A New Decay Mode For Black Holes

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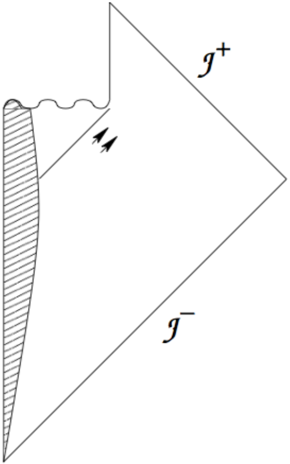
Bard College
joint with C. Rovelli and work of A. Barrau, C. Rovelli and F. Vidotto

July 9th, 2015

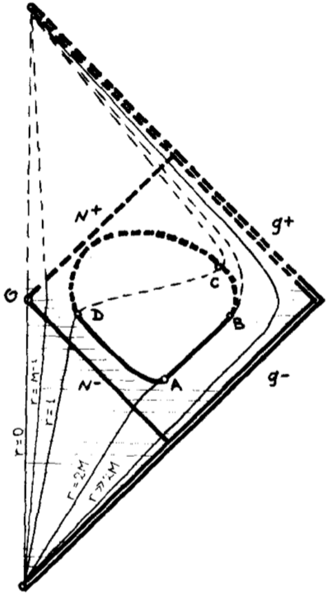
Loops '15
Erlangen, Germany

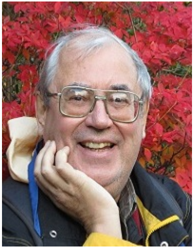
Two deep puzzles we have all wondered about:



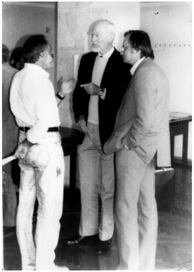
A brief (very incomplete) history of ideas

At MG2 and in a paper '79-'81





Valeri Frolov



Grigori A. Vilkovisky (left)

In '93

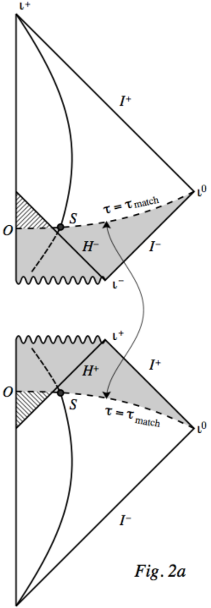


Fig. 2a

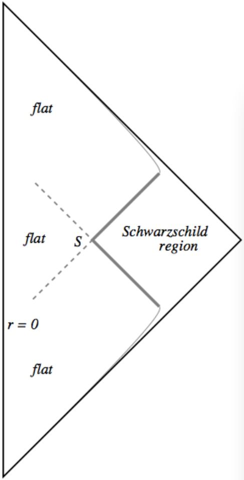
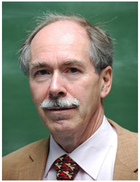


Fig. 2b

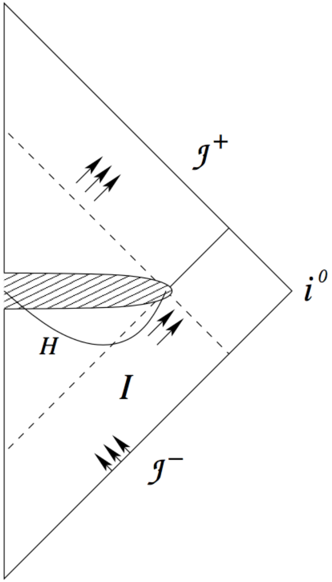
Cristopher R. Stephens



Gerard 't Hooft

Bernard F. Whiting

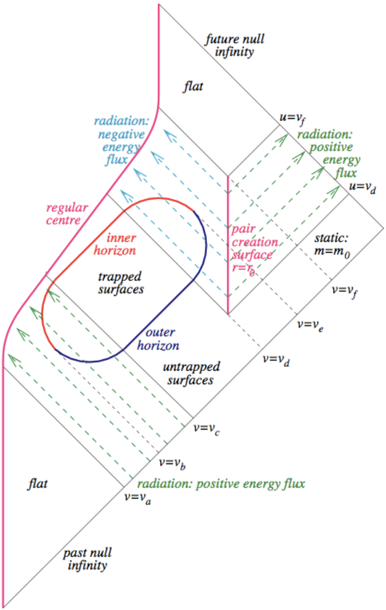
In '05



Abhay Ashtekar

Martin Bojowald

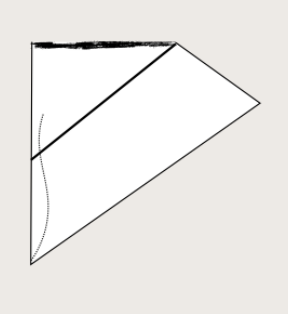
Sean A. Hayward in '06

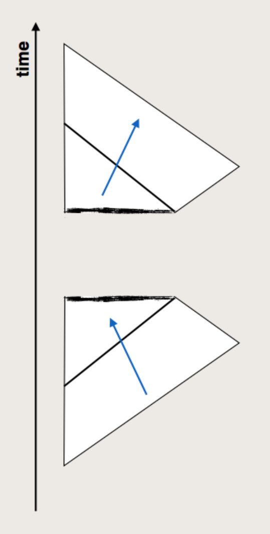


[see M. Smerlak's talk]

A clear theme emerges from these spacetime diagrams:

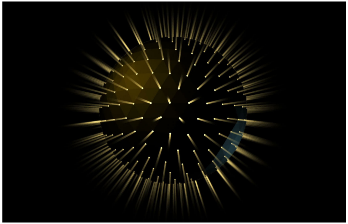
- build a time symmetric model

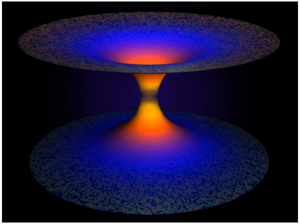




One

Exploding black holes



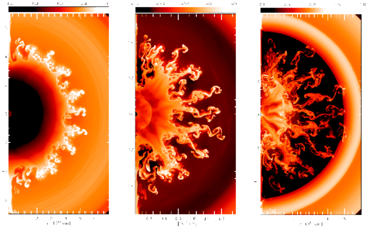


Two

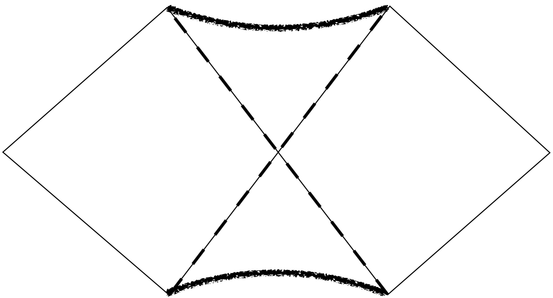
Phenomenology

Three

Blue shifts &
white hole instabilities

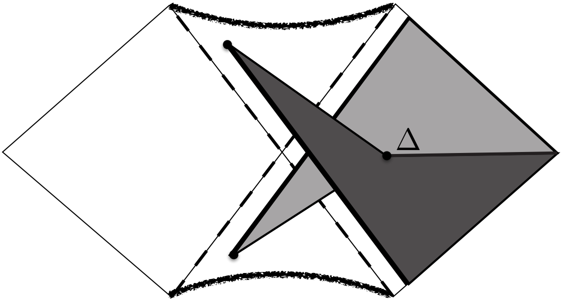


A glued version of these two space times is well known,



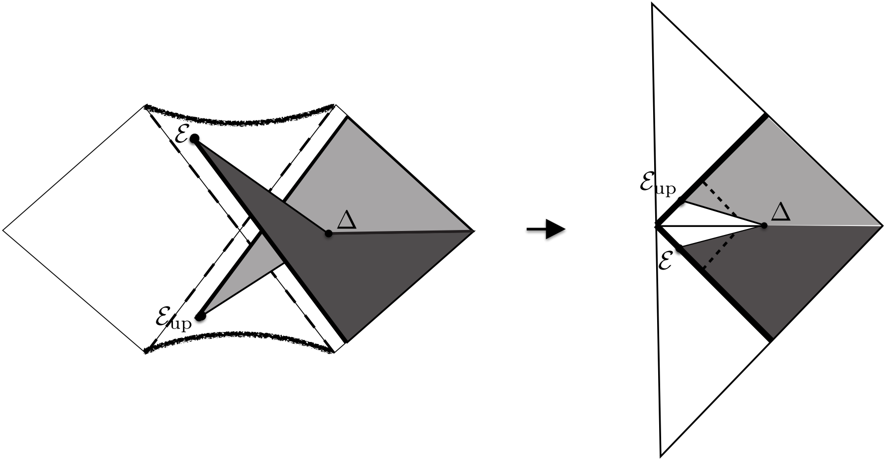
but it's upside down.

So, cut it up...



... and resew to get...

The spacetime

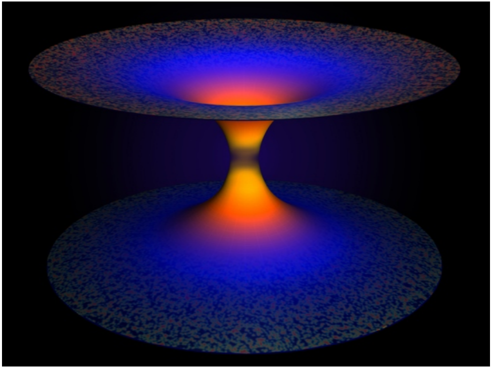


What happens near $r = 0$?

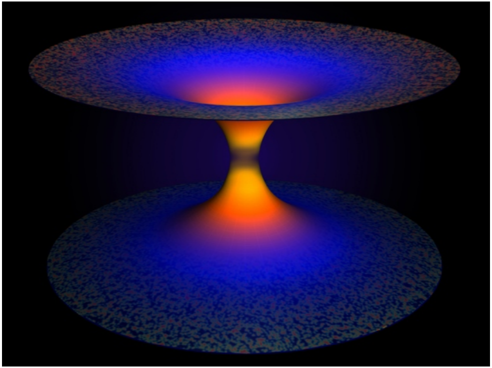
Inspired by LQC we imagine an effective quantum pressure that avoids a singularity

Could this "pressure" push matter back out? Would be like a cosmological bounce.

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



Hawking radiation focuses on the matter—what of the geometry?

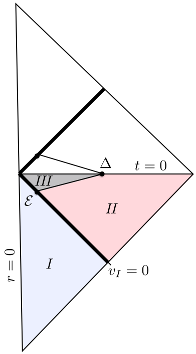


Our ideas:

- E is conserved at $\infty \rightsquigarrow$ elastic bounce
- Neglect Hawking radiation
- Quantum process $\rightsquigarrow$ tunneling of geometry
  Begins outside horizon
- GR is time reversal invariant—black to white hole bounce

This suggests that the central region is a quantum domain

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: $v_I = 0$

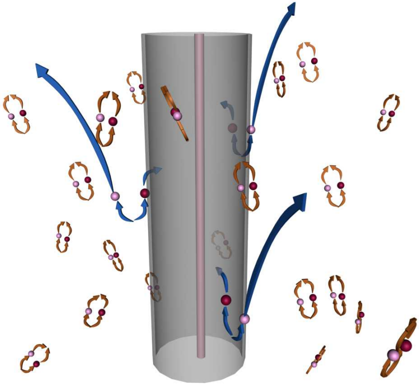
Region II (Schw.): $F(u,v) = \frac{32m^3}{r} e^{\frac{r}{2m}} \qquad \left(1 - \frac{r}{2m}\right) e^{\frac{r}{2m}} = uv.$

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 $\rightsquigarrow$ correct one to be discovered

[see also, e.g. A. Perez]

The vacuum constantly excites pairs of virtual particles



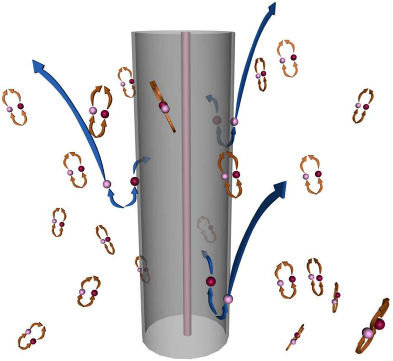
They are virtual because one has $+E$ and one $-E$

The $-E$ particle is forbidden outside the horizon—tunneling inside it becomes allowed

The $+E$ particle can escape to far away and carry some of the black hole's mass

[Parikh & Wilczek]

Because Hawking radiation is due to quantum tunneling we know that it must be slow. But how slow?



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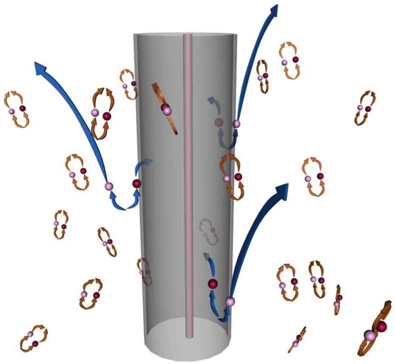


Very, very slow $T_H \sim M^3$. For a solar mass black hole it takes $T_H = 10^{75}$ secs. The age of the universe is $T_U = 10^{17}$ secs.

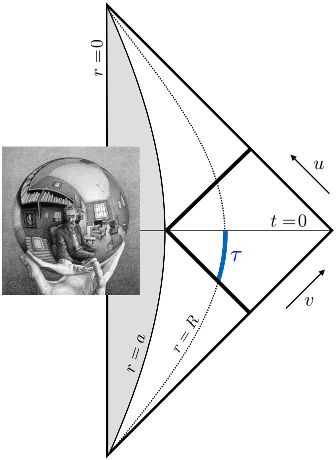
$$\tau_R = \sqrt{1 - \frac{2M}{R}} \left(R - a - 2M \ln \frac{a - 2M}{R - 2M} \right)$$

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 $\tau_q \sim M^2$.



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

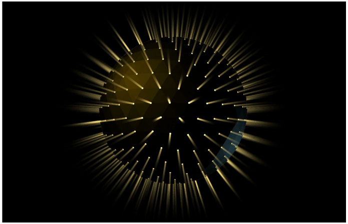
$$e^{-S_E} = e^{-\eta A} = e^{-\eta M^2}$$

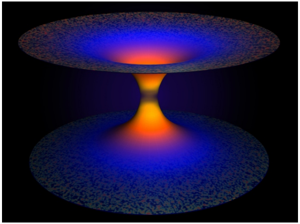
these terms could cancel. [S. Mathur]

Quantum gravity effects may take hold
outside the horizon!

One

Exploding black holes





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Blue shifts &
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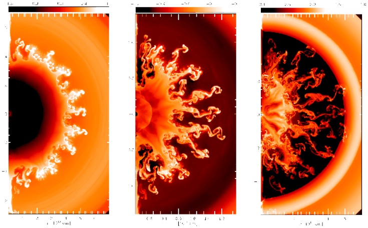


Observational evidence for black holes ($M_\odot \approx 2 \times 10^{33} g$)

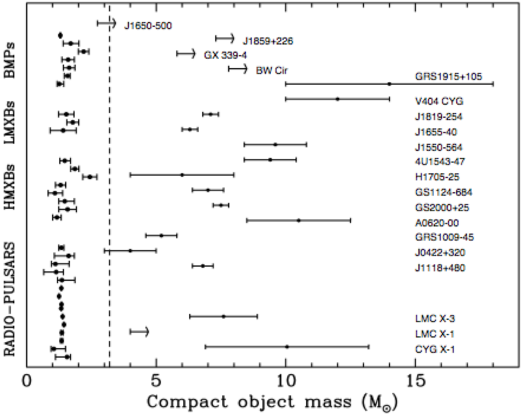
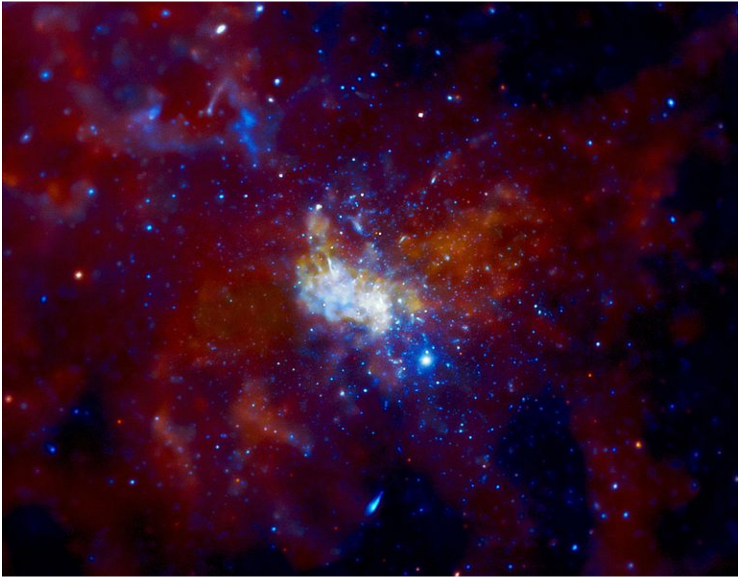
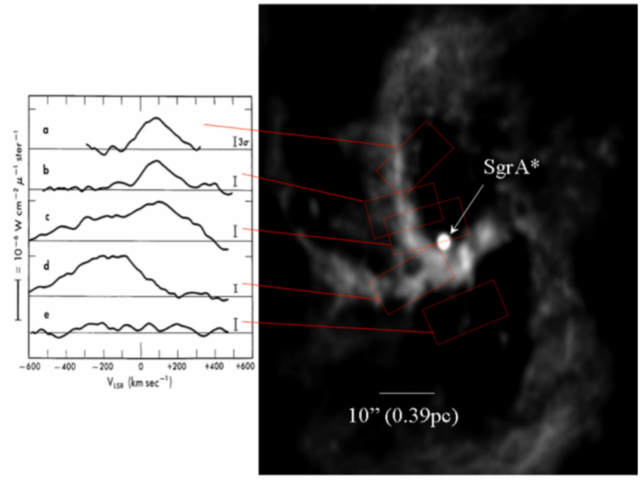


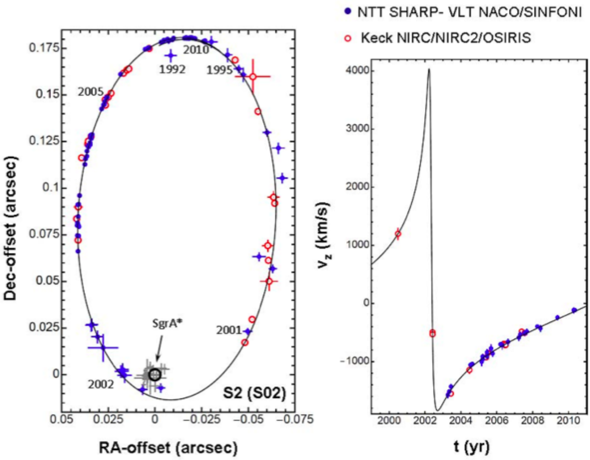
Figure 6. Mass distribution of compact objects in X-ray binaries. Arrows indicate lower limits to BH masses. Figure reproduced from Casares (2007).



The supermassive black hole at the center of our galaxy, Sgr A*



First evidence came from orbiting gas. Gas had radial velocities up to a few hundred km/s. Suggested a central mass of a few times $10^6 M_\odot$.



Began tracking orbiting stars. The star S2, with an eccentricity of $\epsilon = 0.88$ became an important signature. Put central mass at $4 \times 10^6 M_\odot$.

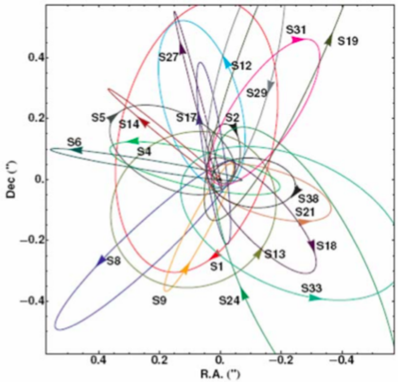


Figure 4.3.2. A summary of 20 of the ~ 30 S-star orbits delineated by the most recent orbital analysis of Gillessen et al. (2009b) [5].

Continued tracking orbiting stars. Accurately put mass at $4.3 \times 10^6 M_\odot$.

Primordial black holes (PBHs)

Light black holes, with $M < M_\odot$, don't easily form via collapse
A scaling argument:

$$\rho \propto \frac{M}{r_\mathsf{S}^3} \propto M^{-2}$$

A black hole of $\sim 10^8 M_\odot$ has the density of water

Several proposed formation mechanisms:

- ■ Collapse of overdense regions from primordial density inhomogeneities
- ♦ Epoch of low pressure
- ♣ Cosmological phase transitions

In most scenarios $M \sim 10^{15} \left(\frac{t}{10^{-23}\mathsf{s}}\right) \mathsf{g} \rightsquigarrow$ huge range of masses

PBHs could provide a substantial fraction of cold dark matter (Limits as of 2010 allow 10^{17}-10^{26}g PBHs to contribute all Ω_{CDM})

Because other mechanisms have not been prominent, searches for primordial black holes have largely assumed evaporation through the Hawking process.

Constraints on their masses are also tied to this mechanism.

[MacGibbon et al]

Taking seriously $\tau \sim M^2$ for black to white explosions gives

$$M = \sqrt{t_H} \sim 10^{26}\text{g}$$

for the mass of a PBH exploding today.

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

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

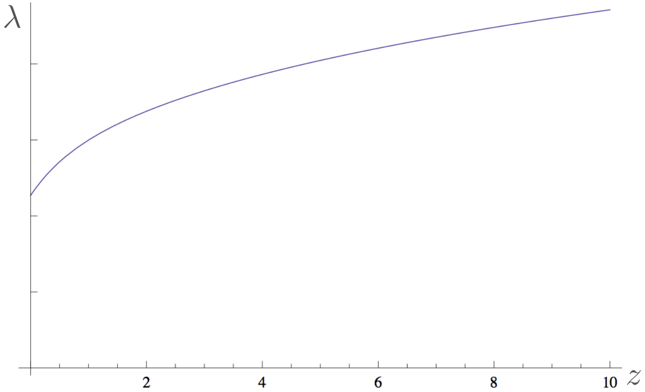
This leads to the expectation of two signals:

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

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

The low energy signal (i) has $\lambda_{\text{predicted}} \gtrsim .02$ cm in the infrared

Variation of λ with distance would give a peculiar and clear signal



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

Interesting to compare Fast Radio Bursts

$\lambda_{\mathsf{obs}} \sim 20\mathrm{cm}$

Estimated total energy of 10^{38} erg

Believed to be extragalactic due to frequency arrival time delays

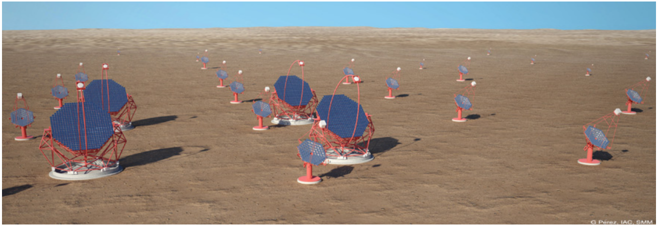
Predicted energies are sufficient and λ's are intriguingly close $\rightsquigarrow$ discrepency possibly due to dissipative phenomena or anisotropies

What about the higher energy component (ii)?

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)

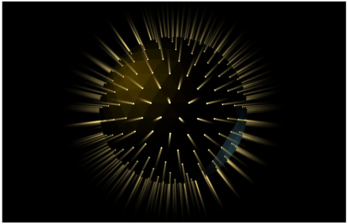


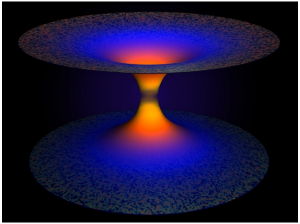
$$\lambda_{\mathsf{obs}} \propto (1+z)\left(\sinh^{-1}\left[\left(\frac{\Omega_\Lambda}{\Omega_M}\right)^{1/2}(z+1)^{-3/2}\right]\right)^{1/4}$$

Only measurable for $z < 0.01$.

One

Exploding black holes





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Phenomenology

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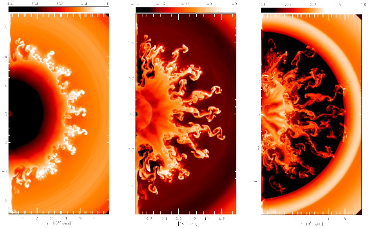
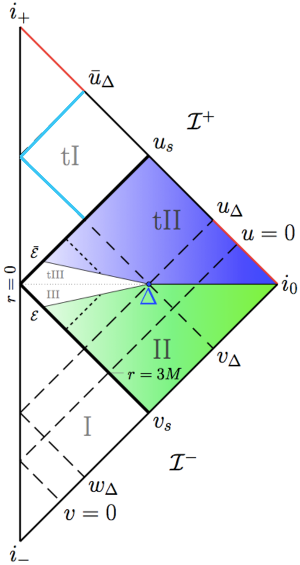
Blue shifts &
white hole instabilities



Exponential blue shifts

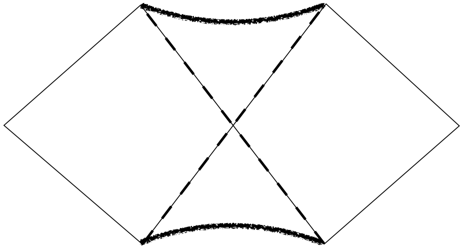


In order that $u_s - u_\Delta \sim M^2$ the ray beginning at v_Δ must pass exponentially close to $r = 2M$

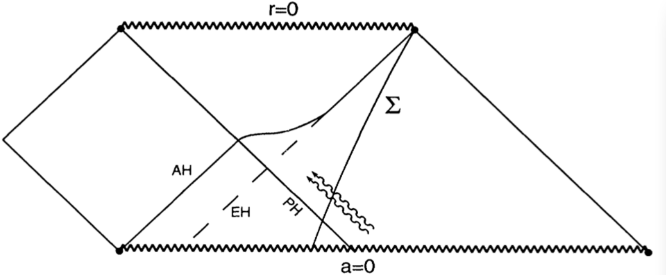
It becomes highly blue shifted in crossing the outcoming shell $\rightsquigarrow$ potential instability

There is a long history of this concern going back to Eardley '74

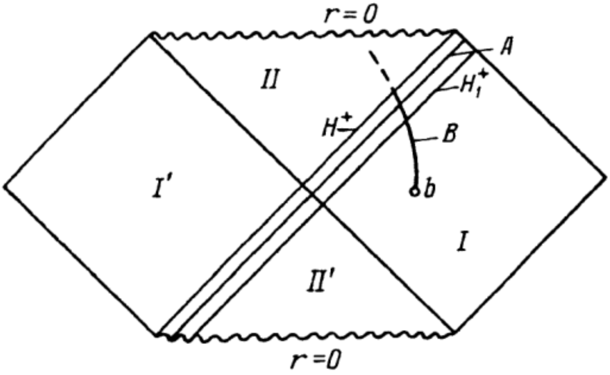
Lake and Roeder '76 compared



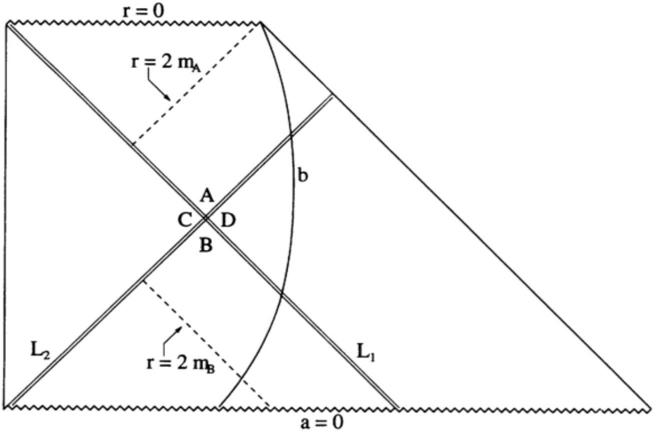
vs.



Nonetheless, white holes are unstable [Blau '89]



Ori and Poisson estimate the dynamical lifetime of a white hole



and find $\tau_d \sim 4M \ln \frac{M}{\delta m}$

Conclusions:

- Collapsing matter bounces in a short time locally but a long time from far away, $\sim M^2$.
  Solar mass: $\tau_q \sim 10^{32}$ sec, $\tau_H \sim 10^{75}$ sec, $\tau_U \sim 10^{17}$ sec.

- Possible to describe using a metric with no singularity, two trapped regions, and all matter exiting $\rightsquigarrow$ all info escapes

- Could a black hole be a bouncing star seen in super slow motion? With the constructed metric we can attack this question rigorously.

- Quantum gravity calculations of this process are extremely exciting: Spinfoarm [Giusti, Rovelli, Speziale]; WKB [HMH]; canonical [?]