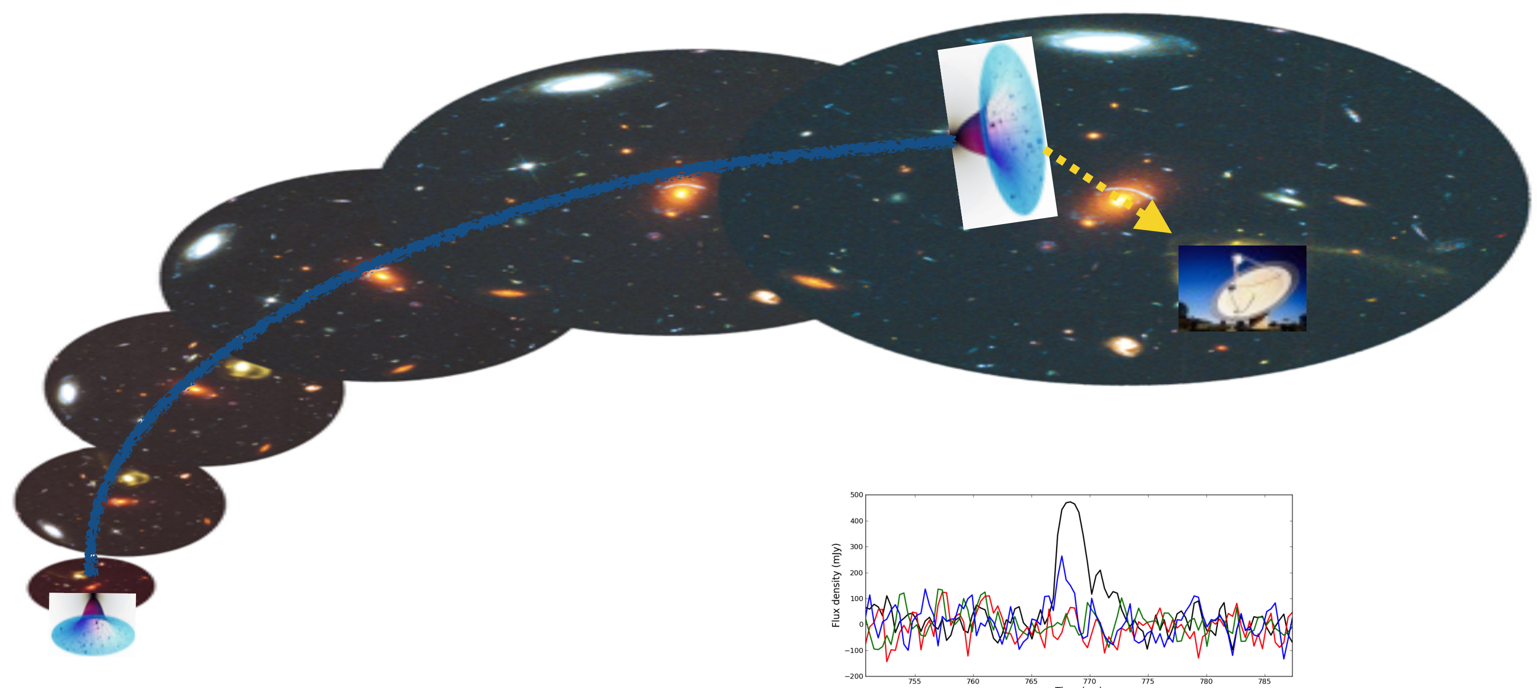
Planck stars (exploding black holes):

A possibly observable quantum gravitational phenomenon

Carlo Rovelli



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i. Why black holes can explode

Because quantum tunnelling allow them to explode

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

Perhaps $T \sim m^2$.   T can be computed in Loop Quantum Gravity.

iii. Can we observe a black hole explosion?

Yes. We might even have already observed explosions of primordial holes.
We can soon find out.

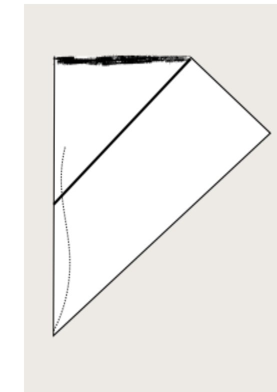
The Universe appears to be full of gravitationally collapsed objects ("Black holes")

What is their lifetime T ?

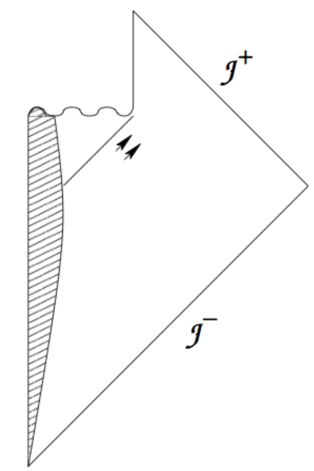
Classical GR:	$T = \infty$	(Event horizon)
QFT on a classical dynamical geometry:	$T \sim m^3$	(Hawking radiation)
Full Quantum Gravity:	$T \sim m^2$	(Black to white hole tunnelling)

For $m \sim 10^{24}$ (Venus), $m^2 \sim 10^{50}$ Hubble times, while $m^3 \sim$ Hubble time

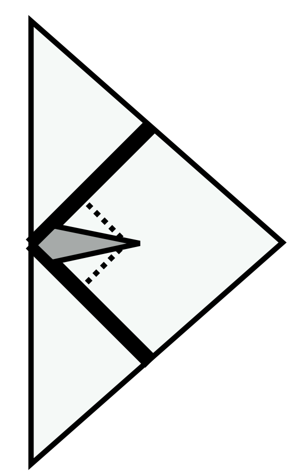
In (the approximation given by) **classical general relativity**, a black hole is stable.

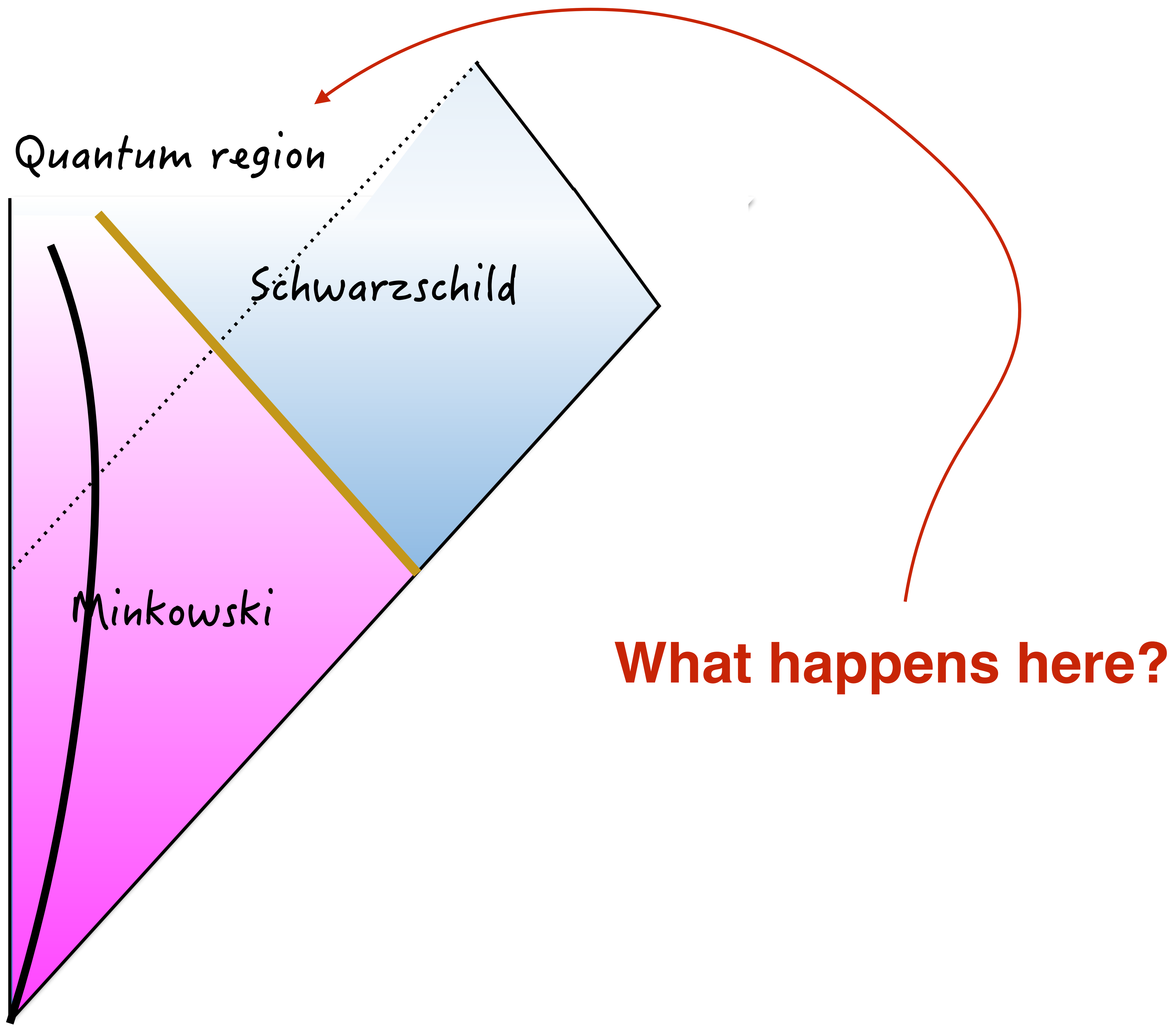


In **quantum field theory on a classical gravitational field**, a black hole decays via Hawking radiation, in an extremely long time. (10^{50} Hubble times, for a stellar bh.)



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




Quantum region
Schwarzschild
Minkowski
What happens here?

Black hole explosions?

QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the Planck time $\approx 10^{-43}$ s.

The β_{ij} will not be zero because the time dependence of the metric during the collapse will cause a certain amount of mixing of positive and negative frequencies. Equating the two expressions for ϕ, one finds that the b_i, which are the annihilation operators for outgoing scalar particles, can be expressed as a linear combination of the ingoing annihilation and creation operators a_i and a_i^+

$$b_i = \sum_j \{\bar{\alpha}_{ij} a_j - \bar{\beta}_{ij} a_j^+\}$$

Thus when there are no incoming particles the expectation value of the number operator $b_i^+ b_i$ of the ith outgoing state is

$$< 0_- |b_i^+ b_i| 0_- > = \sum_j |\beta_{ij}|^2$$

The number of particles created and emitted to infinity in a gravitational collapse can therefore be determined by calculating the coefficients β_{ij}. Consider a simple example in which

the collapse is spherically symmetric. The angular dependence of the solution of the wave equation can then be expressed in terms of the spherical harmonics Y_{lm} and the dependence on retarded or advanced time u, v can be taken to have the form $\omega^{-1/2}\, exp\ (i\omega u)$ (here the continuum normalisation is used). Outgoing solutions $p_{lm\omega}$ will now be expressed as an integral over incoming fields with the same l and m:

$$p_\omega = \int \{\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} \bar{f}_{\omega'}\}\, d\omega'$$

(The lm suffixes have been dropped.) To calculate $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ consider a wave which has a positive frequency ω on I^+ propagating backwards through spacetime with nothing crossing the event horizon. Part of this wave will be scattered by the curvature of the static Schwarzschild solution outside the black hole and will end up on I^- with the same frequency ω. This will give a $\delta(\omega - \omega')$ behaviour in $\alpha_{\omega\omega'}$. Another part of the wave will propagate backwards into the star, through the origin and out again onto I^-. These waves will have a very large blue shift and will reach I^- with asymptotic form

Beckenstein[6] suggested on thermodynamic grounds that some multiple of κ should be regarded as the temperature of a black hole. He did not, however, suggest that a black hole could emit particles as well as absorb them. For this reason Bardeen, Carter and I considered that the thermodynamical similarity between κ and temperature was only an analogy. The present result seems to indicate, however, that there may be more to it than this. Of course this calculation ignores the back reaction of the particles on the metric, and quantum fluctuations on the metric. These might alter the picture.

Further details of this work will be published elsewhere. The author is very grateful to G. W. Gibbons for discussions and help.

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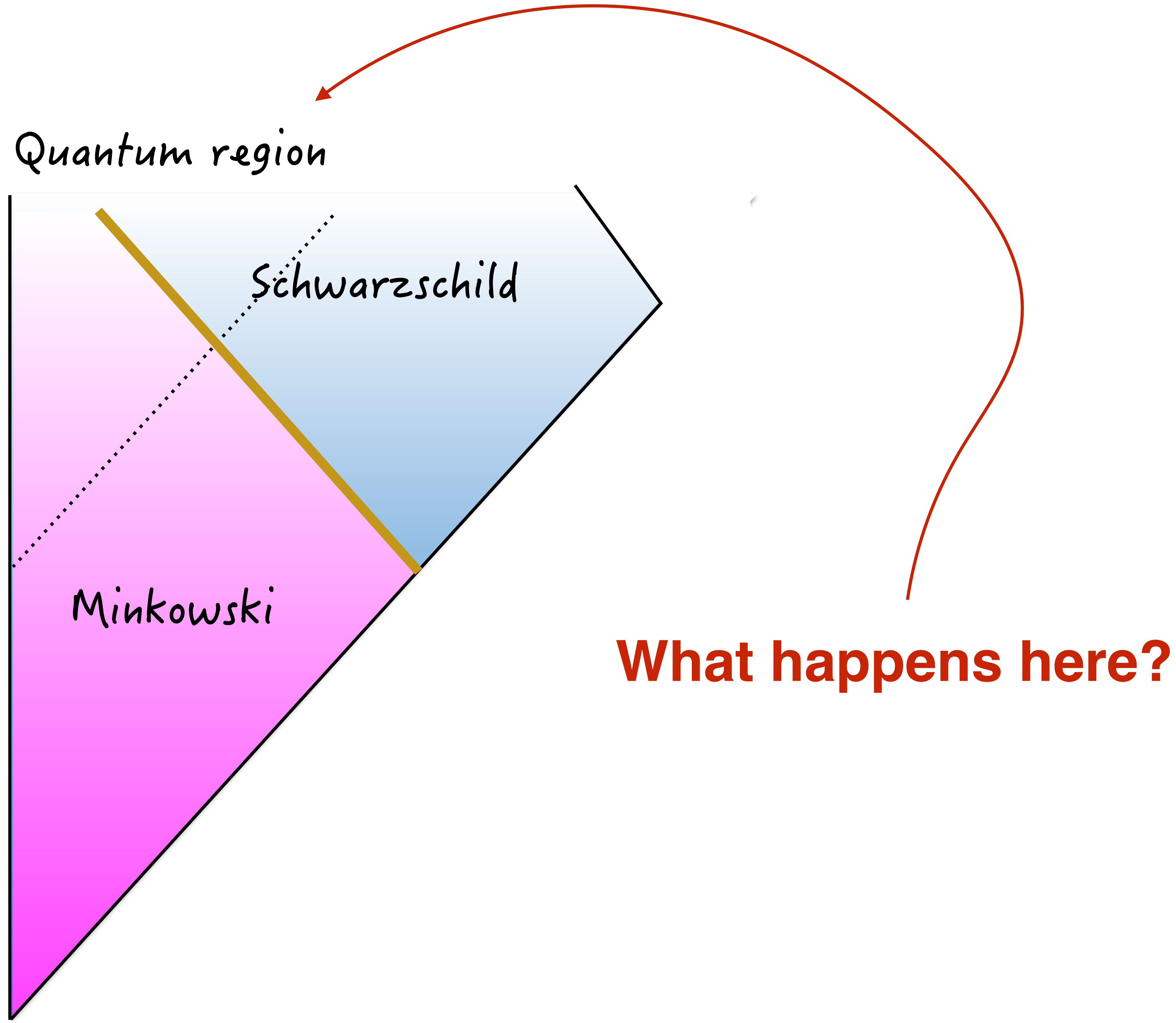
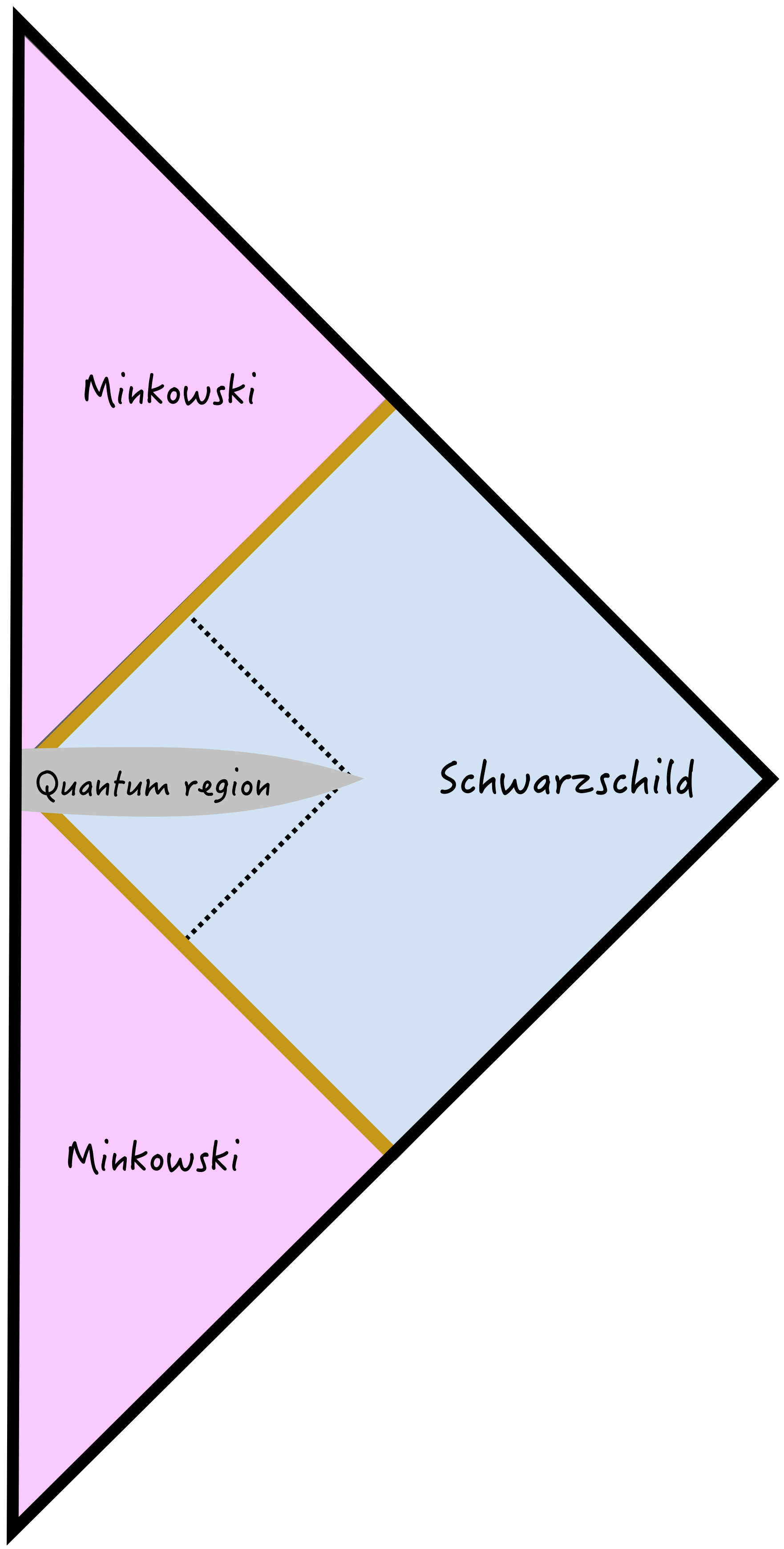
We expect quantum effects when some physical quantity becomes ~ 1 in Planck units.

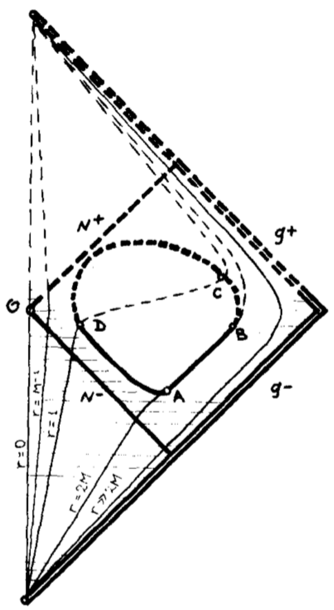
- $R \sim 1$ around singularities

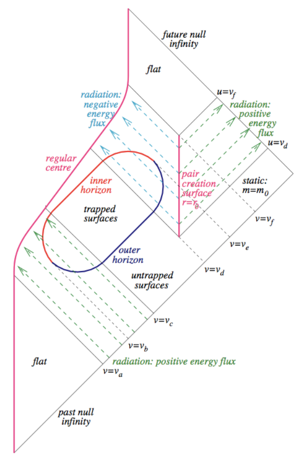
- $RT \sim 1 \rightarrow RT \sim m/r^3\, T = T/m^2 \sim 1 \rightarrow T \sim m^2$

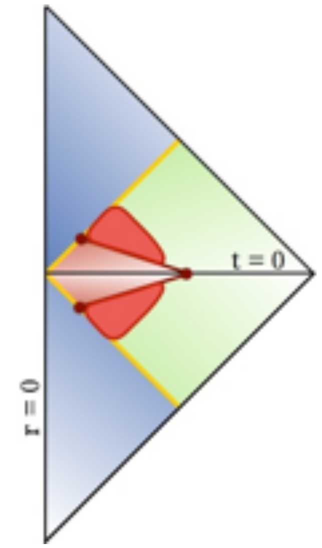

Quantum region
Schwarzschild
Minkowski
What happens here?

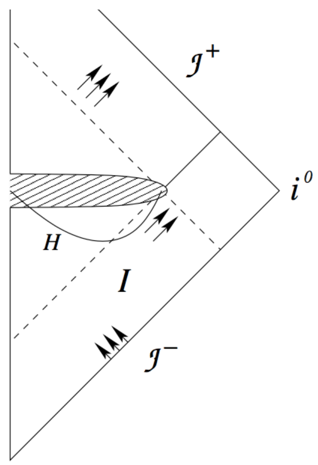

Minkowski
Quantum region
Schwarzschild
Minkowski

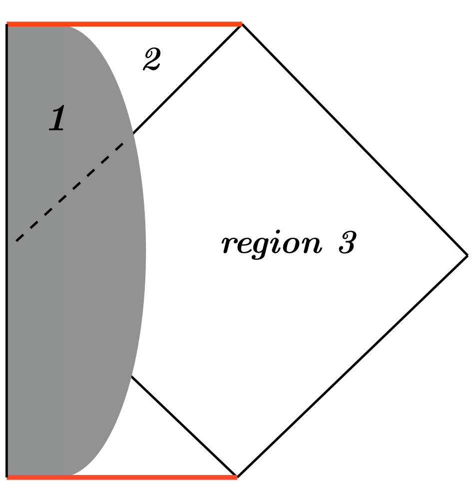
Exploding holes











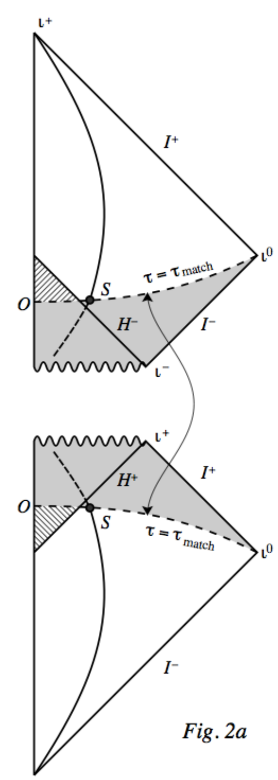


Fig. 2a

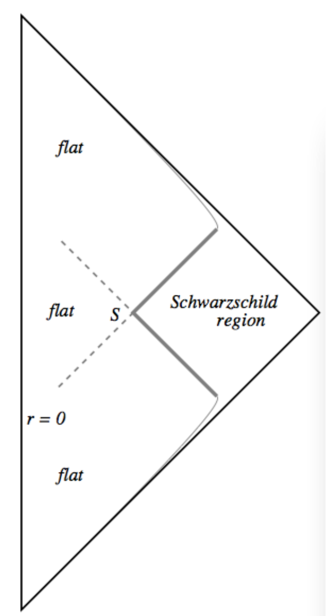
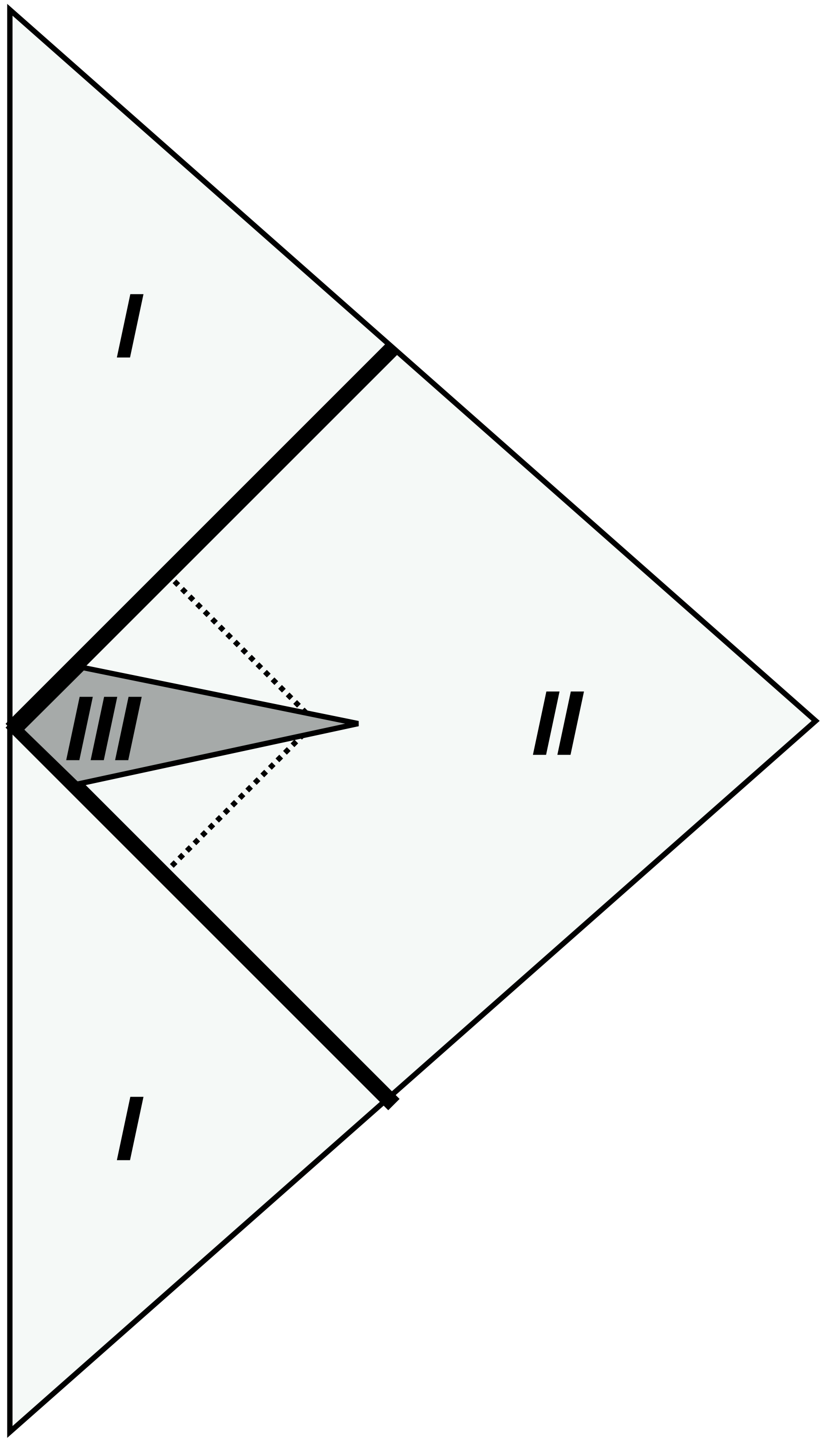


Fig. 2b

- Frolov, Vilkovinski ‘79
- Stephen, t’Hooft, Whithing ‘93
- Ashtekar, Bojowald ’05
- Modesto ‘06
- Hayward ’06
- Haggard, Rovelli ‘15



A technical result in classical GR:

The following metric is an **exact** vacuum solution,
of the Einstein equations outside a finite spacetime region (grey),
plus an ingoing and outgoing null shell,

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

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

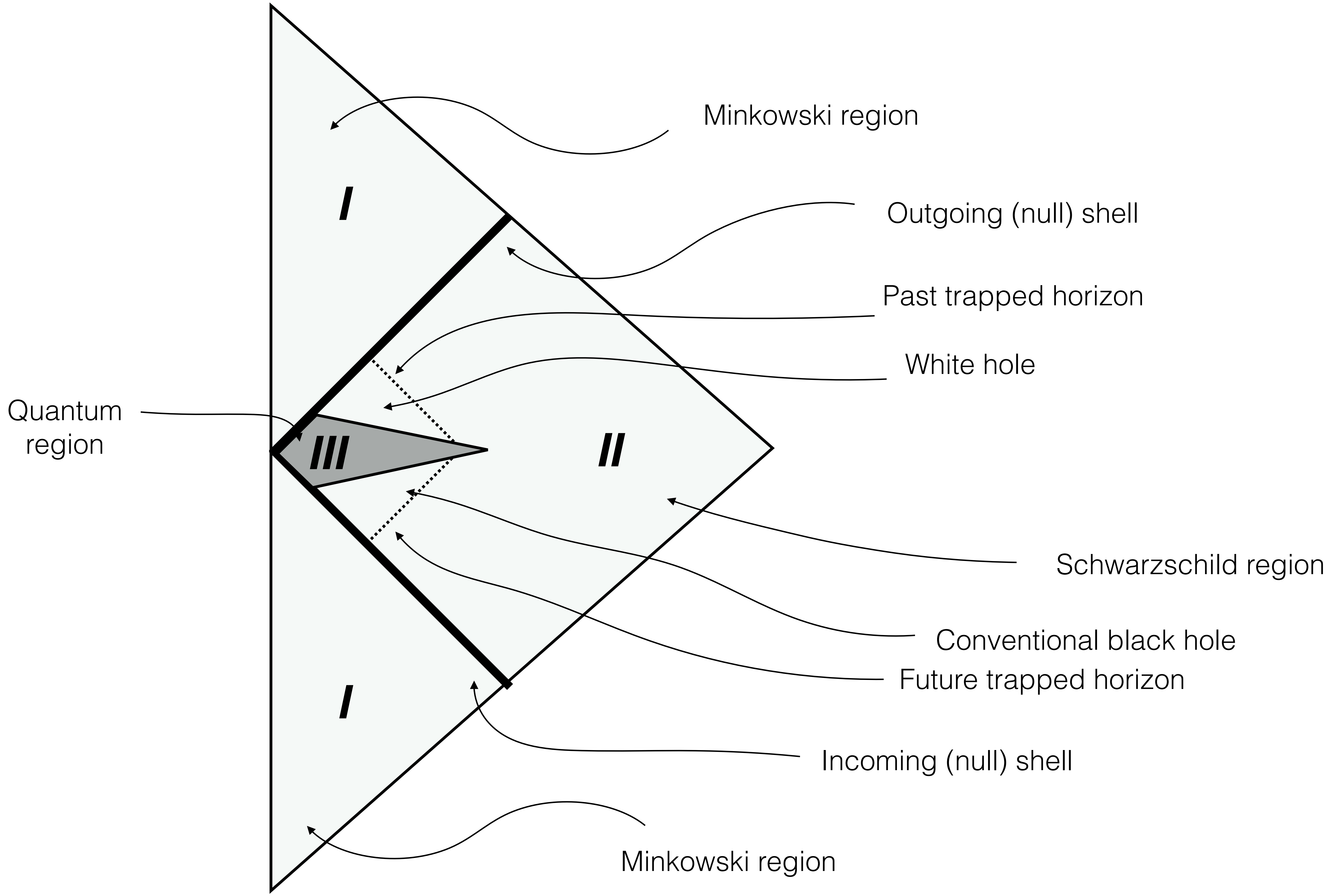
$v_I < 0.$

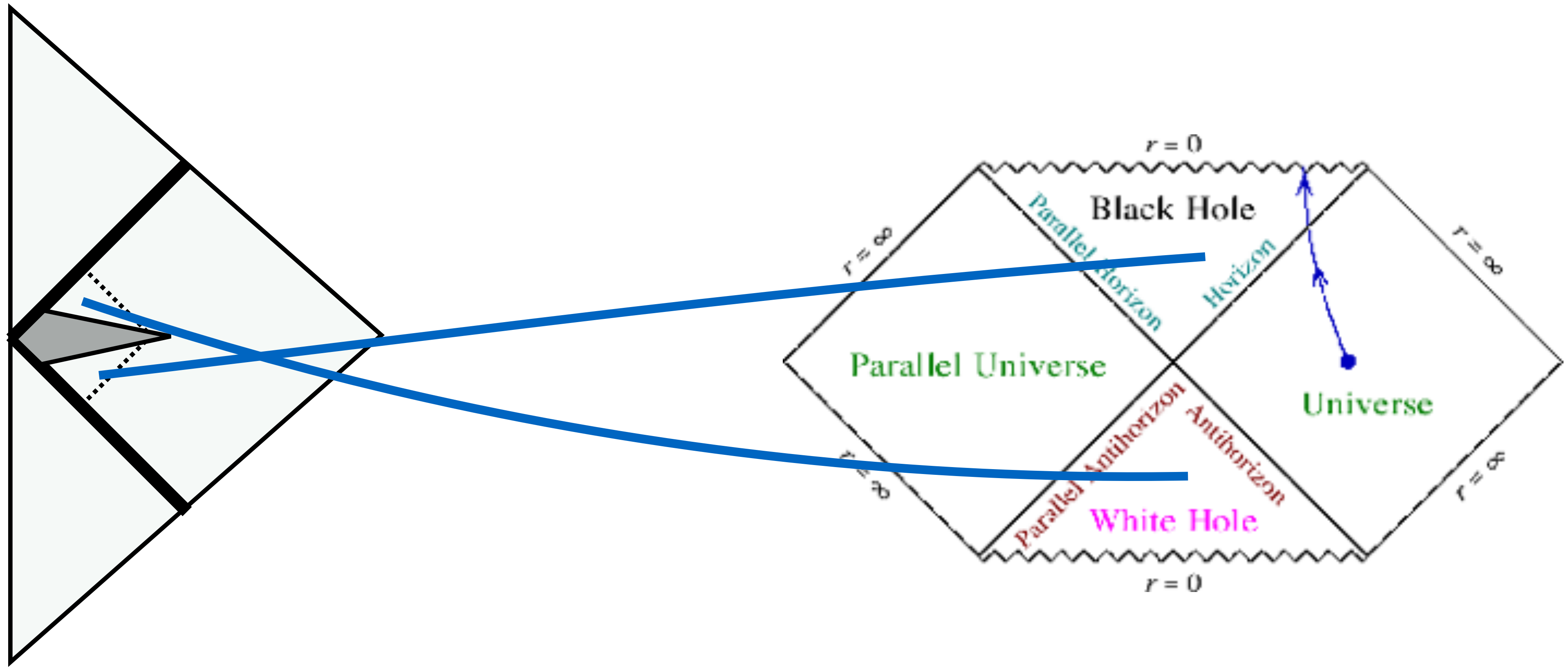
Region II $\quad F(u,v) = \frac{32m^3}{r} e^{\frac{r}{2m}} \qquad \left(1 - \frac{r}{2m}\right) e^{\frac{r}{2m}} = uv.$

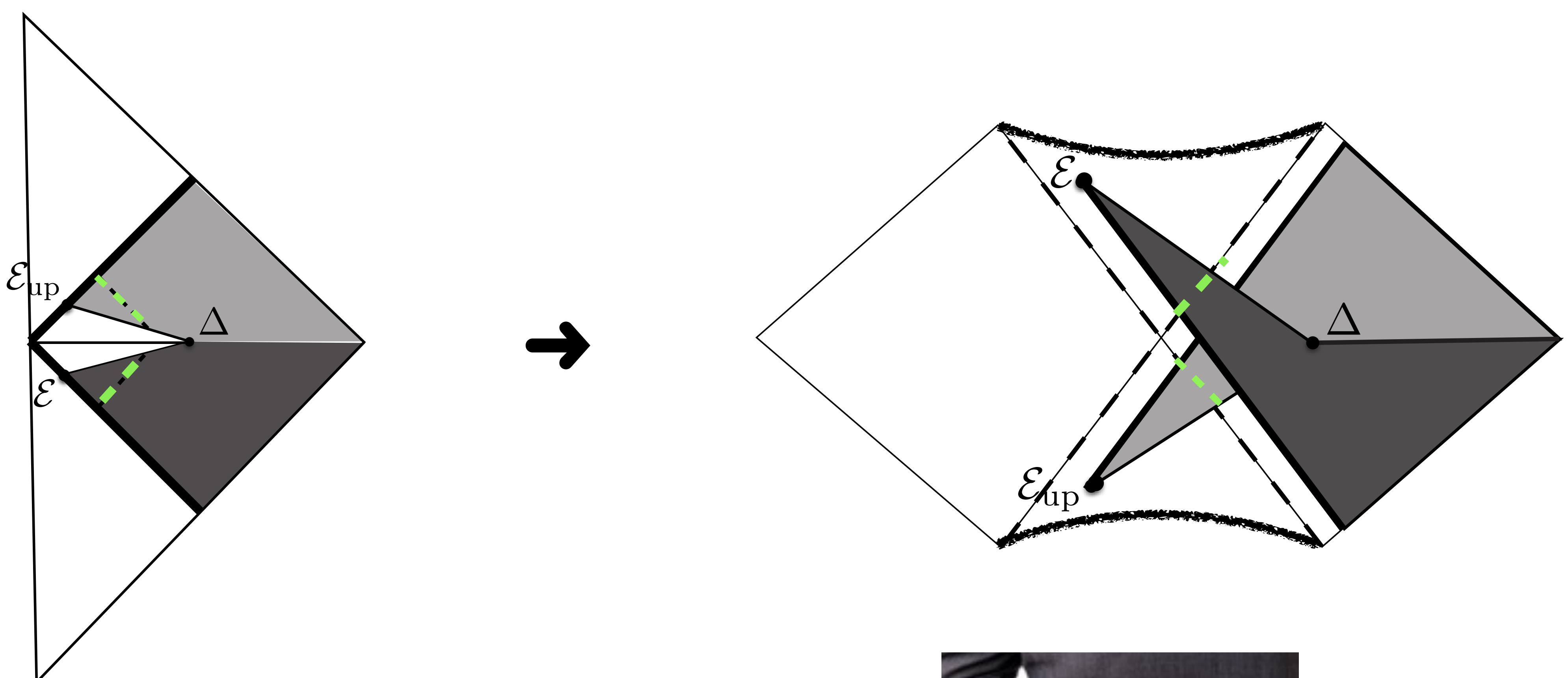
Matching: $\quad r_I(u_I, v_I) = r(u,v) \longrightarrow u(u_I) = \frac{1}{v_o}\left(1 + \frac{u_I}{4m}\right) e^{\frac{u_I}{4m}}.$

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

The metric is determined by two constants: m, T


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



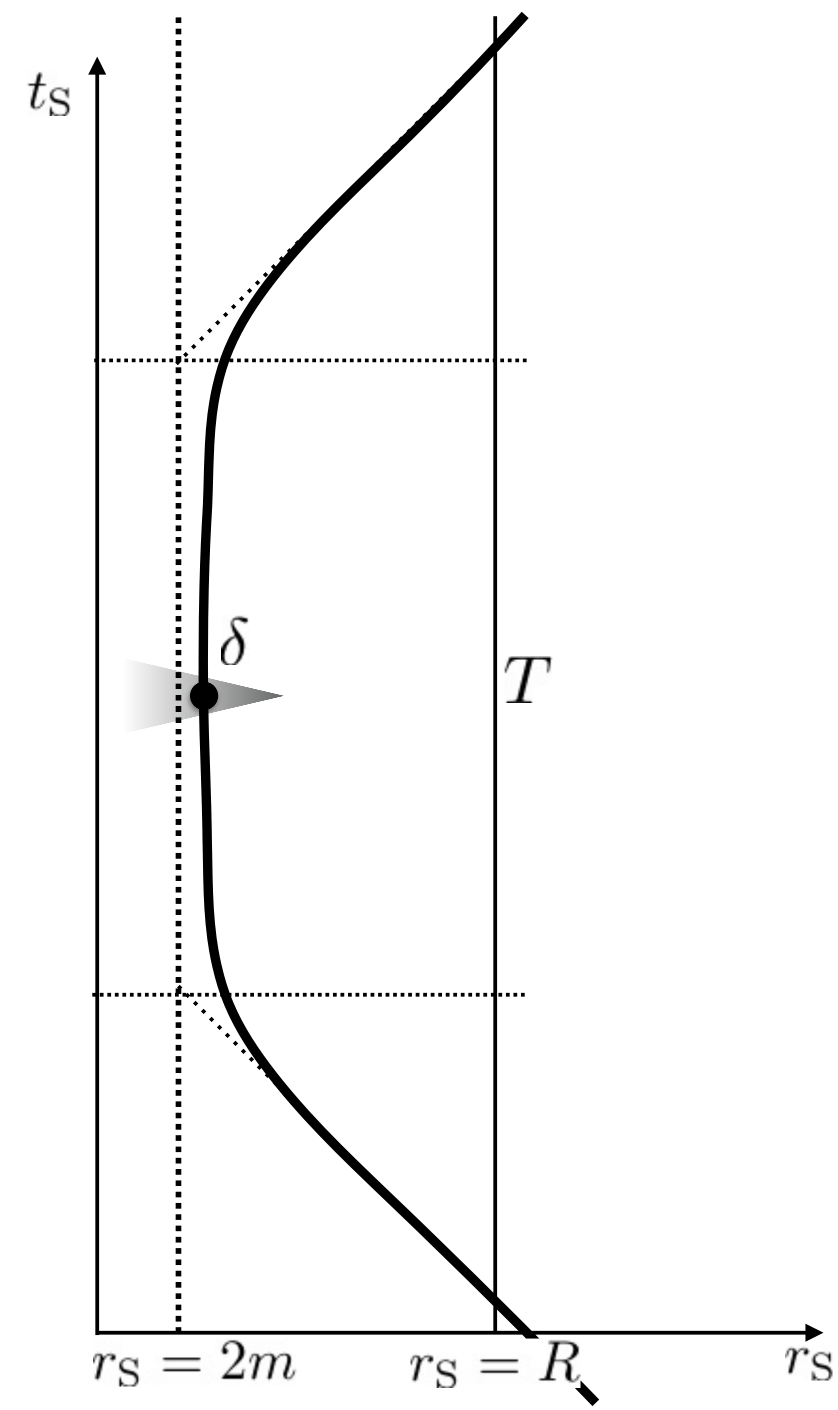


The Fingers Crossed

The external metric is determined by two constants:

- m is the mass of the collapsing shell.

- T is the external bounce time:

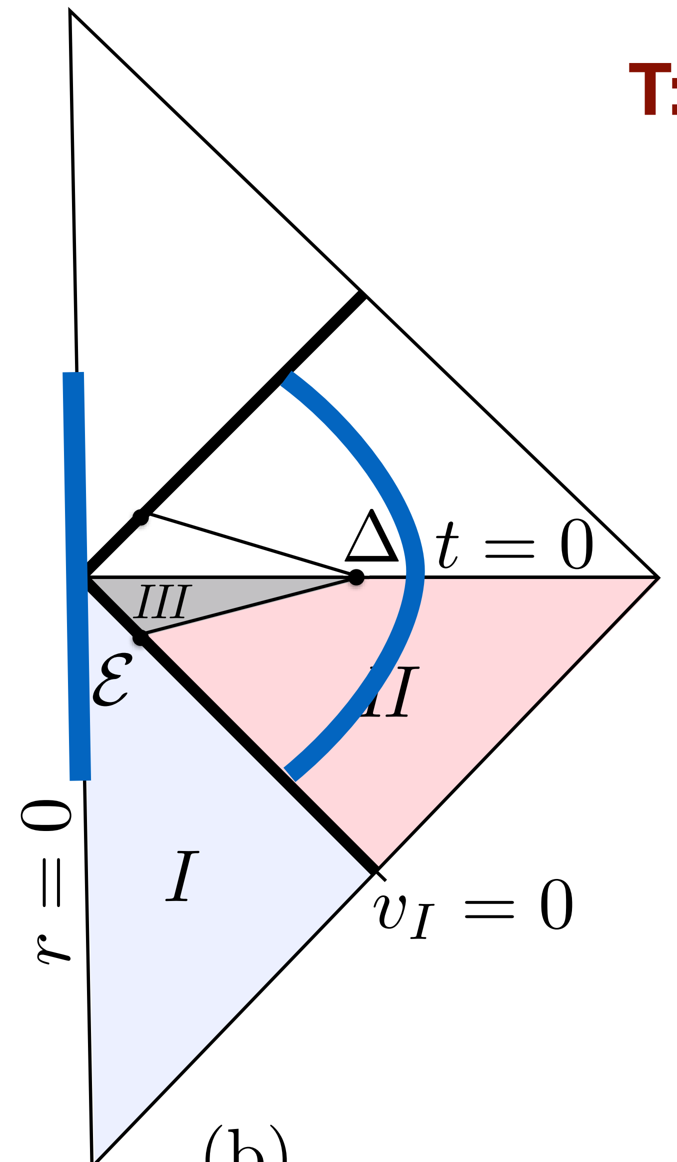


Time dilation

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

T: bounce time (very large)

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



(b)

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

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

What determines **T** ?

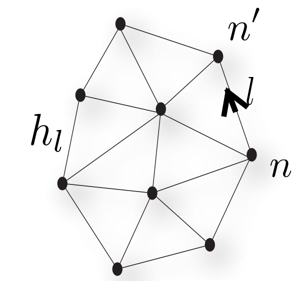
Quantum gravity

Covariant loop quantum gravity. Full definition.

Kinematics **Boundary**

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

Operators: $$\vec{L}_l = \{L_l^i\}, i = 1,2,3 \text{ where } L^i\psi(h) \equiv \frac{d}{dt}\psi(he^{t\tau_i})\Big|_{t=0}$$



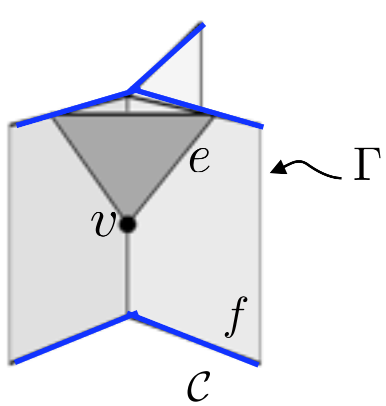
Γ spin network (nodes, links)

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

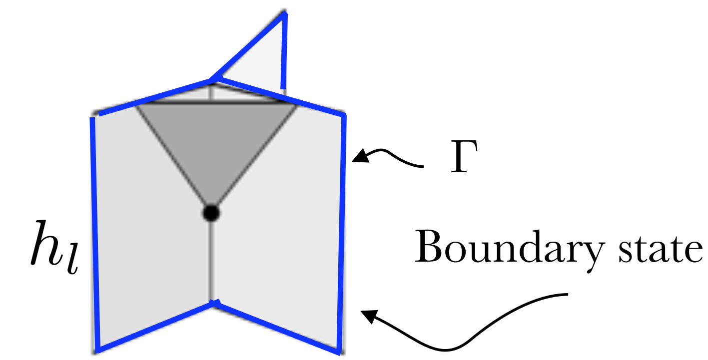


spinfoam (vertices, edges, faces)

$$W = \lim_{\mathcal{C}\to\infty} W_\mathcal{C}$$

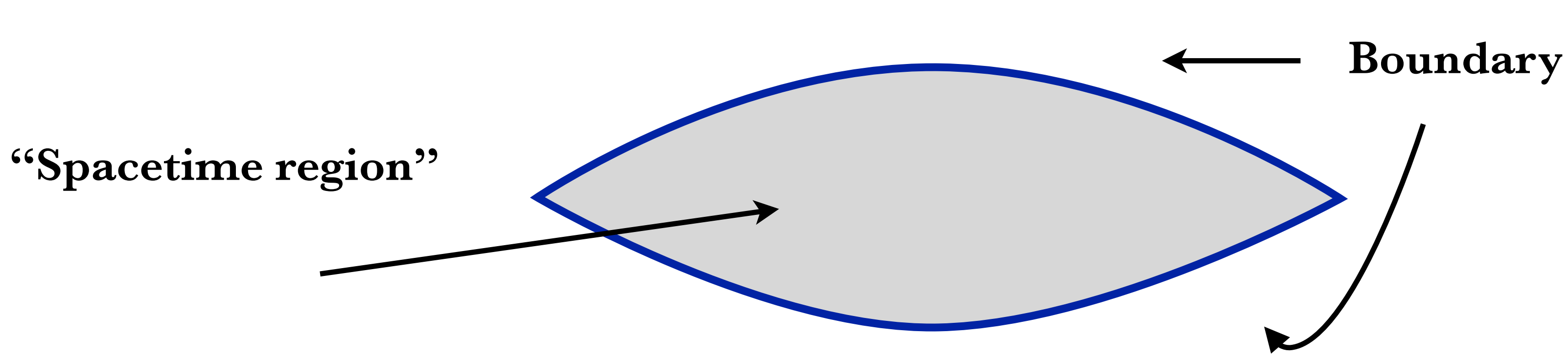
$$8\pi\gamma\hbar G = 1$$

A process and its amplitude



Boundary state $\Psi = \psi_{in} \otimes \psi_{out}$

Amplitude $A = W(\Psi)$

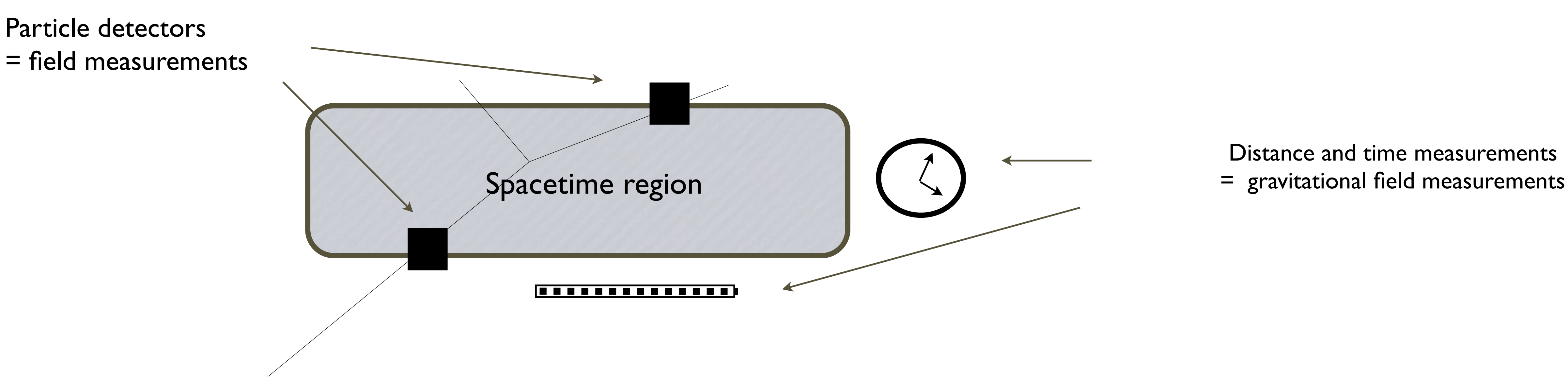


Quantum system = Spacetime region

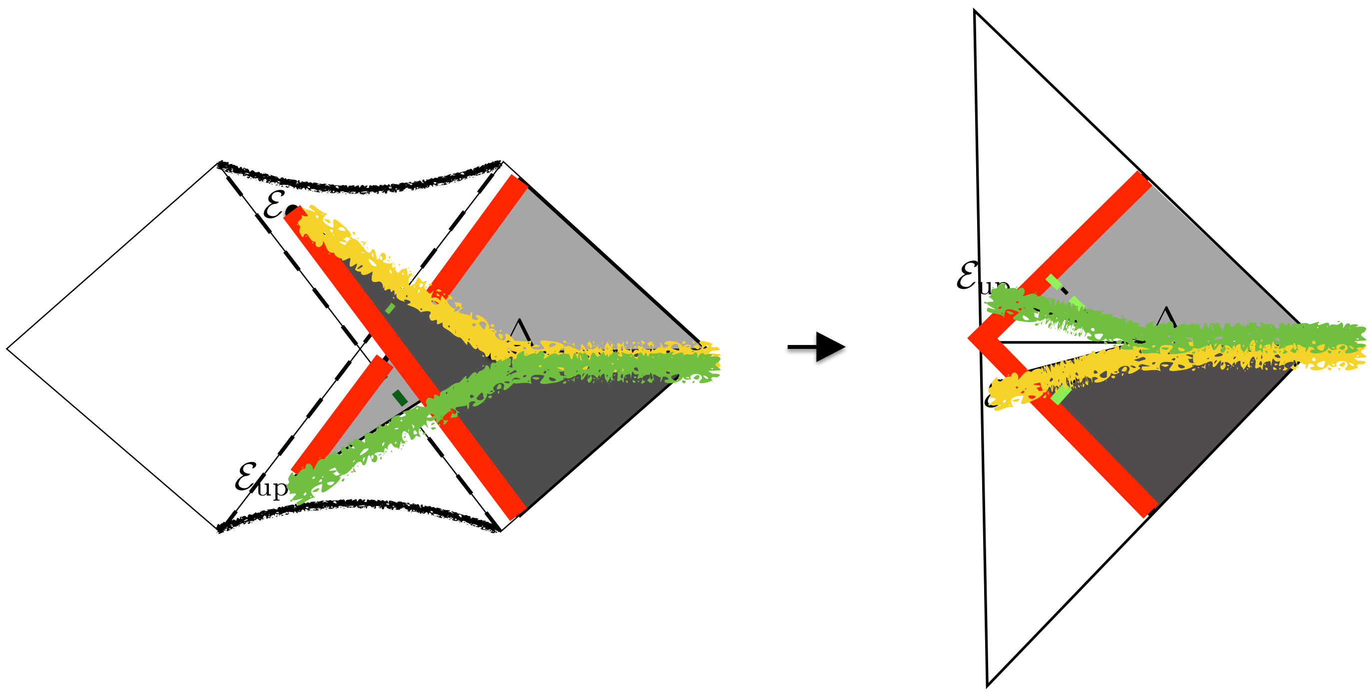
➜ **Hamilton function: S(q,t,q',t')**

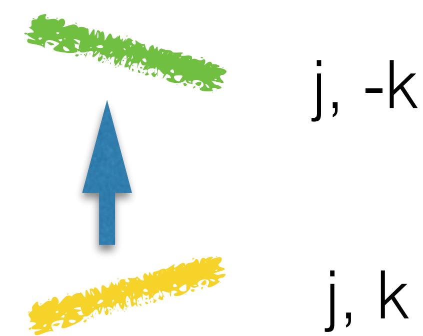
In GR, distance and time measurements are field measurements like any other one: they are part of the **boundary data** of the problem

Boundary values of the gravitational field = geometry of box surface = distance and time separation of measurements



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

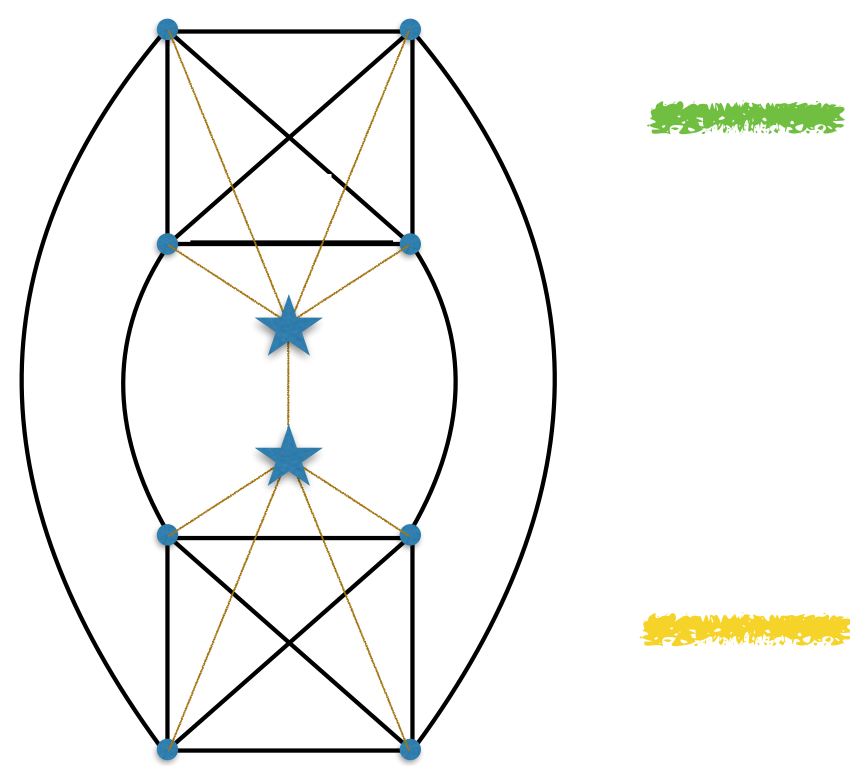


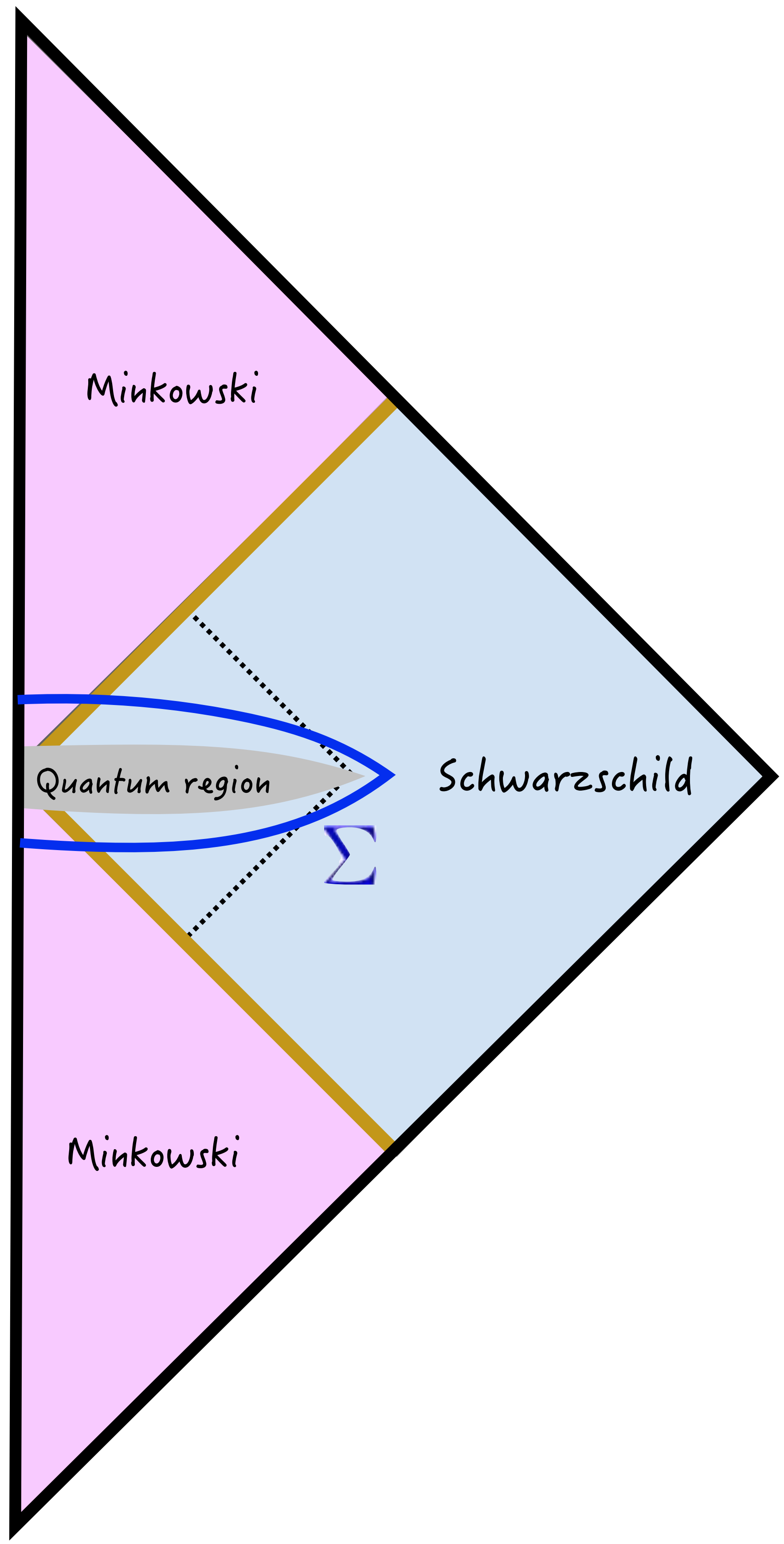


Boundary: B_3 U B_3 (Joined on a S_2)

Each B_3 can be triangulated by 4 isosceles tetrahedra.

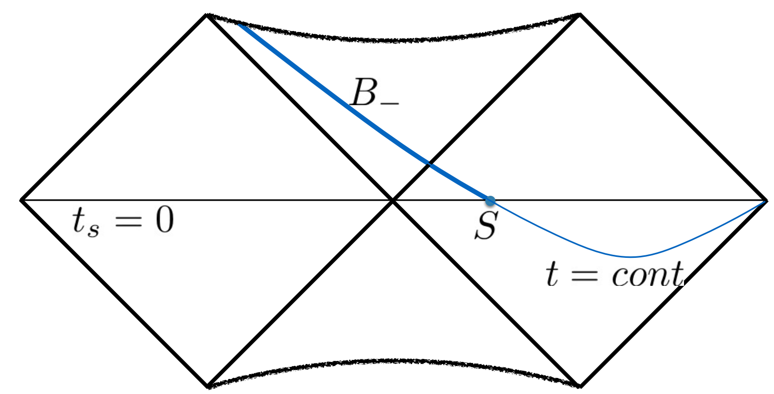
The bulk cal be approximated to first order by two 4-simplices joined by a tetrahedron

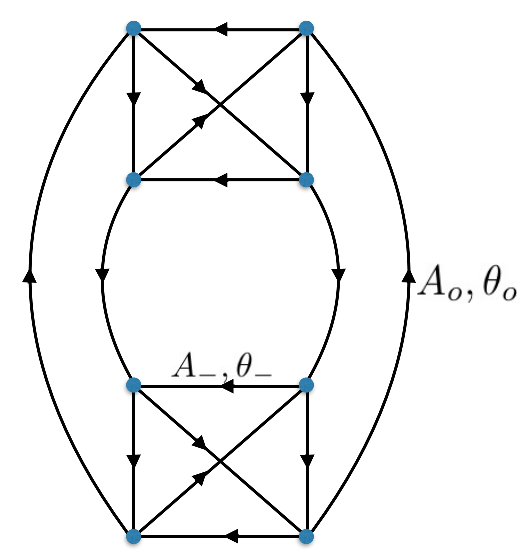


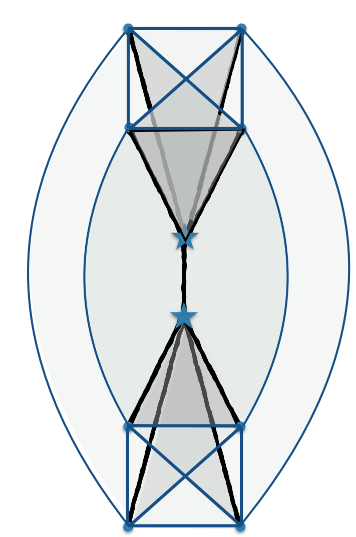


Choose a “Boundary” surface around the quantum region.

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







Full expression for T(m):

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

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

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

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

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

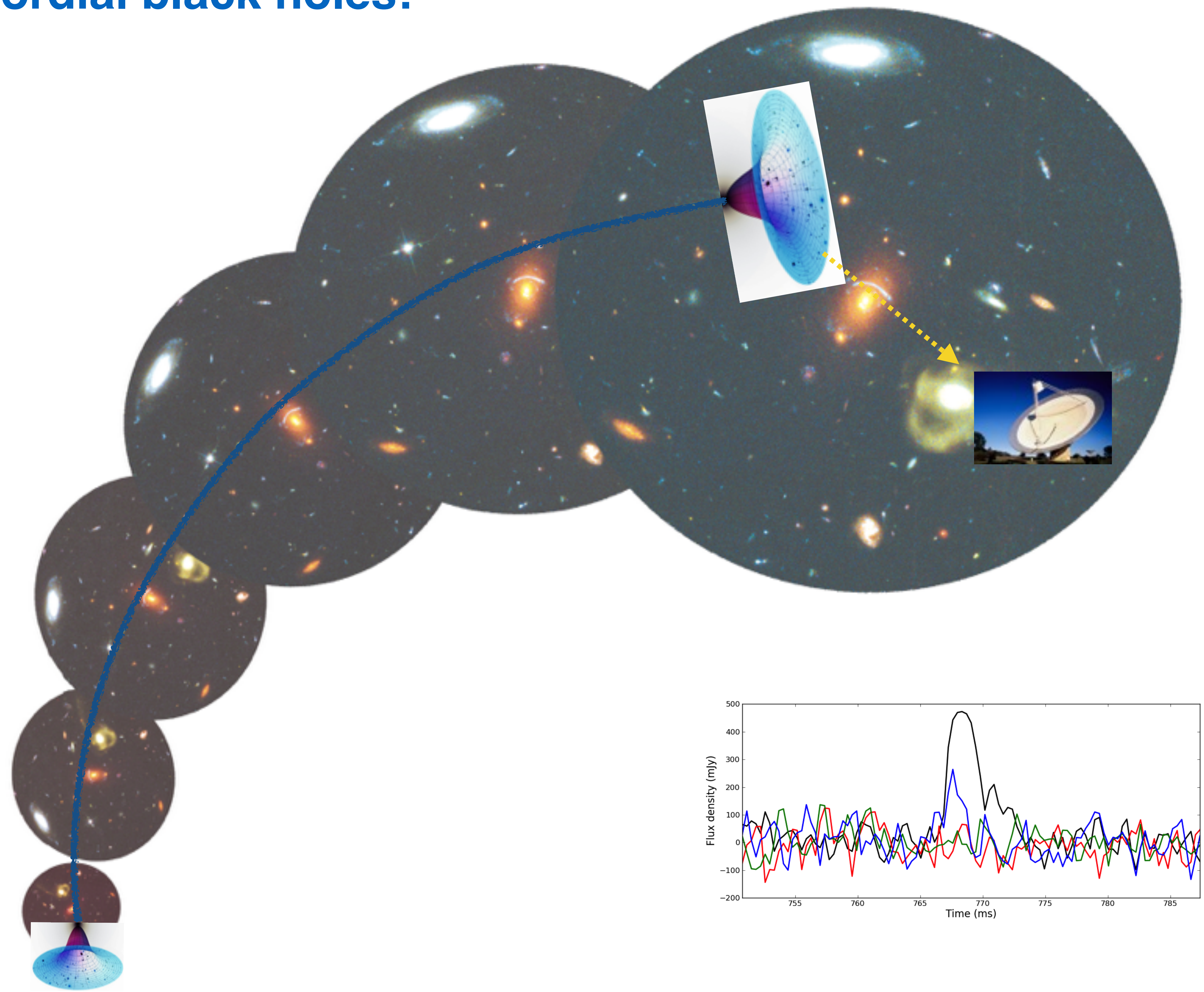
$$T \sim m^2$$

Primordial Black Holes

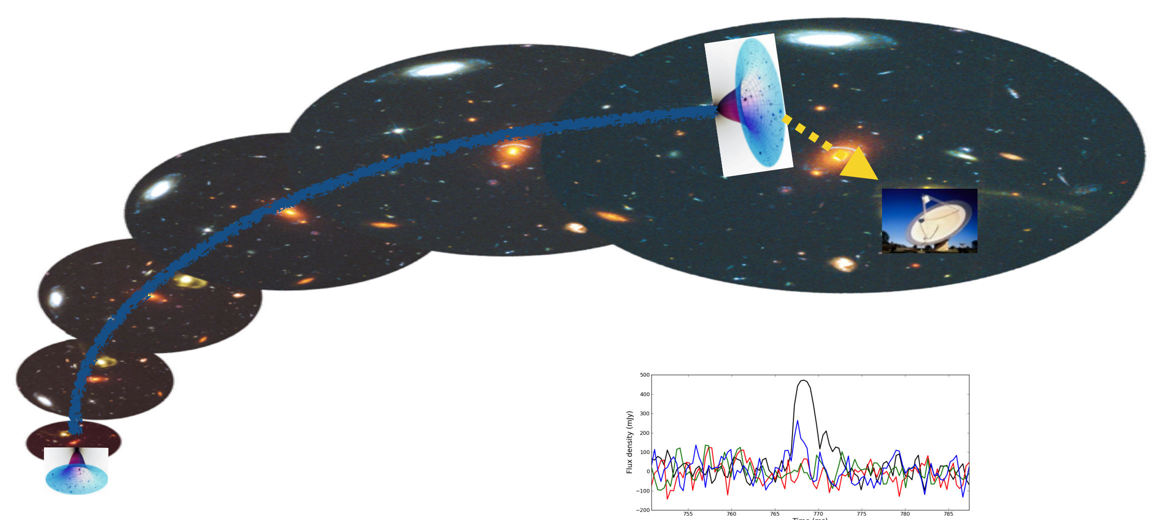
- What? Primordial matter density fluctuations
- When? Early universe (typically reheating)
- Why? Density contrast $\delta \approx 0.45$
- How? Large possible spectrum of PBH

$$M \sim M_H \sim t. \qquad t \sim 0.3 g_*^{-\frac{1}{2}} T^{-2}$$

Primordial black holes!



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

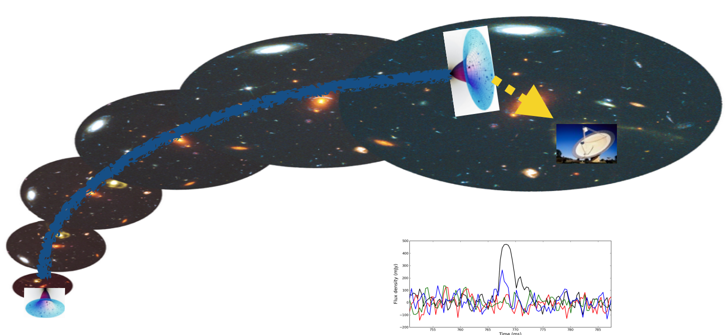


Primordial Black Hole Explosion

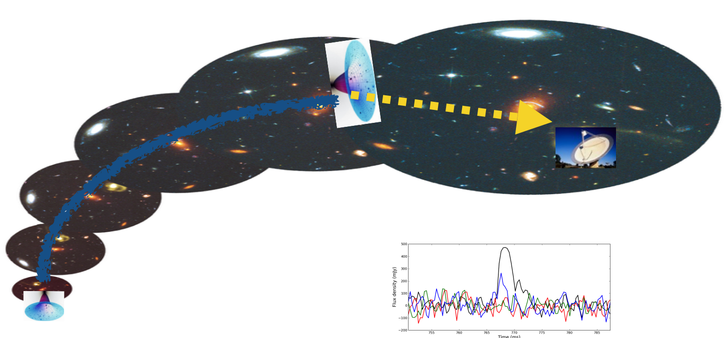
- exploding now: $m(t)|_{t=t_H}$ $R = \frac{2Gm}{c^2}$
- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted}$
- **HIGH ENERGY:** energy of the particle liberated $\approx Tev$
- fast process (few milliseconds?)
- the source disappears with the burst
- very compact object: big flux $E = mc^2$

Signature: distance/energy relation

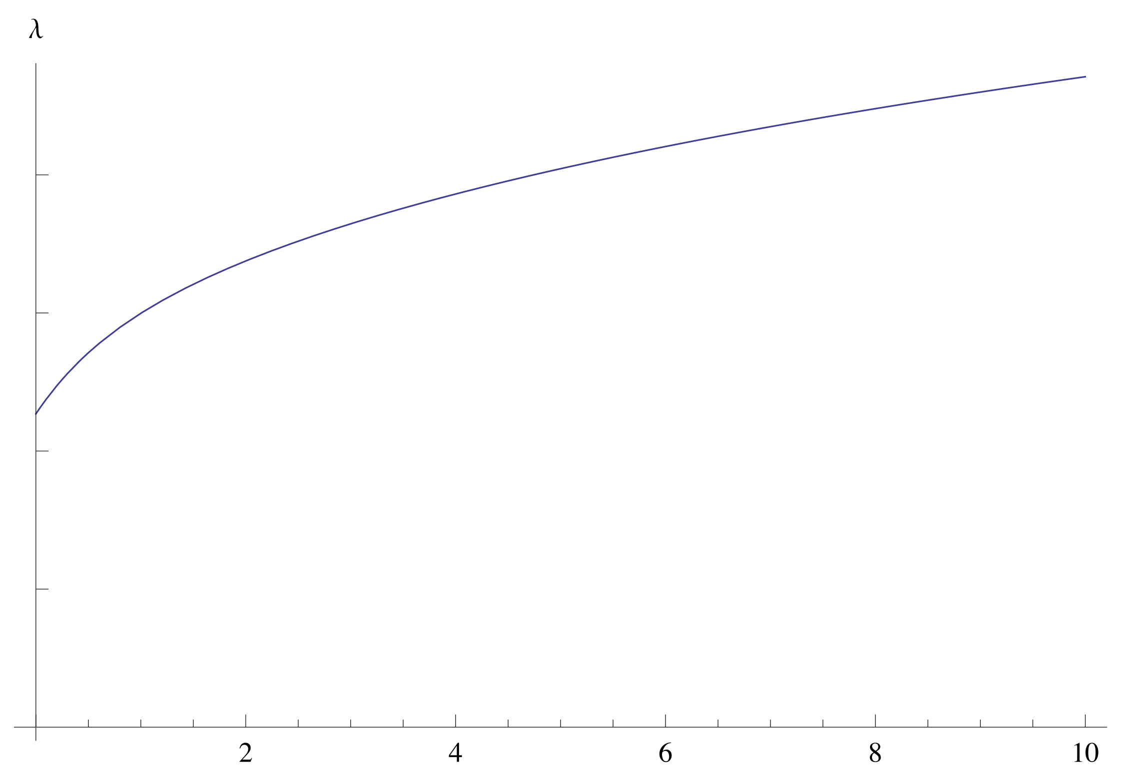
$$\lambda_{obs} \sim \frac{2Gm}{c^2}(1+z)\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}$$



m_1



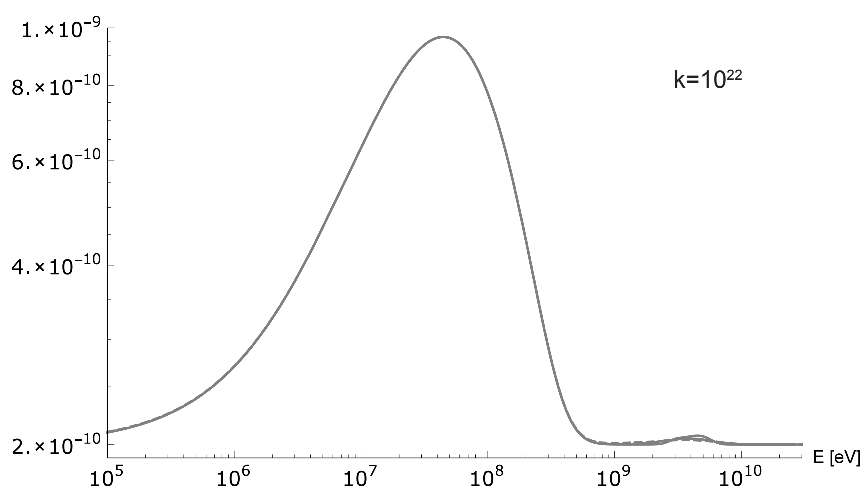
$m_2 < m_1$



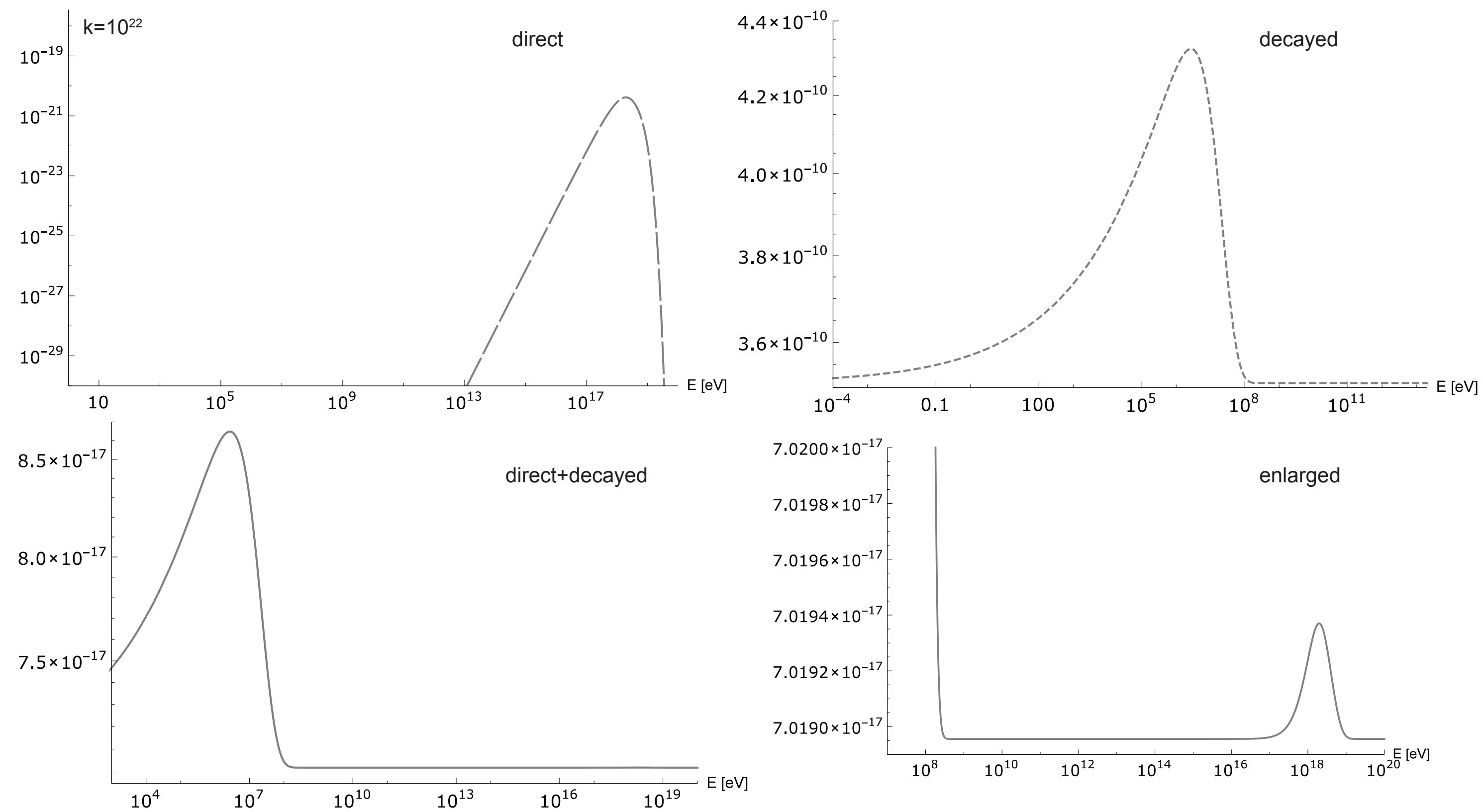
Integrated emission

$\tau \sim m^3$

Low energy channel



High energy channel

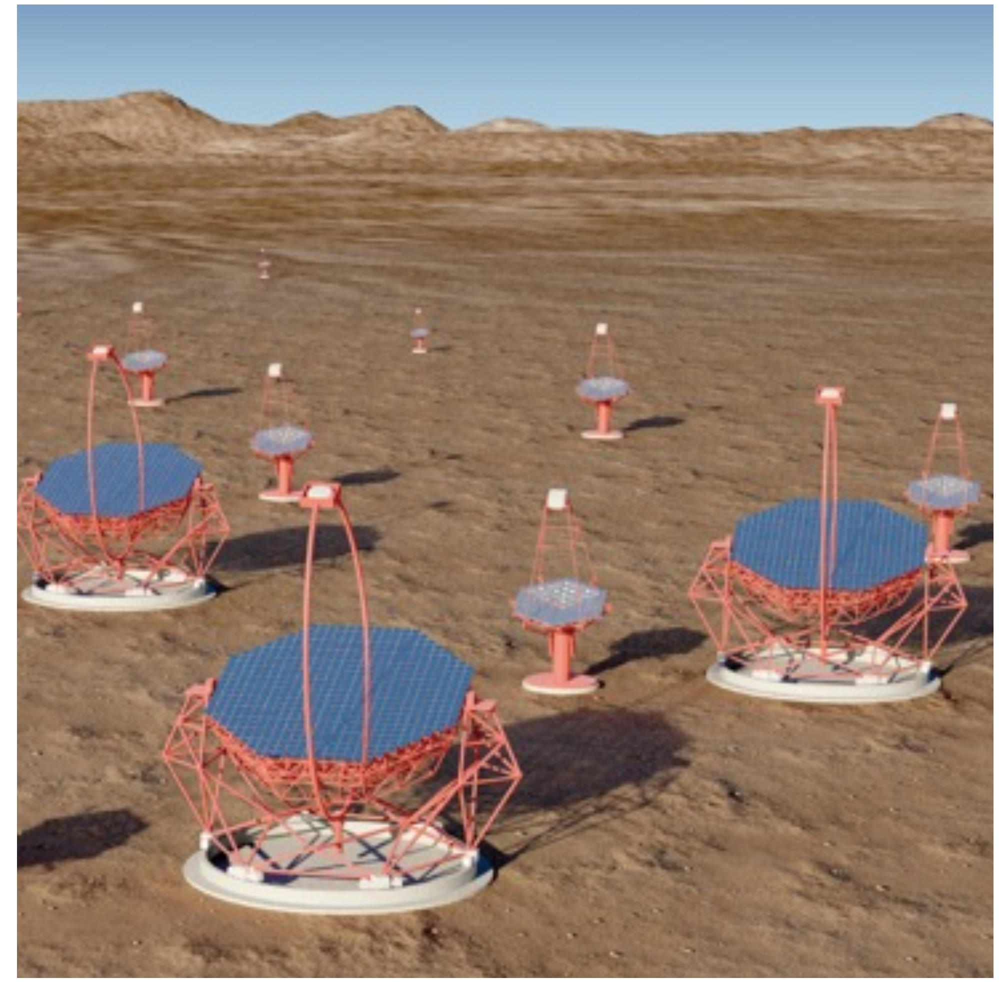


$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E, R) \cdot n(R) \cdot Acc \cdot Abs(E, R) dR$$

- characteristic shape: distorted black body
- depends on how much DM are PBL

Short Gamma Ray Burst

- the white hole should eject particles at the same temperature as the particles that felt in the black hole
- limited horizon due to absorption ~ 100 million light-years / z=0.01
- known GRB have energy ≪ Tev
- telescopes spanning large surfaces needed (CTA?)

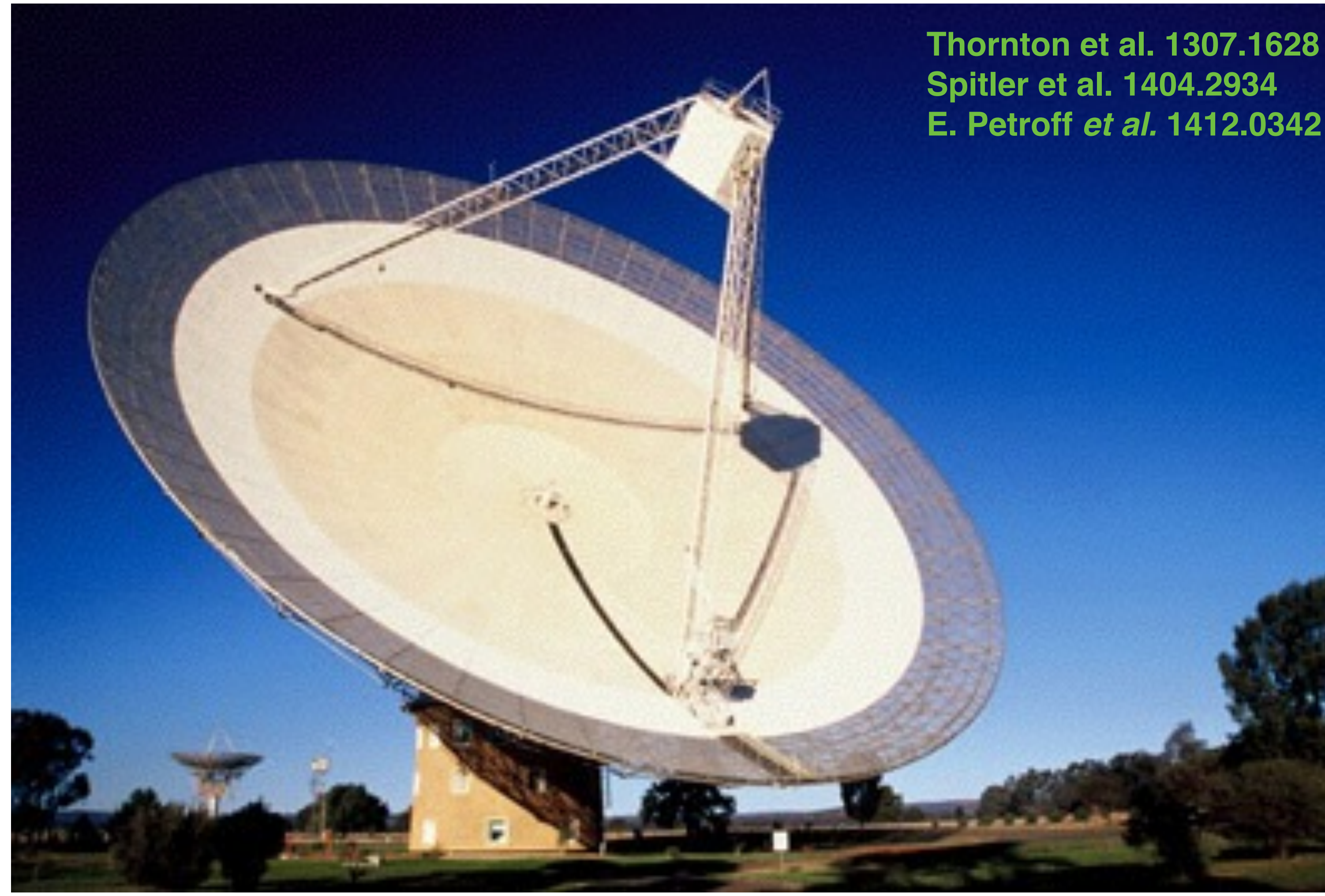


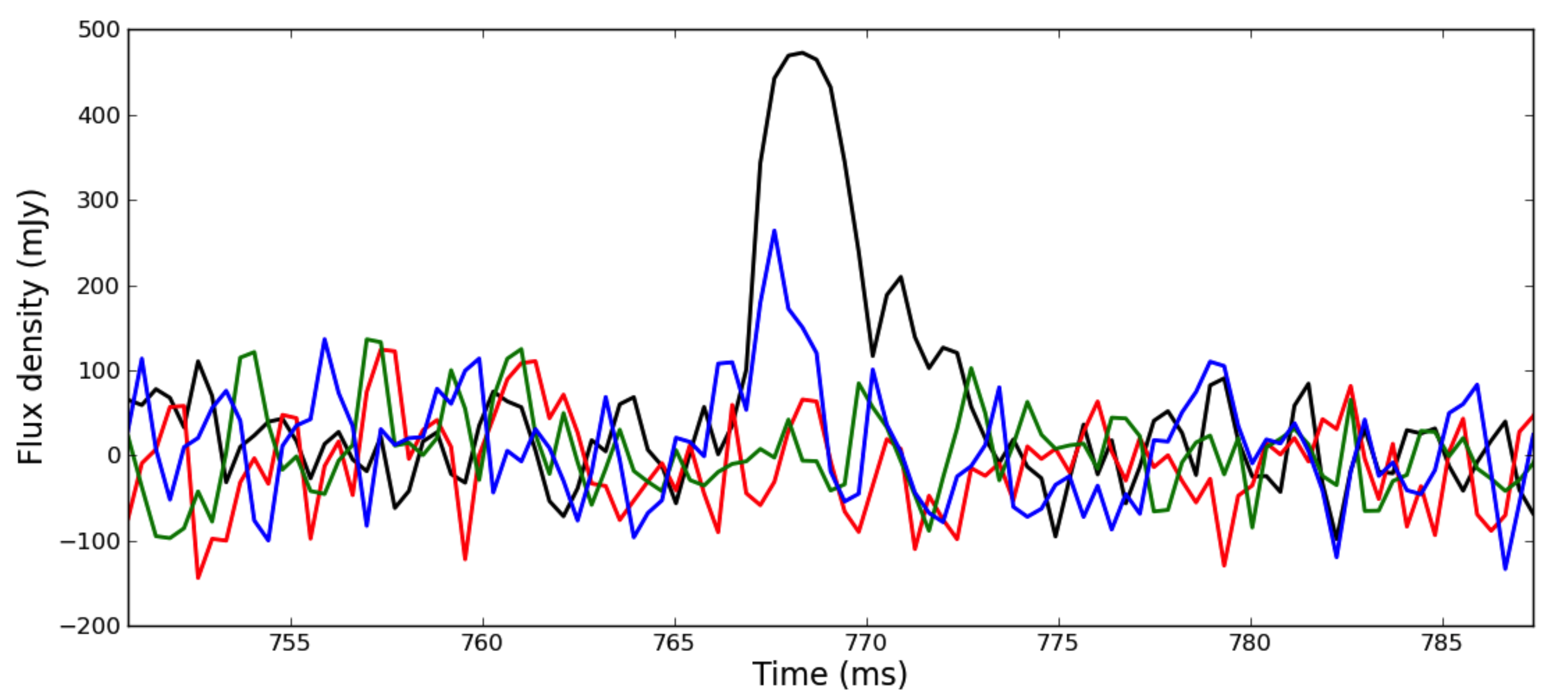
$$\lambda_{obs} \propto (1+z)\left(\sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{\frac{1}{2}}(z+1)^{-\frac{3}{2}}\right]\right)^{\frac{1}{4}}$$

Fast Radio Burst

Unknown source!

- Short
  - Observed width ≃ milliseconds
- No Long GRB associated
  - No Afterglow
- 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?
- Circular polarization
  - Intrinsic





Fast Radio Burst

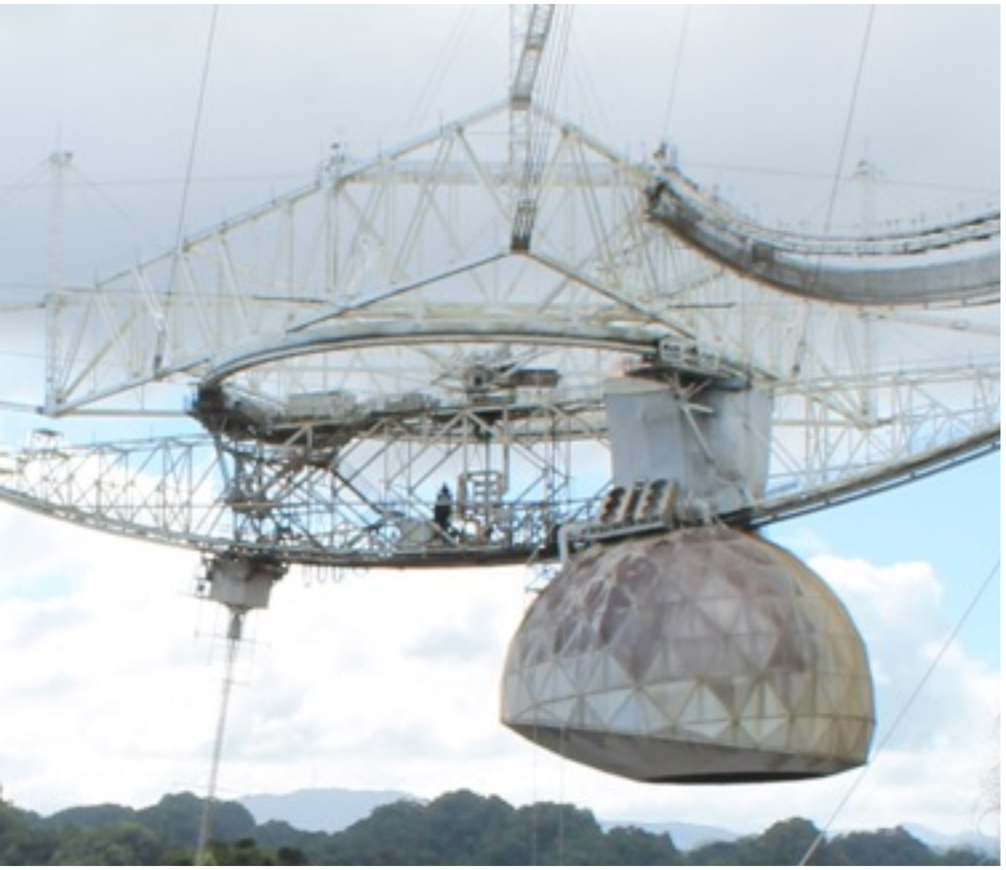
- $\lambda \approx 20$ cm → size of the source $\approx \lambda_{predicted} \gtrsim .02$ cm
- Short
  - Observed width ≃ milliseconds → fast process
- No Long GRB associated
  - No Afterglow → Very short GRB ? gravitational waves ?
- Punctual
  - No repetition → the source disappears with the burst
- Enormous flux density
  - Energy $\lesssim 10^{38}$ erg → very compact object $\longrightarrow 10^{47}$ erg
- Likely Extragalactic
  - Dispersion Measure: $z \lesssim 0.5$ → peculiar distance/energy relation
- 10^4 event/day
  - A pretty common object?
- Circular polarization
  - Intrinsic

Are they bouncing Black Holes?

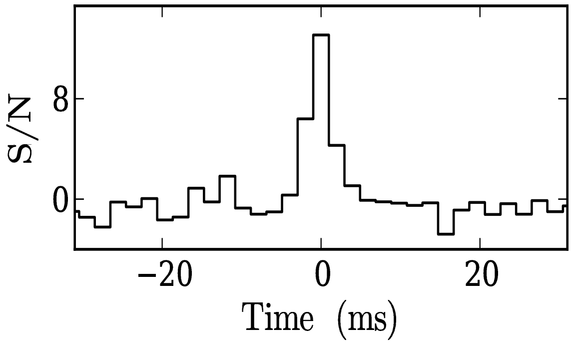
Detectable?
Already detected?

For T~m^3 primordial black hole give signals in the cosmic ray spectrum

For T~m^2 primordial black hole give signals in the radio: Fast Radio Bursts?



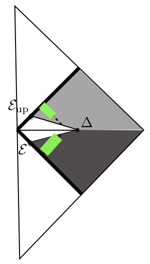
Fast Radio Bursts

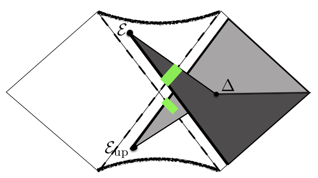


- Duration: ~ milliseconds
- Frequency: 1.3 GHz
- Observed at: Parkes, Arecibo
- Origin: Likely extragalactic
- Estimated emitted power: 10^{38} erg
- Physical source: unknown.

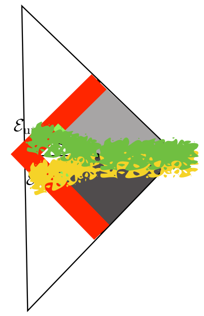
Summary

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

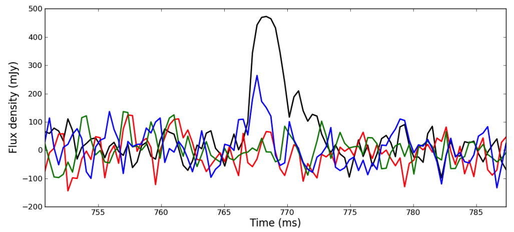




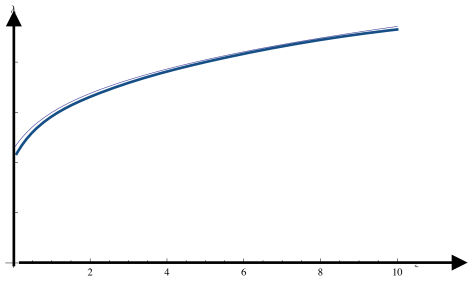
- The tunnelling time can be computed with LQG.



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



- Wavelength-to-distance relation signature.



Main papers

Planck Stars

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.

Improved Black Hole Fireworks: Asymmetric Black-Hole-to-White-Hole Tunneling Scenario
Tommaso De Lorenzo, Alejandro Perez
arXiv:1512.04566

Phenomenology

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

Phenomenology of bouncing black holes in quantum gravity: a closer look
Aurélien Barrau, Boris Bolliet, Francesca Vidotto, Celine Weimer
JCAP 1602 (2016) no.02, 022

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