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Cosmological Relaxation from Dark Fermion Production

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Kadota, Min, SON, Ye 1909.07706

Hierarchy problem (Naturalness problem)

Ubiquitous quantum fluctuation can widely fluctuate particle mass

: natural size predicted by QM

$\delta m_h^2 \sim$ 

$\sim E^2 \leq \Lambda^2$

$\Delta x \, \Delta p \; \geq \hbar, \Delta E \, \Delta t \; \geq \hbar$

where Higgs theory is defined

$\Lambda \sim M_{pl} \sim 10^{18}\,\mathrm{GeV}$

On contrary

$$m_{h\ \mathrm{obs.}}^2 = (125\ \mathrm{GeV})^2$$

: what has been measured

Likely colored

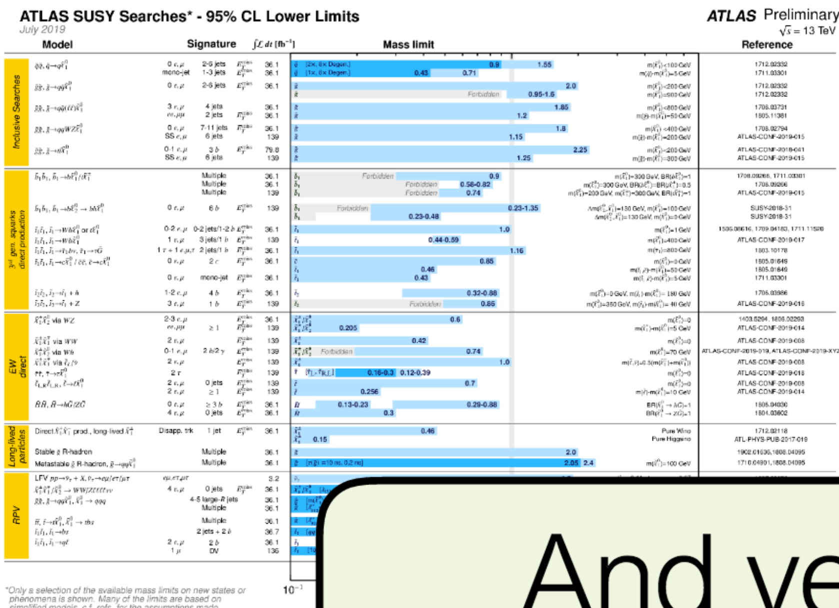
$$\delta m_h^2 \; \propto m_{new}^2$$

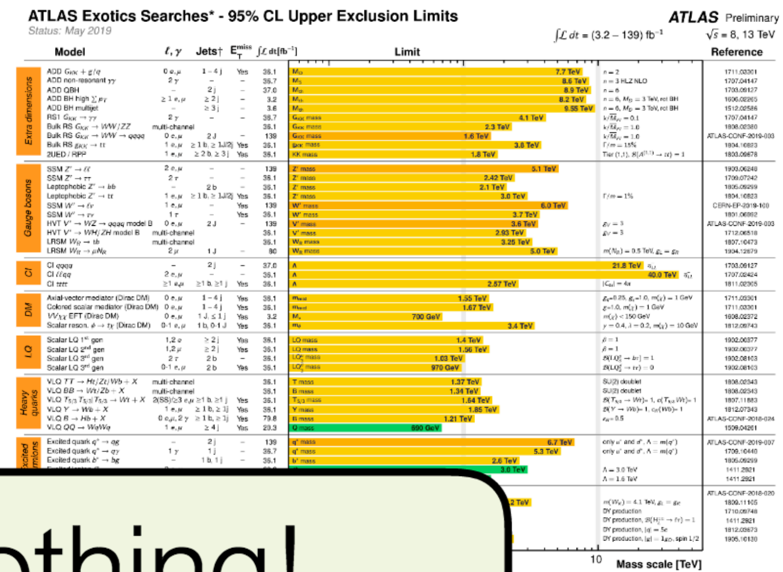
: what traditional New Physics predicts

where LHC kicks in

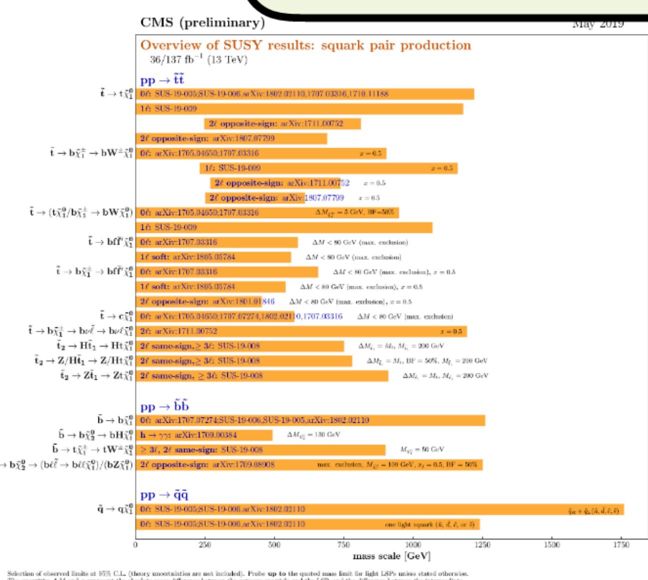
Direct searches

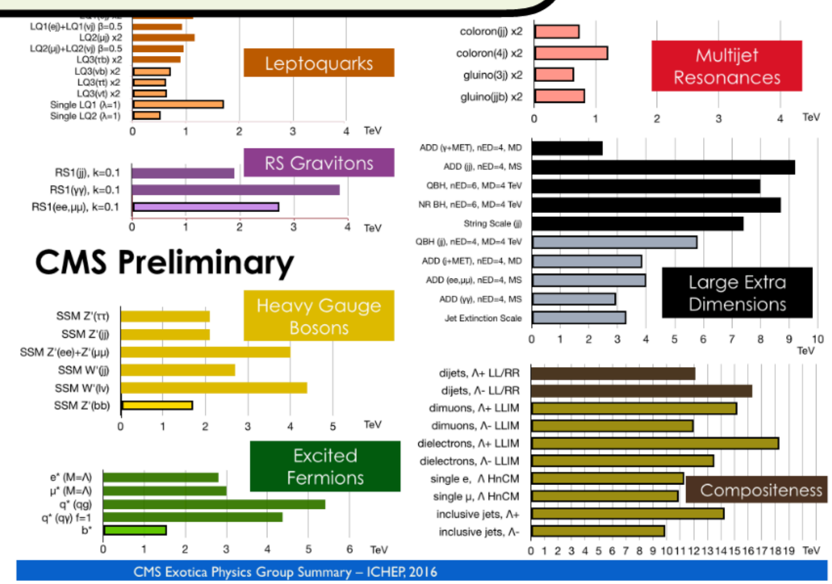
From talk by R. Torre TOP2019





And yet nothing!





Staying on the traditional way

colored

$$\delta m_h^2 \propto \Lambda^2 \times \frac{m_{new}^2}{\Lambda^2} \times \frac{g_{EW}^2}{g_{new}^2} \times \cdots = m_{\tilde{T}}^2 \ll m_{new}^2$$

likely color-blind top partners
future collider

More selection rules to soften quantum fluctuation even more

E.g. neutral Naturalness

Or go along the non-traditional approach

Relaxation : Alternative to softening quantum fluctuation

Graham, Kaplan, Rajendran 15' (GKR)

Dynamical cancellation in cosmological history

$$\mathcal{L} = (-\Lambda^2 + g\phi)hh^+ + (g\Lambda^2\phi + g^2\phi^2 + \cdots) + \Lambda_c^4 \cos\frac{\phi}{f}$$

Represents usual quadratic div. (tree or loop) in SM

Promoted to an evolving $m_h^2(t)$

$$-\Lambda^2 + g\phi \sim -\Lambda^2 + g \times \frac{\Lambda^2}{g} \sim \mu_{EW}^2$$

, or $\delta m_h^2 \sim \Lambda^2 \times \frac{\mu_{EW}^2}{\Lambda^2}$

μ_{EW} is not necessarily associated to New physics at EW scale

A resolution in non-traditional approach

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Represents usual quadratic div. (tree or loop) in SM

Promoted to an evolving $m_h^2(t)$

Engineered to stop evolving Higgs mass at the right place to generate EW scale naturally

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, or $\delta m_h^2 \sim \Lambda^2 \times \frac{\mu_{EW}^2}{\Lambda^2}$

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Represents usual quadratic div. (tree or loop) in SM

Promoted to an evolving $m_h^2(t)$

ϕ is ALP & g is small (tech. natural)

V is approximated by a linear term

Dependency on New Physics via Λ_c

$$-\Lambda^2 + g\phi \sim -\Lambda^2 + g\times\frac{\Lambda^2}{g} \sim \mu_{EW}^2$$

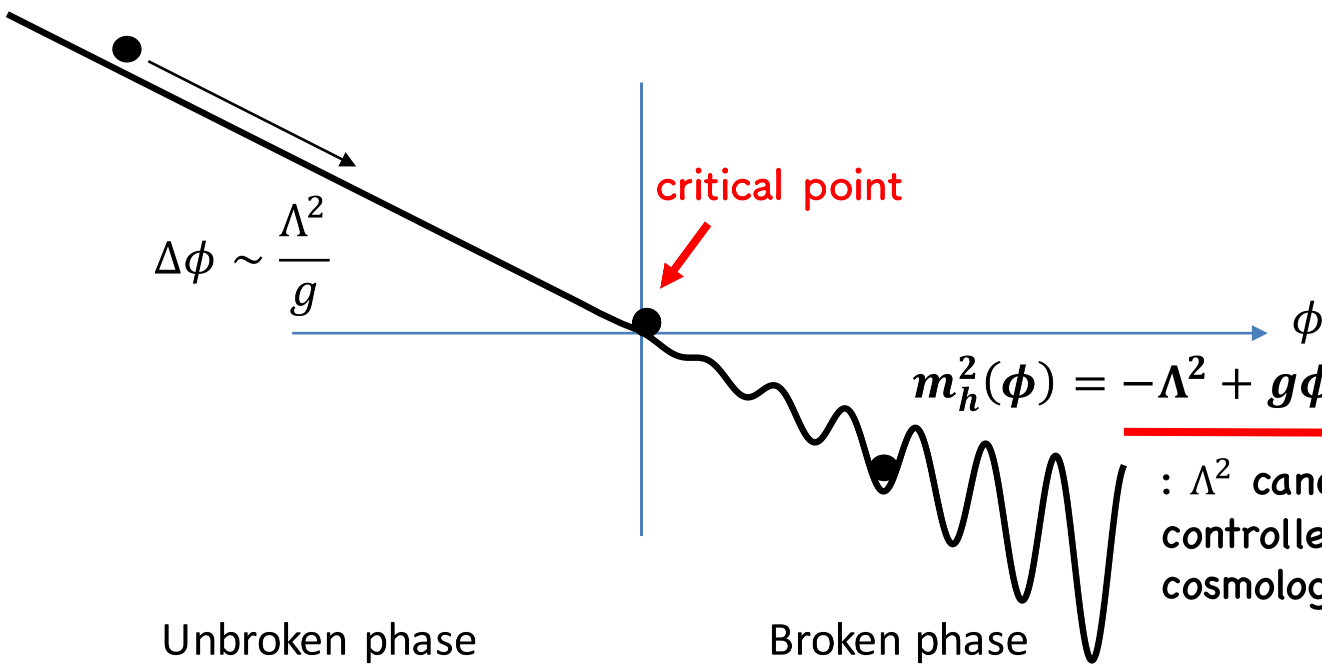
, or $\delta m_h^2 \sim \Lambda^2\times\frac{\mu_{EW}^2}{\Lambda^2}$

Grandparent Relaxation

Graham, Kaplan, Rajendran 15' (GKR)

$$\mathcal{L} = (-\Lambda^2 + g\phi)hh^+ + (g\Lambda^2\phi + \cdots) + \Lambda_c^4 \cos\frac{\phi}{f}$$

w/ $\Lambda_c^4 \propto \langle h \rangle^n$



$$\boldsymbol{m_h^2(\phi) = -\Lambda^2 + g\phi \sim \mu_{EW}^2}$$

: Λ^2 cancellation is controlled by cosmological dynamics

Unbroken phase

$\langle h \rangle = 0$

$m_h^2(\phi; t) = -\Lambda^2 + g\phi > 0$

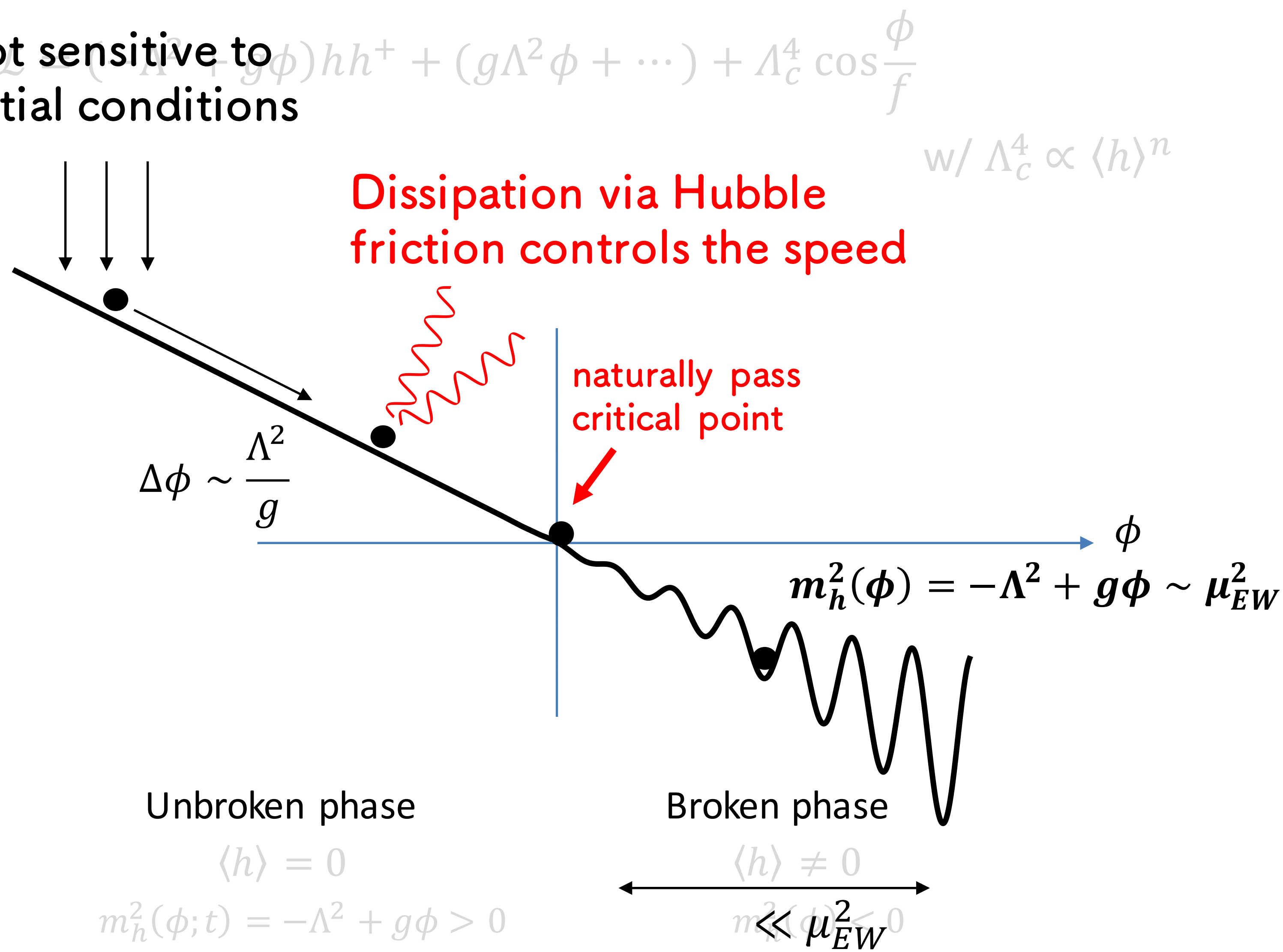
Broken phase

$\langle h \rangle \neq 0$

$m_h^2(\phi) < 0$

Grandparent Relaxation

Graham, Kaplan, Rajendran 15' (GKR)



What it can achieve

combining some consistency conditions gives rise to

$$\Lambda < \left(\frac{\Lambda^4 M_{pl}^3}{f}\right)^{1/6} \sim 10^7 \text{ GeV} \times \left(\frac{10^9 GeV}{f}\right)^{1/6}$$

Graham, Kaplan, Rajendran 15'

Downsides

$$\boldsymbol{g \sim 10^{-30}}$$

1. Super-Planckian field excursion $\Delta\phi \geq \frac{\Lambda^2}{g} \sim 10^{22} M_p$

2. Too large number of e-folding $N_e \geq \frac{H^2}{g} \sim 10^{44}$

   Inflation lasts long enough for ϕ to scan entire range

3. Small inflation scale $H \sim 10^{-4}$ *GeV* < *EW scale*

Grandparent Relaxation (GKR scenario)

: downsides are linked to using Hubble friction force for slow-roll

$$\ddot{\phi} + \underline{3H\dot{\phi} + V_{\phi}} = 0 \longrightarrow 3H\dot{\phi} \sim -V_{\phi}$$

Suppress the role of Inflation

Instead, look for alternative source of E-dissipation
: backreaction via Particle Production

$$\ddot{\phi} + 3H\dot{\phi} + V_{\phi} = \mathcal{B}(\dot{\phi})$$

: sort of drag force

Dissipation via Particle Production

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = \mathcal{B}(\dot{\phi})$$

1. HMT scenario Hook, Marques-Tavares 16’

: exponential tachyonic gauge boson production

$$\Delta\mathcal{L} = \frac{\phi}{f} F\tilde{F}$$

activated near the EW scale

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1. HMT scenario Hook, Marques-Tavares 16'

: exponential tachyonic gauge boson production

$$\Delta\mathcal{L} = \frac{\phi}{f} F\tilde{F}$$

activated near the EW scale

- ✓ It works in the broken phase : requires a specific UV completion
- ✓ Inflation is not necessary ingredient of the scenario
- ✓ It can achieve relatively low-cutoff, according to recent re-analysis

$$\Lambda \sim 10^{4\sim5}\ \text{GeV}$$

SON, Ye, You PRD 2019
Fonseca, Morgante, Servant JHEP 2018

Dissipation via Particle Production

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1. HMT scenario   Hook, Marques-Tavares 16'

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activated near the EW scale

* Other scenarios

: Parametric resonance of Higgs production

Ibe, Shoji, Suzuki 19'

: Axion fragmentation

Fonseca, Morgante, Sato, Servant 19'

Dissipation via Particle Production

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = \mathcal{B}(\dot{\phi})$$

2. Our scenario

Kadota, Min, SON, Ye 1909.07706

: non-exponential fermion production (Pauli-blocking)

$$\Delta\mathcal{L} = \frac{\partial_t \phi}{f_\psi}\bar{\psi}\gamma^0\gamma^5\psi$$

BSM application of Fermion production has been limited

Min, Seo, SON JHEP 2019

Adshead, Pearce, Peloso, Roberts, Sorbo JCAP 2108

Adshead, Sfakianakis JCAP 2015

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The role of backreaction is controling slow-roll of relaxion

$$\ddot{\phi} + 3H\dot{\phi} + \underline{V_\phi = \mathcal{B}(\dot{\phi})} \longrightarrow V_\phi \sim \mathcal{B}(\dot{\phi}) > 3H\dot{\phi}$$

We aim to address only Little hierarchy problem

$$\Lambda \sim 10^{4\sim5}\ \mathrm{GeV}$$

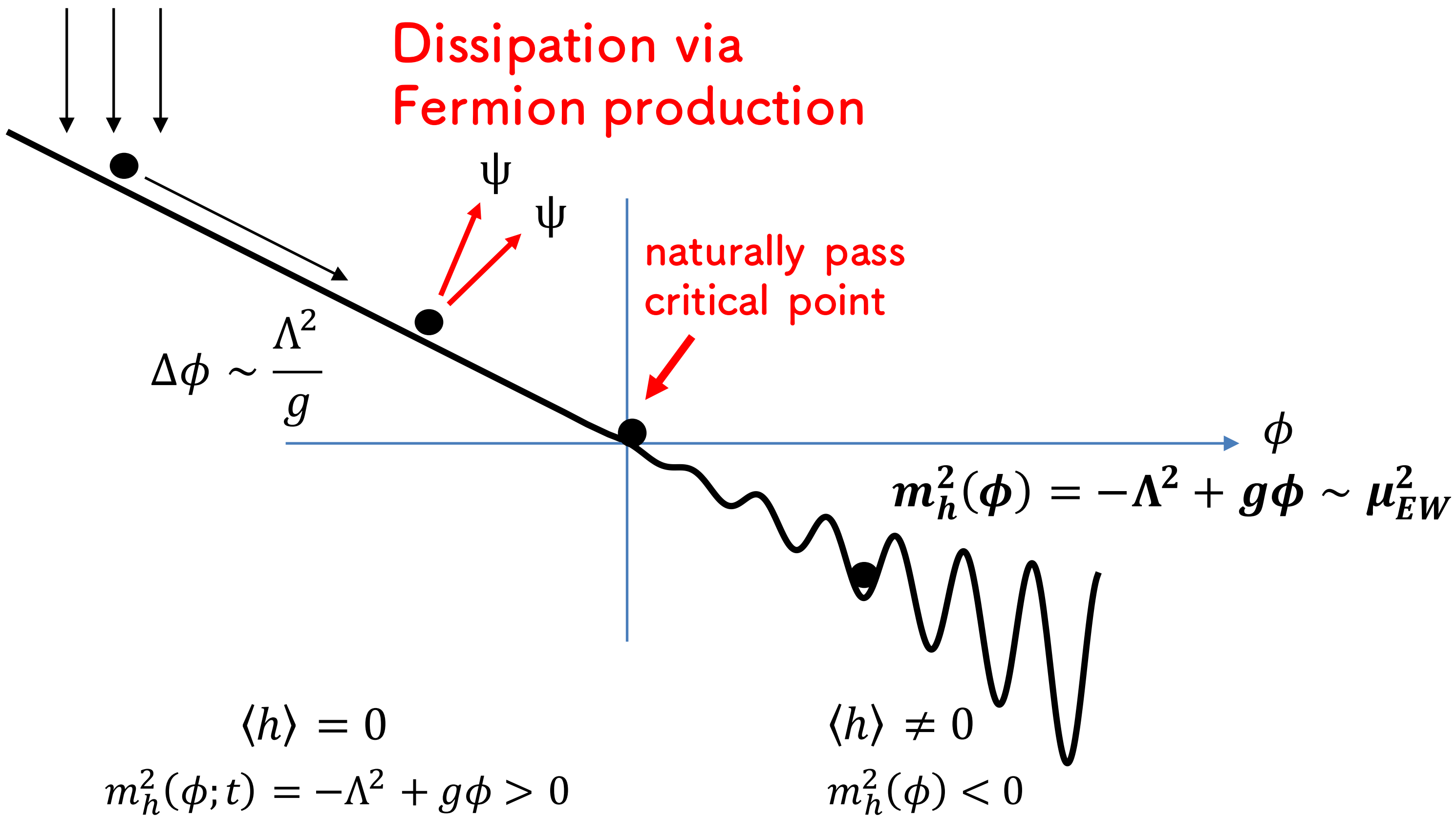
Granddaughter Relaxation

Kadota, Min, SON, Ye 1909.07706

$$\Delta\mathcal{L} = \frac{\partial_\mu \phi}{f_\psi}\bar{\psi}\gamma^\mu\gamma^5\psi + m\bar{\psi}\psi$$

Not sensitive to initial conditions

Dissipation via Fermion production



Our granddaughter Relaxation from fermion production

Kadota, Min, SON, Ye 1909.07706

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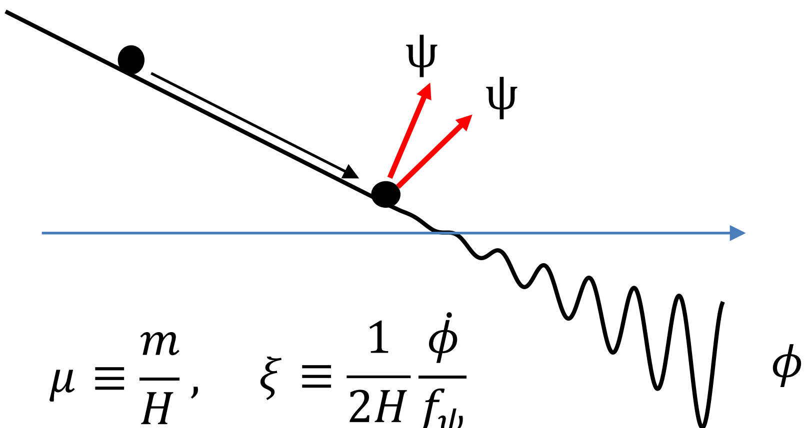

$$\mu \equiv \frac{m}{H}, \quad \xi \equiv \frac{1}{2H}\frac{\dot{\phi}}{f_\psi}$$

Features

- ✓ $g \sim 10^{-5\sim-6}$: sub-Planckian, modest e-folds
  : slow-roll eq. forces $\mathcal{B}$ to depend only on g
- ✓ ψ : massive SM singlet, call it dark fermion, can be warm dark matter
- ✓ A generic issue on $f_\psi \ll \Lambda$ **(downside)**

In this limit, we have an analytic control

In the limit $\mu^2 \ll \xi$ and $1 \ll \xi$

$$V_\phi \sim g\Lambda^2 \sim \mathcal{B}(\dot{\phi}) \sim -\frac{1}{f_\psi}H^4\mu^2\xi^2$$

$$\rightarrow \dot{\phi} \sim \frac{g^{1/2}\Lambda f_\psi^{3/2}}{m}$$

Our granddaughter Relaxation from fermion production

Kadota, Min, SON, Ye 1909.07706

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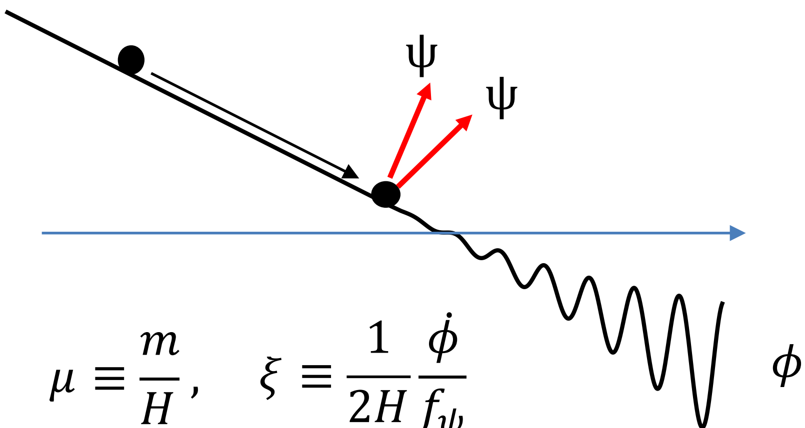

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Constraints on inflaton sector

- ✓ Inflationary Hubble $H \gg H_{\phi\ only} = \Lambda^2/M_P$ to avoid scanning over thermal Higgs mass sq.
- ✓ Inflation ends, when relaxation ends, and it should be quickly subdominant (downside)

Two benchmark scenarios

Dependency on New Physics through $\Lambda_c^4 \cos\frac{\phi}{f}$

1. Non-QCD

$$\Delta\mathcal{L}_{nonQCD} = m_L L L^c + m_N N N^c + y h L N^c + \tilde{y} h^+ L^c N$$

$$\Lambda_c^4 \propto 4\pi f_{\pi'}^3 \frac{y\tilde{y}v^2}{m_L}$$

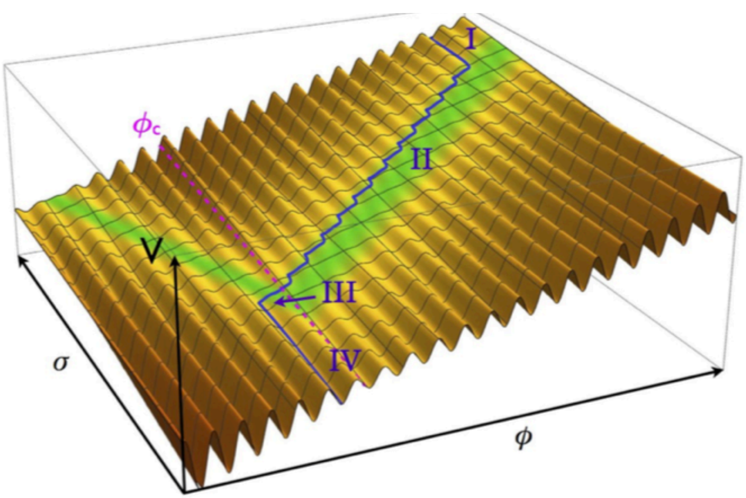
$\boldsymbol{4\pi f_{\pi'} \sim \Lambda_{strong} \ll \Lambda}$
needs NP at EW

2. Double scanner mechanism

$$V(\phi,\sigma,H) = \Lambda^4\left(\frac{g\phi}{\Lambda} + \frac{g_\sigma\sigma}{\Lambda}\right) - \Lambda^2\left(\alpha - \frac{g\phi}{\Lambda}\right)|H|^2 + \lambda|H|^4 + A(\phi,\sigma,H)\cos(\phi/f)$$

where

$$A(\phi,\sigma,H) \equiv \epsilon\Lambda^4\left(\beta + c_\phi\frac{g\phi}{\Lambda} - c_\sigma\frac{g_\sigma\sigma}{\Lambda} + \frac{|H|^2}{\Lambda^2}\right) ,$$



$$\Lambda_c^4 \propto \epsilon\Lambda^2 v^2$$

$\boldsymbol{\Lambda_{strong} \sim \Lambda}$
no needs NP at EW

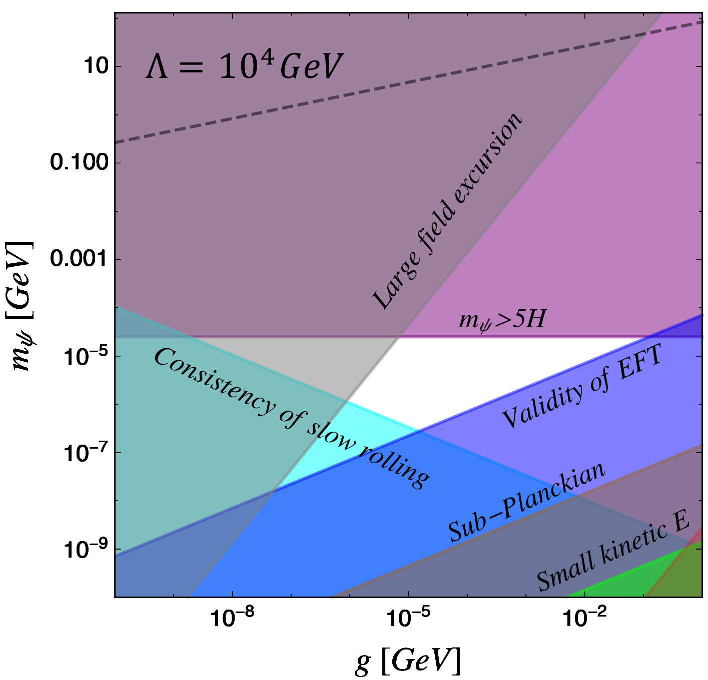
Various theoretical constraints can be recasted as either a lower bound on m or upper bound m

$$F_{min}(g, f_\psi, H, \Lambda, N_e, M_p) < m$$

or $\quad m < F_{max}(g, f_\psi, H, \Lambda, N_e, M_p)$ combined with $g\Lambda^2 \sim \frac{\Lambda_c^4}{f}$

Non-QCD

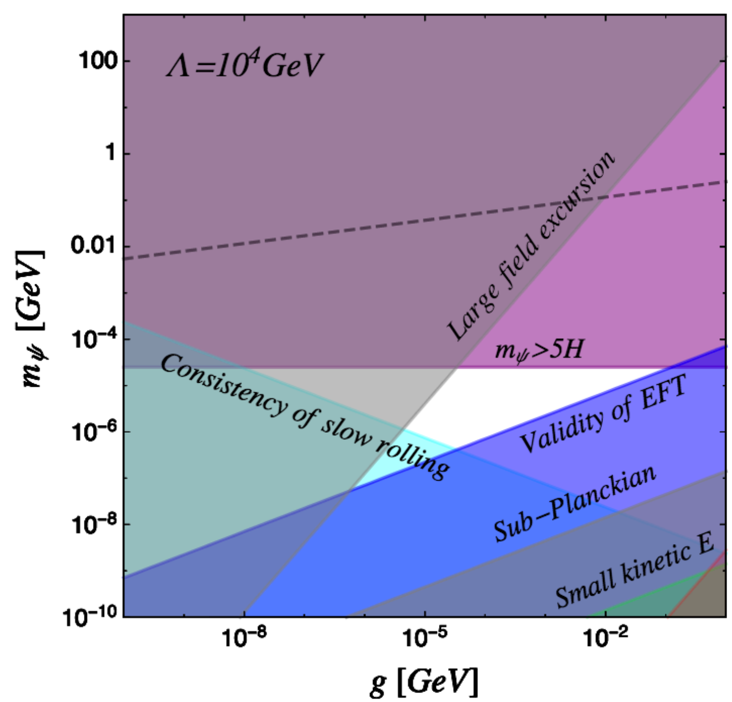
$\Lambda_{strong} \ll \Lambda = 10^4$ GeV



Warning! up to thermalization Issue

Double scanner mechanism

$\Lambda_{strong} \sim \Lambda = 10^4$ GeV



: Our proof of example

Dark Matter

ψ → keV warm DM : likely over abundance in both non QCD and DS

it has to be diluted, e.g. DS

$$\frac{\rho_\psi}{\rho_{crit}} \sim \frac{0.12}{h^2}\left(\frac{m_\psi}{3\times 10^{-3}\mathrm{keV}}\right)\times\frac{g_*(T_0)}{g_*(T_d)}\times\frac{1}{S}$$

ϕ → Decays before BBN

$$\Gamma_{\phi\to\psi\psi} = \frac{1}{2\pi}\frac{m_\psi^2}{f_\psi^2}m_\phi\sqrt{1-\frac{4m_\psi^2}{m_\phi^2}} + \theta_{h\phi}^2\Gamma_h$$

Non-QCD (ψ, ϕ)

σ → Double scanner (DS)

- $m_\sigma > 2m_\psi$: Decays before BBN
- $m_\sigma < 2m_\psi$: few keV (warm) DM → over abundance

It has to be diluted or decoupled

Quick comparison

Landscape of Cosmological Relaxation scenarios	features	
Grandparent Relaxation (GKR) Hubble friction	• Scanning in unbroken EW phase • Barrier backreacted by v • Super-Planckian • Too large e-folding • Low-scale inflation	• Inflation is essential
Granddaughter Relaxation with particle production of spin-1 (HMT)	• Scanning in broken EW phase • Barrier independent of v • Sub-Planckian • O(1) e-folding or no e-folding • Low-scale inflation	• Needs Specific UV completion • Inflation is optional
Granddaughter Relaxation with fermion production (scenario in this talk)	• Scanning in unbroken EW phase • Barrier backreacted by v • keV scale warm dark matter • Sub-Planckian • O(1) e-folding • Low-scale inflation	• Inflation is essential • Specific inflation required • $f \ll \Lambda$ (EFT or strong coupling issue)

Backup slide

In detail

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = \mathcal{B} \sim -\frac{1}{f_\psi} H^4 \mu^2 \xi |\xi|$$ In the limit $\mu^2 \ll \xi$ and $1 \ll \xi$

$$\longrightarrow \quad \dot{\phi} \sim \frac{g^{1/2} \Lambda f_\psi^{3/2}}{m}$$

$$\mu \equiv \frac{m}{H}, \quad \xi \equiv \frac{1}{2H} \frac{\dot{\phi}}{f_\psi}$$

List of consistency conditions (independent of $\boldsymbol{\Lambda_c}$)

Consistency of slow rolling $V_\phi(\phi) > 3H\dot{\phi}$
Validity of EFT $\dot{\phi} > \Lambda^2$
Small dark fermion E density $\rho_\psi < H^2 M_p^2$
Small kinetic E $\dot{\phi}^2 < H^2 M_p^2$
Sub-Planckian $M_p > \Delta\phi \geq \Lambda^2/g$
Classical rolling beats quantum spreading $\dot{\phi}\Delta t > H$
Barrier forms within Hubble scale $H < \Lambda_c$
Relaxion energy being subdominat $\Lambda^4 < H^2 M_p^2$
Precision of mass scanning $\Delta m \sim g\Delta\phi \sim 2\pi f \ll m_h^2$
Scanning over 0 T Higgs mass