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Four-form relaxation of Higgs mass and its cosmological implications

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Ref) HML, 1908.04252, 1910.09171(reheating), 1908.05475 (inflation);
with Y. Kang, A. Menkara, J. Song, 2103. 07592 (dark matter)

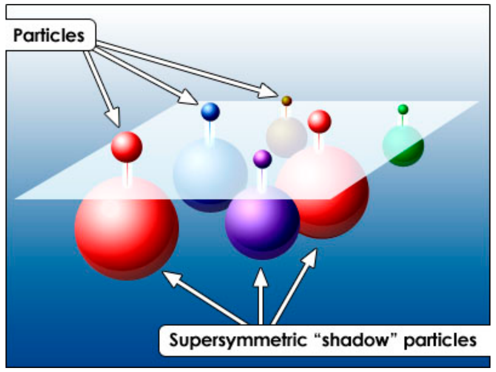
Outline

- Introduction
- Four-form flux for Higgs mass
- Four-form portals for cosmology
- Conclusions

Supersymmetry and colleagues

- Supersymmetry

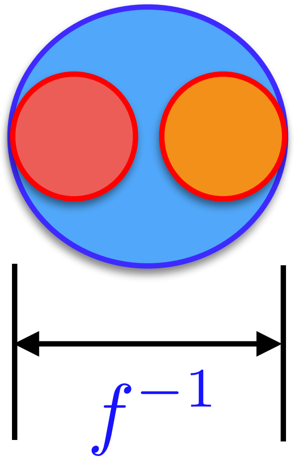
$$m_H^2 \sim \kappa M_{\rm SUSY}^2$$



- Pion-like composite

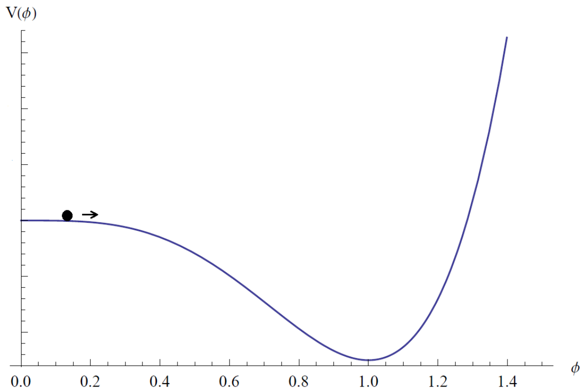
$$H = \bar{Q}'Q'$$

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



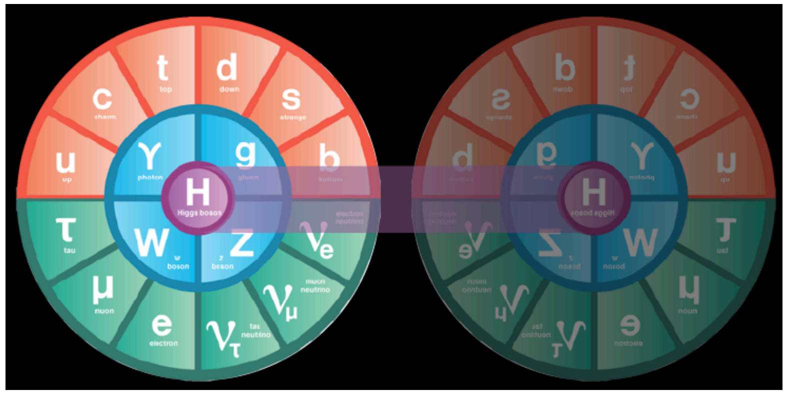
- Scale invariance

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



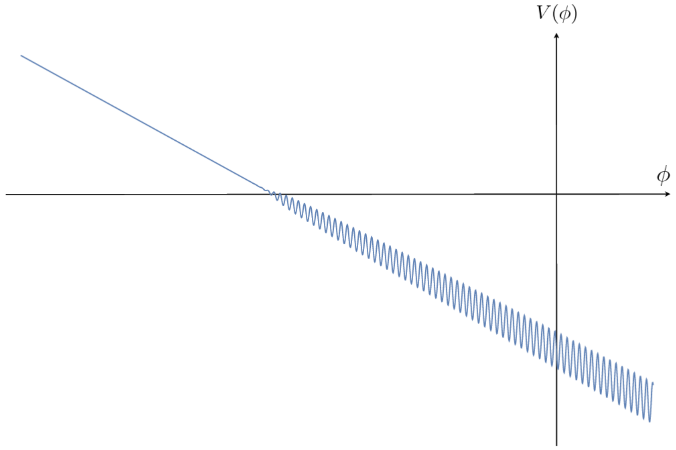
- Discrete symmetries

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



- Cosmological relaxation

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

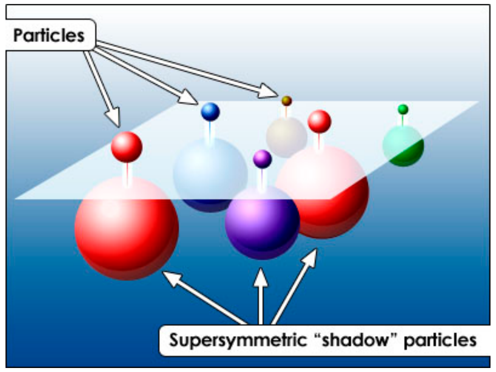


Supersymmetry and colleagues

- Supersymmetry

Superparticles:

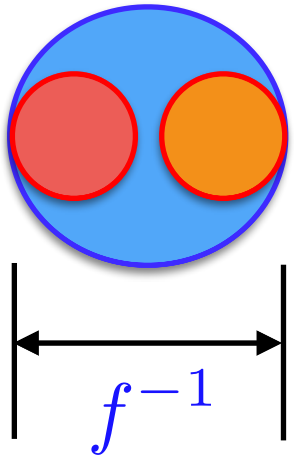
$M_{\mathrm{SUSY}} \sim 1\,\mathrm{TeV}$



- Pion-like composite

Rho-like/top partner:

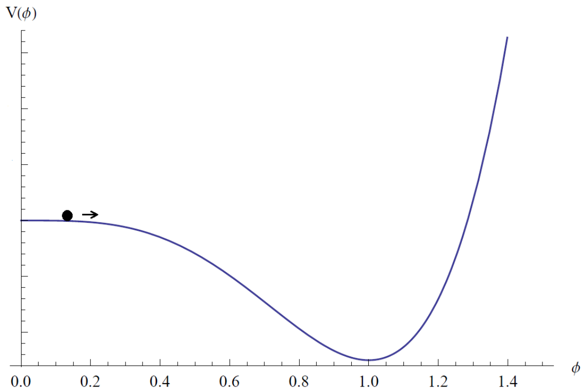
$M_{\rho,T} \sim \mathrm{TeV}$



- Scale invariance

Higgs-like
light scalar:

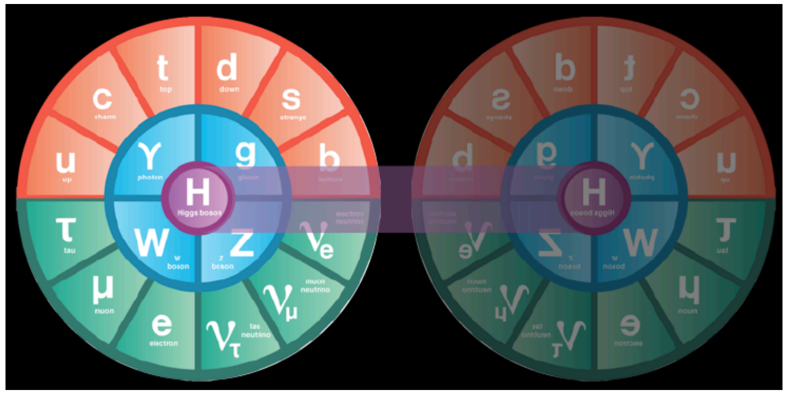
$m_\phi \ll m_h$



- Discrete symmetries

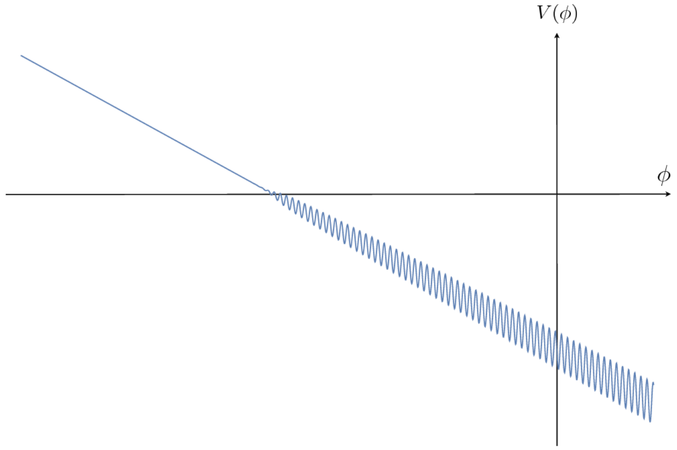
Neutral partners:

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

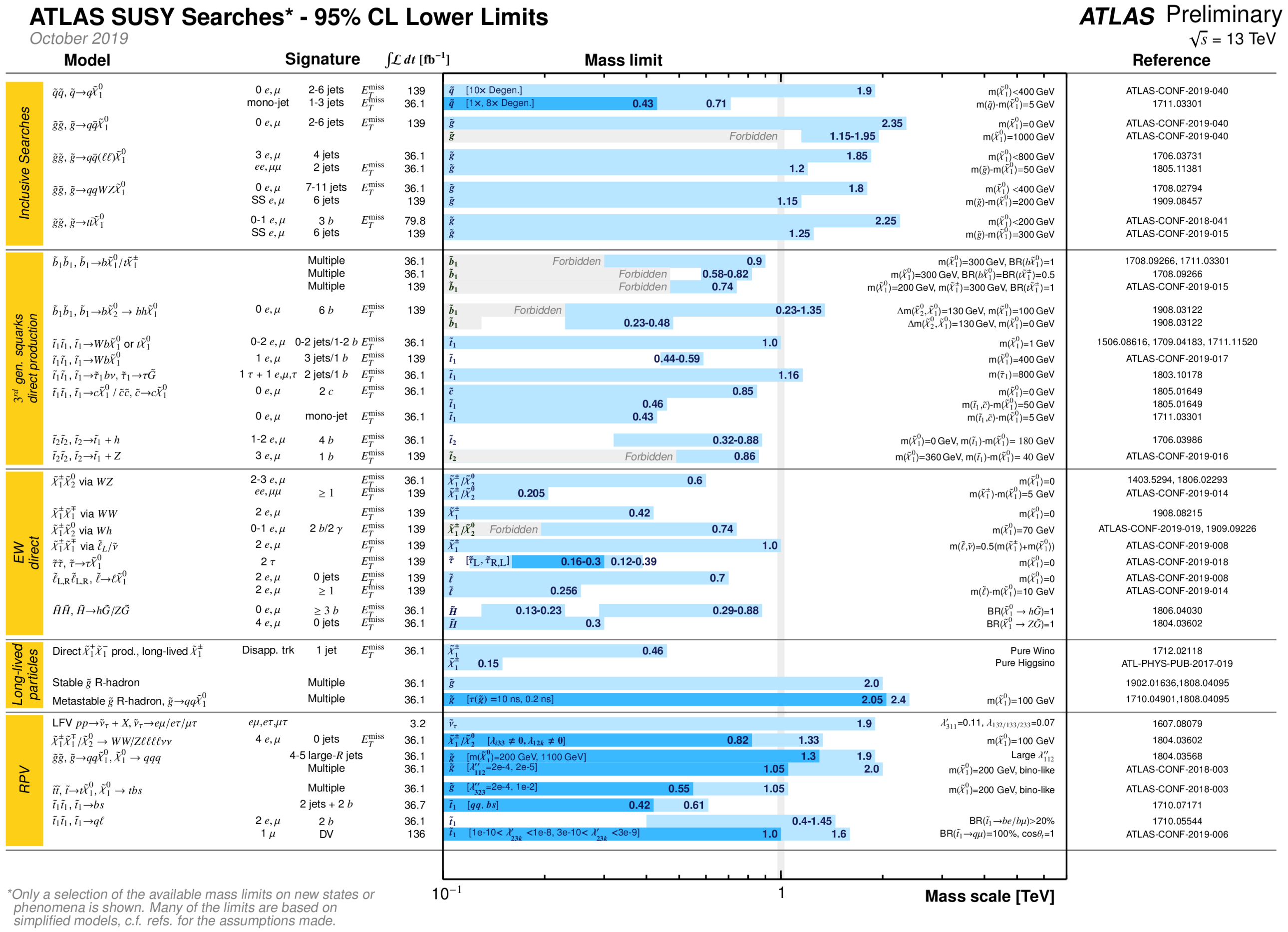


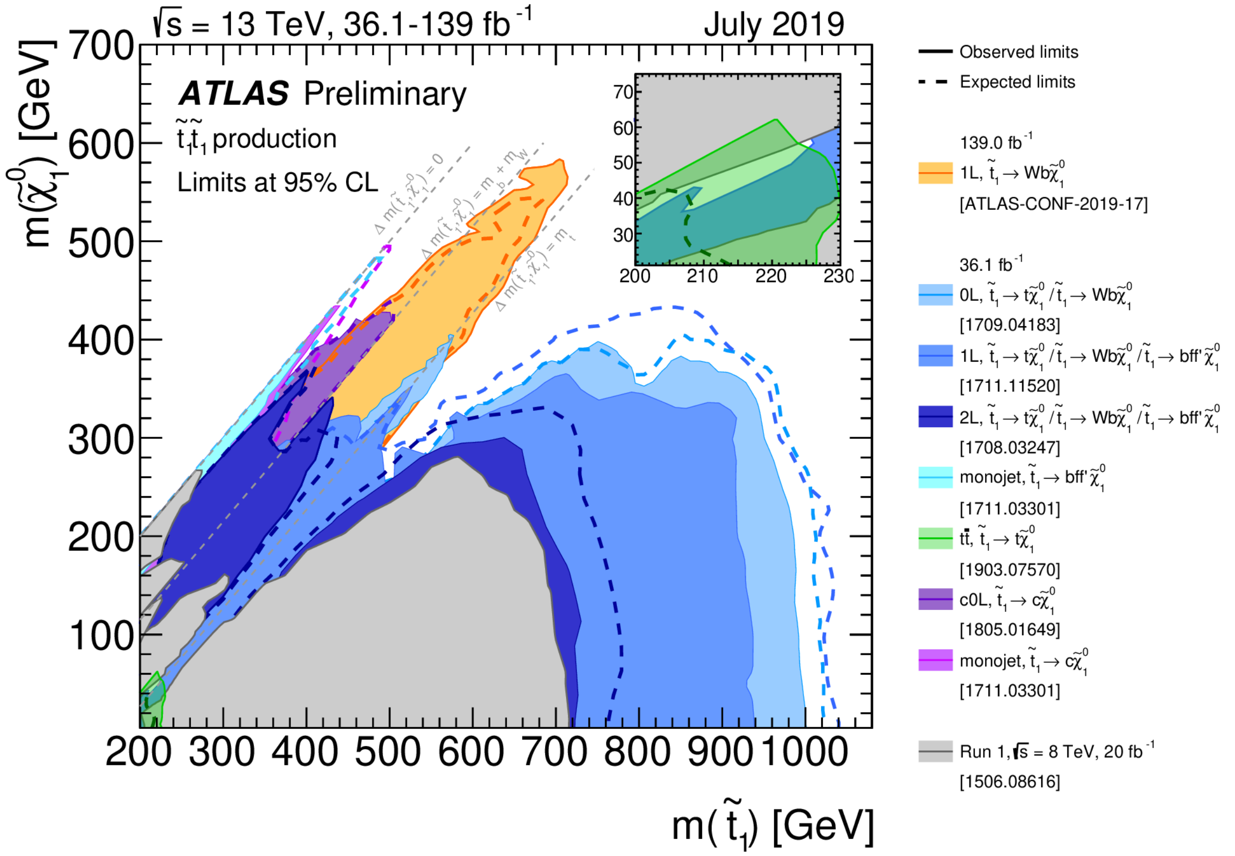
- Cosmological relaxation

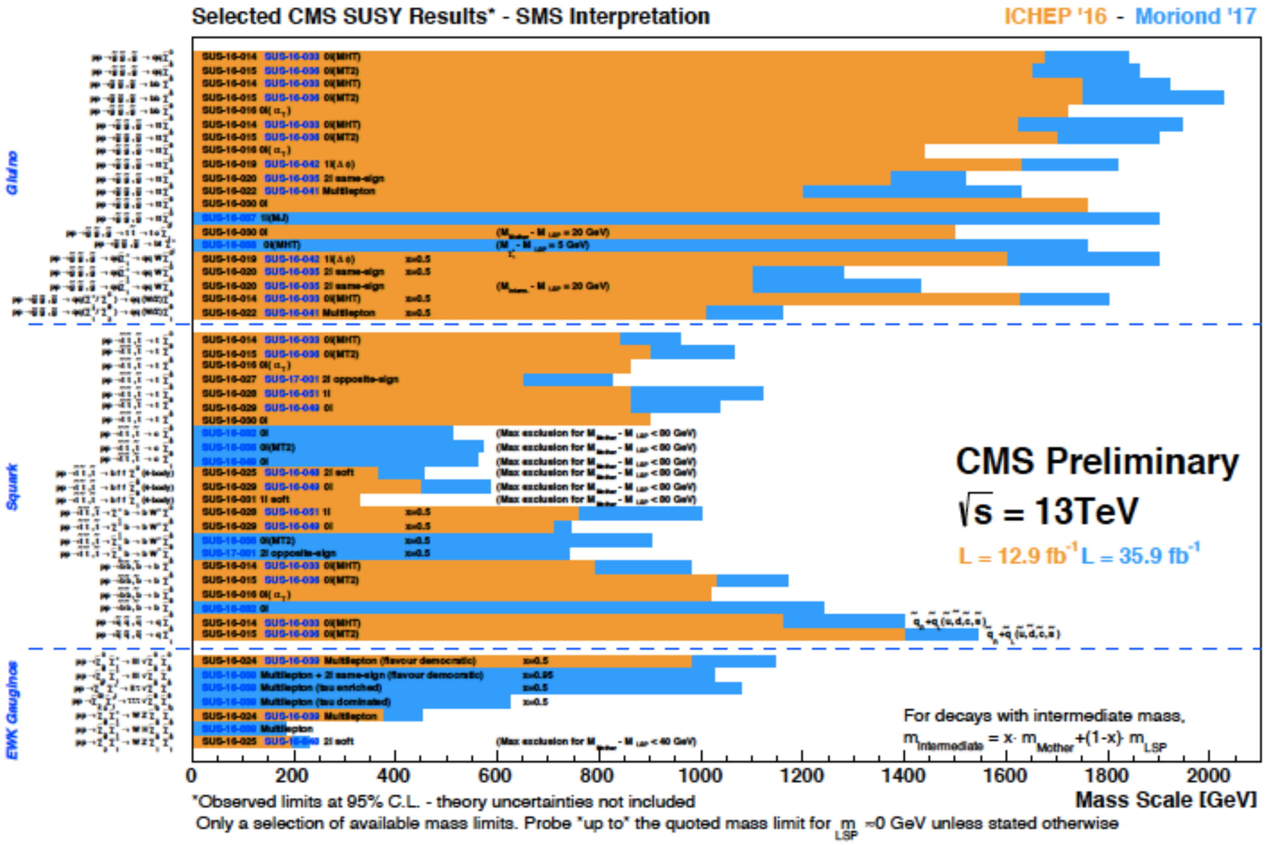
Axion-like relaxion: $m_\phi \ll m_h$

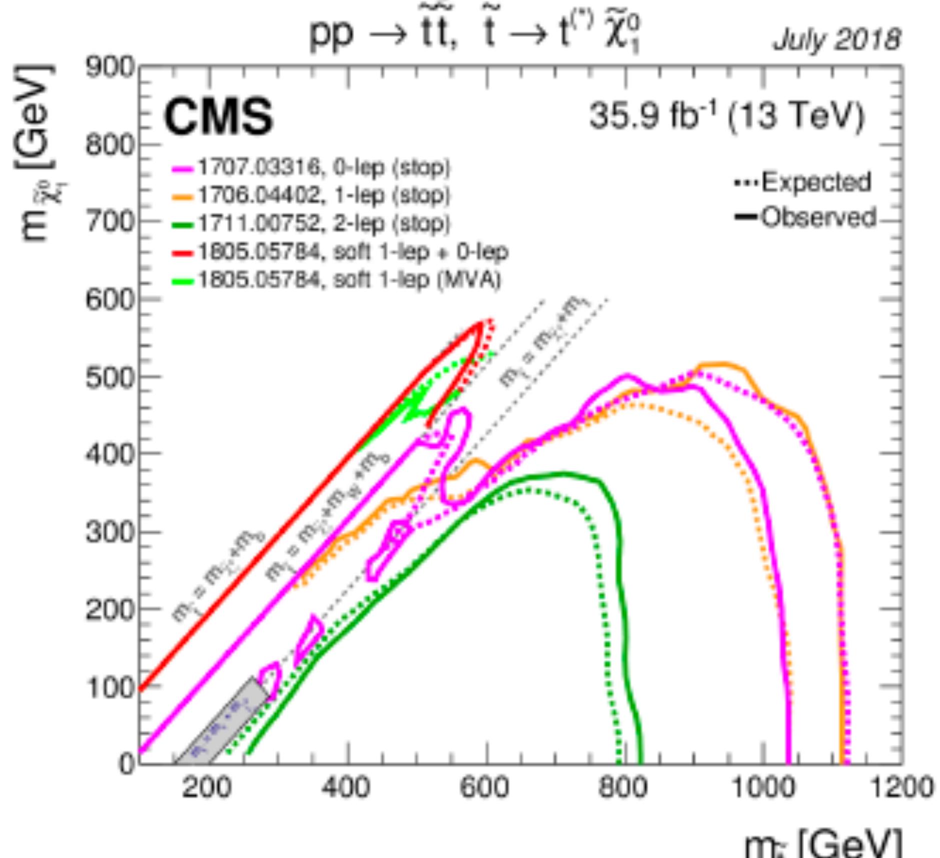


SUSY at LHC

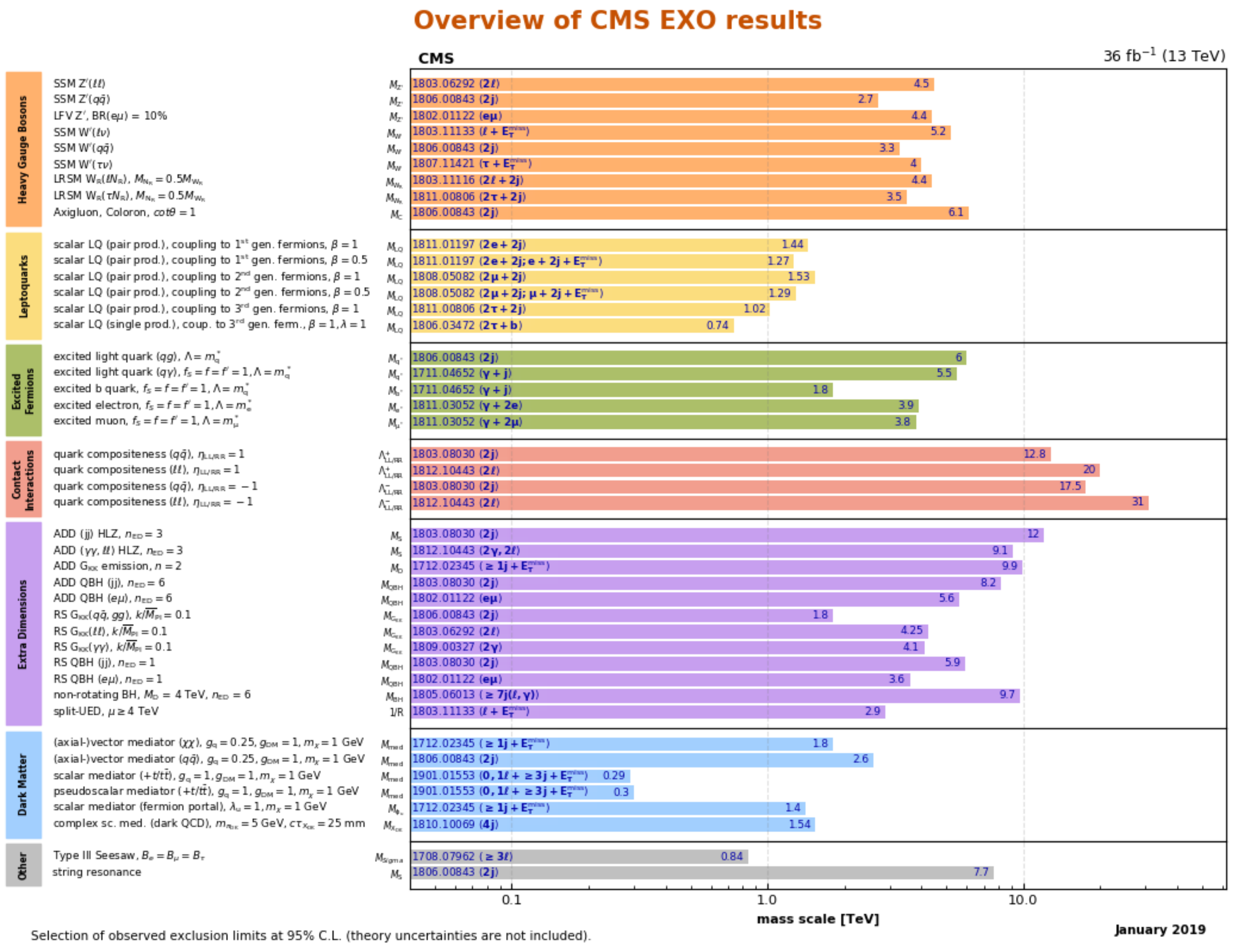

ATLAS SUSY Searches* - 95% CL Lower Limits
October 2019
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV
Model
Signature
$\int \mathcal{L}\,dt$ [fb^{-1}]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
10^{-1}
1
Mass scale [TeV]
*Only a selection of 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]
$\Delta m(\tilde{t}_1, \tilde{\chi}^0_1) = 0$
$\Delta m(\tilde{t}_1, \tilde{\chi}^0_1) = m_b + m_W$
$\Delta m(\tilde{t}_1, \tilde{\chi}^0_1) = m_t$
700
600
500
400
300
200
100
200
300
400
500
600
700
800
900
1000
70
60
50
40
30
200
210
220
230

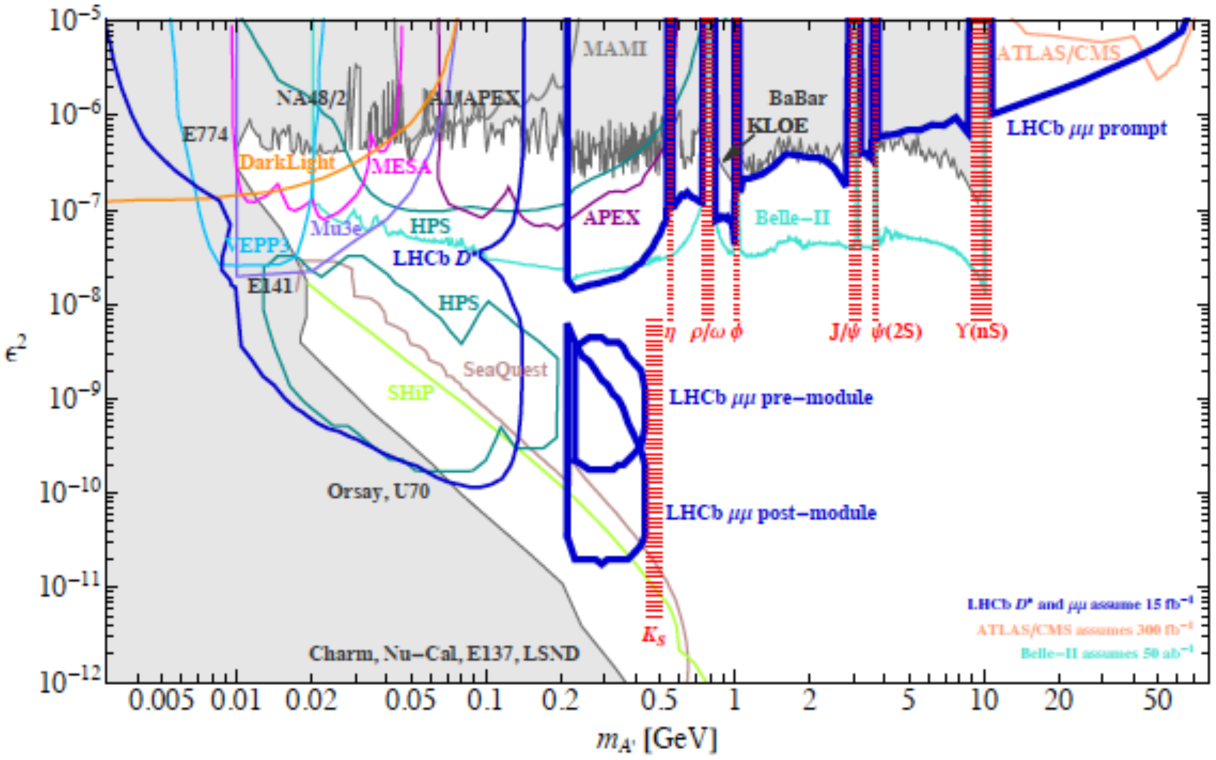

Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
$\sqrt{s}$ = 13TeV
L = 12.9 fb^{-1} L = 35.9 fb^{-1}
For decays with intermediate mass,
$m_{\text{Intermediate}} = x \cdot m_{\text{Mother}} + (1-x) \cdot m_{\text{LSP}}$
0
200
400
600
800
1000
1200
1400
1600
1800
2000
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 → $\tilde{t}\bar{\tilde{t}}$, $\tilde{t} \to t^{(*)}\tilde{\chi}^0_1$
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
$m_{\tilde{t}} = m_{\tilde{\chi}^0_1} + m_t$
$m_{\tilde{t}} = m_{\tilde{\chi}^0_1} + m_W + m_b$
$m_{\tilde{\chi}^0_1}$ [GeV]
$m_{\tilde{t}}$ [GeV]
900
800
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200

Other new physics



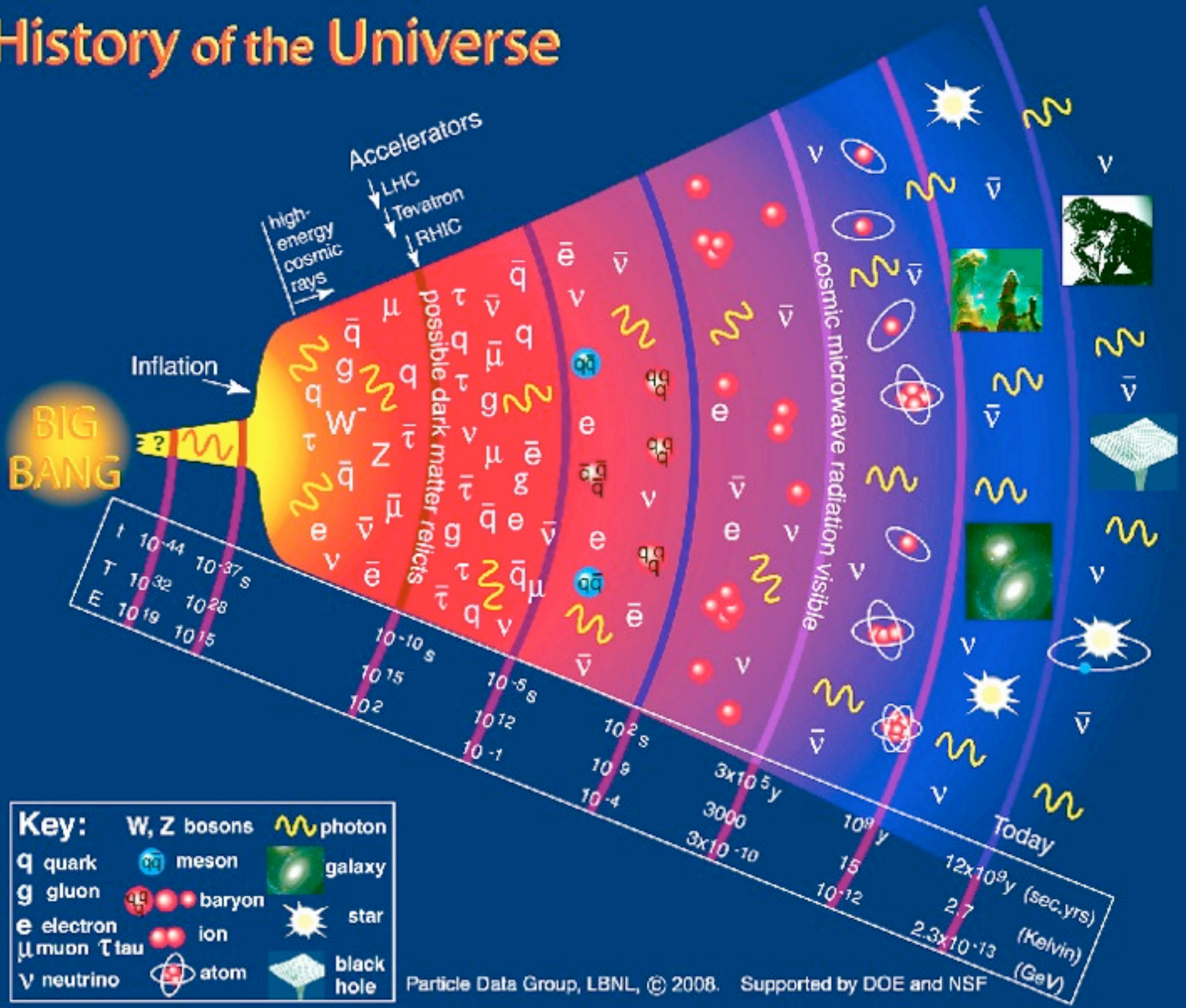
No convincing evidence for superparticles or new physics at a few TeV or below. (except XENON1T, RK,RD, Muon g-2, … ?)



[Ilten et al, 2016]

Have we missed something or do we need new ideas?

History of the Universe



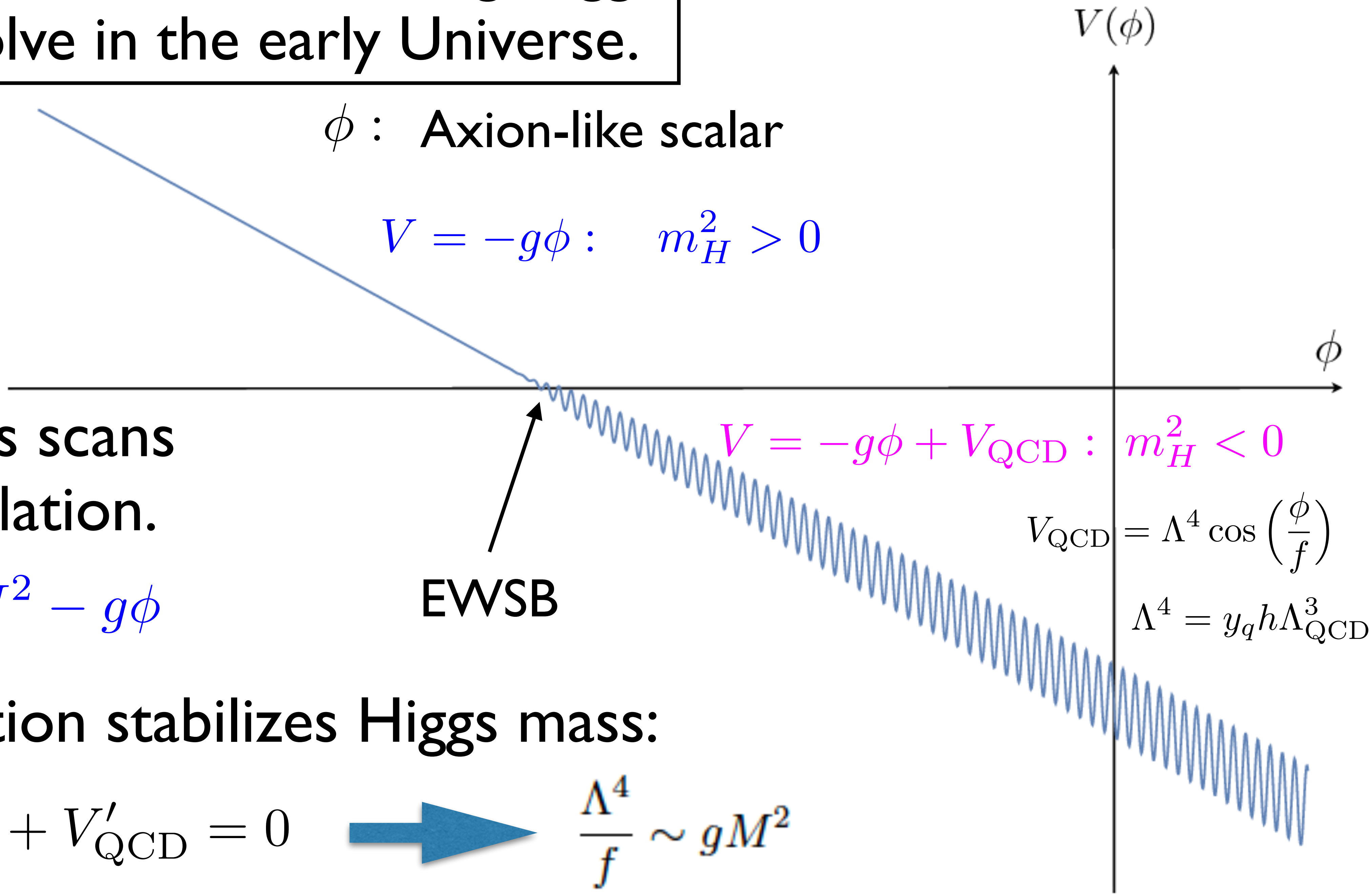
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Cosmological relaxation

[P. Graham et al, 2015]

Physical parameters including Higgs mass evolve in the early Universe.

ϕ : Axion-like scalar



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

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

$V_{\rm QCD} = \Lambda^4 \cos\left(\frac{\phi}{f}\right)$

$\Lambda^4 = y_q h \Lambda_{\rm QCD}^3$

Higgs mass scans during inflation.

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

Back-reaction stabilizes Higgs mass:

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

No new physics needed up to high scale:

$$\boxed{M < \left(\frac{\Lambda^4 M_P^3}{f}\right)^{\frac{1}{6}} \sim 10^7\,{\rm GeV}\left(\frac{10^9\,{\rm GeV}}{f}\right)^{\frac{1}{6}}}$$

Four-form flux and C.C.

- Three-form gauge field is not dynamical, but its field strength (four-form flux) adds to cosmological constant: $F_{\mu\nu\rho\sigma} = 4\partial_{[\mu}A_{\nu\rho\sigma]}$

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

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

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

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]

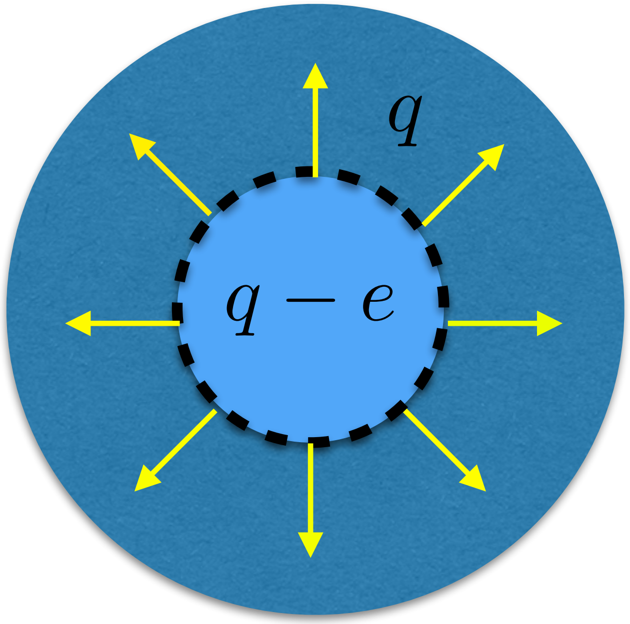
- Multiple four-form fluxes allow for an accurate scanning of C.C. as observed.

[Bousso, Polchinski, 2000]

Membrane nucleation

- The four-form flux in 4D can produce a membrane with charge e, reducing by one unit.

[Brown, Teitelboim, 1987]



4D F-field

$$F_{\mu\nu\rho\sigma} = q\,\epsilon_{\mu\nu\rho\sigma}\,.$$

"Closed membrane" production:
Bounce action for "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]

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

With gravity [~Thin-wall: Coleman, de Luccia, 1980]

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

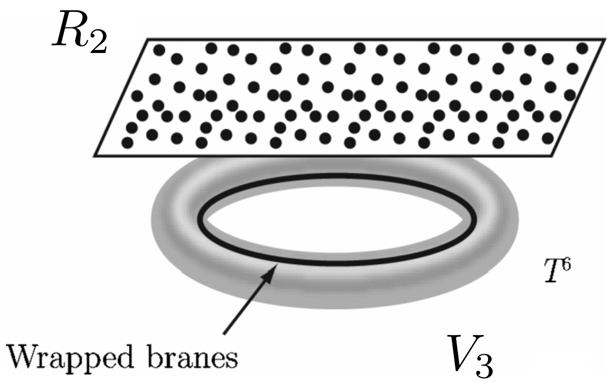
→ Membrane production stops when C. C. is positive and the smallest.

UV origins of four-forms

- Four-form fluxes are dynamical in higher dimensions, e.g. M2-brane and M5-brane in M-theory are sources for four-form fluxes. [Bousso, Polchinski, 2000]

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

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



Small membrane tension and charge for large volume (small M11) on 3-cycles.

Small membrane charge is technically natural.

cf. M2-brane: $\tau_{N_3+1} = 2\pi M_{11}^3, \quad q_{N_3+1} = \frac{(2\pi)^{1/2}}{M_{11}^{3/2} V_7^{1/2}}.$

- 4-form fluxes for scannable SUSY breaking.

cf. Dudas et al, 1912.12839

- cf. 3-form fluxes for modulus stabilization in string theory.

cf. Giddings et al, hep-th/0105037

Four-form landscape

Physical parameters depend on four-form fluxes:

~ Four-form landscape

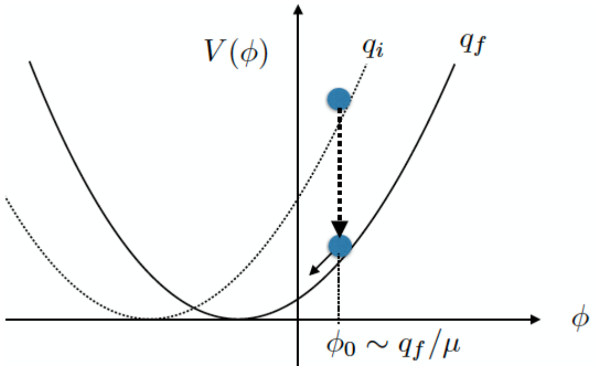
Higgs mass

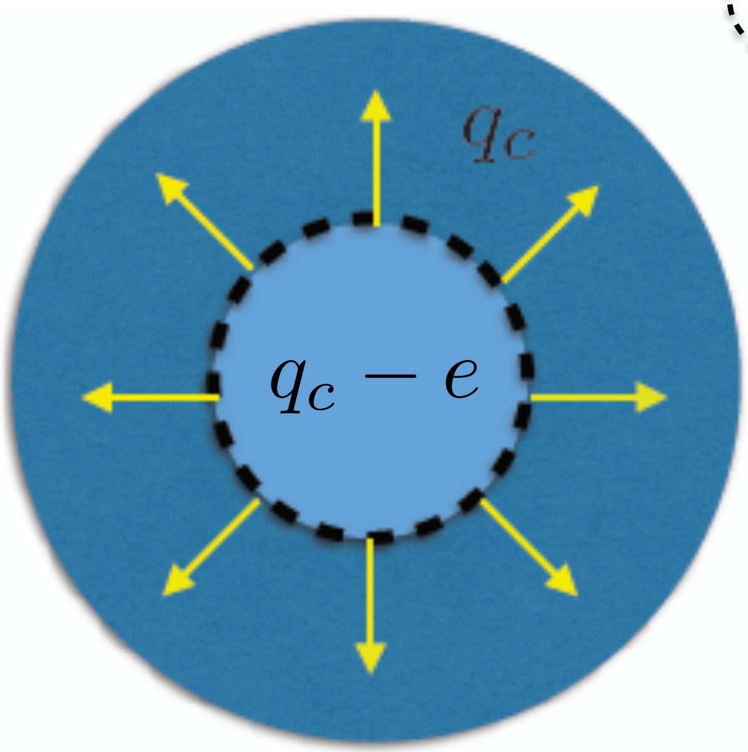
$$c_H\,|H|^2 F_{\mu\nu\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$

Inflation

$$c_1 R\, F_{\mu\nu\rho\sigma}\epsilon^{\mu\nu\rho\sigma},$$

$$\mu\phi\, F_{\mu\nu\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$





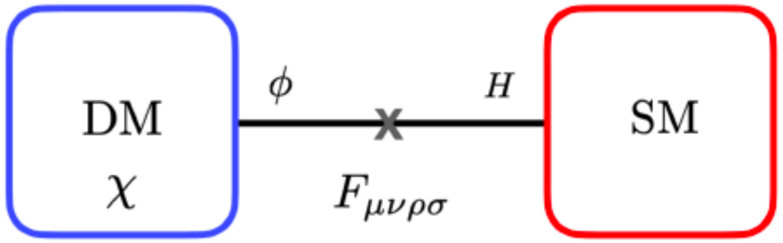
SUSY breaking

$$m^2_{\tilde{f}_{ij}} = \frac{1}{M_P^2}\sum_{\alpha=1}^{N} d_{\alpha,ij} F^\dagger_{T_\alpha} F_{T_\alpha}$$

Cosmological constant

$$\sqrt{-g}\, F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}$$

Dark matter



Four-form flux for Higgs mass

Four-form coupling to Higgs

- Introduce a “dimensionless” four-form coupling to the SM Higgs, scanning the Higgs mass parameter.

[Dvali, Vilenkin, 2003; Giudice, Kehagias, Riotto, 2019;
Kaloper, Westphal, 2019; HML, 2019]

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

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

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

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

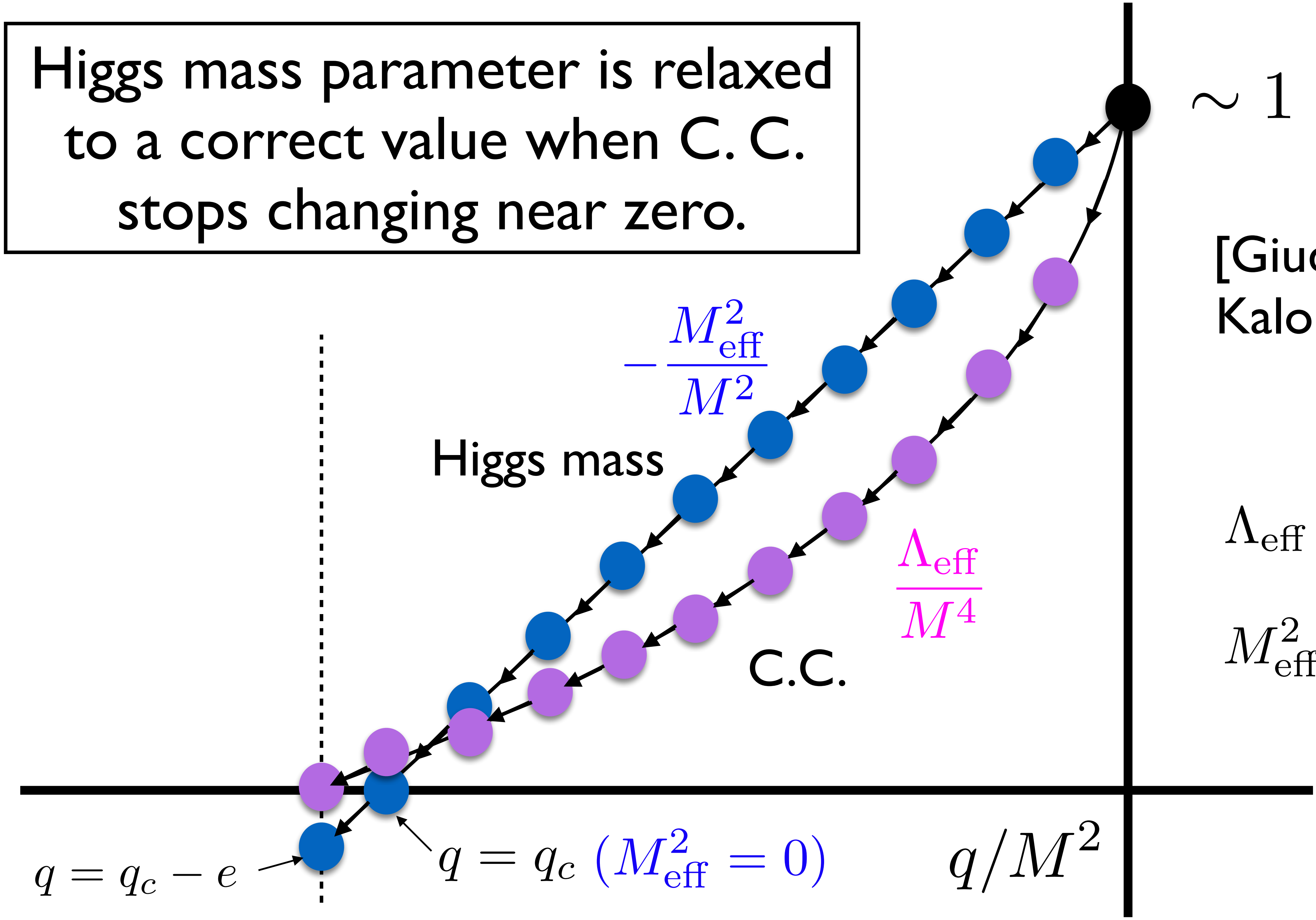
Four-form flux scans C.C. as well as Higgs mass.

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

Higgs quartic coupling has a constant shift.

Higgs mass/CC scanning

Higgs mass parameter is relaxed to a correct value when C. C. stops changing near zero.



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

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

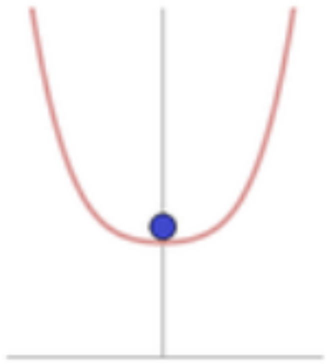
$$M_{\rm eff}^2 = M^2 - c_H q.$$

$M_{\rm eff}^2 = c_H e$ → $e \sim (100\,{\rm GeV})^2$ Membrane charge

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

Four-form & energy bound

★ $q = q_c:$ Last dS phase, No EWSB.

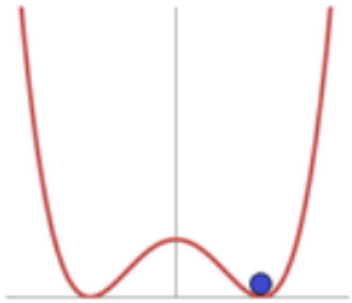


$$M_{\rm eff}^2 = M^2 - c_H q_c = 0 \quad \rightarrow \quad \boxed{q_c = \frac{M^2}{c_H} \sim M_P^2}$$

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

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

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



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

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

Bound on reheating: $\rho_R = \frac{\pi^2}{30} g_* T_{\rm RH}^4 < 3 M_P^2 H_{\rm last}^2$ $\boxed{T_{\rm RH} < 8.5 \times 10^9\,{\rm GeV}}$

Need of reheating dynamics

- Long duration for nucleation would make the Universe settles down to minimum quickly and dilute previously produced particles.

$$\gamma \equiv \bar{r}_0^{-4} e^{-B} \ll H^4$$

- 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 a new field for density perturbations.

Particle production from vacuum

- Change of vacuum states with flux-dependent Higgs VEV produce particles by "non-adiabatic process".

[Giudice, Kehagias, Riotto, 2019]

$$m_P = 0 \to m_P = g_P v$$

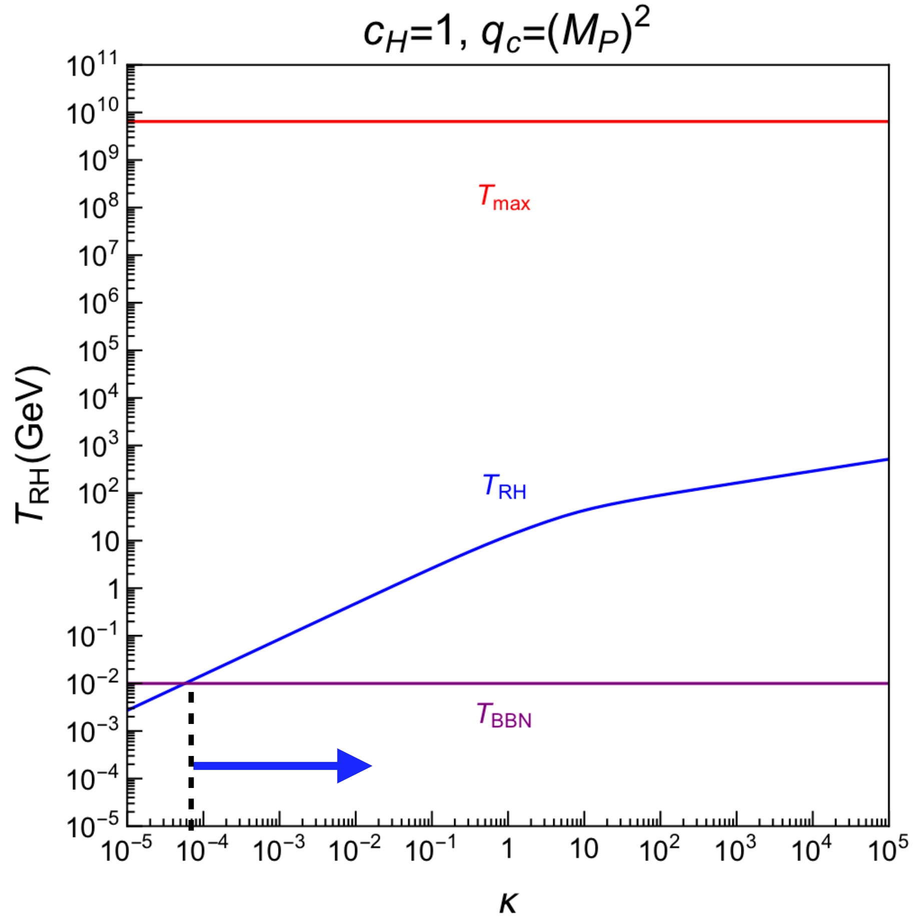
$$m_P^2 = \frac{1}{2} g_P^2 v^2 \Big(1 + \tanh(\kappa H\, t)\Big),$$

κ : Last nucleation rate

e.g. bosons:

$$n_k^B = \frac{\cosh\left(\pi\sqrt{\frac{m_B^2}{\kappa^2 H^2} - 1}\right) + \cosh\left[\frac{\pi(\omega_2 - \omega_1)}{\kappa H}\right]}{2\sinh\left(\frac{\pi\omega_1}{\kappa H}\right)\sinh\left(\frac{\pi\omega_2}{\kappa H}\right)}$$

$$\omega_1 = k \text{ and } \omega_2 = \sqrt{k^2 + m_B^2}.$$



[Giudice, HML, Shakya, unpublished]

Particle production is sensitive to speed of transition.

$$n_P = \frac{N_P}{2\pi^2} T_{\rm eff}^3\, I\Big(\frac{m_P}{T_{\rm eff}}\Big), \quad T_{\rm eff} = \frac{\kappa H}{2\pi}.$$

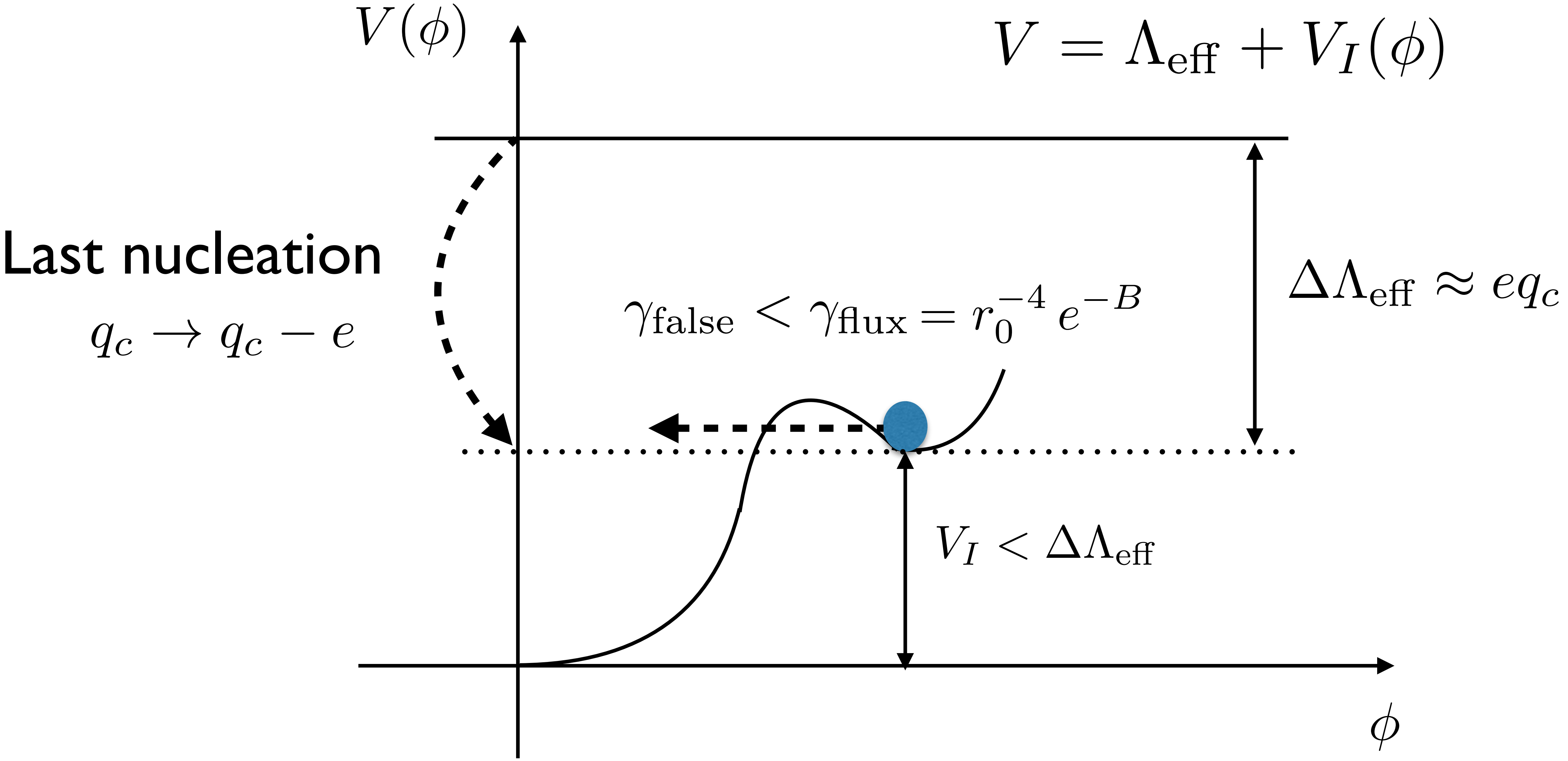
"Effective temperature"

Reheating from trap

- Inflaton is stuck at false vacuum in dS phases.

[Bousso, Polchinski, 2000]

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



$V = \Lambda_{\rm eff} + V_I(\phi)$

Last nucleation

$q_c \to q_c - e$

$\gamma_{\rm false} < \gamma_{\rm flux} = r_0^{-4}\, e^{-B}$

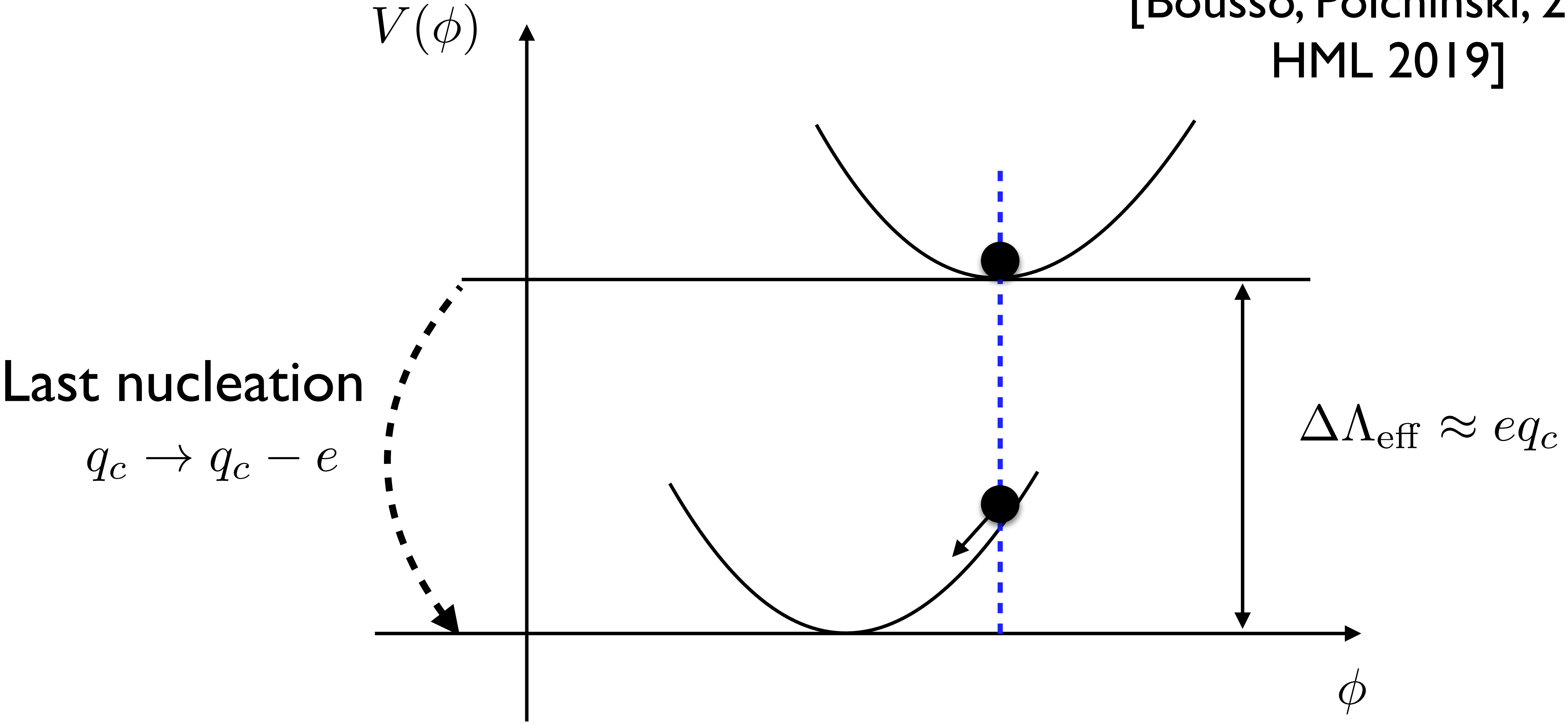
$\Delta\Lambda_{\rm eff} \approx e q_c$

$V_I < \Delta\Lambda_{\rm eff}$

Selfish Higgs → $H_I = \frac{V_I}{3M_P^2} < e \sim (100\,{\rm GeV})^2$

Reheating from displacement

[Bousso, Polchinski, 2000;
HML 2019]



$$V(H,\phi) = V_{\text{eff}}(H) + \underset{\text{“Flux-reheating field”}}{\underline{(k_1\phi^n + q + k_2)^2}} + \underset{\text{“SM coupling”}}{\underline{V_{\text{int}}(\phi, H)}}$$

Shifted minimum (physical observables);
Latent heat after last transition (for reheating)

Four-form portals for cosmology

General four-form couplings

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

[HML, 2019]

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

Gravity Four-form coupling

Higher curvature term for stability

Make the flux parameter q dynamical: extra scalar field!

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

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

Non-tachyonic scalar: $\zeta^2 > c_1^2$

Extra scalar is responsible for inflation and reheating.

Reheating potential

- The effective scalar potential in Einstein frame.

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

[HML, 2019]

$$V_E(H,\bar{\sigma}) = \Lambda_{\rm eff}\, e^{-2\sqrt{\frac{2}{3}}\bar{\sigma}} + \frac{3}{4}m_{\bar{\sigma}}^2\Big(1-(1+c_1 q)e^{-\sqrt{\frac{2}{3}}\bar{\sigma}} - c_1 c_2\, e^{-\sqrt{\frac{2}{3}}\bar{\sigma}}|H|^2\Big)^2$$

$$+e^{-2\sqrt{\frac{2}{3}}\bar{\sigma}}\Big(-M_{\rm eff}^2|H|^2 + \lambda_{H,{\rm eff}}|H|^4\Big)$$

$\langle H\rangle = v/\sqrt{2}$

$$\boxed{V_E(\bar{\sigma}) = V_0(q) + \left[\frac{3}{4}m_{\bar{\sigma}}^2\left(1+c_1\left(q+\frac{1}{2}c_2 v^2\right)\right)^2 + \Lambda_{\rm eff}\right]\left(e^{-\sqrt{\frac{2}{3}}\bar{\sigma}} - e^{-\sqrt{\frac{2}{3}}\bar{\sigma}_{\rm m}(q)}\right)^2,}$$

EWSB

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

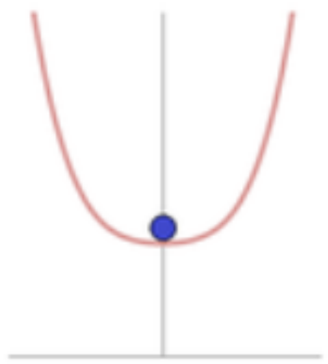
Potential parameters are flux-dependent.

$$V_0(q) = \frac{3m_{\bar{\sigma}}^2\Lambda_{\rm eff}}{3m_{\bar{\sigma}}^2(1+c_1(q+\frac{1}{2}c_2v^2))^2 + 4\Lambda_{\rm eff}}$$: Flux-dep. C.C.

$$e^{-\sqrt{\frac{2}{3}}\bar{\sigma}_{\rm m}(q)} = \frac{3m_{\bar{\sigma}}^2(1+c_1(q+\frac{1}{2}c_2v^2))}{3m_{\bar{\sigma}}^2(1+c_1(q+\frac{1}{2}c_2v^2))^2 + 4\Lambda_{\rm eff}}$$: Flux-dep. minimum

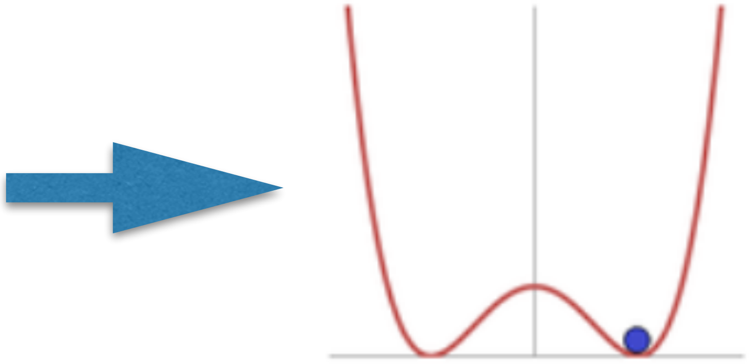
Reheating from displacement

- Scalar VEV shifts after the last nucleation:



$$q_c = \frac{M^2}{c_H},$$

$$v_H = 0$$



$$q = q_c - e,$$

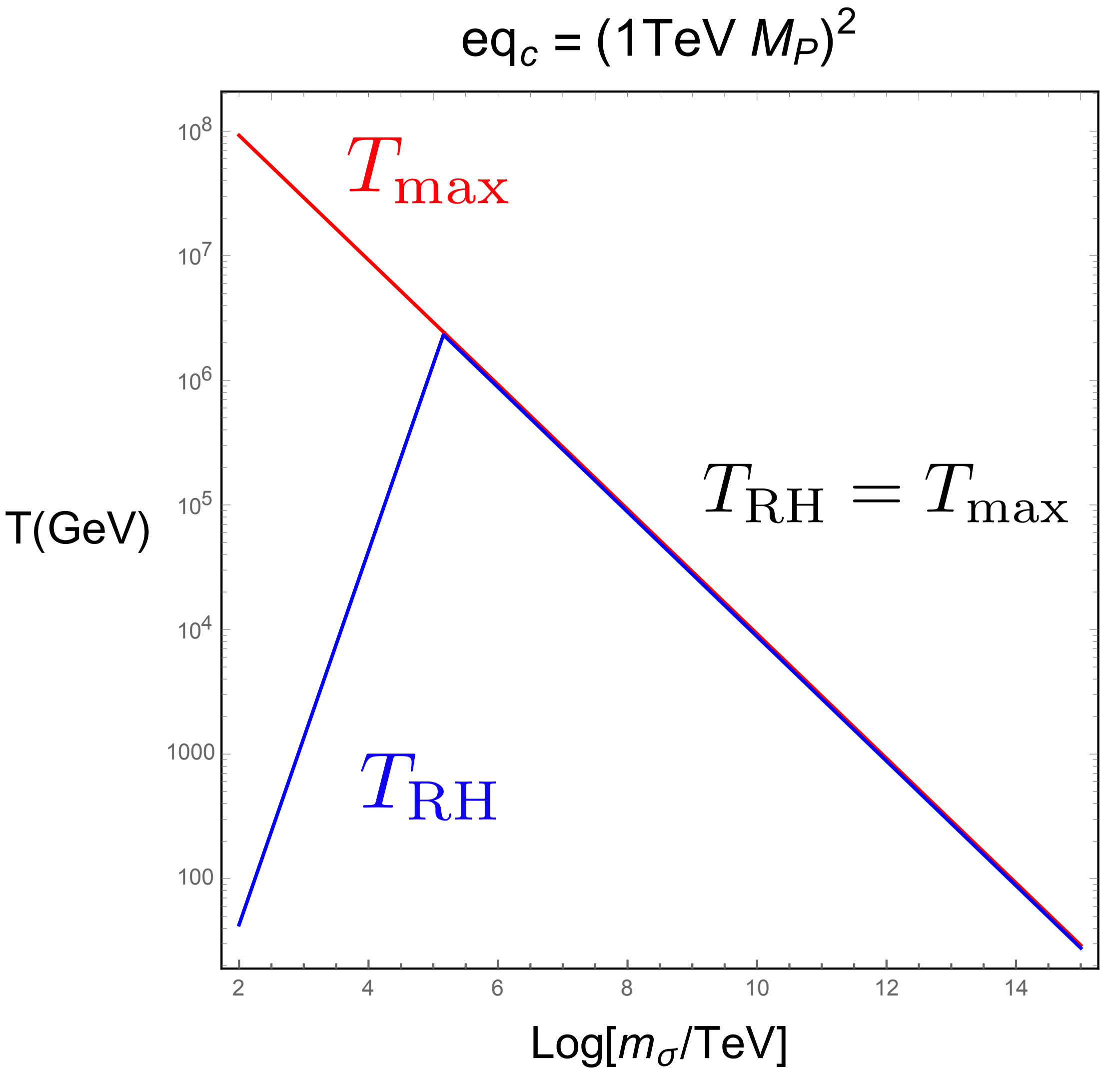
$$v_H \neq 0$$

Large initial potential energy:

$$V_i \equiv V_E(\bar{\sigma}_i) = \frac{12(eq_c)^2 m_{\bar{\sigma}}^2}{(3m_{\bar{\sigma}}^2(1+c_1 q_c)^2 + 4eq_c)^2}$$

$$\lesssim eq_c \sim (\text{TeV}\, M_P)^2$$

Four-form coupling reheats the Universe to a sufficiently high temperature.



Dark matter production

- Perturbative decays of singlet scalar produce dark matter with gravity coupling only.

[HML, 2019]

$$\rho_{\rm DM} = {\rm BR}_{\bar\sigma}\cdot \rho_{\bar\sigma}, \quad \rho_{\bar\sigma} = \rho_R : \qquad Y_{\rm DM} = \frac{\rho_{\rm DM}}{s(T_R)} = \frac{4}{3}{\rm BR}_{\bar\sigma}\,\frac{T_{\rm RH}}{m_{\bar\sigma}}.$$

\- Fermion dark matter: $\Gamma(\bar\sigma\to\bar\chi\chi) = \frac{m_\chi^2 m_{\bar\sigma}}{48\pi M_P^2}, \quad \Gamma(\bar\sigma\to hh) = \frac{3c_1^2c_H^2}{64\pi}\,\frac{m_{\bar\sigma}^3}{M_P^2}$

$$ {\rm BR}_{\bar\sigma} \simeq \Gamma(\bar\sigma\to\bar\chi\chi)/\Gamma(\bar\sigma\to hh) = \frac{4}{9c_1^2c_H^2}\,\frac{m_\chi^2}{m_{\bar\sigma}^2}$$

Chiral suppression!

➡ $\Omega_{\chi+\bar\chi}h^2 = 0.12\left(\frac{100}{g_*(T_{\rm RH})}\right)^{1/4}\left(\frac{m_\chi}{2\,{\rm TeV}}\right)^3\left(\frac{380\,{\rm TeV}}{m_{\bar\sigma}}\right)^{3/2}\frac{1}{|c_1c_H|}.$ "TeV DM"

\- Scalar dark matter: $\Gamma(\bar\sigma\to SS) = \frac{m_{\bar\sigma}^3}{48\pi M_P^2}, \quad {\rm BR}_{\bar\sigma} \simeq \frac{4}{9c_1^2c_H^2}$

No chiral suppression! Large BR!

➡ $\Omega_S h^2 = 0.12\left(\frac{100}{g_*(T_{\rm RH})}\right)^{1/4}\left(\frac{m_S}{55\,{\rm MeV}}\right)\left(\frac{m_{\bar\sigma}}{380\,{\rm TeV}}\right)^{1/2}\frac{1}{|c_1c_H|}.$ "Light DM"

Pseudo-scalar for inflation

- Pseudo-scalar scalar with four-form coupling leads to quadratic inflation. [Kaloper, Sorbo, 2009]

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

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

But, quadratic inflation is ruled out by Planck observation.

- Generalize four-form couplings with shift symmetry:

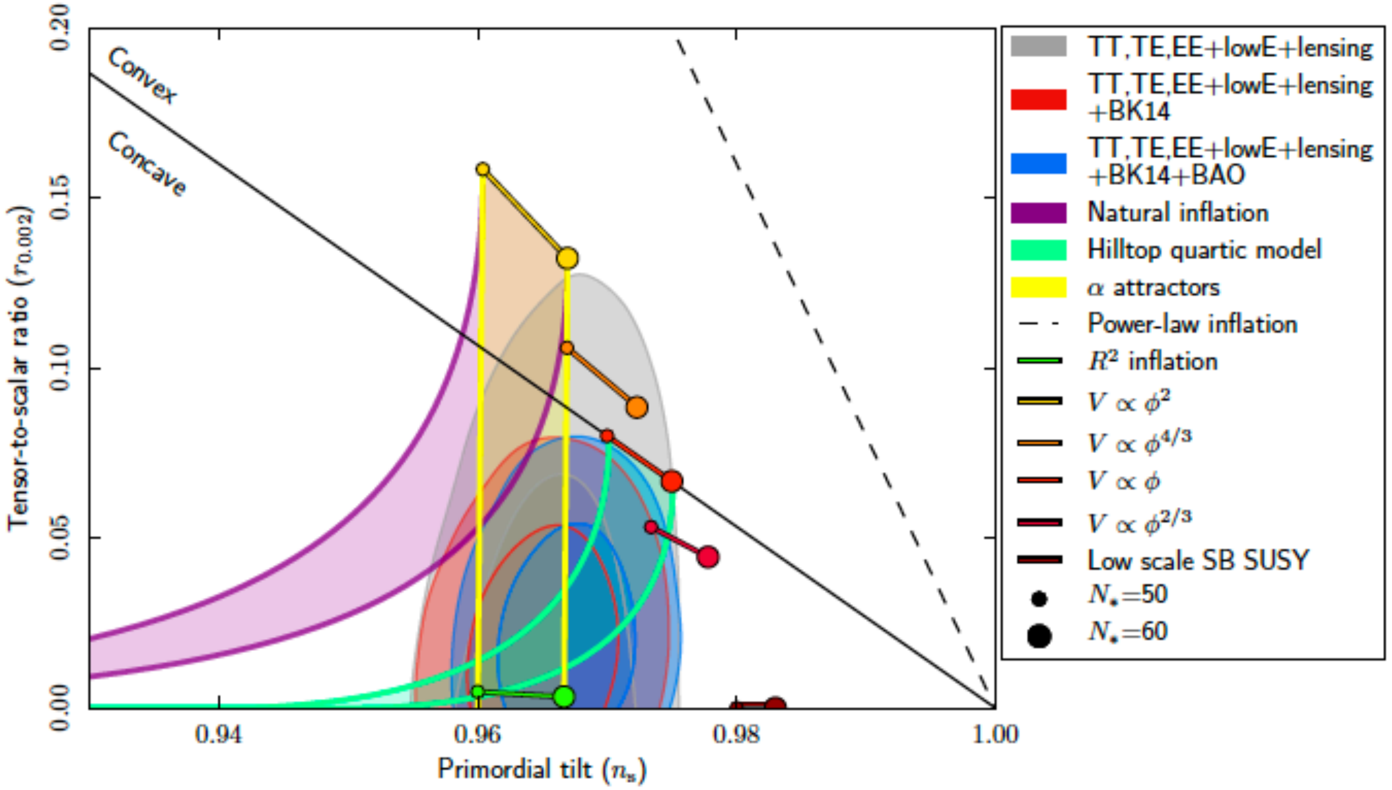
[HML, 2019]

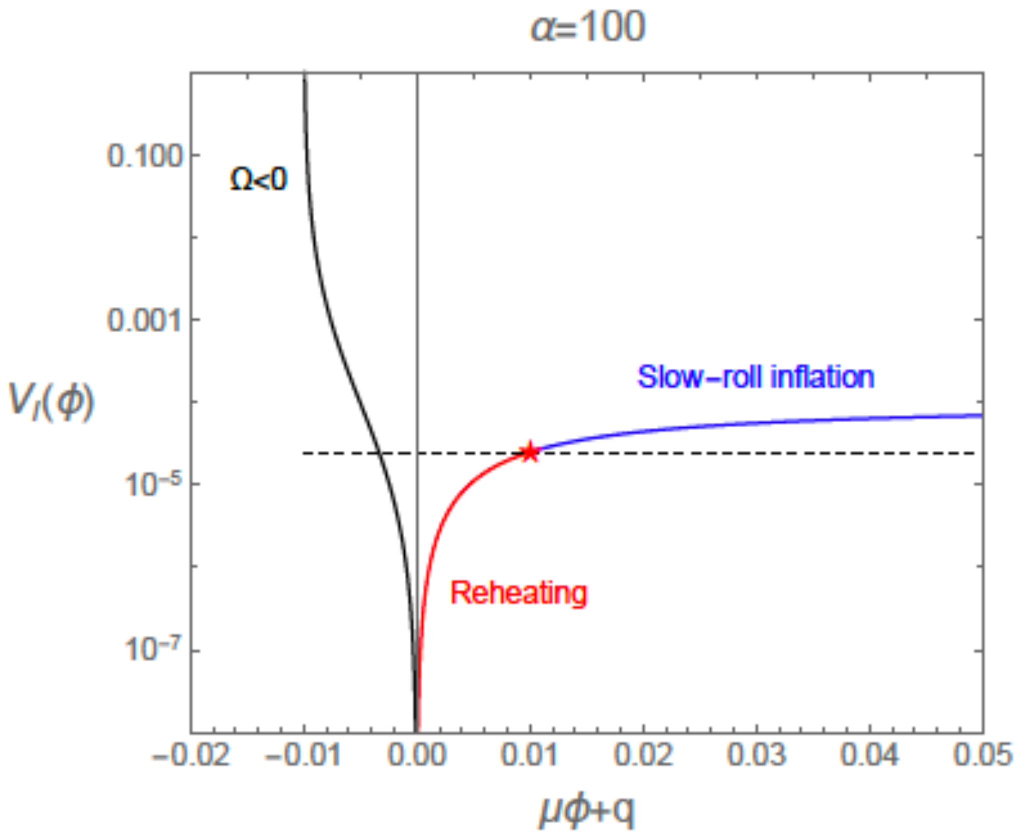
$$\underline{\mathcal{L}_{nm} = -\frac{\alpha}{24}\,\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\,R + \frac{1}{2}\zeta^2\,R^2}$$

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

Higgs, Starobinsky-like inflation with plateau at large fields!

Planck and PS inflation





For $\zeta \gtrsim \alpha$ and $\mu \lesssim M_P$, keep a single pseudo-scalar inflation.

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

Inflaton potential: $V_I(\varphi) = \frac{1}{2\alpha^2}\left(1+\frac{4}{\alpha^2\mu^2\varphi^2}\right)^{-2}.$

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

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

Inflationary predictions agree with Planck.

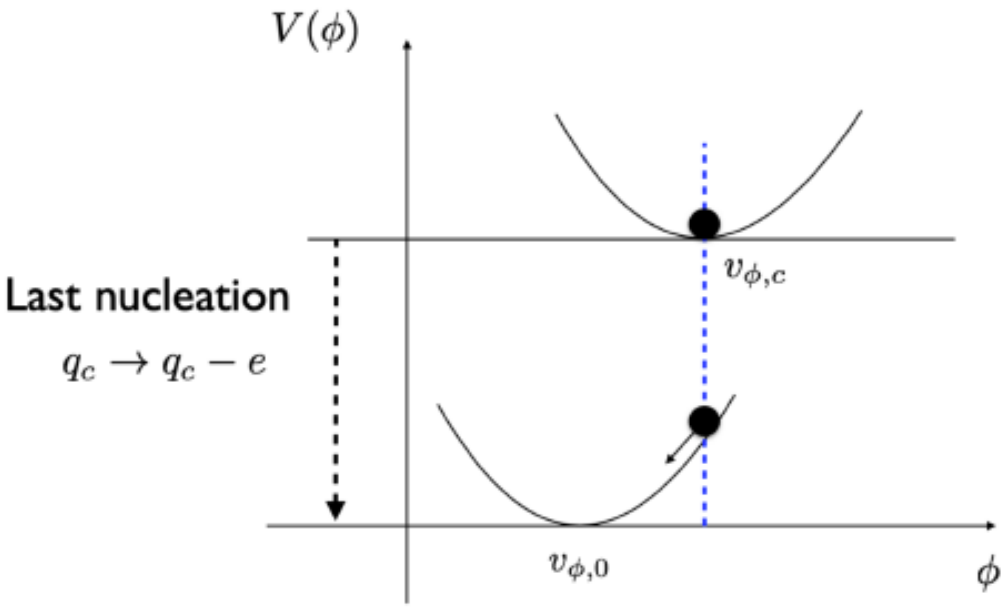
Pseudo-scalar for reheating

- Introduce a pseudo-scalar as reheating field. [HML, 2019]

$$\mathcal{L} \supset -\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 (\phi-\alpha)^2 + \underline{\frac{\mu}{24}\,\epsilon^{\mu\nu\rho\sigma} F_{\mu\nu\rho\sigma}\,\phi} - \frac{\mu}{6}\,\partial_\mu\left(\epsilon^{\mu\nu\rho\sigma}\phi A_{\nu\rho\sigma}\right).$$

$$\longrightarrow \quad \mathcal{L} \supset \quad -\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_\phi^2 (\phi-\alpha)^2 - \boxed{\frac{1}{2}(\mu\phi + c_H|H|^2 + q)^2}$$

- VEV shifts after last nucleation:



$$v_H = 0, \qquad v_\phi = v_{\phi,c}$$

→ EWSB

$$v_H^2 = \frac{m_\phi^2}{\mu^2 + m_\phi^2}\left(\frac{c_H\, e}{\lambda_{H,\mathrm{eff}} - \frac{1}{2}\frac{c_H^2 \mu^2}{\mu^2 + m_\phi^2}}\right),$$

$$v_\phi = v_{\phi,0}$$

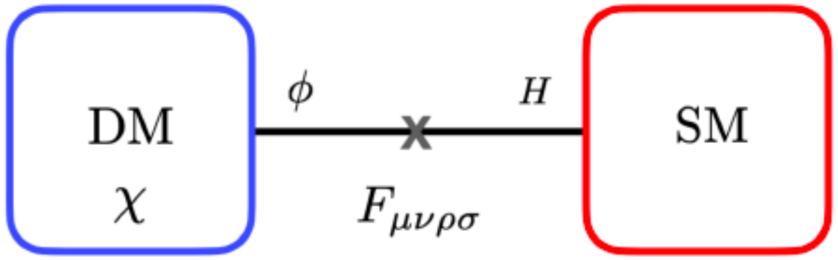
Initial vacuum energy:

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

Four-form coupling reheats! $T_{\rm RH} \sim 100\,\mathrm{GeV}$

Flux-mediated dark matter

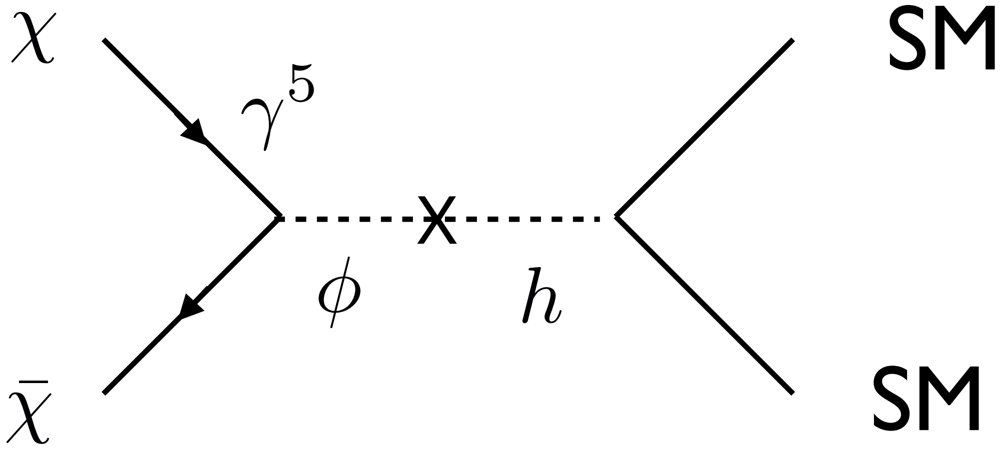
- Four-form couplings communicate dark matter via pseudo-scalar field: "four-form portal”

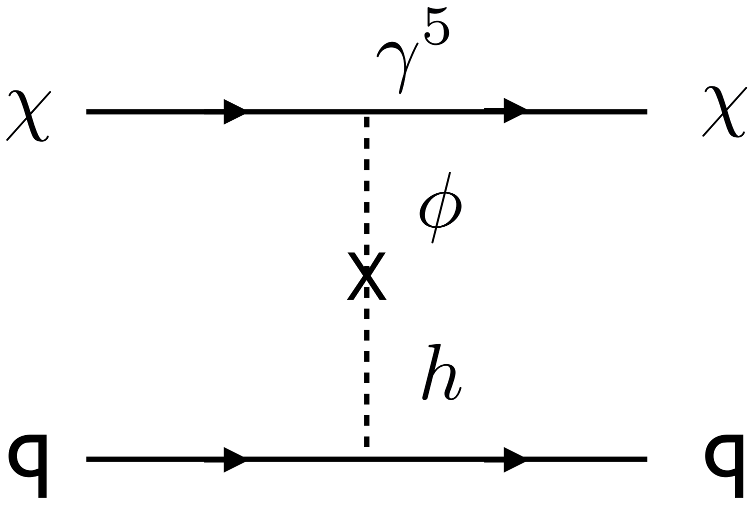


[HML, 2019; Y. Kang, HML, A. Menkara, J. Song, 2021]

Mixing between pseudo-scalar and Higgs fields.

Fermion dark matter: $\mathcal{L}_{\rm DM} = \frac{i m_\chi}{f}\,\phi\,\bar\chi\gamma^5\chi - \frac{1}{2} c_H \mu \phi h^2$



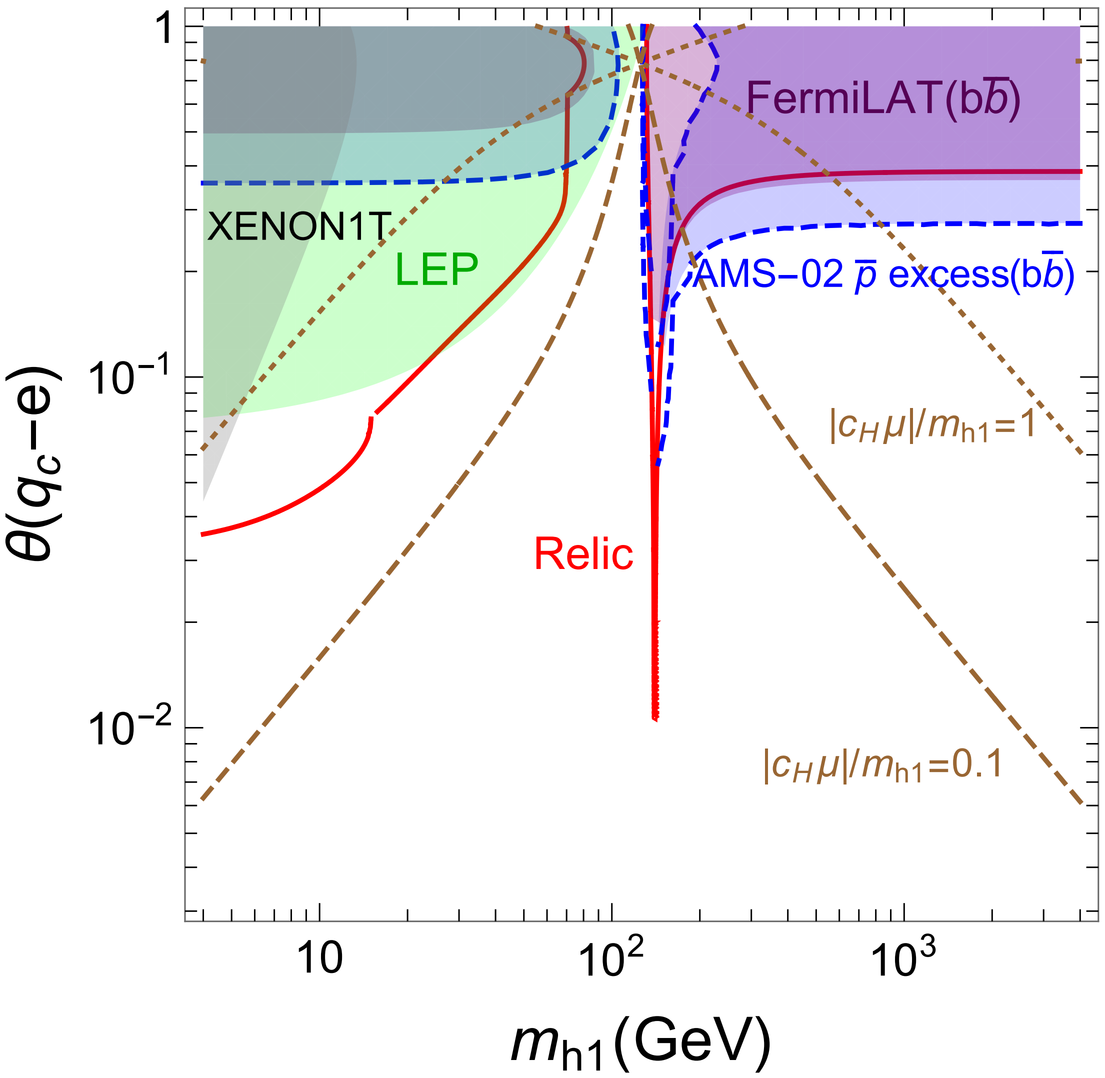


Unsuppressed s-wave
for indirect detection.

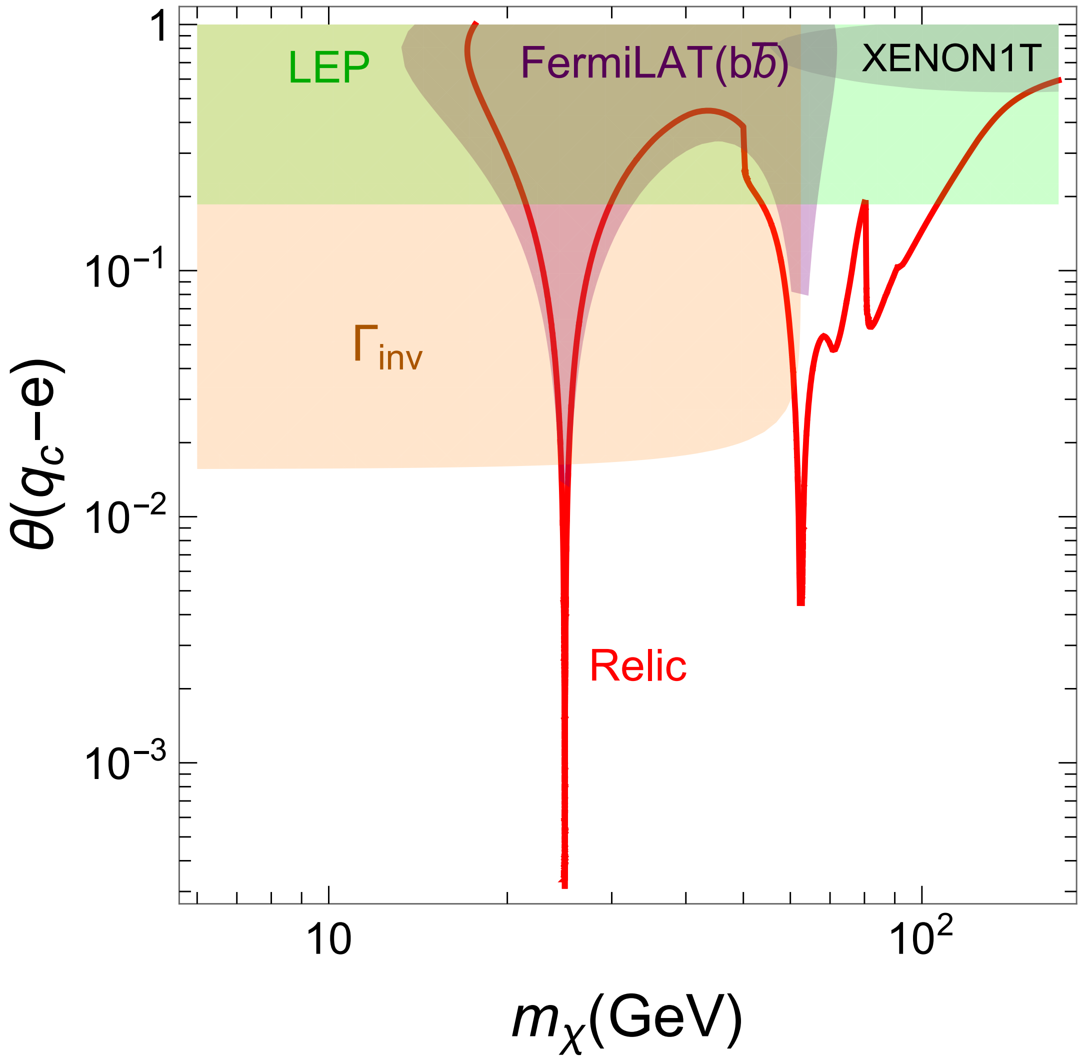
Velocity suppressed
for direct detection

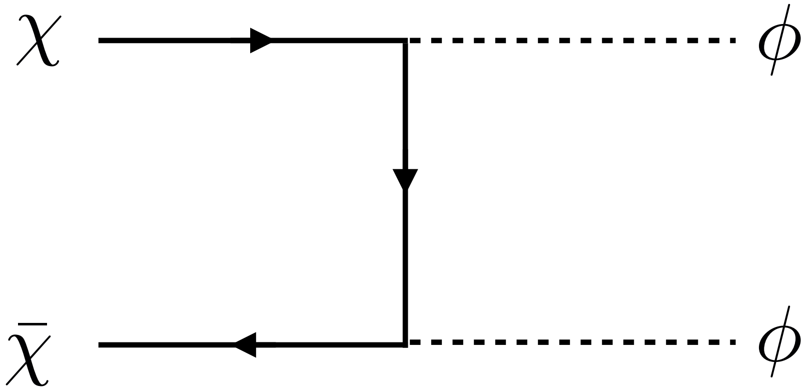
Bounds on four-form portals

m_χ=70 GeV, β=10^{-5}, f=126 GeV



m_{h1}=50 GeV, β=1.5x10^{-4}, m_χ/f=0.645





DM annihilation into a pair of pseudo-scalars is p-wave suppressed but crucial for relic density.

Conclusions

- Four-form flux scans Higgs mass and cosmological constant at the same time, with nucleation of weak-scale membrane charges.

- Sufficient reheating can be achieved by the displacement of an extra scalar field after membrane nucleation.

- Non-minimal coupling four-form coupling to gravity realizes reheating and non-thermal production of dark matter.

- Pseudo-scalar field with four-form couplings can lead to consistent inflation and mediate thermal dark matter.

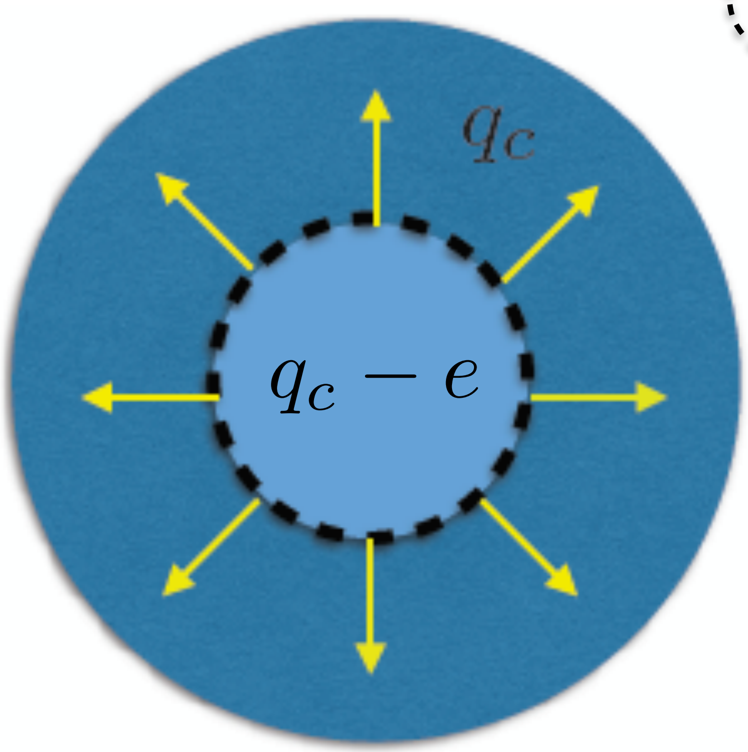
Four-form landscape

Physical parameters depend on four-form fluxes:

~ Four-form landscape

Higgs mass

$$c_H\,|H|^2 F_{\mu\nu\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$



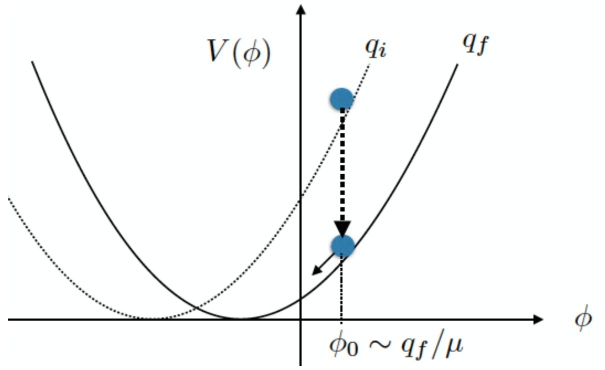
Cosmological constant

$$\sqrt{-g}\,F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}$$

Inflation

$$c_1 R\,F_{\mu\nu\rho\sigma}\epsilon^{\mu\nu\rho\sigma},$$

$$\mu\phi\,F_{\mu\nu\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$$



SUSY breaking

$$m^2_{\tilde{f}_{ij}} = \frac{1}{M_P^2}\sum_{\alpha=1}^{N} d_{\alpha,ij}F^\dagger_{T_\alpha}F_{T_\alpha}$$

Dark matter