Planck Stars

and

Fast Radio Bursts

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with Aurélien Barrau, Hal Haggard, Francesca Vidotto

Planck stars
Francesca Vidotto, C.R.
Int.J.Mod.Phys. D23 (2014) 2026
arXiv:1401.6562

Planck star phenomenology
Aurelien Barrau, C.R.
arXiv:1404.5821

Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling
Hal Haggard, C.R.
arXiv:1407.0989

Fast Radio Bursts and White Hole Signals
Aurélien Barrau, Francesca Vidotto, C.R.
Phys.Rev. D90 (2014) 12, 127503
arXiv:1409.4031
Fast Radio Bursts

- Duration: ~ milliseconds
- Frequency: 1.3 GHz
- Observed at: Parkes, Arecibo
- Origin: Likely extragalactic
- Estimated emitted power: $10^{38}$ erg
- Physical source: unknown.

The FRB 121102 event seen by the Arecibo observatory.
Main message of this talk:

Consider the possibility that this (or similar) signals be of quantum gravity origin.
What is the relation between quantum gravity ($l_{\text{Planck}} \sim 10^{-33}\text{cm}$) and radio waves ($\lambda \sim 1 \text{ cm}$)??

\[
\frac{t_{\text{Hubble}}}{t_{\text{Planck}}} \sim 10^{60}
\]

\[
\lambda \sim \sqrt{\frac{t_{\text{Hubble}}}{t_{\text{Planck}}}} l_{Pl} \sim .02\text{cm}
\]
We see large amount of matter falling into astrophysical black holes

The black hole (here Cygnus X-1) pulls gas of the star orbiting around it. The gas heats up and emits X rays (yellow) as it falls into the black hole.
What happens to all matter falling into a black hole?

GR predict a “singularity”, but this only means that the theory goes wrong: it disregards quantum phenomena.

Black hole in Eddington-Finkelstein coordinates

\[ ds^2 = r^2 d\omega^2 + 2dvdr - F(r,t)du^2. \]

\[ F(r,t) = 1 - \frac{2m}{r}. \]
What happens to all matter falling into a black hole?
An input from quantum cosmology

\[ \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} \rho \left( 1 - \frac{\rho}{\rho_{Pl}} \right) \]

A strong repulsive force when matter reaches the Planck density
Several other similar inputs

- LQC bounce
- Maximal curvature
- Electrons in atoms
- ...

Reasonable hypothesis:

Quantum mechanics prevents the formation of the singularity by developing an effective strong repulsion when matter reaches Planck density.
Planck density does not mean Planck size!

Example: if a star collapses ($M \sim M_\odot$), Planck density is reached at $10^{-12}\text{ cm}$, which is $10^{20}$ times the Planck length!

There is a relevant intermediate scale between the Schwarzschild radius $L_S$ and the Planck scale $L_P$.

$$L \sim \left(\frac{M}{M_P}\right)^{\frac{1}{3}} L_P$$
(Static) Planck star

Static black hole with Planck star

Exemple (out of many possible)

\[ F(r) = 1 - \frac{2mr^2}{r^3 + 2\alpha^2m} \]

[Hayward]
Dynamics of a Planck star, I

Example (out of many possible)

\[ F(r) = 1 - \frac{2m(t)r^2}{r^3 + 2\alpha(t)^2m} \]

Important: matter-energy can escape from the trapped region, independently form Hawking radiation.
What happens to all matter falling into a black hole?
What happened at the big bang?

\[ \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} \rho \]

- Effective repulsive force
  - elastic bounce
Dynamics of a Planck star, I

Non-evaporating black hole

Evaporating black hole

Planck star

What is the physics here?
Physical problem:
- How can matter and energy come out from a quantum region?

Key idea:
- Neglect Hawking radiation in the first approximation.
- Energy conservation at infinity → elastic bounce.
- GR is time reversal invariant! Use this.
Matter falls into a trapped region.

Classically (but not in reality) matters goes into a singularity:

Black hole
Matter *emerges* from a trapped region.

Classically (but not in reality) matters *emerges from* a singularity:

White hole!

But there are no white holes!

Matter *falls* into a trapped region.

Classically (but not in reality) matters *goes into* a singularity:

Black hole
Black holes:

Weinberg’s “Gravitation and cosmology” (1972):

“There is no Schwarzschild singularity [black hole] in the gravitational field of any known object of the universe”

“The Schwarzschild singularity does not seem to have much relevance for the world.”
Black holes:

Are you sure, Steven?
Cygnus-X1. Today there is no decent alternative to its interpretation as black hole.

Astronomers currently estimates that there are 10 millions black holes just in our galaxy.
White holes:

Wald’s “General Relativity” (1984):

“Regions III and IV of the extended Schwarzschild solution [*white holes*] are probably unphysical.”

“There is no reason to believe that the initial configuration of any region of our universe corresponds to these initial conditions, so there is no reason to believe that any region of our universe corresponds to the fully extended Schwarzschild solution.”
White holes:

Are you sure, Bob?
General relativity predicts an extraordinary number of processes and objects, which at first nobody believed (including Einstein):

- Black holes
- Expansion of the universe
- Gravitational waves
- White holes
- ....
White Holes can be out there in the sky
But can an earlier black hole region and a later white hole region stay together?

(in a single spacetime that solves the classical vacuum Einstein equations where there is no matter and no quantum effect?)

Seems impossible...
Take for simplicity an ingoing and the outgoing null shell

This is what we want:

- **Region I:** flat  
  (inside the *shell*)

- **Region II:** Schwarzschild  
  (outside the *shell*)

- **Region III:** Quantum region

- $\mathcal{E}$ well inside the *horizon*!

(seems impossible...
Two ideas to solve the problem!

I: The Crossed Fingers

II: The Crystal Ball
A white hole after a black hole seems impossible, because in a Kruskal diagram the white hole is before, not after the white hole!
II: The Fingers Crossed
Full metric: join the pieces

Spherical symmetry:
\[ ds^2 = -F(u, v)du dv + r^2(u, v)(d\theta^2 + \sin^2 \theta d\phi^2) \]

Region I (Flat):
\[ F(u_I, v_I) = 1, \quad r_I(u_I, v_I) = \frac{v_I - u_I}{2}. \]

Bounded by:
\[ v_I < 0. \]

Region II (Schwarzschild):
\[ F(u, v) = \frac{32m^3}{r} e^{\frac{r}{2m}} \left(1 - \frac{r}{2m}\right) e^{\frac{r}{2m}} = uv. \]

Matching:
\[ r_I(u_I, v_I) = r(u, v) \quad \rightarrow \quad u(u_I) = \frac{1}{v_o} \left(1 + \frac{u_I}{4m}\right) e^{\frac{u_I}{4m}}. \]

Region III (Quantum):
\[ F(u_q, v_q) = \frac{32m^3}{r_q} e^{\frac{r_q}{2m}}, \quad r_q = v_q - u_q. \]

The metric is determined by the constants: \( m, v_o, \delta, \epsilon \)
The metric is determined by four constants: \( m, v_o, \delta, \epsilon \)

- \( m \) is the mass of the collapsing shell.
- \( \epsilon \) is the radius where quantum effect start on the shell \( \epsilon \sim \left( \frac{m}{m_P^3} \right)^{\frac{1}{3}} l_P \).
- \( \delta \) is the minimal distance from the horizon where the theory is entirely classical
- \( v_o \) is the key parameter: it determines the external time the full process takes

What determines the last two constants?
An argument from above:

The **firewall** argument (Almheiri, Marolf, Polchinski, Sully) shows that “something” unusual must happen before the Page time (half of the Hawking evaporation time).

Therefore the hole lifetime must be shorter or of the order of \( \sim m^3 \).
An argument from below:
For something quantum to happen of the validity of the semiclassical approximation must fail.

The classical theory is reliable as long as we are in a “small action” regime (typically in quantum gravity: high curvature). How small? Small effects can pile up (typical example tunnelling: a small probability per unit of time gives a probable effect on a long time.)

Therefore there two possible quantum effects:

(i) when \[ \text{Curvature} \sim (L_p)^{-2} \]
(ii) when \[ \text{Curvature} \times \text{(time)} \sim (L_p)^{-1} \]
“Classicality parameter” \[ q = l_P \mathcal{R} \tau. \]

Look for its max in the radius, and, at the max, for the time it gets to unity. A (long) straightforward calculation give the max radius at

\[ R = \frac{7}{6} \frac{2m}{2l_p}. \]

And the time

\[ \tau = 2c \frac{m^2}{l_P}. \]

Which in turn give

\[ v_o \sim e^{-c \frac{m}{2l_p}}, \quad \delta \sim \frac{m}{3}. \]

The metric is entirely determined by the mass.
The lifetime of the hole is huge

$$\tau = 2c \frac{m^2}{l_P}.$$ 

How can this be compatible with a bounce, which is short?
I: The Crystal Ball

A simple straightforward calculation in the Schwarzschild metric shows that:

at fixed $R$, when $a$ approaches $2m$, $	au$ becomes arbitrary large!

$$\tau = \sqrt{1 - \frac{2m}{R}} \left( R - a - 2m \ln \frac{a - 2m}{R - 2m} \right).$$

$$t = R - a$$
I: The Crystal Ball in Scharzschild-like coordinates:

The external proper time can be arbitrary long.

While the internal proper time is arbitrarily short.

\[ \tau = \sqrt{1 - \frac{2m}{R}} \left( R - a - 2m \ln \frac{a - 2m}{R - 2m} \right) \]

\[ t = R - a \]
Time dilation

$\tau_{\text{internal}} \sim m \sim 1 \text{ ms}$

$\tau_{\text{external}} \sim m^2 \sim 10^9 \text{ years}$

“A black hole is a short cut to the future”
Can all this be observable?


Final stage of the evaporation can be at a radius larger than $L_{\text{Planck}}$!

The mass of a primordial black hole exploding no, for a long lifetime, $r = \sqrt[3]{\frac{t_H}{348\pi} l_p} \sim 10^{-14} \text{ cm}$

In the case of a short lifetime, we can get to $\sim 1 \text{ cm}$ $r \sim \sqrt{\frac{t_H}{t_P}} \sim 1 \text{ cm}$

The ratio of cosmological time to Planck time provides a large multiplicative factor that can make quantum gravity effects observable.
Detectable?  
Already detected?

\[ E_{\text{burst}} = \frac{hc}{2rf} \approx 3.9 \text{ GeV} \]

\~10 \text{ MeV}
From \~200 \text{ light years}
Short gamma-ray burts
Isotropic
One event per day
Detectable?  
Already detected?

- Duration: ~ milliseconds
- Frequency: 1.3 GHz
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Covariant loop quantum gravity. Full definition.

State space
\[ \mathcal{H}_\Gamma = \mathcal{L}^2[SU(2)^L / SU(2)^N]_\Gamma \ni \psi(h_L) \]

Operators:
\[ \tilde{L}_i = \{L^i_L\}, \quad i = 1, 2, 3 \quad \text{where} \quad L^i\psi(h) \equiv \frac{d}{dt}\psi(h e^{t\tau_i}) \bigg|_{t=0} \]

Transition amplitudes
\[ W_C(h_L) = N_C \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf}) \]

Vertex amplitude
\[ A(h_{vf}) = \int_{SL(2,\mathbb{C})} dg'_e \prod_f \sum_j (2j + 1) \ D^j_{mn}(h_{vf}) D^{(j+1)j}_{jmjn}(g_e g_e^{-1}) \]

All you need is here
Quantum transition

\[ \tau \left( \frac{J}{2} \right) = \text{Tr}_{\mathcal{Z}} \mathcal{O} \]

\[ \mathcal{O} = \mathcal{Z} \mathcal{A} \mathcal{M} \mathcal{J} \mathcal{K} \]

\[ A(j, k) = \int_{SL(2C)} dg \int_{SU(2)} dh_- \int_{SU(2)} dh_+ \sum_{j, j'} e^{-(j-j')^2} e^{-(j+j')^2} \]

\[ \text{Tr}_{j_+}[e^{\hat{\sigma}_3 J^+ \hat{Y}_+}] \text{Tr}_{j_-}[e^{\hat{\sigma}_3 J^- \hat{Y}^-}] \]

\[ A(j, k) \sim 1 \quad \rightarrow \quad \text{relation j-k} \]

\[ \text{relation m-time} \]
Physical picture and main messages:

- Collapsing matter **bounces**. In a very short proper time (or order $m$).
- Incoming phase: black hole, Outgoing phase: **white hole**
- No singularity. 2 trapped regions. **Information preserved**.
- **Time dilation**. From the outside, long proper time, order $m^2$. (For a stellar black hole, $m$ is microseconds, $m^2$ is billions of years). “A black hole is a bouncing star seen in super-slow motion”.
- **Observable?** Primordial black holes
- An **LQG calculation** may be doable.

\[
\frac{t_{\text{Hubble}}}{t_{\text{Planck}}} \sim 10^{60}
\]

\[
E_{\text{burst}} = \frac{hc}{2rf} \approx 3.9 \text{ GeV}
\]

Short gamma-ray bursts $\sim 10$ MeV

Isotropic  One event per day

The FRB 121102 event
seen by the Arecibo observatory
Could this really be a quantum gravity signal?