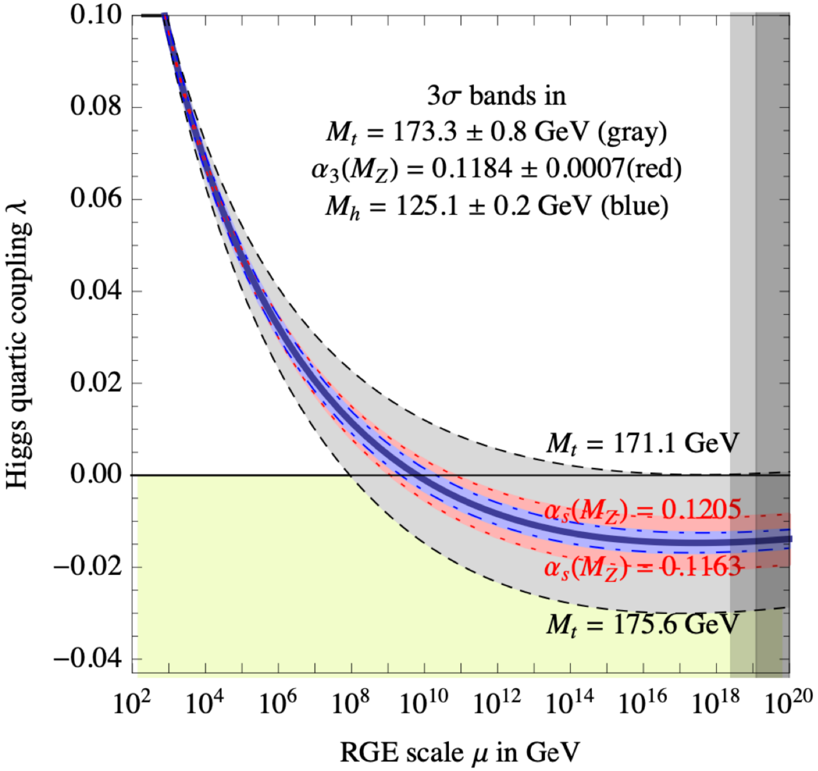
UV Phase: $\langle h\rangle=\frac{\sqrt{2}\,c}{g_*}M$

$$V=\frac{M^4}{g_*^2}\left[-\frac{c^4|\lambda_{\rm UV}|}{g_*^2}+\omega(\varphi)-c^2\,\varphi\right]$$

SOL prediction: $v = e^{-\frac{3}{4}}\,\Lambda_I$

$v/M \sim \exp(-\lambda_{\mathrm{UV}}/2\beta_\lambda)$ natural hierarchy from dimensional transmutation

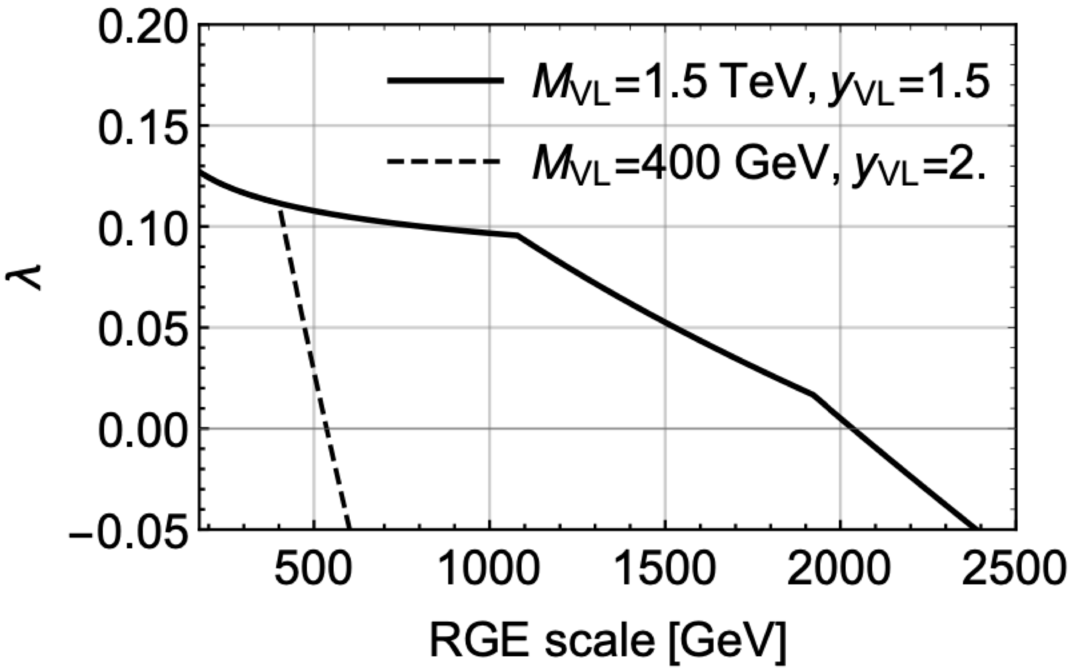
SM ⇒

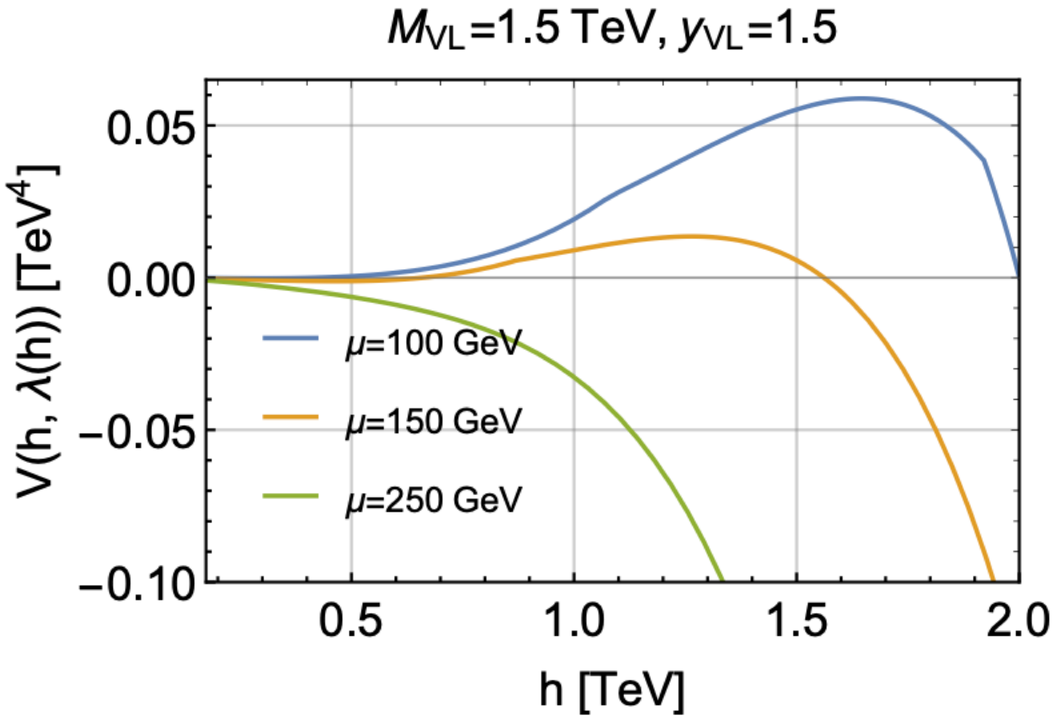


weak doublet χ and a SM singlet ψ

(a) $\mathcal{L} = -y_{VL}\bar{\psi}\chi H_h + \text{h.c.}$

(b) $\mathcal{L} = -y_{VL}\bar{\psi}L H_h + \text{h.c.}$

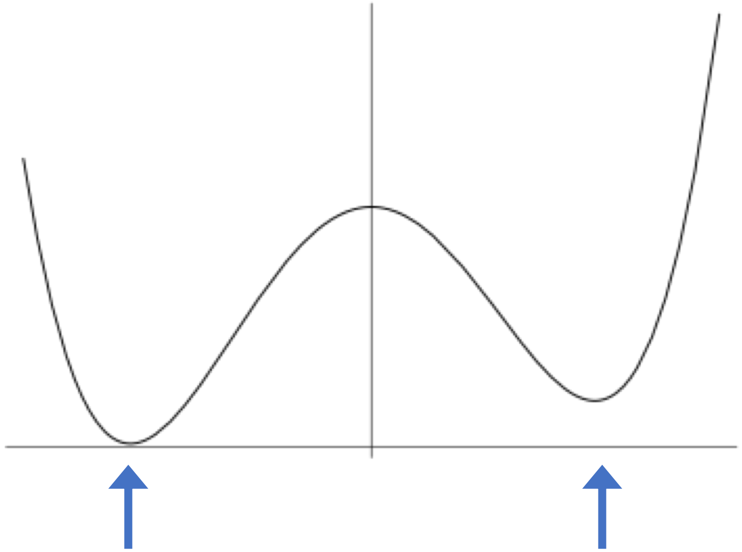




Phenomenological SOL prediction: new matter that modifies β_λ such that the theory is near-critical with respect to variations of the Higgs bilinear.

COSMOLOGICAL CONSTANT

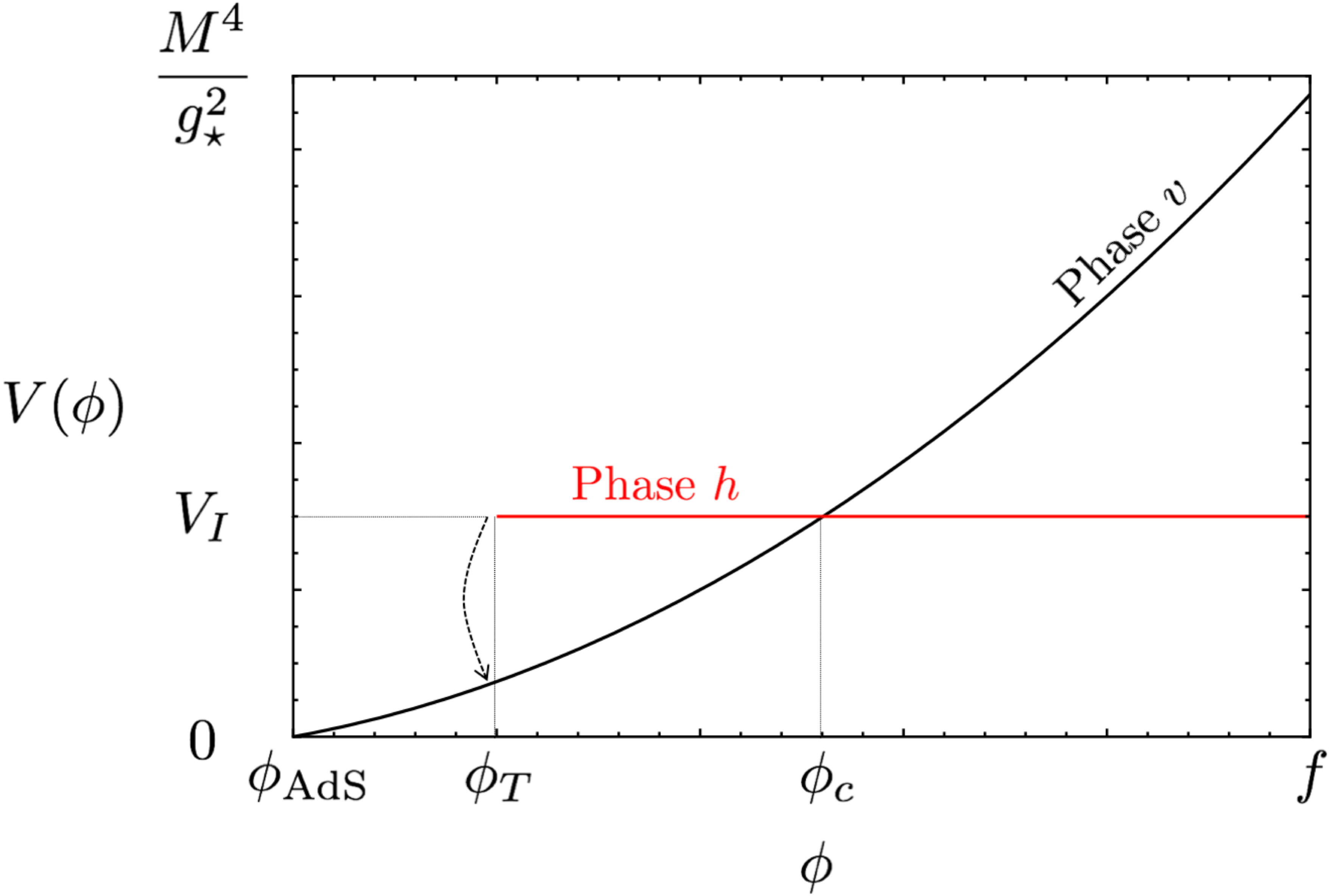
Parameters of a microscopic theory are functions of the apeiron.



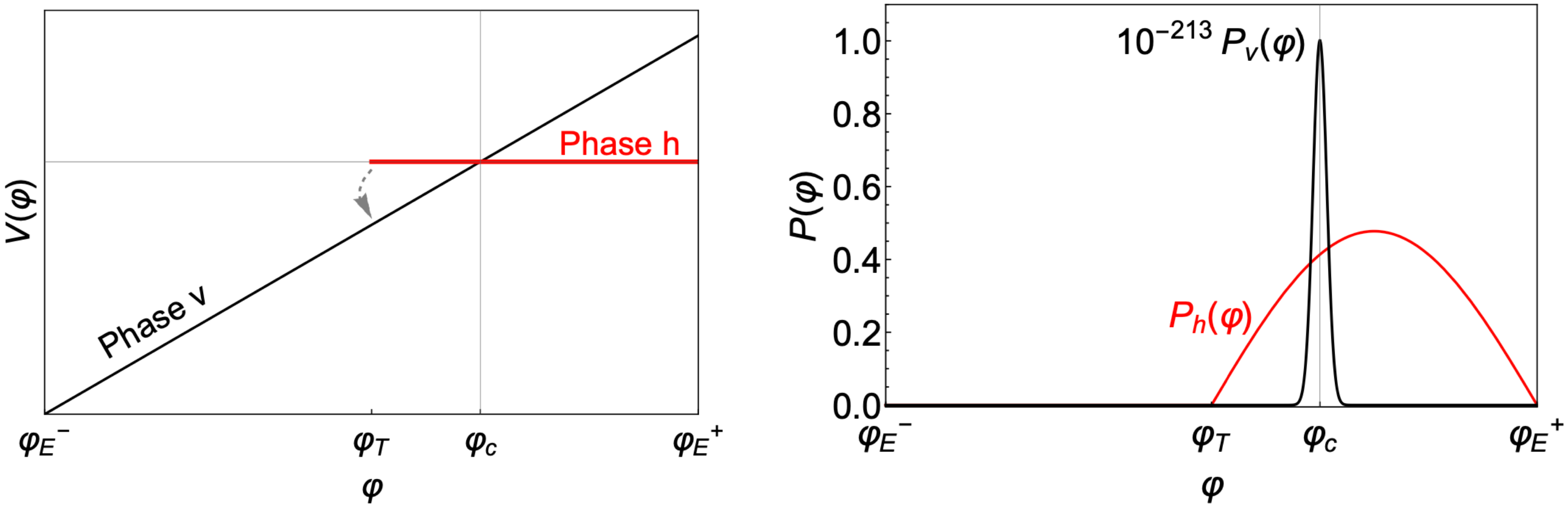
Phase *h*
(supersymmetry
& R-symmetry)

Phase *v*
(visible phase)

Inflaton

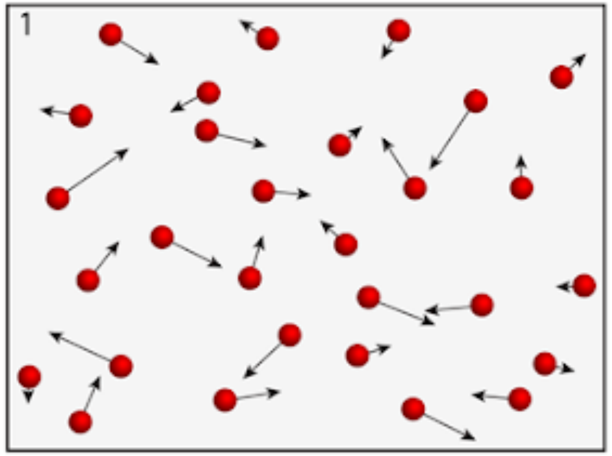


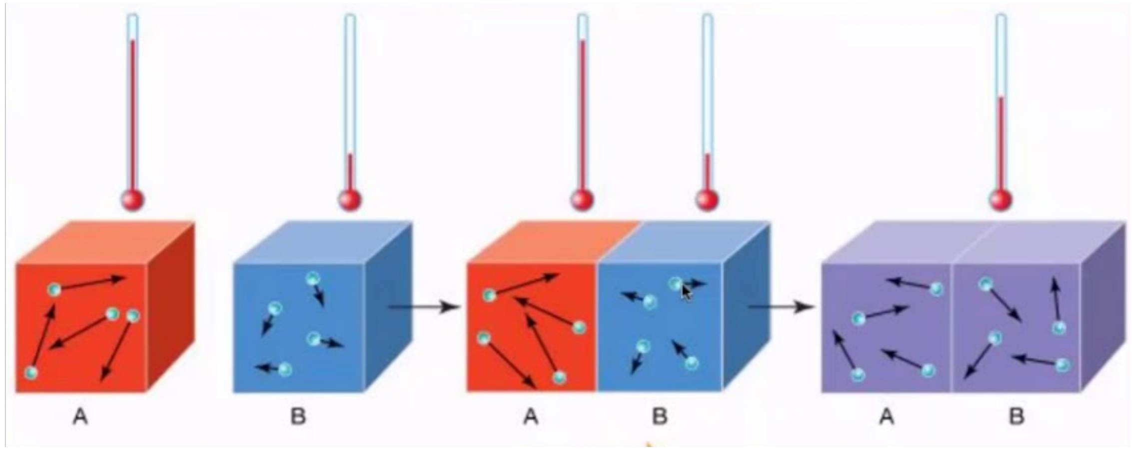
$\frac{M^4}{g_\star^2}$
$V(\phi)$
V_I
0
Phase h
Phase v
ϕ_{AdS}
ϕ_T
ϕ_c
f
ϕ



SOL prediction: the distribution is peaked on phase *v*
at the point where the two phases are degenerate.

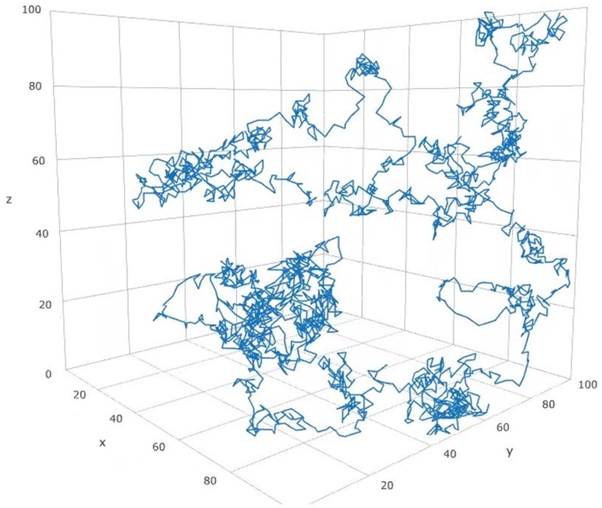
GAS

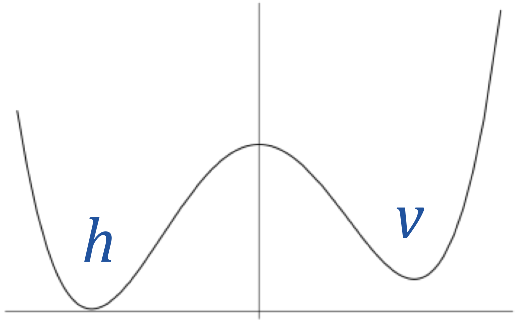




In equilibrium, T in box A and B become equal.

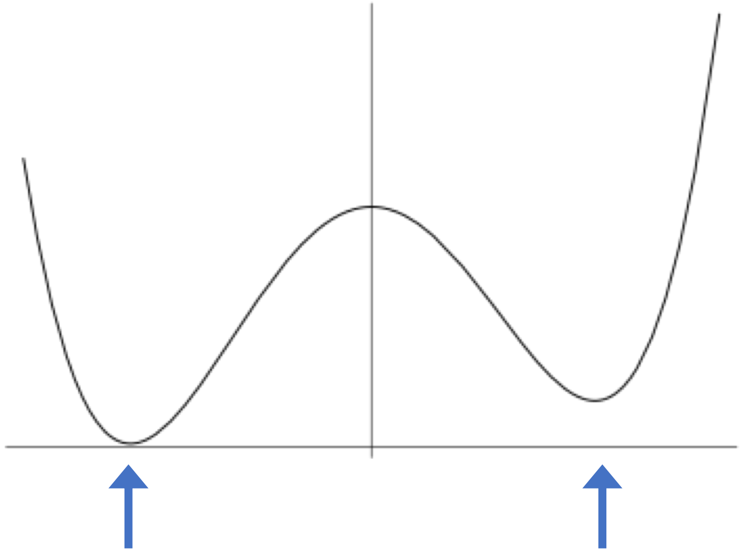
MULTIVERSE





In steady-state, the expansion rates in phase h and v become equal $\Rightarrow$ energy degeneracy.

A NEW WAY OF USING SUPERSYMMETRY



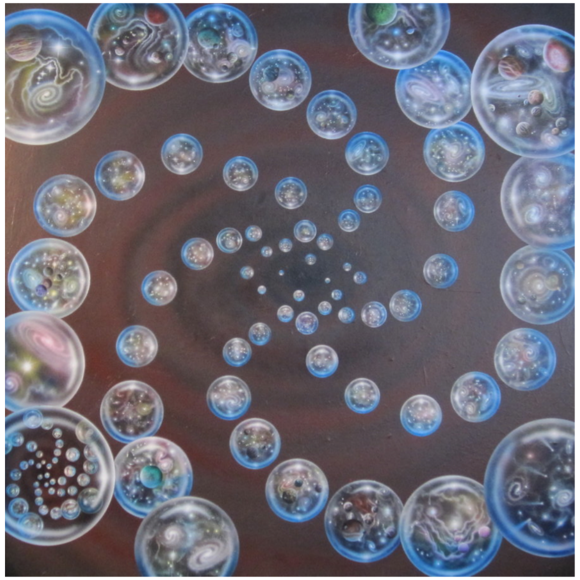
Phase *h*
(supersymmetry
& R-symmetry)

Phase *v*
(visible phase)

Supersymmetry is a hidden feature of the theory to any observer, like us, who lives in phase *v*, and yet it determines parameters measurable in our vacuum.

DARK-ENERGY EQUATION OF STATE

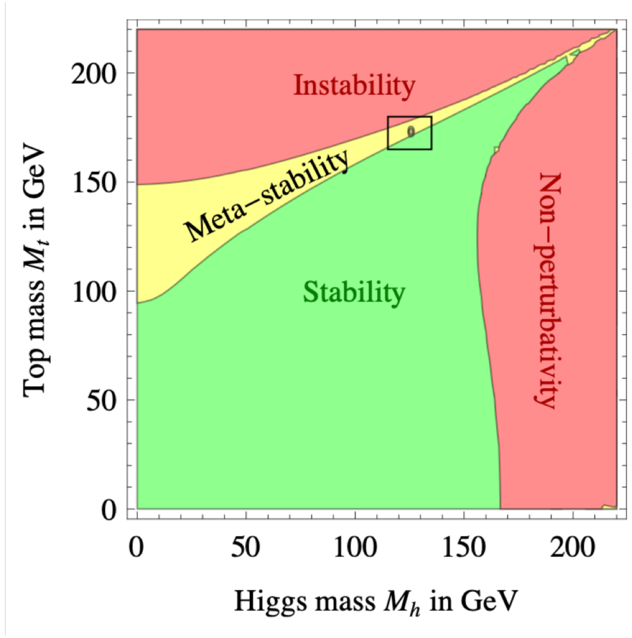
$$w = \frac{P_\phi}{\rho_\phi} = -1 + \left(\frac{V_v'(0)}{3H_{\rm now}\Lambda_{\rm CC}^2}\right)^2 = -1 + \frac{c_\xi^2}{3}$$



TESTING SOL EXPERIMENTALLY?

SOL's smoking gun is phase coexistence.

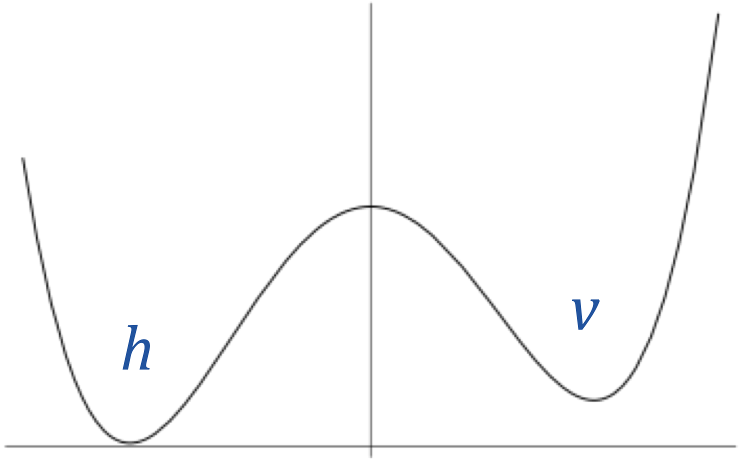
Near-criticality of the Higgs self-coupling



Higgs naturalness

New matter at the TeV makes the SM unstable under variations of the Higgs bilinear.

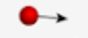
Cosmological constant



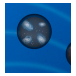
Dark energy EoS

CONCLUSIONS

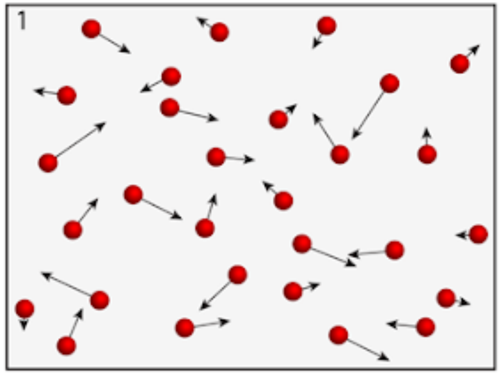
- SOL is an approach radically different from the symmetry paradigm: critical points can become dynamical attractors during inflation and determine low-energy parameters.



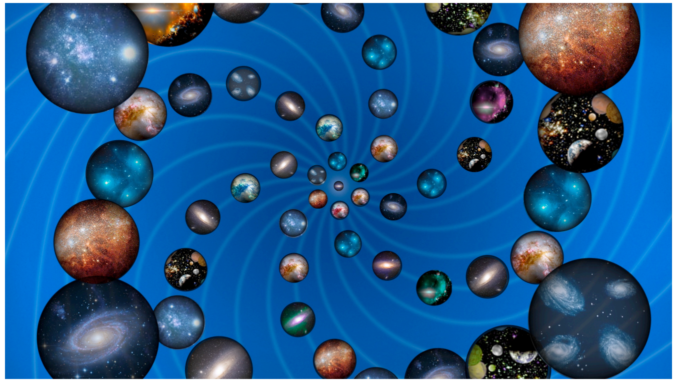
Single atom: energy?



Single Universe: SM parameters?



Gas in statistical equilibrium: probabilistic prediction.



Multiverse in steady-state: probabilistic prediction.

- SOL can address some of the open questions in particle physics.

CONCLUSIONS

- Higgs naturalness remains a great mystery.
- We cannot say that we understand EW breaking until we get to the bottom of the naturalness problem.
- The lesson we have learned from the LHC is that we must expand our horizons.
- Hopefully SOL can help.