Title: Implications of the Quantum Nature Space-time for the Big Bang and Black Holes

Speakers: Abhay Ashtekar

Collection: Emmy Noether Workshop: The Structure of Quantum Space Time

Date: November 19, 2019 - 9:30 AM

URL: http://pirsa.org/19110090

Implication of the Quantum Nature of Space-time For the Big Bang and Black Holes

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Emmy Noether Workshop, PI, November 18-22, 2019

Preamble

The Big Bang and Black Hole singularities of general relativity offer a compelling context to explore the quantum structure of space-time. I will summarize what we know about this structure from Loop Quantum Gravity (LQG).

Basic premise of LQG: Geometry is a physical entity like matter. So, it should have an 'atomic'/quantum structure. LQG provides a specific one based on a detailed and rigorous mathematical framework.

Questions:

What are the implications of this quantum geometry for the Big Bang ("the beginning") and Black holes ("the end") when the continuum of general relativity breaks down and classical physics comes to a halt?

What is the nature of the quantum extension of classical space-time? Can consequences of singularity resolution be tested?

Main messages

1. Quantum geometry underlying LQG is subtle. Detailed calculations show that its effects are negligible not only at the horizon of a solar mass BH, but even at the 'onset' of inflation when curvature is 10^{55} times higher! But these effects rise very quickly near the Planck scale and overwhelm classical attraction, preventing singularities.

2. There are several different levels of quantum geometry manifestations depending on the observables/probes relevant to the physical problem:
(i) Fundamental level at the Planck scale: Described in LQG by *spin networks* and associated geometric operators;

(ii) Coarse grained level where one is interested only in a few macroscopic observables, such as 'average' matter field, or anisotropies or homogeneous part of spatial curvature, or...
Described by a *wave function* that depends on a few degrees of freedom, e.g. $\Psi(a, b_i, \phi, ...)$ in the early universe or $\Psi(r, \phi)$ inside a black hole horizon;

(iii) Geometry seen by quantum fields representing perturbations propagating on quantum space-times. In LQG, represented by a *dressed effective metric* – a smooth tensor field $\tilde{g}_{ab}$ whose coefficients involve Planck's constant. (Possible contact with the Asymptotic safety program.)

Organization

I will summarize the work of many researchers.

1. The Very Early Universe: Implications of Quantum Geometry
   - 1.A Quantum Geometry: Natural resolution of the Big Bang Singularity.
   - 1.B Quantum Geometry seen by Cosmological Perturbations.
   - 1.C A Two way Bridge Between Theory and Observations

2. Black Holes and Information loss: A Three level Analysis
   - 2.A Inclusion of Back-reaction Semi-classical approximation.
   - 2.B Quantum Geometry and Singularity Resolution.
   - 2.C Proposal for the Quantum Extended Space-time.

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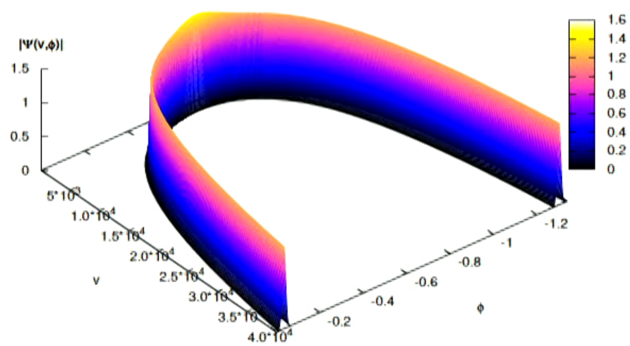
AA, Krishnan, De Lorenzo, Olmedo, Ori, Singh
A lot of related work by many others. Will be happy to discuss during the week.

2.A Quantum Geometry & The Very Early Universe

• In LQG, geometric observables are self adjoint operators with discrete eigenvalues. Of particular importance is the area operator $\hat{A}$. Its smallest non-zero eigenvalue is called area gap, $\mathring{\Delta}$. Classically, curvature can be obtained using holonomies around loops L as $\lim_{\mathrm{Ar}\to 0}(\mathrm{Hol_L} - 1)/\mathrm{Ar}$. LQG curvature operator is: $\lim_{\mathrm{Ar}\to\mathring{\Delta}}(\widehat{\mathrm{Hol_L}} - \hat{\mathrm{I}})/\mathrm{Ar}$. So the area gap $\mathring{\Delta}$ plays a key role in LQG dynamics.

• For the early universe, one truncates the theory to a few degrees of freedom and works with, e.g., states $\Psi(v,\phi)$ (with $v \sim a^3$). One can, if one wishes, 'deparametrize the theory' regard ϕ as providing an 'internal time' with respect to which matter density, curvature 'evolve'.



• Unlike in GR or the standard WDW theory, matter density operator $\hat{\rho}$ has an absolute upper bound

$$\rho_{\rm sup} = \frac{18\pi}{G^2\hbar\mathring{\Delta}^3} \sim 0.41\rho_{\ell_{\rm Pl}}$$

(Similarly $\mathrm{curv_{sup}} \sim 62\ell^2_{\rm Pl}$). The wave function undergoes a bounce once these upper bounds are reached. The Big Bang is replaced by a big bounce.

1.B Cosmological perturbations

- The inflationary paradigm has been remarkably successful in accounting for the tiny inhomogeneities in CMB using vacuum fluctuations of quantum fields representing cosmological perturbations. But it is incomplete because it assumes classical GR all the way back to the big-bang. We need a quantum gravity theory to complete it, i.e., to address issues it leaves open:

(i) Resolution of the big bang singularity.
(ii) A quantum FLRW geometry with which one can work consistently.
(iii) Quantum field theory on a quantum FLRW space-time that can treat the dynamics of cosmological perturbations in a consistent manner; and
(iv) Initial conditions in the Planck era.

- In LQC these issues have been addressed. There is a successful completion of the standard inflationary paradigm over 11 or 12 orders of magnitude in density and curvature, all the way to the Planck scale.

For (i) and (ii), the wave function $\Psi_o(v, \phi)$ replaces the classical FLRW metric used in inflation. I will now discuss issue (iii). (Since we have a well controlled quantum geometry in the Planck regime near the bounce, by addressing (iii), we face the 'trans-Planckian' problems of standard inflation squarely.)

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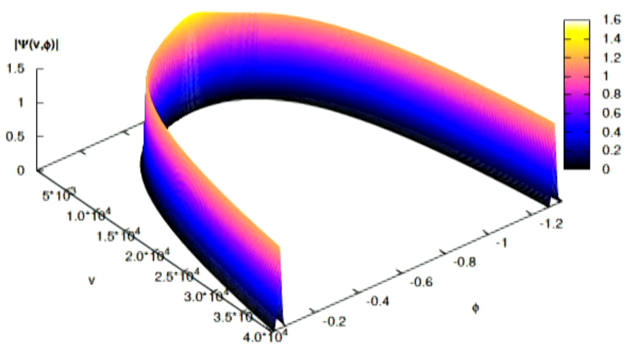

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What is behind this singularity resolution?

• The key modification of Einstein dynamics is well-captured in effective equations. For example, the effective Friedmann equation is:

$$(\dot{a}/a)^2 = (8\pi G\rho/3)[1 - \rho/\rho_{\rm sup}] \quad \text{where} \quad \rho_{\rm sup} = \frac{18\pi}{G^2\hbar\mathring{\Delta}^3} \sim 0.41\rho_{\rm Pl}.$$

Separation of scales: effects become negligible for $\rho << \rho_{\rm Pl}$.

• Mechanism: No unphysical matter or new boundary conditions. Quantum geometry creates a brand new repulsive force in the Planck regime, overwhelming classical attraction. Understood in the Hamiltonian, Path integral and consistent histories frameworks.

• Many generalizations: inclusion of spatial curvature, Λ, anisotropies (Bianchi models), inflationary potentials and inhomogeneous Gowdy models. Qualitative summary: Every time a curvature scalar enters the Planck regime, the quantum geometry repulsive force dilutes it, preventing a blow up.

• Over the last two years, there have been significant advances to arrive at the LQC effective equations starting from full LQG –using fundamental spin network states that capture the cosmological setting in place of $\Psi(v, \phi)$. The singularity resolution has been shown to be robust. (Not surprising: Recall Hydrogen atom.)

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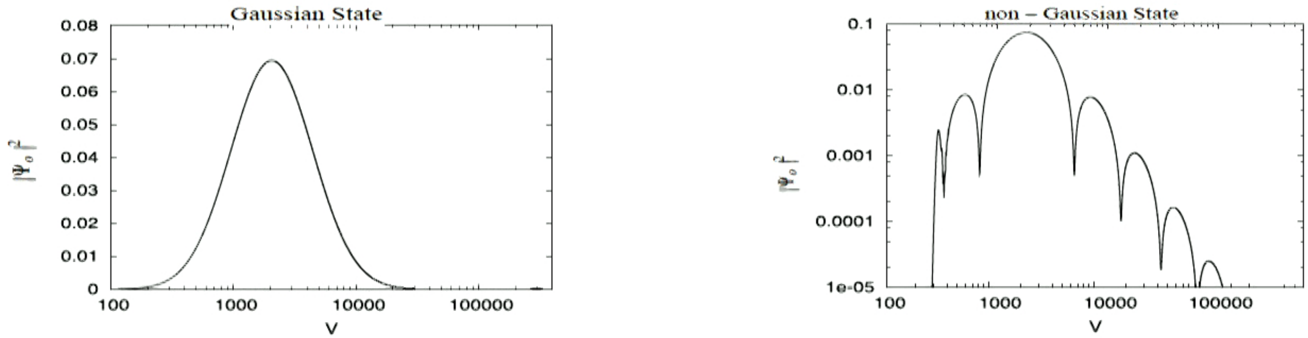
Direct Observations of Quantum Geometry?

- Can observations directly probe full quantum geometry in the Planck regime?

- The only observational tool we currently have to probe the very early universe is cosmological perturbations which only see the dressed effective metric $\bar{g}_{ab}$; not even Ψ_o, let alone spin networks! Furthermore, we can only measure the 2 and 3-point correlation and not the full state ψ of perturbations. Thus, in the passage from Ψ_o to power spectra, there are two levels of filters that remove information in Ψ_o. Can very different Ψ_o then can lead to same power spectra and spectral index?

- Yes! Surprise: very different states with relative dispersion of 170% in the Planck regime can have same predictions as sharply peaked ones with 1% !



With known tools we will not know what the state Ψ_o was in the Planck regime!

Perturbations ψ on the Quantum Geometry Ψ_o

- Strategy: Assume perturbations ψ can be regarded as test fields on the quantum geometry Ψ_o, find solutions $\Psi_o \otimes \psi_{\rm pert}$, and finally check self consistency. Then, the Planck regime is dealt with squarely provided $\rho_{\rm Pert} \ll \rho_{\rm BG}$ from the bounce till we arrive at the classical GR regime.

- Unforeseen Simplification: dynamics of perturbations $\hat{T}^{(1)}, \hat{T}^{(2)}, \hat{\mathcal{R}}$ on the quantum geometry of Ψ_o is mathematically equivalent to that of $\hat{T}^{(1)}, \hat{T}^{(2)}$, $\hat{\mathcal{R}}$ as quantum fields on a smooth space-time with a 'dressed' effective, c-number metric $\bar{g}_{ab}$ (whose coefficients depend on $\hbar$):

$$\bar{g}_{ab}{\rm d}x^a{\rm d}x^b = \bar{a}^2(-d\bar{\eta}^2 + {\rm d}\vec{x}^2)$$

with

$$d\bar{\eta} = \langle \hat{H}_o^{-1/2}\rangle\, [\langle \hat{H}_o^{-1/2}\hat{a}^4\hat{H}_o^{-1/2}\rangle]^{1/2}\, d\phi; \qquad \bar{a}^4 = (\langle \hat{H}_o^{-1/2}\, \hat{a}^4\, \hat{H}_o^{-1/2}\rangle)/\langle \hat{H}_o^{-1}\rangle$$

where H_o is the Hamiltonian governing dynamics of Ψ_o. (For the $\hat{\mathcal{R}}$ there is also a quantum corrected effective potential, $\bar{\mathcal{U}}(\bar{a}, \phi)$.) Analogy with light propagating in a medium.

- Because of this, the mathematical machinery of adiabatic states, regularization and renormalization can be lifted to the QFT on cosmological QSTs under consideration. Result: Full mathematical control on dynamics starting from the deep Planck regime at the bounce.

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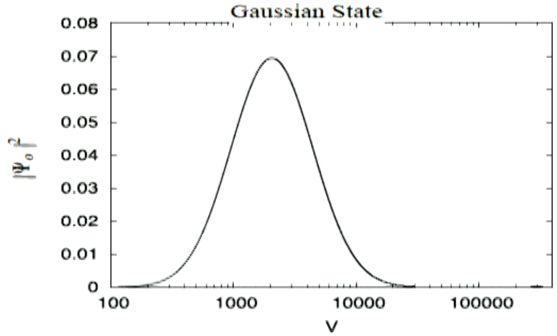

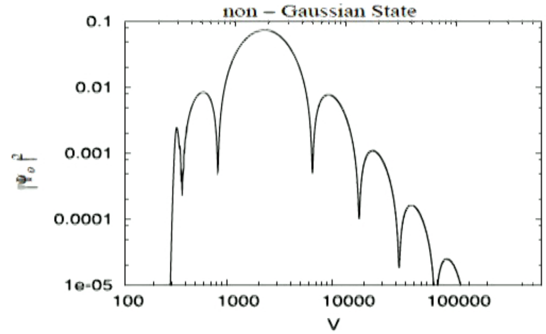

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1.C Interplay Between Theory and Observations?

Planck 2015 results. XVI. Isotropy and statistics of the CMB

Planck Collaboration: P. A. R. Ade[89], N. Aghanim[60], Y. Akrami[65,103], P. K. Aluri[55], M. Arnaud[75], M. Ashdown[72,6], J. Aumont[60], C. Baccigalupi[88], A. J. Banday[100,9 *], R. B. Barreiro[67], N. Bartolo[32,68], S. Basak[88], E. Battaner[101,102], K. Benabed[61,99], A. Benoit[58], A. Benoit-Lévy[26,61,99], J.-P. Bernard[100,9], M. Bersanelli[35,49], P. Bielewicz[85,9,88], J. J. Bock[69,11], A. Bonaldi[70], L. Bonavera[67], J. R. Bond[8], J. Borrill[14,94], F. R. Bouchet[61,92], F. Boulanger[60], M. Bucher[1], C. Burigana[48,33,50], R. C. Butler[48], E. Calabrese[97], J.-F. Cardoso[76,1,61], B. Casaponsa[67], A. Catalano[77,74], A. Challinor[64,72,12]

ABSTRACT

We test the statistical isotropy and Gaussianity of the cosmic microwave background (CMB) anisotropies using observations made by the *Planck* satellite. Our results are based mainly on the full *Planck* mission for temperature, but also include some polarization measurements. In particular, we consider the CMB anisotropy maps derived from the multi-frequency *Planck* data by several component-separation methods. For the temperature anisotropies, we find excellent agreement between results based on these sky maps over both a very large fraction of the sky and a broad range of angular scales, establishing that potential foreground residuals do not affect our studies. Tests of skewness, kurtosis, multi-normality, *N*-point functions, and Minkowski functionals indicate consistency with Gaussianity, while a power deficit at large angular scales is manifested in several ways, for example low map variance. The results of a peak statistics analysis are consistent with the expectations of a Gaussian random field. The "Cold Spot" is detected with several methods, including map kurtosis, peak statistics, and mean temperature profile. We thoroughly probe the large-scale dipolar power asymmetry, detecting it with several independent tests, and address the subject of a posteriori correction. Tests of directionality suggest the presence of angular clustering from large to small scales, but at a significance that is dependent on the details of the approach. We perform the first examination of polarization data, finding the morphology of stacked peaks to be consistent with the expectations of statistically isotropic simulations. Where they overlap, these results are consistent with the *Planck* 2013 analysis based on the nominal mission data and provide our most thorough view of the statistics of the CMB fluctuations to date.

1. Introduction

foreground-cleaned CMB maps, it was generally considered that the case for anomalous features in the CMB had been strengthened. Hence, such anomalies have attracted considerable attention in the community, since they could be the visible traces of fundamental physical processes occurring in the early Universe.

2018 Planck 2018 Results. I. Overview and the cosmological legacy of Planck

...if any anomalies have primordial origin, then their large scale nature would suggest an explanation rooted in fundamental physics. Thus it is worth exploring any models that might explain an anomaly (even better, multiple anomalies) naturally, or with very few parameters.

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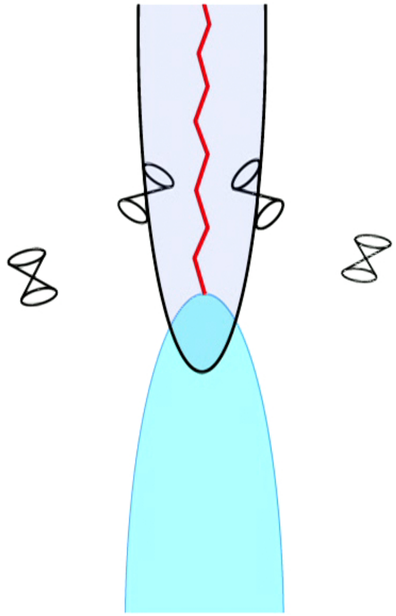
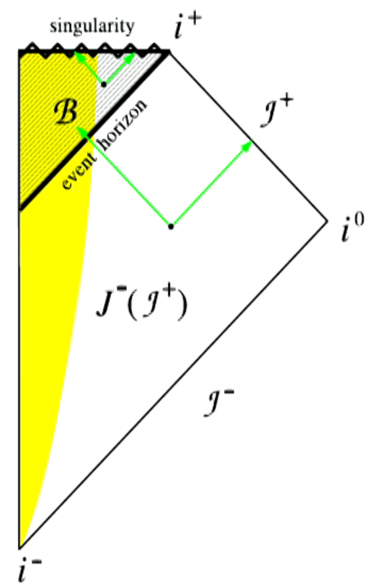
2. Black Holes and Information Loss

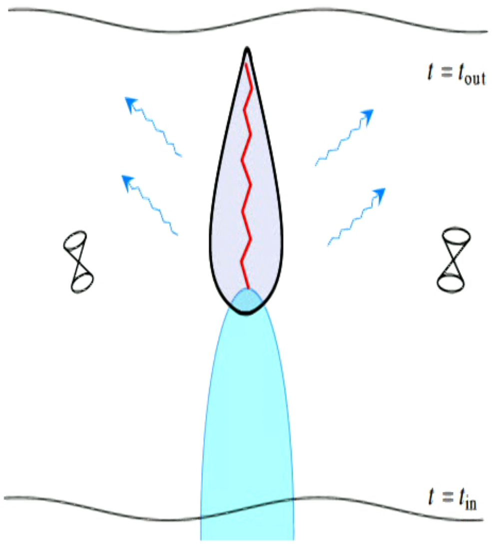
- Information is lost in the classical gravitational collapse: What falls across event horizon is invisible to outside observers. While $\mathcal{I}^-$ is a good 'initial data surface', $\mathcal{I}^+$ is not.



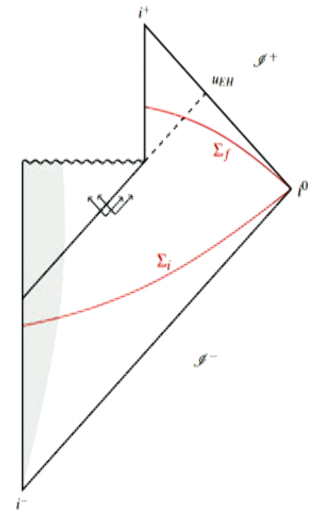
A collapsing star creates an event horizon, the boundary of a trapped region from where even light cannot escape however long you wait. Note: notion of event horizon requires that $\mathcal{I}^+$ is complete.



2.A Hawking Effect with Back Reaction

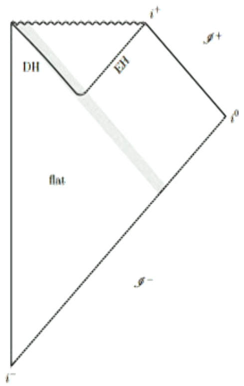


Consider a quantum field in state $|0_{\text{in}}\rangle$. The dynamical curved geometry creates pairs of modes, one falls across the horizon and the other escapes to infinity. Energy flux at infinity $\Rightarrow$ black hole shrinks and eventually disappears.



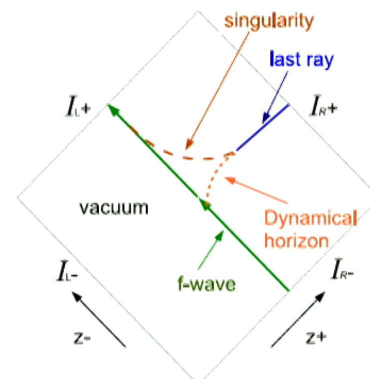
If the a singularity persists, then again there is sink of information. Pure states in the past appear to evolve to mixed states in the future. Most relativists think that if the singularity persists, information would be lost in our asymptotic region. But if one insists on unitarity in this space-time, as some string theorists do, then one is led to invoke novel ideas: first we had quantum xerox machines, then firewalls along the horizon, and now fast scramblers. Firewalls, for example, would imply a surprising failure of semi-classical physics!

Prelude: More realistic Penrose Diagrams



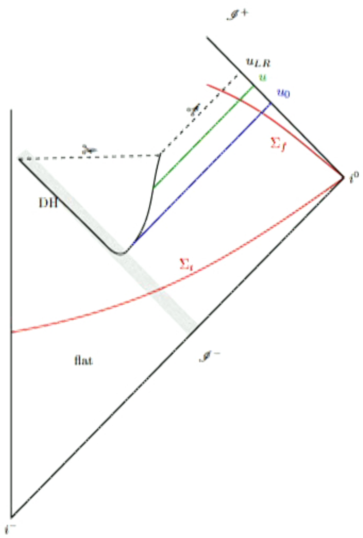
1. In the Hawking derivation, the star that collapsed was an external, classical source; evaporation referred to quantum fields in the vacuum state on $\mathcal{I}^-$.
In the analysis of unitarity and information loss, we need a closed system for consistency: e.g., a collapsing coherent state of a scalar field and analysis of quantum radiation originating in its fluctuations. Note the presence of a Dynamical Horizon (DH) in the collapsing region

2. In the semi-classical region there is no event horizon: $\mathcal{I}^+$ is incomplete. What forms and evaporates is a DH. It is space-like during collapse and becomes timelike during evaporation.
This follows analytically from differential geometry and is seen explicitly in the detailed numerical analysis of semi-classical CGHS BH.



Semi-classical CGHS BH

Quantum effects on Geometry: Semi-classical Region



- A key puzzle already in the semi-classical regime.

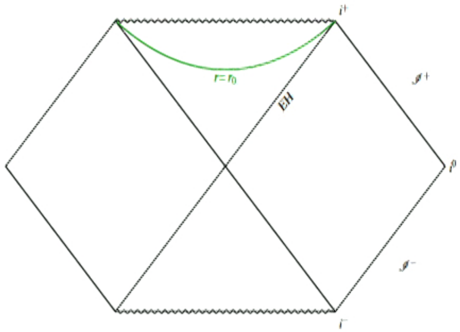
Heuristics: Evaporation of a solar mass BH to lunar mass takes $\sim 10^{63}$ years. $\sim 10^{75}$ modes are emitted to infinity and are correlated with the modes that fell into the BH. How could these modes 'fit in' the ball of radius only 0.1mm, the Schwarzschild radius of a lunar mass BH? Even if they had the 'largest' $\lambda \sim 0.1$mm, their energy would be some 10^{22} times the lunar mass! Quandry:Too little mass to accommodate so many states!

This has been a key reason to seek 'mechanisms for purification' already in the semi-classical regime.

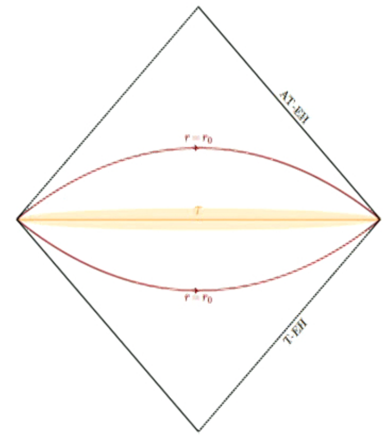
- Surprising Resolution: Semi-classical considerations show that as the area of the dynamical horizon (DH) shrinks, the (e.g. Kretsch = const.) 3-surfaces develop extremely long necks. As a solar mass BH shrinks to a lunar mass the neck grows from $\sim$ kms, to some $\sim 10^{55}$ light years in length! So the modes that have fallen in the DH get enormously stretched –become 'infrared'. They can easily hold a lot of correlations with outside modes even though they have very little total energy.

2.B Singularity Resolution by Quantum Geometry

• Analysis of Quantum Geometry effects near the singularity is more difficult than in cosmology because of the trapped region. A satisfactory effective theory in the LQG paradigm became available only recently. Key feature:



Singularity in Kruskal space-time is replaced by a space-like Transition surface τ to the past of which we have a (BH-type) trapped region and to the future of which we have a (WH-type) anti-trapped region. So τ has very interesting geometry: Both null expansions vanish on it!



• The effective metric $\bar{g}_{ab}$ is everywhere regular. For macroscopic BHs, Einstein's equations are satisfied to an excellent accuracy till very near τ. Then, LQG quantum geometry effects kick in and become very large (pink region). Curvature scalars have universal (mass independent) upper bounds.

Summary: Nature of Quantum Geometry

- The Big Bang and Black Holes offer ideal arenas to probe the *Structure of Quantum Space-time*. Both have been analyzed in Loop Quantum Gravity (LQG). The analysis has led to some striking features of quantum geometry:

(i) Quantum Geometry of LQG creates an effective 'repulsive force' once curvature scalars enter the Planck regime and dilutes it, replacing the classical singularity with a 'bounce'.

(ii) The singularity theorems of classical GR are evaded because Einstein's equations are modified. Interestingly, these modifications are completely negligible until one reaches the Planck regime: 1 part in 10^{-8} at the horizon of a $10^6 M_{\rm Pl}$ BH and 1 part in 10^{-12} at the 'onset' on inflation! But then they rise very quickly and overcome the tremendous classical attraction, diluting the curvature scalars and resolving the classical singularity.

(iii) Physical observables such as curvature scalars and matter density have absolute upper bounds for the Big-Bang and BHs, that arise systematically from the area gap.

(iv) Singularity resolution profoundly alters the conceptual paradigm through concrete effects. But manifestations of the quantum geometry responsible for this shift are indirect. Because of the 'filtering process', unless qualitatively new observational tools become available, we may never be able to directly know the precise state of the quantum geometry that replaces the classical singularity.

(v) Quantum Geometry manifests itself differently depending on the probes used:

$\star$ Fundamental level: Spin networks, Geometric operators, ...
(analogy: Full QED)
$\star$ If only a few DOF are relevant: States like $\Psi_\circ(v, a)$, Observables $\hat{\rho}$, $\hat{R}$, $\widehat{\text{anisotropy}}$, ... (analogy: Dirac's Hydrogen atom)
$\star$ When probed by quantum fields (cosmological perturbations or Hawking modes, Power spectrum, spectral index, Hawking quanta at $\mathcal{I}^+$, ...) (analogy: electrons in a laser beam.)

We have to use all these different manifestations of quantum geometry, emphasizing one over the other depending on the physics of the problem.