NATURALNESS

&

COMPOSITENESS

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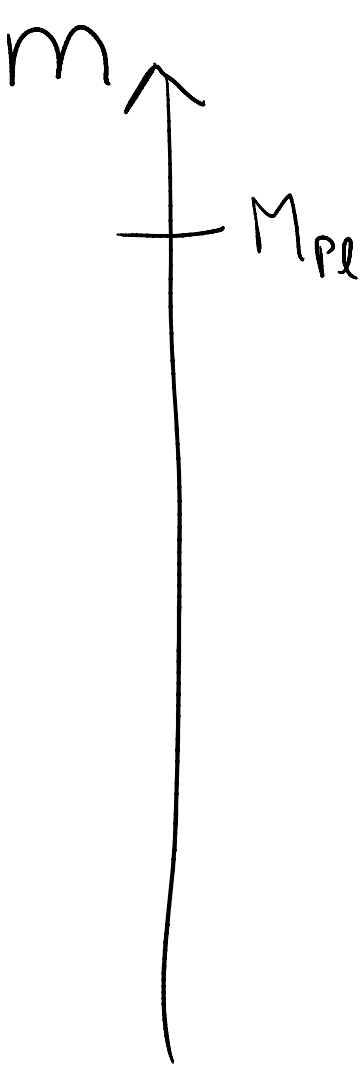
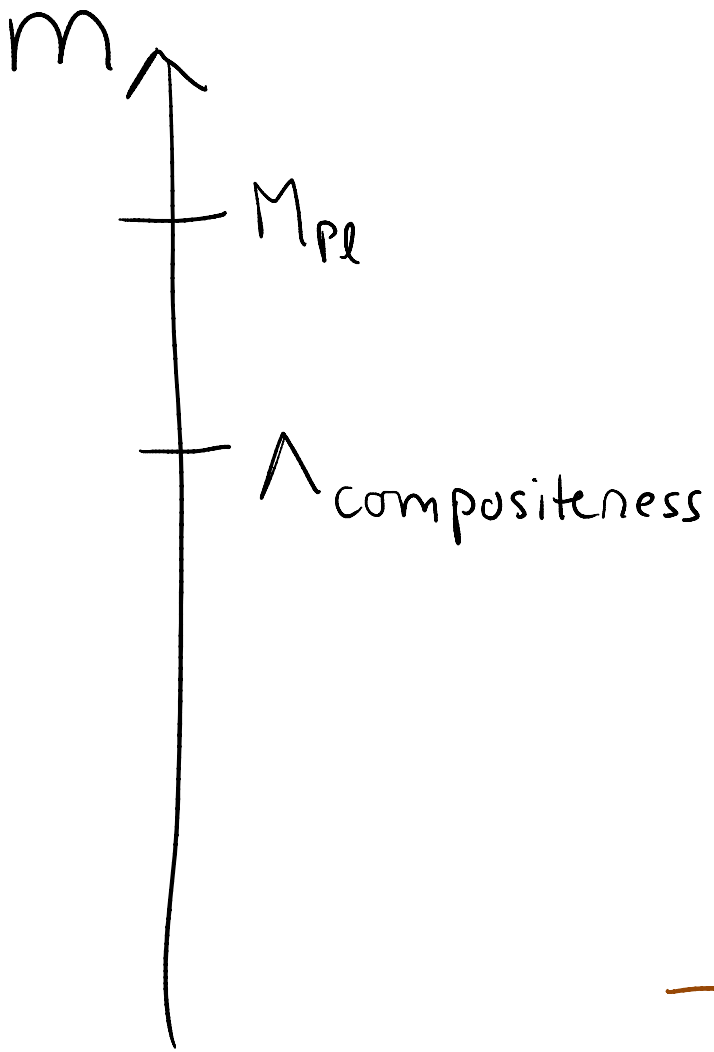
FUNDAMENTAL PHYSICS



Black Holes

Particle Physics

FUNDAMENTAL PHYSICS

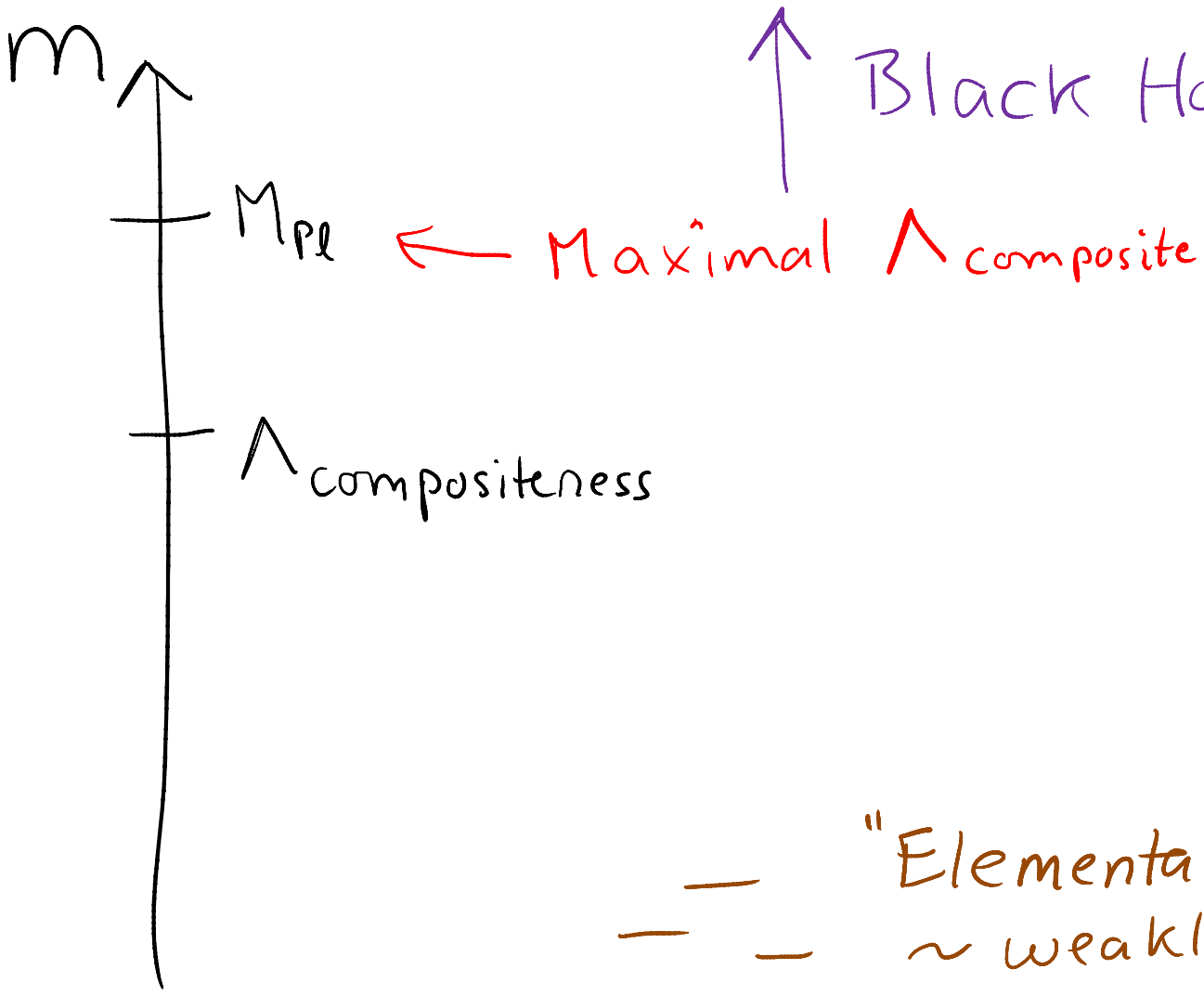


↑ Black Holes

⋮ finite size, form-factors, proliferation of composite excitations

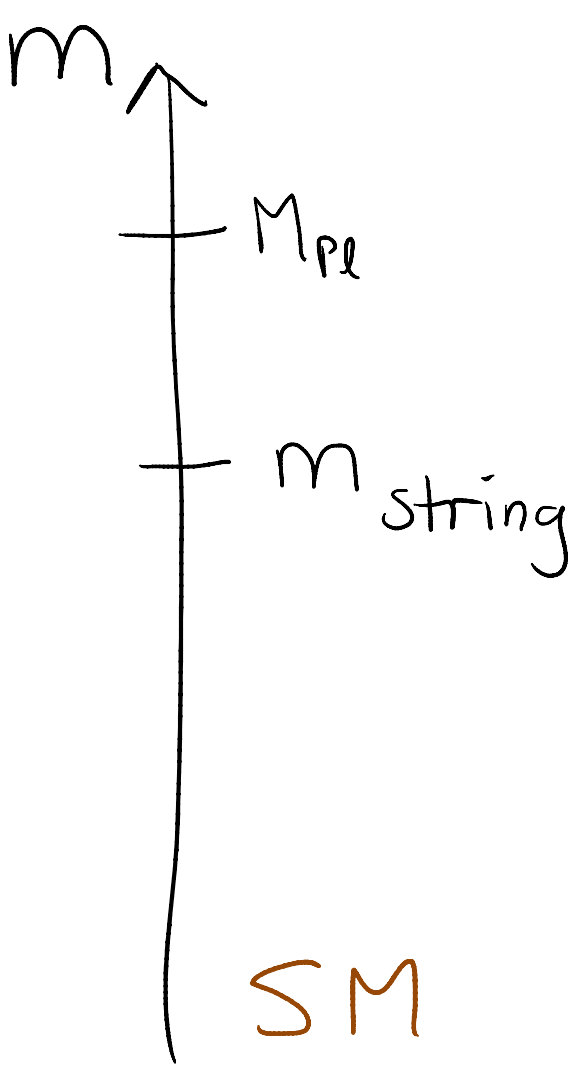
"Elementary Particles" ~ weakly-coupled renormalizable properties, $m \ll \Lambda_{comp.}$

FUNDAMENTAL PHYSICS



"Elementary Particles"
~ weakly-coupled renormalizable properties, $m \ll \Lambda_{comp.}$

FUNDAMENTAL PHYSICS



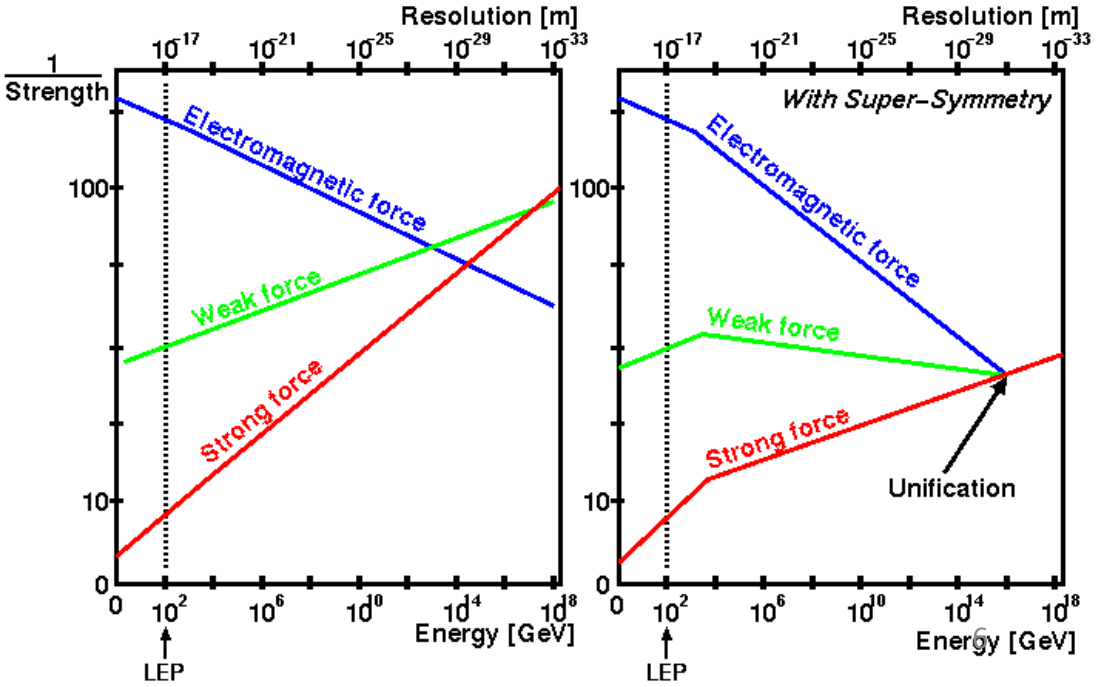
Black Holes

finite size, form-factors, proliferation of ~~composite~~ string excitations

Elementary Particles ~ weakly-coupled renormalizable properties, $m \ll \Lambda_{comp.}$

HIERARCHIES $\gg v_{weak}$ LIKELY EXIST

- G_{Newton} suggests $\lesssim M_{Pl}$ physical scale
- Flavor/~~CP~~/proton-decay tests virtually probe SM to extremely high energies.
- SM gauge coupling strongly hint at GRAND UNIFICATION



ELEMENTARY PARTICLES & NATURALNESS

strongly constrained by (effective) QFT

		DATA
$J=0$	✓	1 (h)
$J=1/2$	✓	>22.5 Dirac
$J=1$	Must be gauge boson	12
$J=3/2$	Must be gravitino	unseen but hard to see by exclusion principle
$J=2$	Must be graviton	1
$J>2$	X	

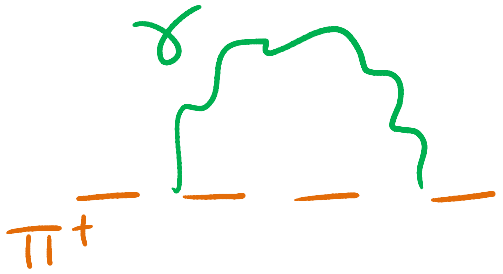
NATURE SEEMS TO ECONOMIZE ON ELEMENTARY SPIN-0

COMPOSITE PION IS NATURAL

$E \ll m_\rho$: $\pi^\pm \approx$ "elementary",
described by scalar QED
$\subset$ chiral lagrangian

THEORY:

$$m^2_{\pi^+} - m^2_{\pi^0} =$$



$$\text{IR} < m_\rho \sim O(1)\frac{\alpha_{em}}{4\pi} m_\rho^2 \qquad \text{UV} > m_\rho \sim O(1)\frac{\alpha_{em}}{4\pi} m_\rho^2$$

$< \infty$ in QCD + QED (QCD Sum Rules)

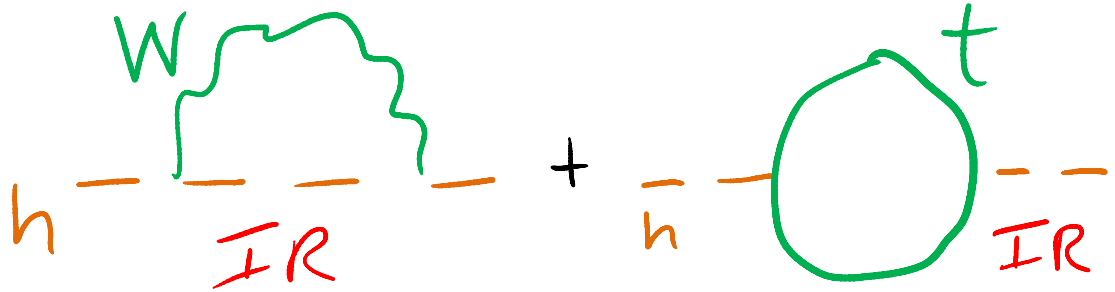
EXPERIMENT: $m^2_{\pi^+} - m^2_{\pi^0} \sim \frac{\alpha_{em}}{4\pi} m_\rho^2$ without fine UV-IR cancellation

COMPOSITE HIGGS UNNATURAL

$E \ll \Lambda_{comp}$: $h \approx$ "elementary", described by SM EFT

THEORY:

$$m_h^2 =$$



$+ \ldots +$

EXPERIMENT: Compositeness, other "naturalizing" new physics unseen

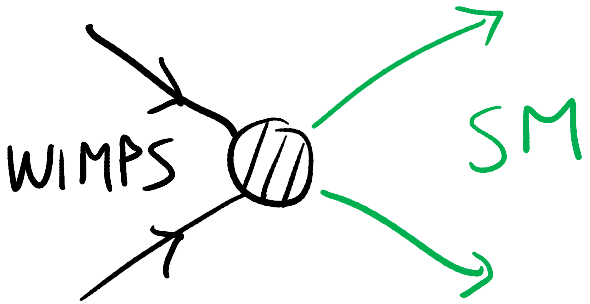
WHY NATURALNESS CAN FAIL

THE MORAL OF THE "PACKAGE DEAL"

Baryogenesis for WIMPS

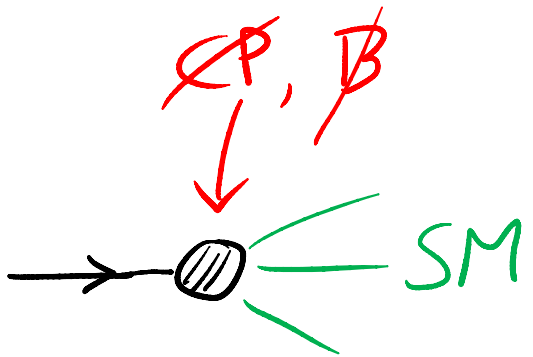
Cui, Sundrum '12
Cui '13
Cui, Shuve

Early Universe:



until WIMP freezeout

but later...

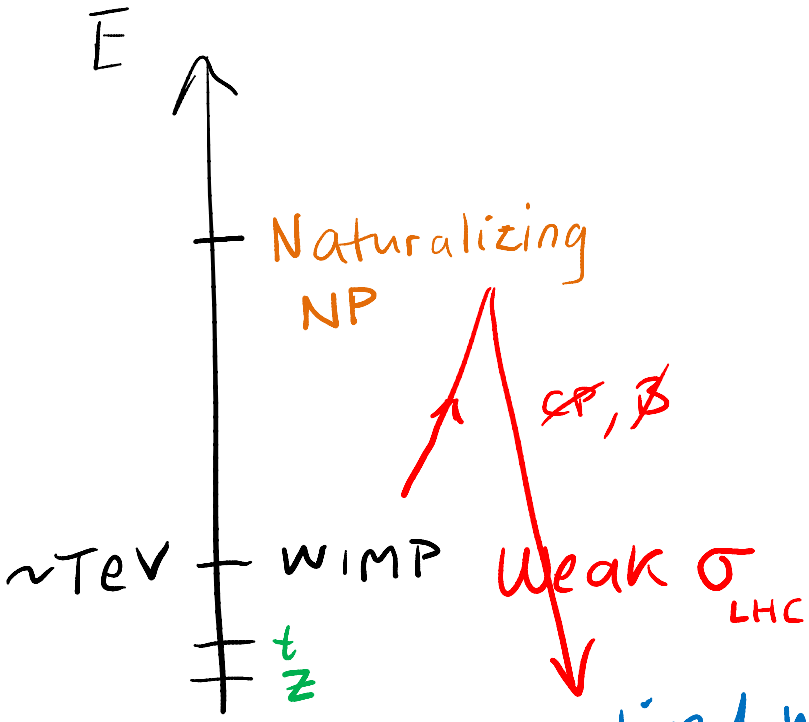


long-lived WIMP decay to baryons (asymmetry)

⇒ "WIMP MIRACLE" FOR BARYOGENESIS

PICK YOUR POISON...

MODEL A

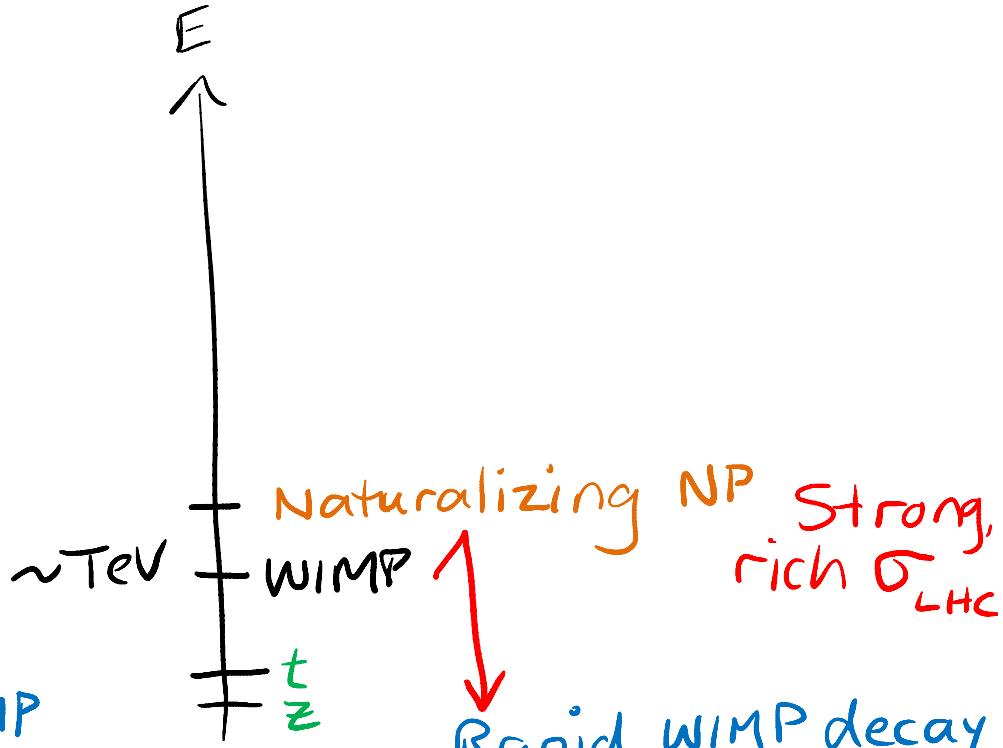


Long-lived WIMP
→ baryon asymmetry

+ Displaced vertex events!

But Little Hierarchy Problem

MODEL B

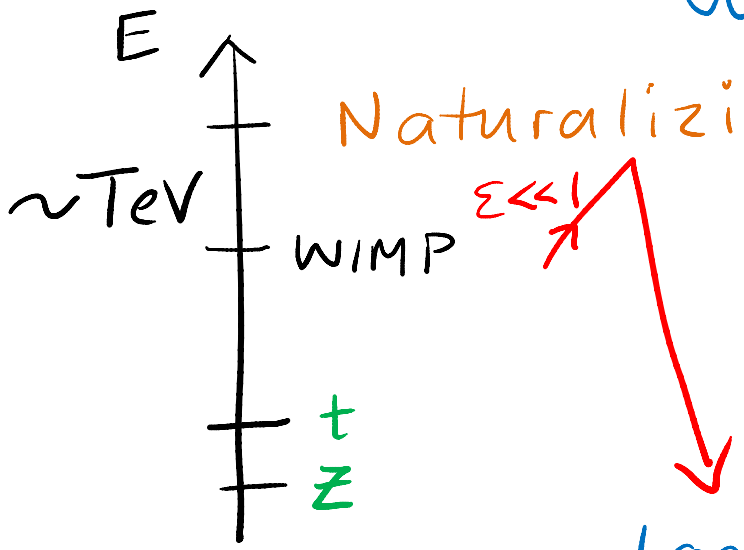


Rapid WIMP decay before Freezeout
⇒ no baryons!

But v. Natural!

In EFT all couplings appear a priori independent...

Why not...



Naturalizing NP

$\varepsilon \ll 1$

long-lived ($\varepsilon \ll 1$)

WIMP → baryon asymmetry

But in UV-complete theories couplings come as package deals.

Maybe $\varepsilon \sim 1$ required

Examples of Package Deals

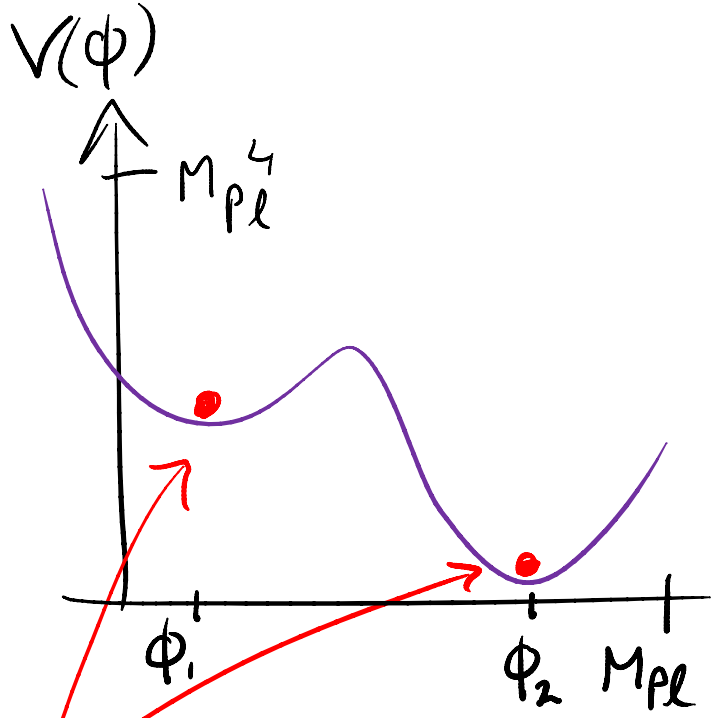
(Massless) QCD $\Rightarrow$ rich world by itself, a "theory of everything", dual to a (difficult) string theory

Only discrete parameters, N_{color}, N_{flavor}

Eg. $N_{color}=4, N_{Flavor}=2$ has similar pion physics to $N_{color}=3, N_{flavor}=2$, slightly different chiral lagrangian couplings.

But $N_{color}=4$ baryons are bosons!

Extremely heavy scalars ARE NATURAL, likely many



$$\mathcal{L}_{UV} \ni \lambda_0 \phi^2 H^2 + \left(\frac{\phi}{M_{Pl}} + \frac{1}{g_0^2}\right) F_{\mu\nu}^2$$

$$\Rightarrow$$

$$\mathcal{L}_{IR} \ni m^2 H^2 + \frac{1}{g^2} F_{\mu\nu}^2$$

$$m_{IR}^2 = \lambda_0 \phi_1^2, \lambda_0 \phi_2^2$$

$$\frac{1}{g_{IR}^2} = \frac{1}{g_0^2} + \frac{\phi_1}{M_{Pl}}, \frac{1}{g_0^2} + \frac{\phi_2}{M_{Pl}}$$

cosmologically meta-stable vacua

String theories ~ rich version of this

Limit of dense set
of UV-complete "package deals"
= EFT naturalness criteria
for gambling

but a rich but still sparse
set of "package deals"
will have correlations in key features
of realism, "fine-tuned" if only tracking
EWSB, with sudden switching of "tour
companies"

My best sense from my (rudimentary) understanding of string theory (or other ways of imagining UV completeness)

$\Rightarrow$ Naturalness is not so compromised as to be useless

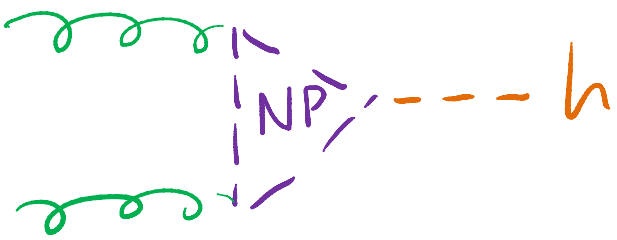
$\Rightarrow$ Hidden Naturalness
- squeezed spectra of NP
- Neutral Naturalness: Twin Higgs, ...

Chacko, Goh, Harnik '06

OR $\exists$ Little Hierarchy ("Problem")

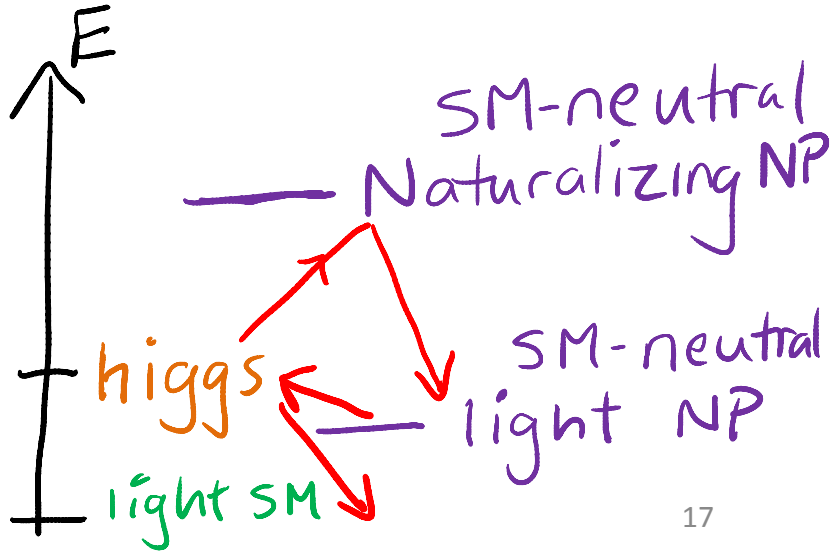
Role for Higgs Boson

Well Known, Higgs sensitive to naturalizing NP without sensitivity to NP decays (squeezed...)

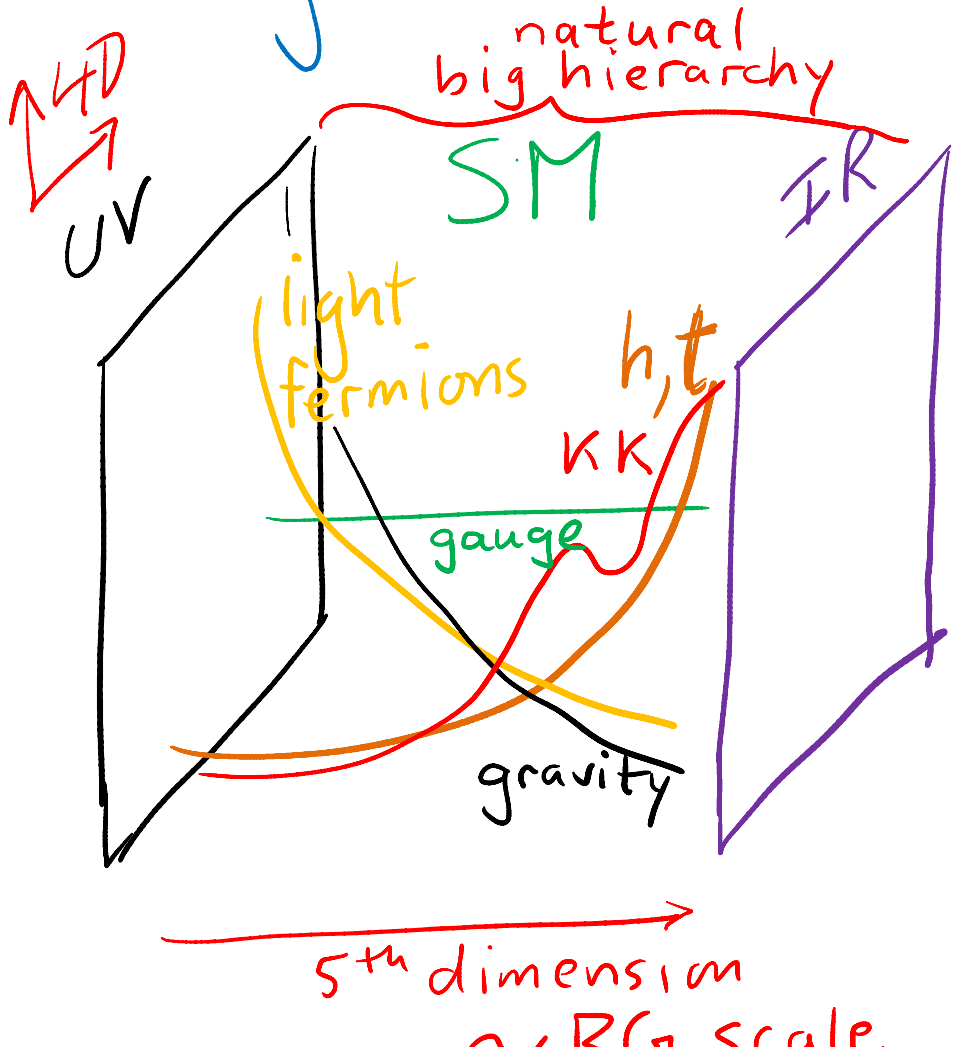


Neutral Naturalness:
Naturalizing NP lies on other side of Higgs Portal
=> Displaced Higgs Decays

Craig, Katz, Strassler, Sundrum '15
Curtin, Verhaaren '15



Warped Extra Dimensions geometrize Composite Higgs,



realizes partial compositeness,

Kaplan '91

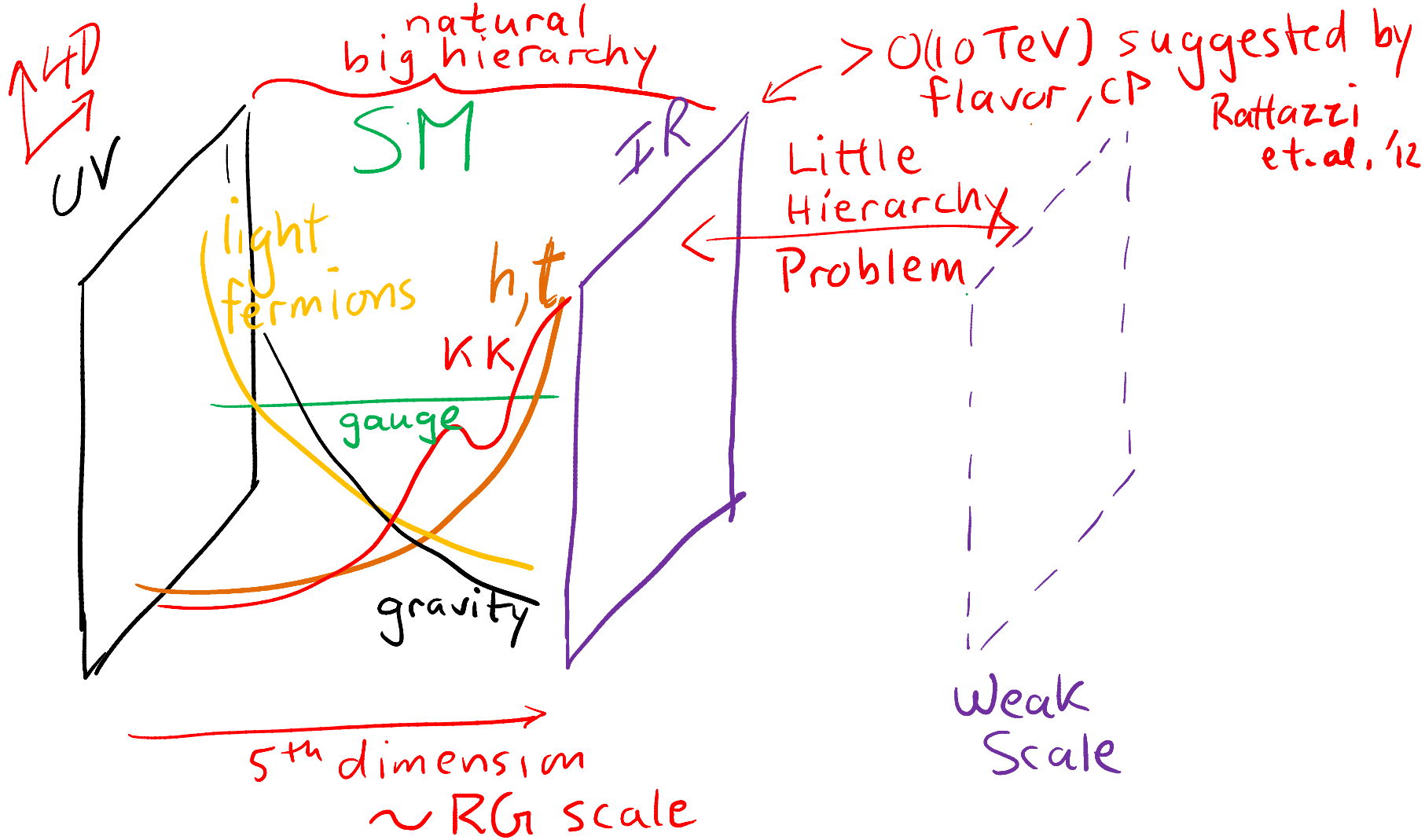
expands systematically in

1/gap in scaling dimensions,

improves on SM unification

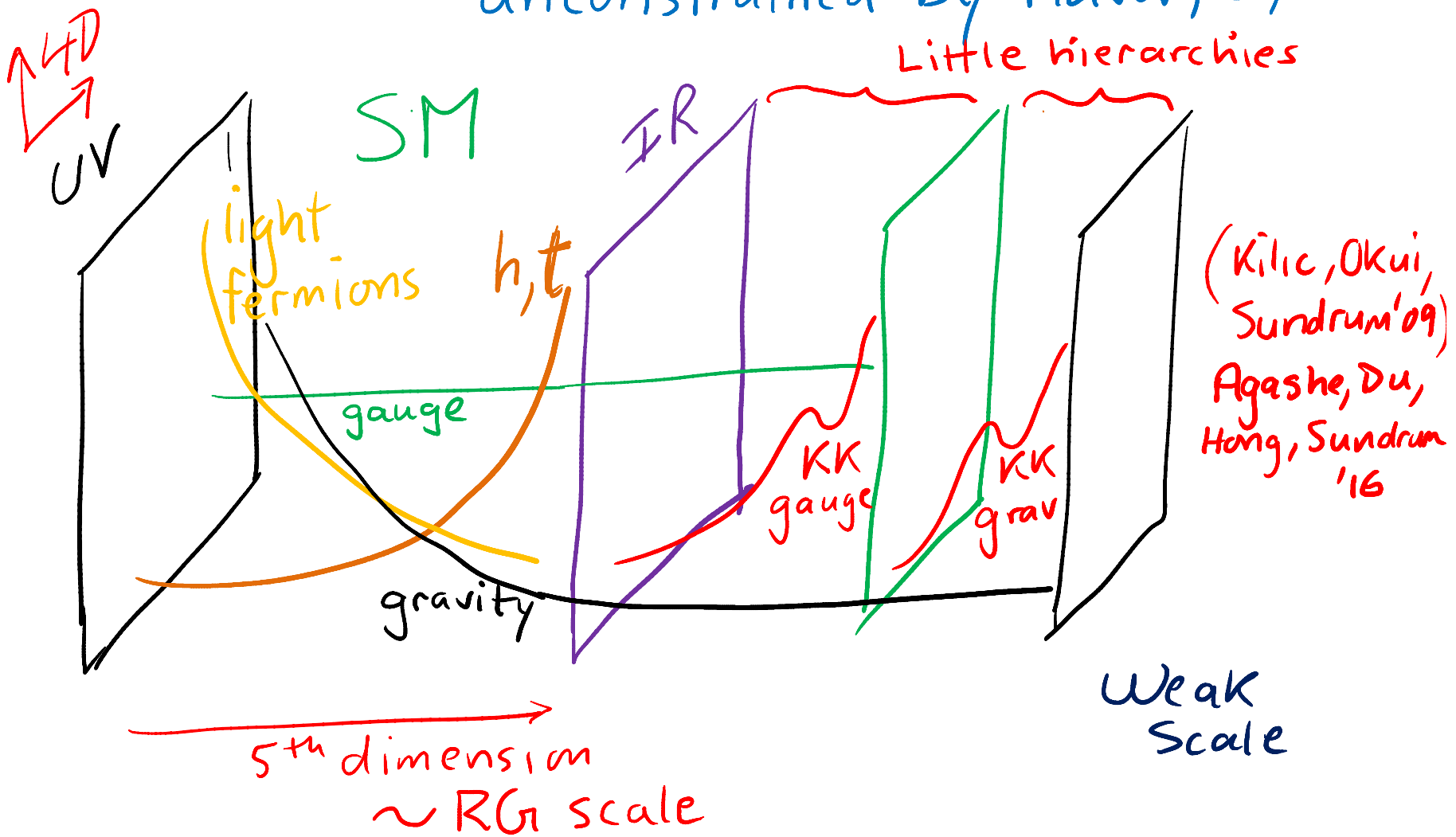
Agashe, Contino, Sundrum '05

The bad side of package deals ?



The good side of package deals

Light vestiges within LHC reach
unconstrained by flavor, CP, EWPT



Here, ~ flavor-blind resonances, subleading decays → h, t

Conclusions

Naturalness is a good guide
but not 0/1, may be frustrated

We need experiment covering all bases
to explore naturalness

We need to explore to higher energies,
but also look for "darker" sectors

MATHUSLA detector proposal to hunt for displaced vertex decays out to ~1sec BBN bounds
Curtin, Chou, Lubatti '16

Higgs is, of course, central to this program