Relaxation of four-form fluxes for Higgs mass, cosmological constant and flattening inflaton potential

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Ref. HML, 1908.04252, 1910.09171 (Higgs),

1908.05475 (Inflation)

Cosmology Seminar
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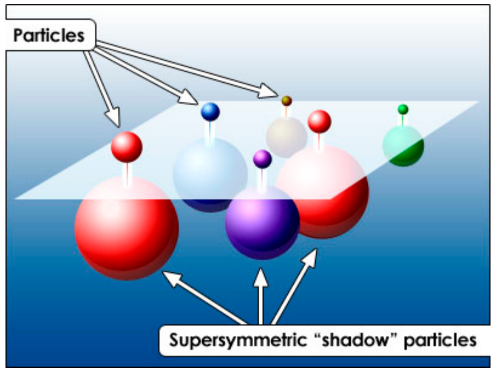
Outline

- Introduction on four-form flux
- Four-form flux and Higgs mass
- Reheating
- Chaotic inflation with four-form flux
- Conclusions

New physics for Higgs mass

- Supersymmetry

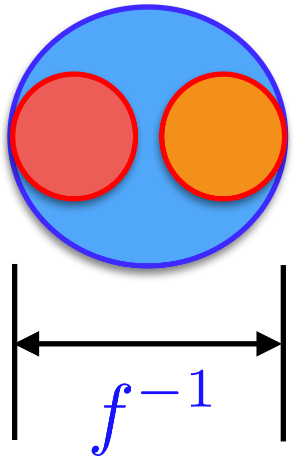
$$m_H^2 \sim \kappa M_{\rm SUSY}^2$$



- Pion-like composite

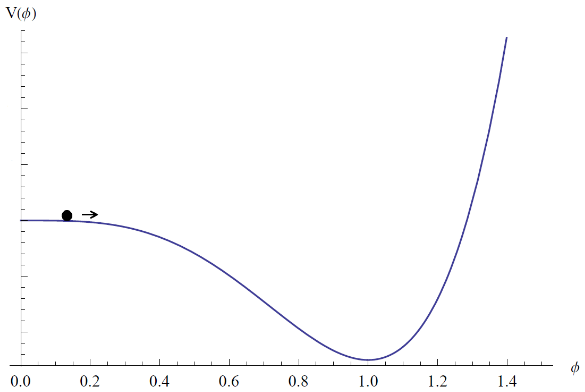
$$H = \bar{Q}'Q'$$

$$m_H^2 \sim \kappa f^2$$



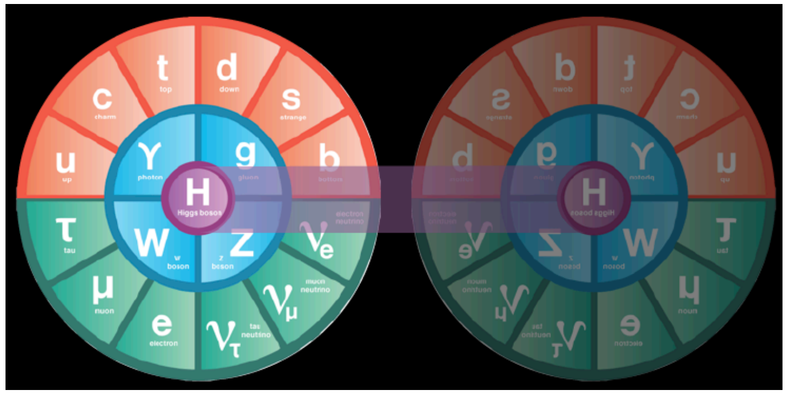
- Scale invariance

$$m_H^2 \sim \lambda' \langle \phi^2 \rangle \ll M_P^2 \sim \xi \langle \phi^2 \rangle$$



- Discrete symmetries

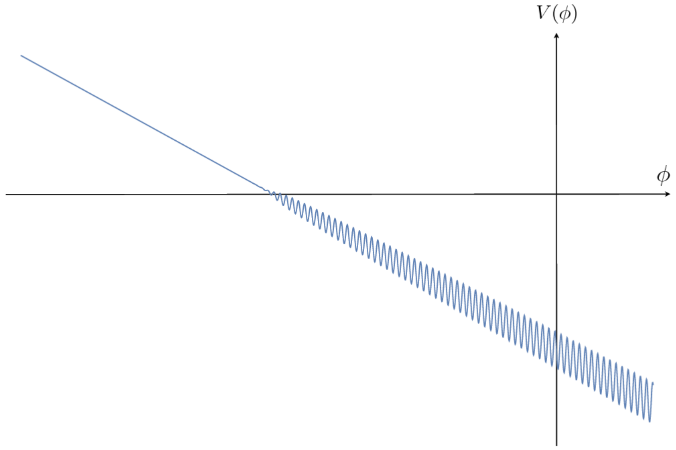
$$m_H^2 \sim \kappa M_{\rm SM'}^2$$



[N. Craig, CERN, 2018]

- Cosmological relaxation

$$m_H^2 = M^2 - g\phi, \qquad g \ll |m_H|$$

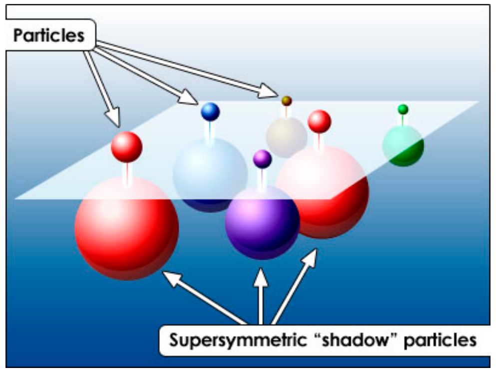


New physics for Higgs mass

- Supersymmetry

Superparticles:

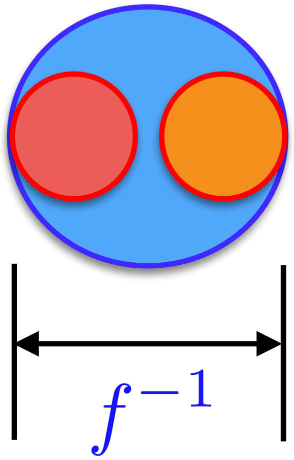
$M_{\mathrm{SUSY}} \sim 1\,\mathrm{TeV}$



- Pion-like composite

Rho-like/top partner:

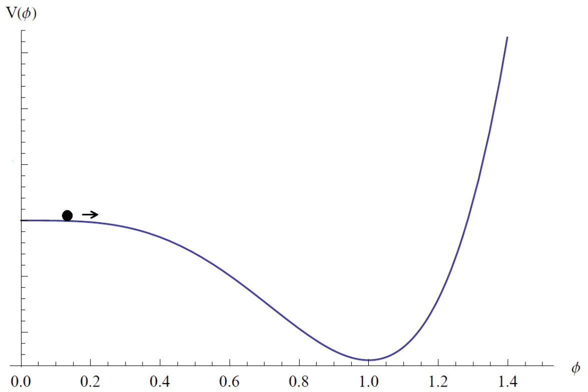
$M_{\rho,T} \sim \mathrm{TeV}$



- Scale invariance

Higgs-like
light scalar:

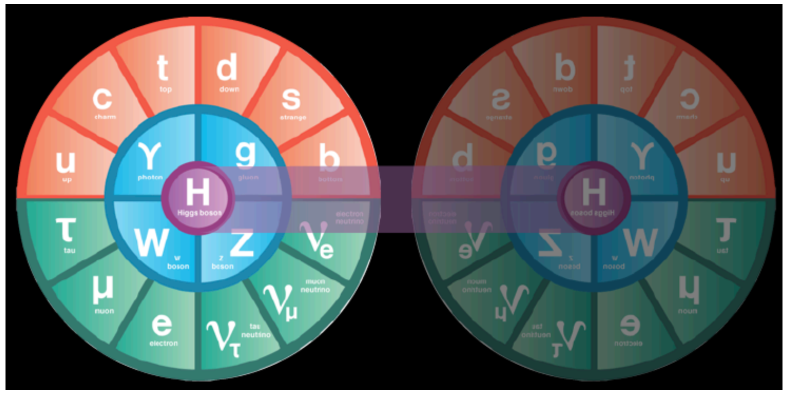
$m_\phi \ll m_h$



- Discrete symmetries

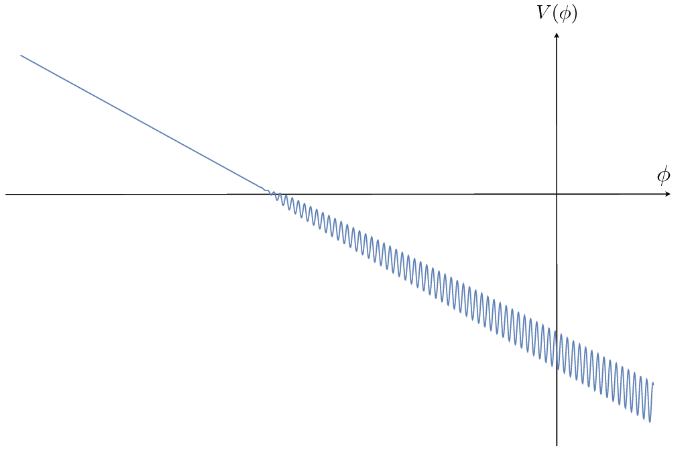
Neutral partners:

$m_{\mathrm{h}'} \sim m_h, \quad \Lambda'_{\mathrm{QCD}} \sim \Lambda_{\mathrm{QCD}}$

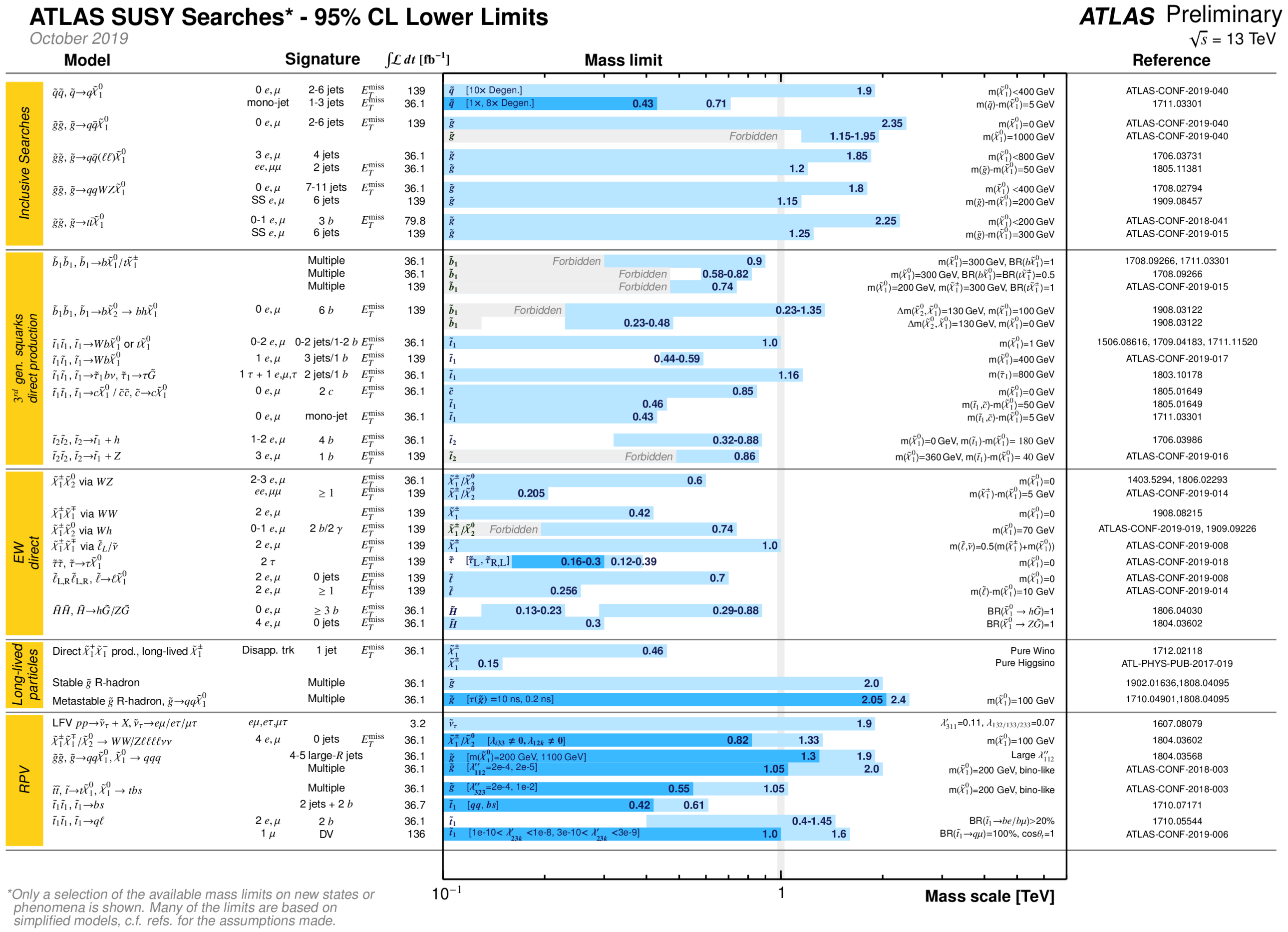


- Cosmological relaxation

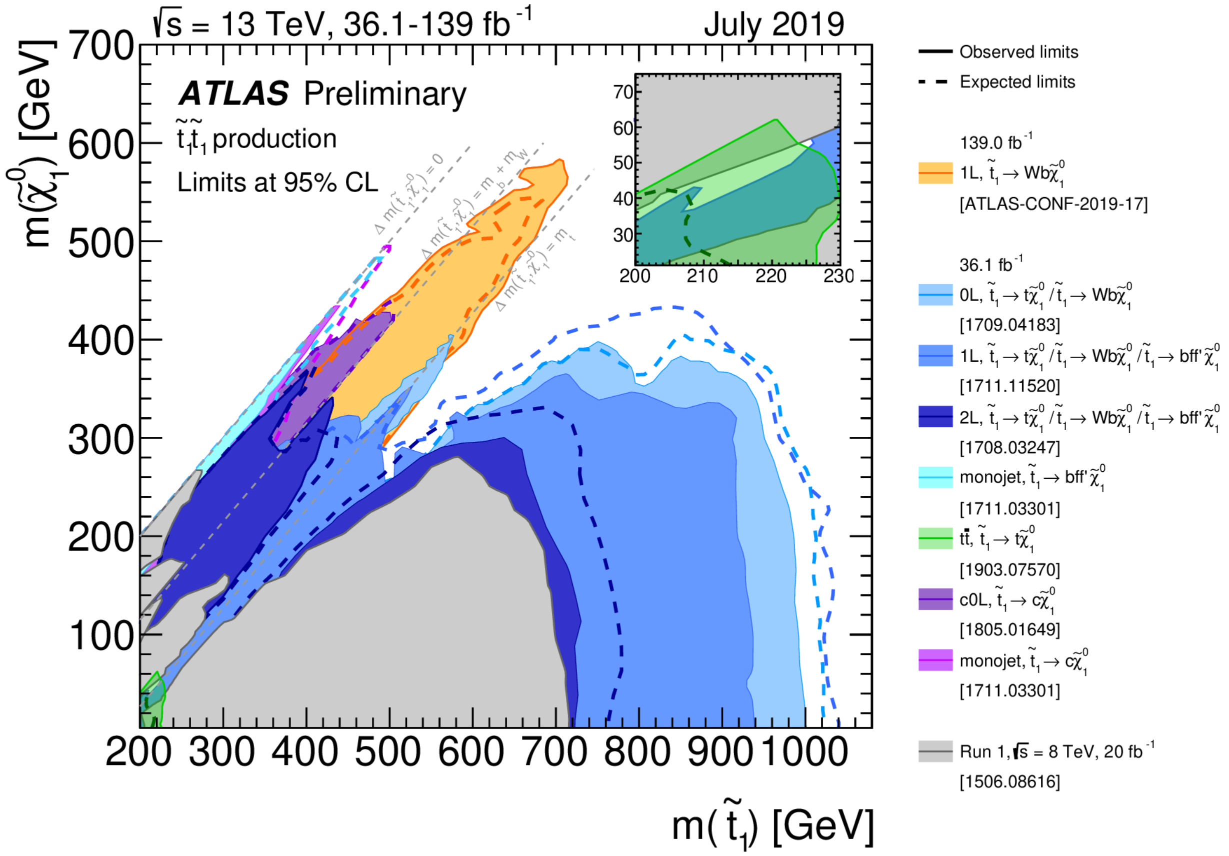
Axion-like relaxion: $m_\phi \ll m_h$



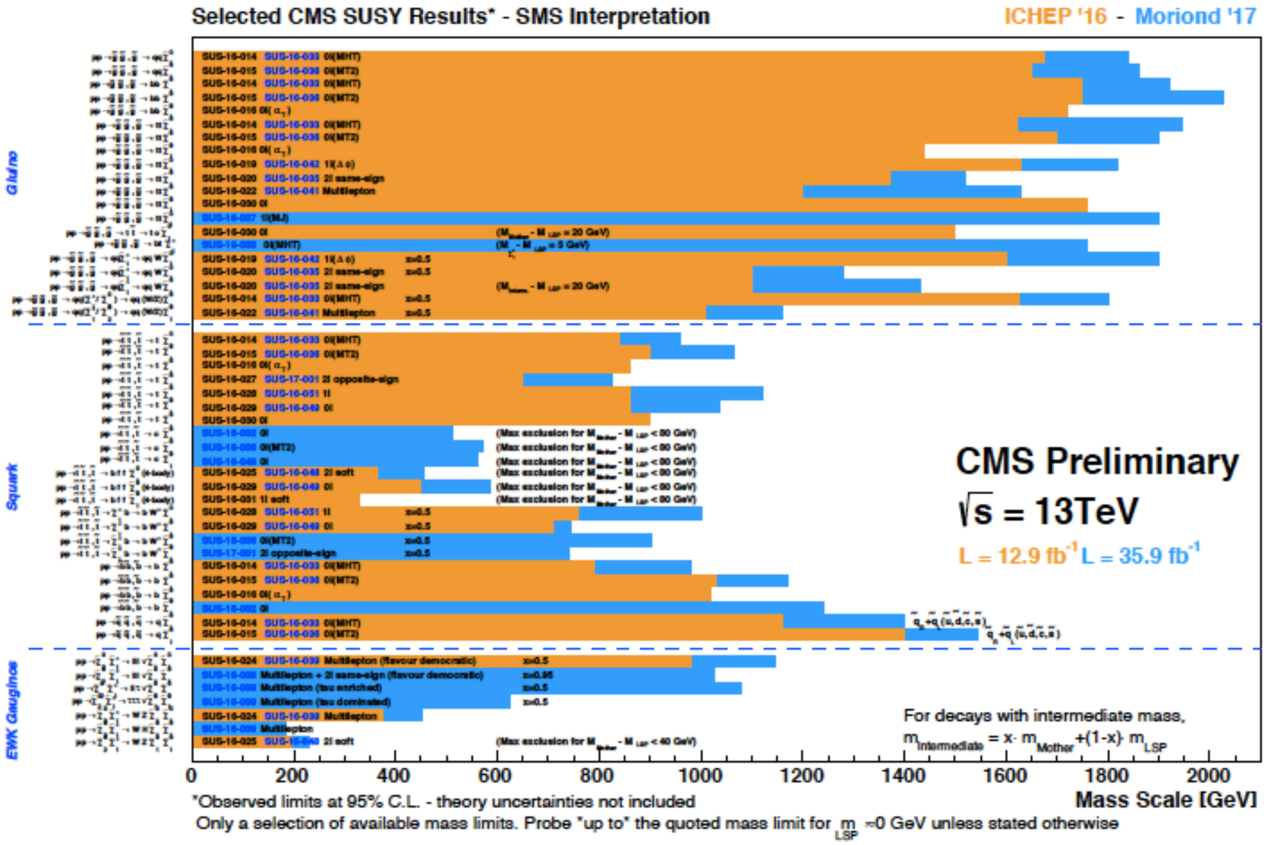
SUSY at LHC



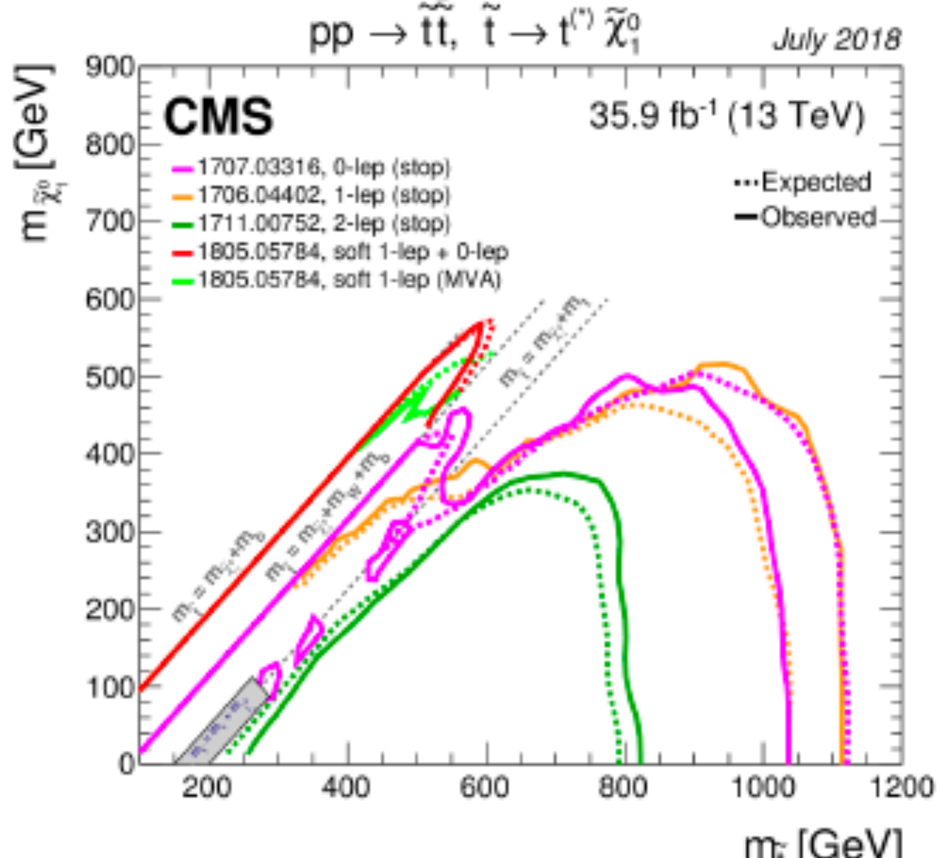
ATLAS SUSY Searches* - 95% CL Lower Limits
October 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\,dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Mass scale [TeV]
10^{-1}
1
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



$\sqrt{s}$ = 13 TeV, 36.1-139 fb^{-1}
July 2019
ATLAS Preliminary
$\tilde{t}_1\tilde{t}_1$ production
Limits at 95% CL
$m(\tilde{\chi}^0_1)$ [GeV]
$m(\tilde{t}_1)$ [GeV]
Observed limits
Expected limits
139.0 fb^{-1}
1L, $\tilde{t}_1 \to Wb\tilde{\chi}^0_1$
[ATLAS-CONF-2019-17]
36.1 fb^{-1}
0L, $\tilde{t}_1 \to t\tilde{\chi}^0_1 / \tilde{t}_1 \to Wb\tilde{\chi}^0_1$
[1709.04183]
1L, $\tilde{t}_1 \to t\tilde{\chi}^0_1 / \tilde{t}_1 \to Wb\tilde{\chi}^0_1 / \tilde{t}_1 \to bff'\tilde{\chi}^0_1$
[1711.11520]
2L, $\tilde{t}_1 \to t\tilde{\chi}^0_1 / \tilde{t}_1 \to Wb\tilde{\chi}^0_1 / \tilde{t}_1 \to bff'\tilde{\chi}^0_1$
[1708.03247]
monojet, $\tilde{t}_1 \to bff'\tilde{\chi}^0_1$
[1711.03301]
$t\bar{t}$, $\tilde{t}_1 \to t\tilde{\chi}^0_1$
[1903.07570]
c0L, $\tilde{t}_1 \to c\tilde{\chi}^0_1$
[1805.01649]
monojet, $\tilde{t}_1 \to c\tilde{\chi}^0_1$
[1711.03301]
Run 1, $\sqrt{s}$ = 8 TeV, 20 fb^{-1}
[1506.08616]

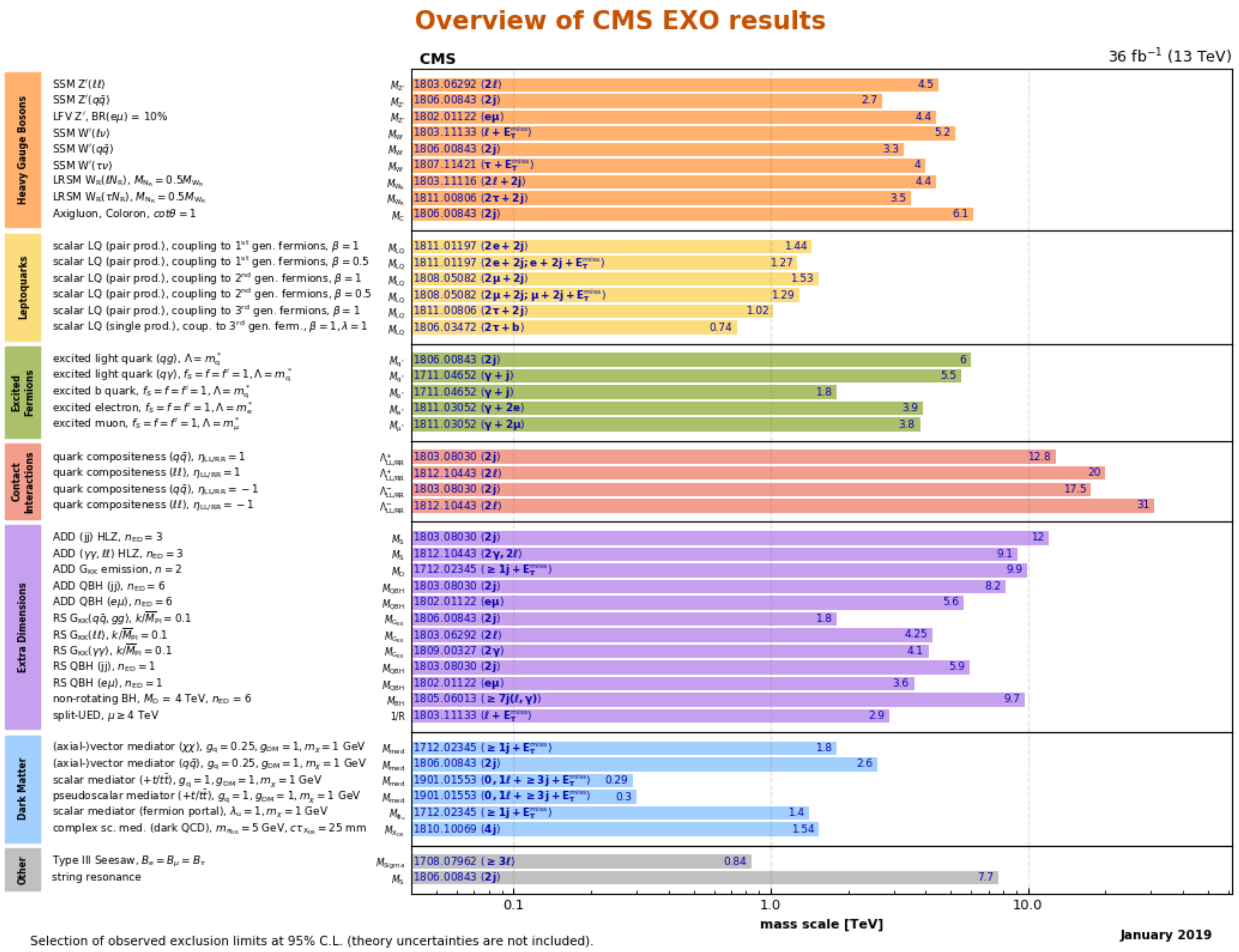


Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
$\sqrt{s}$ = 13TeV
L = 12.9 fb^{-1} L = 35.9 fb^{-1}
For decays with intermediate mass,
$m_{Intermediate} = x \cdot m_{Mother} + (1-x) \cdot m_{LSP}$
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_{LSP} =0 GeV unless stated otherwise



$pp \to \tilde{t}\bar{\tilde{t}}, \; \tilde{t} \to t^{(*)}\tilde{\chi}^0_1$
July 2018
CMS
35.9 fb^{-1} (13 TeV)
1707.03316, 0-lep (stop)
1706.04402, 1-lep (stop)
1711.00752, 2-lep (stop)
1805.05784, soft 1-lep + 0-lep
1805.05784, soft 1-lep (MVA)
Expected
Observed
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}}$ [GeV]

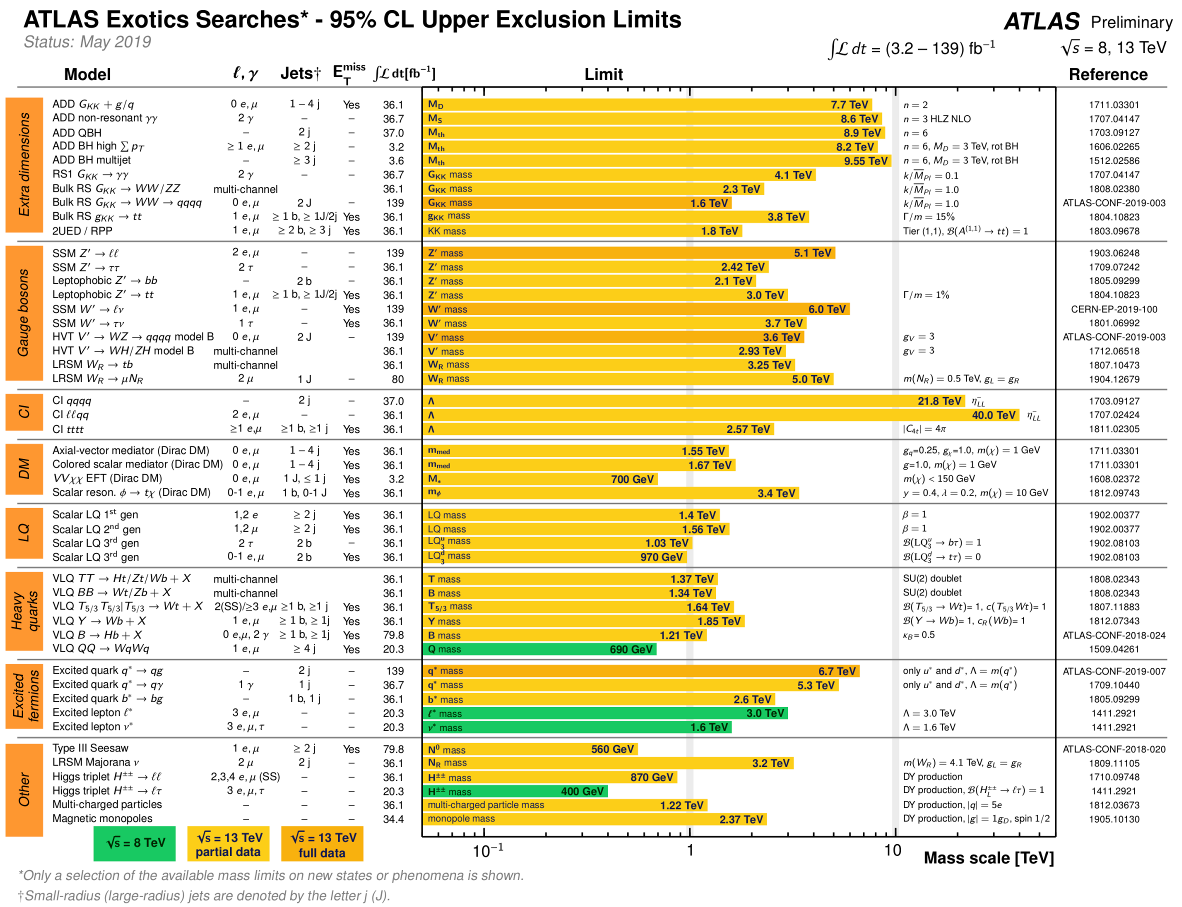
Other new physics at LHC



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

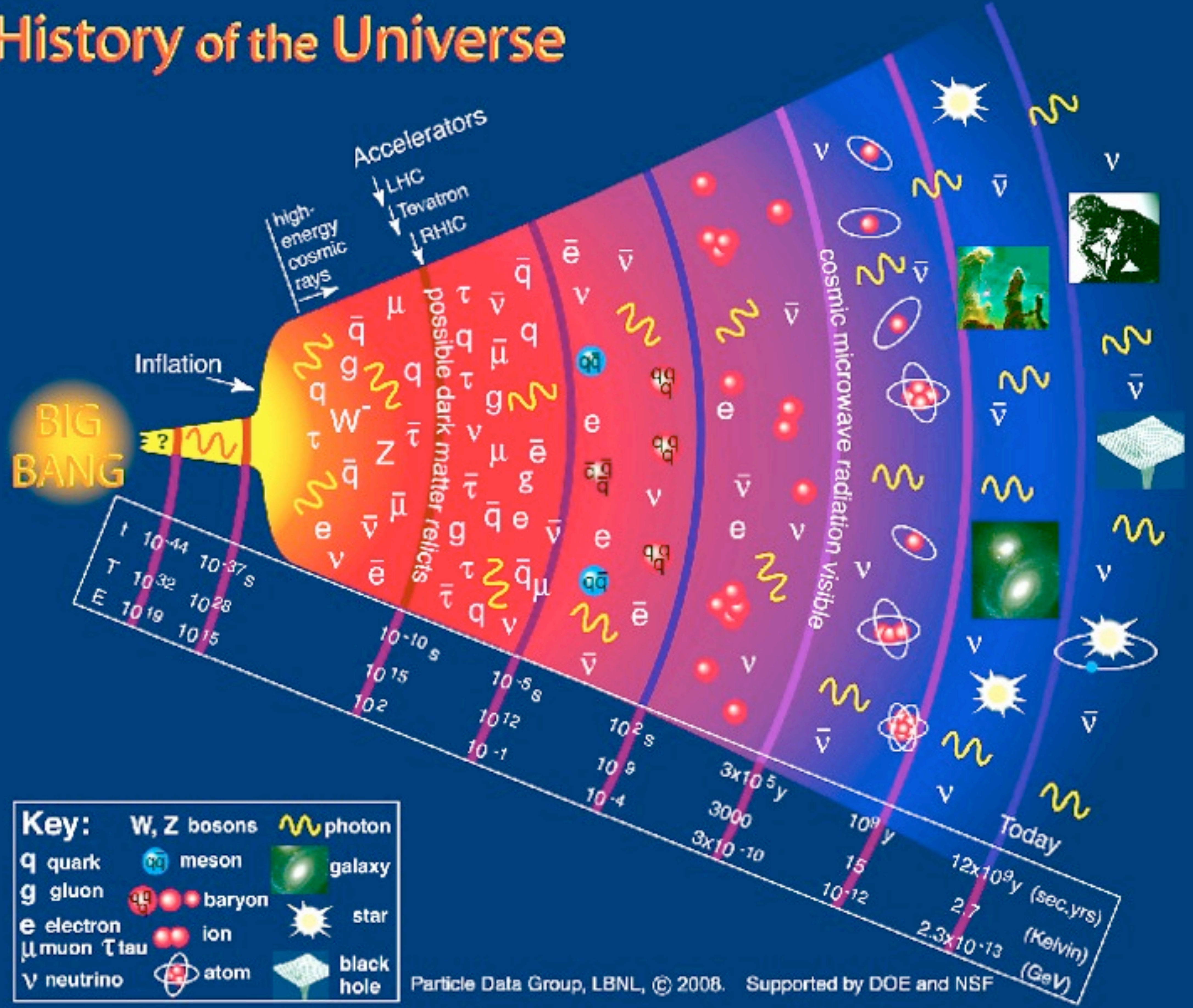
No evidence for new physics at a few TeV at the LHC!

Have we missed something or do we need new ideas?



*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

History of the Universe



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

It is important to understand the evolution of the Universe as a whole in cosmological time scales.

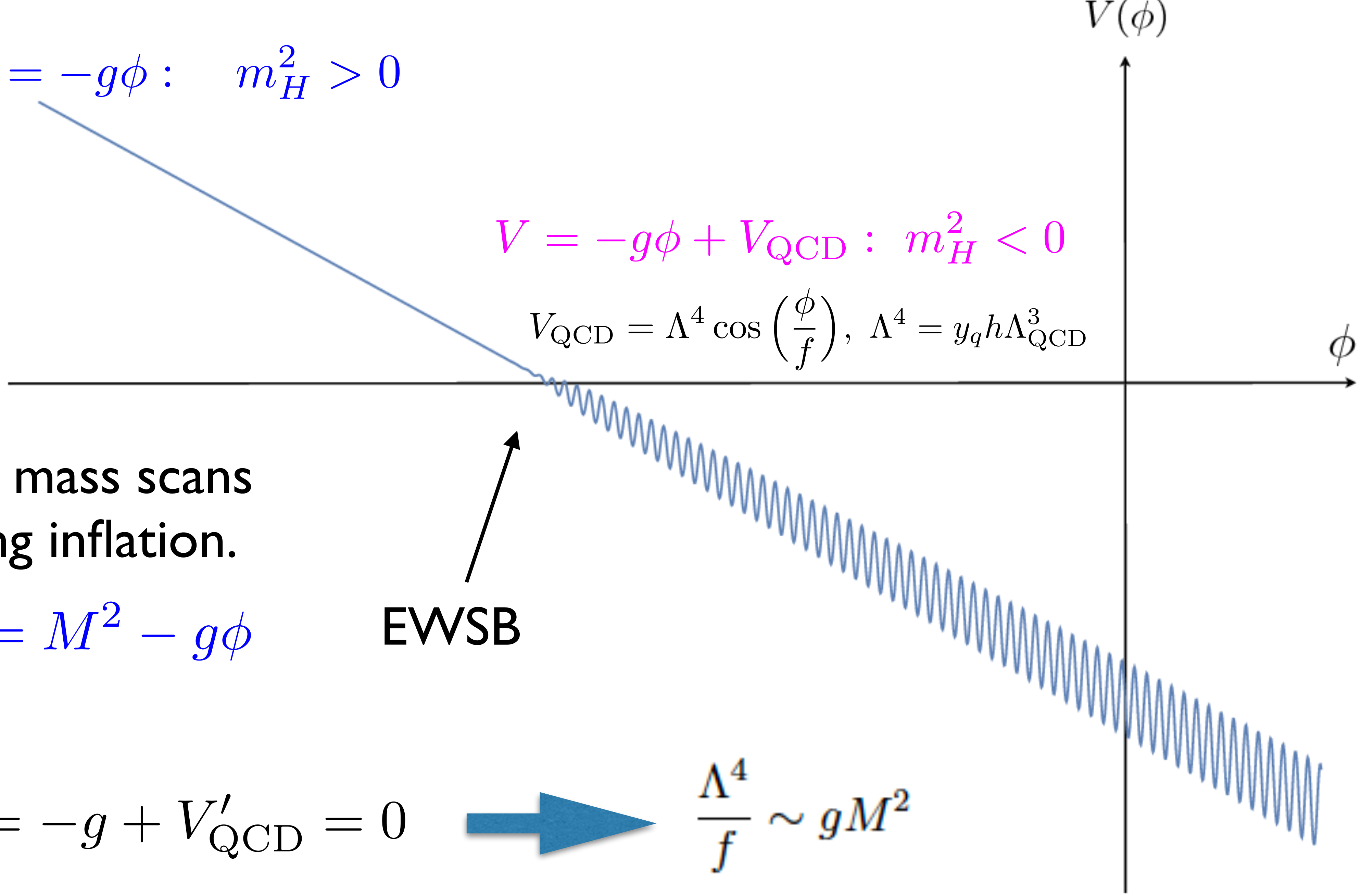
Microscopic parameters in the Standard Model might be generated, because of inflation and cosmological dynamics before BBN.

Cosmological relaxation

[P. Graham et al, 2015]

ϕ : Axion-like scalar

$V = -g\phi : \quad m_H^2 > 0$



$V = -g\phi + V_{\rm QCD} : \; m_H^2 < 0$

$V_{\rm QCD} = \Lambda^4 \cos\left(\frac{\phi}{f}\right), \; \Lambda^4 = y_q h \Lambda_{\rm QCD}^3$

EWSB

Higgs mass scans during inflation.

$m_H^2 = M^2 - g\phi$

$V' = -g + V'_{\rm QCD} = 0$ → $\frac{\Lambda^4}{f} \sim gM^2$

$\frac{M^2}{M_{Pl}} < H_I < \min\left\{(gM^2)^{\frac{1}{3}}, \Lambda\right\}$ → $\boxed{M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{\frac{1}{6}} \sim 10^7\,\mathrm{GeV}\left(\frac{10^9\,\mathrm{GeV}}{f}\right)^{\frac{1}{6}}}$

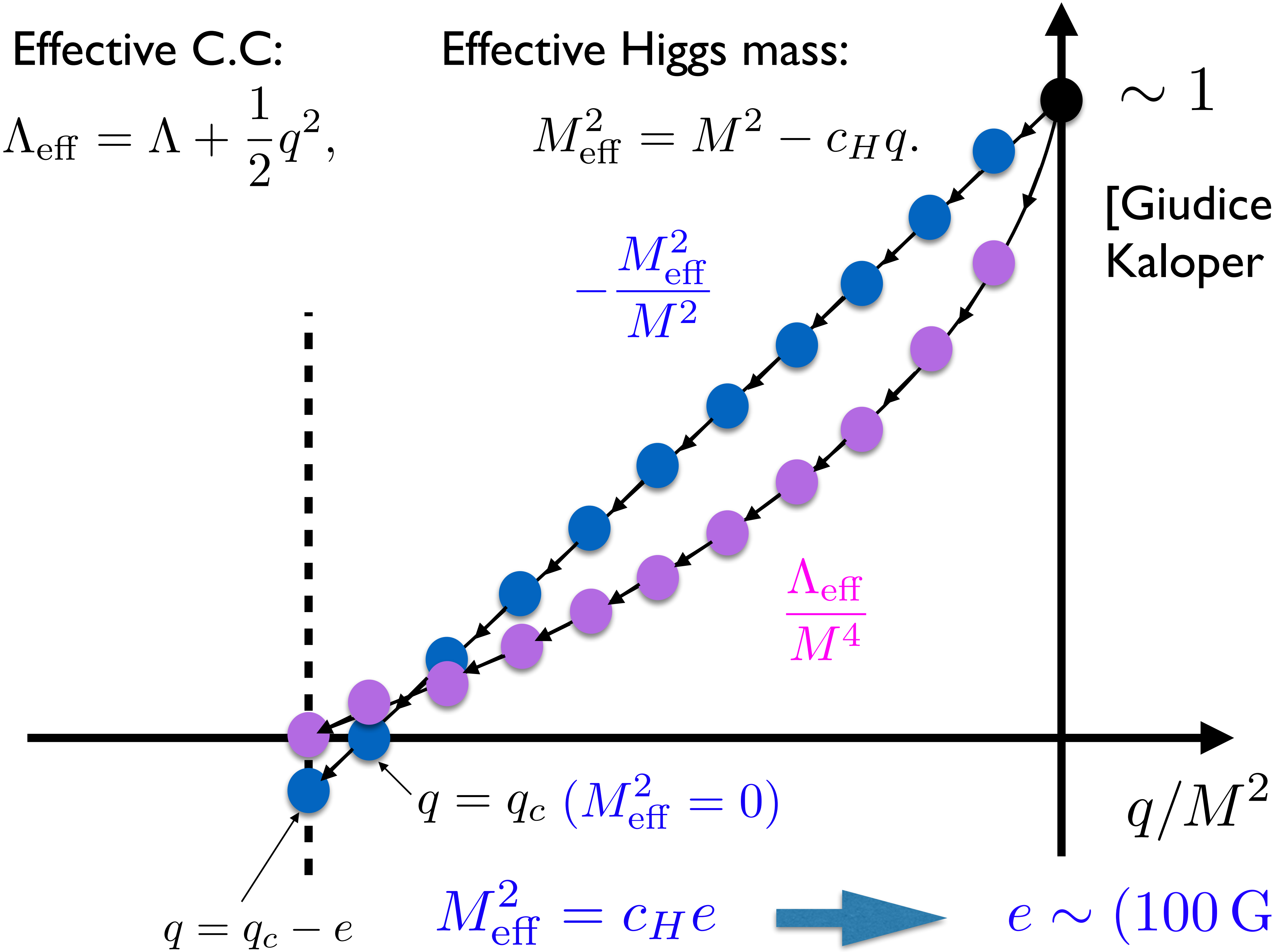
Four-form and Higgs mass

Effective C.C:

$$\Lambda_{\text{eff}} = \Lambda + \frac{1}{2}q^2,$$

Effective Higgs mass:

$$M^2_{\text{eff}} = M^2 - c_H q.$$



[Giudice et al, 2019; Kaloper et al, 2019]

$$M^2_{\text{eff}} = c_H e \quad \rightarrow \quad e \sim (100\,\text{GeV})^2$$

$$\Lambda_{\text{eff}} \approx 0 \quad \rightarrow \quad \Lambda = -\frac{1}{2}(q_c - e)^2 + \Delta\Lambda$$

Four-form flux and C.C.

- Three-form gauge field is not dynamical, but its field strength (four-form flux) adds to cosmological constant:

$$\mathcal{L} = \sqrt{-g}\left(\frac{1}{2}R - \Lambda - \underset{\text{Kinetic term}}{\underline{\frac{1}{48}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}}}\right) + \underset{\text{Surface term}}{\underline{\frac{1}{6}\partial_\mu\left[\sqrt{-g}F^{\mu\nu\rho\sigma}A_{\nu\rho\sigma}\right]}}.$$

$$F_{\mu\nu\rho\sigma} = 4\partial_{[\mu}A_{\nu\rho\sigma]}$$

Equation of motion: $\partial_\mu\left(\sqrt{-g}F^{\mu\nu\rho\sigma}\right) = 0$ or dual transform in 4D:

➡ $F^{\mu\nu\rho\sigma} = \dfrac{1}{\sqrt{-g}}\,q\,\epsilon^{\mu\nu\rho\sigma}$, or $F_{\mu\nu\rho\sigma} = q\,\epsilon_{\mu\nu\rho\sigma}.\quad q = \text{const}$

Effective C.C: $\Lambda_{\text{eff}} = \Lambda + \dfrac{1}{2}q^2$

For $\Lambda < 0$, Four-form flux cancels the bare cosmological constant to zero.

[Duff, van Nieuwenhuizen, 1980;
Witten, 1984;
Henneaux, Teitelboim, 1984;
Baum, 1983, Hawking, 1984]

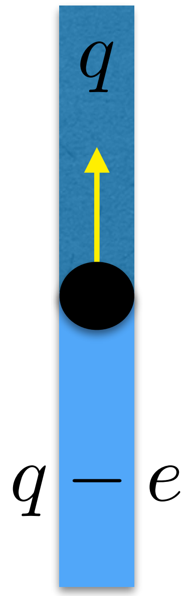
Particles from E-field

- The Maxwell field in 2D analogue is non-dynamical (no polarizations), but electric field can reduce due to charge nucleation.

$$\mathcal{L}_{2D} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - m \int ds_E, \qquad \mathcal{L}_{\text{charge}} = e \int d\xi \, \delta^2(x - x(\xi)) A_\mu \frac{\partial x^\mu}{\partial \xi}.$$

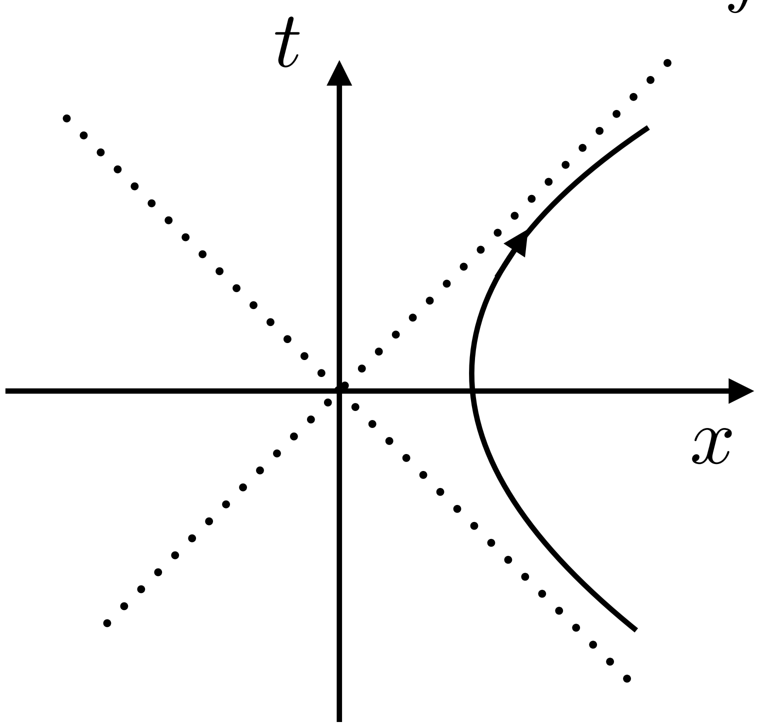
Eqs. of motion: $m \ddot{x}^\mu = e F^{\mu\nu} \dot{x}_\nu,$ [Brown, Teitelboim, 1987]

$$\partial_\mu F^{\mu\nu} = -e \int d\xi \, \delta^2(x - x(\xi)) \frac{\partial x^\nu}{\partial \xi}.$$

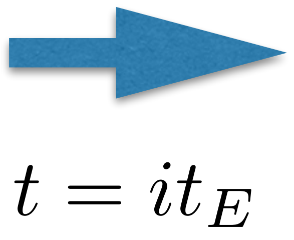


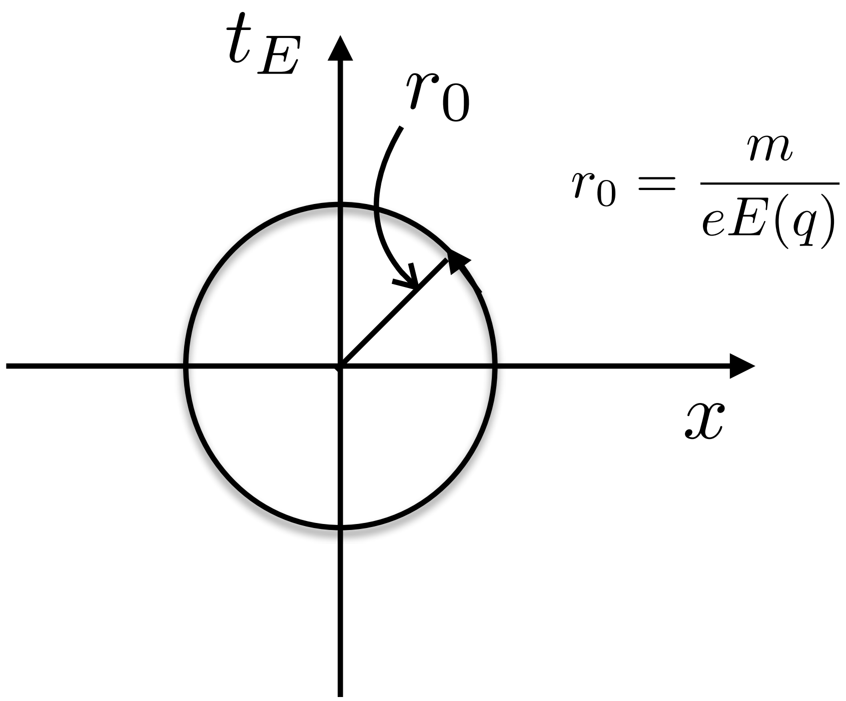
2D E-field

$F_{\mu\nu} = q \, \epsilon_{\mu\nu}$



"accelerating charge"





"circular motion"

Bounce action for particle

$$S_E = m \int ds_E + \frac{1}{4} \int d^2 x_E F_{\mu\nu}^2;$$

$$B = S_E(\text{instanton}) - S_E(\text{background}),$$

$$B = m(2\pi r_0) + \frac{1}{2}[(q-e)^2 - q^2](\pi r_0^2)$$
$$\approx 2\pi m r_0 - \pi e E(q) r_0^2$$

$$\frac{\partial B}{\partial r_0} = 0 \quad \Longrightarrow \quad r_0 = \frac{m}{eE(q)} \quad \Longrightarrow \quad B = \frac{\pi m^2}{eE(q)}$$

1. Charge production (= instanton tunneling to “E=q-e outside and E=q inside”):

$$P(q \to q - e) \approx \exp\Big(-\frac{1}{\hbar} B\Big) = \Big(-\frac{\pi m^2}{\hbar\, eE(q)}\Big)$$

2. Charge production continues, as far as the E-field outside is positive.

Membranes from four-form

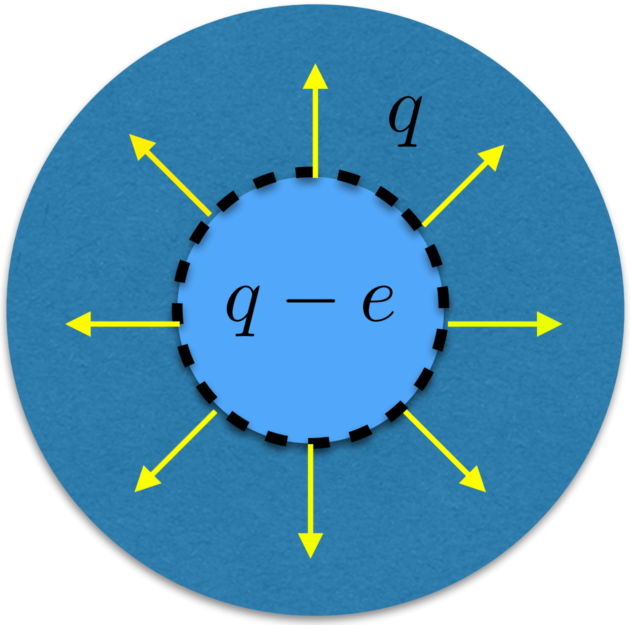
- The four-form flux can reduce due to the membrane nucleation. [Brown, Teitelboim, 1987]

$$\mathcal{L}_{\rm memb} = \frac{e}{6}\int d^3\xi\,\delta^4(x-x(\xi))\,A_{\nu\rho\sigma}\frac{\partial x^\nu}{\partial\xi^a}\frac{\partial x^\rho}{\partial\xi^b}\frac{\partial x^\sigma}{\partial\xi^c}\,\epsilon^{abc}$$

Eq. of motion for flux:

$$\epsilon^{\mu\nu\rho\sigma}\partial_\mu q = -e\int d^3\xi\,\delta^4(x-x(\xi))\,\frac{\partial x^\nu}{\partial\xi^a}\frac{\partial x^\rho}{\partial\xi^b}\frac{\partial x^\sigma}{\partial\xi^c}\epsilon^{abc}.$$

$q = en$: Flux quantization in microscopic theory.



4D 4-form

1. Closed membrane production (= instanton tunneling to "q-e inside and q outside"):

$$B = T\left(2\pi^2 r_0^3\right) - \Delta\Lambda\left(\frac{\pi^2}{2}r_0^4\right), \quad r_0 = \frac{3T}{\Delta\Lambda}$$ [Coleman, 1977]

$$P(q \to q-e) \approx \exp\left(-\frac{27\pi^2 T^2}{2(\Delta\Lambda)^3}\right), \quad \Delta\Lambda = \Lambda_{\rm eff}(q) - \Lambda_{\rm eff}(q-e) > 0.$$

2. Membranes would keep being produced inside as far as the flux outside is nonzero.

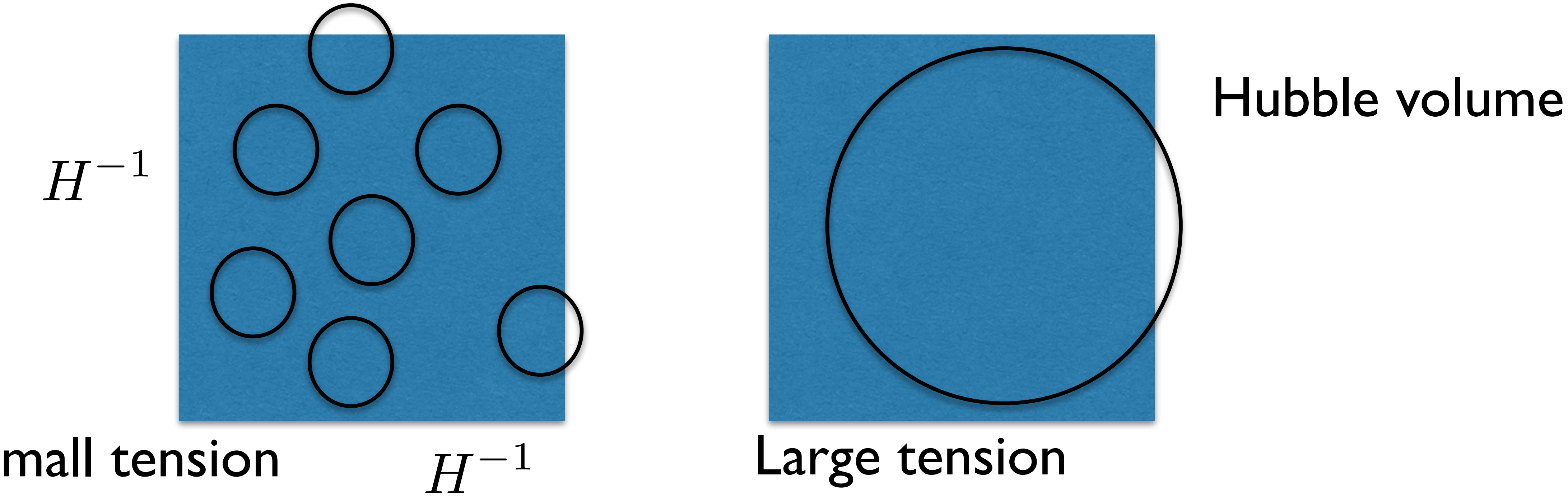
Gravity effects on bubbles

- The tunneling probability is corrected by dS curvature radius as [Coleman, de Luccia, 1980]

$$P(q \to q-e) = \exp\Big(-\frac{27\pi^2 T^2}{2(\Delta\Lambda)^3}\frac{1}{(1+\frac{1}{4}r_0^2H^2)^2}\Big) \approx \exp\Big(-\frac{24\pi^2 M_P^4}{\Lambda_{\rm eff}}\Big).$$

$$\Lambda_{\rm eff} \ll \frac{T^2}{M_P^2}$$

$r_0 = \frac{3T}{\Delta\Lambda}$: Bubble radius with no gravity.



- Membrane production stops when the cosmological constant is positive and the smallest.

[Brown, Teitelboim, 1987]

Origin of four-forms

- Four-form fluxes are dynamical in higher dimension; M-theory contains M2-brane and M5-brane as sources. [Bousso, Polchinski, 2000]

→ Membrane tensions and charges in 4D.

M5-brane wrapped on 3-cycle: $(M_P^2 = 2\pi M_{11}^9 V_7)$

$$\tau_i = 2\pi M_{11}^6 V_{3,i}, \qquad q_i = \frac{(2\pi)^{1/2} M_{11}^{3/2} V_{3,i}}{V_7^{1/2}}, \quad i \le N_3$$

M2-brane:

$$\tau_{N_3+1} = 2\pi M_{11}^3, \qquad q_{N_3+1} = \frac{(2\pi)^{1/2}}{M_{11}^{3/2} V_7^{1/2}}. \qquad \left(q_i^2 = \frac{2\tau_i^2}{M_P^2}\right)$$

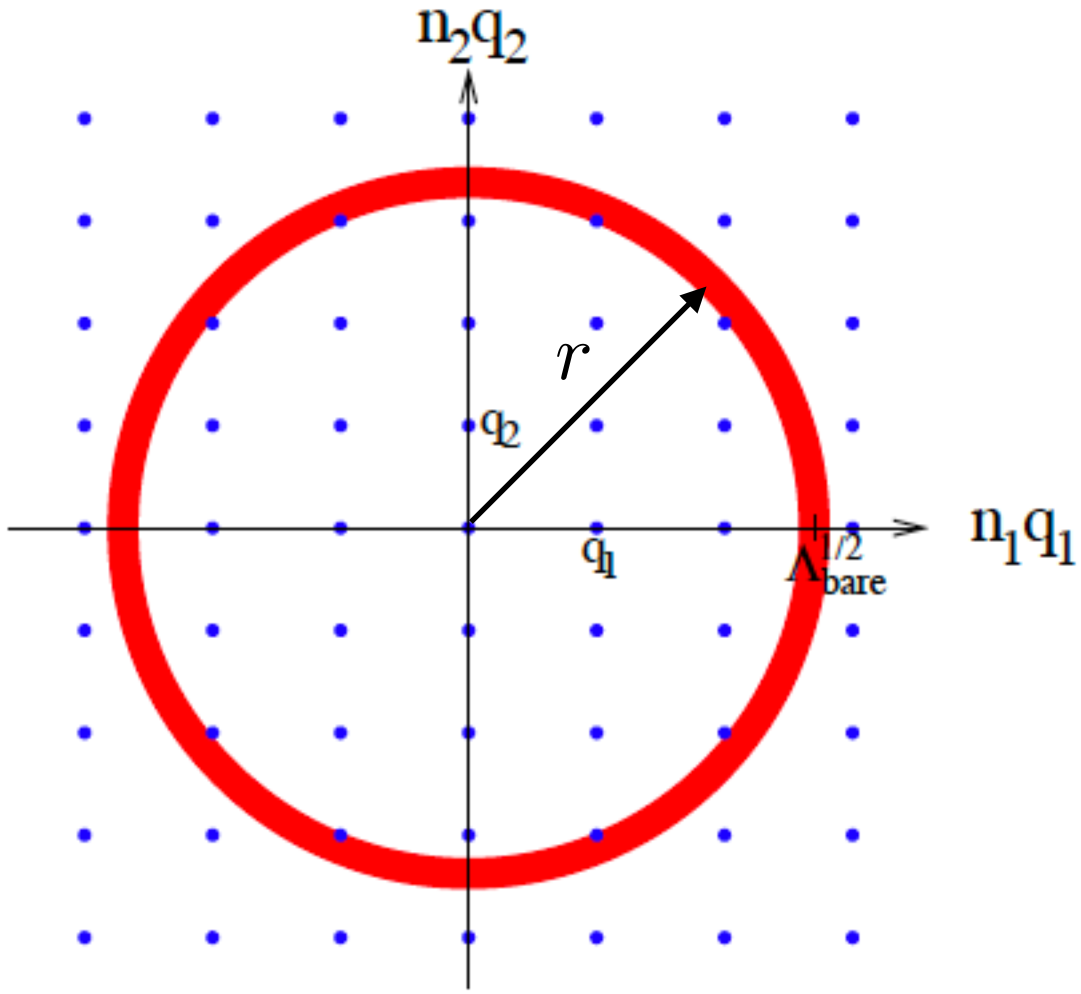
Large volume compactified on 3-cycles
can lead to a small membrane tension and charge.

Membrane tension and charge can be separate
in a non-supersymmetric low energy theory:
a small membrane charge is possible and technically natural.

Multiple four-forms and C.C.

- M-theory compactified on the manifold with multiple 3-cycles leads to enough number of four-form fluxes for the accurate cancellation of C. C.

[Bousso, Polchinski, 2000]



$$\sqrt{2\Lambda} < r = \sqrt{\sum_i n_i^2 e_i^2} < \sqrt{2(\Lambda + \Delta\Lambda)}$$

Shell width: $\Delta r = \dfrac{\Delta\Lambda}{\sqrt{2\Lambda}},$

$$\Delta\Lambda \sim 10^{-120} M_P^4.$$

Sufficient grid points within shell:

$$\prod_i e_i \lesssim \omega_{J-1} r^{J-1} \Delta r$$

⇒ $\Delta\Lambda \sim \dfrac{\prod_i e_i}{|2\Lambda|^{J/2-1}}$

$$\Lambda \sim M_P^4,\ J \sim 100:\ e_i \sim 10^{-1.6} M_P^2$$

Four-form flux and Higgs mass

Four-form and Higgs mass

- Four-form flux has a dimensionless coupling to the SM Higgs, scanning the Higgs mass parameter.

[Dvali, Vilenkin, 2004; Giudice, Kehagias, Riotto, 2019;
Kaloper, Westphal, 2019; HML, 2019]

$$\mathcal{L}_H = M^2|H|^2 - \lambda_H|H|^4 - \underline{\frac{c_H}{24}\,\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\,|H|^2} - \frac{c_H}{6}\partial_\mu\Big(\epsilon^{\mu\nu\rho\sigma}|H|^2A_{\nu\rho\sigma}\Big).$$

$$\Longrightarrow \qquad \mathcal{L}_{\rm eff} = -\Lambda_{\rm eff} + M^2_{\rm eff}|H|^2 - \lambda_{H,{\rm eff}}|H|^4,$$

$$\Lambda_{\rm eff} = \Lambda + \frac{1}{2}q^2,$$

$$M^2_{\rm eff} = M^2 - c_H q,$$

Four-form flux scans C.C.
as well as Higgs mass.

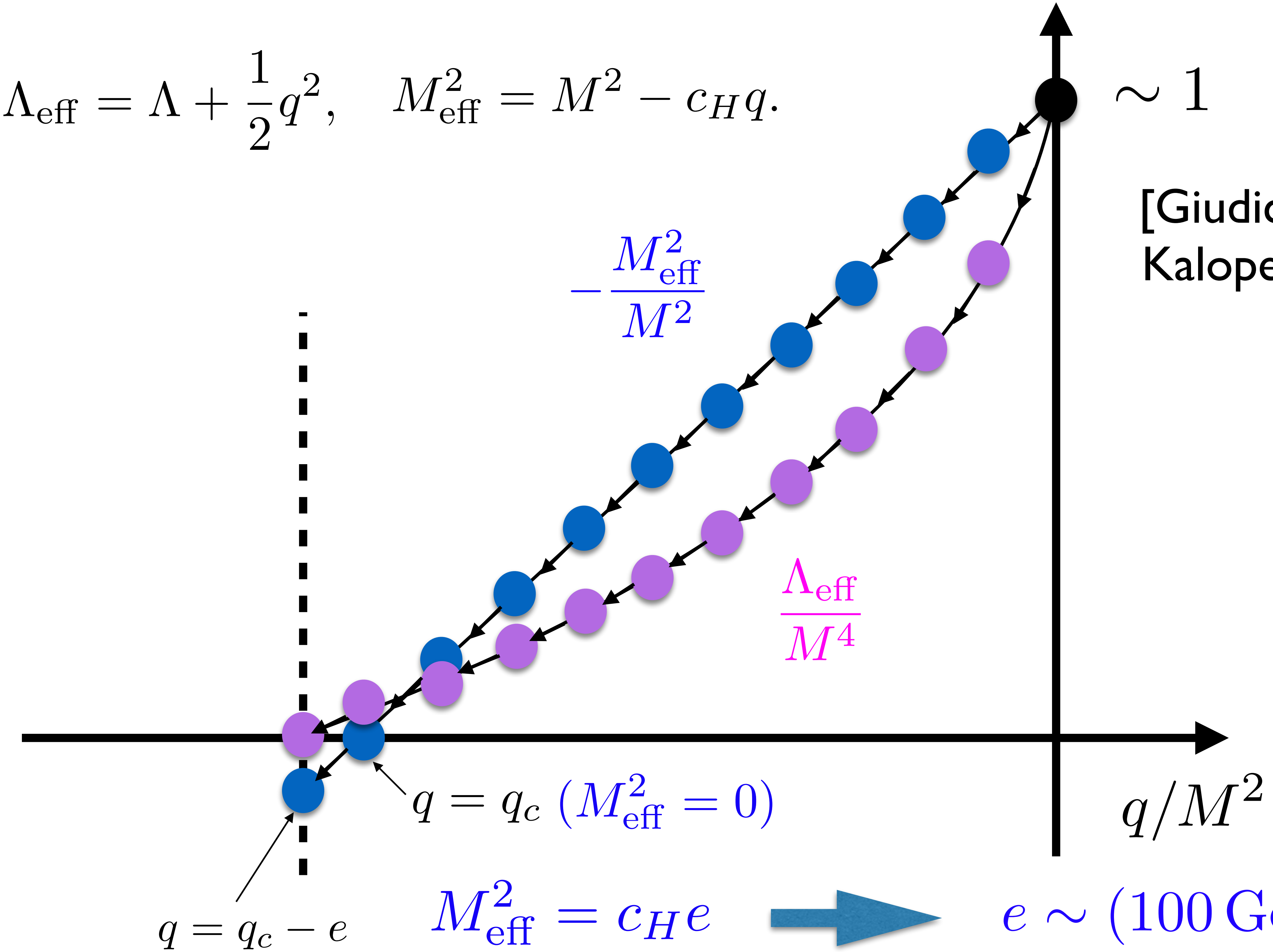
$$\lambda_{H,{\rm eff}} = \lambda_H + \frac{1}{2}c_H^2.$$

Higgs quartic coupling has
a constant shift.

Four-form and Higgs mass

$$\Lambda_{\rm eff} = \Lambda + \frac{1}{2}q^2, \quad M_{\rm eff}^2 = M^2 - c_H q.$$

[Giudice et al, 2019;
Kaloper et al, 2019]



$$M_{\rm eff}^2 = c_H e \quad \Rightarrow \quad e \sim (100\,{\rm GeV})^2$$

$$\Lambda_{\rm eff} \approx 0 \quad \Rightarrow \quad \Lambda = -\frac{1}{2}(q_c - e)^2 + \Delta\Lambda$$

★ $q = q_c :$ Last dS phase, No EWSB.

$$M_{\text{eff}}^2 = M^2 - c_H q_c = 0 \quad \longrightarrow \quad \boxed{q_c = \frac{M^2}{c_H} \sim M_P^2}$$

$$\Lambda_{\text{eff}} = \Lambda + \frac{1}{2} q_c^2 \equiv \Lambda_{\text{last}}$$

★ $q = q_c - e :$ Almost zero C.C., EWSB.

$$M_{\text{eff}}^2 = c_H e \sim (100\,\text{GeV})^2, \qquad \Lambda_{\text{eff}} = \Lambda + \frac{1}{2}(q_c - e)^2 \sim 0$$

$$\longrightarrow \quad \boxed{\Lambda_{\text{last}} \simeq e q_c \sim e\, M_P^2}$$

$$\longrightarrow \quad H_{\text{last}} \sim \frac{\Lambda_{\text{last}}}{M_P} \sim \sqrt{e} \sim 100\,\text{GeV}$$

Reheating constraint: $\rho_R = \frac{\pi^2}{30} g_* T_{\text{RH}}^4 < 3 M_P^2 H_{\text{last}}^2$

$$\longrightarrow \quad \boxed{T_{\text{RH}} < 8.5 \times 10^9\,\text{GeV}}$$

Need of reheating

- Both Higgs mass & C.C. can settle to observed values but the universe would be empty due to the series of dS phases.

→ Reheating mechanism needed.

- We also need density perturbations from inflation.
- Observable consequences of reheating and inflation depend on the efficiency of last membrane nucleation.

$$\gamma \equiv \bar{r}_0^{-4} e^{-B} \qquad \text{vs} \qquad H^4$$

$$B = \frac{27\pi^2}{2} \frac{T^4}{(\Delta\Lambda)^3} \left(1 + \frac{1}{4} r_0^2 H^2\right)^{-2}, \qquad \bar{r}_0 = \frac{r_0}{1 + \frac{1}{4} r_0^2 H^2}$$

Particle production

- Particles can be produced by non-adiabatic process due to flux-dependent Higgs VEV.

[Giudice, Kehagias, Riotto, 2019]

Higgs VEV becomes nonzero only after
the last membrane nucleation.

Assume that the Hubble-dependent mass is absent.

→ Effective frequencies of SM perturbations
depend mainly on the EW phase transition.

$$f_k'' + \omega^2 f_k = 0 \quad \omega^2 = \vec{k}^2 + m_P^2 a^2 + \left(\xi - \frac{1}{6}\right) a^2 R, \qquad m_P = g_P\, v.$$

Particle production is efficient only if $v \sim H_{\text{last}} \sim \sqrt{e}$:

$$n_P = N_P \left(\frac{g_P^2\, v \sqrt{e}}{8\pi c}\right)^{3/2} \exp\left(-c \frac{v}{\sqrt{e}}\right), \qquad c \equiv \frac{\sqrt{3}\,\pi\, g_P\, M_P}{\kappa\, (2\Lambda_0)^{1/4}}.$$

κ : speed of transition.

Kicked inflaton

- Kick the inflaton by quantum fluctuations.

$$\Delta\phi < \delta\phi \quad \longrightarrow \quad H^3 > \frac{1}{\pi} V'$$ [Bousso, Polchinski, 2000]

$$\Lambda_{\rm last} \simeq e q_c = \frac{eM^2}{c_H} \quad \longrightarrow \quad \frac{\pi e^{3/2} M^3}{c_H^{3/2} M_P^3} > V'$$

But, monomial inflation: $V = \alpha_n \phi^n,$ $\begin{cases} \alpha_n \sim \left(\frac{M_P}{\phi_*}\right)^{n+2} \left(\frac{M_{\rm GUT}}{M_P}\right)^4 M_P^{4-n}, \\ \phi_* \sim 10 M_P. \end{cases}$

$$\phi \sim \phi_*, \quad V' \sim 10^{-11} M_P^3$$

$$\longrightarrow \quad \boxed{e^{1/2} > 10^{-4} c_H \left(\frac{M_P^2}{M}\right)} \; : \; M \sim M_P, c_H \sim 1$$

Classical rolling is dominant for $\sqrt{e} \sim 100\,{\rm GeV}$!

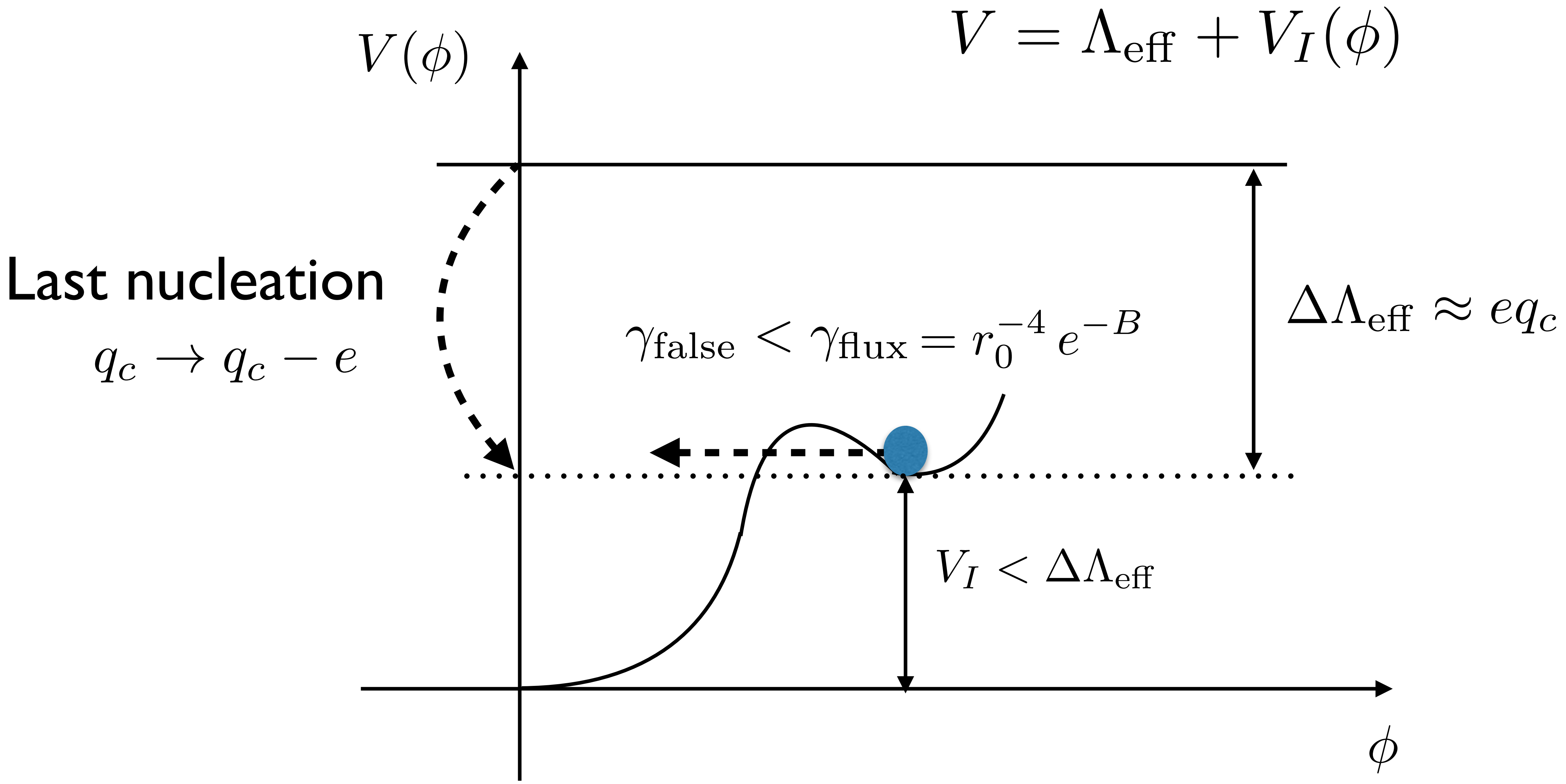
Last transition must occur fast enough,
otherwise no observable slow-roll inflation.

Trapped inflaton

- Inflaton stuck at the false vacuum in dS phases.

[Bousso, Polchinski, 2000]

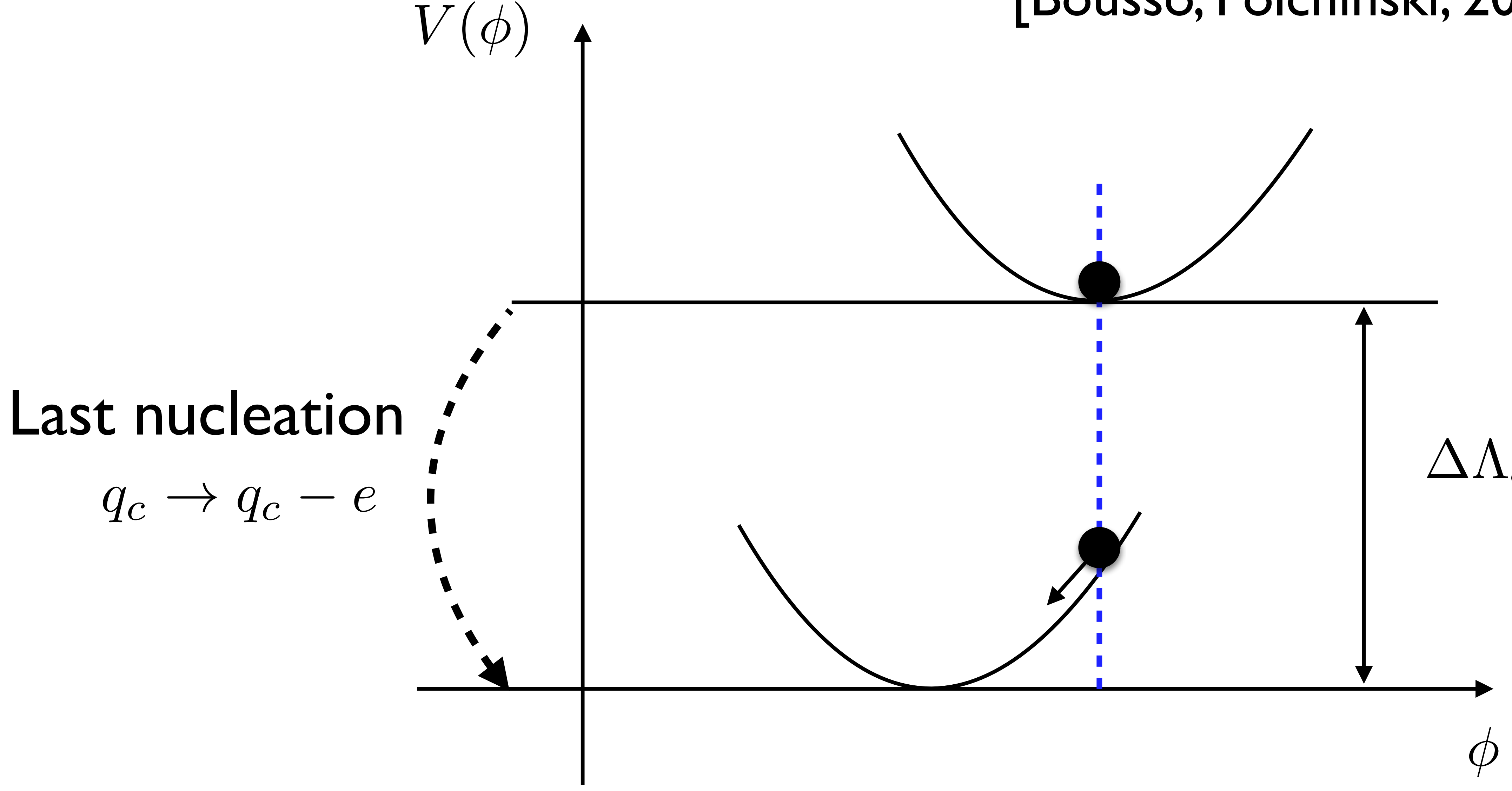
Inflaton tunnels to the true vacuum after last nucleation, and the slow-roll inflation and reheating occur.



Flux-dependent minimum

$$V(H,\phi) = V_{\rm eff}(H) + \underbrace{(k_1\phi^n + q + k_2)^2}_{\text{Flux-dependent}} + \underbrace{V_{\rm int}(\phi, H)}_{\text{Reheating}}$$

[Bousso, Polchinski, 2000; HML 2019]



Flux-dependent coupling kicks the inflaton away.

Reheating from general four-form couplings

General four-form couplings

- The general four-form Lagrangian contains a dimensionless non-minimal coupling to gravity.

[HML, 2019]

$$\mathcal{L}_{\rm non-minimal} = \underline{-\frac{c_1}{24}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\,R} + \underline{\sqrt{-g}\left(\frac{1}{2}\zeta^2R^2\right)} \quad +\frac{c_1}{24}\partial_\mu(\epsilon^{\mu\nu\rho\sigma}RA_{\nu\rho\sigma}).$$

Non-minimal coupling

Higher curvature term for consistency

→ The gauge field for four-form flux becomes dynamical due to graviton mixing.

Naively, $F_{\mu\nu\rho\sigma} = q\,\epsilon_{\mu\nu\rho\sigma}$ → $c_1 q\,\Box h^\mu_\mu$: kinetic mixing

Concretely, $\mathcal{L}_{\rm eff} \sim -F^2_{\mu\nu\rho\sigma} \sim -(q + c_H|H|^2 - c_1R)^2$

→ $-c_Hq|H|^2,\quad \boxed{c_Hc_1|H|^2R,}\quad \boxed{-c_1^2R^2}$

Dual-scalar theory

- R2 gravity is equivalent to scalar-dual theory.

$$\frac{1}{2}(\zeta^2-c_1^2)R^2 \longrightarrow \sqrt{\zeta^2-c_1^2}\,\chi R-\frac{1}{2}\chi^2.$$: Hubbard-Stratonovich transf.

$$\mathcal{L}_{\rm eff}=\underline{\frac{1}{2}\Omega(H,q)R+\frac{1}{2}(\zeta^2-c_1^2)R^2}+M_{\rm eff}^2|H|^2-\lambda_{H,{\rm eff}}|H|^4-\Lambda_{\rm eff},$$

$\Omega(H,q)=1+c_1(c_H|H|^2+q)$: Planck mass also scans!

- Field redefinition: $\sigma=c_H|H|^2+q+\frac{\sqrt{\zeta^2-c_1^2}}{c_1}\chi$

$$\mathcal{L}_{\rm I}=\sqrt{-g}\left[\frac{1}{2}(1+c_1\sigma)R-|D_\mu H|^2-V(H,\sigma,q)\right]$$

$$V(H,\sigma,q)=-M_{\rm eff}^2|H|^2+\lambda_{H,{\rm eff}}|H|^4+\Lambda_{\rm eff}+\boxed{\frac{1}{2}\frac{c_1^2}{\zeta^2-c_1^2}\Big(\sigma-c_2|H|^2-q\Big)^2.}$$

$\zeta^2>c_1^2$: The bare R2 term stabilizes the dual scalar.

Dual-scalar theory

- Einstein frame Lagrangian with $g_{\mu\nu} = g^E_{\mu\nu}/\Omega.$

$$\mathcal{L}_E = \sqrt{-g_E}\left[\frac{1}{2}R(g_E) - \frac{1}{2}(\partial_\mu\bar{\sigma})^2 - e^{-\sqrt{\frac{2}{3}}\bar{\sigma}}\,|D_\mu H|^2 - V_E(H,\bar{\sigma})\right]$$

Canonical scalar: $\sigma = \dfrac{1}{c_1}\left(e^{\sqrt{\frac{2}{3}}\bar{\sigma}} - 1\right)$

$$\begin{aligned} V_E(H,\bar{\sigma}) \;&=\; \Lambda_{\rm eff}\, e^{-2\sqrt{\frac{2}{3}}\bar{\sigma}} + \frac{3}{4}m^2_{\bar{\sigma}}\left(1-(1+c_1 q)e^{-\sqrt{\frac{2}{3}}\bar{\sigma}} - c_1 c_2\, e^{-\sqrt{\frac{2}{3}}\bar{\sigma}}|H|^2\right)^2 \\ &\quad + e^{-2\sqrt{\frac{2}{3}}\bar{\sigma}}\left(-M^2_{\rm eff}|H|^2 + \lambda_{H,\rm eff}|H|^4\right). \end{aligned}$$

$$m_{\bar{\sigma}} = \sqrt{\frac{2}{3}}\frac{M_P}{\sqrt{\zeta^2 - c_1^2}}.$$

Assuming that the Higgs is stabilized during dS phases:

$$V_E(\sigma) = V_0(q) + \left[\frac{3}{4}m^2_{\bar{\sigma}}\left(1 + c_1\left(q + \frac{1}{2}c_H v^2\right)\right)^2 + \Lambda_{\rm eff}\right]\left(e^{-\sqrt{\frac{2}{3}}\bar{\sigma}} - e^{-\sqrt{\frac{2}{3}}\bar{\sigma}_{\rm m}(q)}\right)^2$$

$$\underline{e^{-\sqrt{\frac{2}{3}}\bar{\sigma}_{\rm m}(q)} \;=\; \frac{3m^2_{\bar{\sigma}}(1 + c_1(q + \frac{1}{2}c_H v^2))}{3m^2_{\bar{\sigma}}(1 + c_1(q + \frac{1}{2}c_H v^2))^2 + 4\Lambda_{\rm eff}},} \qquad V_0(q) \;=\; \frac{3m^2_{\bar{\sigma}}\Lambda_{\rm eff}}{3m^2_{\bar{\sigma}}(1 + c_1(q + \frac{1}{2}c_H v^2))^2 + 4\Lambda_{\rm eff}}.$$

Dynamical scalar field with flux-dep.
minimum is achieved!

Reheating after last scan

- No EWSB before the last nucleation:

$$q = M^2/c_2 \equiv q_c \text{ and } v = 0,$$

$$e^{-\sqrt{\frac{2}{3}}\bar{\sigma}_m(q_c)} \approx \frac{1}{1+c_1 q_c}\left(1+\frac{4eq_c}{3m_{\bar{\sigma}}^2(1+c_1q_c)^2}\right)^{-1}, \quad V_0(q_c) \approx \frac{3m_{\bar{\sigma}}^2 eq_c}{3m_{\bar{\sigma}}^2(1+c_1q_c)^2+4eq_c}$$

- EWSB after the last nucleation:

$$q = q_c - e, \quad v \neq 0, \qquad e^{-\sqrt{\frac{2}{3}}\bar{\sigma}_m(q_c-e)} \approx \frac{1}{1+c_1q_c}, \quad V_0(q_c-e) \approx 0.$$

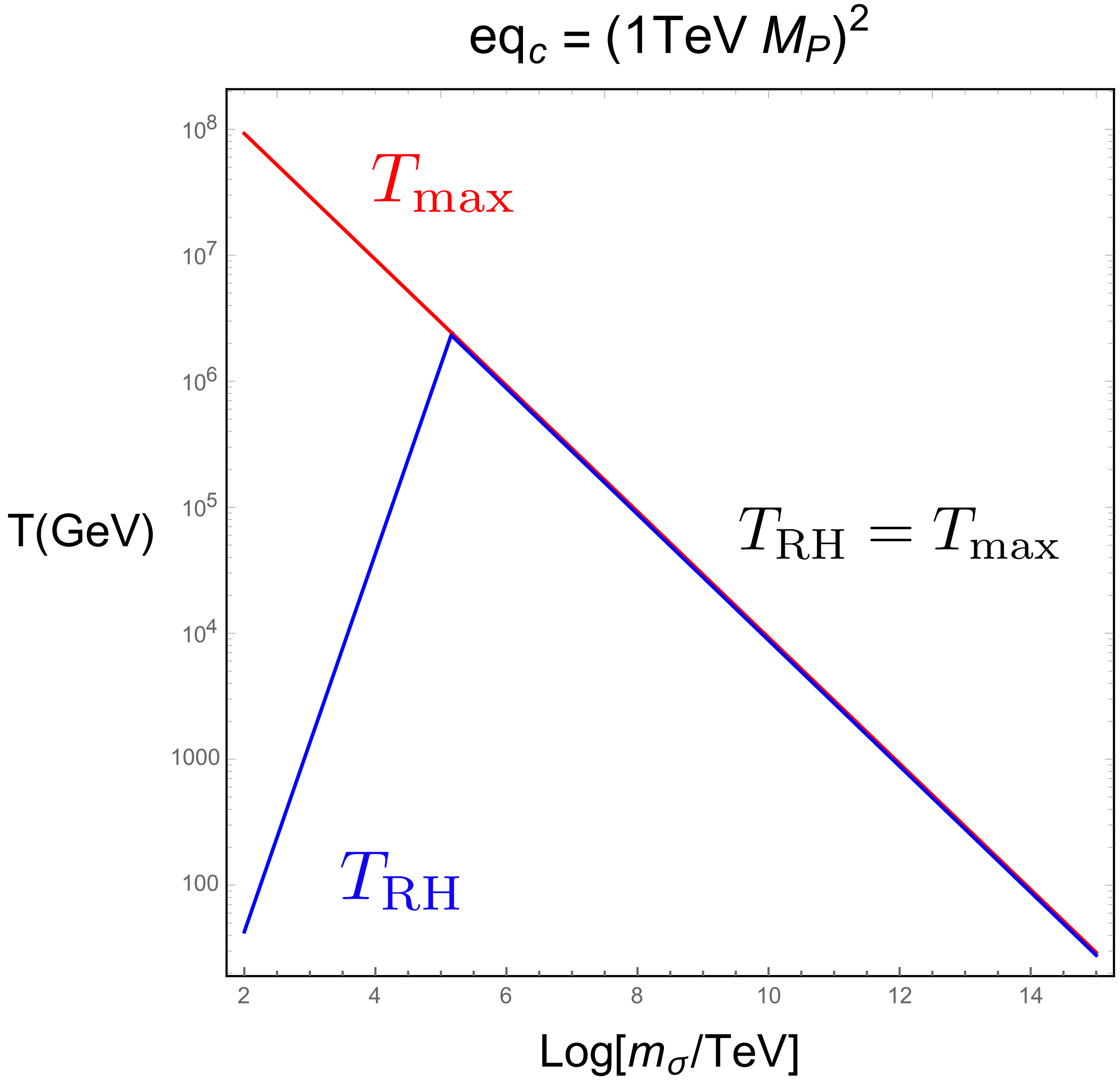
Initial potential energy:

$$V_i \equiv V_E(\bar{\sigma}_i) = \frac{12(eq_c)^2 m_{\bar{\sigma}}^2}{(3m_{\bar{\sigma}}^2(1+c_1q_c)^2+4eq_c)^2} \lesssim eq_c \sim (\mathrm{TeV}\, M_P)^2$$

Maximum reheating temperature:

$$T_{\max} \simeq 1.5\times 10^9\,\mathrm{GeV}\left(\frac{100}{g_*}\right)^{1/4}\left(\frac{eq_c}{(1\,\mathrm{TeV}\cdot M_P)^2}\right)^{1/2}\left(\frac{380\,\mathrm{TeV}}{m_{\bar{\sigma}}}\right)^{1/2}$$

Successful reheating



Inflaton decay rate:

$$\Gamma_{\bar\sigma}=\frac{3c_1^2c_2^2}{64\pi}\frac{m_{\bar\sigma}^3}{M_P^2}$$

Perturbative reheating:

$$T_{\rm RH}=\left(\frac{90}{\pi^2 g_*}\right)^{1/4}(\Gamma_{\bar\sigma}M_P)^{1/2}$$

$$=10\,{\rm MeV}\left(\frac{100}{g_*}\right)^{1/4}\left(\frac{c_1}{1}\right)\left(\frac{c_2}{1}\right)\left(\frac{m_{\bar\sigma}}{380{\rm TeV}}\right)^{3/2}$$

Successful BBN:

$T_{\rm RH}>10\,{\rm MeV},\quad m_\sigma>380\,{\rm TeV}$ (or $\zeta<5.2\times10^{12}$)

Slow-roll inflation: $m_\sigma\ll H_I=8\times10^{13}\,{\rm GeV}(r/0.1)^{1/2}$

Flux coupling to pseudo-scalar

- Consider a pseudo-scalar with approximate shift symmetry.

[HML, 2019]

$$\mathcal{L}_{\rm pseudo-scalar} = -\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + \underbrace{\frac{\mu}{24}\,\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\,\phi}_{\text{Four-form coupling}} \quad -\frac{\mu}{6}\,\partial_\mu\Big(\epsilon^{\mu\nu\rho\sigma}\phi A_{\nu\rho\sigma}\Big).$$

→

$$\mathcal{L}_{\rm II} = M^2|H|^2 - \lambda_H|H|^4 - \frac{1}{2}m_\phi^2\phi^2 - \boxed{\frac{1}{2}(\mu\phi + c_2|H|^2 + q)^2.}$$

“Flux-dependent” VEVs:

$$v_H(q) = \sqrt{\frac{M^2 - c_2(q + \mu v_\phi)}{\lambda_H + \frac{1}{2}c_2^2}},$$

$$v_\phi(q) = -\frac{\mu}{\mu^2 + m_\phi^2}\cdot\Big(\frac{1}{2}c_2 v_H^2 + q\Big).$$

“Flux-dependent” masses & mixing:

$$m^2_{h_{1,2}} = \frac{1}{2}(m_\varphi^2 + m_h^2) \mp \frac{1}{2}\sqrt{(m_\varphi^2 - m_h^2)^2 + 4c_2^2\mu^2 v_H^2(q)}, \qquad \tan 2\theta(q) = \frac{2c_2\mu v_H(q)}{m_\varphi^2 - m_h^2}.$$

$$m_\varphi^2 = m_\phi^2 + \mu^2, \qquad m_h^2 = 2\lambda_{H,\rm eff}v_H^2(q).$$

Reheat with pseudo-scalar

- No EWSB before the last nucleation:

$$q_c = \frac{\mu^2+m_\phi^2}{m_\phi^2}\frac{M^2}{c_2}, \qquad v_H = 0, \qquad v_\phi(q_c) = -\frac{\mu}{m_\phi^2}\frac{M^2}{c_2} \equiv v_{\phi,c},$$

- EWSB just after the last nucleation:

$$q = q_c - e, \quad v_H^2 = \frac{m_\phi^2}{\mu^2+m_\phi^2}\left(\frac{c_2 e}{\lambda_{H,\rm eff} - \frac{1}{2}\frac{c_2^2\mu^2}{\mu^2+m_\phi^2}}\right), \qquad V_0(q_c - e) \approx 0.$$

$$v_{\phi,0} = v_{\phi,c} + \boxed{\frac{\mu}{\mu^2+m_\phi^2}\left(\frac{1}{2}c_2 v_H^2 - e\right)}.$$

"shifted singlet VEV"

→ EW scale: $v_H \sim \sqrt{e}$ for $\mu \sim m_\phi$.

Initial potential energy: $V_i = \frac{1}{2}\frac{\mu^2}{\mu^2+m_\phi^2}\left(e - \frac{1}{2}c_2 v^2\right)^2.$

$\boxed{V_i \sim e^2 \text{ for } \mu \sim m_\phi.}$ independent of pseudo-scalar mass.

Inflaton decays into a Higgs pair & reheats instantaneously.

$$T_{\rm max} = \left(\frac{90V_i}{\pi^2 g_*}\right)^{1/4} \simeq 55\,{\rm GeV}\left(\frac{V_i^{1/4}}{100\,{\rm GeV}}\right)\left(\frac{100}{g_*}\right)^{1/4}$$

Flux coupling to c-scalar

[HML, 2019]

- Consider a complex scalar with U(1) symmetry.

$$\mathcal{L}_{\rm c-scalar} = -|\partial_\mu\Phi|^2 - m_\Phi^2|\Phi|^2 - \lambda_\Phi|\Phi|^4 + \underbrace{\frac{\alpha}{24}\,\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\,|\Phi|^2}_{\text{Four-form coupling}} - \frac{\alpha}{6}\partial_\mu\left(\epsilon^{\mu\nu\rho\sigma}|\Phi|^2 A_{\nu\rho\sigma}\right).$$

$$\mathcal{L}_{\rm III} = M^2|H|^2 - \lambda_H|H|^4 - m_\Phi^2|\Phi|^2 - \lambda_\Phi|\Phi|^4 - \boxed{\frac{1}{2}(\alpha|\Phi|^2 + c_2|H|^2 + q)^2.}$$

Higgs and singlet masses are scanned at the same time.

Flux-dependent VEVs:

$\alpha > 0$ and $m_\phi^2 < 0$,

$$v_\phi(q) = \sqrt{\frac{-m_\phi^2 - \alpha q - \frac{1}{2}\alpha c_2 v_H^2(q)}{\lambda_{\phi,\rm eff}}},$$

$$v_H(q) = \sqrt{\frac{M^2 - c_2 q - \frac{1}{2}\alpha c_2 v_\phi^2(q)}{\lambda_{H,\rm eff}}}.$$

Similar flux-dependent masses & mixing arise!

Reheat with pseudo-scalar

- No EWSB before the last nucleation

$$q_c = \frac{1}{\lambda_\phi}\left(\frac{\lambda_{\phi,\mathrm{eff}}}{c_2}M^2 + \frac{\alpha}{2}m_\phi^2\right), \qquad v_H = 0, \qquad v_\phi^2(q_c) = -\frac{1}{\lambda_\phi}\left(m_\phi^2 + \frac{\alpha}{c_2}M^2\right) \equiv v_{\phi,c}^2.$$

- EWSB just after the last nucleation:

$$q = q_c - e, \quad v^2 = \frac{\lambda_\Phi c_2 e}{\lambda_{\Phi,\mathrm{eff}}\lambda_{H,\mathrm{eff}} - \frac{1}{4}(\alpha c_2)^2}, \qquad \lambda_{\Phi,\mathrm{eff}} = \lambda_\Phi + \frac{1}{2}\alpha^2,$$

$$v_{\phi,0}^2 = v_{\phi,c}^2 + \boxed{\frac{\alpha}{\lambda_{\Phi,\mathrm{eff}}}\left(e - \frac{1}{2}c_2 v^2\right)}.$$

"shifted singlet VEV"

EW scale: $v_H \sim \sqrt{e}$ for $\mu \sim m_\phi$.

Initial potential energy: $$V_i = \frac{1}{2}\frac{\alpha^2}{\lambda_{\phi,\mathrm{eff}}}\left(e - \frac{1}{2}c_2 v^2\right)^2.$$

$V_i \sim e^2$, independent of singlet mass.

Reheating is similar as in pseudo-scalar case with $\mu \sim m_\phi$.

Reheating and new physics

- Non-minimal four-form coupling

Heavy singlet scalar with gravitational coupling:

$$m_\sigma > 380\,\mathrm{TeV} \quad \Longrightarrow \quad T_{\mathrm{RH}} > 10\,\mathrm{MeV}$$

- Minimal four-form couplings

Light singlet scalars with sizable mixing to Higgs:

$$m_\phi \gtrsim m_h/2 \quad \Longrightarrow \quad T_{\mathrm{RH}} < 55\,\mathrm{GeV}$$

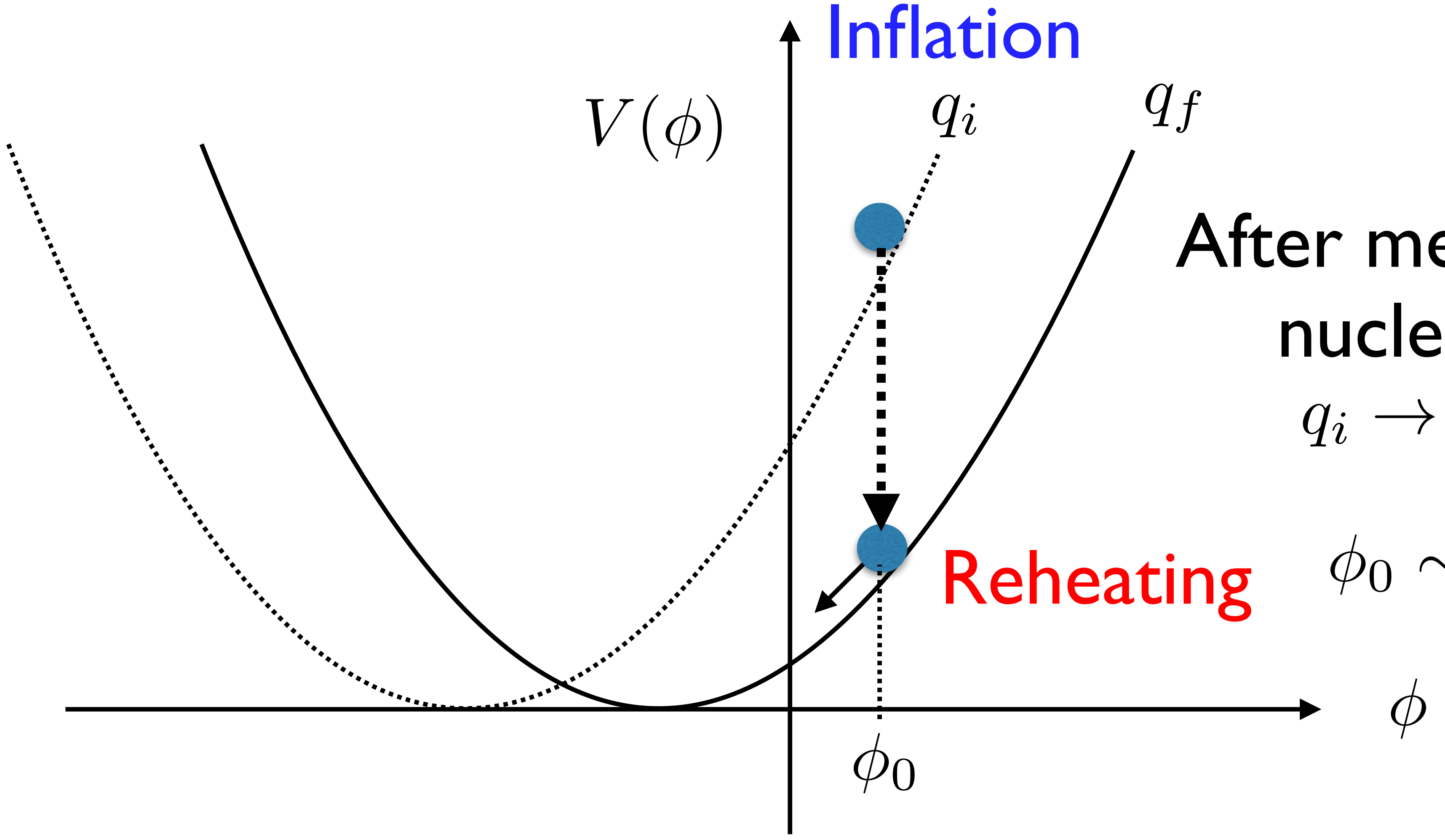
Chaotic inflation with four-form flux

Pseudo-scalar inflation

- Consider a massless pseudo-scalar with four-form coupling. [Kaloper, Sorbo, 2009]

$$\mathcal{L}_{\rm inf} = -\frac{1}{2}(\partial_\mu\phi)^2 + \frac{\mu}{24}\,\epsilon^{\mu\nu\rho\sigma}\,F_{\mu\nu\rho\sigma}\,\phi \longrightarrow \mathcal{L}_{\rm inf} = -\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}(\mu\phi+q)^2.$$

Shift symmetry: $\phi \to \phi + c, \quad q \to q - \mu c.$

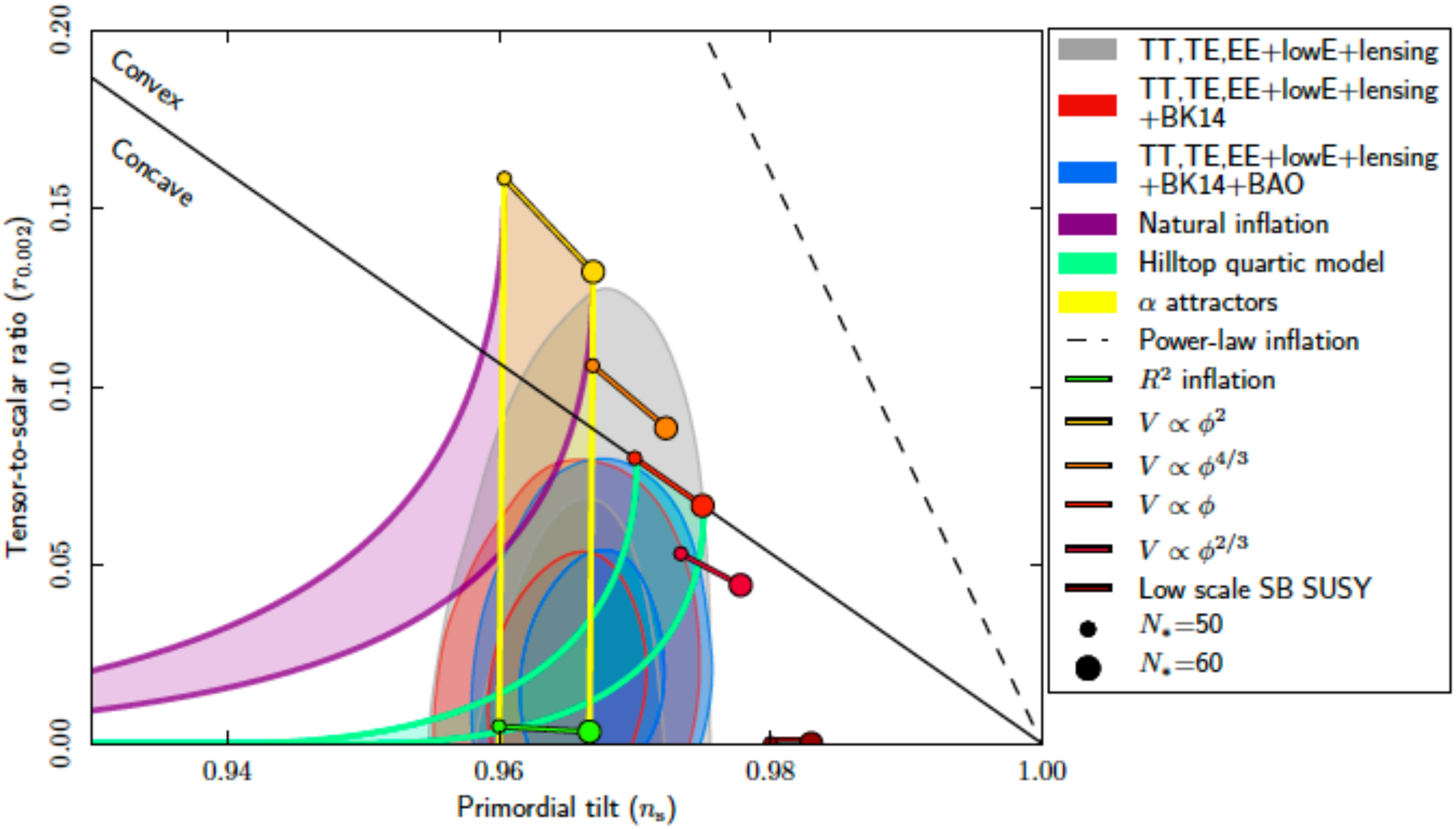


After membrane nucleation

$q_i \to q_f$

$\phi_0 \sim q_f/\mu$

Planck and inflation



Monomial-type inflation models are in a tension with Planck tensor-to-scalar ratio.

→ Beyond quadratic potential for inflaton?

Beyond quadratic potential

- The shift symmetry is maintained for the non-minimal four-form coupling to inflaton.

[HML, 2019]

$$\mathcal{L}_{nm} = -\frac{\alpha}{24}\,\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\,R + \frac{1}{2}\zeta^2\,R^2$$

$$\Longrightarrow \quad \mathcal{L} = \sqrt{-g}\Big[\frac{1}{2}\Big(1+\boxed{\alpha(\mu\phi+q)}\Big)R + \boxed{\frac{1}{2}(\zeta^2-\alpha^2)R^2} - \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}(\mu\phi+q)^2\Big]$$

For $\zeta \gtrsim \alpha$ and $\mu \lesssim M_P$, dual-scalar from R^2 can be decoupled.

Effective action: $\mathcal{L}_E = \sqrt{-g_E}\Big[\frac{1}{2}R(g_E) - \frac{1}{2}K(\phi)(\partial_\mu\phi)^2 - V_I(\phi)\Big]$

$$K(\phi) = \frac{1+\frac{3}{2}\alpha^2\mu^2+\alpha(\mu\phi+q)}{(1+\alpha(\mu\phi+q))^2}, \quad \boxed{V_I(\phi) = \frac{1}{2}\frac{(\mu\phi+q)^2}{(1+\alpha(\mu\phi+q))^2}} \xrightarrow[\phi+q/\mu \gg 1/(\alpha\mu)]{} \frac{1}{2\alpha^2}$$

Potential is flattened by conformal factor!

Inflationary predictions

- Non-minimal four-form coupling makes the potential flat for $\alpha(\mu\phi + q) \gtrsim 1.$ $(\phi, q/\mu \gg 1/\alpha)$

Canonical field: $\mu\phi + q = \frac{1}{4}\alpha\mu^2\varphi^2$

→ $$\boxed{V_I(\varphi) = \frac{1}{2\alpha^2}\Big(1 + \frac{4}{\alpha^2\mu^2\varphi^2}\Big)^{-2}.}$$

Number of efoldings: $N = \int_{\varphi_f}^{\varphi_*} \frac{d\varphi}{\sqrt{2\varepsilon}} \simeq \frac{\alpha^2\mu^2}{64}\varphi_*^4$

Inflationary observables:

$$n_s = 1 - 6\varepsilon_* + 2\eta_* = 1 - \frac{3}{2\alpha\mu}\frac{1}{N^{3/2}} - \frac{3}{2N}$$

$$r = 16\epsilon_* = \frac{4}{\alpha\mu}\frac{1}{N^{3/2}}.$$

cf. CMB: $\alpha = 38000(\alpha\mu)^{1/2}\Big(\frac{N}{50}\Big)^{3/4}.$

$\alpha\mu = 1$ and $N = 50(60)$, → $\boxed{n_s = 0.966(0.972),\ r = 0.011(0.0086)}$

$\alpha = 3.8(4.4) \times 10^4$ and $\mu = 6.3(5.5) \times 10^{13}\,\mathrm{GeV}.$

in perfect agreement with Planck
& observable in LiteBird, CMB S4, etc.

Robustness of predictions

- Unitarity scale is of order Planck scale, being insensitive to four-form coupling.

$$\frac{\bar{\phi}^n}{(\Lambda_n)^{n-4}}, \quad \Lambda_n = M_P\left[\frac{\alpha\mu}{(1+\frac{3}{2}(\alpha\mu)^2)^{1/2}}\right]^{\frac{n}{n-4}}$$: insensitive to $\alpha\mu.$

- Higher order corrections appear in the form,

$$\frac{c_n}{\Lambda^{4(n-1)}}\Big(-\frac{1}{24}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}\Big)^n$$

$$=\frac{c_n}{\Lambda^{4(n-1)}}\Big[(\mu\phi+q)^{2n}-2n\alpha(\mu\phi+q)^{2n-1}R+\cdots\Big]$$

$F_{\mu\nu\rho\sigma}=(\mu\phi+q)\epsilon_{\mu\nu\rho\sigma}$

$$\Lambda = M_P, \qquad c_n\Big(\frac{M_P}{\sqrt{\alpha}}\Big)^{4(n-1)}\lesssim c_n(\mu\phi+q)^{2(n-1)}\lesssim M_P^{4(n-1)}.$$

→ Inflationary predictions remain unchanged for a wide range of parameter space.

$$\frac{M_P}{\sqrt{\alpha}} \ll M_P$$

Model-indep. reheating

- Inflaton couples to the trace of energy-momentum tensor like dilaton, leading to perturbative reheating.

$$\boxed{\mathcal{L}_{\rm int} = \frac{1}{2M_P^2}\,\alpha(\mu\phi + q)\,T^\mu_\mu}$$

→ $$\Gamma_\phi = \frac{m_\phi^3}{32\pi M_P^2}\,\frac{(\alpha\mu)^2}{1+\frac{3}{2}(\alpha\mu)^2}. \qquad (W, Z, h)$$

$$\alpha\mu = 1: \quad T_{\rm RH} = 3.5\times 10^{11}\,{\rm GeV}\left(\frac{100}{g_*}\right)^{1/4}\left(\frac{m_\phi}{10^{14}\,{\rm GeV}}\right)^{3/2}$$

"Robust prediction for reheating”

cf. But, reheating temperature can be higher.

$$\mathcal{L}_{\rm int} = \frac{\phi}{f_\phi}\,G_{\mu\nu}\tilde{G}^{\mu\nu}, \quad f_\phi < M_P.$$

Conclusions

- Cosmological relaxation of Higgs mass may be tied up with the cosmological constant problem.
- Models with non-minimal four-form coupling are the minimal setup for the relaxation of Higgs mass & the successful reheating.
- Minimal four-form couplings to extra scalars are also introduced for which the reheating temperature is of order weak scale.
- Non-minimal four-form coupling can extend the pseudo-scalar chaotic inflation beyond quadratic regime and robust predictions for inflation.