Title: The role of singularities in the search for quantum gravity

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Abstract: Singularities in general relativity and quantum field theory are often taken not only to motivate the search for a more-fundamental theory (quantum gravity), but also to characterise this new theory and shape expectations of what it is to achieve. In this talk, I will explore how different types of singularities play a role in the search for quantum gravity, and how different `attitudes' towards singularities can lead to different scenarios for the new theory. [Based on joint work with Sebastian DeHaro].

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

Why do we need a theory of Quantum Gravity?

- Not motivated by anomalous experimental data
- The search for quantum gravity is motivated, guided and constrained by **philosophical** and **theoretical concerns**
- Different approaches towards QG: different aims, starting points, methodology, …
- How do we assess these? How do we judge success?

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- Different approaches towards QG: different aims, starting points, methodology, …
- How do we assess these? How do we judge success?
- **Project:** Look at the basic motivations for the theory
- Can help us better understand what the theory is supposed to be like, or should be like

Introduction: Singularity Resolution

- Singularities in GR and QFT are often taken to motivate QG: guiding principle
- Singularity resolution often taken as a constraint, or means of confirmation on QG
- **Question:** Why? What's the problem with singularities?
- Do singularities represent an incompleteness of our theories?

Introduction: Singularity Resolution

Lots of quotes…!

Spacetime singularities represent the "breakdown of spacetime"

GR "contains the seeds of its own destruction"

"That GR cannot be true at the most fundamental level is clear from the singularity theorems: under very general conditions, singularities in space-time are unavoidable, signalling the breakdown of GR." (Kiefer 2004, p. 2)

"The theorems in this and the earlier papers probably indicate, not that singularities actually occur in the universe, but that General Relativity breaks down." (Hawking 1967, p. 189)

Introduction: Singularity Resolution

On the other hand…

"Suppose for the sake of discussion that the reader is willing to seriously entertain my position that the fact that GTR entail the existence of spacetime singularities need not mean that it contains the seeds of its own destruction and that a generalized *horror singulariti* is not justified."
(Earman 1995, p. 226)

Introduction: Singularity Resolution

- Singularities in GR and QFT are often taken to motivate QG: guiding principle
- Singularity resolution often taken as a constraint, or means of confirmation on QG
- **Question:** Why? What's the problem with singularities?
- Do singularities represent an incompleteness of our theories?

Physicists tend to say **yes**, and philosophers tend to say **no**!

Why do we need a theory of Quantum Gravity?

- Several different types of singularities in GR and QFT:
    - Which ones are problematic?
    - Why are they problematic?
    - Do they need to be resolved?
    - Do they need to be resolved by QG?

- Can take different “attitudes” towards these questions, and can differ depending on which singularities are being considered (Crowther & De Haro, 2022)
  -- singularities, in general, are not necessarily problematic or unphysical

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  - Do they need to be resolved by QG?
- Can take different “attitudes” towards these questions, and can differ depending on which singularities are being considered (Crowther & De Haro, 2022)
  -- singularities, in general, are not necessarily problematic or unphysical
- Rather than singularity resolution motivating QG -- **consistency** as basic principle

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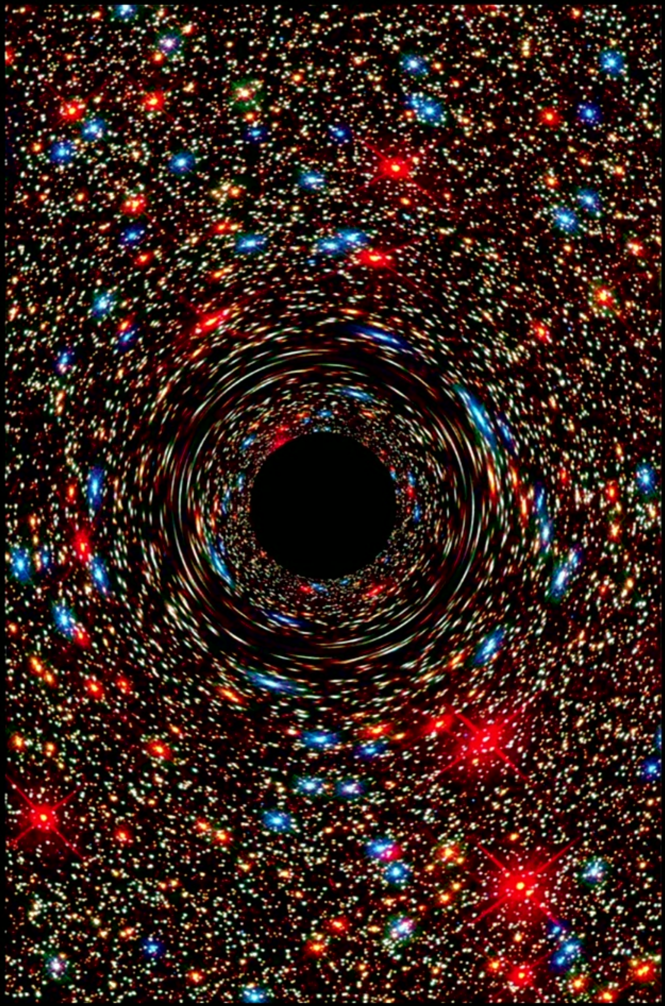

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1. Singularities in GR
2. Singularities in QFT
3. Four attitudes towards singularities

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Singularities in GR

- Singularities in GR are pathologies of the spacetime, and can be of various types
  - Earman (1996): 'A large family of conceptually distinct but interrelated pathologies that can infect relativistic spacetimes'.

- Penrose-Hawking singularity theorems: singularities are unavoidable in GR under very reasonable conditions
  - Notably: Black hole singularities; Big Bang singularity

Two main classes (see Curiel 2019, Earman 1996 for some other types):

1. **Geodesic incompleteness**
2. **Curvature singularities**

Geodesic incompleteness

- **Geodesic incompleteness:** a spacetime is singular if and only if it contains an incomplete, inextendible timelike geodesic ("official definition" of singularities)

- Geodesic incompleteness corresponds to the intuition that "singular points, where the metric tensor is not well-defined, have been cut out"

Does this indicate that GR is incomplete? That it is "missing something"?

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Geodesic incompleteness

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- Geodesic incompleteness corresponds to the intuition that "singular points, where the metric tensor is not well-defined, have been cut out"
- Curiel (2009) argues that it's unclear in what sense spacetime singularities signal incompleteness -- no "missing points" of spacetime
- Earman (1996) "there are no singular points of spacetime where the laws of GTR fail to apply" -- we should take the singularities as a prediction of GR
- Misner (1969) "there is no reasonable point at which to anticipate a failure of the theory"

Geodesic incompleteness: inconsistency

- Geodesic incompleteness leads to a lack of predictability and determinism, when GTR has been set up as deterministic -- and so this indeterminism could indicate that the theory is **inconsistent**

- Curiel (1999): there is a physical worry, because 'particles could pop in and out of existence right in the middle of a singular spacetime, and spacetime itself could simply come to an end, though no fundamental physical mechanism or process is known that could produce such effects'.

- If the breakdown of determinism were visible to external observers, then those observers would be sprayed by unpredictable influences emerging from the singularities -- The laws would `perversely undermine themselves' (Earman 1992)

- Problem is arguably, not the singularity *per se*, not incompleteness of GTR, and not indeterminism *per se*, but the internal inconsistency introduced by the indeterminism

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Geodesic incompleteness: inconsistency

- Problem is arguably, not the singularity *per se*, not incompleteness of GTR, and not indeterminism *per se*, but the internal inconsistency introduced by the indeterminism

- Does this inconsistency mean we have to resolve these singularities?

  And do we need to do so with a theory of QG?

  Maybe, maybe not ….

- Maybe **strong cosmic censorship** holds: no indeterminacy due to geodesic incompleteness is visible ever to anyone, so no inconsistency in GR

- GR not necessarily deterministic anyway*, so no inconsistency introduced by this

  *see work by, e.g., Smeenk, Wüthrich, Doboszewski …

Curvature singularities: Inconsistency

Why is this problematic?

- Argument from EFT: Construct an effective action with higher curvature terms that correct GR
- Can usually neglect these terms, but become important and dominate as we approach the curvature singularity -- at some point they become larger than the Einstein tensor, and GR is no longer a good approximation, need to take into account quantum effects

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Curvature singularities: Inconsistency

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- Can usually neglect these terms, but become important and dominate as we approach the curvature singularity -- at some point they become larger than the Einstein tensor, and GR is no longer a good approximation, need to take into account quantum effects
- This is an inconsistency between GR and *expected* QG effects
- Note: Doesn't show that GR is internally inconsistent
  Also: This inconsistency has nothing to do with the singularities *per se*!

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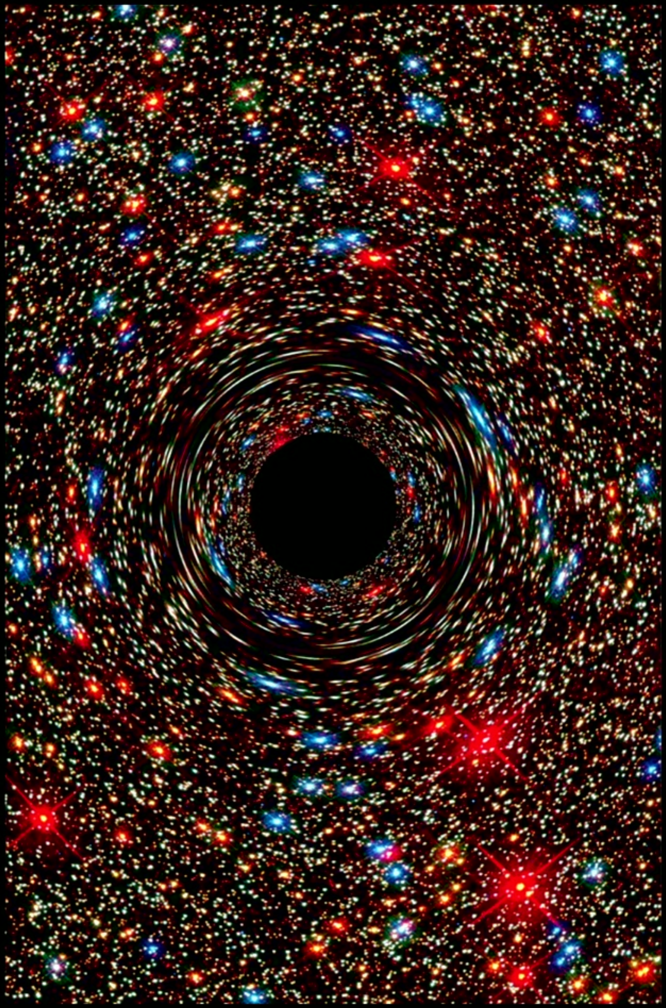

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Divergences in QFT

"*Avoidance of divergences*: It has long been speculated that quantum gravity may lead to a theory devoid of the ubiquitous divergences arising in quantum field theory. This may happen, for example, through the emergence of a natural cutoff at small distances (large momenta). In fact, modern approaches such as string theory or loop quantum gravity (see below) provide indications for a discrete structure at small scales."

(Kiefer, 2007, "Why Quantum Gravity?", p.566)

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(Kiefer, 2007, "Why Quantum Gravity?", p.566)

- Note: We may have other indications - external motivations - for discrete spacetime, but the UV divergences of QFT are not motivation for discreteness!

Singularities in QFT

- Many different divergences, where the theory "blows up to infinity and is unpredictive"...

    - IR-divergences
    - UV-divergences
    - Landau poles

Also: Perturbative non-renormalisability of GR

- Taken by many to be "the" problem of QG

- But: Problem is not the divergence itself, but the fact that the theory is not predictive at the Planck scale, which we expect\want QG to describe

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Landau poles

- Not taken to be merely due to the limitations of perturbative analysis*
- QED: coupling grows with energy scale, becomes infinite at a finite energy scale
- This is avoided if the renormalized charge is set to zero, i.e., if the theory has no interactions ("triviality")
- But, since the theory is supposed to represent physical interactions, the coupling constant should be non-zero
- Problem of consistency

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Landau poles

- Can be interpreted as a symptom of the theory being effective, or incomplete
  -- Internal motivation for treating the theory as effective

  - Challenged by those who argue for a `nonapproximate' formulation of QFT, on this view, the divergences of CQFT are not thought to be inherent to QFT, properly understood

  - AQFT is not an attempt at QG, of more-fundamental physics beyond, but simply a new formulation of QFT **at the level of QFT** – i.e., as a combination of QM and special relativity put on a rigorous mathematical footing, without any singularities in the theory!

  - Instead of introducing informal renormalisation techniques to treat interactions, mathematically rigorous axioms are postulated (axiomatic QFT), and then models of the axioms are constructed (constructive QFT)

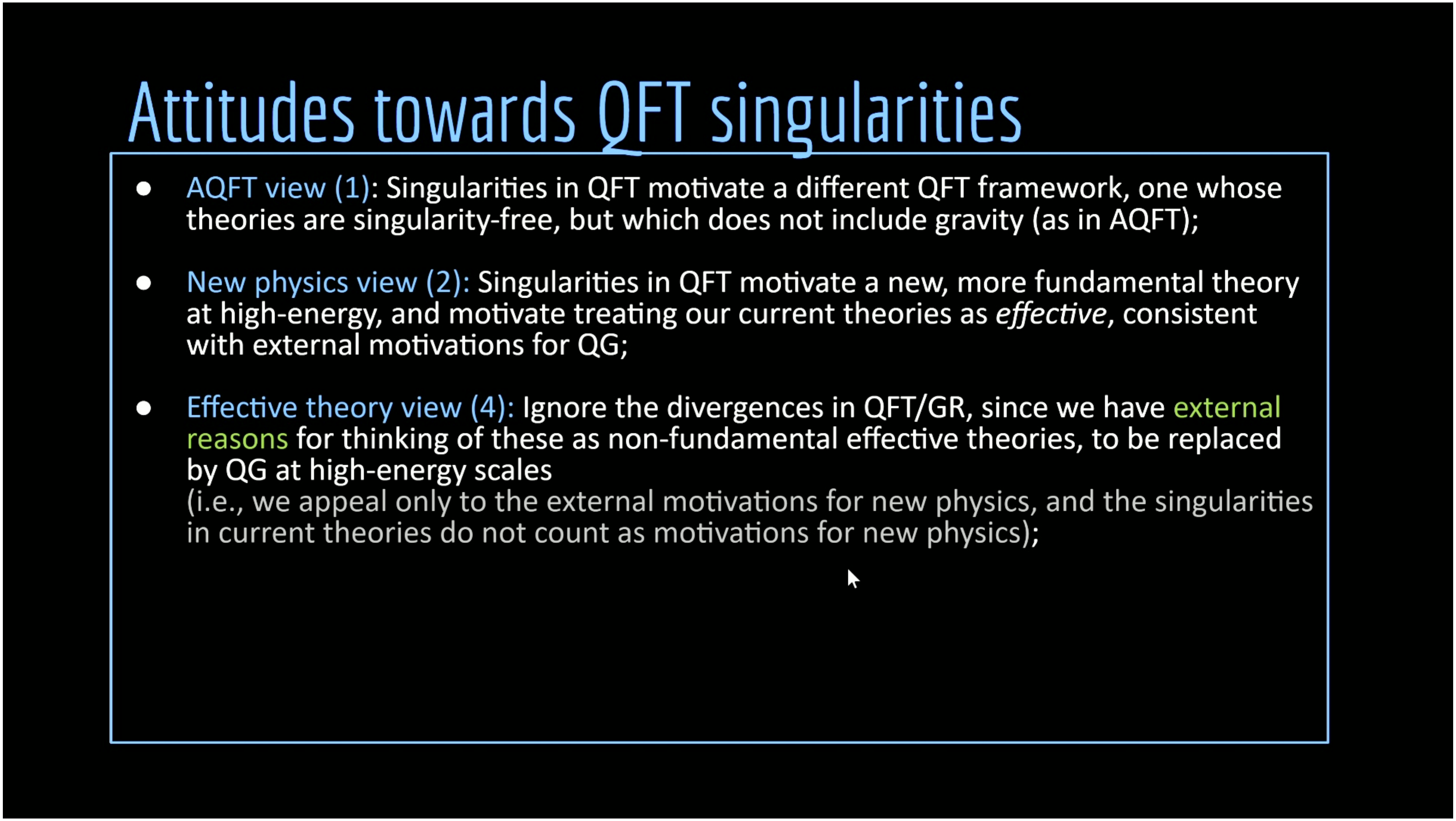
Landau poles

- But Landau poles are usually ignored:
  -- concern an energy scale where QED is not thought to be valid anyway (beyond electroweak scale)
  -- and even where QFT is not thought to be valid anyway (beyond Planck scale)

- These external grounds for treating QFT as effective come from the motivations for QG i.e., reasons for wanting QG that are not based on problems with our current established theories *as they actually stand*

  These external motivations hold regardless of whether or not there are divergences inherent to QFT

  but they are reasons why one might not be concerned with finding a singularity-free theory of QFT in order to describe the world at arbitrarily small length scales


Attitudes towards QFT singularities
AQFT view (1): Singularities in QFT motivate a different QFT framework, one whose theories are singularity-free, but which does not include gravity (as in AQFT);
New physics view (2): Singularities in QFT motivate a new, more fundamental theory at high-energy, and motivate treating our current theories as effective, consistent with external motivations for QG;
Effective theory view (4): Ignore the divergences in QFT/GR, since we have external reasons for thinking of these as non-fundamental effective theories, to be replaced by QG at high-energy scales
(i.e., we appeal only to the external motivations for new physics, and the singularities in current theories do not count as motivations for new physics);

Attitudes towards QFT singularities

- AQFT view (1): Singularities in QFT motivate a different QFT framework, one whose theories are singularity-free, but which does not include gravity (as in AQFT);
- New physics view (2): Singularities in QFT motivate a new, more fundamental theory at high-energy, and motivate treating our current theories as *effective*, consistent with external motivations for QG;
- Effective theory view (4): Ignore the divergences in QFT/GR, since we have external reasons for thinking of these as non-fundamental effective theories, to be replaced by QG at high-energy scales
  (i.e., we appeal only to the external motivations for new physics, and the singularities in current theories do not count as motivations for new physics);
- Asymptotic Safety view (4): These singularities do not motivate new physics according to the asymptotic safety scenario for gravity and the Standard Model; these singularities do not appear in the full (non-perturbative) theory.

Four attitudes to singularities

- Question: do singularities point to the need for quantum gravity?

- We identify four different attitudes to singularities in GR (QFT) found in the literature:

1. Singularities resolved classically
2. **Singularities point to QG**
3. Peace with singularities
4. Indifference to singularities

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Four attitudes to singularities

- Question: do singularities point to the need for quantum gravity?

- We identify four different attitudes to singularities in GR (QFT) found in the literature:

1. Singularities resolved classically
2. **Singularities point to QG**
3. Peace with singularities
4. Indifference to singularities

- Different types of singularities sure to receive different treatments.
  - It is possible to take one attitude with respect to one kind of singularity, and another attitude with respect to a different kind.

- In what follows, our discussion of examples is for illustration of the four attitudes, rather than for evaluation of the claims made in the physics literature

Attitude 1:
Singularities resolved classically, they do not point to QG

- This is the idea that the singularities should be resolved **'at the level of the current theories', i.e. in GR or QFT, without recourse to QG**

Examples:

- Proponents of axiomatic QFT
- Removal of idealizations in GR (e.g. "smearing out a point particle"; Parker 1979, Heinzle and Steinbauer 2001).
- Higher-dimensional resolution of certain black hole singularities: 4D black hole solutions are non-singular in higher dimensions, and evade the Penrose-Hawking singularity theorems (Gibbons Horowitz Townsend 1995).
- Gravastars: take into account the back-reaction of the fields of an imploding star that forms a compact object similar to a black hole (Mazur and Mottola 2005).

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Attitude 2: Singularities resolved in QG

- Singularities in GR (QFT) are to stay, they signal the limitations of these effective theories, and they are to be resolved in QG.
- Motivation for the search for a new theory: give a concrete problem to focus on -- Singularity-resolution as a guiding principle
- Singularity resolution might also serve as as a criterion of theory selection: a prospective theory should not be accepted if it is incompatible with the principle
- May be that GR/QFT singularities are not thought to directly point to or motivate resolution in QG, but that particular approaches to QG naturally feature singularity resolution

  But the fact that the theory resolves given singularities might nevertheless be promoted as evidence in support of the correctness, or pursuit-worthiness of the approach, i.e., non-empirical confirmation

Attitude 2: Singularities resolved in QG

- Most authors that we are aware of assign some sort of physical salience to singularities---they are seen as a ``smoking gun'' for new physics.

- A singularity, more than just indicating the breakdown of the classical theory, is a locus where new physics can be expected:

  "At this point [the big bang singularity] the classical theory completely breaks down, and has to be replaced by a quantum theory of gravity" (Bojowald2001).

Attitude 3: Peace with singularities

- Don't resolve singularities at any level (permits singularities even in fundamental theory)
  There may be reasons for keeping singularities in our theories, other than that they signal the limitations of effective theories:

3a., They can be treated as predictions of the theory without needing to be removed

3b., they are explanatory (without pointing to any new physics);

3c., they are required for stability.

Examples:

- 3a. Misner/Earman tolerance for singularities in GR – treat as predictions, "a source from which we can derive much valuable understanding of cosmology"
- 3b. Batterman/Jackiw "emergent physics view" - singularities necessary for adequate description of low-energy physics
- 3c. Horowitz and Myers (1995) - a modification of GR that is completely non-singular could not have a stable ground state (Schwarzschild sing. avoids negative masses)

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Attitude 4: Indifference to singularities

- Singularities in GR (QFT) do not not matter given that these theories are non-fundamental

- Do not need resolution at the level of GR(QFT)

  But neither do these singularities tell us anything about QG

Examples:

- Effective theory view: we can ignore UV-divergences in QFT because we have external reasons for thinking this is not the right framework at energy scales where the singularities would be a problem, and we won't learn anything from resolving them

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Attitude 4: Indifference to singularities

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- Do not need resolution at the level of GR(QFT)

  But neither do these singularities tell us anything about QG

More examples:

- Curiel (1999) argument that singularities are not a problem for GR, because they are not part of the manifold: they are not part of the theory

- Brandenberger and Vafa (1989) uses some aspects of the physics of strings to argue that, even though a cosmological singularity is present in the metric, it is of no consequence for string theory, whose behaviour near the singularity is completely regular: the string does not ``see'' the cosmological singularity (consequence of T-duality)

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Summary

1. Singularities are resolved classically (or "at the level of current theories")
2. Singularities are resolved in QG
3. Peace with singularities -- don't resolve, have positive reasons to keep them
4. Indifference to singularities -- don't need to resolve, doesn't make a difference

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Summary

- Singularities *by themselves* do not automatically point to new physics
- Argue that singularities themselves do not motivate QG, but rather consistency
- If singularity resolution is not a motivation for QG, cannot serve as a constraint on QG (i.e., a theory of QG could be accepted even if it fails to resolve singularities)

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- Perhaps the *resolution* of curvature singularities can be expected to give new physics, as in some of the examples
- The nature of the new physics depends on the nature of the resolution…

- One's attitude towards singularities depends on your response towards external motivations for QG (those that do not depend on internal problems with GR\QFT)

  … and whether your favourite approach to QG naturally features singularity resolution --in this case, could be used as a means of confirmation (i.e., increasing credence in the theory)

Questions for you!

- Which singularities point to QG? Why?

Bonus: Generalised horror of infinities

- Ellis, Meissner & Nicolai (2018)
  - Infinities lead to paradox
  - Strong conviction that infinity cannot exist in the world, so our physical theories cannot have infinities

Taken as strong motivation for QG (particularly discrete spacetime, Ellis & Co., "The apparent contradictions and inconsistencies that we encounter when we try to extrapolate the known theories to arbitrarily large energies and arbitrarily small distances are widely taken as an indication that the assumption of a spacetime continuum ultimately cannot be viable."