Normal theoretical ideas on vacuum energy

Alessandro Strumia et al. 1906.00986, 1911.01441, 2203.17197, 2301.03620

Talk at Frascati 'DΛrk Energy', 2023/9/12

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At a Frascati 'weird theoretical ideas' workshop I presented weird ideas for Higgs naturalness. Big theory and experimental search for natural interpretations of dark energy and of the weak scale, the two small dimensional parameters of the Standard Models. Now LHC found no natural physics, and ideas got weirder.

$$\text{Unnaturalness} - \text{Naturalness} : 2 - 0.$$

I now discuss the **anthropic** selection interpretation that physicists don't like. Because it's bad for experimental testability and for suggesting new theories.

It just needs 'normal' theory, no need of inventing anything new.
At the School of ~~Natural~~ Sciences: Arkani-Hamed says

$$\text{Radical conservatorism} \to \text{conservative radicalism}$$

and Witten: 'I was actually extremely upset, because of the feeling that it would make the universe harder to understand. I eventually made my peace with it, accepting the fact that the universe wasn't created for our convenience'.

Plausible understanding

Dark energy $V_0 \sim 10^{-123} M_{\rm Pl}^4$

seems 'just' a cosmological constant, unnaturally small because of anthropic selection: galaxy/structure formation needs $V_0 \lesssim \delta^3 T_{\rm eq}^4$ [Weinberg].

The weak scale $M_h^2 \sim 10^{-35} M_{\rm Pl}^2$

seems unnaturally small because of anthropic selection?
1) 100 nuclei and thereby chemistry exist because $m_p \gtrsim m_n$ in the SM

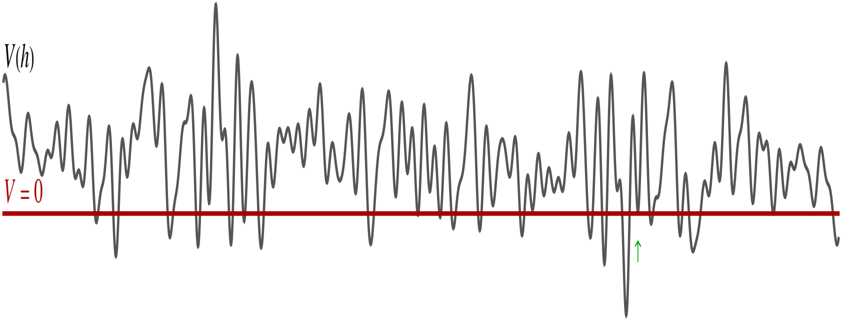
$$m_n - m_p = \underbrace{\mathcal{O}(\alpha_{\rm em}\Lambda_{\rm QCD})}_{-1.0\,{\rm MeV}} + \underbrace{(y_d - y_u)v}_{2.5\,{\rm MeV}}.$$

fixes only yv, favouring SM-like theories with larger v and smaller $y \ll 10^{-6}$.
2) BBN and core-collapse supernovæ change at $v \sim \Lambda_{\rm QCD}^{3/4} M_{\rm Pl}^{1/4}$. Possible anthropic boundary from SN: ν exit on gravitational time, spreading C, N...

Among theories for unnaturalness, the most plausible is the least testable.

From Monovacuism to Polyvacuism

Unnaturalness can be understood in a theory with a landscape of $\gg 10^{123+35}$ different vacua,



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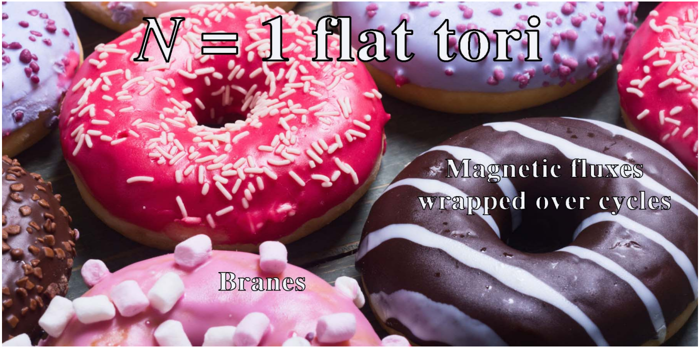
This can arise in super-string theory, where the particles and parameter values of sub-Planckian effective QFTs depend on complex geographies of compactification. So far, focus on compactifications that preserve $N = 1$ supersymmetry.



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Weak-scale supersymmetry would have made the weak scale natural.
But this was not found at LEP and LHC and $M_h = 125\,\text{GeV}$.

$\overset{?}{\Rightarrow}$ The string landscape is statistically dominated by vacua where supersymmetry is broken at the string scale. Predictive if computable?

QFT allows a landscape

Toy model: consider $N \gtrsim 500$ normal scalars ϕ_i and a normal QFT quartic $V(\phi)$.

Can V have 10^{123} vacua with different vacuum energy? A computer cannot tell. Yes, Arkani-Hamed et al. assumed N non-interacting scalars, $V = \sum_i V_i(\phi_i)$, each with 2 minima, so 2^N minima. So far M_h^2 is the same in all vacua.

Can V have 10^{35} vacua with different M_h^2? Yes, we consider an approximate $\mathbb{Z}_2^N$

$$V = V_0 - \frac{1}{2} M_i^2 \phi_i^2 + \frac{1}{4} \lambda_{ij} \phi_i^2 \phi_j^2 + \epsilon V_{\text{odd}}$$

just to control: it has 2^N vacua that persist for small ϵ, and

$$\frac{\delta V}{M^4} \approx \frac{\sqrt{N}\epsilon}{\lambda}, \qquad \frac{\delta m^2}{M^2} \approx \sqrt{N}\epsilon \frac{\lambda_{ij}}{\lambda_{ii}} \qquad \text{can be} \gtrsim 1.$$

Is vacuum decay a problem? Enhanced by N bounces, not by 2^N.

- Accidentally light scalars with large $v \sim M$ have small potential barrier, so vacuum decay is too fast.
- Accidentally light scalars with small or vanishing v: vacuum decay is similarly too fast if V contains $\sim M\phi^3$.
  Vacuum decay is fine **if the cubic is forbidden** and $\lambda \lesssim 10$.

That's the Higgs: only one 2 of $\mathrm{SU}(2)_L$, no cubic, multiple $y_{u,d,e,\nu}$ thanks to $\bar{2} \sim 2$.

Testing the landscape: hopeless? With luck?

Indirect. If the multiverse has 10^{500} computable vacua, it could be tested by measuring more than 500 digits of fundamental constants.

More precisely: by measuring more information than the Shannon entropy of the multiverse. I skip the erudite presentation because the 1st referee report said ‘it took me a while to understand what this paper is about’.

Testing the landscape: hopeless? With luck?

Indirect. If the multiverse has 10^{500} computable vacua, it could be tested by measuring more than 500 digits of fundamental constants. So far:

Symbol	Model description	Number of parameters	Measured bits in base-e including 0	Measured bits in base-e without 0
$g_{1,2,3}$	SM gauge couplings	3	37	36
λ_H	SM Higgs quartic	1	6	6
y_q	SM diagonal Yukawas of quarks	6	50	12
y_ℓ	SM diagonal Yukawas of leptons	3	72	47
$V_{\rm CKM}$	SM off-diagonal Yukawas of quarks	4	21	11
m_ν	Mass matrix of neutrinos	5	46	9
$v^2/M_{\rm Pl}^2, V/M_{\rm Pl}^4$	SM/ΛCDM mass scales	2	371	10
$\Omega_{m,b,r}, A_s, n_s$	ΛCDM cosmological parameters	5	51	19
	All physics	29	655	150

This could be possible even if we already discovered all particles accessible to colliders, shifting their goal to the Kelvin edenavour: *measuring more precisely the SM fundamental constants* that act as SM 'coordinates' in the landscape. Not the Higgs couplings (since better known from masses), not $g-2$ (SM), not $c, \hbar, k_B$.

Direct hints:

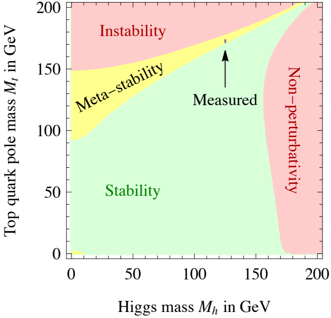
- Bubble collisions in the CMB? Not found, nor needed.
- 1st order cosmological phase transitions give signals so hints: gravitational waves, black holes, DM as bubbles of other remnant vacua.
- Deeper vacua $\Rightarrow$ (Standard Model) vacuum decay.

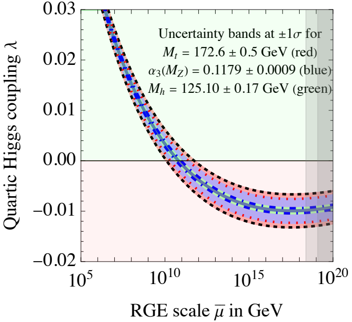
An instability in the Higgs potential?

The Higgs potential extrapolated to high h seems to have **two** different minima:

$$V(h) = V_0 - M_h^2 \frac{h^2}{4} + \lambda(h)\frac{h^4}{4} \qquad \lambda(h) = -\beta_\lambda \ln \frac{h^2}{e^{1/2} h_{\rm top}^2} \qquad \text{with} \qquad \beta_\lambda \approx \frac{0.15}{(4\pi)^2}.$$

λ gets negative around $h_{\rm top} \approx 10^{10}\,\text{GeV}$ for $M_h = 125.1\,\text{GeV}$ and $M_t \gtrsim 170\,\text{GeV}$.



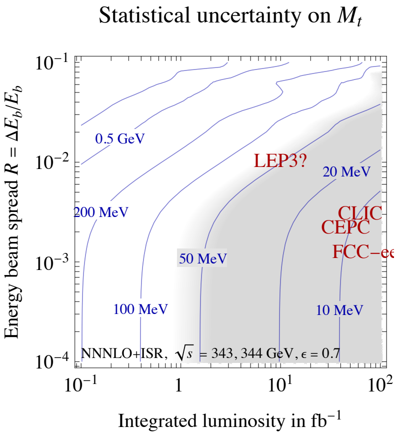


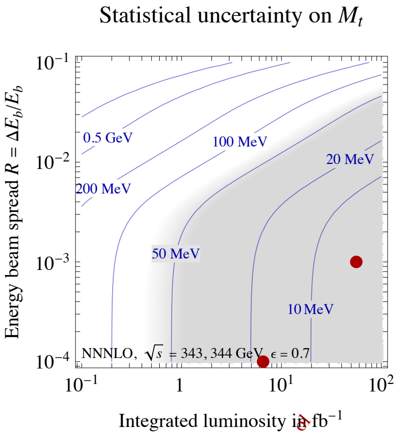
Establishing the Higgs instability

The way to measure M_t accurately enough is a $\ell^-\ell^+$ collider at the $t\bar{t}$ threshold. Little luminosity is enough thanks to low energy beam spread $R = \Delta E_b/E_b$

$$\delta M_t|_{\rm stat} \sim \frac{\Gamma_t}{\sqrt{N_t}} \max\left[1, \frac{M_t R}{\Gamma_t}\right] \qquad \delta M_t|_{\rm syst} \approx (40-70)\,\text{MeV}.$$

Precise estimate, with $\delta M_t|_{\rm syst} > \delta M_t|_{\rm stat}$ in the gray area:





Can SM vacuum decay?

If our universe is not in the deeper minimum, physics tends to fall there.
But it needs to overcome the potential barrier. Ways to go:

- **Quantum tunneling** is negligibly slow, $\gg 10^{100}$ yr.
- **Thermal fluctuations**. When the Universe was hot, it had enough energy to go over the barrier. Thermal effects also increase the barrier. Slow.
- **Inflationary fluctuations** could have brought the Higgs beyond the barrier. But inflation is over and its details are unknown. Self-quenching?
- **Primordial black holes** would have negligibly seeded Higgs vacuum decay.
- **Collisions of particles** (colliders or cosmic rays) can stimulate vacuum decay, but it remains exponentially slow.
- Higgs vacuum decay could be **artificially ignited** using futuristic tools.

$\Gamma \propto e^{-S}$	Predicted action		Experimental limit
Vacuum decay	$S_{\rm vacuum} \approx 8\pi^2/3\lvert\lambda\rvert \sim 2000$	$\gg$	$\ln h_{\rm top}^4/H_0^4 \sim 500$
Thermal decay	$S_{\rm thermal} \approx 2\pi/\lvert\lambda\rvert \sim 600$	$\gg$	$\ln \bar{M}_{\rm Pl}^4/H_0^3 h_{\rm top} \sim 200$
Black hole	$S_{\rm BH} \approx 2\pi/\lvert\lambda\rvert \sim 600$	$\gg$	$\ln N_{\rm BH}\bar{M}_{\rm Pl}^3/h_{\rm top}^3 \sim 50 + \ln N_{\rm BH}$
Collision	$S \approx 2\pi/\lvert\lambda\rvert \sim 600$	$\gg$	$\ln N_{\rm coll}$

Triggering vacuum decay: estimate

Assume $h \sim h_0$ in a region of space ('bubble') with size r_0.
This region evolves falling towards the true deeper minimum if:

1. Inside, the Higgs is beyond its potential barrier, $\boxed{h_0 \gtrsim h_{\rm top} \sim 10^{10}\,\text{GeV}}$.
2. It's big enough that gradient energy cannot stop, $\boxed{r_0 \gtrsim 1/h_0\sqrt{|\lambda|}}$.

Total energy:

$$E = \int dr\, 4\pi r^2 \left[\frac{h'^2}{2} + V\right] \sim 4\pi r_0 h_0^2[1 + \lambda r_0^2 h_0^2] \gtrsim E_{\rm min} \sim \frac{4\pi h_{\rm top}}{\sqrt{|\lambda|}} \sim 500\,\text{Joule}.$$

One Higgs quantum has energy $k \sim 1/r_0$ so the number of quanta is

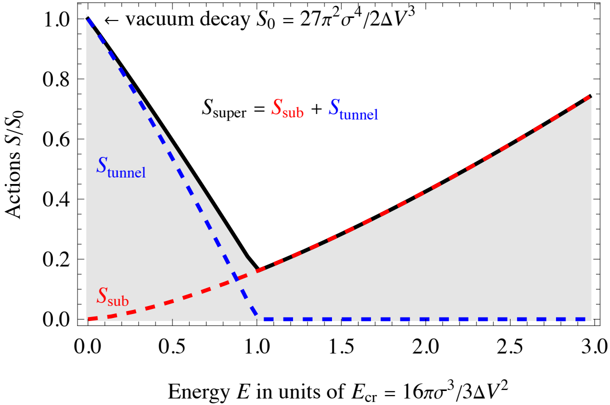
$$N \sim \frac{E}{k} \sim 4\pi(h_0 r_0)^2 \gtrsim N_{\rm min} \sim \frac{E_{\rm min}}{k} \sim \frac{4\pi}{|\lambda|} \sim 1000.$$

Precise SM potential gives $N_{\rm min} \approx 1/\beta_\lambda \approx 1000$ (and $N_{\rm sph} \sim$ few $N_{\rm min}$).

Vacuum decay stimulated by few particles

Rates exponentially suppressed by e^{-S} because quantum transitions between semi-classical states with $N \gg 1$ are suppressed as $\exp[-\mathcal{O}(N)]$. E.g. $|\langle\alpha|\alpha'\rangle|^2 = e^{-|\alpha-\alpha'|^2}$ for coherent states with $N = |\alpha|^2$ of a *free* oscillator. Voloshin found a partial reduction in thin wall approximation using a Landau technique

$$\langle E_2|\mathcal{O}|E_1\rangle \sim \exp\left[-\mathrm{Im}\left(\int_{q_1}^{q_*} p(q,E_1)\,dq + \int_{q_*}^{q_2} p(q,E_2)\,dq\right)\right].$$



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But the thin-wall approximation does not apply to Higgs vacuum decay.

Kuznetsov & Tinyakov found ∼full exponential suppression if $V = \frac{1}{2}m^2h^2 + \frac{1}{4}\lambda h^4$.

The SM potential is nearly scale invariant, SM vacuum tunnelling

$$S_{\text{Fubini}} = 8\pi^2/3|\lambda(h_0)|$$

is dominated by large $h_0 \gg h_{\text{top}}$ where $|\lambda|$ runs bigger. So adding energy $E \sim h_{\text{top}}$ can only stimulate bounces with $h \sim h_{\text{top}}$, that are more exponentially suppressed.

Conclusion: SM vacuum decay is negligibly stimulated by few-particle collisions.

The highest-energy collision in the Universe

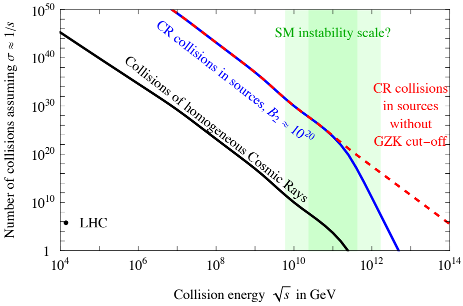
Cosmic Ray collisions up to $\sqrt{s} \sim 10^{11}$ GeV occurred for $\sigma_2 \sim 1/s$ given the flux

$$\frac{d\Phi}{d\ln E} \approx \frac{\text{EeV}^2}{E^2}\frac{100}{\text{km}^2\,\text{yr}\,\text{sr}}.$$

The CR collision rate can be much larger, if CR are produced in N_s sites with duration T_s, size R_s where CR stay for time τ_s:

$$N_2 \to N_2 B_2 \qquad B_2 \approx \frac{\langle n^2\rangle}{\langle n\rangle^2} \sim \frac{1}{N_\text{s}}\frac{\tau_\text{s} T_\text{U}}{T_\text{s}^2}\frac{R_\text{U}^3}{R_\text{s}^3}.$$

Sources unknown. Magnetars reach $B_2 \sim 10^{40-60}$. AGN reach $B_2 \sim 10^{6-30}$.



Possibly extend above the GZK cut-off. Not enough to trigger vacuum decay.

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- Collisions of 3 cosmic rays: $N_3 = B_3 \int d^4x\, n_{\mathrm{CR}}^3 \sigma_3$ with $\sigma_3 \sim 1/E^5$ and

$$B_3 \approx B_2 B_1 \qquad B_1 = \frac{n_\mathrm{s}}{n} \sim \frac{T_\mathrm{U} R_\mathrm{U}^3}{N_\mathrm{s} T_\mathrm{s} R_\mathrm{s}^3} \sim 10^{5-60}$$

- Collisions of N cosmic rays: $B_N/B_{N-1} \sim B_1$ give $N_N/N_{N-1} \sim B_1 n/E^3$.

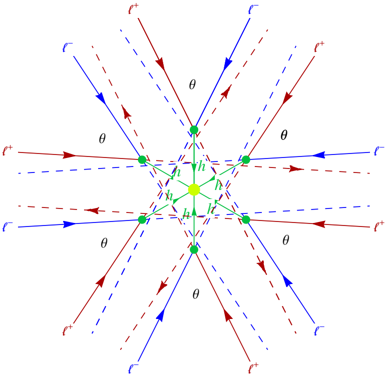
$N_3 > 1$ possible, while $N_{1000} \ll 1$: not enough to trigger vacuum decay.

Artificially triggering Higgs vacuum decay?

Quantum attempts are exponentially suppressed. Find a classical trigger.
Artificially overlap $N \gtrsim 1000$ ultra-high energy Higgs bosons.

Scatterings at $\sqrt{s} \gg v$ don't produce a 'Higgsplosion' of many Higgs.
Cannot use N colliders, need clean h collision to avoid creating a thermal barrier.
Possible way: on-shell $\mu^-\mu^- \to h$ production out of N colliders of N boosted h

$$\tau_h \frac{E_h}{M_h} = 0.37\,\mu\text{m}\,\frac{E_h}{10^9\ \text{GeV}}$$



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The quantum limit on the luminosity of fermionic colliders

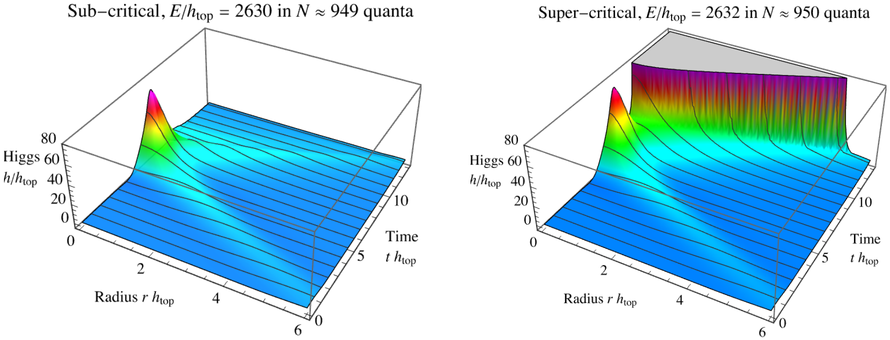
$$\mathcal{L} \sim \frac{1}{\Delta t\,\Delta x^2} \lesssim \Delta E\,\Delta p^2 \qquad (\sim 10^{15}\text{above the luminosity of current colliders})$$

at $\sigma_{\rm peak} \approx 4\pi\,\text{BR}(h \to \mu^+\mu^-)/M_h^2$ implies $\sim \Gamma(h \to \mu^-\mu^+)/M_h$ h per collision.

So $\gg 1000$ $\mu^-\mu^+$ colliders needed. Or bosonic collider e.g. $\gamma\gamma \to h$.

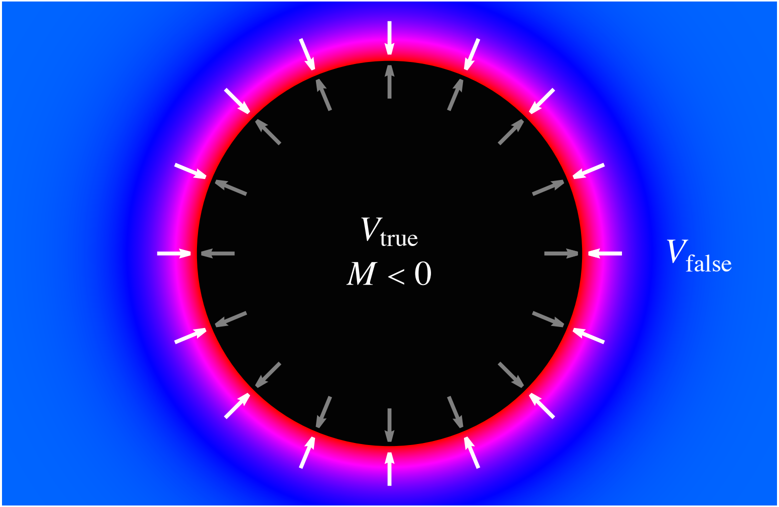
Artificially triggering Higgs vacuum decay?

A collision of $N \gg 1$ Higgs can be approximated as a classical spherical wave, numerical solutions tell if it's sub-critical or super-critical. E.g. assuming $k \sim h_{\rm top}$



Vacuum energy as energy source?

ΔV would be at least 10^{37} times more than nuclear energy. But it never ends. Does fundamental physics allow, at least in theory, to extract energy from the vacuum, by keeping a vacuum bubble nearly sub-critical? Extra particle beams can press the bubble, stabilizing roughly needs a thermal bath with $T \sim \Delta V^{1/4}$.



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The bubble emits $W \sim R^2 T^4$ giving $E \sim R^3 T^4$, getting negative mass $M < 0$.

Profitable until $t \lesssim R$, next stabilising costs more energy than what it gives.

Stronger beams can close the bubble, but no energy gain (energy conservation).

Ways to gain energy respecting its conservation?

- Let $M < 0$ explode behind a pre-existing black hole horizon, get its M.
- Close the bubble when $R \gtrsim M_{\rm Pl}/\Delta V^{1/2}$, such that its gravity is strong. Leaves a new small black hole with $|M| \sim M_{\rm Pl}^3/\Delta V^{1/2}$ made by $h_{\rm top} \ll M_{\rm Pl}$ physics. E.g. $|M| \sim 10^{11}$ kg emits 10^{11} W. One could build a km-size Dyson sphere with $T \sim T_{\rm Earth}$, or a m-size sphere with $T \sim T_{\rm sun}$.

Conclusions

I capoccioni s'hanno frastornati a penzà a ste storie 'e naturalezza.
Se sembrano risolve grazie a 'sta selezione antroppica: ci vo' na paccata d'universi.
Tra le teorie pe' ste' cose strambe, quella mejo è pure quella che nun se po' testà.
Pe' niente o quasi. Magari na speranzella ce l'avimmo:

- Possimo misurà li parametri SM co' 'na cariola de cifre.
  Può diventà 'o scopo 'e futuri collider, se nun c'è gnente.
- È interessante capì se 'sto vôto Higgs è stabbile. 'Na cosa ca nun po' mancà è daje na misurata precisa a 'sta massa 'e stu top one. Se può fà co' poca lumi a la soja $\sqrt{s} = 2M_t$, magari a LEP3 o ar primo collider de $\grave{\mu}$.
- Pur se instabile, le rate quantistiche $e^{-\mathcal{O}(4\pi)/\lambda}$ fanno aspettà assaje.
- Pe' scatenà 'sta instabilità, serve mettecece in modo classico $\sim 10^{10}$ GeV $\sim$ J in $\sim 1000h$ senz'altre particelle altrimenti a bolla la lessamo. Nun se fa. Nun abbasta nemmeno 'e posti 'ndo fanno li raggi cosmici.
- Armeno 'n teoria, pare che le leggi d'o munn co permettano usà l'energia der vuoto come 'na fonte d'energia. O famo un PNRR strano?