Planck Stars:

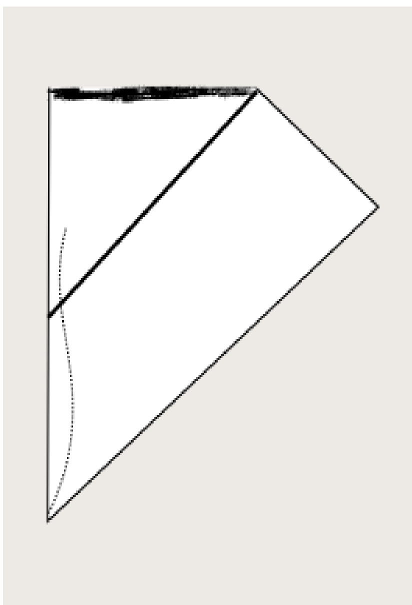
Black-to-white hole tunnelling and Fast Radio Bursts

Carlo Rovelli

Collaborators

Main idea: **Francesca Vidotto**
Classical solution: **Hal Haggard**
Phenomenology: **Aurélien Barrau**, **Francesca Vidotto, Boris Bolliet, Celine Weimer**

(cfr intro talk Akim Kempf)



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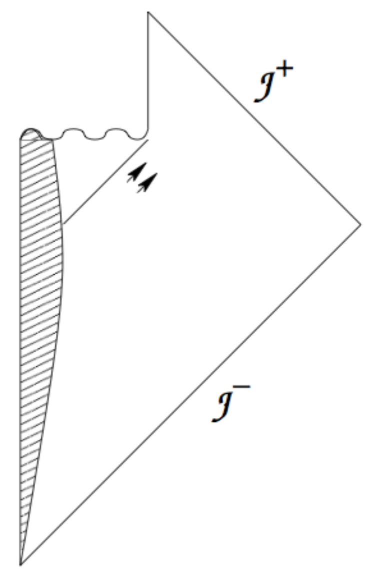

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What is the final fate of a black hole?

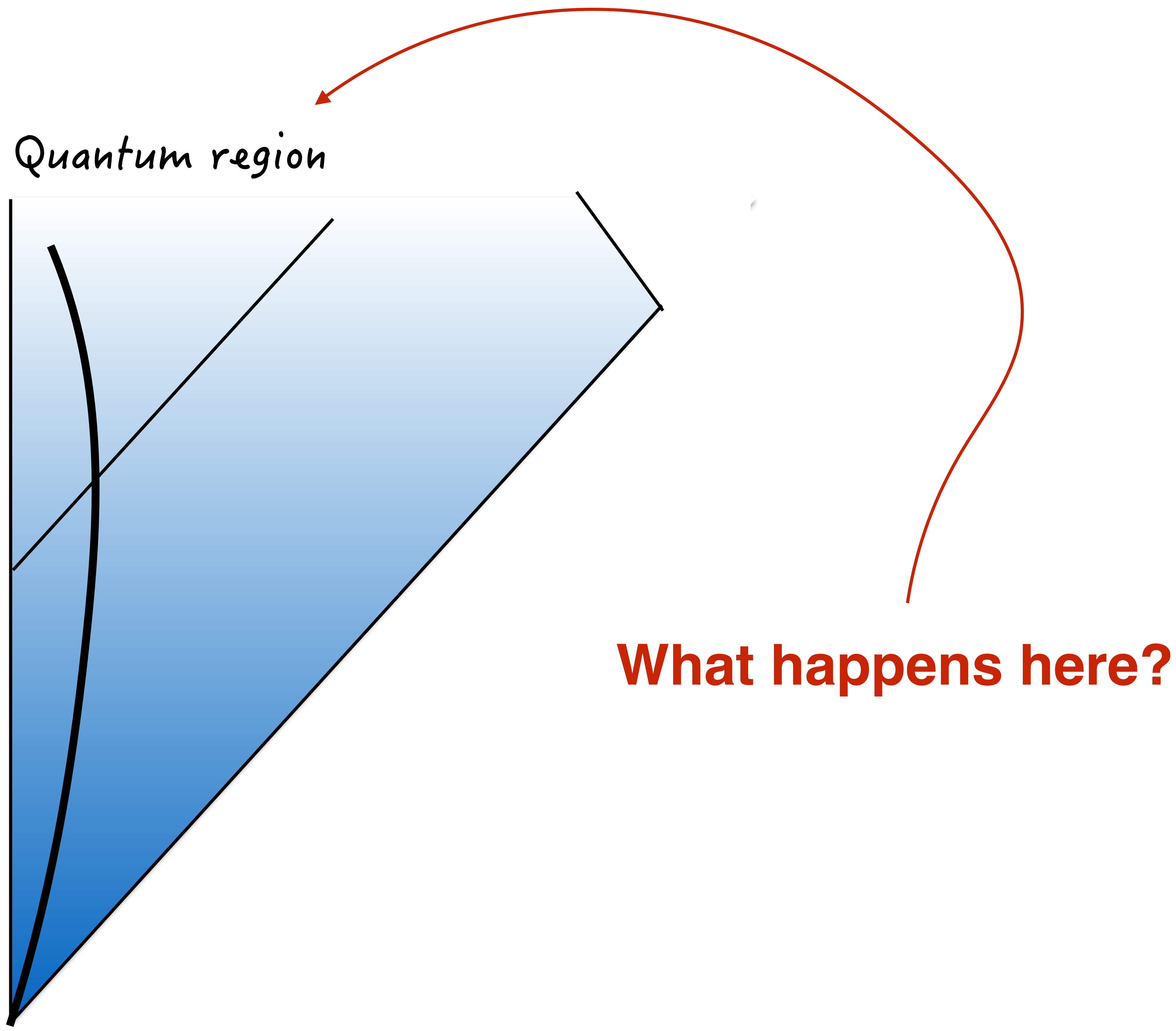
What does **actually** happen at the classical singularity?

What do we miss? Quantum gravity

Quantum gravity is **not**
quantum field theory on a geometry!

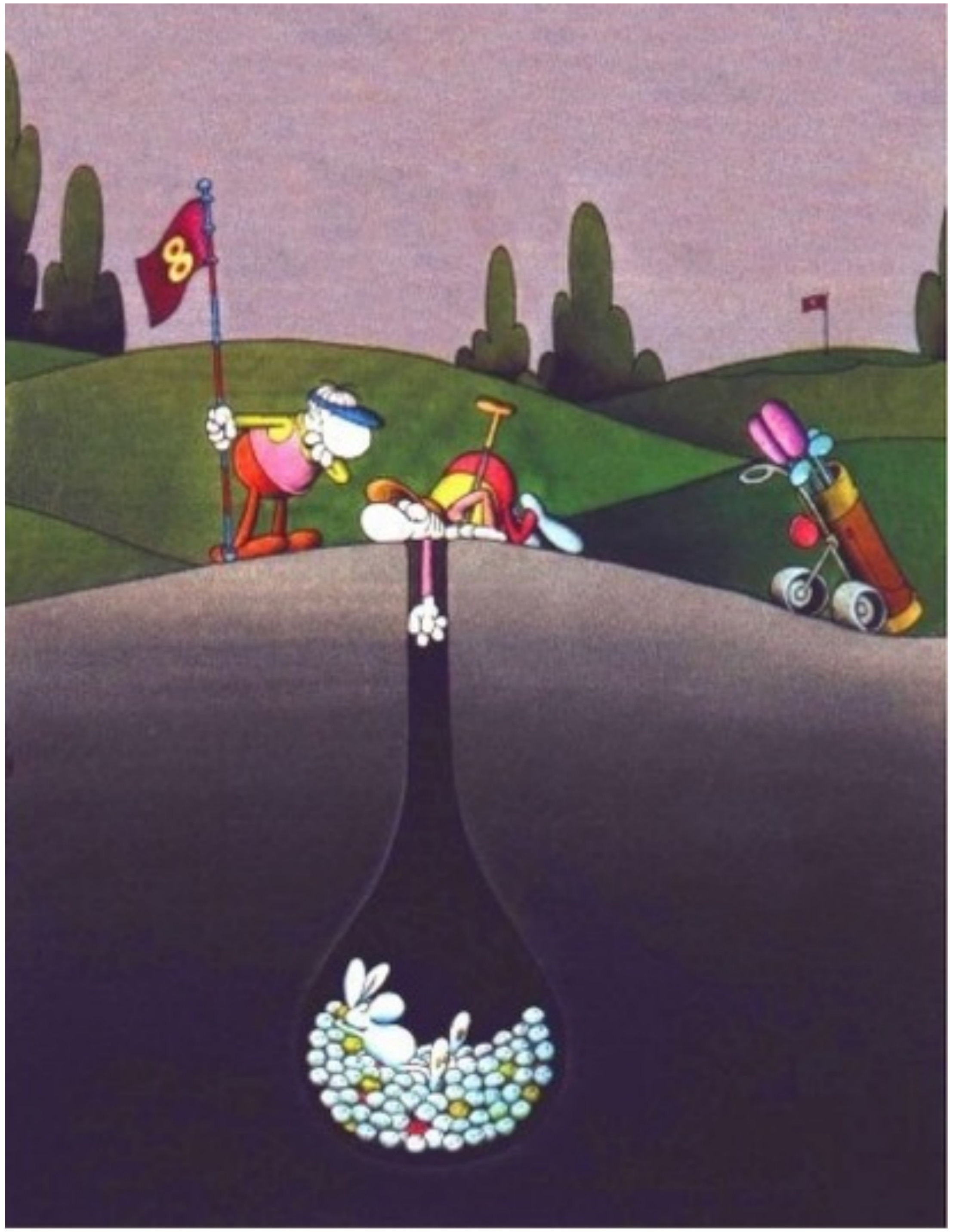
Quantum gravity is
the quantum theory of the geometry

Difficulties remain until we keep thinking
about a classical spacetime and qft over it


Quantum region
What happens here?

General relativity does **not** teach us that there is a singularity

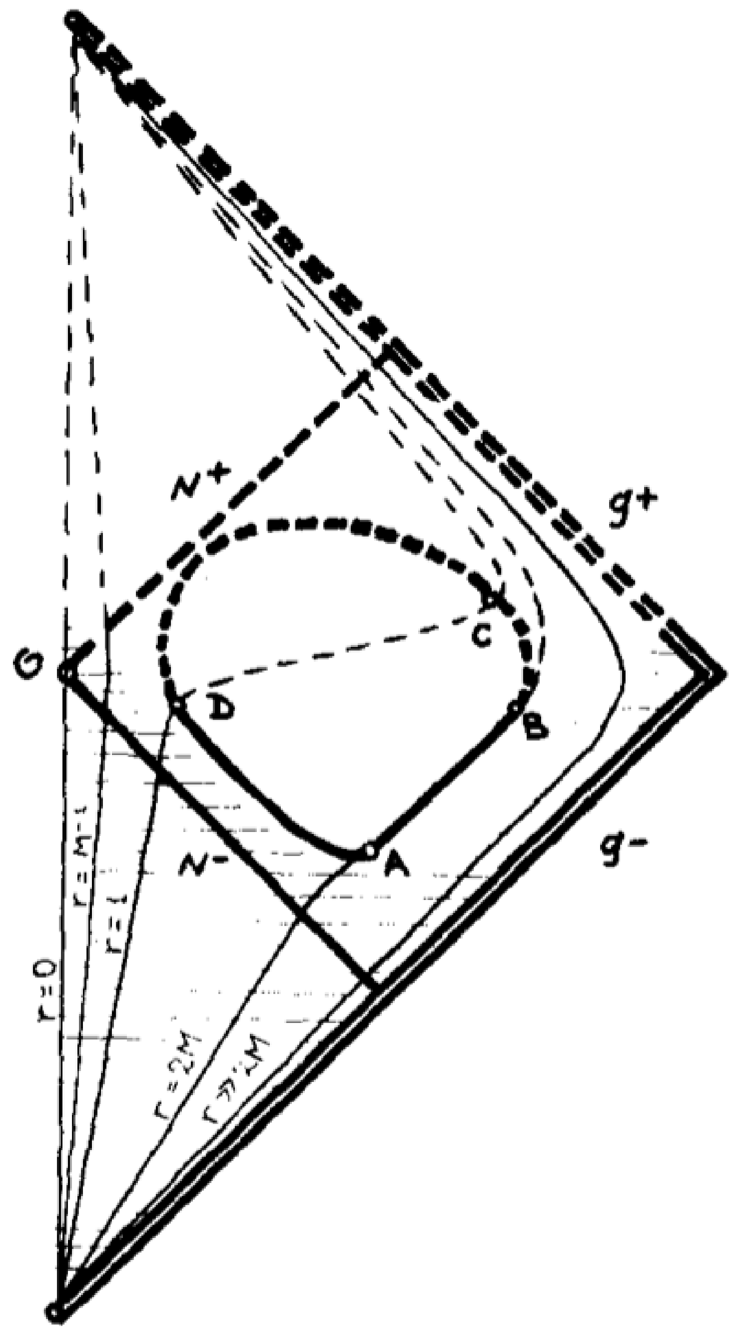
General relativity does teaches us that there is new physics there

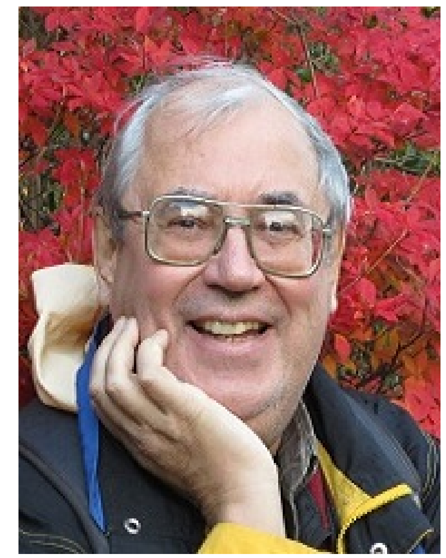


What happens to the matter falling into black holes?

- It disappears (?)
- It creates“another universe” (Smolin)
- It stays there forever (nothing is forever)
- It comes out.

At MG2 and in a paper ’79-’81

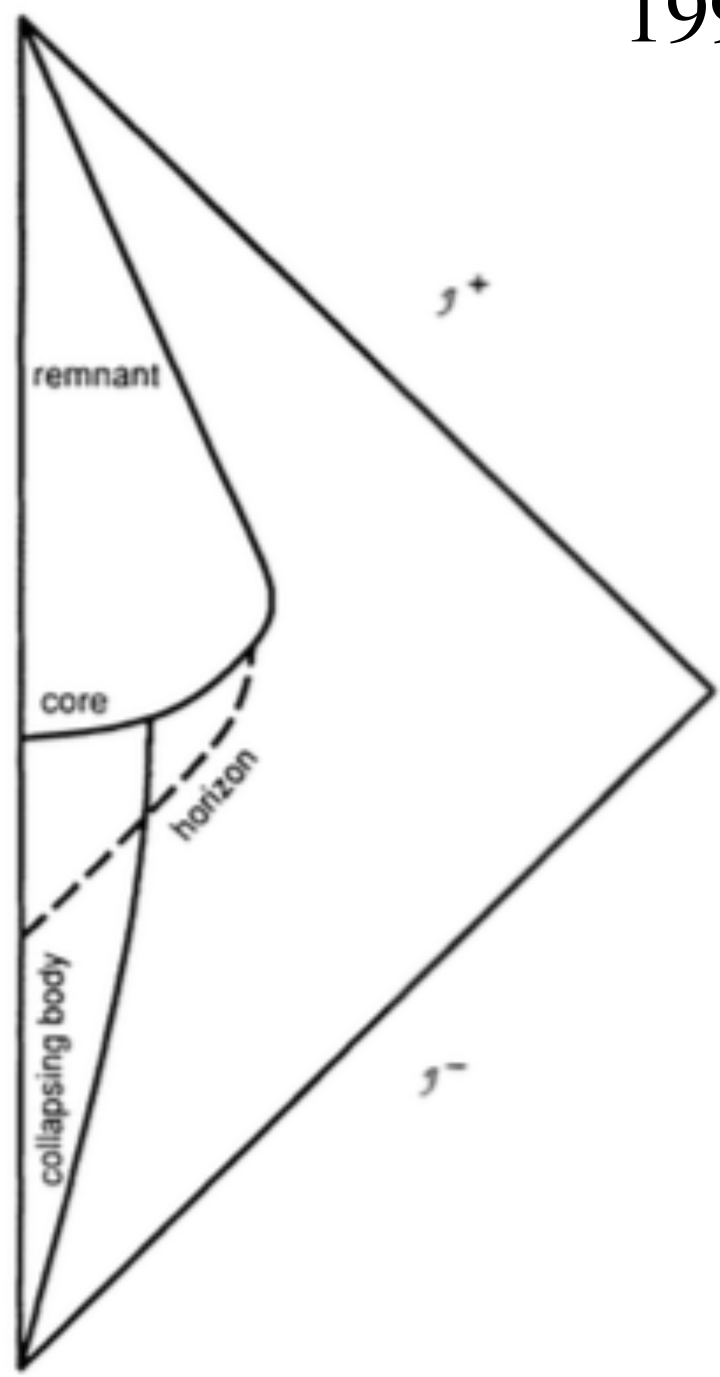




Valeri Frolov

Grigori A. Vilkovisky (left)

1992: remnants



Steve Giddings

In ’93

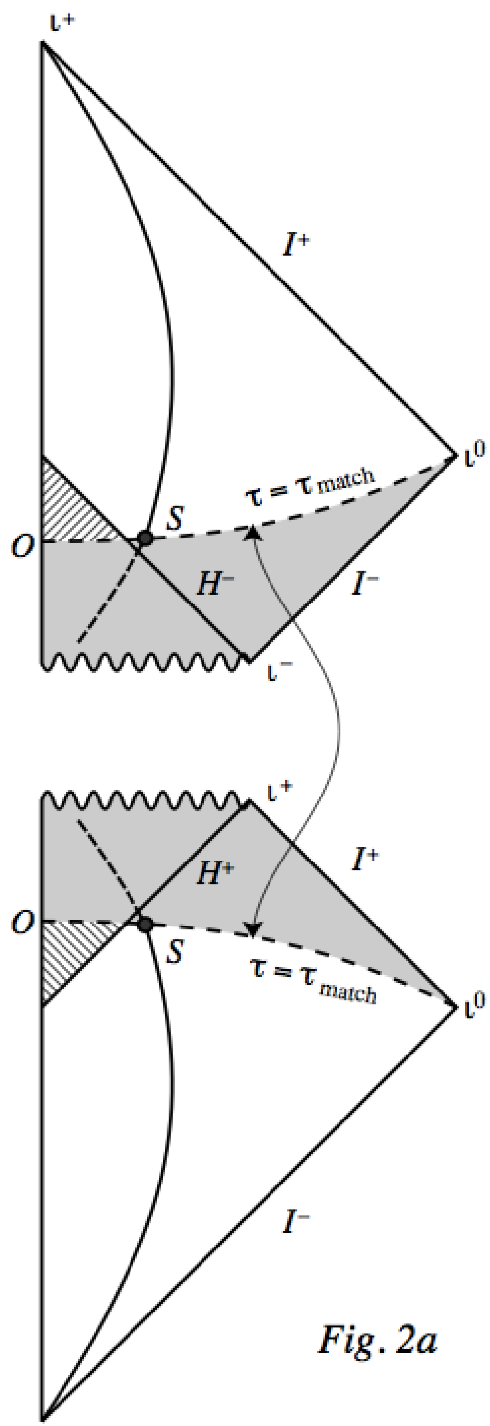


Fig. 2a

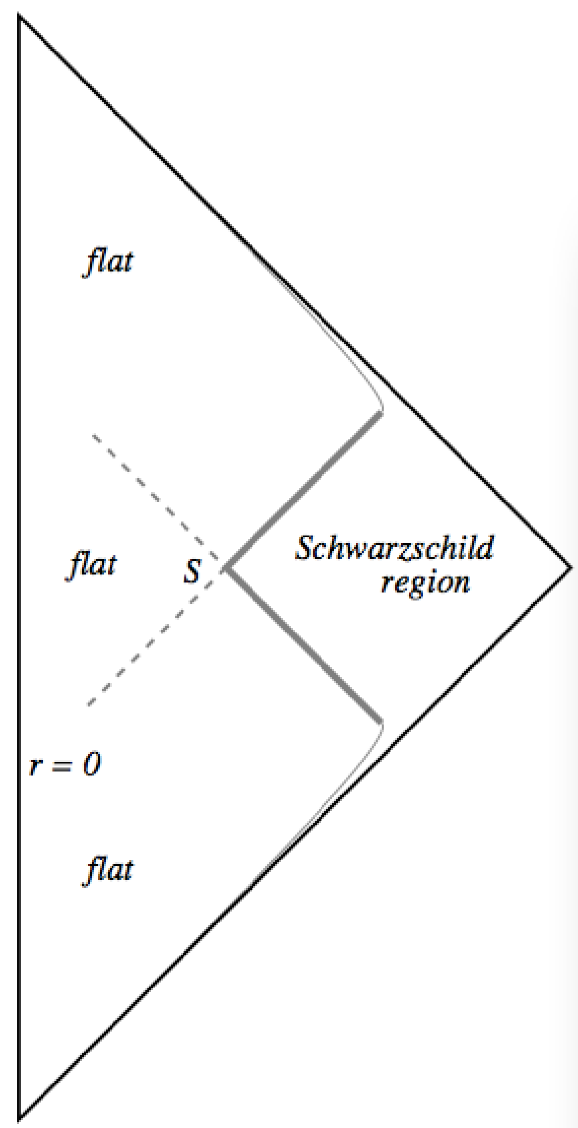
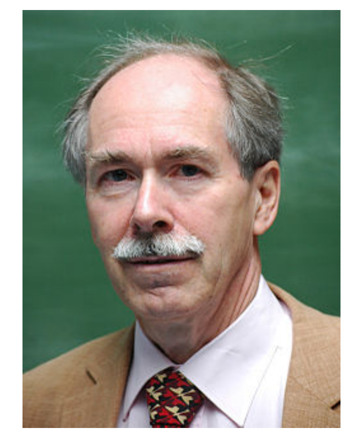
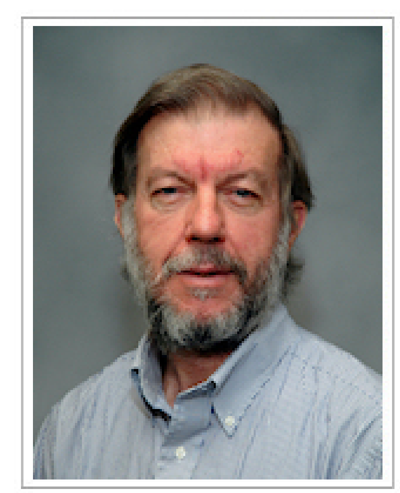


Fig. 2b

Cristopher R. Stephens

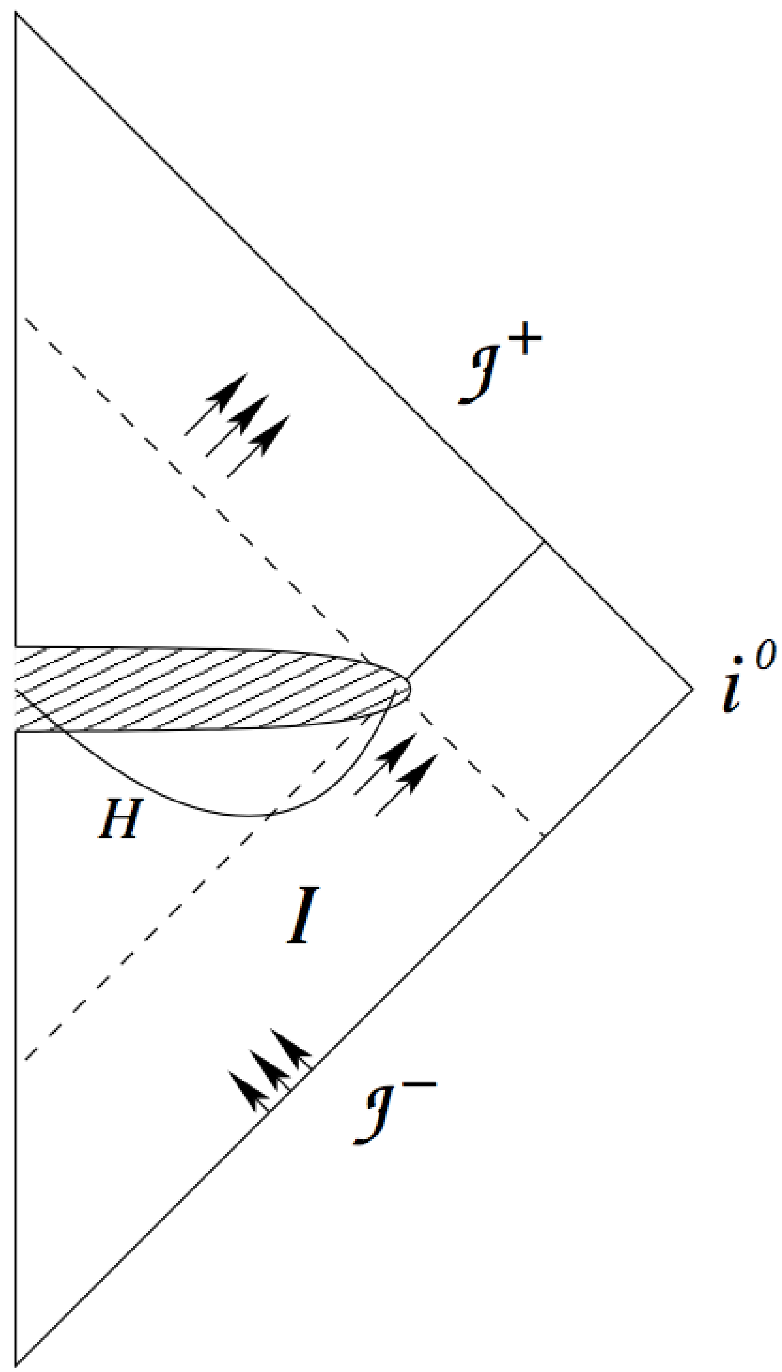


Gerard ’t Hooft



Bernard F. Whiting

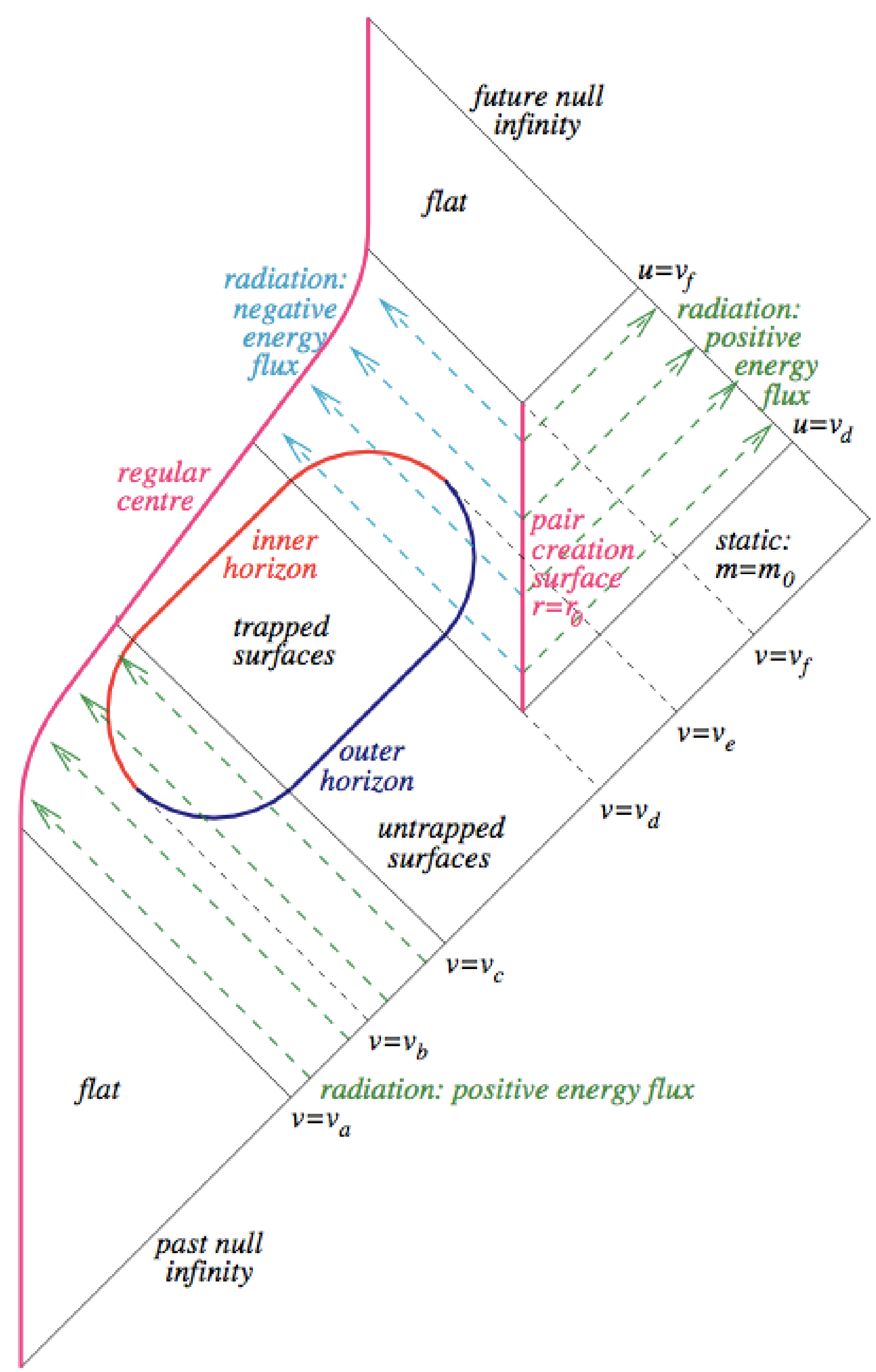
In '05



Abhay Ashtekar

Martin Bojowald

Sean A. Hayward in '06



cfr Sven Koppel

Also:

P. Nicolini
B. Carr
L. Modesto
I. Premont-Schwarz
S. Hossenfelder
J. M. Bardeen
G. Ellis
…

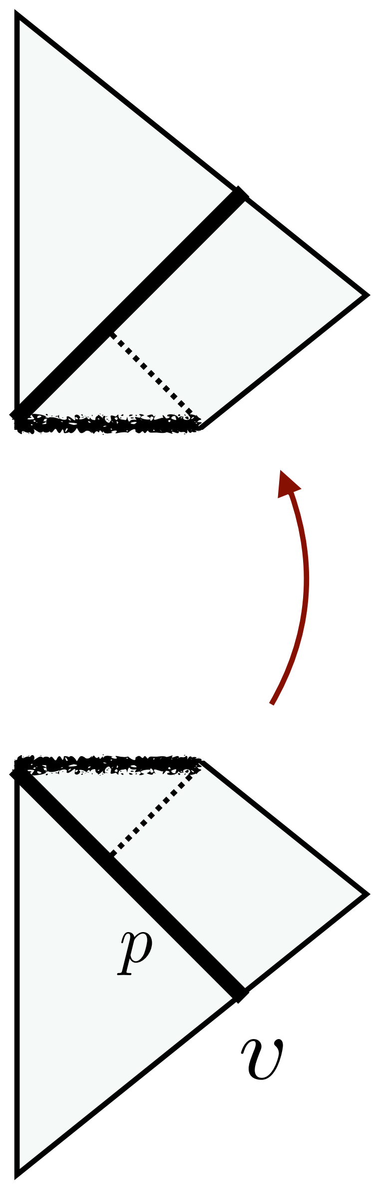
(cfr G Ellis)

(cfr Bernard Carr:
Loop Black Holes)

Quantum mechanics is still missing

The Hajicek-Kiefer bounce

Singularity avoidance by collapsing shells in quantum gravity
Petr Hájíček, Clauss Kiefer.
IJMP D, (2001), 775.



- Spherical symmetry

- Null shell of matter

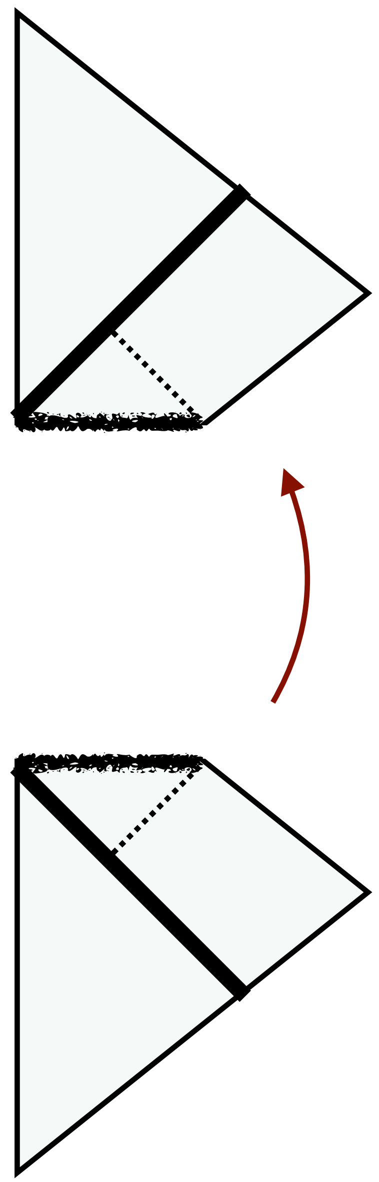
- Classically: Finite dimensional phase space (v,p) separated in two disconnected components:

    - p>0: shell collapsing into white hole (future singularity)

    - p<0: shell emerging from a white hole (past singularity)

- Formal quantization: transition between the two components

- Can a black hole truly tunnel into a white hole?



Intriguing aspects:

- Classical stable objects often unstable via quantum effects (cfr. nuclear decay).

- Hawking radiation takes a huge amount of time ($t \sim m^3$) and is not a full quantum gravitational phenomenon.

Difficulties:

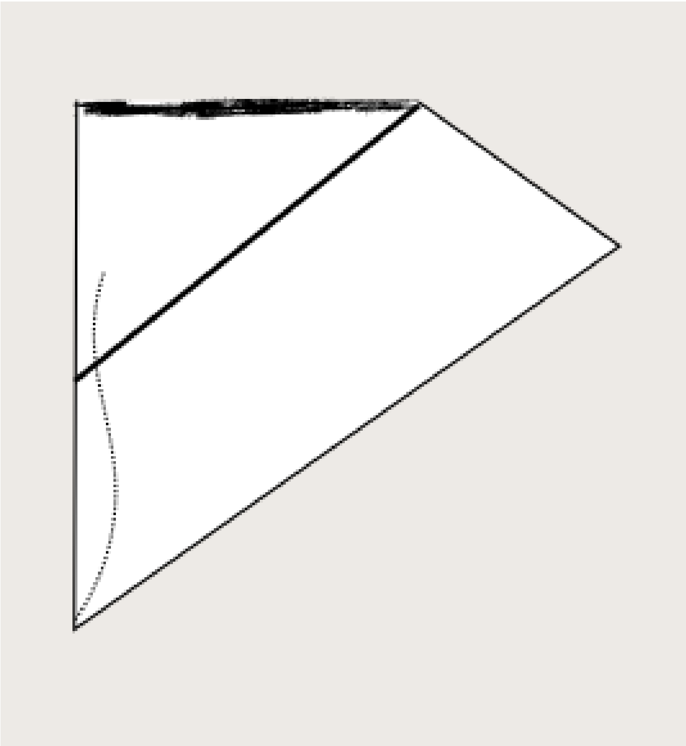
- Two distinct asymptotic regions.

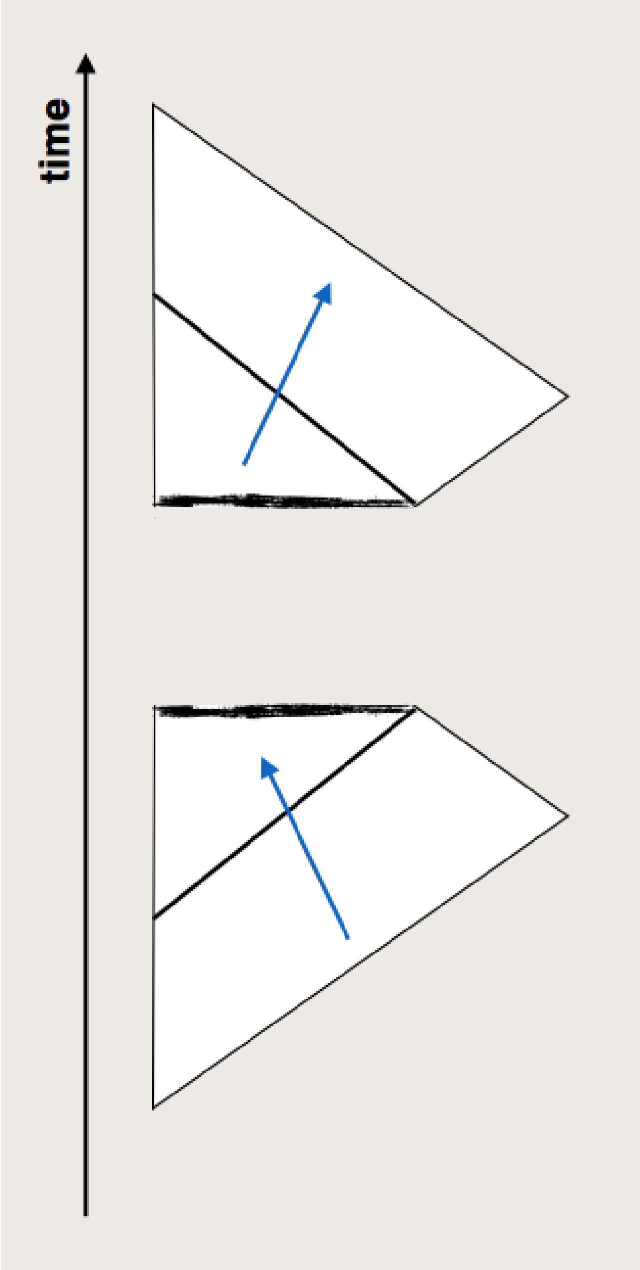
- A quantum jump involving the entire universe.

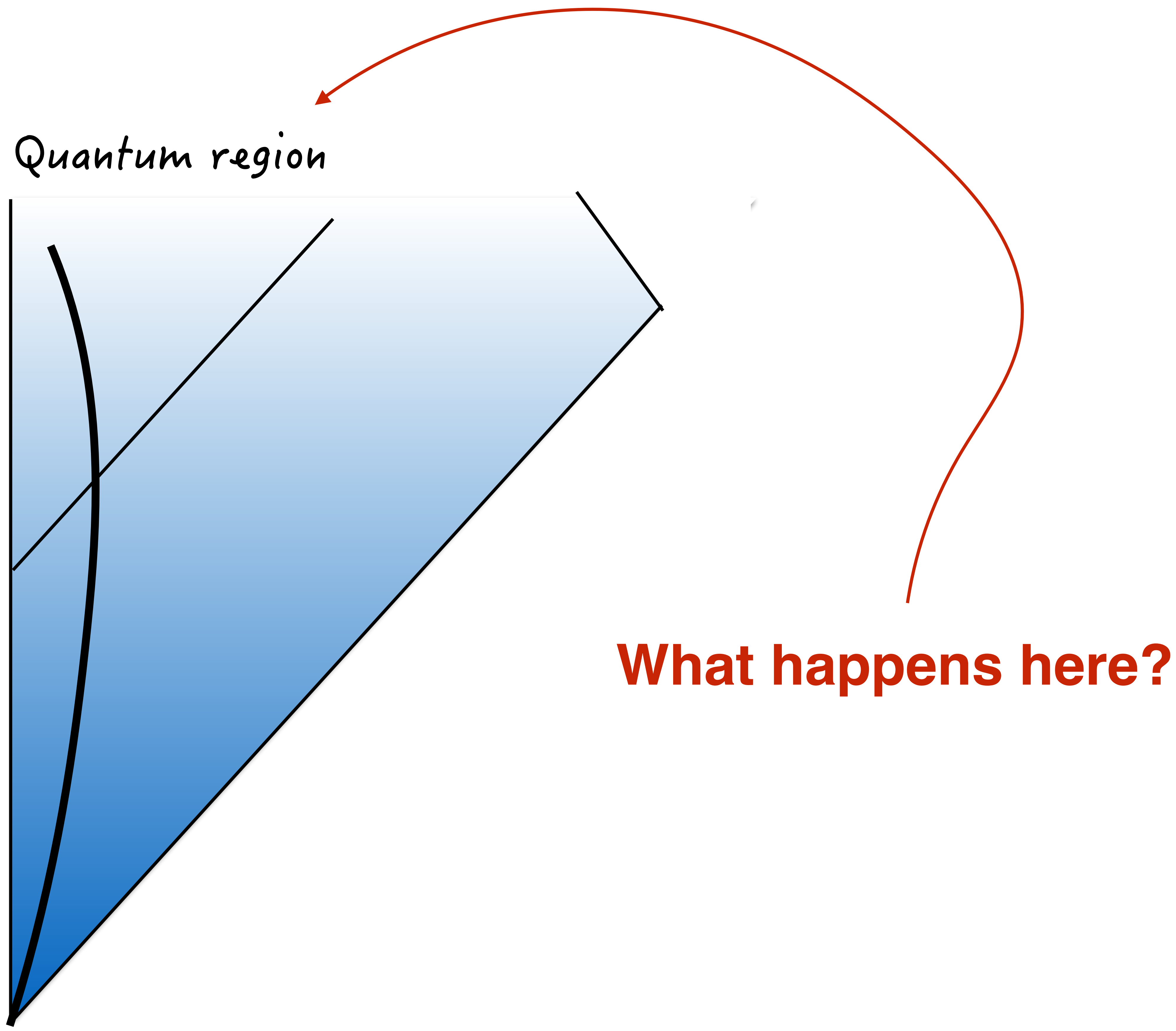
- What could determine the tunneling time?

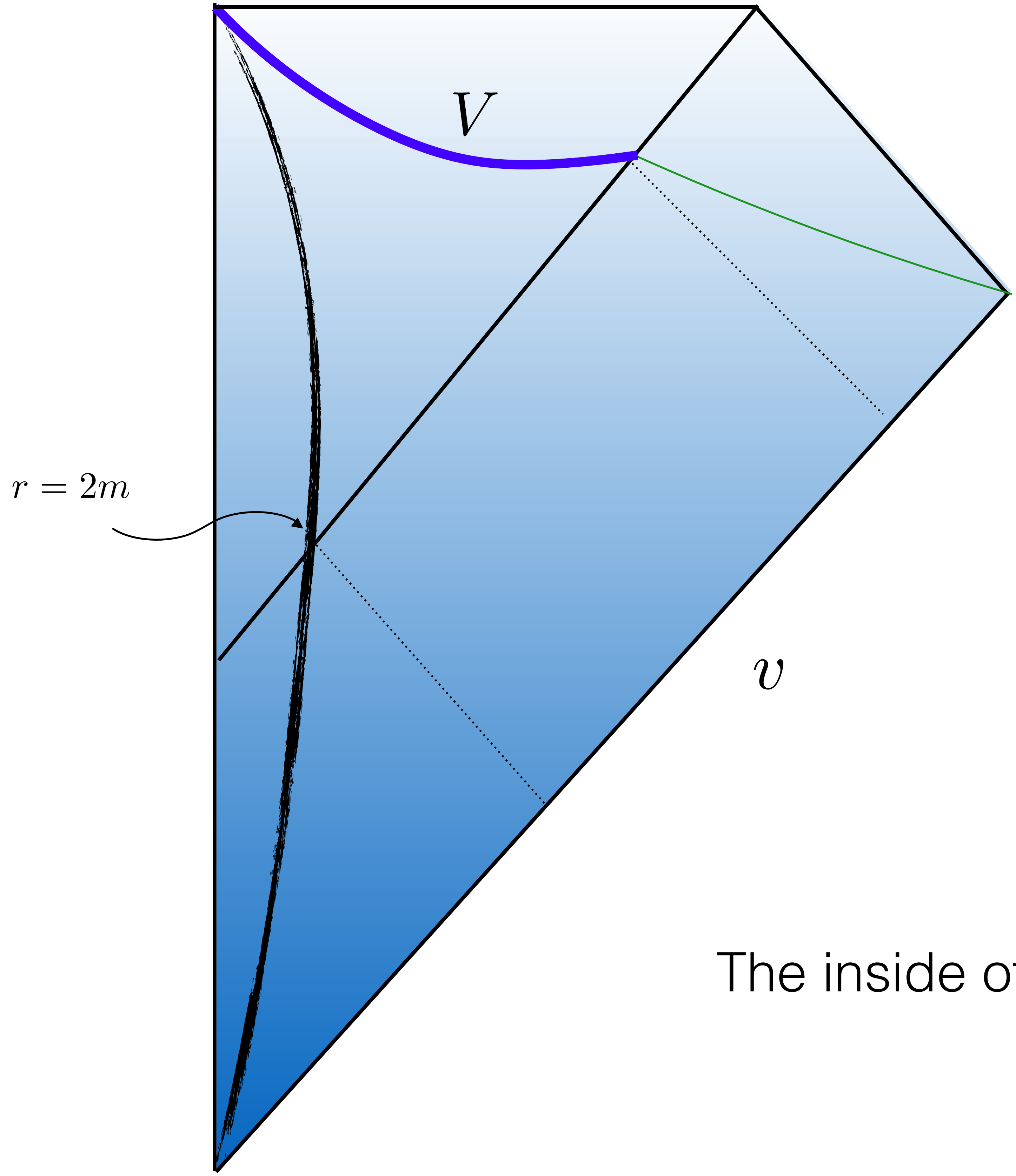
A clear theme emerges from these spacetime diagrams:

♦ build a time symmetric model






Quantum region
What happens here?



How big is a black hole?
Marios Christodoulou, Carlo Rovelli.
Phys.Rev. D91 (2015) 6, 064046

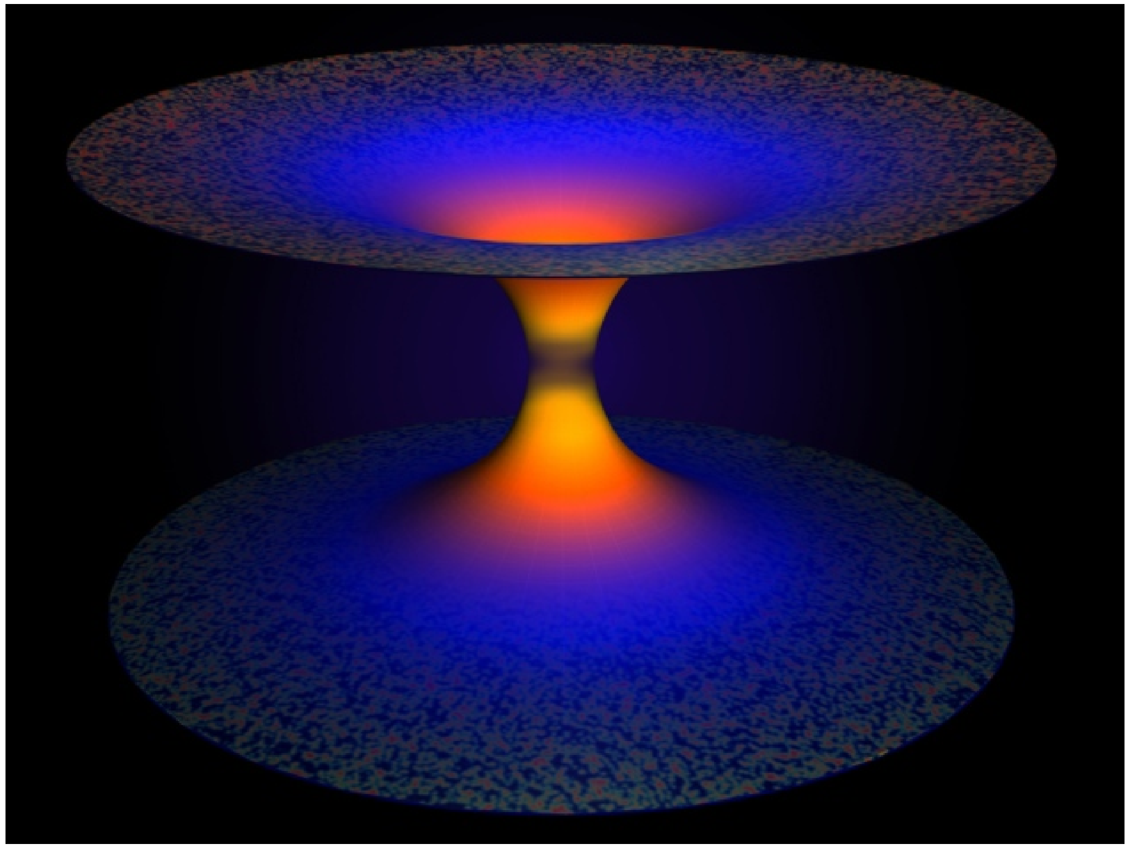
$$V \sim 3\sqrt{3}\,\pi\, m^2 v$$

The inside of a black hole is very large

From Loop Quantum Cosmology:

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

Pressure develops when
matter density reaches
The Planck density



Planck density does not mean Planck size !

(cfr Bernard Carr)

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

Planck length	**Planck star**	black hole	star	
10^{-33}	**10^{-12}**	**10^{5}**	**10^{13}**	cm
$R \sim 1$	$R = m^{\frac{1}{3}}$	$R = 2m$	$R \gg m$	

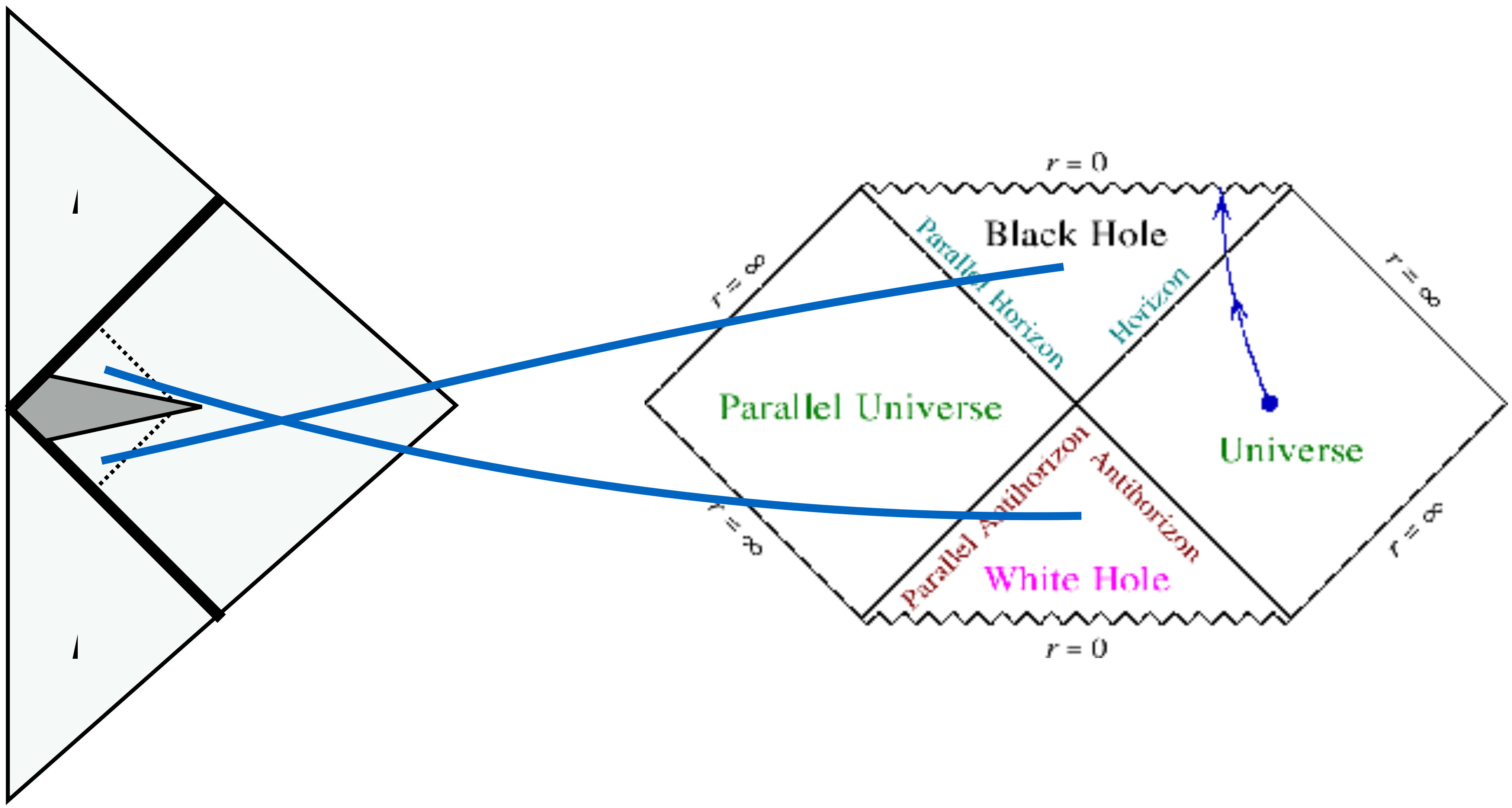
- There is a relevant intermediate scale between the Schwarzschild radius L_S and the Planck scale L_P

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

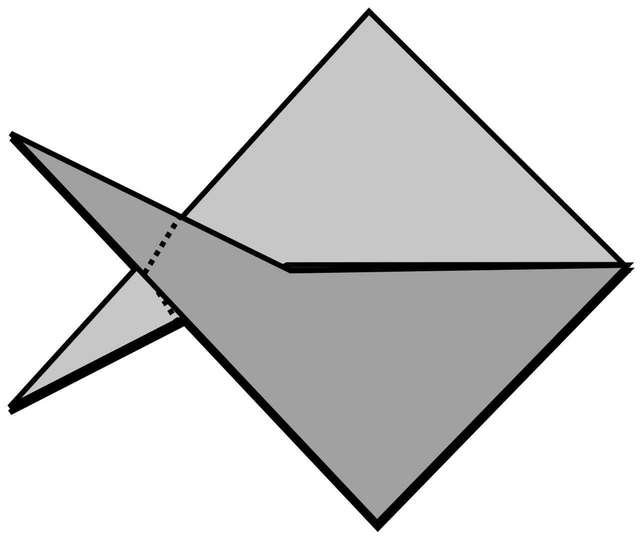
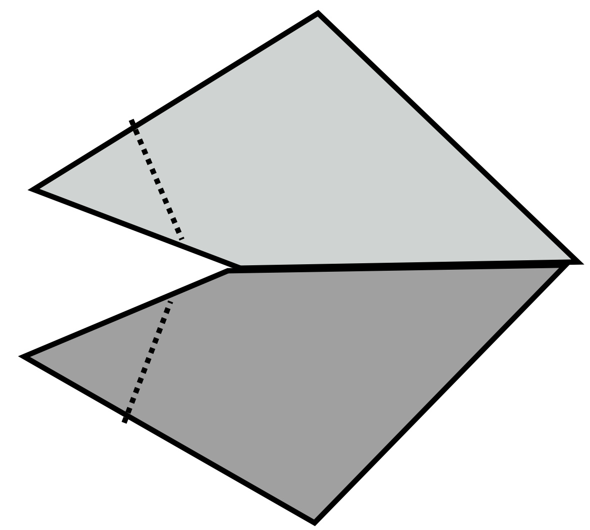
- **Does a star bounces at that scale?**

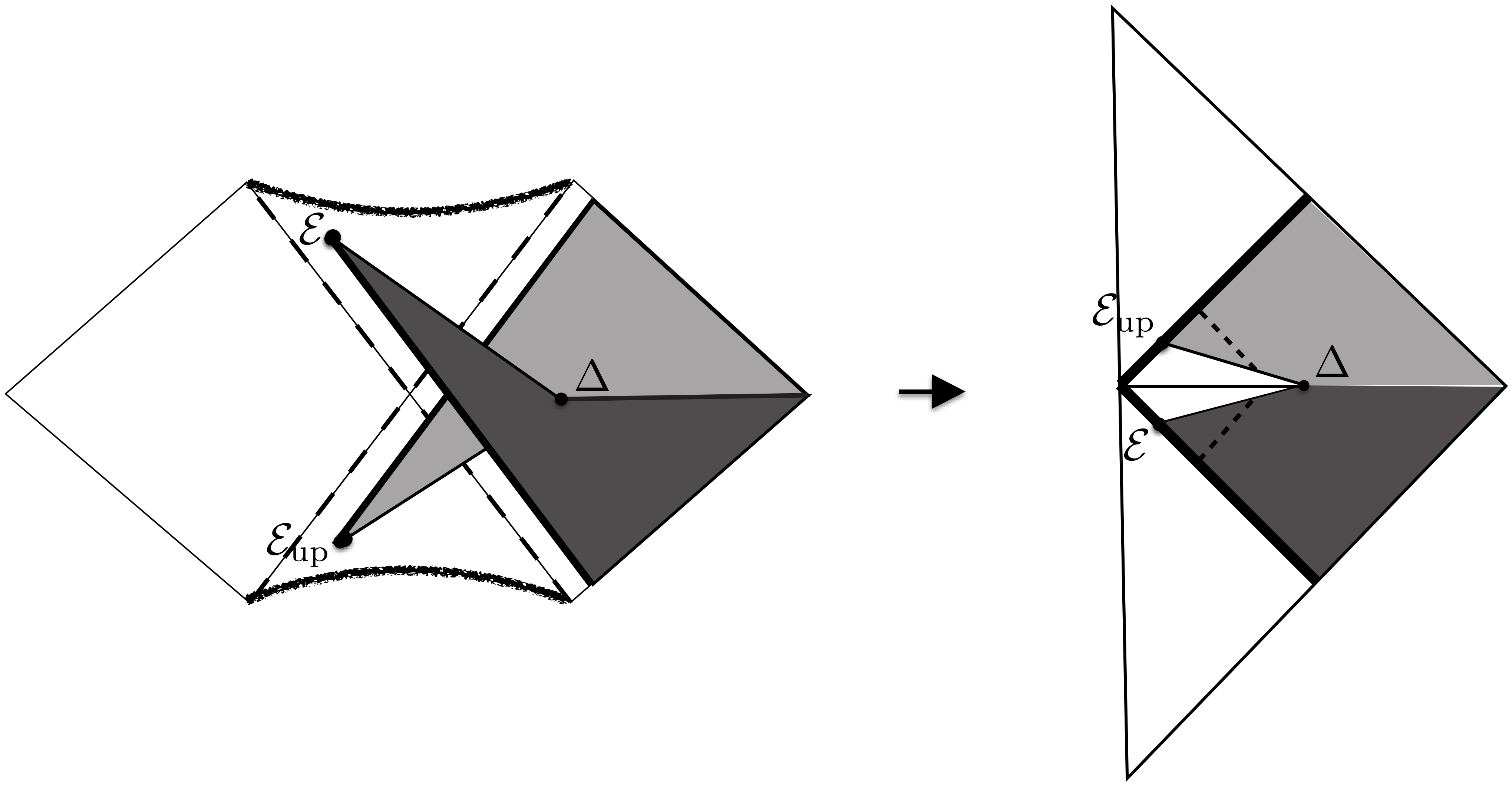
Planck Stars
CR, Francesca Vidotto.
IJMP D23 (2014), 1442026

Is this compatible with external **classical** GR?



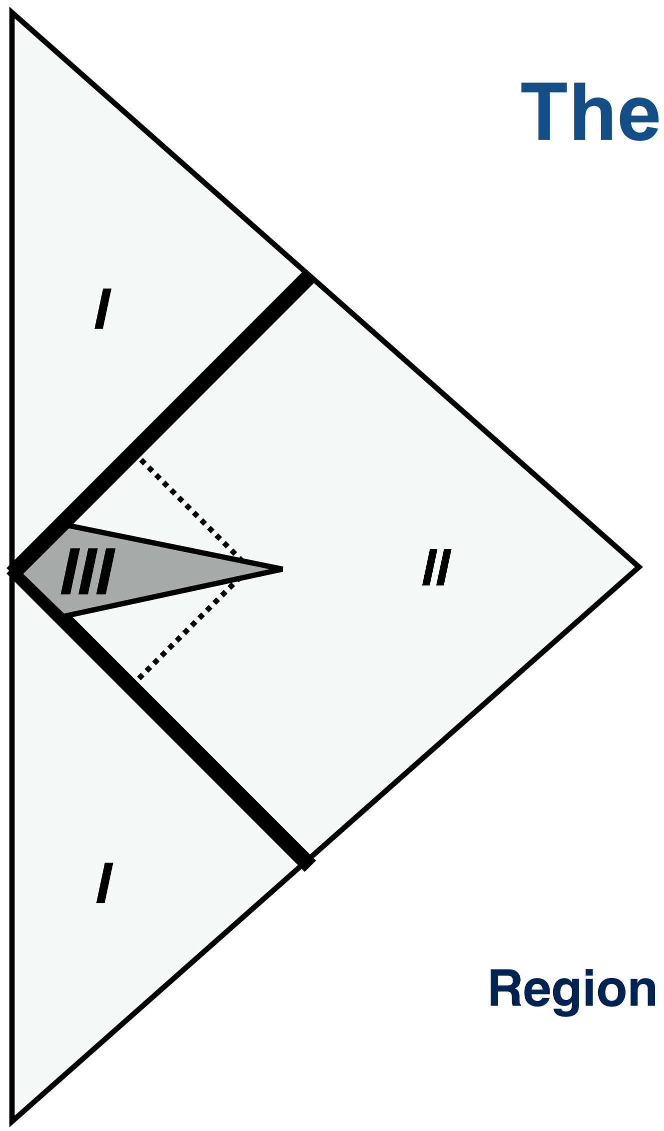
r = 0
Black Hole
Parallel Horizon
Horizon
r = ∞
r = ∞
Parallel Universe
Universe
r = ∞
r = ∞
Parallel Antihorizon
Antihorizon
White Hole
r = 0



$\mathcal{E}$
Δ
$\mathcal{E}_{\rm up}$
$\mathcal{E}_{\rm up}$
Δ
$\mathcal{E}$

The metric of the black-to-white hole transition



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

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

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):

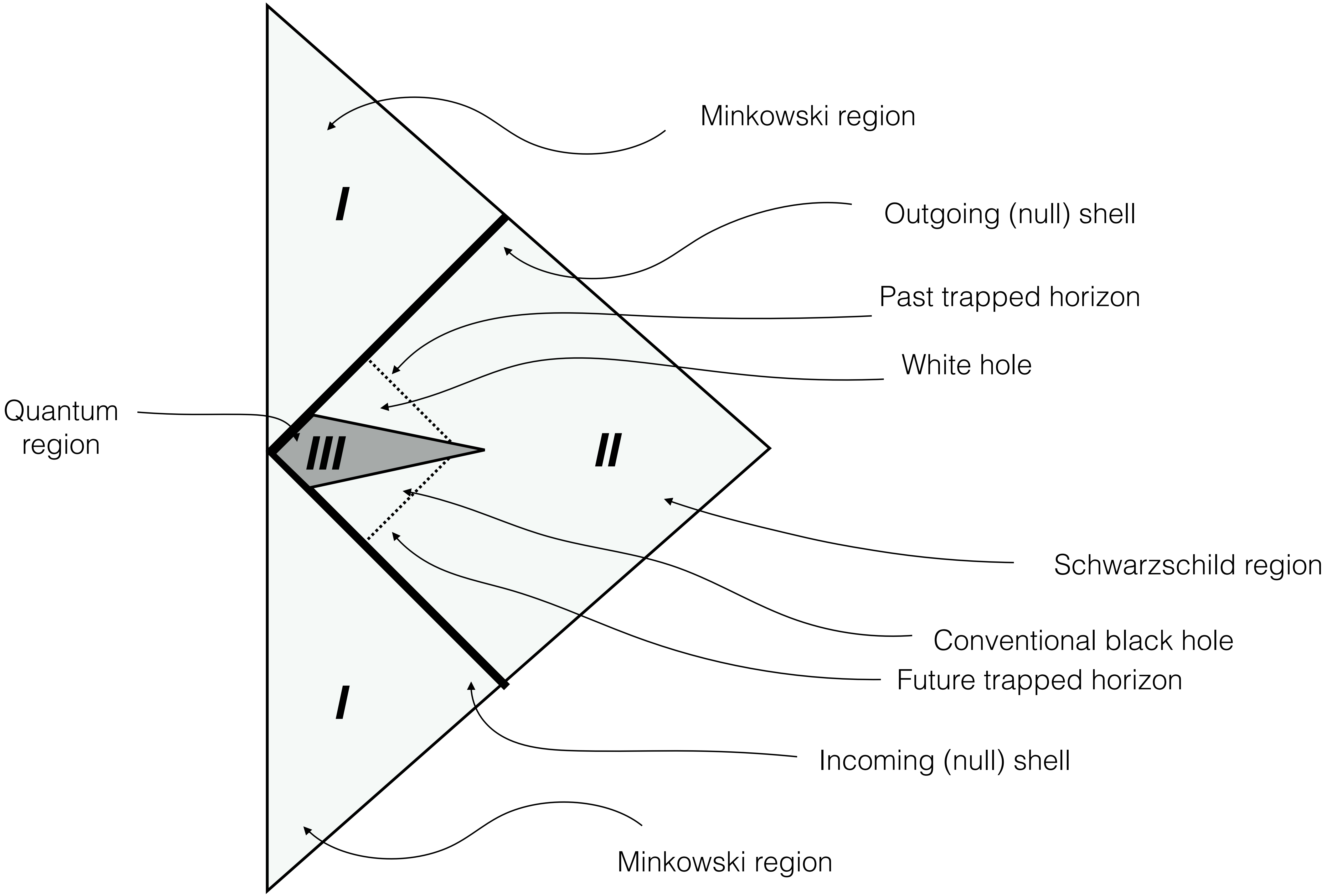
$$F(u,v) = \frac{32m^3}{r} e^{\frac{r}{2m}} \qquad \left(1 - \frac{r}{2m}\right) e^{\frac{r}{2m}} = uv.$$

Matching:

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

Region III (Effective):

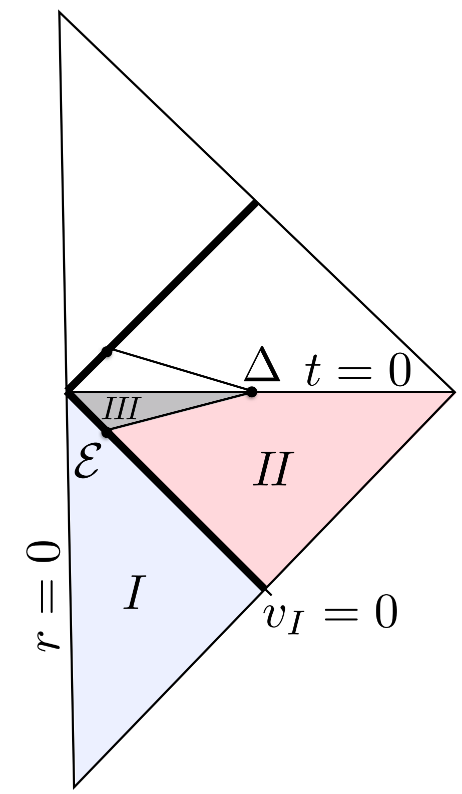
$$F(u_q, v_q) = \frac{32m^3}{r_q} e^{\frac{r_q}{2m}}, \qquad r_q = v_q - u_q.$$


Minkowski region
Outgoing (null) shell
Past trapped horizon
White hole
Quantum
region
I
III
II
Schwarzschild region
Conventional black hole
Future trapped horizon
I
Incoming (null) shell
Minkowski region

The metric of the black-to-white hole transition: parameters

The external metric is determined by two constants:

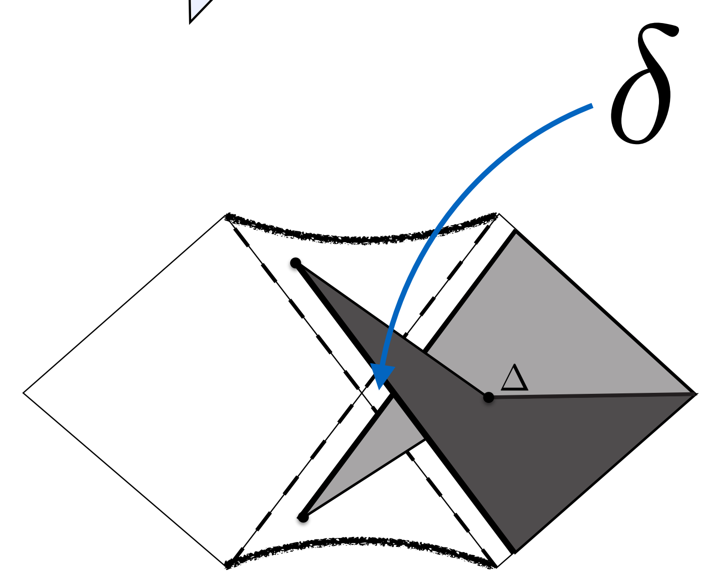
- m is the mass of the collapsing shell.
- δ is the radius at which the two shells meet in the Schwarzschild metric



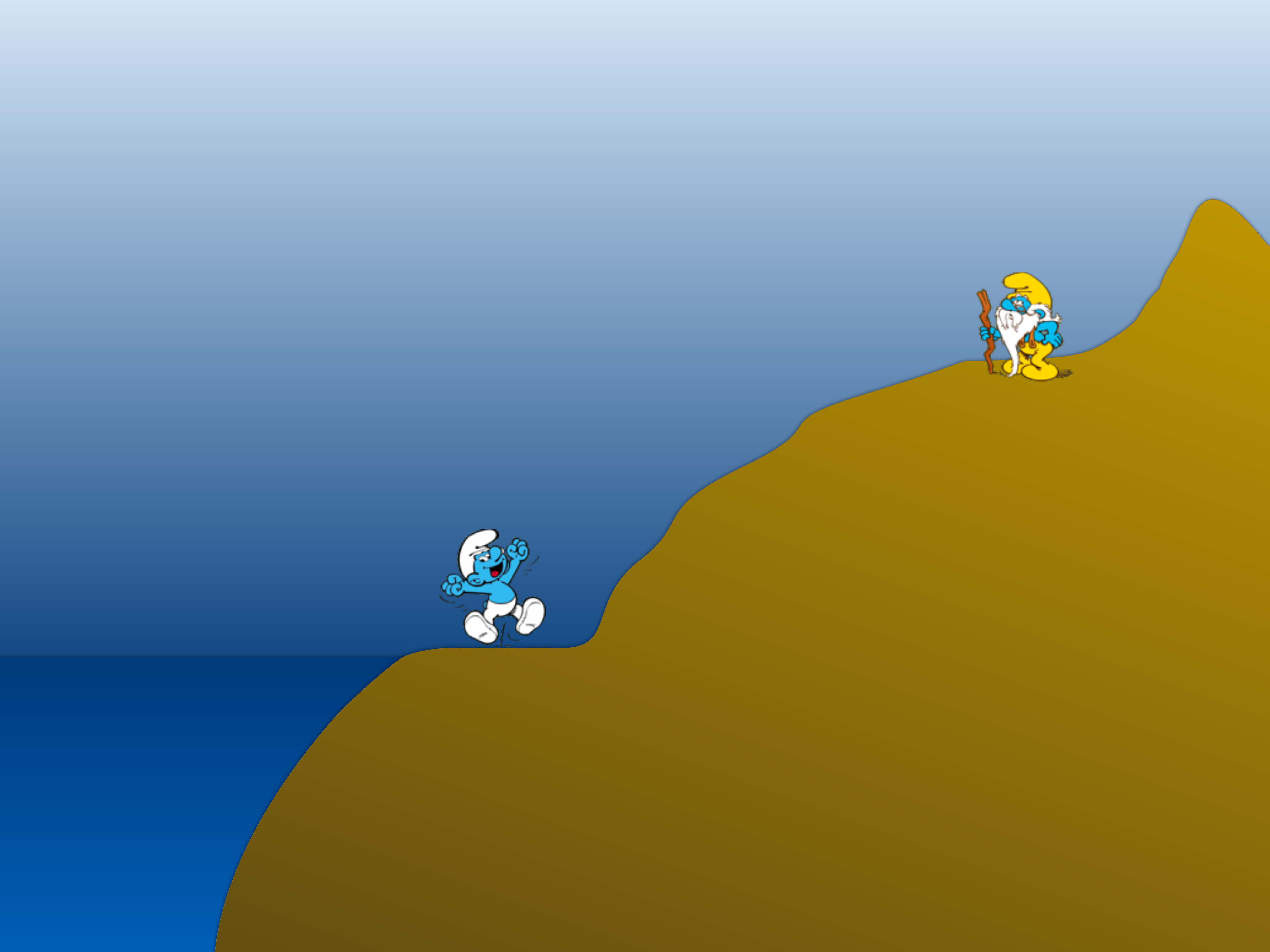
The full metric is determined by four constants:

$$\epsilon \sim \left(\frac{m}{m_P^3}\right)^{\frac{1}{3}} l_P.$$ Shell enters in quantum region

$$\Delta > \delta$$ Maximal extension of quantum region



What does δ represent and what determines it?

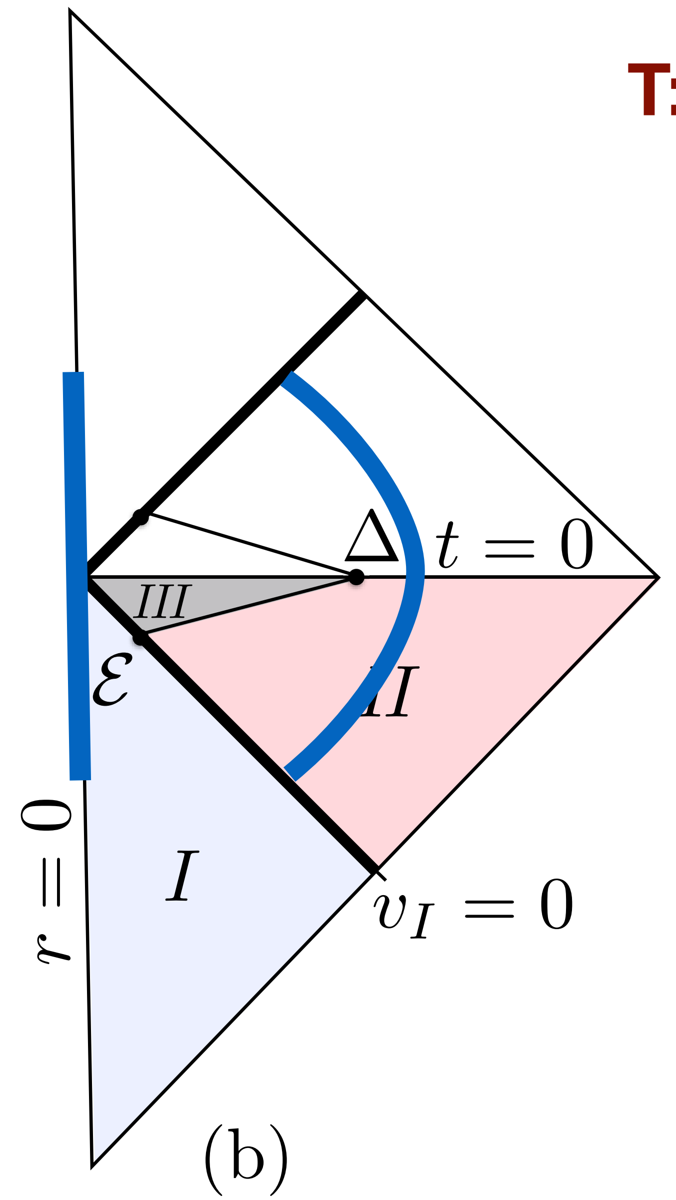


Time dilation

$$\tau_R = 2R - m \ln(\delta/m)$$

T: bounce time (very large)

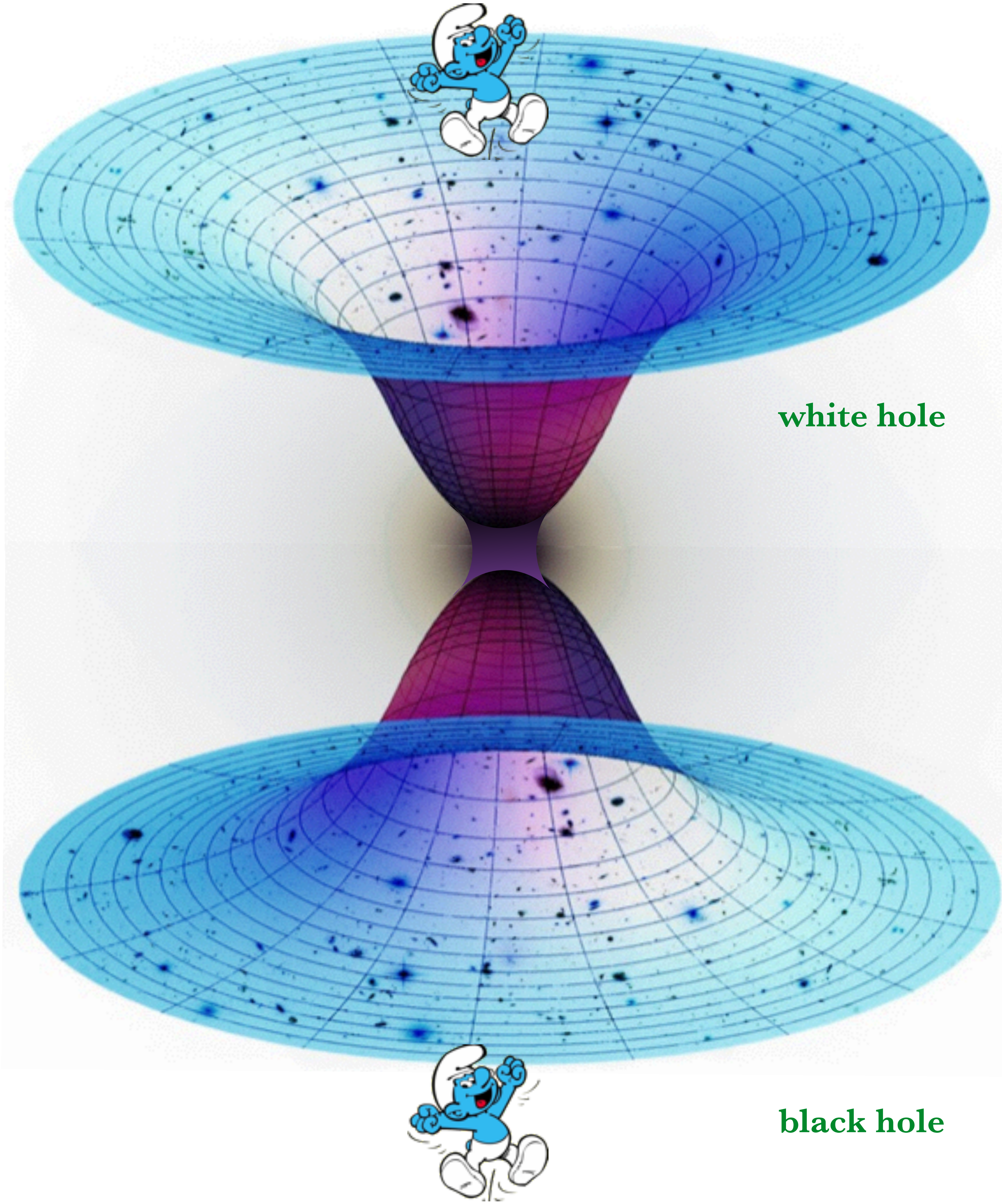
$\tau_{internal} \sim m \sim 1ms$



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

"A black hole is a short cut to the future"

Time inside: 1 ms



Time outside:
10 billions years !

What determines δ ?

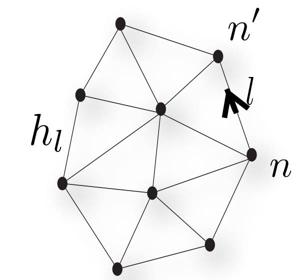
Quantum gravity

Covariant loop quantum gravity.   Full definition.

Kinematics **Boundary**

State space $\mathcal{H}_\Gamma = L^2[SU(2)^L/SU(2)^N]_\Gamma \quad \ni \psi(h_l) \qquad \mathcal{H} = \lim_{\Gamma\to\infty} \mathcal{H}_\Gamma$

Operators [cfr: Steve]: $\vec{L}_l = \{L^i_l\}, i = 1,2,3 \qquad L^i\psi(h) \equiv \frac{d}{dt}\psi(he^{t\tau_i})\Big|_{t=0}$



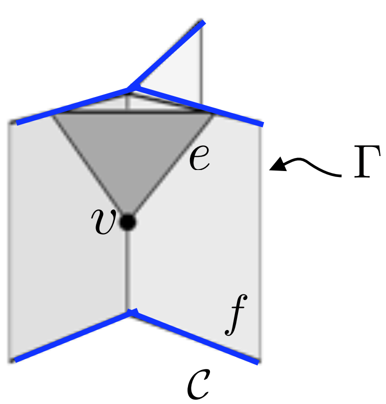
Γ spin network
(nodes, links)

Dynamics **Bulk**

Transition amplitudes $W_{\mathcal{C}}(h_l) = N_{\mathcal{C}} \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf})$

$$h_f = \prod_v h_{vf}$$

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



spinfoam
(vertices, edges, faces)

$$W = \lim_{\mathcal{C}\to\infty} W_{\mathcal{C}} \qquad 8\pi\gamma\hbar G = 1$$

How non perturbative quantum gravity works

Quantum system
=
Spacetime region

Boundary

➜ **Hamilton function: S(q,t,q',t')**

➜ **Boundary formalism**

States: associated to **3d** boundaries of spacetime regions.

Transition amplitudes: associated to **4d** regions

Covariant loop quantum gravity. Full definition.

Kinematics **Boundary**

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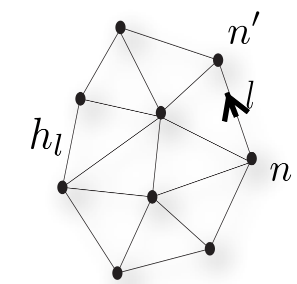

Γ spin network (nodes, links)

Dynamics **Bulk**

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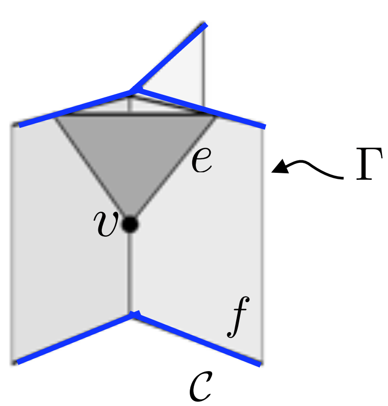
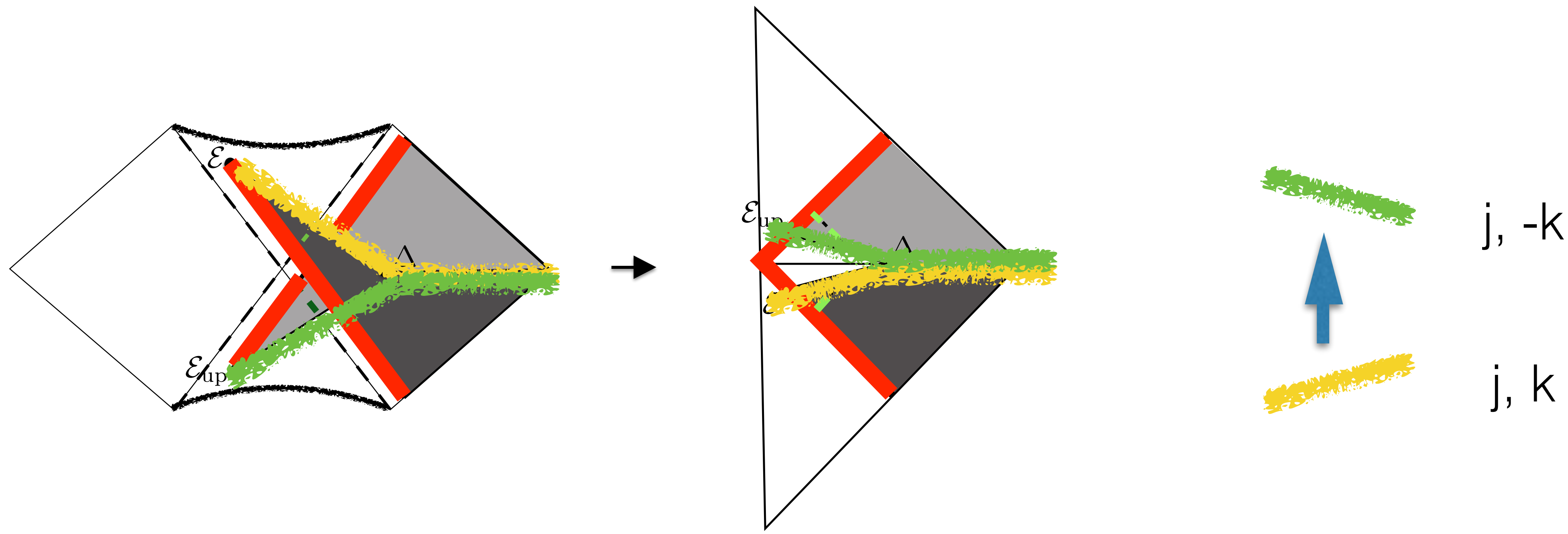
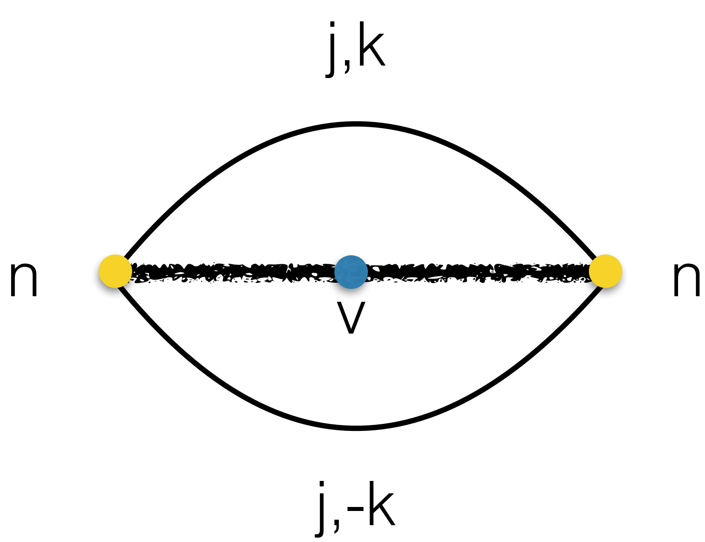


spinfoam (vertices, edges, faces)

$$W = \lim_{\mathcal{C}\to\infty} W_\mathcal{C} \qquad 8\pi\gamma\hbar G = 1$$

Covariant loop quantum gravity. Calculation of T(m).





$$A(j,k) = \int_{SL(2C)} dg \int_{SU2} dh_- \int_{SU2} dh_+ \sum_{j_+ j_-} e^{-(j_+-j)^2} e^{-(j_+-j)^2}$$
$$Tr_{j_+}[e^{k\sigma_3} Y^\dagger g Y] Tr_{j_-}[e^{k\sigma_3} Y^\dagger g Y]$$

$|A(j,k)|^2 \sim 1$ ➜ relation j-k ➜ relation m-time

Can we estimate T(m) ?

(cfr Gia Dvali,
Roberto Casadio,
Andrea Giugno)

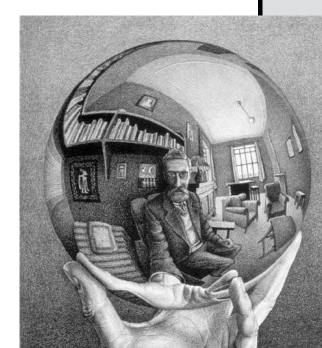
$$\tau_R = \sqrt{1 - \frac{2M}{R}} \left(R - a - 2M \ln \frac{a - 2M}{R - 2M} \right)$$

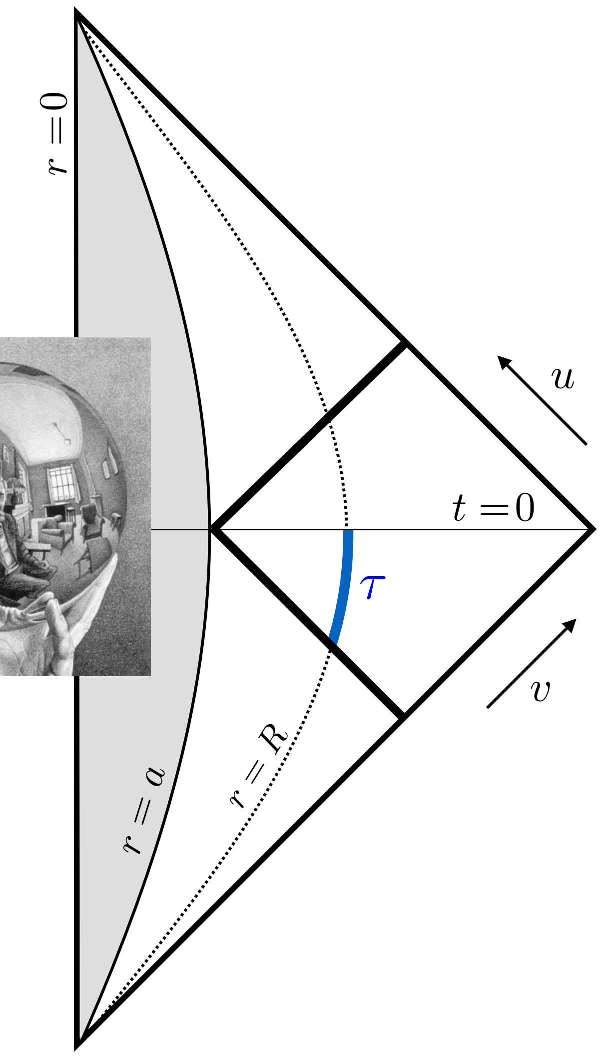
Classicality parameter

$$q = \ell_{\mathsf{Pl}} \mathcal{R} \tau_R,$$

here $\mathcal{R} \sim \frac{M}{R^3}$ measures strength of curvature & $q << 1$ means classical

$q \sim 1$ for $a \sim 2M$ and τ_R large enough. It has a maximum at $R_q = \frac{7}{6}(2M)$ (outside horizon!) and requiring $q \sim 1$ gives $\tau_q \sim M^2$.





Quantum effect leak out the horizon

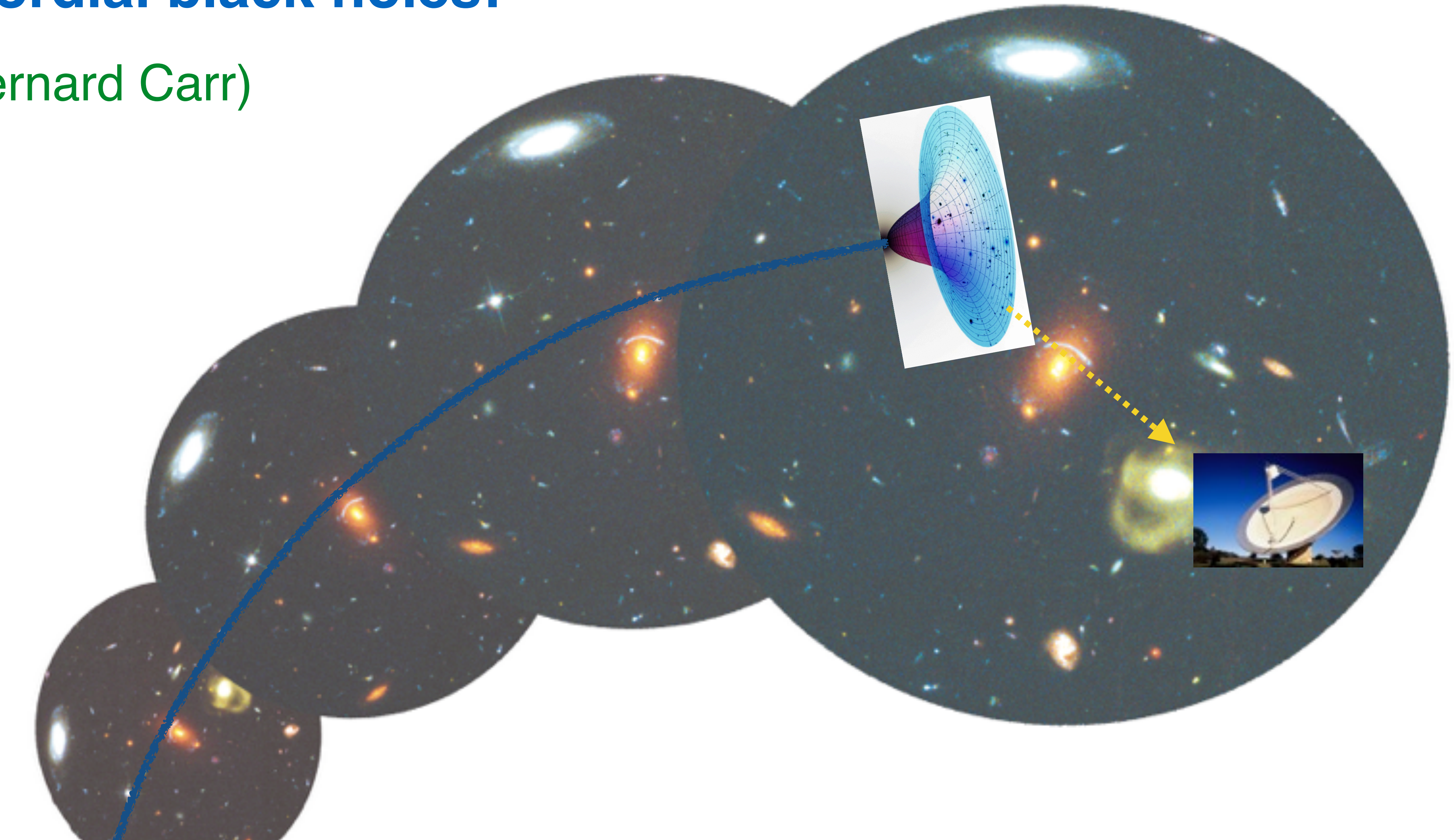
$$T \sim m^2$$

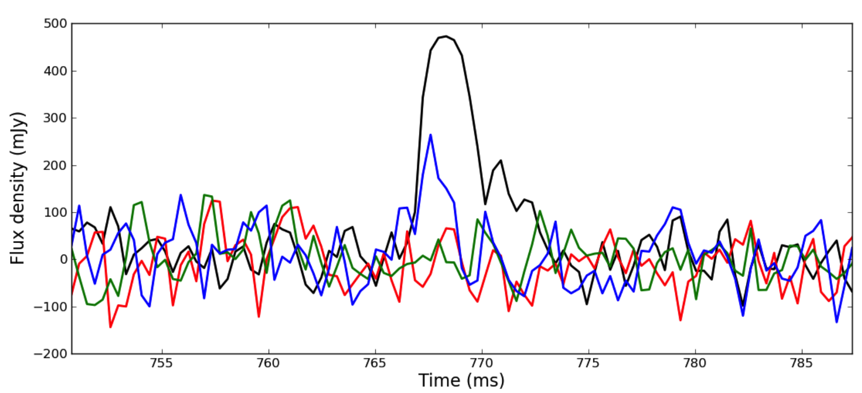
Observable ?

Already observed?

Primordial black holes!

(cfr Bernard Carr)





Phenomenology

See Francesca Vidotto's talk

Because the black to white hole conversion proceeds rapidly compared to the Hawking time

$$E = Mc^2 \sim 10^{47} \text{ ergs}$$

and its size is

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

This leads to the expectation of two signals:

(i) a lower energy signal with $\lambda \sim R$

(ii) a higher energy signal depending on how the content is liberated

Already observed?? Fast Radio Burst

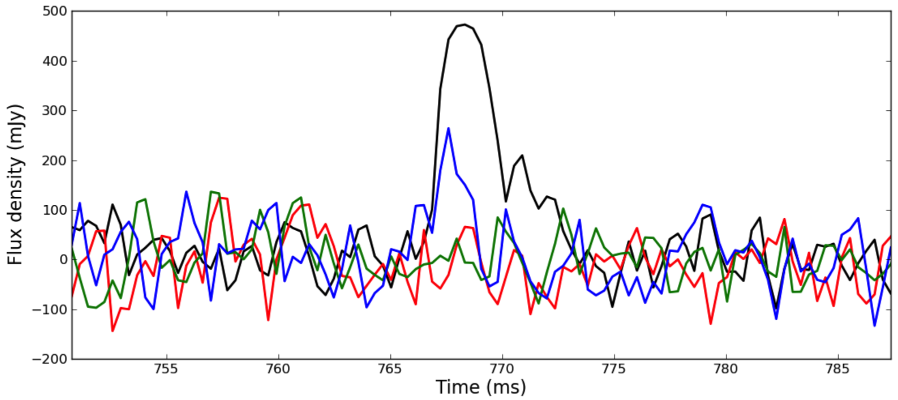
(cfr talk Luciano Rezzolla)

Unknown source!

$$\lambda \sim 20\ cm$$

Thornton et al. 1307.1628
Spitler et al. 1404.2934
E. Petroff *et al.* 1412.0342

- Short
  - Observed width ≃ milliseconds
- No Afterglow
  - No Long GRB associated
- Punctual
  - No repetition
- Enormous flux density
  - Energy ≲ 10^{38} erg
- Likely Extragalactic
  - Dispersion Measure: z≲0.5
- 10^4 event/day
  - A pretty common object?

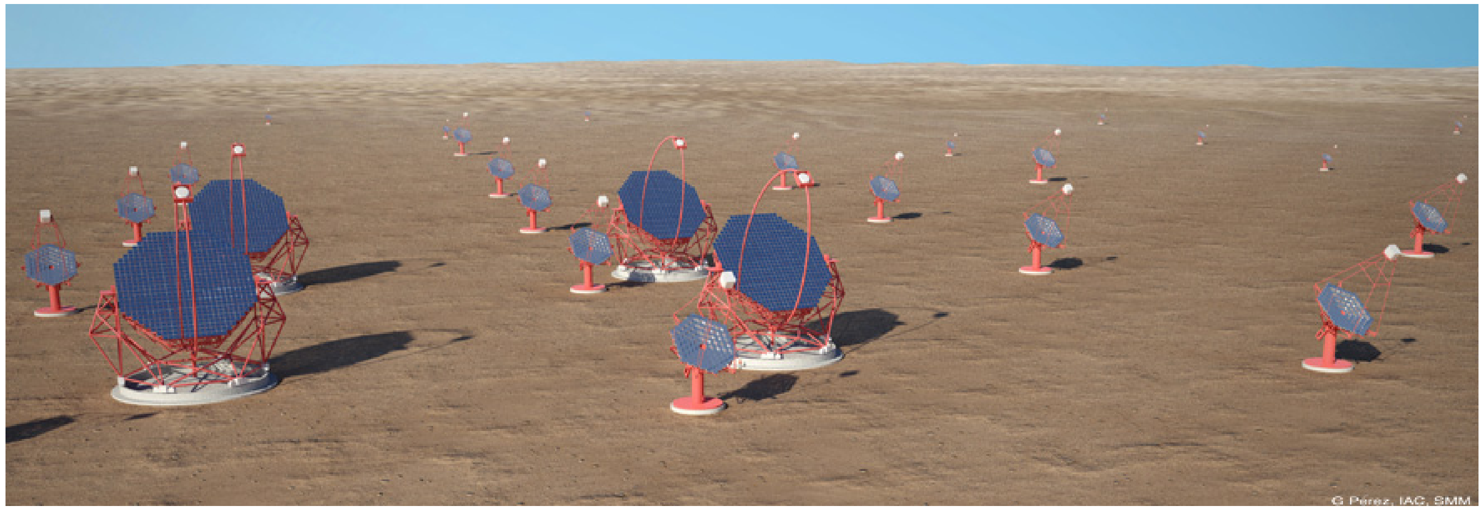


High energy component

Matter forming the black hole experiences a short bounce time, a 2nd scale enters the problem the energy of the matter at formation

For $M \sim 10^{26}$g this occurs when T_U was ~TeV

This suggests a search for high energy Gamma Ray Bursts (CTA)

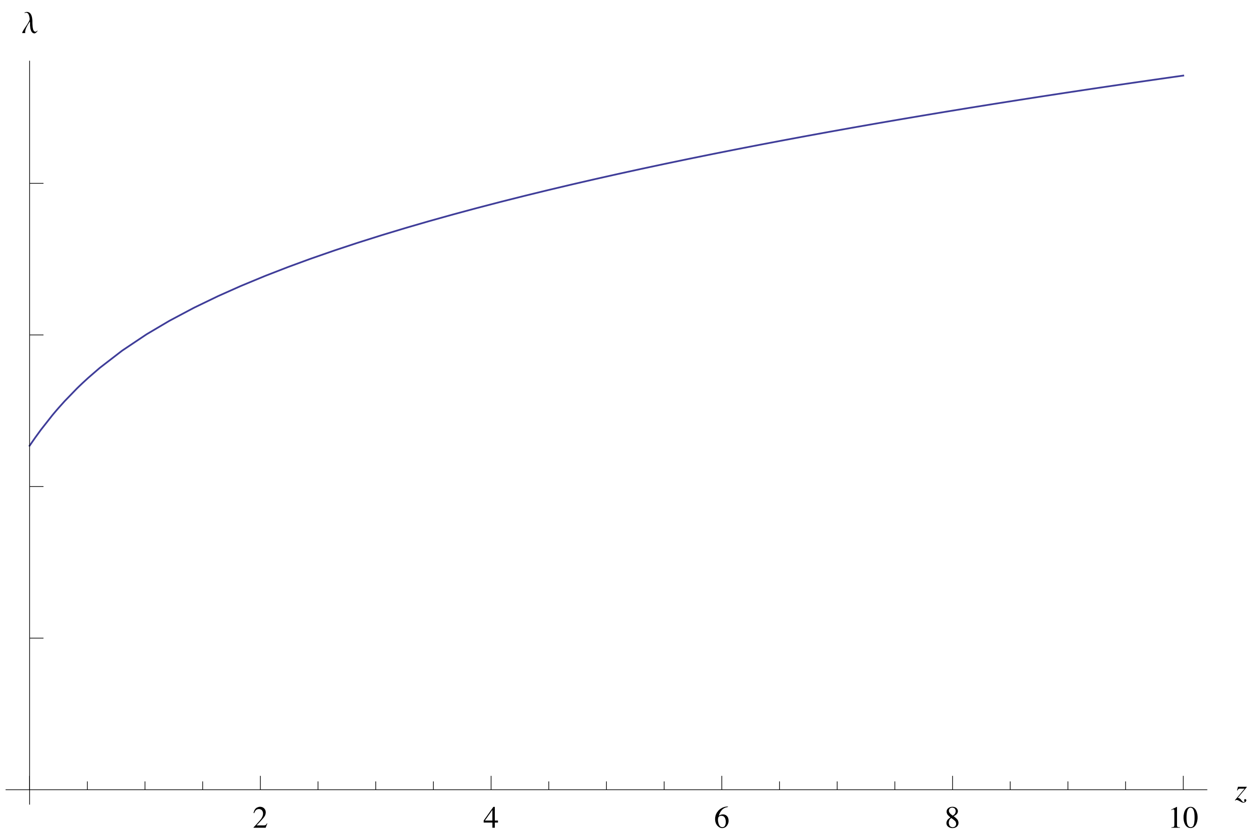


cfr. Dadhich, Narlikar, Appa Rao, 1974

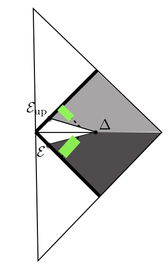
Signature: distance/energy relation

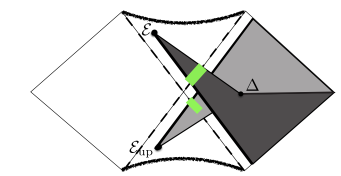
Fast Radio Bursts and White Hole Signals
Aurélien Barrau, CR, Francesca Vidotto.
Phys.Rev. D90 (2014) 12, 127503

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

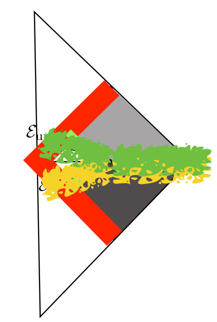


Summary

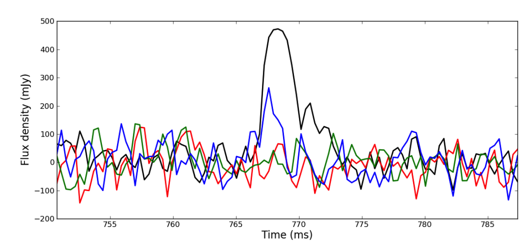




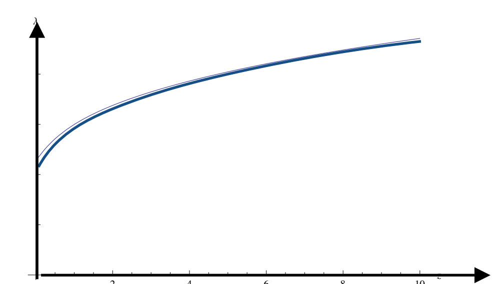
- Technical results: black holes may tunnel to white holes locally.



- The tunnelling time can in principle be computed with LQG.



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



- Wavelength-to-distance relation signature.

Main idea of observability

Planck Stars
CR, Francesca Vidotto.
arXiv:1401.6562

Phenomenology

Planck star phenomenology
Aurelien Barrau, Carlo Rovelli.
Phys.Lett. B739 (2014) 405

Classical solution and T~m²

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

Fast Radio Bursts

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

Appeared yesterday

Phenomenology of bouncing black holes in quantum gravity: a closer look
Aurelien Barrau, Boris Bolliet, Francesca Vidotto, Celine Weimer.
arXiv:1507.05424: