玫瑰星云（NGC2237）

位于麒麟座方向，
距离地球5200光年。
它是银河系内一个
巨大分子云的末端，
正有大批大质量恒星
从这里诞生，它们
发出高能量的光芒
将这里的中性氢气体
电离成美丽的“玫瑰”。
它的直径为130光年，
质量是太阳的1万倍。


星系NGC1512
位于时钟座方向，距离地球3.8千万光年
ESA/Hubble, NASA


星系NGC5643
位于豺狼座方向，距离地球4千万光年远，
星系中心有剧烈的超大质量黑洞吸积周围的
气体，在星系的核心区域释放着巨大的能量


星系NGC1300
位于波江座方向，距离地球6千万
光年远，是一个巨大的棒旋星系


星系NGC3147
位于天龙座方向，距离地球1.3亿光年远，
它是一个巨大的旋涡星系，中心超大质量黑洞
活跃地吞噬周围的气体，释放出巨大的能量

星系NGC4565

位于后发座方向，是一个从侧面看上去
非常薄的盘状星系，又被称为“针状星系”


星系NGC1316
位于天炉座方向，距离地球6千万光年远。
它是一个巨大的椭圆星系，发出强烈的射电辐射，
黑色的条纹显示了在星系尺度上丰富的尘埃结构


UGC1810（上）底部
的旋臂受到它与
UGC1813（下）的
引力相互作用而被
拉得远离星系本身
UGC1813（下）也因为
引力相互作用产生了变型
星系对Arp 273
位于仙女座方向，
距离地球3亿光年


史蒂芬五重星系（Stephen's Quintet）
星系NGC7320
距离地球4千万光年，
刚好在投影方向上
看上去接近右面四个遥
远的相互作用星系
位于飞马座方向，
右边四个星系距离
地球2.9亿光年，
正在经历相互碰撞
韦伯空间望远镜拍摄于2022年7月


NASA, ESA, CSA, and STScI
星系团SMACS 0723
韦伯空间望远镜拍摄宇宙深场照片
该星系团由上千个星系成员构成，位于飞鱼座方向，距离地球46亿光年远。它巨大的引力场将来自背景星系的光线偏折，导致背景星系的影像，被拉伸成窄而长的明亮弧线，这个效应叫作“引力透镜”

物理宇宙学

第一讲：宇宙学导论

时间：周三9:50-12:15
地点：新水利301

- How do galaxies form?
- How do stars form?
- How do planets form?

Galaxy Astrophysics
Stellar Astrophysics
Planet Science

- *Where are we in the Universe (position)?*
- *Where is the Universe from (history)?*
- *Where is the Universe going (future)?*
- *What is the Universe made of (content)?*
- *What governs the Universe's evolution (laws)?*

This is Cosmology.

何为“宇宙”?

“四方上下为宇，往古来今为宙”

The background of all classical and macroscopic motions

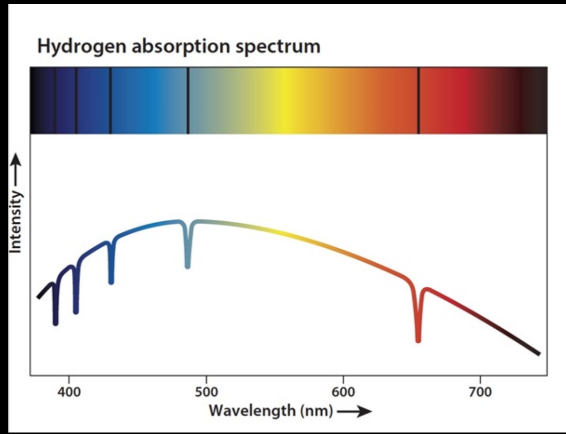
Spacetime

The stage/platform of all microscopic quantum fields

- 中国古代的浑天说 和 古希腊亚里士多德\托勒密的地心说（Geocentrism）
- 文艺复兴时期，哥白尼\布鲁诺日心说（Heliocentrism）
- 20世纪纪初，沙普利和柯提斯的“the great debate of 1920s”
- 爱因斯坦的广义相对论和哈勃的”膨胀宇宙”，开启“大爆炸宇宙论”新时代（hot big bang）

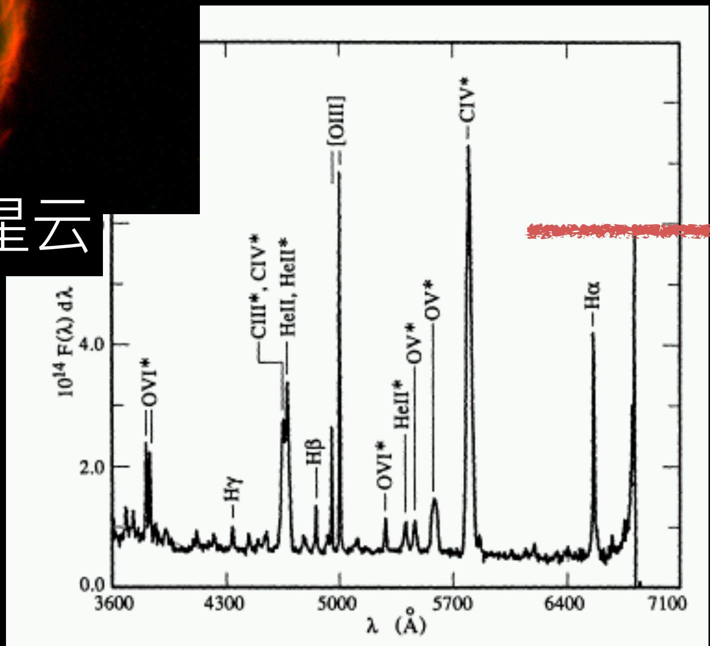
“ 四方上下为宇 ” — *Where are we w.r.t. the Universe?*

In order to know our location with respect to the Universe,
we must first know how to measure distances of objects in the Universe.

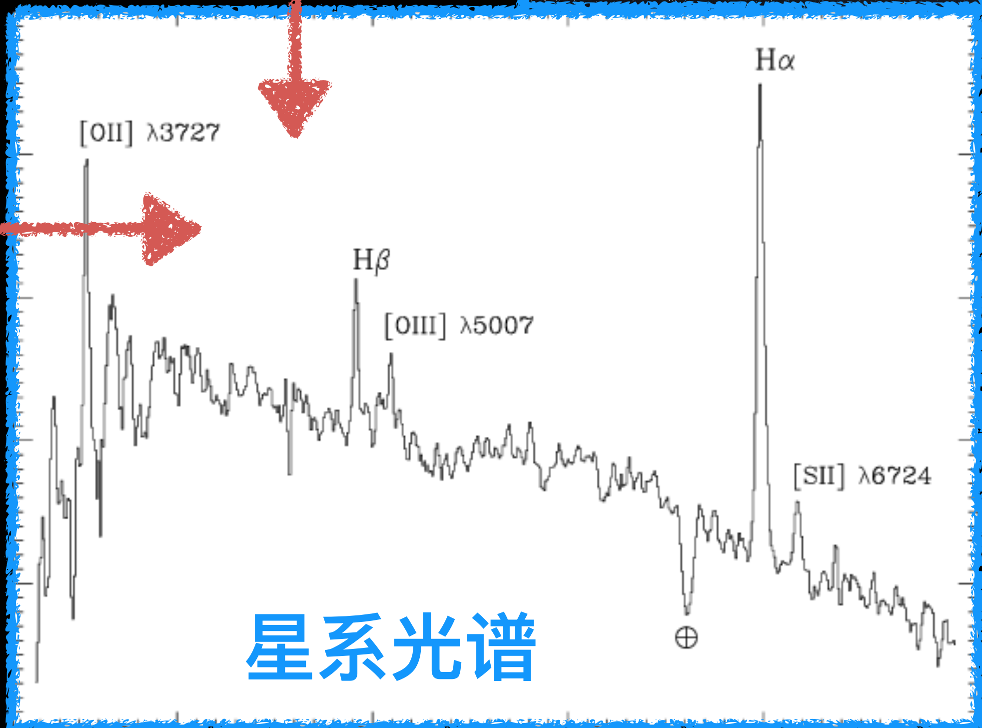


恒星吸收线光谱

行星状星云



星云发射线光谱



星系光谱

光谱是星系的身份证：

（1）星系中恒星的年龄和化学组成；

（2）星系中的恒星形成活跃程度；

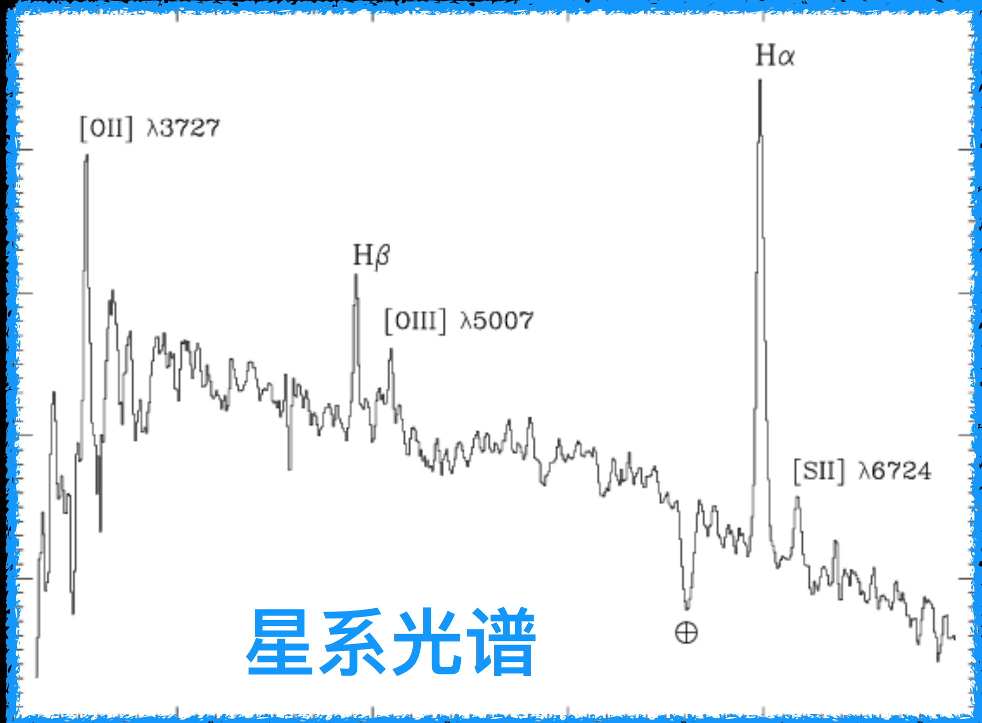
（3）星系中气体的电离状态和化学组成；

（4）星系中恒星和气体的运动状态；

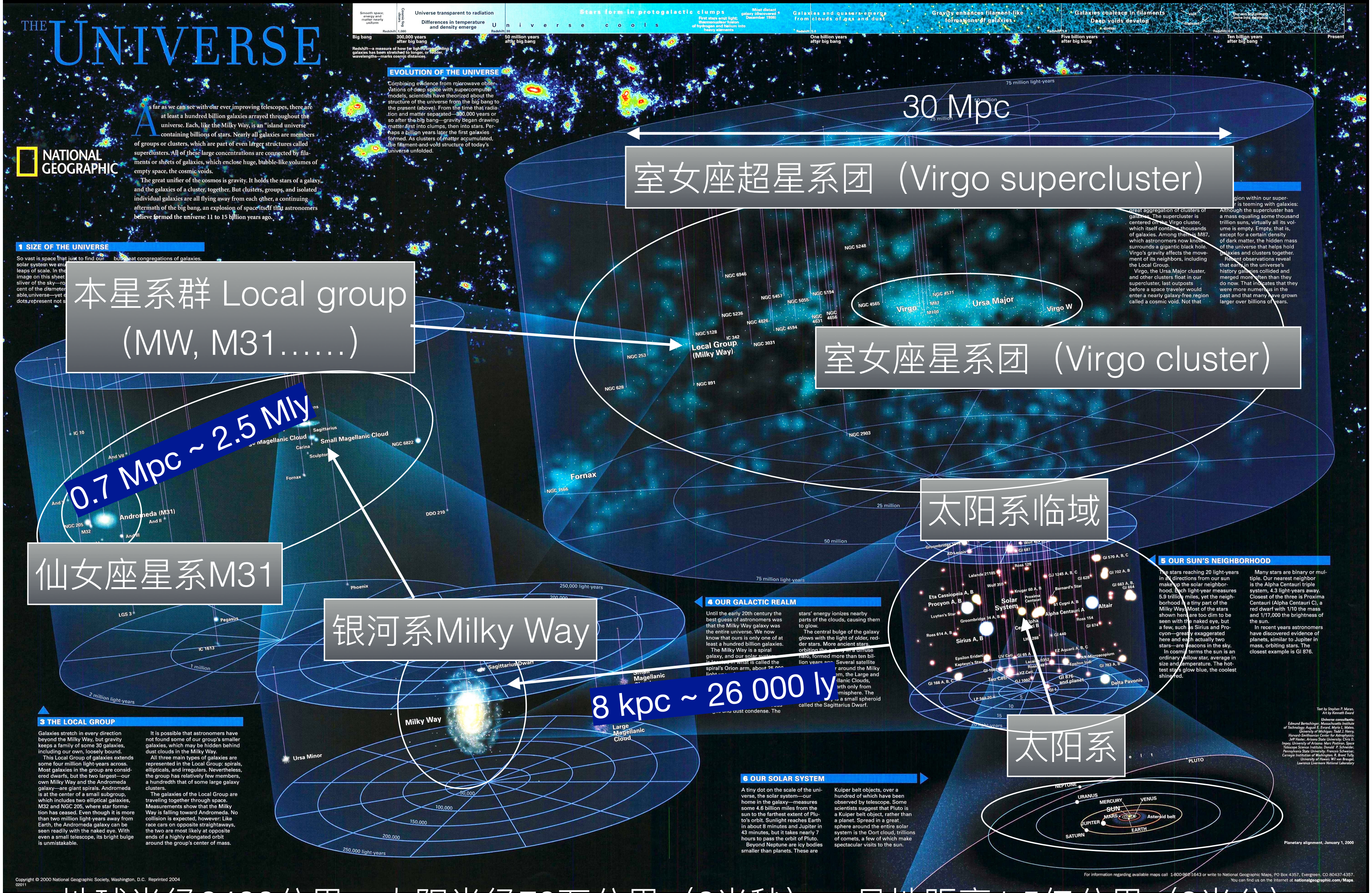
（5）星系本身相对地球的运动速度（红移）；

（6）星系的磁场。。。

（7）宇宙学秘密。。。

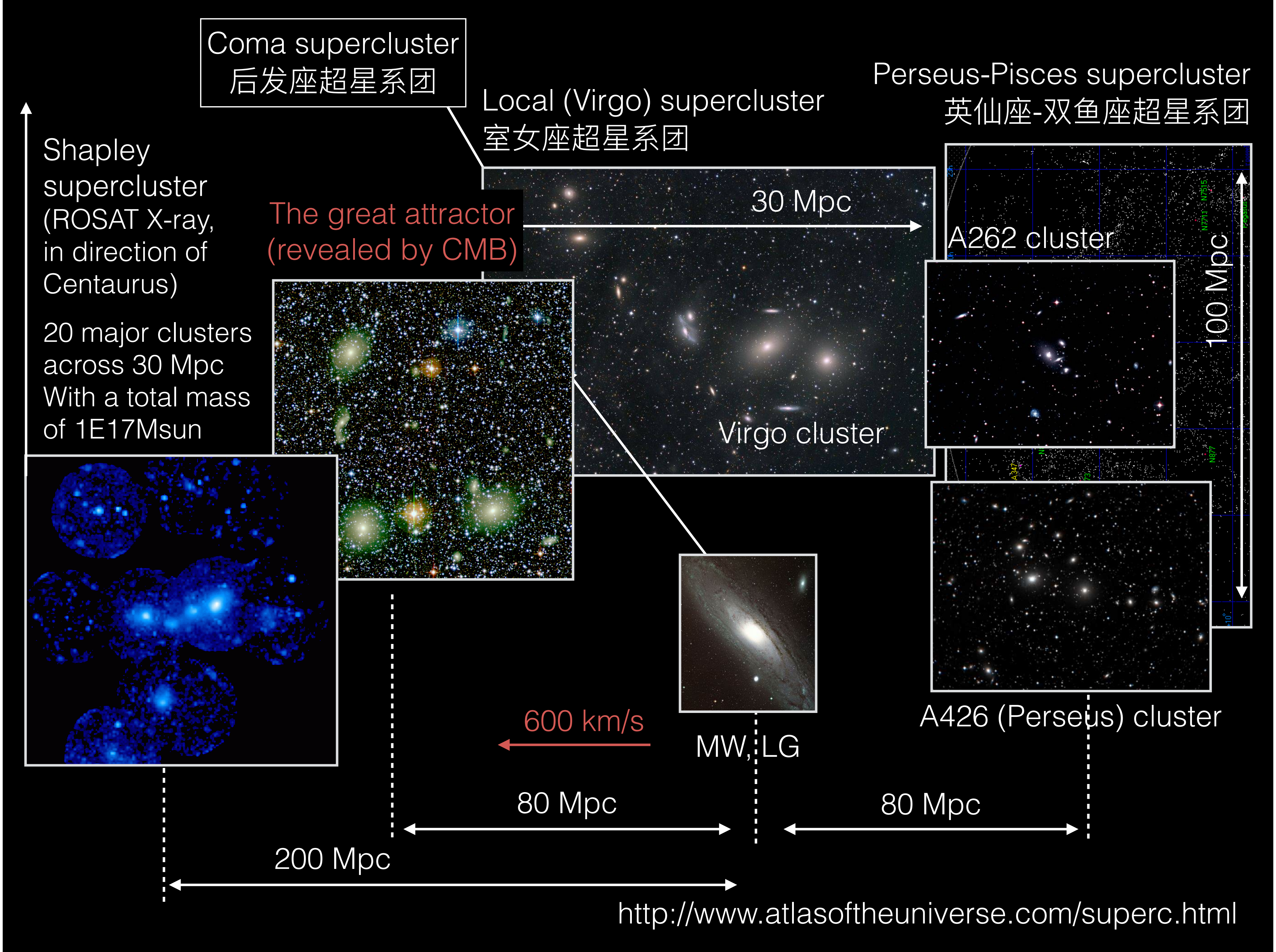


Then what do we know about our location with respect to the Universe?



地球半径6400公里，太阳半径70万公里（2光秒），日地距离1.5亿公里（8光分），

1秒差距（pc） = 206265日地距离 = 3.26 光年


Coma supercluster
后发座超星系团
Local (Virgo) supercluster
室女座超星系团
Perseus-Pisces supercluster
英仙座-双鱼座超星系团
Shapley supercluster (ROSAT X-ray, in direction of Centaurus)
20 major clusters across 30 Mpc With a total mass of 1E17Msun
The great attractor (revealed by CMB)
30 Mpc
A262 cluster
100 Mpc
Virgo cluster
A426 (Perseus) cluster
600 km/s
MW, LG
80 Mpc
80 Mpc
200 Mpc
http://www.atlasoftheuniverse.com/superc.html

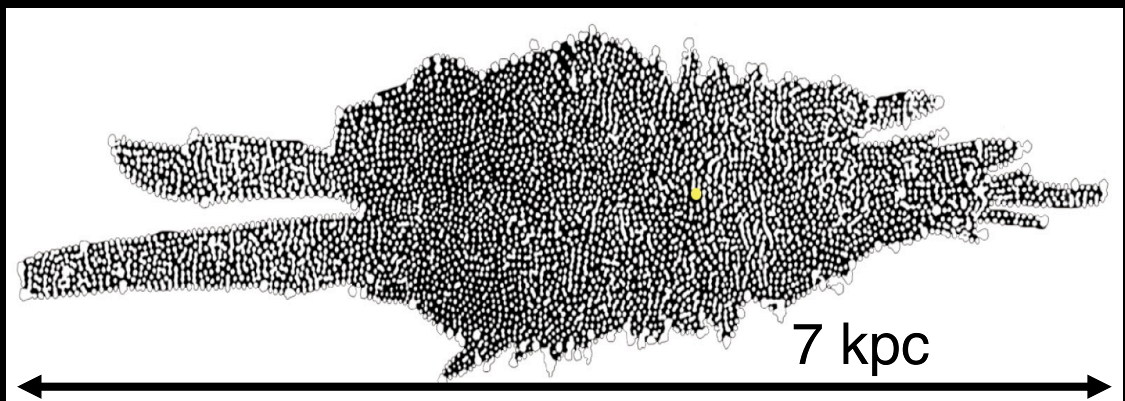
However this wasn't the case at the start of last century…

The Greatest debate in the 20s century

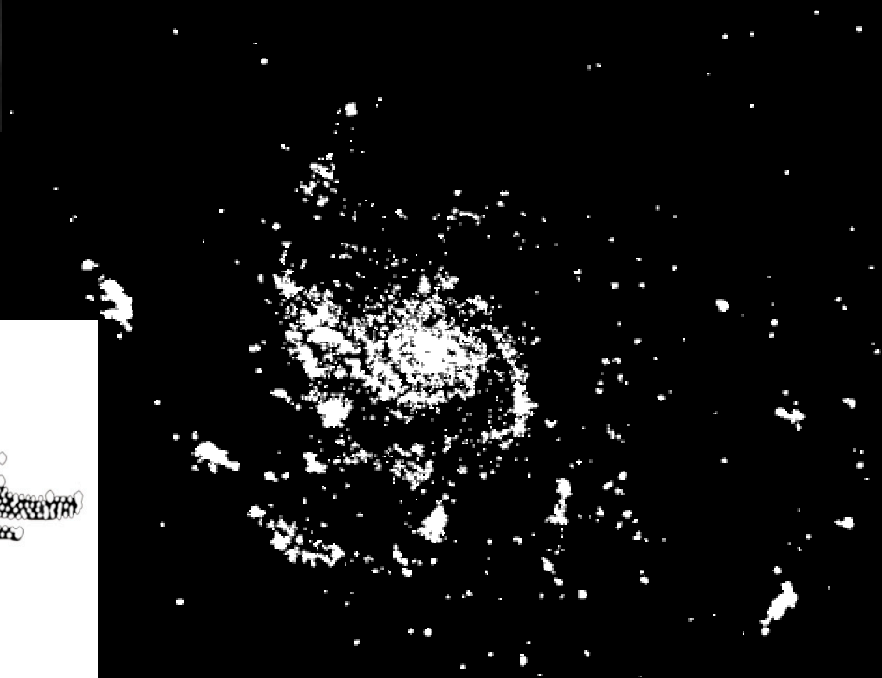
Shapley

Curtis

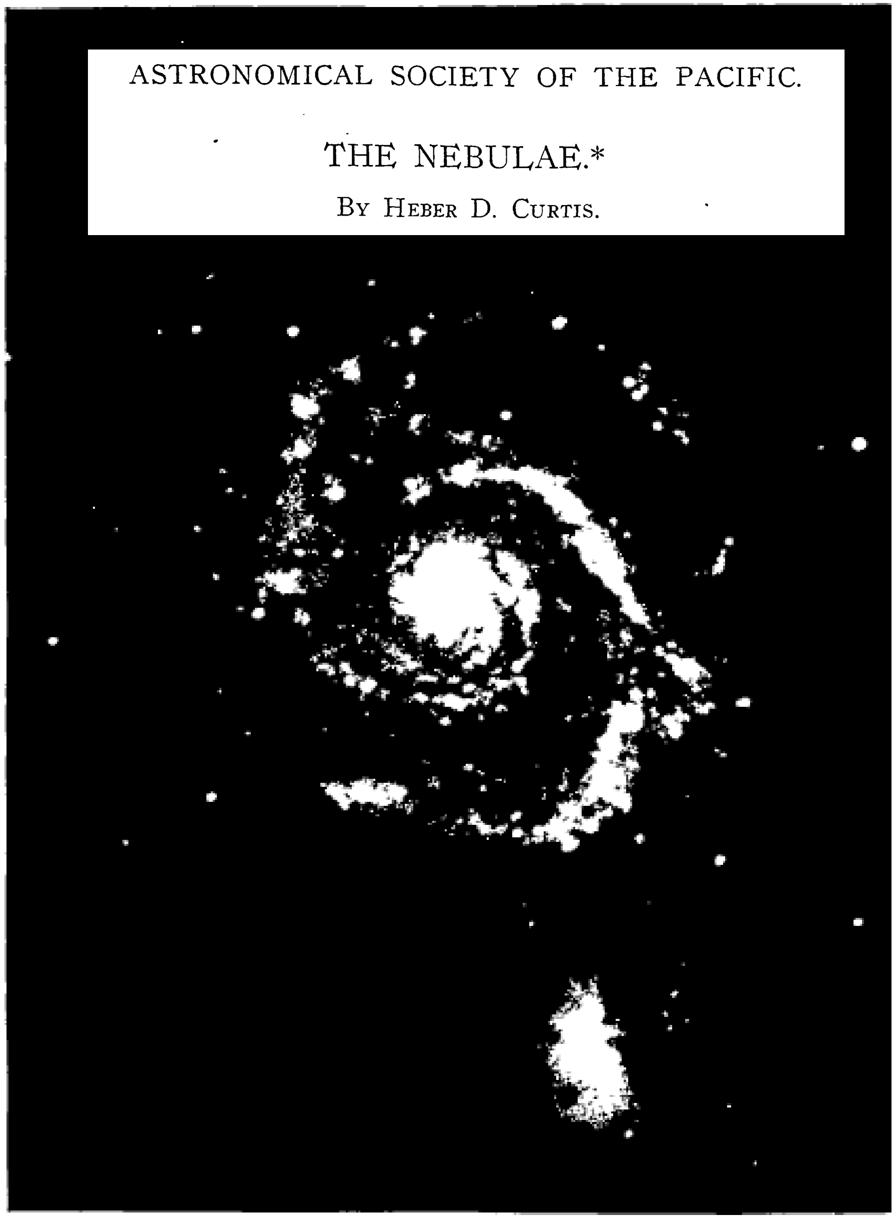
Where is our galaxy with respect to the entire Universe?



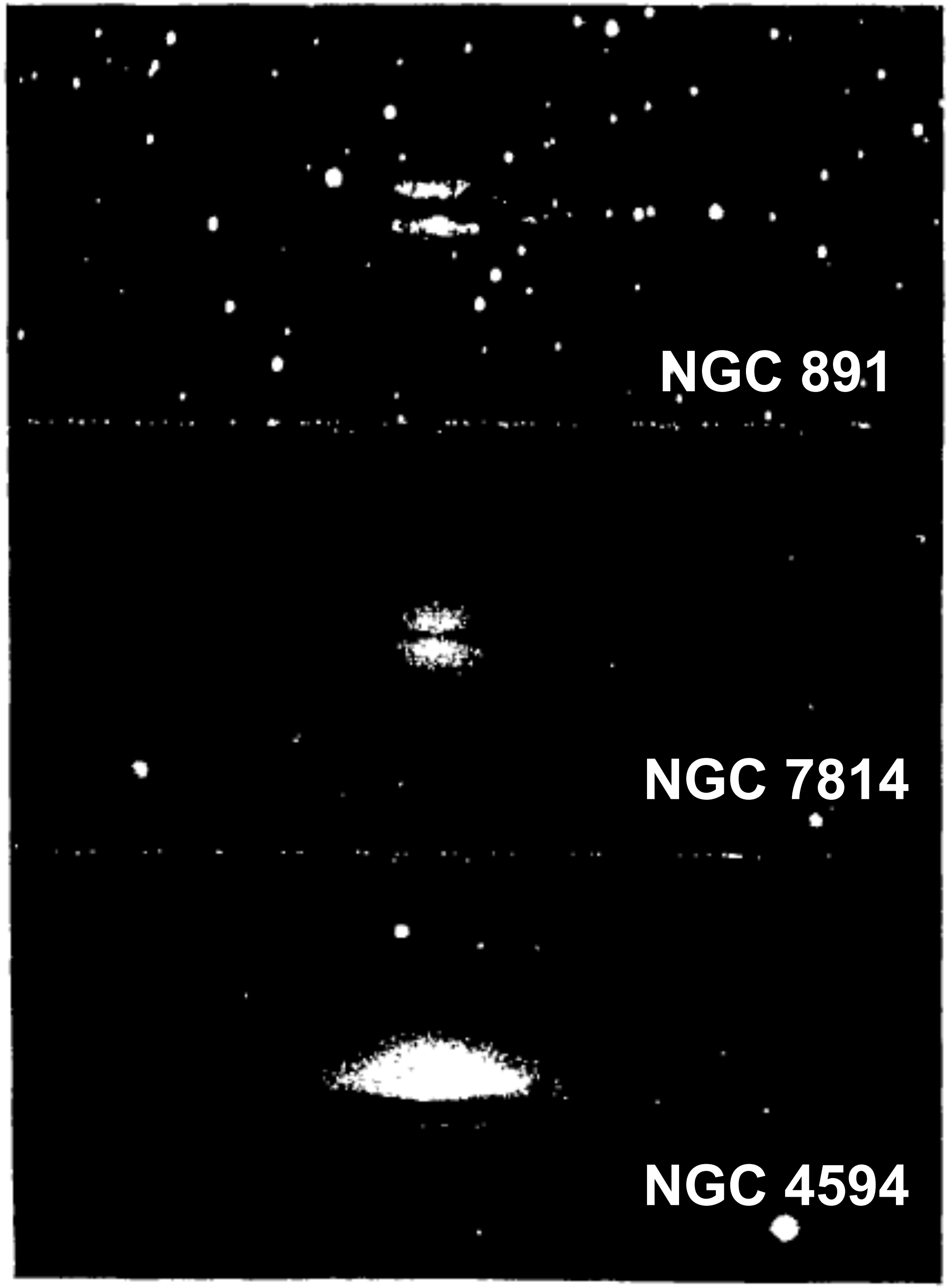
MilkyWay (William Herschel, 1785)



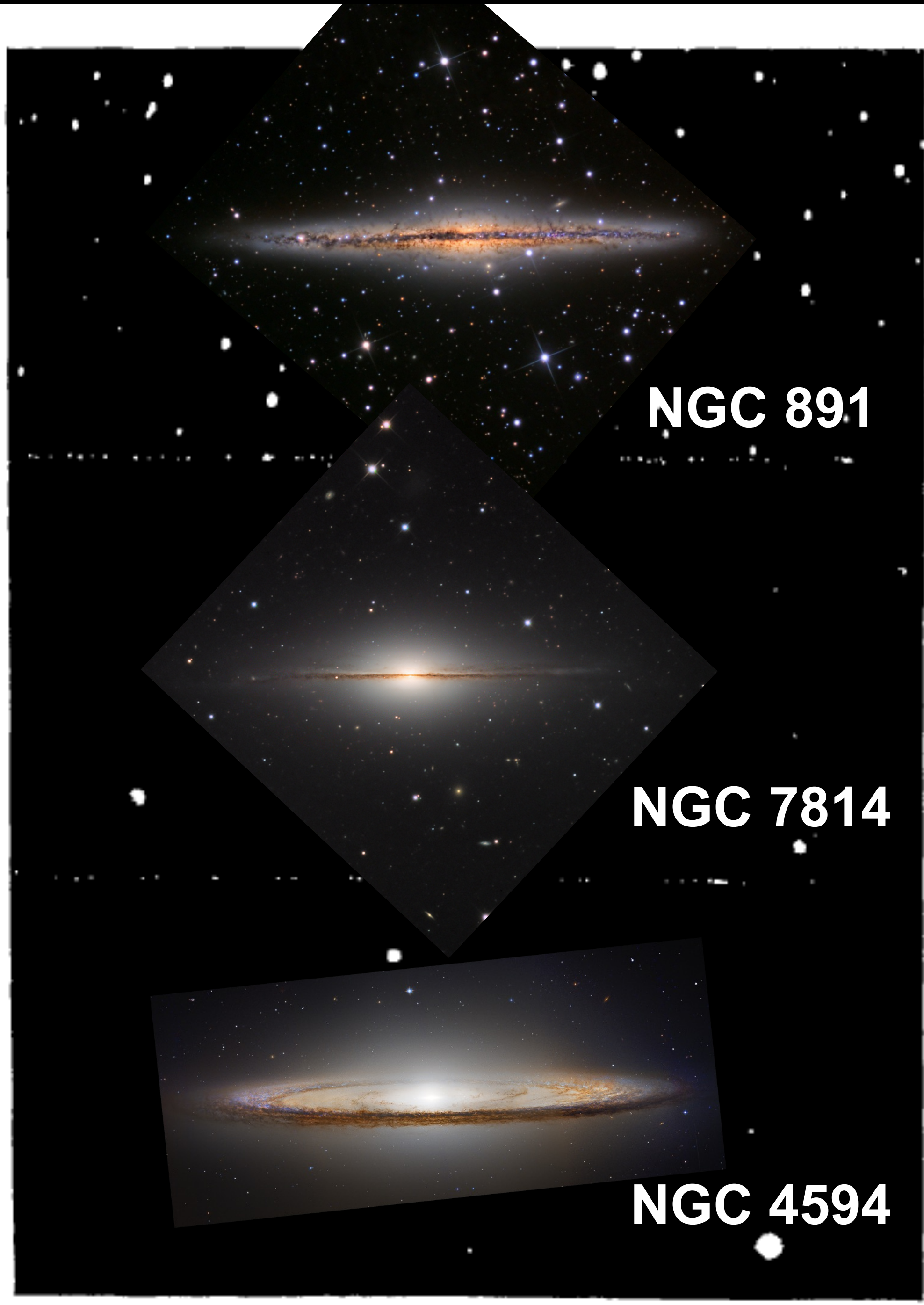
M101(Curtis, 1917)



M51 (whirlpool galaxy)



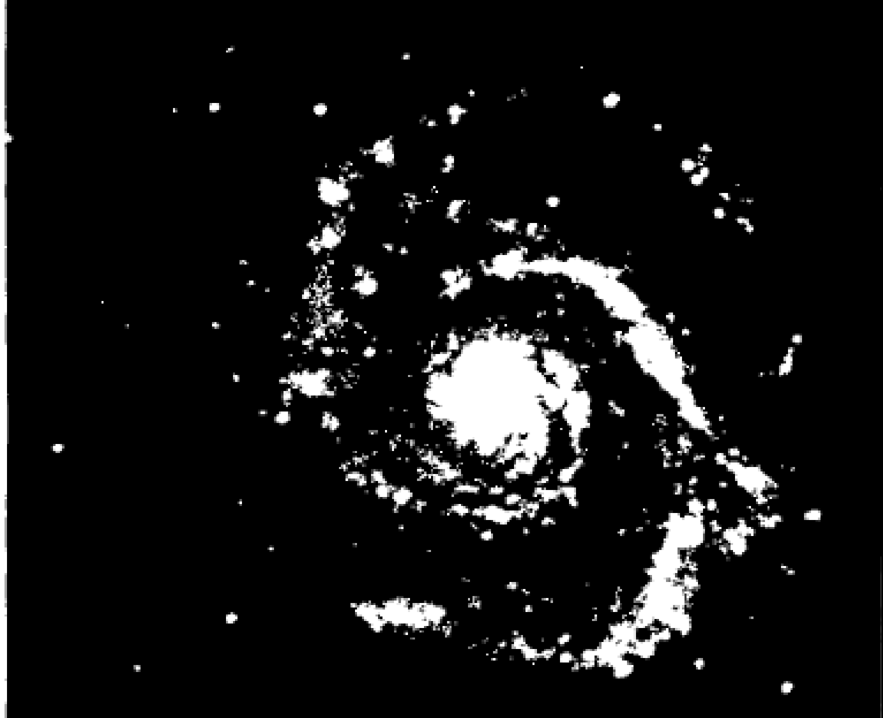
M51 (whirlpool galaxy)

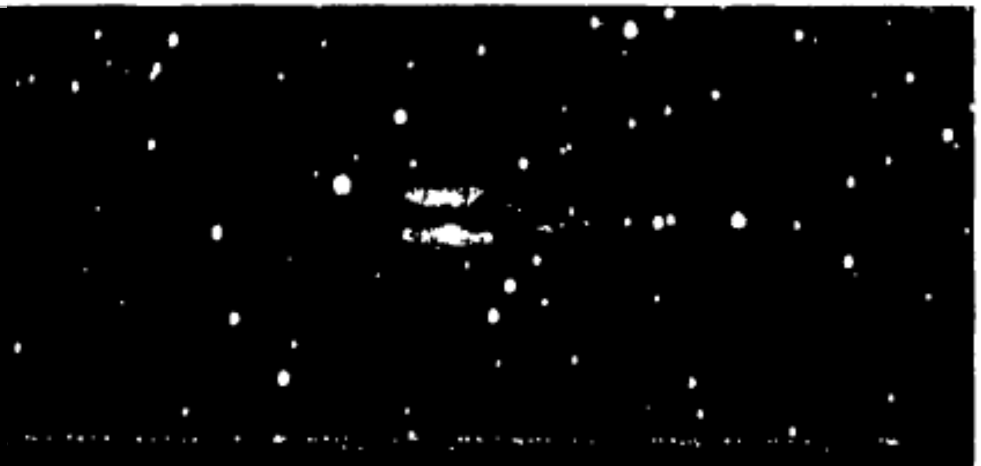


ASTRONOMICAL SOCIETY OF THE PACIFIC.

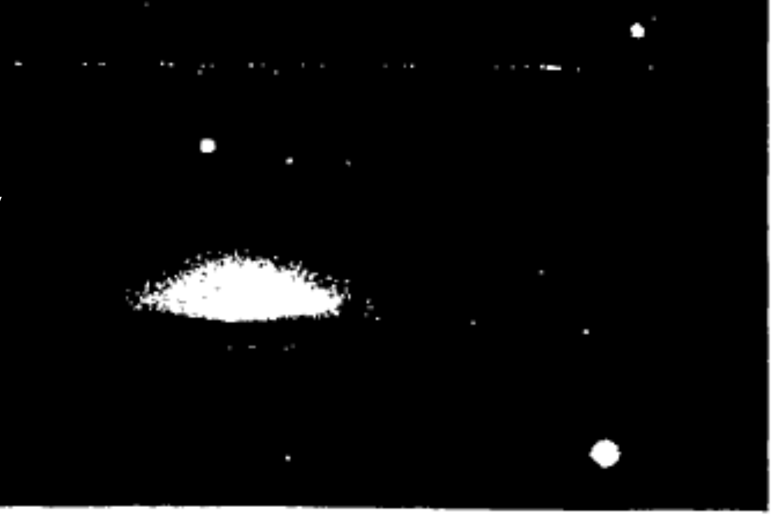
THE NEBULAE.*

BY HEBER D. CURTIS.





Note: Curtis noticed the MW's ring/plane feature and that the spatial distribution of "spirals/nebulae" avoid of the MW plane - insight from observing edge-on "spirals/nebulae".



He also pointed out that the morphology of "spiral nebulae" do not fit in to any stellar evolution theory. Rather their spectra look like that of star clusters.

The Greatest debate in the 20s century

Shapley

Curtis

Having misidentified RR Lyrae variabel stars as Cepheids in GCs, Shapley estimated the size of MW was 100 kpc, and believed measurements of "apparent rotation" of "spiral nebulae".

Curtis was an expert on "spiral nebulare" observations. Having gained insights, he places them beyond our WM (However Curtis' MW was only 10 kpc.).

It was Edwin Hubble's measurements of distances to the "spiral nebulae" (through Cepheid variable starts) that settled the debate. Curtis was right, the "spiral nebulae" are beyond the MW and we are just like any one of them.

“往古来今为宙”— *What is a timeline of our Universe?*

The Cosmic Calendar

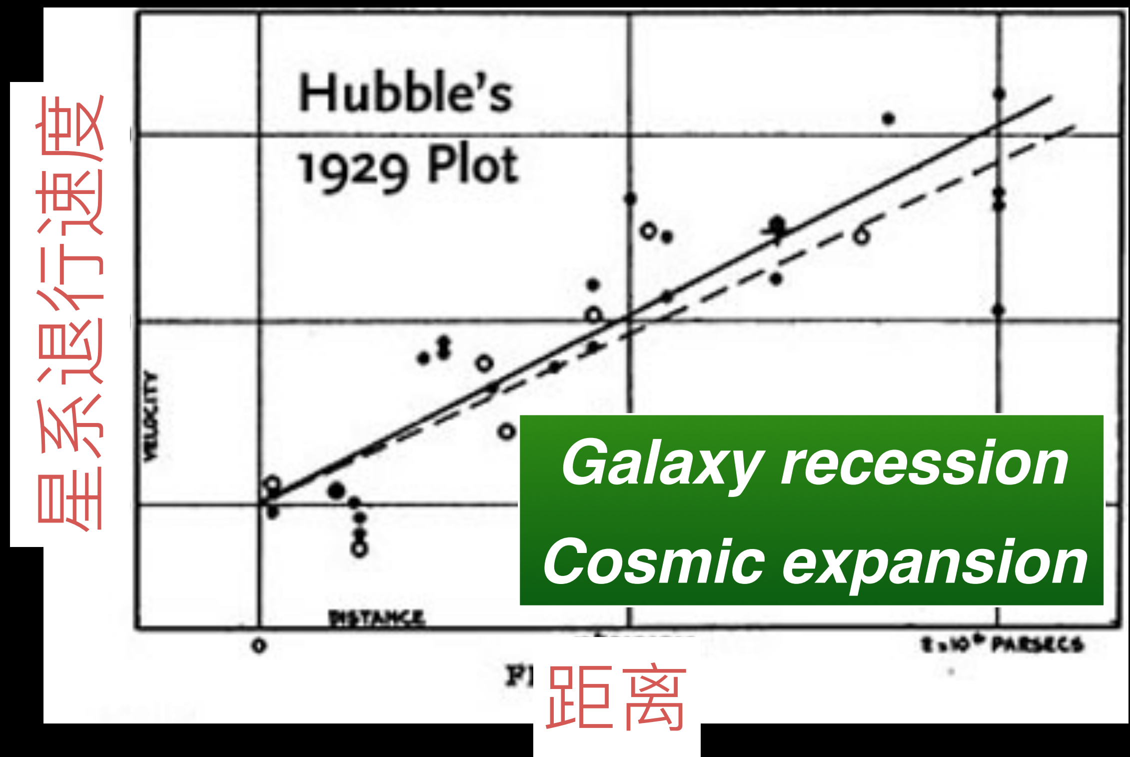
The 13.8 billion year history of the universe scaled down to a single year, where the Big Bang is January 1st at midnight, and right now is midnight 1 year later

A modern view of the Universe

A modern view of the Universe - I

$$V = H_0 D$$

Edwin Hubble



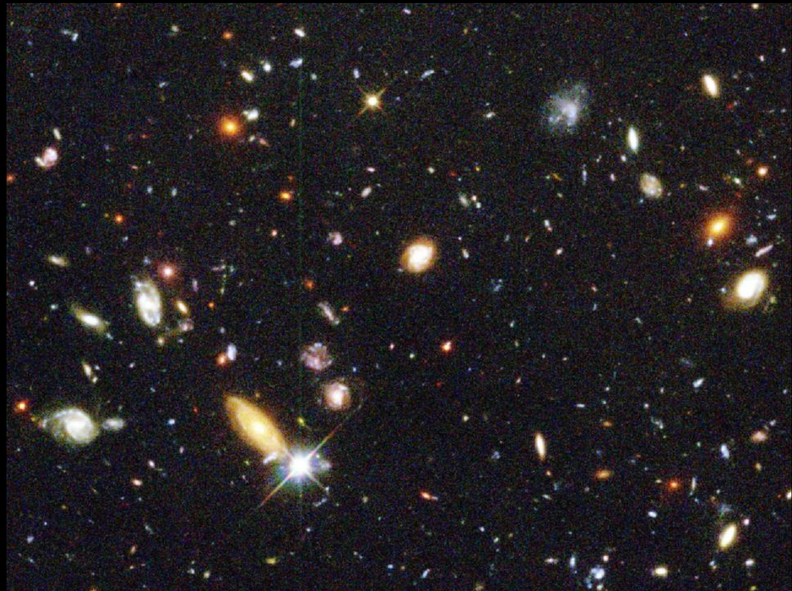
Astronomers measure velocities through spectra

Astronomers measure distances through "distance ladders"

Hubble revealed that galaxies further away are receding from us at a larger velocities — galaxy recession and cosmic expansion.

A modern view of the Universe - I

E. Hubble

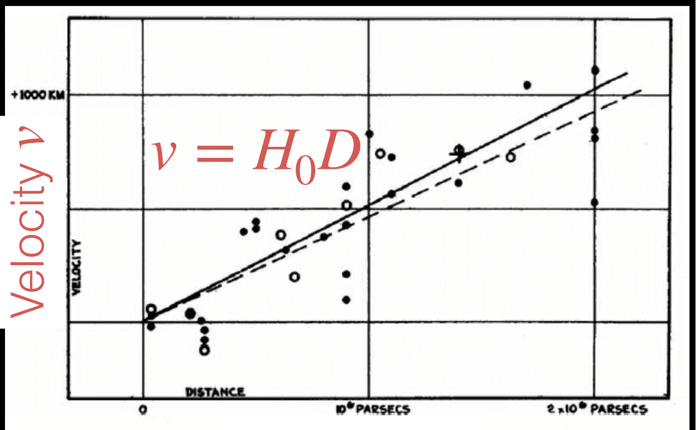


Galaxy recession

Cosmic expansion

H^{-1} indicates time scale of expanding Universe

To 2 Mpc, H_0 ~ 500 km/s/Mpc
Hubble 1920s

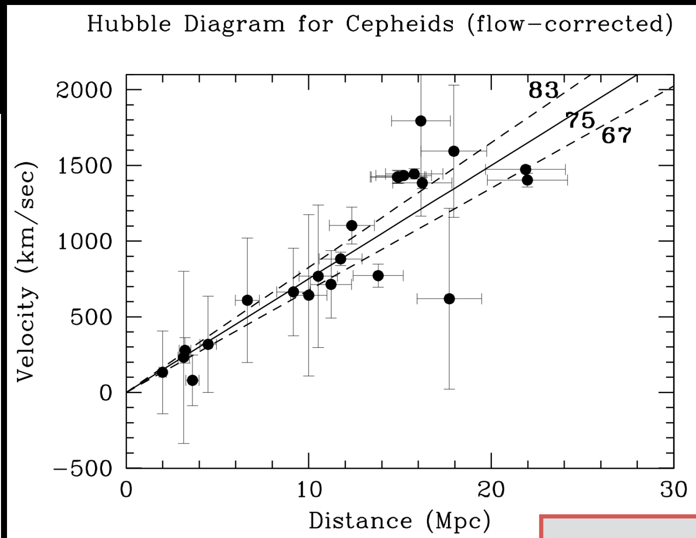


Velocity v

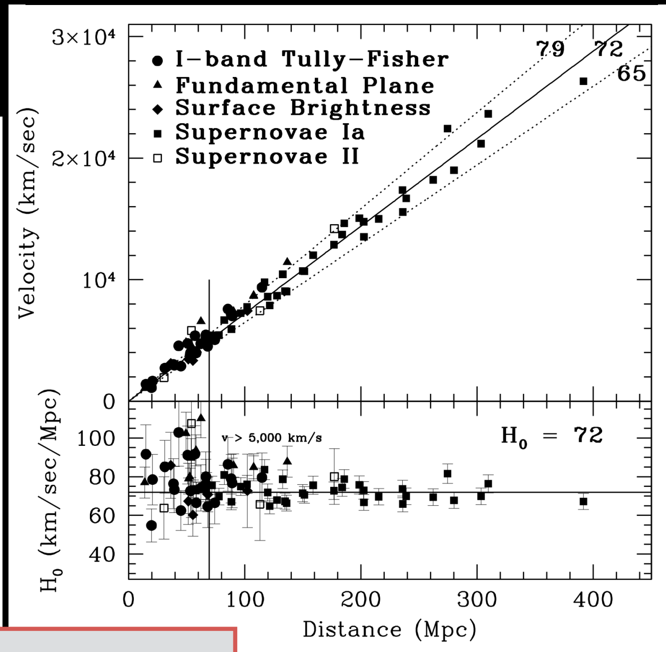
$v = H_0 D$

Distance D

To 25 Mpc, H_0~75 km/s/Mpc
Freedman et al. 2001 (w Cepheids)



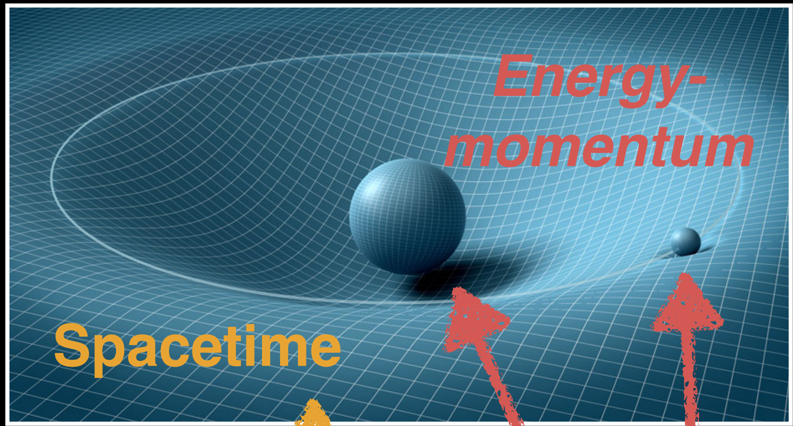
To 400 Mpc, H_0~72 km/s/Mpc
Freedman et al. 2001

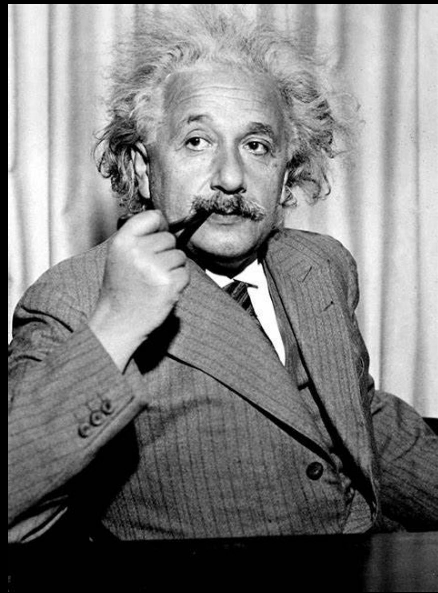


HST key project

A modern view of the Universe - I

E. Hubble





A. Einstein

General Relativity, 1915

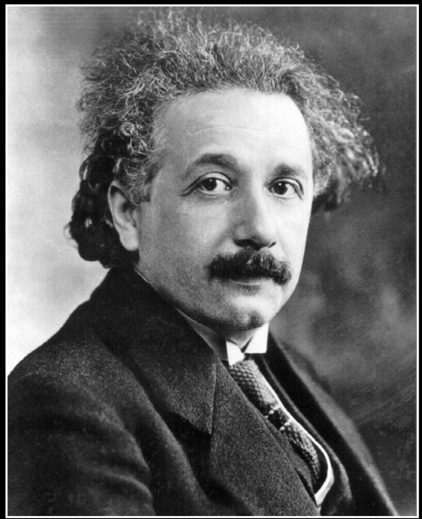
Spacetime tells matter how to move

$$\boxed{G_{\mu\nu}} = \frac{8\pi G}{c^4}\boxed{T_{\mu\nu}}$$

Energy-momentum tells spacetime how to shape

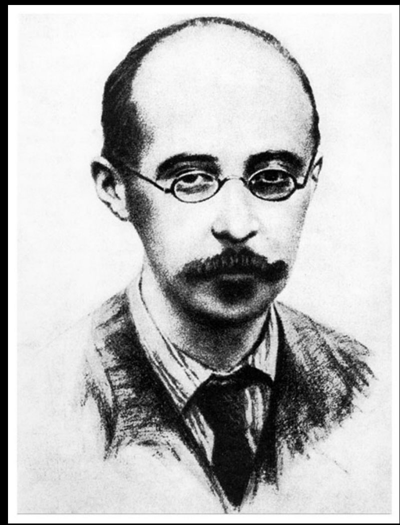
Second-order partial differential equations

A modern view of the Universe - I



Albert Einstein

Georges Lemaître



Alexander Friedmann

Edwin Hubble

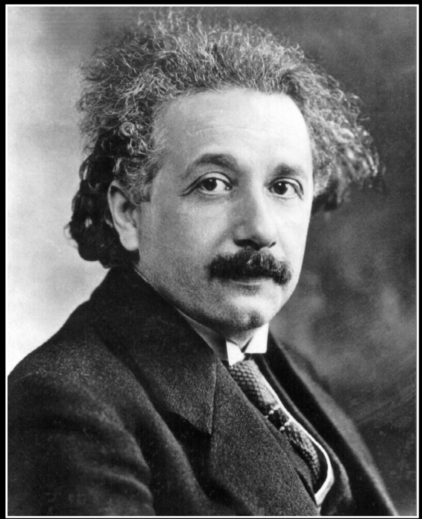
$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-\kappa r^2} + r^2 d\Omega^2\right]$$

Various solutions to the Einstein's field equation (under the **Cosmological Principle** - spatially homogenous and isotropic) were sought, which can describe possible dynamical status, evolution and fate of possible universes.

Galaxy recession and thus an expanding Universe is one of the solution to GR!

A modern view of the Universe - I



Foundation of modern cosmology 1920s-1930s

- *Observation*: galaxy recession => *a "**hot & dense**" start of the Universe.*
- *Theory of GR*: offers a solution to the motion of the Universe.

Albert Einstein But, a static universe won't be stable! *Edwin Hubble*

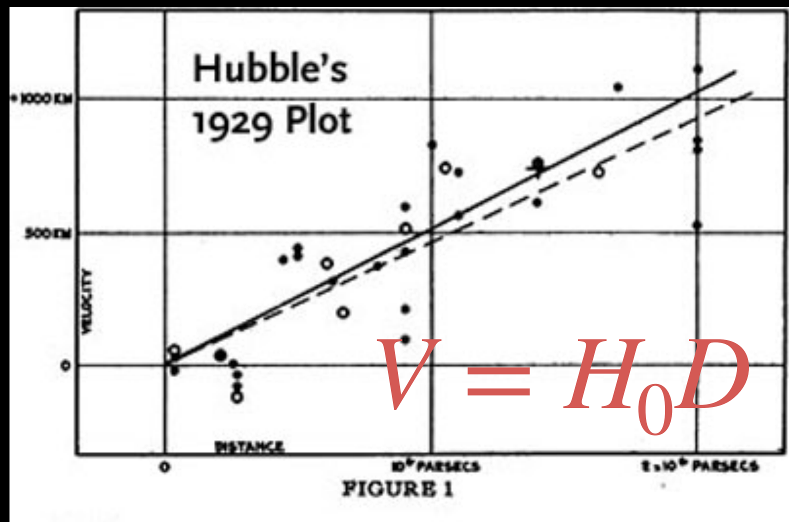
"How to keep the Universe static?" *"No worries! Our Universe is expanding!"*

"To establish a static universe model, let's add a cosmological constant Λ"

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \boxed{\Lambda g_{\mu\nu}} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

"Sigh, then I'll drop Λ…"

Until we bring Λ back to for cosmic acceleration



$$V = H_0 D$$

宇宙物质能量组分**的状态**决定了
宇宙不同的演化历史和命运

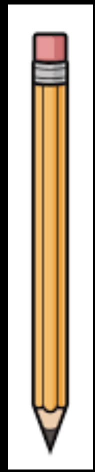
接下来的历史1930s-2000s

天文学和天体物理学	宇宙学	粒子物理学
星系及星系团运动学观测	大爆炸元素核合成	磁单极子问题
暗物质概念的诞生	电离宇宙->中性氢复合，预言3K微波背景辐射	暴涨宇宙Inflation
宇宙微波背景辐射		早期宇宙粒子的产生
宇宙的尺度星系巡天观测	空间平坦问题	早期宇宙相变过程
宇宙学距离的测量	宇宙动力学演化	暗物质粒子理论和探测
哈勃常数测量	结构的形成和演化	
宇宙学参数测量	暗能量本质	

天文系、物理系、高等研究院、数学中心等开设了一系列精彩的相关课程，请感兴趣的同学们关注和参加学习～

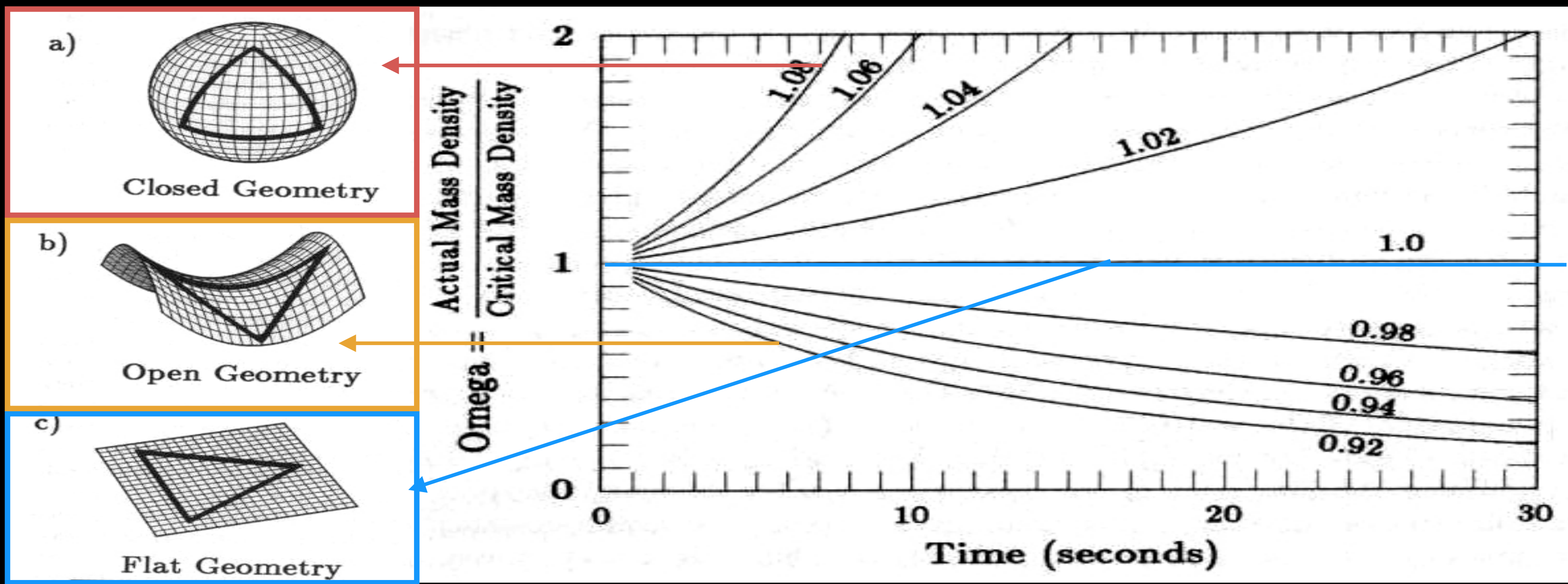

天書奇谭
Secrets Of The Heavenly Book
ONE-DISC 22th ANNIVERSARY EDITION

A modern view of the Universe - II



Richard Dicke

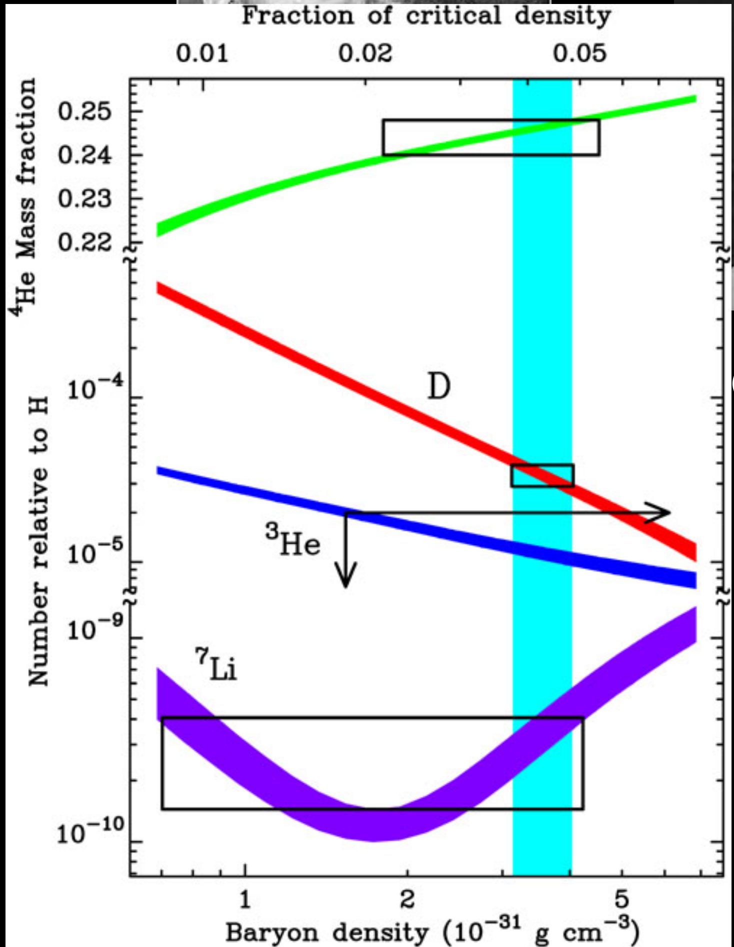
- 1979, 宇宙几何的平坦程度，好像平衡在尖端的铅笔。
- 原初对“平坦”偏离一点，后天偏离飞快！ => 今天宇宙若“平坦”则要求1s时候早期宇宙必须以1E-16水平接近“平坦”，否则宇宙要么塌缩，要么“炸”掉。
- 我们的存在 => 平坦的宇宙



A modern view of the Universe - II

orge Gamow

James Peebles

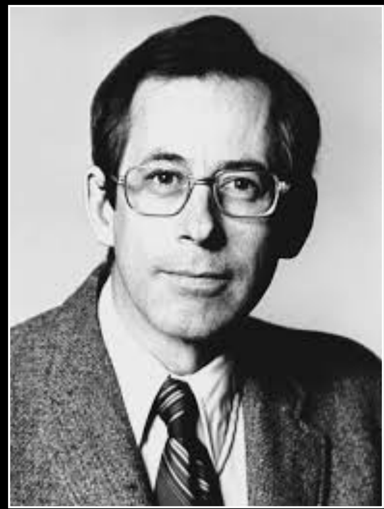


Primordial nucleosynthesis

- 1940s-1960s, 原初宇宙“火球”的元素核合成的计算
- 原初元素丰度（D, He-3, He-4到Li-7）的测量 => 普通物质密度仅占维持平坦宇宙所需物质能量密度的十分之一不到！

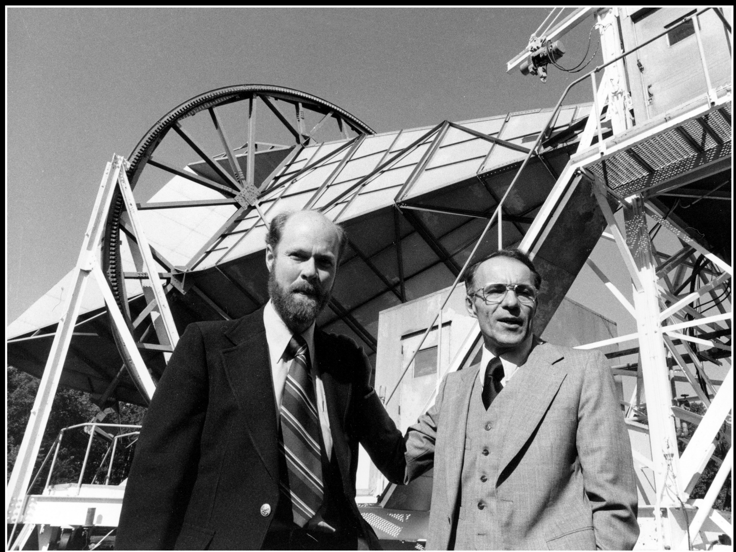
A modern view of the Universe - II

- 宇宙演化到30万年时，原初宇宙“火球”随膨胀降温到3000度时，自由电子被质子俘获，结合成中性氢原子；原本与自由电子频繁散射的光子开心地“奔跑”起来。。。
- 这些光子跑到今天会形成一个**微波**波段的**背景辐射**，是一个拥有温度为～3K (零下270度！)的黑体辐射。

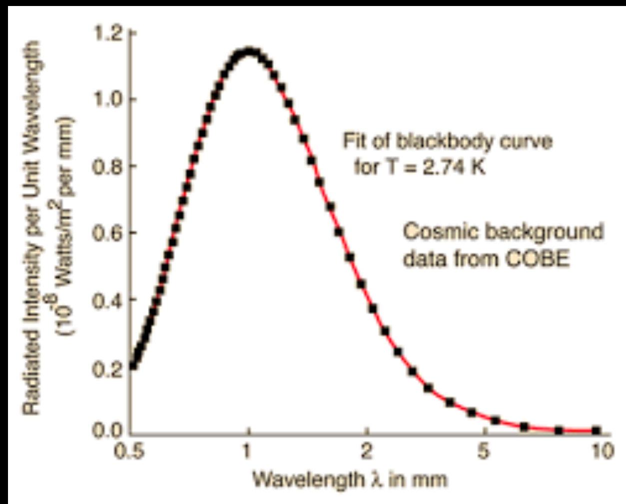


James Peebles

- 1965年，测到宇宙微波背景辐射

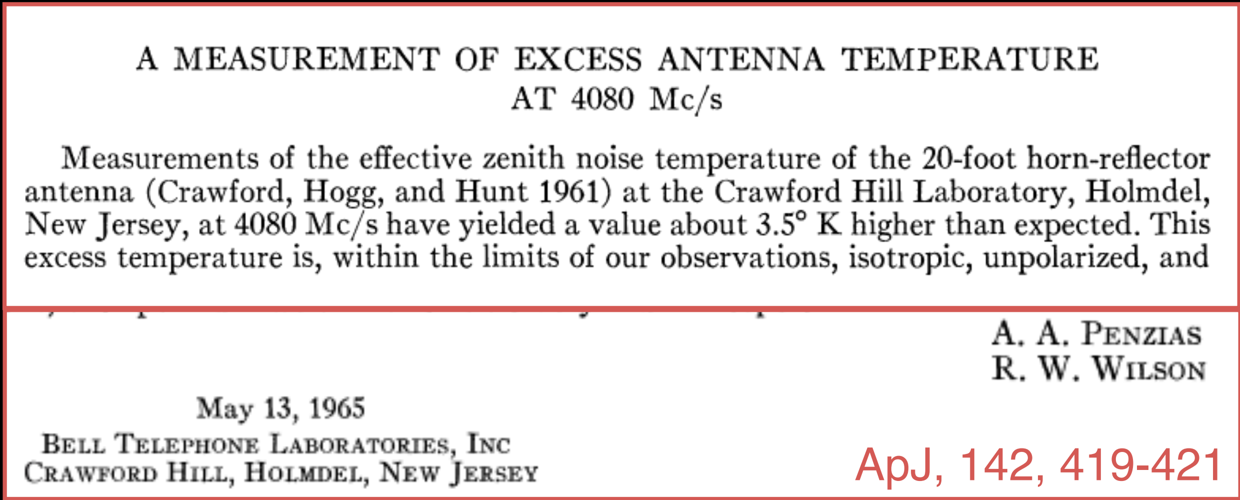


Penzias & Wilson



A modern view of the Universe - II

Cosmic Microwave Background (CMB)



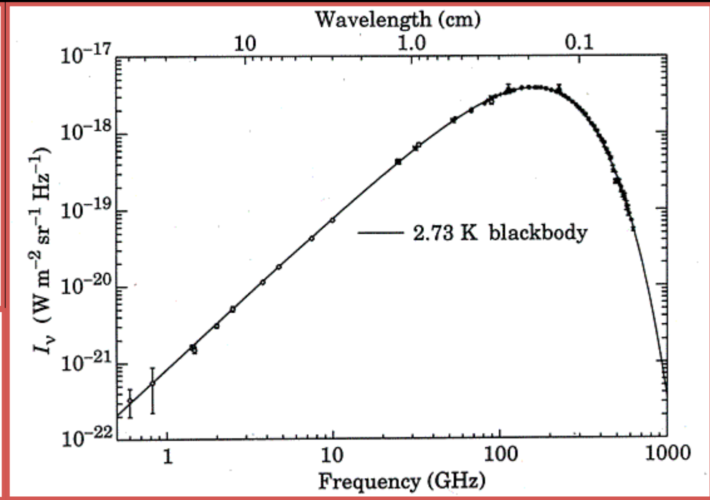
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

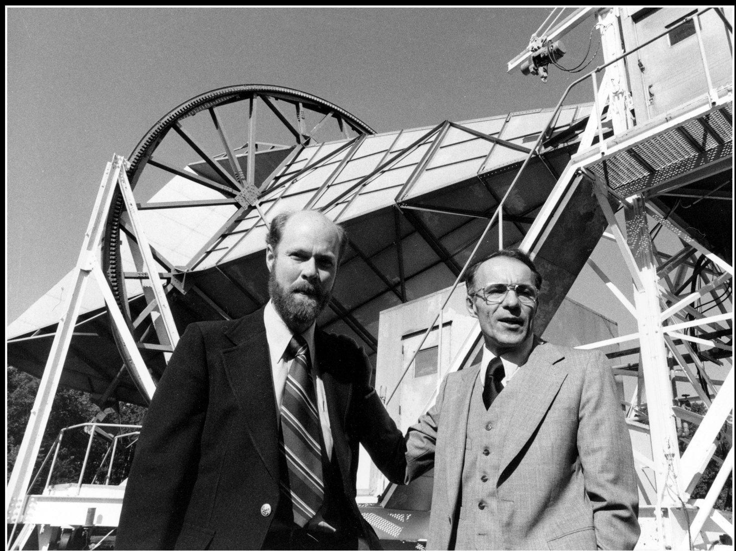
A. A. PENZIAS
R. W. WILSON

May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

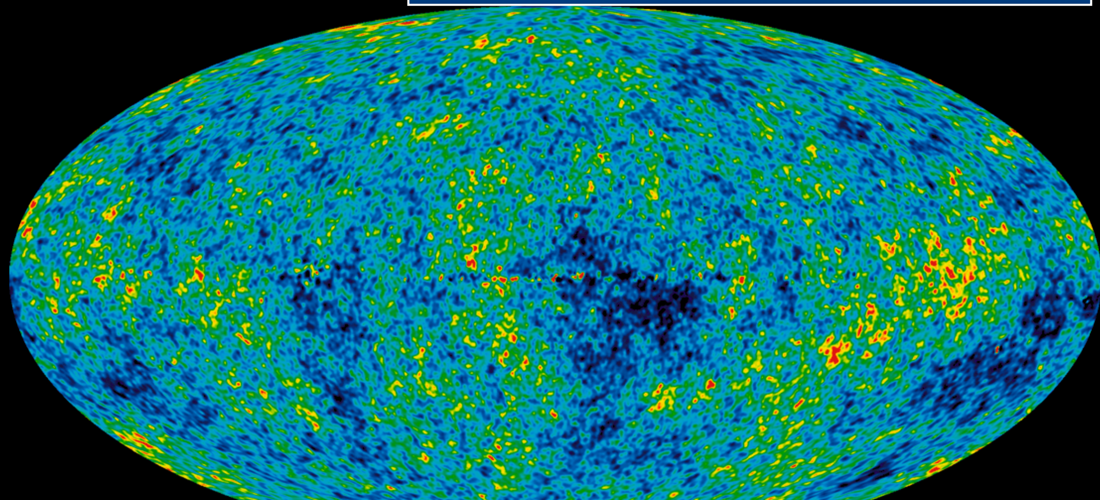
ApJ, 142, 419-421



Isotropic $T \sim 3K$ black body



Penzias & Wilson



Anisotropic $\Delta T/T \sim 10^{-5}$

A modern view of the Universe - II

Cosmic Microwave Background (CMB)

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise te… antenna (Crawford, Hogg, and Hunt 1961) at th… New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our obs…

A. A. PENZIAS
R. W. WILSON

May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

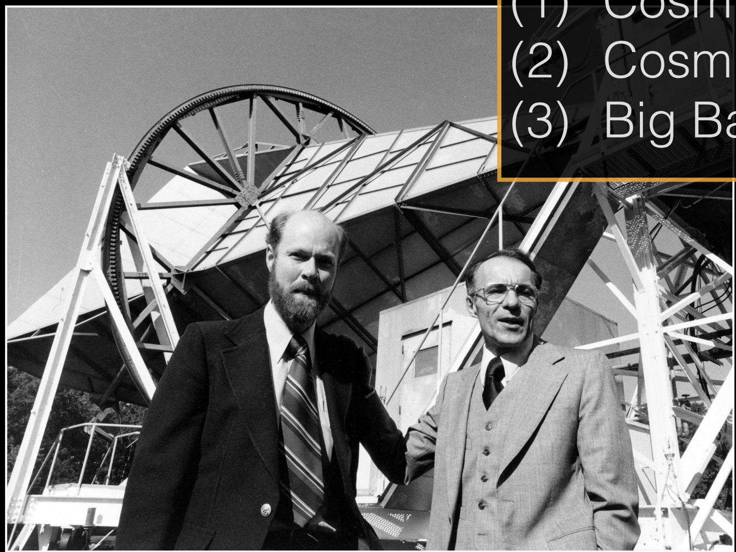
ApJ, 142, 419-421

Big Bang Cosmology

The Universe started from a primordial plasma of *high temperature, high density and high pressure*, supported by:

(1) Cosmic/Hubble expansion;
(2) Cosmic Microwave Background;
(3) Big Bang Nucleosynthesis.

James Peebles



Penzias & Wilson

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar … field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. DICKE
P. J. E. PEEBLES
P. G. ROLL
D. T. WILKINSON

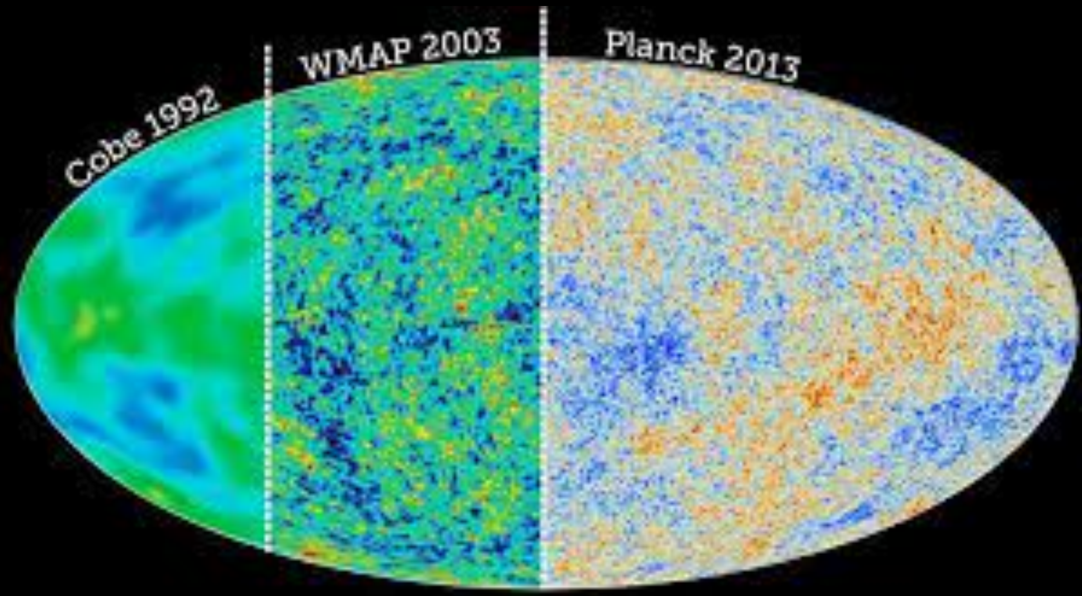
May 7, 1965
PALMER PHYSICAL LABORATORY
PRINCETON, NEW JERSEY

ApJ, 142, 414-419

宇宙微波背景辐射

1970s-1990s - 至今

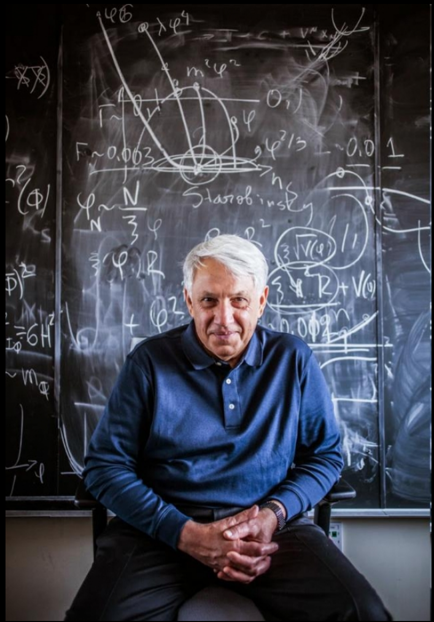
扣除银河系前景和运动，背景的温度差异在0.00001的水平，反应了光子“诞生地”物质密度分布异常均匀！

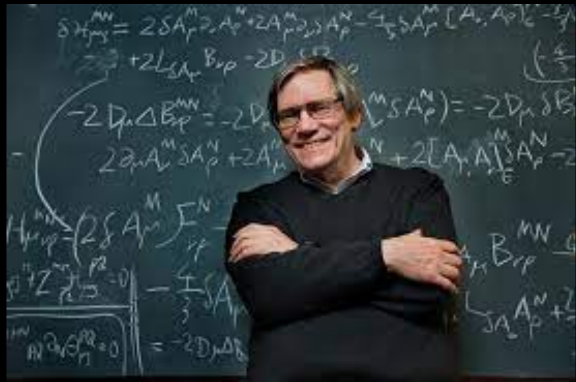


Problems yet to understand

早期密度场的均匀程度，需要以相互作用以超光速传播来解释！— 视界问题

还记得刚刚讲过， 宇宙“平坦”到无法解释！— 平坦问题





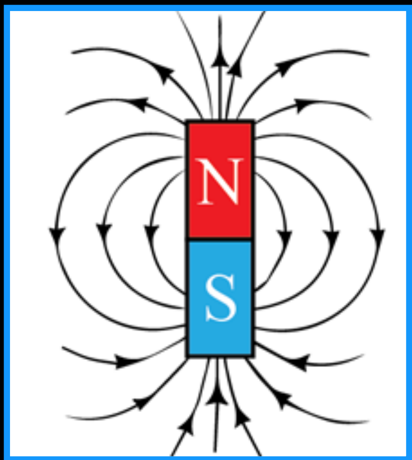
Alan Guth

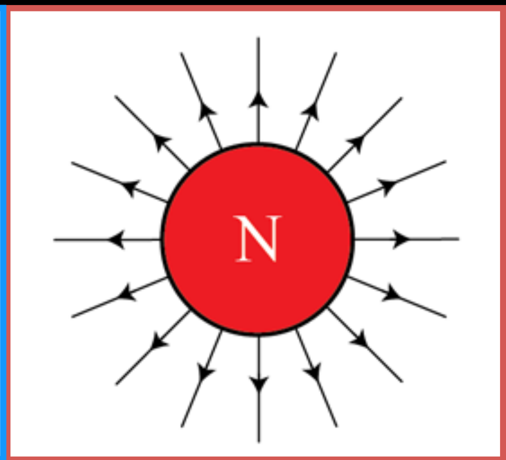
Andrei Linde

磁单极子问题

（1980s）

为了抑制磁单极子的数量，宇宙必须经历一个疯狂的暴涨时期（*Inflation*）！这个时期的能量密度为正，压强为负，互相排斥，在短短1E-32秒，宇宙大小60次翻翻！极大地稀释了磁单极子的密度！也终于翻出了大爆炸初始状态滚烫的“热粥”！

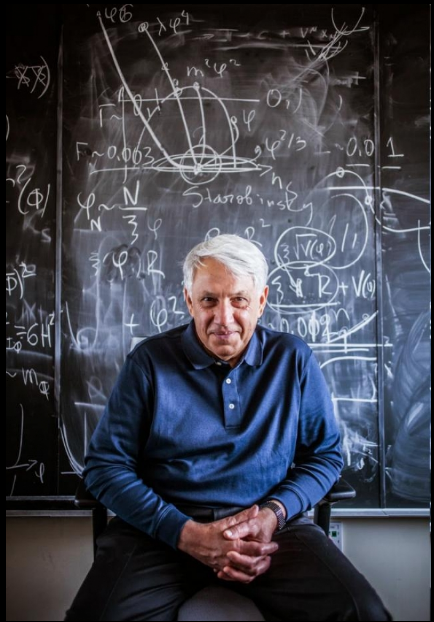


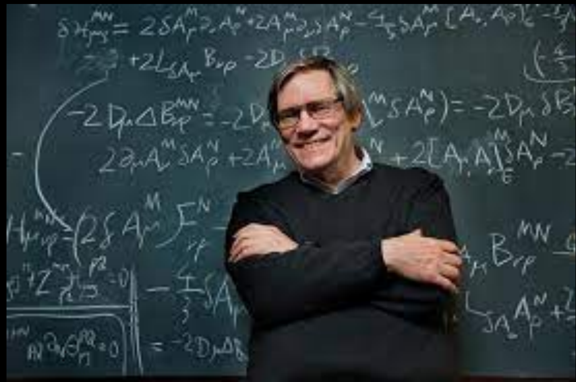


这个我家有 这个宇宙从未见

这个宇宙疯狂的暴涨阶段，居然同时解决了宇宙的“平坦”和“视界”问题！

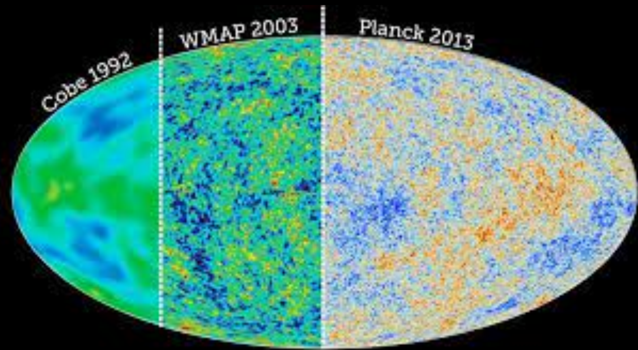
磁单极子问题
（1980s）

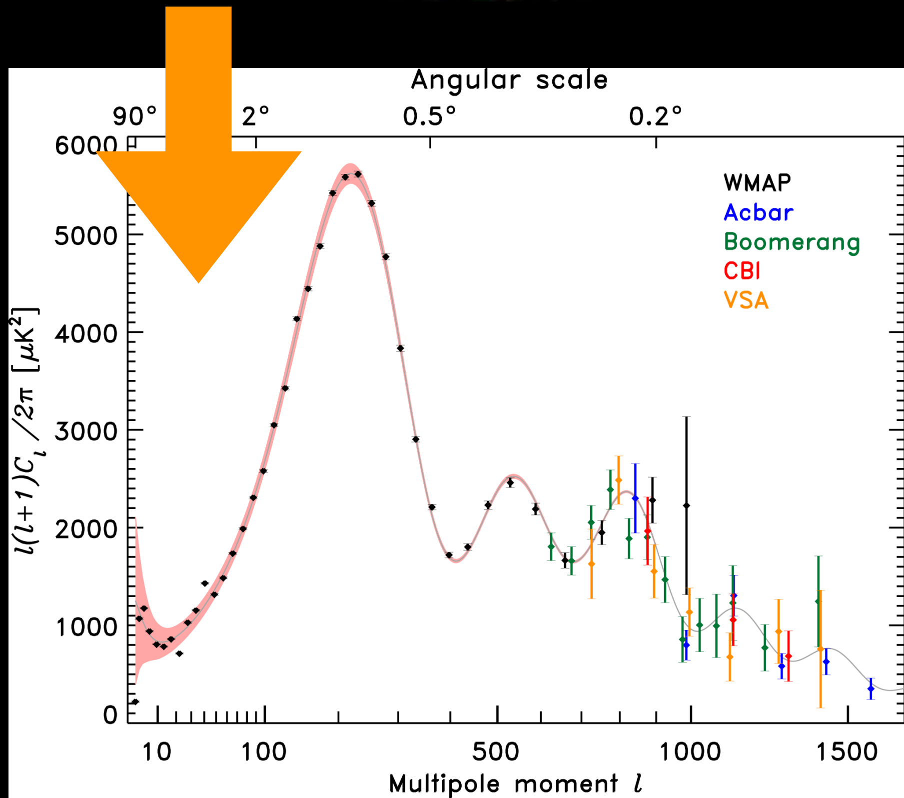




Alan Guth

Andrei Linde





暴涨宇宙模型**预言**了留在微波背景辐射的功率谱上期待的信号；

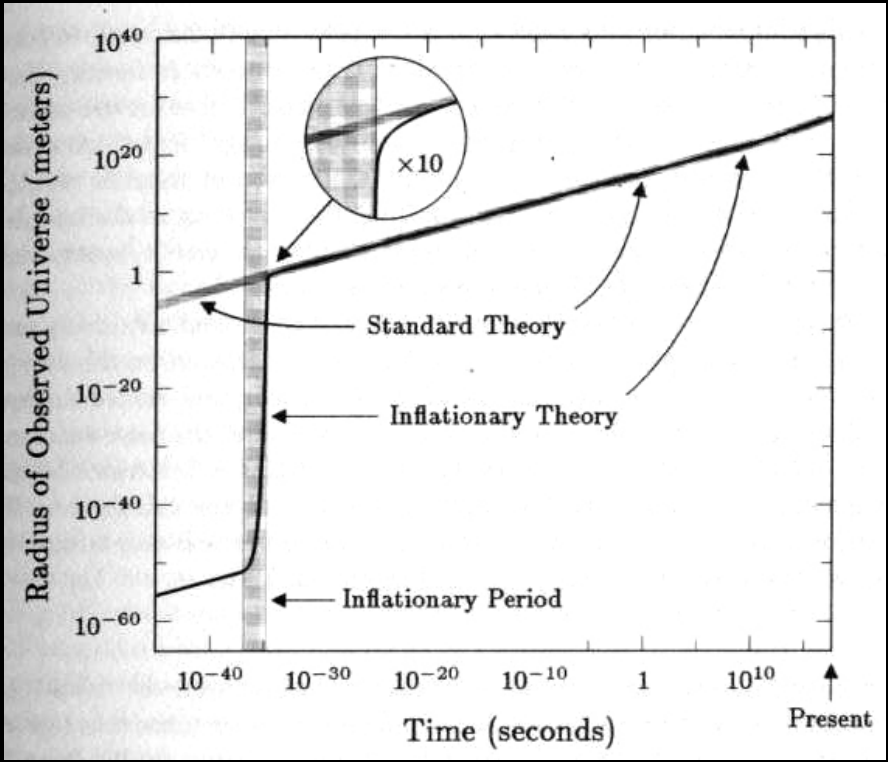
1990s被COBE卫星证认，大家留下了激动的泪花。。。

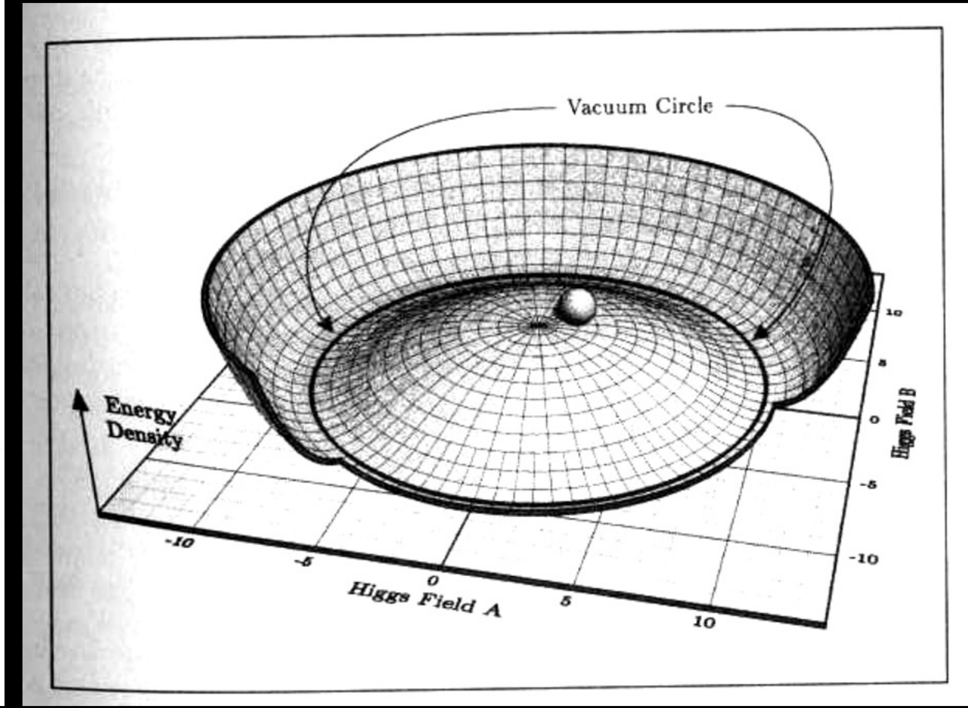
A modern view of the Universe - III

Inflation theory

Solved all three problems and its *reheating* can also explain the initial condition of the *hot big bang.*

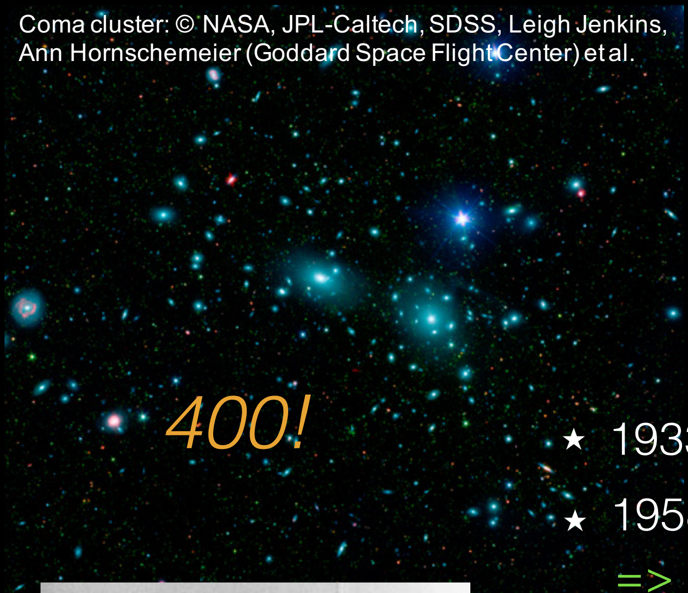
1. CMB isotropy —> a horizon problem
2. Pencil tip balance —> a flatness problem
3. Null observation of *magnetic monopole*

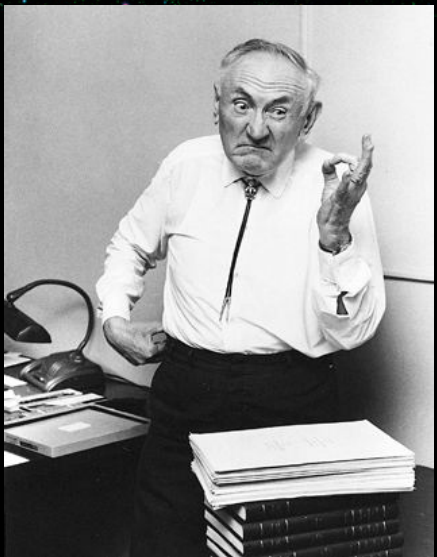




Inflaton field

A modern view of the Universe - IV





Fritz Zwicky
1933 (dark matter)

"Missing mass" problem exists at all scale: a non-baryonic matter distribution is required to go beyond visible (stellar) region of a galaxy
— dark matter

- ⋆ 1933, Zwicky: motion of cluster galaxies requests unseen matter
- ⋆ 1958, Hubble Constant H_0 ~ 75 km/s/Mpc (A. Sandage)
  => critical density of the Universe $\rho_{\rm cr} \sim 10^{-29}$ g/cm^3
- ⋆ 1960s, BBN (He, Li) => a baryonic density $\rho_{\rm bar}$ ~3×10^{-31} g/cm^3, which is only a few percent of $\rho_{\rm cr}$
- ⋆ 1974, Ostriker & Einasto: motion of satellite galaxies around the Milky Way and M31 => request unseen matter
- ⋆ 1973 - 1980, Roberts & Rots; Rubin et al.: flat rotation curves of nearby galaxies traced by HI 21cm => request unseen matter
- ⋆ 1979, Dicke & Peebles: pencil-tip balancing flatness problem
  => Universe total density $\rho_{\rm tot} \sim \rho_{\rm cr} \gg \rho_{\rm bar}$
- ⋆ 1990s, CMB observation of $\Delta T/T \sim 10^{-5}$ —> galaxy formation requires larger pre-existing density contrast!

暗物质（Dark matter）

Coma cluster: © NASA, JPL-Caltech, SDSS, Leigh Jenkins, Ann Hornschemeier (Goddard Space Flight Center) et al.

解释星系团成员运动规律：

广义相对论+普通物质+暗物质

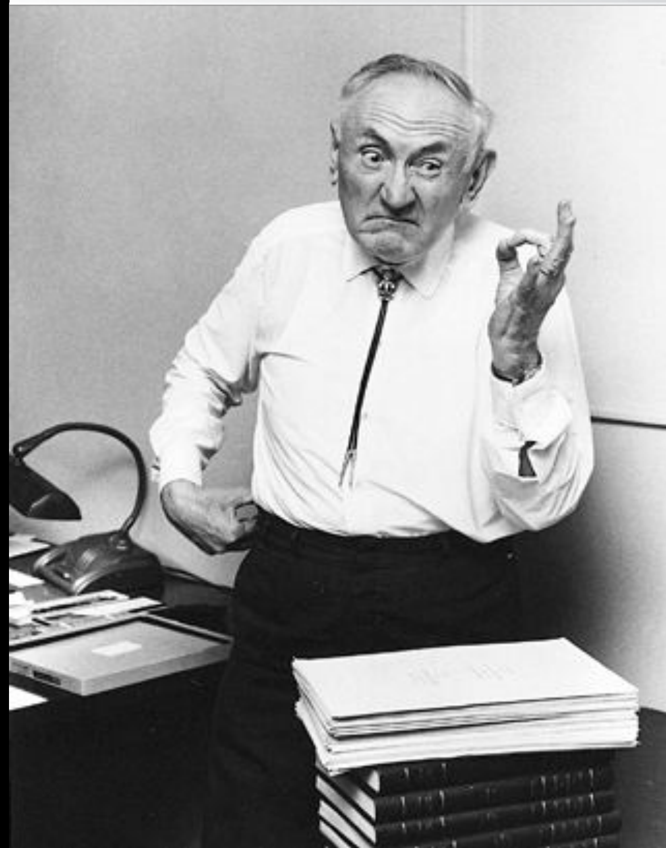
修正引力模型（MOND）

熵引力模型（entropy gravity）

There is more than just meets the eye!

— **dark matter** (83%)

ordinary matter (17%)



Fritz Zwicky 1930s

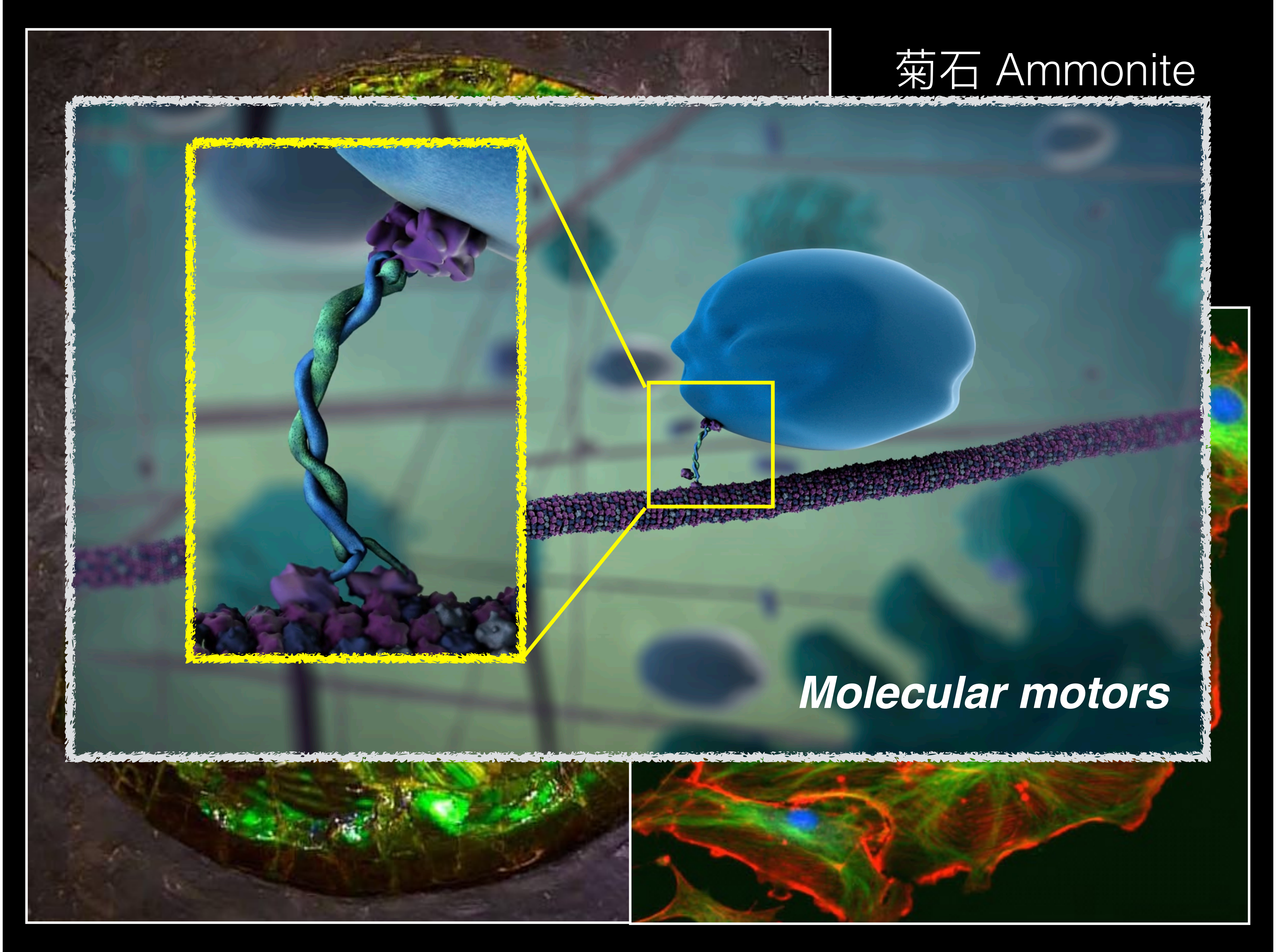
暗物质（Dark matter）

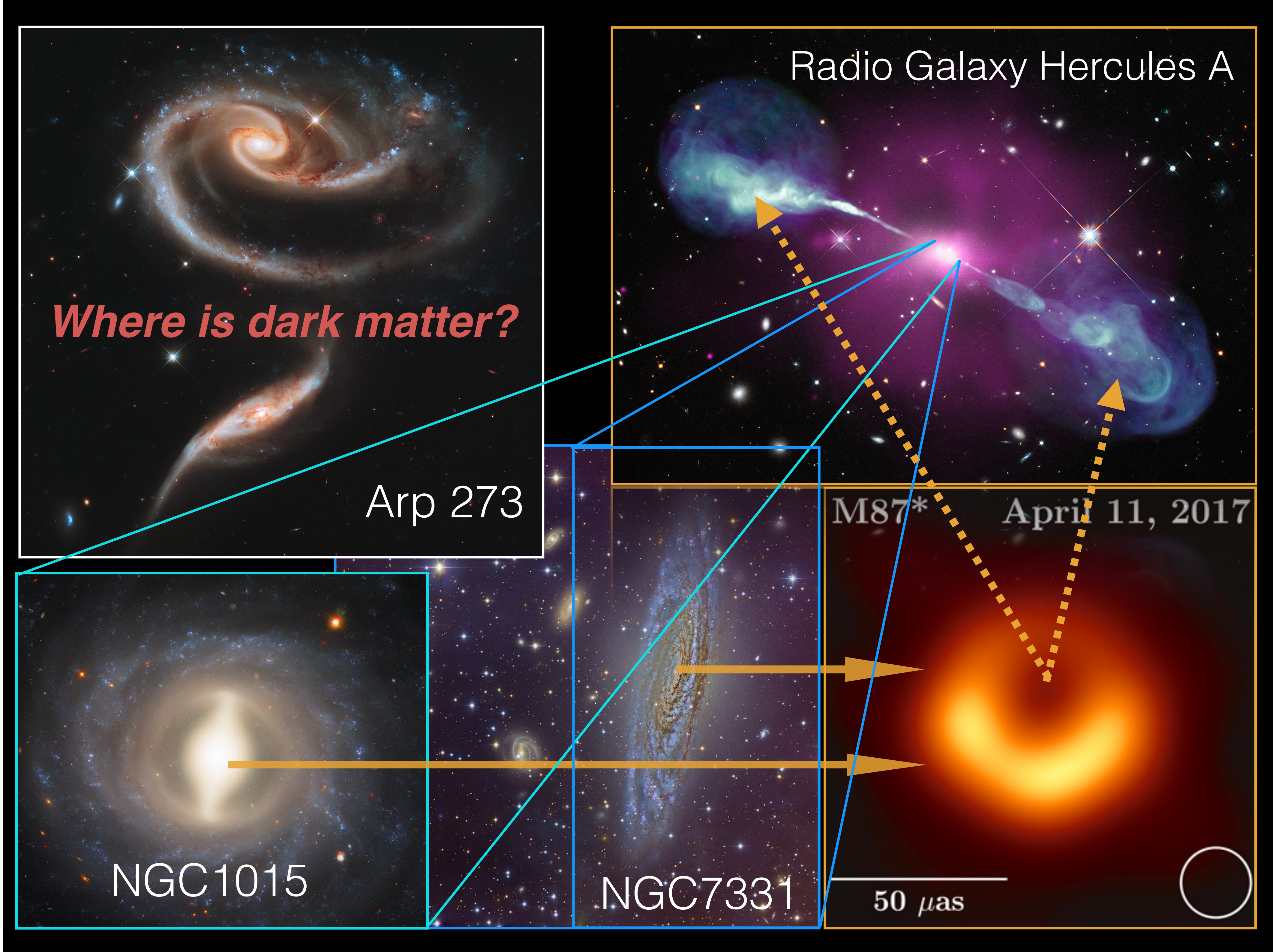
Where is dark matter?

What is dark matter?

How abundant is dark matter?

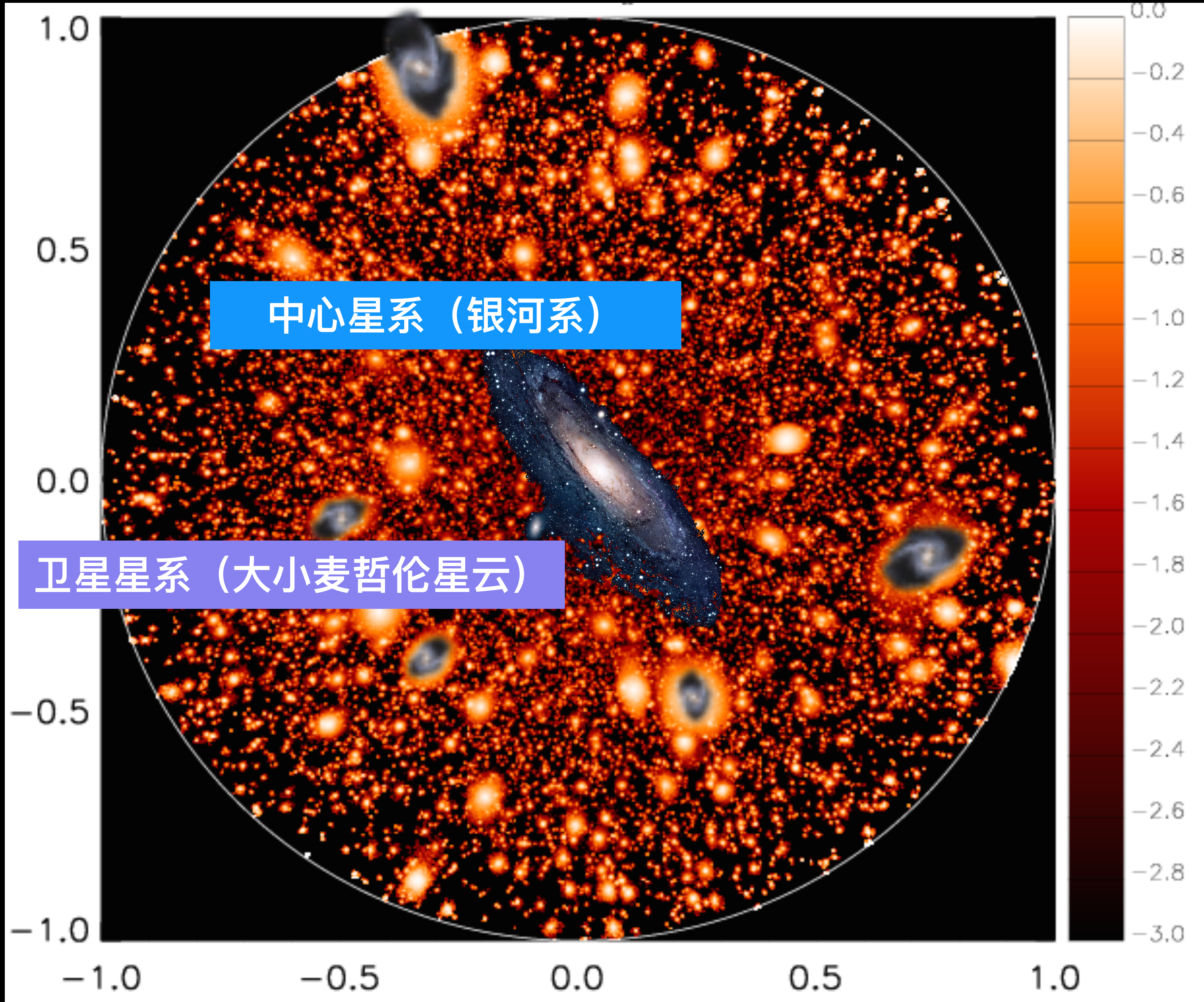
- Sub-galactic scale
- Galaxy and cluster scale
- Large-scale backbones


菊石 Ammonite
Molecular motors



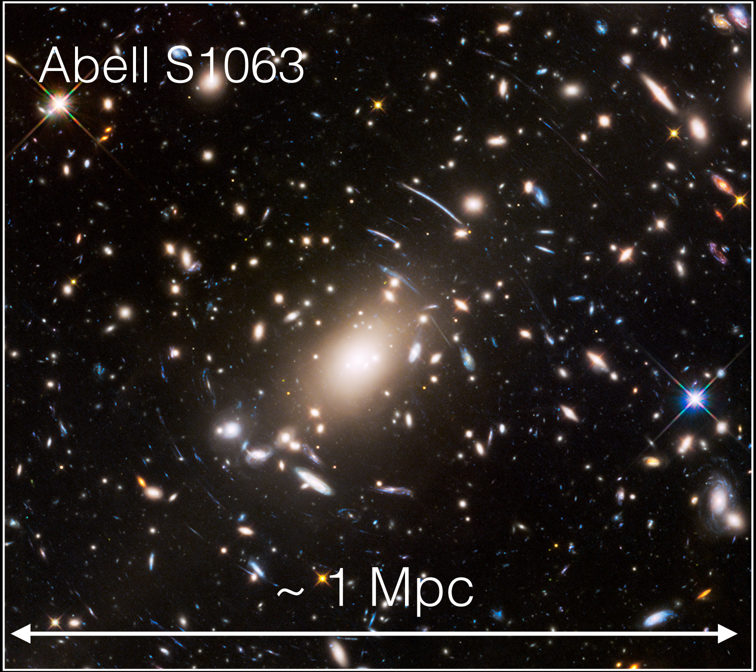
Radio Galaxy Hercules A
Where is dark matter?
Arp 273
M87*
April 11, 2017
NGC1015
NGC7331
50 μas

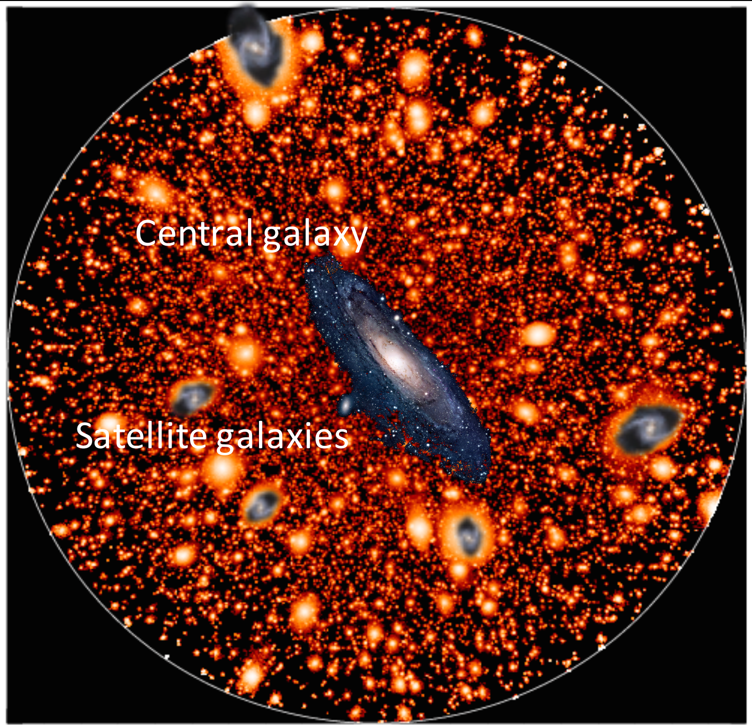
Aquarius simulation, Springel et al. (2008)



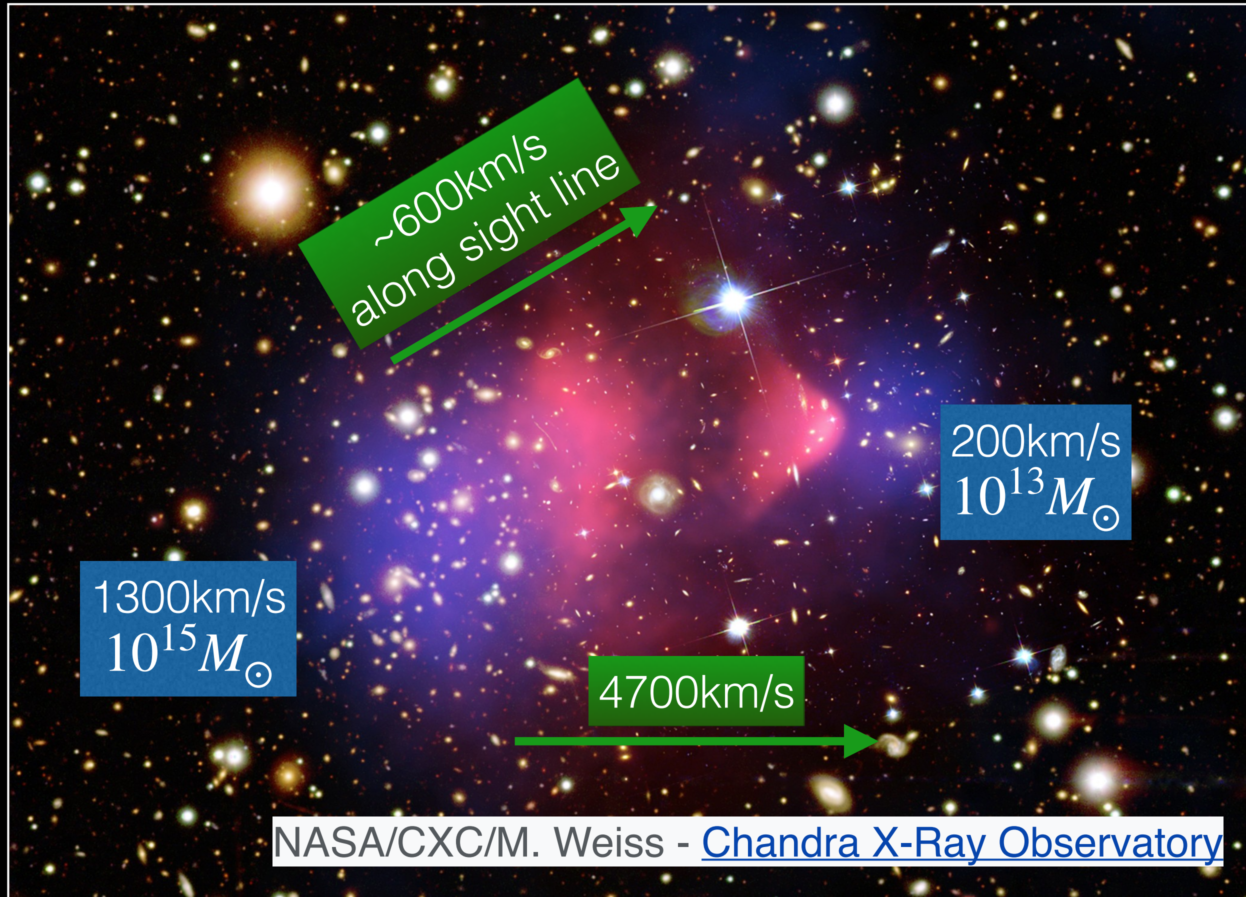
“小”尺度上——星系尺度

子弹星系团：Galaxy cluster 1E0657-56（Bullet Cluster）
背景星系图像: Magellan和HST望远镜.
粉色：两个碰撞星系团中热气体发射的X-射线 (Chandra Telescope)
蓝色：弱引力透镜方法重构出的两个星系团中所有物质质量分布





~ 500 kpc

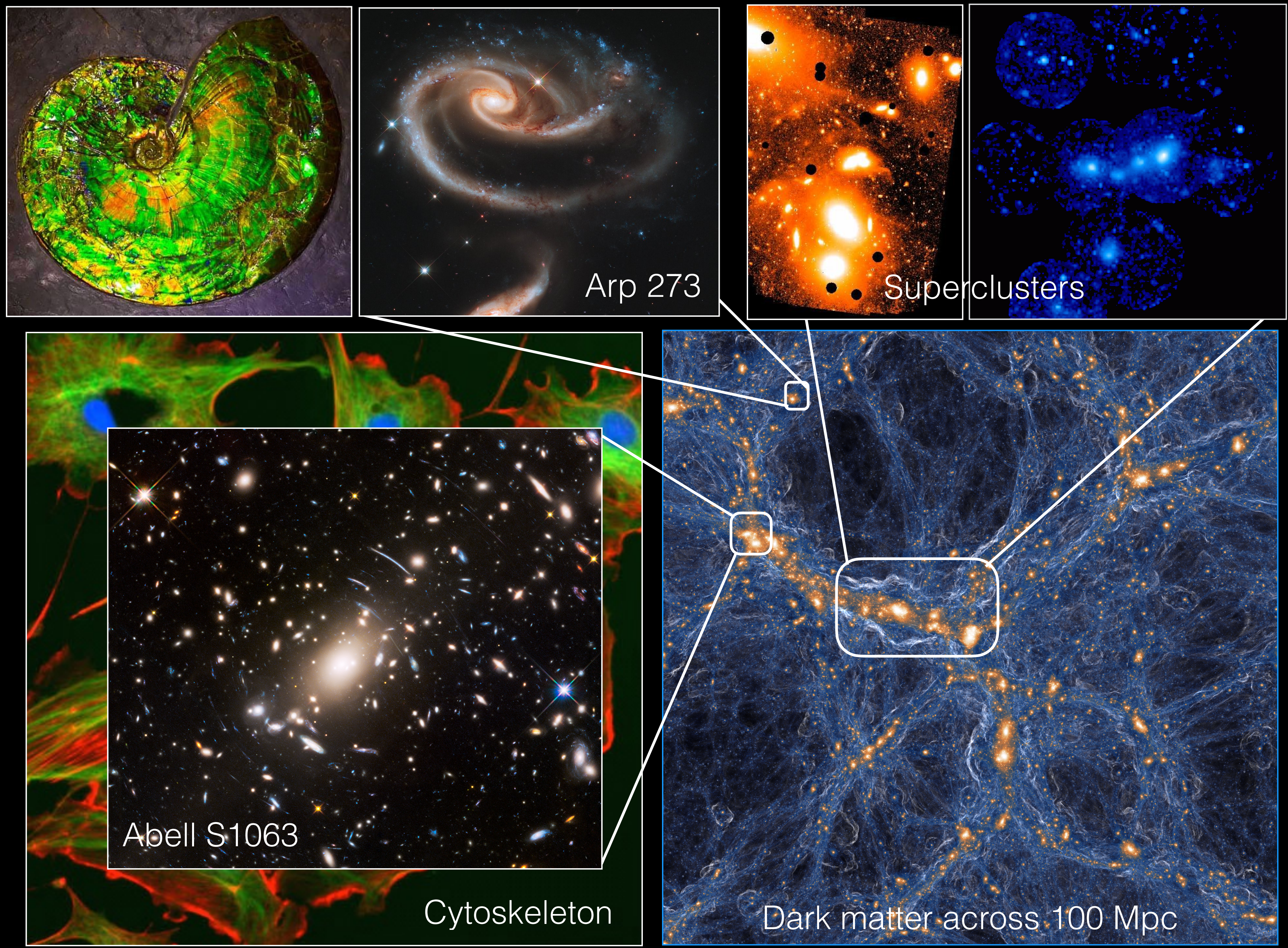


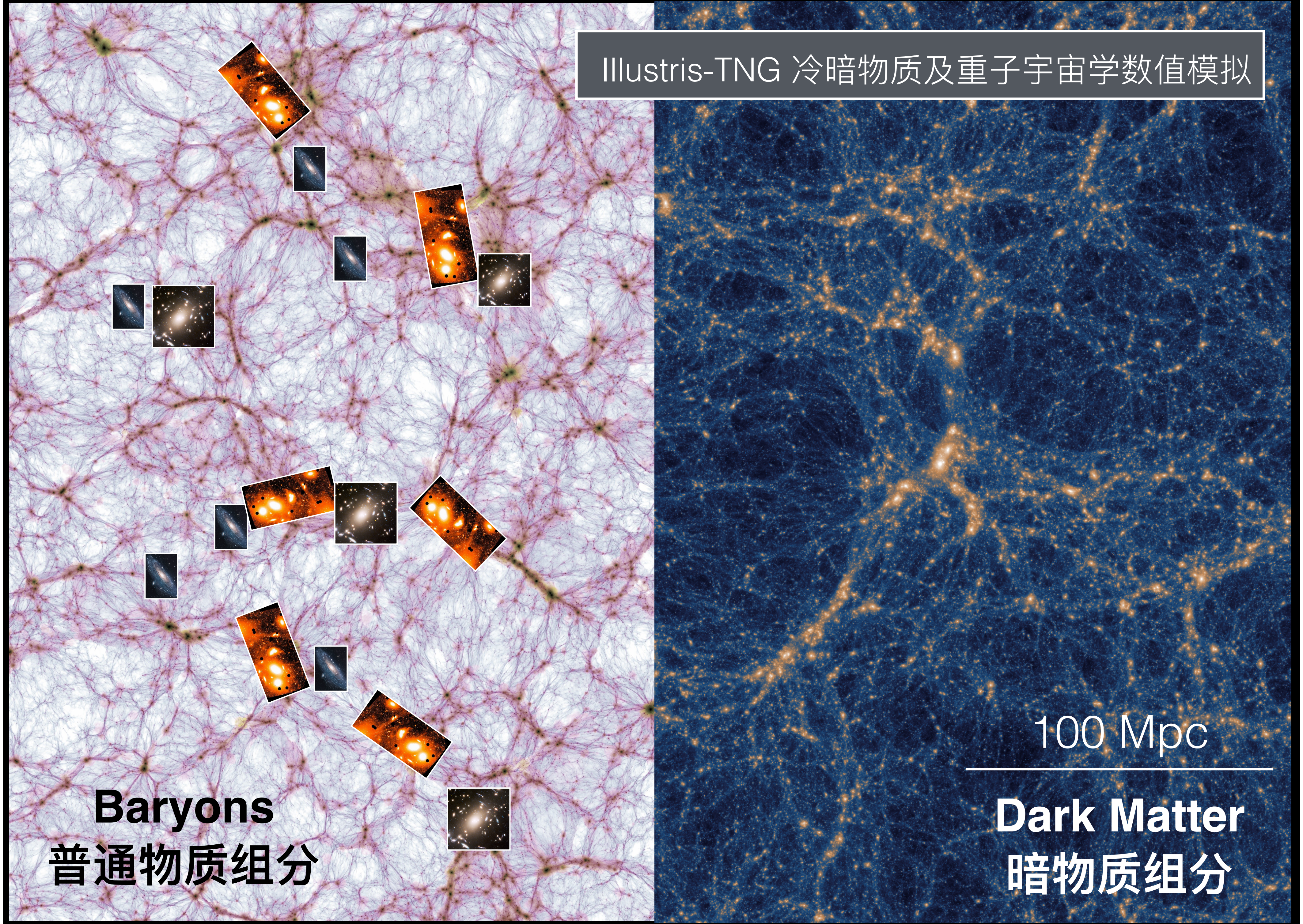
A few Mpc

较大尺度上——星系团尺度

HST Deep Field Survey
哈勃空间望远镜深场巡天

M31/仙女星系
@ Robert Gendle
Ritchey-Chrétien telescope


Arp 273
Superclusters
Abell S1063
Cytoskeleton
Dark matter across 100 Mpc


Illustris-TNG 冷暗物质及重子宇宙学数值模拟
100 Mpc
Baryons
普通物质组分
Dark Matter
暗物质组分


如意宝册
天書奇谭
Secrets Of The Heavenly Book
ONE-DISC 22th ANNIVERSARY EDITION
DedeCmsV3

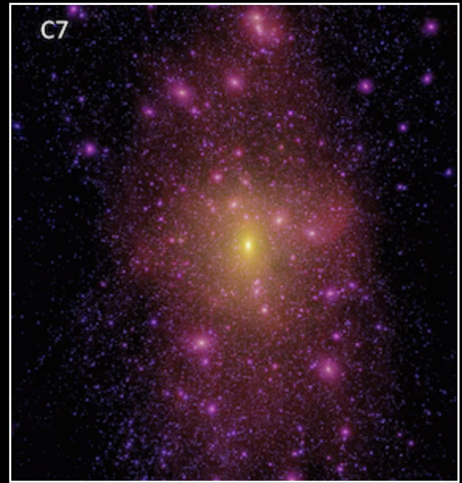
标准模型：冷暗物质CDM

Where is dark matter?

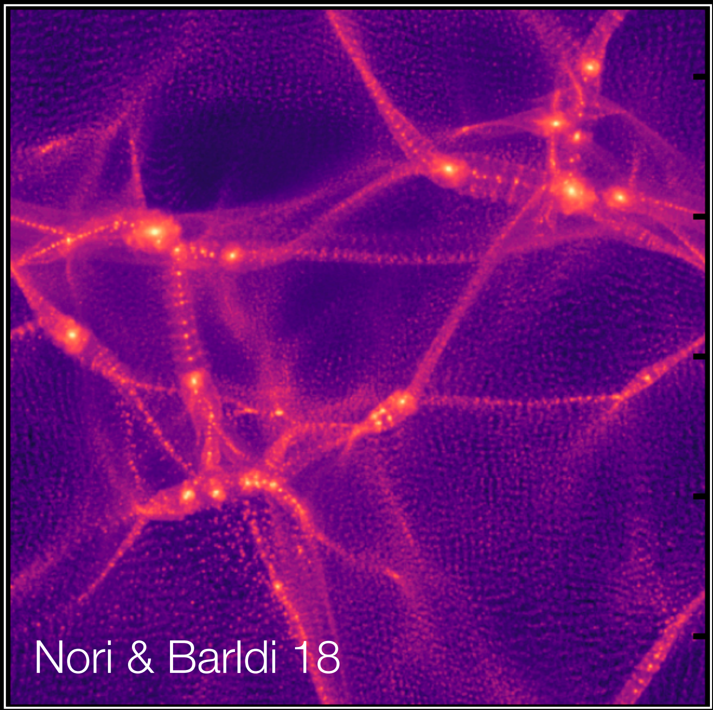
What is dark matter?

How abundant is dark matter?

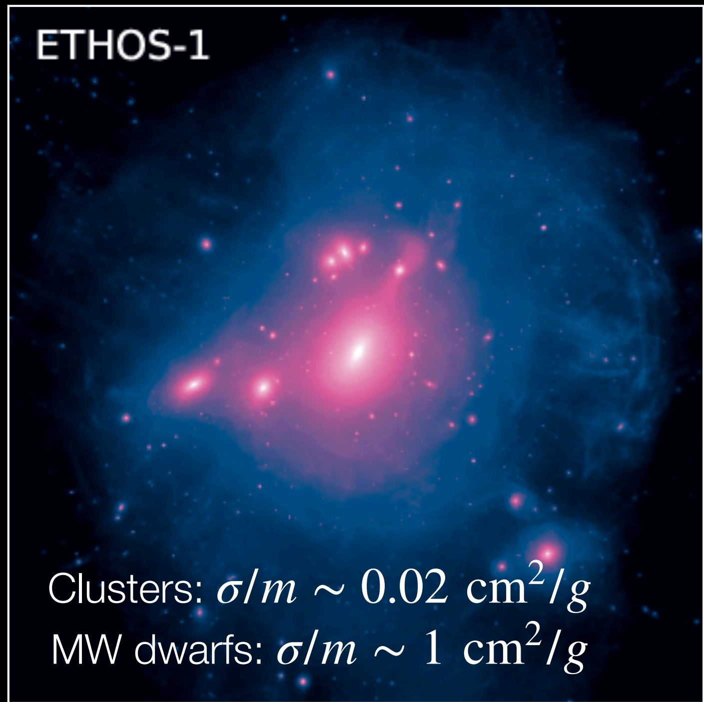
All solution proposals are beyond the standard model!



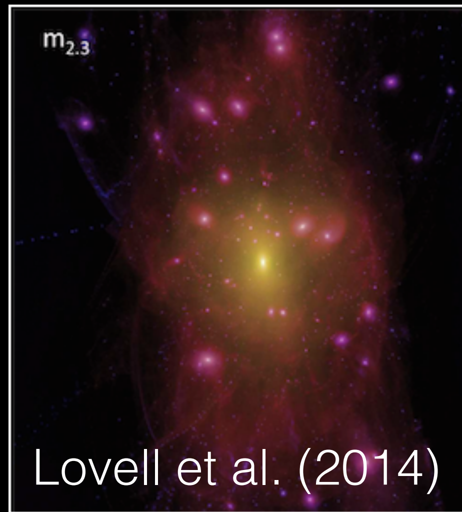
Cold Dark Matter
(WIMP, ~ 100 GeV)



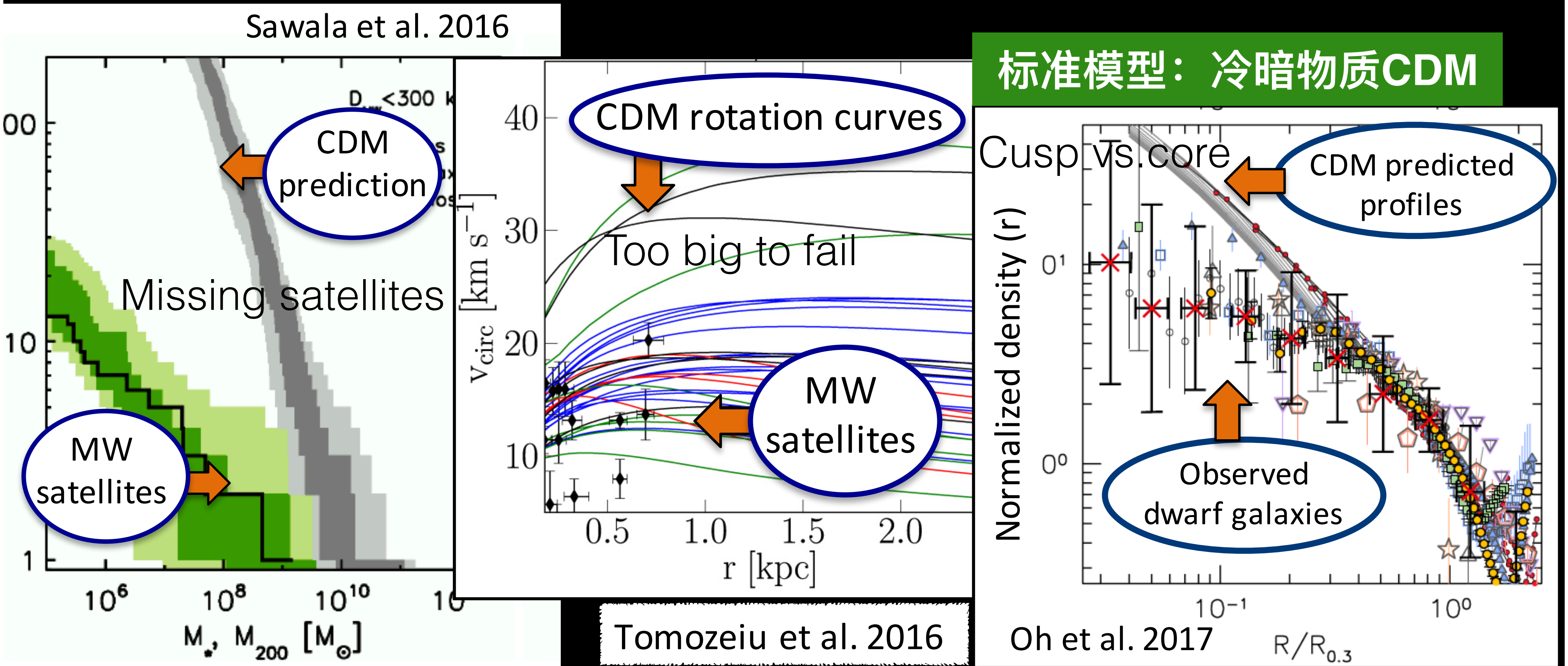
Fuzzy (wave) dark matter
(Ultralight axions, ~ 10^{-22} eV)



Vogelsberger+ 16, ETHOS
Self-Interacting dark matter



Warm Dark Matter
(Sterile neutrino ~ keV)



CDM小尺度问题。。。

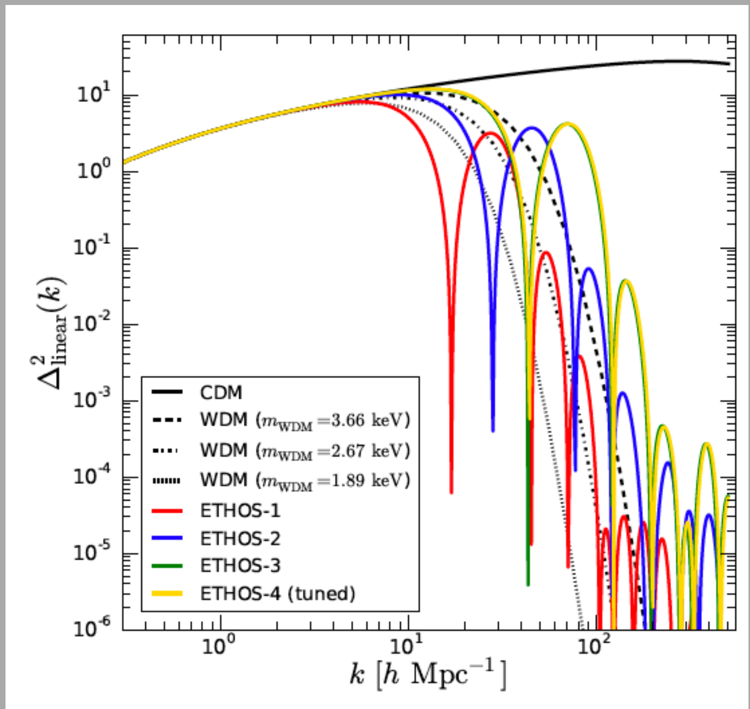
预言的卫星星系数量过高
预言的明亮的卫星星系质量过大
预言的暗弱的卫星星系中心密度过高

需要某暗物质模型解决：

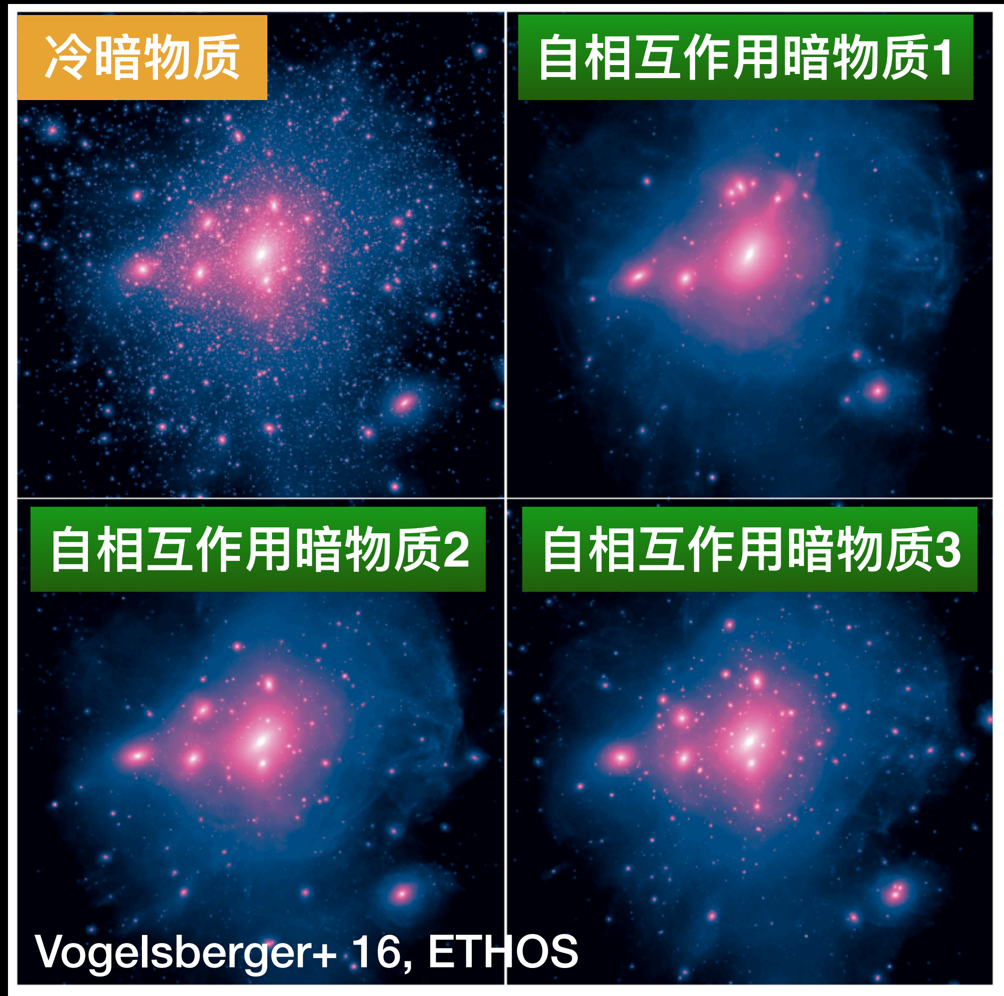
减少小尺度结构的数量?
削弱小尺度结构的质量?
削弱小尺度结构中心密度?

自相互作用暗物质 (Self-interacting dark mattere)

Clusters: $\sigma/m \sim 0.02\ \mathrm{cm}^2/g$ MW dwarfs: $\sigma/m \sim 1\ \mathrm{cm}^2/g$ —> velocity dependent cross-section

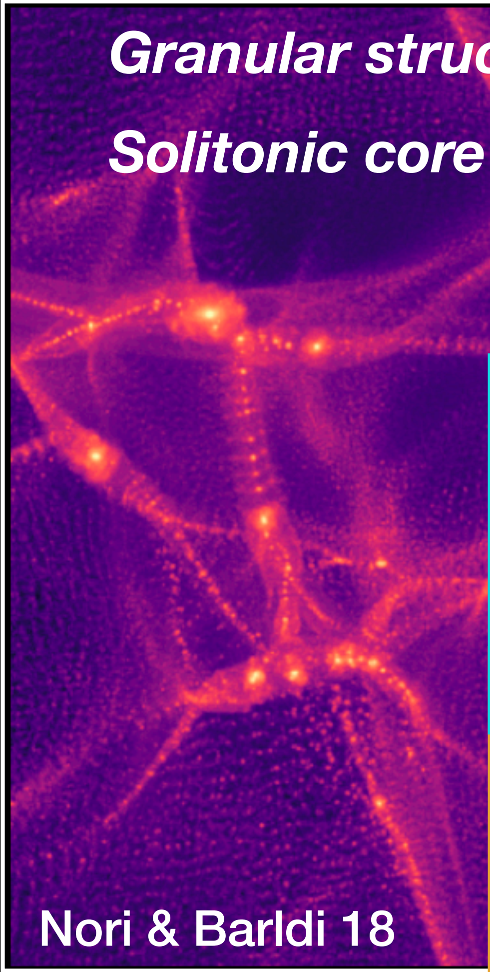


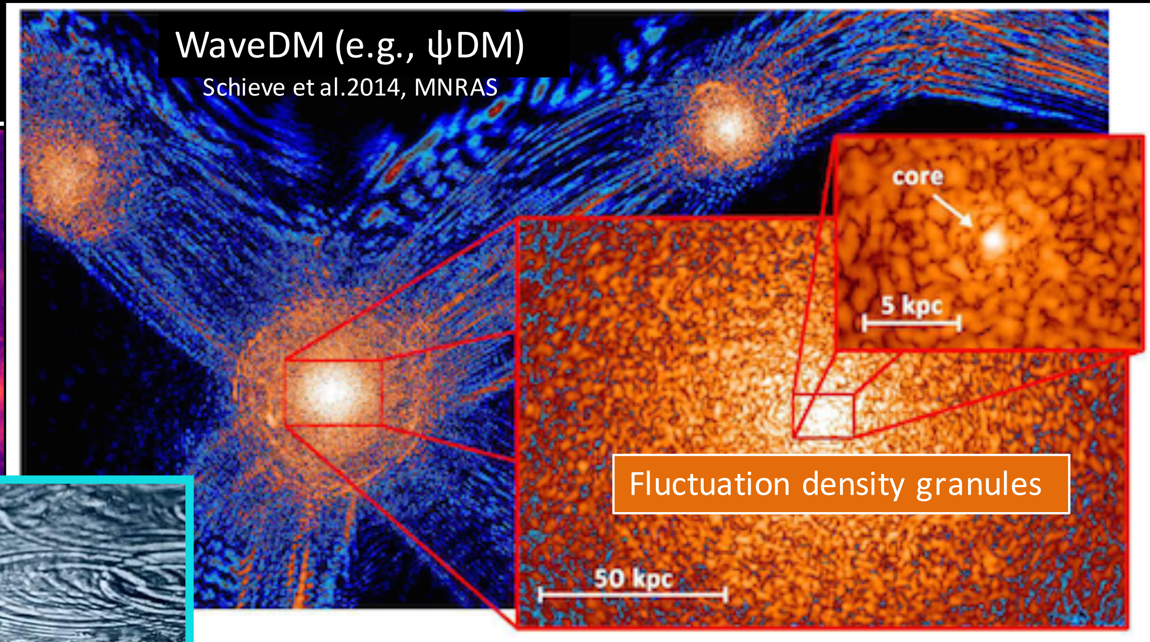
Damping and "dark" acoustic oscillation feature due to interaction between SIDM and photons and dark radiation
ETHOS: Vogelsberger+ 16



波暗物质 （Fuzzy/wave dark matter）

✤ Smoking-gun observations:





量子力学：波粒二象性
暗物质粒子（超轻轴子）的波动性
表现—波的干涉产生星系结构。
Galactic structure formation due to the quantum interference of the wave-natured ultra-light Axions

不同的暗物质模型

Milky-Way simulations	冷暗物质	温暗物质	自相互作用暗物质	波动暗物质	暗物质+重子物理
卫星星系数量过高	✗	✓	✓ Vogels ger+1512.05349 ETHOS	✓ Hui et al. 1610.08297	✓
卫星星系恒星运动速度过大	✗	✓	✓	✓ Marsh et al. 1307.1705	✓
卫星星系中心密度过高	✗	✗ Shao et al.1209.5563	✓	✓ Zhang et al. 1809.09848	✓

Pauli Exclusion <= Fermionic nature

费米子->泡利不相容原理

Bosonic nature => Uncertainty Principle

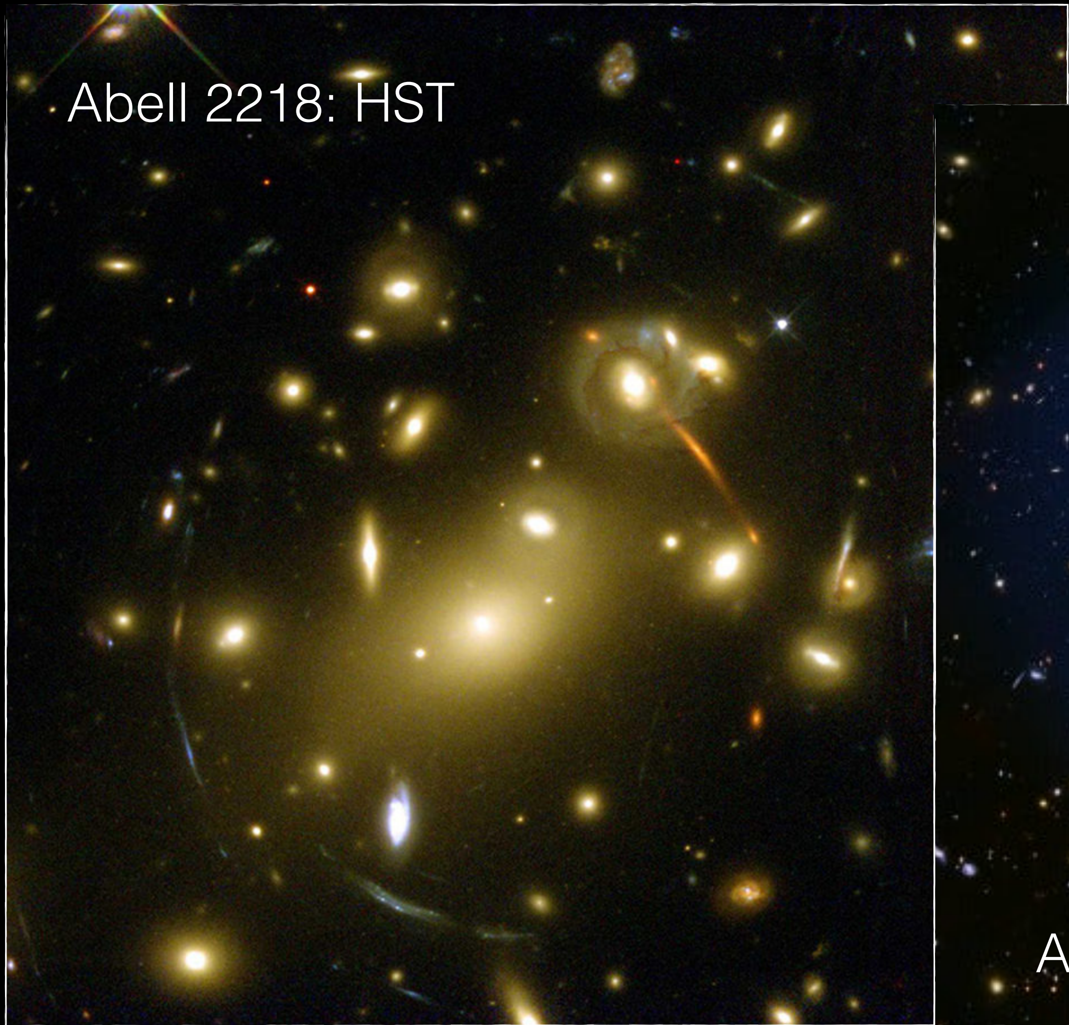
波色子->不确定性原理

Where is dark matter?

What is dark matter?

How abundant is dark matter?

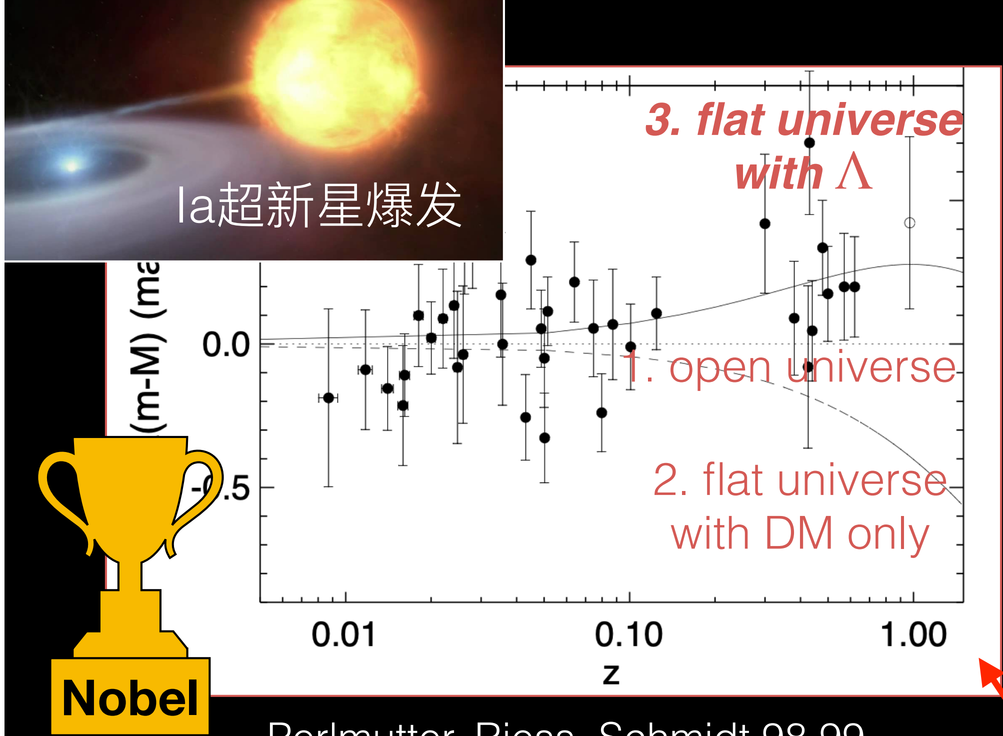
Pure dynamical measurements as revealed by cluster dynamics, gravitational lensing and X-ray observation in clusters of galaxies: $\rho_{\rm dm} \sim 0.2 - 0.3\,\rho_{\rm cr}$ (today)



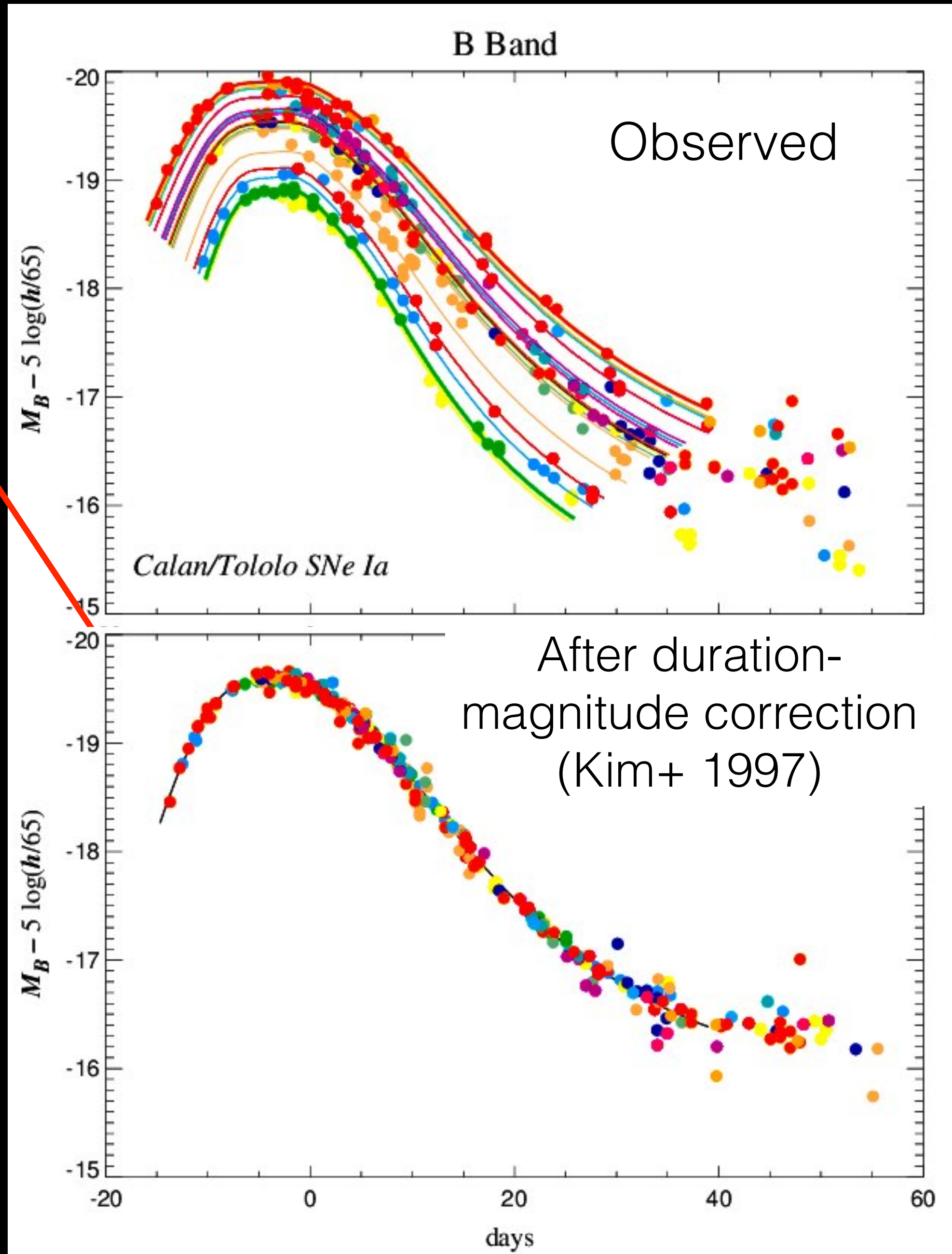
How abundant is dark matter?
— not an independent question!

If dark matter can only account for 20-30% of the total matter-energy required to balance a flat expanding universe *today*, then what other contributors could there be — given that our Universe has to be flat (i.e., total actual density = critical density)?

How abundant is dark matter? — not an independent question!



Perlmutter, Riess, Schmidt 98,99
SNIa cosmological distances to z=1

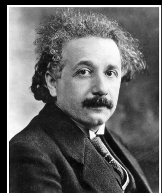


1. Open universe:

$$\rho_{\rm tot} = \rho_{\rm dm} \sim 0.2 - 0.3\,\rho_{\rm cr}$$

2. Flat universe with DM only:

$$\rho_{\rm tot} = \rho_{\rm dm} = \rho_{\rm cr}$$



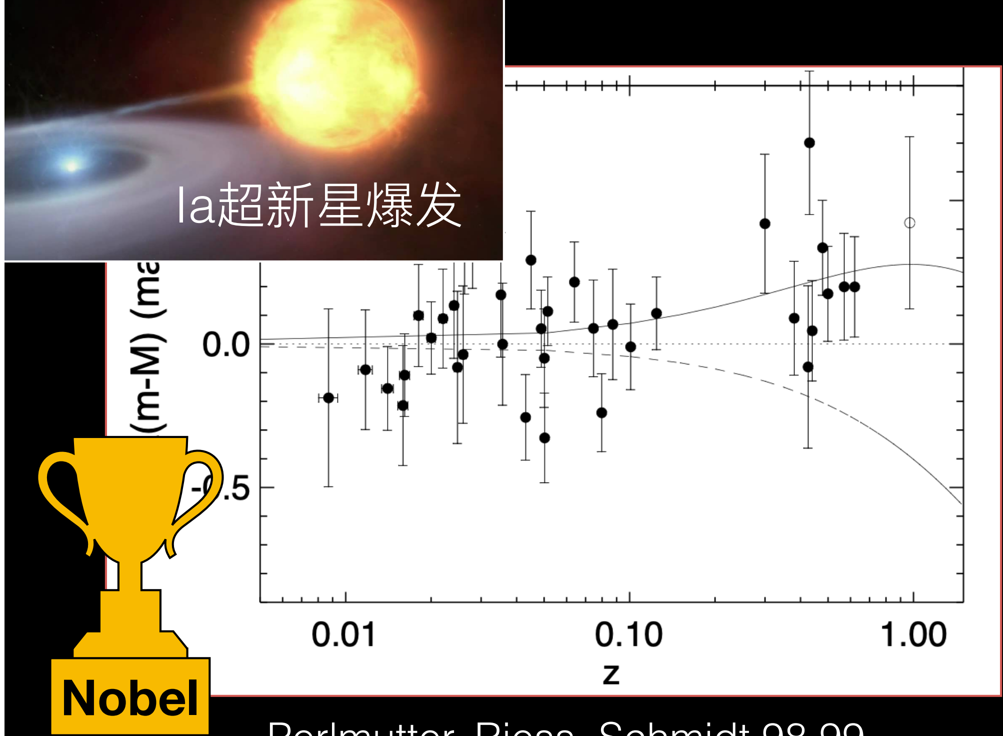
3. Flat universe with Λ (and DM):

$$\rho_{\rm tot} = \rho_{\rm dm} + \rho_\Lambda = \rho_{\rm cr}$$ Acceleration

with $\boxed{P_\Lambda < 0}$ and $\rho_{\rm dm} \sim 0.2 - 0.3\,\rho_{\rm cr}$

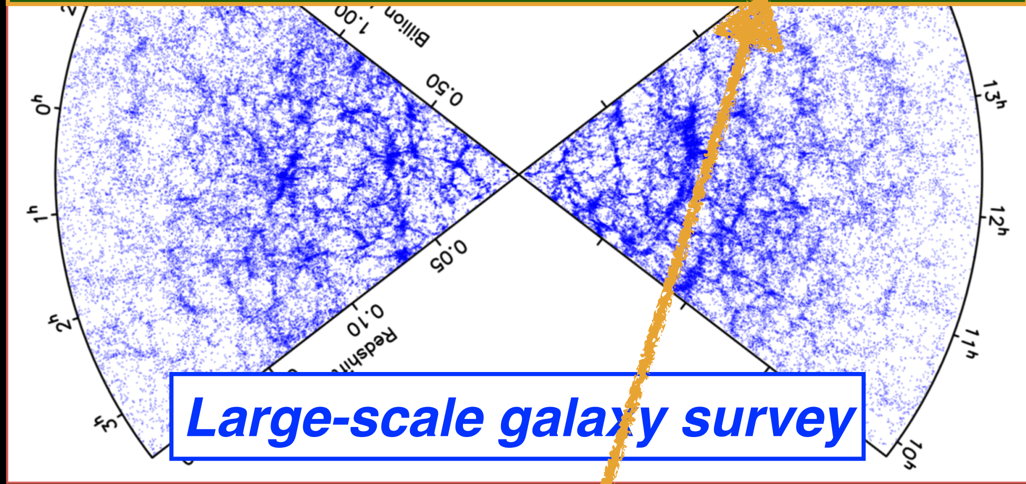
High-z SNIa appear fainter than local counterparts

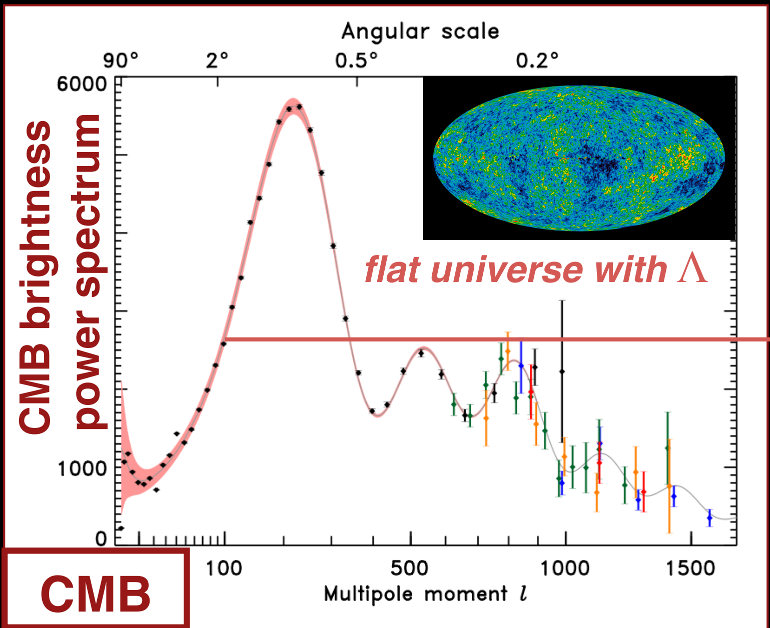
How abundant is dark matter?
— not an independent question!

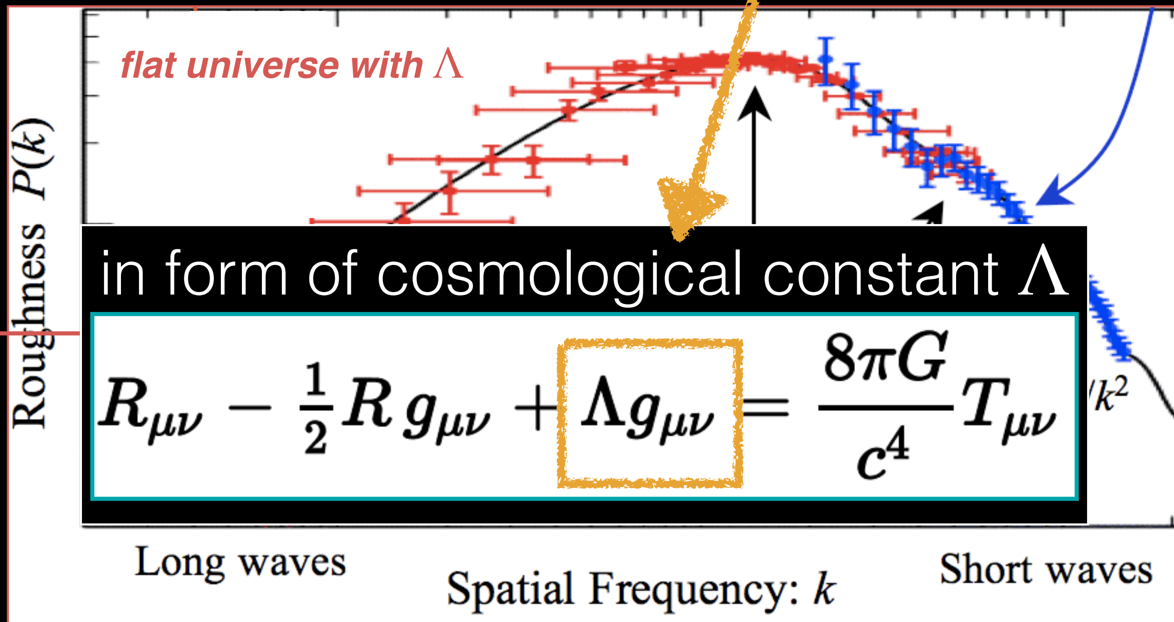


Perlmutter, Riess, Schmidt 98,99
SNIa cosmological distances to z=1

We need a new ingredient that causes *acceleration of cosmic expansion* and we named it — the *Dark Energy*







in form of cosmological constant Λ

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \boxed{\Lambda g_{\mu\nu}} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

How abundant is dark energy Λ?

Observations indicate $\rho_\Lambda \sim 0.7\,\rho_{\rm cr}$ (today)

Where is dark energy?

- $\rho_\Lambda \sim 0.7\,\rho_{\rm cr} \sim 7 \times 10^{-30}{\rm g/cm^3}$ (today)
- $\rho_{\rm galaxy} \sim 200\rho_{\rm cr} \sim 2 \times 10^{-27}{\rm g/cm^3}$ (today)
- $\rho_{\rm water} \sim 1{\rm g/cm^3}$

To accumulate similar amount of dark energy as that of dark matter in galaxies, we can equal: $\rho_\Lambda r_{\rm LS}^3 \sim \rho_{\rm galaxy} r_{\rm galaxy}^3$. This gives $r_{\rm LS} \sim 6.6 r_{\rm galaxy} \sim 1-2{\rm Mpc}$, meaning that dark energy can only dominate at above Mpc scales.

What is dark energy?

Observations at cosmological scales require a substance that causes the observed cosmic acceleration.

According to GR, this will translate into a requirement that $\ddot{a} \propto -(\rho + 3P) > 0$, which essentially put constraints on the dark-energy equation of state: $w = P/\rho < -1/3$ (assuming $c = 1$ here and throughout this lecture). *Dark energy* is then the substance with w that meets this requirement.

Einstein introduced a cosmological constant Λ, assigning it with a positive density and a negative pressure, i.e., $\rho_\Lambda > 0$, $P_\Lambda = -\rho_\Lambda$ ($w = -1$).

标准宇宙学模型

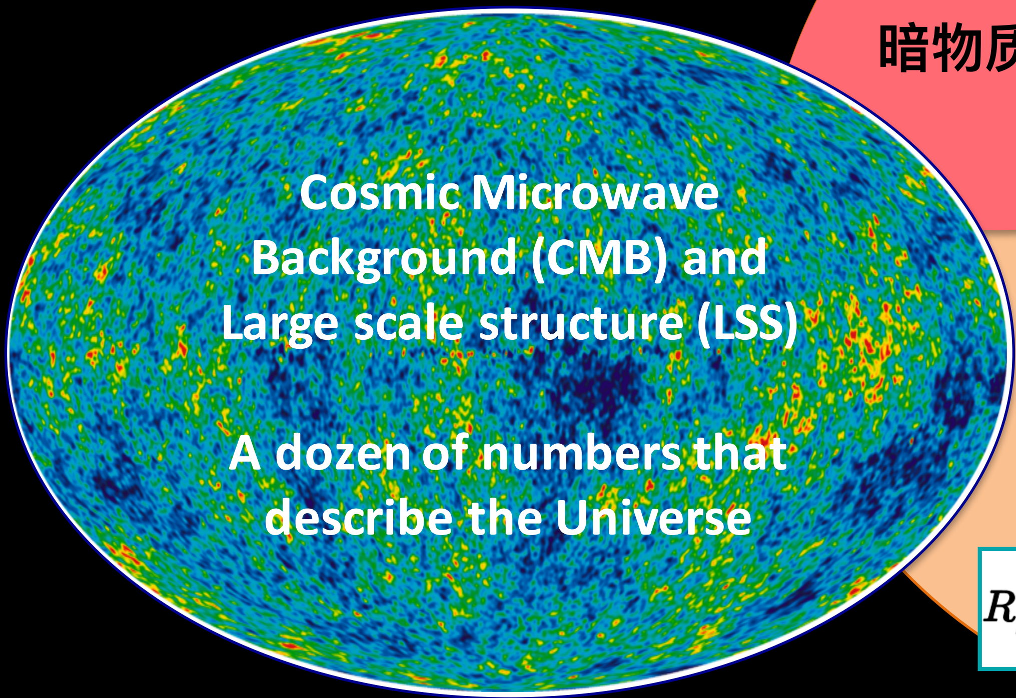
An almost complete description of the Universe

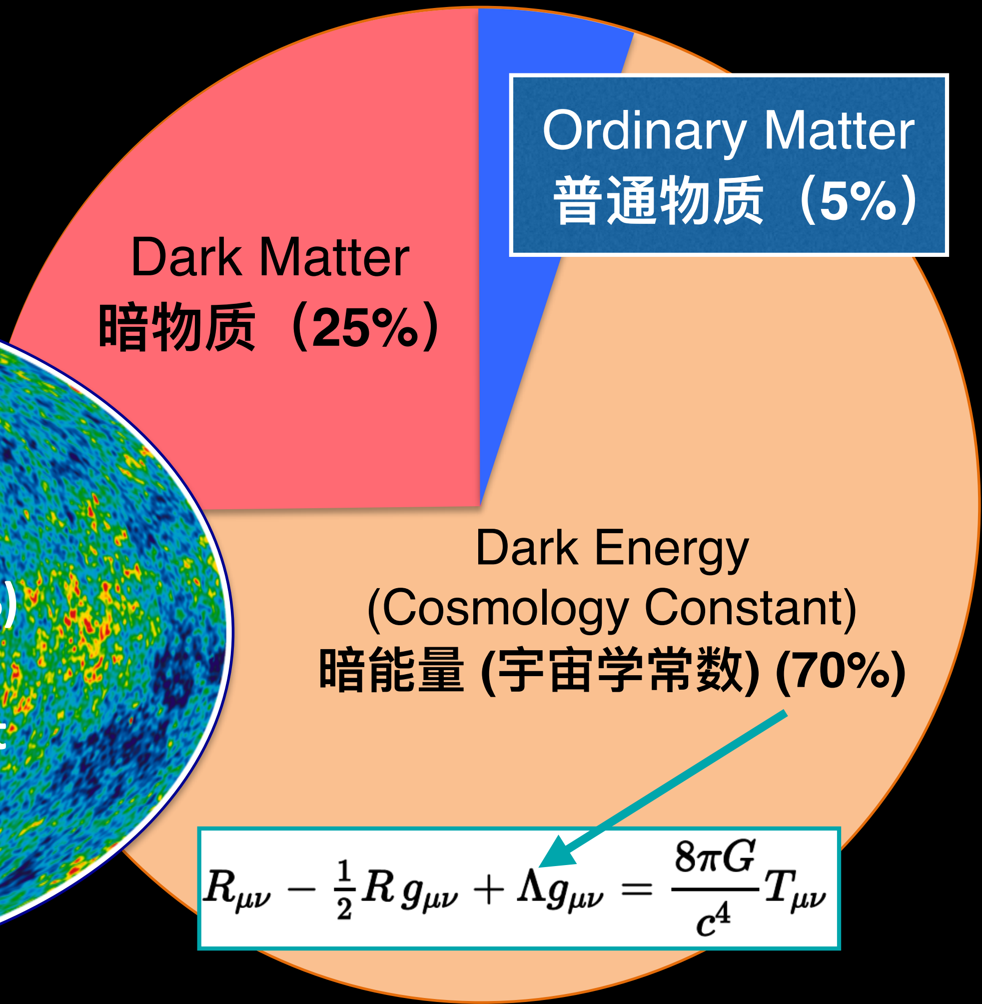
A consistent (and convenient) story…

ΛCDM
Inflation + Big Bang
Hierarchical formation
General Relativity

宇宙学参数
Cosmological Parameters

$\Omega_b h^2$	Baryonic matter density
$\Omega_c h^2$	Dark matter density
Ω_{tot}	Total matter density
w	Dark energy *EOS*
H_0	Hubble Constant





$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

宇宙物质能量组分整体动力学演化

A consistent (and convenient) story…

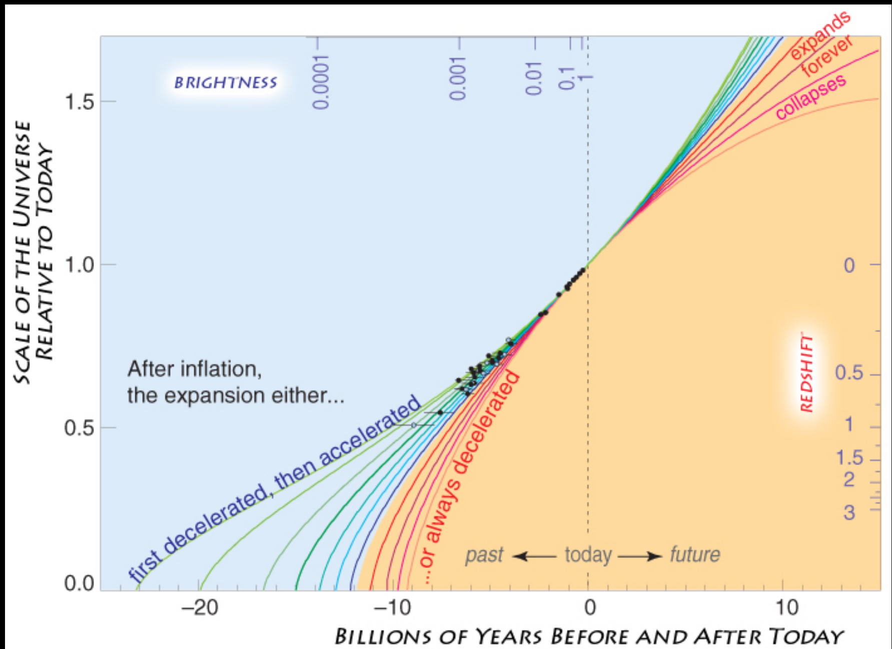
Inflation era: $\rho_{\text{vac}}(a) \propto \text{const} \quad a(t) \propto \exp(Ht)$

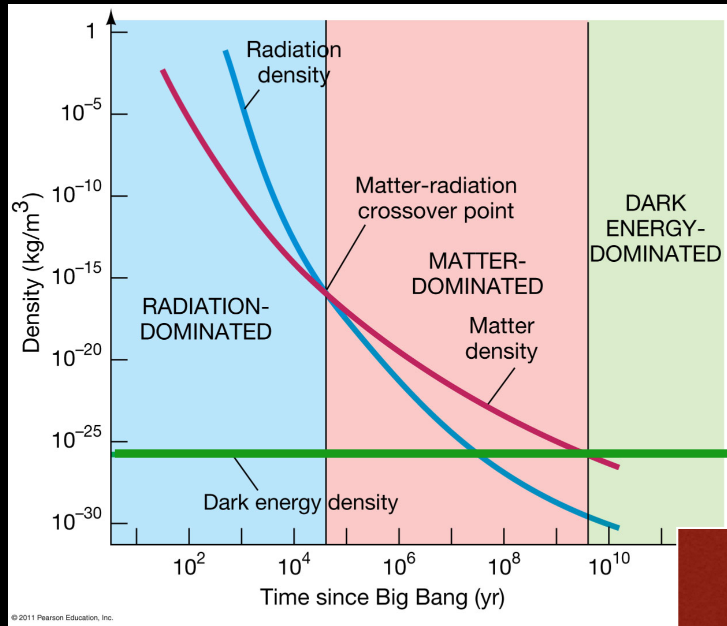
Radiation era: $\rho_{\text{rad}}(a) \propto a^{-4} \quad a(t) \propto t^{1/2}$

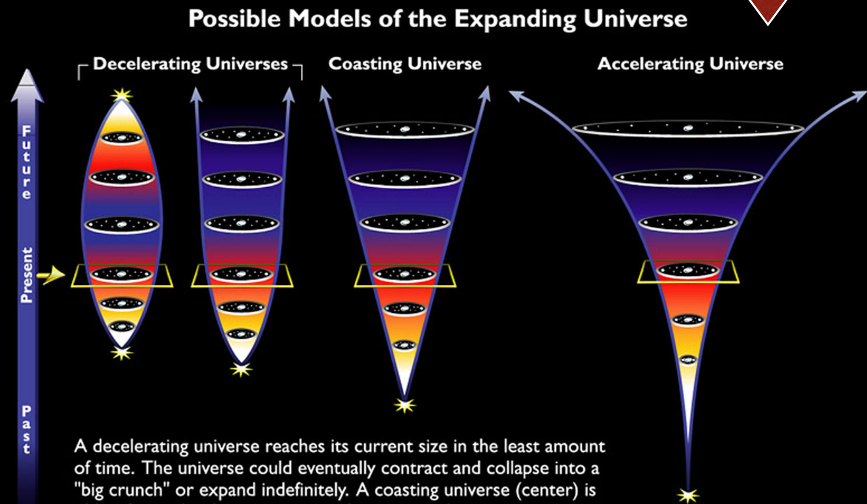
Matter era: $\rho_{\text{m}}(a) \propto a^{-3} \quad a(t) \propto t^{2/3}$

Dark energy era: $\rho_{\Lambda}(a) \propto \text{const} \quad a(t) \propto \exp(Ht)$

* *a is an expansion factor, called the scale factor.*



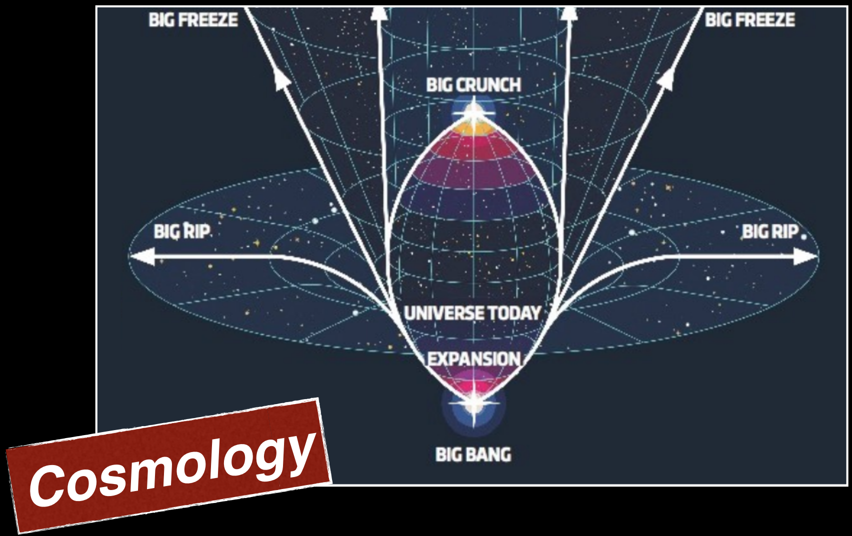




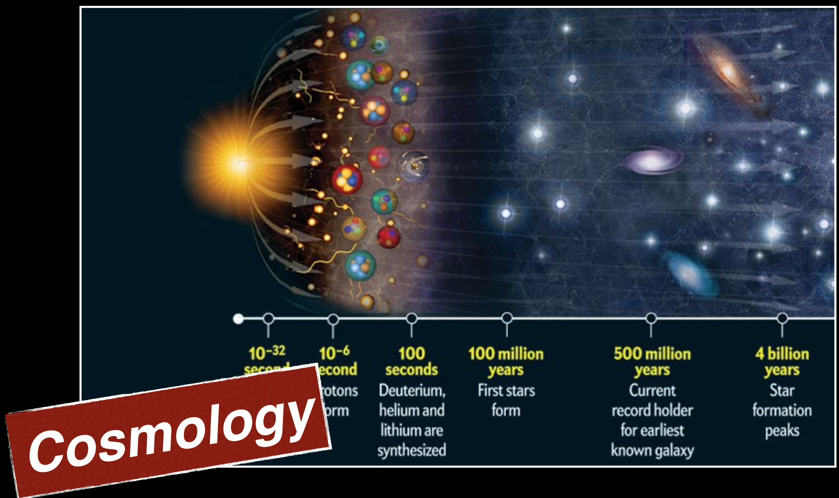
A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.

The matter/energy content decides (1) the geometry of the Universe, which affects the expansion rate $\dot{a}/a$; (2) the acceleration of cosmic expansion $\ddot{a}$, which is independent of the geometry [*as shall be seen in Friedman equations, think why so*].

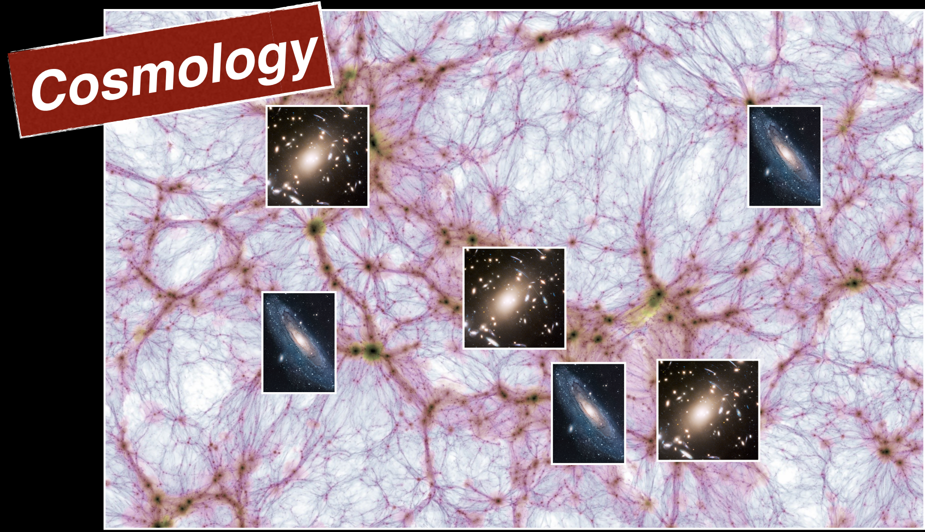
宇宙物质能量组分整体动力学演化



宇宙早期物质组分的热学演化



宇宙结构的形成：
起源于原初密度扰动（微观->宏观）



Linear perturbation theory

- Superhorizon scales (超视界)
- Subhorizon scales (亚视界)

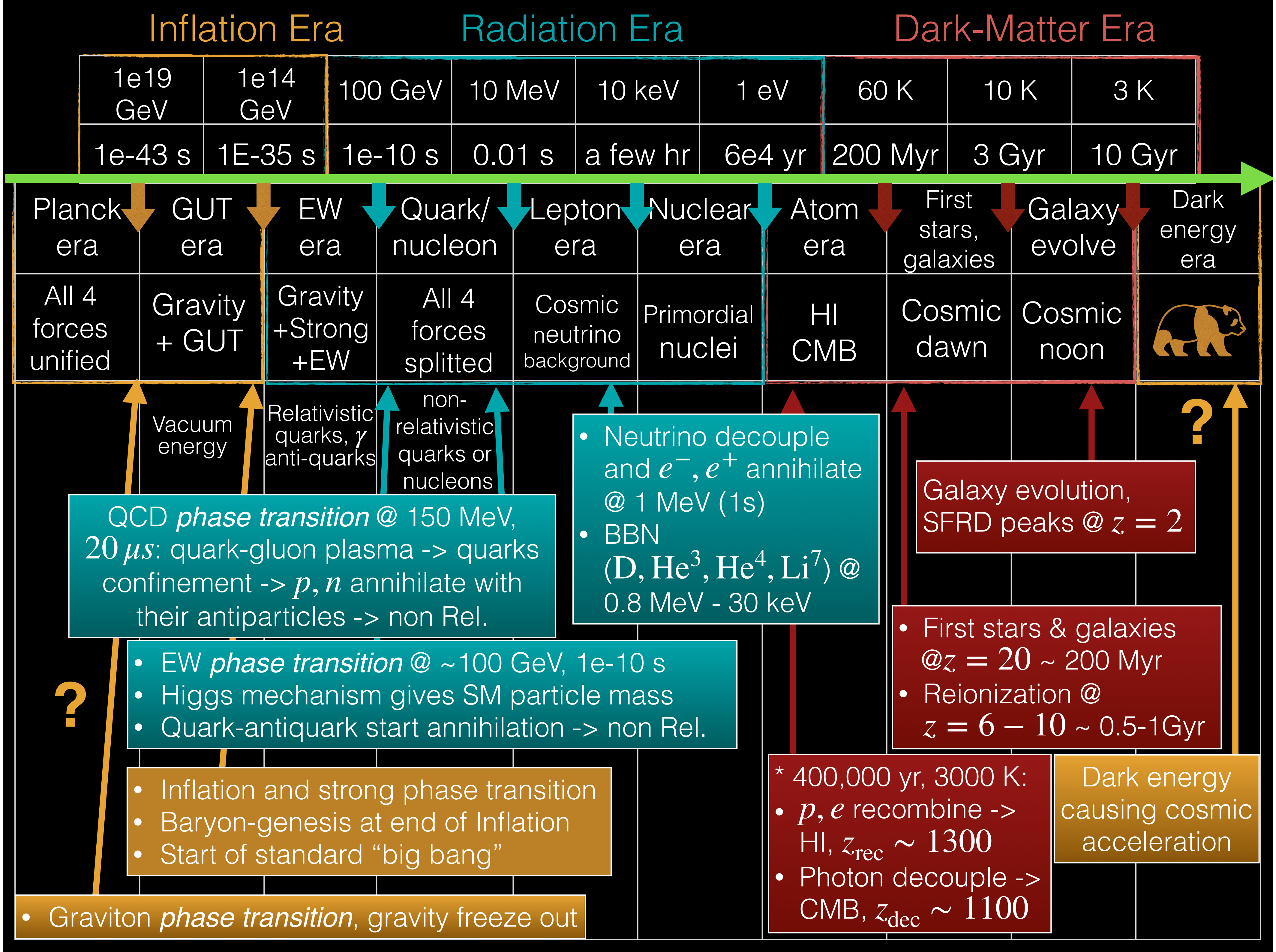
Galaxy formation and evolution

Non-linear (mass-dependent) cosmic structure formation：

1. Halo and galaxy formation
2. Hierarchical structure growth via merger and accretion

Formation of a massive "late-type", star-forming disk galaxy in a 500 kpc region: rapid ongoing star formation in an extended, clumpy disk, a late-time merger (at z ~ 0.3) with a nearly equal mass companion (IlustrisTNG simulation).

Formation of an "early-type", quiescent elliptical galaxy in a 1 Mpc region:
a large number of galaxy mergers which bring in stars and other material,
building up the final spheroidal morphology (IlustrisTNG simulation).



Inflation Era
Radiation Era
Dark-Matter Era
1e19 GeV
1e14 GeV
100 GeV
10 MeV
10 keV
1 eV
60 K
10 K
3 K
1e-43 s
1E-35 s
1e-10 s
0.01 s
a few hr
6e4 yr
200 Myr
3 Gyr
10 Gyr
Planck era
GUT era
EW era
Quark/ nucleon
Lepton era
Nuclear era
Atom era
First stars, galaxies
Galaxy evolve
Dark energy era
All 4 forces unified
Gravity + GUT
Gravity +Strong +EW
All 4 forces splitted
Cosmic neutrino background
Primordial nuclei
HI CMB
Cosmic dawn
Cosmic noon
Vacuum energy
Relativistic quarks, γ anti-quarks
non-relativistic quarks or nucleons
?
• Neutrino decouple and e^-, e^+ annihilate @ 1 MeV (1s)
• BBN $(\mathrm{D}, \mathrm{He}^3, \mathrm{He}^4, \mathrm{Li}^7)$ @ 0.8 MeV - 30 keV
Galaxy evolution, SFRD peaks @ $z = 2$
QCD *phase transition* @ 150 MeV, $20\,\mu s$: quark-gluon plasma -> quarks confinement -> p, n annihilate with their antiparticles -> non Rel.
• First stars & galaxies @$z = 20$ ~ 200 Myr
• Reionization @ $z = 6 - 10$ ~ 0.5-1Gyr
?
• EW *phase transition* @ ~100 GeV, 1e-10 s
• Higgs mechanism gives SM particle mass
• Quark-antiquark start annihilation -> non Rel.
* 400,000 yr, 3000 K:
• p, e recombine -> HI, $z_{\rm rec} \sim 1300$
• Photon decouple -> CMB, $z_{\rm dec} \sim 1100$
Dark energy causing cosmic acceleration
• Inflation and strong phase transition
• Baryon-genesis at end of Inflation
• Start of standard “big bang”
• Graviton *phase transition*, gravity freeze out

Current standard cosmological model LCDM

~ but a consistent and convenient story…

The 3 basic ingredients in cosmology model:

1. *Dark matter*
2. *Dark energy*
3. *Gravity*

课后阅读：

1. *THE 1920 SHAPLEY-CURTIS DISCUSSION: BACKGROUND, ISSUES, AND AFTERMATH:* Virginia Trimble, 1995, Publications of the Astronomical Society of the Pacific, Volume 107, 1133
2. *Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant:* Freedman et al. 2001, ApJ, Volume 553, Issue 1, 47
3. *Cosmology* (S. Weinberg) 1.3 & 1.6 (distances at small and large redshifts)

课程基本内容简介：

课程编号：**70430213** - 课程名称：物理宇宙学 - 英文名称：**Physical Cosmology**

课程类型：研究生专业基础课 - 总学时：48 - 学分：3

适用对象：天体物理专业及数理方向研究生或高年级本科生

先修课程：基础物理四大力学。建议在观测天文学、热力学与统计物理、量子力学和广义相对论方面有一定知识基础（已修或自学）。

1. 基本内容及目标：

（1）了解标准宇宙学模型的内涵、大爆炸理论的产生背景及经典观测证据；

（2）了解早期宇宙的热物理过程及观测特征，其中包括：

- 宇宙暴涨理论的发展历史、物理过程及经典观测证据；
- 从中微子退耦到大爆炸原初核合成的物理过程；
- 氢原子复合到宇宙微波背景辐射产生的物理过程；
- 宇宙微波背景辐射揭示的重要物理图像。

（3）了解宇宙学框架下的各种距离与时间的定义；

（4）掌握描述宇宙时空几何与动力学演化的FRW度规和Friedmann方程；
会求解宇宙不同组分主导时期的动力学过程；计算给定红移的宇宙距离和时间；

（5）了解宇宙结构的形成和线性演化；

（6）了解主流的宇宙学的探针（观测方法论的基础和核心部分）。

课程基本内容简介：

2. 推荐教材和参考书：

- Kurki-Suonio Cosmology (电子教材)
- Steven Weinberg, Cosmology, Oxford University Press, 2008
- Scott Dodelson, Modern Cosmology, Academic Press, 2003

3. 考核方式：

- 平时作业：5次，共占30%。
- 课堂分组报告：占10%。
- 期中考试：1次，占30%，闭卷笔试考试。
- 期末考试：1次，占30%，闭卷口试考试。

4. 开放时间及联系方式：

- 物理楼E221，周二下午1:30-3:00
- email：dandanxu@tsinghua.edu.cn

群聊: 物理宇宙学
2024秋

该二维码7天内(9月16日前)有效，重新进入将更新

教学日历

第一周（9.11）：标准宇宙学模型简介
第二周（9.18）： 广义相对论回顾
第三周（9.25）：整体演化主线之动力学演化-I:
第四周（10.9）：整体演化主线之动力学演化-II:
第五周（10.16）：整体演化主线之动力学演化-III:
第六周（10.23）：整体演化主线之动力学演化– IV:
第七周（10.30 -> 10.26）： 整体演化主线之早期热历史 - I:
第八周（11.6）：整体演化主线之早热历史 - II:
第九周（11.13）：整体演化主线之早期热历史 – III: 期中考试（随堂）
第十周（11.20）：整体演化主线之早期热历史 – IV:
第十一周（11.27）：特邀报告 — 现代宇宙学观测及统计方法 （赵成）
第十二周（12.4）：扰动演化主线之微观扰动
第十三周（12.11）：扰动演化主线之超视界宏观扰动:
第十四周（12.18）：扰动演化主线之亚视界宏观扰动:
第十二周（12.25）：宇宙学探针（反转课堂）

"The more the universe seems comprehensible, the more it also seems pointless.....The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce, and gives it some of the grace of tragedy." — Steven Weinberg

Closing Remark

★ *Let's explore the Universe and have fun in this lecture!*

Open minded!

Hard working!