

Perspectives on

Nature's Greatest Puzzles

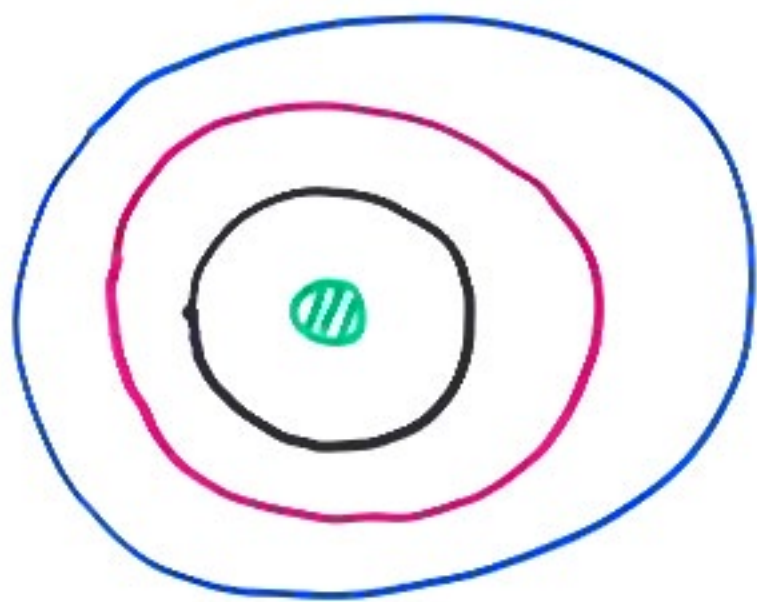
Nima Arkani-Hamed

# Disclaimer

- What we think of as being greatest puzzles may not end up being the right questions.
- Often we don't know what the right questions till we're close to the right answers.
- But we proceed! First rule of progress in science - better to follow your nose than twiddle your thumb.

Ancients:

Planets go around in circles around  
the sun

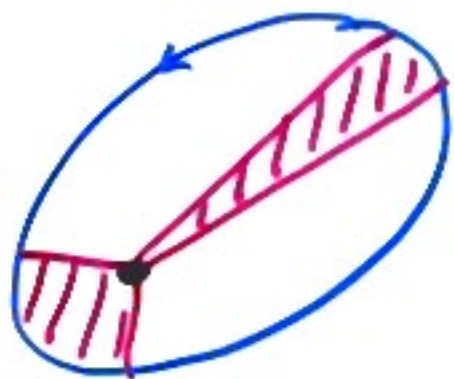


Most perfect shape! Goal of astronomy  
→ predict orbit radii.

∴  
...Culminates in Keplerian model  
of nested perfect solids....

But, Kepler also discovered...

They aren't circles!



- Crushes ancient dream + old questions.
- But also led to discovery of Kepler's laws  $\Rightarrow$  Newtonian Gravity + Dynamics  $\Rightarrow$  Birth of modern physics, with a slew of new questions suitable to fundamental physics.

. The SM has been set since since ~ late 70's.

. Ever since, in the absence of striking new data from colliders, we have been in search of the right questions to ask - and the right organizing principles - to guide us beyond the SM.

- The SM provides us with many mysteries...

Baryogenesis

Quantum Gravity

why 3 gen?

strong CP?

Hierarchy Problem

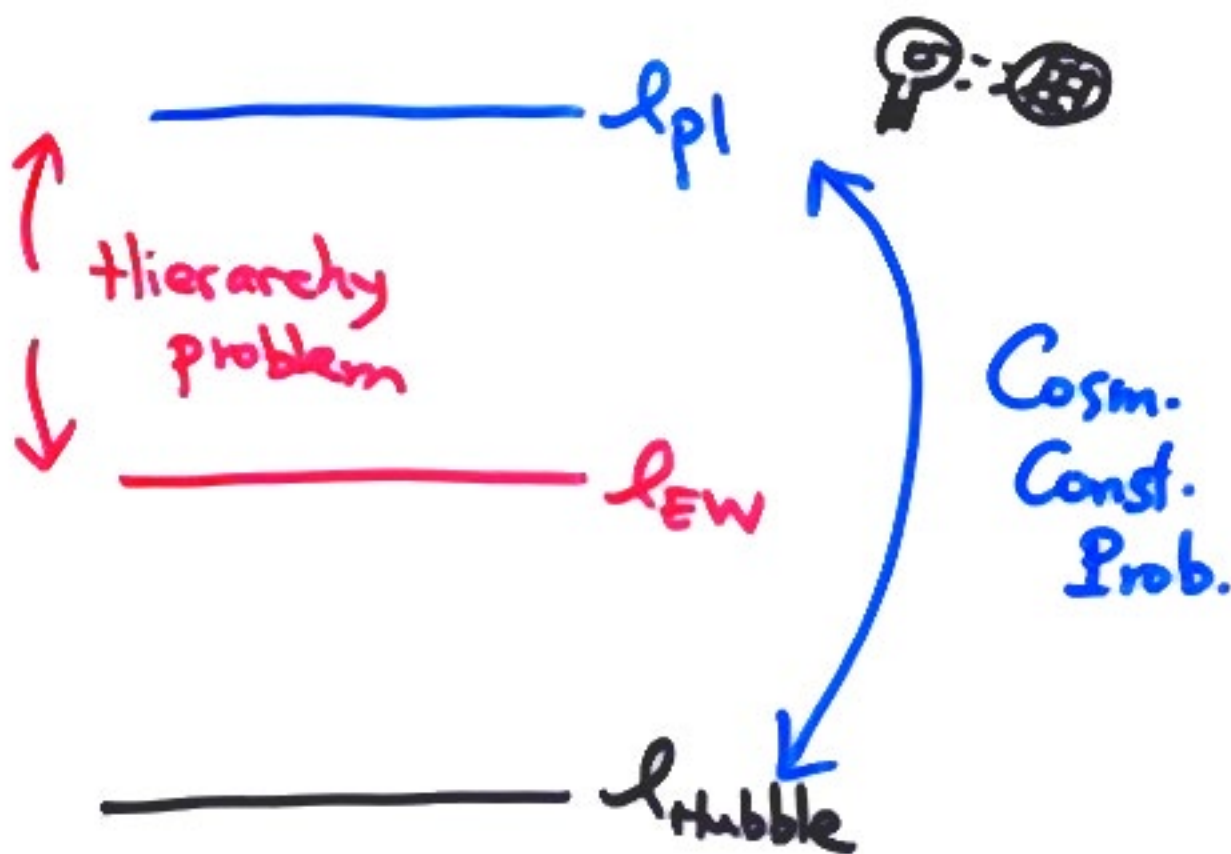
$\nu$  masses?

$m_{\nu L}$ ?

CP?

$\Lambda$

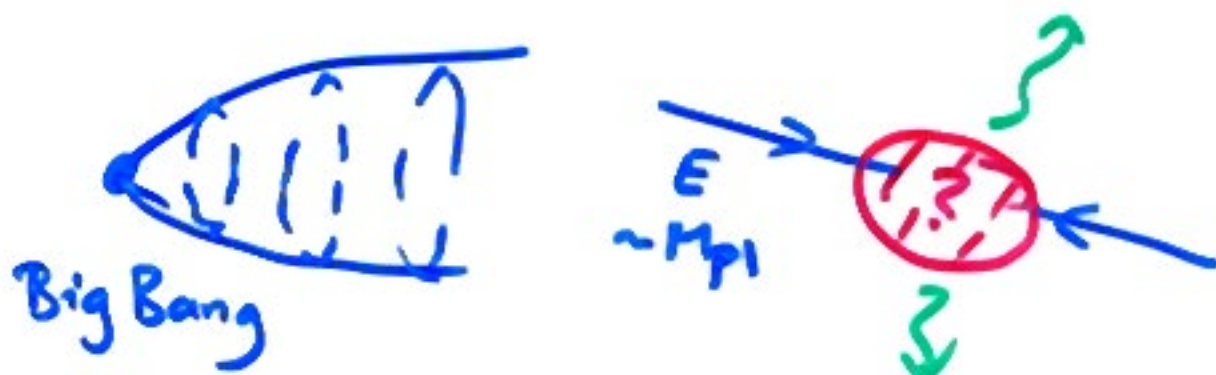
WHY such a sharp focus  
on these questions?



- They are simple to state, clear, huge problems
- Seem more fundamental than the others
  - knowing answer would teach us much more than resolution of these puzzles.

- Quantum gravity

$\Rightarrow$  we are missing new physics;  
our current theories just break  
down ...




- The other problems have a different character ... not associated with a blatant contradiction, only with a ridiculous level of “un-natural fine-tuning”.



# Naturalness + Fine-tuning Problems

In SM

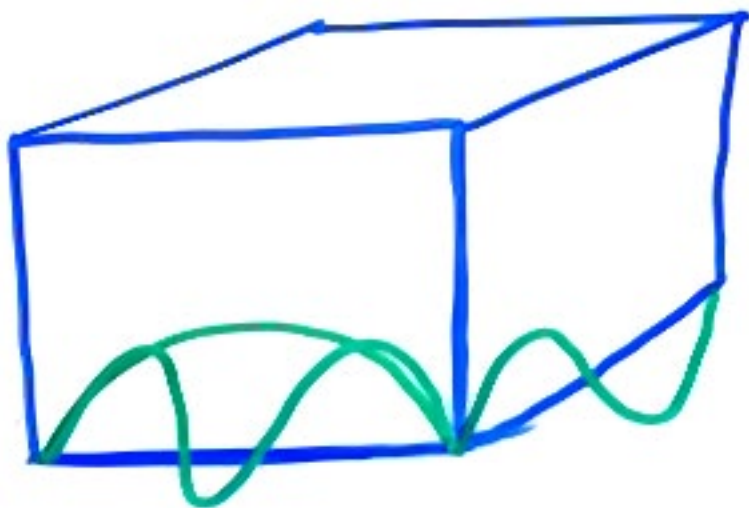
$$S = \int d^4x \sqrt{-g} \left[ \Lambda + m_h^2 |h|^2 + \text{dimless couplings...} \right]$$


Only two dimensionful parameters  
in the theory

$$\Lambda \sim 10^{-120} M_{pl}^4 !!$$

$$m_h^2 \sim 10^{-32} M_{pl}^2 !$$

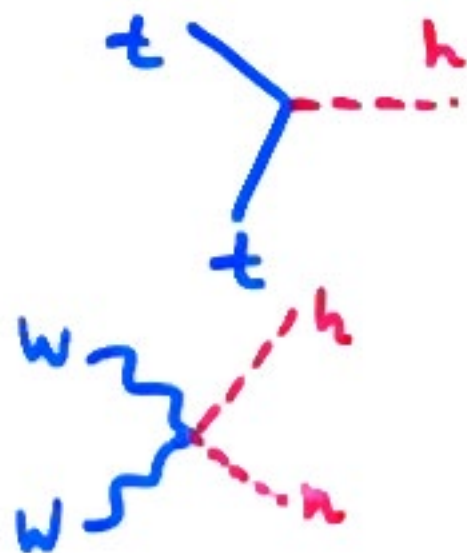
# Fine-tuning



$$E_{vac} = \sum_{\text{bosons}} \frac{1}{2} \hbar \omega_{\vec{k}} - \sum_{\text{fermions}} \frac{1}{2} \hbar \omega_{\vec{k}}$$

$$\omega_{\vec{k}} = \sqrt{\vec{k}^2 / L^2 + m^2}$$

In SM



$$m_t \sim \lambda_t h$$

$$m_W \sim g h$$

So,

$$E_{\text{quant}} = (\text{Volume}) \int d^3k$$

$$\times \frac{1}{2} \left( \sqrt{\vec{k}^2 + g^2 |h|^2} - \sqrt{\vec{k}^2 + \lambda^2 |h|^2} \right)$$

$$\Rightarrow E_{\text{quant}} \sim k_{\text{max}}^4 + (g^2 - \lambda^2) k_{\text{max}}^2 |h|^2$$

$$\text{SM} + \text{grav} \Rightarrow k_{\text{max}} \sim M_{\text{Pl}}$$

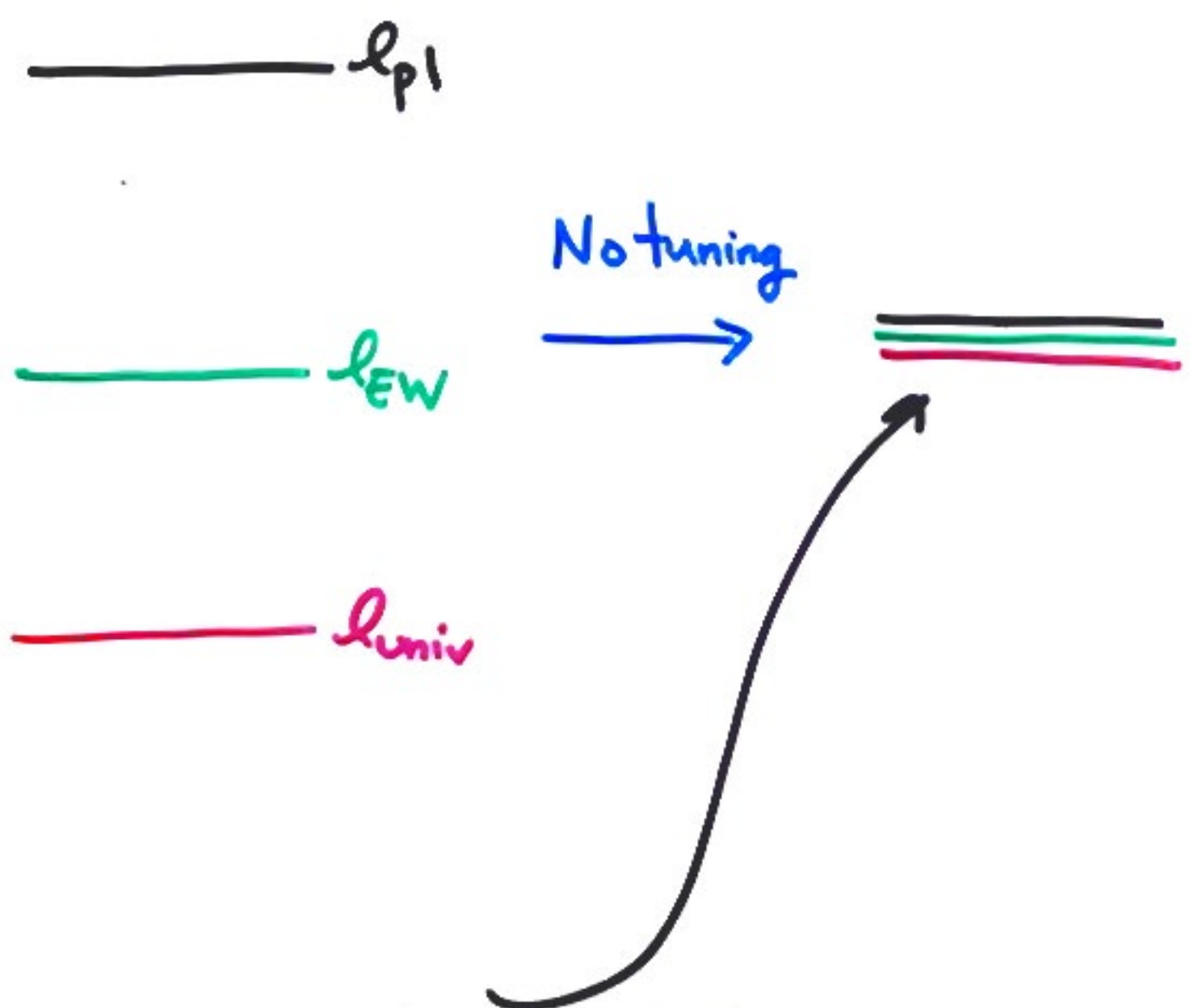
$$\Rightarrow \Lambda_{\text{quant}} \sim M_{\text{Pl}}^4 \quad \blacktriangle$$

$$m_h^2_{\text{quant}} \sim M_{\text{Pl}}^2 \quad \blacktriangle$$

$$\Lambda_{\text{obs}} = \Lambda_{\text{quant}} + \Lambda_{\text{bare}} - \text{Tuned to } 10^{-120}!$$

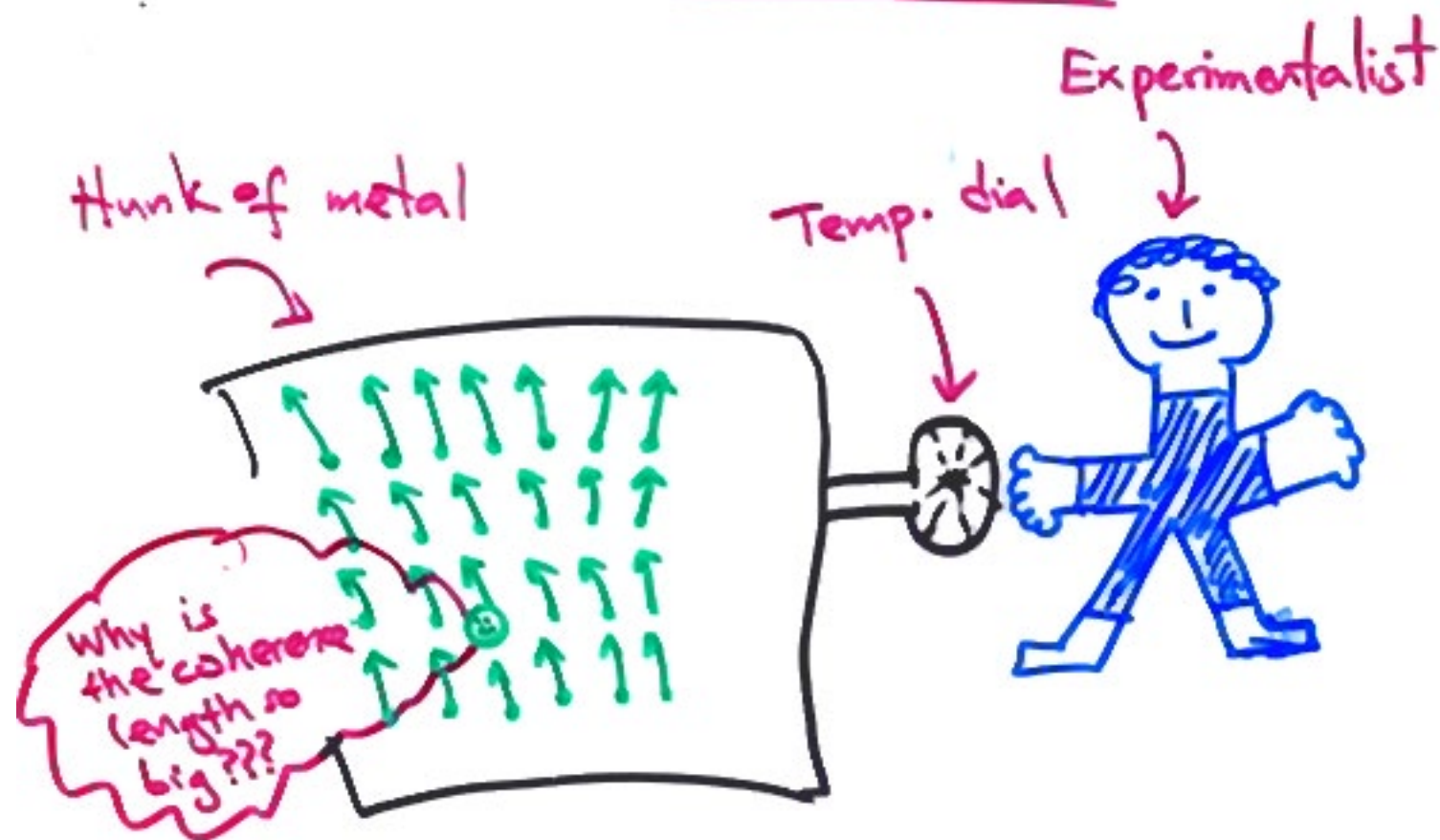
$$m_h^2 = m_h^2_{\text{quant}} + m_h^2_{\text{bare}} - \text{Tuned to } 10^{-30}!$$

CAN'T BE TRUE !?!



Incredibly Unpleasant  
Universe

# Unstated Rationale



NO "DIVINE" INTERVENTION

For a natural theory  
of electroweak breaking,

require

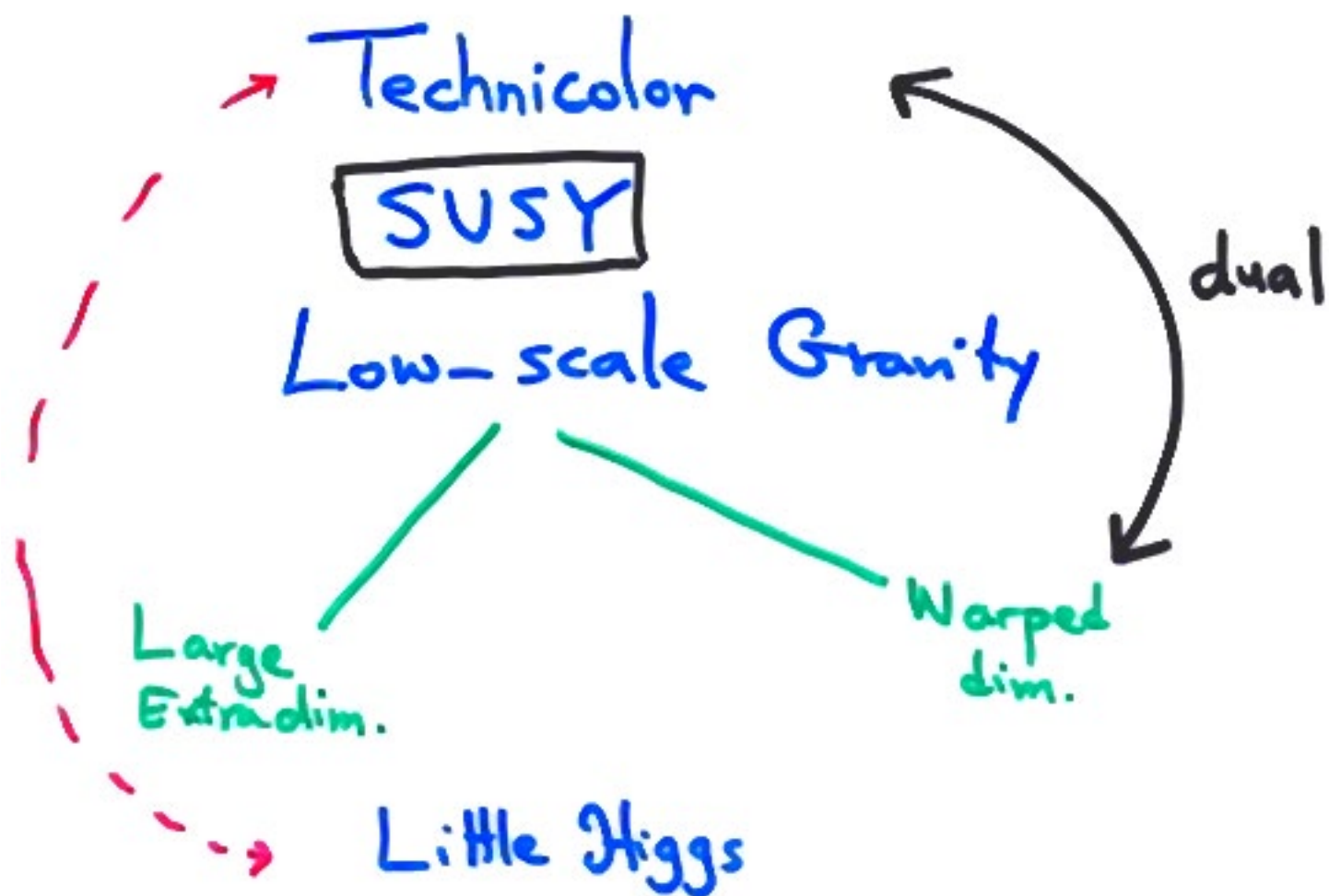
$k_{\max} \sim \text{TeV}$   
↑  
squishy

⇒ New Physics at TeV scale

Our Mantra:

LHC + L.C. will reveal  
natural theory of the  
weak scale

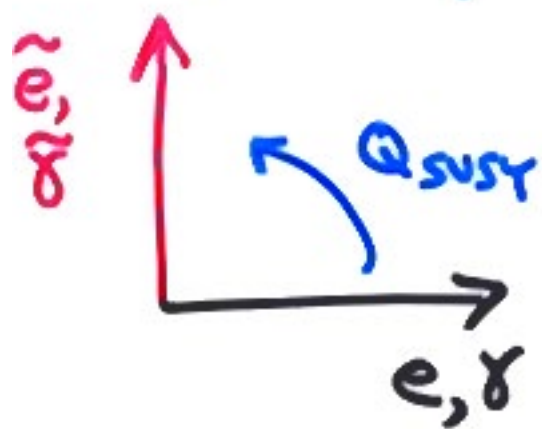
Approaches to a natural solution to the hierarchy problem:



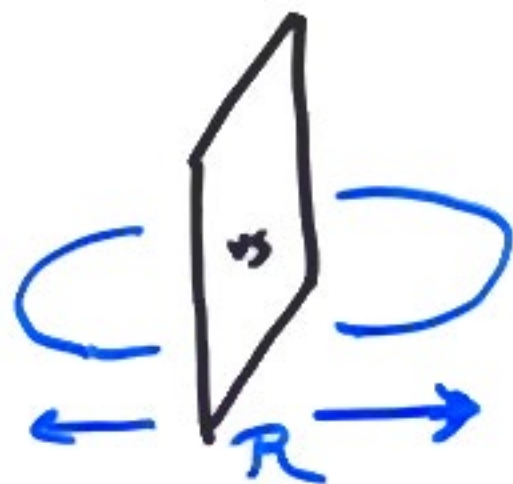
L.H.C + Linear Collider

could well discover new dimensions

of spacetime :



Fermionic



Bosonic

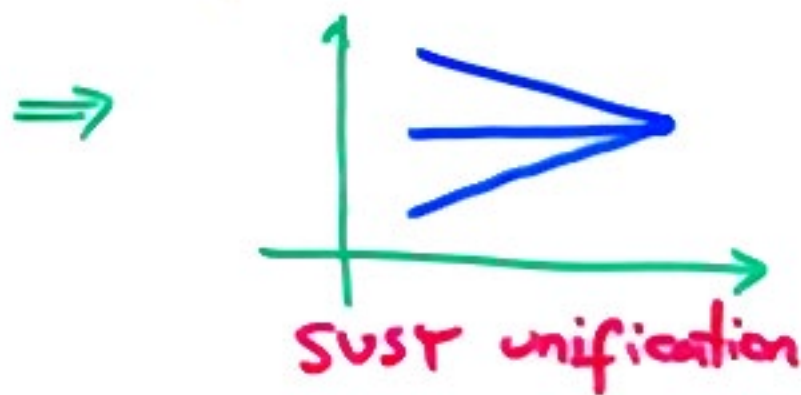
A BIG DEAL.

It would be a permanent part  
of the general knowledge of  
all humanity!



# Milestones of Naturalness

- Early '70s, Wilson introduced it.  
not taken seriously ("it's just philosophy!")
- Technicolor<sup>77</sup>: example of a natural theory  
from philosophy  $\rightarrow$  physics.
- SUSY SM '81: Proposed when  $\sin^2 \theta_W$   
agreed with SM  
candidate  $p$ -decay  
events seen!  
("Why use a camel when you can have  
a horse?")
- SLC/LEP I '91/2



CELEBRATION!

... But the persistent lack of  
any new evidence for BSM physics  
is getting a little troubling...

No new FCNC? EDM's?  $(g-2)$ ?

No deviations in precision EW?

No HIGGS?

↑  
particularly troubling for SUSY,  
which is already looking tuned  
at  $\sim$  few % level.

Look back to some historical precedents ... principles of naturalness have often led us to correct physics (or could have!). For instance, theory of classical electrons had a "hierarchy problem"



$$\begin{aligned}
 &\text{Energy } E+M \\
 &\int d^3r \frac{1}{2} \vec{E}^2 \\
 &\propto e^2 \int \frac{d^3r}{r^4} \\
 &\sim e^2/a \sim e^2 k_{\text{max}}
 \end{aligned}$$

$$\delta m_e \sim \alpha k_{\text{max}}$$

Fine-tuned for  $k_{\text{max}} \gg m_e \dots$

In this case, "new physics" came to the rescue - the position! - just at the scale it had to.

⇒ Extended spacetime symmetry

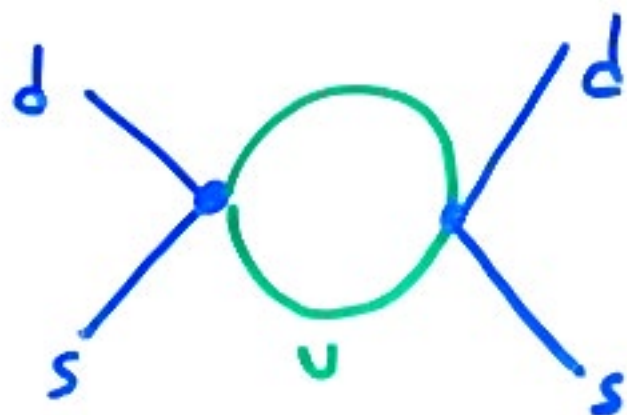
⇒ Doubling of d.o.f.

$\begin{pmatrix} e_{\uparrow}^{-} \\ e_{\downarrow}^{-} \end{pmatrix}$   
rotations

⇒

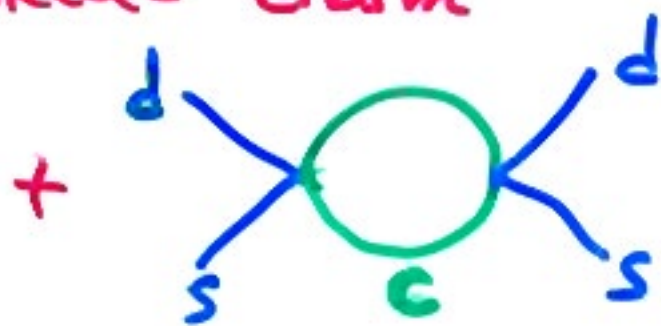
$\begin{pmatrix} e_{\uparrow}^{+} \\ e_{\downarrow}^{+} \\ e_{\uparrow}^{-} \\ e_{\downarrow}^{-} \end{pmatrix}$   
Lorentz

A more recent example:



$$\Rightarrow \frac{\Delta m_K}{m_K} \sim G_F \Lambda^2 \Rightarrow \Lambda \sim 2 \text{ GeV}$$

needed charm



$$\Rightarrow m_c \sim 2 \text{ GeV}$$

✓ Worked!

But there are also examples where fine-tuning happens unaccompanied by any dynamics ...

e.g. in nuclear physics



$$m_{\pi} \sim f_{\pi} \sim 100 \text{ MeV}$$

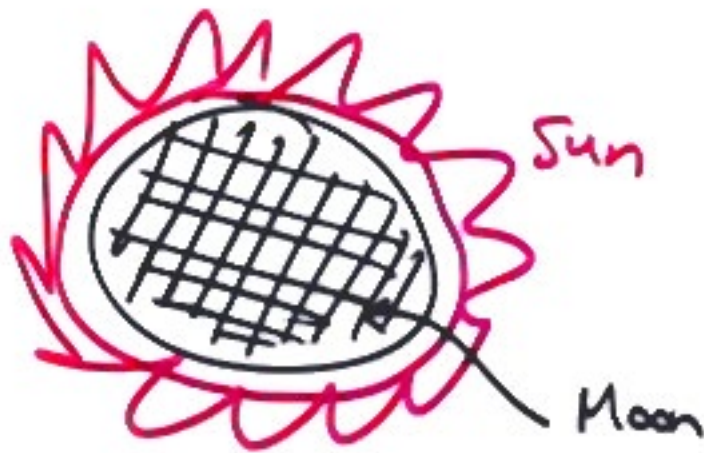


De

De binding energy  $\neq 100 \text{ MeV}$   
 $\sim 2 \text{ MeV}$ .

Just tuned. [Worse in scattering length]

A sillier example:

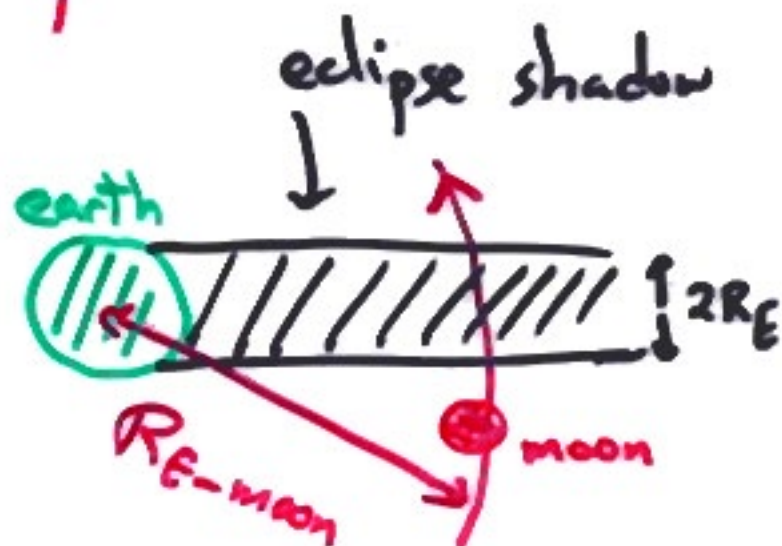


Why does moon almost fully eclipse the sun?

No Dynamics!

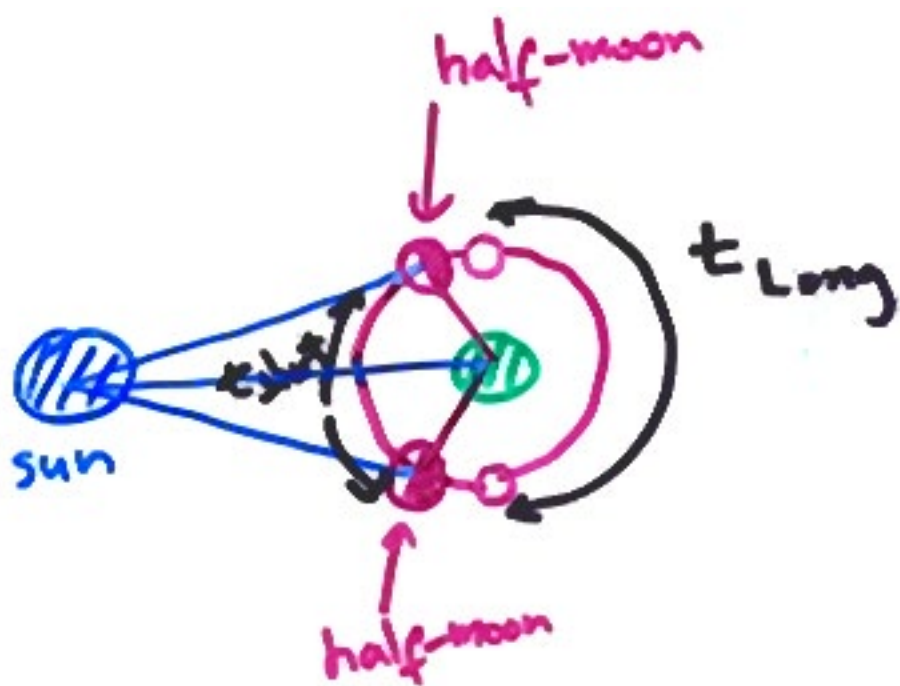
• Sometimes, notions of naturalness have blinded people from seeing the right answer.

ex: Aristarchos (B.C. a lot) determined the earth-moon-sun geometry brilliantly:



$$\frac{R_E}{R_{E-moon}} = \frac{t_{\text{eclipse}}}{1 \text{ month}}$$





$$\frac{R_{E-\text{moon}}}{R_{E-\text{sun}}} = \frac{t_{\text{Long}} - t_{\text{short}}}{1 \text{ month}}$$

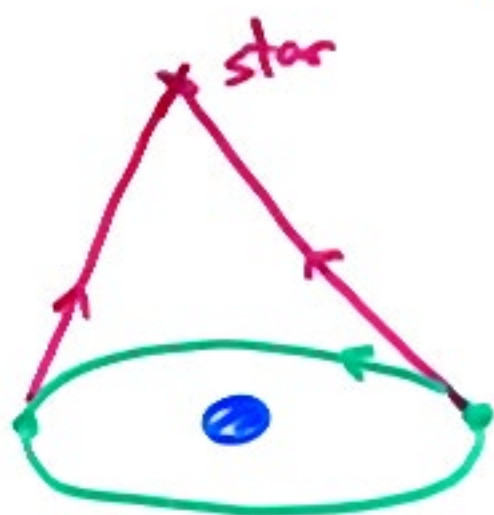
↑ Aristarchos measure this!

The  $R_{E-\text{sun}}$  he got was  
 $\sim \frac{1}{5}$  the right answer.....

BUT HE FELT IT WAS RIDICULOUS

**BIG**

Still, he <sup>first</sup> considered the possibility  
that the earth goes around the  
sun...



and realized this would predict  
parallax of distant stars!

Parallax can't be seen with naked  
eye. Aristarchos realized that this  
could be OK if the stars were  
even much further away than the  
sun!

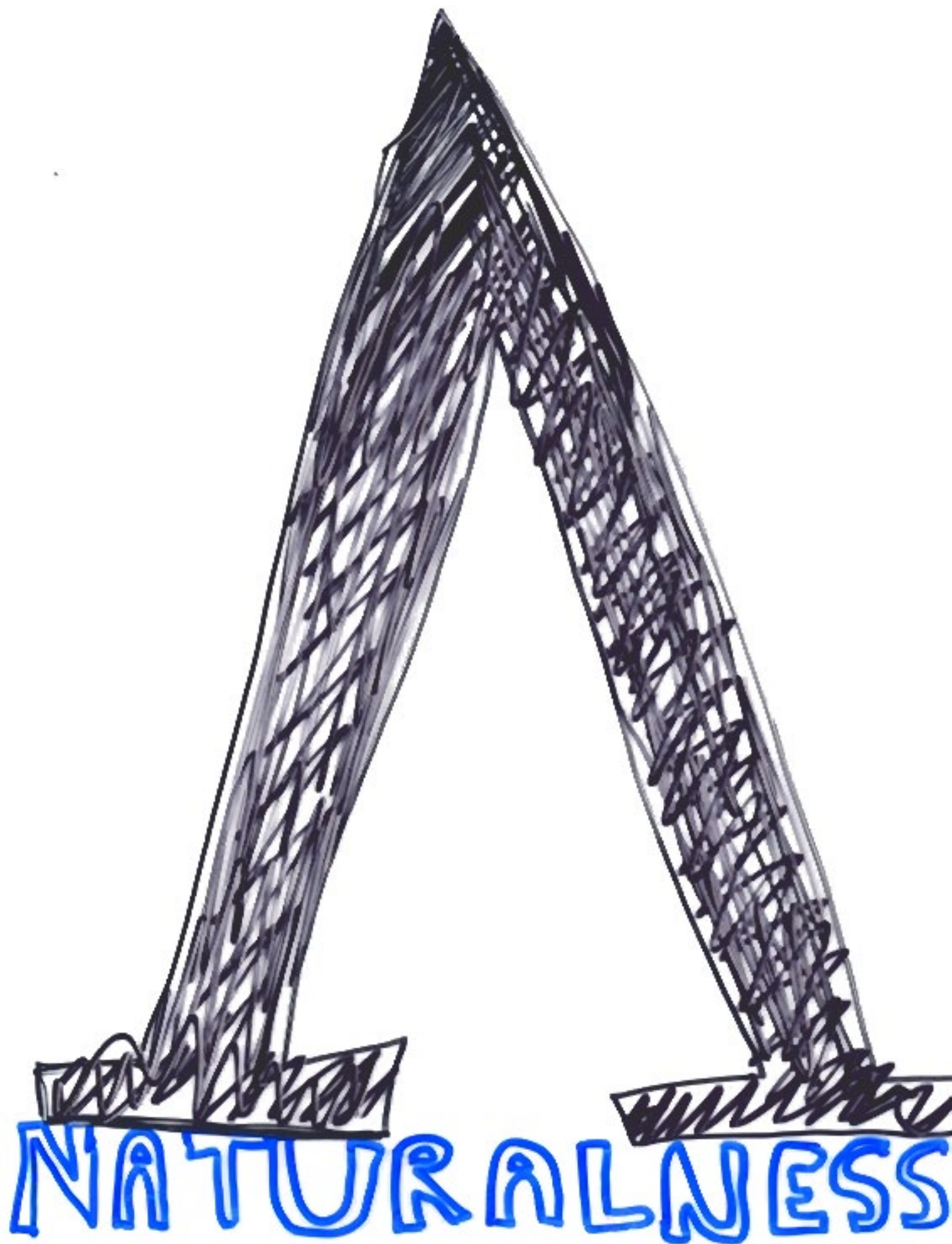
... but this badly violated his notion of naturalness!

Already  $R_{\text{sun}}$  was huge...  
to then invoke even larger distances to explain absence of parallax seemed ridiculous

(how could every one of those stars be so much further away???)

⇒ For perfectly reasonable reasons, this was rejected in favor of sun going around earth!!

Took over 1000 yrs to finally get it right!



NATURALNESS

Observed

$$\Delta \lesssim (10^{-3} \text{ eV})^4$$

↓↓ Naturalness

New physics at  $10^{-3} \text{ eV}$ .

(could have been SUSY!)

HAVEN'T SEEN

IT

. Because of this problem,  
most theorists assumed that  
some deep new physics sets  
 $\Lambda = 0$ .

. Then comes the shock:  
Accelerating universe!  
Simplest explanation;  $\Lambda \neq 0$ !

Biggest discovery of last ~20 yrs.  
Can't overestimate its impact  
on our thinking.

(Reasonable) usual attitude:

$\Delta$  associated with gravity

= deep = mysterious

= let's ignore it for now

• Meanwhile let's make sure Higgs is as natural as possible!

Someday we'll also solve C.C. problem.

• May very well be right.

... But it is a little disquieting  
that both a HUGE thing ( $\Delta$ )  
and a bunch of nagging little things  
(absence of  $(g-2)$ , EDM, FCNC,  
sparticles, Higgs...)  
are hinting that something is  
wrong.

COULD WE BE MISSING  
SOMETHING BIG?



Recall logic for why e.g.

SUSY scale should be  $m_S \sim m_W$ :

- Nature may be SUSY in UV
- Must be broken
- To keep  $m_h^2 \ll m_S^2$  requires tuning - absurd!

SUSY  $\neq$  tuning!!

- So,  $m_h^2 \sim m_S^2 \lesssim (\text{TeV})^2$

But every concrete theory

we study is both SUSY

+ finely tuned, with an enormous  
tuning for the C.C!

$$\Lambda \neq m_s^4$$

but

$$\Lambda \sim E_4 m_s^4, \quad E_4 \ll 10^{-60}$$

Could it be that there  
is some fine-tuning  
mechanism in nature that  
takes care of

$\Delta$ ,  $m_h^2$  together?

$10^{120}!!$

Meady  $10^{30}$

$$\Lambda \sim E_4 m_S^4, \quad m_h^2 \sim E_2 m_S^2$$



← Open  
Paranthesis  
on a  
(for the time  
being)  
philosophical  
discussion

. Naturalness problems are severe if the fund. theory gives us one (or few) low- $E$  theories + parameters.

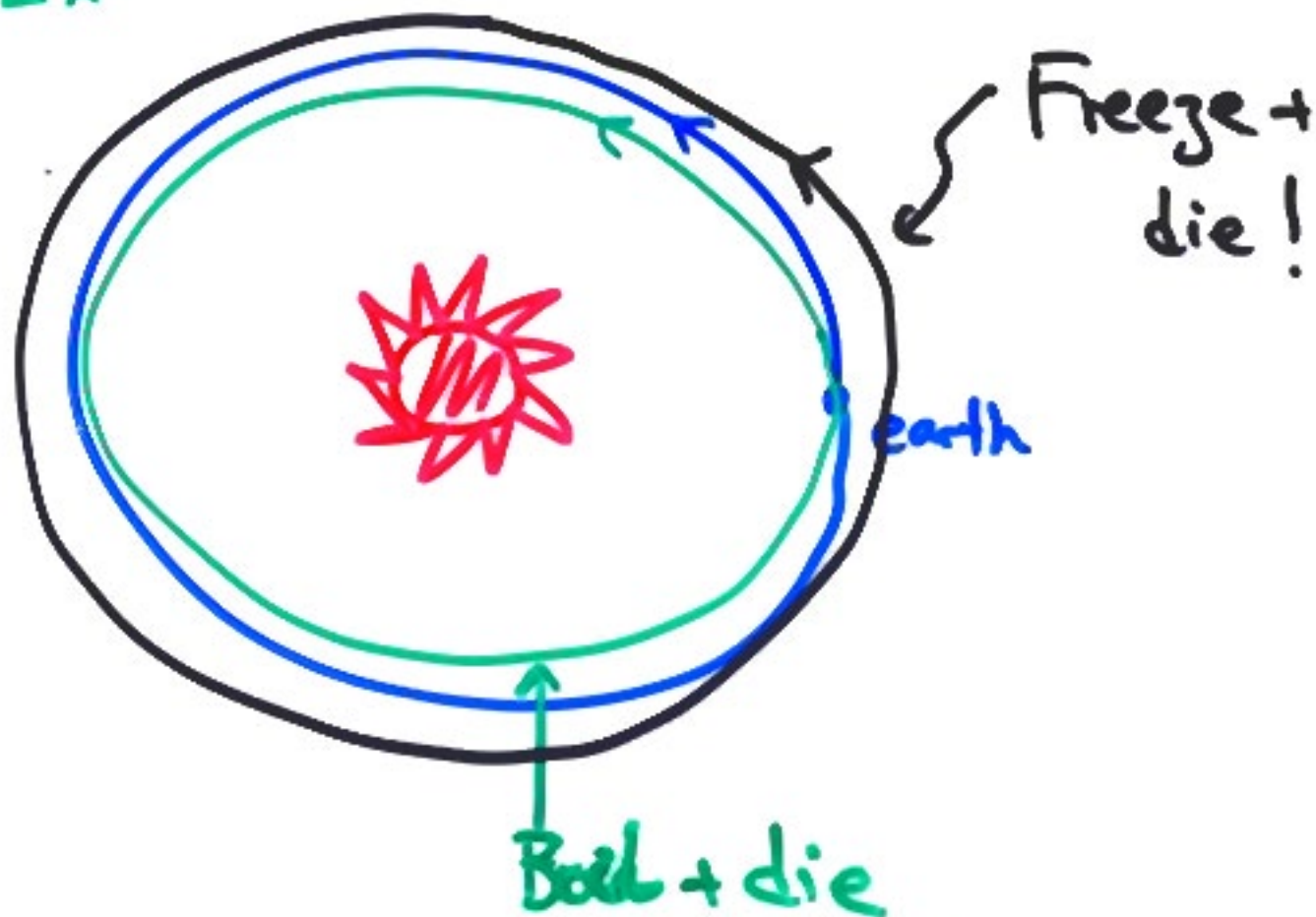
If a parameter is observed to be tuned, only explanations are:

- Divine Intervention!
- A mechanism!

. Character of question changes dramatically if fund. theory produces  $10^{1000}$  different low-E worlds.

. As do the character of possible answers, which can now rely of selection/historical contingency.

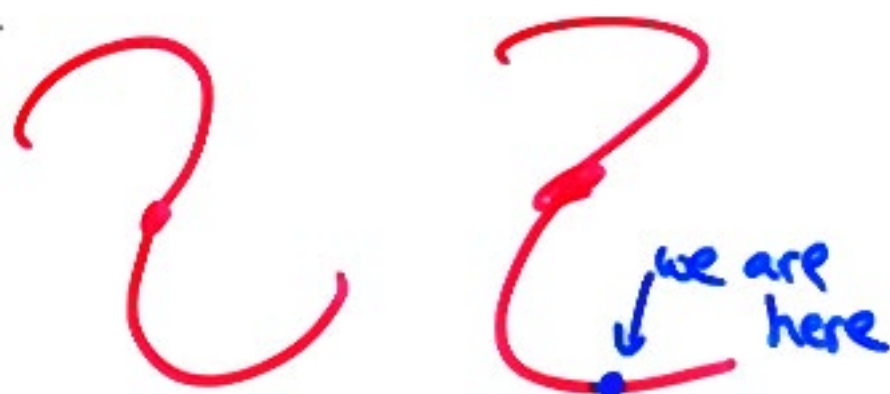
Ex:



Delicate adjustment!

God? Mechanism?

Neither!



Zillions of planets ; not  
surprising that we find  
ourselves where it is  
hospitable...



## Related problem



vast  
emptiness  
of Cosmos

$$\frac{V_{\text{earth}}}{V_{\text{univ}}} \sim 10^{-60} !$$

But we can't be in empty space!

“Structure Principle”

OK, can't live in empty space...  
but why not in e.g. Nebulae?

$$\frac{V_{\text{earth}}}{V_{\text{Nebulae}}} \sim 10^{-50}$$

- Again, not so mysterious; only H, He, ... out there, very inert, not too diff from empty space

"Atomic Principle"

(Banks, Linde, ...) Weinberg:

If  $\Lambda \gtrsim 100 \Lambda_{\text{obs}}$ ,

accelerated expansion rips  
apart galaxies before they

can form  $\Rightarrow$  EMPTY UNIVERSE

If there are  $\gtrsim 10^{120}$  vacua  
with varying C.C. + a mechanism  
to populate them, "structure

principle" can explain why we

find ourselves in a universe

with tiny C.C.

• Weinberg used this argument to predict a non-zero cosm. constant! These ideas have recently gained momentum given that

(A) String theory may well have an enormous "landscape" of metastable vacua

(SLAC/  
Stanford  
group)  
Kachru, Kallosh, Linde,  
Trivedi

(B) Eternal inflation provides a plausible mechanism to populate vacua

Linde

# CONTROVERSIAL!

Many loopholes ...

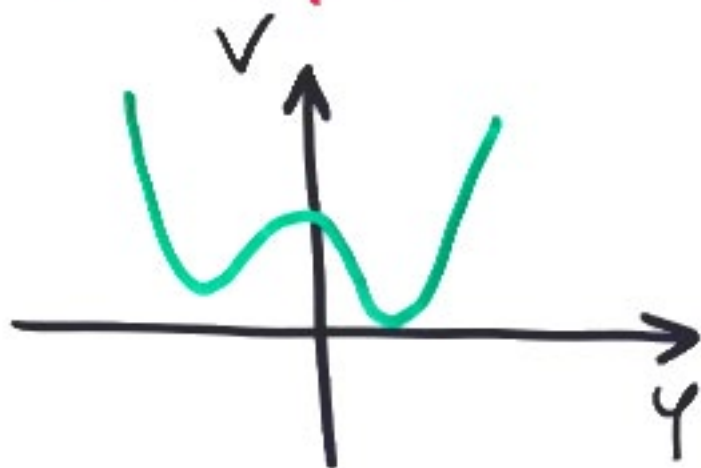
- Maybe landscape doesn't exist
  - Maybe cosmology picks out unique vacuum
- } could be

• If you vary more param than  $\Delta$ , you can do anything

But plausible rule: only parameters,  
like  $\Delta, m_h^2$  that can't be  
protected by symmetries  
are effectively scanned

They are the ones that  
are different after all!

- Toy model for a "landscape":



$$V = m^2 \varphi^2 + \mu \varphi^3 + \lambda \varphi^4$$

2 minima.

- Suppose we have  $N$  such sectors...

$2^N$  minima!

need  $N \sim 200$  ... not a big deal.

SM has 45 complex = 90 real Fermions. Why not 200 real scalars?

... clearly vacuum energy is  
"scanned" in these  $2^N$  vacua.

Lets now couple this sector to  
SM.

Only allowed renorm. couplings

$$(c_i \psi_i) h^\dagger h \quad \lambda_{ij} \psi_i \psi_j h^\dagger h$$

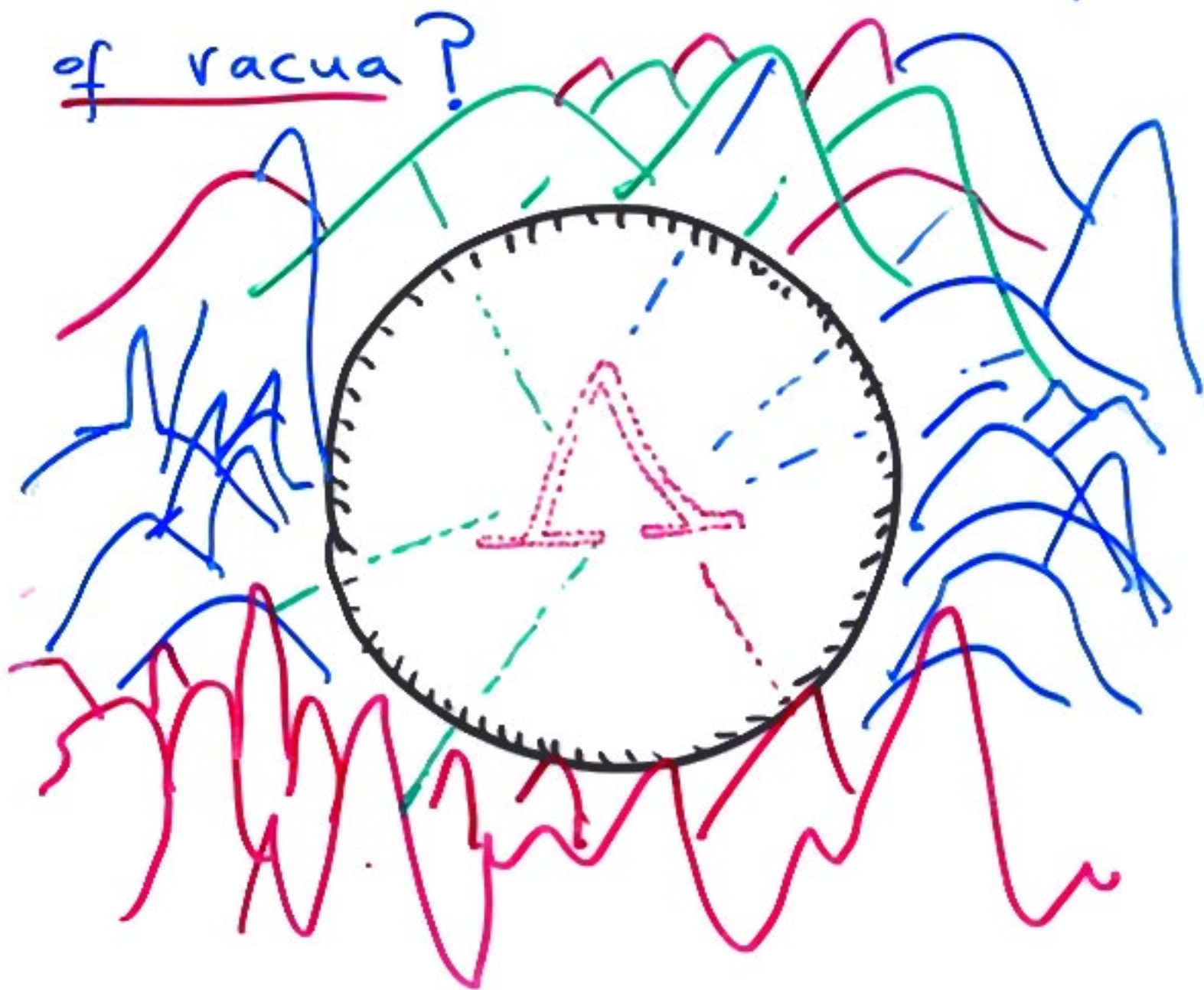
Vary from vacuum to  
vacuum

$\Rightarrow$  scan  $m_h^2$ !

$\sum_{\mathbb{Z}_2}$ , scan  $\Delta, m_h^2$ , nothing  
else!



$I_s \quad \Lambda \neq 0$  the first hint  
that we are part of a vast  
multiverse with a huge landscape  
of vacua?



IF this picture

of the world is correct,  
it will be perhaps the  
biggest scientific discovery of  
our time.

• But how can we know?

Can't (yet!) "see" other  
universes behind the horizon...

Already predicted non-zero C.C.!

Not nearly good enough, not

sharp. No one is convinced that

$\Lambda$  is really finely tuned.

[... It's gravity, cosmology, not well under control....]

Is there anything that could convince us?

Can particle physics experiments weigh in on this issue?

**SHARP, CONTROLLED**

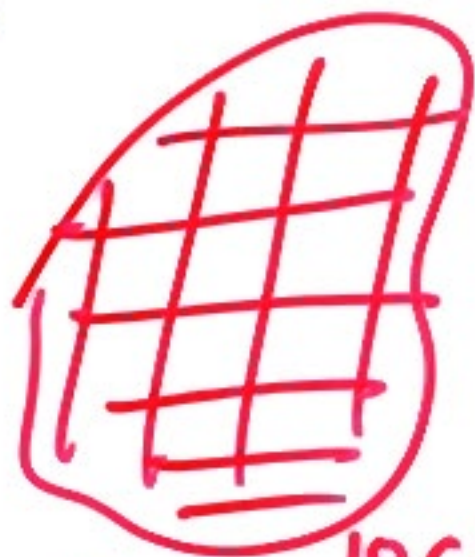
Well, what are the possible implications of the "landscape" for particle physics?

Should we still expect  $m_S^2 \sim m_W^2$ ?

New "Landscape" notion of naturalness  
- don't know!



$m_S \sim \text{TeV}$   
Higgs natural  
only  $10^{40}$  vacua!  
Not enough for CC!



$m_S \sim 10^{10} \text{ GeV}$   
 $m_H \sim \text{TeV}$  + tuned  
But  $\sim 10^{200}$ , plenty empty

Why should  $m_h^2$  be tuned?

Donoghue  
et al.

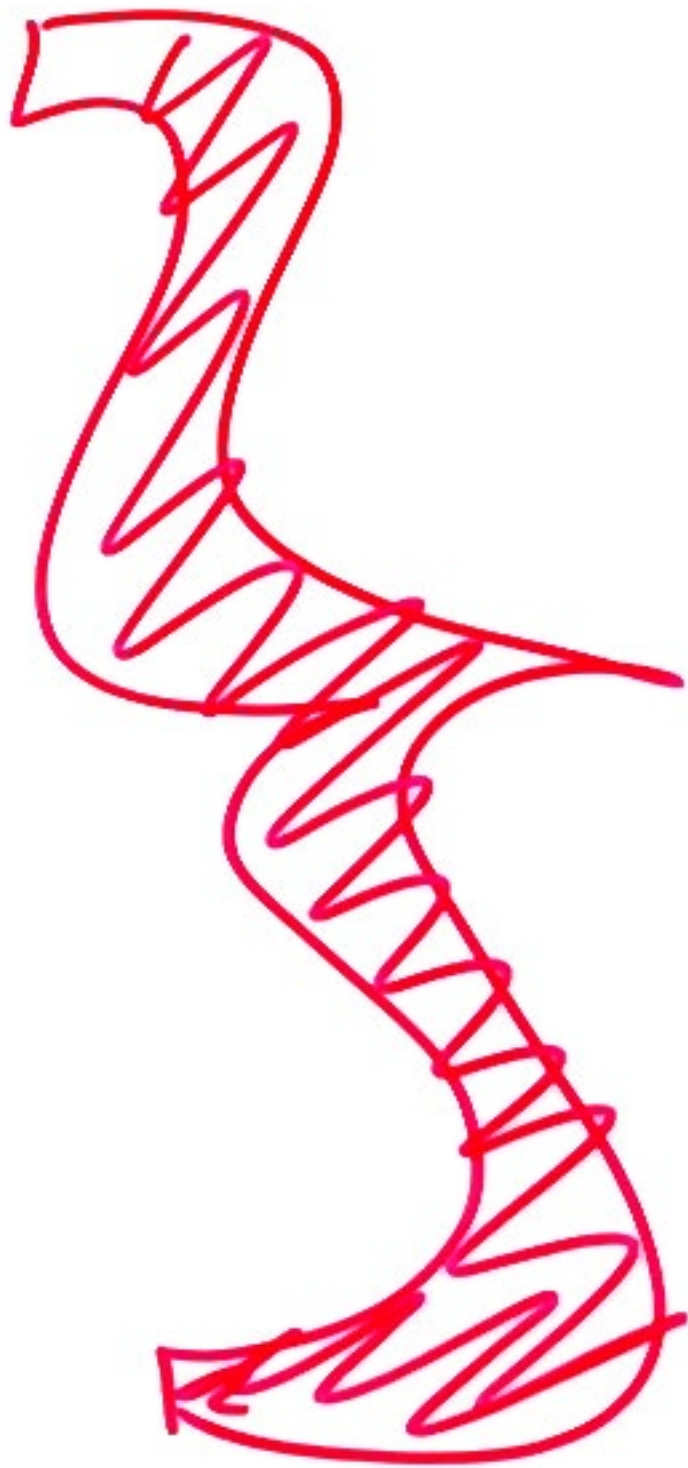
No atoms, or only H or He!

"Atomic Principle"

[Further explains proximity  
of  $\Lambda_{QCD}$ ,  $m_W$ ]

With these motivations,  
consider theories where  
 $m_S \gg \text{TeV}$ , and a  
fine-tuning keeps Higgs light,  
related to whatever solves C.C.

(For instance, "structure"  
+ "atomic" principles on a  
vast landscape)



# Nightmare scenario

Only Higgs @ LHC.

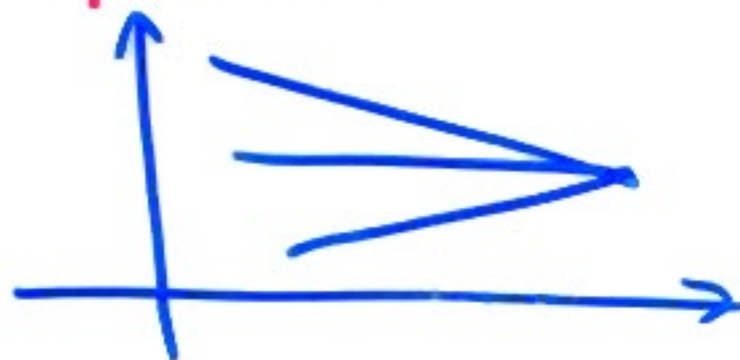
Would this convince of tuning?

NO! [Convince us we needed SSC]

• But, what about

Dark Matter?

+ Coupling Unification?

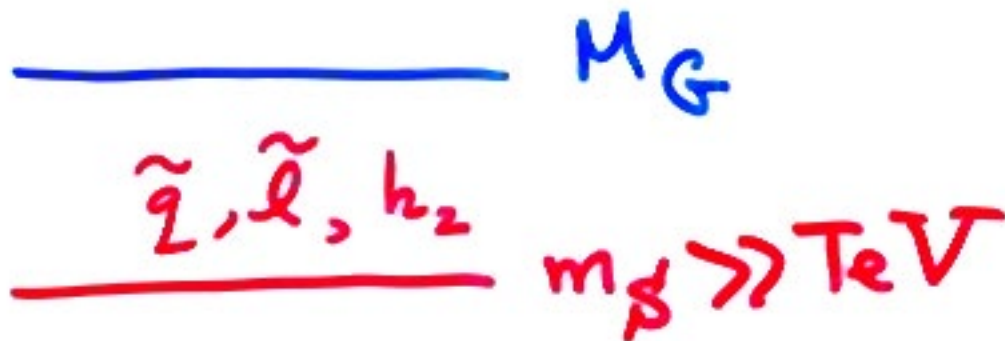




# Split Supersymmetry

MAH  
Dimopoulos

E  
↑



+ Fermions  
of SUSY  
{ Higgsinos,  
Gauginos }

Can  
be light  
because  
Fermions!

LSP dark matter

$\Rightarrow \tilde{g}, \tilde{w}, \tilde{b}, \tilde{h}_{1,2}$

at TeV scale

$\Rightarrow$  Gauge coupling Unification

Exactly as in SSM

(in fact slightly better)

• With one step we eliminate every phenom. difficulty of SUSY

No p-decay

FCNC

EDM's

$(g-2)$

Gravitino

Moduli

problems...

All to do with Scalars

Amusing: all concrete successes  $\Rightarrow$  Fermions

all problems

Scalars (only needed for naturalness)

# Effective Lagrangian:

$$\Delta \mathcal{L} = M_3 \tilde{g} \tilde{g} + M_2 \tilde{w} \tilde{w} + M_1 \tilde{b} \tilde{b} + \mu \tilde{h}_u \tilde{h}_d$$

$$+ \sqrt{2} K_u h^\dagger \tilde{w} \tilde{h}_u + \sqrt{2} K_d h \tilde{w} \tilde{h}_d$$
$$+ \sqrt{2} K'_u h^\dagger \tilde{b} \tilde{h}_u + \sqrt{2} K'_d h \tilde{b} \tilde{h}_d$$
$$- \lambda (h^\dagger h)^2$$

5 dimless coupling, set by  
SUSY at scale  $m_S$

$$K_u = g_2 \sin \beta \quad K_d = g_2 \cos \beta$$

$$K'_u = g_1 \sin \beta \quad K'_d = g_1 \cos \beta$$

$$\lambda = \frac{(g_1^2 + g_2^2)}{4} \cos^2 2\beta$$

• Run down to low energies!

• Higgs mass prediction

$$120 \text{ GeV} \lesssim m_h \lesssim 160 \text{ GeV}$$

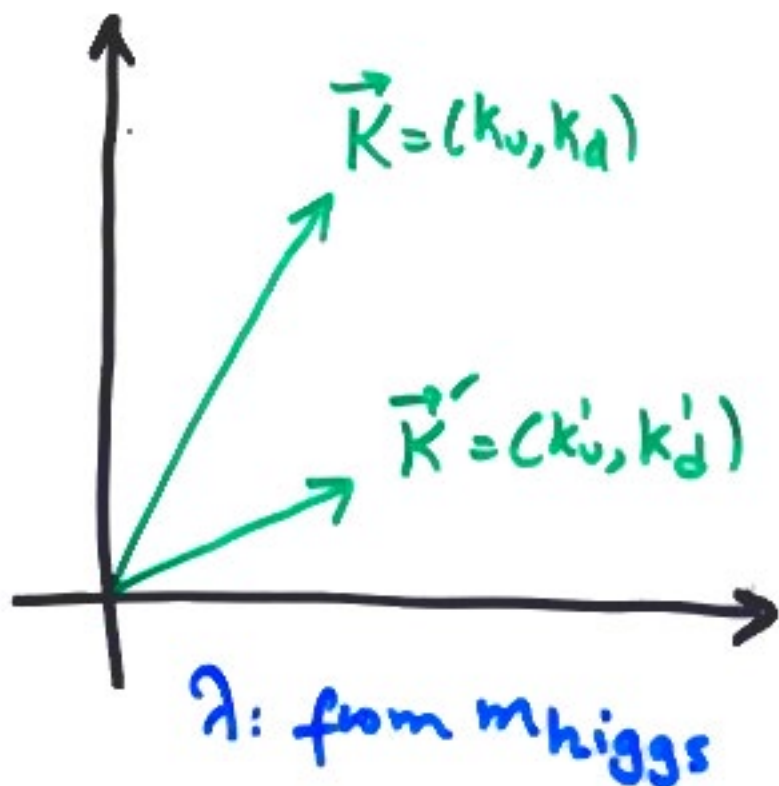
$$m_S = 10^6 \text{ GeV}$$

$$m_f = 10^{12} \text{ GeV}$$

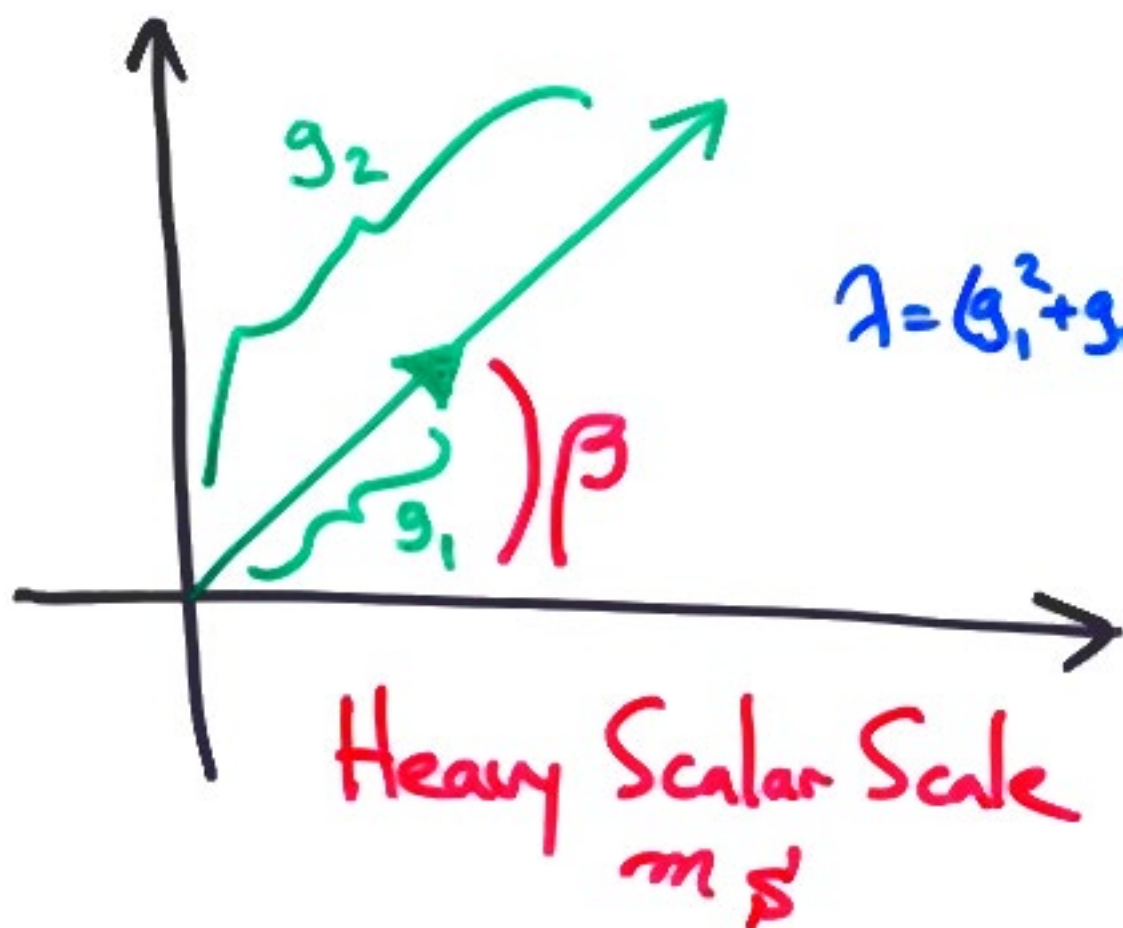
• Measure  $K_{u,d}$ ,  $K'_{u,d}$ ,  $\lambda$  at low  $E$ . Run to high  $E$ .

All  $S$  must hit SUSY values at same scale  $m_S$ :

TeV scale



Run  
 $\Rightarrow$   
 $U_P$



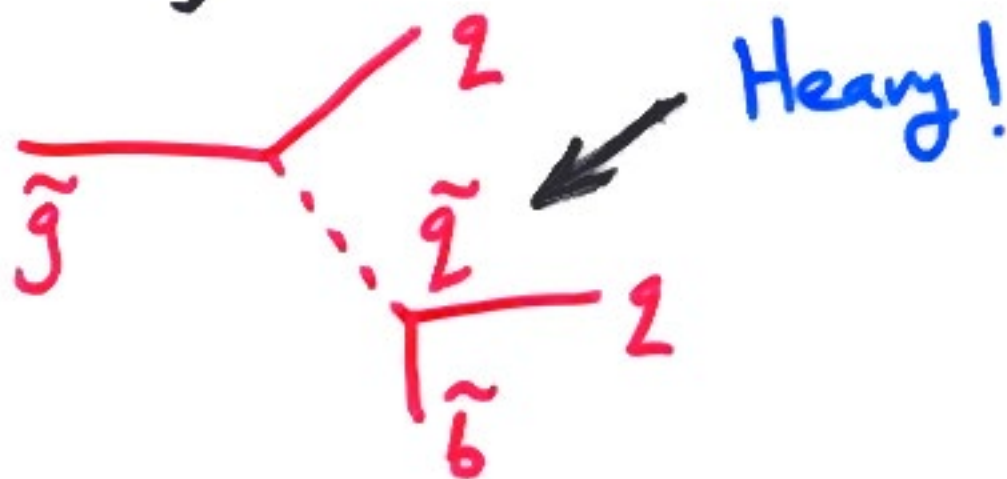
⇒ DISCOVERY  
OF HIGH SCALE  
SUSY

⇒ SHARP, QUANTITATIVE  
EVIDENCE THAT  
 $m_h^2$  IS TUNED.

[Lin. Coll. clearly crucial  
for this]

# Long Lived Gluino as probe of Tuning

Striking qualitative prediction  
decisively distinguishing it from  
hierarchy motivated SUSY



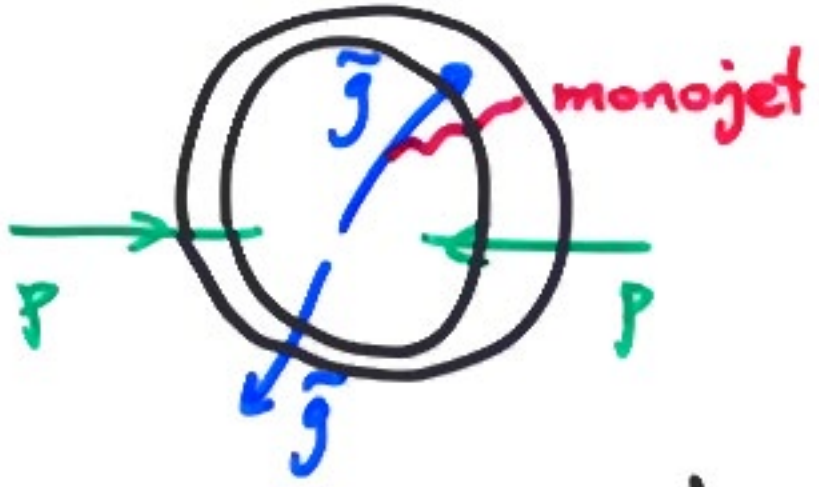
$$\tau \sim 10^{-1} \text{ s} \left( \frac{m_S}{10^9 \text{ GeV}} \right)^4 \left( \frac{\text{TeV}}{m_{\tilde{g}}} \right)^5$$



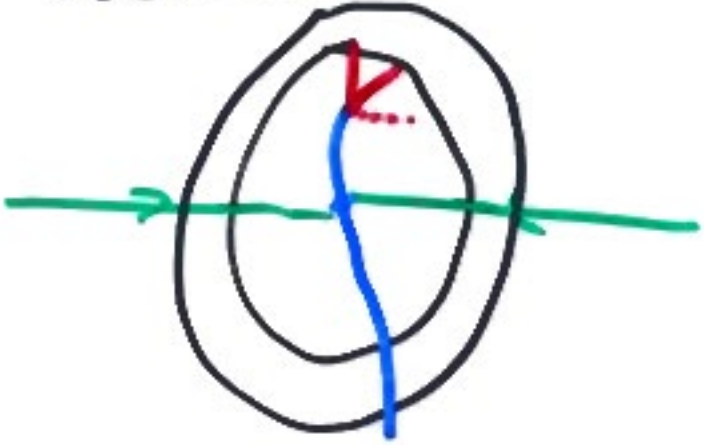
- $m_S \gtrsim 10^8 \text{ GeV}$

Typical gluinos decay  
far outside detector!

Little E in hadr. calorimeter



Some fraction can decay inside  
detector!



- Stopped gluinos  
in walls,  
earth, ..  
decaying  
after months  
years?

$$m_s \gtrsim 1000 \text{ TeV}$$

Gluinos decay inside detector but observably displaced from beam.

- In all cases: can definitely distinguish from standard scenario with scalars just barely too heavy to be seen (say  $\sim 5-10$  TeV)

# Tests of Split SUSY

- $120 \lesssim m_{\text{higgs}} \lesssim 160$
  - Gauginos + Higgsinos
  - DM
  - Gluino lifetime reveals  $m_{\text{scalar}}$
  - $\vec{K}'s, \lambda$  in terms of  $t_{\text{top}}, m_{\text{scalar}}$
- predictions, 4 indep. tests
- ⇒ Strong evidence for tuning mechanism — sharp — particle physics — indep. of subtleties of gravity

## Usual View

LHC will discover natural theory of EWSB

## Alternate view : split SUSY

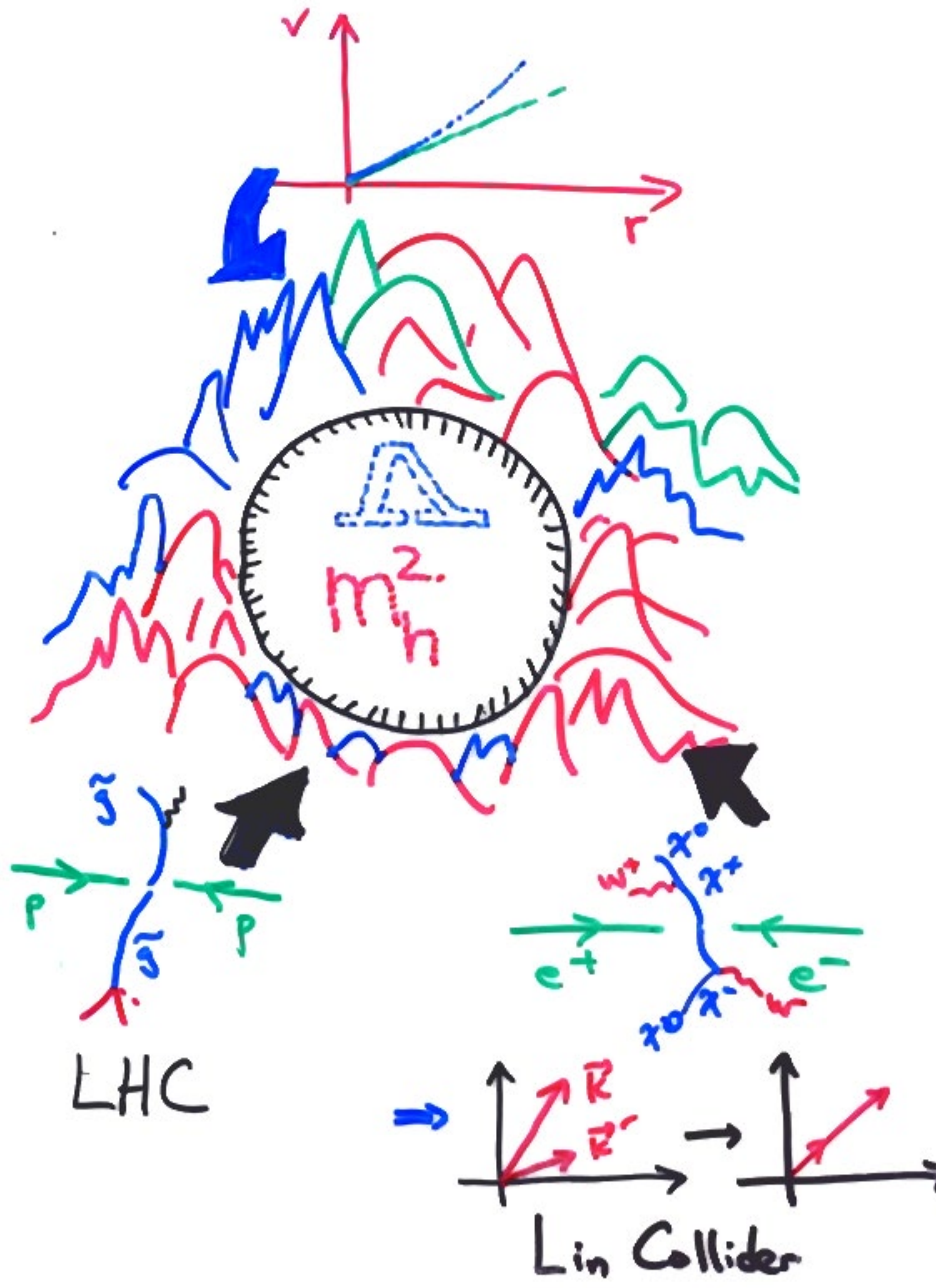
LHC/LC will provide striking evidence that world is tuned!

Old successes (CDM, unification)

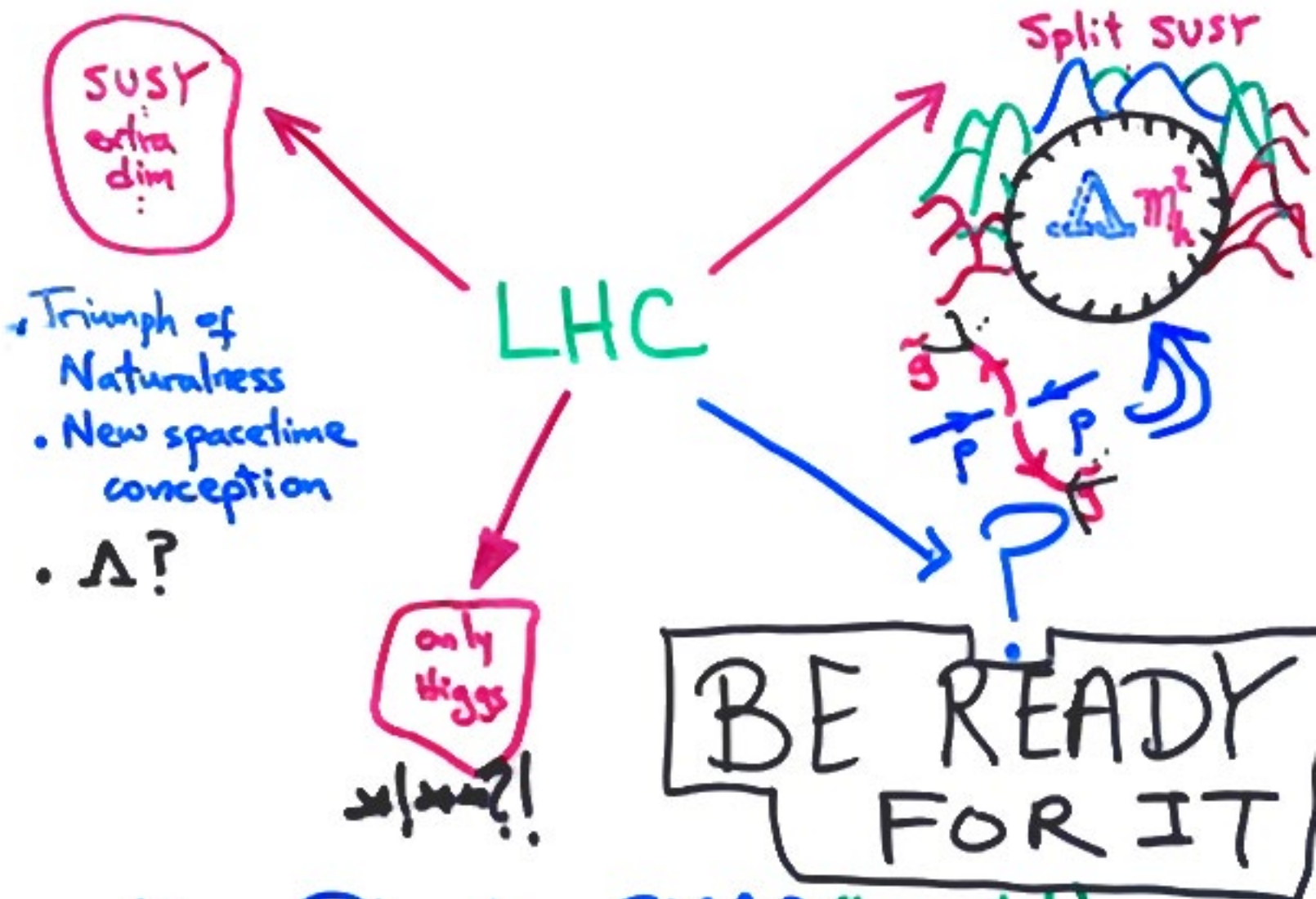
NOT ACCIDENTS, but hints

misread. In fact evidence

for high-scale SUSY



. In 3-4 years ( $\approx$  grad student career length!)



. Also Planck, SNAP (hopefully!) ...  
determine whether  $DE = \Lambda$   
(if  $w = -0.95 \Rightarrow$  Death of Landscape)