



Universidade Federal do ABC



SOCIEDADE BRASILEIRA DE FÍSICA

**MNPEF** Mestrado Nacional  
Profissional em  
Ensino de Física



## Marcos no Desenvolvimento da Física

**Marco #9: A radiação cósmica de fundo**

*Prof. Marcelo Augusto Leigui de Oliveira*

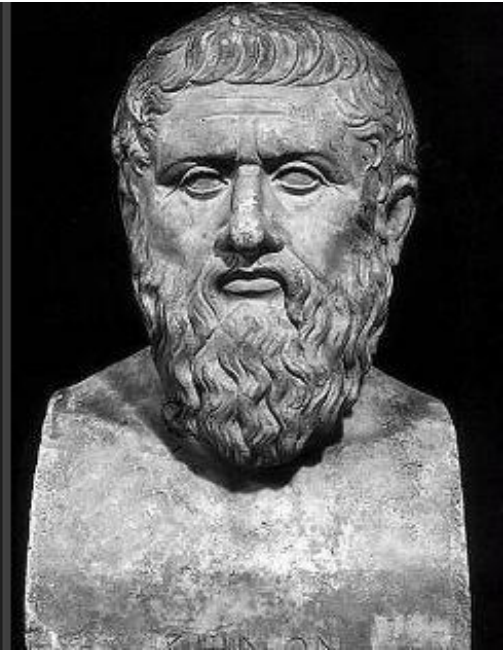
[leigui@ufabc.edu.br](mailto:leigui@ufabc.edu.br)

# GREGOS

"A Astronomia obriga a nossa alma a olhar para cima e a levar-nos do nosso mundo para outro."

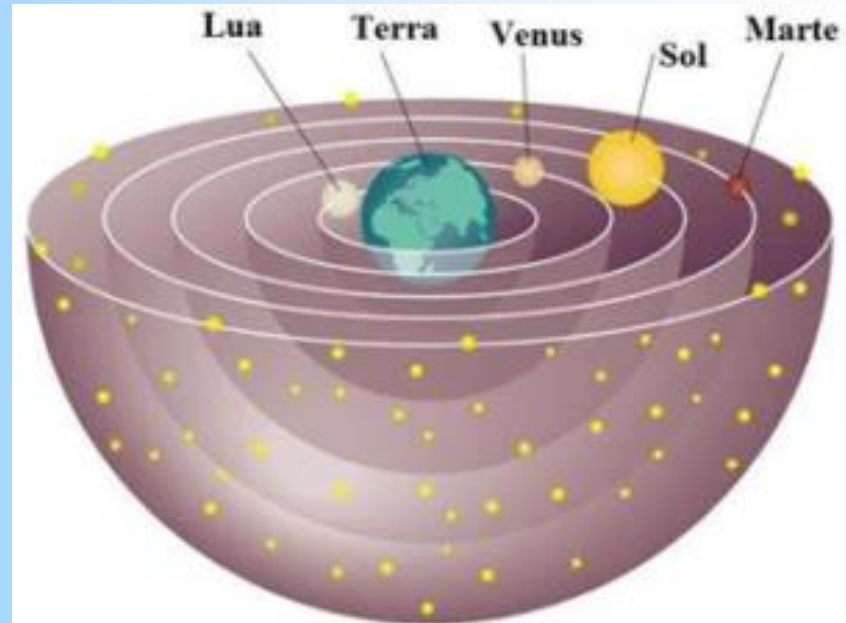
Platão

 PENSADOR



Platão (c 427-347 a.C.)

- Terra fixa no centro do universo (teoria geocêntrica).
- Planetas em espirais fixas.



# GREGOS

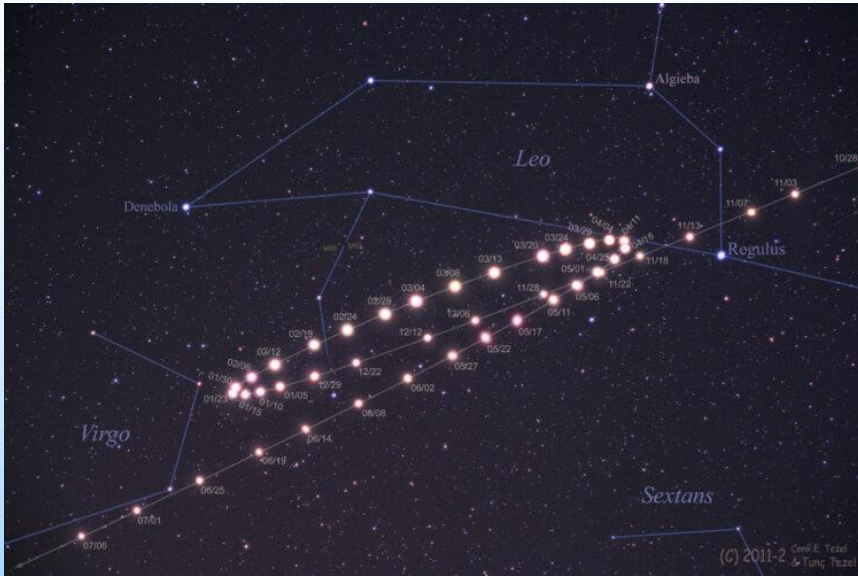


**Platão** (c 427 – c 347 a.C.)  
e **Aristóteles** (384 – c 322 a.C.),  
seu discípulo.



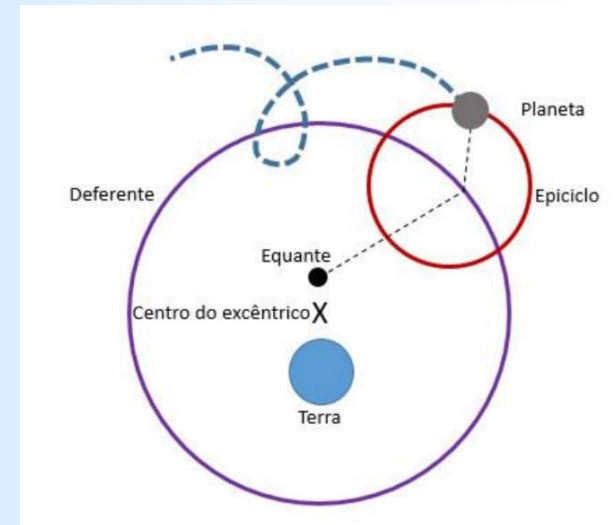
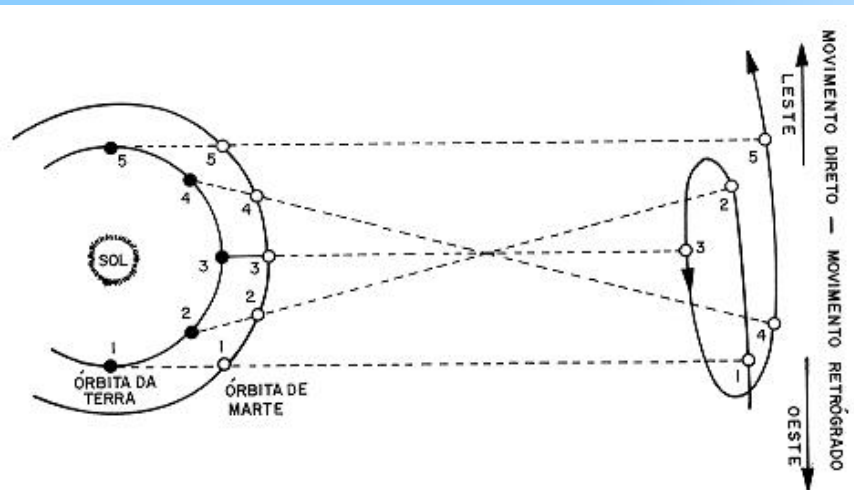
- Universo geocêntrico (e finito);
- Esferas naturais dos elementos (“caem” para elas);
- Mundo mutável e imperfeito (sublunar) e mundo imutável e perfeito (supralunar), feito de *éter* ;
- Camada de “ar superior” entre a esfera de fogo e a lunar, onde os fenômenos *meteorológicos* acontecem.

# SISTEMA PTOLOMAICO



Claudio Ptolomeu (90 – 168 d.C.)

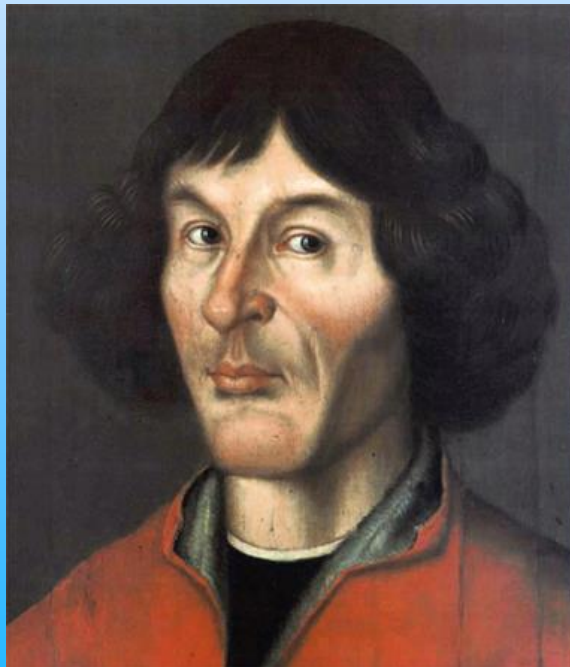
Movimento retrógrado dos planetas (“laçadas”).



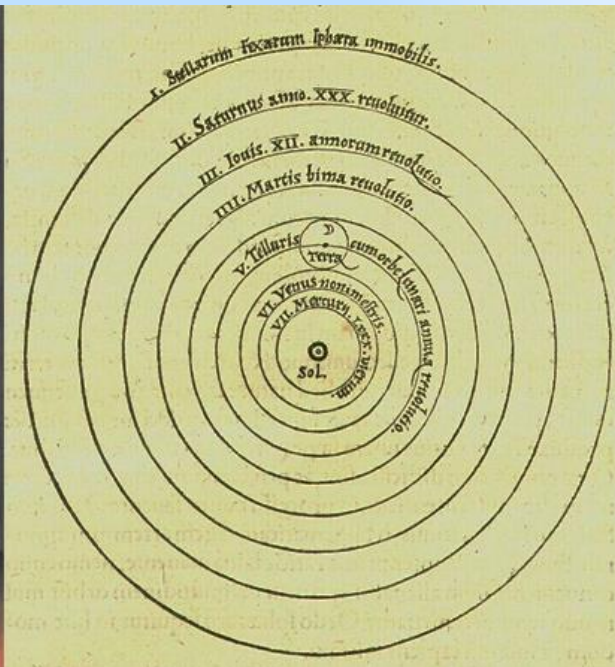
Movimento planetário de Ptolomeu.

# REVOLUÇÃO COPERNICANA

- Copérnico tinha conhecimento de que observações cuidadosas não confirmavam o sistema ptolomaico;
- Os equantes quebravam a “regra do movimento absoluto”, segundo a qual todos os corpos celestes deveriam mover-se a velocidades constantes;
- Posicionando o Sol no centro do universo e a Terra como mais um planeta, Copérnico criou um sistema cosmológico bem mais simples (heliocêntrico);
- *De Revolutionibus Orbium Coelestium* (1543), ou *Sobre a Revolução dos Corpos Celestes*, foi publicado em Nuremberg pouco antes de sua morte.

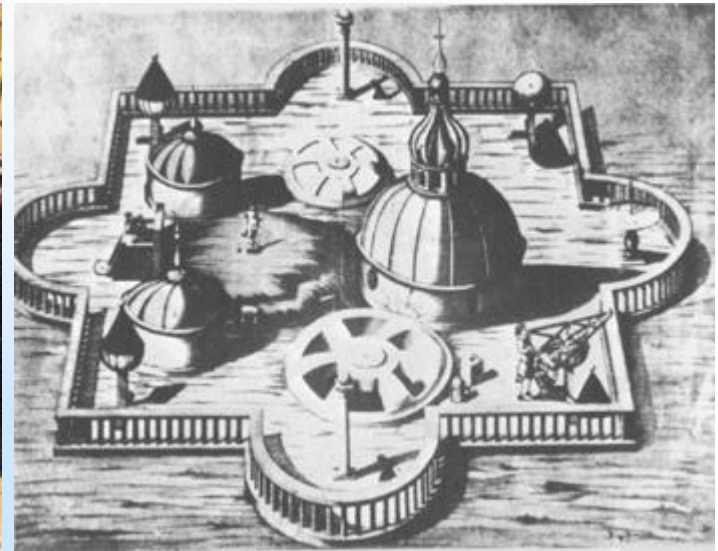


Nicolau Copérnico (1473 – 1543).

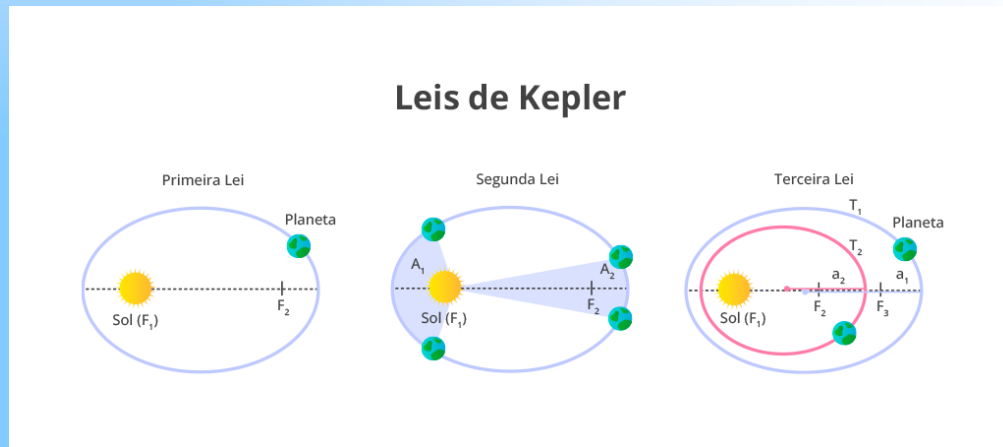
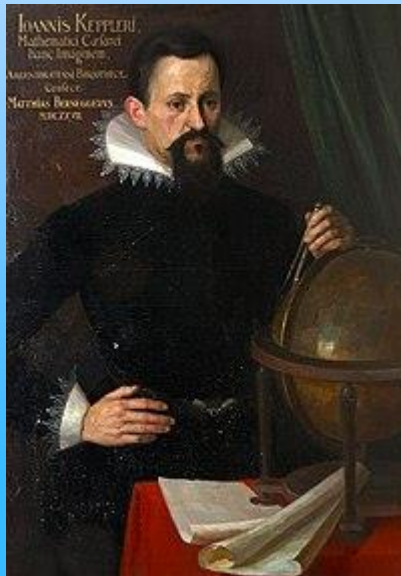


*De Revolutionibus Orbium Coelestium* (1543).

# REVOLUÇÃO COPERNICANA



Tycho Brahe (1546 – 1601) e seu observatório de astronomia na ilha de Hven (Copenhagem).

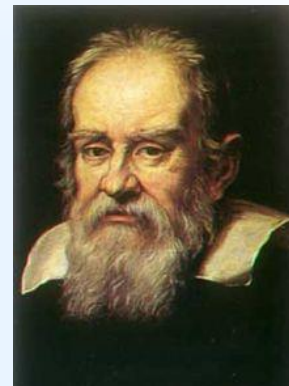
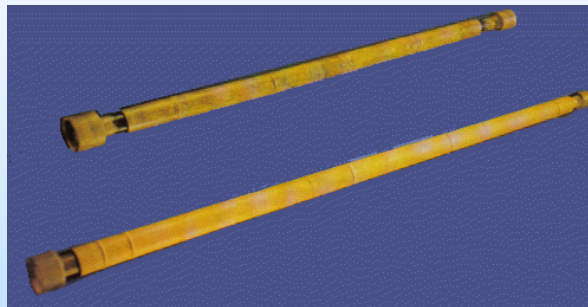


Johannes Kepler (1571 – 1630).

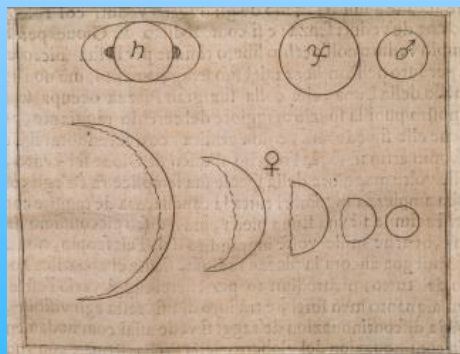
# INVENÇÃO DO TELESCÓPIO



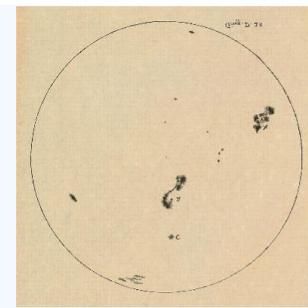
Em **1608**, o óptico holandês Hans Lippershey (1570 – 1619) deposita a patente da invenção do telescópio.



Em **1609**, o italiano Galileu Galilei (1564 - 1642) aperfeiçoa o instrumento e o aponta para o céu. Suas descobertas foram relatadas no livro *Mensageiro Sideral*, de **1610**.



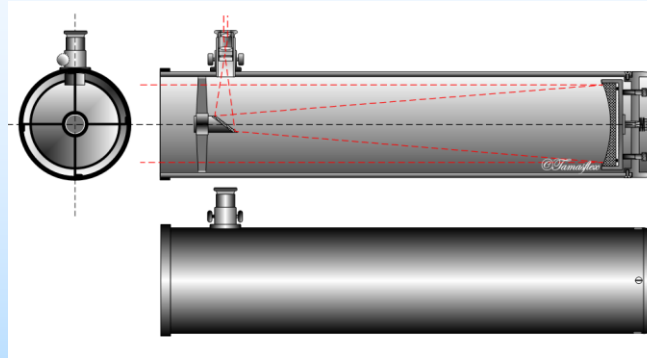
Ori.	*	*	○	*	Occ.
Ori.	○	*	*	*	Occ.
Ori.	*	*	○		Occ.



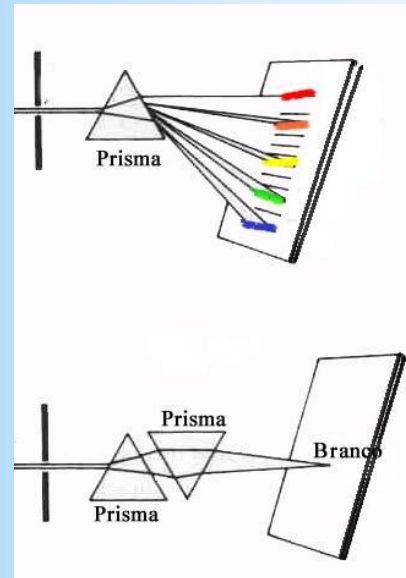
# TELESCÓPIO NEWTONIANO

Newton deu várias contribuições para a óptica, sintetizadas em seu livro *Optiks* (1704).

- Construiu o primeiro telescópio refletor (ou newtoniano):



- Descobriu que a luz branca era uma composição de várias cores refratadas diferentemente por um prisma:

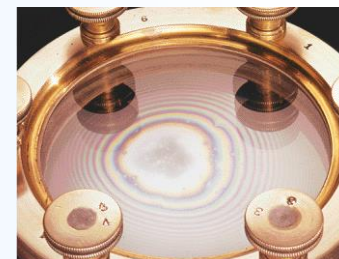


- E realizou o *experimentum crucis*:

- Apresentou também os *anéis de Newton*:



Sir Isaac Newton (1642-1727)

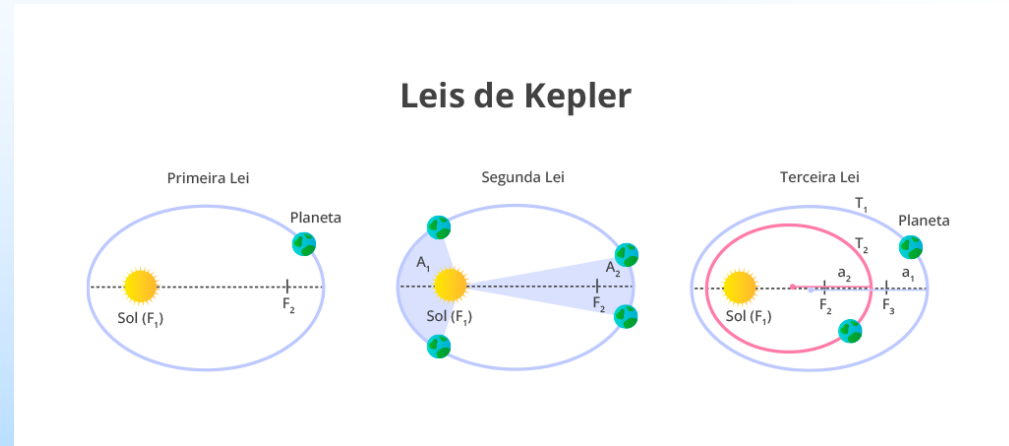




# TELESCÓPIO NEWTONIANO



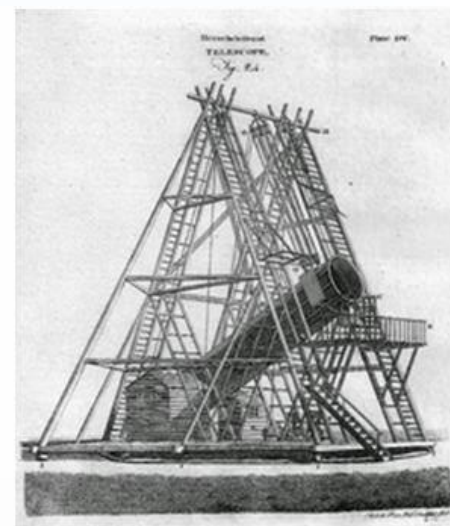
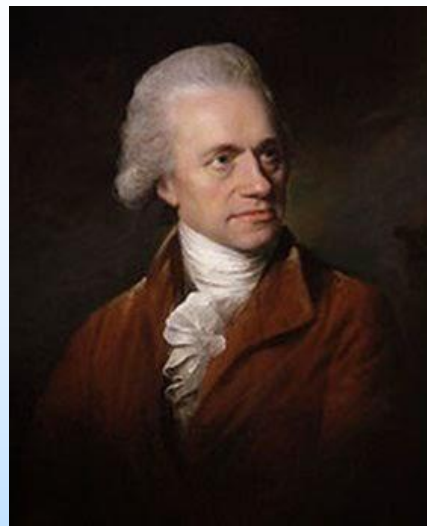
$$F \propto \frac{1}{r^2} \Rightarrow$$



Sir Isaac Newton  
(1642-1727)

- Em 1679, Newton voltou ao seu trabalho sobre mecânica celeste, considerando a gravitação e seu efeito nas órbitas dos planetas, com referência às leis de Kepler.
- O cometa Halley ressurgiu na virada dos anos 1680-1681. Após uma visita de Edmund Halley, em 1684, Newton fica sabendo que Robert Hooke demonstrara que as órbitas elípticas são resultado da força proporcional ao inverso do quadrado da distância. Newton responde que já havia feito esta demonstração, mas não encontrava o documento. Em 1685, Newton comunica o resultado a Edmund Halley, em "[De motu corporum in gyrum](#)" (Sobre o movimento dos corpos em uma órbita).
- Halley financiou e ajudou Newton a publicar o Principia.

# AMPLIANDO O ALCANCE



William Herschel (1738 - 1822) e seu telescópio (1778) com um espelho de 16 cm.



Telescópios do Observatório do Monte Wilson: à esquerda o de 150 cm e à direita o de 250 cm.



Edwin Hubble (1889 - 1953) em Monte Wilson.

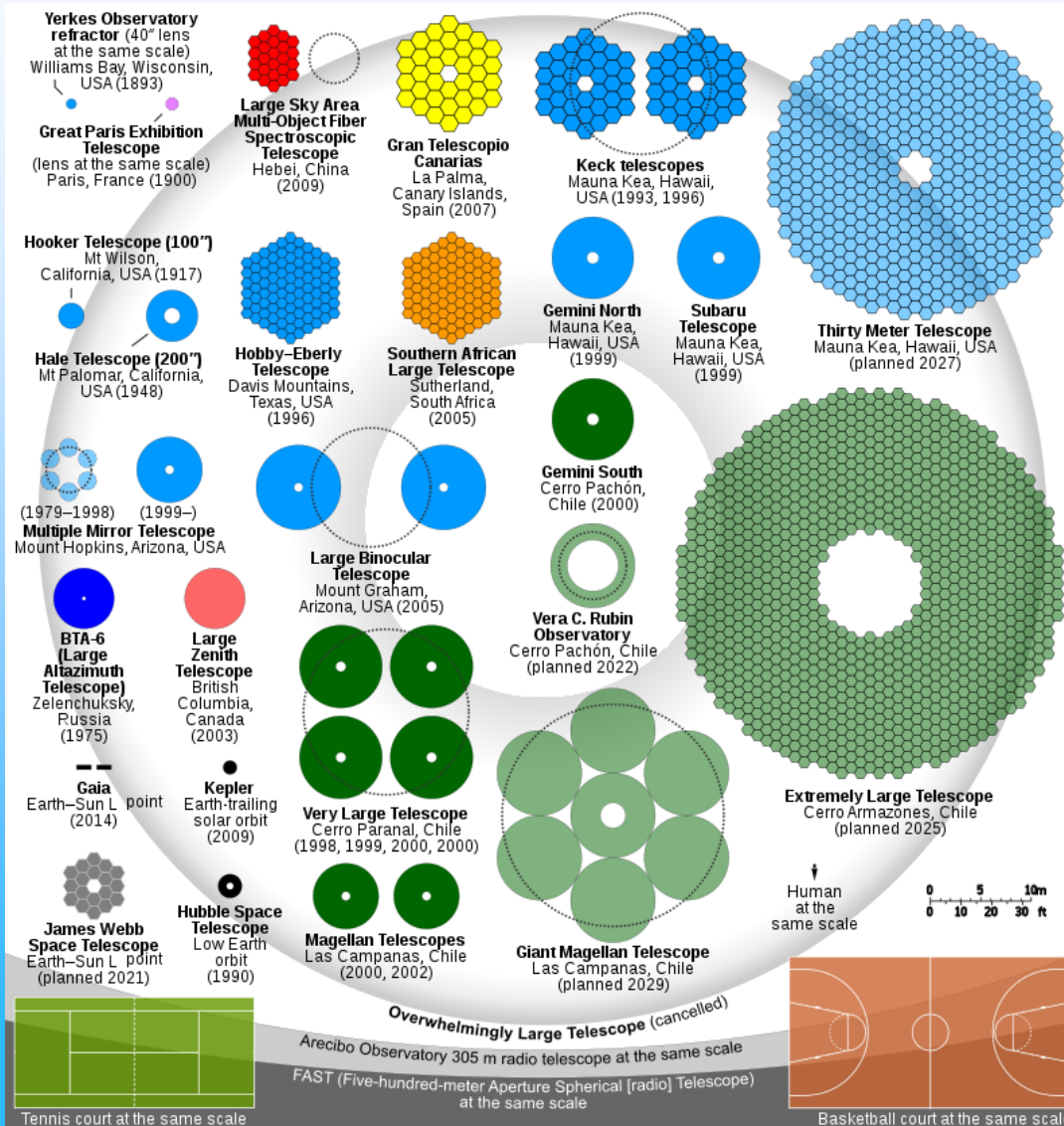
# AMPLIANDO O ALCANCE



Reflecting telescopes

Name	Image	Effective aperture	Mirror type	Nationality / Sponsors	Site	First light
Large Binocular Telescope (LBT)		11.9 m (469 in) (combined) <sup>[2]</sup>	Multiple Two 8.4 m (331 in) mirrors	USA, Italy, Germany	Mount Graham International Observatory, Arizona, USA	2004
Gran Telescopio Canarias (GTC)		10.4 m (409 in)	Segmented 36 hexagonal segments	Spain, Mexico, USA	Roque de los Muchachos Obs., Canary Islands, Spain	2006
Hobby-Eberly Telescope (HET)		10 m (394 in) (effective) <sup>[3]</sup>	Segmented 91 × 1 m (39 in) hexagonal segments forming a 11 m × 9.8 m mirror	USA, Germany	McDonald Observatory, Texas, USA	1997 Aperture increased 2015
Keck 1		10 m (394 in)	Segmented 36 hexagonal segments	USA	Mauna Kea Observatories, Hawaii, USA	1993
Keck 2		10 m (394 in)	Segmented 36 hexagonal segments	USA	Mauna Kea Observatories, Hawaii, USA	1996
Southern African Large Telescope (SALT)		9.2 m (362 in) (effective) <sup>[4]</sup>	Segmented 91 × 1 m (39 in) hexagonal segments forming a 11 m × 9.8 m mirror	South Africa, USA, UK, Germany, Poland, New Zealand	South African Astronomical Obs., Northern Cape, South Africa	2005
Subaru (JNLT)		8.2 m (323 in)	Single	Japan	Mauna Kea Observatories, Hawaii, USA	1999
VLT UT1 – Antu		8.2 m (323 in)	Single	ESO Countries, Chile	Paranal Observatory, Antofagasta Region, Chile	1998
VLT UT2 – Kueyen		8.2 m (323 in)	Single	ESO Countries, Chile	Paranal Observatory, Antofagasta Region, Chile	1999
VLT UT3 – Melipal		8.2 m (323 in)	Single	ESO Countries, Chile	Paranal Observatory, Antofagasta Region, Chile	2000
VLT UT4 – Yepun		8.2 m (323 in)	Single	ESO Countries, Chile	Paranal Observatory, Antofagasta Region, Chile	2001
Gemini North (Gillett)		8.1 m (319 in)	Single	USA, UK, Canada, Chile, Australia, Argentina, Brazil	Mauna Kea Observatories, Hawaii, USA	1999
Gemini South		8.1 m (319 in)	Single	USA, UK, Canada, Chile, Australia, Argentina, Brazil	Cerro Pachón (CTIO), Coquimbo Region, Chile	2001
MMT (current optics)		6.5 m (256 in)	Single	USA	F. L. Whipple Obs., Arizona, USA	2000
Magellan 1 (Walter Baade) <sup>[5]</sup>		6.5 m (256 in)	Single	USA	Las Campanas Obs., Atacama Region, Chile	2000

# AMPLIANDO O ALCANCE

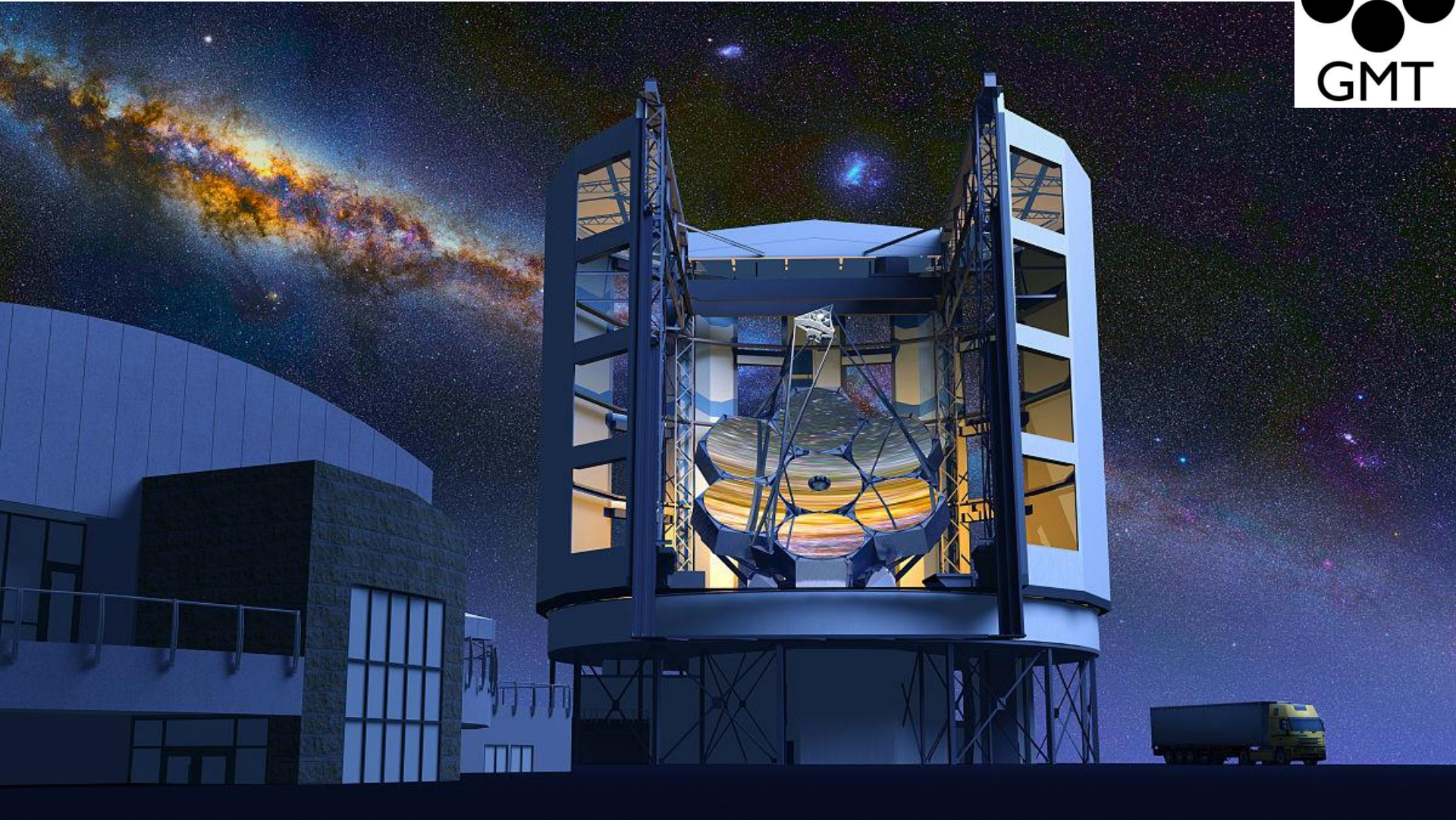


Gran Telescopio Canarias



Keck telescopes

# AMPLIANDO O ALCANCE

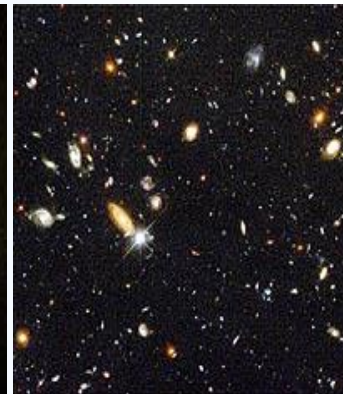
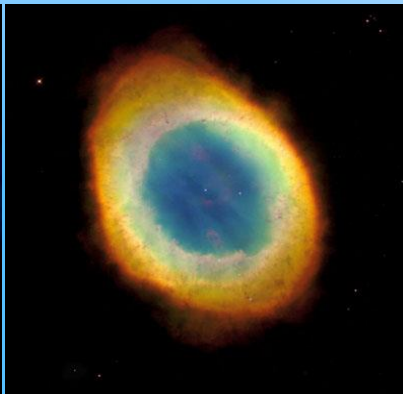


Giant Magellan Telescope

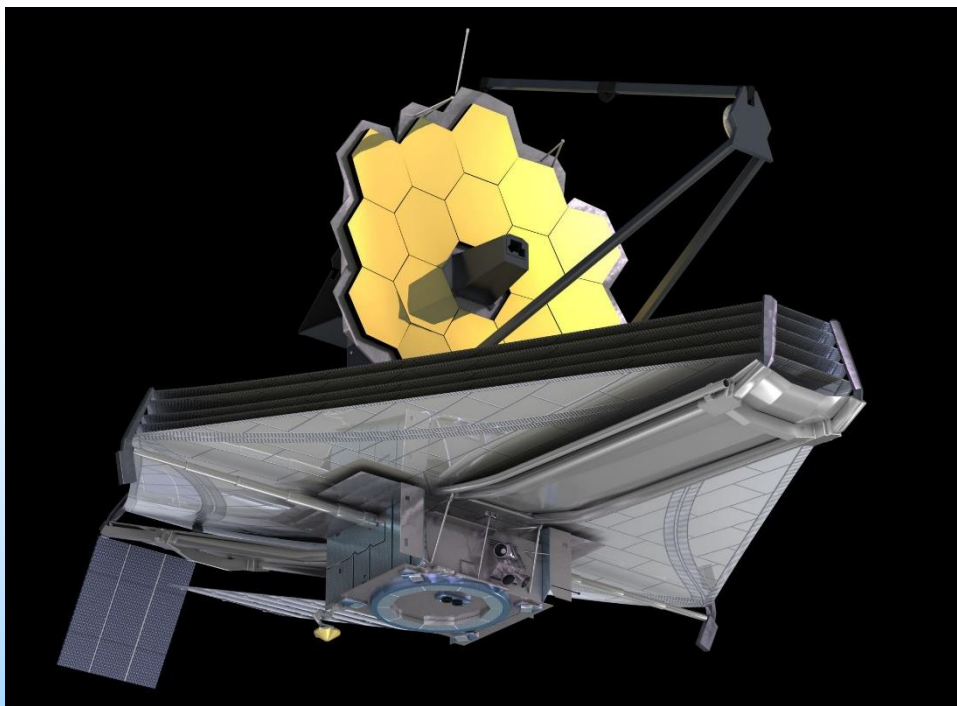
# AMPLIANDO O ALCANCE



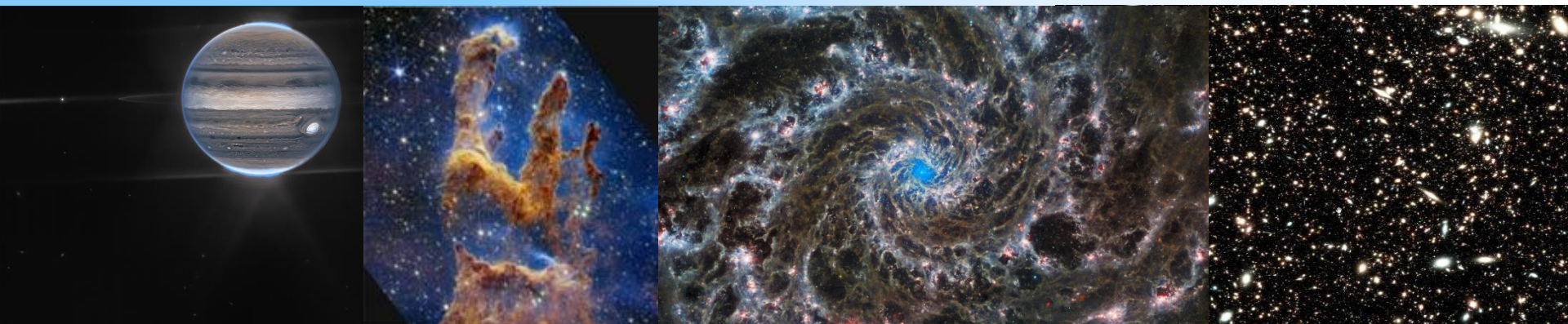
Telescópio Espacial Hubble.



# AMPLIANDO O ALCANCE



Telescópio Espacial James Webb.

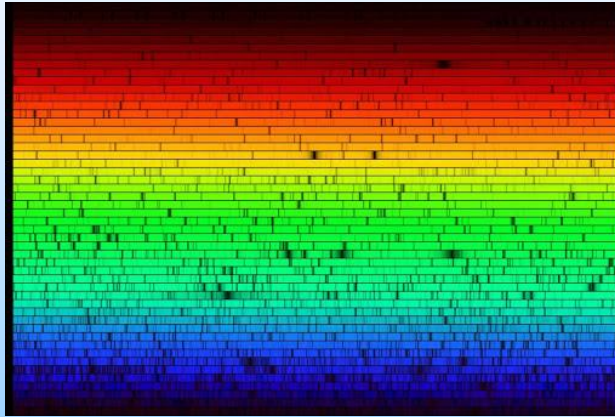


# MEDINDO A COMPOSIÇÃO (ESPECTROSCOPIA)



Joseph Fraunhofer  
(1787-1826)

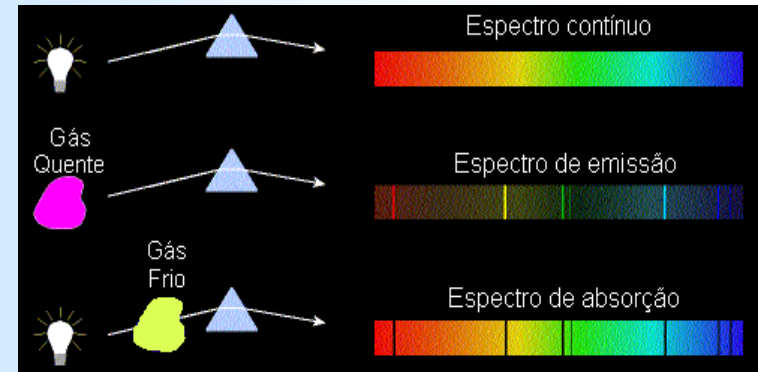
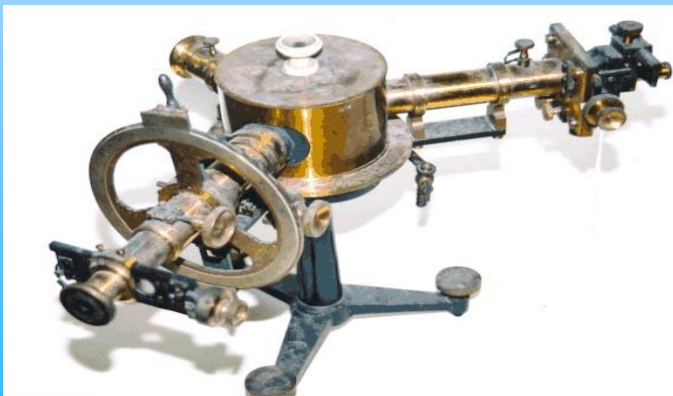
**1814** Fraunhofer inventou o espectroscópio e descobriu 574 linhas de absorção no espectro do Sol e linhas diferentes no espectro de Sírius.



Gustav Robert Kirchhoff  
(1824-1887)

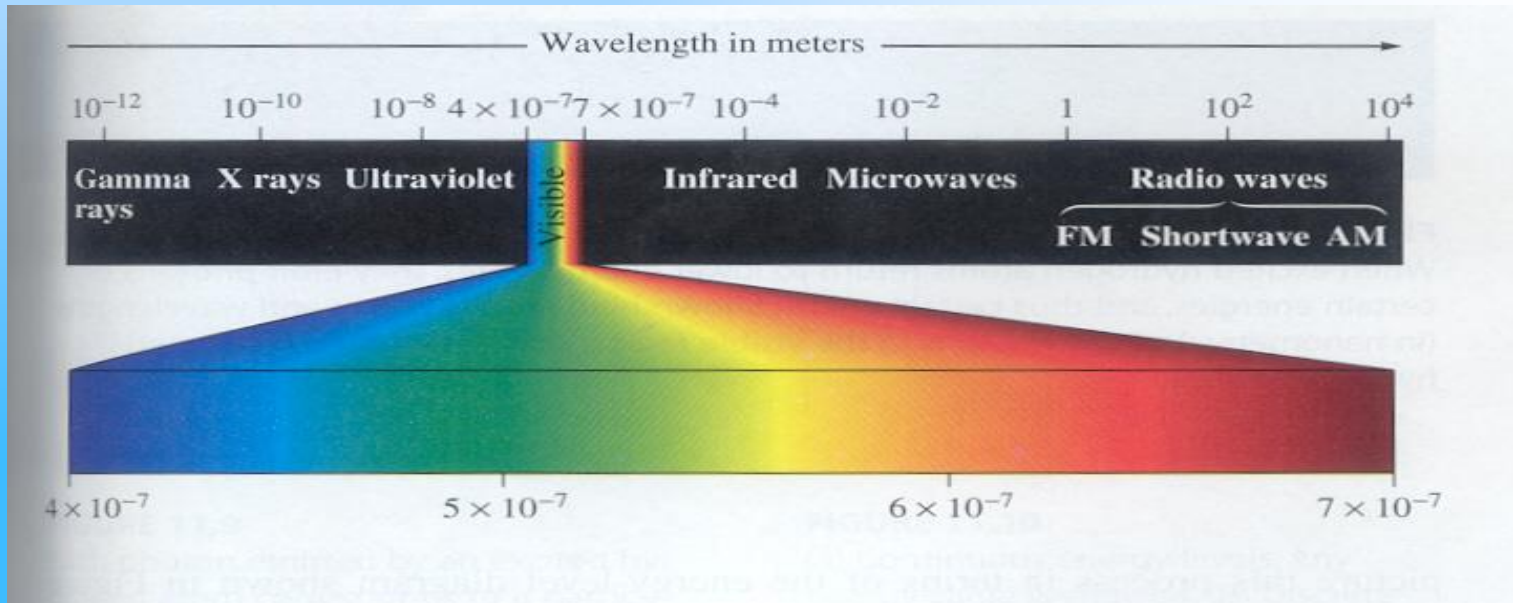
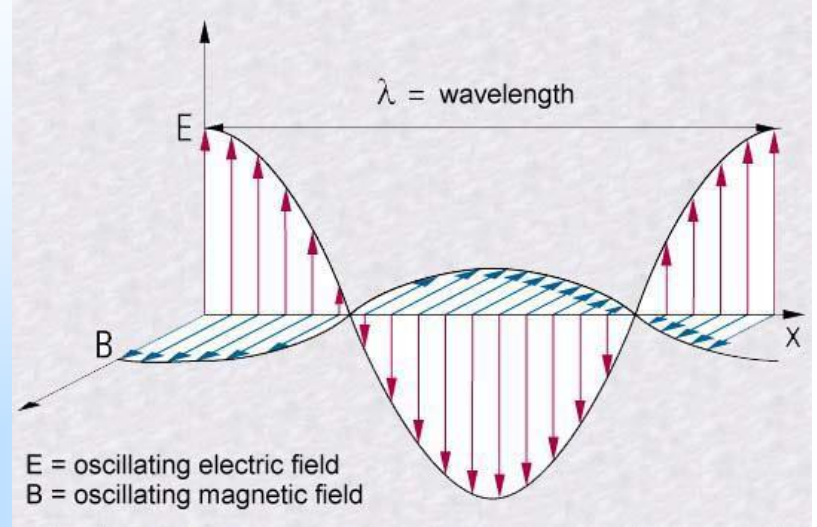
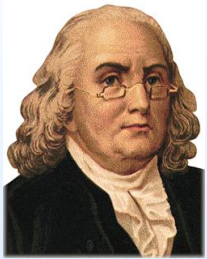
Robert Wilhelm Bunsen  
(1811-1899)

**1860** Kirchhoff e Bunsen mostraram que as linhas de Fraunhofer estão associadas aos elementos químicos presentes nas estrelas.

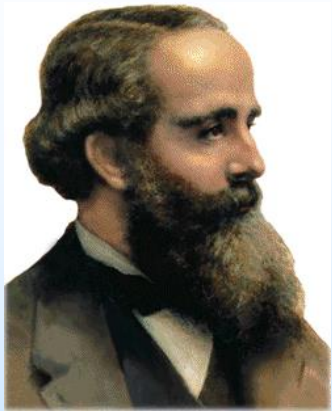




# AMPLIANDO A JANELA DE OBSERVAÇÃO

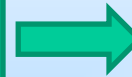


# AMPLIANDO A JANELA DE OBSERVAÇÃO



**1864** James C. Maxwell (1831-1879) descreve as 4 equações do eletromagnetismo, verificando que delas pode-se deduzir equações de onda.

$$\begin{aligned}\nabla \cdot \vec{E} &= \frac{\rho}{\epsilon_0} \\ \nabla \cdot \vec{B} &= 0 \\ \nabla \times \vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ \nabla \times \vec{B} &= \mu_0 \left( \vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right)\end{aligned}$$



$$\begin{aligned}\nabla^2 \vec{E} &= \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} \\ \nabla^2 \vec{B} &= \frac{1}{c^2} \frac{\partial^2 \vec{B}}{\partial t^2}\end{aligned}$$

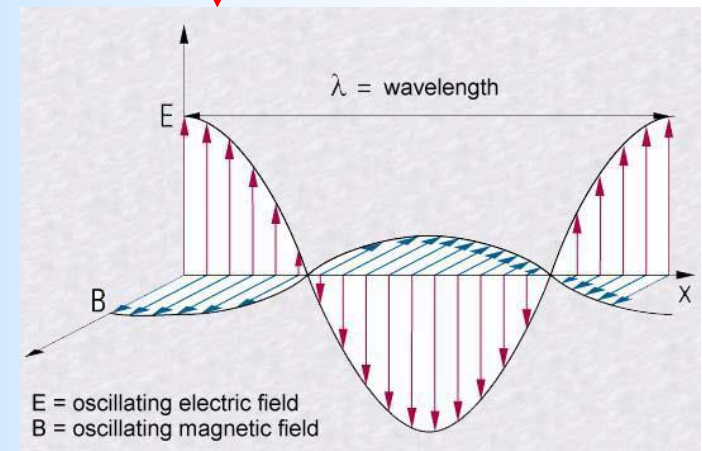
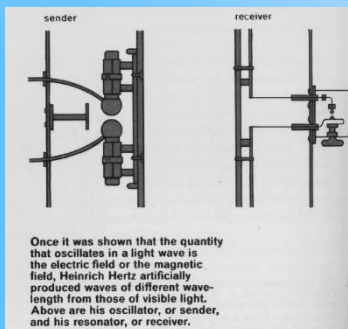
onde:

$$c = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

$\approx 300.000 \text{ km/s}$



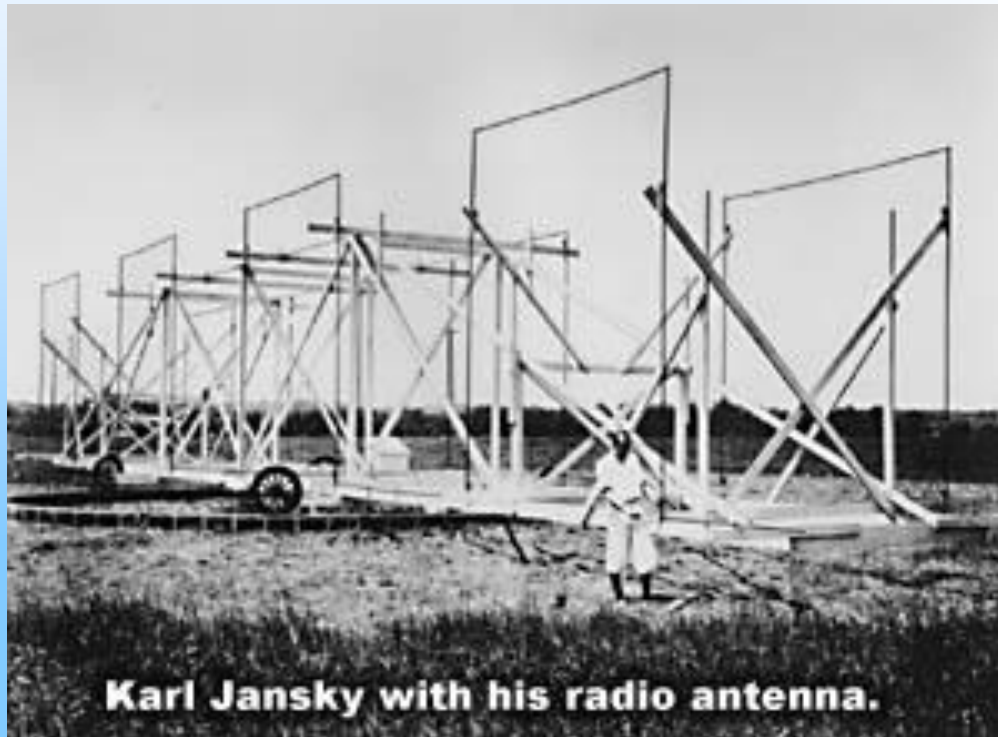
**1888** Heinrich Hertz (1857-1894) detecta ondas eletromagnéticas.



# AMPLIANDO A JANELA DE OBSERVAÇÃO



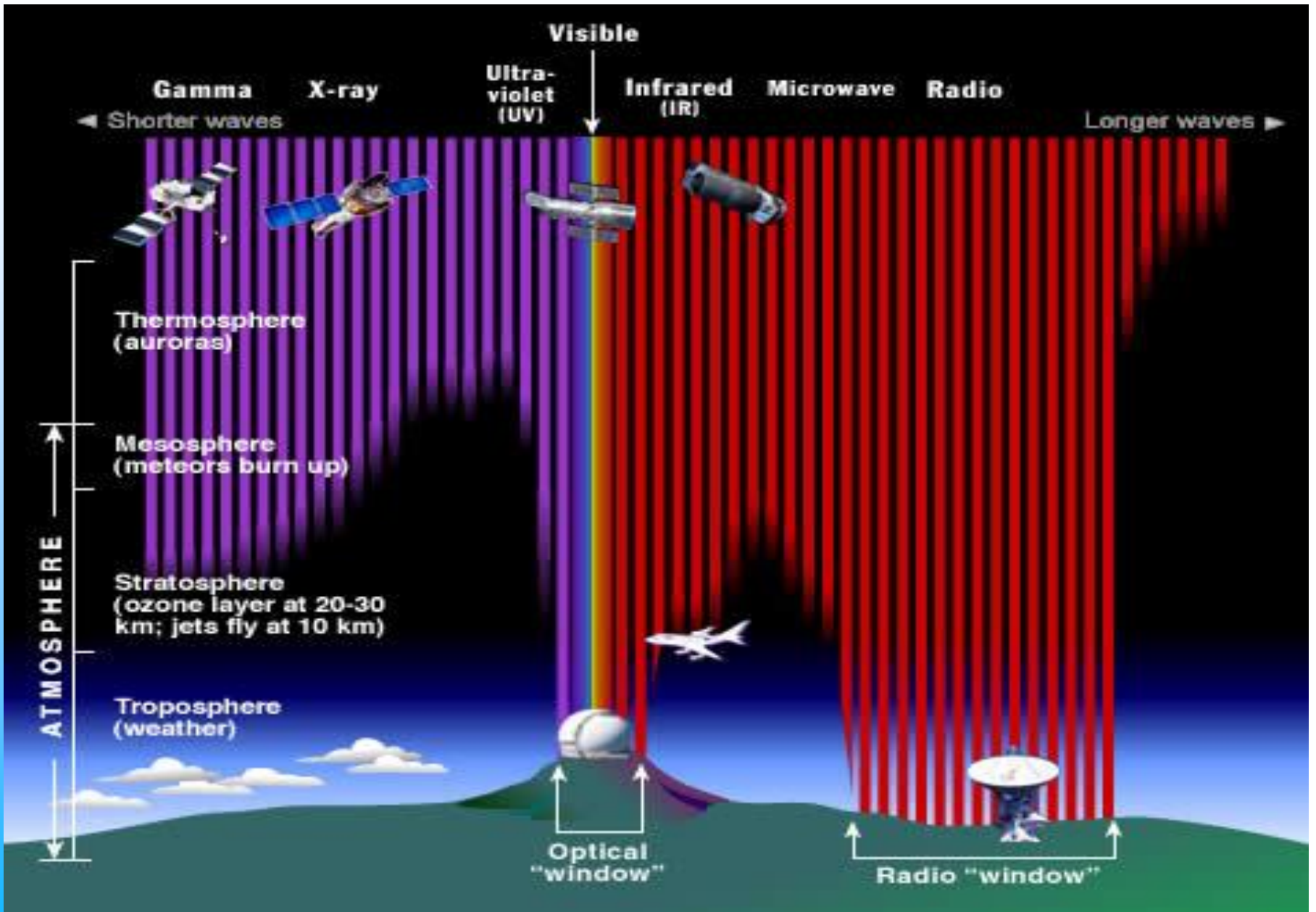
Karl Jansky  
(1905-1950)



**Karl Jansky with his radio antenna.**

**1932** Karl Jansky descobre ondas de rádio sendo emitidas pela nossa galáxia, a Via-Láctea.

# AMPLIANDO A JANELA DE OBSERVAÇÃO



# AMPLIANDO A JANELA DE OBSERVAÇÃO



# AMPLIANDO A JANELA DE OBSERVAÇÃO



FAST: radio  
telescópio chinês  
(~500 m diâmetro)

Very Large Array  
(Novo México, EUA)



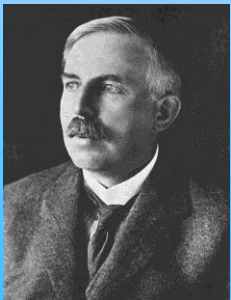
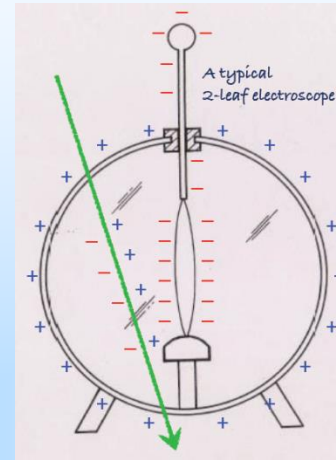
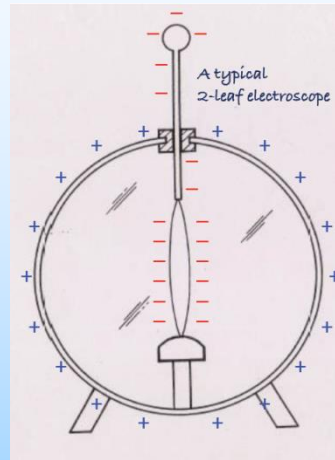


Charles Thomson  
Rees Wilson  
(1869-1959)



**1927**  
(Wilson &  
Compton)

- **1900** Wilson notou que eletroscópios perdem carga mesmo quando muito bem isolados.



Ernest Rutherford  
(1871 - 1937)



**1908** (Química)

- E. Rutherford teorizou que a maior parte da ionização seria devida à radiação natural, mas essa radiação era muito mais penetrante.

- **1910** Theodor Wulf mediu uma queda de  $22,25 \text{ ions/cm}^3 \text{ s}$  ( $\sim$  ao nível do mar) para  $15,7 \text{ ions/cm}^3 \text{ s}$ , no topo da Torre Eiffel (330 m), mas deveria ter caído à metade em 80 m;



Phys. Zert. 11, 811 (1910)

Datum	Ort	Ionen ccm sec
28. März	Valkenburg . . . . .	22,5
29. "	Paris, Boden . . . . .	17,5
30. "	" Eiffelturm . . . . .	16,2
31. "	" "	14,4
1. April	" "	15,0
2. "	" "	17,2
3. "	" Boden . . . . .	18,3
4. "	Valkenburg . . . . .	22,0

Daraus ergeben sich als Mittelwerte für die drei Orte

Valkenburg . . . . .	22,25	Ionen ccm · sec
Paris Boden . . . . .	18,0	"
Paris Eiffelturm . . . . .	15,7	"



**1912** Victor Hess subiu num balão a 5 km e mediu um aumento na ionização (4 x mais descargas a 4880 m): deve haver uma radiação de origem cósmica ionizando a atmosfera.



Victor Franz Hess  
(1883-1964)



**1936** (Hess &  
Anderson)



Victor F. Hess (1912).



# NO SÉCULO XX



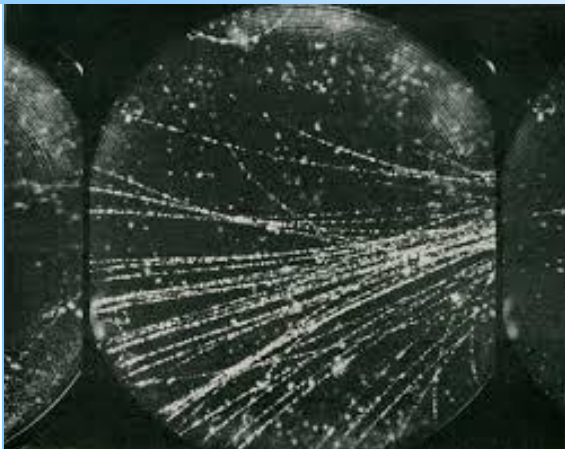
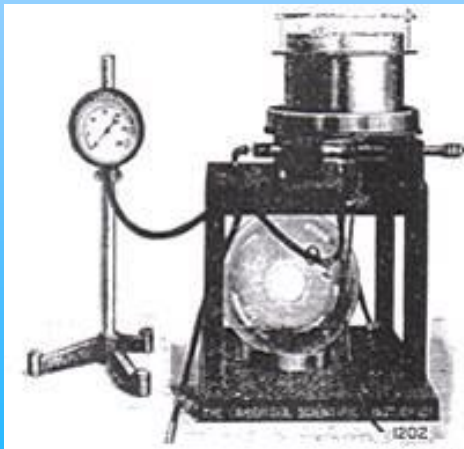
Victor Franz Hess  
(1883-1964), físico  
austriaco-americano.

**1912** Victor Hess descobre radiações de origem cósmica (raios cósmicos).



**1936** Hess & Anderson

**1912** Charles Wilson desenvolve a câmara de núvens.

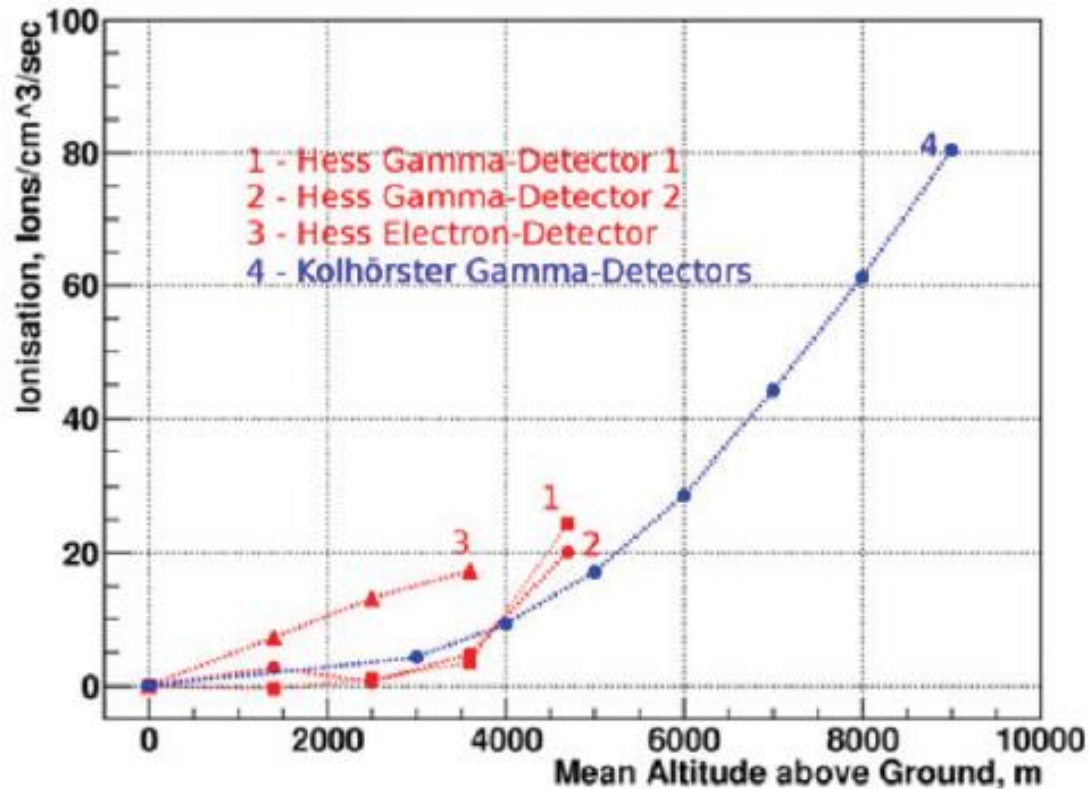


**1927**  
Wilson &  
Compton



Charles Thomson  
Rees Wilson  
(1869-1959),  
físico escocês.

# NO SÉCULO XX



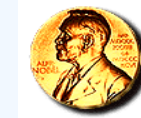
**Fig. 2.** Number of ions  $\text{cm}^{-3} \text{s}^{-1}$  measured by Hess at the seventh flight in August 1912 (1-3) [Hess 1912] and by Kolhörster (4) in 1914 [Kolhörster 1914].

# NO SÉCULO XX

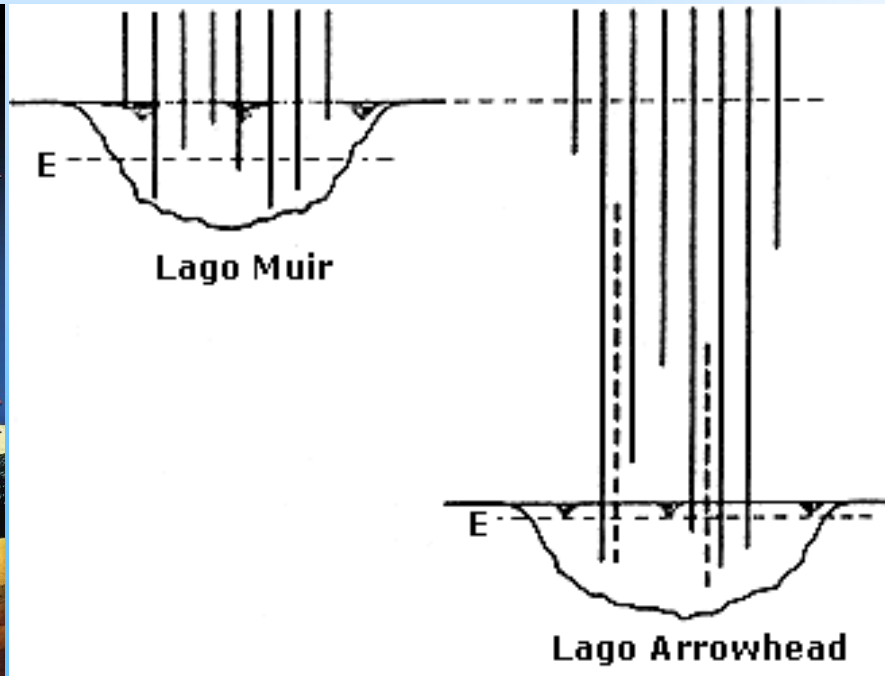
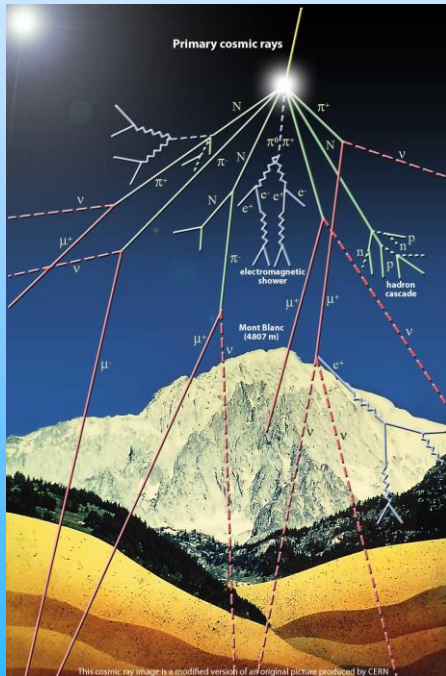
- Victor F. Hess called them "*ultra-gamma radiation*";
- Egon von Schweidler called them "Hess rays"
- Werner H. G. Kolhörster called them "*Höhenstrahlung*" (altitude radiation);
- R.A. Millikan coined the term "*cosmic rays*".



Robert Andrews Millikan  
(1868 - 1953)



1923 Millikan



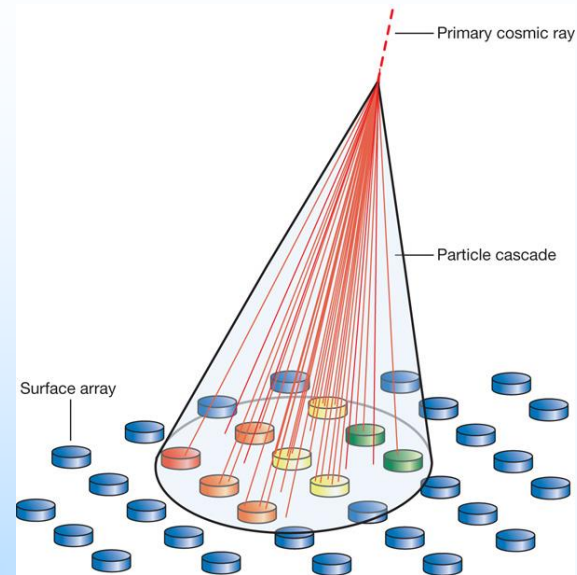
"Birth cry" of created atoms.  
The New York Times, 23rd November 1925.

# NO SÉCULO XX

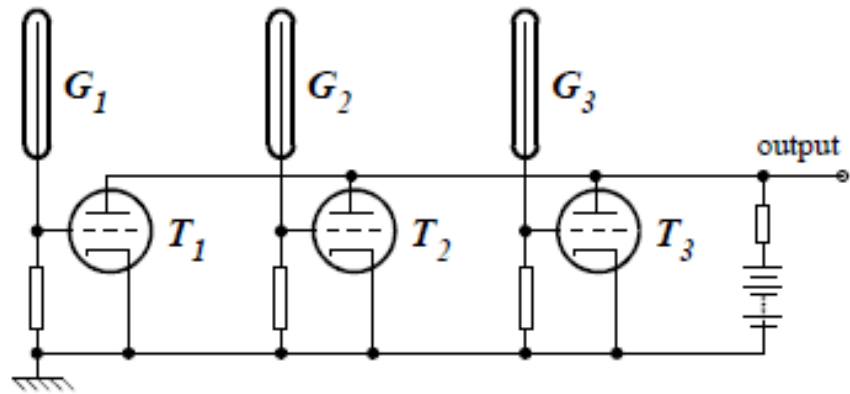
(1938)



Pierre Victor Auger (1899 - 1993)



Chuveiros atmosféricos extensos

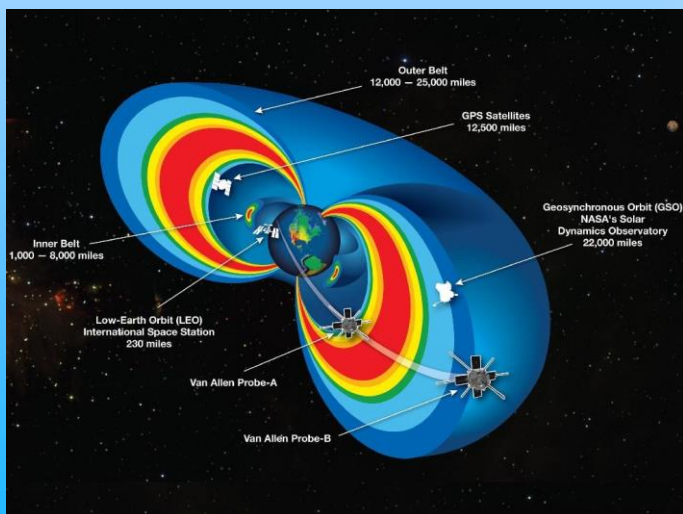
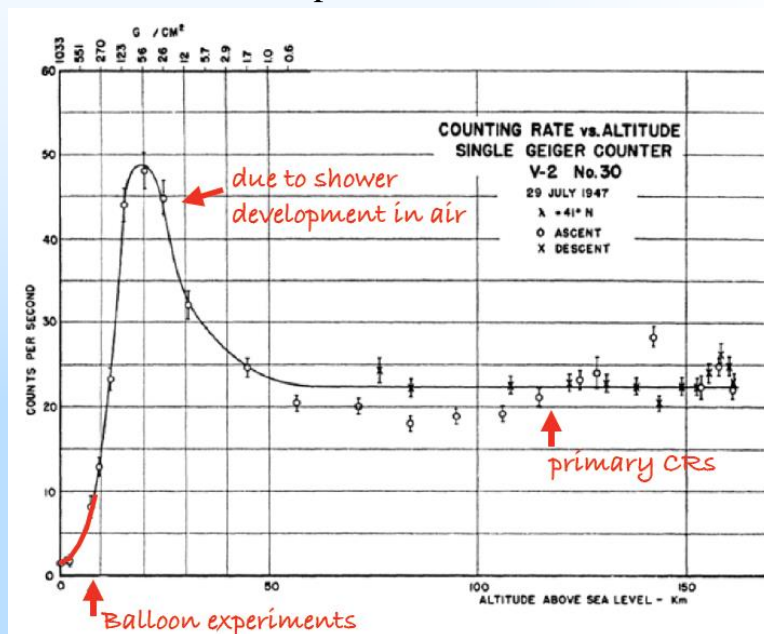


# NO SÉCULO XX



James Alfred Van Allen  
(1914-2006)

1948-1954 Van Allen lançou foguetes levando a bordo instrumentos para medir raios cósmicos.



1958 Cinturões de Van Allen.

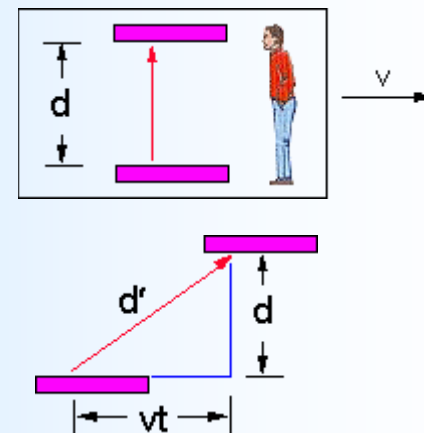
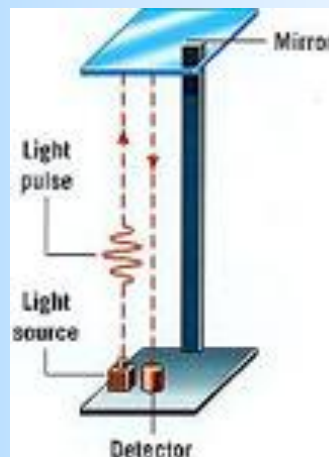
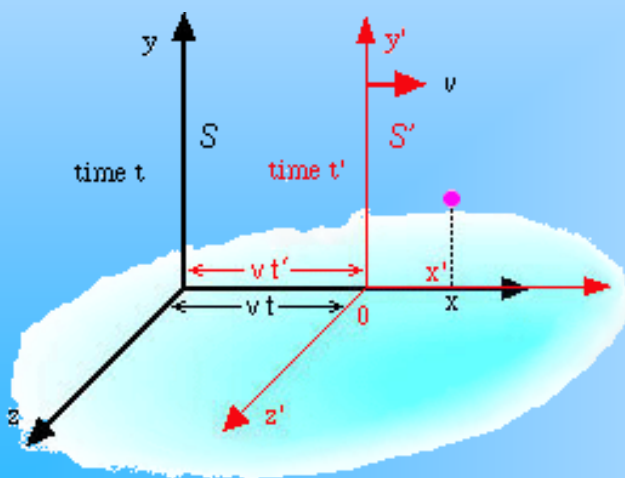
# NO SÉCULO XX



Albert Einstein  
(1879 - 1955)

**1905** Albert Einstein formula a teoria da relatividade, utilizando as transformações de Lorentz e estabelecendo 2 postulados:

- ➡ As leis da Física são as mesmas em todos os referenciais inerciais;
- ➡ A velocidade da luz é invariante em transformações de referenciais.



# *NO SÉCULO XX*

**1912** Albert Einstein tem “a idéia mais feliz de sua vida”.



**Princípio da Equivalência:** Um sistema inercial no qual há um campo de gravitação uniforme com aceleração da gravidade é equivalente a um sistema não-inercial, sem campo de gravitação, com a mesma aceleração.



# NO SÉCULO XX



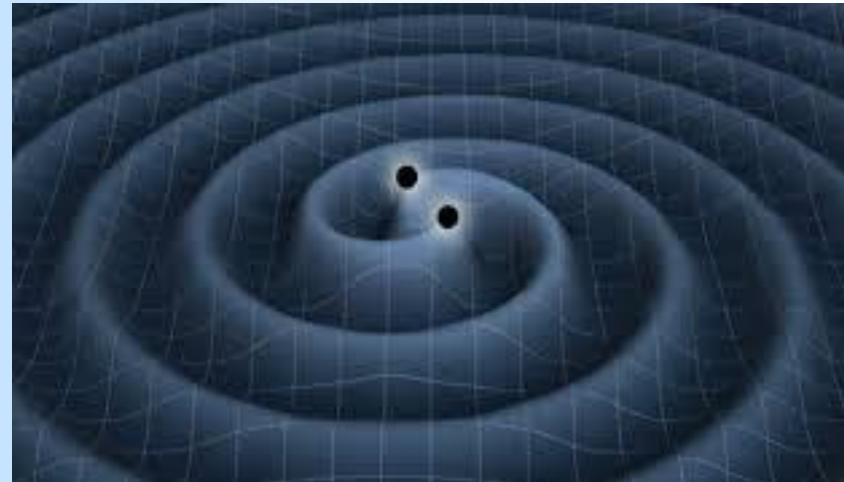
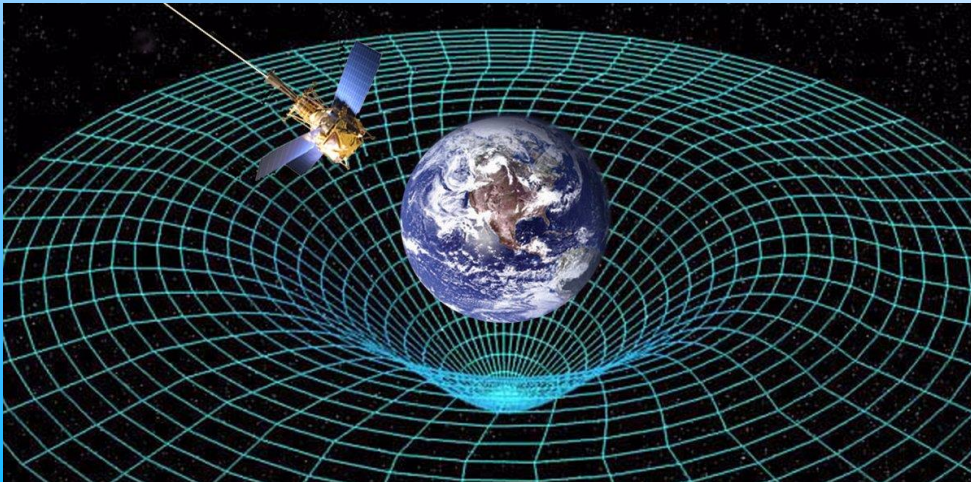
**1916** Albert Einstein publica “Os Fundamentos da Teoria da Relatividade Geral”.

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

(teoria geométrica da gravitação).

Previsões:

- curvatura trajetória da luz;
- ondas gravitacionais;
- Buracos negros.



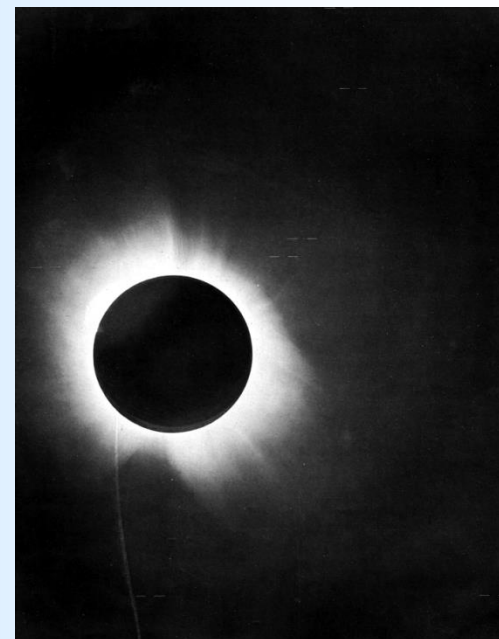
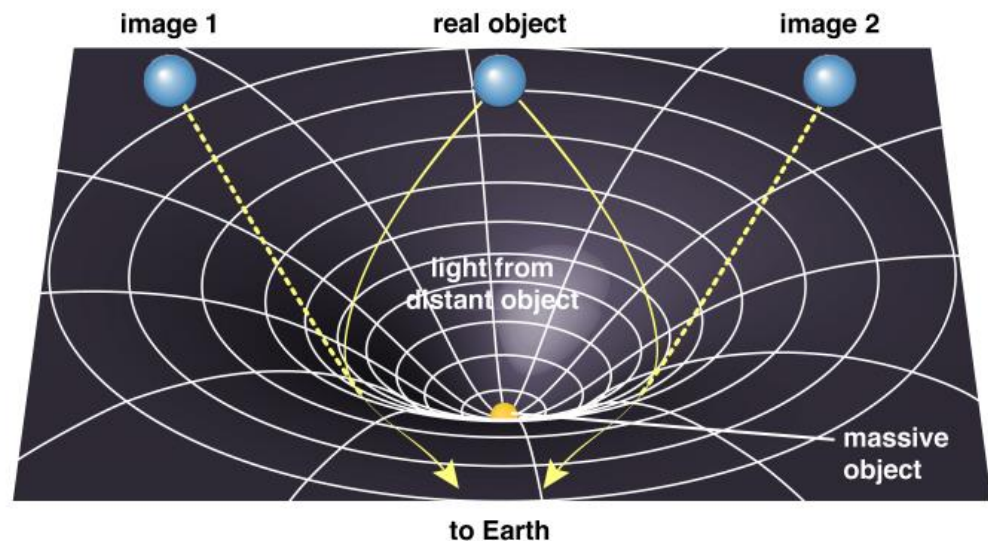
# *NO SÉCULO XX*

Eclipse solar de 29/05/1919:

**1919** Sir Arthur Eddington chefiou uma expedição à ilha de Príncipe (África) para tirar fotografias de um eclipse total. Ele observou um desvio na luz das estrelas que passavam pela vizinhança do Sol, confirmando a previsão de Einstein.



Arthur Eddington  
(1882 - 1944)

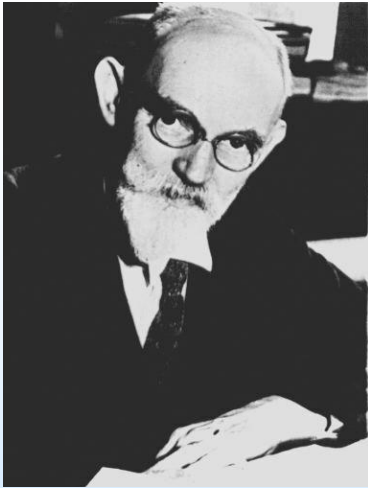


1917 Willem de Sitter produz um modelo de universo com expansão acelerada.



Willem de Sitter  
(1872-1934)

## *NO SÉCULO XX*



Willem de Sitter  
(1872-1934)

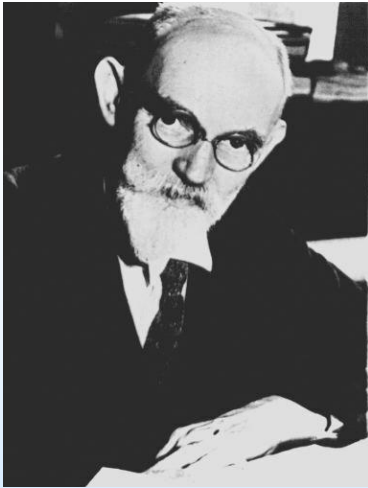
**1917** Willem de Sitter produz um modelo de universo com expansão acelerada.

**1916** Karl Scharzchild deu uma solução para o campo gravitacional de uma massa pontual.



Karl Scharzchild  
(1873-1916)

## *NO SÉCULO XX*



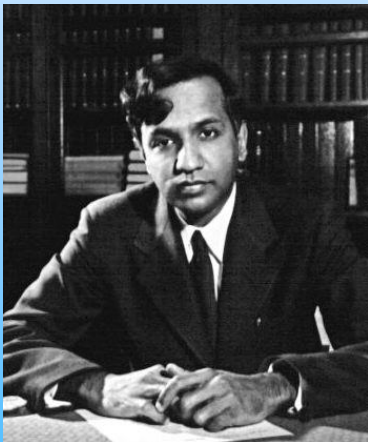
Willem de Sitter  
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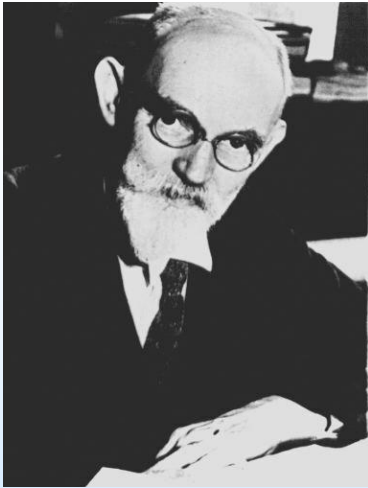
Karl Scharzchild  
(1873-1916)



Subrahmanyan  
Chandrasekhar  
(1910-1995)

**1920** Subrahmanyan Chandrasekhar mostrou que um corpo não radiante acima de uma certa massa colapsaria.

## *NO SÉCULO XX*



Willem de Sitter  
(1872-1934)

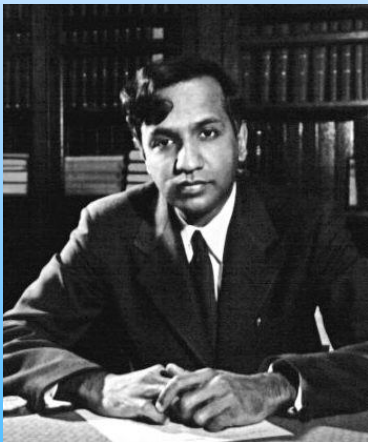
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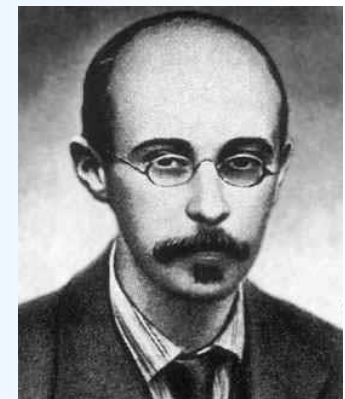
Karl Scharzchild  
(1873-1916)

**1920** Subrahmanyan Chandrasekhar mostrou que um corpo não radiante acima de uma certa massa colapsaria.



Subrahmanyan  
Chandrasekhar  
(1910-1995)

**1922** Alexander Friedmann elabora modelos do universo em expansão e em contração.



Alexander A.  
Friedmann  
(1888-1925)



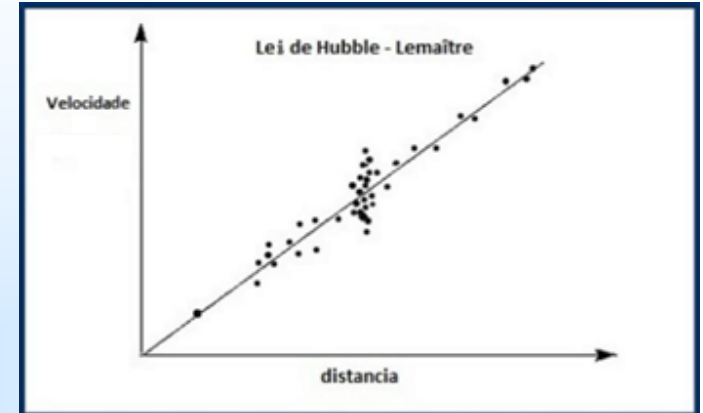
**1927** Geoges LeMaître elabora a teoria do Big-Bang e deduz a constante de Hubble.

Georges H. J. E.  
LeMaître  
(1872-1934)



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LeMaître  
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**1929** Edwin Hubble confirma a expansão do universo observando o desvio Doppler das linhas espectrais de galáxias distantes.



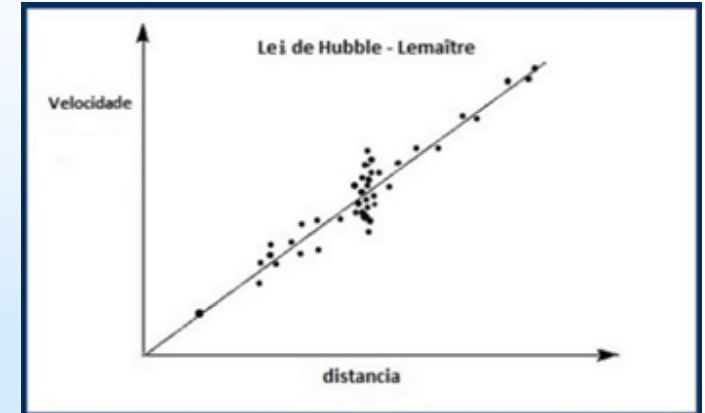
Edwin P. Hubble  
(1889-1953)





Georges H. J. E.  
LeMaître  
(1872-1934)

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**1931** Geoges LeMaître publica a teoria do átomo primordial.



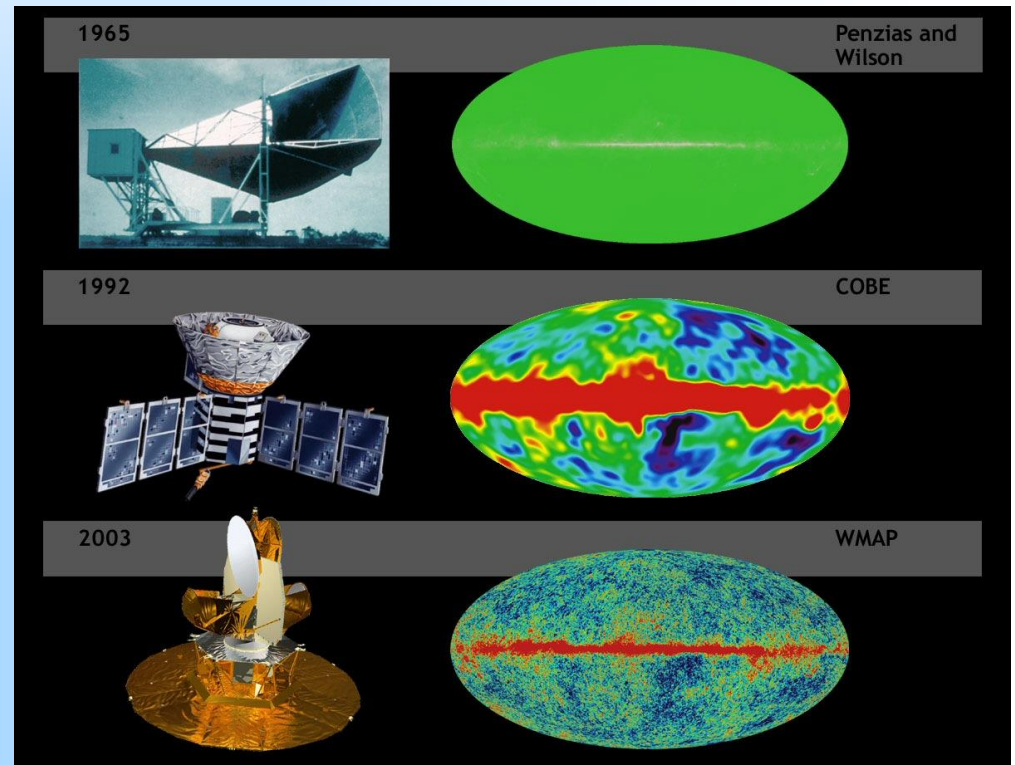
Edwin P. Hubble  
(1889-1953)

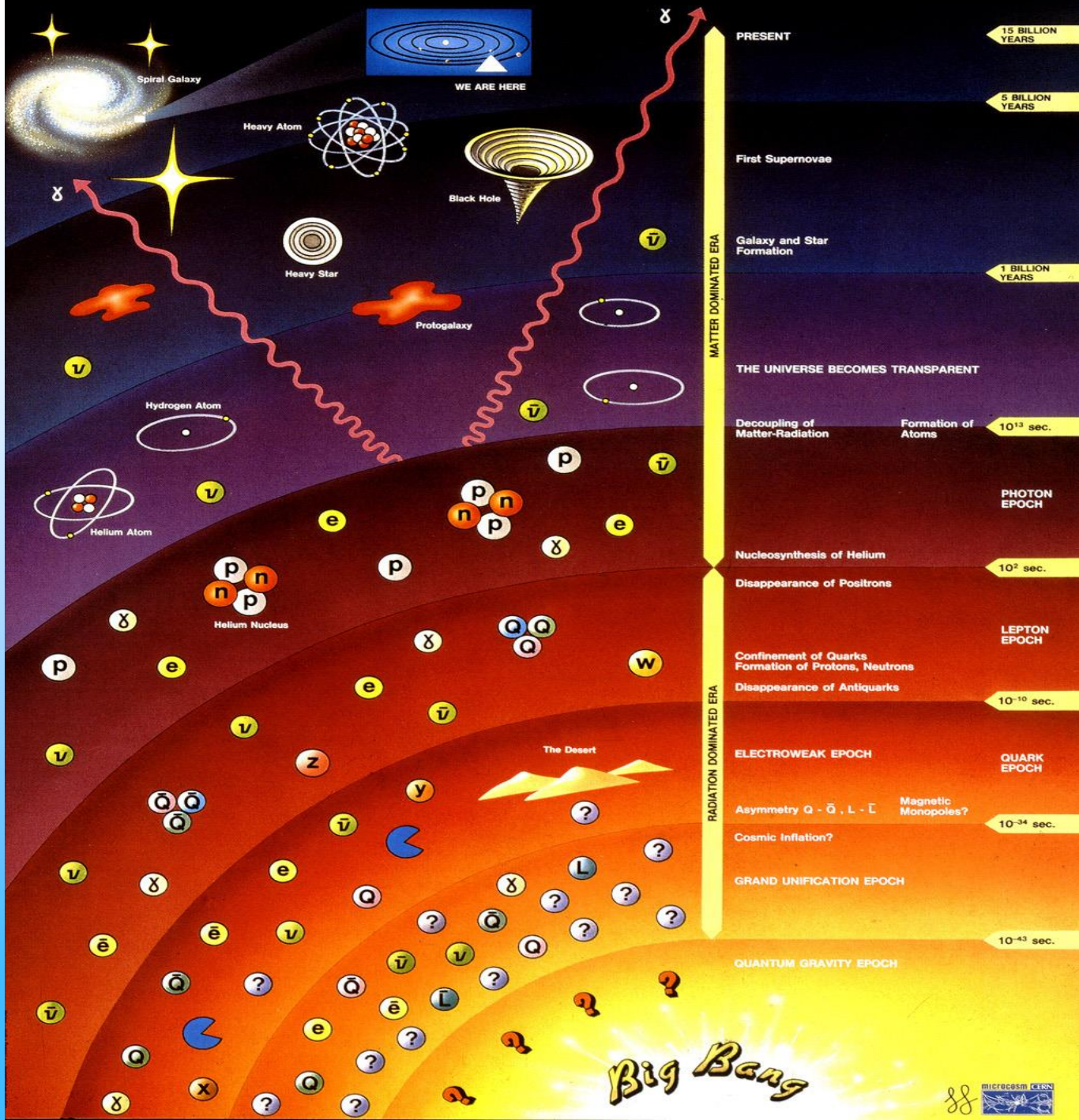
# *NO SÉCULO XX*



Robert Wilson (1936-) e Arno Penzias (1933-).

**1965** Penzias e Wilson detectam a radiação cósmica de fundo nas frequências de microondas.





**1783** John Michell (1724-1793) computou que um corpo com 500 vezes o raio do Sol e a mesma densidade teria em sua superfície sua velocidade de escape igual à velocidade da luz, então seria invisível.

**1783** John Michell (1724-1793) computou que um corpo com 500 vezes o raio do Sol e a mesma densidade teria em sua superfície sua velocidade de escape igual à velocidade da luz, então seria invisível.

**1796** Pierre-Simon de Laplace publicou a mesma idéia na 1ª edição do seu livro *Exposition du Systeme du Monde*.



Pierre-Simon de  
Laplace  
(1749-1827)

# NOS SÉCULOS XVIII & XX

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**1967** John Archibald Wheeler inventou o termo *buraco negro*.

John Archibald  
Wheeler  
(1911-2008)



Pierre-Simon de  
Laplace  
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# NOS SÉCULOS XVIII & XX

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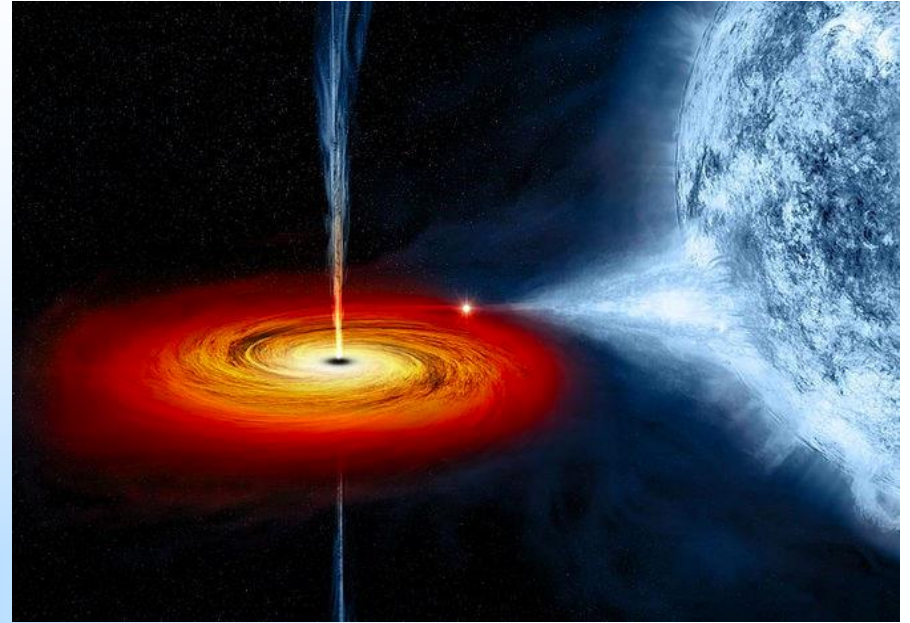
Roger Penrose  
(1931-)



Stephen W. Hawking  
(1942-2018)

**1967** Roger Penrose e Stephen Hawking mostram que os buracos negros são características inevitáveis da teoria da gravitação de Einstein e estudam suas diversas propriedades.

# Buracos negros





M87

*Nova imagem (2021) obtida pelos astrônomos do Event Horizon Telescope mostra luz saindo do buraco negro.*

# Sinal de uma colisão cósmica invisível

Ondas gravitacionais geradas em galáxia distante viajaram 1,3 bilhão de anos-luz até chegar à Terra

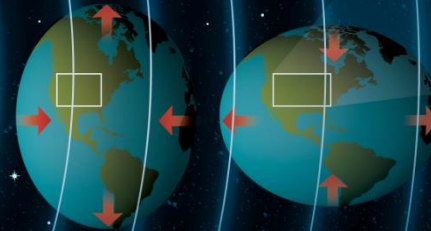


**COLISÃO DE BURACOS NEGROS**  
Em uma galáxia muito distante e ainda desconhecida, dois buracos negros emitem ondas gravitacionais enquanto espiralam um ao redor do outro até colidirem e se fundirem, formando um novo buraco negro

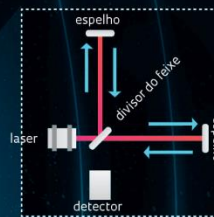
FONTE: LIGO SCIENTIFIC COLLABORATION

## TERRA DISTORCIDA

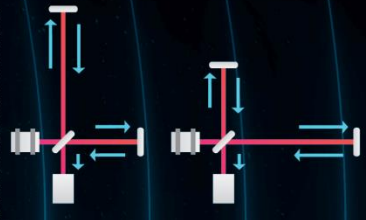
Ao atravessarem a Terra, as ondas gravitacionais deformam o planeta, ora esticando em uma direção, ora comprimindo em outra



## DETECTOR LIGO



O Ligo usa lasers e espelhos para monitorar variações minúsculas no tamanho de seus dois braços perpendiculares

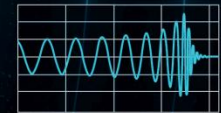


Ondas gravitacionais primeiro esticam um dos braços enquanto outro encolhem o outro

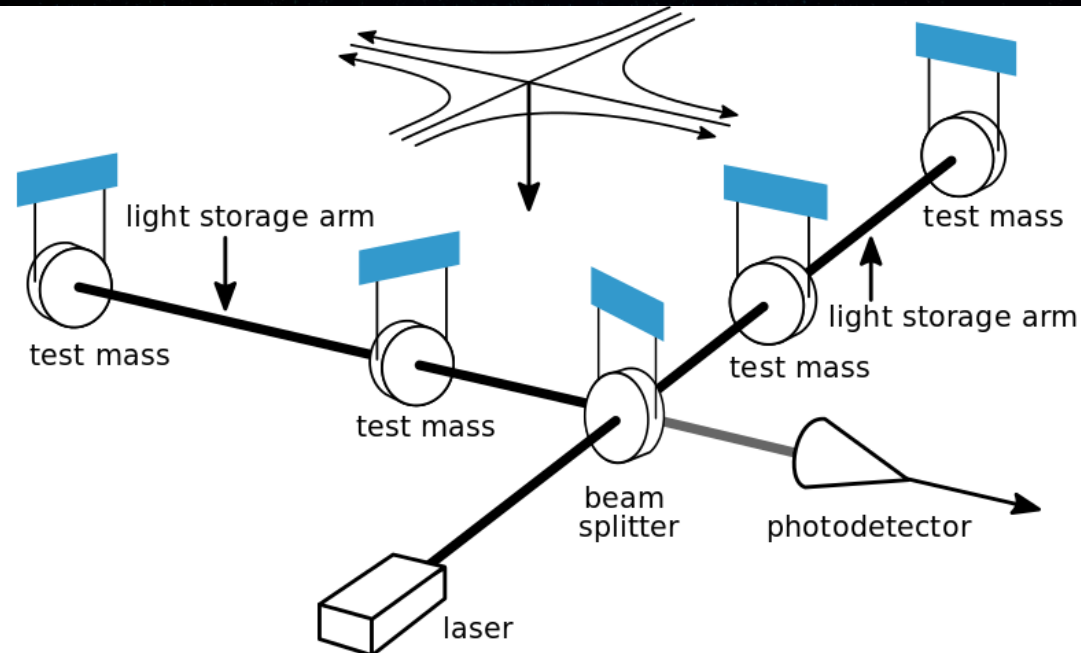
Em seguida, as ondas fazem o contrário, comprimem o braço que esticaram anteriormente e vice-versa

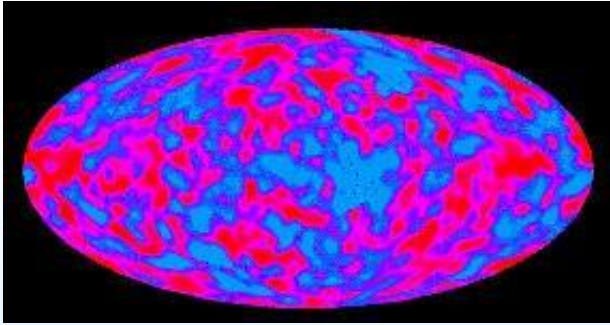
## ONDA DETECTADA

Mudanças na amplitude e na frequência do estica e puxa das ondas revelam detalhes do movimento dos buracos negros



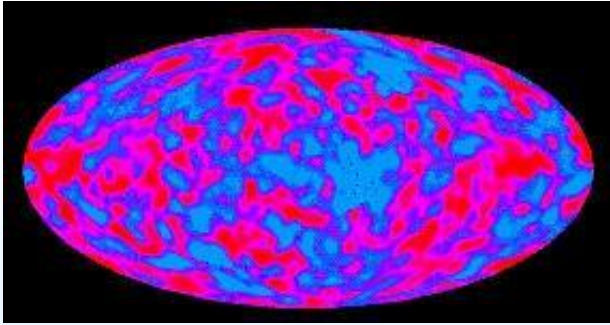
Em **14/09/2015**, os detectores do LIGO (Laser Interferometer Gravitational-Wave Observatory) captaram o sinal da fusão de 2 buracos negros há 1,3 bilhão de anos-luz da Terra.





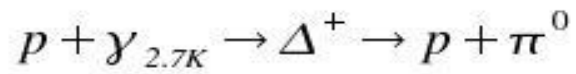
**CMB:**

A. A. Penzias and R. Wilson, *Astroph. J.*, **142** (1965) 419



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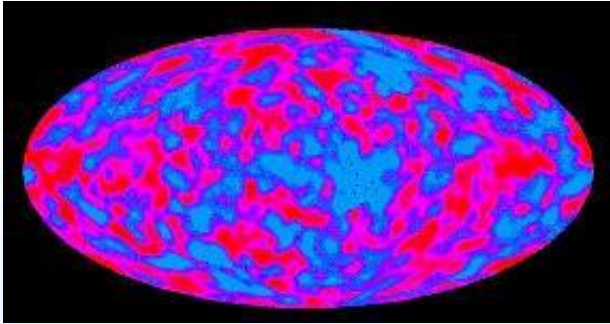


K. Greisen, *Phys. Rev. Lett.*, **16** (1966) 748

G. T. Zatsepin, V. A. Kuz'min, *Pis'ma Zh. Eksp. Theor. Fiz.* **4** (1966) 53

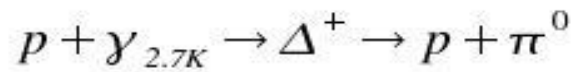


Kenneth Greisen (1918-2007),  
Georgiy Zatsepin (1917-2010) &  
Vadim Kuz'min (1937-).



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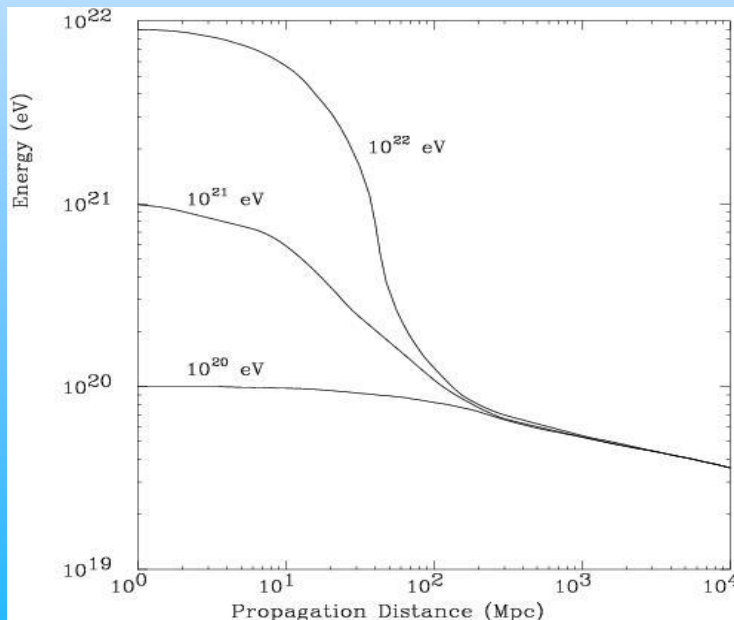


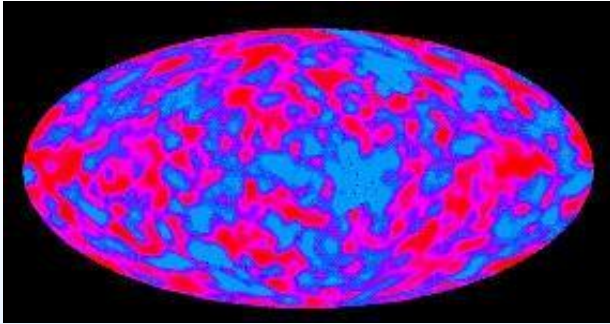
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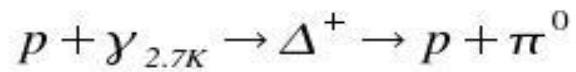
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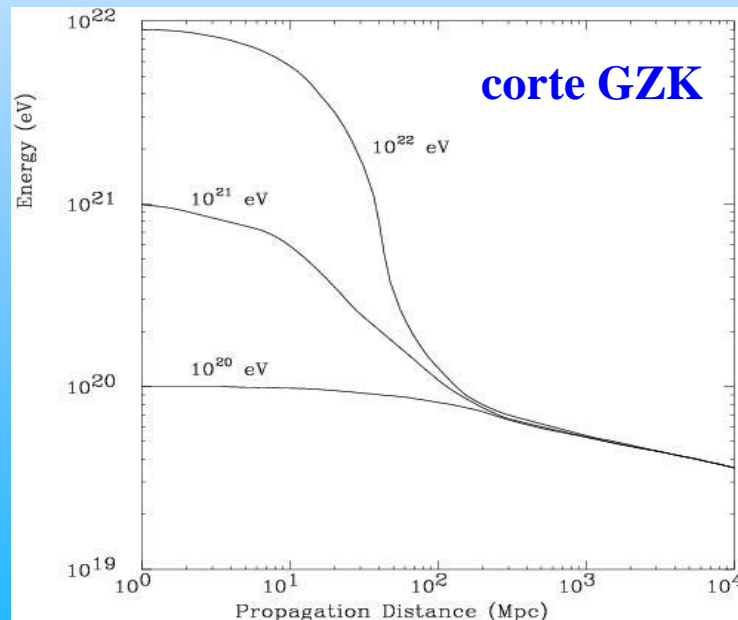


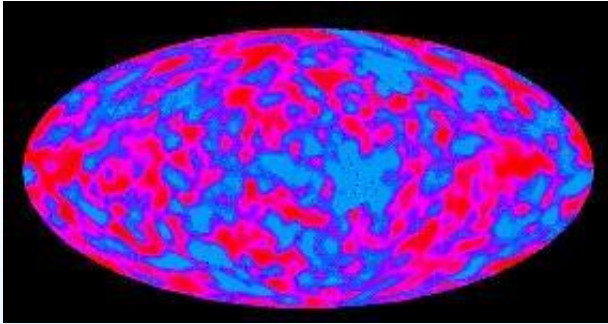
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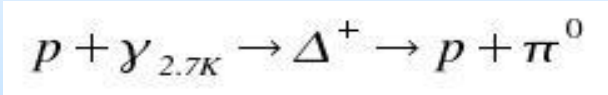
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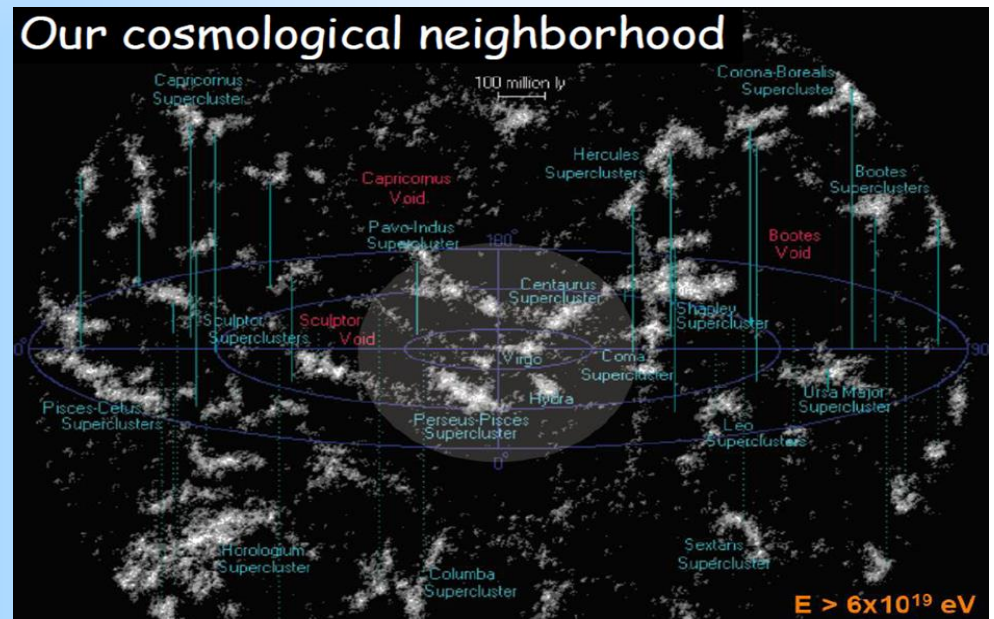
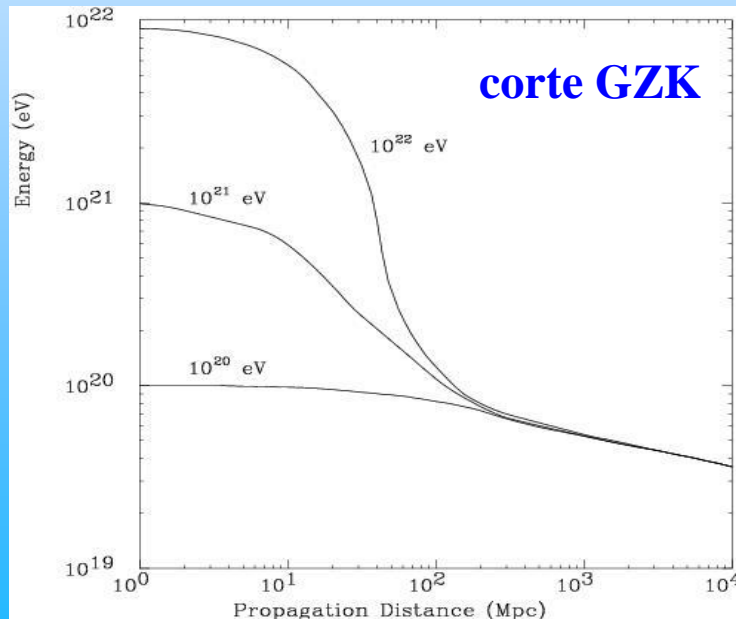


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Kenneth Greisen (1918-2007),  
Georgiy Zatsepin (1917-2010) &  
Vadim Kuz'min (1937-).



(1962)

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY  $10^{20}$  eV†

John Linsley

Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

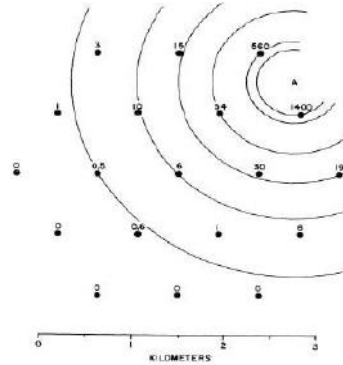
(Received 10 January 1963)

MIT Volcano Ranch (1962):

$N = 5 \times 10^{10}$  particles

$E_0 = 1 \times 10^{20}$  eV

$1.6 \times 10^{19}$  eV = 1 Joule

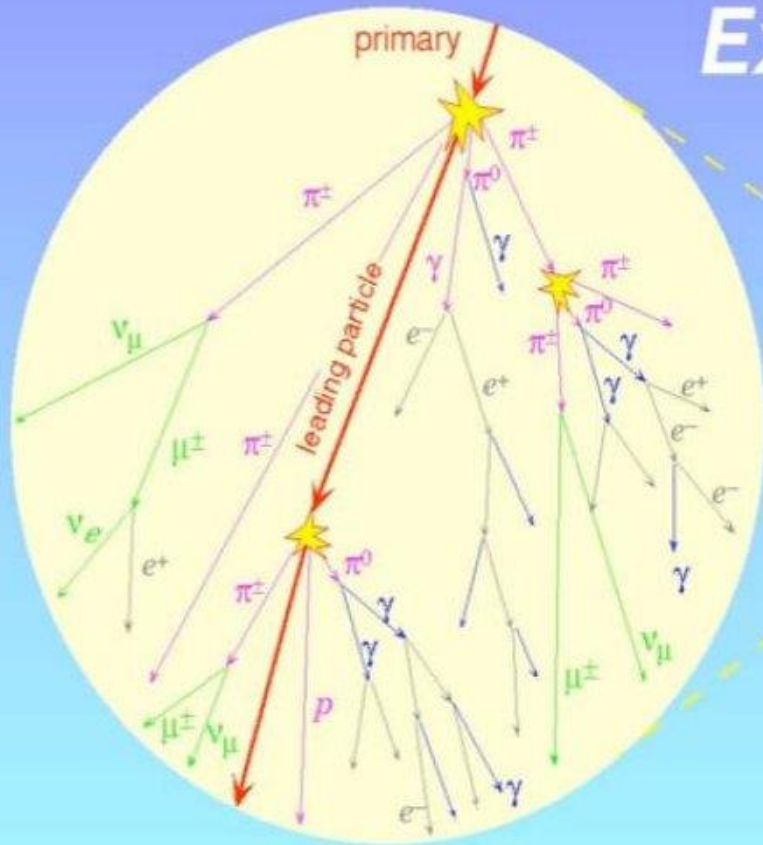


John David Linsley (1925-2002)



# Extensive Air Shower (EAS)

$$E > 10^{14} \text{eV}$$



Particle Composition at ground:	
$\approx 80\%$ photons	
$\approx 18\%$ electrons	
$\approx 1.7\%$ muons	
$\approx 0.3\%$ hadrons	
$\approx 10^6$ secondaries	for $10^{15}$ eV proton



$\approx 1$  m thickness  
 $U \approx C$

Fluorescence,  
Cherenkov light

sh detector array

hadron calorimeter

ca. 100-200 m

Some EAS arrays:

- Volcano Ranch, USA (1959-1962);
- Haverah Park, UK (1968-1987);
- SUGAR, Australia (1968-1979);
- Yakutsk, Russia (1969 -1990);
- Akeno, Japan (1980 ++);
- AGASA, Japan (1986 ++ );
- EASTOP , Italy (1989-1999);
- CASA/MIA, USA (1990 ++);
- Kascade, Germany (1995 ++);
- Pierre Auger Observatory, Argentina (2001++).

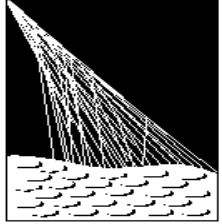


1994 The AGASA Group in Japan and the Yakutsk group in Russia each reported an event with an energy of  $E = 2 \times 10^{20}$  eV.

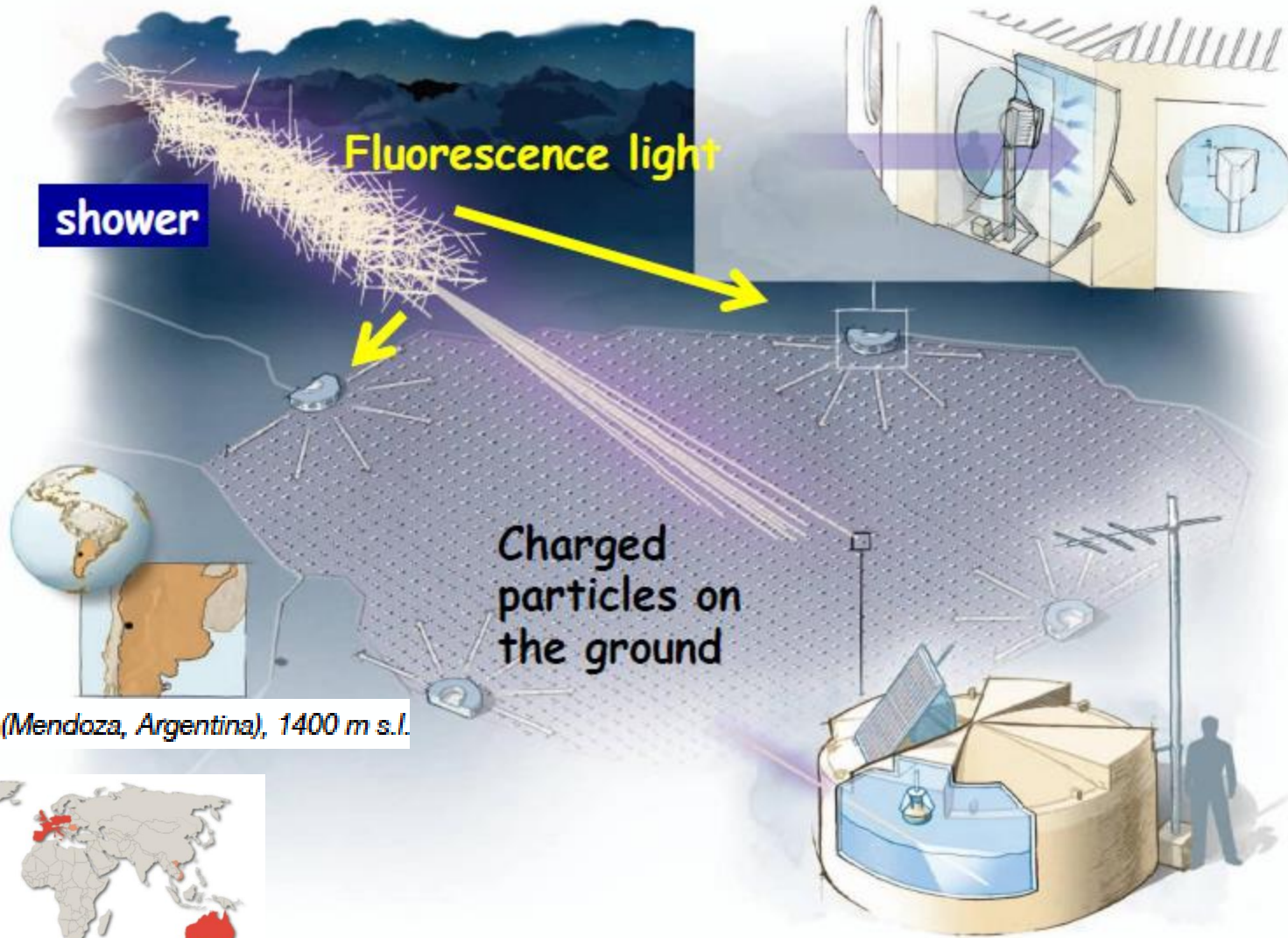


Pierre Auger Observatory

# Pierre Auger Observatory layout

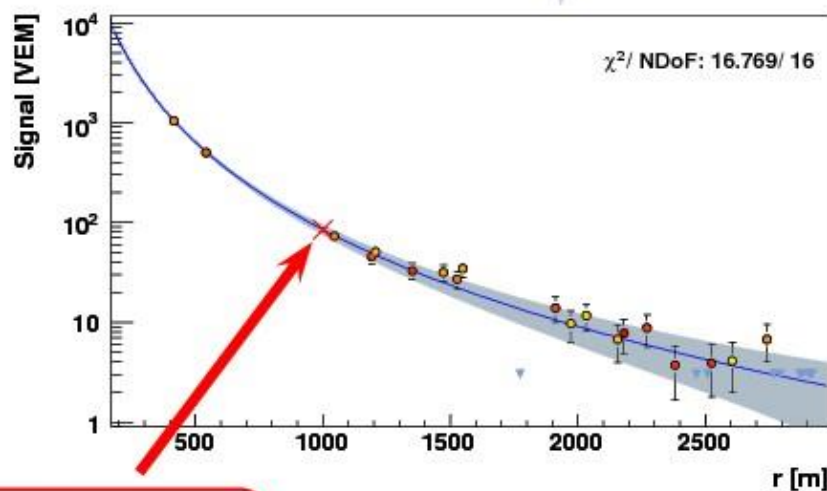
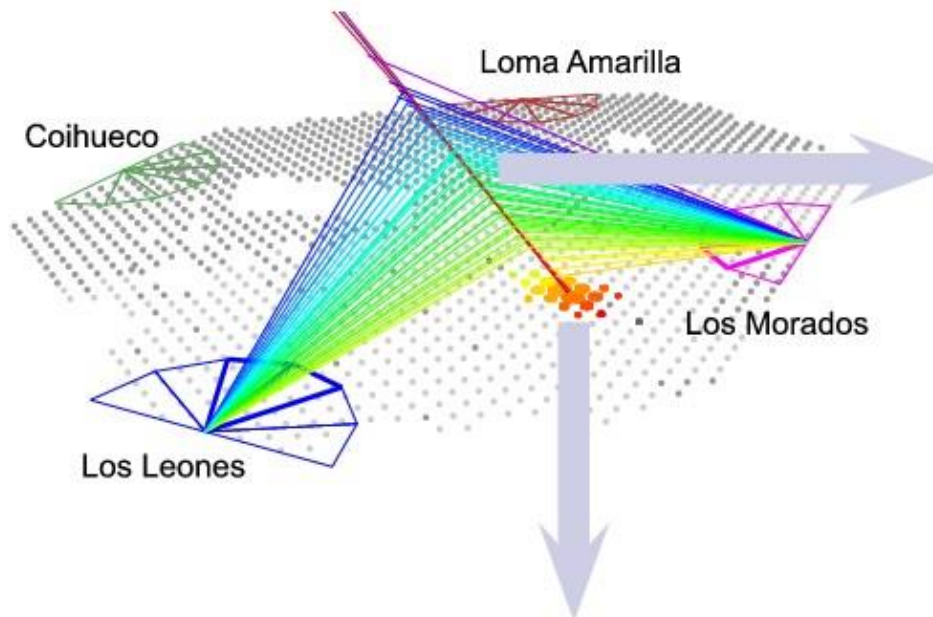
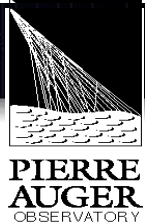


**PIERRE  
AUGER**  
OBSERVATORY



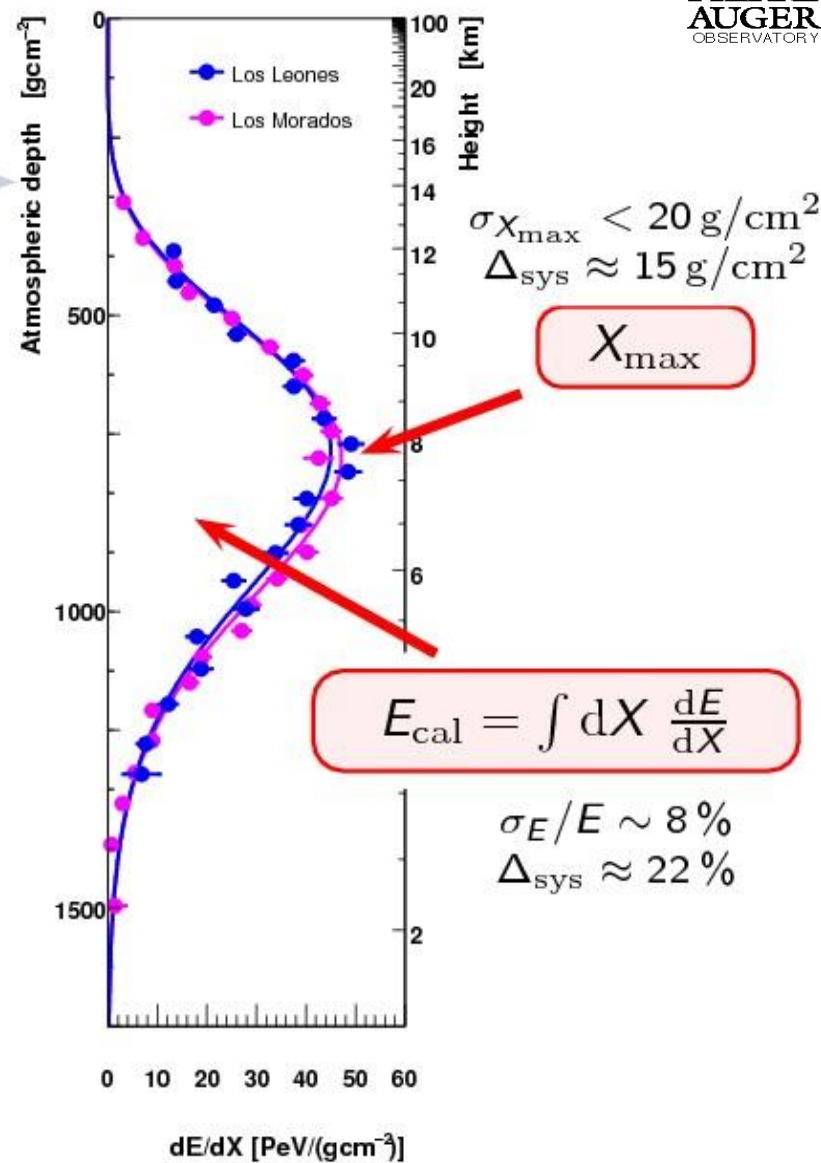
17 countries, ~ 500 physicists

# Data and Observables at the Pierre Auger Observatory



$S_{1000}$

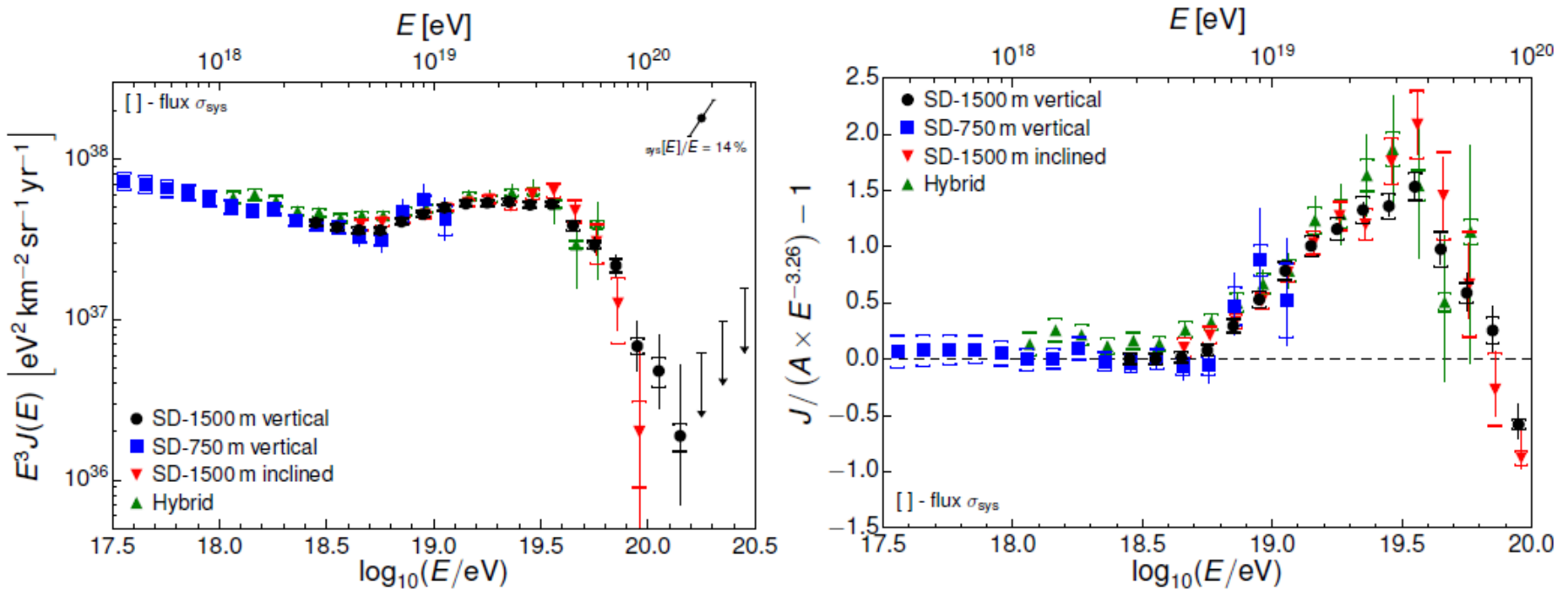
$$E_{\text{surface}} = f(S_{1000}, \theta)$$



$$E_{\text{cal}} = \int dX \frac{dE}{dX}$$

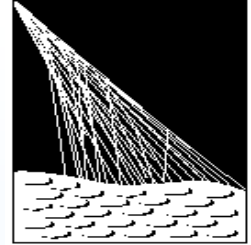
$\sigma_E/E \sim 8\%$   
 $\Delta_{\text{sys}} \approx 22\%$

# UHECR spectrum



- systematic uncertainty on the energy scale: 14%
- flux uncertainty: 6% (SD)

Science (Nov/2007)



**PIERRE  
AUGER**  
OBSERVATORY

AAAS

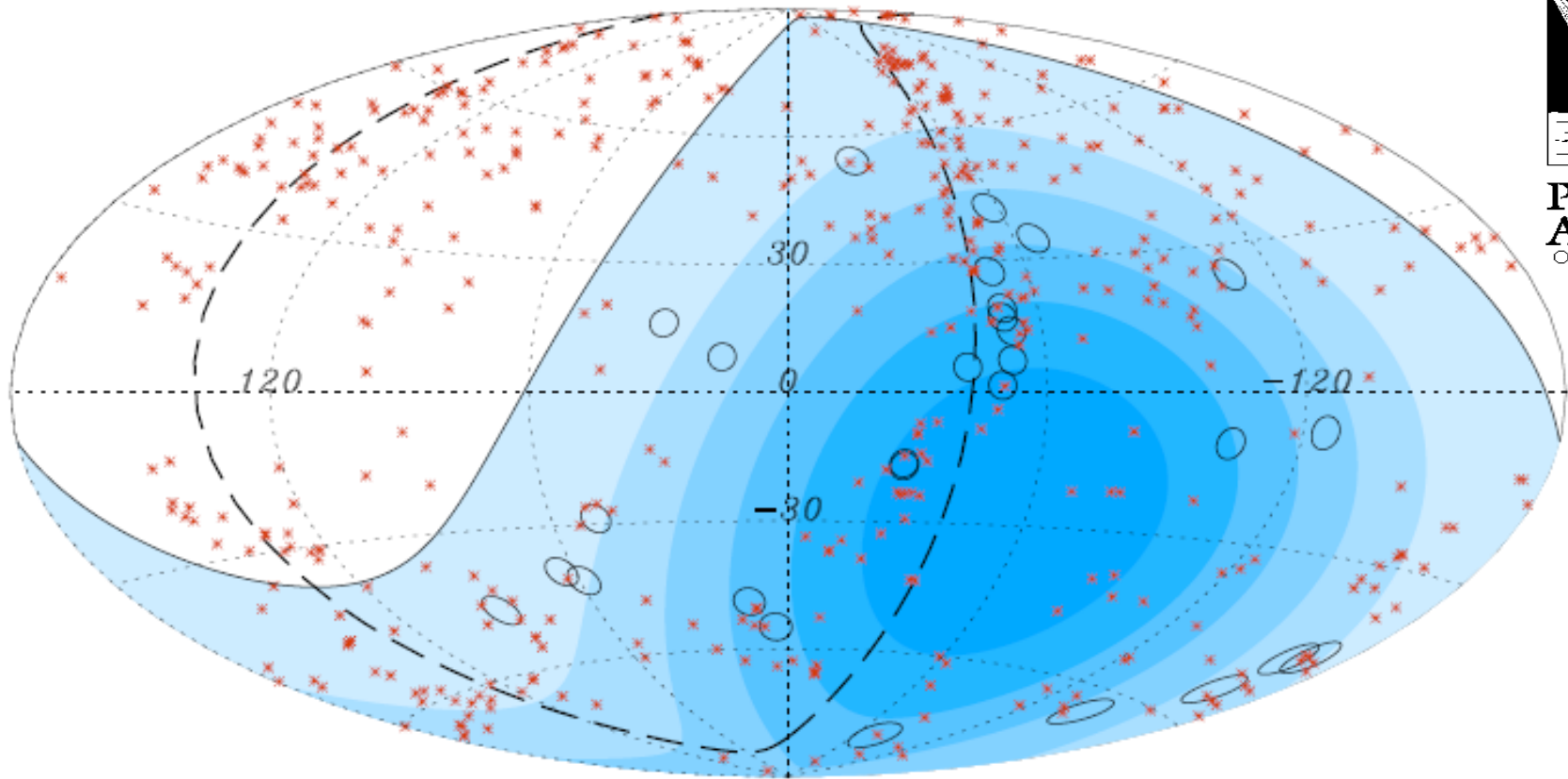


Figure 1: Aitoff projection of the celestial sphere in galactic coordinates with circles of radius  $3^\circ$  centered at the arrival directions of the 28 cosmic rays with highest energy (above approximately 60 EeV) detected by the Pierre Auger Observatory. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift  $z \leq 0.018$  ( $D < 75$  Mpc) from the 12<sup>th</sup> edition of the catalog of quasars and active nuclei (9) are indicated by red asterisks. The solid line draws the border of the field of view (zenith angles smaller than  $60^\circ$ ). Darker colour indicates larger relative exposure. Each coloured band has equal integrated exposure. The dashed line is, for reference, the supergalactic plane. A significant correlation of the arrival directions is observed over angular scales in the range between 3 and 6 degrees, with the AGN that are at distances smaller than a maximum between 50 and 100 Mpc from Earth.

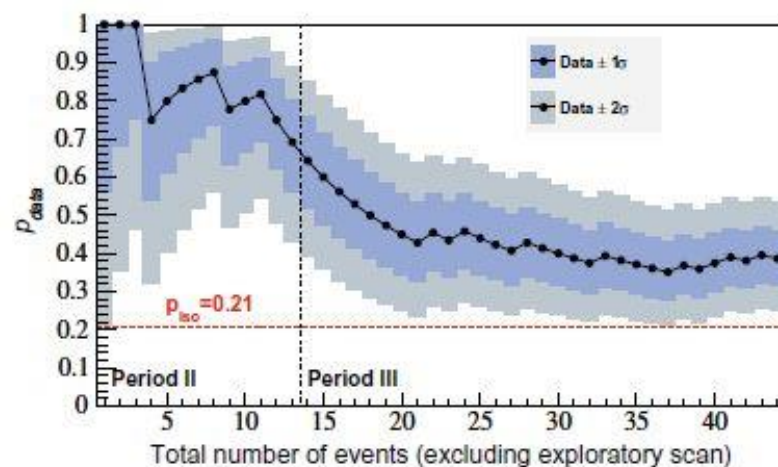
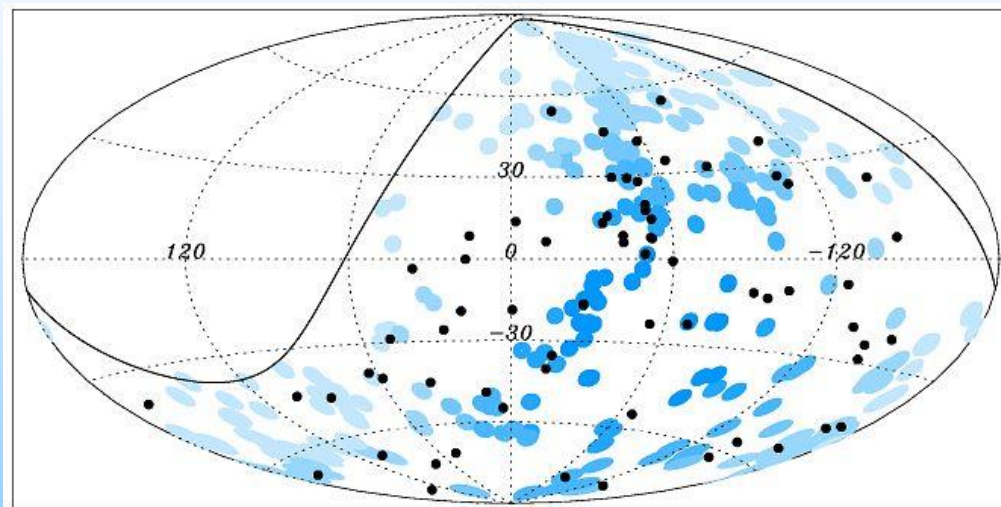


Figura 1.5: À esquerda: Direção de chegada de 69 eventos medidos pelo Auger com energias acima de  $5.5 \times 10^{19}$  eV (pontos pretos) e a de galáxias com núcleos ativos distantes de até 75 Mpc (círculos azuis, onde a cor mais escura indica maior exposição relativa do observatório); à direita: evolução do grau de correlação ( $p_{data}$ ) em função do número total de eventos ordenados (estima-se atualmente uma correlação de  $0.38 \pm 0.07$ , ou seja,  $> 2\sigma$  do esperado para uma distribuição isotrópica).



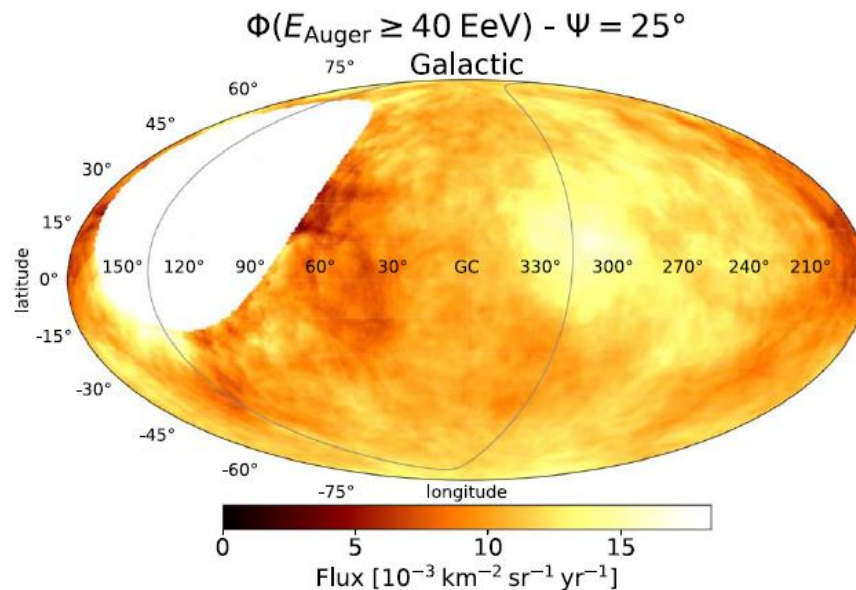


Figure 8. Flux map at energies above 40 EeV with a top-hat smoothing radius of  $\Psi = 25^\circ$  in Galactic coordinates. The supergalactic plane is shown as a gray line. The blank area is outside the field of view of the Pierre Auger Observatory. The complete figure set (49 images), which shows the map as a function of energy threshold, is available in the online journal.

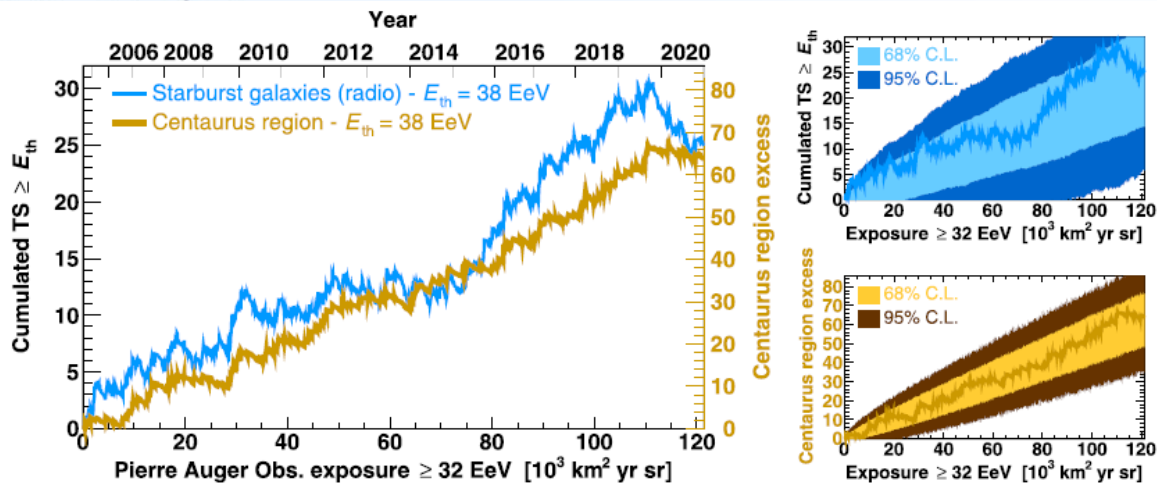
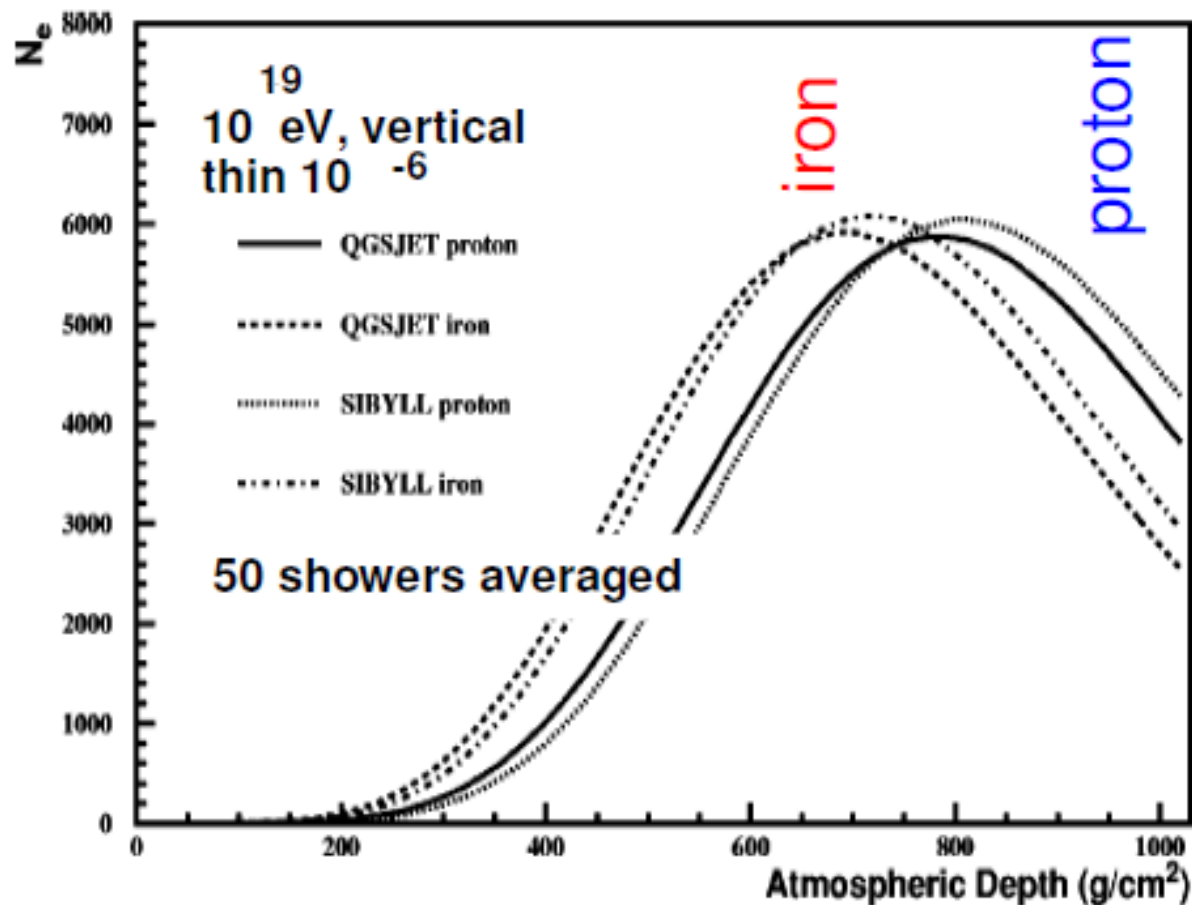
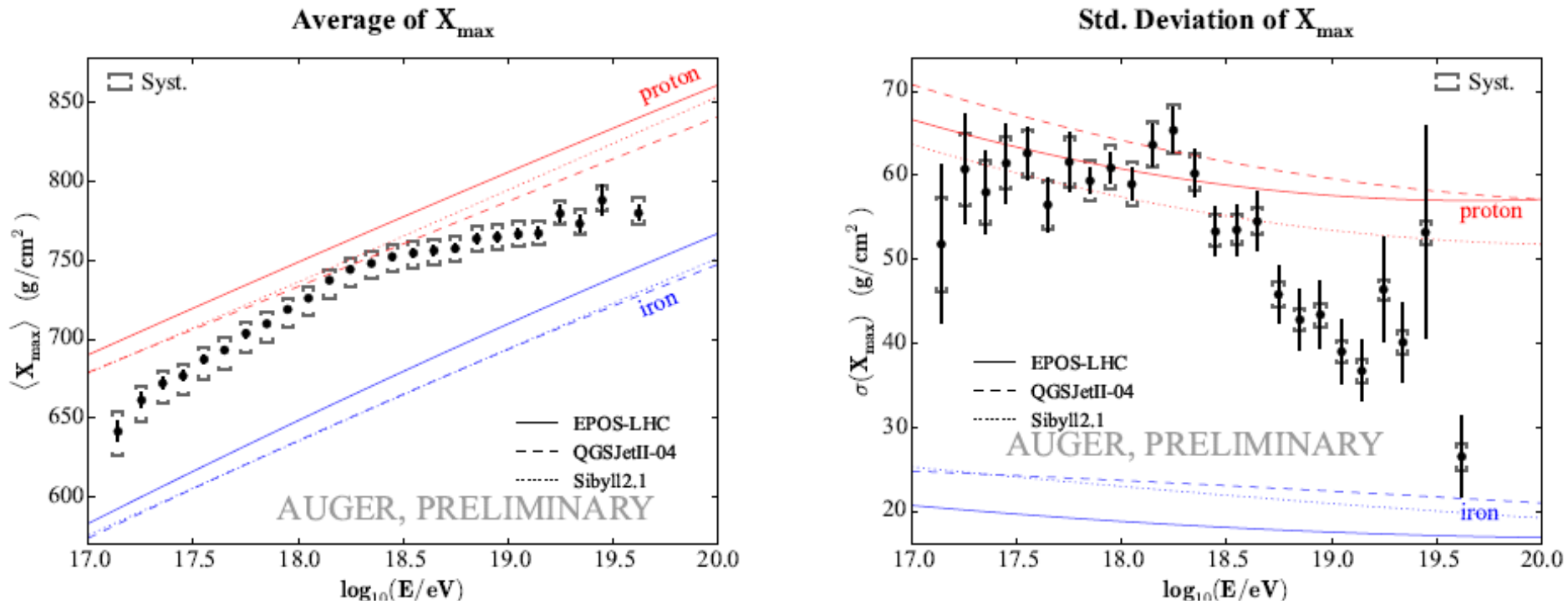


Figure 7. TS of the starburst model and excess in the Centaurus region above the best energy threshold as a function of exposure accumulated by the Pierre Auger Observatory. The fluctuations around the expected linear behavior are consistent with those expected from signal simulations, as illustrated in the right-most panels.

# Average Longitudinal profiles for proton and iron primaries according to EAS simulations.

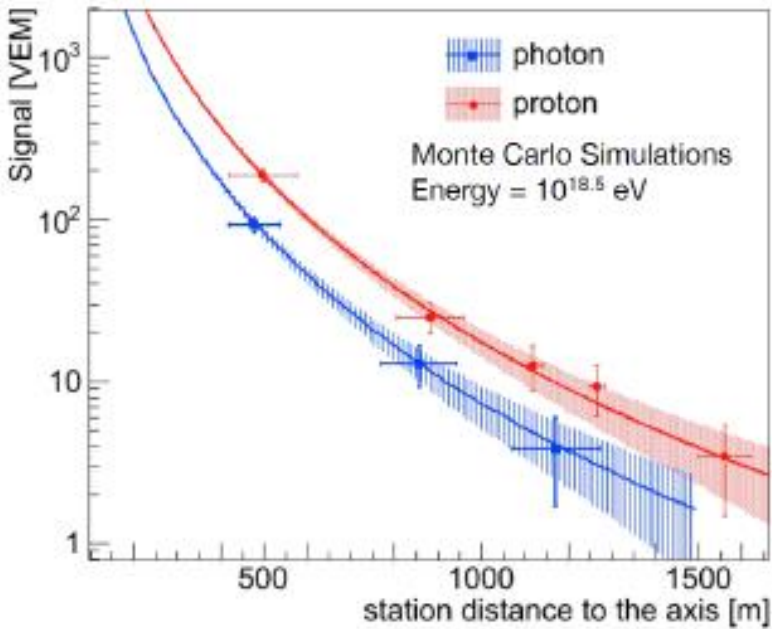
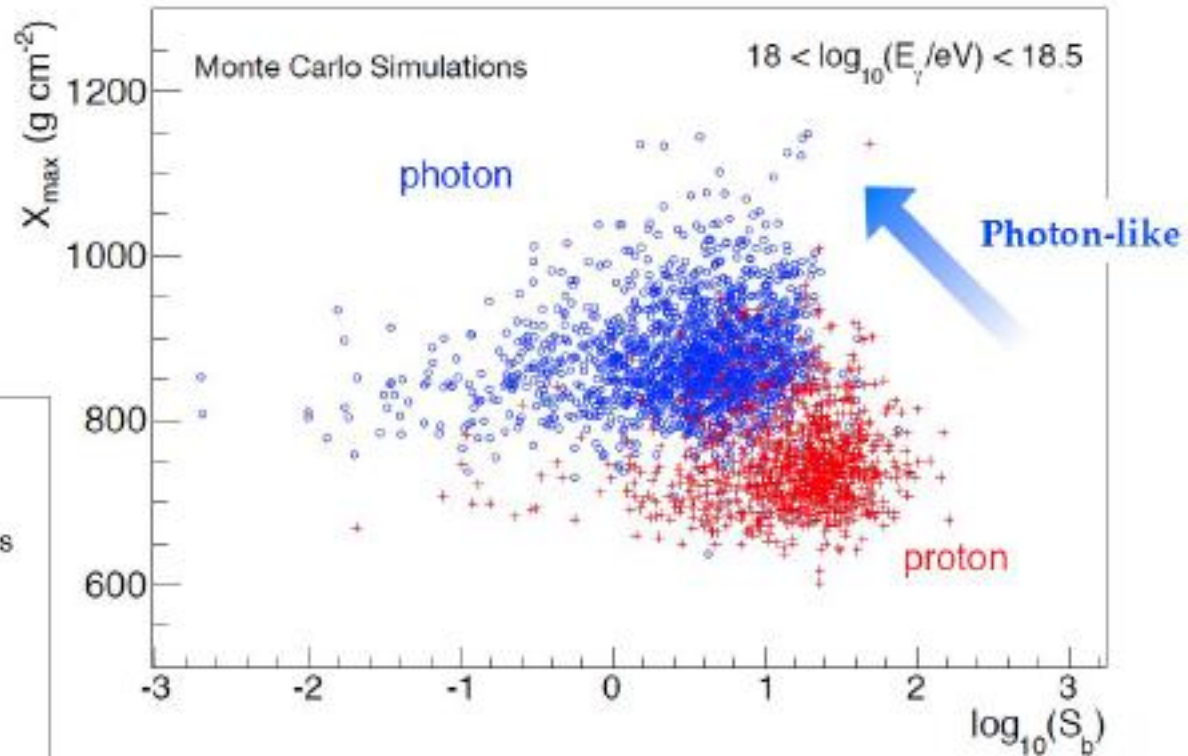
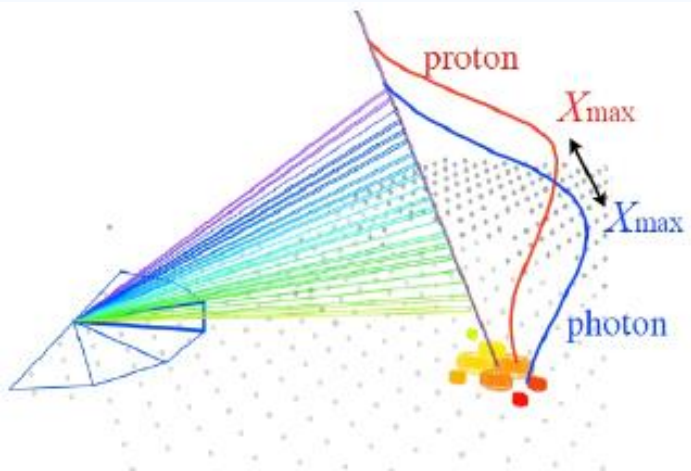


# Shower maximum & composition

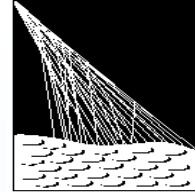


**Figure 7.**  $X_{\max}$  (left) and  $\sigma(X_{\max})$  (right) as a function of primary energy, and comparison to the expectations from simulated showers with different hadronic models for proton (red) and iron (blue) primaries.

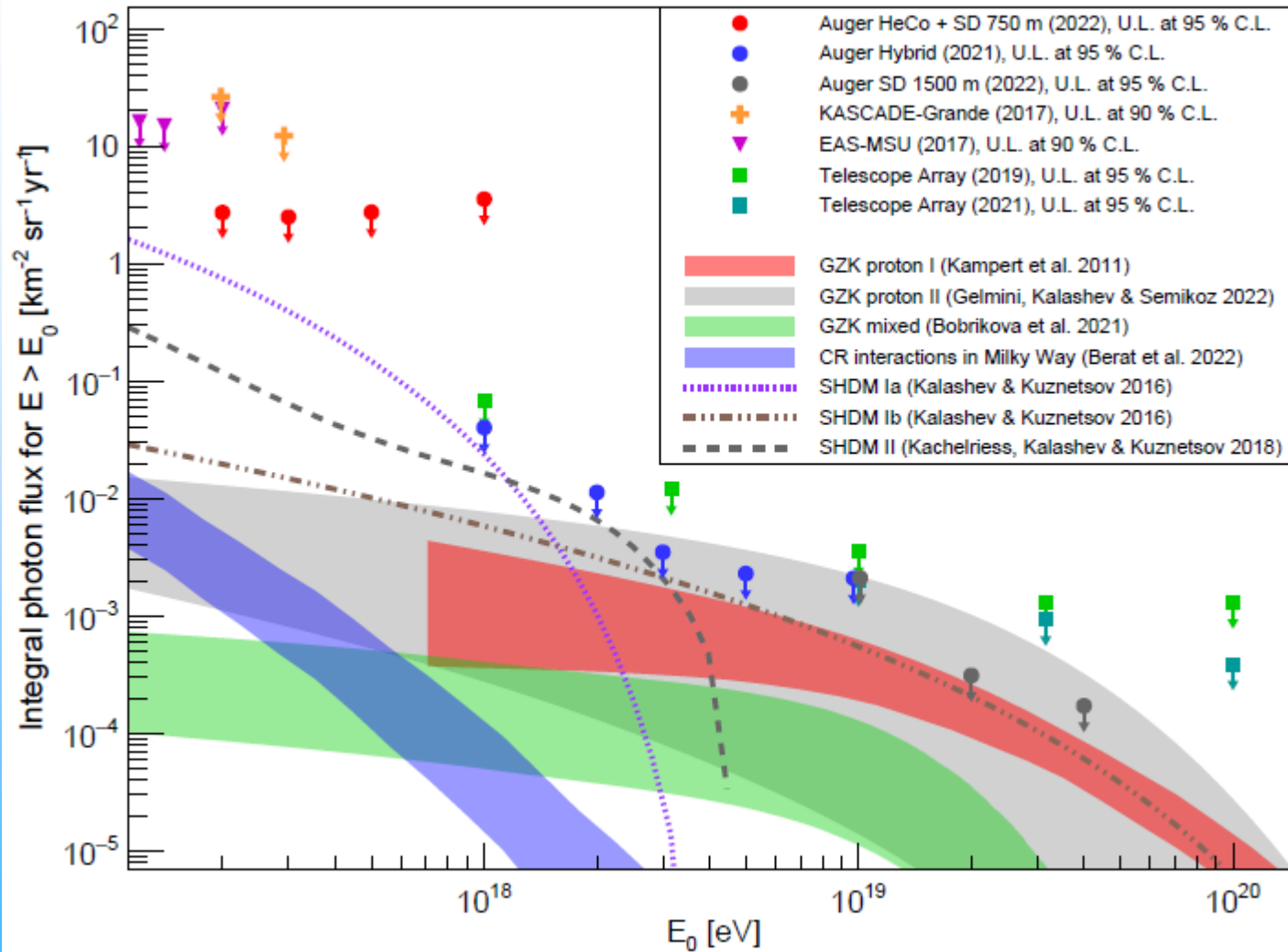
# Photon induced showers



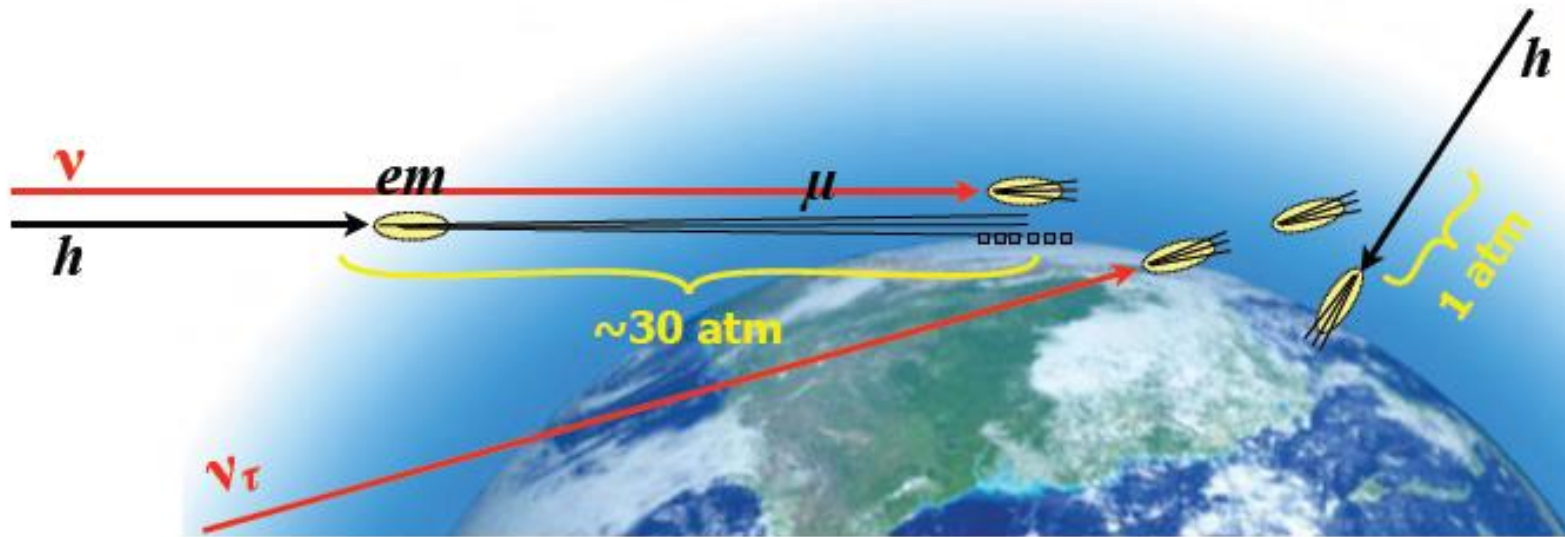
# Upper limits on UHE photons



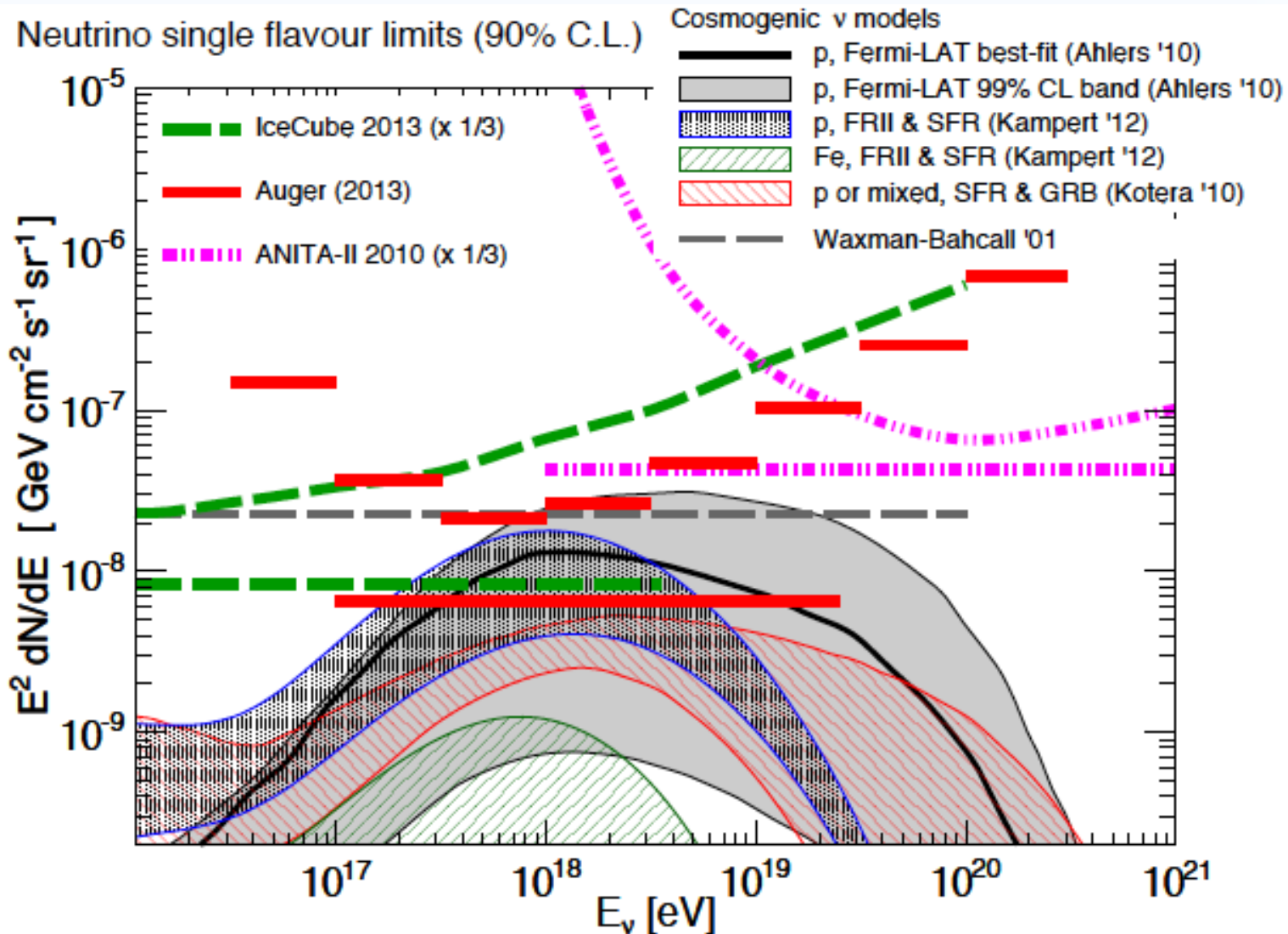
PIERRE  
AUGER  
OBSERVATORY



# Neutrino induced showers



# Diffuse UHE neutrino limits





## Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*\*

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

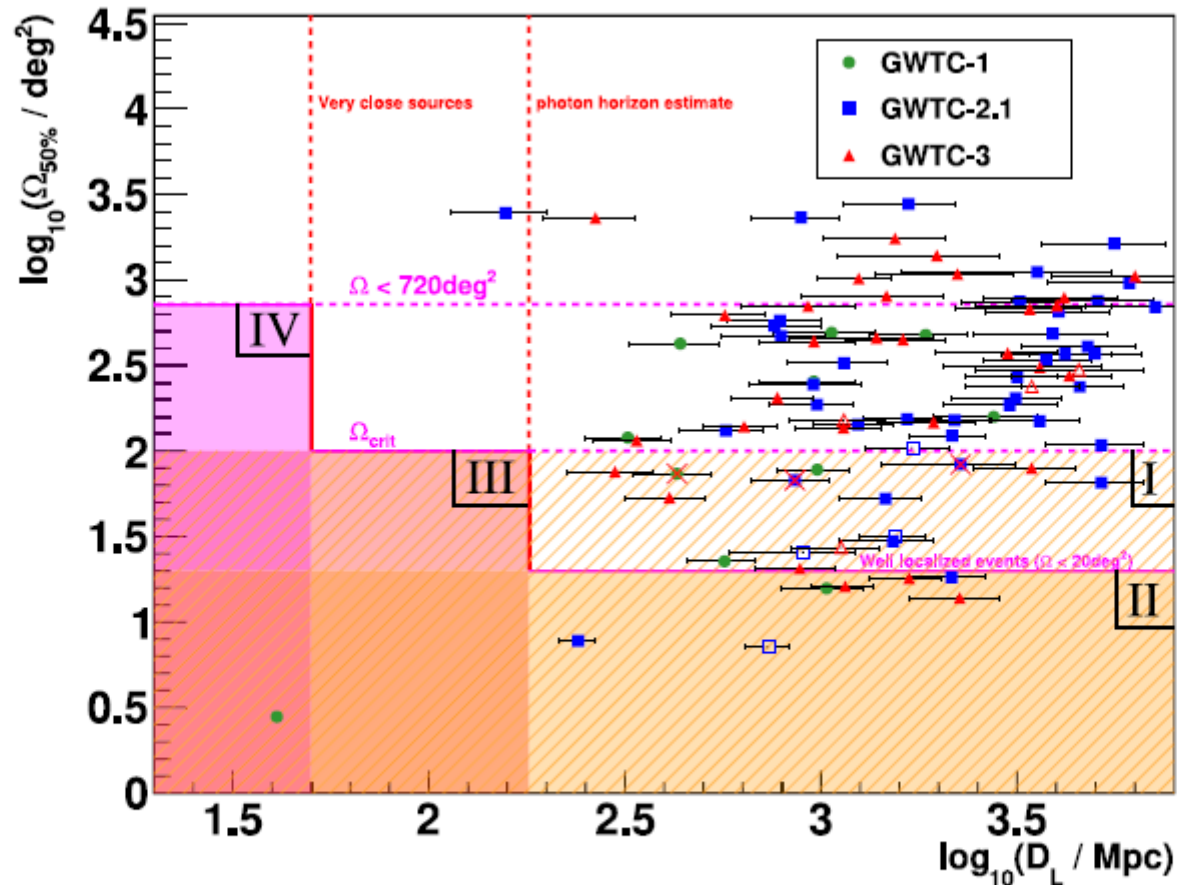
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of  $1.0 \times 10^{-21}$ . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than  $5.1\sigma$ . The source lies at a luminosity distance of  $410_{-180}^{+160}$  Mpc corresponding to a redshift  $z = 0.09_{-0.04}^{+0.03}$ . In the source frame, the initial black hole masses are  $36_{-4}^{+2} M_{\odot}$  and  $29_{-4}^{+4} M_{\odot}$ , and the final black hole mass is  $62_{-4}^{+4} M_{\odot}$ , with  $3.0_{-0.2}^{+0.5} M_{\odot} c^2$  radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102





# Correlation of UHE photons and Gravitational Waves



**Figure 2.** All GW events from GWTC-1 (green dots), GWTC-2.1 (blue squares), and GWTC-3 (red triangles) in the space of source distance  $D_L$  and localization  $\Omega_{50\%}$ . Events which are not within the field of view in the 1 day time window are drawn with empty markers, while events which do at least partially overlap have solid markers. Three red crosses mark the events which pass the selection criteria for the short time window and also have an overlap with the field of view during that time. The shaded regions define the set of accepted events according to the selection criteria described in the text. The hatched region marks class I, which is solely relevant for the short analysis time window, and the solid regions mark classes II, III, and IV.

***E NO FUTURO?***

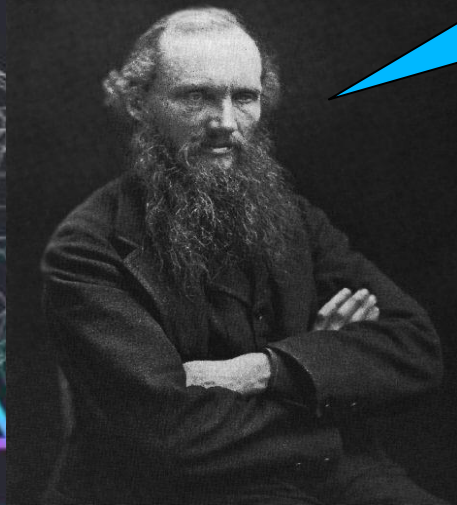


# NO SÉCULO XXI++

$$\hat{H} = \sum_{n=1}^N \frac{\hat{p}_n^2}{2m_n} + V(x_1, x_2, \dots, x_N)$$

$$E^2 - (pc)^2 = (mc^2)^2,$$

“A física está completa!” ?



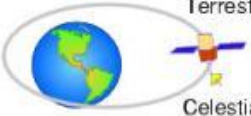
$$-(q\phi)^2 - (pc - qA)^2 = (mc^2)^2.$$



$$\frac{-\hbar^2}{2m} \frac{\partial^2 \Psi(x,t)}{\partial x^2} + U(x) \Psi(x,t) = i\hbar \frac{\partial \Psi(x,t)}{\partial t}$$

$$H(t) |\Psi(t)\rangle =$$

Terrestrial mechanics




Celestial mechanics


**Universal Gravitation**  
Inertial vs. Gravitational mass  
(I. Newton, 1687)

---

Electricity




Magnetism




**Electromagnetism**  
Electromagnetic waves (photon)  
(J.C. Maxwell, 1860)

---

Electromagnetism



Weak force



**Electroweak**  
Intermediate bosons W, Z  
(1970-83)

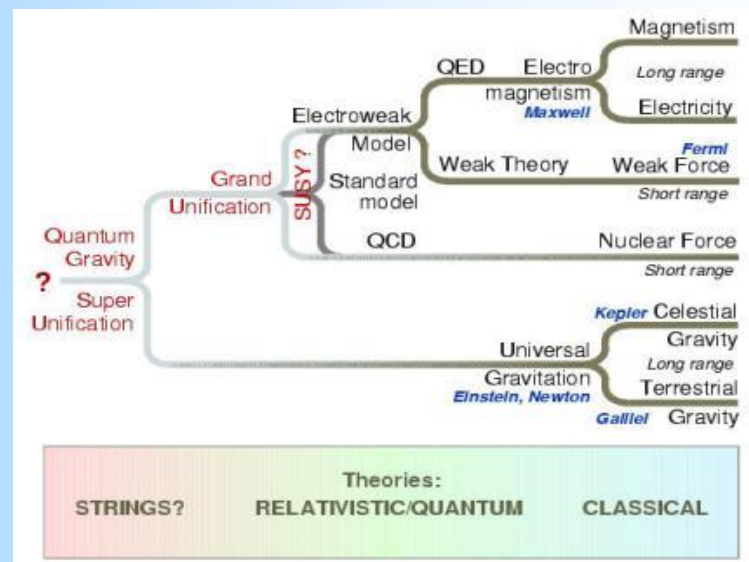
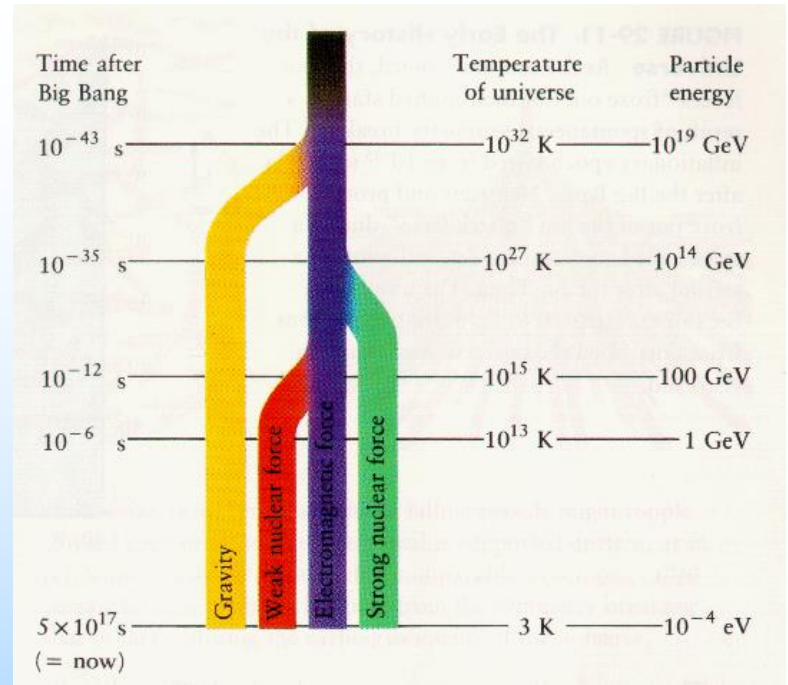
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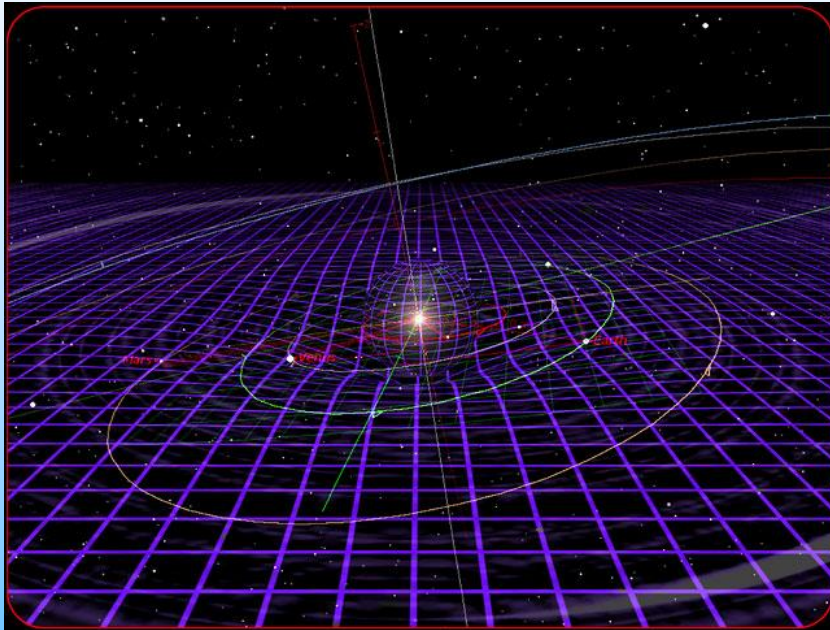
Probing shorter distances reveals deeper regularities

?

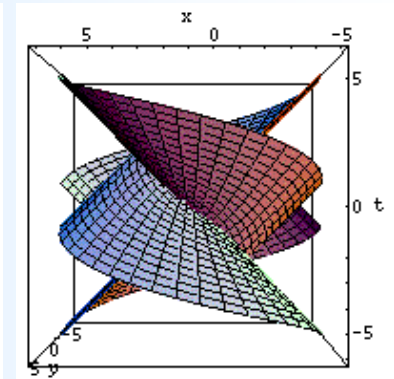
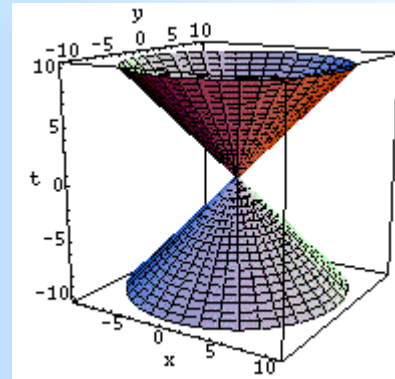
**UNIFIED DESCRIPTIONS**

Particles and forces

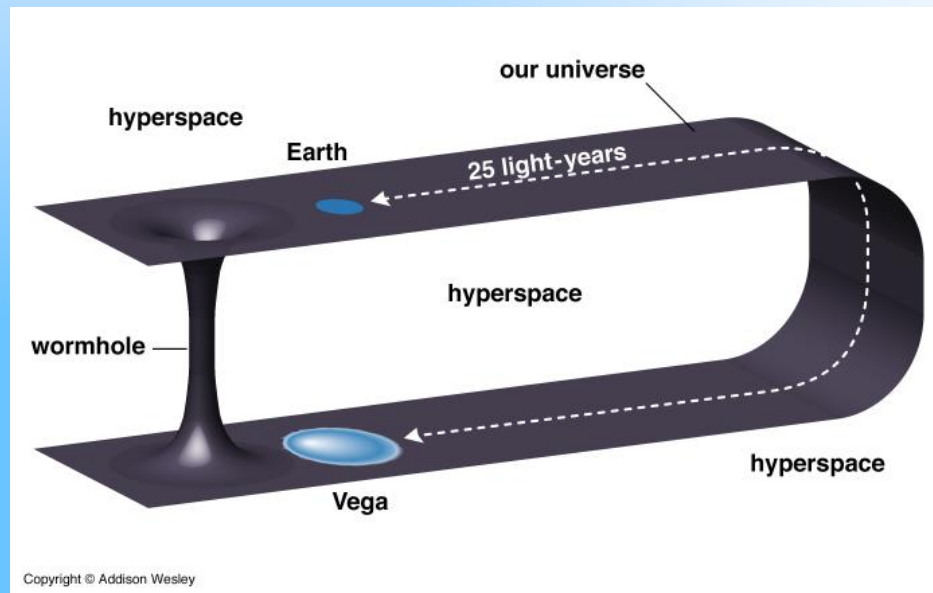
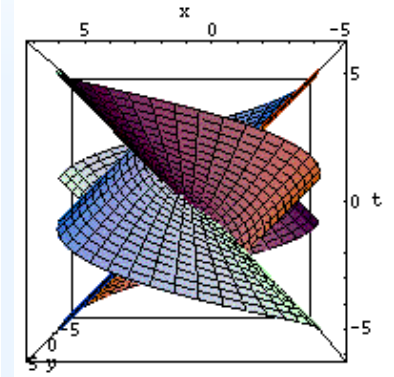
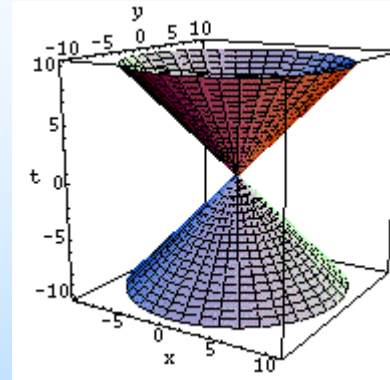
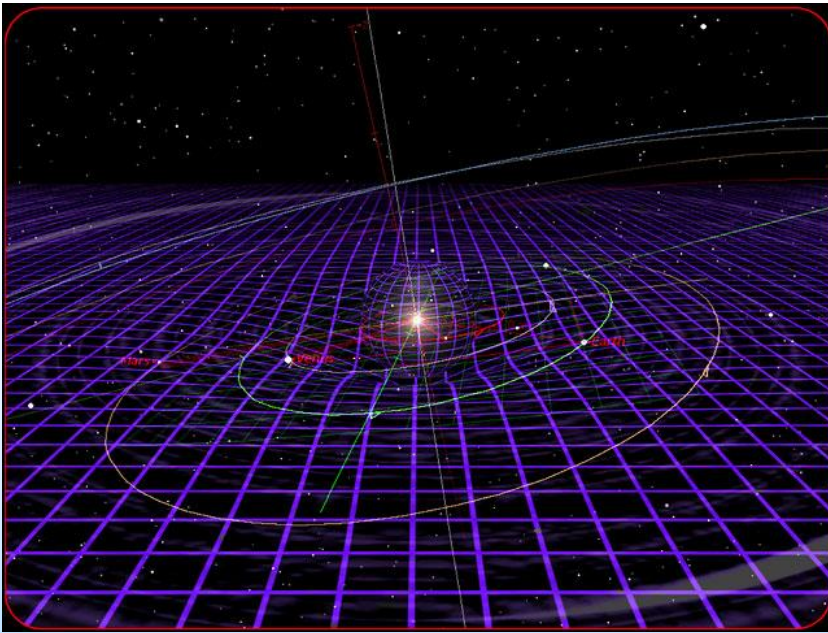




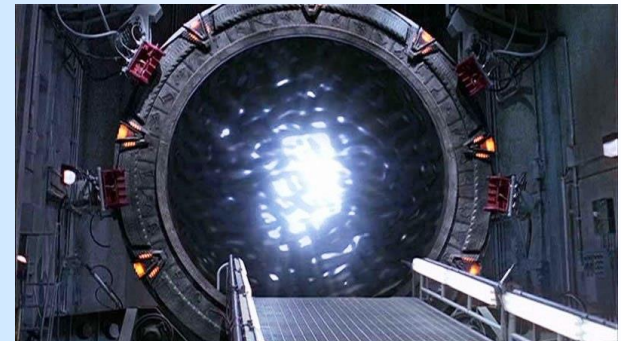
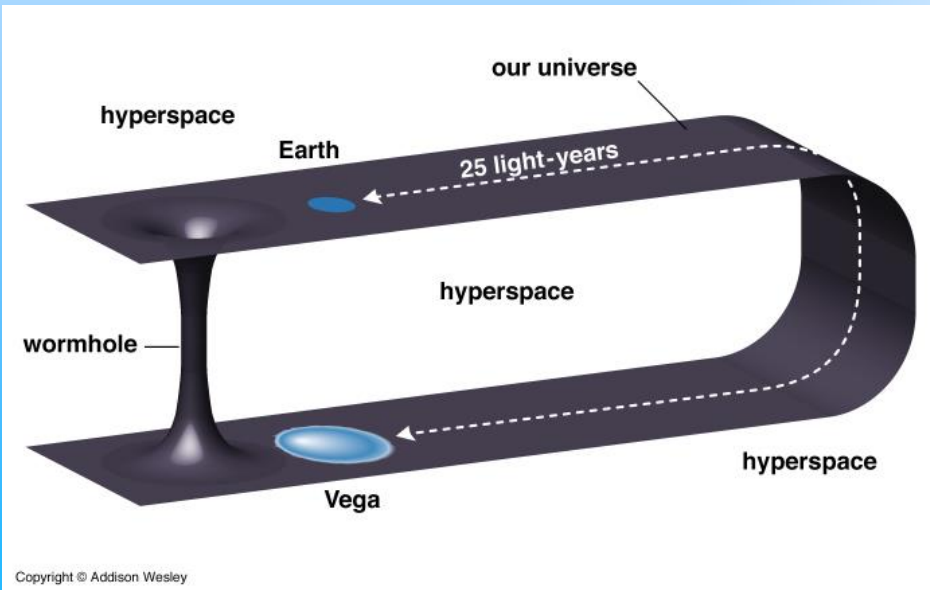
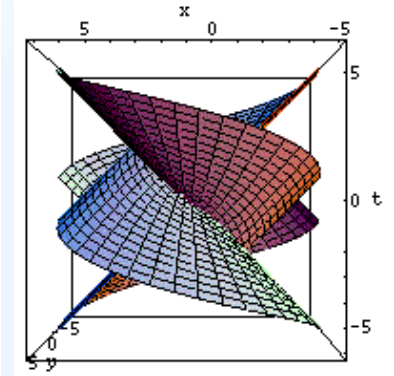
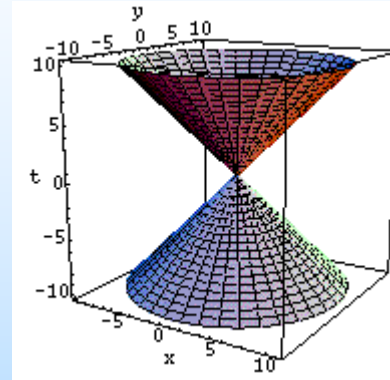
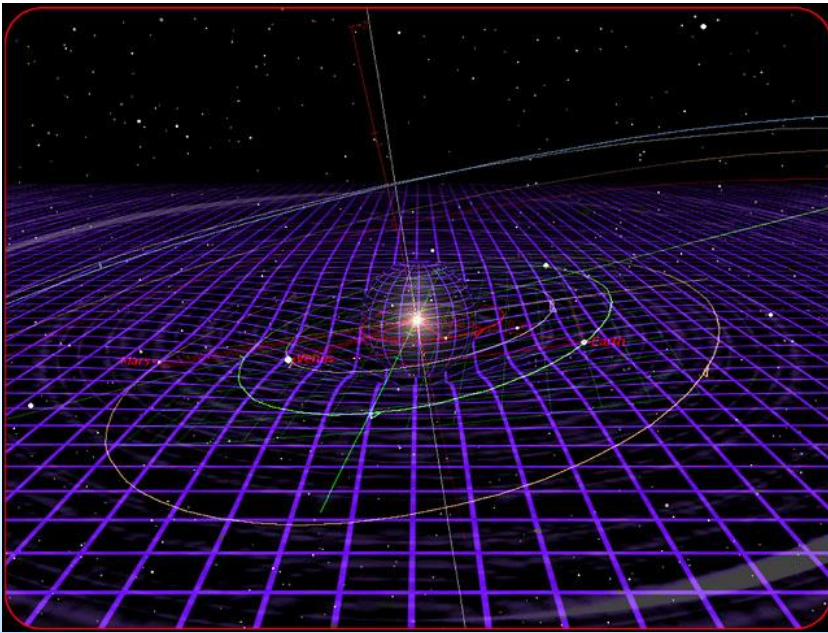
$$\Lambda g_{\mu\nu} + G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



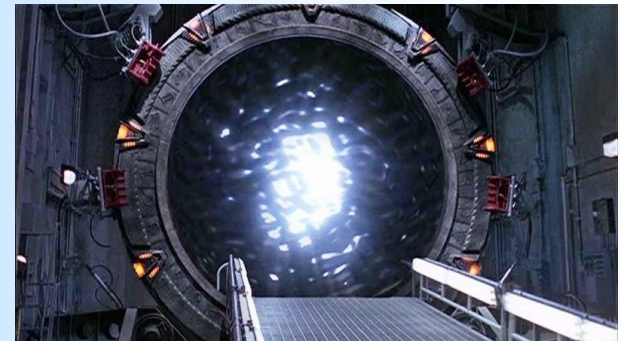
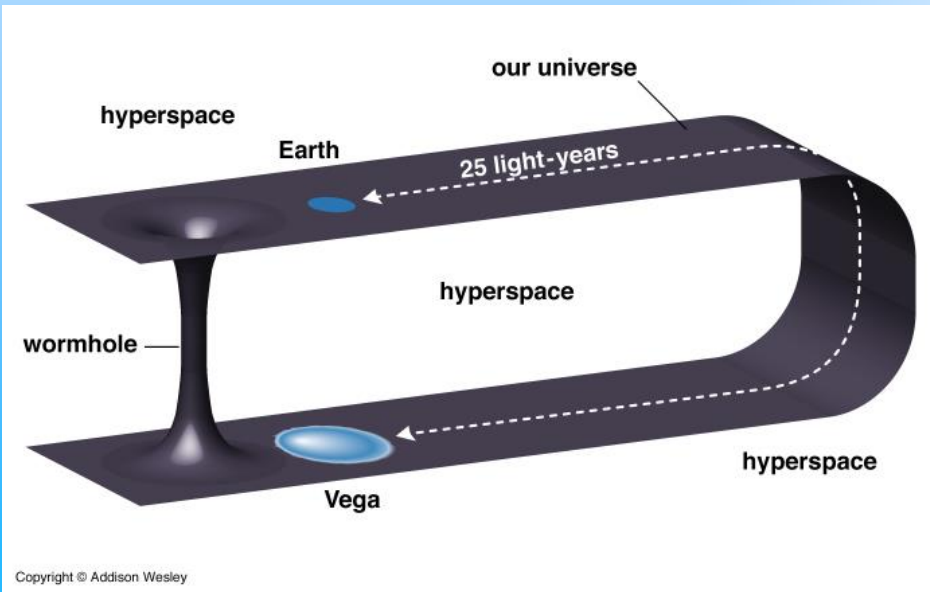
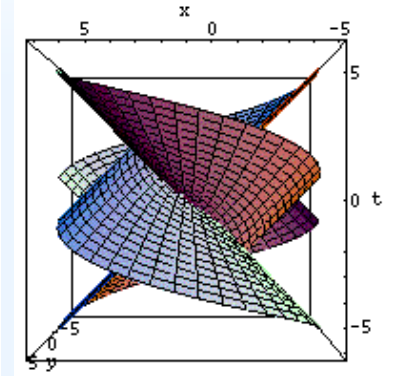
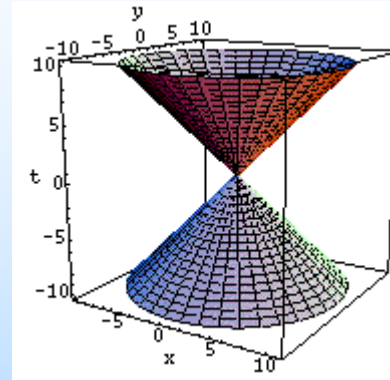
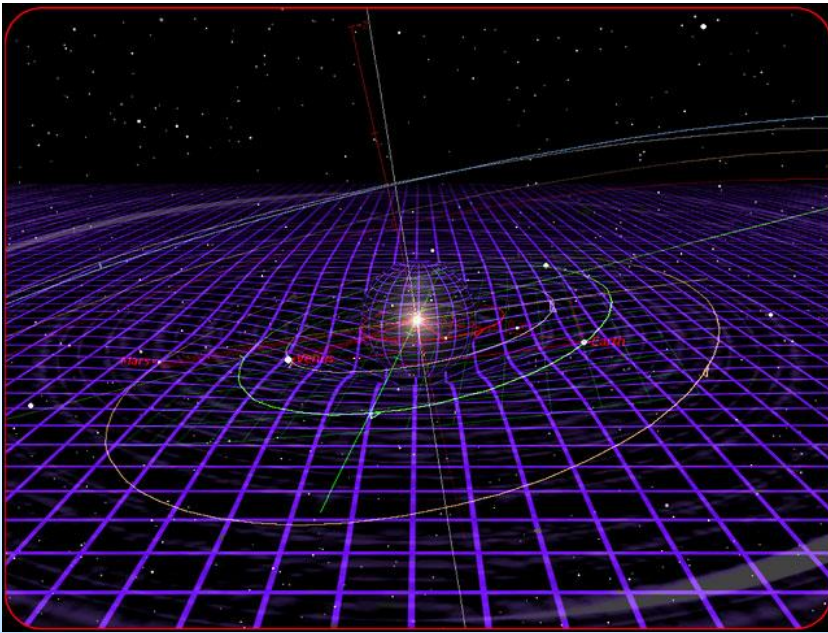
$$\Lambda g_{\mu\nu} + G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



$$\Lambda g_{\mu\nu} + G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

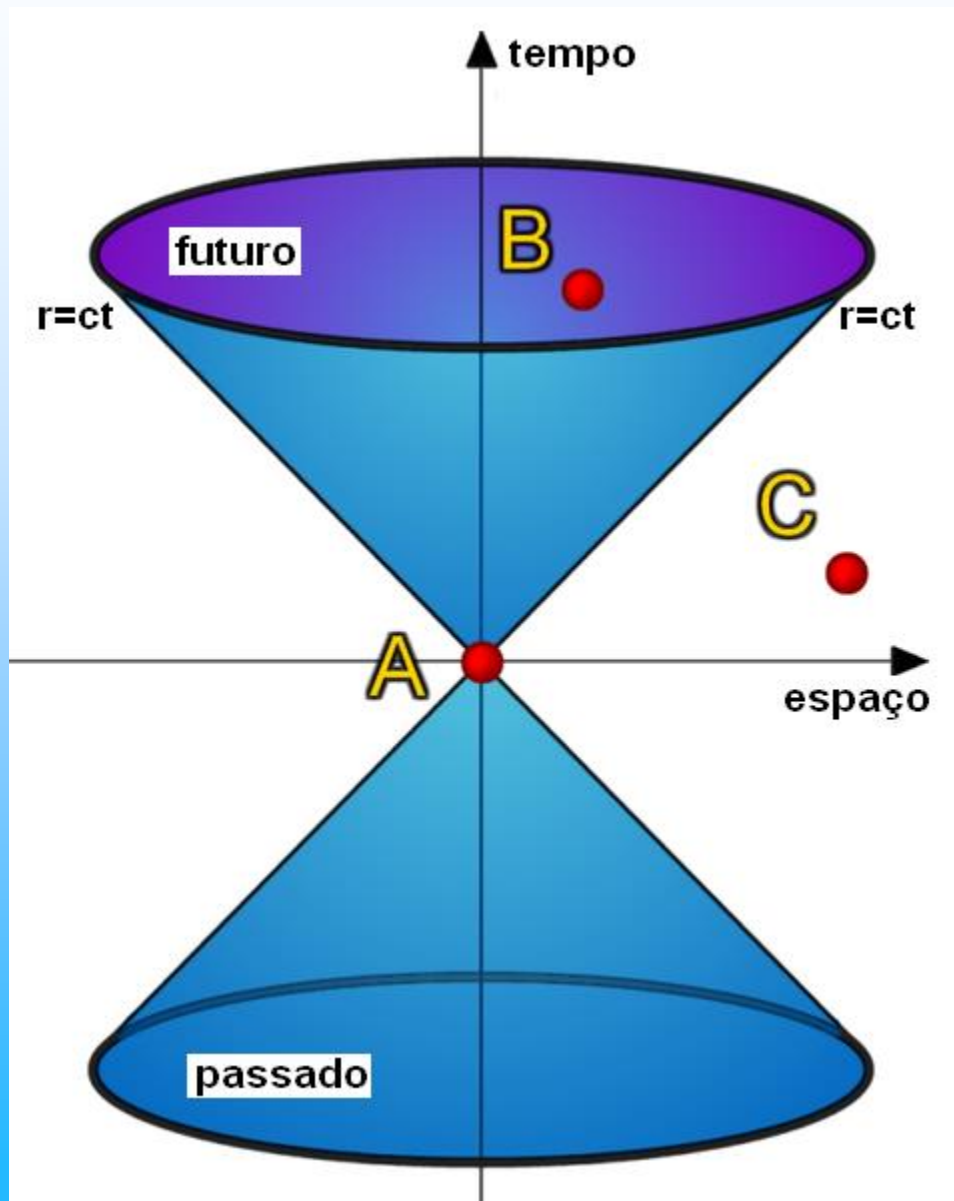


$$\Lambda g_{\mu\nu} + G_{\mu\nu} = 8\pi G T_{\mu\nu}$$





# Espaço-tempo quadridimensional



No espaço de Minkowsky definimos o *evento*:

$$\mathfrak{X} = (ct, x, y, z) = (ct, \vec{r})$$

O intervalo entre este evento e o evento nulo pode ser de 3 tipos:  $s^2 = 0 \Rightarrow ct = r$

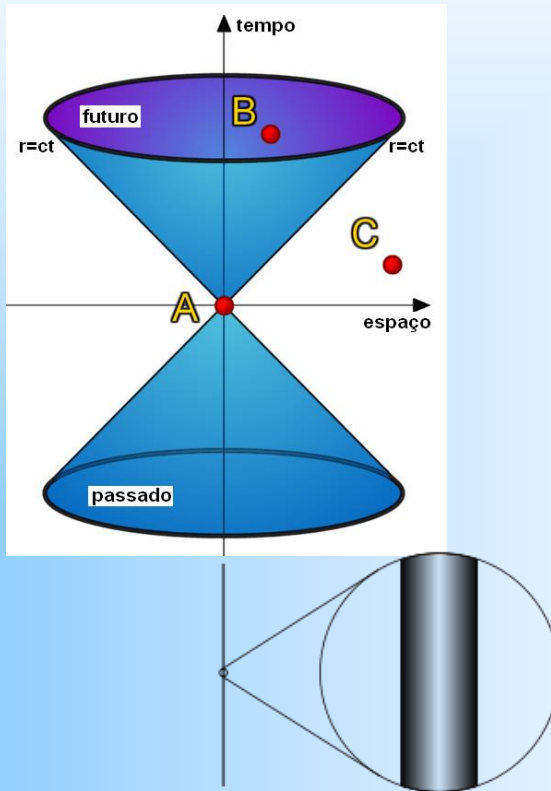
A) Tipo luz:  $s^2 > 0 \Rightarrow ct > r$

B) Tipo tempo:  $s^2 < 0 \Rightarrow ct < r$

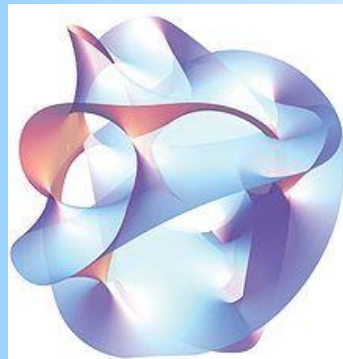
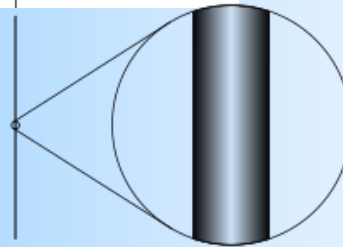
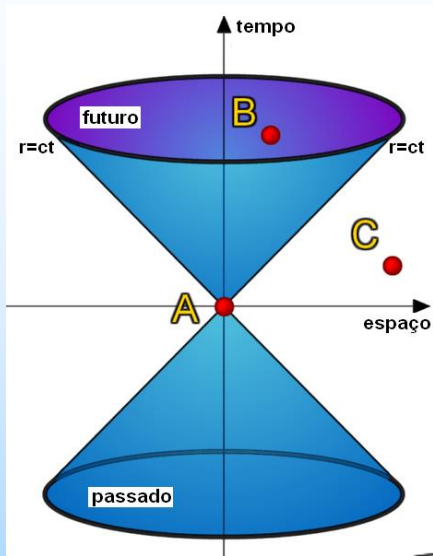
C) Tipo espaço:

Eventos são conectados causalmente somente se forem tipo tempo ou tipo luz.

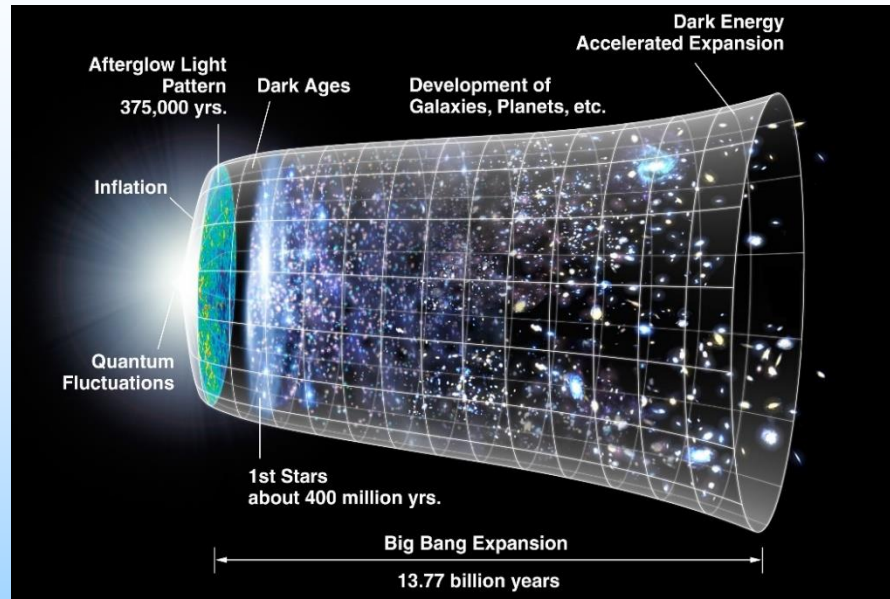
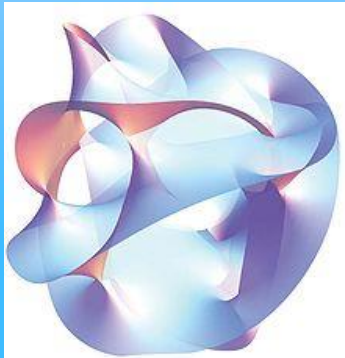
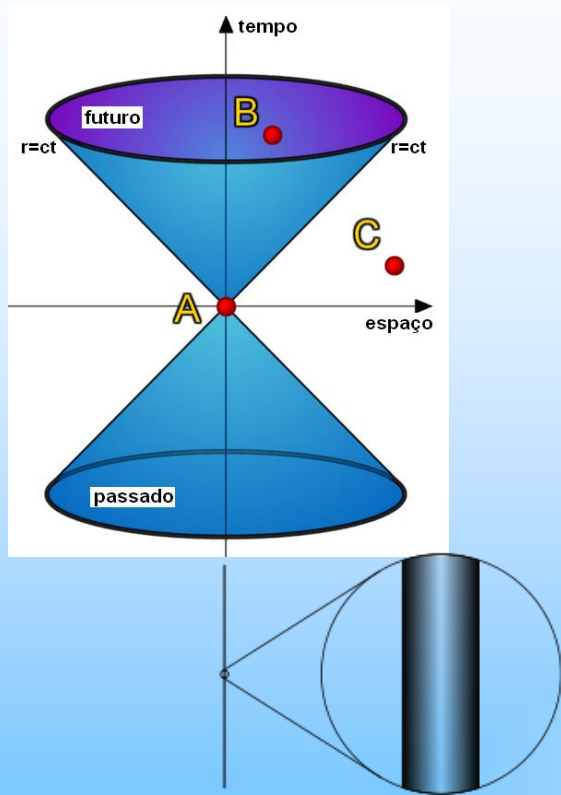
# Existem outras dimensões?



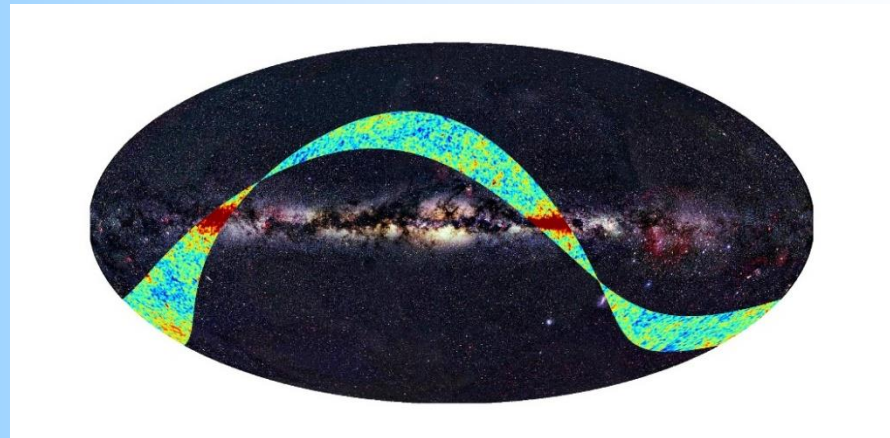
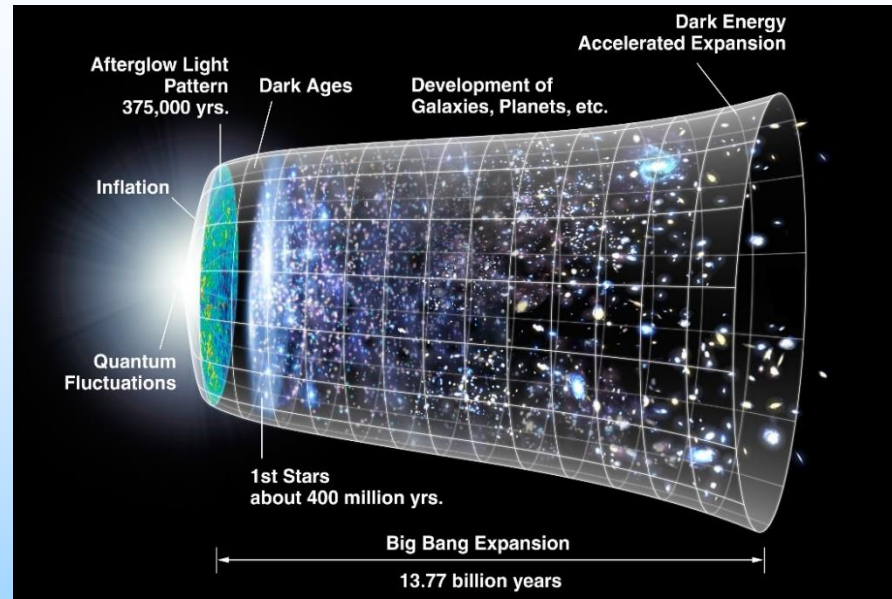
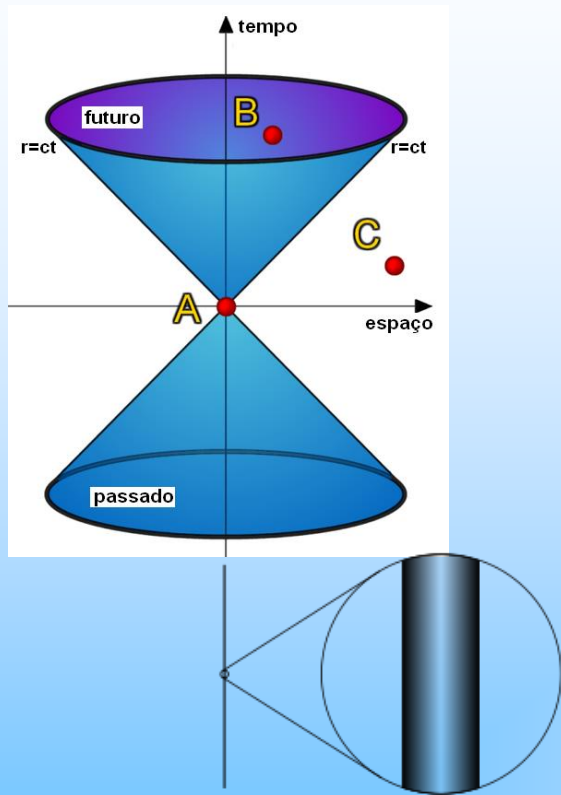
# Existem outras dimensões?



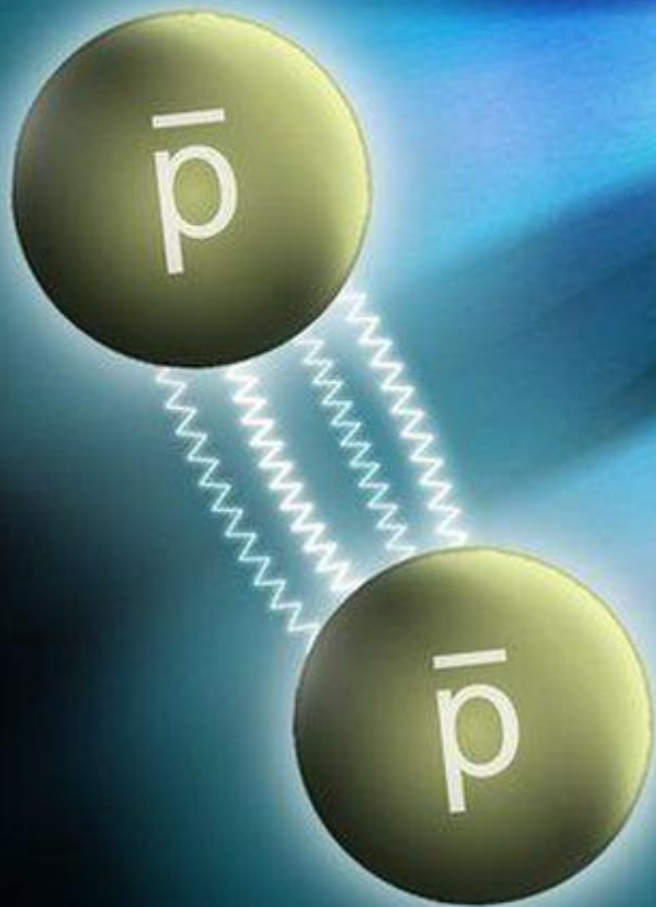
# Existem outras dimensões?



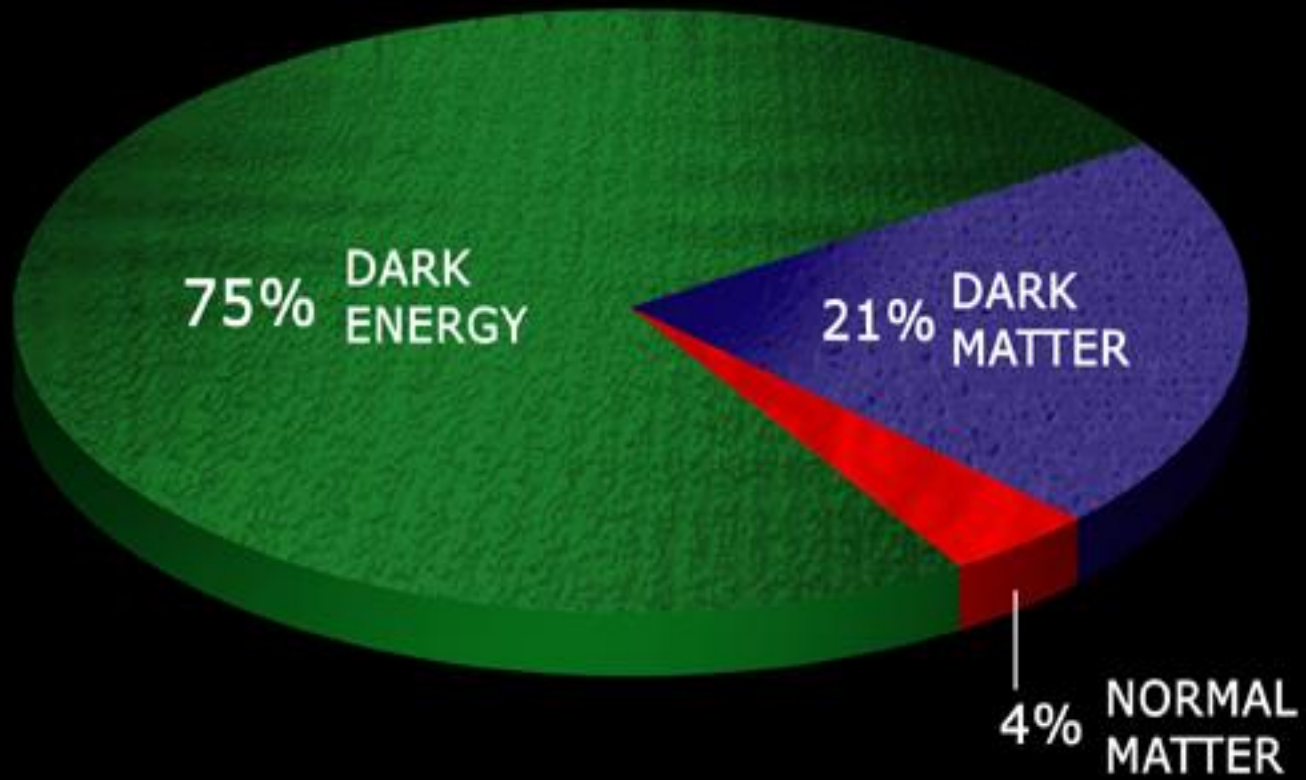
# Existem outras dimensões?



Assimetria entre a  
matéria e a antimatéria



## Matéria e energia escura

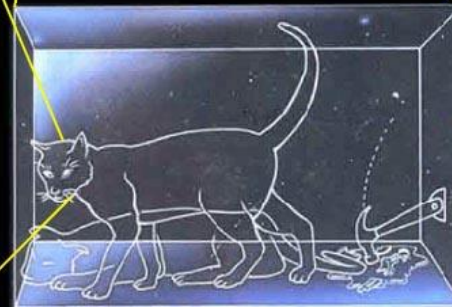
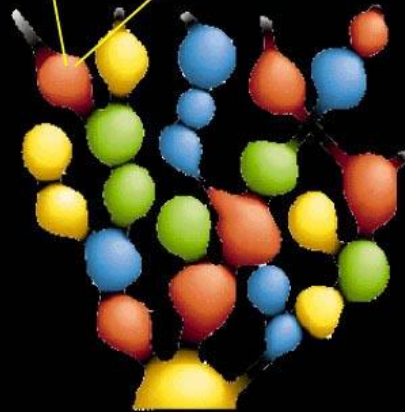
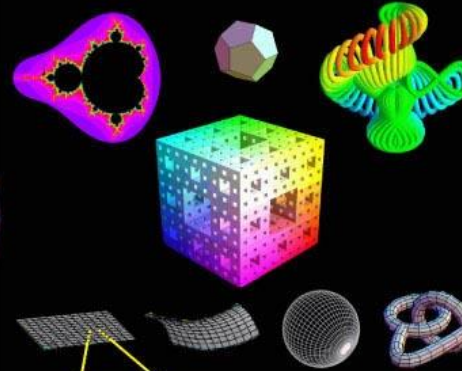
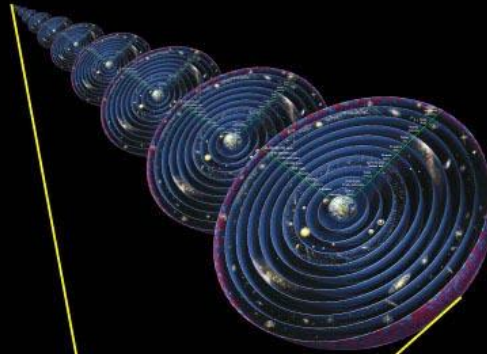


### Level 1: Regions beyond our cosmic horizon

**Features:** Same laws of physics, different initial conditions  
**Assumptions:** Infinite space, ergodic matter distribution  
**Evidence:**  
- Microwave background measurements point to flat, infinite space, large-scale smoothness  
- Simplest model

### Level 4: Other mathematical structures

**Features:** Different fundamental equations of physics  
**Assumption:** Mathematical existence = physical existence  
**Evidence:**  
- Unreasonable effectiveness of math in physics  
- Answers Wheeler/Hawking question: "why these equations, not others?"



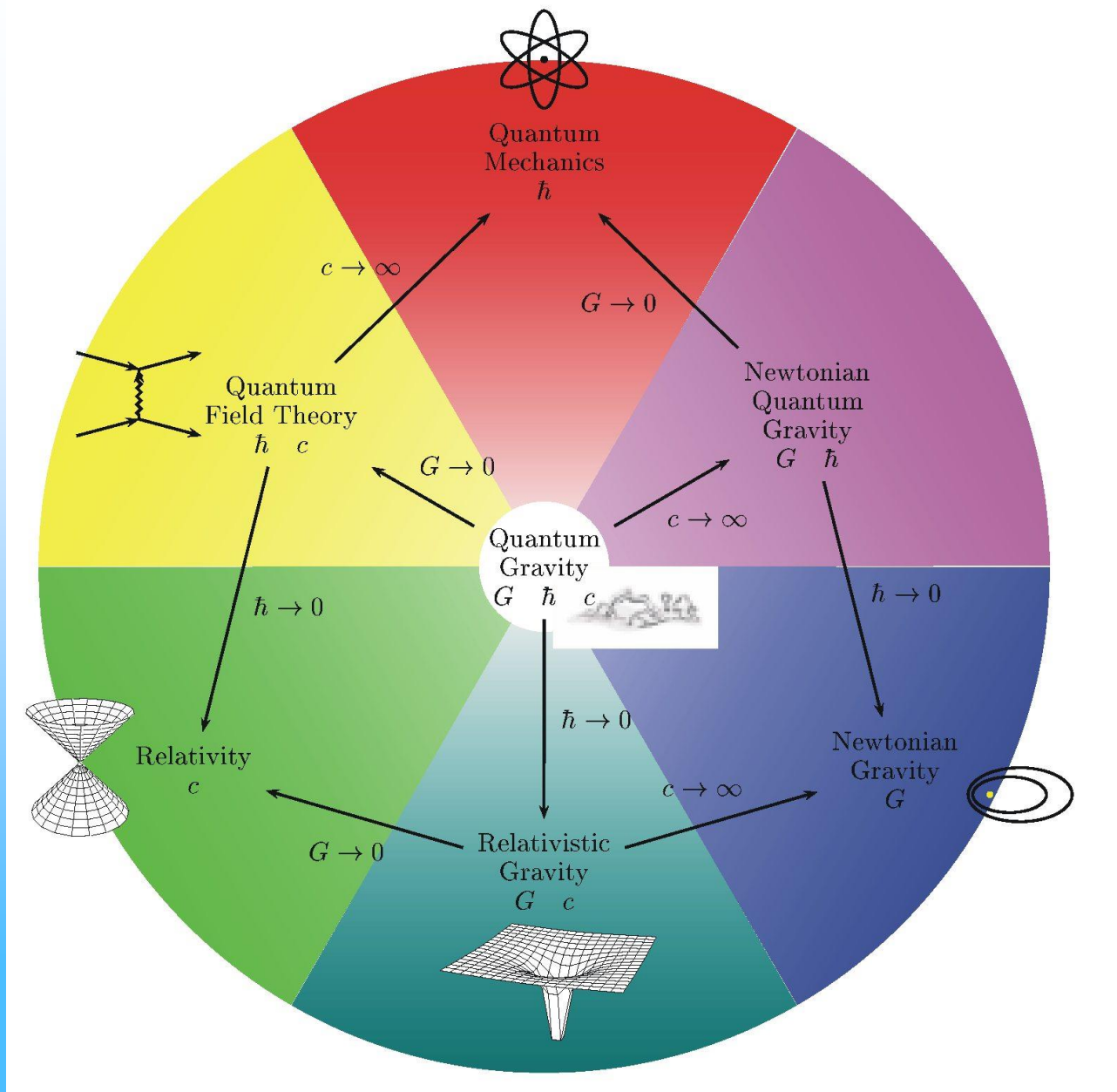
### Level 2: Other post-inflation bubbles

**Features:** Same fundamental equations of physics, but perhaps different constants, particles and dimensionality  
**Assumption:** Chaotic inflation occurred  
**Evidence:**  
- Inflation theory explains flat space, scale-invariant fluctuations, solves horizon problem and monopole problems and can naturally explain such bubbles  
- Explains fine-tuned parameters

### Level 3: The Many Worlds of Quantum Physics

**Features:** Same as level 2  
**Assumption:** Physics unitary  
**Evidence:**  
- Experimental support for unitary physics  
- AdS/CFT correspondence suggests that even quantum gravity is unitary  
- Decoherence experimentally verified  
- Mathematically simplest model







Universidade Federal do ABC



SOCIEDADE BRASILEIRA DE FÍSICA

**MNPEF** Mestrado Nacional  
Profissional em  
Ensino de Física

**Obrigado!**



***Prof. Marcelo Augusto Leigui de Oliveira***  
***[leigui@ufabc.edu.br](mailto:leigui@ufabc.edu.br)***

