Title: Promising Paths: What Have We Learned So Far About Quantum Gravity?

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Abstract: In LQG we work in the spirit of Antonio Machado: "Traveler, there is no path; Paths are made by walking." I will present a bird's eye view of some of the paths that have emerged since Loops 11 and offer a few suggestions.

I try to make the point about what we know and what we do not yet know about the possibility of writing a quantum theory of gravity.

LOOPS 13

- A few final comments

Carlo Rovelli

- News from Nature
- News from this conference
- Some controversial issues
- Where to go? (What does keep me up at night…)

News from Nature

- CERN:

- No low-energy supersymmetry where expected.
- No new physics where expected.
- Standard Model once more triumphs
- Many alternative models (minimal SUSY) ruled out.

- PLANCK:

- No deviation from GR.
- Rapid expansion phase supported (inflation?)
- Many alternative models (fancy inflations) ruled out.

What is Nature telling us?

- Take current physics more seriously.

- Current attempts to "guess" Beyond SM physics are a bit in trouble
- String theory requires supersymmetry
- Take GR seriously.
- A window for quantum gravity effects in the CMB might be open.

- Historical example.

- 1870-1900: how to modify the ("low energy") Maxwell equations "to get to the underlying physics" ?
- 1887-1905: Michelson Morley.
- Einstein: build on successful theory.

- Non perturbative quantum GR looks increasingly more as a good idea: find a quantum theory whose classical limit is GR.

- Highlights from this conference (for me)

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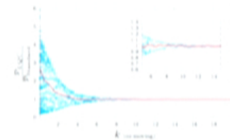
- Predictions about CMB are possible



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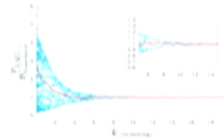
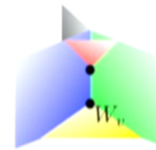


- Finiteness of q-deformed SF transition amplitudes $W(K, h, \tilde{h}) < \infty$



$$W(K, h, \tilde{h}) < \infty$$

- A complete ***finite*** family of transition amplitudes related to GR exists.

- Let's study them!

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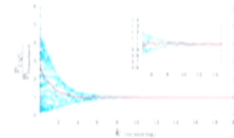

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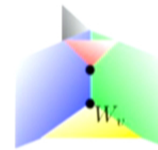

- New understanding of BH's.

$$E = \langle j|aK|j\rangle = \gamma j = \frac{Aa}{8\pi G}\,,\quad T = \frac{a\hbar}{2\pi} \;\rightarrow\; S = \frac{A}{4\hbar G}$$

entanglement entropy.

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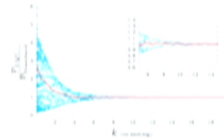

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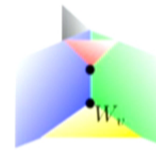

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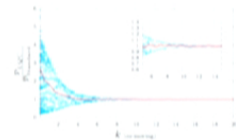

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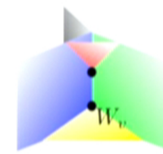

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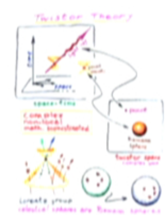
- Twistors' and spinors' role in QG



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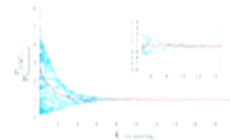

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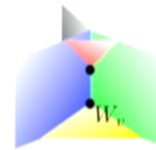

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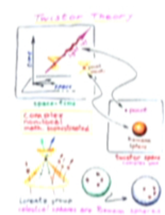
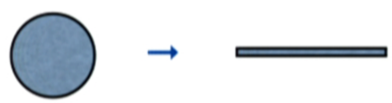


- Dimensional reduction ?



- Quantum gravity is the theory of a fundamental scale in nature.

  - Nature is finite
    - Maximal velocity: c
    - Minimal action (minimal information): $\hbar$
    - Minimal length scale: L_{Planck}

Theories

With fundamental scale finite: no infinite renormalization.	Without fundamental scale requiring infinite renormalization
- Loops - Strings - (Causal Sets)	- Asymptotic Safety, - CDT, - Tensor Models - ...

Continuous limit

$$S[q] = \frac{m}{2} \int dt \left(\dot{q}^2 - \omega^2 q^2\right) \qquad S_N(q_n) = \frac{m}{2} \sum_n a \left(\frac{(\Delta q_n)^2}{a^2} - \omega^2 q_n^2 \right)$$

$$S[q,t] = \frac{m}{2} \int d\tau \; \dot{t}^2 \left(\frac{\dot{q}^2}{\dot{t}^2} - \omega^2 q^2 \right) \qquad S_N(q_n, t_n) = \frac{m}{2} \sum_n a \left(\frac{\frac{(\Delta q_n)^2}{a^2}}{\frac{\Delta t_n}{a}} - \frac{\Delta t_n}{a} \omega^2 q_n^2 \right)$$

$$= \frac{m}{2} \sum_n \left(\frac{(\Delta q_n)^2}{\Delta t_n} - \Delta t_n \omega^2 q_n^2 \right)$$

- Systems evolving in time: $N \to \infty$, $a \to 0$
- General covariant systems: **only** $N \to \infty$

Examples: Lattice qcd, Regge calculus ...

Continuous limit

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$$W(q_f,t_f;q_i,t_i) = \lim_{N\to\infty}\int dQ_n\, dT_n\ e^{iS_N(Q_n,T_n)}$$

Finite scale: $E = \frac{1}{2}\hbar\omega$

- The approximation is already very good for small N, and W becomes rapidly insensitive to N for large N. "Ditt-invariance" (From Bianca Dittrich)

This is what keeps me up at night

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- For large N, the physically trajectory is nearly flat, and the discrete Lagrangian becomes the exact Hamilton function, which is topological invariant.

- Does the same "Ditt-invariance" happen in LQG?

- Near flatness there are extra quasi-symmetries. Gauges? Diff invariance gives infinities?

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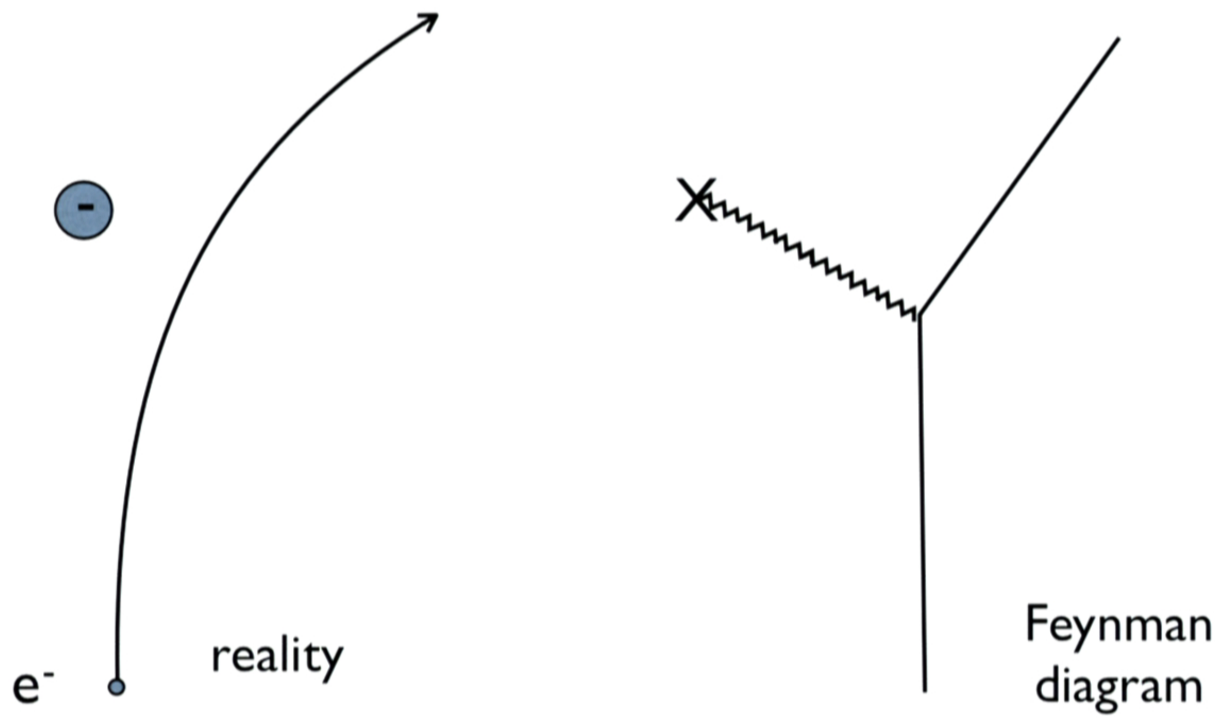
Continuous limit in covariant LQG



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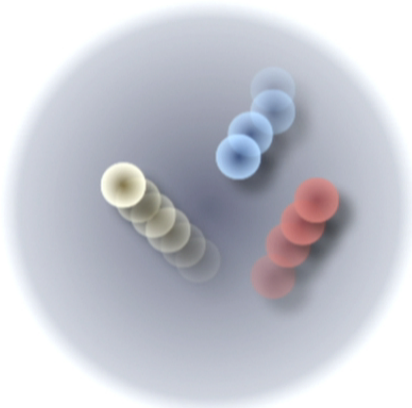

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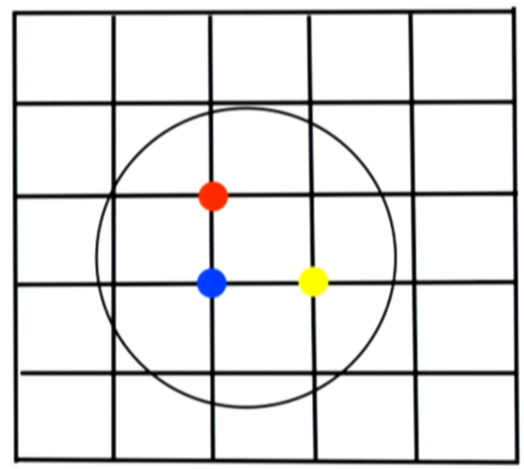
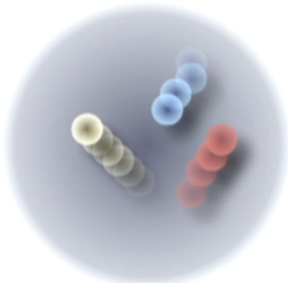
"reality"



Lattice
QCD

Continuous limit in covariant LQG



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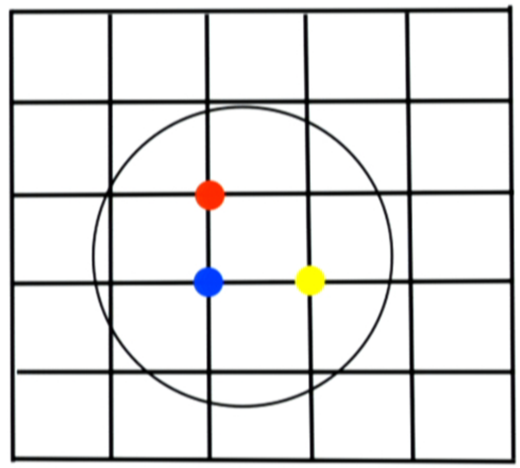
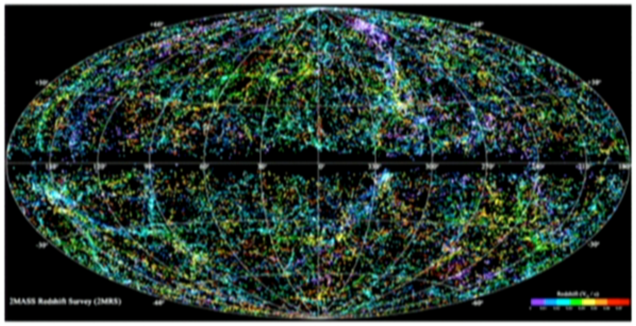


Lattice QCD

The number of cells needed in a real Lattice QCD calculation is determined by the maximum scale in the physics divided by the minimum scale

Continuous limit in covariant LQG

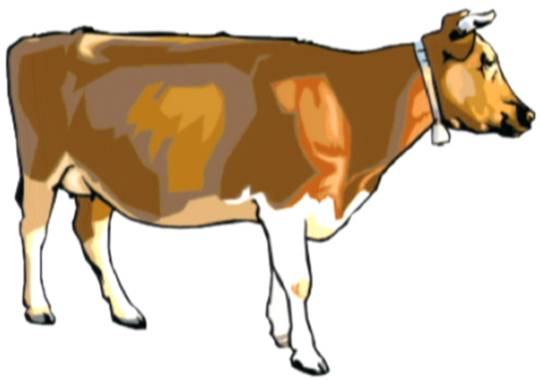


$$ds^2 = -dt^2 + a^2(t)\, d\vec{x}^2$$

reality

Our equations

- Continuous limit in covariant LQG



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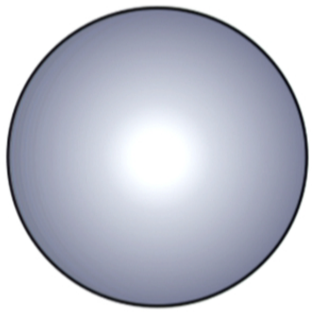
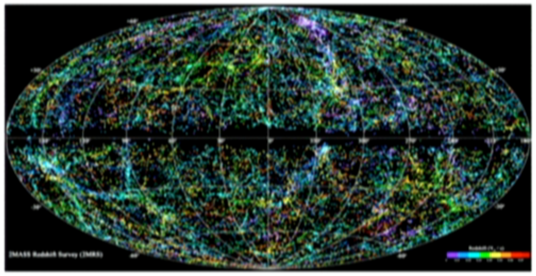


Physicists picture

- Continuous limit in covariant LQG



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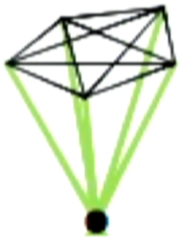


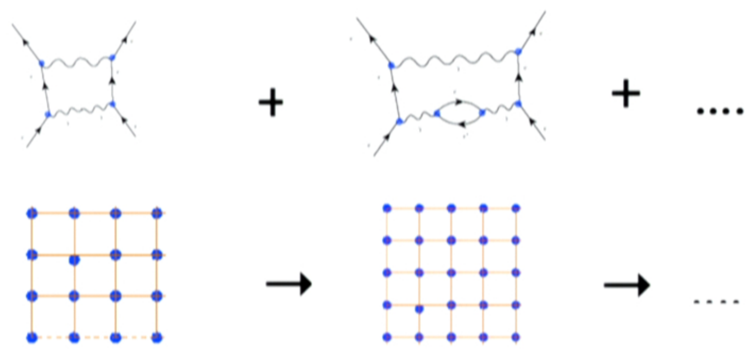
Physicists
picture

Continuous limit in covariant LQG

- Do not confuse a calculation devise with a realistic picture of reality!!
- A calculation in spinfoam is a tool for computing transition amplitudes (Like Feynman diagrams, like Lattice QCD). Not a portrait of reality!!
- "We do not live in a large tetrahedron" is a silly comment. We leave in a nearly flat space, where curvature is small, which is well approximated by a Regge geometry with few cells.
- We make few macroscopic measurements, not infinite microscopic ones. Therefore the boundary state we are interested in must reflect these ***few*** degrees of freedom.

Convergence between the QED and the QCD pictures ontinuous limit in covariant LQG

- *All* physical QFT are constructed via a *truncation* of the *d.o.f.* (cfr: QED: particles, QCD Lattice).
- The limit in which all *d.o.f.* is then recovered is pretty different in QED and QCD:



What about Quantum Gravity?

Lattice site = small region of space = excitations of the gravitational field = quanta of space = quanta of the field. Diff invariance!

- So what is the continuous limit in covariant LQG?

  Two different sources of possible concern (intertwined):
  - Large j
  - Fine triangulations

- Is the vertex approximation a good approximation? In which regimes?
- Does a finer cellular decomposition give a different result?
- Do radiative corrections destroy the good classical limit?
- In particular, how do the amplitudes behave in the limit of a very large triangulation?

Some other issues

- What is the role of the causal structure in spinfoams?
  See: Causal set, CDT, dimensional reduction.

- Constraints on the curvature. $j \to \infty$ limit at fixed two-complex and fixed boundary data is probably ***not*** the good limit.
  Concrete examples of calculation contradict the hypotheses of the theorem (Oliveira-Barrett poster).
  However, there is something not yet clear. Going around a face, the frame comes back rotated in the plane of the face (Wieland).
  Getting the geometry right? Getting the limits right? Modification of the measure term?

- What is the best way to study coarse graining in spin networks and spinfoams?

What really "keeps me up at night"

Thermodynamics:

- There is no consistent formulation of general covariant thermodynamics and statistical mechanics.
- I think we need it.
- Thermal time, relation between statistical and quantum fluctuations, relation between gravity, horizons, entanglement, entropy, and temperature, in the boundary formalism gravitational states are statistical...
- I hope that in the next LOOP meeting there will be a lively session on this problem.

- The field is developing very fast and impressive results are many and surprising

- Nature hasn't given us any "yes" ,
but the hints are in our favor.

- Beautiful questions remain open:
  - *Ditt*-invariance realized ?
  - Cosmological physical effects ?
  - Dimensional reduction ?
  - General relativistic thermodynamics ?

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- Nature hasn't given us any "yes" **yet**, but the hints are in our favor.
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I am confident that LOOPS 15 will give us new answers.

Promising Paths

Abhay Ashtekar
Institute for Gravitation & the Cosmos, Penn State

Loops13 conference, Perimeter Institute, Canada, July 26th 2013

Organization

1. Hamiltonian Theory
2. Cosmology: The very early Universe
3. Quantum Black Holes

This discussion will complement Carlo's on spin foams.

"Traveler, there is no path.
Paths are made by walking."
~Antonio Machado

1. Hamiltonian/Canonical Theory

- LQG kinematics: had have complete control ; Novel & physically interesting quantum geometry. In contrast, status of full dynamics remains unsatisfactory. Powerful Hint: Demand off-shell closure.

$$\{H(N),\, H(M)\} = D(\vec{V}), \quad \text{with } V^a = q^{ab}(M\partial_b N - N\partial_b M).$$

- **Advances in the 90s**: Thiemann: Regularization of $\hat{H}(N)$ Gambini, Lewandowski, Marolf, Pullin: Closure. But both sides vanished on the chosen `habitat'.

- **New path since Loops11**: Laddha, Varadarajan, Casey, Henderson
  *Draw distinction between c-number and q-number shifts. Study the diff constraint with q-number shifts in their own right.
  * Elementary q-number shifts (EQNS): $N_i^a := N E_i^a$

- In the original spinorial variables, the Diff and the Hamiltonain constraints constraints naturally combine: $(E^a E^b F_{ab})_A{}^B = 0$. This suggests they can be treated in a unified manner. Indeed, we can represent the Hamiltonian $H(N) = \epsilon^{ijk}\,(NE_i^a)\; E_j^b F_{abk}$ constraint as a (`twisted') diffeo generated by an EQNS so that
  $\{H(N),\, A_a^j\} = \epsilon^{ijk}\,\mathcal{L}_{NE_i}\; A_{ak}$ & similarly for E_i^a .

** **Action of the H constraint is geometric in connection variables!** **

- Brand new insight $\{H(N),\, H(M)\} = \sum_i \{D(M_i),\, D(N_i)\}$.

- Thus, the problem is now focused on understanding the action of (twisted) diffeos with EQNS on quantum states. Entirely new perspective on the quantum Hamiltonian constraint.

Quantum Theory: Euclidean, $U(1)^3$

- Careful regularization (which requires a specific choice of density weights) shows that there is a precise sense in which one has off-shell closure

$$[\hat{H}(N),\, \hat{H}(M)] = \sum_i [\hat{D}(M_i),\, \hat{D}(N_i)]$$

  No anomalies & the classical algebra is faithfully mirrored in the quantum theory.

- Neither side vanishes on the new habitat. Furthermore, do not have to to first solve the standard diff constraint to define $\hat{H}(N)$.

- Covariance of the construction greatly reduces the freedom in the choice of auxiliary structures used in regulartization & streamlines the procedure.

Promising Paths

- Extend quantum theory from $U(1)^3$ to $SU(2)$
- Inner product on the space of solutions to the constraints.
- Extracting Physics from solutions: Matter fields as clocks to make $\hat{H}(N)$ a true Hamiltonian. Action geometric, creates new vertices, intuitive.
- Approximation methods: Develop reliable effective equations systematically. (Obvious tension with the current `anomaly free' strategy based on educated guesses.)

2. Cosmology & the Very Early Universe

- Quantum gravity effects negligible during inflation unless an intermediate scale is introduced by hand. So, **since Loops11,** attention focused on pre-inflationary dynamics. Several groups.

An emerging Picture

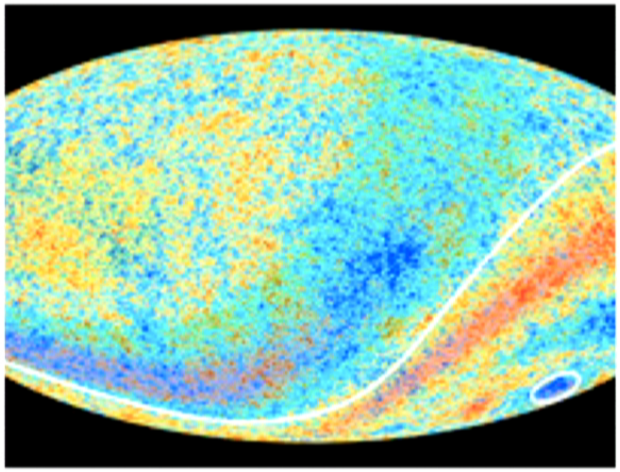
- New parameter from LQG : $\phi_{\rm B}$ (or, at the end of super-inflation)
- `Almost all' initial data at the bounce enter a slow roll inflation compatible with the 7 year WMAP data within its error bars.
- Observable universe: ball of radius $< 10\ell_{\rm Pl}$ at the bounce. Need initial state to be homogeneous at this scale only.
- New element from LQG; Repulsive force of quantum geometry origin dilutes inhomogeneities precisely at this scale.
- If $\phi_{\rm B} > 1.2{\rm m}_{\rm pl}$, there is a self consistent completion of the inflationary scenario. If $\phi_{\rm B} < 1.2{\rm m}_{\rm pl}$, potential for new physics

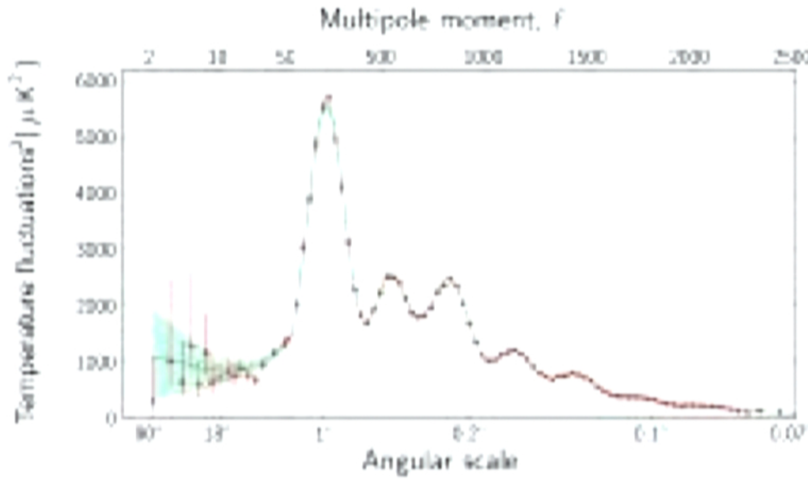
Promising Paths

- A much more detailed examination of the $\phi_{\rm B} < 1.2 {\rm m}_{\rm pl}$ regime: Back reaction? CMB-fast; 3-point functions; …..
- Initial state at the bounce (or end of superinflation): Add general principles. Example: Quantum version of Penrose's `Weyl Curvature hypothesis.
- Can one make the repulsive force idea precise?
- Analyze alternatives to inflation using LQG

Need to be ahead of future observations. Planck mission has taught us that the universe is simpler than we had imagined (as with BH coalescence in GR & quantum evaporation). Should not be held back by all the weight of all the potential complications.

Planck Data: Illustrations of windows for new physics





Puzzles raised by large scale anisotropies: Bianchi models reduce the anomalies but then there is tension with data at small angular scales. This *requires us to be more creative in developing plausible extensions of the standard model.*
…. Krzysztof M. Górski

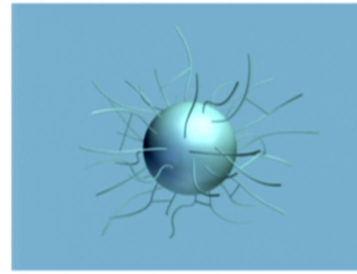
George Efstathiou was even more explicit in the ESA Press conference.

- But on the fundamental side, we should keep in mind that these models are short-cuts. Like the Dirac model of the hydrogen atom which works extremely well till we come to the Lamb shift but is completely incorrect conceptually. Very important to connect with the full theory. (Engle's talk)

- Hamiltonian theory: Apply the Varadarajan-Laddha framework to Bianchi I models. Mutual benefits.
- Spin-foams: New directions recently opened using GFT (Gielen, Oriti & Sindoni's talks)

3. Quantum Aspects of BHs

- **Advances in the 00s**: sector of GR representing a BH in equilibrium (IHs); Quantum geometry of IHs; Number theory techniques to calculate the number of micro-states.



- **Plus:** Precise notion of a Quantum IH (operator eq relating horizon and bulk geometries.)
- **Problem**: No contact with semi-classical physics. Area remained rather barren.

- **Since Loops11**: Big shift (Perez & Bianchi talks) . Rindler horizon; boost Killing field; effective quantum gravity (low energy phenomena); entanglement; $\delta S_{\rm hor}$ Vs $S_{\rm hor}$

  Breath of fresh air.

Promising Paths

Relation between non-perturbative LQG & these fascinating semi-classical advances (Perez, Bianchi, Neiman talks) ?

- Currently, tension between the two. Examples: In the semi-classical discussions Is a horizon even necessary? What is the ensemble whose entropy is being calculated? The QIH boundary condition seems to play no role. What would be the role of the near horizon stationary observer at a distance ℓ in full LQG ?

- Healthy, but we need to fully recognize and resolve this tension between fundamental statistical mechanical counting, Planck scale physics, …. and thermodynamic semi-classical ideas, effective field theory, … Otherwise, danger of a swamp of muddled ideas!

- If the tension can be resolved, there will be BIG dividends, well beyond LQG.

Outward Bound

- Better balance & harmony between levels of precision and heuristics used in various sub-areas.

- Younger researchers need to interact much more with other areas of physics, mathematics & cosmology. Can we make non-trivial advances on issues they are interested in? Better yet: solve any of their problems? Important both in terms of raw science & sociology.

- At Loops conferences we have had talks from other areas (At Loops13: Asymptotic safety, CDT, Causal sets, phenomenology, QFT in CST; Analog systems, Quantum information, …). For LQG, this cross fertilization essential. I hope experts in other areas agree & will continue to interact & reciprocate.