Expansion of the universe
宇宙的膨胀

Ricardo Moreno, Susana Destua,
Rosa M. Ros, Beatriz García

International Astronomical Union
Colegio Retamar de Madrid, Spain
Space Telescope Science Institute, USA
Technical University of Catalonia, Spain
ITeDA and Technological National University, Argentina

Goals
目标

- Understand the expansion of the universe
- 理解宇宙的膨胀
- Understand that there is no centre to the universe
- 理解宇宙没有中心
- Understand the Hubble-Lemaître Law
- 理解哈勃定律
- Understand how to detect dark matter
- 理解如何探测暗物质

Presentation
介绍

This workshop is about:本章节的主要内容有：

- The origin of the universe: the Big Bang
- 宇宙的起源：大爆炸理论
- The galaxies: they do not “move” through space, the space is that expands
- 星系：并不是星系在空间中运动，而是空间本身在膨胀。
- The Hubble’s Constant : $v = H \times d$ 哈勃常数
- There is no centre to the universe 宇宙没有中心
- The microwave background 微波背景辐射
- Gravitational lenses 引力透镜

Models, predictions, verification: Experiment with a tablecloth
模型、预测与验证：桌布实验

Prediction: if you pull a tablecloth very quickly nothing on the table will fall down. If we are able to verify this, our prediction is fulfilled.

预测：如果你快速抽出桌上的桌布，那桌上的物品并不会掉落。如果我们验证了，就证明预测应验了。

Models, predictions, verification: Experiment with a tablecloth
模型、预测与验证：桌布实验

If one pulls the tablecloth quickly, frictional forces do not have time to act on the objects on the table, which explains why they do not fall. The experiment is successful because physics is a science which predicts what will happen.

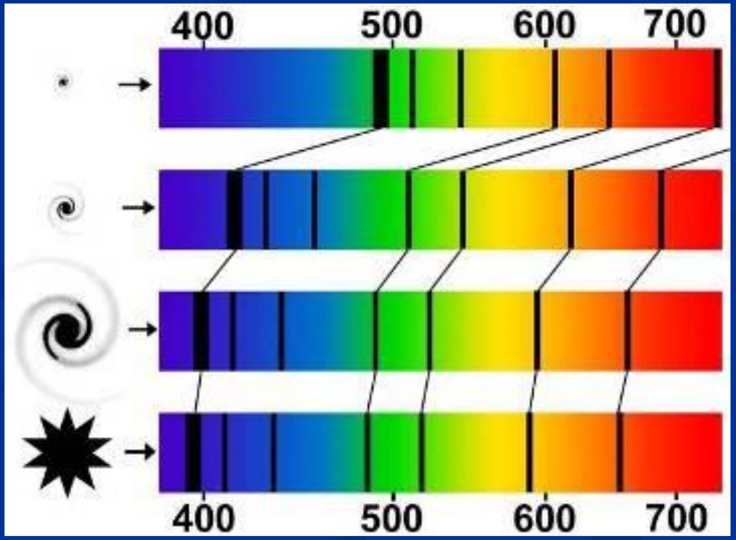
这个实验会奏效是因为物理这个学科能够预测将会发生的情况：如果足够快速抽出桌布，那么摩擦力将来不及影响桌布上的物体，这就解释了物品为什么没有掉落。

The Physics that we developed on the Earth is the same one that we apply to the rest of the Universe.

地球上的物理学家所做的与天文学家应用于宇宙中的是一样的

Movement towards the red 红移

- The absorbed light of each chemical element shows lines. It is its spectrum and it is characteristic of each element.
- 各种元素的散射光线中有着如右图所示的线条：这就是光谱，是每种元素的特征
- When we observe the light from galaxies, we can see that the lines are shifted toward the red end of spectrum. The further away the galaxy, the greater the redshift.
- 通过观察星系的光谱，我们发现谱线向红端发生了移动，而且越是遥远的星系，移动幅度越大。
- This is interpreted as a result of the galaxy's movement away from us.
- 这是星系在远离我们而带来的现象。



Movement towards the red 红移

- Nearby galaxies have relatively small and irregular movements: the Large Magellanic Cloud +13 km/s, the Small Magellanic Cloud -30 km/s, Andromeda Galaxy -60 km/s, M32 +21 km/s.
- 临近的星系相对运动幅度较小，且为不规则运动：大麦哲伦云为+13 km/s，小麦哲伦云为-30 km/s，仙女座为-60 km/s，M32 为+21 km/s。
- In the Virgo cluster, (50 million lyr away), all galaxies are moving away from us at speeds of between 1 000 and 2 000 km/s.
- 在室女座星系团（五千万光年外），所有的星系都在以1000~2000 km/s的速度远离我们。
- In the Coma Berenice supercluster (300 million lyr away) the speeds are between 7 000 and 8 500 km/s.
- 在后发座超星系团中（三亿光年外），星系的退行速度达到7000~8500 km/s。

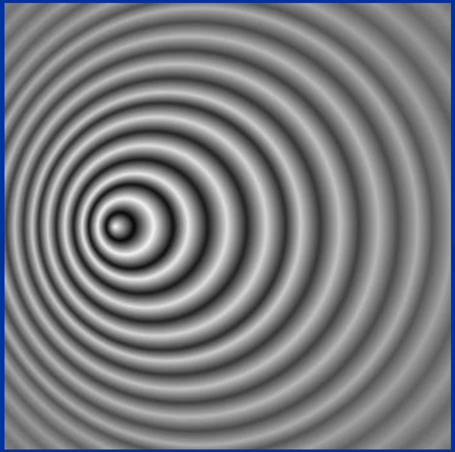
Movement towards the red 红移

- In the opposite direction，M 74 moves away at 800 km/s and M 77 at -1 130 km/s.
- 在另一侧，M74的退行速度为800 km/s ，M 77 为 1130 km/s。
- If we observe distant and faint galaxies, the recession velocity is even greater: the galaxy NGC 375 moves away at 6 200 km/s, NGC 562 at 10 500 km/s and NGC 326 at 14 500 km/s.
- 如果我们观察那些遥远而且暗弱的星系就会发现，它们的退行速度更大： NGC 375 为6200 km/s，NGC 562 为 10500 km/s ，NGC 326 为14500 km/s。
- Independent of the direction in which we observe, all except the very close galaxies are moving away from us.
- 通过我们的观测发现，除了那些临近的星系，其他各个方向上的所有星系都在离我们而去。

Doppler Effect多普勒效应

In the same way as in the tablecloth example, we can apply other physical principles to the study of the universe.
就像桌布实验，我们可以用其他基本物理原理来研究宇宙。

- If an ambulance, a motorcycle or a train is approaching, we will hear a higher pitched sound. When they move away we hear a lower pitched sound.
- 当行驶中的救护车、摩托车或者火车从身边经过时，我们总能听见尖利的声音。当它们远离我们时，我们会听到低沉的声音。
- Higher pitch → the wavelength is shortened
- 高音→ 声波被压缩
- Lower pitch → the wavelength is lengthened
- 低音 → 声波被拉伸



Activity 1: Doppler Effect
活动 1：多普勒效应

- The Doppler effect can be heard by rotating an alarm clock or buzzer in a horizontal plane.
- 利用一个在水平面上绕转的闹钟或蜂鸣器，我们就能“听到”多普勒效应。
- When it approaches the listener, λ is shortened and the pitch of the sound is higher.
- 当它靠近观众时，波长λ就被压缩，音调变高。
- When it moves away, λ is stretched and the pitch of the sound is lower.
- 当它远离观众，波长λ就被拉伸，音调变低。

Activity 1: Doppler Effect
活动 1：多普勒效应

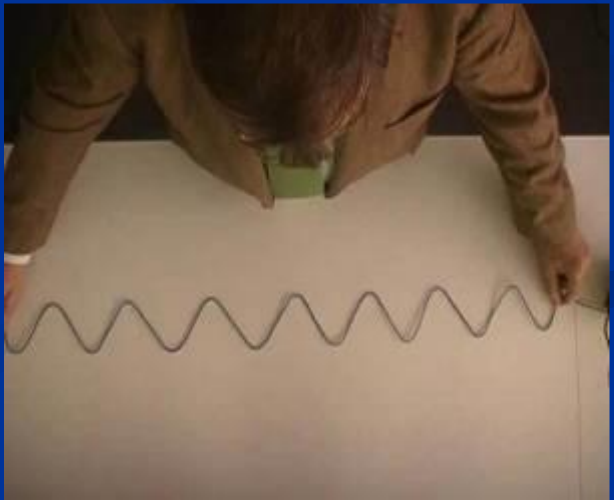
- This happens with the sounds of motorcycles, ambulances, trains…
- 上面的现象和摩托车、救护车、火车经过我们身边产生的声音变化是同样的原理。

The Doppler effect we detect here is due to the displacement. But it is not the same one that galaxies have due to expansion.

上述现象是由于位移引起了多普勒效应。但是星系扩张形成的多普勒效应，和上述并不一样。

Activity 2: "Stretching" of photons
活动 2：光子的"拉伸"

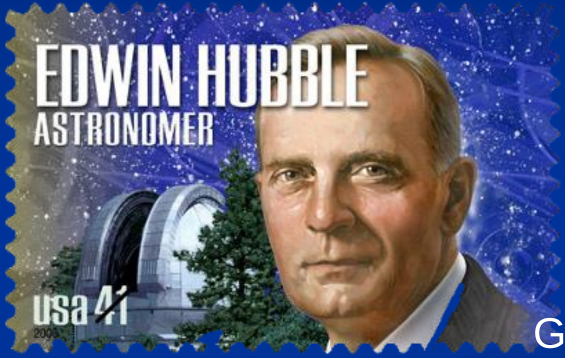
- The universe, when it expands, "stretches" the photons in it.
- 当宇宙膨胀时，其中的光子会被"拉伸"。
- You can make a model of that stretching using a semi-rigid cable of the type used in domestic wiring.
- 你可以利用家用电器里的半刚性电缆来做一个拉伸模型。
- The longer the photon's path, the more they are stretched.
- 光子运动的时间越长，它的形变越明显。



Hubble-Lemaître Law 哈勃定律

Between 1920 and 1930, George Lemaître and Edwin Hubble realized that the most distant galaxies are moving away faster than nearby ones.

1920至1930年，爱德温・哈勃发现距离越远的星系退行速度越快。



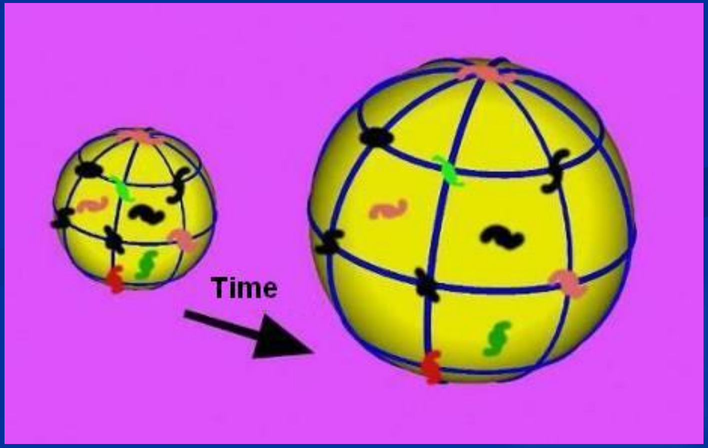
George Lamaître

Hubble-Lemaître Law:

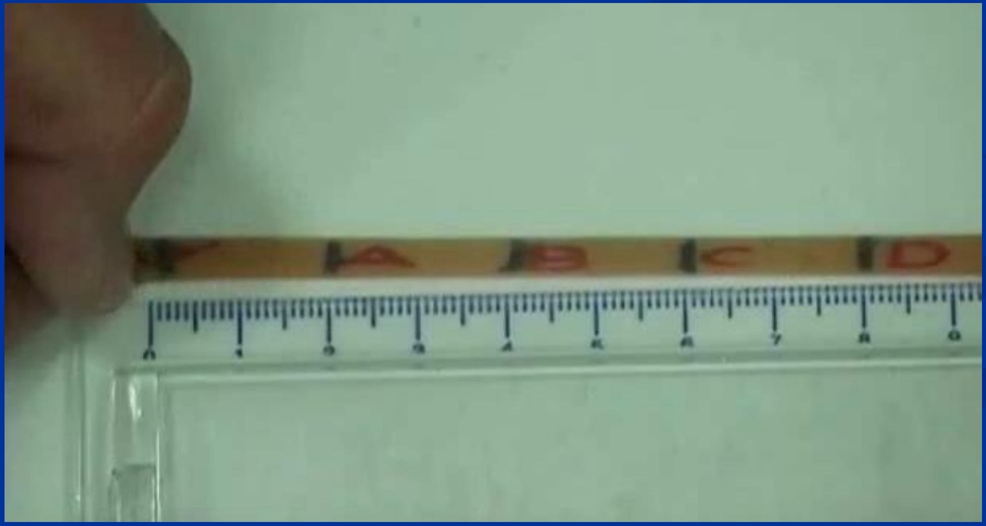
哈勃定律： $v = H \times d$

The galaxies don't move through the space: it is the space which expands, dragging the galaxies.

星系并没在空间中移动，而是空间发生了膨胀，并把星系间的距离也拉大了。



Activity 3: The universe in an elastic band
活动 3：橡皮筋宇宙模型



Activity 4: The universe in a balloon
活动 4：气球宇宙模型

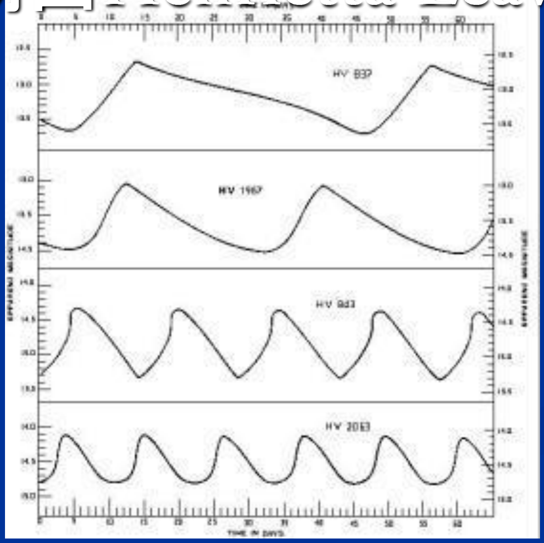
- The distance between the galaxies increases with the expansion.
- 随着气球的膨胀，“星系”间的距离也随之变大。
- The galaxies are not moving through the balloon
- 星系本身并未在气球上发生移动。
- Locating ourselves in any “galaxy” on the balloon we see that the others move away from us.
- 当我们处于气球上任意代表我们所在的“星系”中时，会发现其他星系都在远离我们。

Expansion of the universe 宇宙的膨胀

1) The distance to the nearest galaxies can be obtained from the period-luminosity relation of the Cepheid variable stars

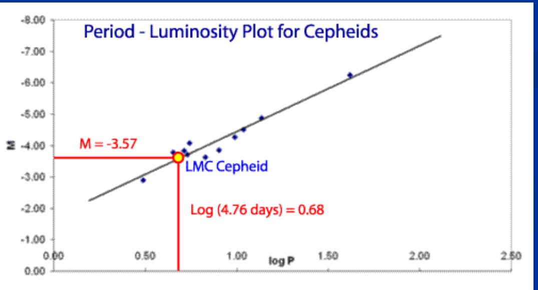
我们与近邻星系间的距离主要是通过造父变星的周光关系得到的(discovered by Henrietta Leavitt, at Harvard, early in 20th century)

（20世纪早期由Henrietta Leavitt在哈佛发现。）



Expansion of the universe 宇宙的膨胀

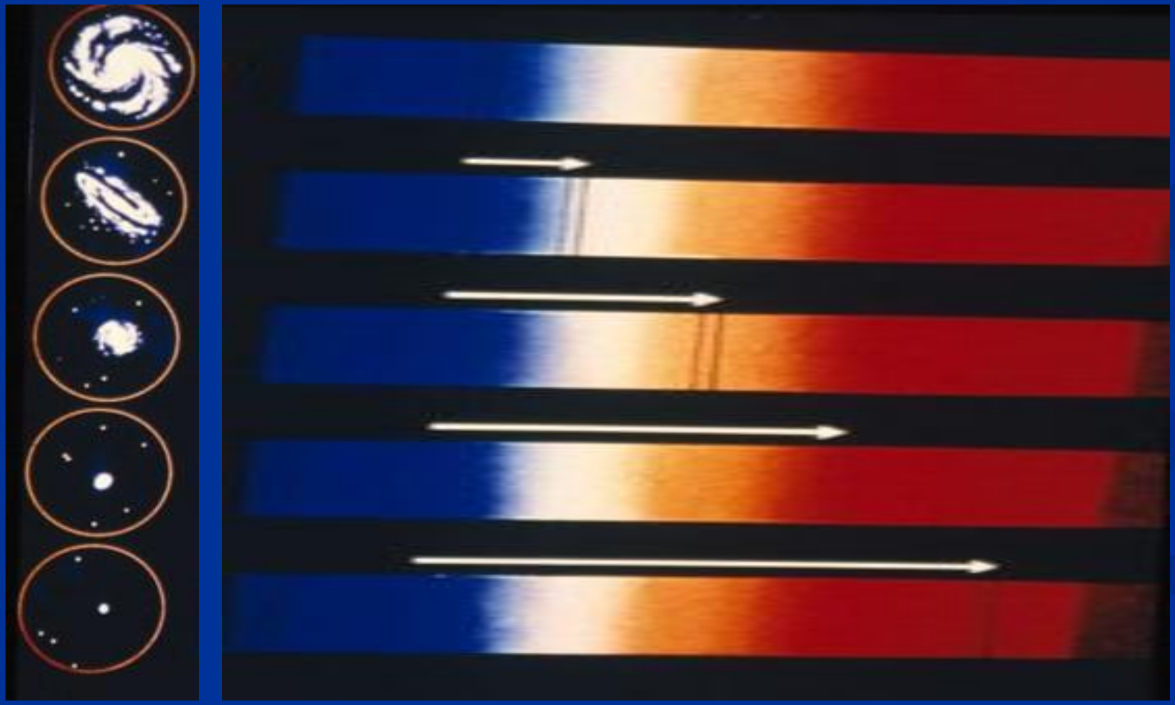
- From the light curve it is possible to obtain the period P
- 利用光变曲线可以得到周期P
- From the relation period-luminosity we can get the absolute magnitude M
- 利用周光关系可以得到绝对星等M
- With M and m, it is possible to measure the distance to the galaxy $d=10^{(m-M+5)/5}$ parsec
- 利用以上参量可以计算出距离
- To determine distances of the most distant galaxies the astronomers can use a particular type of supernova (type Ia) which have similar peak luminosities.
- 天文学家利用一类具有接近光度的超新星（Ia型）来确定最遥远星系的距离



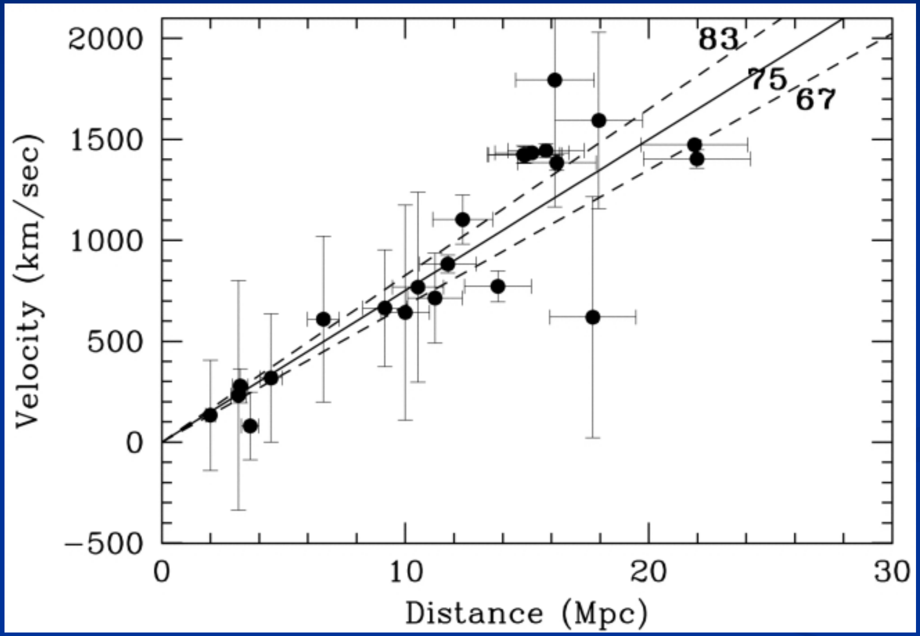
Expansion of the universe 宇宙的膨胀

2) The recession velocity is measured from the shift of the absorption lines in the spectrum, using the equation:
退行速度可根据光谱中的吸收线测得

$$v = (\Delta \lambda / \lambda) \times c$$



Expansion of the universe 宇宙的膨胀

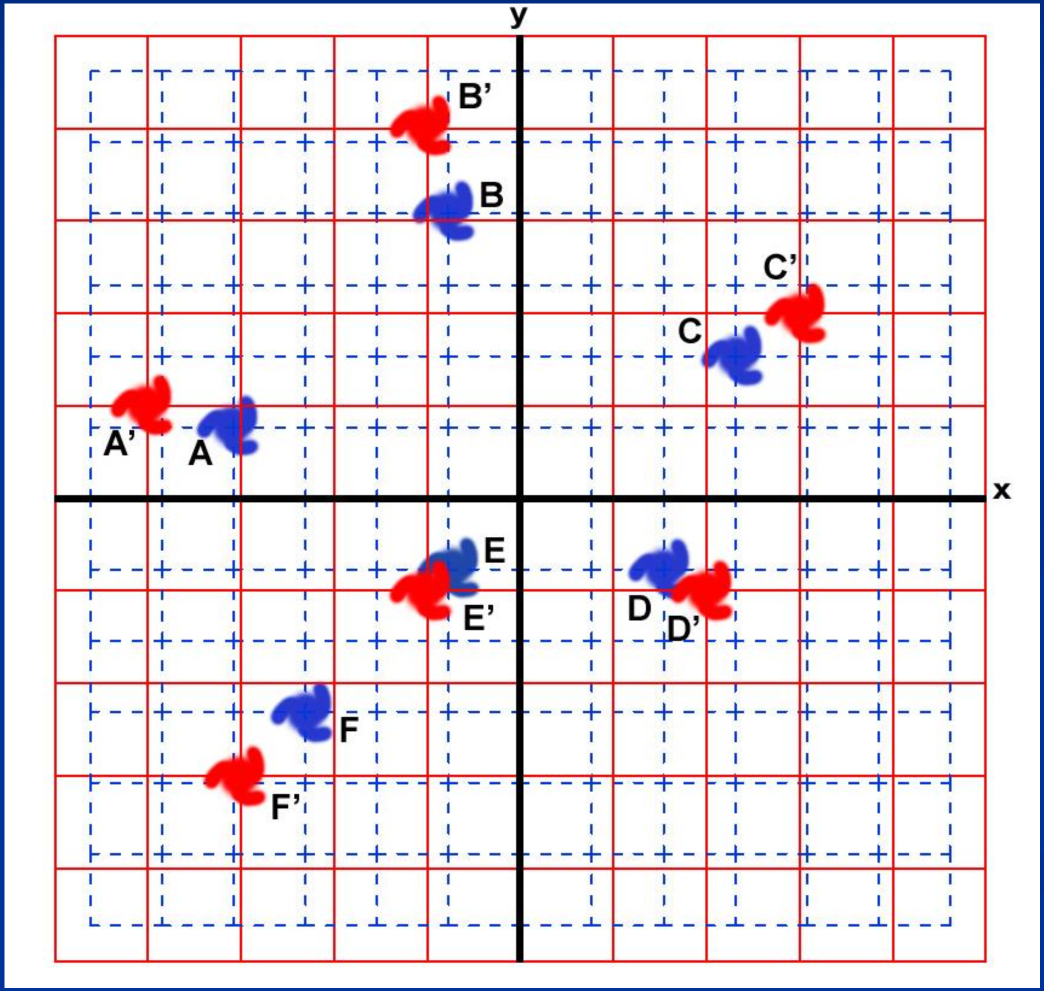


(from Freedman et al, 2001, ApJ, vol 553, p47)

3. The Hubble constant is the slope of the relation: v = H_0 x d, where H_0 is the rate of expansion of the universe: H_0 = 72 km/s.Mpc

该直线的斜率即为哈勃常数，其中H_0是宇宙的膨胀速率

Activity 5: Calculation of the Hubble-Lemaître constant
活动5：计算哈勃常数



Blue = Universe before expanding

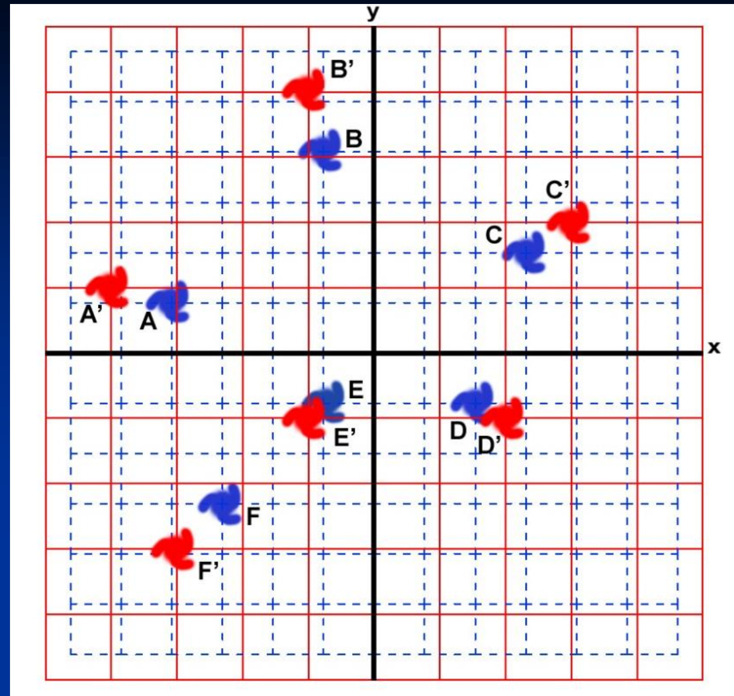
蓝色是宇宙膨胀前的星系位置

Red = Universe after expanding

红色是宇宙膨胀后的星系位置

Activity 5: Calculation of the Hubble-Lemaître constant
活动5：计算哈勃常数

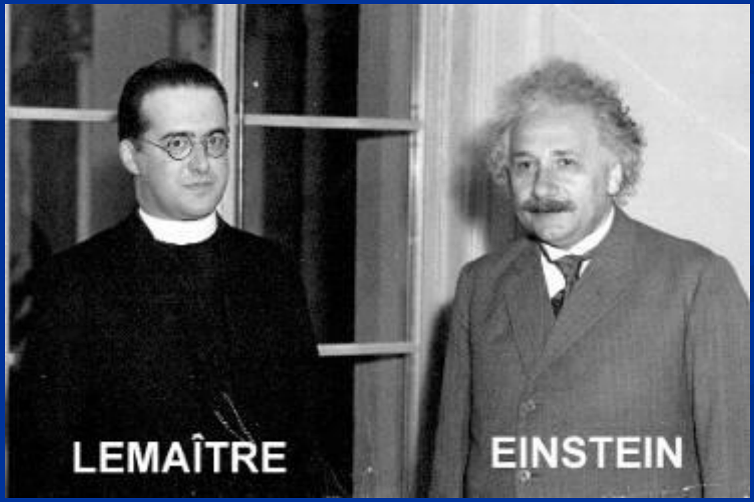
Galaxy	Coordinates x,y	d=distance to origin	Δd	$v = \frac{\Delta d}{\Delta t}$	$H = \frac{v}{d}$
A					
A'					
B					
B'					
C					
C'					
D					
D'					
E					
E'					
F					
F'					



Galaxy	Coordinates x,y	d=distance to origin	Δd	$v = \frac{\Delta d}{\Delta t}$	$H = \frac{v}{d}$
A	(-4, 1)				
A'	(-4, 1)				
B	(-1, 4)				
B'	(-1, 4)				
C	(3, 2)				
C'	(3, 2)				
D	(2, -1)				
D'	(2, -1)				
E	(-1, -1)				
E'	(-1, -1)				
F	(-3, -3)				
F'	(-3, -3)				

The Big Bang 大爆炸

- If we go back, there was a time when everything was united: universe in expansion.
- 如果时光倒流，我们会发现在某一刻宇宙万物都集中于一体：宇宙在不断膨胀。
- Georges Lemaître, solving the equations of relativity, came to the idea of an expanding universe that began as a “cosmic egg”.
- 乔治・勒梅特解出了相对论方程的结果，并萌生了正在膨胀的宇宙是源于“宇宙蛋”的想法。



The Big Bang 大爆炸

- Name of the Big Bang: big explosion.
- 大爆炸理论，顾名思义就是大规模的膨胀。
- Fred Hoyle, with certain anti-religious prejudices, thought it seemed too consistent with the idea of a Creator.
- 这个名字本来是天文学弗雷德・霍伊尔出于偏见想出来的，他认为这个名字就像“造物主”这个词一样可笑。
- S & T made a competition to rename it. There were 12 000 proposals. None was better!
- 美国的《天空望远镜》杂志针对“大爆炸”发起了一次更名活动。活动共收到 12000 份建议，但却无一能够撼动原本的“大爆炸”这个名字。

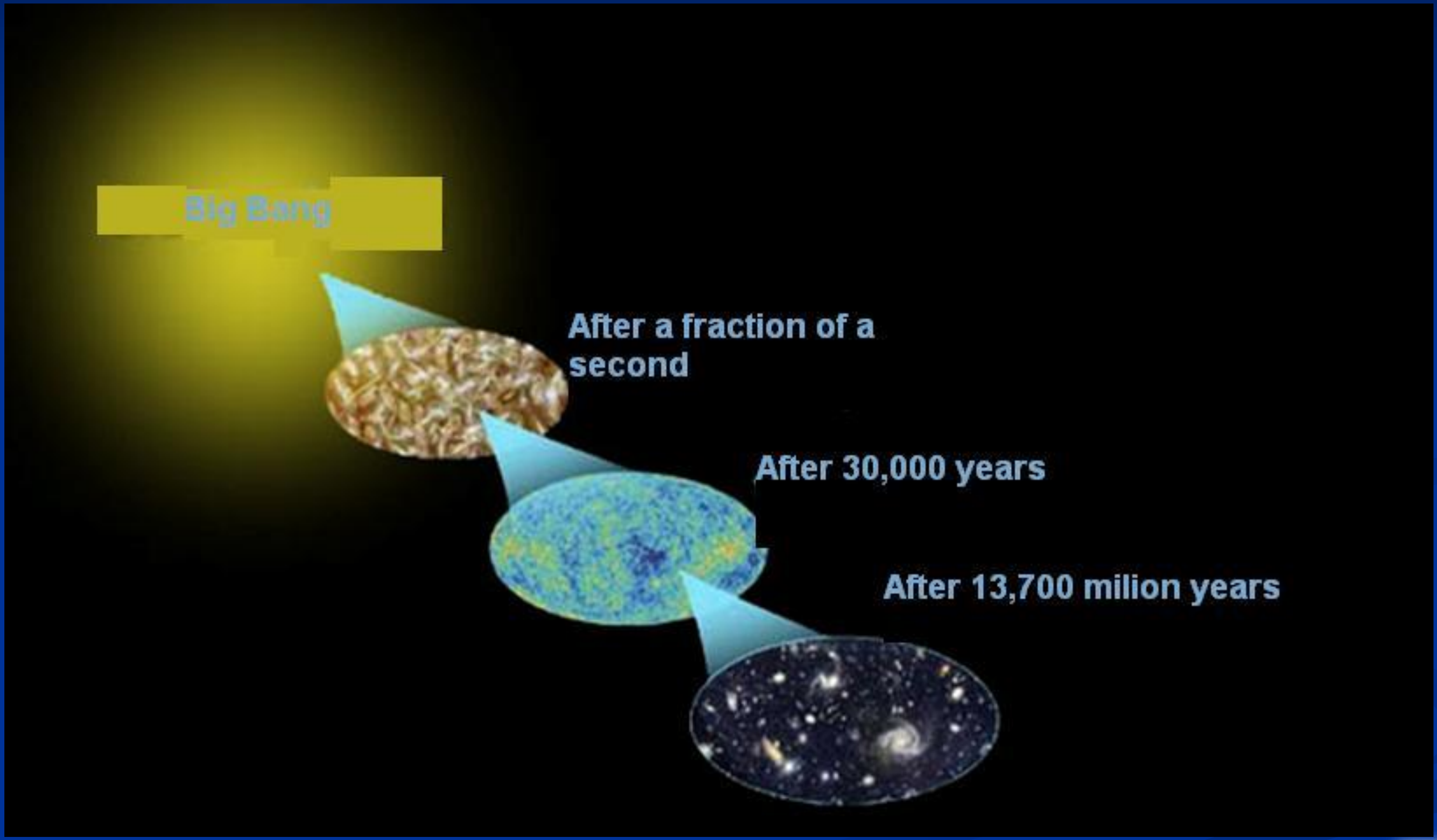
The Big Bang 大爆炸

- Before the Big Bang? We do not know anything.
- 对于大爆炸开始之前的事情，我们一无所知。
- What was the cause? Why did it happen? Why does it observe the same physical laws everywhere?
- 发生的起因是什么？为什么会发生呢？为什么会遵循这些物理规律？
- Physics is about how the existing things work，not about why do they exist.
- 物理学家关心的是这些存在的物质是如何相互作用的，他们并不研究这些存在的理由。
- Physics studies the matter from its origin (since the Big Bang), not before, nor does it study the reason or purpose of why it exists. These are philosophical and religious questions but not scientific questions.
- 物理学家会研究这些物质自产生之时（大爆炸时期）起的种种，但并不会研究这之前的情况，也不会研究这些存在的理由和目的

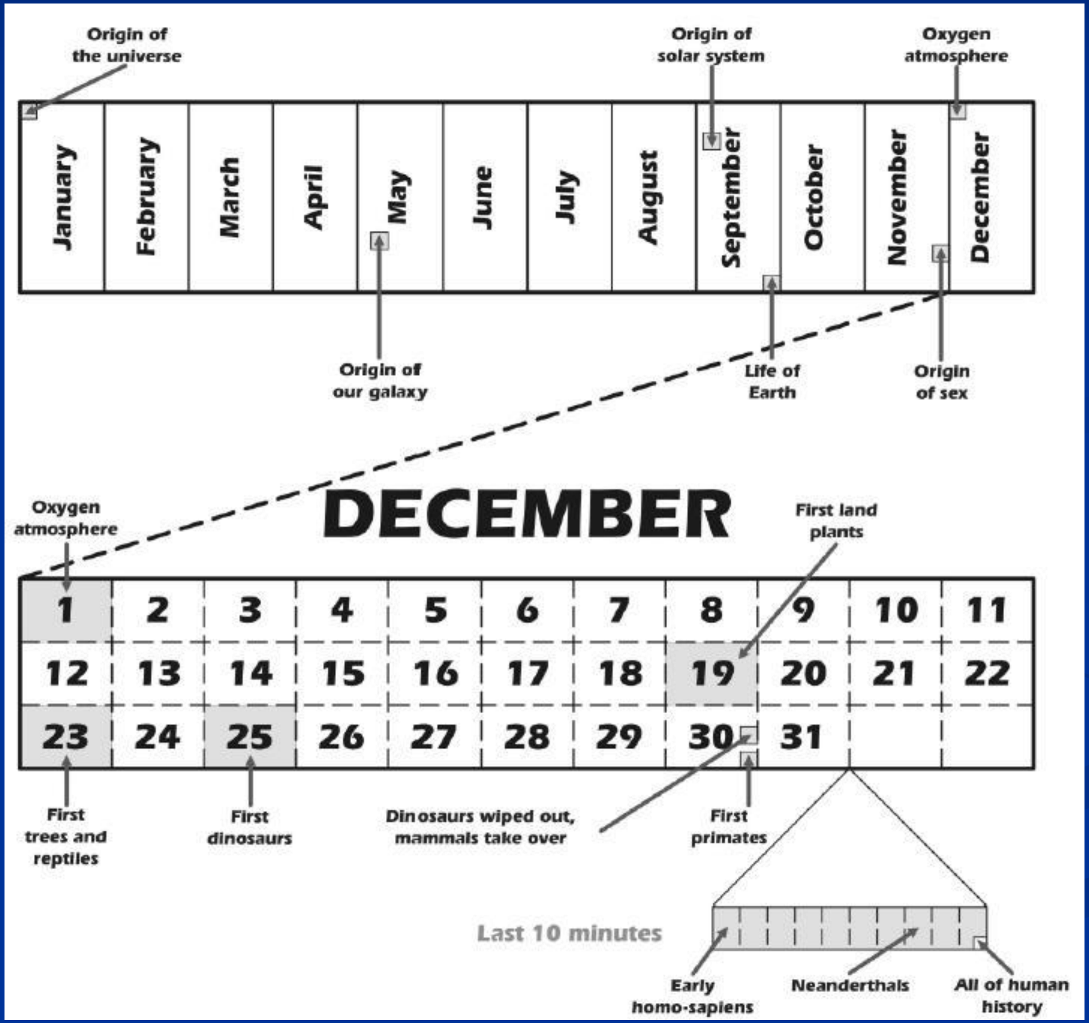
The Big Bang 大爆炸

- Fluctuation of the quantum vacuum?
- 空间的量子涨落?
- Emptiness is not nothing, it exists.
- 量子真空不是一无所有，而是存在的。
- Multiple universes? Indemonstrable by definition.
- 多重宇宙？它的定义无法核实。

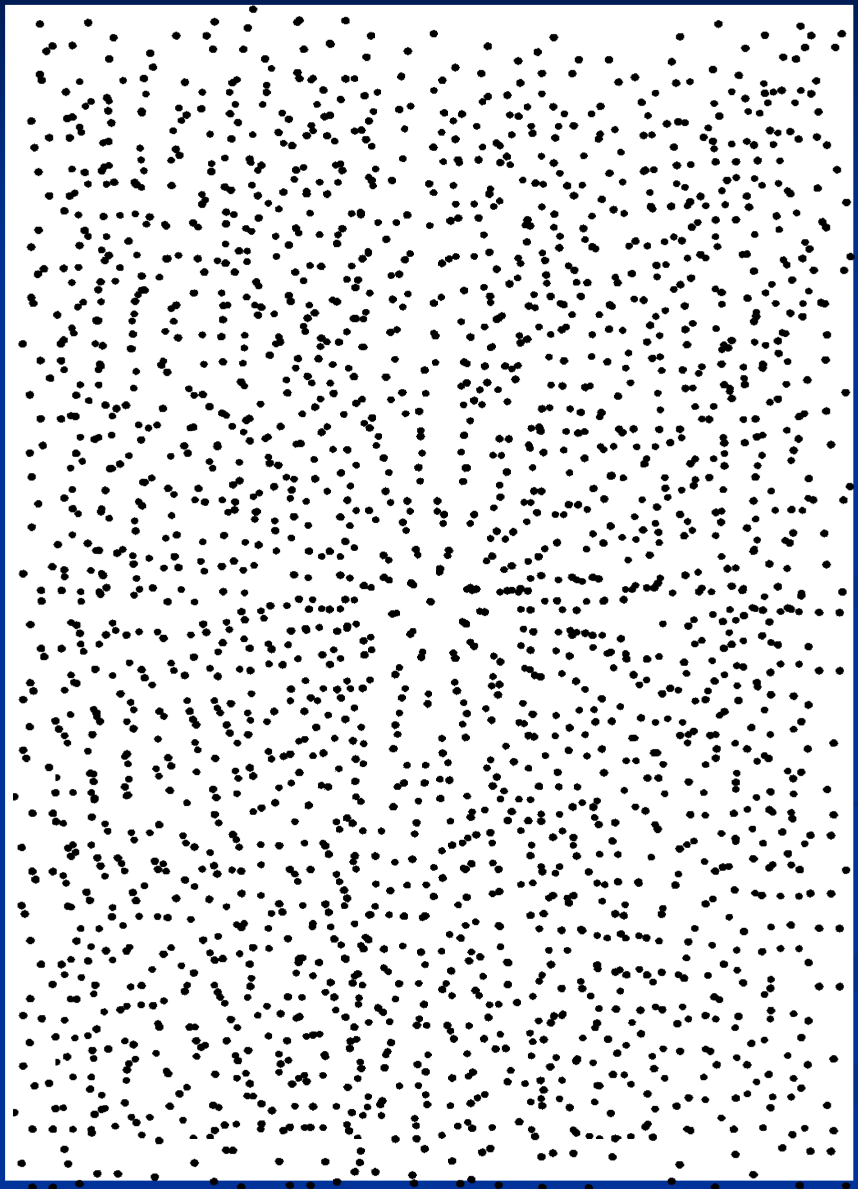
Evolution of the universe
宇宙的演化



Development of the universe in a year
用一年的时间表示宇宙的发展历史



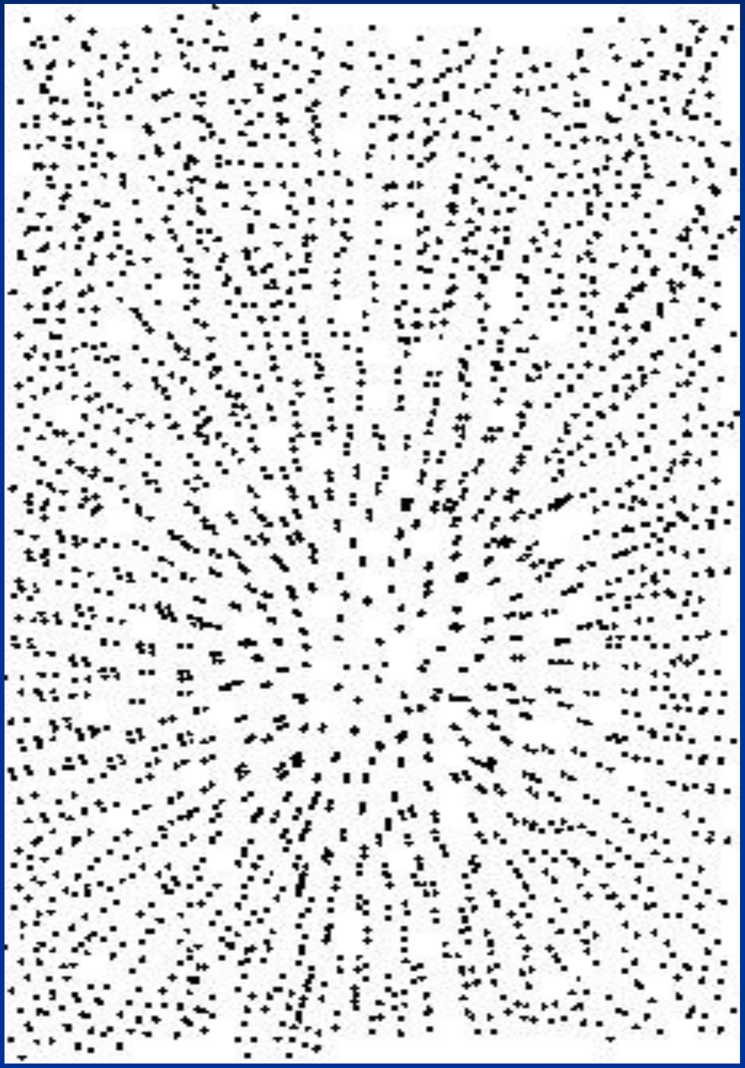
Activity 6: There is no center of expansion
活动 6：无中心的膨胀

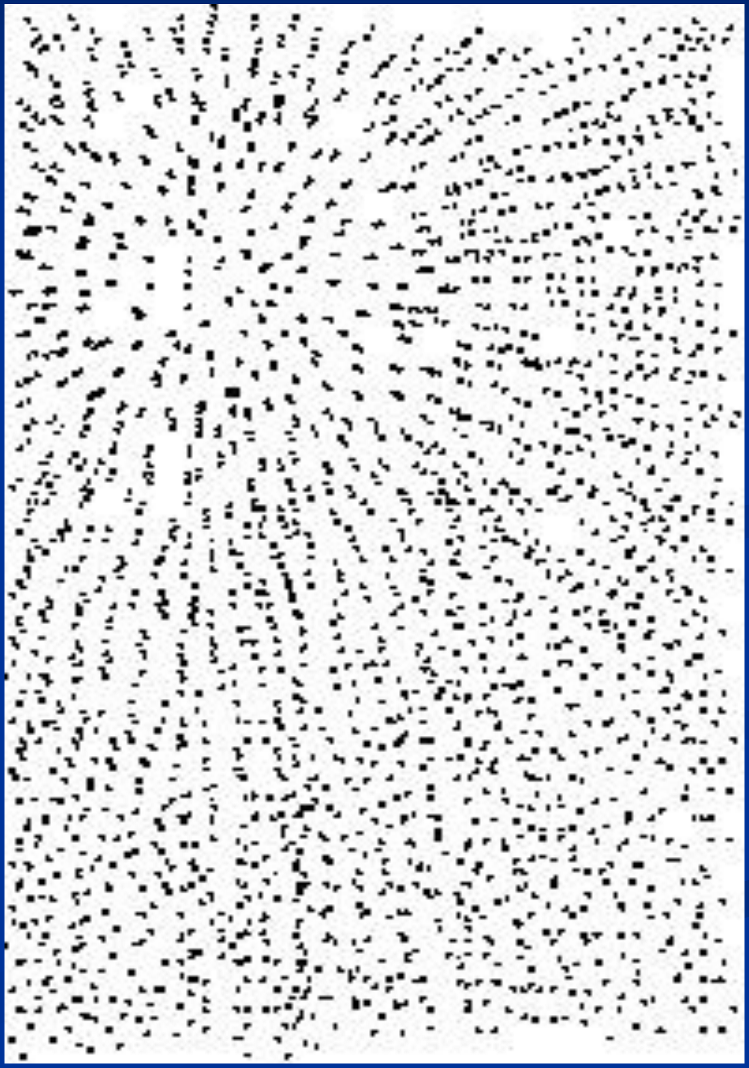


100%

105%

Activity 6: There is no center of expansion
活动 6：无中心的膨胀

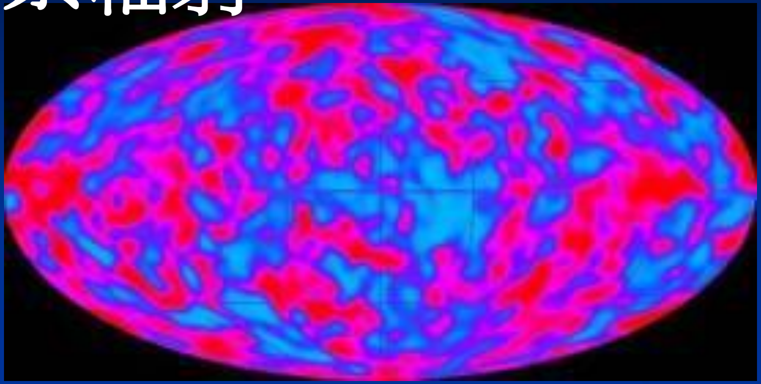


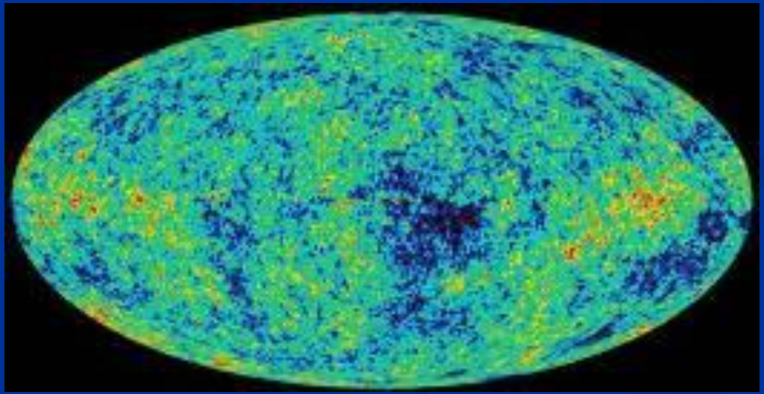


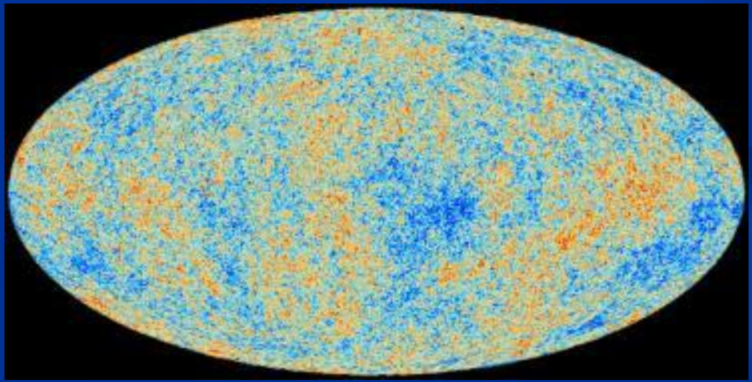
Cosmic Microwave Background (CMB) Radiation
宇宙微波背景辐射

- Radiation which became free at 380 000 years after the Big Bang.
- 在大爆炸发生后的38万年，产生了微波背景辐射。
- Over time, as space expands, the CMB photons expanded in their wavelength.
- 随着时间流逝，空间发生膨胀，光子波长也变大了。
- They are now in the m
- 目前处于微波波段。

Cosmic Microwave Background (CMB) Radiation
宇宙微波背景辐射







- The COBE, WMAP and PLANCK missions made a map of the sky of CMB radiation, every time with more detail. They detected small fluctuations: imprints of lumps of matter from which galaxies began to form.
- COBE, WMAP和PLANCK卫星都对天空中的辐射给出了分布示意图，并且越来越细节，连微小的涨落也都探测到了： 图中块状的物质分布的印记就是星系开始形成的地方。

Activity 7: Cosmic background radiation
活动7：宇宙背景辐射

• More than 300 000 years after the Big Bang, the photons separated from matter and began to travel freely through the universe.

•在大爆炸过后的三十万年，光子从物质中分离出来，**开始在宇宙**间自由穿梭。

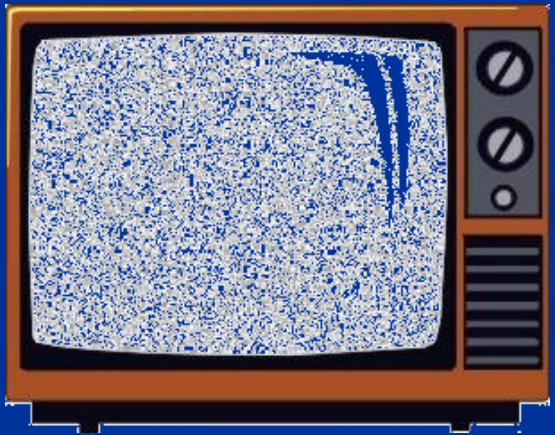
•By expanding the space, photons extended their wavelength, currently λ = 2 mm, equivalent to T = 2.7 K = -270 °C.

•随着空间的膨胀，光子的波长也被拉大了。目前λ = 2 mm，相当于温度为 2.7 K（即 -270 ° C）。

Activity 7: Cosmic background radiation
活动7：宇宙背景辐射

We can detect CMB with an analogue TV. In an empty channel, one out of ten points comes from microwave background radiation. A similar effect can be heard on a VHF radio which is tuned off-station.

我们可以利用一台普通的电视来探测微波背景辐射。把电视转到一个空台，其中，10% 的雪花就来自于宇宙微波背景辐射。



Dark Mater: Spin table which compensates for the attraction of terrestrial gravity
暗物质：旋转的台面抵消了地心引力

Black Holes are invisible, but we know that they exist because their gravitational force makes the stellar systems to move around them.
黑洞是观测不到的，但我们始终知道它的确存在，因为在其周围绕转的物体都会受到其引力的作用。

Although the dark matter is invisible, one way to detect it is by observing and studying the motion of the spiral arms of galaxies.
暗物质也是不可见的，探测其的方法之一就是观察其附近天体的运动轨迹。

Another way to detect dark matter: gravitational lensing
探测暗物质的其他方法：引力透镜

The mass of a gravitational lens acts like an optical lens distorting the surrounding space and deflecting the light of a distant object.

与光学透镜类似，大质量的引力透镜体会使周围的空间 遥远天体发出的光线出现偏折。

Gravitational lenses
引力透镜

Light always follows the shortest possible path

光线总是沿着两点间的最短路径传递。

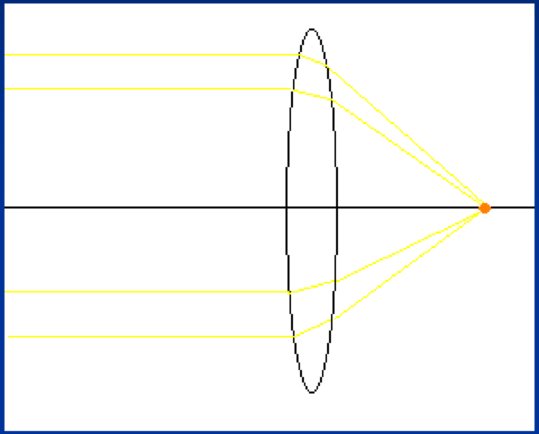
If the surface is curved, the line is curved

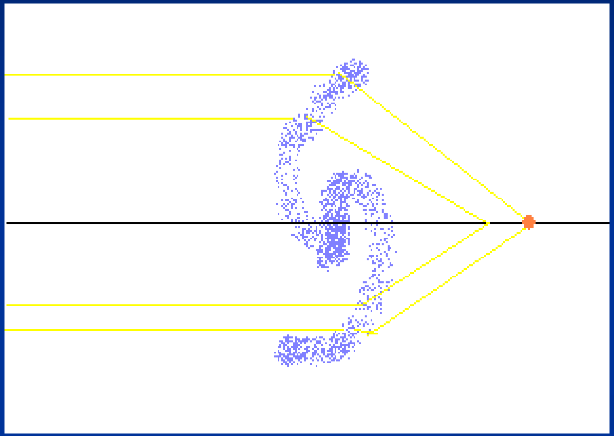
如果空间是弯曲的，那么两点间的最短路径也是弯的。

Why light bends when passing near a body?
当光线经过某个天体附近时为何会发生偏折？

- If there is a mass, the space is curved and the shortest path between two points is a curve.
- 如果空间中某处存在一定质量，那么空间就会弯曲，那么两点间的最短路径也是弯的。
- A similar situation can be seen using an Earth globe.
- 这种情况在地球仪上也同样存在。

How do gravitational lenses work?
引力透镜的原理是什么？

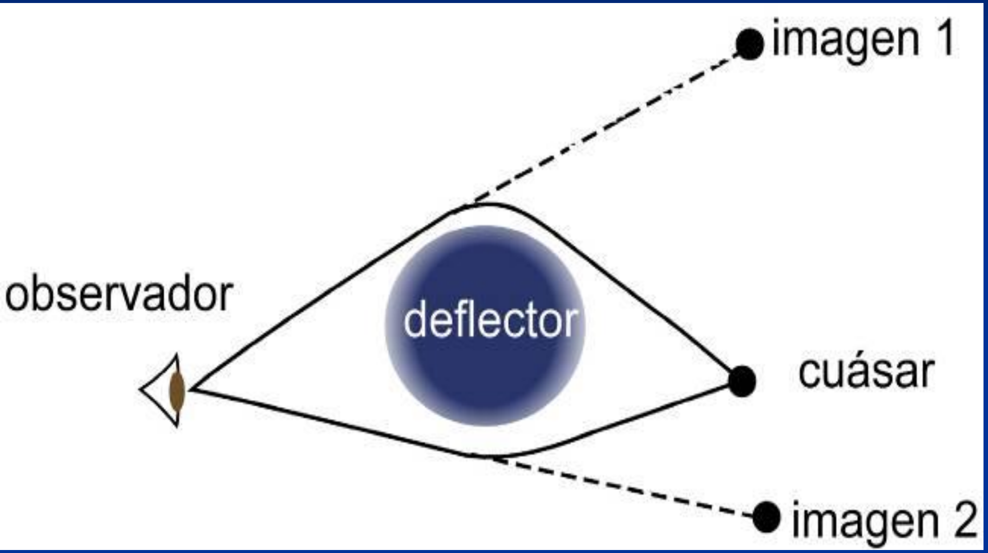


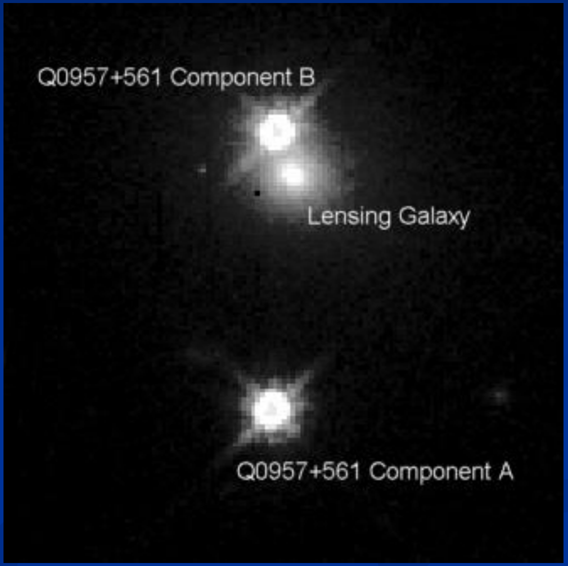


- A convex optical lens focuses parallel rays of light into one point: the focus.
- 凸透镜会把多路平行光聚焦到一点：焦点。
- A gravitational lens (e.g. galaxy or group/cluster of galaxies) focuses the light rays into a line instead of a point; this can introduce several distortions in the image.

引力透镜体（如星系或星系群/星系团）不会将光线聚焦到一点，而是聚焦在一条线上，这会造成图像的多种扭曲。

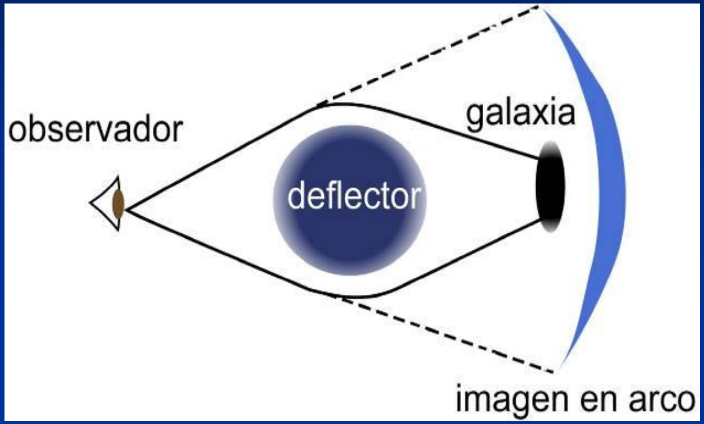
Position changes and multiplication
位移和多重成像

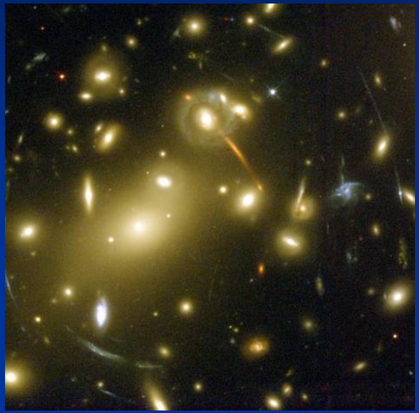


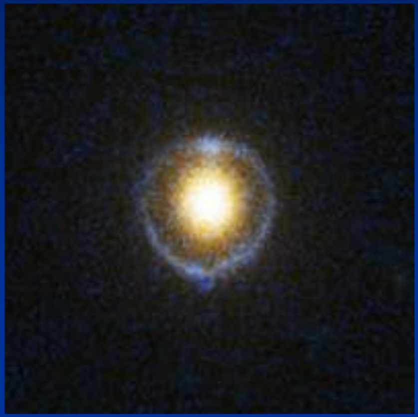


- The deflection produces the apparent position of star, galaxy or quasar.
- 恒星、星系和类星体会出现明显的视位置偏离。
- Gravitational lenses are not perfect, the largest ones can produce multiple images.
- 引力透镜也非完美，最大的透镜体甚至可形成多重成像。

Deflection 形变



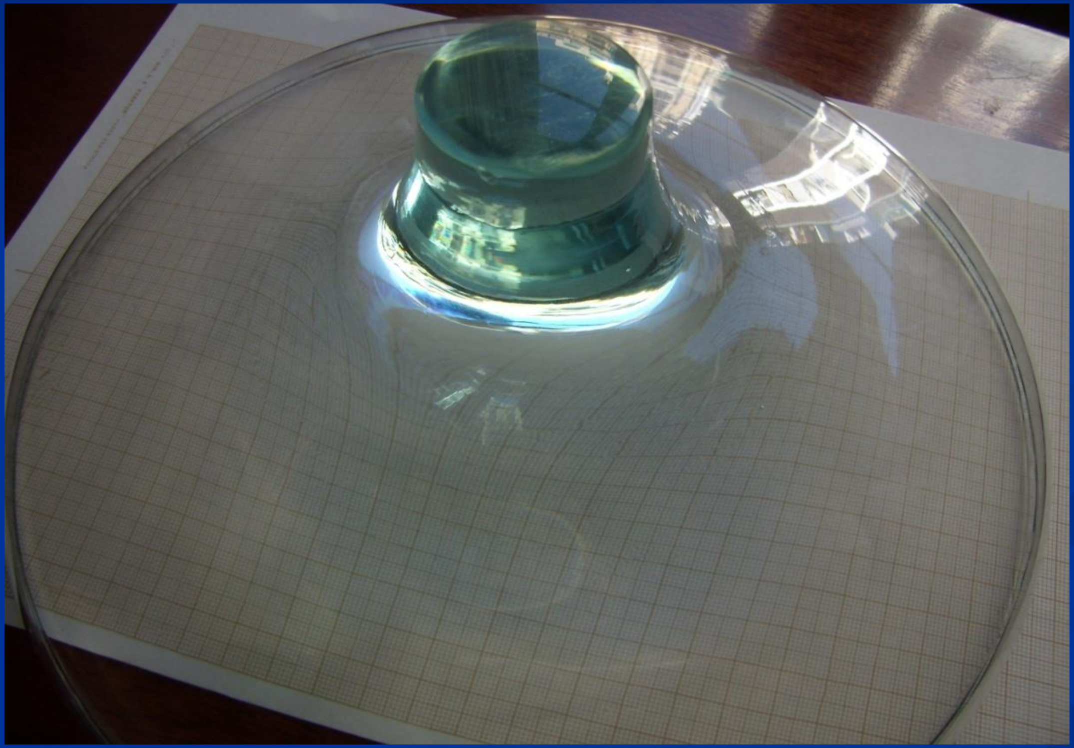




- If the deflecting body is an extended astronomical source, the resulting images are a set of bright arcs.
- 如果背景天体是展源，图像会被拉伸成光弧状。
- If the lens system is perfectly symmetrical, the rays converge and the result is a ring - an Einstein Ring.
- 如果透镜系统是完美对称的，那么光线会汇合，并形成一个完整的光环——爱因斯坦环
- If the deflecting body is a star or a quasar, the image is a point.
- 如果背景天体是恒星或者类星体，那么图像将仍是点状。

Activity 8: Simulation of the deformation with the foot of a wine glass

活动 8：利用一杯酒模拟空间形变



If we place the base of a wine glass on a graph paper we can see the deformation.

把玻璃杯底座放在一张坐标纸上，你会看到坐标线变形了。

Activity 8: Simulation of the deformation with the foot of a wine glass
活动 8：利用玻璃杯底座模拟形变

Just cut the bottom off the glass.
切掉玻璃杯的底座。

+

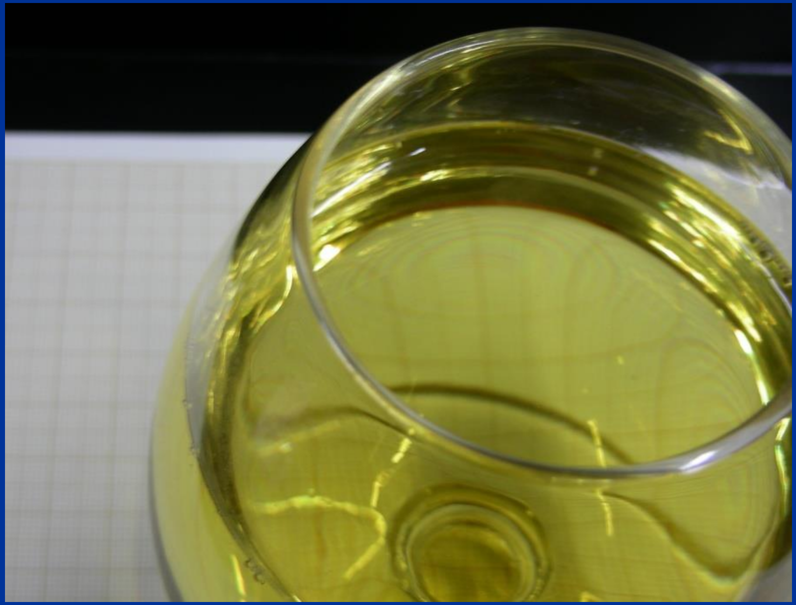
=

Arc fragment
弧形

Einstein Cross
爱因斯坦十字

Einstein ring
爱因斯坦环

Activity 9: Simulation of the space deformation with a glass of wine
活动9：利用一杯酒模拟空间形变



If you put a glass of white wine on graph paper and look through the wine, you can see this deformation.

把玻璃杯放在一张坐标纸上，加入白葡萄酒，透过液体观察坐标纸，你会看到坐标线变形了。

Activity 9: Fix a flashlight and move slowly while looking through a glass of wine 活动9：固定手电后，透过装有红酒的酒杯观测，并缓慢移动

This simple model shows that “matter” can reproduce distortions in images observed through it.这个简单的模型说明，透过“物质”看到的图像是会由于“物质”的影响而发生扭曲的。

(The wine can be replaced by another translucent liquid可以用其他半透明的液体代替红酒)

Activity 9: Fix a flashlight and move slowly while looking through a glass of wine
活动9：固定手电后，透过装有红酒的酒杯观测，并缓慢移动

Fragment of arc
光弧

Amorphous figure
不规则图像

Einstein cross
爱因斯坦十字

Einstein’s Ring
愛因斯坦指環

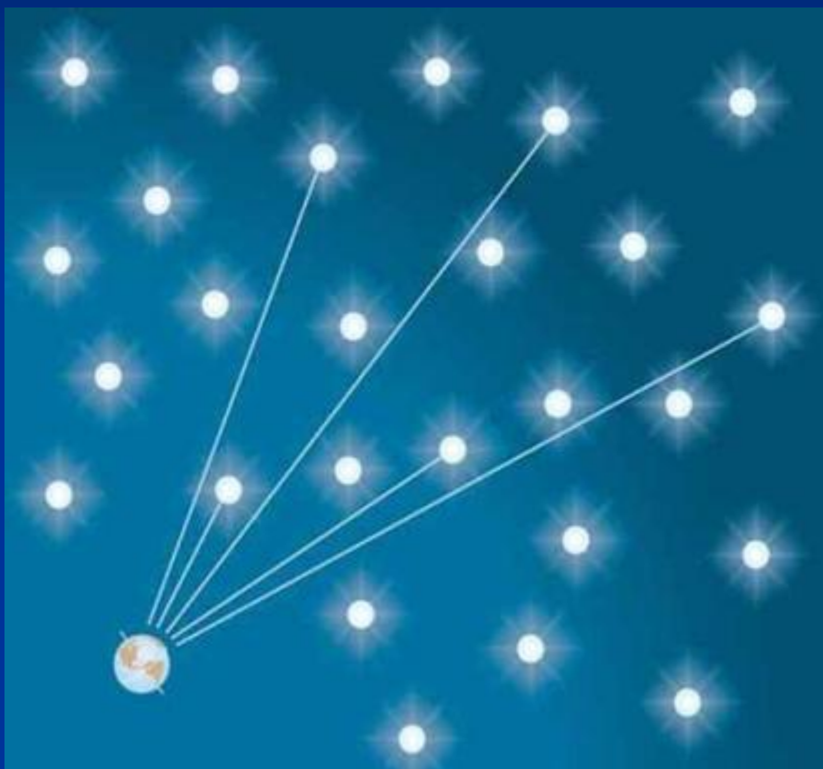
A theme outside the workshop: Why is the sky dark at night?
拓展问题：为什么夜晚是黑色的？

In 1923 Olbers suggested that if:

1923年，奥伯斯提出假设：

- The universe is infinite in extent.
- 宇宙的面积是无穷大的。
- The stars are uniformly distributed throughout the universe.
- 恒星大体上均匀地分布在宇宙中。
- All stars have a similar luminosity throughout the universe, then…
- 全宇宙中恒星的亮度是相似的，那么……

A theme outside the workshop:
Why is the sky dark at night?
拓展问题：为什么夜晚是黑色的？



… an infinite universe will have an infinite number of objects and should be bright during the night.

无穷大的宇宙中将有无穷多的天体，所以夜空应该是亮如白昼的。

Why is the sky dark at night?
为什么夜晚是黑色的？

Then :那么：

- Any point on the sky would be bright, not dark, since there would be always a distant star shining.
- 由于在任何方向上都应该有遥远的恒星在闪烁，所以夜空在各个方向上都应该是明亮如昼的，而非黑色的。
- The number of stars in each "onion layer" of the sky is proportional to r^2, and their light is inversely proportional to r^2, where each layer provides the same amount of light at the Earth. If there are an infinite number of layers, the sky should appear bright at night.
- 夜空中，每一层中星星的数目正比于r^2，它们的亮度与r^2成反比，所以在地球上接收到的每一层的光线总量应该是相同的。如果有无数个这样的壳层，夜空就应该看起来亮如白昼。

Why is the sky dark at night?
为什么夜晚是黑色的？

But there are errors in this reasoning:

但其实是存在错误的：

- The stars look redder the further away they are because of the expansion. They are less luminous because their distance.
- 较远的星星看起来更红是由于膨胀。离得越远，亮度越暗。
- But above all, the universe doesn't have an infinite age. There are no infinite layers of stars.
- 更重要的是，宇宙的年龄也不是无限的，所以也没有无穷多的恒星分布壳层。

Edgar Allan Poe was the one who correctly explains the phenomena in his essay "Eureka", published in 1848.

Edgar Allan Poe在他1848年发表的《Eureka》中解释了这个现象。

The night can be dark!夜晚是黑色的！

Thank you very much
for your attention!
谢谢！