

Muon Collider against the Backdrop of FUNDAMENTAL PHYSICS

Raman Sundrum

University of Maryland

(lesser) member of N. Craig et. al. "Muon Smasher's Guide"

ALL ABOUT....ME

MECHANISM/MODEL
BUILDER

string
theorist

Phenomenologist

ALL ABOUT THEMES

MECHANISM/MODEL
BUILDER

string
theorist

Phenomenologist

THERE EXIST VARIETY OF BRILLIANT,
AMBITIOUS MECHANISMS & MODELS

NONE ARE PERFECT!

BUT THEY PROVIDE ROBUST PHYSICS THEMES
& DESIRED CAPABILITIES FOR COLLIDER EXPLORATION

The HIGGS ENIGMA

2012 Higgs discovery revealed a new QUANTUM
FUNDAMENTAL FORCE, with a

SCALAR "EQUIVALENCE PRINCIPLE" (EP):

COUPLING \propto MASS
to Higgs boson

from Higgs Mechanism
+ QUANTUM CORRECTIONS

The HIGGS ENIGMA

2012 Higgs discovery revealed a new QUANTUM FUNDAMENTAL FORCE, with a

SCALAR "EQUIVALENCE PRINCIPLE" (EP):

COUPLING \propto MASS

to Higgs boson

from Higgs Mechanism

+ QUANTUM CORRECTIONS

$m_h = 125 \text{ GeV} \Rightarrow$ rich in accessible production/decay channels.

\Rightarrow SHOULD SIGNIFICANTLY IMPROVE PRECISION TESTS OF quantum-corrected "EP": Yukawas, di-Higgs, couplings to gauge bosons, EWPT

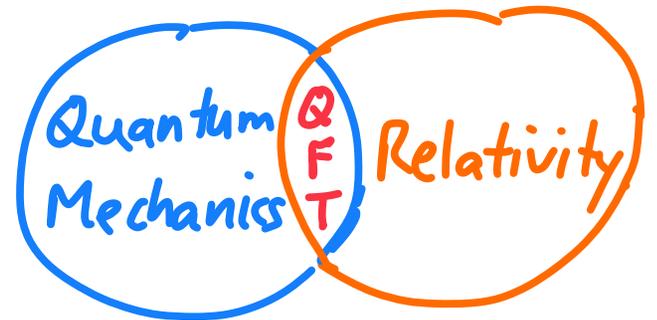
SM accommodates, but does not explain:

Overall mass scale $v_{\text{weak}} \sim \langle H \rangle \lll M_{\text{Pl}}$ Hierarchy Problem

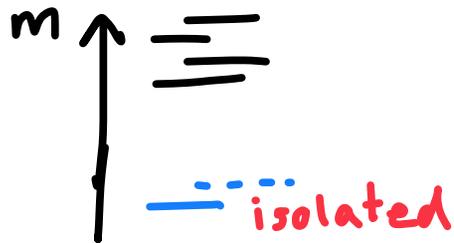
Relative mass scales, mixing angles exhibit mysterious patterns (gauge coupling unification) Flavor Puzzle

And yet, attractive explanatory mechanisms may be within reach...

NATURE SEEMS TO PLAY EVERY TRICK IN THE ^{QFT} BOOK



"Elementary"



SPIN

0	$\frac{1}{2}$	1	$\frac{3}{2}$	2	$\frac{5}{2}$	3	...
h?	lots seen	lots seen	must be gravitino of SUSY	must be graviton seen force field	X	X	
Nature v. stingy with these!							

"Composite"



lots lots lots lots lots lots lots ...

HIGGS MAY BE LIGHT COMPOSITE OF NEW SECTOR

Model (in)dependently testing Higgs
for compositeness presents classic goal
for experimental exploration.

Higgs Compositeness \Rightarrow small violations of "EP"
 \Rightarrow precision Higgs, EW tests

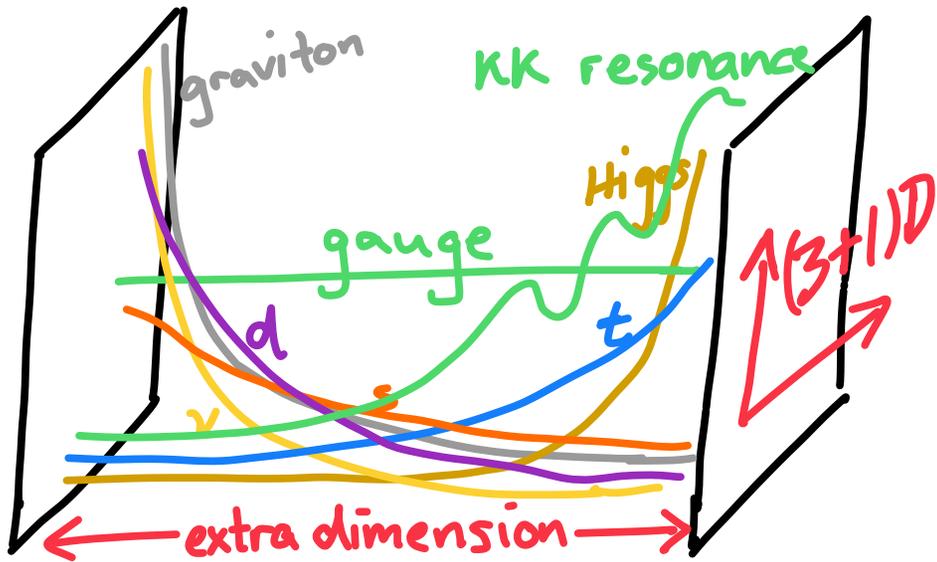
+ more indirectly, FCNCs & ~~CP~~
in flavor tests, EDMs

HIGGS COMPOSITENESS

(& PARTIAL COMPOSITENESS)

Theoretically tough due to strong confining coupling.
But can be "geometrized" via AdS/CFT duality:

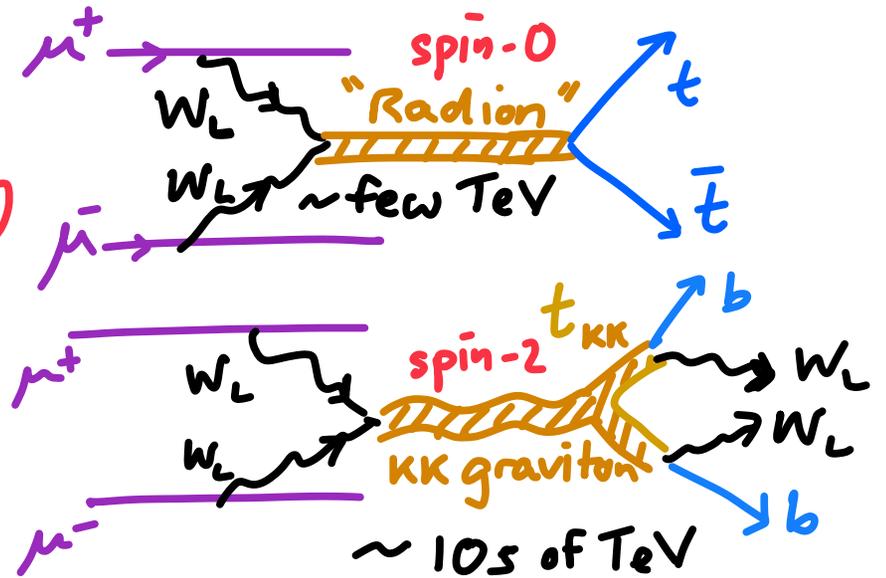
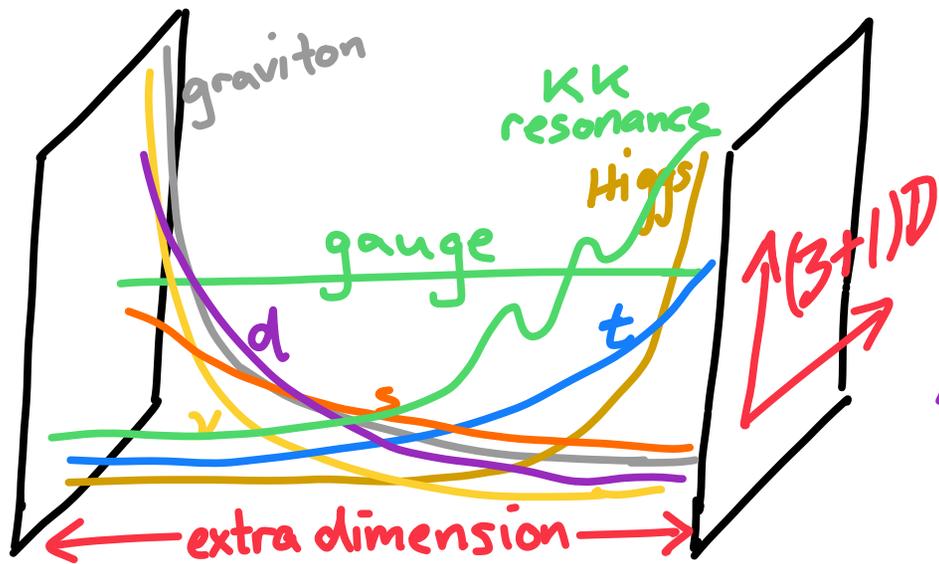
Strong Coupling $\xrightarrow{\text{Quantum Magic}}$ Emergent "Warped" Extra Dimension



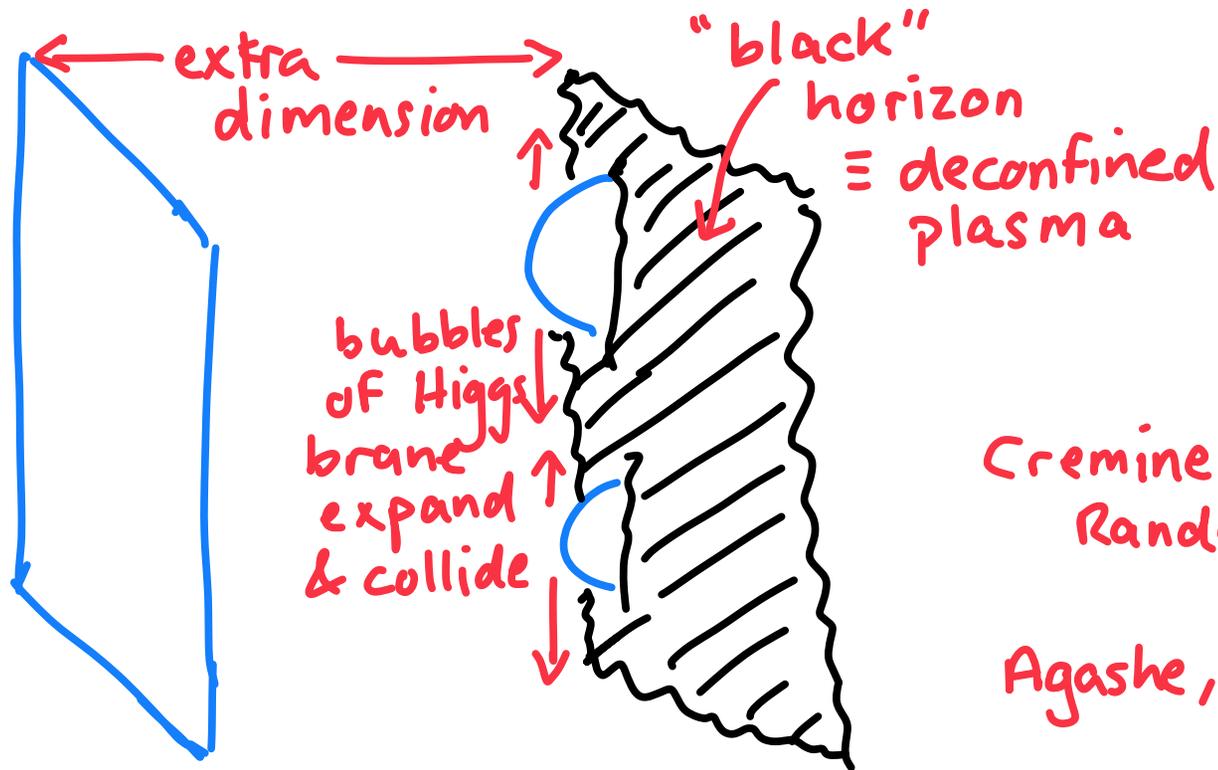
WARPED EXTRA DIMENSION

Extra-dimensional wavefunction overlaps \rightarrow attractive resolutions of Hierarchy Problem + Flavor Puzzle.

Known models can have Kaluza-Klein resonances typically at $\gtrsim 20$ TeV consistent with stringent flavor/CP tests. But some resonances could be significantly lighter:



(DE)CONFINEMENT PHASE TRANSITION of Composite Higgs sector in v. Early Universe

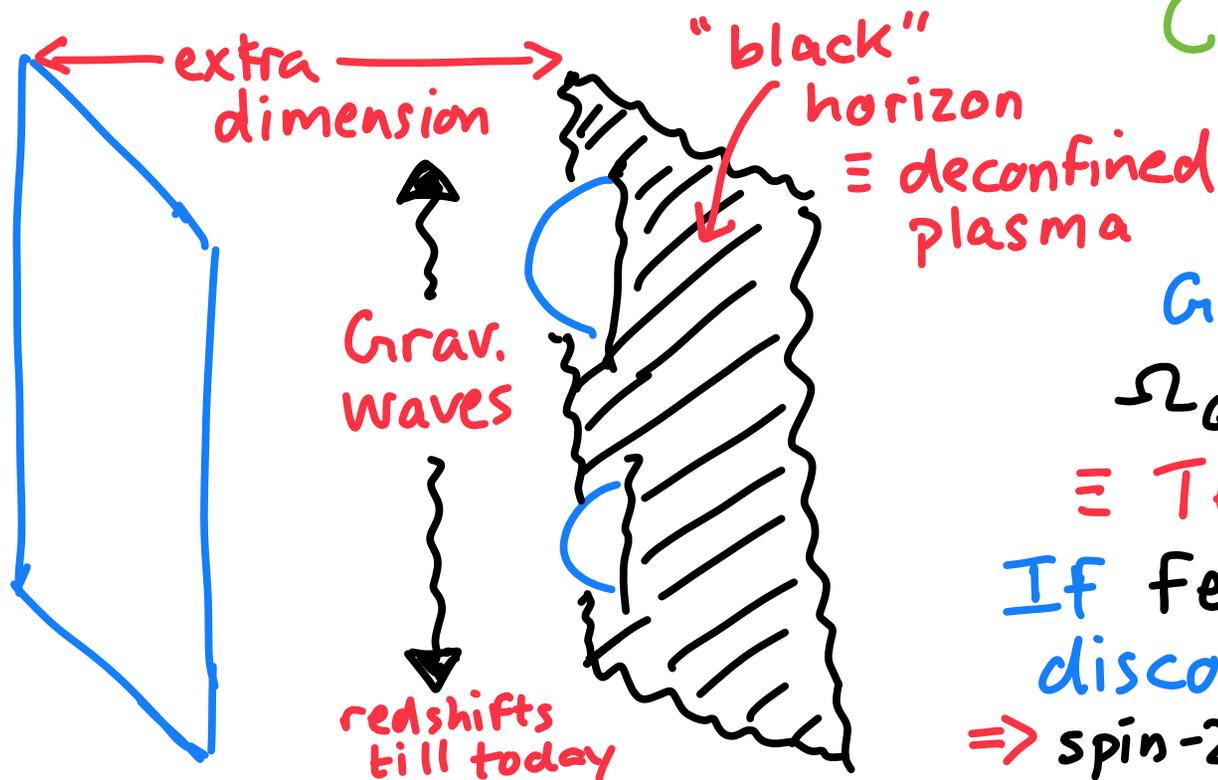


Creminelli, Nicolis, Rattazzi '02
Randall, Servant '06

⋮
Agashe, Du, Ekhterachian, Kumar,
Sundrum '20

GRAVITATIONAL WAVES

← (DE)CONFINEMENT PHASE TRANSITION



COLLIDER COMPLEMENTARITY

Eg. Proposed LISA detector may see 1mHz GW stochastic background

$$\Omega_{GW} \sim \text{few} \cdot 10^{-10}$$

≡ TeV critical Temperature

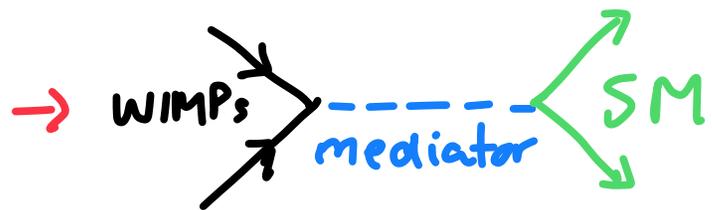
IF few TeV scalar radion discovered at collider

⇒ spin-2 KK graviton ≈ 20 TeV

THE HEART OF THE MATTER

Dark Matter WIMP "Miracle":

Early Universe equilibrium ...
 $WIMP \leftrightarrow SM$



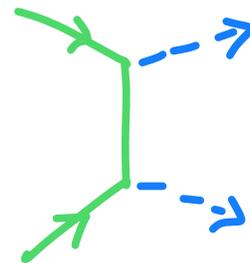
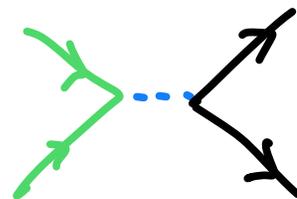
Freezes out
 as universe expands

Energy fraction of universe today:

$$\Omega_{WIMP} \approx 0.1 \left(\frac{g_{weak}}{g_{WIMP}} \right)^4 \cdot \frac{m_{mediator}^4}{m_{WIMP}^2 \text{TeV}^2}$$

\Rightarrow TeV WIMPs attractive

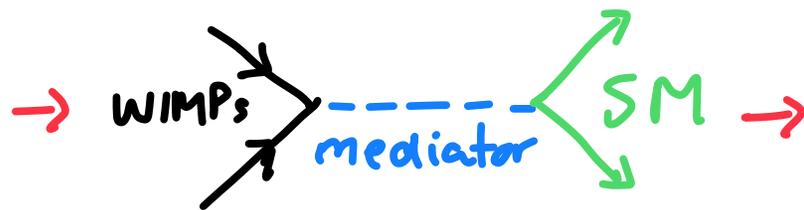
Broadest
 Collider exploration
 \rightarrow with optimal E detection,
 complementary to DM
 detection experiments



THE HEART OF THE MATTER S

Dark Matter WIMP "Miracle":

Early Universe
equilibrium ...
WIMP \leftrightarrow SM



Freezes out
as universe expands

Energy fraction of
surviving WIMPs today

$$\Omega_{\text{WIMP}} \approx 0.1 \left(\frac{g_{\text{weak}}}{g_{\text{WIMP}}} \right)^4 \frac{m_{\text{mediator}}^4}{m_{\text{WIMP}}^2 \text{TeV}^2}$$

BUT WHAT ABOUT THAT OTHER

FORM OF MATTER - US?!

ie. Baryons

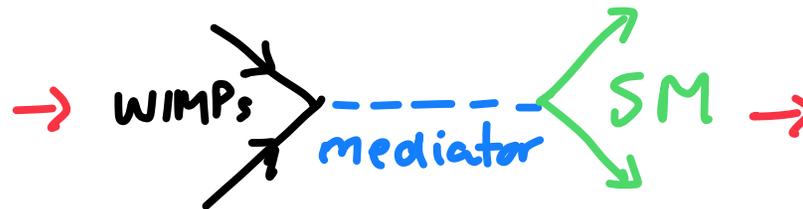
BARYOGENESIS FOR WIMPS!

Cui, Sundrum '12

Baryogenesis WIMP "Miracle":

Energy fraction of surviving WIMPs

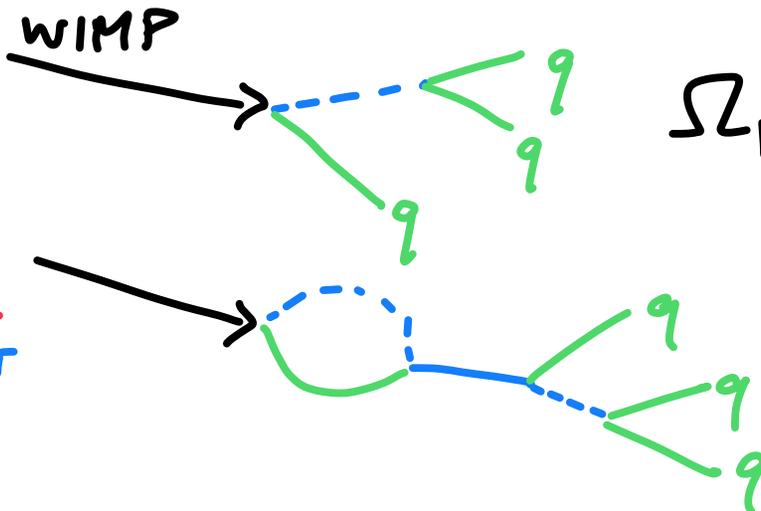
Early Universe equilibrium ...
WIMP \leftrightarrow SM



freezes out as universe expands

$$\Omega_{\text{WIMP}} \approx 0.1 \left(\frac{g_{\text{weak}}}{g_{\text{WIMP}}} \right)^4 \frac{m_{\text{mediator}}^4}{m_{\text{WIMP}}^2 \text{TeV}^2}$$

long-lived unstable WIMP
O(1) ~~CP~~
Baryon number ~~number~~

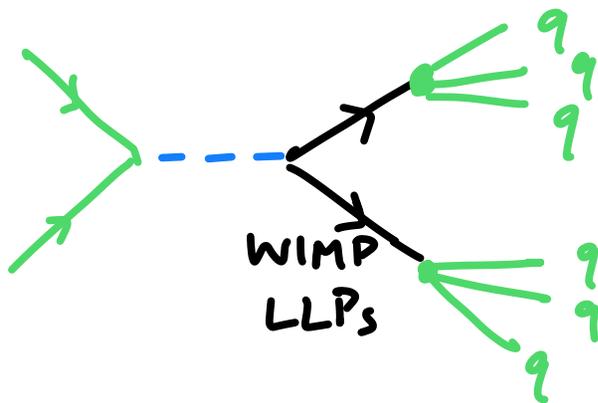


$$\Omega_{\text{baryon}} \approx \text{loop} \cdot \frac{m_{\text{proton}}}{m_{\text{WIMP}}} \Omega_{\text{WIMP}}$$

O(1) differences in stable/unstable WIMPs can accommodate $\Omega_{\text{baryon}} \sim 1/5 \Omega_{\text{DM}}$

BARYOGENESIS FOR WIMPS!

→ Broadest Collider Exploration
with optimal sensitivity to v. weakly
produced Long-Lived Particles (LLPs)
 $\tau_{\text{WIMP}} \gtrsim \text{cm}$ for out-of-equilibrium WIMP decay
after freezeout.



Challenge: Can we detect
baryon asymmetry in
LLP decays?

SUPERSYMMETRY

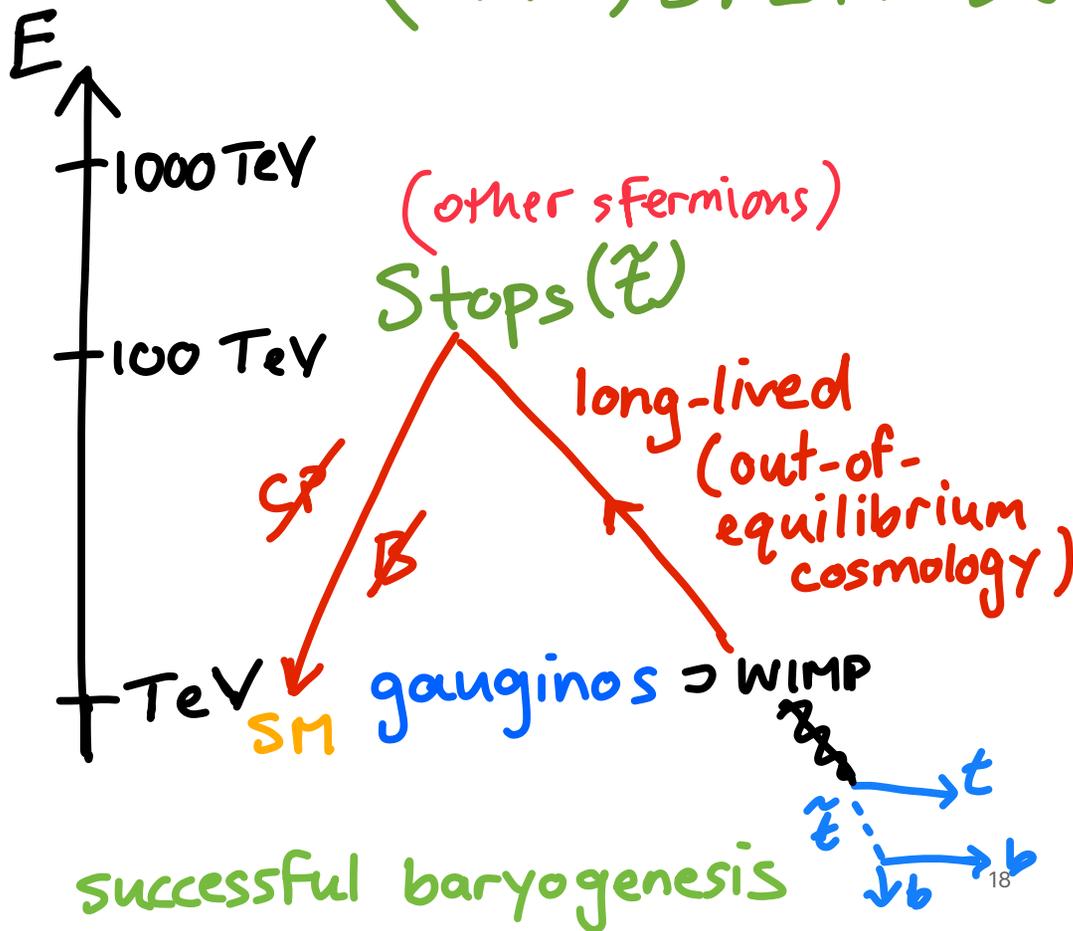
remains a strongly motivated paradigm for resolving Hierarchy Problem, & scaffolding for other mechanisms (eg. DM, Baryogenesis, ...)

$m_h = 125 \text{ GeV}$ (+ absence of superpartners @ LHC) suggests $M_{\text{stops}} \gtrsim 10 \text{ TeV}$

BARYOGENESIS FOR WIMPS in (mini-)SPLIT SUSY

Cui, Sundrum '12
Cui '13

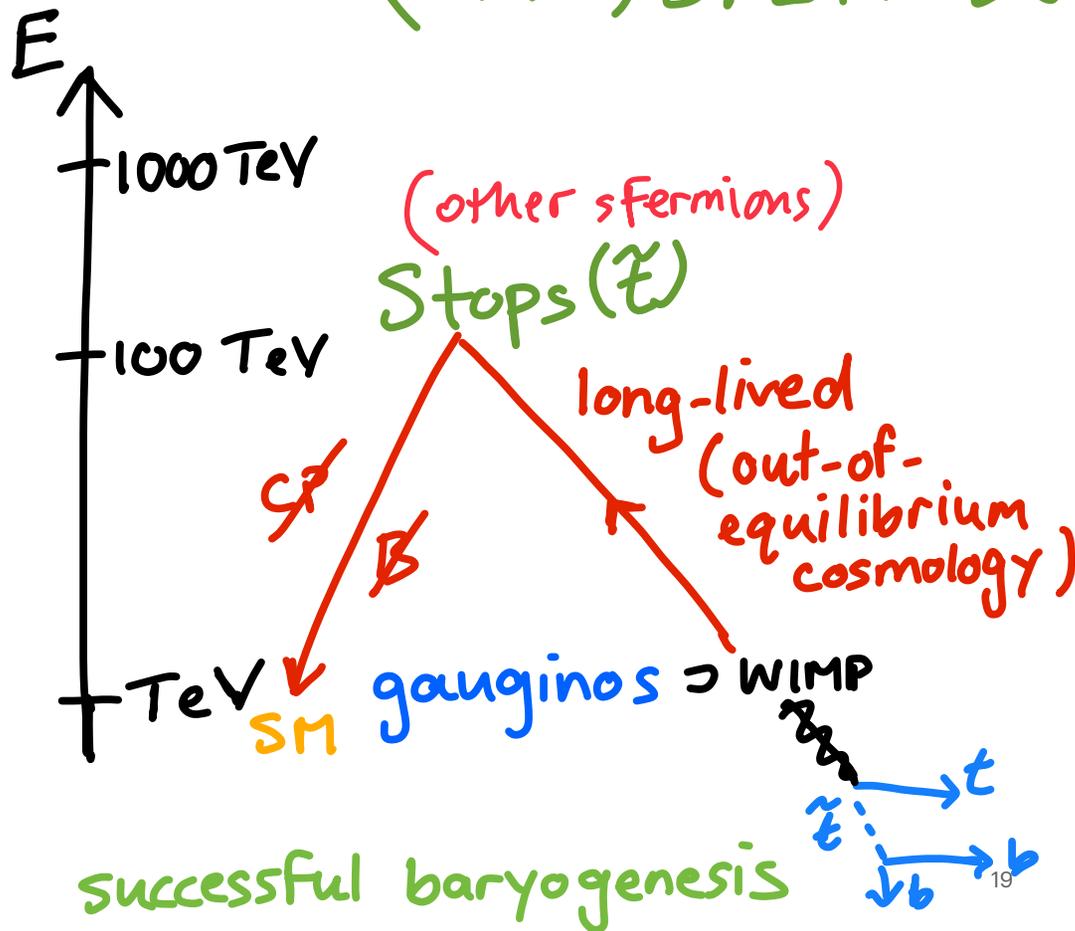
R-Parity violating
SUSY



BARYOGENESIS FOR WIMPS in (mini-)SPLIT SUSY

Cui, Sundrum '12
Cui '13

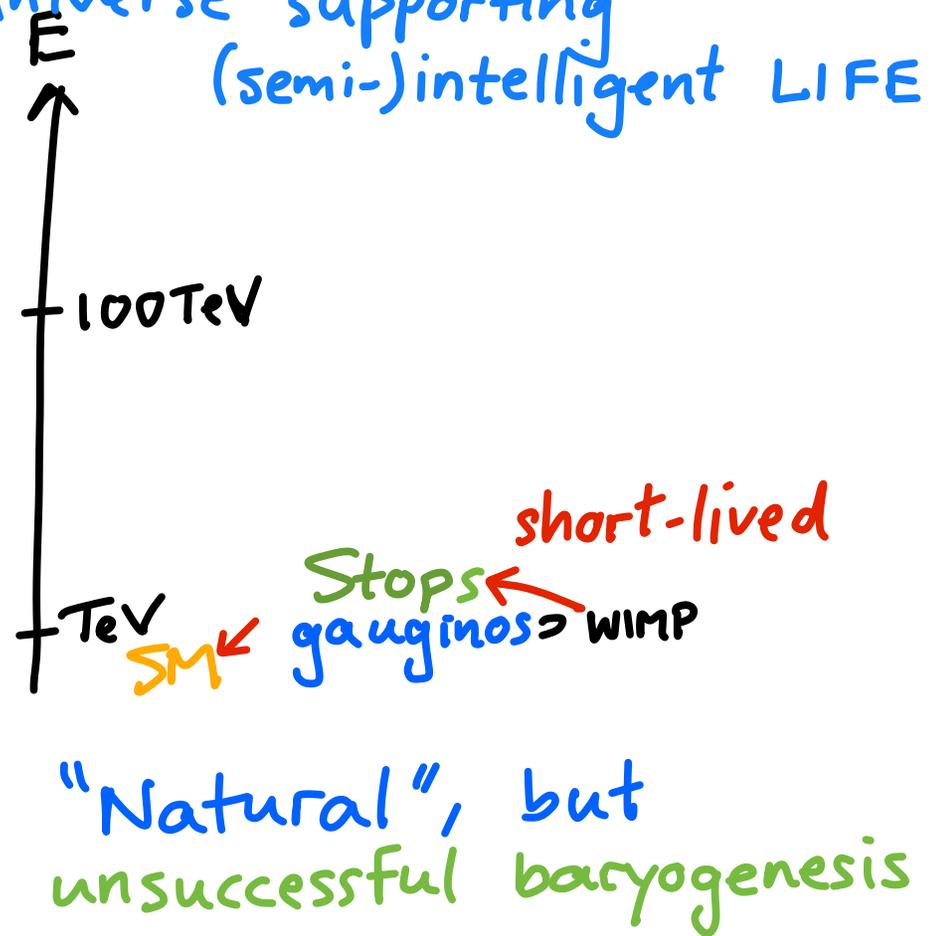
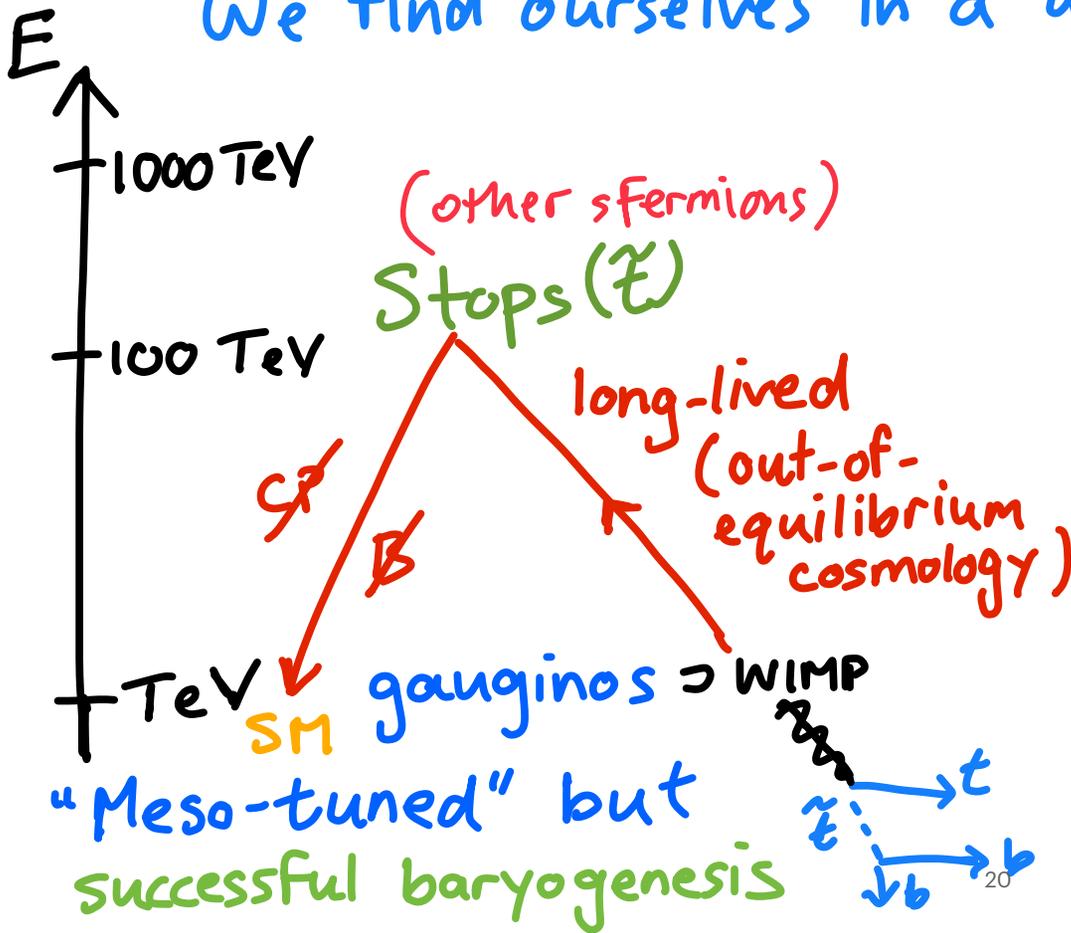
R-Parity violating
SUSY



BUT
Why is SUSY
not more natural?
Less fine-tuned in
Solving Hierarchy
Problem?

ANTHROPIC PRINCIPLE FOR WIMPS!

The MEGaverse \Rightarrow many universes over which L_{EFT} varies
 We find ourselves in a universe supporting
 (semi-)intelligent LIFE



ANTHROPIC PRINCIPLE FOR WIMPS!

The MEGaverse \Rightarrow many universes over which L_{EFT} varies
We find ourselves in a universe supporting
(semi-)intelligent LIFE

Note to self : QUIT WORRYING

ABOUT THE ANTHROPIC PRINCIPLE
+ WHY LHC HASN'T ^{yet!} SEEN BSM PHYSICS.
WE HAVE TO EXPLORE FURTHER, GIVEN
SIGNIFICANT DISCOVERY POTENTIAL

ARE WE ALONE ?

Gauge Field Theory naturally divides into "socially-distanced pods" (sectors) of gauge fields & charged matter.

SM is one such, but are there other "ghostly" gauge sectors awaiting discovery?

In Supergravity models, EWSB radiatively triggered by ~~SUSY~~ $\sim m_{\text{gravitino}}$. Same mechanism can naturally lead to weak-scale "ghost" sectors

SPECIES versus POPULATION

Massless and/or stable "ghost" populations are constrained:

$$\Delta N_{\text{eff}} < 0.4$$

cosmological constraints on new relativistic particles

$$\Omega_{\text{dark}} < 0.2$$

massive stable particles must fit within DM.

Even 1000's of new gauge sectors allowed phenomenologically/string-theoretically (!) if poorly "reheated" post-inflation, or unstable to SM decay.

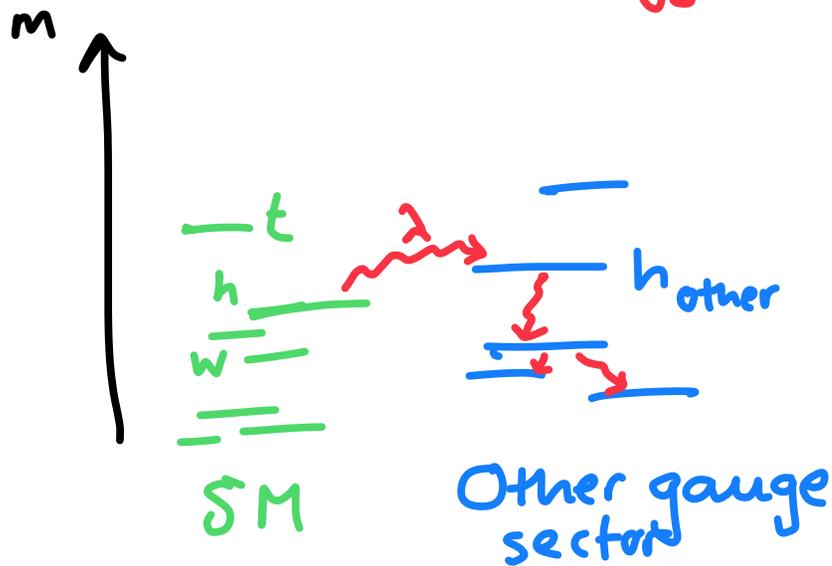
THE HIGGS PORTAL

to other gauge sectors

$$\mathcal{L} \supset \lambda \langle H_{SM}^\dagger \rangle H_{SM} H_{other}^\dagger \langle H_{other} \rangle$$

Higgs mixing

is special,
renormalizable
(ie. efficient)
window of opportunity



\Rightarrow Exotic Higgs decays,
important to confidently
detect modest ~~E~~ at
modest rates

THE HIGGS PORTAL

to other gauge sectors

$$\mathcal{L} \supset \lambda \langle H_{SM}^\dagger \rangle H_{SM} H_{other}^\dagger \langle H_{other} \rangle$$

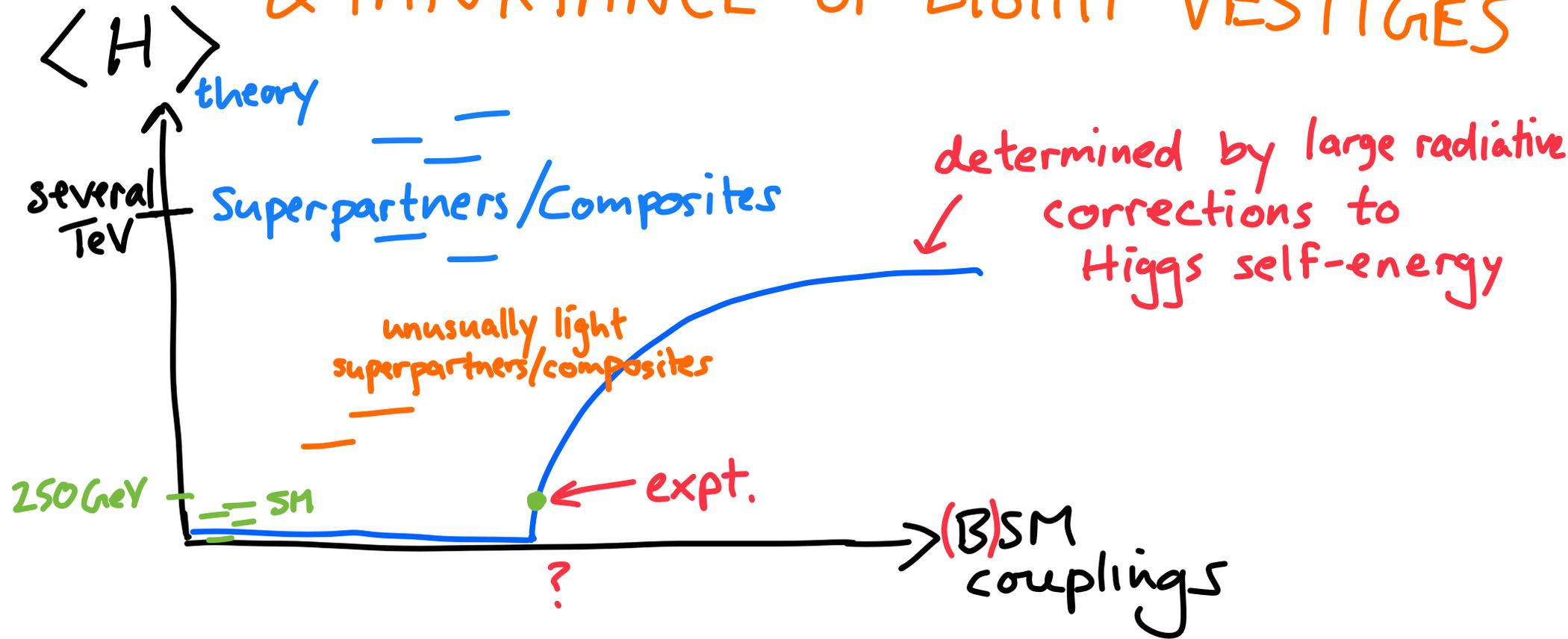
Higgs mixing

is special
renormalizable
(ie. efficient)
window of opportunity



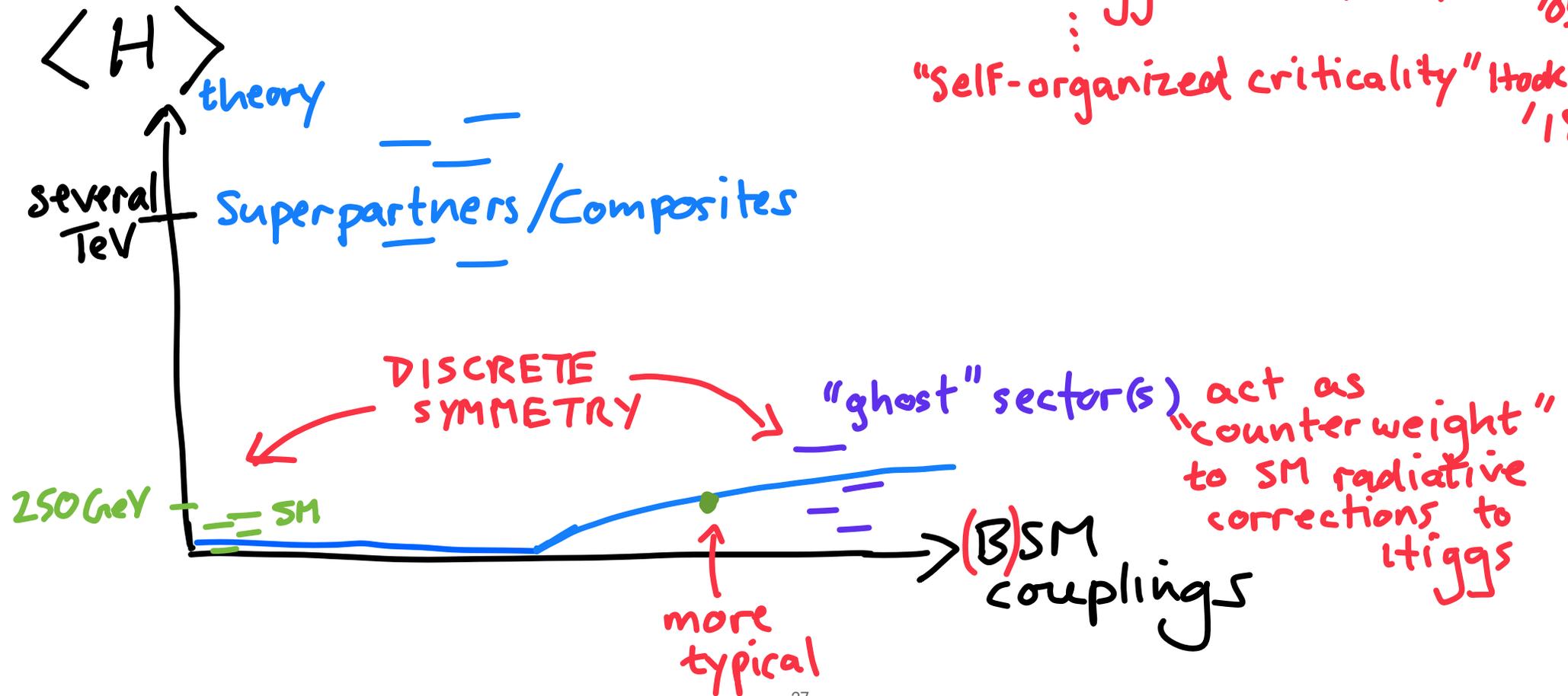
\Rightarrow Important to detect long-lived decays from other sectors back to SM.

THE (LITTLE) HIERARCHY PROBLEM & IMPORTANCE OF LIGHT VESTIGES



NEUTRAL NATURALNESS

"Twin Higgs" Chacko, Groh, Harnik '05
⋮
"Self-organized criticality" Hodge '18

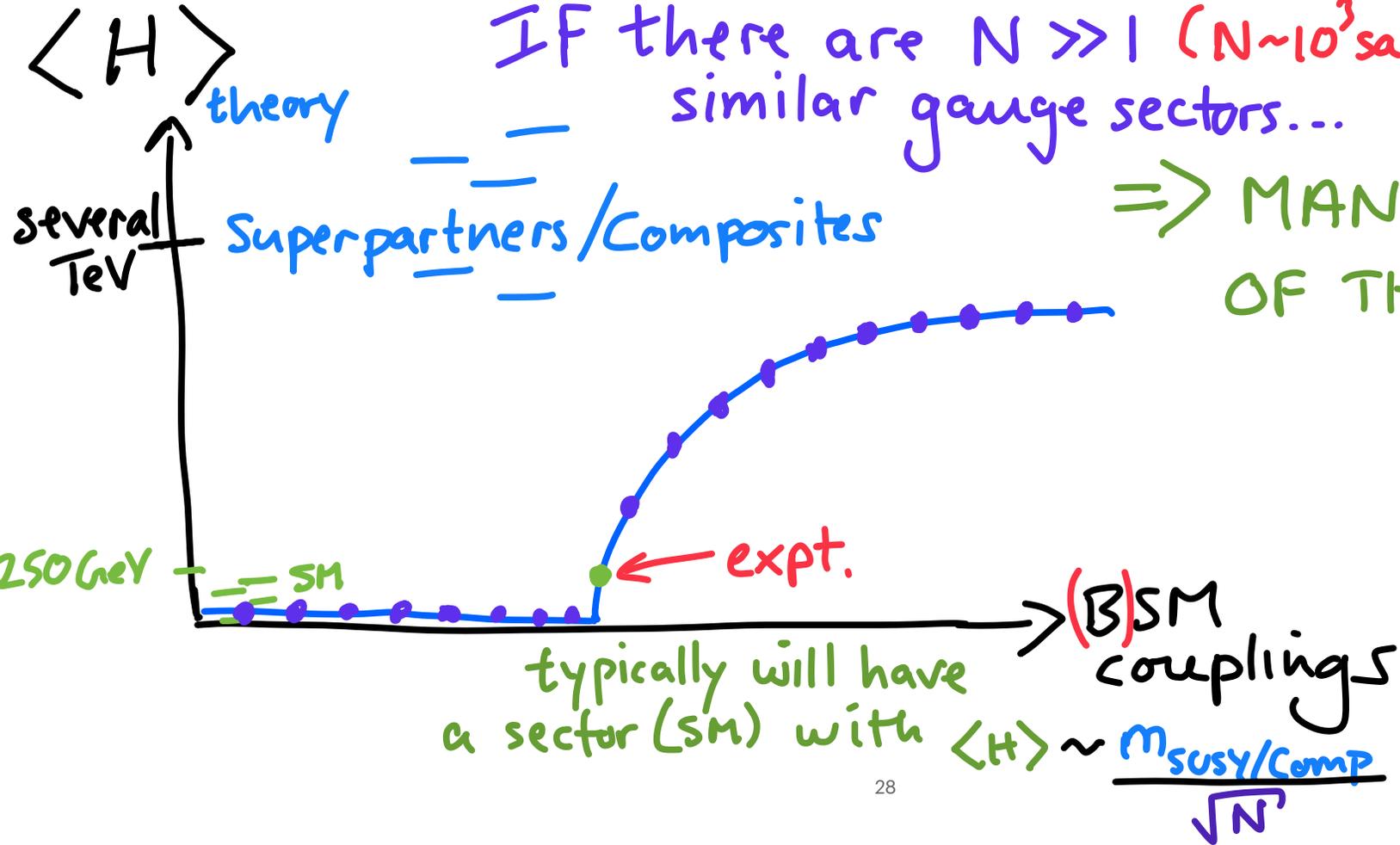


Alternately, N NATURALNESS

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

IF there are $N \gg 1$ ($N \sim 10^3$ say)
similar gauge sectors...

\Rightarrow MANY THROWS
OF THE DICE!

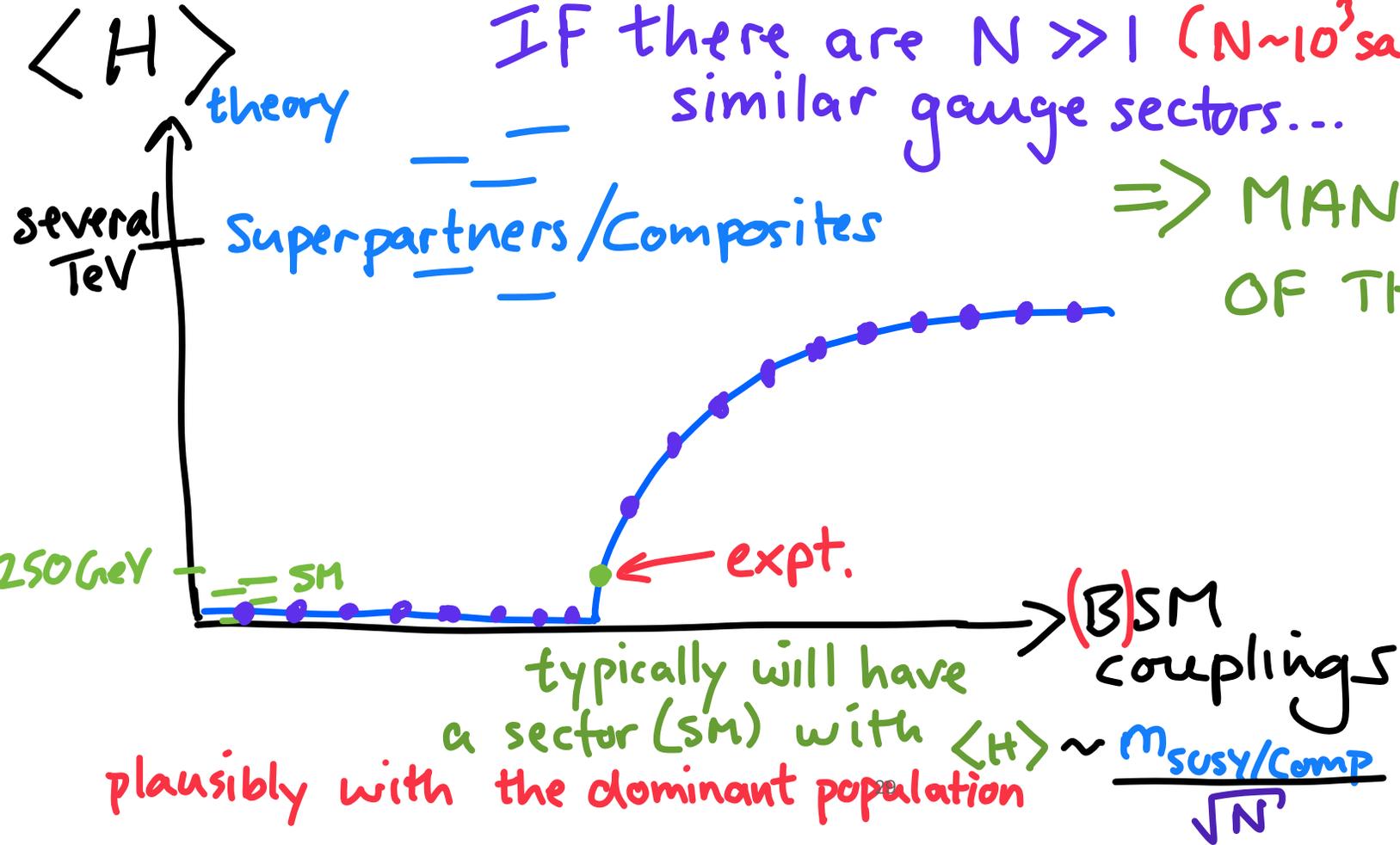


Alternately, N NATURALNESS

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

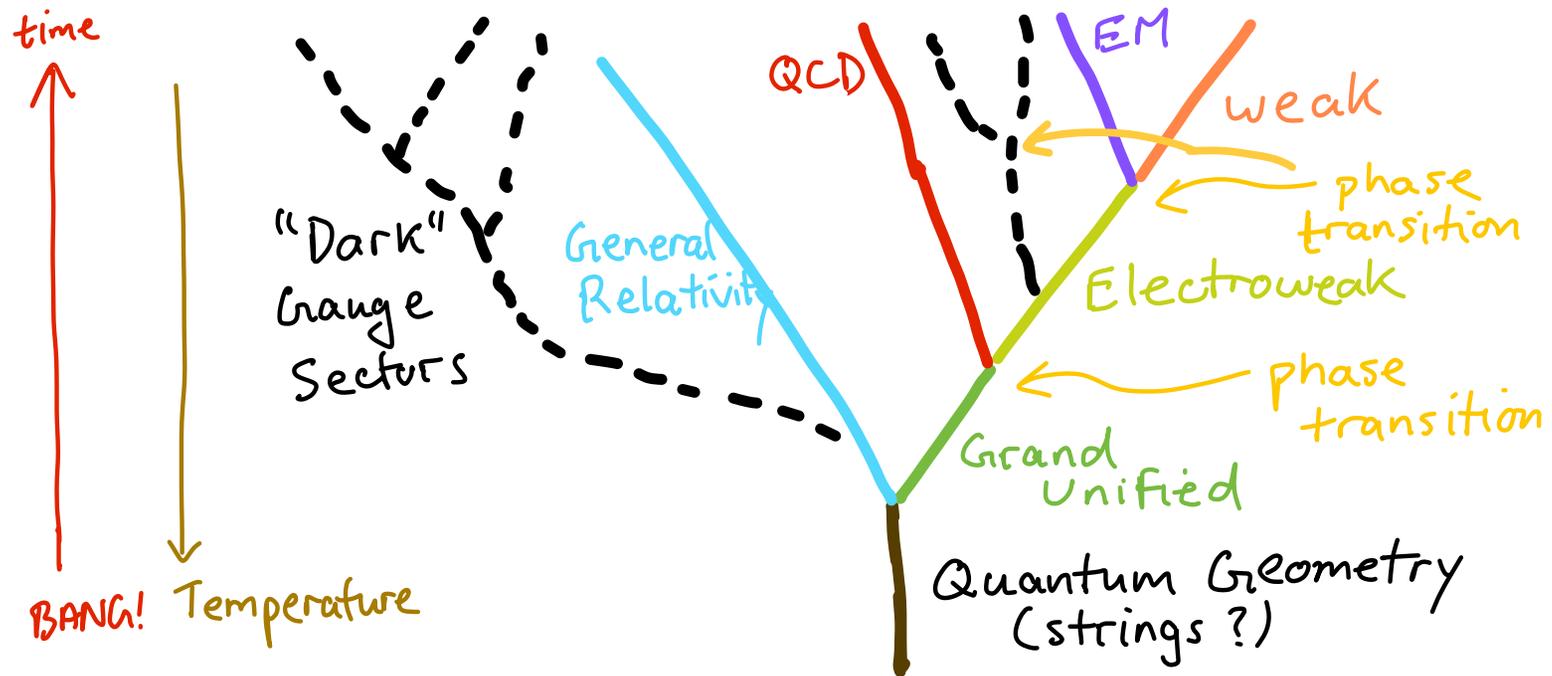
IF there are $N \gg 1$ ($N \sim 10^3$ say)
similar gauge sectors...

\Rightarrow MANY THROWS
OF THE DICE!



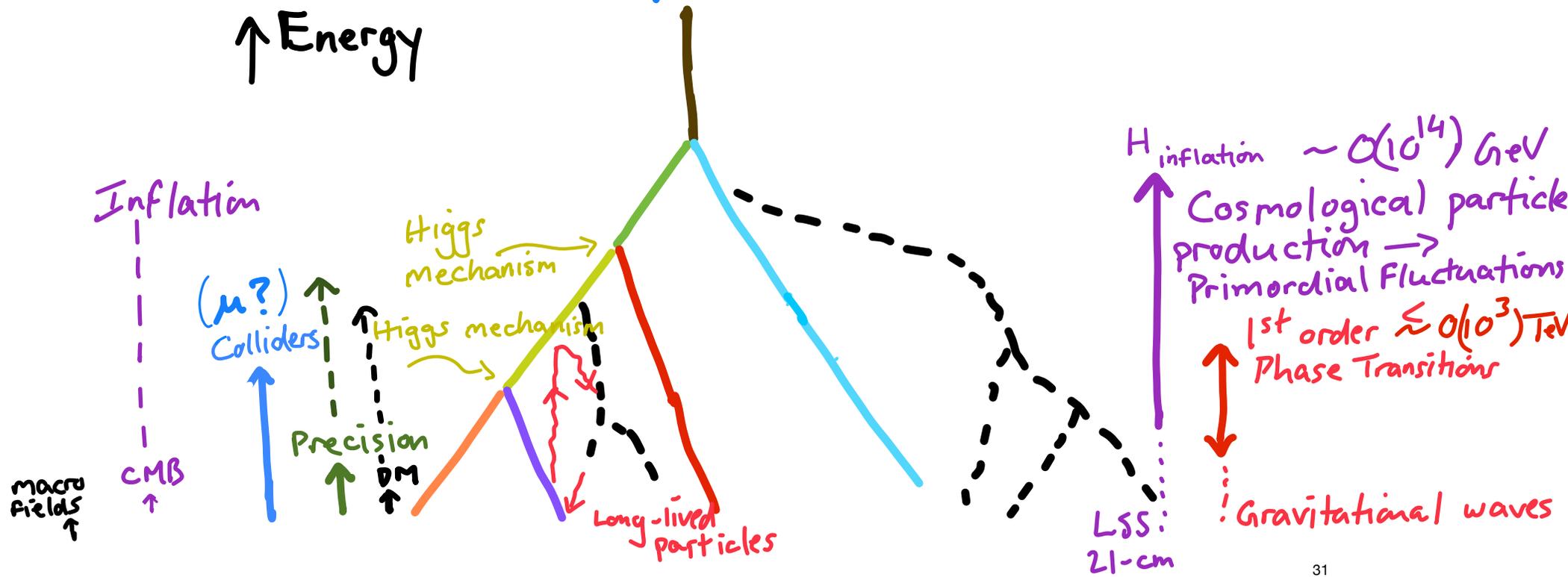
Superpartners/Composites

FAMILY TREE OF FUNDAMENTAL PHYSICS



FAMILY TREE OF FUNDAMENTAL PHYSICS

A muon collider would fit into a diverse & heroic push to map Nature's laws.



CONCLUSIONS

There are BROAD EXCITING PHYSICS THEMES to pursue at a future collider:

Dark Matter, Baryogenesis, SUSY, Compositeness, flavor origins, parallel gauge sectors, long-lived particles, precision Higgs structure

Need a collider at highest energies, clean enough & with sensitive enough detectors, to pursue both high mass &/or weakly coupled BSM at high precision & to excite & challenge next generation of experimentalists.

If new physics (dimly) seen in DM, flavor, EDM, precision, gravitational wave, cosmological expts., we need collider with reach/precision to complement, corroborate, clarify