The Standard Models of Particle Physics & Cosmology

粒子与宇宙标准模型

Chao-Qiang Geng

耿朝强

日程安排	2023/6/20 周二	2023/6/21 周三	2023/6/22 周四	2023/6/23 周五	2023/6/24 周
09:00-10:30		开场报告（王贻芳）	中微子物理综述（邢志忠）	自然源中微子（王喆）	自然源中微（王喆）
10:30-11:00	注册	茶歇	茶歇	茶歇	茶歇
11:00-12:30		中微子物理综述（邢志忠）	中微子探测技术（温良剑）	粒子与宇宙标准模型（耿朝强）	量子场论与场论（廖益
12:30-14:00	午餐	午餐	午餐	午餐	午餐
14:00-15:30		中微子探测技术（温良剑）	粒子与宇宙标准模型（耿朝强）	中微子宇宙学（夏俊卿）	中微子与暗（安海鹏）
15:30-16:00	注册	茶歇	茶歇	茶歇	茶歇

Lecture 1: Introduction to Particle Physics and Cosmology

Lecture 2: Some Basic Backgrounds of the Standard Model of Particle Physics

Lecture 3: Some Basic Backgrounds of the Standard Model of Cosmology, Dark Matter, Dark Energy, Gravitational Waves and Black Holes

Outline

- Introduction
- Seven periods of modern particle physics
- Three dark clouds in modern particle physics

DC1. Cosmic microwave fluctuations
DC2. Dark energy
DC3. Neutrino oscillations

Lecture 2: Some Basic Backgrounds of the Standard Model of Particle Physics

Outline

- Introduction
- Some basic concepts
- Anomalies in four-dimension
- Uniqueness of fermion representations and charges in the standard model
- Family problem
- Broken symmetry and mass generation

Lecture 3: Some Basic Backgrounds of the Standard Model of Cosmology, Dark Matter, Dark Energy, Gravitational Waves and Black Holes

Outline

- Introduction
- Some basic concepts in cosmology
- Dark Matter
- Dark Energy
- Gravitational Waves and Black Holes

Outline

- **Introduction**
- **Seven periods of modern particle physics**
- **Three dark clouds in modern particle physics**

DC1. Cosmic microwave fluctuations
DC2. Dark energy
DC3. Neutrino oscillations

● Introduction

July 1, 2005
Science Magazine
125th anniversary

THE QUESTIONS

The Top 25

Essays by our news staff on 25 big questions facing science over the next quarter-century.

What is the Universe made of ? #1

宇宙是由什么组成的？

> How Much Can Human Life Span Be Extended?

Can the laws of physics be unified ? #5

物理定律可以统一吗？

> Are We Alone in the Universe?

27.是什么驱动宇宙膨胀？31. 黑洞的本质是什么？
32. 正物质为何多于反物质？33. 质子会衰变吗？
34. 引力的本质是什么？ 36. 夸克有结构吗？
37. 中微子是其自己的反粒子吗？

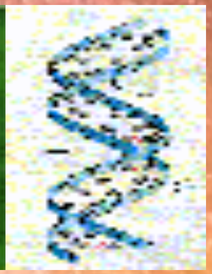
#125 Does the Standard Model of particle physics rest on solid mathematical foundations?

粒子物理的标准模型是否建构在坚固的数学基础上?

What is the Universe made of ?

宇宙是由什么组成的？

它是我們所看到的物质世界吗?



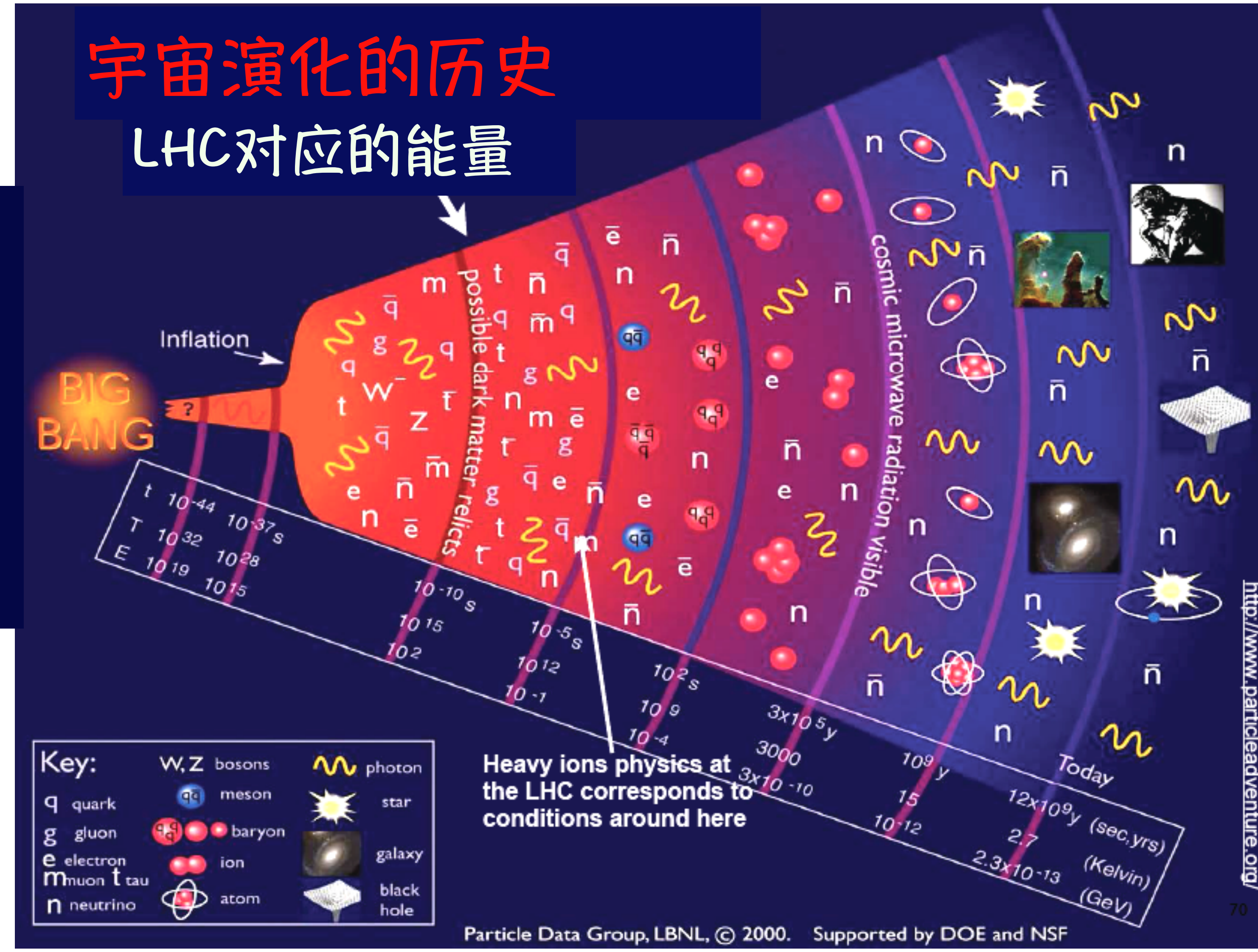
What do we know about our Universe?

我們对于宇宙了解多少 ？

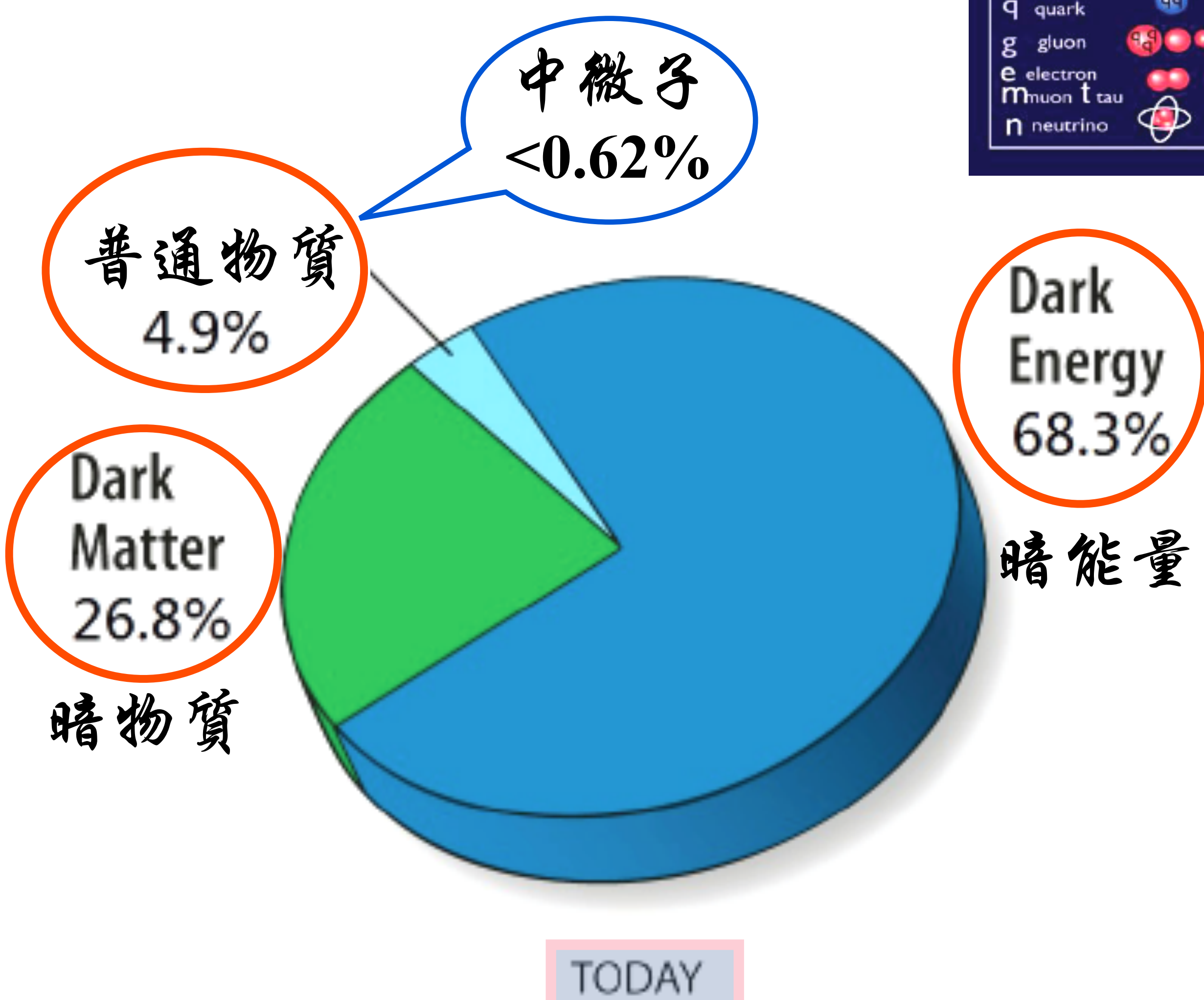
对于宇宙
知道的很多
但了解的很少

We know much but
we understand very little

微观极小



宏观极大



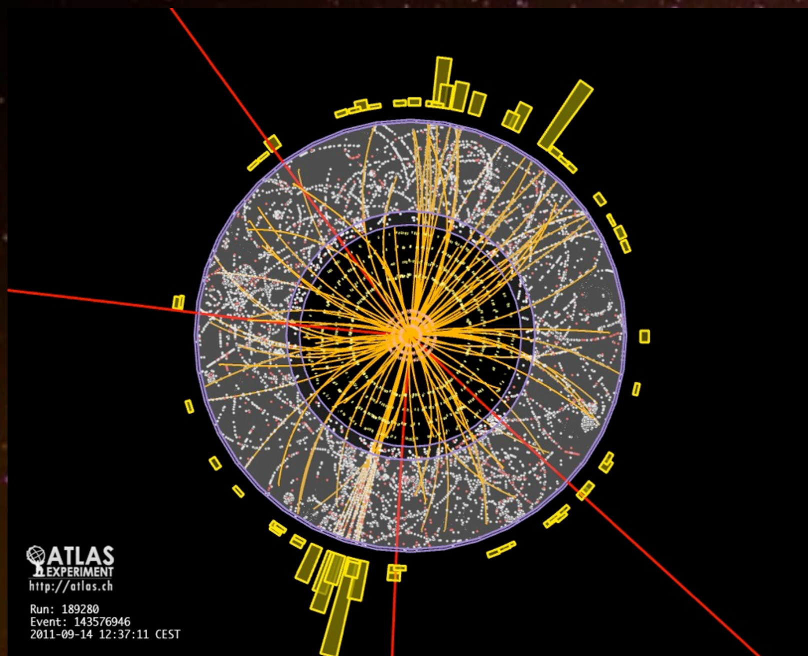
95%的宇宙物质／能量还是个迷。目前也无法在地球上最好的实验室中观测到。

95% of the cosmic matter/energy is still a mystery, which has not been observed in the best labs on Earth yet.

大尺度

展望外太空意味着回顾过去。当你看一百万光年外的星系时，你正在看它就像一百万年前一样。晚上仰望星空，就像在阅读宇宙的历史。

小尺度



观察物质内部结构，事实上也是回顾过去。今天的高能实验以尽可能高的能量将粒子碰撞在一起，以渗透到物质的最深处。能量的巨大集中导致新物质的产生，就像在宇宙开始的大爆炸后的最初时刻首次创造物质一样。

因此，高能粒子物理学中对宇宙中最小结构与宇宙学对宇宙最大结构的研究密切相关。粒子物理学和宇宙学之间的交汇点是现代物理学最迷人的方面之一。事实上，通过大爆炸的情景，宇宙学中的观测对粒子物理学产生了可检验的结果，反之亦然。

微观极小 ⟷ 宏观极大

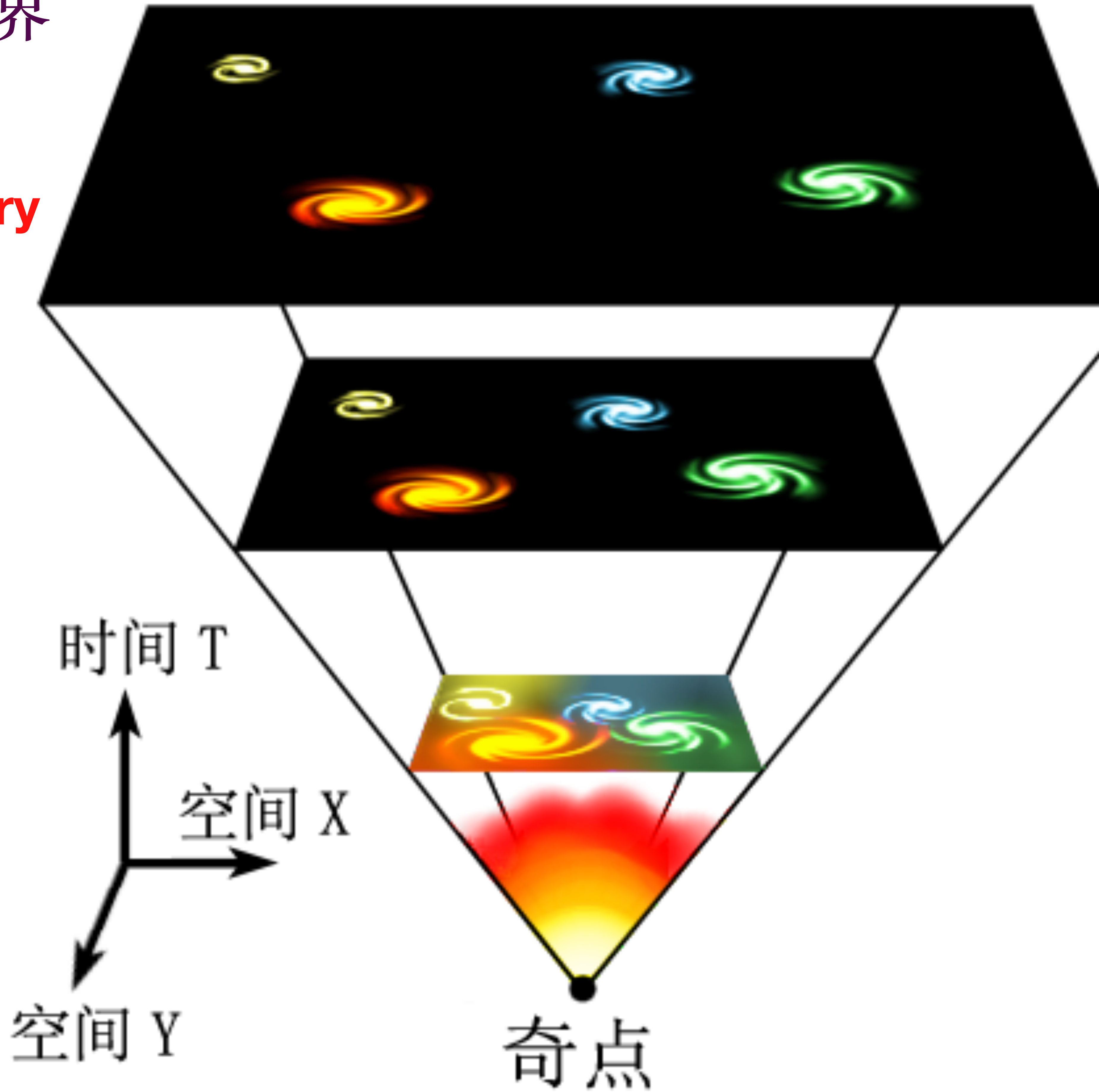
粒子物理学　　宇宙学

粒子宇宙物理：探索无穷，一边层层撩下物质的神秘面纱，揭开“无穷小”的物质结构；另一边点点将视角往外拓，发现“无穷大”的宇宙图景。

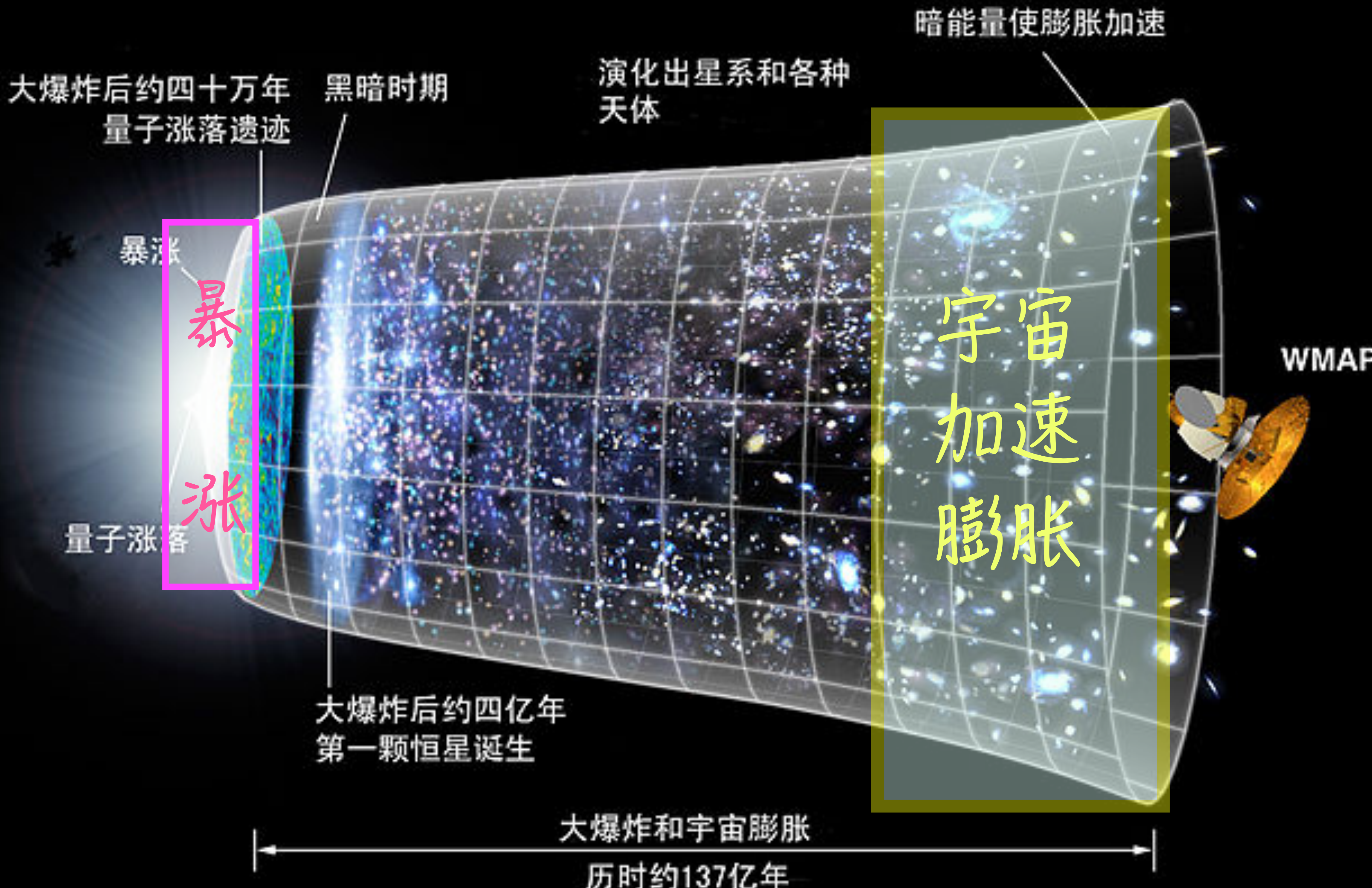
宏观极大之宇宙世界

宇宙大爆炸理论
The Big-Bang Theory

科学家将宇宙最初的形态简化为了一个密度很大的点：奇点（singularity），类似于物理学中把一个物体看作一个质点，它们都符合物理学模型的基本特点之一：简单。



宇宙演化的历史

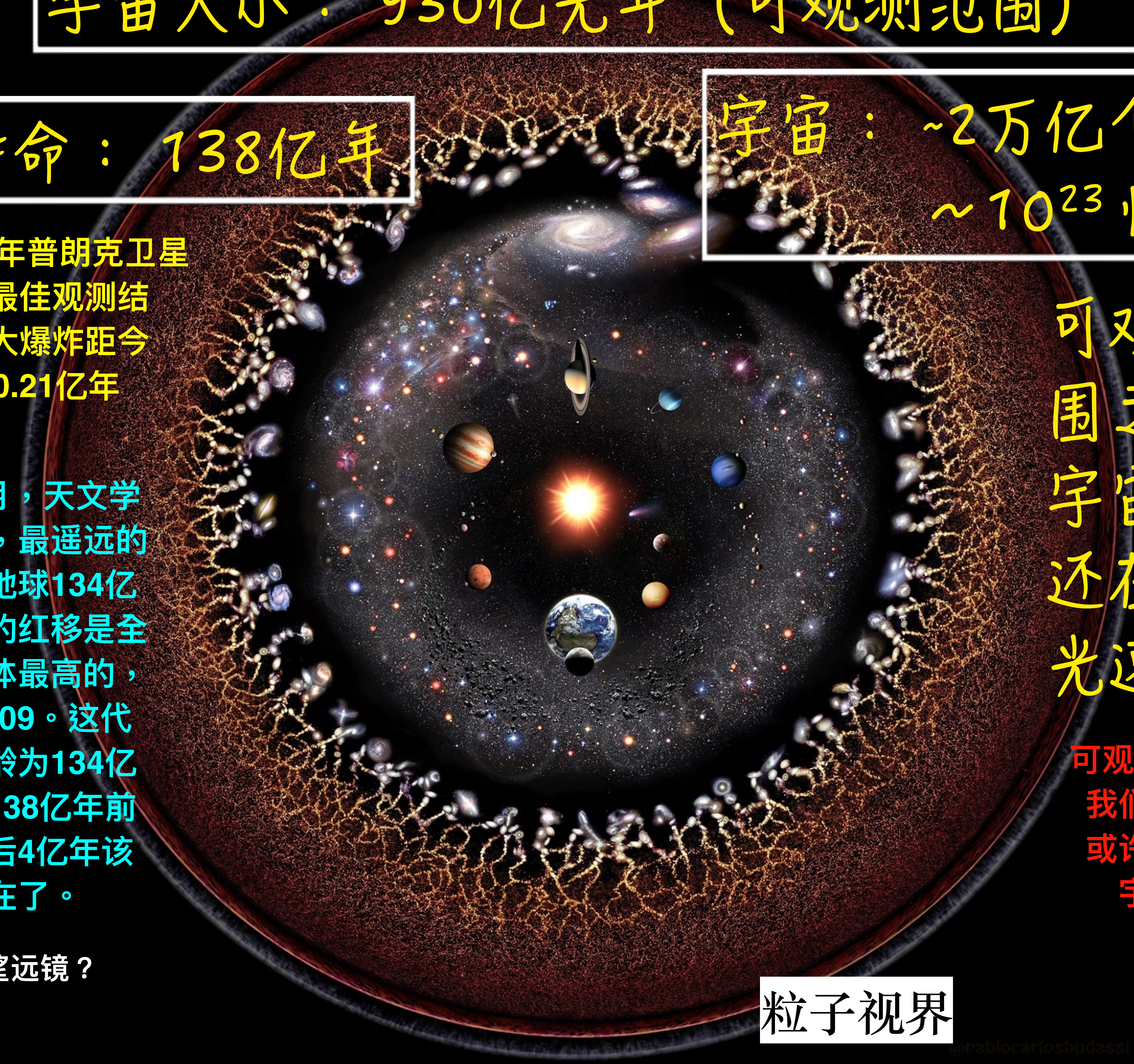

暗能量使膨胀加速
演化出星系和各种
天体
大爆炸后约四十万年
量子涨落遗迹
黑暗时期
暴涨
暴
涨
量子涨落
宇宙
加速
膨胀
WMAP
大爆炸后约四亿年
第一颗恒星诞生
大爆炸和宇宙膨胀
历时约137亿年

宇宙大小：930亿光年（可观测范围）

宇宙寿命：138亿年

宇宙：~2万亿个星系
~10^{23}恒星

根据2015年普朗克卫星所得到的最佳观测结果，宇宙大爆炸距今137.99 ± 0.21亿年



2016年8月，天文学者新发现，最遥远的天体距离地球134亿光年。它的红移是全部已知天体最高的，达到z=11.09。这代表它的年龄为134亿年，代表138亿年前大爆炸以后4亿年该星系就存在了。

韦伯太空望远镜？

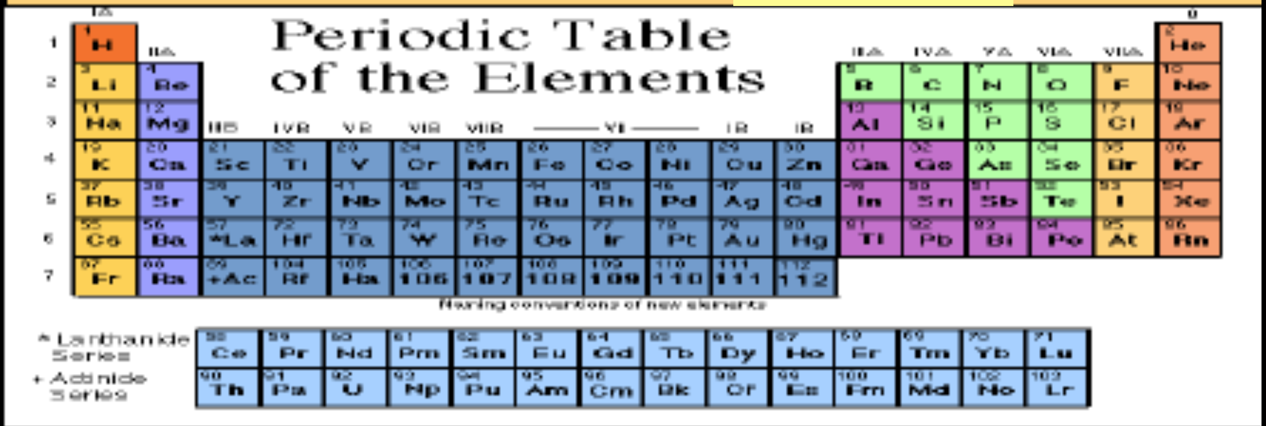
可观测范围之外，宇宙空间还在以超光速扩张

可观测宇宙之外我们一无所知或许是无尽的宇宙空间

物质世界是由什么组成的？

已知(标准)物质：四种“可见”的物质

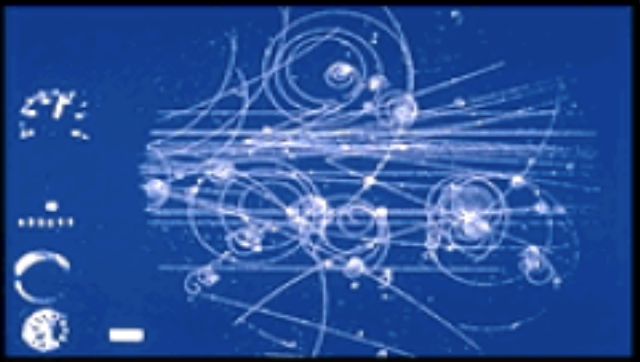
ordinary matter 普通物质



cosmic matter 宇宙物质

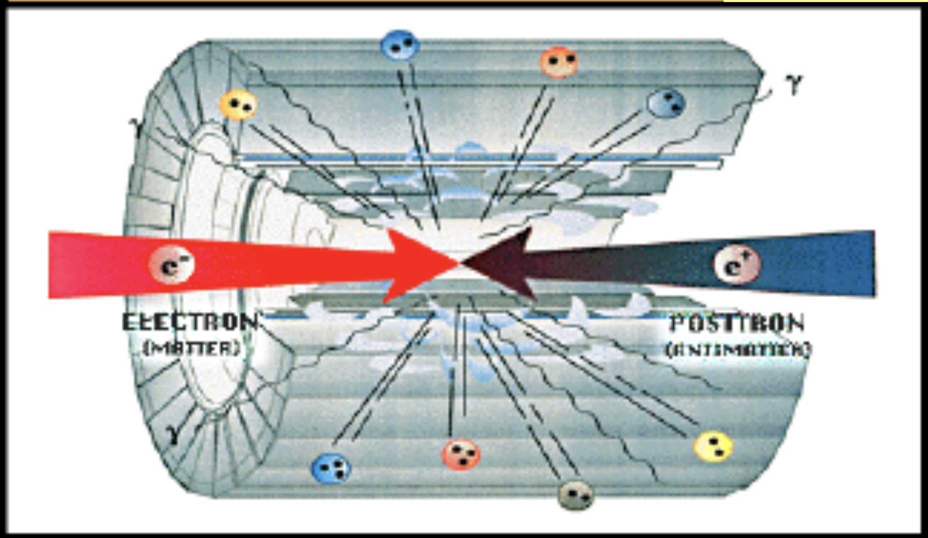
宇宙射线中存在地面上没有的物质，这些基本粒子比原子有所需的更多成分。除了电子、电子中微子、上夸克和下夸克，我们还需要μ子、μ中微子和奇夸克。

High-energy matter 高能物质



为了在更可控的条件下研究高能粒子碰撞，粒子物理学家使用欧洲粒子中心等实验室，在那里高能粒子对撞中的高能粒子碰撞所产生的能量与宇宙存在的第一瞬间中的能量相同，从而产生质量很大的高能基本粒子。

Antimatter 反物质



对于物质的每个基本粒子，还有一个镜像版本，即反粒子，其中电荷等性质与粒子相反。

> 10
诺贝尔
物理学奖

粒子物理标准模型

1979年诺贝尔物理学奖
Glashow, Weinberg, Salam

普通物質 标准物質
5%

黑格斯
玻色子

作用力

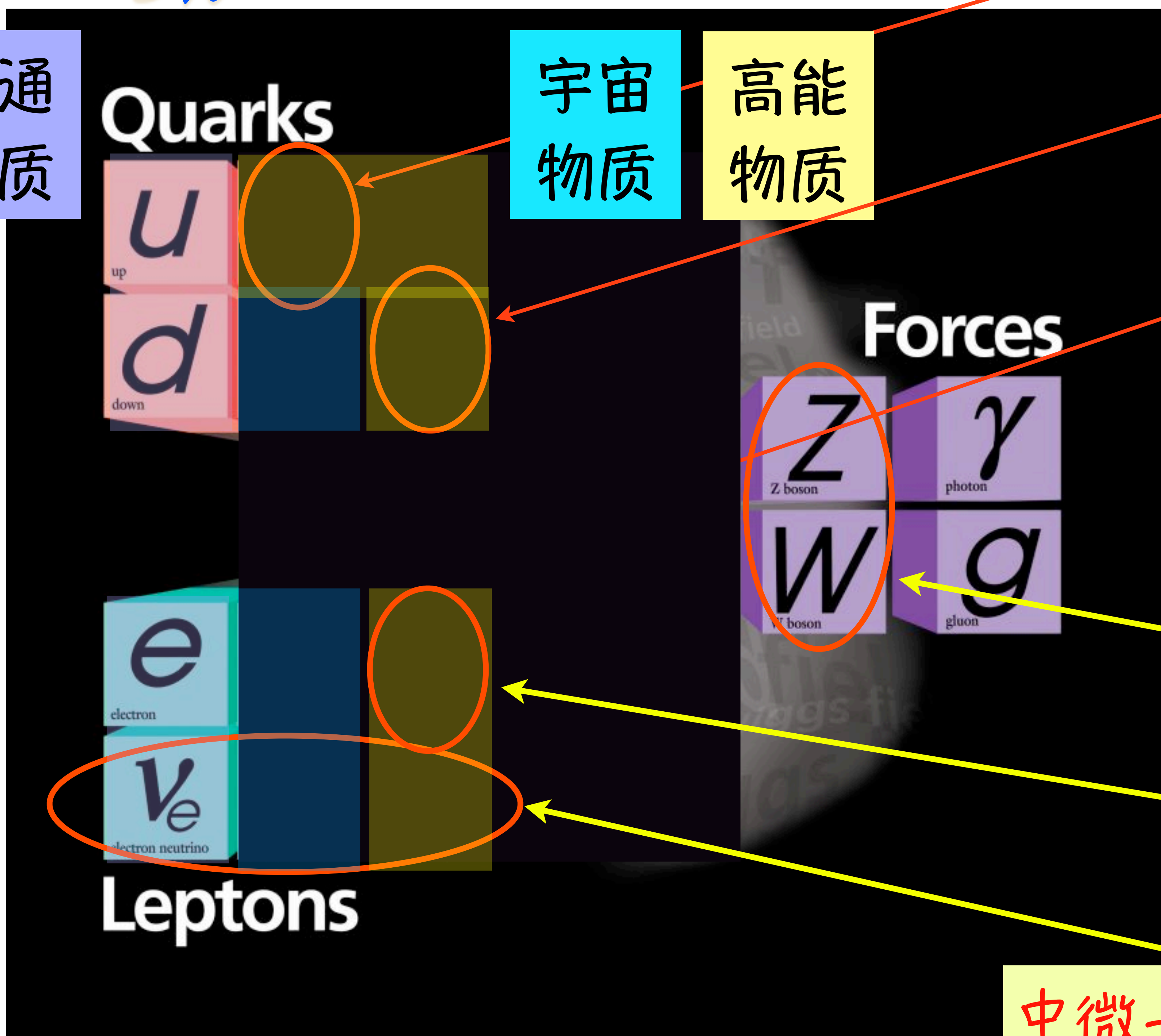
1976年诺贝尔物理学奖
丁肇中，Richter

1977年观测到
Lederman 1988年N.P

普通
物质

宇宙
物质

高能
物质



黑格斯玻色子
2012年在LHC实验观测
2013年诺贝尔物理学奖
Englert & Higgs

标准模型的最后一个基本粒子

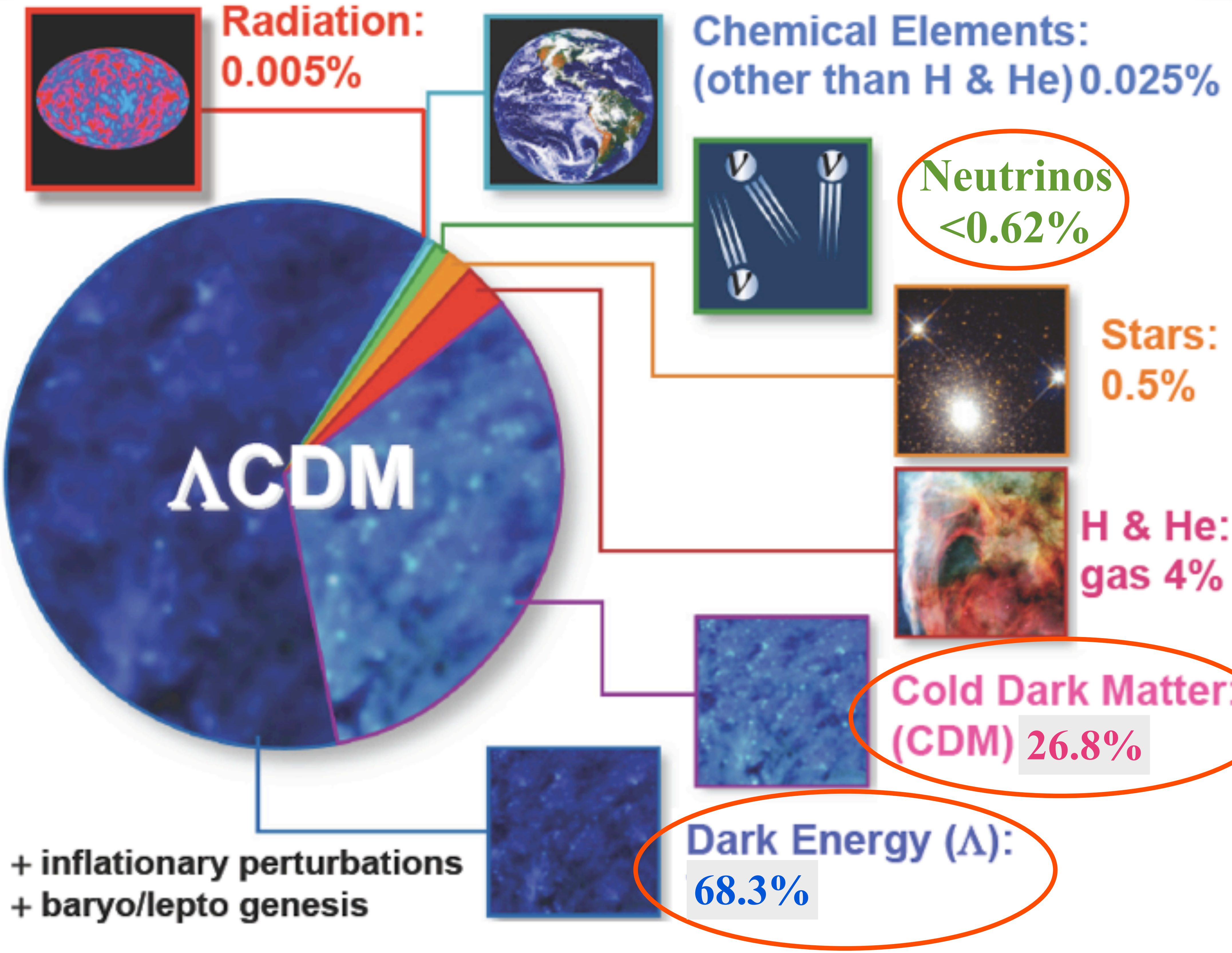
1984年诺贝尔物理学奖
C. Rubbia

1995年诺贝尔物理学奖
M. Perl

中微子

1988，1995，2002，2015年
诺贝尔物理学奖

"The Standard Model" in Cosmology



+ inflationary perturbations
+ baryo/lepto genesis

• Seven periods of modern particle physics

Modern Particle Physics: 7 Periods

1. ***< 1945 -- Pre-Modern Particle Physics Period***
2. ***Startup Period (1945 -- 1960) : Early contributions to the basic concepts of modern particle physics.***
3. ***Heroic Period (1960 -- 1975):Formulation of the standard model of strong and electroweak interactions.***
4. ***Period of Consolidation and Speculation (1975 -- 1990): Precision tests of the standard model and theories beyond the standard model.***
5. ***"Frustration" and "Waiting" Period (1990 -- 2005)***
6. ***Preparation Period (2005--2020)***
7. ***Super-Heroic Period (2020--2035)***

英雄歲月

一暗一黑
暗物质、黑洞

3 Dark Clouds 三朵烏雲

1992: Cosmic microwave fluctuations (2006 Nobel Prize)
1998: Dark energy (2011 Nobel Prize)
1998,2001: Neutrino oscillations (2015 Nobel Prize)

+ something unexpected?

LHC: ...
GW: LISA，太極，天琴 *2030*
100 TeV Collider *2030*

● Three dark clouds in modern particle physics

三朵烏雲

In the 5th period of ``Frustration” and ``Waiting” (1990- 2005):

DC1. Cosmic microwave fluctuations (1992→2006 Nobel Prize)

DC2. Dark energy (1998→2011 Nobel Prize)

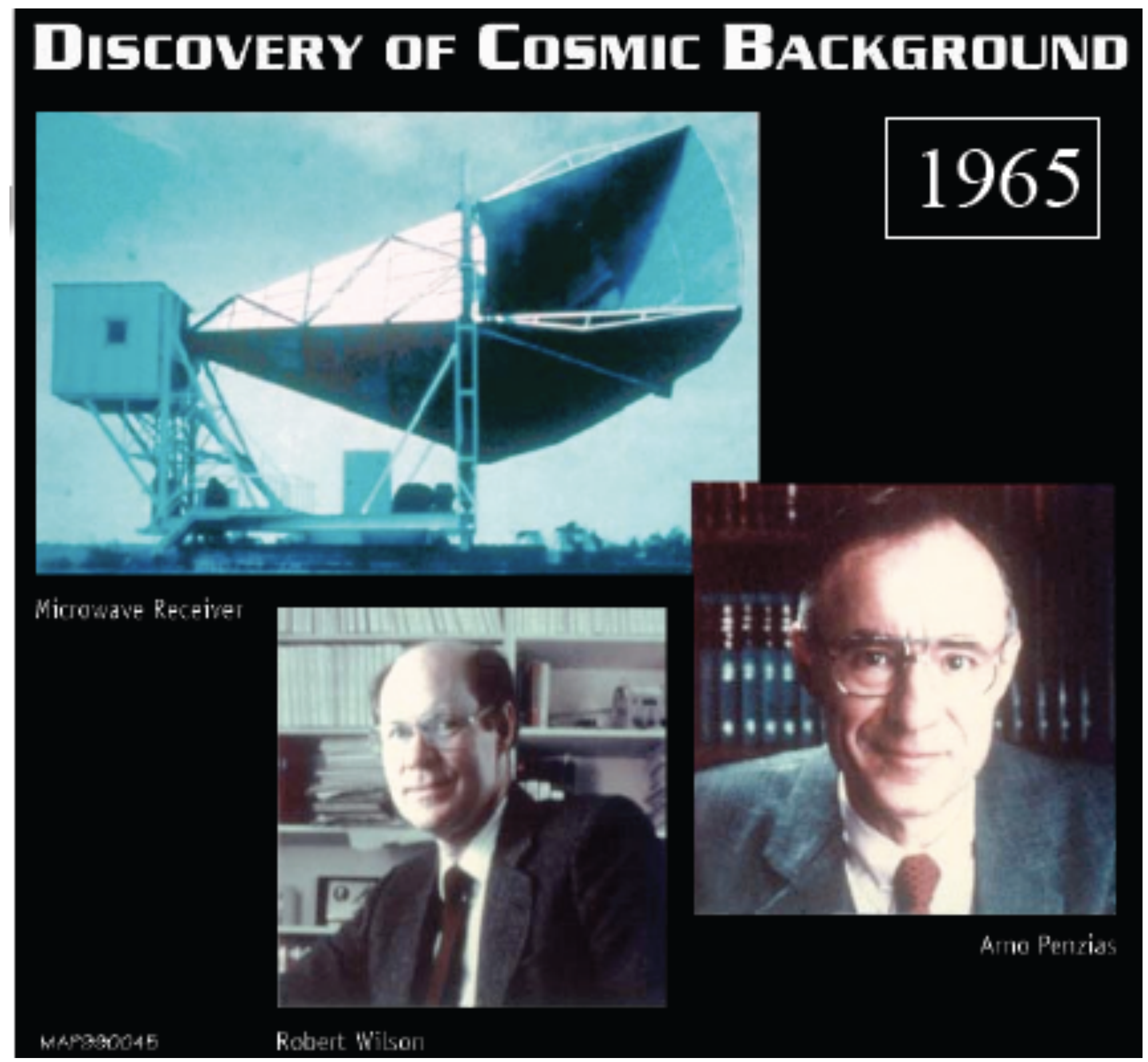
DC3. Neutrino oscillations (1998-2001→2015 Nobel Prize)

DC1. Cosmic microwave fluctuations

Cosmic Microwave Background (CMB)

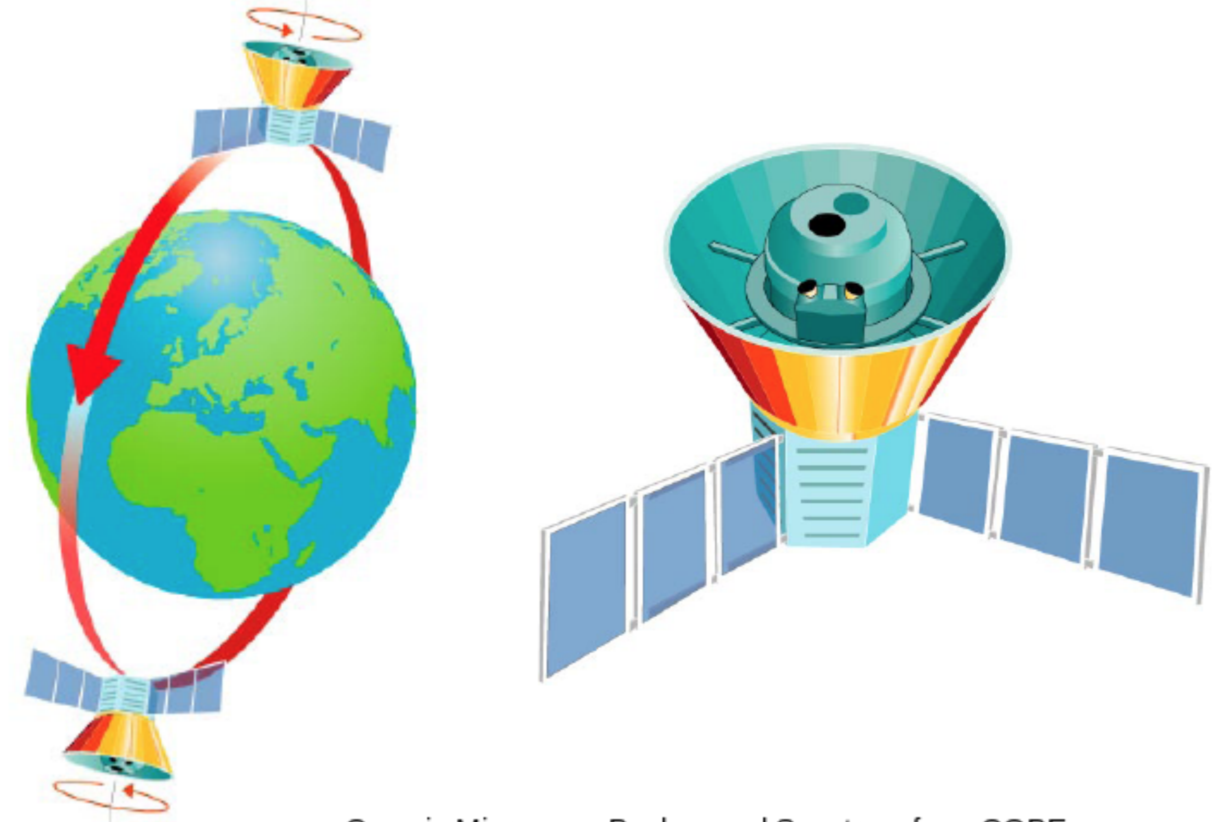
very cold (-270.275 C, 2.725 K) and nearly uniform relic radiation left over from the hot big bang

1965 英雄歲月 → Physics Nobel Prize 1978

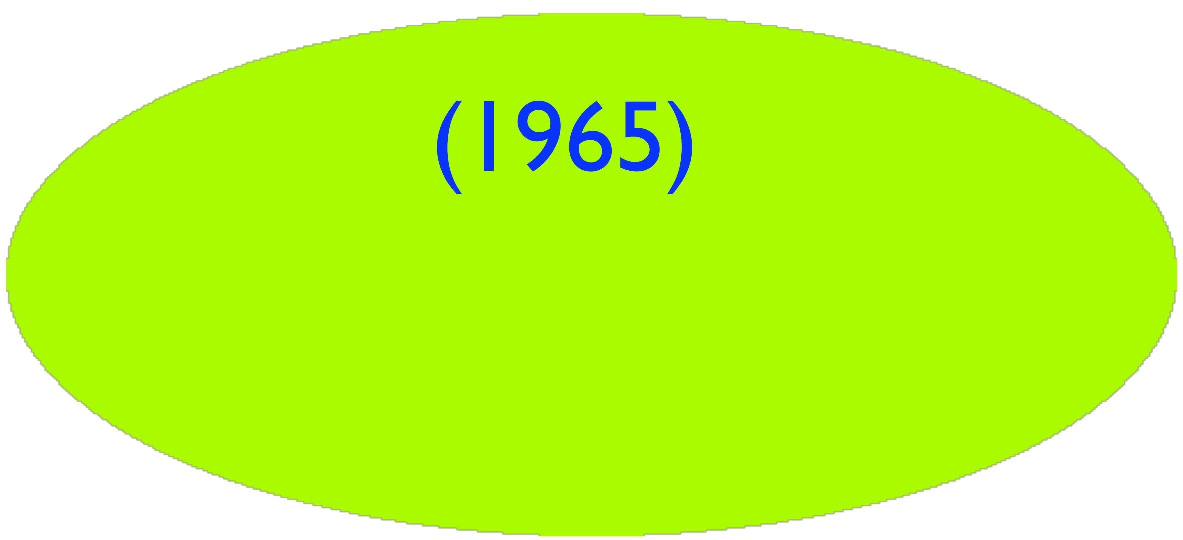


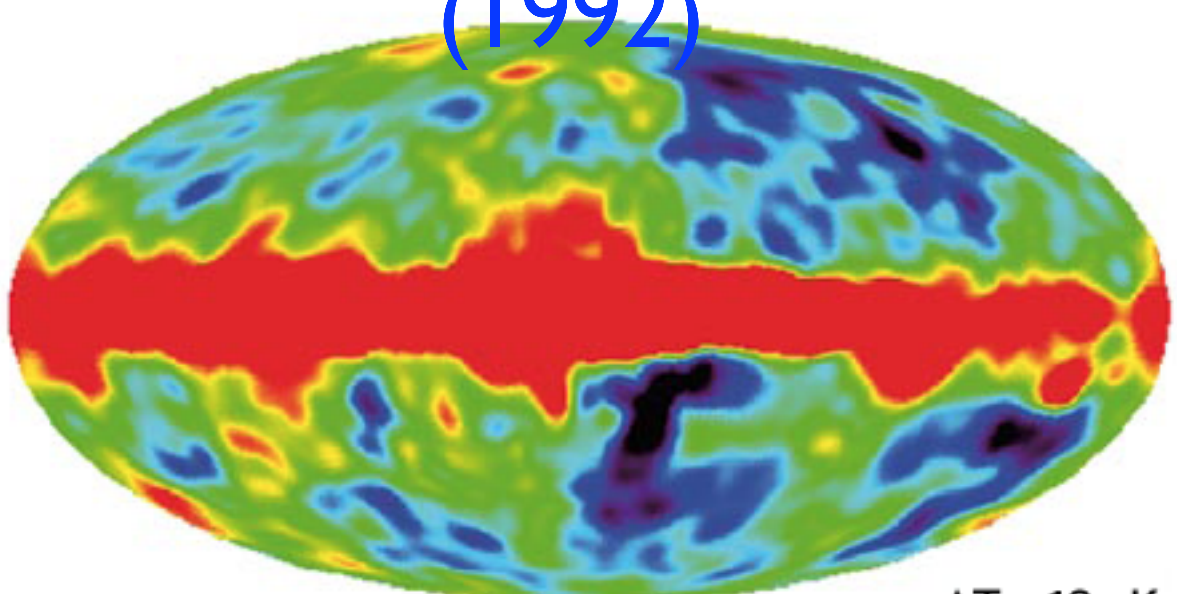
Cosmic Microwave Background

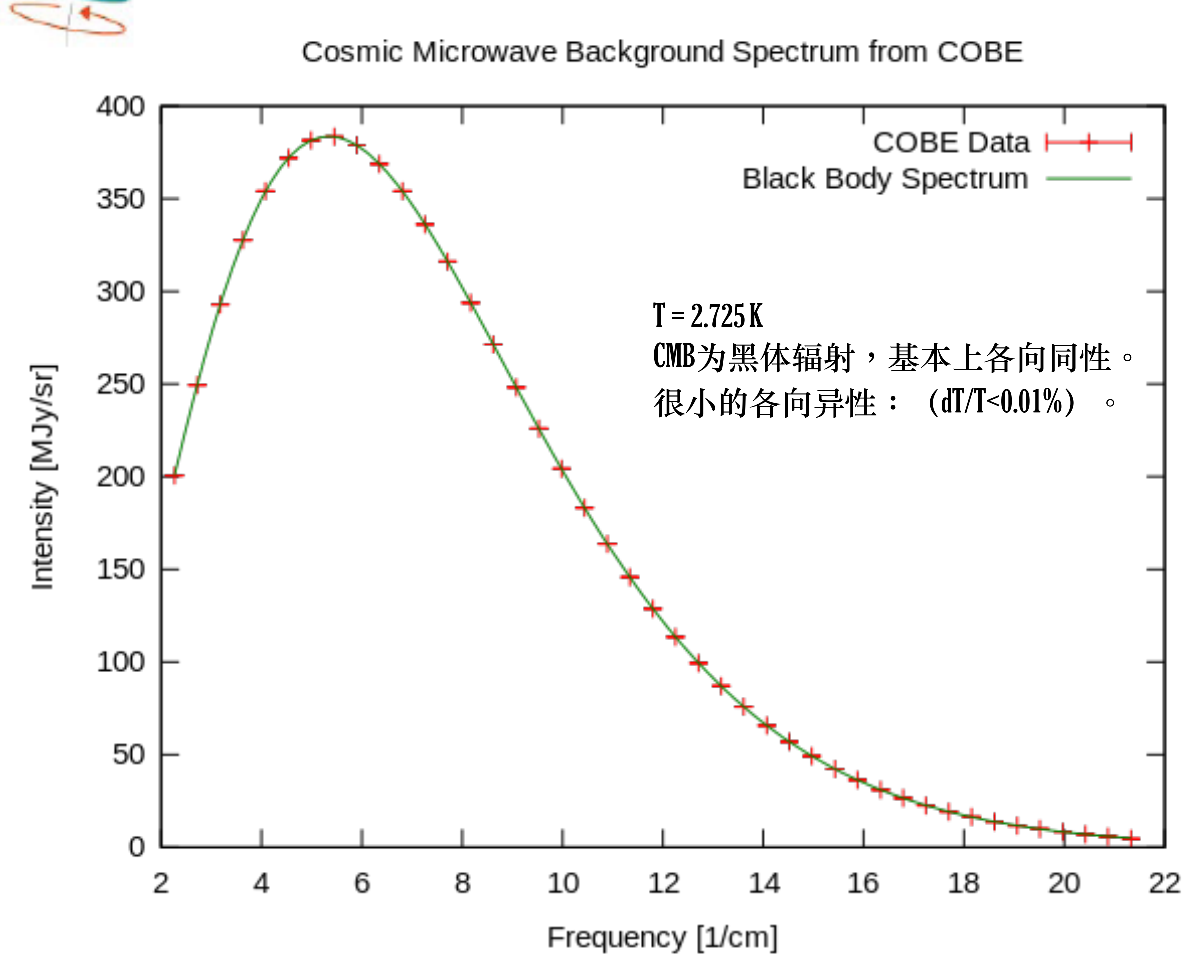
The COBE satellite (1992) enabled measurement of the CMB in all directions.



If you had microwave eyes:







$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

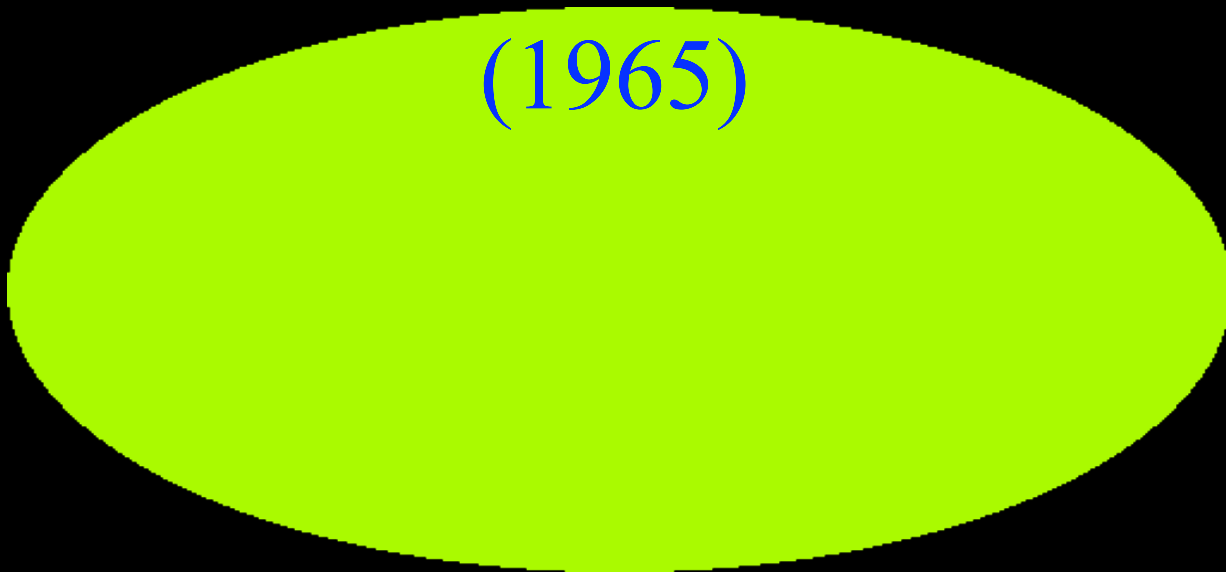
The Nobel Prize
in Physics 2006

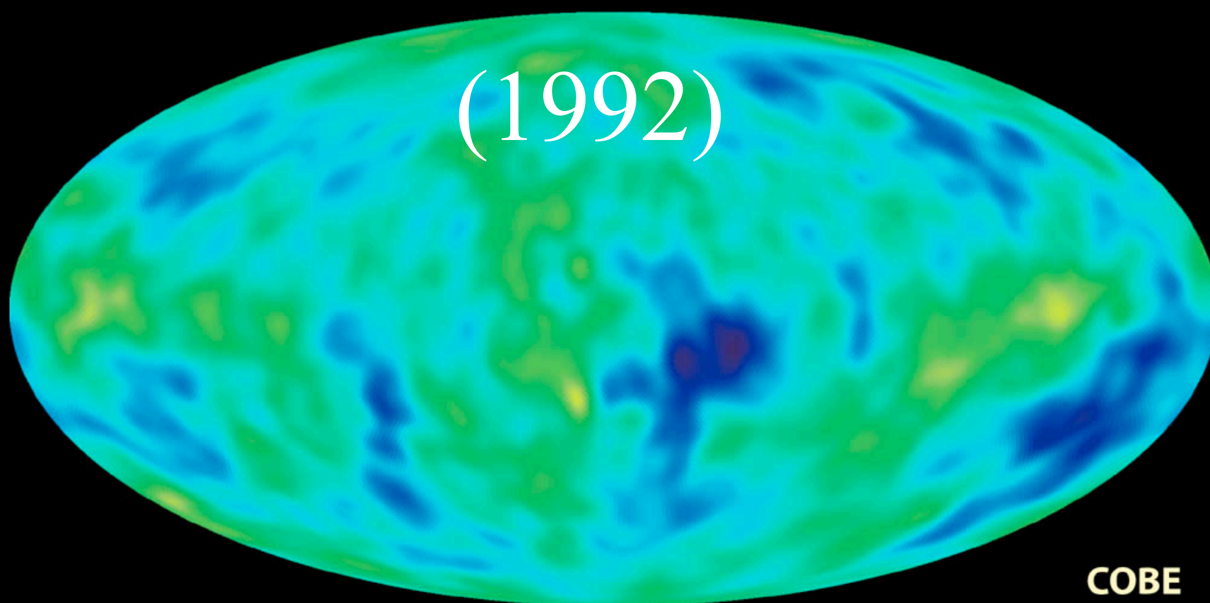
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

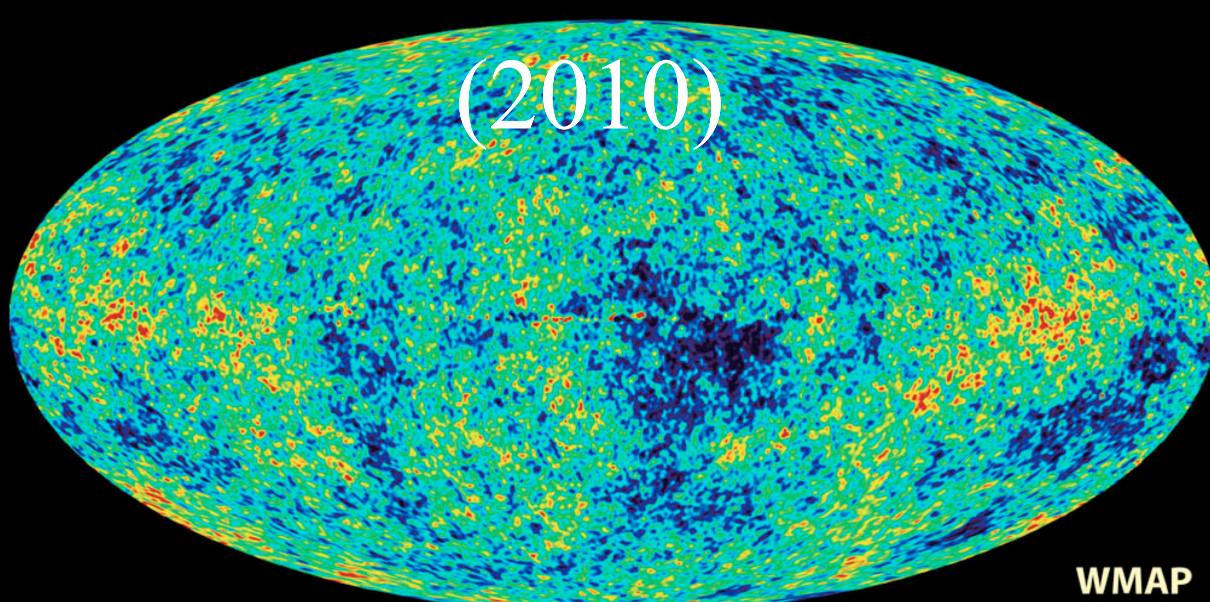
John C. Mather
NASA

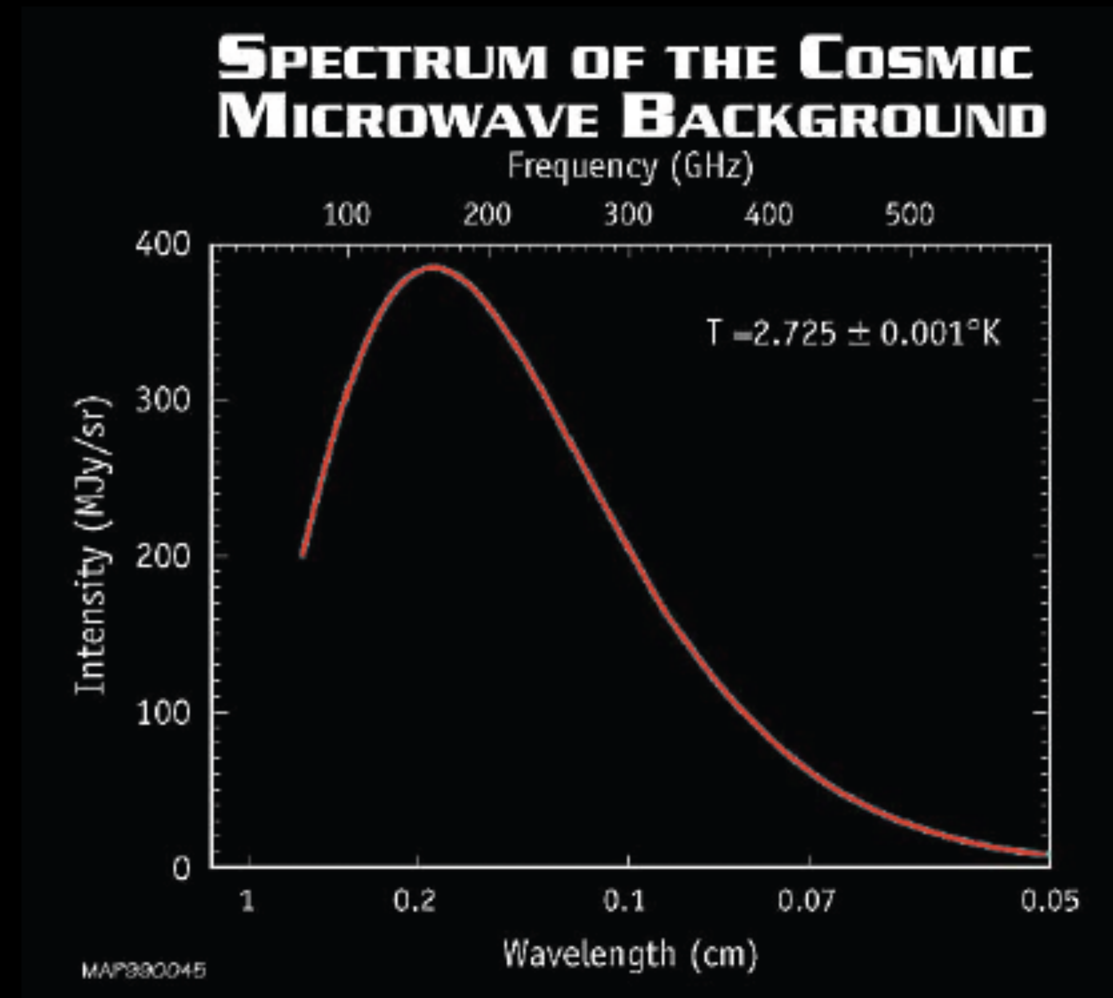
George F. Smoot
University of California, Berkeley

If you had microwave eyes:

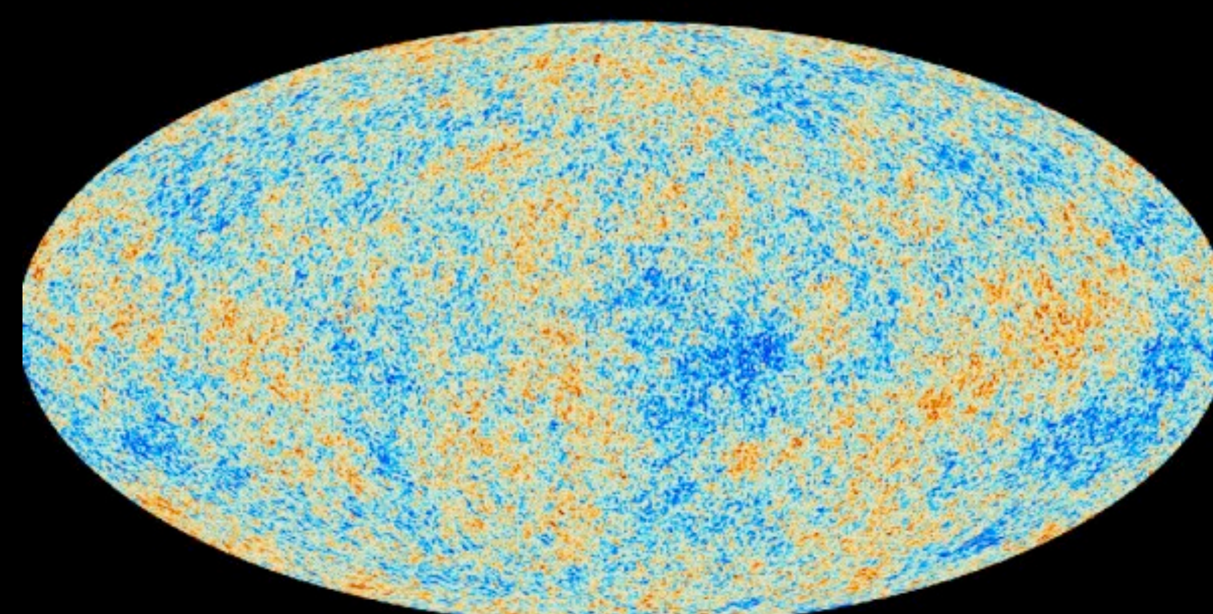


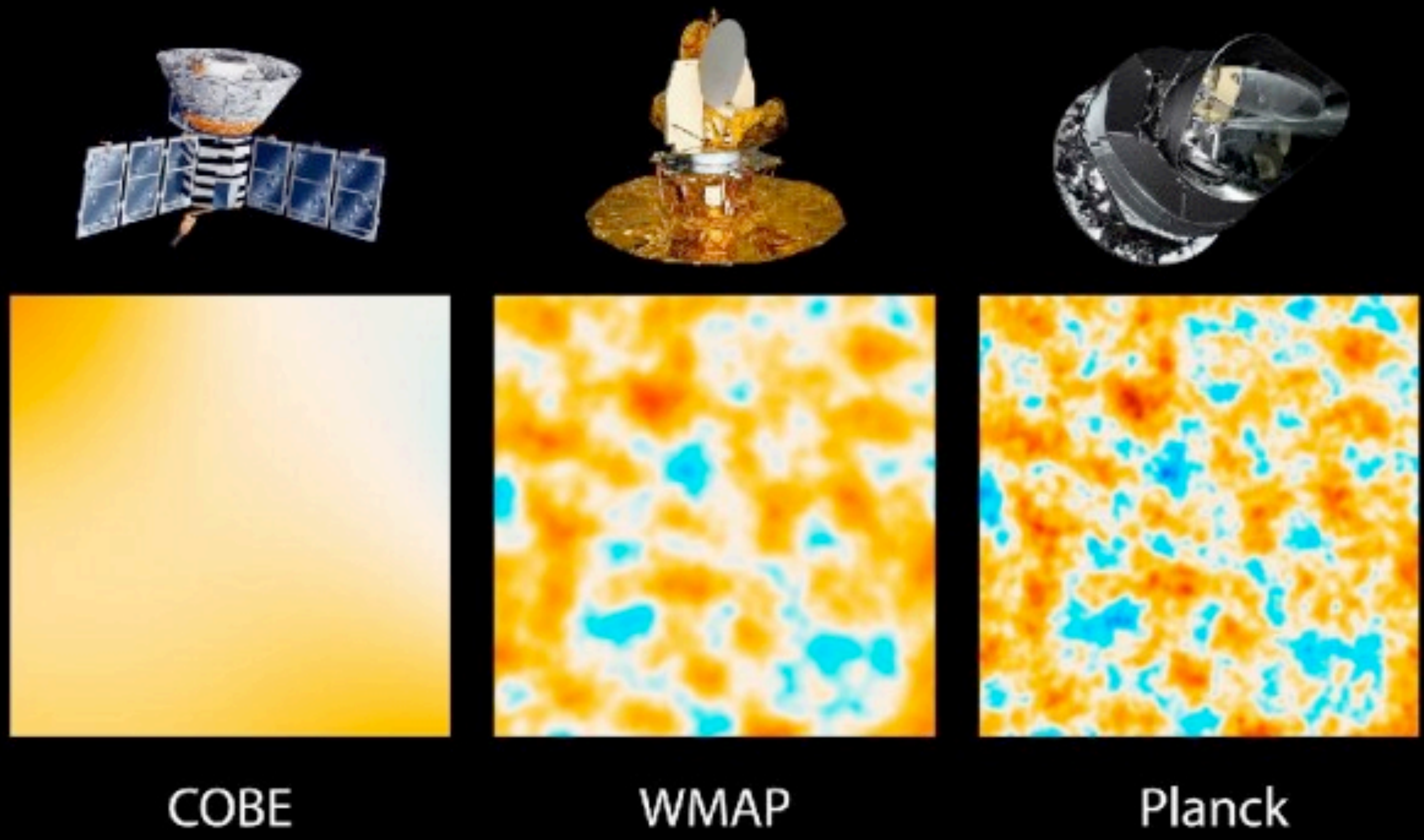




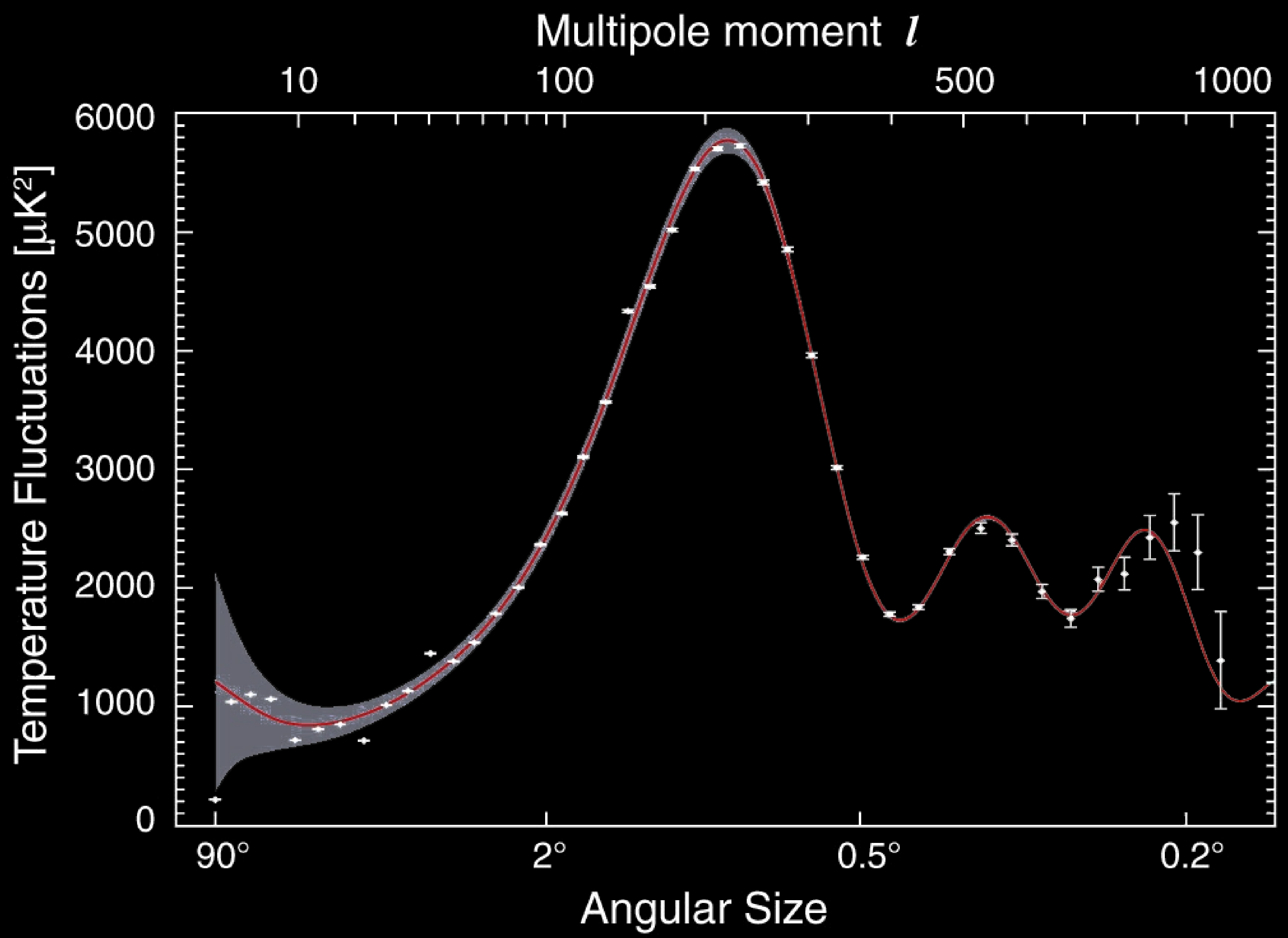


Planck (2013)





1992 2003 2013

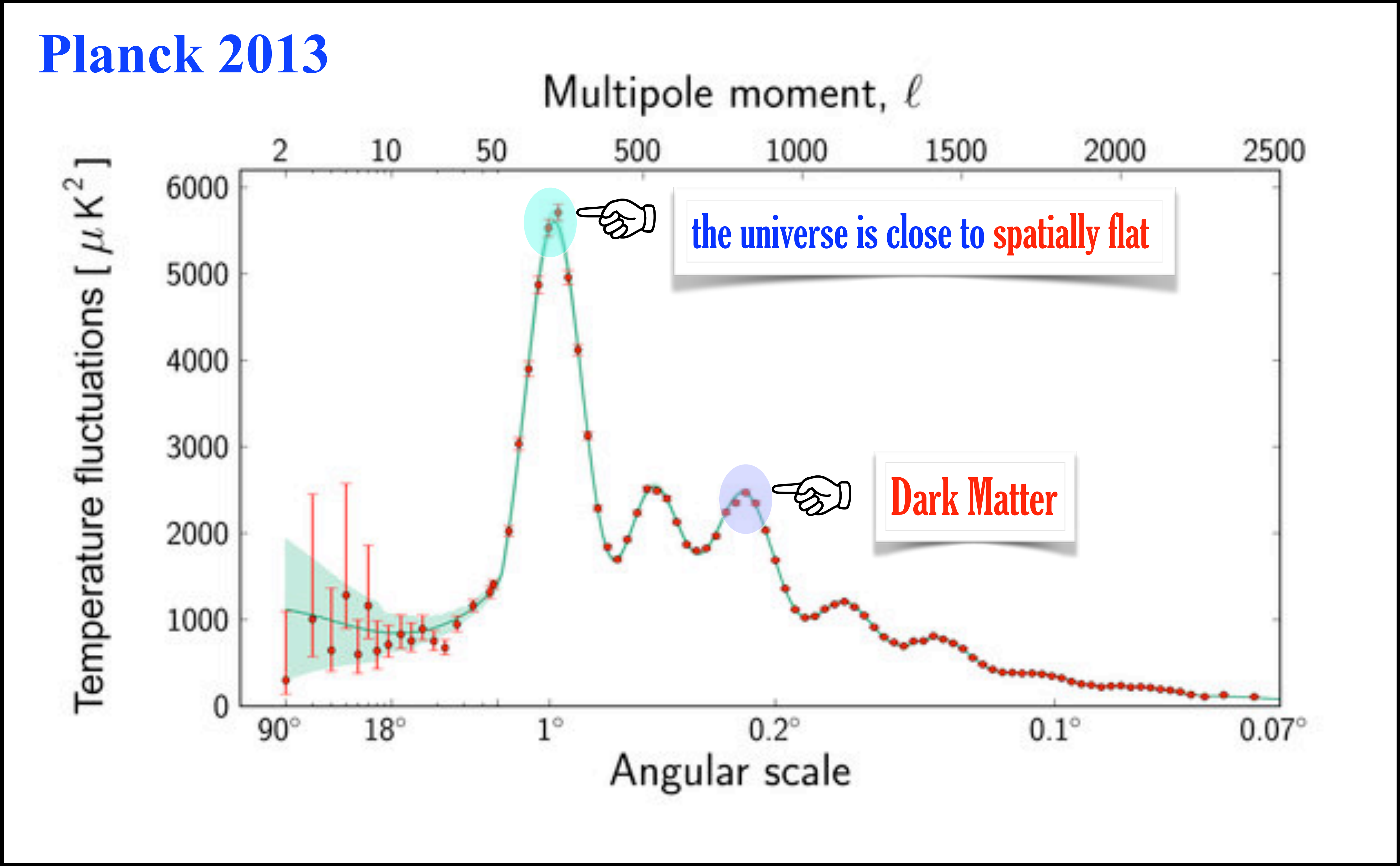


White points:
WMAP (2010)
7-year data

Red curve: Theoretical prediction for a universe made of

70% dark energy, 25% dark matter, 5% atoms

Cosmic Microwave Background (CMB)



68.3% dark energy, 26.8% dark matter, 4.9% atoms

DC2. Dark Energy

The Acceleration Universe

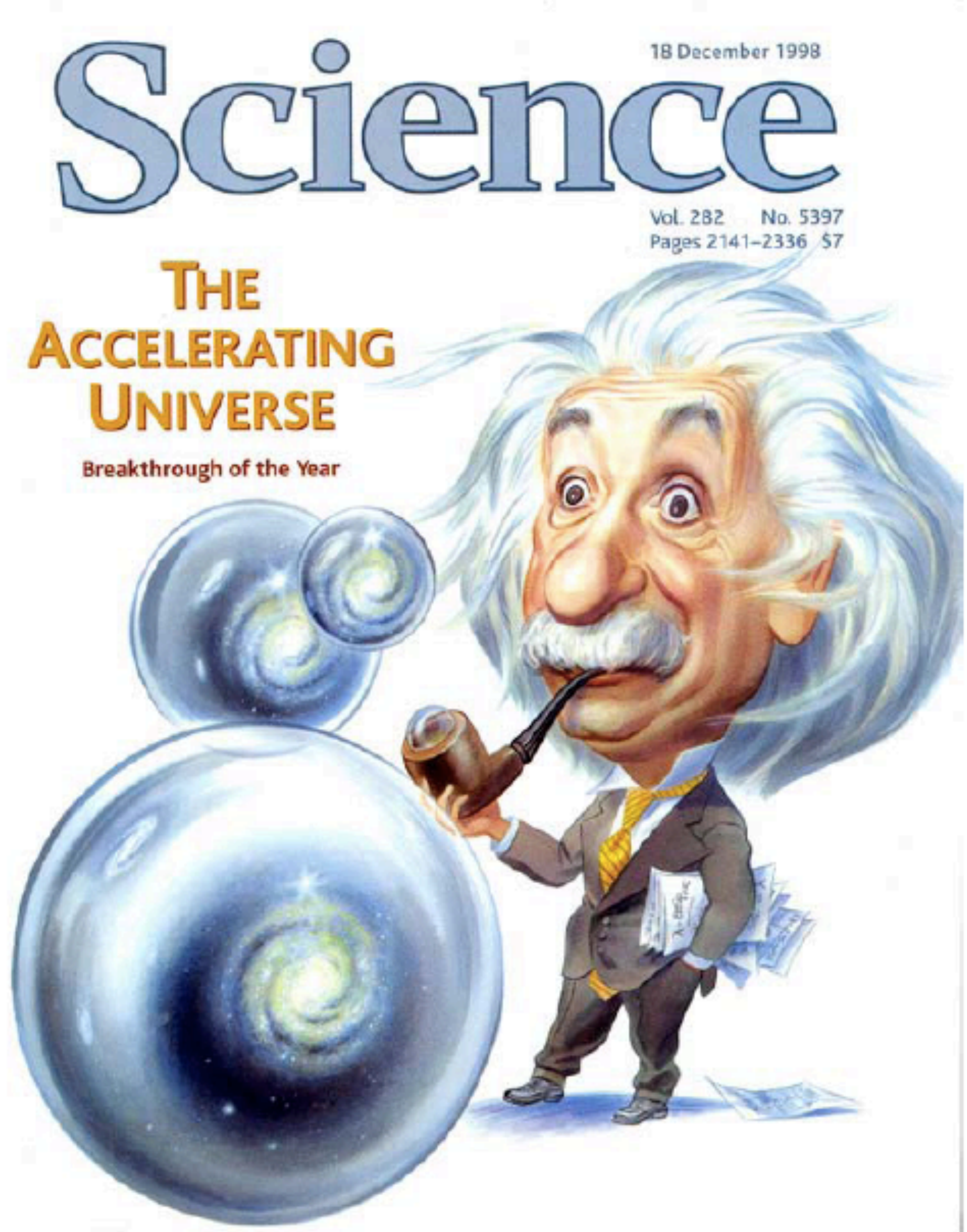
Big News in 1998!

High-Z Team

Riess et al. (1998)

Supernova Cosmology Project

Perlmutter et al. (1999)



The Nobel Prize
in Physics 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

Photo: Homewood Photography

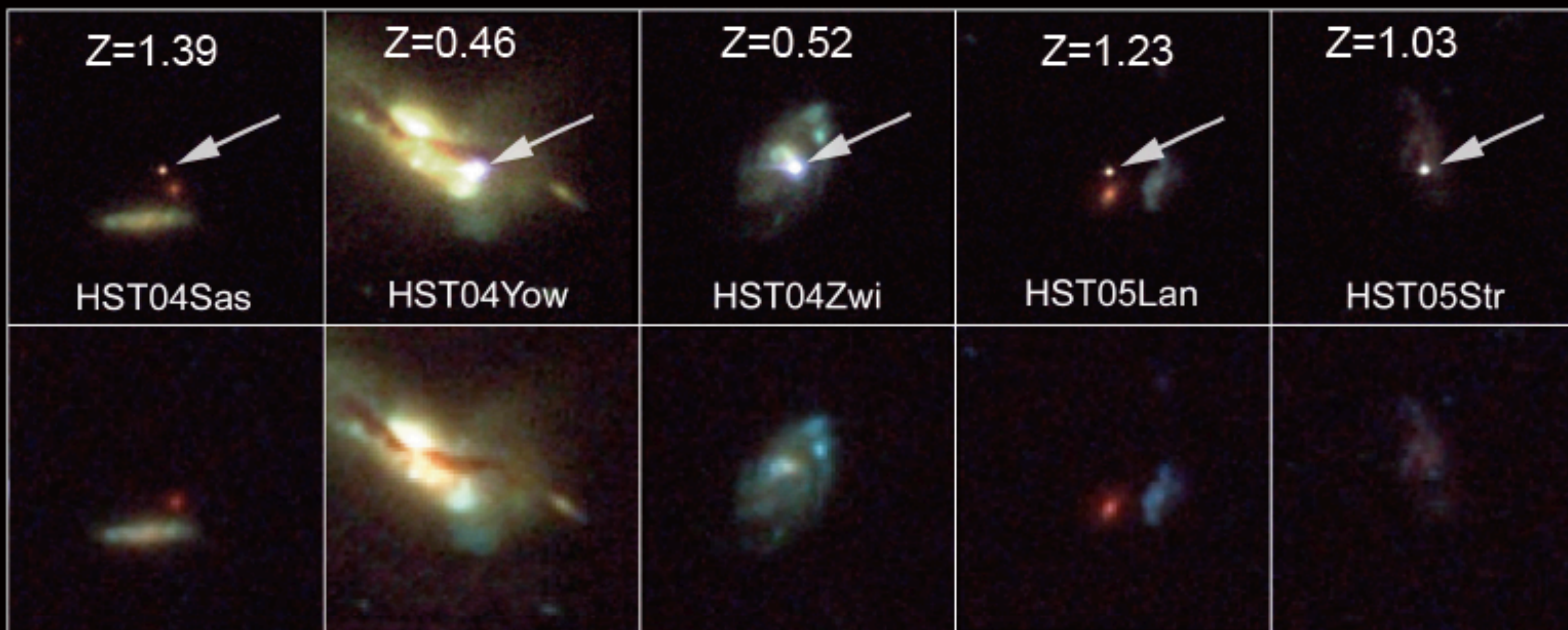
Adam G. Riess

Distant supernovae

Higher-z SNe Ia from HST

After

Before



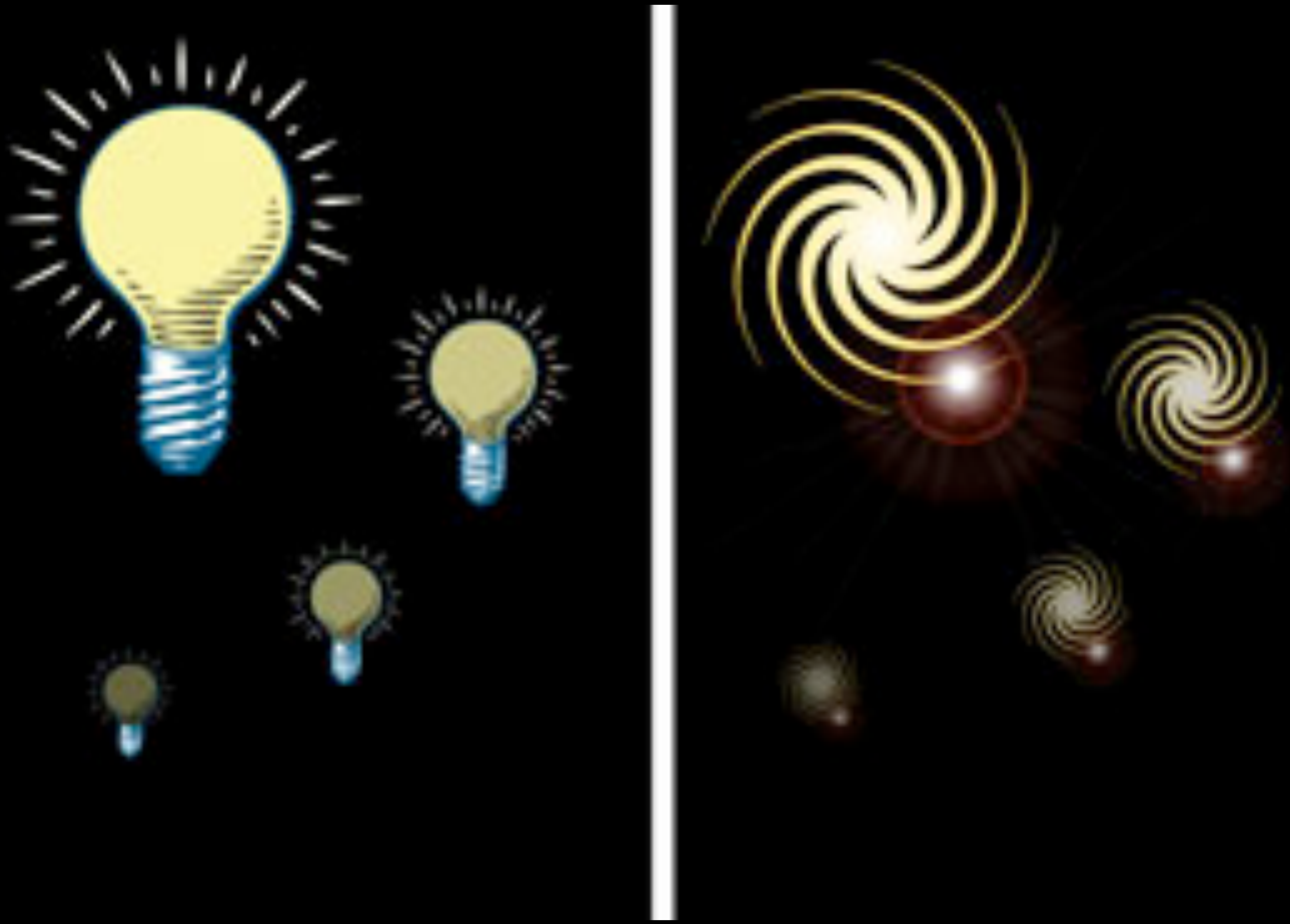
Host Galaxies of Distant Supernovae
Hubble Space Telescope ▪ Advanced Camera for Surveys

50 SNe Ia, 25 at z>1

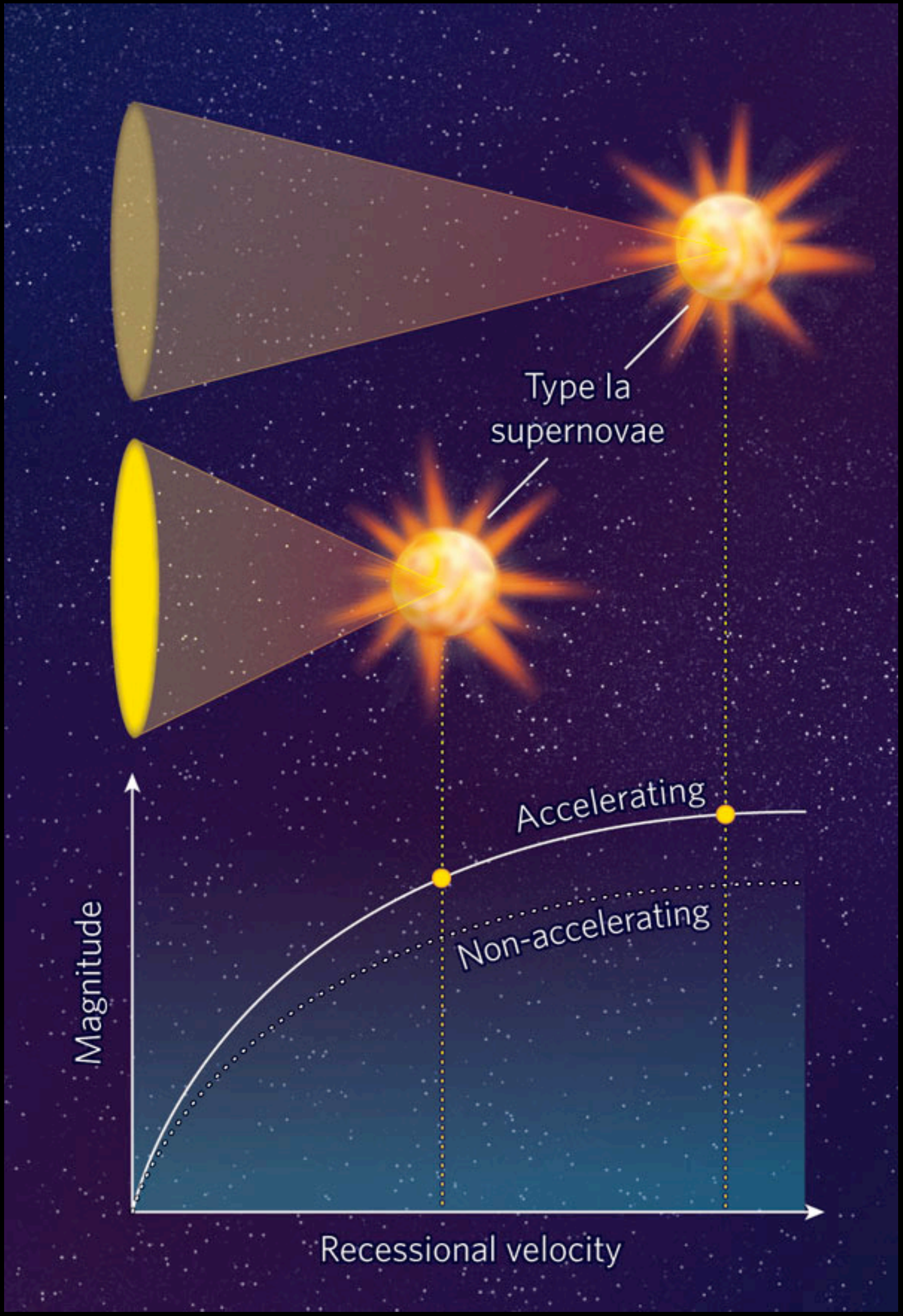
Riess, etal

Distant supernovae

Standard candles:
Their intrinsic luminosity is known
Their apparent luminosity can be measured



Distant SN as standard candles



Luminosity distance:

$$d_L^2 = \frac{L_s}{4\pi \mathcal{F}}$$

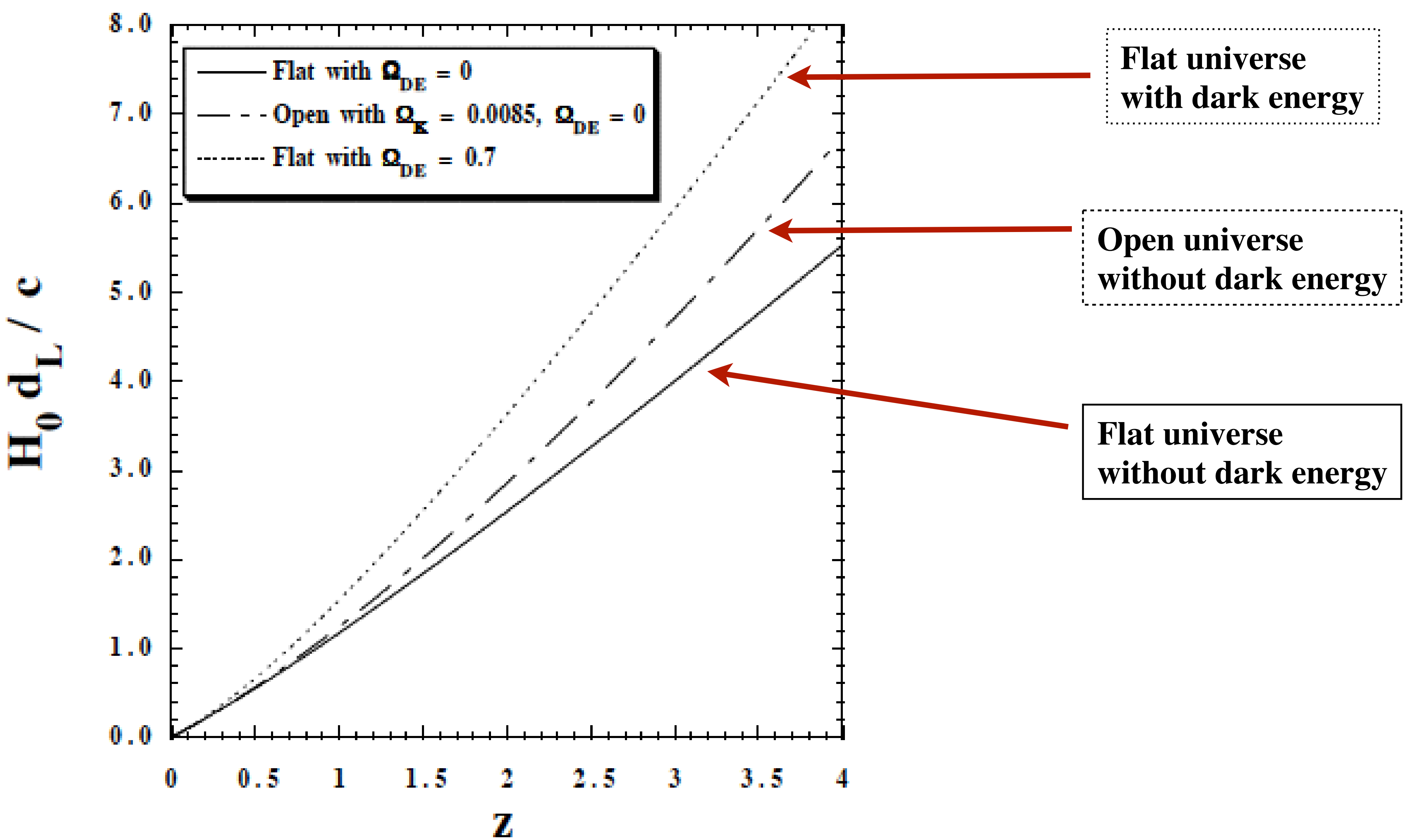
L_s the absolute luminosity of the source
F observed flux

$$d_L = \frac{c(1+z)}{H_0\sqrt{-K_0}} \sinh\left(\sqrt{-K_0}\int_0^z \frac{dz'}{E(z')}\right)$$

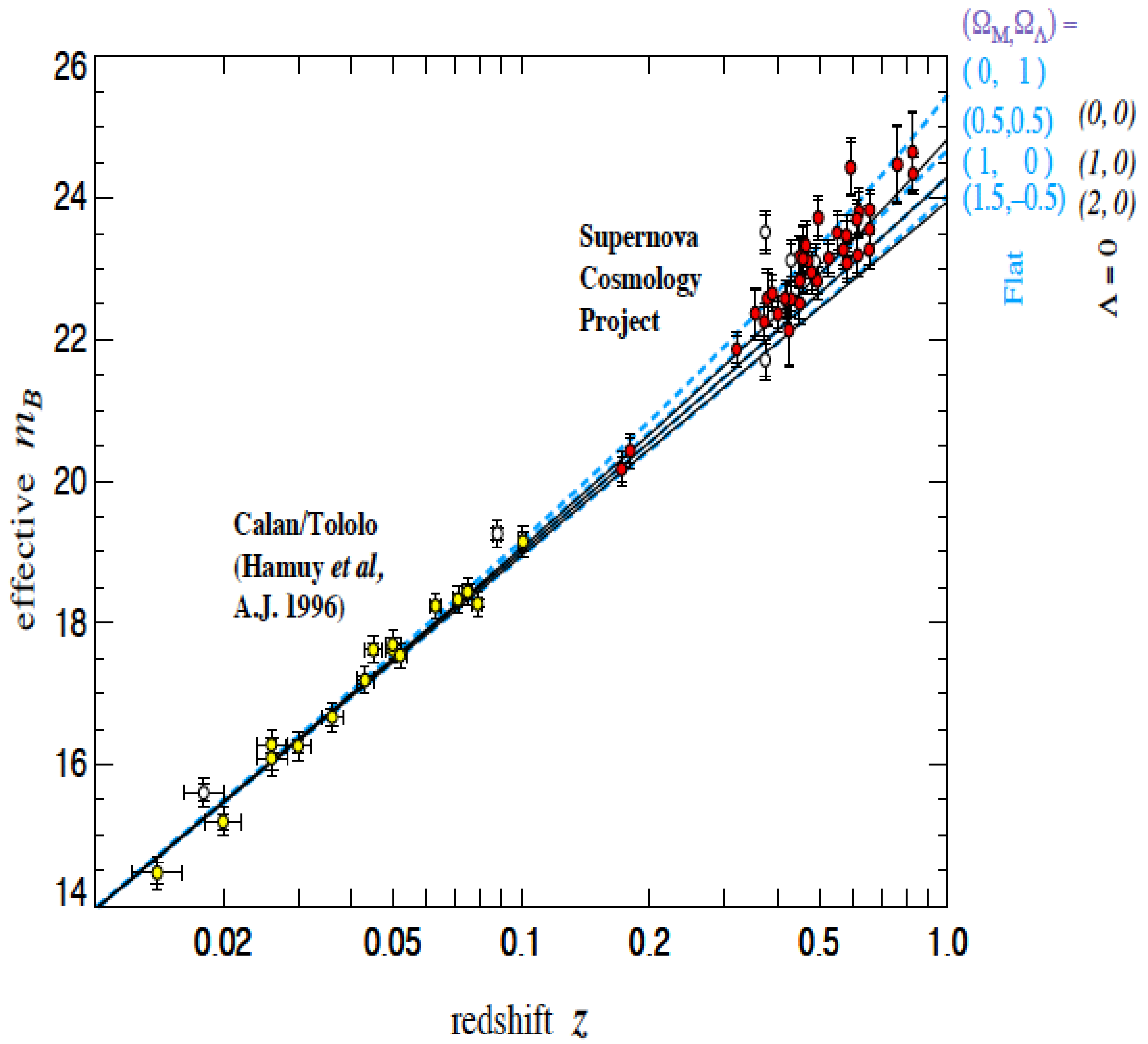
K>0: closed
K=0: flat
K<0: open

$$K_0 = Kc^2/a_0^2 H_0^2$$

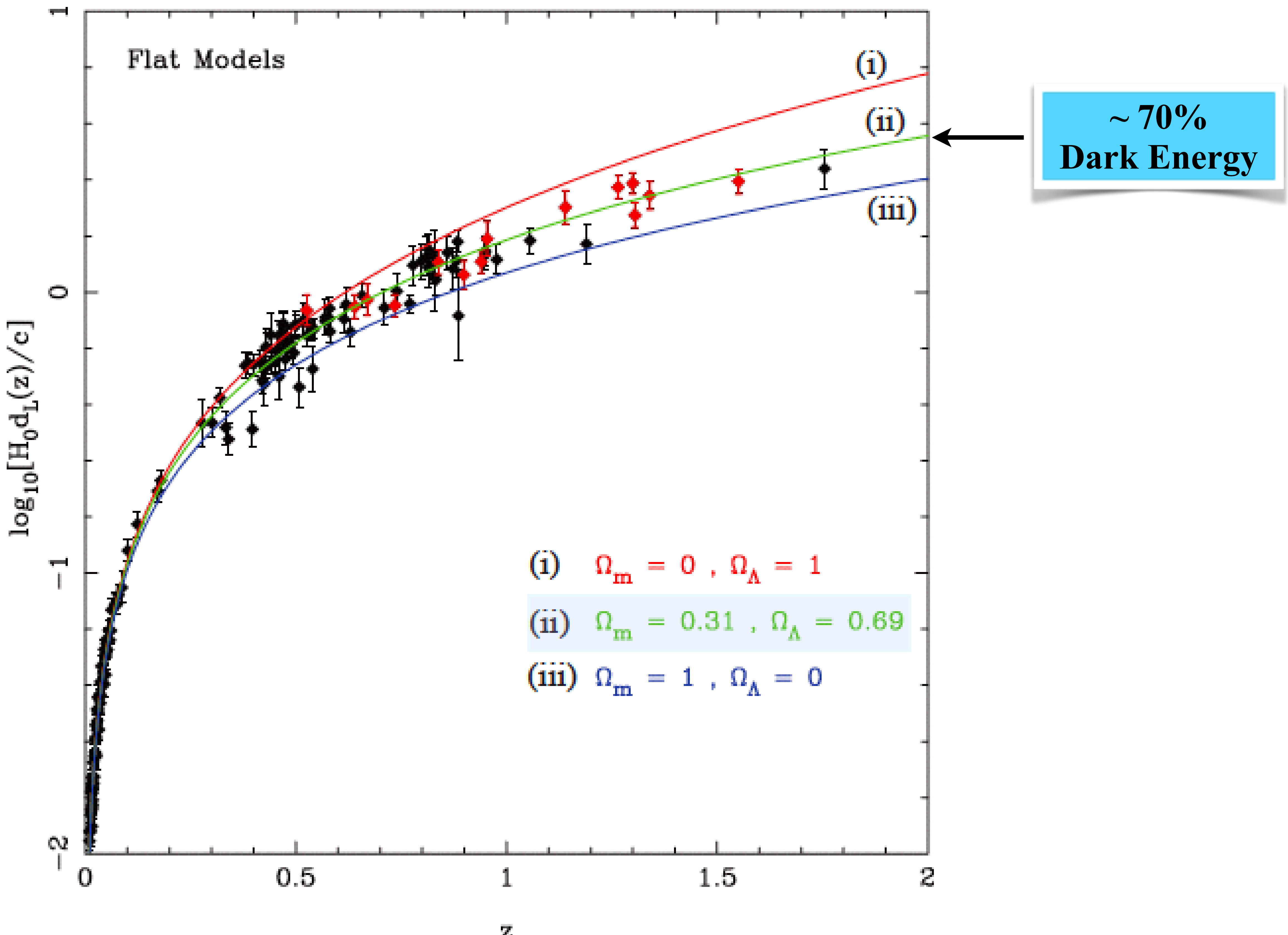
$$E(z) = \left[\Omega_m^{(0)}(1+z)^3 + \Omega_K^{(0)}(1+z)^2 + \Omega_{DE}^{(0)} \exp\left\{\int_0^z \frac{3(1+w_{DE})}{1+z'} dz'\right\}\right]^{1/2}$$



Perlmutter et al and Riess et al (1998)



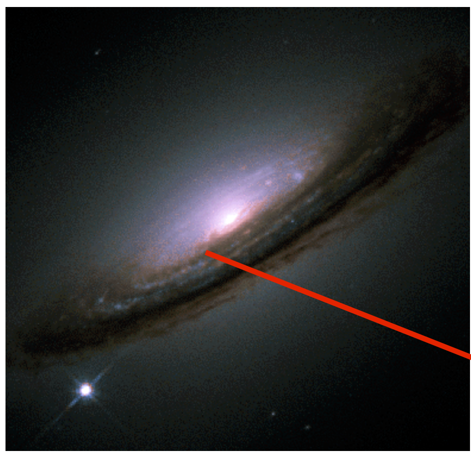
More data over the past 10 years



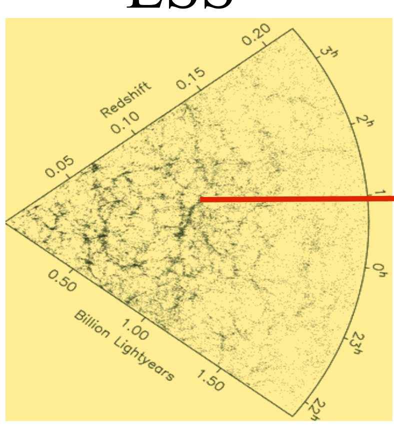
暗能量

Concordance region:
68% dark energy
27% dark matter
5% atoms

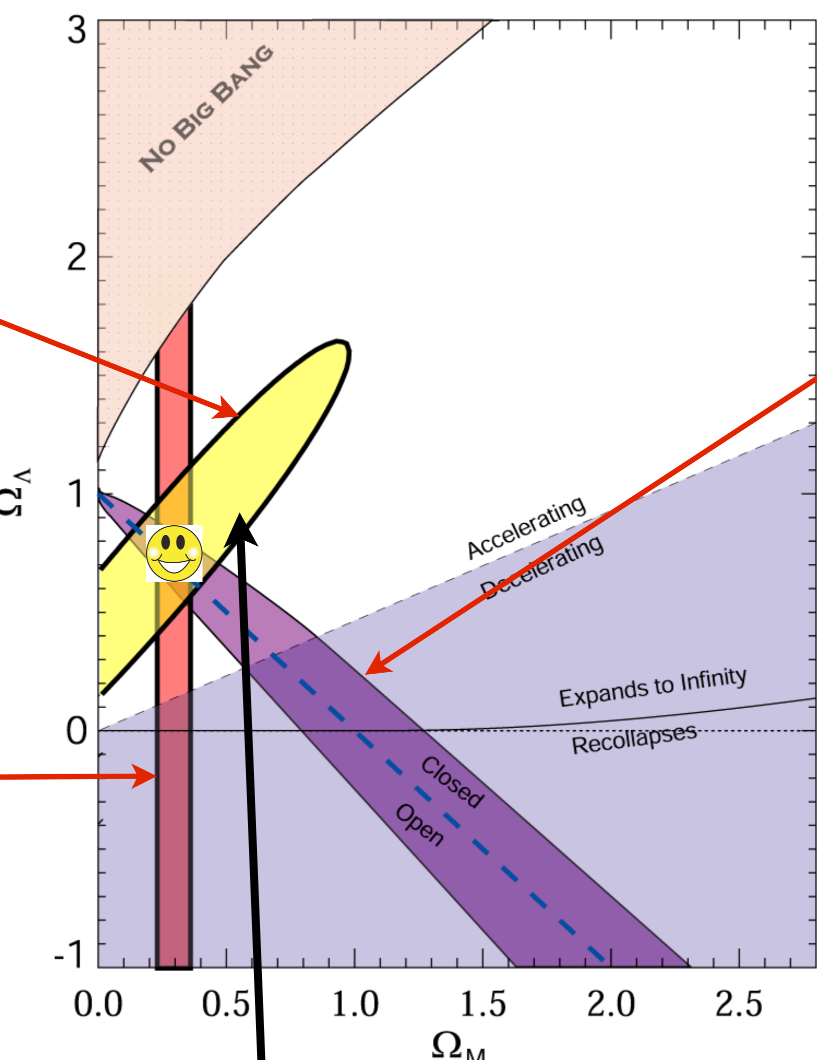
SNe Ia



LSS

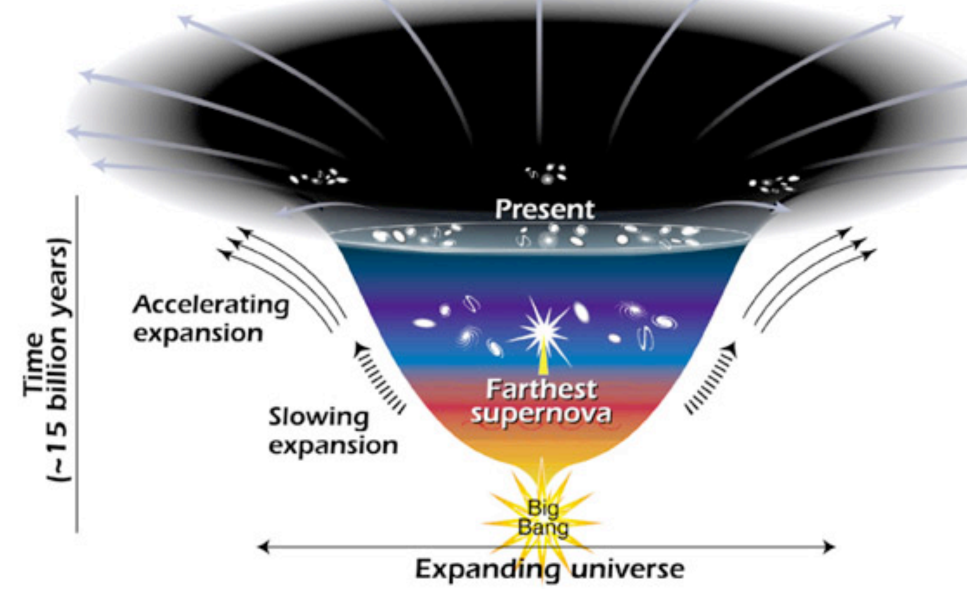


暗能量



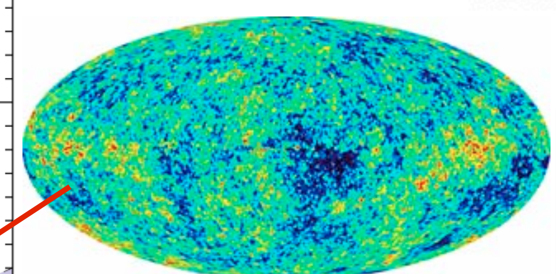
物質

2011 N.P. in Physics



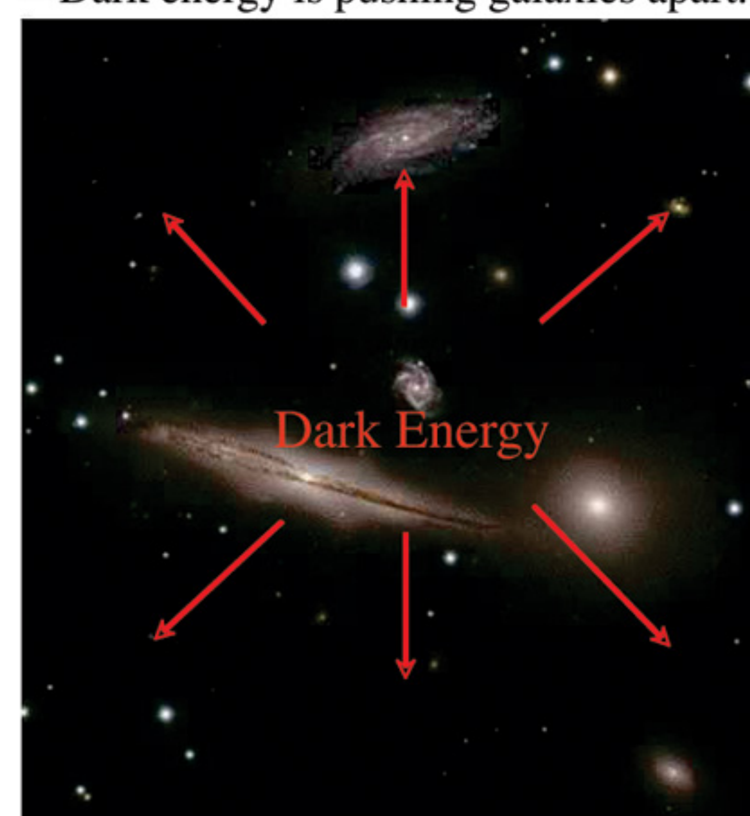
This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

CMB



The current universe is accelerating!

Dark energy is pushing galaxies apart.



Edward Witten

IAS, Princeton

W语录

W

'Most embarrassing observation in physics' – that's the only quick thing I can say about dark energy that's also true."

W

W语录

Dark Energy

- One of the most important discoveries in cosmology
- No 1. in Science Magazine's top 10 science problems of our time
- Nothing short of a revolution required to understand
- Challenges fundamental physical laws and the nature of the cosmos

Neutrino Oscillations
中微子振盪

The Nobel Prize in Physics 2015

Takaaki Kajita, Arthur B. McDonald

「發現中微子振盪，顯示中微子有質量」

``for the discovery of neutrino oscillations, which shows that neutrinos have mass”

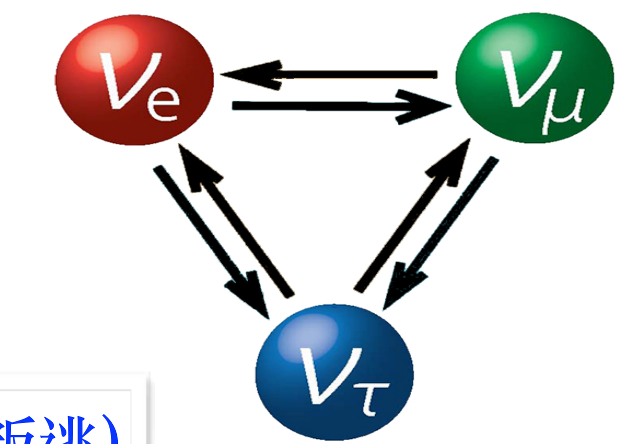
這項發現改變了我們對物質最內部運作方式的了解，證實了標準模型理論已無法成為解釋宇宙基本構成的完整理論。

This discovery has changed our understanding of the innermost workings of matter and showed that the Standard Model cannot be the complete theory of the fundamental constituents of the universe.

Solution to Solar and Atmospheric Neutrino Problems

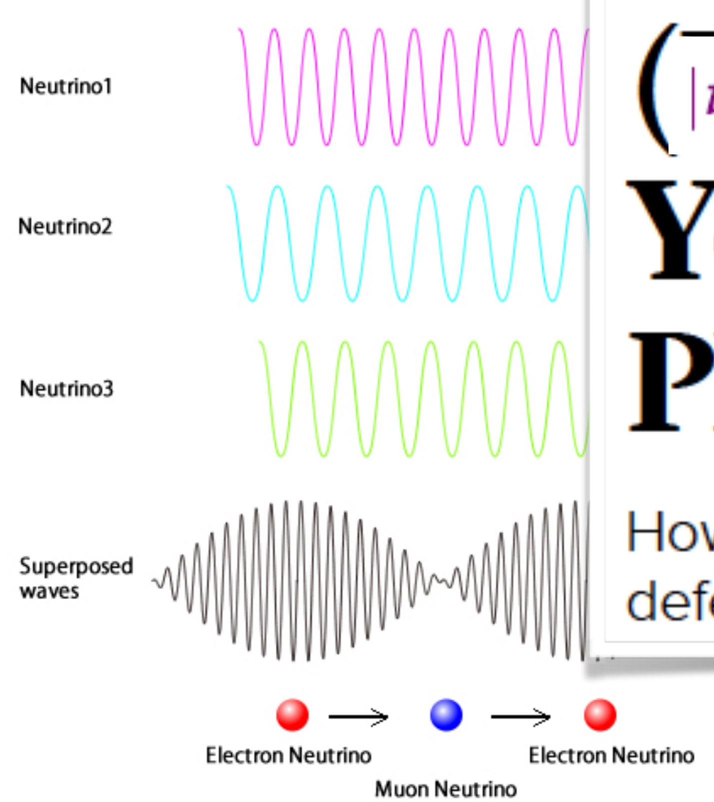
Neutrino Oscillations

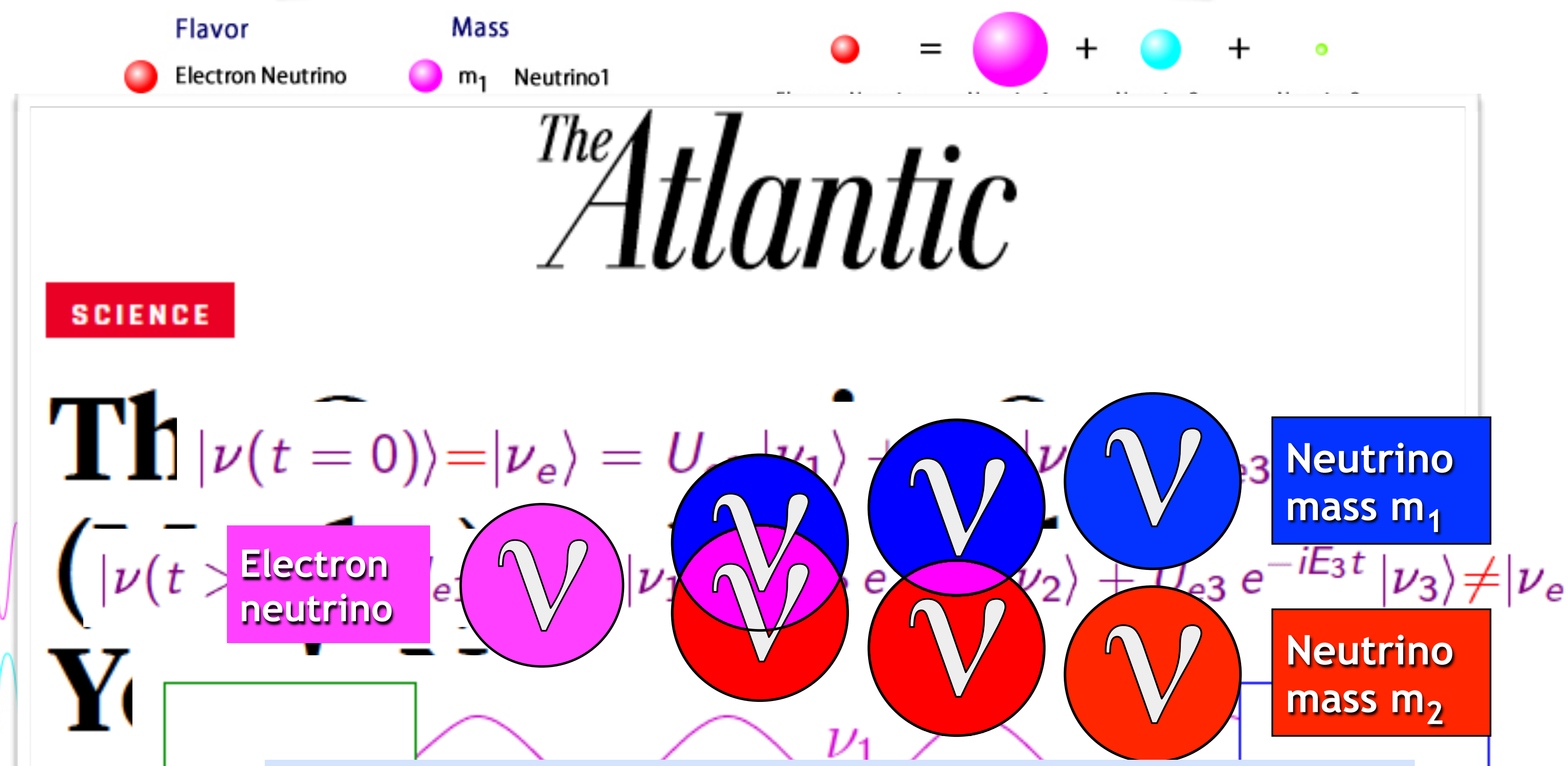
中微子振盪

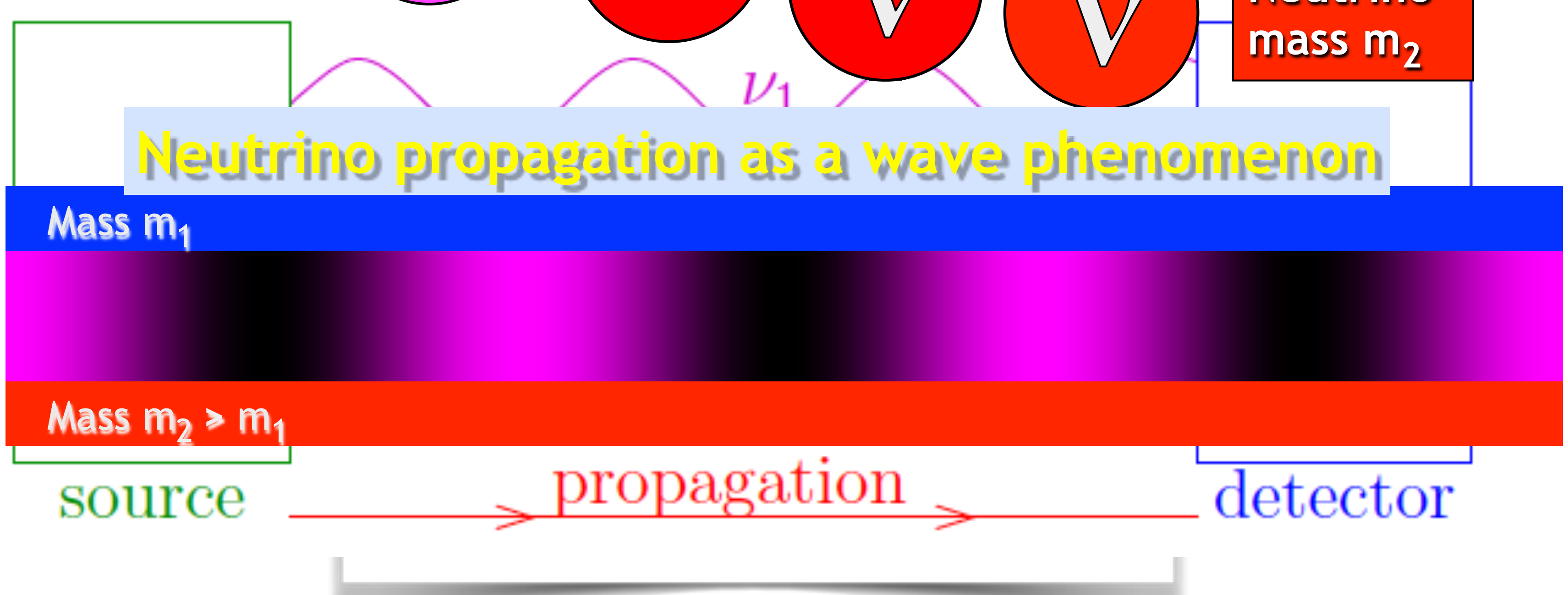


1957年: 義大利物理學家龐蒂科夫
(Bruno Pontecorvo1913-1993)

1950年失蹤，1955年出現在前蘇聯(叛逃)







Origin of Neutrino Masses

中微子質量之根源

粒子物理的標準模型無法提供中微子質量
故無法成為宇宙基本構成的完整理論
Dirac 或 Majorana 粒子？
中微子的小質量反映了標準模型的不完備性
它是通往新理論，新發現，新物理的窗口