宇宙之光明與黑暗面

Dark and Visible Sides of the Universe

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Outline

- 引言
- 可見物質，基本粒子及交互作用力
- 暗物質與暗能量
- 大統一場理論， 超對稱，TOE
- 尚未解決之問題
- 未來展望與結束語

- 引言

Science
AAAS

American Association for the Advancement of Science (AAAS)

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
- What is the Biological Basis of Consciousness?
- Why Do Humans Have So Few Genes?
- To What Extent Are Genetic Variation and Personal Health Linked?
- Can the Laws of Physics Be Unified?
- How Much Can Human Life Span Be Extended?
- What Controls Organ Regeneration?
- How Can a Skin Cell Become a Nerve Cell?
- How Does a Single Somatic Cell Become a Whole Plant?
- How Does Earth's Interior Work?
- Are We Alone in the Universe?
- How and Where Did Life on Earth Arise?
- What Determines Species Diversity?
- What Genetic Changes Made Us Uniquely Human?
- How Are Memories Stored and Retrieved?
- How Did Cooperative Behavior Evolve?
- How Will Big Pictures Emerge from a Sea of Biological Data?

What is the Universe made of ?
宇宙是由什麼組成的？

它是我們所看到的物質世界嗎？

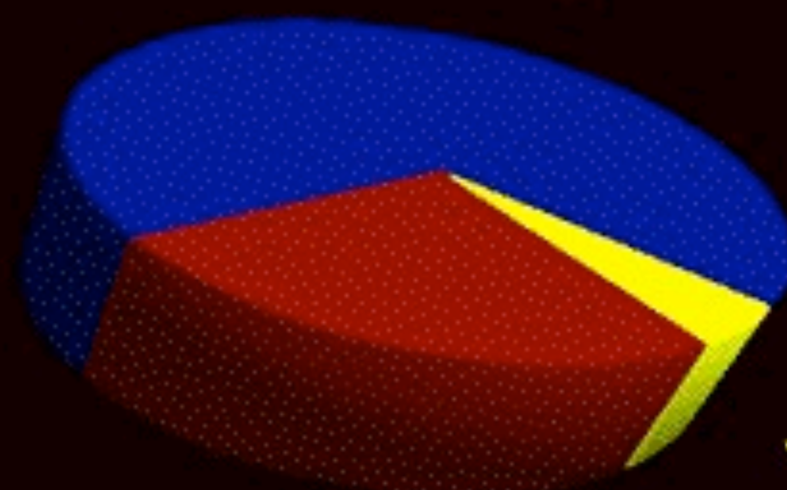
What do we know about our Universe?

We know much, we understand very little.

70% of the universe: the energy of empty space (dark energy)

暗能量

95% of the cosmic matter/energy is a mystery. It has never been observed even in our best laboratories

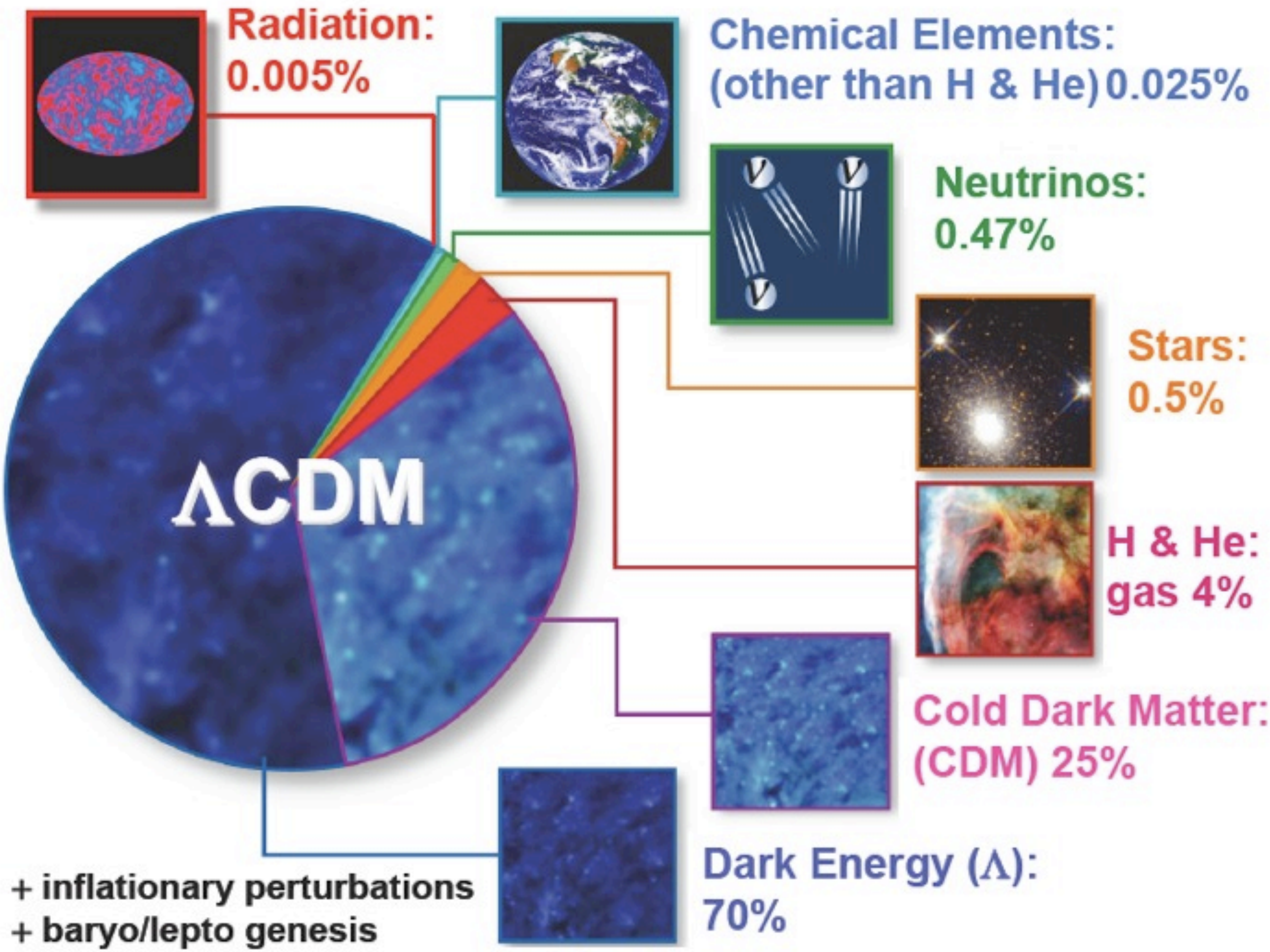


5% of the universe: ordinary matter

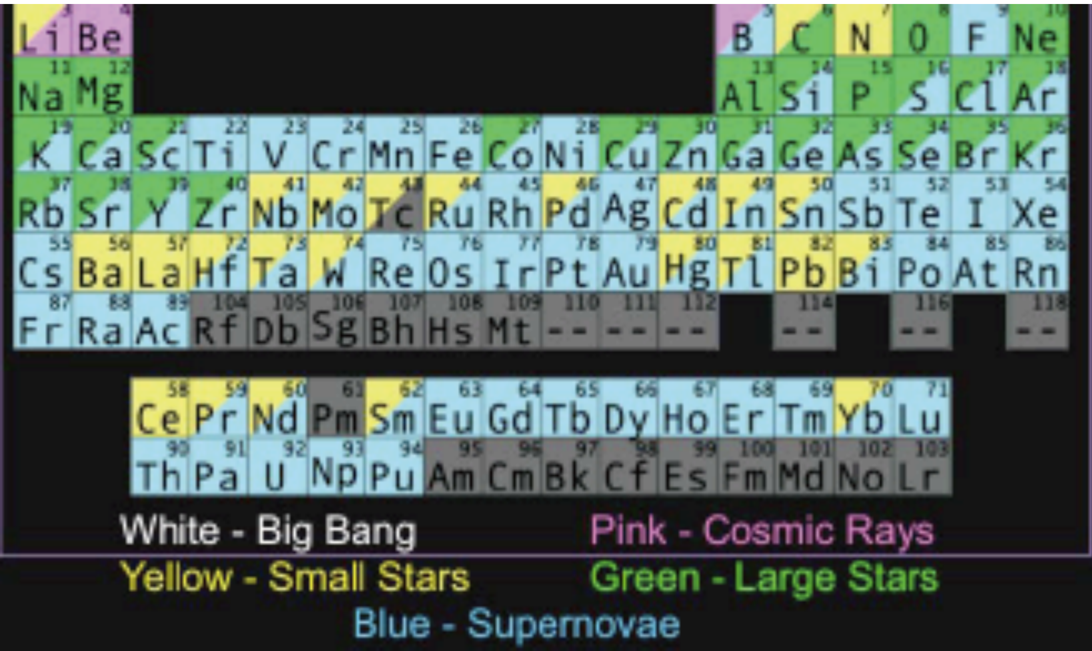
普通物質

25% of the universe: a mysterious new particle (dark matter)

暗物質



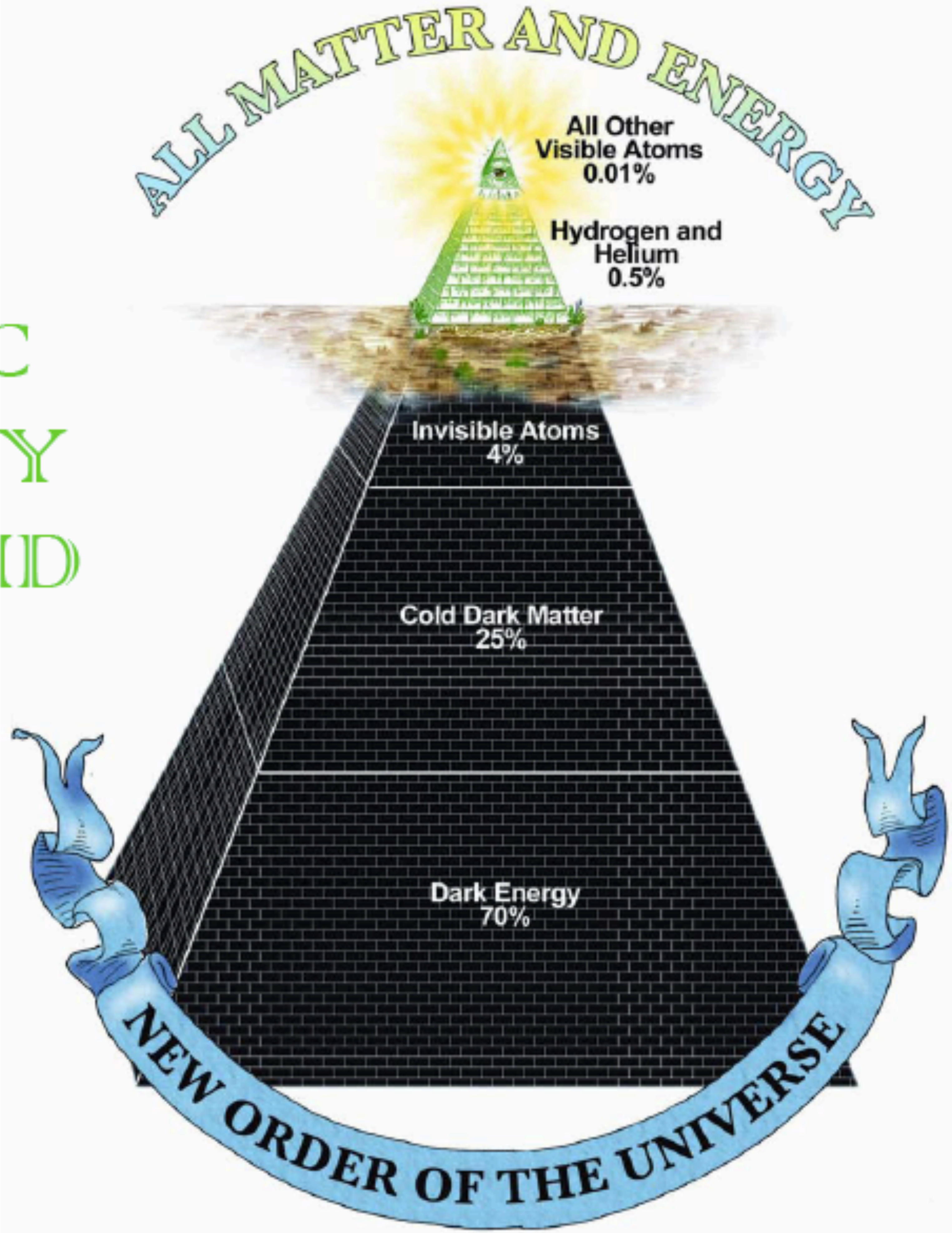
Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.47%
Stars:
0.5%
ΛCDM
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
+ inflationary perturbations
+ baryo/lepto genesis

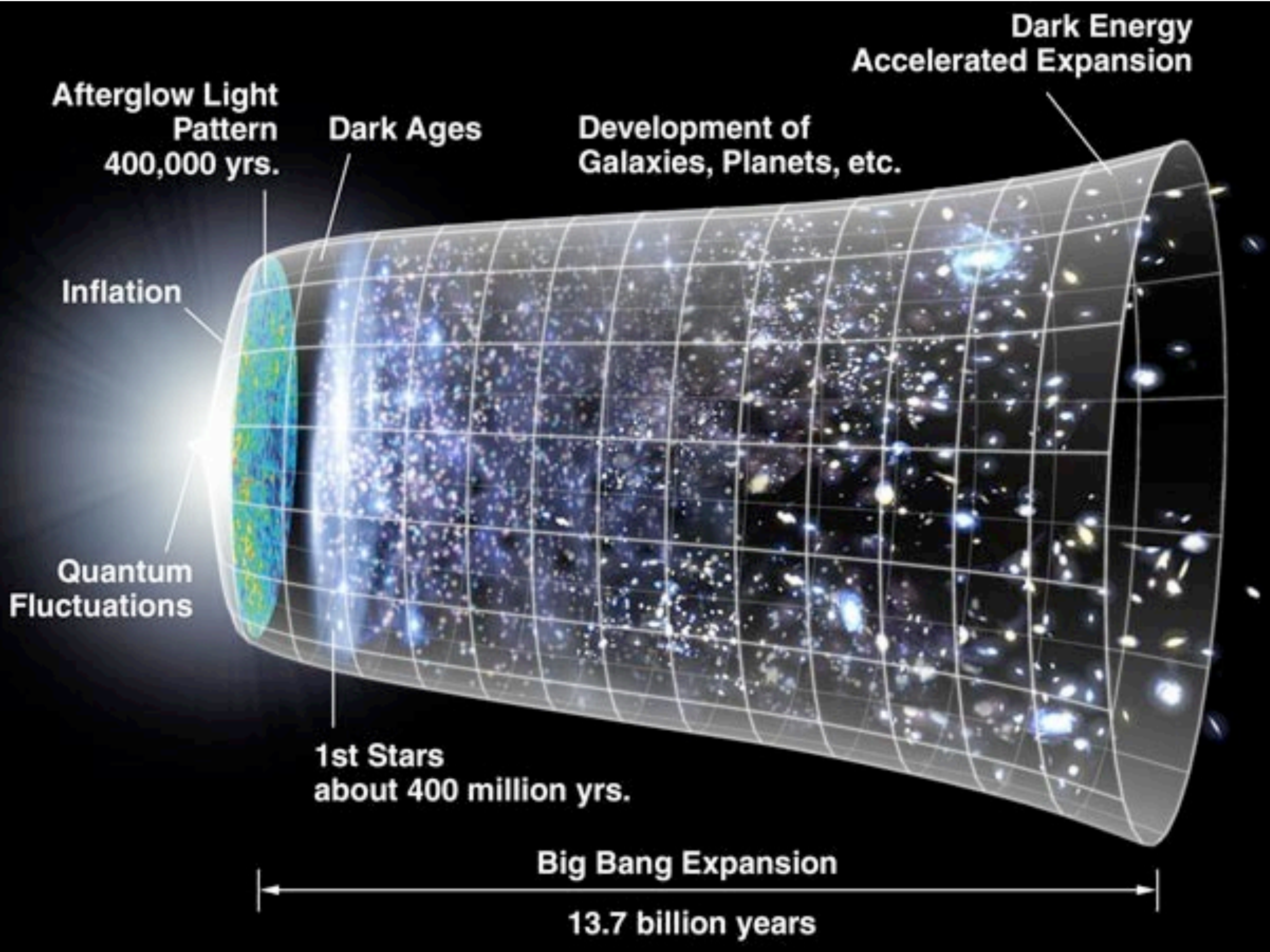


stardust

stars

COSMIC DENSITY PYRAMID




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

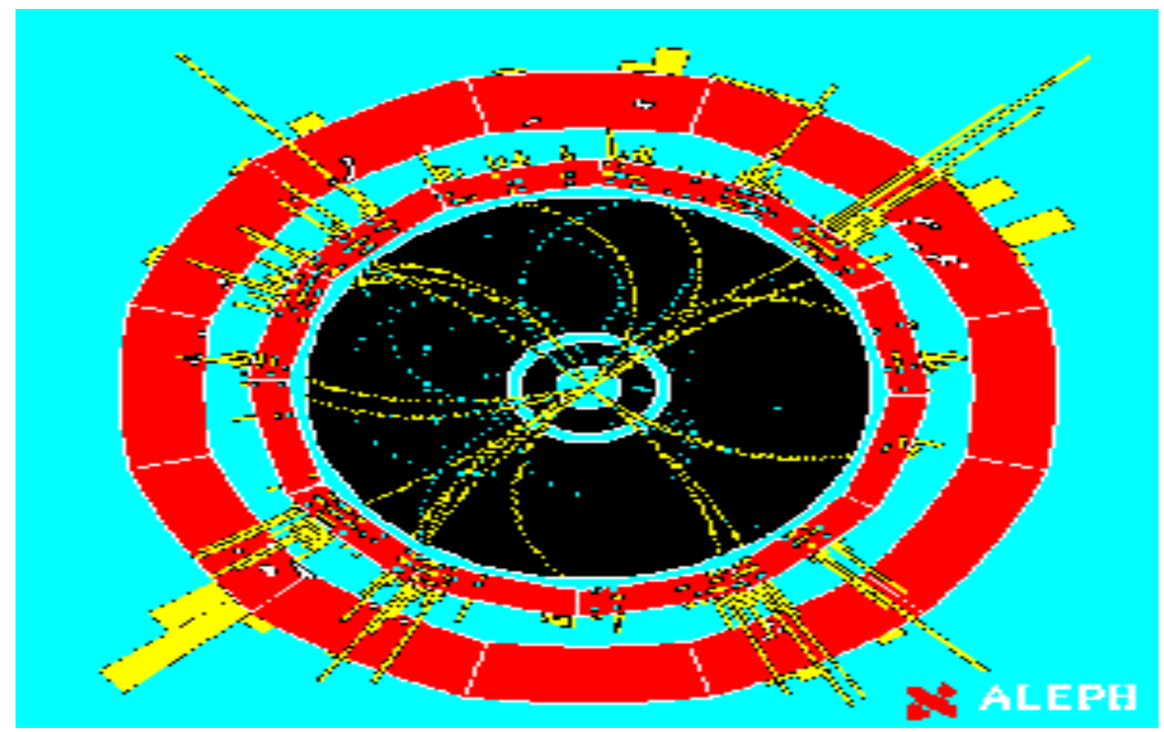
大
尺
度

The Andromeda galaxy

Looking into outer space means looking back in time. When you look at a galaxy a million light years away, you are looking at it as it was a million years ago. Looking at the sky at night is like reading the history of the Universe.

小
尺
度

Looking into inner space - into the structure of matter - also provides a view back in time. Experiments today collide together particles at the highest possible energies in order to penetrate into the deepest layers of matter. The enormous concentration of energy leads to the creation of new matter just as when matter was first created in the initial instants after the Big Bang with which the Universe began.



Studies of the smallest structures in the Universe, in high energy particle physics are therefore intimately linked with observations in astronomy of the largest structures. This meeting point between particle physics and cosmology is one of the most fascinating aspects of modern physics. Indeed, through the scenario of the Big Bang, observations in astronomy have testable consequences in particle physics and vice versa.

高能粒子物理 ←→ 天體物理

- 可見物質，基本粒子及交互作用力

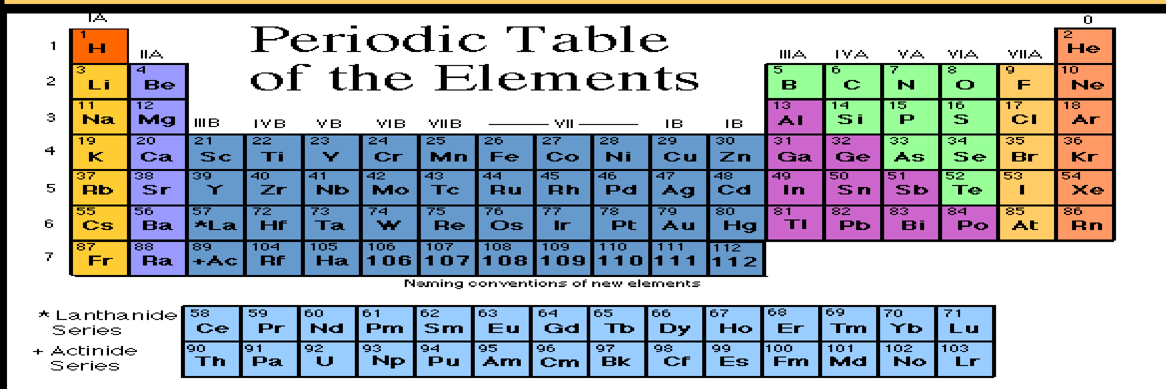
物質世界是由什麼組成的？

古代中國文明：世界是由五種星組成

金，木，水，火，土

已知（標準）物質：“可見” 的物質

ordinary matter 普通物質

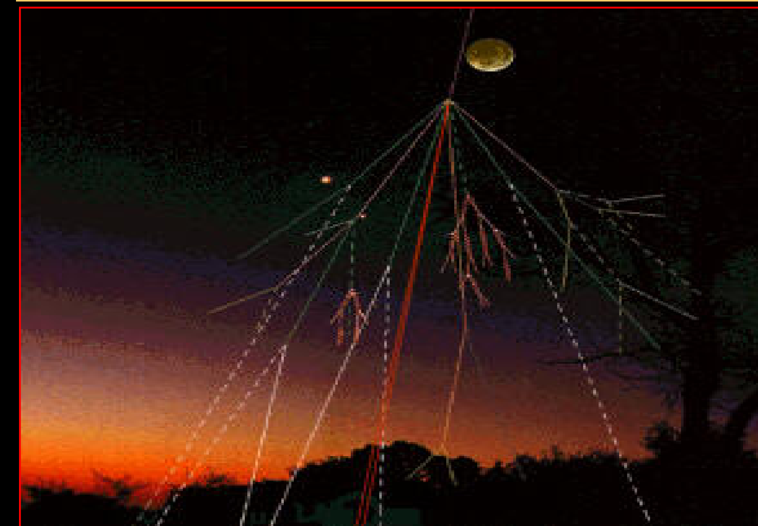

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII	VII	VII	IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

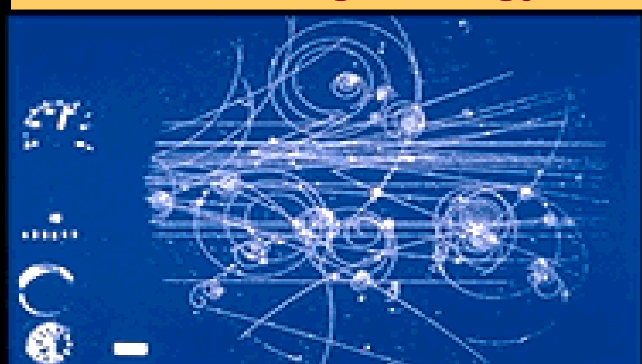
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

cosmic matter 宇宙物質



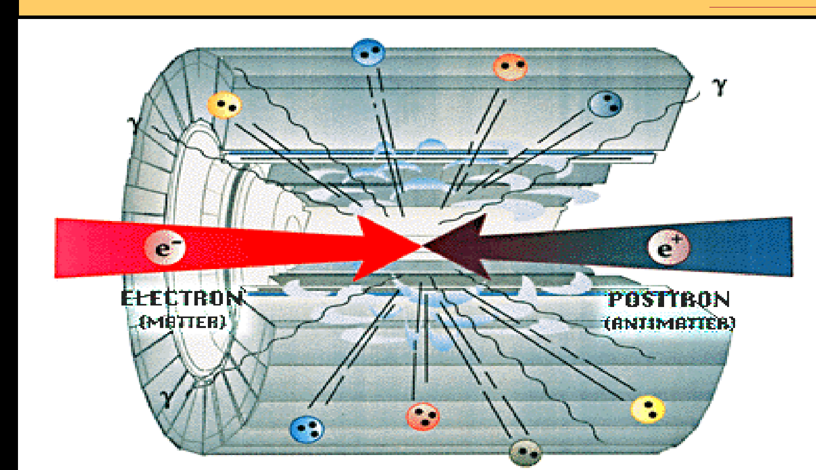
*So to understand the matter that exists as cosmic rays, we need more components than we need to make atoms. In addition to the electron, electron-neutrino, up quark and down quark, we need the **muon**, the **muon-neutrino** and the **strange quark**.*

High-energy matter 高能物質



To study high energy particle collisions under more controlled conditions, particle physicists use laboratories such as CERN, where high-energy particle colliders mimic the actions of cosmic rays in the atmosphere. Nowadays, these experiments reach energies that were common in the Universe only in the first instants of its existence.

Antimatter 反物質



For each of the basic particles of matter, there also exists a "mirror" version - or antiparticle - in which properties such as electric charge are reversed.

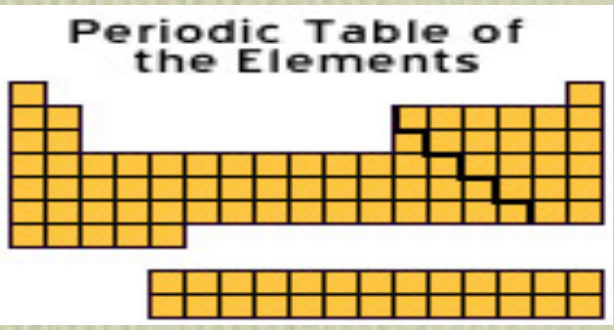
What is Fundamental?

物質是無限可分的嗎？

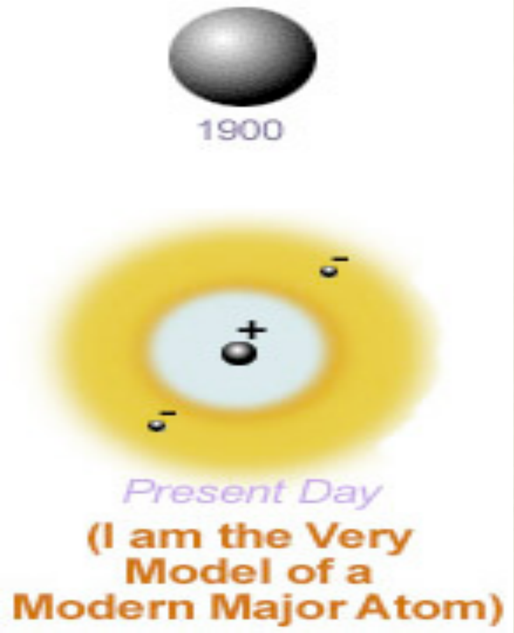
一尺之捶， 日取其半， 萬世不竭

莊子天下篇第三十三（ 300 B.C.）

Is the Atom Fundamental ?



People soon realized that they could could categorize atoms into groups that shared similiar chemical properties (as in the Periodic Table of the Elements). This indicated that atoms were made up of simpler building blocks, and that it was these simpler building blocks in different combinations that determined which atoms had which chemical properties.



Moreover, experiments which "looked" into an atom using particle probes indicated that atoms had structure and were not just squishy balls. These experiments helped scientists determine that atoms have a tiny but dense, positive nucleus and a cloud of negative electrons (e^-).

Is the Nucleus Fundamental?

Because it appeared small, solid, and dense, scientists originally thought that the nucleus was fundamental. Later, they discovered that it was made of protons (p^+), which are positively charged, and neutrons (n), which have no charge.

So, then, are protons and neutrons fundamental?

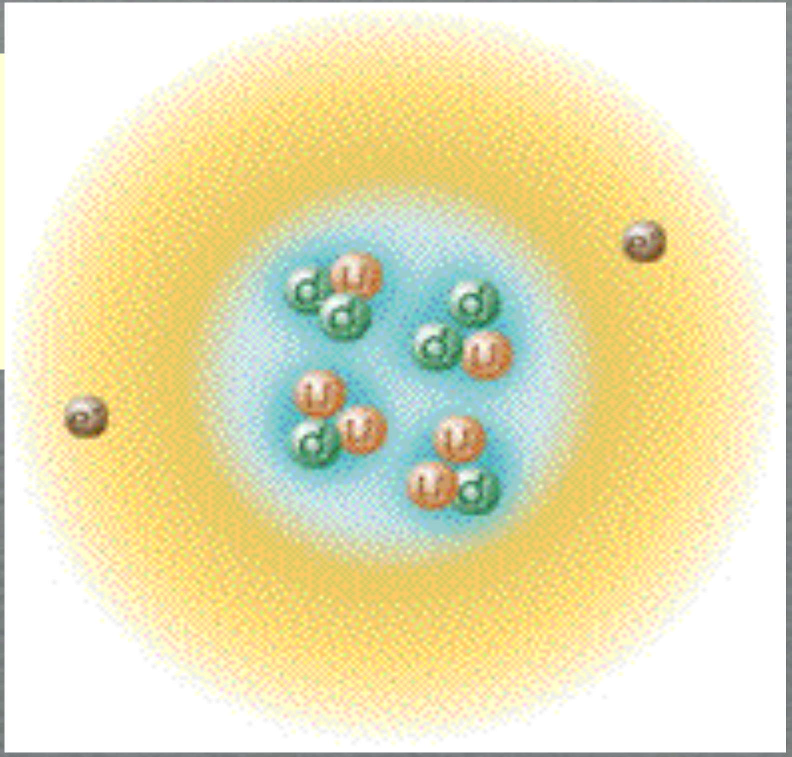
Physicists have discovered that protons and neutrons are composed of even smaller particles called **quarks**.

As far as we know, quarks are like points in geometry. They're not made up of anything else.

After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental

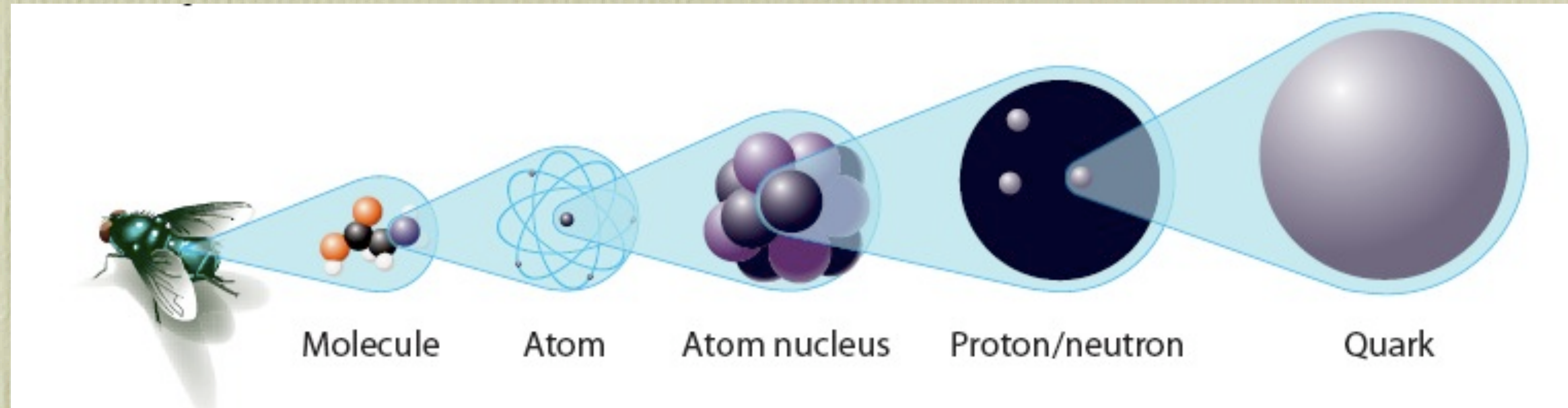
The Modern Atom Model

Electrons are in constant motion around the nucleus, protons and neutrons jiggle within the nucleus, and quarks jiggle within the protons and neutrons.



This picture is quite distorted. If we drew the atom to scale and made protons and neutrons a centimeter in diameter, then the electrons and quarks would be less than the diameter of a hair and the entire atom's diameter would be greater than the length of thirty football fields! 99.999999999999% of an atom's volume is just empty space!

ordinary matter 普通物質



Only four kinds of building block are needed to account for all of ordinary matter.

up-quarks and down-quarks 上和下夸克

electrons and electron-neutrinos 電子和電子中微子

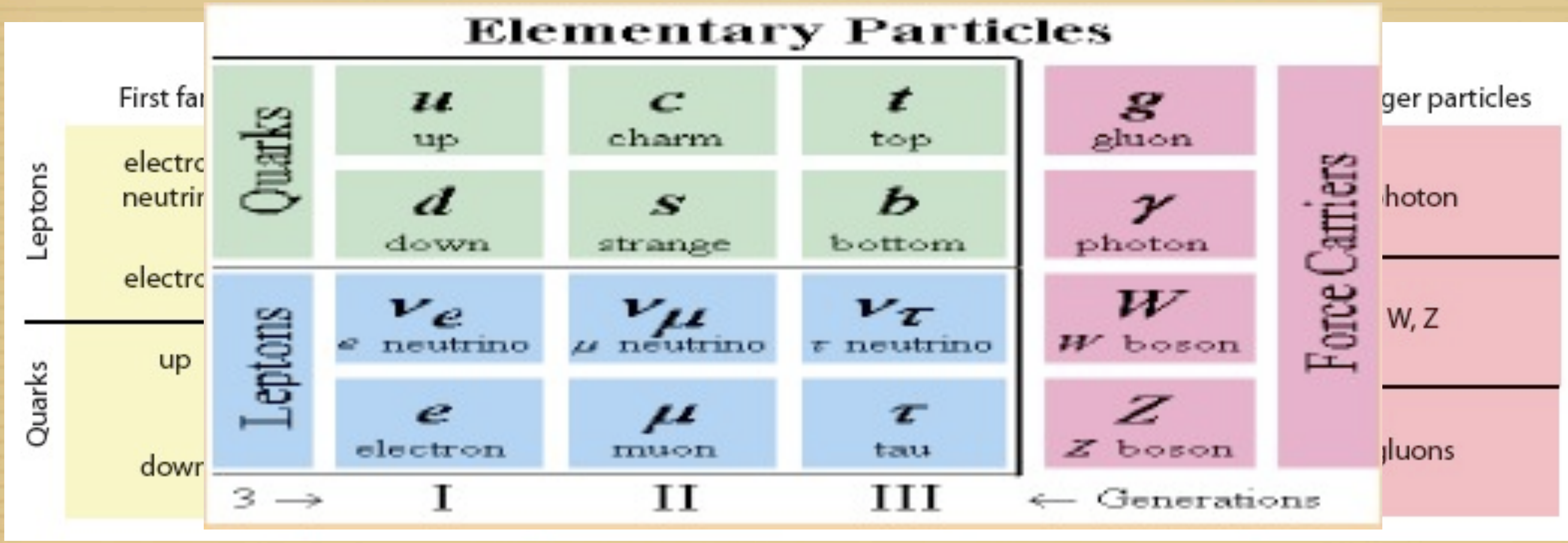
是什麼結合它在一起？

Particles are stuck together by forces: four kinds of forces

gravity 重力 **weak** 弱作用力 **electromagnetic** 電磁作用力 **strong** 強作用力

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

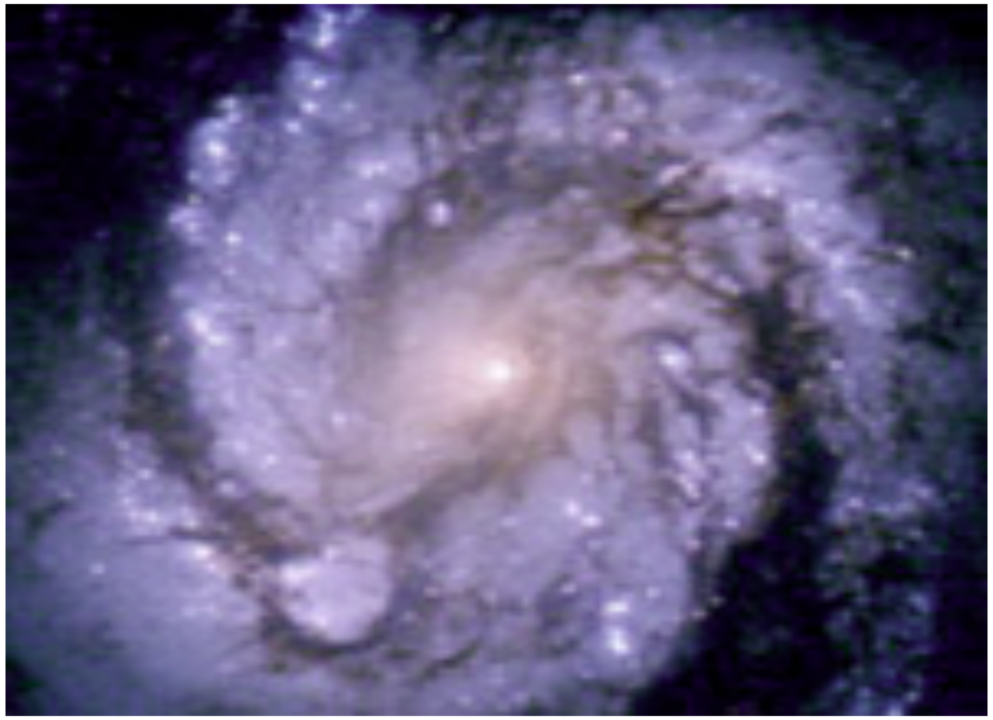
The Standard Model



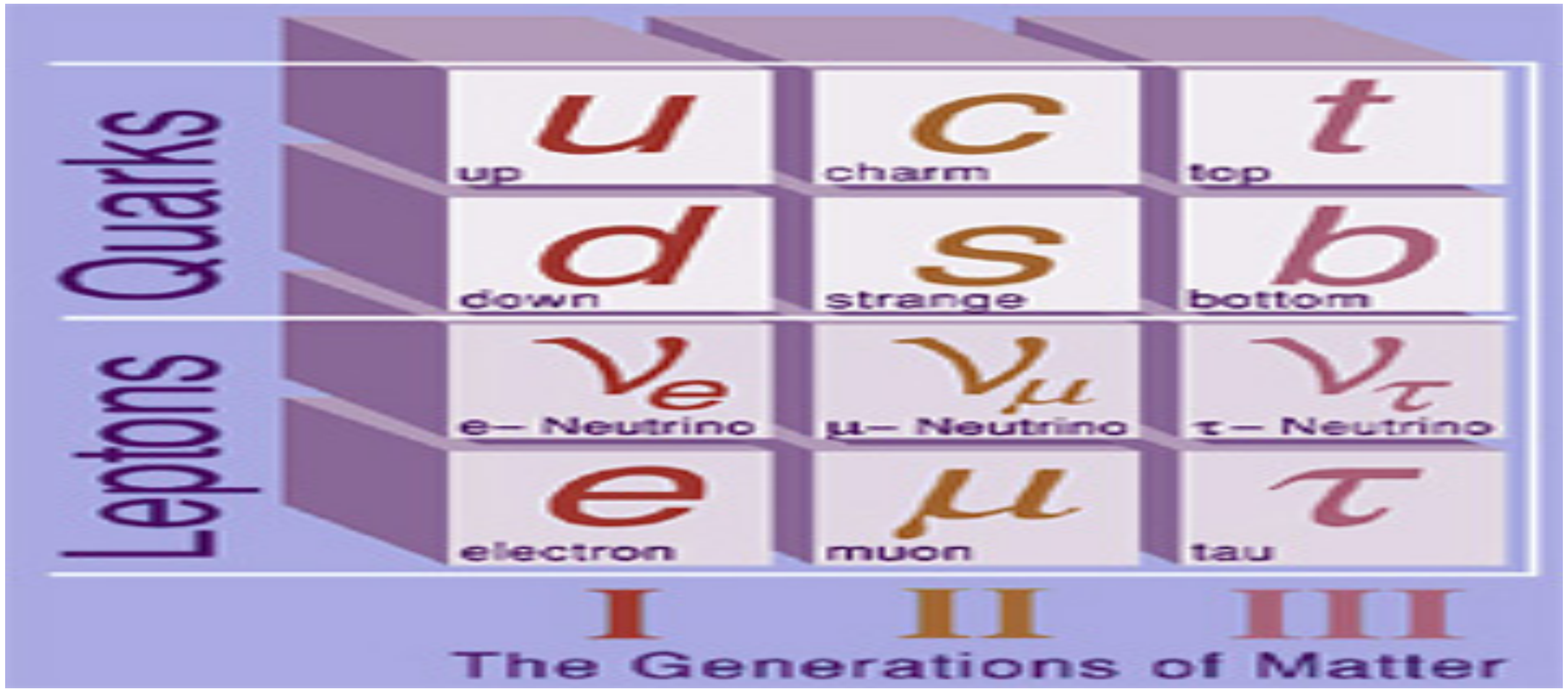
The Standard Model is a good theory. Experiments have verified its predictions to incredible precision.

已知的物質是由什麼組成的？

Quarks and Leptons



As you have read, everything from galaxies to mountains to molecules is made from quarks and leptons. But that is not the whole story. Quarks behave differently than leptons, and for each kind of matter particle there is a corresponding antimatter particle.



In fact, when the muon was discovered physicist I.I. Rabi asked,

So why do we have generations of matter at all? Why three of them?

為什麼物質要有代呢？ 為什麼又只有三代？

Broken Symmetry

破缺的對稱性

The Nobel Prize in Physics 2008

「發現對稱破缺的起源，預測自然界存在三代夸克」

Why is there something instead of nothing? Why are there so many different elementary particles? This year's Nobel Laureates in Physics have presented theoretical insights that give us a deeper understanding of what happens far inside the tiniest building blocks of matter.

Yoichiro Nambu　Makoto Kobayashi　Toshihide Maskawa

Substructure

物質是無限可分的嗎？？？

夸克和輕子也有結構嗎？

夸克
輕子

→ **Preon** 先子

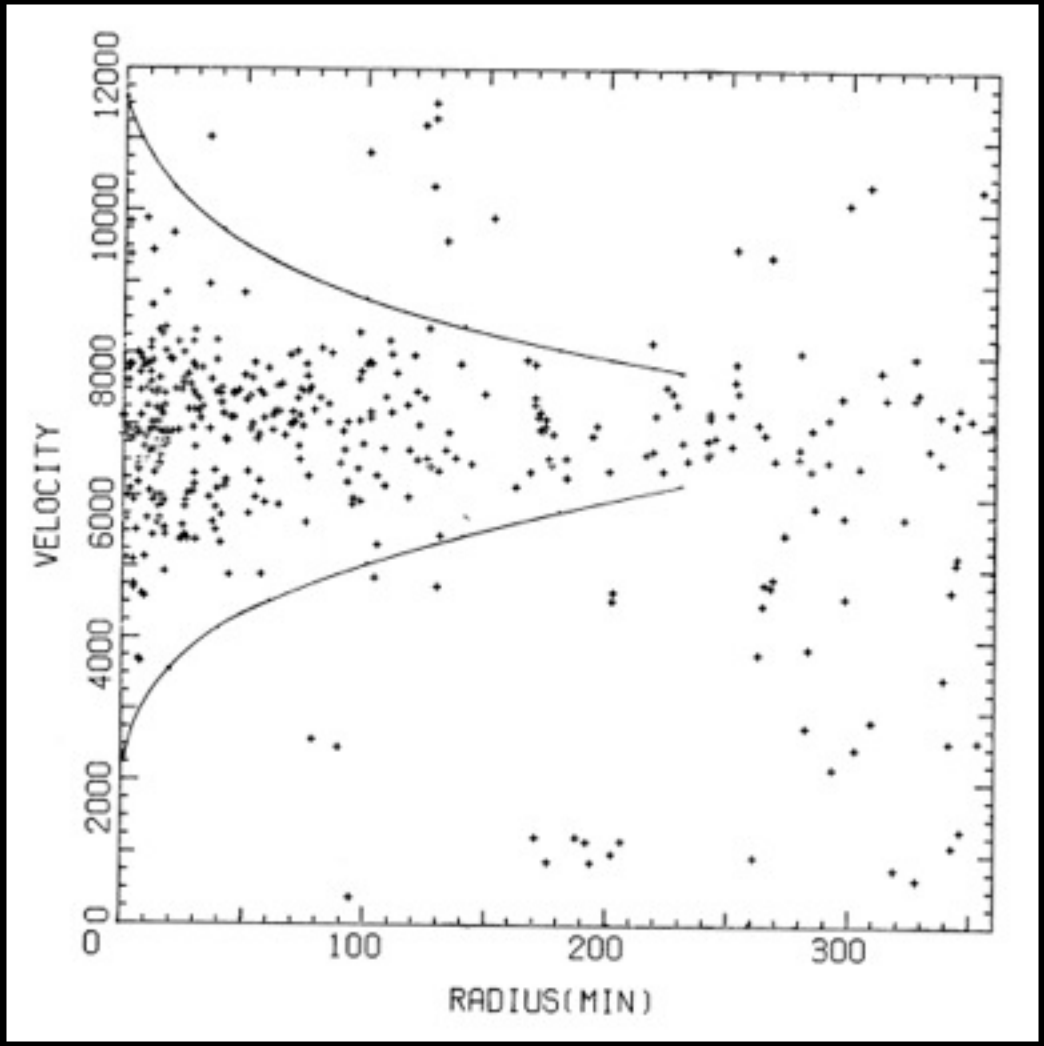
本人1987年的博士論文
導師：R.Marshak （弱作用理論的創造者之一）

結論 （到目前為止） 理論： 沒有任何可信之模型
實驗： 沒有任何跡象 （10^{-16} cm)

- 暗物質與暗能量

Evidences for Dark Matter:

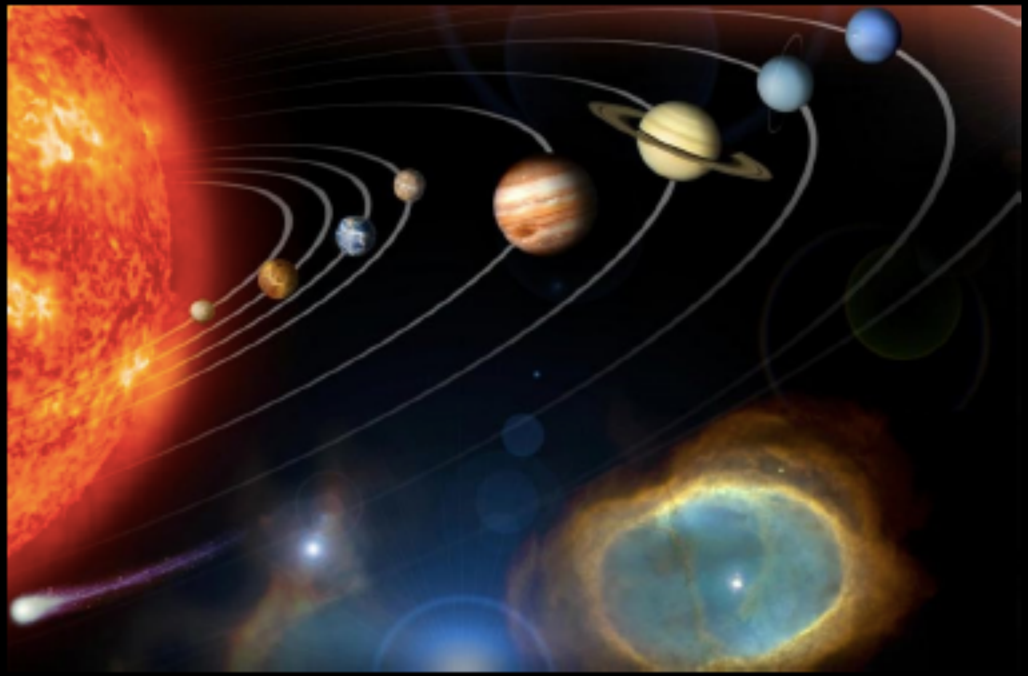
Zwicky (1933) used the radial velocity dispersion in the Coma cluster to conclude that the M/L ratio was >100X larger than M/L for the luminous matter near the Sun.



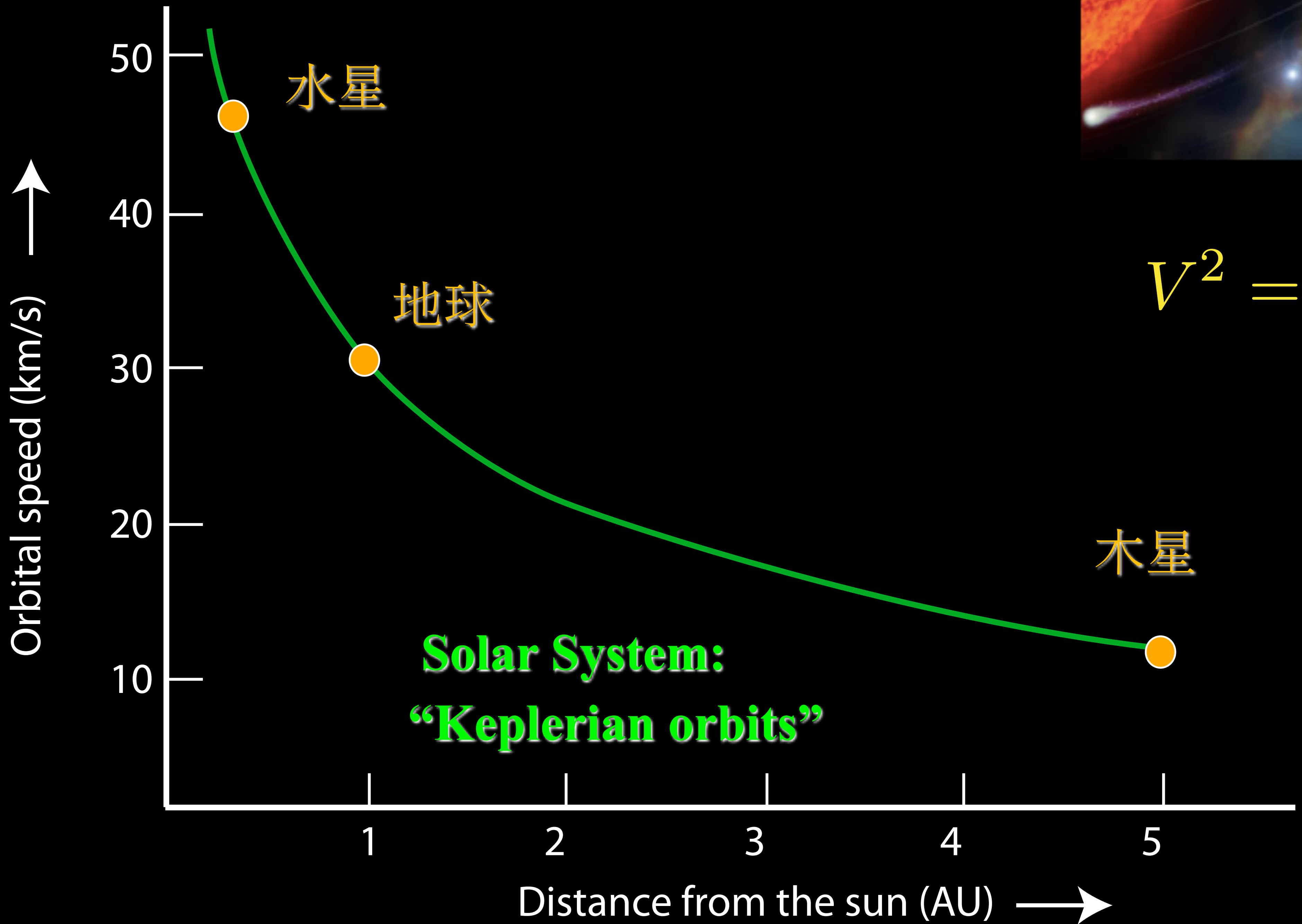
COMA cluster

F. Zwicky 1933

Solar System:



$$V^2 = \frac{GM(<r)}{r}$$



1970 ApJ 159, 379

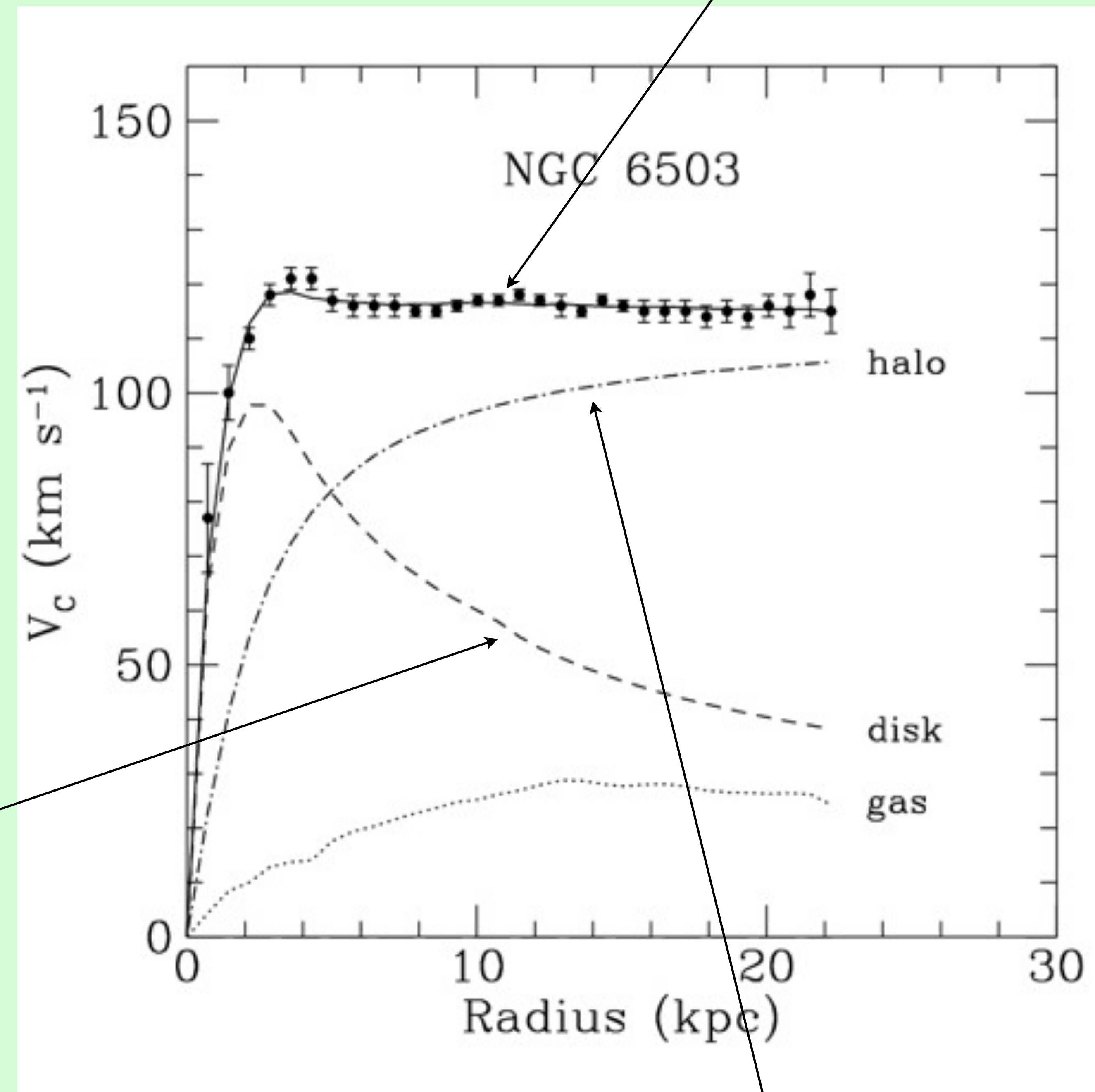
ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

Spiral galaxy

$$\frac{GM(<r)}{r^2} = \frac{v^2}{r}$$

v~constant



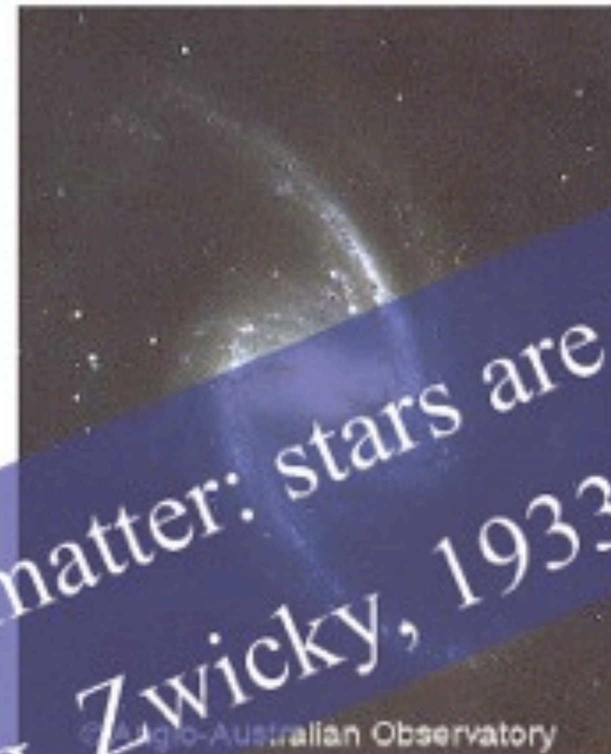
A spherical dark matter halo

Stars would be moving too fast if there were only luminous matter

Most -72%- large galaxies have spiral structures

An evidence for dark matter: stars are rotating too fast!
(e.g. Zwicky, 1933)

M83



NGC 1365

M100 SABbc

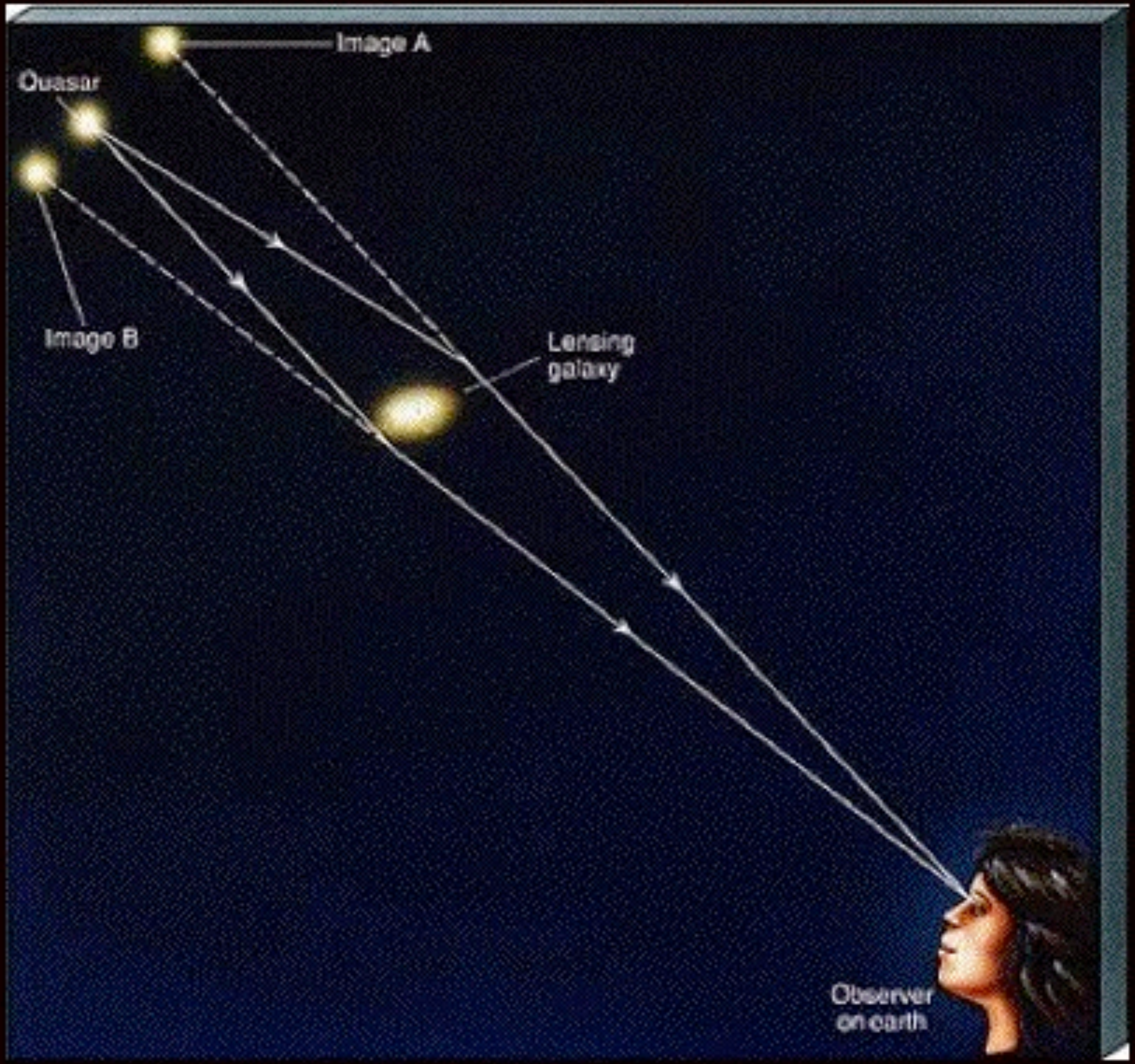
M 31

NGC 2997

NGC 1313

One way to "weigh" things in the universe:

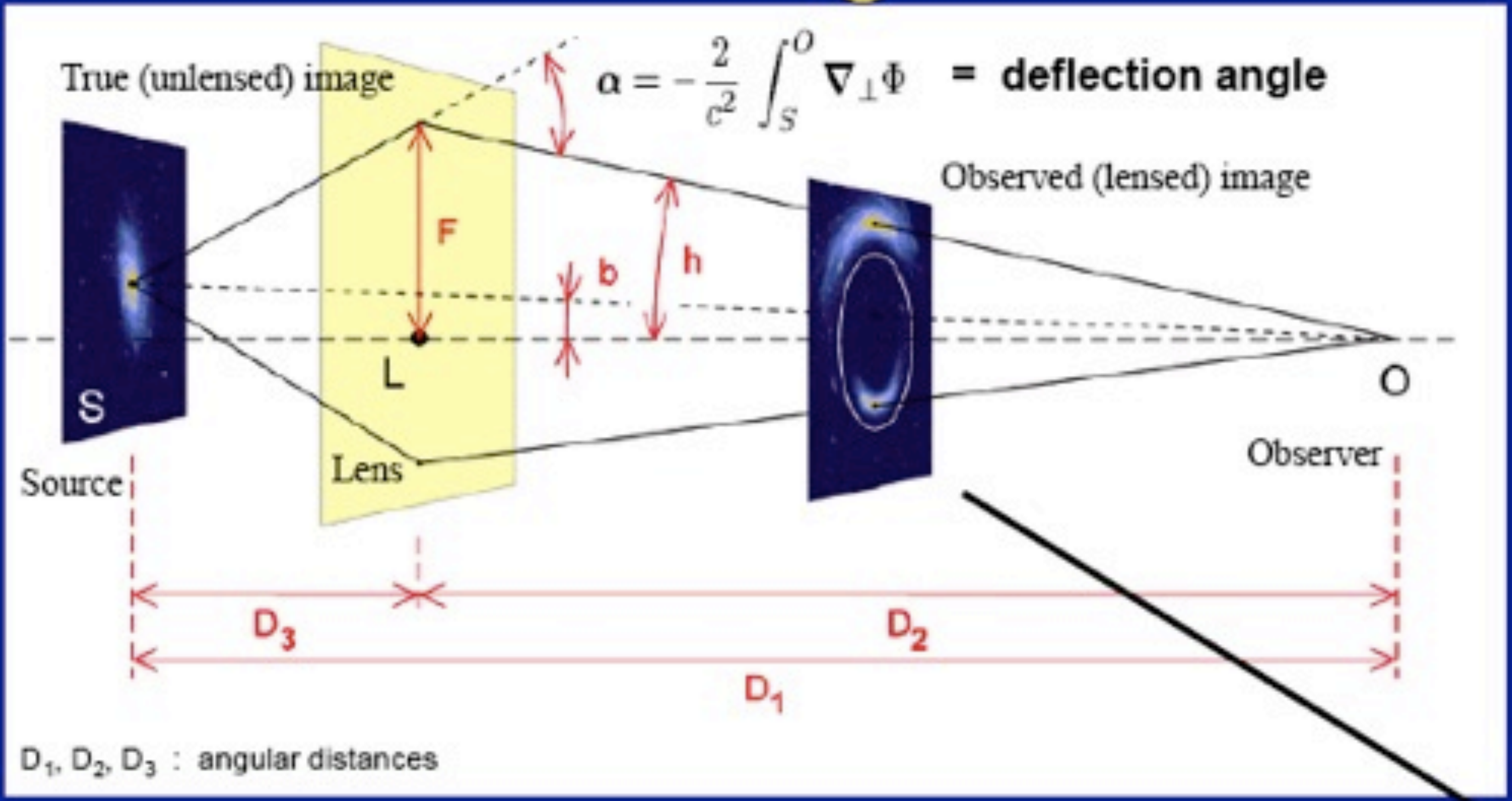
Gravitational lensing.



The gravitational field of a galaxy (or cluster of galaxies) deflects passing light; the more mass, the greater deflection.

So we can infer the existence of matter even if we can't see it.

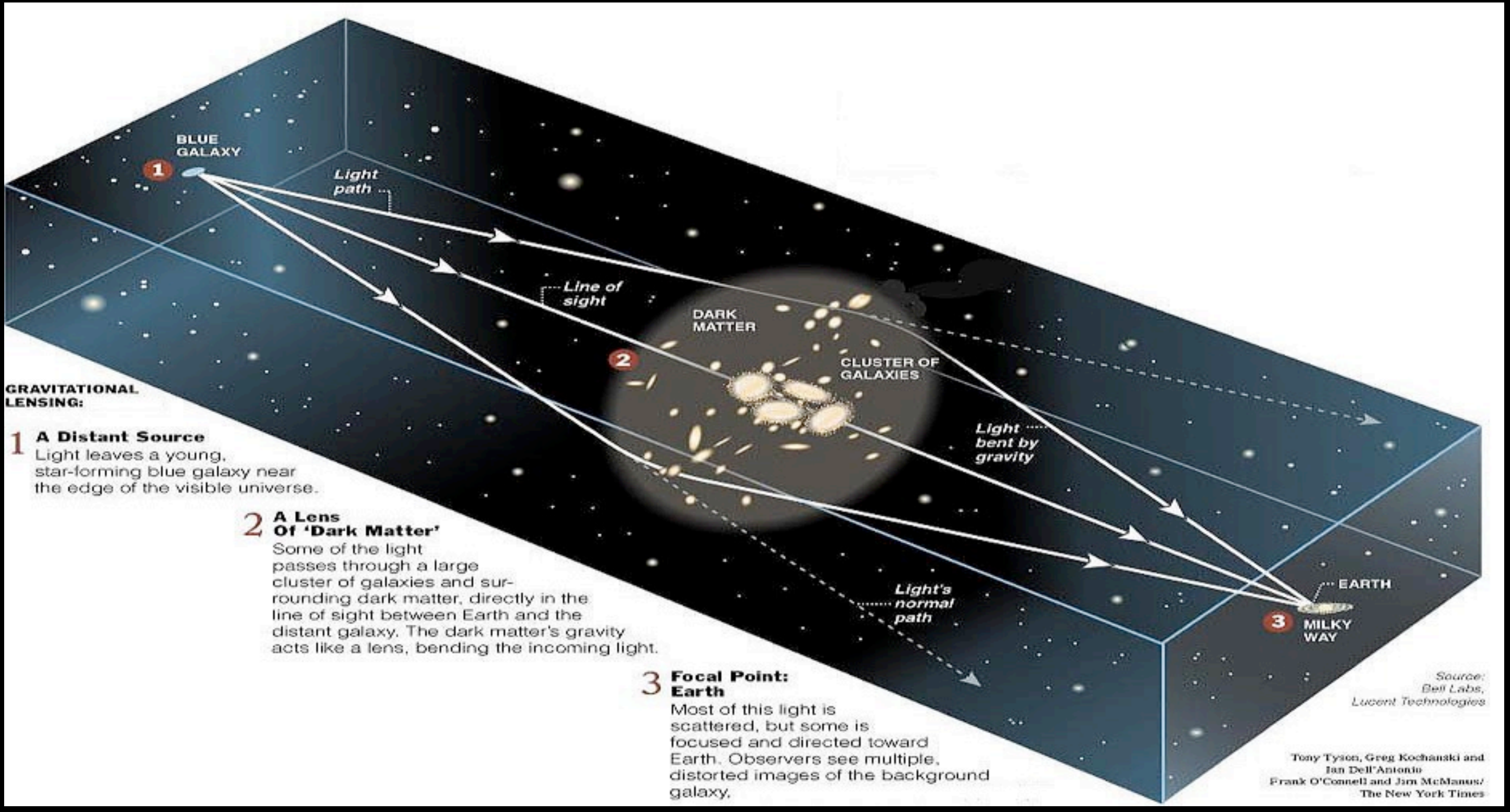
Gravitational lensing on extended source: rings and arcs



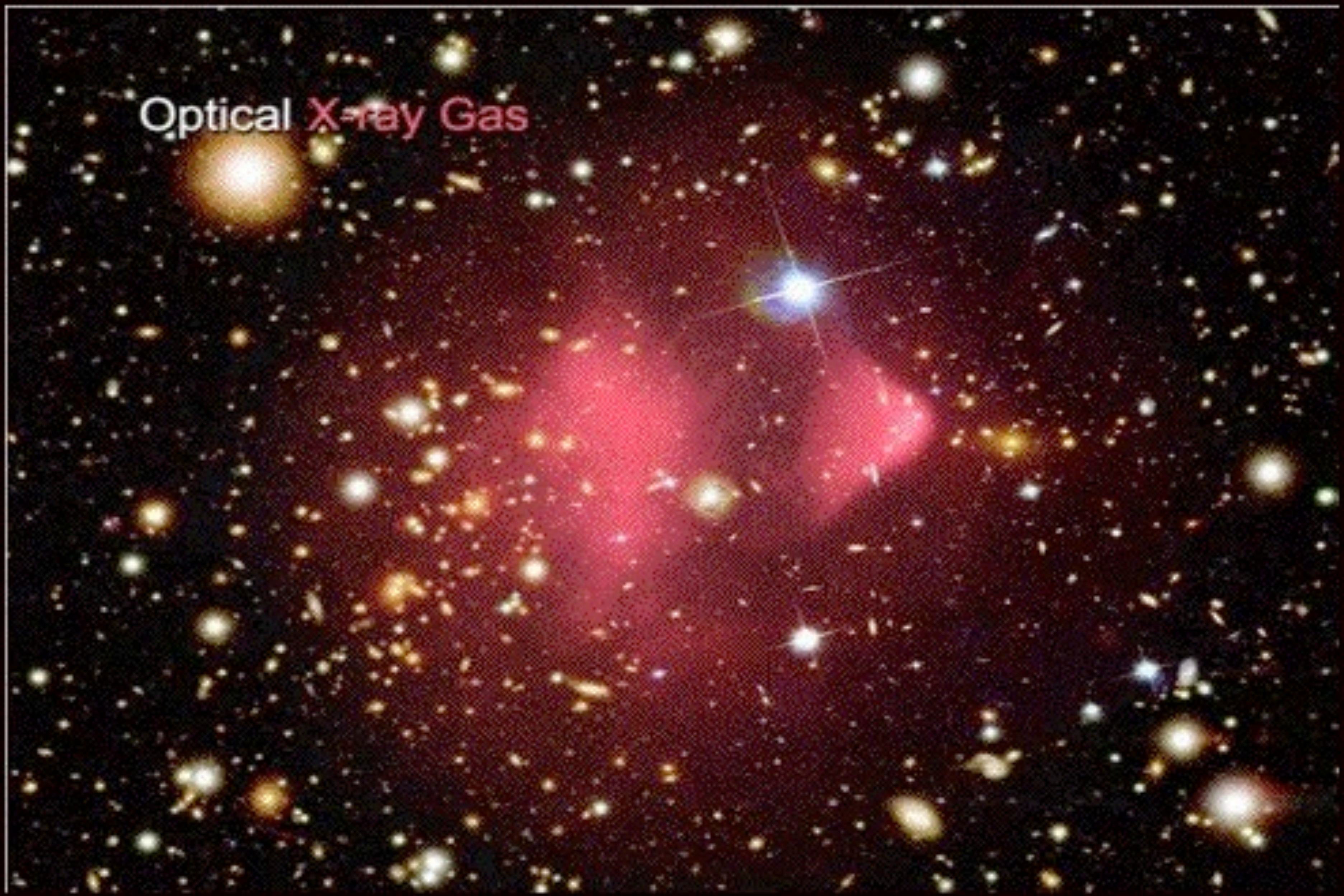
Perfect source-lens-observer alignement

Gravitational Lensing

Gravitational Lensing



Bullet Cluster

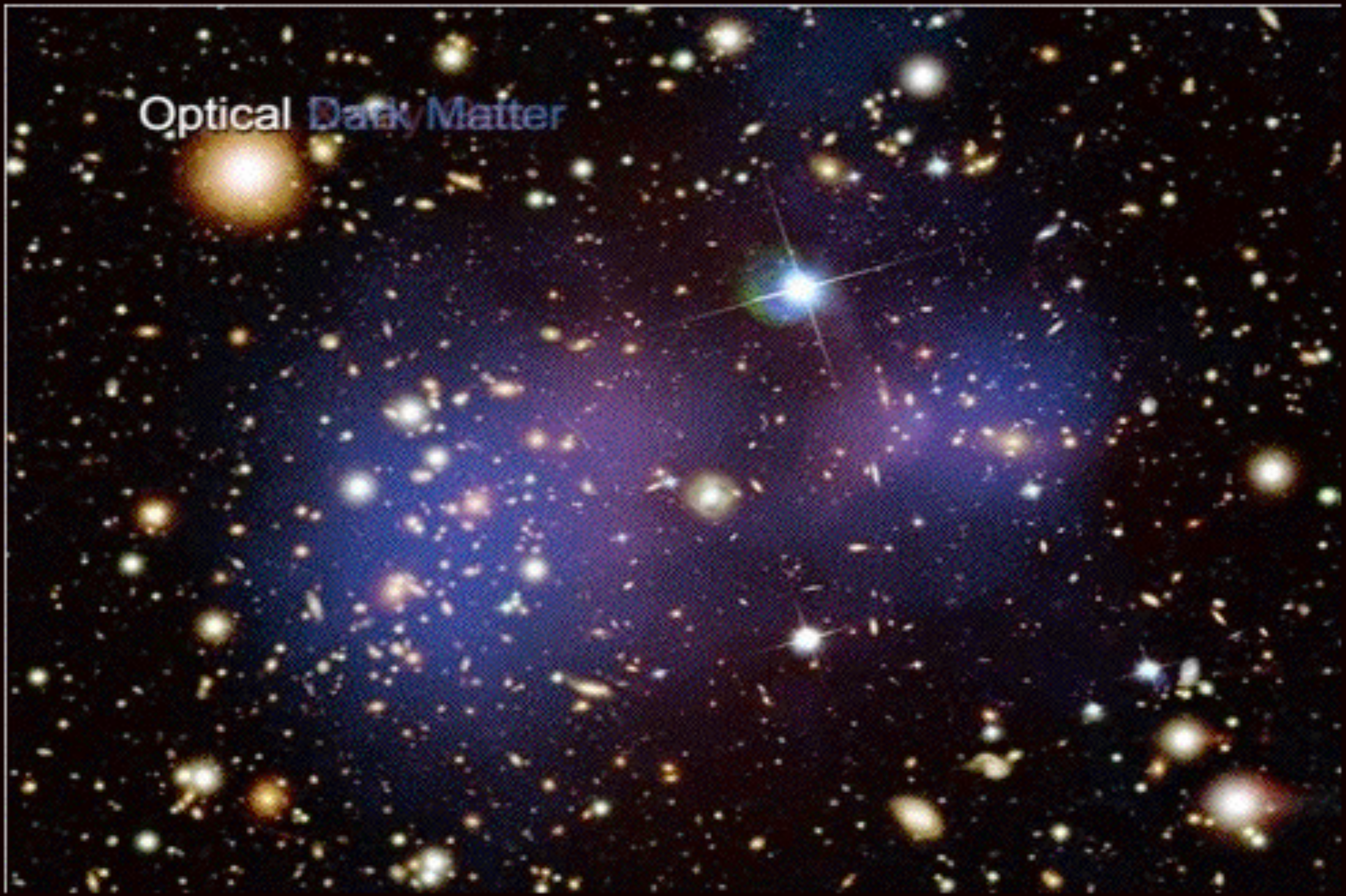


[Clowe et al.]

Bullet Cluster

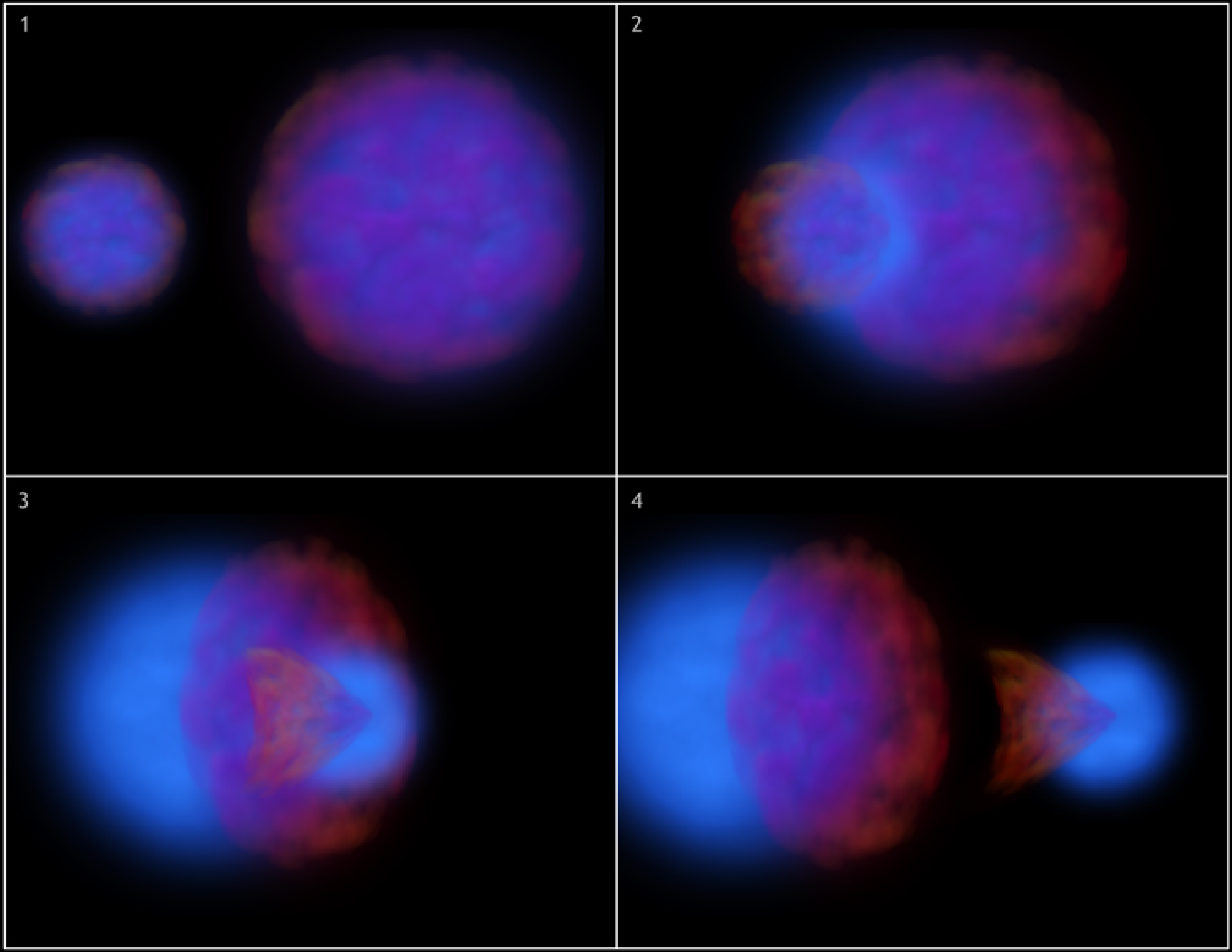
[Clowe et al.]

Bullet Cluster



[Clowe et al.]

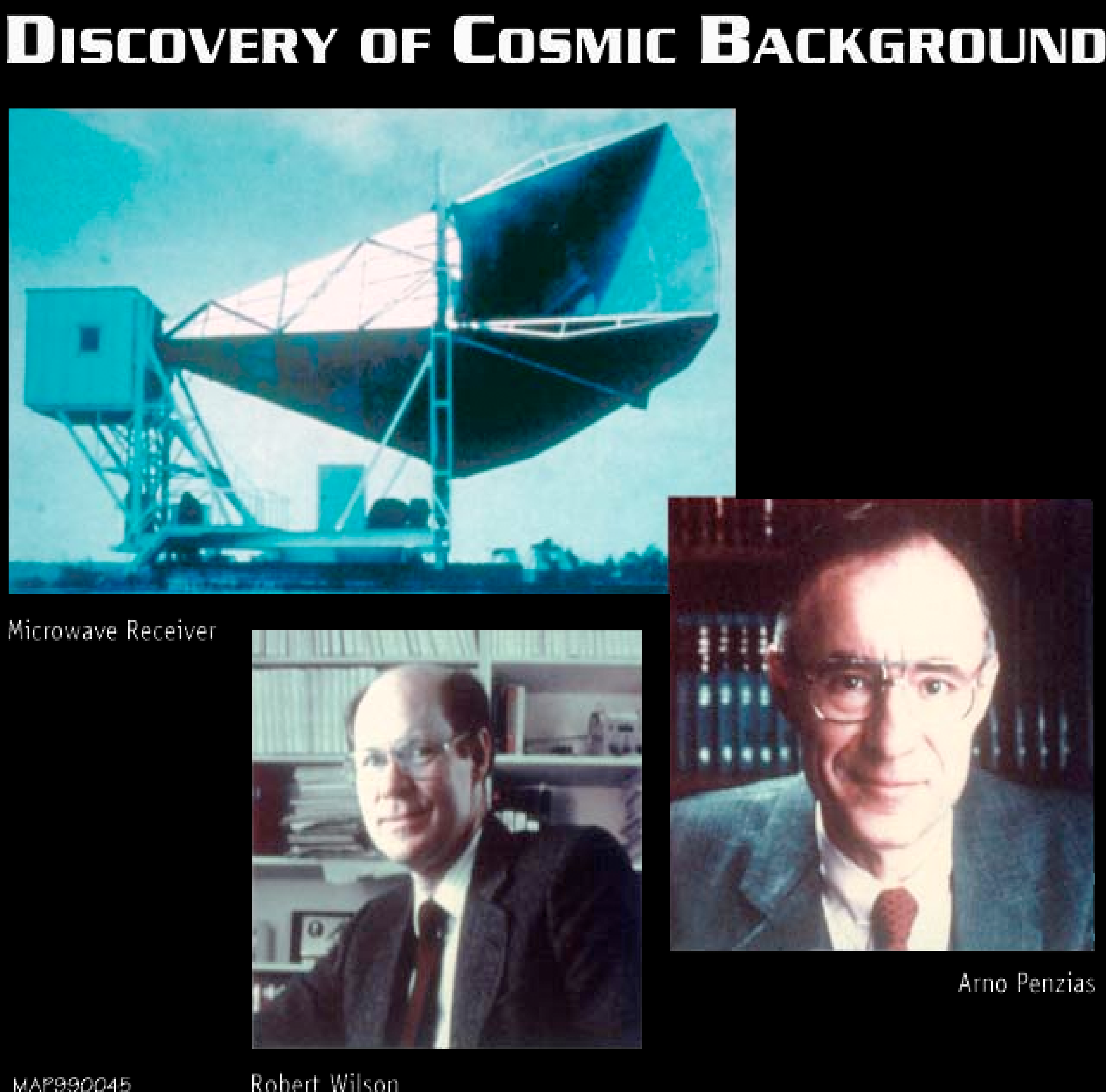
Merging Clusters

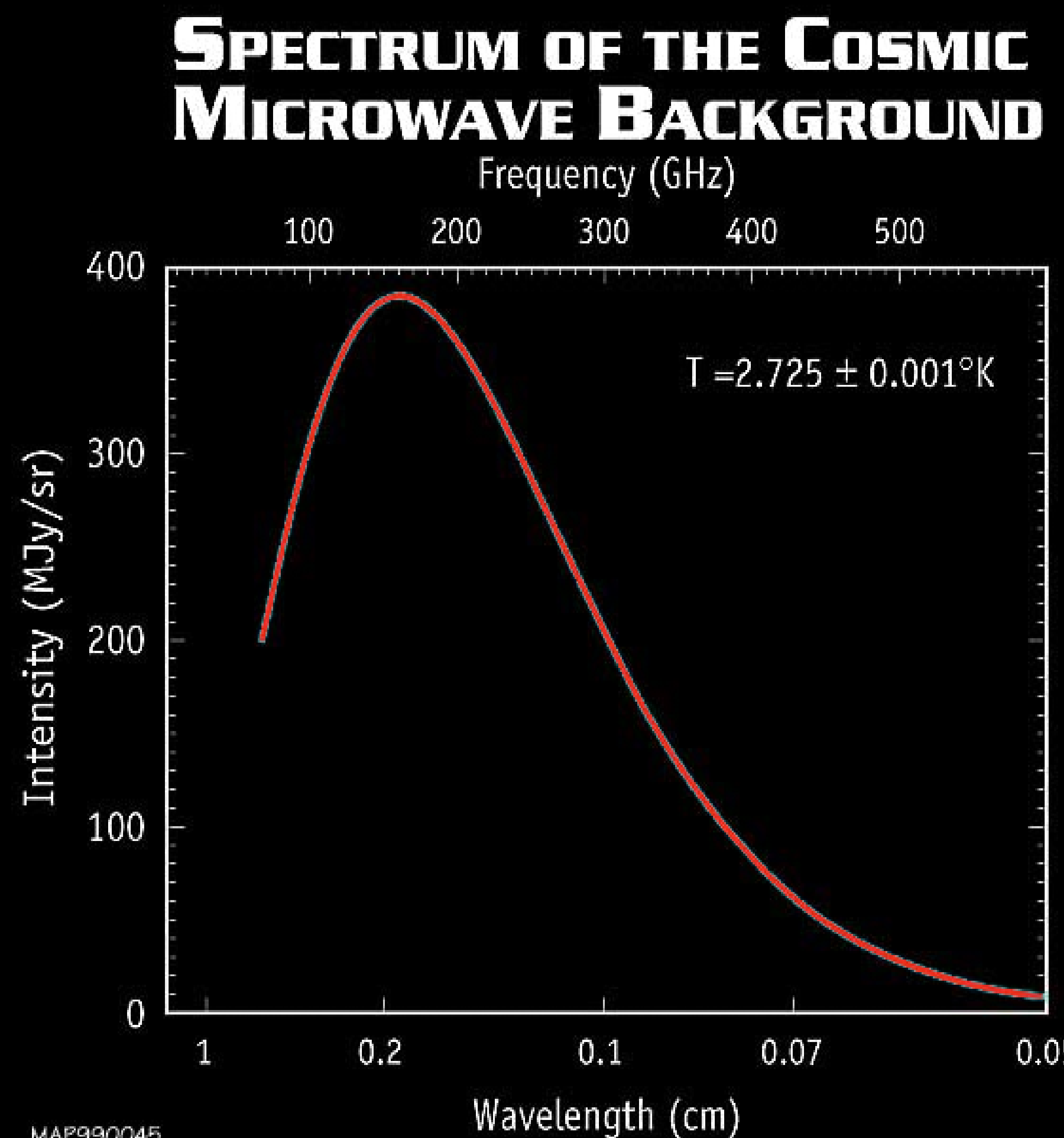


artists' rendition

Cosmic Microwave Background (CMB)

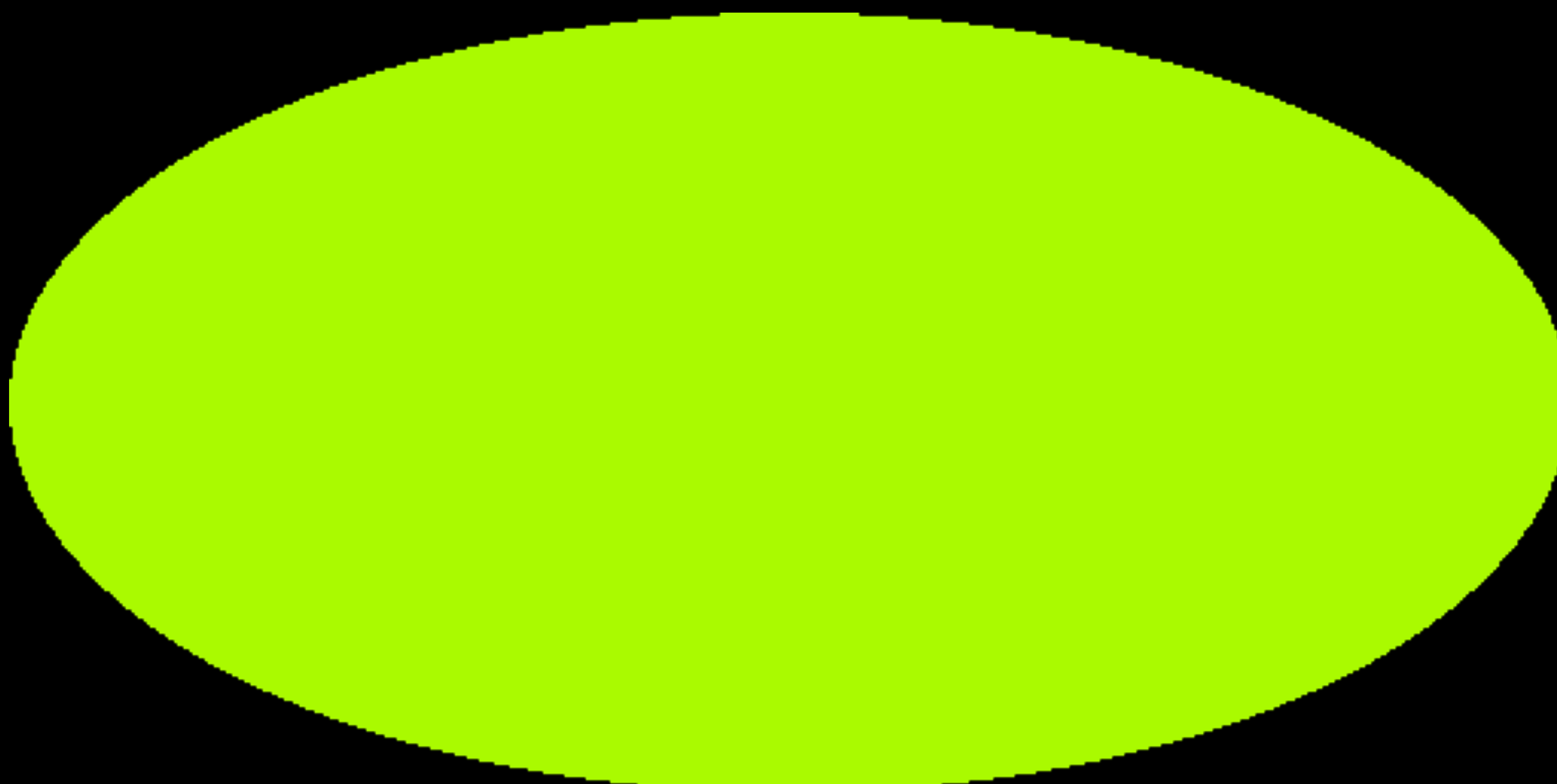
very cold (-270.275 C, 2.725 K) and nearly uniform relic radiation left over from the hot big bang



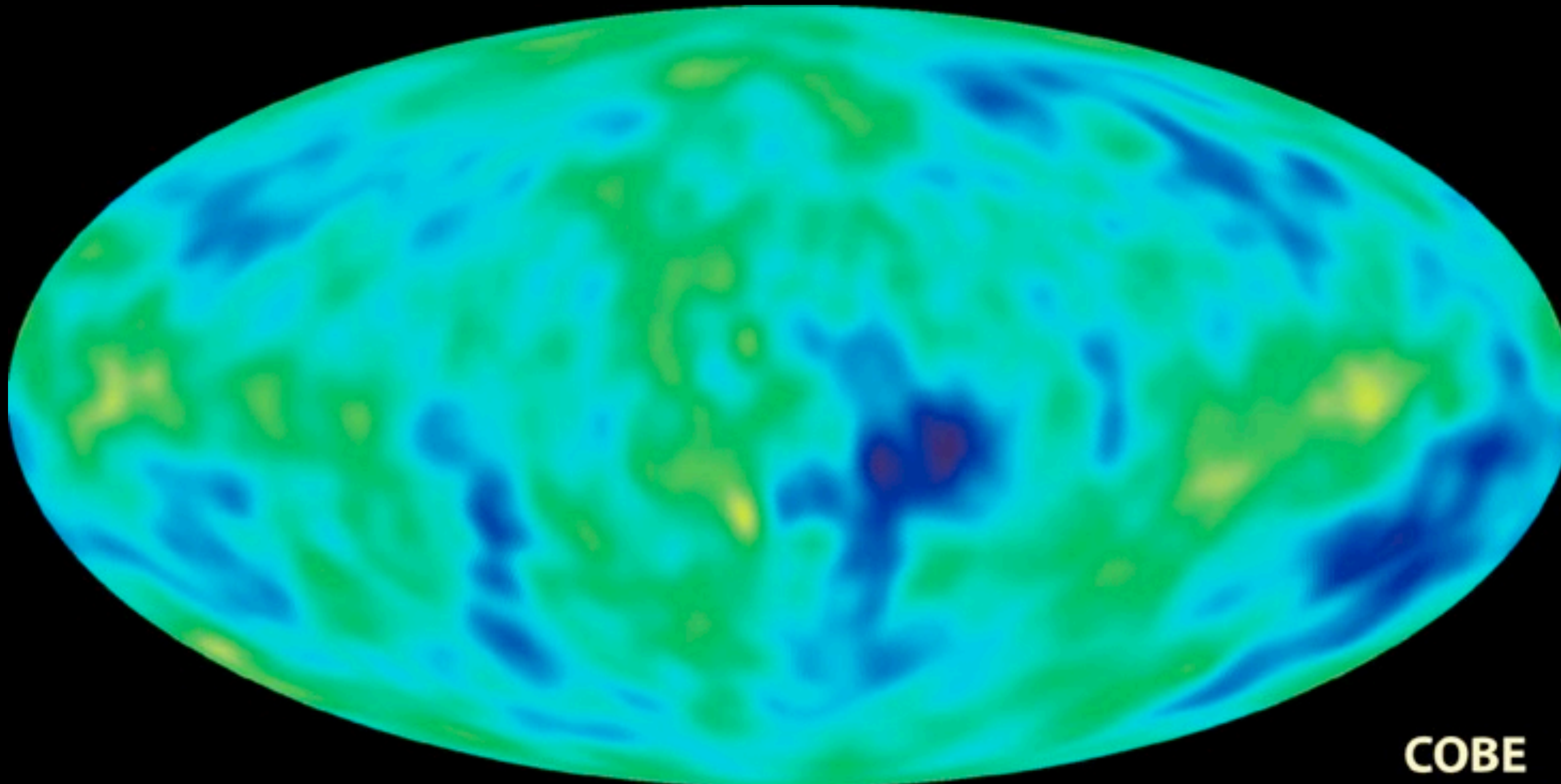


Cosmic Microwave Background

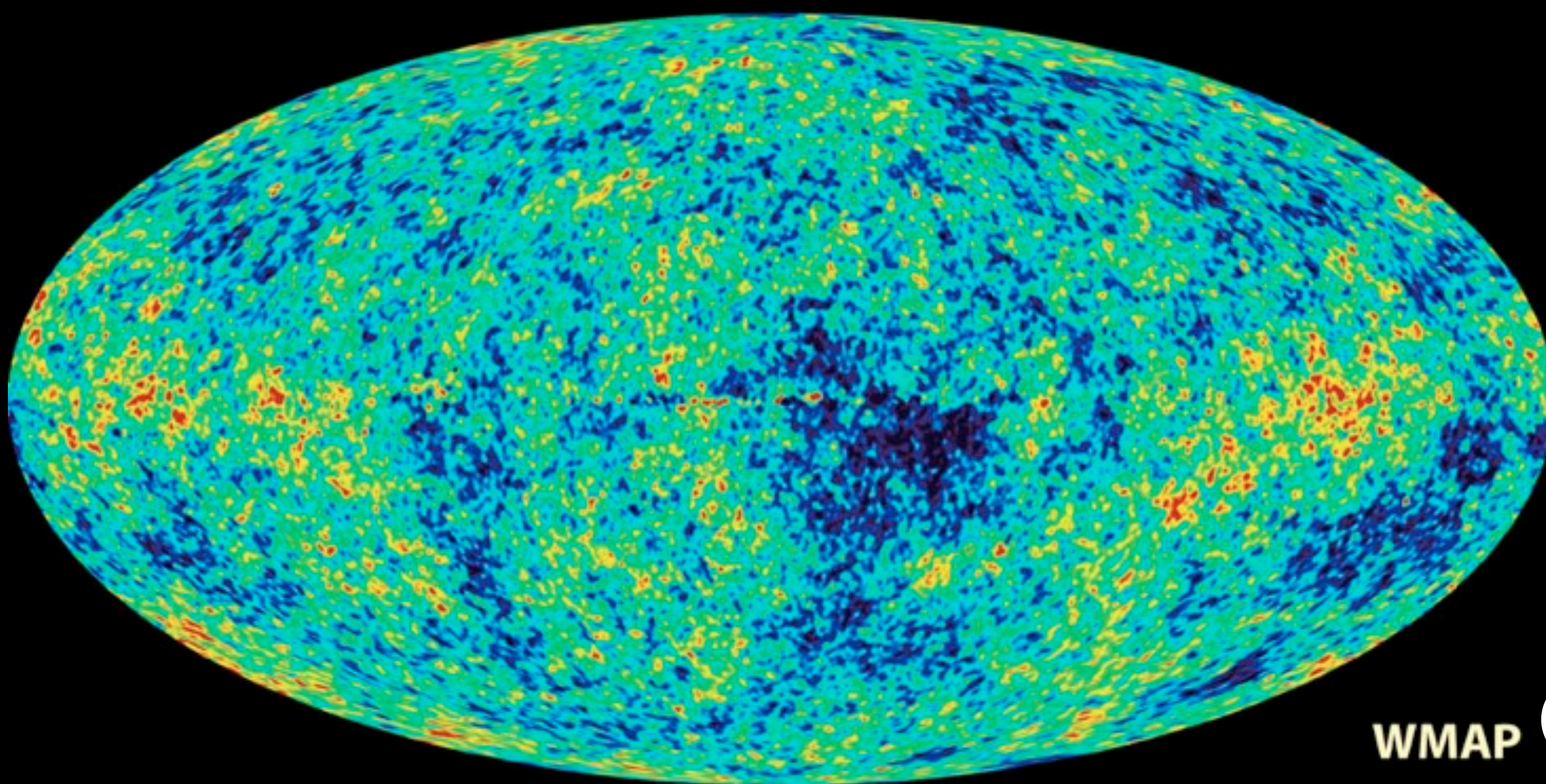
If you had microwave eyes:



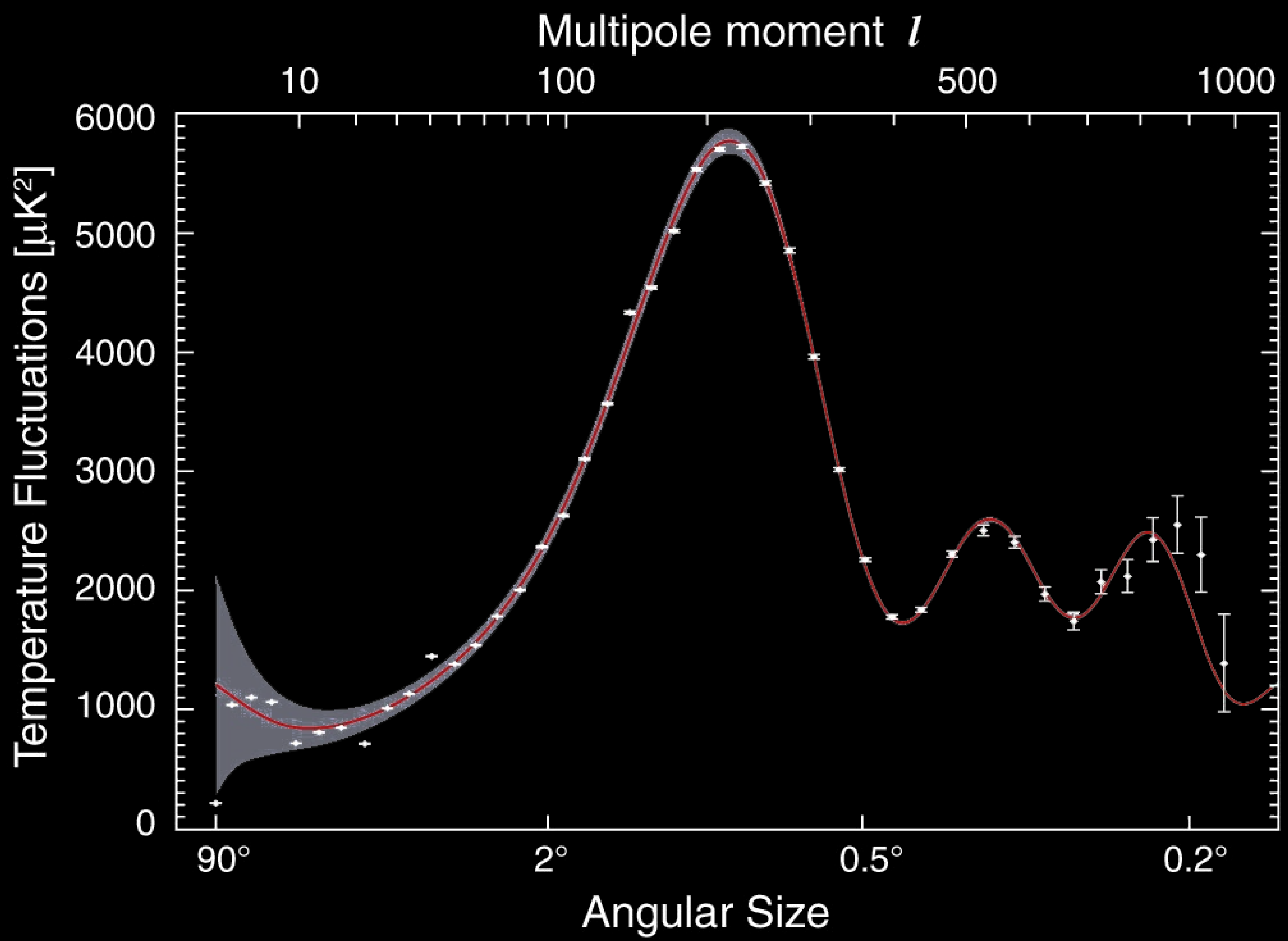
(1965)



COBE (1992)



WMAP (2010)



White points: WMAP (2010) 7-year data

Red curve: Theoretical prediction for a universe made of

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

The Acceleration Universe: Dark Energy

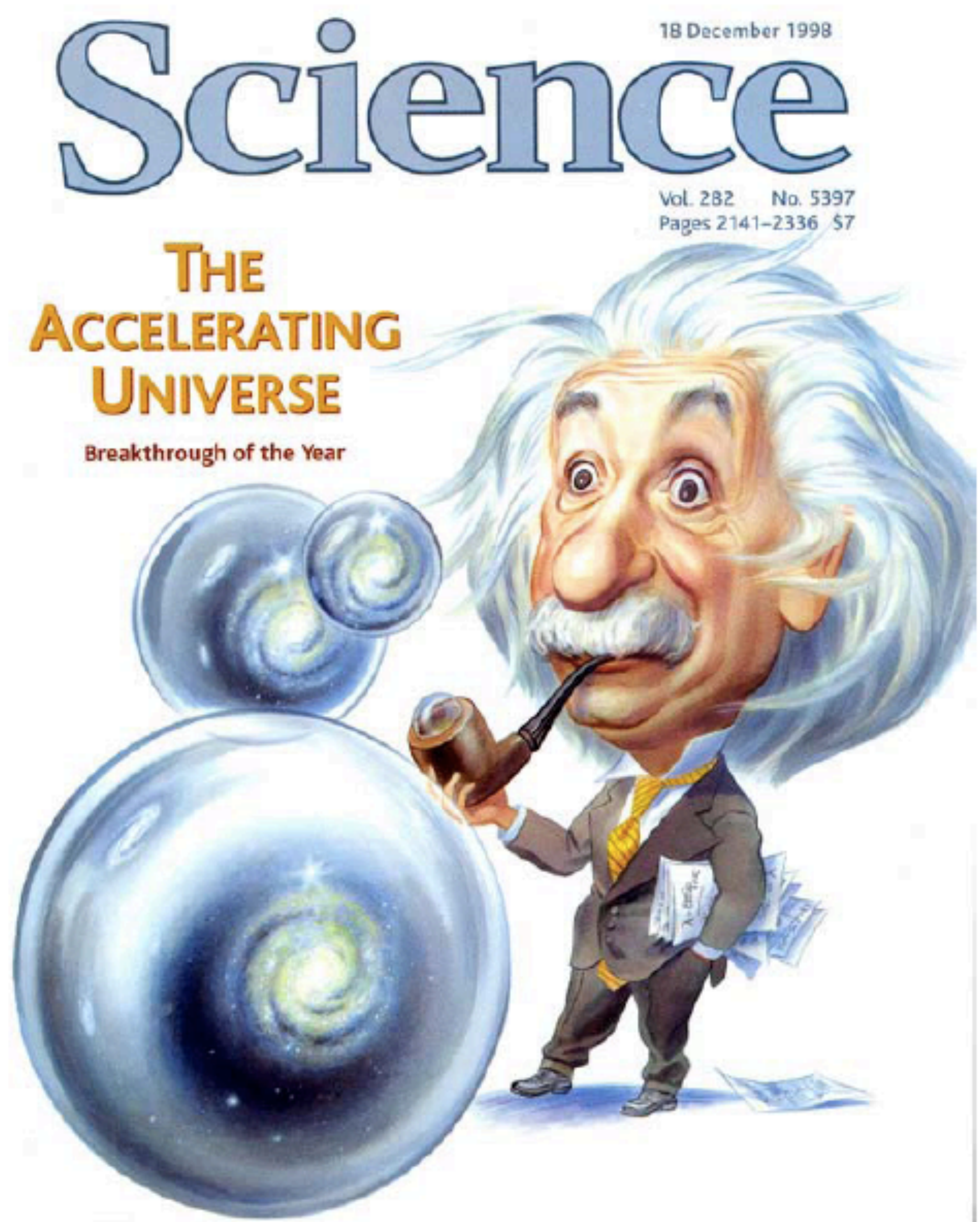
Big News in 1998!

High-Z Team

Riess et al. (1998)

Supernova Cosmology Project

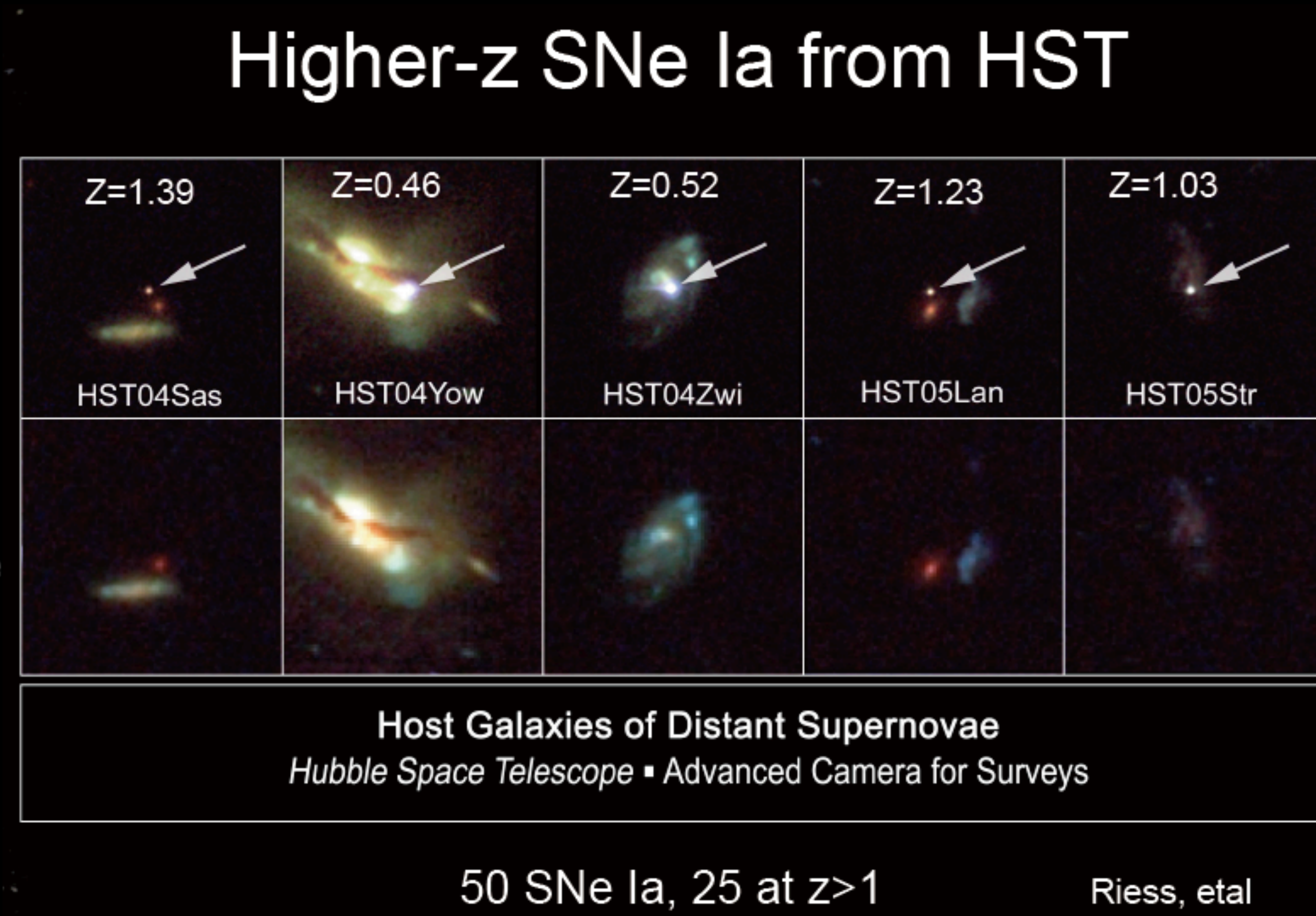
Perlmutter et al. (1999)



Distant supernovae

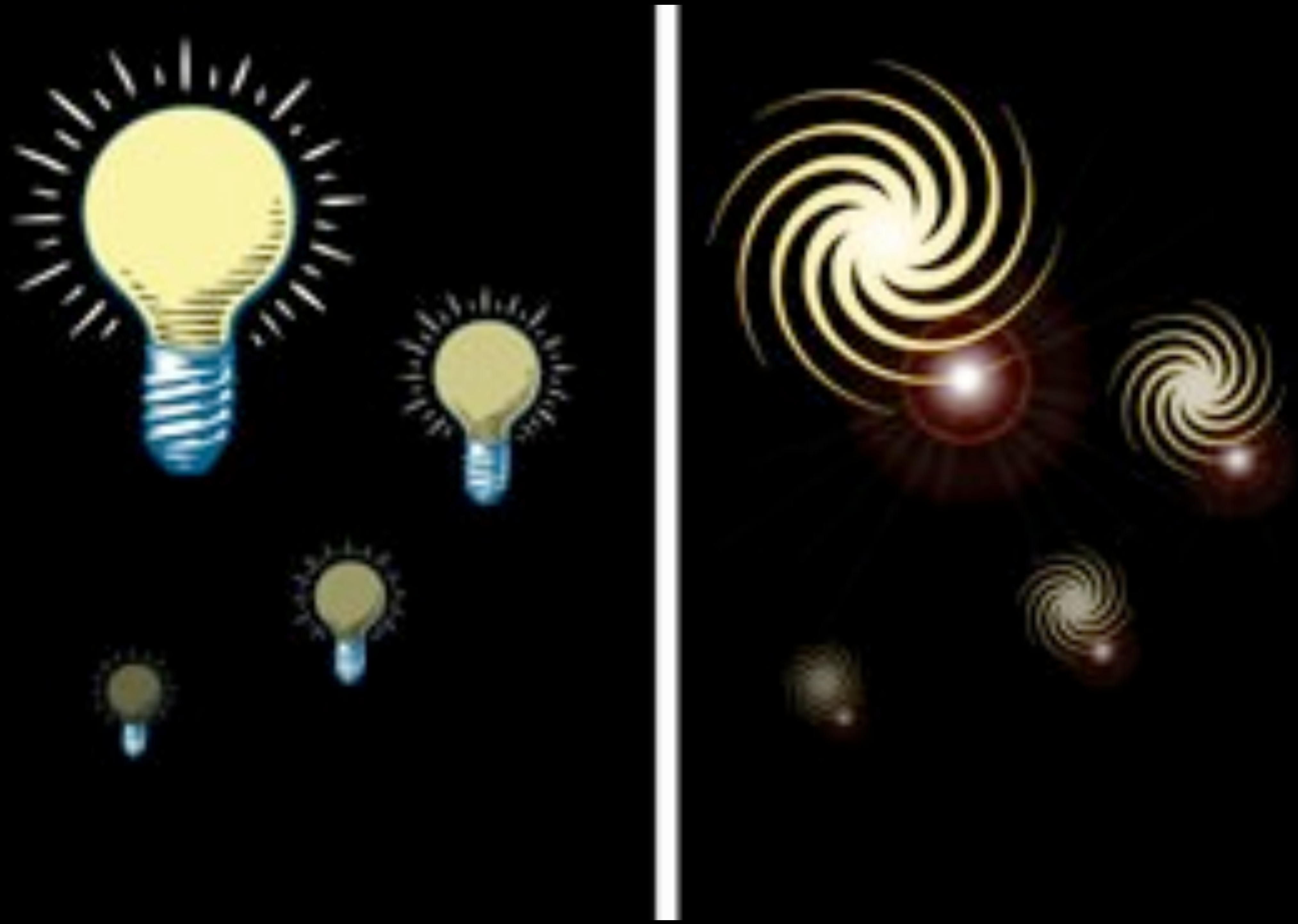
After

Before

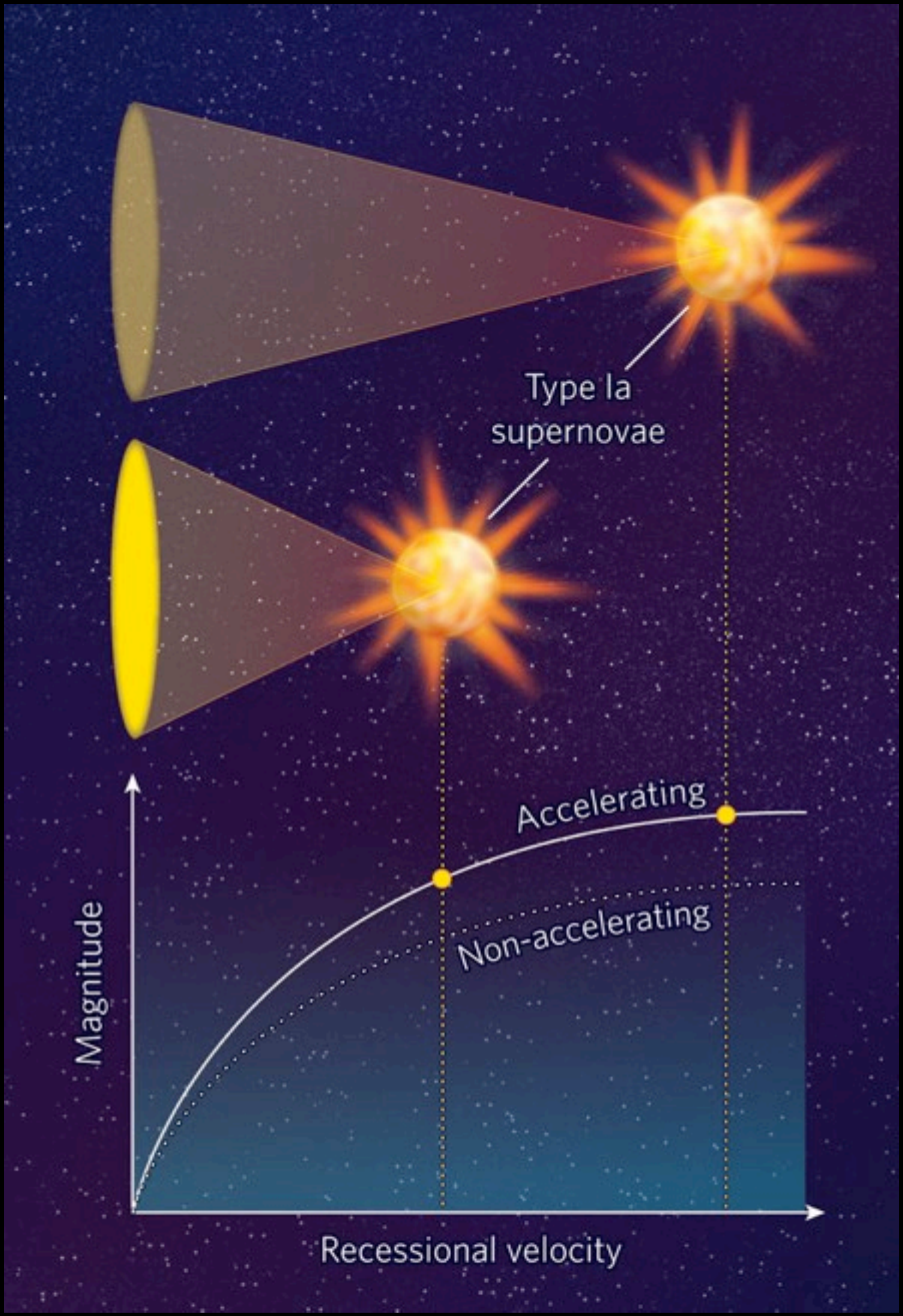


Distant supernovae

Standard candles
Their intrinsic luminosity is know
Their apparent luminosity can be measured



Distant SN as standard candles



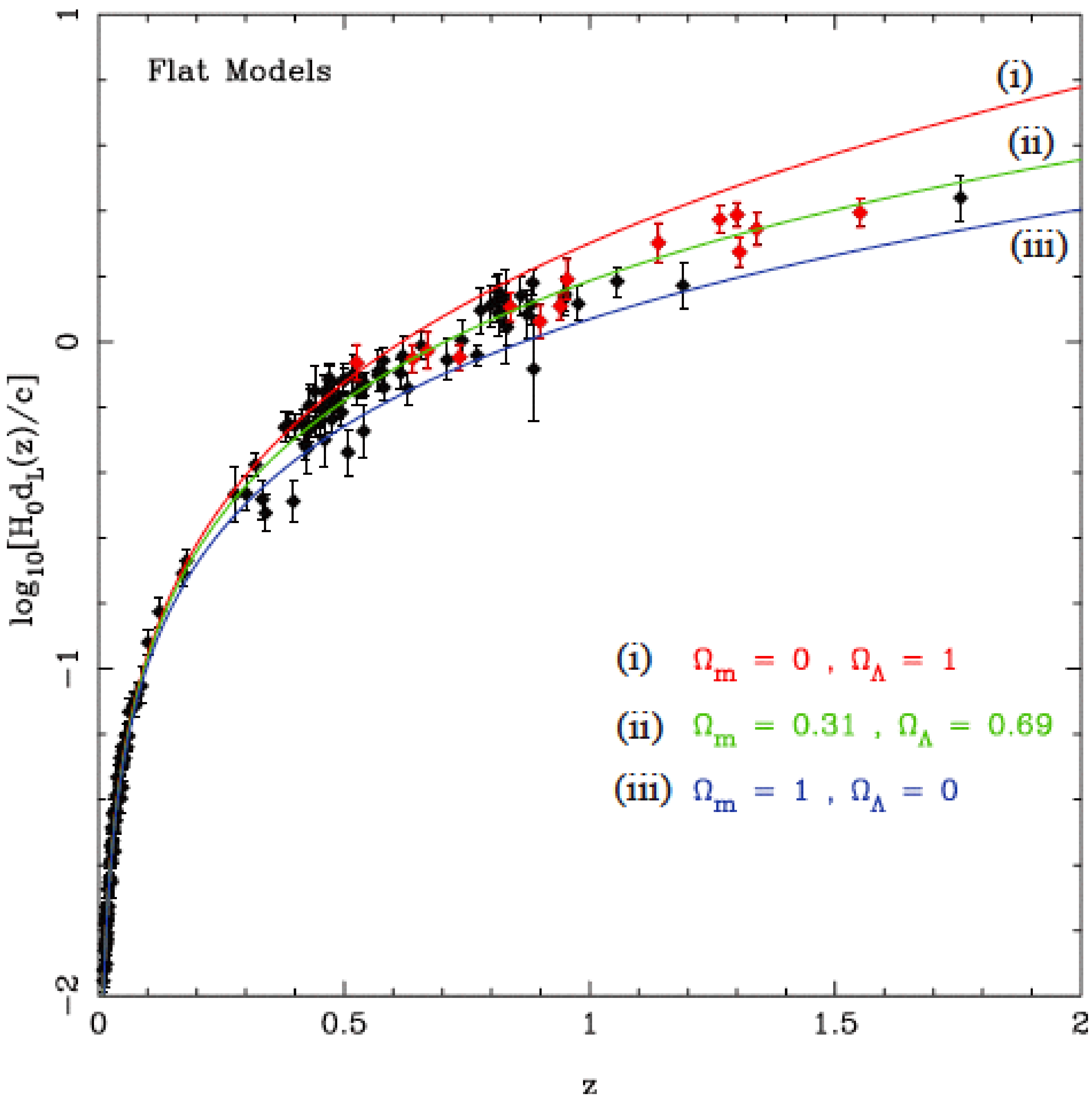
Luminosity distance:

$$d_L(z) = \frac{c}{H_0}\left[z + \frac{1}{4}\left(1 - 3w_{\rm DE}\Omega_{\rm DE}^{(0)} - \frac{K}{a_0^2 H_0^2}\right) z^2 + \mathcal{O}(z^3)\right]$$

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

L_s the absolute luminosity of the source
F observed flux

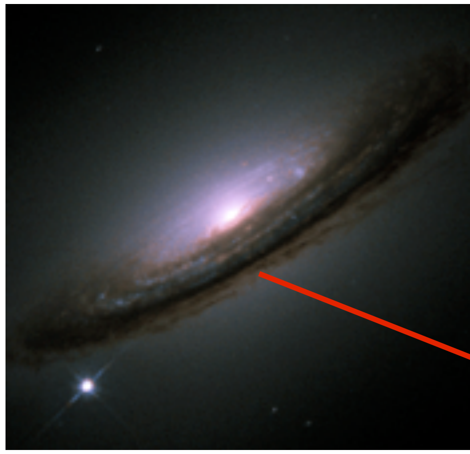
More data over the past 10 years



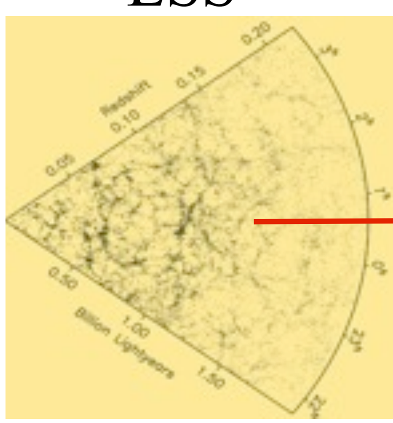
Dark Energy & Dark Matter

Concordance region:
70% dark energy
25% dark matter
5% atoms

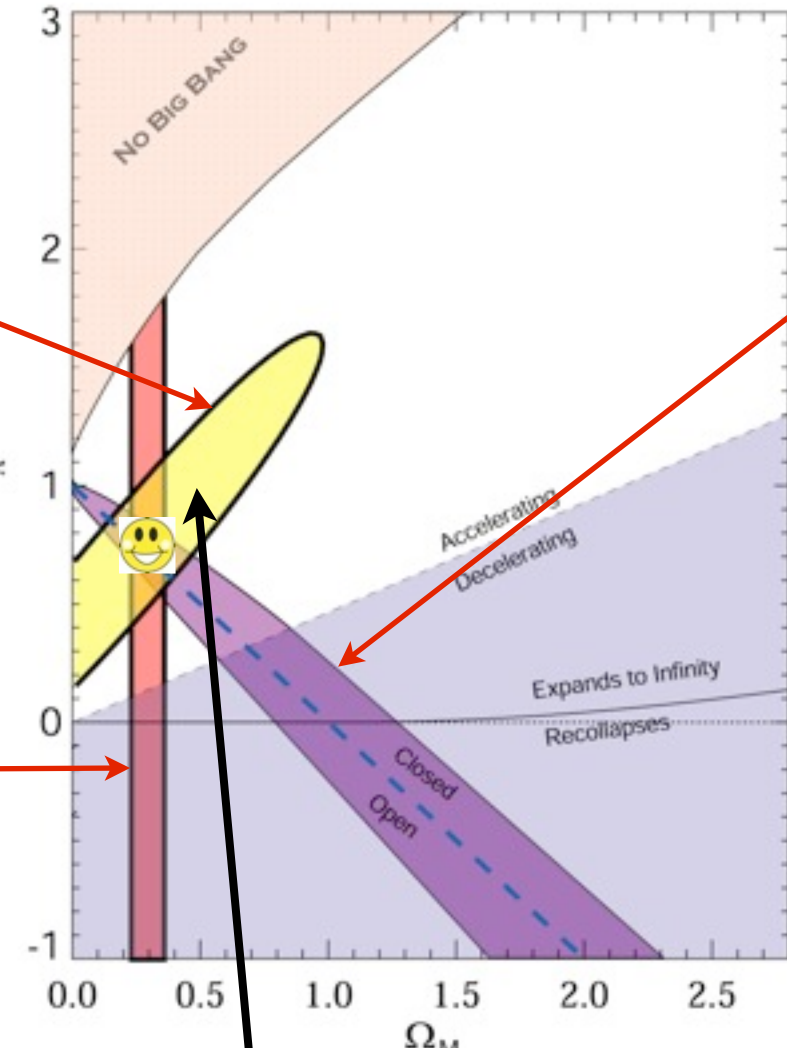
SNe Ia



LSS

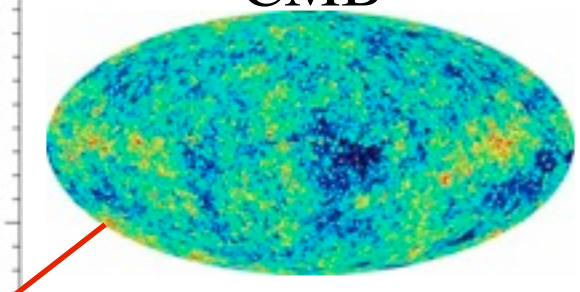


暗能量



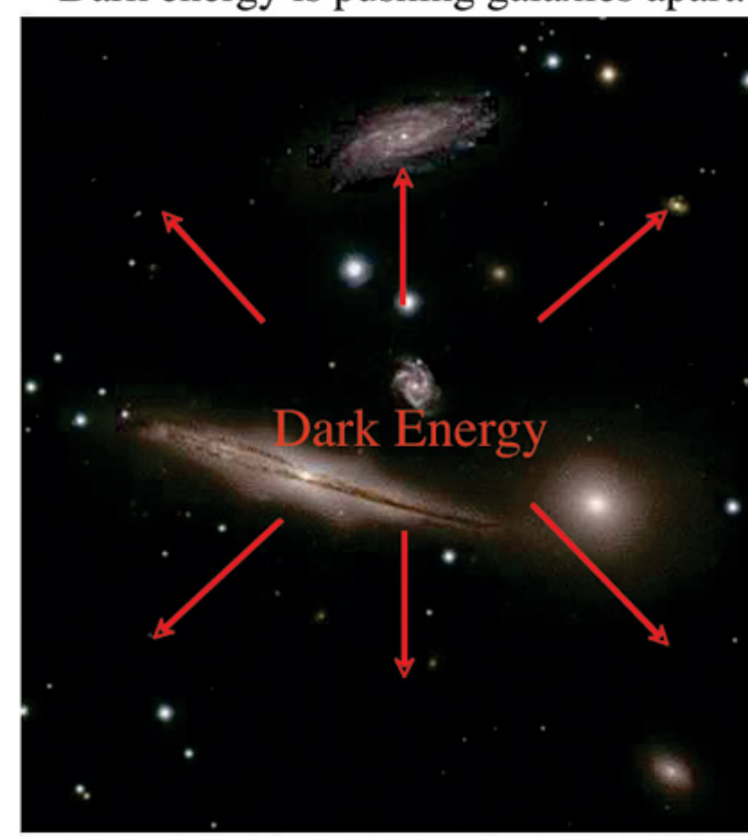
暗物質

CMB



The current universe is accelerating!

Dark energy is pushing galaxies apart.



Thomson Reuters prediction of 2010 N.P. in Physics

- Saul Perlmutter
  Professor, Department of Physics, University of California Berkeley, Berkeley, CA USA, and Senior Scientist, Lawrence Berkeley National Laboratory, Berkeley, CA USA
  WHY: for discoveries of the accelerating rate of the expansion of the universe, and its implications for the existence of dark energy

- Adam G. Riess
  Professor, Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD USA, and Senior Member, Space Telescope Science Institute, Baltimore, MD USA
  WHY: for discoveries of the accelerating rate of the expansion of the universe, and its implications for the existence of dark energy

- Brian P. Schmidt
  Australian Research Council Federation Fellow, Research School of Astronomy and Astrophysics, Australian National University, Weston Creek, Australia
  WHY: for discoveries of the accelerating rate of the expansion of the universe, and its implications for the existence of dark energy

邵逸夫獎

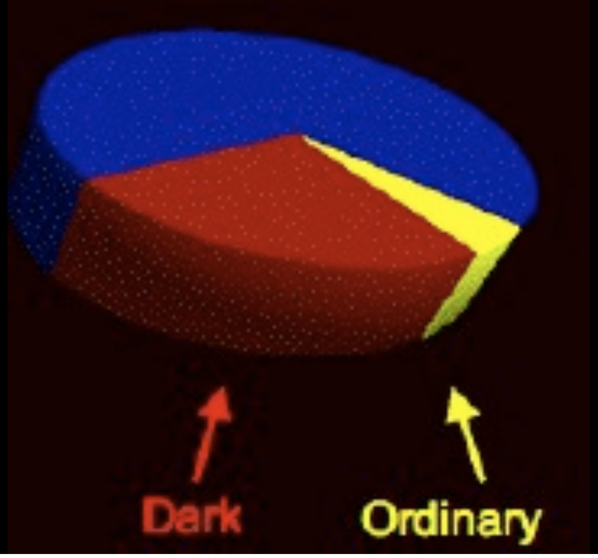
Note: Perlmutter, Riess, and Schmidt received 2006 Shaw Prize

Frank Hsu (2009 Shaw Prize), former president of NTHU :
Dark Energy > 10 Nobel Prizes

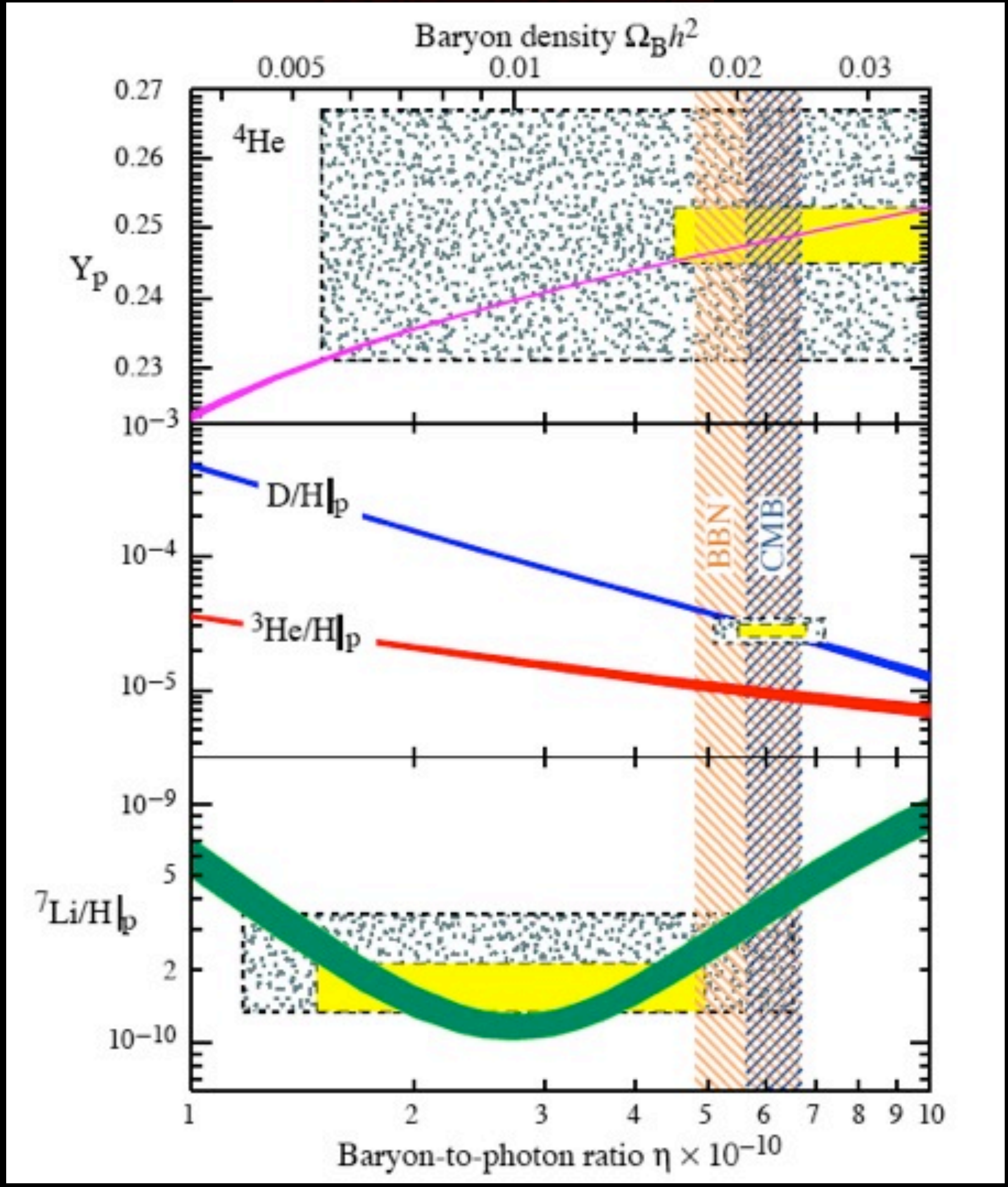
US Decadal survey (Astro2010) 2012-2021

The top-ranked projects in "New Worlds, New Horizons in Astronomy and Astrophysics" include studies of dark energy and dark matter.

Dark Matter: 25%



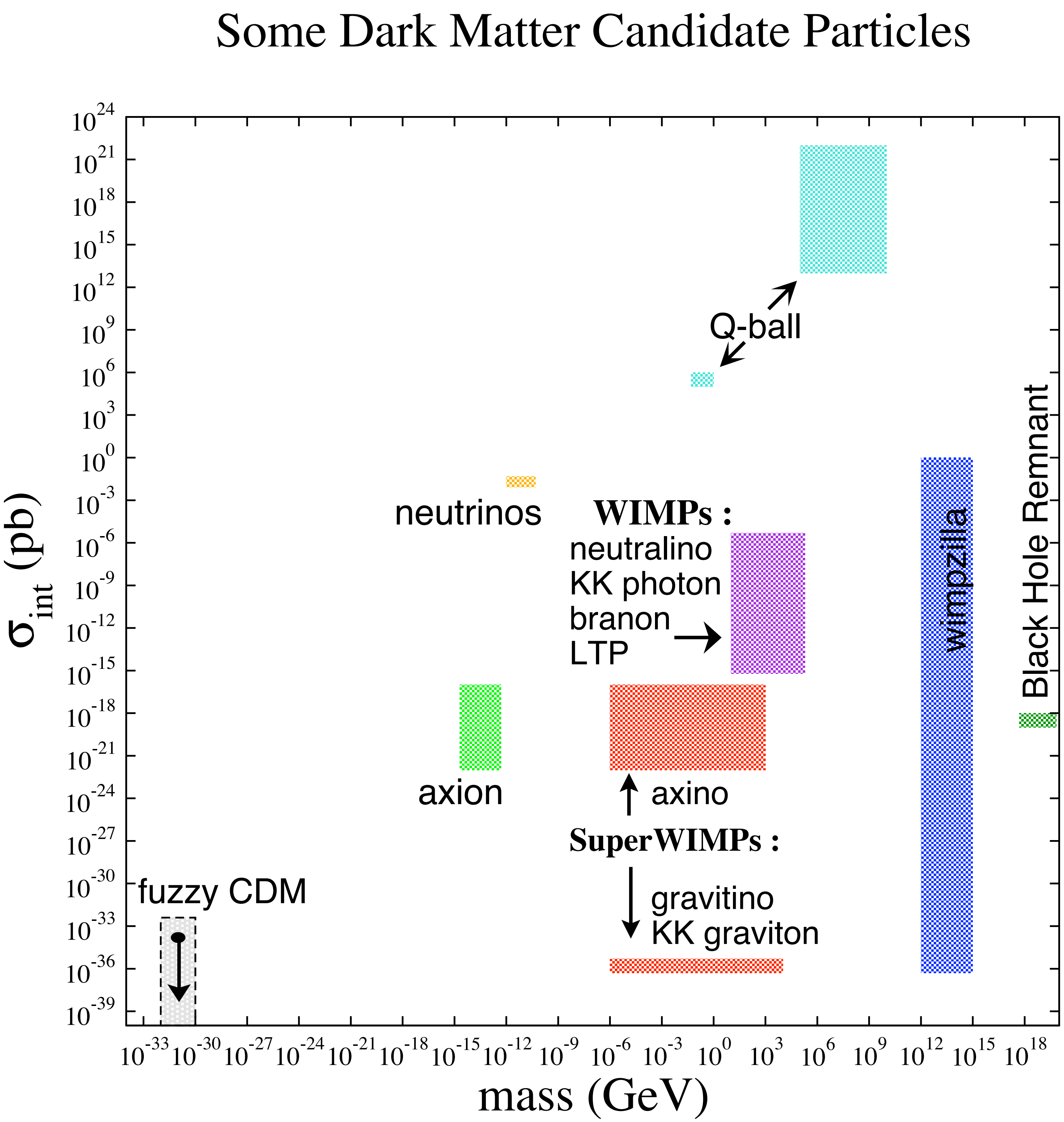
Independent methods (using primordial nucleosynthesis & the microwave background) convince us that the dark matter is a completely new kind of particle.



Dark matter cannot be the particle in the standard model, which has to be WIMP

Weakly Interacting Massive Particles

Supersymmetric neutralinos?

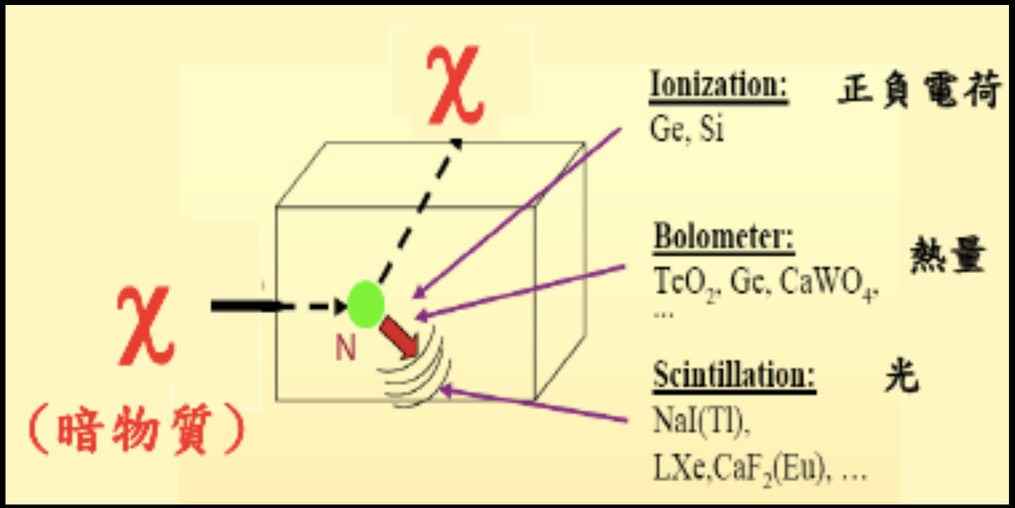


- neutrino ν – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino $\tilde{a}$
- gravitino $\tilde{G}$
- wimpzilla,. . .

How to observe dark matter?

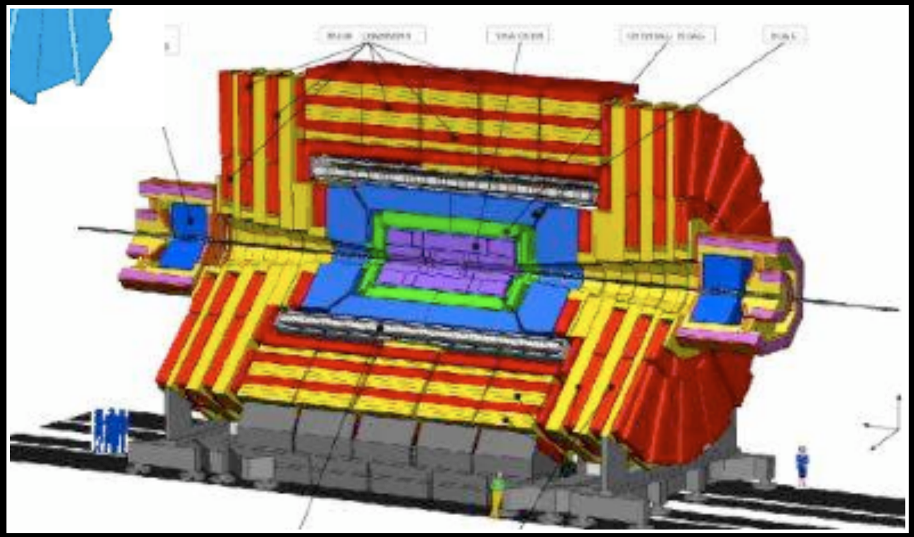
Search for Dark Matter:

Direct detection:
(underground experiments)

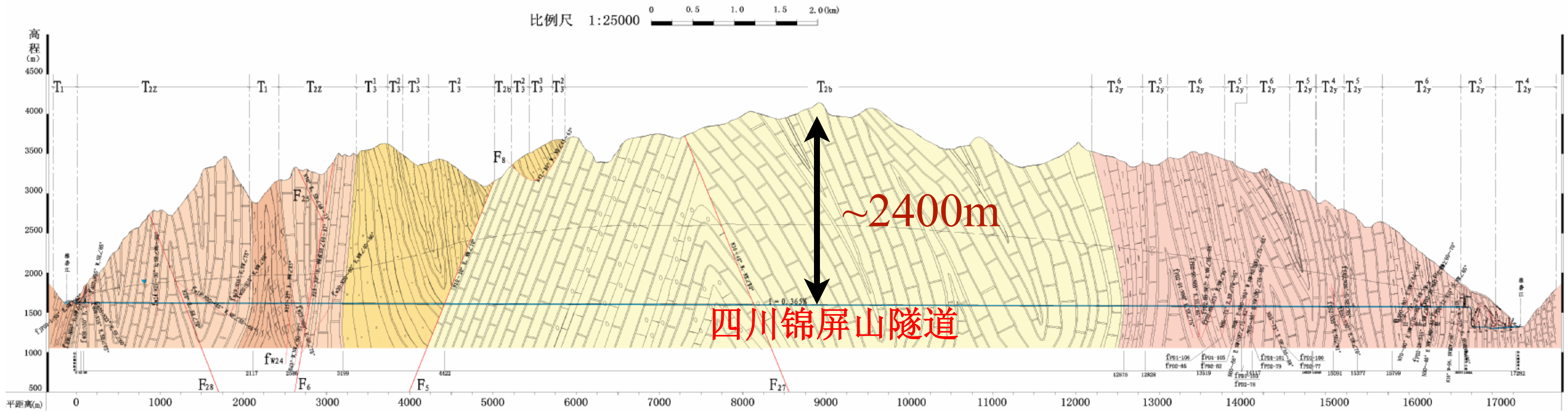


Indirect detection:
(cosmic-ray experiments)

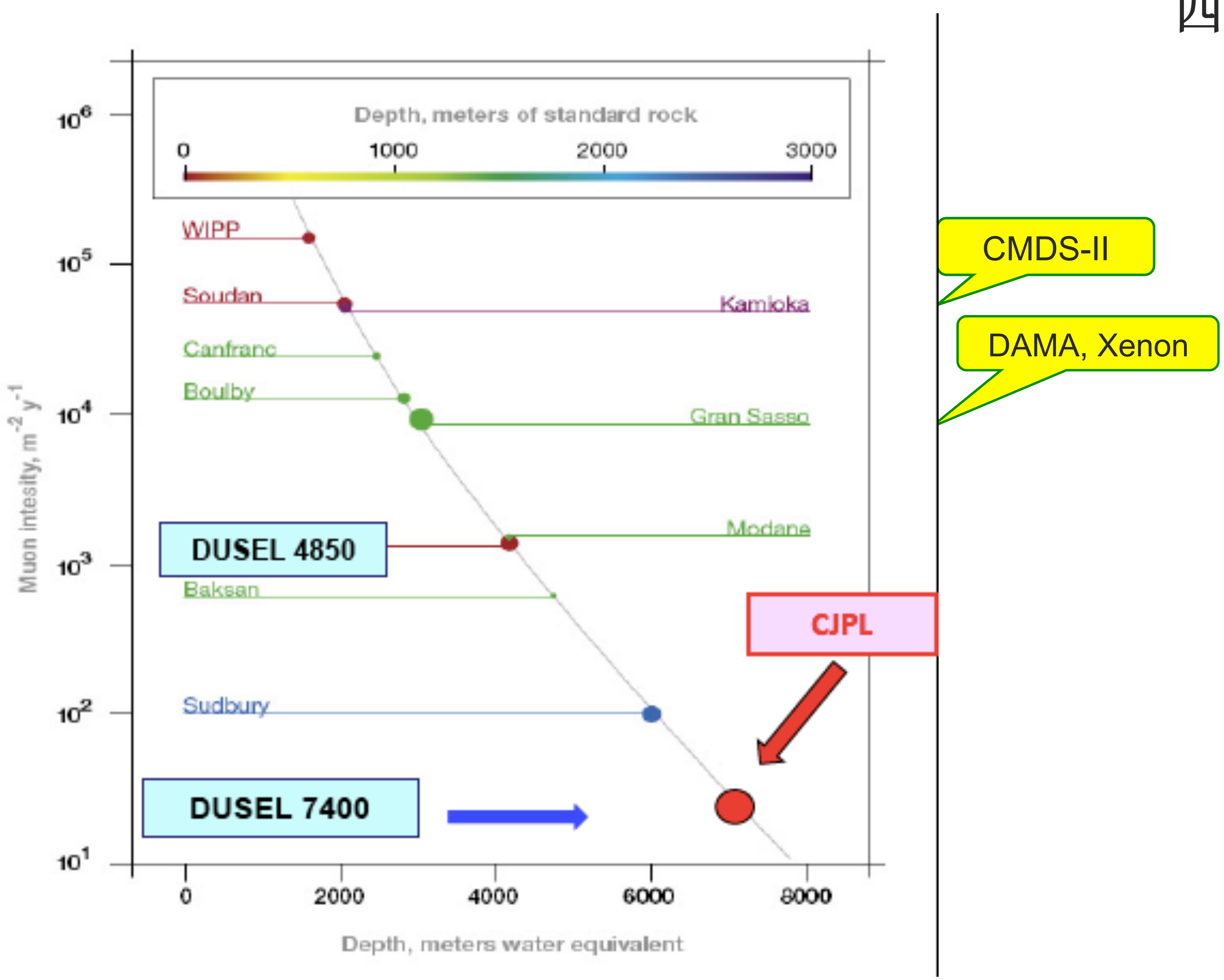
Collider searches: (LHC)

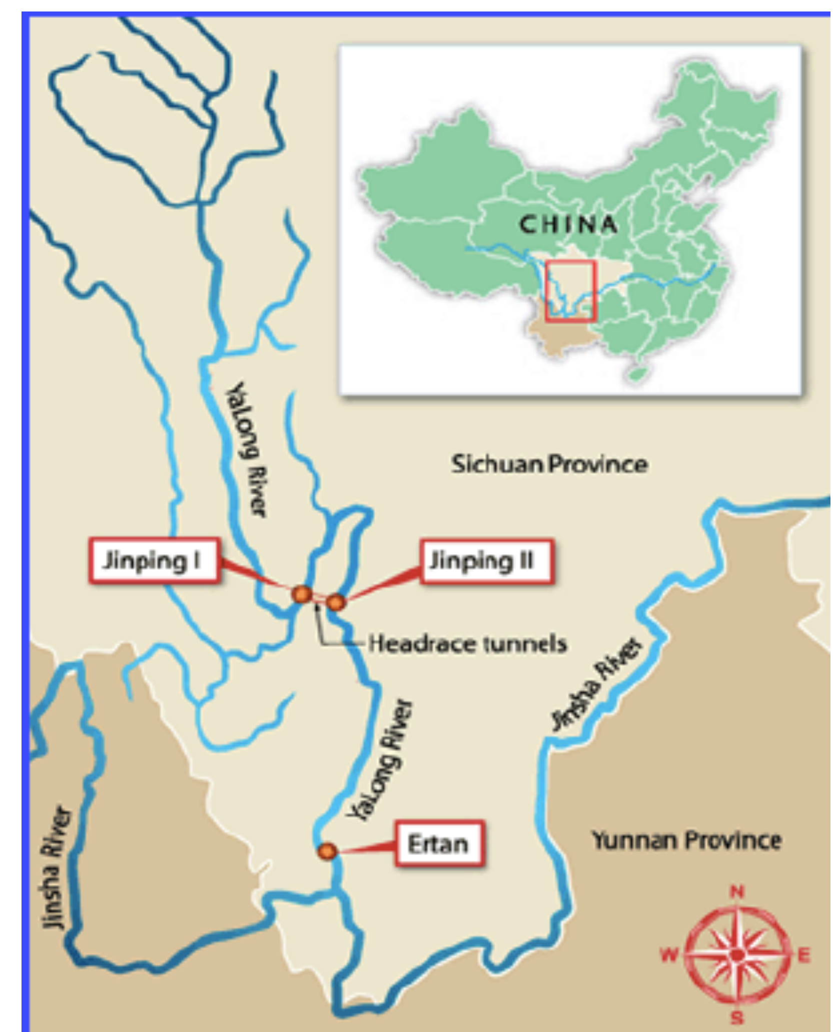


錦屏地下實驗室(CJPL): 中國首個、世界最深的地下實驗室



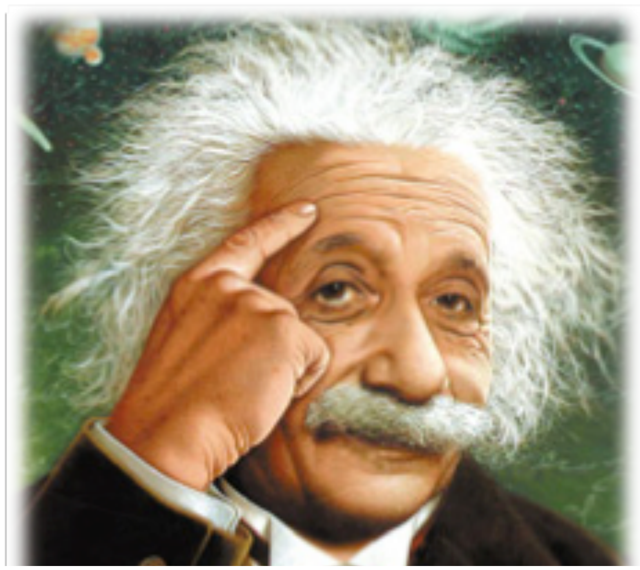
四川省锦屏山地形示意图





Dark Energy:

ΛCDM model:



Cosmological constant:

``biggest blunder''

Cosmological constant Λ causes accelerating expansion.

- Action

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\,(R - 2\Lambda) + S_m$$

- Einstein equation

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

$$= 8\pi G\left(T_{\mu\nu} + T^{\mathrm{DE}}_{\mu\nu}\right)$$

- Dark energy $T^{\mathrm{DE}}_{\mu\nu} = -\frac{\Lambda g_{\mu\nu}}{8\pi G}, \quad w_{\mathrm{DE}} \equiv \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}} = -1$

This corresponds to the energy scale $\rho_\Lambda = \frac{3H_0^2}{8\pi G} = 10^{-47}\ GeV^4$

If this originates from vacuum energy in particle physics, $\rho_{vac} \sim m_{pl}^4 = 10^{76}\ GeV^4$

☞ $\frac{\rho^{\mathrm{obs}}}{\rho^{\mathrm{th}}} = 10^{-120}$

A difference of 120 orders of magnitude

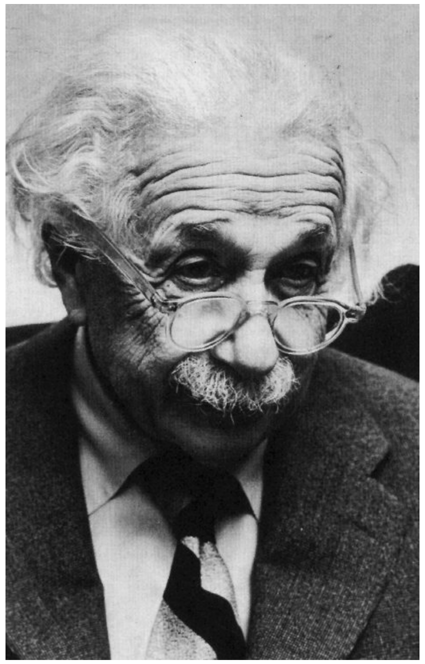
Cosmological constant problem

cc1: Why so small? **Fine-tuning problem** ☜

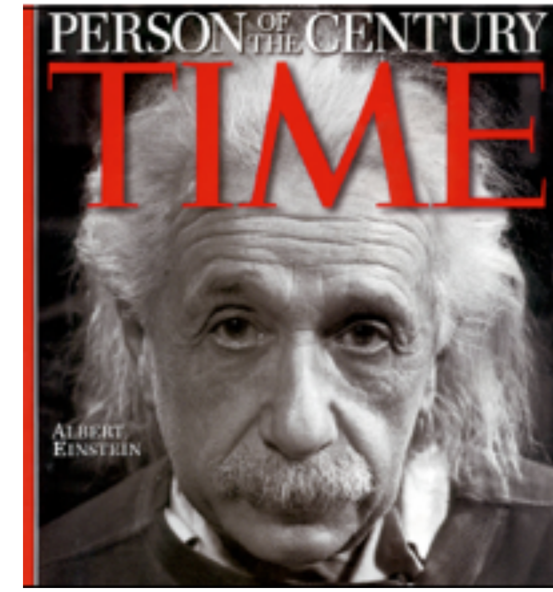
(known even before the discovery of dark energy)

cc2: Why now? $\rho^0_\Lambda \sim \rho^0_{\mathrm{M}}$ **Coincidence problem** ☜

There are two approaches to dark energy.



$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$ (Einstein equations)



(i) Modified gravity

f(R) gravity models,
Scalar-tensor models,
Braneworlds,
.....

(ii) Modified matter

Quintessence,
K-essence,
Tachyon,
Chaplygin gas,
.....

$\Rightarrow$ $w \neq -1$

$\Rightarrow$ These models generally give the dynamically changing equation of state w =p/ρ

The simplest candidate: Cosmological constant $\Rightarrow$ $w = -1$

Experimental Searches for Dark Energy: a very difficult task

From the Dark Energy Task Force report (2006)

www.nsf.gov/mps/ast/detf.jsp (astro-ph/0690591)

Dark energy appears to be the dominant component of the physical Universe, yet there is no persuasive theoretical explanation. The acceleration of the Universe is, along with dark matter, the observed phenomenon which most directly demonstrates that our fundamental theories of particles and gravity are either incorrect or incomplete. Most experts believe that nothing short of a revolution in our understanding of fundamental physics will be required to achieve a full understanding of the cosmic acceleration. For these reasons, the nature of dark energy ranks among the very most compelling of all outstanding problems in physical science. It demands an ambitious observational program to determine the dark energy properties as soon as possible.

Future Dark Energy Surveys

(an incomplete list)

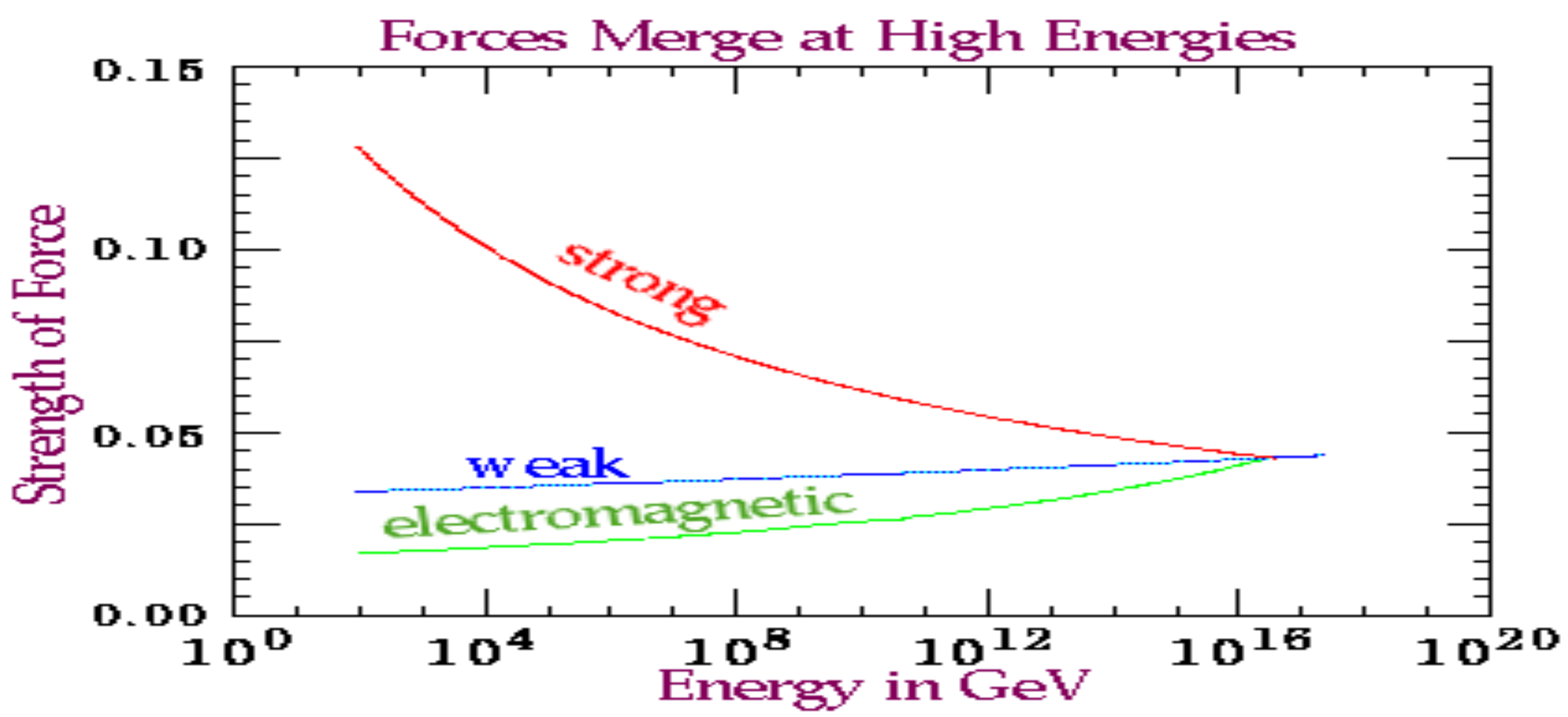
- Essence (2002-2007): 200 SNe Ia, $0.2 < z < 0.7$, 3 bands, $\Delta t \sim 2d$
- Supernova Legacy Survey (2003-2008): 2000 SNe Ia to $z=1$
- CFHT Legacy (2003-2008): 2000 SNe Ia, 100's high z SNe, 3 bands, $\Delta t \sim 15d$
- ESO VISTA (2005?-?): few hundred SNe, $z < 0.5$
- Pan-STARRS (2006-?): all sky WL, 100's SNe y^{-1}, $z < 0.3$, 6 bands, $\Delta t = 10d$
- WiggleZ on AAT using AAOmega (2006-2009): 1000 deg^2 BAO, $0.5 < z < 1$

- ALPACA (?): 50,000 SNe Ia per yr to $z=0.8$, $\Delta t = 1d$, 800 sq deg WL & BAO with photo-z
- Dark Energy Survey (?): cluster at $0.1<z<1.3$, 5000 sq deg WL, 2000 SNe at $0.3<z<0.8$
- HETDEX (?): 200 sq deg BAO, $1.8 < z < 3$.
- WFMOS on Subaru (?): 2000 sq deg BAO, $0.5<z<1.3$ and $2.5<z<3.5$

- LSST (2012?): 0.5-1 million SNe Ia y^{-1}, $z < 0.8$, > 2 bands, $\Delta t = 4\text{-}7d$; 20,000 sq deg WL & BAO with photo-z
- JDEM (2017?): several competing mission concepts [ADEPT, DESTINY, JEDI, SNAP]

- *大統一場理論*

The theory which (we hope!) will unify the **strong, weak, and electromagnetic interactions** is called the "Grand Unified Theory." If a Grand Unification of all the interactions is possible, then all the interactions we observe are all different aspect of the same, unified interaction. However, how can this be the case if strong and weak and electromagnetic interactions are so different in strength and effect? Strangely enough, current data and theory suggest that these varied forces merge into one force when the particles being affected are at a high enough energy.



Contemporary work on GUT also suggests new force-carrier particles that could cause the proton to decay. Such decays must be extremely rare; otherwise our world would not exist today. Measurement tells us the lifetime of the proton is greater than 10^{32} (10 to the power of 32) years!

大乘金剛般若波羅蜜經

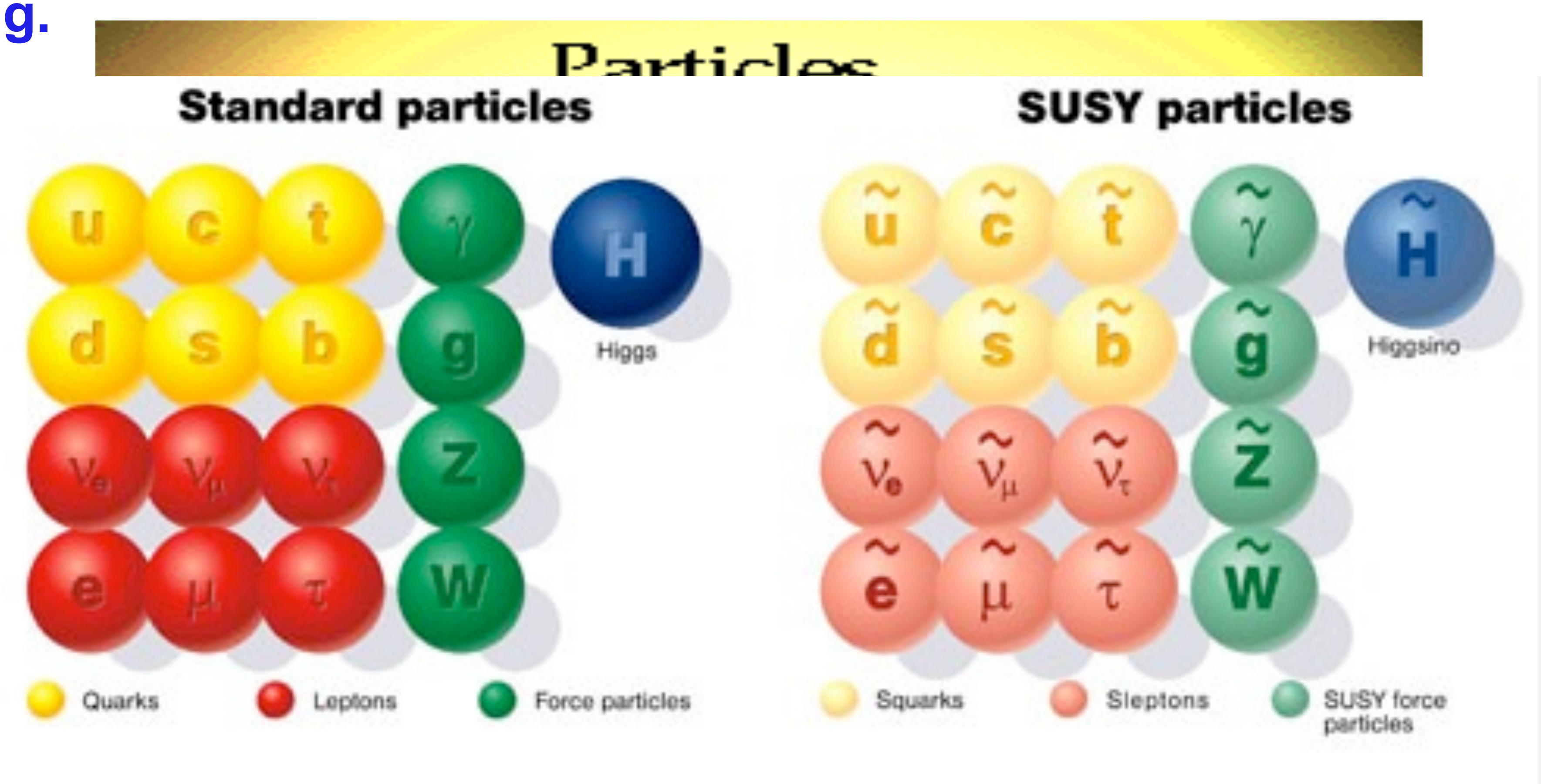
南無本師釋迦牟尼佛

啟經香讚

爐香乍爇。法界蒙熏。諸佛海會悉遙聞。隨處結祥雲。誠意方慇。諸佛現全身。

Supersymmetry　超 對 稱

Many physicists have developed theories of supersymmetry, particularly in the context of Grand Unified Theories. The supersymmetric theories postulate that every particle we observe has a massive "shadow" particle partner. For example, for every quark there may be a so-called "squark" tagging along.



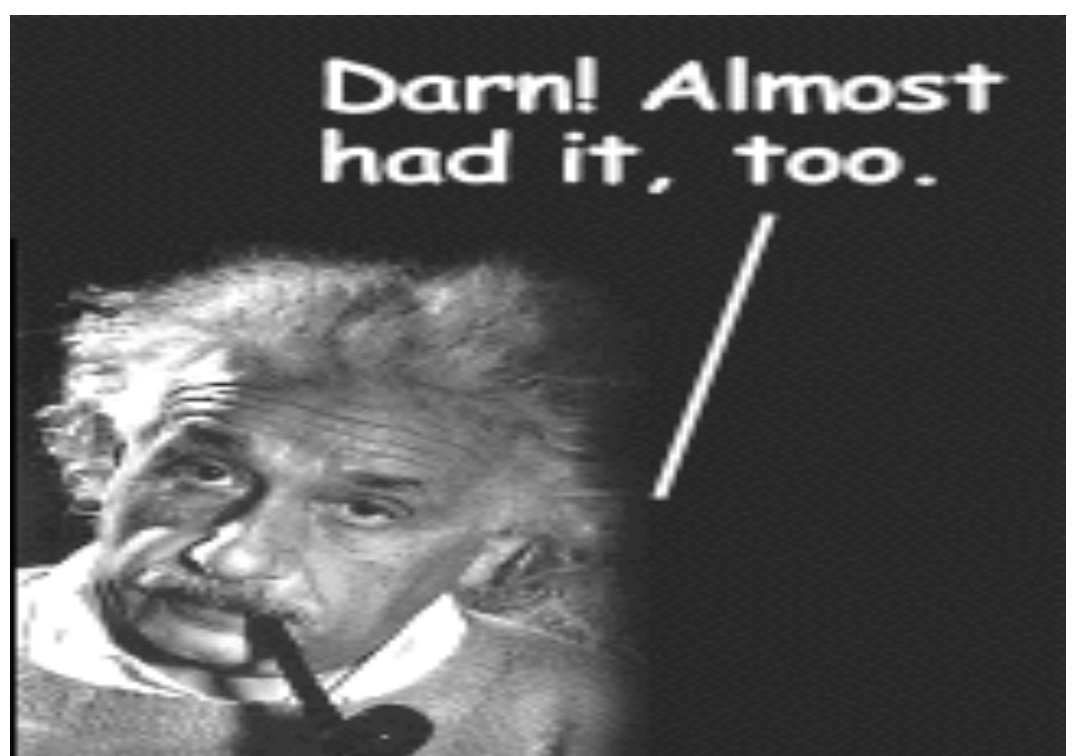
No supersymmetric particle has yet been seen, but experiments underway at CERN are searching for the partner of the W boson, and experiments at Fermilab are looking for the partners of the quarks and gluons. One of the supersymmetric particles (the "neutralino") might make up the missing dark matter in the universe.

The Theory of Everything (TOE)

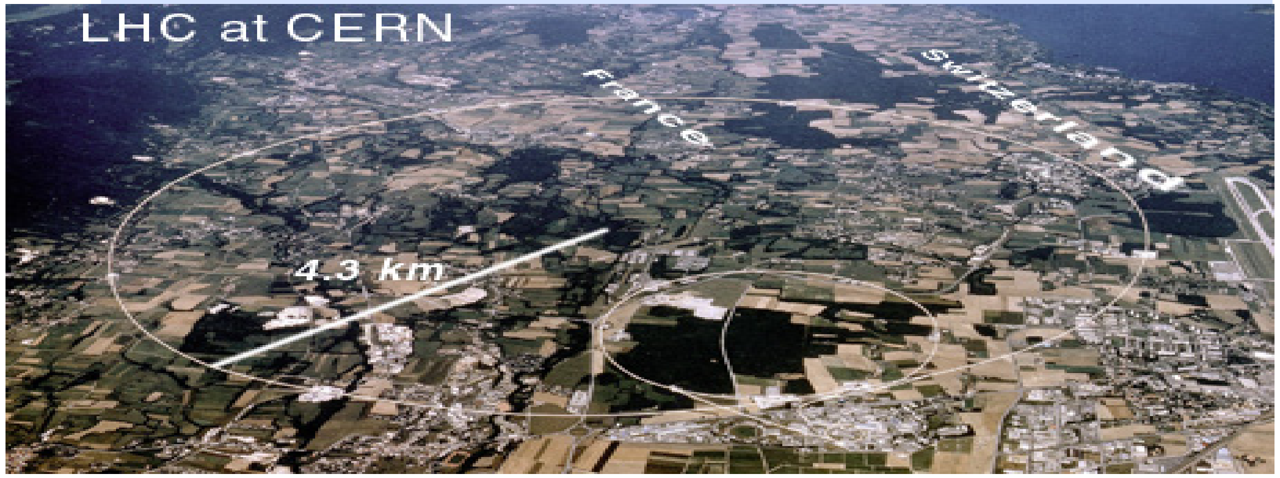
The long range goal of physics is to unify all the forces, so that gravity would be combined with the future version of the Grand Unified Theory. Then the gravitational interaction would be thought of as quantized, like the other forces, so that the gravitational force is transmitted by particles called *gravitons*.

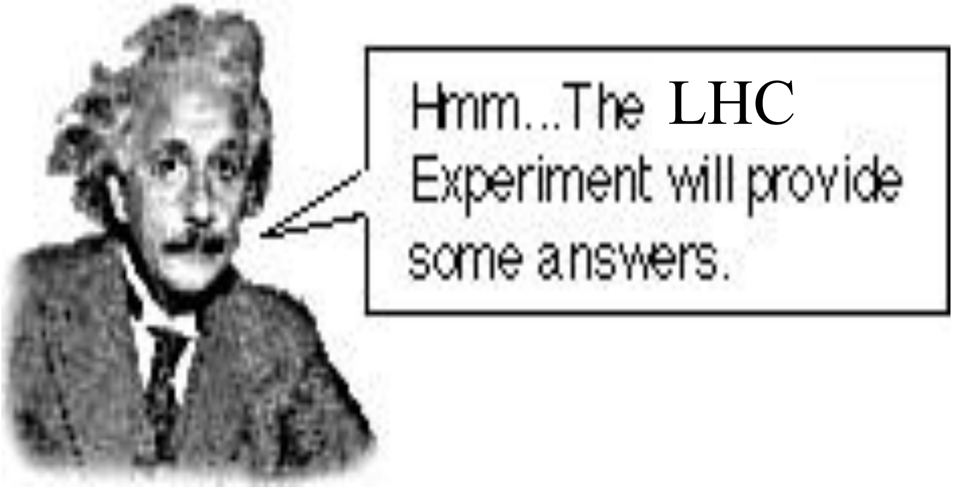
This poses a formidable problem. Einstein showed us that the gravitational force arises due to curvature in the fabric of spacetime. Thus, the task is to quantize spacetime to produce the desired gravitons. Achieving this type of quantum field theory is quite a challenge both conceptually and mathematically.

The HEP Experiment may guide us toward a Grand Unified Theory, so that ultimately humankind will understand a complete, unified Theory of Everything.



尚未解決之問題 *The Higgs particle at the LHC?*





March 30,2010:能量 7 TeV

- ***Why are there three types of quarks and leptons?***
- ***Is there some pattern to their masses?***
- ***Are there more types of particles and forces to be discovered at yet higher energy accelerators?***
- ***Are the quarks and leptons really fundamental, or do they, too, have substructure?***
- ***How to include the gravitational interactions in the SM?***
- ***How to understand dark matter and dark energy in the universe?***

未來展望與結束語

近代粒子物理之發展可分為六個階段：

1. ***1945之前 -- 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. ***Super-Heroic Period (2005 –2020)***

Neutrino oscillations
Cosmic microwave fluctuations
Dark energy

Heroic Period (1960 -- 1975):

Nobel Prizes in Particle Physics: [work done]
20xx: ?
20xx: Goldstone, Higgs – Higgs particle [1961,1964]
2008: Nambu,Kobayashi,Maskawa–broken symmetry [1961,1973]
2004: Gross, Politzer, Wilczek–asymptotic freedom [1973]
1999: 't Hooft, Veltman–electroweak force [1972]
1995: Perl,Reines–tau lepton [1975], electron neutrino [1953]
1990: Friedman, Kendall, Taylor–quark model [1972]
1988: Lederman,Schwartz,Steinberger -muon neutrino [1962]
1980: Cronin, Fitch–symmetry breaking (CP violation) [1964]
1979: Glashow, Salam, Weinberg–electroweak theory [1961,67]
1976: Richter,Ting–charm quark (J/Psi) [1974]
1969: Gell-Mann–classification of elementary particles [1964]

more?

=10

How many Nobel Prizes in Particle Physics for the Super-Heroic Period?

>10

Thank you!

謝謝！