Title: Loop quantum gravity and bounces : cosmology and black hoes

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Abstract: In his talk I will review some recent results concerning the cosmological bounce in loop quantum gravity. In particular I will show how the predicted duration of inflation in affected by the choices of initial conditions, amount of shear and inflaton potential shape. Then I will show how those ideas can be used in black holes physics and comment on the associated phenomenology?

A remark on covariance in LQC

Following Olmo & singh

Can we find a covariant description of the modified Friedmann equation (whereas no new d.o.f is introduced) ?

Requiring second-order equations and covariance, one is uniquely led to the Einstein-Hilbert lagrangian → no ?

But, in formulations with actions involving higher order derivatives of the metric one assumes the compatibility of the spacetime connection with the metric.
→ Here Ashtekar-Barbero connection.
→ Metric-affine theory → Palatini (geodesics of the Levi-Civita connection)

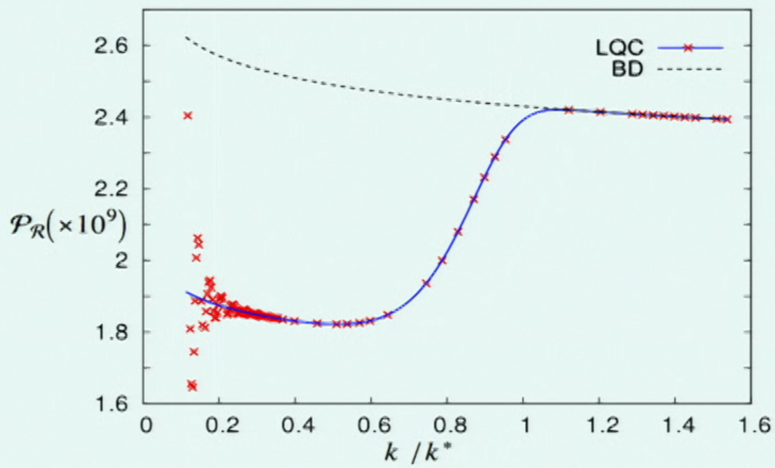
$$f(\mathcal{R}, \mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu}, \mathcal{R}_{\alpha\beta\gamma\delta}\mathcal{R}^{\alpha\beta\gamma\delta}, \ldots)$$

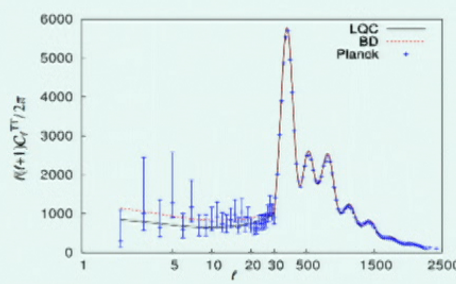
The field eq. have the same number of d.o.f. as GR. → the independent connection satisfies a constraint equation (rather than a dynamical evolution) → solution can be expressed as the Levi-Civita connection of an auxiliary metric.
→ In f(R), same configuration space as GR, but dynamics is different. The role of the Palatini lagrangian f(R) is just to change the way matter generates the spacetime curvature. (In metric formulation more degrees of freedom)

→ This inverse problem has been solved. (Non local)

Focus on the background
First a few words on perturbations

1) **Dressed metric approach (Ashtekar, Agullo, Nelson)**
Hybrid quantization (E. Wilson-Ewing)





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Focus on the background
First a few words on perturbations

2) Deformed algebra approach (initiated by Bojowald)

→ Emphasis on consistency and gauge issues taking into account the specificity of gravity.

- **Implement holonomy corrections (with some freedom) in the constrains**
- **Calculate the tensor, vector and scalar perurbations**
- **Add counterterms (with some freedom) vanishing in the classical limit**
- **Require all the anomalies to vanish → first class Dirac algebra**

→ There exists a solution. This solution is unique (under some hypotheses)
→ The solution works for all kind of pertubations
→ The solution is also found in other approaches using the longitudinal gauge
→ The solution agrees with the BKL conjecture and opens interesting possibilities for the emergence of time
→ The solution is encoded in a quite simple algebraic structure

$$\begin{aligned}
\{D_{tot}[N_1^a], D_{tot}[N_2^a]\} &= 0, \\
\{H_{tot}[N], D_{tot}[N^a]\} &= -H_{tot}[\delta N^a \partial_a \delta N], \\
\{H_{tot}[N_1], H_{tot}[N_2]\} &= D_{tot}\left[\Omega \frac{\bar{N}}{\bar{p}} \partial^a (\delta N_2 - \delta N_1)\right]
\end{aligned}$$

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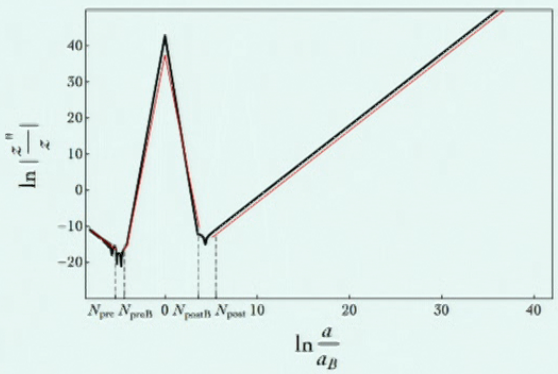
Focus on the background
First a few words on perturbations

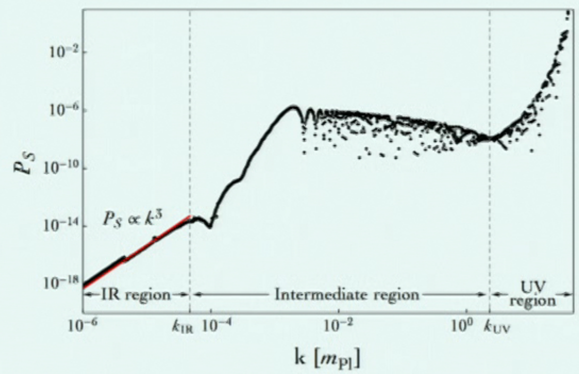
The tensor power spectrum was shown to be incompatible with data. Exponential UV groth. Fine-tuning the initial conditions does not solve the problem (deflation appears).

Recently, we have calculated the scalar power spectrum

$$\frac{z''}{z} = -a^2\left(m^2 - 2H^2 + 2\kappa m^2 \frac{\bar{\phi}\dot{\bar{\phi}}}{H} + \frac{7}{2}\kappa\Omega\dot{\bar{\phi}}^2 - \kappa^2\Omega^2\frac{\dot{\bar{\phi}}^4}{2H^2} - 3\kappa\frac{\dot{\bar{\phi}}^4}{\rho_c}\right).$$

$$\ddot{\mathcal{R}}_k - \left(3H + 2m^2\frac{\bar{\phi}}{\dot{\bar{\phi}}} + 2\frac{\dot{H}}{H}\right)\dot{\mathcal{R}}_k + \Omega\frac{k^2}{a^2}\mathcal{R}_k = 0.$$





→ Transplanckian effects
→ MDR change the game
(Brandenberger et al.)

$$k^2 \rightarrow k^2_{\rm eff}(k,\eta) \equiv a^2(\eta)\omega^2_{\rm phys}\left[\frac{k}{a(\eta)}\right]$$

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Back to the background.
Singularity resolution in LQC: robustness

Following P. singh

- Exactly solvable model (flat, isotropic with a massless scalar)
- In presence of spatial curvature k = ±1
- Bianchi models
- Negative cosmological constant
- Positive cosmological constant
- φ2 inflationary potential
- Extremely wide states not corresponding to a classical universe at late times
- Non-gaussian and highly squeezed states corresponding to highly quantum universes
- For a wide range of equations of states for barotropic matter

Under quite general conditions conditions, the quantum evolution can be approximated by a continuum effective spacetime description

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A few words on GFT and QRLG on this issue

Most attemps converge to the same result.

$$\left(\frac{\dot{a}}{a}\right)^2 = (8\pi G\,\rho/3)\left(1 - \frac{\rho}{\rho_{\rm crit}}\right)$$

Group field theories (GFTs) are quantum field theories on a group manifold, characterized by a peculiar type of combinatorially non-local interactions.

The Universe as a condensate (Oriti, Gielen, Wilson-Ewing et al.)

A recent derivation in GFT also confirms this dynamics.

$$\left(\frac{V'}{3V}\right)^2 = \frac{4\pi G}{3}\left(1 - \frac{\rho}{\rho_c}\right) + \frac{V_{j_o}E_{j_o}}{9V}$$

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A few words on GFT and QRLG on this issue

In QRLG the situation is slightly different (Alesci et al.).

Intuitively, in QRLG one quantizes before performing the symmetry reduction but the price to pay is a gauge fixing.

QRLG is based on implementing in the kinematical Hilbert space of LQG the gauge conditions imposing diagonal metric tensor and triads. This leads to a reduced Hilbert space, whose elements are based at cuboidal graphs and described at links by U(1) group elements, projected from SU(2) ones.

$$b = \gamma \frac{\dot{a}}{a} \qquad v = \mathcal{V}_0 \frac{a^3}{2\pi\gamma}$$

$$H_{QRLG} = -\frac{3v}{4\Delta\gamma} \sin^2(b\sqrt{\Delta}) + \frac{P_\phi^2}{4\pi\gamma v} - \frac{b^2\Delta^{3/2}}{24\pi\gamma^2} \cos(2b\sqrt{\Delta})$$

$$\rho_{\rm g} = -\frac{\Delta^{3/2}b^2}{9V}, \quad \bar{\rho}_{\rm cr} = -\frac{1}{\Delta}, \quad \Omega_{\rm g} = -\Delta\,\rho_{\rm g} = \frac{\rho_{\rm g}}{\bar{\rho}_{\rm cr}}, \quad \Omega_{\rm m} = \frac{\rho_{\rm m}}{\rho_{\rm cr}}.$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \left(\frac{8\pi}{3}\rho_{\rm m} + \frac{\rho_{\rm g}}{\gamma^2}\right)(1-2\Omega_{\rm g})^{-1}\left(1 - \frac{\Omega_{\rm m}-\Omega_{\rm g}}{1-2\Omega_{\rm g}}\right) \left(1 + \frac{2\Omega_{\rm g}}{b\sqrt{\Delta}}\cot(2b\sqrt{\Delta}) - 2\Omega_{\rm g}\right)^2. \quad (17)$$

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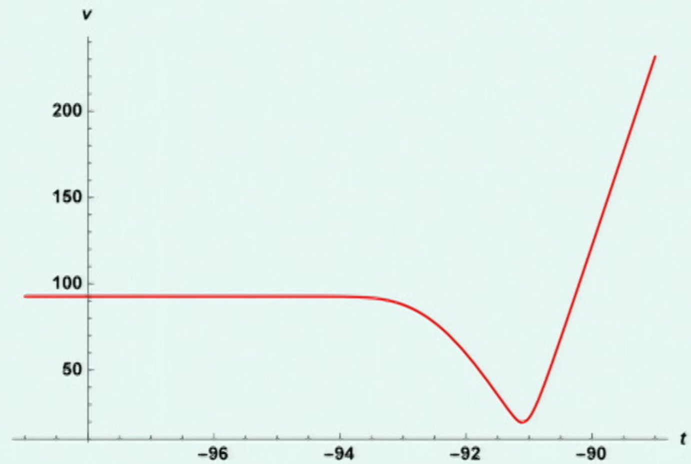
A few words on GFT and QRLG on this issue



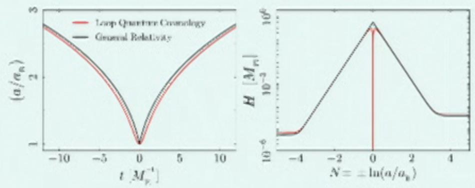
But … This raises conceptual issues ! How to make sense of the volume ?

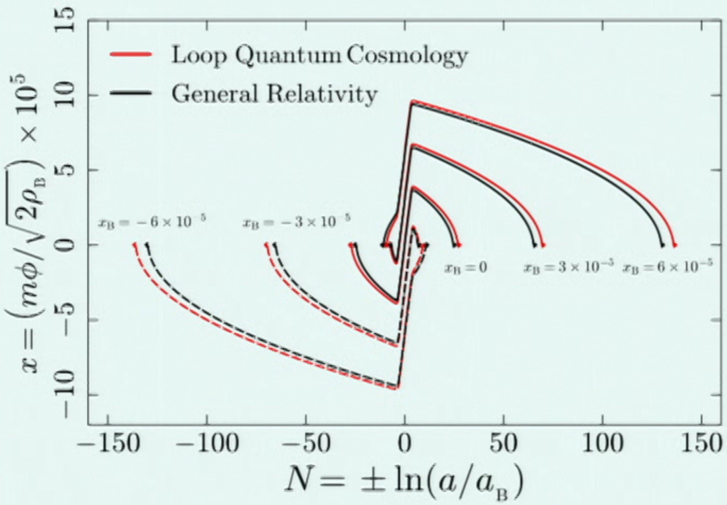
$$H_{QRLG} = -\frac{3v}{4\Delta\gamma}\sin^2(b\sqrt{\Delta}) + \frac{P_\phi^2}{4\pi\gamma v} - \frac{b^2\Delta^{3/2}}{24\pi\gamma^2}\cos(2b\sqrt{\Delta})$$

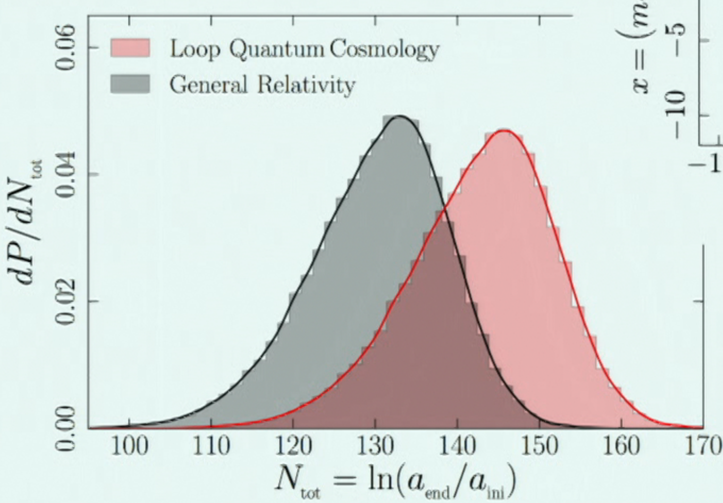
News on the background : a detail

Importance of the details of the LQC modification ?

(An interesting connection with the Gibbons & Turok calculation.)

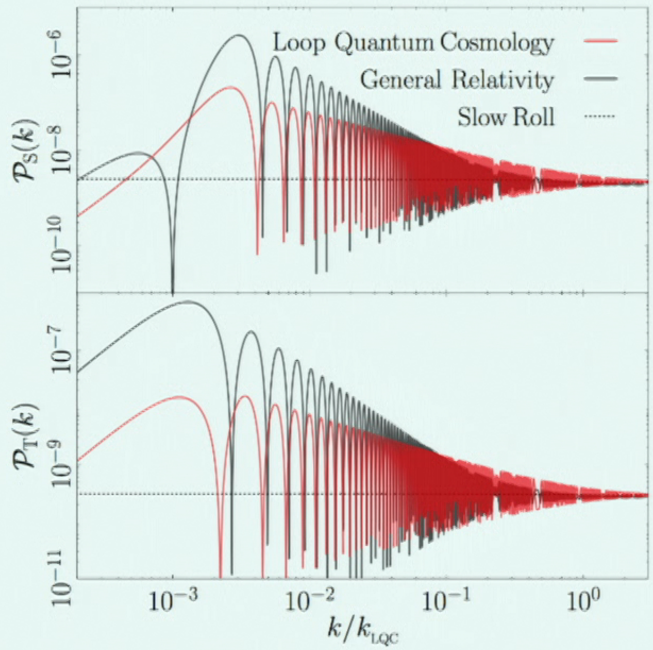






News on the background : a detail

Effects can also be calculated for the spectra



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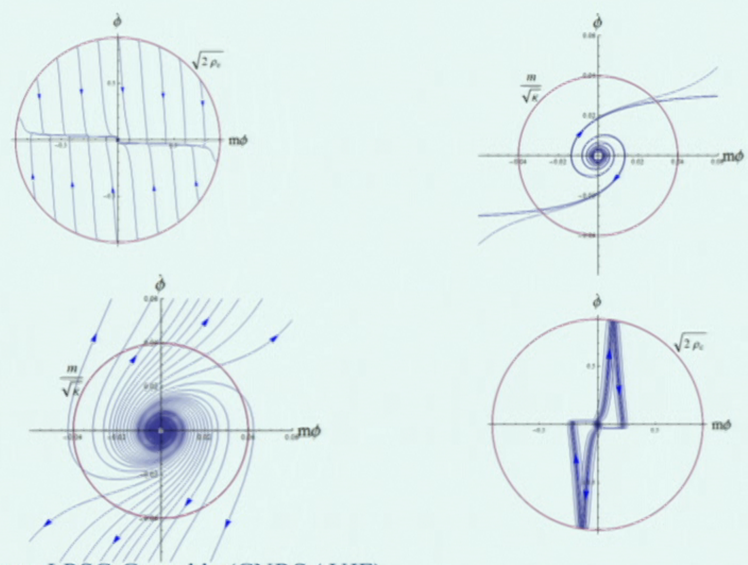
News on the background : systematic investigation

We estimate the duration of inflation varying:

- **The amount of shear**
- **The shape of the inflaton potential**
- **The initial conditions**

A reminder on initial conditions



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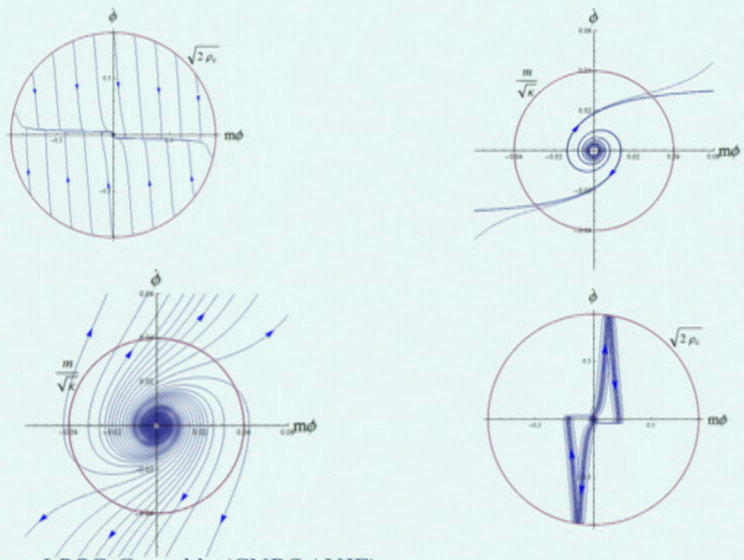

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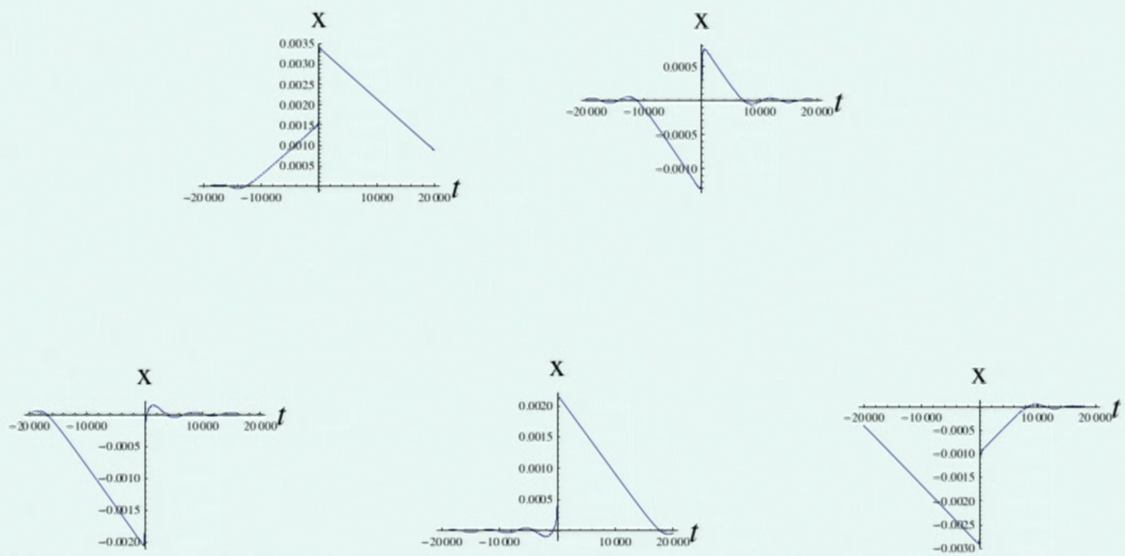
Everything is possible in LQC !



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News on the background : systematic investigation

Equations for the Bianchi-I LQC background

$$H^2 = \sigma_Q^2 + \frac{\kappa}{3}\rho - \lambda^2\gamma^2\left(\frac{3}{2}\sigma_Q^2 + \frac{\kappa}{3}\rho\right)^2,$$

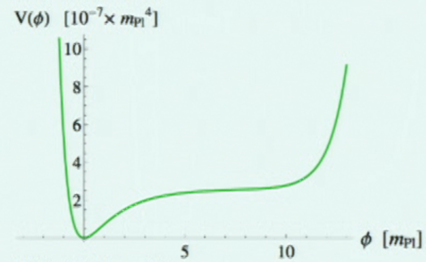
$$\sigma_Q^2 := \frac{1}{3\lambda^2\gamma^2}\left(1 - \frac{1}{3}\left[cos(h_1 - h_2) + cos(h_2 - h_3) + cos(h_3 - h_1)\right]\right).$$

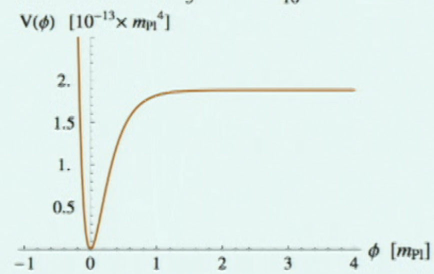
Potentials :

$$V(\Phi) = \frac{1}{2}m^2\Phi^2. \qquad V(\Phi) = \Lambda^3\Upsilon|\Phi|,$$

$$V(\Phi) \simeq \frac{C_2}{\langle\nu\rangle^{10/3}}\left[(3 - R) - 4(1 + \frac{1}{6}R)e^{-\frac{\Phi}{\sqrt{3}}} + (1 + \frac{2}{3}R)e^{-\frac{4\Phi}{\sqrt{3}}} + Re^{\frac{2\Phi}{\sqrt{3}}}\right],$$

$$V(\Phi) = \frac{3m^2}{4\kappa}\left(1 - e^{-\sqrt{\frac{2\kappa}{3}}\Phi}\right)^2.$$





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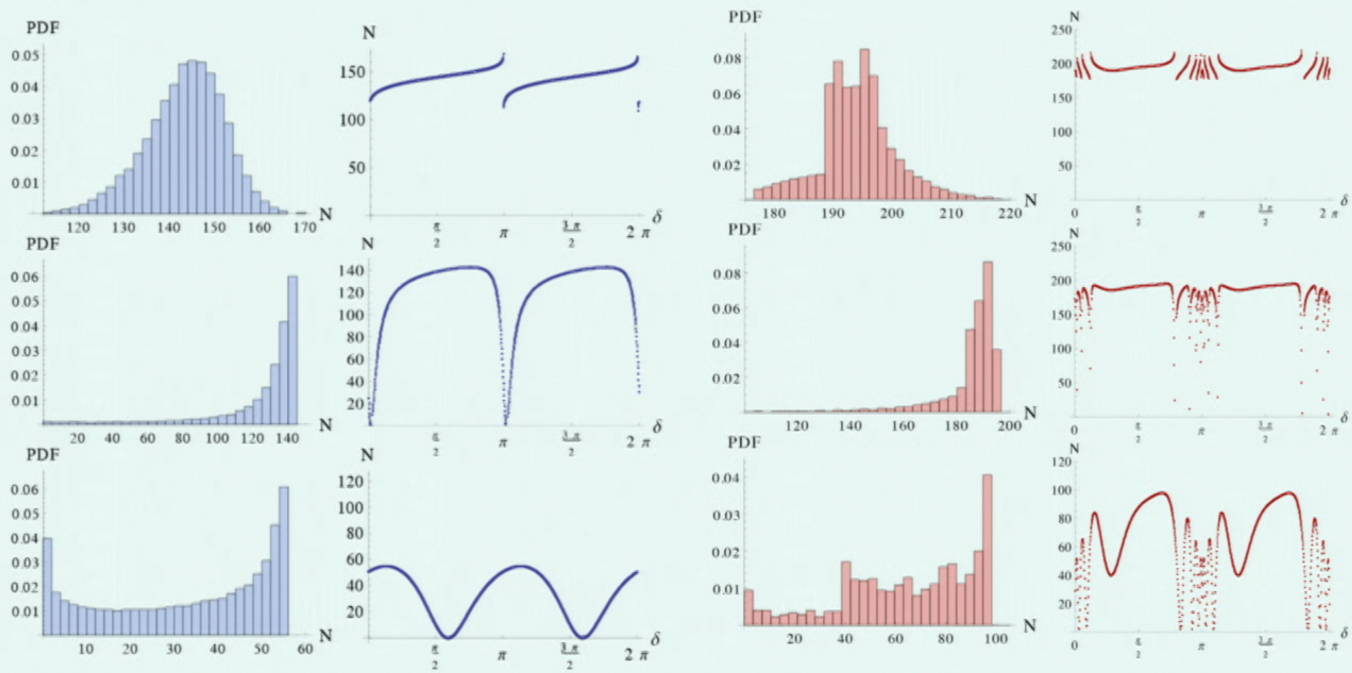
News on the background : systematic investigation

IC in the remote past



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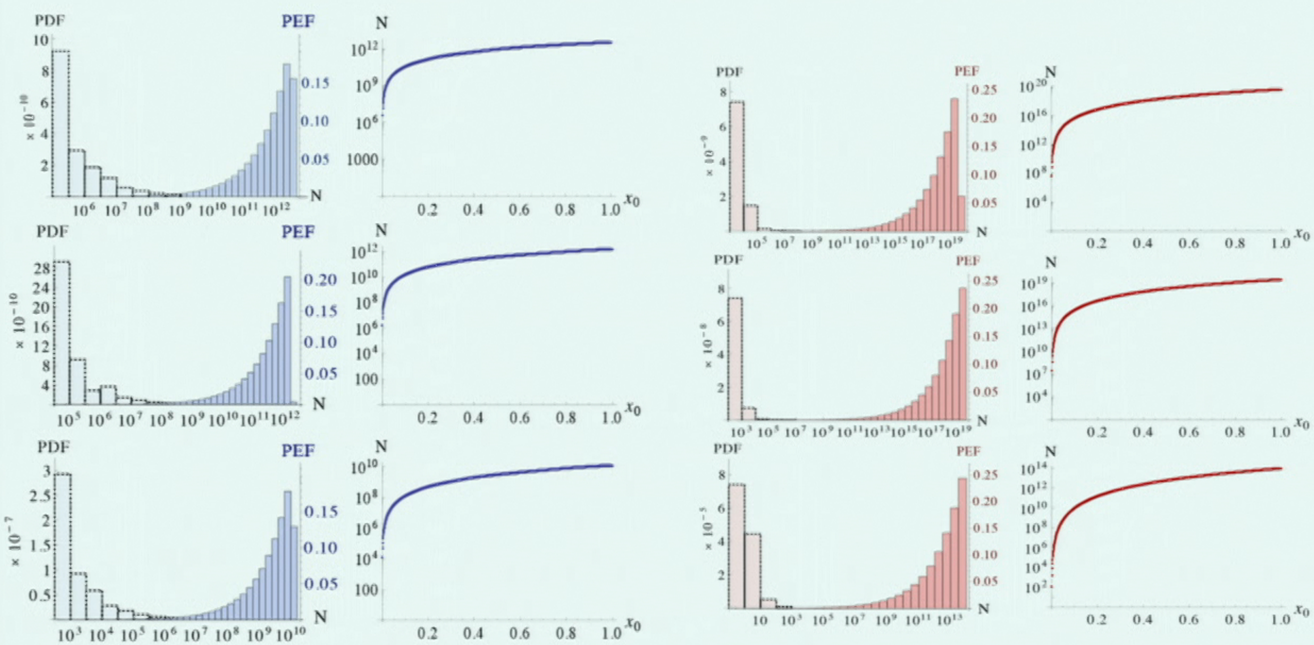
IC in at the bounce



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Initial conditions :

If the word "initial" is taken in its literal sense, it is certainly reasonable to set IC in the remote past and respect the causal evolution of the system. The evolution across the bounce is not time symmetric.

It seems that assigning a flat PDF to the phase of the field in the remote past of the contracting branch is a better choice than assigning a flat PDF to the fraction of potential energy at the bounce. Because :

1) the vicinity of the bounce is the most "quantum" period in the history of the Universe.
2) a flat PDF for the fraction of potential energy is a completely arbitrary choice.
3) a flat PDF assigned to the phase is preserved over time.

There are two kinds of "predictive powers" that need to be distinguished at this stage:

- "weak predictive power" : the PDF for the number of e-folds is known.
- "strong predictive power" : the number of e-folds of inflation is (roughly) known. This requires that the PDF is not only known (that is, the weak case) but also requires that it is highly peaked.

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Conclusions :

(i) As far as the capability of the model to predict the distribution of the number of e-folds is concerned, it is more appealing to set initial conditions in the remote past of the classical contracting branch of the Universe.

(ii) Furthermore, in this case, the duration of inflation is indeed severely constrained, and most interestingly to values which are not much higher than the minimum value required by observations (but only for "confining" potentials).

(iii) When anisotropies are taken into account the PDF of the number of e-folds is widened and its mean value decreases confirming the strong predictive power of LQC for a massive scalar field.

(iv) For potentials with a plateau such that the favored value of the amount of potential energy at the beginning of the slow-roll phase is larger than the height of the plateau, the predicted number of e-folds can become very large and the predictive power is only weak.

(v) When the potential is asymmetric, the PDF can become bimodal.

(vi) When initial conditions are set at the bounce, even the weak predictive power of LQC is basically lost as everything is then determined by the arbitrary choice of the variable to which a known PDF is assigned.

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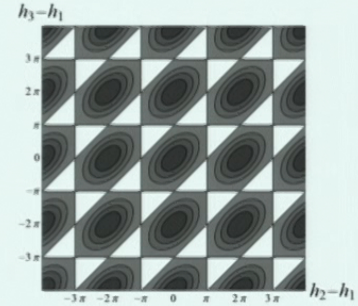
if the shape of the inflaton potential can be experimentally determined (this is already partially the case) and if, following the logics of causality, the initial conditions are set in the remote past, there is an obviously interesting predictive power of LGC for the duration of inflation.

This predictive power is strong if the potential is confining and weak if the potential has a plateau-like shape. It is not so because of the specific quantum dynamics but because of the existence of a preferred amount of potential energy at the onset of inflation which is naturally selected by the semiclassical trajectory.

The most difficult point to address remains the one of anisotropies as no simple physical argument allows one to choose a preferred amount of shear. If the potential is confining enough this is however not necessarily a problem as the predicted number of e-folds is then restricted to a quite small interval which happens to be the most interesting one for phenomenology.

→ Shear IC @ the bounce ?



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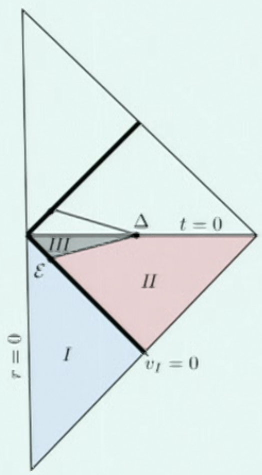
Bouncing black holes

Basic idea (Rovelli, Vidotto, Haggard)



There might be a classical metric satisfying the Einstein equations outside a finite spacetime region where matter collapses into a black hole and then emerges from a white hole. A black hole can thus quantum-tunnel into a white hole. For this to happen, quantum gravity should affect the metric also in a small region outside the horizon: this is not forbidden by causality or by the semiclassical approximation, because quantum effects can pile up over a long time.

$$\tau = -8m \ln v_o > \tau_q = 4k \frac{m^2}{l_p}$$

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Bouncing black holes

Fully quantum LQG calculation (Christodolou, Rovelli, Speziale, Vilensky)

Quantum bounce is non perturbative → not captured by small quantum fluctuations around a classical solution of GR → can only be described by a background-free quantum theory of gravity.
LQG provides a non-perturbative definition of QG which is tailor-made for this calculation, because in its covariant formulation it associates an amplitude to any compact region of spacetime, as a function of the boundary geometry. In a Planck star bounce, we know the initial and final geometry, no classical solution interpolates between the two, and we need the probability for a quantum transition from the first to the second. This is precisely what the amplitudes of covariant LQG provides.
This is also a concrete example of how a background-free quantum theory of gravity can be used to predict observable quantities.

$$W(m,T) = \sum_{\{j_a, j_{ab}^{\pm}\}} w(z_0, z_{\pm}, j_a, j_{ab}^{\pm})\, (-1)^{\sum_{\ell\in\Gamma} j_\ell} \times \sum_{\{J_a^{\pm}, K_a^{\pm}, l_a, l_{ab}^{\pm}\}} \left(\bigotimes_{a,\pm} \delta_{j_a l_a} N^{J_a^{\pm}}_{\{j_a^{\pm}\}}(\nu_{\ell\in a^{\pm}})\, f^{J_a^{\pm}, K_a^{\pm}}_{\{j_a^{\pm}\}\{l_a^{\pm}\}} \right) \left(\bigotimes_{a,\pm} i^{K_a^{\pm}, \{l_a^{\pm}\}} \right)$$

where the weight function is

This supports τ ~ m^2

$$w(z_0, z_{\pm}, j_a, j_{ab}^{\pm}) = c(\eta, \eta_0) \left(\prod_a d_{j_a} e^{-\frac{1}{2\eta}(j_a - \frac{(2\eta^2-1)}{2})^2} e^{i\gamma\zeta j_a} \right) \left(\prod_{ab,\pm} d_{j_{ab}^{\pm}} e^{-\frac{1}{2\eta_0}(j_{ab}^{\pm} - \frac{(2\eta_0^2-1)}{2})^2} e^{i\gamma\zeta_0 j_{ab}^{\pm}} \right)$$

with

$$c(\eta, \eta_0) = \left(e^{\frac{1}{2\eta_0}\left(\frac{(2\eta_0^2-1)}{2}\right)^2} \right)^4 \left(e^{\frac{1}{2\eta}\left(\frac{(2\eta^2-1)}{2}\right)^2} \right)^{12}$$

Phenomenology of Bouncing black holes

Taking the lower bound on k :

$$m = \sqrt{\frac{t_H}{4k}} \sim 1.2 \times 10^{23} \text{ kg}$$

$$R = \frac{2Gm}{c^2} \sim .02 \text{ cm}$$

$$E = mc^2 \sim 1.7 \times 10^{47} \text{ erg}$$

Two possible components :
- Low energy (driven by size)
- High energy (driven by history)

The low energy component might be related with FRB.
→ PACS abd SPIRE in Herschel

The high energy component is around a TeV
→ CTA

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Phenomenology of Bouncing black holes

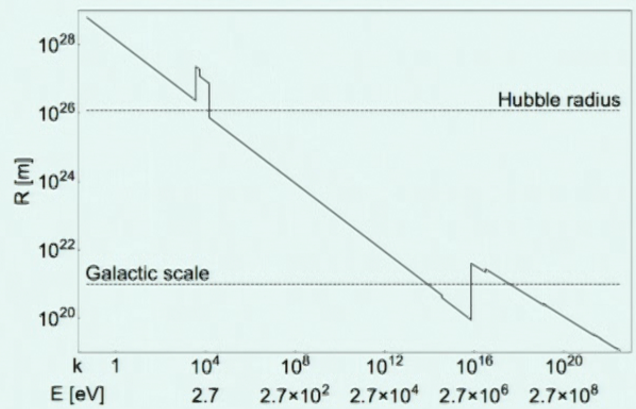
A closer look

1) Single event detection, varying k

When k increases <E> increases but for different reasons

The max distance depends on
-The size of the detector
-The absorption during the propagation over cosmological distances.
-The number of measured photons required for the detection to be statistically significant

Low energy component :



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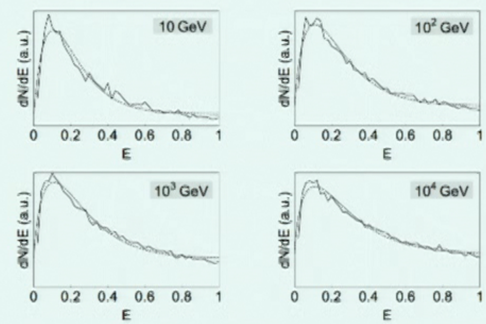
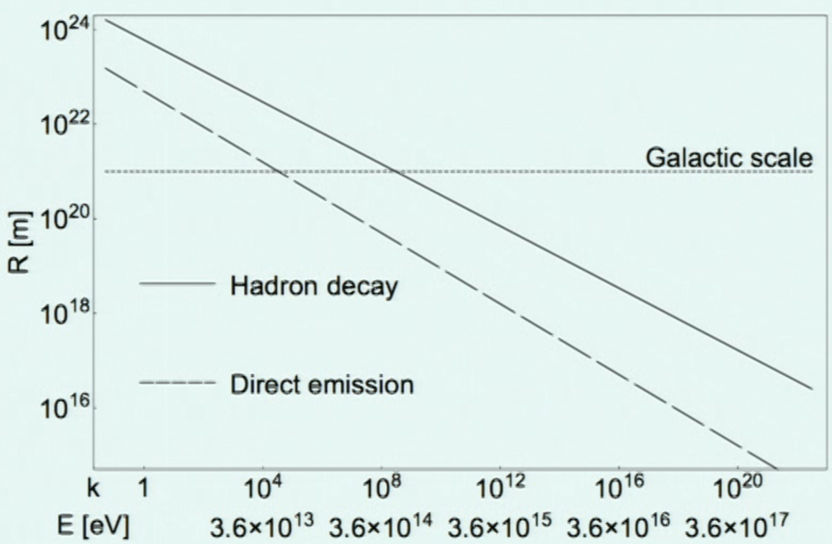
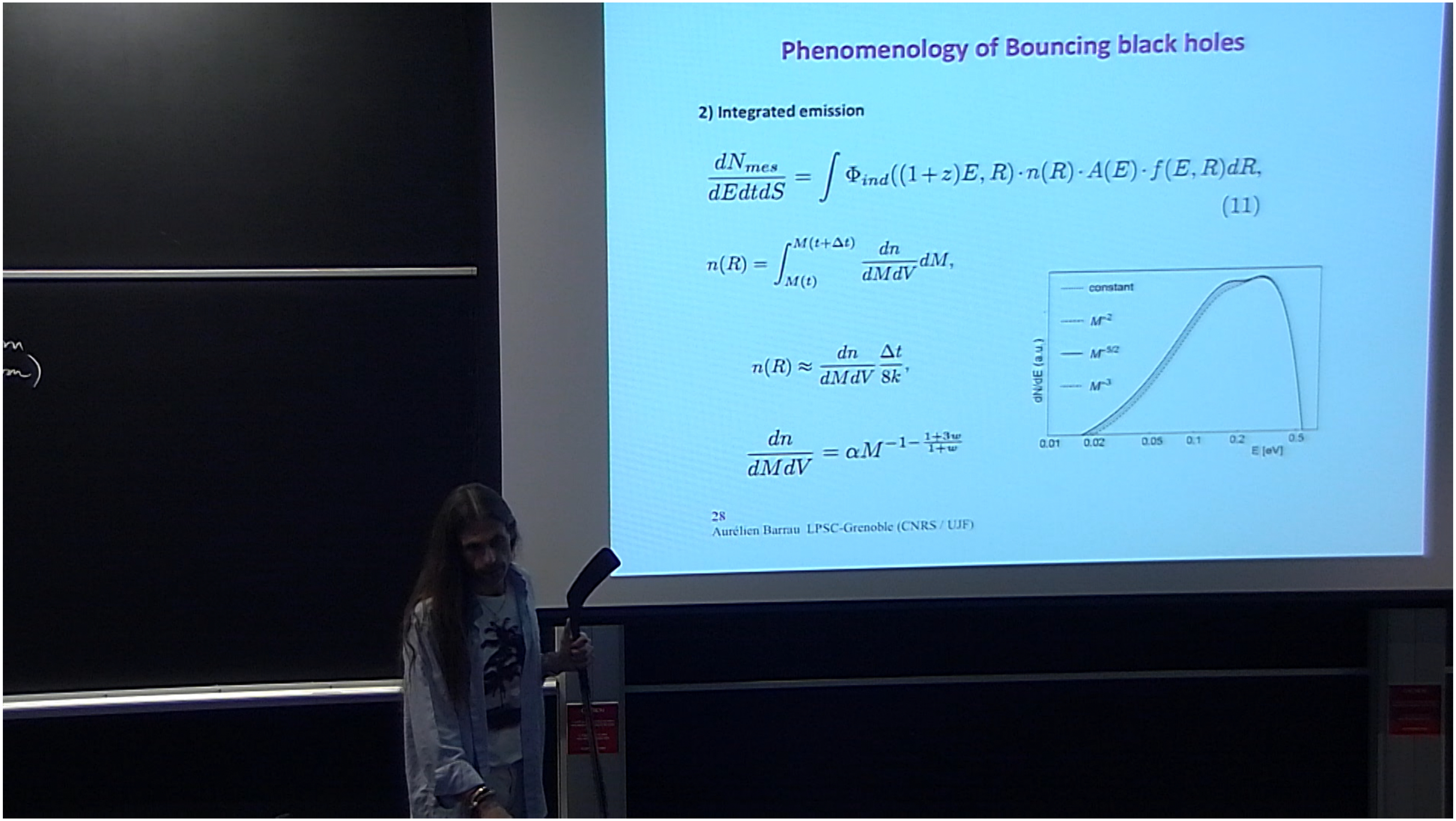
Phenomenology of Bouncing black holes

High energy component :

Full Monte-Carlo simulation






Phenomenology of Bouncing black holes
2) Integrated emission
$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E, R) \cdot n(R) \cdot A(E) \cdot f(E, R) dR, \quad (11)$$
$$n(R) = \int_{M(t)}^{M(t+\Delta t)} \frac{dn}{dMdV} dM,$$
$$n(R) \approx \frac{dn}{dMdV} \frac{\Delta t}{8k},$$
$$\frac{dn}{dMdV} = \alpha M^{-1-\frac{1+3w}{1+w}}$$
constant
M^{-2}
$M^{-5/2}$
M^{-3}
dN/dE (a.u.)
0.01
0.02
0.05
0.1
0.2
0.5
E [eV]
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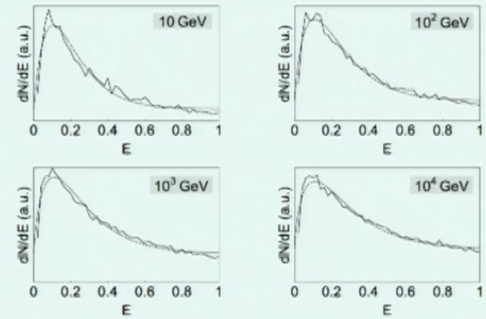
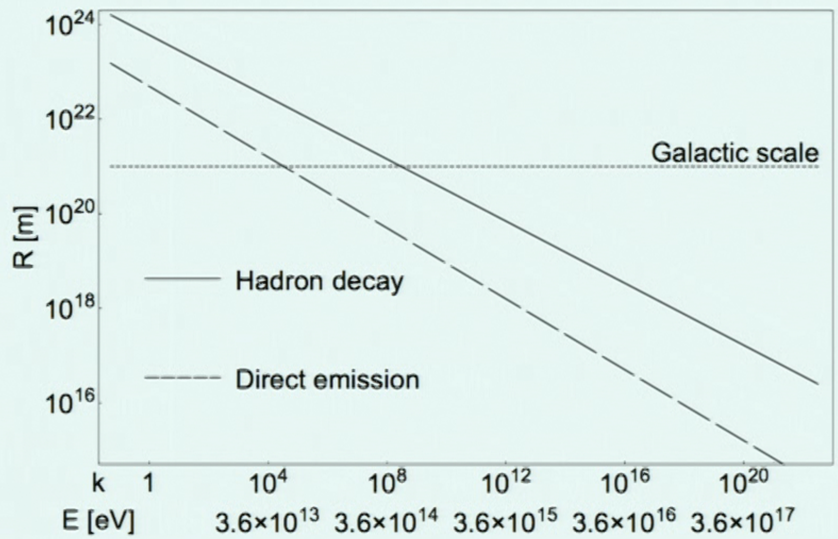
Phenomenology of Bouncing black holes

High energy component :

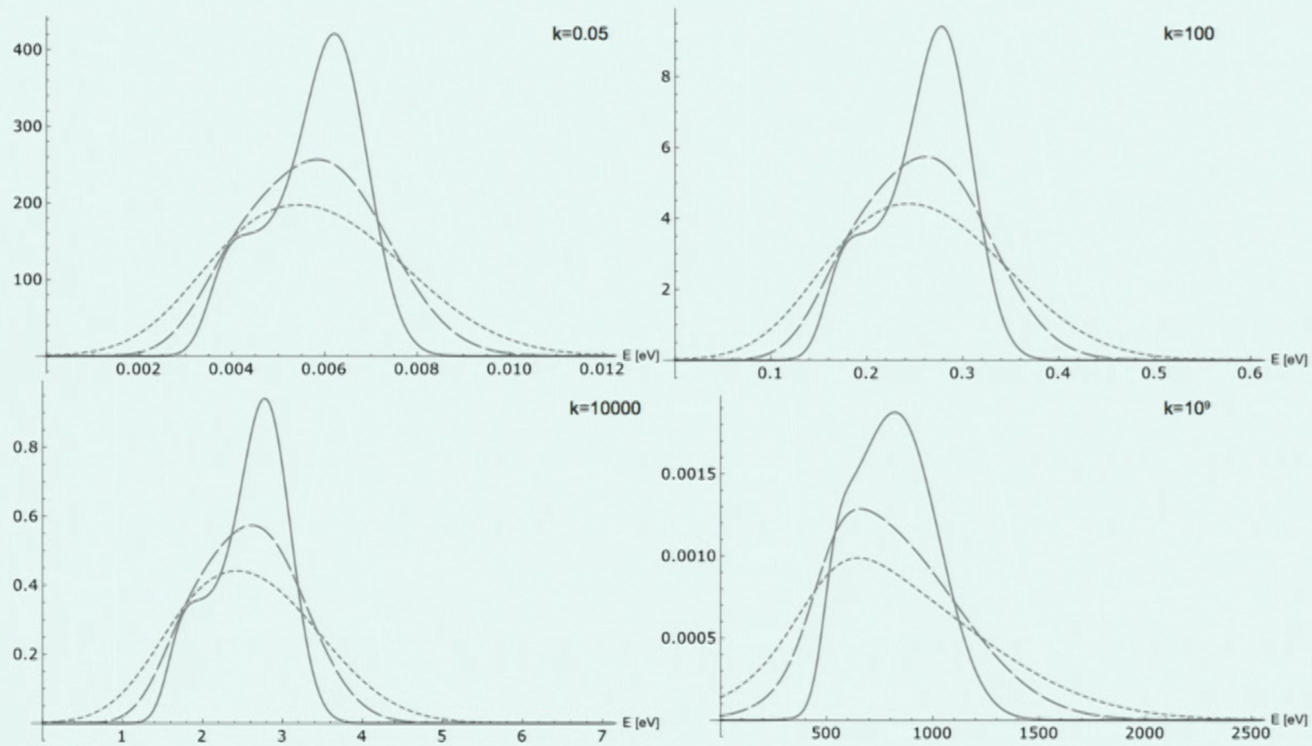
Full Monte-Carlo simulation





Phenomenology of Bouncing black holes

Low energy component :



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Phenomenology of Bouncing black holes

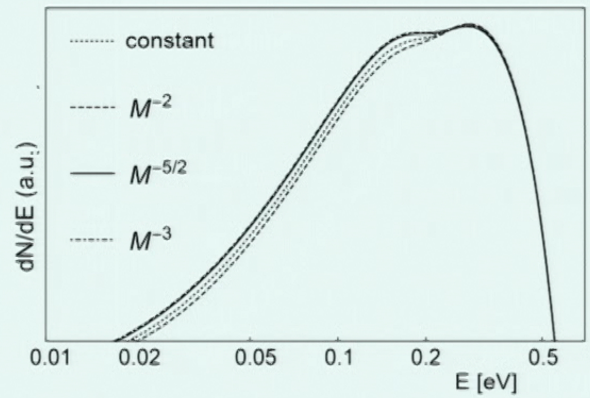
2) Integrated emission

$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E, R) \cdot n(R) \cdot A(E) \cdot f(E,R) dR, \quad (11)$$

$$n(R) = \int_{M(t)}^{M(t+\Delta t)} \frac{dn}{dMdV} dM,$$

$$n(R) \approx \frac{dn}{dMdV} \frac{\Delta t}{8k},$$

$$\frac{dn}{dMdV} = \alpha M^{-1-\frac{1+3w}{1+w}}$$



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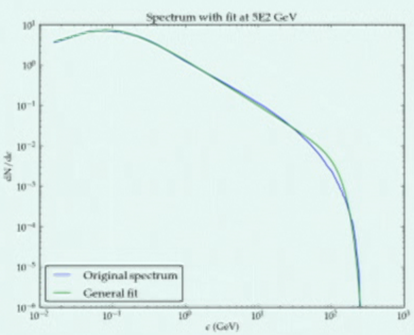
Phenomenology of Bouncing black holes

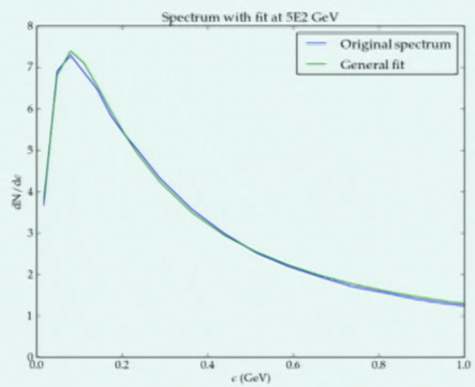
Fermi excess

To have an emitted energy of the order of 1 GeV, that is of order 1E−19 E_Pl, the size of the black hole should be of the order of 1E19 L_Pl and its mass of the order M ~ 1E19M_Pl. The Hubble time is tH ~ 1E60 t_Pl. Requiring the Hubble time to be equal to the bouncing time leads to k ~ 1E22. How does this compare with the Hawking time? The Hawking time is of the order of 1E60 t_Pl for the mass we are interested in. This is of the same order of magnitude than the bouncing time. This is not a random value of k.

the high-energy component of the signal emitted by bouncing black holes cannot explain the Fermi excess but the low-energy component might do so if the free parameter k is chosen near its highest possible value.



$$f(E,\epsilon)=\frac{a\epsilon^b}{\pi\gamma}\left[\frac{\gamma^2}{(\epsilon-\epsilon_0)^2+\gamma^2}\right]e^{-\left(\frac{4\epsilon}{E}\right)^3},$$



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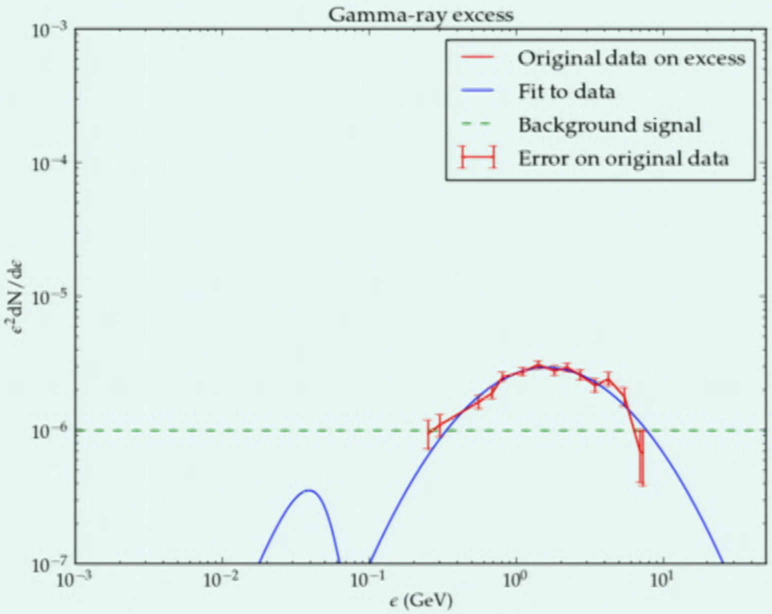
$$Ae^{-\frac{(\epsilon-E)^2}{2\sigma^2}} + 3N\sqrt{2\pi}A\sigma f(E,\epsilon),$$



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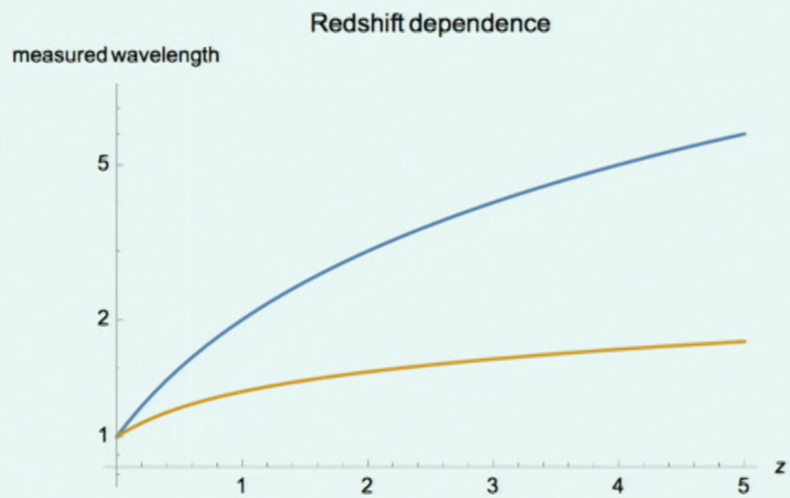
$$\lambda_{obs}^{BH} \sim \frac{2Gm}{c^2}(1+z) \quad \times \qquad (5)$$
$$\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]},$$



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Conclusion

LQC/LQG bounces (cosmology/black holes) lead to an interesting phenomenology.

Important conceptual and technical questions are still open.

Background dynamics is about to be understood.

Dealing with perturbations in a consensual way is hard.

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