

IS FOR MYSTERY

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# Explorer's Map of FUNDAMENTAL PHYSICS

Energy BLACK HOLES

$M_{Pl} \sim 10^{18} \text{ GeV}$  Quantum Gravity

Grand Unification

$10^5 \text{ TeV}$  flavor tests

EDM tests

M-COLLIDER

LHC

SM

$H_0 \sim 10^{-33} \text{ eV}$

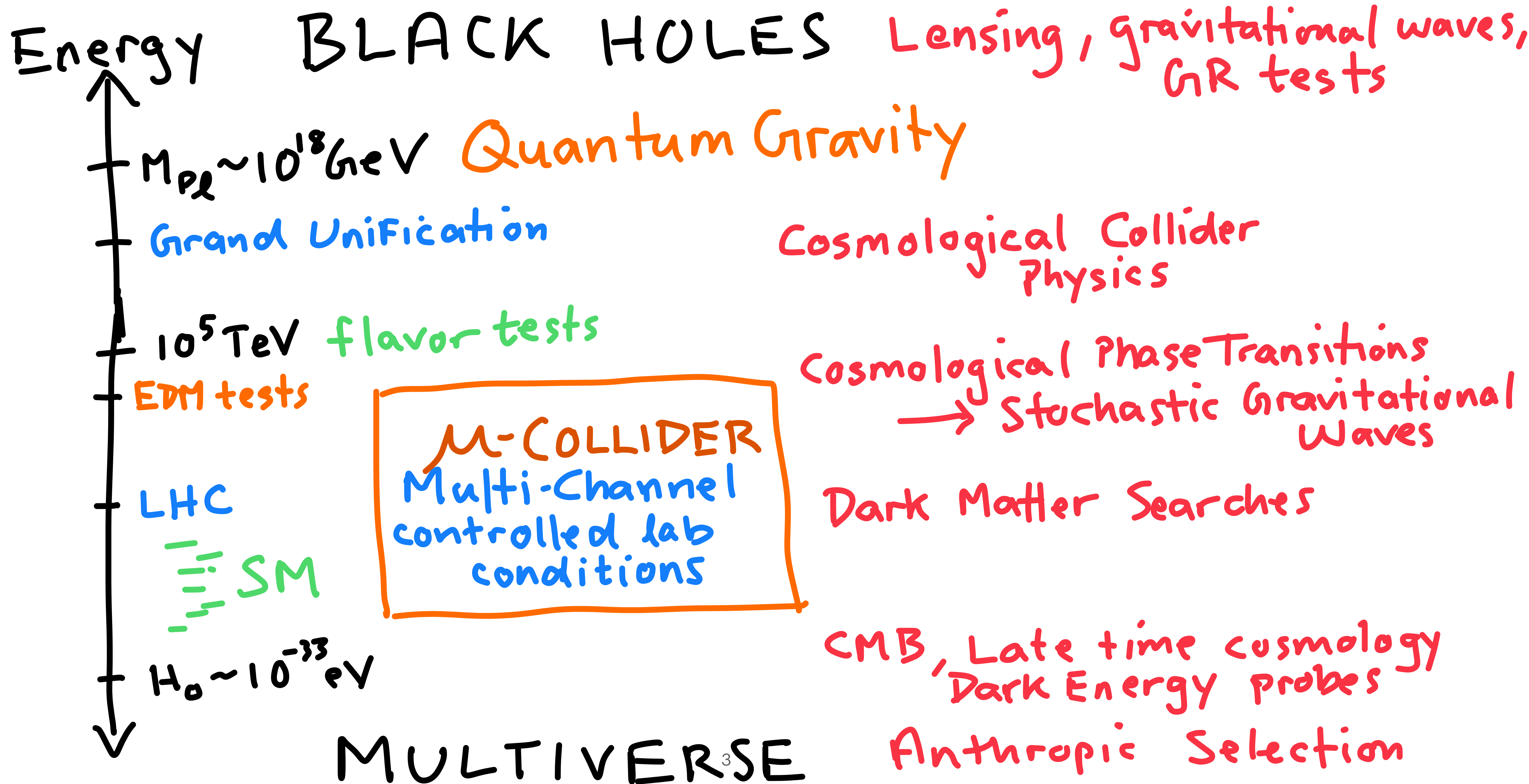
MULTIVERSE<sup>2</sup>

20-135 THz

PM-HD3

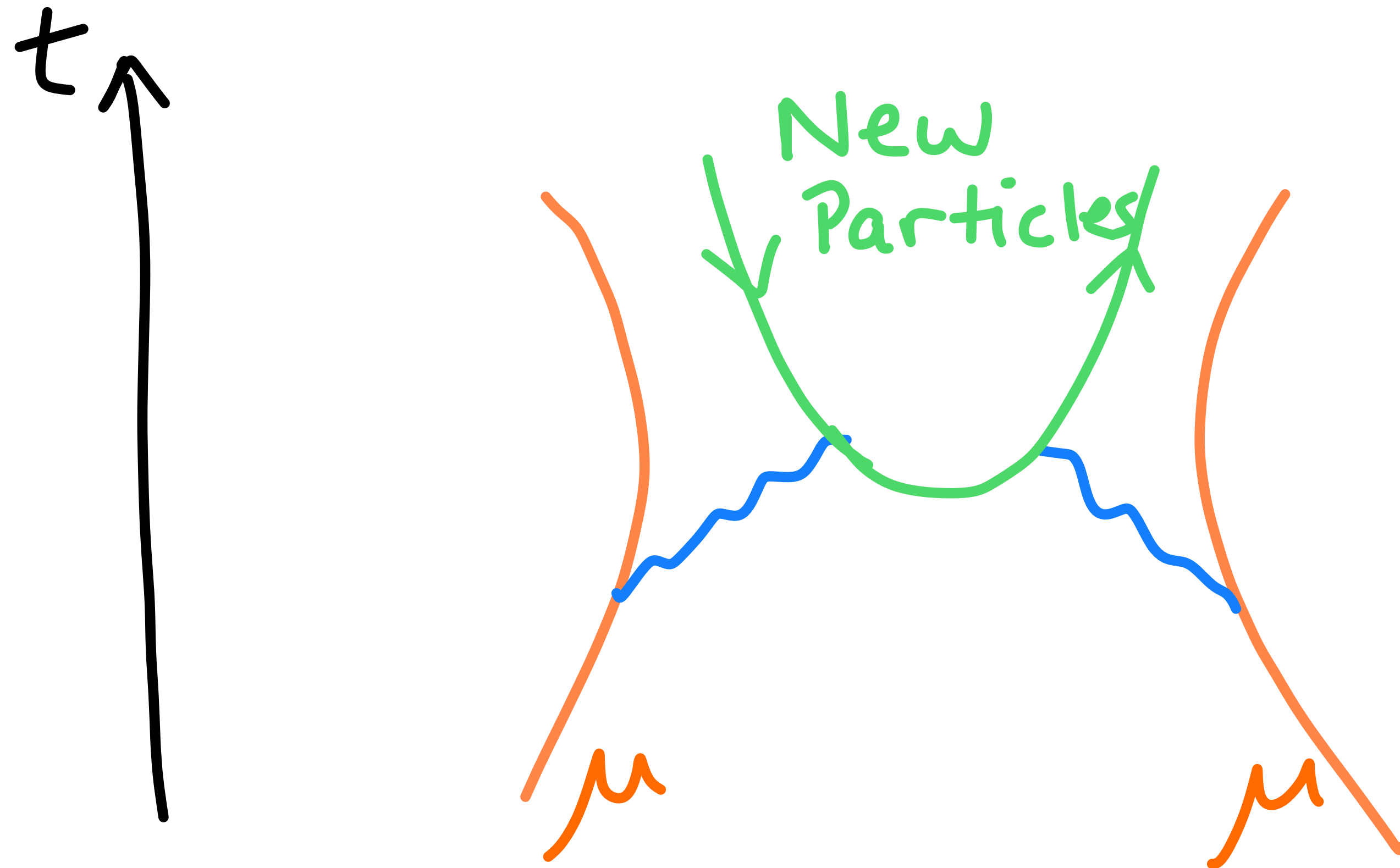
SSM

# Explorer's Map of FUNDAMENTAL PHYSICS



$E = mc^2$  IS MAGIC!

High Energy Colliders are its  
CREATIVE FRONTIER



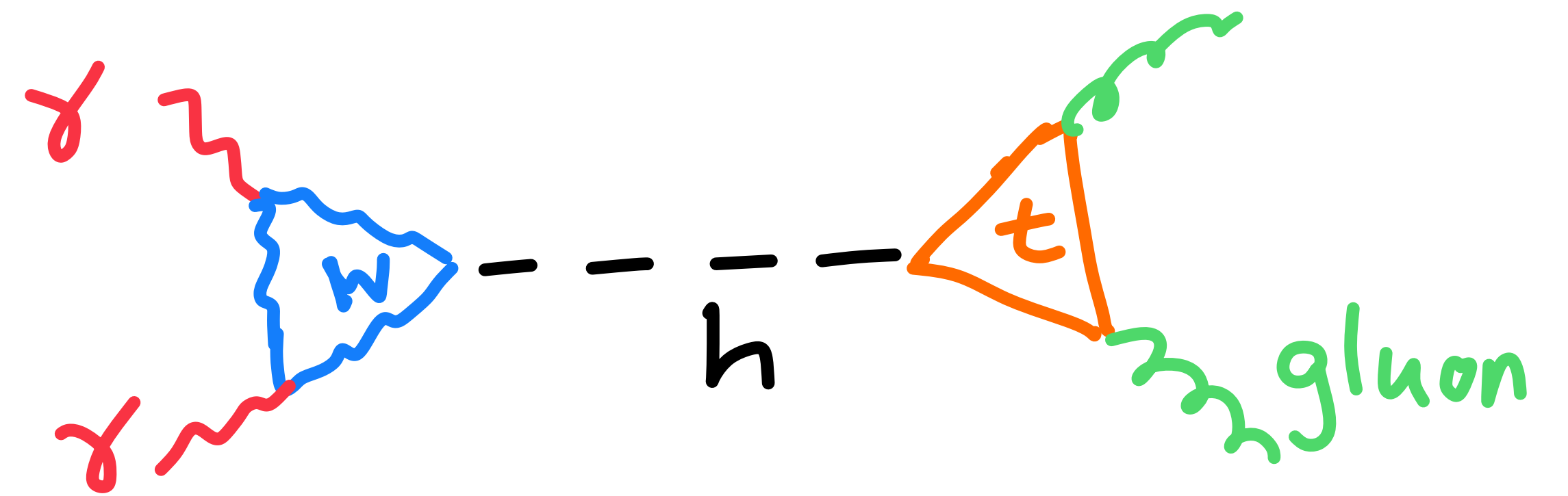
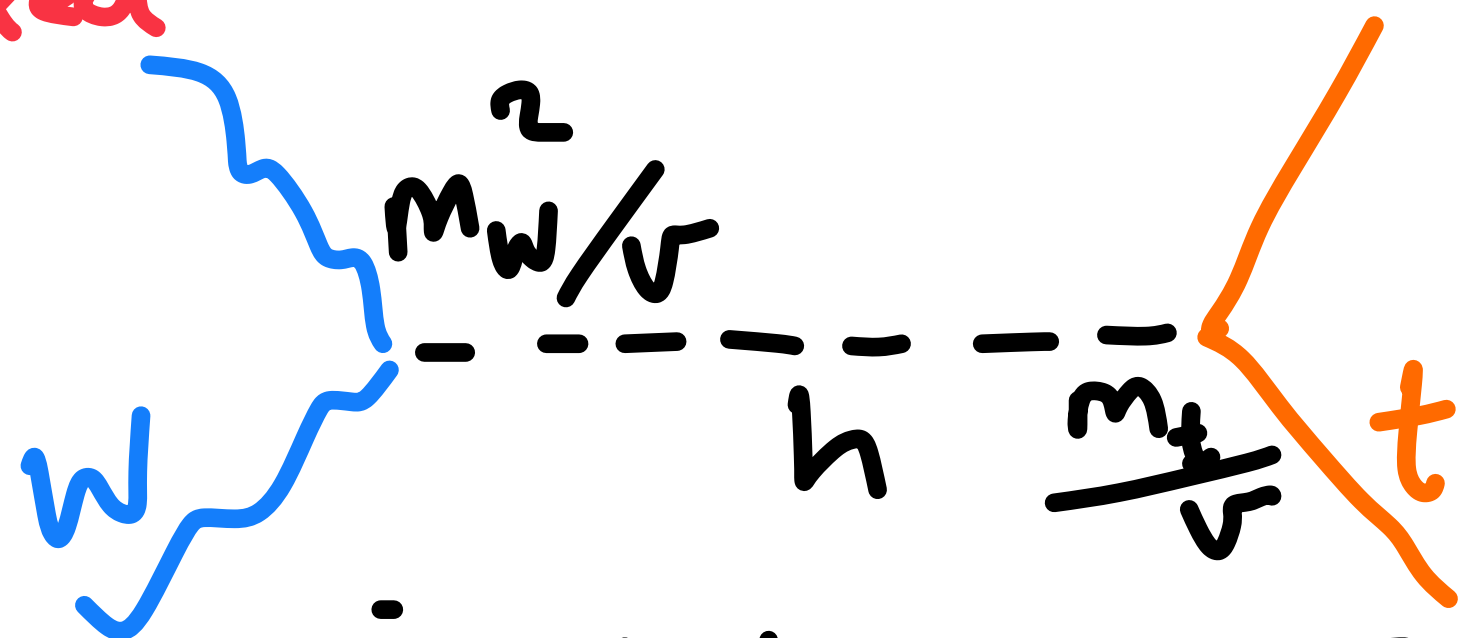
# GRAVITAS OF THE HIGGS

Higgs boson is quantum of new force field,  
 ~ short-range "gravity"

Tree-level "Equivalence Principle"

with Calculable  
 Quantum Corrections

→ 1st relativistic gravity theory  
 Nordstrom-Einstein-Fokker  
 1912-1914  
 $m_h \rightarrow 0$   
 $v$  fixed



Coupling to  $h = \text{mass}/v_{\text{weak}}$

This new "Equivalence Principle" should be tested as diversely  
 & precisely as possible, to fully establish it or find "cracks" to new  
 physics

Why is the sky blue?

& other "dumb" questions...

Some dumb questions → deep questions when enough is understood to crystallize them.

→ New deep theoretical mechanisms to resolve them

→ Sufficient development of experimental art to test them.

Why is particle physics so hierarchical?

(charged fermions, neutrinos, weak/Planck scales)

Why is there (much) more matter than antimatter?

What is Dark Matter<sup>6</sup>?

# CAN NEW COLLIDERS ADDRESS DEEP QUESTIONS

GIVEN THAT ~~FLAVOR~~ & ~~CP~~ TESTS  
HAVE VIRTUALLY PROBED  
FAR ABOVE COLLIDER ENERGIES?

Energy

$M_{Pl} \sim 10^{18} \text{ GeV}$

$10^5 \text{ TeV}$  flavor tests

EDM tests

$\mu$ -COLLIDER

LHC

SM

Why is particle physics so hierarchical?

There are powerful, elegant theoretical mechanisms offer quite satisfying explanations.

$$v_{\text{weak}}/M_{\text{Pl}}, m_i/m_j, V_{ij}^{\text{CKM}} \sim e^{-\alpha(i)/\alpha}$$

Realistic proposals  $\Rightarrow$  major upgrades to SM, & yet can robustly satisfy flavor/CP/EW constraints while remaining within reach of colliders

Remarkably, most realistic & complete models require extensions of Relativistic Spacetime!

SUSY, Supergravity, WARPED EXTRA DIMENSIONS



# SUSY ~~EW~~

Supersymmetry breaking sculpts Higgs potential



$$m_h^2 = \lambda v_{\text{weak}}^2 \sim 2 m_Z^2$$

$\Rightarrow$  strongly suggests  $m_{\text{stop}} \gtrsim 10 \text{ TeV}$

# Light Vestiges of Major Mechanisms

Stop, gluinos are central players in SUSY/Higgs interplay

Such central players are the most exciting, but may be too heavy to produce.

Less central but associated new particles may be lighter, but often more weakly coupled to us.

For example, sleptons can consistently be  $O(100)$  lighter,  $\sim 100s$  GeV, yet may readily hide from LHC.

Of course, a muon collider could have both high energy reach and high visibility

# DARK MATTER

Diverse range of experiments is hunting for a diverse range of Dark Matter incarnations!

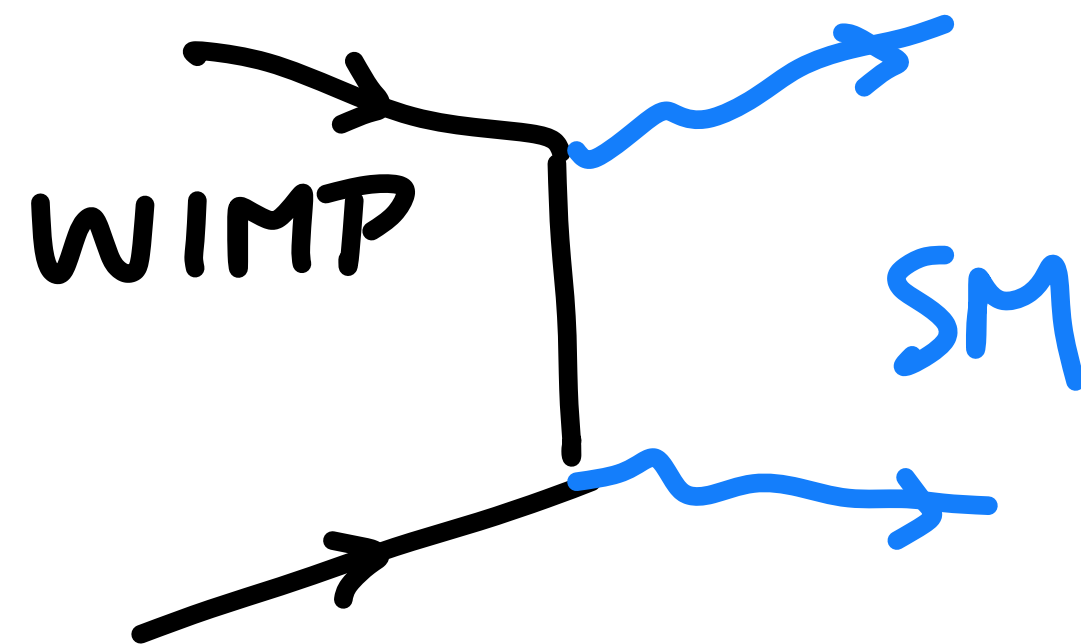
Separately robust & elegant mechanisms for dark matter and for Baryogenesis are jointly very fine-tuned in achieving

$$\rho_{DM} \sim 5 \rho_{\text{baryons}}$$

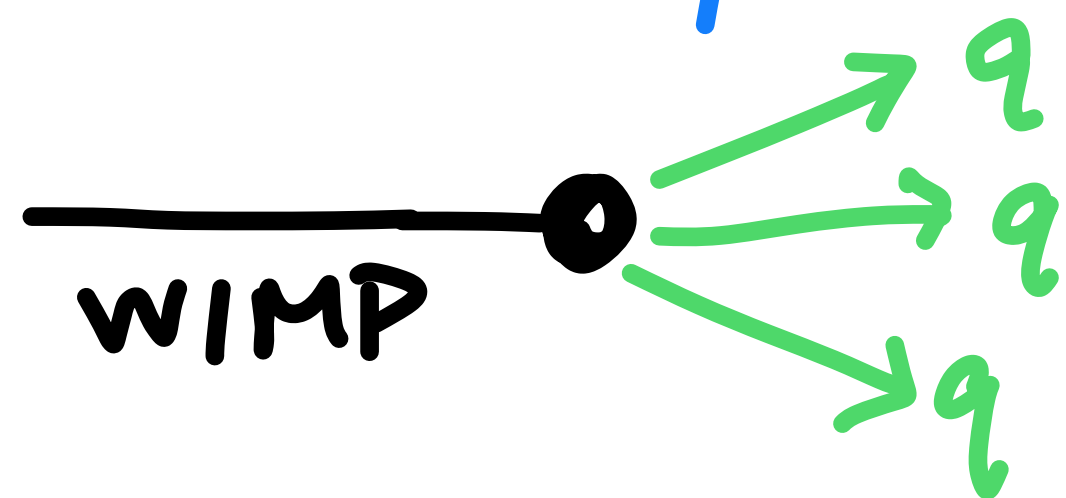
Strongly suggests close connection of DM to SM, hence discoverability at muon collider.

# BARYOGENESIS FOR WIMPS

Just as stable WIMPs can have a thermal relic abundance of DM from early universe annihilations,



relic long-lived WIMPs can subsequently ( $c\tau_{\text{WIMP}} > \text{cm}$ ) decay (~~CP, B~~) into baryons (fewer antibaryons),



appearing as Long-Lived Particles (LLPs) (displaced vertex events) at colliders

# HIGGS MAY BE 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

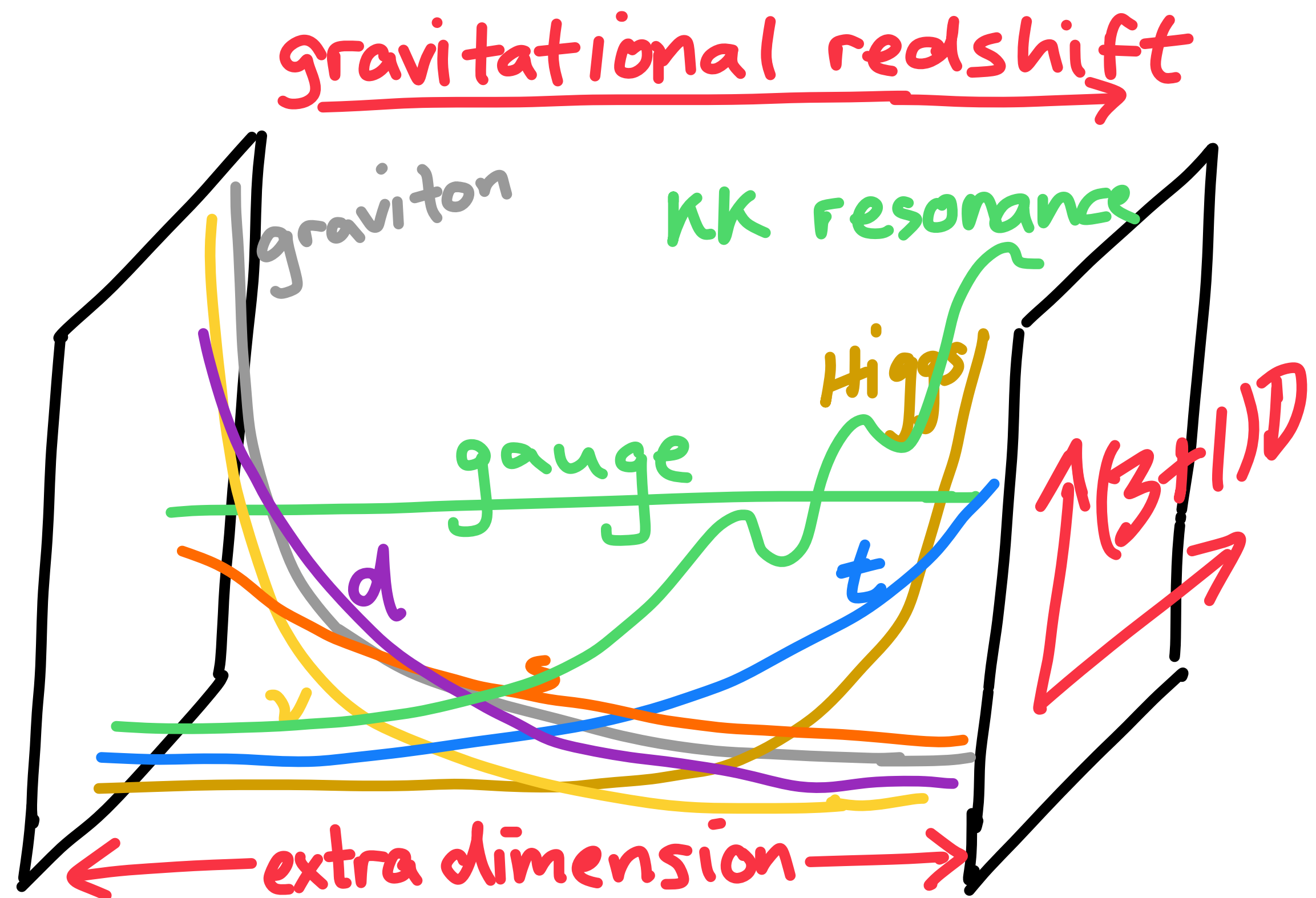
# PARTIAL COMPOSITENESS

$$|\text{mass eigenstate}\rangle = \alpha |\text{elementary}\rangle + \beta |\text{composite}\rangle$$

**BUT** theoretically v. difficult due to strong confining coupling.

Tractable regime:

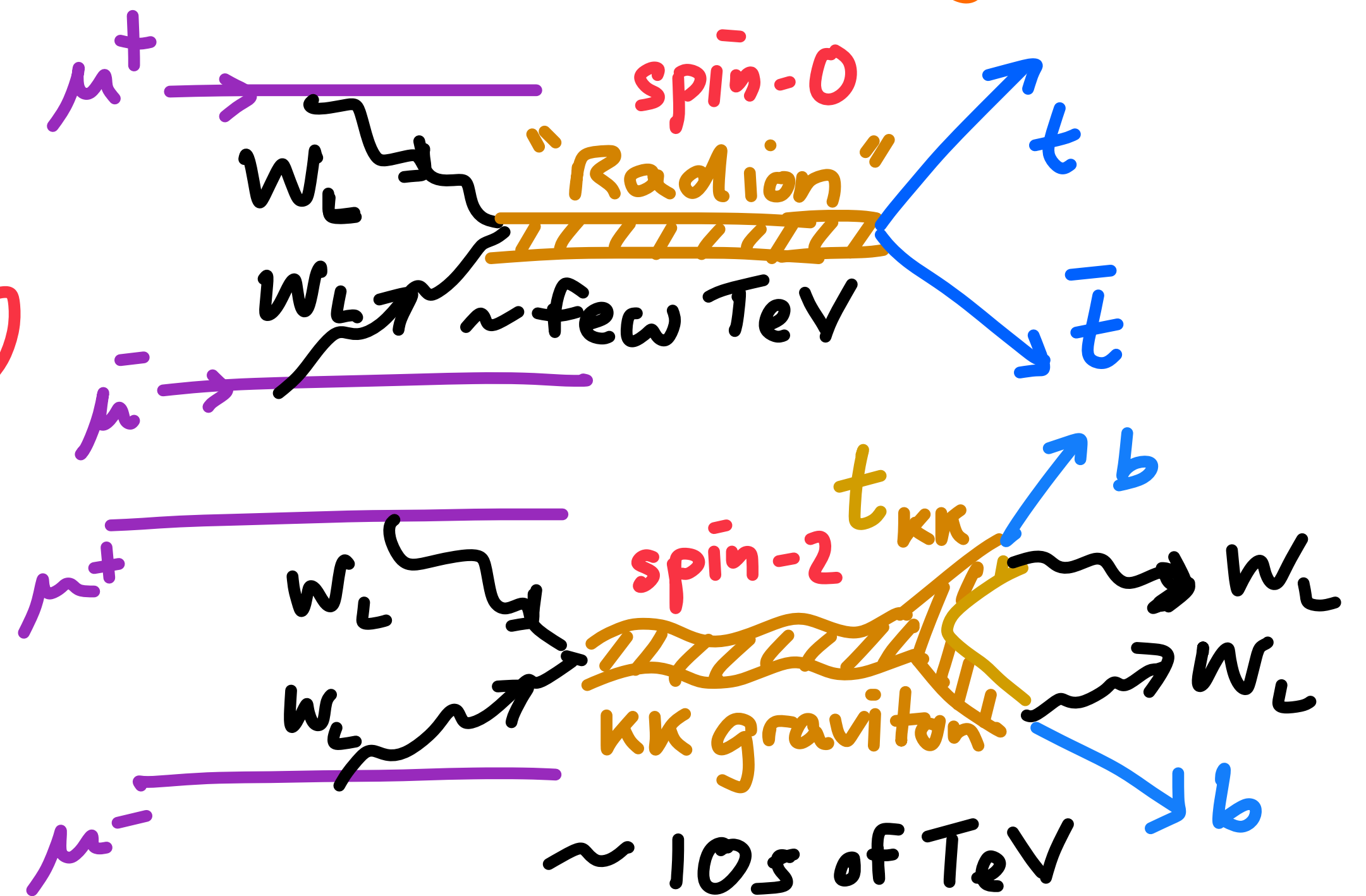
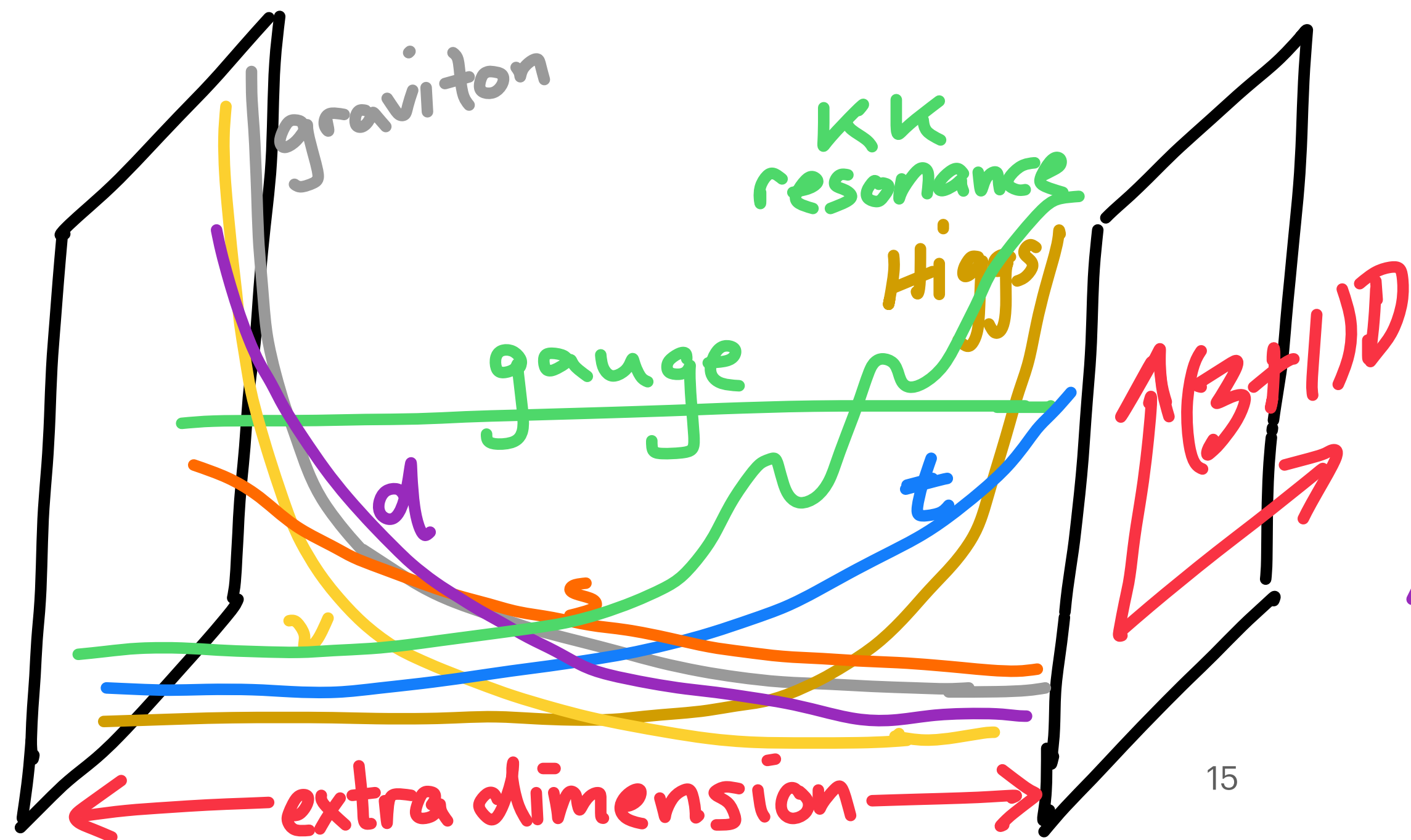
strong coupling  $\xrightarrow{\text{AdS/CFT (Quantum magic)}}$  Emergent Warped Extra Dimension



# WARPED EXTRA DIMENSION

Extra-dimensional wavefunction overlaps  $\rightarrow$   
attractive origin for EW & Flavor hierarchies

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:



# ARE WE ALONE ?

Gauge Field Theory naturally divides into "social clubs" of gauge fields & charged matter. SM is one such, but are there other "ghostly" dark gauge sectors awaiting discovery?

Supergravity models trigger ~~EW~~  $\lesssim m_{\text{gravitino}}$   
Warped models trigger ~~EW~~ by extra-dimensional Redshift

These spacetime features can naturally lead to dark sectors  $\sim v_{\text{weak}}$   
Dark sectors may explain why visible new physics  $> \text{TeV}$   $\overline{\text{1 twin Higgs}}$   $\overline{\text{N Naturalness}}$

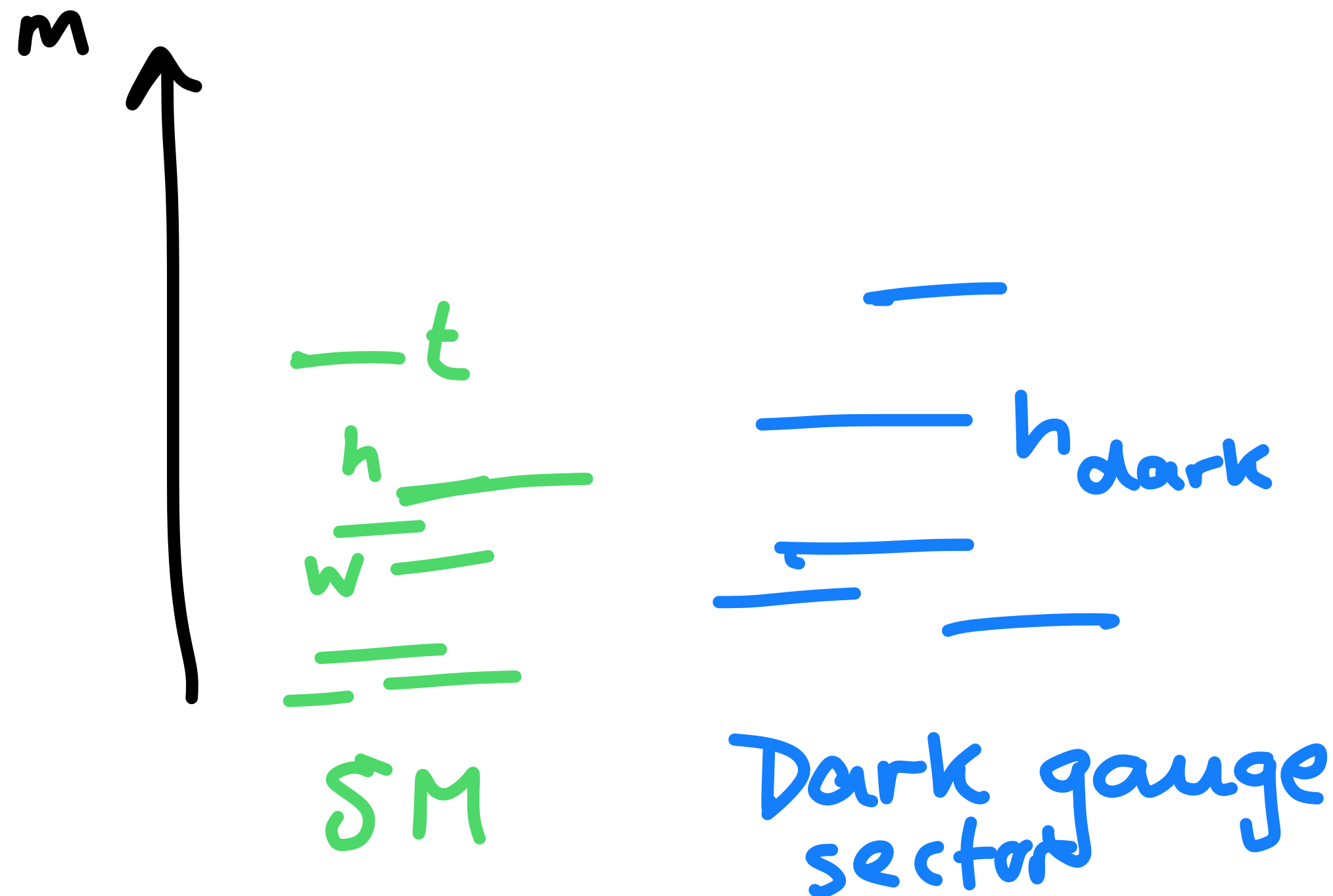


# THE HIGGS PORTAL

to dark gauge/Higgs sectors

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

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



# THE HIGGS PORTAL

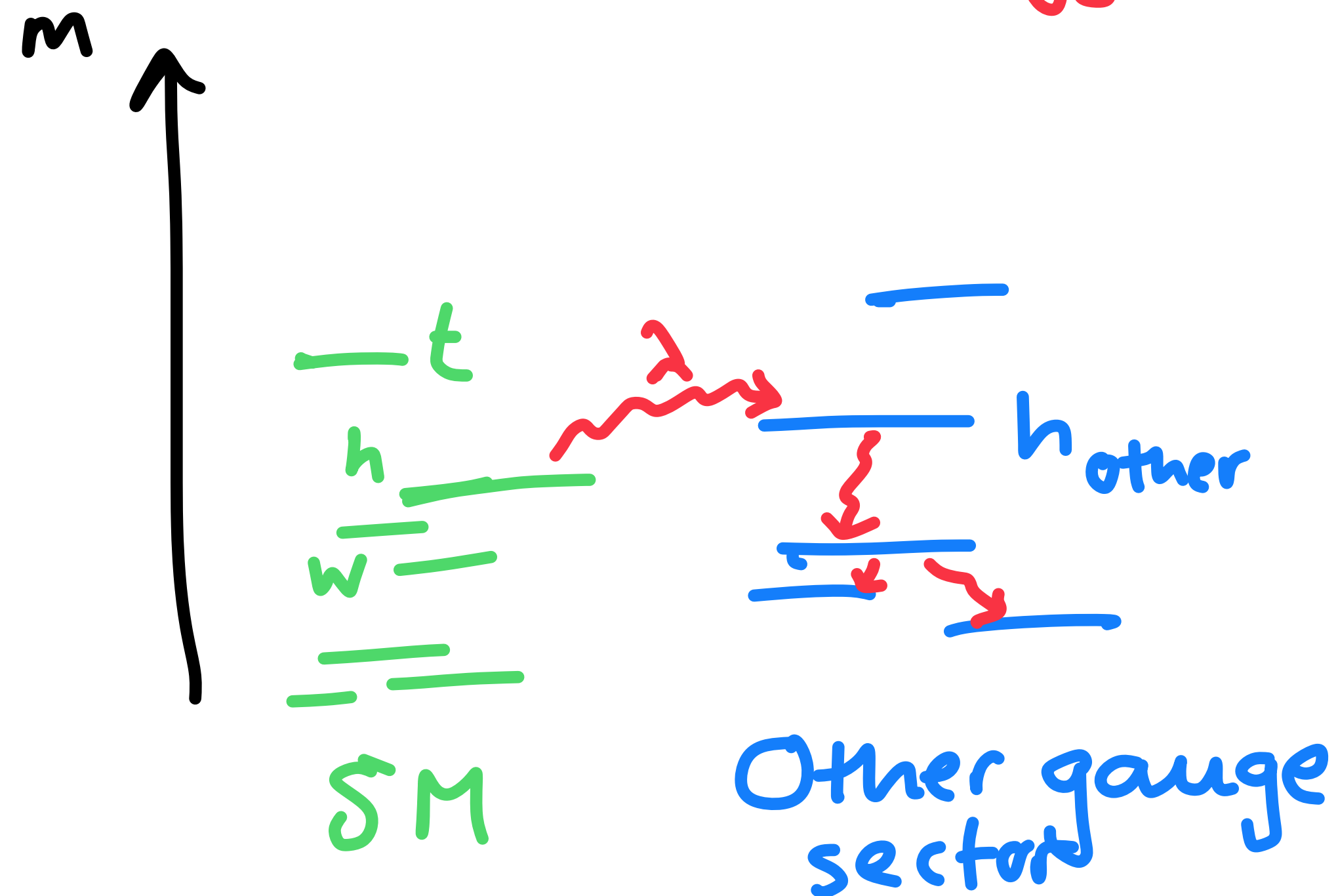
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$$\mathcal{L} \supset \lambda \langle H_{SM}^\dagger \rangle H_{SM} H_{other}^\dagger \langle H_{other} \rangle$$

Higgs mixing

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window of opportunity



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

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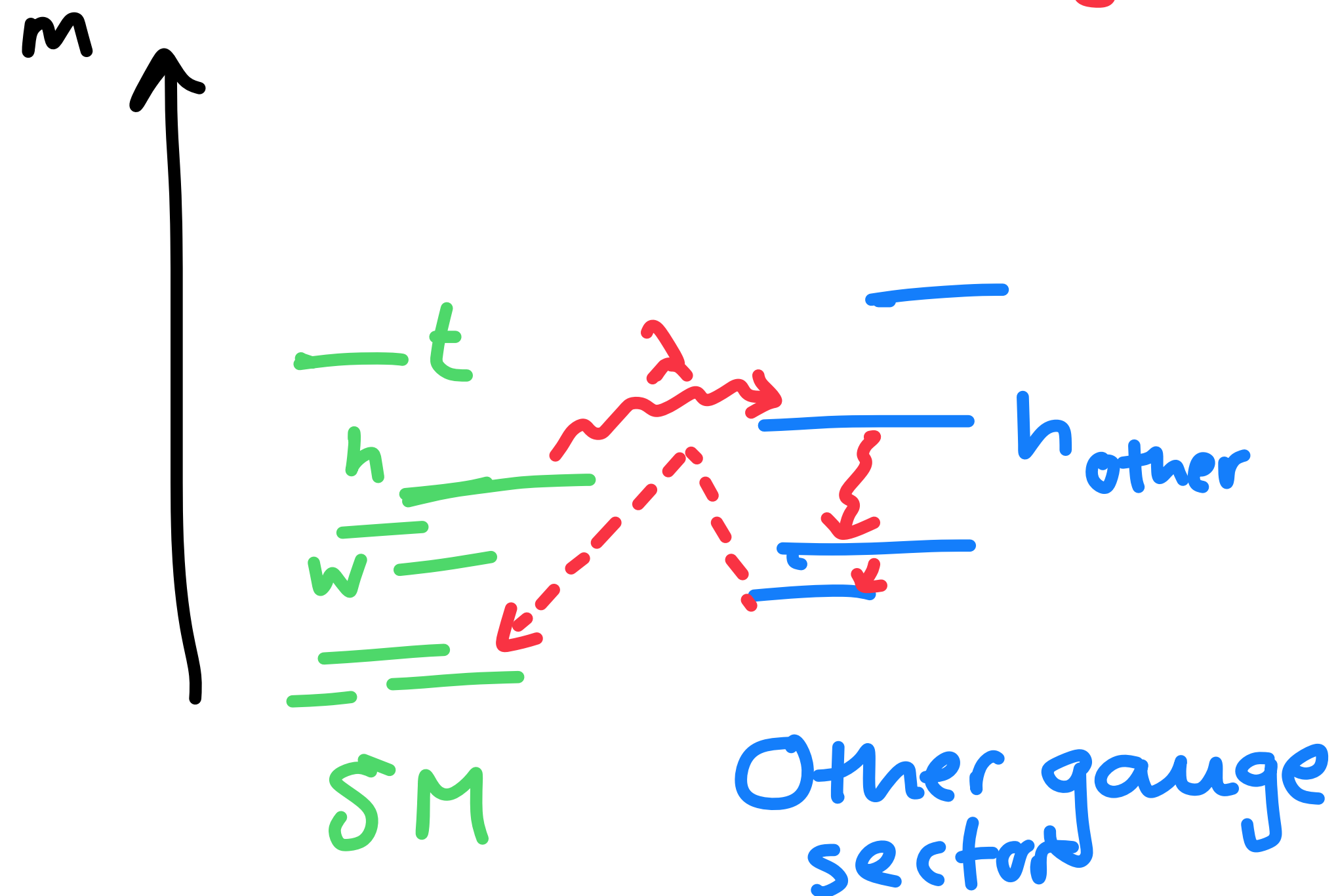
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Higgs mixing

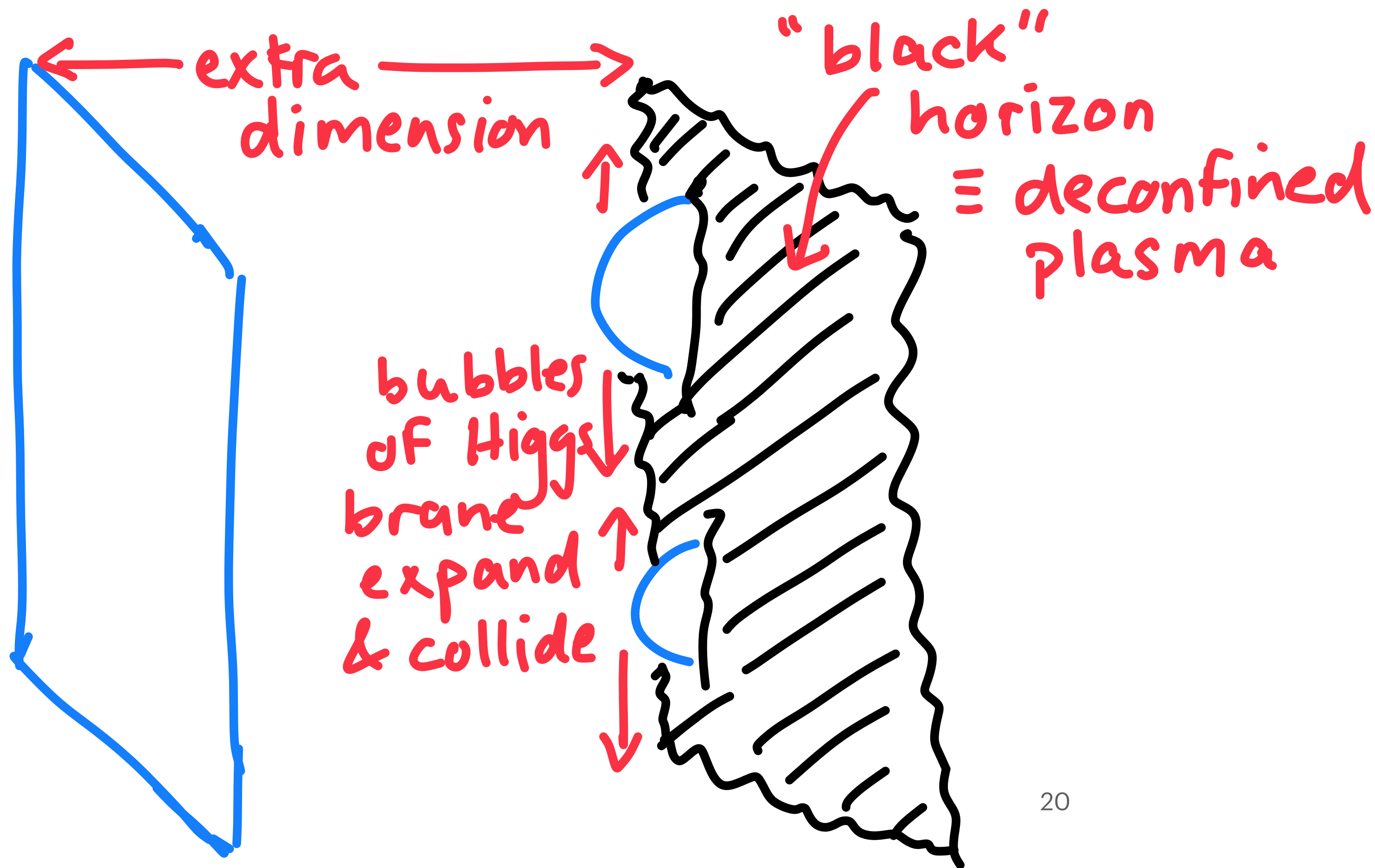
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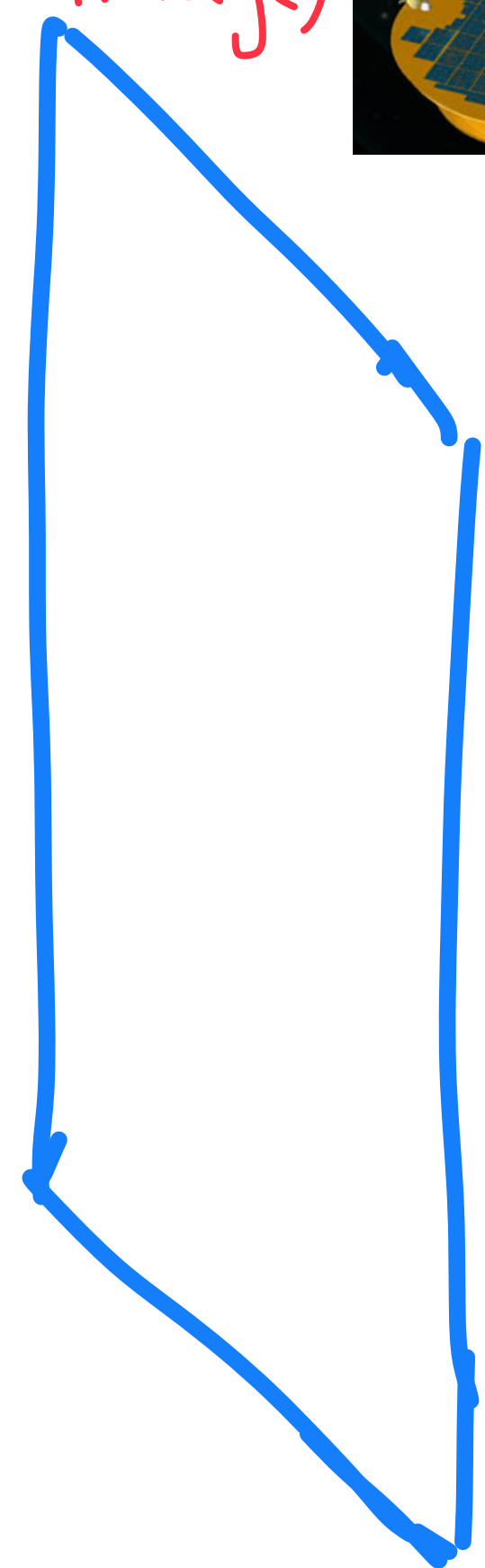
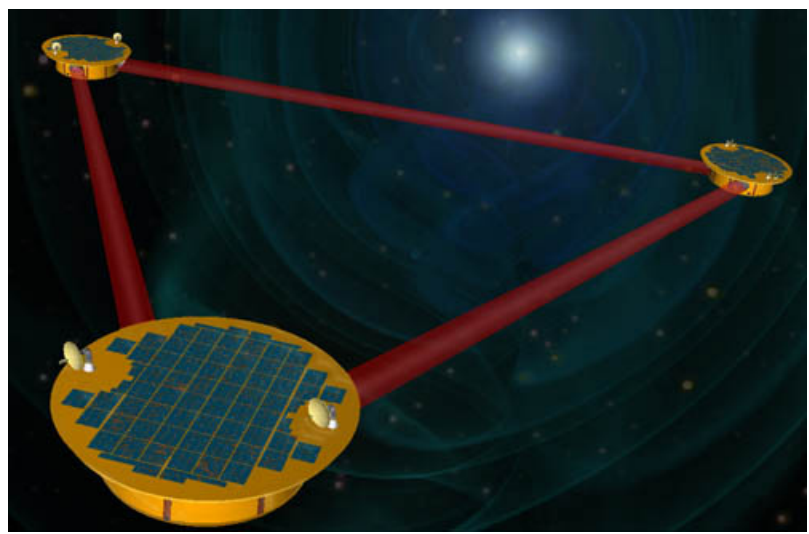
⇒ Important to detect long-lived decays from other sectors back to SM.

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



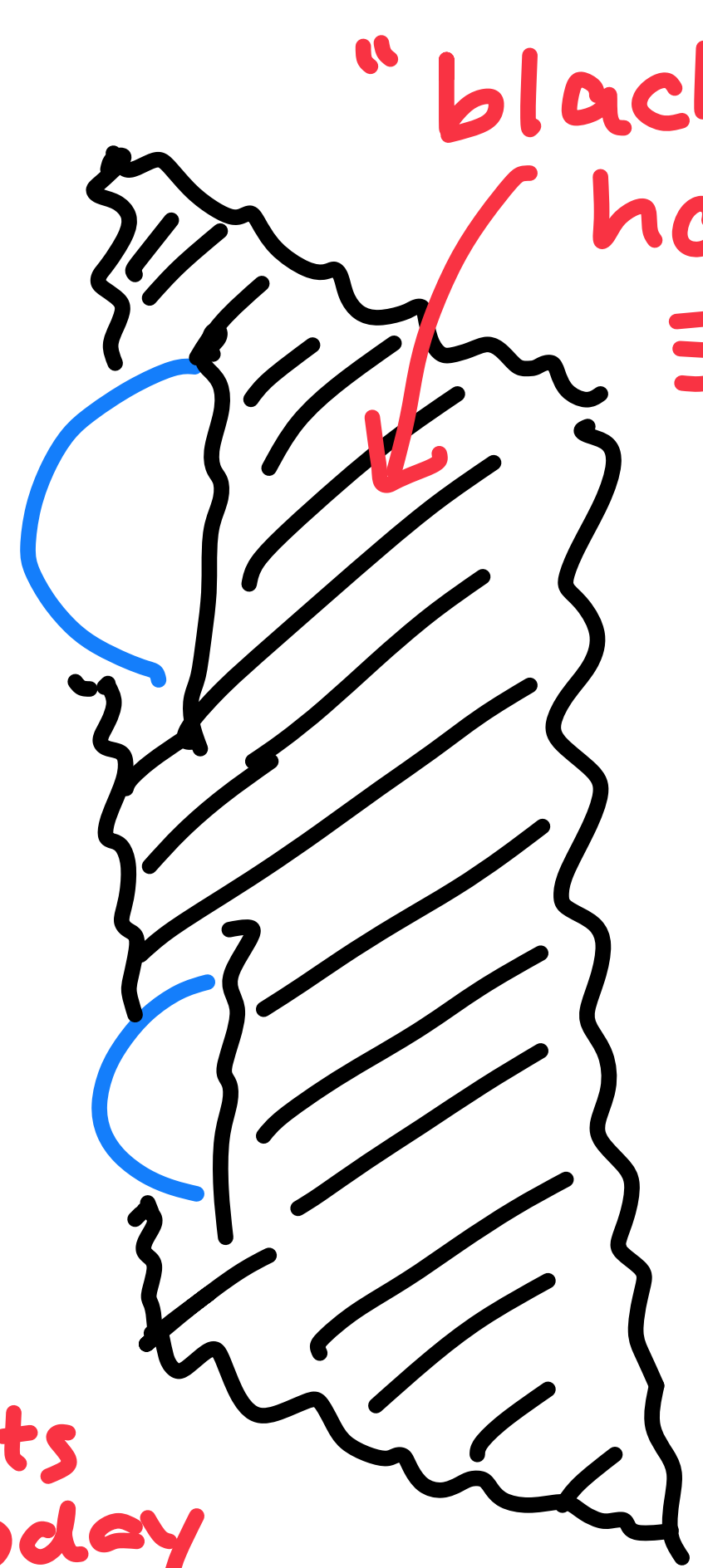
# GRAVITATIONAL WAVES from (DE)CONFINEMENT PHASE TRANSITION

LISA GW Detector (NASA image)



Grav. Waves

redshifts till today



"black" horizon  
≡ deconfined plasma

COLLIDER COMPLEMENTARITY

Eg. Proposed LISA detector may see mHz GW stochastic background  
≡ TeV critical Temperature would be matched by multi-TeV KK resonances at colliders

# IMPORTANCE OF EVEN NOT SEEING BSM PHYSICS AT $\mu$ COLLIDER

Example: Stochastic Gravitational Waves from cosmological Phase Transition may be detected, perhaps understood well enough to point to BSM  $\sim$  several TeV.

But not seeing BSM physics at a (relatively clean) muon collider would strongly constrain form of transitioning physics, such as a dark sector

# CONCLUSIONS

There are BROAD EXCITING PHYSICS THEMES to pursue at a muon 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