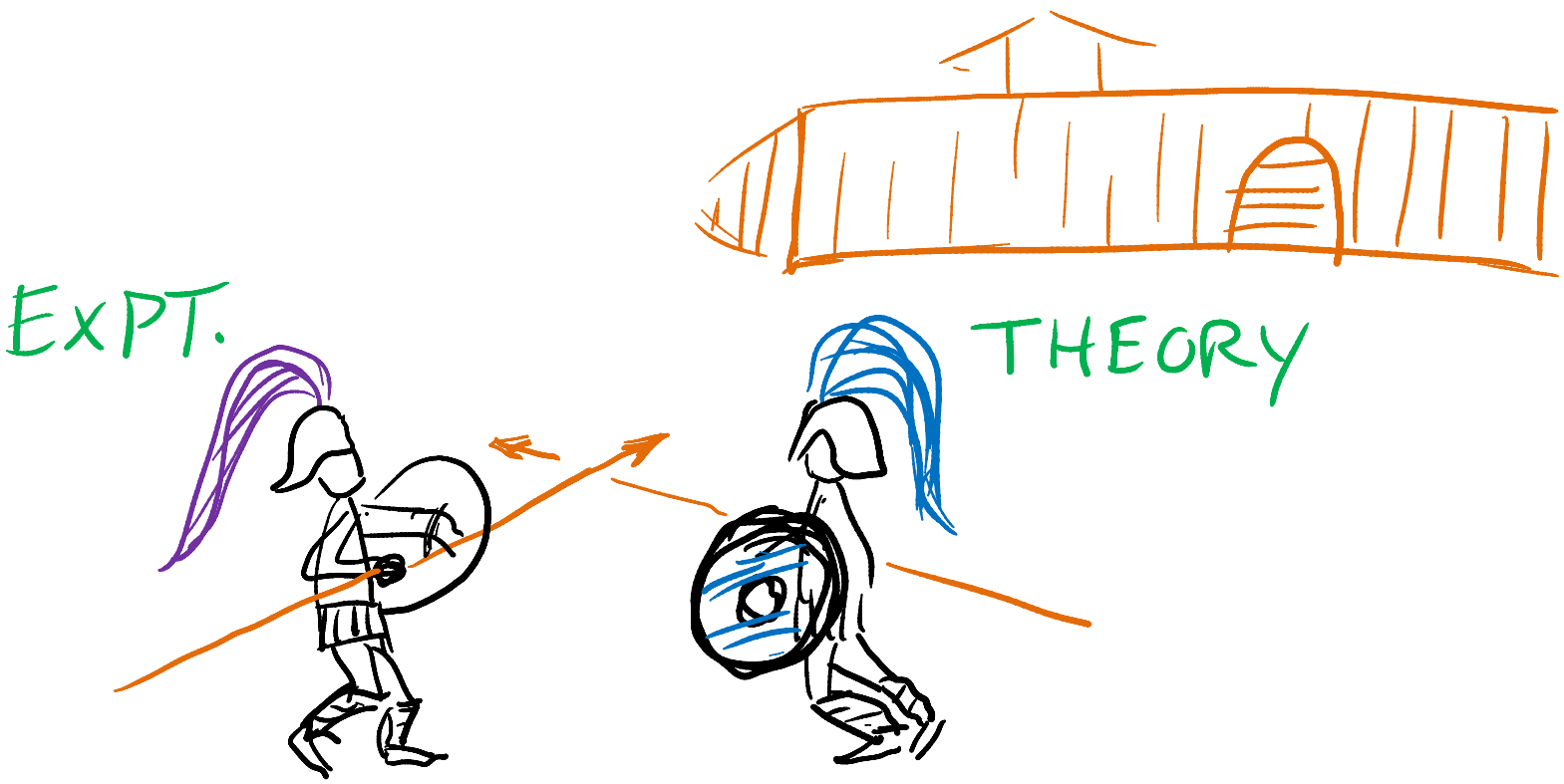
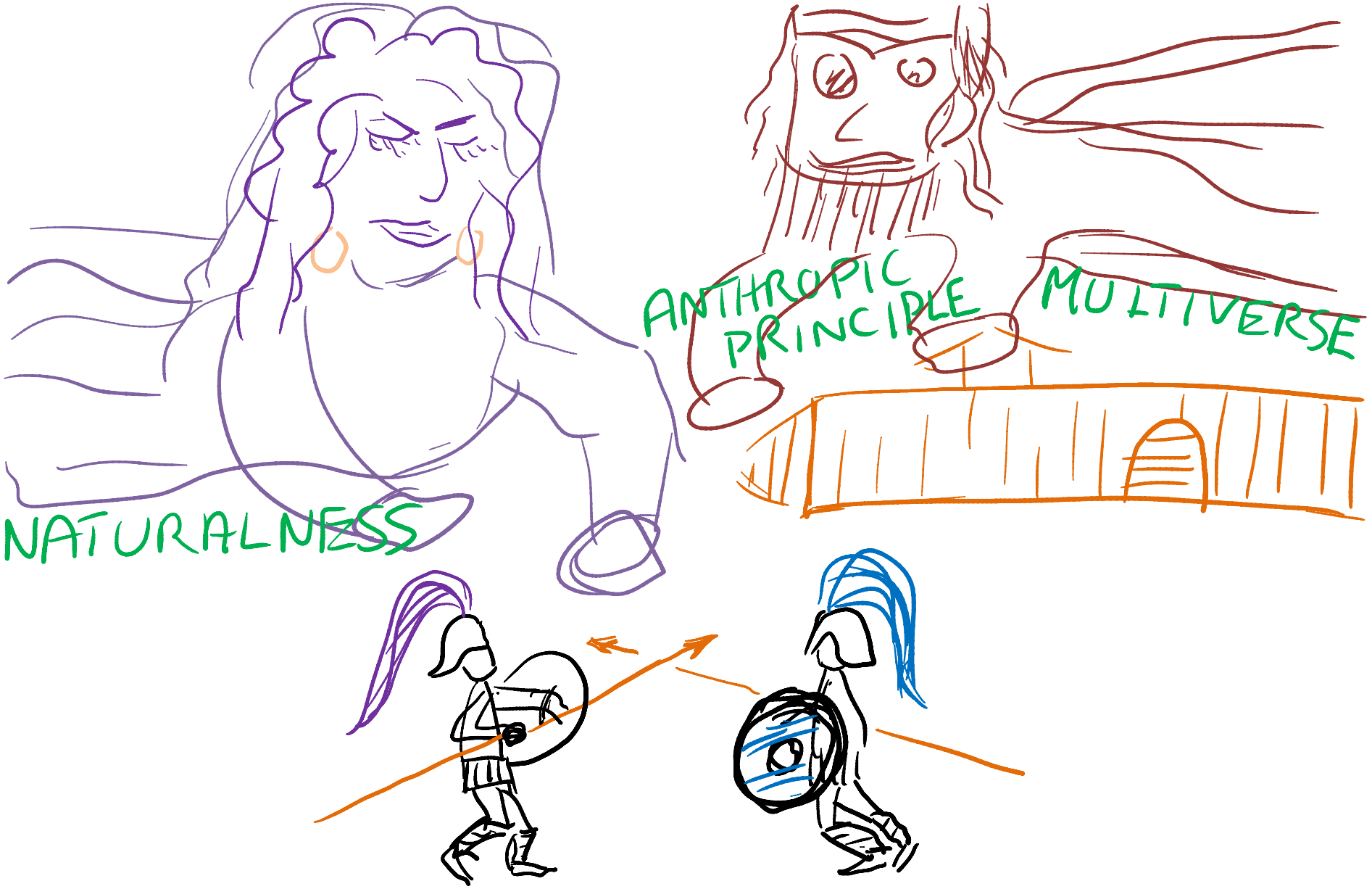
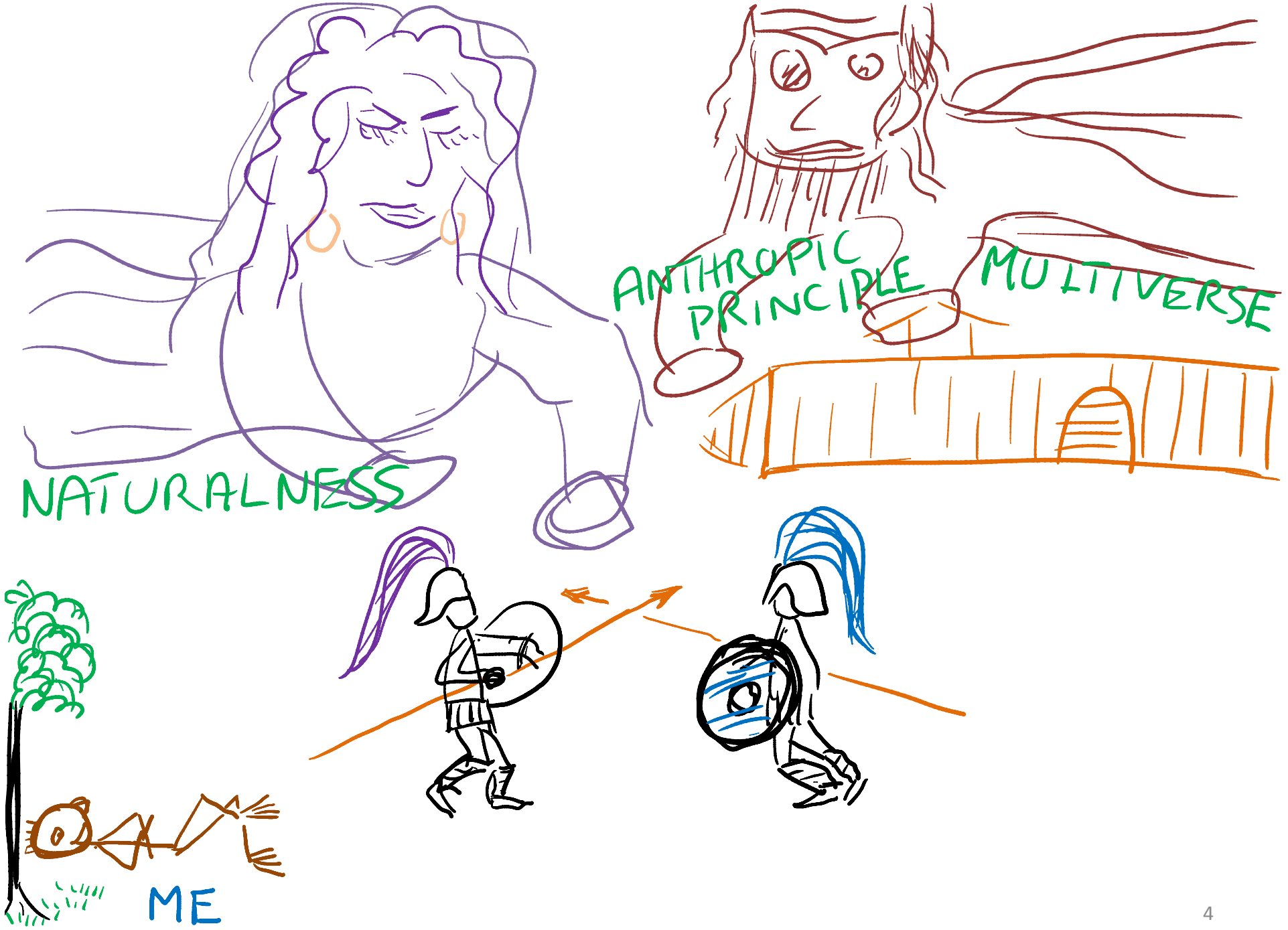
Super-Natural vs. Other-Worldly in Fundamental Physics

Raman Sundrum
University of Maryland

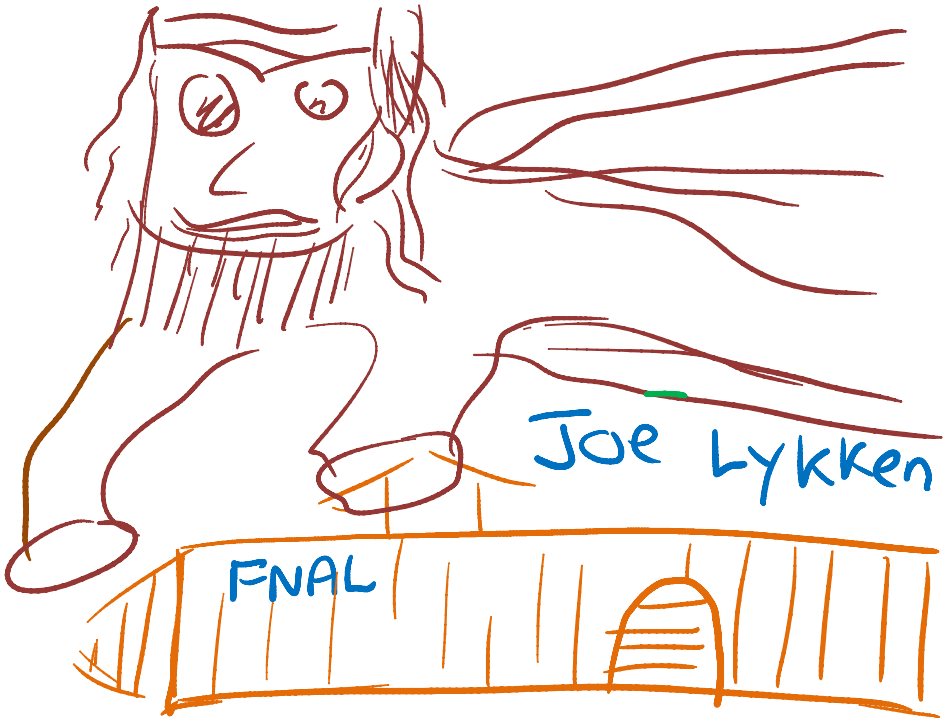

EXPT.
THEORY

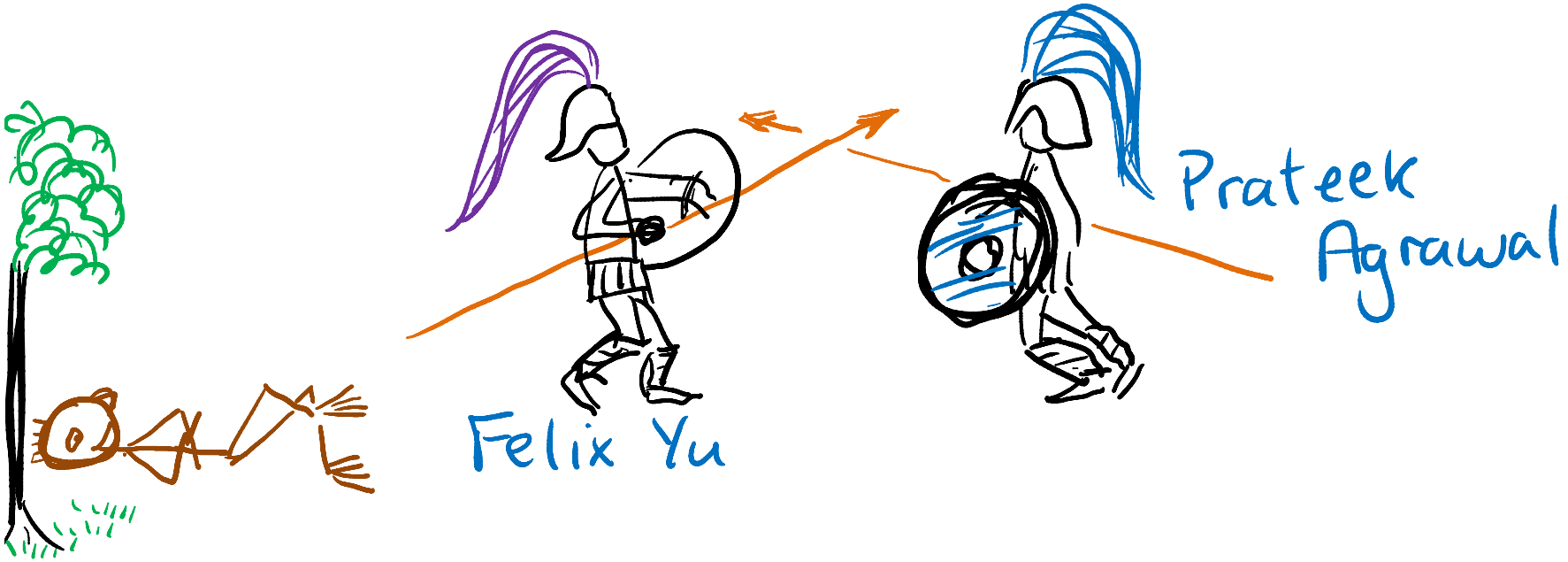

NATURALNESS
ANTHROPIC PRINCIPLE
MULTIVERSE


NATURALNESS
ANTHROPIC PRINCIPLE
MULTIVERSE
ME

Nature Guiding Theory Workshop

Aug. 21-23





OUTLINE

Naturalness

Multiverse

Anthropic Reasoning

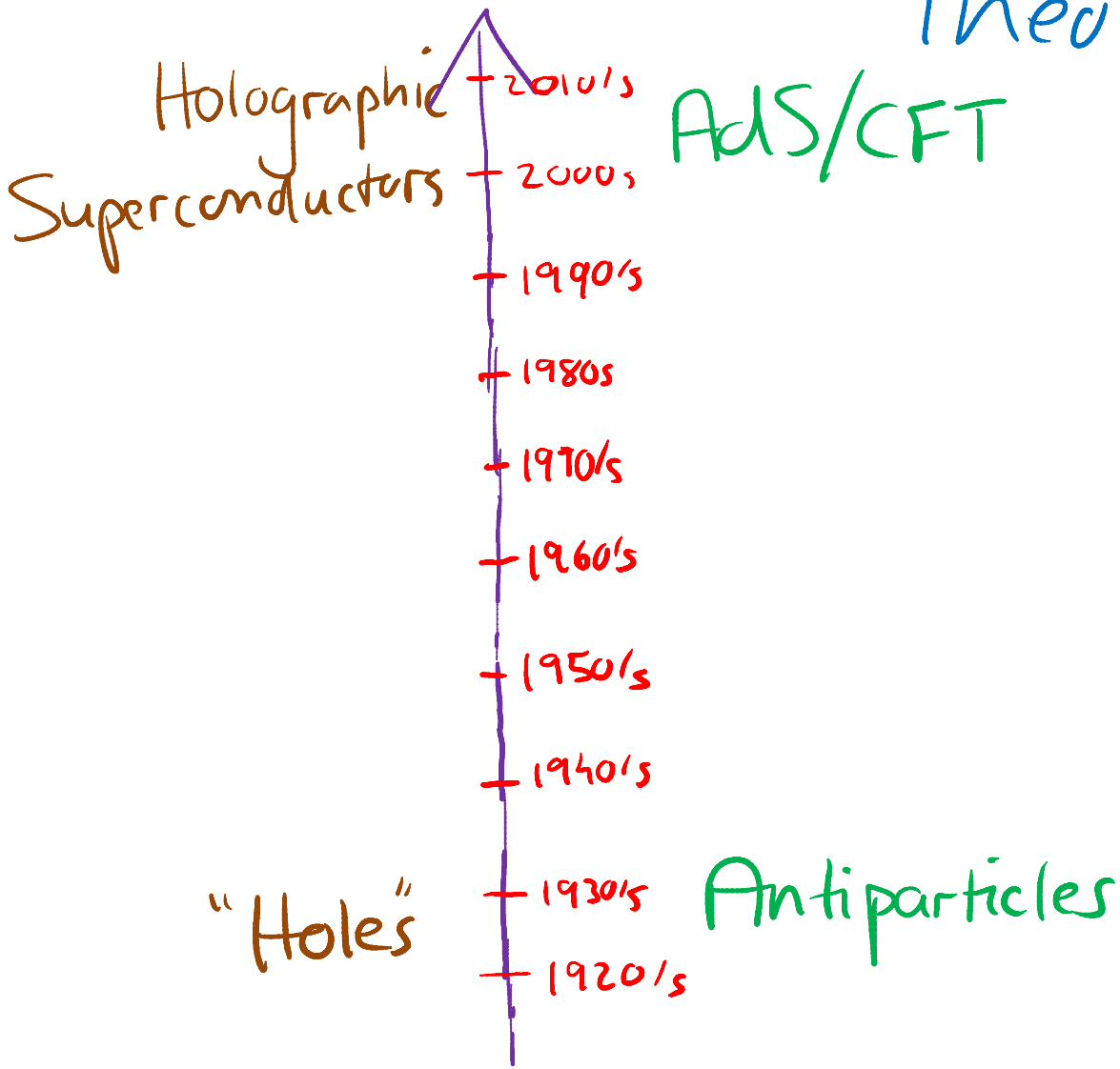
Ruthless Over-simplification

Poorly-conceived ideas

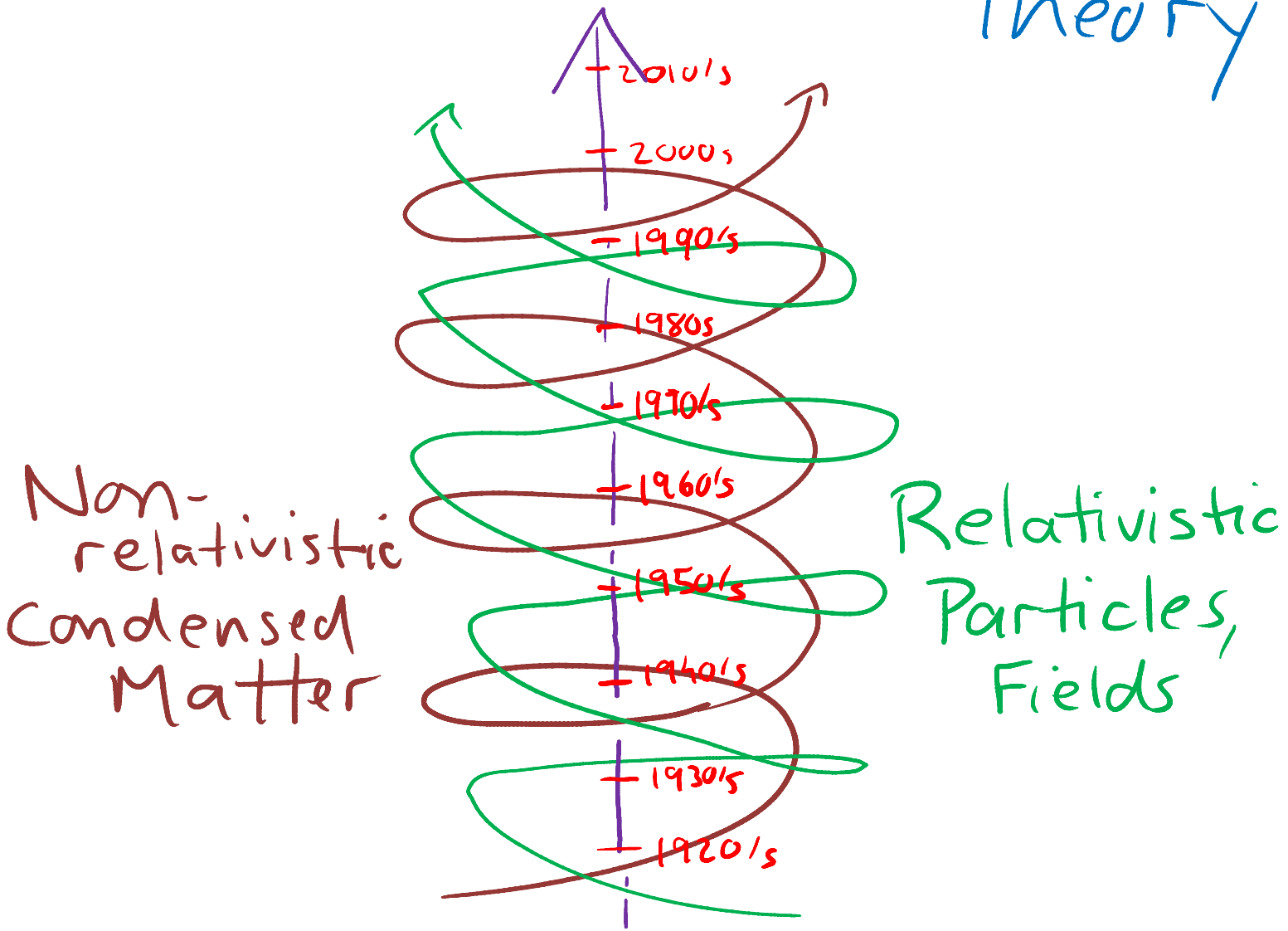
Meso-tuning

Nature  Theory ?

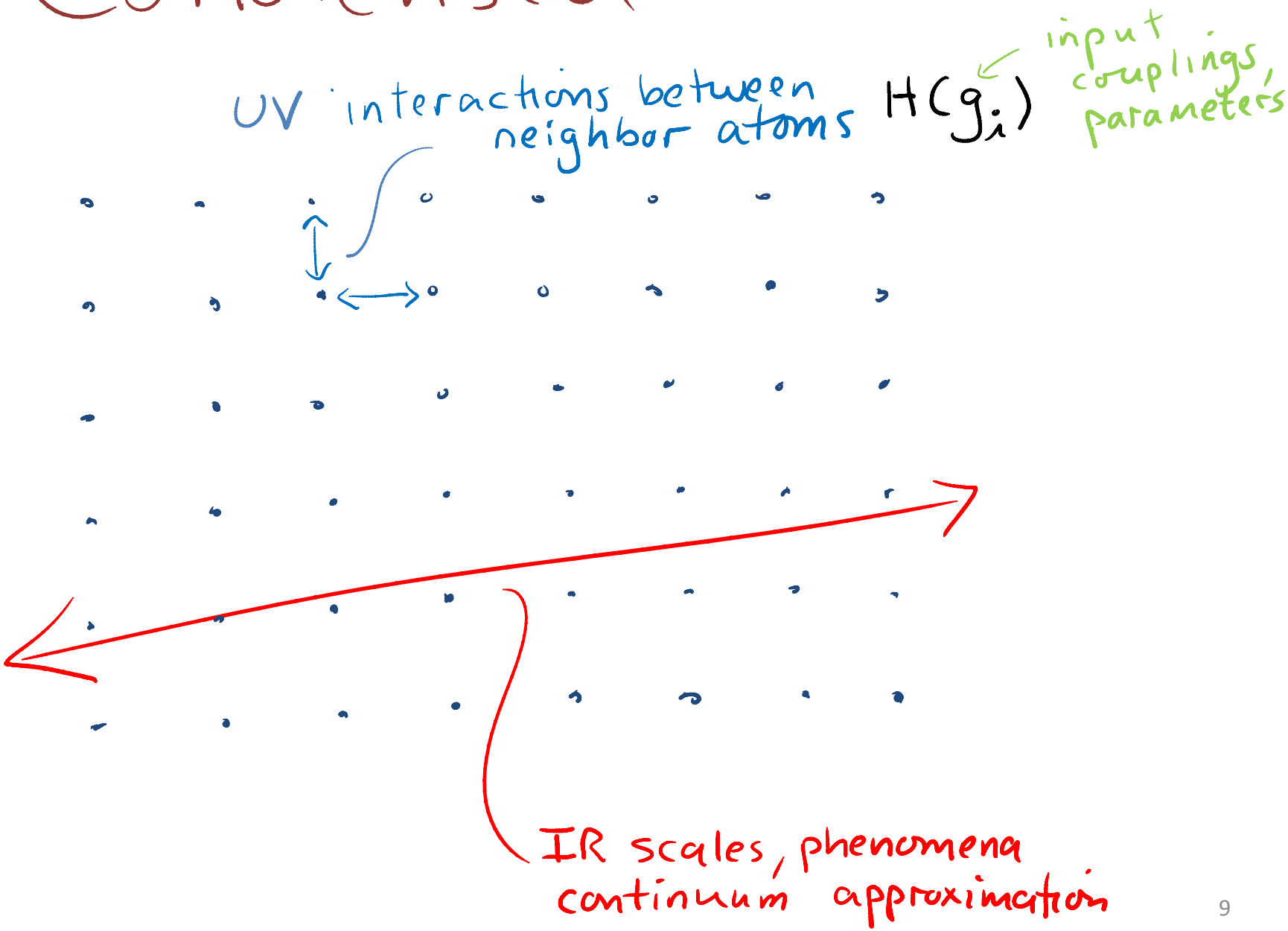
Evolution of Quantum Field Theory



Evolution of Quantum Field Theory



Condensed Matter



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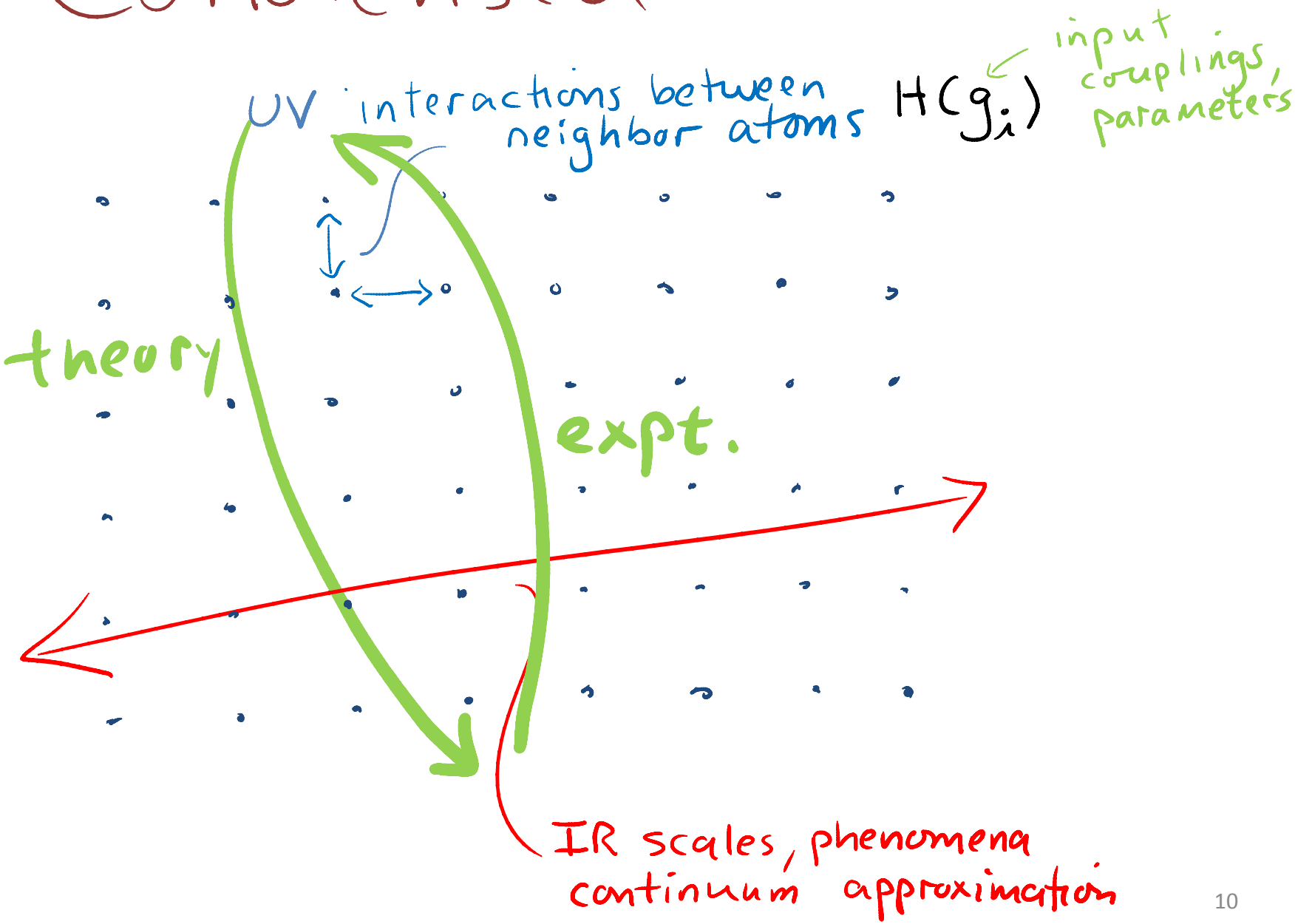
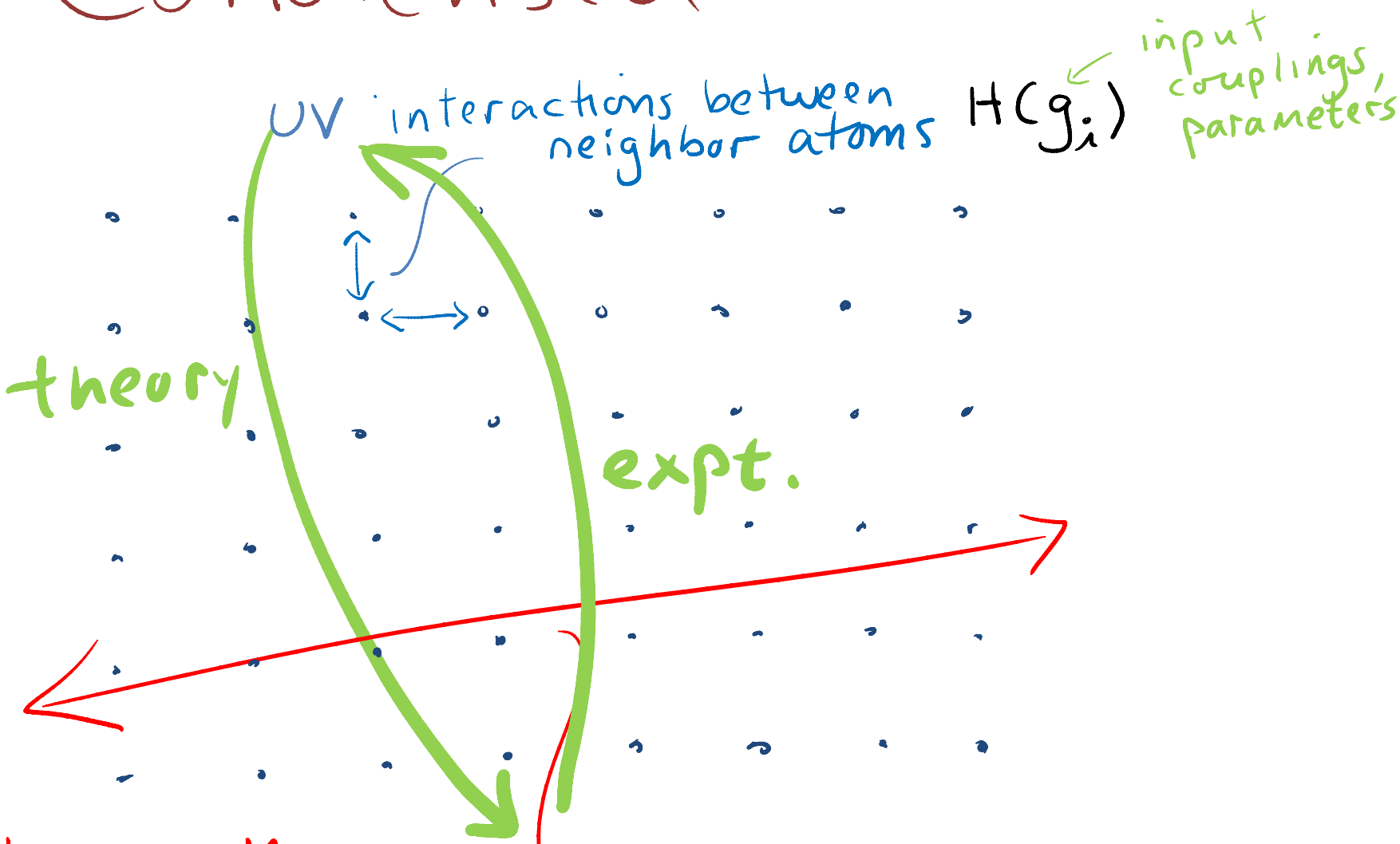


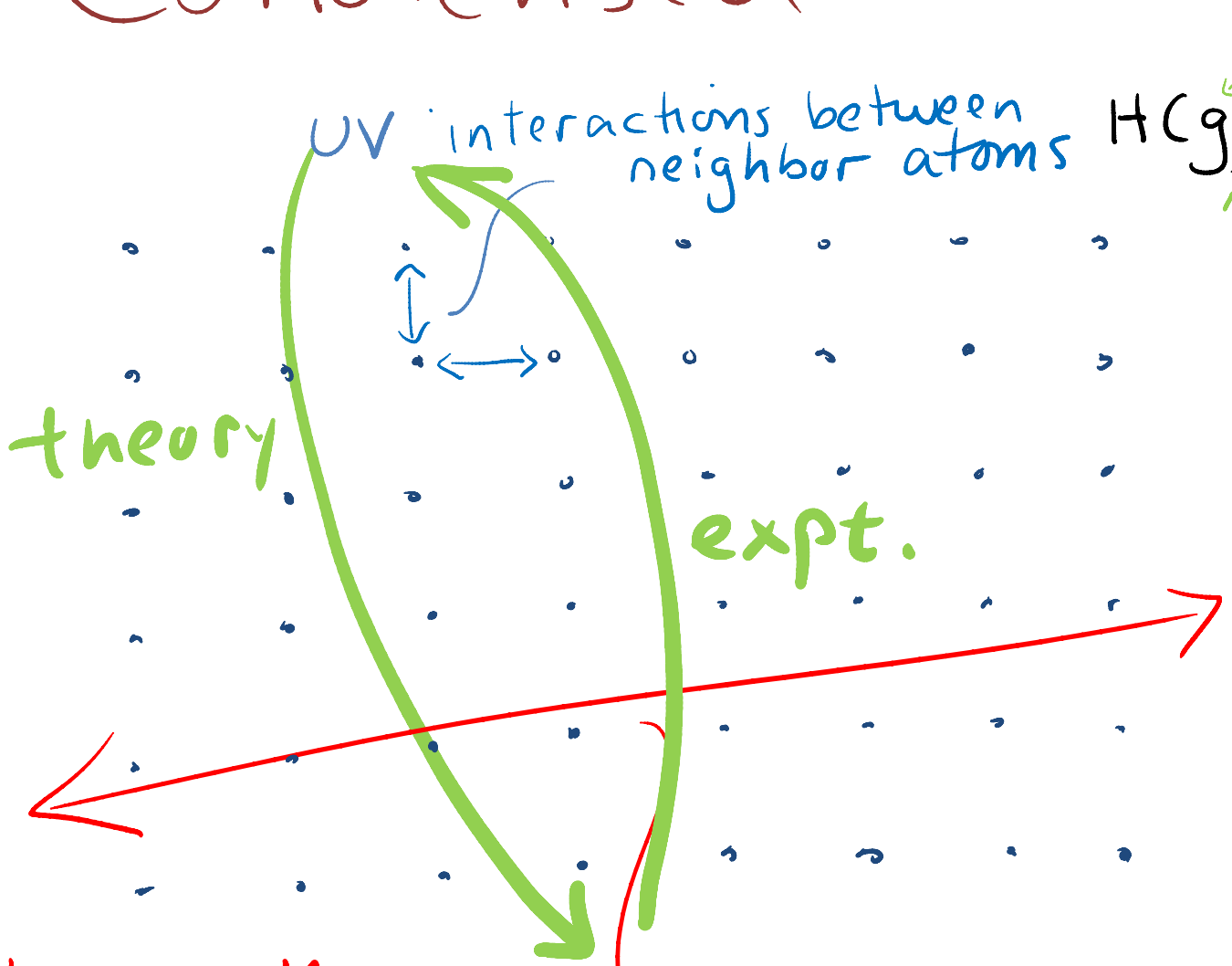
Condensed Matter



Why are there IR length scales at all?

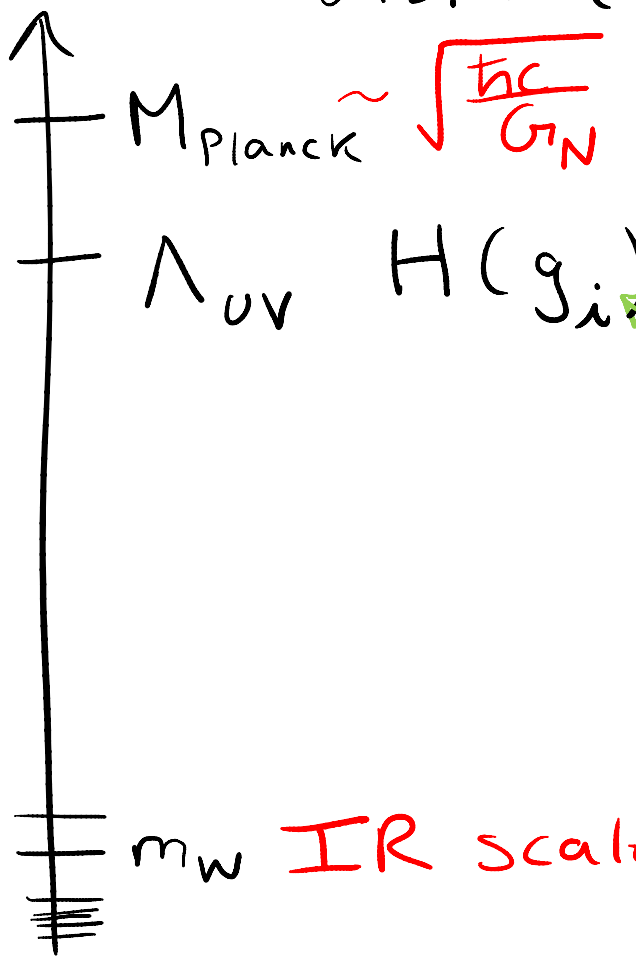
IR scales, phenomena continuum approximation

Condensed Matter



Relativistic Particles

$$E \sim \frac{\hbar c}{\text{distance}}$$



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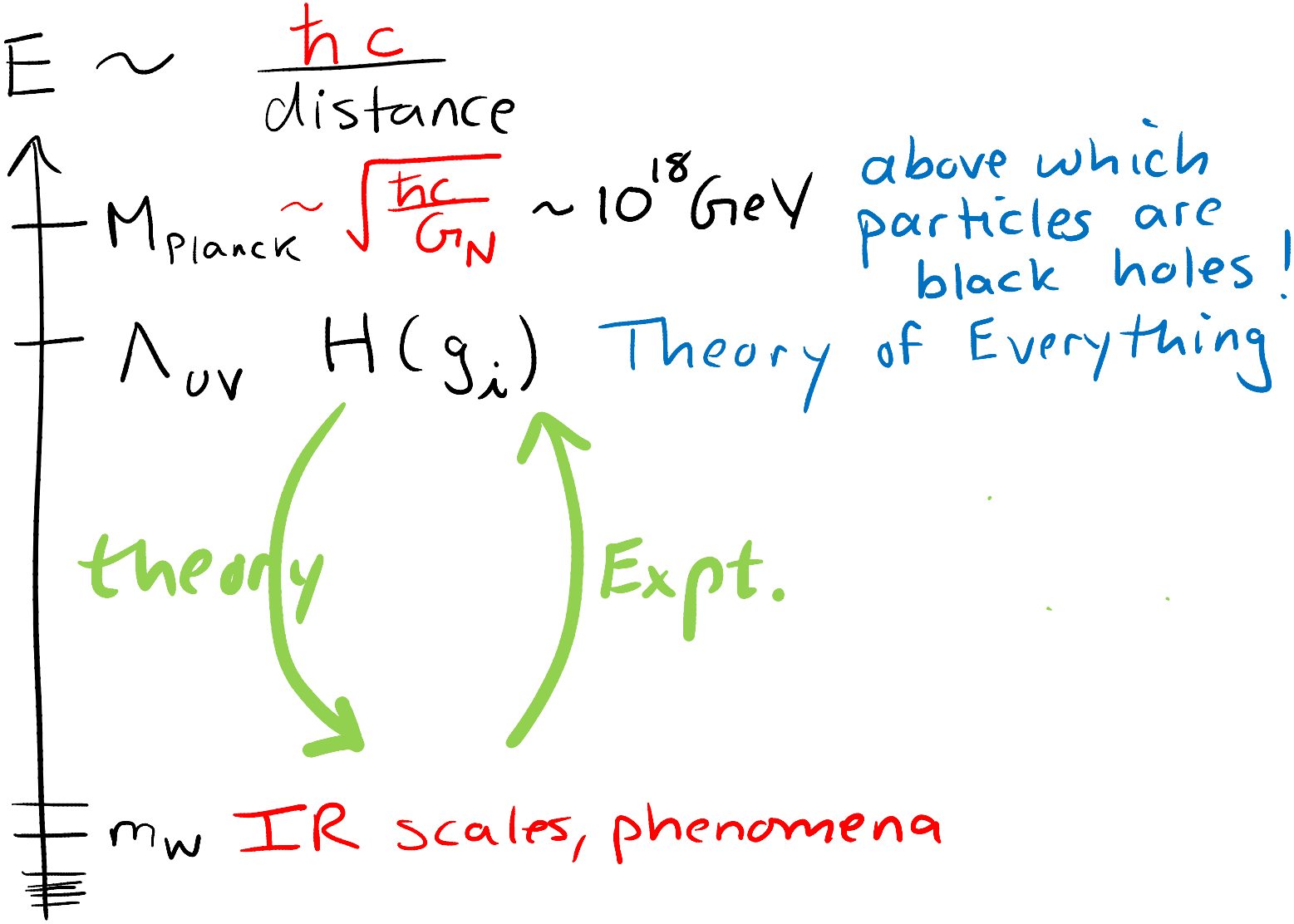

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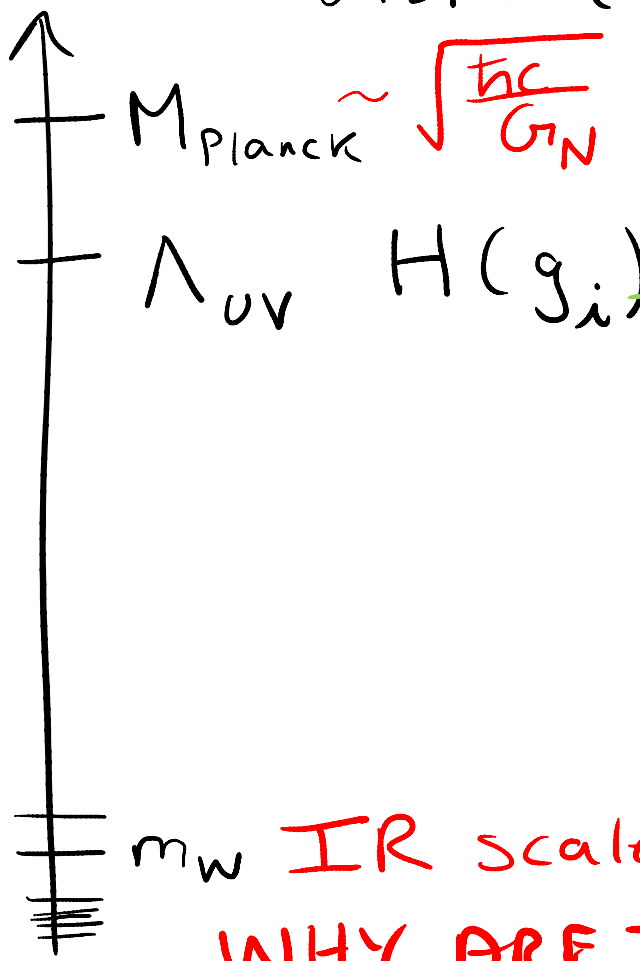
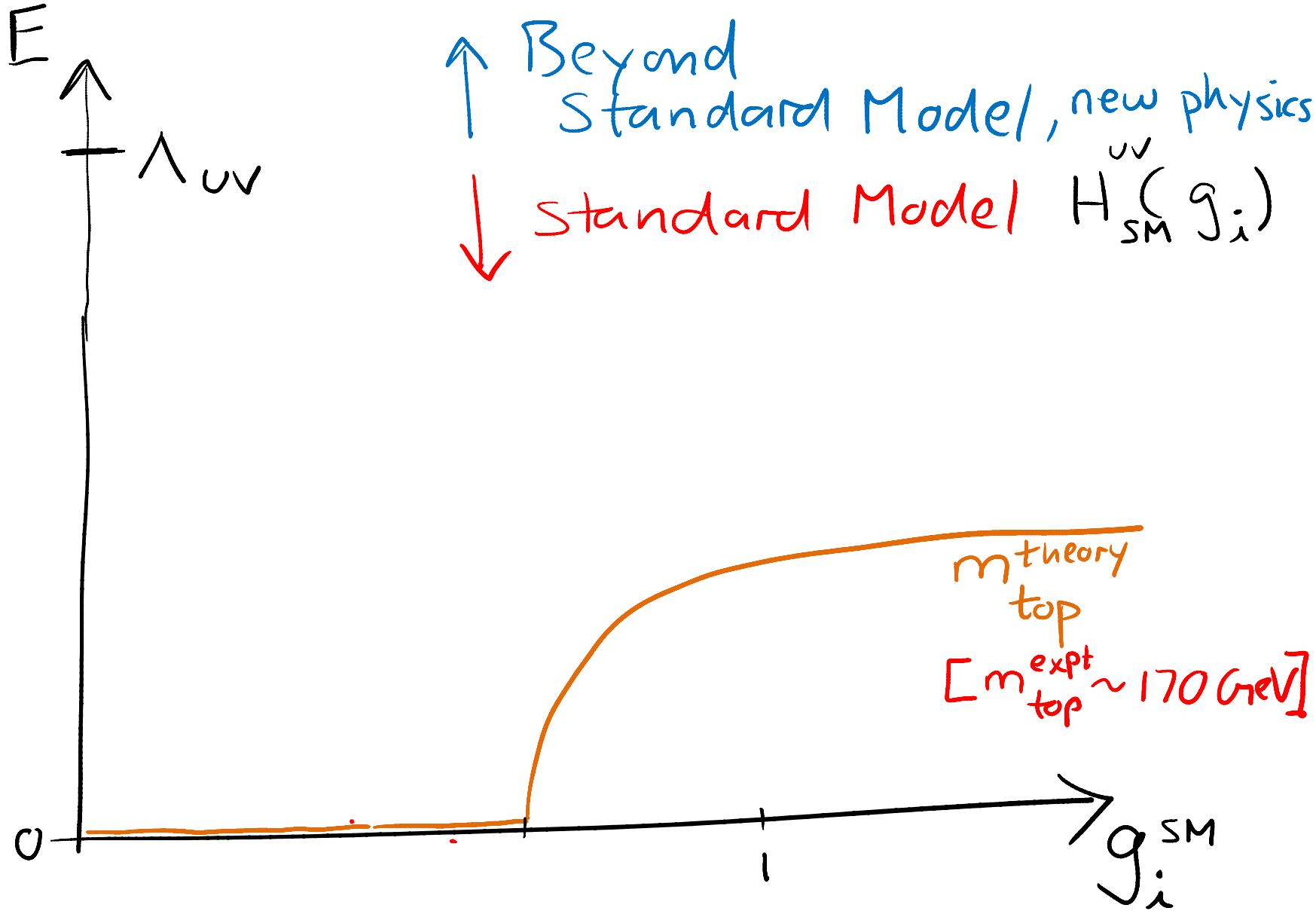


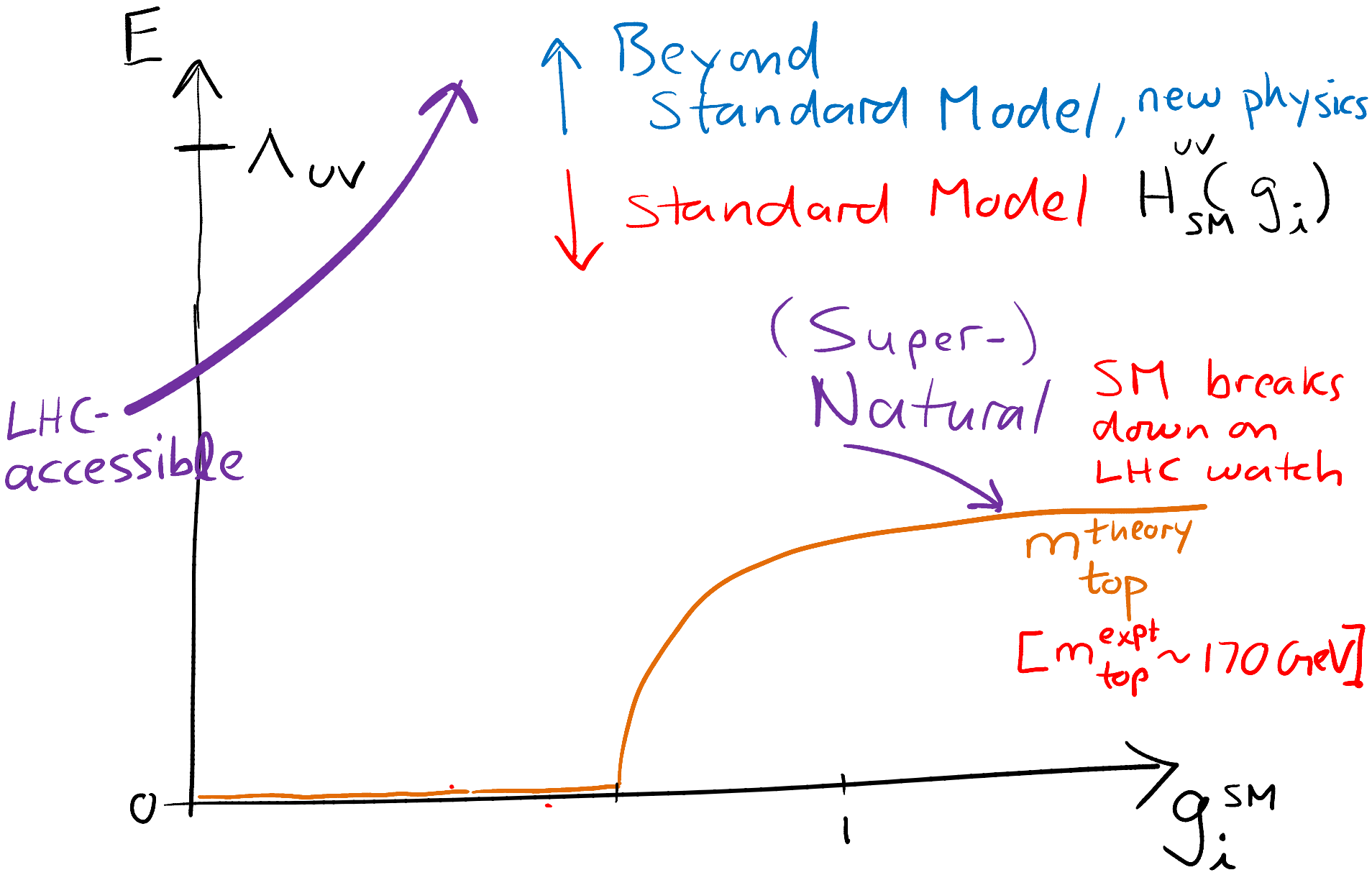
Are IR phenomena robust against modest changes of g_i^{UV}?
"Typical" of what might have been?

WHY ARE THERE IR SCALES AT ALL?

ElectroWeak HIERARCHY PROBLEM



ElectroWeak HIERARCHY PROBLEM



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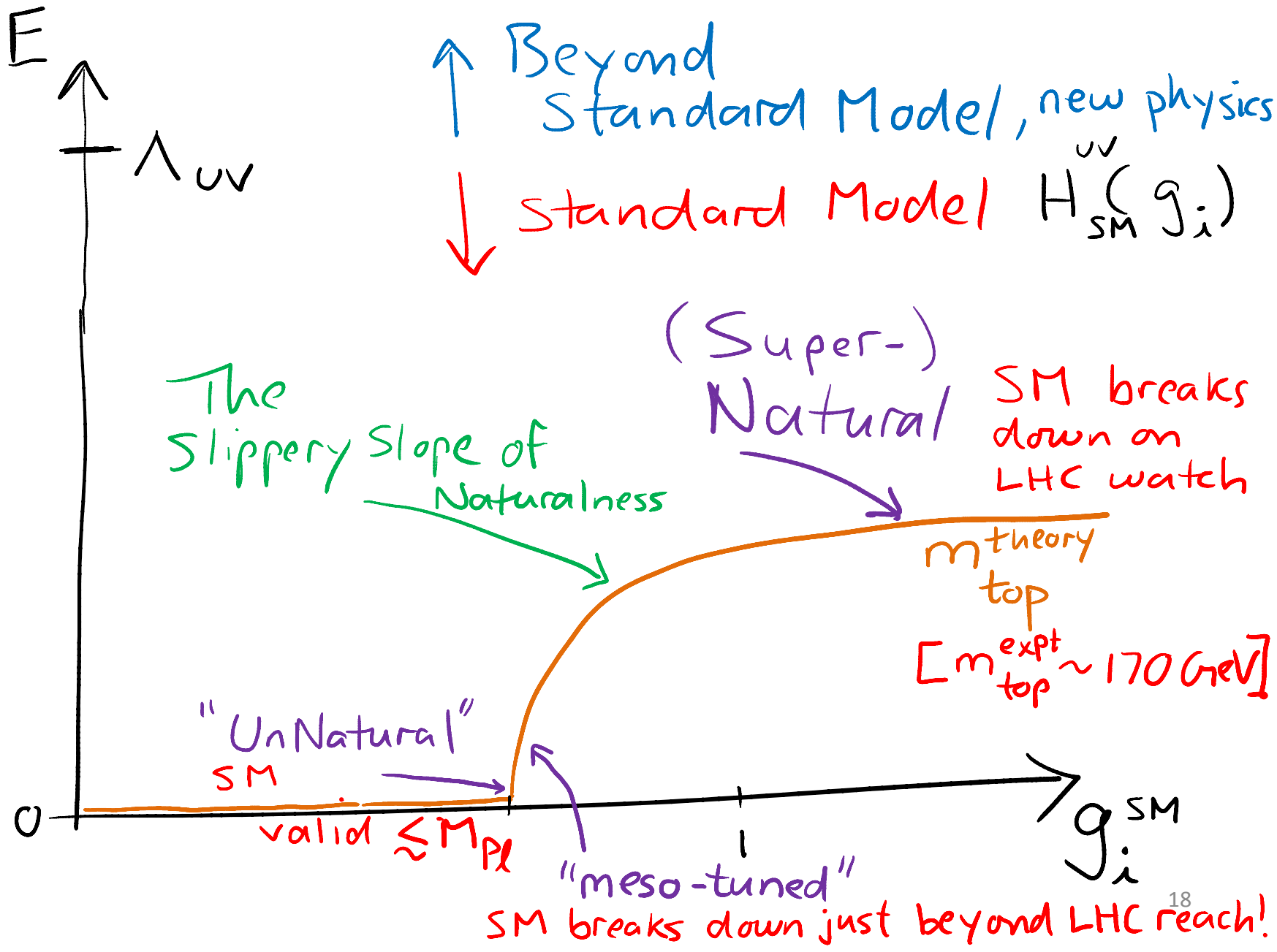

The $E = mc^2$ of Beyond SM Physics

$$m_{\text{new physics}} \gtrsim \text{weak scale} \sim M_{Pl}\, e^{-4\pi^2/g^2_{UV}}$$

modestly small $\Rightarrow$ vast hierarchy

[QCD: $m_{\text{proton}} \sim M_{Pl}\, e^{-4\pi^2/g^2_{UV}}$]

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2 root mechanisms:

Compositeness of Higgs sector (at least)

Supersymmetry

No fully, FULLY satisfactory theoretical model, but great modules, mechanisms.

COMPOSITENESS

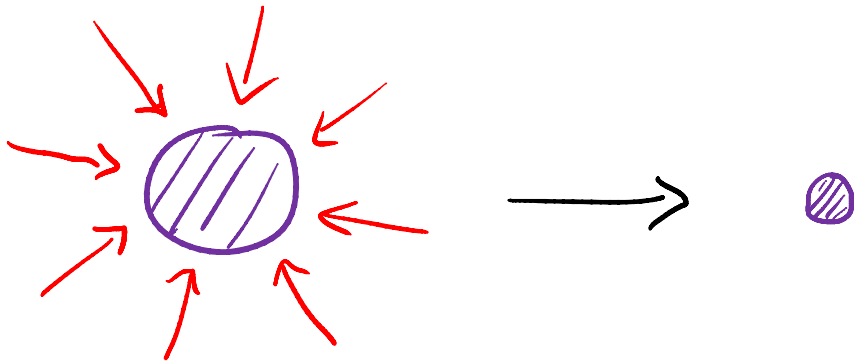
- Higgs compositeness requires STRONG COUPLING, heroic progress & yet poorly understood.
- Brilliant "frontal attacks" ∋ Technicolor, Walking technicolor, Topcolor/condensate Composite Higgs, partial compositeness, Little Higgs, ...
- But there is a back door, a "hydrodynamic" description of compositeness:

Geometrizing Compositeness

AdS/CFT Correspondence

Maldacena '97; Gubser, Klebanov, Polyakov '98; Witten '98

Composite particles have an internal structure that can be excited:



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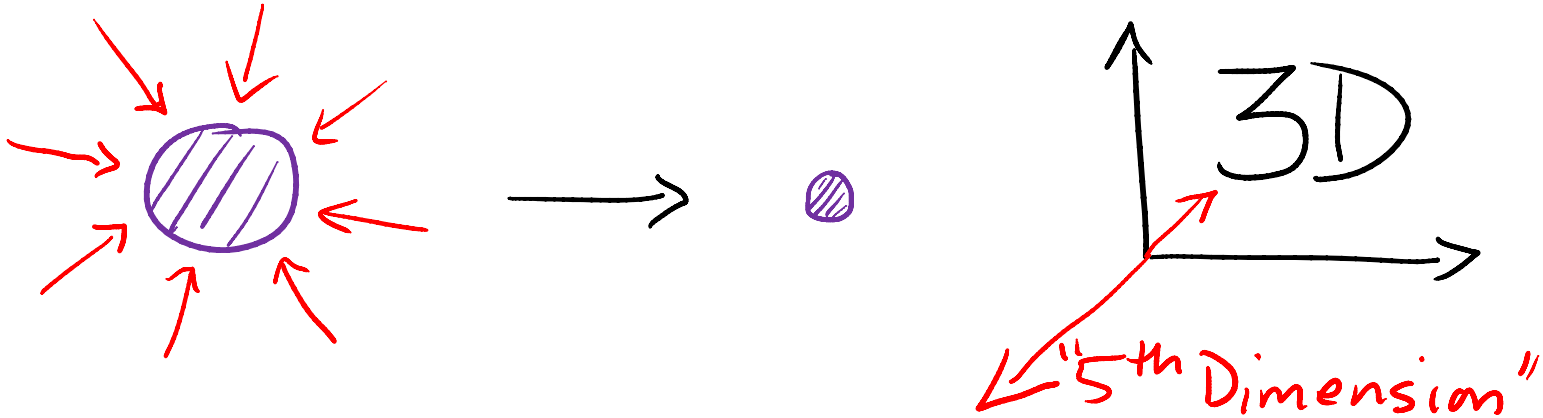
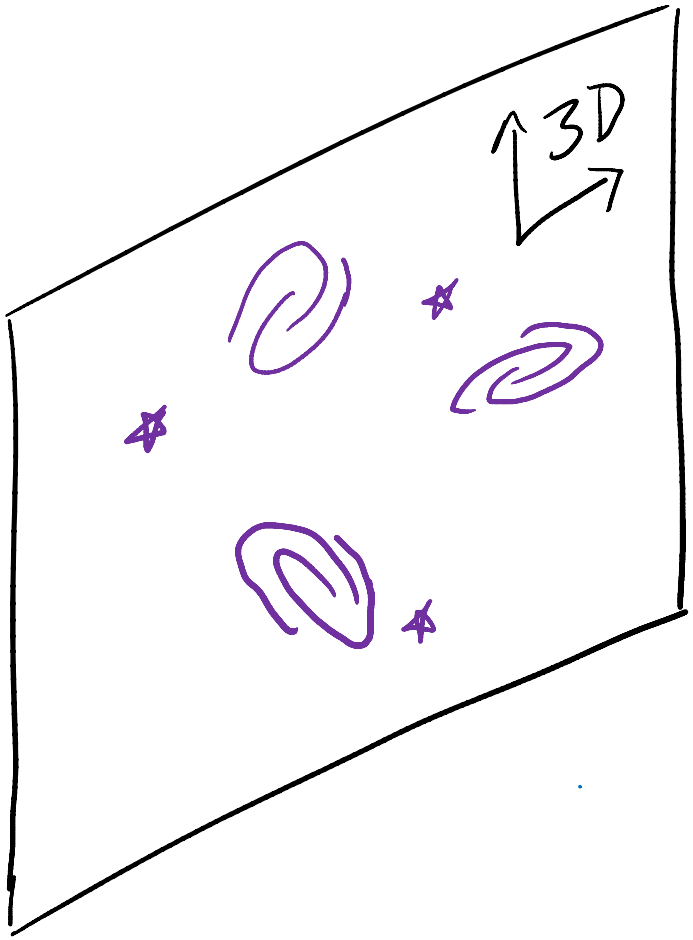


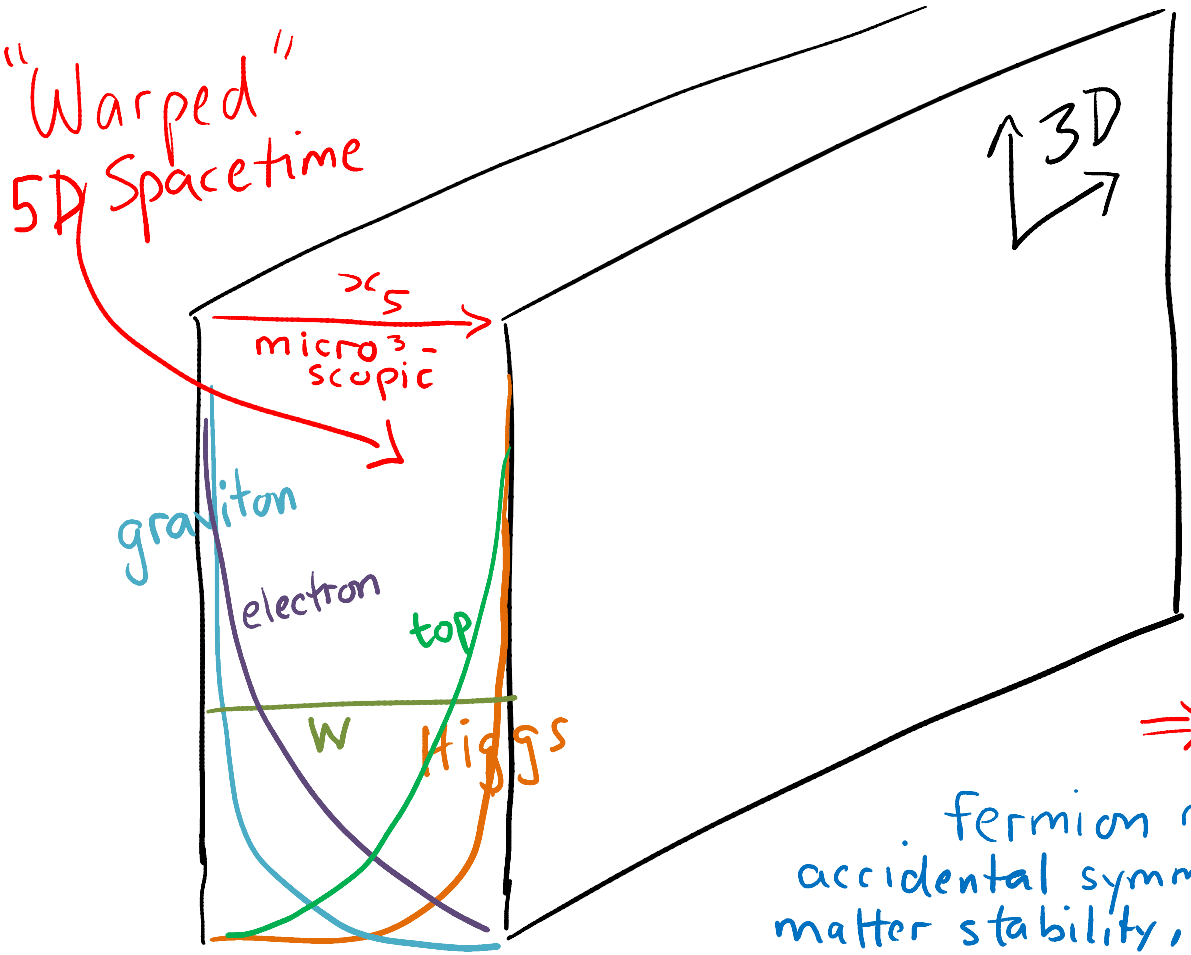
This can be represented as thinking of them as "close up" or "far away" in a fictitious dimension.

4D COSMOS

3+1 D



4D COSMOS from 5D CHAOS!



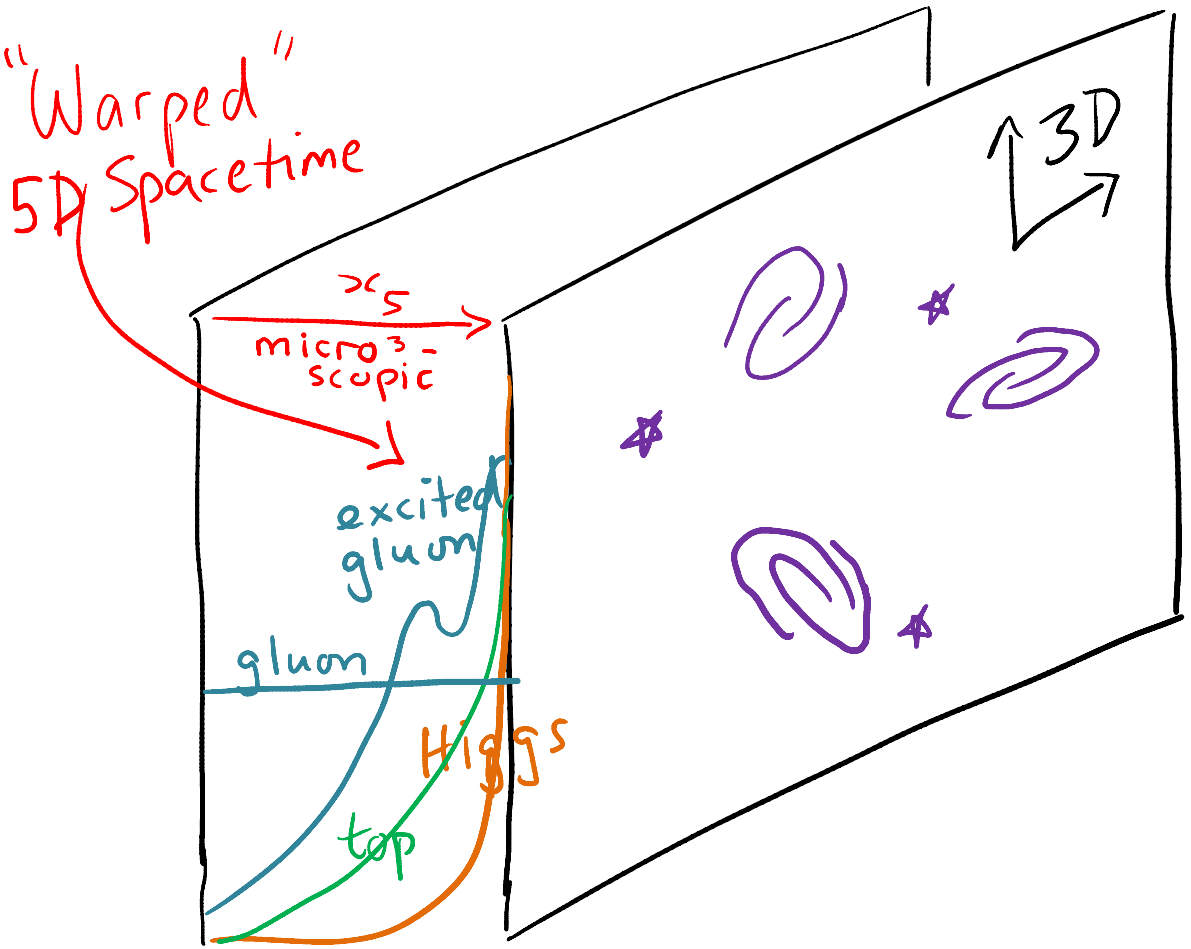
Randall, Sundrum '99
Goldberger, Wise '99
Gherghetta, Pomarol '00
⋮

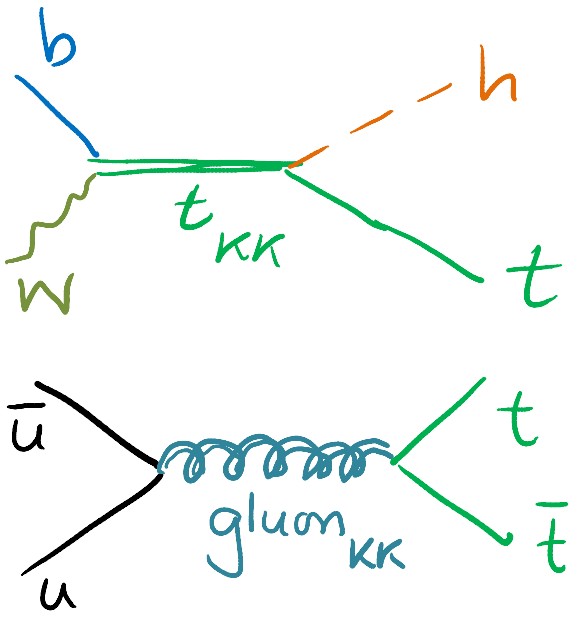
Different species have different exponential falloffs, boundary conditions

⇒ Weak/Planck hierarchy, fermion mass hierarchy, CKM hierarchy, accidental symmetries (baryon no., dark matter stability, gauge unification, ...

Higher harmonics ≡ "Kaluza-Klein" excitations

Eg. gluon_{KK}, top_{KK}





SuperSymmetry

= fermionic extra dimension

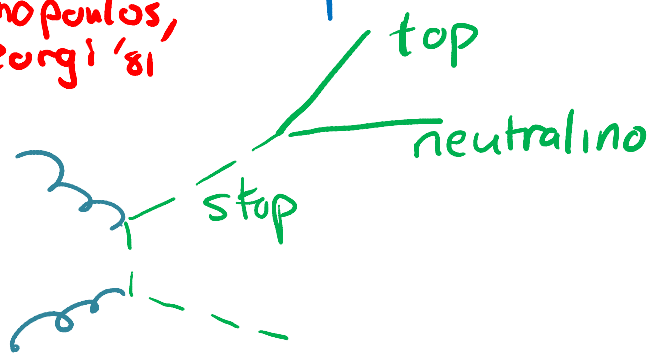
$$\psi(\vec{x}, t, x_5) \rightarrow \psi(\vec{x}, t, \theta)$$

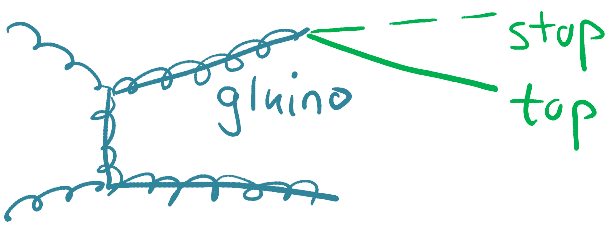
$$x x' = x' x \qquad \theta\theta' = -\theta'\theta$$

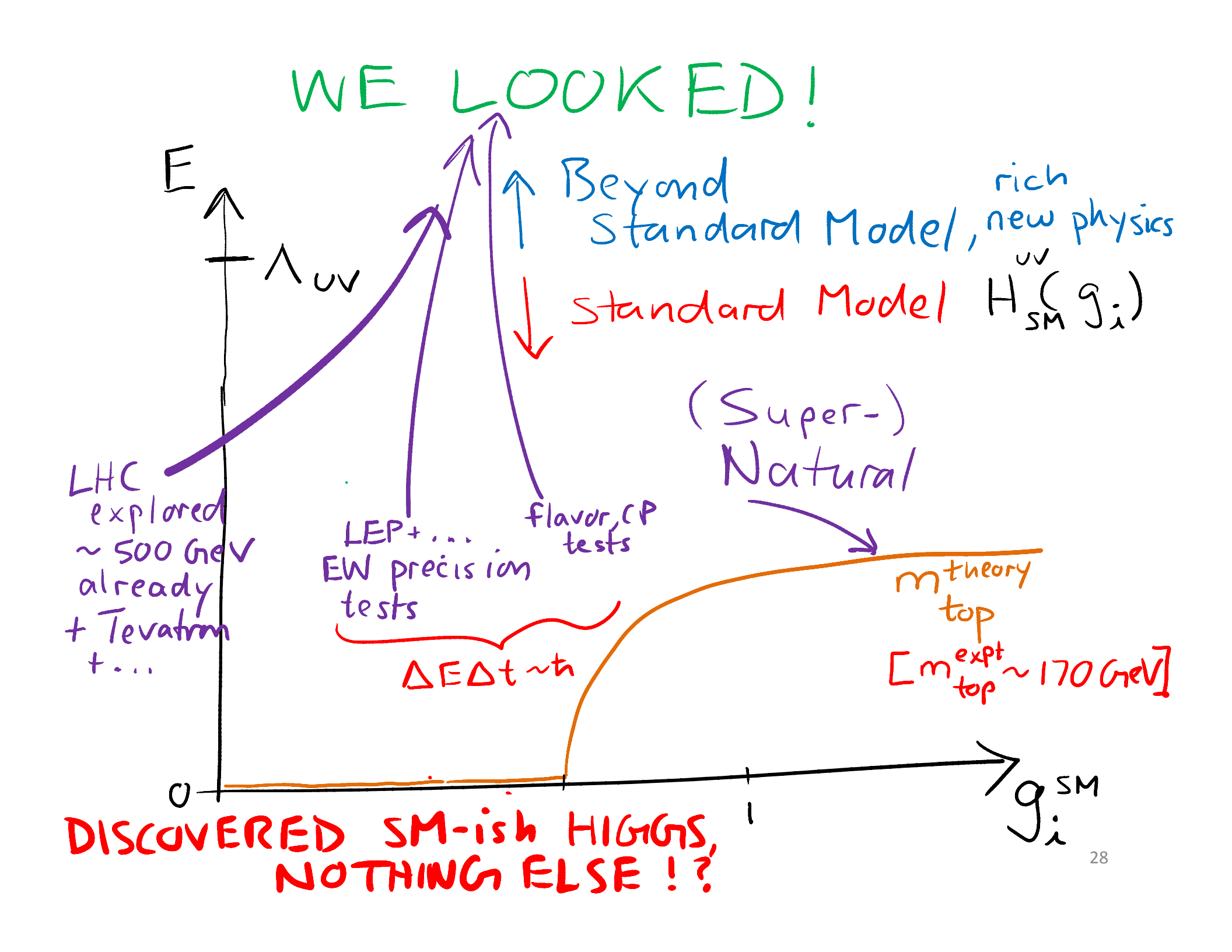
MSSM $\Rightarrow$ Dimopoulos, Georgi '81

Super Partners. eg. spin-0 stop

spin-$\frac{1}{2}$ gluino






WE LOOKED!
E
Λ_{UV}
Beyond Standard Model, rich new physics
Standard Model
$H^{UV}_{SM}(g_i)$
(Super-) Natural
LHC explored ~ 500 GeV already + Tevatron + ...
LEP + ... EW precision tests
flavor, CP tests
$\Delta E \Delta t \sim \hbar$
m^{theory}_{top}
$[m^{expt}_{top} \sim 170\ GeV]$
0
1
g_i^{SM}
DISCOVERED SM-ish HIGGS, NOTHING ELSE !?

WHERE IS THE RICH NEW PHYSICS ??

LHC 13-14 TeV

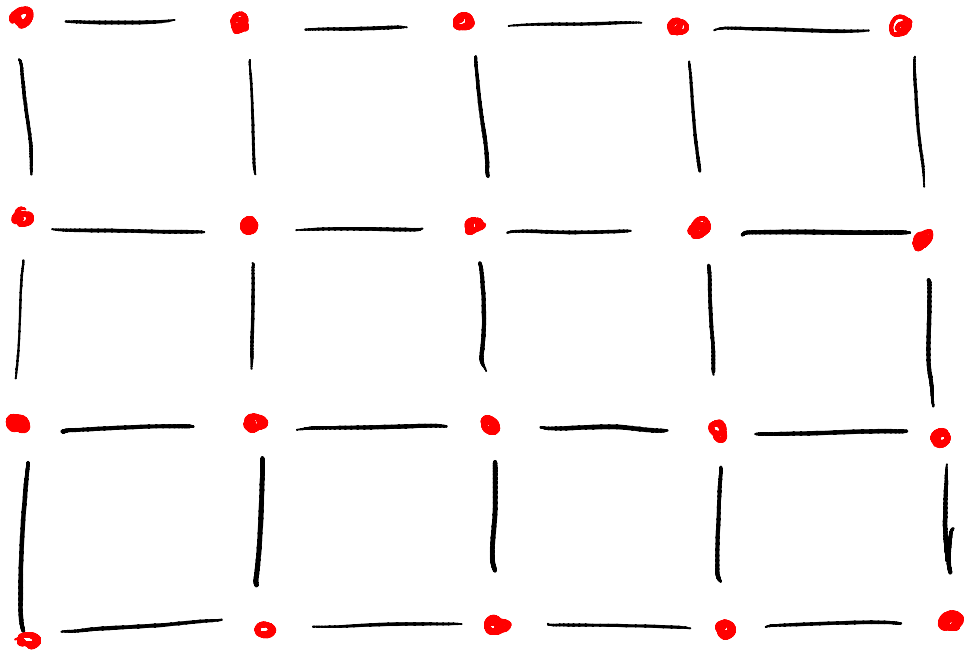
- redoubled efforts, energies still v. exciting
- Expect the Unexpected: bottom-up plots for hidden naturalness. Eg. "Twin Higgs"

Chacko, Goh, Harnik '06

CONDENSED MATTER

Many different ground states:

different molecules, bonds



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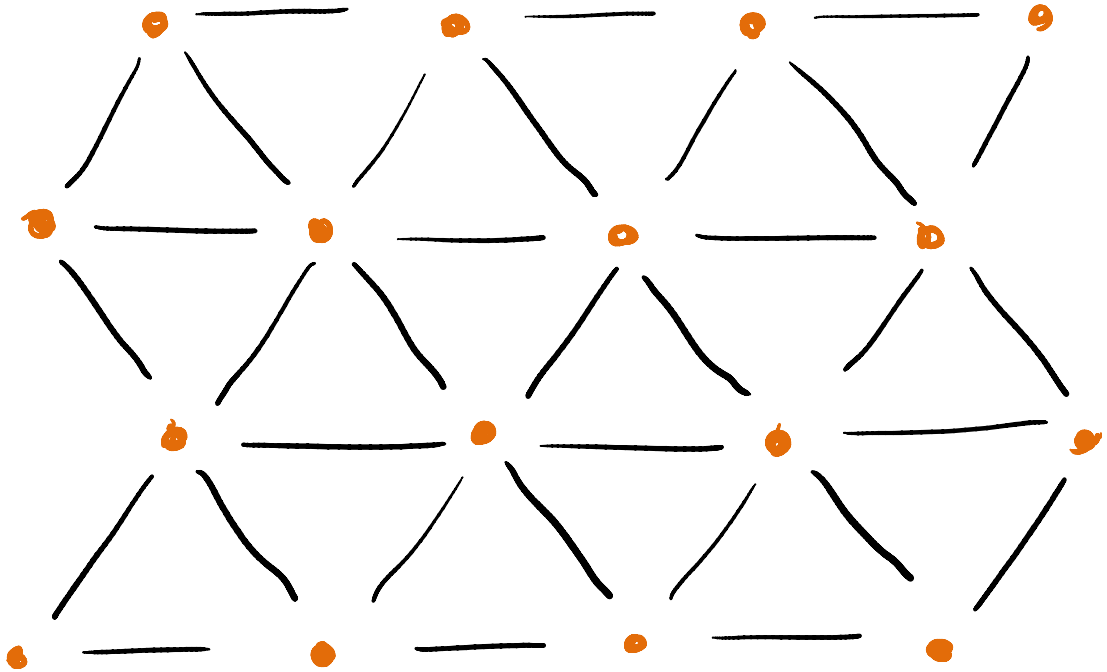
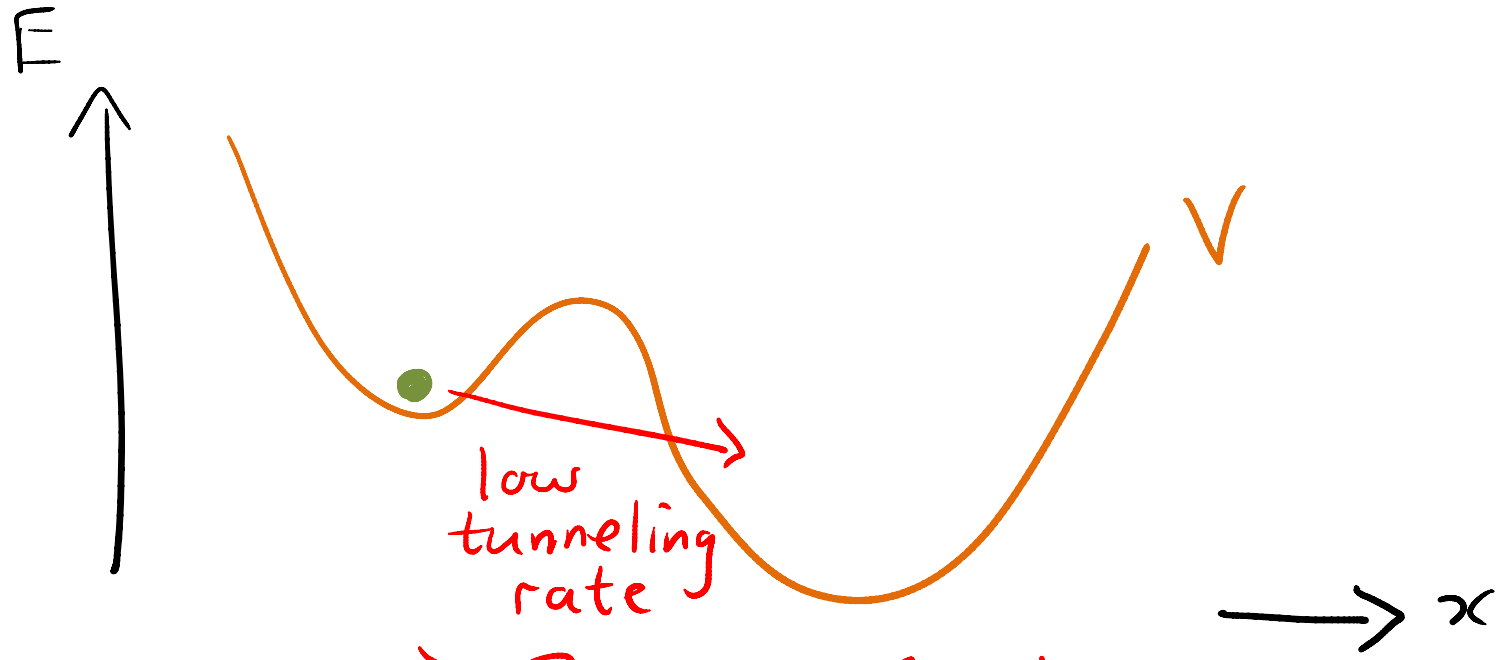


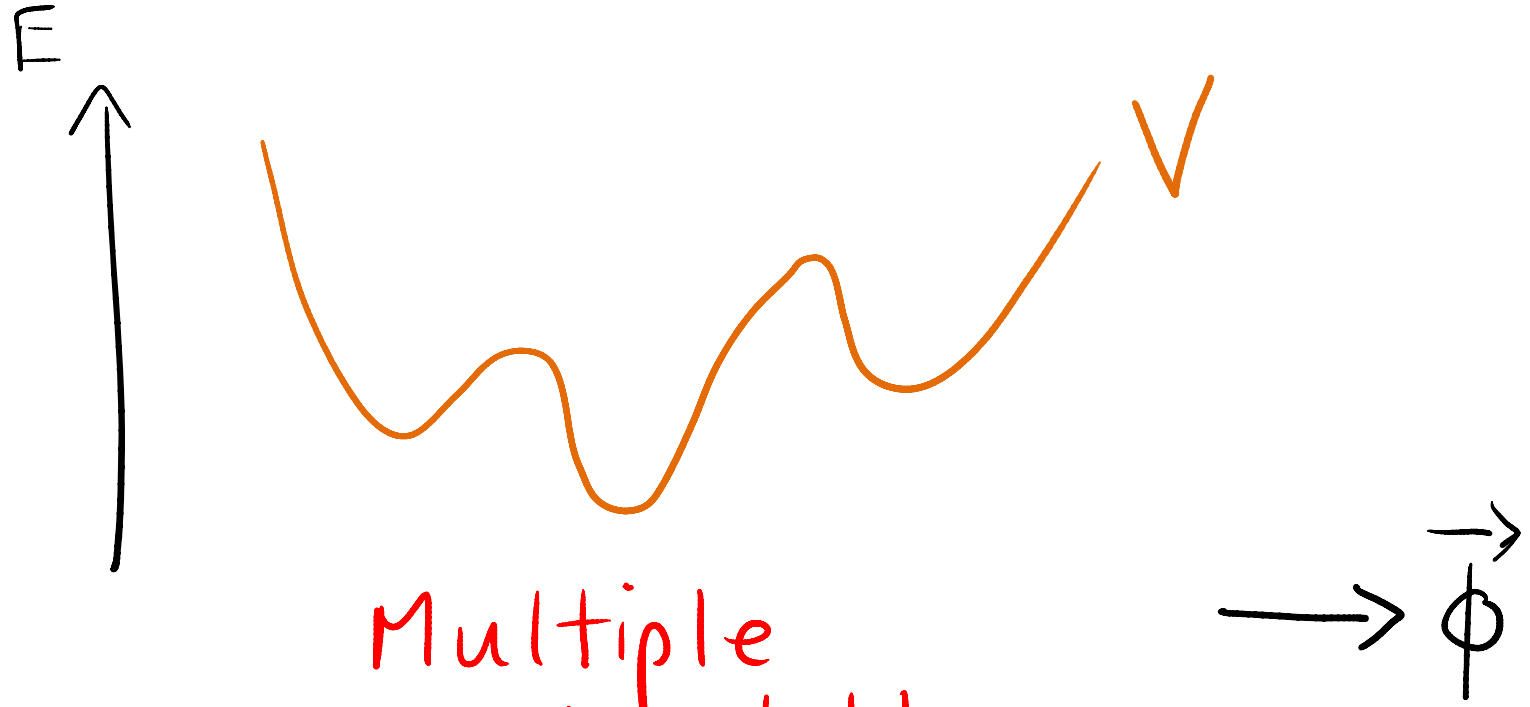
$\Rightarrow$ Large Discretum $\Rightarrow$ Large number of IR effective theories

QUANTUM MECHANICS



=> 2 approximate "ground" states

QUANTUM FIELDS



Multiple meta-stable vacua

STRING THEORY "LANDSCAPE" ("DISCRETUM")

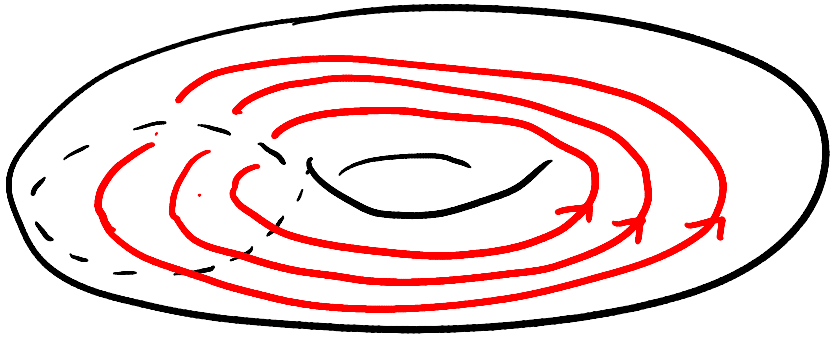
Enormous number (10^{500} ?) of vacua, apparently self-consistent ways of tying up extra dimensions, quantized fluxes, branes.

Bousso, Polchinski '00;
Kachru, Kallosh, Linde, Trivedi...

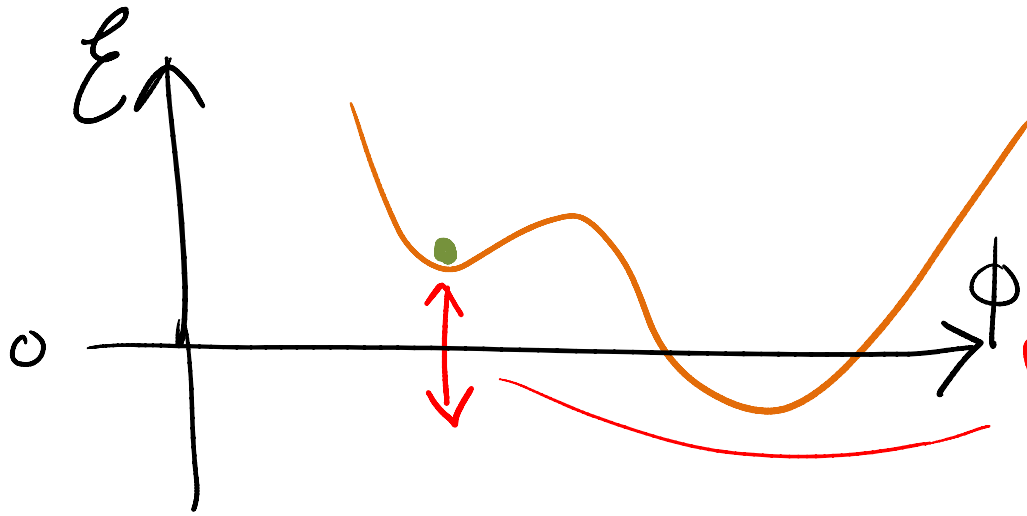
STRING THEORY

"LANDSCAPE"

("DISCRETUM")



ACCELERATION OF THE UNIVERSE



Particle physics scales $\gg TeV^4$

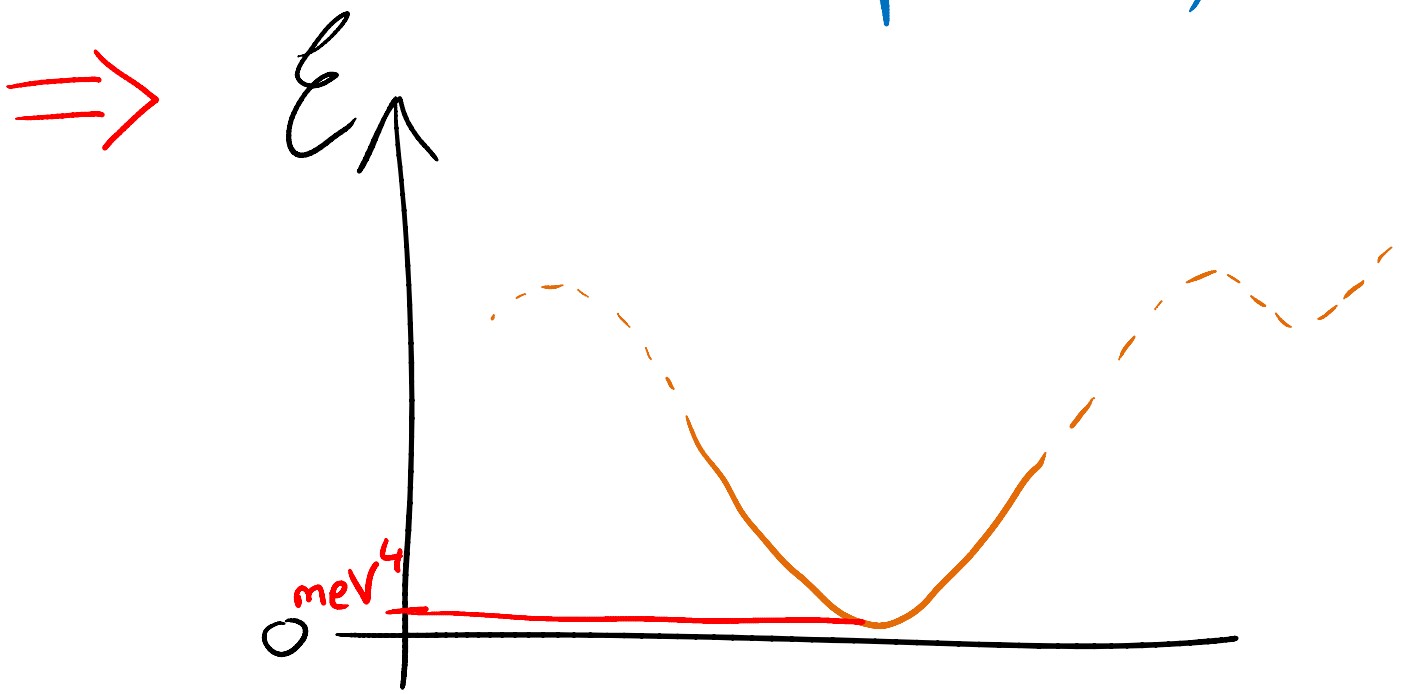
Equivalence Principle $\Rightarrow$ Vacuum energy gravitates

Typically $V_{\text{local-min.}} \neq 0$

Curvature = $\mathcal{E}$ $\Rightarrow$ Extremely rapid, accelerating expansion of Universe

OBSERVATION

Supernovae, CMB, ...



No known natural mechanism for such "coincidence" (that is generally agreed upon).

Some reasons to think no such mechanism exists, partly because many experiments $\gg$ meV, naively scale at which natural mechanism should appear

DARK ENERGY

If there is secret mechanism, there may be modified equation of state of vacuum => modified details of current expansion

$$\left(\frac{\dot{a}}{a}\right)^2 \propto \frac{1}{a^{3(1+w)}}$$

Cosmic scale factor

$w = -1$ "normal" vacuum energy

$w = 0$ matter

$w = 1/3$ radiation

SUB-mm GRAVITY

Maybe secret mechanism hidden in modified gravity at meV momentum transfers

$\equiv \sim 100\mu m$

$$F = G_{Newton}\frac{m_1 m_2}{r^2} \; ? \; r < 100\mu m$$

Thus far, yes for $r > 50\mu m$

Adelberger et.al. '06

V. Large Discretum of Vacua

$\Rightarrow$ V. large assortment of $V_{\text{local-min.}}$

Can choose from among tiny fraction $\ll 10^{-60}$ with $V_{\text{local-min}} \sim \text{meV}^4$ by random cancellation of $\gg \text{TeV}^4$ effects.

BUT WHO CHOOSES?

ANTHROPIC PRINCIPLE

CONDITIONAL PROBABILITY ~ O(1)?

HIGH probability of tiny vacuum energy if we pick randomly among those supporting life

Galaxy formation would have been impossible if cosmic acceleration too large

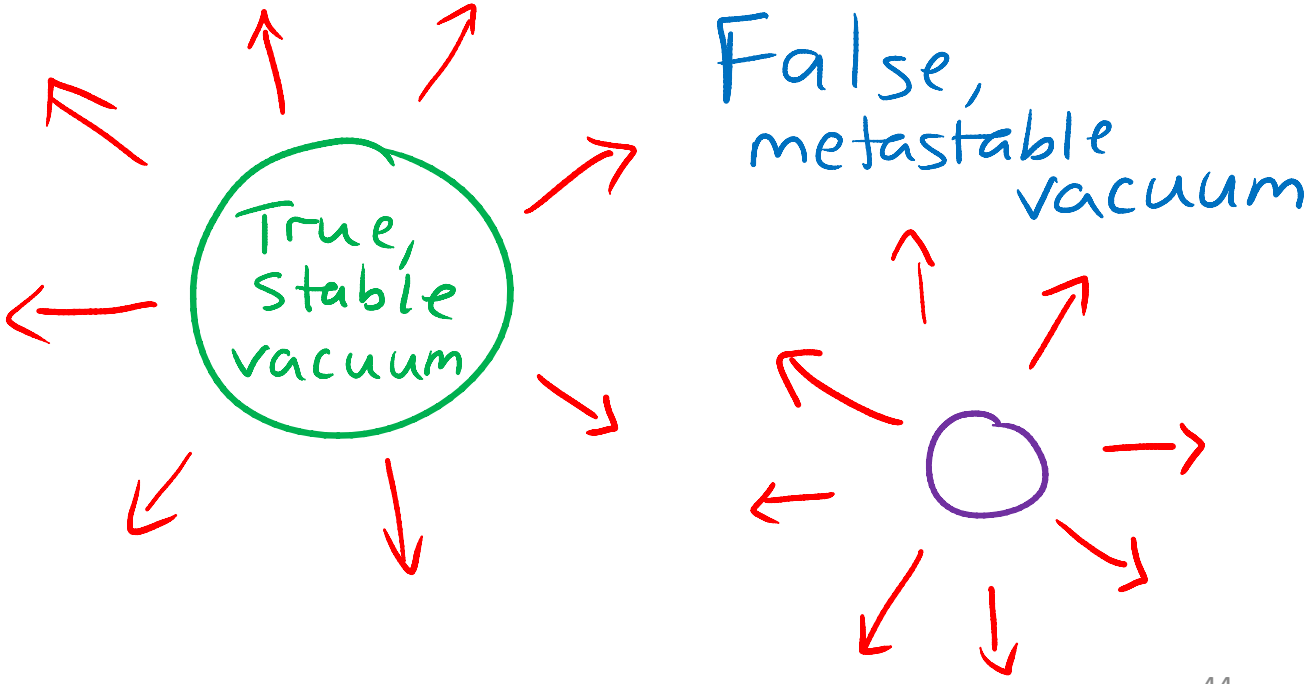
Weinberg '87

BUT WHY ARE WE LUCKY ENOUGH TO EXIST?

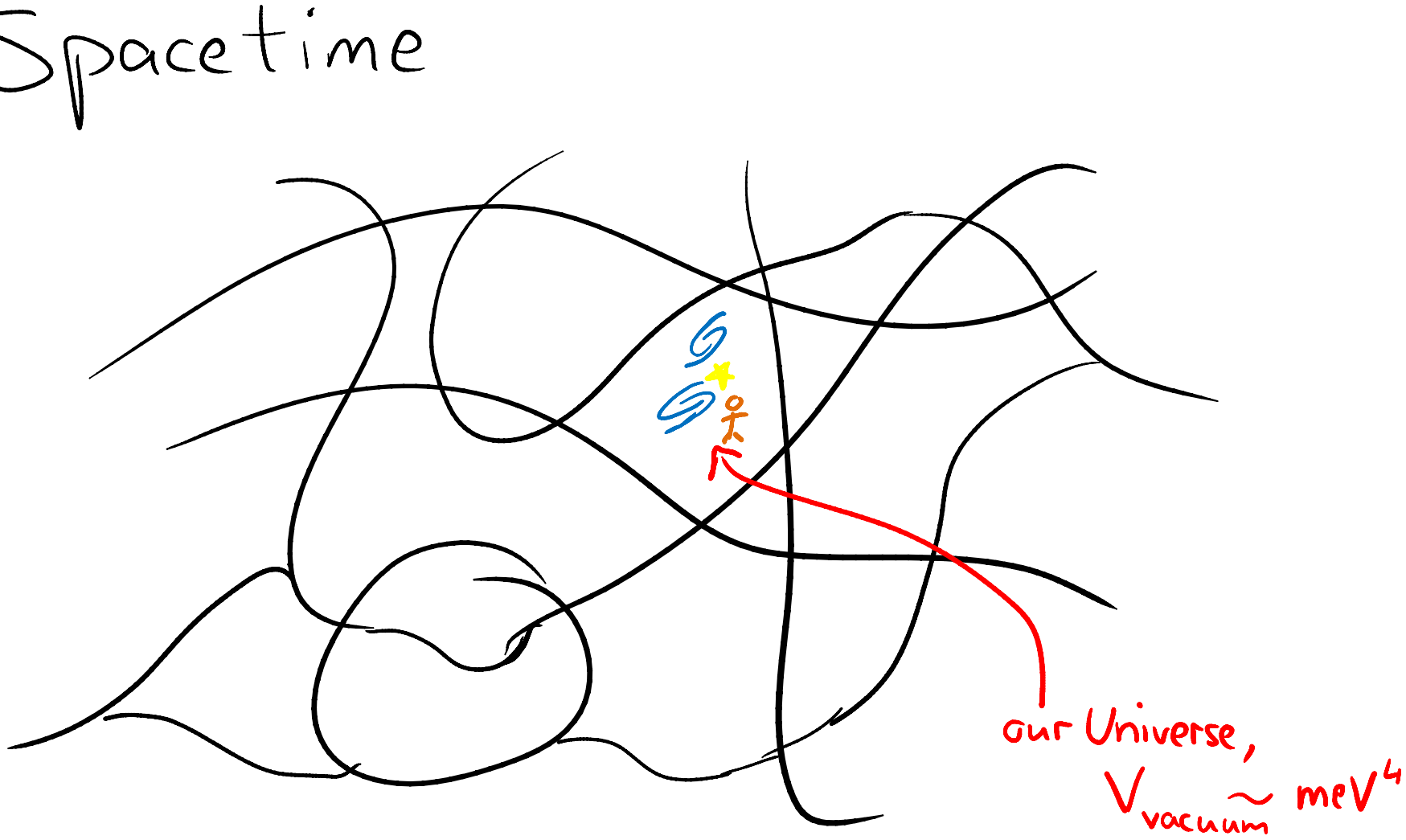
MANY TRIALS?

Different "phases", vacua, can co-exist in a vast spacetime

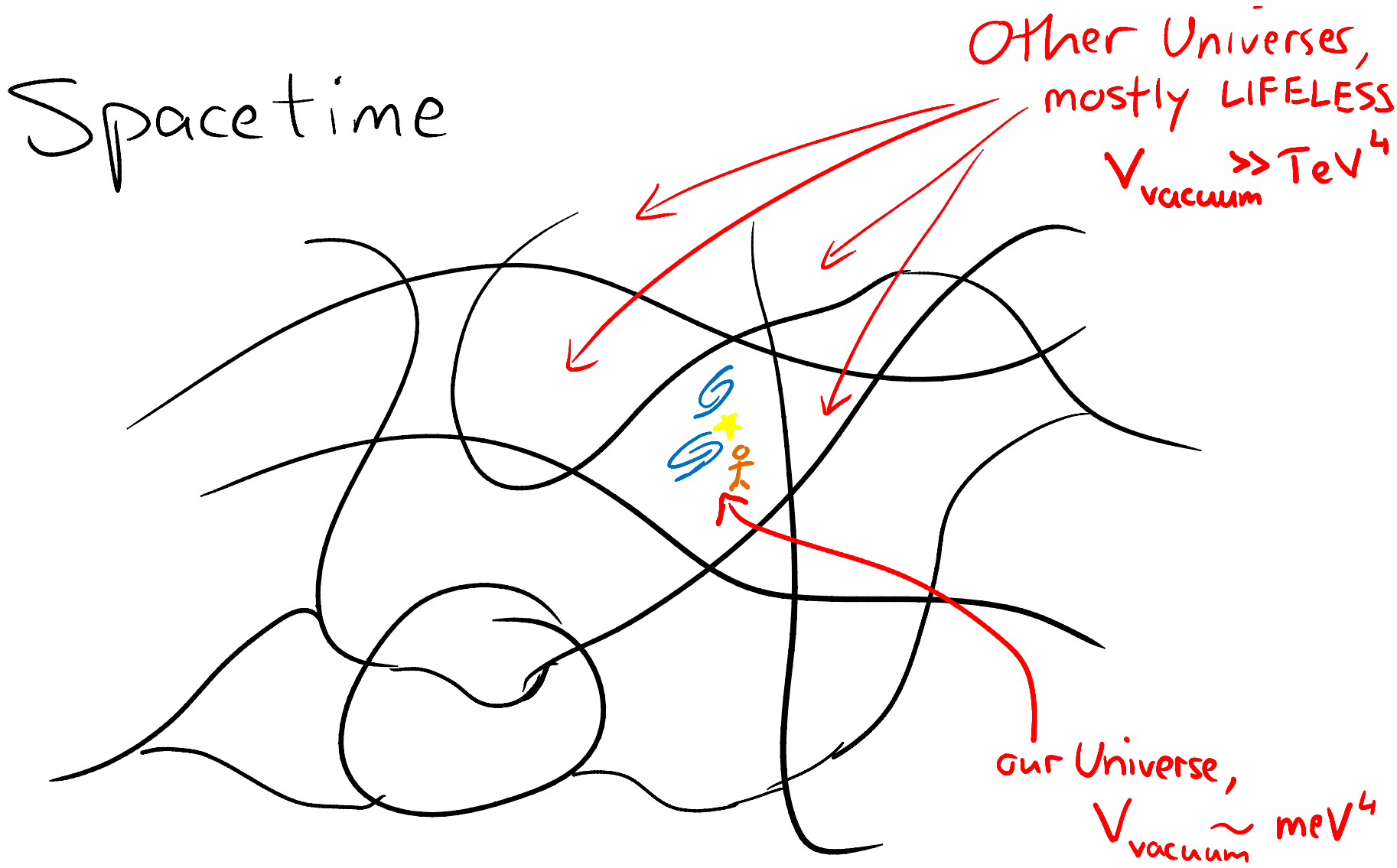
Eg.



MULTI-VERSE



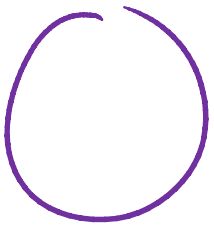
MULTI-VERSE



Many aspects of picture (nature of cosmological horizons, distributional aspects, evolution, ...) remain to be understood.

ANALOGOUS TO OTHER WORLDS ?

AND THEIR VARYING CLIMATES & CHEMISTRIES



extra-solar

Pluto

Earth

Life is rare, but highly likely

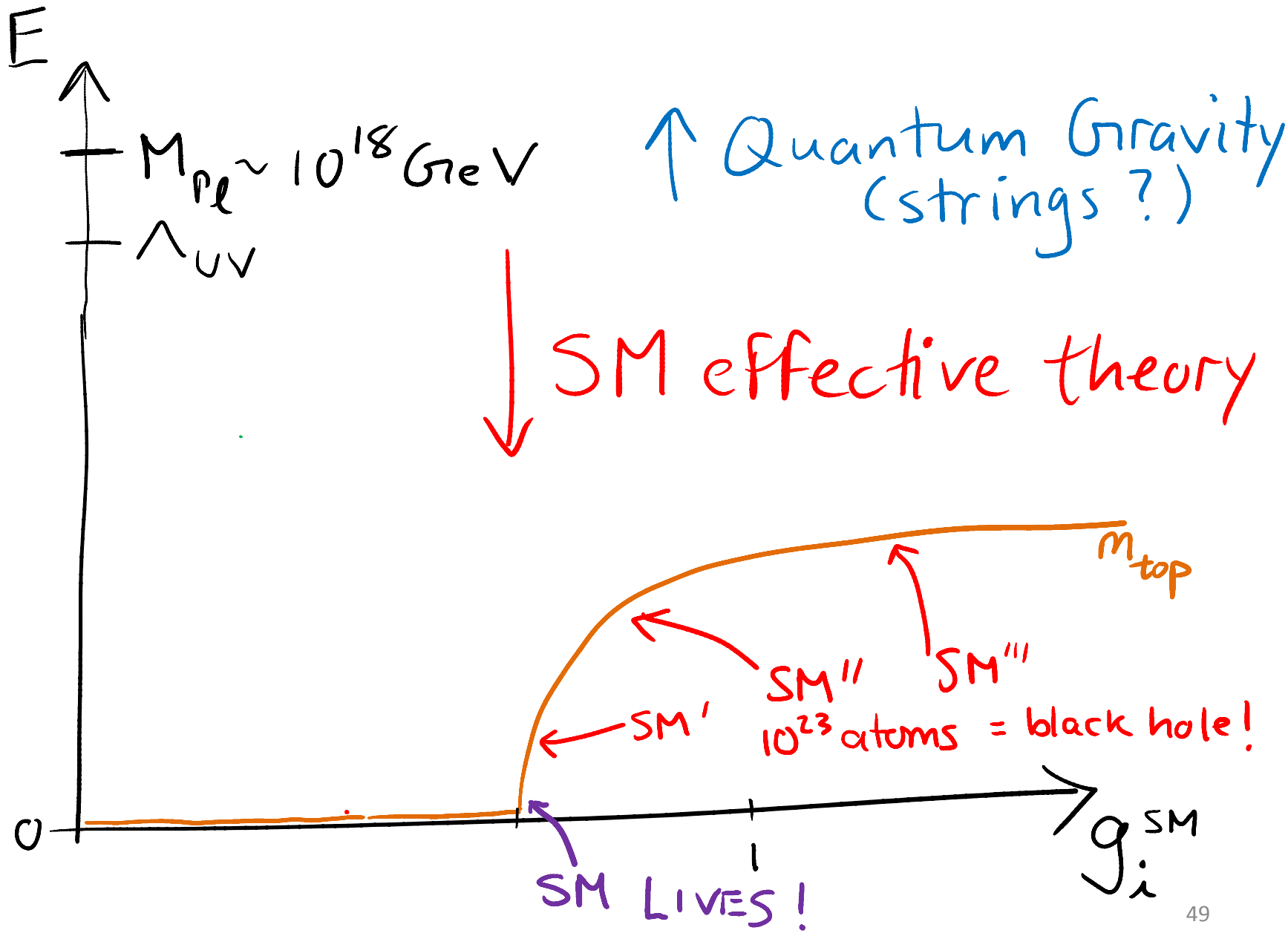
Mercury

ANTHROPIC GENIE WON'T GO BACK IN BOTTLE

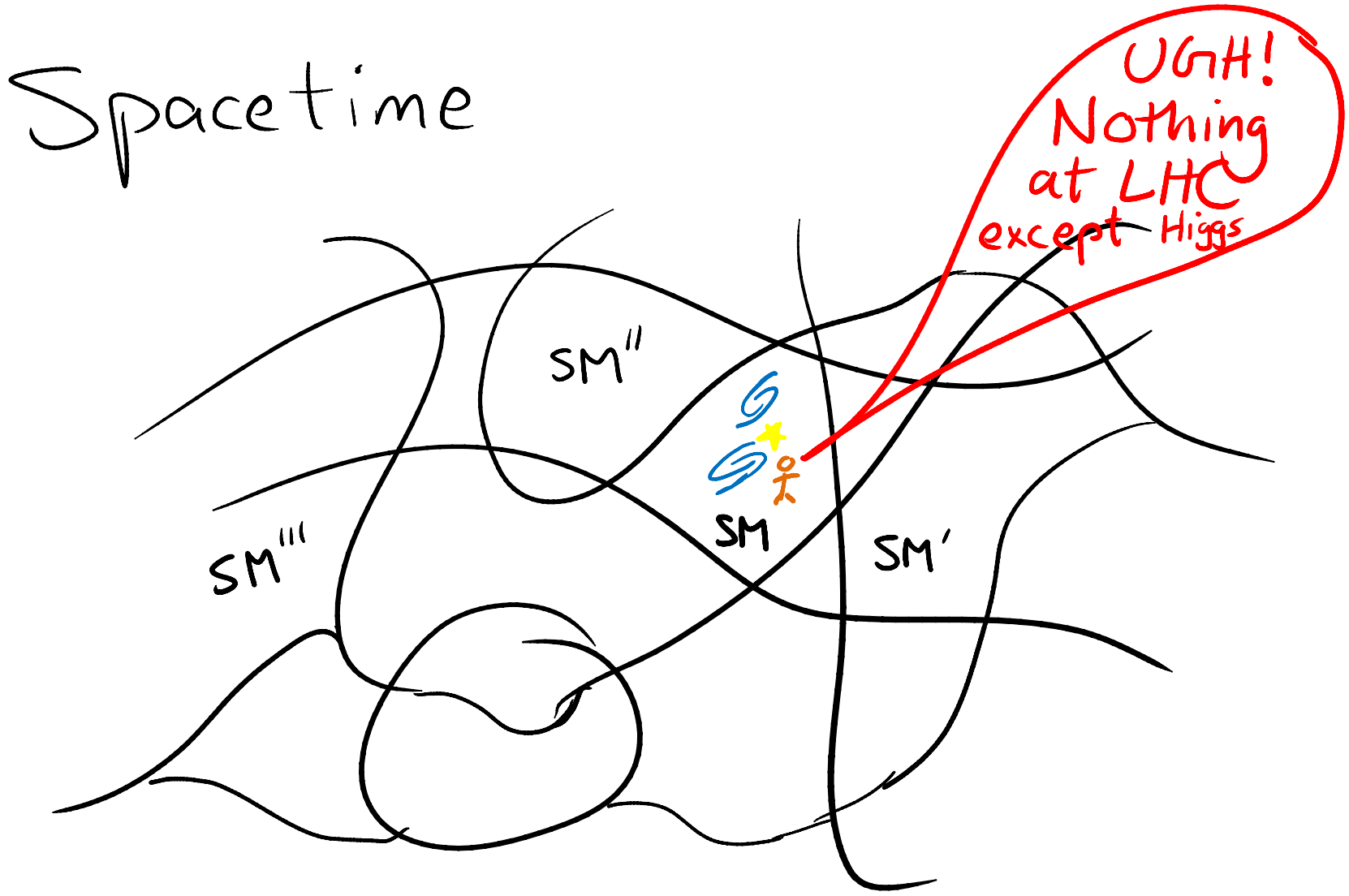
Super-Natural vs. Other-Worldly:

Could anthropic principle solve electroweak Hierarchy Problem (finely-tuned SM) instead of a natural mechanism (with new physics beyond SM within LHC reach)?

Agrawal, Barr, Donghue, Seckel '97; Arkani-Hamed, Dimopoulos '04; Giudice, Romanino '04; ...


E
$M_{Pl} \sim 10^{18}$ GeV
Λ_{UV}
↑ Quantum Gravity (strings ?)
SM effective theory
m_{top}
SM''
SM'''
SM'
10^{23} atoms = black hole!
0
1
g_i^{SM}
SM LIVES!

MULTI-VERSE



But ANTHROPIC IMPERATIVES
(say, ensuring weak scale ≪ Planck scale)
SHOULD TAKE ADVANTAGE OF
NATURAL MECHANISMS
(say Higgs compositeness/ warped dimensions)

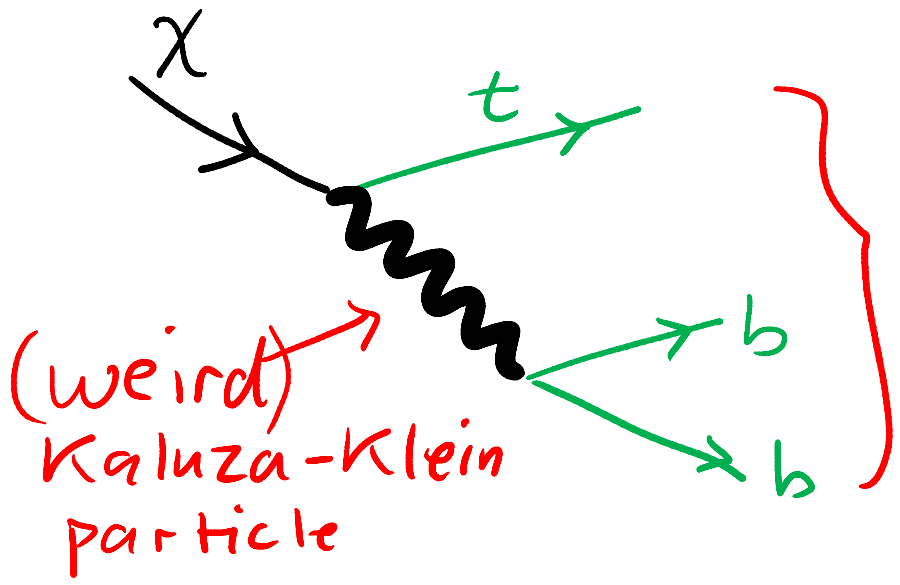
BUT CAN ALSO TEMPER
NAIVE NATURALNESS
EXPECTATIONS

WHY ARE WE HERE?

MATTER-ANTIMATTER ASYMMETRY

The baryons

WIMPy Parent: $\chi = \bar{\chi}$ its own antiparticle



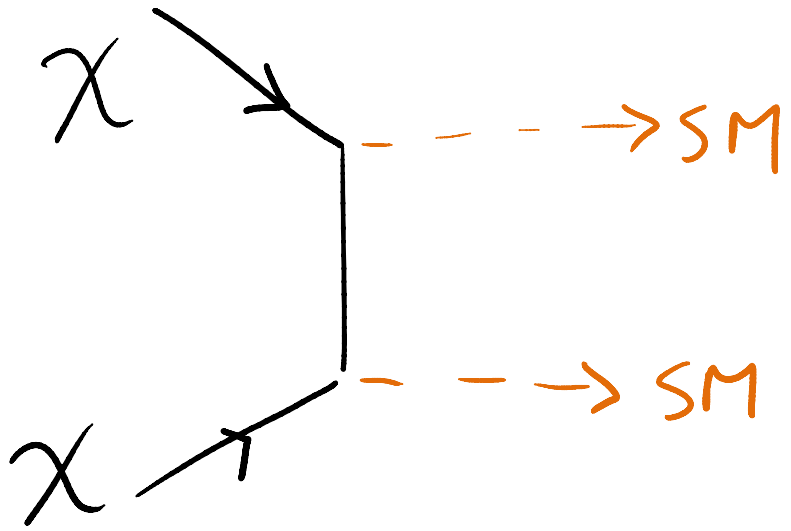
→ proton/neutron + mesons

+ quantum corrections

can preferentially decay to baryons over anti-baryons

Cui, Sundrum '13; Cui '13

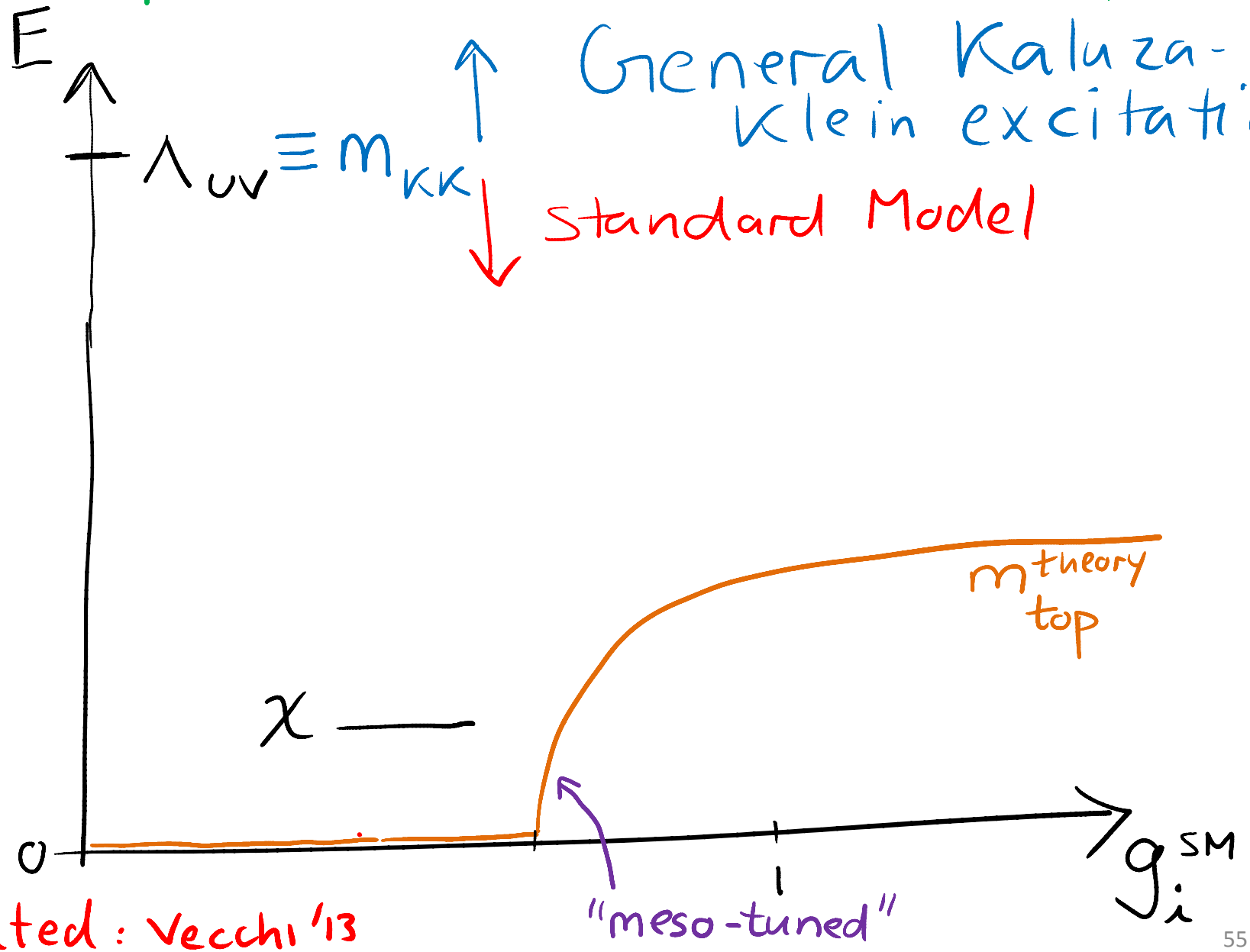
BUT WHY ARE THERE ANY χ IN EARLY UNIVERSE?



- χ out of equilibrium once temperature low enough
- annihilates away until can't find partners

- Then decays to baryons. But this requires long χ lifetime: $m_{KK} \gg m_\chi > m_t$

MESO-TUNING



related : Vecchi '13

Meso-tuning is poorly understood but affects experimental strategy:

- broader searches for light vestiges of naturalness mechanism, main players may be out of reach
- 100 TeV collider?

CONCLUSIONS

Naturalness, anthropic selection, Multiverse are **Meta-theories.**

The collection of naturalness-related experiments — LHC, flavor, axion searches, tests of Inflation (eg. BICEP2, ...), Dark Matter search, form a **Meta-experiment**

Changes mode of operation, what is plausibly worth hunting for, when to give up.

Even half-baked ideas can move us forward if they prompt new experimental directions!