

# NATURAL INCLINATIONS & HIDDEN MOTIVES

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MAKE  
NATURALNESS  
GREAT  
AGAIN!

# OUTLINE

Naturalness & Detectivework  
EW Hierarchy Problem  
Baryon Asymmetry & Dark Matter  
Waiting for Godot particles  
Anthropic Principle  
Frustrated Naturalness  
Frustrated Ambitions  
The Crumbs of Naturalness  
Universal Values

# NATURALNESS

DON'T BELIEVE IN COINCIDENCE...



# NATURALNESS

DON'T BELIEVE IN COINCIDENCE...

THERE ARE LOTS OF COINCIDENCES...

# NATURALNESS

DON'T BELIEVE IN COINCIDENCE...

... for significant things

THERE ARE LOTS OF COINCIDENCES...

... for insignificant things

# NATURALNESS

DON'T BELIEVE IN COINCIDENCE...

... for significant things

UNLESS YOU ARE THE COINCIDENCE...

THERE ARE LOTS OF COINCIDENCES...

... for insignificant things

# NATURALNESS

DON'T BELIEVE IN COINCIDENCE...

... for significant things

UNLESS YOU ARE THE COINCIDENCE...

BUT YOU'RE NOT...

THERE ARE LOTS OF COINCIDENCES...

... for insignificant things

# NATURALNESS

DON'T BELIEVE IN COINCIDENCE...

... for significant things

UNLESS YOU ARE THE COINCIDENCE...

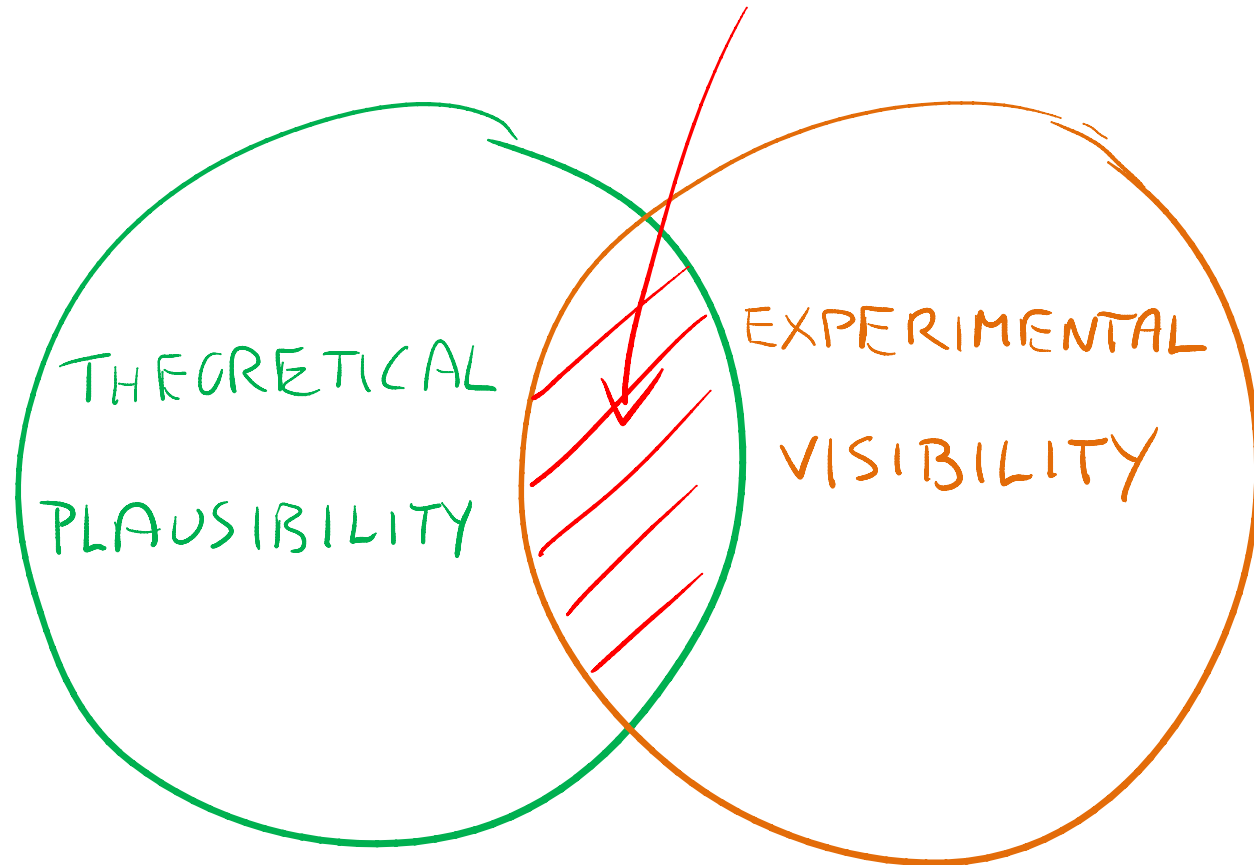
BUT YOU'RE NOT...

UNLESS YOU MUST BE.

THERE ARE LOTS OF COINCIDENCES...

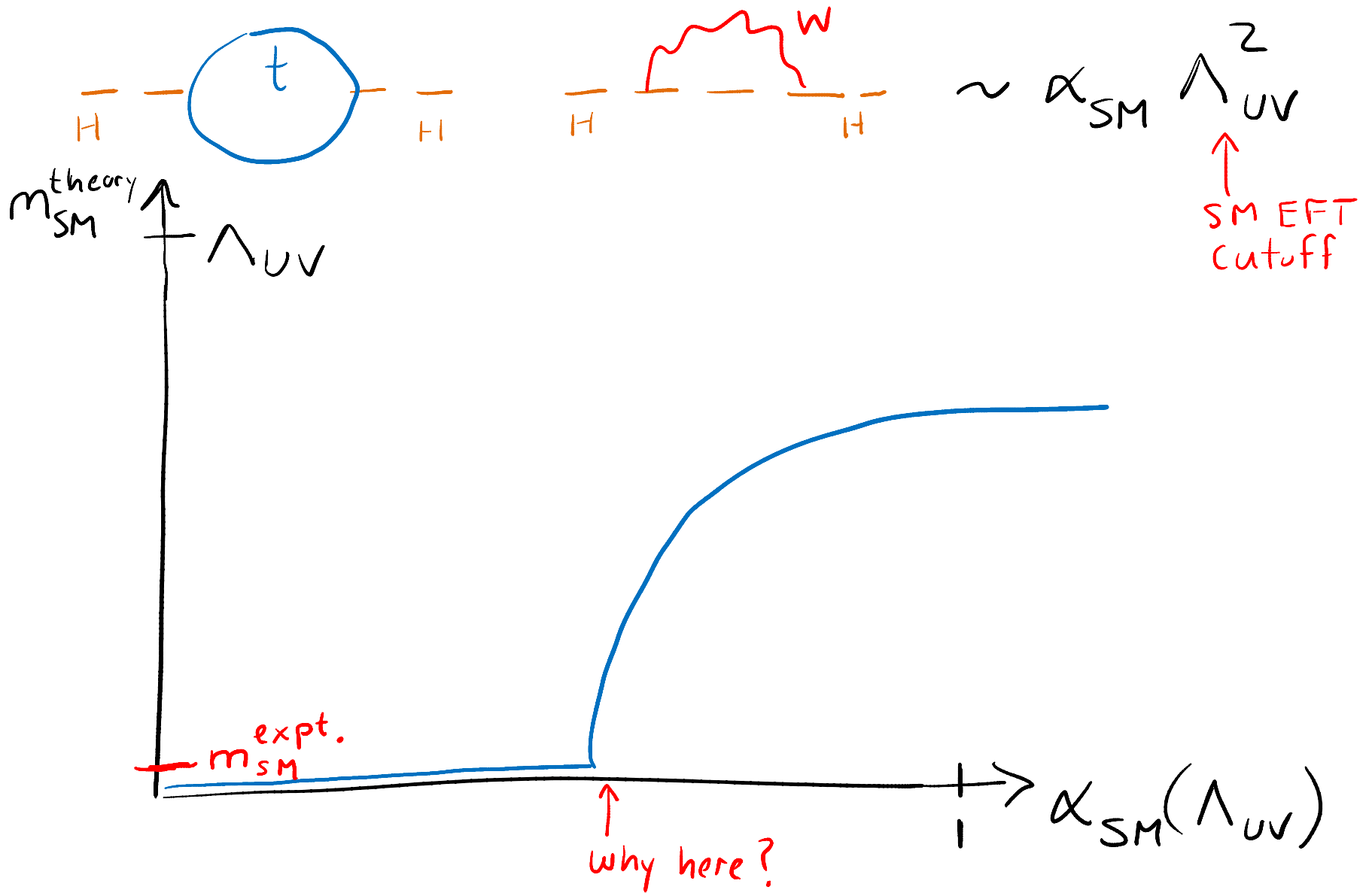
... for insignificant things

LOOK HERE!

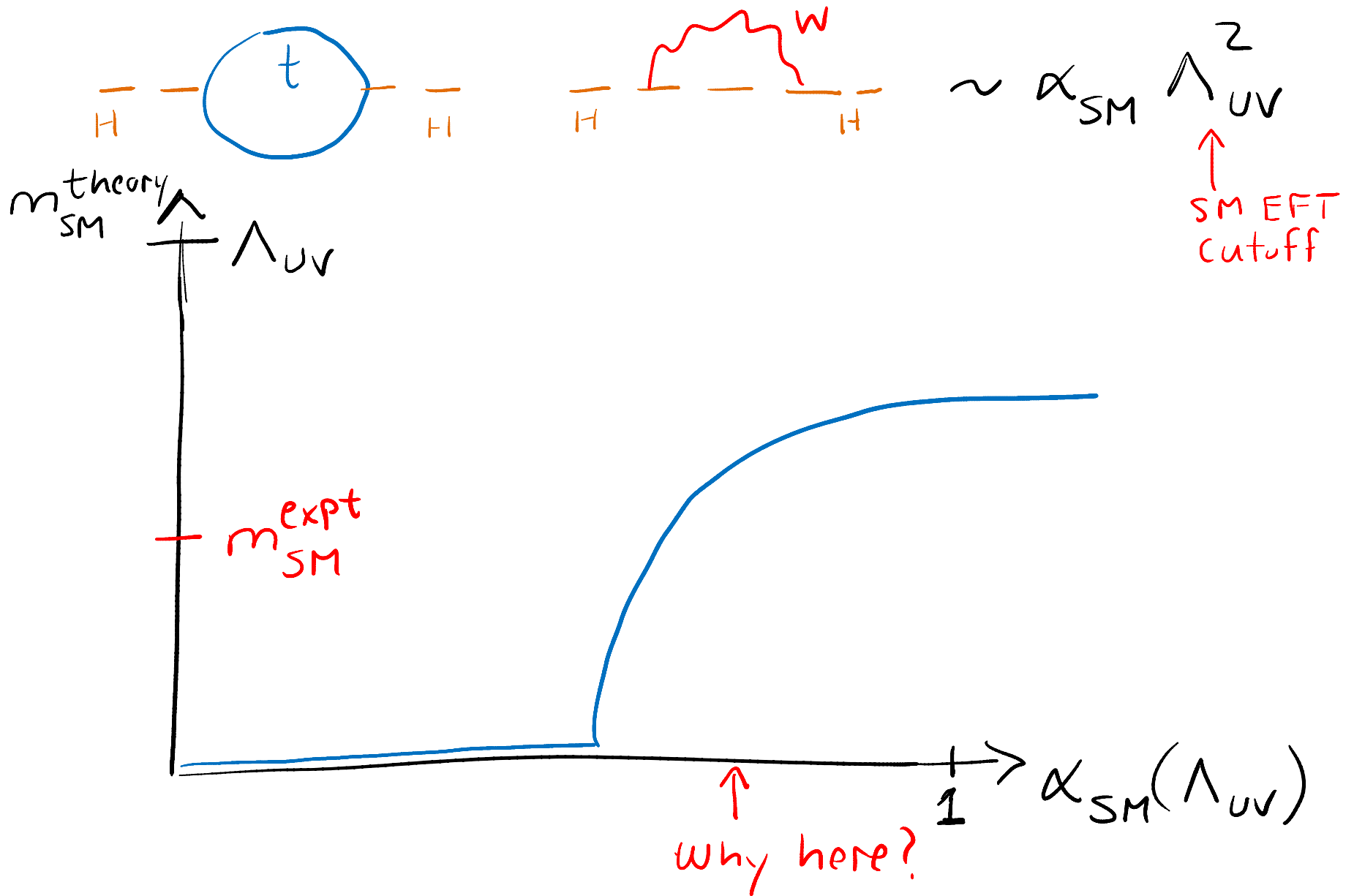


There ARE rich set of quantum field theoretical mechanisms, but few beautiful & complete models. WE must guide expts. to LEAD the way

# HIERARCHY PROBLEM

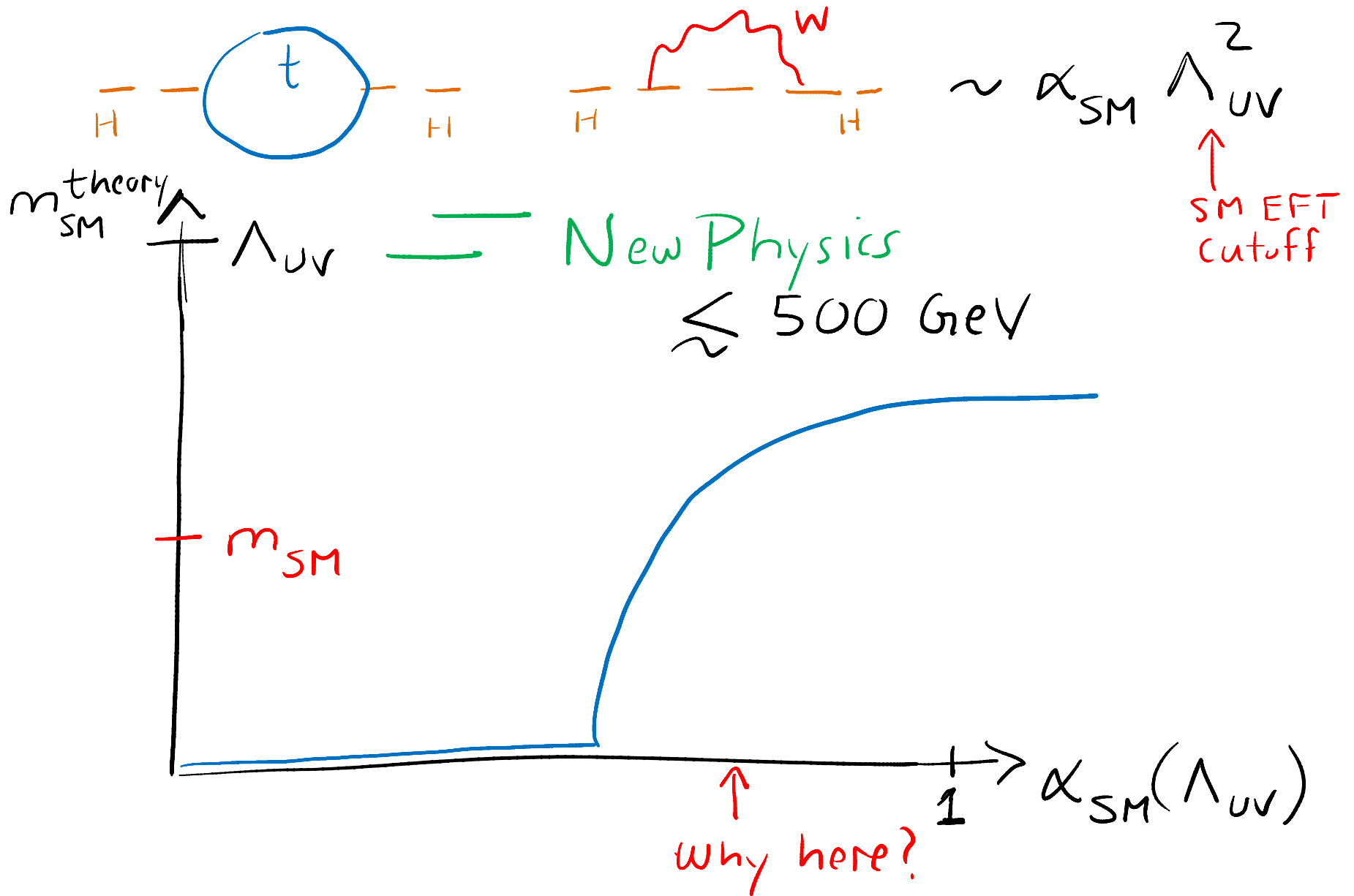


# HIERARCHY PROBLEM

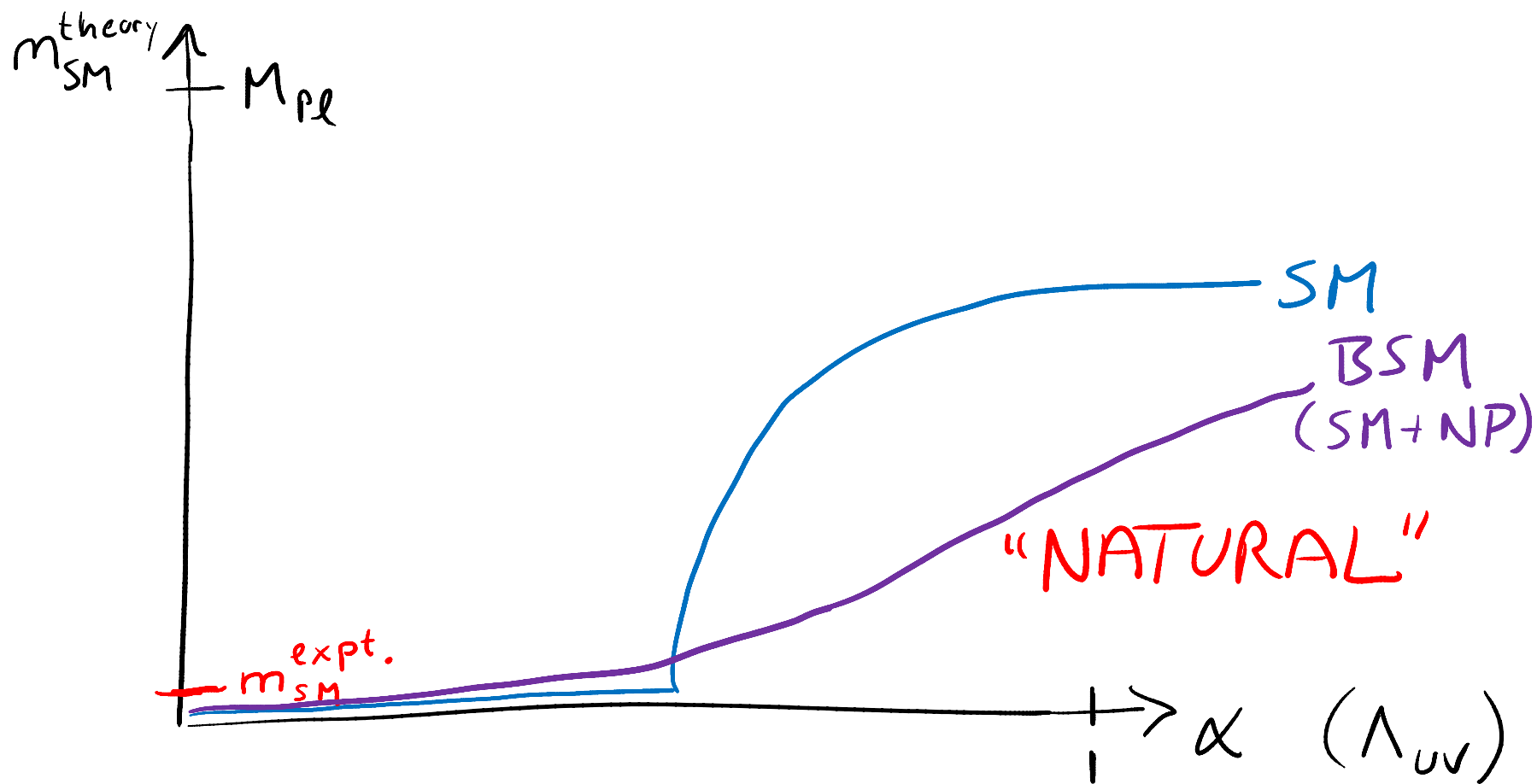




# HIERARCHY PROBLEM



# HIERARCHY PROBLEM



# EVIDENCE


∃ lots of elementary spin- $\frac{1}{2}$  & spin-1,  
assorted flavors & colors.

∃ elementary spin-2

Maybe elementary spin- $\frac{3}{2}$ , hard to see

Higher spins CAN'T be elementary

But till Higgs, no elementary spin-0

Composite  $\pi^+$    $\sim \alpha_{SM} \Lambda_{hadronic}^2 \sim (m_{\pi^+}^2 - m_{\pi^0}^2)$   
expt.

# COMPOSITE HIGGS?

Georgi, Kaplan '84

$$\mathcal{L}_{\text{SM EFT}} = \mathcal{L}_{\text{SM}}^{\text{renormalizable}} + \frac{\alpha_{\text{SM}}^k \mathcal{O}_{\text{SM}}^{\text{higher dim.}}}{\Lambda_{\text{composite}}^n}$$

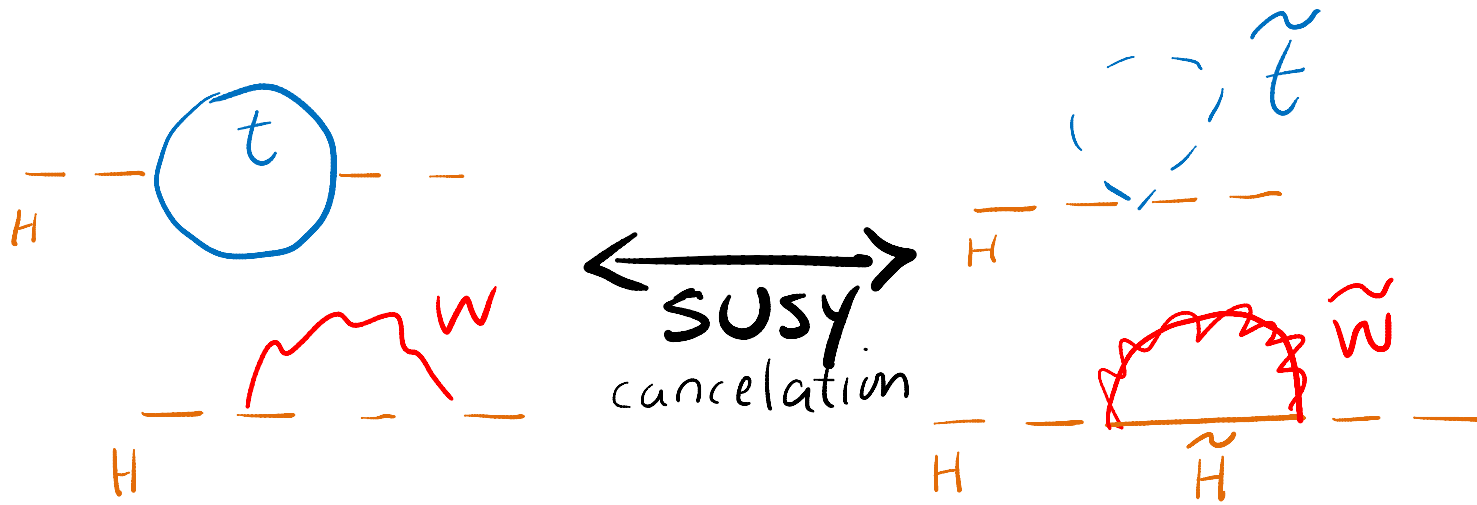
TeV  $\sim$   $\Lambda_{\text{composite}}$

So far EW/Higgs couplings don't see compositeness effects.

But sensitivity runs out  $\Lambda_{\text{composite}} > \text{few TeV}$

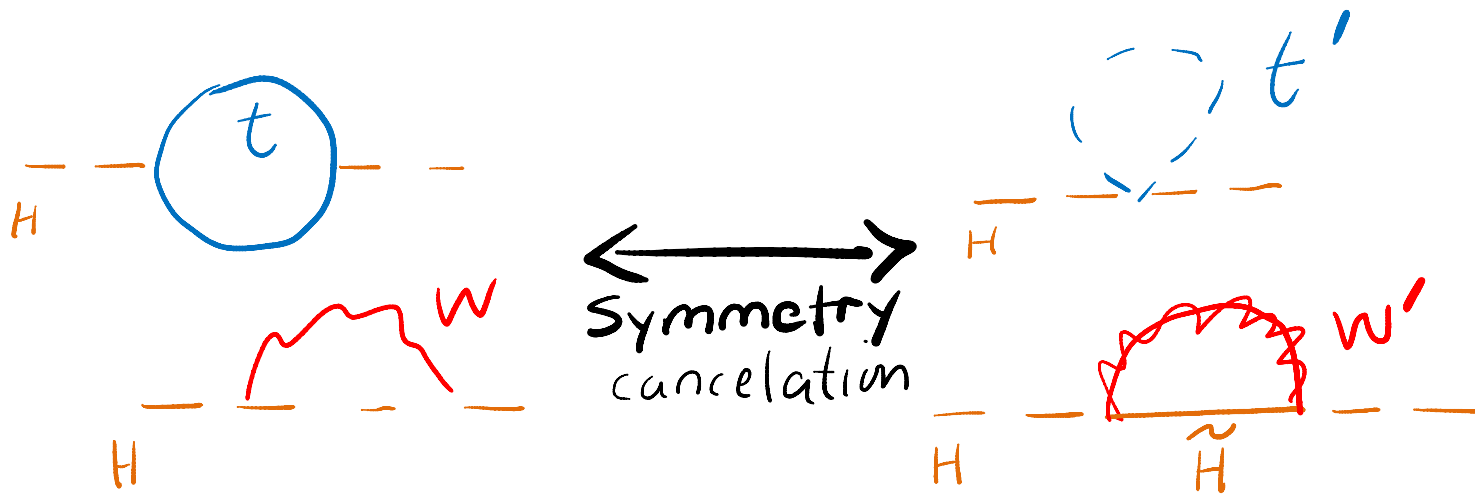
DISCONCERTING, BUT NOT YET DECISIVE

# SUSY



SUSY searches not yet decisive, but discouraging  
 $m_{\text{higgs}} = 125 \text{ GeV}$  larger than simple estimates

# OTHER SYMMETRIES?

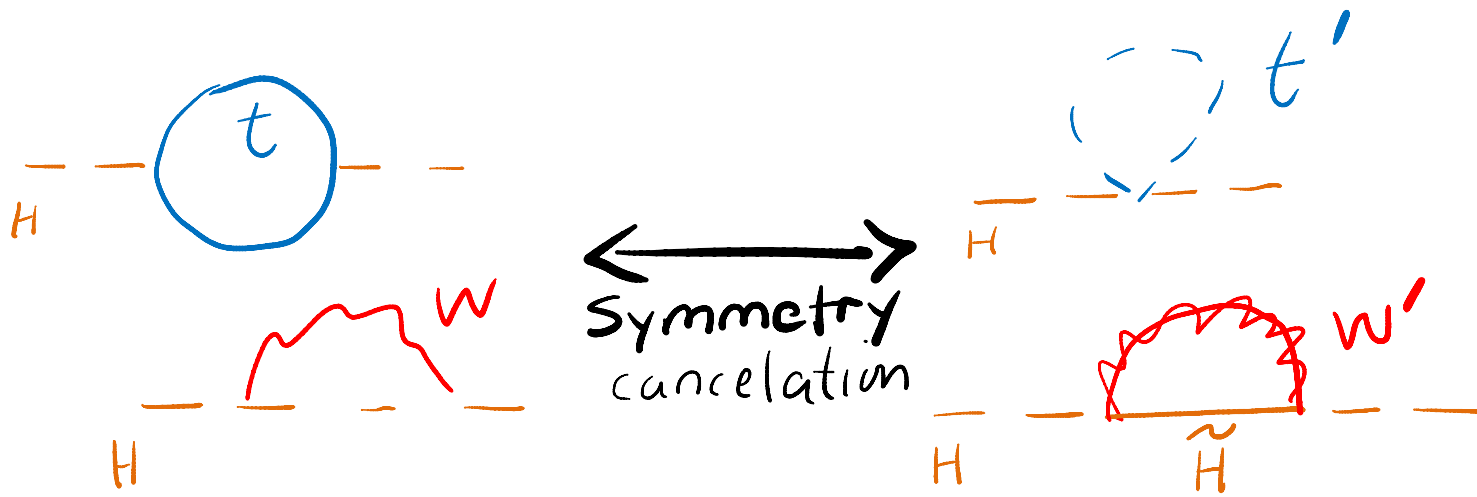


$$[\text{Protective Sym.}, G_{SM}] = 0$$

$\Rightarrow$   $t'$  colored  $W'$  EW coupled  $\sim$  few 100 GeV

LHC searched agnostically in many channels,

# OTHER SYMMETRIES?



[Protective Sym.,  $G_{SM}$ ]  $\neq 0$

$\Rightarrow$   $t'$   $W'$  ... need not carry SM charges

# TWIN HIGGS

Chacko, Goh, Harnik '06

Higgs  $\mathcal{H} = 4$  of  $SU(4) \supset SU(2)_{EW} \times SU(2)_{twin}$

$(H_{EW}, H_{twin})$

$\downarrow$  SSB  $f \sim \text{TeV}$

$SU(3) \supset SU(2)_{EW}$

7 Nambu-Goldstone bosons  
= SM-ish Higgs EW 2  
+ eaten by  $SU(2)_{twin}$

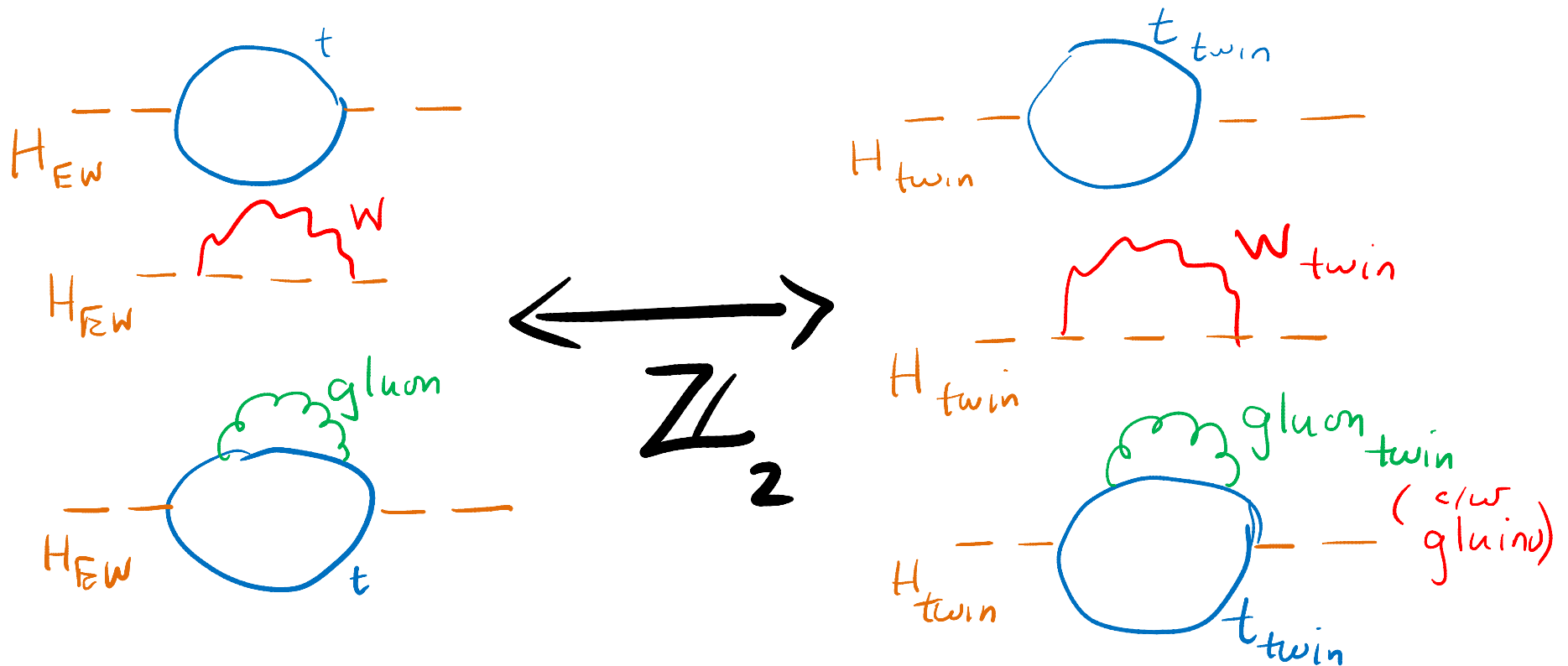
PROTECTIVE  $\mathbb{Z}_2$ :  $G_{SM} \longleftrightarrow G_{twin}$

accidentally protects  $SU(4)$  (&  $\therefore$  light  $H_{SM-ish}$ )

$$V_{\mathbb{Z}_2}(\mathcal{H}) \supset \alpha \Lambda_{UV}^2 (|H_{EW}|^2 + |H_{twin}|^2) + \dots$$



# $Z_2$ RADIATIVE CORRECTIONS



## MINIMAL "FRATERNAL TWIN" HIGGS

Craig, Katz, Strassler, Sundrum '15

(c/w "Natural SUSY")

Look for TWIN 3<sup>rd</sup> generation &  $SU(2)_{twin} \times SU(3)_{twin}$

# SIGNALS/CONSTRAINTS

$h_{\text{physical}} = \text{mix of } H_{EW}, h_{\text{twin}}$

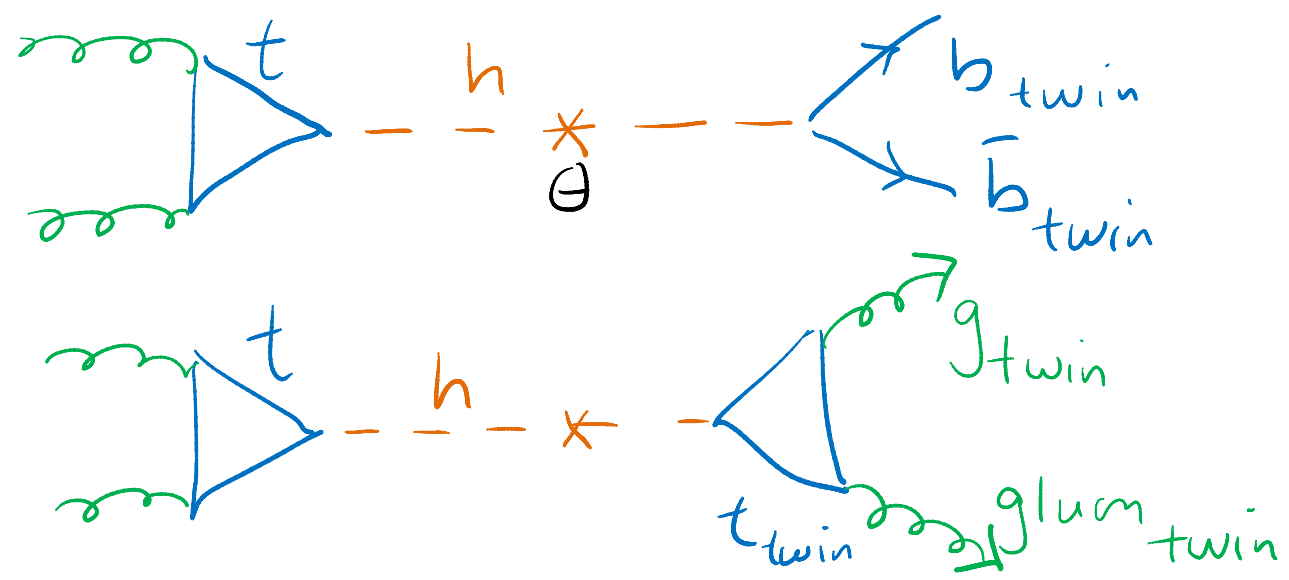
$$\Theta \sim v_{\text{weak}}/f$$

$\Rightarrow$  precision  $\sim (v/f)^2$  deviation  
from SM

$$\Rightarrow v/f \lesssim 1/3$$

Hierarchy tuning  $\sim \frac{v^2}{f^2}$

# THROUGH THE "HIGGS PORTAL"



≡ v. low rates of MISSING ENERGY

v. hard to detect at LHC...



# COSMIC COINCIDENCE

$$\rho_{DE} \gtrsim \boxed{\rho_{DM} \gtrsim \rho_{\text{baryons}}} \quad \text{Common mechanism for origins}$$

within an order of magnitude

## Dark Matter as thermal relic stable WIMP

eg.  $\tau_{\text{twin}}$  <sup>Craig, Katz '15</sup>

Hot Big Bang  $T \gg m_{\text{WIMP}} \sim \mathcal{O}(\text{TeV})$  abundant in thermal bath

$T \lesssim m_{\text{WIMP}}$  Boltzmann suppression via WIMP annihilation

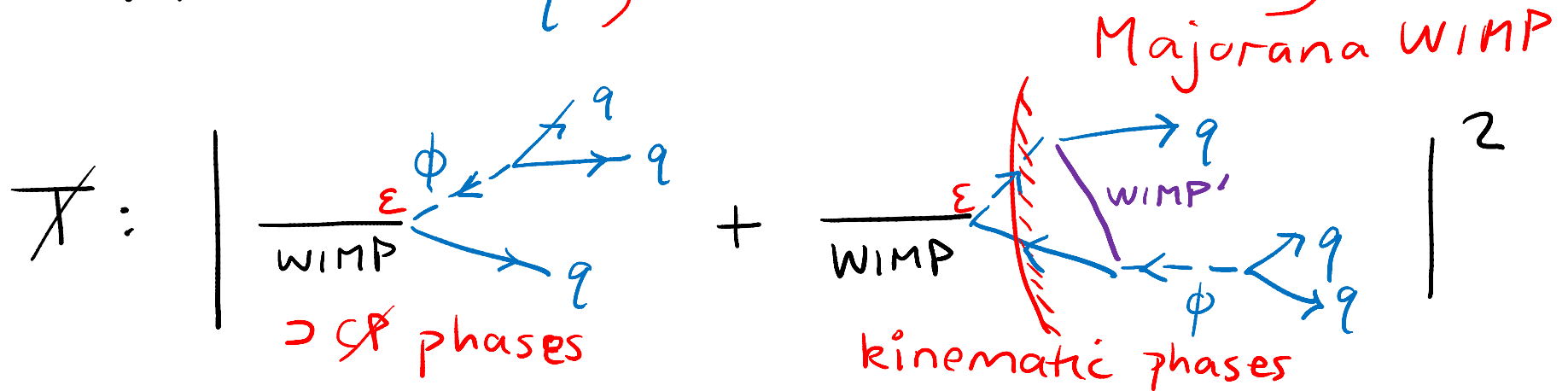
$T < T_{\text{freezeout}}$  WIMPs out of equilibrium, annihilations stop

$$\rho_{\text{WIMP}} \sim \rho_{\text{DM}}^{\text{observe}} \left( \frac{g_{\text{EW}}}{g_{\text{ann.}}} \right)^4 \left( \frac{m_{\text{mediator}}^4}{M_{\text{WIMP}}^2 \text{TeV}^2} \right) \quad \text{WIMP MIRACLE}$$

# BARYOGENESIS FOR WIMPS

Cui, Sundrum '13

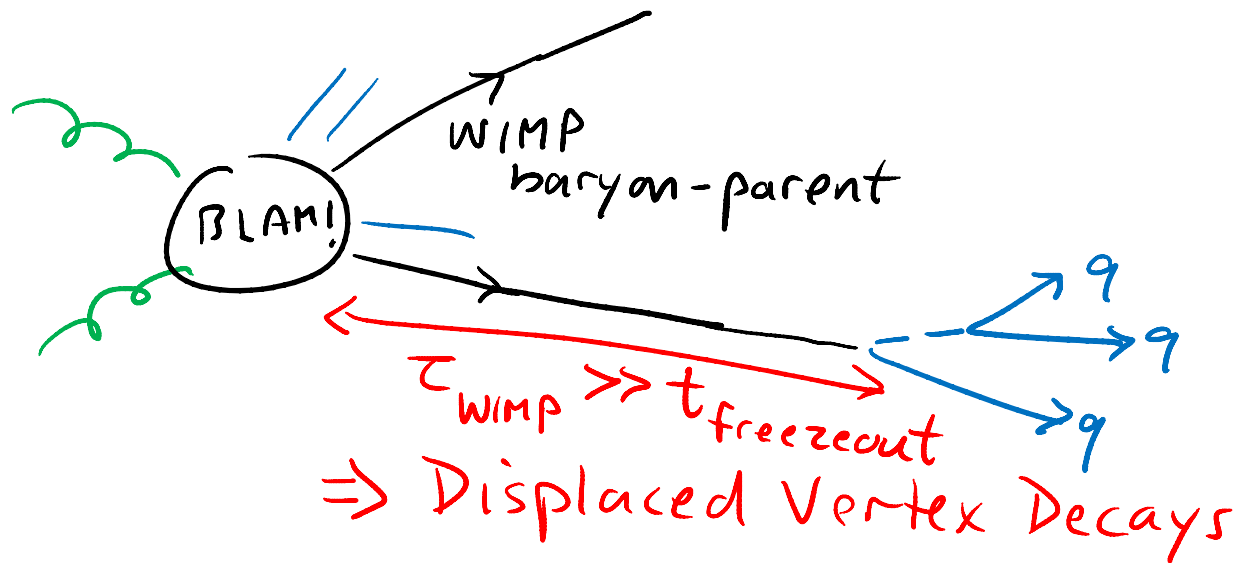
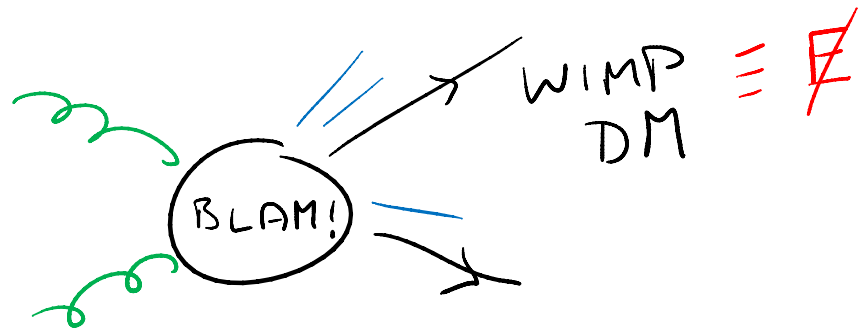
Unstable, but long-lived WIMP



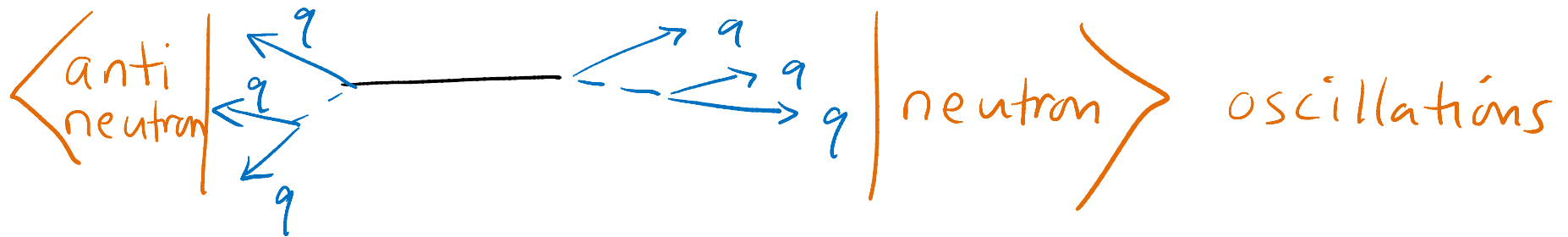
$$\rho_{\text{baryon}} \sim \frac{1}{8\pi} \frac{m_{\text{baryon}}}{m_{\text{WIMP}}} \rho_{\text{stable WIMP}}$$

This  $\Rightarrow$   $\rho_{\text{baryon}} \sim \rho_{\text{DM}}$  at the (crude) level of WIMP miracle.

# WIMPS AT LHC



# LOW-ENERGY CONSTRAINTS & SIGNALS



## Electric Dipole Moments

within stringent bounds if  $q = 3^{\text{rd}}$  generation  
due to CKM suppressions.

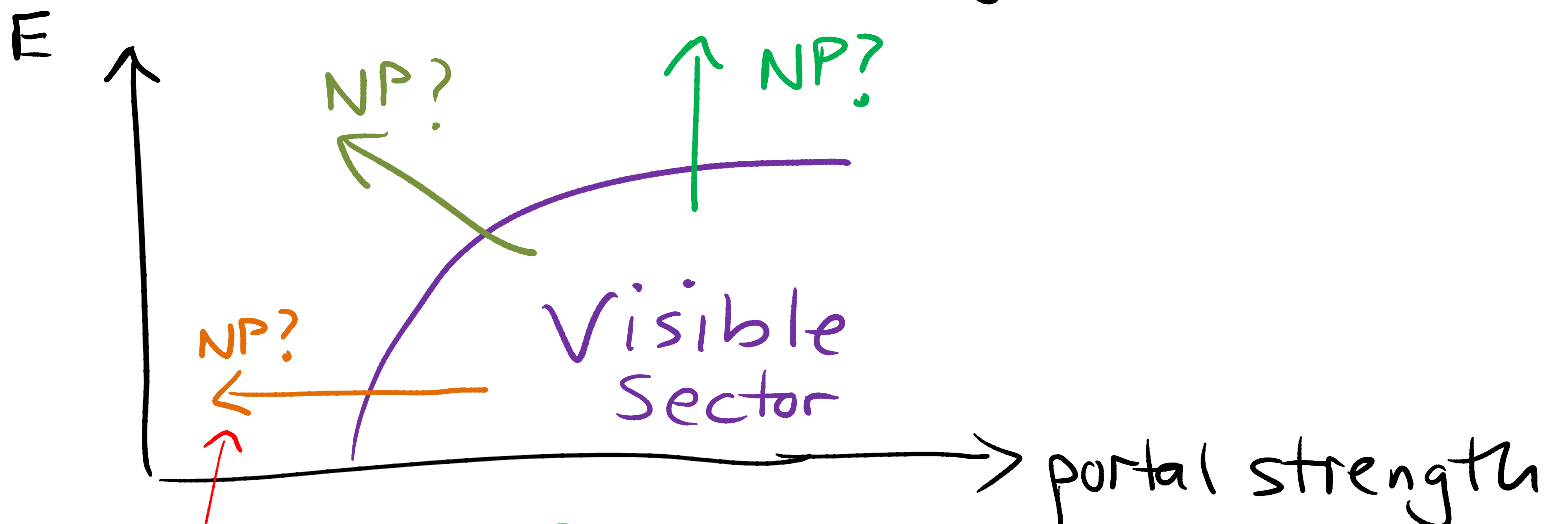
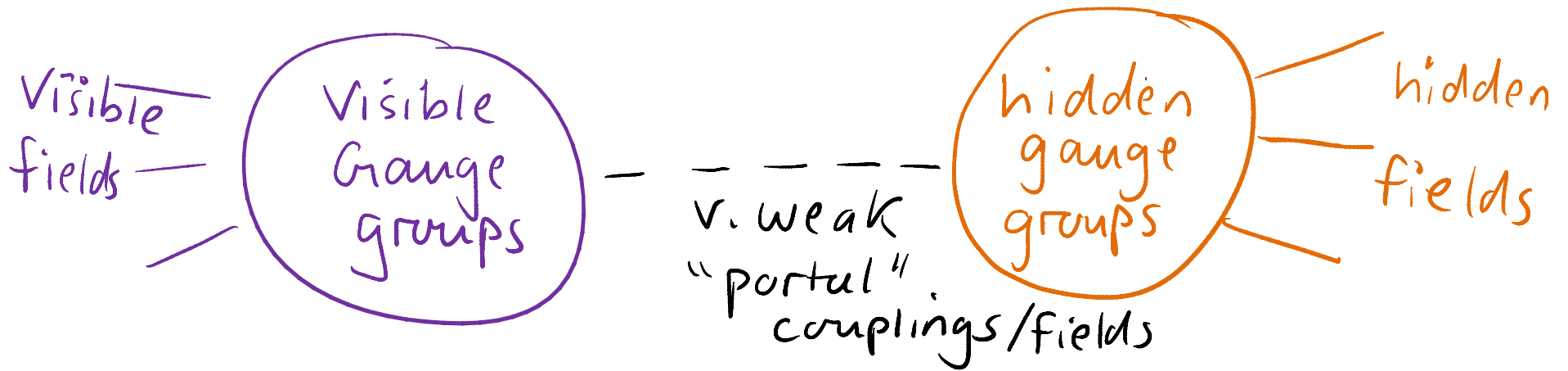
FCNCs consistent with constraints

BUT CLOSE TO BOUNDS



# MORALS

## Gauge Theories Rule!



LOW PRODUCTION, BUT ROBUST OPPORTUNITY IN DV events

# EXISTING LHC DETECTORS

have ongoing DV searches  
for variety of final SM states

They will greatly improve over time

But how long can lifetimes be?

$\tau_{\text{WIMP}} < 1 \text{ second}$  to not disrupt

BIG BANG NUCLEOSYNTHESIS

Displaced events  
on Moon!

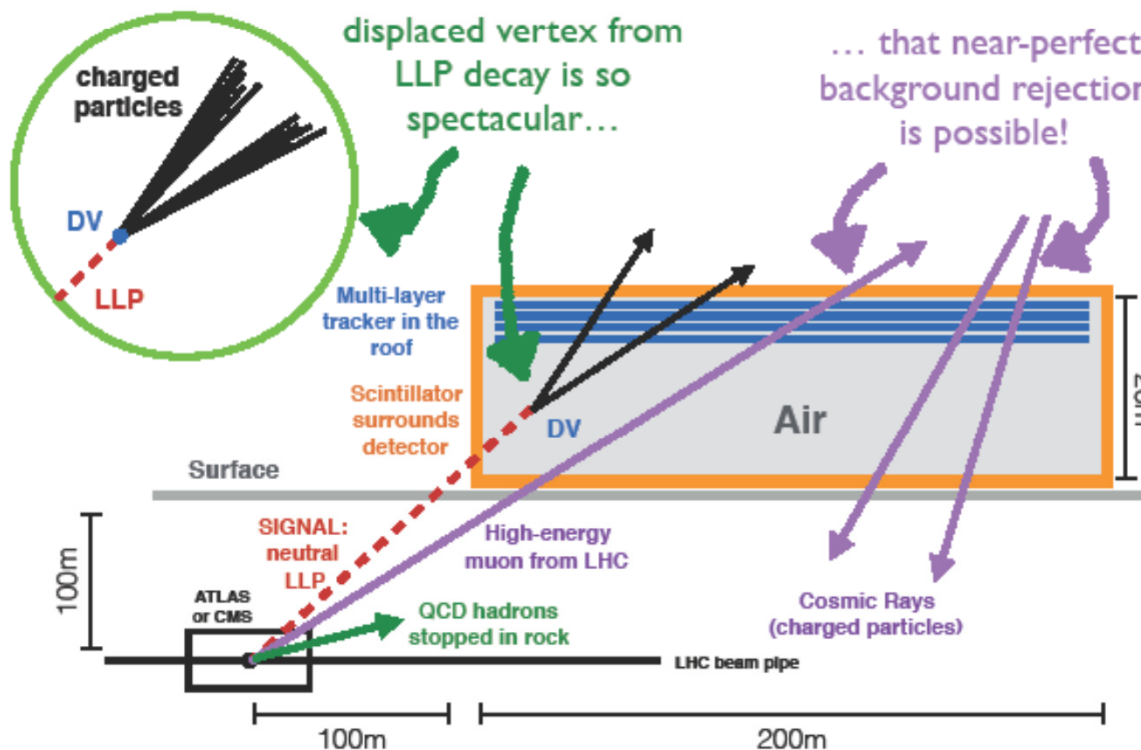
# New Displaced Vertex Detector Proposal



John-Paul Chou  
David Curtin  
Henry Lubatti  
1606.06298



MAssive Timing Hodoscope for Ultra-Stable Neutral PArticles



On schedule for

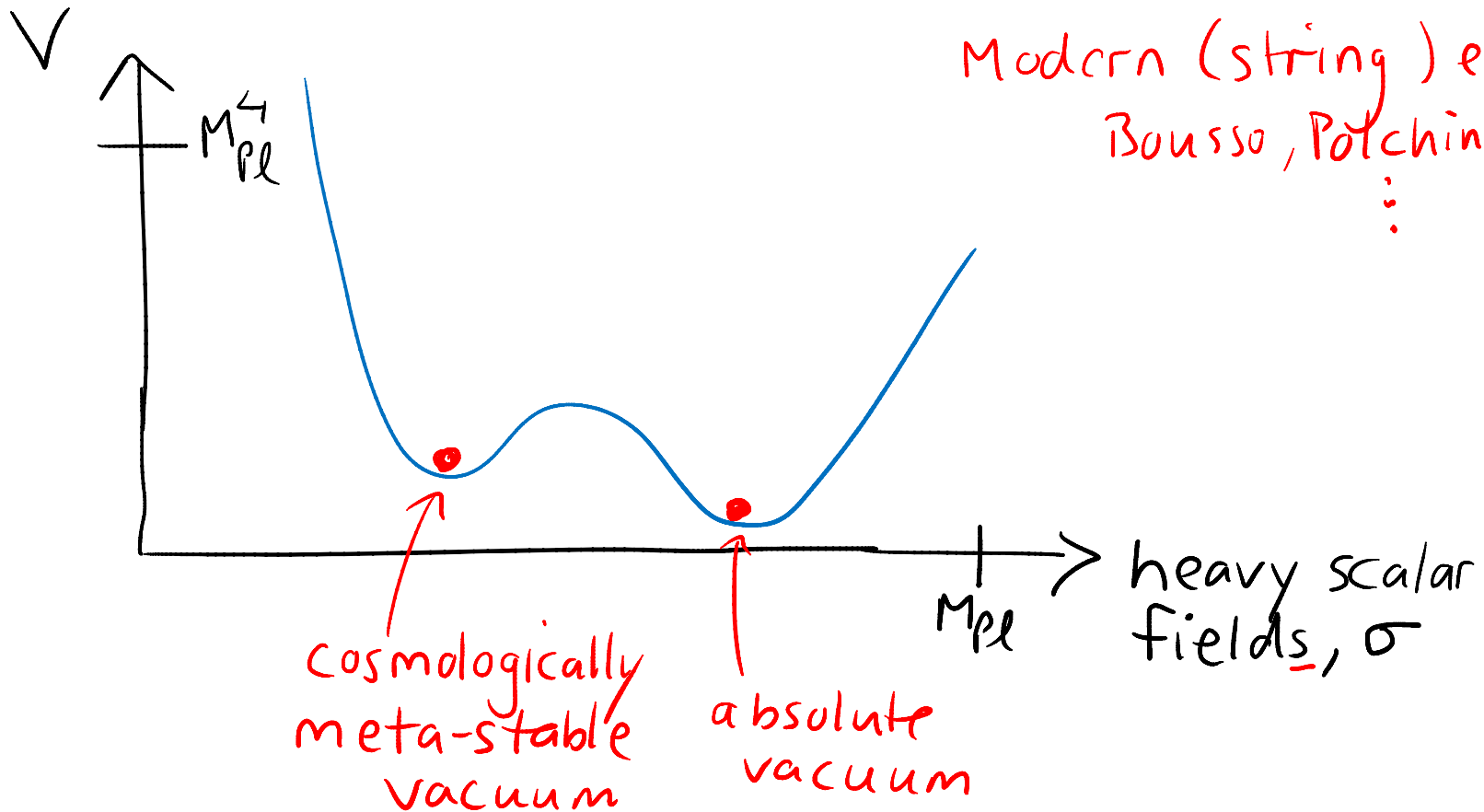
prototype  
mid 2017  
letter of intent  
end 2017

theory  
white paper  
mid 2017

Figure Credit: Curtin, Sundrum, submitted to Physios Today

Eg. sensitive to 10%  $h \rightarrow DV$  events,  $\tau \sim 1$  second

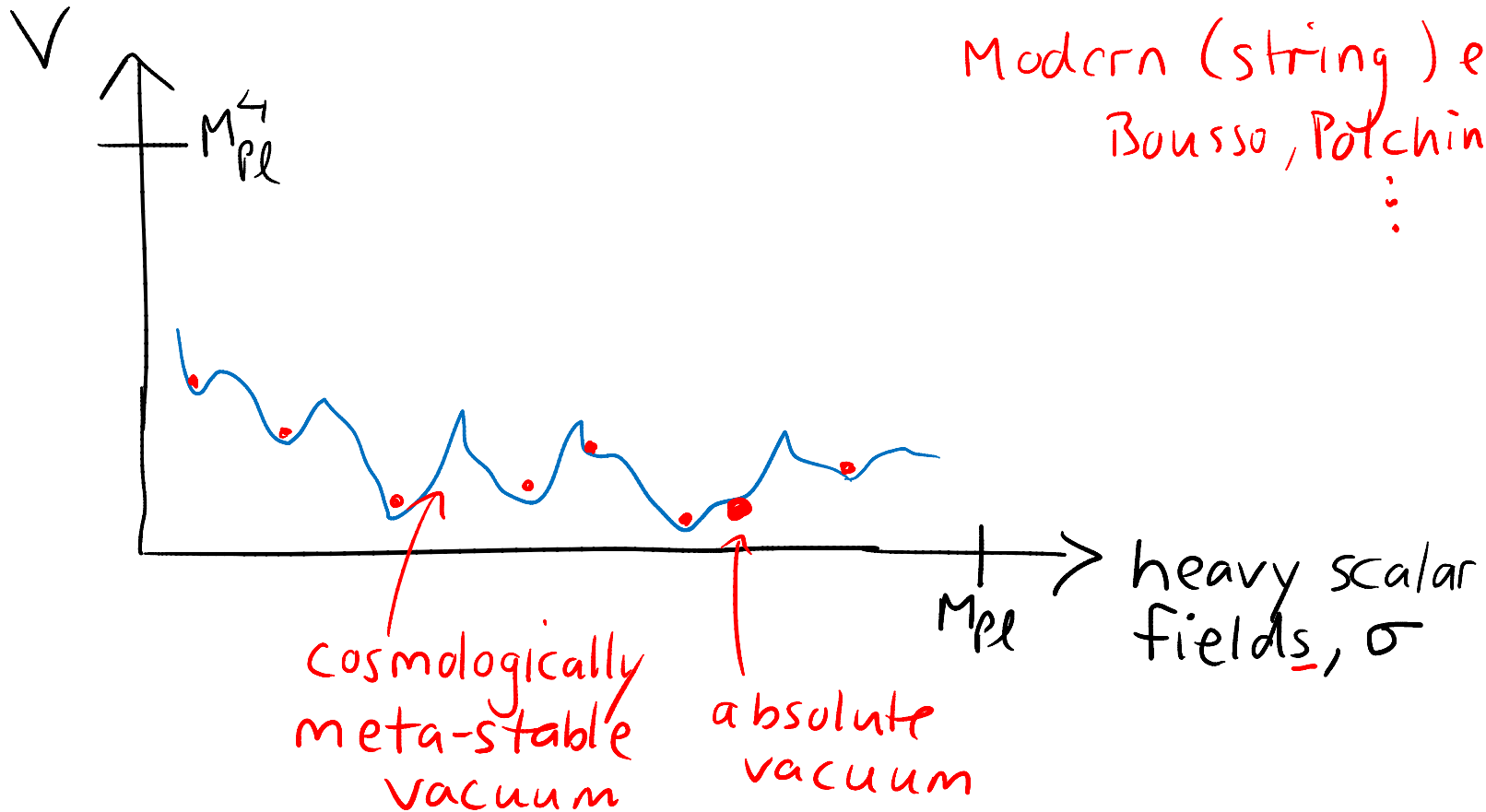
# LANDSCAPING



$$\mathcal{L}_{UV} \supset \left( -\frac{1}{4g^2} + \frac{\langle \sigma \rangle_i}{M_{pl}} \right) F_{\mu\nu}^2$$

$-\frac{1}{4g_{eff,i}^2}$  DISCRETUM of EFTs

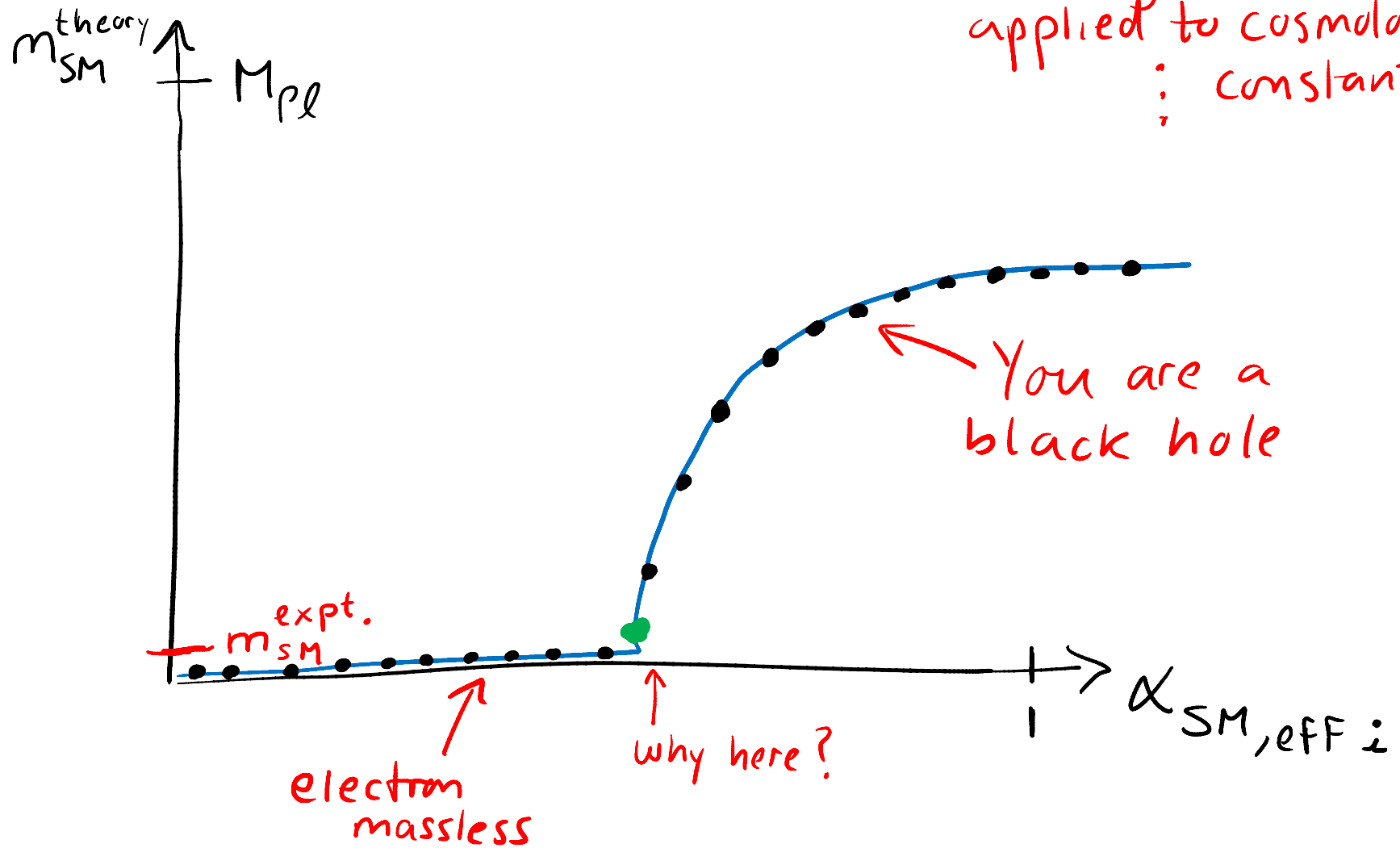
# LANDSCAPING



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# ANTHROPIC PRINCIPLE

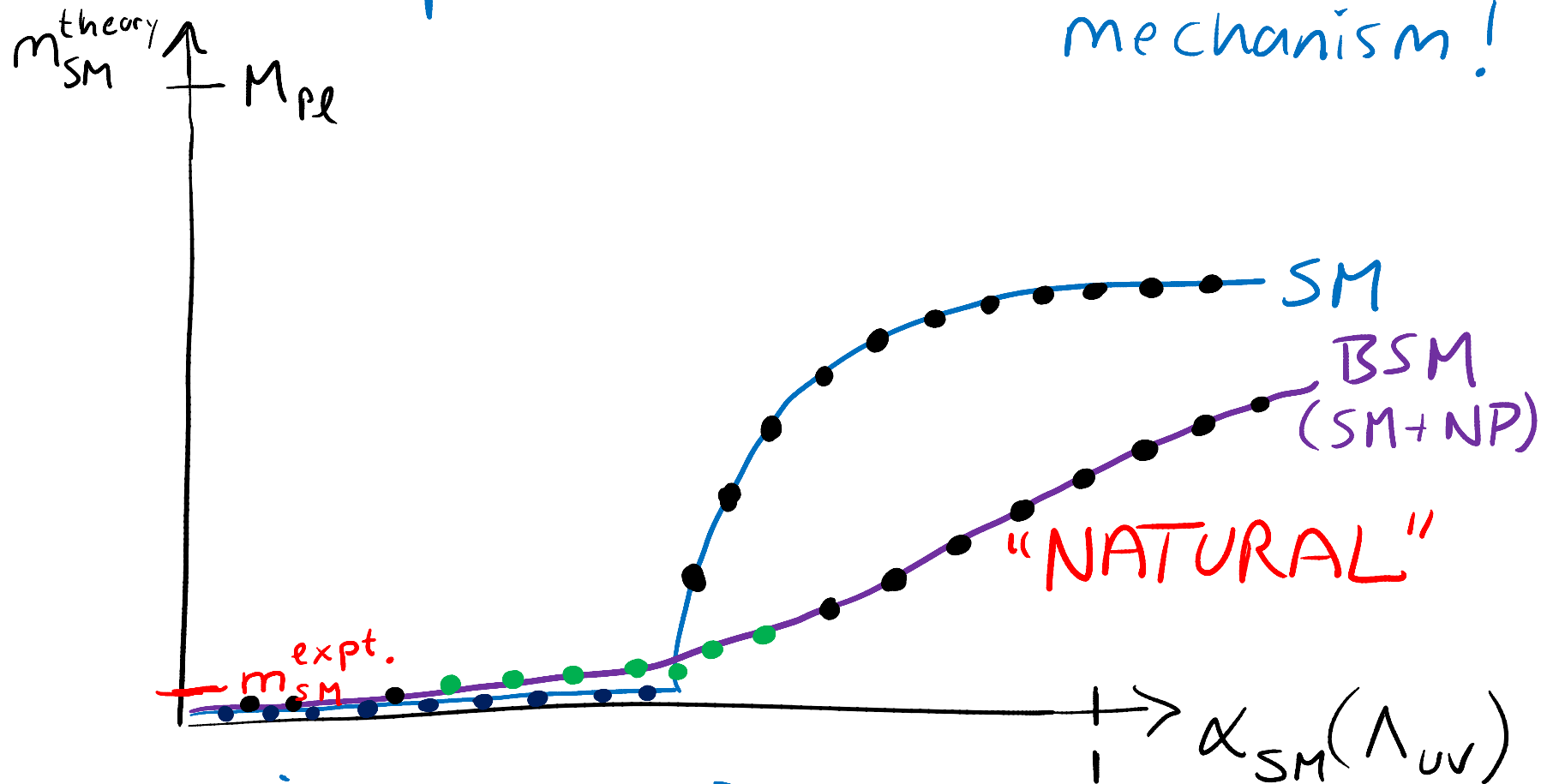


Modern era:  
Weinberg '89  
applied to cosmological  
; constant

# ANTHROPIC PRINCIPLE

IS PRINCIPLE OF LAST RESORT

Compared with NATURAL EFT  
mechanism!



Cosmological Constant Problem has no known  
natural mechanism. AP may well underlie PDE Weinberg '89

# FRUSTRATED NATURALNESS

Eg. WIMP Baryogenesis in  
RPV SUSY

See Cui '13

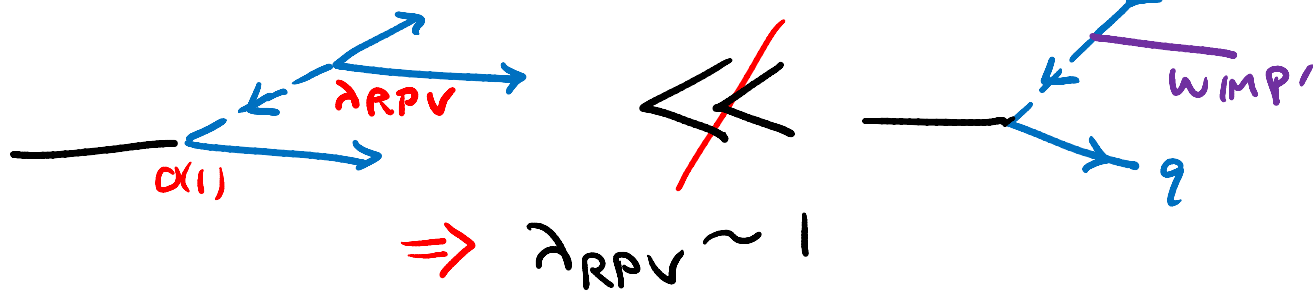


## NATURAL SPECTRUM

--- squark w. RPV

— } WIMPS = SUSY "-inos" have only  $\alpha(1)$  coupling

≡ SM idealize all  $\sim 100$  GeV for simplicity





# FRUSTRATED NATURALNESS

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NATURAL  
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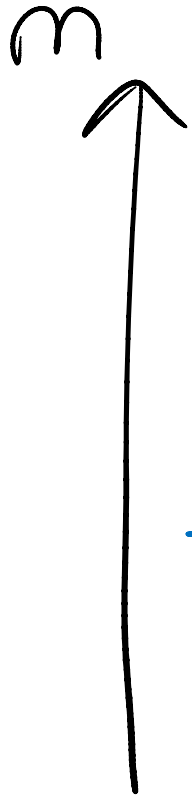
≡ SM idealize all  
 $\sim 100 \text{ GeV}$   
for simplicity



BUT THEN BARYON PARENT WIMP DECAYS PROMPTLY!

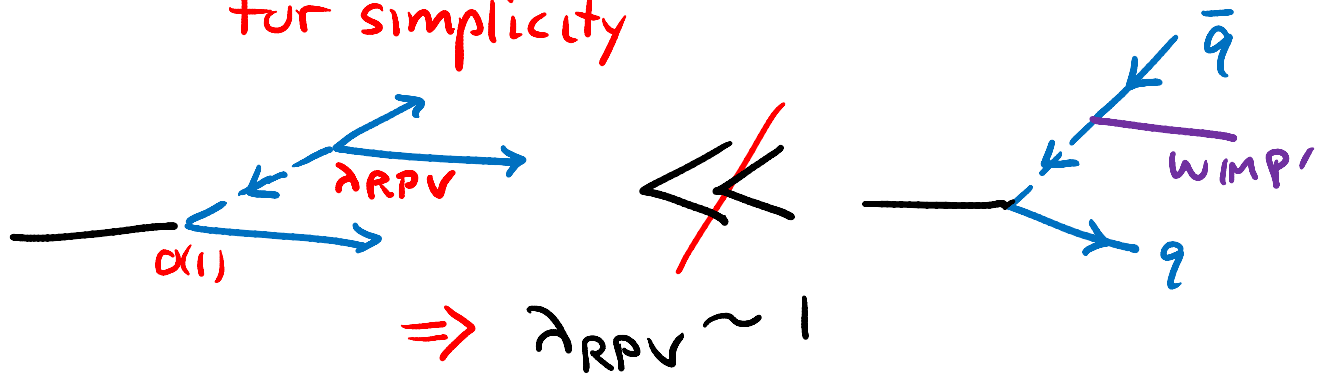
# FRUSTRATED NATURALNESS

Eg. WIMP Baryogenesis in  
RPV SUSY see Cui '13



NATURAL SPECTRUM BUT NO ONE THERE TO SEE IT!

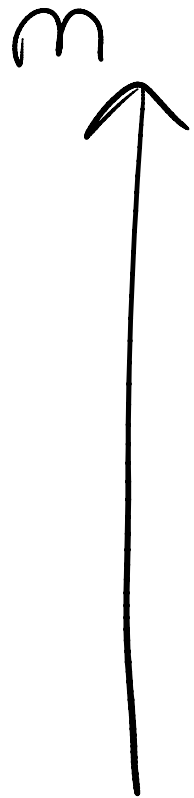
- squark w. RPV
- } WIMPS = SUSY "-inos" have only  $\alpha(1)$  coupling
- ≡ SM idealize all  $\sim 100$  GeV for simplicity



BUT THEN BARYON PARENT WIMP DECAYS PROMPTLY!

# FRUSTRATED NATURALNESS

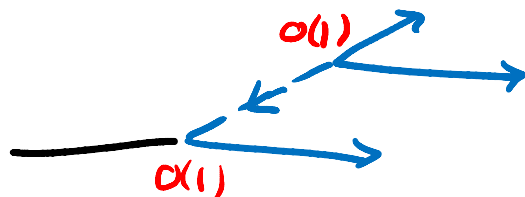
Eg. WIMP Baryogenesis in  
RPV SUSY see Cui '13



--- squark

MESO-TUNED SPECTRUM

--- } WIMPS = SUSY "-inos" have only  $\alpha(1)$  coupling  
--- SM

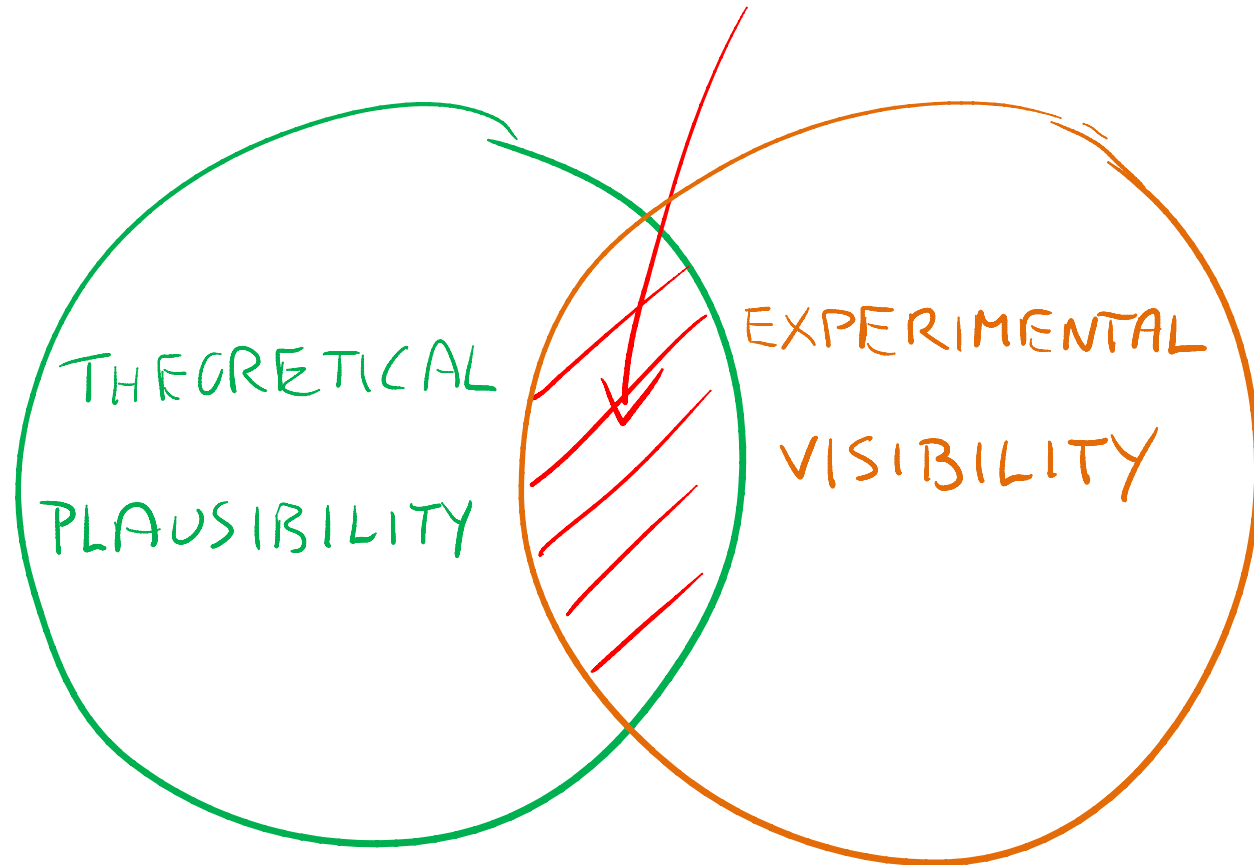


LONG-LIVED

$\Rightarrow$  BARYOGENESIS  
SUCCEEDS

after WIMP freezeout

LOOK HERE!



Must gamble on the cup of naturalness being more full than empty.

# COMPOSITE HIGGS

Non-perturbatively strong new couplings to bind Higgs

Hunt other composites BSM

But can't calculate! - lattice BSM,

Analytic:  $\mu \frac{d}{d\mu} \mathcal{O}_{\text{composite}}(x; \mu_{\text{RG}}) \sim \delta(\alpha_{\text{new}}(\mu)) \mathcal{O}$

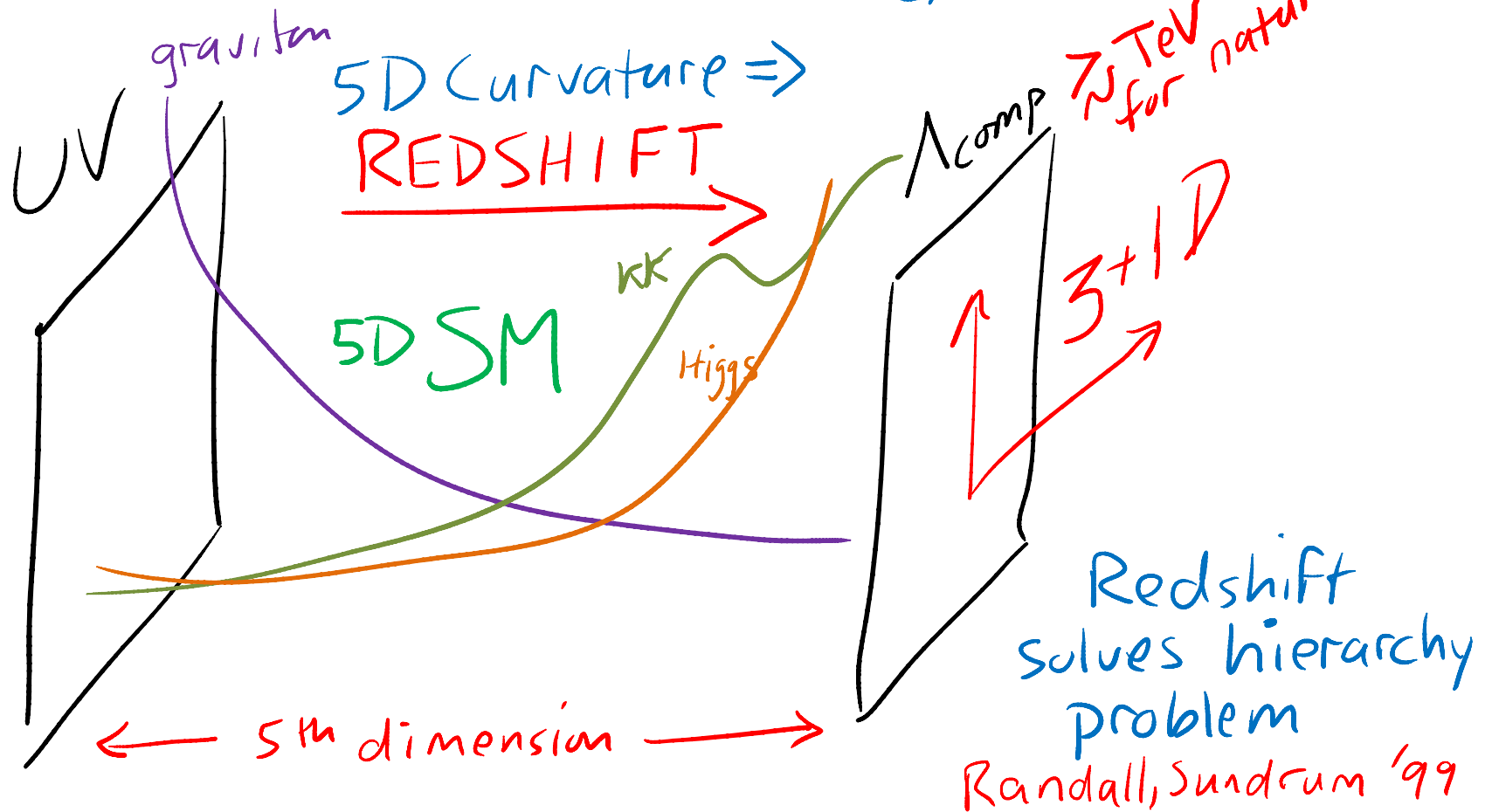
If  $\alpha_{\text{new}}(\mu) \gg 1$  over hierarchy of  $\mu$ ,

CAN EXPAND IN  $1/\delta \dots$

# RS1 Warped 5D models

by AdS/CFT

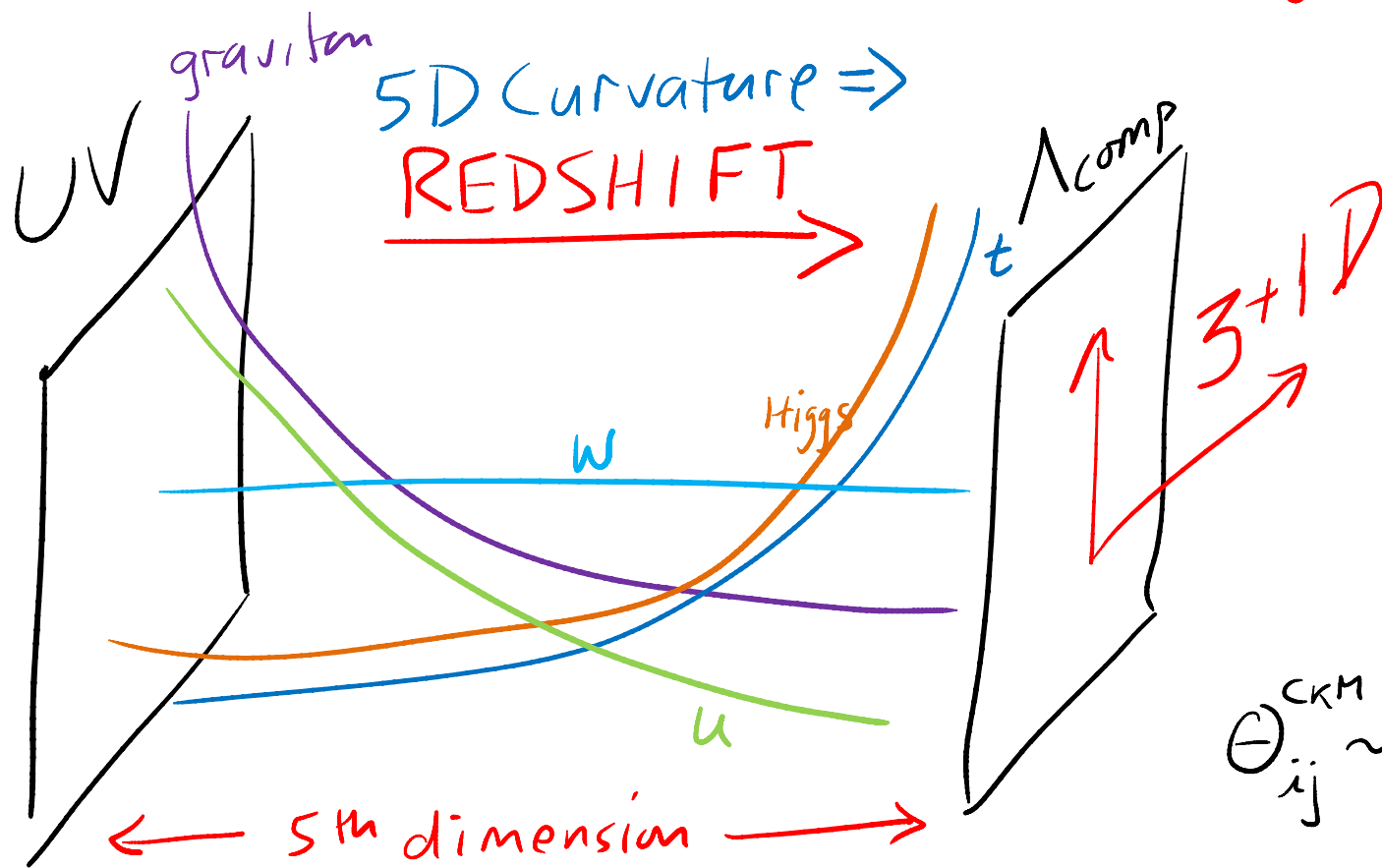
New composites  $\equiv$  Kaluza-Klein excitations



# RS1 Warped 5D models

ALSO Theory of Flavor

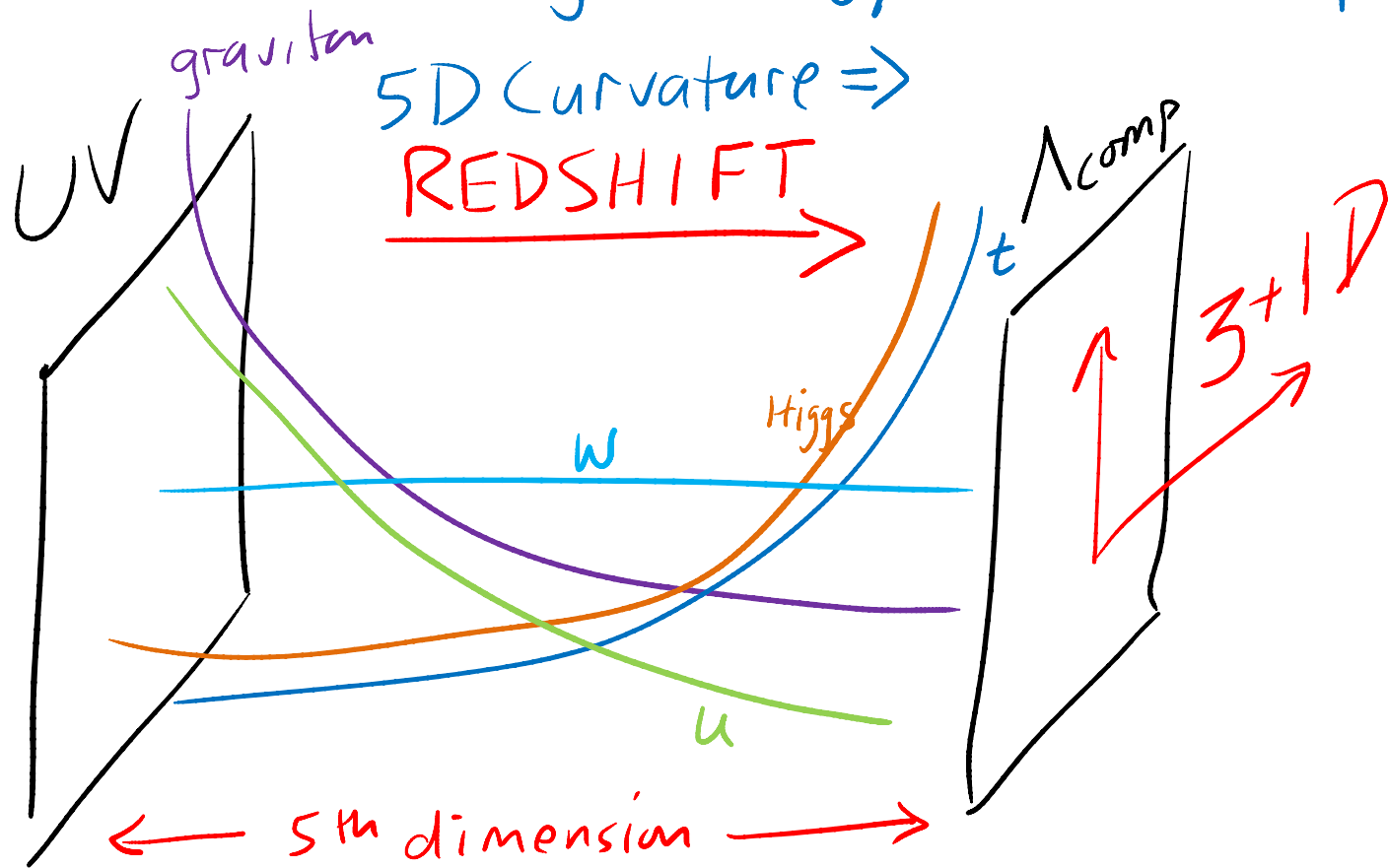
Kaplan '91  
Gherghetta, Pomarol  
⋮



$$\Theta_{ij}^{CKM} \sim \sqrt{\frac{m_i}{m_j}}$$

# RS1 Warped 5D models

Warped EFT – exclusive description of low-lying composite resonances  
– describes v. high energy inclusive processes

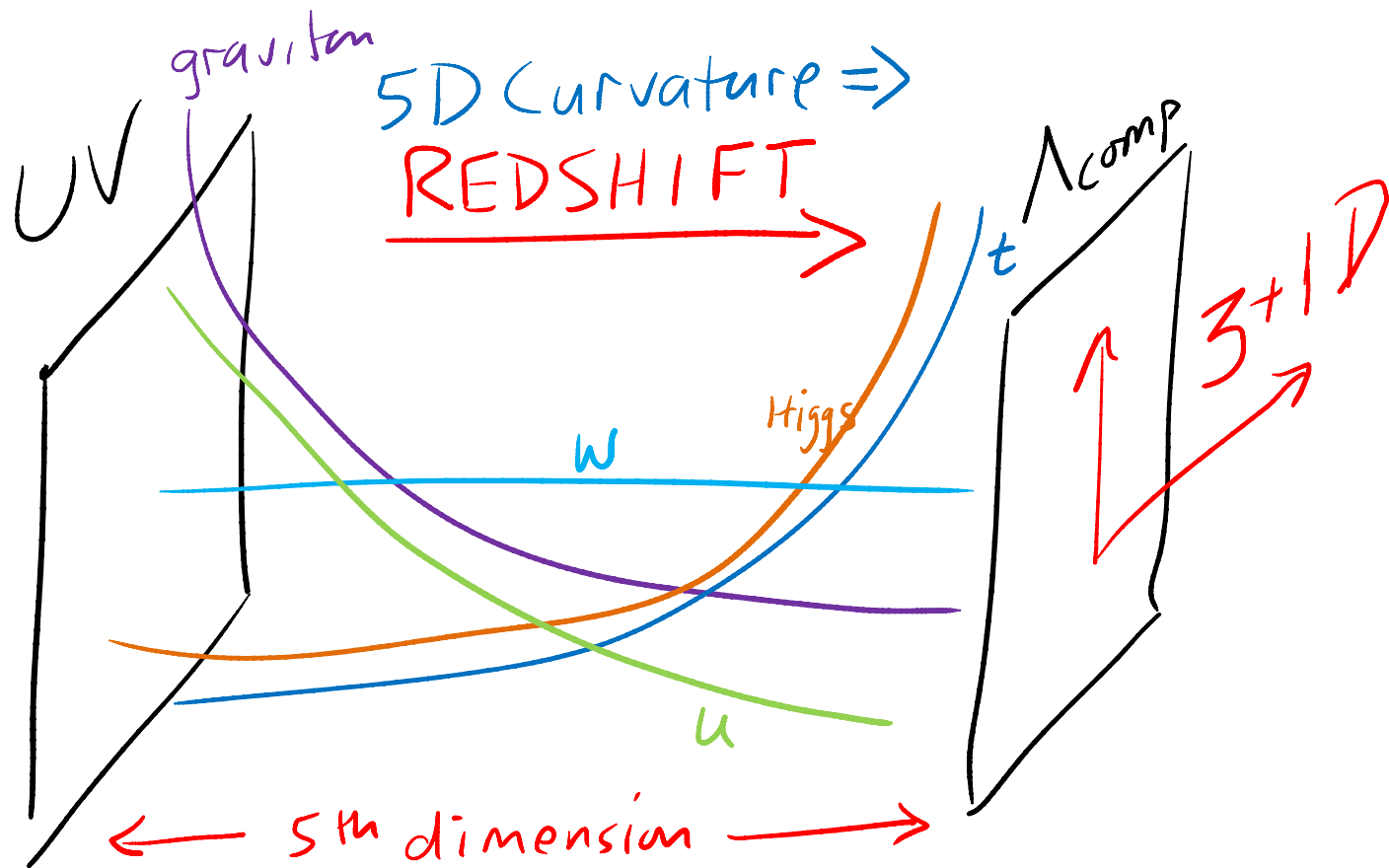




# RS1 Warped 5D models

UV (string) completions still in infancy

non-SUSY: see Kachru, Simic, Trivedi '09

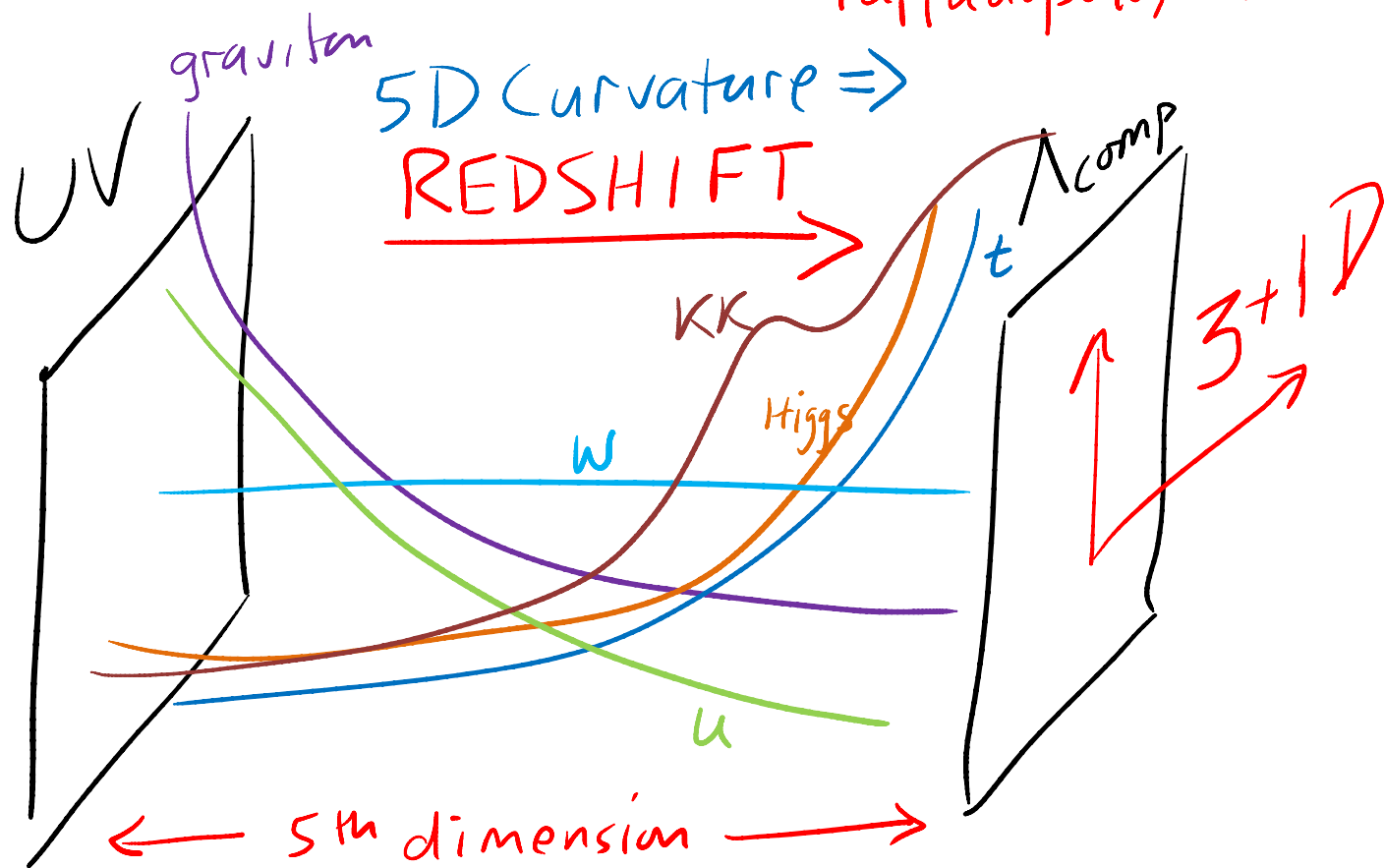


"GIM, she's dead..."

Elegant GIM extension, but imperfect

Flavor/CP constraints  $\Lambda_{\text{comp}} \gtrsim 10 \text{ TeV}$

Keren-Zur, Lodone, Nardecchia,  
Pappadopulo, Rattazzi, Vecchi '12

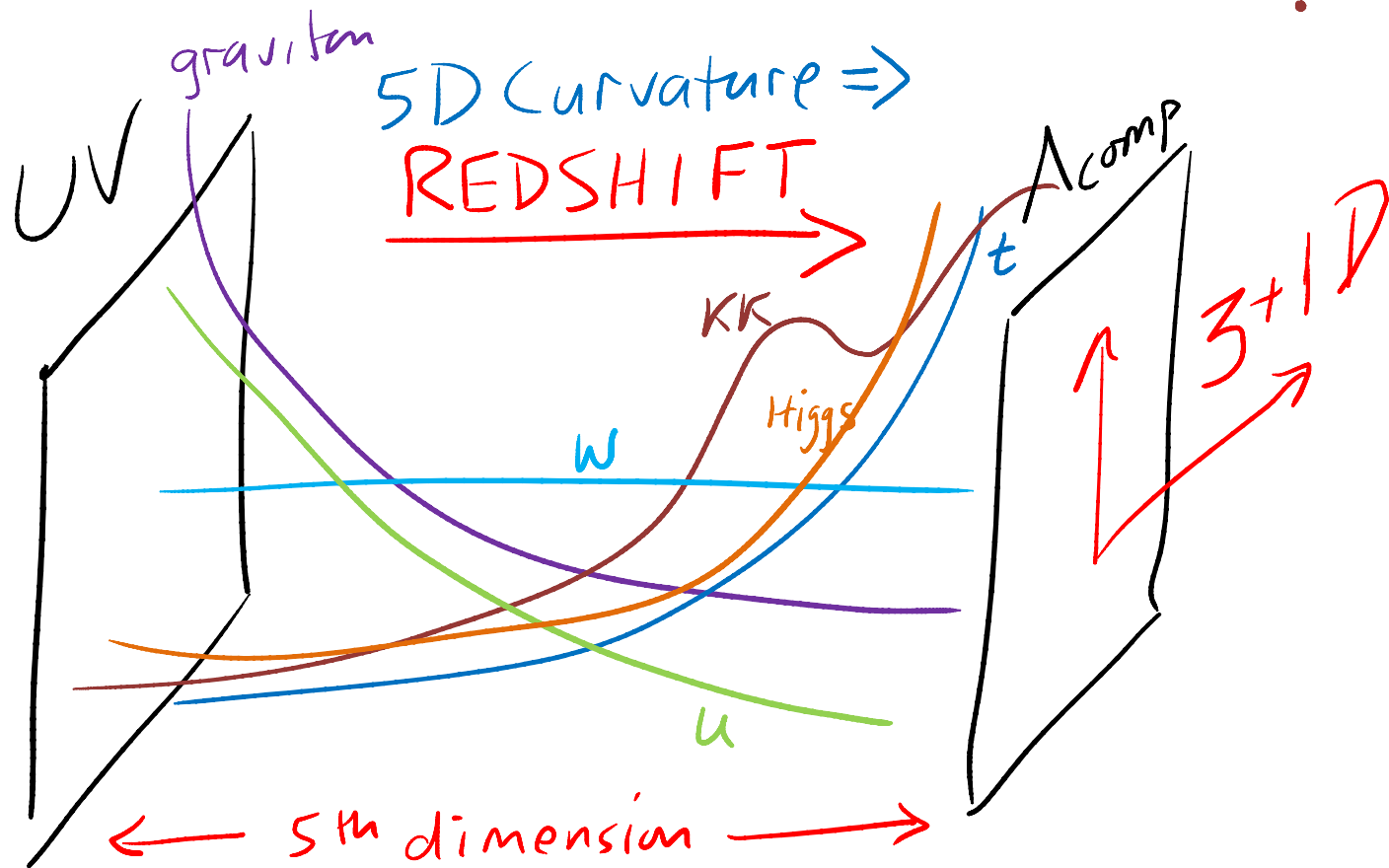


"GIM, she's dead???"

Elegant GIM extension, but imperfect

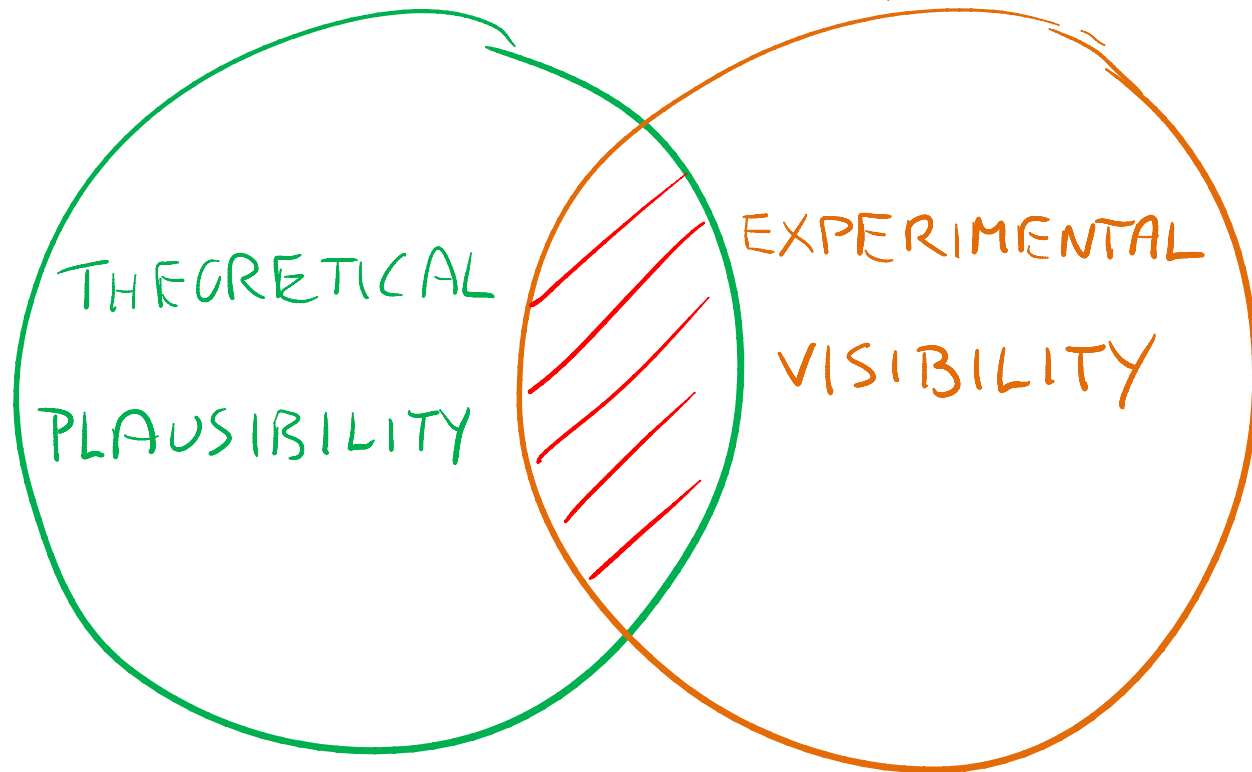
Flavor/CP constraints  $\Lambda_{\text{comp}} \gtrsim 10 \text{ TeV}$

FRUSTRATED? 100 TeV collider!



# LIGHT VESTIGES OF NATURALNESS

(my own focus over last decade)



Eg. light  $\ll \Lambda_{\text{comp}}$  composites, light & flavor-safe for robust structural reasons.  
Subleading or long-lived decays to  $h, t, W_L, Z_L$

# COSMOLOGY

Naturalness considerations  
span particle physics, DM,  
cosmology  $\Rightarrow$

rich array of signals from  
colliders to CMB  
but no guarantees.