Loop Quantum Gravity: Some Recent Advances

Abhay Ashtekar
Institute for Gravitation and the Cosmos, Penn State

GR21, New York, July 11-15, 2016

1. Preamble

• The goal of my talk is to provide a broad setting for the 7 hours of LQG talks that will follow. Since GR20, advances have occurred in many different directions and I cannot possibly cover them all. Broadly, there is progress on issues internal to LQG and those which are common to all approaches to QG.

• Examples of Internal Issues:

⋆ Construction of squeezed, entangled states in the kinematical Hilbert space, which know of long distance correlations. Important for the semi-classical sector. (Bianchi, Guglielmon,Hackl, Yokomizo)

⋆ Continuum limit, coarse graining, renormalization group flows. (Dittrich, Bahr, Bonzom, Geiller, Kaminski, Mireza, Steinhaus ...)

⋆ Arriving at LQC from LQG (Alesci, Ciafrani, Engle, Gielen, Hanusch, Oriti, Wilson-Ewing, ...)

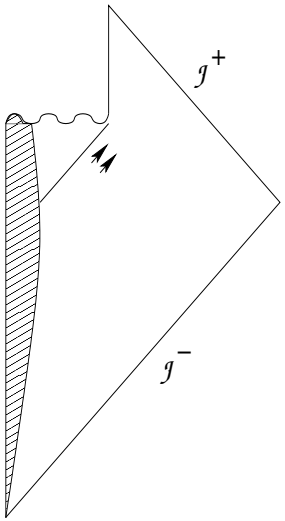
• In this talk I will focus on issues that are common to all approaches, of interest to the broader community.

Organization of the rest of the talk

2. Black Holes
3. The Very Early Universe

Coming of age: The mathematical formalism of LQG has matured sufficiently to analyze issues of direct physical interest. Over the last five years, there is increasing emphasis on relating first principle calculations to observations.

2. BH evaporation

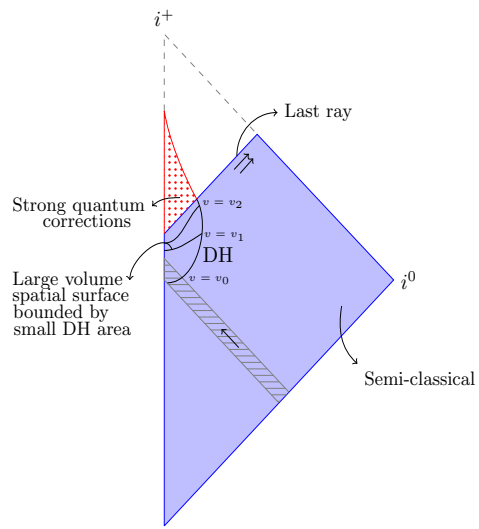


- Firewalls in the AF context: Explicit or implicit assumption include: 1. The space-time diagram is the one given by Hawking, with a future singularity;
2. The space-time has an event horizon, which serves as an absolute 1-way membrane.

Then, if the S-matrix is unitary, quantum monogamy implies that one of the assumptions is incorrect. Favored the possibility: semi-classical physics will fail to hold at the horizon already when the BH is macroscopic; there is a firewall.

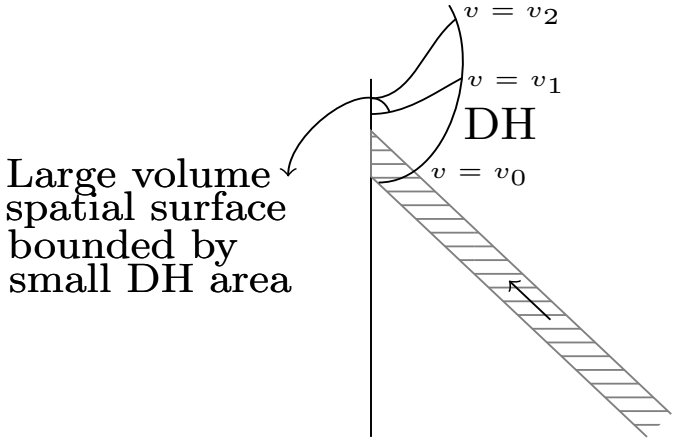
- By and large, in the GR community, unitarity in this space-time seems absurd.

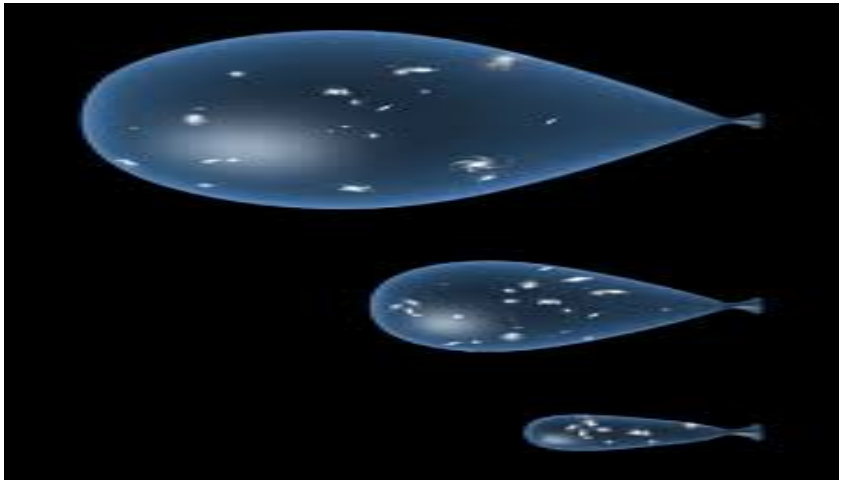
- LQG mainstream paradigm: (AA & Bojowald, ...) Singularity will be resolved by quantum geometry effects. There is no event horizon. What forms and evaporates is a dynamical horizon DH. Space-time region shown in blue is well-described by semi-classical gravity. Purification occurs on $\mathcal{I}^+$ beyond this region to the future of the last ray. Thus, the implicit assumption in the firewall scenario is violated: No problem with quantum monogamy.



Quandary: So little energy but need so many states!

- If purification happens after the DH has shrunk to a microscopic radius of, say, $10^3\ell_{\rm Pl}$, the mass 'inside' the dynamical horizon is only $m_{\rm DH} \lesssim 10^3 m_{\rm Pl}$. But since the Hawking radiation has been thermal for a long time ($t_{\rm Haw} \sim M^3 \sim 10^{55}$ Gy for a solar mass BH!), purification at $\mathcal{I}^+$ requires a HUGE number of states 'inside' the DH when its area has shrunk to $10^3\ell_{\rm Pl}$. How is this possible?





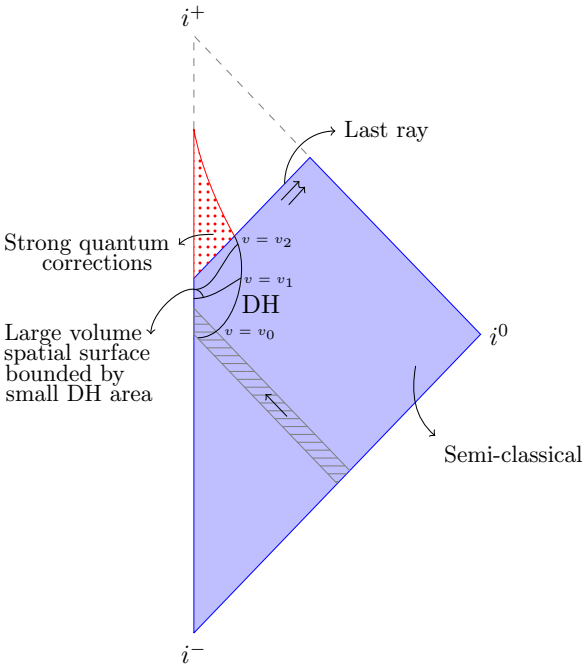
- Wheeler's bags of gold! (AA & Ori; Christodoulou, de Lorenzo & Rovelli; Bengtsson & Jacobsson)

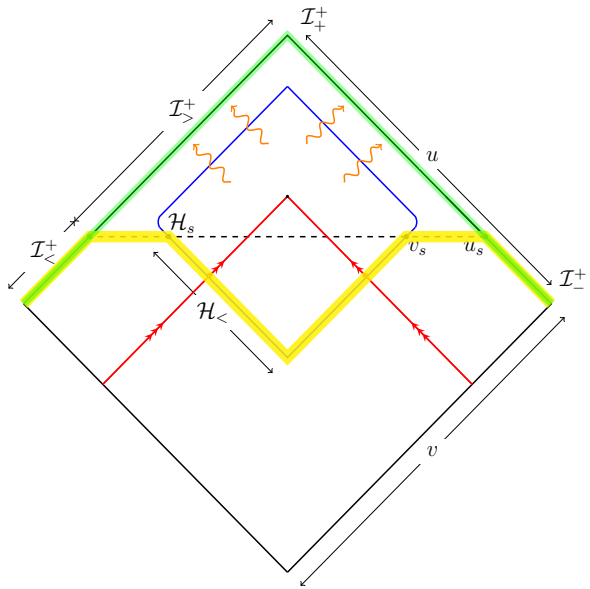
- Consider an evaporating BH with initial mass M_o. Focus on the semi-classical space-time to the future of the collapse. Assume the metric has the Vaidya form with $m(v)$ satisfying the standard Hawking equation $\frac{dm(v)}{dv} = -\frac{\hbar}{m^2 G^2}$. Examine the geometry of the r=const 3-surfaces inside the DH. They get very elongated:

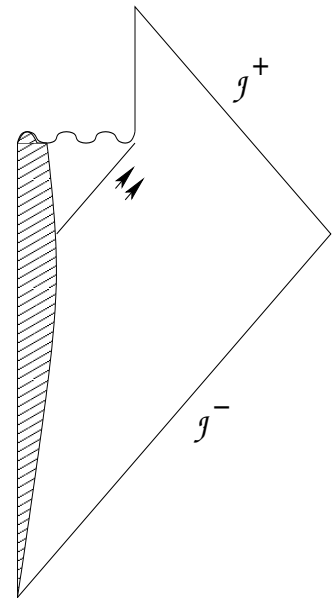
(iii) Mass $= 2 \times 10^3 m_{\rm Pl}$ $\ell = 10^{79}$ly!!
(ii) Lunar Mass: $r = 1$mm; $\ell = 10^{55}$ ly!
(i) 1/10th solar mass: $r = 300$m; proper length of the cylinder $\ell = 10^{50}$ ly!

Comparison

Figs: 1. LQG paradigm 2. HPS 3. Hawking's original Proposal







- Similarities: Note that the middle (HPS) Penrose diagram is similar to the first on the left (LQG) (and very different from the one on the right (earlier Hawking's proposal)). No singularity. No firewall. Seemingly thermal modes that reach $\mathcal{I}^+$ at 'intermediate times' are correlated with the late time infrared/soft state.

- Differences: But the 'horizons' in HPS seem rather mysterious since they are neither event horizons nor dynamical. Apparent differences in the notion of 'horizon hair'. They call the diagram 'semi-classical space-time' but because there is no singularity, perhaps they mean 'effective, dressed' space-time a la LQG.

Concrete calculations

Concrete calculations are now being done to explore the general LQG paradigm. The situation is rapidly evolving.

- Hamiltonian methods (Campiglia, Gambini, Pullin, Olmedo, ...)

Spherically symmetric collapse in LQG (midi-superspace) resulting in singularity resolution. Quantum fields analyzed on the quantum geometry of vacuum spherically symmetric LQG (using the framework developed in LQC). Concrete avenue to analyze how quantum geometry tames UV divergences of QFT. Example: Casimir effect.

- Path-integral/ Spin-foam methods (Christodoulou, Haggard, Rovelli, Speziale, Vilensky...)

Dynamics of the 'quantum region' transition amplitudes. Focus on calculating the 'tunneling time' measured far way as a function of mass. Very promising template to calculate non-perturbative physical effects from spin foams. Does the time for the 'bounce process' go as M_0^2? or M_0^3? or M_0^4? ... Relation to the first principle constraints on the process assuming an effective space-time geometry (Bianchi and Smerlak)?

- Phenomenology (Barrau, Haggard, Rovelli, Vidotto, ...)

Possibility of effects around $(7/6)r_S$ of Sgr $A^\star$; Loosening constraints opens new possibilities for primordial BHs and suggests possible a explanation of the GeV excess seen by Fermi. Necessarily qualitative and more speculative but exciting because of potential connection with observations.

3. The Very Early Universe

• The early investigations focused on resolution of the big-bang singularity in a variety of cosmological models, including FLRW with and without Λ and inflationary potentials; Bianchi models, Gowdy model, ... Quantum geometry effects resolve all strong curvature singularities in cosmological models.
Over the last 5 years, the focus has shifted to observational predictions..

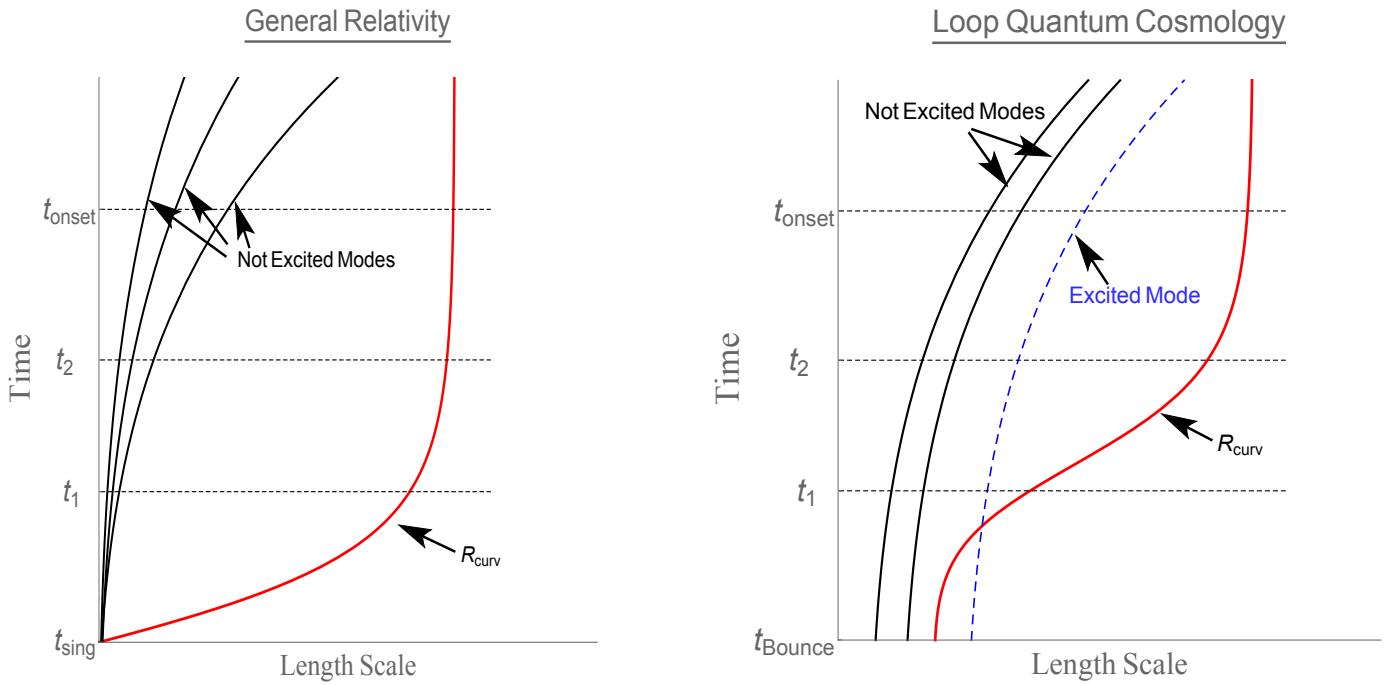
• Interestingly, PLANCK (and WMPAP) see certain anomalies –i.e. departures from standard inflation based on the Bunch-Davies vacuum– at the largest angular scales $\ell \lesssim 30$ i.e., for the longest wave-length modes. They could be statistical artifacts, or have origin in late time physics (e.g., ISW effect). But they could also be a window into Planck scale physics. To quote Planck paper XII,

> *"the anomalous features in the CMB .... could be the visible traces of fundamental physical processes occurring in the early universe."*

• Thus, there is potential to see Planck scale physics in the sky! Researchers in LQC have worked very hard to exploit this opportunity to create a niche for inflation within a fundamental theory. Calculations much more detailed and results firmer/clearer than for BHs. Several closely related but different approaches. I will focus on the one that is most developed.

Why Planck scale dynamics matters

Contrary to a wide-spread belief, pre-inflationary dynamics does matter because modes with $\lambda_{\rm phys} > R_{\rm curv}$ (the curvature radius) in the pre-inflationary era are excited and populated at the onset of inflation. They can leave imprints on CMB, naturally leading to 'anomalies' at low ℓs .



The UV LQC regularization tames the FLRW singularity. The new FLRW dynamics in turn affects the IR behavior of perturbations!

Deep interplay between UV and IR!

(Agullo, AA, Nelson)

Developments in LQC

- Over the last 2-3 years, the community has:

(Agullo, AA, Gupt, Kaminski, Lewandowski, Morris, Nelson,...)

(i) Extended QFT on FLRW space-times to QFT on quantum FLRW space-times.

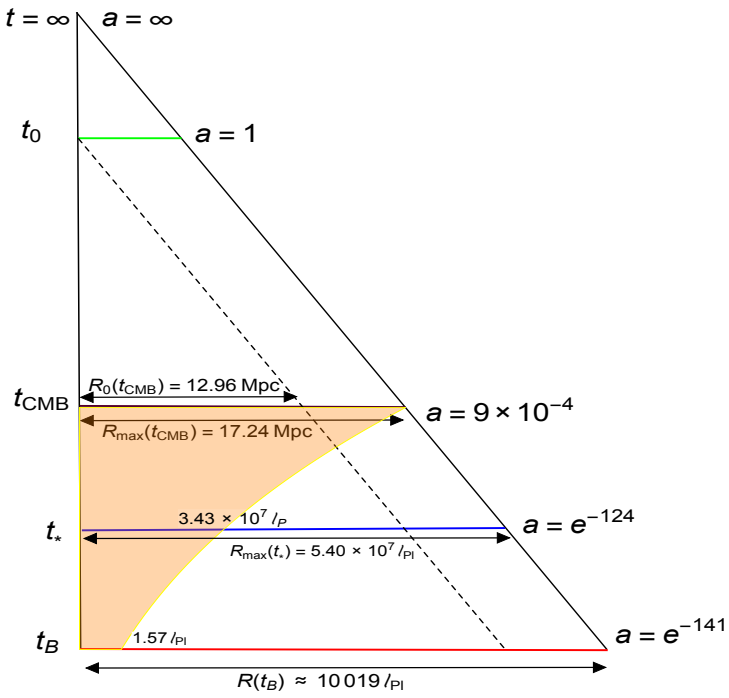
(ii) Used it to study in detail the evolution of quantum fields representing first order perturbations from the bounce to the onset of slow roll inflation (for the Starobinsky and $m^2\phi^2$ Potentials), spanning the 11 orders of magnitude in curvature and density.

(iii) Proposed a candidate set of principles (based on quantum geometry & quantum Weyl curvature hypothesis) to narrow down the initial conditions at the bounce.

(iv) Shown that this extension of inflationary scenario to the Planck regime is consistent with current observations and provides a better fit to the PLANCK data for $\ell \gtrsim 30$ and for hemispherical anisotropy, than standard inflation. Furthermore, there are predictions for the future observations (of T-E and E-E correlations). PLANCK team should release the data soon!

- The analysis depends on basic LQC as well as the principles used to select initial conditions. May be ruled out by future observations. And there may be alternate explanations. But it is notable that quantum gravity has now begun to descend from its high, mathematical physics perch and making bridges to observations.

History of the universe from the bounce to infinite future



LQC + PLANCK data

Extension of inflation over 11 orders of magnitude in curvature all the way to the LQC bounce: There is a maximum size $R_{\rm max}(t_{\rm CMB})$ to the observable universe at the CMB time even if one waits for an infinite time. An elementary ball of area $\sim 31\ell_{\rm Pl}^2$ at the bounce time expands out to fill this entire region!

Epoch	a	n_e	R_0	$R_{\rm max}$
t_0	1	0	0	5.51 Gpc
$t_{\rm CMB}$	9×10^{-4}	7	12.76 Mpc	17.24 Mpc
t_*	e^{-124}	124	$2.32 \times 10^7\ \ell_{\rm pl}$	$5.4 \times 10^7\ \ell_{\rm pl}$
$t_{\rm B}$	e^{-141}	141	$1.16\ \ell_{\rm pl}$	$10^4\ \ell_{\rm pl}$

LQG: Some Recent Advances

Coming of age: The mathematical formalism of LQG has matured sufficiently to analyze issues of direct physical interest. Over the last five years, there is increasing emphasis on relating first principle calculations to observations.