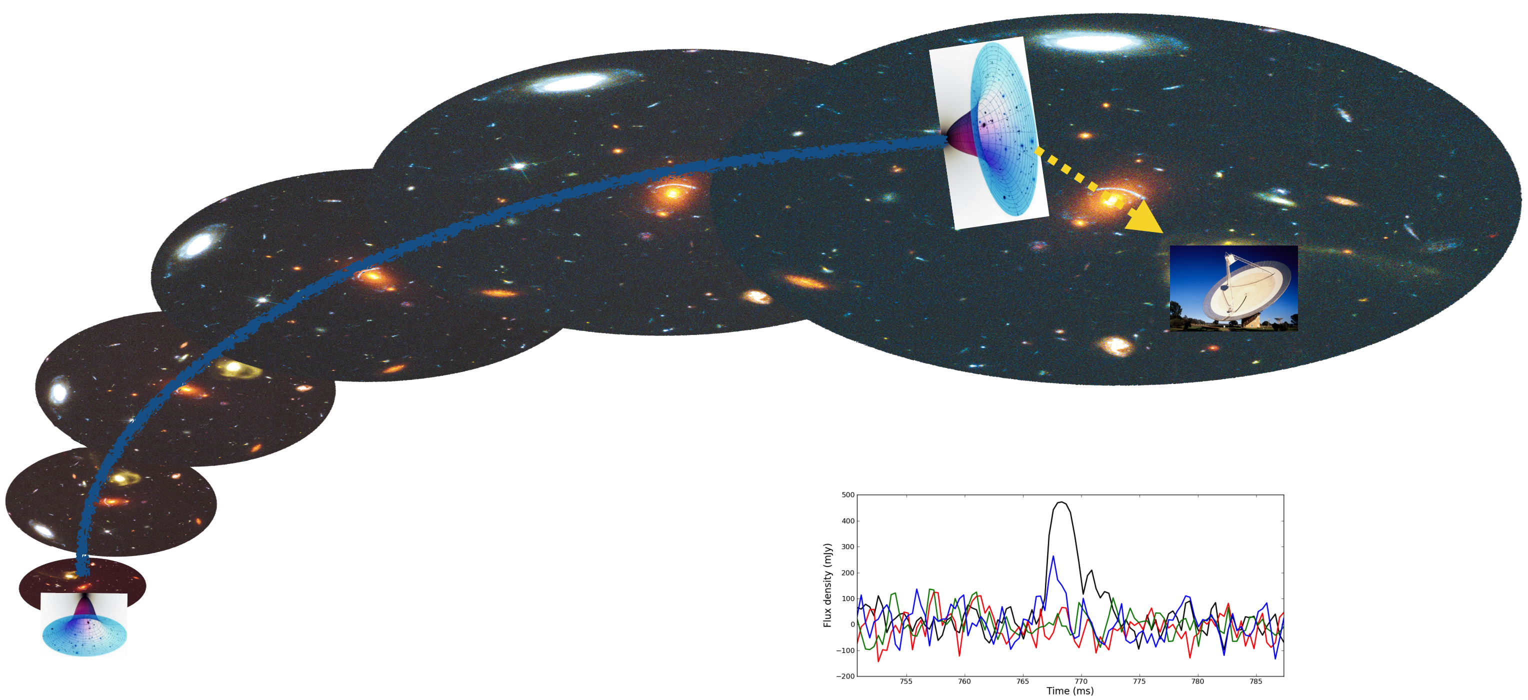
A possible observable quantum-gravity phenomenon:

Planck stars (exploding black holes)

Carlo Rovelli



i. Why black holes can explode

Because quantum **tunnelling** allow them to explode

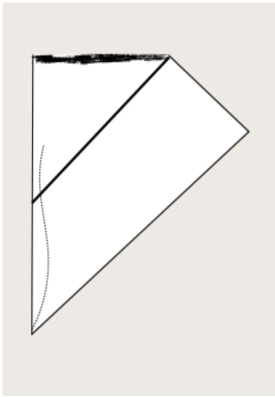
ii. How long does it take a black hole to explode

T can be computed in Loop Quantum Gravity. Indication: **$T \sim m^2$.**

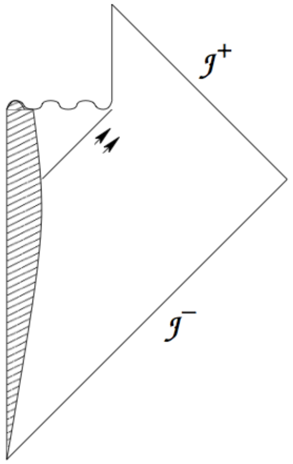
iii. Can we observe a black hole explosion?

Yes.
We might even have already observed explosions of primordial holes in **Fast Radio Bursts**.
We can soon find out, because of **flattened Red Shift**.

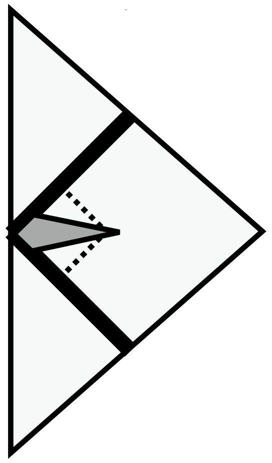
In (the approximation given by) **classical general relativity**, a black hole is stable.



In **quantum field theory on a classical gravitational field**, a black hole decays via Hawking radiation, in an extremely long time. (10^{50} Hubble times, for a stellar bh.)

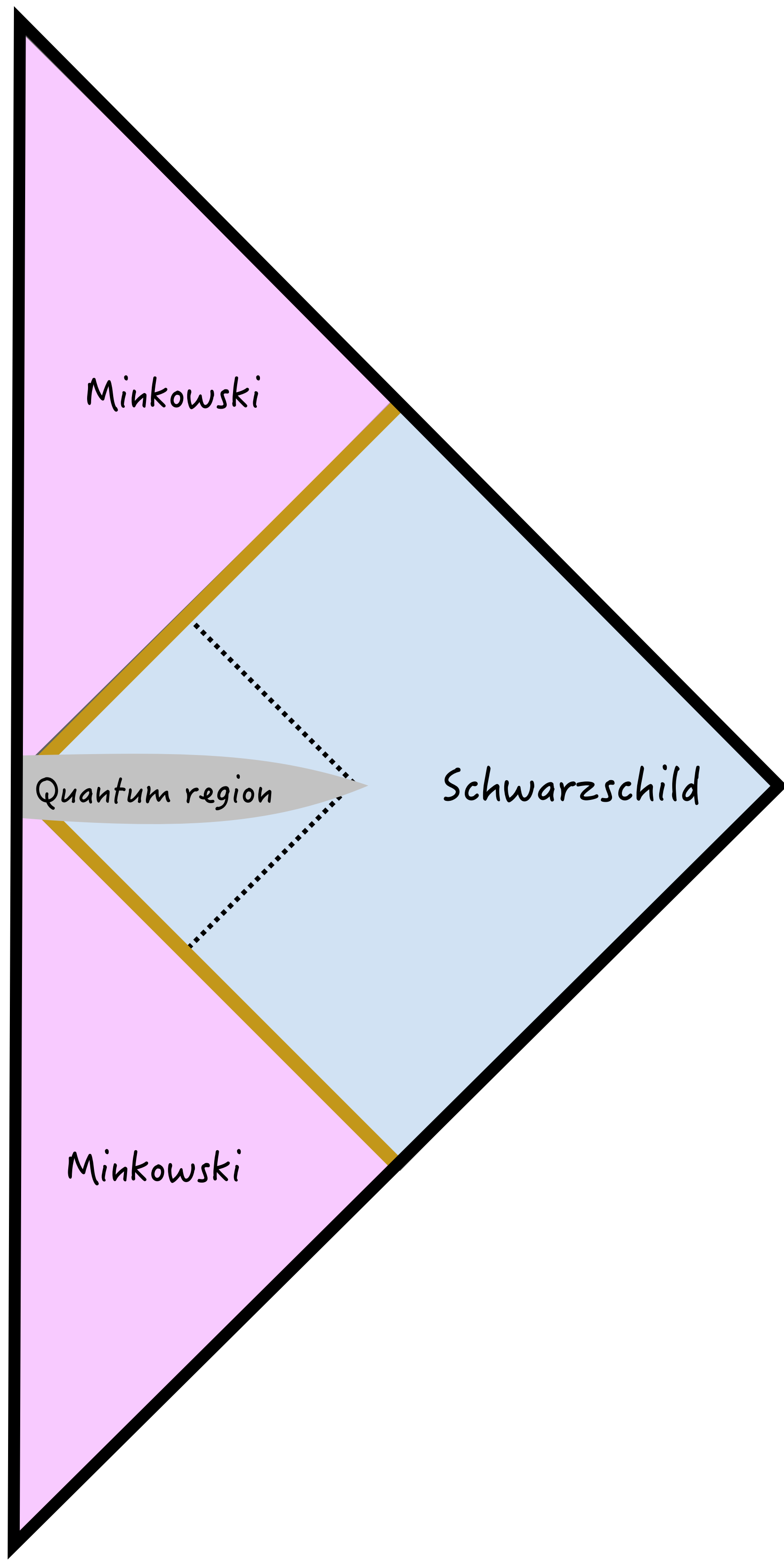


In **quantum gravity**, a black hole can decay via a non perturbative quantum tunnelling.



Frolov, Vilkovinski ’79, Stephen, t’Hooft, Whithing ’93,
Ashtekar, Bojowald ’05, Hayward ’06, Kiefer Hájíček 06, …

Planck stars
Carlo Rovelli, Francesca Vidotto
Int. J. Mod. Phys. D23 (2014) 12, 1442026



$$ds^2 = -F(u,v)dudv + r^2(u,v)(d\theta^2 + sin^2\theta d\phi^2)$$

Region I (Flat):

$$F(u_I, v_I) = 1, \qquad r_I(u_I, v_I) = \frac{v_I - u_I}{2}.$$

$$v_I < 0.$$

Region II (Schwarzschild):

$$F(u,v) = \frac{32m^3}{r} e^{\frac{r}{2m}} \qquad \left(1 - \frac{r}{2m}\right) e^{\frac{r}{2m}} = uv.$$

Matching:

$$u(u_I) = \frac{1}{v_o}\left(1 + \frac{u_I}{4m}\right) e^{\frac{u_I}{4m}}.$$

The metric is determined by two constants: m, T

Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling
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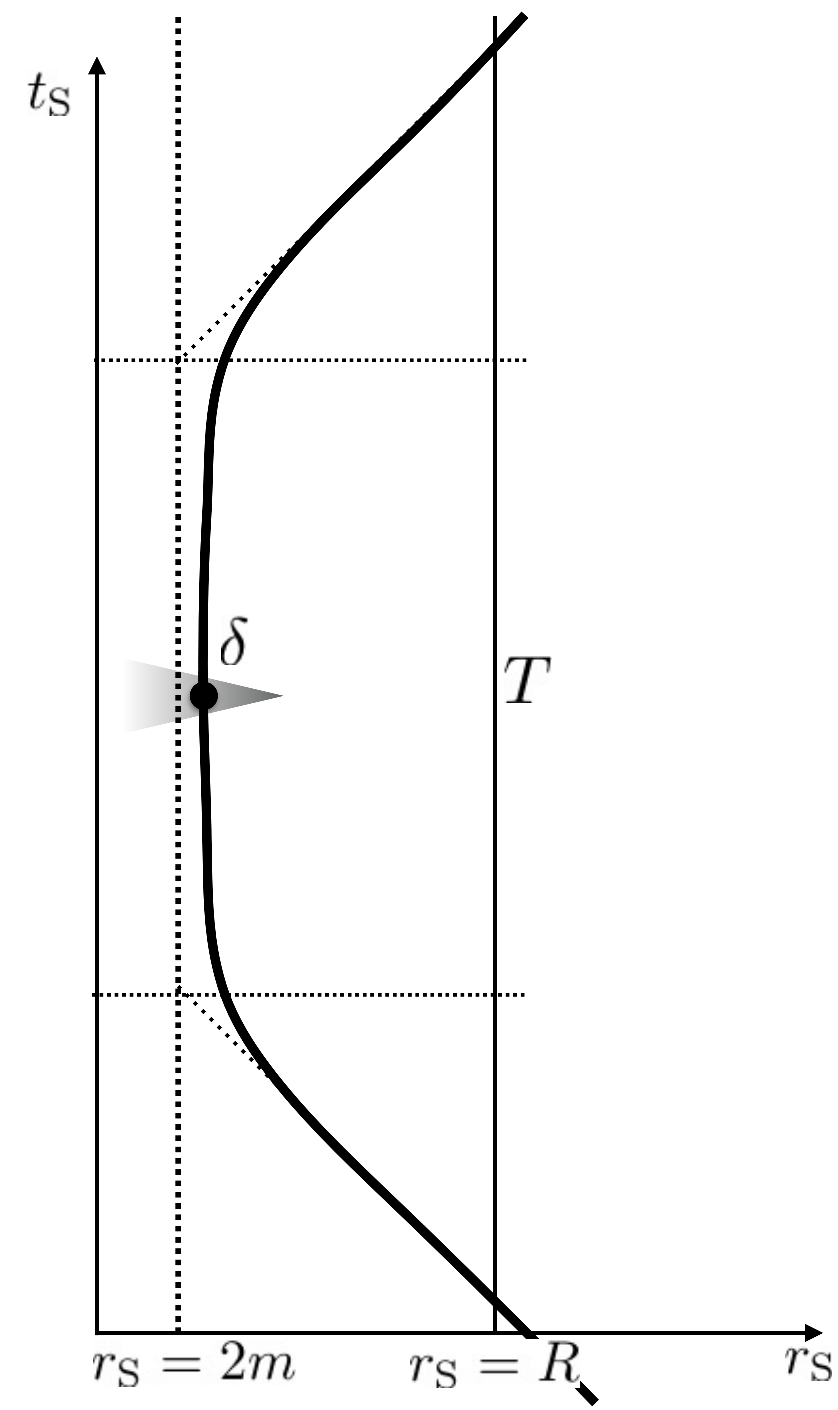
Phys. Rev. D.92.104020.

The external metric is determined by two constants:

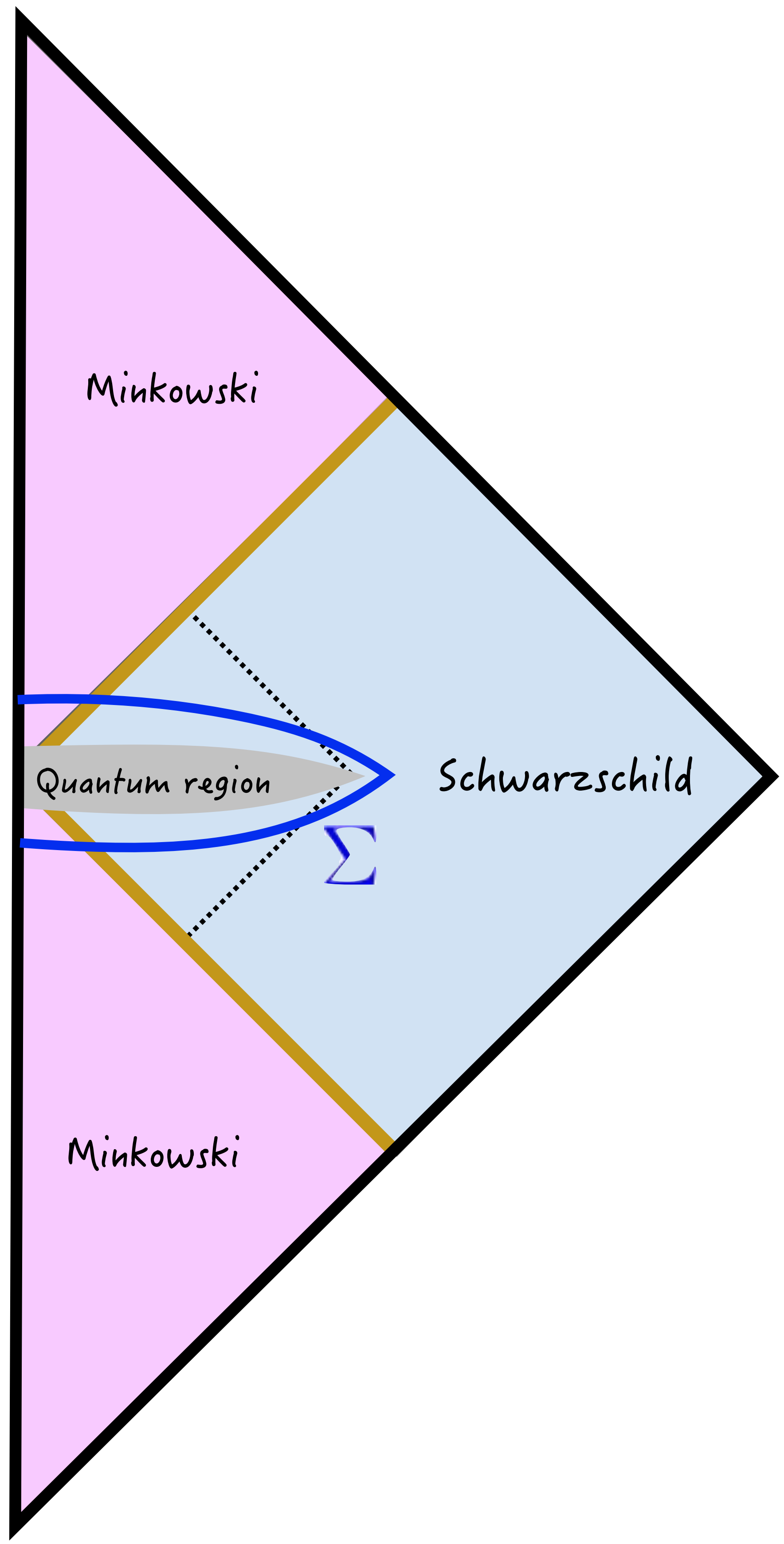
- m is the mass of the collapsing shell.

- T is the external bounce time:



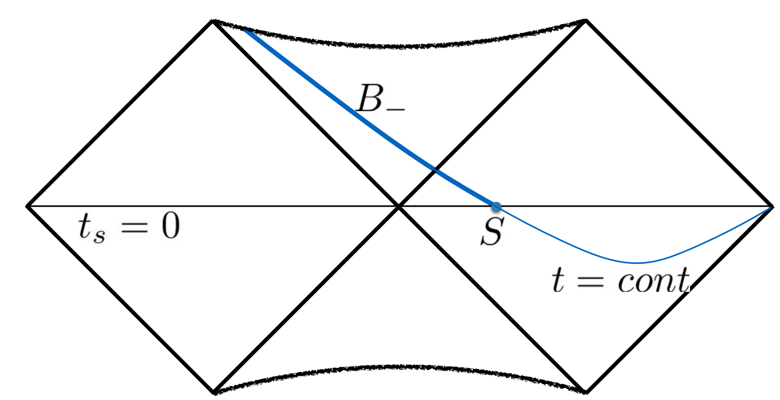
What determines **T** ?

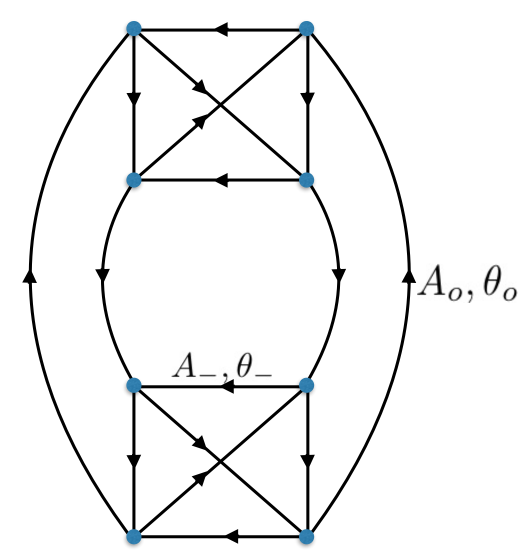
Quantum gravity

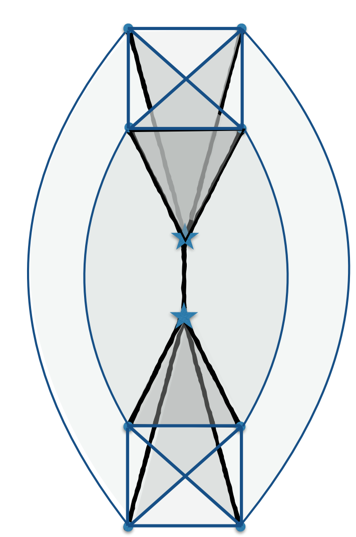


Choose a “Boundary” surface around the quantum region.

$$\Sigma = B_- \cup B_+$$







Full expression for T(m):

$$W(m,T) = \sum_{\{j_\ell\}} w(m,T,j_\ell) \sum_{\{J_n\},\{K_n\},\{l_\ell\}} \left(\bigotimes_n N^{J_n}_{\{j_n\}}(\{\nu_n\},\{\alpha_n\})\, f^{J_n,K_n}_{\{j_n\}\{l_n\}} \right) \left(\bigotimes_n i^{K_n,\{l_n\}} \right)_\Gamma$$

$$w(m,T,j_\ell) = c(m) \prod_\ell d_{j_\ell} e^{-\frac{1}{2\eta_\ell}(j_\ell - \frac{(2\eta_\ell^2-1)}{2})^2} e^{i\gamma\zeta_\ell j_\ell} \quad , \ \eta_\ell^2 \sim m^2$$

$$N^{J_n}_{\{j_n\}} = \left(\overleftarrow{\bigotimes_{\ell\in n}} D^{j_\ell}_{m_\ell j_\ell}(\{\nu_n\},\{\alpha_n\}) \right) i^{J_n,\{j_n\}}_{\{\overrightarrow{m}_n\}}$$

$$f^{K_n,J_n}_{\{j_n\}\{l_n\}} \equiv d_{J_n}\ i^{J_n,\{j_n\}}_{\{\overrightarrow{p}_n\}} \left(\int dr_n \frac{\sinh^2 r_n}{4\pi} \overrightarrow{\bigotimes_{\ell\in n}} d_{j_\ell l_\ell p_\ell}(r_n) \right) i^{K_n,\{l_n\}}_{\{\overleftarrow{p}_n\}}\ d_{K_n}$$

$$\int_0^{\tau(m)} P(m,T)\, dT = 1 - \frac{1}{e}$$

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ArXiv: 1605.05268

$$T \sim m^2$$

We expect quantum effects when some physical quantity becomes ~ 1 in Planck units.

- $R \sim 1$ around singularities

- $RT \sim 1$ → $RT \sim m/r^3\, T = T/m^2 \sim 1$ → $T \sim m^2$

Black hole lifetime in LQG
Fabio D'Ambrosio, Marios Chistodoulou.
To appear.

Primordial black holes!

$$T = T_{Hubble}$$

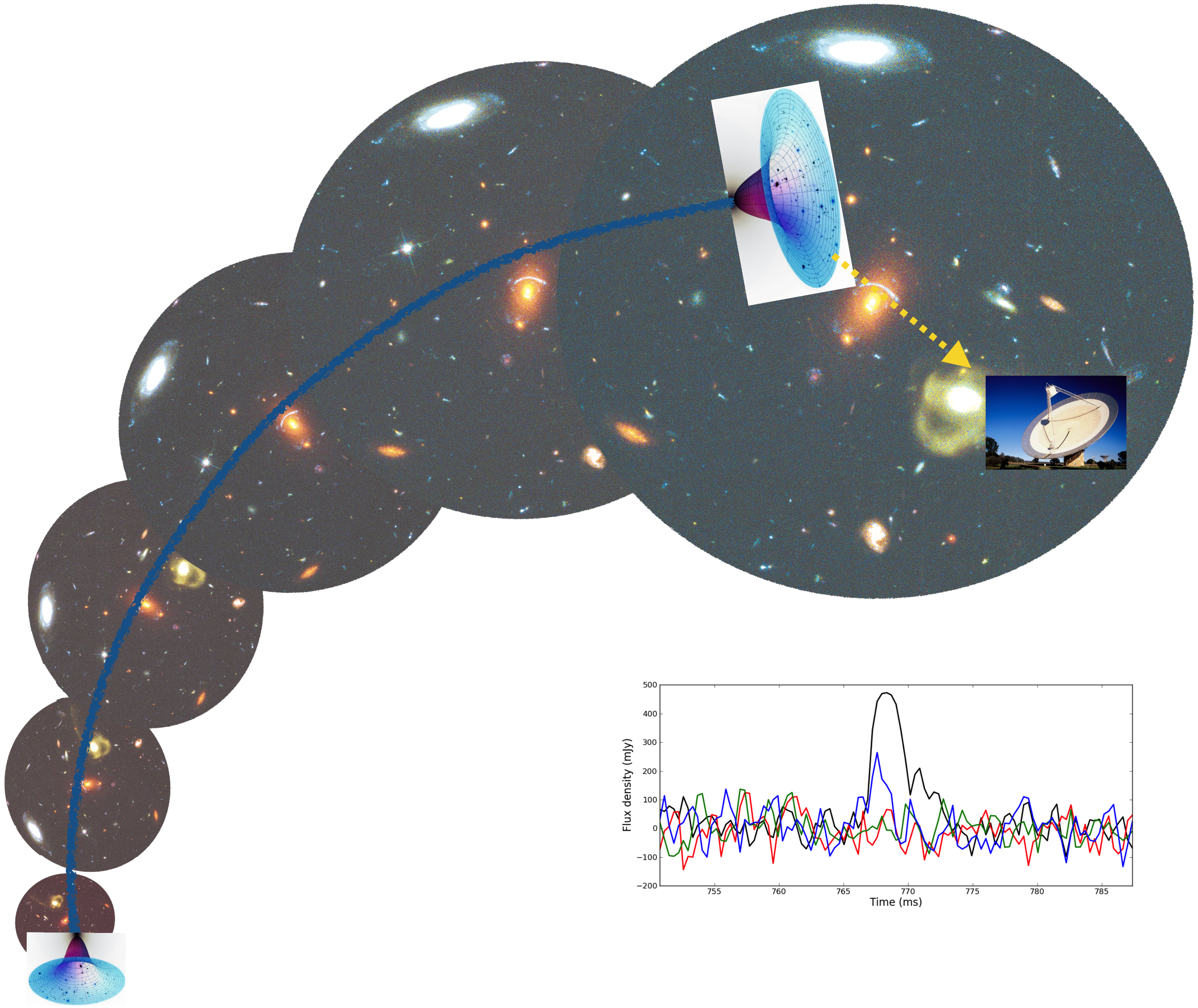
$$\downarrow$$

$$m \sim .1\, M_{\oplus}$$

$$\downarrow$$

$$\lambda \sim .1\, cm$$

$$\downarrow$$



Fast Radio Bursts!

Fast Radio Bursts and White Hole Signals
Aurélien Barrau, CR, Francesca Vidotto.
Phys.Rev. D90 (2014) 12, 127503

Signature: flattened red shift

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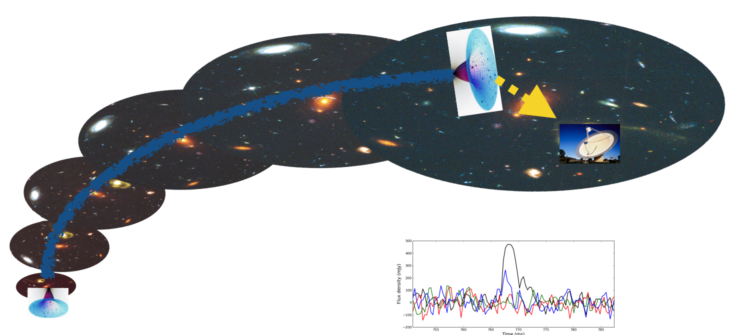
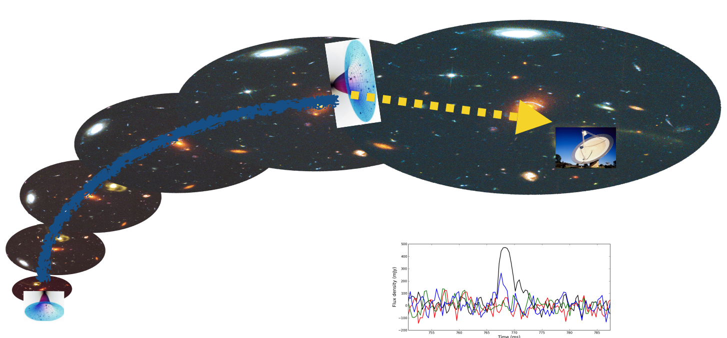
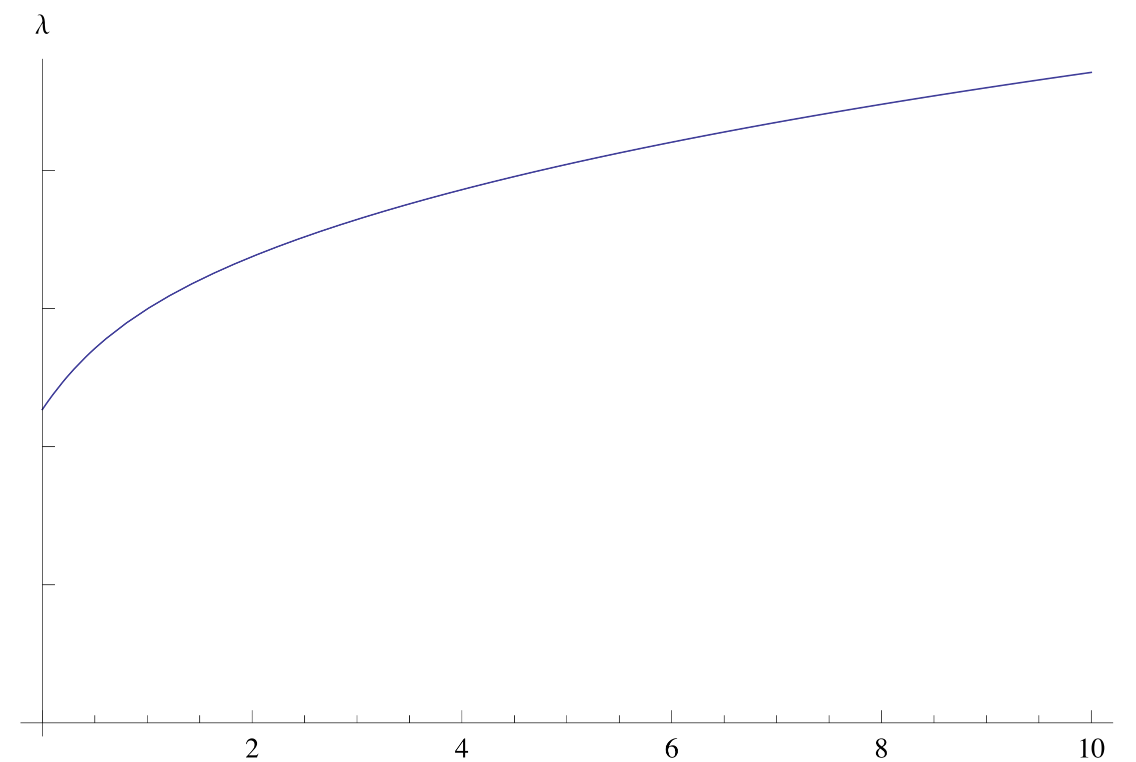
$$\lambda_{obs} \sim \frac{2Gm}{c^2}(1+z)\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}$$



m_1



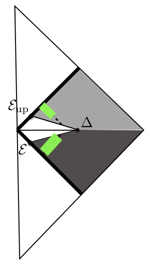
$m_2 < m_1$

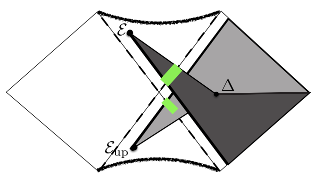


See Francesca Vidotto's talk

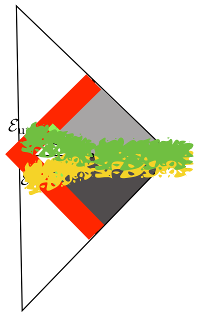
Summary

- Technical results: black holes may tunnel to white holes locally and explode.

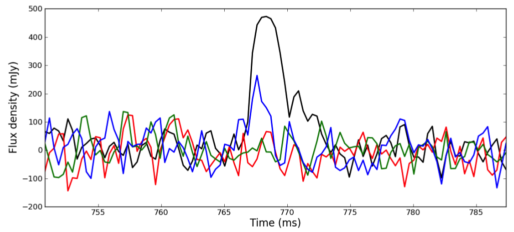




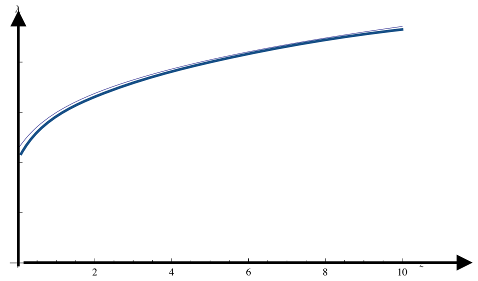
- The tunnelling time can be computed with LQG.



- $T \sim m^2$: Fast Radio Bursts and high energy Gamma phenomenology: first quantum gravity signals?



- Wavelength-to-distance relation signature.



Initial idea	**Planck stars** Carlo Rovelli, Francesca Vidotto **Int. J. Mod. Phys. D23 (2014) 12, 1442026**
Classical metric	**Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling** Hal Haggard, Carlo Rovelli **Phys. Rev. D.92.104020.**
Phenomenology	**Planck star phenomenology** Aurelien Barrau, Carlo Rovelli. **Phys. Lett. B739 (2014) 405**
Fast Radio Bursts	**Fast Radio Bursts and White Hole Signals** Aurélien Barrau, Carlo Rovelli, Francesca Vidotto. **Phys. Rev. D90 (2014) 12, 127503**
LQG lifetime calculation	**Computing a Realistic Observable in Background-Free Quantum Gravity: Planck-Star Tunnelling-Time from Loop Gravity** Marios Chistodoulou, Carlo Rovelli, Simone Speziale, Ilya Vilensky. **ArXiv: 1605.05268**