Cosmology and general relativity in upper secondary school through new targeted teaching materials

a study on student learning and motivation

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The Mathematics of Physics

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UNIVERSITÉ DE GENÈVE

FACULTÉ DES SCIENCES

Didactique de la physique

Cosmology and general relativity (C&GR) in upper secondary through new targeted teaching materials

arXiv:

- Background and motivations
- Research questions and design of the study
- Description of the intervention and examples of activities
- Results
- Conclusions and perspectives

C&GR in upper secondary

- Part of the larger perspective of integrating modern physics (MP) in secondary school [ISCED , UNESCO, 2011]

Learning:

- Studies show that students taking classes on MP significantly improve
  - Learning, including topics of **classically taught physics**, due to the reactivation in the application to new contexts ("cumulative learning") [Baum98]
  - Understanding of the **nature of science** and its specifics [Kragh14]
- However
  - An **excessive simplification** to make MP more accessible, can have negative effects on students' understanding [Lev13]
  - The abstract level of MP and the **lack of targeted material** is a major difficulty to this aim

Background & motivations

Motivation:

- Astrophysics and cosmology are perceived, among science subjects, as **most interesting** by young people

  ☞ equally for **girls and boys**

  (research ROSE, [Sj&Schr07])

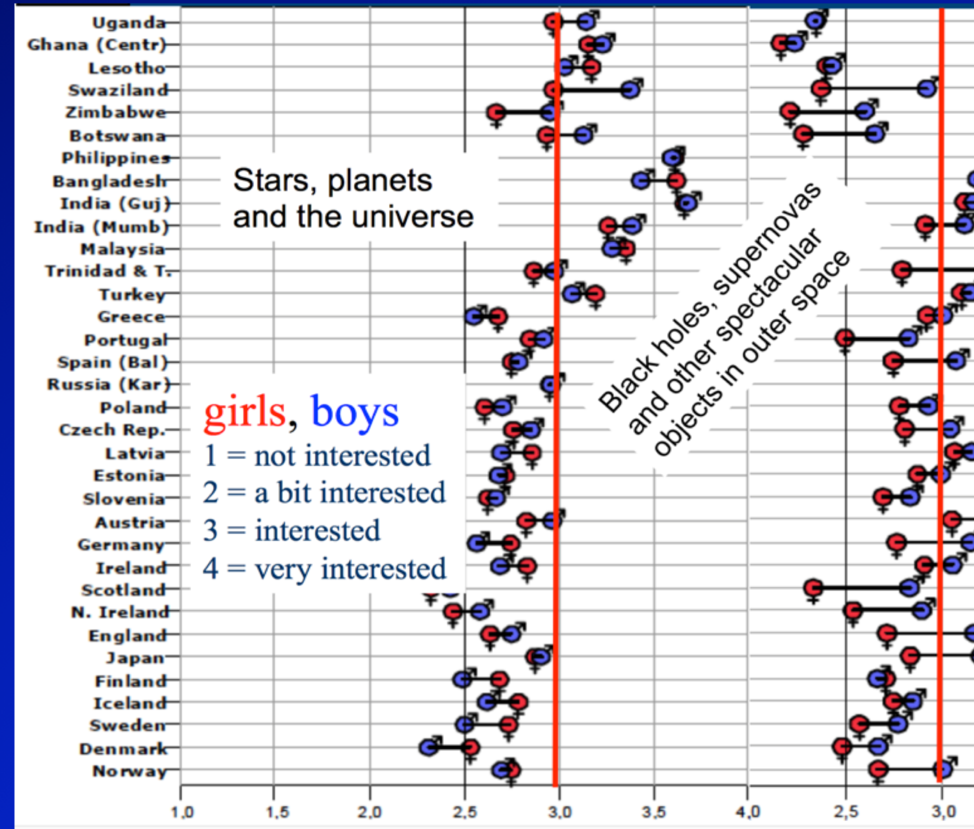
- Inherent capacity of C&GR to evoke a set of emotions* known as **awe** ("overview effect")

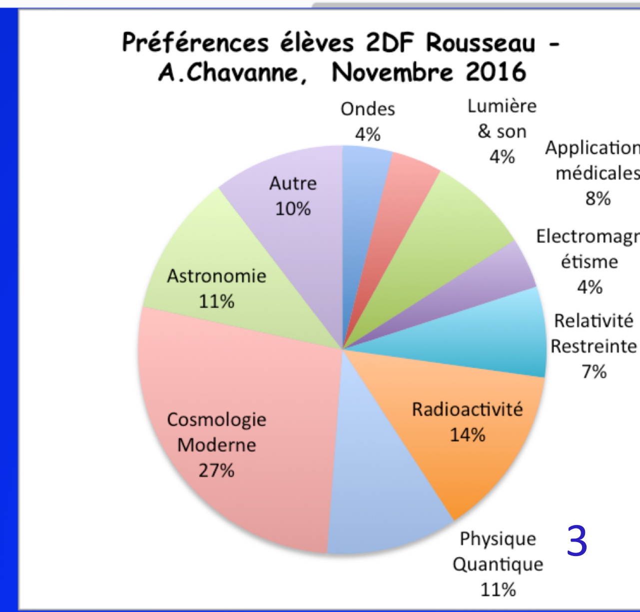
  [Had22] [VSB17] [Yaden16]

  ⇨ poetic experience of science (vs prosaic)

  ⇨ potential positive effect on motivation

*such as wonder, fear, fulfillment, reverence





Research questions

1. To what extent is it possible to develop and deliver a C&GR course at upper secondary level, technically deep enough to fully exploit the physical and philosophical potential for the students?

2. What is the impact of such a course on learning of C&GR?

3. What is the impact of such a course on affective variables such as interest, curiosity, self-concept, and relevance of science?

+ Aim to contribute to the **creation of targeted educational material**

- fairly in-depth **without becoming technically inaccessible**
- maintaining the benefits of a **deep and global vision** of these subjects

Sample (Classroom research)

- Last year high-school students choosing the PHY complementary option (CO) course
  - ⇨ **not** physics specialized maturity (PHY specific option)
- 4 class-groups form 2020 to 2024, with global **ratio gender of 1.2**

School year	N	N_F	N_F / N_M complementary option CO)	N_F / N_M specialized physics courses (SO)	N_F / N_M in the high school
2020-21	16	8	1.0	0.28	1.3
2021-22	22	12	1.2	0.30	1.3
2022-23	20	12	1.5	0.33	1.2
2023-24	12	6	1.0	0.27	1.2
Total	70	38	1.2	0.30	1.3

Duration: one semester, from August to January (36 periods)

Content: Universe scales, structures, composition, acceleration, basics of GR, gravitational lensing, black holes

Variables and instruments:

Pre/post comparison with MCQ tests on

- Affective scales (IN; CS; SC; RS; CT) based standard tests items
- Conceptual learning on cosmology: 14 newly created items, based on the course content
- Completed by qualitative interviews of 15 participants

Variable	Pre test	Post test	School
Learning achievement pre/post **LPR/LPO**	CV	DV	
Self concept **SC**	CV	DV	
Interest **IN**	CV	DV	
Relevance of science **RS**	CV	DV	
Curiosity as a state **CS**	CV	DV	
Curiosity as a trait **CT**	CV		
Gender			CV
Prior Physics grade			CV
School year			CV

CV = control variable

DV = dependent variable

Study features

Content based on a course* of 8 chapters

- Theory (book, 2018 & 2023 in FR; 2024 in IT; EN planned in 2025)
- Exercises & activities (with full corrections)

https://nccr-swissmap.ch/school-teachers-children/general-relativity

https://physalice.ch/cosmologie/

Table des matières

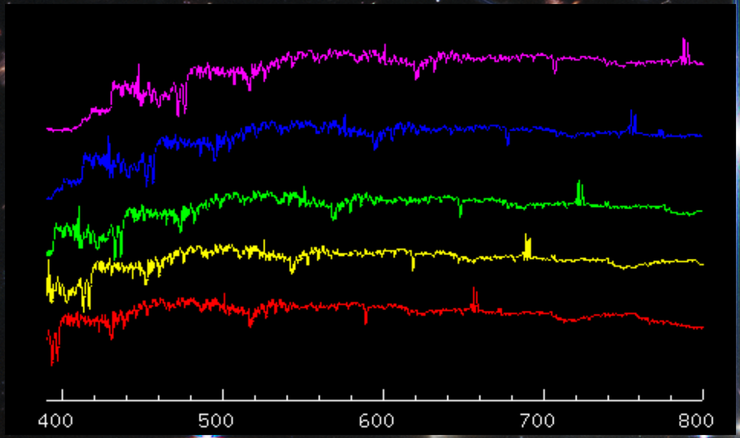
- Course built over 8 years in parallel with practice by more than 10 teachers and their class-groups in CH, FR, CA and BE

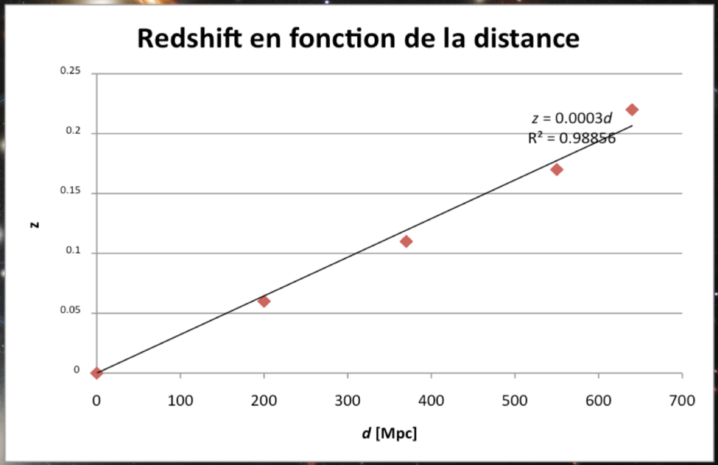
- Content and structure cross-evaluated and validated by university experts (RG, cosmology and physics education) and as part of the publication of the book and scientific bulletins
(see e.g. SPS n. 55 or SSPMP n. 137)

*recognized by the international "Contemporary Physics Education Prize" (CPEP) in 2020

Scales, expansion, redshift and distances (ch. 1 and 2)

- Find Hubble-Lemaître law by comparing nearby galaxies spectra



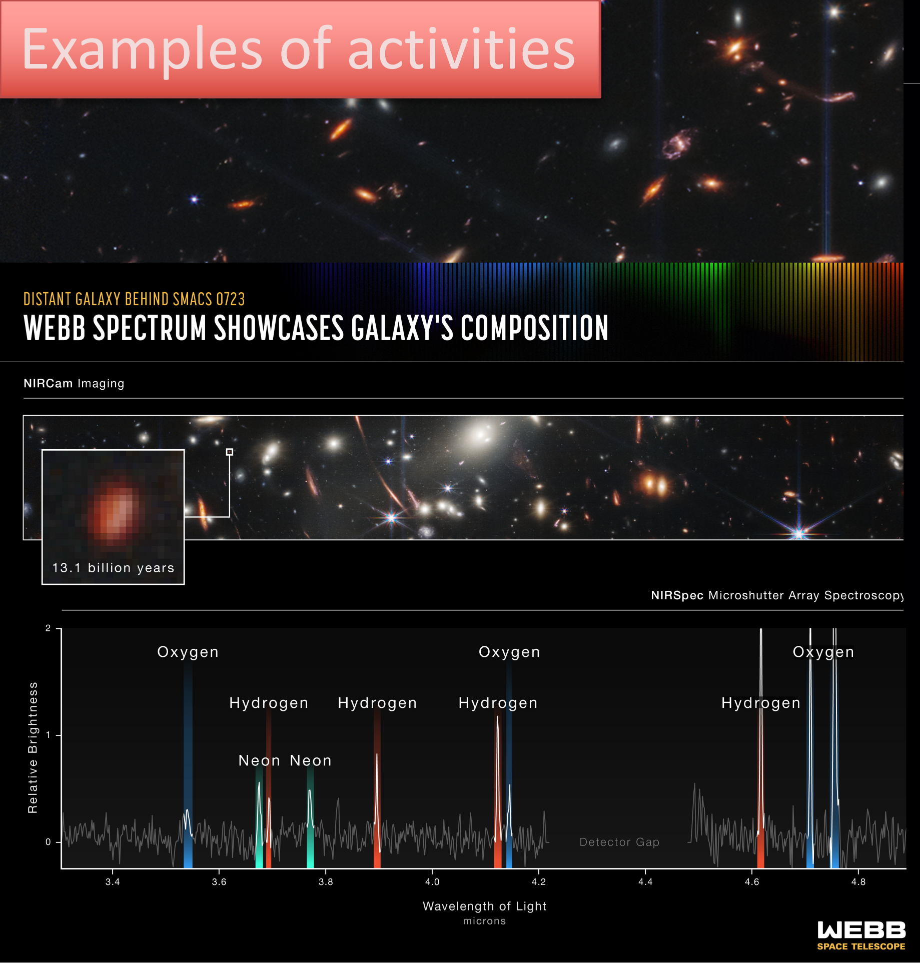


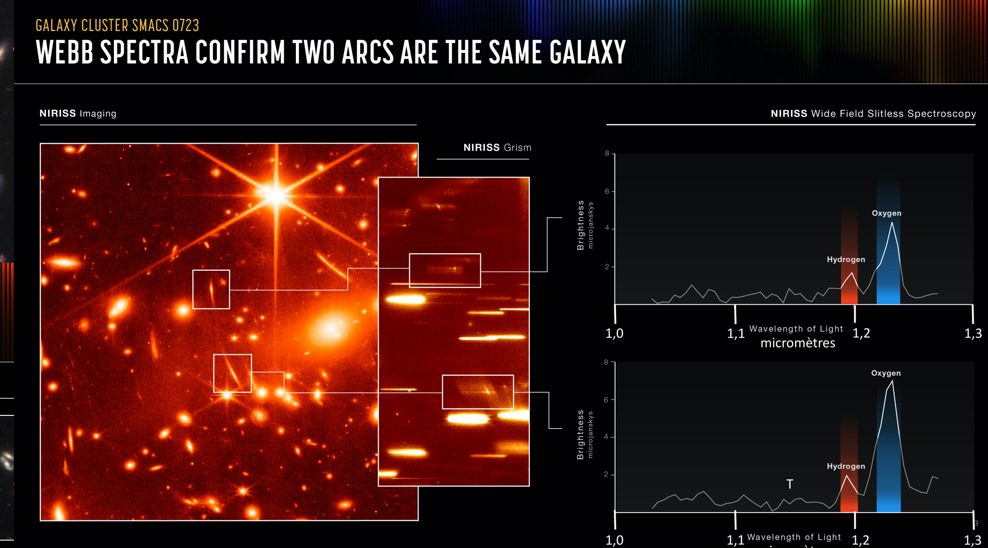
- Compare the rate of the expansion's speed at different scales

H_0 = 70 km/s /Mpc = … /km = … /Gpc

- Difference between
  - ➢ Doppler effect and cosmological redshift
  - ➢ Hubble radius ($z < 1$) and horizon ($z < \infty$)

Examples of activities





b) *En lisant dans le graphique la valeur de la longueur d'onde observée pour la ligne de l'oxygène OIII, calculer son redshift.*

On peut lire sur le graphique $\lambda_0 = 1,2\,\mu m$ et on sait que $\lambda = 0,486\,\mu m$ donc

$$\Rightarrow z = \frac{\lambda_0 - \lambda}{\lambda} = \frac{1,2 - 0,486}{0,486} = 1,5$$

c) *Est-ce que cette source se trouve à l'intérieur du rayon de Hubble ? Pourquoi ? Expliquer sa réponse par les formules.*

Non, car le rayon de Hubble est le rayon délimitant la zone autour de nous avec $z < 1 \iff v > c$, c'est à dire tout point à distance d tel que

$$z = \frac{v}{c} < 1 \quad \iff \quad v = H_0 \cdot d < c \quad \iff \quad d < \frac{c}{H_0} = r_H$$

de cette source dépasse 1.

c) *En lisant dans le graphique la valeur de la longueur d'onde observée pour la ligne de l'oxygène OIII, émise il y a environ 13,1 milliards d'années par cette source lointaine, calculer son redshift.*

On peut lire sur le graphique $\lambda_0 = 4,75\,\mu m$ et on sait que $\lambda = 0,5007\,\mu m$, donc

$$z = \frac{\lambda_0 - \lambda}{\lambda} = \frac{4,75 - 0,5007}{0,5007} = 8,49 \approx 9\,.$$

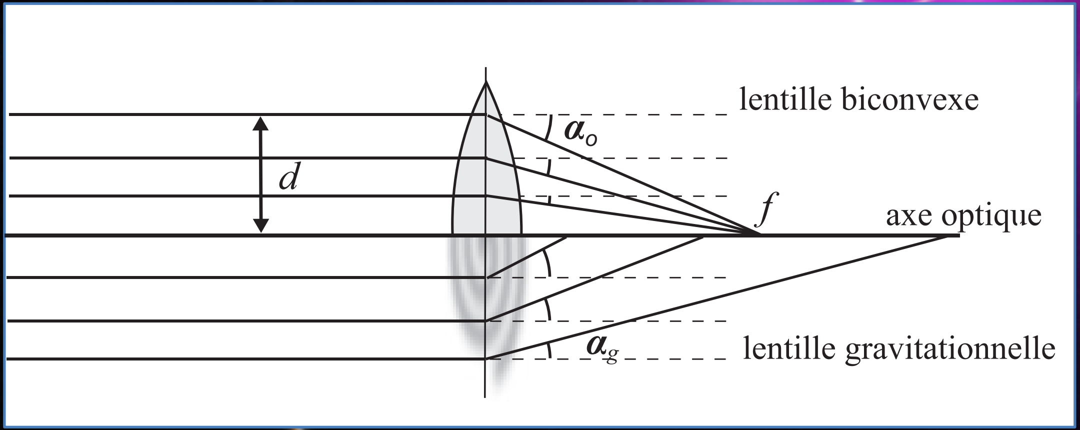
d) *Vérifier que la réponse trouvée au point c) est cohérente avec le temps de traversée de la lumière annoncé dans la figure, en comparant le résultat avec les valeurs du tableau sur le site http://lcogt.net/spacebook/redshift.*

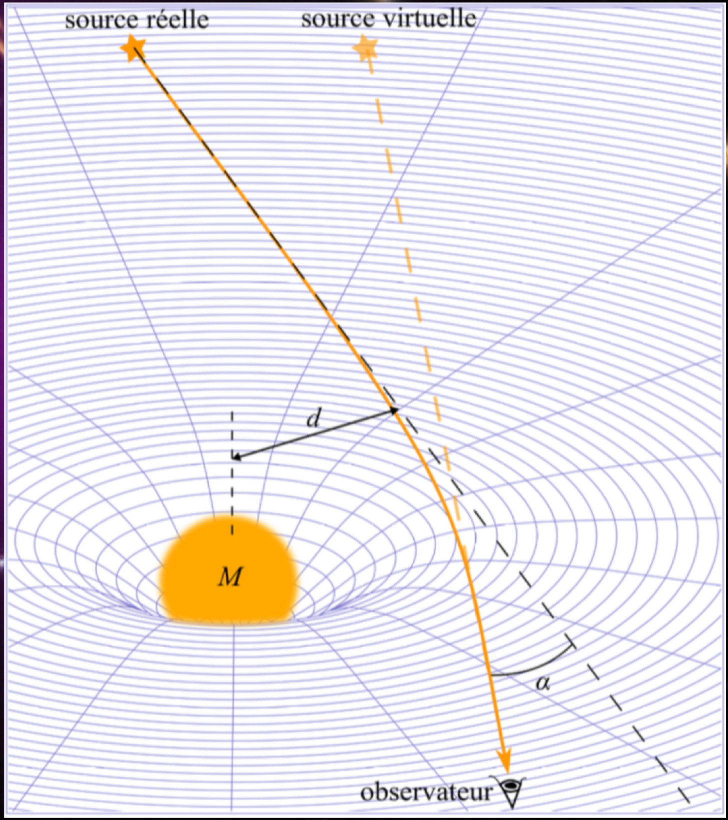
Dans le tableau $z = 8$ correspond à un temps de traversé de la lumière de 13,014 milliards d'années et $z = 9$ correspond à 13,110 milliards d'années. Donc nous avons trouvé un résultat cohérent avec 13,1 milliards d'années, annoncé dans la figure.

Examples of activities

Gravitational Lensing (ch. 4)

- Deflection angle
    - Parallel geodetics behaviour
    - Dimension analysis
    - Newtonian derivation (factor ½)





$$\alpha \propto \frac{GM}{c^2 d}$$

- How to demonstrate this $1/d$ behaviour ?

Examples of activities

- Integrate to find the corresponding optical lens profile

) *Puisque i est l'angle entre le rayon incident (vertical) et la normale à la courbe $y(x)$ au point P, la tangente à cette courbe en ce point est $y'(x) = dy/dx = -i(x)$. Remplacer l'expression obtenue au point d) pour $i(x)$ puis intégrer cette équation pour trouver le profil $y(x)$.*

$$f'(x) \cong \frac{dy}{dx} = -i(x) = -\frac{4GM}{c^2(n-1)\cdot x}$$

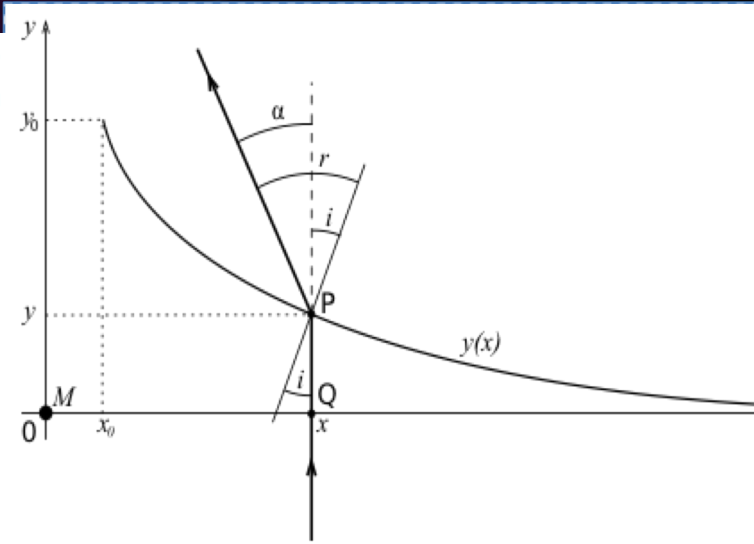
$$\Rightarrow \quad y(x) \cong -\frac{4GM}{c^2(n-1)} \cdot \ln\left(\frac{x}{x_0}\right) + y(x_0)$$

$$\Rightarrow \quad y(x) \cong \frac{4GM}{c^2(n-1)} \cdot \ln\left(\frac{x_0}{x}\right) + y_0$$

où $y_0 = y(x_0)$.

Donc le profil est proportionnel au logarithme de l'inverse de x :

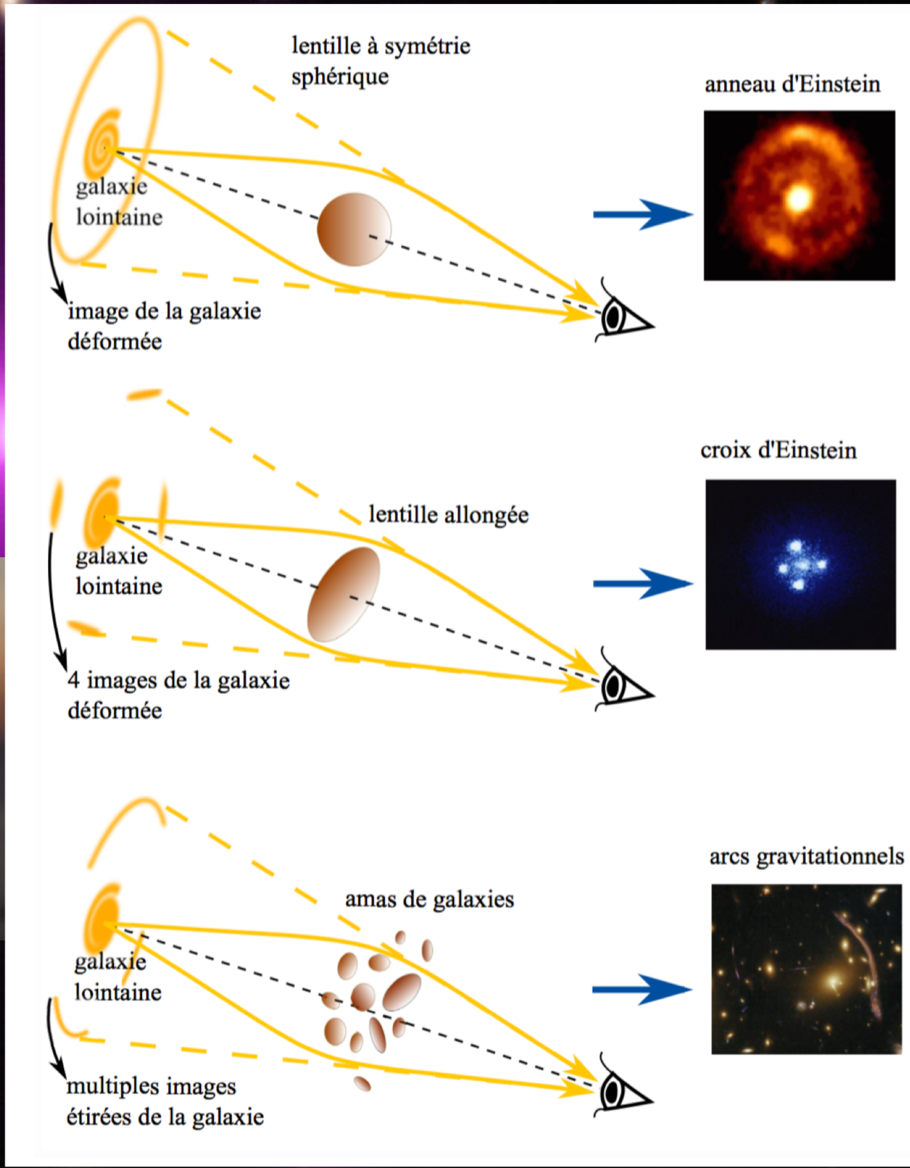
$$y(x) \propto \ln\left(\frac{1}{x}\right) .$$



- Trigonometry + algebra to find *M* as a function of θ_{Einst}

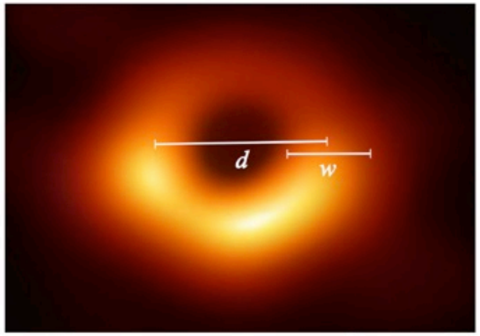
$$\theta_{Einst} = \sqrt{\frac{4GMD_{SL}}{c^2 D_{SO} D_{LO}}}$$

Examples of activities



Black holes (ch. 5)

b) Expliquer pourquoi l'image du disque d'accrétion est un anneau, même si son axe de rotation ne pointe pas vers l'observateur. De quel phénomène s'agit-il ? (Faire un schéma si nécessaire.)



Crédit : Jifeng, L. *et al.*, Nature, Vol. 575, 618–621 (2019).

THE ASTROPHYSICAL JOURNAL LETTERS, 875:L1 (17pp), 2019 April 10

Table 1
Parameters of M87*

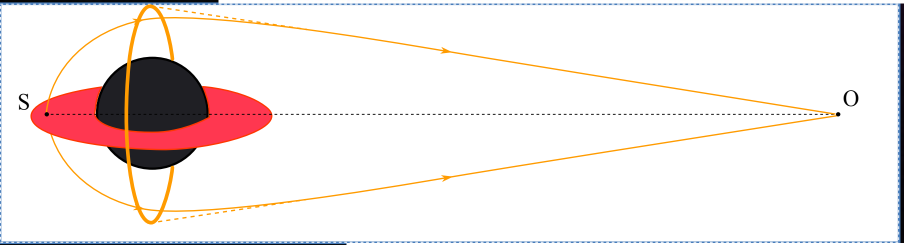
Parameter	Estimate
Ring diameter [a] d	$42 \pm 3\ \mu$as
Ring width [a]	$<20\ \mu$as
Crescent contrast [b]	$>10{:}1$
Axial ratio [a]	$<4{:}3$
Orientation PA	150°–200° east of north
$\theta_g = GM/Dc^2$ [c]	$3.8 \pm 0.4\ \mu$as
$\alpha = d/\theta_g$ [d]	$11^{+0.5}_{-0.3}$
M [c]	$(6.5 \pm 0.7) \times 10^9\ M_\odot$
Parameter	**Prior Estimate**
D [e]	(16.8 ± 0.8) Mpc
M(stars) [e]	$6.2^{+1.1}_{-0.6} \times 10^9\ M_\odot$
M(gas) [e]	$3.5^{+0.9}_{-0.3} \times 10^9\ M_\odot$

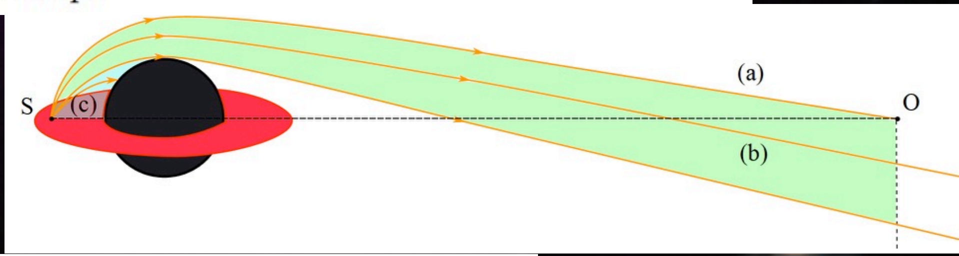
Notes.
[a] Derived from the image domain.
[b] Derived from crescent model fitting.
[c] The mass and systematic errors are averages of the three methods (geometric models, GRMHD models, and image domain ring extraction).
[d] The exact value depends on the method used to extract d, which is reflected in the range given.
[e] Rederived from likelihood distributions (Paper VI).

Pour les calculs qui suivent, utiliser les données ci-dessous :

Masse du trou noir : $M = 6,5 \cdot 10^9 M_\odot$

Distance entre la Terre et M87* : $D = 16,8$ Mpc





$$r_{\text{ombre}} = \theta_{\text{ombre}} \cdot D = 53 \cdot 10^{-12} \cdot 52 \cdot 10^{22} = 28 \cdot 10^{12}\ \text{m}\ > r_S$$

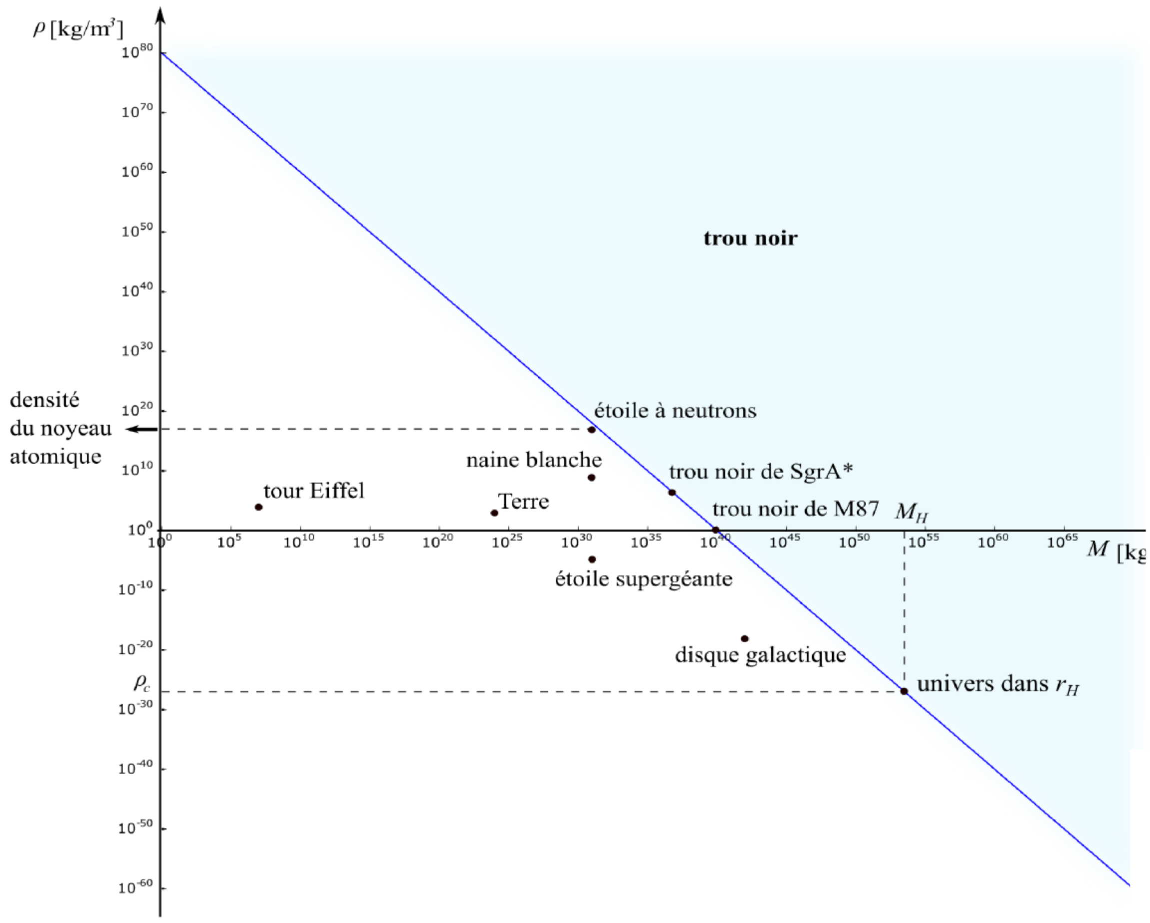
$$\Rightarrow \quad \frac{r_{\text{ombre}}}{r_S} = \frac{28 \cdot 10^{12}\ \text{m}}{19 \cdot 10^{12}\ \text{m}} = 1,5\ .$$

Examples of activities

e) *Calculer la densité moyenne de Sgr A* et la comparer avec celle d'un trou noir stellaire.*
On peut trouver ρ à partir de la formule dérivée au cours ou en calculant le rapport entre la masse et le volume du trou noir :

$$\rho = \frac{M}{V} = \frac{M}{4/3\pi\, r_S^3} = \frac{8,28 \cdot 10^{36}}{4/3\pi \cdot 12,3^3 \cdot 10^{27}} = 1,06 \cdot 10^6 \text{ kg/m}^3 \,.$$

Non, il est 11 ordres de grandeur moins dense qu'un trou noir stellaire, dont la densité se situe en dessus de la densité nucléaire ($> 10^{17}$ kg/m^3)



- Calculate the density of Sgr A*
- Find the general formula of the density of a BH, decreasing as M^{-2}
- Tide effect and density of a BH

$$g(M) = \frac{c^2}{2r_S} = \frac{c^2}{2 \cdot 2GM/c^2} = \frac{c^4}{4GM}$$

$$g'(M) = -\frac{c^2}{2r_S^2} = -\frac{c^2}{2 \cdot (2GM/c^2)^2} = -\frac{c^6}{8G^2M^2}$$

$$\frac{g'(M)}{\rho(M)} = -\frac{c^6}{8G^2M^2} \Big/ \frac{3c^6}{32\pi G^3 M^2} = \frac{4\pi G}{3}$$

Results

Conceptual learning (RQ 1 and RQ 2)

Instrument					
Learning post test (LPO)	Difficulty P	Discrimination D	r_{it}	α	K
Mean(SD)	0.76(.15)	0.44(.15)	0.38(.11)	0.56	14
[range of values]	[0.43 -> 0.93]	[0.18 -> 0.70]	[0.23 -> 0.53]		

PRE/POST comparaison				
Index	P_{pre} (SD)	P_{post} (SD)	Cohen's d	Gain = $(\langle P_{post}\rangle - \langle P_{pre}\rangle)/(1- \langle P_{pre}\rangle)$
Mean(SD)	**0.35(.18)**	**0.76(.15)**	**2.8*****	**63%**
[range of values]	[0.06 -> 0.60]	[0.43 -> 0.93]	[0.44* -> 1.59**]	[39% -> 90%]

Medium (*) to large (**) positive size effect on each item, and very large (***) overall effect (t-tests with $p < .001$)

None of the affective CV (curiosity trait, gender, school year) had an effect on LPO

Results

Conceptual learning: 10 items out of 14 revealed a misconception, overtaken after the intervention. Some examples:

Item **keywords** (translated from French)	Right answer	Percent of right answers PRE → POST	Related misconception	% of answers related to the misconception PRE → POST
We can observe other **galaxies** …	… moving away more quickly as their distance is greater	37% → 76%	… moving away with the same speed/almost at rest	46% → 24%
We call "**dark matter**" …	matter which does not interact electromagnetically	31% → 93%	… particles of antimatter	37% → 0%
The "**cosmic microwave background**" is the radiation …	… emitted in the primordial universe when neutral atoms were formed	25% → 91%	… emitted during the formation of the first galaxies	37% → 6%
By "**dark energy**" we mean …	… the energy at the origin of the change in volume of empty space	31% → 87%	… the energy of dark matter	41% → 3%
A **BH 100 times more massive** than the other is	10000 times less dense	6% → 43%	… the same / 100 / 10000 times denser	71% → 25%

Results

Affective outcomes (RQ 3):

Variable and example of item	Scale characteristics (SD)	PRE	POST
Interest (K=5) **IN**3: I liked the physics classes	Mean	**3.94**(.82)	**4.08**(.92)
	r_{it}	0.66(.05)	0.73(.01)
	α	0.65	0.77
	Cohen's *d*	**0.17**	
Curiosity state (K = 5) **CS**4: The course aroused my curiosity on the topics covered.	Mean	**3.93**(1.02)	**4.40**(.98)
	r_{it}	0.80(.05)	0.84(.08)
	α	0.87	0.89
	Cohen's *d*	**0.46***	
Self-concept (K = 5) **SC**2: My classmates thought I was good at physics.	Mean	**3.76**(.99)	**4.02**(1.04)
	r_{it}	0.80(.04)	0.80(.06)
	α	0.85	0.86
	Cohen's *d*	**0.26***	
Relevance of science (K = 8) **RS**2: Everyone should study the topics covered in the course.	Mean	**3.67**(.88)	**3.68**(.89)
	r_{it}	0.66(.09)	0.65(.07)
	α	0.81	0.80
	Cohen's *d*	**0.01**	

Small (*) positive size effect on curiosity state (p = .001) and self-concept (p =.09)

Conclusions

1. Strong impact of the course on *conceptual learning* of cosmology, strengthened by the low level of prior knowledge on these topics

2. Small effect of the intervention on *curiosity as a state* and *self-concept* in relation to the course

   ↳ Participants' interviews confirm that this can be explained by the adequate structure of the course, tailored to the targeted level

3. Variables *interest* and *relevance of science* remain unchanged

   ↳ Students' responses indicate how a structured and in-depth treatment of certain subjects may not increase their interest, as they are satisfied with learning at their current level, but they remain willing to learn more, aware that this would require a higher level of mathematics and physics

Conclusions

4. Although the course did not significantly change perception of the relevance of science (3.7/6 - relatively high in the sample), participants stated they could better understand:

   - how research is conducted
   - the uncertain nature of scientific knowledge
   - the usefulness of applying concepts learned in basic courses (accelerated or circular motion, inertia, free fall, the Doppler effect, …)
   - how making connections and apply the concepts learned in the context of other disciplines, such as philosophy

Perspectives

- Starting from school year 2024-25 the course of C&GR is offered over 2 semesters
  - ↳ Possibility to complete the 8 chapters
  - ↳ Also in Italian (Ticino Canton)
  - ↳ Classes of different teachers participating to a new study

- A network teachers and researchers will continue to collaborate
  - ↳ to improve and expand questioners and interviews to evaluating the impact on students' learning and motivation
  - ↳ to update the C&GR educational resources, following the evolution of scientific actualities
  - ↳ to create new collaborations for observations (Stellarium Gornergrat, OFXB in Saint Luc)
  - ↳ to offer teachers' continuum professional development formations

https://nccr-swissmap.ch/school-teachers-children/general-relativity

https://physalice.ch/cosmologie/

Thank you

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Students' quotes

About interest in cosmology and the course:

- *" I watch a lot of videos, I find cosmology and modern physics very fascinating"*
- *"The course came at a very good time because the day after we covered the subject, we saw photos of the black hole in the center of our galaxy in the newspapers and were able to study it" (about the M87 black hole by the EHT)*
- *"The book is incredible, excellent, it has everything in it"*
- *"The documents were very precise and very well explained, the book is very well done, the files with summaries helped a lot"*
- *"It was the most interesting course of the year, I loved it, I suggest that it always be integrated into the physics course"*

About curiosity versus interest

- *"Curiosity grew because the subject is truly interesting, and there's so much we don't yet know. But interest might decrease a bit because once you know the basics, the course inevitably gets more technical with math and physics. As for me, I like astronomy, but I wouldn't go further now"*

Students’ quotes

Awareness about the physics courses and relevance of science

- *"I thought Newtonian mechanics was insufficient for calculating, for example, the Schwarzschild radius. I discovered that Newtonian mechanics can actually provide good approximations for more complex results”*
- *"As for Newton's laws and waves, I can explain them now, and I feel more confident about these topics”*
- *"It's actually the more philosophical side that is highlighted, thanks to the quantitative data, but also to my personal research”*
- *"I had never realized how many things we don’t know: so many things that are still unknown to us!"*
- *"Understanding that we are nothing compared to the universe, realizing that we are a tiny part of what surrounds us, was very striking to me”*
- *“This allowed me to understand the notion of time and the limits of the physics of our world”*
- *“I didn't think the temperature of the universe was that low. Our intuition is distorted by our senses and our daily experience”*