Title: Where effective field theory fails: Windows into quantum gravity?

Speakers:

Collection: Quantum Spacetime in the Cosmos: From Conception to Reality

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Abstract: Effective field theory is a computationally powerful and flexible theoretical framework, finding application in many areas of physics. In particle physics, Weinberg's folk theorem also promises that any theory that reproduces the predictions of the Standard Model will, at low energies, look like an effective field theory. In one sense the power of this framework should be a cause for pride in the progress of physics and discovery of real structural features of the world. But given the inability to fully unite quantum theory and gravity into a consistent theoretical picture, there is also cause for pessimism: indirect tests of candidate theories of quantum gravity will ultimately reduce to something like an effective field theory, undermining efforts to find low-energy windows into new physics. One way around this pessimism is to look at where and why effective field theory breaks down in current physical theories. I will point to familiar breakdowns (the cosmological constant, inflation, the hierarchy problem), offering a take on what these breakdowns tell us about the shape of physics beyond the Standard Model. Cracks in the wall of effective field theory allow for a dim glimpse of what might lie beyond.

Zoom Link: https://pitp.zoom.us/j/95721802052?pwd=TE1iTGxGLzNqeTFSZlNGRXRYMHBCZz09

WHERE EFFECTIVE FIELD THEORY FAILS

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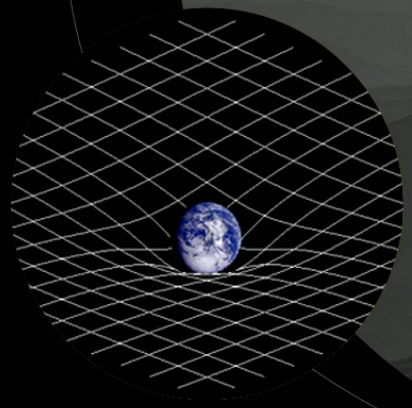
May 9,2023

PI: Quantum Spacetime in the Cosmos



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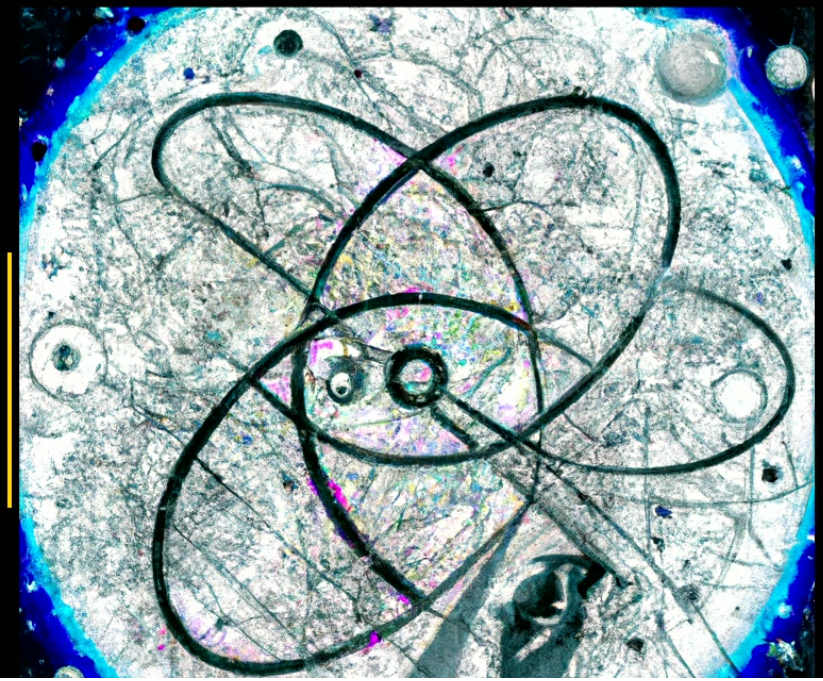
INTRODUCTION



The frustrating success of EFTs?

Philosophical starting point

- Look for path to QG via cracks in our current best theories
- Start with particle physics and EFTs, pay attention to theoretical and empirical anomalies
- Compliments approaches that start from fundamental theoretical models to work down
- Focus on methodology and justification for that methodology
- Pay attention to the community aspect of physics

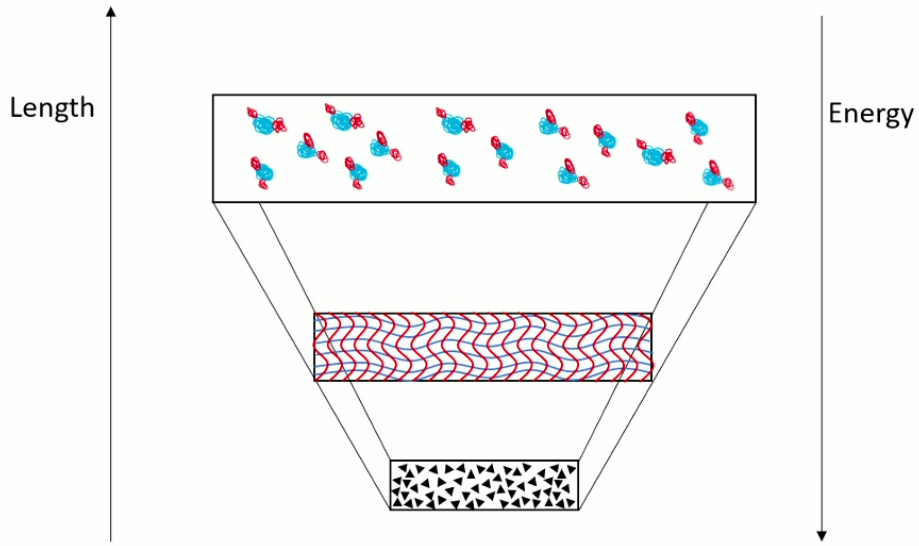
The Success of EFTs

- EFT perspective on quantum field theory has been powerful for constructing theories fit for a certain range of energy scales
- Target the appropriate degrees of freedom for a given scale, describe dynamics via local interactions of fields respecting symmetries
- Dependent on renormalization group and autonomy of scales

Tower of EFTs

Cao & Schweber 1993, Williams 2019, Wallace 2019

- Provides a worldview compatible with both reduction and emergence
- Reduction of higher level theories to lower level via coarse-graining
- Emergence of novel, autonomous ontology at higher levels
- View that any successor theory will be expressible as an EFT



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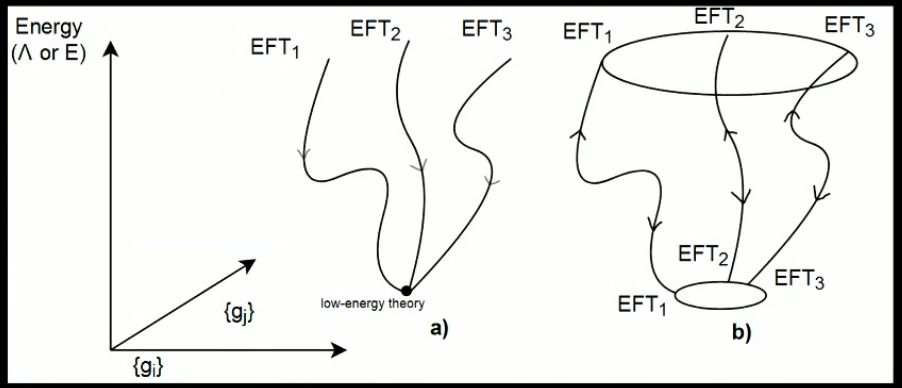
SEPARATION OF SCALES



Renormalization group flow

- As long as the energy scale for new physics (Λ) is significantly higher than the scales at which an EFT is constructed (E), high-energy effects are limited to setting the numerical values of couplings in the EFT
- Non-renormalizable terms are suppressed by powers of $\frac{E}{\Lambda}$, only appear when $E \approx \Lambda$
- High-energy physics is irrelevant for most low-energy treatments

Are EFTs *too* successful?

- SMEFT: so far no detection of non-renormalizable terms
- New anomalies (W, muon g-2, etc.) keep getting resolved
- Seems that the autonomy of scales is empirically more well-confirmed than theory would indicate!
- Weinberg folk theorem: *any* high-energy theory will look like a QFT at low energies
- Where can we find low-energy windows into quantum gravity? Look for anomalies!

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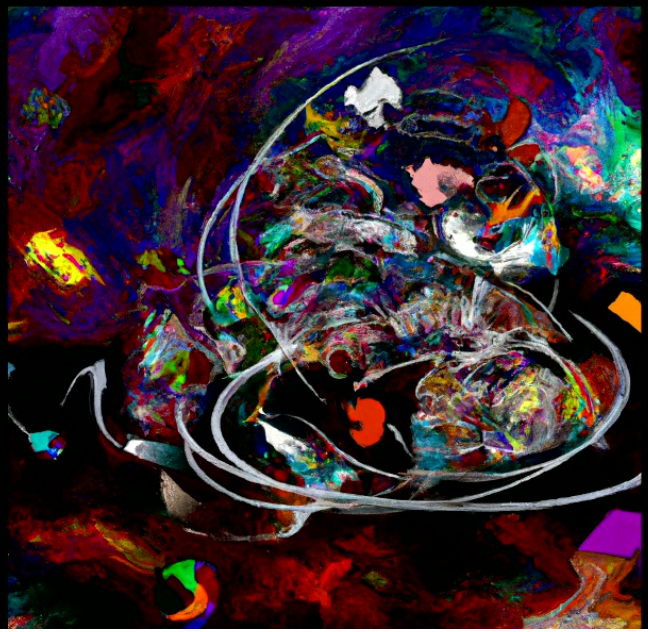
THEORETICAL ANOMALIES



I. Hierarchy Problem

II. Cosmological Constant Problem

Two-pronged attack

- Theoretical anomalies suggest that the (renormalizable) SM is more robust than EFT perspective would imply
- Search for hints both *empirically* and *theoretically*

- **Theory:** Re-examine foundations of EFT perspective – where does it break down? What conceptual change is necessary? (AK& Smeenk 2022)
- **Experiment:** Search for significant evidence of discrepancies between SM and measurement (AK 2023, AK& Smeenk 2020)

The Hierarchy Problem

- Naturalness considerations should fix the Higgs mass to be proportional to the scale at which SMEFT breaks down: $M^2 \approx \Lambda^2$
- $M = 125\ GeV$ implies that $\Lambda < 1\ TeV$
- But success of SM implies $\Lambda \gg 1\ TeV$
- Either new physics should be observable at LHC now, or theoretical understanding of relevant scaling parameters is incorrect

The Cosmological Constant Problem

- Similar issue to hierarchy problem: worse in one respect, less of an issue in another
- **Worse**: vacuum energy density (and therefore the cosmological constant) scales with Λ^4, so mismatch between observed and expected $\langle\rho\rangle$ is much larger (40-120 orders of magnitude)
- **Less of an issue**: only arises in merging SM with GR, no direct observable relevance for $\langle\rho\rangle$ outside this context

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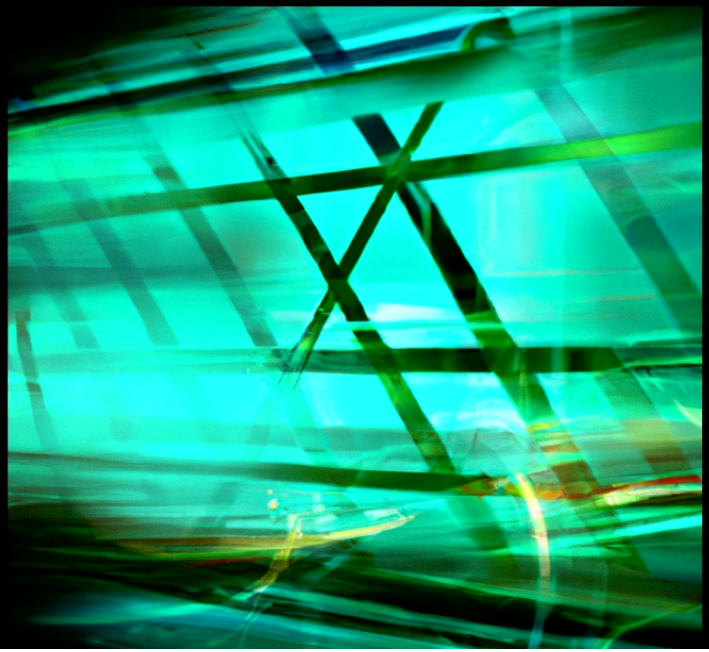
Conceptual Change



History and Philosophy of Physics

- Looking at the history of theory development in physics, striking contrast between *continuity* and *radical change*
- **Continuity** of empirical results: new theory must explain, accommodate and correct old theory's successes
- **Radical change** of conceptual framework and resulting methodology for understanding the world (cf. Kuhn 1962)

Anomalies Indicate Conceptual Change

- Though no strict method of discovery exists, one should take anomalies of EFT framework seriously for theory construction
- Theoretical anomalies are more striking for EFTs. Launch point for conceptual change
- Shared anomaly structure for hierarchy and CCP, potentially different lessons

Common Lessons

- EFT & RG reasoning seems to break down for relevant parameters in the SM
- Empirically determined/estimated values for parameters far lower than would be expected using RG
- Little evidence of non-renormalizable terms in SM indicates $\Lambda \gg TeV$

Lessons from Hierarchy Problem

- Direct empirical evidence of failure of naturalness
- Amendment attempts to restore naturalness have failed

Lessons from Cosmological Constant Problem

- Failure of global extrapolation from local physics
- Empirical irrelevance of $\langle\rho\rangle$ within particle physics
- Lack of background symmetry structure to define EFTs and global QFT states

(AK& Smeenk 2022)

How to go forward? What concepts need to change?

- Reformulations of QFT in a more local setting?
- Move beyond EFT framework for QG?
  - UV/IR mixing; failure of scale separation
  - Breakdown of locality
  - Failure of local to global extension
- Think about continuity: in what relevant limits of QG will EFTs/classical GR be predictively accurate?

- Continue to search for low-energy empirical anomalies: take EFT seriously!

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Closing the loop

In Praise of Precision Measurement: Confirmation and empirical anomalies

- Precision measurement does more than just further confirm a given theory
- Helps “close the loop” between models of phenomena and the phenomena themselves
- Discrepancies help reveal new physical details that make a difference to the phenomena
- Value of “anomaly chasing” if done the right way

(cf. Smith 2010, 2014)

Methodology of Science

- Tradition of the methodology of science inspired by Newton, and resulting program of Newtonian astronomy.
- Newton's rule 4 for reasoning:

  In experimental philosophy, propositions gathered from phenomena by induction should be considered either exactly or very nearly true not withstanding any contrary hypotheses, *until yet other phenomena make such propositions either more exact or liable to exception.* (emphasis added)
- View science as using a theoretical framework to guide a program of inquiry (Stein, Smith)

Howard Stein and George E. Smith

Smith 2010, 2014, Stein 1994

- Start with some theoretical framework, supplying concepts, tools and motivating problems to solve in a domain
- A fruitful line of inquiry is predicated on this theoretical background
  - Reliability of measurement informed by theory
  - Temporally extended analysis: fruitful lines of inquiry defined by their success in explaining new phenomena or old phenomena with greater precision

Howard Stein and George E. Smith

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  - Reliability of measurement informed by theory
  - Temporally extended analysis: fruitful lines of inquiry defined by their success in explaining new phenomena or old phenomena with greater precision
- Mutual interplay between theory and phenomena to refine concepts, discover new causal details

Closing the Loop and Theory Change

- Precision measurements allow for the discovery of new dynamical details that are relevant to the phenomena (e.g., virtual hadronic effects on electron's magnetic moment)
- These are thoroughly theory-mediated in their relevance and interpretation
- We close the loop by using current theory's resources to find robust physical sources for discrepancies between theory and measurement
- **Must try hard to resolve discrepancies using resources from current theory!**
- Persistent discrepancies point the way to new physics

Closing the Loop and Theory Change

- Focus on theoretical anomalies will help develop new conceptual frameworks on the way to QG
- But new theories must predict observable results to test their empirical viability
- Precision testing can reveal persistent empirical anomalies for new theories to predict/explain

Conclusions

- Tension between search for new principles and finding robust empirical anomalies
  - For theoretical anomalies with EFTs, re-examine assumptions needed for framework; failure of natural solutions indicates the way forward is to step outside EFT framework
  - Empirical anomalies must continue to be sought, this is necessarily done within EFT framework
  - Attitudes: conservativism of current theory; creativity for insight into new conceptual framework
- Science as temporally extended enterprise, predicated on theory to successively close the loop though adding details that make a difference

Thanks!