Strongly Coupled New Physics & a 100 TeV Collider

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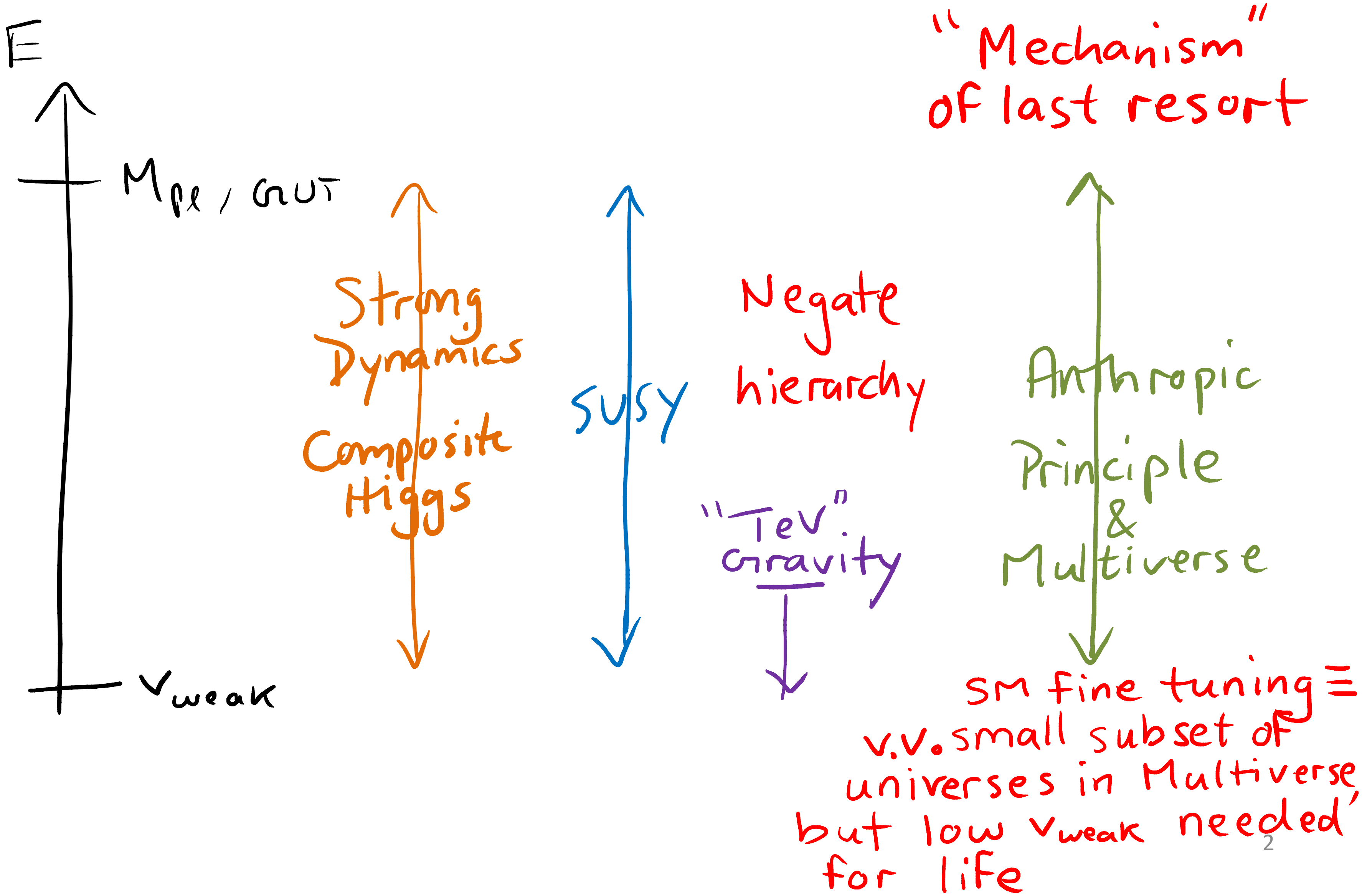
ONE OF V. FEW known APPROACHES TO HIERARCHY PROBLEM



SUSY MIGHT FAIL

SUSY MIGHT FAIL

EW Hierarchy Problem is little brother of

COSMOLOGICAL CONSTANT PROBLEM

EW HIERARCHY PROBLEM IS LITTLE BROTHER OF CCP

In Supergravity, 2 forms of vacuum energy → Cosmo. Constant :

review : Douglas, Kachru '07

SUSY-preserving < 0 ← May be $\lesssim M_{Pl}^4$ in most of Multiverse (still unclear)

~~SUSY~~ > 0

Total $\sim (10^{-3}\,eV)^4 \approx 0$

If so ⇒ high scale ~~SUSY~~
SUSY does not survive to TeV

Strong Dynamics does not have this vulnerability

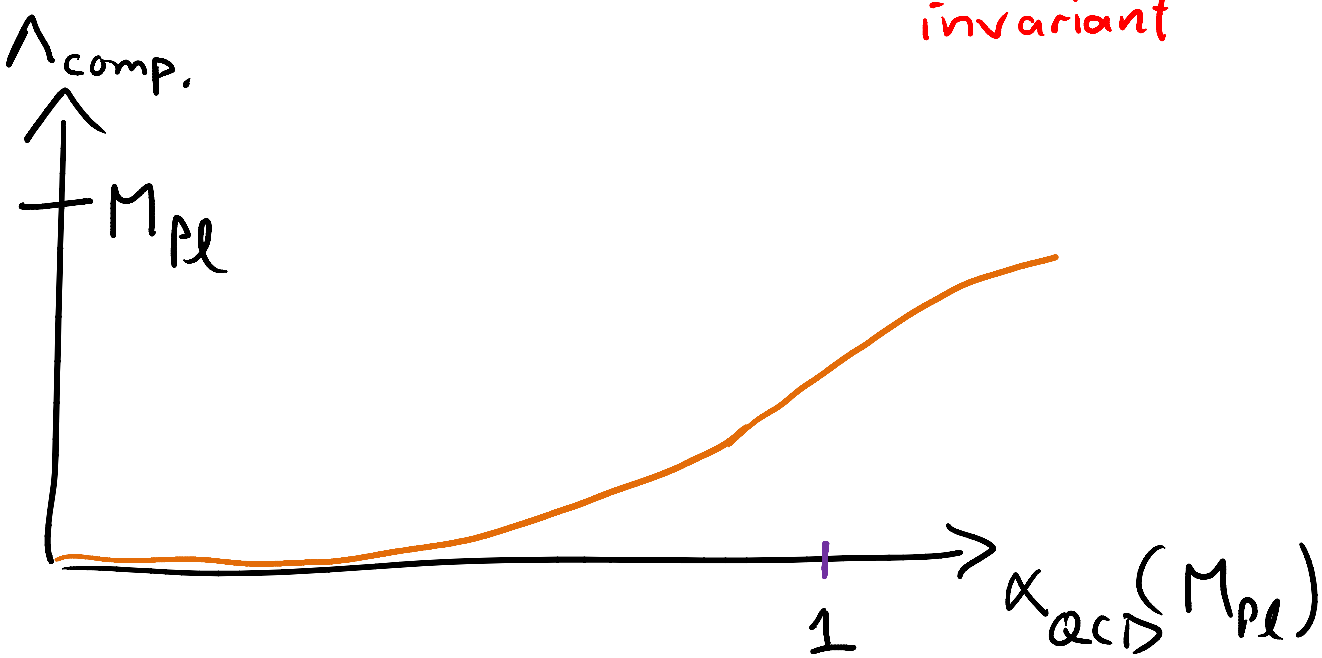
A STRONG PLOT

with its own vulnerabilities...

WHY HADRONS ARE LIGHT

$$\mathcal{L}_{QCD} = -\frac{1}{4} G_{\mu\nu}^2 + \bar{\Psi} i \not{D} \Psi \qquad \Psi \equiv \begin{pmatrix} u \\ d \end{pmatrix}$$

$$\Lambda_{\text{composites}} \sim \Lambda_{QCD} \underset{\text{RG invariant}}{\sim} M_{Pl}\, e^{-\frac{O(1)}{\alpha_{QCD}(M_{Pl})}} \underset{\text{expt.}}{\sim} \text{GeV}$$



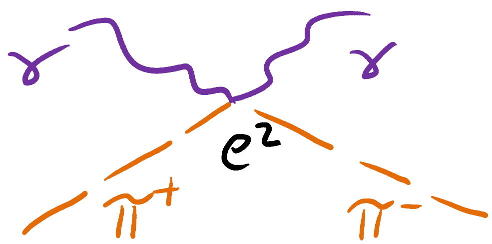
WHY PIONS ARE LIGHTER

They are Nambu-Goldstone bosons (of chiral ~~symmetry~~)

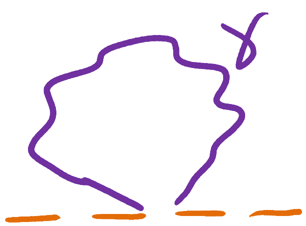
WHY CHARGED PIONS ARE LIGHTER

$$\mathcal{L}_{QCD+QED} = -\frac{1}{4} {G^a_{\mu\nu}}^2 - \frac{1}{4} F_{\mu\nu}^2 + \bar{\psi} i \not{D} \psi$$

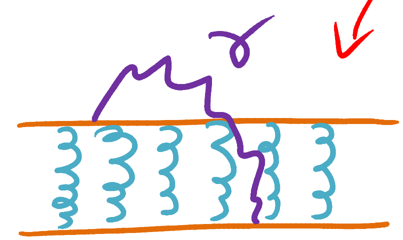
$\pi^\pm$ has non-Goldstone (non-∂) couplings



$\int d^4q$ $\ll \Lambda_{QCD}$



$+ \int d^4q$ $\gtrsim \Lambda_{QCD}$



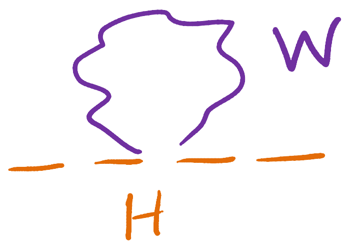
$$\Rightarrow m^2_{\pi^+} \sim \frac{\alpha_{em}}{4\pi} \Lambda^2_{QCD} \ll \Lambda^2_{QCD}$$

Works well!

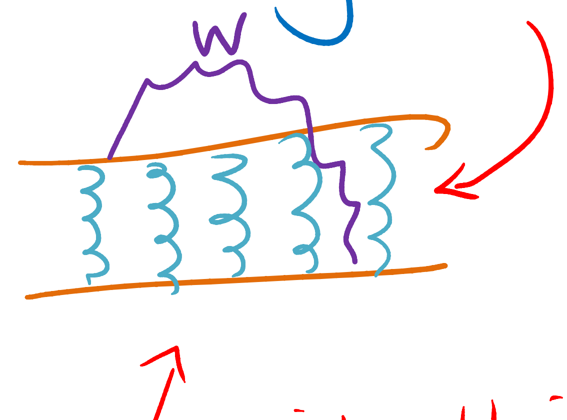
WHY HIGGS DOUBLET MIGHT BE LIGHT

It is composite of NEW strong force

$$\int_{\ll \Lambda_{comp}} d^4q$$



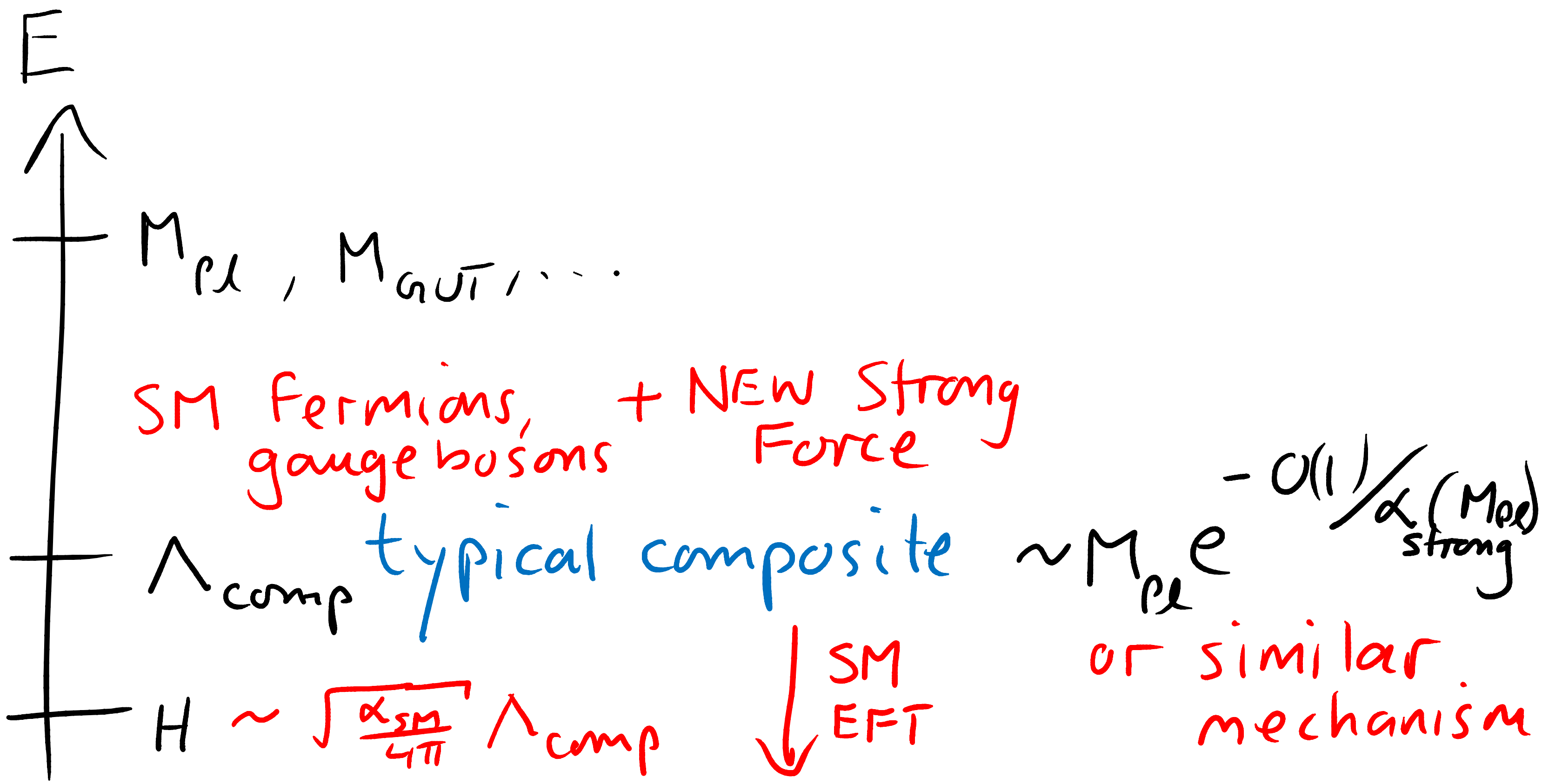
$$+ \int_{\gtrsim \Lambda_{comp}} d^4q$$



Composite Higgs

$\Rightarrow$ Higgs mass^2-parameter $\sim \dfrac{\alpha_{SM}}{4\pi} \Lambda_{comp}^2$

$\ll \Lambda_{comp}^2$


E
M_Pl , M_GUT , . . .
SM Fermions, gauge bosons
+ NEW Strong Force
Λ_comp
typical composite
∼ M_Pl e^(−O(1)/α_strong(M_Pl))
H ∼ √(α_SM/4π) Λ_comp
SM EFT
or similar mechanism

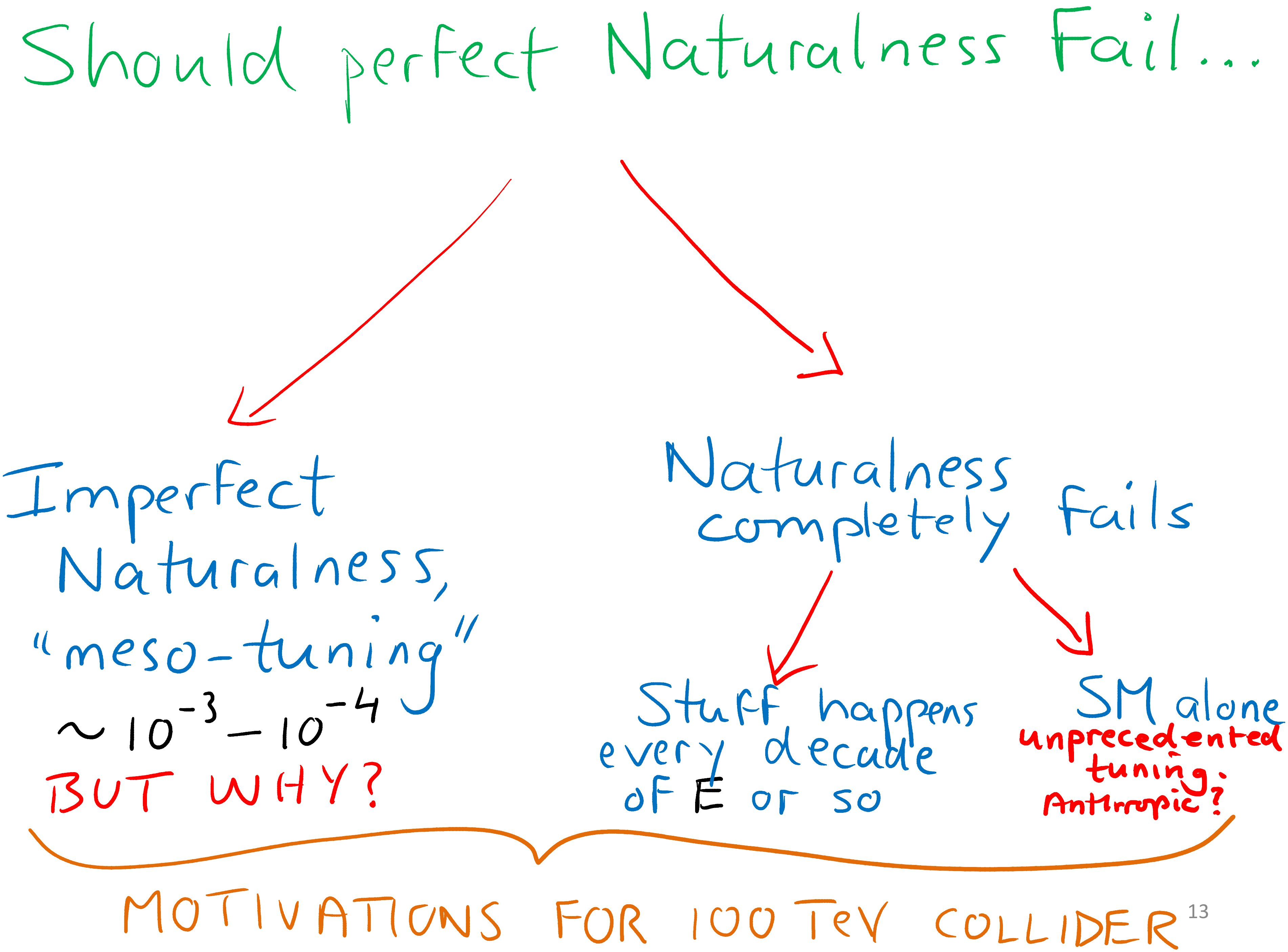
EW Naturalness

(Higgs mass^2 parameter $\sim$ typical radiative corrections)

$\Rightarrow$ New Physics $\lesssim$ TeV & $O(1)$ coupled to SM } LHC accessible

Perfect Naturalness

seems increasingly unlikely, but not yet convincingly & broadly excluded by LHC


Should perfect Naturalness Fail...
Imperfect Naturalness, "meso-tuning"
~10^-3 – 10^-4
BUT WHY?
Naturalness completely Fails
Stuff happens every decade of E or so
SM alone
unprecedented tuning:
Anthropic?
MOTIVATIONS FOR 100 TeV COLLIDER

Should perfect Naturalness succeed

↓

Study constituents of Higgs
& the new strong force
that binds them

MOTIVATION FOR 100 TeV COLLIDER

"SHE'S DEAD, GIM!"

(EXTENDED) TECHNICOLOR E(TC) =

Weinberg '79; Susskind '79 (Dimopoulos, Susskind '79; Eichten, Lane '80)

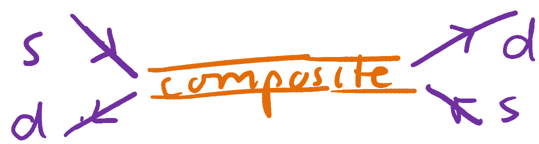
"MODEL T FORD" OF STRONG DYNAMICS

Theoretical control by close analogy with QCD

But conflict with EW tests,

Holdom, Terning '90
Peskin, Takeuchi '90
Golden, Randall '91

no GIM mechanism suppressing FCNCs,



& has no light, narrow h-resonance!

But (E)TC ≠ Strong Dynamics just as Model T ≠ Automobile

MODERN COMPOSITE HIGGS SCENARIO

E

M_{Pl}, M_{GUT}, …

SM fermions, gauge bosons + NEW Strong Force

Λ_{comp} typical composite $\sim M_{Pl}\, e^{-O(1)/\alpha_{strong}(M_{Pl})}$

or similar mechanism

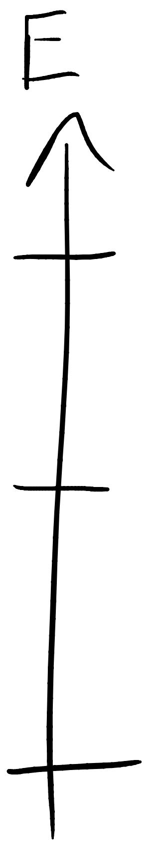
$\downarrow$ SM EFT

$H \sim \sqrt{\frac{\alpha_{SM}}{4\pi}}\, \Lambda_{comp}$

$\ni$ light, narrow composite Higgs scalar, h

Georgi, Kaplan '85

MODERN COMPOSITE HIGGS SCENARIO



M_{Pl}, M_{GUT}, ...

Λ_{comp} typical composites

↓ SM EFT

$H \ll \sqrt{\frac{\alpha_{SM}}{4\pi}}\,\Lambda_{comp}$

by finely-tuned cancelations among $\frac{\alpha_{SM}}{4\pi}\Lambda_{comp}^2$ radiative corrections

$\Lambda_{comp}\uparrow$ & decouples from précision/flavor tests

WALKING (VS. "RUNNING") COUPLING

$$\beta_{strong}(\alpha_{strong}) \ll 1$$

even though $\alpha_{strong} \sim O(1)$

$\Rightarrow$ strong coupling over large hierarchy

Holdom '85 ; Miransky '85; Appelquist, Karabali, Wijewardhana '87; Bando, Morozumi, So, Yamawaki '87

PARTIAL COMPOSITENESS

of fermions

Kaplan '91

E

M_{Pl}, M_{GUT}, ...

$$\mathcal{L} \ni \psi_L^{SM} \mathcal{O} + \psi_R^{SM} \mathcal{O}' + \bar{\psi}_L \psi_R \mathcal{O}''$$

Fermionic composite operators of strong sector

Λ_{comp}

H

$$\mathcal{L}_{eff} \ni \mathcal{O}(1)_{ij} \left(\frac{\Lambda_{comp}}{M}\right)^{\gamma_i + \gamma_j} \bar{\psi}_L^i \psi_R^j H$$

Strong RG effects ⟶ Hierarchical SM fermion mass matrices :

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

PARTIAL COMPOSITENESS of fermions

E

M_{Pl}, M_{GUT}, ...

$$\mathcal{L} \ni \psi_L^{SM} \mathcal{O} + \psi_R^{SM} \mathcal{O}' + \bar{\psi}_L \psi_R \mathcal{O}''$$

Λ_{comp}

H

$$\mathcal{L}_{eff} \ni \mathcal{O}(1)_{ij} \left(\frac{\Lambda_{comp}}{M}\right)^{\gamma} \bar{\psi}_L \psi_R H$$

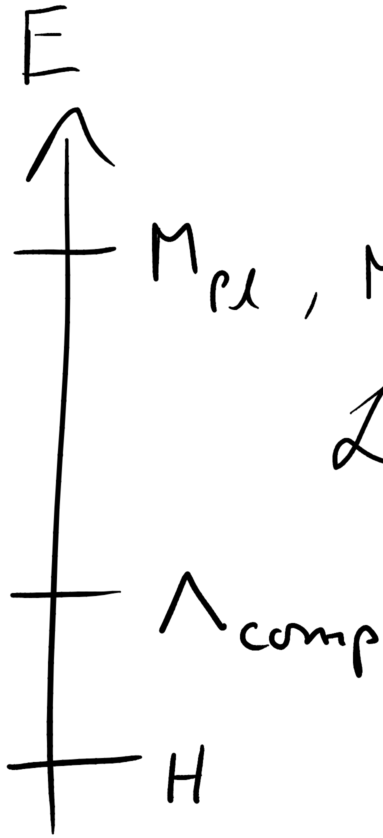
subdominant except for v. light fermions → Neutrino anarchy

Agashe, Okui, Sundrum '08

$$\theta_{ij} \sim \mathcal{O}(1)_{ij}$$

PARTIAL COMPOSITENESS

of fermions



$$\mathcal{L} \ni \psi_L^{SM}\,\mathcal{O} + \psi_R^{SM}\,\tilde{\mathcal{O}}$$

$$\mathcal{L}_{eff} \ni \left(\frac{\Lambda_{comp}}{M}\right)^{\gamma_i+\gamma_j+\gamma_k+\gamma_l} \frac{\bar{\psi}_i \psi_j \bar{\psi}_k \psi_l}{\Lambda_{comp}^2}$$

GIM-ish suppression of FCNCs:

FLAVOR DATA $\Rightarrow$ $\Lambda_{comp} > \mathcal{O}(10\,\text{TeV})$

...Csaki, Falkowski, Weiler '08
Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi '12

WEAK IS STRONG

- Excellent theoretical control of weakly coupled renormalizable QFTs to model BSM over large hierarchies
- What you see in $\mathcal{L}$ is what you get
- Hierarchy Problem of scalars is generic
- Central concern is EXPERIMENT

STRONG IS WEAK

- Very poor theoretical control over strong dynamics
  (lattice simulations are up & coming.)
- What you see in $\mathcal{L}$ is not what you get
- Hierarchy Problem not generic for strongly coupled scalars
- 2 FRONTS Concerned with EXPERIMENT & even with THEORETICAL EXISTENCE of realistic models.

DESPERATE MEASURES FOR THEORETICAL CONTROL

Treat Strong Sector as black box
coupled to ψ_{SM}, A_μ^{SM}

Identify composite operators must have:

$T_{\mu\nu}$ ⇐ strong dynamics is some QFT

$T_\mu^{\ \mu}$ small ⇐ weak breaking of scale invariance generates large hierarchies (eg. ~ $\alpha_{QCD} G^2_{\mu\nu}$ in QCD)

J^μ ⇐ gauged by A_μ^{SM}

Fermionic operators ⇐ Partial Compositeness

Strong is Weak
(in a good way)

At strong coupling, true scaling dimension $\neq$ engineering dimension

ASSUME other composite operators (not products of above list) have scaling dimension $\gg 1$

Expand in $\frac{1}{\text{gap in scaling dimensions}} \ll 1$!!

Eg. Heemskerk, Penedones, Polchinski, Sully '09; Sundrum '11

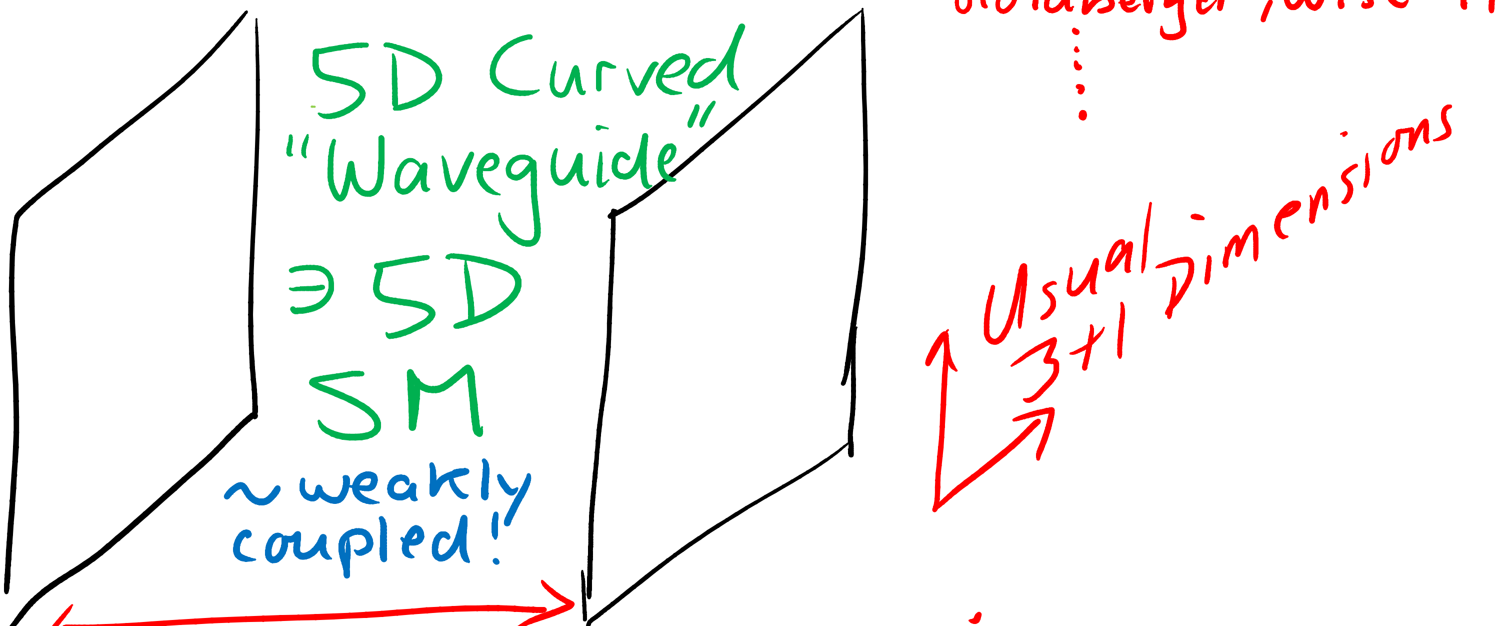
$\Longrightarrow$ AdS/CFT

H.Verlinde '99; Arkani-Hamed, Porrati, Randall '00; Rattazzi, Zaffaroni '00

Warped Extra Dimension

(Randall-Sundrum models)

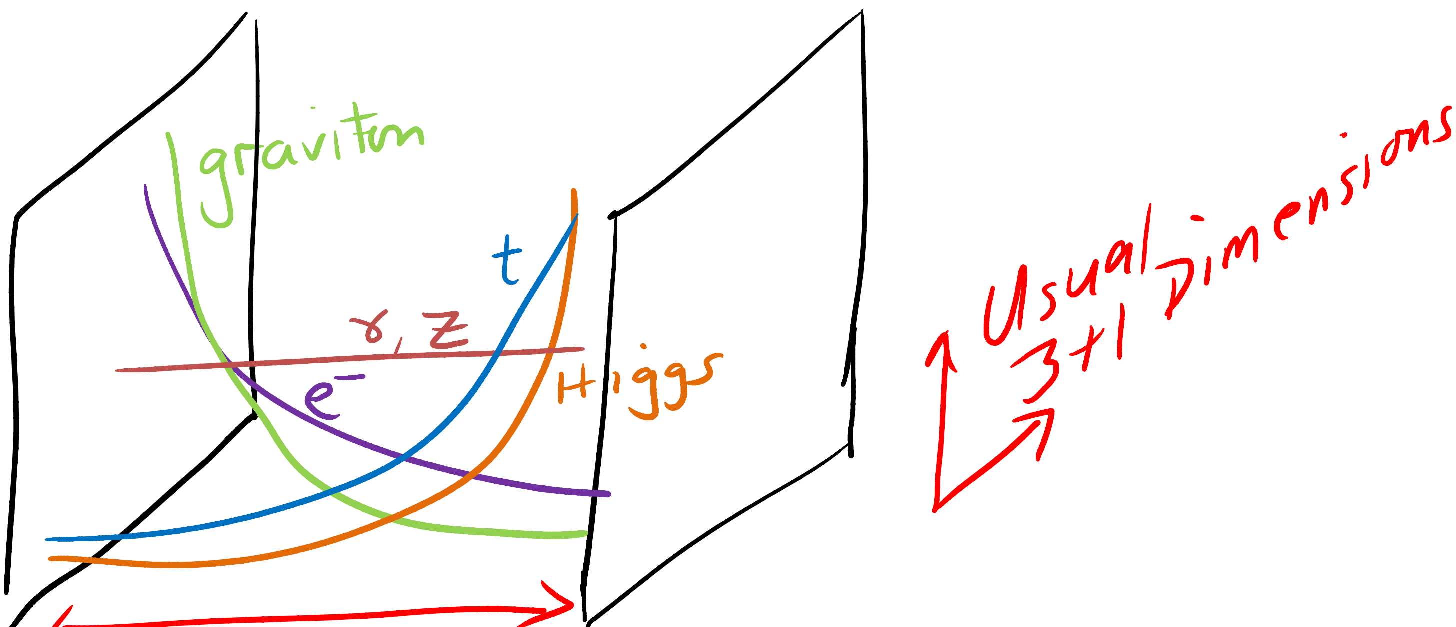
Randall, Sundrum '99
Goldberger, Wise '99
⋮



small Emergent extra dimension, not what you see in $\mathcal{L}$

Warped Extra Dimension

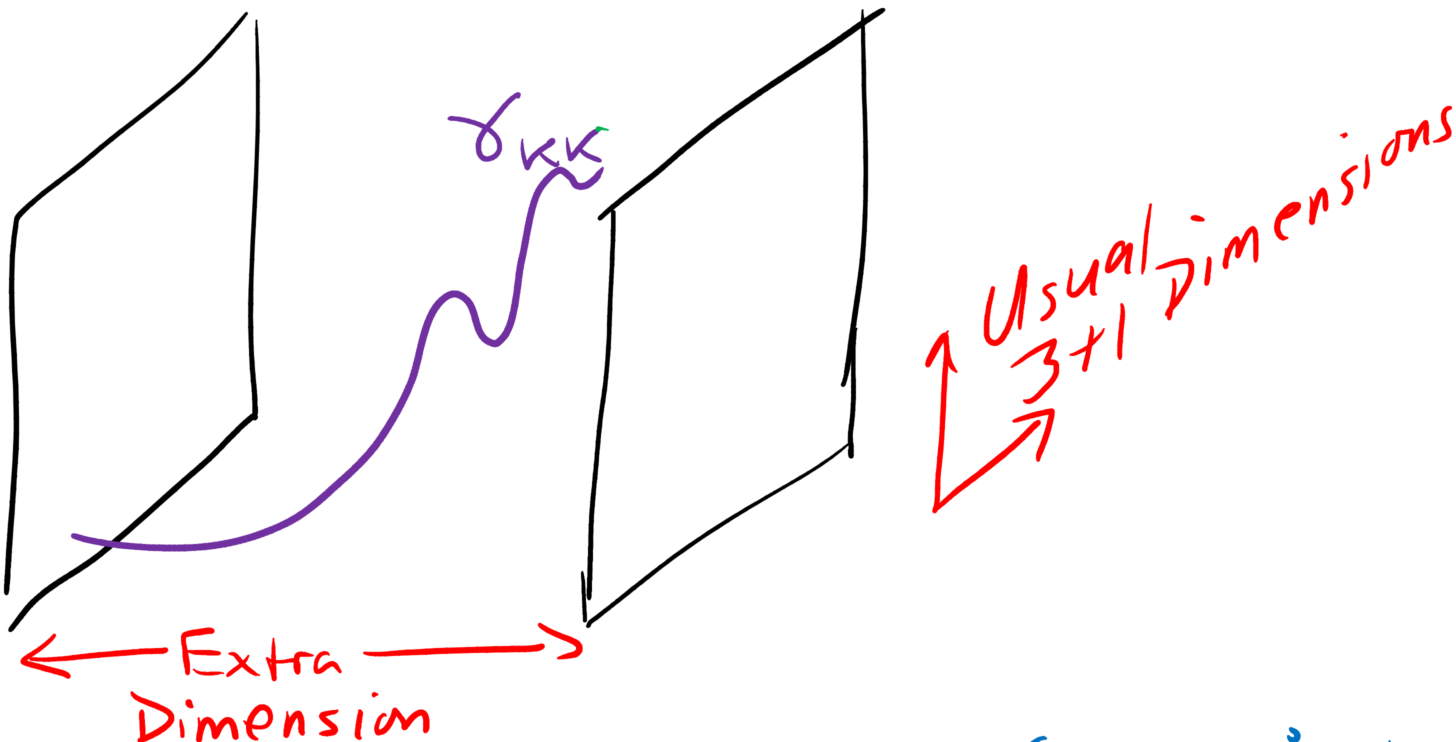
(Randall-Sundrum models)



Lowest (least wiggly) modes ≡ Observed SM particles

Wavefunction overlaps → hierarchical SM couplings

Warped Extra Dimension
(Randall-Sundrum models)



"Kaluza-Klein" Excitations (more wiggly modes)

≡ Lightest new composites of strong Force

WARPED VALUES

- First-pass self-consistency of ideas
- Geometrizes (visualizes) abstract/strong dynamics
- Partial UV completeness
  - Beautiful description of inclusive processes $\gg \Lambda_{comp}$
  - Exclusive processes $< \Lambda_{comp}$
- Blueprint for stringy full UV completion
  Strassler '03; Kachru, Simic, Trivedi '10
- Laboratory for new mechanisms, pheno.
- SM-ish structures emerge from fairly typical, structureless 5D SM

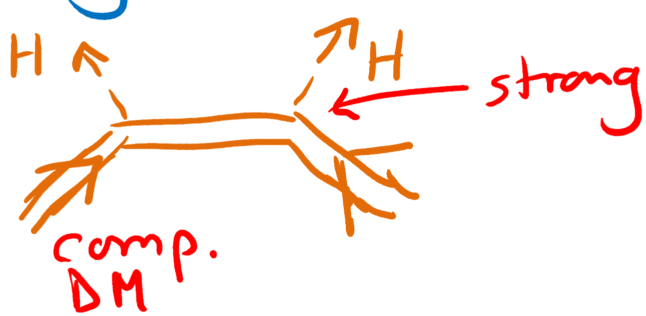
MESO-TUNING can arise from conflicting anthropic pressures in MULTIVERSE

Vecchi '13

Eg. proton stability ← accidental baryon symmetry of QCD

Accidental symmetries might stabilize a new composite $\sim \Lambda_{comp}$ → DARK MATTER?

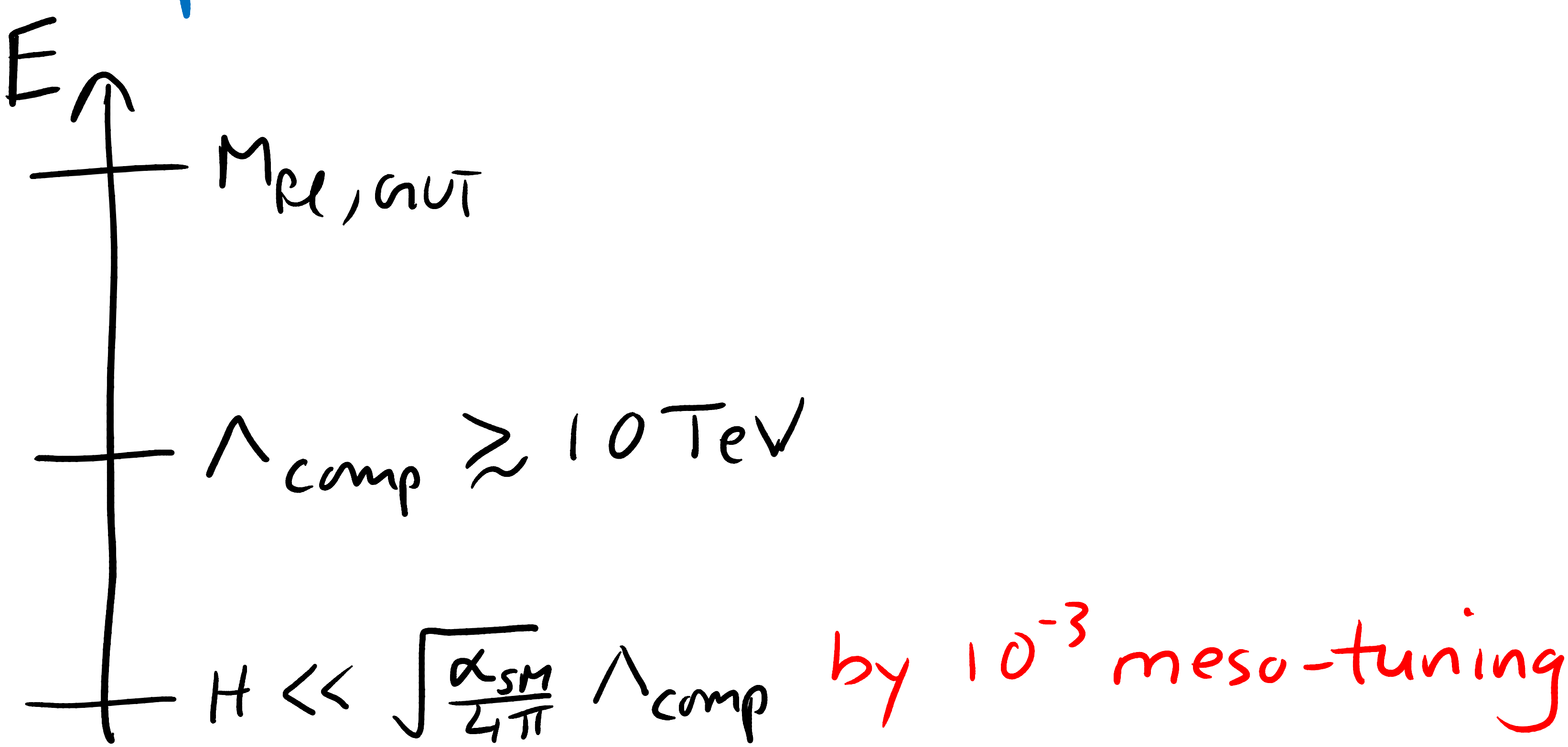
Strong annihilations in Early Universe



⇒ Very low relic abundance unless

$$\Lambda_{comp} \sim \mathcal{O}(10)\,\mathrm{TeV}$$

If Dark-Matter Dominated Galaxies & our low EW scale are ANTHROPICALLY PREFERRED, most prevalent solution in Multiverse:



PHENO

= COMPOSITES

TOP PARTNERS

Fermionic top partners
(Little Higgsy structure)
are to Strong Dynamics
what natural SUSY light stops
are to SUSY

That is, possibility that composites
most "urgently" need for hierarchy
problem appear first (are lightest)
An intelligent gamble ...

TOP PARTNERS

BUT WE KNOW V.V. LITTLE ABOUT STRONG DYNAMICS

OPTIONS!

Possibly fermionic ~~top partners~~

→ Twin Higgs colorless top partners

Chacko, Goh, Harnik '06

TOP PARTNERS

OR EVEN (RE-) EMERGENT SUSY

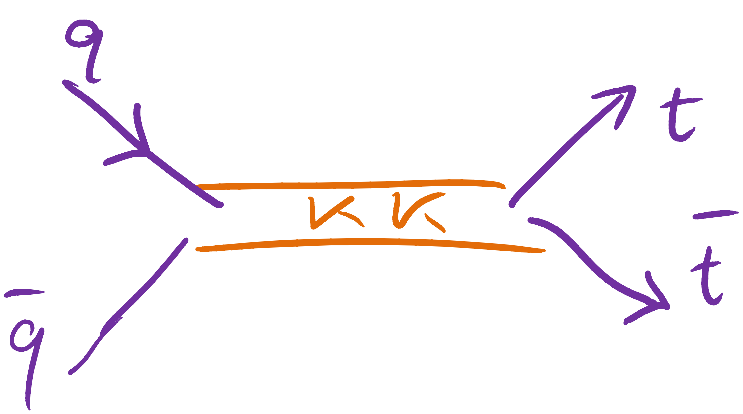
⇒ bosonic "stop"
top partners
+ gluinos, ...
} Natural SUSY pheno

Sundrum '09

building on Gherghetta, Pomarol '03
Luty '02
Goh, Luty, Ng '03

KK GLUONS

are to strong dynamics what gluinos are to SUSY, necessary & when within reach can be spectacular



$t\bar{t}$ RESONANCES

Agashe, Belyaev, Krupovnickas, Perez, Virzi '06; Lillie, Randall, Wang '07

MORE SCALAR COMPOSITES,

$\not{E}$ (Dark Matter related?) Signals,

Rare Higgs processes,

agnostic searches

Low-energy flavor, ~~CP~~ tests

are all good bets

Gauge Coupling Unification

A reasonably precise gauge (coupling) unification plot emerges if a "unified" symmetry ≡ global symmetry of strong dynamics

Agashe, Contino, Sundrum '05

Strong is Strong

Strong Dynamics is strongly motivated @ 100 TeV even if LHC does not see new physics

Poorly understood, may come in many guises, especially if meso-tuned.

Theoretical control, existence PARAMOUNT