Indications of new physics in the cosmic neutrino spectrum

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TAE. September 19, 2019

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Indications of new physics

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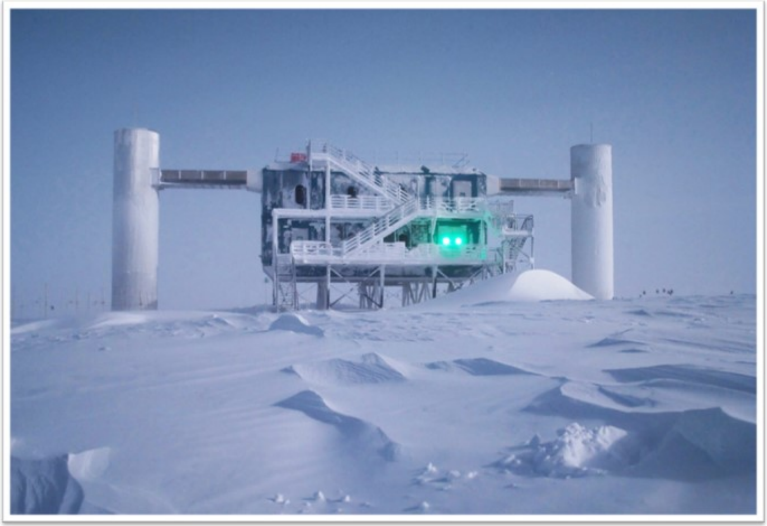

Figure 1: IceCube Laboratory (Amundsen-Scott Station. South Pole)

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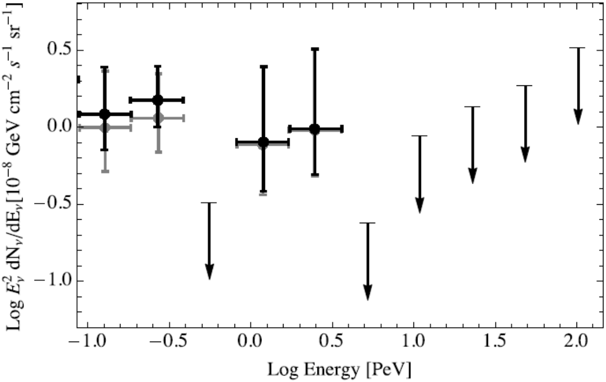

Figure 2: IceCube events (log-scale)

Indications of new physics

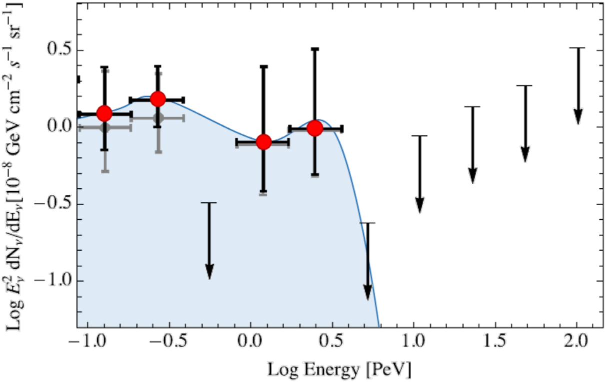

Figure 3: IceCube events (log-scale) and interpretation of the flux

Indications of new physics

We expect neutrinos in that range due to...

- ... extrapolation of the espectrum at lower energies: $\Phi \sim E_d^{-2}$.
- ... we should see effects of the Glashow resonance at $E \sim 6.5\,\mathrm{PeV}$.

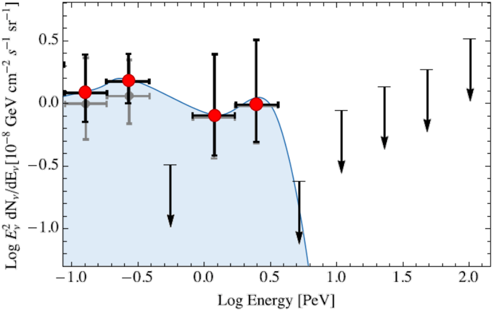

Figure 4: IceCube events (log-scale) and interpretation of the flux

Indications of new physics

It has been proposed, among other possibilites, that the cut-off is produced by intrinsic propagation effects.

This kinds of effects exist by the own nature of the neutrino and cause energy loss along the trayectory. If the influence of the effects are strong enough, this might explain the origin of the cut-off.

One intrinsic effect along the propagation is the universe expansion. However, this is not enough to explain the cut-off, so we need to look for effects of new physics. For that, we use the Lorentz Invariance Violation.

Indications of new physics

The effects of the Lorentz Invariance Violation manifest, in the framework of the neutrino propagation, as a modified dispersion relation for particles:

$$E^2 - p^2 = m^2 \quad \rightarrow \quad E^2 - p^2 = m^2 + \frac{p^{2+n}}{\Lambda^n} \ , \tag{1}$$

where Λ is a scale of energy and n is the order of the correction.

The positive extra term destabilize the neutrino, allowing two new methods of disintegration.

Indications of new physics

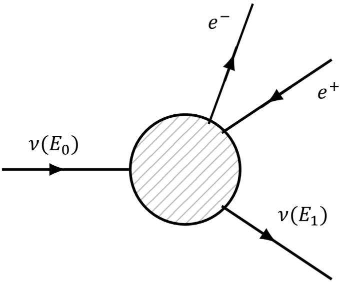

Figure 5: Vacumm Pair Emision.

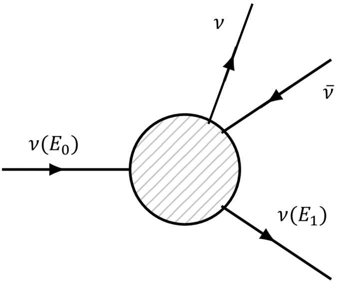

Figure 6: Neutrino Splitting.

Both effects, in addition to the expansion of the universe, produce energy loss in the neutrinos along their trajectories.

Stecker *et al.* have used this approach to perform Montecarlo simulations (for several values of the parameters).

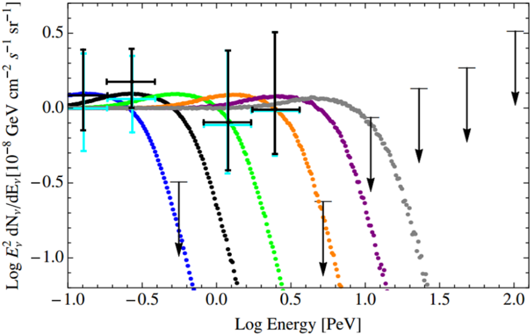

Figure 7: IceCube events and Montecarlo simulations (Expansion + VPE)

A neutrino's voyage

A neutrino's voyage

We wil fix one neutrino, and analyse how its energy evolves since the emision (at z_e with energy E_e) to the detection (at $z = 0$ with energy E_d).

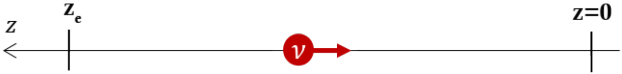

Figure 8: Trajectory of one neutrino

We use the redshift coordinate z to label the different positions along the trajectory.

A neutrino's voyage

- Expansion of the universe

- Pair production

- Neutrino splitting

A neutrino's voyage

- Expansion of the universe ✓ (always present)

$$\nu_d = \frac{\nu_e}{(1+z)} \quad \rightarrow \quad \frac{dE}{E} = \frac{1}{(1+z)}\, dz\ . \tag{2}$$

- Pair production

- Neutrino splitting

A neutrino's voyage

- Expansion of the universe ✓ (always present)

$$\nu_d = \frac{\nu_e}{(1+z)} \quad \rightarrow \quad \frac{dE}{E} = \frac{1}{(1+z)}\, dz\ . \tag{2}$$

- Pair production ✓ (only if $E_\nu > E^*$)

$$\frac{dE}{dt} = -\alpha_n E^{6+3n} \quad \rightarrow \quad \frac{dE}{E} = \frac{\alpha_n E^{5+3n}}{H(z)(1+z)}\, dz\ . \tag{3}$$

- Neutrino splitting

A neutrino's voyage

- Expansion of the universe ✓ (always present)

$$\nu_d = \frac{\nu_e}{(1+z)} \quad \rightarrow \quad \frac{dE}{E} = \frac{1}{(1+z)}\, dz \; . \tag{2}$$

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- Neutrino splitting × (changes the number of neutrinos)

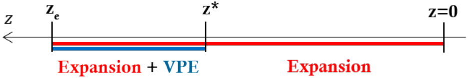
A neutrino's voyage

Taking into account that pair emission only occurs if $E_\nu > E^*$, we need to distinguish three kinds of trayectories:

- Type 1: $E_d < E^*$ and $E_e < E^*$ $\qquad E_d \Downarrow$

- Type 2: $E_d > E^*$ (so necessarily $E_e > E^*$) $\qquad E_d \Uparrow$

- Type 3: $E_d < E^*$ and $E_e > E^*$ $\qquad E_d \Downarrow$



A neutrino's voyage

- Type 1:

$$\frac{dE}{E} = \frac{1}{(1+z)}\, dz \; . \tag{4}$$

$$\int_{E_d}^{E_e} \frac{dE}{E} = \int_{z_d}^{z_e} \frac{dz}{(1+z)} \; . \tag{5}$$

$$\rightarrow \quad E_e = F_1(z_e, E_d) = (1+z_e)E_d \; . \tag{6}$$

A neutrino's voyage

- Type 2:

$$\frac{dE}{E} = \frac{1}{(1+z)}\,dz + \frac{\alpha_n E^{5+3n}}{H(z)(1+z)}\,dz\ . \tag{7}$$

$$\widetilde{E} = \frac{E}{1+z}\ ;\ t = (1+z)^3 \quad \rightarrow \quad \frac{d\widetilde{E}}{\widetilde{E}^{6+3n}} = \frac{\alpha_n}{3H_0}\,\frac{t^{2/3+n}}{\sqrt{\Omega_m\,t + \Omega_\Lambda}}\,dt\ . \tag{8}$$

$$\int_{\widetilde{E}_d}^{\widetilde{E}_e} \frac{d\widetilde{E}}{\widetilde{E}^{6+3n}} = \frac{\alpha_n}{3H_0}\,\underbrace{\int_{(1+0)^3}^{(1+z_e)^3} \frac{t^{2/3+n}}{\sqrt{\Omega_m\,t + \Omega_\Lambda}}\,dt}_{J(z_e,0)} \quad \rightarrow \tag{9}$$

$$E_e = F_2(z_e, E_d) = (1+z_e)\left(E_d{}^{-(5+3n)} - (5+3n)\frac{\alpha_n}{3H_0}J(z_e,0)\right)^{-\frac{1}{(5+3n)}}\ . \tag{10}$$

- Type 3:

$$\begin{cases} E_e = (1+z_e)\left(\widetilde{E^*}^{-(5+3n)} - (5+3n)\frac{\alpha_n}{3H_0}J(z_i,z^*)\right)^{-\frac{1}{(5+3n)}} \\ E^* = (1+z^*)E_d \end{cases} . \quad (11)$$

$$E_e = F_3(z_e, E_d) = (1+z_e)\left(E_d^{-(5+3n)} - (5+3n)\frac{\alpha_n}{3H_0}J(z_e,z^*)\right)^{-\frac{1}{(5+3n)}} . \quad (12)$$

Neutrinos do not travel alone

Neutrinos do not travel alone

We detect indivual neutrino detections, but we modelize it like a flux of neutrinos (n° of neutrinos of energy E_d per time & surface):

$$\underbrace{\delta\Phi(E_d)}_{\text{Detected flux}} = \int_{z_1}^{z_2} \underbrace{\phi_{E_d}(z)}_{\text{One source flux}} \cdot \underbrace{f(z)\, dz}_{\text{Number of sources}} \quad . \tag{13}$$

We can express the detected flux from one source located at z as:

$$\phi_{E_d}(z) = dn_e(E_e) \cdot \frac{1}{4\pi a_0^2 r^2(z)} \cdot \frac{1}{dt_d} \, . \tag{14}$$

Neutrinos do not travel alone

Substituting $k(z) = a_0 r(z)$ and $dt_d = (1+z)dt_e$ we obtain:

$$\phi_{E_d}(z) = \frac{1}{4\pi} \underbrace{\frac{dn_e(E_e)}{dt_e}}_{\delta L(E_e)} \frac{1}{(1+z)} \frac{1}{k^2(z)} \ . \tag{15}$$

We can modelize the brightness as a power law of E_e:

$$\delta L(E_e) = E_0^2 / E_e^2 \quad \rightarrow \quad \delta L(F_i(z_e, E_d)) \ . \tag{16}$$

The detected neutrino flux of energy E_d is:

$$\delta\Phi(E_d) = \frac{1}{4\pi} \int_{z_1}^{z_2} \frac{\delta L(F_i(z_e, E_d))\, f(z)}{k^2(z)(1+z)} dz \ . \tag{17}$$

Neutrinos do not travel alone

In order to compute the flux we need to split it in two cases: $E_d > E^*$ and $E_d < E^*$. So, the flux is defined as a piecewise function of E_d:

$$\delta\Phi_2(E_d) = \frac{1}{4\pi}\int_{z_1}^{z_2} \frac{L(F_2(z_e, Ed))\, f(z)}{k^2(z)(1+z)} dz\ . \qquad (E_d > E^*) \tag{18}$$

$$\begin{aligned}\delta\Phi_1(E_d) = &\frac{1}{4\pi}\int_{z_1}^{z^*} \frac{\delta L(F_1(z_e, E_d))\, f(z)}{k^2(z)(1+z)} dz \quad + \\ &\frac{1}{4\pi}\int_{z_*}^{z_2} \frac{\delta L(F_3(z_e, E_d))\, f(z)}{k^2(z)(1+z)} dz\ . \qquad (E_d < E^*)\end{aligned} \tag{19}$$

Bye, physics. Hi, computing

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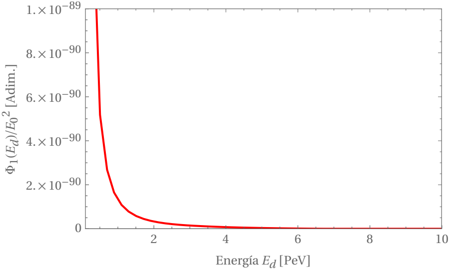


Figure 9: Detected flux for $E_d < E^*$

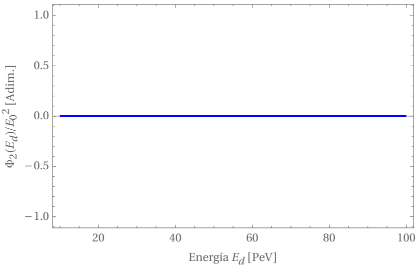


Figure 10: Detected flux for $E_d > E^*$

No flux for $E_d > E^*$. For $E_d < E^*$ it looks like a $\Phi \sim E_d^{-2}$ dependency. In order to check the existence of a cut-off we multiply by E_d^2 and normalize.

Bye, physics. Hi, computing

Now the cut-off is visible. We use log-scale in order to compare with Stecker *et al.* plots.

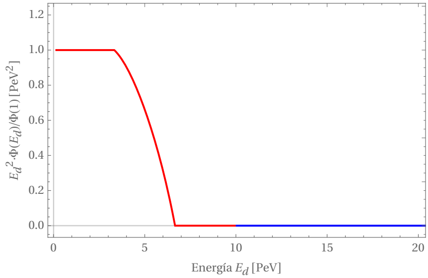


Figure 11: Analytic simulation of the flux

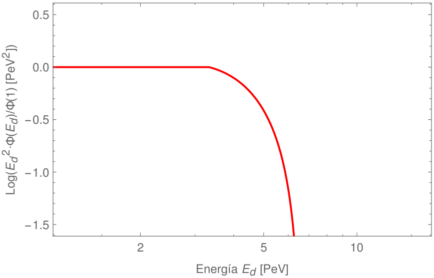


Figure 12: Logaritmic representation of the flux

Conclusion and discussion

Conclusion and discussion

- We are able to recreate the expected cut-off:

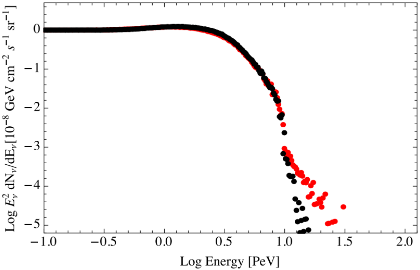


Figure 13: Montecarlo simulation of flux (Expansion + VPE)

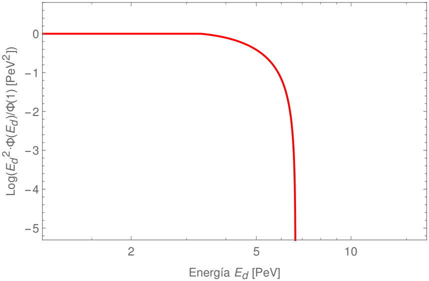


Figure 14: Analytic simulation of flux (Expansion + VPE)

Conclusion and discussion

- The cut-off is produced by the existence of a limiting source $z_c(E_d)$, which is the furthest source able to contribute to $\Phi(E_d)$.

$$\frac{1}{(5+3n)}\left(\widetilde{E_d}^{-(5+3n)} - \cancelto{\infty}{\widetilde{E}_c}^{-(5+3n)}\right) = \frac{\alpha_n}{3H_0}\, J(z_c, z^*)\, dt \qquad (20)$$

$$\left.\frac{1}{(5+3n)}\,\frac{1}{E_d^{5+3n}} = \frac{\alpha_n}{3H_0}\, J(z_c, z^*)\, dt \quad \right\} \text{ Equation for } z_c(E_d) \qquad (21)$$

This critical distance z_c is closer as E_d increases, so the number of sources contributing to the flux decreases quickly.

- The cut-off happen before the threshold energy E^*, in a new scale energy which emerges naturally from the equations:

$$\frac{d\widetilde{E}}{\widetilde{E}^{6+3n}} = \frac{\alpha_n}{3H_0}\,\frac{t^{2/3+n}}{\sqrt{\Omega_m\,t+\Omega_\Lambda}}\,dt \quad \rightarrow \quad \frac{d\widetilde{E}}{\widetilde{E}} = \frac{\widetilde{E}^{5+3n}}{\left(\frac{3H_0}{\alpha_n}\right)}\,j(t)\,dt\ , \tag{22}$$

Defining the denominator as an energy:

$$E_n = \left(\frac{3H_0}{\alpha_n}\right)^{\frac{1}{5+3n}} \quad \rightarrow \quad \frac{d\widetilde{E}}{\widetilde{E}} = \left(\frac{\widetilde{E}}{E_n}\right)^{5+3n} j(t)\,dt\ . \tag{23}$$

Conclusion and discussion

- And this energy scale is always in the same order that the threshold energy.

$$E^* = \left(4m_e^2\Lambda^n\right)^{\frac{1}{2+n}} \propto \left(m_e^2\Lambda^n\right)^{\frac{1}{2+n}} \sim \text{ PeV} \tag{24}$$

$$E_n = (3H_0/\alpha_n)^{\frac{1}{5+3n}} \propto \left(H_0\Lambda^{3n}/G_F^2\right)^{\frac{1}{5+3n}} \sim \text{ PeV} \; . \tag{25}$$

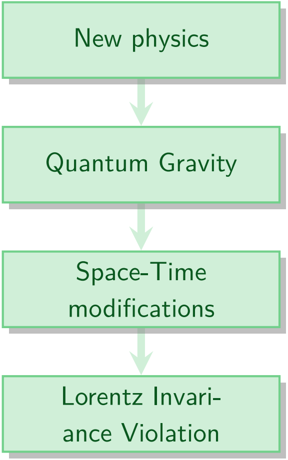
Thanks for your attention!

There exist three different ways to approach to the problem of the abscence of neutrinos above $2\,\mathrm{PeV}$:

The cut-off in the detection spectrum is due to...

- ...a cut-off in the emision spectrum.
  Problem: There is not a cut-off in other messenger particles.
- ...extrinsic propagation effects.
  Problem: We need to identify the external entity and explain its opacity dependency with the energy.
- ...intrinsic propagation effects.
  Problem: Only exist one classical intrinsic effect. May need new physics.

Why Lorentz Invariance Violation?



- We look for new physics.
- Quantum Gravity looks like a natural way.
- Gravity is related to the space-time.
- Lorentz Invariance reflects the structure of the space-time.
- CPT violation implies Lorentz Invariance violation (not in the other way).

We should characterize the distribution of sources.

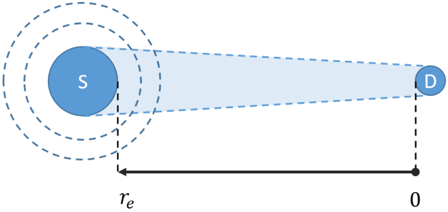


Figure 15: Conical-trunk of trajectories of neutrinos

When the distance is large enough, the conical-trunk tends to a one-dimensional line. So we can characterize the distribution of sources as a one-dimentional function $f(z)$.

Possible sources: Active Galactic Nuclei (AGN) and γ-Ray Bursts (GRB). They are distributed according to the Star Formation Rate:

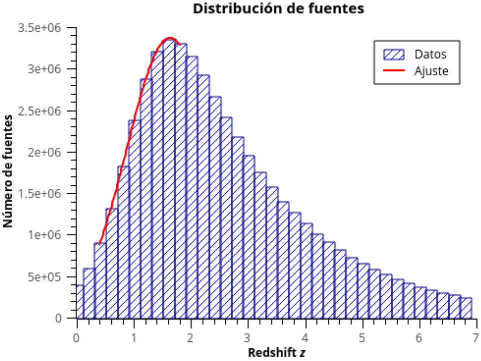


Figure 16: Star formation rate as a function of z

In the case $n = 1$ (CPT-violating) the ν are superluminical and the $\bar{\nu}$ not (or viceversa), so we do not have any cut-off:

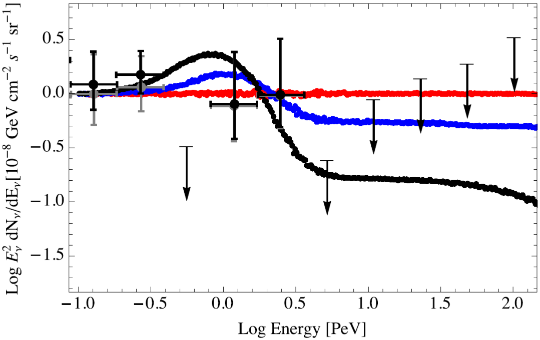


Figure 17: Montecarlo simulations for $n = 1$

We call Glashow Resonance to the resonant formation of a W boson in antineutrino-electron collisions: $\bar{\nu}_e + e^- \to W^-$.

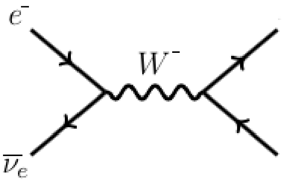


Figure 18: Glashow resonance

Different diagrams for the Vacumm Pair Production.

The second one is only relevant 1/6 of all times. So the Z^0 channel is the relevant one.

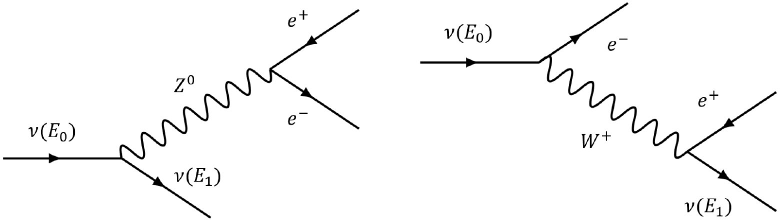


Figure 19: Vacumm Pair Production

Different diagrams for the Neutrino Splitting.

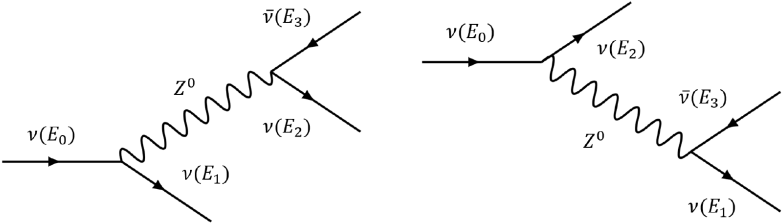


Figure 20: Neutrino Splitting

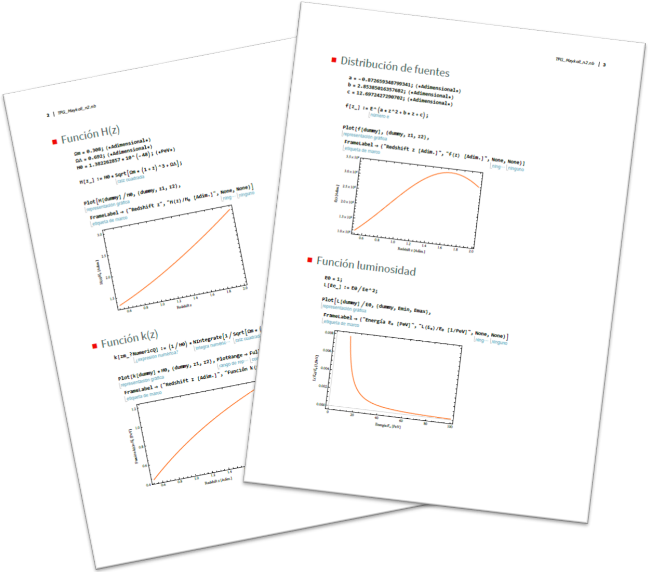


Figure 21: Screenshot of the script in Wolfram Mathematica

For more information you can google
“indicaciones de nueva física”: