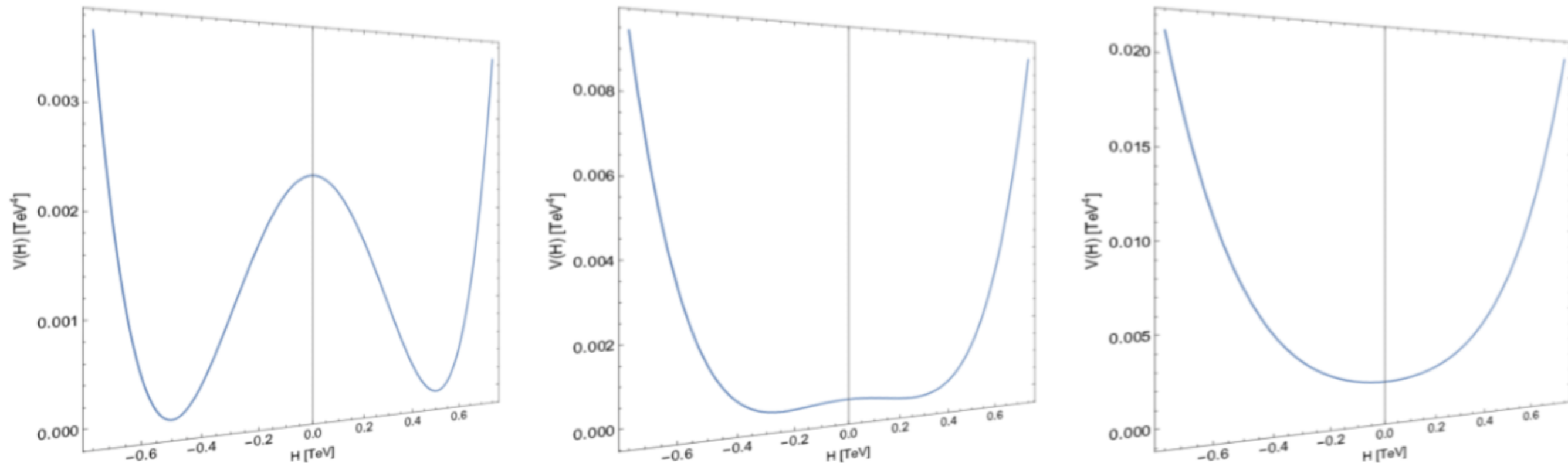


Higgscitement: Cosmological Dynamics of Fine Tuning

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Harvard University
February 16, 2018

**Based on 1802.00444 with Mustafa Amin, JiJi Fan, and
Kaloian Lozanov**

A Fine-Tuned Higgs?



Is our universe precariously balanced between unbroken EWSB and badly broken EWSB? If so, how can we tell?

We want to suggest some possible new ways to think about these questions.

Status of the Higgs Fine-Tuning

Without going into details on what the LHC has taught us, I would characterize the current situation as:

- Indirect tests (Higgs properties) require a factor of 5-10 fine tuning.**
- Direct particle searches require a factor of ~30-100 fine tuning, but are model-dependent (have loopholes)**
- Specific models may be even more constrained (in the MSSM, for instance, the Higgs mass of 125 GeV requires much more tuning)**
- “Neutral naturalness”-type models attempting to evade bounds might manage a mere factor 5 or 10 tuning, but at the cost of great added complexity.**

The bottom line is: nature is probably tuned.

An Opinion

No new physics at the LHC is not a crisis.

It's probably more of a small accident.

We're unlucky enough to live in a corner of the multiverse where we didn't get our SUSY (or other) discovery yet.

So What?

One easy answer is to sit back and wait for more data.

We can also plan for higher-energy colliders if the LHC isn't quite enough.

But another question is: could there be a *positive* signal of fine-tuning?

Fine-tuning in *Field Space*

The idea of tuning in *theory space* is too abstract to do much with. If heavy particles coupled differently to the Higgs, our vacuum would be very different. But we can't change how particles couple.

Or can we? **Couplings depend on VEVs.**

In the early universe, various scalar fields could have had large VEVs, so effective couplings were different.

Could have had unbroken EWSB or much more badly broken EWSB.

Even better, could have ***dynamics, fine-tuning in time.***

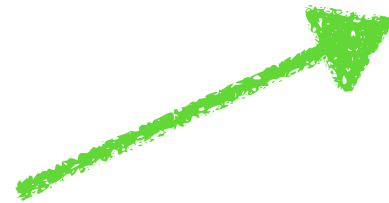
Well motivated theories supply lots of good candidates for large variations in field space: saxions, moduli, D-flat directions.

Let's explore what can happen!

Coupling a modulus to the Higgs

Consider a coupling linear in the modulus:

$$V(\phi, H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + M^2 \frac{\phi}{f} \left(H^\dagger H - \frac{v^2}{2} \right) + \frac{1}{2} m_\phi^2 \phi^2 + \dots$$



Higgs mass term depends on the modulus value.

Global minimum at $H/\sqrt{2} = v$, $\phi = 0$.

Scales: μ : Standard Model Higgs mass param

f : Modulus field range (\sim Planck?)

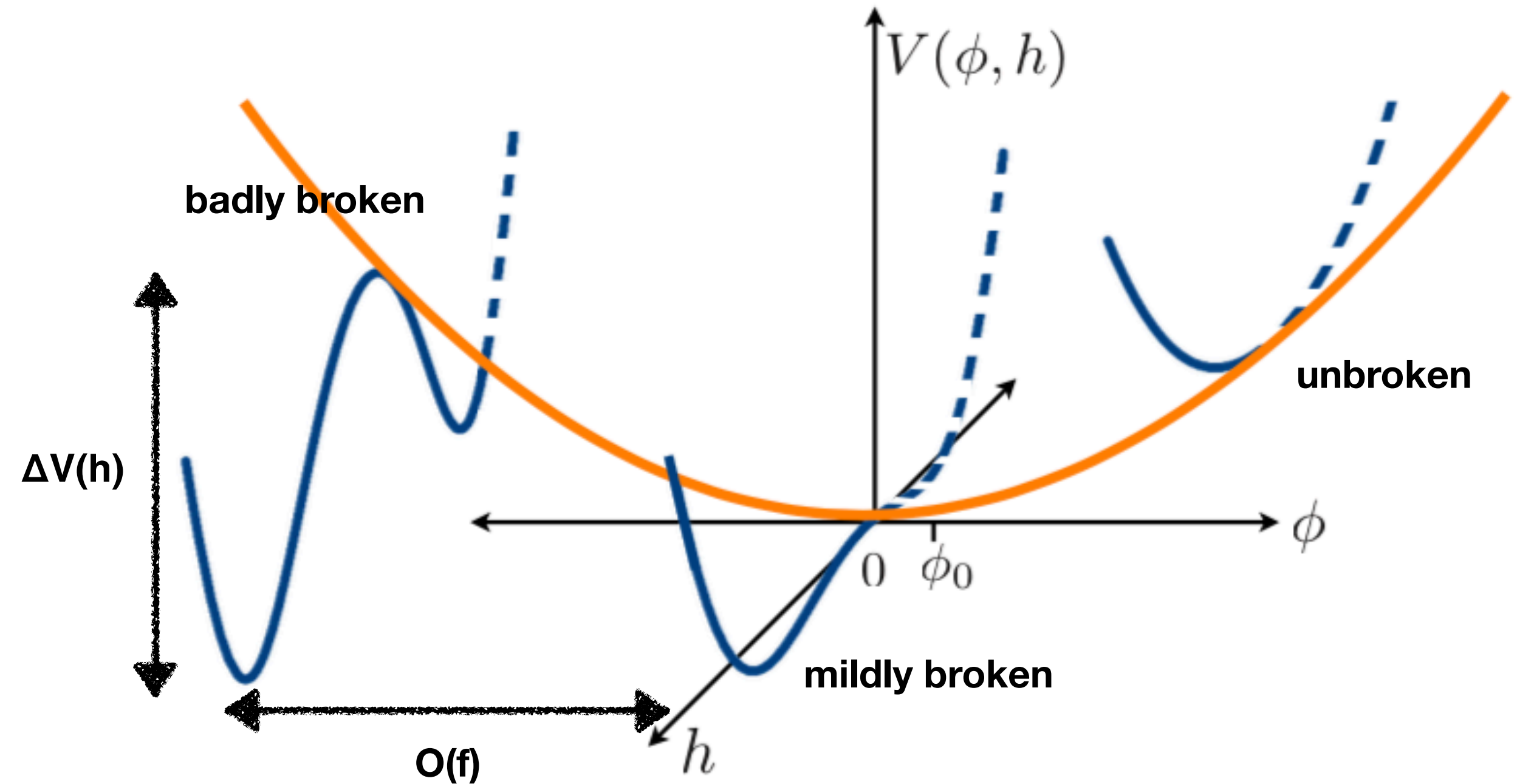
M : “Natural” Higgs mass param (\sim 100s TeV?)

m_ϕ : Modulus mass (\sim 100s TeV?)

Possible hierarchies: $\mu \ll m_\phi \lesssim M \ll f$

(Worth considering other variations too)

Modulus-Higgs potential



Fine tuning is the coincidence between the minimum of the ϕ potential and the point of marginal EWSB.

Oscillating between EWS and EWSB

Ignoring backreaction, the modulus starts oscillating when Hubble is below its mass. Assuming a modulus-dominated universe,

$$\phi(t) \approx \frac{\xi_\phi f}{m_\phi t} \cos(m_\phi(t - t_0)).$$

The Higgs will flip between tachyonic and not tachyonic if

$$|M^2 \phi(t)/f| > |\mu^2|$$

This flipping stops when

$$m_\phi t \gtrsim \xi_\phi \frac{M^2}{\mu^2}$$

But M^2/μ^2 is a measure of tuning!

The number of EW-flipping oscillations probes fine tuning.

Tachyonic particle production

As the modulus oscillates, if m_ϕ is at least a little bit small compared to M , the Higgs has time to respond.

That is, there is a tachyonic particle production process when the Higgs flips to the tachyonic side, converting modulus energy into the Higgs energy.

Tachyonic resonance efficiency parameter:

$$q \equiv \frac{M^2}{m_\phi^2} \gg 1$$

The problem of backreaction

As the modulus oscillates, if m_ϕ is at least a little bit small compared to M , the Higgs has time to respond.

That is, there is a tachyonic particle production process.

This potentially depletes energy from the modulus. But: create too many Standard Model particles, and they backreact.

Simple estimate: the process shuts off once

$$\rho_{\text{SM}} \sim \rho_\phi$$

Crudely, can think of this as the quartic

$$\lambda h^4 \sim \lambda \langle h^2 \rangle h^2$$

turning into a positive mass for the Higgs (more discussions later)

Numerics

Saying what happens after backreaction occurs is difficult.

Use a modified version of LatticeEasy (Felder, Tkachev '00).

These are *classical field theory* calculations on a lattice with stochastic initial conditions.

They are valid only for a limited range of times. Power transferred to small scales eventually invalidates the calculation.

Still, we can learn at least a couple of useful parametric statements from the results.

For some parameters, the dynamics are violent, the modulus fragments, and we get an interesting *interacting phase*.

This scenario is similar to “tachyonic preheating”: Dufaux, Felder, Kofman, Peloso, Podolsky, hep-ph/0602144.

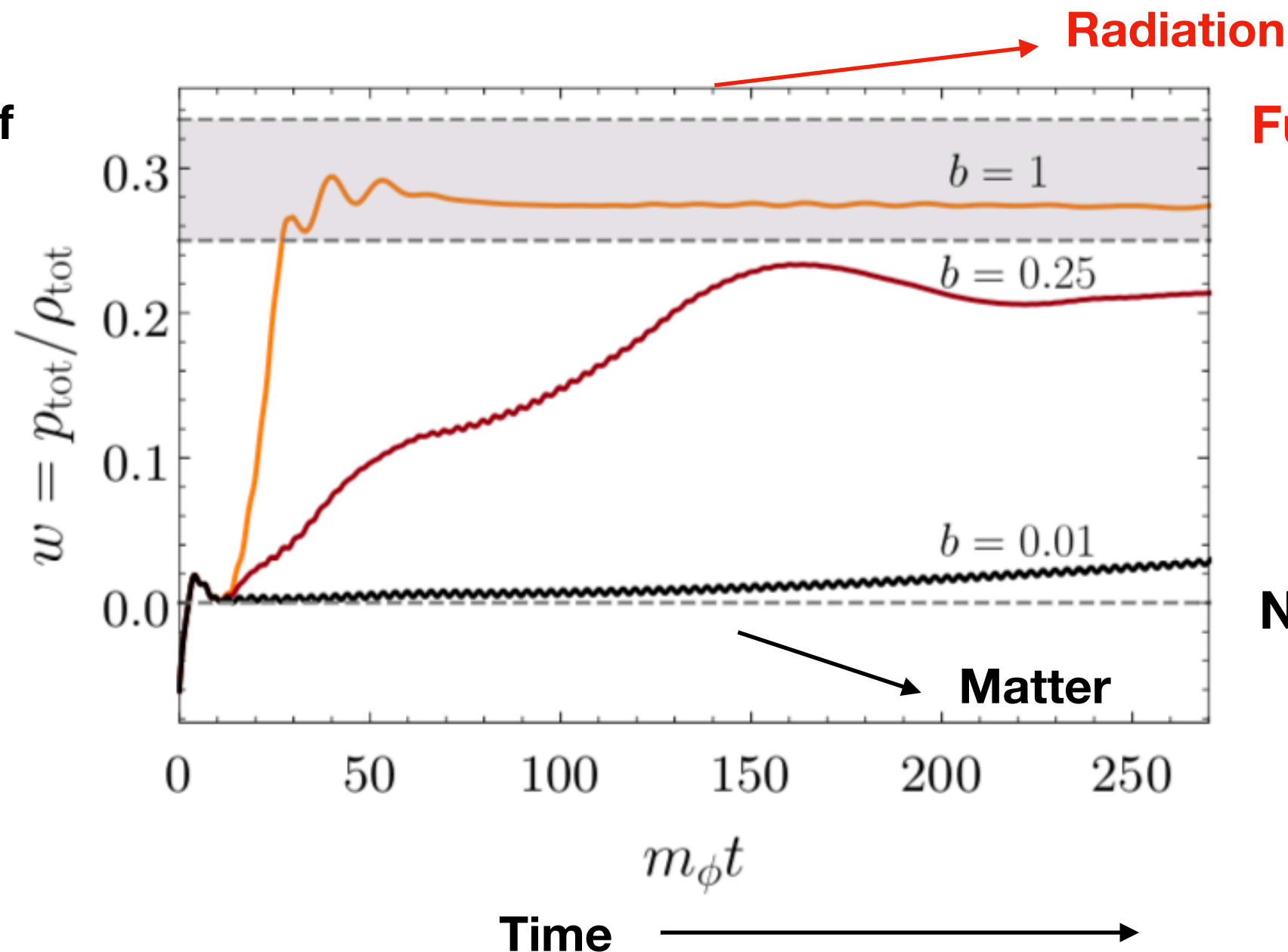
Results: fragmentation and equation of state

Fragmentation of the modulus due to back-reaction is controlled by

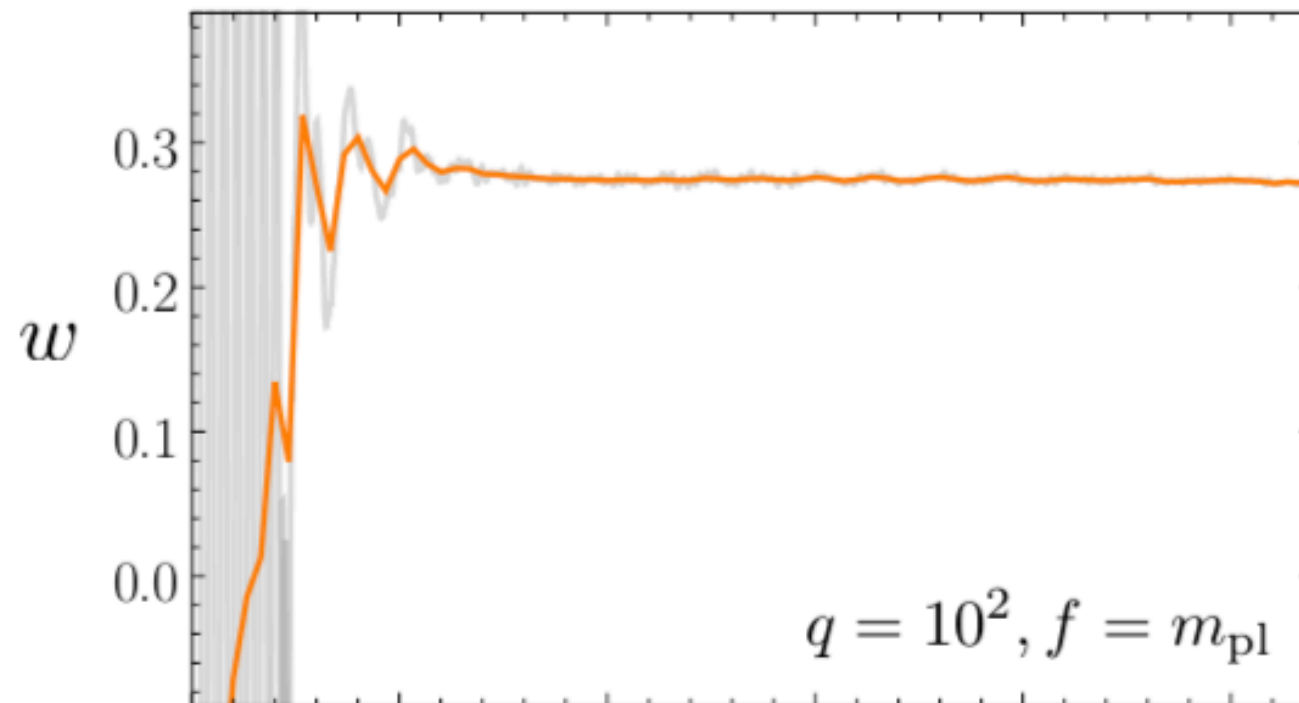
$$b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \leq 1$$

potential is positive definite

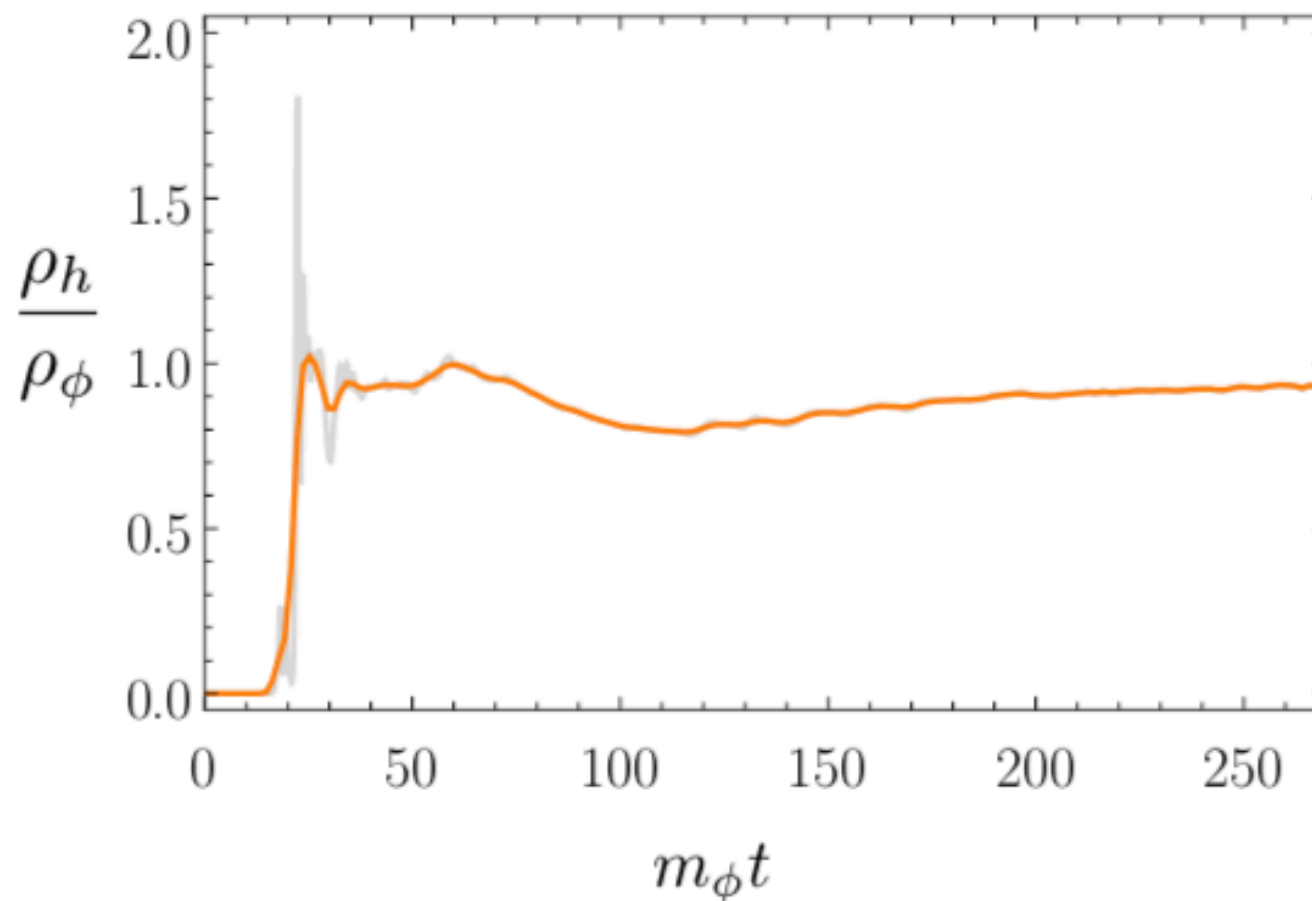
equation of state



Full fragmentation



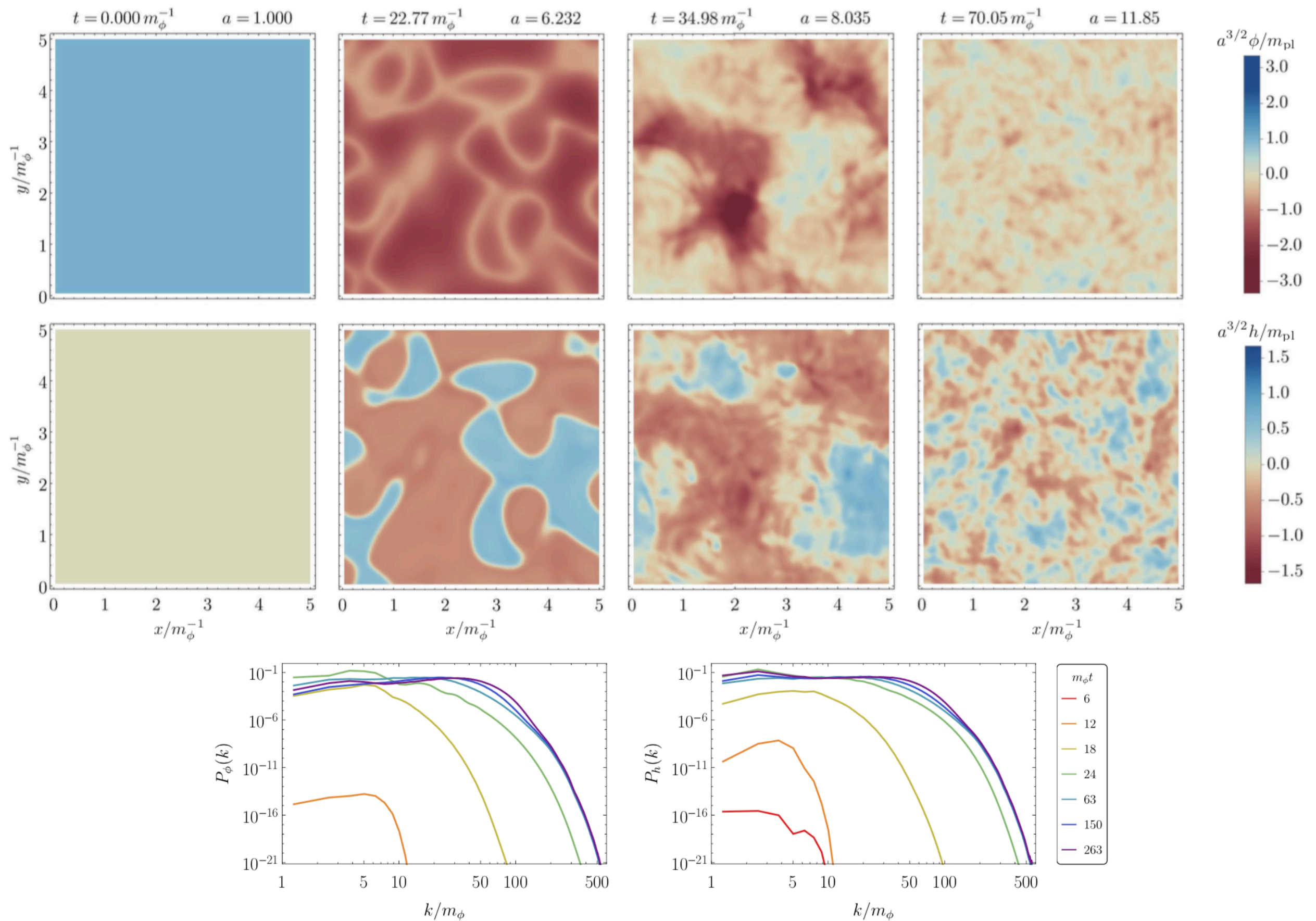
Coupled phase: neither matter domination nor radiation domination.



The modulus and the lighter field remain at comparable energy density.

$$\rho(h)/\rho(\phi) \approx 1$$

Evolution of the Fields



Large dynamical effect?

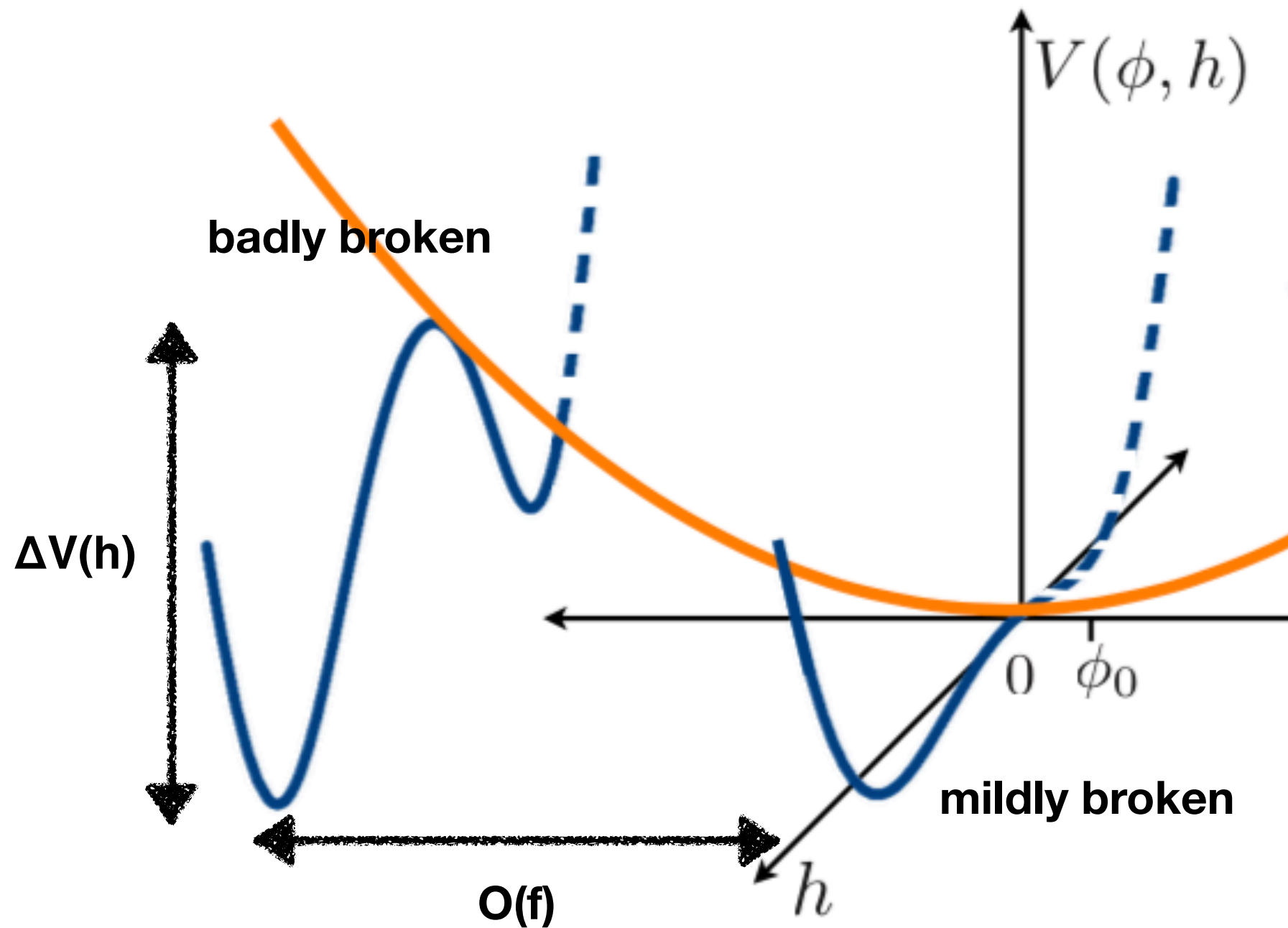
What the
numerics tells us
is that we need
 $\Delta V(h) \sim V(\phi)$.

$$\Delta V(h) \sim M^4 / \lambda$$

$$V(\phi) \sim m_\phi^2 f^2$$

$$\frac{M^4}{\lambda} \sim m_\phi^2 f^2$$

$$\Rightarrow b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \sim 1$$



Summary of the numerical results

Backreaction efficiency parameter: $b \equiv \frac{M^4}{2\lambda f^2 m_\phi^2} \leq 1$

Tachyonic resonance efficiency parameter: $q \equiv M^2 / m_\phi^2$

$$b \sim 1, q \gg 1 : \quad w \approx 1/3$$



Efficient conversion of modulus energy into Higgs (radiation)

Parametrics: Can We Get an Effect?

What the numerics are showing is that to get a significant period of coupled, out-of-equilibrium modulus/Higgs dynamics, we need

$$M^4 \sim \lambda m_\phi^2 f^2 \quad \left(M^2 \frac{\phi}{f} H^\dagger H \right)$$

This could be satisfied in:

$$a) m_\phi \lesssim M \ll f \sim M_{\text{pl}}, \lambda \ll 1$$

$$b) m_\phi \ll M \ll f \sim M_{\text{pl}}, \lambda \sim 1$$

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*For a), **small quartics can arise along D-flat directions in SUSY.***

If we think in the full SUSY 2HDM, the Higgs getting a large VEV can be $H_u = H_d$. This is the possibility we'll discuss in the most detail.

Gravitational Wave Production

Easter, Lim '06; Amin, Hertzberg, Kaiser, Karouby '14

Violent dynamics, like fragmenting the modulus field, produces GW background with amplitude

$$\Omega_{\text{gw}}(f_0) \sim \Omega_{r0} \delta_\pi^2 \beta^2,$$

/F the universe remains radiation dominated after GW production until the usual matter-radiation equality

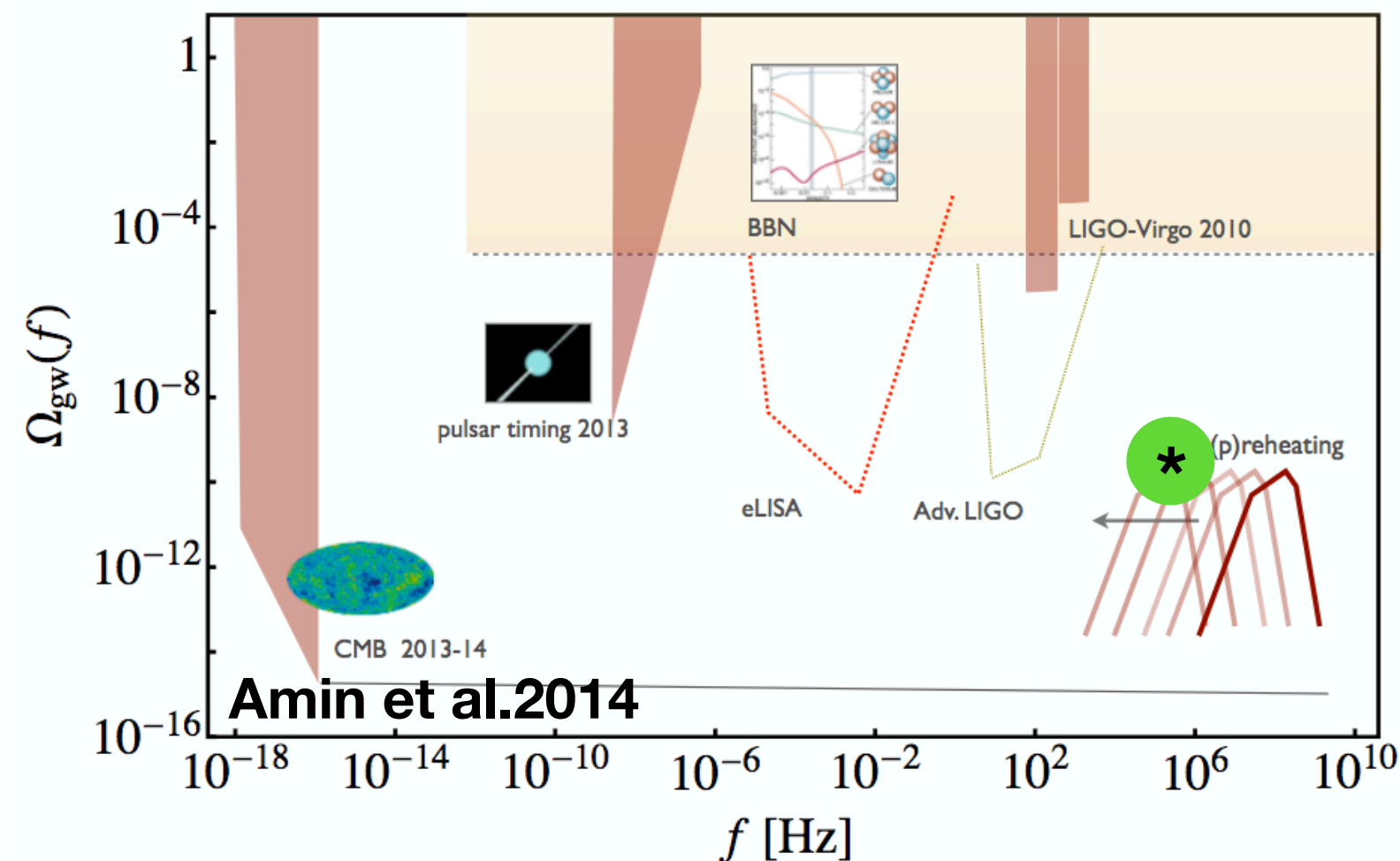
δ_π : fraction of energy in quadrupoles
($\sim 10^{-1}$)

β : relation between GW peak wavelength and Hubble ($\sim 10^{-1}$)

Gravitational Waves from Moduli

If the out-of-equilibrium dynamics immediately converts all of the moduli to radiation, these simple estimates yield ($\beta \sim q^{-1/2}$):

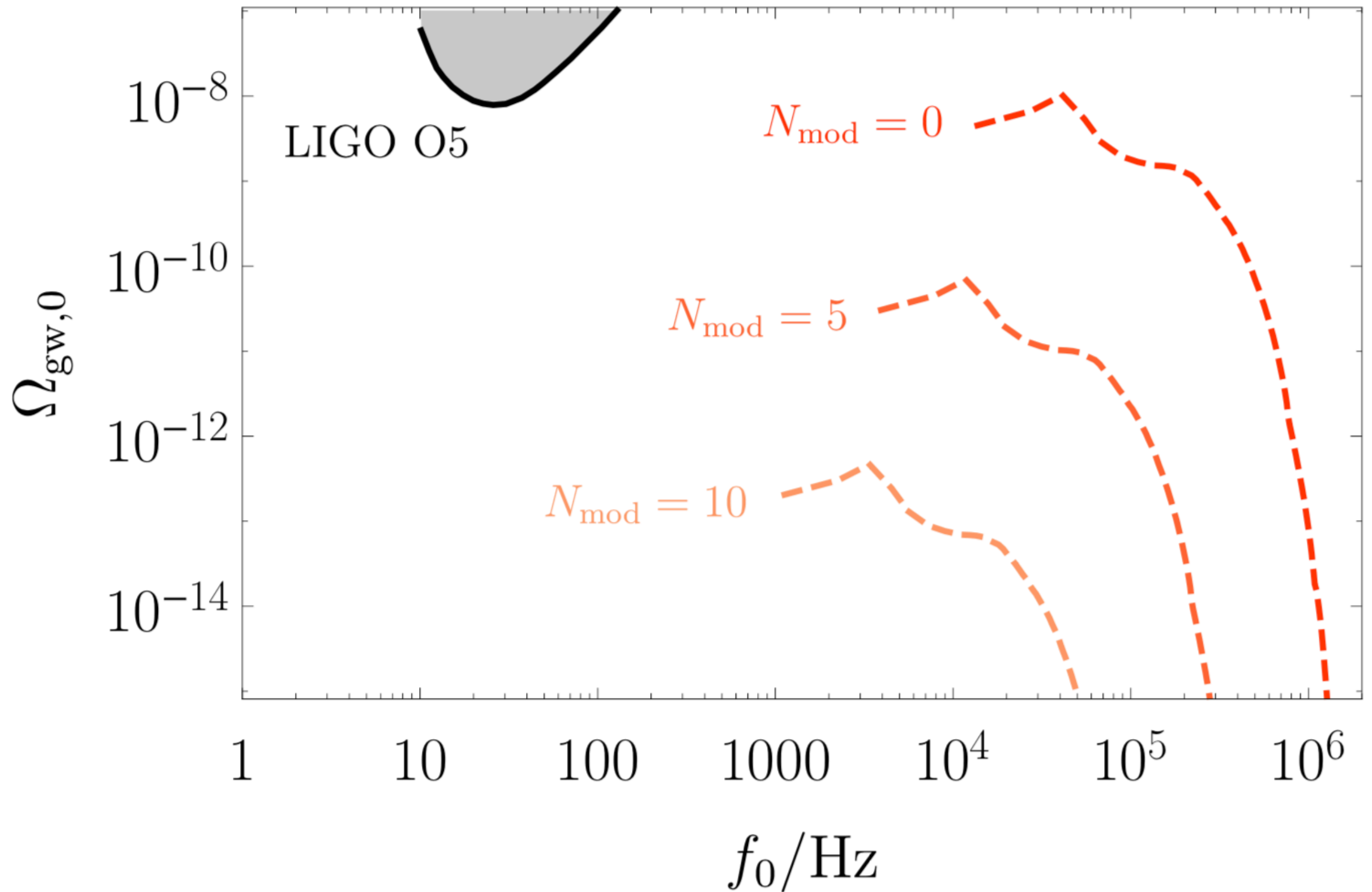
$$f_0 \sim \frac{a_{\text{osc}}}{a_0} \beta^{-1} H_{\text{osc}} \sim 10^5 \beta^{-1} \text{ Hz} \left(\frac{m_\phi}{10^5 \text{ TeV}} \right)^{1/2}$$



This frequency is above the LIGO band. Need new technologies (Akutsu et al. '08; Goryachev, Tobar '14; Arvanitaki and Geraci '12).

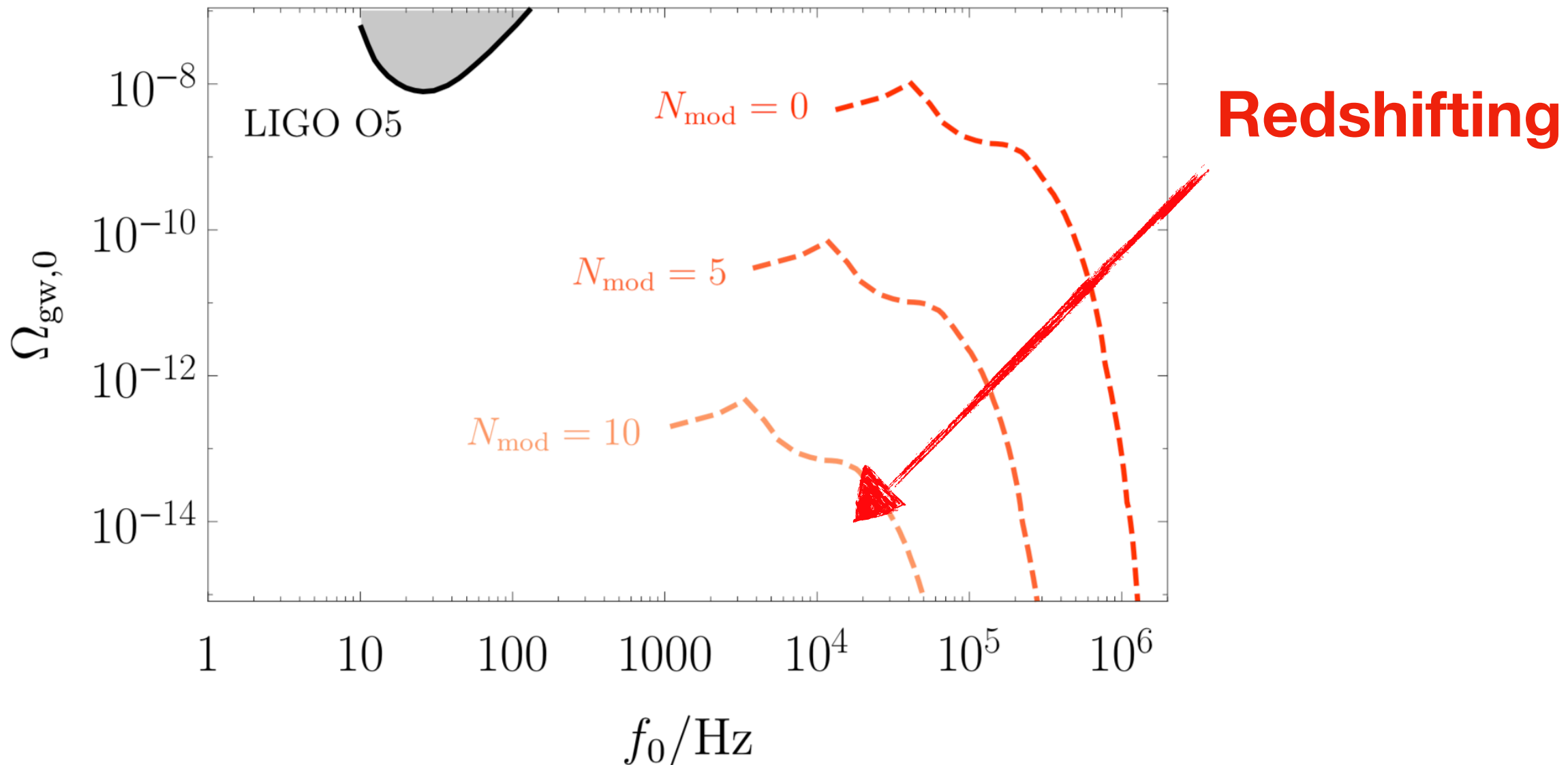
The *amplitude* isn't terrible, and astrophysical backgrounds are low at high frequencies.

Numerical GW Spectrum



computed with HLattice (Z. Huang '11)

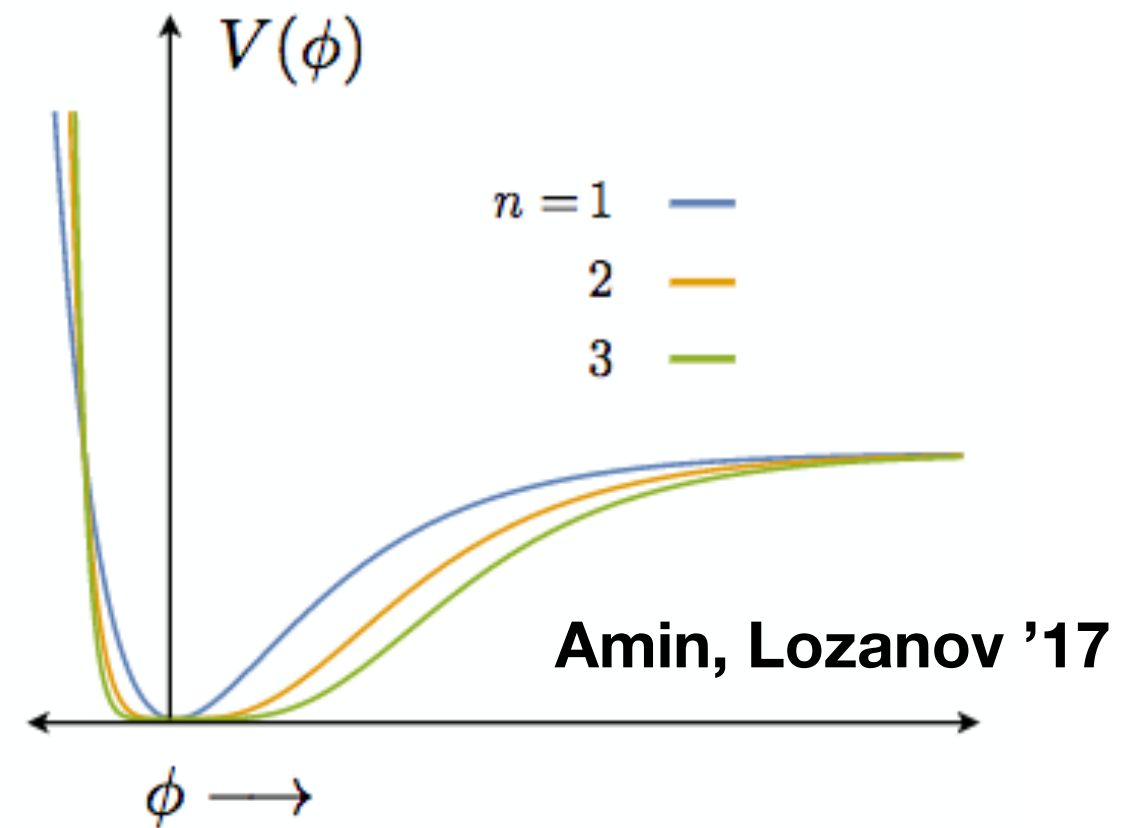
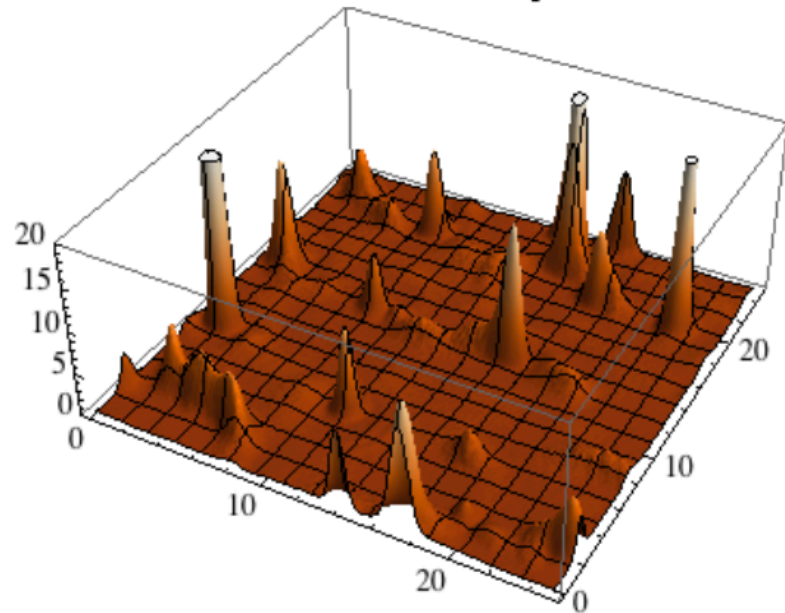
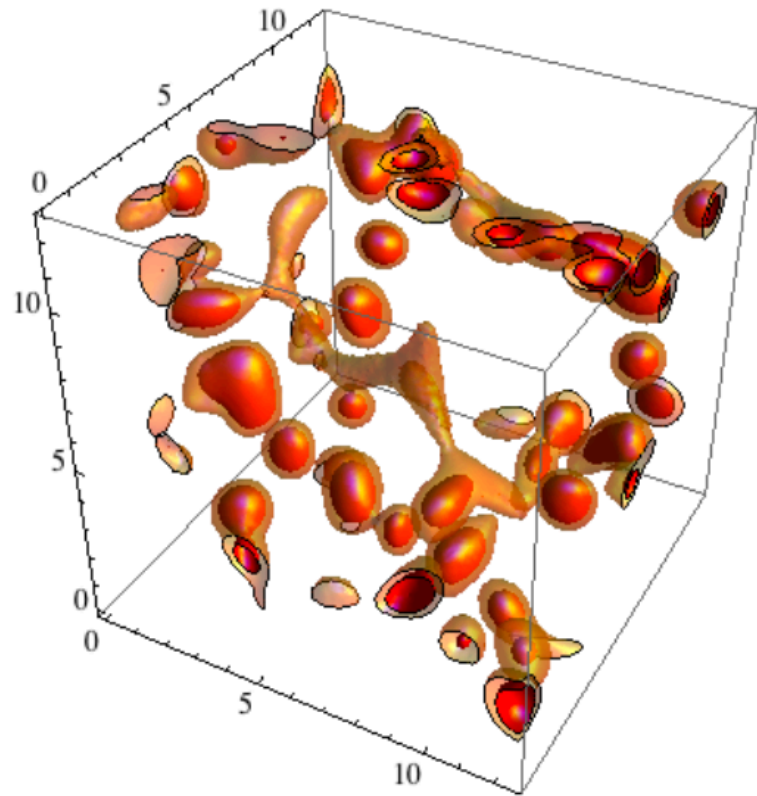
Numerical GW Spectrum



A difficulty is that we do *not* expect the moduli will instantly decay fully into radiation. From the numerics we expect an extended phase of $w \sim 0.3$, possibly reverting to standard moduli cosmology at some time.

This means *more redshift*: smaller f and smaller Ω_{gw} .

One More Ingredient: Oscillons

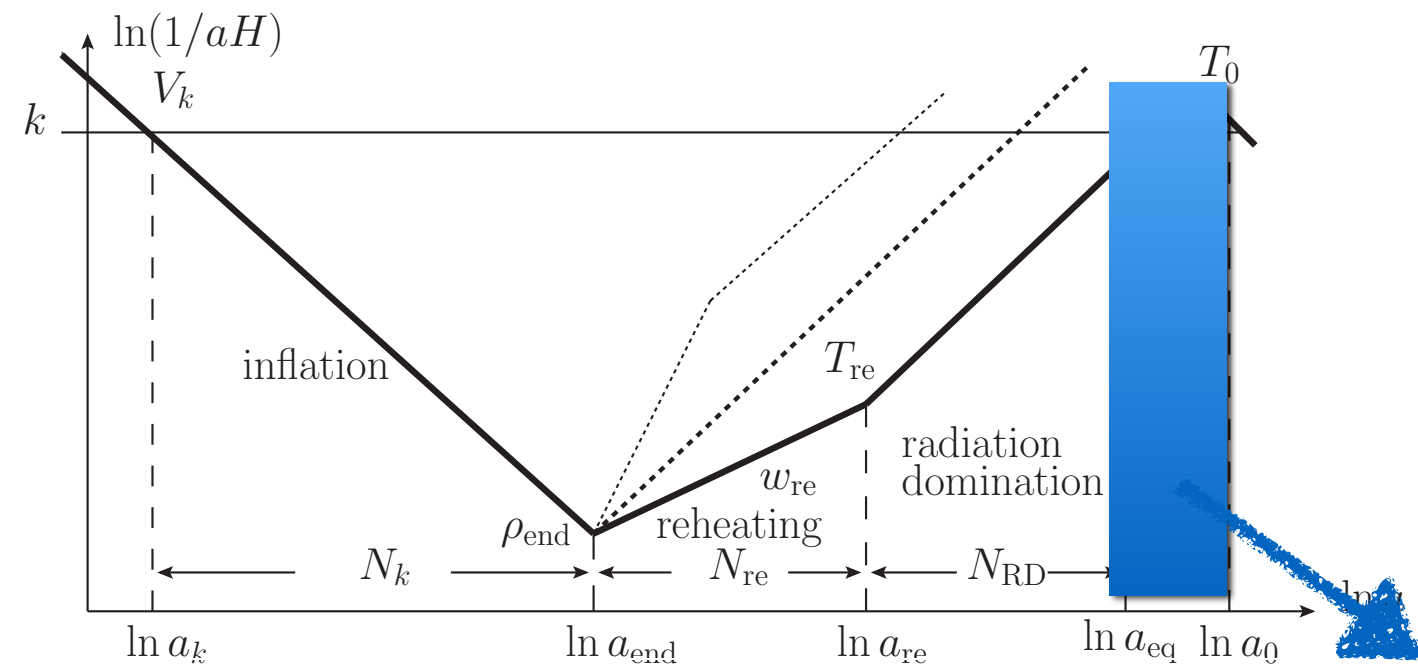


The shapes of potentials that arise for moduli can lead to formation of “oscillons”—localized lumps of oscillating field.

This could change our story in interesting ways, as the modulus doesn’t redshift inside the oscillon. More mass sign flipping and less backreaction?

No conclusions yet! Need more studies.

(n_s, r) and the Time Interval After Inflation

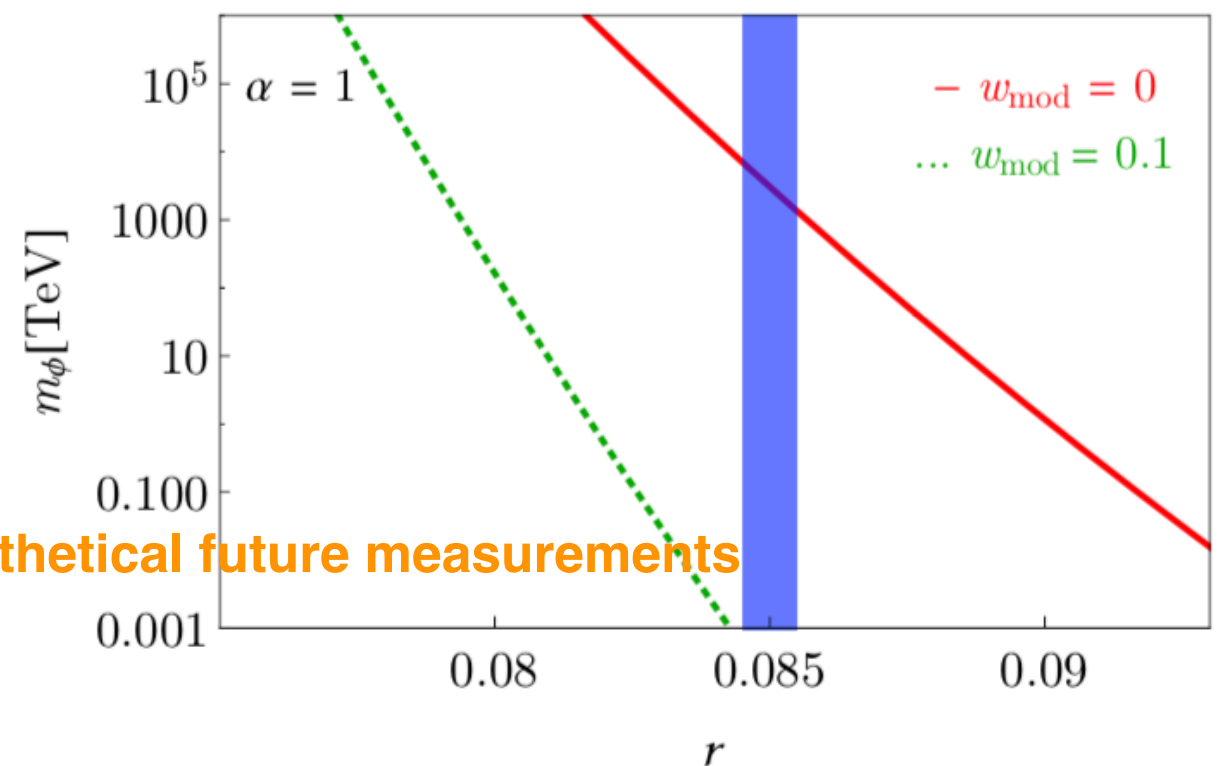
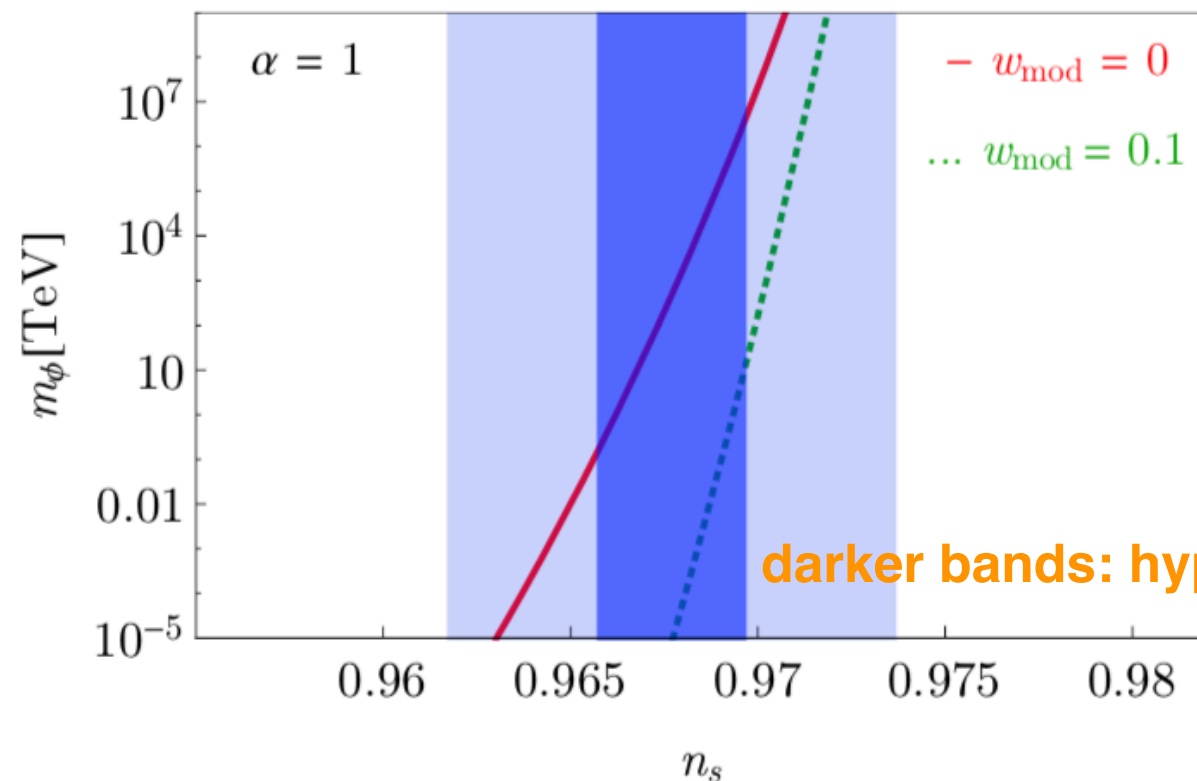


Given a cosmological history,
 N_k related to the total number of e-folds
 between end of inflation and today;
 energy density during inflation related to
 energy density today.

Liddle, Leach '03

Easter, Galvez, Ozsoy, Watson '13

early-time matter domination



darker bands: hypothetical future measurements

For some inflation models, *disfavors* extended period of moduli domination (Dutta, Maharana)

More realistic model: SUSY

How to achieve small Higgs quartic? $m_\phi \lesssim M \ll f \sim M_{\text{pl}}, \lambda \ll 1$

Reminder:

The tree-level MSSM has a Higgs quartic coupling from D-terms, completely fixed by the Higgs' electroweak representations:

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (bH_u^0H_d^0 + \text{c.c.}) \\ + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2$$

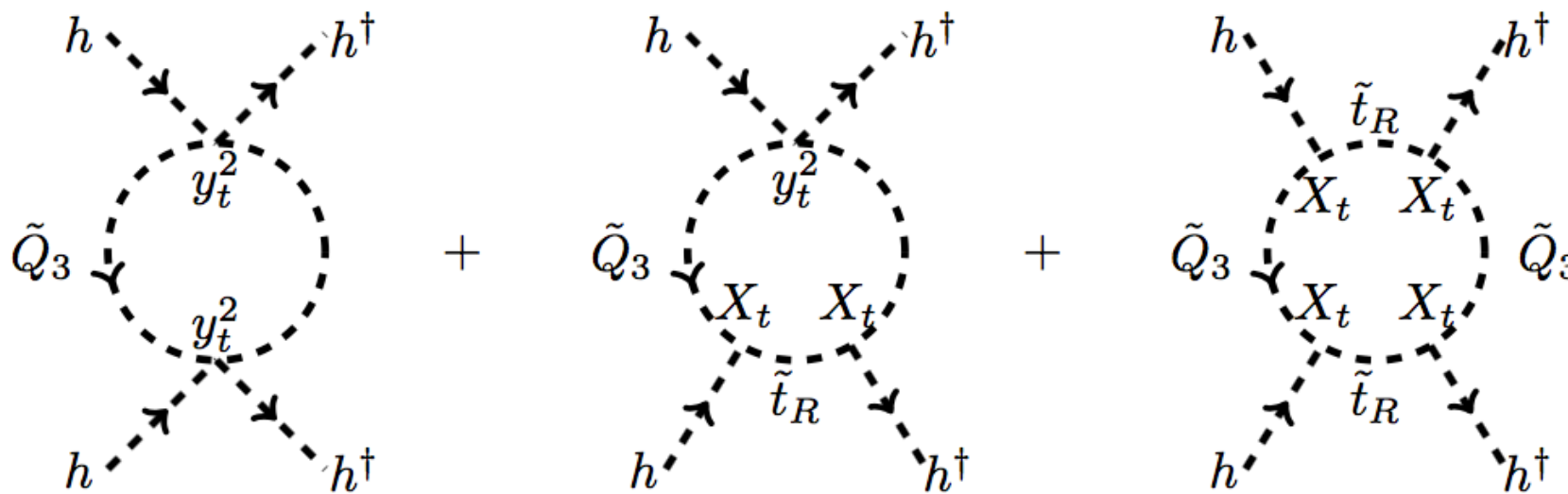
Notice the D-flat direction: $|H_u^0| = |H_d^0|$

The Higgs quartic coupling

In addition to the tree-level potential,

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (bH_u^0H_d^0 + \text{c.c.}) \\ + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2$$

a SUSY-breaking contribution to the Higgs quartic comes from loops of stops:



$$V_{1\text{-loop}} \approx \frac{3y_t^4}{16\pi^2} (H_u^\dagger H_u)^2 \left[\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{1}{12} \frac{X_t^2}{m_{\tilde{t}}^2} \right) \right]$$

Non-vanishing along the D-flat direction. Does it stop us?

EWSB Along the Flat Direction

Suppose there is a tachyonic direction pointing along the flat direction, that is, that we have

$$\begin{pmatrix} 1 & 1 \end{pmatrix} \begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -b \\ -b & |\mu|^2 + m_{H_d}^2 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2 - 2b < 0$$

How large will the Higgs VEV be? At first, you would expect to be stopped by the loop-level quartic coupling:

$$V_{1\text{-loop}} \approx \frac{3y_t^4}{16\pi^2} (H_u^\dagger H_u)^2 \left[\log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{1}{12} \frac{X_t^2}{m_{\tilde{t}}^2} \right) \right]$$

But importantly, the stop mass here is the geometric mean of the *physical* stop masses,

$$m_{\tilde{t}}^2 \approx m_{Q_3, \bar{u}_3}^2 + y_t^2 |H_u^0|^2$$

and as we move far out along the flat direction the stop and top become degenerate:

$$\langle H_u^0 \rangle \gg M_{\text{soft}} \Rightarrow m_{\tilde{t}} \approx m_t$$

Approximate SUSY suppresses the quartic by a factor of M_{soft}^2/H^2 , allowing Higgs VEVs much larger than soft masses!

Higher-Dimension Operators

Lifting the Flat Direction

Flat directions should always be lifted at very large field values.

Kähler corrections are compatible with VEVs of order the cutoff:

$$\int d^4\theta \frac{X^\dagger X}{\Lambda^4} (H_u^\dagger H_u)^2 \rightarrow \frac{m_{\text{soft}}^2}{\Lambda^2} (H_u^\dagger H_u)^2$$

Superpotential terms at first glance appear more dangerous.

$$\int d^2\theta \left(\mu H_u \cdot H_d + \frac{1}{M} (H_u \cdot H_d)^2 \right)$$

gives rise to quartics:

$$\frac{\mu^\dagger}{M} (H_u^\dagger H_u) (H_u \cdot H_d) + \dots \Rightarrow \langle h \rangle \sim \sqrt{\mu M}$$

but given that some spurion forbids the mu term we expect

$$\frac{1}{M} \lesssim \frac{\mu}{\Lambda^2} \Rightarrow \langle h \rangle \sim \Lambda$$

Summary

Cosmology allows us to see the effects of fine-tuning in *field space*.

Time-dependent VEVs of moduli explore regions where the Higgs potential can be very different than in our late-time universe.

This can lead to a *coupled dynamical evolution* of the modulus and the Higgs, with exotic equation of state w near $1/3$.

The modulus can fragment and produce *gravitational waves*.

However, that requires unusual parameter choices, for instance *tiny quartic couplings*.

In SUSY, such tiny quartics occur when venturing out along the *D-flat directions*! The fact that our universe is tuned might make it easy to access such regions of field space.

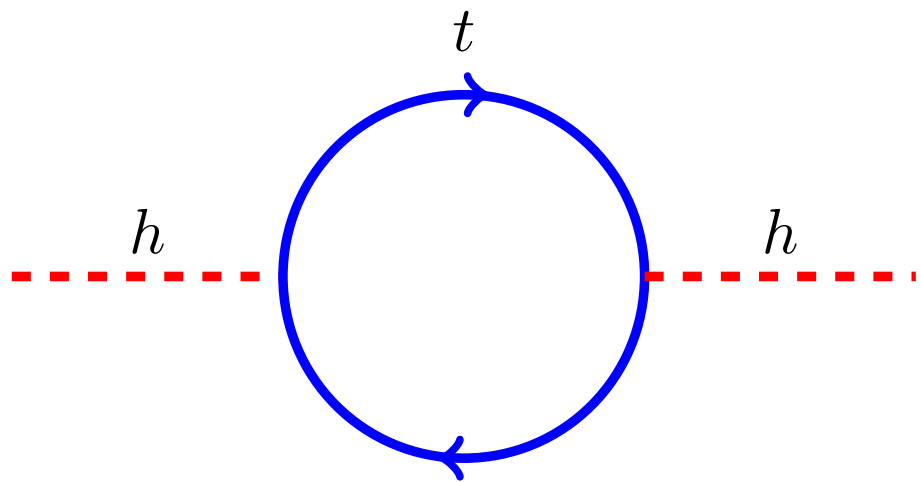
Thank you!

Back-up:

Some more general remarks about physics and naturalness near D-flat directions in SUSY (some in collaboration with Prateek Agrawal)

Some more speculative comments about cosmology

The Higgs Boson and Fine Tuning



The Standard Model loop correction generates a term in the Higgs potential that is quadratically divergent,

$$V(h) \sim \frac{y_t^2}{16\pi^2} \Lambda^2 h^\dagger h$$

This means that the Higgs boson is exquisitely sensitive to new physics at high energies. Slightly different couplings of very heavy particles could lead to dramatically different EWSB.

How do we *know* if the Higgs boson we are seeing is really fine-tuned?

Naturalness in a Multiverse

The notion of naturalness is then a statement about **a *space of theories***. Within that space, we are either living at a “typical” point, or at a very atypical point. The latter case is fine-tuned.

This is very abstract. We can’t move around in the space of theories and see what other points look like, except through calculating.

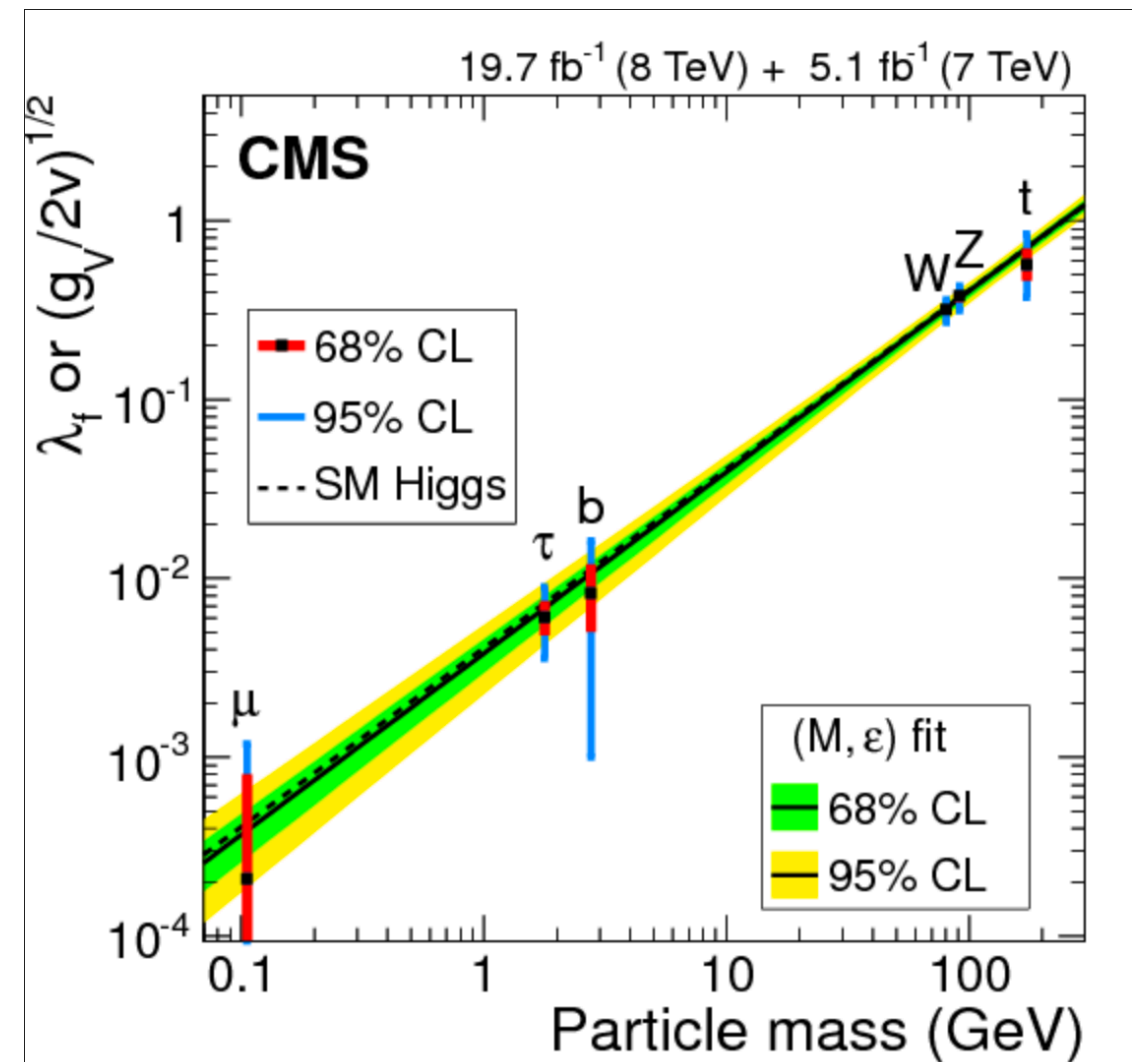
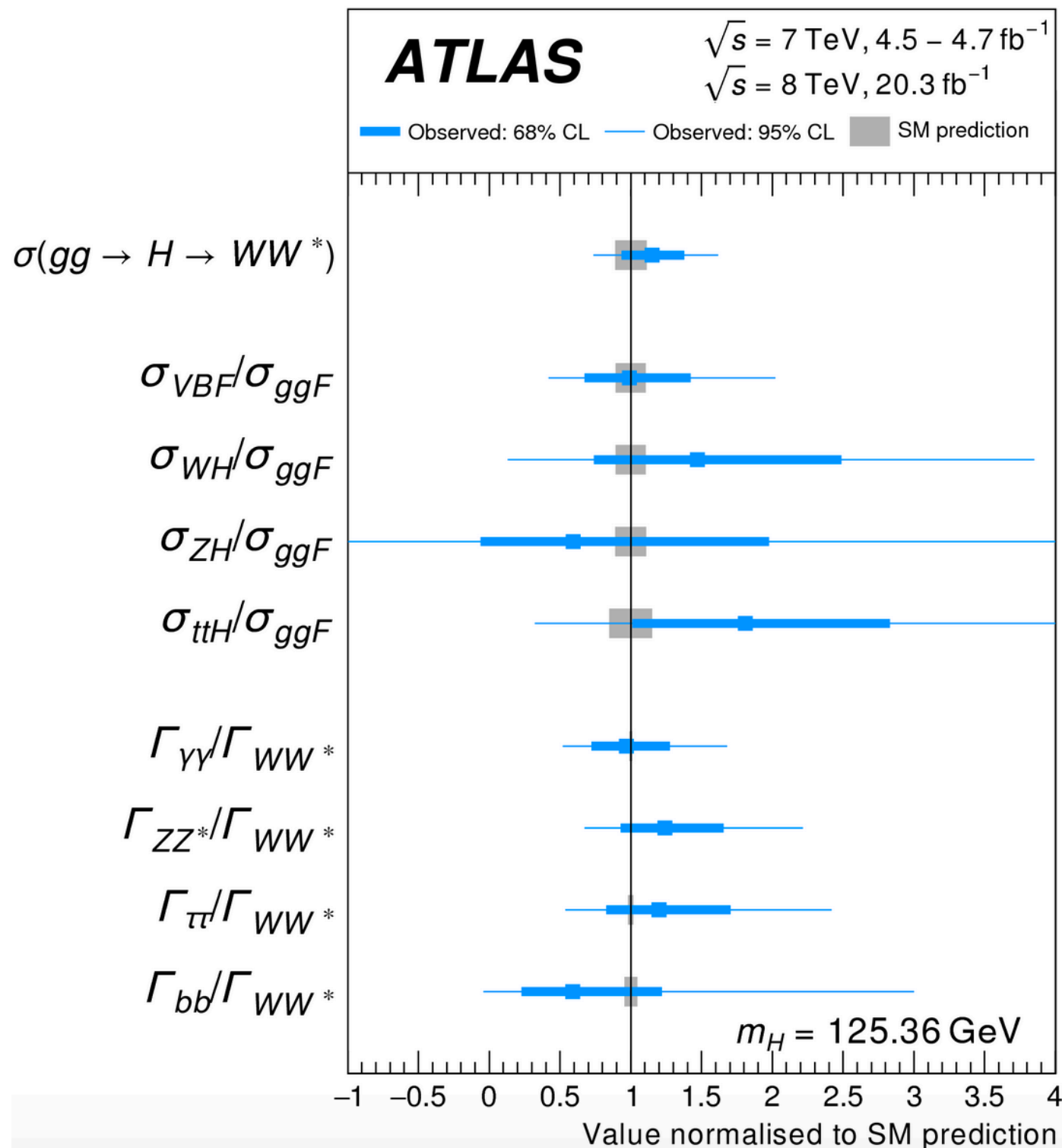
Usually, we test the naturalness of the Higgs in two ways:

1. Look for deviations of the Higgs’s properties from SM predictions.
2. Dream up a concrete natural theory, like SUSY or composite Higgs, and look for the new particles it predicts.

These both give evidence for fine-tuning in a *negative* way, that is, we look for deviations and don’t find them.

Later in this talk: can we find a *positive* signal of fine-tuning?

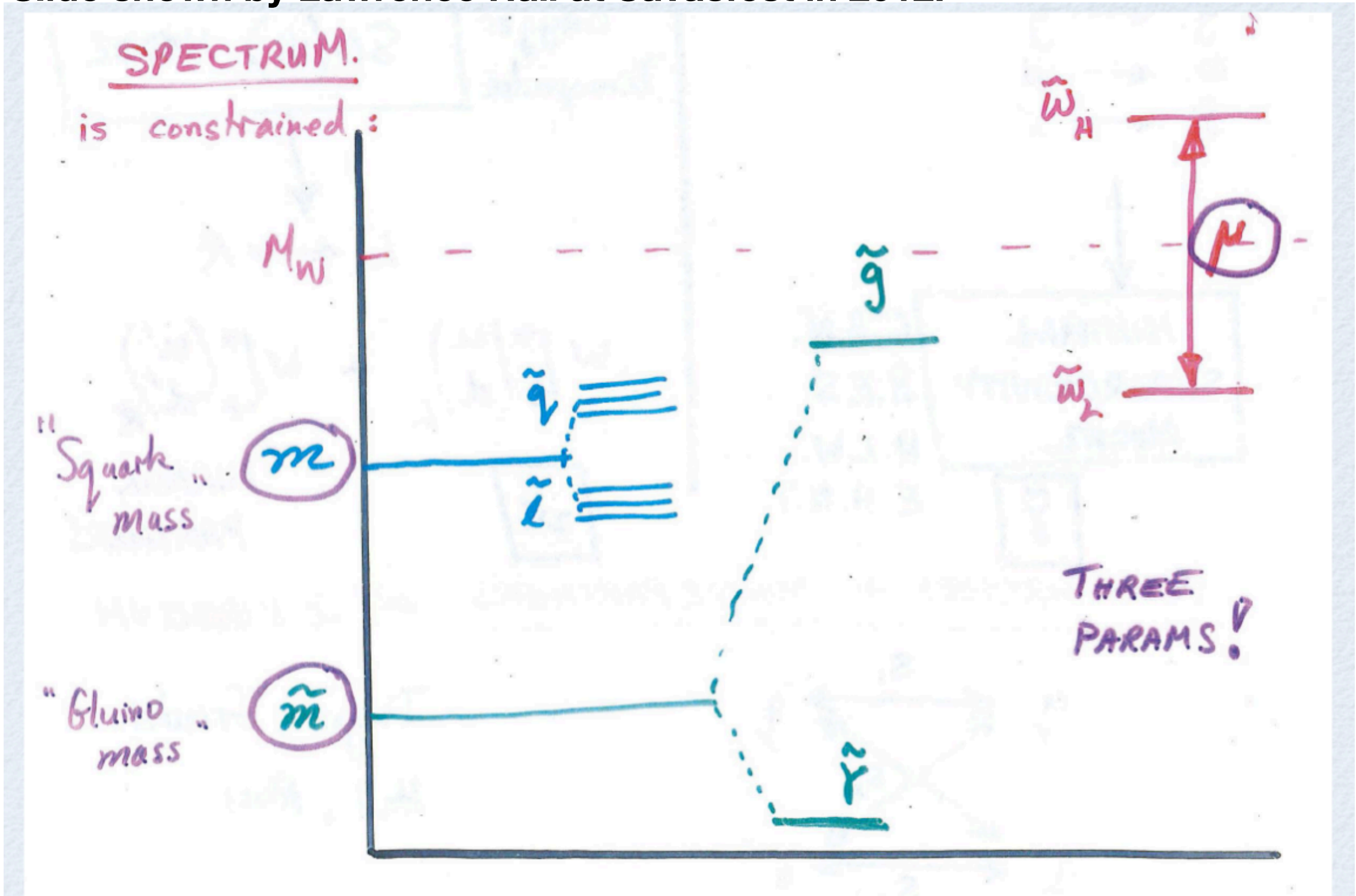
Is the *Observed* Higgs Boson Fine-Tuned?



The Higgs the LHC is seeing looks Standard Model-like, which is *incompatible* with being fully natural.

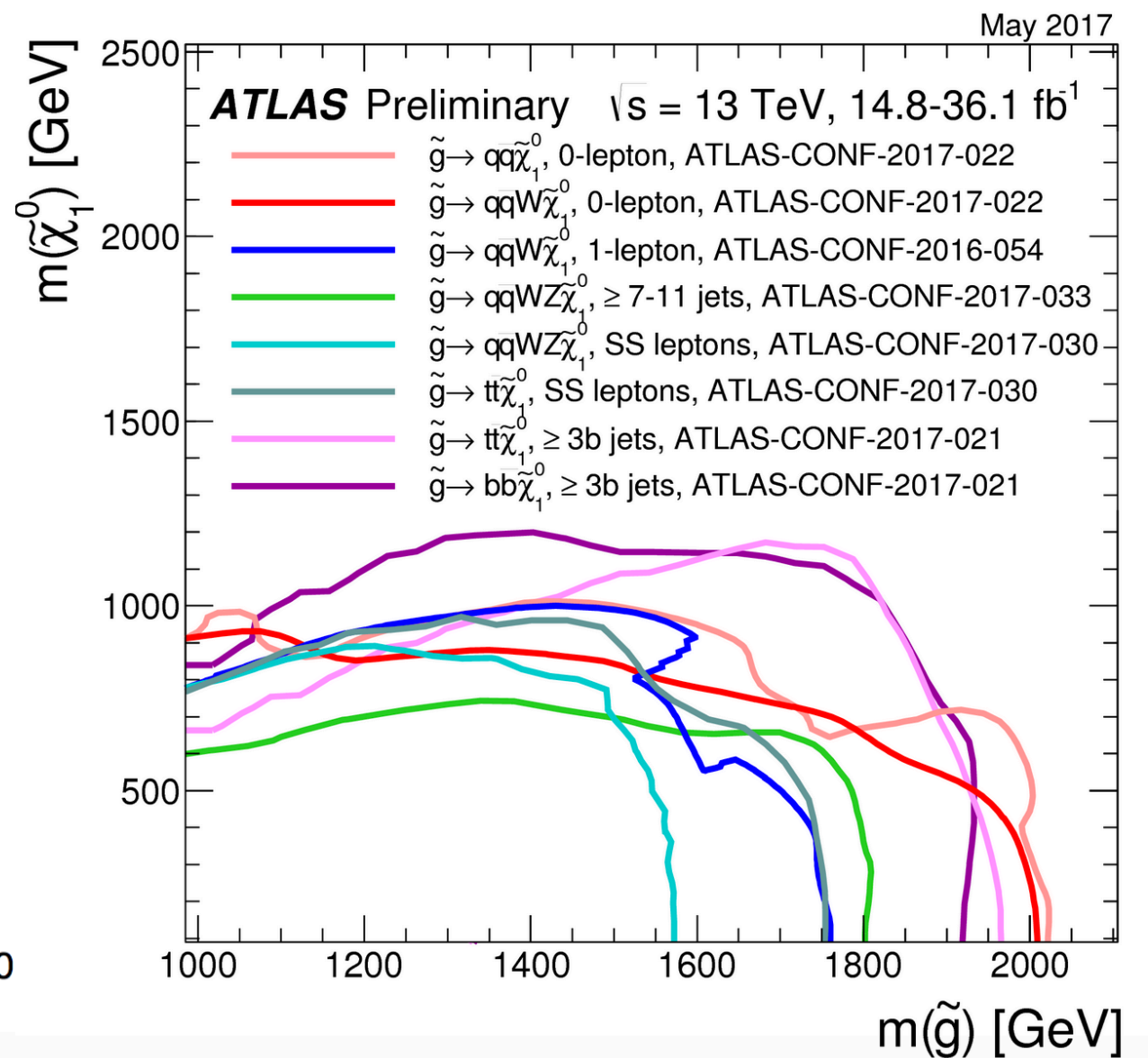
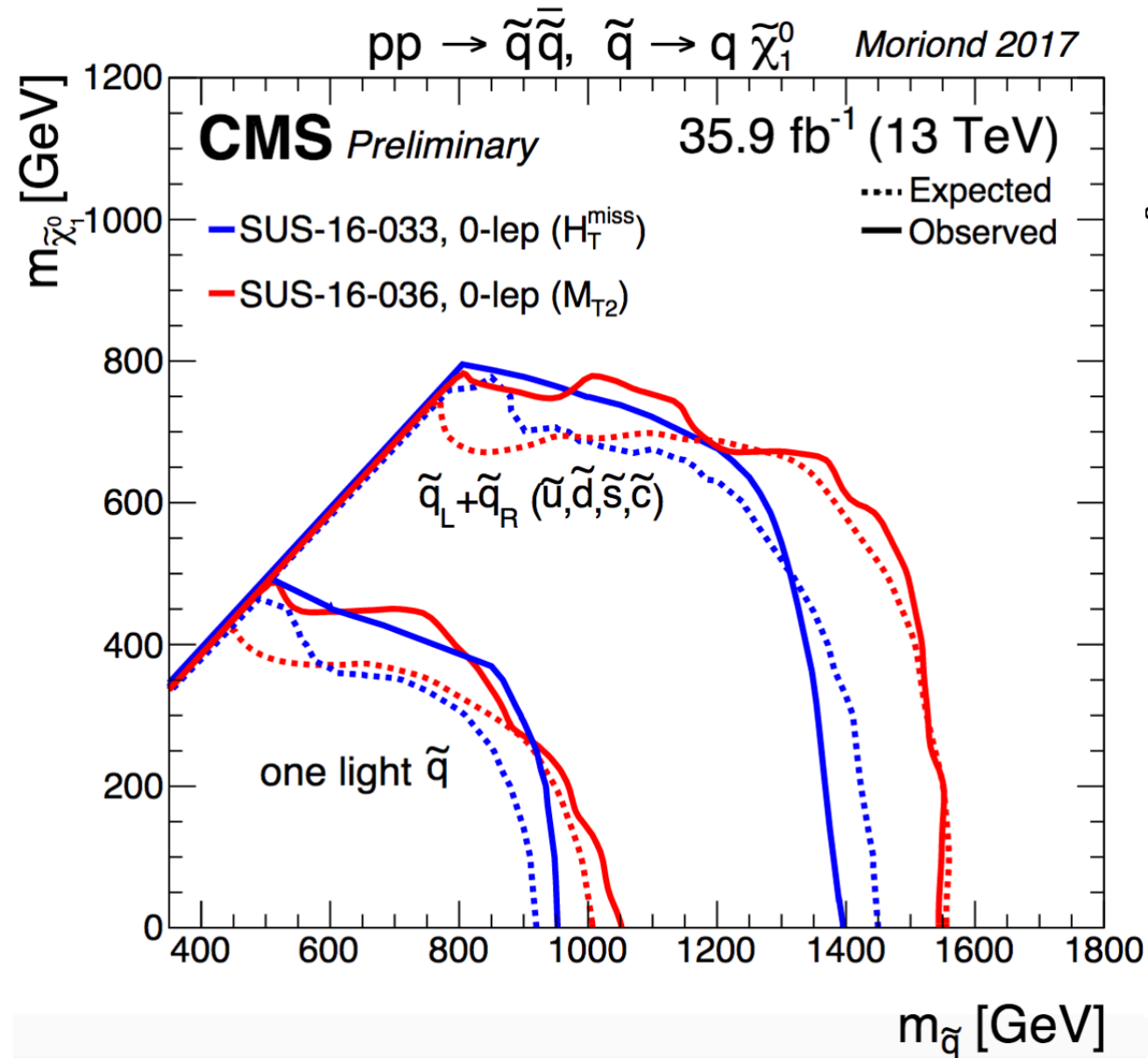
Directly looking for superpartners: the expectation in 1984

Slide shown by Lawrence Hall at Savasfest in 2012:



Over 3 decades of susy: seismic shifts!

Direct SUSY searches: status in 2017



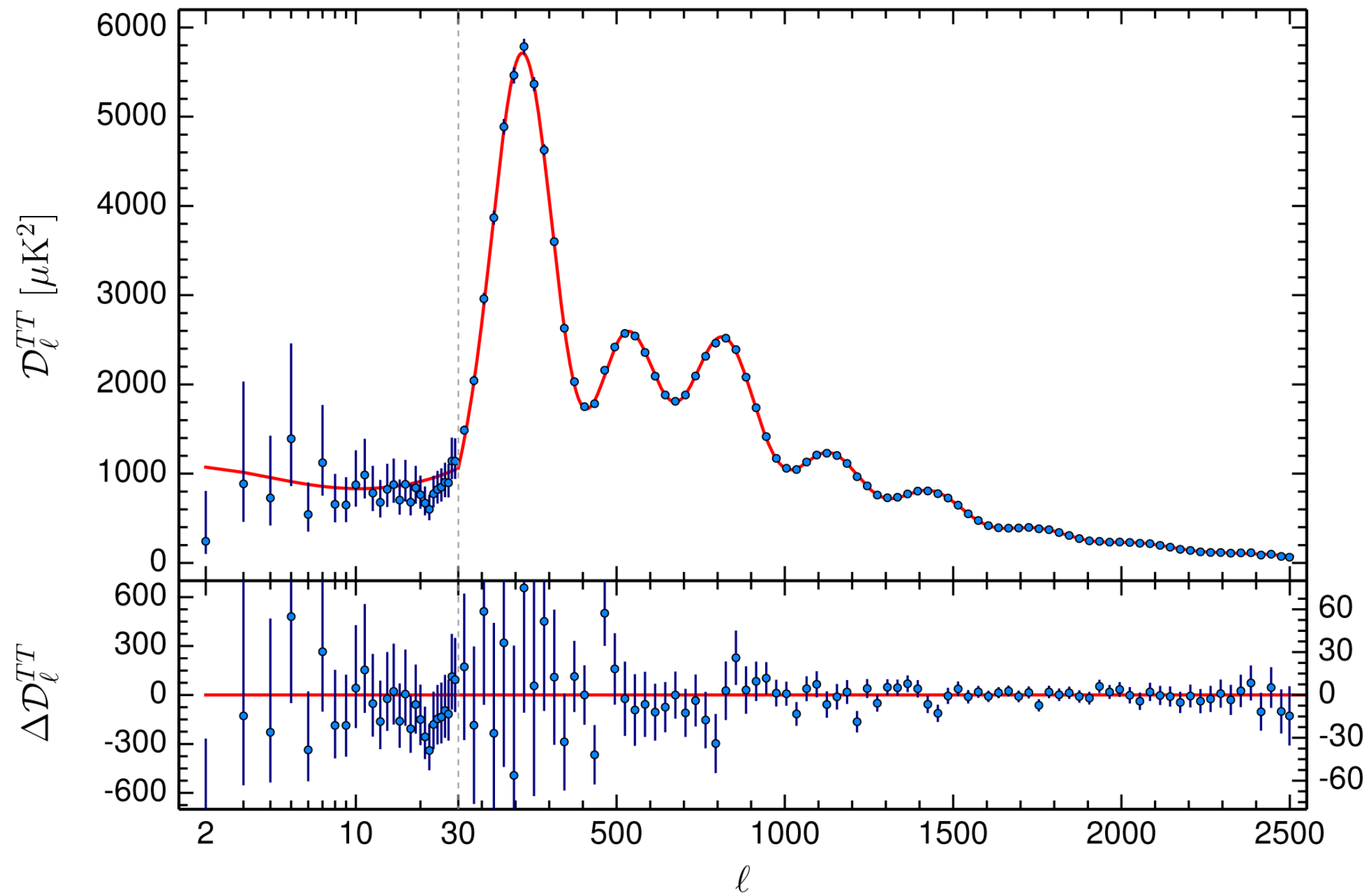
The squarks certainly don't seem to be below the W mass. In fact, they don't seem to be below 20 times the W mass.

The Higgs looks anomalously light compared to other scalars, which are yet to be found.

When Do We Panic? A Comparison

Sometimes a low-probability feature is just an accident of our universe.

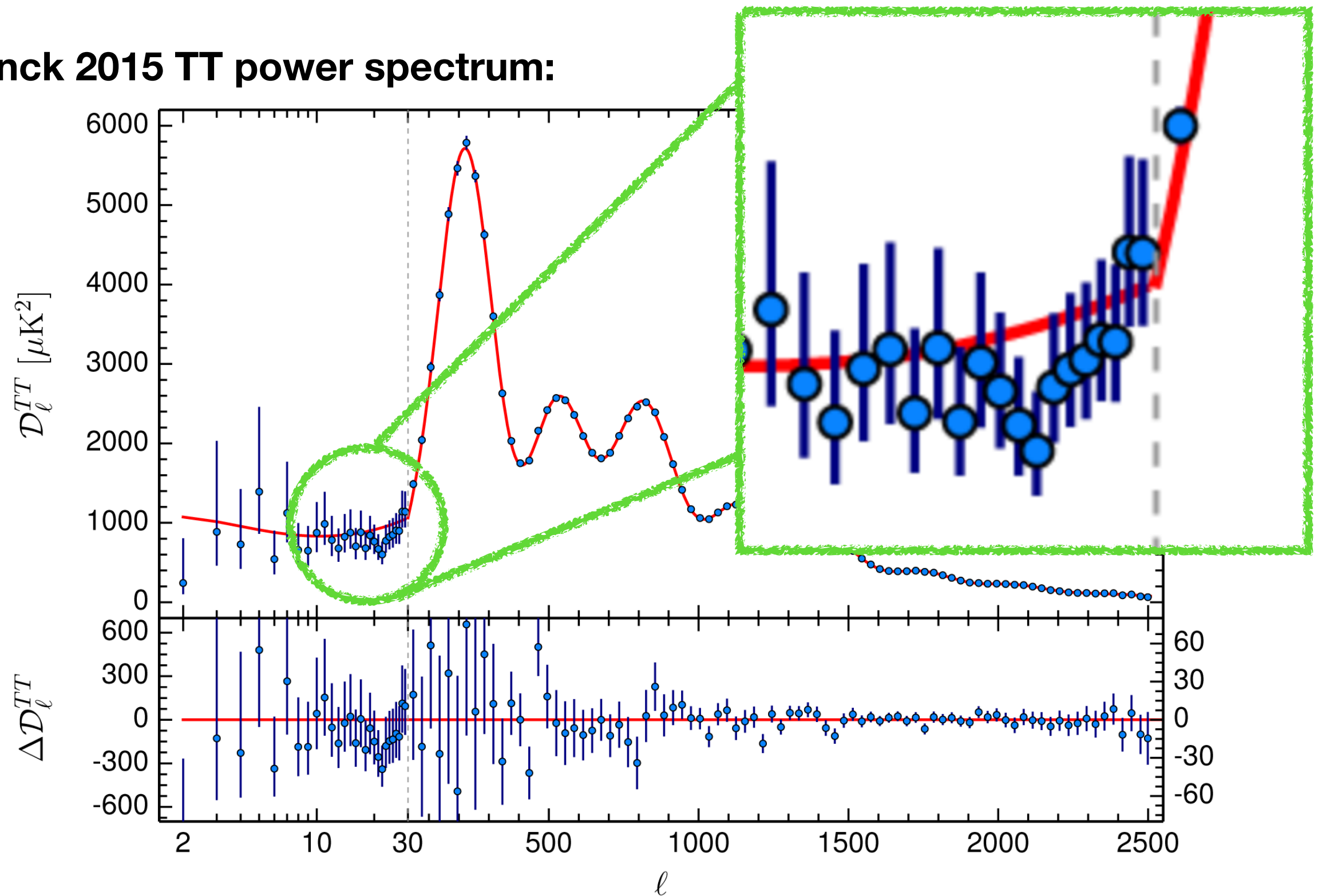
Planck 2015 TT power spectrum:



When Do We Panic? A Comparison

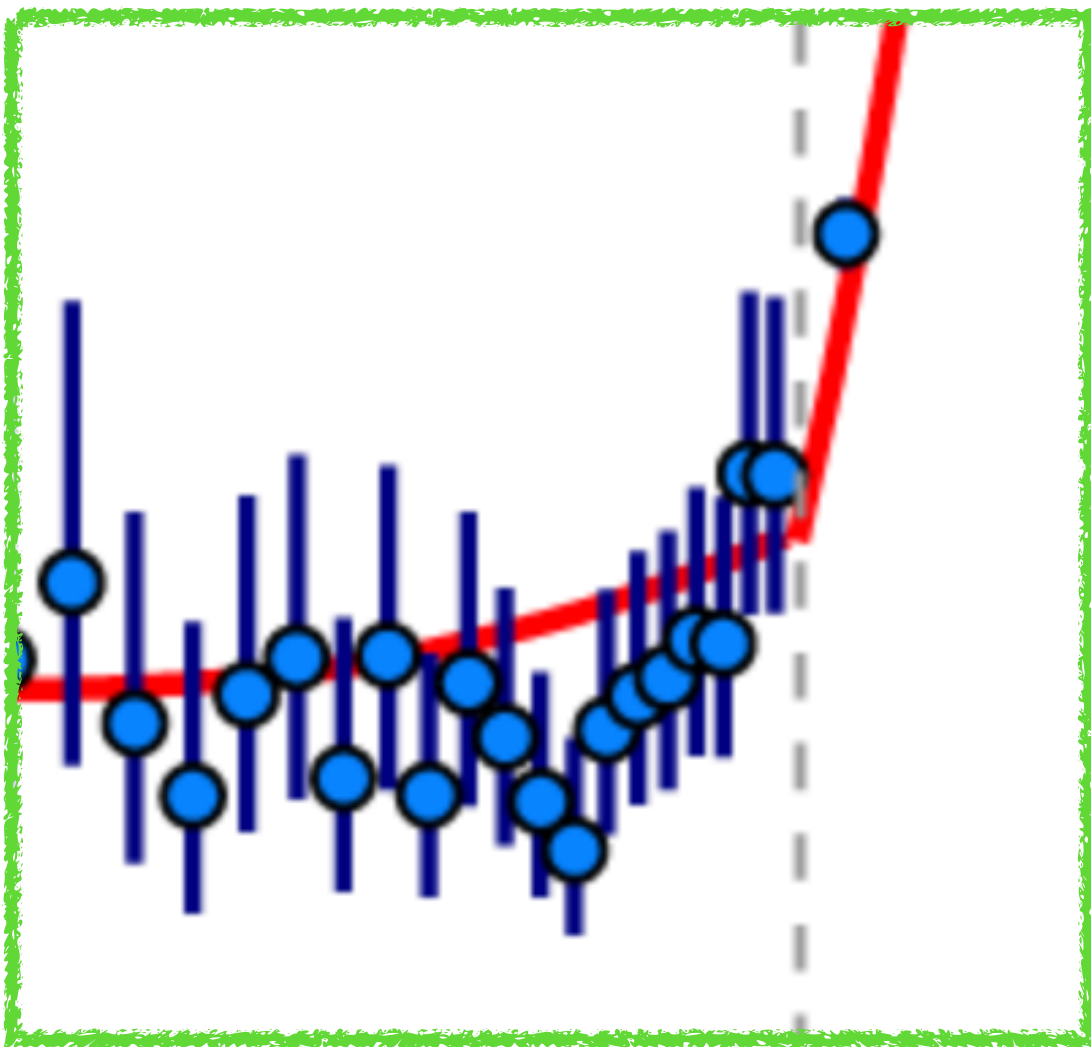
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Planck 2015 TT power spectrum:



Cosmic Variance

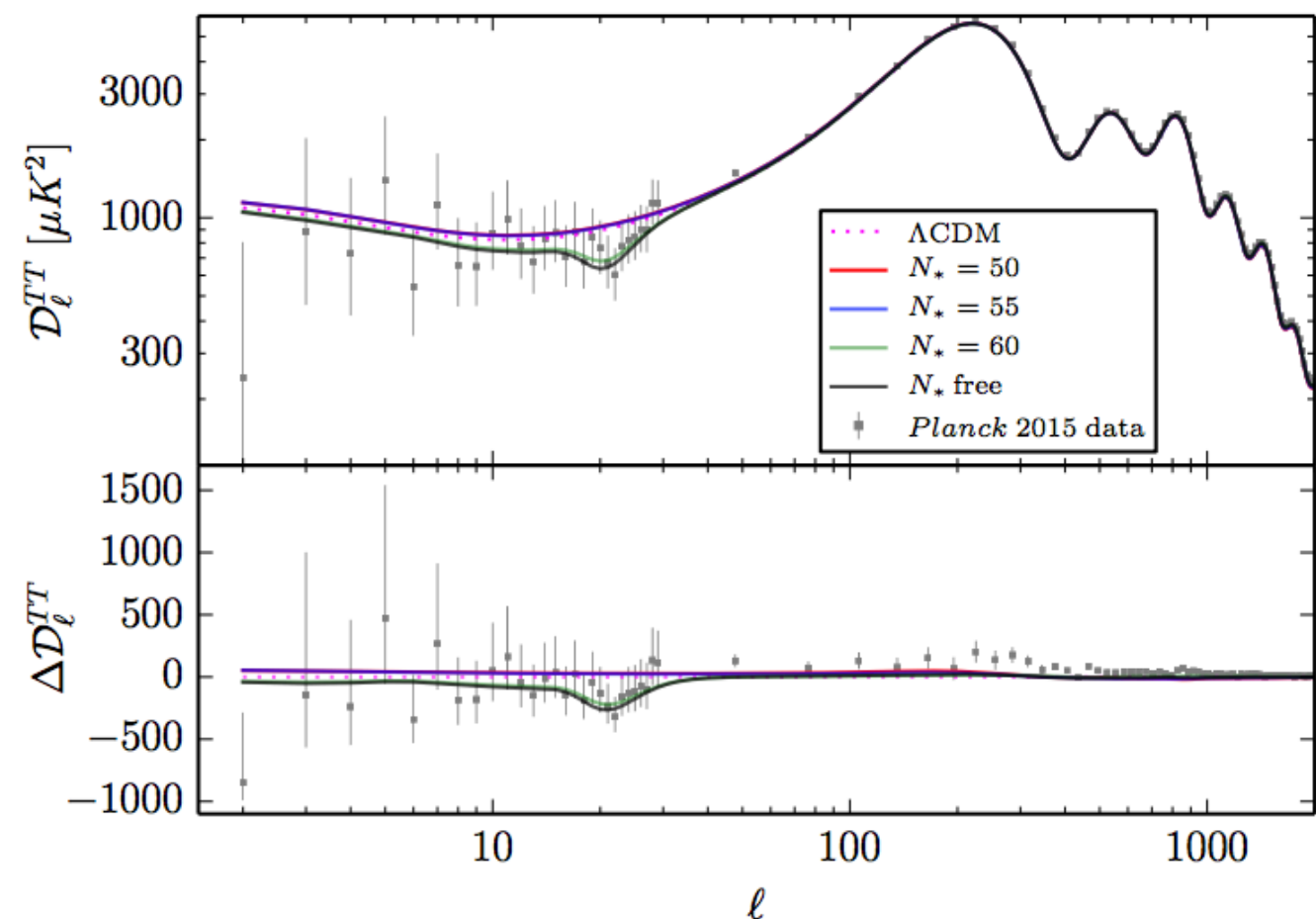
There is an interesting structure in the CMB at multipoles $\ell \sim 20$ -30.



But mostly: *neither panic nor excitement* in the cosmology community.

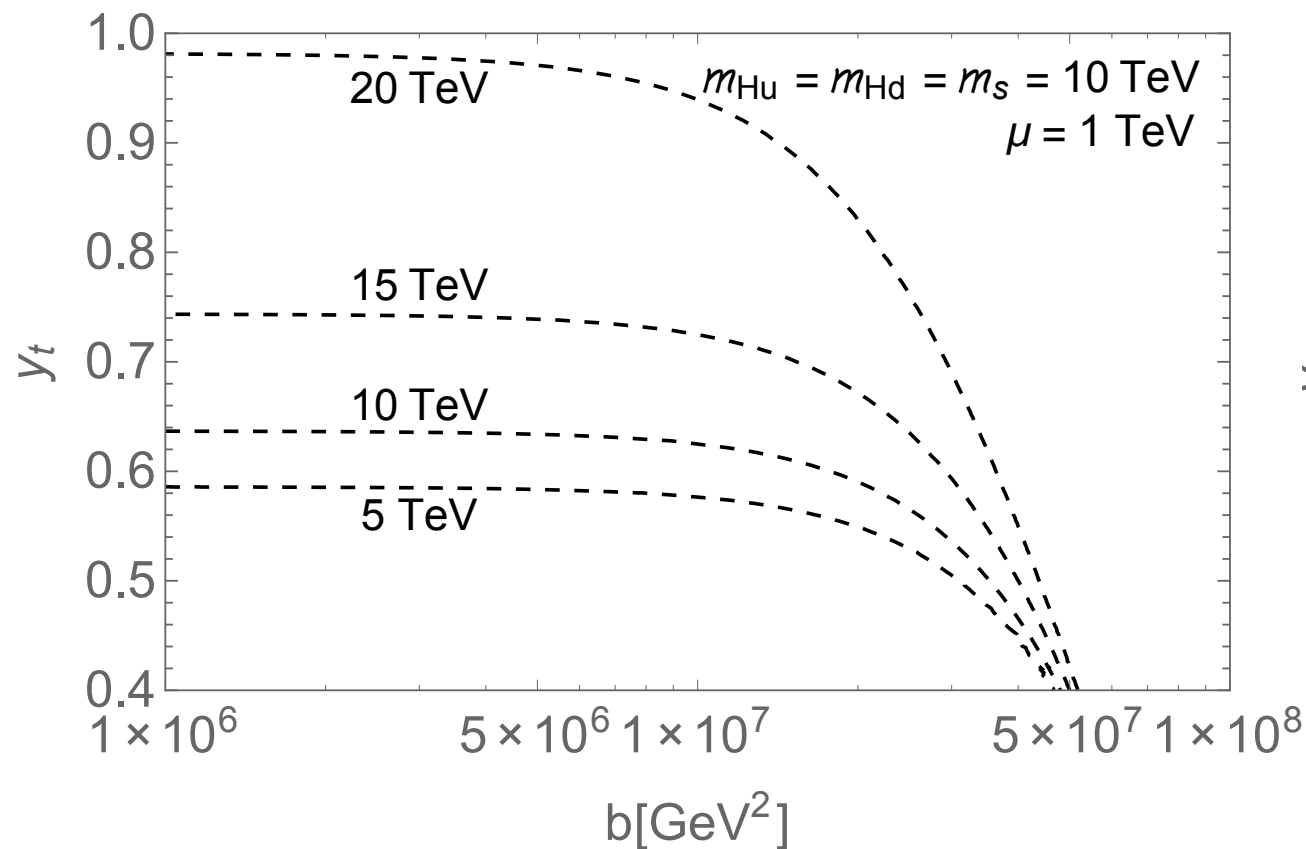
This is just our universe—part in 100-1000 accident!

Could try to fit this feature with model with a step in potential (Cai, Ferreira, Hu, Quintin 1507.05619). Obtain $\Delta\chi^2 \sim -10$.

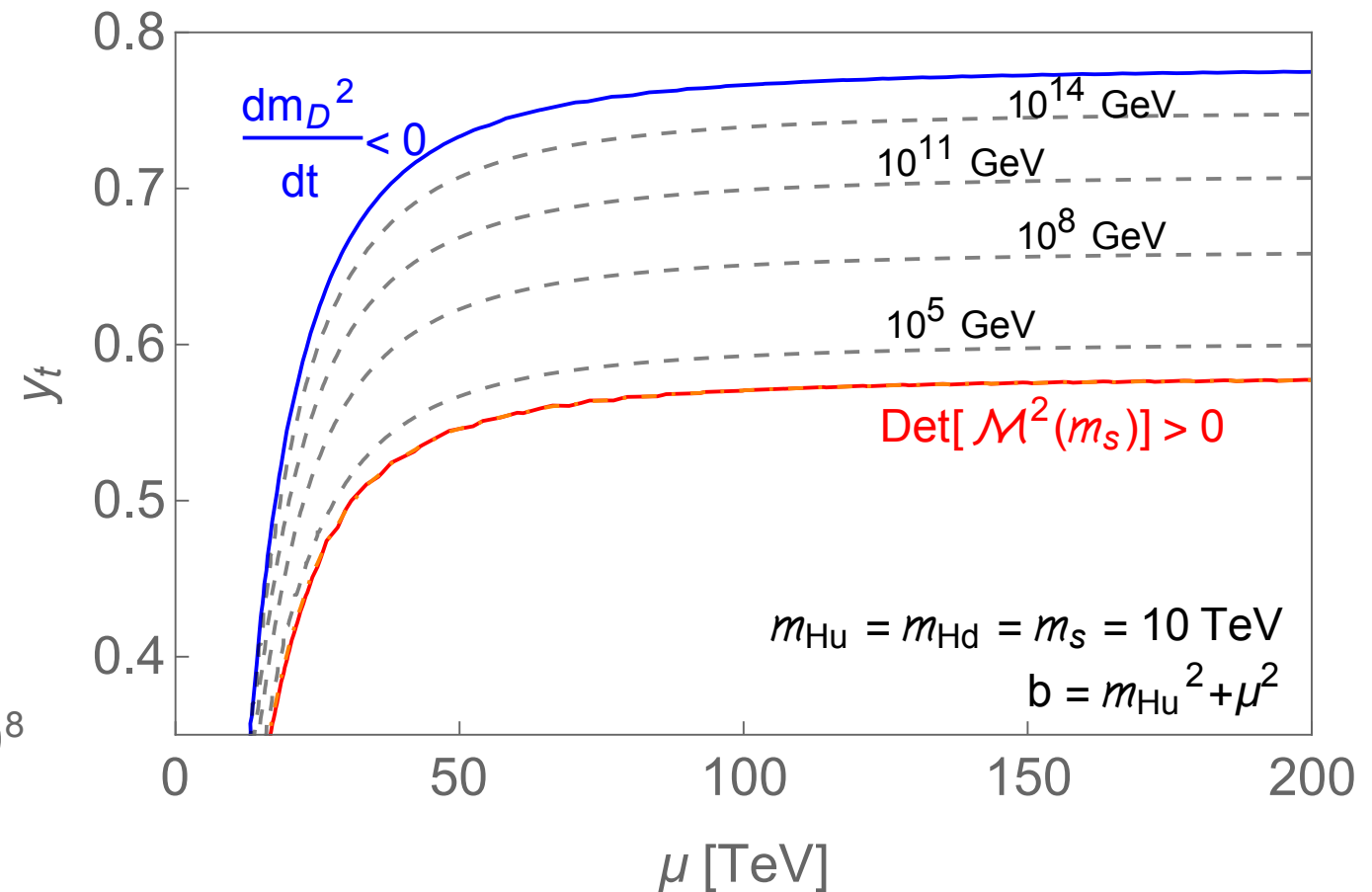


An alternative for what is natural in SUSY:

“Standard SUSY”



“Flat-Higgs SUSY”



The typical SUSY naturalness story is that as we vary input UV parameters, the Higgs VEV should change by $O(1)$ amounts. But in theories where the Higgs has a (badly broken!) shift symmetry, we will find *exponential* sensitivity of the VEV to UV parameters.

Radiative Breaking in the MSSM

Let's review the most familiar story for EWSB in SUSY.

All of the scalars in the MSSM have a characteristic mass scale M_{soft}

At some mediation scale, we have $m_{H_u}^2 \sim M_{\text{soft}}^2$

Renormalization group running, driven by the large Yukawa coupling, tends to drive the up-type Higgs negative:

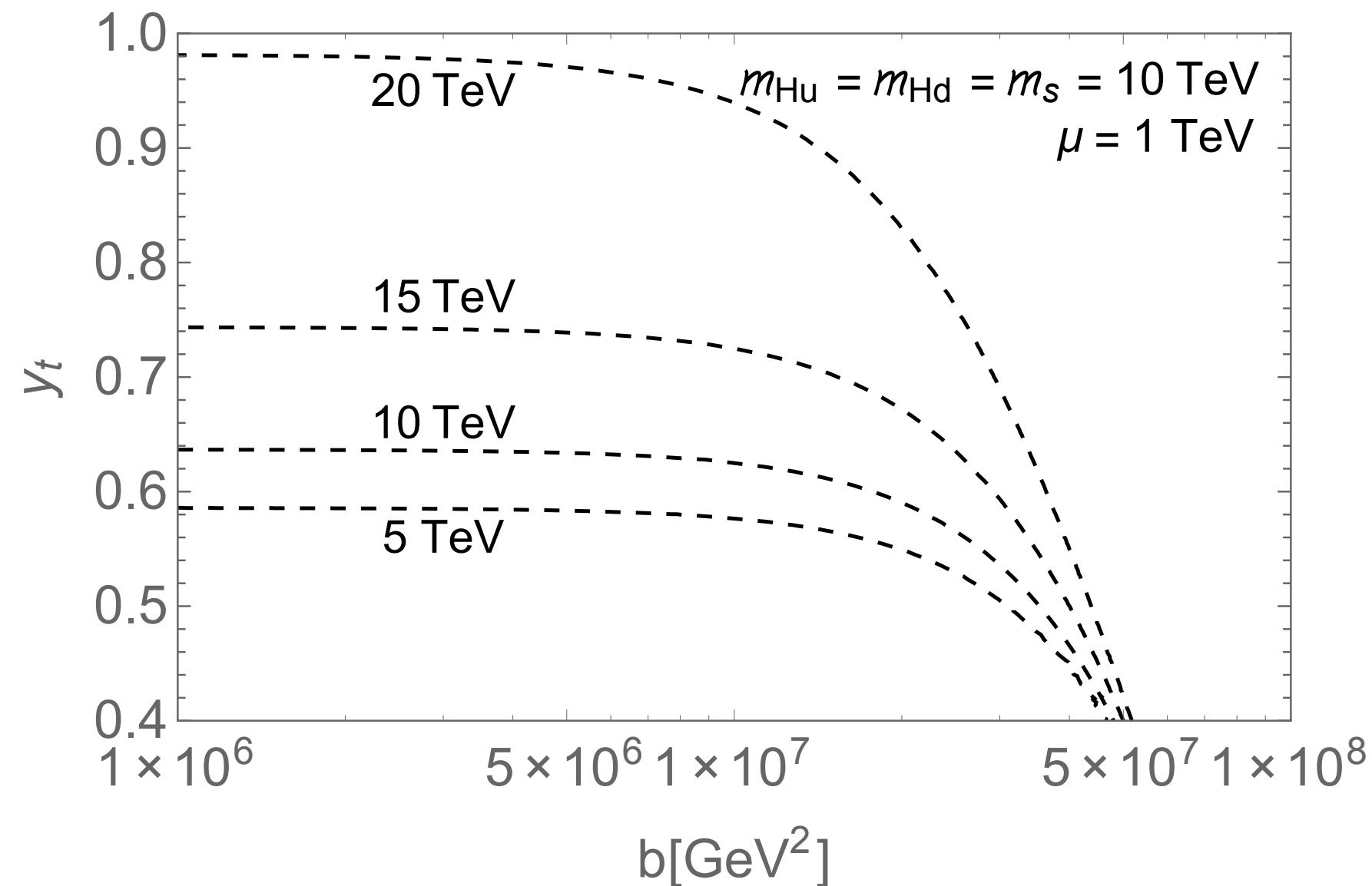
$$\frac{d}{dt}m_{H_u}^2 = \frac{1}{16\pi^2} [6|y_t|^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 6|a_t|^2 - 6g_2^2|M_2|^2 + \dots]$$

Compare the stops, which run more slowly:

$$\begin{aligned}\frac{d}{dt}m_{Q_3}^2 &= \frac{1}{16\pi^2} [2|y_t|^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 2|a_t|^2 - 32/3g_3^2|M_3|^2 + \dots] \\ \frac{d}{dt}m_{\bar{u}_3}^2 &= \frac{1}{16\pi^2} [4|y_t|^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 4|a_t|^2 - 32/3g_3^2|M_3|^2 + \dots]\end{aligned}$$

This naturally favors electroweak breaking with $\langle h \rangle \sim M_{\text{soft}}$

A Typical Supersymmetric Scenario



Naturalness: visualize how EWSB changes as we vary UV parameters.

Higgs VEV \sim Soft masses $\sim 10 \text{ TeV}$.

Right-hand side: we have b -driven EWSB instead of radiative EWSB.

Here the VEV runs away to large values. More on this soon.

A Shift-Symmetric Kähler Potential

A range of theories, including various forms of “Gauge-Higgs Unification,” predict that the *tree-level* Kähler potential has the form

$$f(X, X^\dagger) \left| H_u + H_d^\dagger \right|^2$$

which is invariant under the continuous shift symmetry

$$H_u \rightarrow H_u + c, \quad H_d \rightarrow H_d - c^\dagger$$

This symmetry is explicitly broken—for instance, the top Yukawa coupling **breaks it badly**. Nonetheless, it can have a profound effect on the physics of the theory.

An incomplete list of references for such symmetries:

Lopes Cardoso, Luest, Mohaupt '94; Antoniadis, Gava, Narain, Taylor '94; Brignole, Ibáñez, Muñoz '96; Burdman, Nomura '02; Choi, Haba, Jeong, Okumura, Shimizu, Yamaguchi '03; Hebecker, March-Russell, Ziegler '08; Brümmer, Fichet, Hebecker, Kraml '09; Hebecker, Knochel, Weigand '12; Ibáñez, Valenzuela '13

Consequences of the Tree-Level Shift Symmetry

The F-term VEVs of the various fields X (e.g. moduli) determine the Higgs soft masses, the μ term, and the B term. But the symmetry constrains the mass matrix to have the form:

$$\begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -b \\ -b & |\mu|^2 + m_{H_d}^2 \end{pmatrix} = b \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}$$

At tree level, there is **one massless eigenvalue** which is oriented **along the D-flat direction** $H_u = H_d$.

We must compute loop corrections to understand the fate of this flat direction, but it raises the possibility that *these realizations of SUSY prefer*

$$\langle h \rangle \gg M_{\text{soft}}$$

Obviously the real world doesn't obey this. But it alters the way we think about the hierarchy problem. Let's explore further.

RG Running and Electroweak Breaking

In the UV this theory is on the edge of breaking EWSB. Let's work in a limit where *gaugino masses and A-terms are negligible*, to start.

The evolution of the mass matrix $\begin{pmatrix} |\mu|^2 + m_{H_u}^2 & -b \\ -b & |\mu|^2 + m_{H_d}^2 \end{pmatrix}$

depends mostly on $m_{H_u}^2$ wanting to run tachyonic and on μ , which gets either larger or smaller depending on how big the top Yukawa is relative to the gauge coupling:

$$\frac{d}{dt}\mu \approx \frac{1}{16\pi^2}\mu \left(3|y_t|^2 - 3g_2^2 - \frac{3}{5}g_1^2 \right)$$

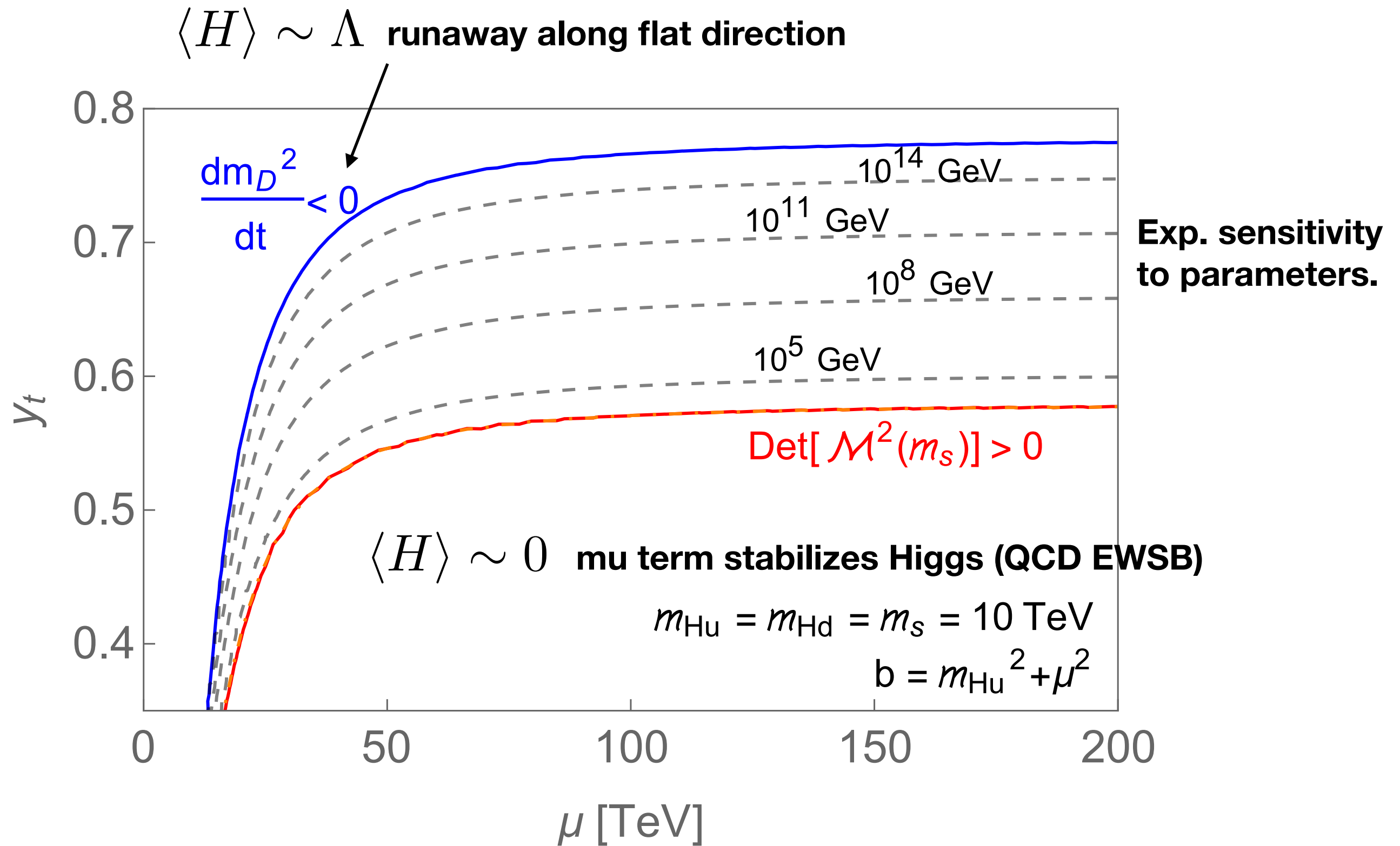
Let's explore the toy landscape where we vary the UV values of

$$y_t, \frac{\mu^2}{m_{H_u}^2}, \frac{m_{Q_3}^2}{m_{H_u}^2} = \frac{m_{u_3}^2}{m_{H_u}^2}$$

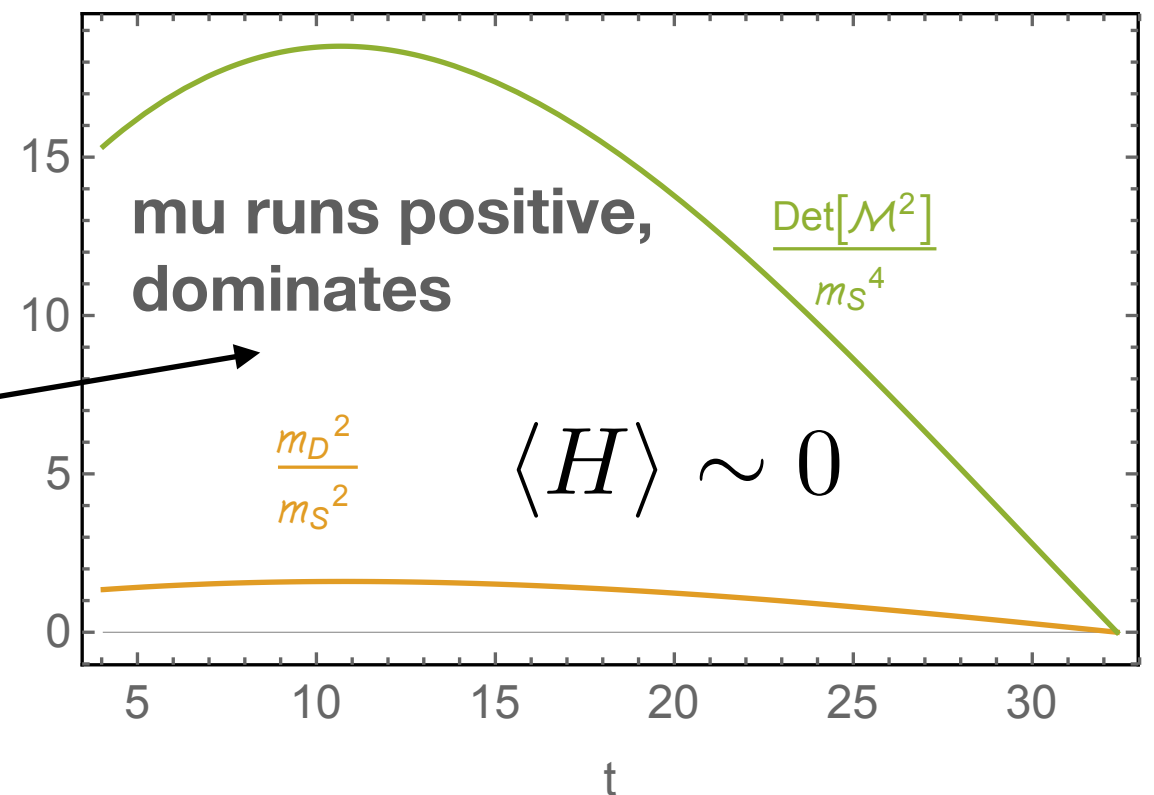
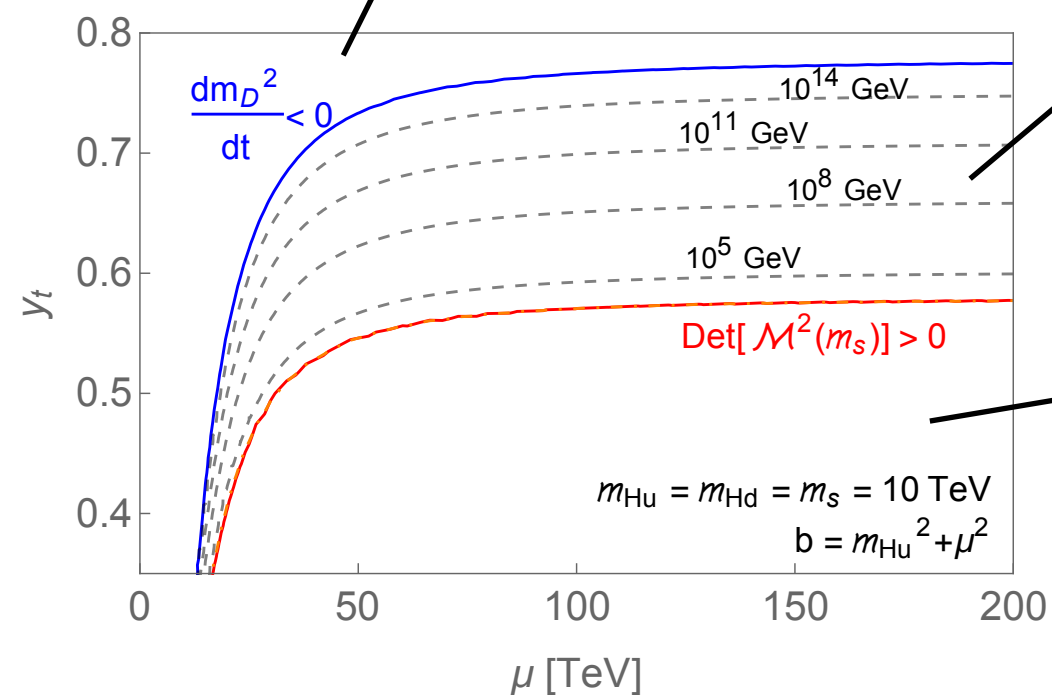
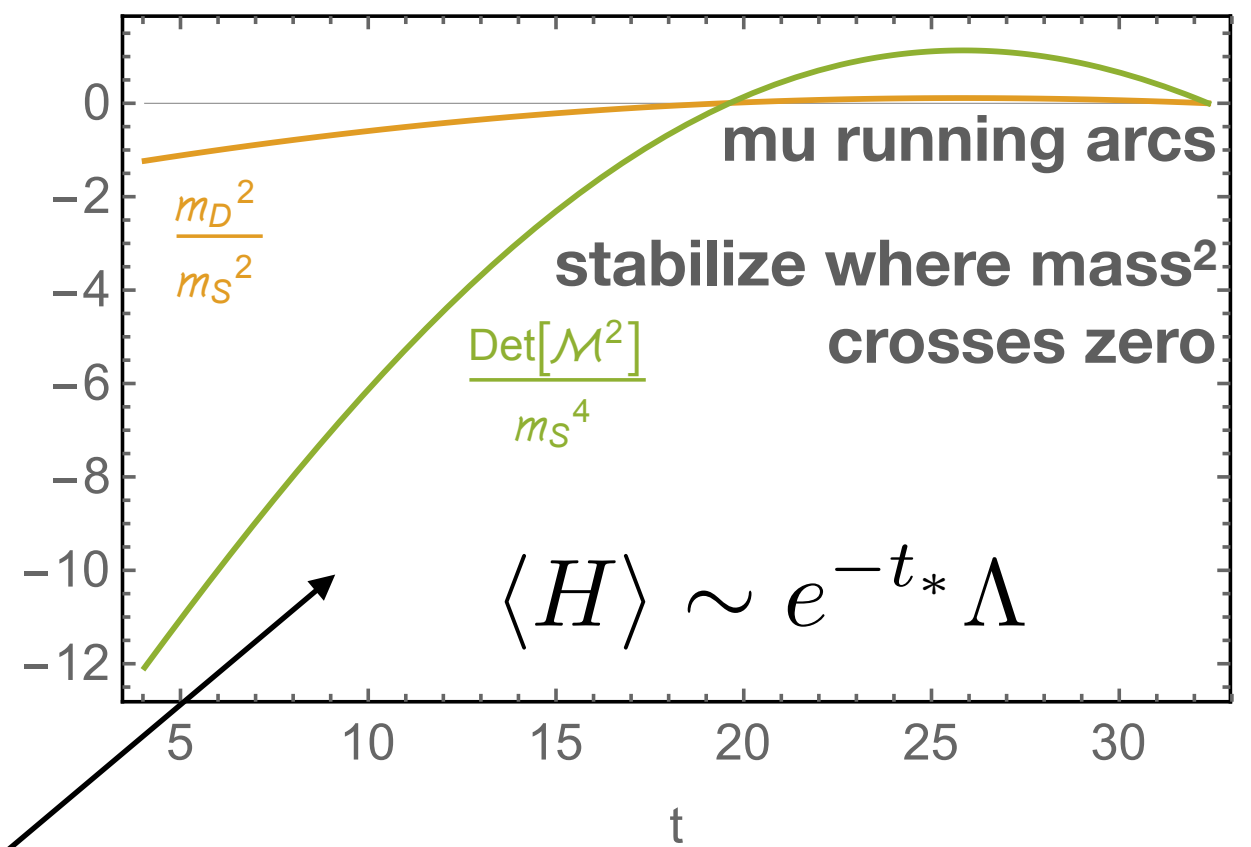
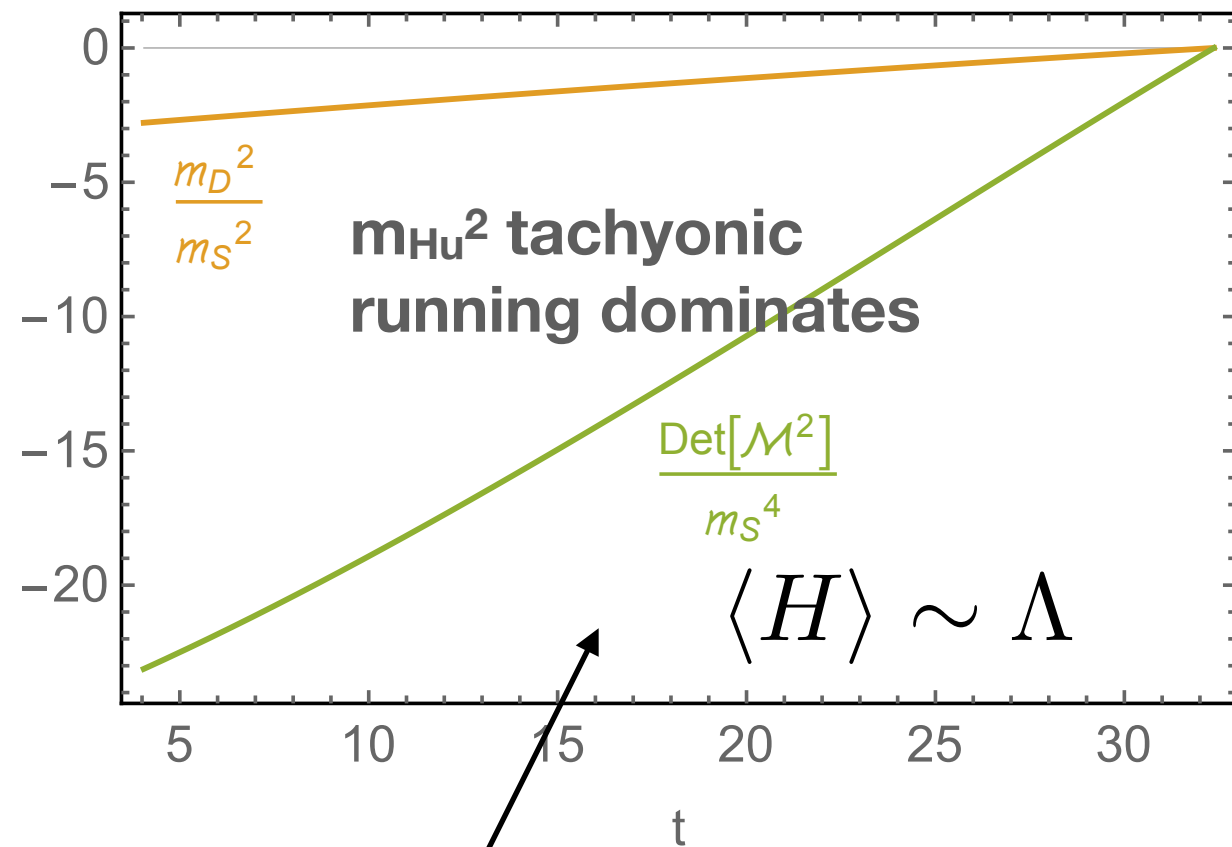
keeping the other parameters fixed and keeping the shift-symmetry conditions

$$m_{H_u}^2 = m_{H_d}^2 = b - |\mu|^2$$

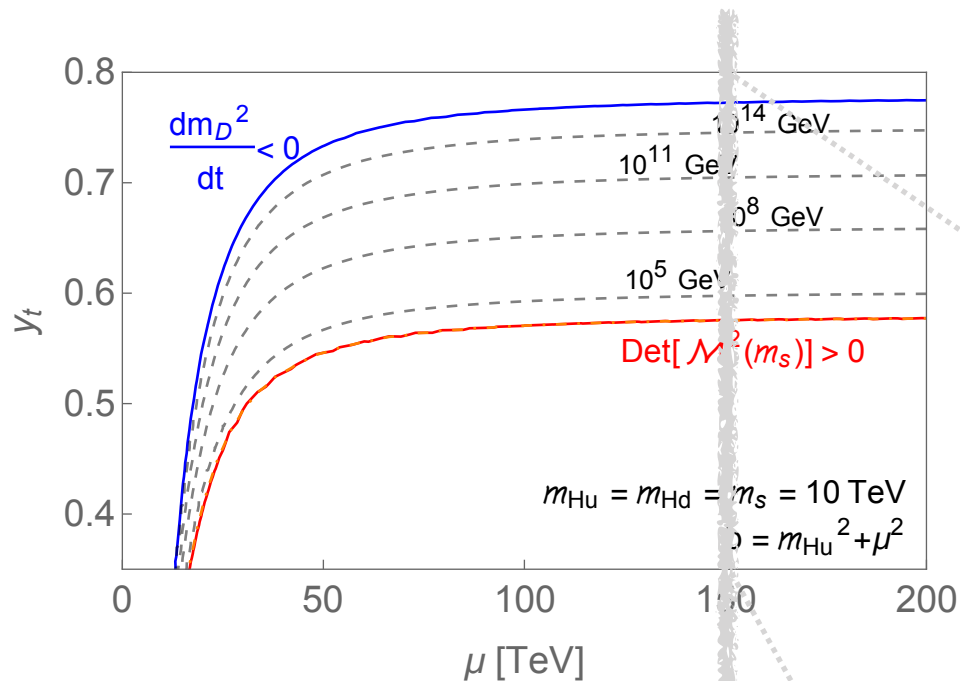
SUSY Near a Cliff



SUSY Near a Cliff: RGE Running Behaviors

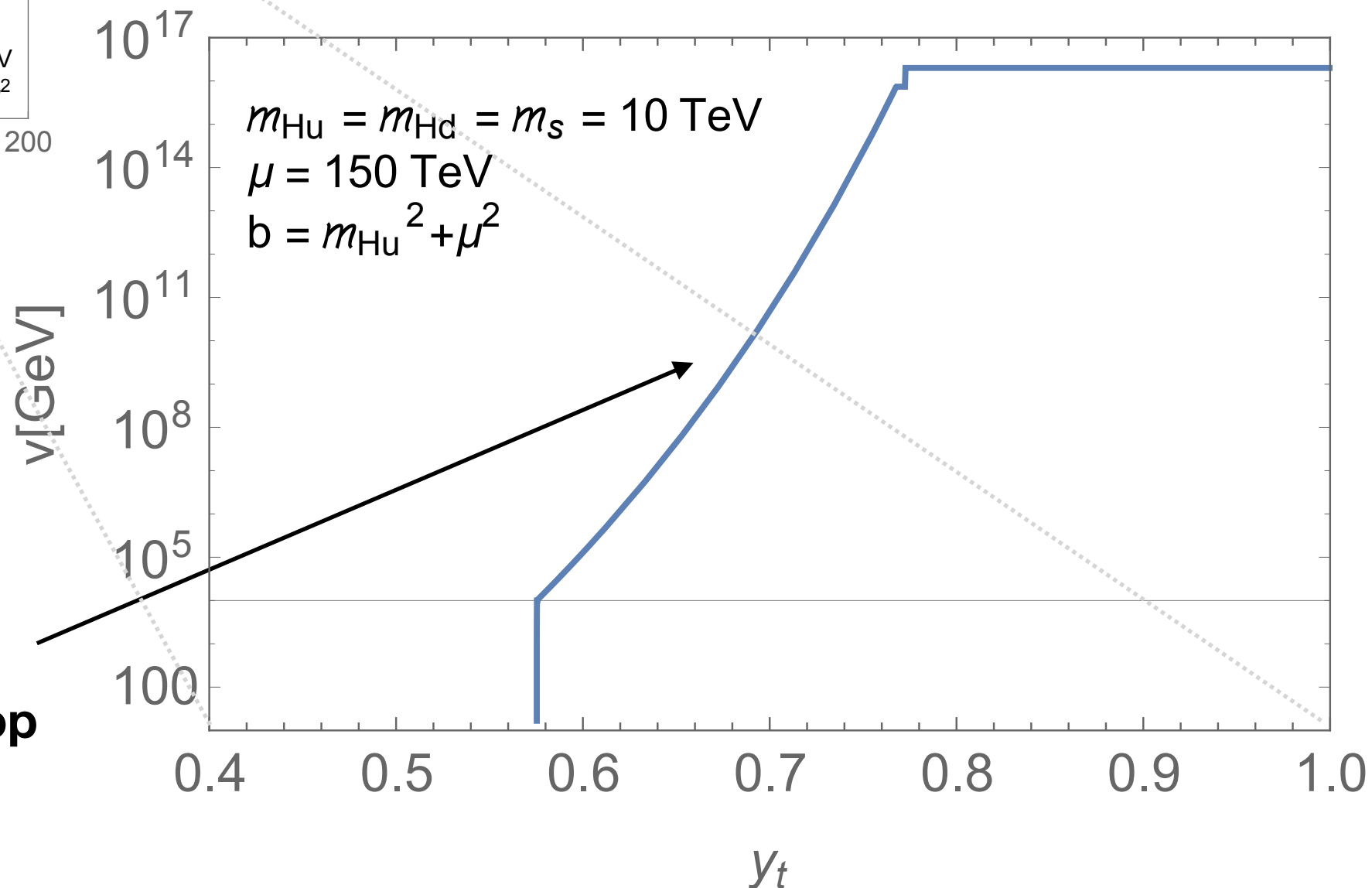


SUSY Near a Cliff: Dimensional Transmutation



The ratio v/M_{soft} is exponentially sensitive to the parameters!

Taking a slice through the plot:



Exponential variation in the Higgs VEV as we change input parameters like the top Yukawa coupling.

Summary of “Flat Higgs” SUSY:

We typically expect that in a supersymmetric theory, the soft scale and the Higgs VEV are closely related,

$$\langle H \rangle \approx M_{\text{soft}}$$

If there is a good UV reason for a tachyon to point along the flat direction, this is replaced by something more dramatic:

$$\textit{usually} \quad \langle H \rangle \approx \Lambda \quad \text{or} \quad \langle H \rangle \approx 0$$

but there is a slice of parameter space where

$$\langle H \rangle \approx 10^x M_{\text{soft}} \quad \text{with} \quad -1 \lesssim x \lesssim 12$$

which looks more like how we understand the origin of the QCD scale (i.e., **dimensional transmutation**). Also resembles **Coleman-Weinberg**.

This could change how we think about fine-tuning in SUSY.

Realism

The minimal version of this story has viable vacua only with

$$m_h < m_Z$$

We can deform the story to get less minimal theories, but we want UV boundary conditions that stick close to a flat direction to have an interesting story.

Still exploring different options for doing this.

Anthropics

Can this help us find a nice anthropic explanation of the weak scale?

In the large swath of parameter space where $\langle H \rangle \sim \Lambda$, no large structures form in the universe.

In other parts of parameter space, it is less clear if there is a “simple” anthropic argument. Would like to not have to appeal to all the details of chemistry or nuclear physics.

Consequences for Hidden Sectors?

In general, string compactifications predict the existence of hidden sectors: particles not charged under the Standard Model gauge group.

From cosmology, we have at least a mild “Missing Hidden Sector Problem.”

Planck constraint on relativistic degrees of freedom (“effective neutrinos”):

$$N_{\text{eff}} = 3.15 \pm 0.23 \ (1\sigma)$$

Standard Model expectation:

$$N_{\text{eff}}^{\text{SM}} = 3.046$$

If there are ultraviolet reasons for many hidden sectors to lie near a flat direction, then large VEVs could decouple large numbers of these particles.

Could ameliorate the Missing Hidden Sector Problem. Massless dark photons and their superpartners—photini with masses near the SUSY breaking scale—could survive.

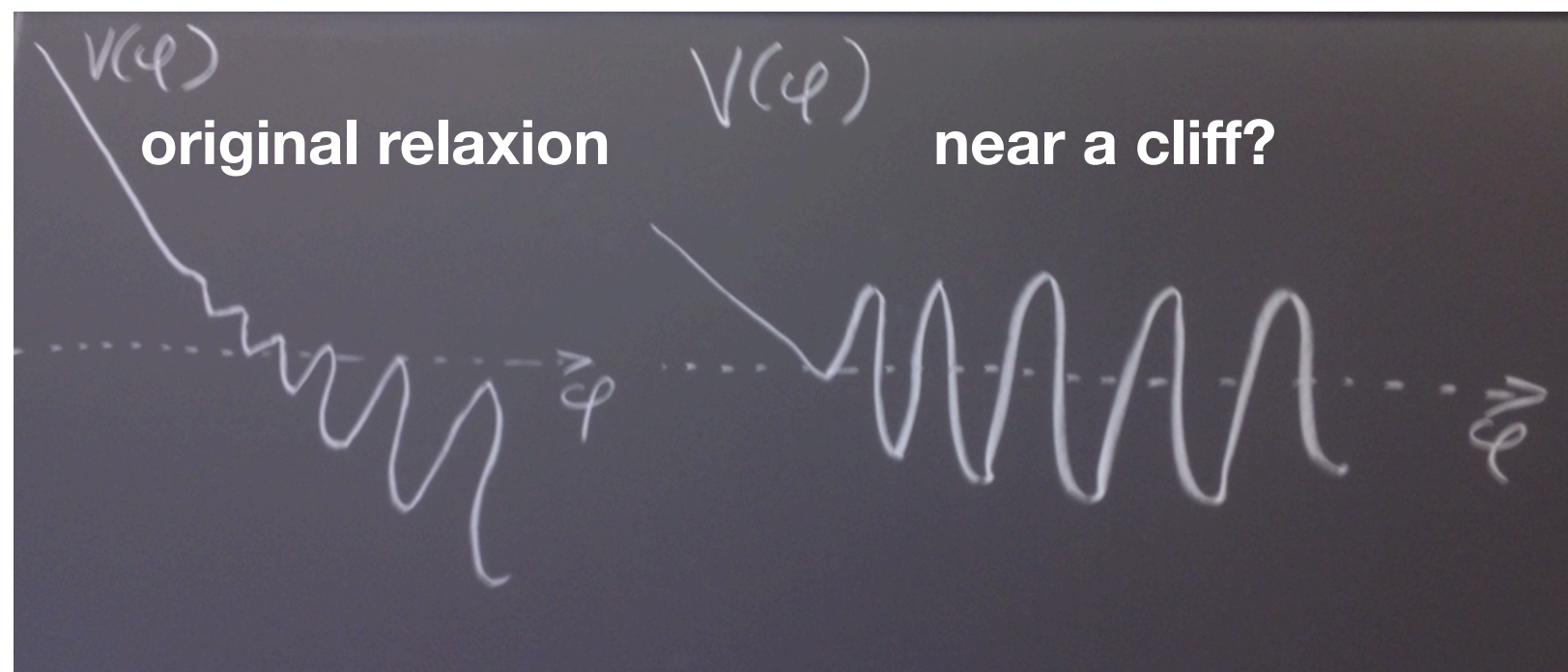
Photini phenomenology: Arvanitaki, Craig, Dimopoulos, Dubovsky, March-Russell '09; Baryakhtar, Craig, Van Tilburg '12; Acharya, Ellis, Kane, Nelson, Perry '16

Relaxion Prospects?

Idea of Graham, Kaplan, Rajendran arXiv:1504.07551:

$$g\phi h^\dagger h + V(h) + \frac{\phi}{f} G_{\mu\nu}^a \tilde{G}^{a\mu\nu}$$

Suppose we realize a variation on this idea close to a SUSY flat direction. Not far from our vacuum, the Higgs VEV can be *much* bigger, raising the QCD scale —and hence the potential barrier height—significantly.



Can we use the trick of living near a flat direction to improve the relaxion scenario? (Smaller field range, less need for strong dissipation, fewer e-folds....)?

Outlook

Cosmology gives us a potential way to directly look for *dynamical effects* of fine-tuning, via the effect of VEVs of scalar fields on the Higgs.

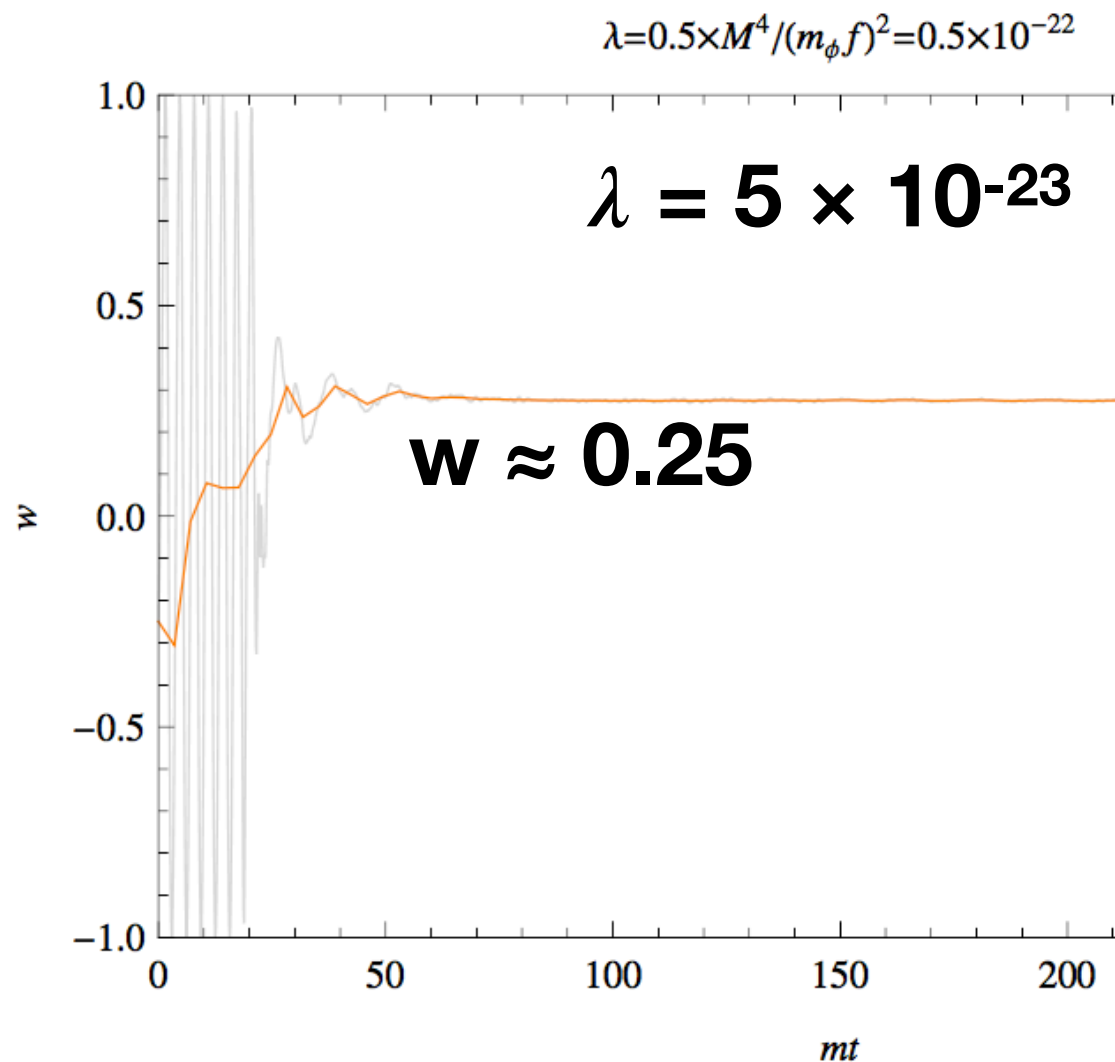
Leads to out-of-equilibrium dynamics, produces gravitational waves, gives a period with an exotic equation of state.

Difficult to calculate—much more to explore.

Numerics show that this works at small quartics. In SUSY, these can arise along D-flat directions.

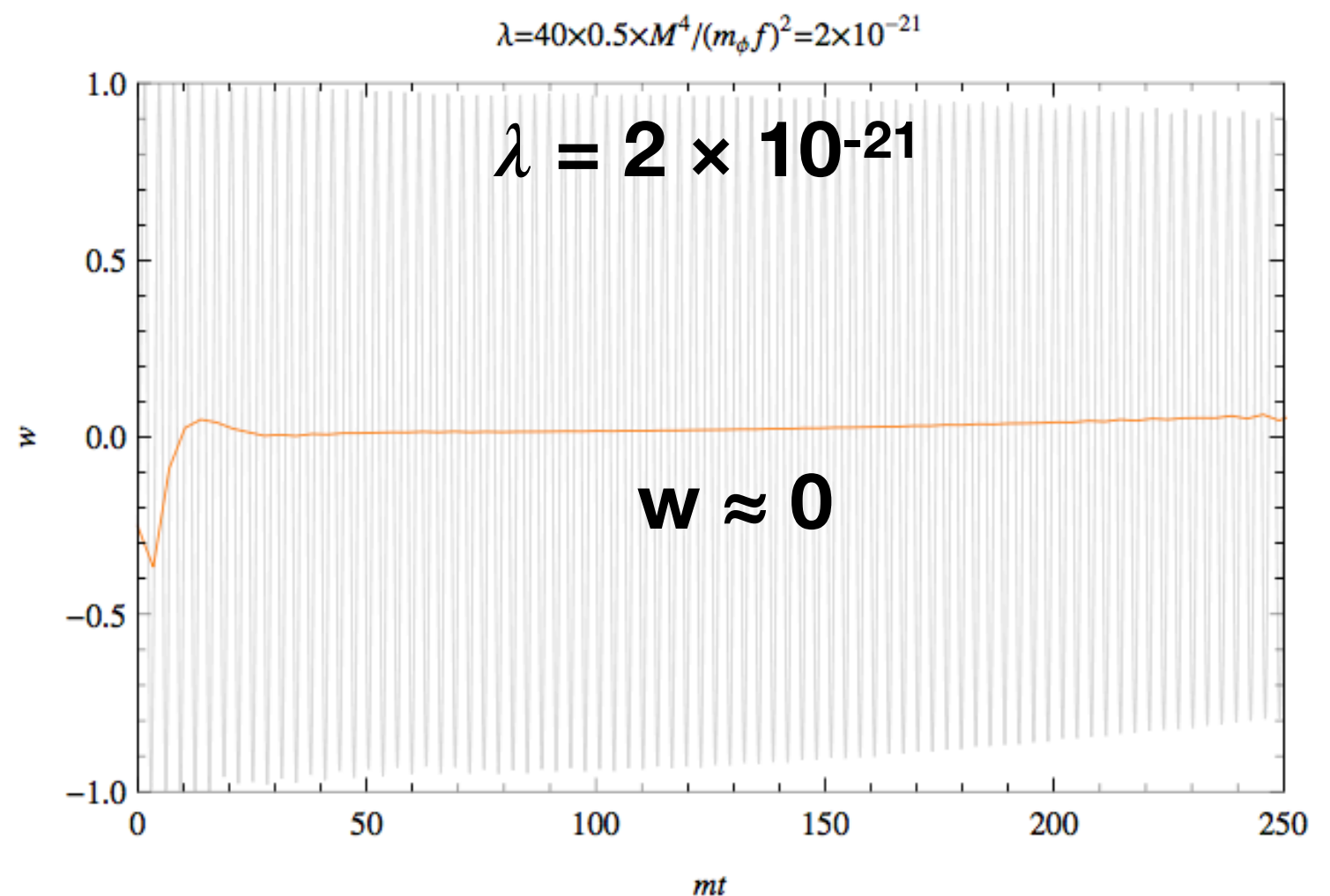
More generally, physics near D-flat directions in SUSY deviates from our standard notions of naturalness. Is this useful?

Equation of State: Need for Tiny Quartic



A sustained time interval with equation of state different from matter domination requires a small quartic coupling.

A really small quartic coupling: even far below the SM size, returns to matter domination almost instantly.



Qualitative Features are Robust

$$\rho(h)/\rho(\phi) \approx 1$$

