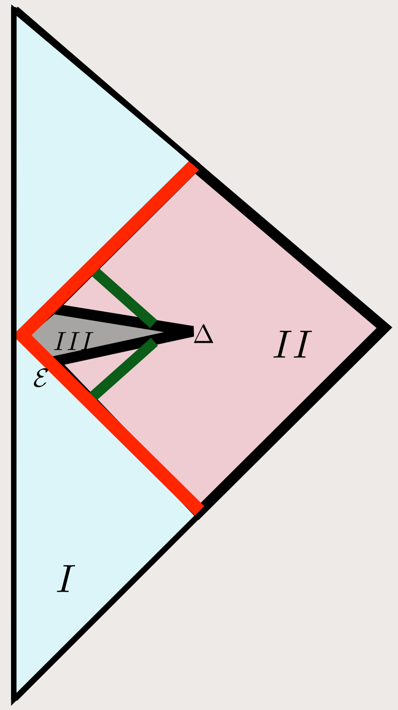
Searching for quantum gravitational observations

Carlo Rovelli



Work with: Hal Haggard, Francesca Vidotto and Aurélien Barrau

- Vidotto CR: *Planck Stars*, arXiv:1401.6562
- Barrau CR: *Planck star phenomenology*, arXiv:1404.5821"
- Haggard CR: *Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling*, arXiv:1407.0989
- Barrau Vidotto CR: *Fast Radio Bursts and White Hole Signals*, arXiv: 1409.4031

Physics from loop quantum gravity:
Key general result in loop 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**
- **Maximal acceleration** [Vidotto CR 13]
- **Electrons in atoms**
- **…**

Reasonable general hypothesis:

Quantum mechanics prevents the formation of the singularity by developing an effective strong repulsion, (or simply making attraction weaker), when matter reaches Planck density.

→ **The same physics should affects black holes**

[Modesto 04, Asktekar-Bojowald 05, Hossenfelder-Modesto-Premont-Schwarz 10, GambiniPullin 13, …]

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.*"

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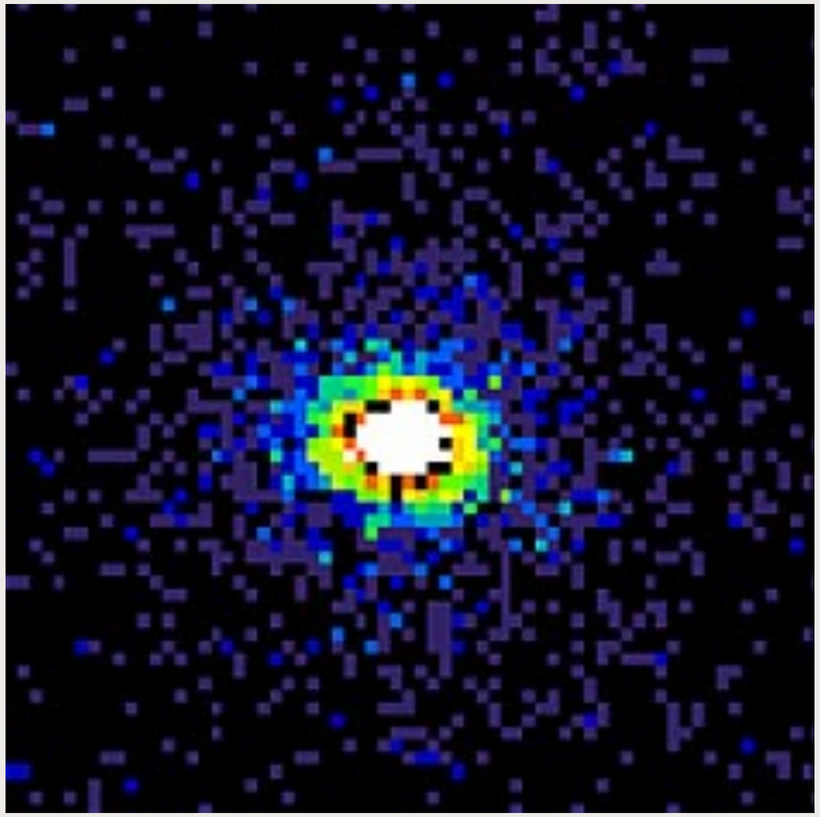
Are you so sure, Steven?

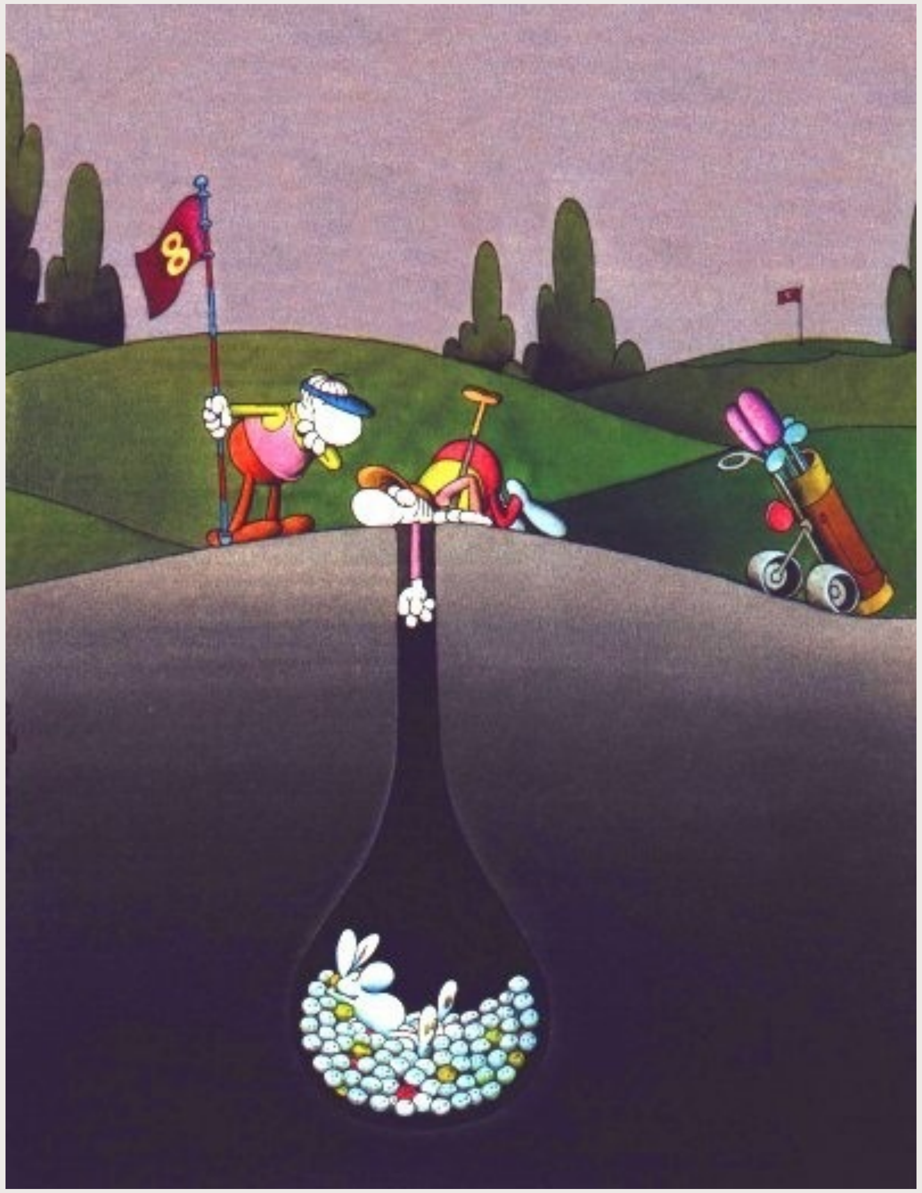
We see very many black holes in the sky,

and we see large amount of matter falling into them



The black hole (here Cygnus X-!) 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?



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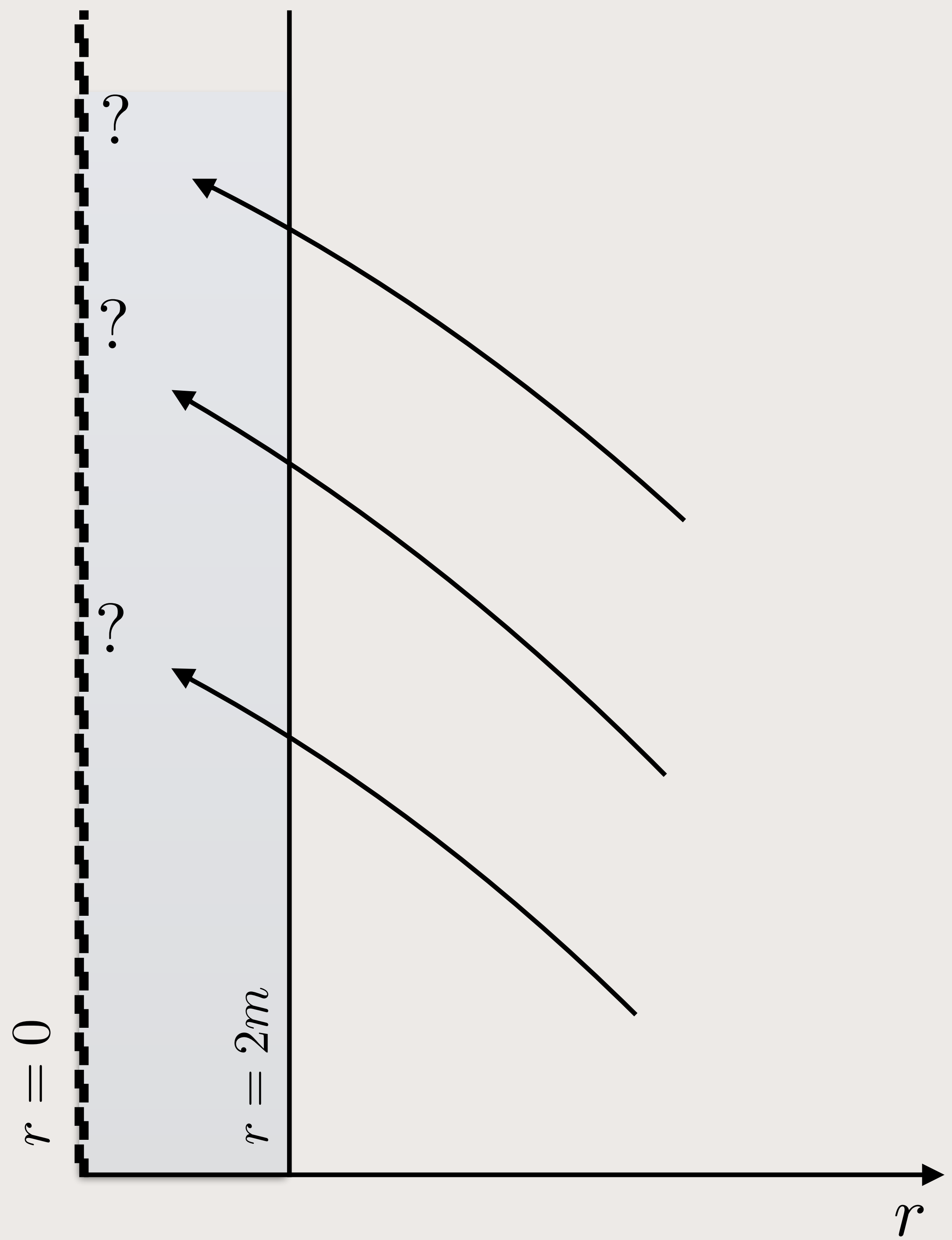


GR predict a “singularity”, but this only means that the theory goes wrong: it disregards quantum phenomena.

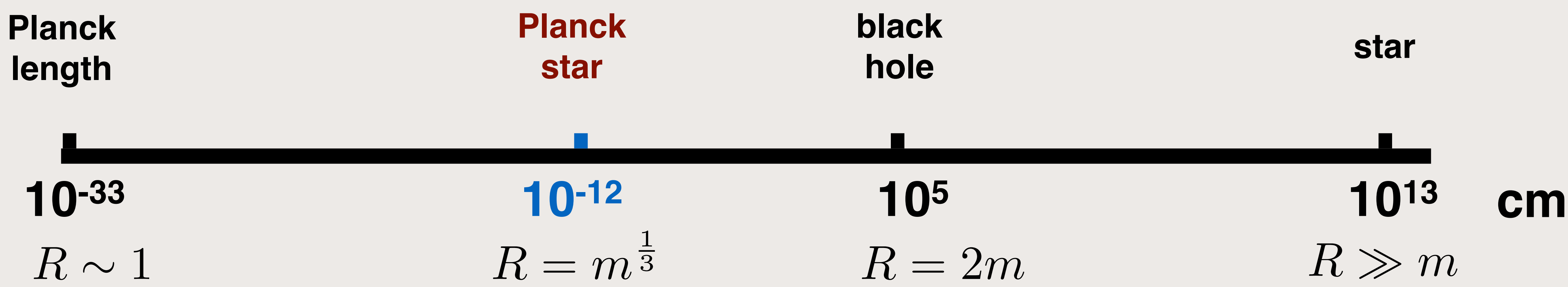
Black hole in Eddington-Finkelstein coordinates

$$ds^2 = r^2 d\omega^2 + 2dv\, dr - F(r,t) du^2.$$

$$F(r,t) = 1 - \frac{2m}{r}$$

Planck density does not mean Planck size !

Example: if a star collapses ($M \sim M_\odot$), Planck density is reached at 10^{-12} 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

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

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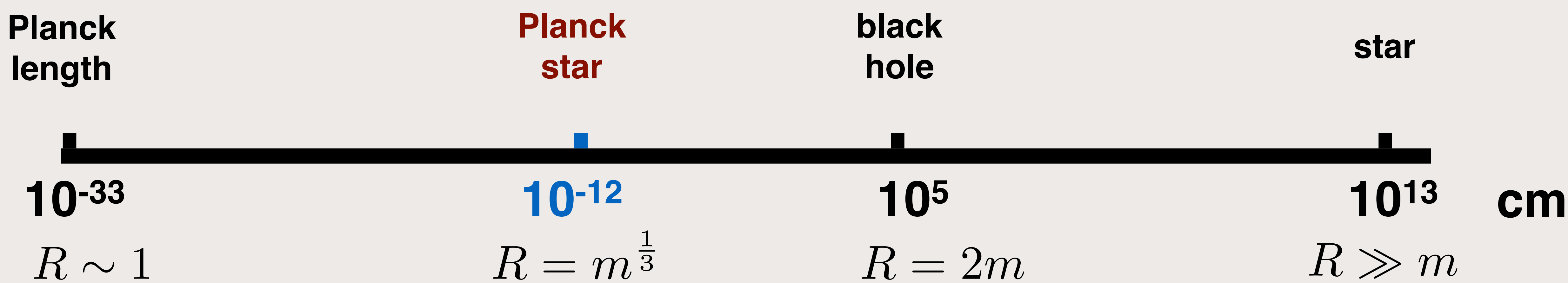


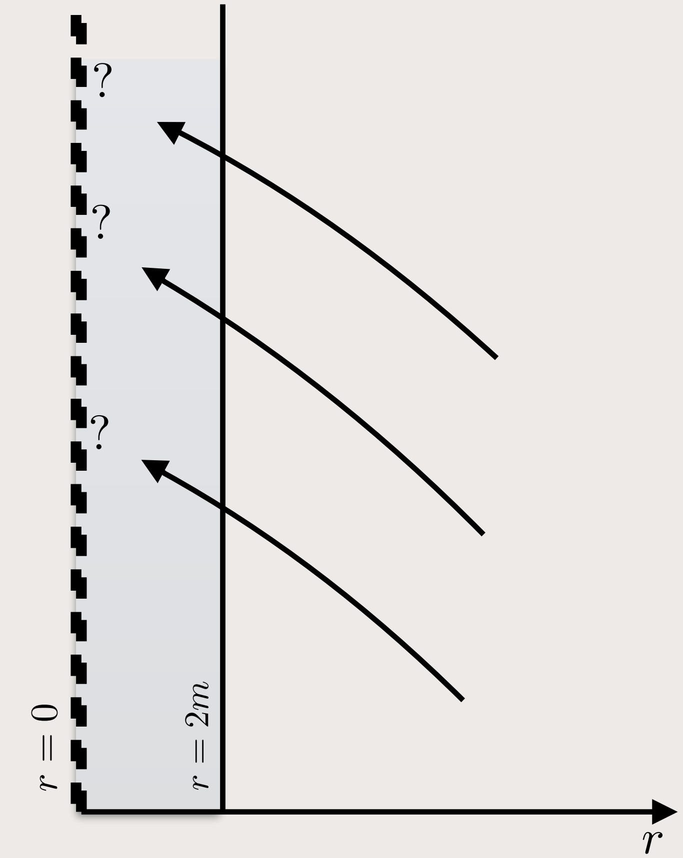
Quantum gravity becomes relevant here

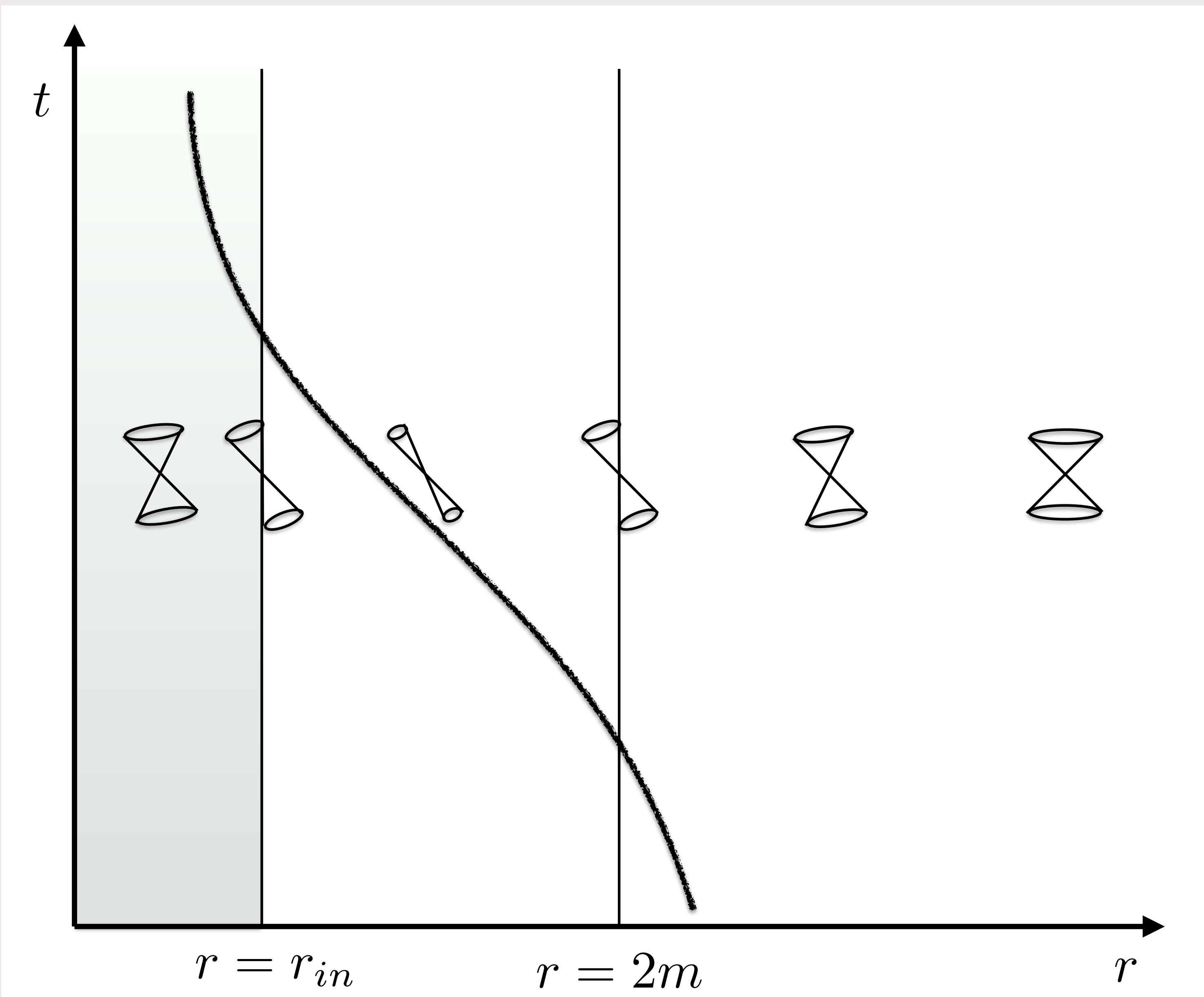
[Ashtekar, Pawlowski, Singh 06]

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





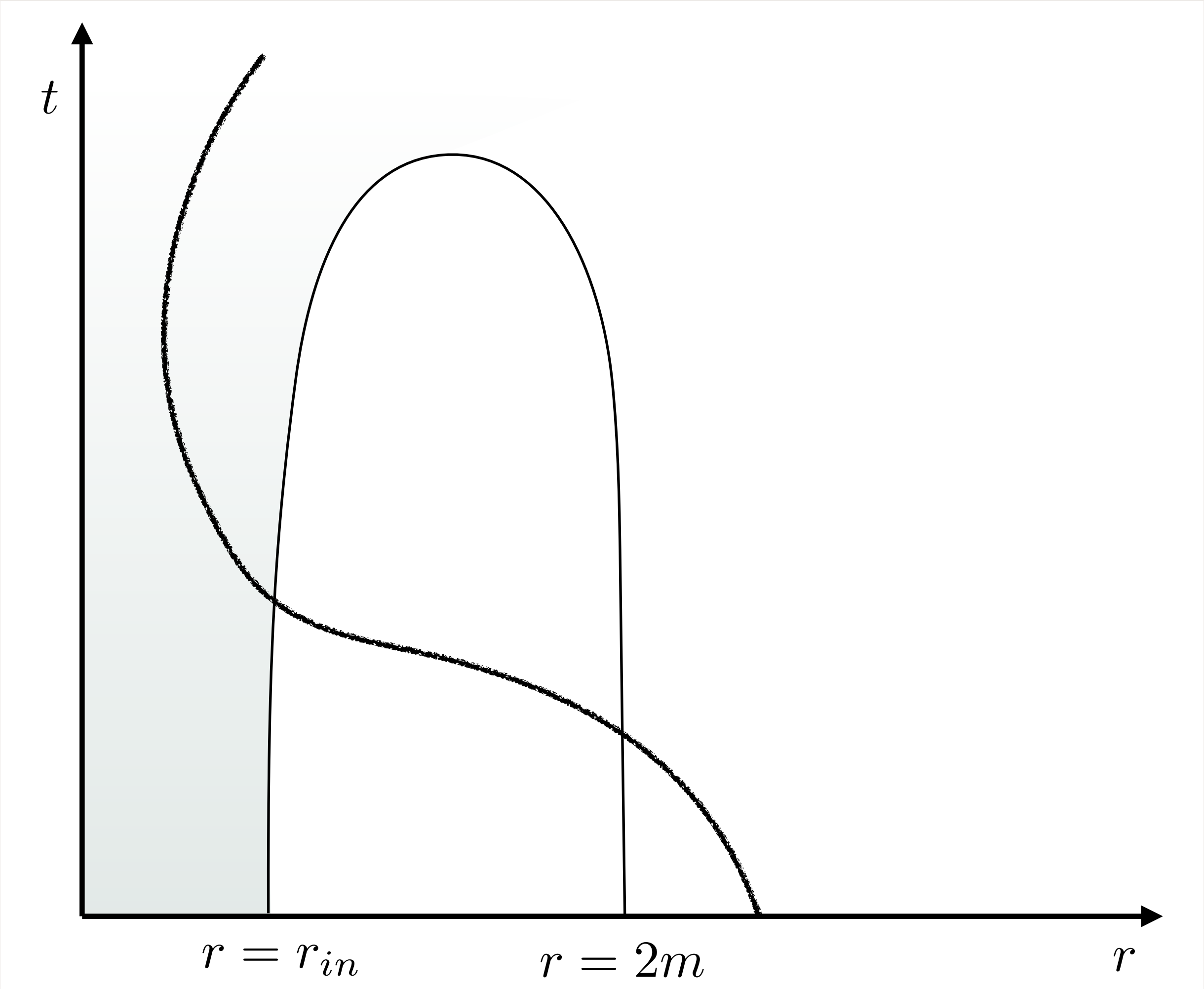
Static black hole with Planck star

Exemple (out of many possible)

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

[Hayward 06]

Dynamics of a Planck star, I

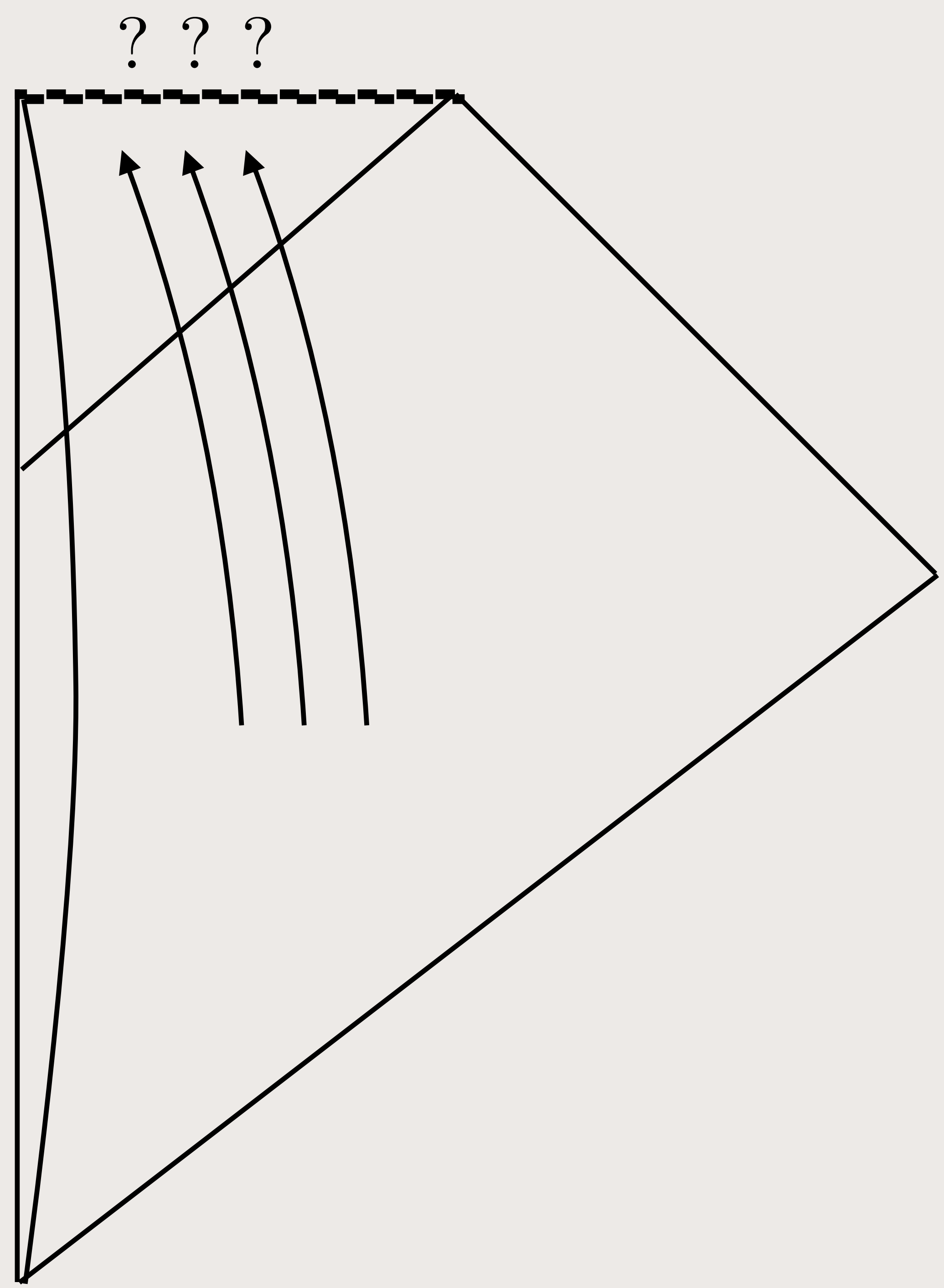


Example (out of many possible)

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

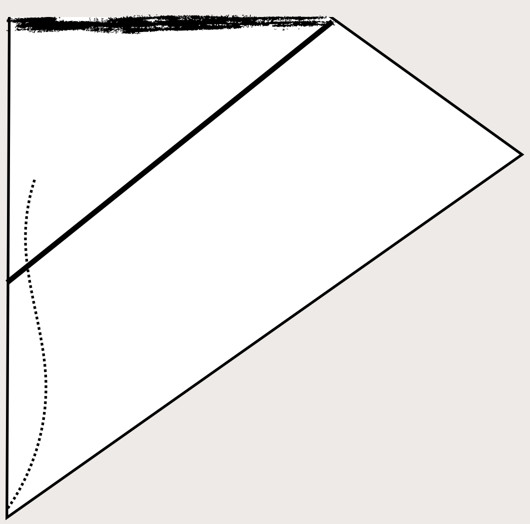
Important: matter-energy can escape from the trapped region, independently form Hawking radiation.

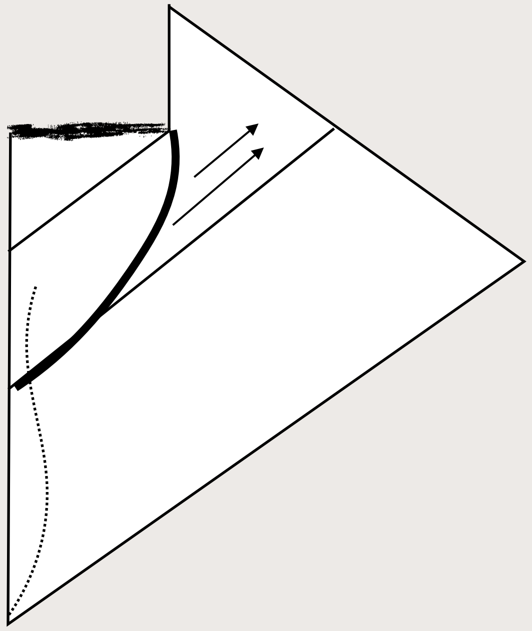
What happens to all matter falling into a black hole?

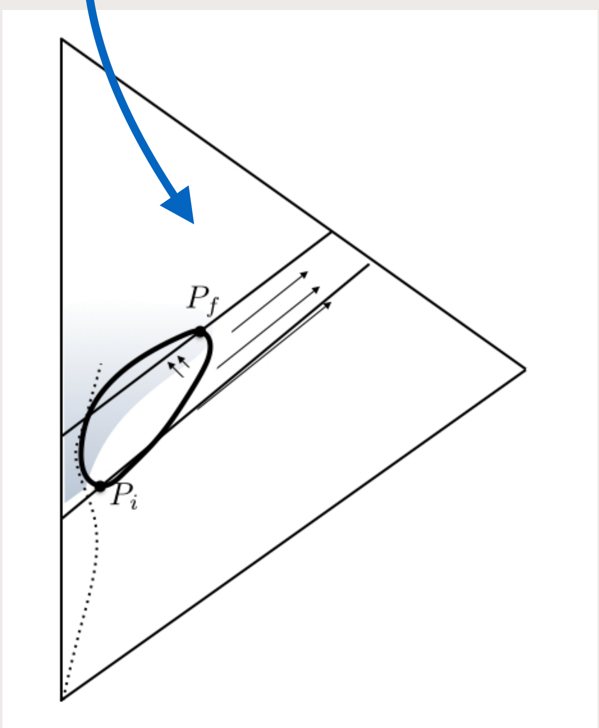


Dynamics of a Planck star, I

What is the physics here?







Non-evaporating black hole

Evaporating black hole

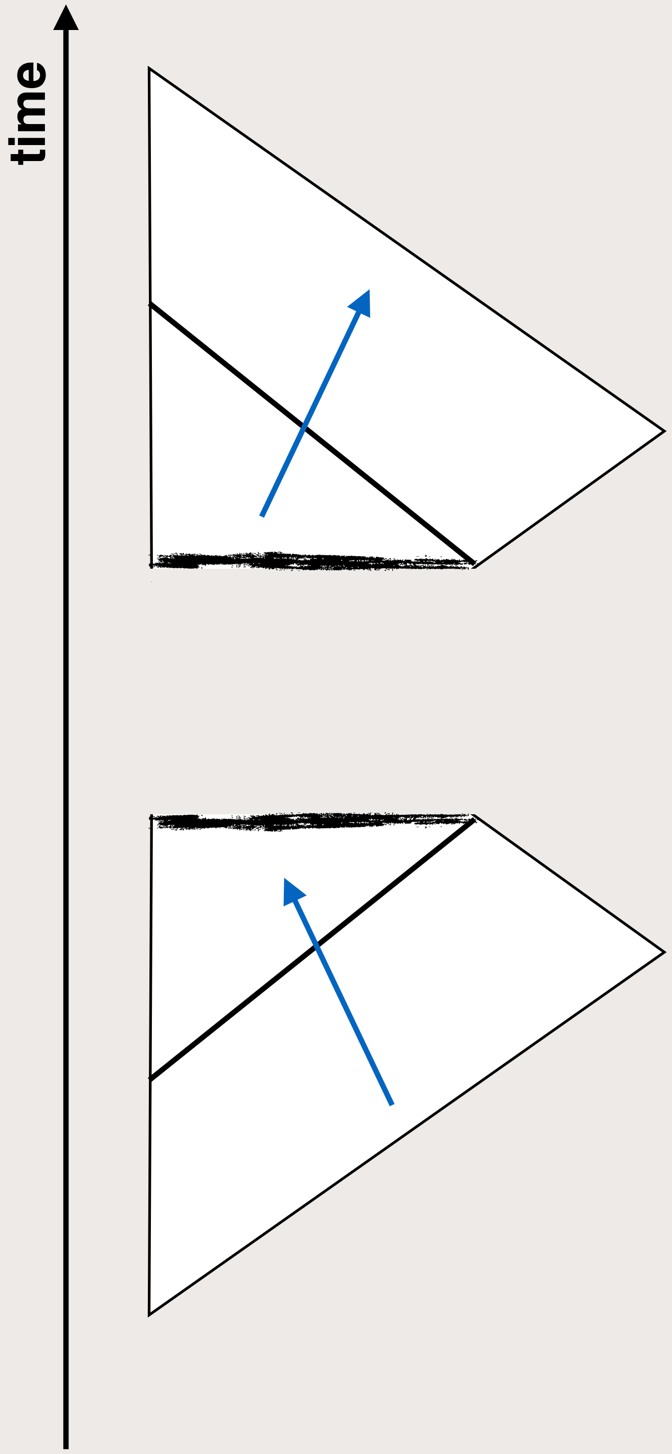
Planck star

Physical problem:

- How can matter and energy come out from a quantum region?

Key idea:

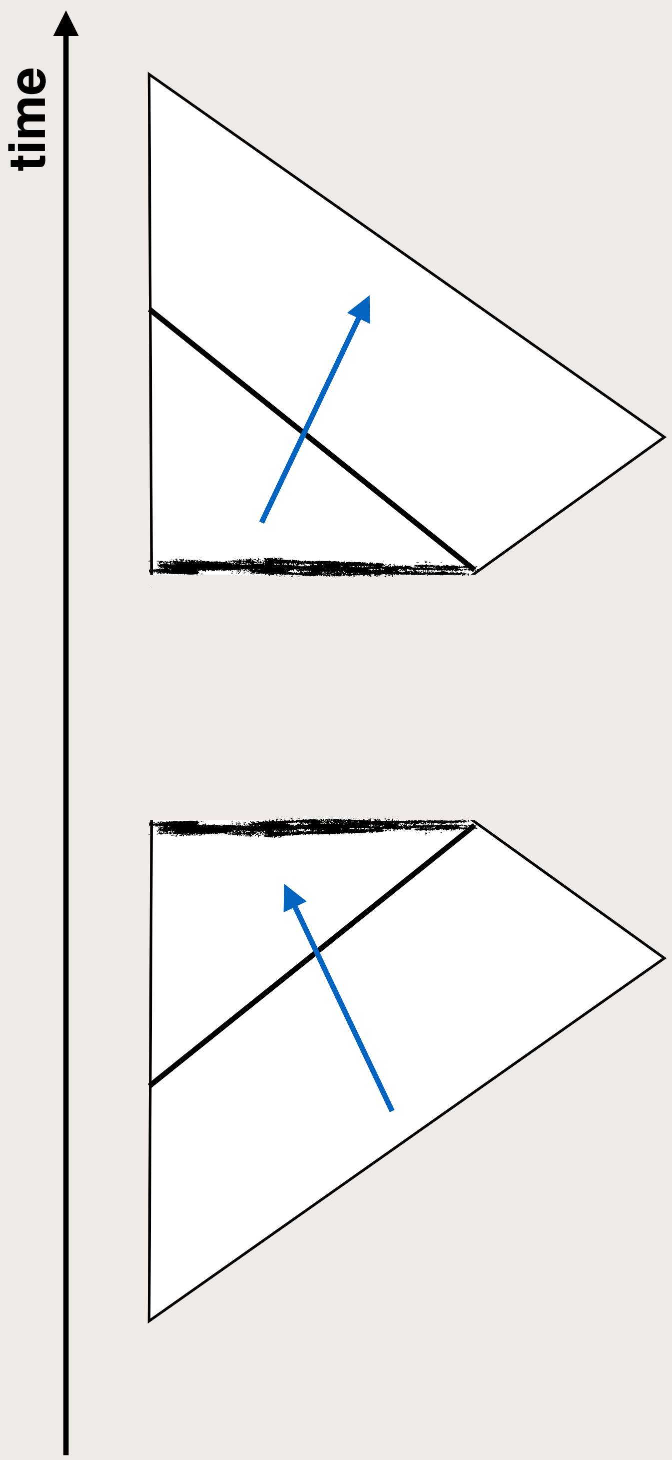
- Neglect Hawking radiation in first approximation.
- Energy conservation at infinity → elastic bounce.
- GR is time reversal invariant! Use this.



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!

Matter falls into a trapped region.

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

Black hole

But there are no white holes!

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"
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Are you so sure, Steven?

Black holes:

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Are you so sure, Steven?

White holes:

Wald's "General Relativity" (1984):

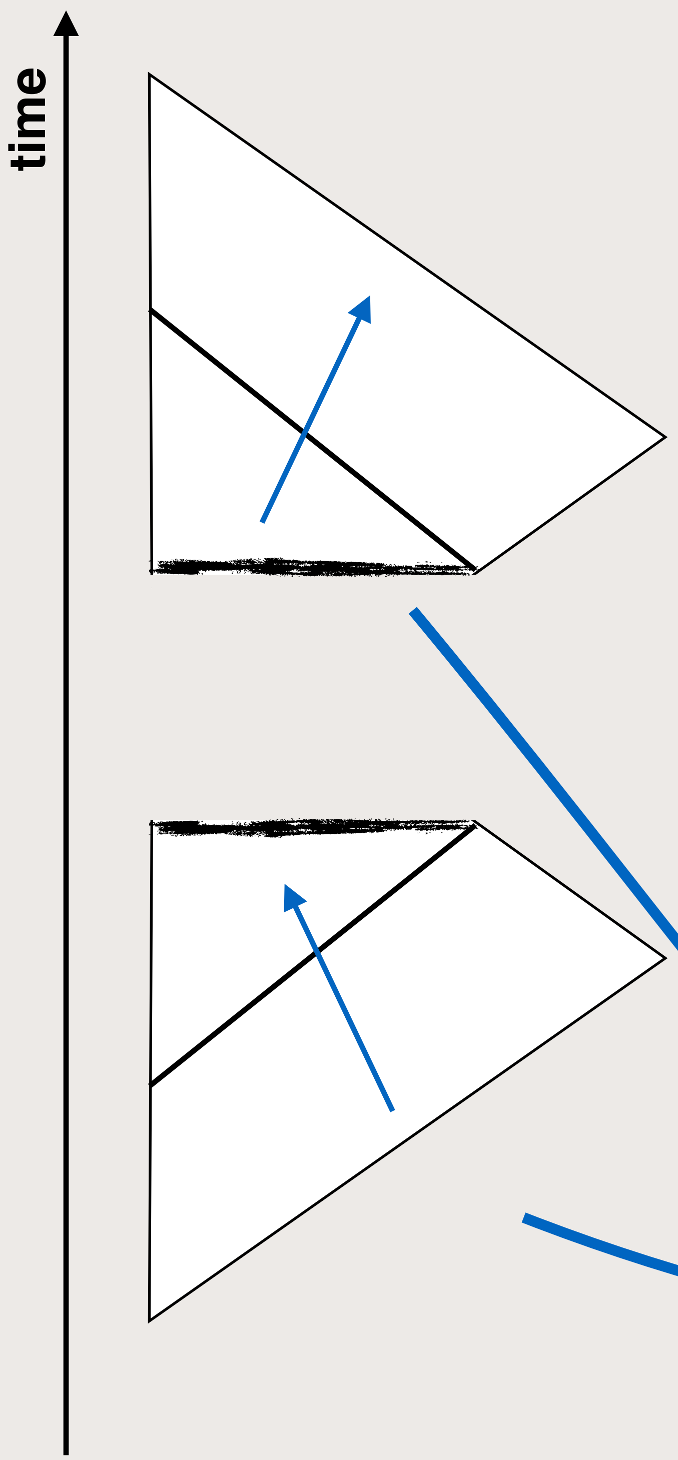
"Regions III and IV of the extended Schwarzschild solution [white hole] are probably unphysical."
"There is no reason to believe that the initial configuration of any region of our universe corresponds to these initial conditions, so there is no reason to believe that any region of our universe corresponds to the fully extended Schwarzschild solution."

Are you so sure, Bob?

General relativity predicts an extraordinary sequence of processes and objects, which at first nobody believed (including Einstein):

- **Black holes**
- **Expansion of the universe**
- **Gravitational waves**
- **White holes**
- **….**

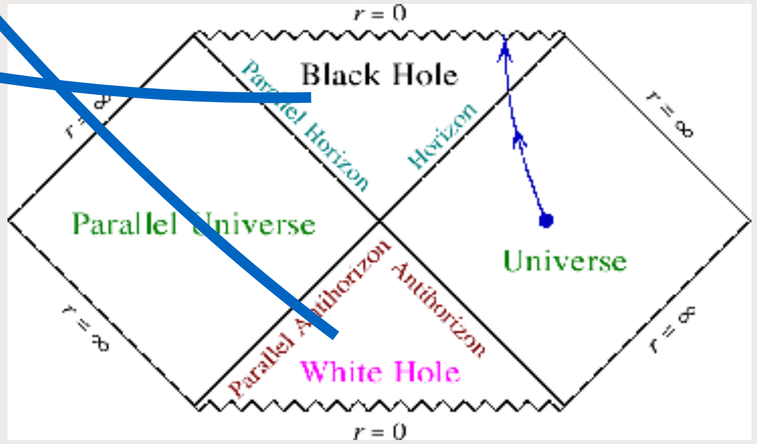
White Holes can be out there in the sky



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 mater and no quantum effect?)

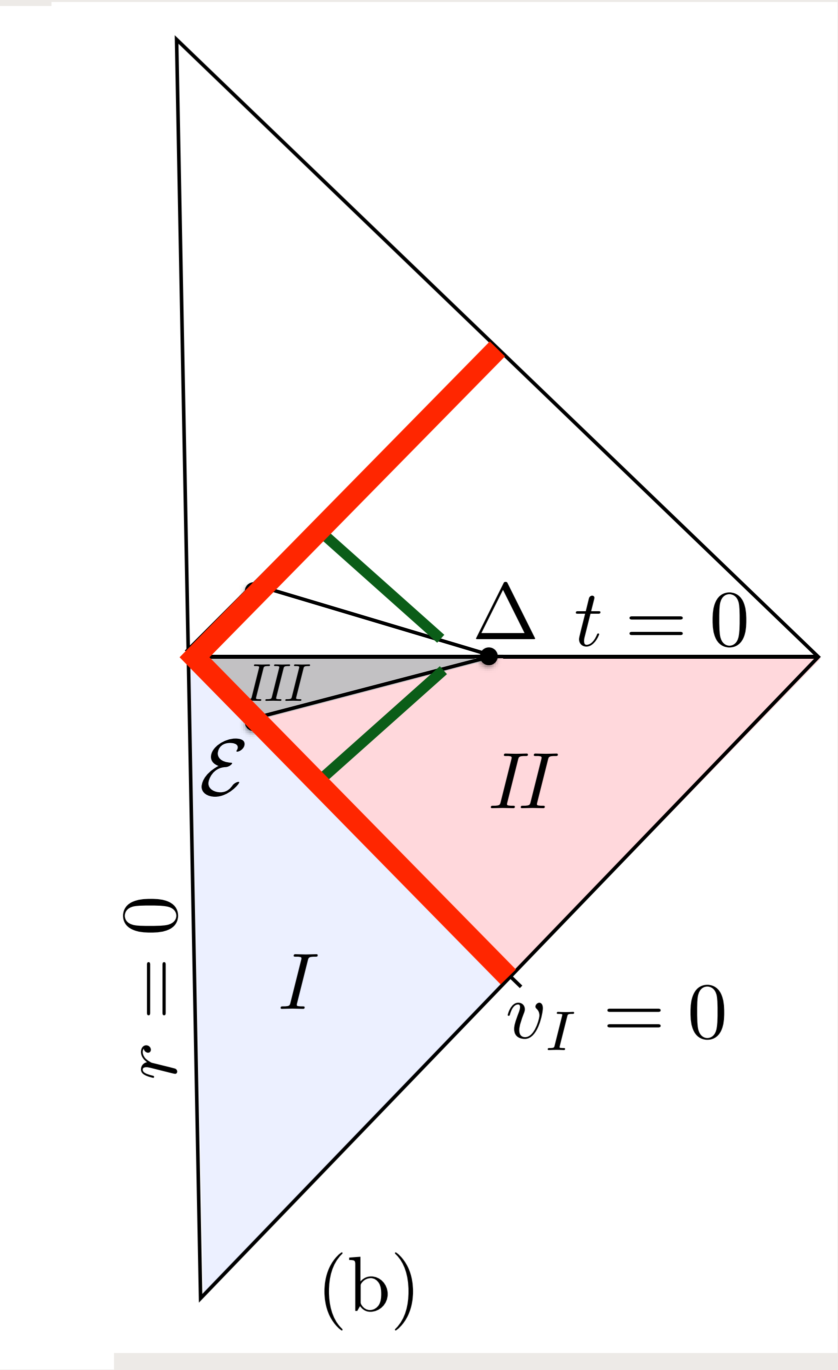
Seems impossible…



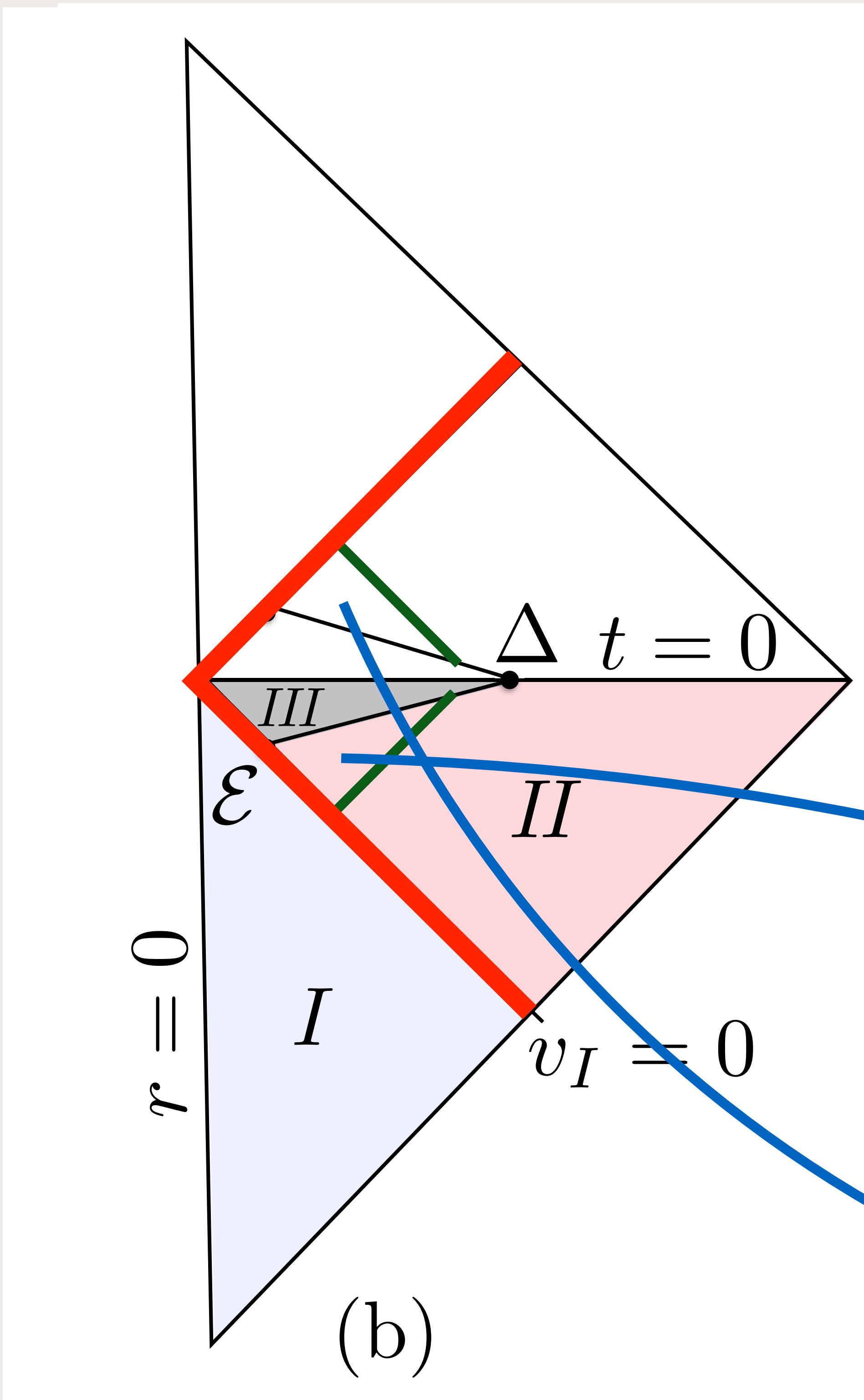
Take for simplicity an ingoing and the outgoing null shell

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...)

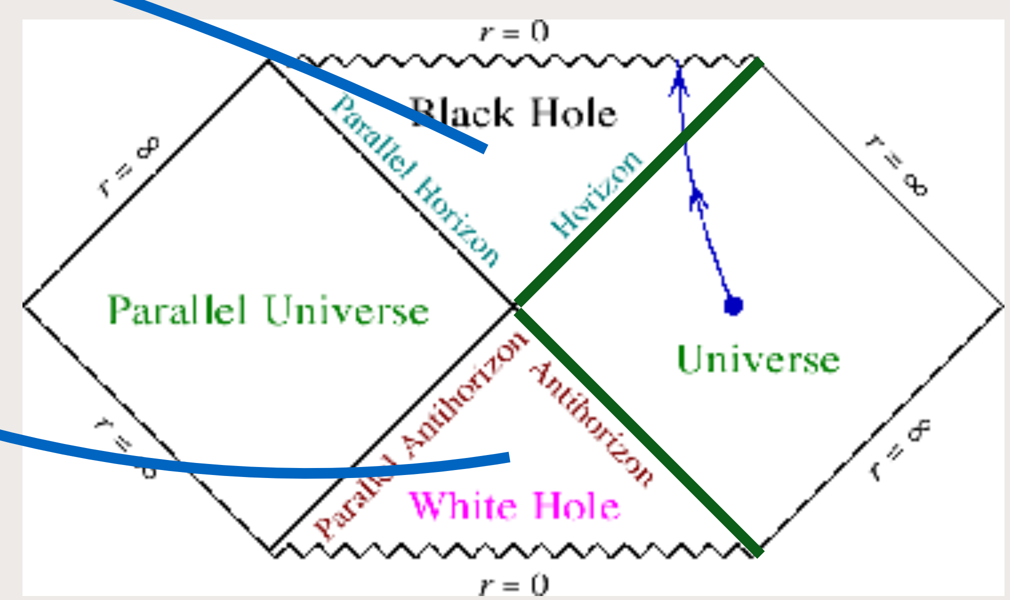


A white hole after a black hole

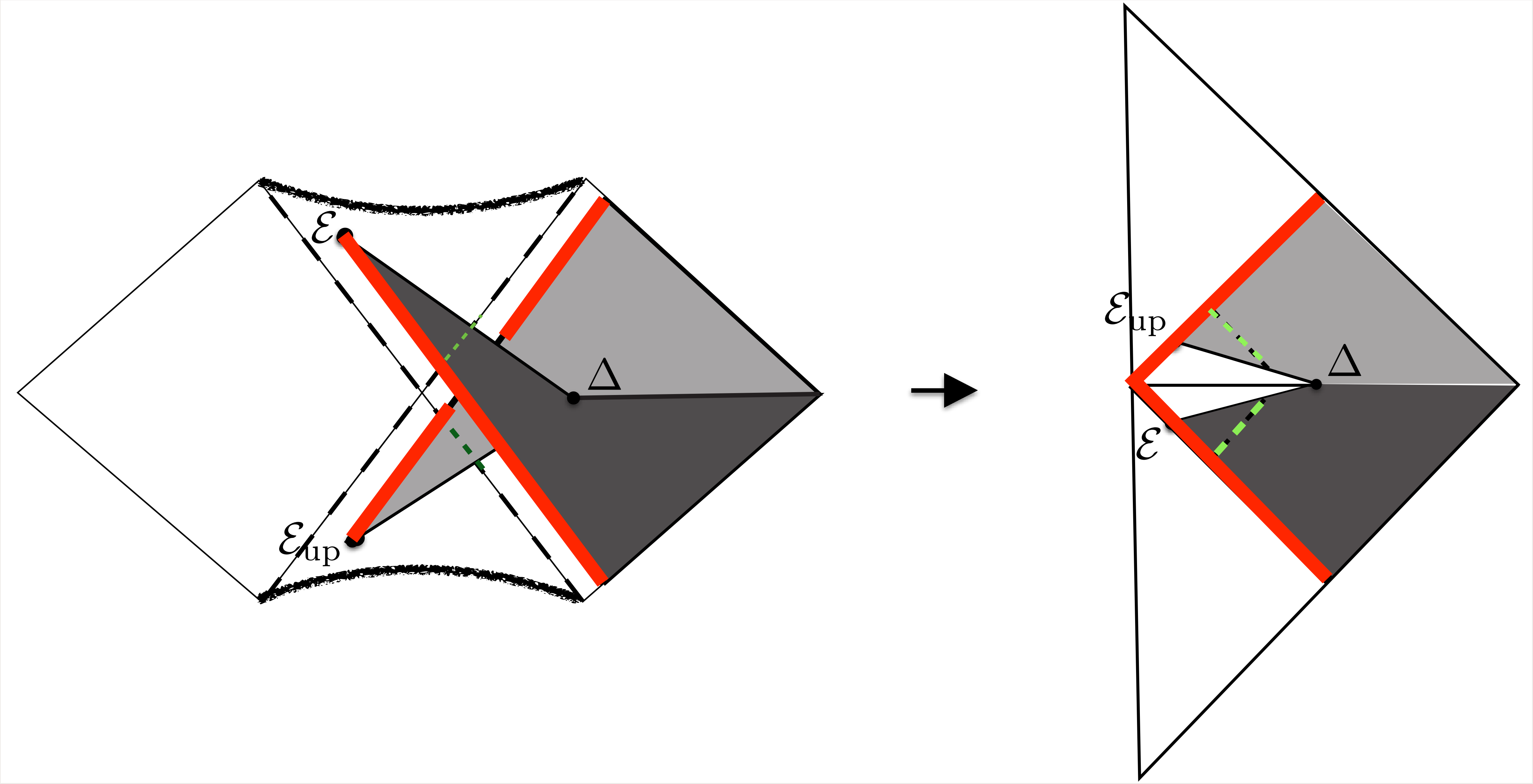
seems impossible, because

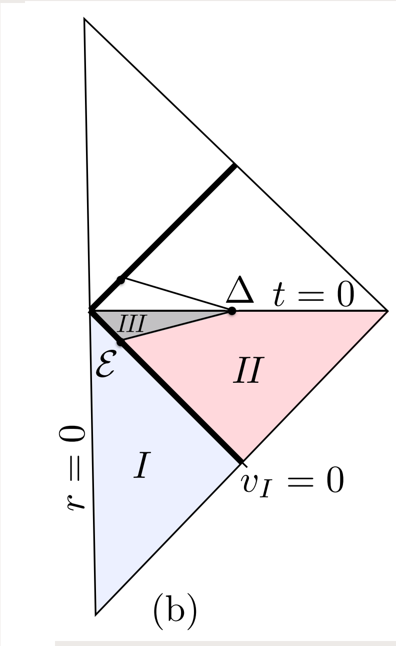
in a Kruskal diagram the white hole

is before, not after the white hole!



The Fingers Crossed





Full metric: join the pieces

[Haggard CR 14]

Spherical symmetry:

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

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

Bounded by: $v_I < 0.$

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

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

The metric is determined by the constants: m, v_o, δ, ϵ

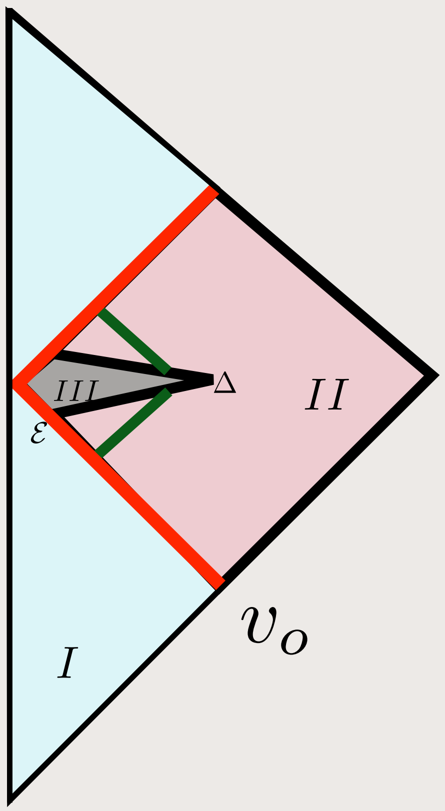
The metric is determined by four constants: m, v_o, δ, ϵ

- m is the mass of the collapsing shell.

- ϵ is the radius where quantum effect start on the shell $\epsilon \sim \left(\frac{m}{m_P^3}\right)^{\frac{1}{3}} l_P.$

- δ 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 he order of ~ 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 <u>two</u> possible quantum effects:

(i) when Curvature $\sim (L_P)^{-2}$

(ii) when Curvature $\times$ (time) $\sim (L_P)^{-1}$

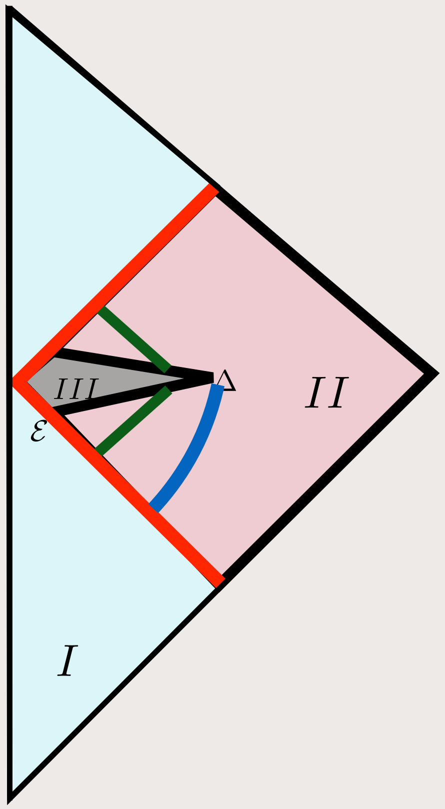
"Classicality parameter" $\quad q = l_P\, \mathcal{R}\, \tau.$

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

$$R = \frac{7}{6}\ 2m$$

And the time $\quad \tau = 2c\ \frac{m^2}{l_P}.$

Which in turn give $\quad v_o \sim e^{-c\ \frac{m}{2l_P}}, \qquad \delta \sim \frac{m}{3}.$



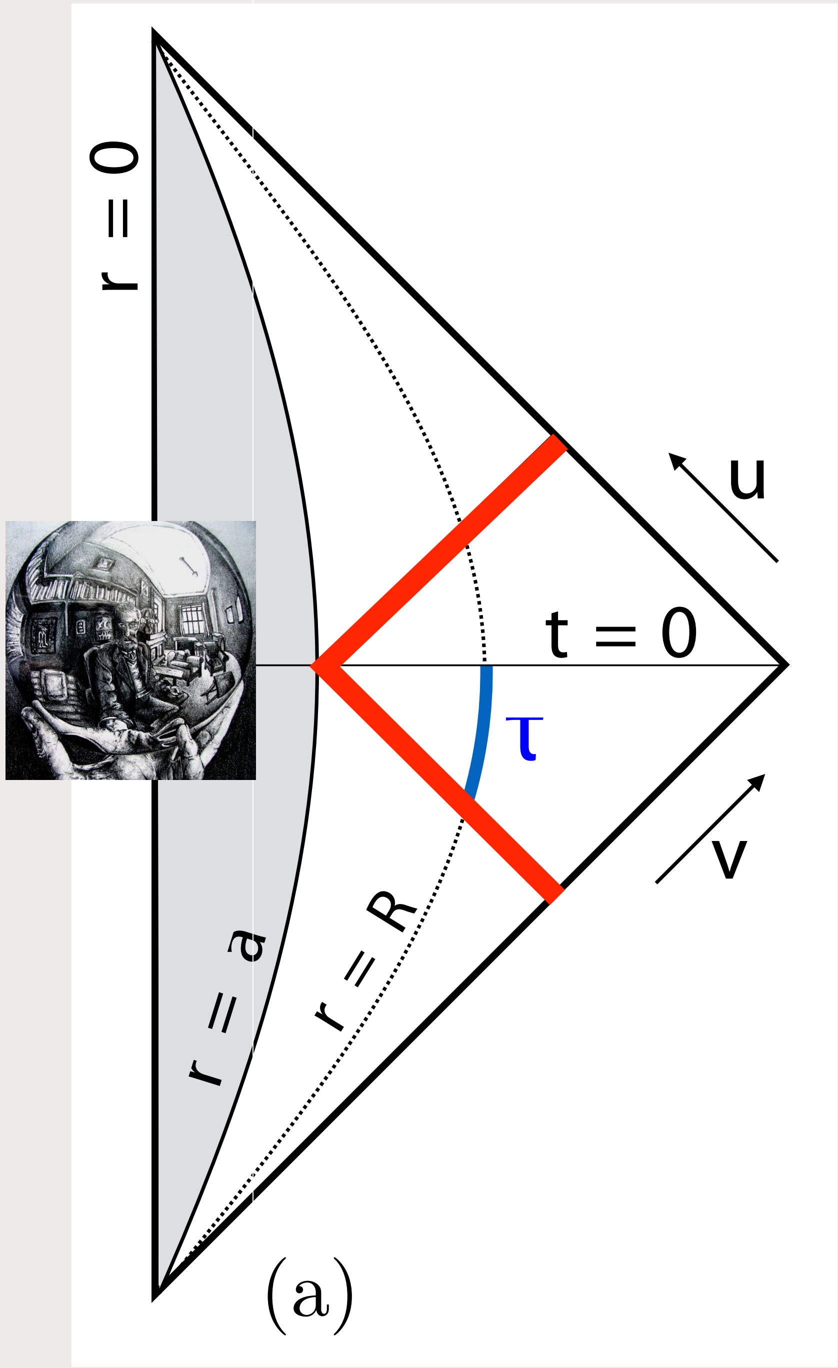
The metric is entirely determined by the mass.

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 ?

The Crystal Ball



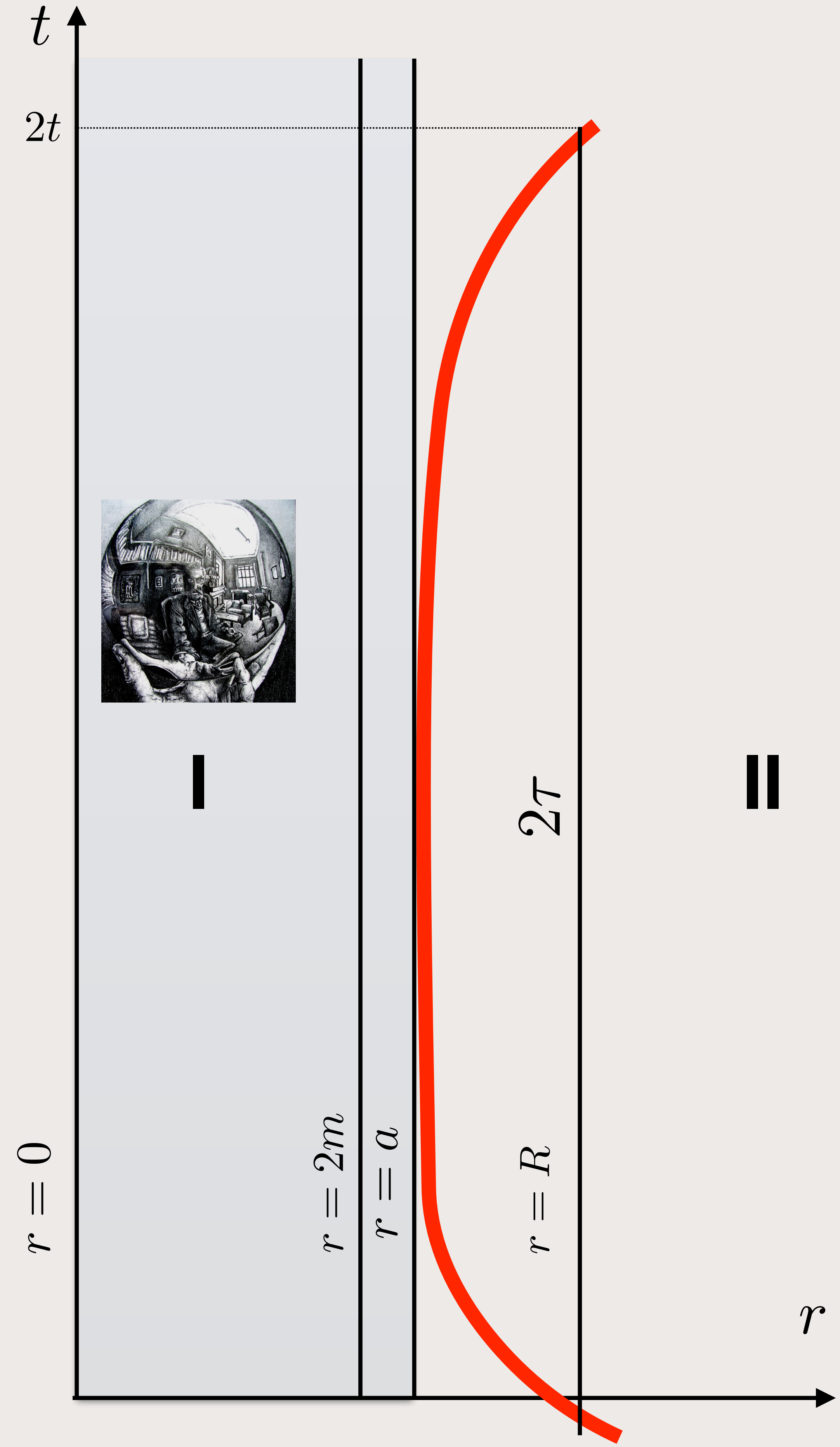
A simple straightforward calculation in the Schwarzschild metric shows that:

at fixed R, when a approaches $2m$,

τ 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.

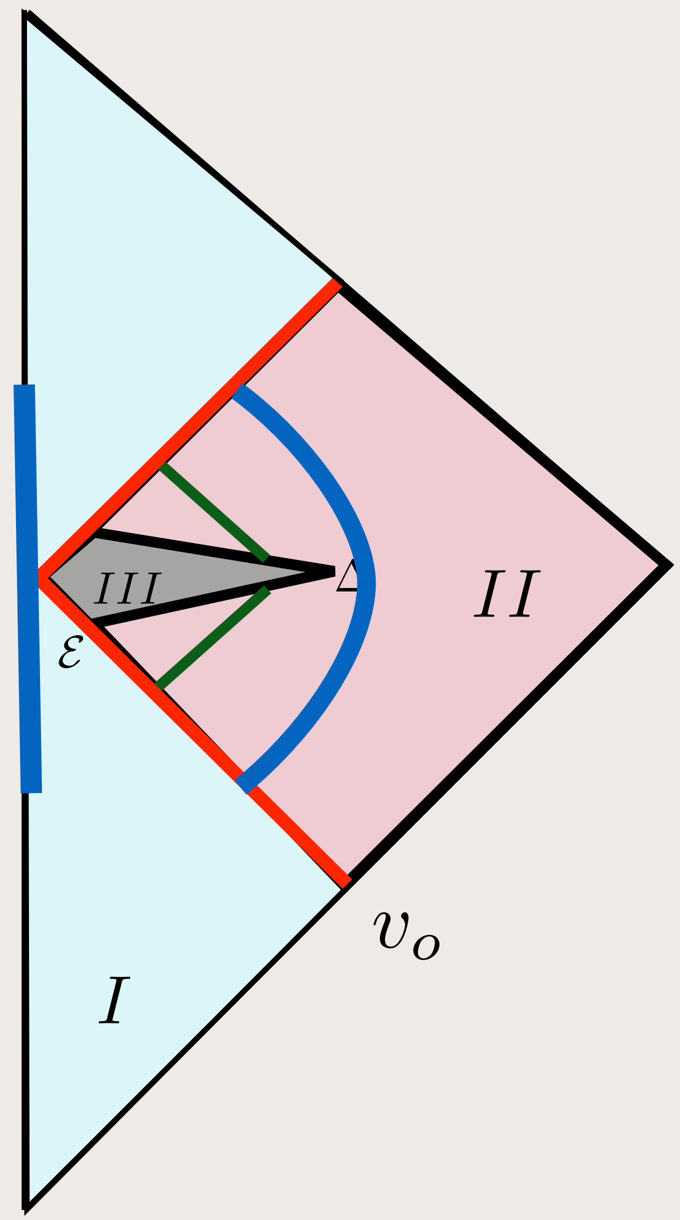
While the internal proper time is arbitrarily short.

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

$$t = R - a$$

Time dilation

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



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

“A black hole is a short cut to the future”

Can all this be observable?

[Vidotto CR, 2014. Barrau CR, 2014]

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

Primordial black holes!

The mass of a primordial hole exploding now,

$$m \sim \sqrt{\frac{t_{Hubble}}{t_{Planck}}}\, m_{Planck} \sim 10^{23}\, Kg$$

The radius,

$$r \sim \sqrt{\frac{t_{Hubble}}{t_{Planck}}}\, l_{Planck} \sim 1\, mm$$

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

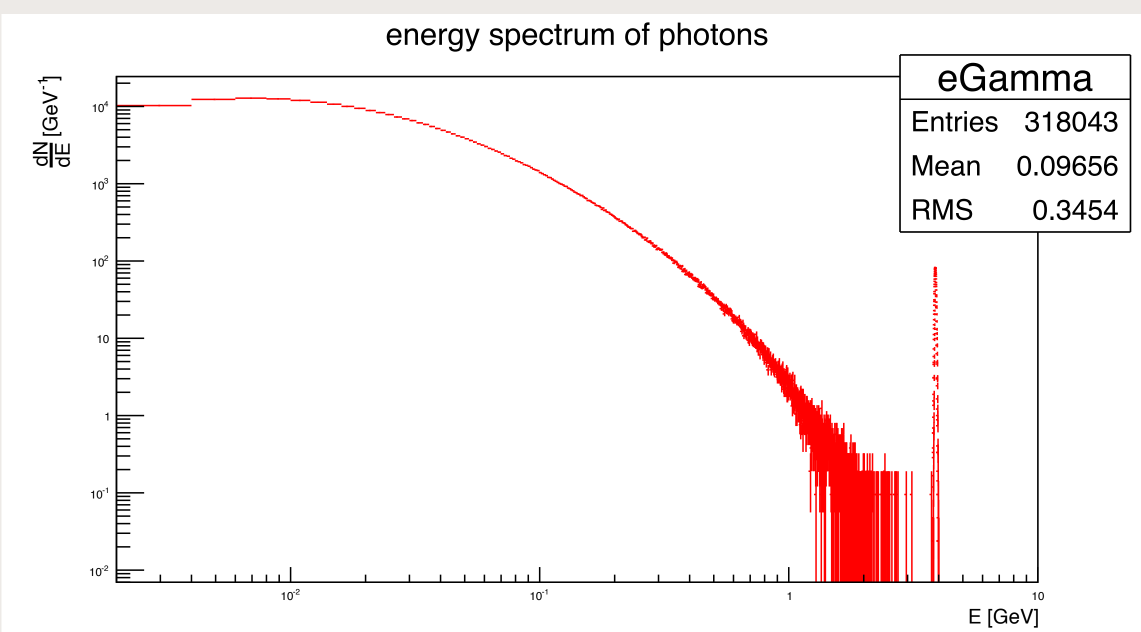
$$\frac{t_{Hubble}}{t_{Planck}} \sim 10^{60}$$

What is the relation between quantum gravity ($l_{Planck} \sim 10^{-33}$cm) and radio waves ($\lambda \sim 1$ mm) ??

$$\lambda \sim \sqrt{\frac{t_{Hubble}}{t_{Planck}}}\, 10^{-33}\, cm \sim 1\, mm$$

Detectable? High energy component

The energy of the photons trapped into the hole remains constant: at collapse time it was comparable with the Hubble radius. This gives an energy in the Tev range at emission. A component of short gamma ray bursts?



~10 MeV

From ~200 light years

Isotropic

One event per day

[Vidotto CR 2014]

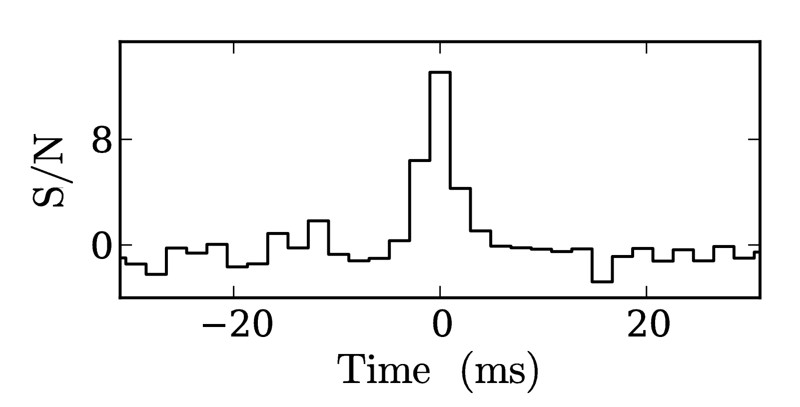
[Barrau CR 2014]

Detectable? Low energy component [Barrau,Vidotto, CR 14]

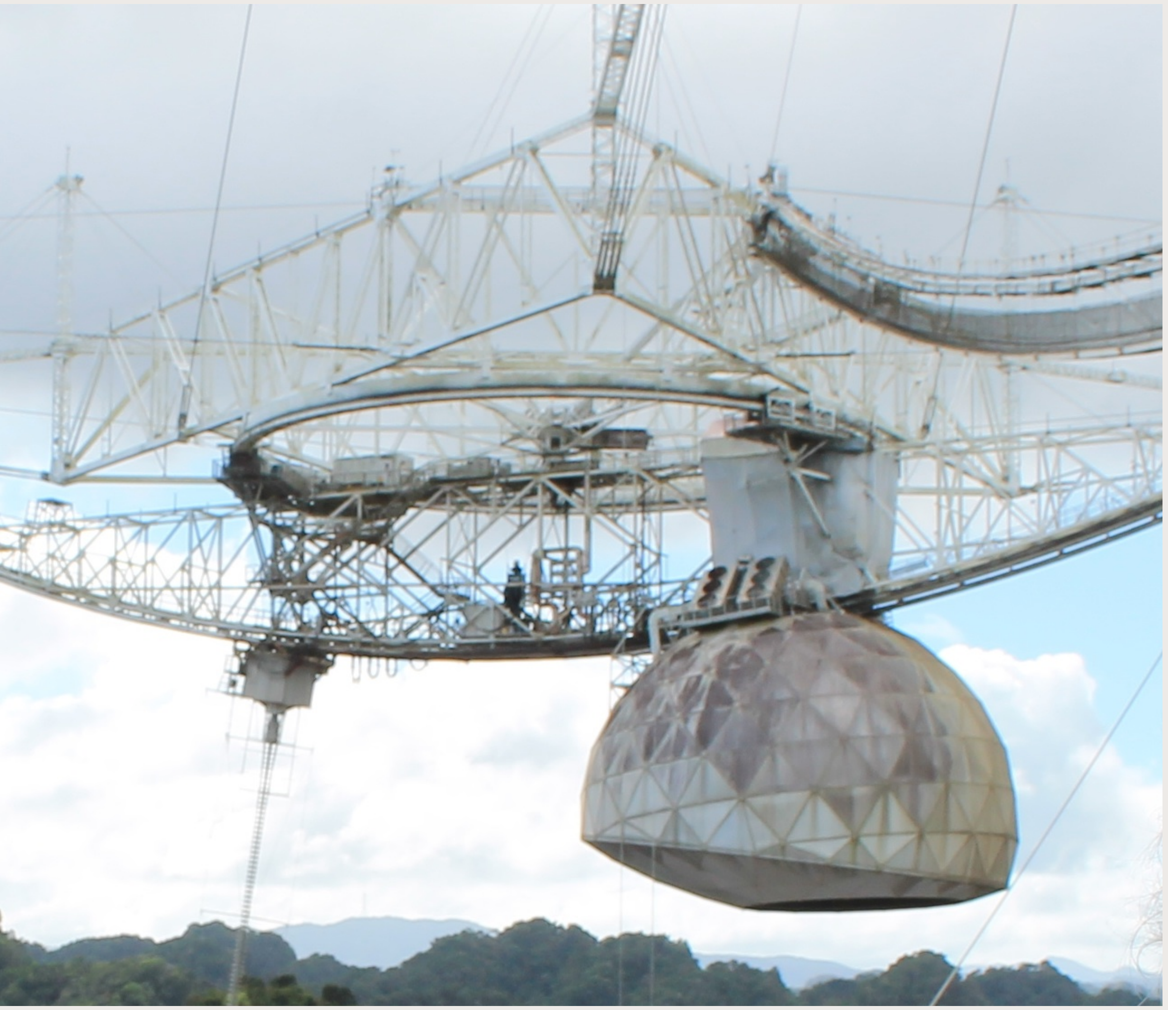
Predicted :

- **Powerful bursts of short duration**
- **Extragalactic**
- **Wavelength ~ 1 cm**

Fast Radio Bursts



The FRB 121102 event
seen by the Arecibo observatory



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

Detectable? Low energy component

Predicted :

- Powerful bursts of short duration
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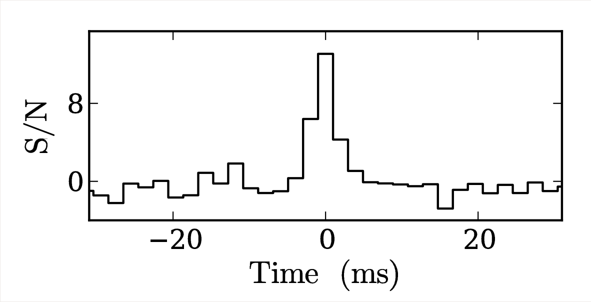
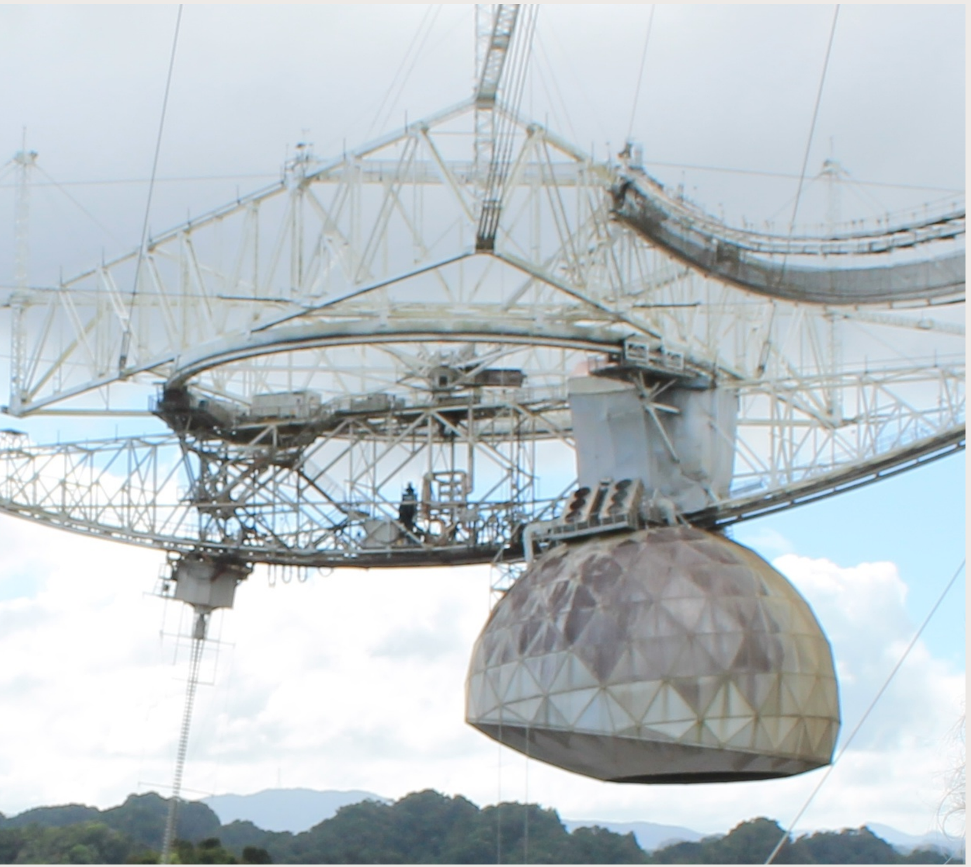
- Wavelength ~ 1 cm

Observed :





- Observed at: Parkes, Arecibo
- Duration: ~ milliseconds
- Origin: Likely extragalactic
- Wavelength: ~ 20 cm
- Estimated emitted power: 10^{38} erg
- Physical source: unknown.

Main message:

Consider the possibility that this (or similar) signals be of quantum gravity origin.

Summary I : Main technical result

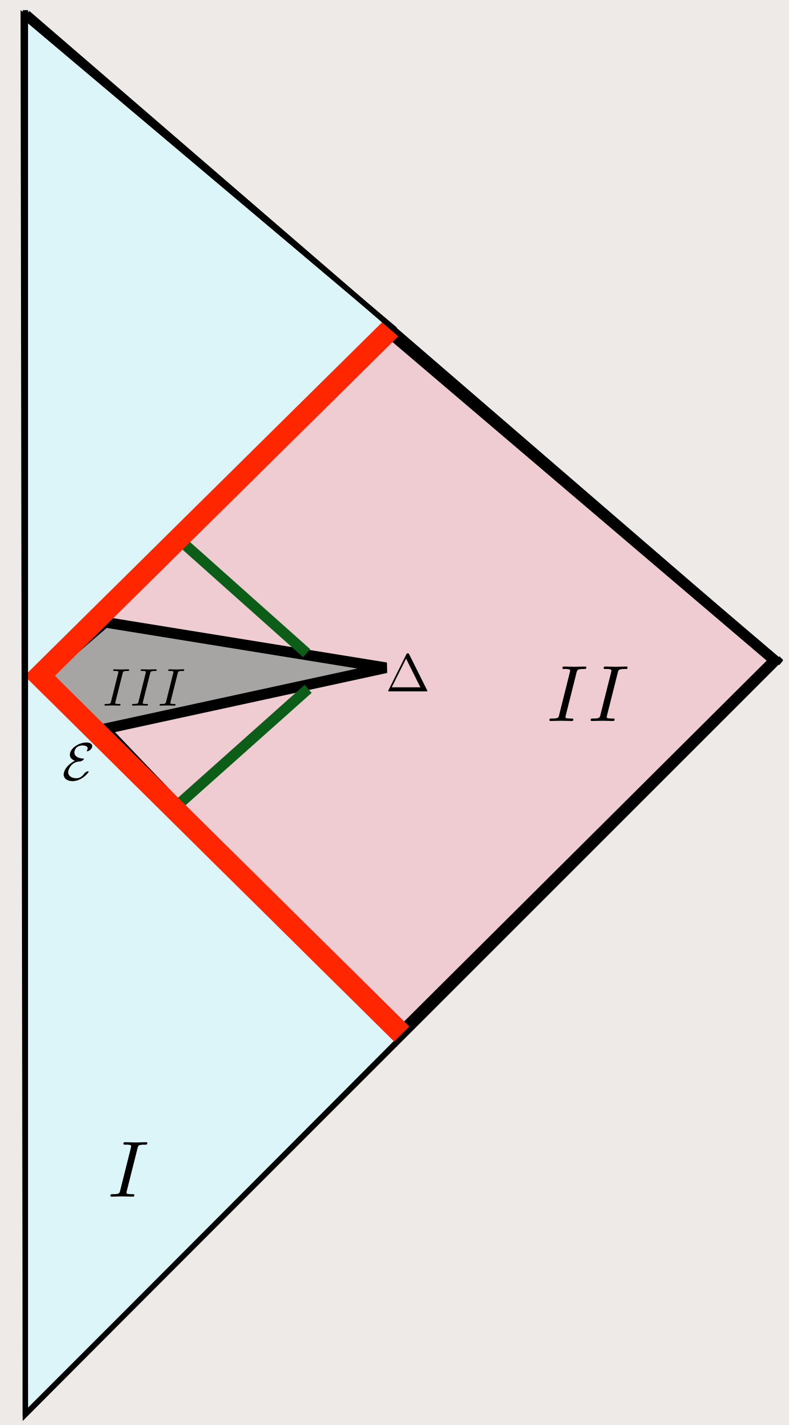
There is an exact solution of the classical Einstein equations which is everywhere vacuum, except for

- an incoming (collapsing) shell,

- an outgoing (exploding) shell, and

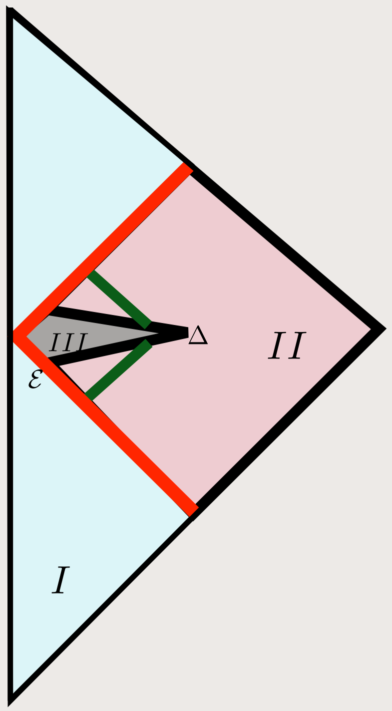
- a <u>finite</u> region is space and time.

I	***Minkowski***
II	***Schwarzschild***
III	***Quantum region***

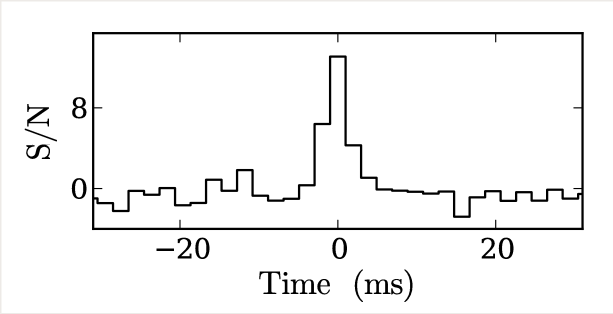


Summary II: a physical scenario

- **Incoming phase: black hole,**
  Outgoing phase: white hole
- **No singularity. 2 trapped regions.**
  Information preserved.
- **Time dilation. Rapid bounce, order m, but from the outside, long proper time, order m². (For a stellar black hole, *m* is microseconds, m² is billions of years).**



"A black hole is a bouncing star seen in super-slow motion".



$$\frac{t_{Hubble}}{t_{Planck}} \sim 10^{60}$$

The FRB 121102 event
seen by the Arecibo observatory

- **Observable?**
- **Primordial black holes**

Summary III: physical messages

i. Quantum gravity can set-in when a star is 20 orders of magnitudes larger than the Planck scale.

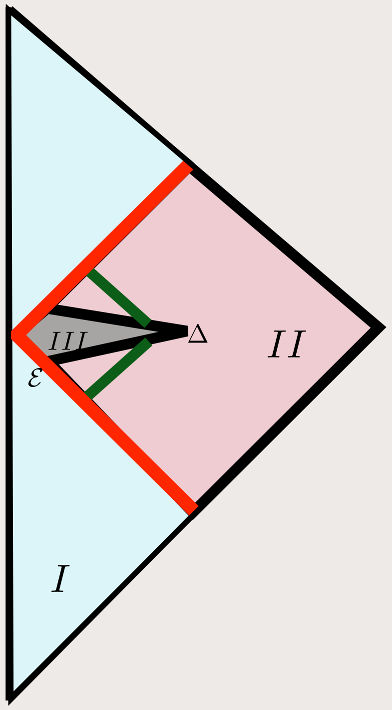
ii. White holes solutions are likely to describe spacetime after the the quantum region.

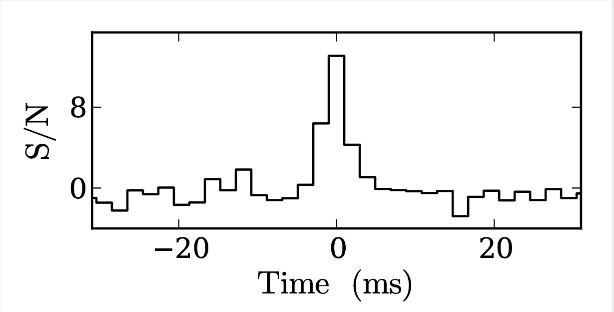
iii. There is no reason that nothing quantum happens before the (immensely huge) Hawking evaporation time.

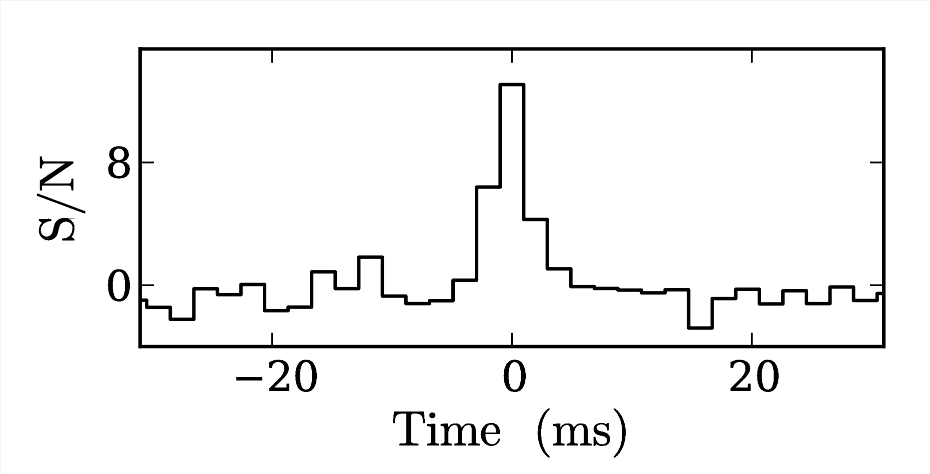
iv. Time inside a Planck star is very different from time outside it: a black hole can be a bouncing star seen in super-slow motion.

v. High energy gamma ray bursts may carry quantum gravity signals from exploding primordial black holes.

vi. Radio/infrared signals might be related to exploding primordial black holes.







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Could this be a quantum gravity signal?

?