### Seminar 2

### Overview of astrophysics

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### What is astrophysics?

- 1
- An applied field of physics, so very messy!







"""kepler\_90".jpg





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"""protoplanetary_disk".jpg
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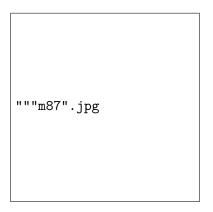




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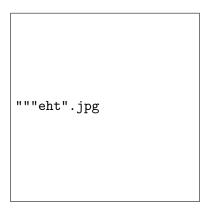






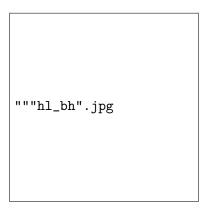












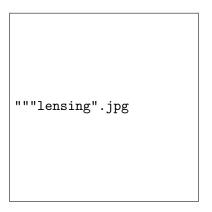






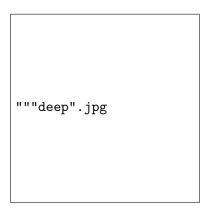






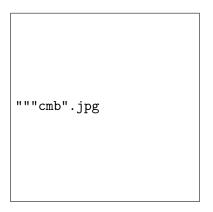
















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"""big_bang".jpg
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• We mentioned that transits were not so reliable:

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"""tabby".png
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"""tabby\_2".jpg

• What is wrong with this light curve?





"""dyson".png

• Illustration of multiple **Dyson rings**:





• HabEx – atmospheric backlighting in our own solar system:

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"""pluto_atmosphere".jpg
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"""pluto".jpg

• Which planet, if any?





"""coronograph".png





• Solar coronograph:

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





• Distance to space:  $1 \times 10^2$  km







• Distance to the moon:  $4 \times 10^5 \, \text{km}$ 







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

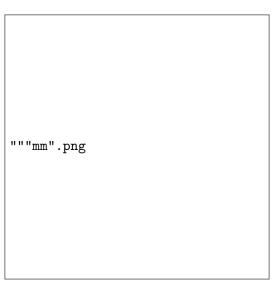




- ullet The speed of light c has the value  $3 imes 10^8 \, \mathrm{m/s}$
- The earth has radius  $6.4 \times 10^6$  m, so how many times would light travel around the earth?
- ullet The speed of light is **fixed**, it doesn't matter how you change you own velocity, c will always give the same value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











- 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
- $\bullet$  massive particles (such as yourselves!) are free to move at any speed below c





- 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





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





- 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





- Moving out...
- Distance to Proxima Centauri: 4.2 ly
- Distance to TRAPPIST-1: 40 ly
- Distance to Sag A\*:  $2.6 \times 10^4$  ly
- $\bullet$  From this we get the length scale of our galaxy:  $1\times 10^4\,\text{ly}$





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







- Distance to LMC and SMC:  $1 \times 10^5 \, \text{ly}$
- Distance to Andromeda galaxy:  $2.5 \times 10^6$  ly
- Distance to M87:  $16.4 \times 10^6$  pc





 $\bullet$  Finally distance to the edge of the known universe:  $14\times10^9\,\text{pc}$ 





- Once we are in the realm of  $1 \times 10^6\,\mathrm{pc}$  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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"""hubbel".png
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- 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...





- 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  $\phi$
- ullet In Euclidean space take r to be dimensionful,  $\phi$  dimensionless
- $\bullet$  Then add dimensionful time t, and re-parameterise the radial coordinate with dimensionful R(t) and dimensionless r





Euclidean case:

$$v^2 dt^2 - dr^2 - r^2 d\phi^2 = 0$$
,  $c^2 dt^2 - dr^2 - r^2 d\phi^2 = 0$ 

Non-Euclidean case:

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

$$c^{2}dt^{2} - R(t)^{2}dr^{2} - R(t)^{2}r^{2}d\phi^{2} = 0$$







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







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

$$c^{2}dt^{2} - R(t)^{2}dr^{2} = 0 \implies \frac{cdt}{R(t)} = dr$$

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

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





• 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:

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





- 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  $1.4 \times 10^{10}$  yr:
  - M87 at z = 0.00428
  - Sombrero galaxy at z = 0.003416
  - GN-z11 at z = 11.09

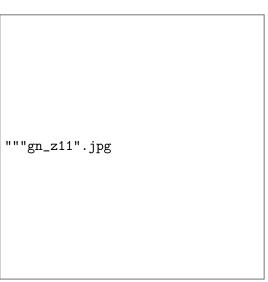




 Main point is that the most distant observable objects are significantly further away than light could have travelled over the entire age of the universe











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









