Naturalness
standard searches and the relaxing way

Scalars 2017

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Christophe Grojean

DESY (Hamburg)

Humboldt University (Berlin)

(christophe.grojean@desy.de)

What is physics beyond the Standard Model?

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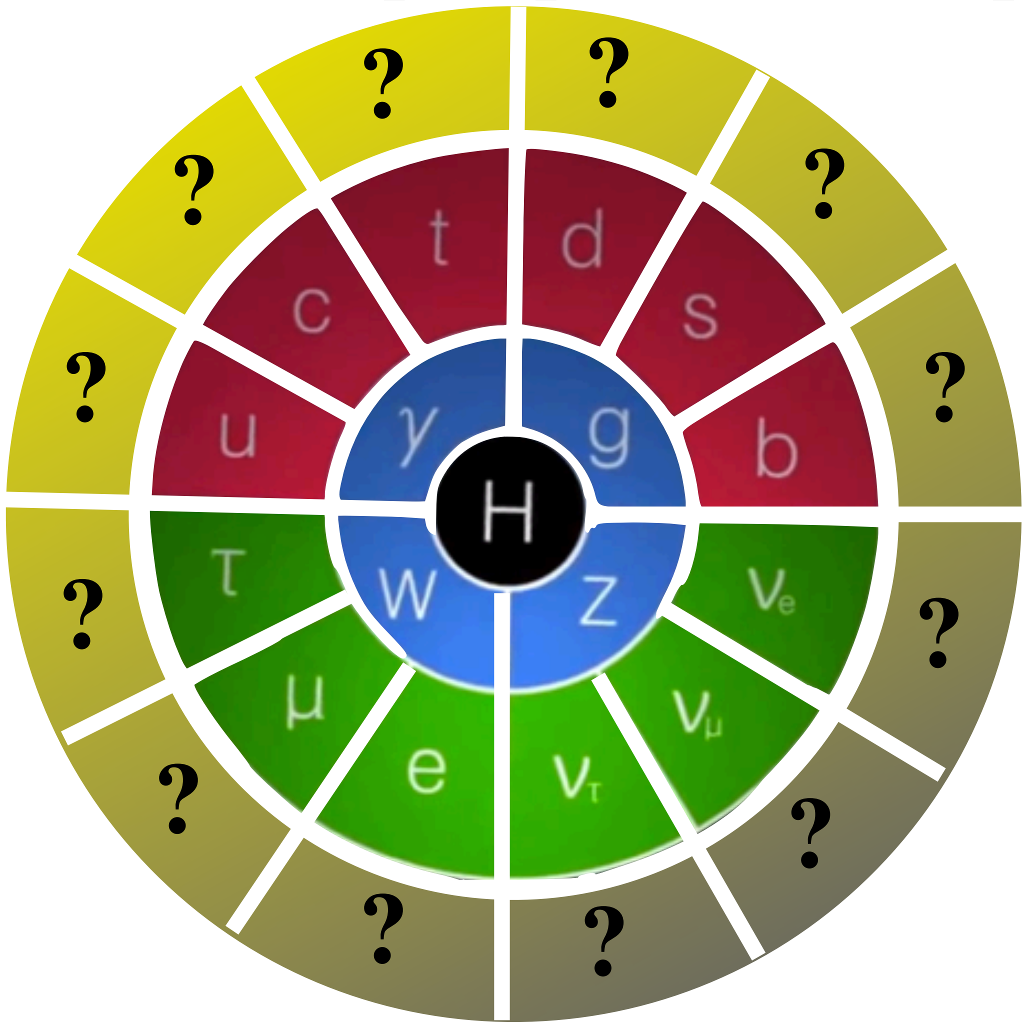

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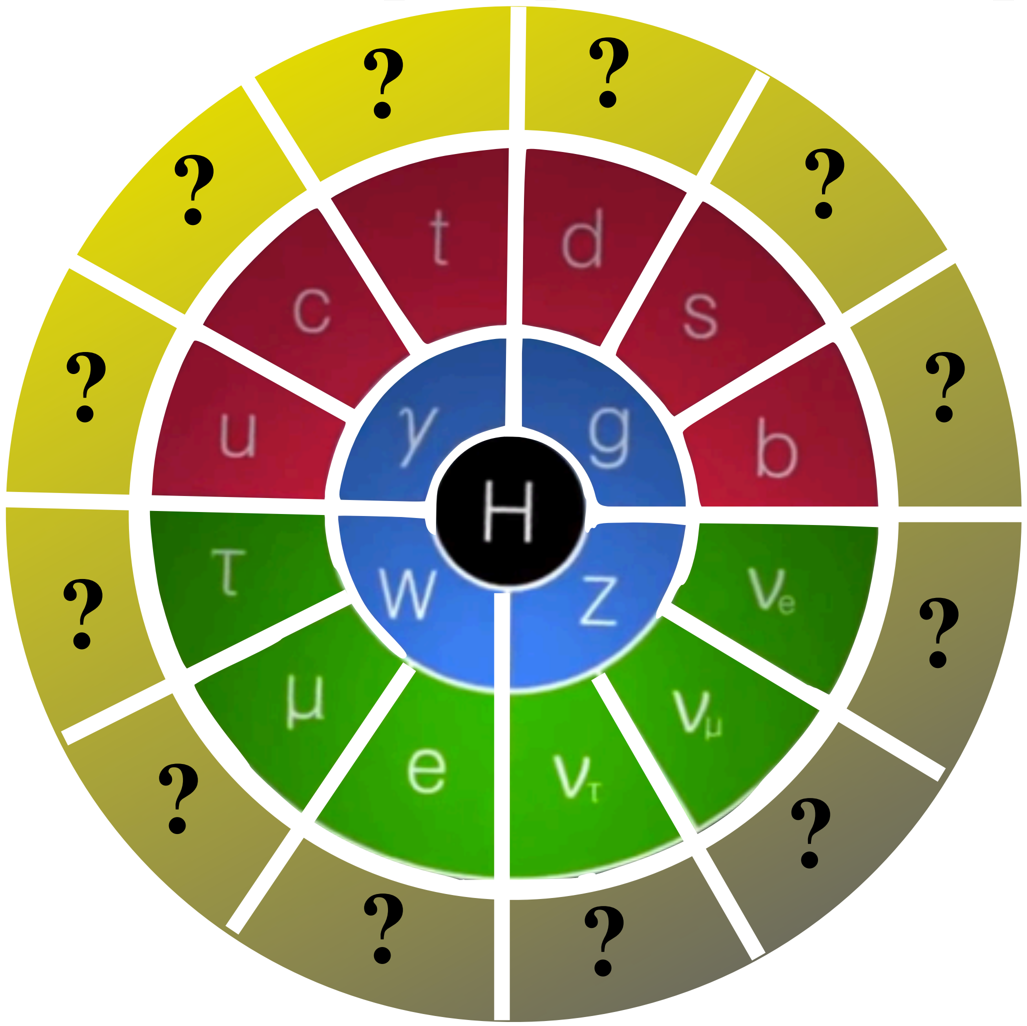


I don't know. Nobody knows [If it were known, it would be part of the SM!]

Many evidences that BSM exist

We just don't know what it is

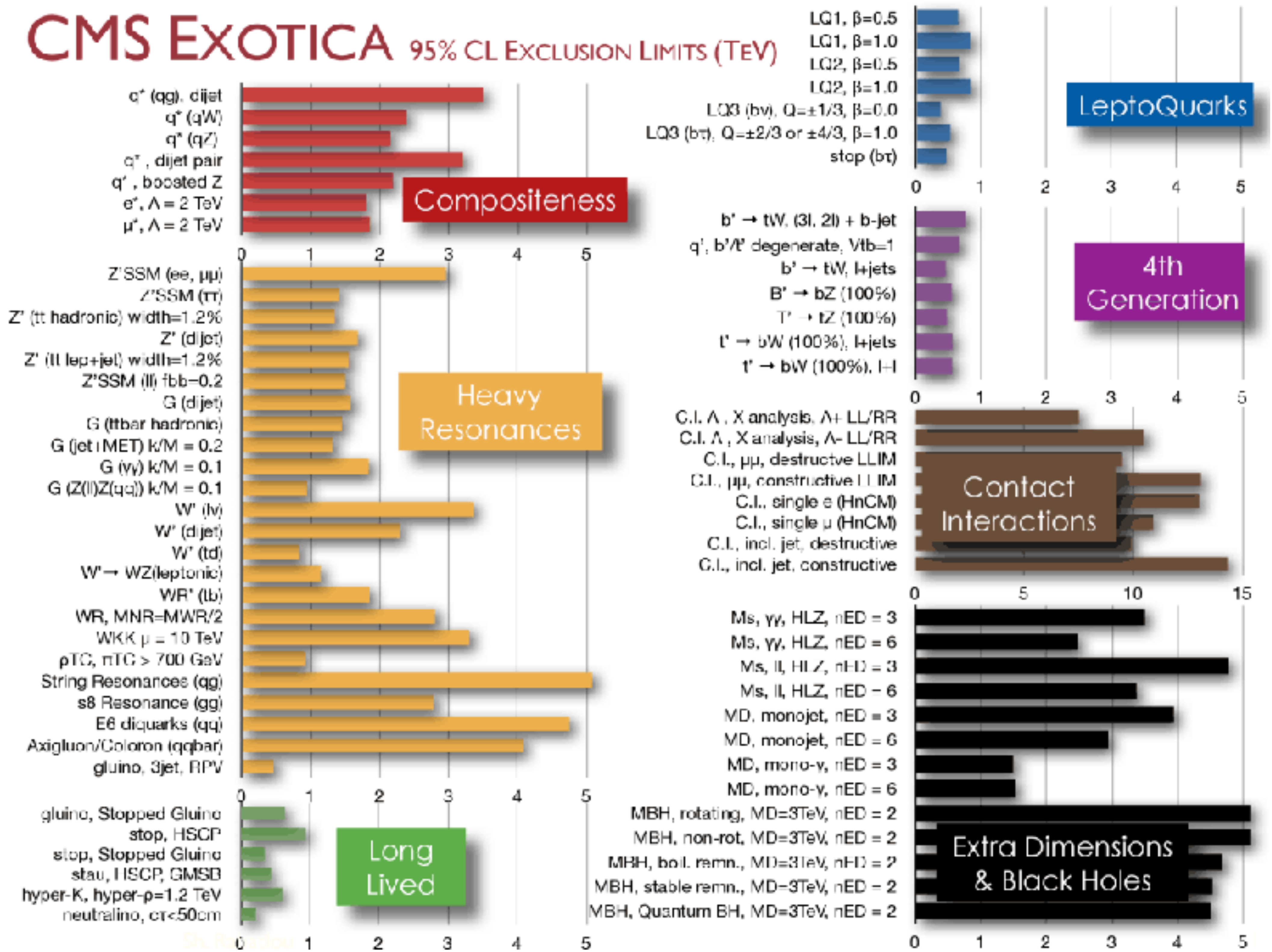
We have plenty of good ideas and there are rich opportunities

But no guarantee we are on the right track

We should stay open-minded and also learn from our failures

" Looking and not finding is different than not looking"

Current status of BSM searches



Current status of BSM searches

lost in translation: Babel tower!

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the ultimate goal

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lost in translation: Babel tower!

the ultimate goal

theorists and experimentalists also need
to start speaking a common language

What is the scale of New Physics?

High Scale Wishes

small FCNC: $\dfrac{gF_{\mu\nu}\bar{\psi}H\sigma^{\mu\nu}\psi}{M_{\rm NP}^2}$

tiny neutrino masses: $\dfrac{(LH)^2}{M_{\rm NP}}$

slow proton decay: $\dfrac{UUDE}{M_{\rm NP}^2}$

Low Scale Wishes

small EDMs: $\mathrm{arg det Y} \leq 10^{-10}$

↺ axion?

tiny vacuum energy: $\Lambda \approx M_{\rm NP}^4 \gg \left(10^{-3}\mathrm{eV}\right)^4$

↺ ?

light Higgs boson: $m_H^2 \approx M_{\rm NP}^2 \gg (125\mathrm{GeV})^2$

↺ light susy?

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Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- **compressed spectra**
- **displaced vertices**
- **no MET, soft decay products, long decay chains**
- **uncoloured new physics**

$\not{R}$-susy

Neutral naturalness
(twin Higgs, folded susy)

Relaxion

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Two approaches to make progress:

⦿ Theoretically motivated: UV gives constraints on IR (string, GUT, naturalness…)

⦿ Data driven: infer UV completions from IR data

Best objects at our disposal: Higgs, top, heavy mesons???
In this talk, I'll focus on the Higgs and I'll discuss both approaches.

▹ **uncoloured new physics**

Relaxion ◃

HEP with a Higgs boson

HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP
but it hasn't taught us much about **BSM** yet

typical Higgs coupling deformation: $$\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_*^2\, v^2}{\Lambda_{\rm BSM}^2}$$

current (and future) LHC sensitivity
O(10-20)% ⇔ $\Lambda_{\rm BSM}$ > 500(g_*/g_{SM}) GeV

not doing better than direct searches unless in the case of strongly coupled new physics
(notable exceptions: New Physics breaks some structural features of the SM
e.g. flavor number violation as in h→$\mu\tau$)

Higgs precision program is very much wanted
to probe BSM physics

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
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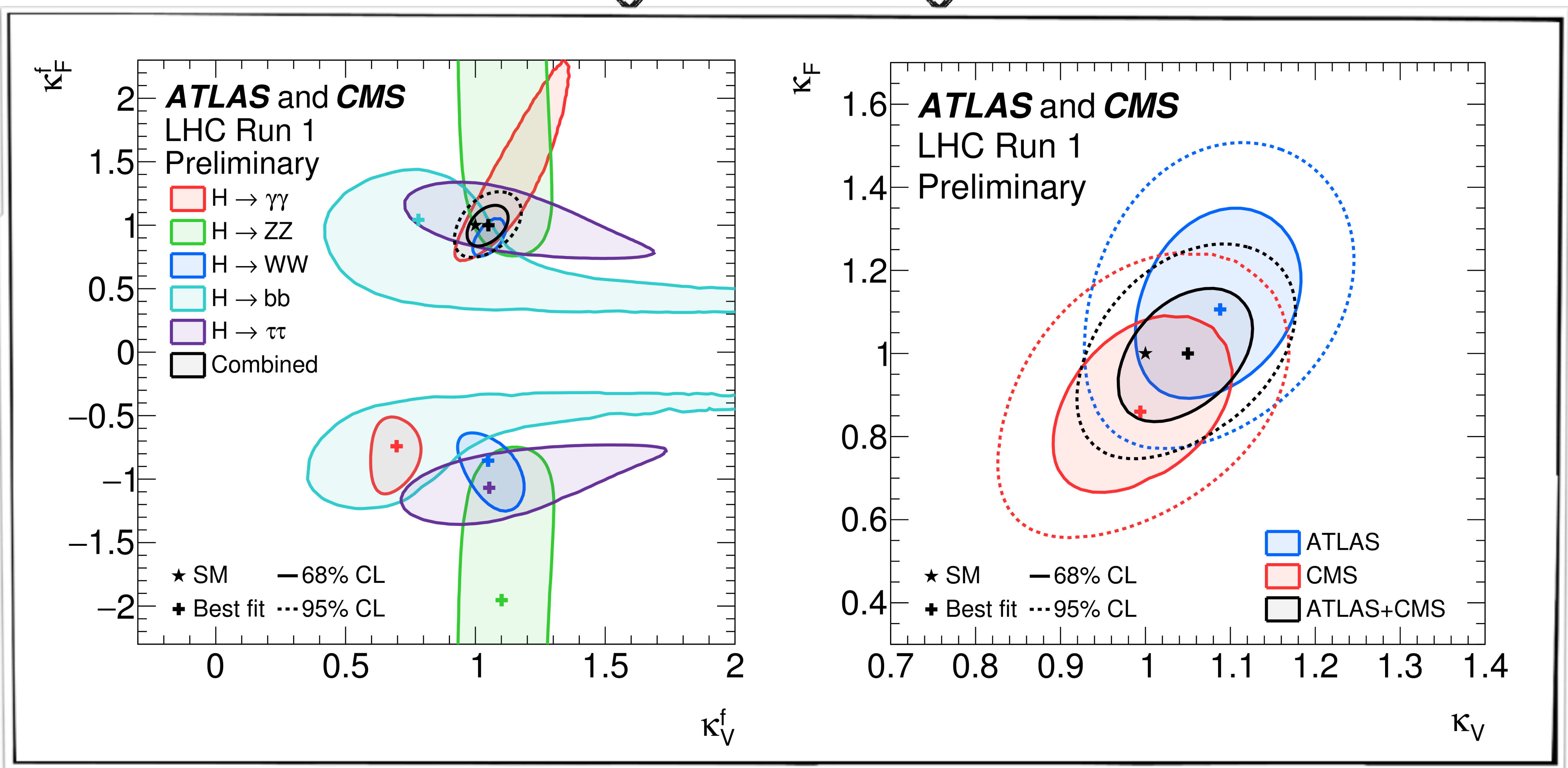

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⇩ ⇩

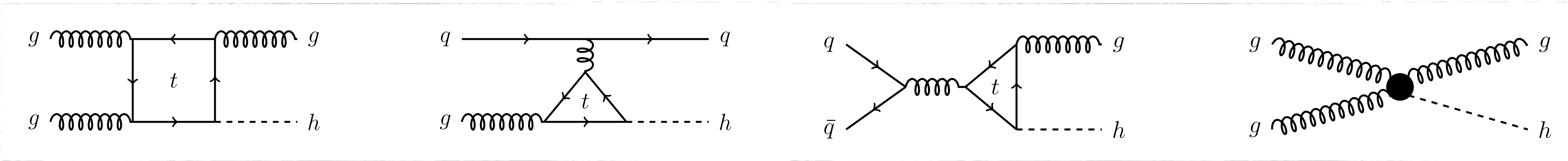
access to Higgs couplings @ m_H

Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

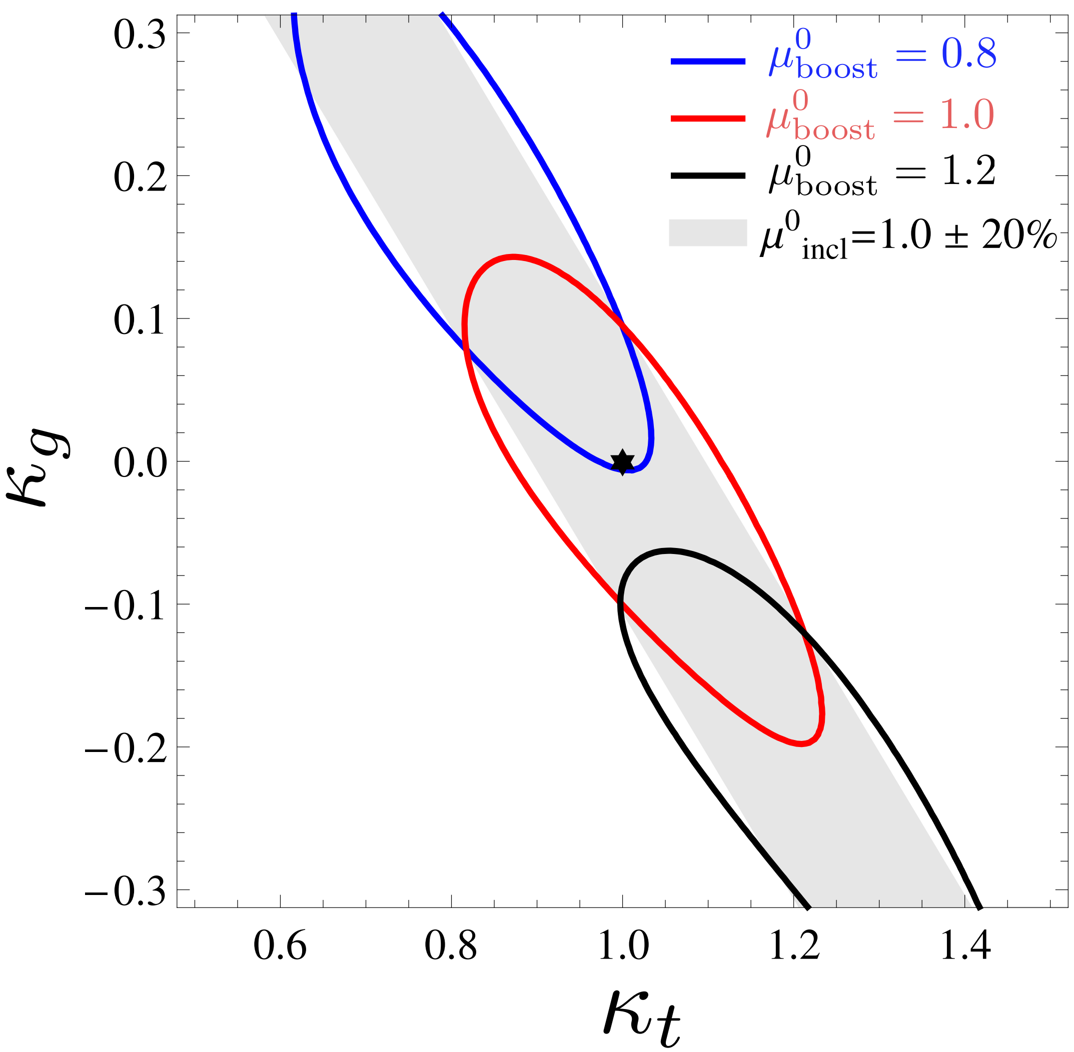
Examples of interesting channels to explore further:

1. off-shell $gg \to h^* \to ZZ \to 4l$
2. boosted Higgs: Higgs+ high-p_T jet
3. double Higgs production

Boosted Higgs+jet



Grojean, Salvioni, Schlaffer, Weiler '13
see also Azatov, Paul '13



high p_T tail discriminates
short and long distance physics contribution to gg → h

$$\sqrt{s} = 14 \text{ TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650 \text{ GeV}$$

(partonic analysis in the boosted "ditau-jets" channel)

see Schlaffer et al '14 for a more complete analysis including WW channel

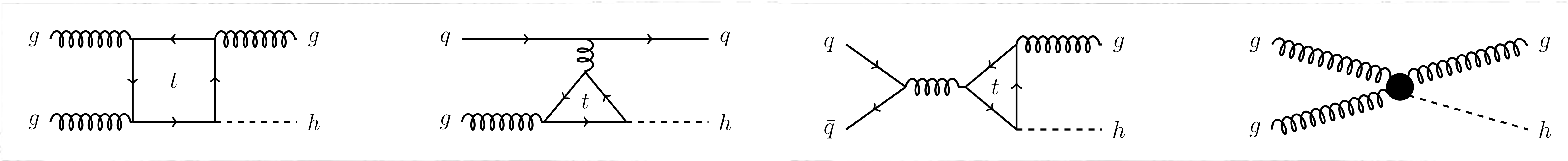
10-20% precision on κ_t

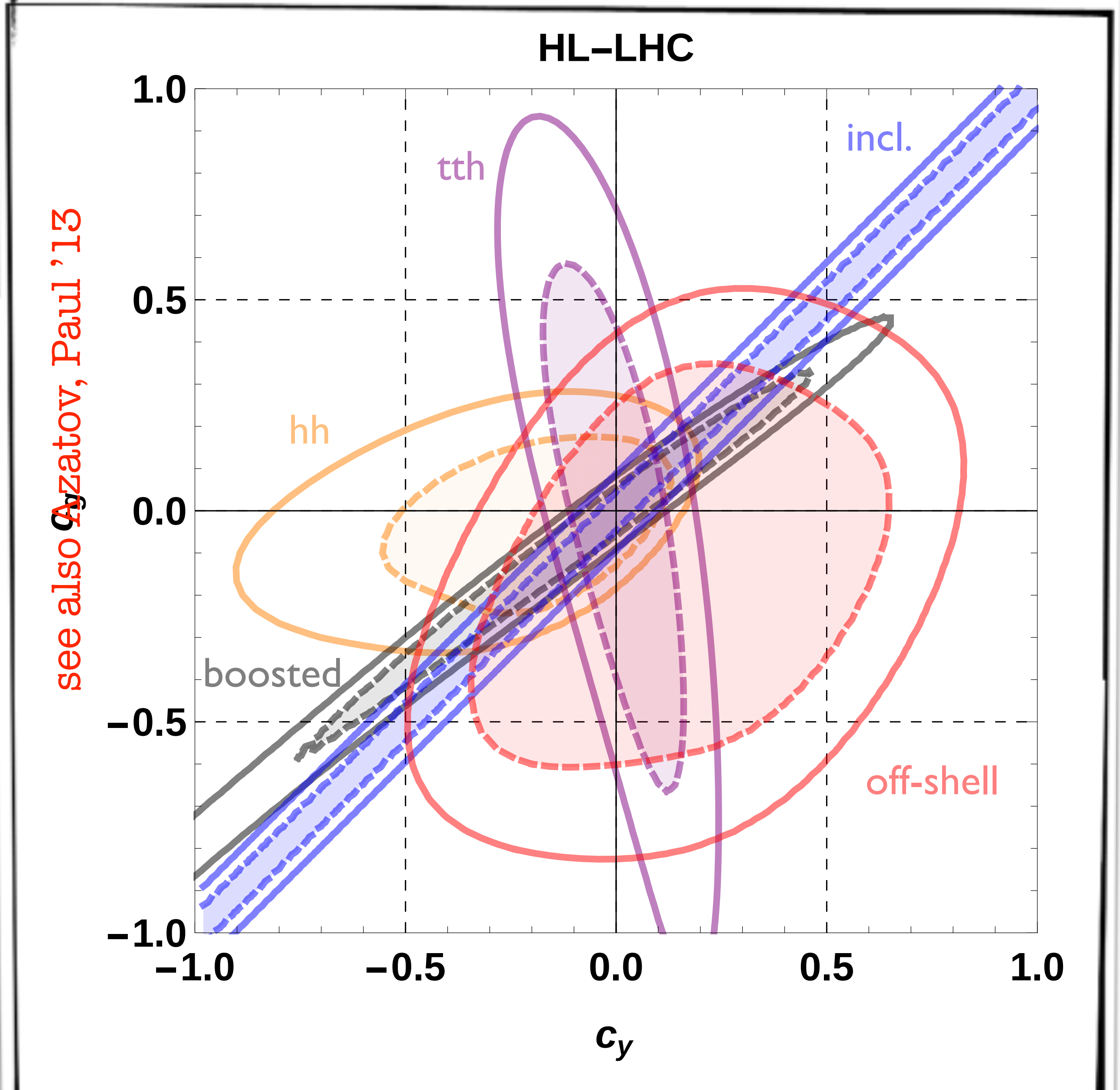
⇓ ⇓

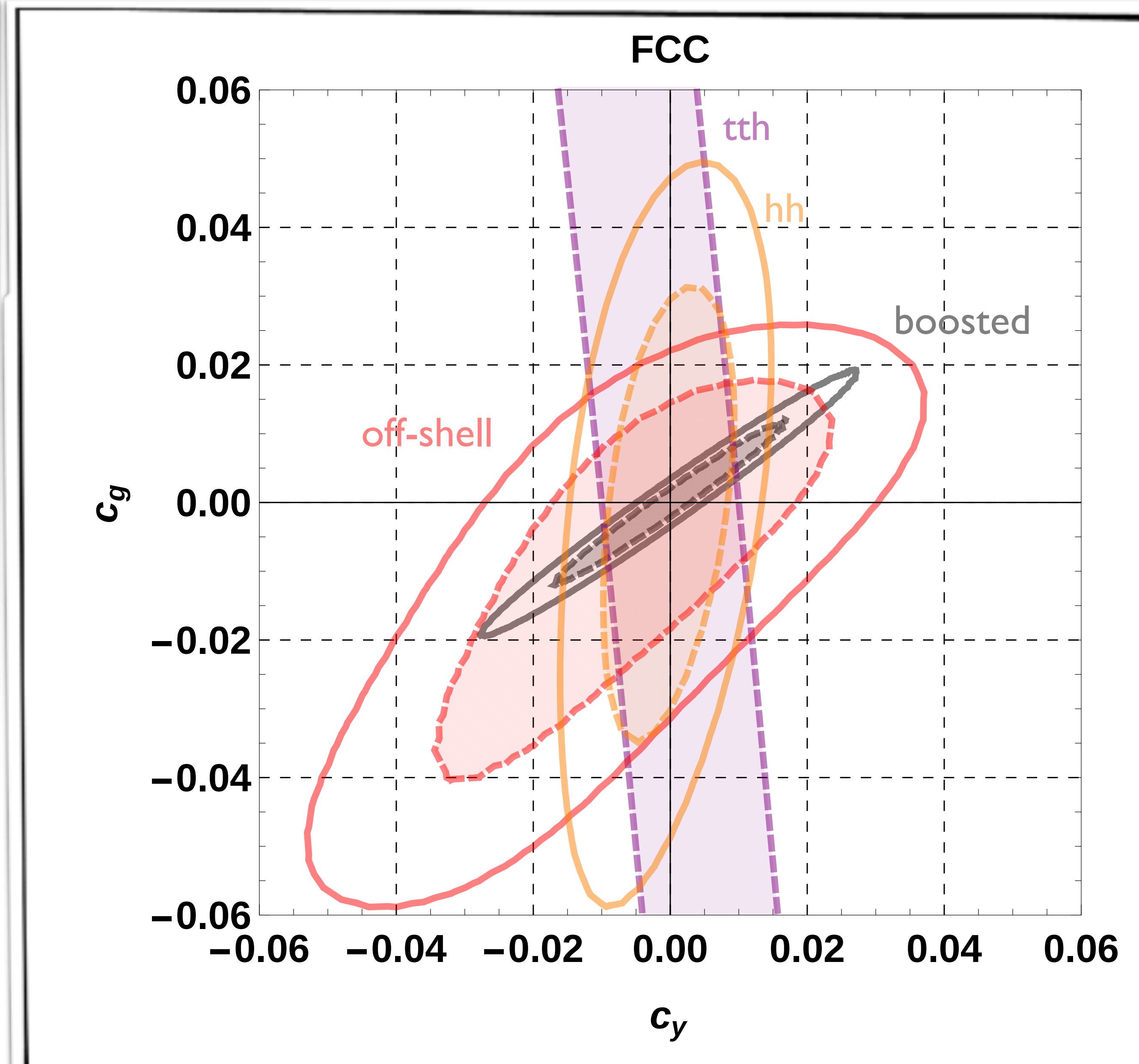
competitive/complementary to htt channel
for the measure the top-Higgs coupling

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted Higgs+jet







Azatov, Grojean, Paul, Salvioni '16

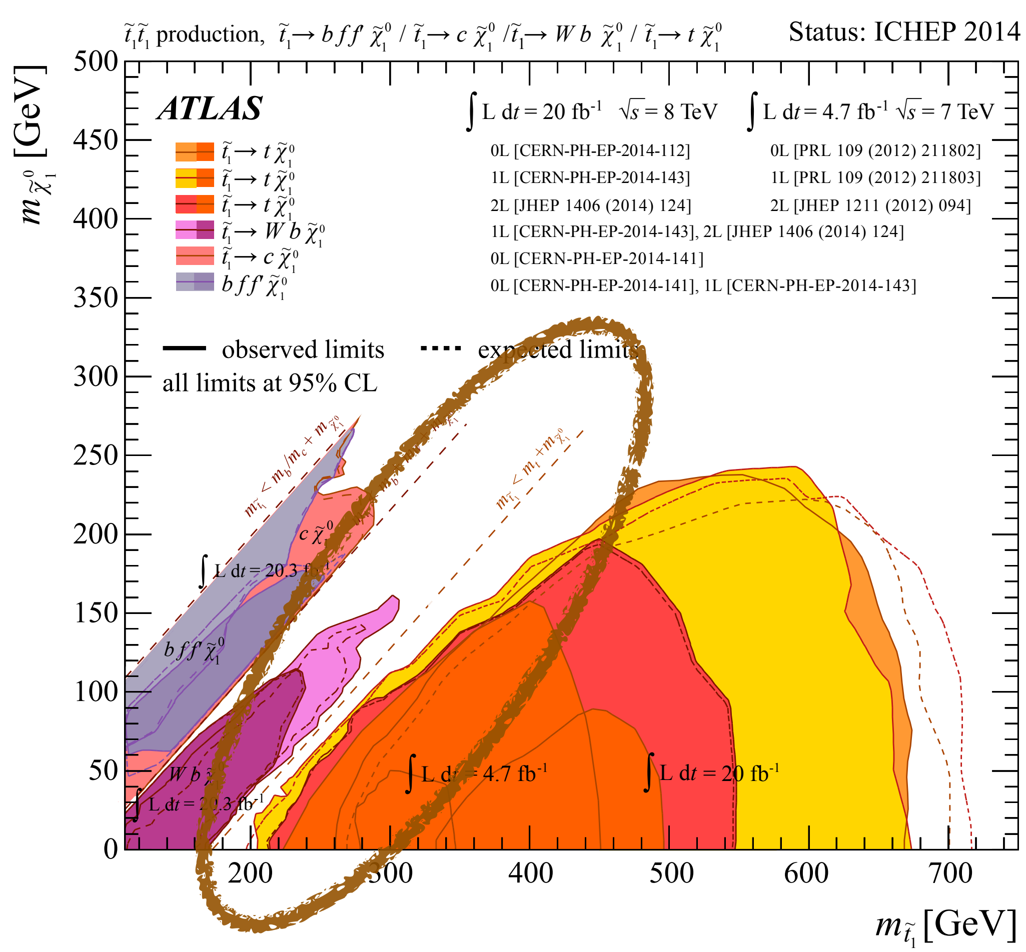
Light stop searches from Higgs+jet

natural susy calls for light stop(s) that can affect the Higgs physics

$$\frac{\Gamma(h \leftrightarrow gg)}{\Gamma(h \leftrightarrow gg)_{\rm SM}} = (1+\Delta_t)^2\ , \qquad \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = (1-0.28\Delta_t)^2 \qquad \text{with} \quad \Delta_t \approx \frac{m_t^2}{4}\left(\frac{1}{m_{\tilde t_1}^2}+\frac{1}{m_{\tilde t_2}^2}-\frac{X_t^2}{m_S^2}\right)$$

... or not if $\Delta_t \approx 0 \Rightarrow$ light stop window in the MSSM

(stop right ~200-400GeV ~ neutralino w/ gluino < 1.5 TeV)



There are various arguments that favour this light stop region

- ✦flavor constraints (ε_K, $B \to X_s + \gamma$)
- ✦ RG evolution
- ✦ DM

Delgado et al '12

inclusive Higgs measurements cannot rule out light stop
and difficult direct search (trigger on stop+extra jet)

One prime example where large statistics opens up new search strategy

Light stop searches from Higgs+jet

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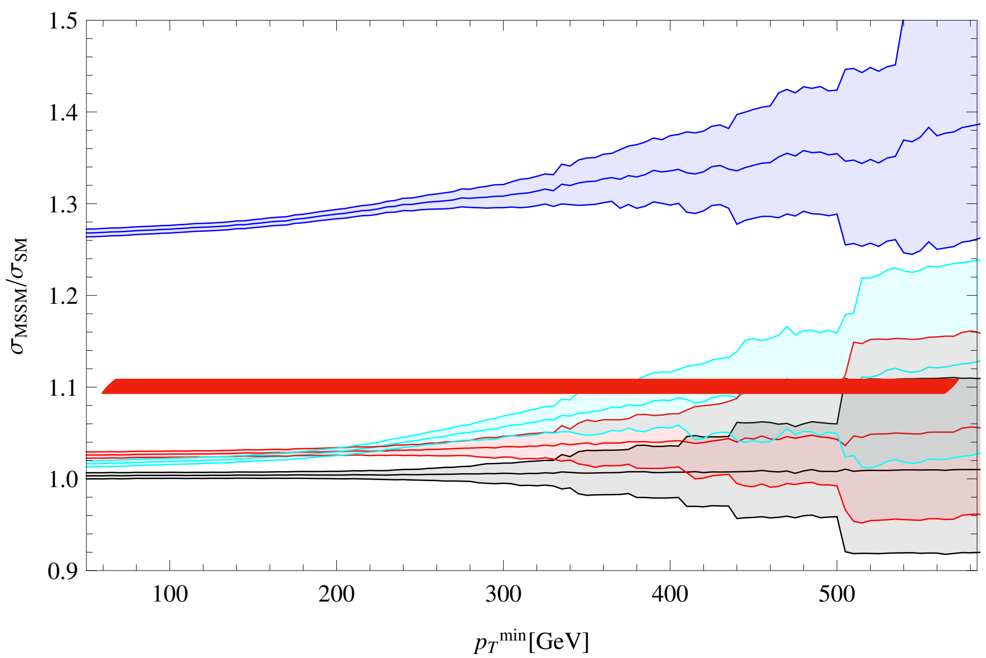


Grojean, Salvioni, Schlaffer, Weiler '13

There are various arguments that favour this light stop region

P1: mt1=395, mt2=2412, At=2420, Δt=0.002
P2: mt1=192, mt2=1224, At=1220, Δt=0.01
P3: mt1=259, mt2=1212, At=0, Δt=0.12
P4: mt1=226, mt2=484, At=532, Δt=0.015

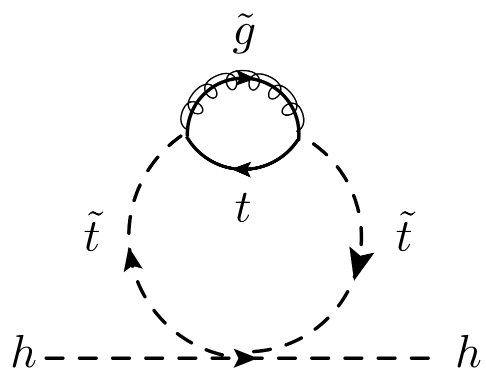
Light stop benchmark
that leaves no signal in inclusive rate
but predicts different tail in p_T
distribution

inclusive Higgs measurements cannot rule out light stop

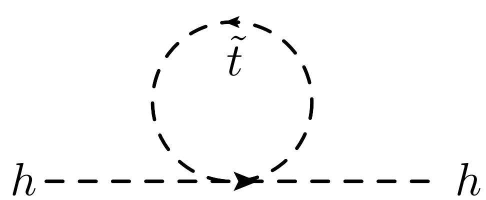
but O(10%) sensitivity on boosted h+j can
close up the light stop window
Low rate ⇔ large luminosity needed

One prime example where large statistics opens up new search strategy

Probing natural SUSY

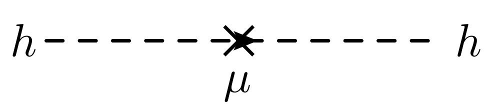


$$\delta m_H^2 \sim -\frac{y_t^2}{\pi^2}\frac{\alpha_s}{\pi} m_{gluino}^2 \left(\log\frac{\Lambda}{m_{gluino}}\right)^2$$



$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{stop}^2 \log\frac{\Lambda}{m_{stop}}$$

light stops, light gluinos!
well tested @ LHC
but most questionable predictions
(RG effects)



$$\delta m_H^2 \sim |\mu|^2$$

light Higgsinos!
very low sensitivity @ LHC
ILC needed to probe the other side

Probing natural SUSY

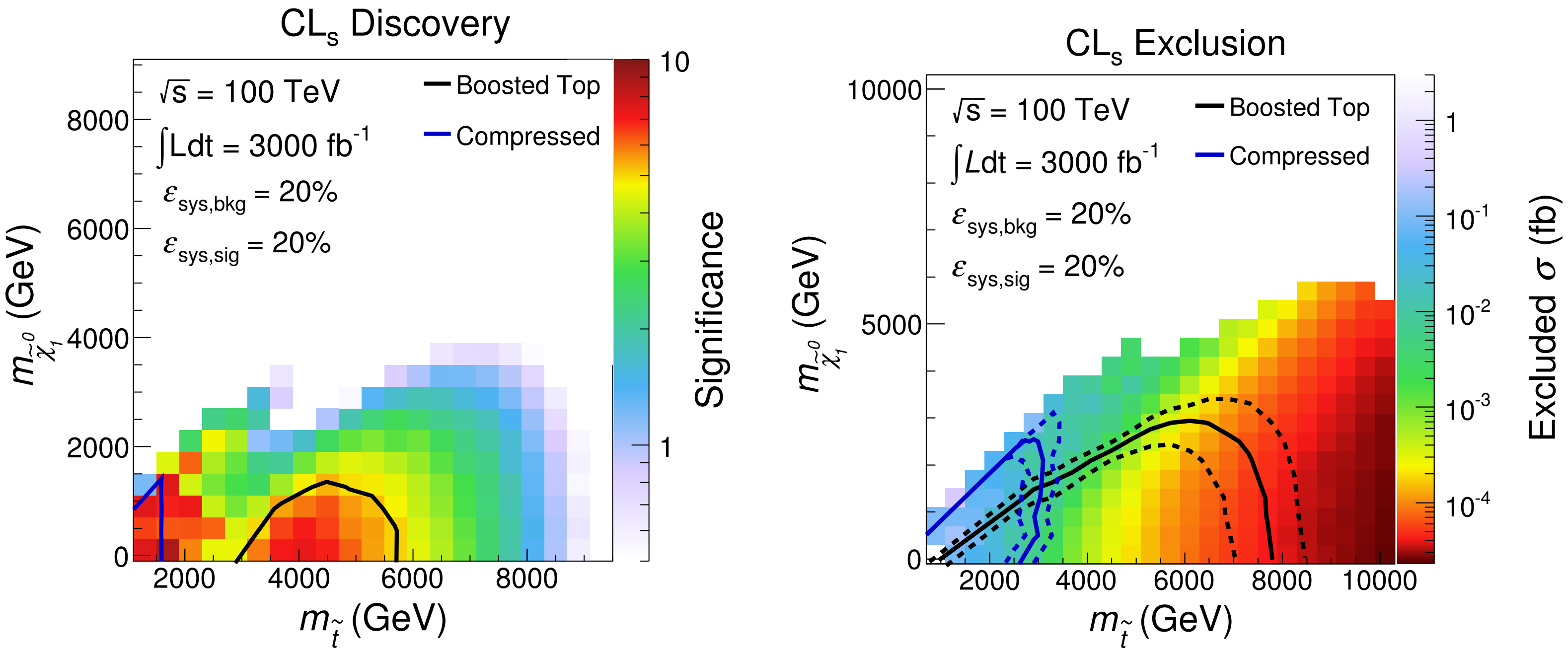


Fig. 12: Left: Discovery potential and Right: Projected exclusion limits for 3000 fb^{-1} of total integrated luminosity at $\sqrt{s} = 100$ TeV. The solid lines show the expected discovery or exclusion obtained from the boosted top (black) and compressed spectra (blue) searches. In the boosted regime we use the $\not\!\!E_T$ cut that gives the strongest exclusion for each point in the plane. The dotted lines in the left panel show the $\pm1\sigma$ uncertainty band around the expected exclusion.

Collider	Energy	Luminosity	Cross Section	Mass
LHC8	8 TeV	20.5 fb^{-1}	10 fb	650 GeV
LHC	14 TeV	300 fb^{-1}	3.5 fb	1.0 TeV
HL LHC	14 TeV	3 ab^{-1}	1.1 fb	1.2 TeV
HE LHC	33 TeV	3 ab^{-1}	91 ab	3.0 TeV
FCC-hh	100 TeV	1 ab^{-1}	200 ab	5.7 TeV

Probing natural SUSY

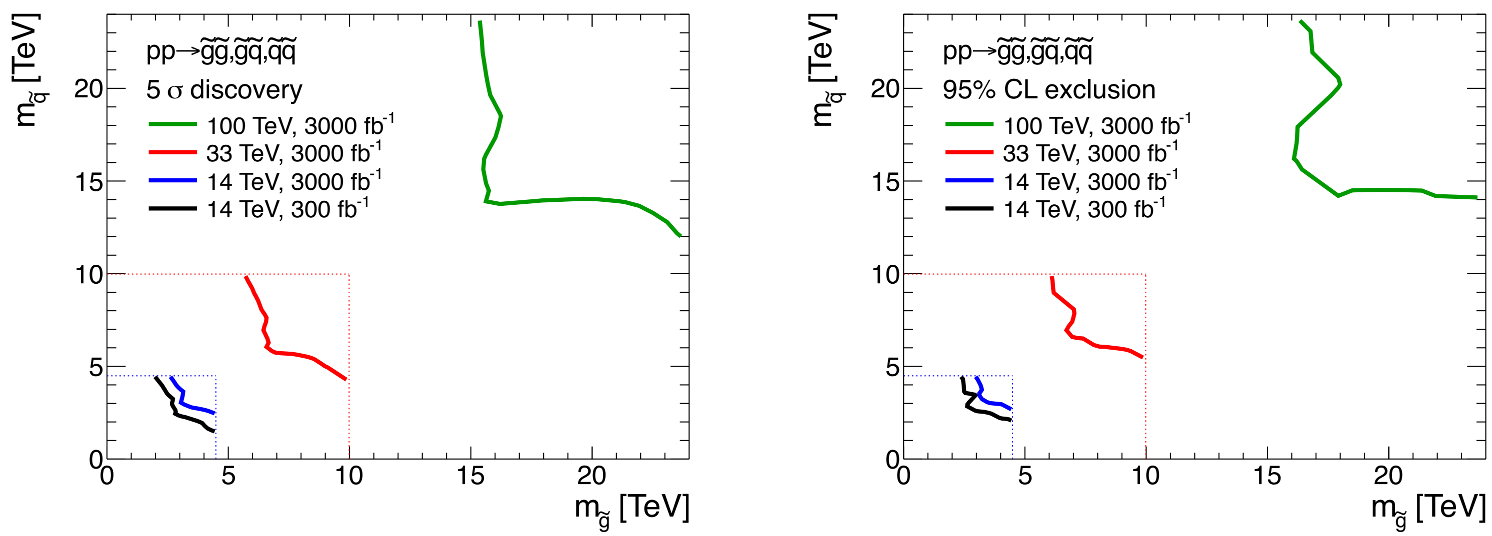
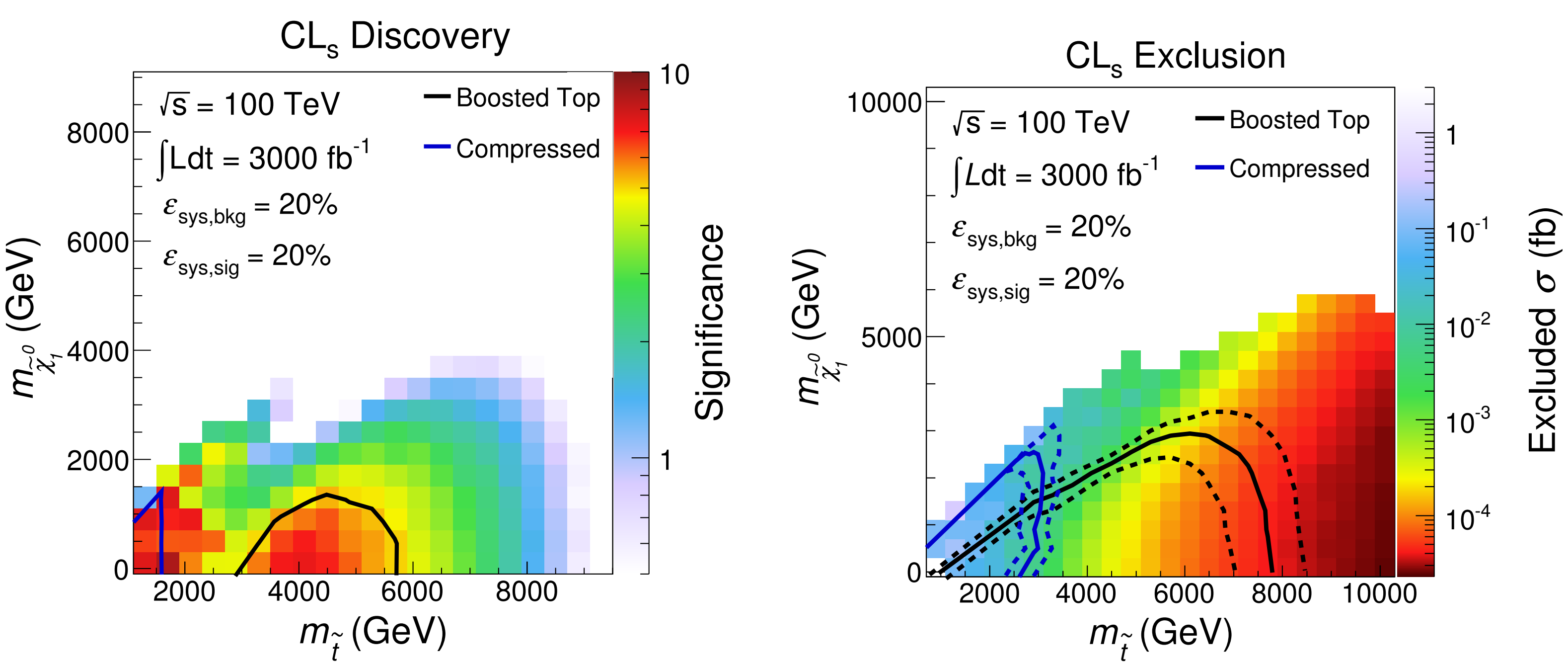


Fig. 16: Results for the gluino-squark-neutralino model. The neutralino mass is taken to be 1 GeV. The left [right] panel shows the $5\,\sigma$ discovery reach [95% CL exclusion] for the four collider scenarios studied here. A 20% systematic uncertainty is assumed and pile-up is not included.



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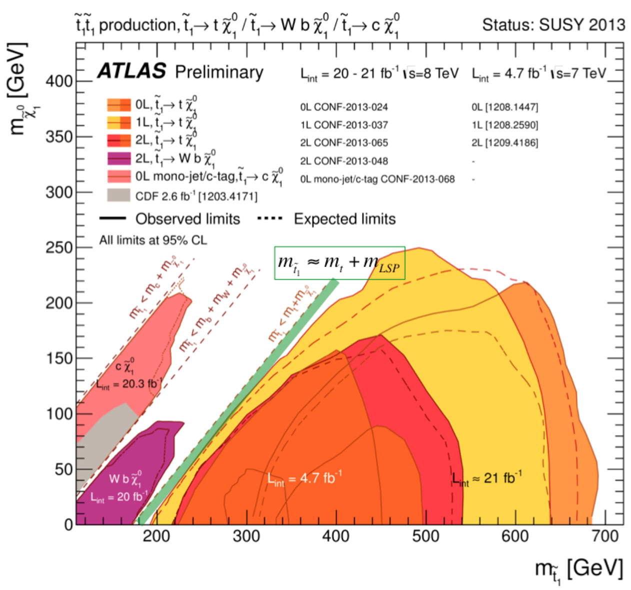
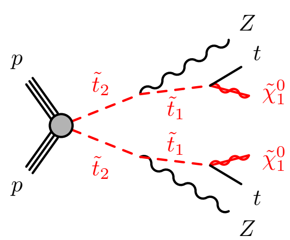
Natural SUSY: beyond standard searches

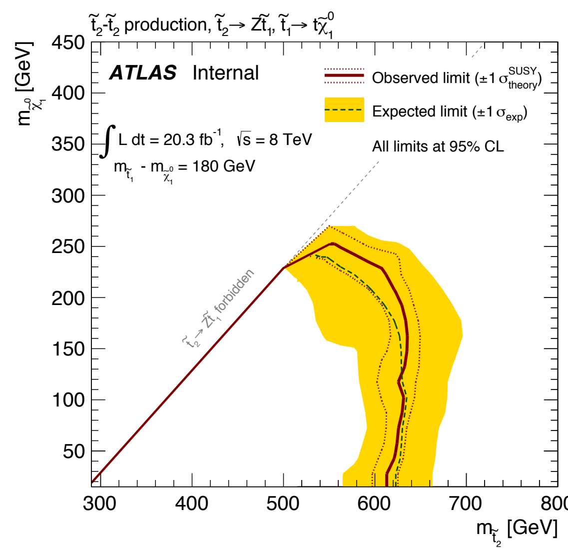
Searching for light stop from heavy stop decay

~ RUN 1 ~



- 2012 (20 fb^{-1}): stops searches based on $\tilde{t}_1\tilde{t}_1$ production, with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ or $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$
- No sensitivity for $\tilde{t}_1 \to t\tilde{\chi}_1^0$ with $m_{\tilde{t}_1} \gtrsim m_{\tilde{\chi}_1^0} + m_t$: very similar to SM $t\bar{t}$
- **[New at the LHC]** Production of the heavier stop mass eigenstate ($\tilde{t}_2$) relying on the $\tilde{t}_2 \to Z\tilde{t}_1$ decay to reduce $t\bar{t}$ → Signature: $Z(\ell^+\ell^-)+\ell+b+E_T^{\rm miss}$
- Eur. Phys. J. C **74** (2014) 2883 (20 fb^{-1})

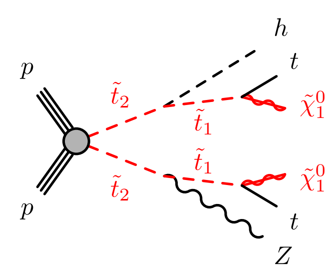


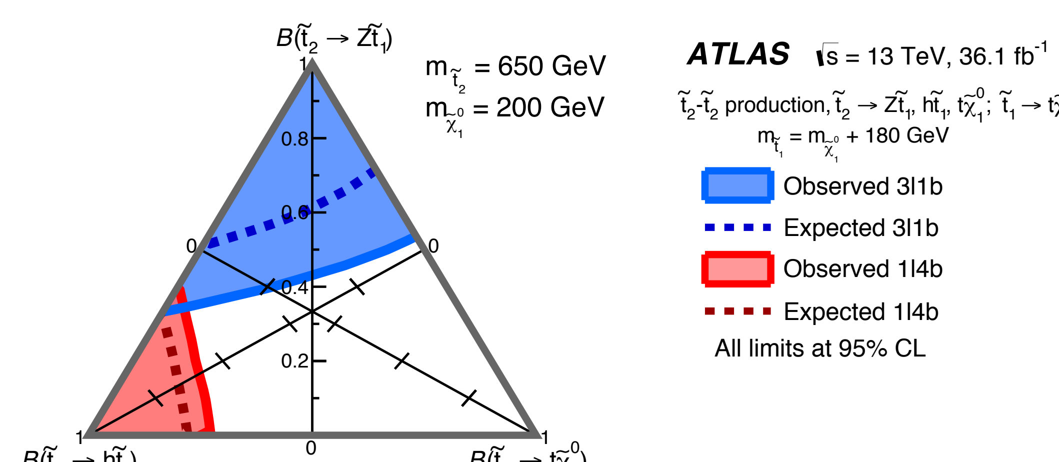


X. Poveda @ DESY'17

~ RUN 2 ~

- ATLAS-CONF-2016-038 (13 fb^{-1}): explore $\tilde{t}_2 \to Z\tilde{t}_1$ with $3\ell+b+E_T^{\rm miss}$
- JHEP **1708** (2017) 006 (36 fb^{-1}): analysis extended to $\tilde{t}_2 \to h\tilde{t}_1$ with $1\ell+4b+E_T^{\rm miss}$
- Interpretations for varying BRs in $\tilde{t}_2 \to h\tilde{t}_1/Z\tilde{t}_1$ and also for $\tilde{t}_1 \to t\chi_2^0$, $\chi_2^0 \to h/Z\tilde{\chi}_1^0$





Naturalness principle @ work

Following the arguments of Wilson, ‘t Hooft (and others):
only small numbers associated to the breaking of a symmetry survive quantum corrections

Beautiful examples of naturalness to understand the need of “new” physics

see for instance Giudice ’13 (and refs. therein) for an account

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- the need of the positron to screen the electron self-energy: $\Lambda < m_e/\alpha_{\rm em}$
- the rho meson to cutoff the EM contribution to the charged pion mass: $\Lambda^2 < \delta m_\pi^2/\alpha_{\rm em}$
- the kaon mass difference regulated by the charm quark: $$\Lambda^2 < \frac{\delta m_K}{m_K} \frac{6\pi^2}{G_F^2 f_K^2 \sin^2\theta_C}$$
- the light Higgs boson to screen the EW corrections to gauge bosons self-energies
- ...
- new physics at the weak scale to cancel the UV sensitivity of the Higgs mass?

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Apparent fine-tunings have always pointed to new degrees of freedom

The different paths to Higgs naturalness

- Single vacuum

the low Higgs mass is screened from large quantum corrections by

1. a symmetry (Susy, PQ)
2. a form factor (composite Higgs)
3. a low UV scale (xdim, RS, large N…)
4. a combination of the above

- Multiple vacua

many metastable vacua
with a vast range of values for m_H
Dynamical (or anthropic selection) of $m_H \ll \Lambda$

1. anthropic multiverse
2. NNaturalness with 10^{16} copies of SM
3. relaxion and cosmological scanning with non-trivial back reaction

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

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Graham, Kaplan, Rajendran ’15

- Higgs mass-squared promoted to a field
- The field evolves in time in the early universe and scans a vast range of Higgs mass
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-evolution of the dynamical system

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Self-organised criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

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hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

$$\Lambda^2 \left(-1 + f\left(\frac{g\phi}{\Lambda}\right)\right) |H|^2 + \Lambda^4 V\left(\frac{g\phi}{\Lambda}\right) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

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potential needed to force
ϕ to roll-down in time
(during inflation)

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Higgs mass depends on ϕ

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Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling
that will seed the potential barrier stopping the rolling when the Higgs develops its vev

$$\Lambda^3_{\rm QCD}\, h\, \cos\frac{\phi}{f}$$

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

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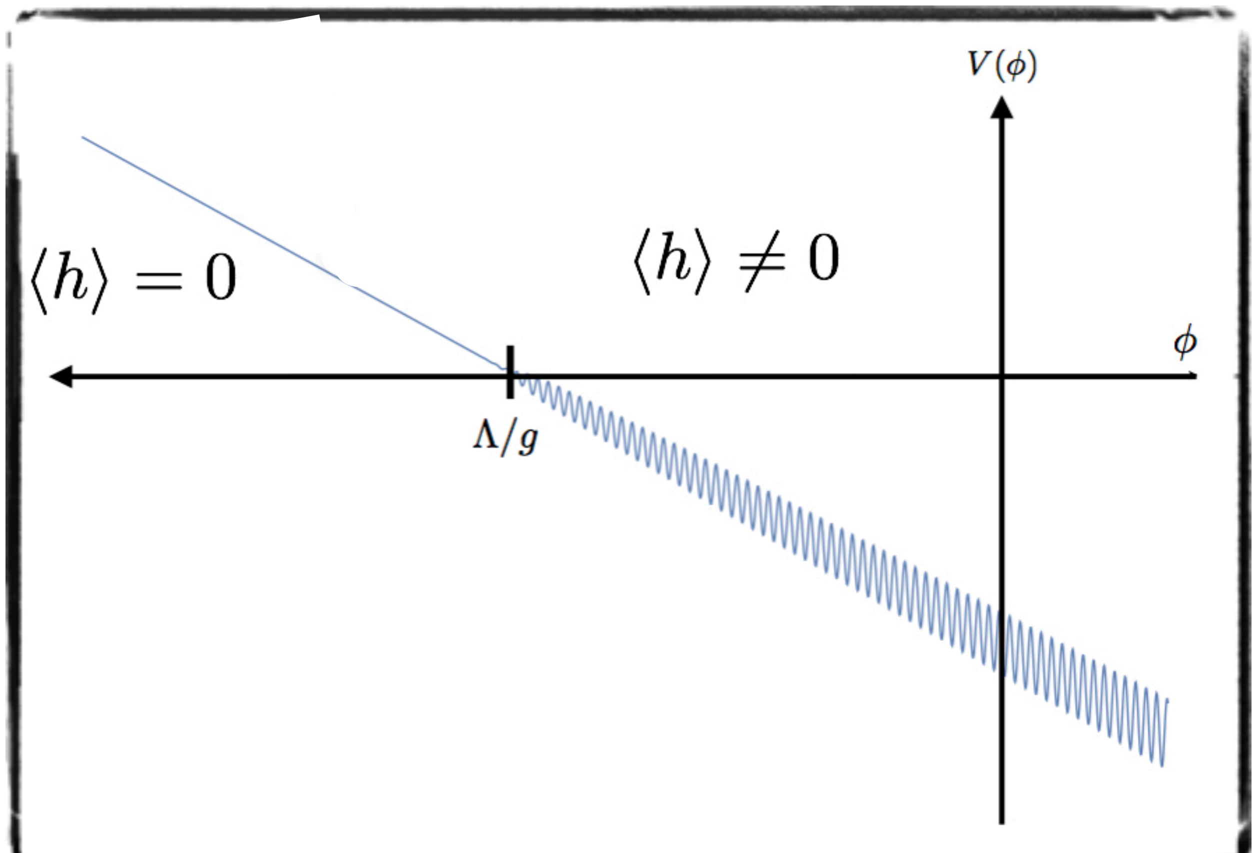
potential needed to force ϕ to roll-down in time (during inflation)

axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev



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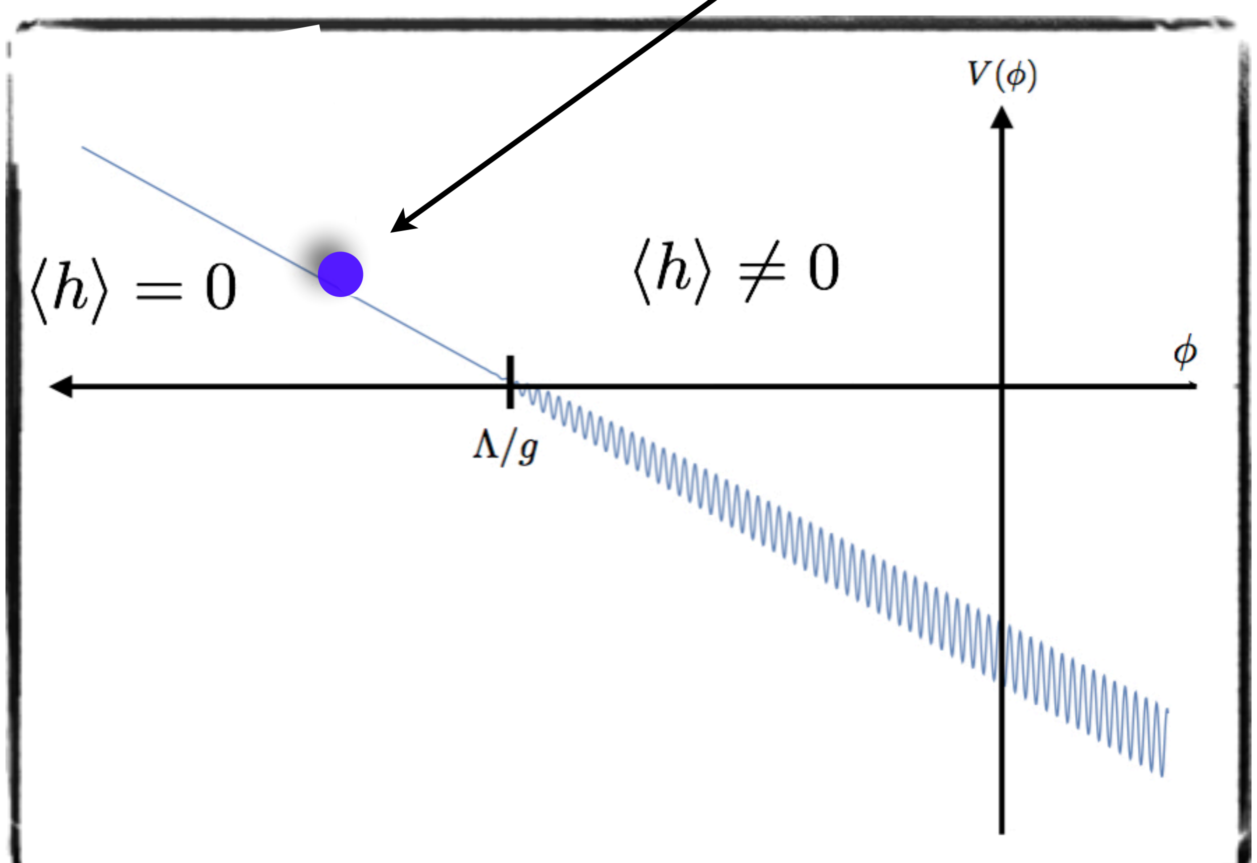

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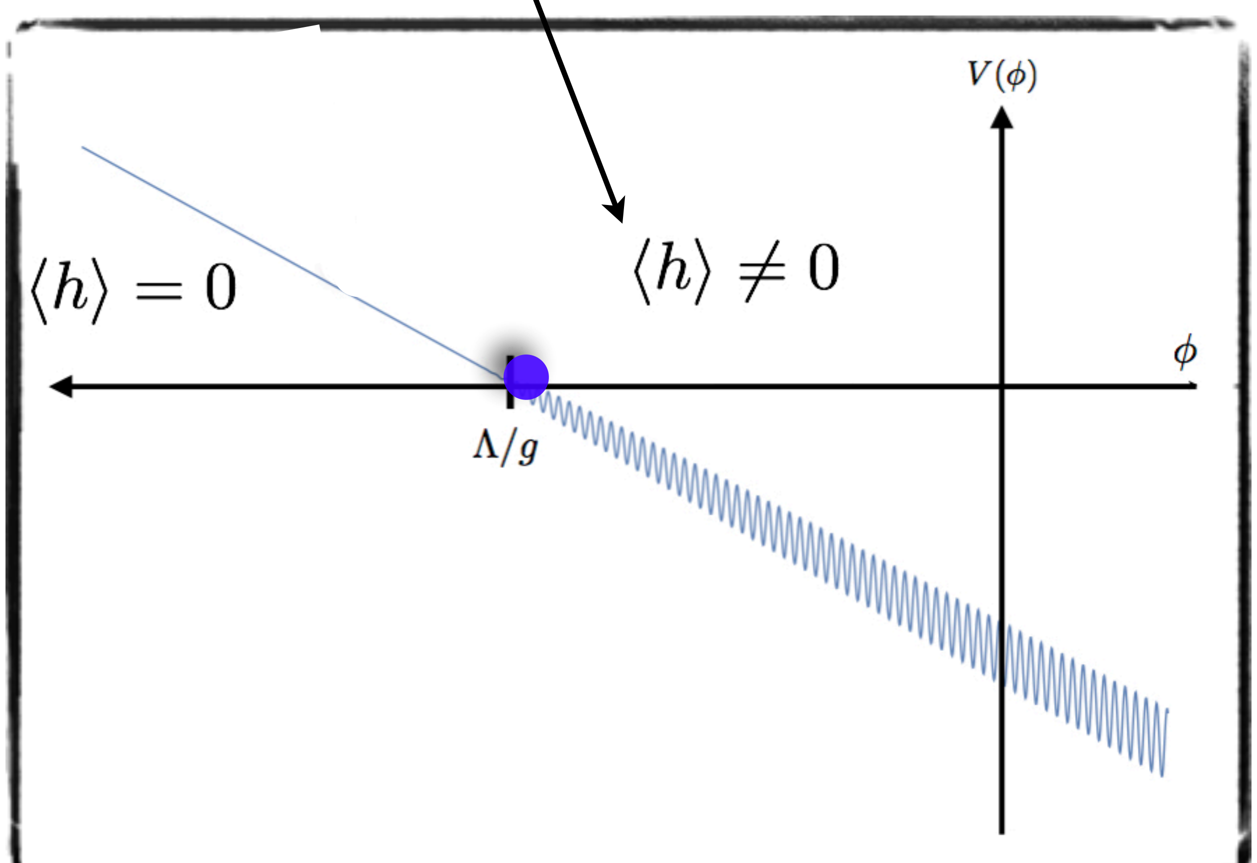

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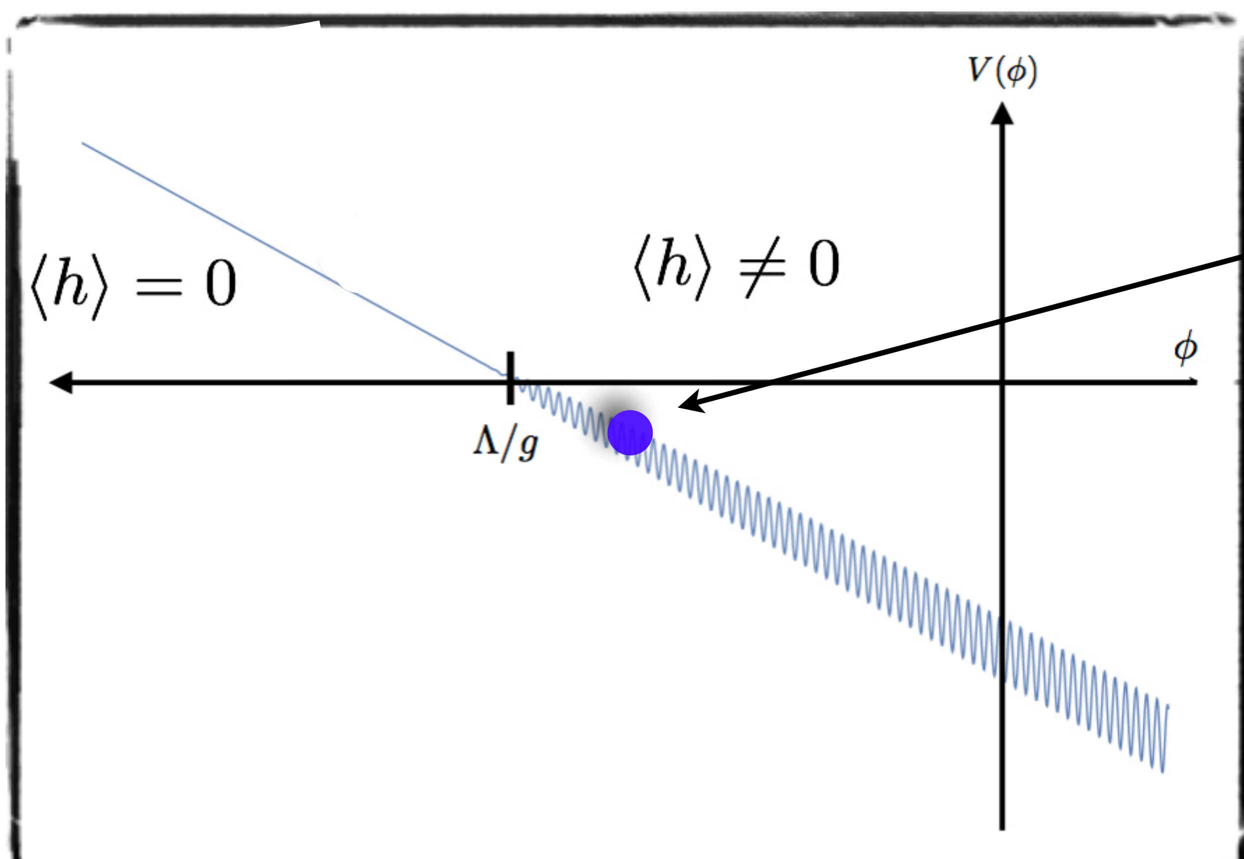

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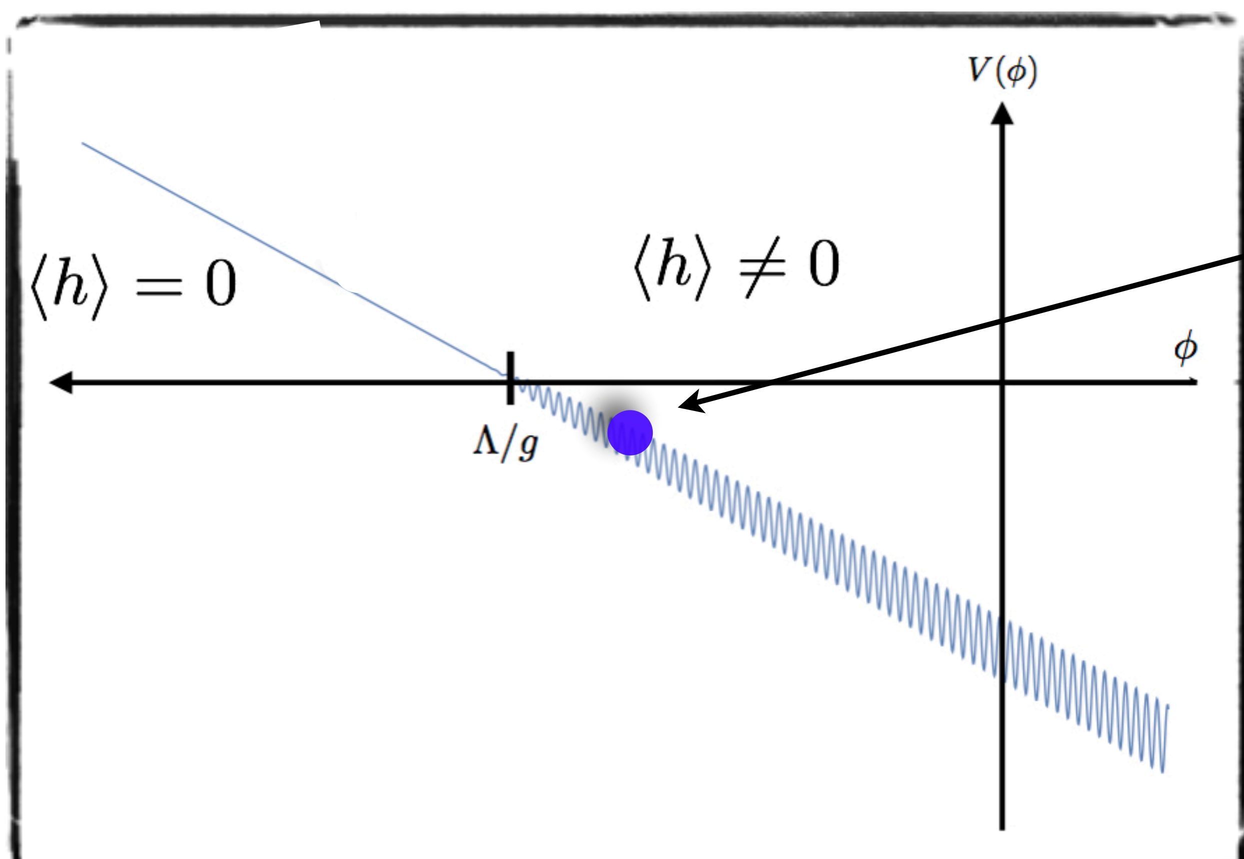

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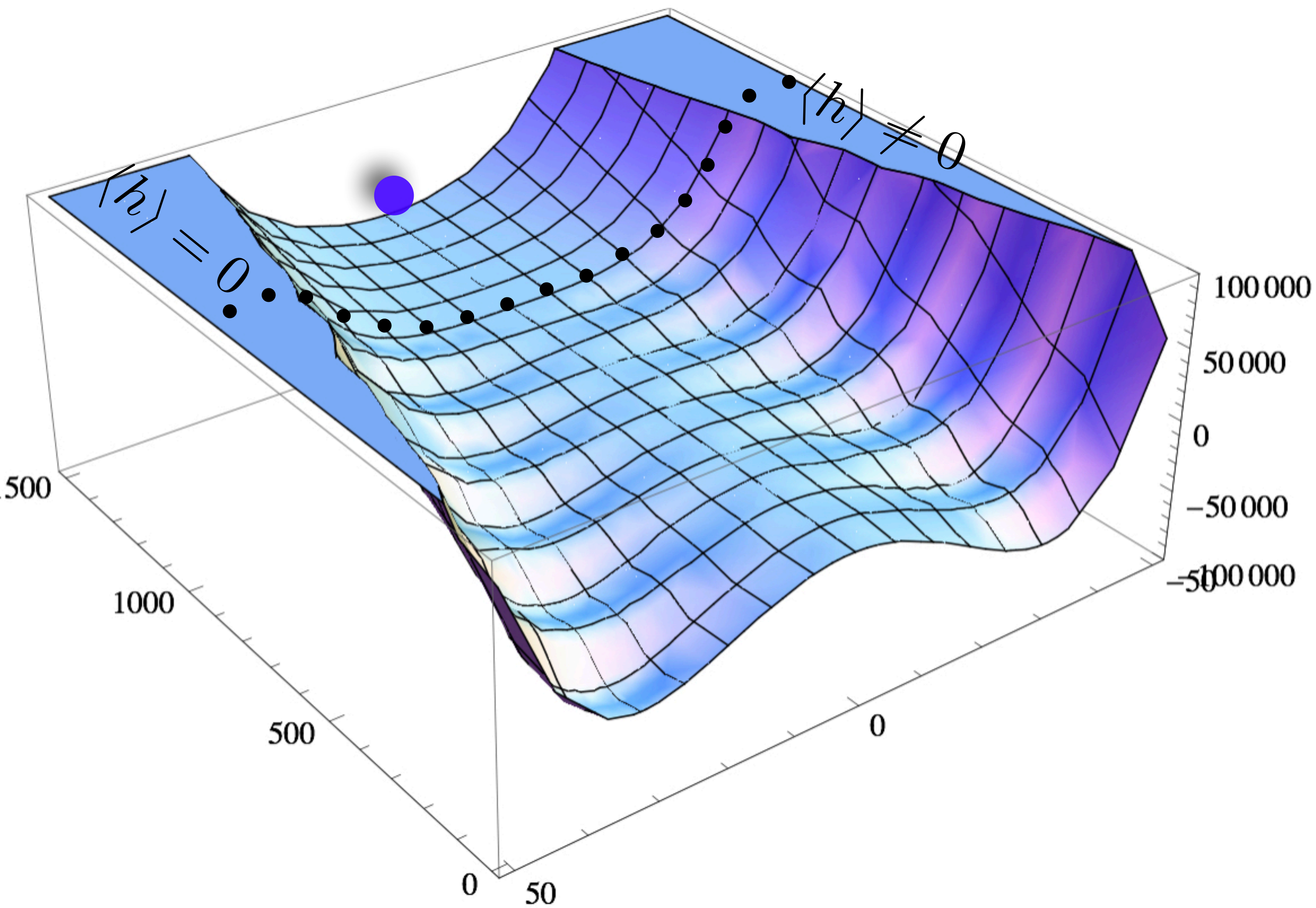

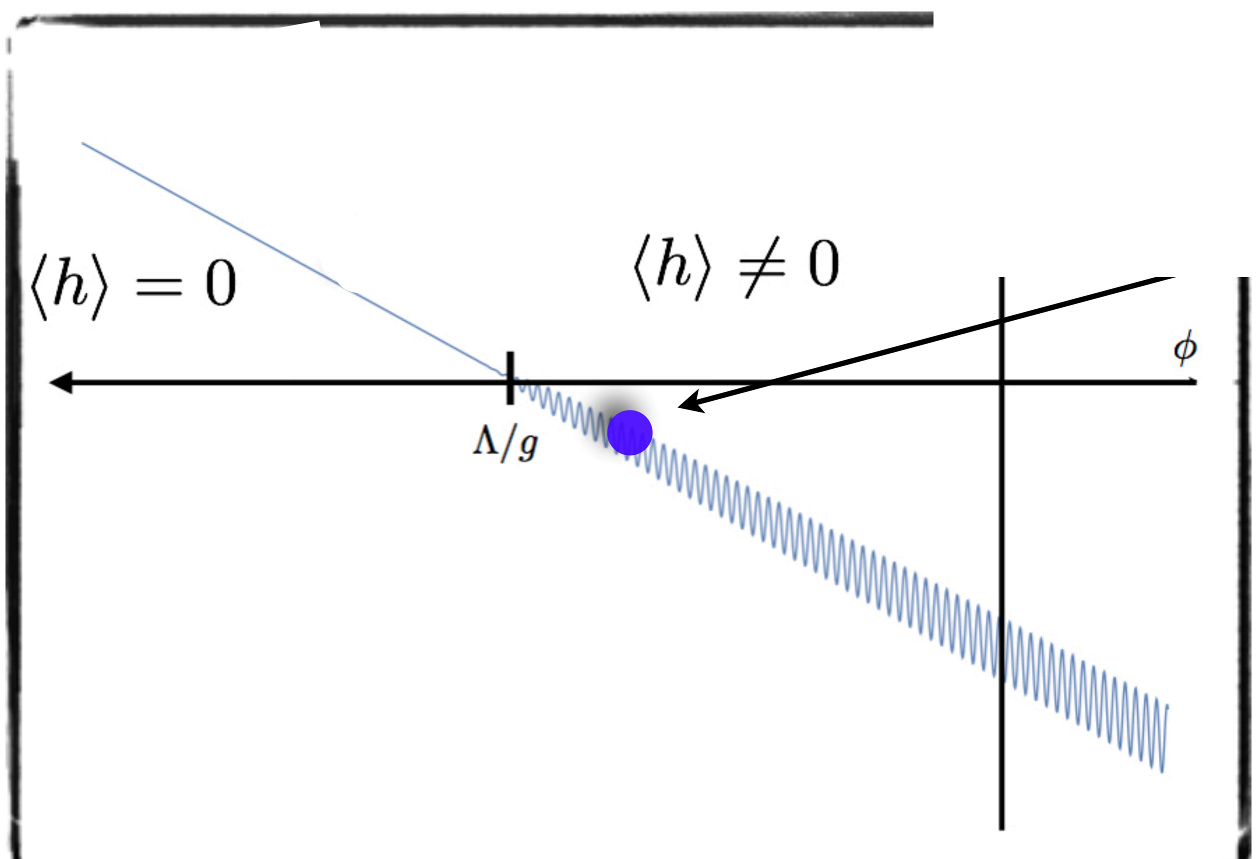

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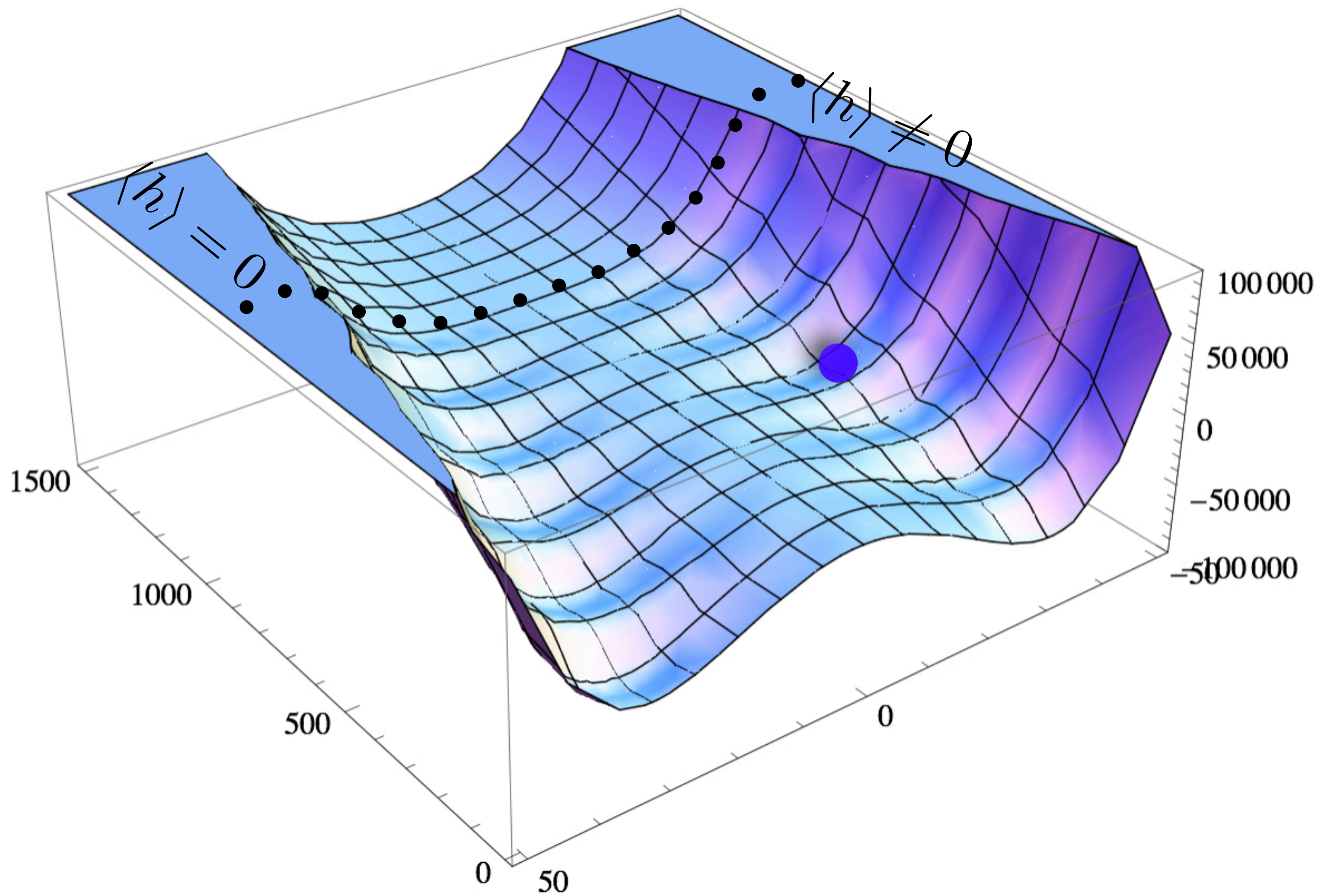

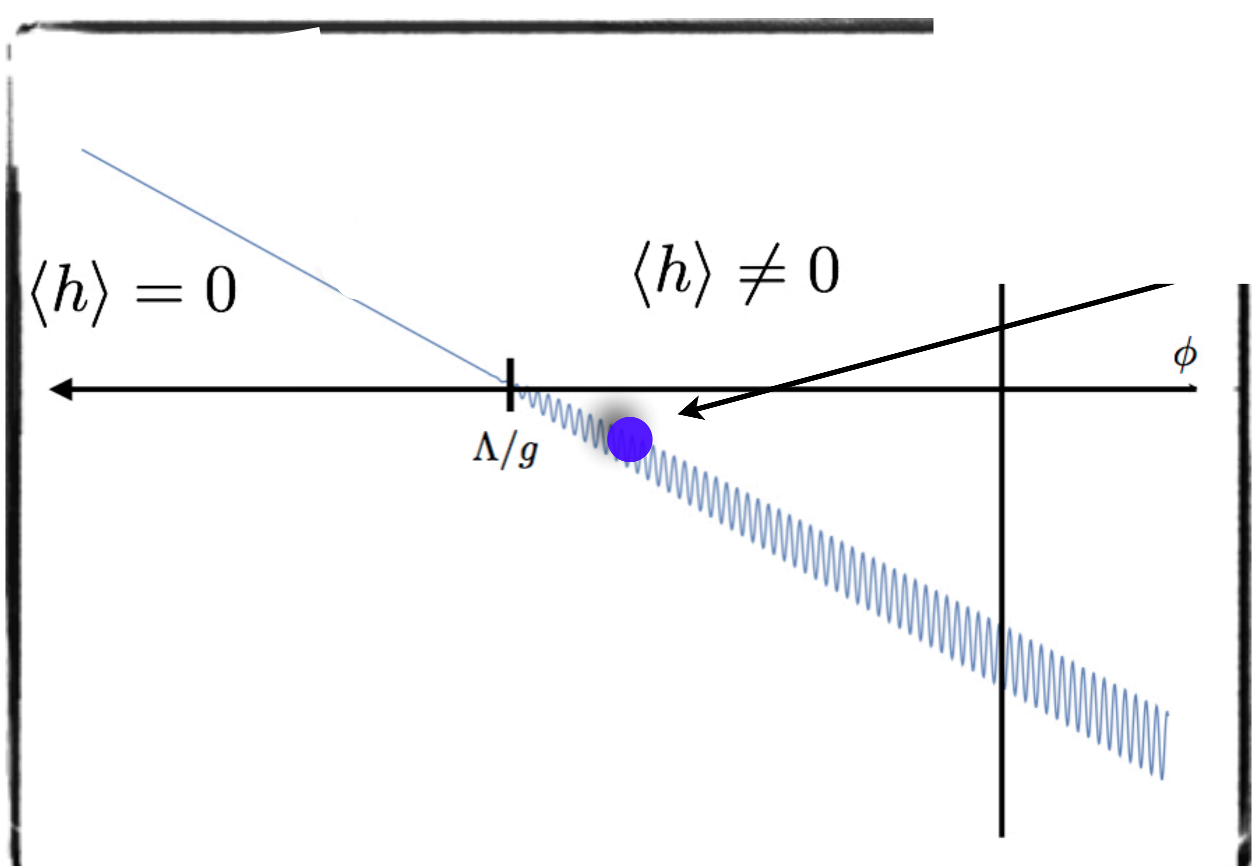

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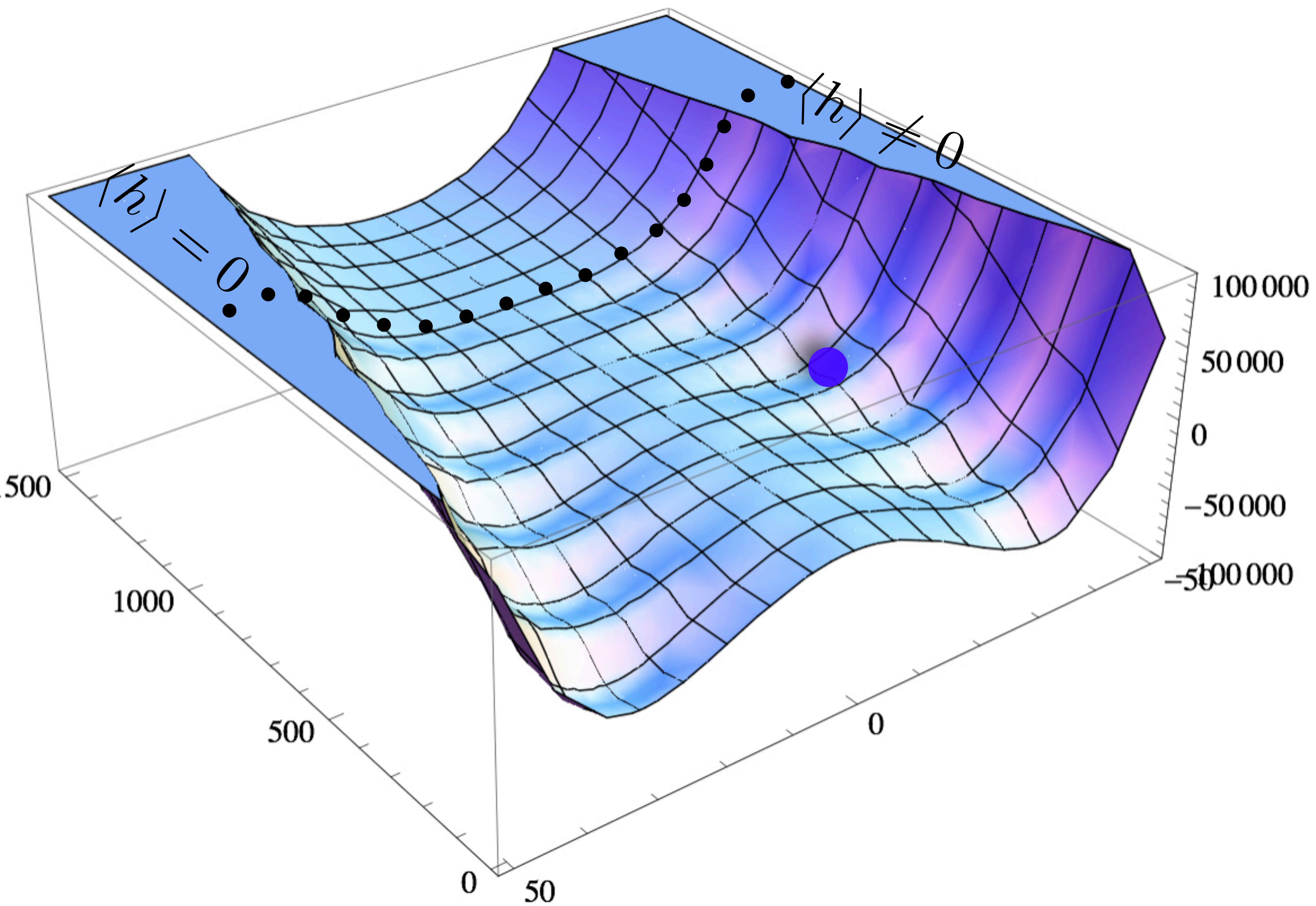

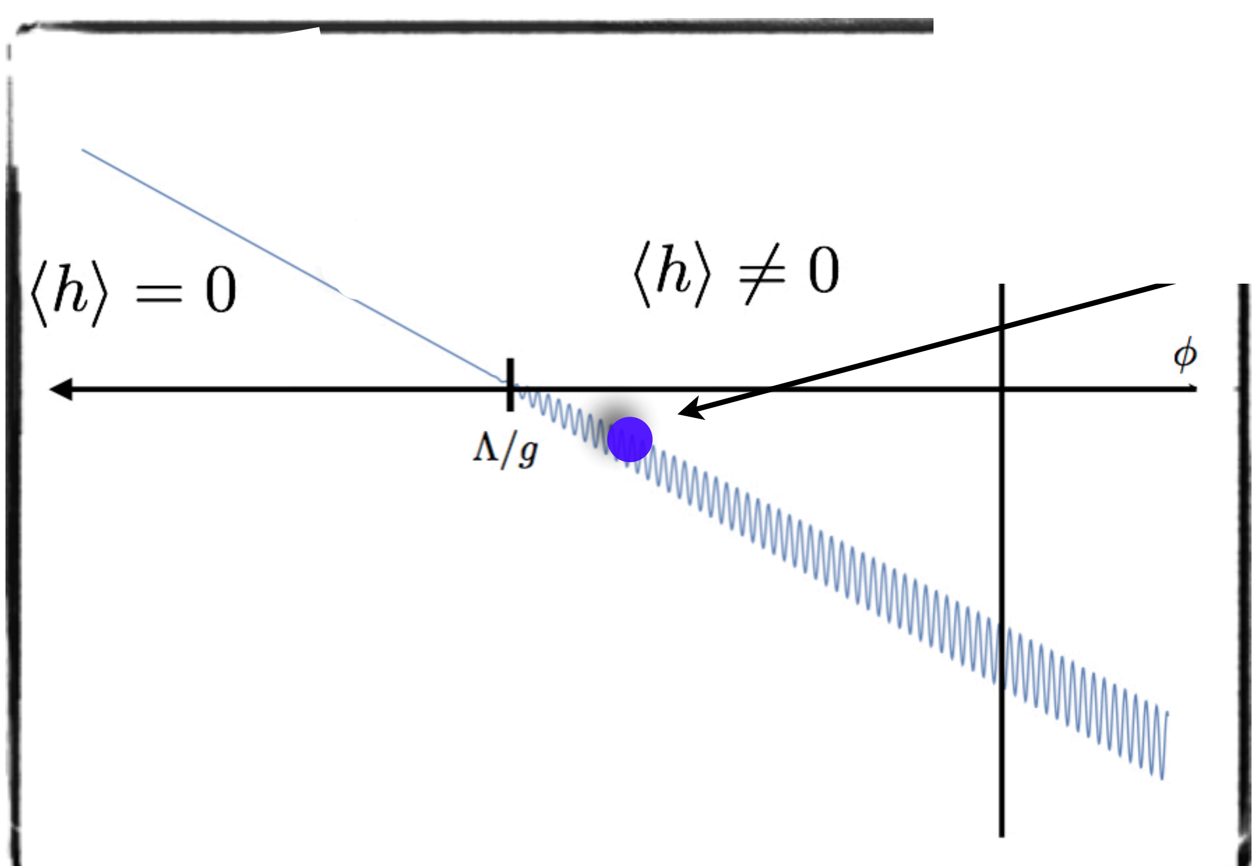

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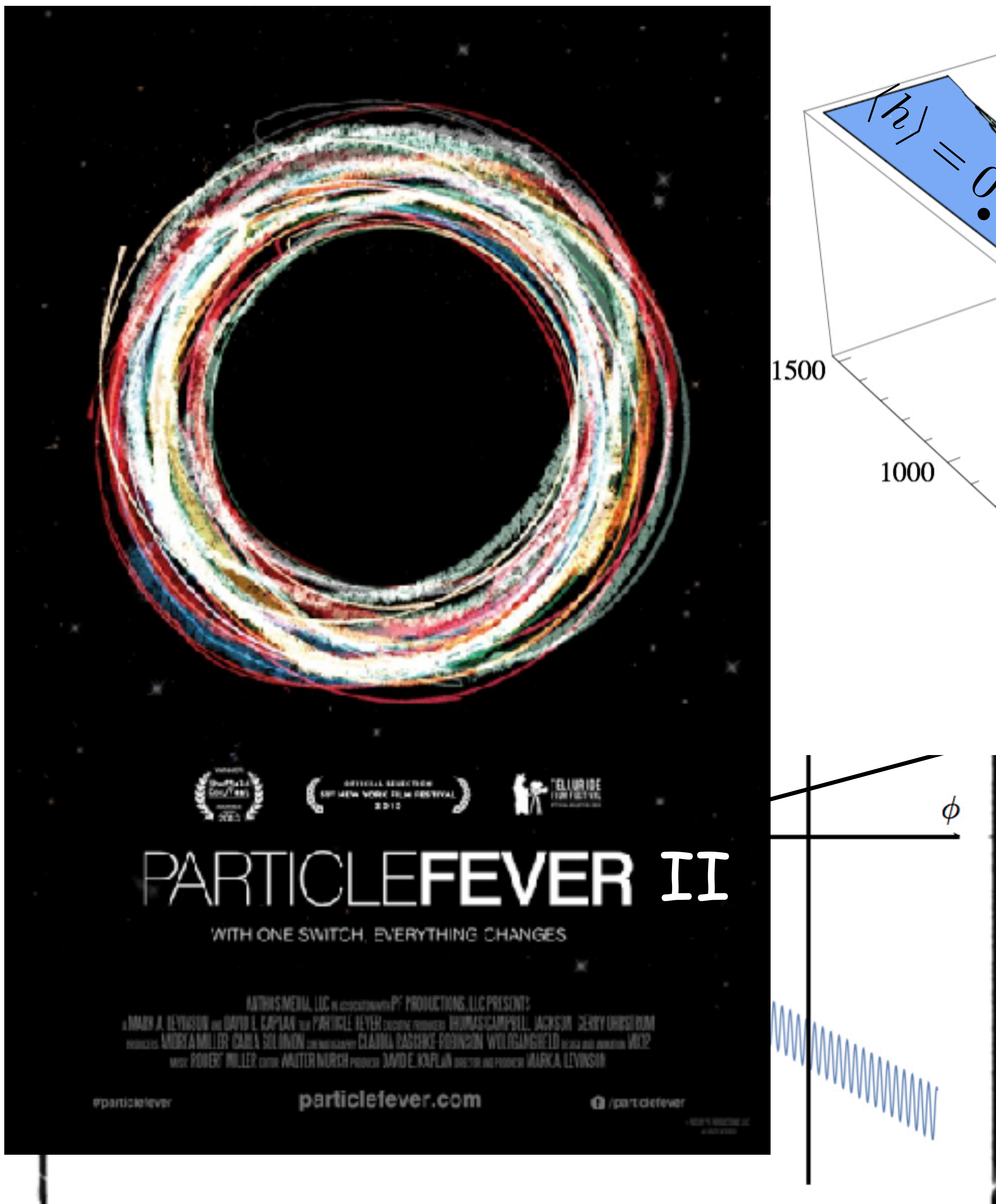

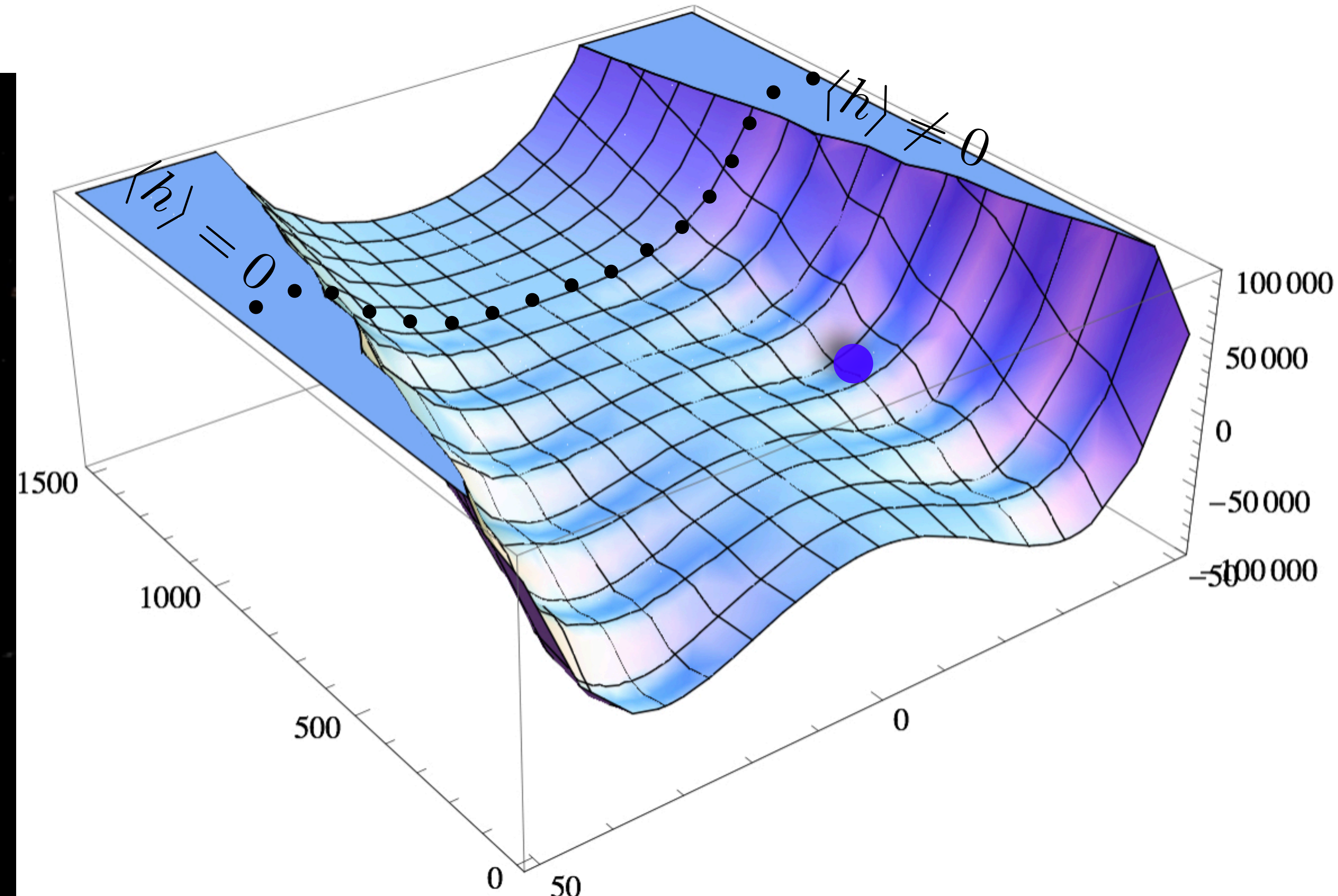

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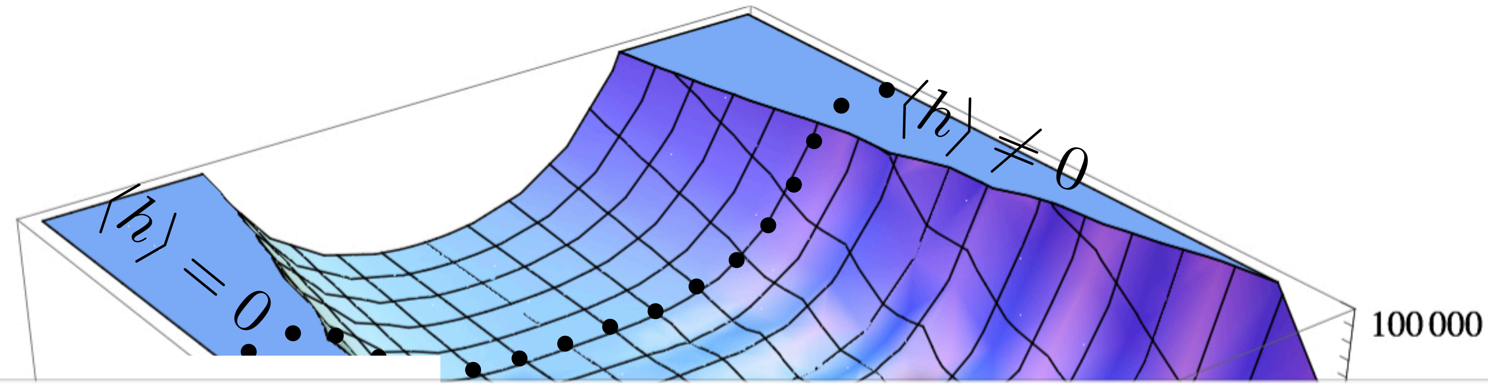
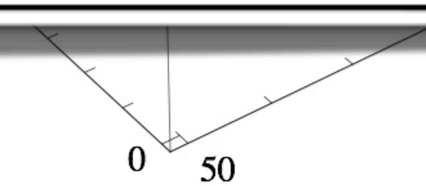
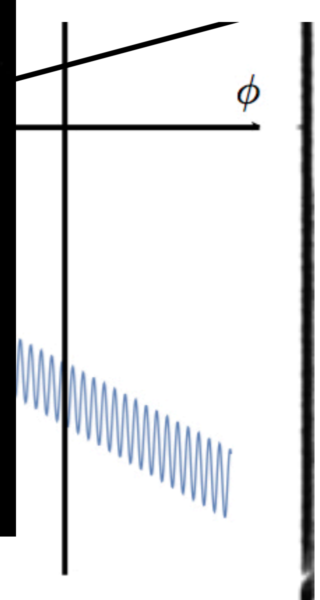


Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics





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Two classes of relaxion models (so far)

- H-dependent potential barrier

Graham, Kaplan, Rajendran '15

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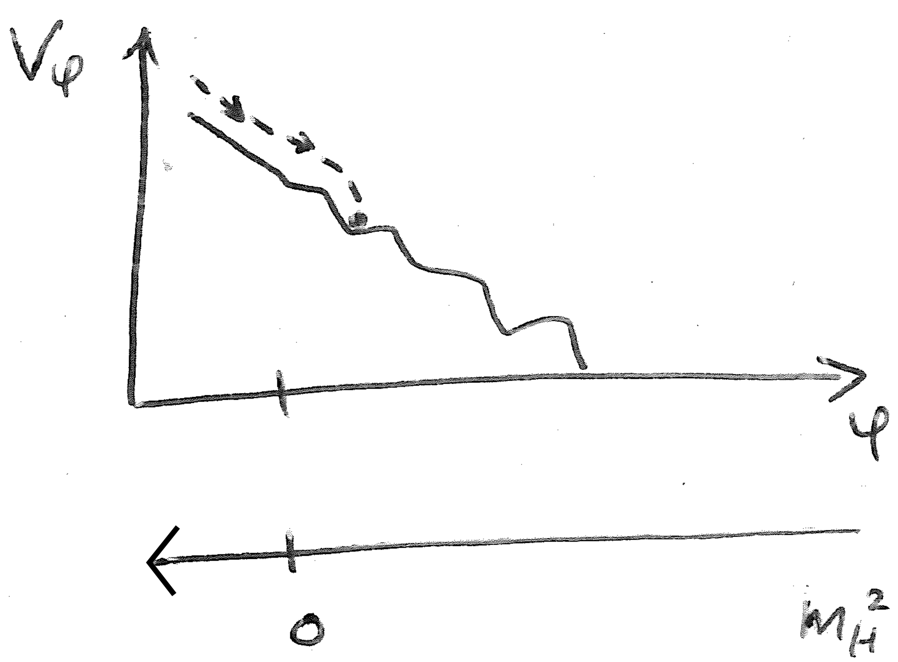
potential barriers in the relaxion potential appear soon after EWSB occurs and the relaxion gets trapped in one minimum



drawings borrowed from A. Matsedonskyi, DESY workshop seminar '17

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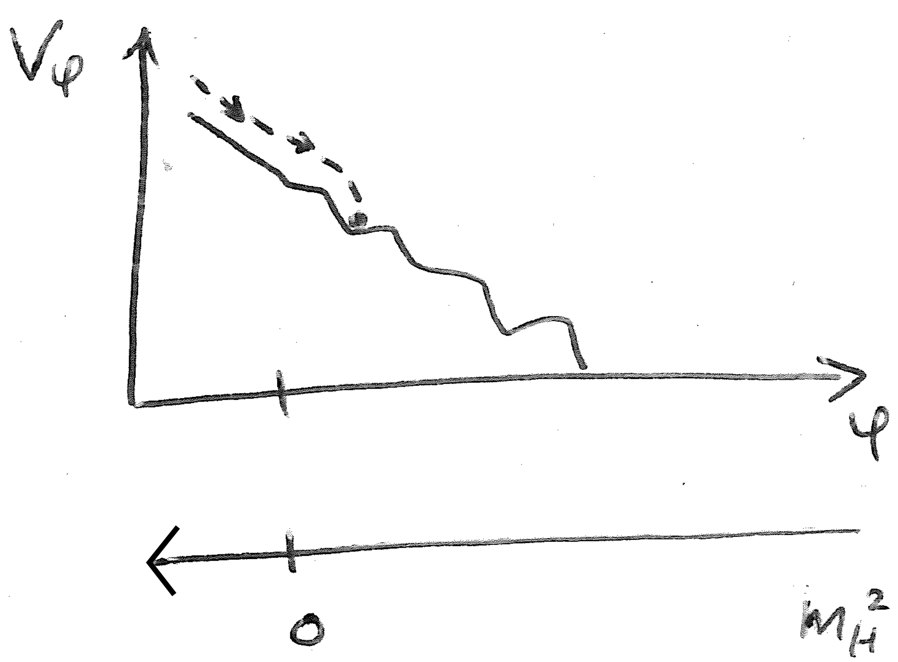
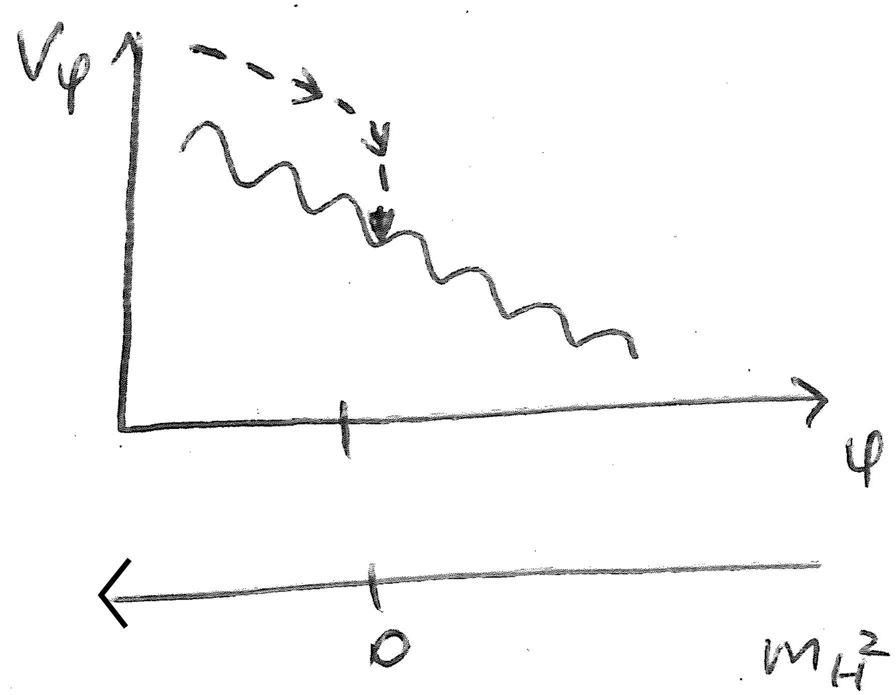
- H-dependent friction

Hook, Marques-Tavares '16

You '17

the potential barriers in the relaxion potential always exist but there is no friction to stop the relaxion in one the minimum until the Higgs vev approaches a critical value





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- **Higgs vev stops cosmological rolling**

$$\Lambda_{\rm QCD}^3 \frac{v}{f} \sim \frac{\partial}{\partial\phi}\left(\Lambda^4 V(g\phi/\Lambda)\right) \simeq g\Lambda^3$$

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note: v<<Λ provided that g<<1. It doesn't explain why the coupling is small (that question can be postponed to higher energies, requires more model-building engineering, relaxion=PGB?) but it ensures that the solution is stable under quantum correction.

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classical displacement over one Hubble time

$$\frac{1}{H_I}\frac{d\phi}{dt} = \frac{1}{H_I^2}\frac{dV}{d\phi} = \frac{g\Lambda^3}{H_I^2}$$

>

quantum fluctuation

$$H_I$$

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Important issues:

1. θ_{QCD}~ 1 ≫10^{-10}. Can be solved but Λ < 30 TeV
2. large field excursion: $\Delta\phi \sim \Lambda/g \sim f\Lambda^3/(v\Lambda_{QCD}^3) \gg 1$, $N_e \sim \frac{f^2\Lambda^8}{v^2\Lambda_{QCD}^6 M_P^2} \gg 1$

Quantum stability of relaxing Lagrangians...

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \Lambda_B^4\cos(\phi/f) + \ldots$$

$$\Lambda_B^4 = \Lambda_{B(0)}^4 + \Lambda_{B(1)}^3 h + \Lambda_{B(2)}^2 h^2 + \ldots$$

necessary condition for the Higgs vev to stop the relaxion: $\Lambda_B^4 < v^4$

- **n=1:** need another source of EWSB
  - QCD condensate <qq>~ Λ_{QCD}
  - new strongly-coupled sector à la Technicolor

    ⊩ new physics @ TeV, coincidence problem? ⫣

- **n=2:** no extra source of EWSB needed
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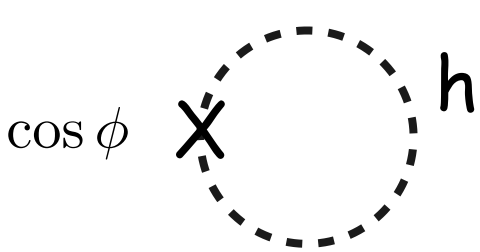

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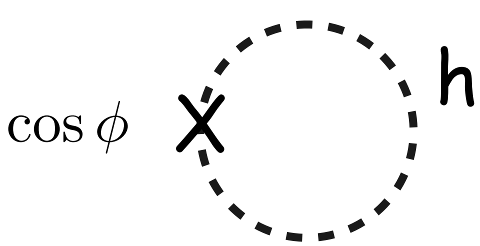

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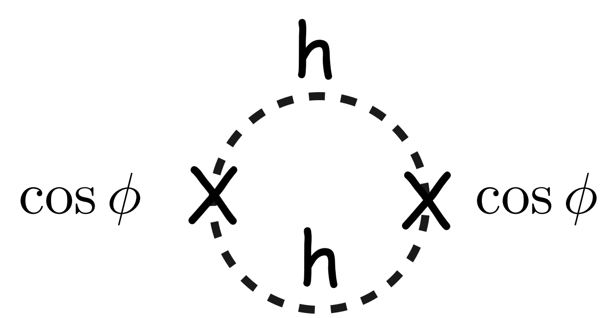

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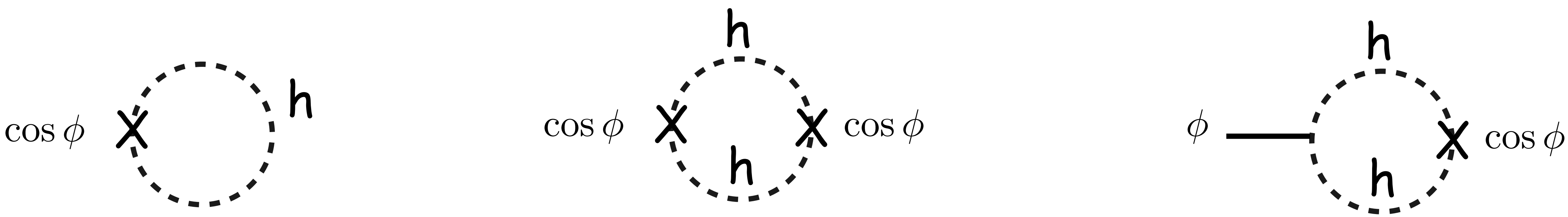

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Cosmological Higgs-Axion Interplay (CHAIN)

Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant '15

introduce a second field to scan the potential barrier

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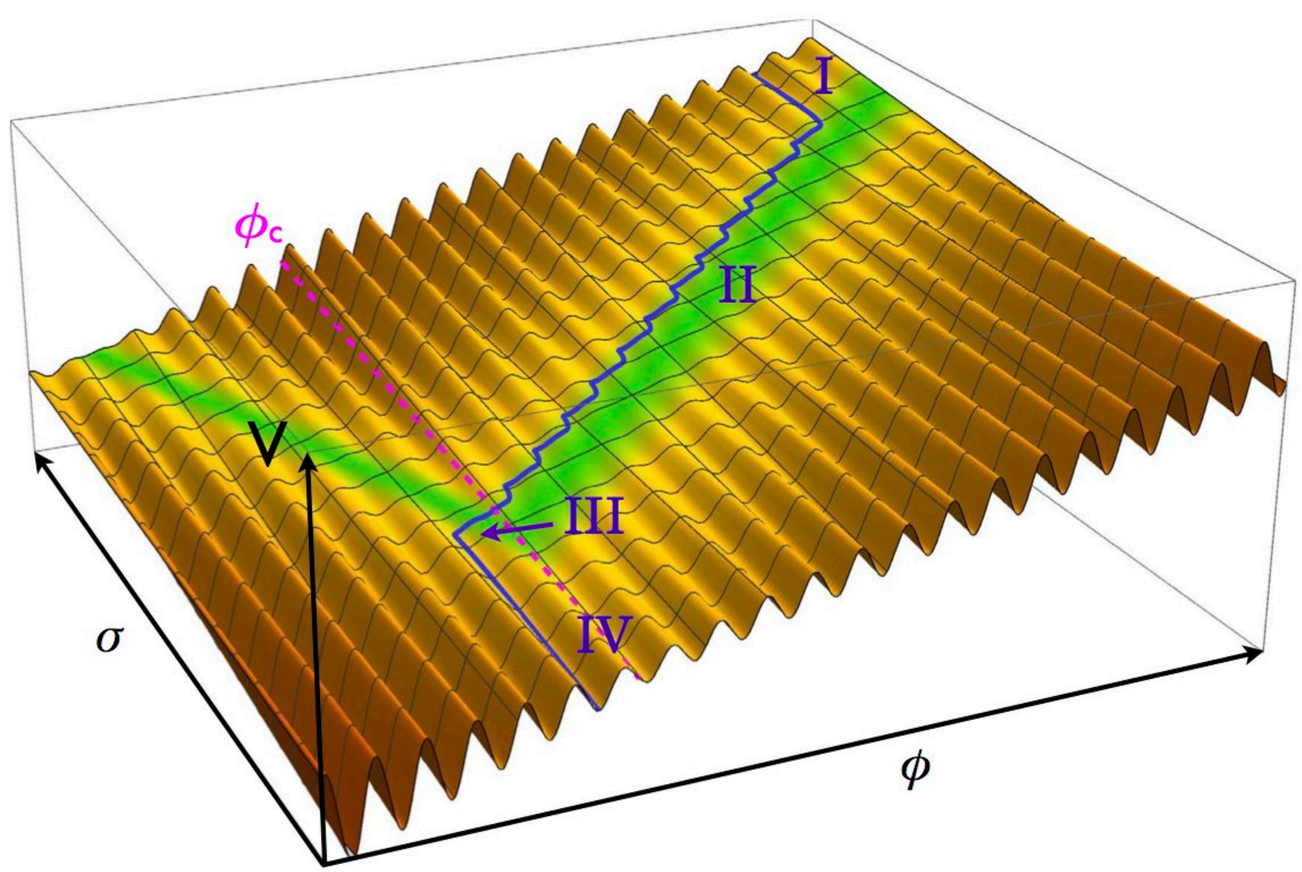

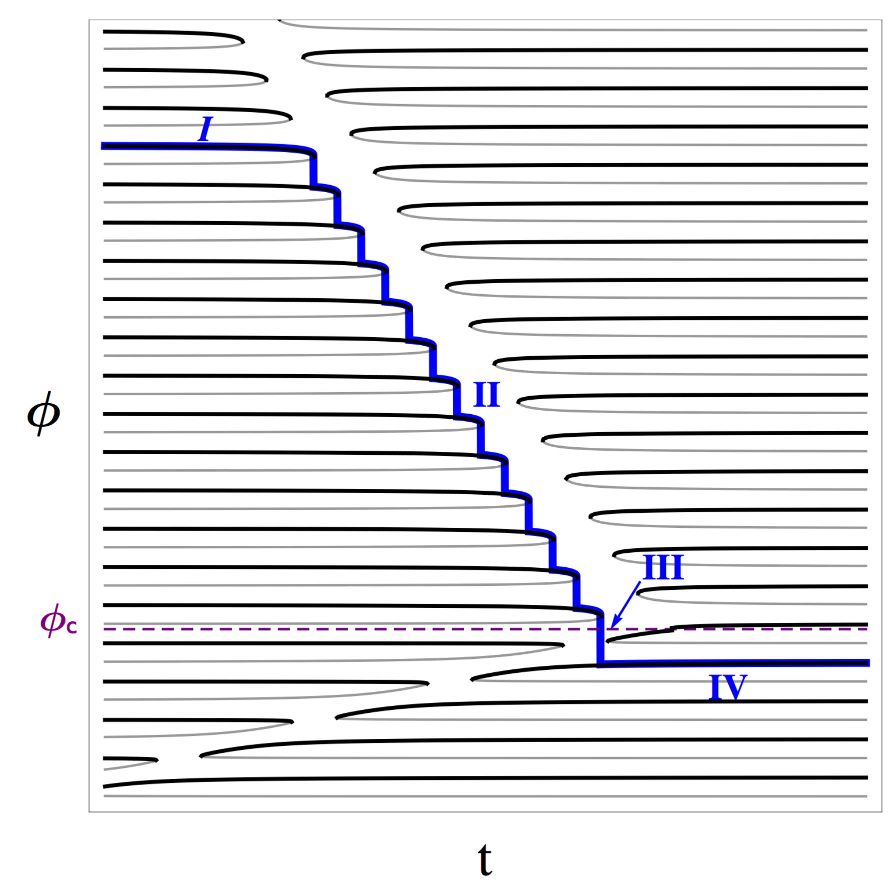

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- Quantum stability of the potential $\epsilon \lesssim v^2/\Lambda^2$

ensures that terms $\epsilon^2\Lambda^4\cos^2(\phi/f)$ don't affect the tracking solution

Ex.

$\epsilon^2\Lambda^4\cos^2(\phi/f)$

should be subleading compared to $\epsilon\Lambda^2 h^2 \cos(\phi/f)$

Requires $\epsilon \lesssim v^2/\Lambda^2$

courtesy to JR Espinosa

large potential barrier allowed: $\Lambda_B^4 < v^2\Lambda^2$

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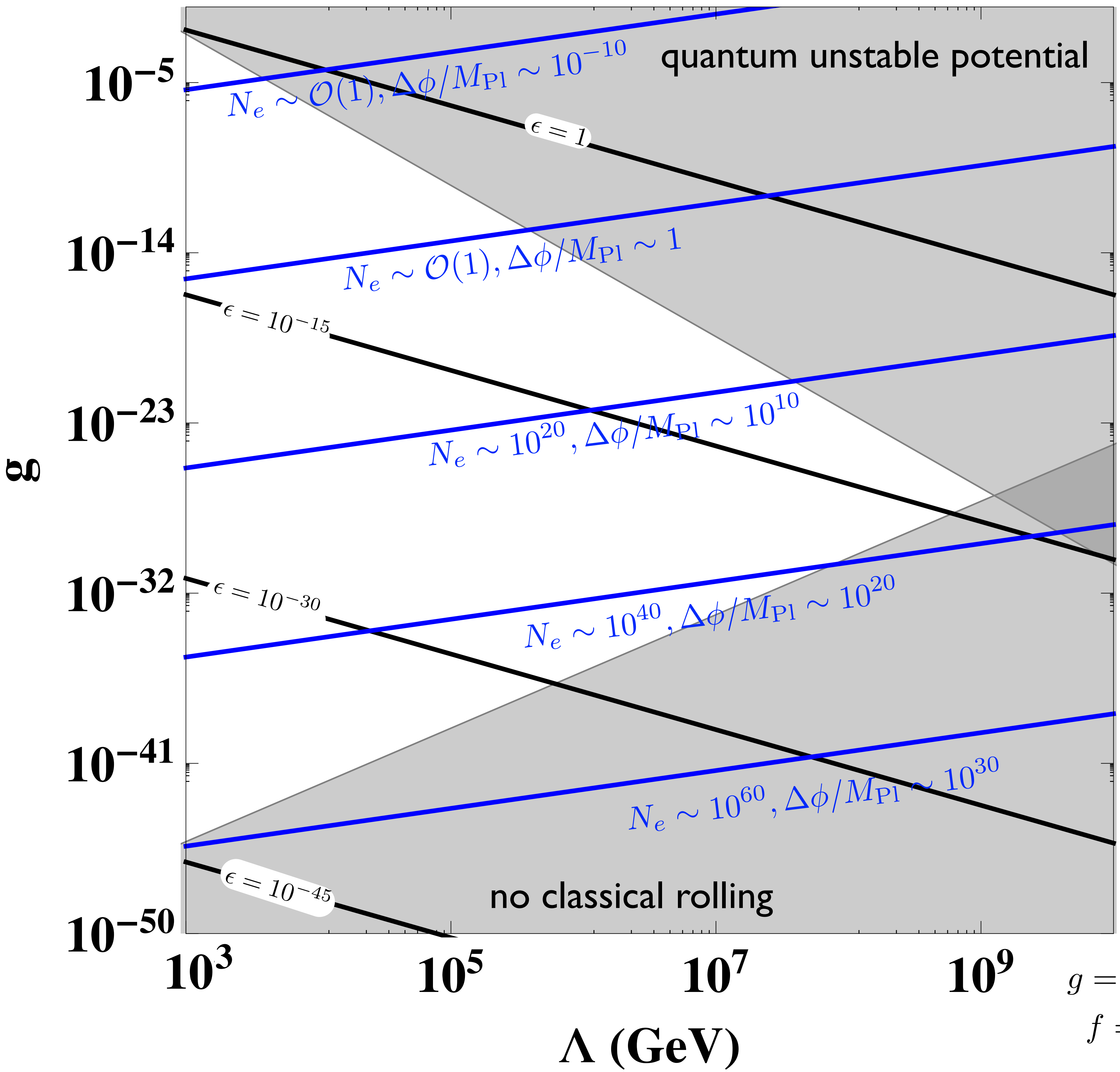
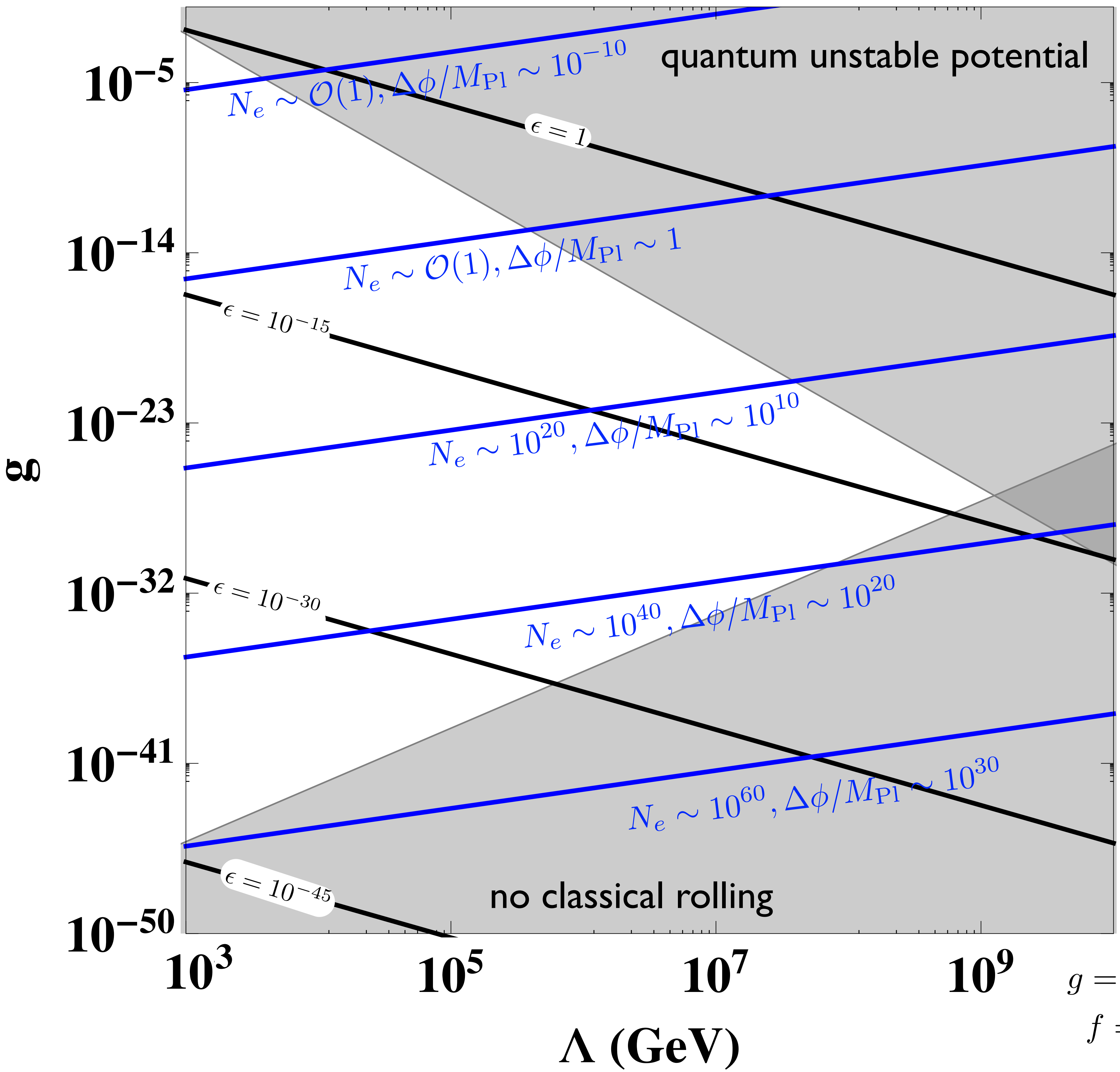
Consistency conditions



$g = 10 g_\sigma$

$f = \Lambda$

Consistency conditions



Long epoch of **inflation** to allow the field to explore large range values and reach the critical point without fine-tuning

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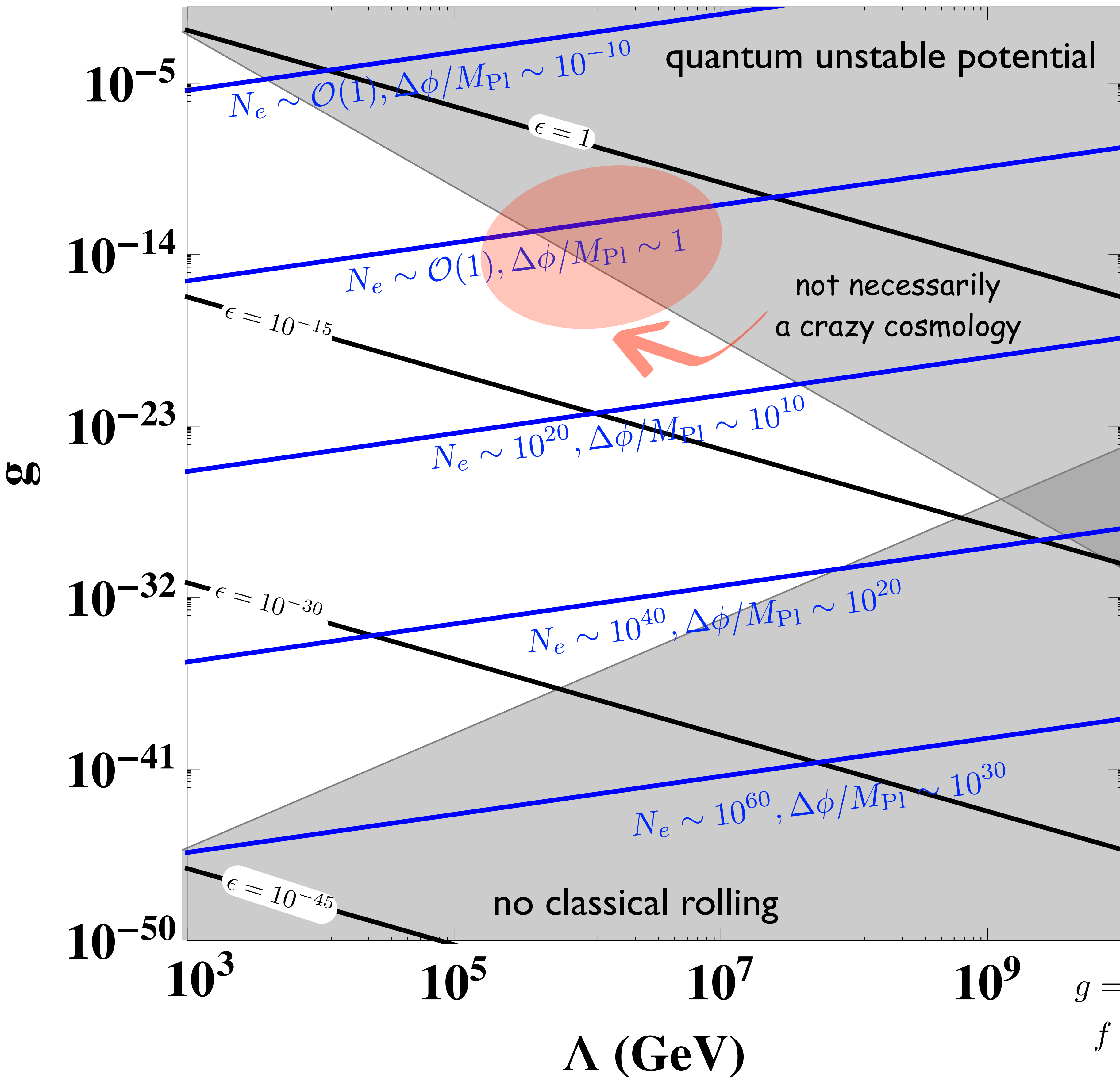

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Best solution to little hierarchy pb?

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Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

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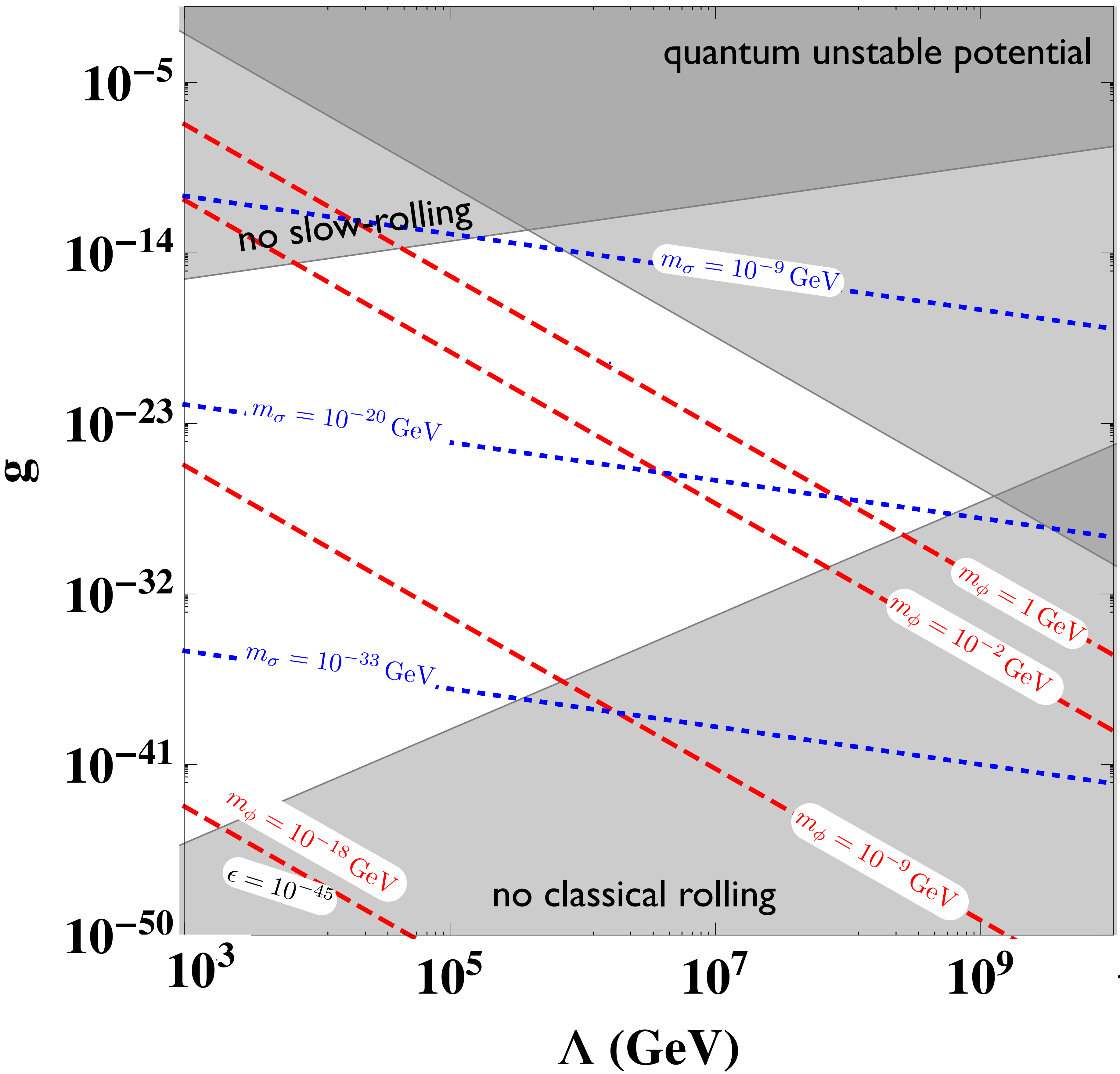
only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim \left(\frac{g\,\Lambda^5}{f\,v^2}\right)^{1/2} \sim (10^{-20} - 10^2)\,\mathrm{GeV}$$

$$m_\sigma \sim g_\sigma \Lambda \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

Phenomenological signatures



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Phenomenological signatures

A QFT rationale for light and weakly coupled degrees of freedom

Espinosa et al '15

Flacke et al '16

~interesting cosmology signatures~

- BBN constraints
- decaying DM signs in γ-rays background
- ALPs
- superradiance

Choi and Im '16

~interesting signatures @ SHiP~

- production of light scalars by B and K decays

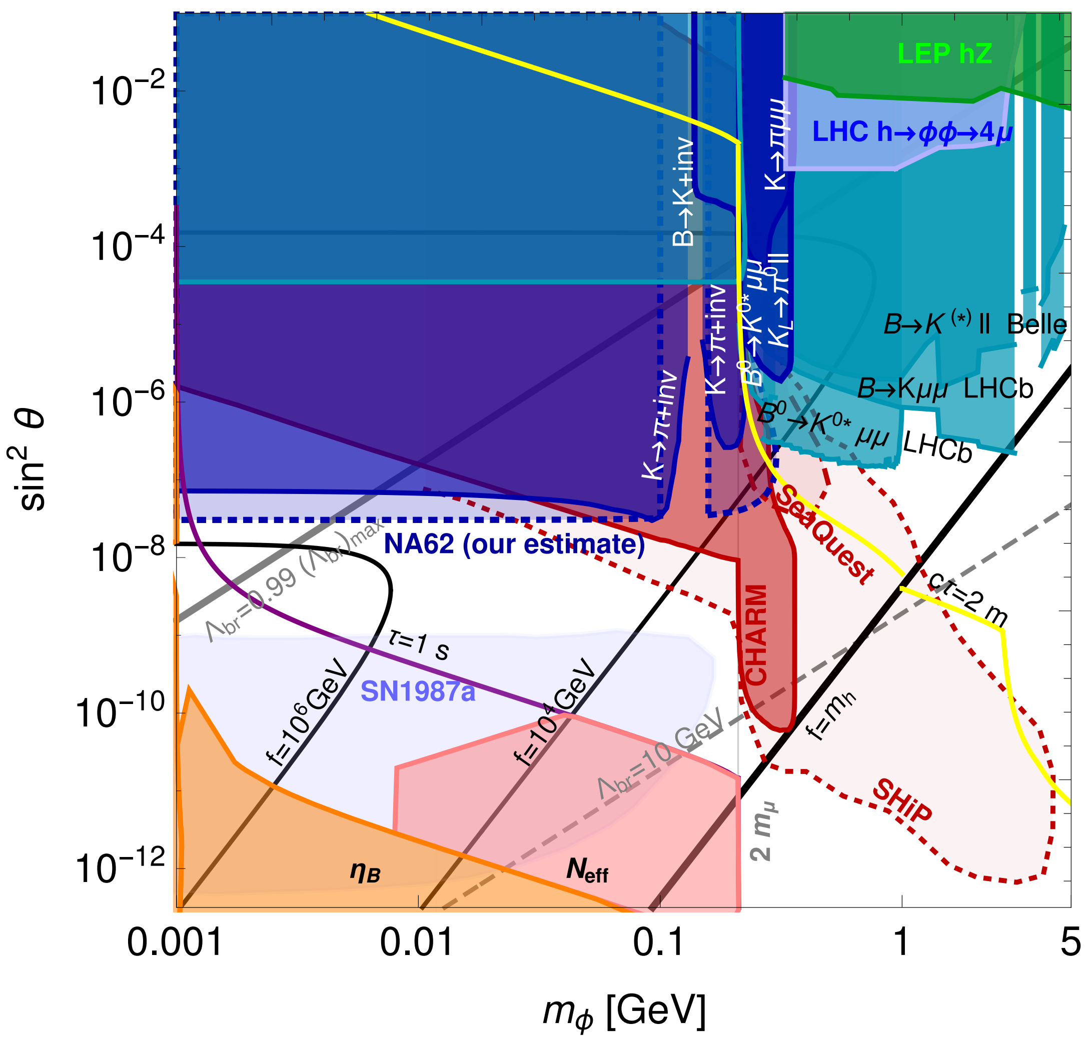
~interesting atomic physics~

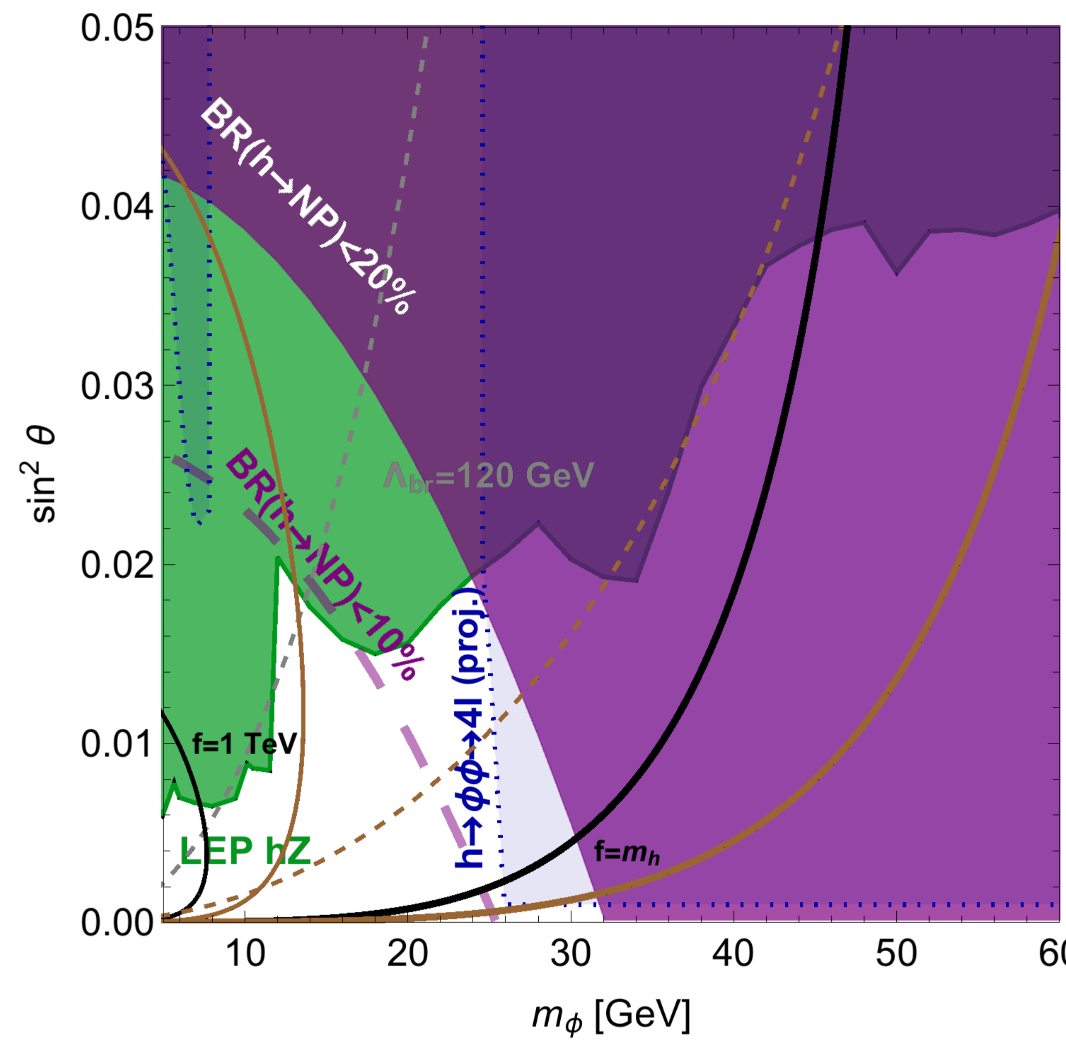
- change of atom sizes

G. Perez et al 'in progress

Phenomenological signatures

Phenomenological signatures are very model-dependent
Results shown before are for CHAIN model w/o new physics till Λ
Pheno of models w/ TeV scale new physics to generate potential barrier studied by Weizmann people





Flacke et al '16

Relaxing without multiple vacua: pole attractors

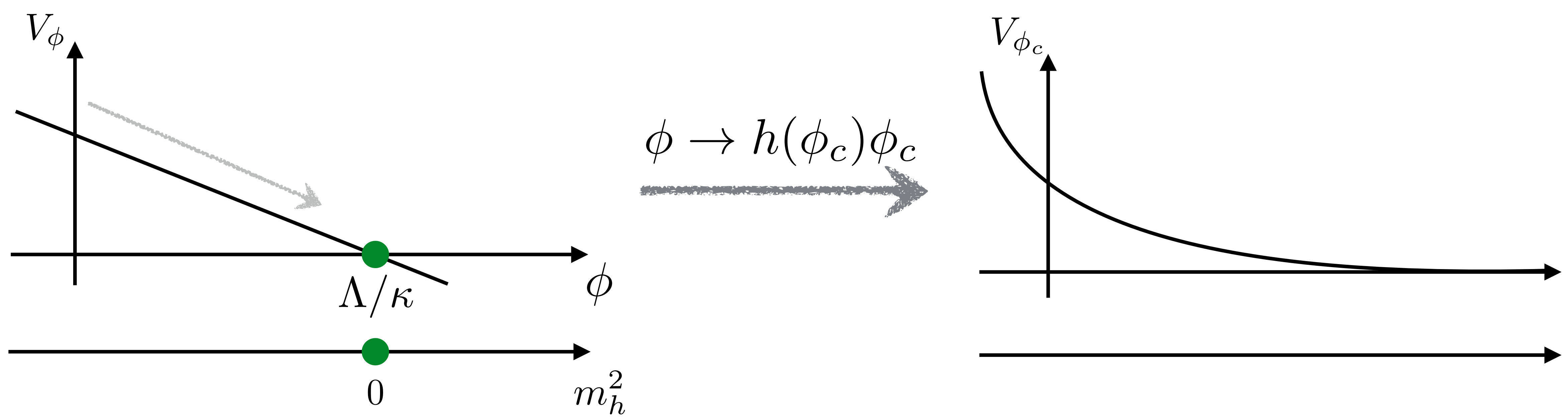
Matsedonskyi, Montull '17

- The Higgs mass is scanned by the relaxion field ϕ

$$V_h \supset \left(-\Lambda^2 + \kappa\Lambda\phi\right) h^2 \qquad\qquad (V_\phi = -\kappa\Lambda^3\phi)$$

- The relaxion has a non canonical kinetic term $\frac{1}{h^{2n}}(\partial_\mu\phi)^2$

- When $\phi \to \Lambda/\kappa$ then $h \to 0$ and the kinetic term grows.



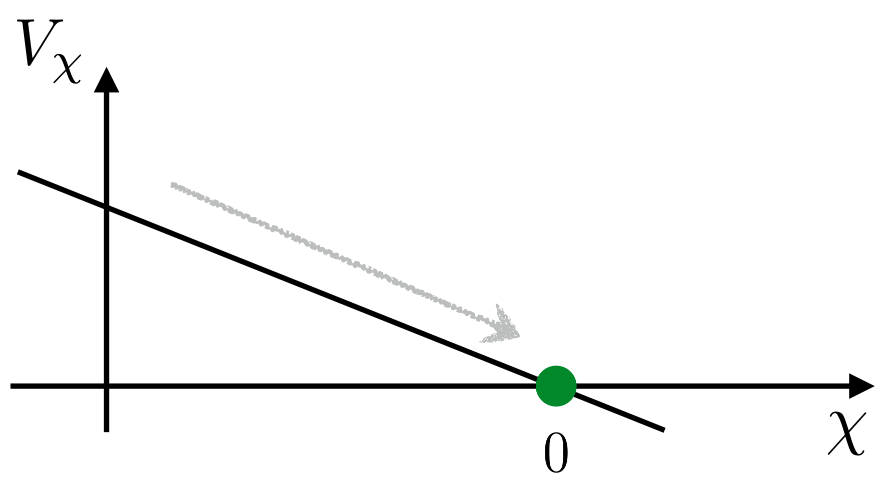
- The slope of the relaxion potential and coupling to the Higgs decrease and the scanning effectively stops.

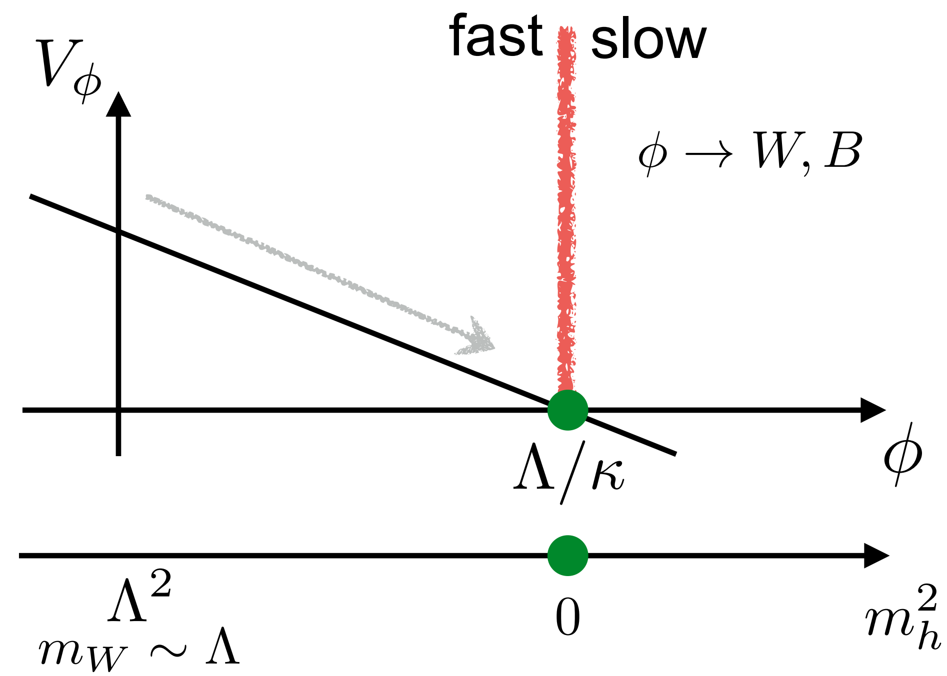
- derivative Higgs-relaxion couplings becomes non-perturbative

- UV completions unknown

Pole attractors: minimal realistic model

Matsedonskyi, Montull '17





1) kinetic terms controlled by a new field χ

$$\frac{1}{\chi^2}\left\{(\partial\chi)^2 + (\partial\phi)^2\right\}$$

motivated by SUSY-based inflation models

2) χ provides a limited time for a scan until it gets to zero and blocks all the evolution

3) ϕ moves quickly before reaching h~0, and after it's slowed down by particle friction provided

$$\dot\phi \gtrsim m_W\, f$$

* f controls particle friction

4) remaining part of the <u>limited</u> time relaxion is very slow, almost no scan is possible

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What does it imply?

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- Any in case: The energy frontier might be different than what we thought for many years!

BACKUP SLIDES

Phenomenological signatures

interesting signatures in cosmology and possibly at SHiP

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ϕ and σ couple to SM matter via their mixing with the Higgs

$$\theta_{\phi h} \sim \frac{g\Lambda v}{m_h^2}\ , \quad \theta_{\sigma\phi} \sim \frac{g_\sigma f v^2}{\Lambda^3}\ , \quad \theta_{\sigma h} \sim \mathrm{Max}\left\{\theta_{\sigma\phi}\theta_{\phi h}\ ,\ \frac{g^2}{16\pi^2}\frac{g_\sigma \Lambda^7}{f^2 v^3 m_h^2}\right\}$$

from oscillatory potential

tree-level

quantum mixing from ϕ-loop

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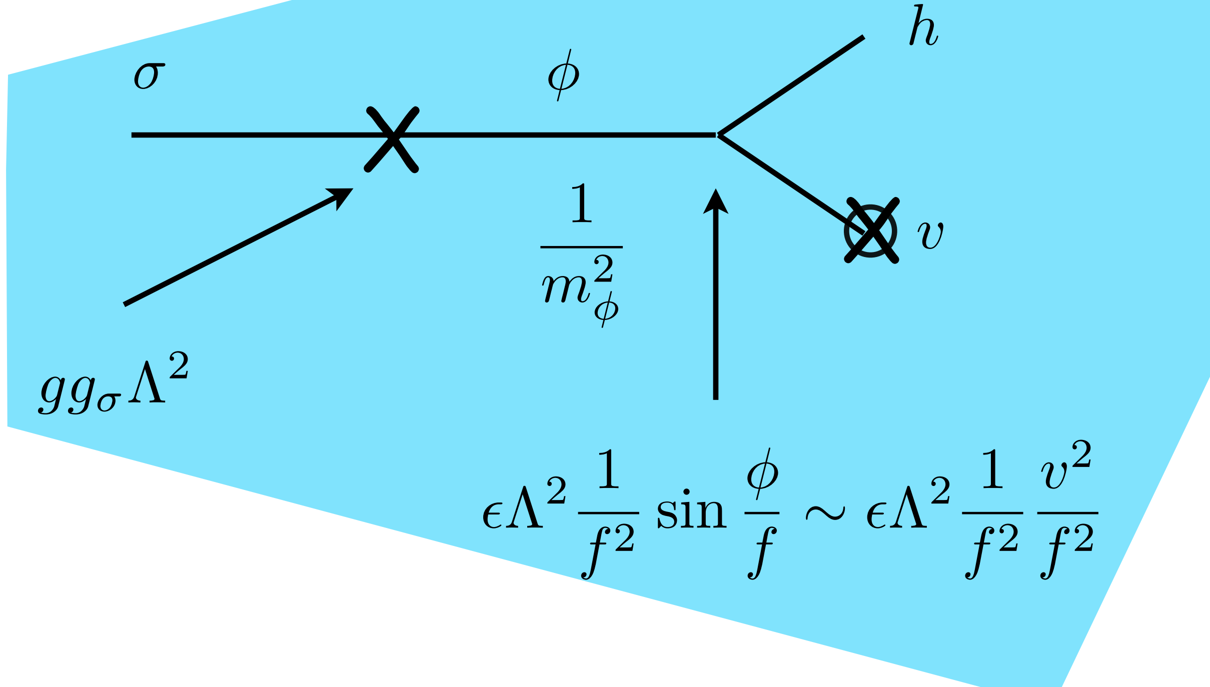

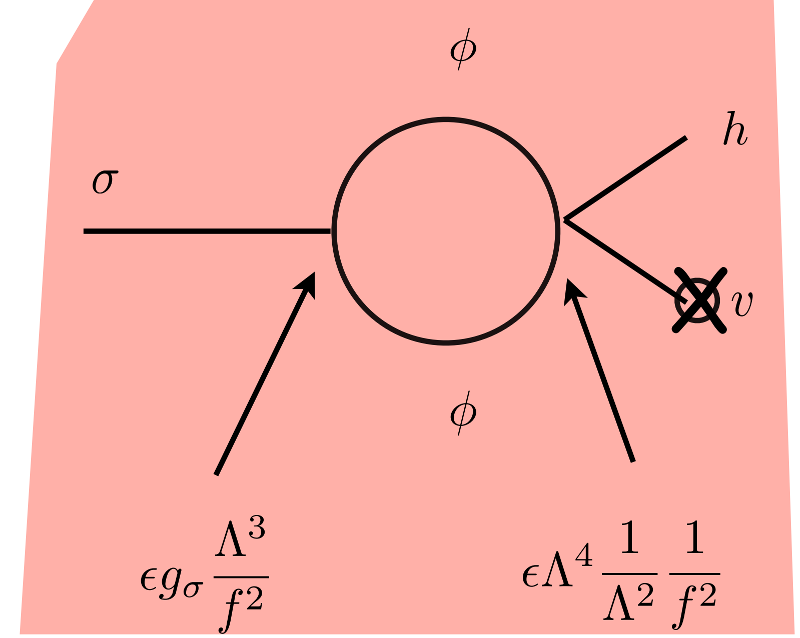

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ϕ and σ decay to SM particles
(mostly photons in a large region of parameter space)

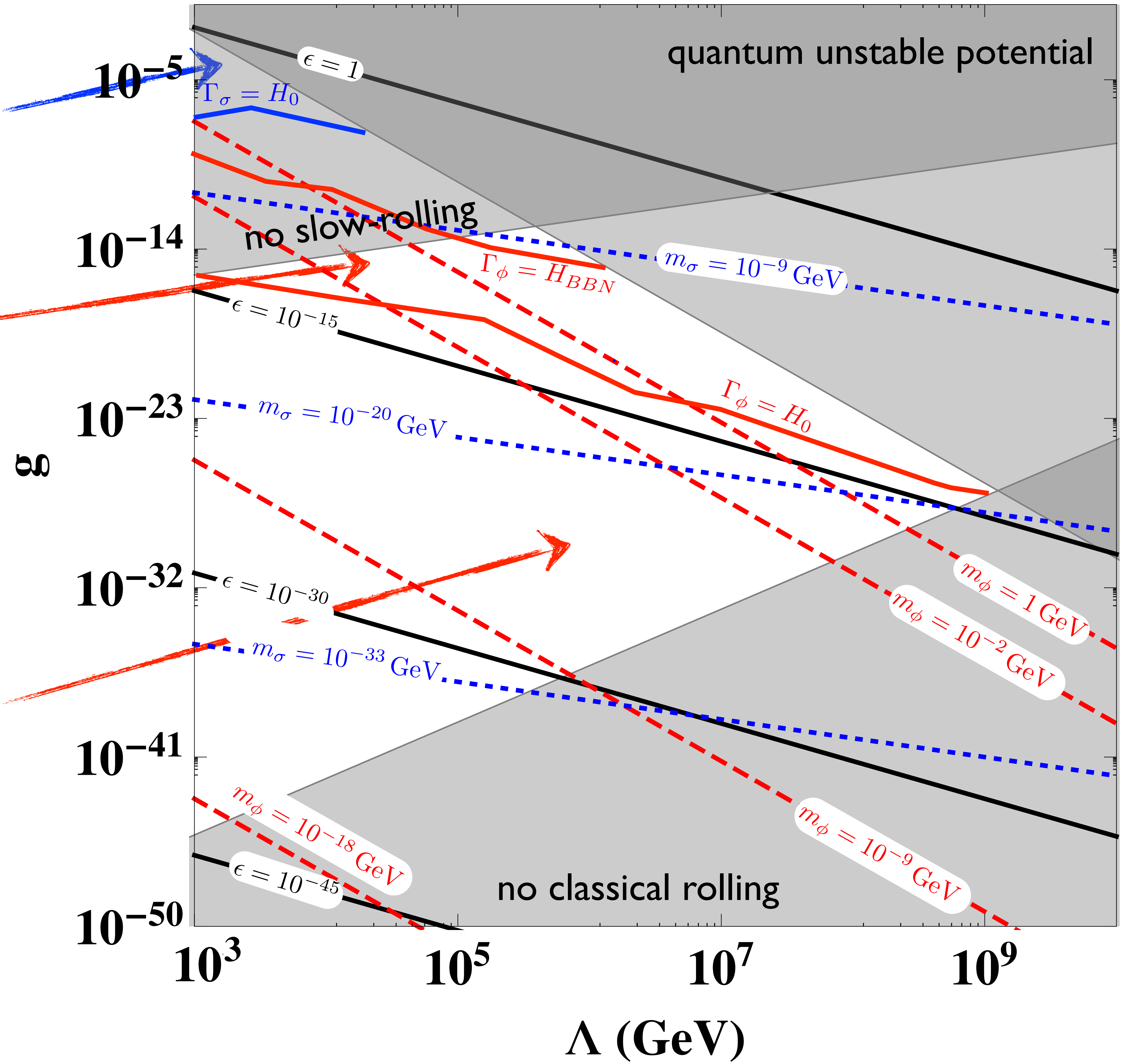
$$\Gamma_\phi \sim \theta_{\phi h}^2 \Gamma_h(m_\phi)\ , \quad \Gamma_\sigma \sim \theta_{\sigma h}^2 \Gamma_h(m_\sigma)$$

Phenomenological signatures

σ decays within the age of the Universe

ϕ decays after BBN

ϕ cosmologically stable



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the energy density is then redshifted till today

$$\Omega_\sigma \sim \left(\frac{4\times 10^{-27}}{g_\sigma}\right)^{3/2} \left(\frac{\Lambda}{10^8}\,{\rm GeV}\right)^{13/2}$$

Ω_ϕ always very small since $m_\phi \gg m_\sigma$ i.e. $T^\phi_{\rm osc} \gg T^\sigma_{\rm osc}$

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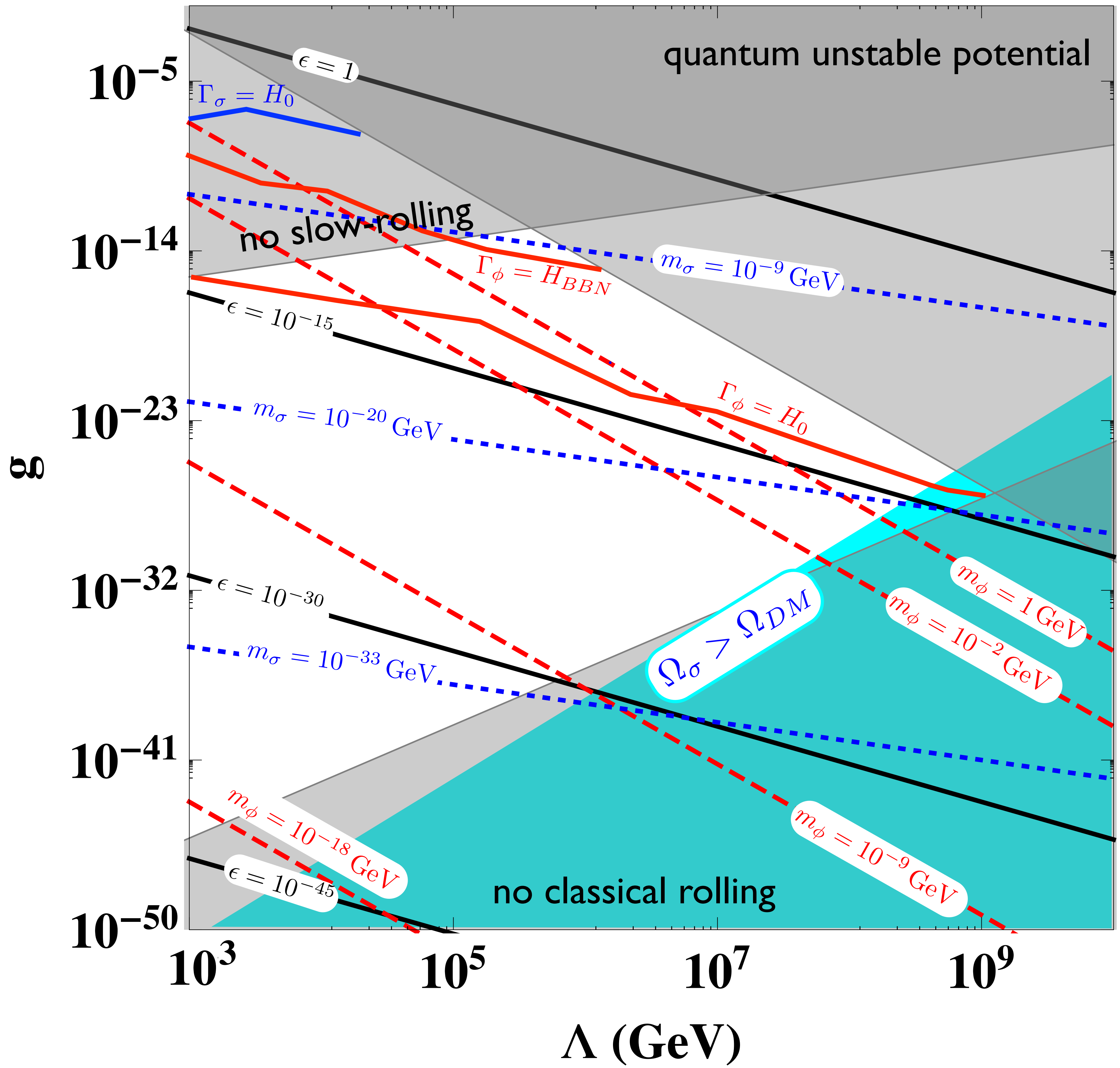

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◎ BBN constraints

◎ distortions in galactic and extra galactic diffuse X-ray and γ-ray backgrounds

Phenomenological signatures