Title: General Relativity for Cosmology Lecture - 120523

Speakers: Achim Kempf

Collection: General Relativity for Cosmology

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GR for Cosmology, Achim Kempf — Lecture 23

More on singularity theorems

- Assume a set of symmetries of matter and spacetime has been chosen.
- Assume an exact solution or at least its asymptotic properties at early times have been found.
- Assume, we choose a timelike congruence e.g. of geodesics.

$\Rightarrow$ We can now explicitly calculate the twist, shear and expansion along the congruence:

$$\Theta_{\mu\nu} := \sigma_{\mu\nu} + \frac{1}{3}\theta h_{\mu\nu}$$

symmetric part of $B_{\mu\nu}$ — shear — projector $\perp$ to the timelike u-field — expansion scalar.

- $\Theta_{\mu\nu}$ is fully spacelike and symmetric $\Rightarrow$ $\Theta_{\mu\nu}$ can be diagonalized in suitable ON frame $\{e_0, e_1, e_2, e_3\}$:

$$\Theta_{\mu\nu} = \begin{pmatrix} 0 & & & 0 \\ & \theta_1 & & \\ & & \theta_2 & \\ 0 & & & \theta_3 \end{pmatrix}$$

3 space-like directions.

with the traditional expansion being the trace (because

The Hubble functions:

In particular, we can see how the expansion or contraction of the universe behaves dynamically e.g. when the condition of perfect isotropy is relaxed:

- Now we have different expansions in different directions, nonlinearly influencing another.
- Recall:
  The expansion in one direction can be enhanced by shear, as long as shear shrinks other directions.
- Definition:
  We define a rate of expansion tensor that includes shear:

- **Definition:**

We use H_i, H to define local directional and general scale factors ℓ_i, ℓ:

The ℓ_i, ℓ are defined as the solutions to:

$$\frac{\dot{\ell}_i}{\ell_i} = H_i$$

$$\frac{\dot{\ell}}{} = H$$

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- Assume an exact solution or at least its asymptotic properties at early times have been found.
- Assume, we choose a timelike congruence e.g. of geodesics.

⇒ We can now explicitly calculate the twist, shear and expansion along the congruence:

$$\underbrace{\theta_{\mu\nu}}_{\text{symmetric part of } B_{\mu\nu}} := \overbrace{\sigma_{\mu\nu}}^{\text{shear}} + \frac{1}{3}\underbrace{\theta}_{\text{expansion scalar.}} \overbrace{h_{\mu\nu}}^{\text{projector} \perp \text{ to the timelike u-field}}$$

- $\theta_{\mu\nu}$ is fully spacelike and symmetric ⇒ $\theta_{\mu\nu}$ can be diagonalized in suitable ON frame $\{e_0, e_1, e_2, e_3\}$:

$$\theta_{\mu\nu} = \begin{pmatrix} 0 & & & 0 \\ & \theta_1 & & \\ & & \theta_2 & \\ 0 & & & \theta_3 \end{pmatrix}$$

3 space-like directions.

with the traditional expansion being the trace (because $\sigma_{\mu\nu}$ is traceless): $\theta = \theta_1 + \theta_2 + \theta_3$

- **Definition:**

$H_i := \frac{1}{3}\theta_i$ Local Hubble expansion function in direction e_i.

why $\frac{1}{3}$? Recall that $Tr(h_{\mu\nu}) = 3$ ⇒ is not quite projector

$H := \frac{1}{3}\theta$ Overall local Hubble expansion function.

- Now we have different expansions in different directions, nonlinearly influencing another.
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The ℓ_i, ℓ are defined as the solutions to:

$$\frac{\dot{\ell}_i}{\ell_i} = H_i$$

$$\frac{\dot{\ell}}{\ell} = H$$

Here, the time derivative is defined as:

$$\dot{\ell} = u(\ell) = u^{\mu}\frac{\partial}{\partial x^{\mu}}\ell$$

recall: u is timelike.

- What behavior can occur in the far past?

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$$\Theta_{\mu\nu} = \begin{pmatrix} 0 & & & \\ & \theta_1 & & 0 \\ & & \theta_2 & \\ 0 & & & \theta_3 \end{pmatrix}$$ 3 space-like directions.

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$\Rightarrow$ is not quite projector

why $\frac{1}{3}$? Recall that $Tr(h_{\mu\nu}) = 3$

Definition: $H_i := \frac{1}{3}\theta_i$ Local Hubble expansion function in direction e_i.

$H := \frac{1}{3}\theta$ Overall local Hubble expansion function.

Full set of cases not yet known.

But:

Explicit examples are known where e.g.:

- All $\ell_i \to 0$ as in FL cosmologies
- $\ell_1, \ell_2 \to 0$, $\ell_3 \to \infty$ "cigar singularity"
- $\ell_1, \ell_2 \to 0$, $\ell_3 \to$ const "barrel singularity"
- $\ell_1, \ell_2 \to$ const, $\ell_3 \to 0$ "pancake singularity"

Note: For homogeneous, isotropic FL models, H is the regular Hubble parameter and ℓ is its scale factor.

The ℓ_i, ℓ are defined as the solutions to:

$$\frac{\dot{\ell}_i}{\ell_i} = H_i$$

$$\frac{\dot{\ell}}{\ell} = H$$

Here, the time derivative is defined as:

$$\dot{\ell} = u(\ell) = u^\mu \frac{\partial}{\partial x^\mu}\ell$$ recall: u is timelike.

- What behavior can occur in the far past?

Singularity theorems for black holes

In 1915, Schwarzschild found this black hole solution to the Einstein equation:

Mass of black hole

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = \left(1 - \frac{2M}{r}\right)dt^2 - \left(1-\frac{2M}{r}\right)^{-1}dr^2 - r^2(d\theta^2 + d\varphi^2 \sin^2\theta)$$

Singularity: $r = 0$

Horizon: $r = 2M$

Here, $x = (t, r, \varphi, \theta)$ are called the Schwarzschild coordinates.

Schwarzschild coordinates long misled intuition:

- The singularity at $r = 2M$ is not real: it disappears in other coordinate systems. The curvature is smooth across $r = 2M$.

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Singularity theorems for black holes

In 1915, Schwarzschild found this black hole solution to the Einstein equation:

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = \Big(1 - \frac{2\overset{\text{Mass of black hole}}{M}}{r}\Big)dt^2 - \Big(1-\frac{2M}{r}\Big)^{-1}dr^2 - r^2(d\theta^2 + d\varphi^2 \sin^2\theta)$$

Singularity: $r = 0$

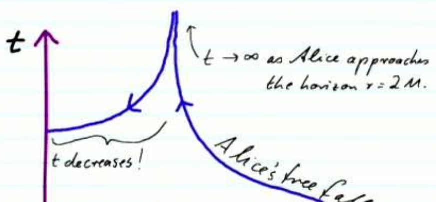
Horizon: $r = 2M$

Here, $x = (t, r, \varphi, \theta)$ are called the Schwarzschild coordinates.
Schwarzschild coordinates long misled intuition:

- The singularity at $r = 2M$ is not real: it disappears in other coordinate systems. The curvature is smooth across $r = 2M$.

- Due to the sign changes across $r = 2M$, for $r < 2M$ dt is spacelike and dr is timelike for $r < 2M$.

- Consider, for example, a traveler, Alice, who is freely falling from $r = r_0$ to $r = 0$:



$$r(\alpha) = \frac{r_0}{2}(1 + \cos(\alpha))$$

$$t(\alpha) = \Big(\frac{r_0}{2} + 2M\Big)w\alpha + \frac{r_0}{2}w\sin(\alpha) + 2M\log\left|\frac{w + \tan(\alpha/2)}{w - \tan(\alpha/2)}\right|$$

$$\tau(\alpha) = \frac{r_0}{2}\Big(\frac{r_0}{2M}\Big)^{1/2}(\alpha + \sin(\alpha))$$

Simplification:

For now, we drop the φ and θ coordinates.

First design of a new cds (T, R) - Alice's choice (for $r_0 = 2M$):

- Require $g_{\mu\nu}(T, R)$ to be regular across $r = 2M$.

- Require $g_{\mu\nu}(0,0) = \eta_{\mu\nu}$ at $r = 2M$. If there's really no singularity at $r = 2M$ this must be possible.

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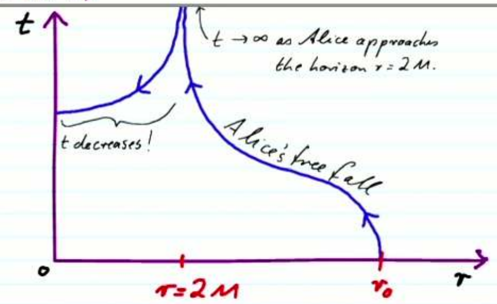


$r(\alpha) = \frac{r_0}{2}(1 + \cos(\alpha))$

$t(\alpha) = \left(\frac{r_0}{2} + 2M\right) w\alpha + \frac{r_0}{2} w \sin(\alpha)$

$\quad + 2M \log\left|\frac{w + \tan(\alpha/2)}{w - \tan(\alpha/2)}\right|$

$\tau(\alpha) = \frac{r_0}{2}\left(\frac{r_0}{2M}\right)^{1/2}(\alpha + \sin(\alpha))$

Here. $0 < \alpha < \pi$ and $w := \left(\frac{r_0}{2M} - 1\right)^{1/2}$

$\Longrightarrow$ need better choices of coordinate systems!

- Require $g_{\mu\nu}(T,R)$ to be regular across $r = 2M$.
- Require $g_{\mu\nu}(0,0) = \eta_{\mu\nu}$ at $r = 2M$. If there's really no singularity at $r = 2M$ this must be possible.
- Extend this cds so that $g_{\mu\nu}(T,R) = f(T,R)\,\eta_{\mu\nu}$

$\Rightarrow$ Alice's choice are the Kruskal-Szekeres coordinates (T,R):

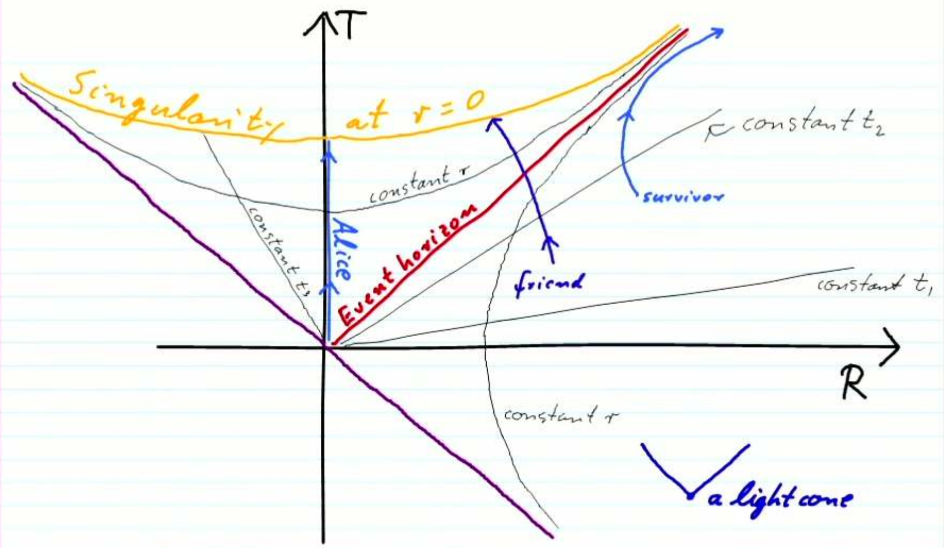
$$T(t,r) := 4M\left|\frac{r}{2M} - 1\right|^{1/2} e^{\frac{r-2M}{4M}}\left(\sinh\left(\frac{t}{4M}\right)\theta(r-2M) + \cosh\left(\frac{t}{4M}\right)\theta(2M-r)\right)$$

$$R(t,r) := 4M\left|\frac{r}{2M} - 1\right|^{1/2} e^{\frac{r-2M}{4M}}\left(\cosh\left(\frac{t}{4M}\right)\theta(r-2M) + \sinh\left(\frac{t}{4M}\right)\theta(2M-r)\right)$$

This map is, in principle, invertible, to obtain $t(T,R)$, $r(T,R)$.

The Schwarzschild metric now takes this form:

$$ds^2 = \underbrace{\frac{2M}{r(T,R)}\, e^{1 - \frac{r(T,R)}{2M}}}_{\text{Conformal prefactor } = 1 \text{ as } r \to 2M} \underbrace{\left(dT^2 - dR^2\right)}_{\eta_{\mu\nu}} \qquad \text{Obeys all conditions!}$$



- Alice was at rest at the event horizon.
- The singularity is at $T(R) = \left(R^2 + \frac{16M^2}{e}\right)^{1/2}$ and is spacelike.

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⇒ Alice's choice are the Kruskal-Szekeres coordinates (T,R):

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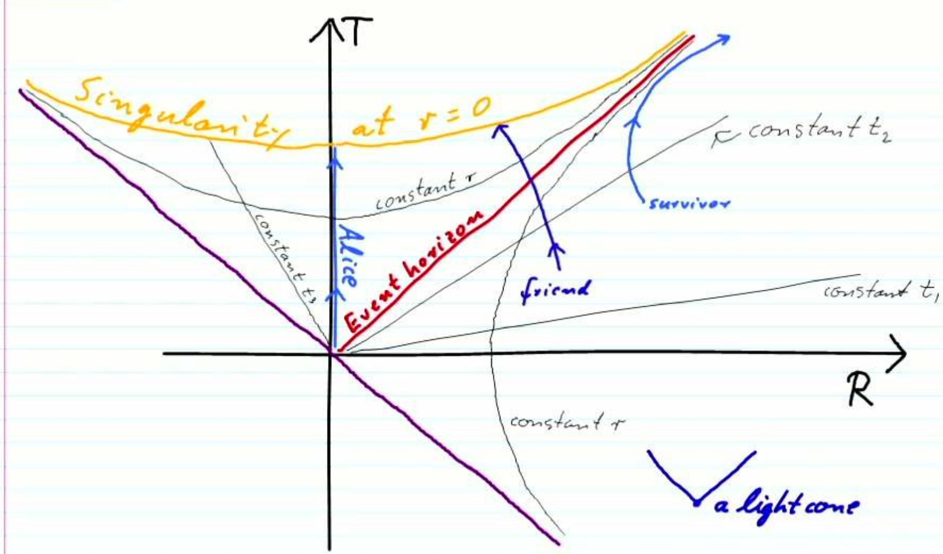
Obeys all conditions!



□ Alice was at rest at the event horizon.

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Alice's light cone coordinates:

$$u := T-R, \quad v := T+R$$

Metric: $$ds^2 = \underbrace{\frac{2M}{r(u,v)}\, e^{1-\frac{r(u,v)}{2M}}}_{\substack{\text{conformal factor}\\ \text{(which is 1 at horizon)}}}\ \underbrace{du\,dv}_{\substack{\text{light cone}\\ \text{Minkowski}}}$$

⇒ The action $S[\phi] = \frac{1}{2}\int g^{\alpha\beta}\phi_{,\alpha}\phi_{,\beta}\sqrt{g}\, d^2x$ becomes:

Bob's choice of coordinate system

Bob is far from the black hole.

He wants a cds in which:

□ $g_{\mu\nu}(x) \to \eta_{\mu\nu}$ as $r\to\infty$.

□ $g_{\mu\nu}(x) = f(x)\,\eta_{\mu\nu}$ everywhere.

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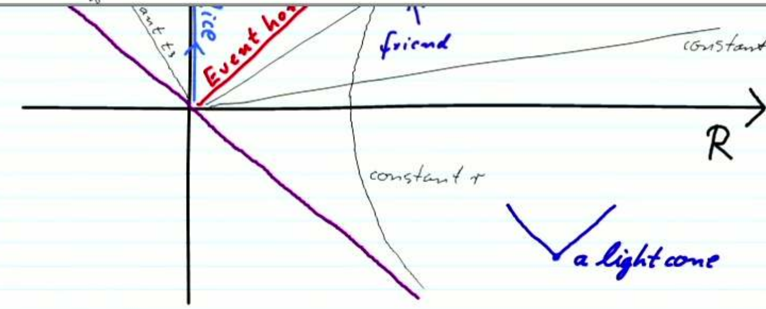
$K(t,r) := 4M\left|\frac{r}{2M}-1\right| e^{\frac{r}{4M}} \left(\cosh\left(\frac{t}{4M}\right)\theta(r-2M)+\sinh\left(\frac{t}{4M}\right)\theta(2M-r)\right)$

This map is, in principle, invertible, to obtain $t(T,R)$, $r(T,R)$.

The Schwarzschild metric now takes this form:

$$ds^2 = \underbrace{\frac{2M}{r(T,R)}\, e^{1-\frac{r(T,R)}{2M}}}_{\text{Conformal prefactor } =1 \text{ as } r\to 2M} \underbrace{\left(dT^2 - dR^2\right)}_{\eta_{\mu\nu}}$$

Obeys all conditions!



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$\Rightarrow$ The action $S[\phi] = \frac{1}{2}\int g^{\alpha\beta}\phi_{,\alpha}\phi_{,\beta}\sqrt{g}\, d^2x$ becomes:

$$= \frac{1}{2}\int_{T>-R} \left(\partial_T\phi(T,R)\right)^2 - \left(\partial_R\phi(T,R)\right)^2 dT\, dR$$

$$= 2\int_{-\infty}^{\infty}\int_{0}^{\infty} \left(\partial_u\phi(u,v)\right)\left(\partial_v\phi(u,v)\right) dv\, du$$

$\leftarrow$ b/c region $T>-R$ means $T+R>0$, i.e. $v>0$.

$\Rightarrow$ Eqn of motion: $\partial_u\partial_v\phi(u,v) = 0$

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Bob is far from the black hole.

He wants a cds in which:

- $g_{\mu\nu}(x) \to \eta_{\mu\nu}$ as $r\to\infty$.
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This is so that in his cds too

- photons travel at $45°$
- equations of motion of matter fields will be simple (useful in QFT!)

$\rightsquigarrow$ Bob's choice is the Tortoise coordinate system.

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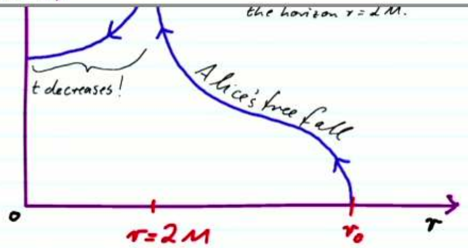

$t(\alpha) = \left(\frac{r_0}{2} + 2 \ldots\right.$

$+2M \log\left|\frac{w+\tan(\alpha/2)}{w-\tan(\alpha/2)}\right|$

$\tau(\alpha) = \frac{r_0}{2}\left(\frac{r_0}{2M}\right)^{1/2}(\alpha + \sin(\alpha))$

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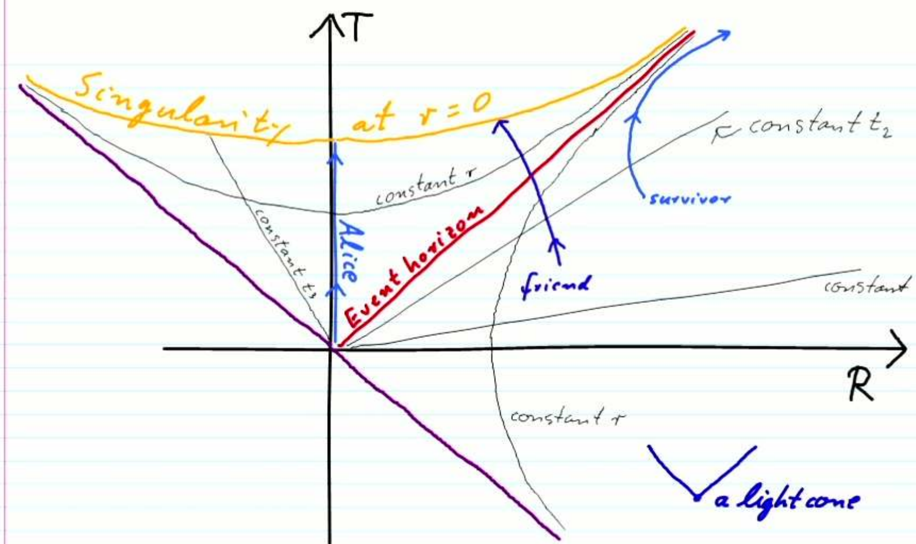

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Alice's light cone coordinates:

Bob's choice of coordinate system

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(which is 1 at horizon)

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$\rightsquigarrow$ Bob's choice is the Tortoise coordinate system.

Tortoise cds (t^*, r^*):

- In terms of the Schwarzschild cds:

$$t^* := t$$

$$r^* := r - 2M + 2M \log\left(\overbrace{\frac{r}{2M} - 1}^{\text{must require } r>2M\,!}\right)$$

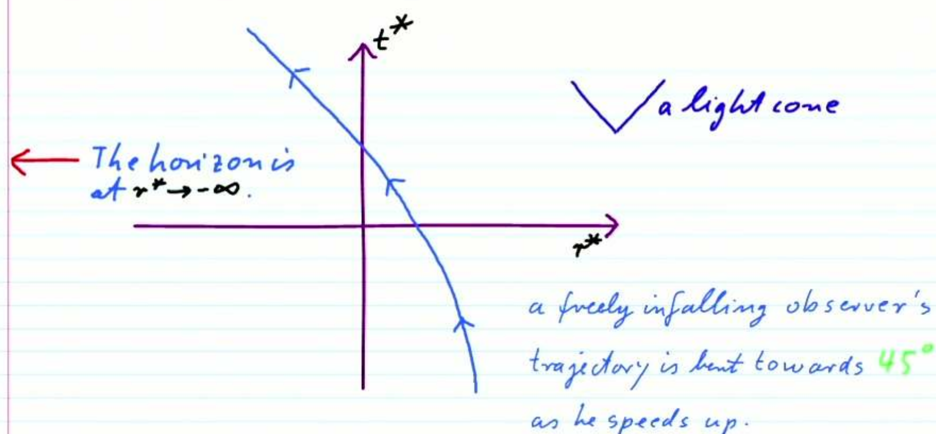
$\Rightarrow$ Important: This is in principle invertible, to obtain

$r = r(r^*)$

but only for $r > 2M$!

$\Rightarrow$ The tortoise cds only cover the BH's outside!

Metric: $$ds^2 = \underbrace{\left(1 - \frac{2M}{r(r^*)}\right)}_{\text{Conformal factor} \to 1 \text{ as } r\to\infty, \text{ as planned but } \to 0 \text{ at horizon.}} \left(dt^{*2} - dr^{*2}\right)$$



Bob's light cone coordinates: $\bar{u} := t^* - r^*$, $\bar{v} := t^* + r^*$

The metric is then: $$ds^2 = \underbrace{\left(1 - \frac{2M}{r(\bar{u},\bar{v})}\right)}_{\to 1 \text{ as } r\to\infty \text{ and } \to 0 \text{ as } r\to 2M} d\bar{u}\, d\bar{v}$$

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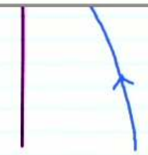
Metric: $$ds^2 = \underbrace{\left(1 - \frac{2M}{r(r^*)}\right)}\left(dt^{*2} - dr^{*2}\right)$$

Conformal factor $\to 1$ as $r \to \infty$, as planned but $\to 0$ at horizon.



a freely infalling observer's trajectory is bent towards 45° as he speeds up.

Bob's light cone coordinates: $\bar{u} := t^* - r^*$, $\quad \bar{v} := t^* + r^*$

The metric is then: $$ds^2 = \underbrace{\left(1 - \frac{2M}{r(\bar{u},\bar{v})}\right)}_{\to 1 \text{ as } r\to\infty \text{ and } \to 0 \text{ as } r \to 2M} d\bar{u}\, d\bar{v}$$

$\Rightarrow$ The action:

$$S[\phi] = \frac{1}{2}\int g^{\alpha\beta}\,\phi_{,\alpha}\,\phi_{,\beta}\sqrt{g}\, d^2x \quad \text{becomes:}$$

$$= \frac{1}{2}\int_{\mathbb{R}^2}\left(\partial_{t^*}\phi(t^*,r^*)\right)^2 - \left(\partial_{r^*}\phi(t^*,r^*)\right)^2 dt^* dr^*$$

$$= 2\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(\partial_{\bar{u}}\phi(\bar{u},\bar{v})\right)\left(\partial_{\bar{v}}\phi(\bar{u},\bar{v})\right) d\bar{v}\, d\bar{u}$$

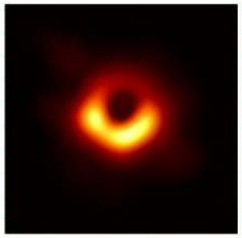
$\Rightarrow$ Eqn of motion: $\partial_{\bar{u}}\partial_{\bar{v}}\phi(\bar{u},\bar{v}) = 0$

Do real black holes possess a singularity?

Sagittarius A^*

- 4 Mio stellar masses
- Diameter 44 Mio km
- 26000 light years away at centre of Milky Way.

$\to$ Observation of M87 by the Event Horizon Telescope (in mm band) with enough resolution to see the event horizon:



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$$= \frac{1}{2}\int_{\mathbb{R}^2} \left(\partial_t \phi(t,r)\right)^2 - \left(\partial_r \phi(t,r)\right)^2$$

$$= 2\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left(\partial_{\bar{u}} \phi(\bar{u},\bar{v})\right)\left(\partial_{\bar{v}} \phi(\bar{u},\bar{v})\right) d\bar{v}\, d\bar{u}$$

$\Rightarrow$ Eqn of motion: $\partial_{\bar{u}}\partial_{\bar{v}} \phi(\bar{u},\bar{v}) = 0$

...ameter ... km

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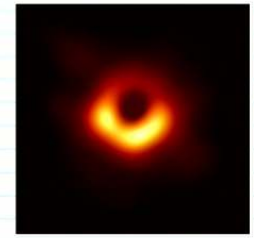


How to model properties of real black holes roughly?

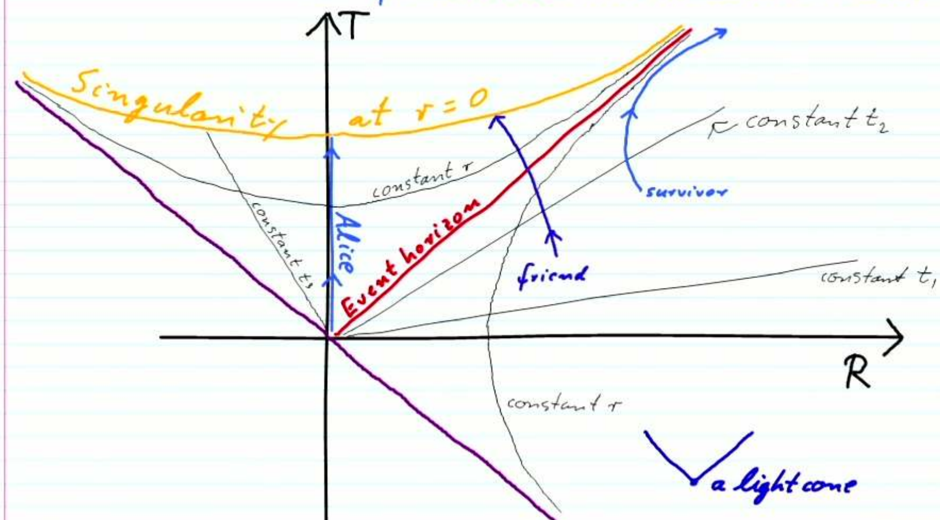
Singularity theorems suitable for black holes involve the concept and assumption of a trapped surface:

Def:

- Let Σ be a spacelike hypersurface. (Note: Σ is 3-dimensional)
- Let $T \subset \Sigma$ be a compact, 2-dimensional smooth spacelike submanifold of Σ. Consider the ingoing and the outgoing future-directed null geodesics that are orthogonal to T.
- If all these geodesics possess negative expansion, $\theta < 0$, then T is called a trapped surface.

Examples of trapped surfaces:

All spheres $r = $ const. inside a Schwarzschild black hole.



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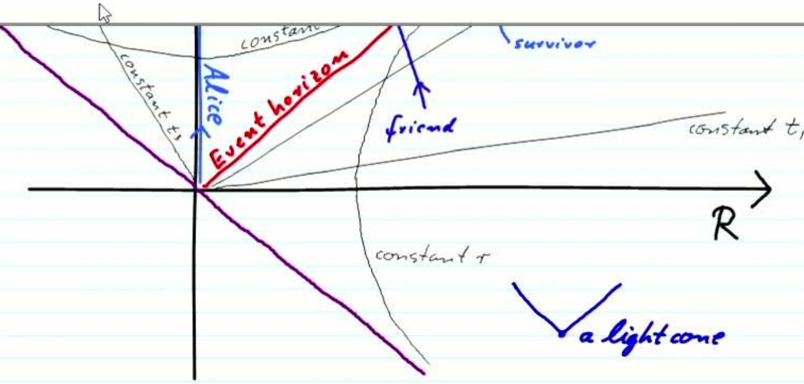
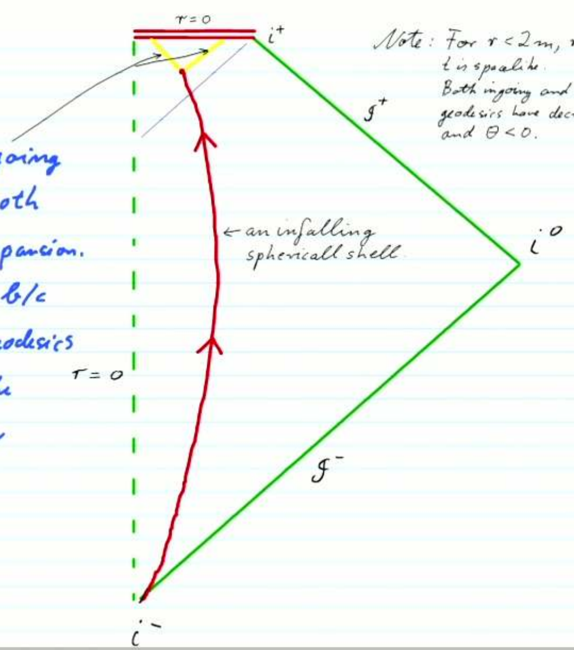
- Let Σ be a spacelike hypersurface. (Note: Σ is 3-dimensional)
- Let $T \subset \Sigma$ be a compact, 2-dimensional smooth spacelike submanifold of Σ. Consider the ingoing and the outgoing future-directed null geodesics that are orthogonal to T.
- If all these geodesics possess negative expansion, $\theta < 0$, then T is called a **trapped surface**.



Generally:

The in- and outgoing null geodesics both have negative expansion. Can't see it here b/c the neighboring geodesics are neighbors in the suppressed angular directions.



Note: For $r < 2m$, r is timelike and t is spacelike.
Both ingoing and outgoing null geodesics have decreasing r, and $\theta < 0$.

Def: Let Σ be a spacelike hypersurface.

Then, the (3-dim. spacelike) union, $\mathfrak{T}$, of all trapped surfaces $T \subset \Sigma$ is called the **trapped region** of Σ.

Def: The boundary $\partial\mathfrak{T} \subset \Sigma$ is called the **apparent horizon** of the spacelike hypersurface Σ.

Note: $\partial\mathfrak{T}$ is 2-dimensional.

Def: If we foliate spacetime into spacelike hypersurfaces

$$\Sigma_\alpha, \ \alpha \in I \subset \mathbb{R}$$

each with its apparent horizon, $\mathfrak{T}_\alpha$, then their union

$$\mathcal{A} := \bigcup_\alpha \mathfrak{T}_\alpha$$

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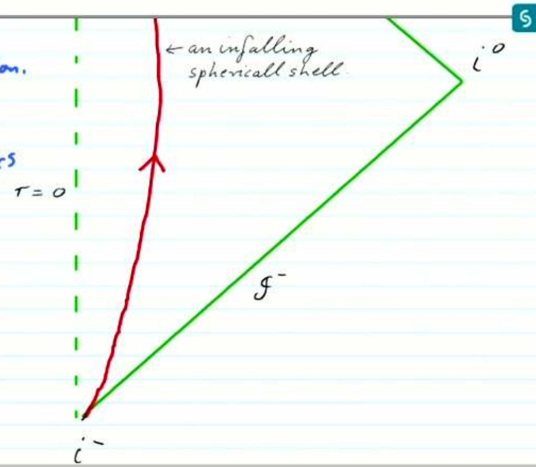

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Remarks:

- To check for the existence of an event horizon
  $$\mathscr{J}^- \text{ (worldline to } i^+)$$
  in principle requires knowledge of the full future.

- But one can check for the existence of an apparent horizon in any spacelike hypersurface by calculating the expansions only at that time!

- The notion of apparent horizons is dependent on the the choice of foliation of spacetime into spacelike hypersurfaces.

- For static Schwarzschild black holes the event and apparent horizons coincide.

- Singularity theorems for black holes make assumptions of apparent horizons.

Comment:

Hawking radiation is usually thought to emanate from the apparent horizon.

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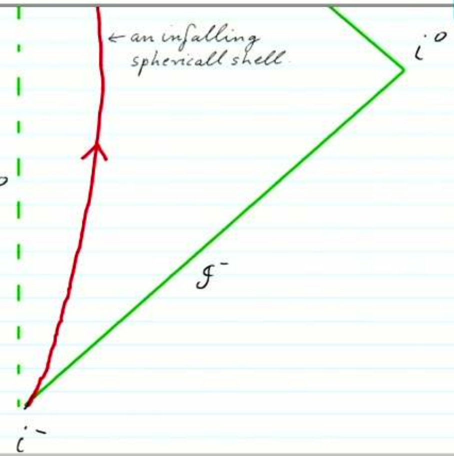

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