...Relatividade Geral!

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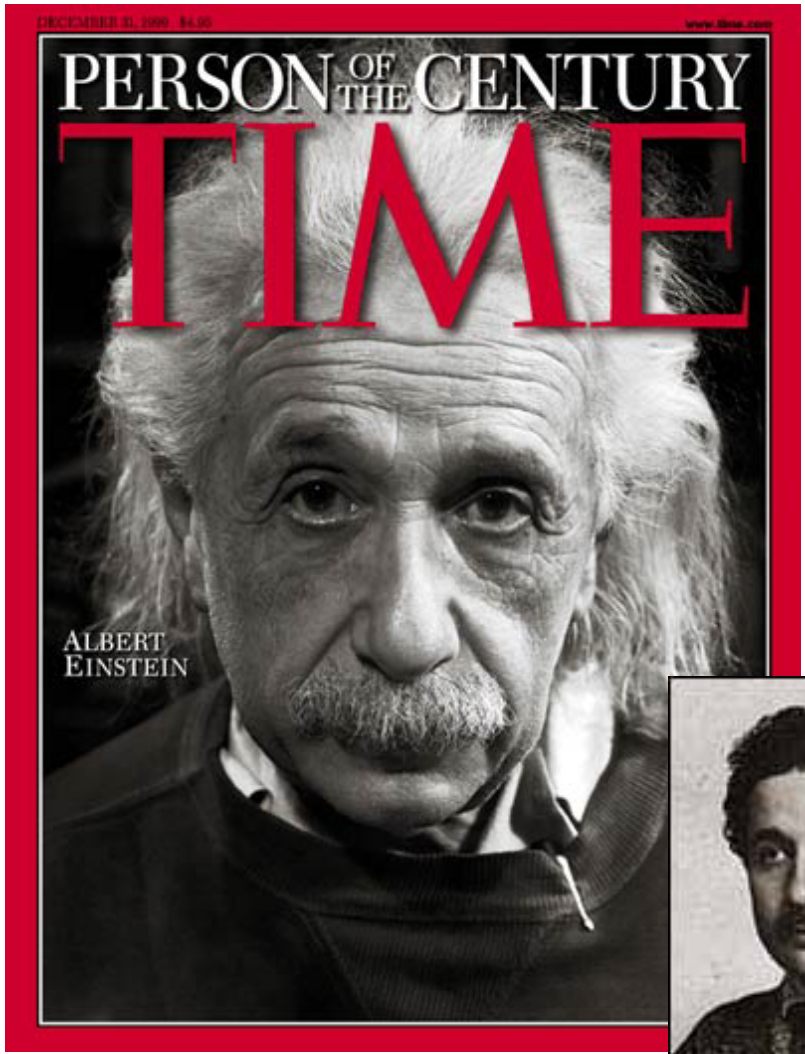
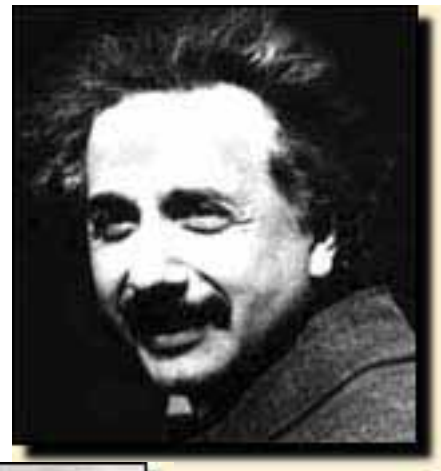
Mecª&Ondas,LE(E+GI),2ºSemestre 2005/2006, IST@Tagus

Albert Einstein

Ulm [, Alemanha]
14 de Março, 1879

18 de Abril, 1955
Princeton, NJ, USA





World Year of PHYSICS 2005

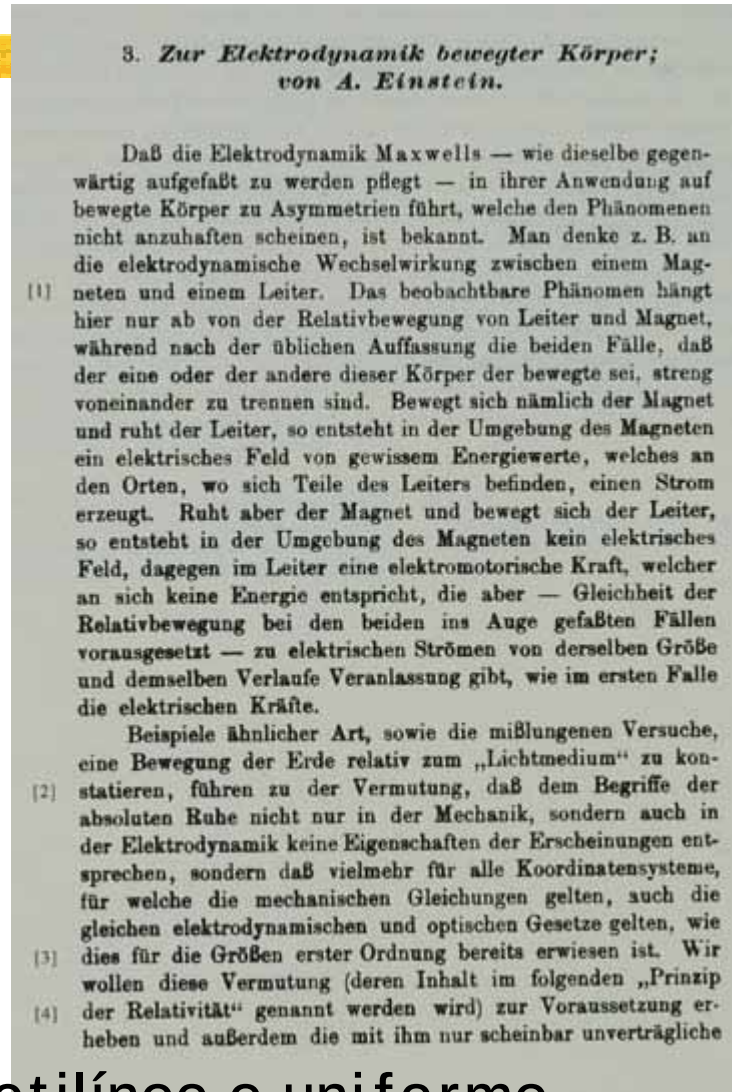
1905 - O ano milagroso de Einstein

- Efeito fotoeléctrico
  →*Mecânica Quântica*
- Explicação do movimento Browniano
  → átomos e moléculas!
- Teoria da Relatividade
  →*novo espaço-tempo*

  Restrita (1905) ⇒

  Referenciais em movimento rectilíneo e uniforme

  Equivalência Massa-Energia: $E=mc^2$



3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt [1] hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche, eine Bewegung der Erde relativ zum „Lichtmedium" zu kon- [2] statieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie [3] dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip [4] der Relativität" genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche

Princípio da Relatividade

Não se pode realizar nenhuma experiência, de qualquer natureza, que nos permita distinguir se um referencial (em **movimento rectilíneo e uniforme**) está ou não em movimento!

Não existem referenciais absolutos!

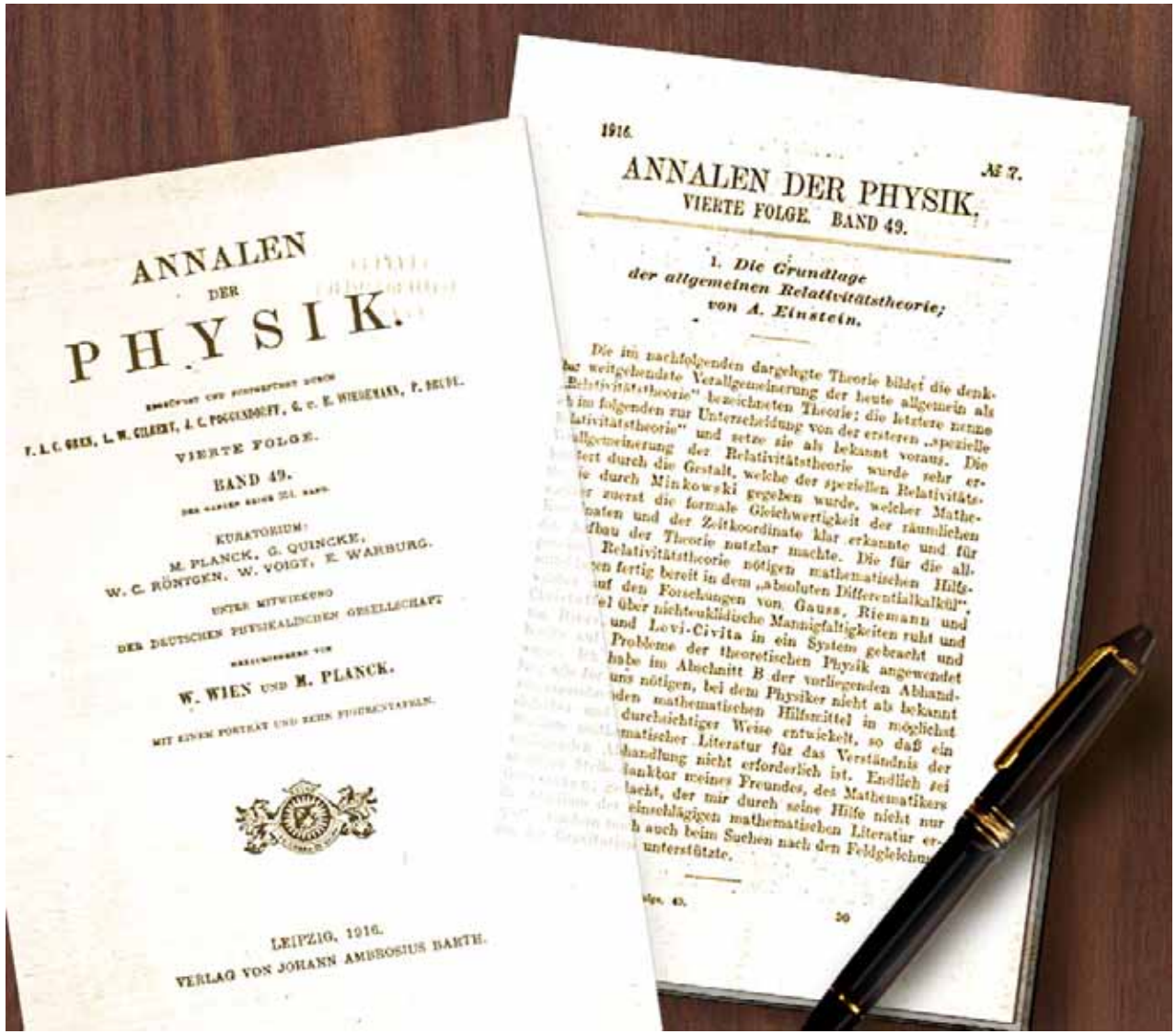
TUDO É RELATIVO !

Relatividade Geral:

E para referenciais acelerados ?!

Artigo

1916



Princípio de Equivalência:

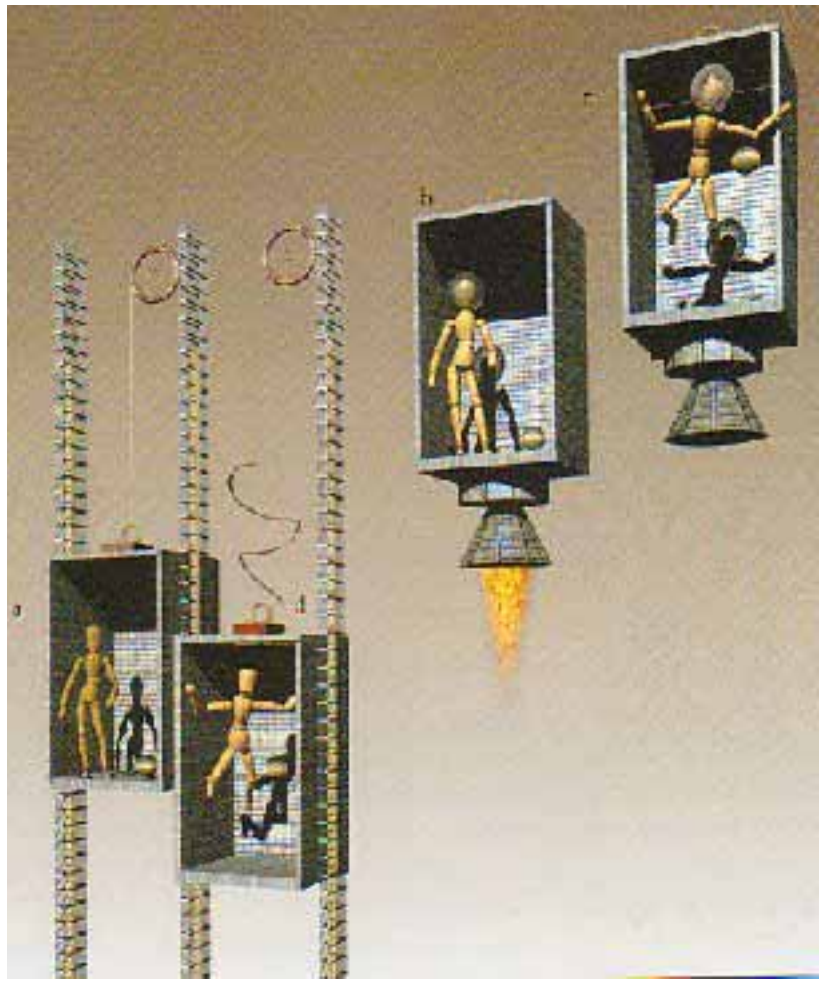
Relatividade Geral

Não se pode realizar nenhuma experiência, de qualquer natureza, que nos permita distinguir um referencial acelerado e um referencial sujeito à gravidade!

Então e se ligar uma

...**lanterna** ?!

$$m_g = m_I = m$$

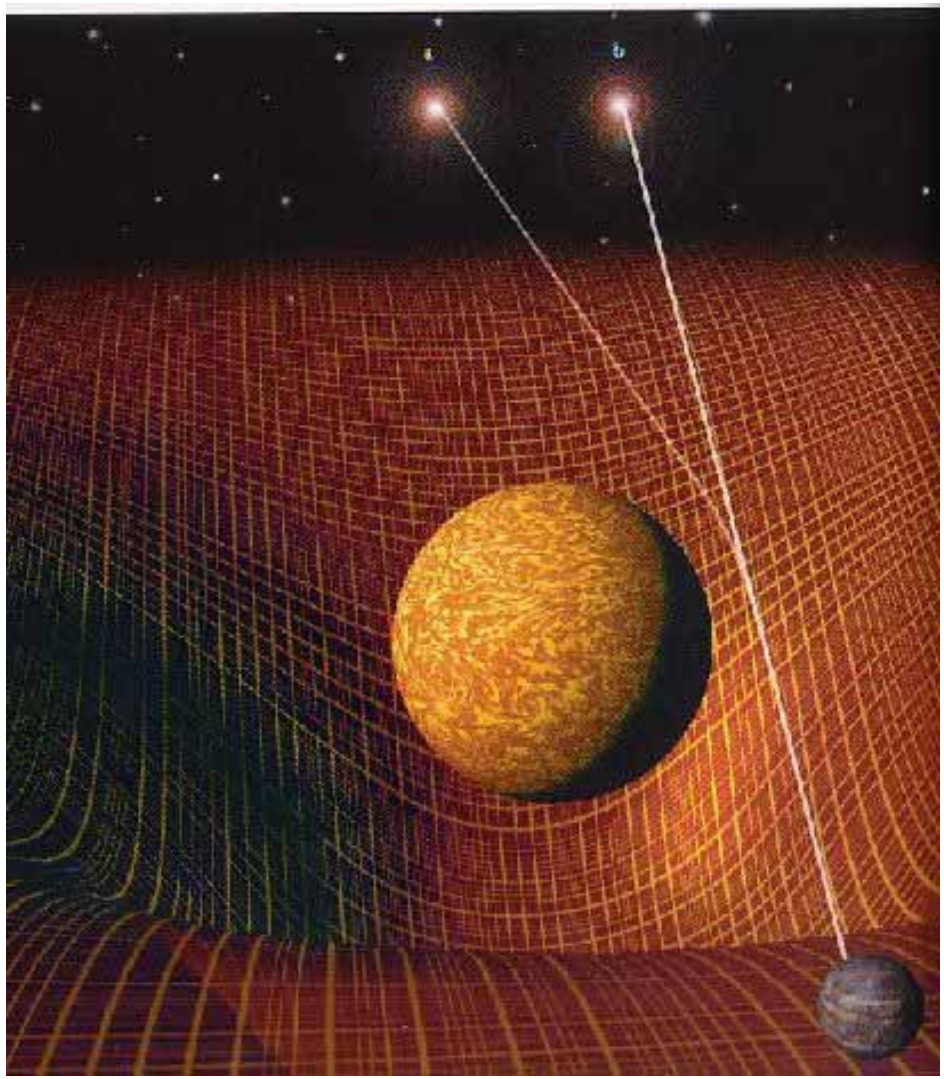


R.G. : Luz é atraída pela gravidade!

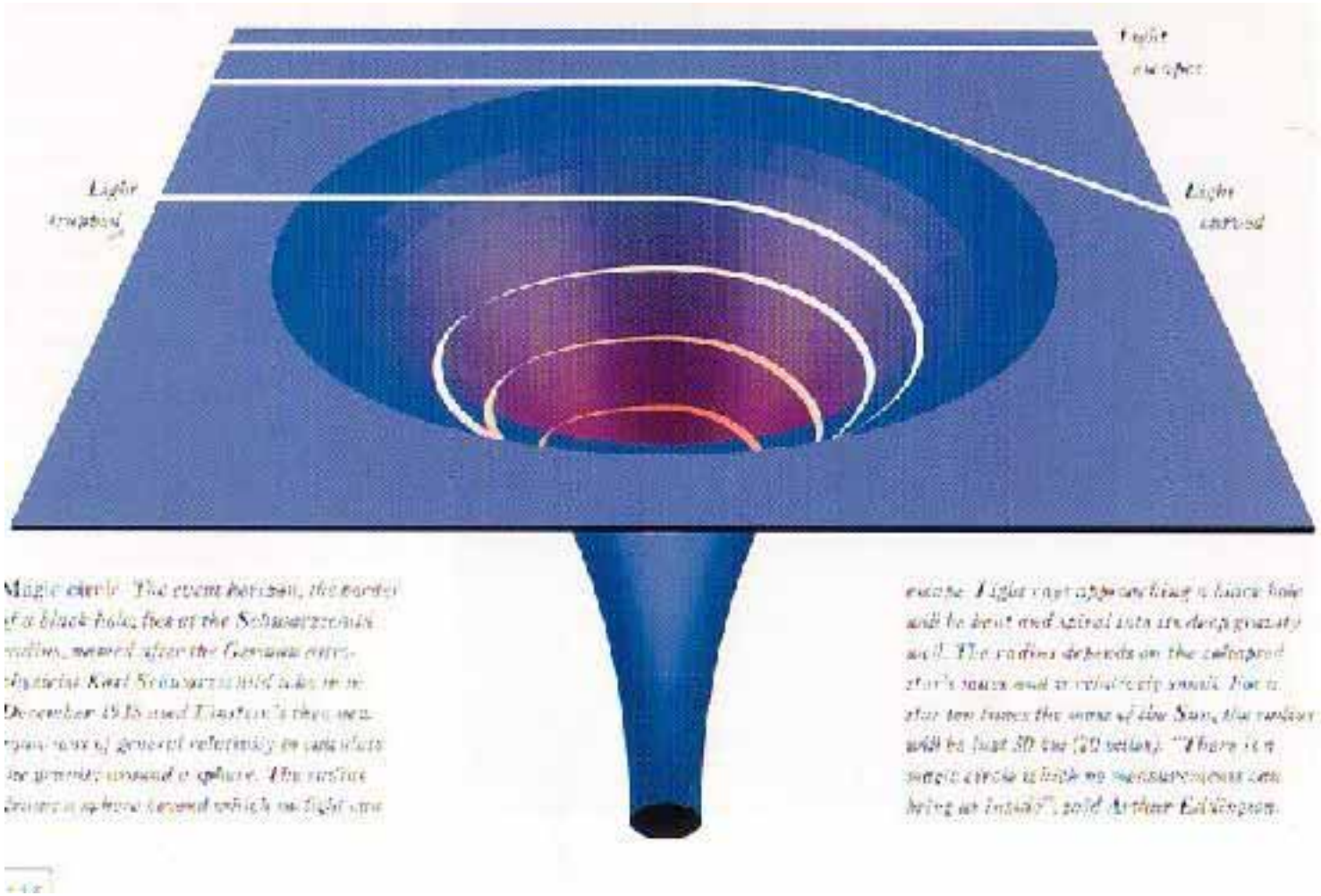
Medições da MESMA estrela, separadas de 6 meses, e uma das medições efectuadas num eclipse solar total

(Ilha do Príncipe, Sir Arthur Eddington)

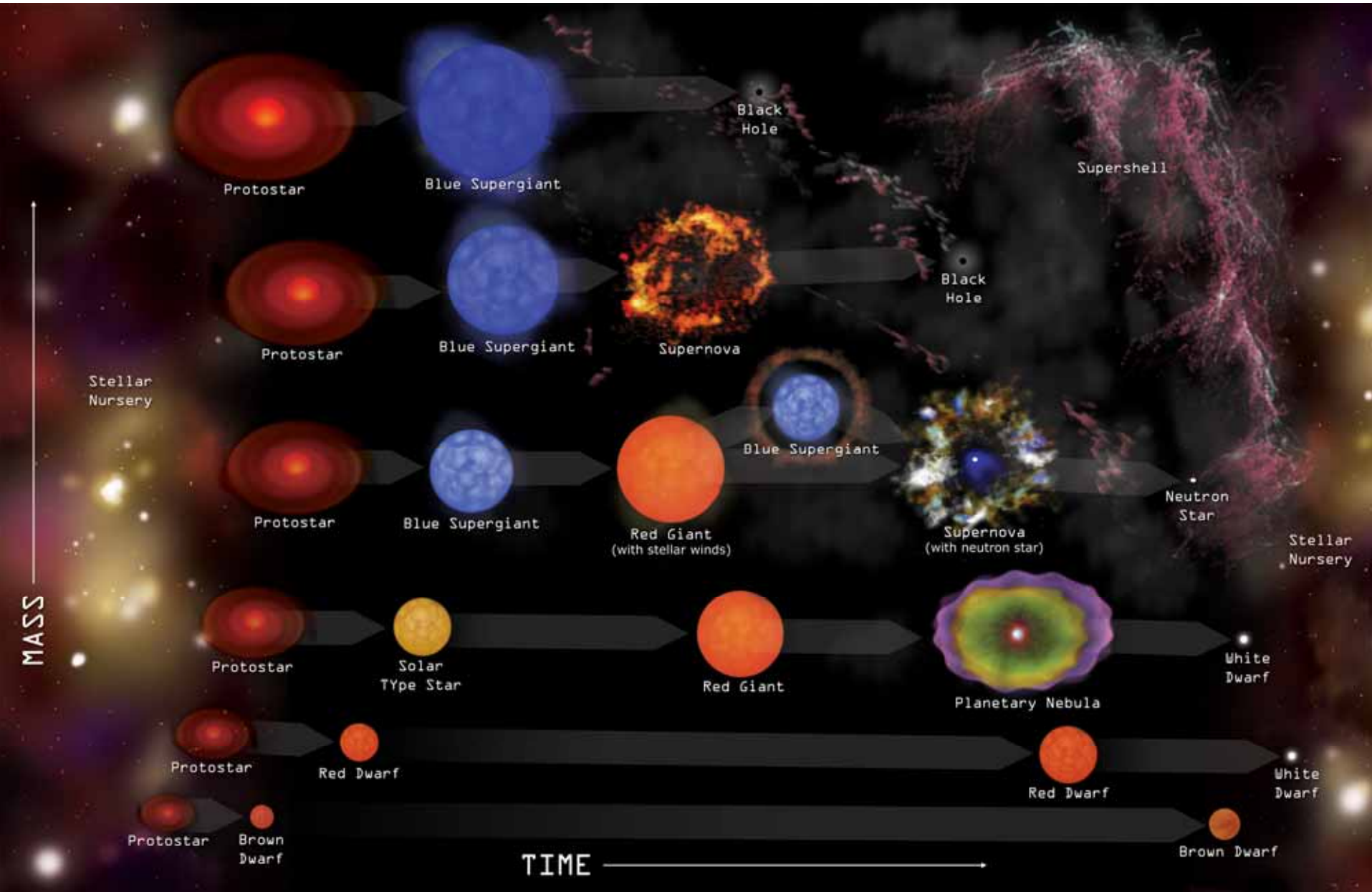
$$G\mu\nu = 8\pi T\mu\nu$$



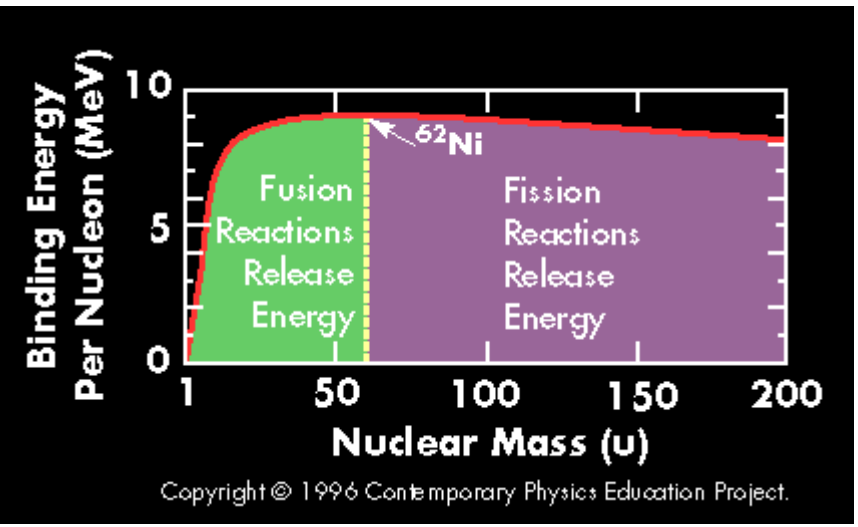
Caso limite: Buraco Negro!

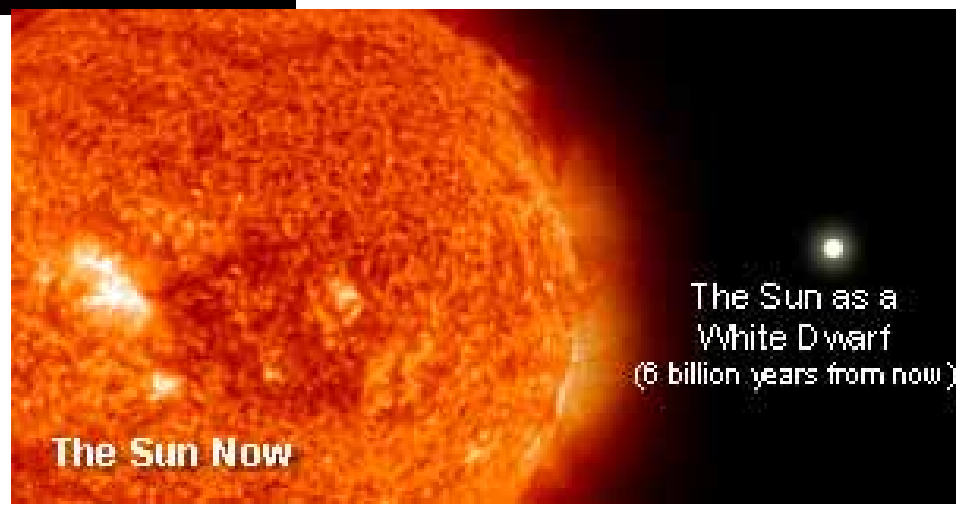


A vida de uma estrela (função(massa) !)



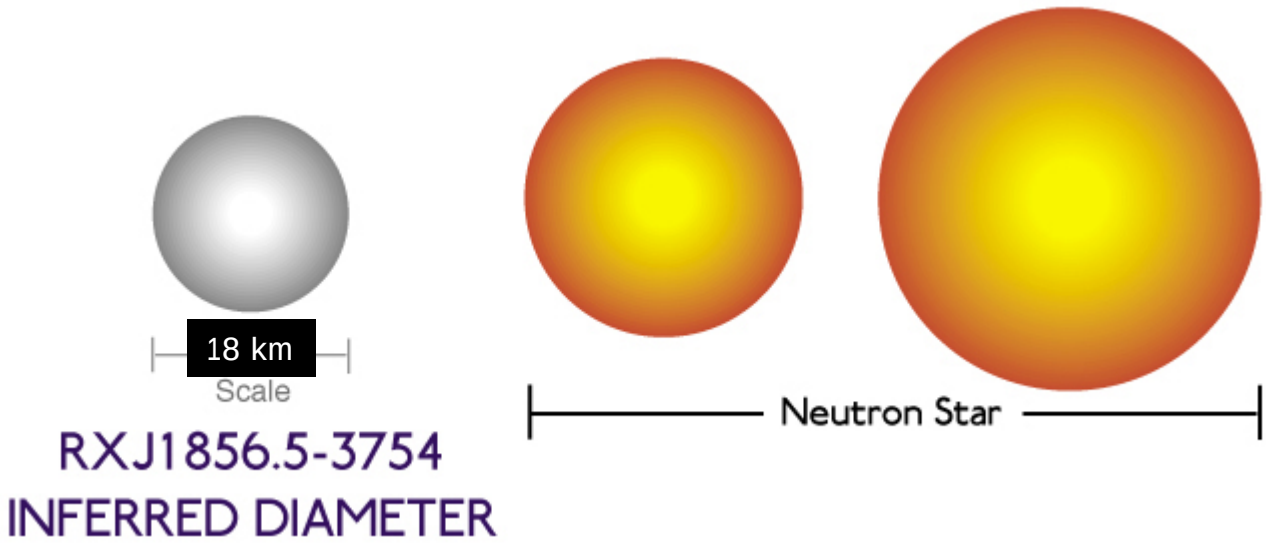
A estrela típica (Sol)



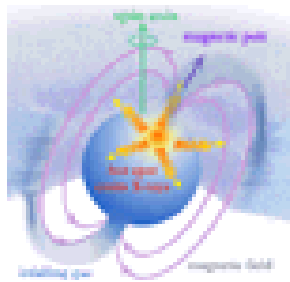


Uma estrela gordinha (>1.4 $M_\odot$)

Torna-se uma
ESTRELA DE NEUTRÕES...



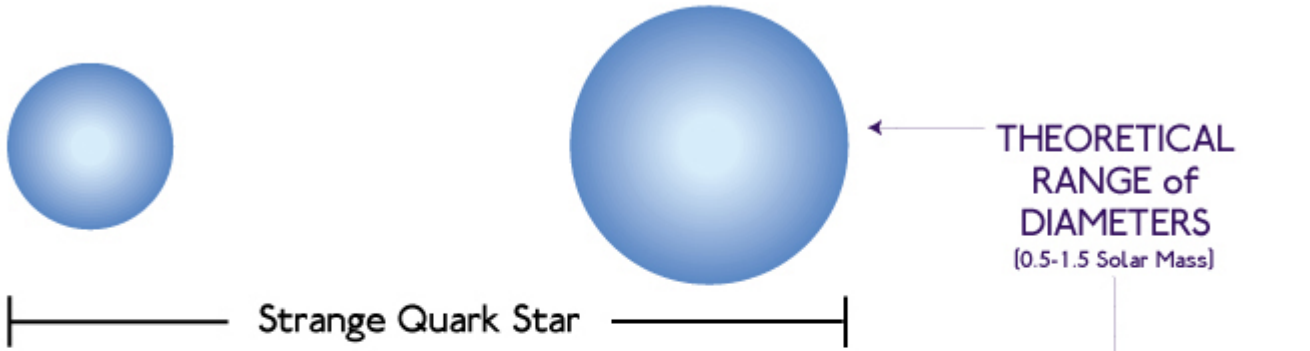
...Um pulsar !...

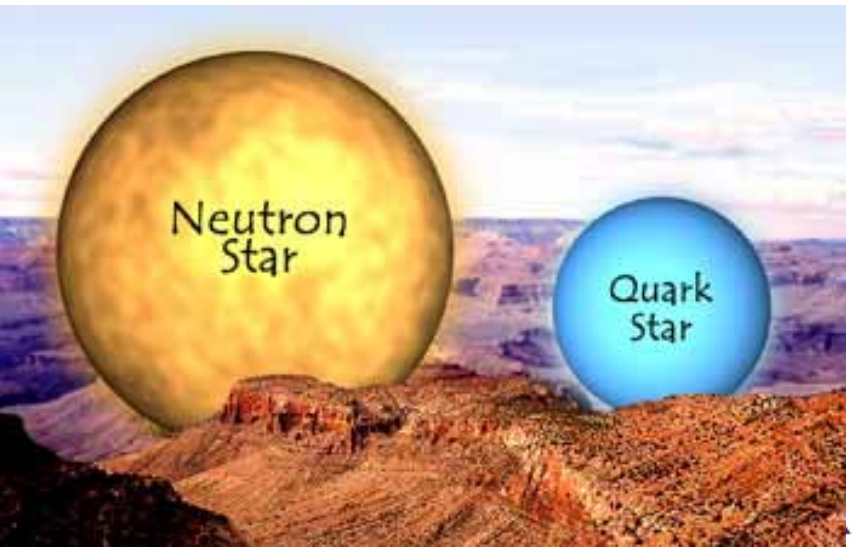


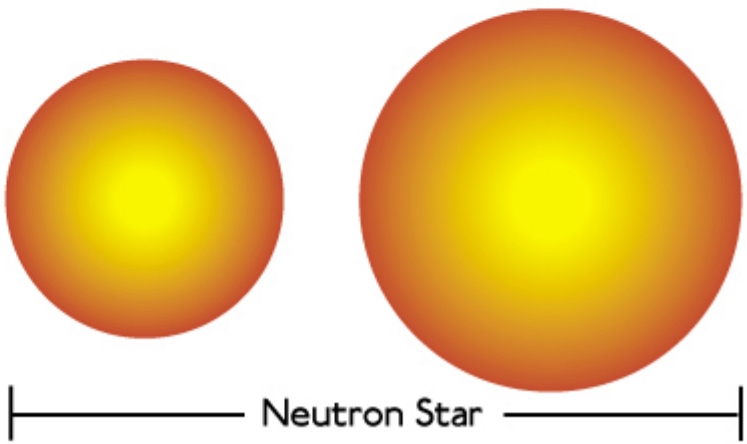
(animado)

ou algo mais...

RXJ 1856.5-3754







Uma estrela bem gorda (>3$M_{\odot}$)

...torna-se um buraco negro!

...nem a luz escapa!

Detecção indirecta de B.Negros

Equações da Relatividade Geral (1):

$$R_{\eta\eta} = -\frac{2a^2\frac{\partial\psi}{\partial\delta}\cot\theta}{\delta\psi} + \frac{2ac\frac{\partial\psi}{\partial\eta}\cot\theta}{\delta\psi} + \frac{a\frac{\partial c}{\partial\eta}\cot\theta}{\delta} - \frac{\frac{\partial a}{\partial\eta}c\cot\theta}{2\delta} - \frac{a\frac{\partial a}{\partial\delta}\cot\theta}{2\delta} - \frac{2a^2\frac{\partial^2\psi}{\partial\theta^2}}{\delta\psi}$$

$$- \frac{2a^2\left(\frac{\partial\psi}{\partial\delta}\right)^2}{\delta\psi^2} + \frac{4ac\frac{\partial\psi}{\partial\eta}\frac{\partial\psi}{\partial\delta}}{\delta\psi^2} - \frac{a^2\frac{\partial d}{\partial\delta}\frac{\partial\psi}{\partial\delta}}{\delta d\psi} + \frac{ac\frac{\partial d}{\partial\eta}\frac{\partial\psi}{\partial\delta}}{\delta d\psi} + \frac{2a\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\delta}}{\delta\psi} - \frac{\frac{\partial a}{\partial\eta}c\frac{\partial\psi}{\partial\delta}}{\delta\psi}$$

$$- \frac{3a\frac{\partial a}{\partial\delta}\frac{\partial\psi}{\partial\delta}}{\delta\psi} - \frac{2a^2c\frac{\partial c}{\partial\delta}\frac{\partial\psi}{\partial\delta}}{\delta^2\psi} + \frac{2a^2b\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\delta}}{\delta^2\psi} - \frac{a^2\frac{\partial b}{\partial\eta}c\frac{\partial\psi}{\partial\delta}}{\delta^2\psi} - \frac{a\frac{\partial a}{\partial\eta}bc\frac{\partial\psi}{\partial\delta}}{\delta^2\psi} + \frac{a^3\frac{\partial b}{\partial\delta}\frac{\partial\psi}{\partial\delta}}{\delta^2\psi}$$

$$+ \frac{a^2\frac{\partial a}{\partial\delta}b\frac{\partial\psi}{\partial\delta}}{\delta^2\psi} - \frac{2ab\frac{\partial^2\psi}{\partial\eta^2}}{\delta\psi} - \frac{2\frac{\partial^2\psi}{\partial\eta^2}}{\psi} + \frac{4ac\frac{\partial^2\psi}{\partial\eta\partial\theta}}{\delta\psi} - \frac{2ab\left(\frac{\partial\psi}{\partial\eta}\right)^2}{\delta\psi^2} + \frac{6\left(\frac{\partial\psi}{\partial\eta}\right)^2}{\psi^2}$$

$$+ \frac{ac\frac{\partial d}{\partial\delta}\frac{\partial\psi}{\partial\eta}}{\delta d\psi} - \frac{ab\frac{\partial d}{\partial\eta}\frac{\partial c}{\partial\eta}}{\delta d\psi} - \frac{2c\frac{\partial c}{\partial\eta}\frac{\partial c}{\partial\eta}}{\delta\psi} + \frac{\frac{\partial a}{\partial\delta}c\frac{\partial\psi}{\partial\eta}}{\delta\psi} - \frac{2a\frac{\partial b}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta\psi} + \frac{\frac{\partial a}{\partial\eta}b\frac{\partial\psi}{\partial\eta}}{\delta\psi}$$

$$+ \frac{2a^2b\frac{\partial c}{\partial\delta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} - \frac{2abc\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} - \frac{a^2\frac{\partial b}{\partial\delta}c\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} - \frac{a\frac{\partial a}{\partial\delta}bc\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} + \frac{a^2b\frac{\partial b}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} + \frac{a\frac{\partial a}{\partial\eta}b^2\frac{\partial\psi}{\partial\eta}}{\delta^2\psi}$$

$$+ \frac{a\frac{\partial c}{\partial\eta}\frac{\partial d}{\partial\delta}}{2\delta d} - \frac{\frac{\partial a}{\partial\eta}c\frac{\partial d}{\partial\delta}}{4\delta d} - \frac{a\frac{\partial a}{\partial\delta}\frac{\partial d}{\partial\delta}}{4\delta d} - \frac{\frac{\partial^2 d}{\partial\eta^2}}{2d} + \frac{\left(\frac{\partial d}{\partial\eta}\right)^2}{4d^2} - \frac{c\frac{\partial c}{\partial\eta}\frac{\partial d}{\partial\eta}}{2\delta d}$$

$$+ \frac{\frac{\partial a}{\partial\delta}c\frac{\partial d}{\partial\eta}}{4\delta d} + \frac{\frac{\partial a}{\partial\eta}b\frac{\partial d}{\partial\eta}}{4\delta d} + \frac{a\frac{\partial^2 c}{\partial\eta\partial\theta}}{\delta} - \frac{a\frac{\partial^2 b}{\partial\eta^2}}{2\delta} - \frac{a\frac{\partial^2 a}{\partial\theta^2}}{2\delta} + \frac{ac\frac{\partial c}{\partial\eta}\frac{\partial c}{\partial\delta}}{\delta^2}$$

Equações da Relatividade Geral (2):

$$
\begin{aligned}
&- \frac{a \frac{\partial a}{\partial \theta} c \frac{\partial c}{\partial \theta}}{2\delta^2} - \frac{a \frac{\partial a}{\partial \eta} b \frac{\partial c}{\partial \theta}}{2\delta^2} - \frac{a \frac{\partial b}{\partial \eta} c \frac{\partial c}{\partial \eta}}{2\delta^2} - \frac{a^2 \frac{\partial b}{\partial \theta} \frac{\partial c}{\partial \eta}}{2\delta^2} + \frac{a \frac{\partial a}{\partial \eta} \frac{\partial b}{\partial \theta} c}{4\delta^2} - \frac{a \frac{\partial a}{\partial \theta} \frac{\partial b}{\partial \eta} c}{4\delta^2} \\
&+ \frac{a^2 \frac{\partial a}{\partial \theta} \frac{\partial b}{\partial \theta}}{4\delta^2} + \frac{a^2 \left(\frac{\partial b}{\partial \eta}\right)^2}{4\delta^2} + \frac{a \frac{\partial a}{\partial \eta} b \frac{\partial b}{\partial \eta}}{4\delta^2} + \frac{a \left(\frac{\partial a}{\partial \theta}\right)^2 b}{4\delta^2}
\end{aligned}
$$

$$
\begin{aligned}
R_{\eta\theta} = &- \frac{2ac \frac{\partial \psi}{\partial \theta} \cot\theta}{\delta\psi} + \frac{2ab \frac{\partial \psi}{\partial \eta} \cot\theta}{\delta\psi} - \frac{2 \frac{\partial \psi}{\partial \eta} \cot\theta}{\psi} - \frac{\frac{\partial d}{\partial \eta} \cot\theta}{2d} - \frac{\frac{\partial a}{\partial \theta} c \cot\theta}{2\delta} + \frac{a \frac{\partial b}{\partial \eta} \cot\theta}{2\delta} \\
&- \frac{2ac \frac{\partial^2 \psi}{\partial \theta^2}}{\delta\psi} - \frac{2ac \left(\frac{\partial \psi}{\partial \theta}\right)^2}{\delta\psi^2} + \frac{4ab \frac{\partial \psi}{\partial \eta} \frac{\partial \psi}{\partial \theta}}{\delta\psi^2} + \frac{2 \frac{\partial \psi}{\partial \eta} \frac{\partial \psi}{\partial \theta}}{\psi^2} - \frac{ac \frac{\partial d}{\partial \theta} \frac{\partial \psi}{\partial \theta}}{\delta d\psi} + \frac{ab \frac{\partial d}{\partial \eta} \frac{\partial \psi}{\partial \theta}}{\delta d\psi} \\
&- \frac{\frac{\partial d}{\partial \eta} \frac{\partial \psi}{\partial \theta}}{d\psi} + \frac{2a \frac{\partial c}{\partial \theta} \frac{\partial \psi}{\partial \theta}}{\delta\psi} - \frac{3 \frac{\partial a}{\partial \theta} c \frac{\partial \psi}{\partial \theta}}{\delta\psi} + \frac{2a \frac{\partial b}{\partial \eta} \frac{\partial \psi}{\partial \theta}}{\delta\psi} + \frac{\frac{\partial a}{\partial \eta} b \frac{\partial \psi}{\partial \theta}}{\delta\psi} - \frac{2a^2 b \frac{\partial c}{\partial \theta} \frac{\partial \psi}{\partial \theta}}{\delta^2\psi} \\
&+ \frac{2abc \frac{\partial c}{\partial \eta} \frac{\partial \psi}{\partial \theta}}{\delta^2\psi} + \frac{a^2 \frac{\partial b}{\partial \theta} c \frac{\partial \psi}{\partial \theta}}{\delta^2\psi} + \frac{a \frac{\partial a}{\partial \theta} bc \frac{\partial \psi}{\partial \theta}}{\delta^2\psi} - \frac{a^2 b \frac{\partial a}{\partial \eta} \frac{\partial \psi}{\partial \theta}}{\delta^2\psi} - \frac{a \frac{\partial a}{\partial \eta} b^2 \frac{\partial \psi}{\partial \theta}}{\delta^2\psi} - \frac{2bc \frac{\partial^2 \psi}{\partial \eta^2}}{\delta\psi} \\
&+ \frac{4ab \frac{\partial^2 \psi}{\partial \eta \partial \theta}}{\delta\psi} - \frac{6 \frac{\partial^2 \psi}{\partial \eta \partial \theta}}{\psi} - \frac{2bc \left(\frac{\partial \psi}{\partial \eta}\right)^2}{\delta\psi^2} + \frac{ab \frac{\partial d}{\partial \theta} \frac{\partial \psi}{\partial \eta}}{\delta d\psi} - \frac{\frac{\partial d}{\partial \theta} \frac{\partial \psi}{\partial \eta}}{d\psi} - \frac{bc \frac{\partial d}{\partial \eta} \frac{\partial \psi}{\partial \eta}}{\delta d\psi} \\
&+ \frac{2b \frac{\partial c}{\partial \eta} \frac{\partial \psi}{\partial \eta}}{\delta\psi} - \frac{3 \frac{\partial b}{\partial \eta} c \frac{\partial \psi}{\partial \eta}}{\delta\psi} + \frac{a \frac{\partial b}{\partial \theta} \frac{\partial \psi}{\partial \eta}}{\delta\psi} + \frac{2 \frac{\partial a}{\partial \theta} b \frac{\partial \psi}{\partial \eta}}{\delta\psi} + \frac{2ab c \frac{\partial c}{\partial \theta} \frac{\partial \psi}{\partial \eta}}{\delta^2\psi} - \frac{2ab^2 \frac{\partial c}{\partial \eta} \frac{\partial \psi}{\partial \eta}}{\delta^2\psi}
\end{aligned}
$$

Equações da Relatividade Geral (3):

$$+\frac{a\,b\,\frac{\partial b}{\partial \eta}\,c\,\frac{\partial \psi}{\partial \eta}}{\delta^2\,\psi}+\frac{\frac{\partial a}{\partial \eta}\,b^2\,c\,\frac{\partial c}{\partial \eta}}{\delta^2\,\psi}-\frac{a^2\,b\,\frac{\partial b}{\partial \theta}\,\frac{\partial \psi}{\partial \eta}}{\delta^2\,\psi}-\frac{a\,\frac{\partial a}{\partial \theta}\,b^2\,\frac{\partial \psi}{\partial \eta}}{\delta^2\,\psi}+\frac{\frac{\partial d}{\partial \eta}\,\frac{\partial d}{\partial \theta}}{4\,d^2}-\frac{\frac{\partial a}{\partial \theta}\,c\,\frac{\partial d}{\partial \theta}}{4\,\delta\,d}$$

$$+\frac{a\,\frac{\partial b}{\partial \eta}\,\frac{\partial d}{\partial \theta}}{4\,\delta\,d}-\frac{\frac{\partial^2 d}{\partial \eta\,\partial \theta}}{2\,d}-\frac{\frac{\partial b}{\partial \eta}\,c\,\frac{\partial d}{\partial \eta}}{4\,\delta\,d}+\frac{\frac{\partial a}{\partial \theta}\,b\,\frac{\partial d}{\partial \eta}}{4\,\delta\,d}-\frac{\frac{\partial c}{\partial \eta}\,\frac{\partial c}{\partial \theta}}{\delta}+\frac{\frac{\partial a}{\partial \theta}\,\frac{\partial c}{\partial \theta}}{2\,\delta}$$

$$+\frac{c\,\frac{\partial^2 c}{\partial \eta\,\partial \theta}}{\delta}+\frac{\frac{\partial b}{\partial \eta}\,\frac{\partial c}{\partial \eta}}{2\,\delta}-\frac{\frac{\partial^2 b}{\partial \eta^2}\,c}{2\,\delta}-\frac{\frac{\partial^2 a}{\partial \theta^2}\,c}{2\,\delta}-\frac{\frac{\partial a}{\partial \eta}\,\frac{\partial b}{\partial \theta}}{4\,\delta}+\frac{\frac{\partial a}{\partial \theta}\,\frac{\partial b}{\partial \eta}}{4\,\delta}$$

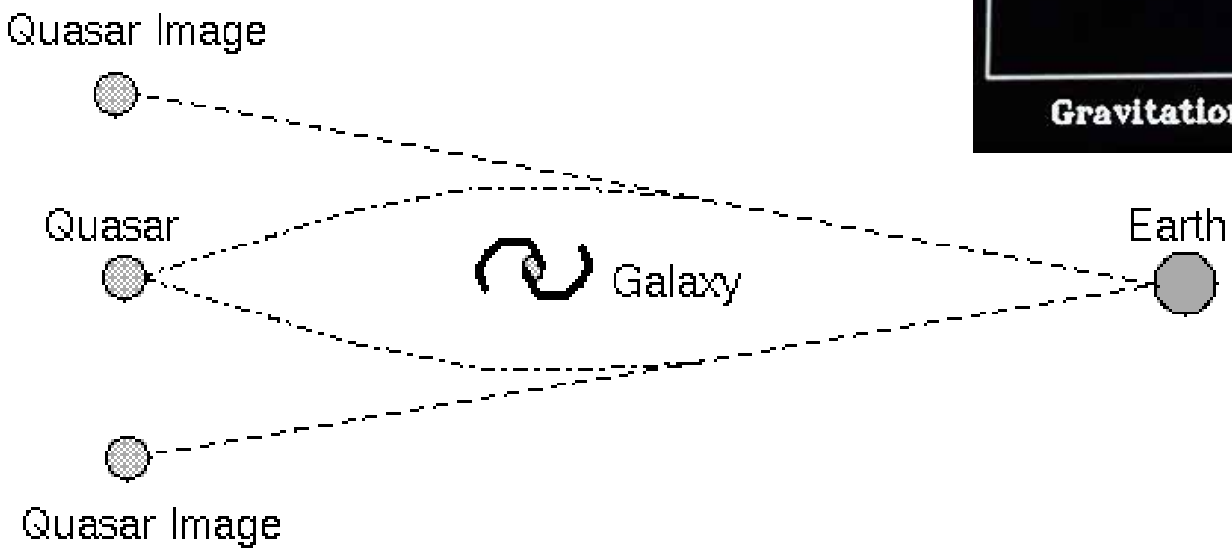
$$+\frac{a\,b\,\frac{\partial c}{\partial \eta}\,\frac{\partial c}{\partial \theta}}{\delta^2}-\frac{\frac{\partial a}{\partial \eta}\,b\,c\,\frac{\partial c}{\partial \theta}}{2\,\delta^2}-\frac{a\,\frac{\partial a}{\partial \theta}\,b\,\frac{\partial c}{\partial \theta}}{2\,\delta^2}-\frac{a\,\frac{\partial b}{\partial \theta}\,c\,\frac{\partial c}{\partial \eta}}{2\,\delta^2}-\frac{a\,b\,\frac{\partial b}{\partial \eta}\,\frac{\partial c}{\partial \eta}}{2\,\delta^2}+\frac{a\,\frac{\partial a}{\partial \theta}\,\frac{\partial b}{\partial \theta}\,c}{4\,\delta^2}$$

$$+\frac{a\,(\frac{\partial b}{\partial \eta})^2\,c}{4\,\delta^2}+\frac{\frac{\partial a}{\partial \eta}\,b\,\frac{\partial b}{\partial \eta}\,c}{4\,\delta^2}+\frac{(\frac{\partial c}{\partial \theta})^2\,b\,c}{4\,\delta^2}+\frac{a\,\frac{\partial a}{\partial \eta}\,b\,\frac{\partial b}{\partial \theta}}{4\,\delta^2}-\frac{a\,\frac{\partial a}{\partial \theta}\,b\,\frac{\partial b}{\partial \eta}}{4\,\delta^2}$$

$$R_{\theta\varphi}=-\frac{2\,a\,b\,\frac{\partial a}{\partial \theta}\cot\theta}{\delta\,\psi}+\frac{2\,b\,c\,\frac{\partial \psi}{\partial \eta}\cot\theta}{\delta\,\psi}-\frac{\frac{\partial d}{\partial \theta}\cot\theta}{d}-\frac{c\,\frac{\partial c}{\partial \theta}\cot\theta}{\delta}+\frac{\frac{\partial b}{\partial \eta}\,c\cot\theta}{2\,\delta}+\frac{a\,\frac{\partial b}{\partial \theta}\cot\theta}{2\,\delta}$$

$$-\frac{2\,a\,b\,\frac{\partial^2 \psi}{\partial \theta^2}}{\delta\,\psi}-\frac{2\,\frac{\partial^2 \psi}{\partial \theta^2}}{\psi}-\frac{2\,a\,b\,(\frac{\partial \psi}{\partial \theta})^2}{\delta\,\psi^2}+\frac{6\,(\frac{\partial \psi}{\partial \theta})^2}{\psi^2}+\frac{4\,b\,c\,\frac{\partial \psi}{\partial \eta}\,\frac{\partial \psi}{\partial \theta}}{\delta\,\psi^2}-\frac{a\,b\,\frac{\partial d}{\partial \theta}\,\frac{\partial \psi}{\partial \theta}}{\delta\,d\,\psi}$$

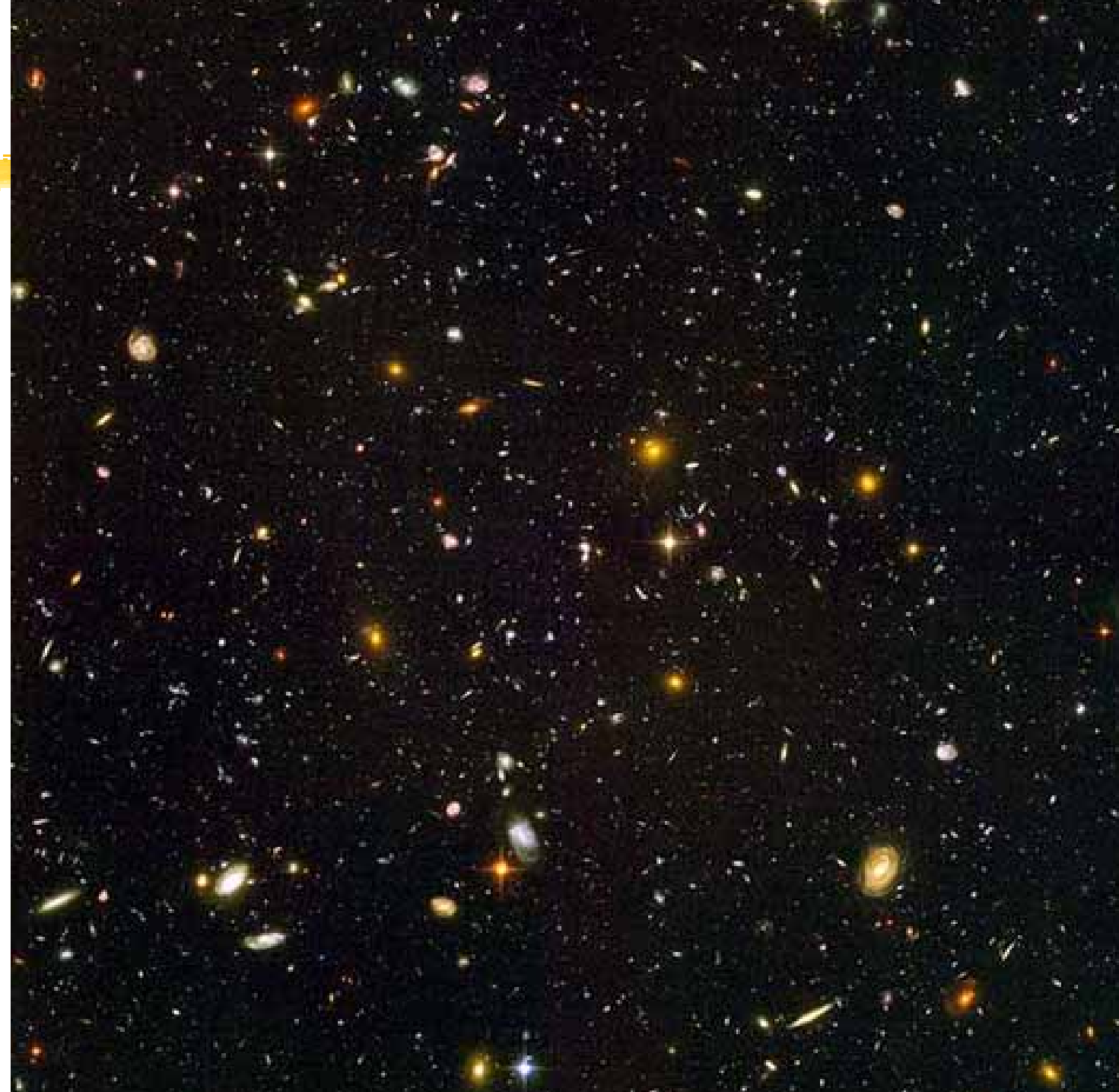
Observações da Rel. Geral (1)



Obs.
R.G.
(2)

(HST)

E o nosso Universo ?



A Teoria do Big Bang