A (PERSONAL) VISION OF PARTICLE PHENOMENOLOGY

Raman Sundrum
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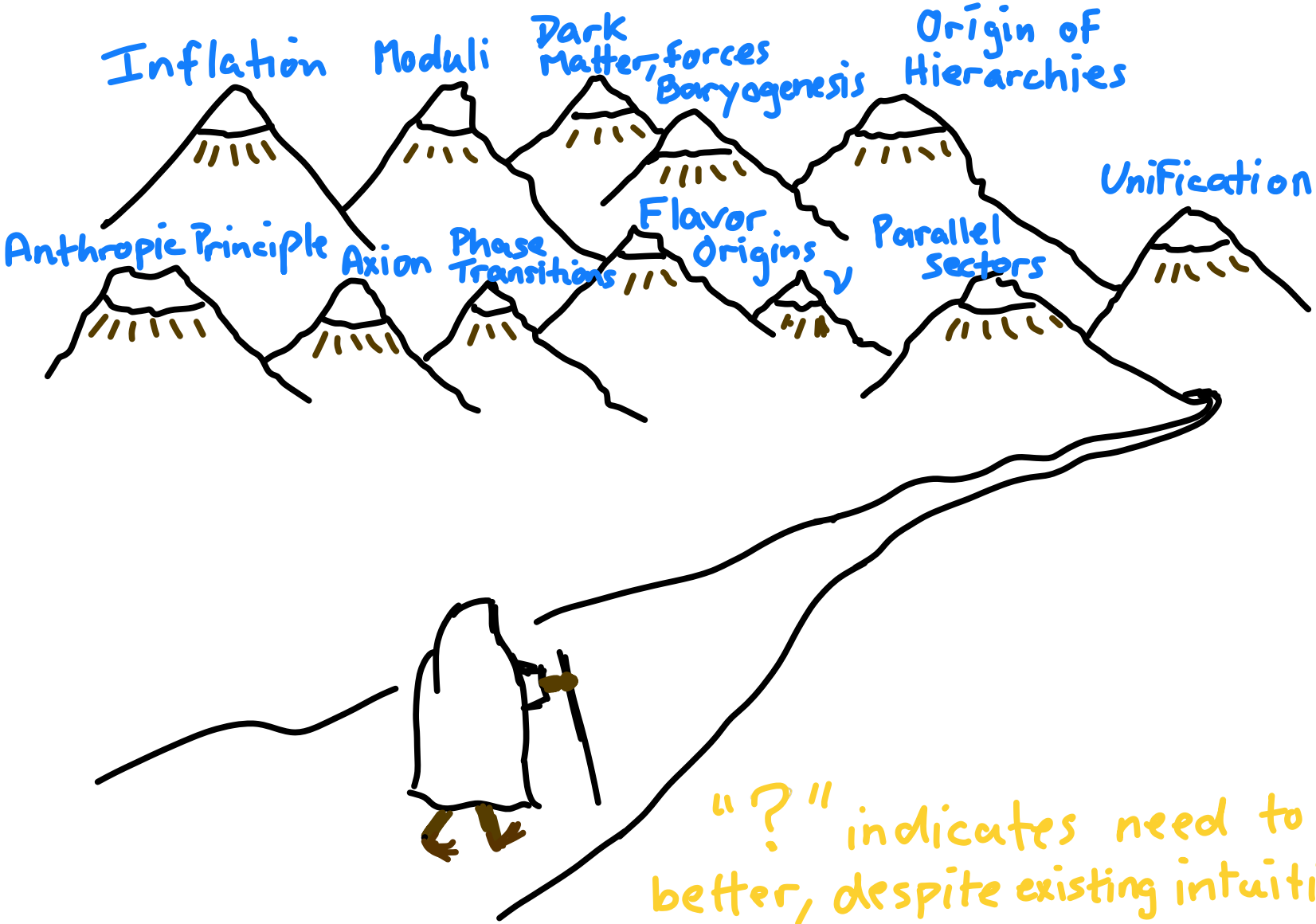
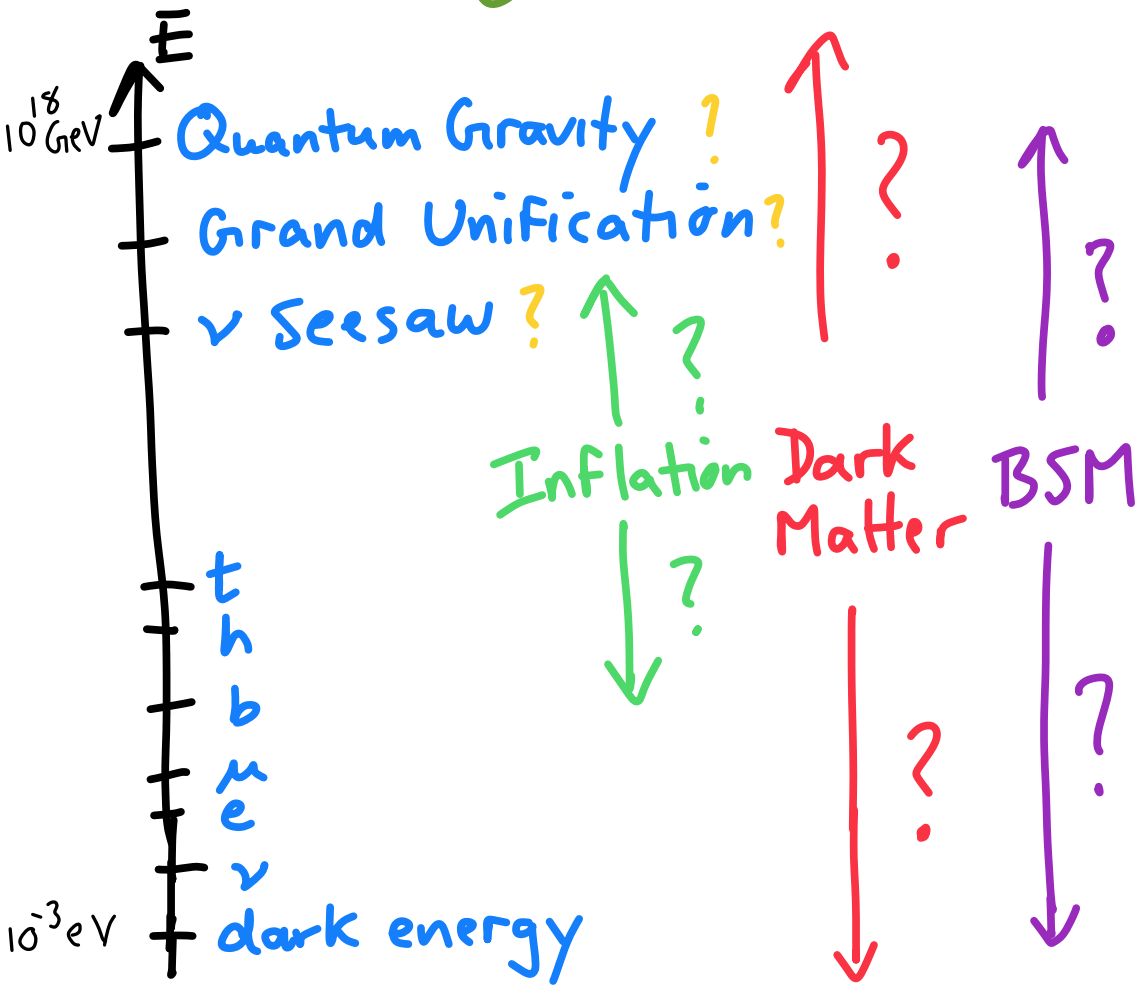

Inflation
Moduli
Dark Matter, forces
Baryogenesis
Origin of Hierarchies
Unification
Anthropic Principle
Axion
Phase Transitions
Flavor Origins
ν
Parallel Sectors
"?" indicates need to understand better, despite existing intuition & examples

Origin of the Hierarchies



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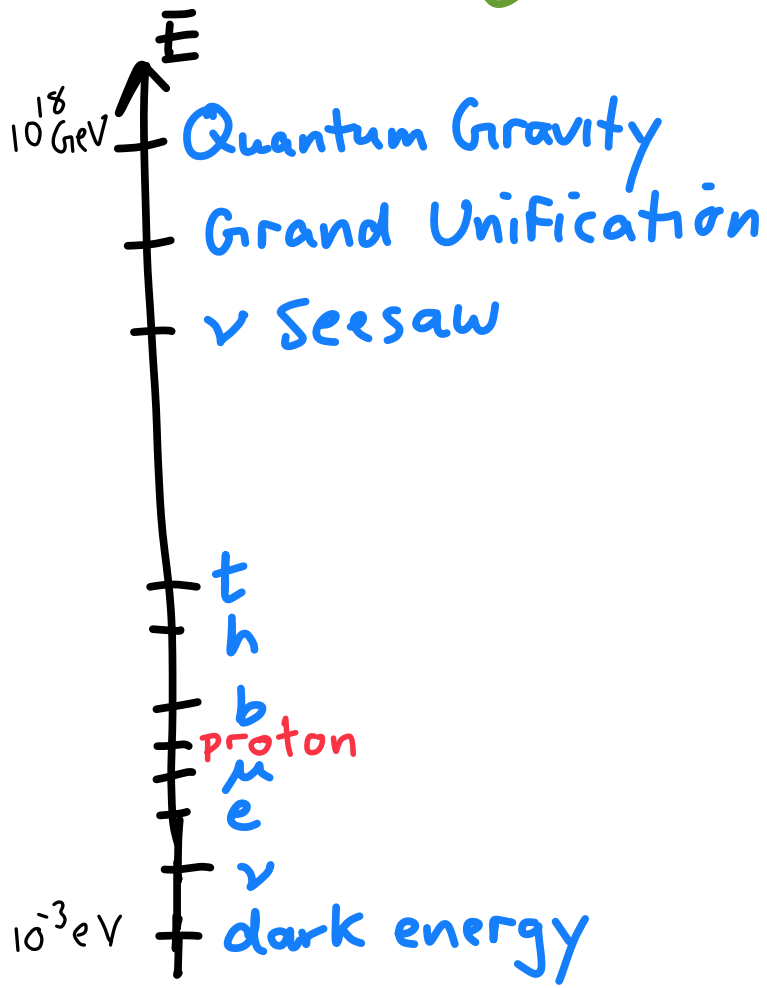


NON-PERTURBATIVE EFFECTS ?

$$m_{proton} \sim \Lambda_{QCD} \sim M_{Pl}\, e^{-\frac{O(4\pi)}{\alpha_s(M_{Pl})}}$$

=> Deeply satisfying explanation of

$$m_{proton} \ll M_{Pl} :$$

COMPOSITE HIGGS

$$v_{weak}, m_h, m_W \sim \Lambda_{comp.} \sim M_{Pl}\, e^{-O(4\pi)/\alpha_{comp.}(M_{Pl})}$$

TASI review: Csaki, Lombardo, Telem '18

DYNAMICAL SUSY BREAKING

TASI review: Dine '96

$$\Lambda_{\cancel{SUSY}} \sim M_{Pl}\, e^{-O(4\pi)/\alpha_{hidden\ sector}(M_{Pl})}$$

In "Gravity"-mediated ~~SUSY~~

$$v_{weak}, m_h, m_W \sim m_{superpartners} \sim \frac{\Lambda^2_{\cancel{SUSY}}}{M_{Pl}} \sim m_{gravitino}$$

Warped Compactifications

Geometric hierarchies from REDSHIFTS
in higher-dimensional EFT & String Theory
Randall, Sundrum '99
Giddings, Kachru, Polchinski '02

$\equiv$ AdS/CFT dual "grammar" of 4D Strong Coupling+...

Traded for weakly coupled extra dimensions

RS1, Warped SM

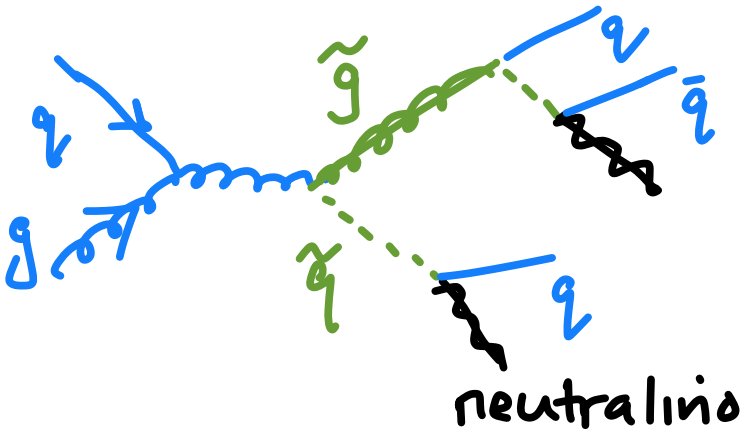
$$v_{weak} / m_h / m_W \lesssim m_{KK} \sim M_{Pl} e^{-\alpha_1 \frac{M_{Pl,5D}^2}{m_{5D}^2}}$$

Goldberger-Wise '99
5D scalar mass

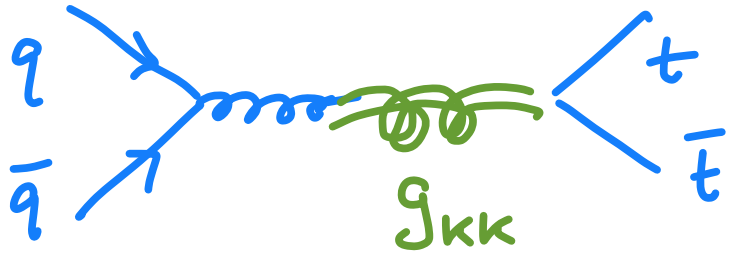
TASI Csaki, Lombardo, Telem '18
TASI Sundrum '04

Little HIERARCHY ~~PROBLEM~~ Puzzle

$$v^2_{weak} \approx \sum (\text{loop factor})\, m^2_{KK/superpartners} \quad \text{(x logs)}$$



$m_{gluino} \gtrsim 2\,TeV$



$m_{KK\,gluon} \gtrsim 4\,TeV$

+ Precision Higgs, EW tests

Little HIERARCHY ~~PROBLEM~~ Puzzle

$$v^2_{weak} \overset{\text{radiative EWSB}}{\sim} \sum (\text{loop factor})\, m^2_{KK/\text{superpartners}} \quad (\times \text{logs})$$

IF central new states constrained to multi-TeV

$\Rightarrow$ Chance Fine-cancelation $\sim 10^{-4}$-10^{-3}

OR

SOME NON-MINIMAL STRUCTURE ?

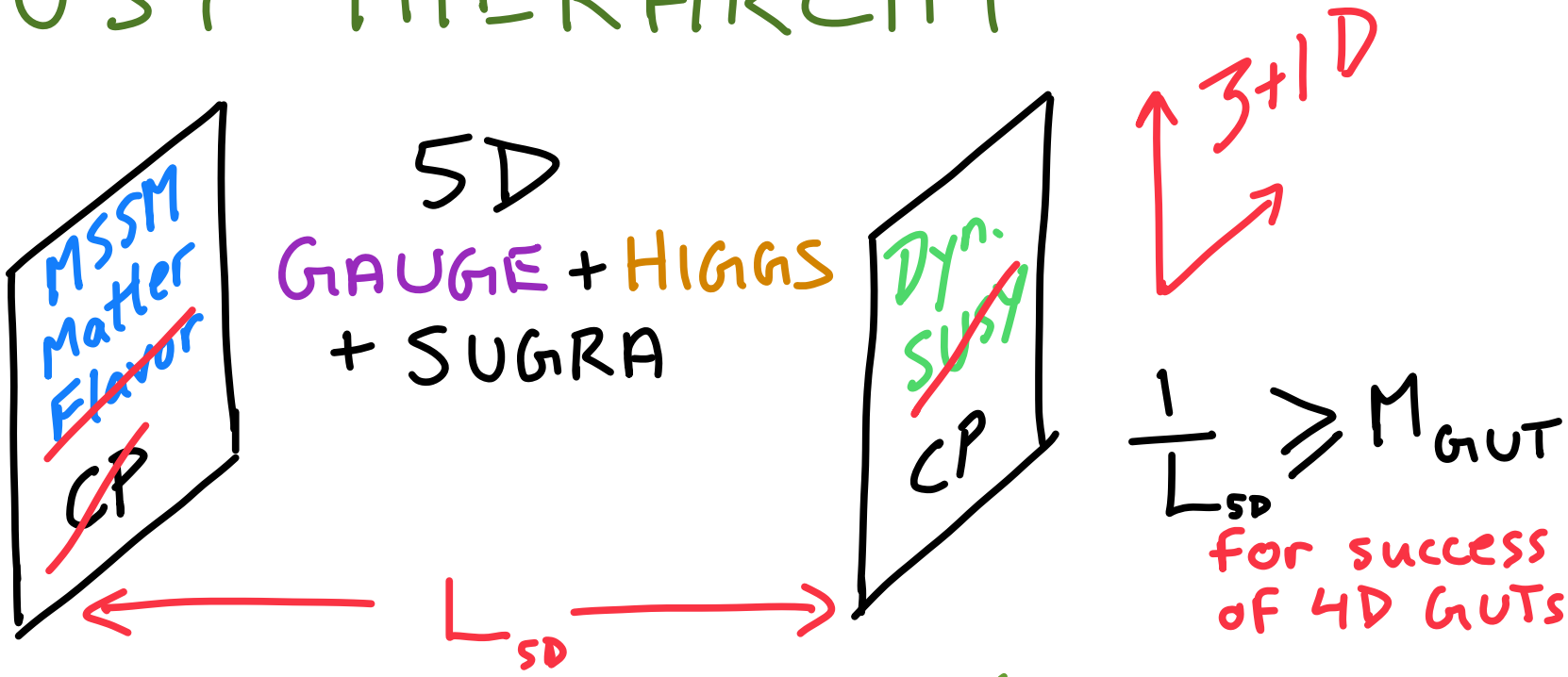
COMPREHENSIVE &

PANORAMIC

PARTICLE PHYSICS

MODELS EXIST!?

SUSY HIERARCHY



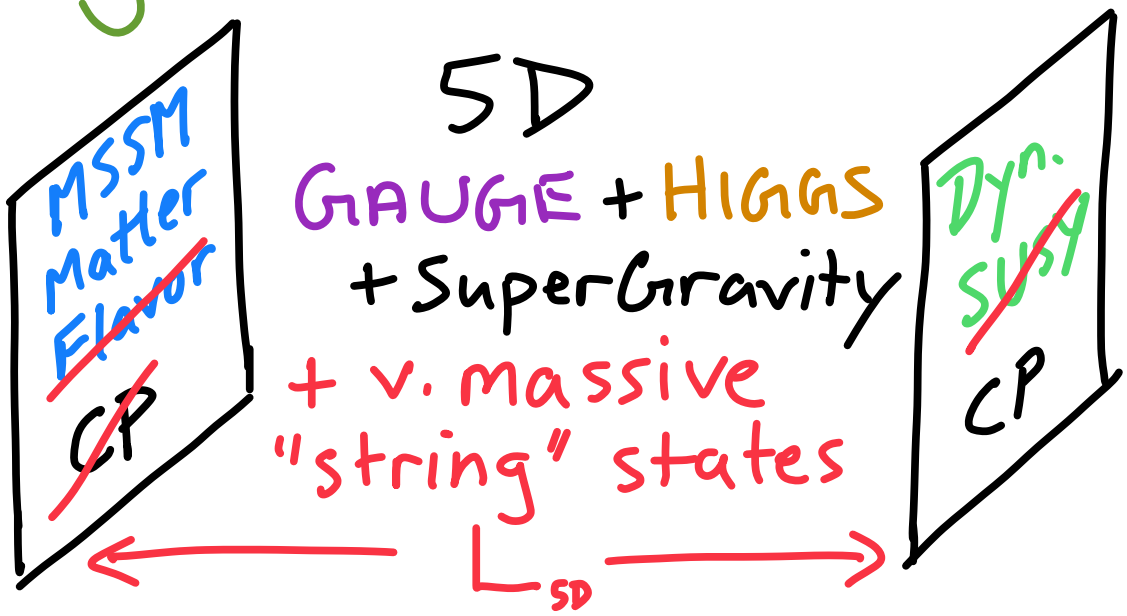
⇒ Sequestering

"gaugino-mediated" SUSY Breaking ($\tilde{g}$mSB) Chacko, Luty, Nelson, Ponton '00; Kaplan, Kribs, Schmaltz '00

⇒ Yukawa matrices only ~~flavor~~, ~~CP~~ ⇒ GIM intact!

Giudice-Masiero mechanism works for thorny μ-problem

Hunting Residual ~~Flavor~~, ~~CP~~

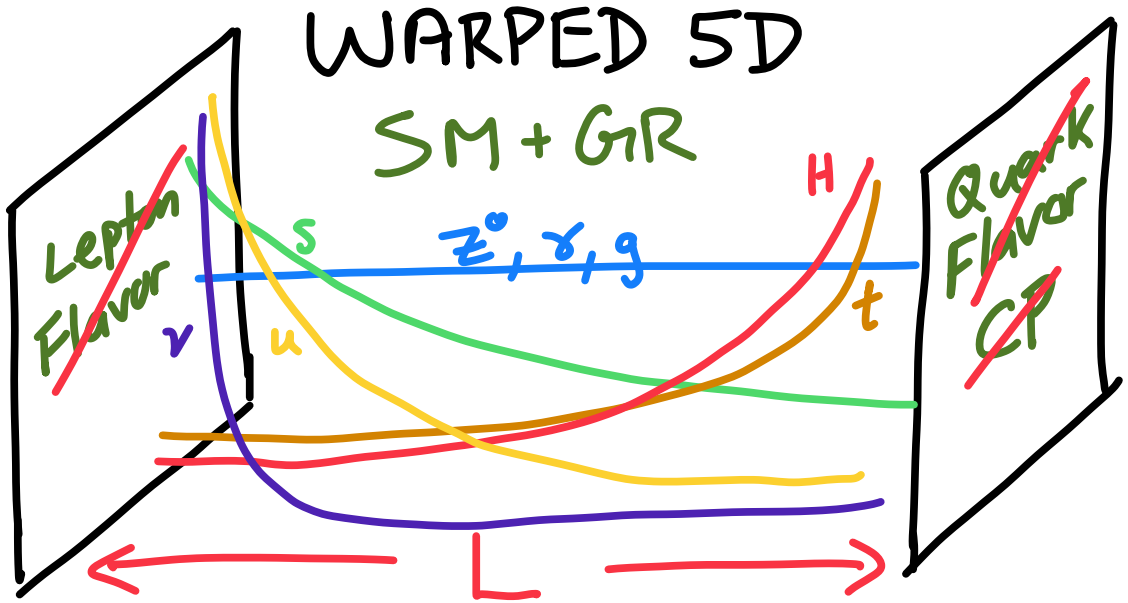


~~Flavor~~, ~~CP~~ $\propto e^{-m_{string} L_{5D}} \ll 1$ leaks into $m^2_{superpartners}$

$\Rightarrow$ small, but potentially observable FCNCs, EDMs, ...

ORIGIN OF THE FLAVOR HIERARCHIES

Eg.

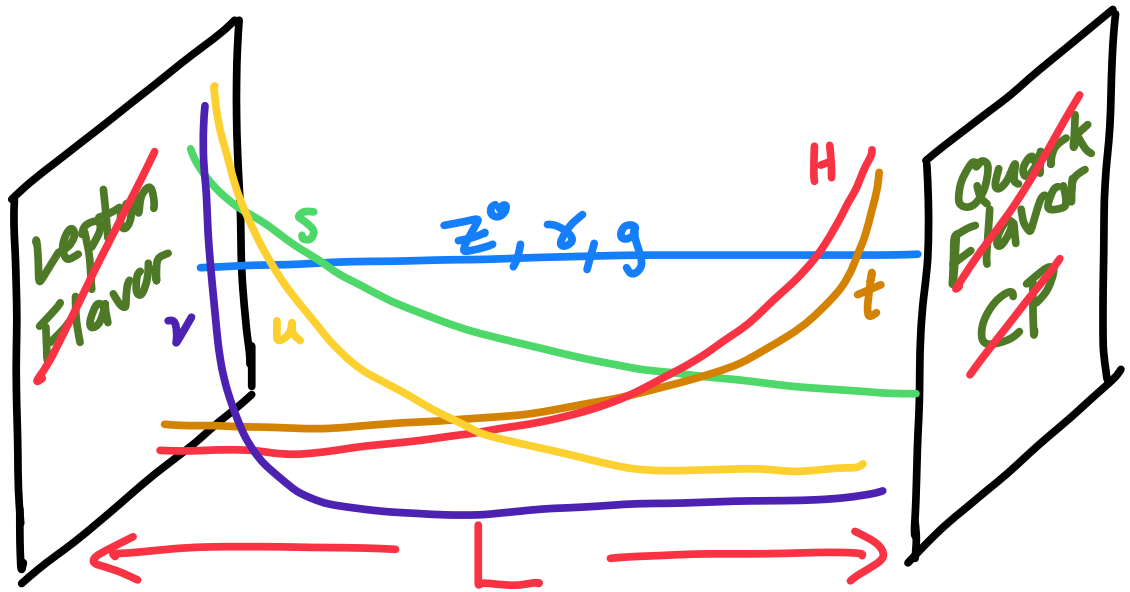


3+1D ?

Gherghetta, Pomarol '00
Huber, Shafi '00
⋮

$$Y_{ij} \sim \underbrace{O(1)_{ij}\, e^{-m_{5D,i}L}\, e^{-m_{5D,j}L}}_{\widetilde{AdS/CFT}\ \text{Partial Compositeness}\ \text{D.B. Kaplan '91}} + O(1)_{ij}\, e^{-m_{5D}R}$$

HOW CLOSE CAN FLAVOR/CP ORIGINS BE?



SURPRISINGLY CLOSE!

?

Warped GIM mechanism powerful but IMPERFECT

Agashi, Perez, Soni '04

Csaki, Falkowski, Weiler '08; Keren-Zur et.al. '12

Generically (without flavor tuning): $m_{KK} > 20\text{-}30\ \text{TeV}$

Control Knobs of the Universe ?

Scalar fields whose VEVs determine (renormalizable) couplings of EFTs.

QED: $\mathcal{L} = -\frac{1}{4} F^2 + \bar{\psi}(i\not{D} - m_e)\psi$

SM: $y_e \bar{\psi}_L \langle H \rangle \psi_R + \text{h.c.}$

QCD: $\mathcal{L} = -\frac{1}{4} G^2 + \bar{\psi}(i\not{D} - m_q)\psi + \bar{\theta}\, G\tilde{G}$ × loop-factor

$\bar{\theta} \lll 1$ EDM bounds

Strong CP Axion: $\left(\bar{\theta}_{\text{bare}} + \frac{\langle a \rangle}{f_a}\right) G\tilde{G}$

EXTRA-DIMENSIONAL / STRING RADIONS / MODULI

$$\int d^4x \int dx_5 \; \frac{-1}{4 g_{5D}^2} F^2 \supset \int d^4x \; - \underbrace{\frac{2\pi \langle R_5(x) \rangle}{4 g_{5D}^2}}_{\equiv \frac{-1}{4 g_{4D,\,\mathrm{EFF.}}^2}} F^2$$

- Macro forces (SUSY) Dimopoulos, Giudice '96
- Quintessence ~ Dark Energy
  Review Tsujikawa '13
- Relaxion EWSB Graham, Kaplan, Rajendran '15

SEARCHING FOR CONTROL $\phi(x)$

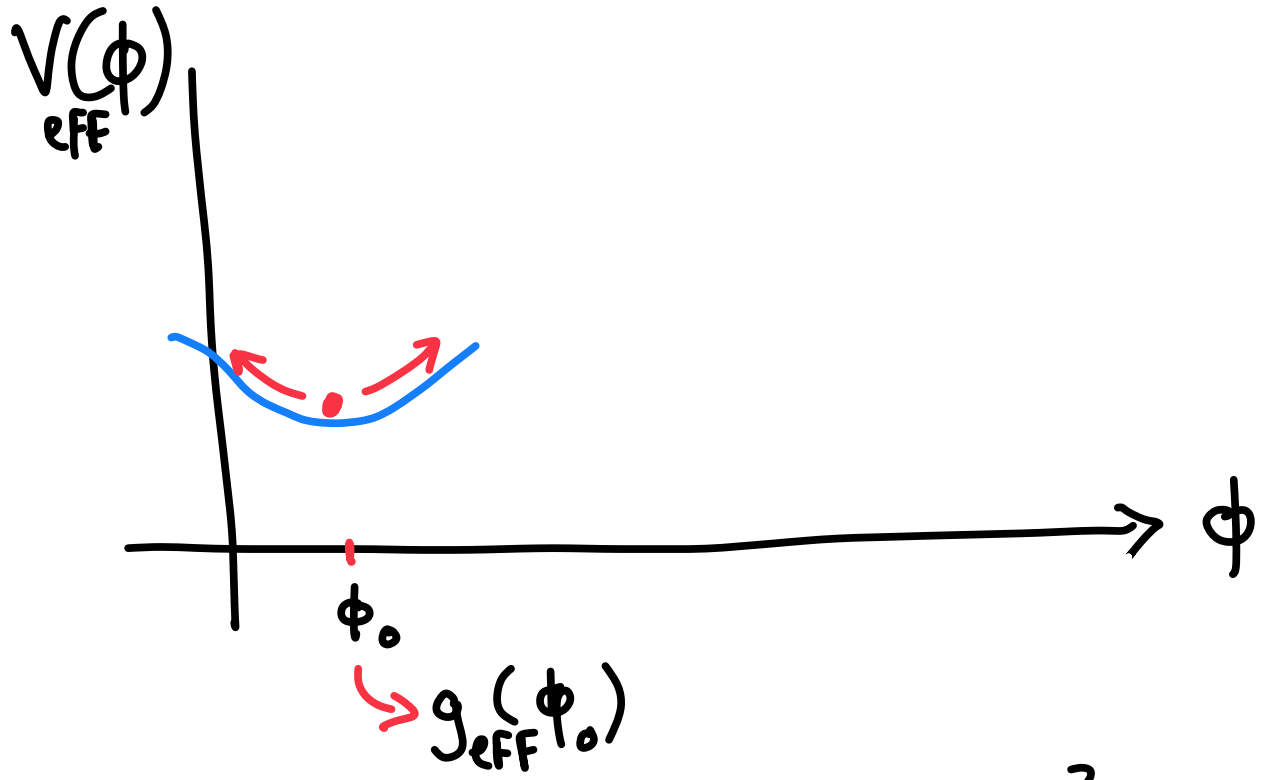
Hard to create/detect ϕ excitations as they are heavy and/or weakly-coupled. (Even 2012 Higgs discovery was hugely challenging!)

$\phi(x)$ may be excited cosmologically, in lab, as 5th force, or variable "constants" of Nature. Eg. Damour '02

Light ϕ: axion dark matter, lab-produced axion fields, light moduli

Heavy ϕ: RS "Higgs-ish" Radion at colliders, cosmo excitation of v. heavy moduli

WHO CONTROLS THE CONTROLLERS ??



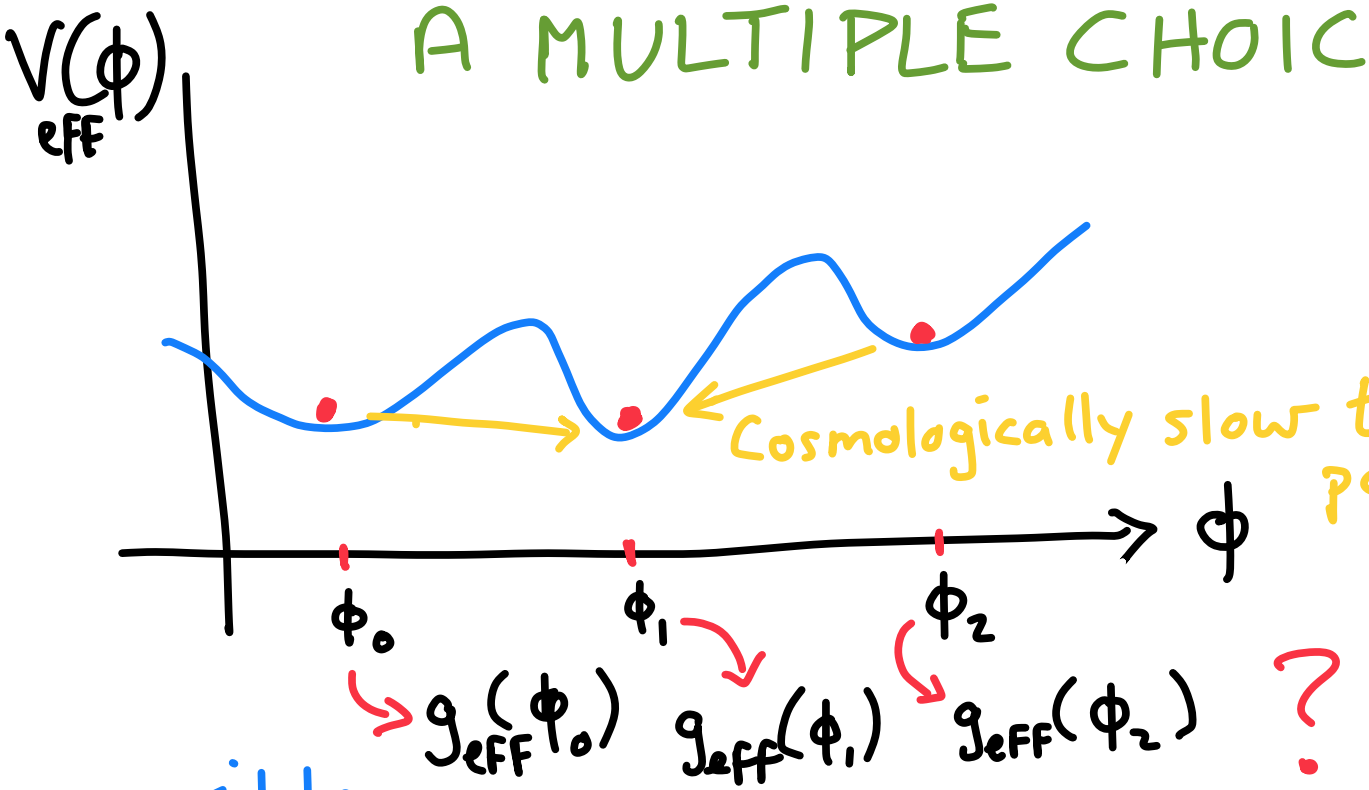
CP Axion : $V_{QCD}(a) \sim -m_{quark}\Lambda_{QCD}^3 \cos\left(\frac{a}{f_a} + \bar{\theta}_{bare}\right)$

$\frac{\langle a \rangle}{f_a} + \bar{\theta}_{bare} = 0$

Radiative ~~EW~~ : $V_{~~susy~~}(H)$

WHO CONTROLS THE CONTROLLERS ?

A MULTIPLE CHOICE QUESTION



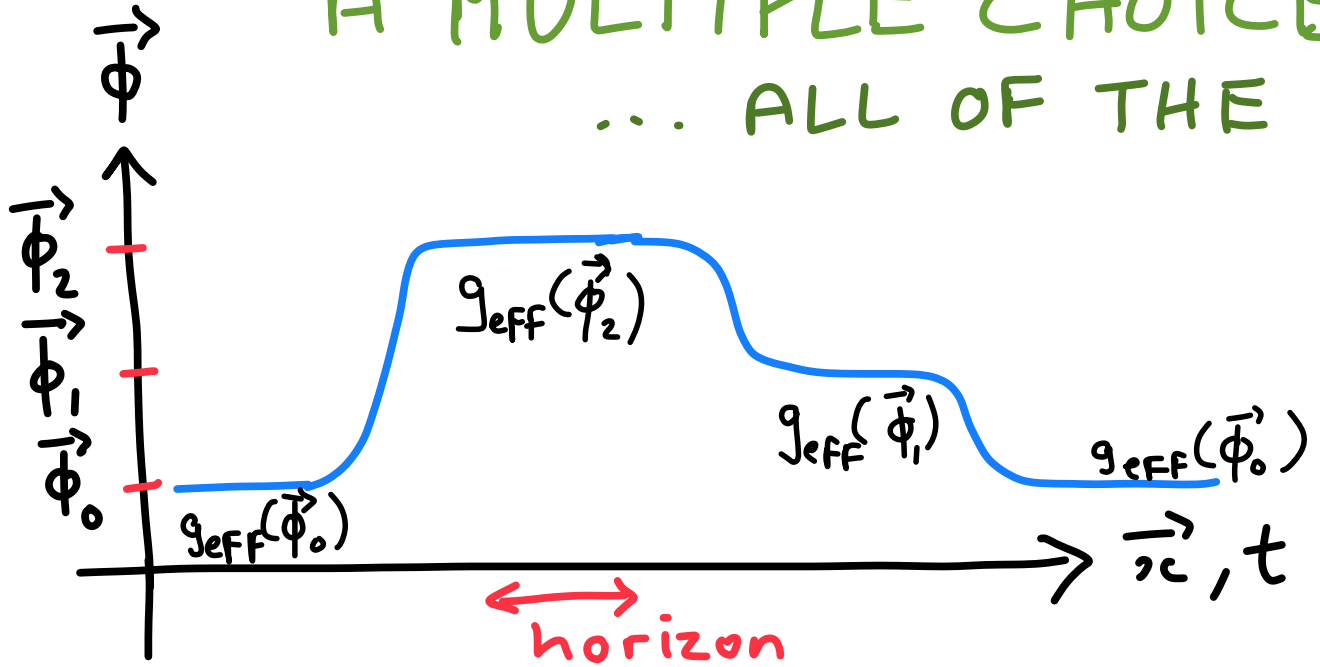
Many possible EFTs based on different possible meta-stable vacua

Eg. Bousso, Polchinski '00 ; Arkani-Hamed, Dimopoulos, Kachru '05

WHO CONTROLS THE CONTROLLERS ?

A MULTIPLE CHOICE QUESTION

... ALL OF THE ABOVE !



Excited states of controller fields + (Eternal) Inflation ??

⇒ EFT DOMAINS on superhorizon scales ⇒ MULTIVERSE?

Review: Bousso '06

ANTHROPIC PRINCIPLE ?

(Observer Bias in Multiverse)

may partly explain key hierarchies:

Weinberg '87
Agrawal, Barr, Donoghue, Seckel '98
Arkani-Hamed, Dimopoulos, Kachru '05

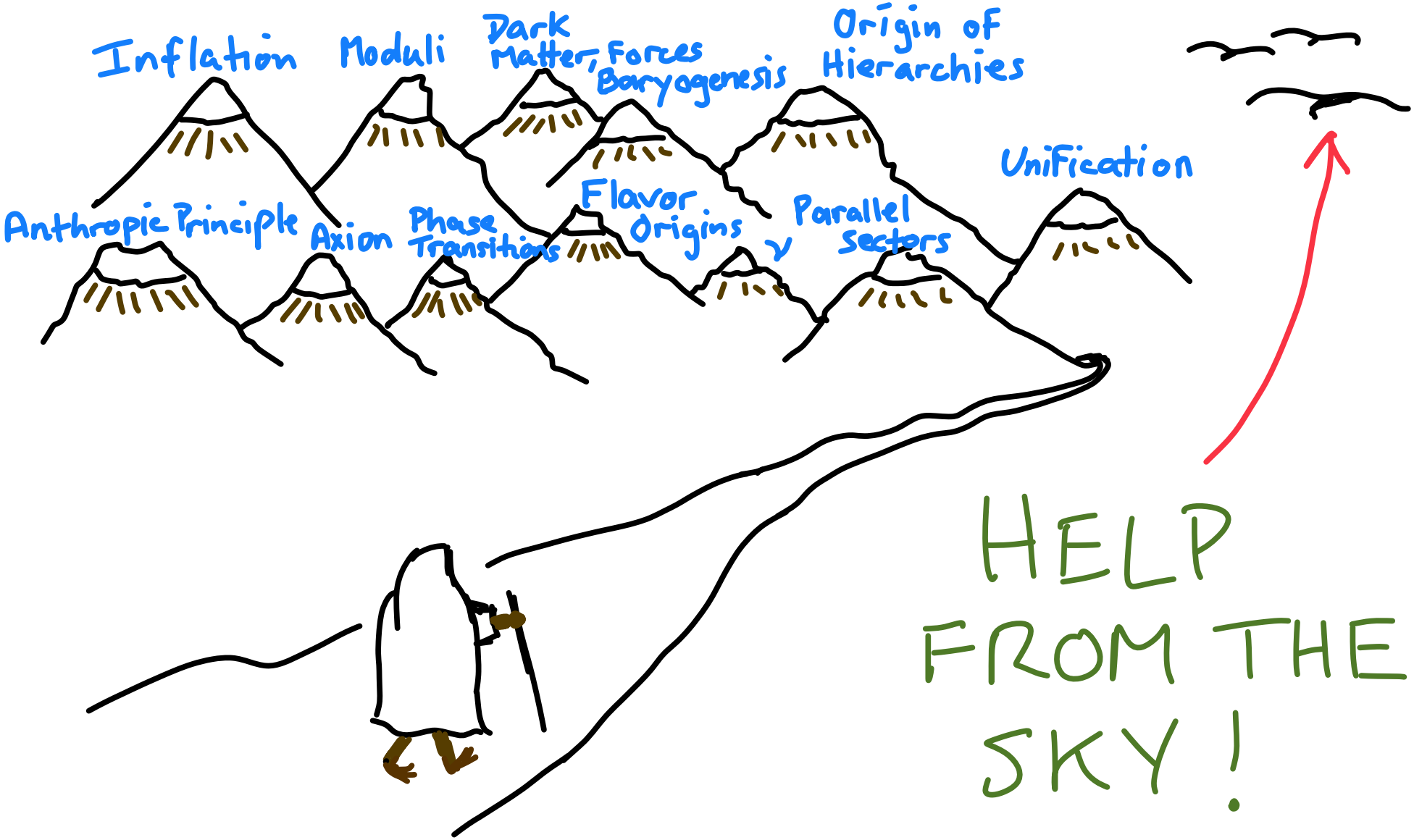
$$\text{Cosmological Constant}^{1/4} \ll v_{\text{weak}} \ll M_{Pl}$$

Big, old universe

our bodies don't collapse to black holes (w. O(1) couplings)

But notoriously difficult to model & assess.

UNDERCUTS HIERARCHY MECHANISMS??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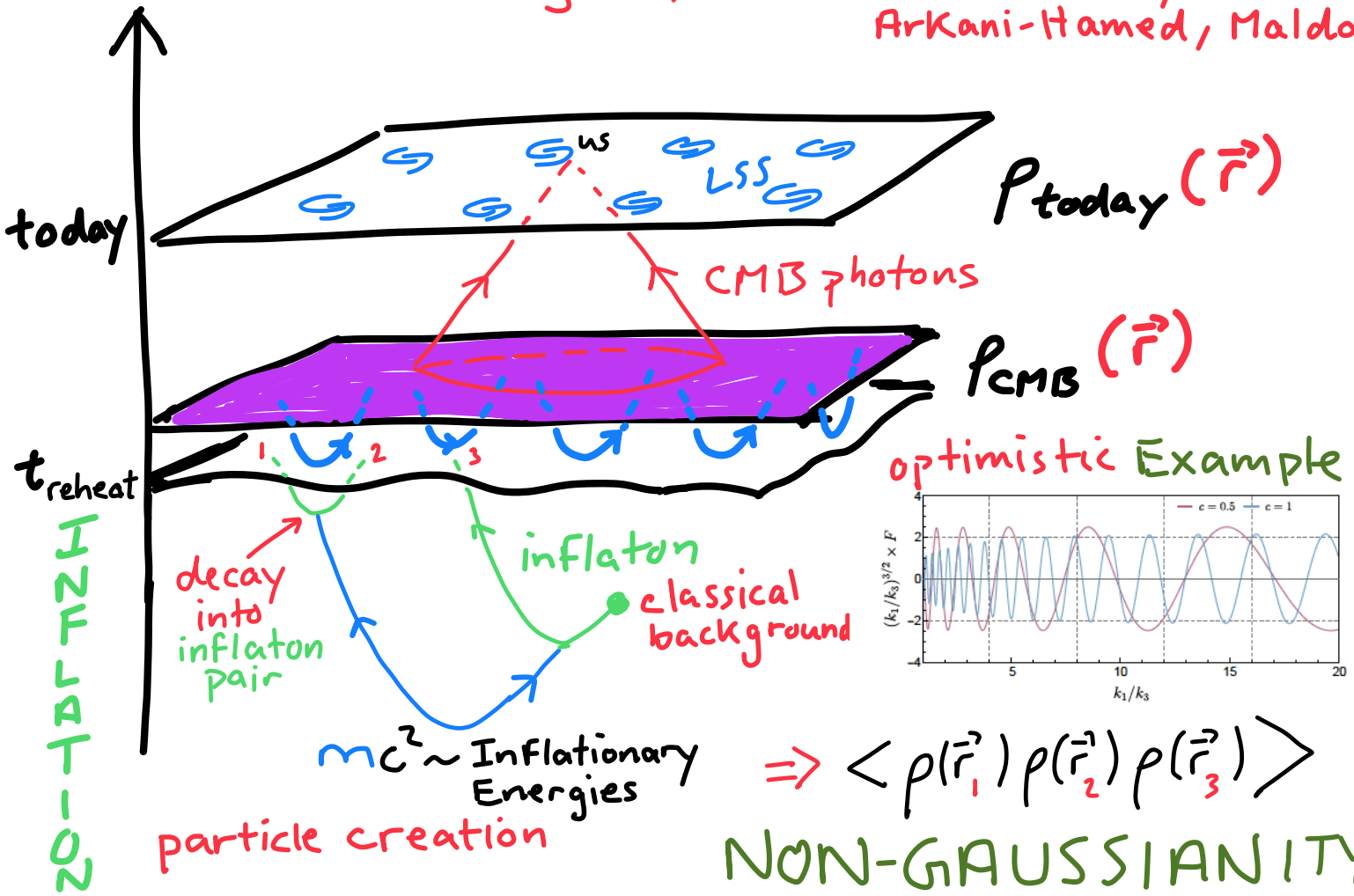
HELP FROM THE SKY!

COSMOLOGICAL COLLIDER PHYSICS ?

Chen, Wang '09; Baumann, Green '11; Noumi et. al. '12; Arkani-Hamed, Maldacena '15, ...



optimistic Example

$m \sim 10^{15}$ GeV

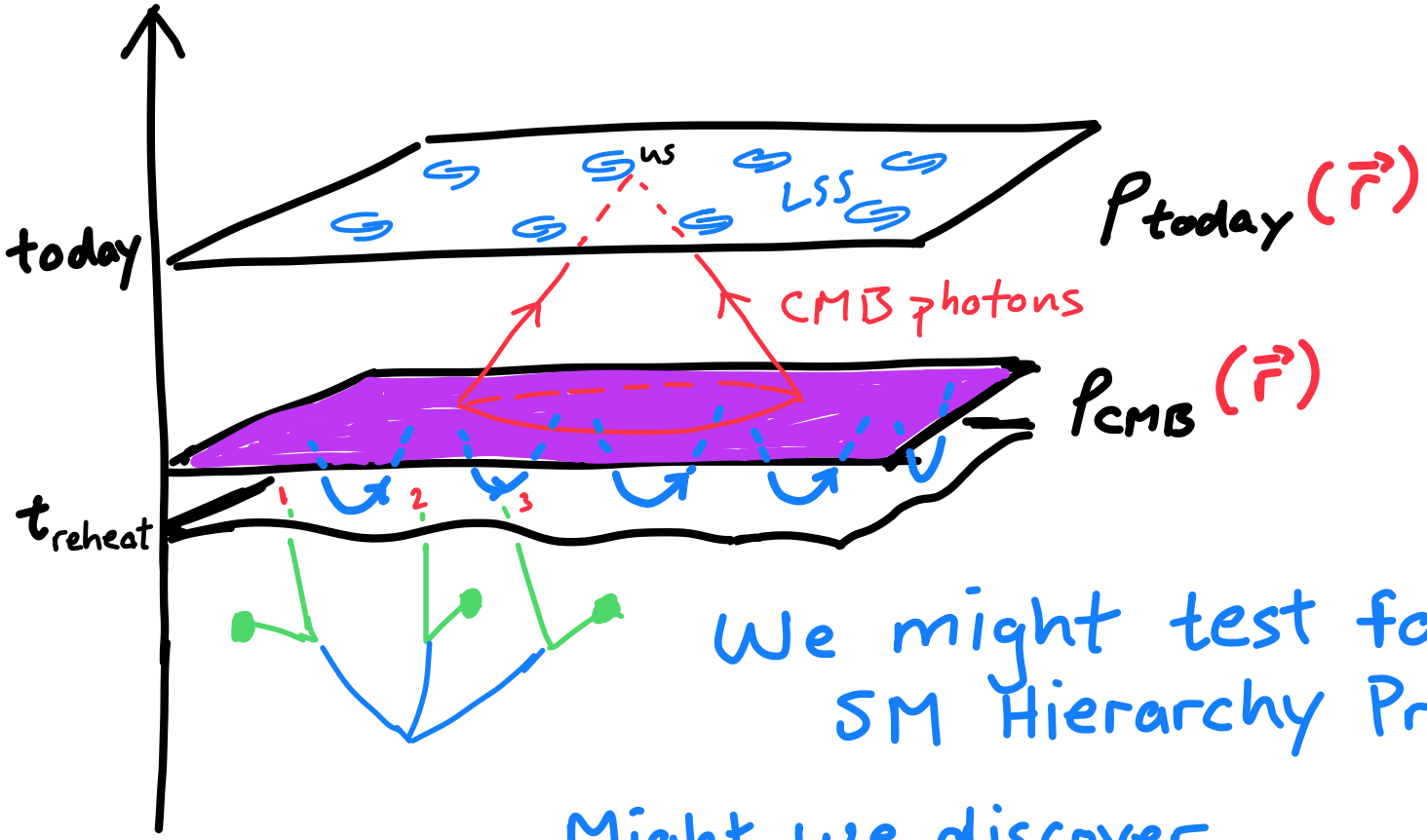
$m \sim 10^{14}$ GeV

Bodas, Kumar, Sundrum '20

$\Rightarrow \langle \rho(\vec{r}_1)\rho(\vec{r}_2)\rho(\vec{r}_3) \rangle$

NON-GAUSSIANITY

COSMOLOGICAL COLLIDER PHYSICS



We might test fate of SM Hierarchy Problem ?

Kumar, Sundrum '17

Might we discover v. massive controllers $\phi(x), V(\phi)$? ?

ANTHROPIC PRINCIPLE

(Observer Bias in Multiverse)

may partly explain key hierarchies, BUT

LIKELY SYMBIOTIC WITH MECHANISMS

if these exist within EFT

Eg. $m_{proton} \sim M_{Pl} e^{-\frac{O(4\pi)}{\alpha_s(M_{Pl})}} \ll M_{Pl}$

We are not black holes

Even if Anthropic constraints $\Rightarrow$ the ENDS

Mechanisms can $\Rightarrow$ efficient MEANS to those ENDS

∴ ON THE GROUND...

1st PASS: ~~Anthropic Principle~~

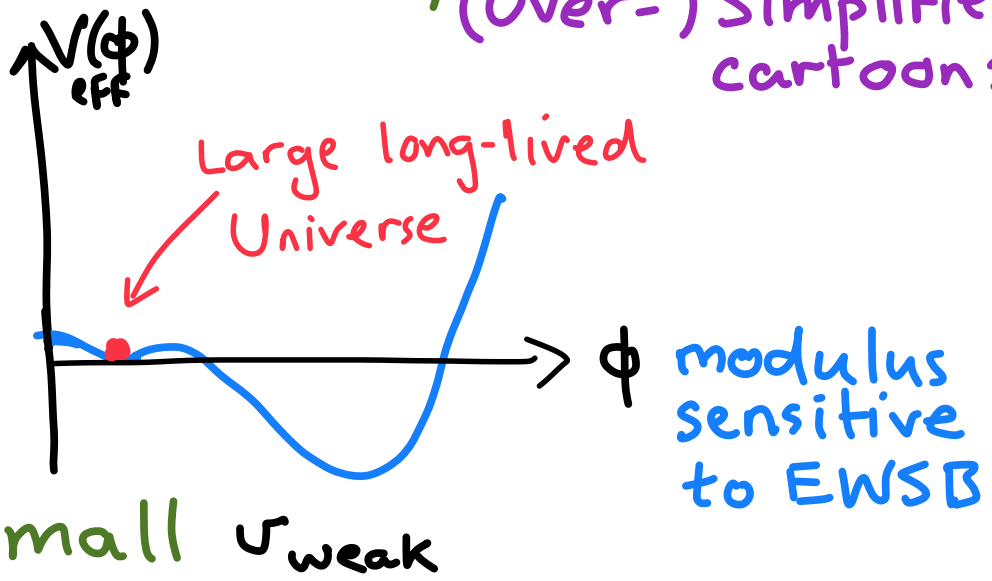
Fully explore, develop & experimentally hunt
HIERARCHY MECHANISMS

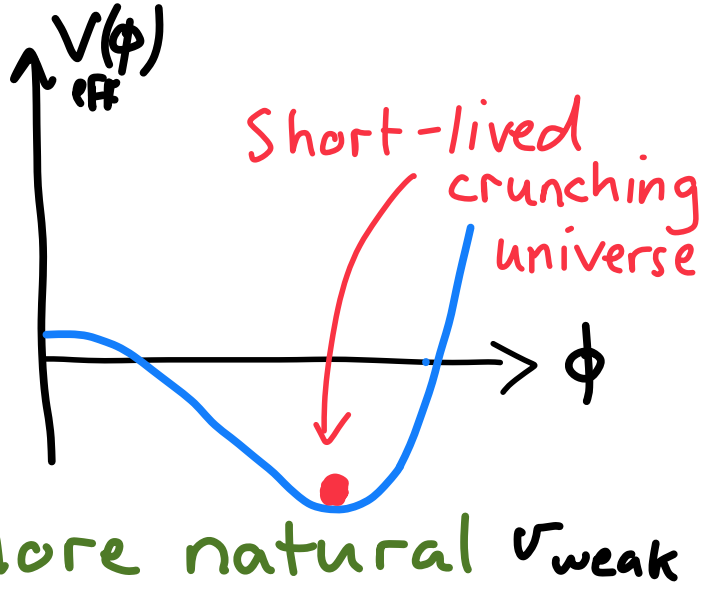
∴ ON THE GROUND...

2nd PASS: ANTHROPIC PRINCIPLE can play a more "active" role in coordination with BSM mechanisms

Eg. "Crunchy & Natural" Csaki, D'Agnolo, Geller, Ismail '20 ?

(Over-)Simplified cartoon:





DARK MATTER

remains outstanding mystery. ??

No stone is being left unturned in developing DM theories and associated new experiments in diverse regimes

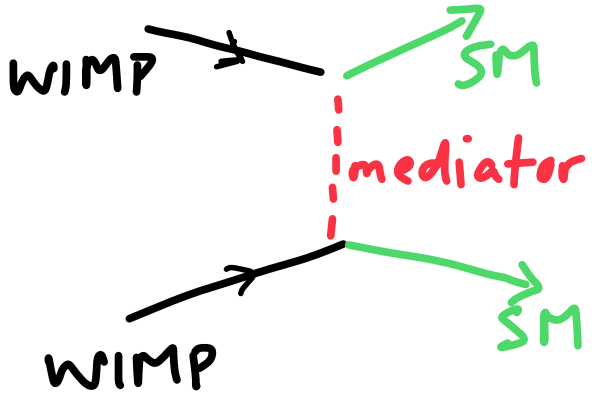
Eg. Axion DM theory & experiments TASI Hook '18

Such well-crafted creative efforts are exciting, scientifically warranted & welcome counterpoint to mega-experiments

But thermal relic WIMP DM stands out if new physics underlies EW hierarchy

TASI: Lisanti '16

Early Universe FREEZEOUT of stable WIMP annihilations when



$\sim$ Hubble Expansion

"WIMP MIRACLE"

strongly pursued in direct detection expts. but still has simple viable variants.

Eg. "Higgsino" DM

$$\Rightarrow \rho_{WIMP}^{today} \sim \rho_{DM}^{observed} \left(\frac{g_{EW}}{g_{WIMP}} \right)^4 \frac{m_{mediator}^4}{m_{WIMP}^2 \, TeV^2}$$

That other MATTER...

BARYOGENESIS & the UN-HIERARCHY PROBLEM

Review: Bödeker, Buchmüller '21

It is mind-boggling (to me) that

$$\rho_{DM} \sim 5\, \rho_{baryons} \; ?$$

Anthropic explanation?
Eg. Bousso, Hall '13

Different mechanisms for DM & Baryon asymmetry a priori suggests $\rho_{DM} \gg \text{OR} \ll \rho_{baryon}$

Comparable ρ suggests COMMON, UNIFIED ORIGIN

Eg. Asymmetric DM ... Kaplan, Luty, Zurek '09; Review: Zurek '13

But ordinarily this gives up on WIMP miracle!

Can baryon asymmetry enjoy its own "WIMP Miracle"?

BARYOGENESIS FOR WIMPS

Cui, Sundrum '13

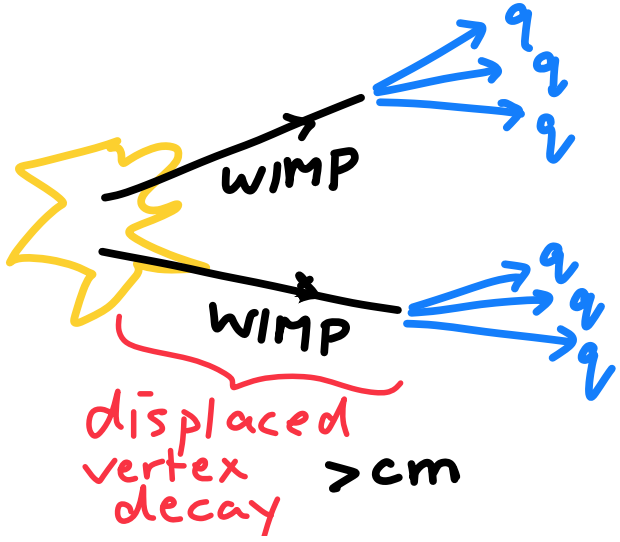
Long-lived WIMP freezes out before its ~~CP~~, ~~B~~ decay.

$$\rho_{\text{baryon}} \sim \cancel{\varepsilon_{CP}} \frac{m_{\text{proton}}}{m_{\text{WIMP}}} \rho_{\text{WIMP}}$$

"if" it had been stable

Like WIMP DM production, Baryogenesis may replay at colliders!

WIMP = Long-Lived Particle (LLP)



Can baryon asymmetry enjoy its own "WIMP Miracle"?

BARYOGENESIS FOR WIMPS

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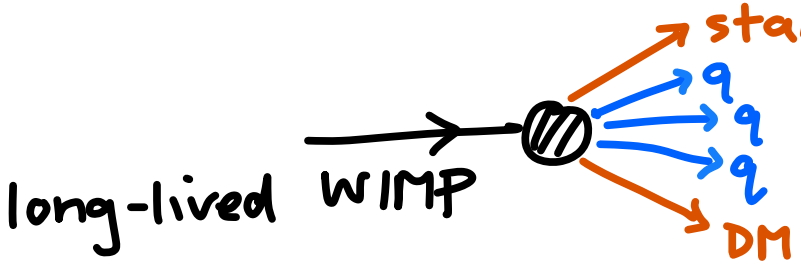
$$\rho_{\text{baryon}} \sim \cancel{\varepsilon_{CP}} \frac{m_{\text{proton}}}{m_{\text{WIMP}}} \rho_{\text{WIMP}}$$

"if" it had been stable

ASYMMETRIC DM FOR WIMPS

Cui, Shamma '20



? But I hope for even more satisfying explanation

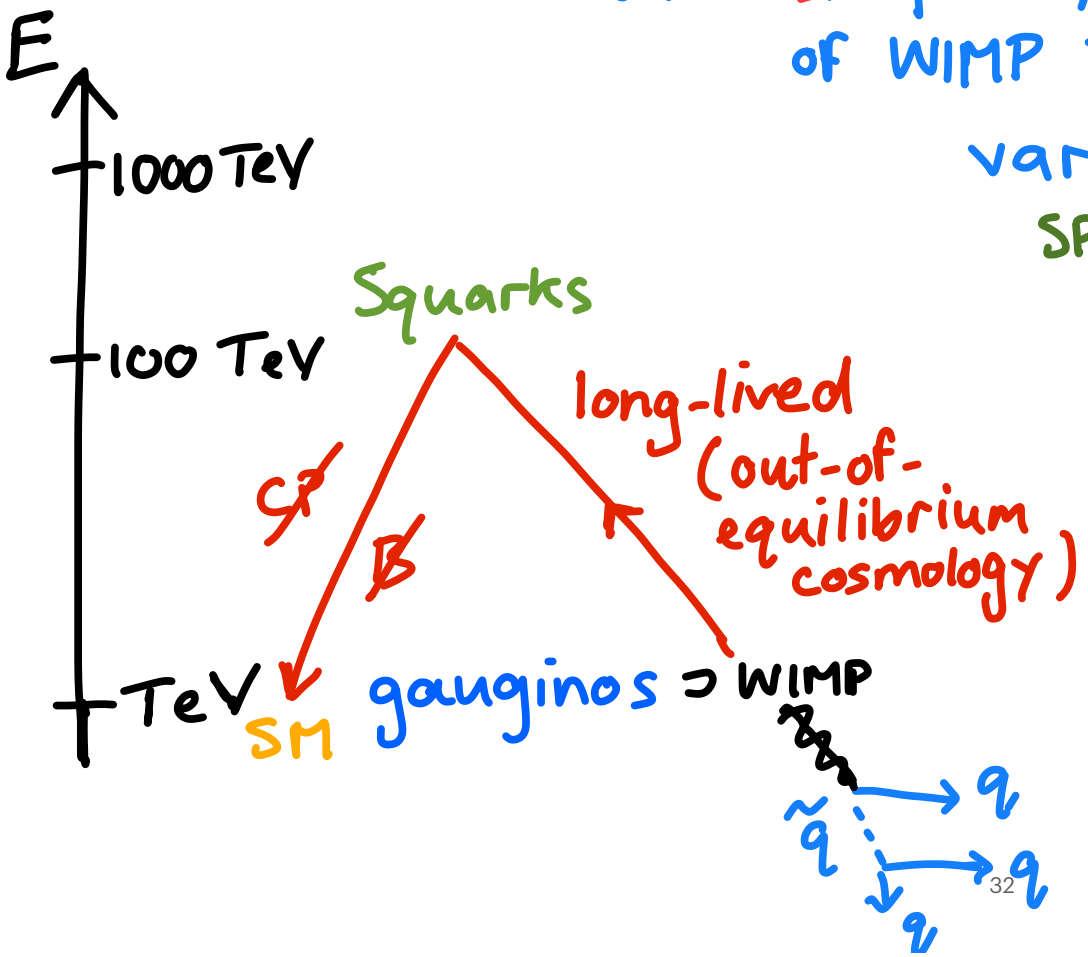
FOOD FOR THOUGHT...

within ~~R-parity~~ MSSM implementation of WIMP Baryogenesis Cui '13

variant of R-parity conserving

SPLIT SUSY Wells '03, '04; Arkani-Hamed, Dimopoulos '04 Giudice, Romanino '04

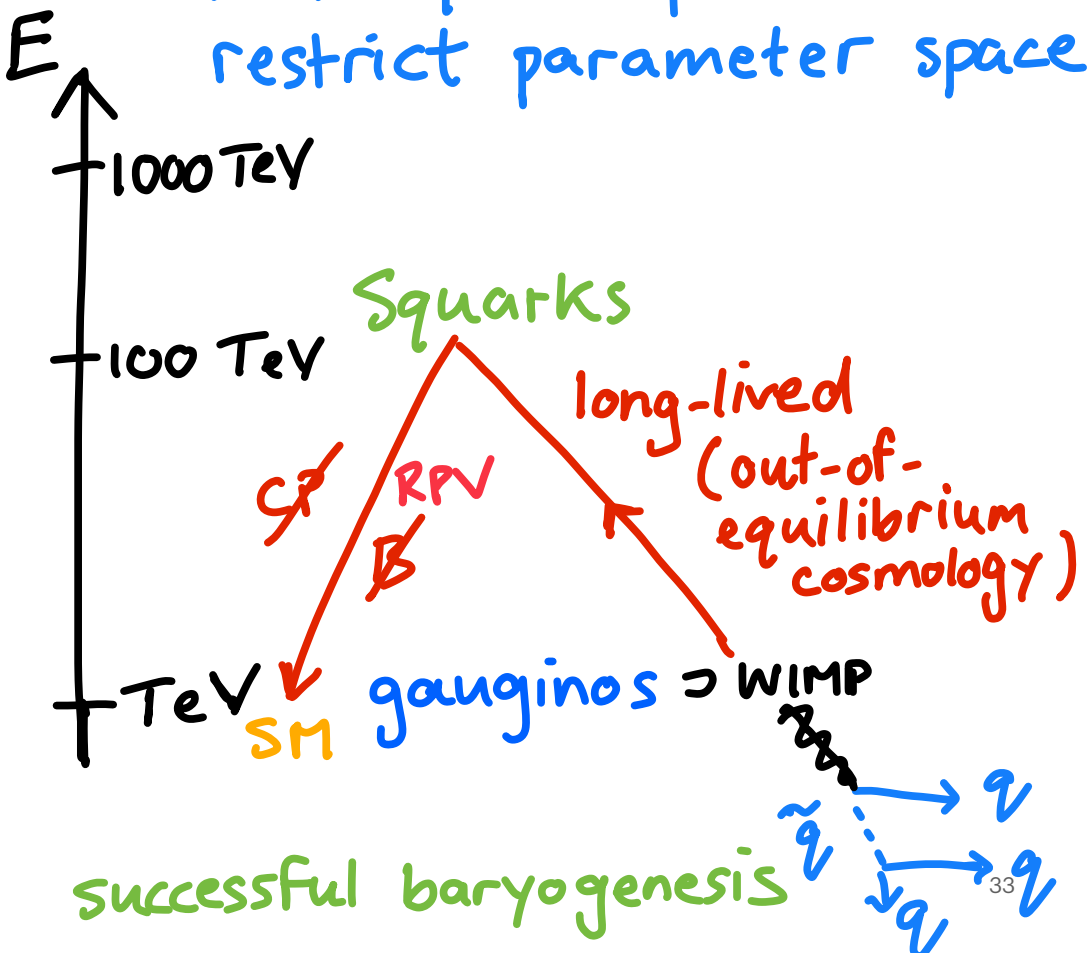
& MINI-SPLIT Arvanitaki, Craig, Dimopoulos, Villadoro '12; Arkani-Hamed et. al. '12



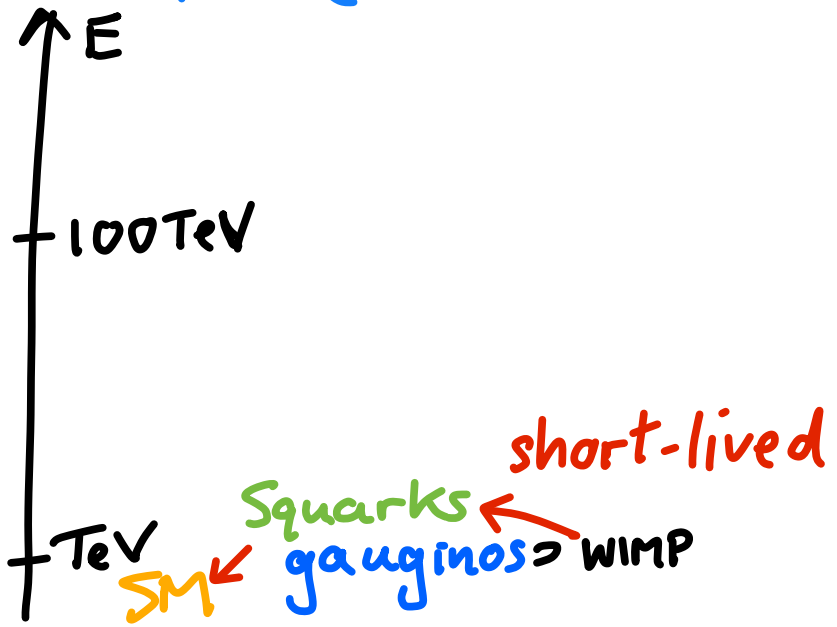
WHY IS THERE THIS UNNATURAL LITTLE HIERARCHY?

... FRUSTRATED NATURALNESS

Anthropic imperatives (baryogenesis here) may restrict parameter space to force "Little Hierarchy"?



successful baryogenesis

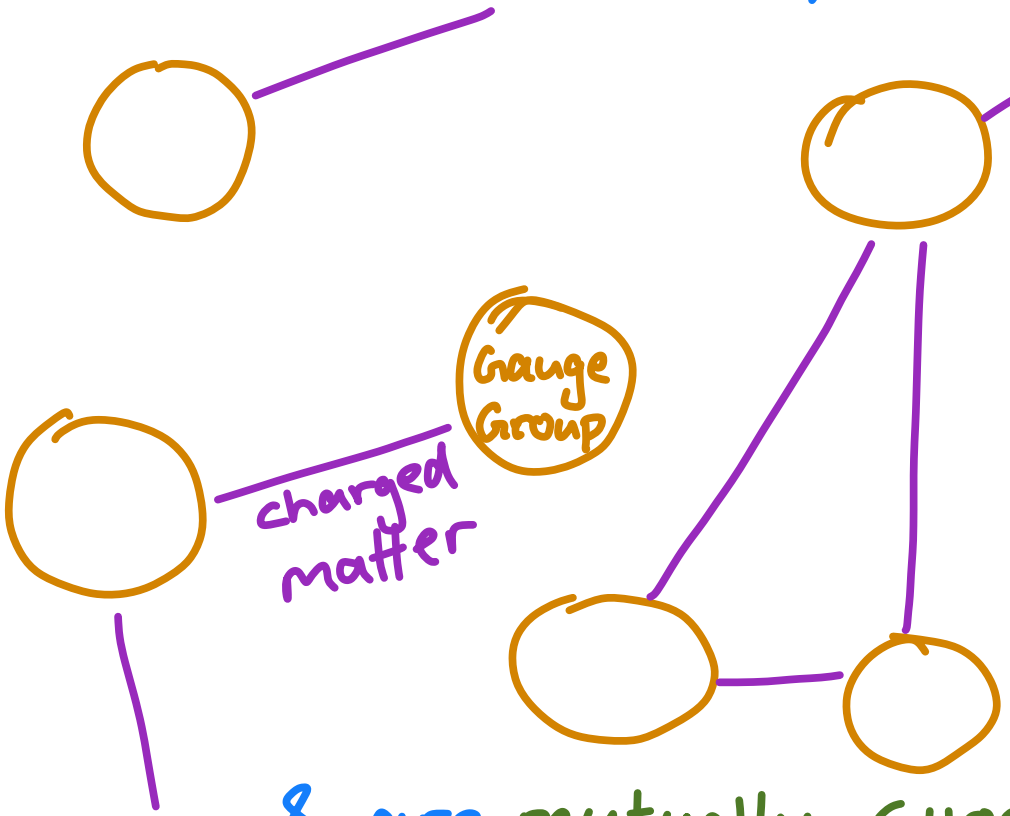


More natural spectrum without baryogenesis

PARALLEL SECTORS

Gauge fields & charged matter readily partition into isolated, self-interacting sectors

one of which is Standard Model

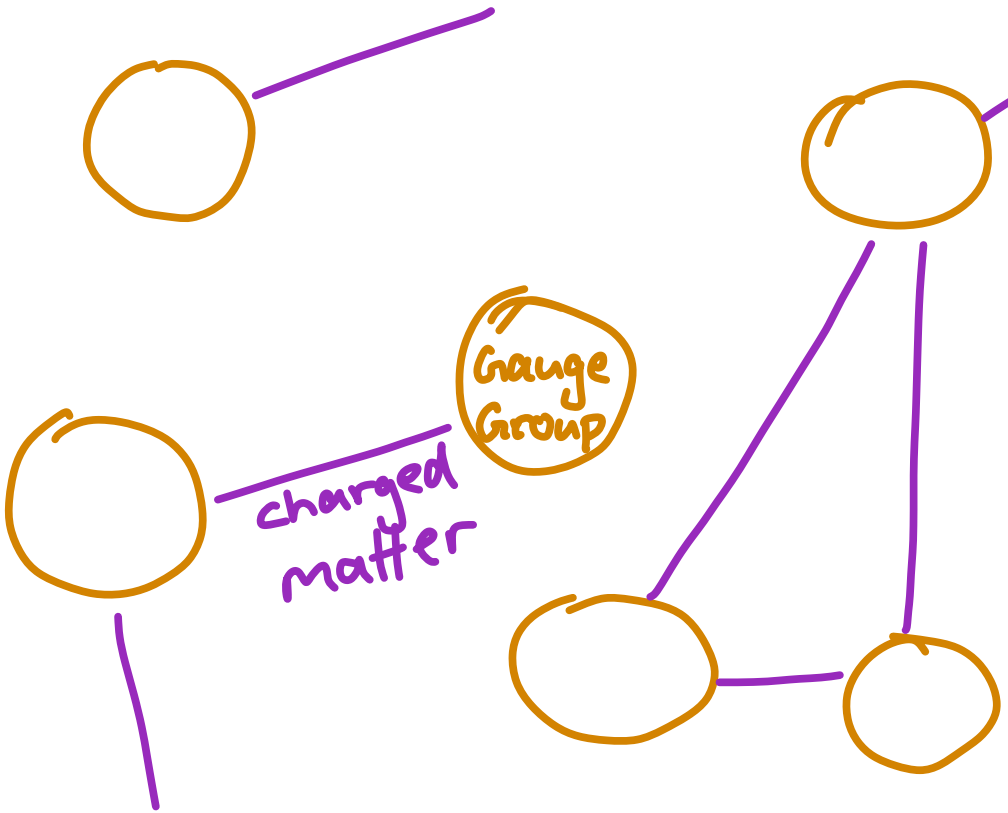


& can further fragment upon Higgs-ing

& are mutually GHOSTLIKE in behavior!

PARALLEL SECTORS

Characteristic mass scales



plausibly $\sim v_{weak}$

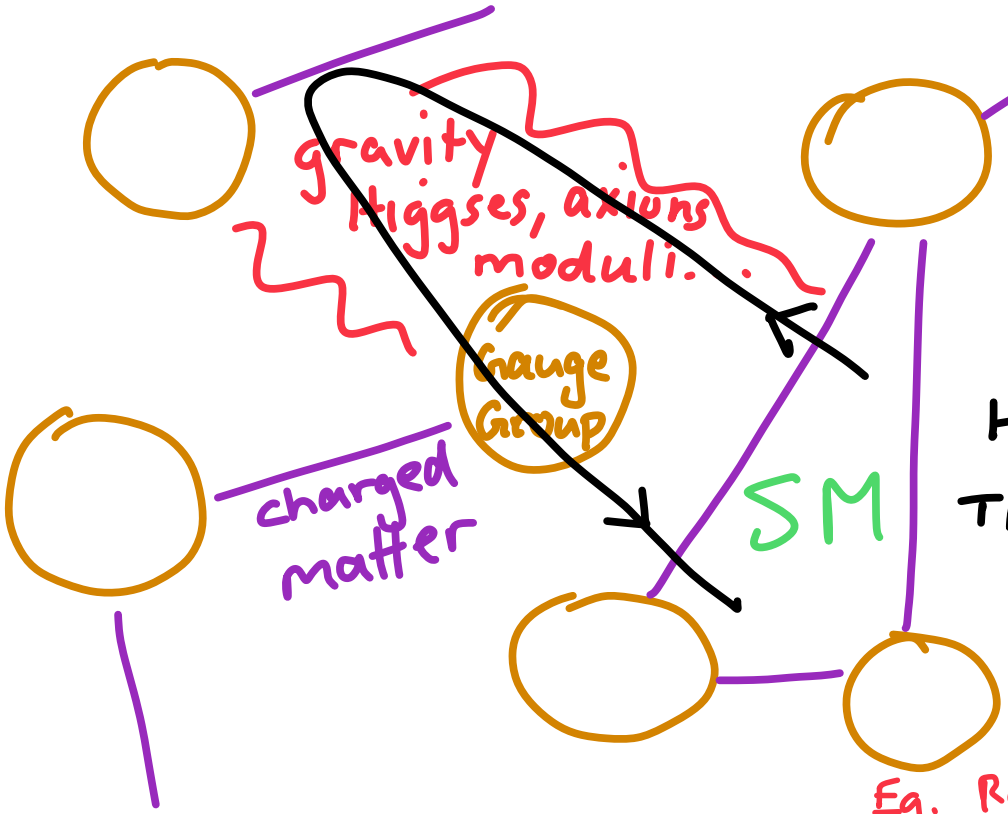
Eg. "Gravity"-mediated SUSY

$v_{//} \lesssim m_{//\,superpartners} \sim m_{gravitino}$

paralleling MSSM radiative EWSB.

PARALLEL SECTORS

Clearly, exciting to discover! ?



May contain some or all DM + dark radiation.

Eg. Mirror Stars

Foot '99; ...; Curtin, Setford '19

H_0 tension ? Eg. Aloni, Berlin, Joseph, Schmaltz, Weiner '21

THERE AND BACK AGAIN:

V. small cross-sections → parallel sectors, v. small decay rate (LLPs!) → SM

Eg. Review for MATHUSLA LLP detector: hep-ph/1806.0739

PARALLEL SECTORS

may strongly mitigate fine-tuning puzzles

if they are (approximate) SM DUPLICATES ?

Twin Higgs Cartoon: $V_{loop}(H) \sim \underbrace{\Lambda^2 f^2 \sin^2 H/f}_{\sim \Lambda^2 H^2 \text{ SM}} + \underbrace{\cos^2 H/f}_{\text{Parallel contribution}}$

Chacko, Goh, Harnik '06

$\Rightarrow$ Importance of Higgs precision tests, rare (LLP) decays

"Triplet Higgs" Hook '18 Parallel sectors coupled via modulus ϕ

$\Rightarrow g_{eff}(\phi), m_{eff}(\phi) \Rightarrow V_{loop,eff}(\phi)$

Discrete Symmetry $\Rightarrow$ Little Hierarchy for $v_{SM}(\langle\phi\rangle)$

$\Rightarrow$ Range of modulus phenomenology

PARALLEL SECTORS

may be numerous,
mitigating little hierarchy problem
by repeated "throws of the dice" ?

NNaturalness [sic]

Arkani-Hamed, Cohen, D'Agnolo, Hook, H.D. Kim, Pinner '16

⇒ improved cosmological/astro searches
for new (relativistic) species

The last GHOSTS to depart our "world"

Neutrinos

- Flavor structure, origins ?
- Unique astrophysical, cosmological probes ?
- Portal to other sectors ?

The First GHOST to depart our "world"

Gravitational Waves

- Unique astrophysical, cosmological probe
  - before universe transparent to light
  - Review: Caprini, Figueroa '20
- Stochastic GW Background spectrum sensitive to "control knob" of "phase transitions" $T_{crit.} \sim TeV$ => OBSERVABLE!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ν
Parallel Sectors
LAST, BUT NOT LEAST
Dumb Luck
Compute, calculate, fit, understand better
LHC backgrounds, LLP fakes
$(g-2)_\mu$, flavor processes
Astro/Cosmo/GW Cosmo
(Eternal) Inflation...
?

Conclusion: Theory can develop fundamental mechanisms + capitalize on & help further inspire the

RICH EXPERIMENTAL ECOSYSTEM

Small-scale experiments

Large Scale Structure

Flavor experiments

Dark matter detection

21-cm cosmo

HL LHC

LLP detectors

Polarized CMB

future mega-collider

Dark force detection

Higgs factory

Dark energy probes

Neutrino factories/observatories

Grav. wave detection

Astro probes