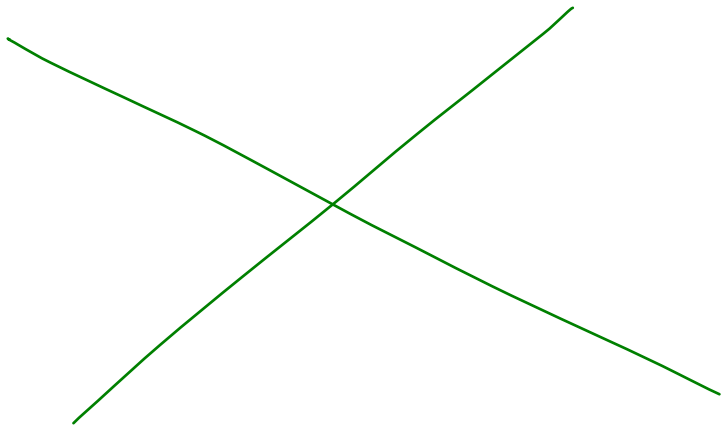
Gravity as an EFT

The Cosmological Constant

WHY QFTP

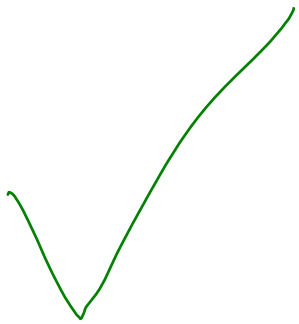
Because we see classical field theories in Nature and should quantize them



WHY QFTP

Because quantum fields offer a useful formalism to describe

PARTICLES with LOCAL INTERACTIONS



INEVITABILITY IN GRAND ARCHITECTURE OF PHYSICAL LAWS

What is a Particle?

"Unitary Irrep of Poincaré"

Spacetime Symmetries

Quantum Mechanics

$$p = L(p,k)\,k \quad \leftarrow \text{reference momentum}$$

$$|p,\sigma\rangle \equiv U(L(p,k))\,|k,\sigma\rangle \quad \text{Defines } \sigma$$

$$U|p,\sigma\rangle = D_{\sigma\sigma'}(W(\Lambda,p))\,|\Lambda p,\sigma'\rangle$$

$(WK) = K$; Transform Under Little Group

Particles ⟶ Fields as Convenience

★ $|p_1 p_2 \ldots\rangle \equiv a^\dagger_{p_1} a^\dagger_{p_2} \ldots |\text{vac}\rangle$ Defines $a^{(\dagger)}_p$

★ Want to build H_{int}, so scattering amplitudes satisfy minimal notion of locality — $S^{\text{connected}}$ should contain only one $\delta\left(\sum_{\text{all } i} p_i\right)$.

$$H_{int} = \int d^3x \, \mathcal{H}\left(\left[\varphi^{\pm}\right] \leftarrow \int_p a_p^{(\dagger)} e^{\pm ipx}\right)$$

★ Finally with Lorentz Invariance:

$$\left[\mathcal{H}(x), \mathcal{H}(y)\right] = 0 \quad (x-y)^2 < 0$$

$\longrightarrow$ $\mathcal{H}\left[\varphi(x)\right]$, antiparticles + spin-statistics

Fields + Pol. Vectors → Particles

$$\mathcal{A}^{(p_1,\dots,p_n)}_{\sigma_1 \dots \sigma_n} = \varepsilon^{\mu_1}_{\sigma_1} \dots \varepsilon^{\mu_n}_{\sigma_n} \mathcal{M}^{(p_1,\dots,p_n)}_{\mu_1 \dots \mu_n}$$

Little Group Indices

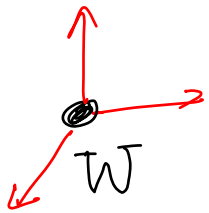
Pol. Vectors Lorentz-Little Indices "put fields on-shell"

Computed From Local Fields/ Feynman Diagrams

Dramatic Difference: Massless vs. Massive with Spin

Massive Spin S: $(2S+1)$ d.o.f

$SO(D-1)$



Massless Spin S: 1 (x 2 if Parity) d.o.f.

$SO(D-2)$

Helicity

Extra Challenge For Field Description

Spin 1 : ε^μ with 4 d.o.f.

Massive Spin 1 : Impose $\varepsilon \cdot p = 0 \Rightarrow$ 3 d.o.f.

Massless Spin 1 : No Lorentz-inv. way of getting down to 2, can shift as $\varepsilon^\mu \to \varepsilon^\mu + \alpha(p) p^\mu$!

Must declare REDUNDANCY : hel. states are labelled by equivalence classes :

$\{ \varepsilon^\mu \mid \varepsilon^\mu \sim \varepsilon^\mu + \alpha p^\mu \}$ spin 1 "Linearized Gauge Transf"

$\{ \varepsilon^{\mu\nu} \mid \varepsilon^{\mu\nu} \sim \varepsilon^{\mu\nu} + p^\mu \alpha^\nu + p^\nu \alpha^\mu \}$ spin 2 "Linearized Diff."

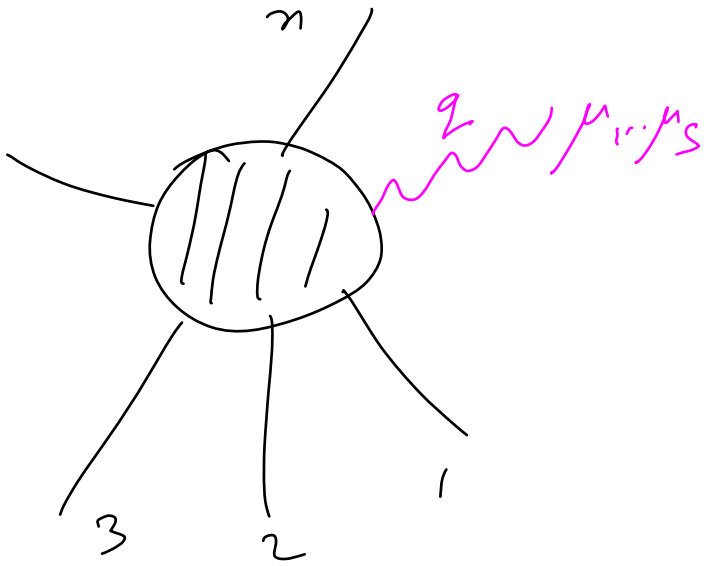
Huge Constraint on Massless Particles with Spin.

Spin 1 : $p_\mu \mathcal{M}^{\mu \cdots}(p, \cdots) = 0$

Spin 2 : $p_\mu p_\nu \mathcal{M}^{\mu\nu \cdots}(p, \cdots) = 0$

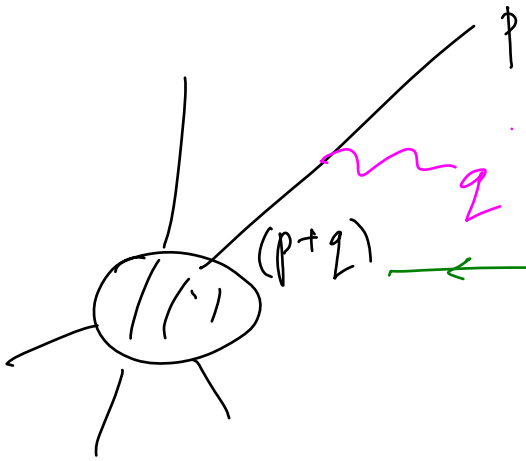
{ "On-shell Ward Identities" in conventional approach, but here they are primary, and in Weinberg's hands, astonishingly restrictive + powerful }

Weinberg's Soft Theorems: All Consistent Long Range Forces



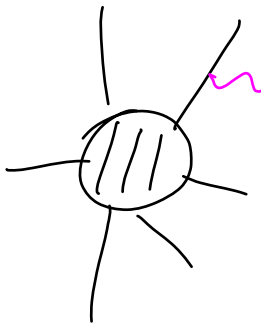
What is leading amplitude as $q \to 0$?

Only singularity emit off external legs only



$$\frac{1}{(p+q)^2 - M^2} = \frac{1}{2p \cdot q}$$

Leading Behavior.



$$: \mathcal{M}_n \times \begin{cases} \sum \dfrac{e_i p_i^{\mu} \varepsilon_{\mu}}{2 p_i \cdot q} & \text{spin 1} \\ \sum \dfrac{\kappa_i p_i^{\mu} p_i^{\nu} \varepsilon_{\mu\nu}}{2 p_i \cdot q} & \text{spin 2} \\ \sum \dfrac{s_i p_i^{\mu} p_i^{\nu} p_i^{\sigma} \varepsilon_{\mu\nu\sigma}}{2 p_i \cdot q} & \text{spin 3} \\ \vdots \end{cases}$$

...BUT, MUST CHECK INVAR. UNDER

$\varepsilon^{\mu_1 \ldots \mu_s} \rightarrow \varepsilon^{\mu_1 \ldots \mu_s} + p^{\mu_1} \alpha^{\mu_2 \ldots \mu_s} \ldots$

Leading Behavior.

$$0 = \sum \frac{e_i (p_i \cdot q)}{p_i \cdot q} = \sum_i e_i$$

Charge Cons!

$$0 = \sum \frac{K_i \, p_i^{\mu} (p_i \cdot q)}{p_i \cdot q} = \sum K_i p_i^{\mu}$$

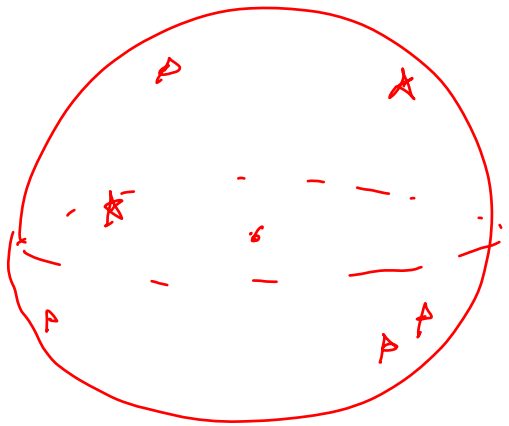
Only possible if all $K_i = k$, Princ. of Equiv!

$$0 = \sum \frac{S_i \, p_i^{\mu} p_i^{\nu} (p_i \cdot q)}{2 p_i \cdot} = \sum S_i p_i^{\mu} p_i^{\nu}$$

Impossible in $D > 2$!

YM + GR are unique leading (2-der) theories for interacting massless spin 1/2 particles!!!

In recent years, Weinberg Soft Theorems, in $D=4$, have been interpreted as associate with ∞ symmetries on the Celestial Sphere



Modern On-Shell Approach.

Directly inspired by Weinberg — to focus on on-shell amplitude with correct little group transformation properties. But fateful early departure — NO LOCAL QUANTUM FIELDS, NO POL. VECTORS, NO GAUGE REDUNDANCY etc. SPACETIME STUM. MANIFEST. PRICE: MUST CHECK LOCALITY + UNITARITY

Spinor – Kinematic → Little Group

$$\star\ p^\mu \longrightarrow \begin{pmatrix} p^0+p^3 & p^1-ip^2 \\ p^1+ip^2 & p^0-p^3 \end{pmatrix} \equiv p_{\alpha\dot\alpha}$$

$SL(2) \times \widetilde{SL}(2)$ Complex Lor.

$\star$ Massless $\quad p^2=0 \Longrightarrow \det p_{\alpha\dot\alpha}=0 \Longrightarrow p_{\alpha\dot\alpha}=\lambda_\alpha\tilde\lambda_{\dot\alpha}$

$\lambda_\alpha \longrightarrow t\lambda_\alpha$.

NOTE: $\tilde\lambda_{\dot\alpha} \longrightarrow t^{-1}\tilde\lambda_{\dot\alpha}$

$p_{\alpha\dot\alpha} \longrightarrow p_{\alpha\dot\alpha}$

THIS IS LITTLE GRP!

$$\mathcal{M}(t_a\lambda_a, t_a^{-1}\tilde\lambda_a) = t_a^{-2h_a}\mathcal{M}(\lambda_a,\tilde\lambda_a)$$

Manifests correct Little grp/Lorentz Symmetry!

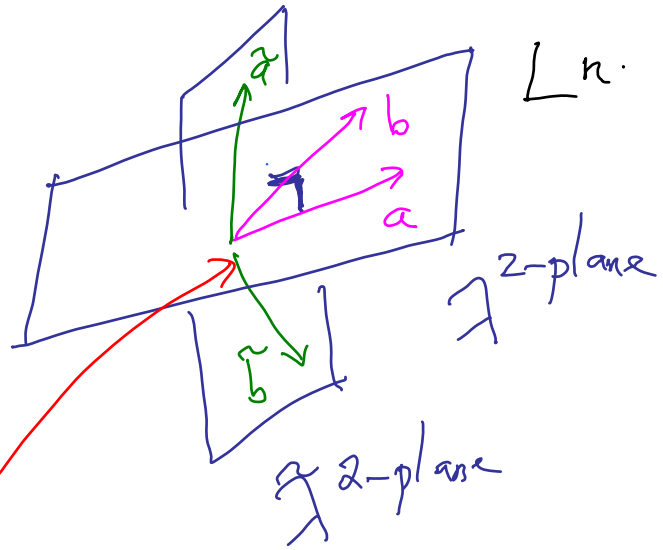
... NO NEED FOR REDUNDANT POL. VECTORS ...

Geometry of Kinematic Data.

* Invariants $\varepsilon^{\alpha\beta}\lambda_{i\alpha}\lambda_{j\beta} \equiv \langle ij\rangle$, simil. $[ij]$

$$(\lambda_1 \cdots \lambda_n) = \begin{pmatrix} a_1 & \cdots & a_n \\ b_1 & & b_n \end{pmatrix}$$

$$(\tilde\lambda_1 \cdots \tilde\lambda_n) = \begin{pmatrix} \tilde a_1 & & \tilde a_n \\ \tilde b_1 & & \tilde b_n \end{pmatrix}$$

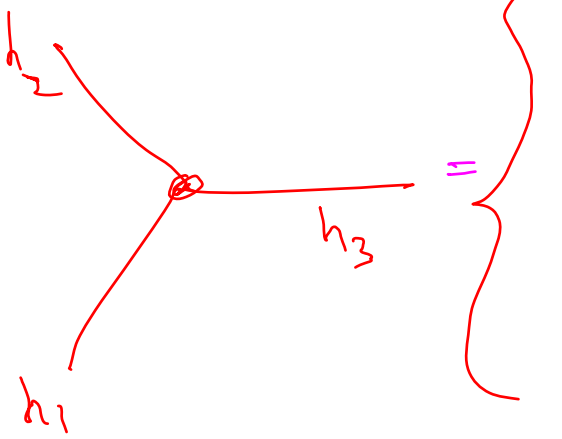


Momentum Conservation $\sum_a \lambda_{a\alpha}\tilde\lambda_{a\dot\alpha} = 0$

$\Longrightarrow$ λ 2-plane, $\tilde\lambda$ 2-plane are orthogonal !

Three-Particle Amplitudes

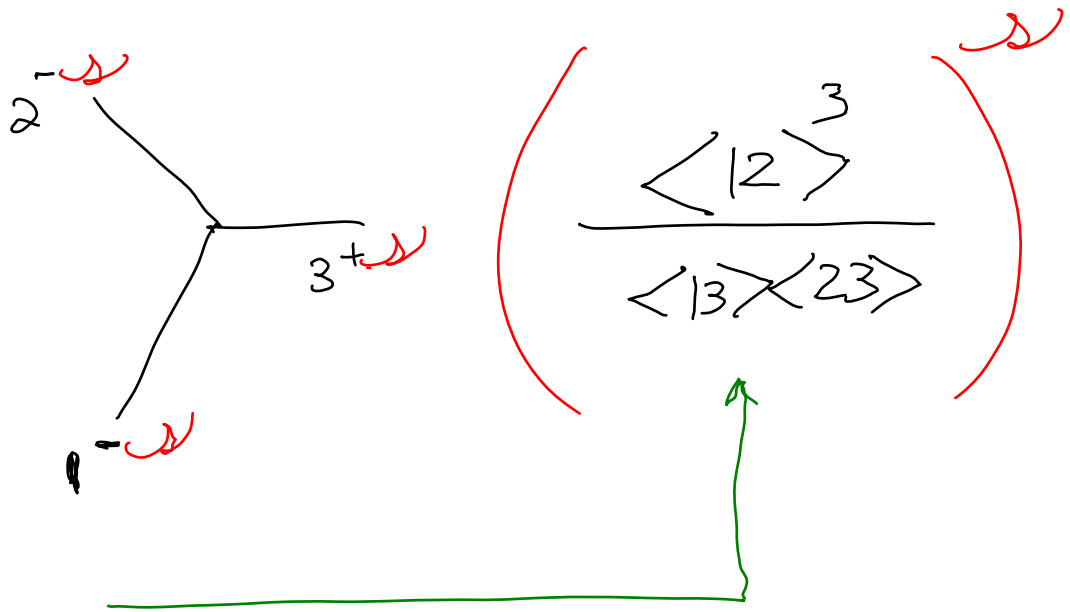
$\tilde{\lambda}_1 \propto \tilde{\lambda}_2 \propto \tilde{\lambda}_3$ or $\lambda_1 \propto \lambda_2 \propto \lambda_3$



$$g\,\langle 12\rangle^{h_3-h_1-h_2}\langle 23\rangle^{h_1-h_2-h_3}\langle 31\rangle^{h_2-h_3-h_1} \quad (\Sigma h<0)$$

$$\tilde{g}\,[12]^{h_1+h_2-h_3}[23]^{h_2+h_3-h_1}[31]^{h_3+h_1-h_2} \quad (\Sigma h>0)$$

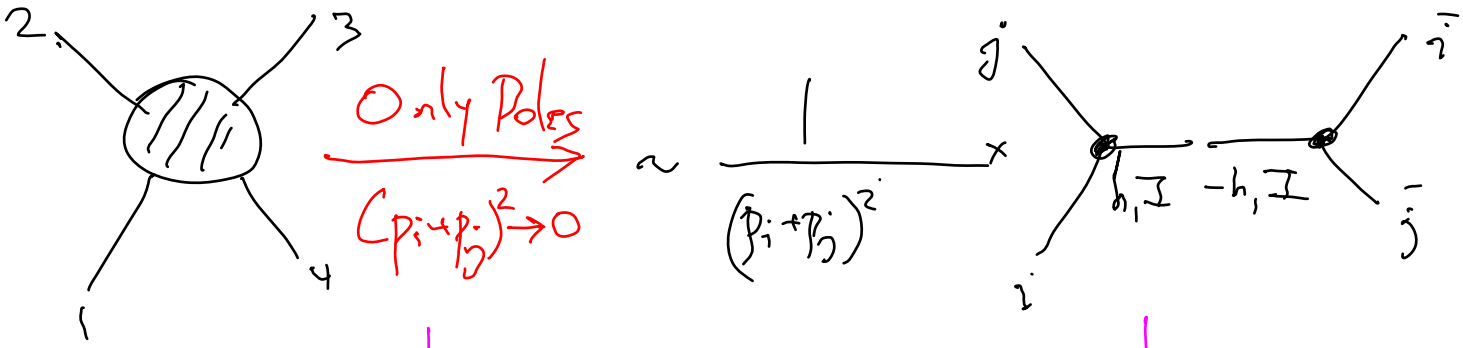
COMPLETELY FIXED (UP TO STRENGTH) BY POINCARÉ



So e.g. GR $= (4M)^2$ [Totally unobvious from $\mathcal{L}_{GR/YM}$!]

{But note interesting "pole" for $s>0$}

4 Particle Consistency Check.

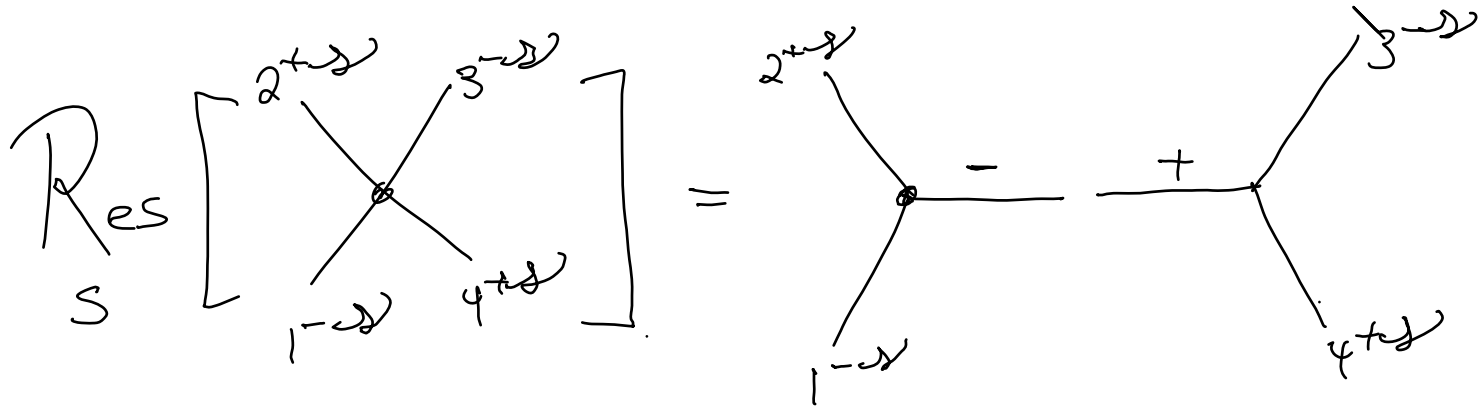


Locality

Unitarity.

"Consistent Factorization".

$$\underset{s}{\text{Res}}\Big[\;\Big] =$$



$$= g^2\left(\langle 13\rangle^2[24]^2\right)^{s}\left(\frac{1}{t^{s}}\right).$$ For $s=0$,

$$\underset{s}{\text{Res}} = \underset{t}{\text{Res}} = \underset{u}{\text{Res}} = g^2,$$ so trivial to match

$$\mathcal{A} = g^2\left(\frac{1}{s}+\frac{1}{t}+\frac{1}{u}\right).$$ But not trivially possible for $s>0$!

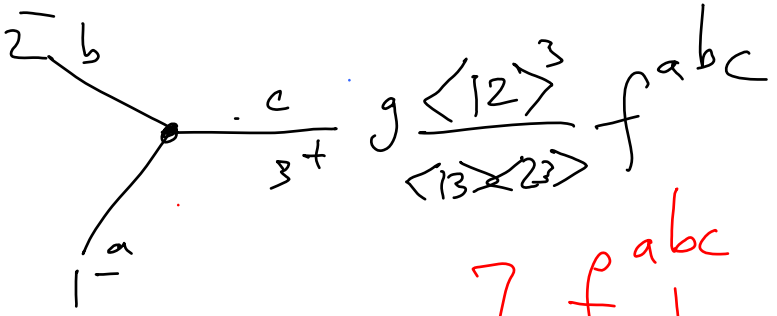
$\mathcal{N}=4$

★ Must have $A = \langle 13\rangle^2 [24]^2 \left(\frac{A}{st} + \frac{B}{tu} + \frac{C}{us} \right)$

Match residues $(A-C)=1, (B-A)=1, (C-B)=1,$

impossible!

★ If many spin 1



$g \frac{\langle 12\rangle^3}{\langle 13\rangle\langle 23\rangle} f^{abc}$

$$A^{a_1a_2a_3a_4} - C^{a_1a_2a_3a_4} = f^{a_1a_2e} f^{ea_3a_4}$$

$$B^{a_1a_2a_3a_4} - A^{a_1a_2a_3a_4} = f^{a_2a_3e} f^{ea_4a_1}$$

$$C^{a_1a_2a_3a_4} - B^{a_1a_2a_3a_4} = f^{a_4a_1e} f^{ea_2a_3}$$

f^{abc} must satisfy Jacobi!

$\mathcal{N}=2$

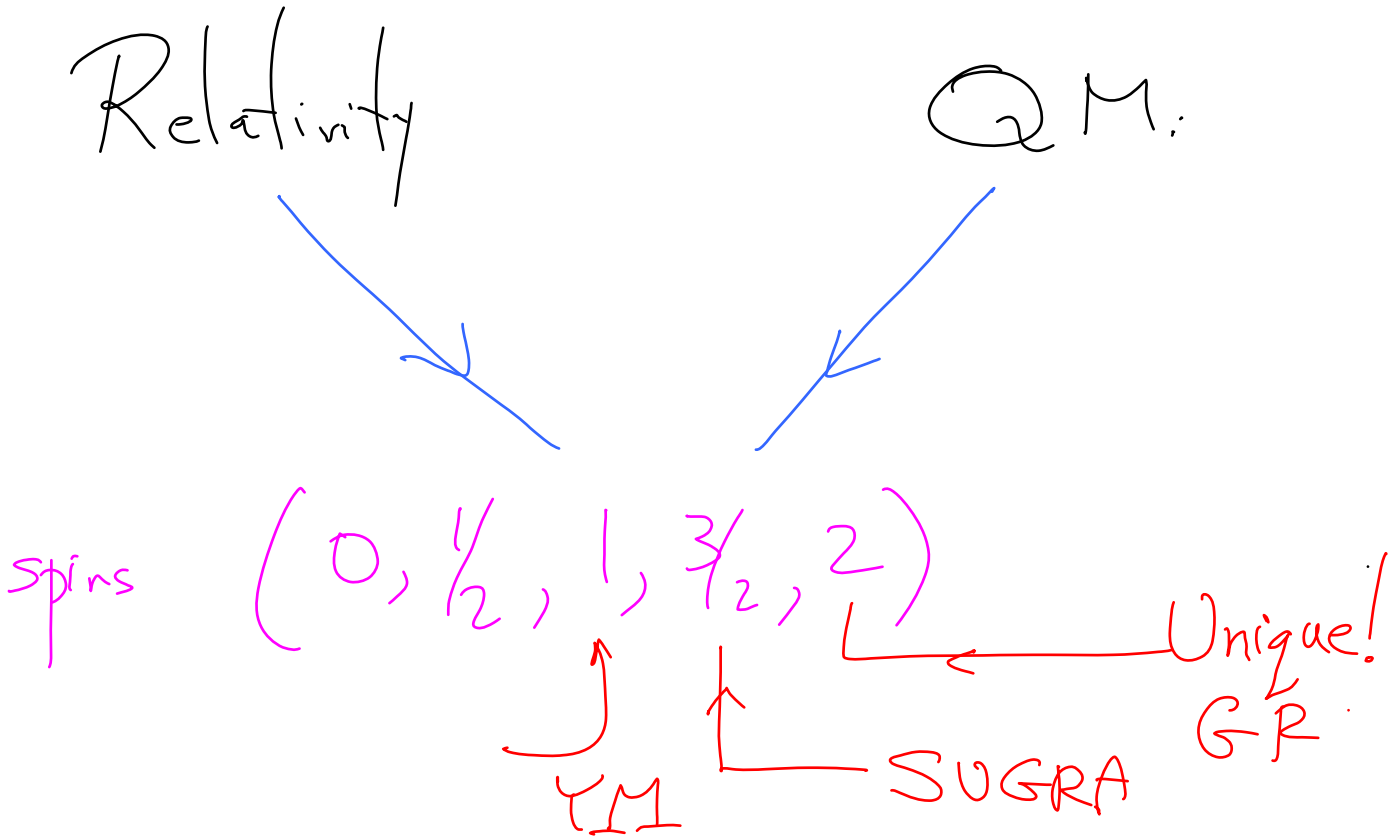
Now, $\underset{s=0}{Res} = \dfrac{\langle 13\rangle^4 [24]^4}{t^2}$ ← naively bad!

But this is on $s=0$, so t^2 also $= -tu$

$$\Downarrow$$

$$\mathcal{A} = -G_N \frac{\langle 13\rangle^4 [24]^4}{stu}\,!$$

* Can't have multiple massless spin 2 interacting.
* Higher spins impossible

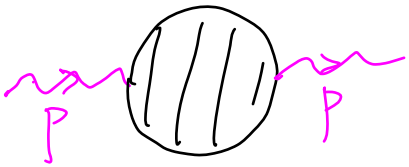


WEINBERGIAN

"INEVITABILITY"

Non-renormalizable ⟶ Energy Expansion.

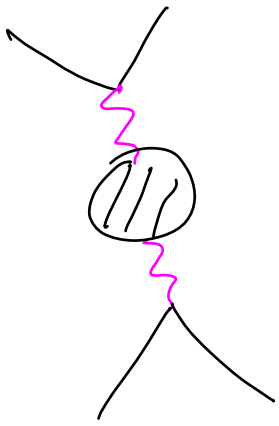
Non-analytic Quantum Logs Calculable.



$$G_N p^4 \left(A + B \log p^2\right)$$

Unknown UV physics

Calculable in low-E theory.



$$\delta V(r) \sim \frac{A}{\ell_{pl}^2}\,\delta^3(r)$$

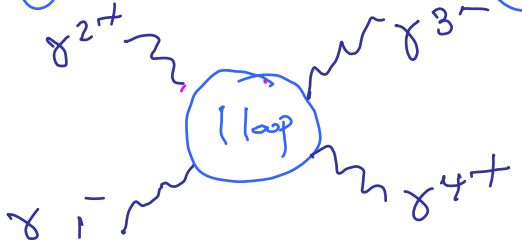
CONTACT, CAN'T COMPUTE IN EFT

$$\delta V(r) \sim \frac{B\,\ell_{pl}^2}{r^3}.$$

TINY, BUT LONG-DISTANCE + CALCULABLE IN EFT.

Non-renormalizable $\longrightarrow$ Energy Expansion.

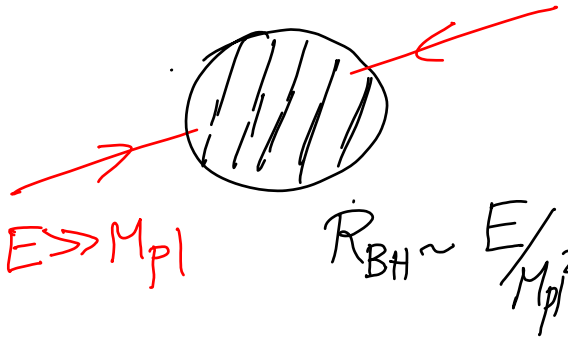
Non-analytic Quantum Logs Calculable.

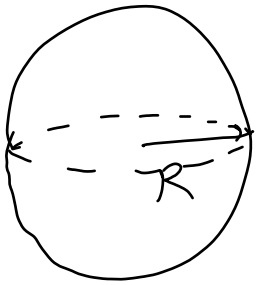


$$\mathrm{M}^{-+-+} = \frac{G_N^2\langle 13\rangle^2[24]^2}{240}\left[\left(-7+290\left(\frac{s}{u}\right)+90\left(\frac{s}{u}\right)^2+60\left(\frac{s}{u}\right)^3\right)\log\left(\frac{s}{\Lambda_{UV}^2}\right)\right.$$
$$\left.-\left(267+290\left(\frac{s}{u}\right)+90\left(\frac{s}{u}\right)^2+60\left(\frac{s}{u}\right)^3\right)\log\left(\frac{t}{\Lambda_{UV}^2}\right)+\text{UV finite}\right]$$

Calculable Quantum Gravity Corrections.

... Gravity IS Special ...





$S_{max} \sim S_{BH} \sim Area/\ell_{pl}^2$ vs. Vol/ℓ_{pl}^3

UV/IR ENTROPY BOUNDS

ALSO

NO PRECISE LOCAL OBSERVABLES

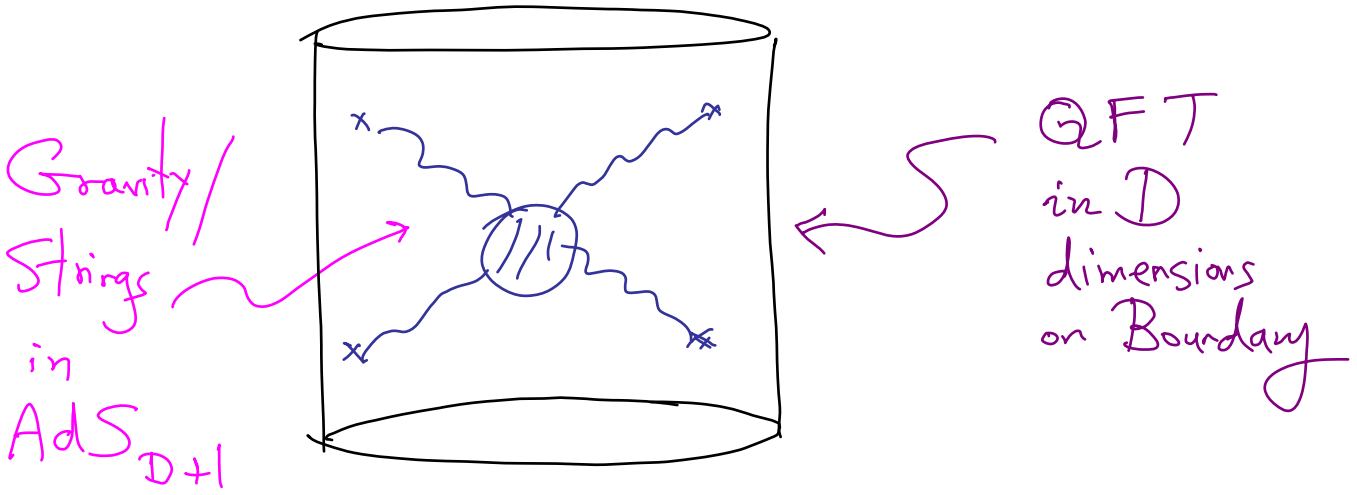
... Gravity IS Special ...

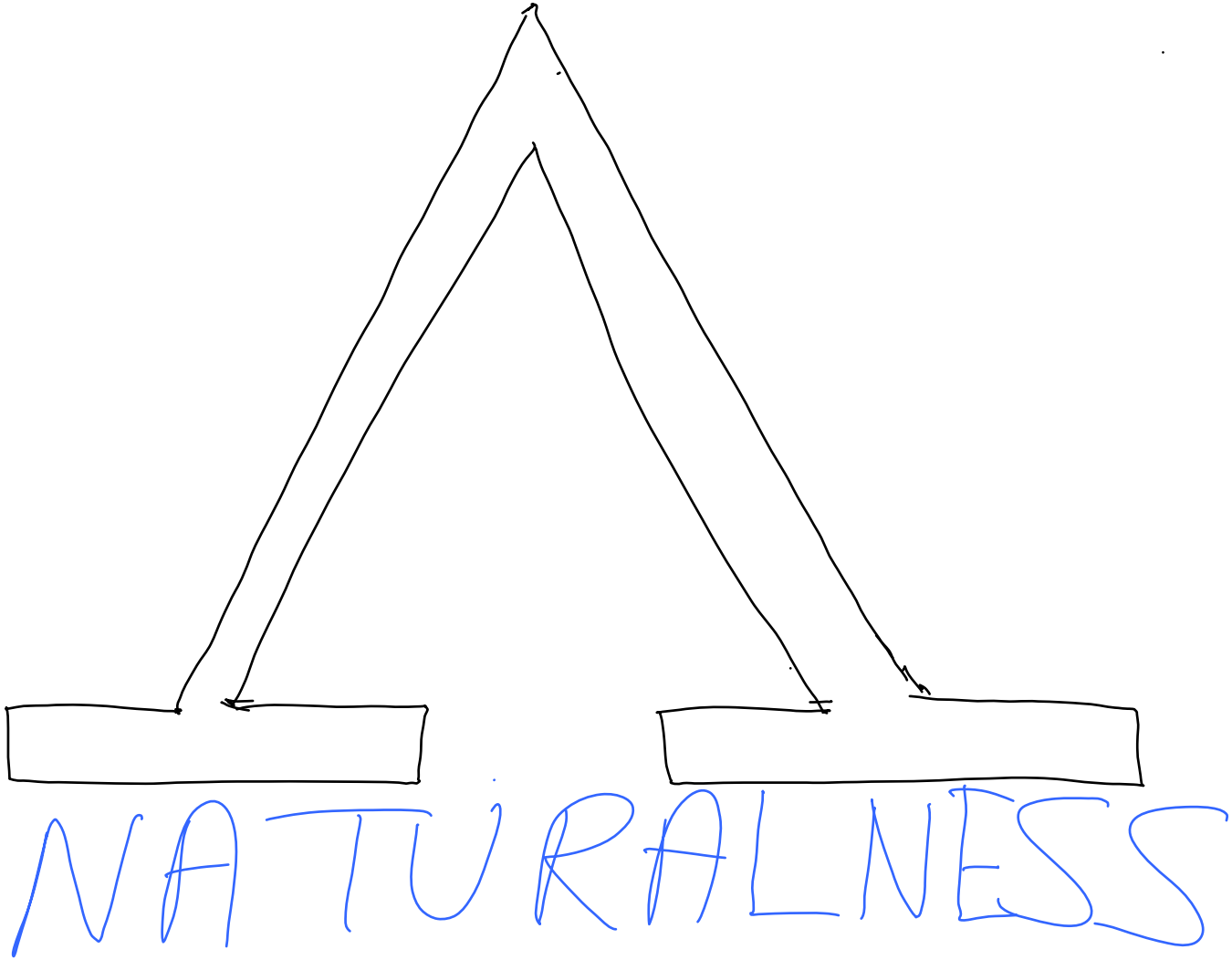
* Graviton in D dimensions can't be composite particle" from local QFT dynamics in D dimensions: Weinberg-Witten.

{ We saw an on-shell avatar of this in the impossibility of having multiple interacting massless spin 2 }

... Gravity IS Special ...

* Graviton in (D+1)-dim CAN BE "composite particle" from local QFT dynamics in D dimensions:




NATURALNESS

Weinberg no-go for "Adjustment" Mechanisms.

Look for solutions where $(g_{\mu\nu}, \psi_i)$ are constant in space. Can we have that

$$g_{\mu\nu}\frac{\partial \mathcal{L}}{\partial g_{\mu\nu}} = \sum_i \frac{\partial \mathcal{L}}{\partial \psi_i} f_i(\psi)$$

$$\Lambda = 0 \quad \Longleftarrow \quad \text{Matter EOM}$$

Weinberg no-go for "Adjustment" Mechanisms.

NO! Equivalent to scale invariance.

$\delta g_{\mu\nu} = 2\epsilon g_{\mu\nu}$, $\delta\psi_i = -\epsilon f_i(\psi)$

$\delta\phi = -\epsilon$, $\delta\sigma_a = 0$

$\Rightarrow (g_{\mu\nu}, \phi)$ in combination $\hat{g}_{\mu\nu} = g_{\mu\nu} e^{2\phi}$

$\Rightarrow \mathcal{L}\big|_{\substack{\text{const.}\\ \text{fields}}} = \sqrt{-\hat{g}}\, V_0 = \sqrt{-g}\, e^{4\phi} V_0$

$\Rightarrow$ Either $V_0 = 0$, or runaway potential for ϕ [dragging all masses $\to 0/\infty$].

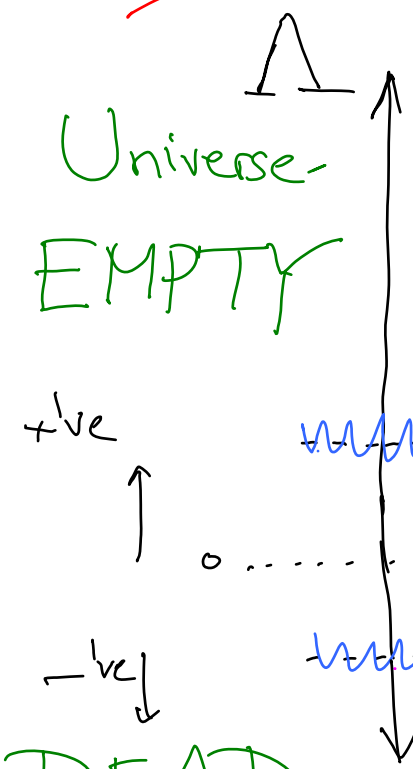
"Degravitate" Vacuum Energy?

$$T^{\mu\nu} = \begin{pmatrix} \rho & \\ & p\,\mathbb{1} \end{pmatrix} = \begin{pmatrix} \rho_m & \\ & 0 \end{pmatrix} + \begin{pmatrix} \rho_R & \\ & \frac{1}{3}\rho_R\,\mathbb{1} \end{pmatrix} + \begin{pmatrix} \rho_\Lambda & \\ & -\rho_\Lambda\,\mathbb{1} \end{pmatrix}$$

Can't "locally" pick off ρ_Λ — need.

acausality { ρ_Λ survives in deep future! }

Weinberg's Anthropic Argument



Universe-
EMPTY

Galaxies Ripped Apart
Before They Can Form

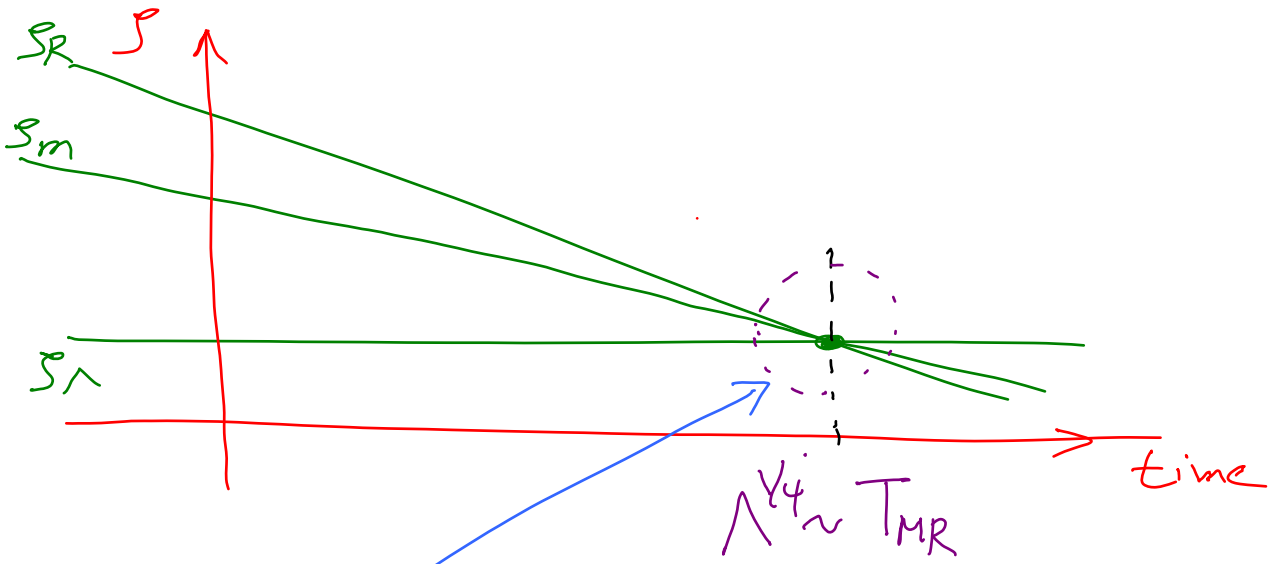
~10-100 Λ_{us}

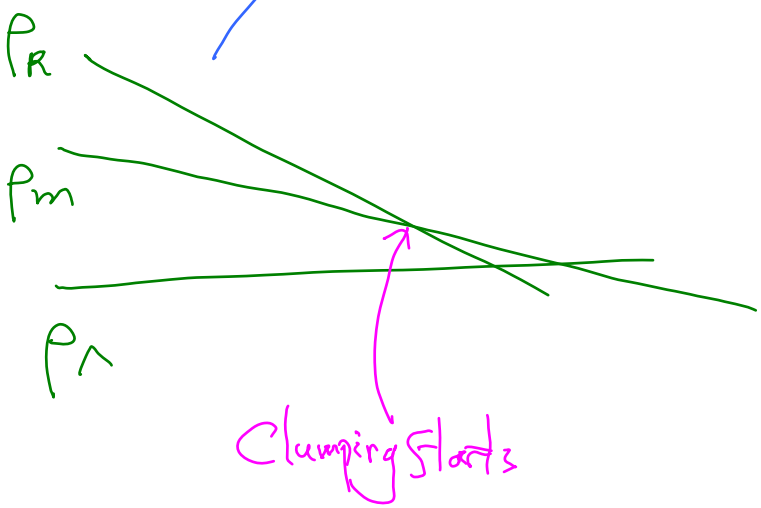
DEAD
Universe.

Universe Crunches
Before Galaxies Can Form

Correctly Predicted Non-Zero Λ!

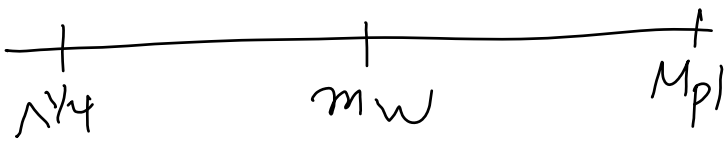
Predicts "triple coincidence"





$$\Lambda^{1/4} \sim T_{MR} \left(\frac{\delta\rho}{\rho}\right)^{3/4}$$

WIMP's + Equidistant Scales



$$\Lambda^{1/4} \sim \frac{m_W^2}{M_{Pl}}$$

Thermal Relic: $T_{MR} \sim \frac{1}{\sigma_{ann.} M_{Pl}} \sim \frac{m_{DM}^2}{(\alpha^2 M_{Pl})}$.

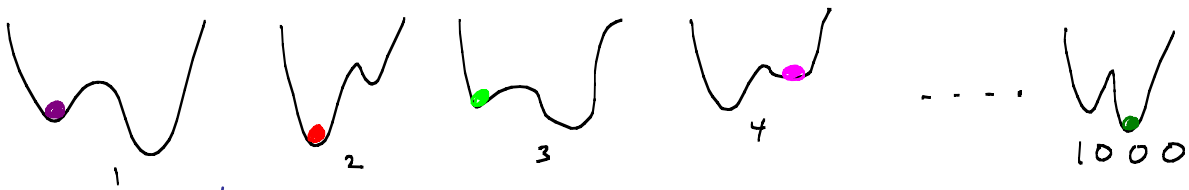
$$\Lambda^{1/4} \sim T_{MR} \left(\frac{\delta\rho}{\rho}\right)^{3/4} \sim \left(\frac{\delta\rho}{\rho}\right)^{3/4} \frac{1}{\alpha^2} \frac{m_{DM}^2}{M_{Pl}} \sim \frac{m_W^2}{M_{Pl}}$$

Weinberg — Relic — WIMP

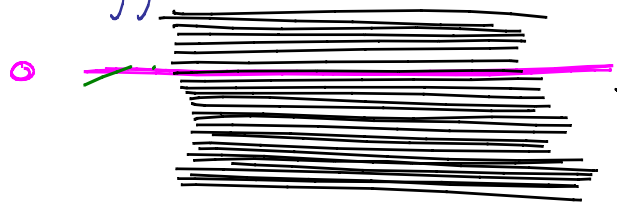
Theoretical Support

(A) String theory is unique, but has enormous landscape ($\sim 10^{1000's}$) of metastable non-SUSY vacua.

* Toy model $\mathcal{L}^{\text{unique}} = \mathcal{L}_{SM} + \sum_{i=1}^{N} (\partial\varphi_i)^2 - V(\varphi_i)$



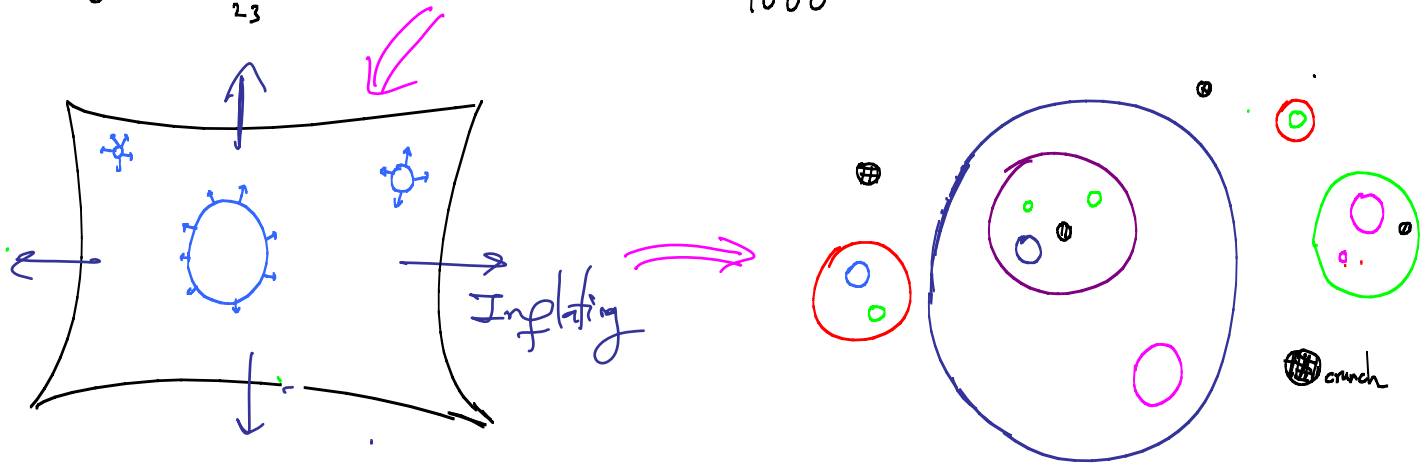
$\Rightarrow 2^N$ different values of energy

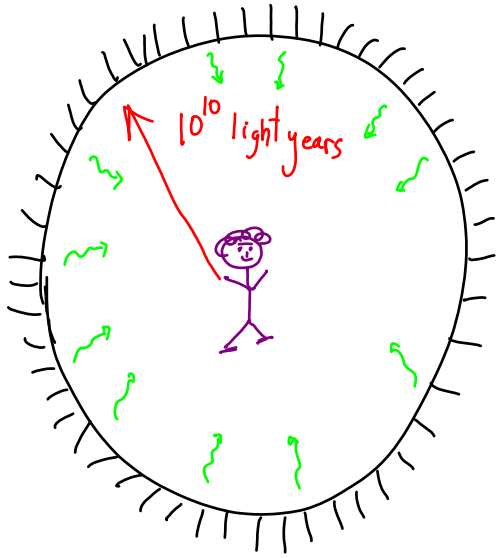


$\pm 2^{-N} M_*^4$ splittings

Theoretical Support

(B) Eternal inflation gives a plausible mechanism for populating landscape



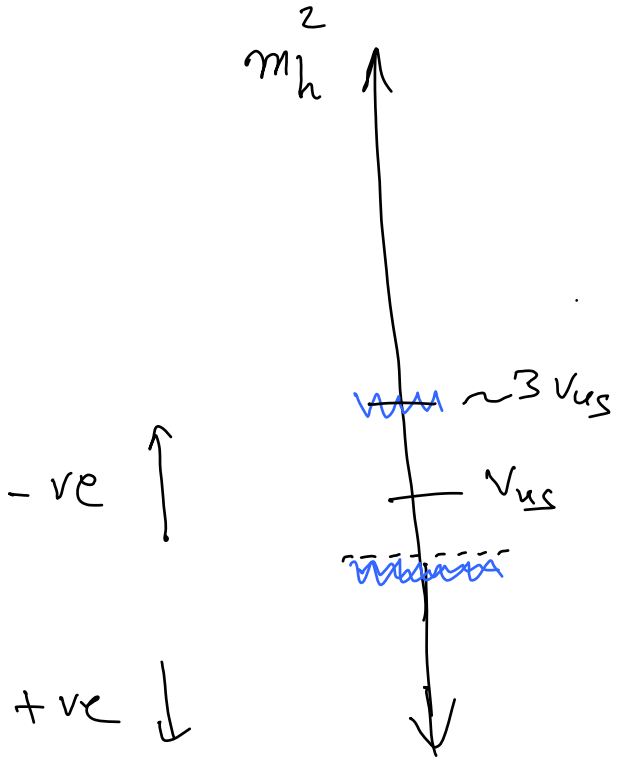


Suspicions that other vacua are out here, beyond our cosmological horizon...

[But like inside of BH, might outside be encoded inside in a scrambled way?].

But Note: Landscape of e.g. N scalars can in principle be seen by experiments in our universe! Can confirm W, W, W, W... picture, can make bubbles of other vacua + verify couplings rang etc. This part not "metaphysics".

Anthropics for the Higgs?

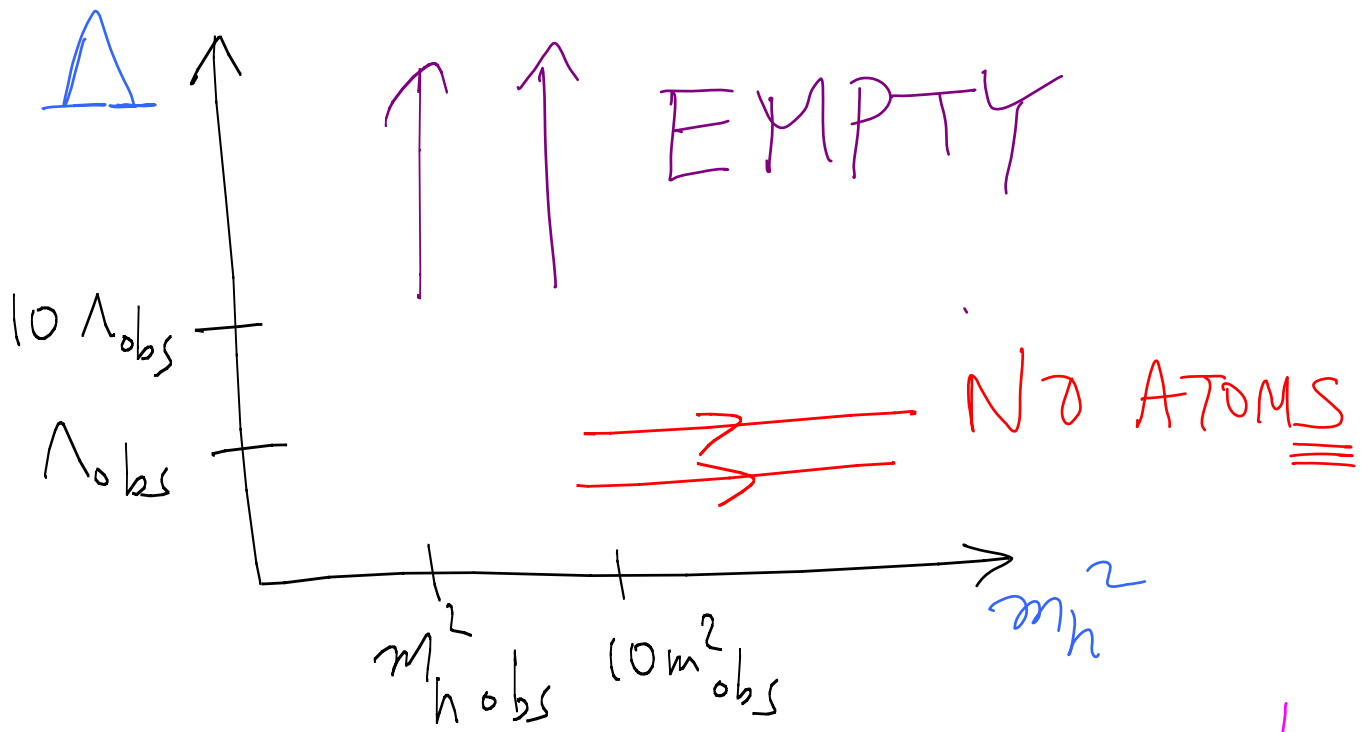


$(m_n - m_p) >$ nucl. binding energy,

NO ATOMS

QCD Breaks EW symm.

NO BARYONS



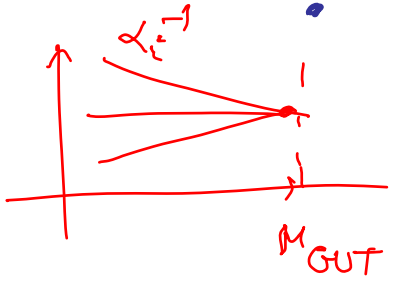
Striking — didn't have to be!

"Just a Curious Fact" in unique-vacuum worldview

Central Tension of BSM Physics

Natural vs. Un-Natural

SUSY!



+ DM

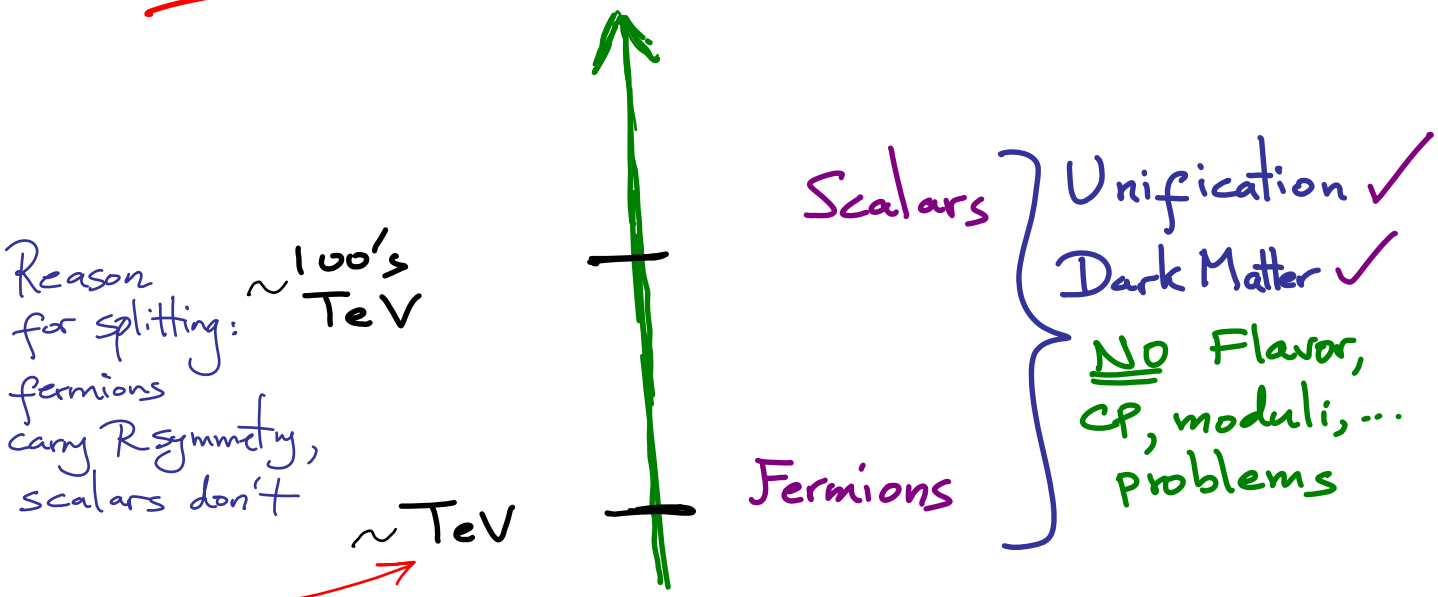
Fall in Our Laps!

Λ!

NO FCNC's, EDM's, ...

+ WHERE THE *!? IS EVERYBODY?

Minimal Split SUSY

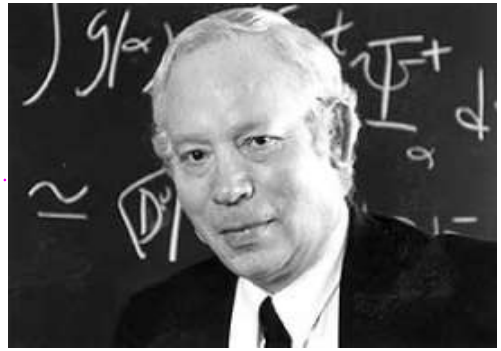


* Simplest DM 1→3 TeV, accessible to 100 TeV collider
* Correctly predicted $120\ \text{GeV} \lesssim m_h \lesssim 135\ \text{GeV}$

CRAZY PICTURE WITHOUT LANDSCAPE, PLAUSIBLE WITH IT

Weinberg Is My Hero and Ideal

Formalism with a Deep Physical Point



Experiment and Phenomenology

RIGHT ABOUT THE REAL WORLD, OVER + OVER