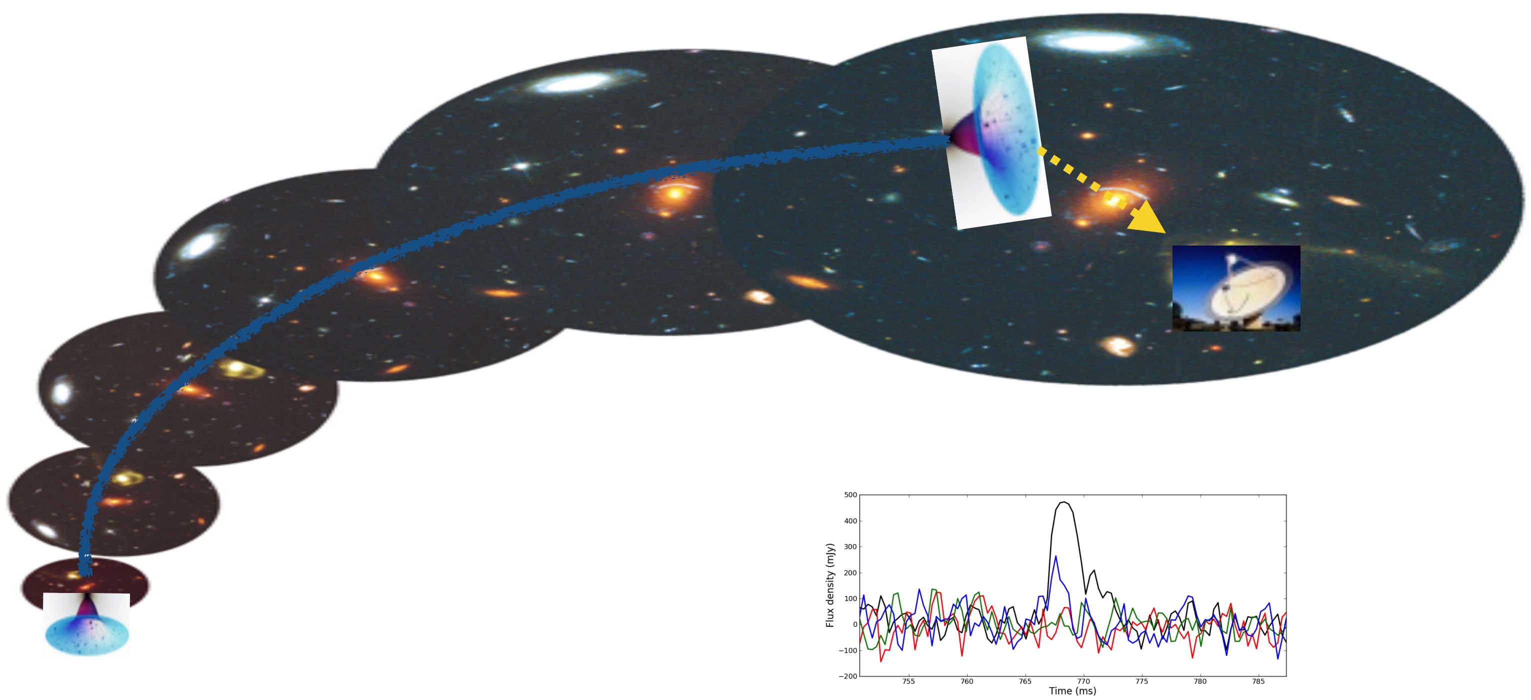
Planck stars

An observable quantum gravity phenomenon?

Carlo Rovelli



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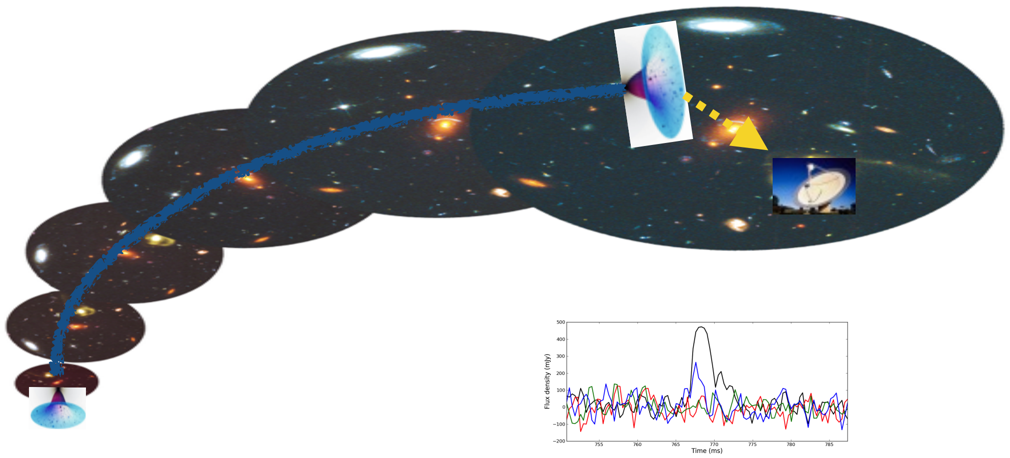


Collaborators

Main idea “Planck Stars": **Francesca Vidotto**
Classical solution: **Hal Haggard**
Phenomenology: **Aurélien Barrau**, **Francesca Vidotto, Boris Bolliet, Celine Weimer**
Loop quantum gravity calculation: **Simone Speziale, Marios Christodoulou, Ilya Vilensky**

Planck stars

An observable quantum gravity phenomenon?

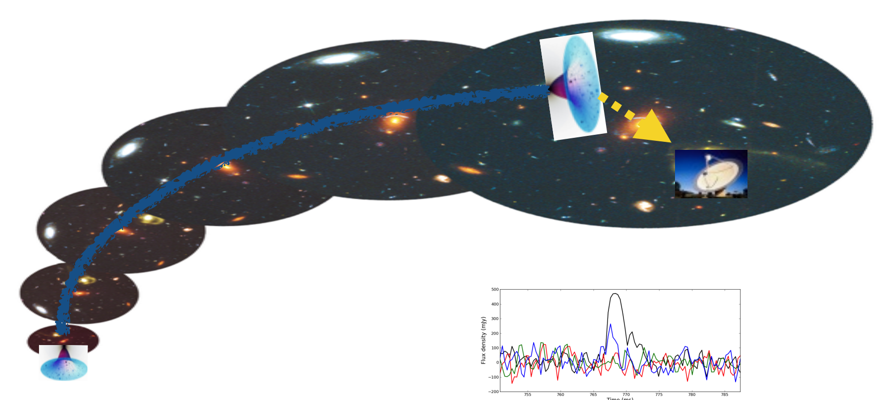
i. Black holes can decay non-perturbatively via quantum gravitational tunnelling, and explode.

ii. Decay time can be estimated, and computed using Loop Quantum Gravity.

iii. Primordial black holes could be exploding today, producing high and/or low energy components signals.

iv. The expected low-energy frequency is close to that of the observed Fast Radio Bursts.

v. Both signals have a characteristic distance-frequency curve.



Planck stars

An observable quantum gravity phenomenon?

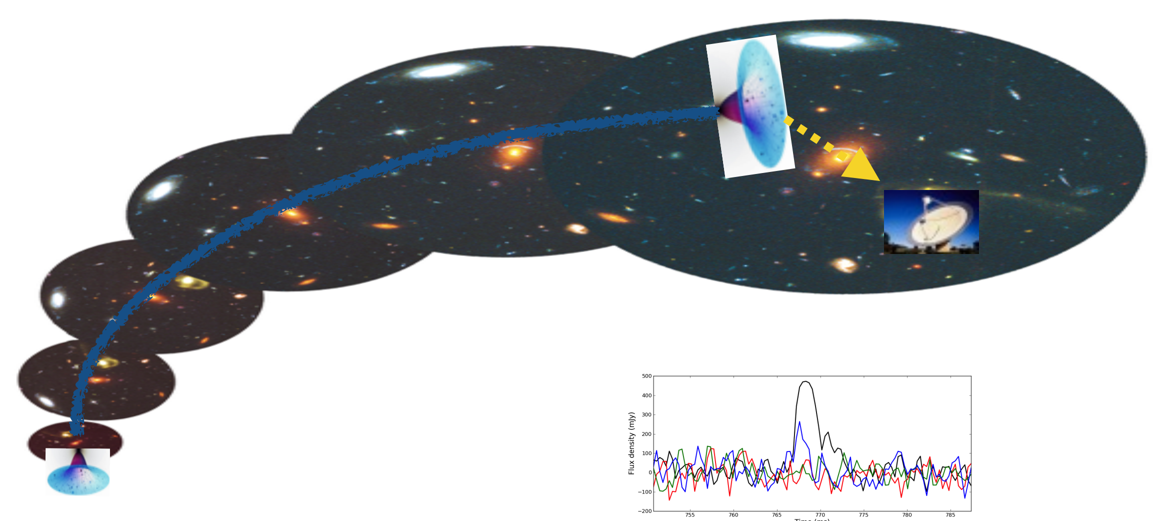
I. Basics of black hole tunneling decay

II. Decay time

III. Observations: High energy: gamma.

IV. Observations: Low energy signal: Fast Radio Bursts?

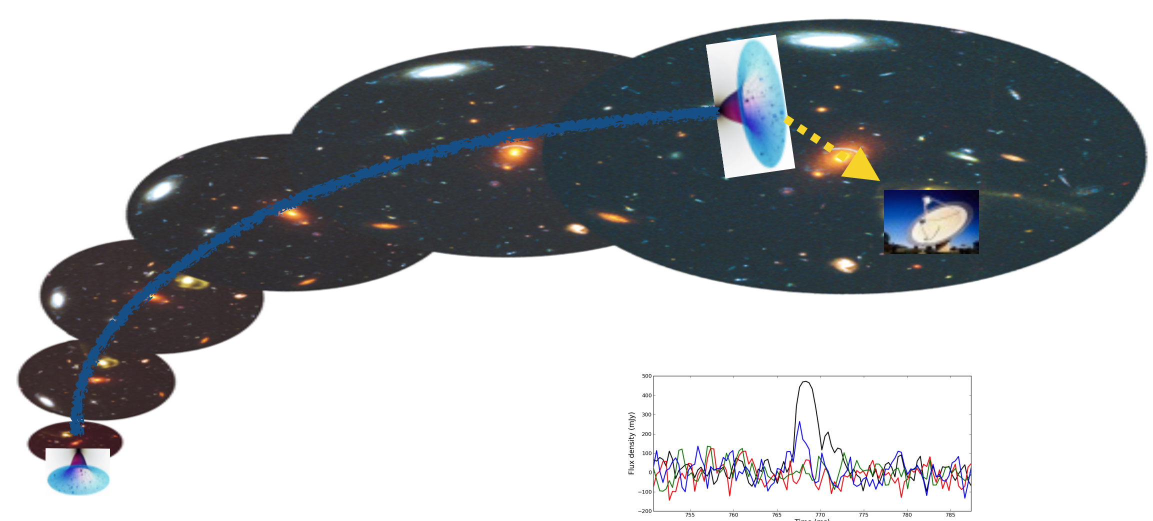
V. Distance-frequency curve



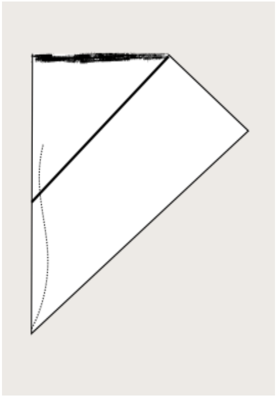
Planck stars

An observable quantum gravity phenomenon?

I. Basics of black hole tunneling decay



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



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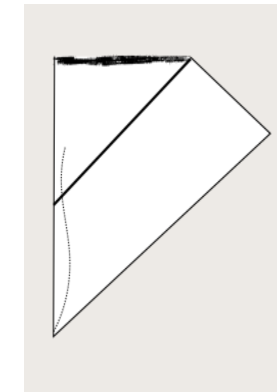
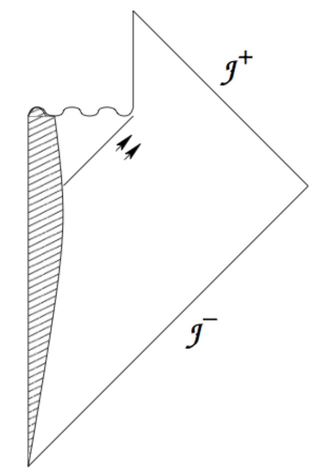


In **quantum field theory on a classical gravitational field**, a black hole decays via Hawking radiation, in an extremely long time. (10^{50} Hubble times, for a stellar bh.)



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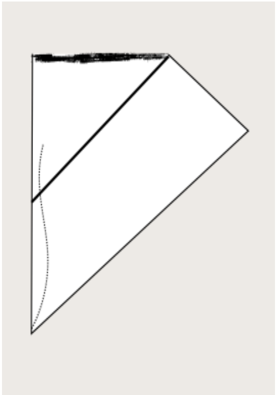

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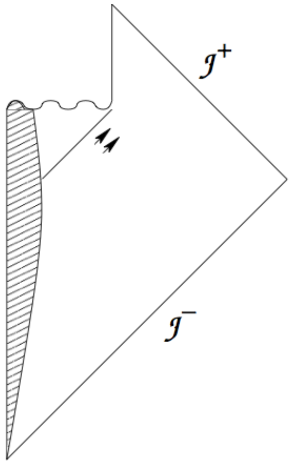
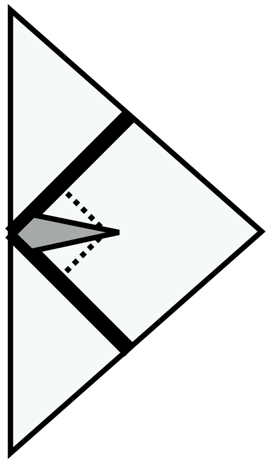
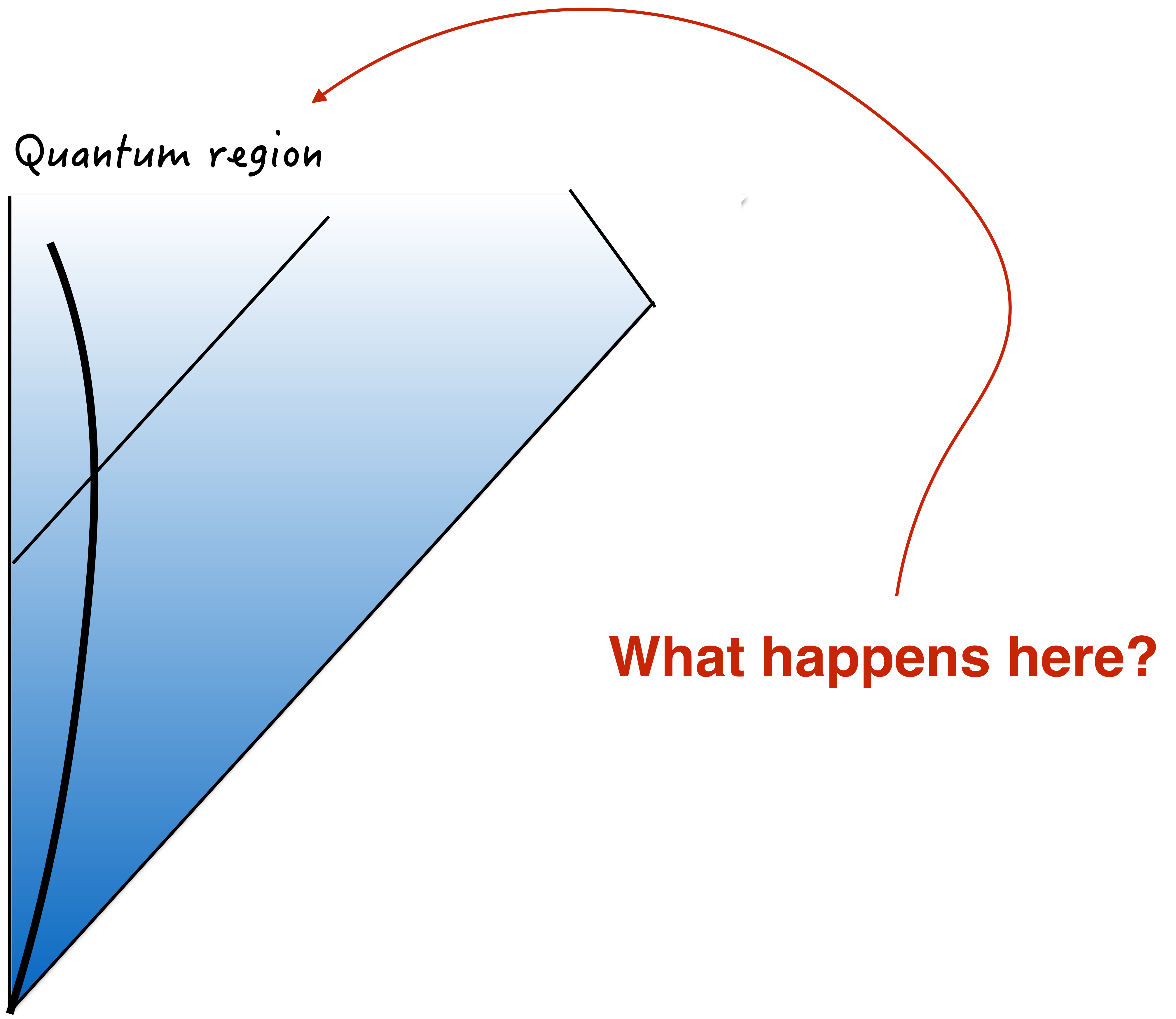
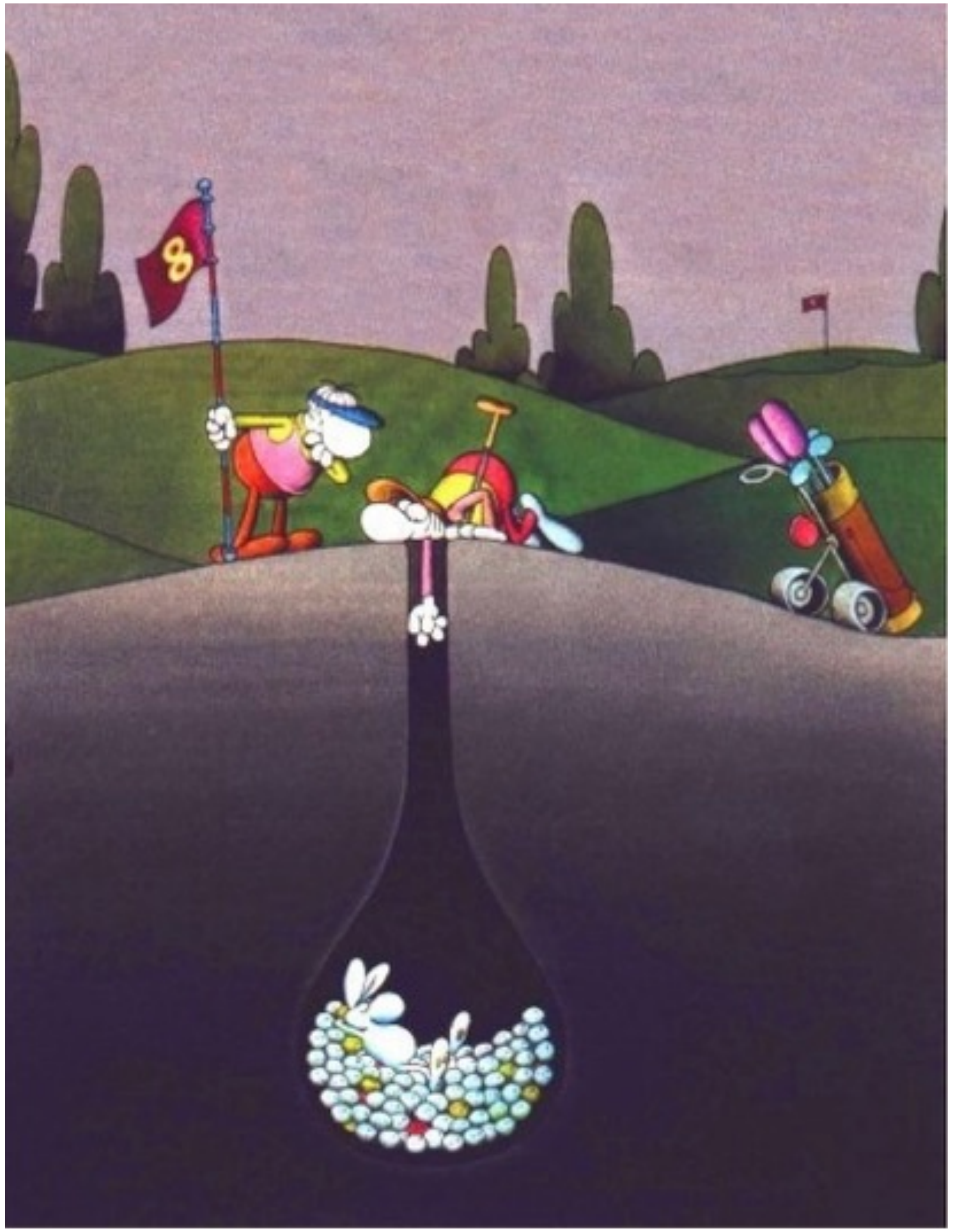


In **quantum gravity**, a black hole can decay via a non perturbative quantum tunnelling.




Quantum region
What happens here?

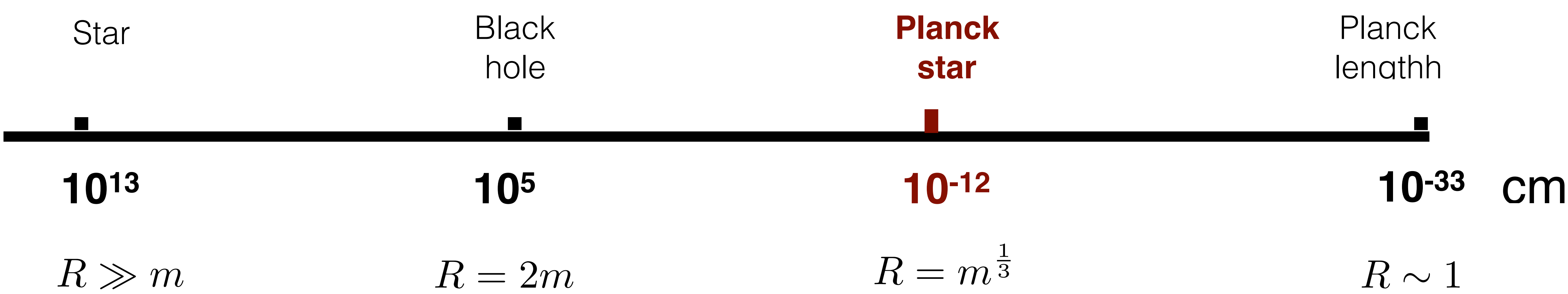


What happens to the matter falling into black holes?

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

The relevant scale: Planck density

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



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

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

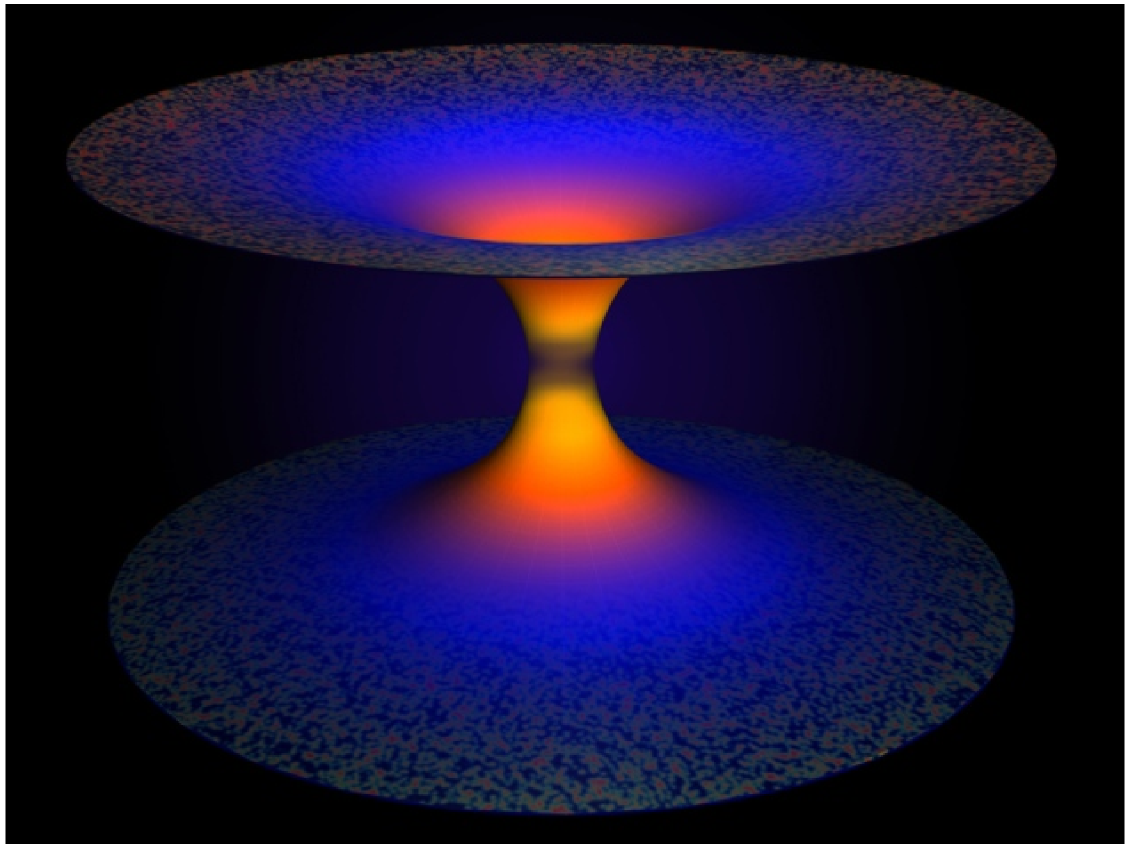
- **A star can bounce at that scale**

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

From Loop Quantum Cosmology:

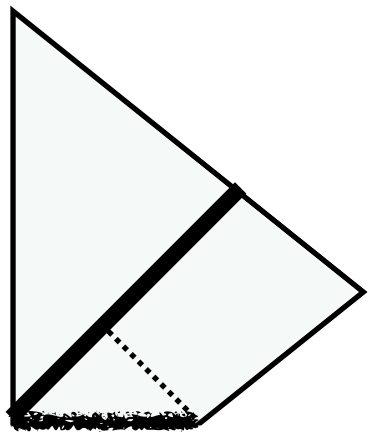
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho \left(1 - \frac{\rho}{\rho_{Pl}}\right)$$

Pressure develops when
matter density reaches
The Planck density

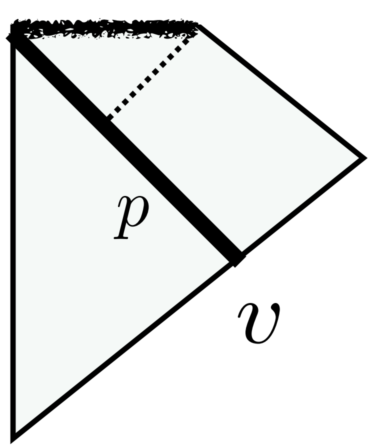


The Hajicek-Kiefer bounce

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)



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

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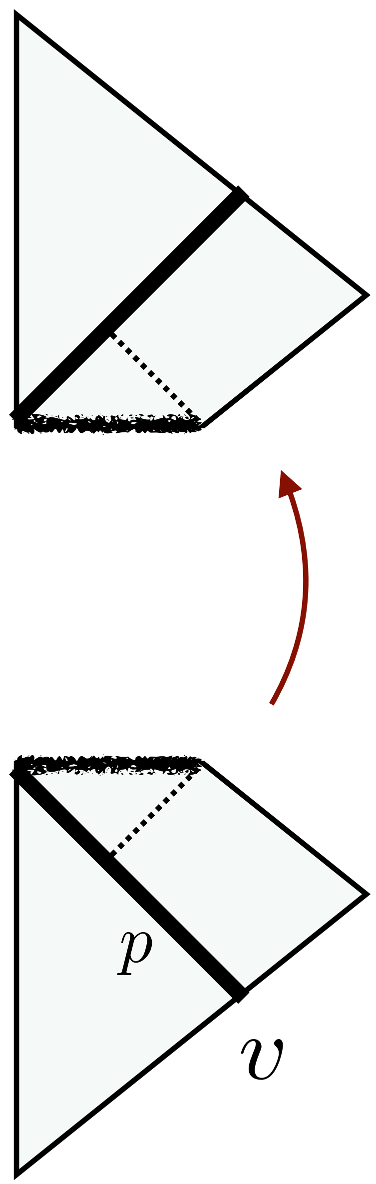

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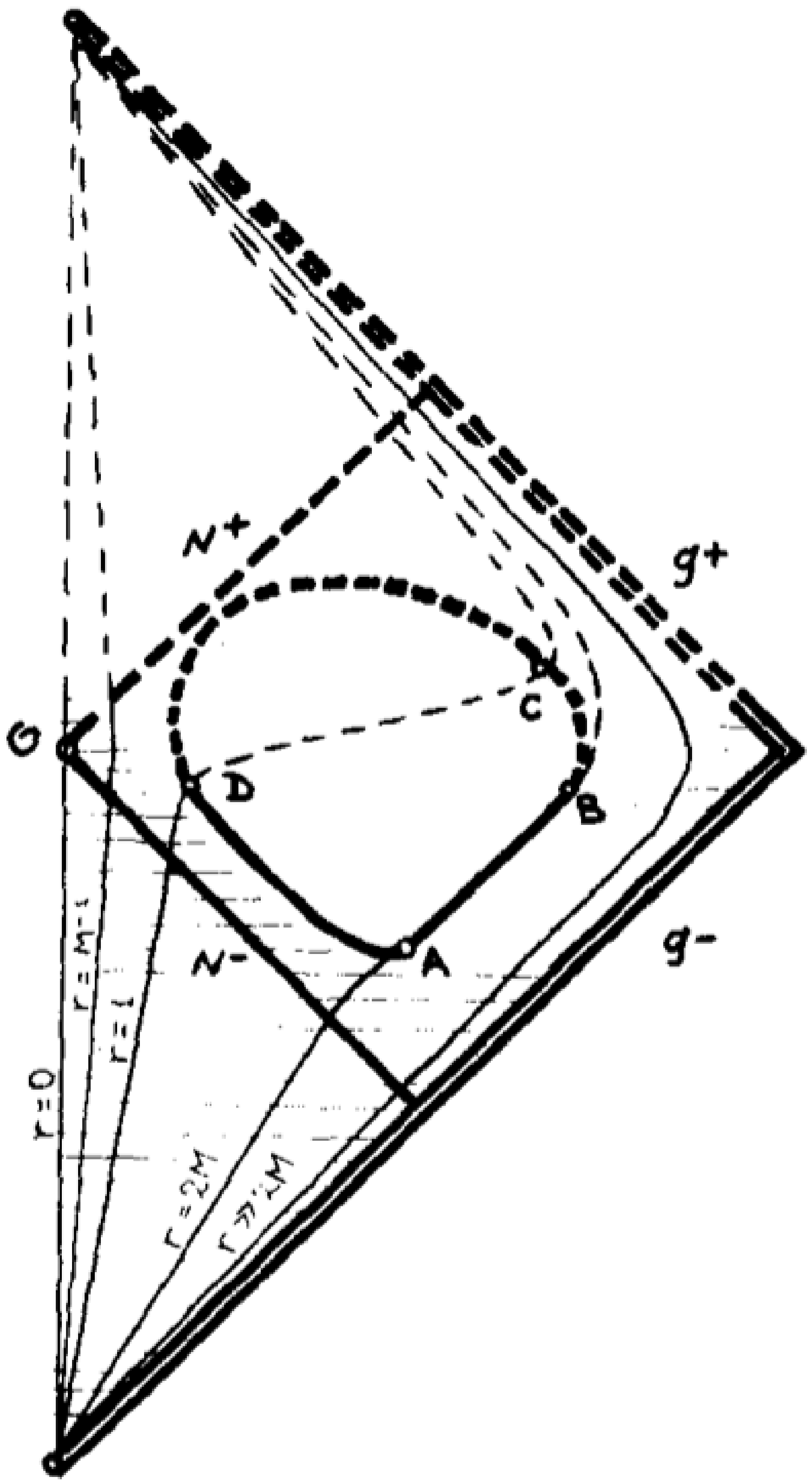
- Classically: Finite dimensional phase space (v,p) separated in two disconnected components:
    - p>0: shell collapsing into white hole (future singularity)
    - p<0: shell emerging from a white hole (past singularity)
- Formal quantization: transition between the two components
- **Can a black hole truly tunnel into a white hole?**

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

Exploding holes

Exploding holes



- Frolov, Vilkovinski '79

Exploding holes

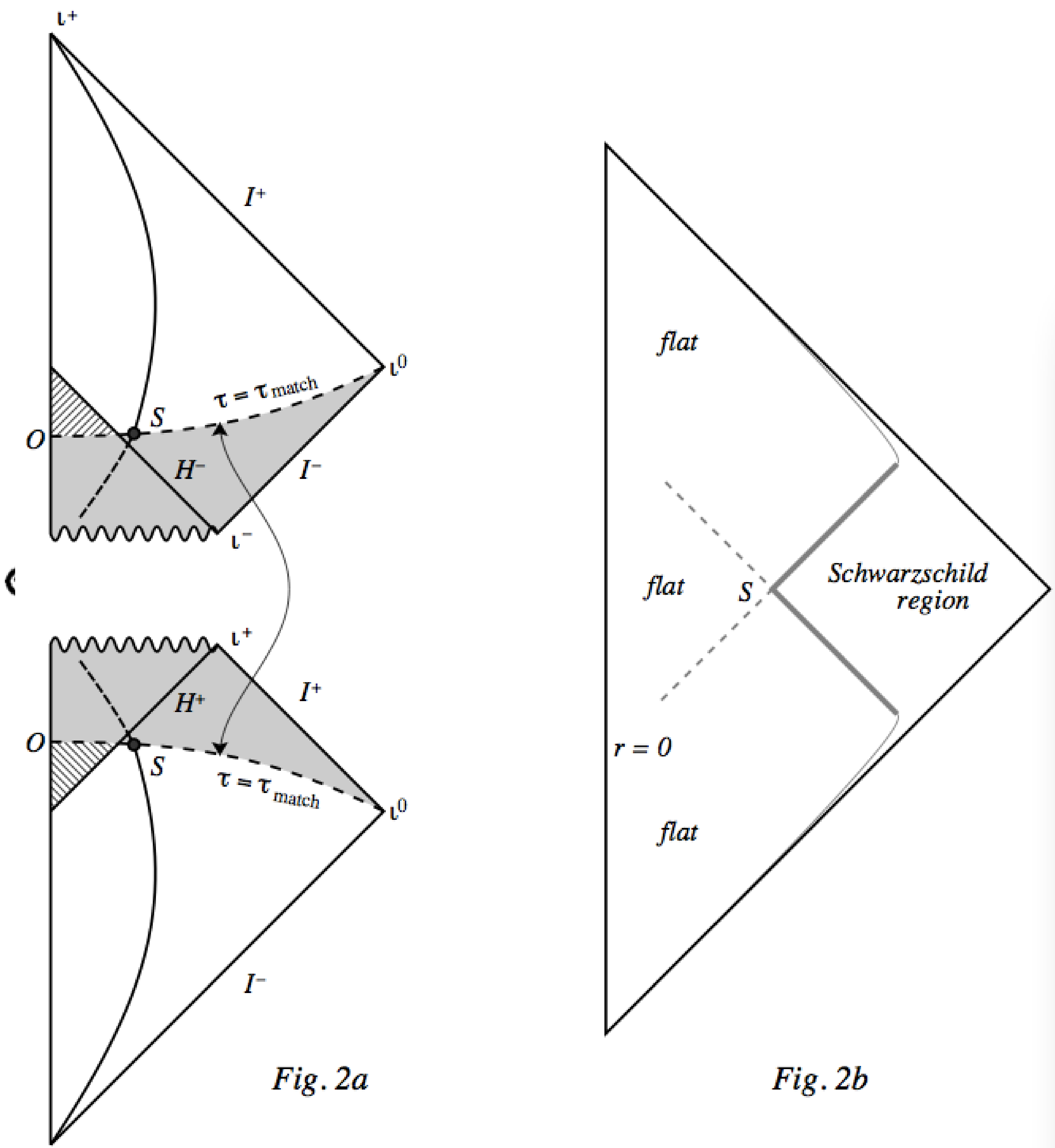
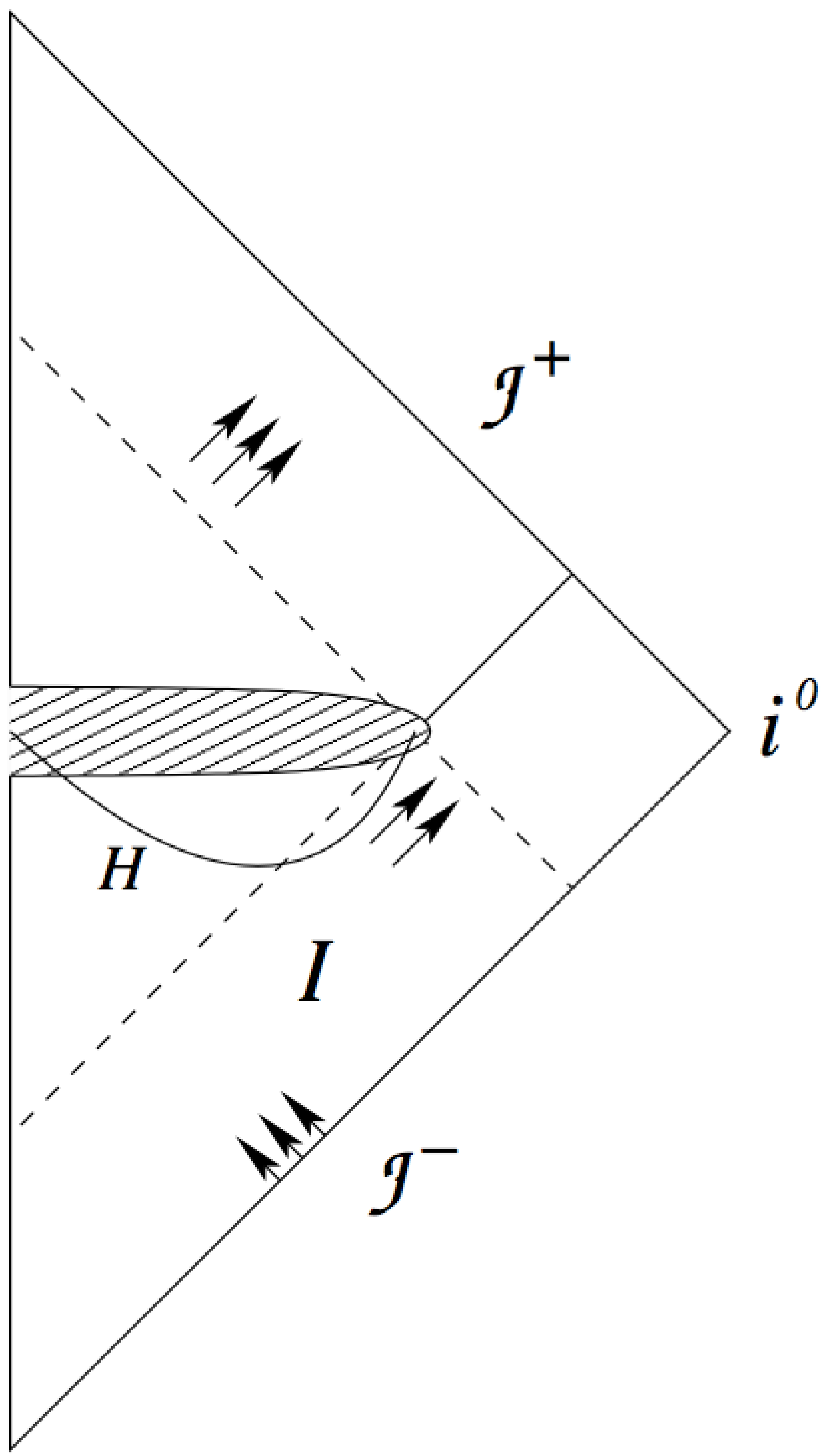


Fig. 2a *Fig. 2b*

- Frolov, Vilkovinski ‘79
- Stephen, t’Hooft, Whithing ‘93

Exploding holes



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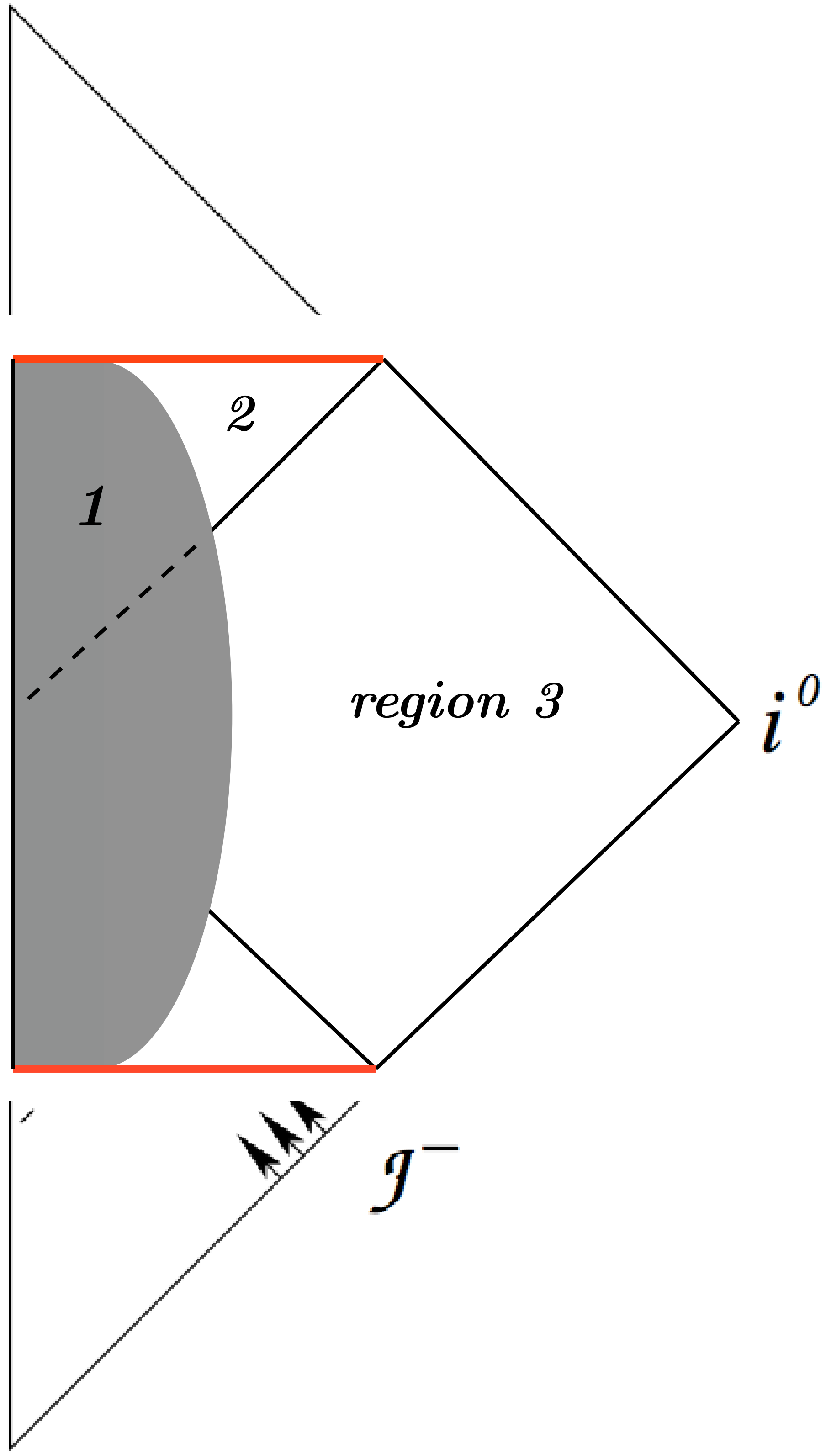
- Ashtekar, Bojowald '05

Exploding holes



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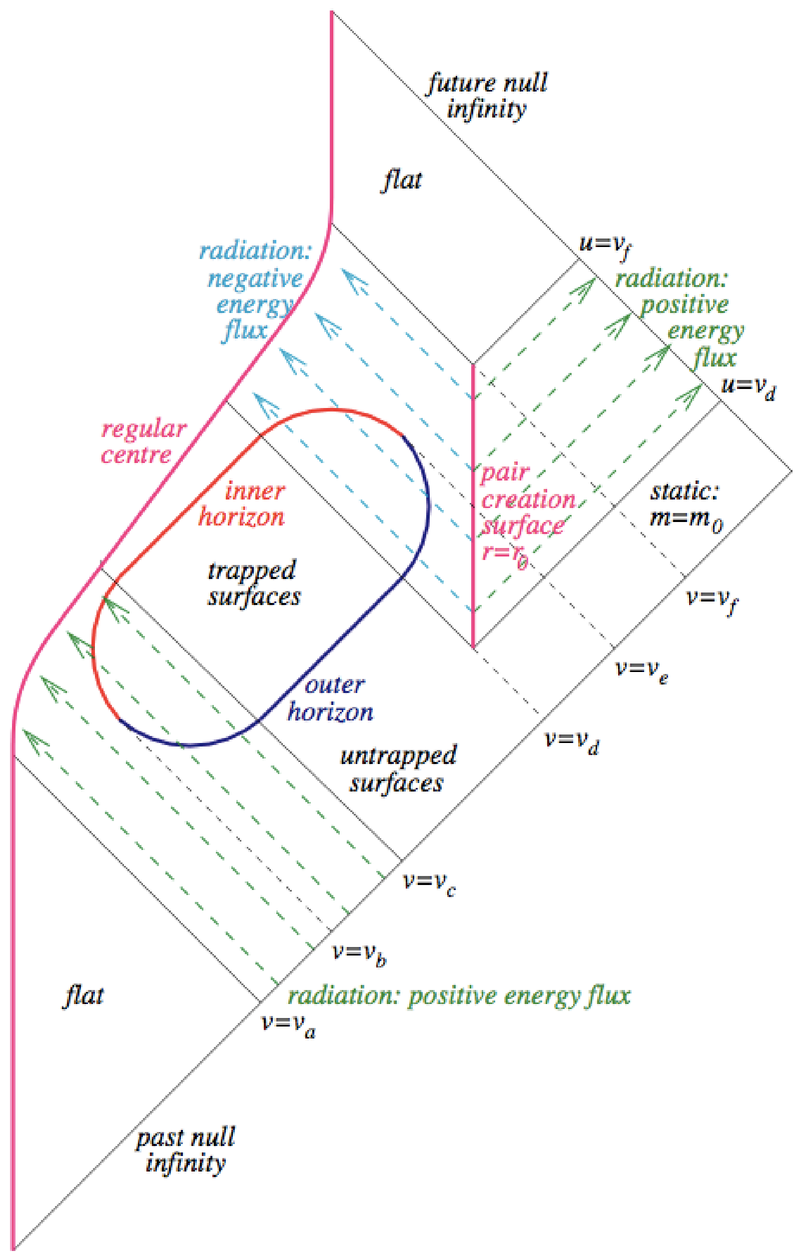
- Modesto '06

Exploding holes



- Frolov, Vilkovinski ‘79
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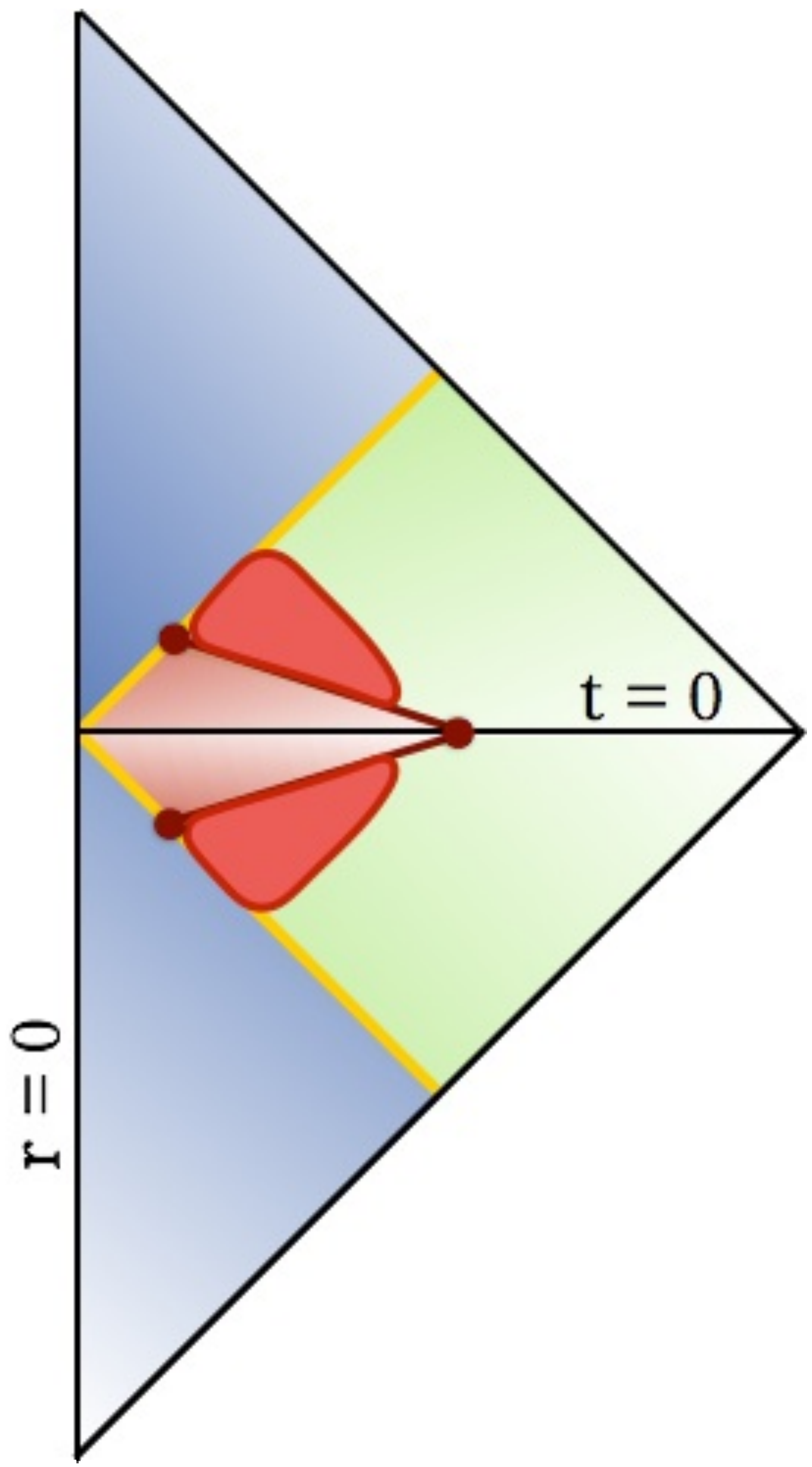
Exploding holes



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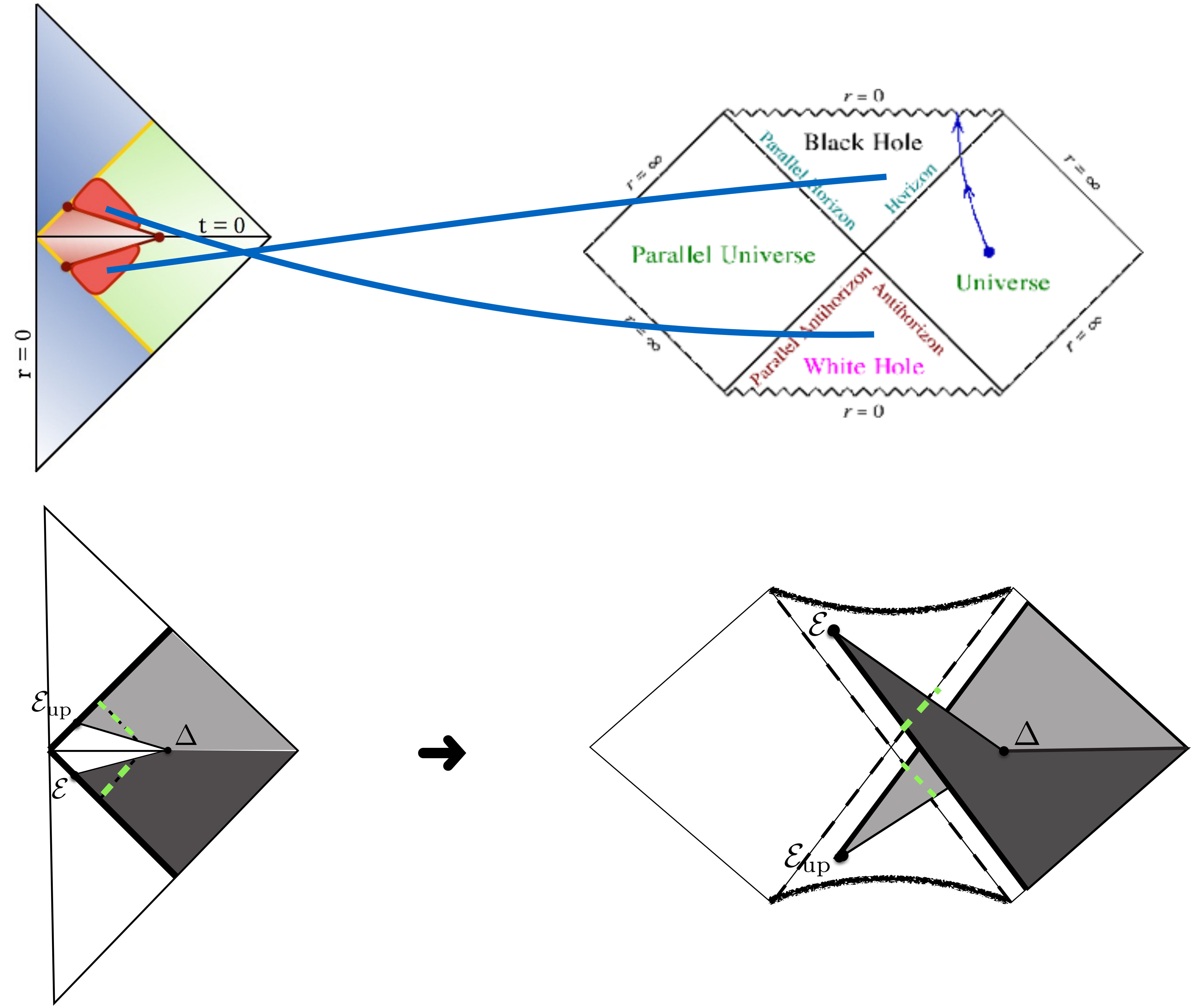
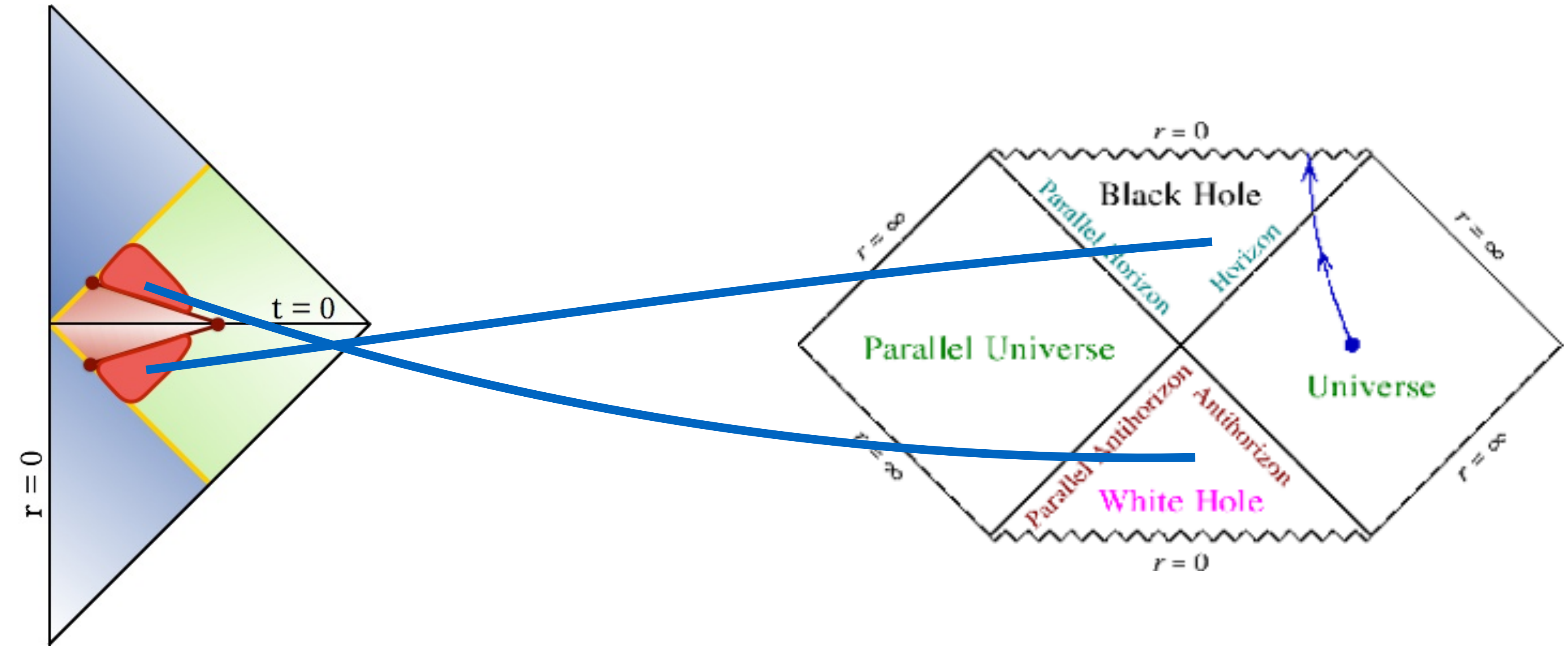
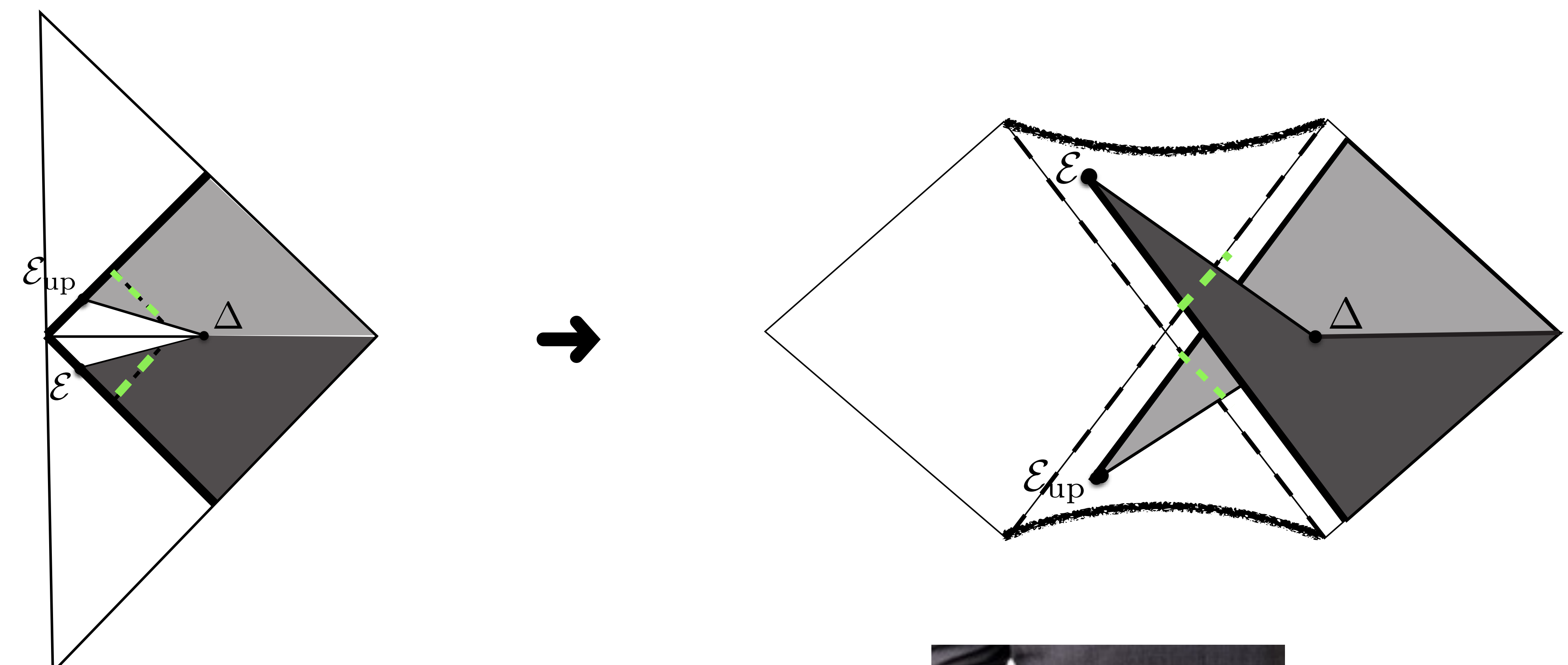
- Modesto '06
- Hayward '06
- Haggard, Rovelli '15



t = 0
r = 0
r = 0
Black Hole
Parallel Horizon
Horizon
r = ∞
Parallel Universe
Universe
Antihorizon
Parallel Antihorizon
White Hole
r = 0
$\mathcal{E}_{\rm up}$
$\mathcal{E}$
Δ
$\mathcal{E}$
$\mathcal{E}_{\rm up}$
Δ

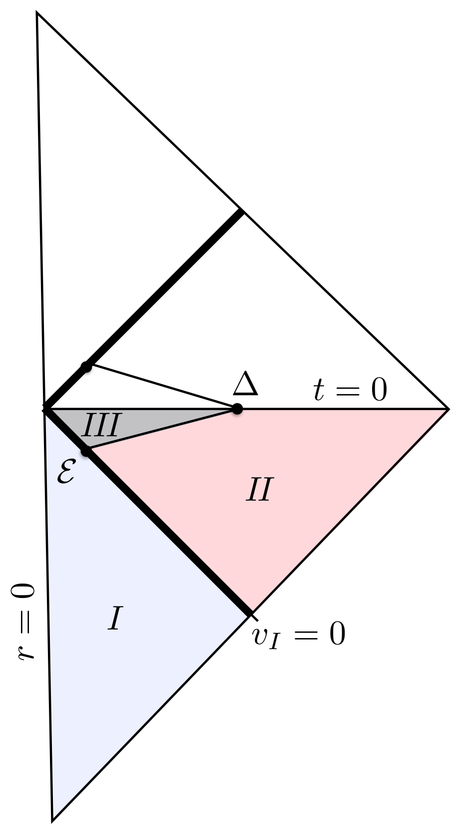




The Fingers Crossed

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

The metric:



Spherical symmetry:

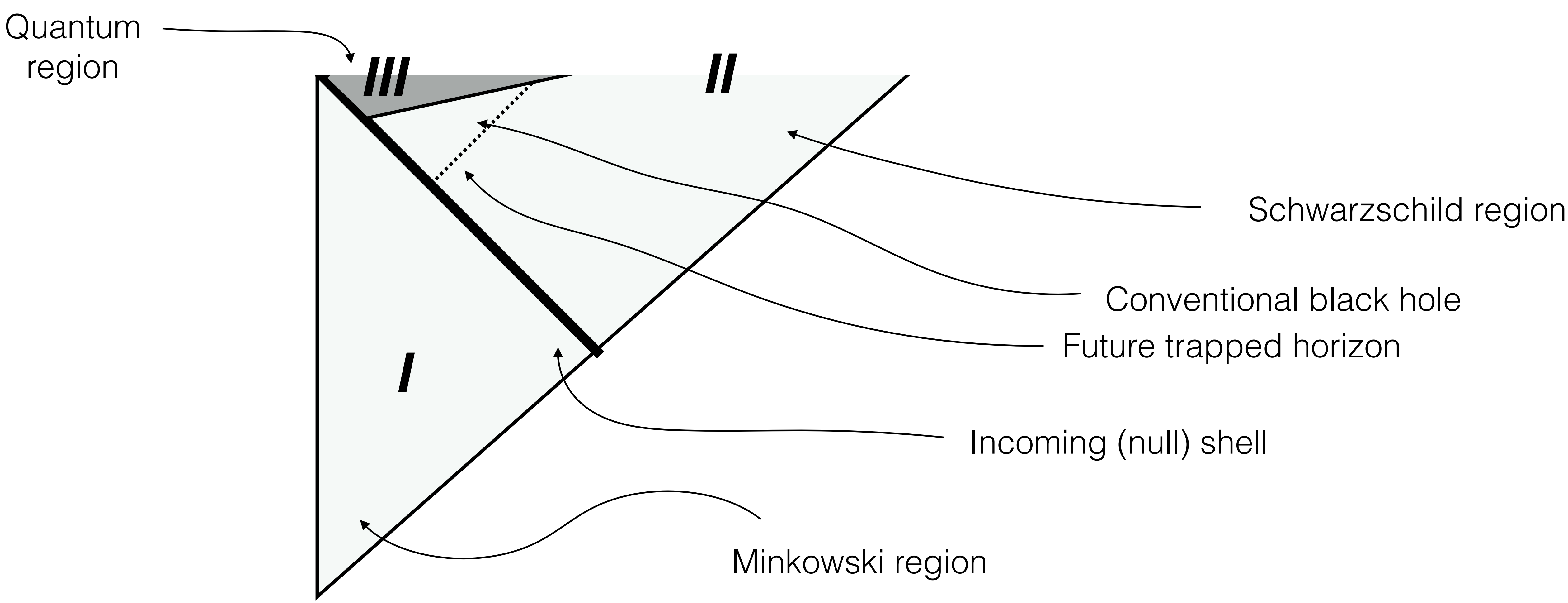
$$ds^2 = -F(u,v)\,du\,dv + r^2(u,v)(d\theta^2 + \sin^2\theta\, d\phi^2)$$

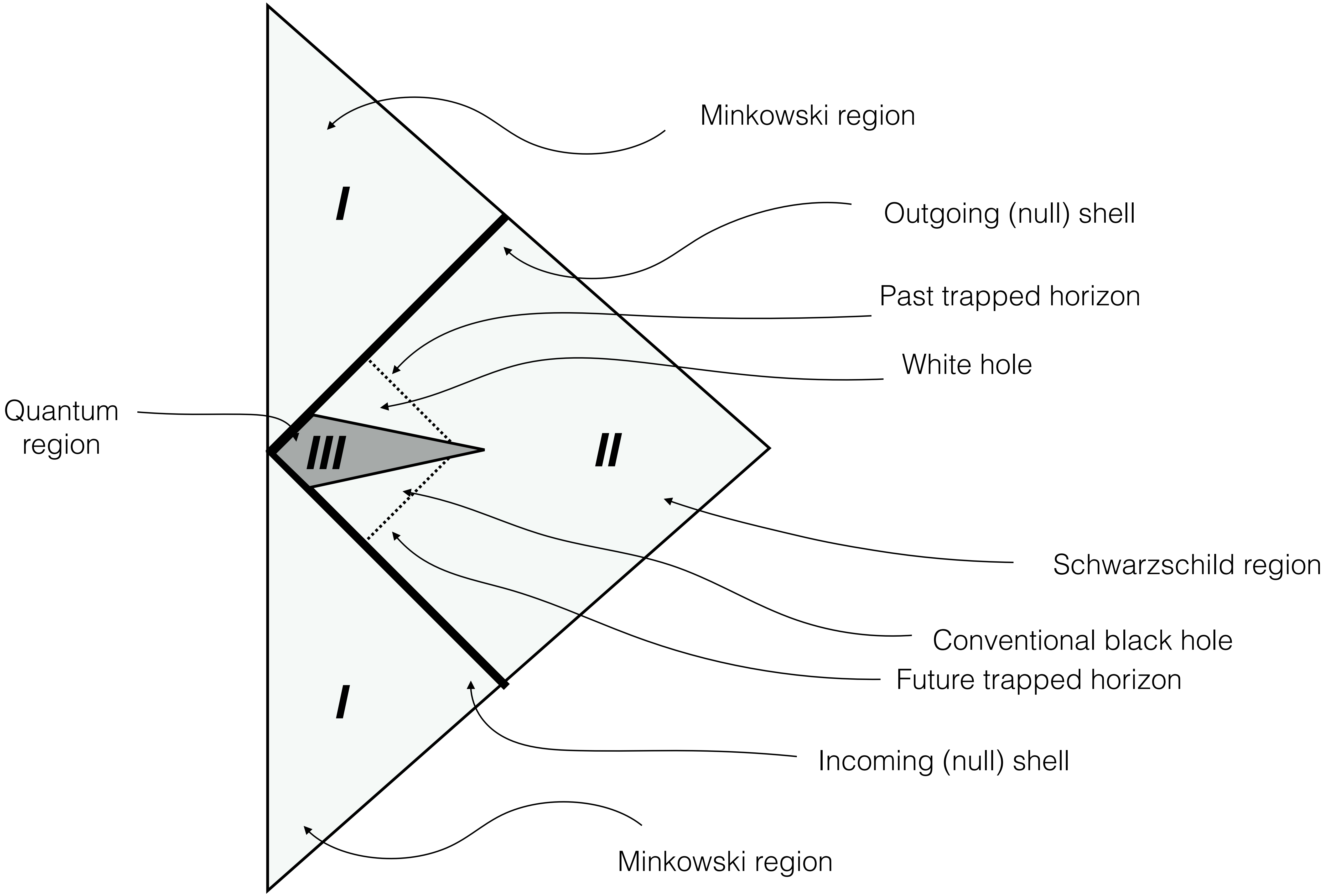
Region I (Flat):
$F(u_I, v_I) = 1, \qquad r_I(u_I, v_I) = \frac{v_I - u_I}{2}$
Bounded by: $v_I = 0$

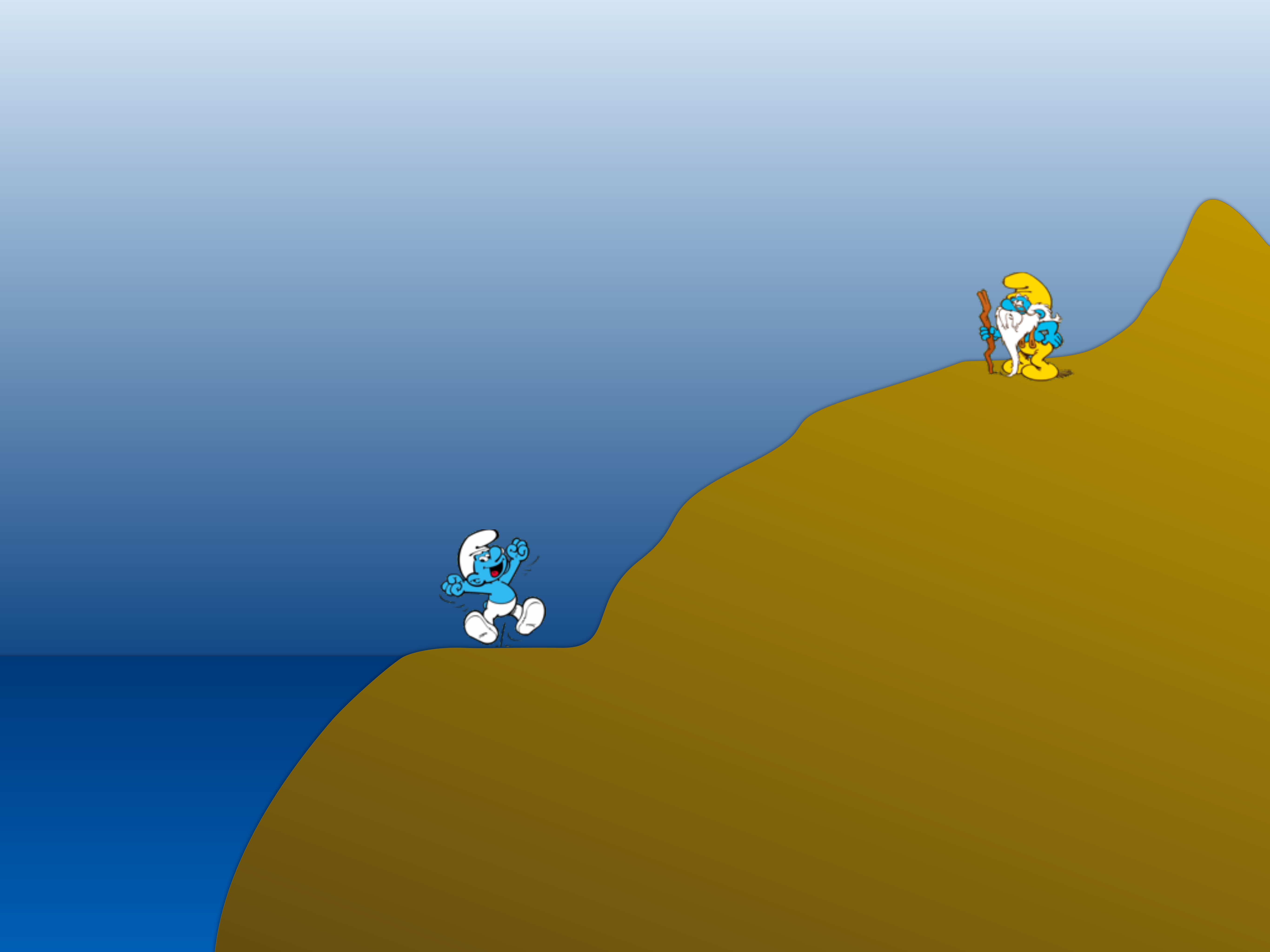
Region II (Schw.): $F(u,v) = \frac{32m^3}{r}\, e^{\frac{r}{2m}} \qquad \left(1 - \frac{r}{2m}\right) e^{\frac{r}{2m}} = uv.$

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

Region III (Quantum): a smooth interpolation


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


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

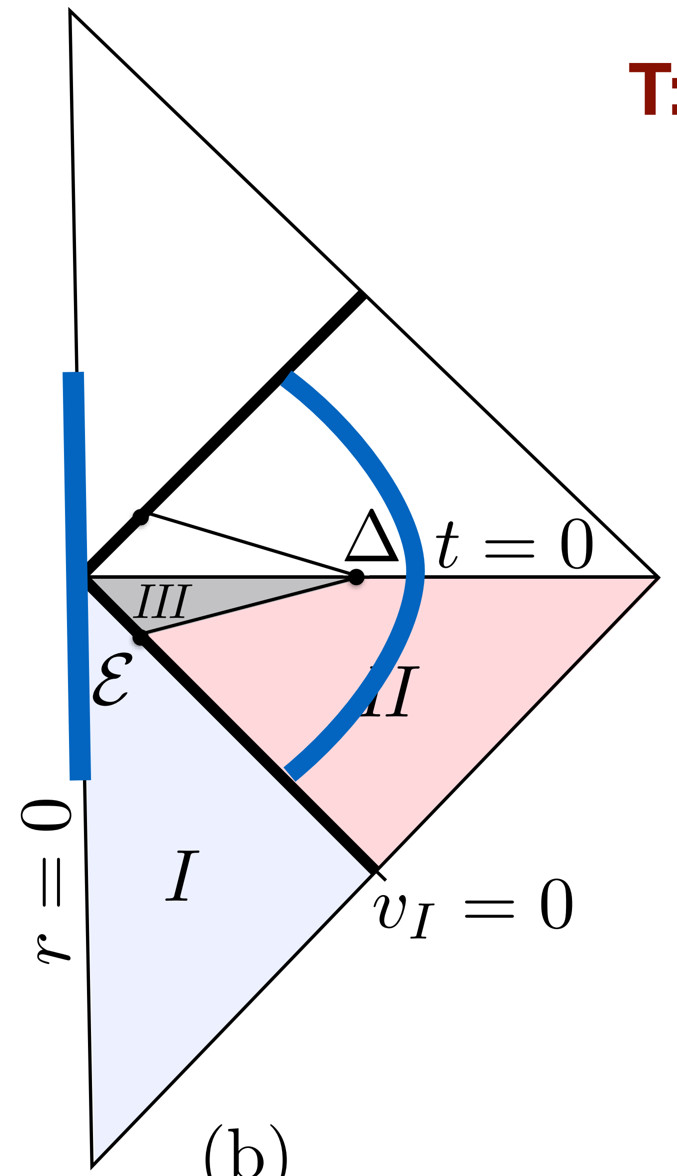


Time dilation

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

T: bounce time (very large)

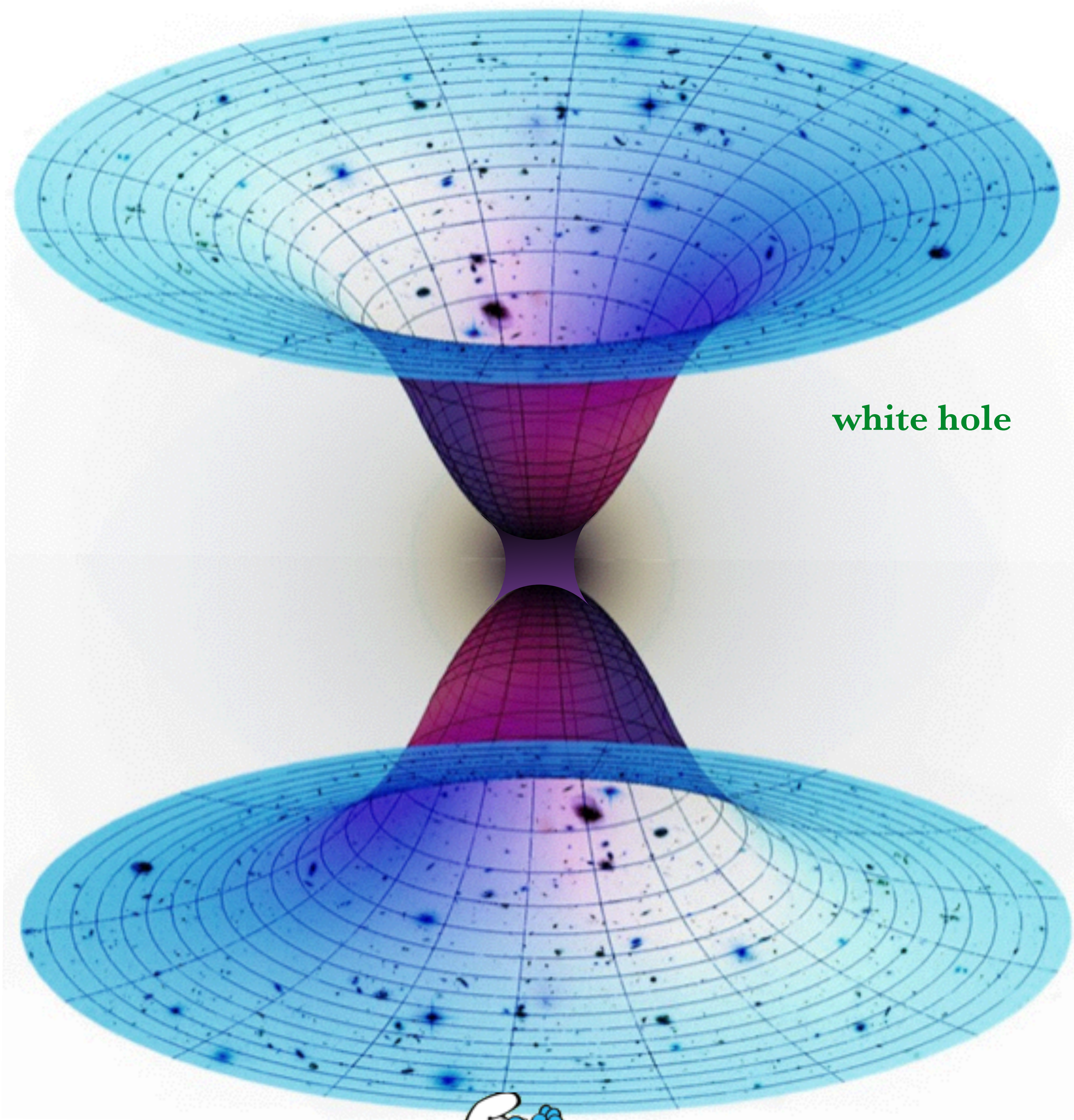
$\tau_{internal} \sim m \sim 1ms$



(b)

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

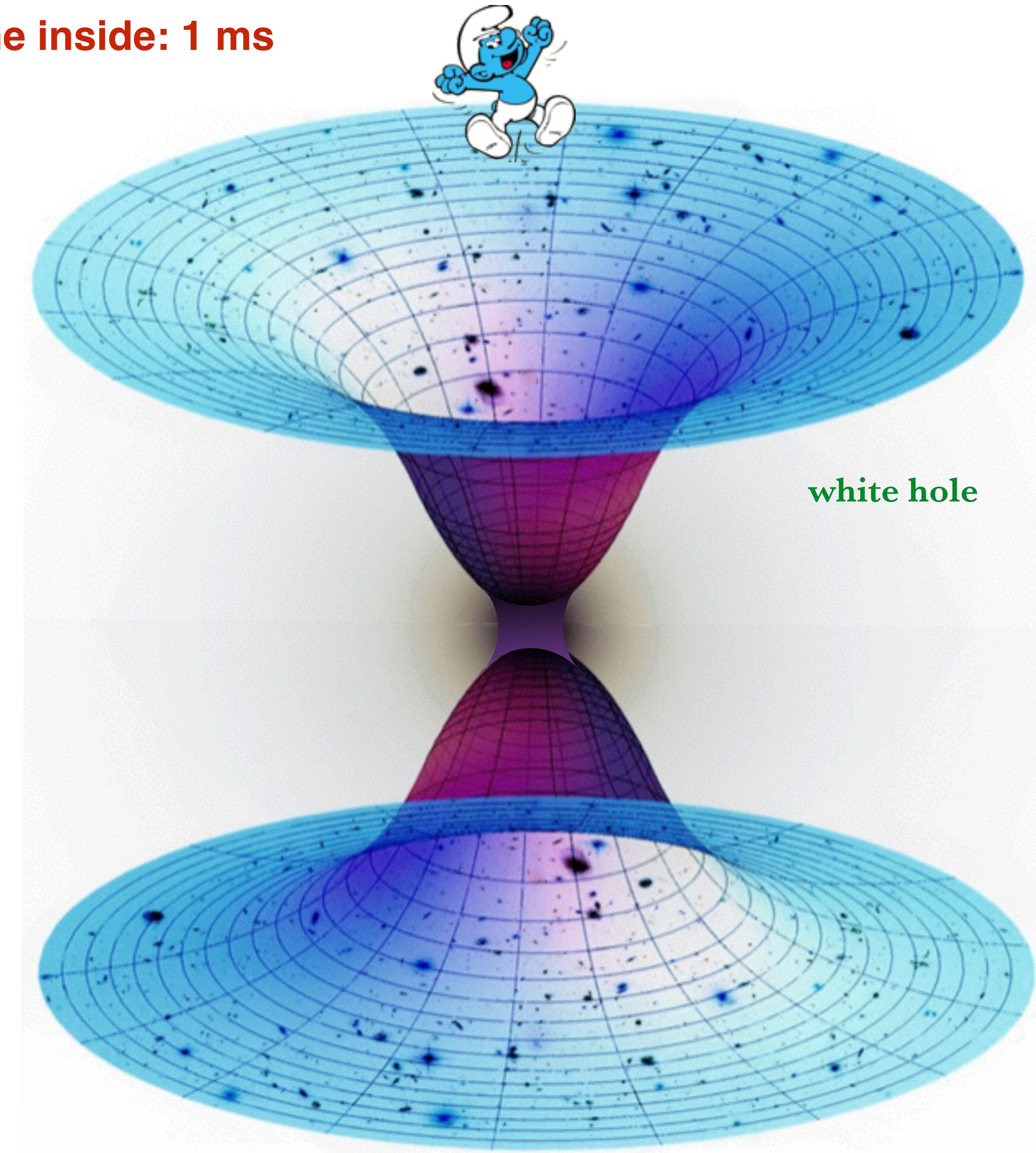
"A black hole is a short cut to the future"



white hole

black hole

Time inside: 1 ms

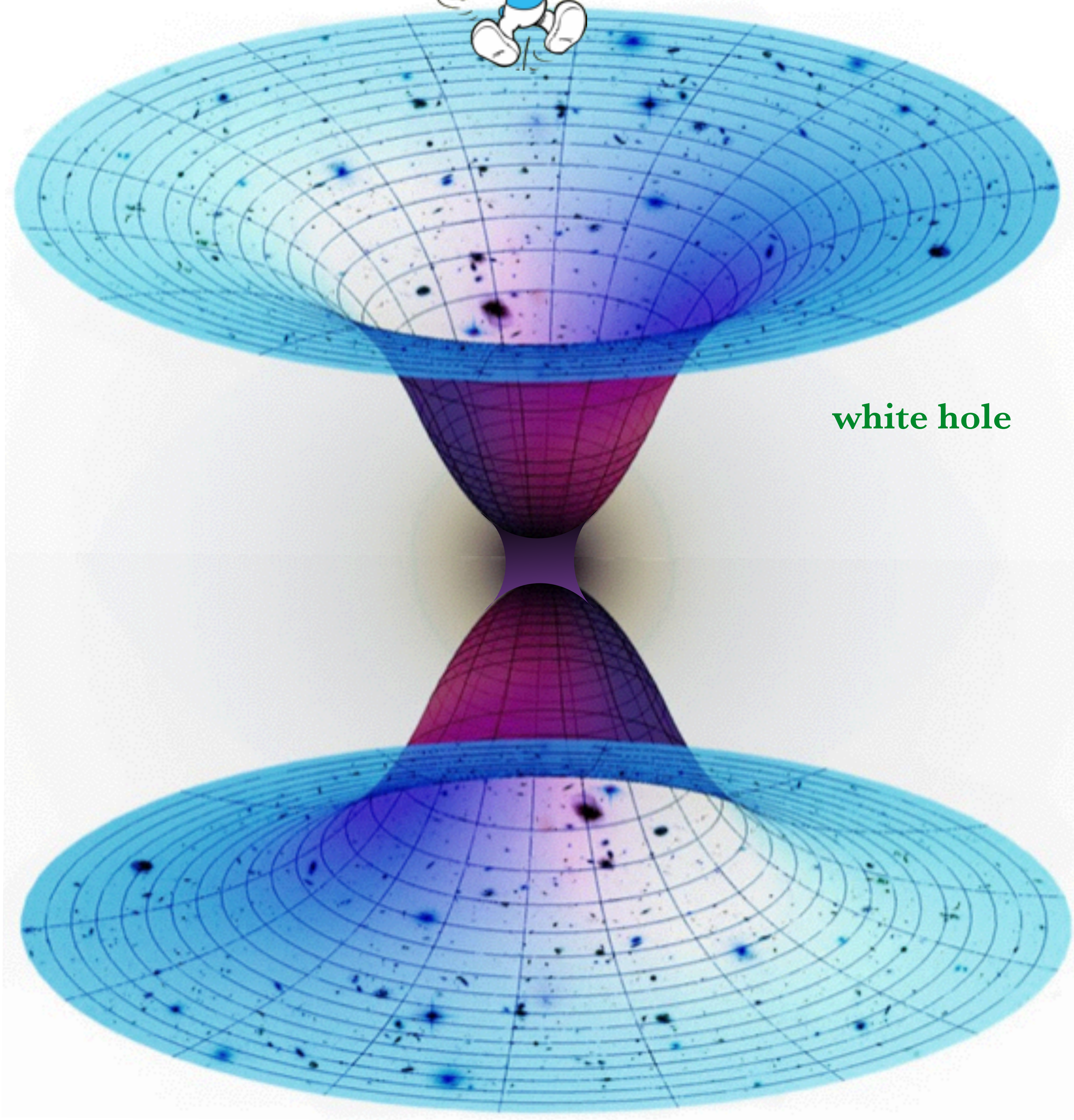


white hole

black hole

Time inside: 1 ms

Time outside:
10 billions years !



white hole

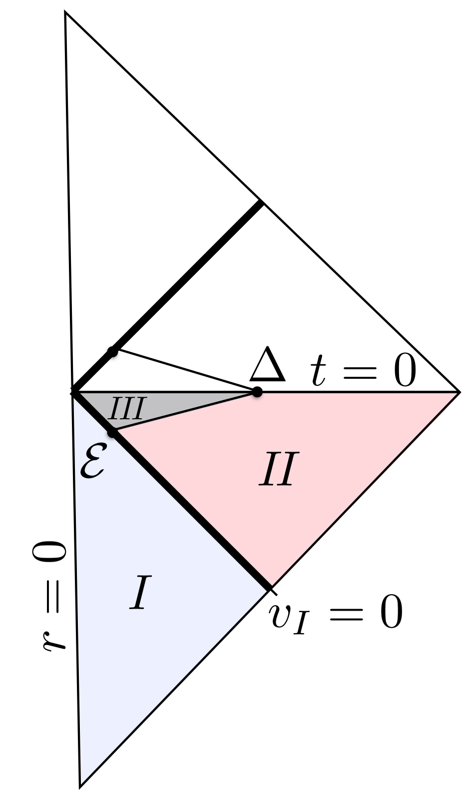
black hole

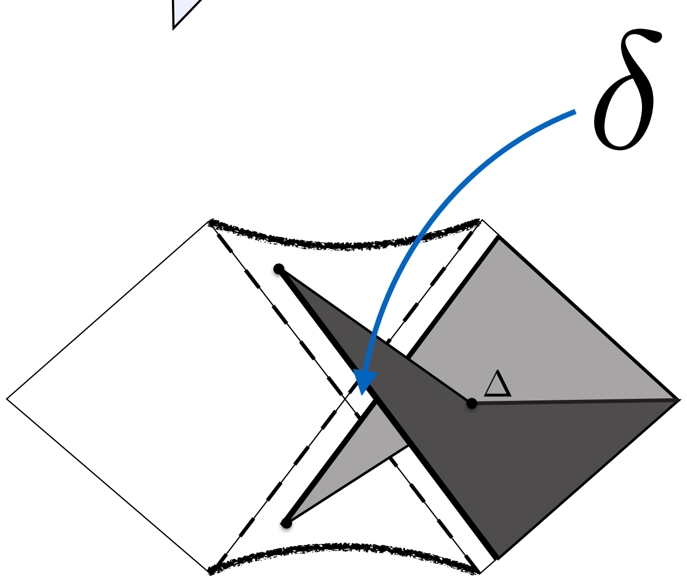
The metric of the black-to-white hole transition: parameters

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, which determines the external bounce time





What does δ represent and what determines it?

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

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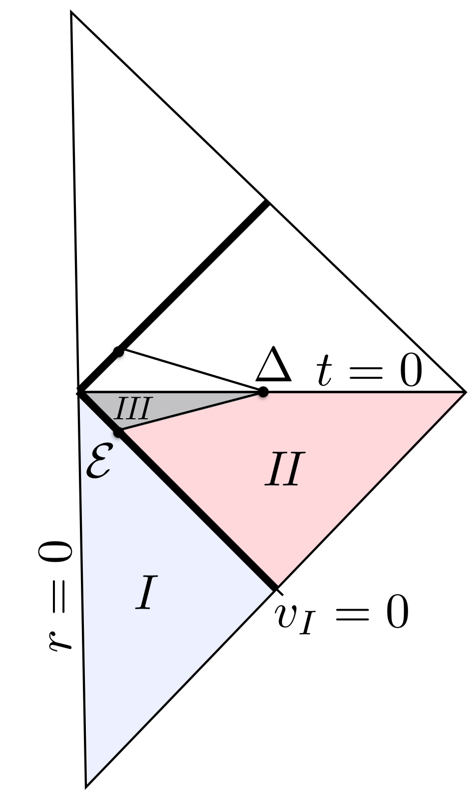
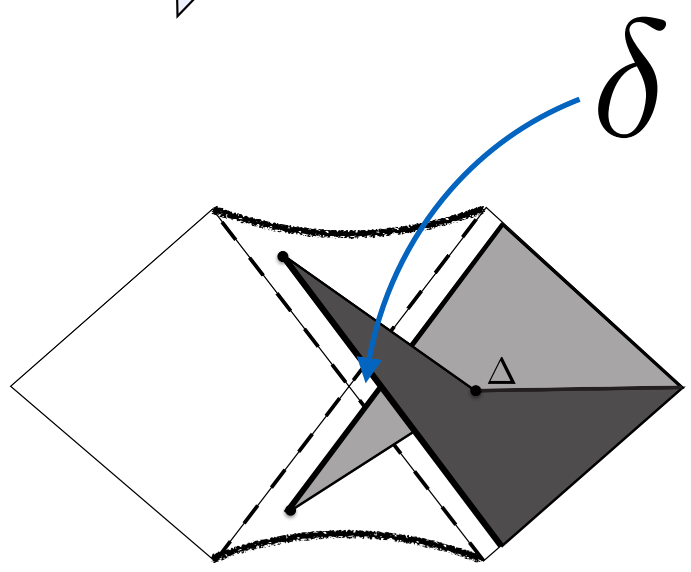


The full metric is determined by four constants:

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

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



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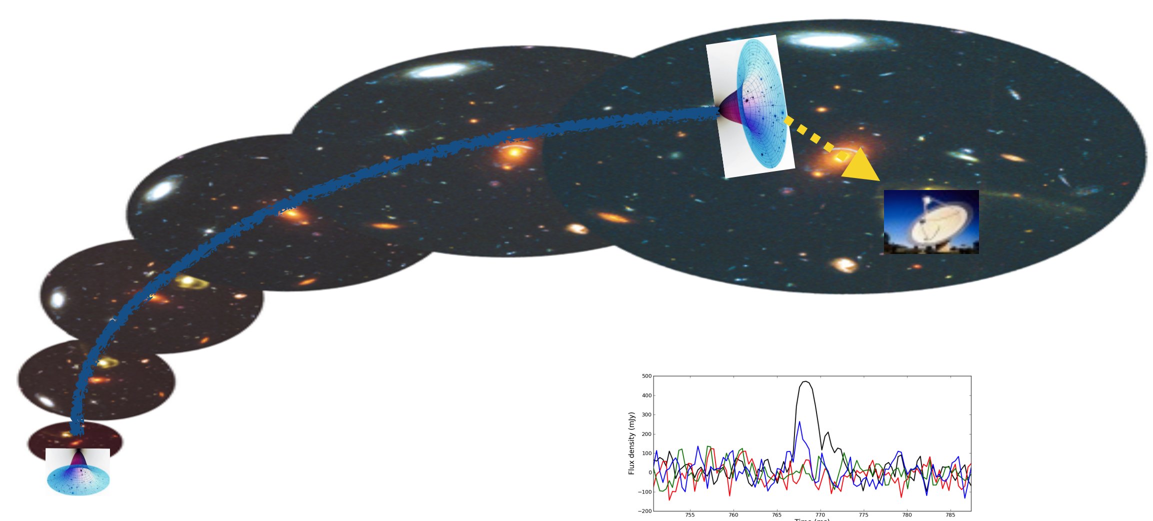


What determines δ ?

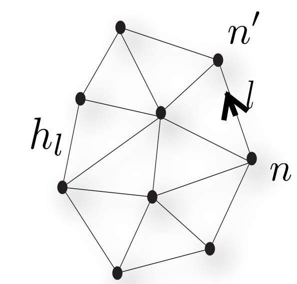
Quantum gravity

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



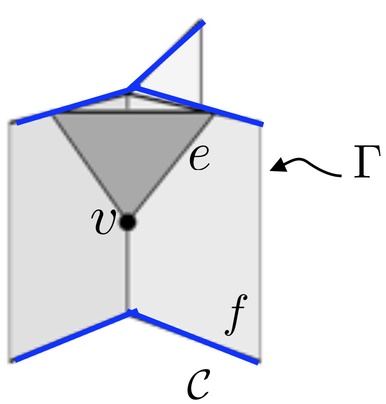
Γ spin network (nodes, links)

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

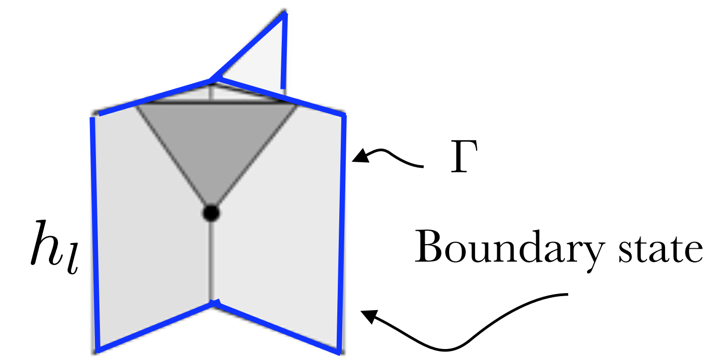


spinfoam (vertices, edges, faces)

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

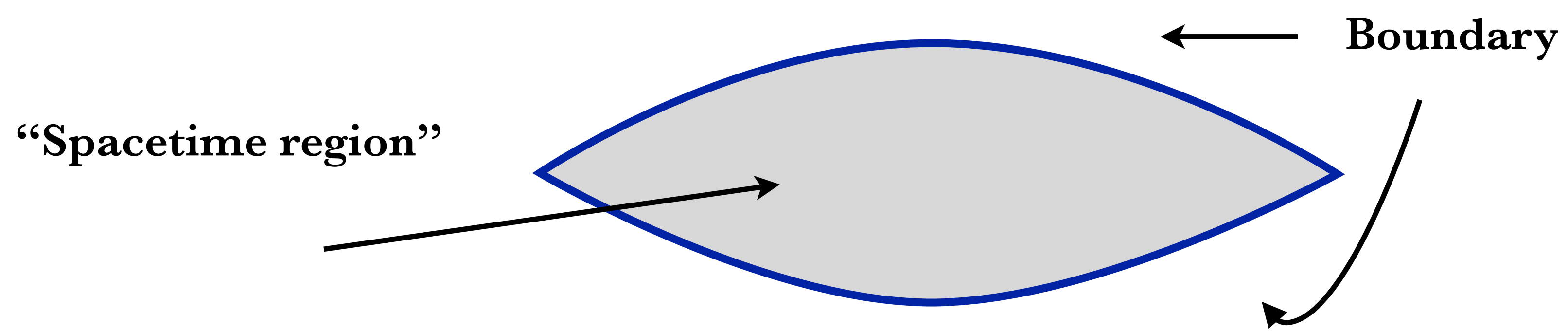
$$8\pi\gamma\hbar G = 1$$

A process and its amplitude



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

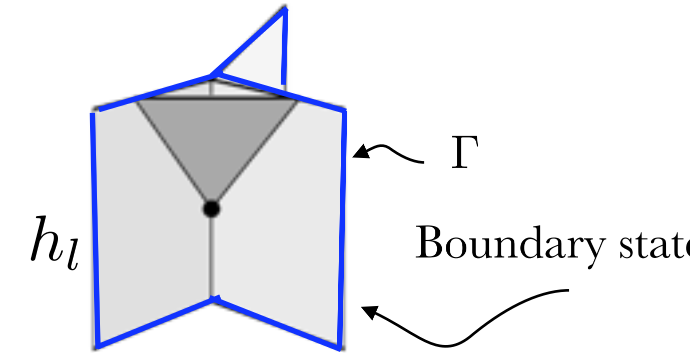
Amplitude $A = W(\Psi)$



Quantum system
=
Spacetime region

➜ **Hamilton function: S(q,t,q',t')**

A process and its amplitude



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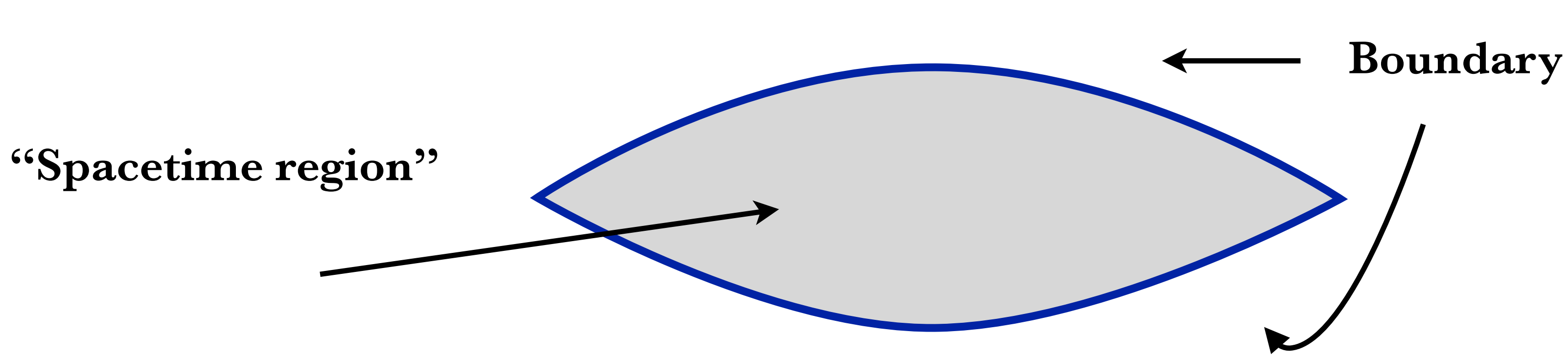


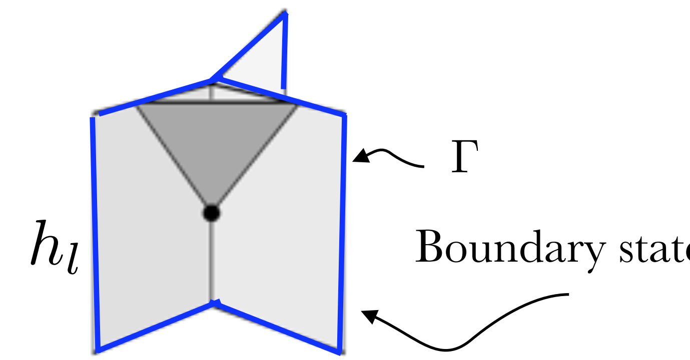
Quantum system = Spacetime region

➜ **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

A process and its amplitude



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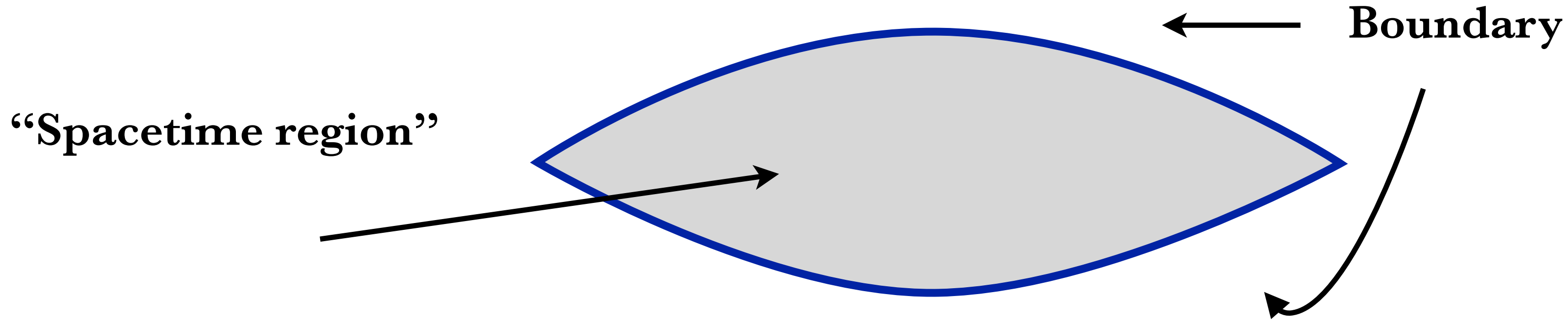

Quantum system
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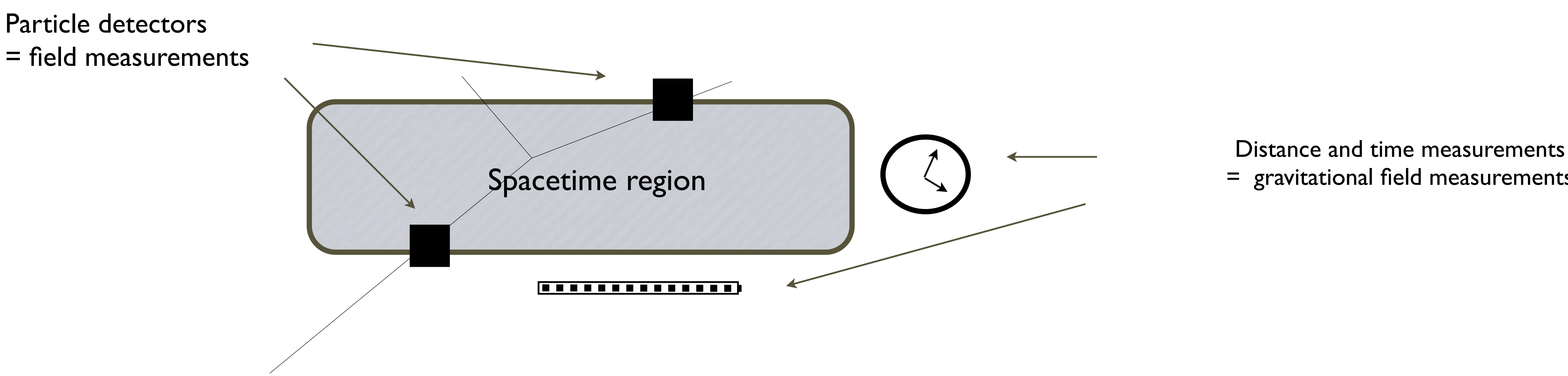
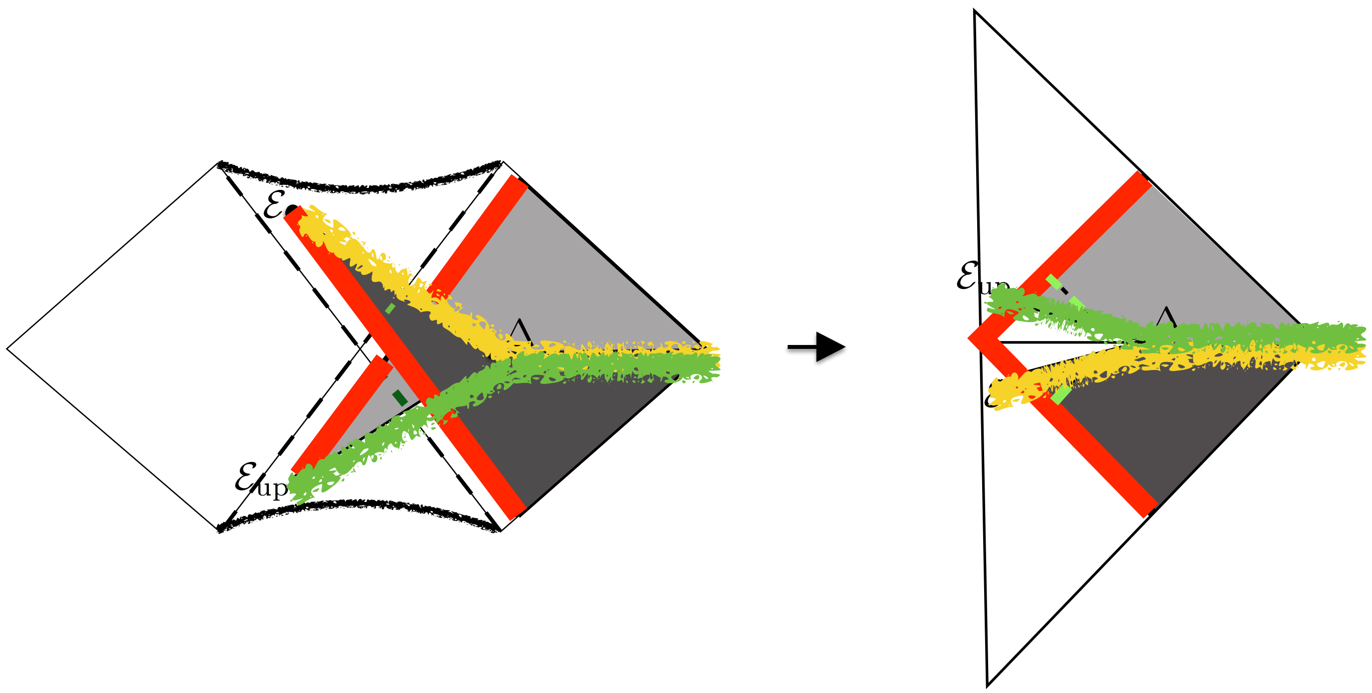
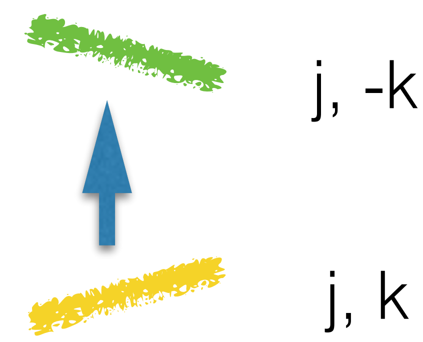


Covariant loop quantum gravity.   Calculation of T(m).

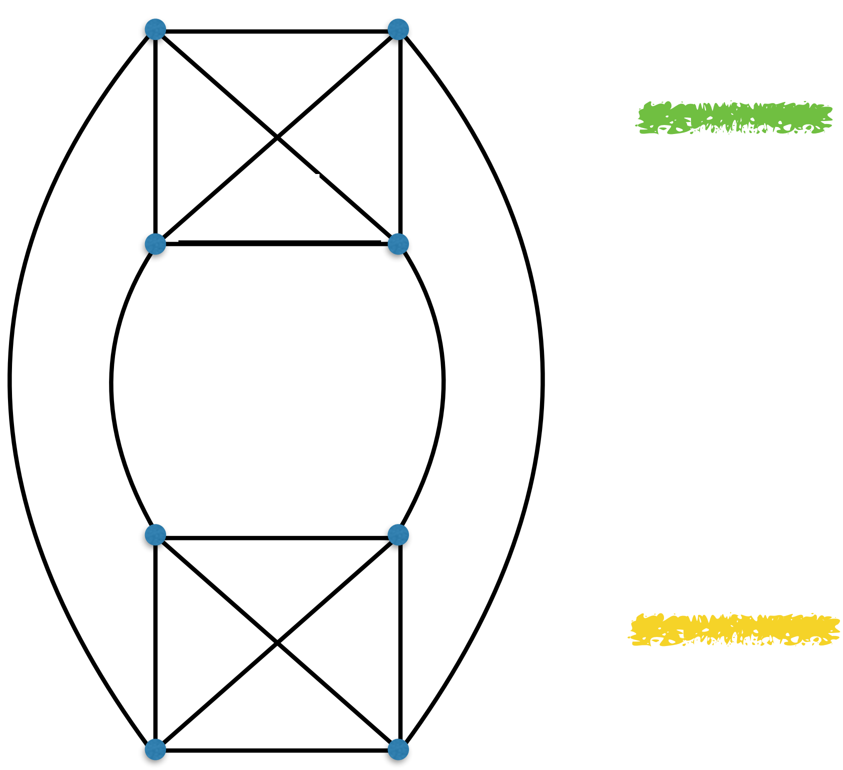




Boundary: B_3 U B_3 (Joined on a S_2)

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



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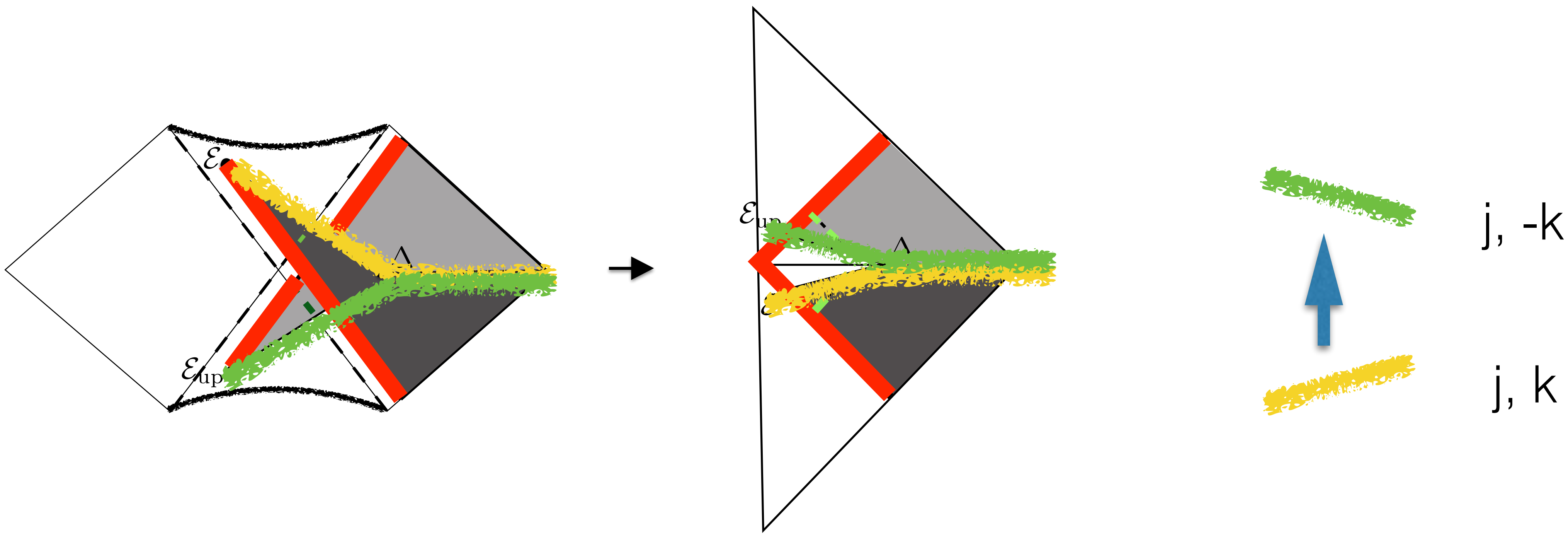

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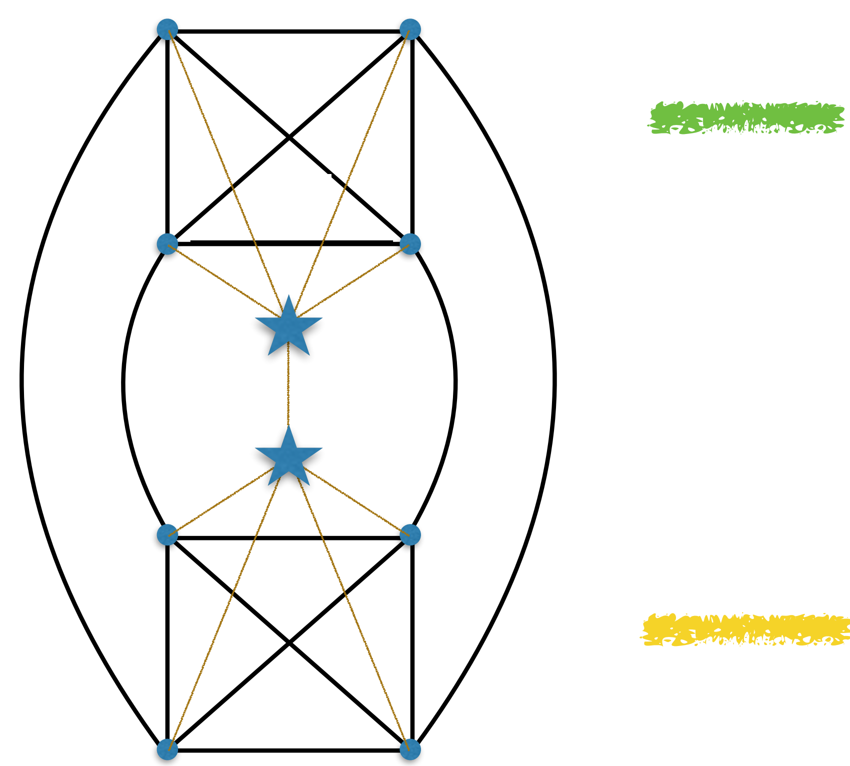


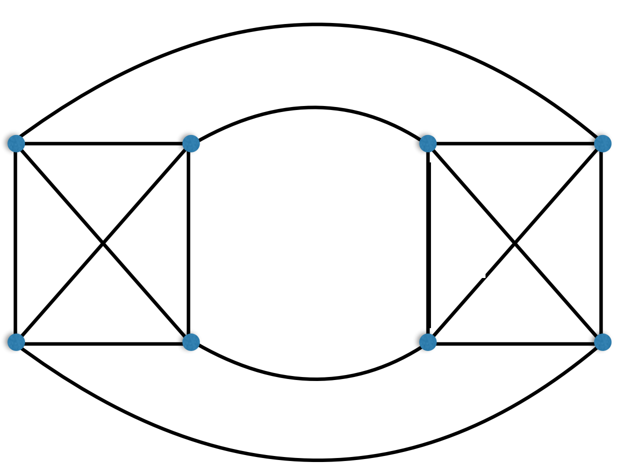
Covariant loop quantum gravity. Calculation of T(m).

$$W(z,z') = \sum_{j_a, j^\pm_{ab}, l_a, l^\pm_{ab}} \left(\prod_a d_{j_a}\right)\left(\prod_{ab\pm} d_{j_{ab}}\right) e^{\sum_a (j_a(j_a+1)/\sigma^2 + z j_a) + \sum_{ab\pm}(j^\pm_{ab}(j^\pm_{ab}+1)/\sigma^2 + (z'+\phi_{ab}-\phi_{ba}) j_{ab})}$$

$$\times \sum_{M^\pm_a, N^\pm_a} \left(\bigotimes_{a,\pm} f(M^\pm_a, N^\pm_a, j_a, j^\pm_{ab}, l_a, l^\pm_{ab}) \;\; i^{N^\pm_a, j_a, j_{ab}}_{m, j_{ab}} \;\; R_{m, j_a}(\hat\theta)\right) \;\; \left(\bigotimes_{a,\pm} i^{M^\pm_a, l_a, l_{ab}}\right)_\Gamma .$$

$$f(M,N,j_a,l_a) = \sum_{p_1,p_2,p_3,p_4} \int_0^\infty dr \, \left(\bigotimes_a \; d_{j_a l_a p_a}(r)\right) \;\; i^{N, j_1, j_2, j_3, j_4}_{p_1, p_2, p_3, p_4} \;\; i^{M, l_1, l_2, l_3, l_4}_{p_1, p_2, p_3, p_4},$$

$$d_{jlp}(r) = \sqrt{d_j}\sqrt{d_k} \int_0^1 dt \;\, d^j_{jp}(2t-1) \;\, d^l_{jp}\left(\frac{te^{-r} - (1-t)e^r}{te^{-r} + (1-t)e^r}\right) \;\; (te^{-r} + (1-t)e^r)^{i\gamma j - 1},$$



Probability ~ 1 ➜ relation j-k ➜ relation m-time

What do we expect?

$$T = \begin{cases} \sim e^{m^2} \\ \sim m^3 \\ \sim m^2 \\ \sim m \ln m \end{cases}$$

Naive expectation from analogy with tunnelling in space
Balanced by phase space factor?

Page time. Requiring that AMPS firewall are avoided

Minimal failure of local qft: $RT > L_{Planck}^{-1}$

First contribution from degenerate triangulation
(too short!) Time from for Hawking radiation to emerge.

Estimating T(m) ?

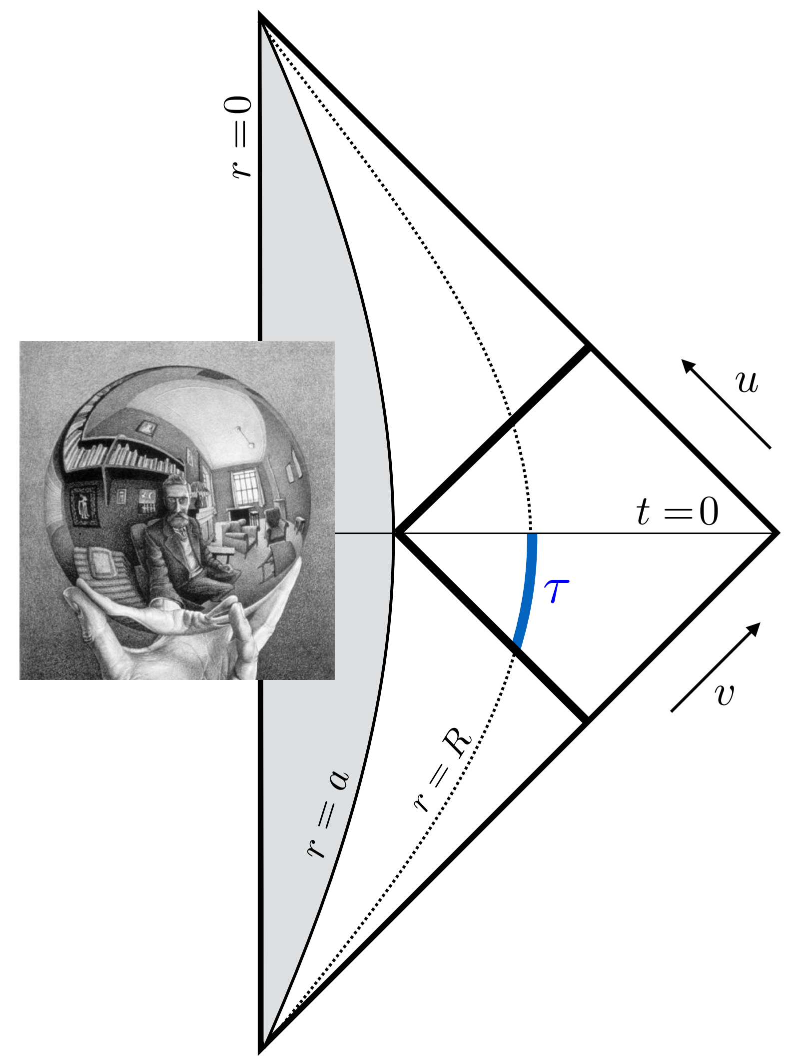
$$\tau_R = \sqrt{1 - \frac{2M}{R}} \left(R - a - 2M \ln \frac{a - 2M}{R - 2M} \right)$$

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

$$T \sim m^2$$

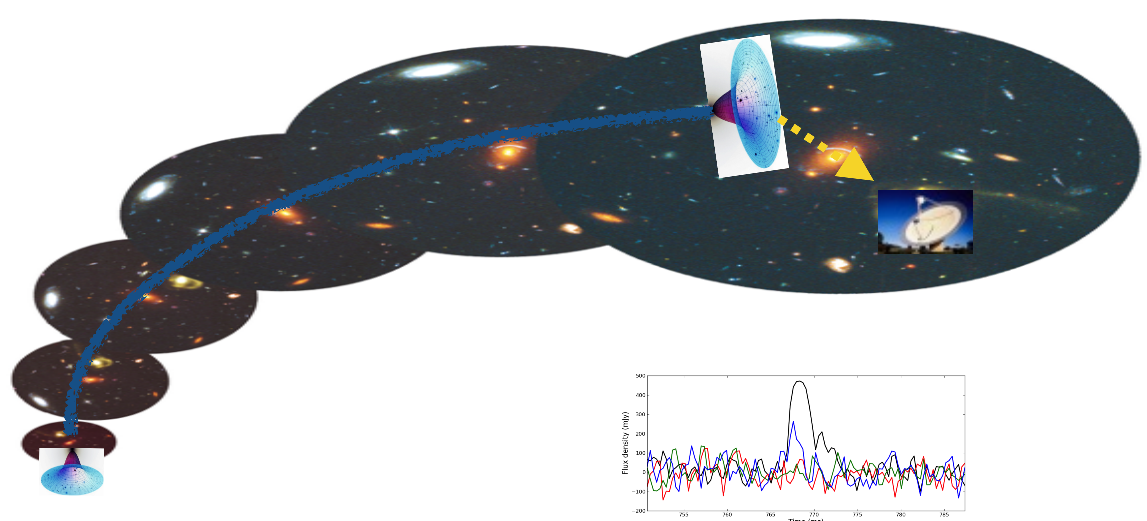
Planck stars

An observable quantum gravity phenomenon?

I. Basics of black hole tunneling decay

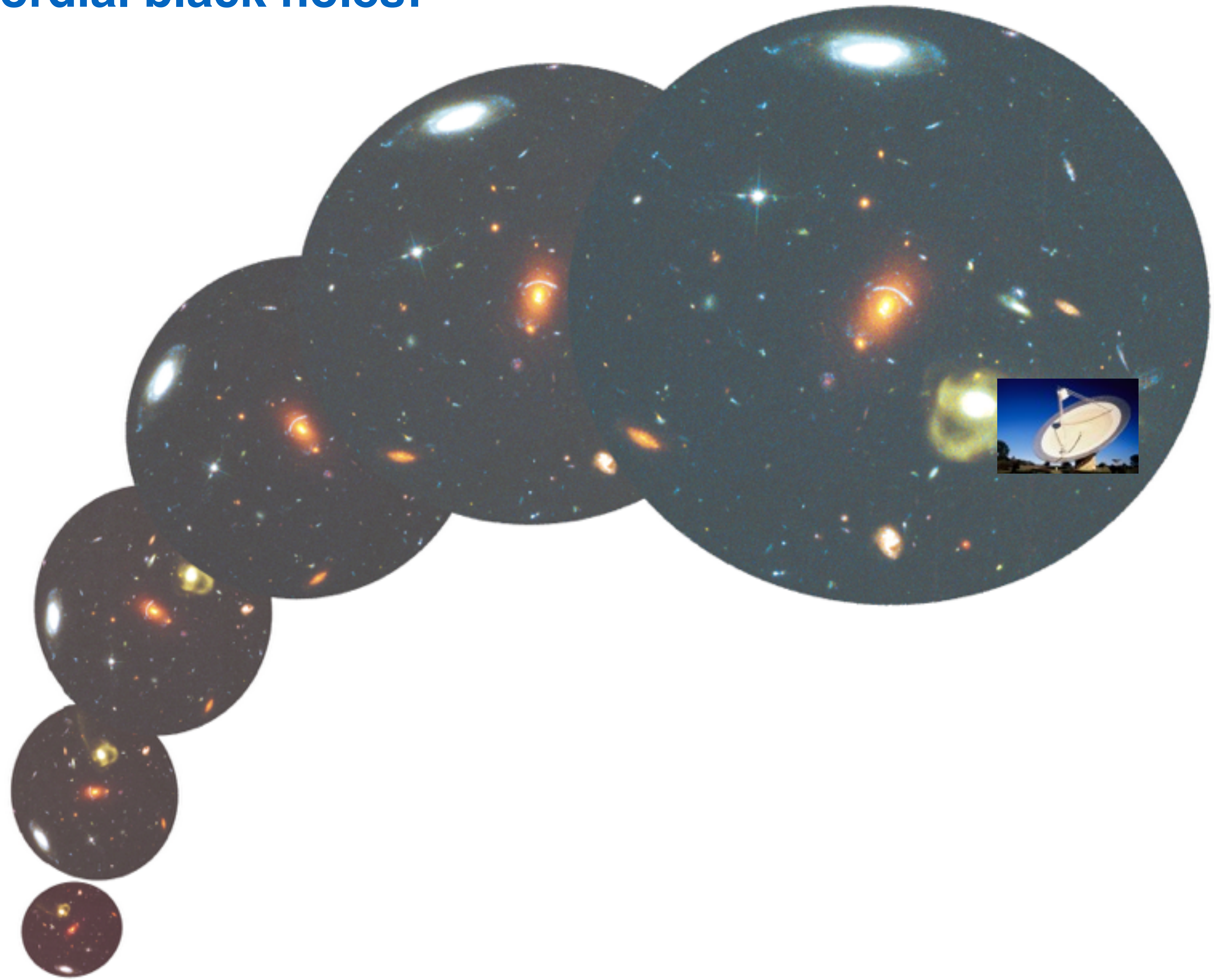
II. Decay time

III. Observations: High energy signal

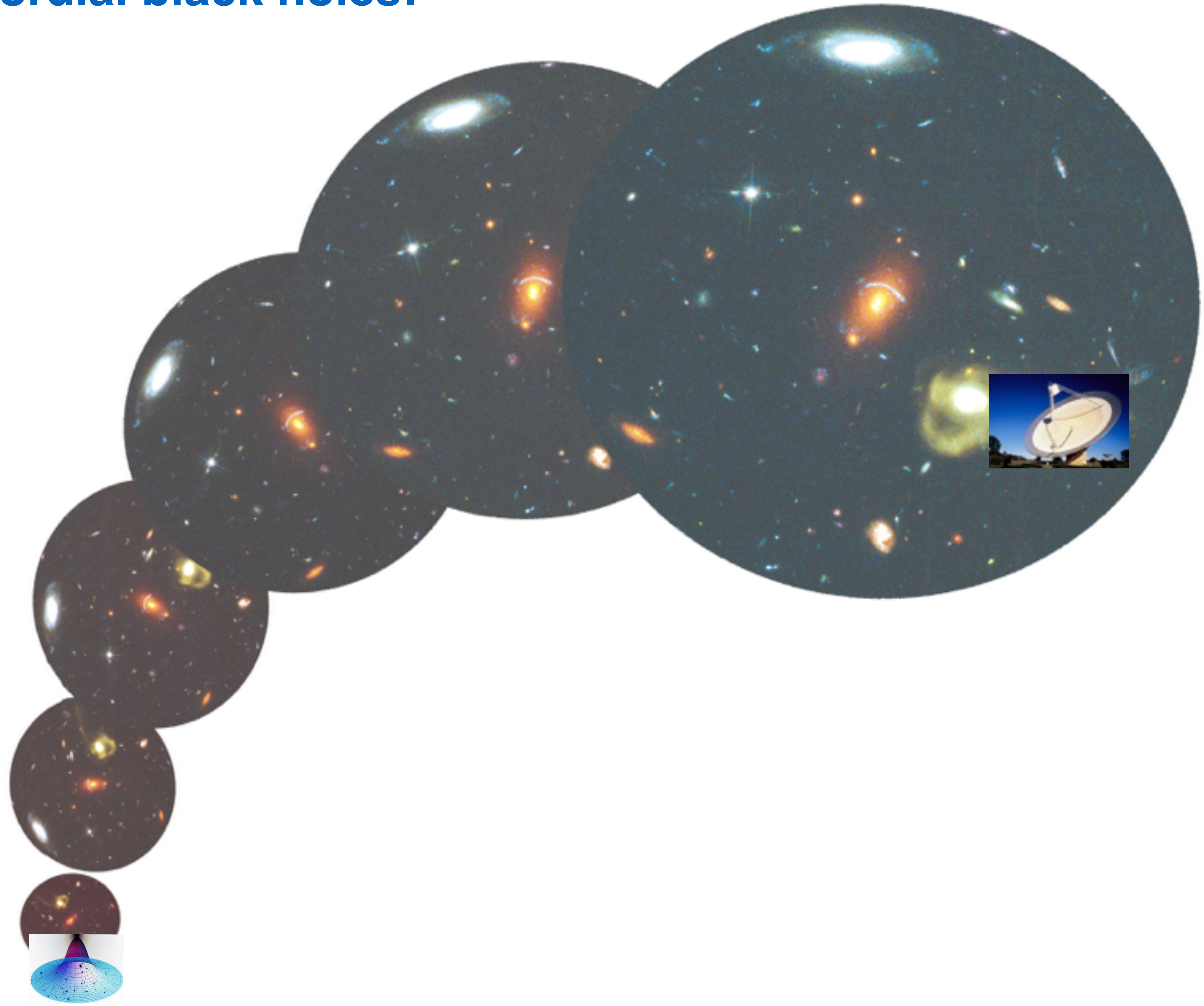


$$T \sim m^2$$

Primordial black holes!



Primordial black holes!



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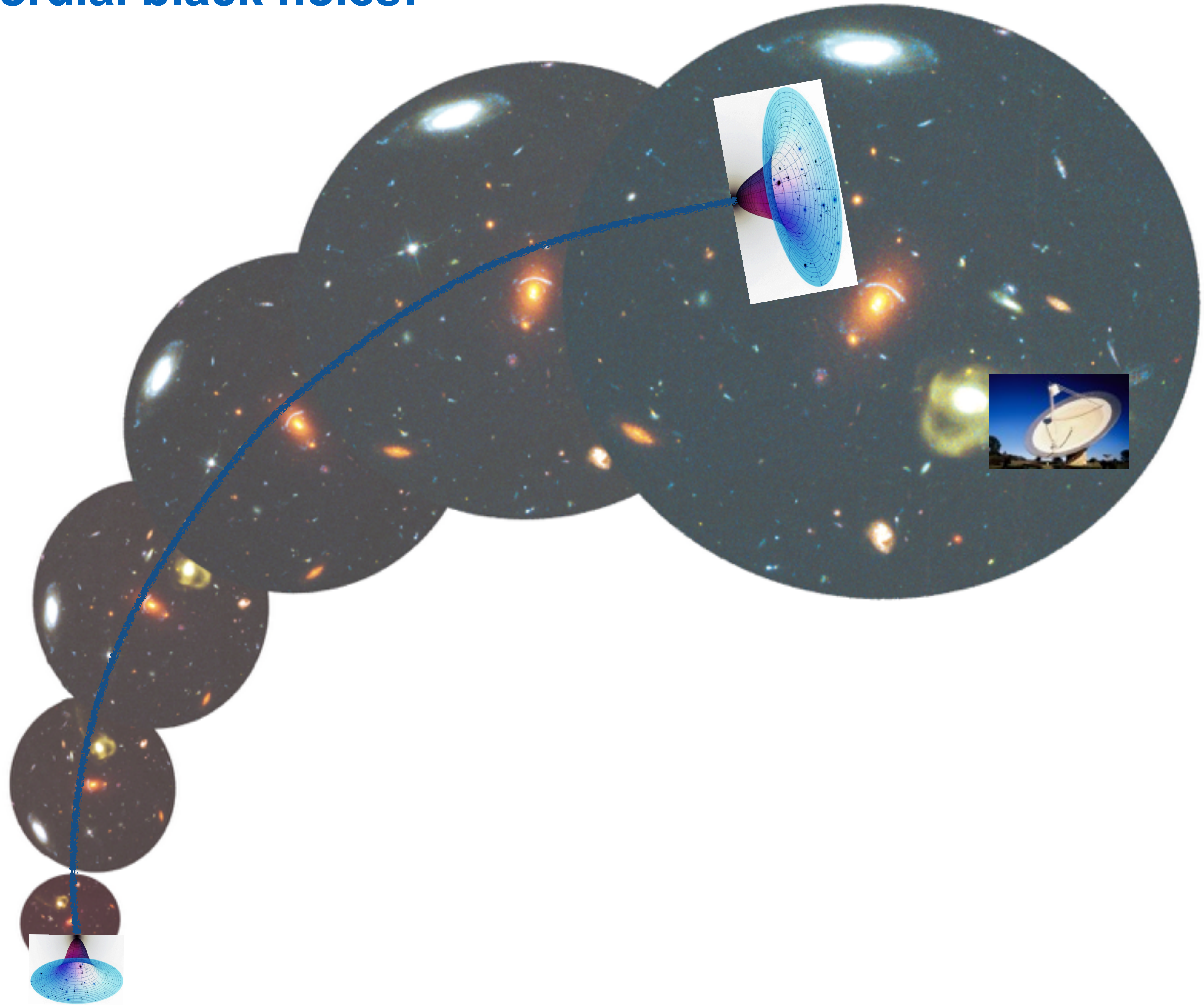

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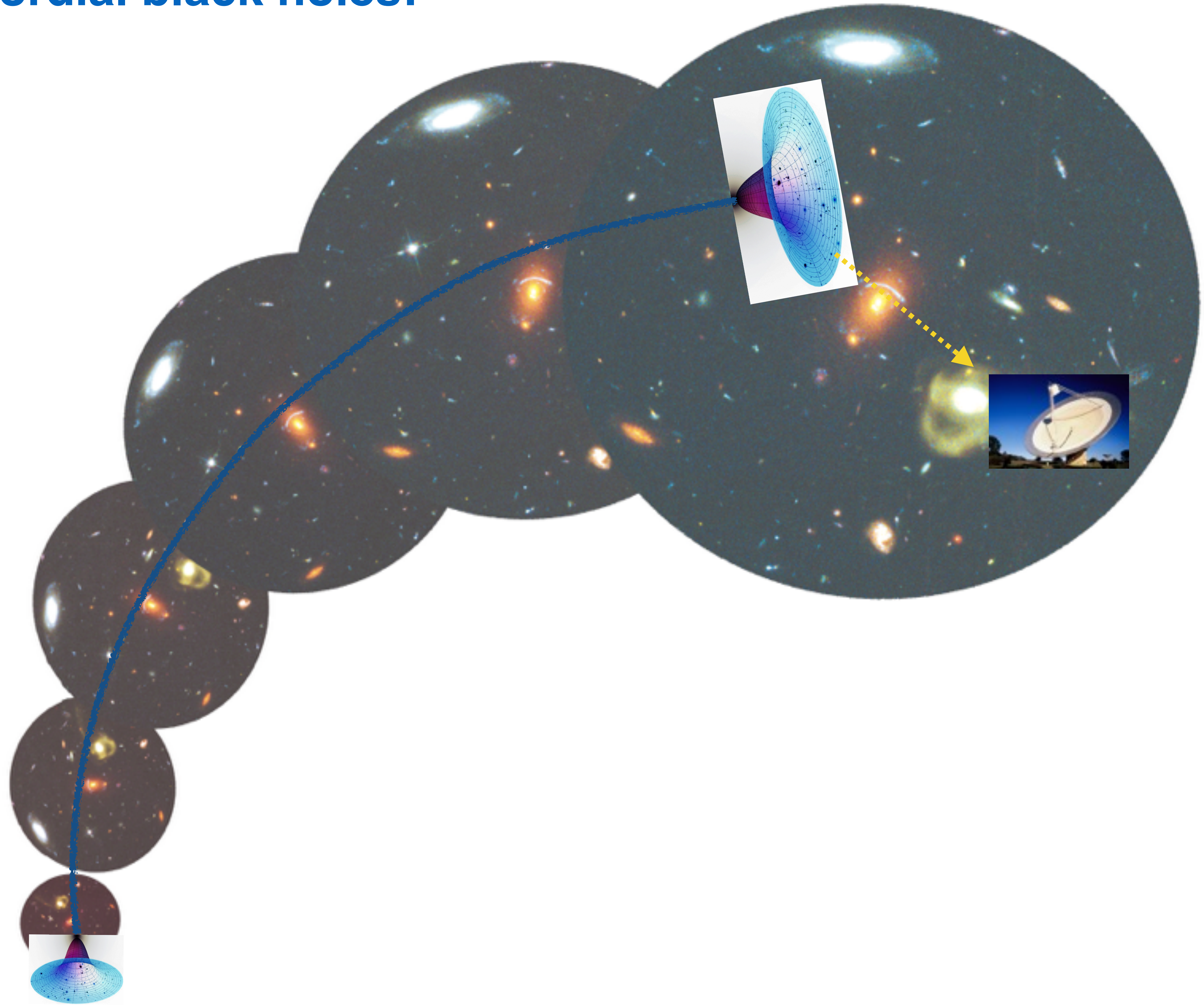

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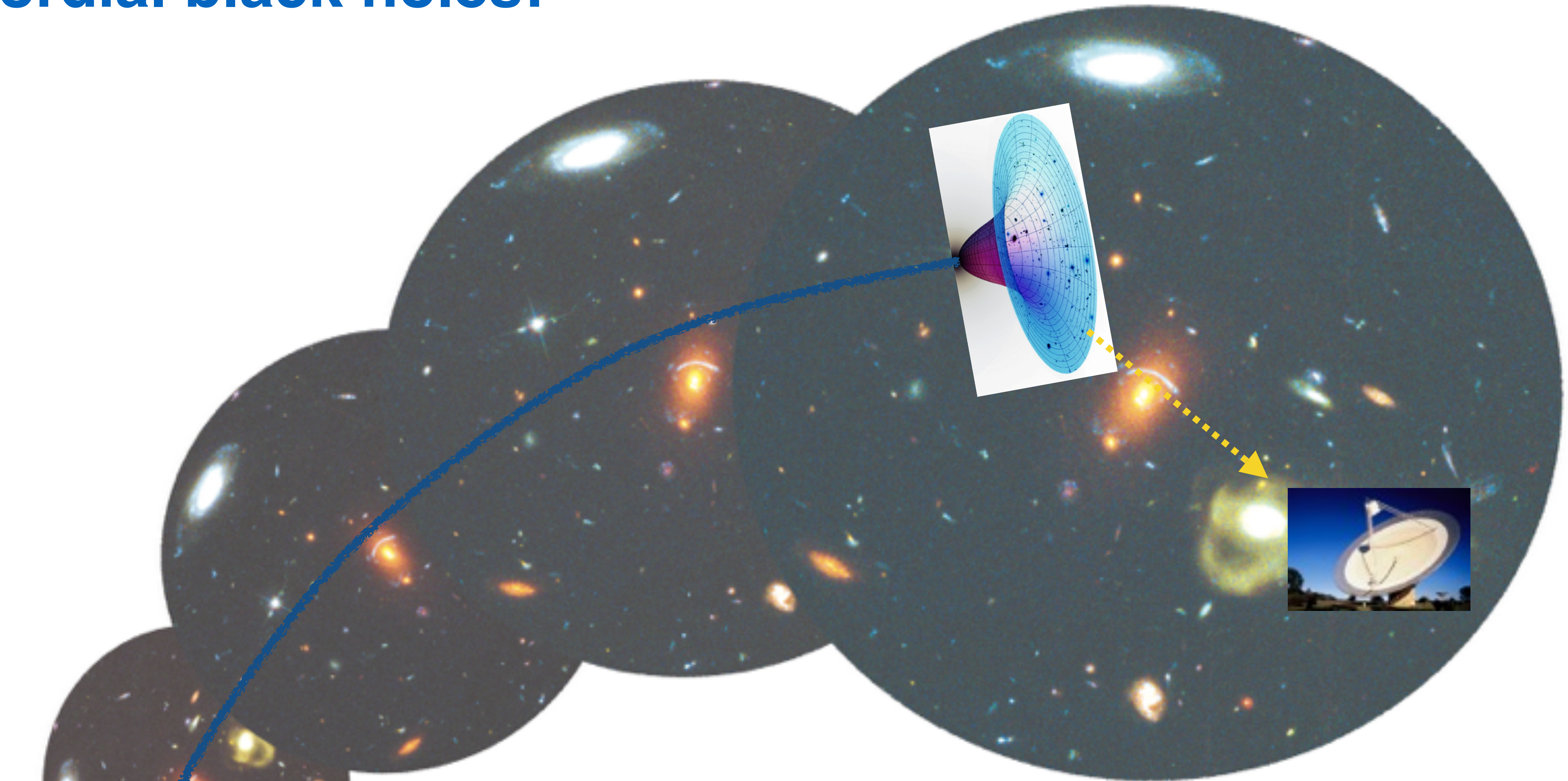

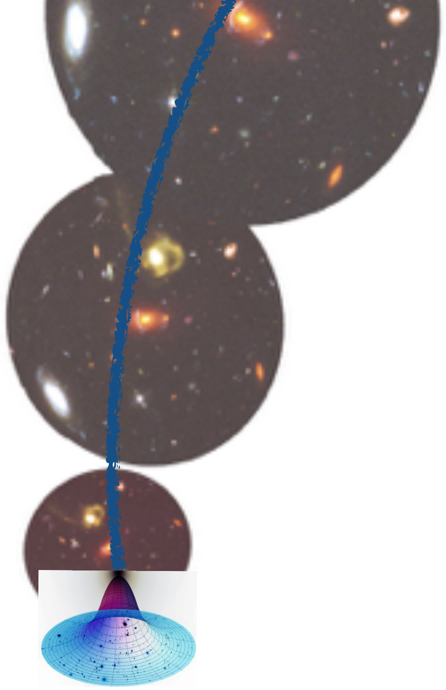

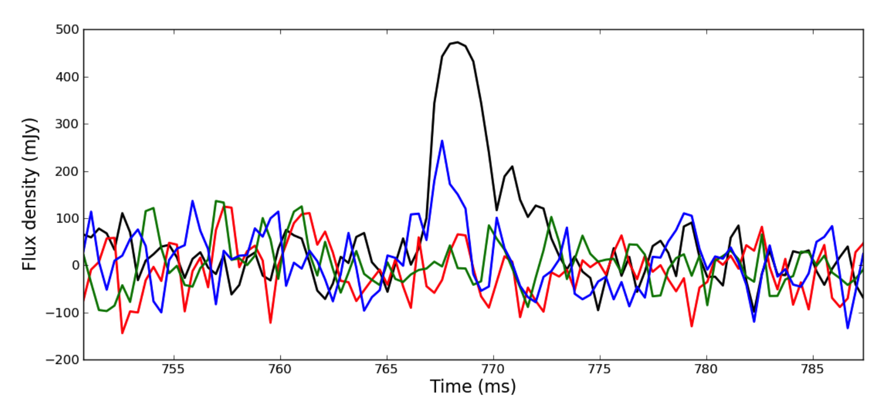

Primordial Black Holes

Green 1403.1198

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

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

Phenomenology

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

Primordial Black Hole Explosion

- exploding now: $m(t)|_{t=t_H}$ $R = \frac{2Gm}{c^2}$

$\{$

Barrau, Rovelli, Vidotto 1409.4031

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 particles liberated

Barrau, Rovelli, Vidotto 1409.4031

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- very compact object: big flux $E = mc^2$

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Exponential decay: m^2 is favorite

- exploding now: $m = \sqrt{\frac{t_H}{4k}} \sim 1.2 \times 10^{23}$ kg $\quad R = \frac{2Gm}{c^2} \sim .02$ cm

- **LOW ENERGY:** size of the source $\approx$ wavelength $\lambda_{predicted} \gtrsim .02$ cm
- **HIGH ENERGY:** energy of the particles liberated $\approx Tev$

- fast process ?
- the source disappears with the burst ?
- very compact object: big flux $\quad E = mc^2 \sim 1.7 \times 10^{47}$ erg

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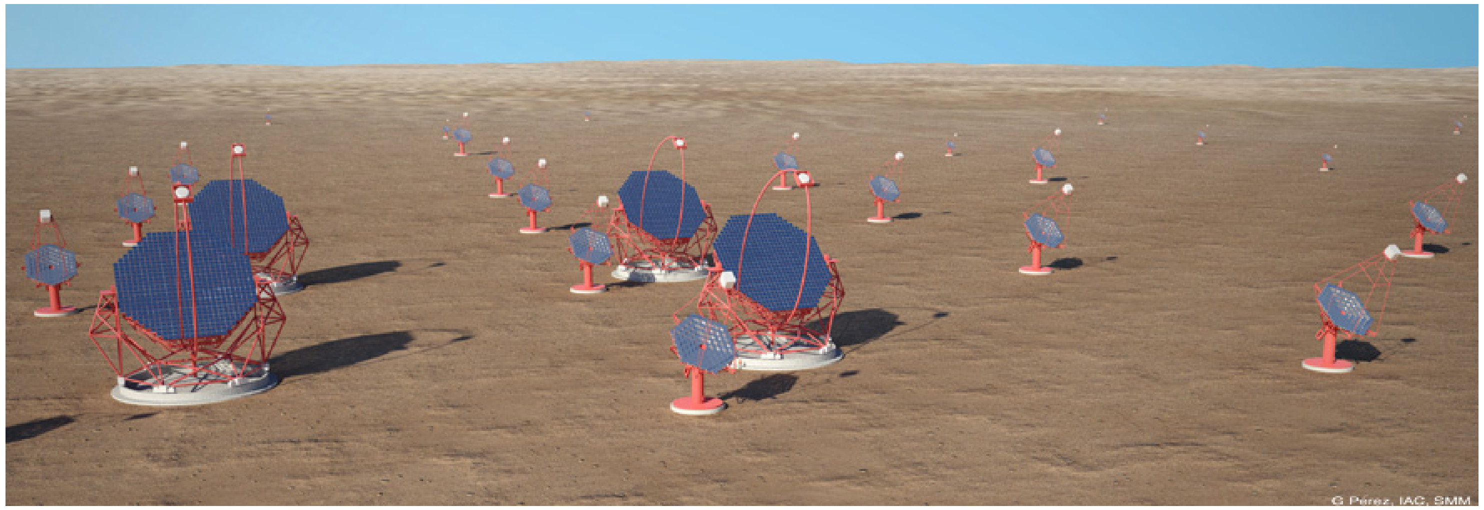
High energy component

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 $\sim$TeV

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



cfr. Dadhich, Narlikar, Appa Rao, 1974

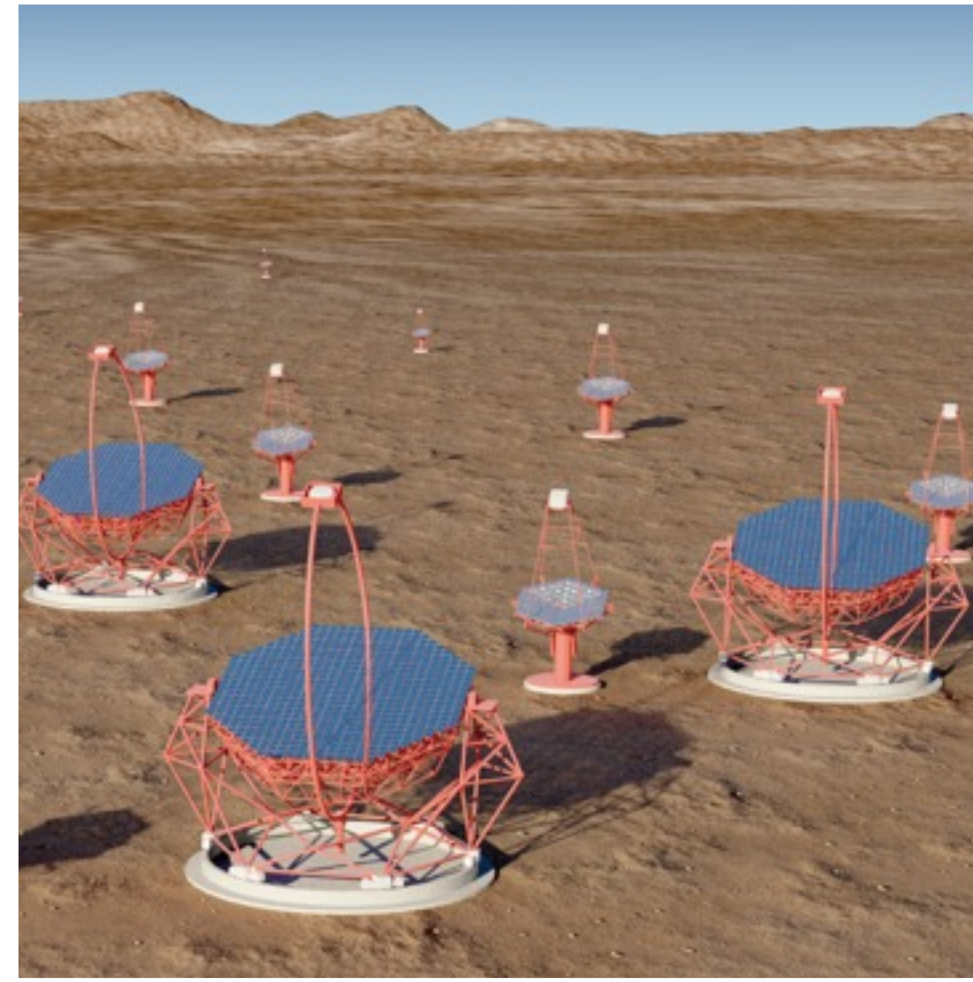
Short Gamma Ray Burst

- 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?)



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Planck stars

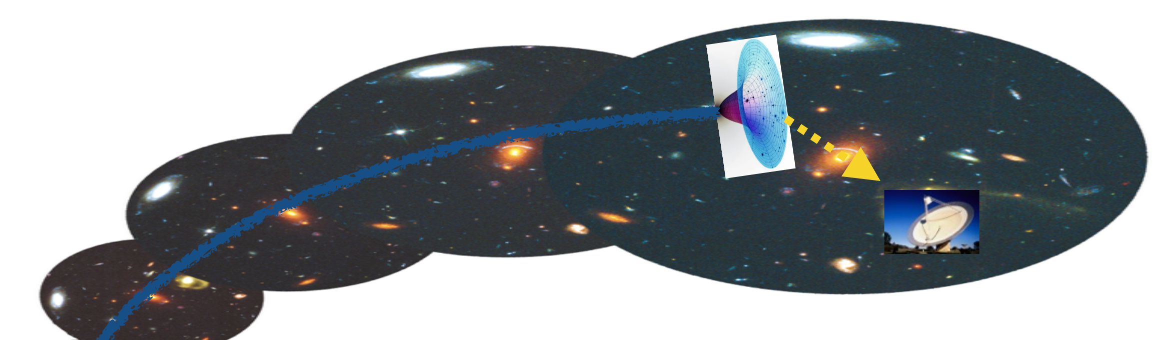
An observable quantum gravity phenomenon?

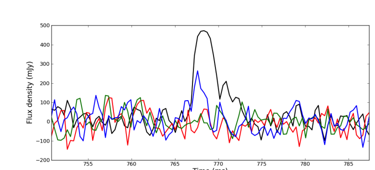
I. Basics of black hole tunneling decay

II. Decay time

III. Observations: High energy signal

IV. Observations: Low energy signal and Fast Radio Bursts





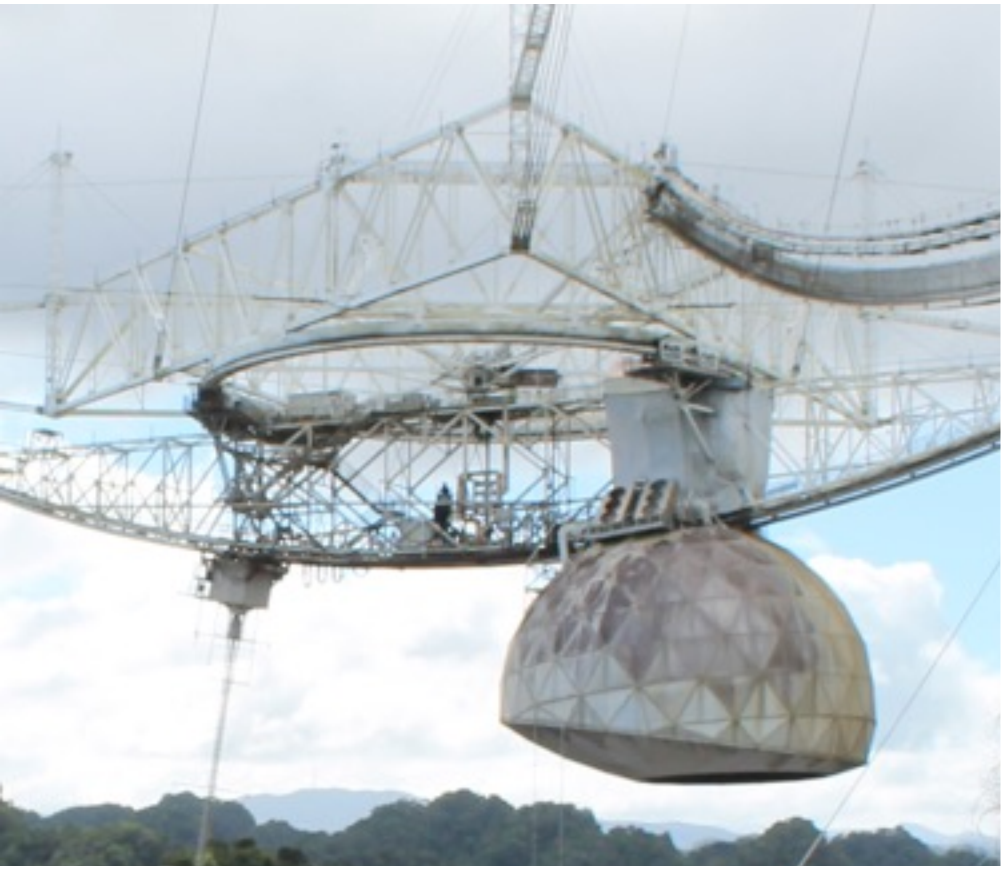
Detectable?
Already detected?

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

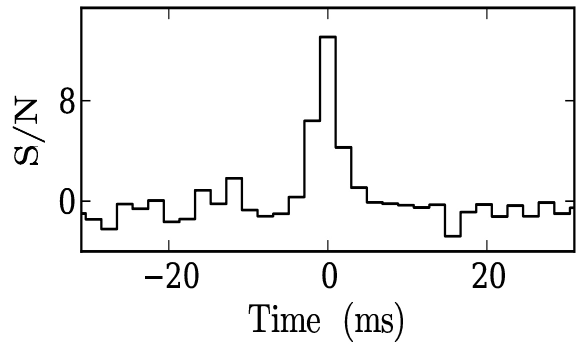
Fast Radio Bursts and White Hole Signals
Aurélien Barrau, Carlo Rovelli, Francesca Vidotto.
Phys.Rev. D90 (2014) 12, 127503

$$\lambda = 20\ cm$$

For T~m² primordial black hole give signals in the radio: Fast Radio Bursts?



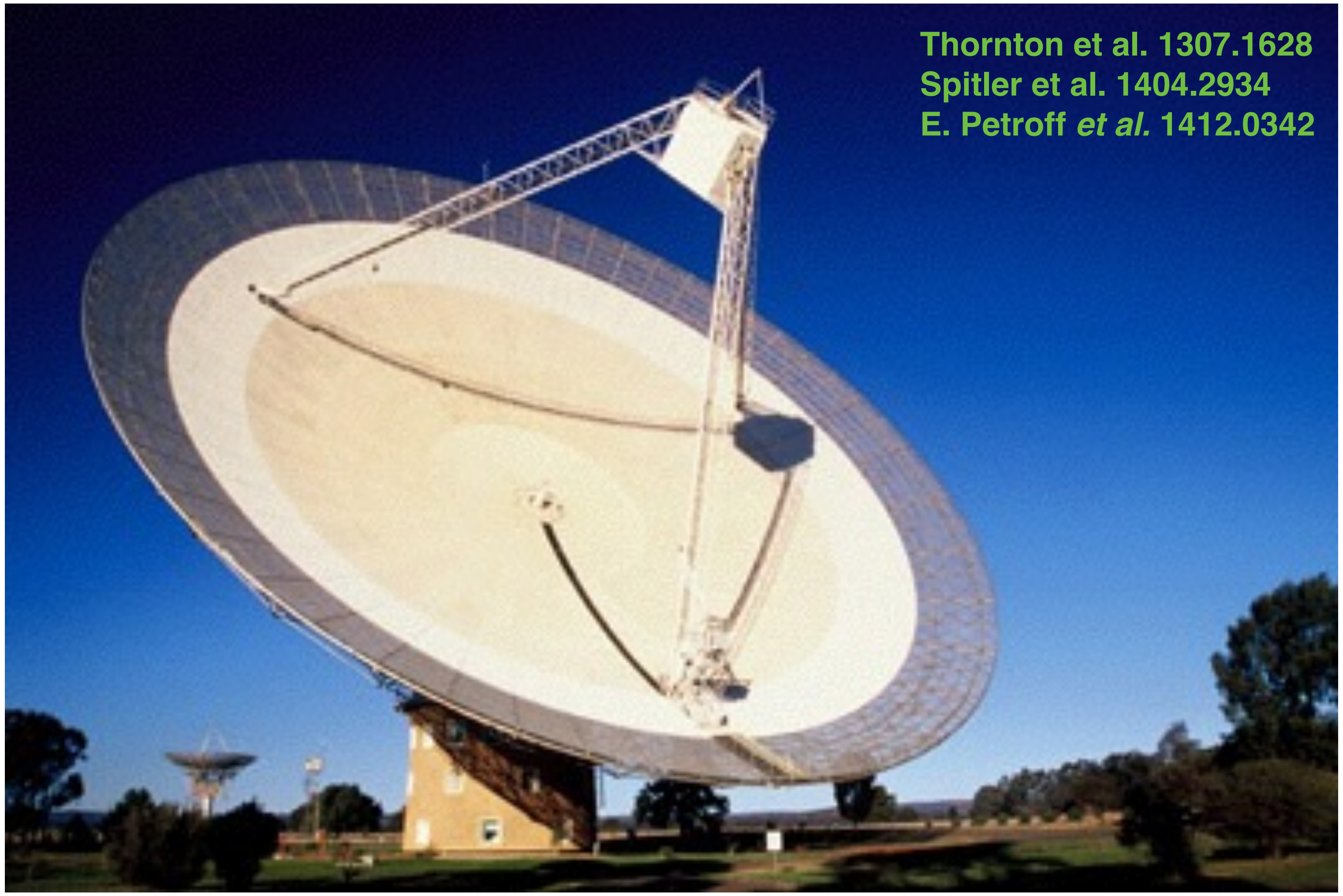
Fast Radio Bursts

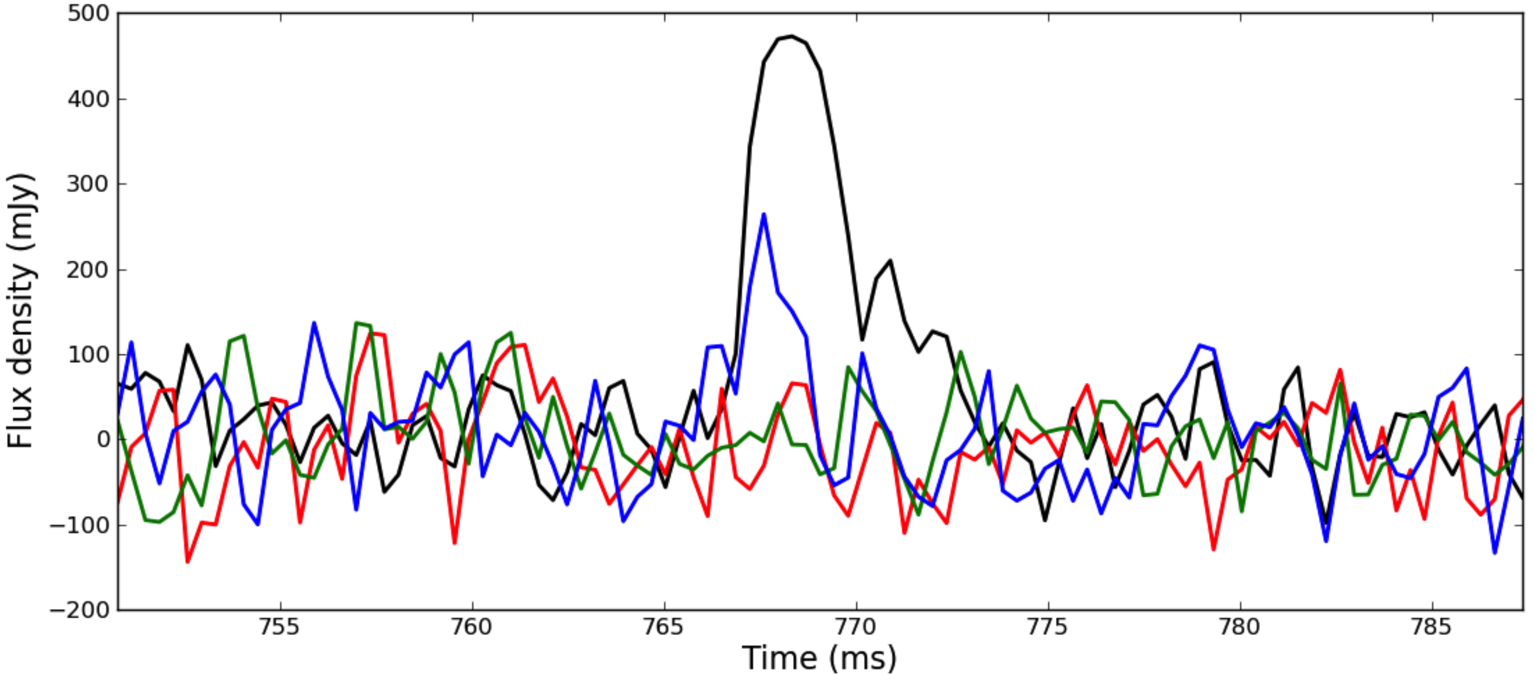


- Duration: ~ milliseconds
- Frequency: 1.3 GHz
- Observed at: Parkes, Arecibo
- Origin: Likely extragalactic
- Estimated emitted power: 10^{38} erg
- Physical source: unknown.

Fast Radio Burst

- Short
  - Observed width ≃ milliseconds
- No Long GRB associated
  - No long 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?





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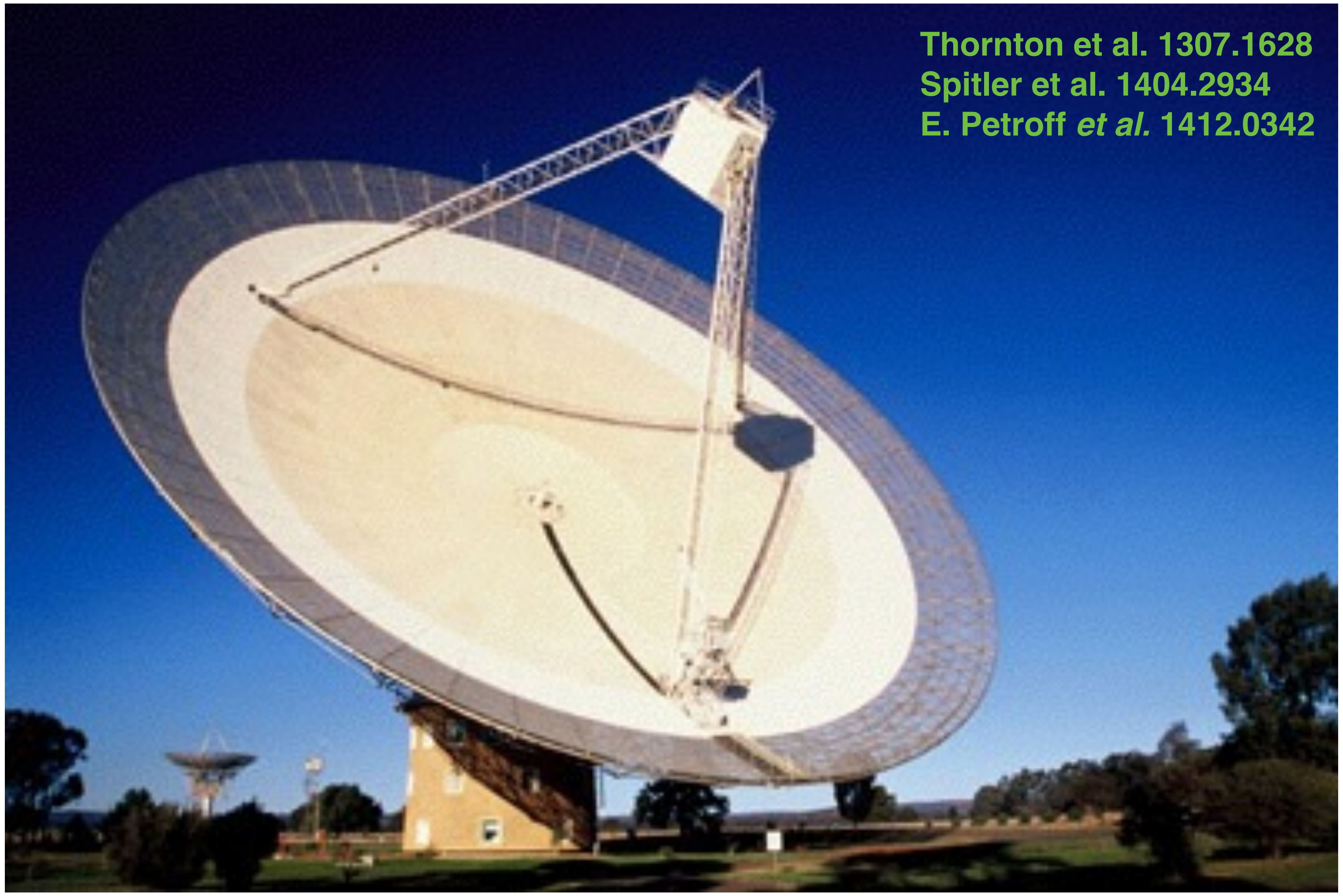

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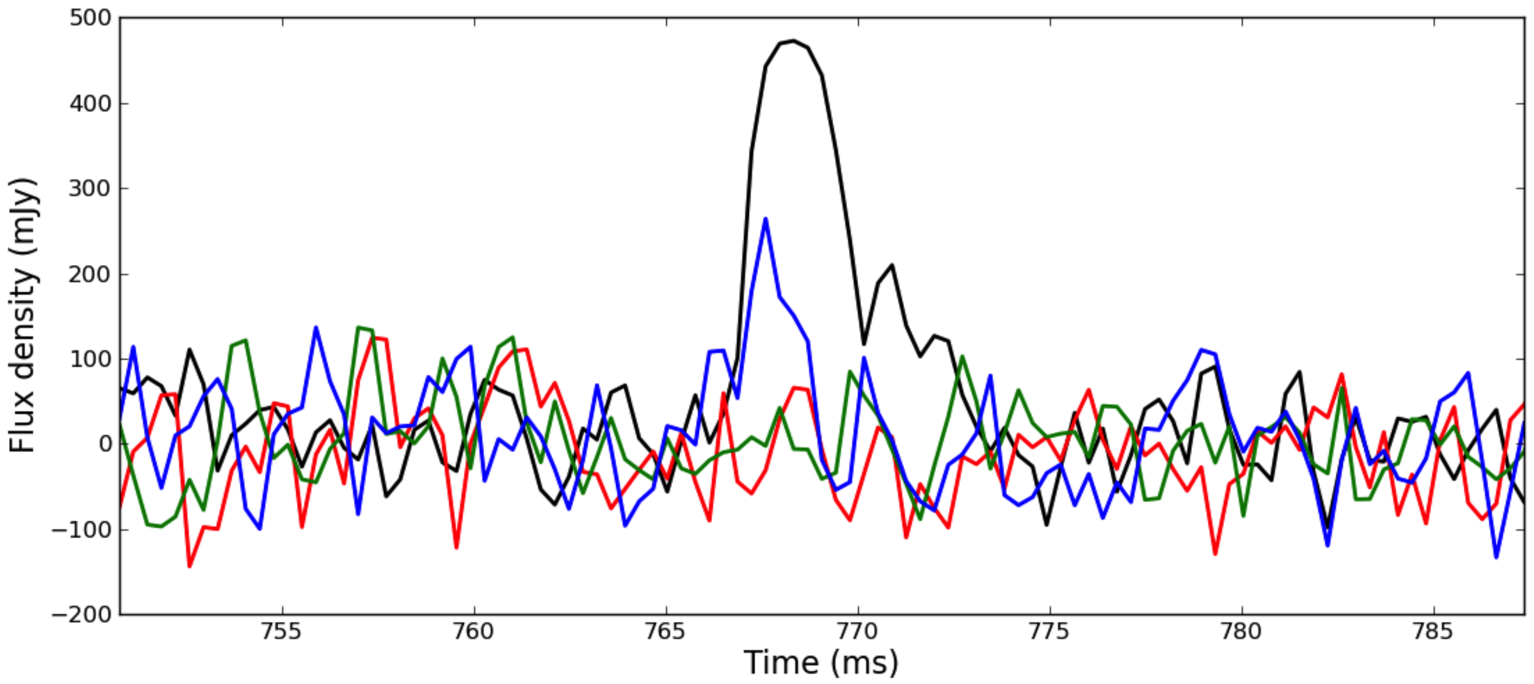

Fast Radio Burst

Barrau, Rovelli, Vidotto 1409.4031

- $\lambda \approx 20$ cm
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Are these bouncing Black Holes?

Fast Radio Burst

Barrau, Rovelli, Vidotto 1409.4031

- $\lambda \approx 20$ cm → size of the source $\approx$ $\lambda_{predicted} \gtrsim .02$ cm
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Barrau, Rovelli, Vidotto 1409.4031

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Barrau, Rovelli, Vidotto 1409.4031

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Barrau, Rovelli, Vidotto 1409.4031

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Fast Radio Burst

Barrau, Rovelli, Vidotto 1409.4031

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Barrau, Rovelli, Vidotto 1409.4031

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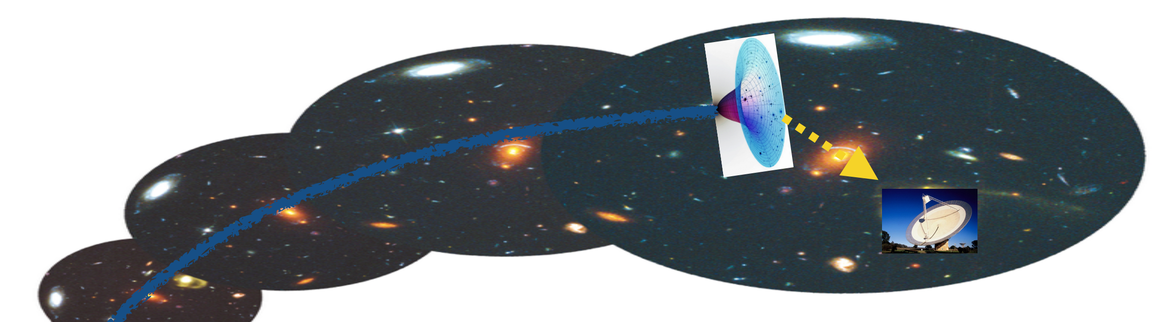
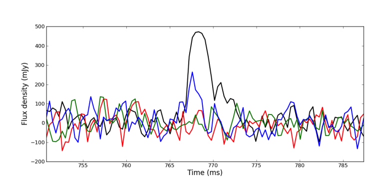
Are these bouncing Black Holes?

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





Planck stars

An observable quantum gravity phenomenon?

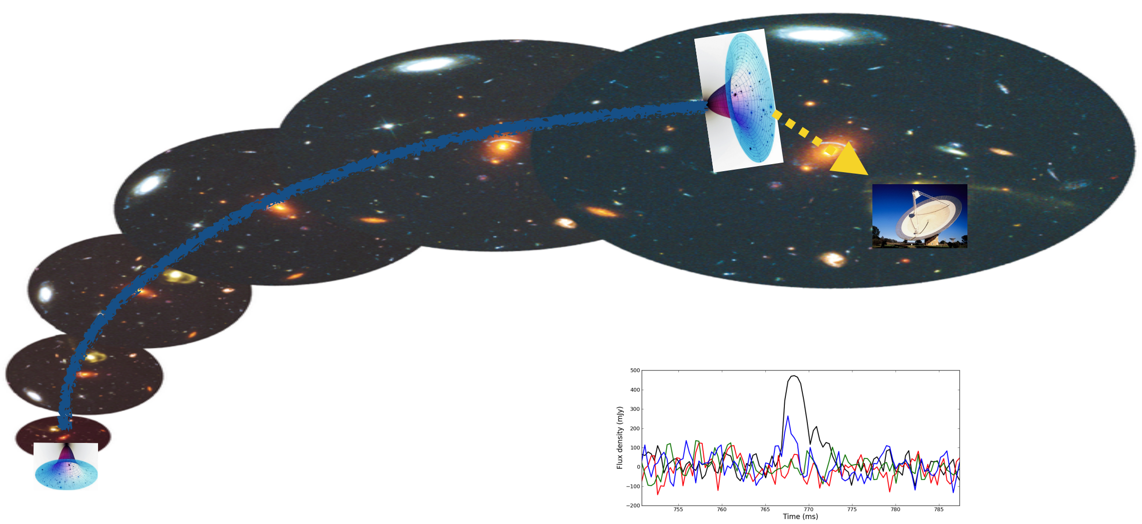
I. Basics of black hole tunneling decay

II. Decay time

III. Observations: High energy: gamma.

IV. Observations: Low energy signal: Fast Radio Bursts?

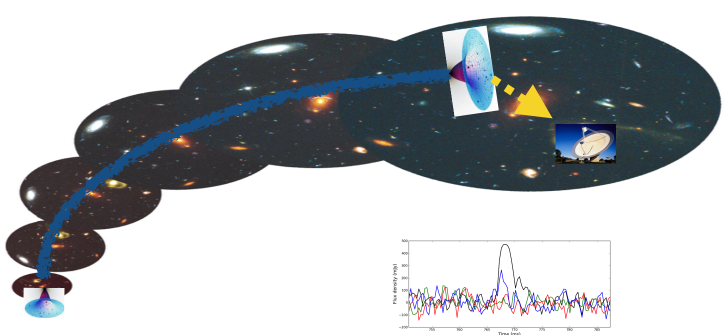
V. Distance-frequency curve



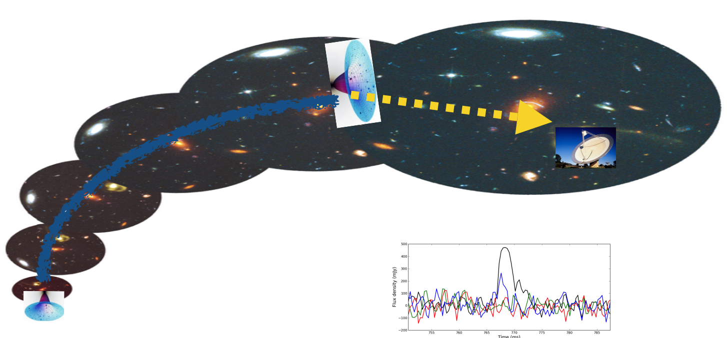
Signature: distance/energy relation

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

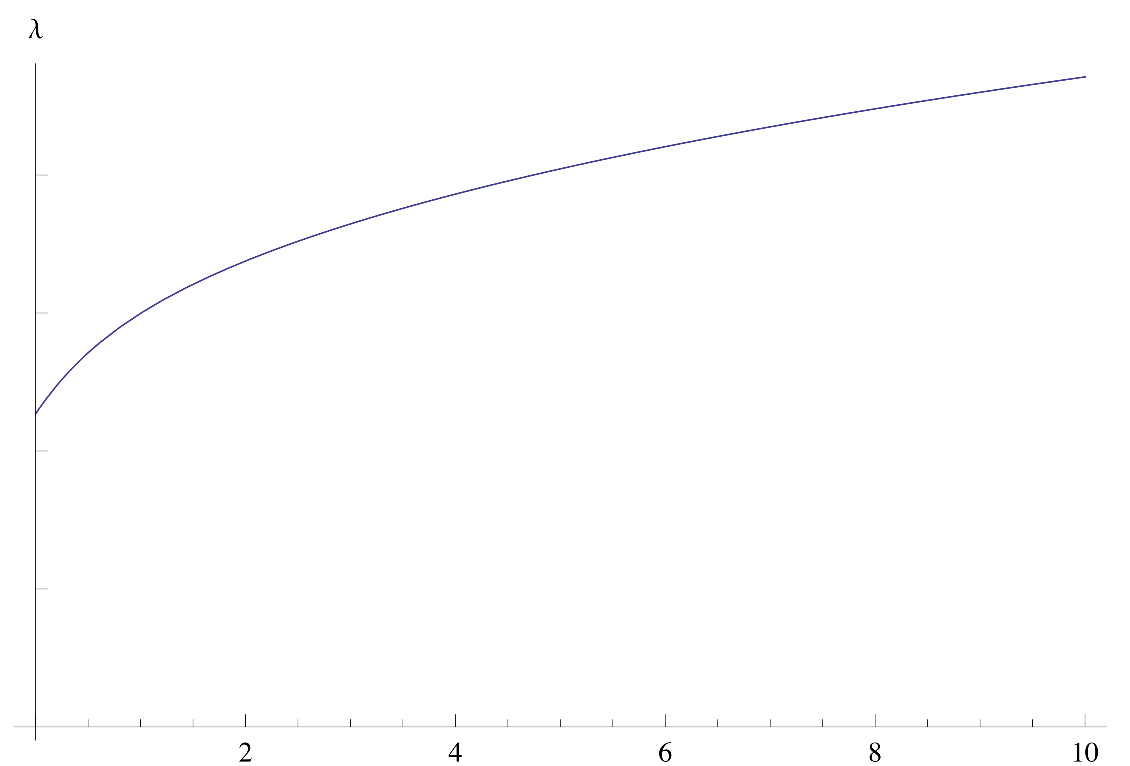
$$\lambda_{obs} \sim \frac{2Gm}{c^2}(1+z)\sqrt{\frac{H_0^{-1}}{6\,k\Omega_\Lambda^{1/2}}\ \sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]}$$



m_1



$m_2 < m_1$

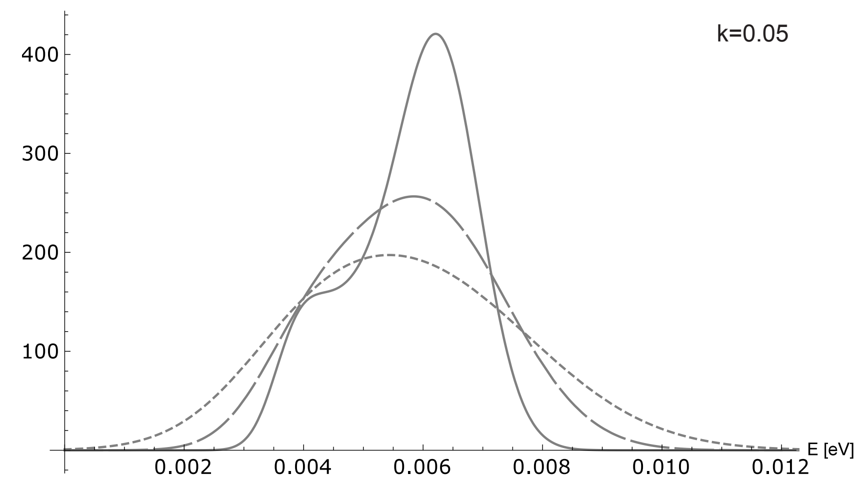


Integrated emission

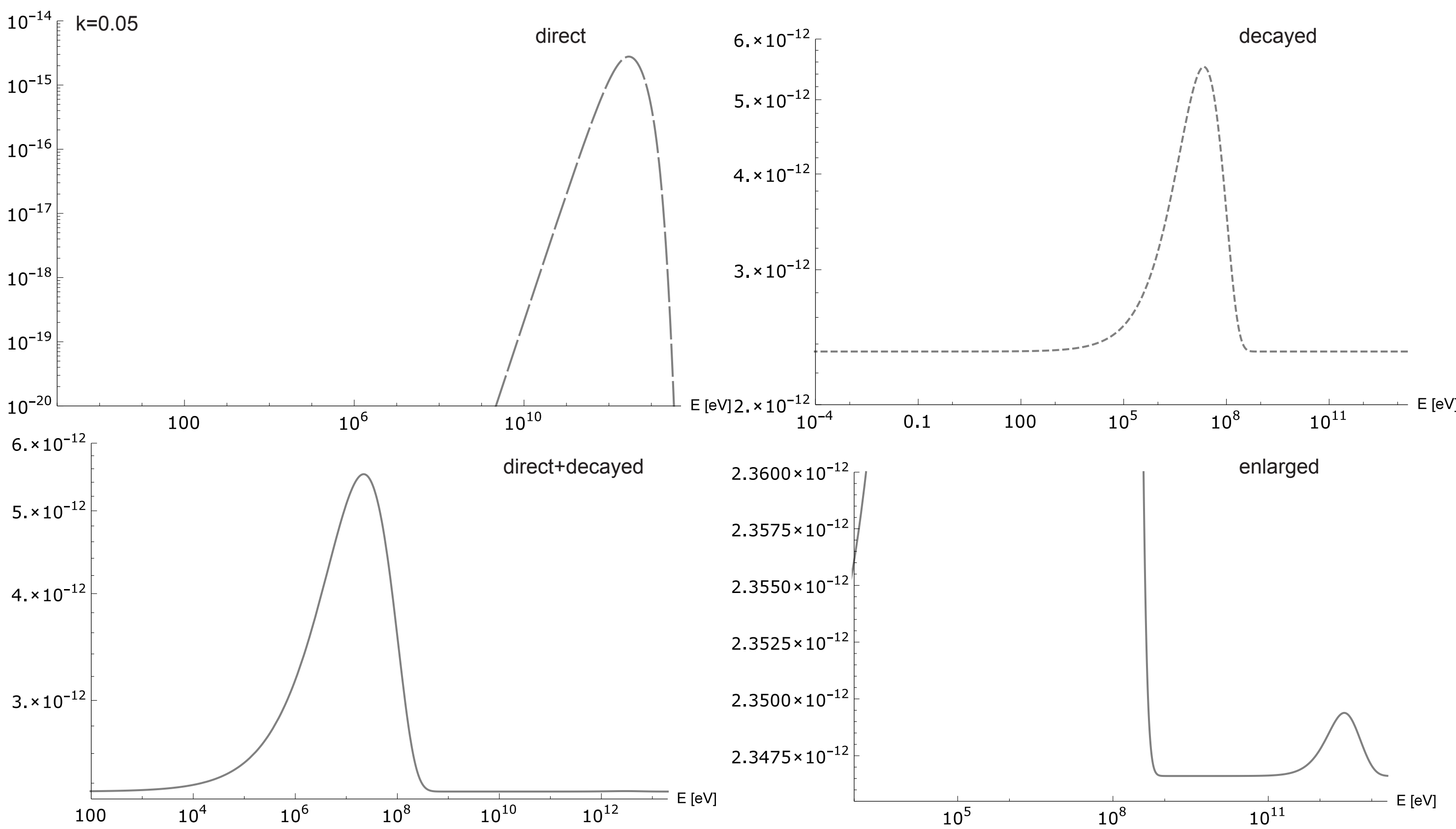
Barrau, Bolliet, Vidotto, Weimer 1507.1198

$$\tau \sim m^2$$

Low energy channel



High energy channel

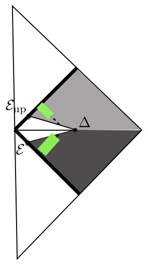


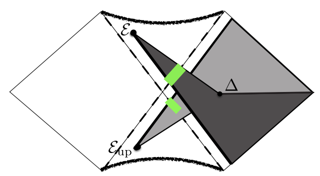
$$\frac{dN_{mes}}{dEdtdS} = \int \Phi_{ind}((1+z)E, R) \cdot n(R) \cdot Acc \cdot Abs(E, R) dR$$

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

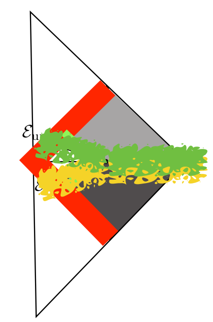
Summary

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

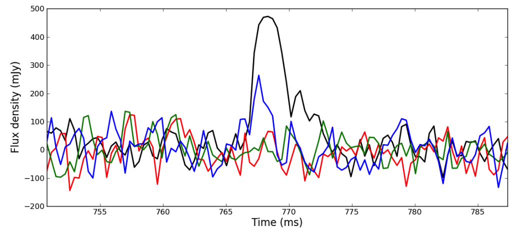




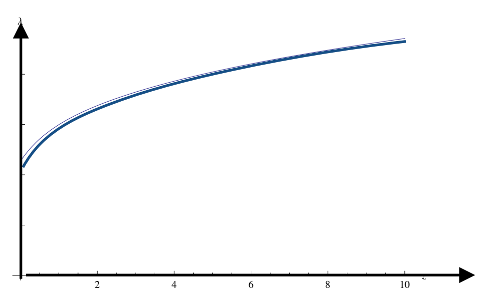
- The tunnelling time can be computed with LQG.



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



- Wavelength-to-distance relation signature.



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

Phenomenology

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

Why consider a classicality parameter with power scalings and not the exponential decay of a tunneling process?

$$q = \ell_{\mathsf{Pl}} \mathcal{R} \tau_R \qquad \text{vs.} \qquad q = \mathcal{N} e^{-S_E}$$

If we take $\mathcal{N}$ to be the large number of states of the black hole

$$\mathcal{N} \sim e^{S_{\mathsf{BH}}}$$

and the Euclidean action comes from a corner term

$$e^{-S_E} = e^{-\eta A} = e^{-\eta M^2}$$

these terms could cancel. [S. Mathur]

Quantum gravity effects may take hold
outside the horizon!