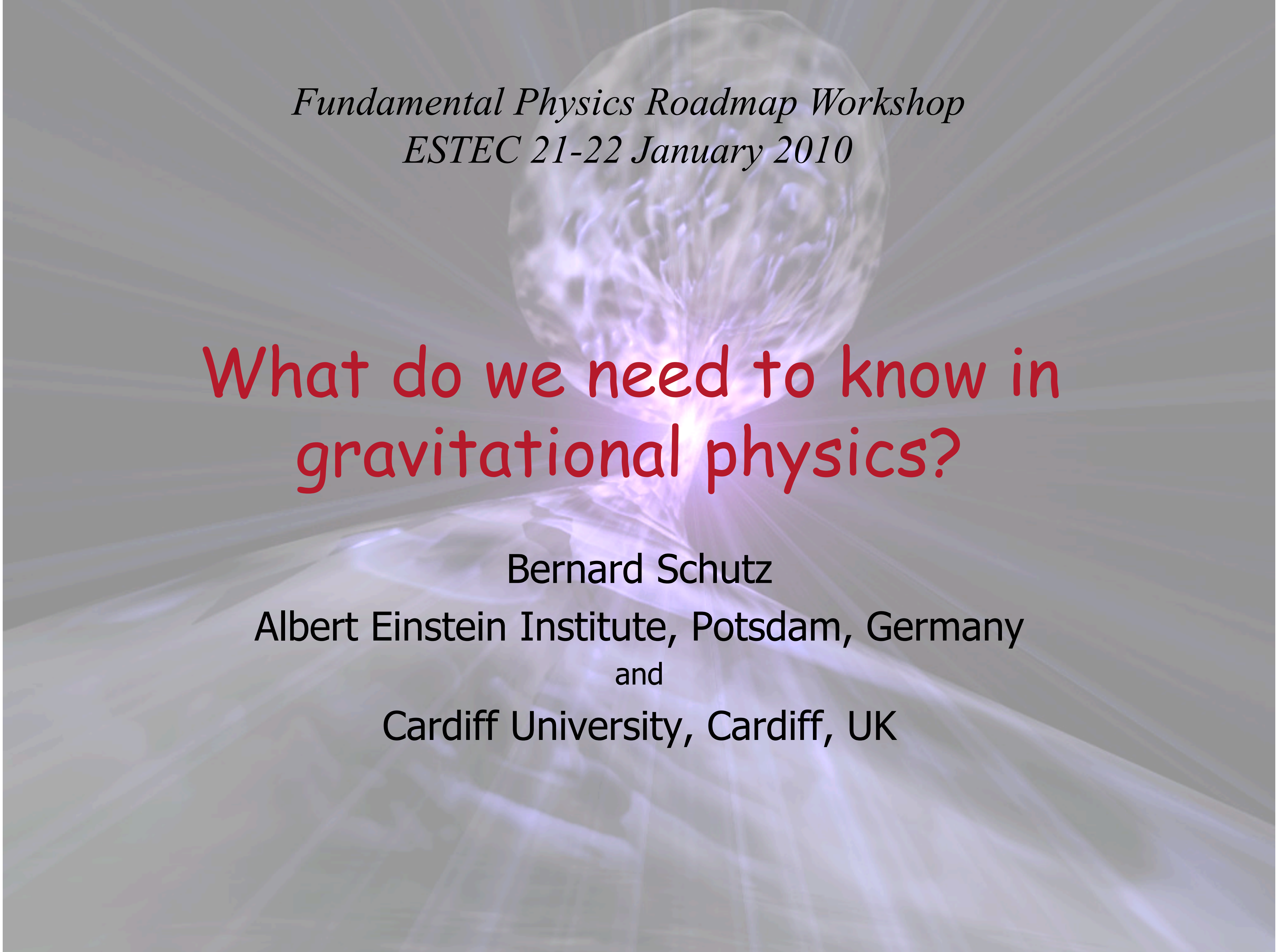

Fundamental Physics Roadmap Workshop
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What do we need to know in gravitational physics?

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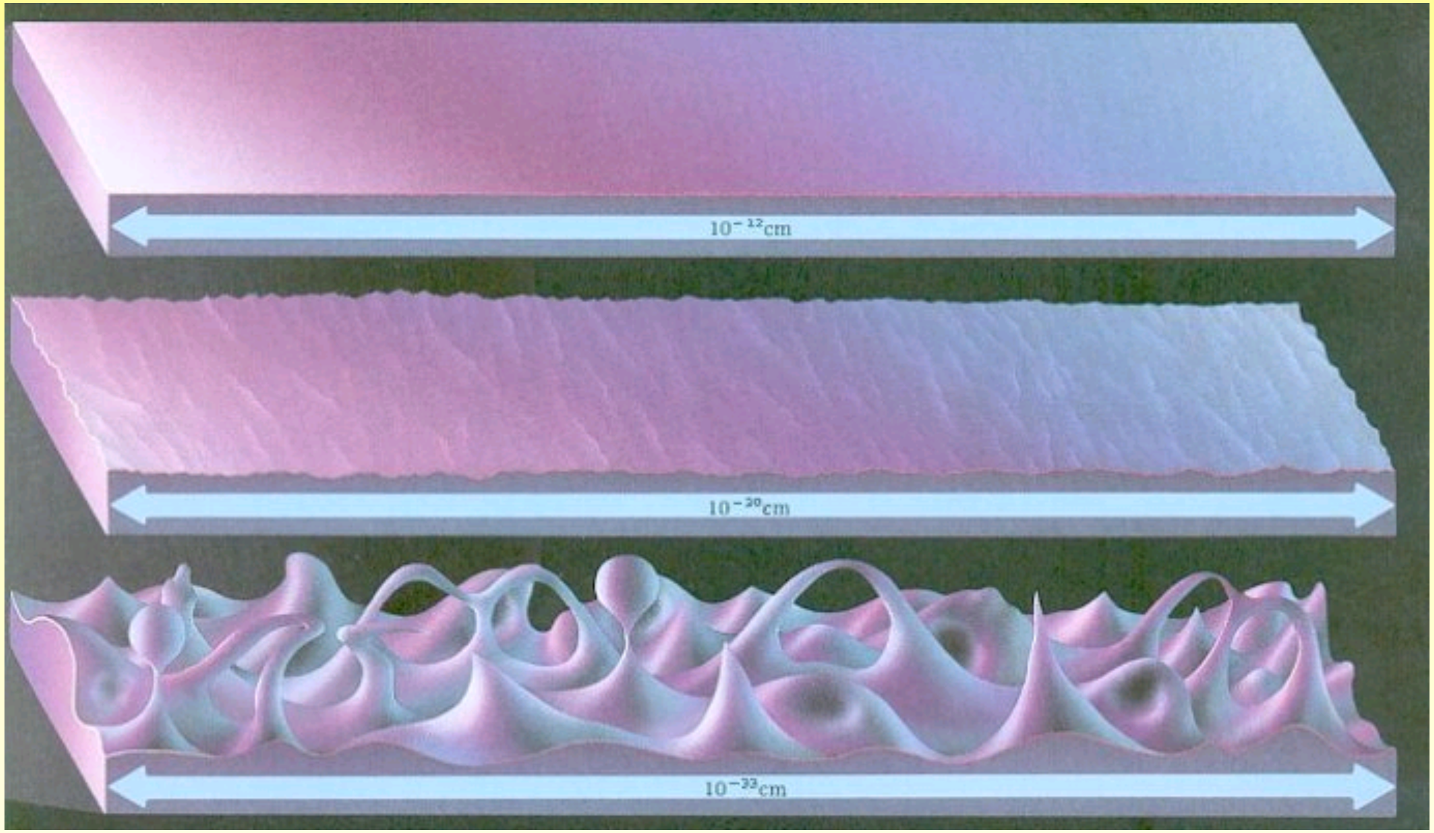
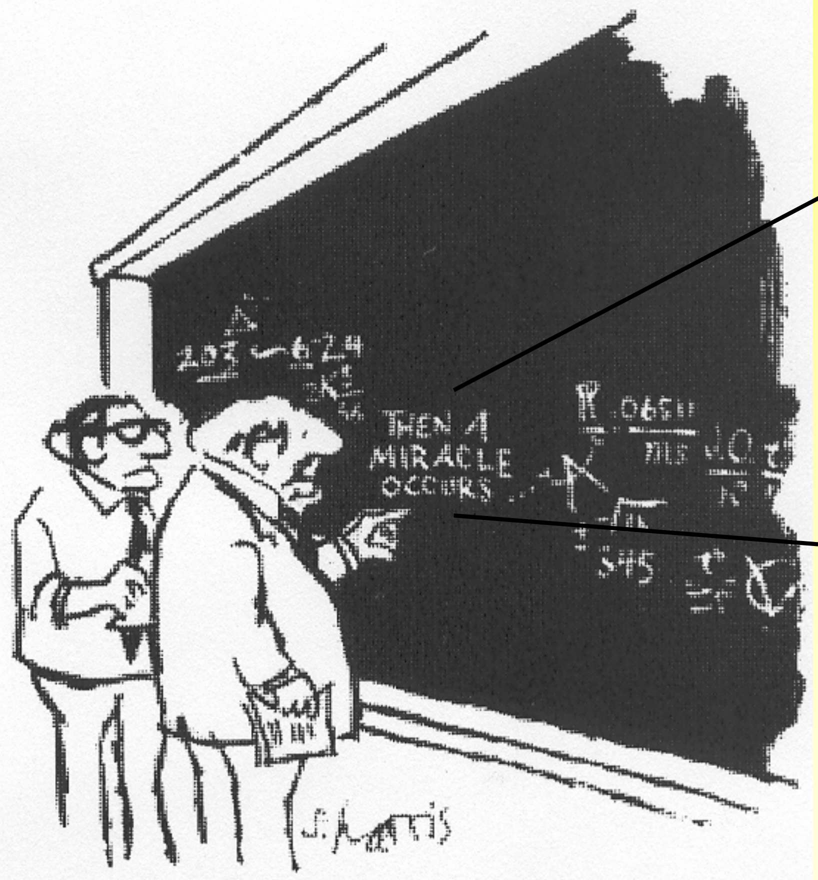
From Classical Theory to Quantum Gravity

Classical Theory

Quantum Gravity



From Classical Theory to Quantum Gravity



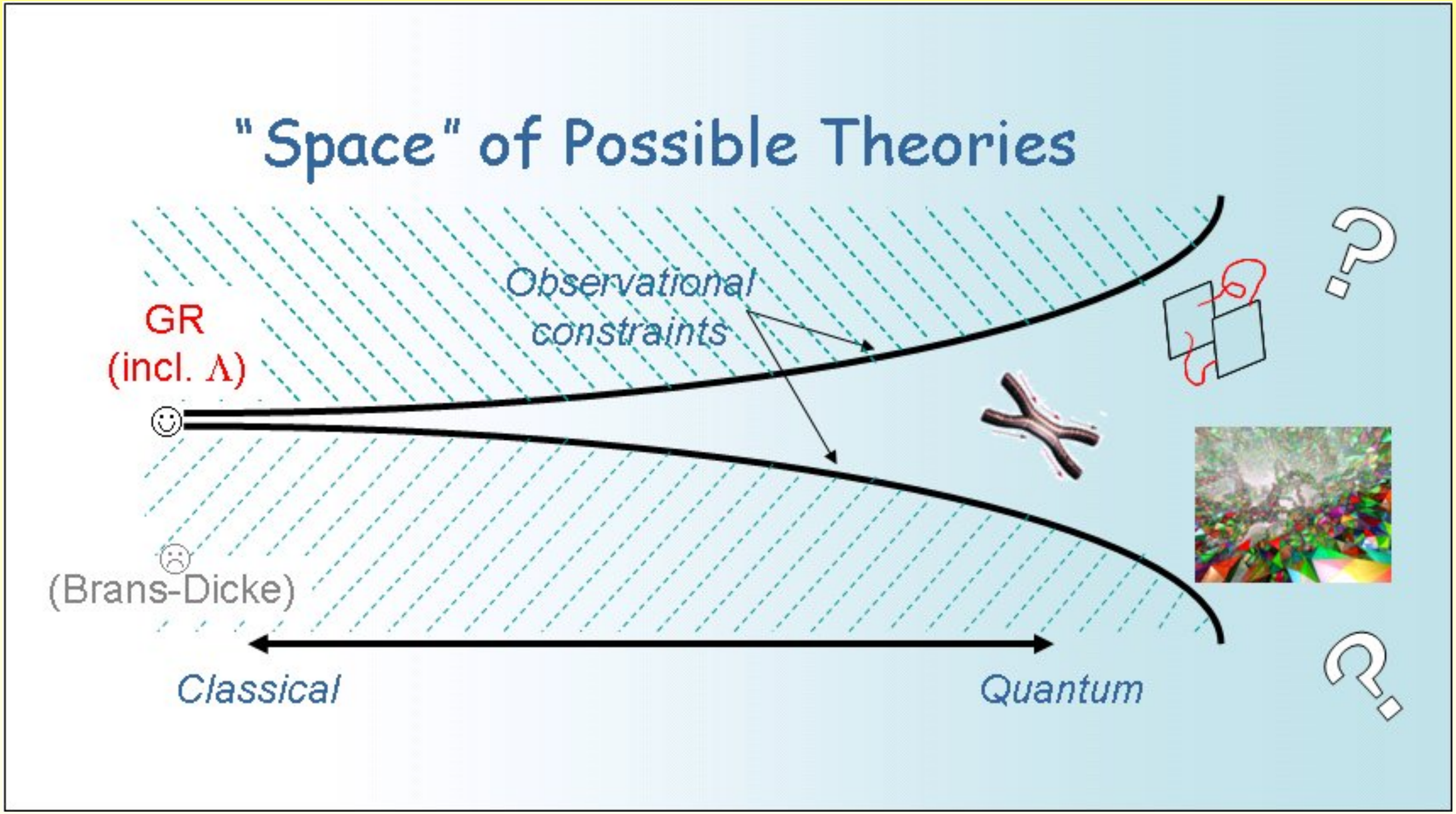
"I think you should be more explicit here in step two."

Will the miracle be experiment?

Classical GR

- At present, there is no firm evidence for any deviation from Λ-GR at the precision of current experiments.
  - Gravity appears to require just a metric coupled to matter via the EEP, generated by a local stress-energy tensor + Λ
- But there are reasons to expect this happy situation to fail
  - Compelling: quantum theory and Λ-GR are incompatible
  - Plausible: Dark energy might not be a cosmological constant: it might evolve or have an EOS with $w \neq -1$.
  - Possible: why do we need to invoke dark matter to explain inconsistencies between observation and models based on standard GR? What happens if dark matter is NOT detected? What is the origin of the Pioneer and fly-by anomalies?

Toward Quantum Gravity



Gravity and the Quantum

- Since $\ell_{PL} = (G\hbar/c^3)^{1/2} = 1.6\times10^{-35}$ m, quantum corrections ought to be too small to be accessible to direct experiment. They should occur only at very high energies, near $m_{PL}c^2 = (\hbar c^5/G)^{1/2} = 1.2\times10^{28}$ eV.
  - Our closest approach to these scales is UHECRs, currently observed at 10^{21}-10^{22} eV.
  - Understanding these rare collisions well enough to look for corrections at parts in 10^7 is a huge challenge!
- If experiment is to be a guide to the development of quantum gravity, there must be detectable lower-energy effects. Theorists have focused on what these could be. Some are plausible, others require special contrivances.
- But what *is* quantum theory? Issues in measurement theory (state reduction, role of the observer) may need to be resolved in order to develop consistent quantum theories of gravity. When there is no outside observer, what do the probabilities mean? This has led to many speculations, eg Everitt-Wheeler, the Multiverse, etc., but few are testable.

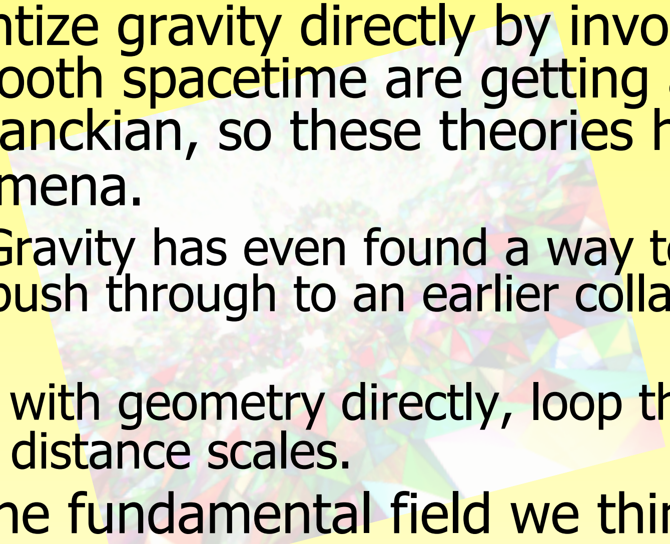
Low-Energy Quantum Effects

- Superstring theory, which is the preferred model of the majority of theoretical physicists working on quantum gravity, is really an arena within which many possible low-energy effective theories are possible.
    - Supersymmetry might be verified by the LHC. sParticles could account for the dark matter.
    - Most low-energy effective theories involve extra fields coupled to matter in ways that violate the EP. The coupling strengths are typically free parameters.
    - String Theory assumesGrand Unification (GUT), within which spontaneous symmetry breaking could have produced many so-far undiscovered families of heavy or non-interacting particles (e.g. shadow matter).
- Fundamental strings might get inflated into a population of cosmic strings, detectable through their emission of gravitational radiation. (Damour & Vilenkin 2000) Alternatively, spontaneous symmetry breaking might itself produce cosmic strings or other detectable defects.
- Holographic ideas from AdS/CFT and BH entropy may be fundamental in spacetime structure, and may lead to observable effects (Hogan 2008).

Branes

- String theory/M-Theory is attractive because it can produce a finite, mathematically consistent theory. But this happens only in 11 dimensions, and this leads naturally to multi-dimensional generalizations of strings, called branes.
- Our 4-dimensional universe could be a brane, within which all forces except gravity are confined. The other dimensions (the bulk) could be compact, or some could be large.
- Gravity could leak out into the other dimensions, changing short-range gravity, and allowing interactions with other nearby branes.
  - The scale could be set by the size of the compact dimensions, or by the distance to another brane. This additional length scale might be much larger than the Planck length, leading to new low-energy phenomena.
  - Gravity could become much stronger below this length because the n-dimensional Euclidean Poisson equation has a 'Newtonian' force ~ $1/r^{(n-1)}$.
- Brane interactions could (speculatively) produce gravitational waves, dark-matter-type effects, or even the big bang itself. (See Living Review by Maartens)

Topological Theories/Emergent Gravity



- Theories that quantize gravity directly by invoking topological structure that limits to a smooth spacetime are getting a lot of attention. Structure is sub-Planckian, so these theories have difficulty predicting low-energy phenomena.
  - Loop Quantum Gravity has even found a way to eliminate the Big Bang Singularity and push through to an earlier collapsing universe. (Bojowald 2007)
  - Because it deals with geometry directly, loop theory might lead to violations of SR over large distance scales.
- GR might not be the fundamental field we think it is, but might instead be an *emergent phenomenon*, analogous to the way superfluidity emerges from detailed molecular interactions.
  - In this case, the Planck scale is an illusion caused by the weakness of gravity, whereas the fundamental physics from which gravity emerges has other energy scales, perhaps much lower than Planck.
- Classical alternative theories (eg MOND) could be low-energy limits of some unknown quantum theory. At present they seem contrived but ultimately they must be tested, provided they can make falsifiable predictions.

Cosmological Constant/Dark Energy

- Λ is an energy field that is invariant under Lorentz Transformations, which forces it to have negative pressure, $p = -\rho$. Vacuum energy in relativistic field theories has this property. But it is typically extremely high and has to be renormalized away.
- Within superstring theory, Λ might still come from the vacuum energy, made extremely weak by the cancellations induced by supersymmetry.
- Theorists have constructed low-energy theories with extra scalar fields that have a variable equation of state, which under some circumstances can produce large negative pressures, acting as the dark energy. These are generally called *quintessence* (= ether) theories. Some "track" the matter density so that $w \sim -1$ at all times.
- Emergent theories also naturally lead to a cosmological constant, but not trivially to a very small one.
- Within loop quantum gravity and other topological approaches to quantum spacetime, theorists have also been able to find ways of producing a dark energy.

What to look for (1)?

- Cosmological-scale physics:
  - Precise characterization of dark energy EOS (*w* to ±< 1%), search for time-dependence (LISA: w variations of 30% to z=2). (EUCLID/JDEM, LISA; ground-based surveys)
  - Cosmological GW background: could indicate cosmic strings, phase transitions from symmetry breaking, non-standard inflation, brane-brane effects, shadow matter. (LISA, CMB polarization missions; LIGO, VIRGO, ET, pulsar timing with SKA)
- GW propagation effects:
  - Massive graviton leads to observable GW time-delays, signal dispersion. (LISA; LIGO, VIRGO, ET)
  - Chern-Simons term coupled to gravity leads to birefringent propagation of GW polarization, detectable in SMBH mergers: Alexander & Yunes 2009. (LISA)

What to look for (2)?

- Violations of SR and local physics:
  - Violation of the equivalence principle: could point directly to new low-energy fields. (STEP, MICROSCOPE, …)
  - Variation of the fundamental constants: could indicate unexpected couplings between fields, or incomplete homogenization by inflation (new space missions offer interesting possibilities)
  - Anisotropy of space: could indicate new tensor fields. (Laboratory and space experiments)
  - Failure of local Lorentz invariance: new long-range fields could establish a preferred frame. (Lab and space)
- Violations of GR:
  - New polarization modes of GWs, indicating extra fields. (LISA; LIGO, VIRGO, ET)
  - Kerr BH uniqueness theorem, cosmic censorship, Hawking area theorem. (LISA)
  - Anomalous radiation-reaction in binary and EMRI systems -- generalizing the Hulse-Taylor test to SMBHs -- looking for extra fields or non-GR metrics and dynamics. (LISA; LIGO, VIRGO, ET)
  - PPN-type tests of weak-field GR in the Solar System (high-precision satellite tests)

What to look for (3)?

- Violations of Newtonian $1/r^2$ at short range:
  - Brane-effect violations could in principle occur at any scale, even mm. (Laboratory tests)
- Quantum effects at long range:
  - While a direct observation of quantum effects in the gravitational interactions of bodies seems out of reach, anomalies may occur when quantum states are spread over macroscopic regions where gravity plays a role.
  - Experimental investigations of coherence and decoherence could help resolve the issues of interpretation in quantum theory that become especially sharp in quantum gravity.
  - Novel space experiments might provide sufficient range for new effects to be seen.

Cautiously into the Future!

- While it is plausible that pointers to quantum gravity exist at low energy, their strength and experimental accessibility are completely unknown. Theories are not sufficiently well developed to set targets for the sensitivity of experiments. It could happen that GR is “clean” right down to the Planck scale!!
- I think this is unlikely. Considering how complex known low-energy non-gravitational physics is, and how much still remains to be discovered at and below the GUTs scale, it seems implausible that none of today’s speculations will turn out to be relevant. But which are the ones that we should follow …??
- The strategy for proposing and choosing space missions to follow these goals must be well-informed by fundamental theory (which ideas are plausible?) and by physics and technology (which experiments give clear results, or are simple to perform, or are by-products of missions with other goals)? And the community must form a consensus around the best ones!