



Quando l'universo vibra: Virgo e le onde gravitazionali

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Università degli Studi di Milano-Bicocca
EGO-Virgo

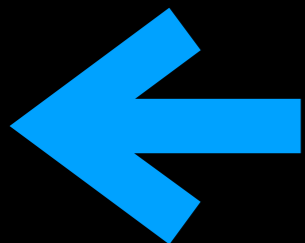
Vi piace la Fisica?

Un po'



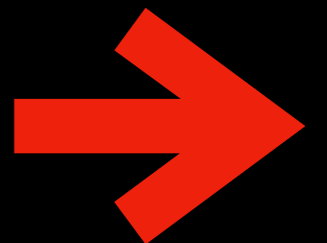
Indica in
alto

Sì



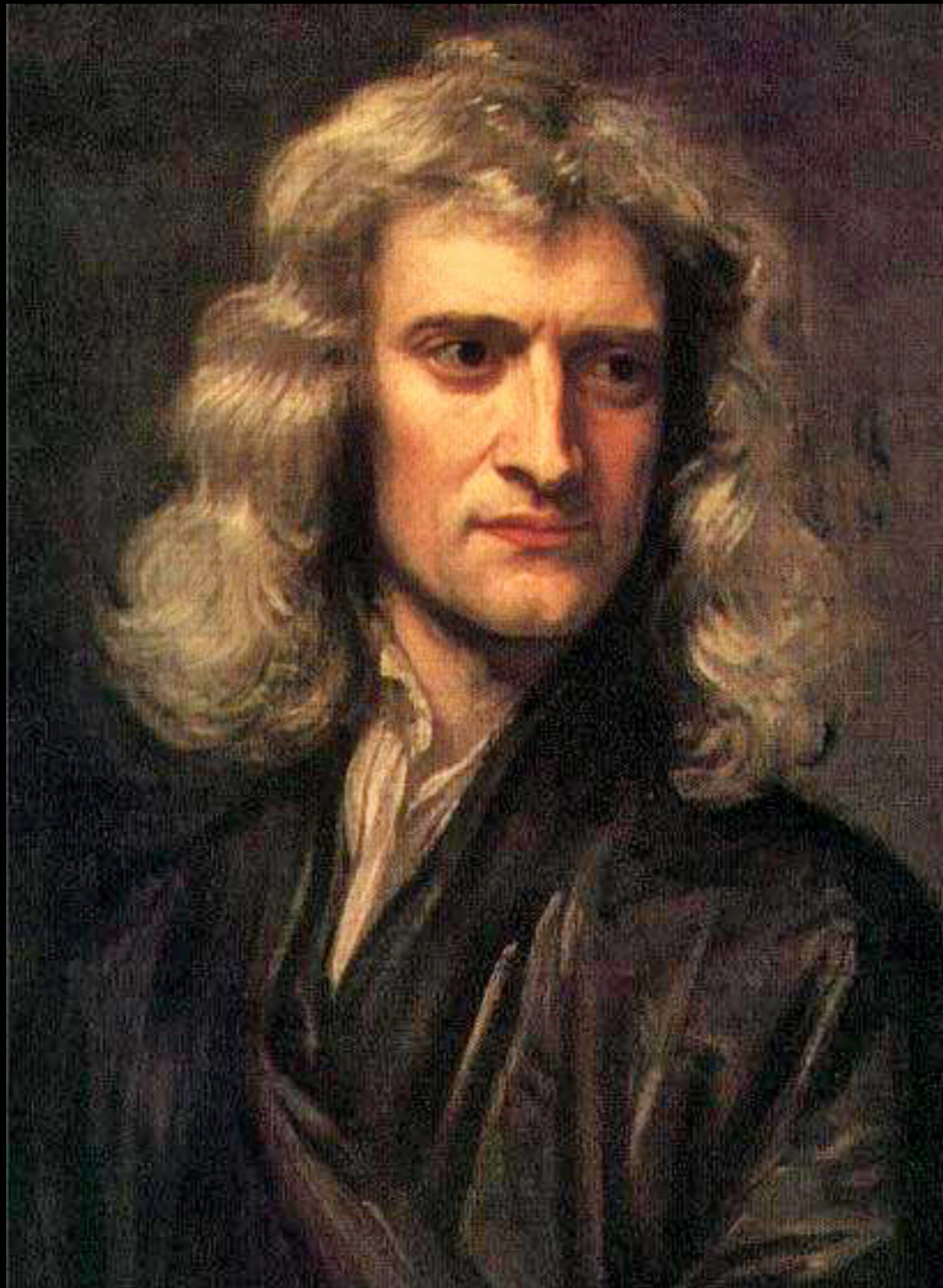
Indica a
sinistra

No

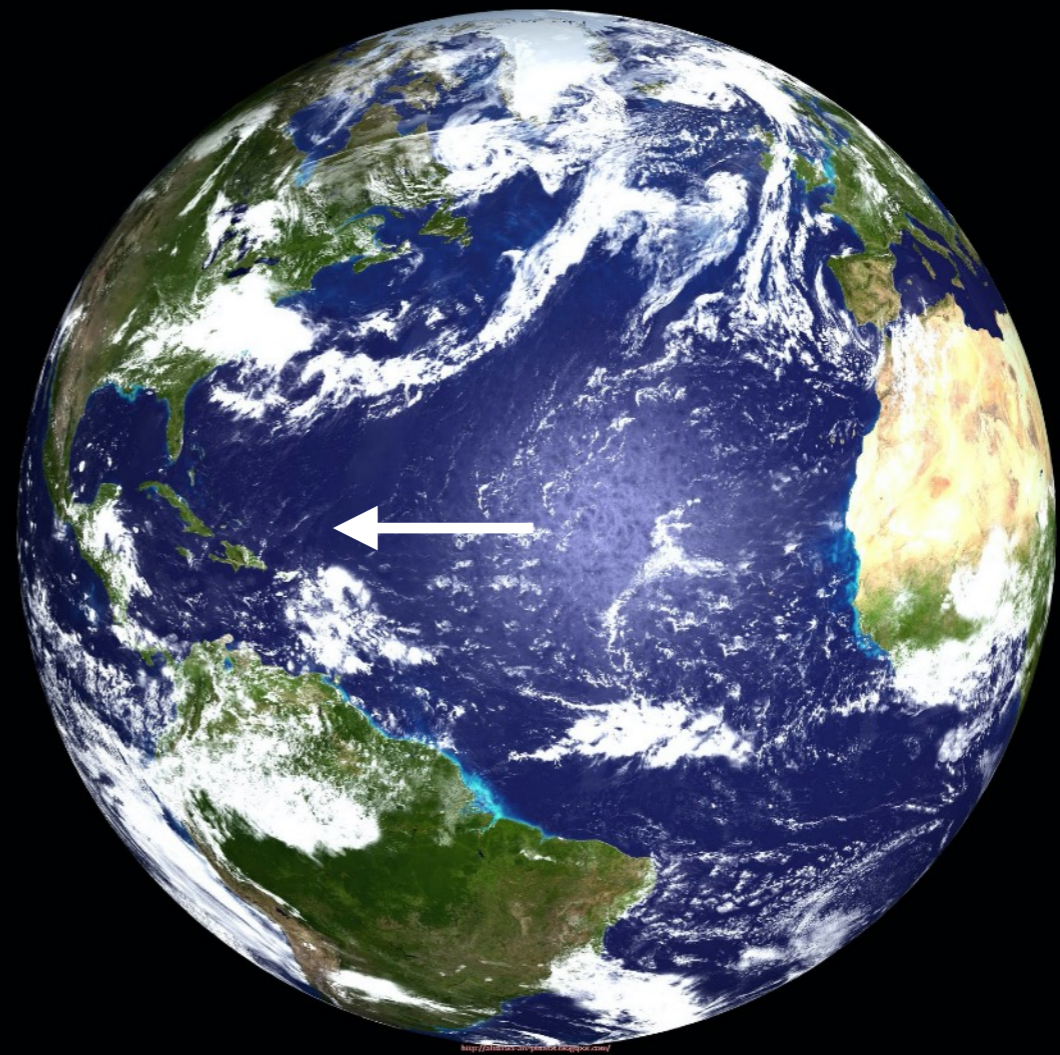
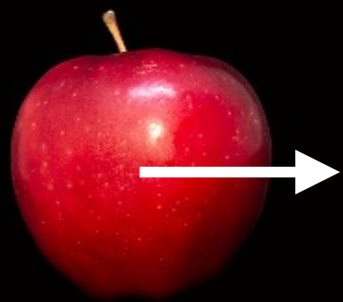


Indica a
destra





$$F_{\text{grav}} = G \frac{M_{\text{mela}} M_{\text{Terra}}}{r^2}$$



Principio di Equivalenza

$$\cancel{M_{\text{mela}}^{\text{inerz.}}} a = G \frac{\cancel{M_{\text{mela}}^{\text{grav.}}} M_{\text{Terra}}^{\text{grav.}}}{r^2}$$

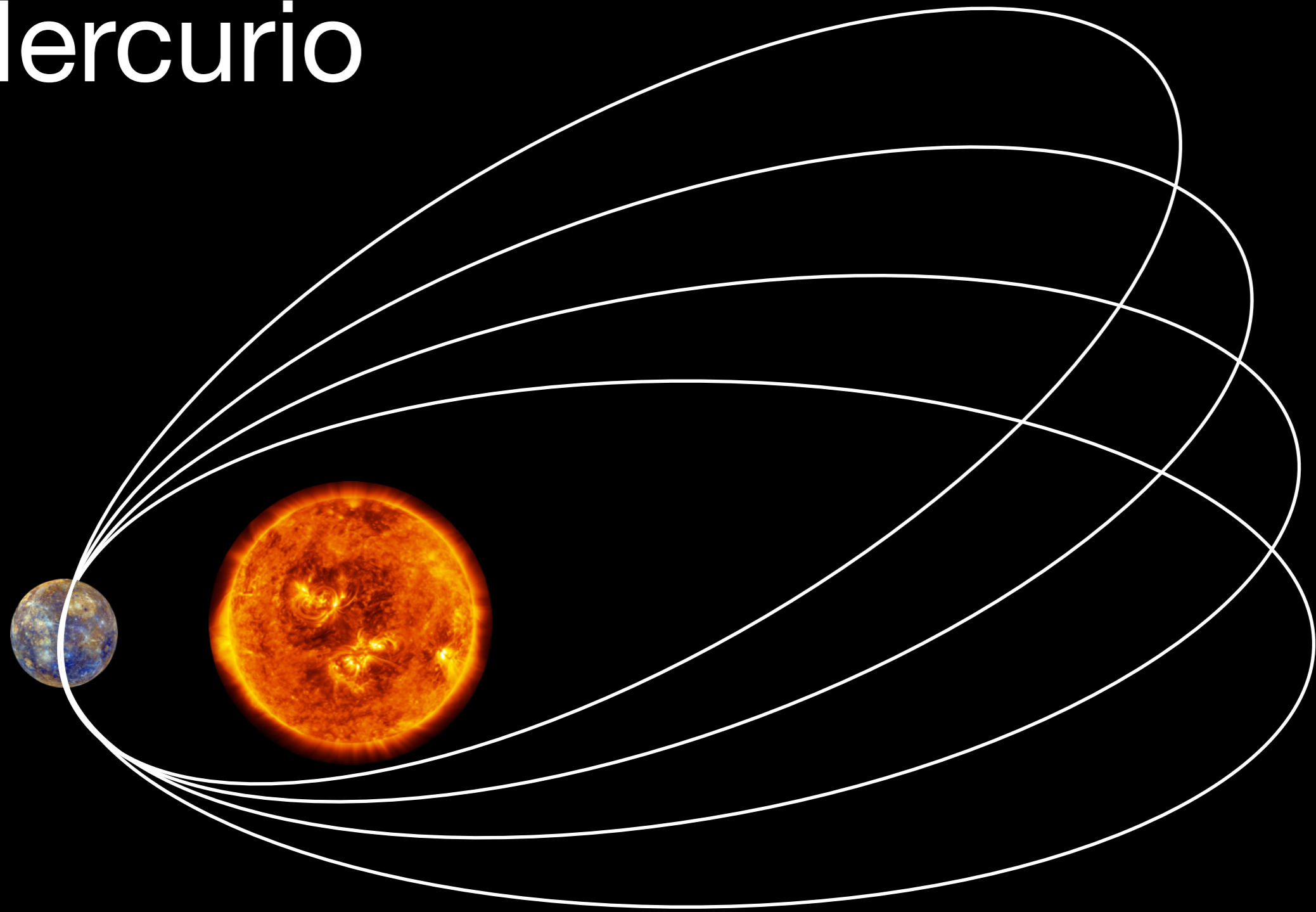
Principio di Equivalenza

$$\cancel{M_{\text{mela}}^{\text{inerz.}}} a = G \frac{\cancel{M_{\text{mela}}^{\text{grav.}}} M_{\text{Terra}}^{\text{grav.}}}{r^2}$$

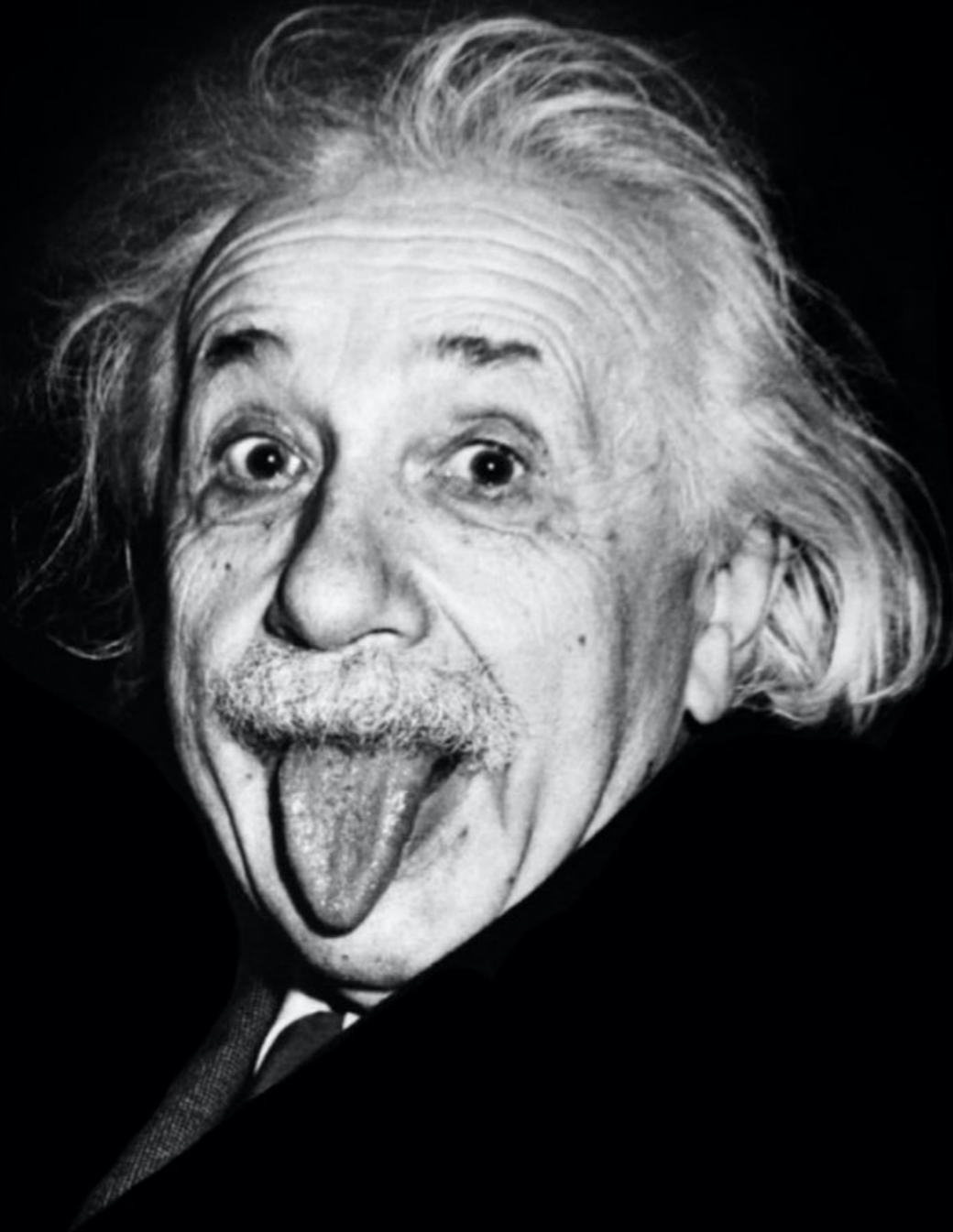
↓

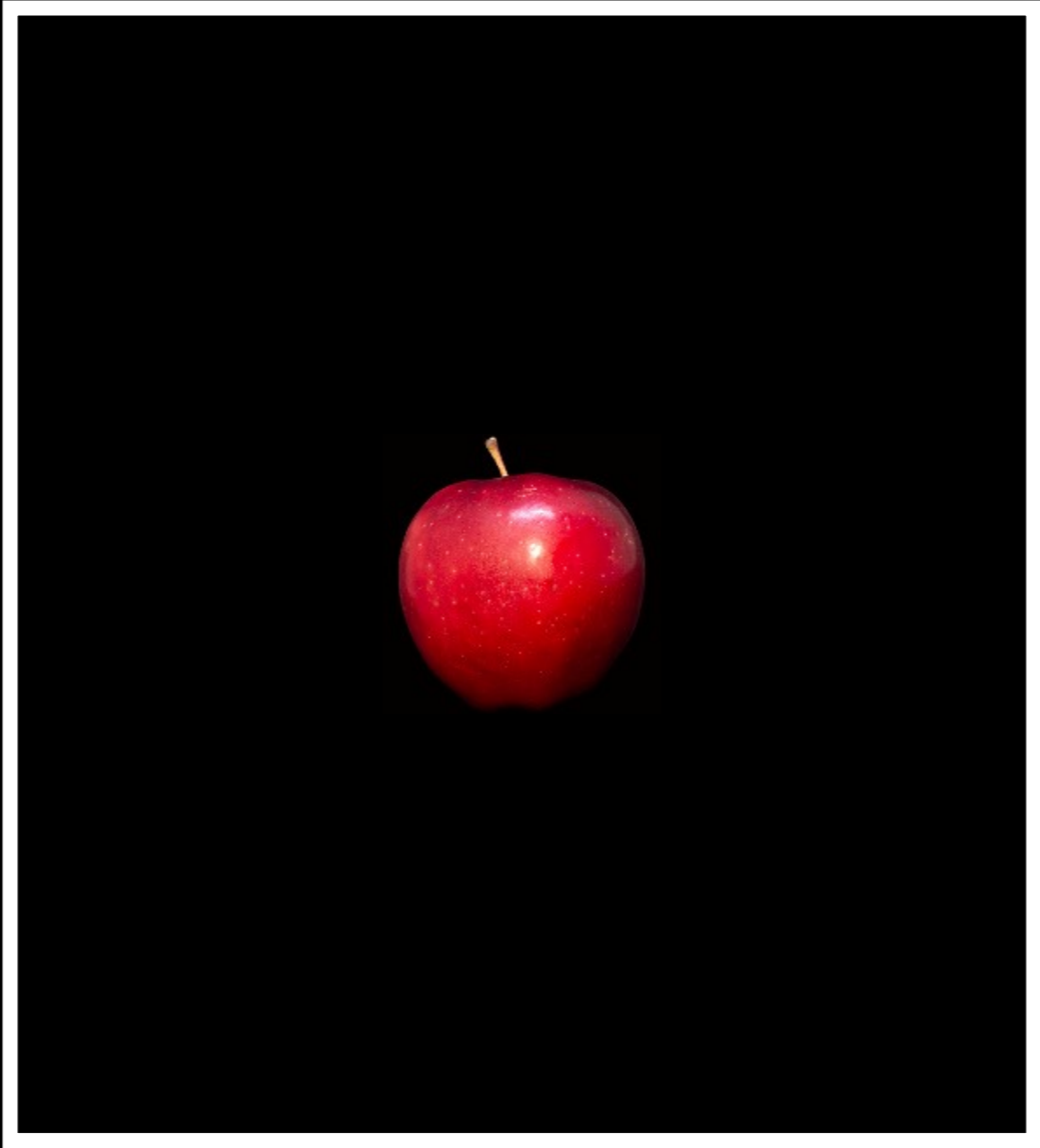
$$g = 9.81 \text{ m/s}^2$$

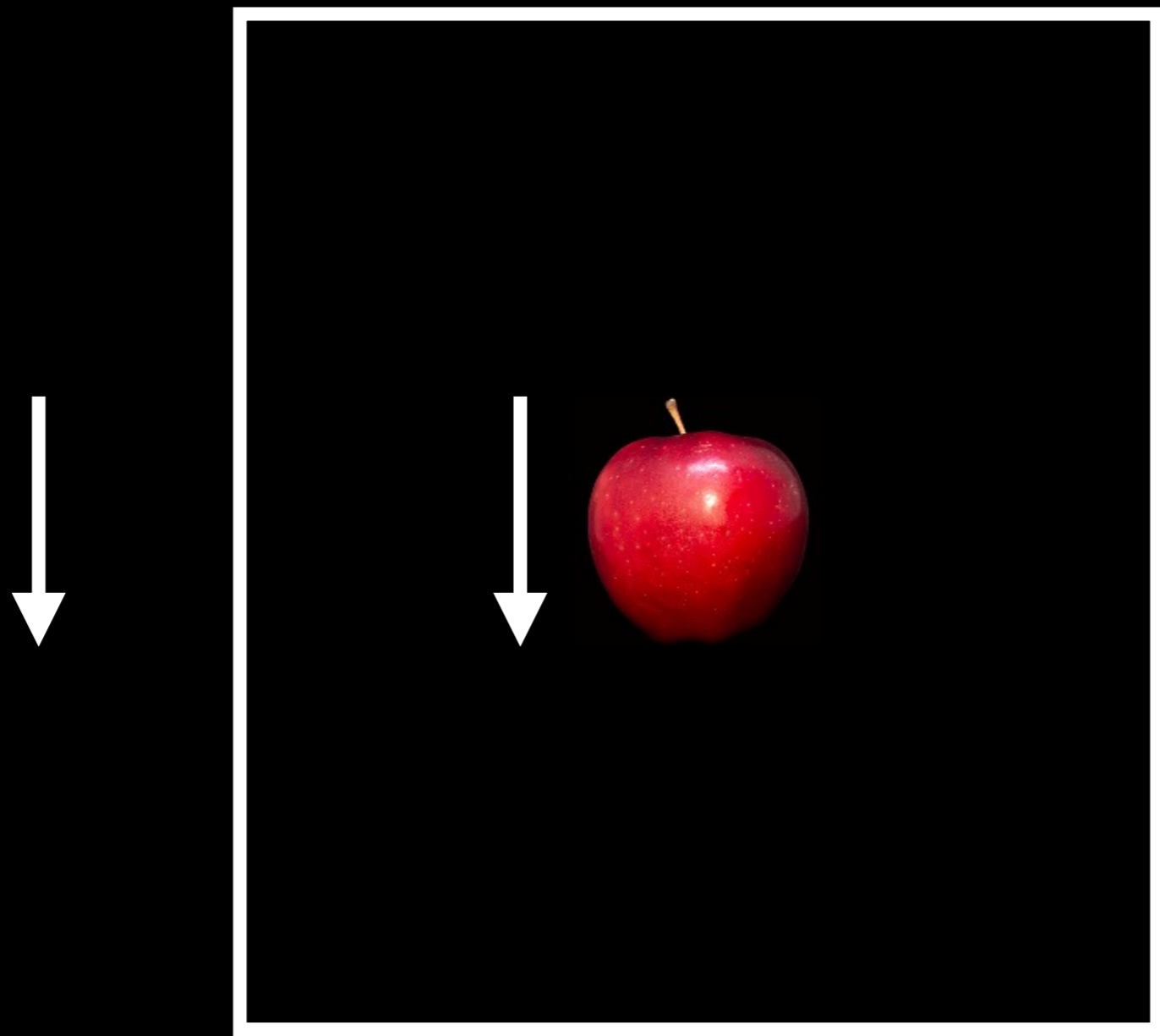
Mercurio



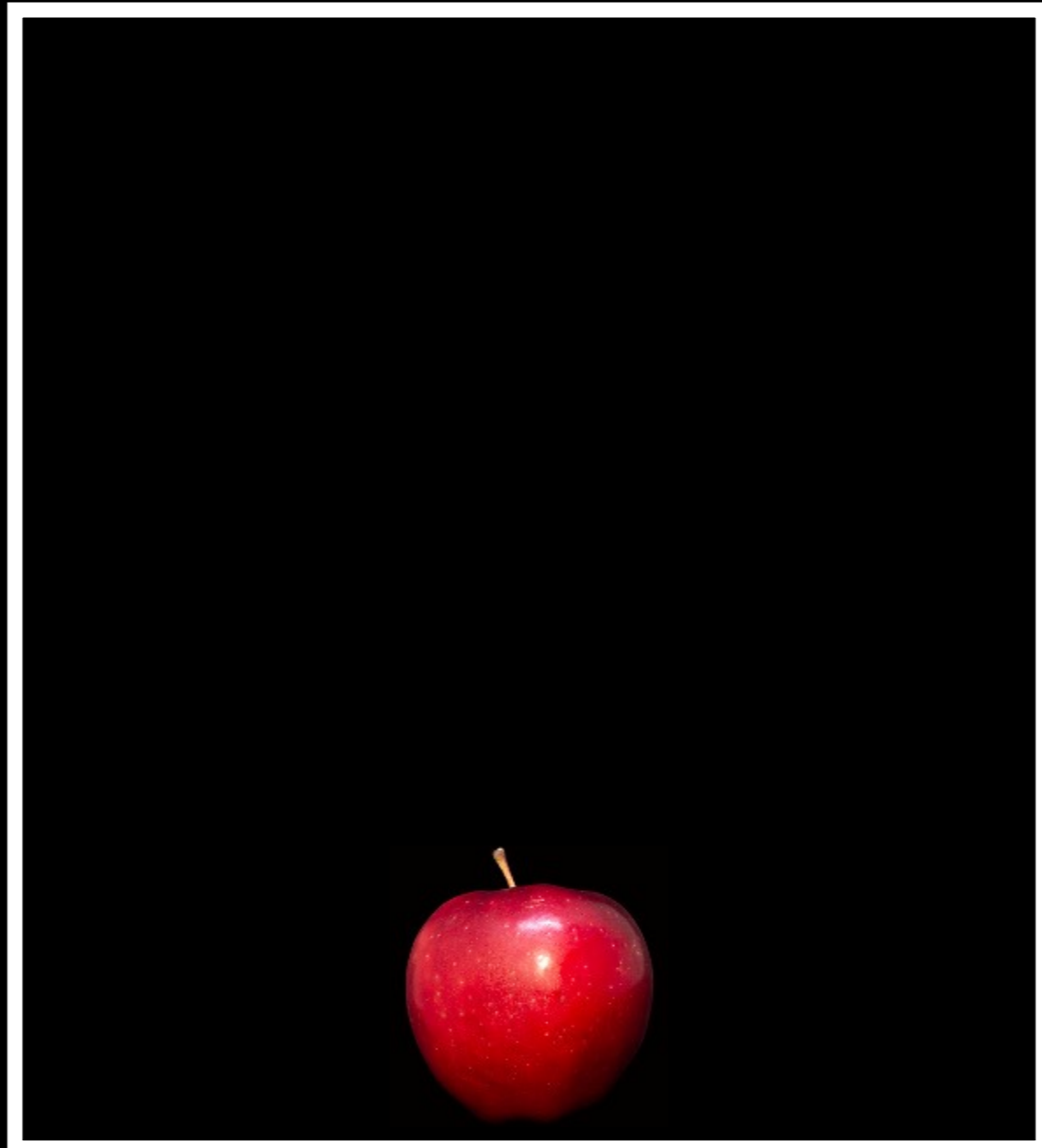
Cosa succede quando cado dal tetto?







Sto cadendo o sono nello spazio?



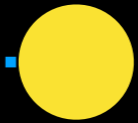
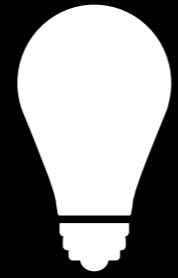


Sono sulla Terra o su un'astronave?

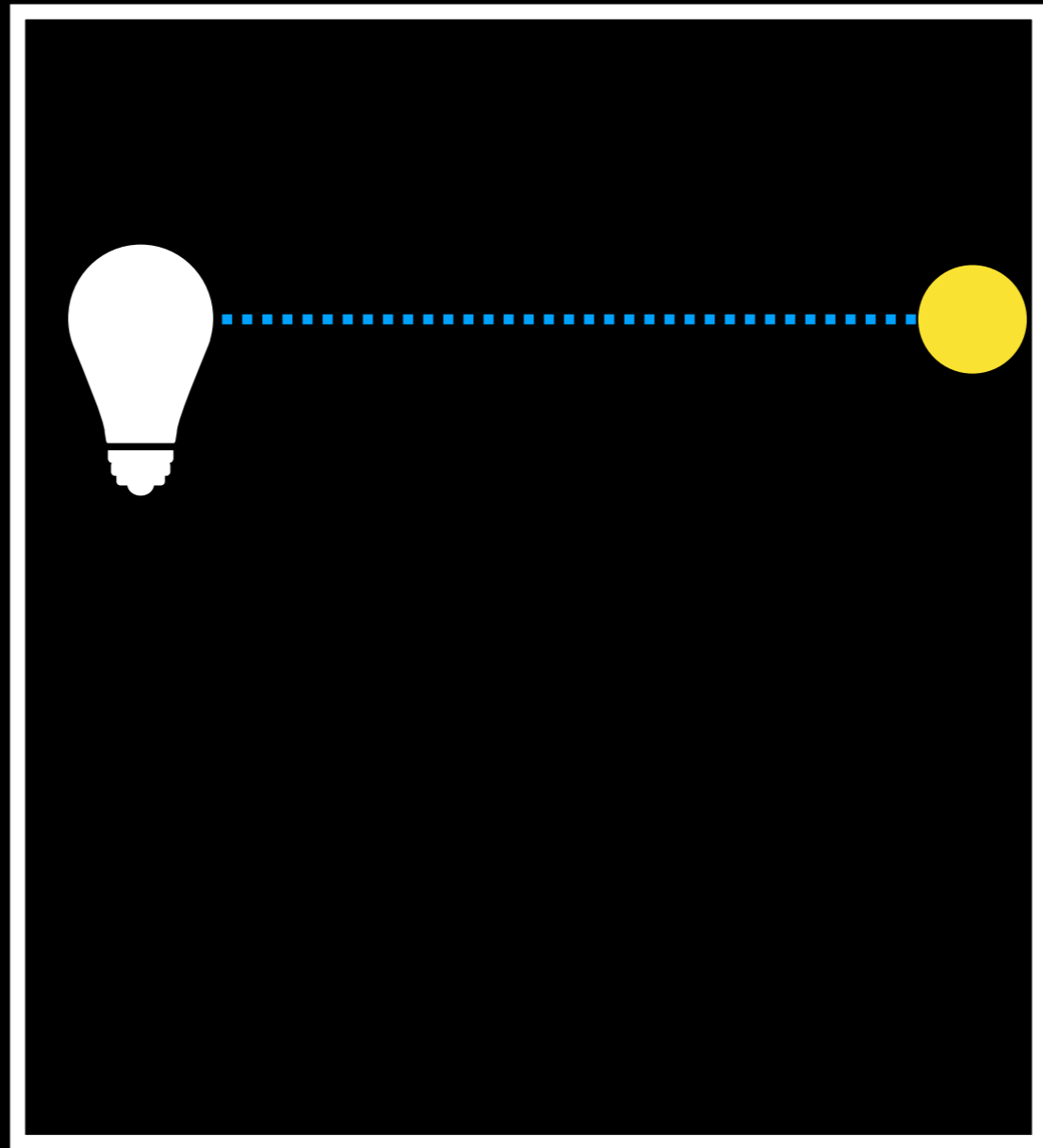
A



A



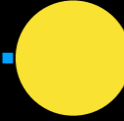
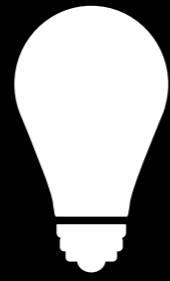
B



A

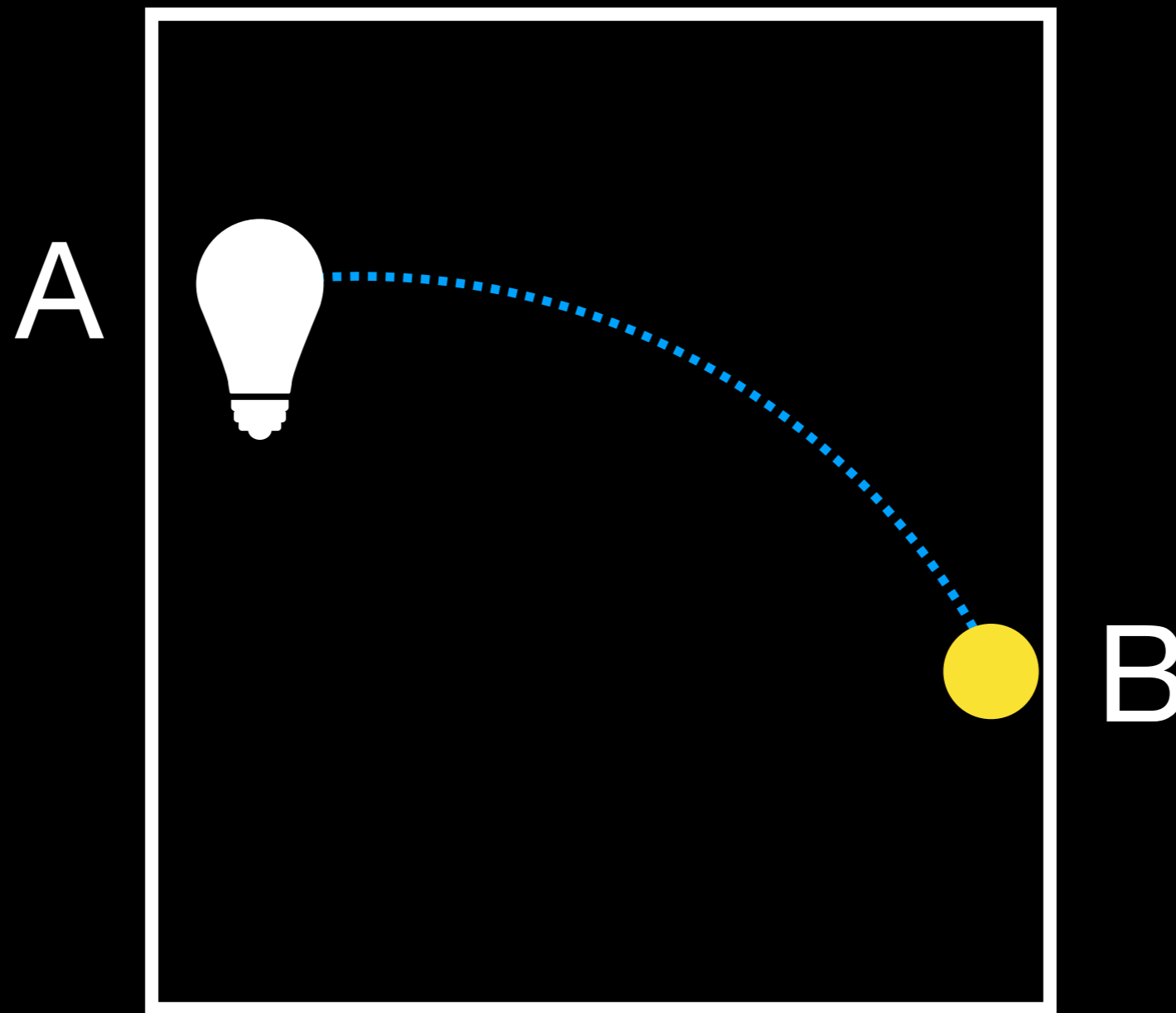


A



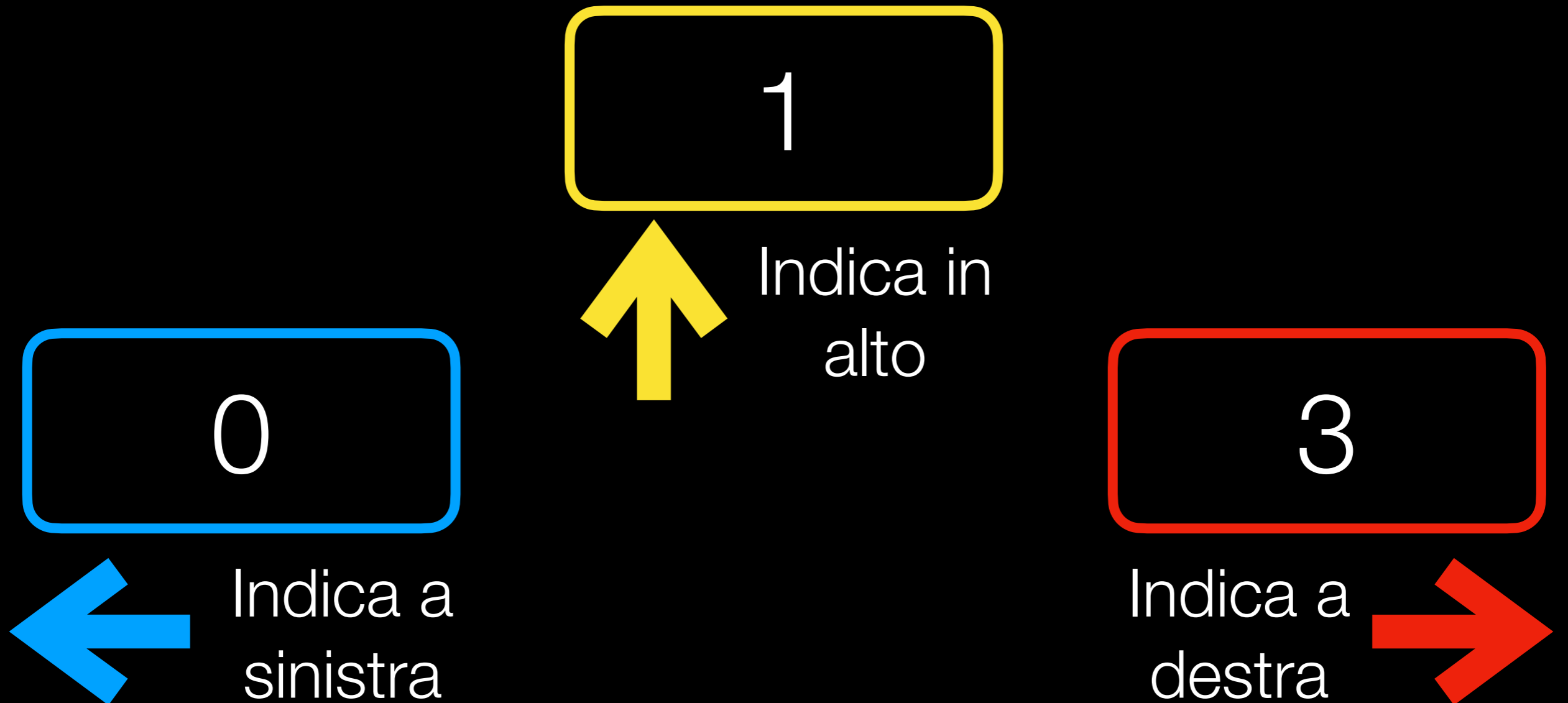
B



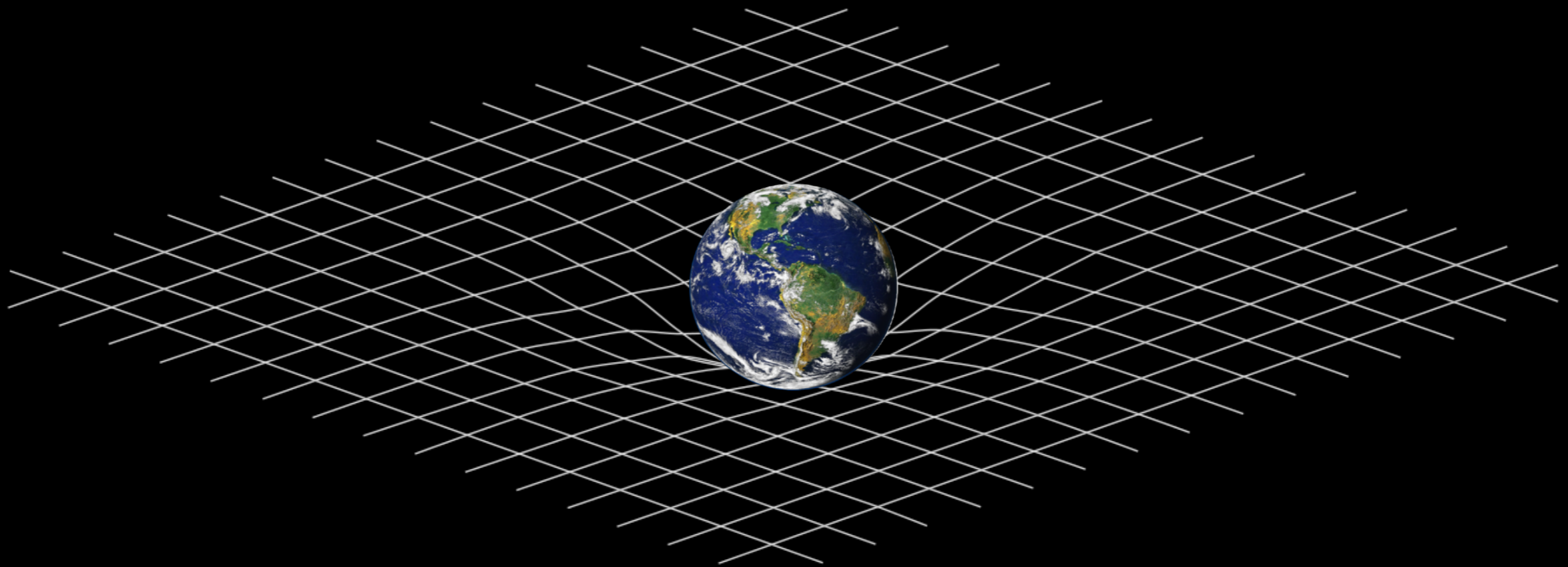


La gravità curva la luce
o lo spazio è curvo?

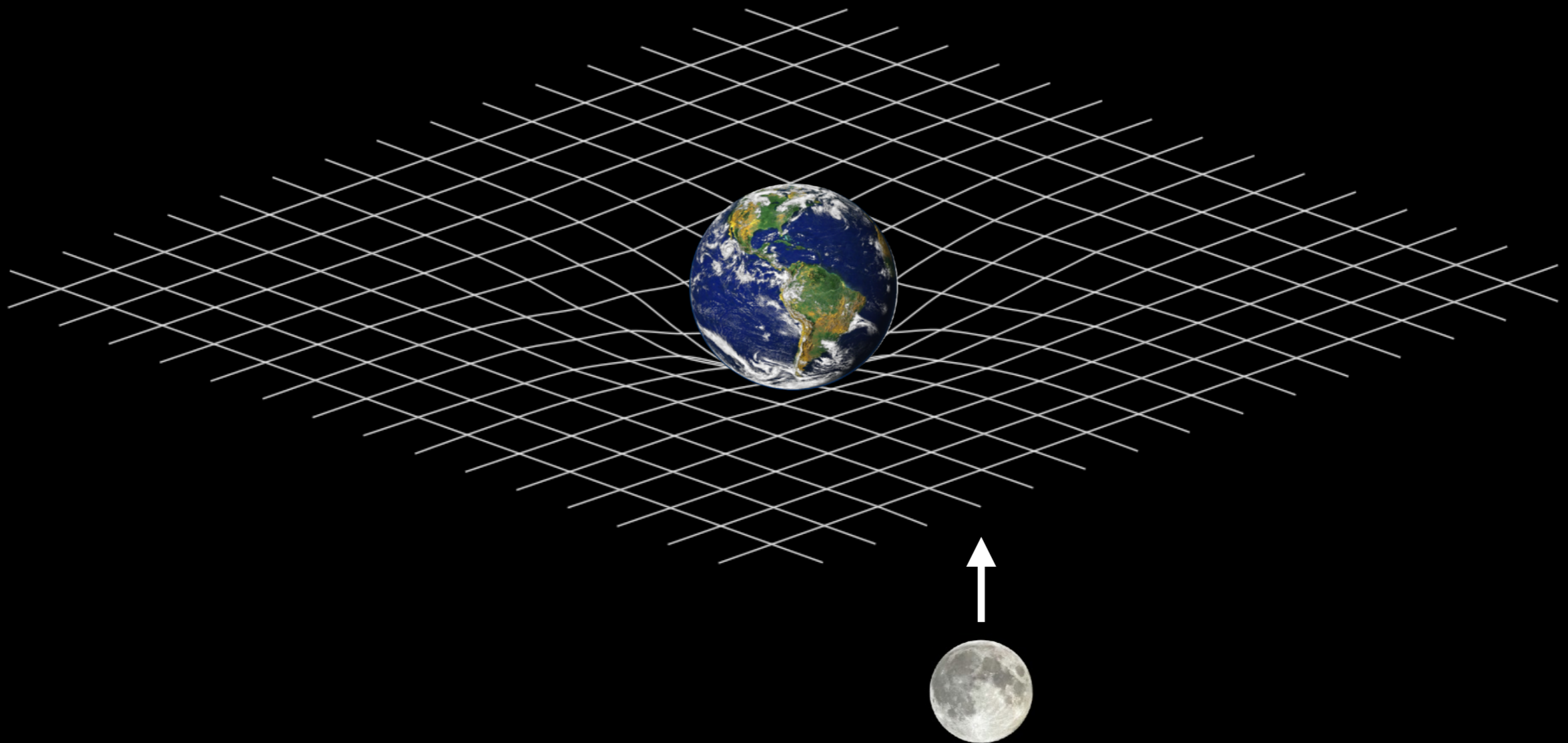
Quante dimensioni ha il tempo?



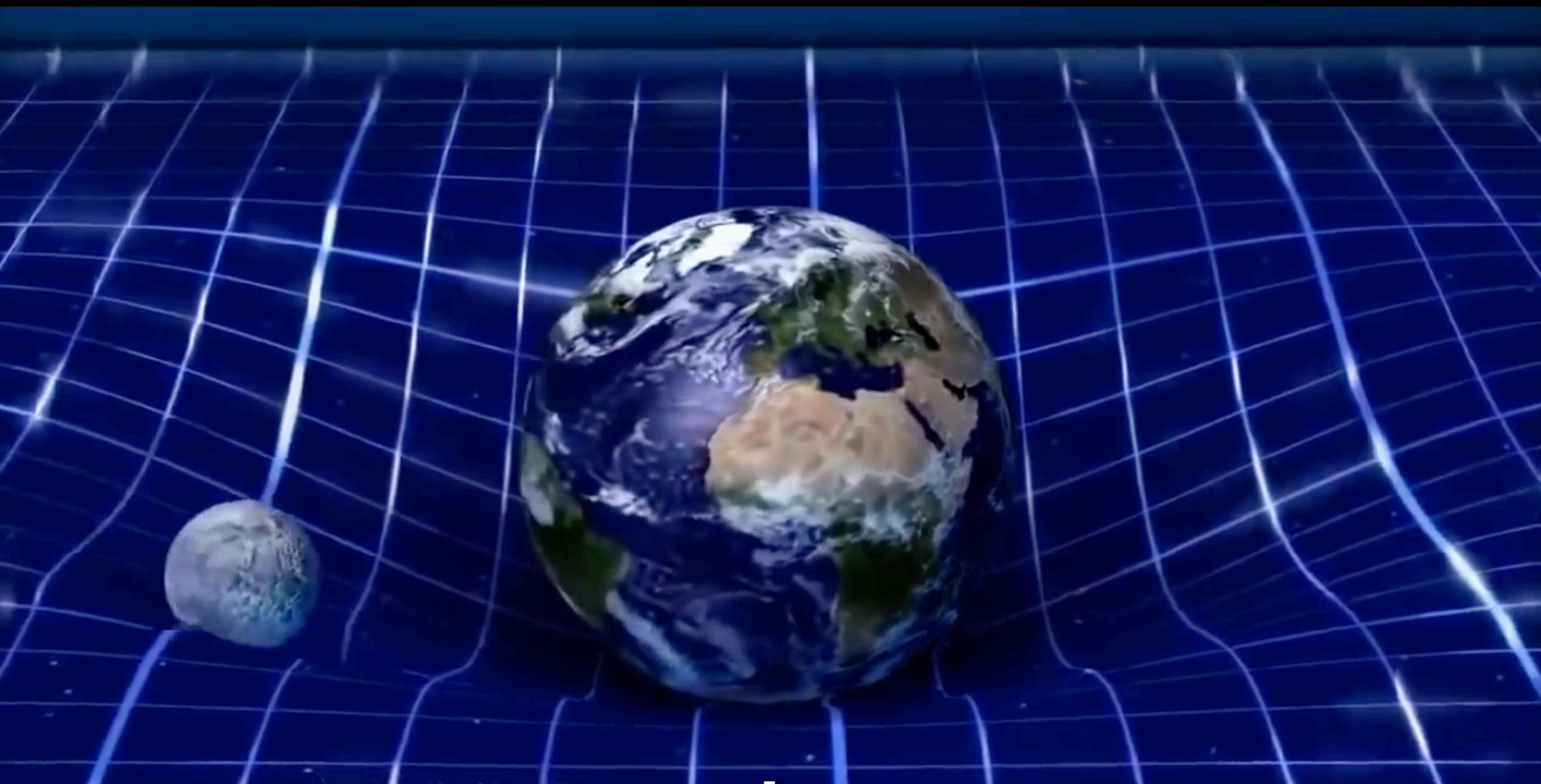
Lo spazio-tempo



Lo spazio-tempo



La gravità non è una forza



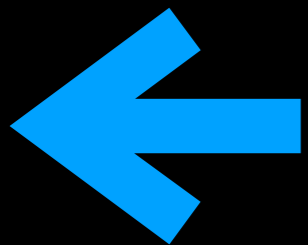
Quanto avete capito?

Un po'



Indica in
alto

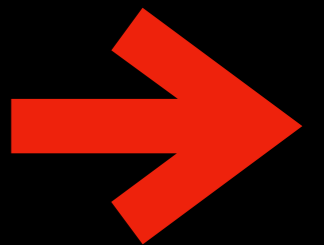
Niente



Indica a
sinistra

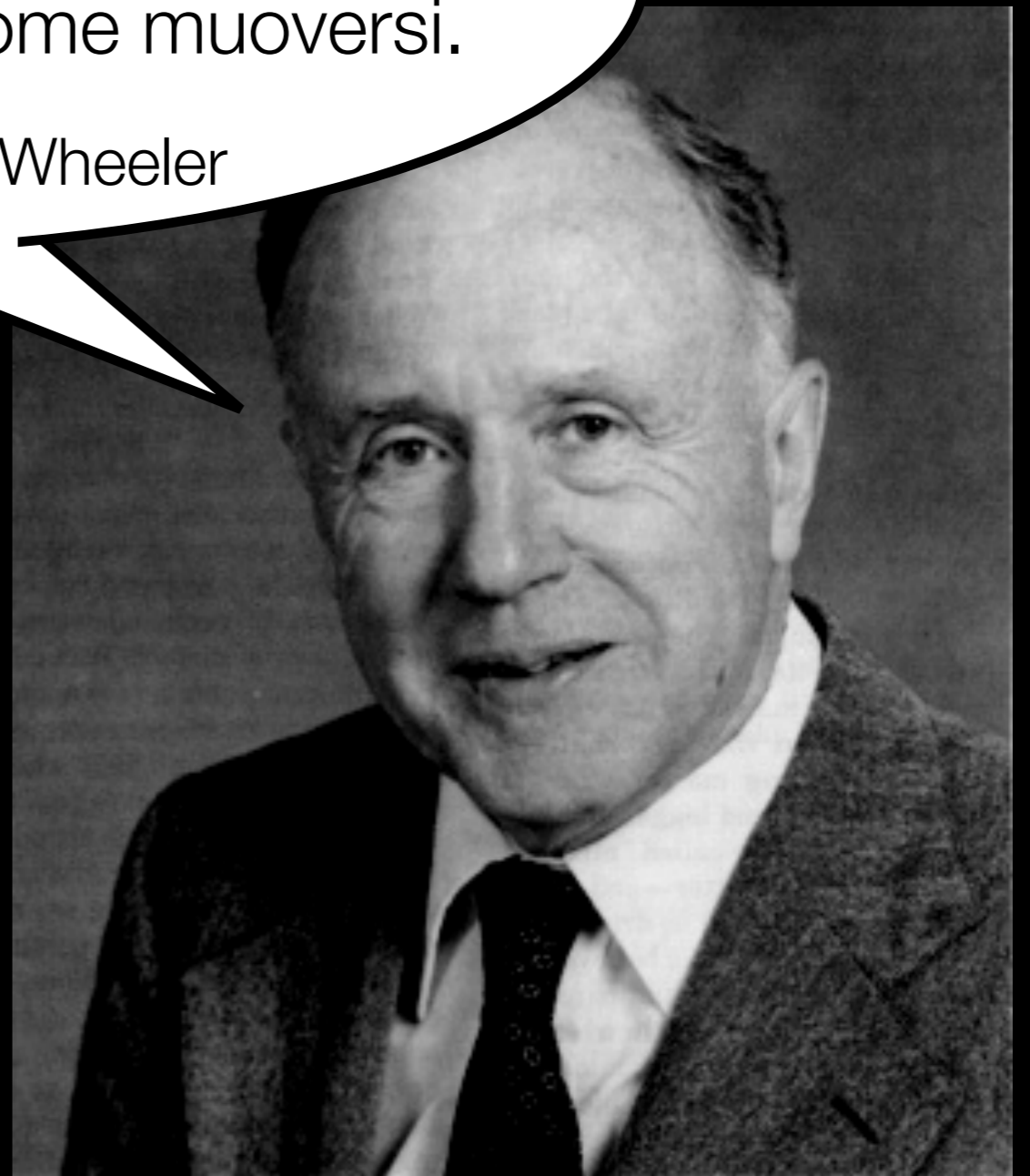
Tutto

Indica a
destra



La materia dice allo spazio come curvarsi,
lo spazio dice alla materia come muoversi.

- J.A. Wheeler



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

$$R_{\alpha\beta} - \frac{1}{2}Rg_{\alpha\beta} + \Lambda g_{\alpha\beta} = 8\pi T_{\alpha\beta} \quad \Leftrightarrow \quad R_{\alpha\beta} = 8\pi \left(T_{\alpha\beta} - \frac{1}{D-2}g_{\alpha\beta}T \right) + \frac{2}{D-2}\Lambda g_{\alpha\beta}.$$

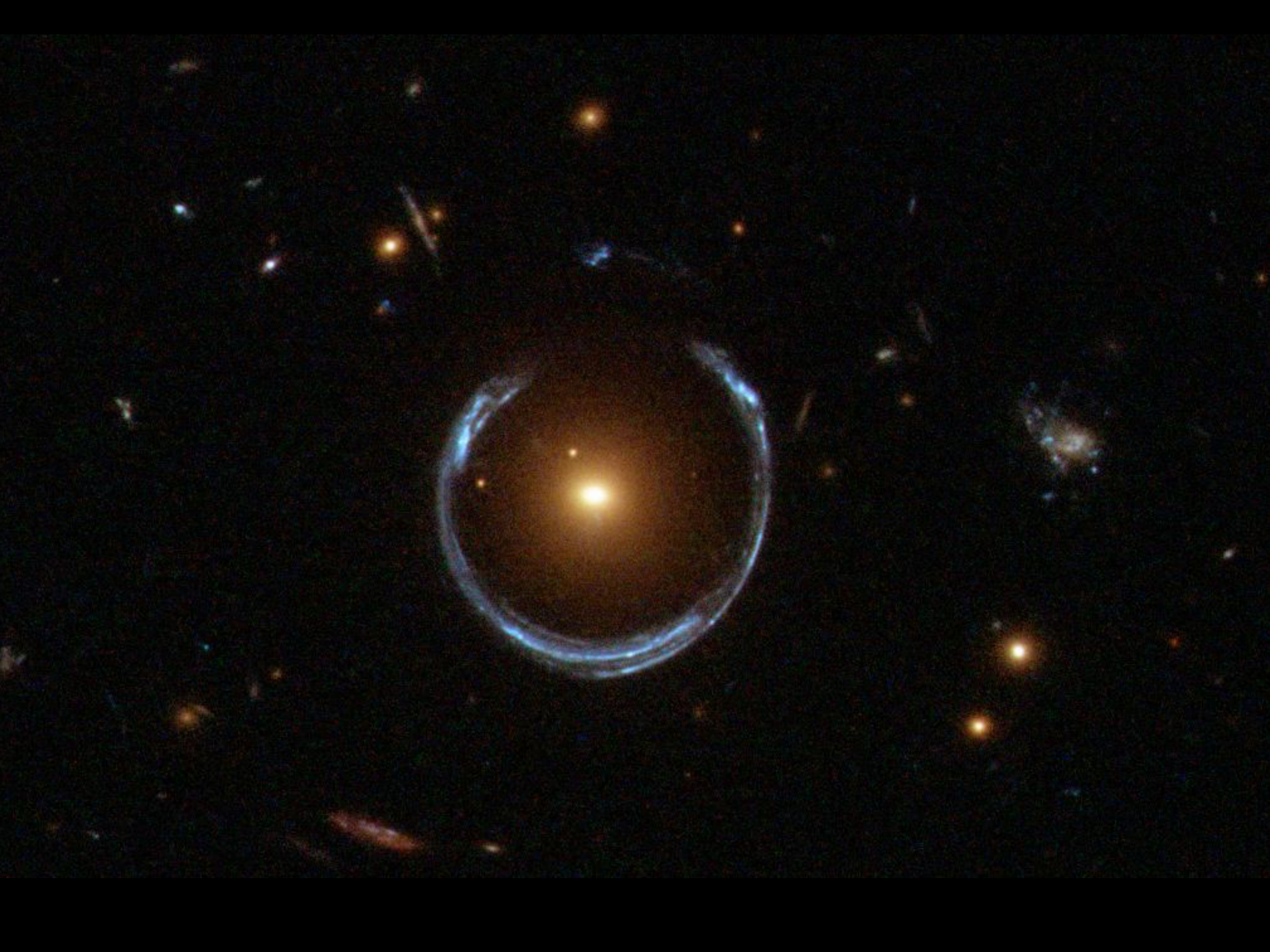
$$\begin{aligned} \frac{4\pi(\rho + S)}{D-4} &= (D-5)\frac{\chi}{\zeta}\frac{\tilde{\gamma}^{yy}\zeta - 1}{y^2} - \frac{2D-7}{4\zeta}\tilde{\gamma}^{mn}\partial_m\eta\partial_n\chi - \chi\frac{\tilde{\Gamma}^y}{y} + \frac{D-6}{4}\frac{\chi}{\zeta^2}\tilde{\gamma}^{mn}\partial_m\zeta\partial_n\zeta \\ &\quad + \frac{1}{2\zeta}\tilde{\gamma}^{mn}(\chi\tilde{D}_m\partial_n\zeta - \zeta\tilde{D}_m\partial_n\chi) + (D-4)\frac{\tilde{\gamma}^{ym}}{y}\left(\frac{\chi}{\zeta}\partial_m\zeta - \partial_m\chi\right) - \frac{KK_\zeta}{\zeta} - \frac{K^2}{3} \\ &\quad - \frac{1}{2}\frac{\tilde{\gamma}^{ym}}{y}\partial_m\chi + \frac{D-1}{4}\tilde{\gamma}^{mn}\frac{\partial_m\chi\partial_n\chi}{\chi} - (D-5)\left(\frac{K_\zeta}{\zeta} + \frac{K}{3}\right)^2, \end{aligned}$$

$$\begin{aligned} \frac{8\pi\chi S_{ij}^{\text{TF}}}{D-4} &= -\left(\frac{K_\zeta}{\zeta} + \frac{K}{3}\right)\tilde{A}_{ij} + \frac{1}{2}\left[\frac{2\chi}{y\zeta}(\delta^y_{(j}\partial_{i)}\zeta - \zeta\tilde{\Gamma}_{ij}^y) + \frac{1}{2\chi}\partial_i\chi\partial_j\chi - \tilde{D}_i\partial_j\chi + \frac{\chi}{\zeta}\tilde{D}_i\partial_j\zeta\right. \\ &\quad \left. + \frac{1}{2\chi}\tilde{\gamma}_{ij}\tilde{\gamma}^{mn}\partial_n\chi\left(\partial_m\chi - \frac{\chi}{\zeta}\partial_m\zeta\right) - \tilde{\gamma}_{ij}\frac{\tilde{\gamma}^{ym}}{y}\partial_m\chi - \frac{\chi}{2\zeta^2}\partial_i\zeta\partial_j\zeta\right]^{\text{TF}} \end{aligned}$$

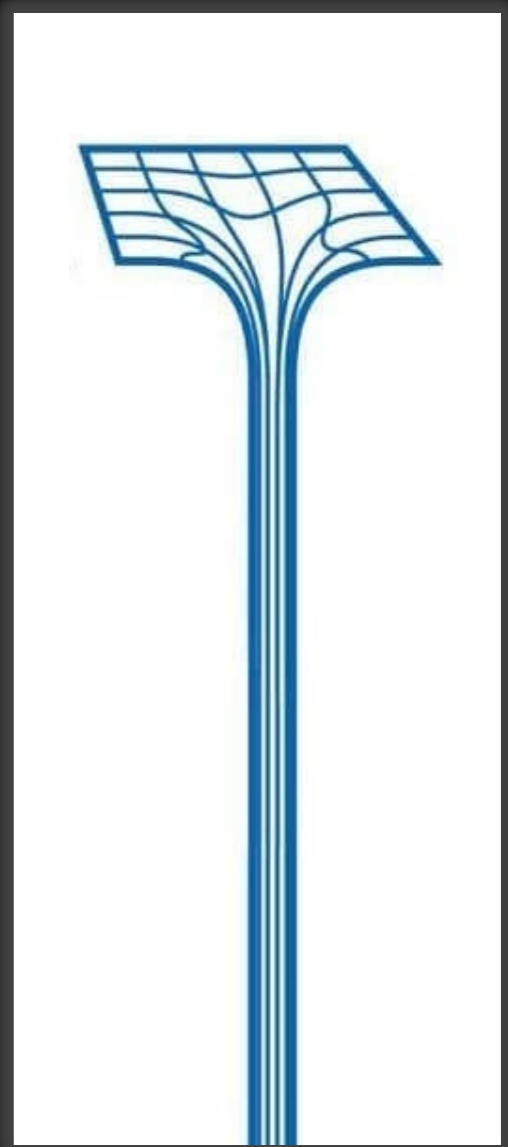
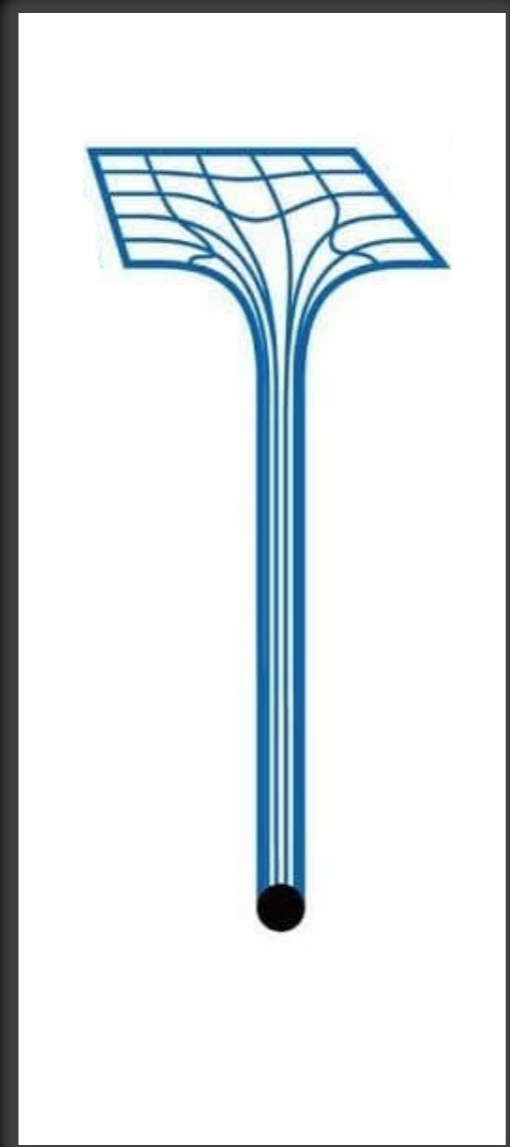
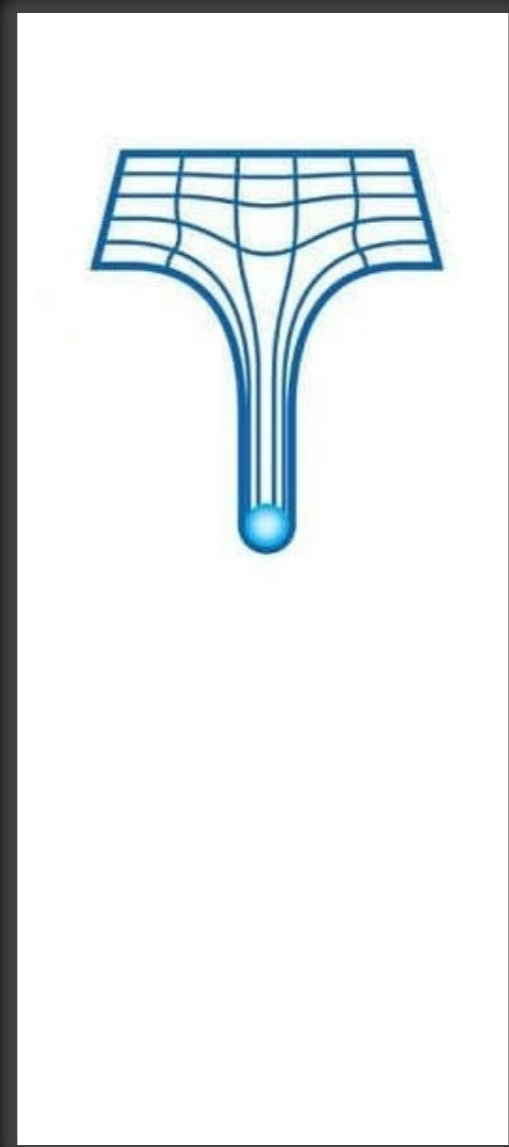
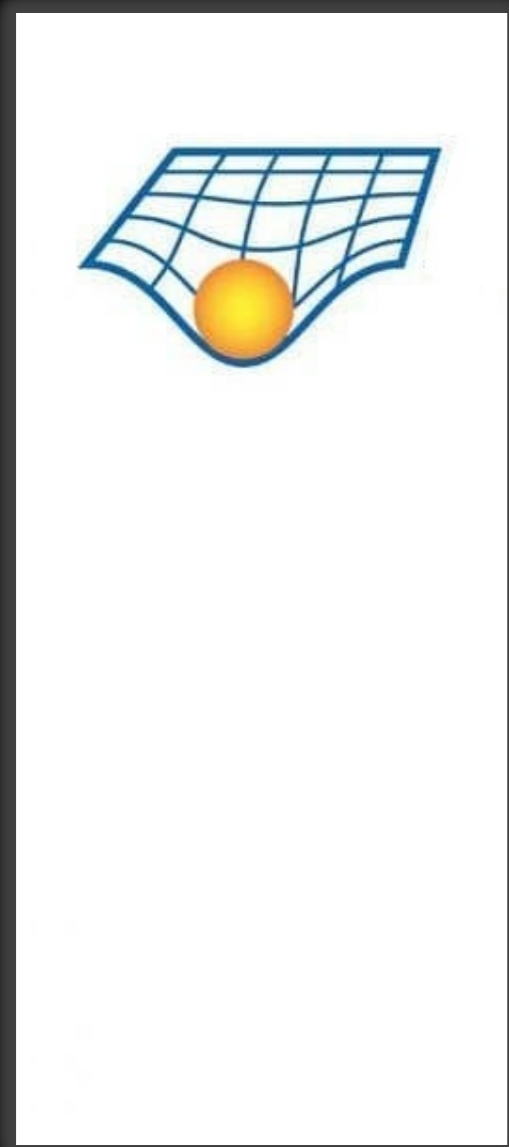
$$\begin{aligned} \frac{16\pi j_i}{D-4} &= \frac{2}{y}\left(\delta^y_i\frac{K_\zeta}{\zeta} - \tilde{\gamma}^{ym}\tilde{A}_{mi}\right) + \frac{2}{\zeta}\partial_i K_\zeta - \frac{K_\zeta}{\zeta}\left(\frac{1}{\chi}\partial_i\chi + \frac{1}{\zeta}\partial_i\zeta\right) + \frac{2}{3}\partial_i K \\ &\quad - \tilde{\gamma}^{nm}\tilde{A}_{mi}\left(\frac{1}{\zeta}\partial_n\zeta - \frac{1}{\chi}\partial_n\chi\right). \end{aligned}$$

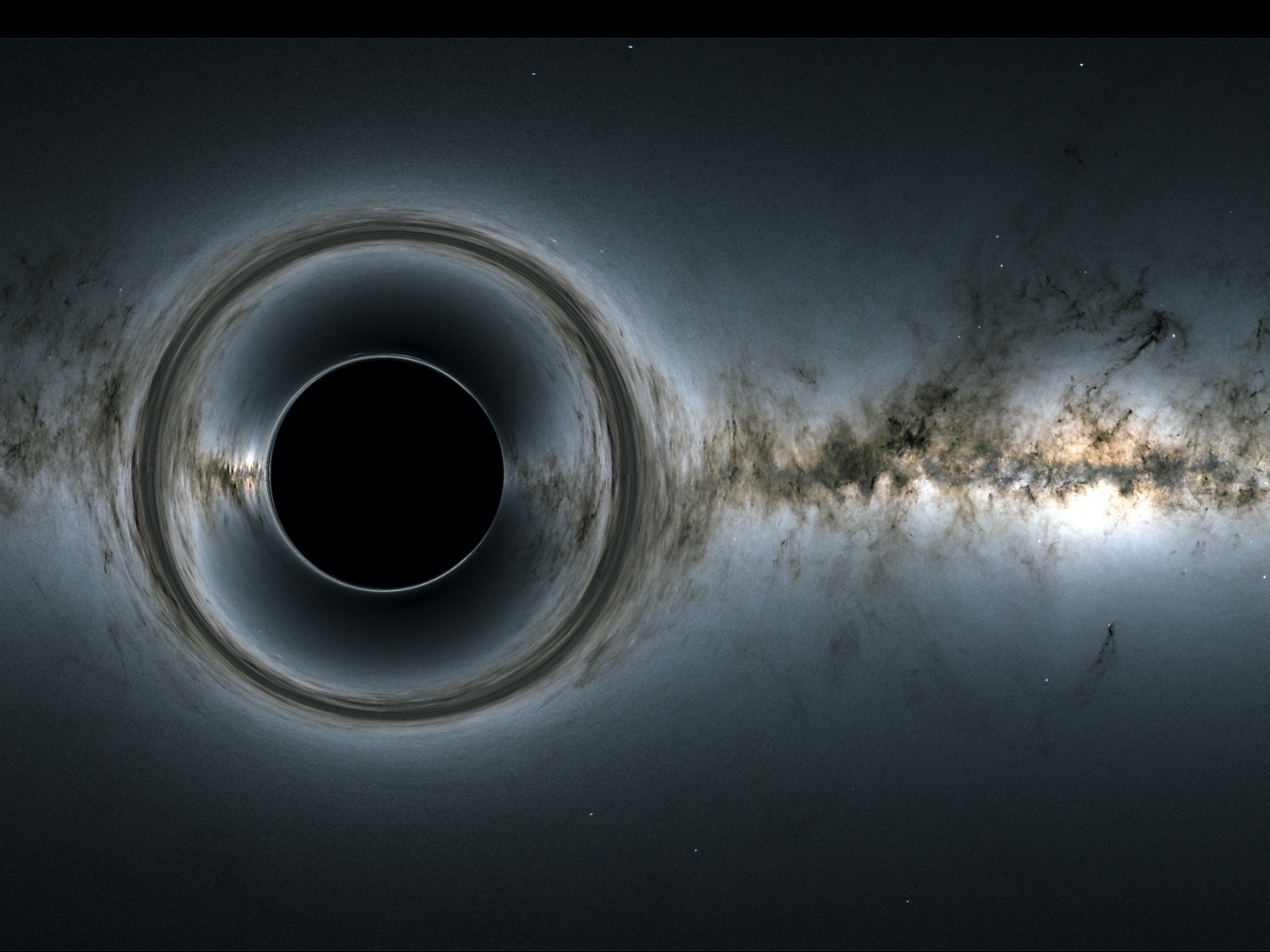
$$\partial_t\zeta = \beta^m\partial_m\zeta - 2\alpha K_\zeta - \frac{2}{3}\zeta\partial_m\beta^m + 2\zeta\frac{\beta^y}{y},$$

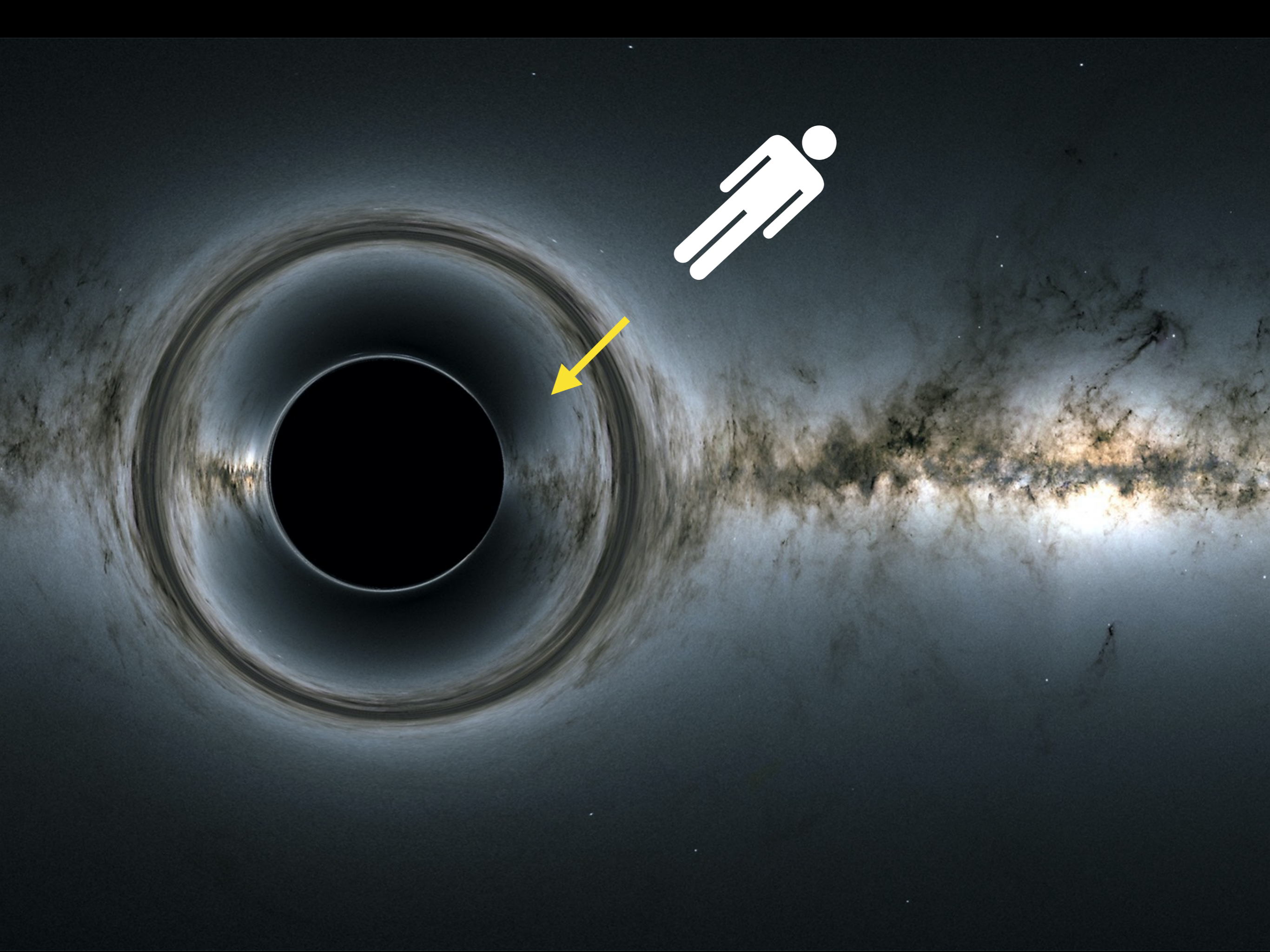
$$\begin{aligned} \partial_t K_\zeta &= \beta^m\partial_m K_\zeta - \frac{2}{3}K_\zeta\partial_m\beta^m + 2\frac{\beta^y}{y}K_\zeta - \frac{1}{3}\zeta(\partial_t - \mathcal{L}_\beta)K - \chi\zeta\frac{\tilde{\gamma}^{ym}}{y}\partial_m\alpha \\ &\quad - \frac{1}{2}\tilde{\gamma}^{mn}\partial_m\alpha(\chi\partial_n\zeta - \zeta\partial_n\chi) + \alpha\left[(5-D)\chi\frac{\zeta\tilde{\gamma}^{yy}-1}{y^2} + (4-D)\chi\frac{\tilde{\gamma}^{ym}}{y}\partial_m\zeta\right. \\ &\quad \left. + \frac{2D-7}{2}\zeta\frac{\tilde{\gamma}^{ym}}{y}\partial_m\chi + \frac{6-D}{4}\frac{\chi}{\zeta}\tilde{\gamma}^{mn}\partial_m\zeta\partial_n\zeta + \frac{2D-7}{4}\tilde{\gamma}^{mn}\partial_m\zeta\partial_n\chi\right. \\ &\quad \left. + \frac{1-D}{4}\frac{\zeta}{\chi}\tilde{\gamma}^{mn}\partial_m\chi\partial_n\chi + (D-6)\frac{K_\zeta^2}{\zeta} + \frac{2D-5}{3}KK_\zeta + \frac{D-1}{9}\zeta K^2\right. \\ &\quad \left. + \frac{1}{2}\tilde{\gamma}^{mn}(\zeta\tilde{D}_m\partial_n\chi - \chi\tilde{D}_m\partial_n\zeta) + \chi\zeta\frac{\tilde{\Gamma}^y}{y}\right]. \end{aligned}$$

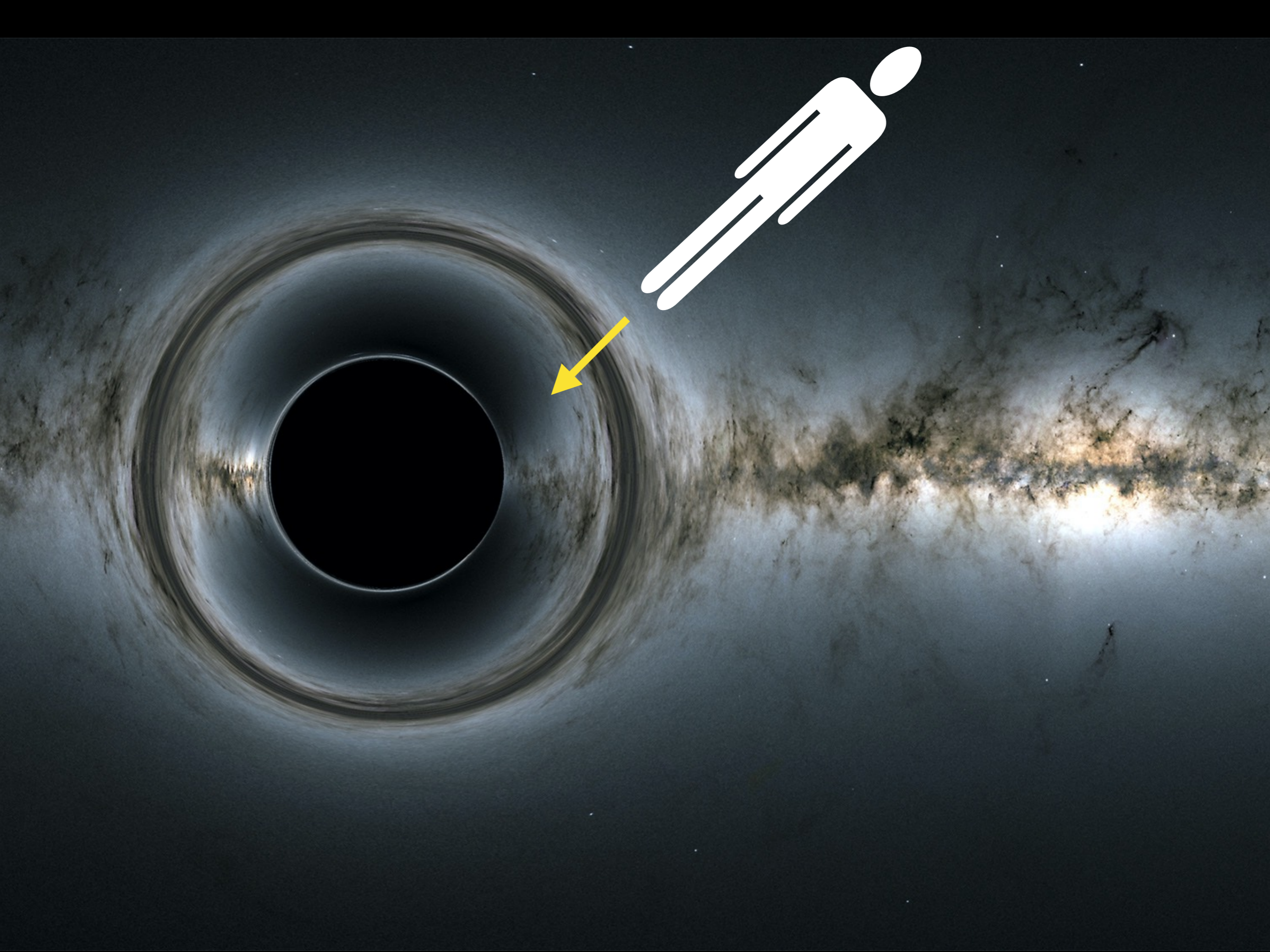












Spaghetttification



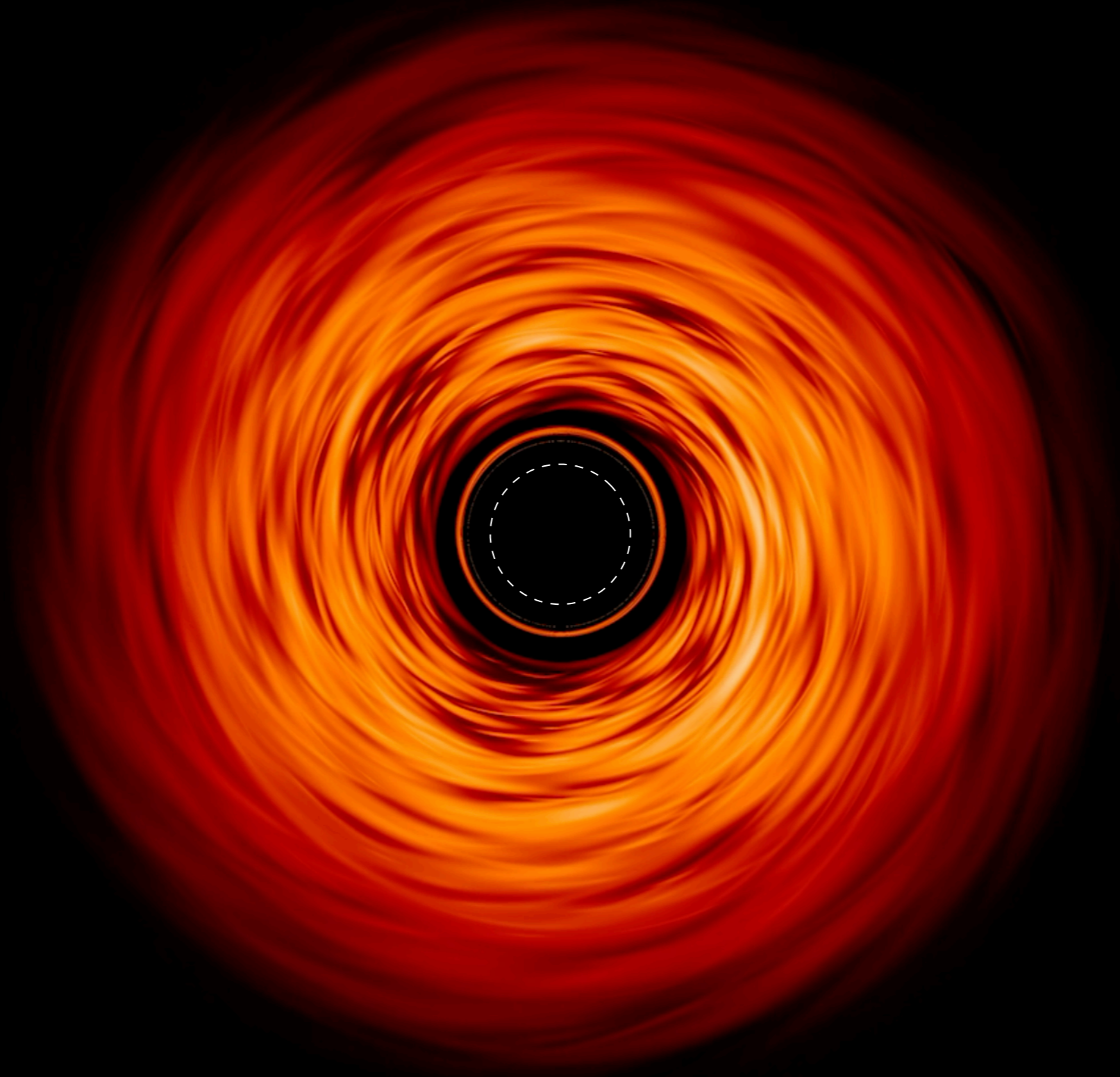
Barilla

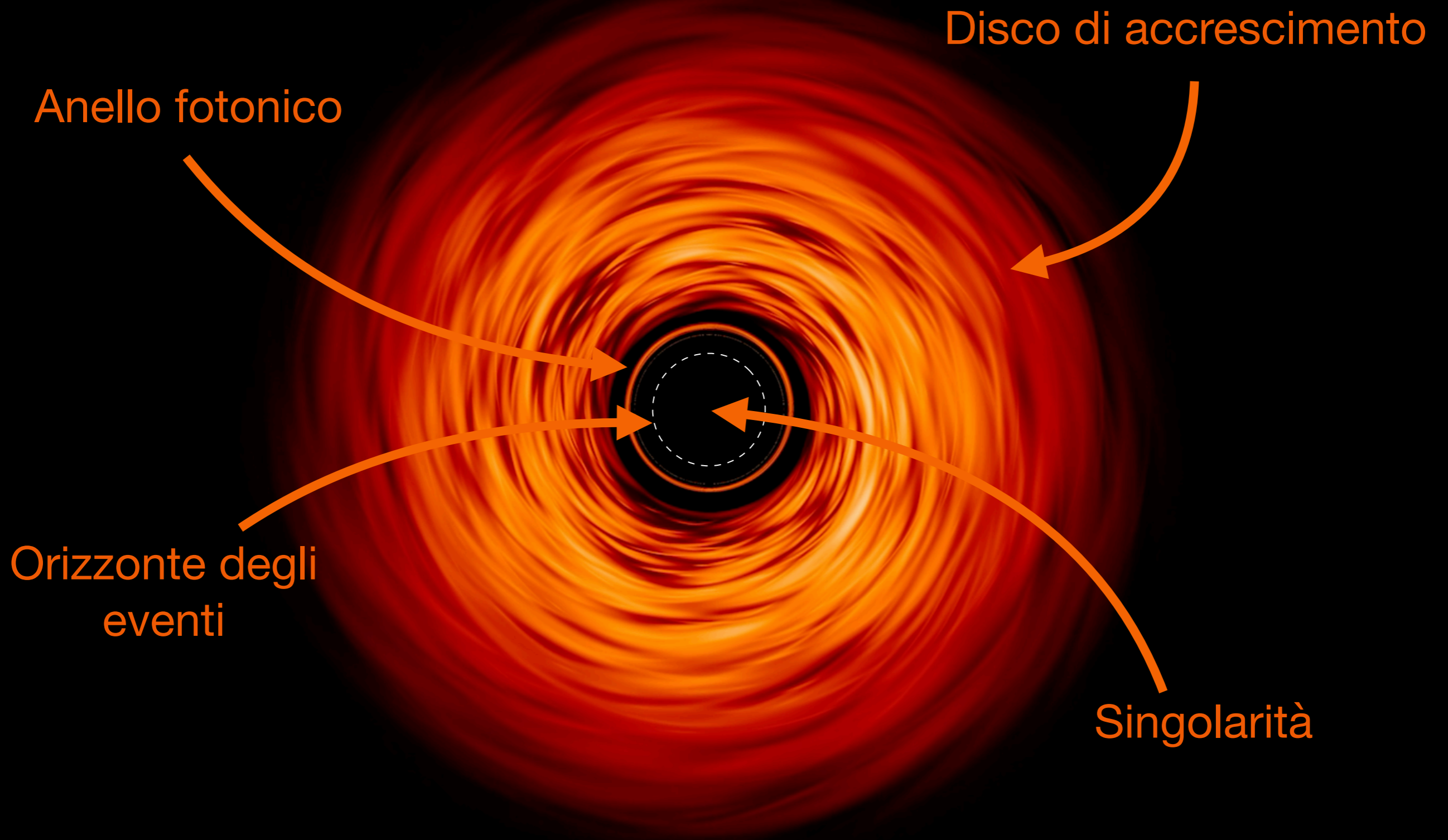
SPAGHETTI n.5
COTTURA 9 MINUTI

I NUOVI SPAGHETTI BARILLA
ANCORA PIÙ BUONI

1Kg
CONVENIENZA

The advertisement features a dark blue background. On the left is the Barilla logo. In the center, there is a rectangular image of uncooked spaghetti. To the right of the spaghetti is a close-up of a fork with a bite of spaghetti topped with tomato sauce and a basil leaf. In the bottom right corner, there is a red square logo with '1Kg' and 'CONVENIENZA' written in white.





Disco di accrescimento

Anello fotonico

Orizzonte degli
eventi

Singolarità

Doppler beaming

Immagine della parte
posteriore del disco

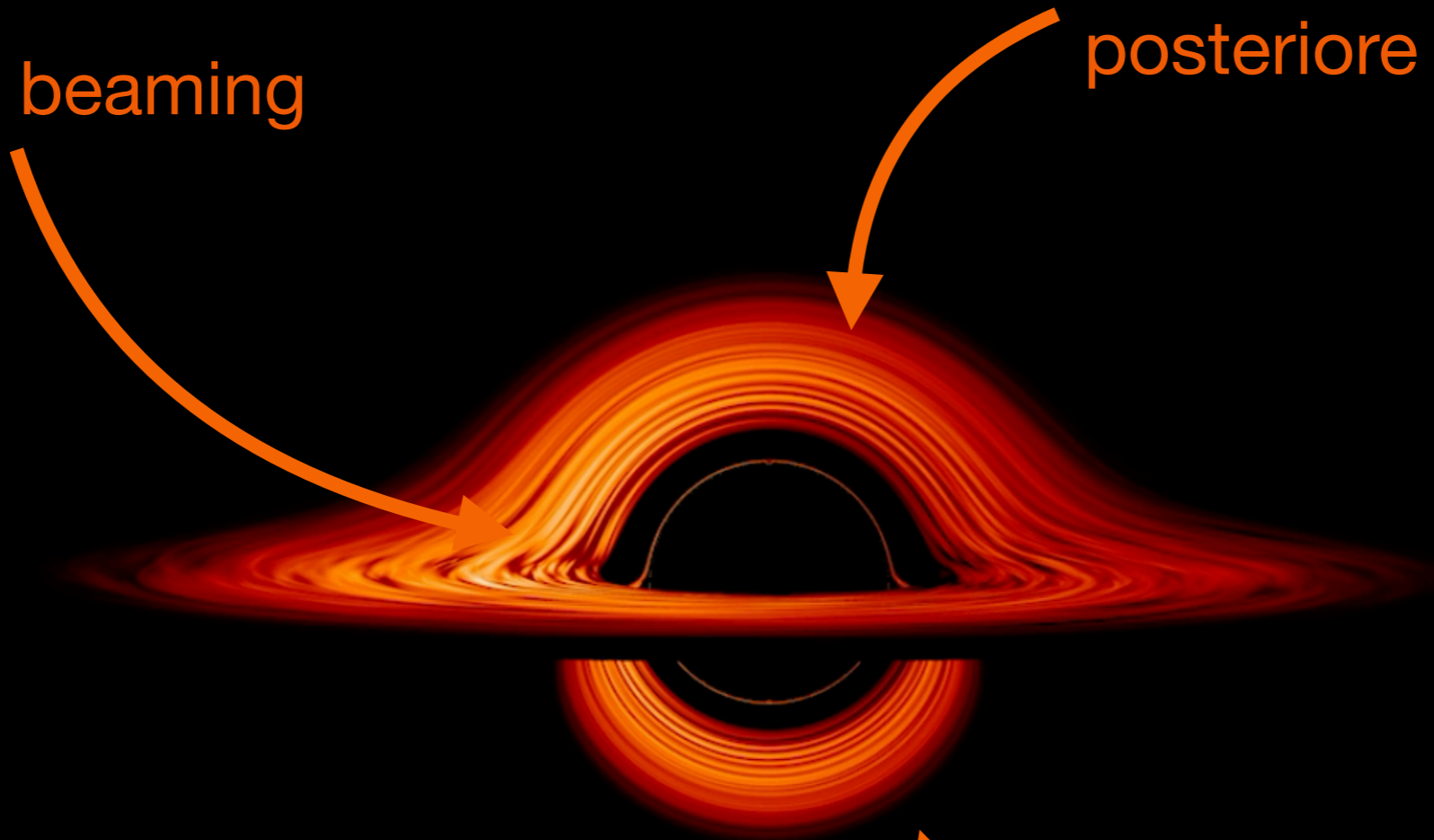


Immagine della parte
posteriore del disco

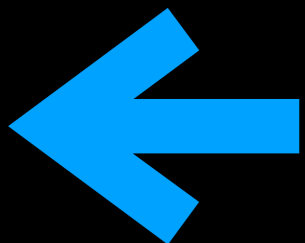
Quanto dobbiamo comprimere la Terra?

Lombardia



Indica in
alto

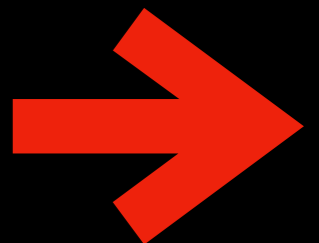
Milano



Indica a
sinistra

Biglia

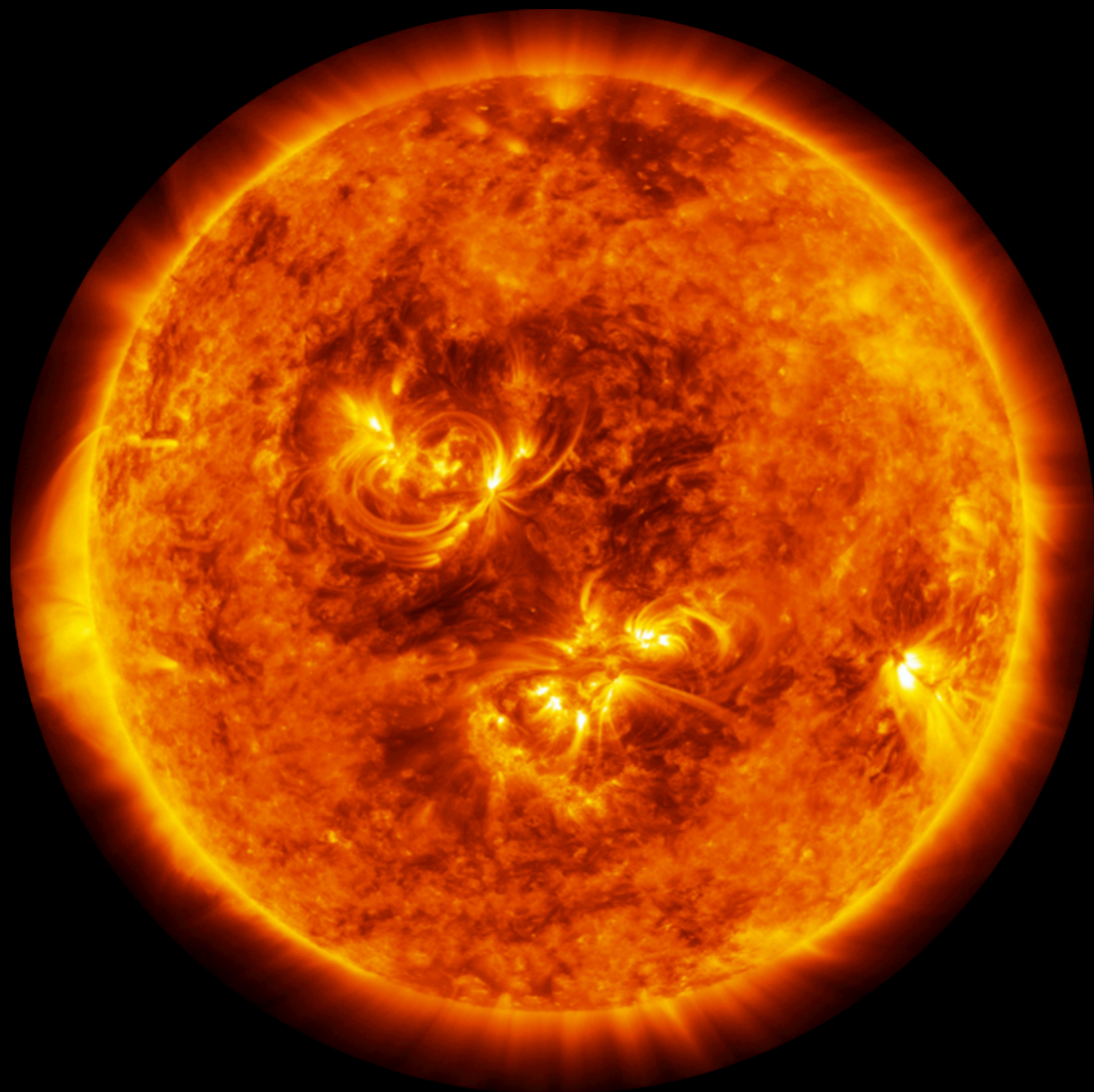
Indica a
destra

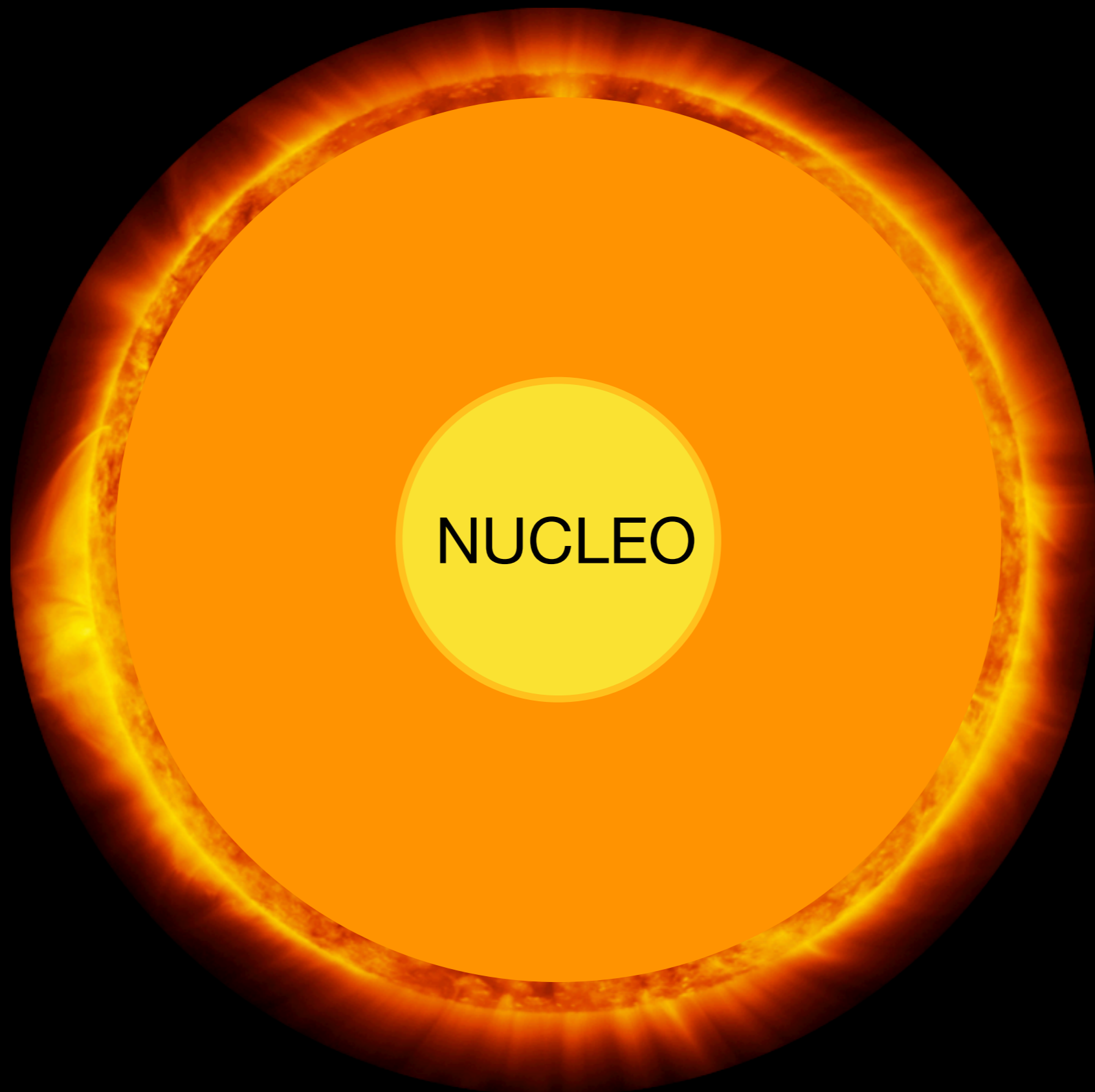


$$r_S = \frac{2G_N M}{c^2}$$

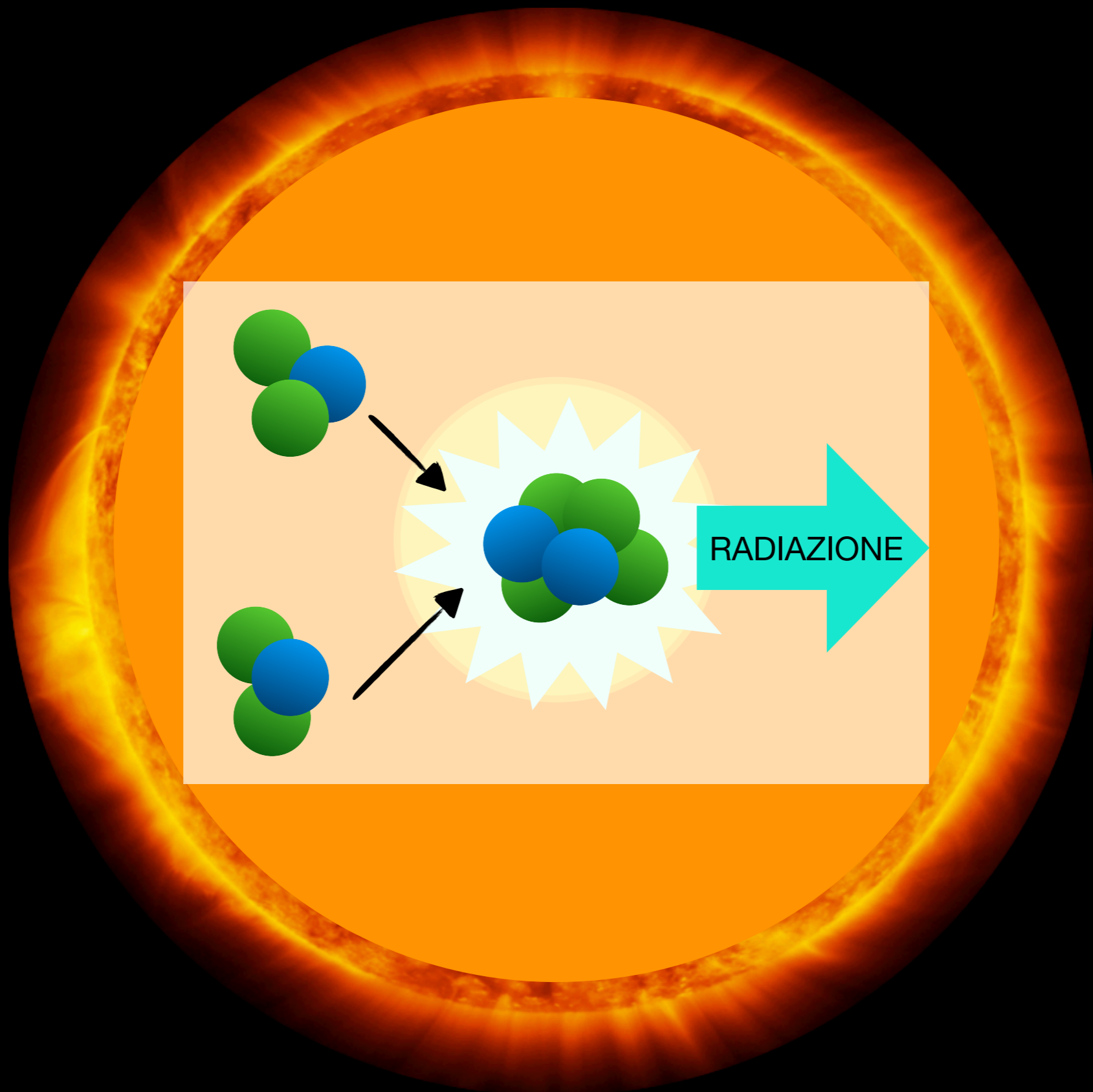
$$ds_{\text{Schw}}^2 = - \left(1 - \frac{2G_N M}{c^2 r} \right) dt^2 + \frac{1}{\left(1 - \frac{2G_N M}{c^2 r} \right)} dr^2 + r^2 (d\theta^2 + \sin^2(\theta) d\varphi^2)$$







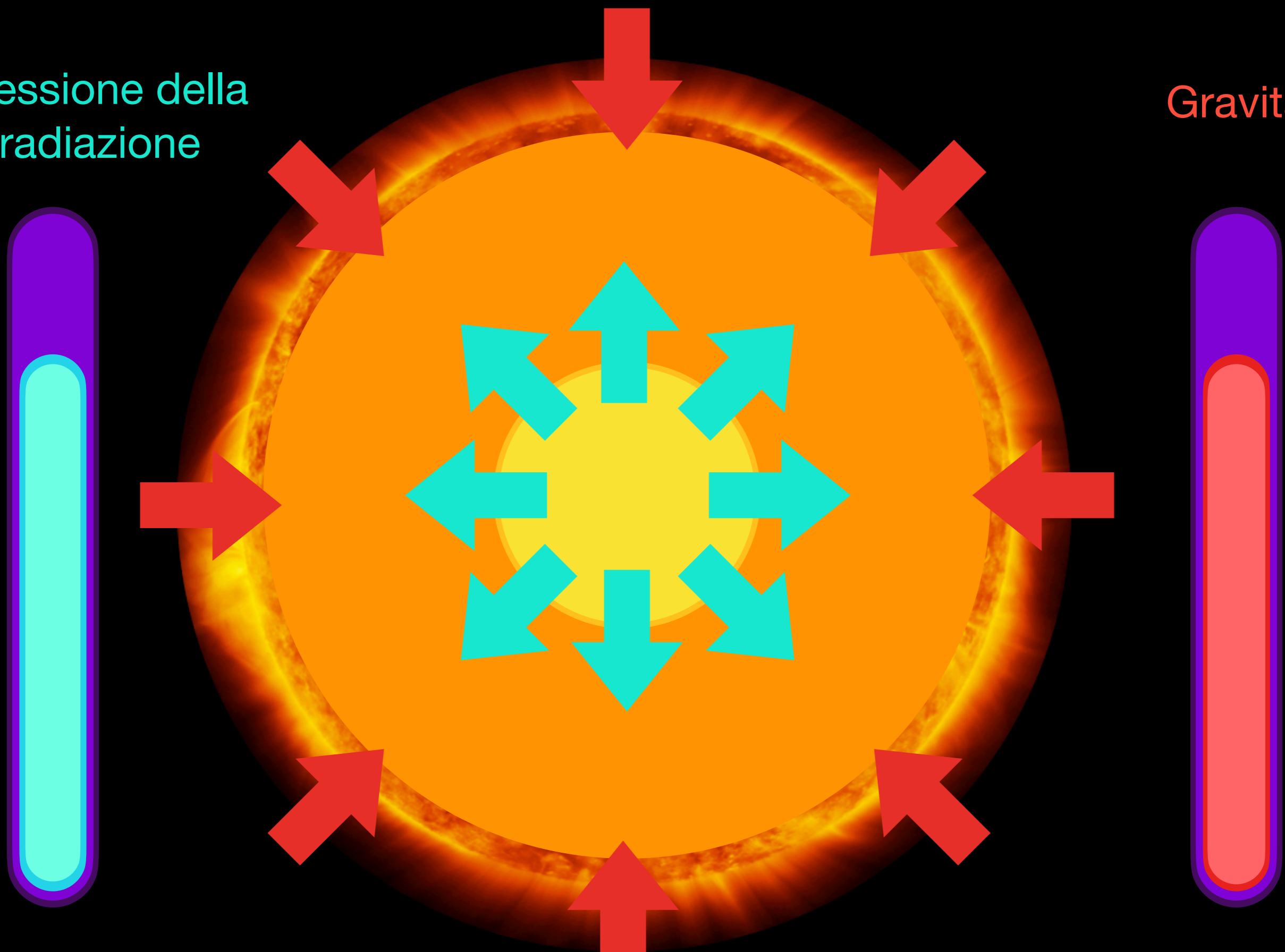
NUCLEO



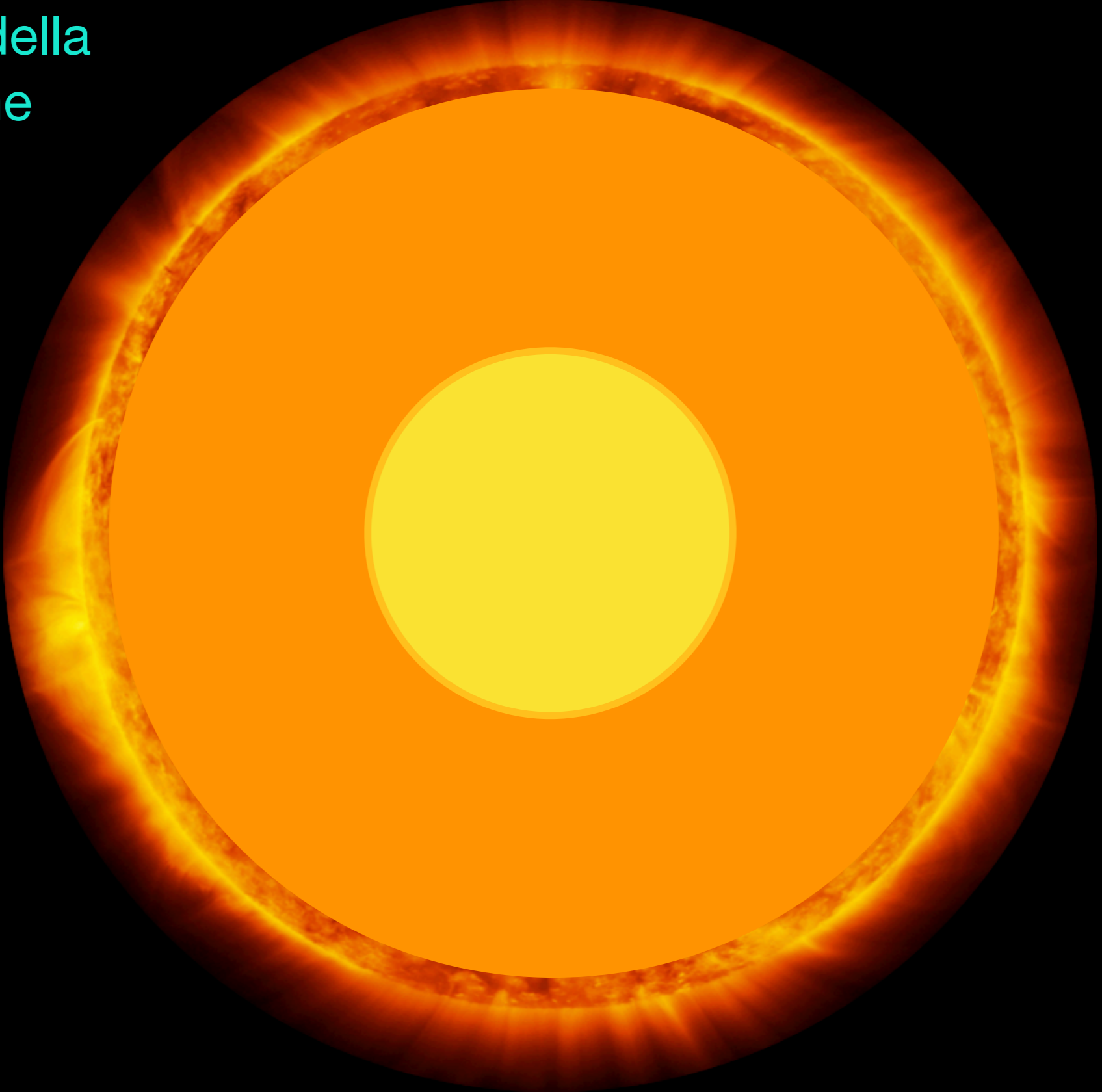
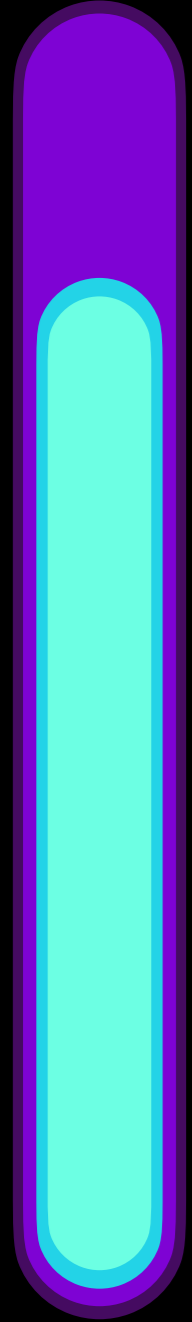
RADIAZIONE

Pressione della radiazione

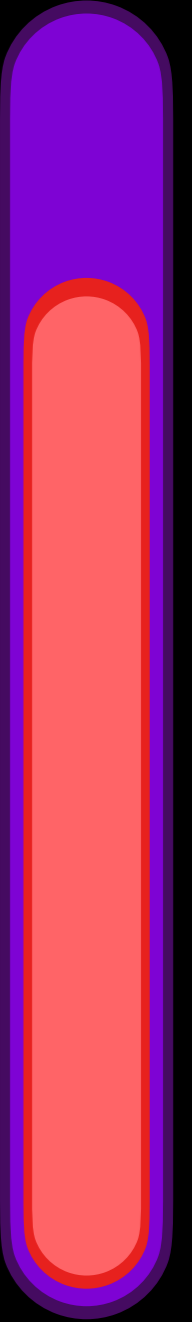
Gravità



Pressione della
radiazione



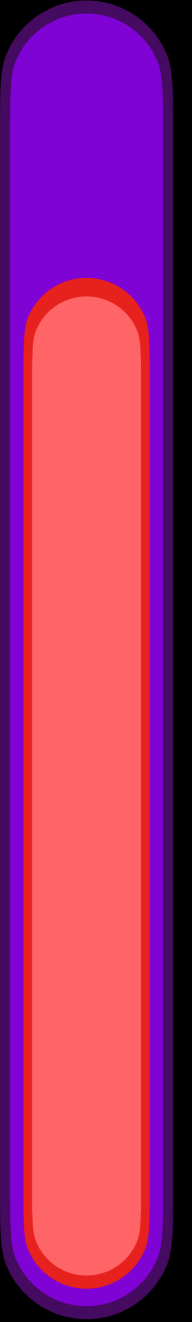
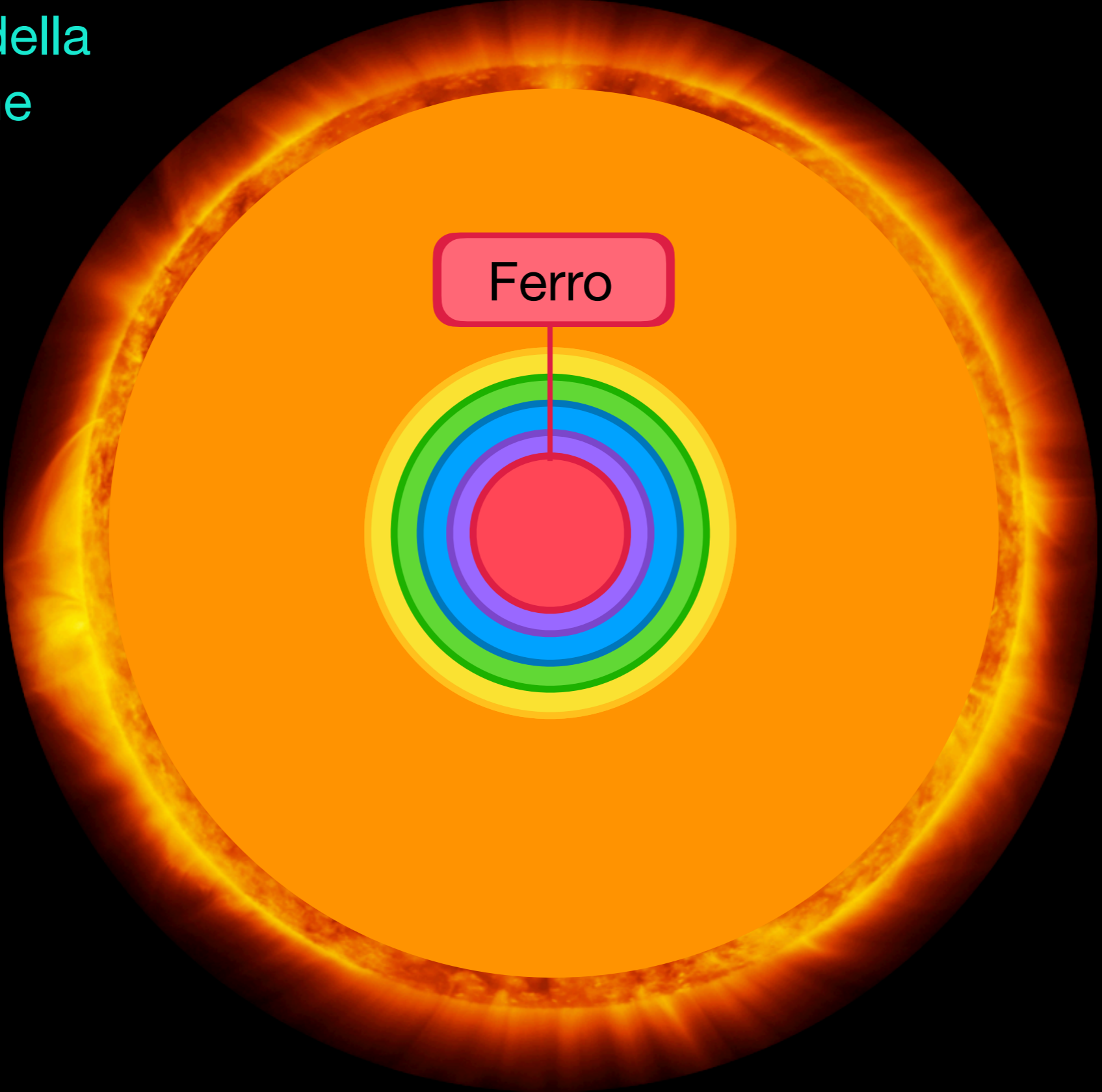
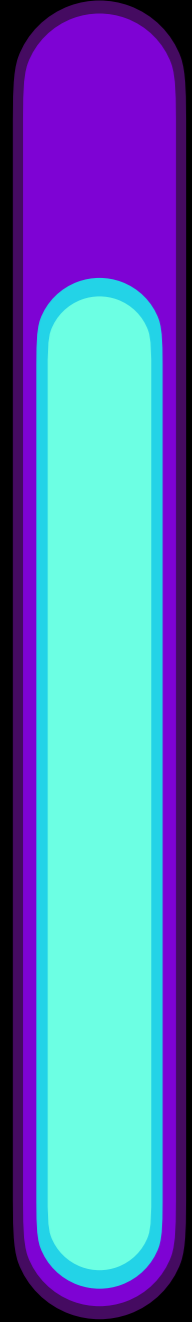
Gravità



Pressione della radiazione

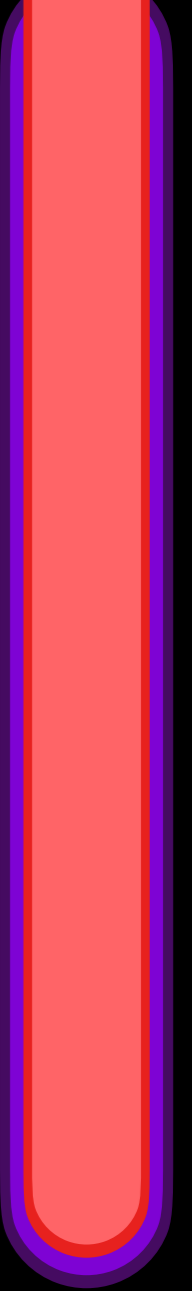
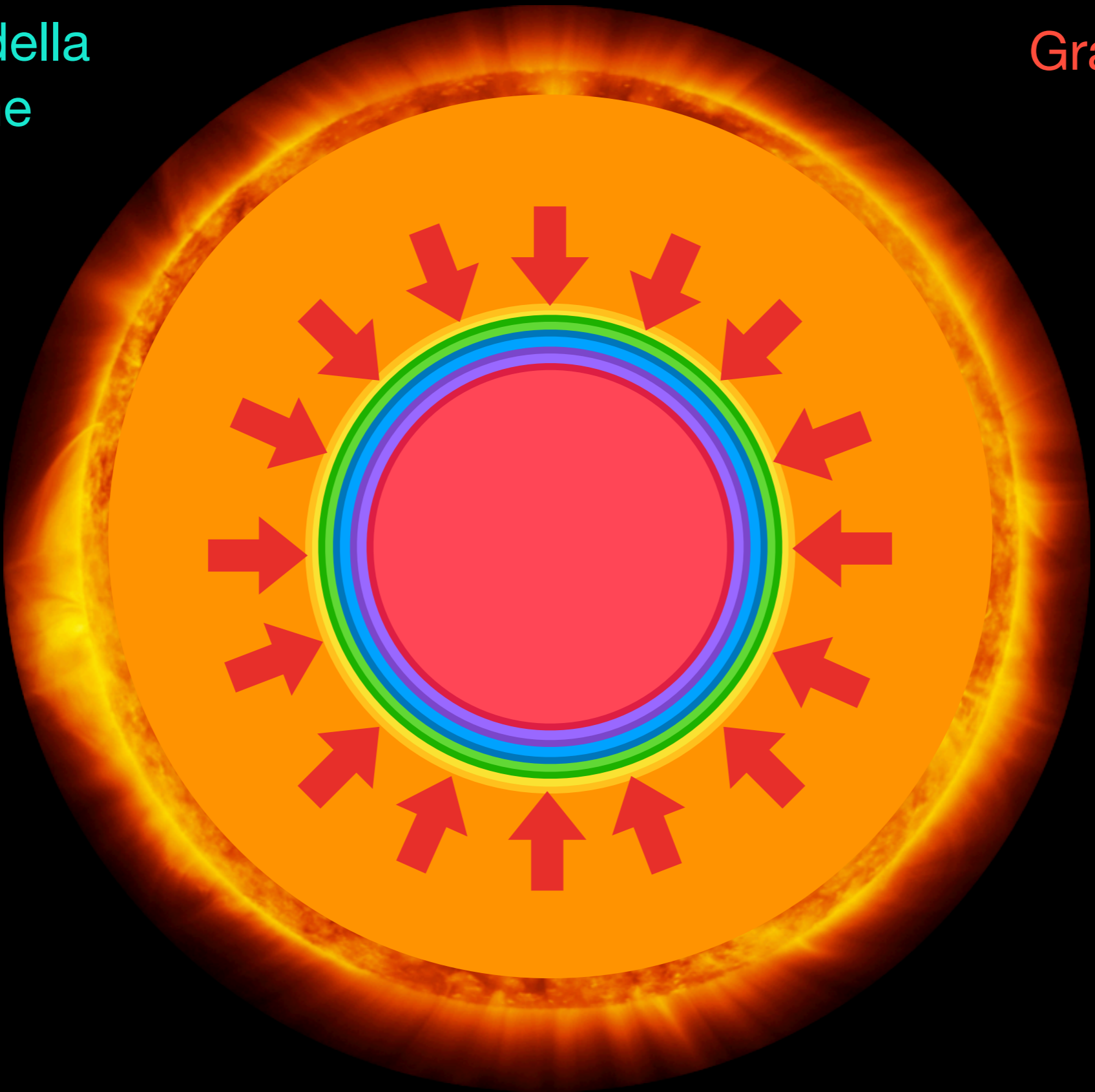
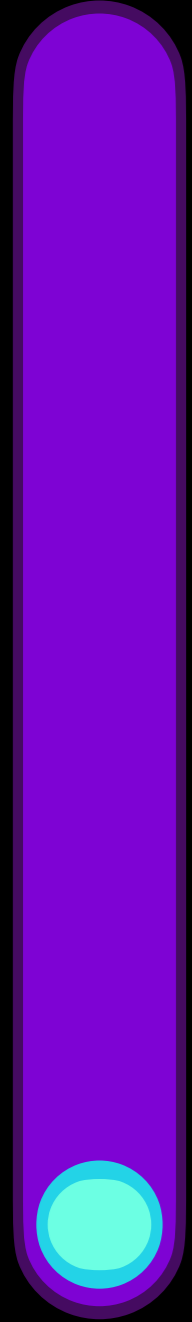
Gravità

Ferro



Pressione della radiazione

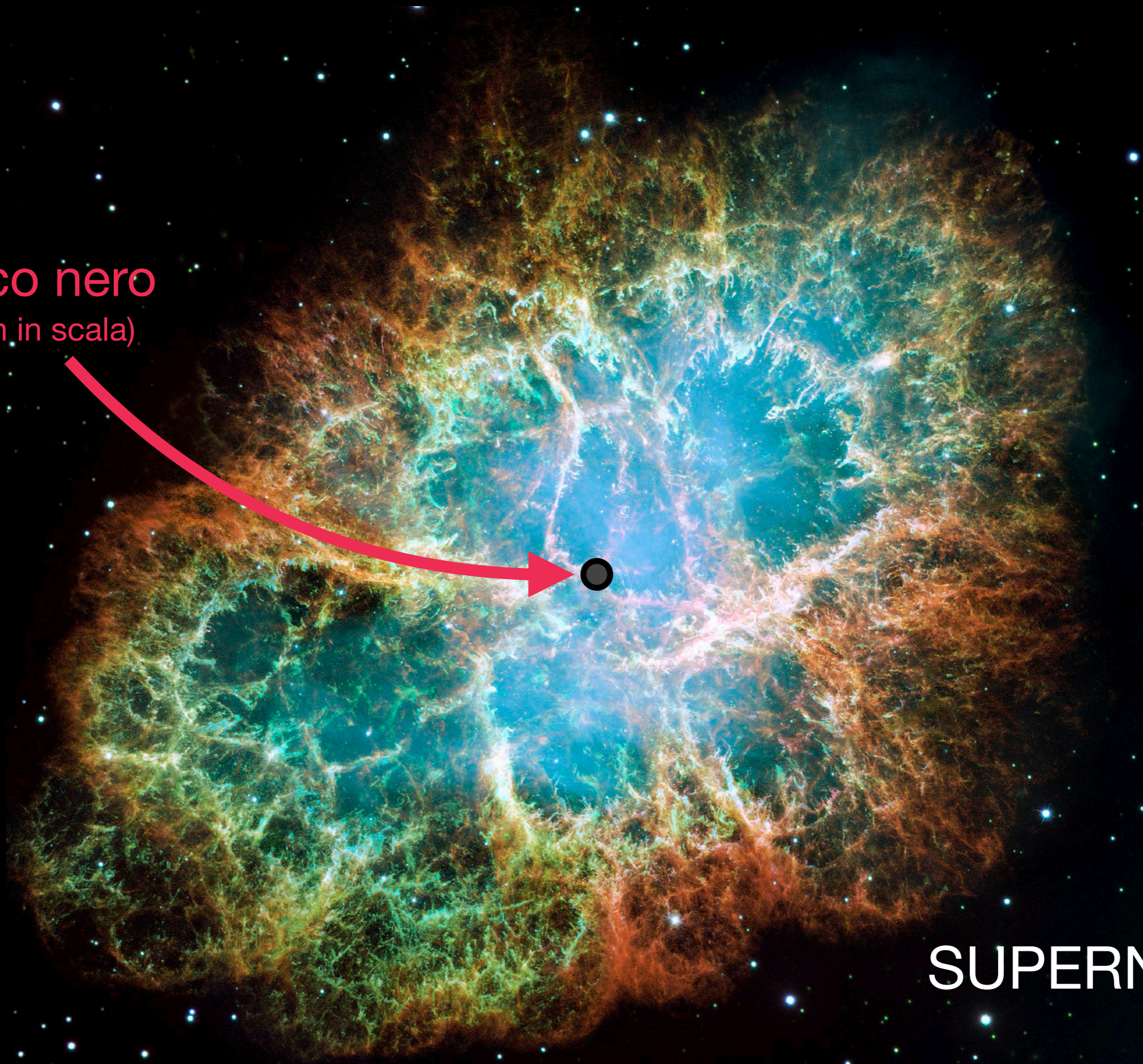
Gravità



Buco nero
(Non in scala)



SUPERNOVA



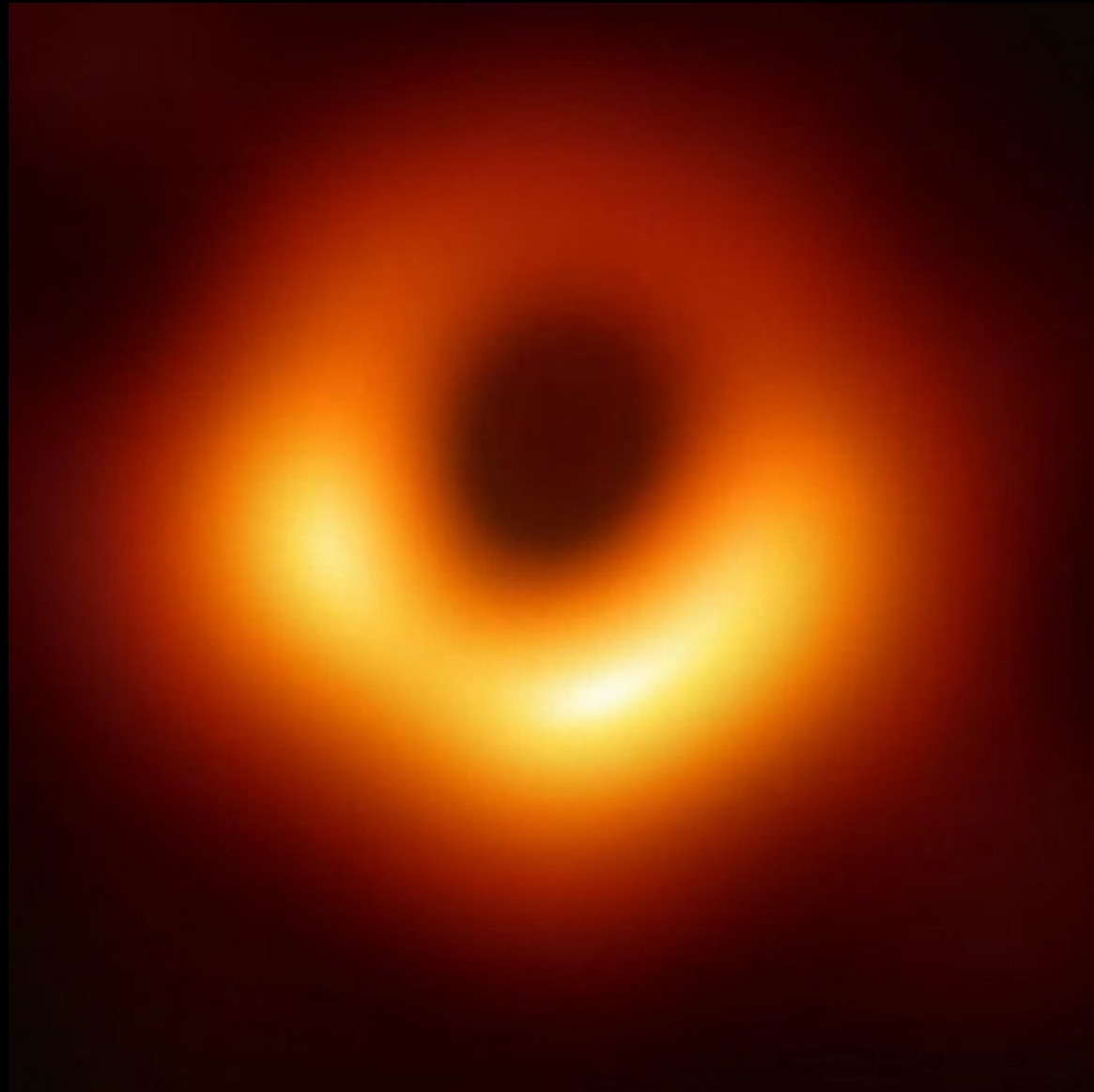


STELLARI

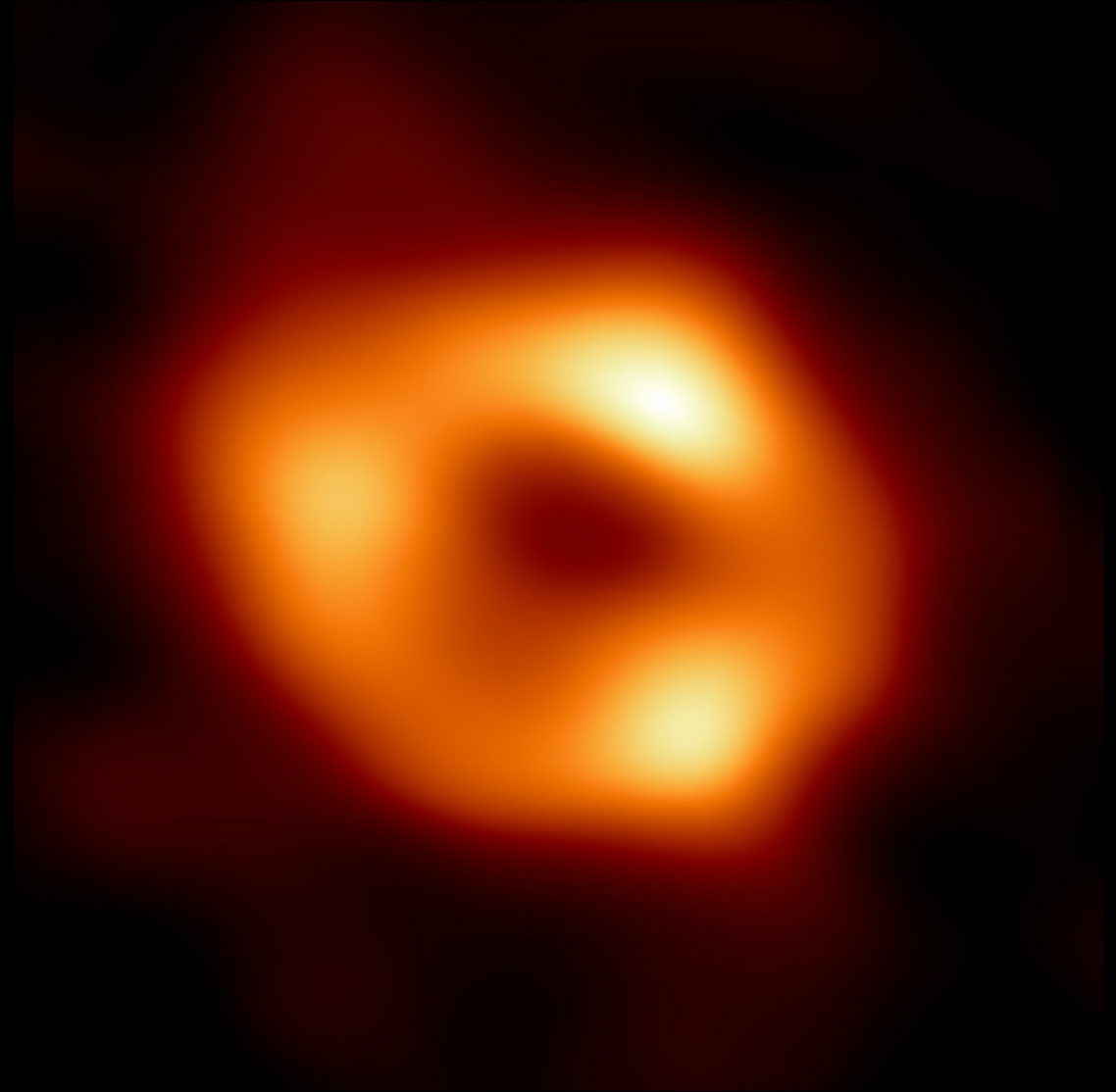
decine - centinaia
di masse solari

SUPERMASSICCI

1 milione - 10 miliardi di
masse solari



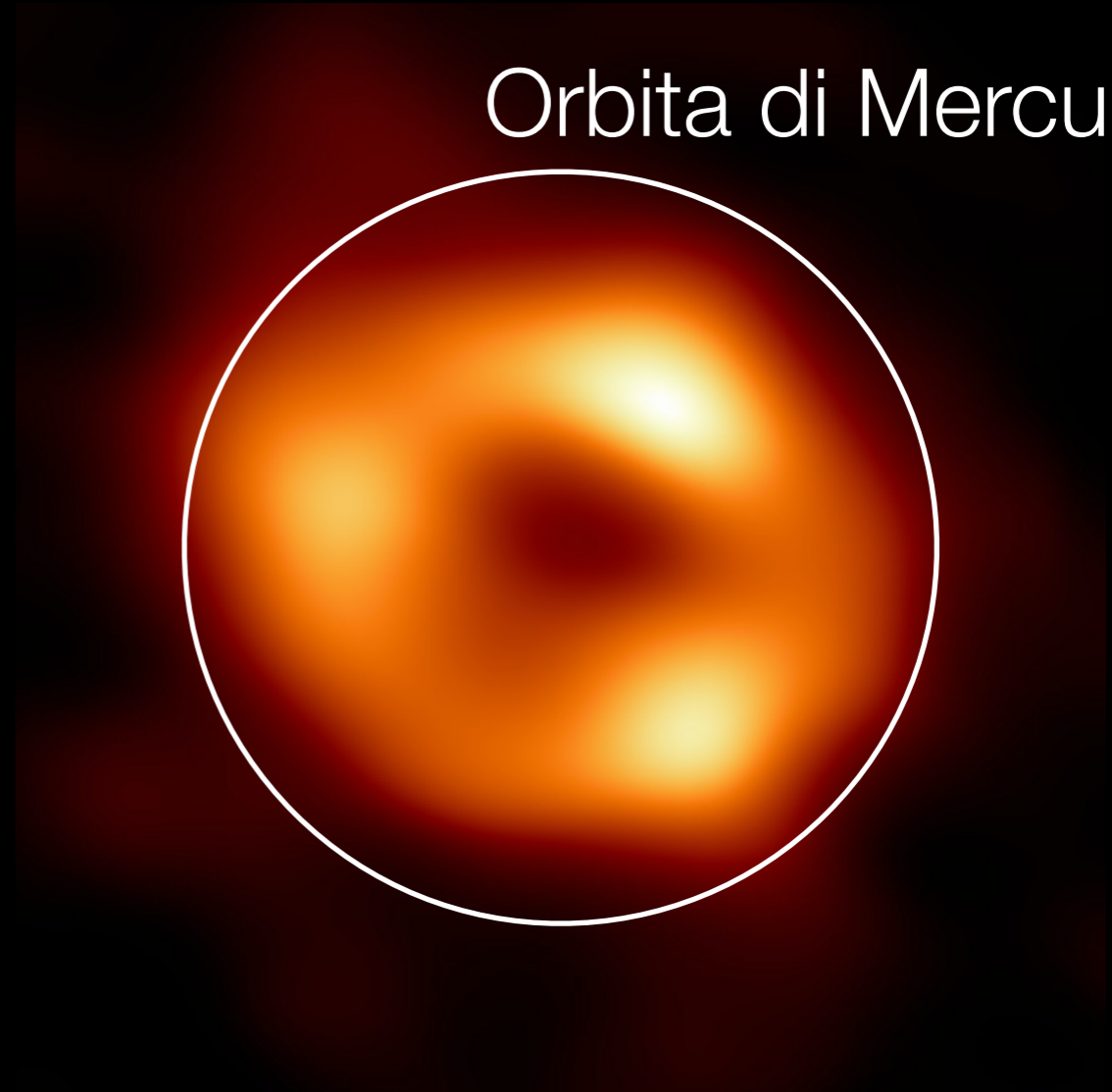
M87



SAGITTARIUS A*

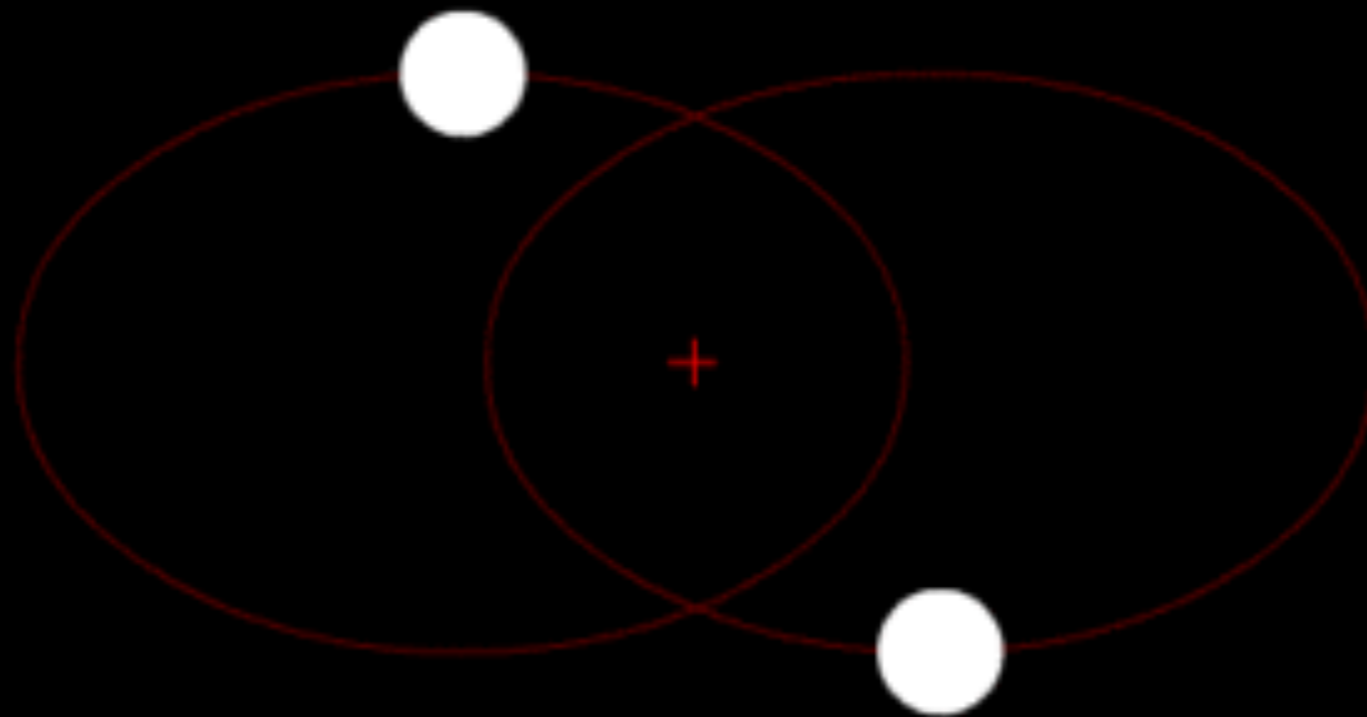


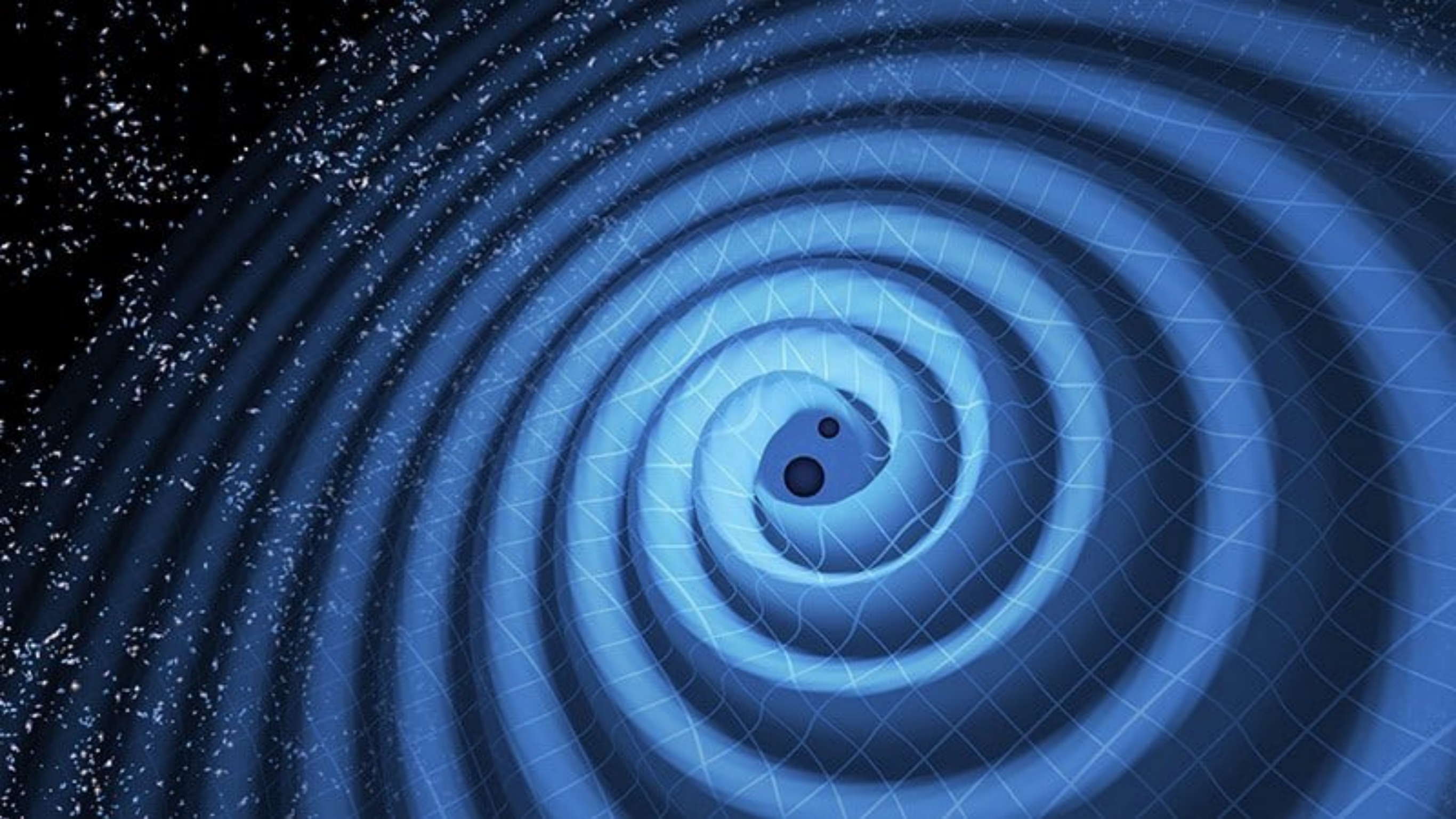
M87



SAGITTARIUS A*

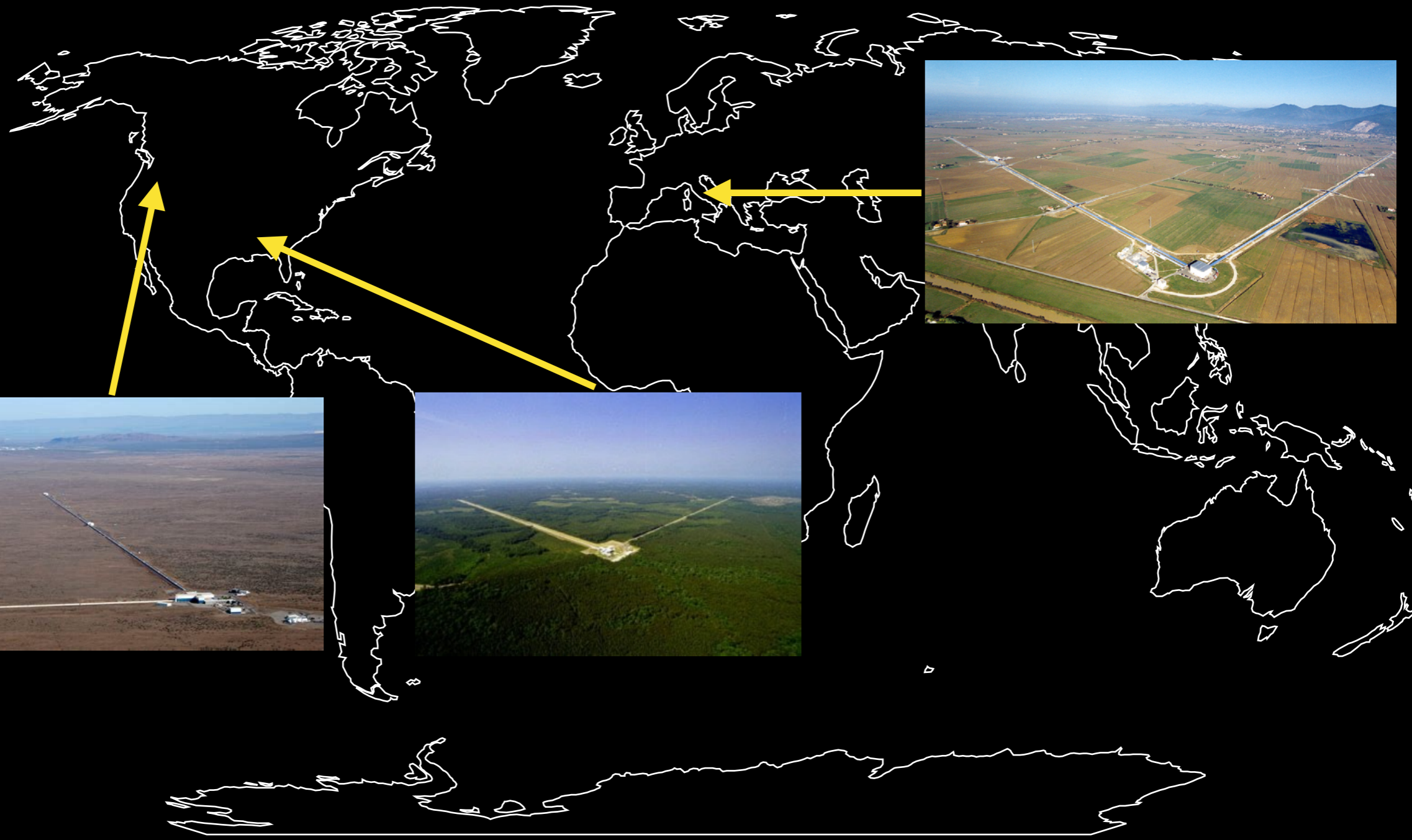
Una binaria di stelle

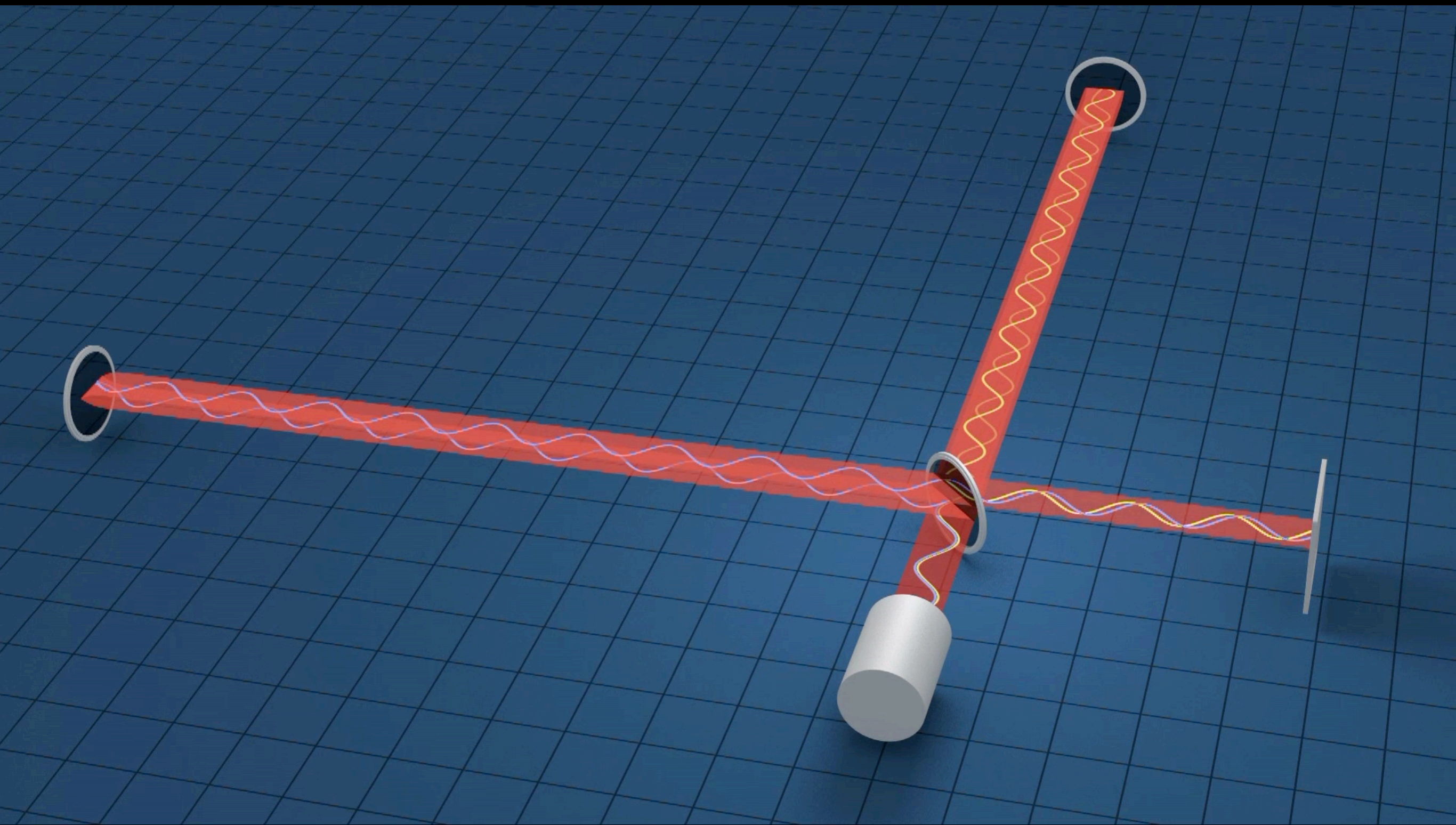




Cosa succede quando passa
un'onda gravitazionale?

<https://www.youtube.com/watch?v=FIDtXIBrAYE>





<https://www.youtube.com/watch?v=FIDtXIBrAYE>



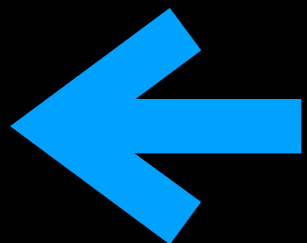
Di quanto si comprime il braccio di Virgo?

Millimetri



Indica in
alto

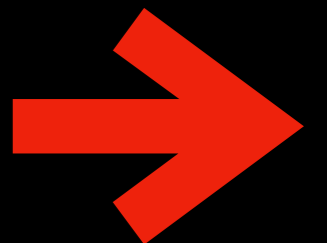
Metri

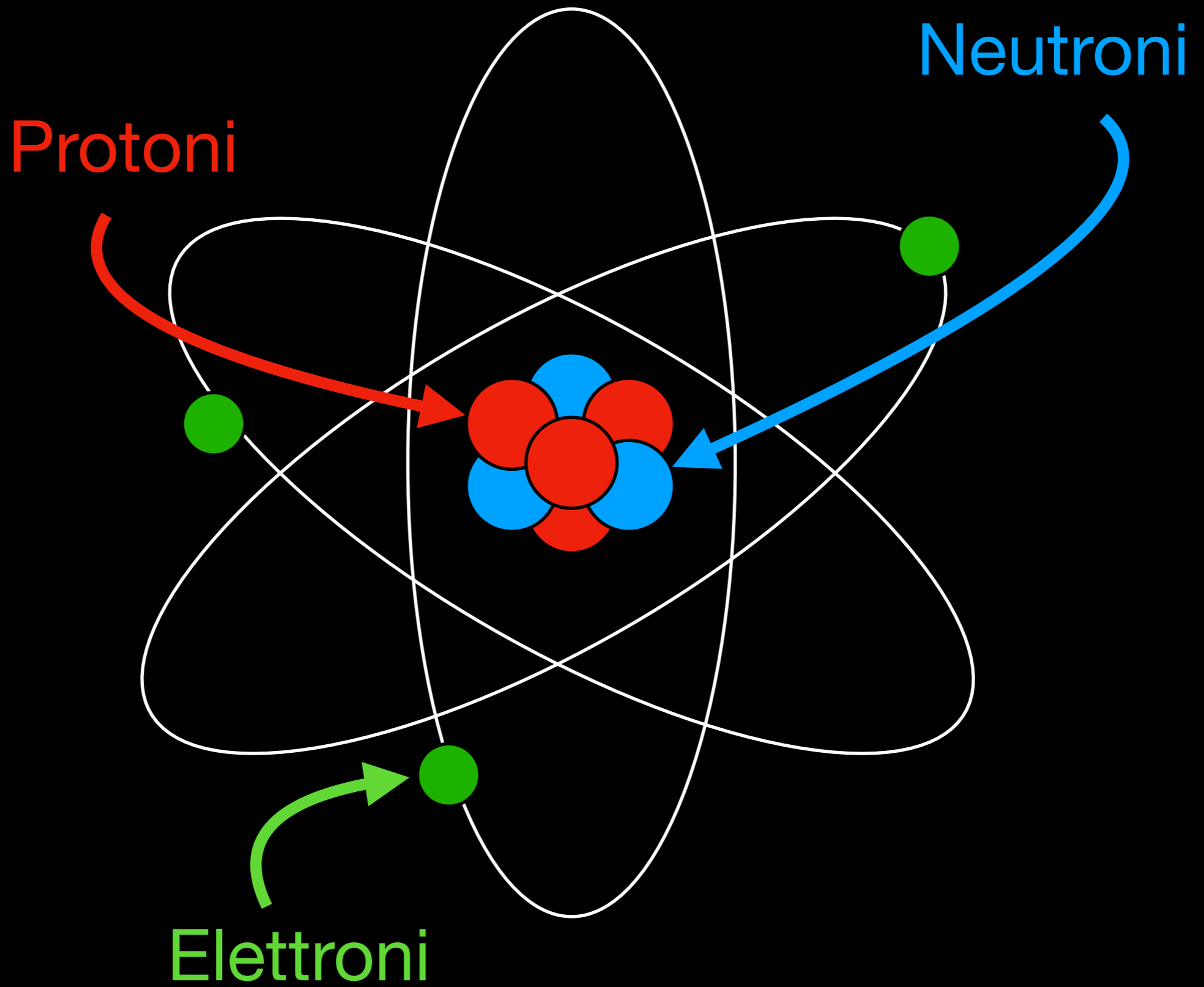


Indica a
sinistra

Nanometri

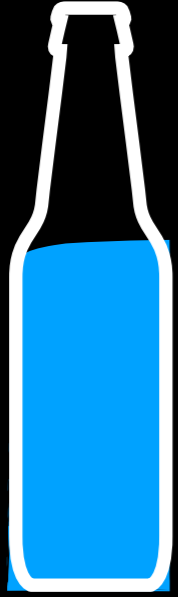
Indica a
destra





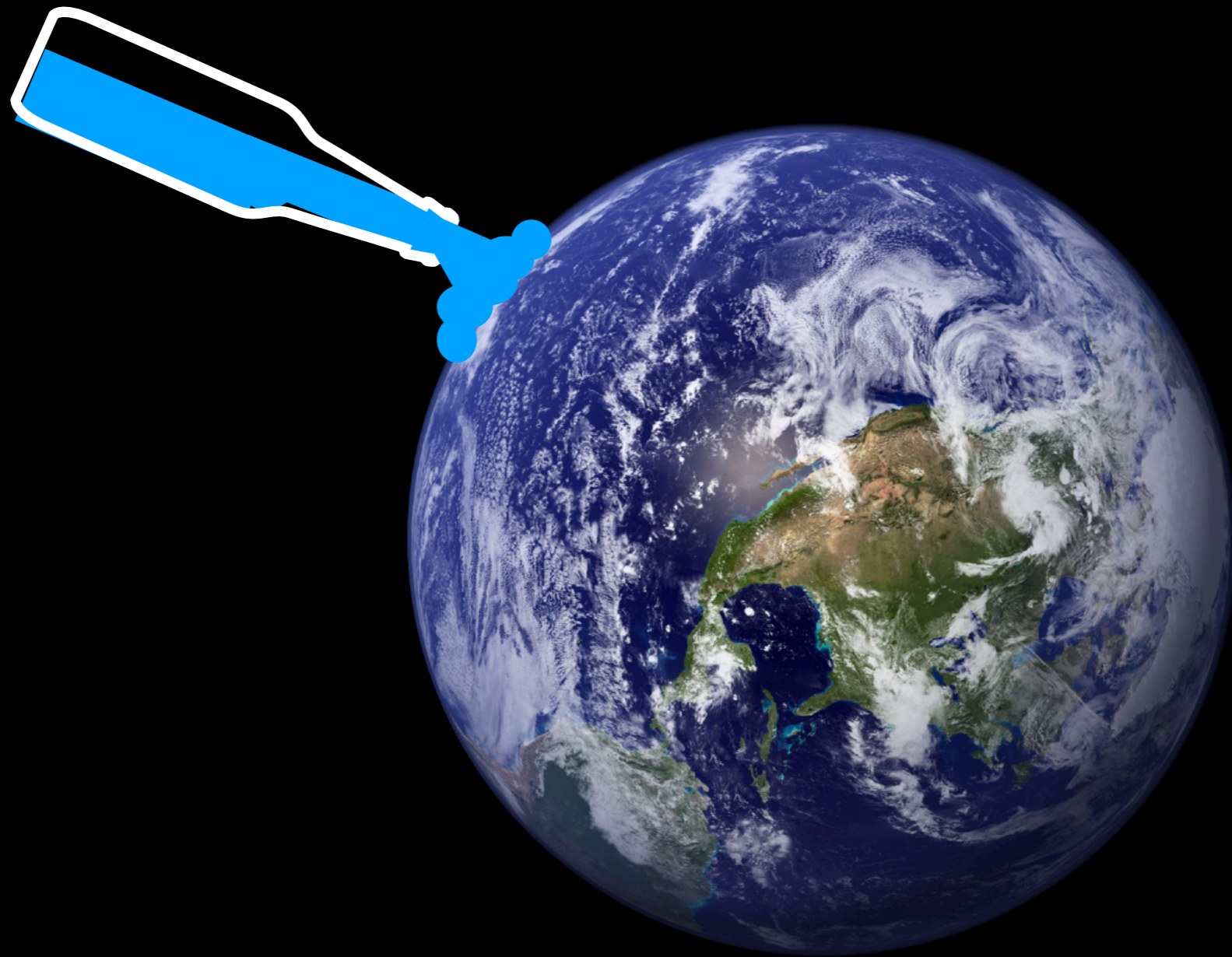
10^{-18} m

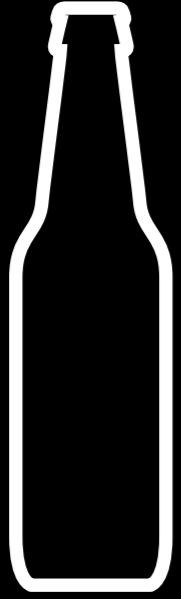


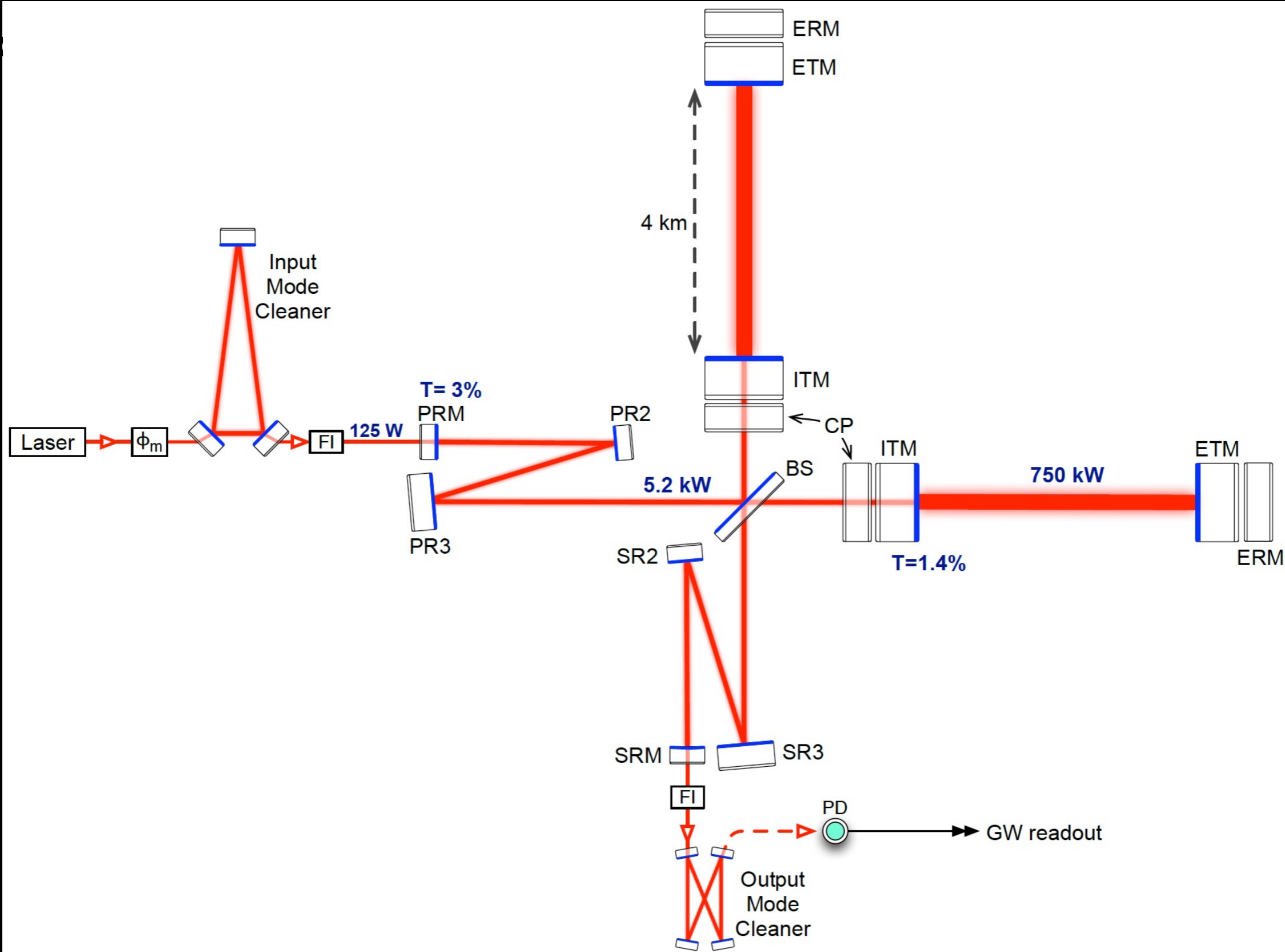


1 L







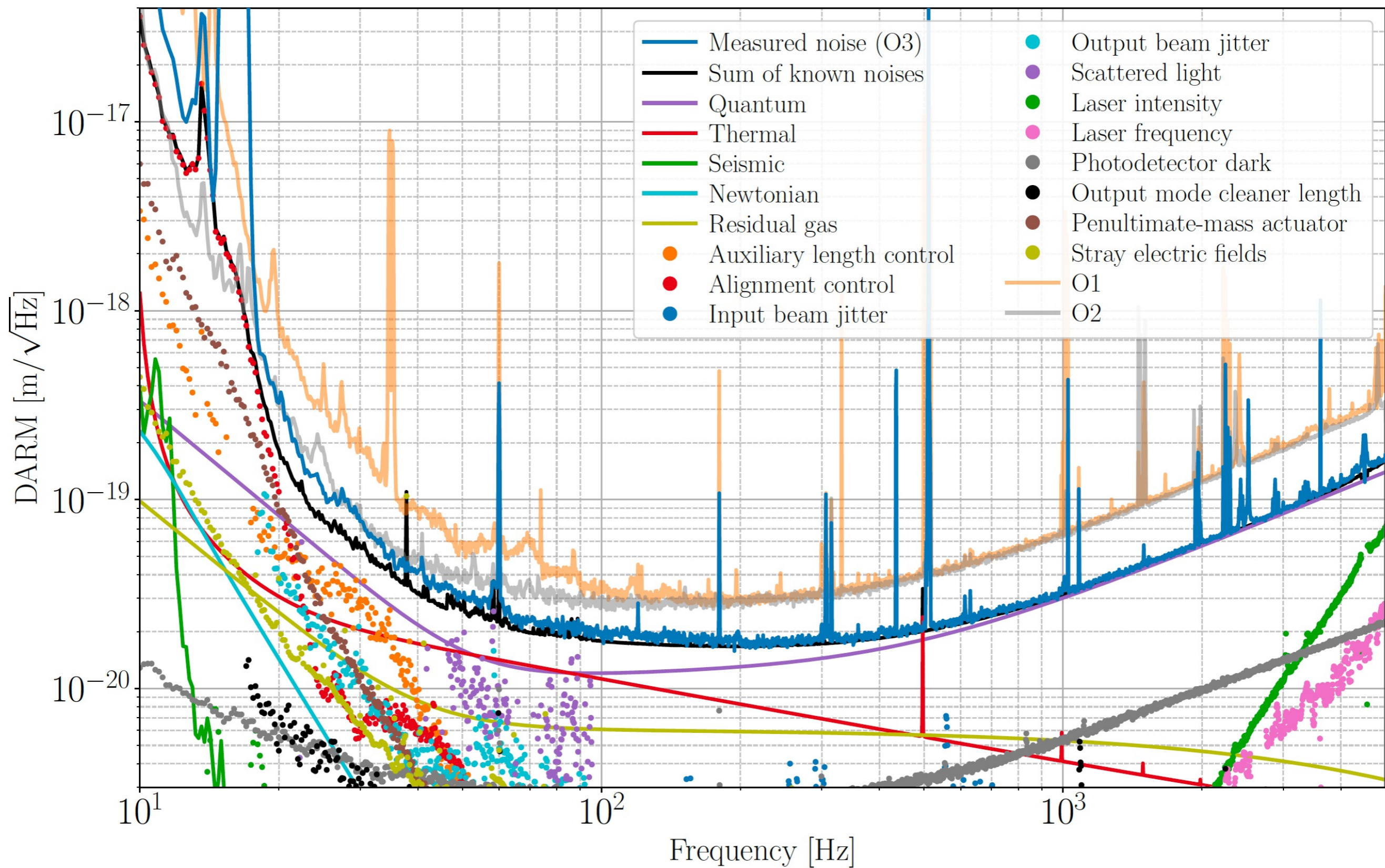






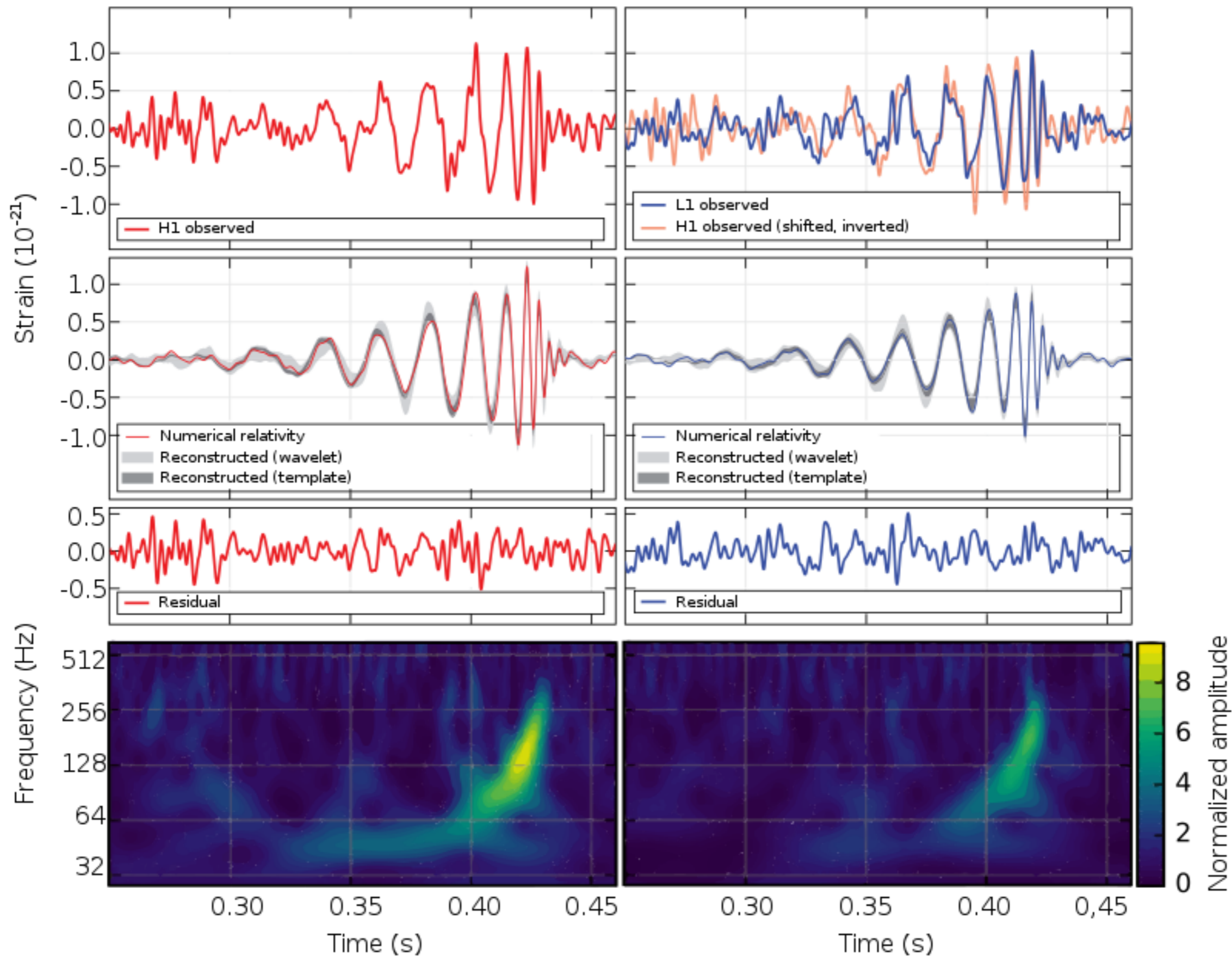
Diversi tipi di rumore

- Sismico
- Termico
- Quantistico



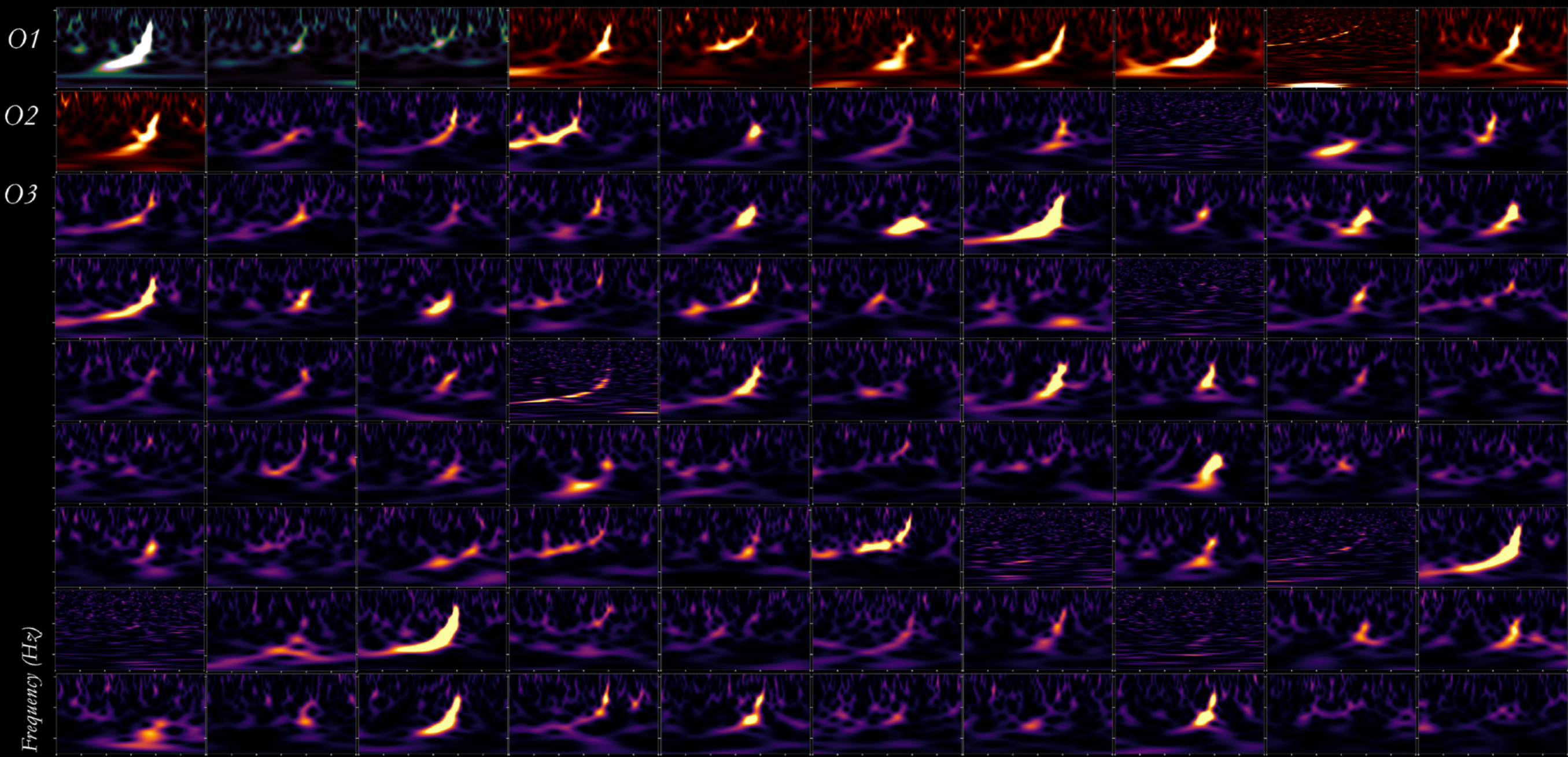
Hanford, Washington (H1)

Livingston, Louisiana (L1)



$$f_{\text{GW}}(t) = \frac{5^{3/8}}{8\pi} \left(\frac{GM_c}{c^3} \right)^{-5/8} (t_0 - t)^{-3/8}$$

$$M_c = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$$



Time (s)

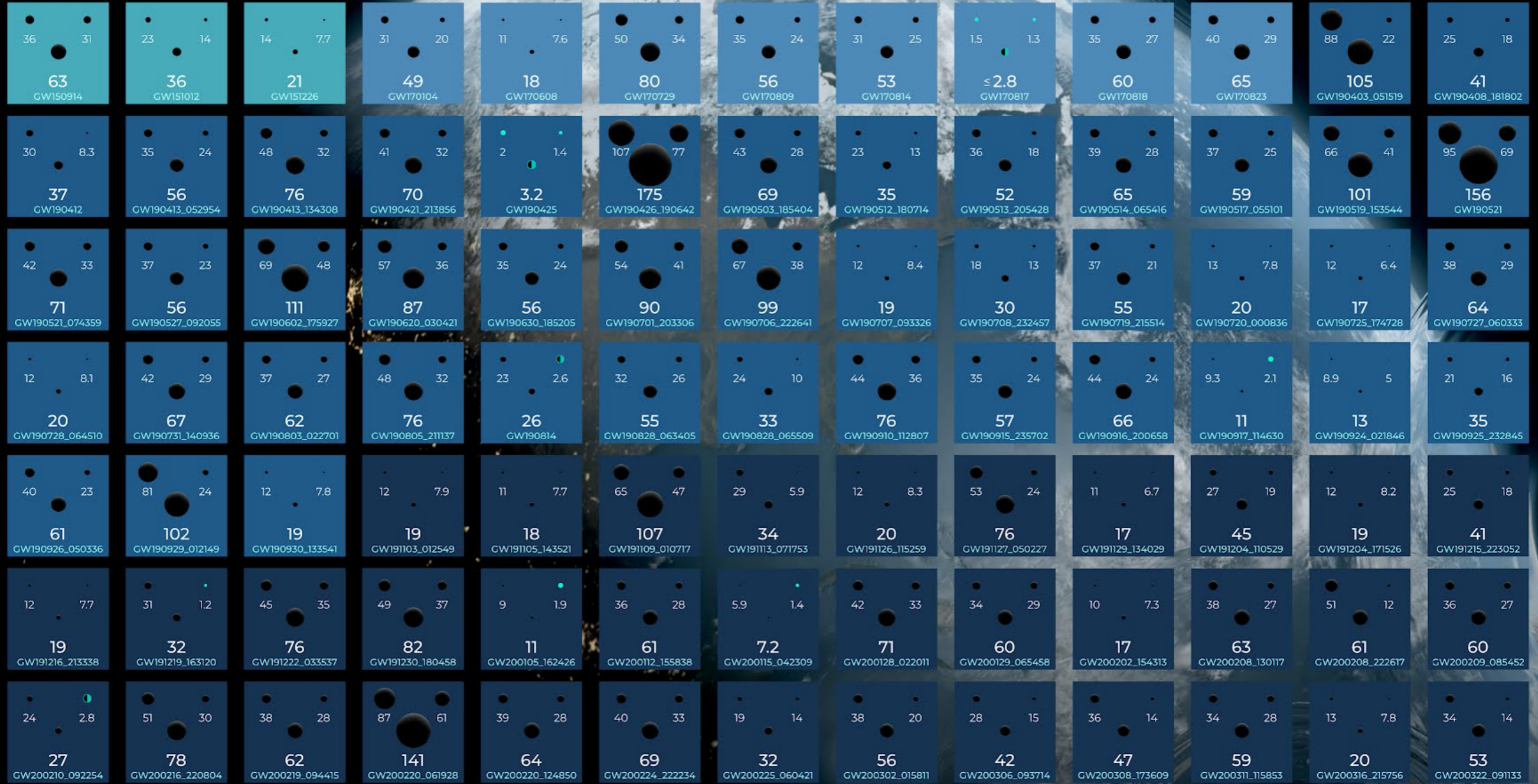
Sudarshan Ghonge | Karan Jani



Georgia Tech



VANDERBILT UNIVERSITY



KEY

- BLACK HOLE
- NEUTRON STAR (SHOWN AT X10 SCALE)
- UNCERTAIN OBJECT
- PRIMARY MASS
- SECONDARY MASS
- FINAL MASS
- DATE(_TIME)

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989×10^{30} kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

GRAVITATIONAL WAVE MERGER DETECTIONS

SINCE 2015



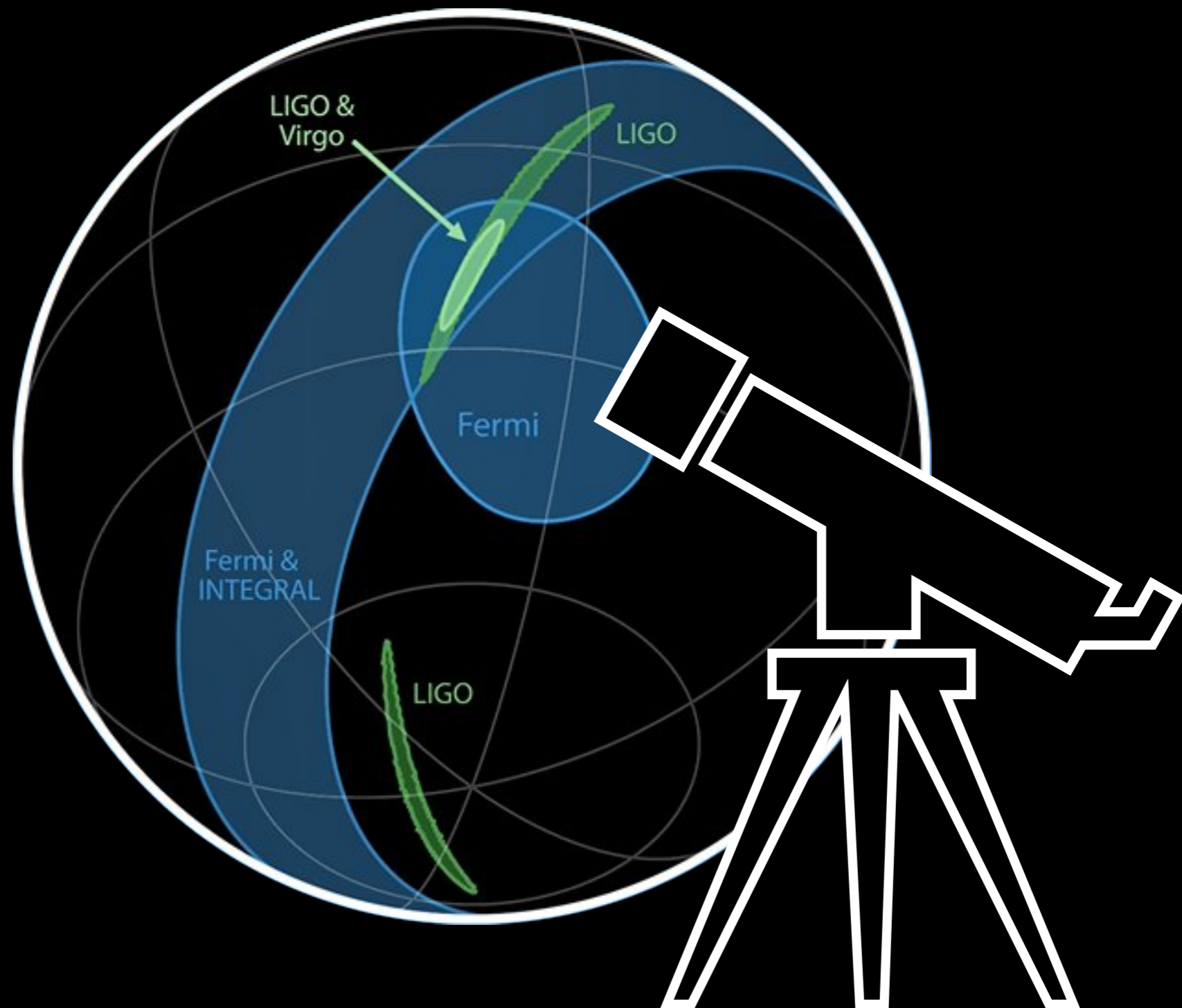


Una stella di neutroni

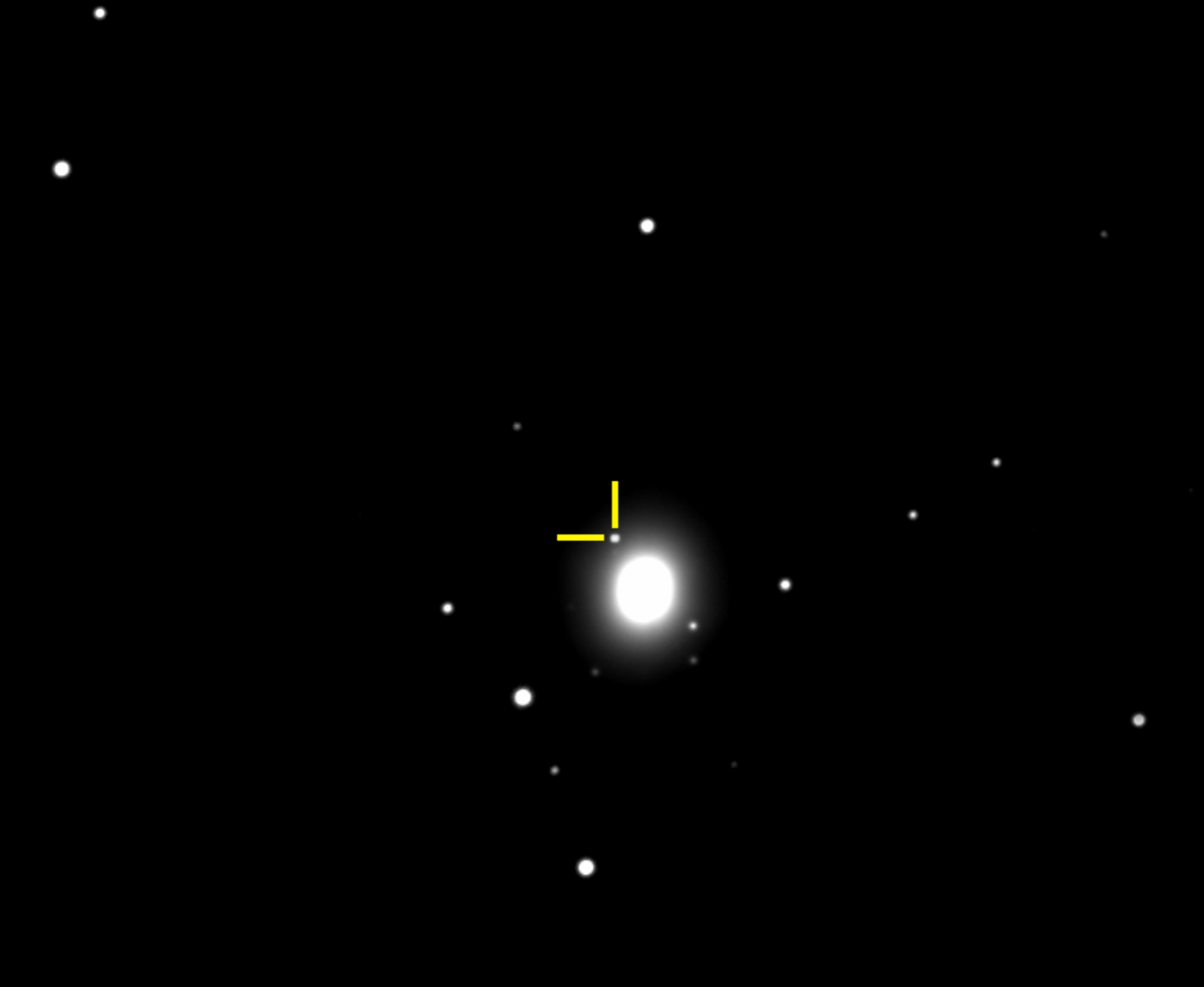
120 milioni di anni fa...

https://www.youtube.com/watch?v=x_Akn8fUBeQ

17 Agosto 2017

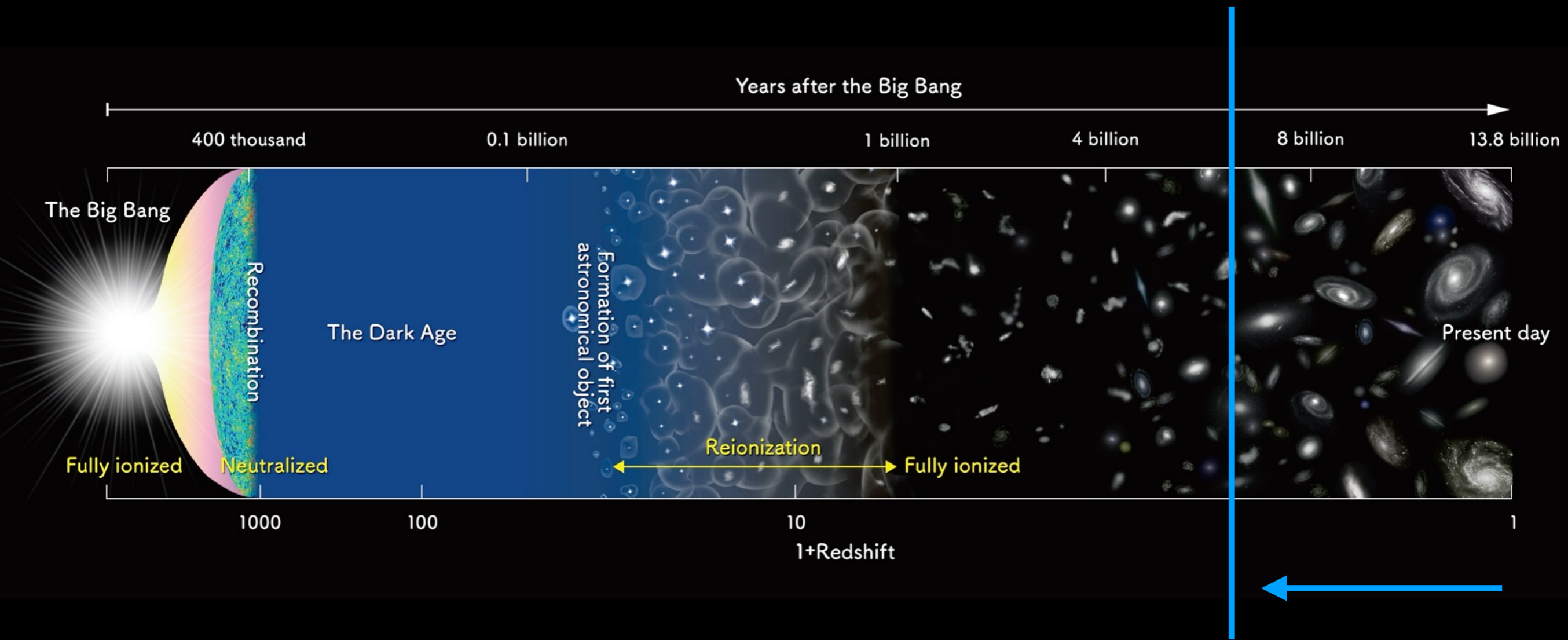


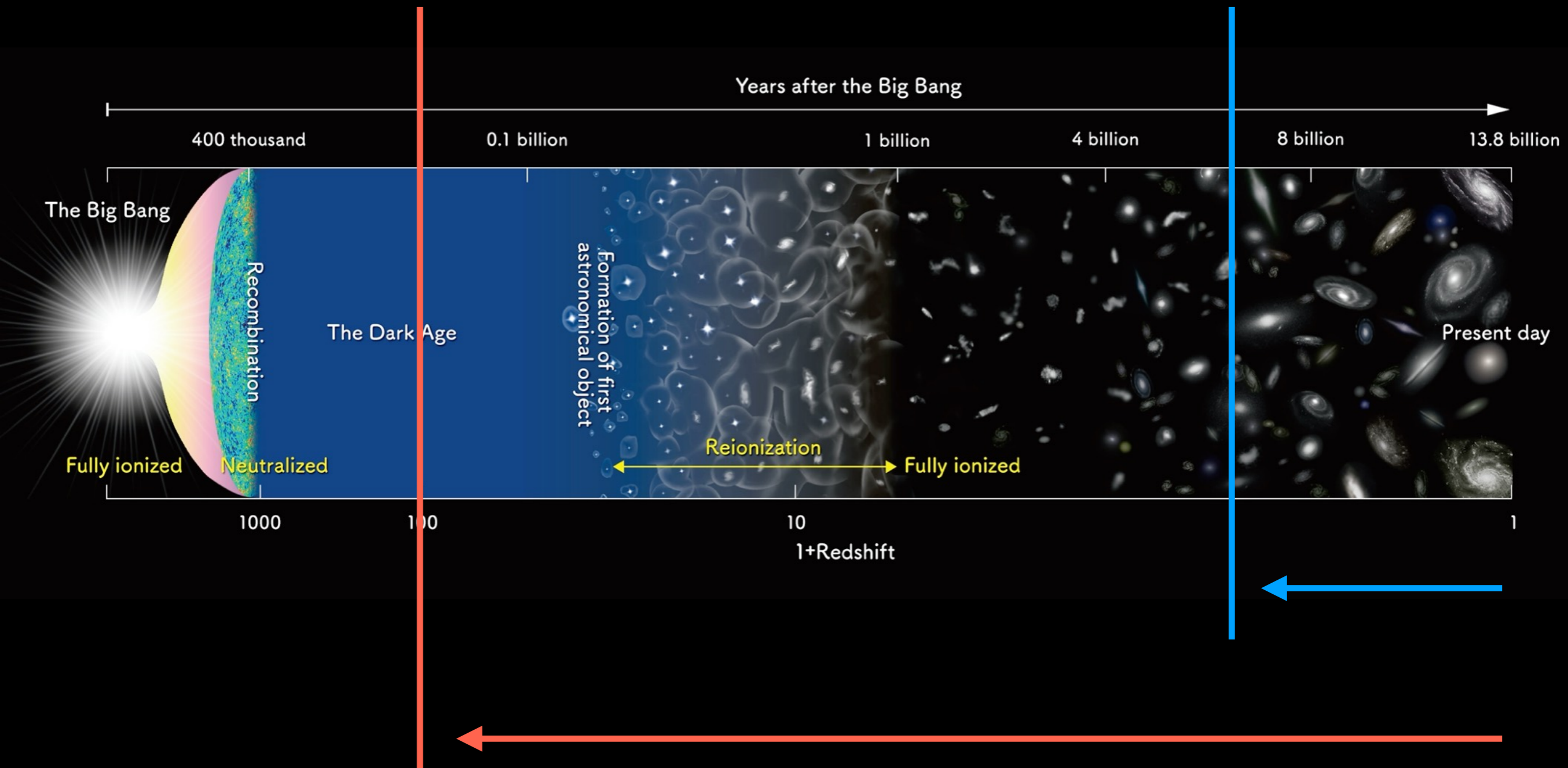
+0.5 days



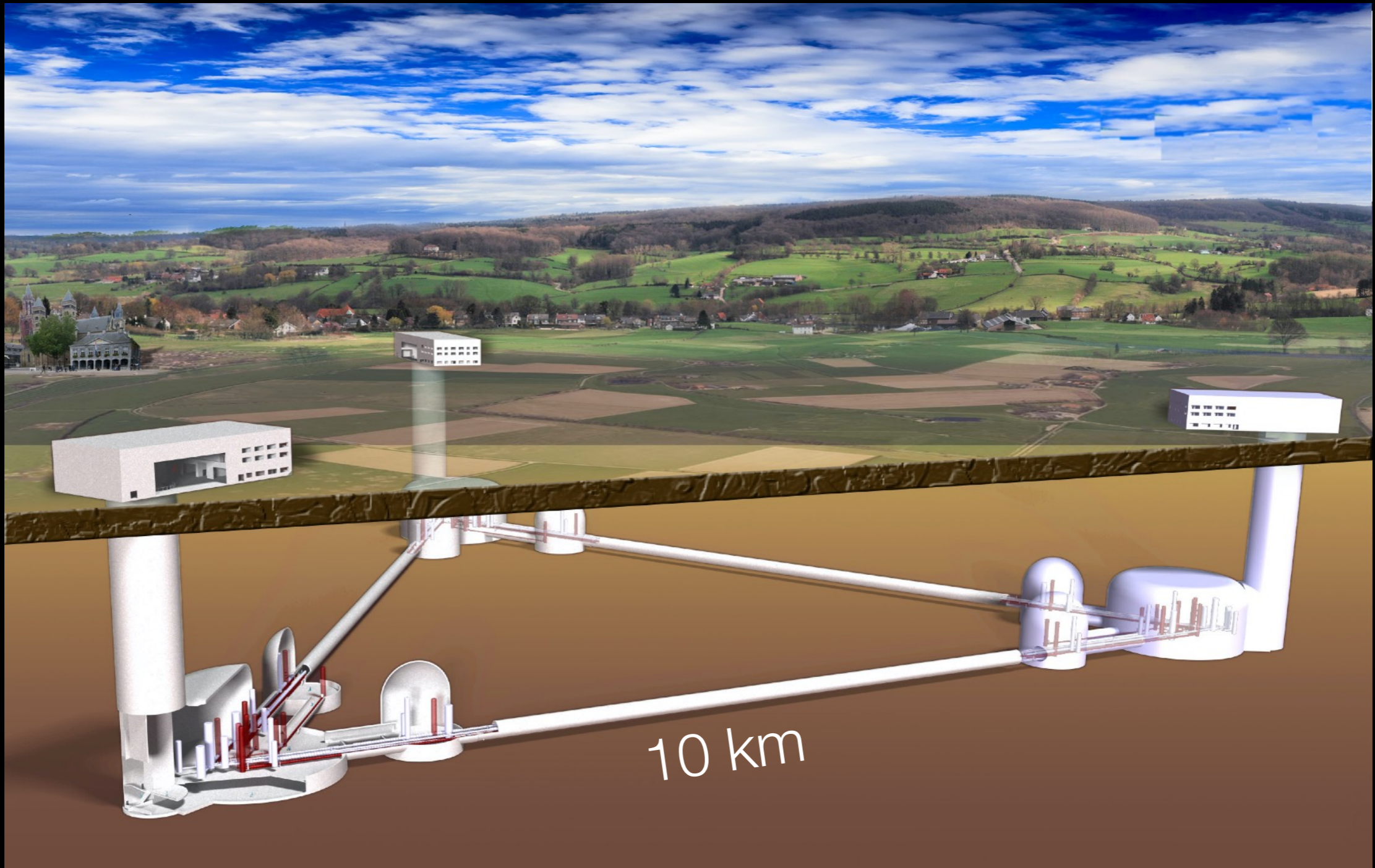
Marica Branchesi





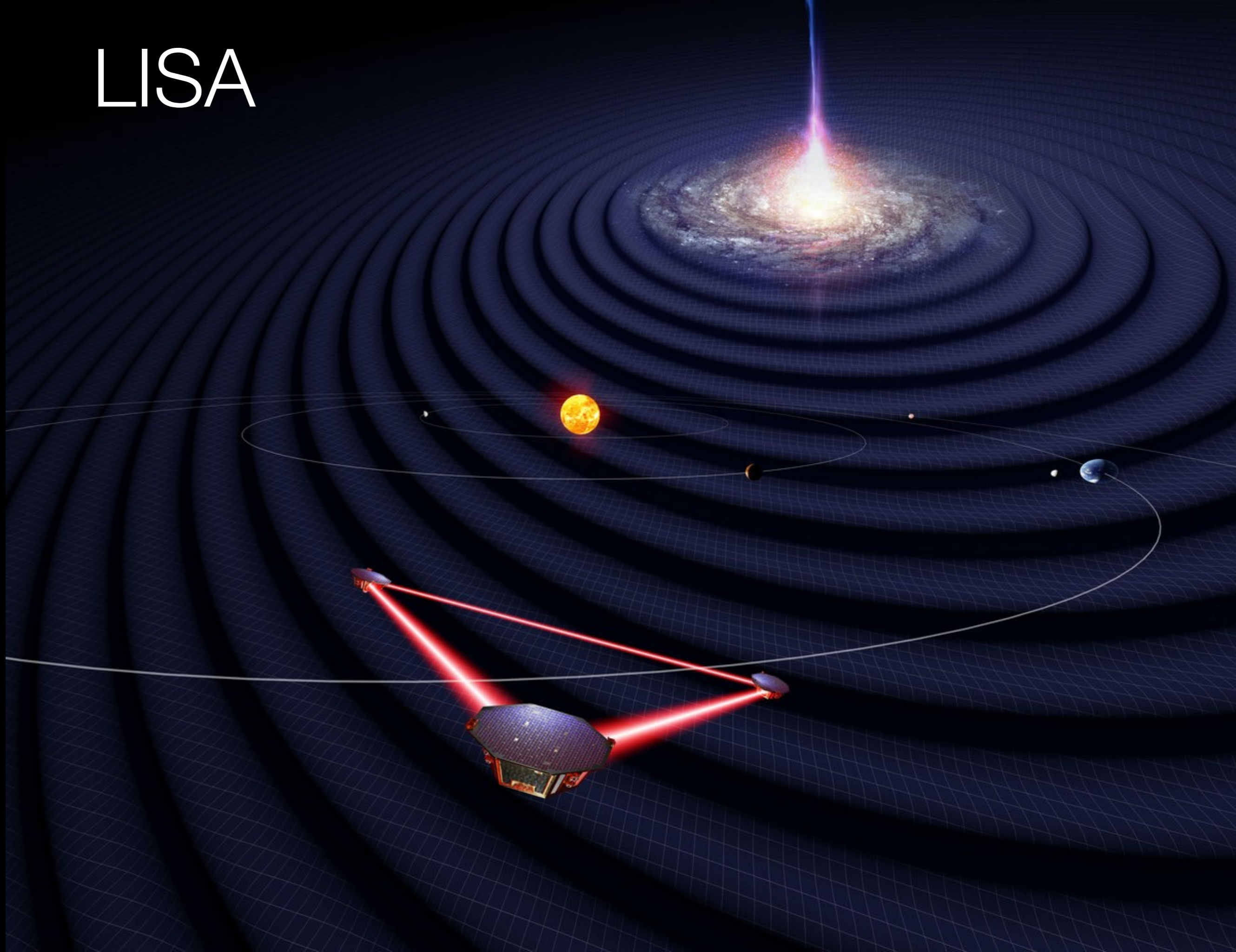


Einstein Telescope





LISA





MATERIA OSCURA



Vera Rubin





MATERIA
ORDINARIA



MATERIA
OSCURA



ENERGIA
OSCURA



Relatività
Generale



Meccanica
Quantistica

Relatività
Generale

The diagram consists of a large white outer oval containing two smaller ovals. The left oval is blue and contains the text 'Relatività Generale'. The right oval is red and contains the text 'Meccanica Quantistica'. Below these two ovals, centered, is the text 'GRAVITÀ QUANTISTICA' in white.

Meccanica
Quantistica

GRAVITÀ
QUANTISTICA

“Dal big bang ai buchi neri. Breve storia del tempo” - Stephen Hawking

“La guerra dei buchi neri” - Leonard Susskind

“Buchi neri e salti temporali” - Kip Thorne

“L’universo elegante” - Brian Green

“La trama del cosmo” - Brian Green

“Il fiume del tempo” - Igor Novikov

“L’ordine del tempo” - Carlo Rovelli

“Il lungo viaggio delle onde gravitazionali” - Paola Catapano

“L’Universo come non si era mai visto” - Gabriele Ghisellini

“Metamorfosi” - Emanuele Coccia

“Trent’anni che sconvolsero la Fisica” - George Gamow

Grazie!