(Mis)guided advice towards facing the unknown

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Weizmann

(1st) Meeting on the future of ***Experimental HEP*** post LHC (in particular in Israel)

Dec. 2017. Weizmann

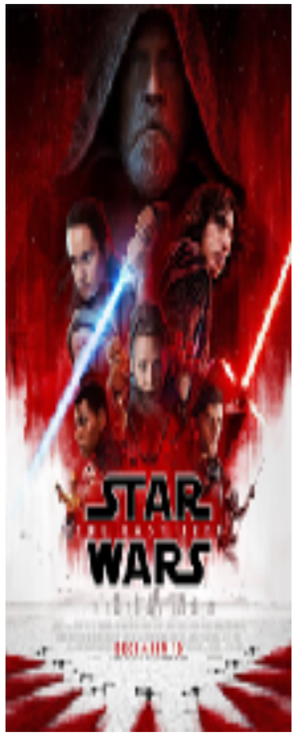
This is an experimental discussion; I don't have answers, just try to give perspective

- Pragmatic, th.-free approach & its limitation - the "what have learnt" reduction problem.

- Observationally-based: a special moment in HEP, the logarithmic crisis.

- Why things are naturally-speaking worse ? From LHC-data to relaxion-th..
  (tiny encouragement: relaxion and the edge of the log scale …)

(- Standard candles)



- Summary.

pragmatic approach #1: th.-free search strategy

- Right now @ the LHC we are searching in model indep' manner…

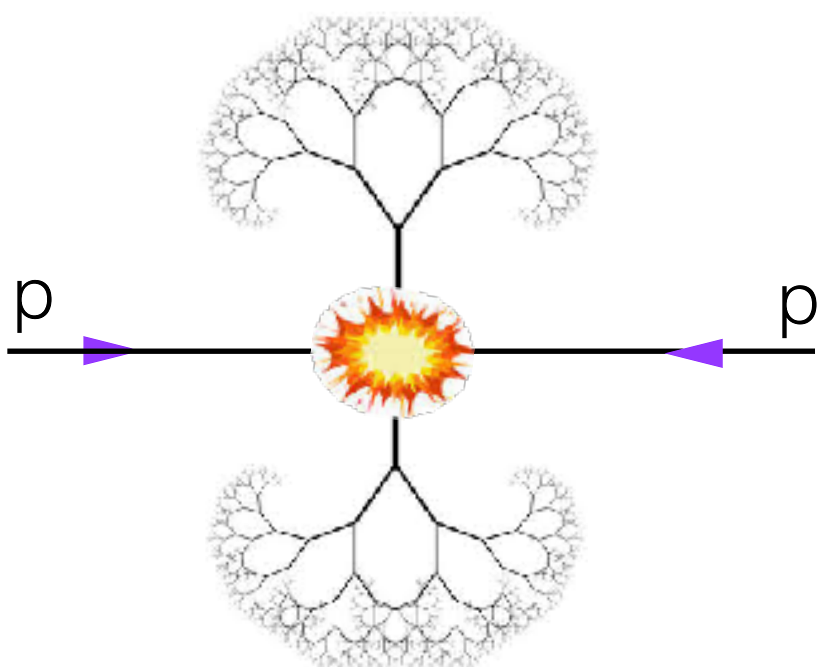
pragmatic approach #1: th.-free search strategy

- Right now @ the LHC we are searching in model indep' manner…

Not true: we filter ~10^{10} Hz of data down to 10^3 Hz (because it's boring …)

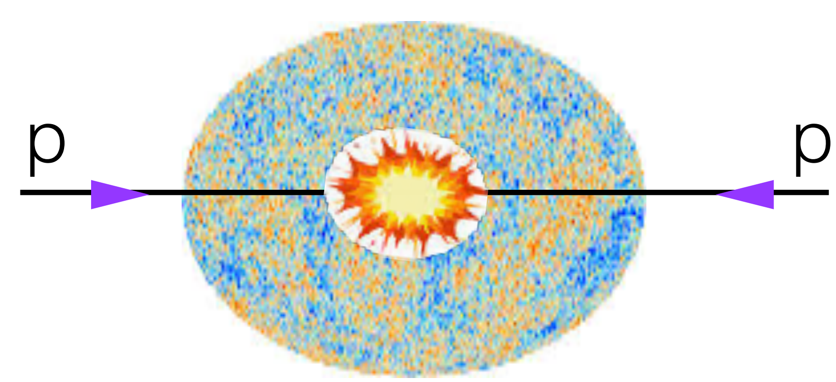
We mostly throw away everything that is soft; what if soft is everything?

Feynman - showering as self similar process



Wolf, Dremin & Kittel (95); Strassler & Zurek (06)

conformal hidden sector



Hofman & Maldacena (08); Georgi (07);
Cai, Cheng, Medina & Terning (09);

Pragmatic #2: th.-free approach to future exp.

How to compare different possibilities?

Energy ?

FCC

Luminosity ?

SHiP

Search for Hidden Particles

Precision ?

LINEAR COLLIDER COLLABORATION

CLIC ILC P&D

Pragmatic #3: just compare amount of data

- Number of different type of bits per exp':

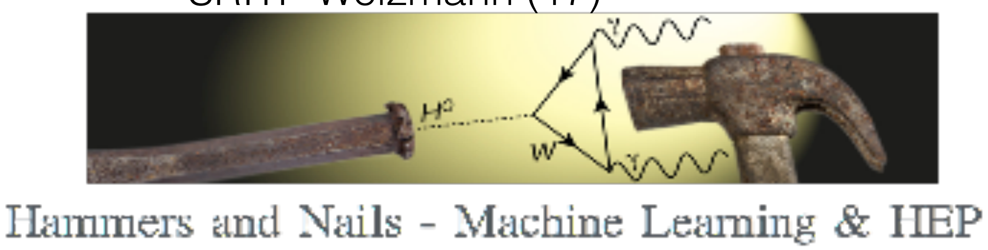
# of bits	LHC	NA62	SHiP	FCChh	ILC	SARAF
Ps/es/ POT	"10^{16}"	10^{18}	10^{20}	"10^{18}"		10^{22}
Kaon Produced		10^{14}	10^{16}		smaller	0
B's Produced	10^{12-14}	10^{8}	0	10^{16} ?	smaller	0
Higgses S/B	10^{5} 10^{-3}	0	0	10^{9} 10^{-4} ?	10^{5} $10^{0,-1}$	0

However, comparing # of protons to # of (clean) Higgsses is insane …

pragmatic approach #4: machine learning, automization will improve our large-data-searches

- Machine learning (ML) can potentially significantly boost the field.

SRITP Weizmann (17)



- In what sense (from experts):

K. Cranmer: Jets, Higgs-EFT, https://indico.physics.lbl.gov/indico/event/546/, Berkeley.

Brehmer, Cranmer, Kling & Plehn (16)

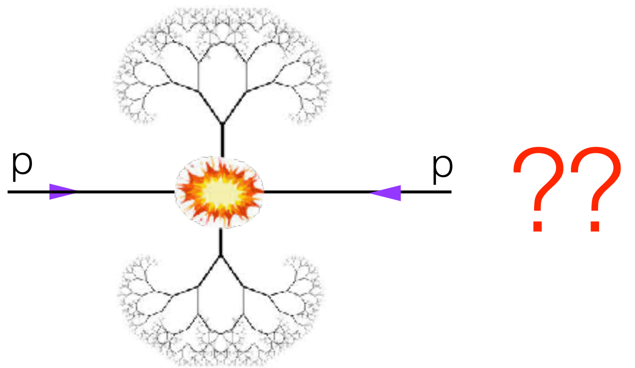
E. Gross: Jets, improving detector simulation …

S. Bressler: (not necessarily related to ML, but linked to above theme)
"generating signal hypotheses from the data - a data focused paradigm"

Two thoughts on “pragmatism”

♦ At present I don’t see a phase transition.

But, it might be too early.



♦ Generically, there is no attempt to deal with the following problem:

What do we learn if there is a null result ?!

Understanding the potential impact of large operation is a must and requires some level of reductionism.

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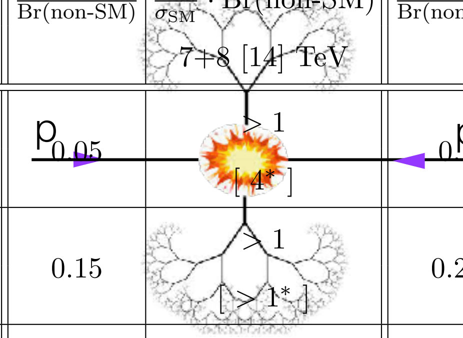


??

- Generically, there is no attempt to deal with:

What do we learn if there is a negative result ?!

Understanding the potential impact of large operation is a must and requires some level of reductionism.

Some guidance: Implications of conflict with observations (moving to log scale)

The Standard Model (SM) is incomplete

New particle and forces must exist:

Masses of right handed neutrinos 10^{-9} – 10^{15} GeV

Mass of Dark Matter particle 10^{-31} – 10^{20} GeV

Mass of new particles required for baryogenesis 10^{-2} - 10^{15} GeV

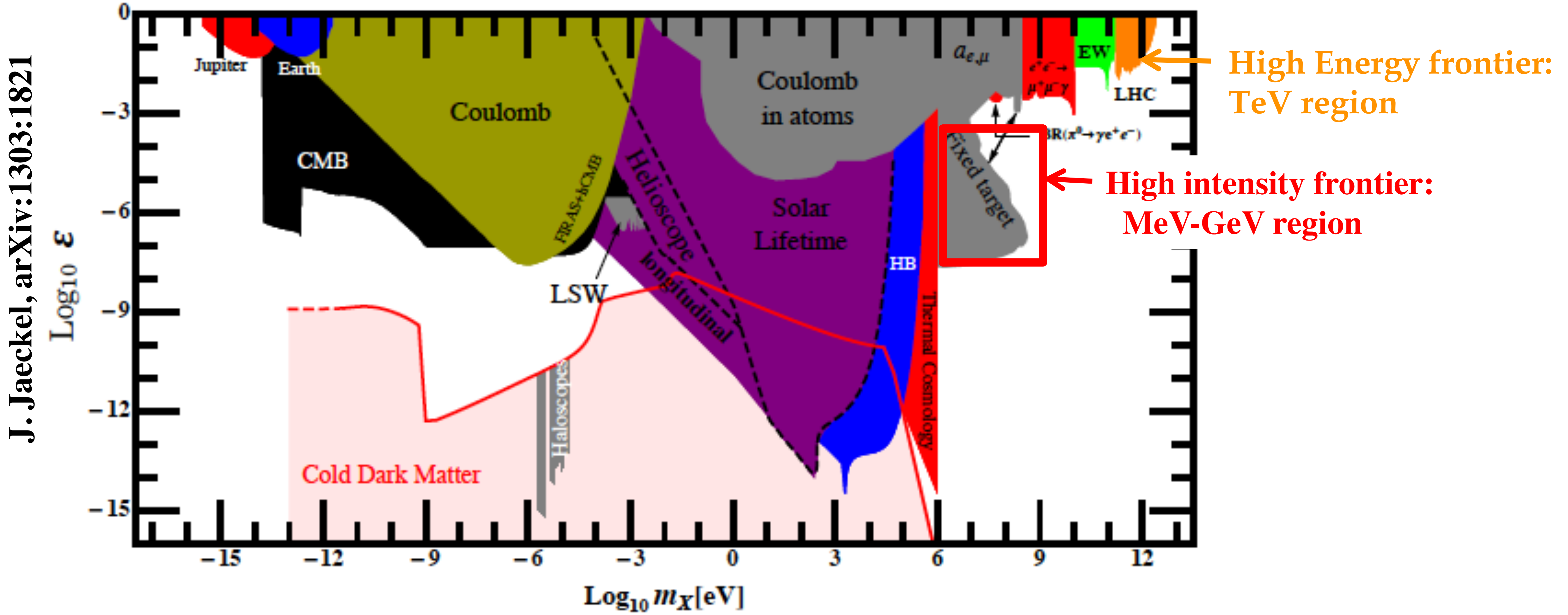
Scale of inflation probably (could be) very high, but at largely unknown …

The 21st century frustration:

we know that new physics exists but we don't know where …

Search for motivated new physics with no preferred energy scale - the *logarithmic crisis*

kinetic mixing of a dark photon-ordinary photon versus mass of dark photon



.... lost among the orders of magnitude ....

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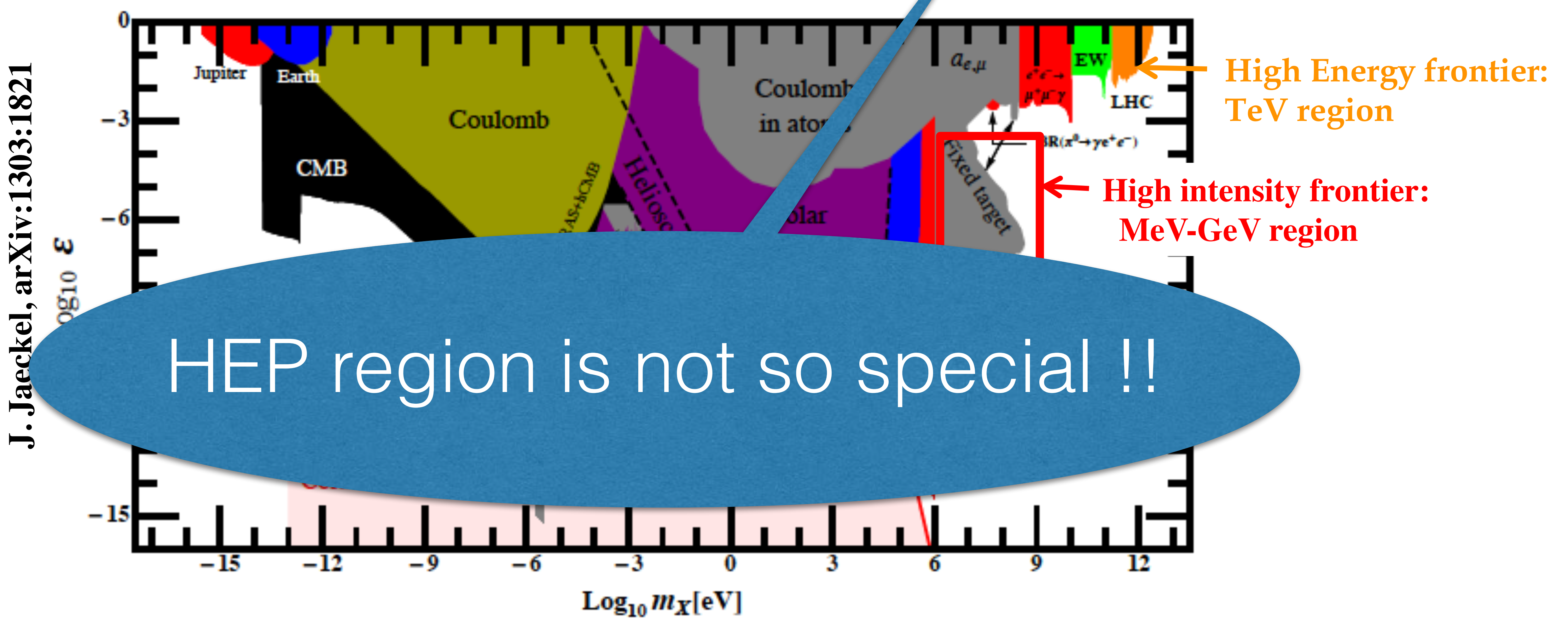

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Theoryfull strategy, status of naturalness

- Few slides to demystify naturalness.

- Despite results why is it embarrassingly still the best motivation for new physics in HEP.

- Why things are possibly actually worse conceptually ? The relaxion & the naturalness logarithmic crisis.

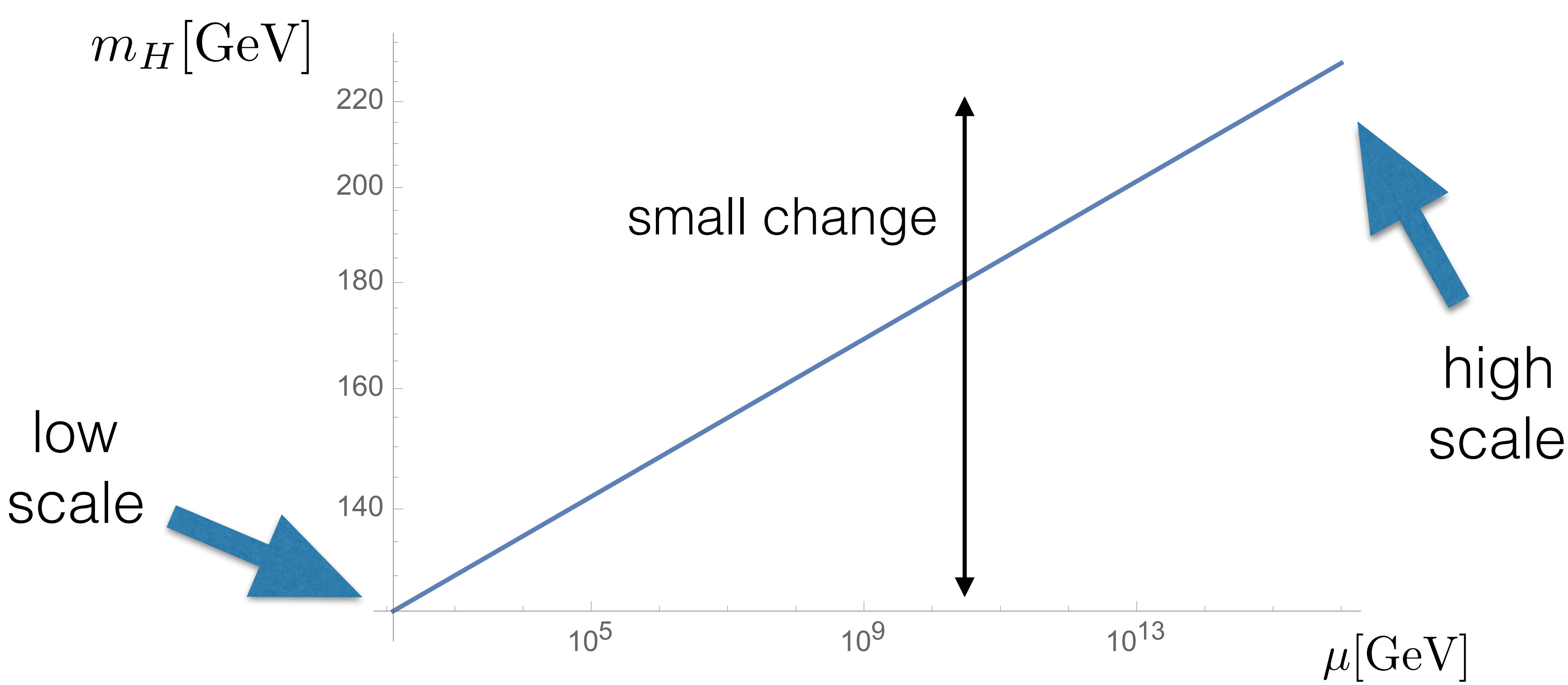
The Higgs hierarchy/naturalness/fine-tuning problem

Giudice (13)

- Without new-dynamical scale the fine tuning problem problem is ill define;

  => Higgs naturalness is a UV problem.

Higgs RGE, bottom up is natural: $$\frac{dm_H^2}{d\ln\bar{\mu}^2} = \beta_m^{\rm SM} m_H^2, \qquad \beta_m^{\rm SM} = \frac{3}{4}\frac{4y_t^2 + 8\lambda - 3g^2 - g_Y^2}{(4\pi)^2}.$$



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Add particle w coupling λ_N & mass M $\Rightarrow$ Farinaa, Duccio Pappadopulo & Strumia (14)

Higgs finite additive correction: $$\frac{dm_H^2}{d\ln\bar{\mu}^2} = \frac{4\lambda_N^2}{(4\pi)^2}M^2 + \beta_m^{\rm SM} m_H^2$$

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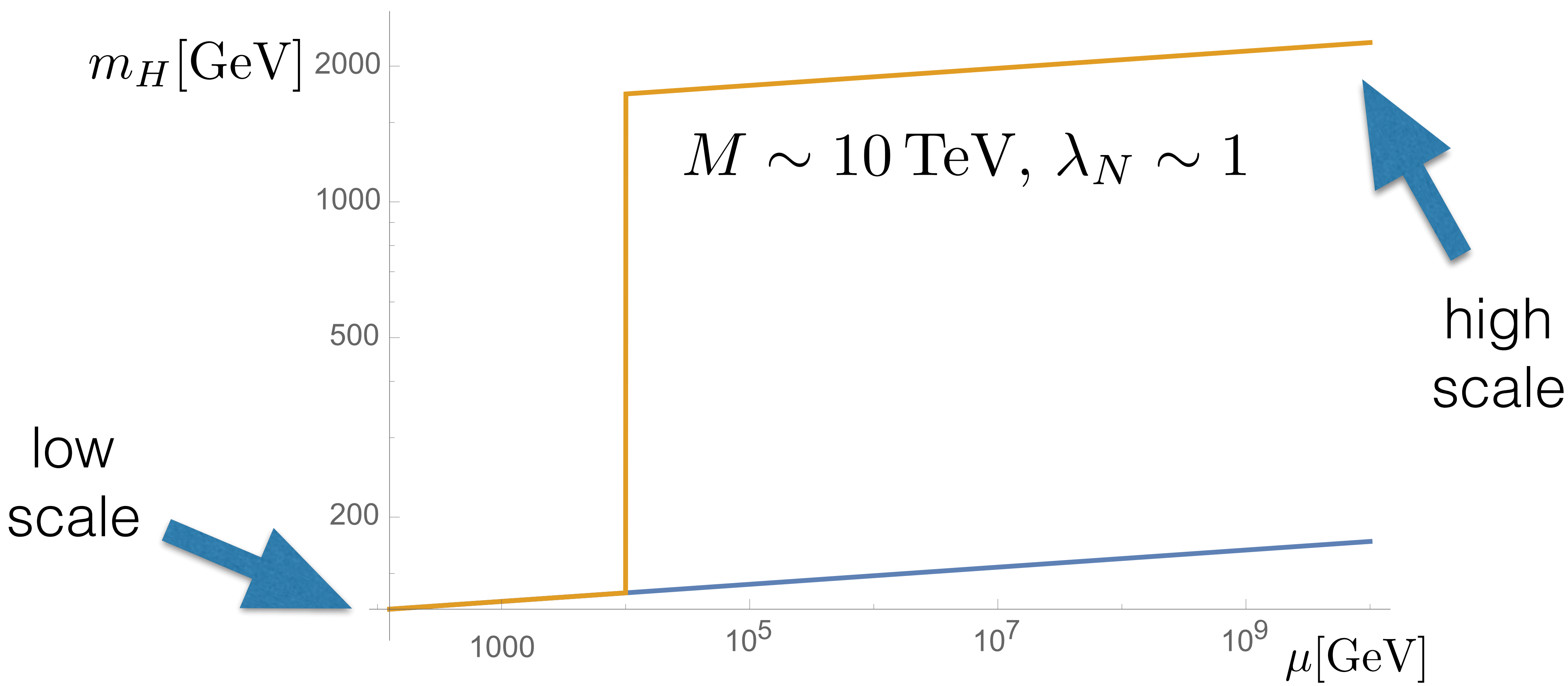

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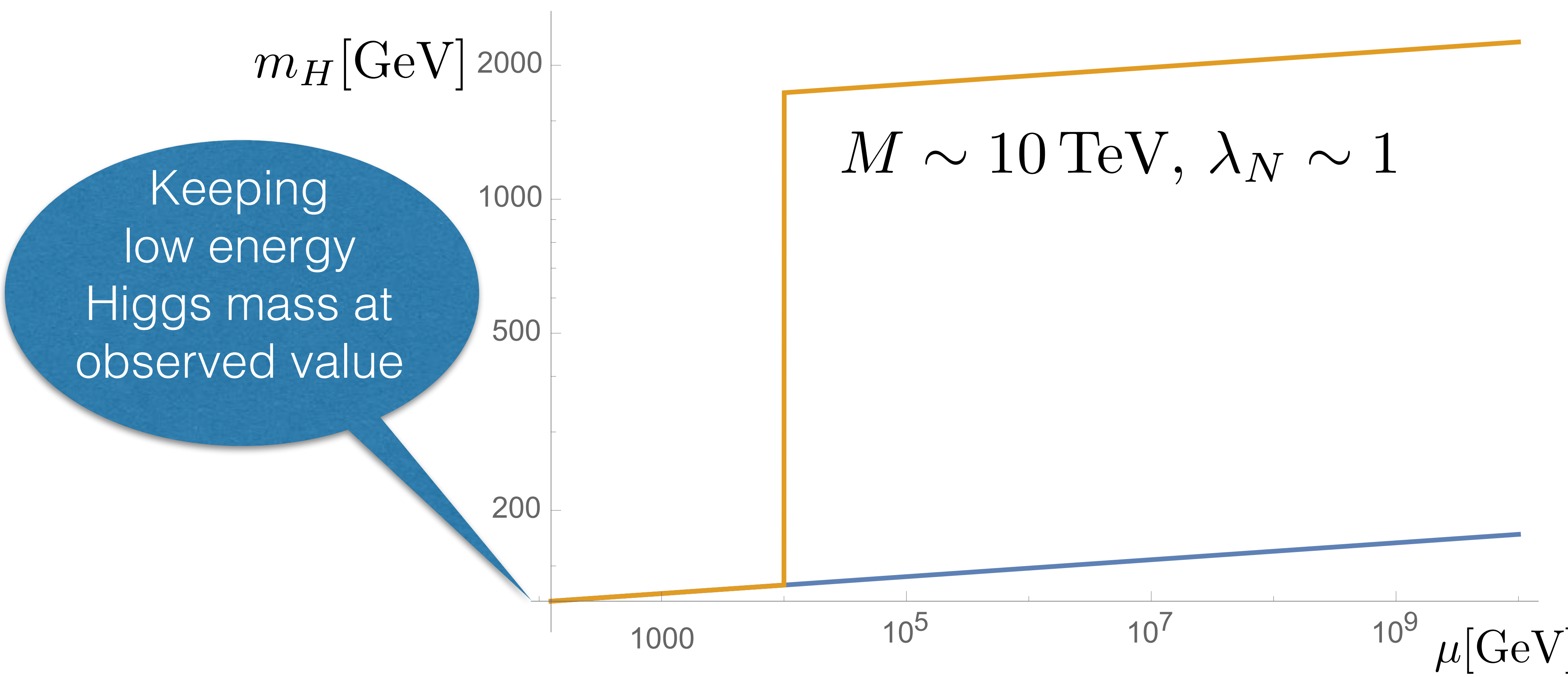

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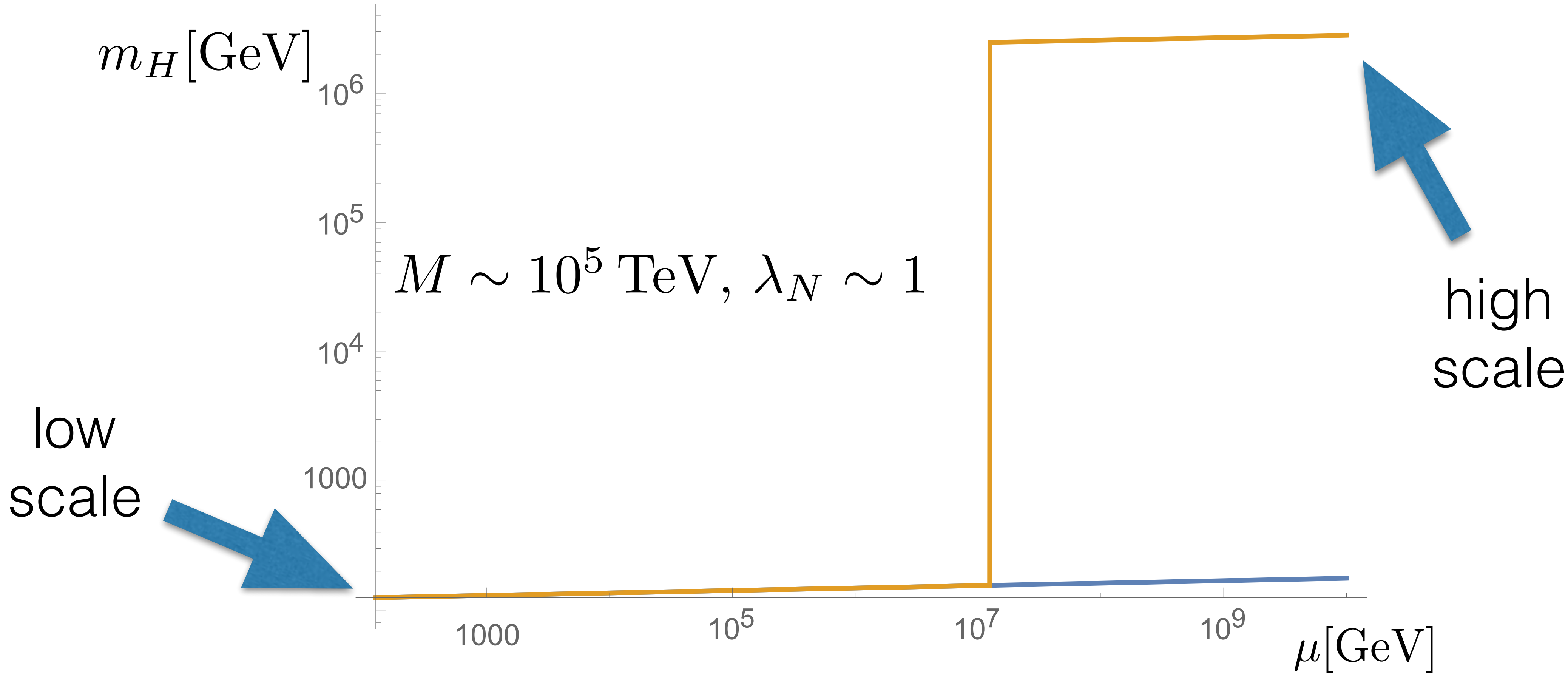

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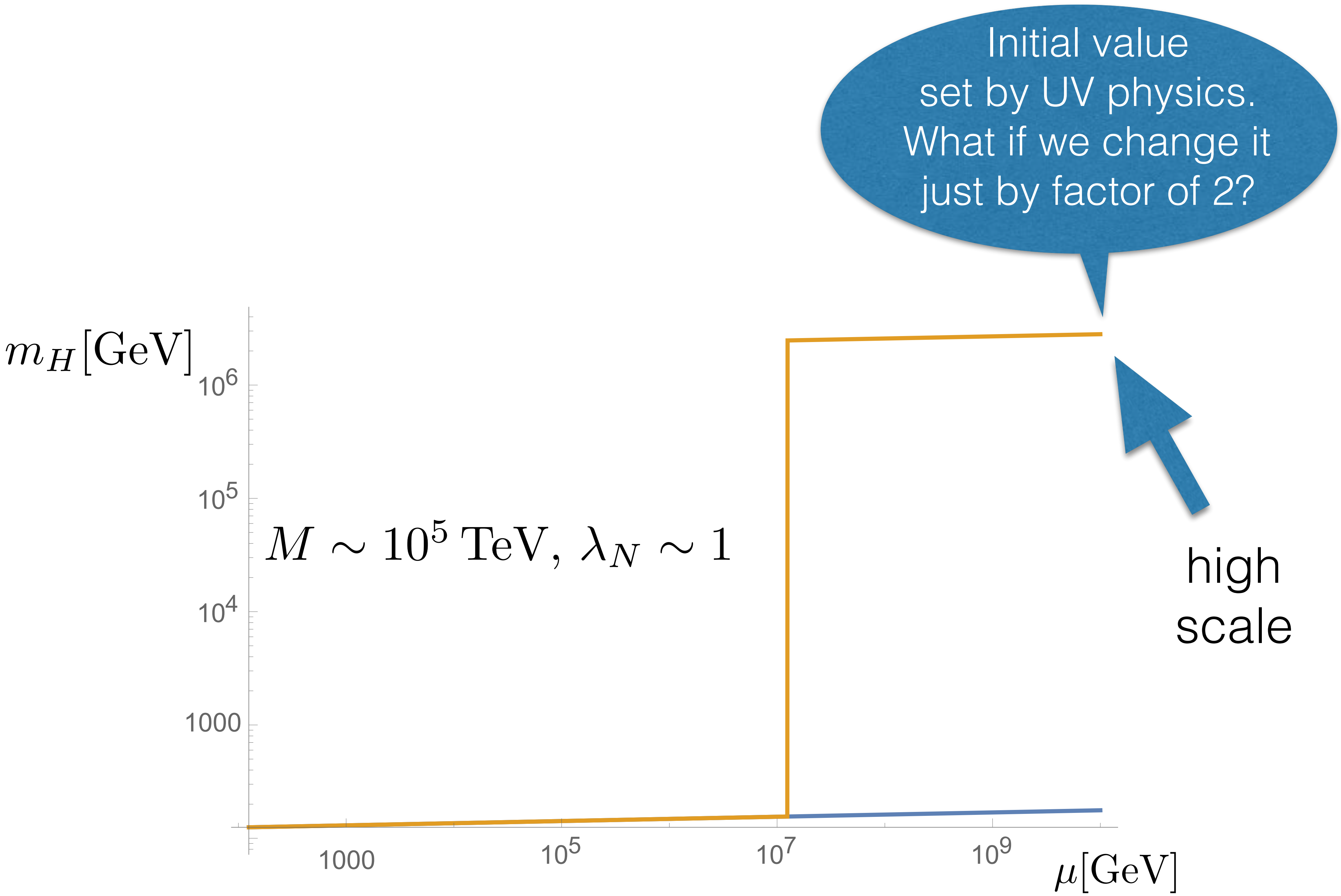

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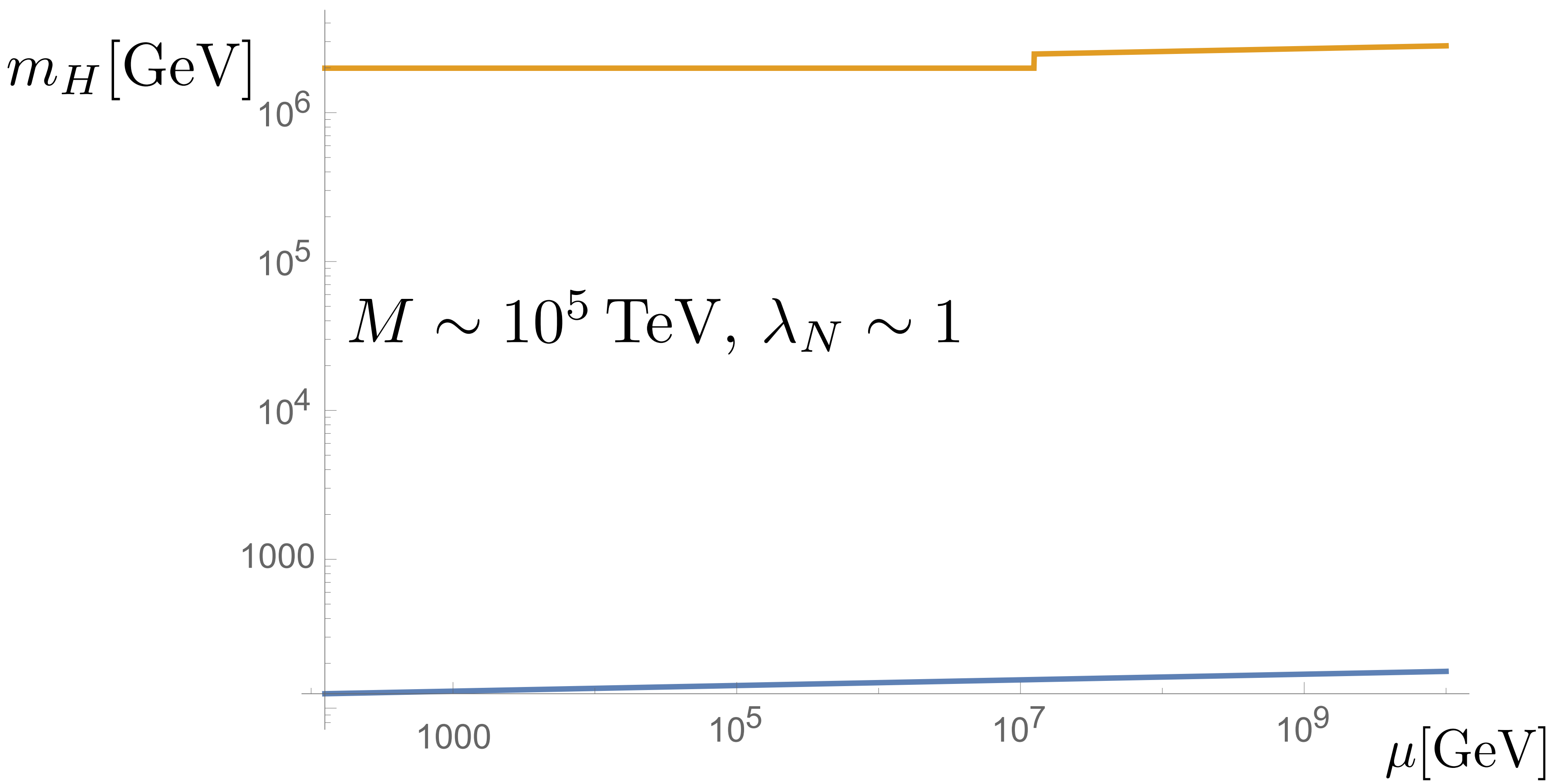
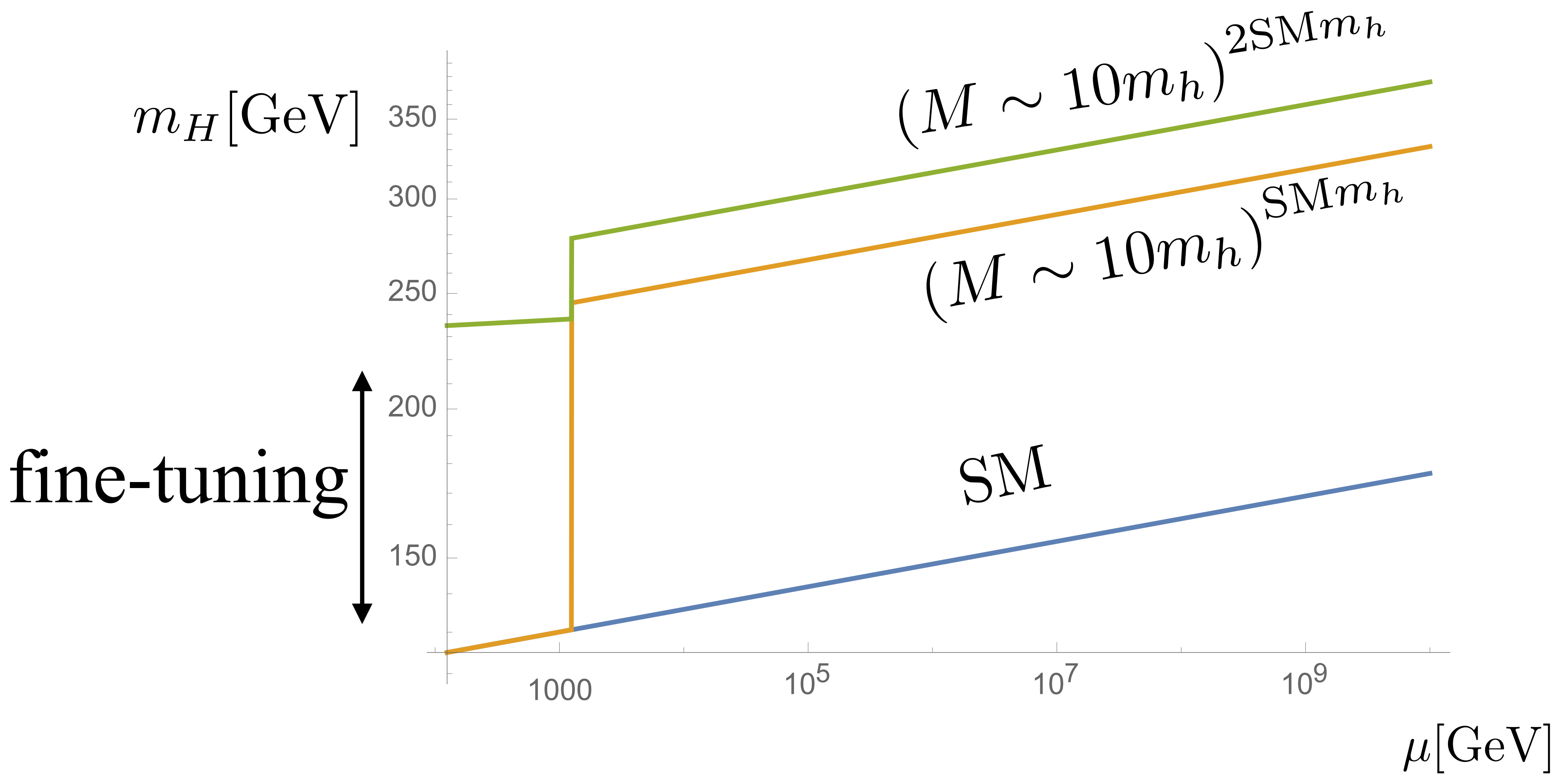
The Higgs mass pushed to M => inconsistent \w data.

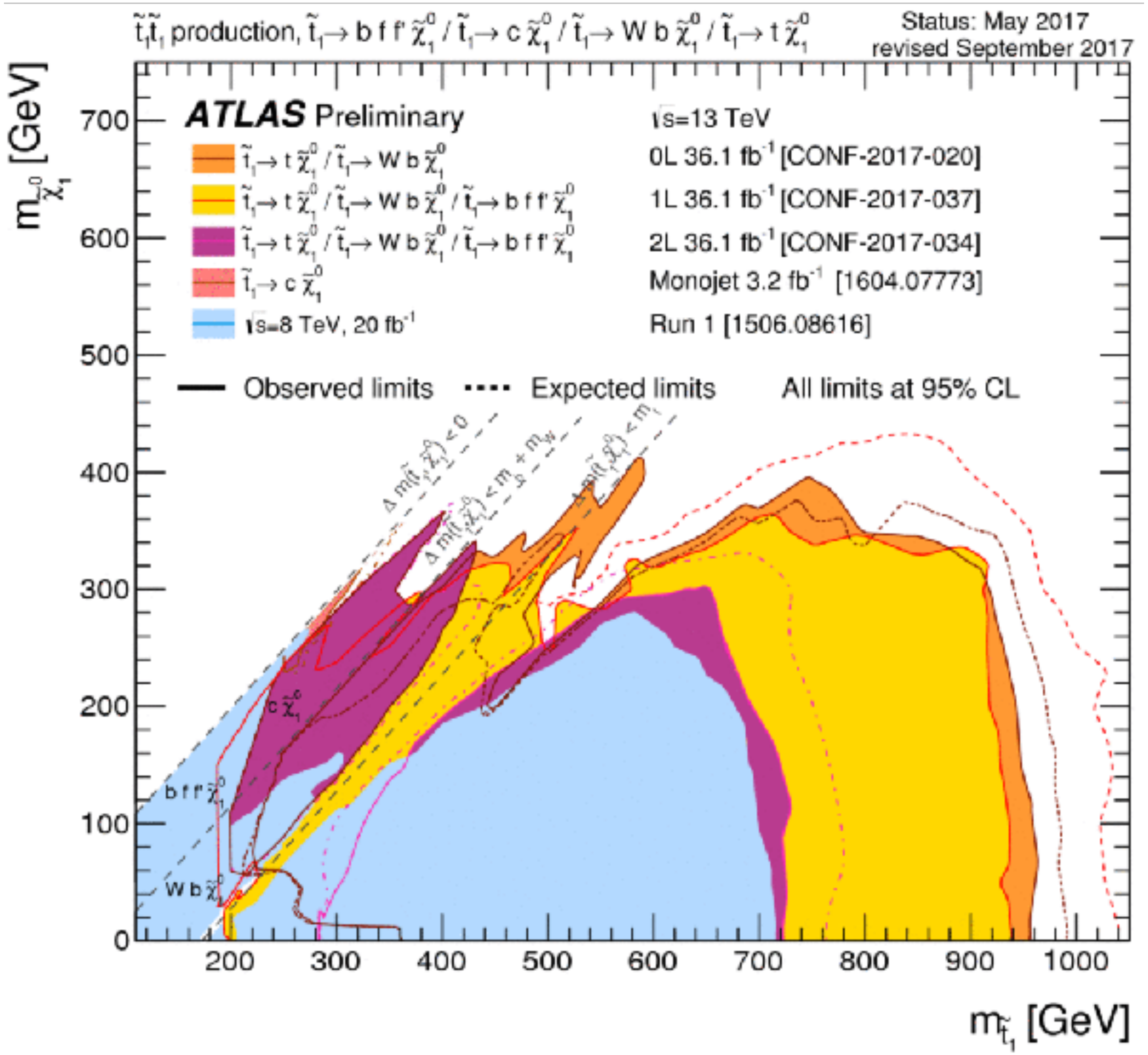


Naturalness gives us motivation to look for $\lesssim$ TeV new particles

Higgs mass evolution in natural theories



The LHC depression - “naturalness is dead”

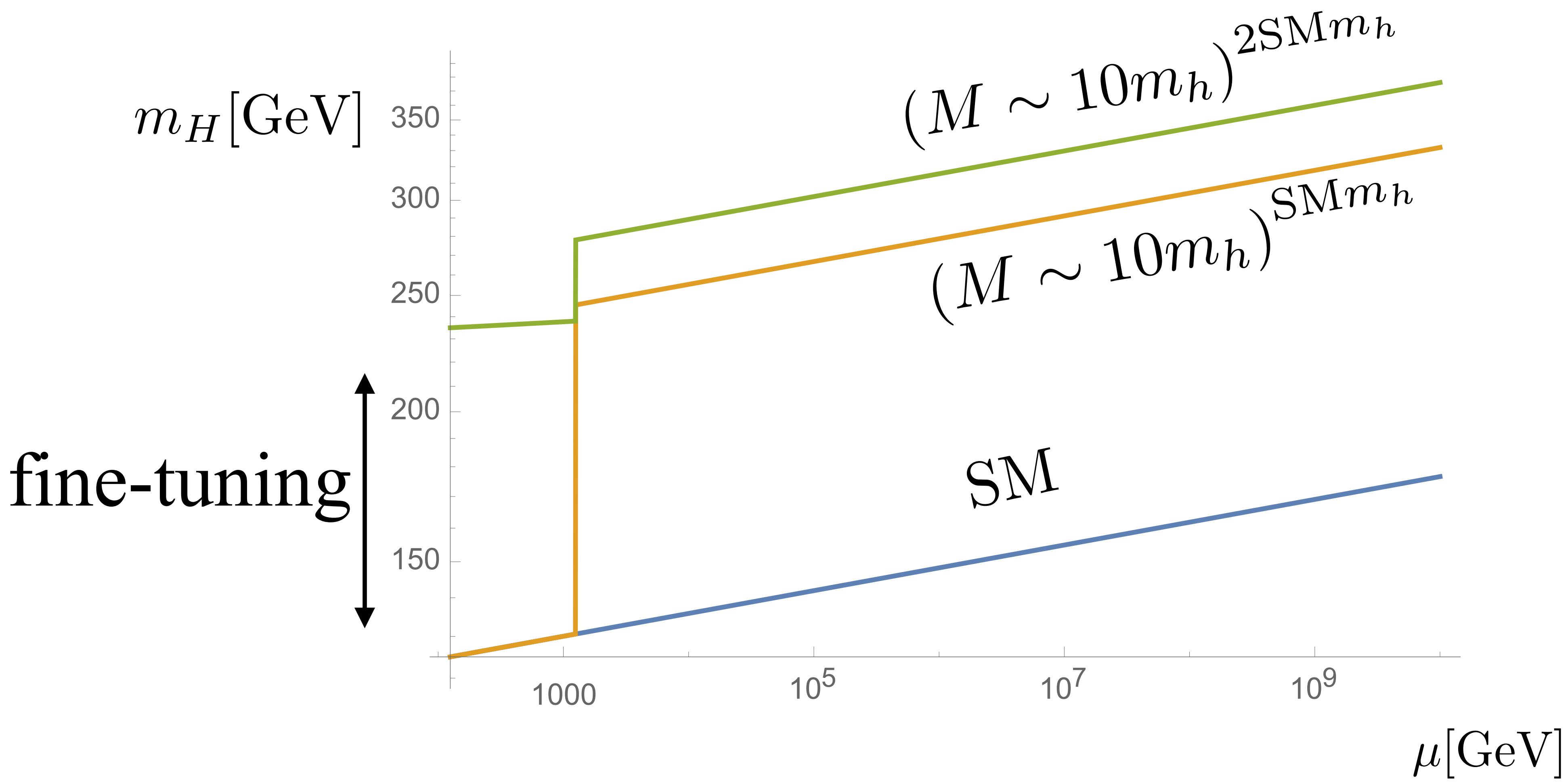


However:

Two reasons for why this logic is not bullet proof:

(i) for the high-energy colliders
(ii) new & welcome lepton-colliders

First: naturalness is *not* black & white measure



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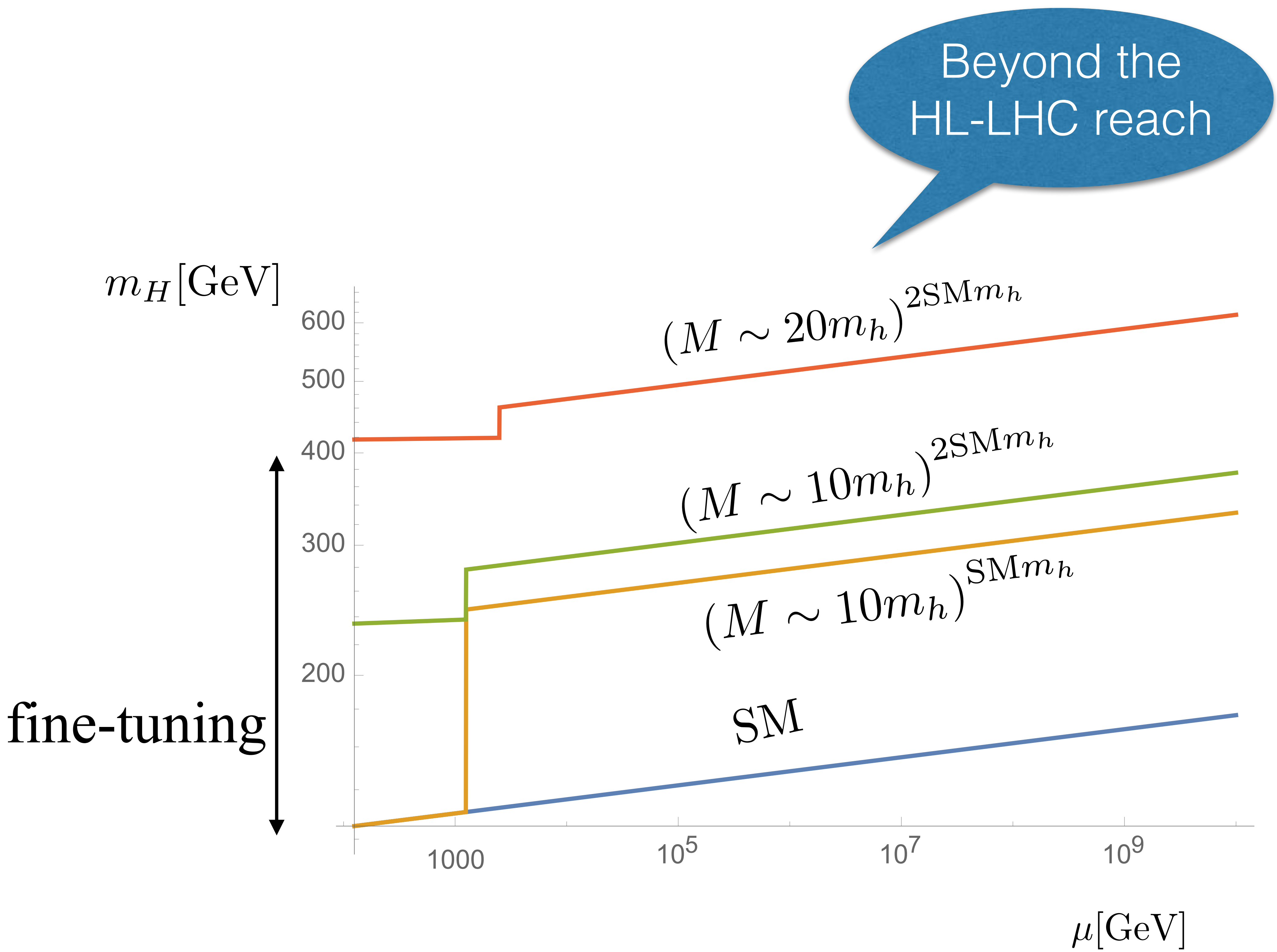

Second: relaxion - naturalness ≠> TeV new physics

Graham, Kaplan & Rajendran (15)

- A dynamical solution/amelioration of the Higgs fine-tuning problem:

(i) Add a scalar (relaxion) Higgs dependent mass: $\overbrace{\left(\Lambda^2 - g^2\phi^2\right)}^{\mu^2(\phi)} H^\dagger H$.

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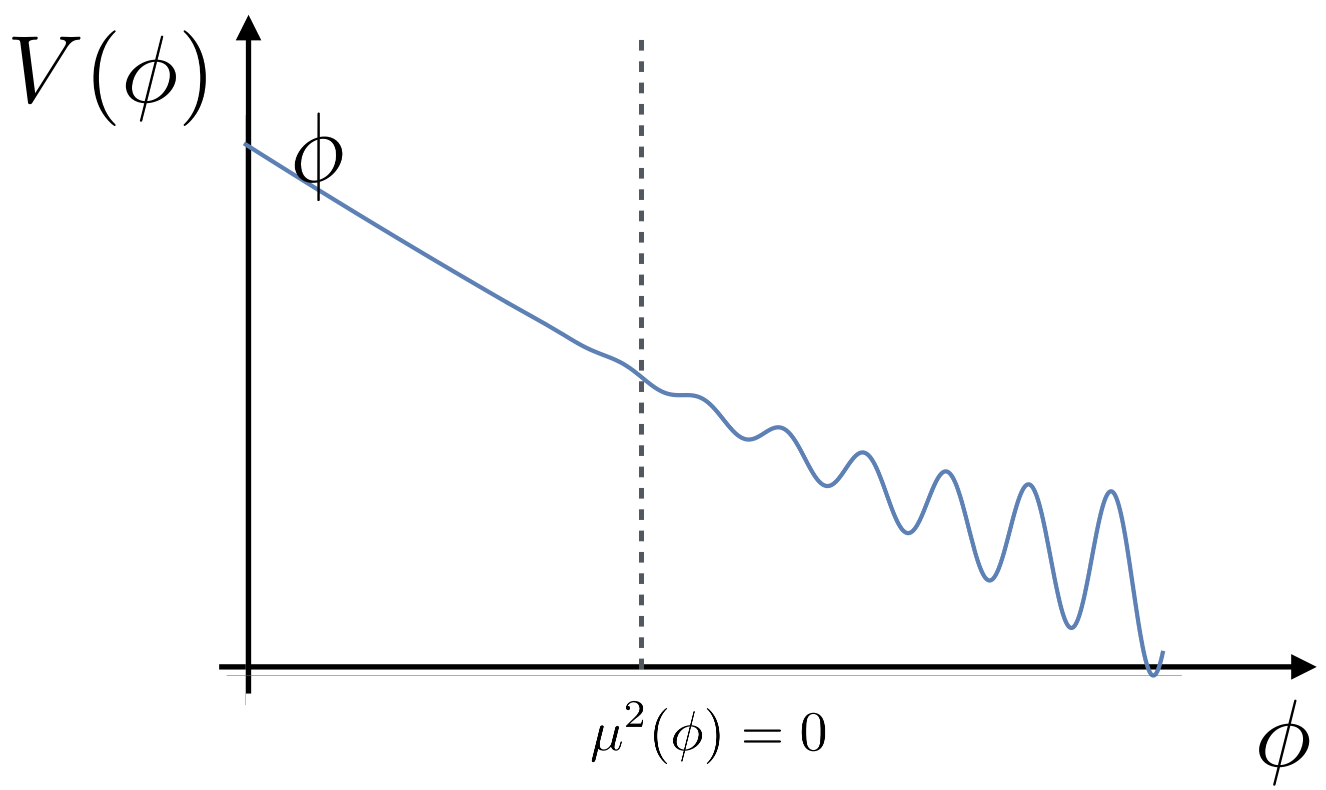
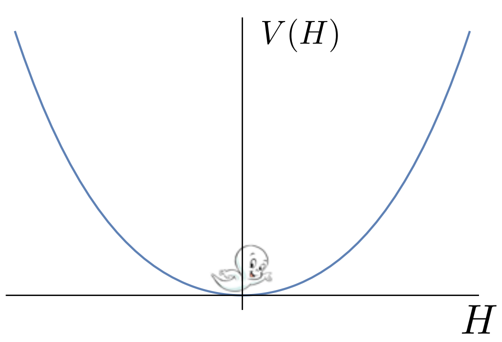




Focus shifts from Higgs to relaxion dynamics

- Can we even search for relaxion? Yes! How?

- Different pheno', no partners. (stops/t', gauginos/KK Z's …)

- In most (but not all) cases, the relaxion is a pseudo-Nambu-Goldstone-Boson that (due to CP violation) mixes w the Higgs.

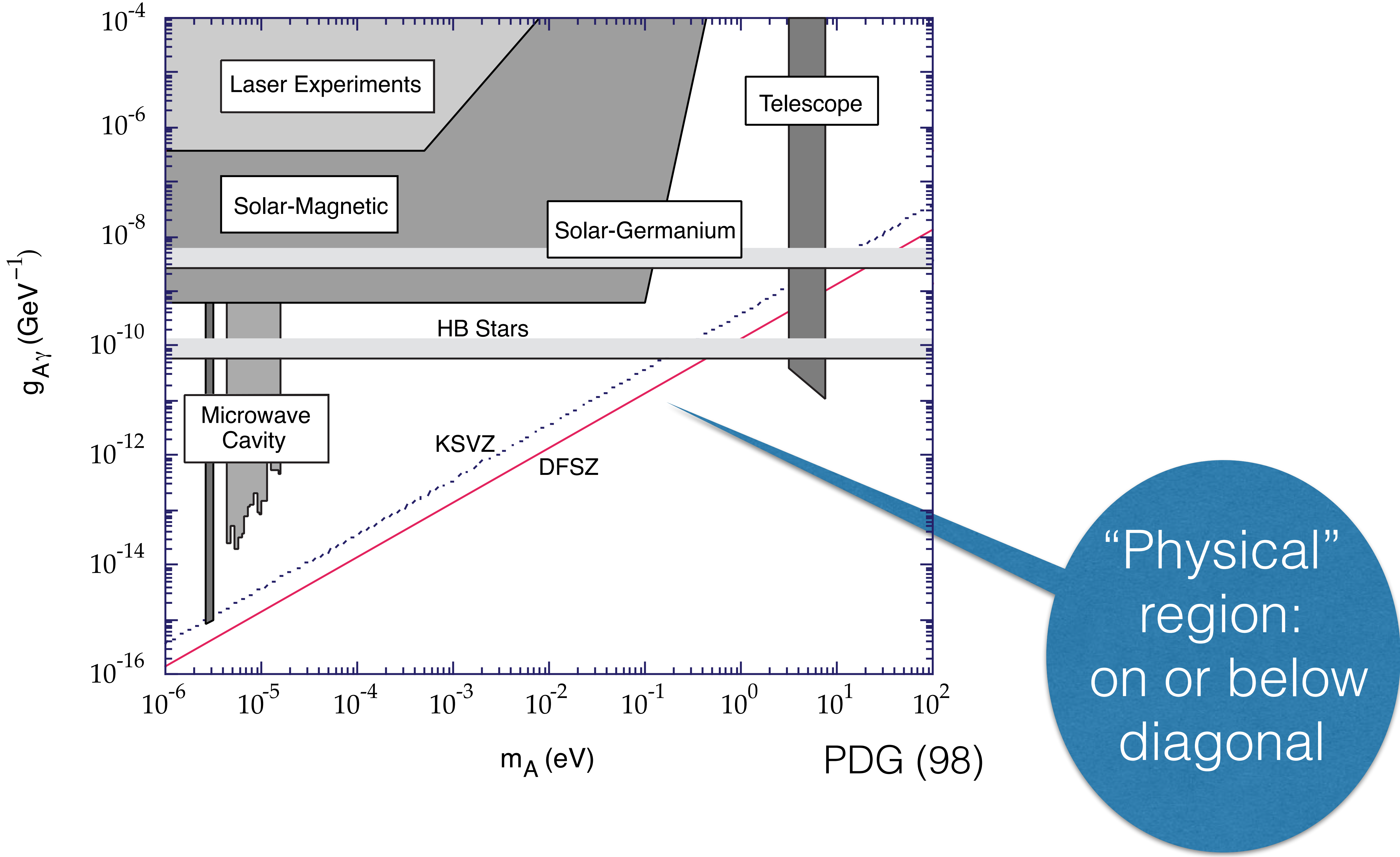
Flacke, Frugiuele, Fuchs, Gupta & GP; Choi & Im (16)

- It implies that we can simplify its coupling to two parameters, mass & Higgs-mixing angle, with:

$$\sin\theta \lesssim \frac{m}{v} \lesssim 10\%\,, \qquad m \lesssim \frac{v^2}{f} \lesssim 30\,\mathrm{GeV} \times \frac{f}{\mathrm{TeV}}\,. \qquad (v = 174\,\mathrm{GeV})$$

The relaxion parameter space, first analogy w axion

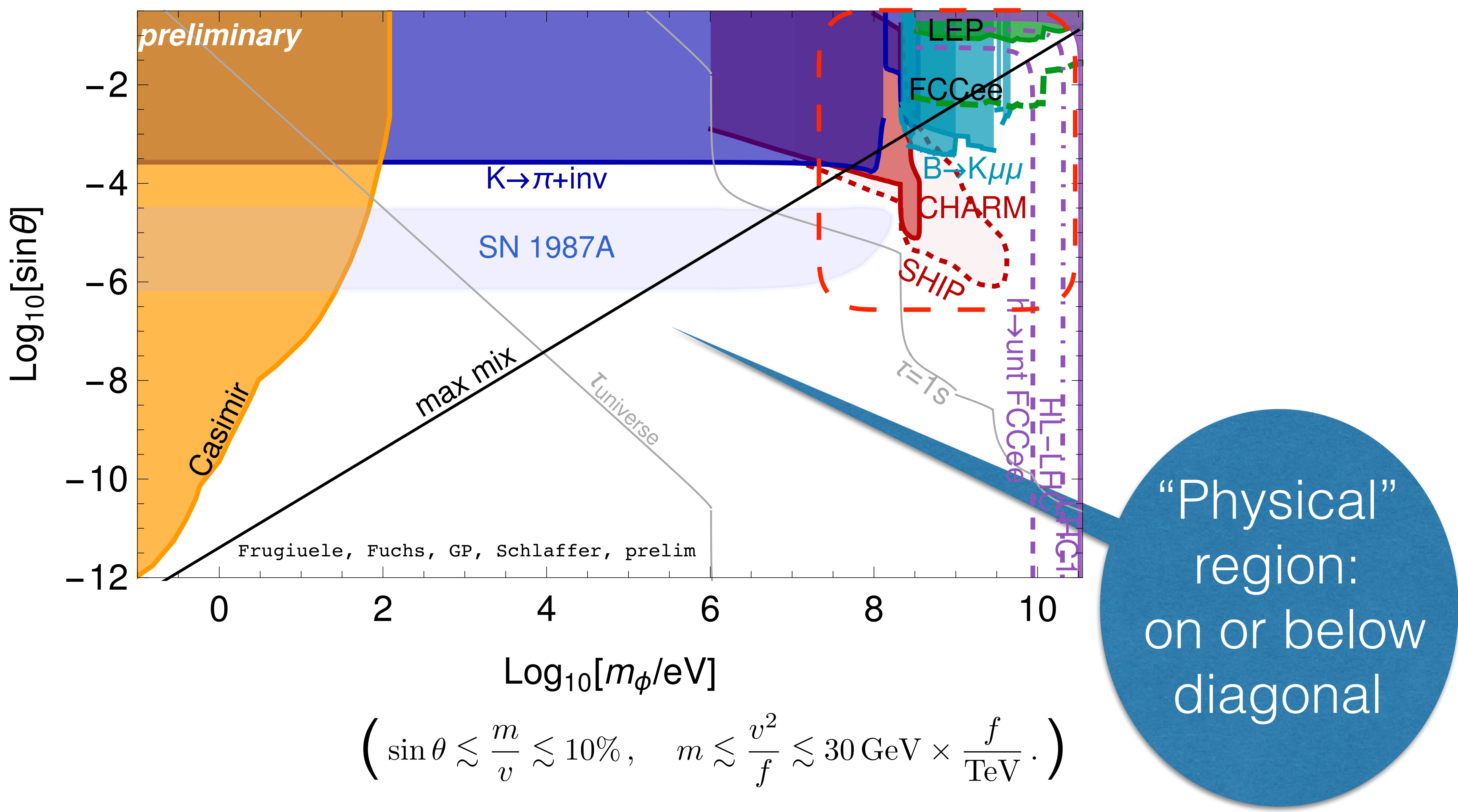
(back to *log* scale }-;)



The relaxion parameter space, overview plot

Frugiuele, Fuchs, GP, Schlaffer, in preparation.

Bad news: *log* scale naturalness searches;
Good news: it seems that hep/colliders can probe physical region!

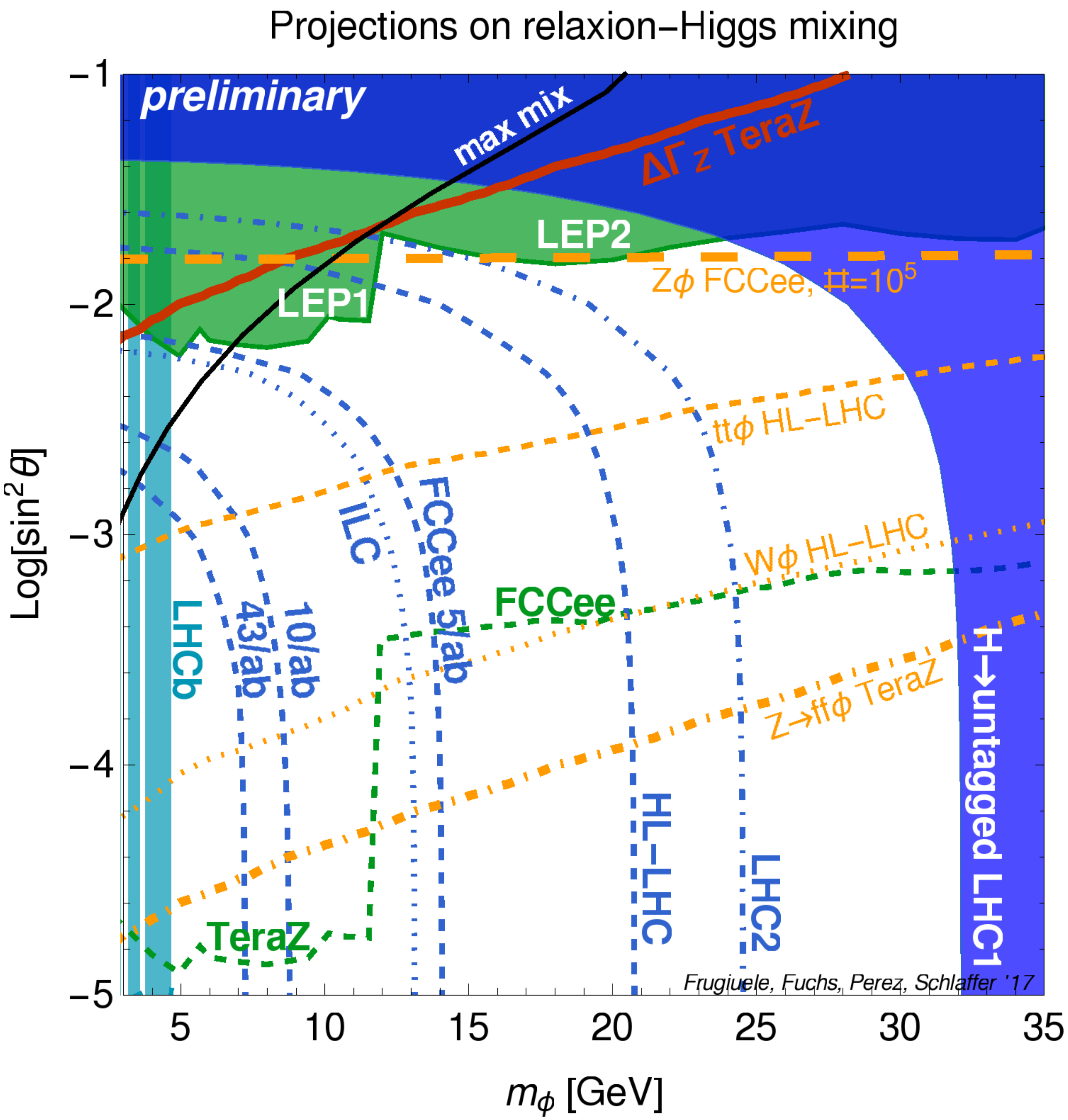


$$\left(\sin\theta \lesssim \frac{m}{v} \lesssim 10\% \,, \quad m \lesssim \frac{v^2}{f} \lesssim 30\,\text{GeV} \times \frac{f}{\text{TeV}} \,. \right)$$

Zooming in on the region accessible to colliders

Frugiuele, Fuchs, GP, Schlaffer, in preparation.

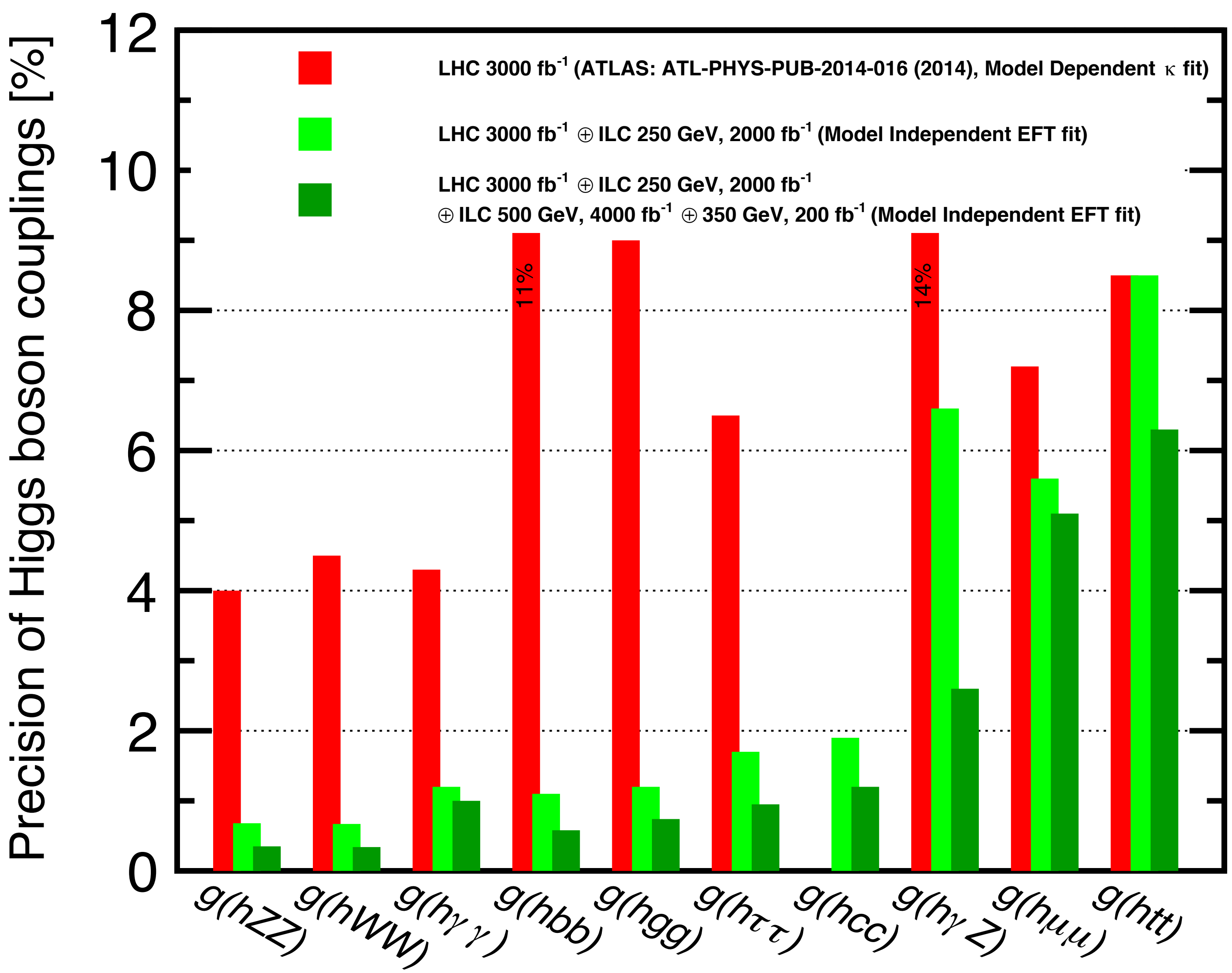
Lepton machines with large # of Z/H probe sizable region!
Same holds for HL-LHC & SHiP.



One slide on standard candles

Several SM coupling have not yet observed directly

♦ A conservative approach would be to attempt and measure these, in particular within the Higgs sector.



Fujii et al (2017)

♦ Lighter generation couplings required to establish the SM flavor picture are not shown.

Summary

♦ HEP was special => energy (E) frontier guaranteed discoveries.

♦ Reaction => discard theory - pragmatically move to signature based strategy - limited when planning to the future (what learnt?).

♦ Observationally-driven approach => log-crisis.

♦ Naturalness => possibly best motivation for E-frontier.

♦ Relaxion => undermine the energy frontier however motivates for Higgs precision frontier via relaxion-Higgs mixing.

Backups

Relaxion's basic structure

- QFT consistent constructions are of the form:

Choi, Kim & Yun (2014) Choi & Im; Kaplan & Rattazzi; Gupta, Komargodski, GP & Ubaldi (15)

$$V(\phi, H) = H^\dagger H[\Lambda^2 - \overbrace{M^2}^{(\text{GKR: } g\sim M/f)} \cos(\phi/f)] + r\Lambda^2 M^2 \cos(\phi/f) + H^\dagger H \tilde{M}^2 \cos(n\phi/f)\,.$$

$$V'(\phi_*, v) = 0 \;\Rightarrow\; r\Lambda^4 \sin(\phi_*/f) \simeq v^2 n \tilde{M}^2 \sin(n\phi_*/f) \;\Rightarrow\; \phi_* \text{ is generic.} \quad (M\sim\Lambda)$$

- It implies that generically:

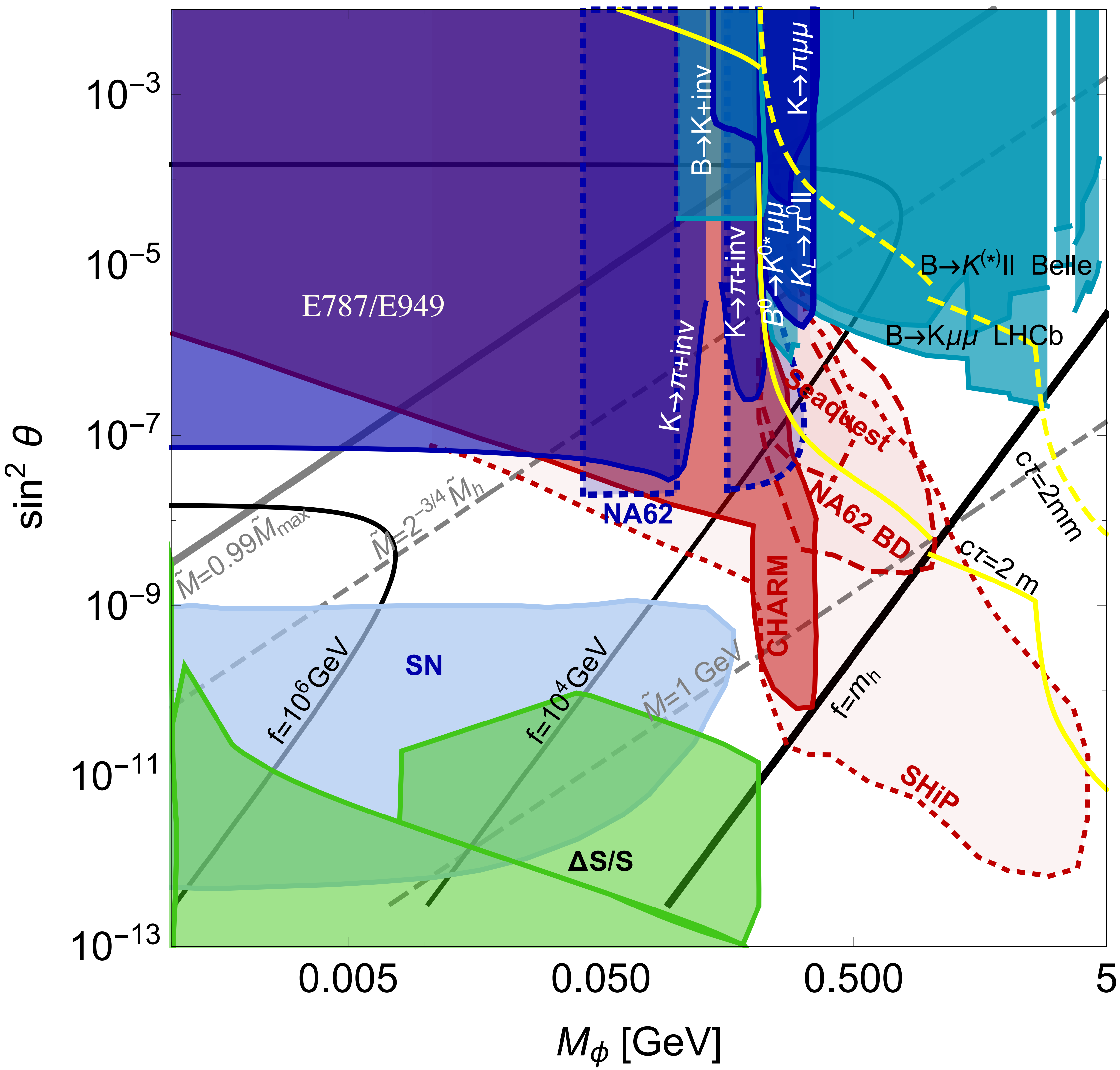
(i) CP violation is spontaneously induced (problematic for axion-relaxion models);

(ii) Higgs-relaxion mixing is induced:

$$V_{\rm mix} \sim \frac{nv\tilde{M}^2}{f}\sin(n\phi_*/f)\times H\phi_{\rm phys} \simeq \frac{r\Lambda^4}{vf}\sin(\phi_*/f)\times H\phi_{\rm phys}\,.$$

Relaxion beams, relaxion flavor

Flacke, Frugiuele, Fuchs, Gupta & GP (16).



Back to Original Relaxion Proposal

Graham, Kaplan & Rajendran (15)

$$\left(\Lambda^2 - g^2\phi^2\right) H^\dagger H \;\Rightarrow\; \phi_{\rm relaxed} \sim \frac{\Lambda}{g}\,; \quad (\text{assume} : \Lambda \gg v)$$

$$V(\phi) = r^2 g^2 \Lambda^2 \phi^2 - v^n M_X^{4-n} \cos(\phi/f) \;(\text{expect} : M_X < 4\pi v;\; 4 \geq n > 0)$$

$$V'(\phi) = 0 \;\Rightarrow\; \frac{\phi_{\rm relaxed}}{f} \gtrsim \left(\frac{\Lambda}{4\pi v}\right)^4 \times r^2 \qquad \left[g \lesssim \left(\frac{4\pi v}{\Lambda}\right)^4 \times \frac{\Lambda}{f r^2}\right]$$

Gupta, Komargodski, GP & Ubaldi (15)

$\Lambda \gg$ TeV $\Rightarrow \langle\phi\rangle \gg f$ required to be physical.

The (compact) Relaxion Proposal

Gupta, Komargodski, GP & Ubaldi (15)

$$\Lambda \gg \text{TeV} \Rightarrow \langle\phi\rangle \gg f \text{ required to be physical.}$$

However, finite dim' EFT: pNGB => compact manifold.

Again: $\phi \to \phi + 2n\pi f \ \ (n \in \mathcal{Z})$ lead to same physics.

This is a redundant description of the theory <=> discrete gauge sym' (no example \w local operator that breaks it)

As long as relaxion potential is controlled by global internal sym' EFT locality seems to implies compactness of pNGB manifold:

$$\langle\phi\rangle \lesssim f\,.$$

Brief: Comments on the Relaxion Proposal

Gupta, Komargodski, GP & Ubaldi (15)

Hence upon the identification:

$$\text{axion} \leftrightarrow \phi\,,\ \mathrm{U}(1) \leftrightarrow \mathrm{PQ}\,,\ \text{ and}$$

$$y_u H f_\pi^3 \ \text{ or } \ y_u^2 H^\dagger H f_\pi^2 \leftrightarrow m_L m_N y y_c H^\dagger H\,,$$

we expect a similar bound to hold:

$$\Lambda \lesssim 10\,\mathrm{TeV} \times \frac{\left[(yv)^{1,2} f_\pi^{3,2}\right]^{\frac{1}{4}}}{4\pi v} \times \left(\frac{1}{4\pi r}\right)^{\frac{1}{2}} \times \left(\frac{n}{10}\right)^{\frac{1}{4}}$$

Note: axion realisations also suffer from inflated n => irrelevant operators => tiny backreaction/fine tuning/monstrous beta function.

The hierarchion:
relaxion-familon-Nelson-Barr model

Davidi, Gupta, GP, Redigolo & Shalit (17)

Solving the CP problem - relaxion-Nelson-Barr

- The problem: relaxion spontaneously lead to order one CP Breaking.

- Nelson-Barr models solves the strong CP problem based on:

  (i) CP being spontaneously broken.

  (ii) Structure such the O(1) CP phase induce the O(1) CKM phase

  (unlike lore a potential advantage compare to axion models …)

If relaxion can be integrated to Nelson-Barr's structure => perfect marriage:

(i) Nelson-Barr reminder; (ii) Relaxion-Nelson-Barr.

Nelson-Barr (NB @ tree level)

Nelson; Barr (84)

real — complex, relaxion the only source of CP breaking.

$$\mathcal{L}_{\rm NB} = (\psi, Q) \begin{pmatrix} (\mu)_{1\times1} & (B_N(\phi))_{1\times3} \\ (0)_{3\times1} & (HY^d)_{3\times3} \end{pmatrix} \begin{pmatrix} \psi^c \\ d_i^c \end{pmatrix} + Y_u Q u^c H + h.c.$$

real

$$\mathrm{Arg}(\det M_q^{7\times7}) = \mathrm{Arg}(\det M_u)\mathrm{Arg}(\mu \cdot \det(vY^d)) = 0\,.$$

No strong CP phase.

CKM: Integrating out heavy fermions, assuming $\mu^2 + B_n B_n^* \gg v^2 Y_{ik}^d Y_{jk}^d$,

$$\left[M_d^{eff} M_d^{eff\dagger}\right]_{ij} \sim v^2 Y_{ik}^d Y_{jk}^d - \frac{v^2 Y_{ik}^d B_k B_\ell^* Y_{j\ell}^d}{\mu^2 + B_n B_n^*}$$

O(1) CKM phase.

Relaxion-Nelson-Barr (NB)

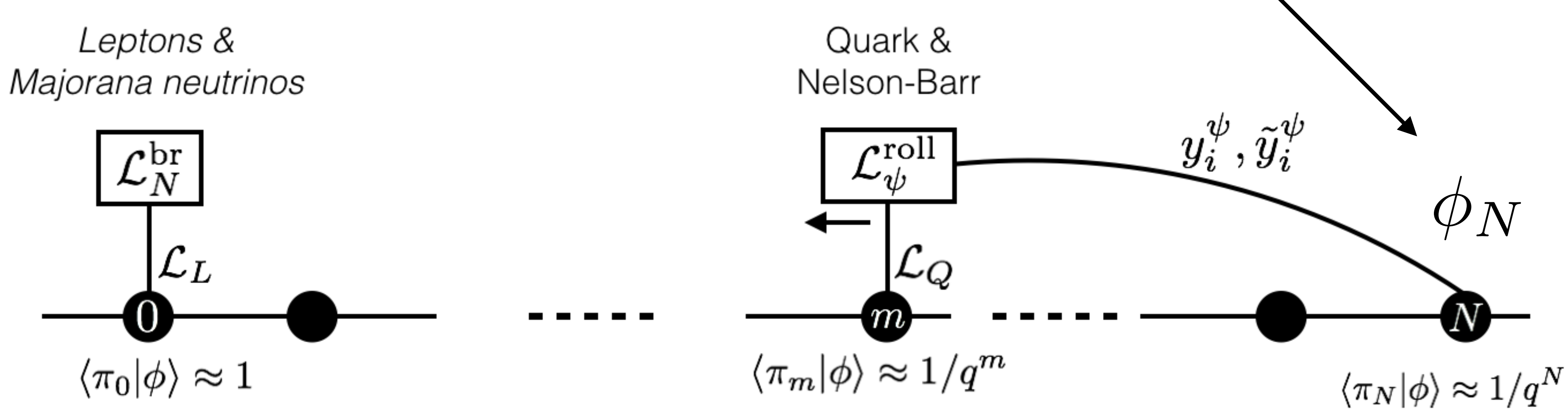
- Challenge - how to transmit relaxion's complex VEV to quark matrix:

$$\text{Original model - } B_i \leftrightarrow (g\phi + \tilde{g}\phi^*)\,\psi d^c\,.$$

$$\text{Relaxion-NB - } B_i \leftrightarrow (g\phi_N + \tilde{g}\phi_N^*)\,\psi d^c\,.$$

$$\phi_N \sim \rho_N \exp\left(i\phi/3^N f\right)$$

Inducing a phase + rolling potential!



Relaxion-familon

- U(1) preserving int' on site 1st & *m*'th => quark+lepton hierarchies.
- Traceless quark charges to avoid generating theta term.
- Explicit breaking on lepton sector a la Gupta et al yield backreaction.

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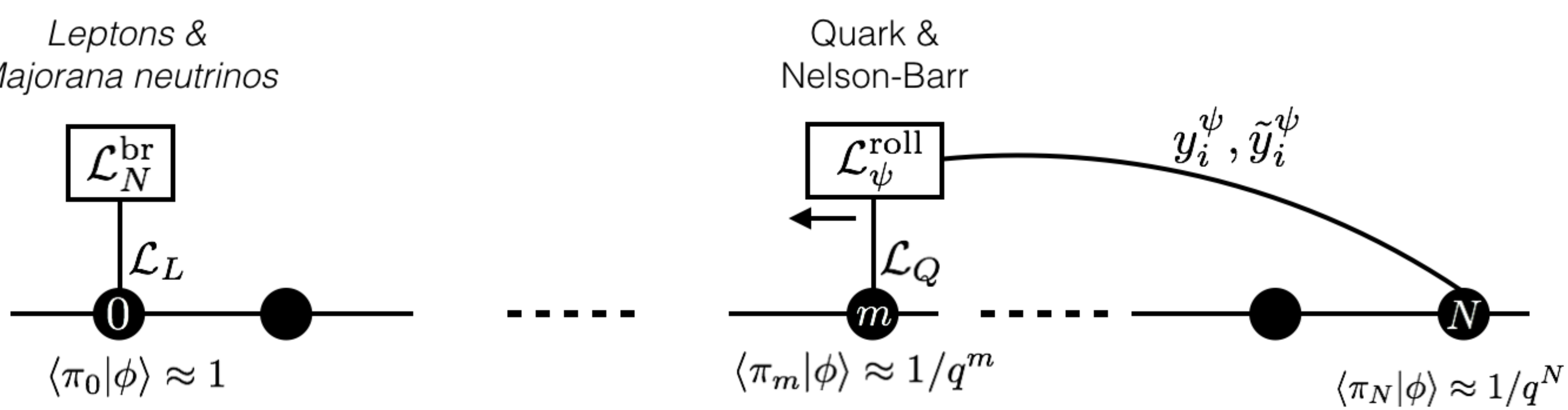
Hierarchion = Relaxion-familon-Nelson-Barr model of hierarchies



The main idea

Graham, Kaplan & Rajendran (15)

Relaxion's physics

Graham, Kaplan & Rajendran (15)

- A dynamical solution/amelioration of the Higgs fine-tuning problem:

(*i*) Add a scalar (relaxion) Higgs dependent mass: $\overbrace{\left(\Lambda^2 - g^2\phi^2\right)}^{\mu^2(\phi)} H^\dagger H$.

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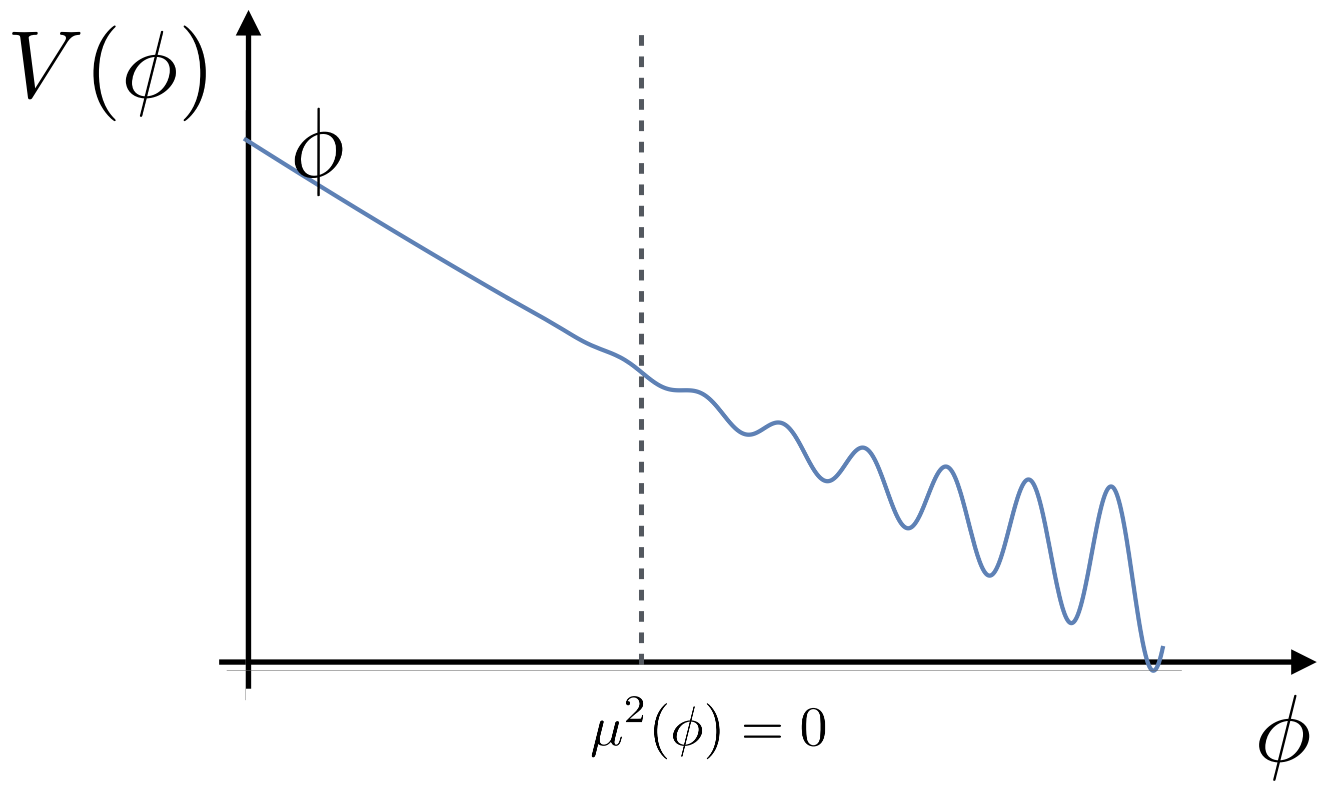

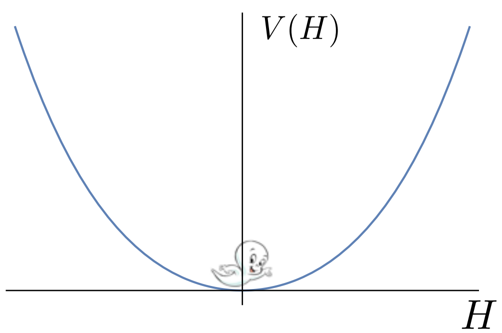

Relaxion mechanism

Graham, Kaplan & Rajendran (15)

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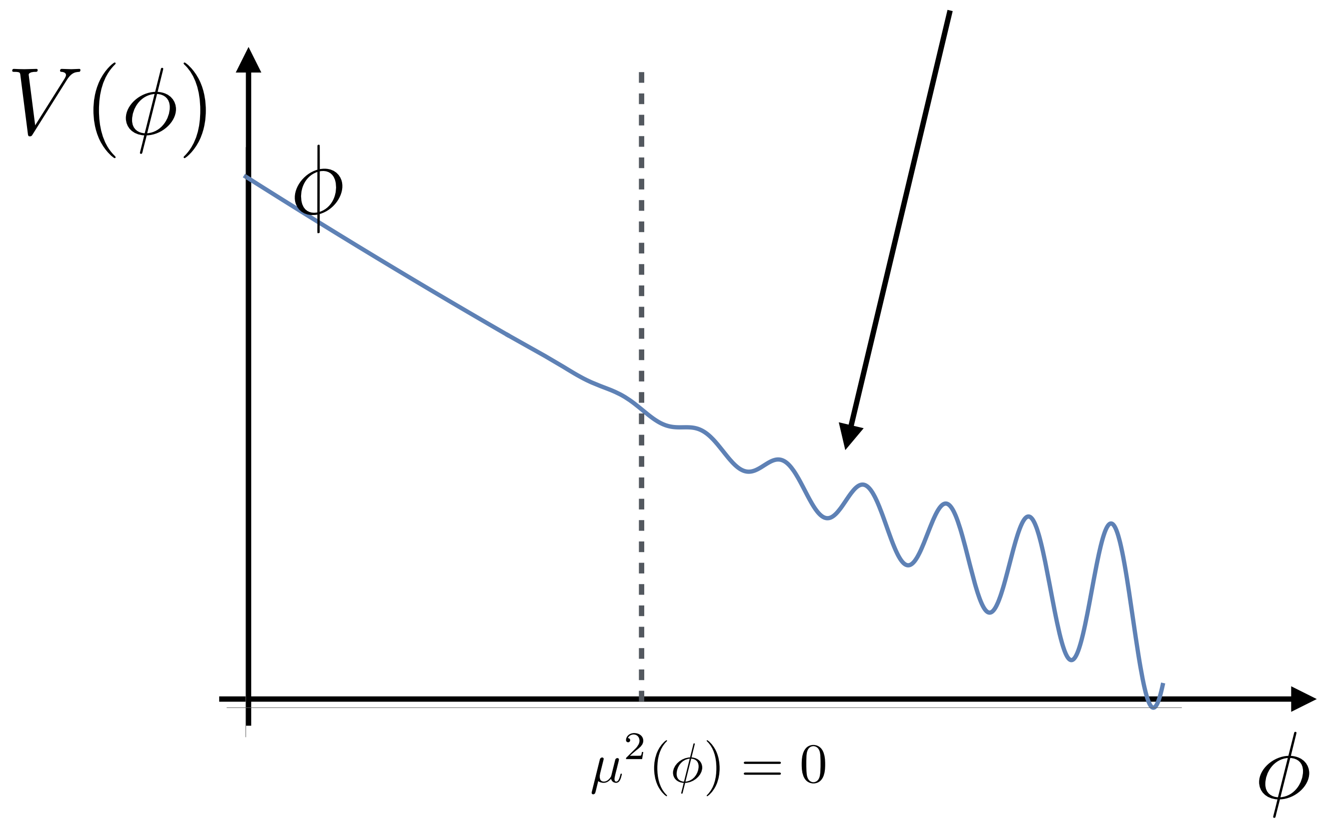

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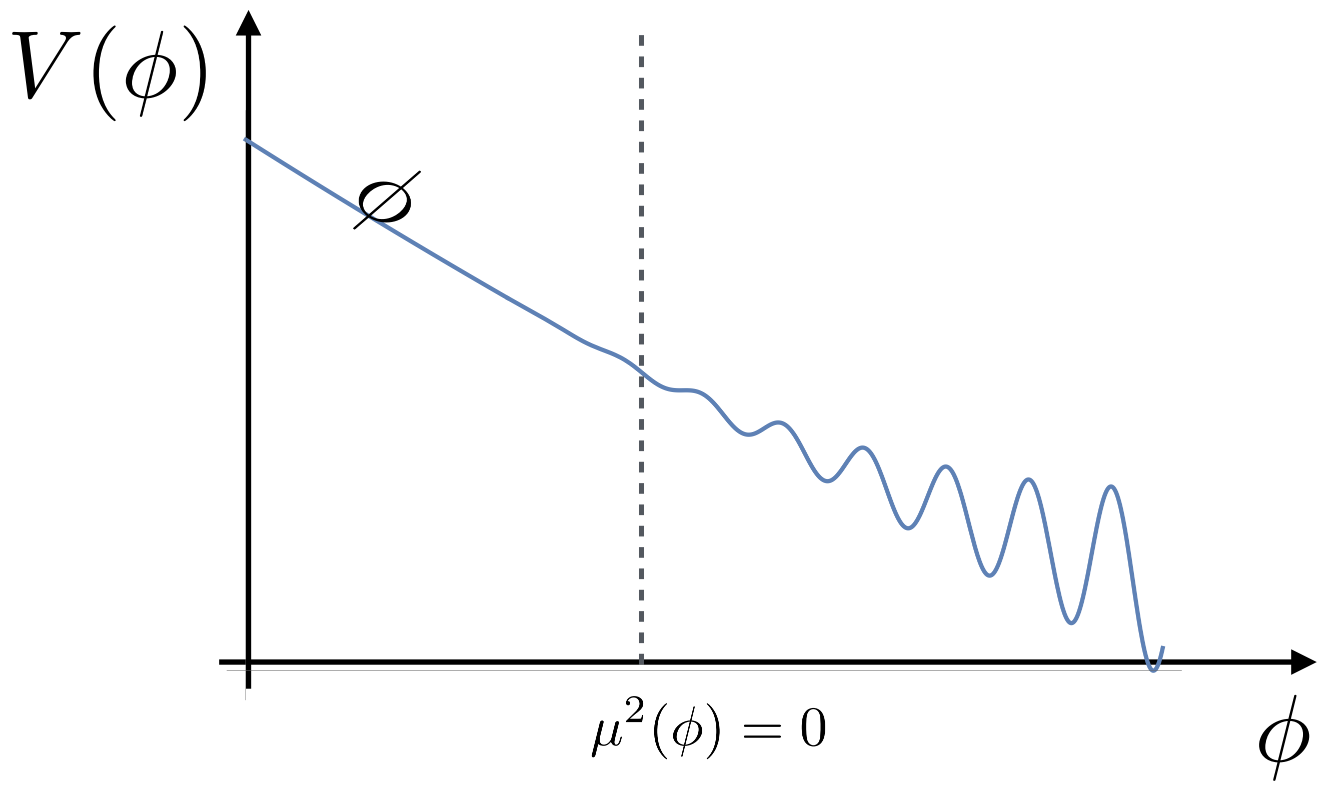

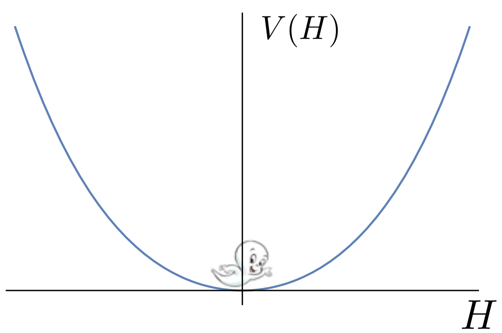

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Graham, Kaplan & Rajendran (15)

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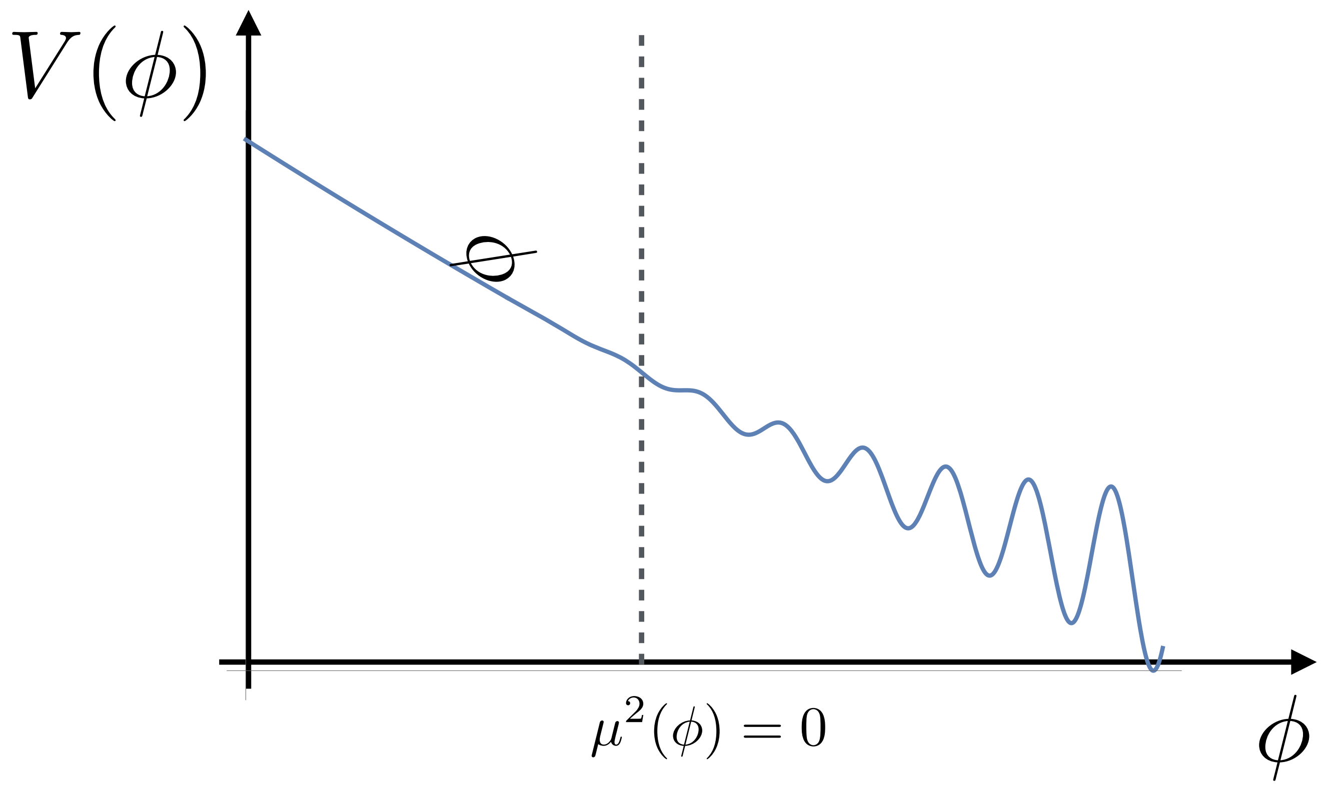

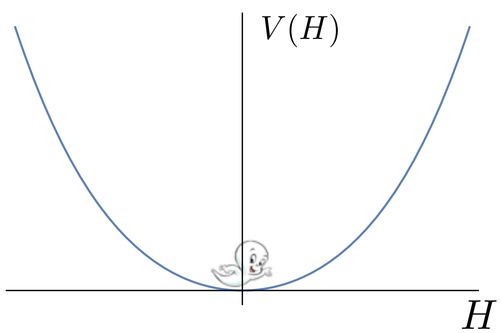

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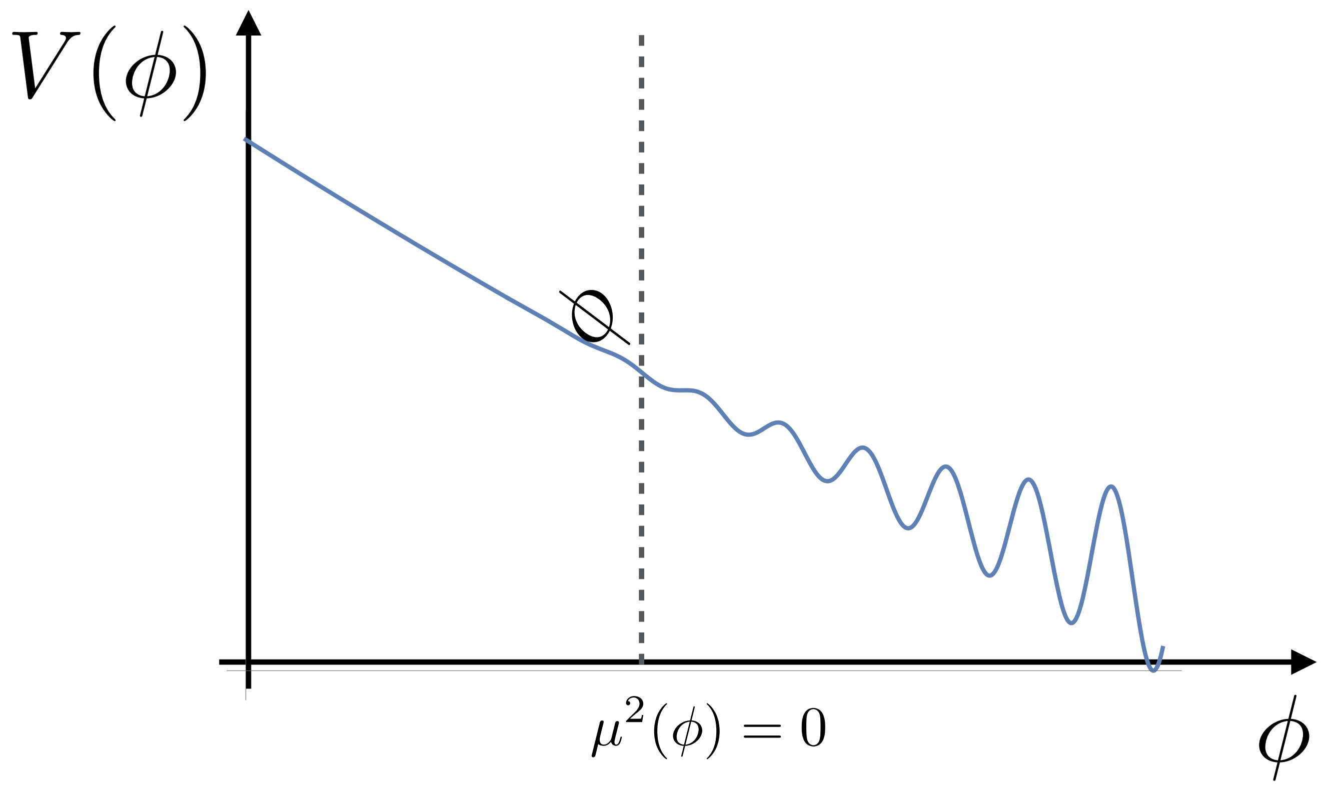

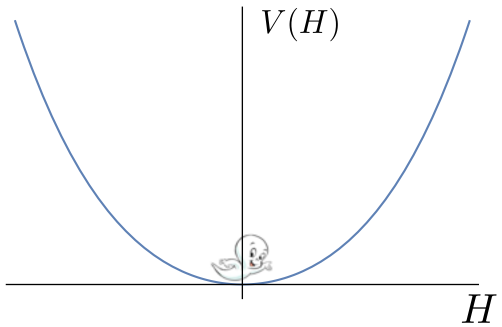

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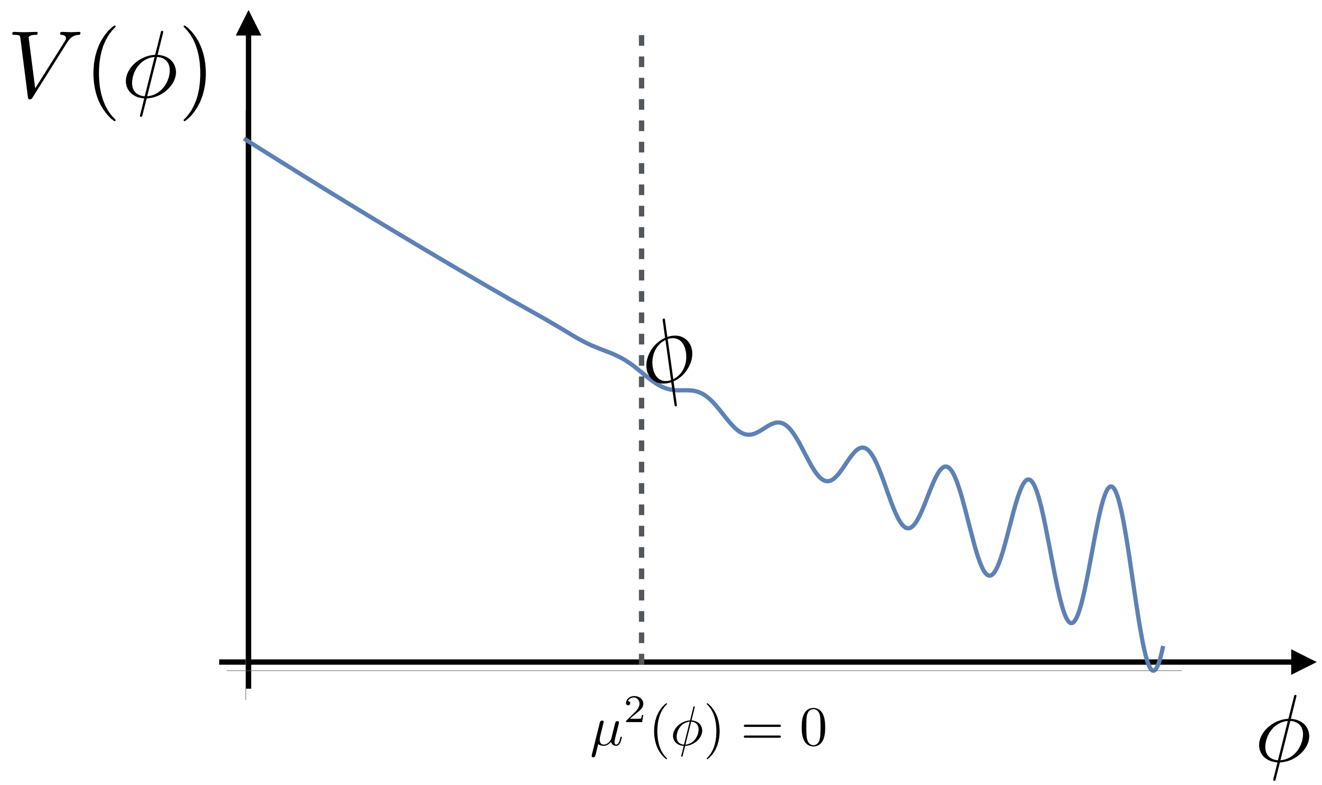

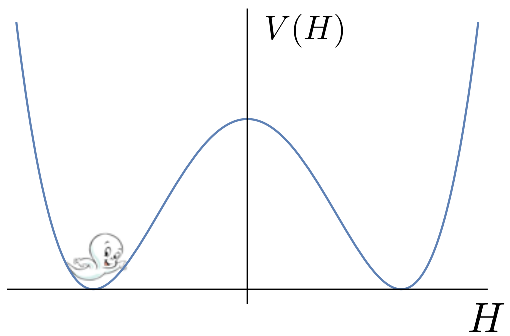

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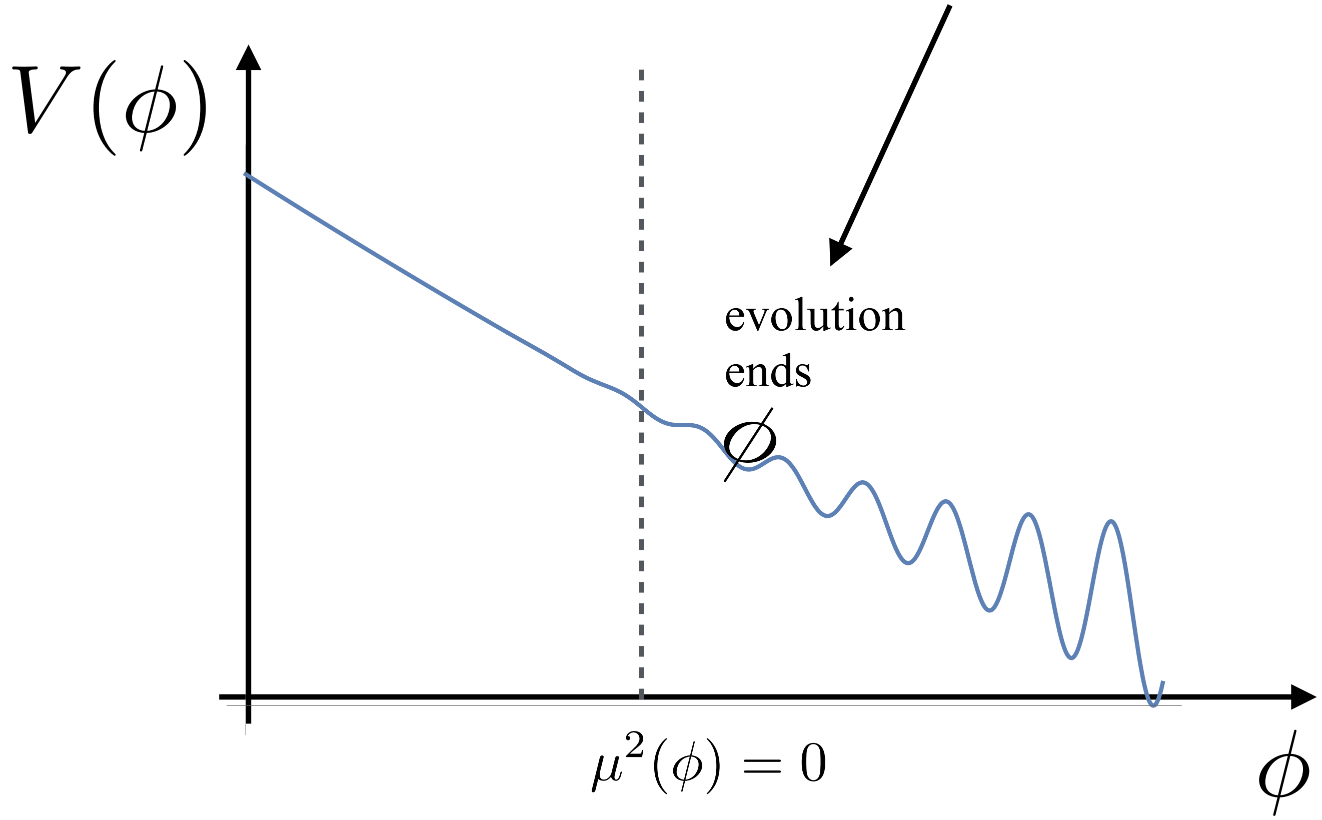

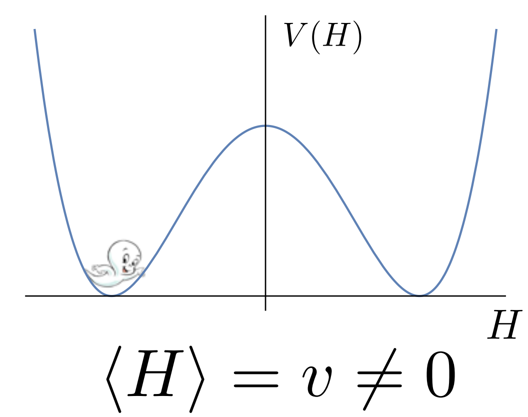

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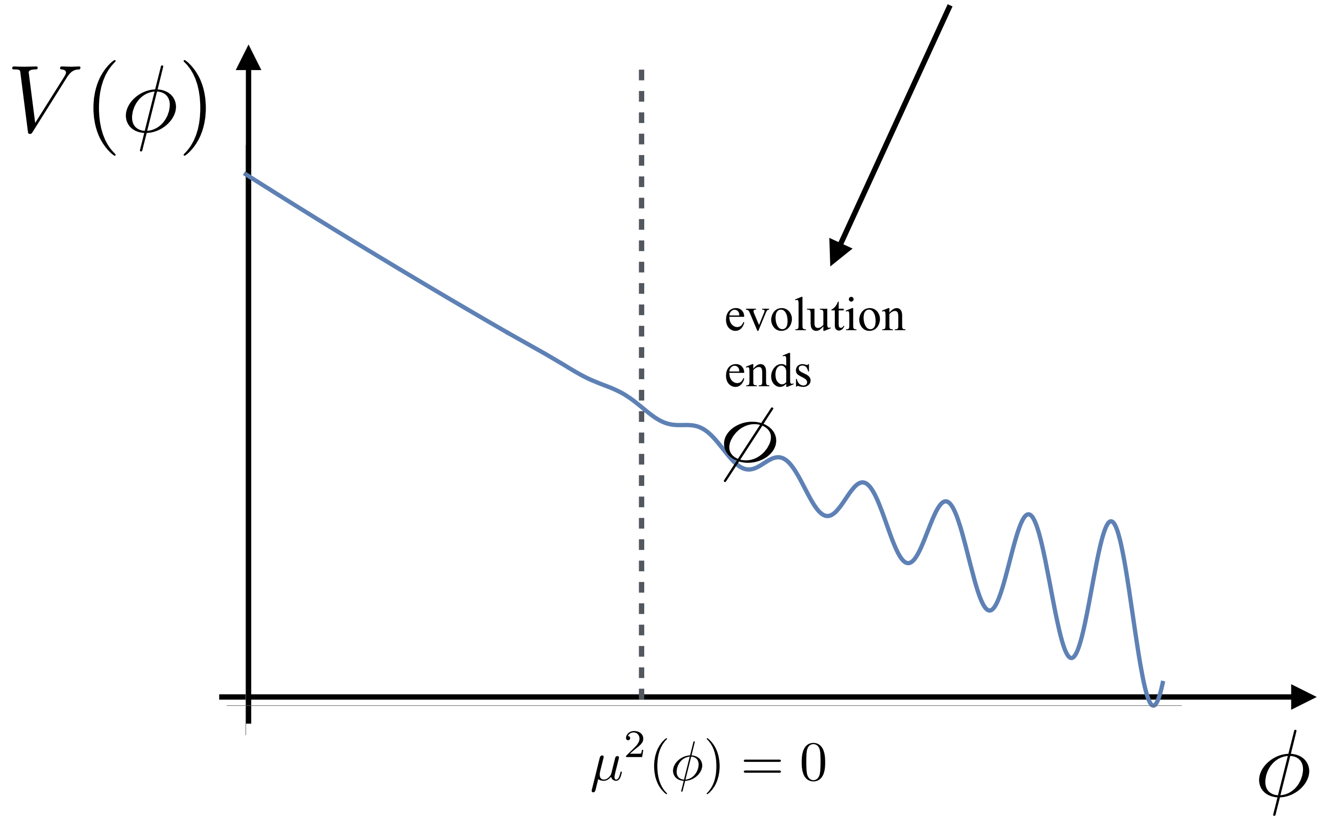

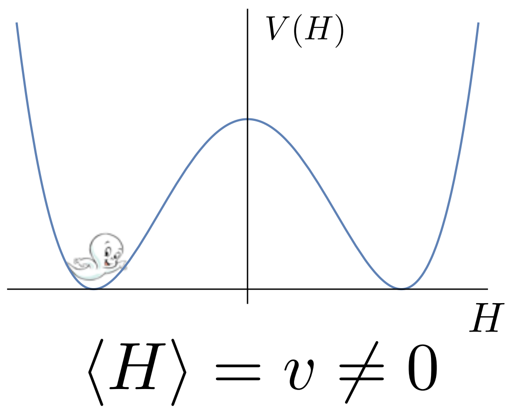

$$\text{Roughly } \Lambda/v \lesssim n^{1/4} \sim (f_{\rm UV}/f_{\rm IR})^{1/4} \sim 3^{N_{\rm clock}/4} \ .$$

For $v \ll \Lambda$ progress achieved.