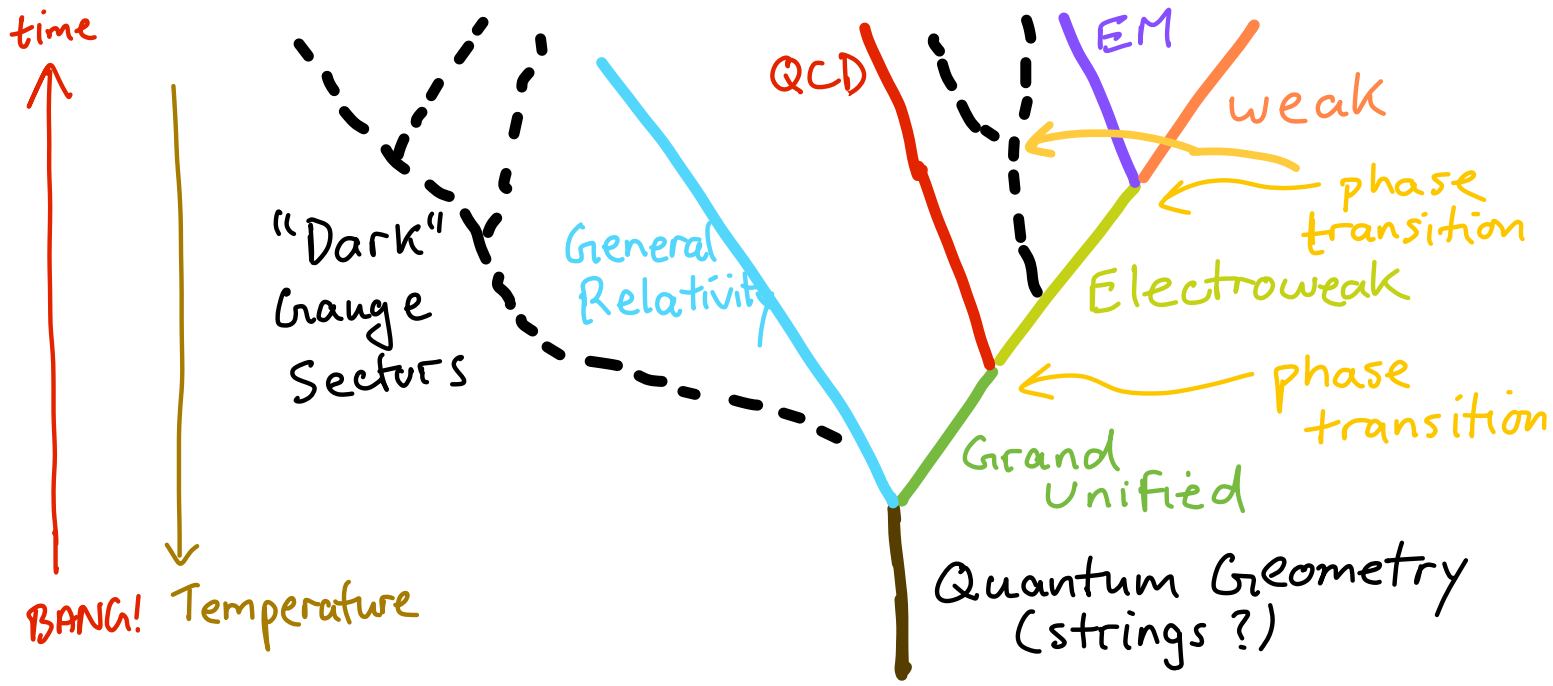
BSM FOR FUTURE COLLIDERS

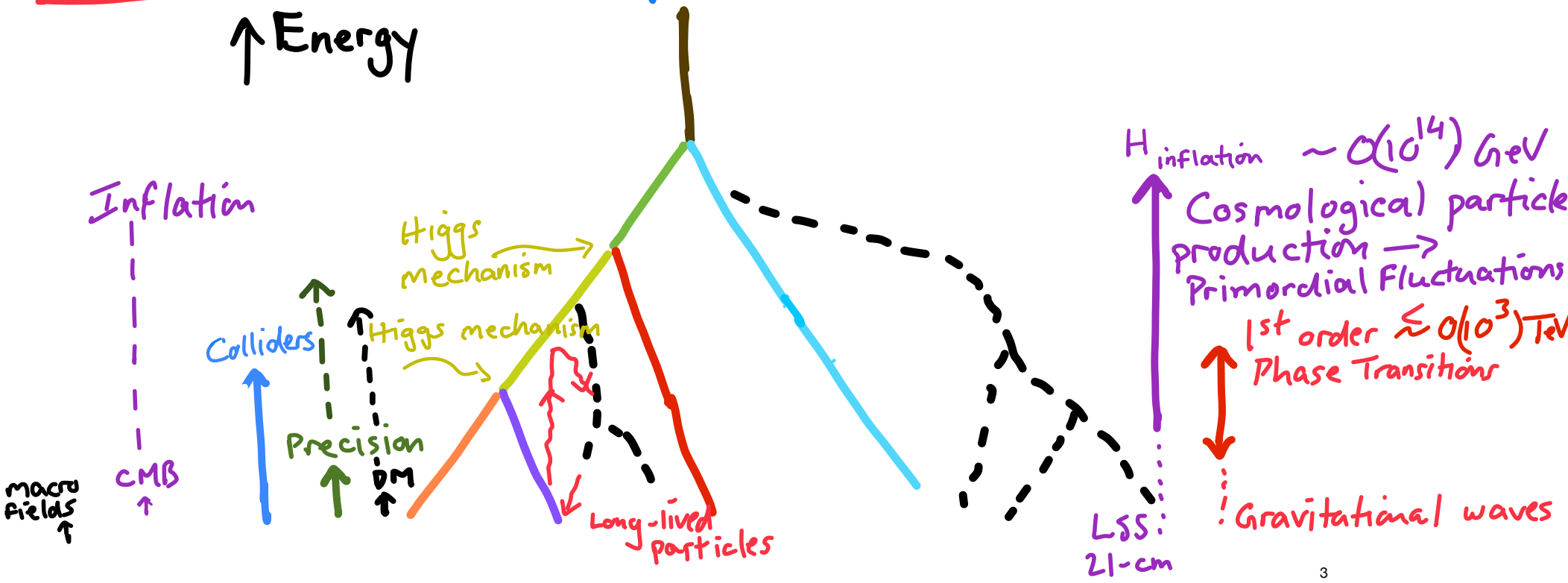
Raman Sundrum
University of Maryland

FAMILY TREE OF FUNDAMENTAL PHYSICS



AN EXPLORER'S MAP

Future colliders would fit into a diverse & heroic push to map Nature's laws.



OUTLINE

Higgs-ploration

Composite Resonances

Gravitational Waves from Cosmological Phase Transitions

WIMP Dark Matter

Matter-Antimatter Asymmetry

Long-Lived Particles

Supersymmetry

The Little Hierarchy Problem & the Anthropic Principle

Ghost ("dark") Sectors

Higgs Portal

Hidden Naturalness

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

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COUPLING $\propto$ MASS

to Higgs boson — from Higgs Mechanism + QUANTUM CORRECTIONS

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

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

SM accomodates, but does not explain:

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

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

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

HIGGS MAY BE LIGHT COMPOSITE OF NEW SECTOR

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

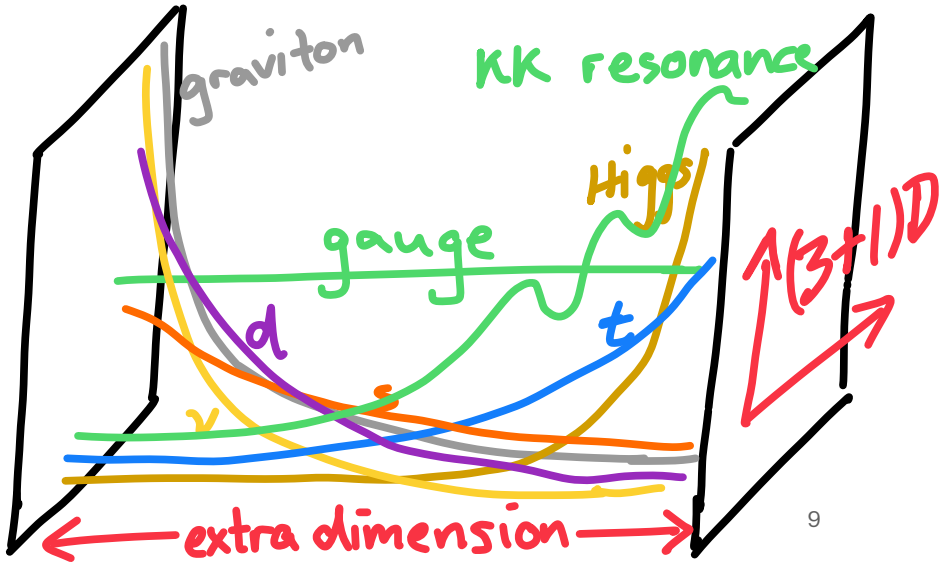
Higgs Compositeness ⇒ small violations of "EP"
⇒ precision Higgs, EW tests

+ 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:

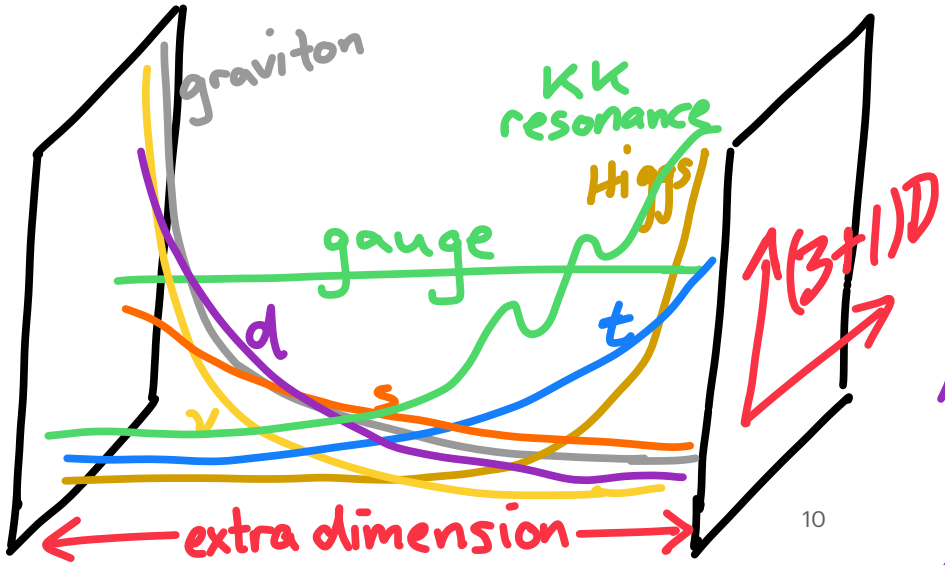
Strong Coupling → Quantum Magic → Emergent "Warped" Extra Dimension

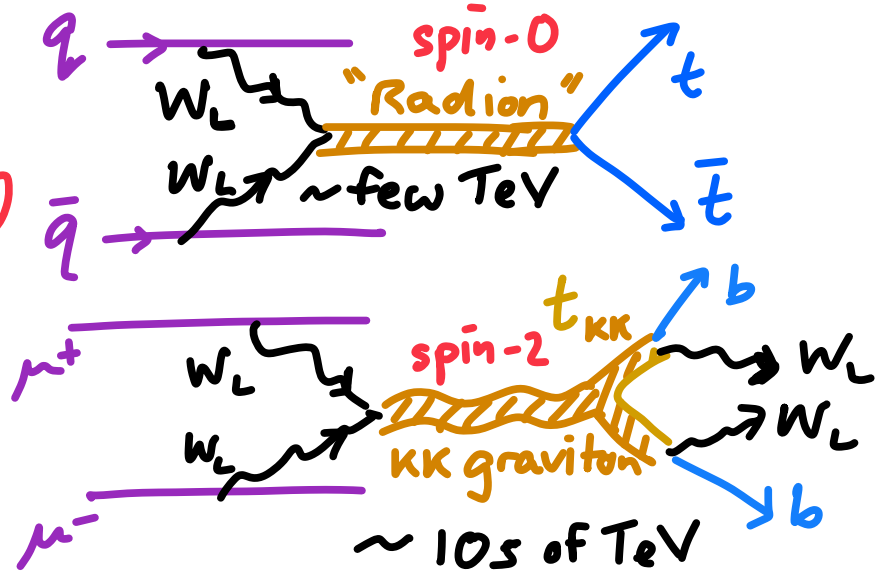


WARPED EXTRA DIMENSION

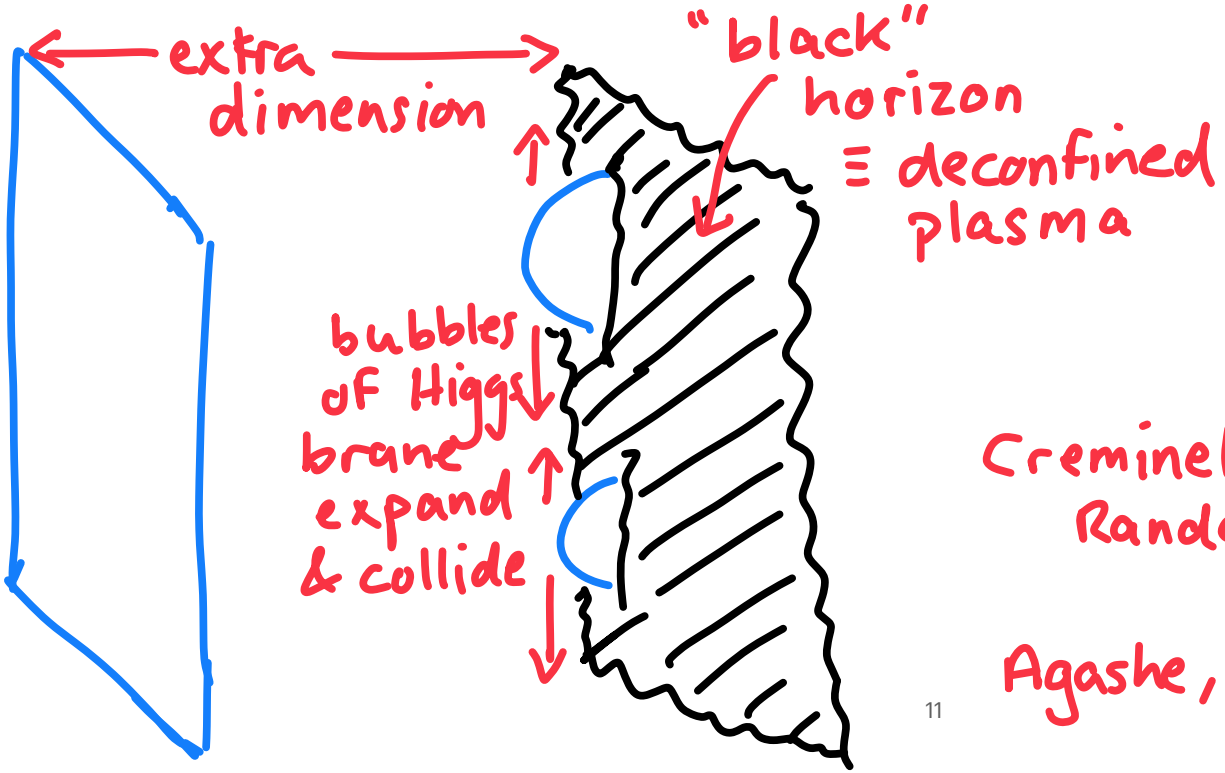
Extra-dimensional wavefunction overlaps ⟶ attractive resolutions of Hierarchy Problem + Flavor Puzzle.

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:





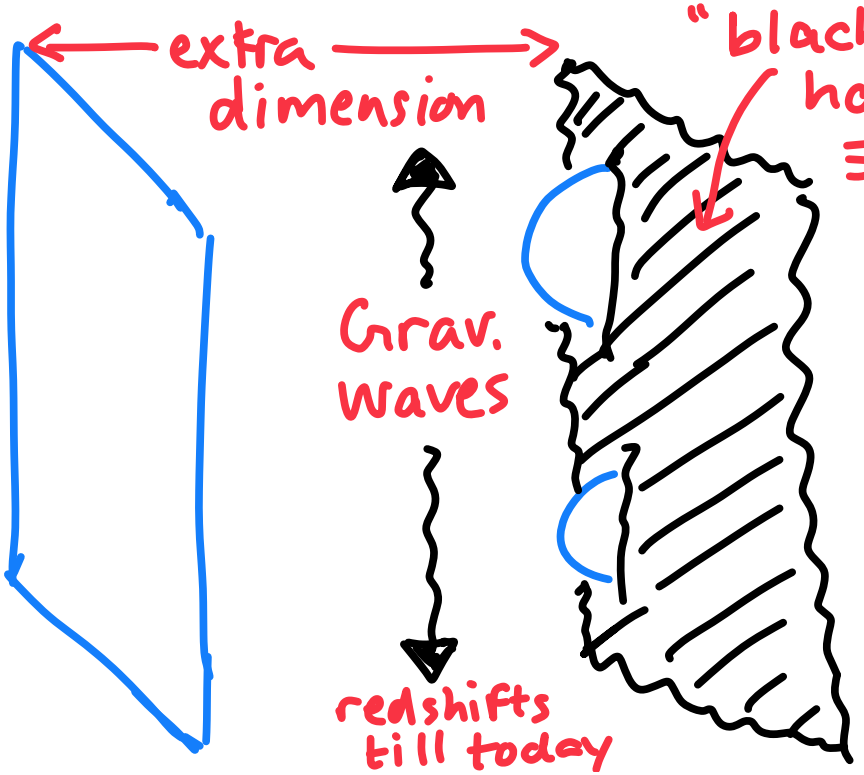
(DE)CONFINEMENT PHASE TRANSITION of Composite Higgs sector in v. Early Universe



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

$\Omega_{GW} \sim$ few. 10^{-10}

≡ TeV critical Temperature

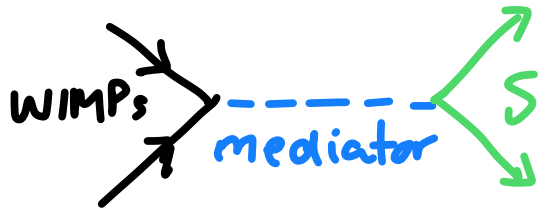
If few TeV scalar radion discovered at collider

⇒ spin-2 KK graviton $\approx$ 20 TeV

THE HEART OF THE MATTER

Dark Matter WIMP "Miracle":

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



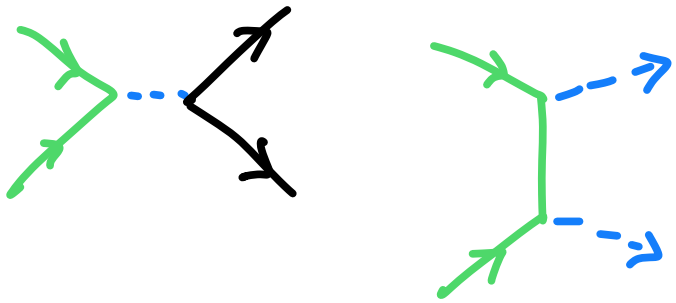
$\rightarrow$ Freezes out as universe expands

Energy Fraction of universe today:

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

$\Rightarrow$ TeV WIMPs attractive

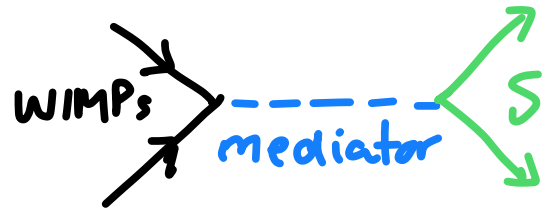
$\rightarrow$ Broadest Collider exploration with optimal $\not{E}$ detection, complementary to DM detection experiments



THE HEART OF THE MATTERS

Dark Matter WIMP "Miracle":

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



Freezes out as universe expands

$\rightarrow$ Energy fraction of surviving WIMPs today

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

BUT WHAT ABOUT THAT OTHER FORM OF MATTER — US?!

ie. Baryons

BARYOGENESIS FOR WIMPS!

Baryogenesis WIMP "Miracle":

Cui, Sundrum '12

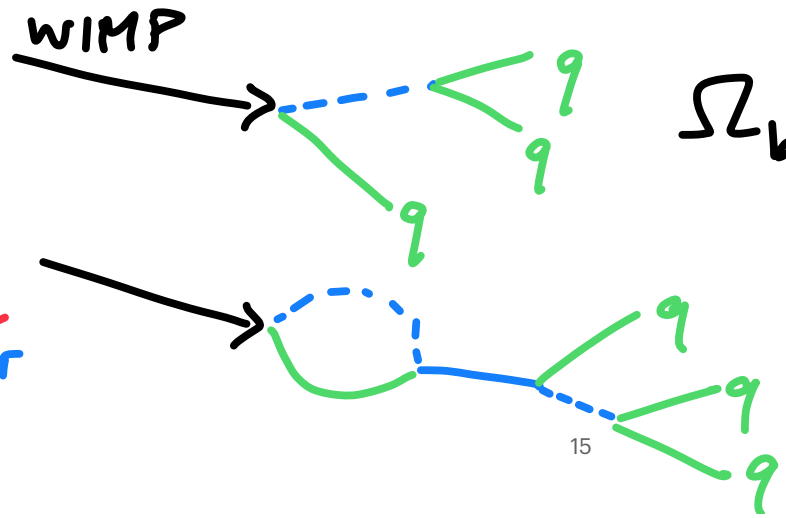
Early Universe equilibrium ... WIMP $\leftrightarrow$ SM $\rightarrow$ WIMPs — mediator — SM $\rightarrow$ Freezes out as universe expands

Energy fraction of surviving WIMPs

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

long-lived unstable WIMP

O(1) ~~CP~~ Baryon ~~number~~



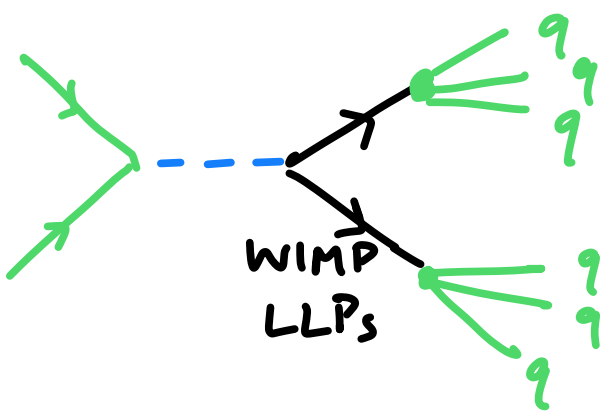
$$\Omega_{baryon} \approx loop \cdot \frac{m_{proton}}{m_{WIMP}} \Omega_{WIMP}$$

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

BARYOGENESIS FOR WIMPS!

→ Broadest Collider Exploration with optimal sensitivity to v. weakly produced Long-Lived Particles (LLPs)

$\tau_{WIMP} \gtrsim$ cm for out-of-equilibrium WIMP decay after freezeout.



Even more broadly, other baryogenesis mechanisms, EW or other phase transition physics, may be within reach.

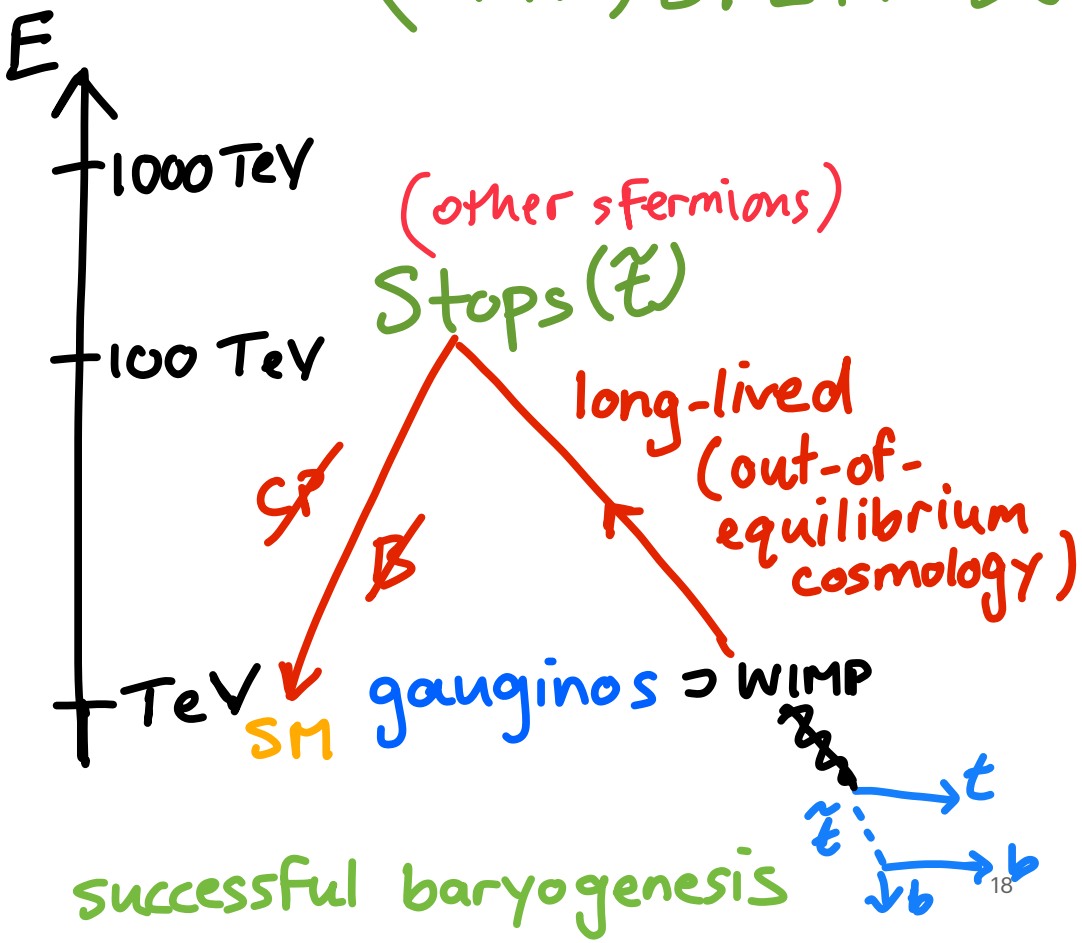
SUPERSYMMETRY

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

$m_h = 125$ GeV (+ absence of superpartners @ LHC) suggests $m_{stops} > 10$ TeV

BARYOGENESIS FOR WIMPs in (mini-) SPLIT SUSY

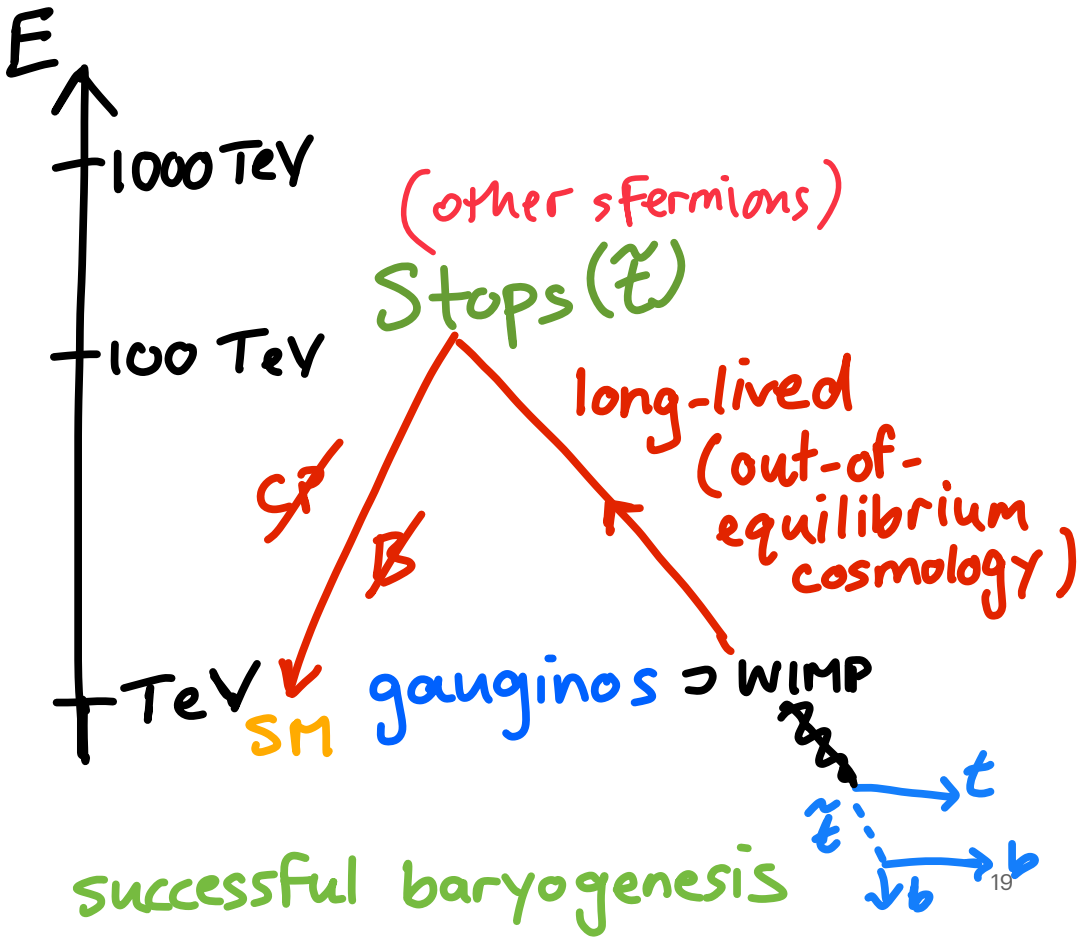
Cui, Sundrum '12
Cui '13
R-Parity violating SUSY



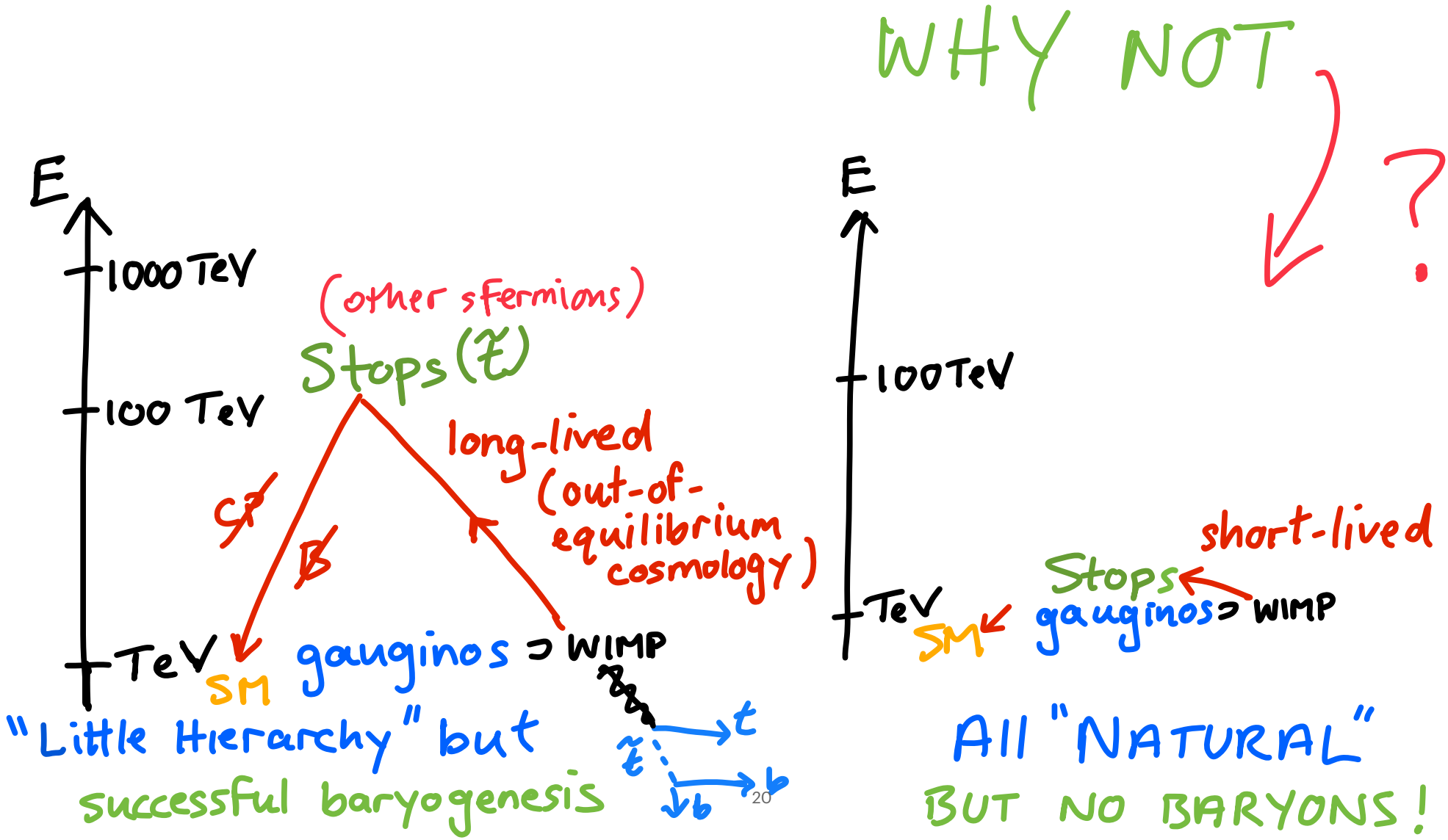
successful baryogenesis

BARYOGENESIS vs. SUSY ?

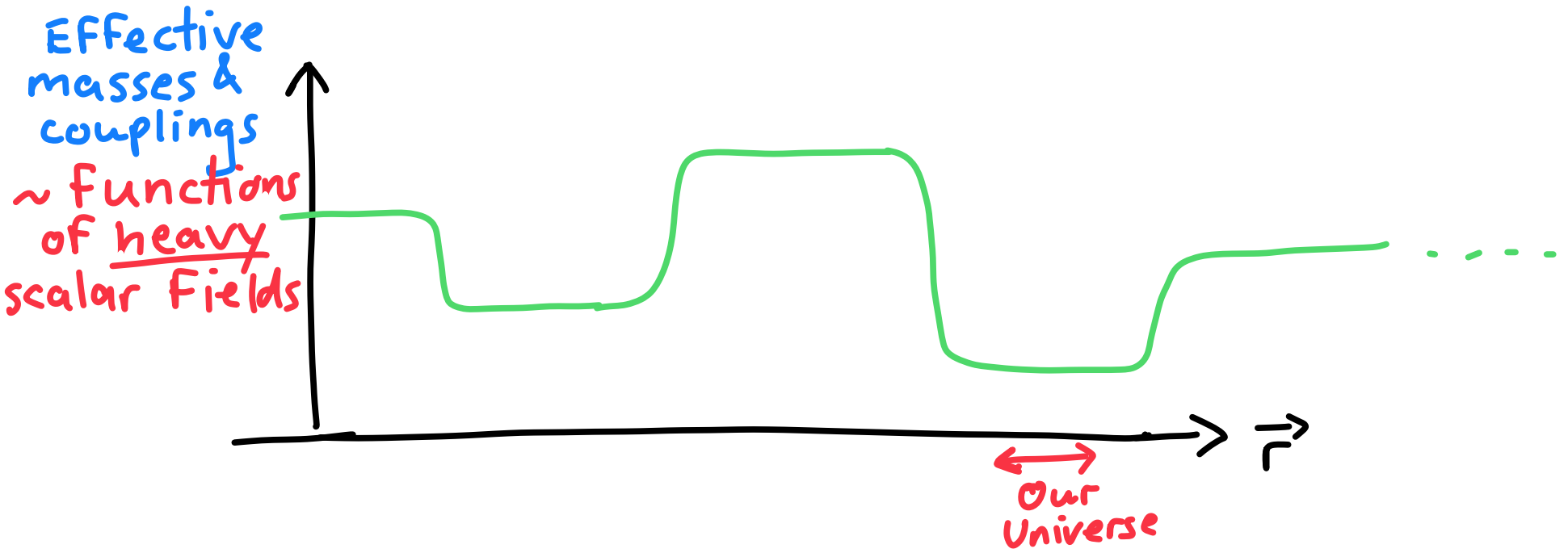
Cui, Sundrum '12
Cui '13
R-Parity violating SUSY



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


E
1000 TeV
100 TeV
TeV
(other sFermions)
Stops ($\tilde{t}$)
long-lived
(out-of-equilibrium cosmology)
SM
gauginos ⊃ WIMP
t
$\tilde{t}$
b
"Little Hierarchy" but
successful baryogenesis
WHY NOT
?
E
100 TeV
TeV
short-lived
Stops
gauginos ⊃ WIMP
SM
All "NATURAL"
BUT NO BARYONS!

SATELLITE VIEW OF THE MULTIVERSE



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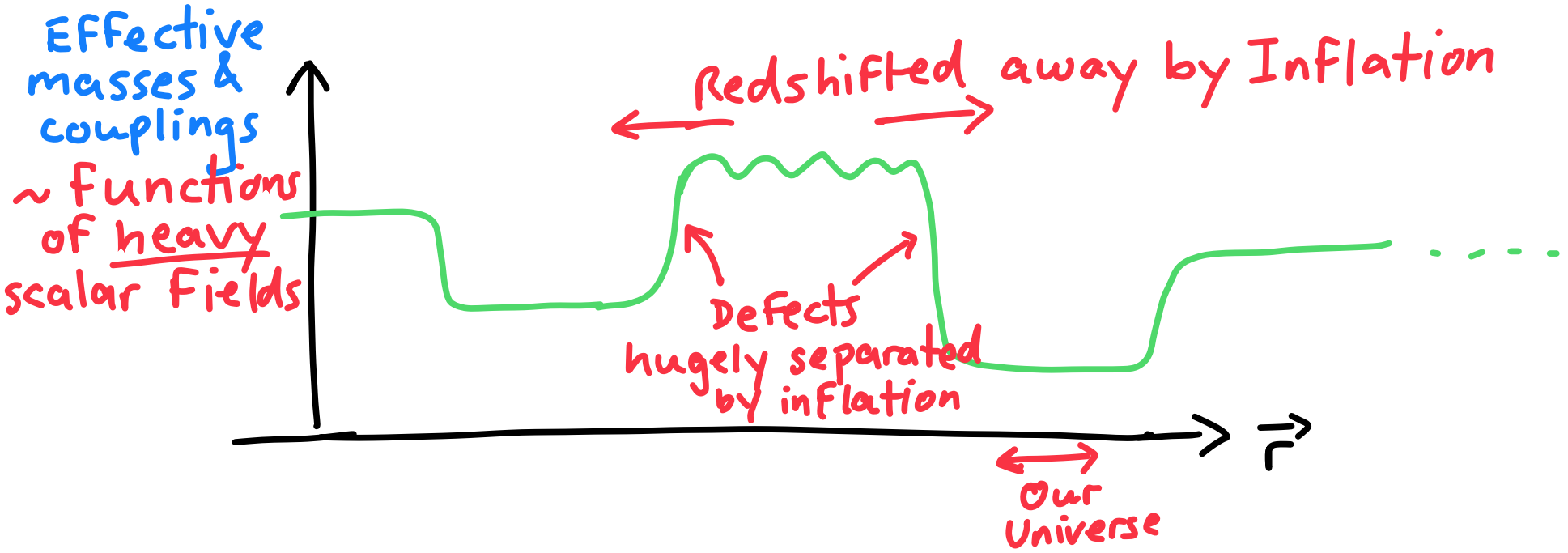

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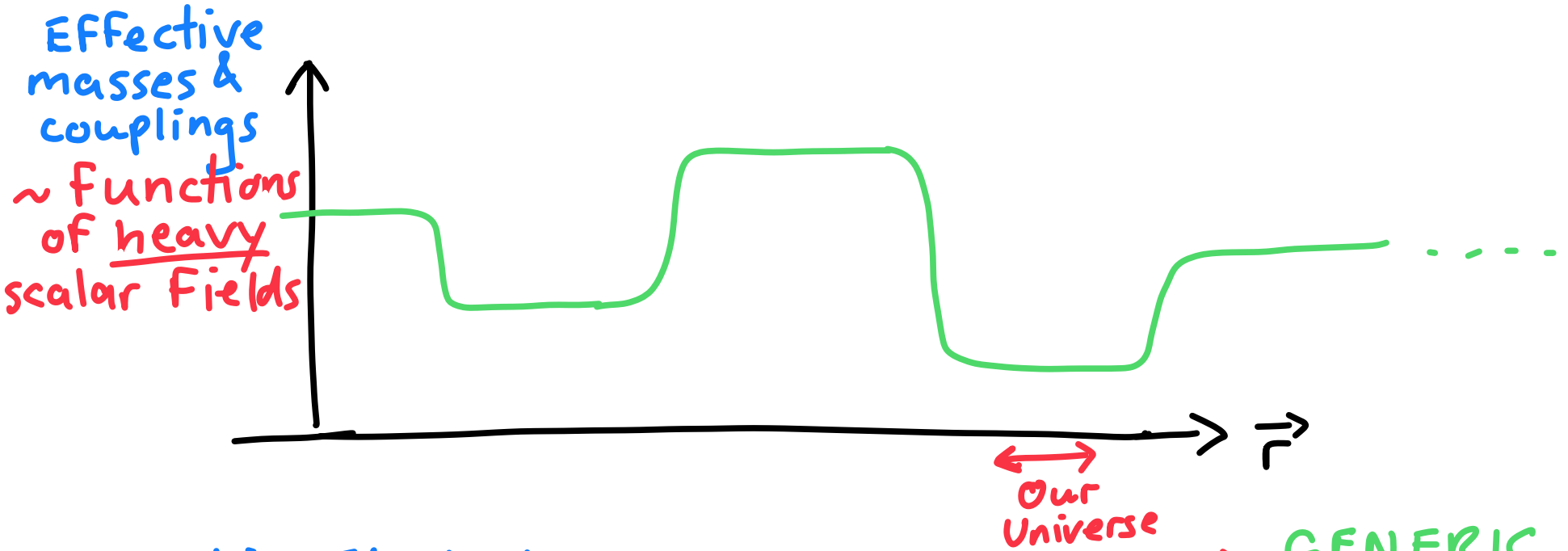
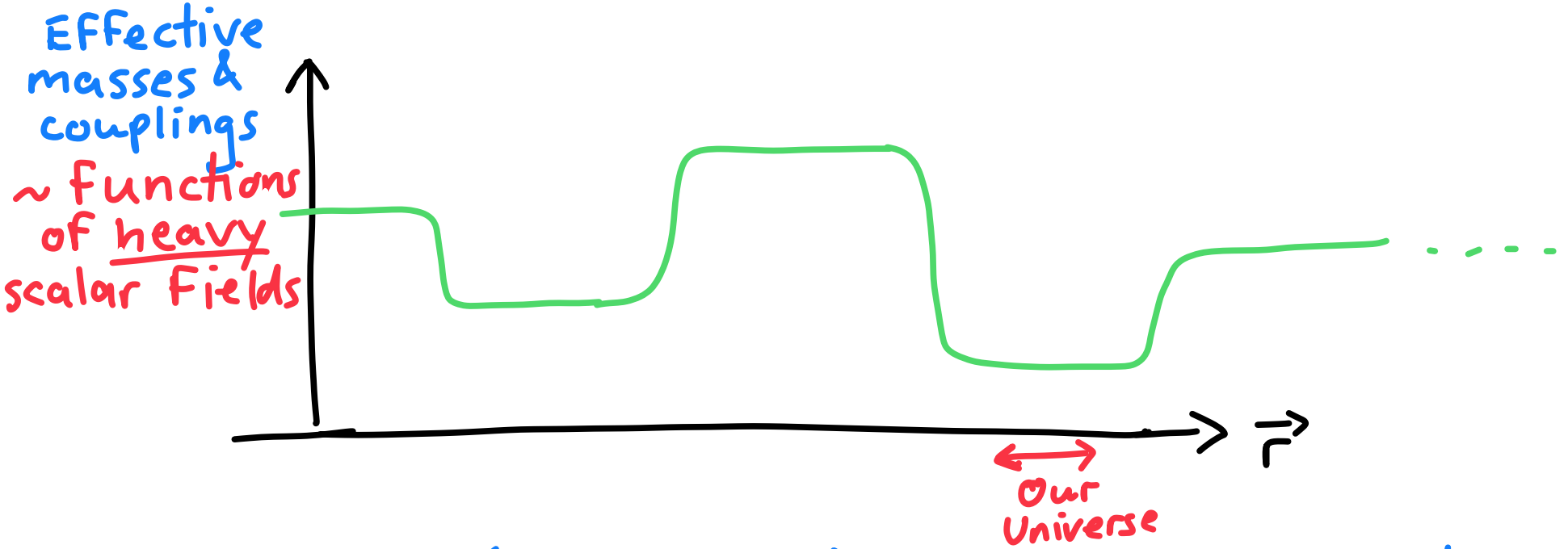


EFFective Field Theory NATURALNESS $\Rightarrow$ GENERIC IN MULTIVERSE

best estimate

FRUSTRATED NATURALNESS



There is a (lop-sided) competition between Naturalness (genericity) & ANTHROPIC requirements (eg. baryons) → LITTLE HIERARCHY "PROBLEM"

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:

$\Delta N_{eff} < 0.4$

$\Omega_{dark} < .2$

cosmological constraints on new relativistic particles

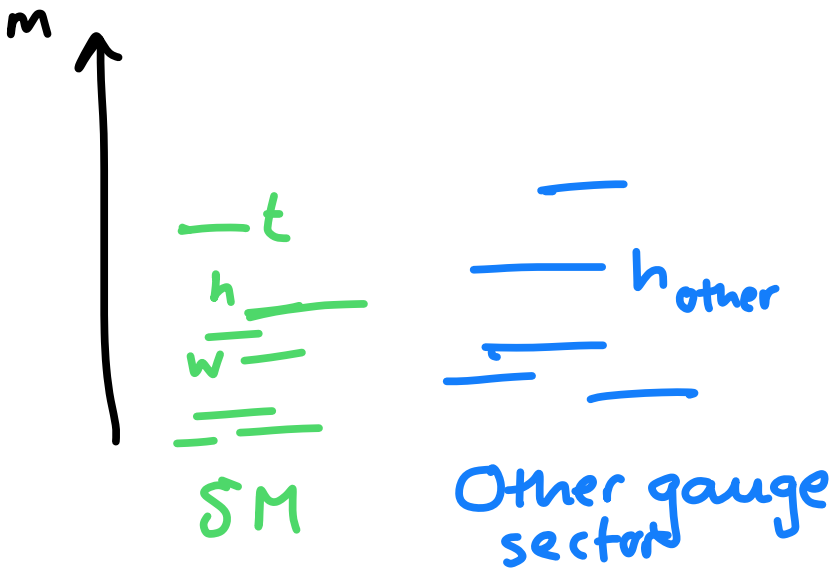
massive stable particles must fit within DM.

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

$\mathcal{L} \supset \lambda H^{\dagger}_{SM} H_{SM} H^{\dagger}_{other} H_{other}$

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



THE HIGGS PORTAL
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$$\mathcal{L} \supset \lambda \langle H^\dagger_{SM} \rangle H_{SM}\, H^\dagger_{other} \langle H_{other} \rangle$$

Higgs mixing

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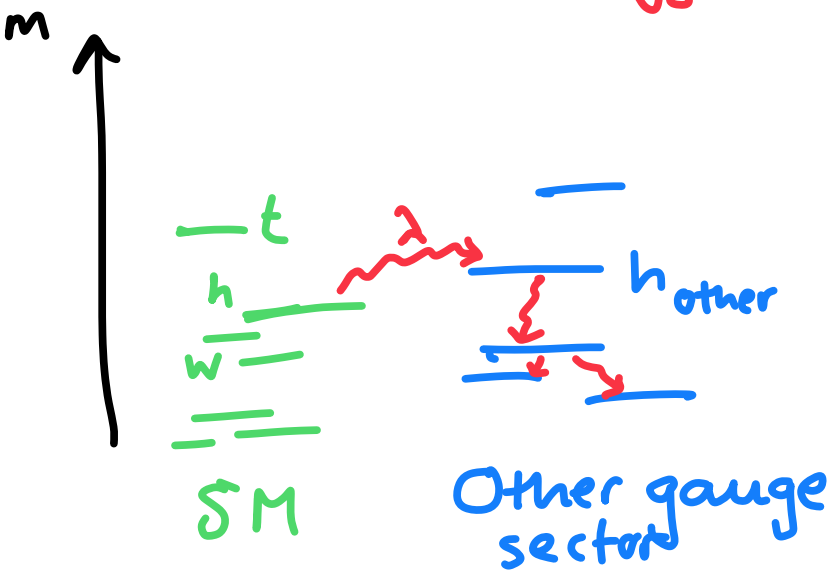

⇒ Exotic Higgs decays, important to confidently detect modest ~~E~~ at modest rates

THE HIGGS PORTAL
to other gauge sectors

$\mathcal{L} \supset \lambda \langle H^\dagger_{SM} \rangle H_{SM} \, H^\dagger_{other} \langle H_{other} \rangle$

Higgs mixing

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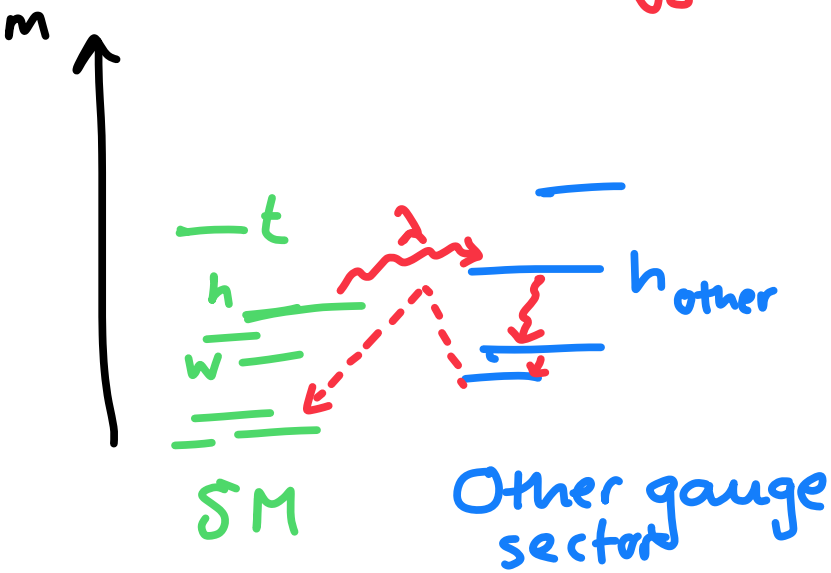
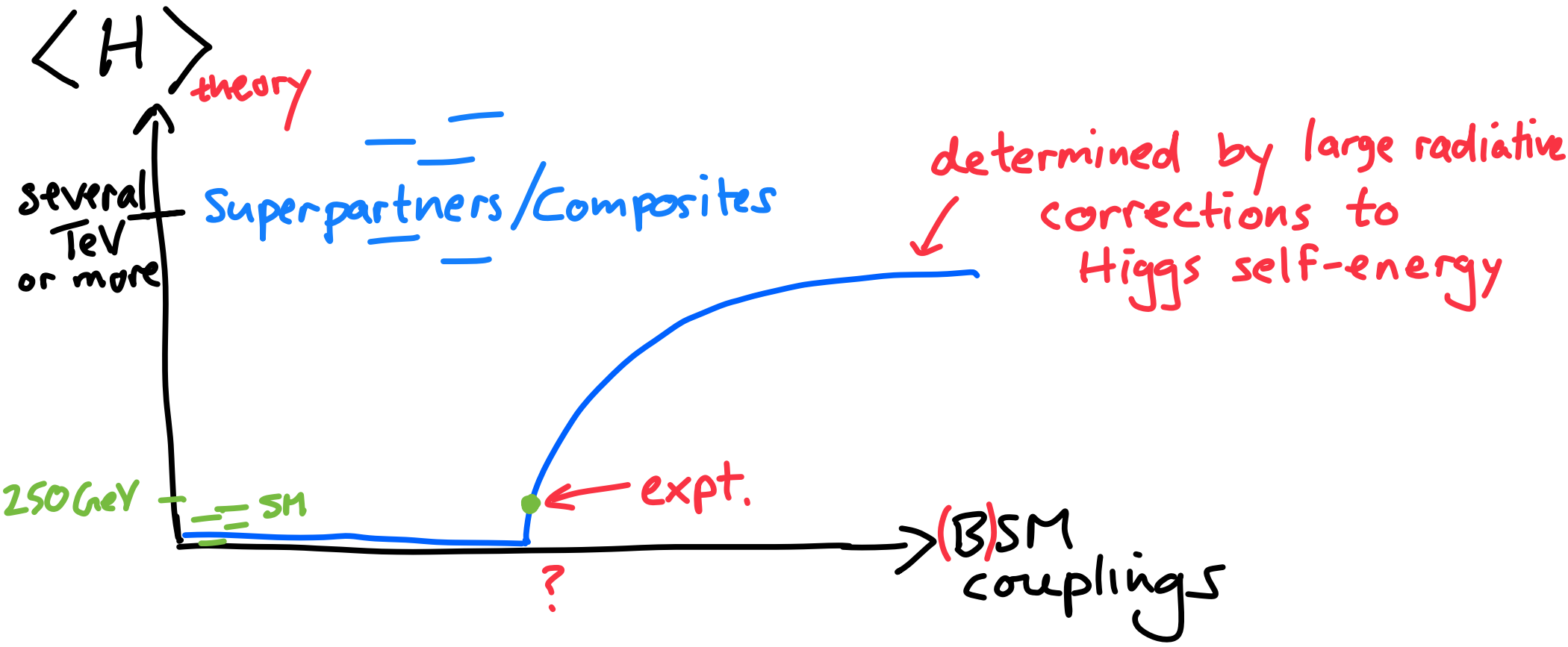
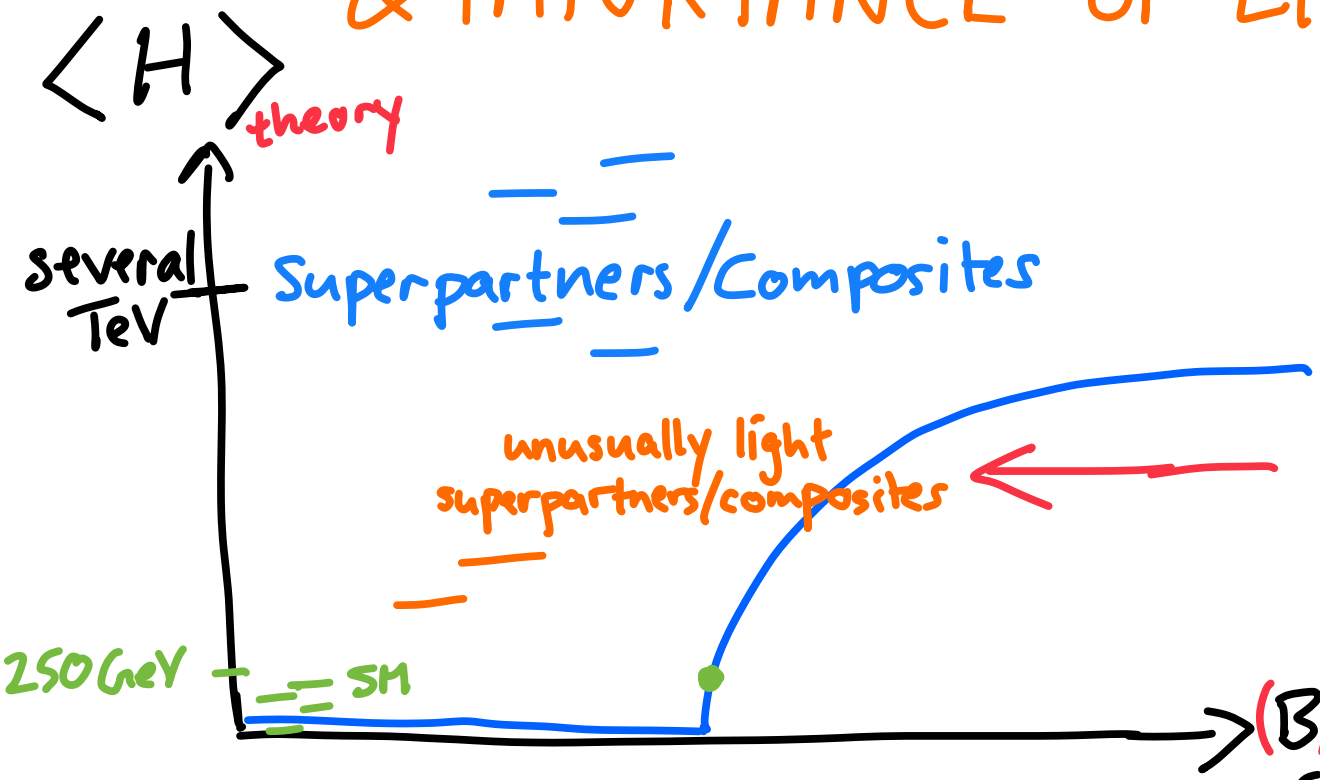


⇒ Important to detect long-lived decays from other sectors back to SM.

THE (LITTLE) HIERARCHY



THE (LITTLE) HIERARCHY & IMPORTANCE OF LIGHT VESTIGES

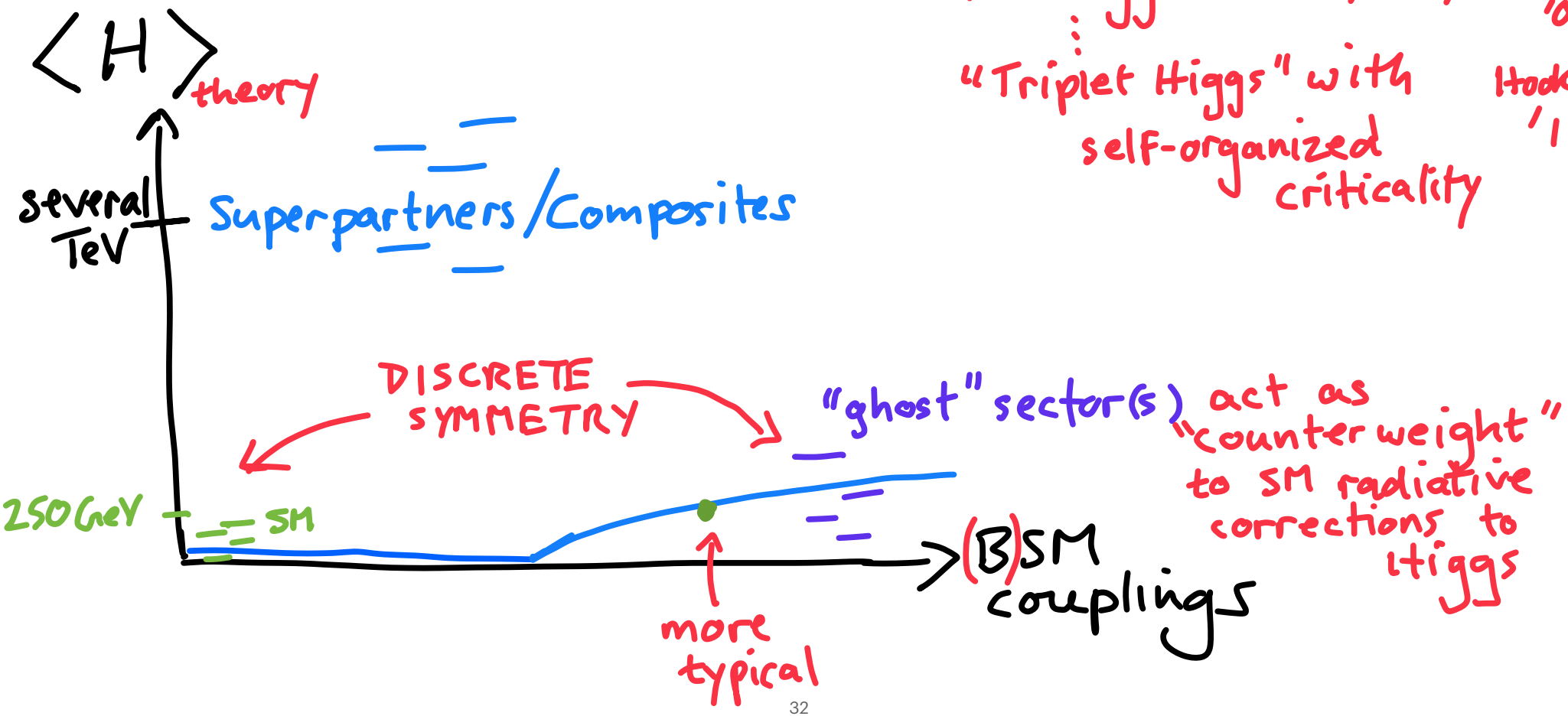


- First to discover
- May explain FRUSTRATED NATURALNESS
- May underlie anomalies in precision tests eg. $(g-2)_\mu$

NEUTRAL (HIDDEN) NATURALNESS

"Twin Higgs" Chacko, Goh, Harnik '05

"Triplet Higgs" with self-organized criticality Hook '18

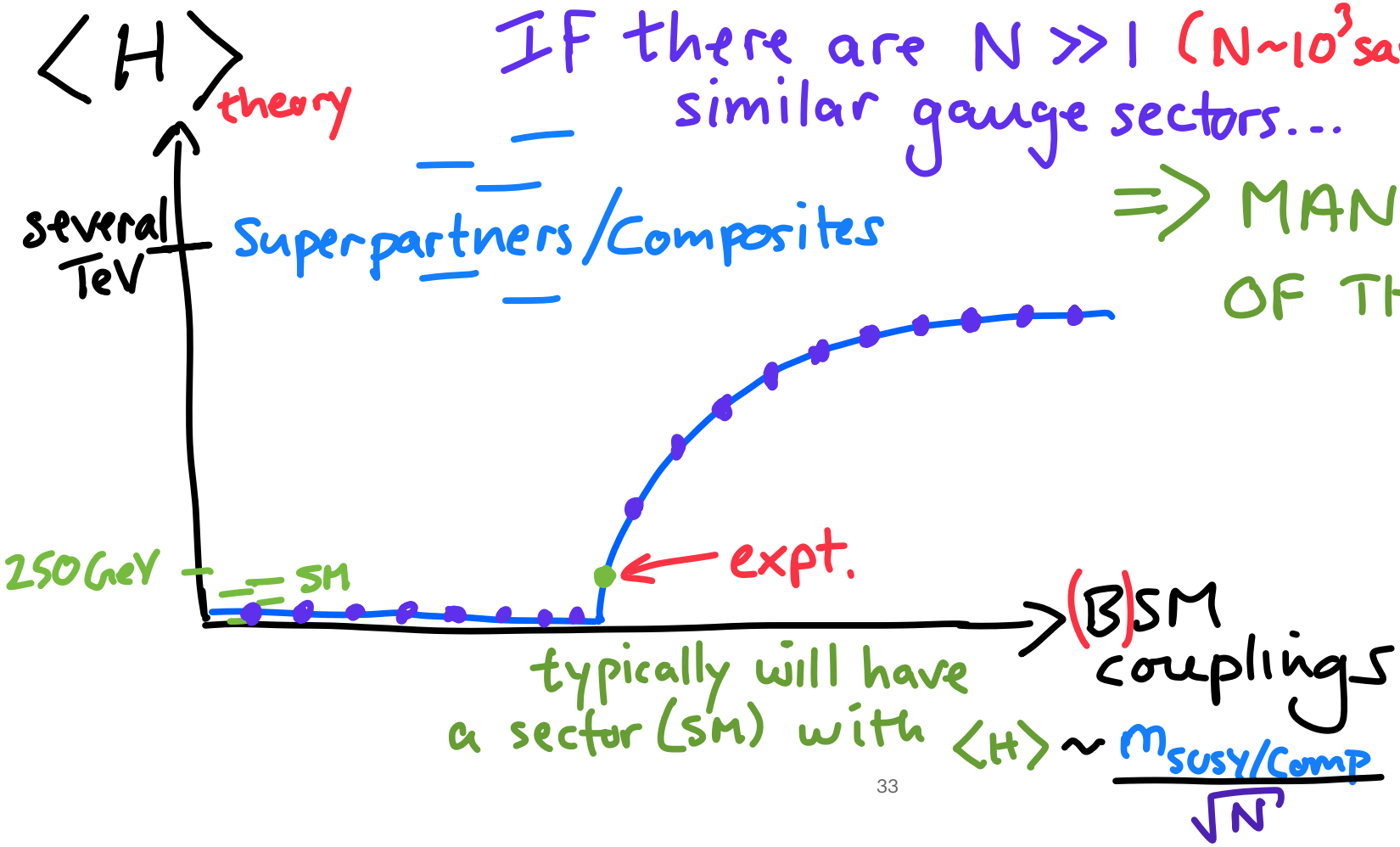


Alternately, N NATURALNESS

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!



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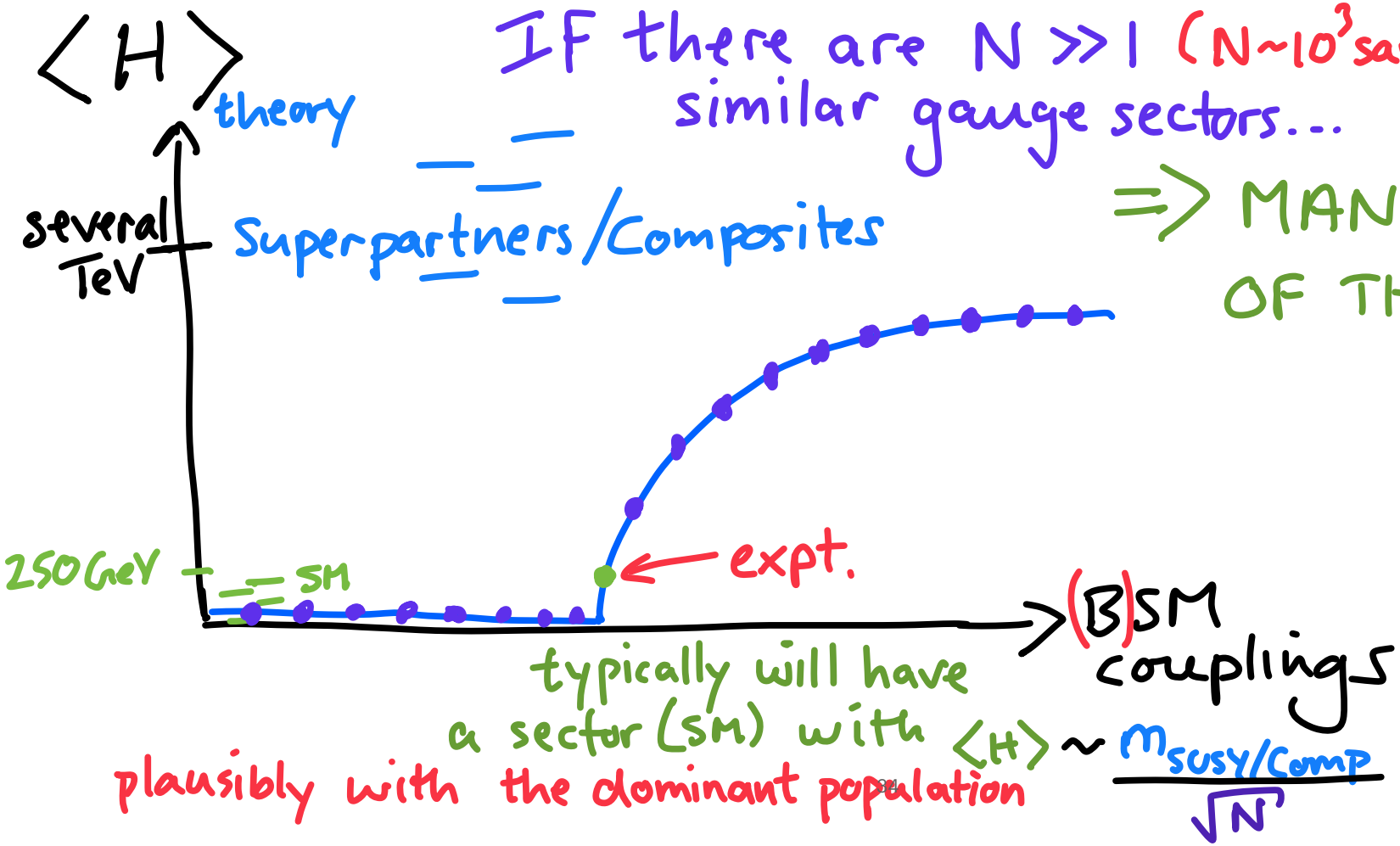

CONCLUSIONS

There are BROAD EXCITING PHYSICS THEMES to pursue at future colliders:

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