Seminar 2

Overview of astrophysics

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What is astrophysics?

- $\uparrow$
- **An applied field of physics, so very messy!**

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Astrophysical phenomena

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Astrophysical phenomena

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Astrophysical phenomena

"""sombrero".jpg

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Astrophysical phenomena

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Astrophysical phenomena

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Astrophysical phenomena

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Astrophysical phenomena

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- We mentioned that transits were not so reliable:

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Exoplanet miscellanea

- What is wrong with this light curve?

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Exoplanet miscellanea

- Illustration of multiple **Dyson rings**:

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Exoplanet miscellanea

- HabEx – atmospheric backlighting in our own solar system:

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Exoplanet miscellanea

- Which planet, if any?

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Exoplanet miscellanea

- Solar coronograph: """coronograph".png

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Astrophysical scale

- By definition, astrophysics will involve a wide range of **length scales**

Astrophysical scale

- Distance to space: 1×10^2 km

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Astrophysical scale

- Distance to the moon: 4×10^5 km

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Astrophysical scale

- Before we proceed further, we need to get to grips with the speed of light. . .

Astrophysical scale

- The speed of light c has the value 3×10^8 m/s
- The earth has radius 6.4×10^6 m, so how many times would light travel around the earth?
- The speed of light is **fixed**, it doesn't matter how you change you own velocity, c will always give the same value upon measurement

Astrophysical scale

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Astrophysical scale

- Counter-intuitively c has **nothing** to do with light or electromagnetism, rather it is a unit-conversion between **space** and **time** – which as we will see in Seminar 4 and 5, are the same thing
- Field theories (such as electromagnetism) have a mathematical structure such that (at the level of QFT) they contain **massless particles**
- **Special relativity** tells us that massless particles **always** move at c, or for every bit of time which elapses, they move through an **equal** bit of space
- **massive particles** (such as yourselves!) are free to move at any speed below c

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Astrophysical scale

- Electromagnetism and quantum electrodynamics are not unique in that they contain massless **photons**
- Quantum chromodynamics (strong force) contains massless **gluons** and **classical** theories of gravity predict **gravitational waves** moving at c
- We expect that any quantum theory of gravity would therefore contain a massless **graviton**

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Astrophysical scale

- ... back to astrophysics: because c is so large, it is fairly useful for talking about scale
- The light minute: 1.8×10^7 km
- The light year: 9.5×10^{12} km
- Clearly we are now talking about vast distances

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Astrophysical scale

- Distance to the sun: 8.5 lm
- Distance to the edge of the solar system: 1 ld
- Let's pause here to define the **parsec**:
  - The distance at which one 1 au subtends one **arcsecond**

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Astrophysical scale

- Moving out...
- Distance to Proxima Centauri: 4.2 ly
- Distance to TRAPPIST-1: 40 ly
- Distance to Sag A*: 2.6×10^4 ly
- From this we get the length scale of our galaxy: 1×10^4 ly

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Astrophysical scale

- Since I mentioned Proxima b:
  - https://www.youtube.com/watch?v=lysJduOqads
  - https://www.youtube.com/watch?v=RoCm6vZDDiQ

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Astrophysical scale

- Distance to LMC and SMC: 1×10^5 ly
- Distance to Andromeda galaxy: 2.5×10^6 ly
- Distance to M87: 16.4×10^6 pc

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Astrophysical scale

- Finally distance to the edge of the known universe: 14×10^9 pc

Astrophysical scale

- Once we are in the realm of 1×10^6 pc we should really be talking about **redshift**
- You will have heard about redshift in the context of fast-moving objects
- When we observe distant galaxies, we find that redshift **increases** with distance, and furthermore it does so **linearly** – this is **Hubble's Law**
- The observed redshift indicates that distant objects are moving **away from us** at a rate known as H, the Hubble constant

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Astrophysical scale

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Astrophysical scale

- Early estimates based on both CMB and light geodesics agree
- More recently they are diverging, so-called **Hubble tension**
- Evidence perhaps that **general relativity is lacking. . .**

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Astrophysical scale

- To see what this has to do with redshift, we need to understand how light moves through an expanding universe
- Easiest with **plane-polar coordinates**, r and ϕ
- In Euclidean space take r to be dimensionful, ϕ dimensionless
- Then add dimensionful time t, and re-parameterise the radial coordinate with dimensionful $R(t)$ and dimensionless r

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Astrophysical scale

- Euclidean case:

$$v^2\mathrm{d}t^2 - \mathrm{d}r^2 - r^2\mathrm{d}\phi^2 = 0, \quad c^2\mathrm{d}t^2 - \mathrm{d}r^2 - r^2\mathrm{d}\phi^2 = 0$$

- Non-Euclidean case:

$$v^2\mathrm{d}t^2 - R(t)^2\mathrm{d}r^2 - R(t)^2r^2\mathrm{d}\phi^2 = 0,$$
$$c^2\mathrm{d}t^2 - R(t)^2\mathrm{d}r^2 - R(t)^2r^2\mathrm{d}\phi^2 = 0$$

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Astrophysical scale

- Time-permitting, an aside on **proper time** vs **coordinate time**. . .

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Astrophysical scale

- So now we know how light behaves in an expanding universe:

$$c^2\mathrm{d}t^2 - R(t)^2\mathrm{d}r^2 = 0 \implies \frac{c\mathrm{d}t}{R(t)} = \mathrm{d}r$$

- We can take this and **integrate** over the passage of a light wave from **early** t_1 to **contemporary** t_0:

$$\frac{\delta t_1}{R(t_1)} = \frac{\delta t_0}{R(t_0)}$$

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Astrophysical scale

- Now we get to re-express this in terms of wavelength, frequency etc:

$$c\delta t_1 = \lambda_1, \quad c\delta t_0 = \lambda_0$$

- Define the redshift (should be $z > 0$ for an **expanding** universe):

$$z = \frac{\lambda_0}{\lambda_1} - 1$$

- So finally we have:

$$\frac{\delta t_1}{R(t_1)} = \frac{\delta t_0}{R(t_0)} \implies z + 1 = \frac{R(t_0)}{R(t_1)}$$

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Astrophysical scale

- Hence, redshift depends on the size of the universe at emission and detection
- If the universe is **matter dominated** general relativity suggests $R(t) \propto t^{2/3}$
- Try to find the observed age of these galaxies in the matter dominated universe, given t_0 is 1.4×10^{10} yr:
  - M87 at $z = 0.00428$
  - Sombrero galaxy at $z = 0.003416$
  - GN-z11 at $z = 11.09$

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Astrophysical scale

- Main point is that the most distant **observable** objects are significantly further away than light could have travelled over the entire age of the universe

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Astrophysical scale

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- Hopefully we will get on to some astrophysical fluid dynamics, but we need **vector calculus** to do that

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