Dark Matter, Dark Energy & Neutrino Mass
暗物质，暗能量和中微子质量

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理论物理前沿暑期讲习班——暗物质，中微子与粒子物理前沿
中山大学广州校区南校园 *2017*年*7*月*3-28*日

中山大學
SUN YAT-SEN UNIVERSITY

Lecture 1: Introduction to Particle Physics and Cosmology

何小刚：CP破坏及其相关问题

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

何小刚：CP破坏及其相关问题

Lecture 3: Neutrino Mass Generation

第3周(17-21) 邢志忠：中微子的基础知识与前沿问题

第4周(24-28) 廖益：中微子质量起源、暗物质、标准模型有效场论及应用

Lecture 4: Theoretical Understanding of Dark Matter Detections

第4周(24-28)
毕效军（周一到周三）：暗物质的间接探测
余钊焕（周四到周五）：暗物质的直接探测与对撞机探测
廖益：中微子质量起源、暗物质、标准模型有效场论及应用

Lecture 5: Dark Energy and Gravitational Waves

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

- ***Future Prospects***

• Introduction

Where Do We Come From?
我們從哪裡來？

What Are We?
我們是誰？

Where Are We Going?
我們到哪裡去？

Paul Gauguin （1848-1903）

Stephen Hawking: Questioning the universe

How did the universe begin?

How did the life begin?

Are we alone?

July 1, 2005
Science Magazine
125th anniversary

American Association for the Advancement of Science (AAAS)

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☜

宇宙是由什麼組成的？

> How Much Can Human Life Span Be Extended?
> What Controls Organ Regeneration?
> How Can a Skin Cell Become a Nerve

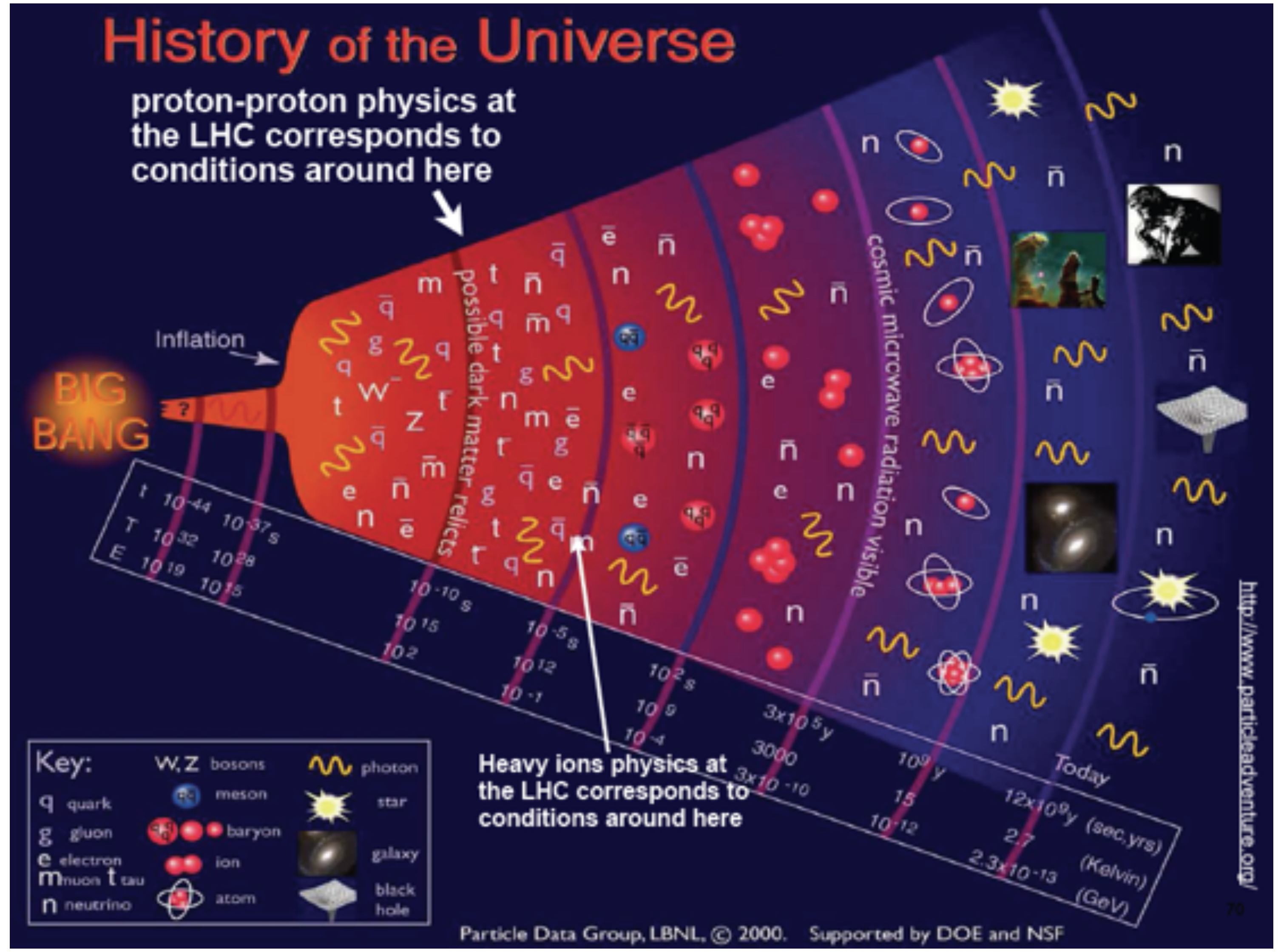
☞#125

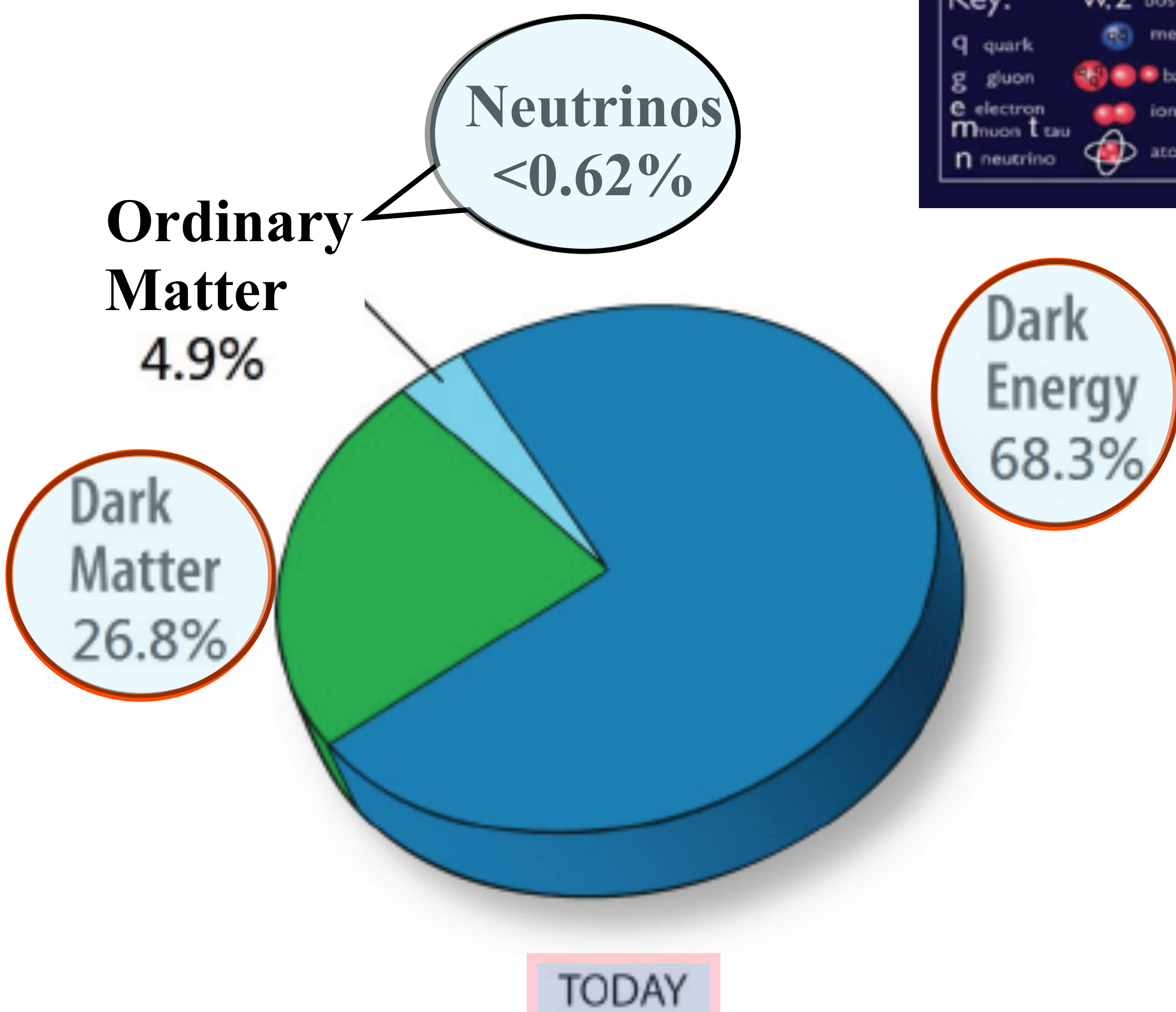
Does the Standard Model of particle physics rest on solid mathematical foundations?

粒子物理的标准模型是否建构在堅固的数学基础上?

對於宇宙
知道的很多
但了解的很少

We know much but
we understand very little





95%的宇宙物質/能量
還是個謎。目前也無
法在地球上最好的實
驗室中觀測到。

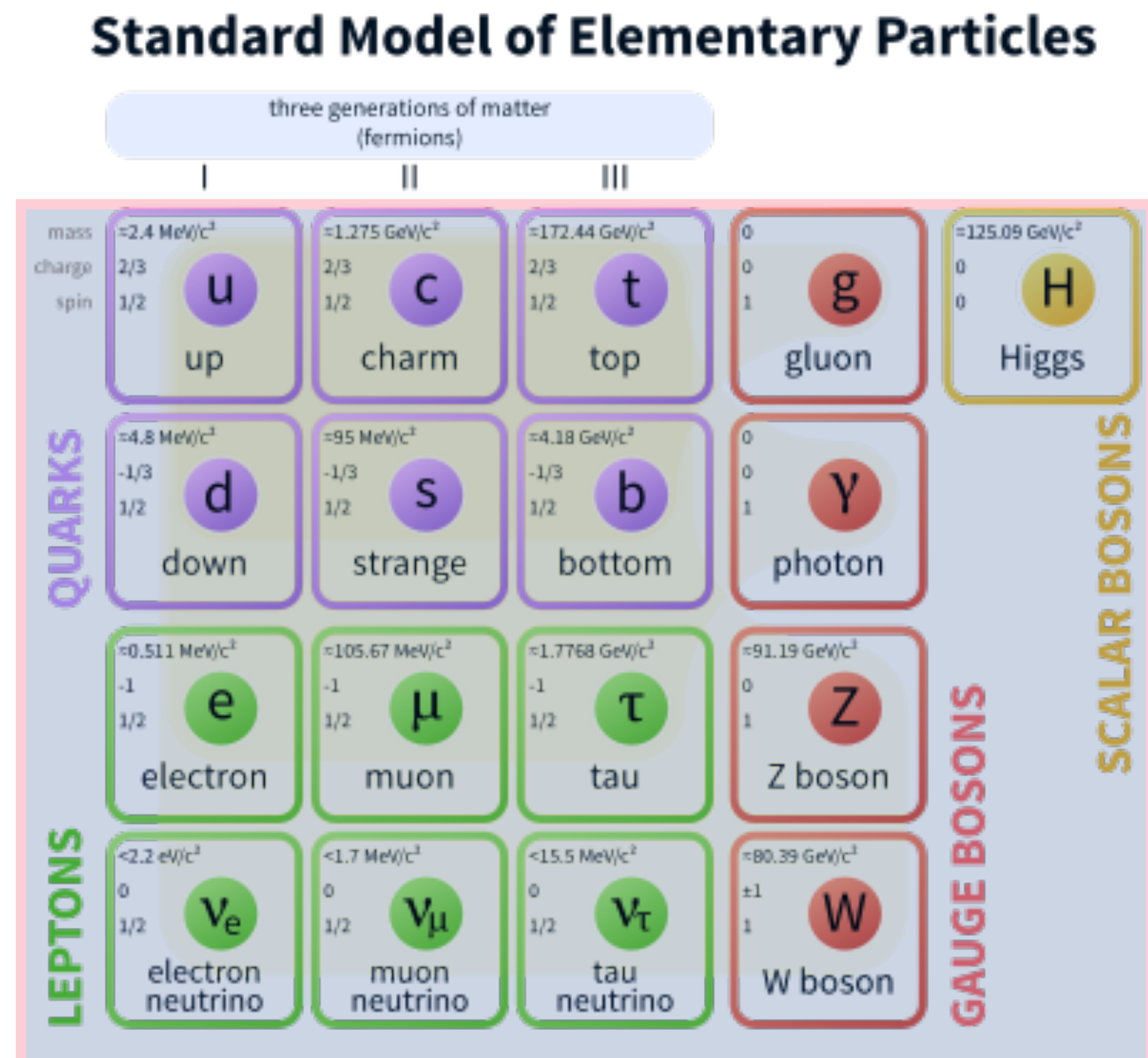
95% of the cosmic matter/energy
is still a mystery.

The Standard Model in Particle Physics

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

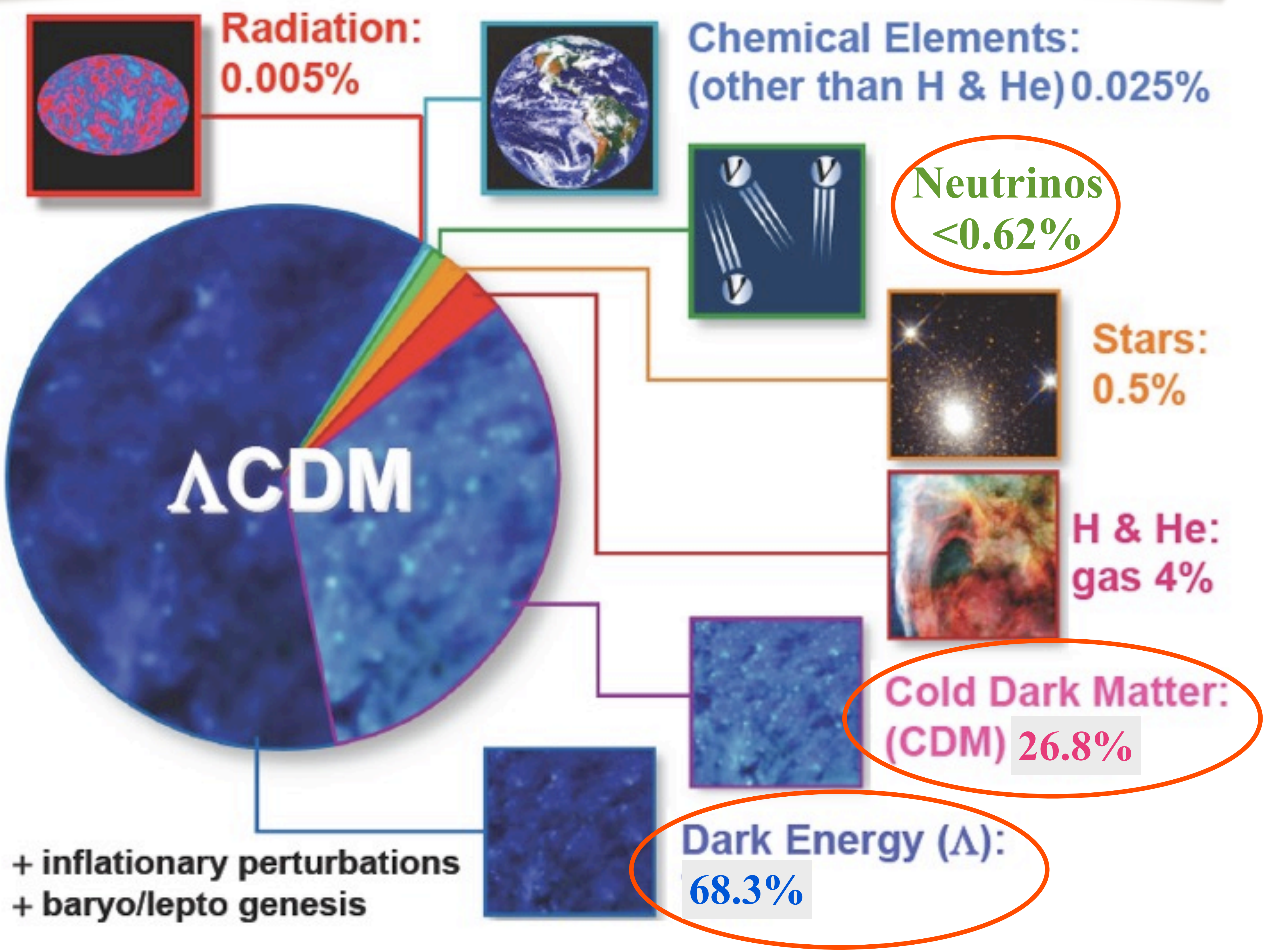
Strong Interaction — Electroweak Interaction

Particles $(i = 1, 2, 3)$	$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_L^i$	3		2		$\frac{1}{3}$
$u_L^{c\,i}$	$\overline{3}$		1		$-\frac{4}{3}$
$d_L^{c\,i}$	$\overline{3}$		1		$\frac{2}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_L^i$	1		2		-1
$e_L^{c\,i}$	1		1		2



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

“The Standard Model” in Cosmology



● 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

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* (中國秦皇島？)

● 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)

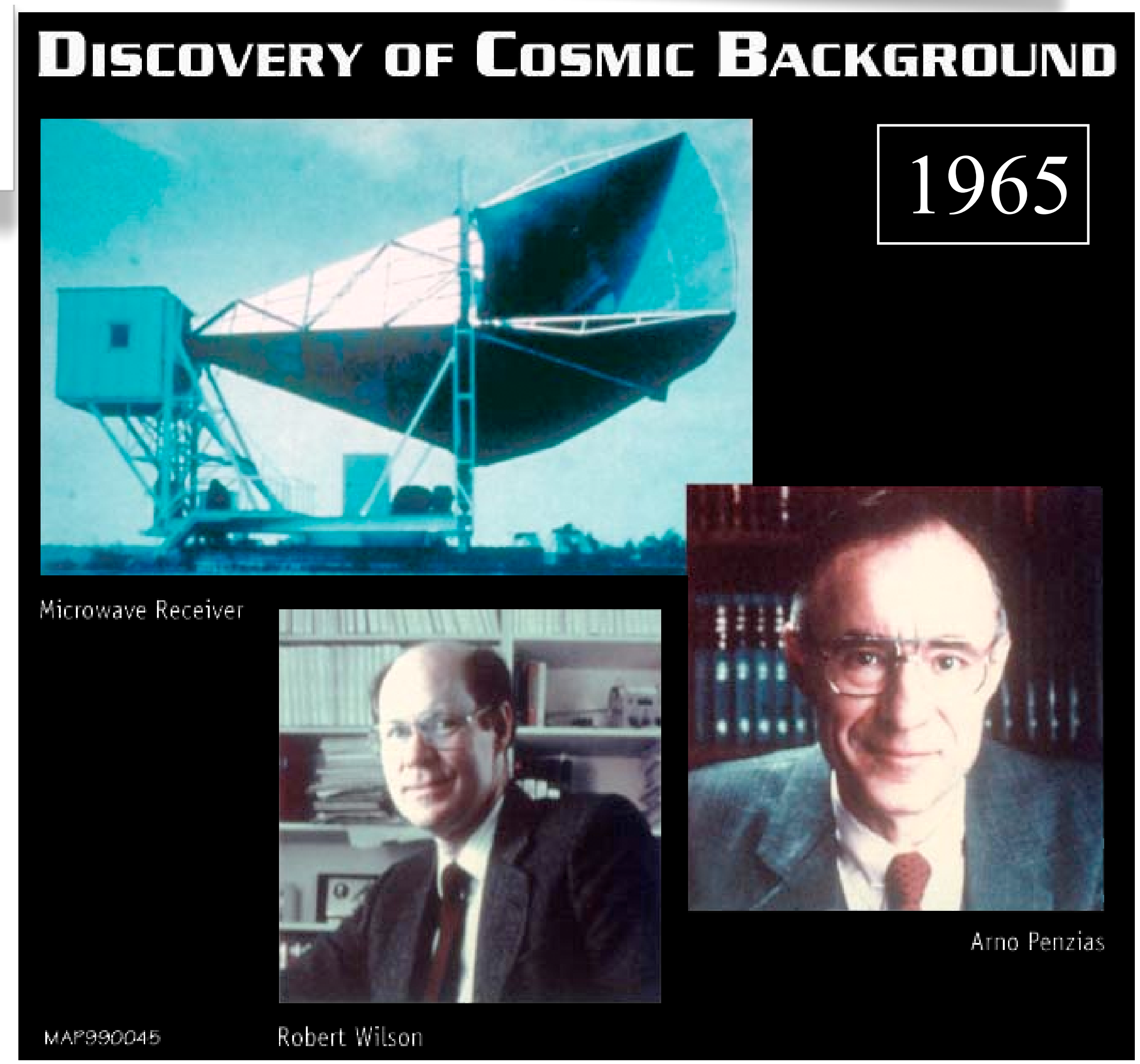
DC3. Neutrino oscillations (1998-2001→2015 Nobel Prize)

DC1. Cosmic microwave fluctuations

Cosmic Microwave Background (CMB)

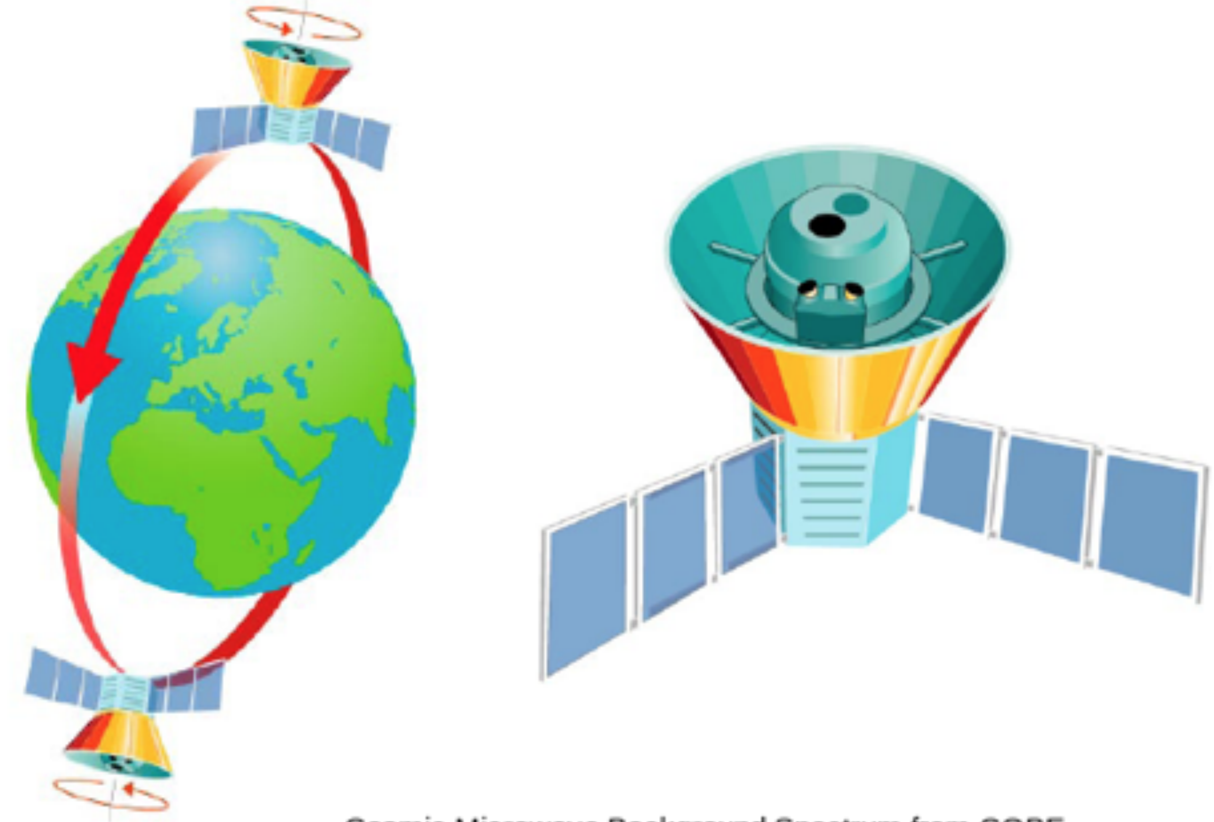
very cold (-270.275 C, 2.725 K) and nearly uniform relic radiation left over from the hot big bang

1965 英雄歲月 → Physics Nobel Prize 1978

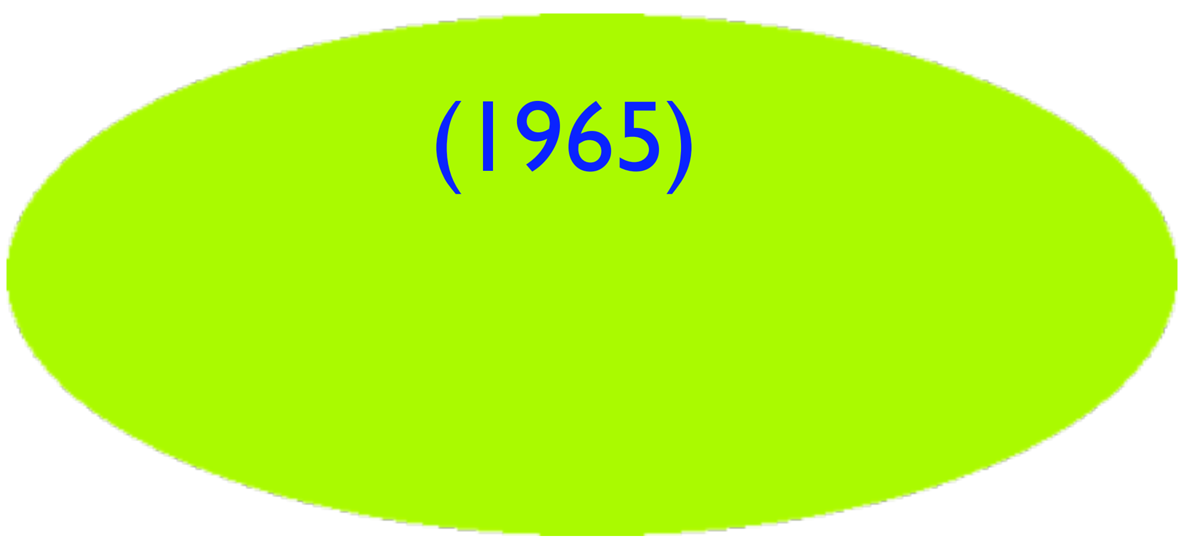


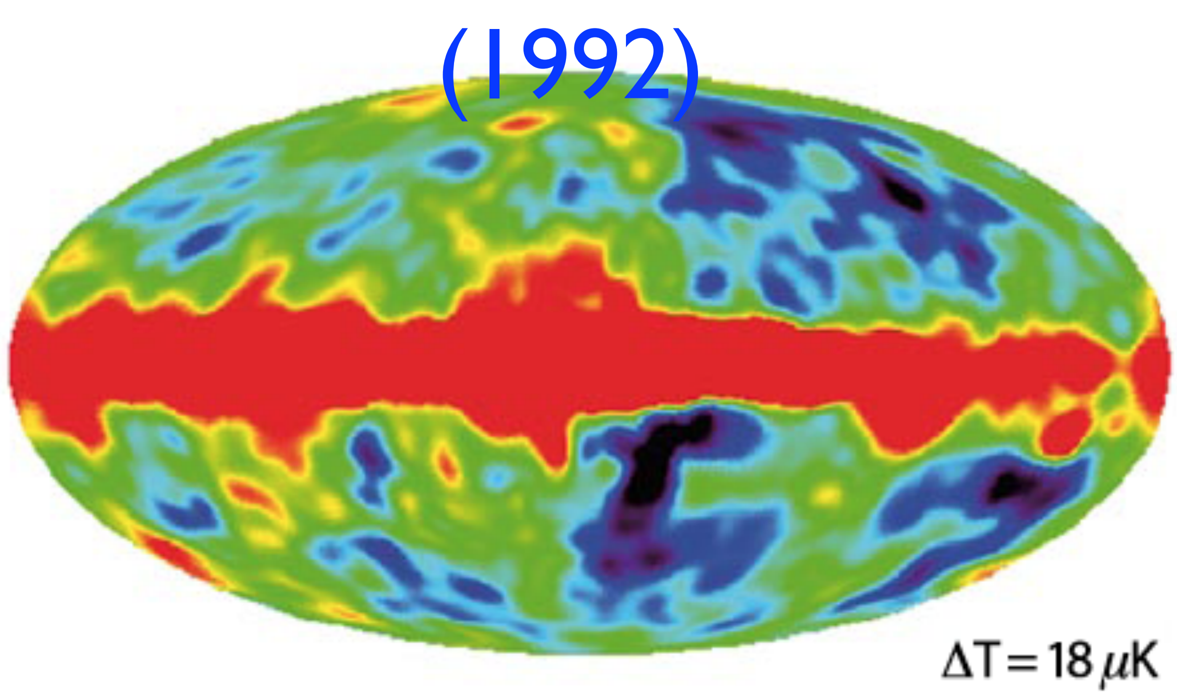
Cosmic Microwave Background

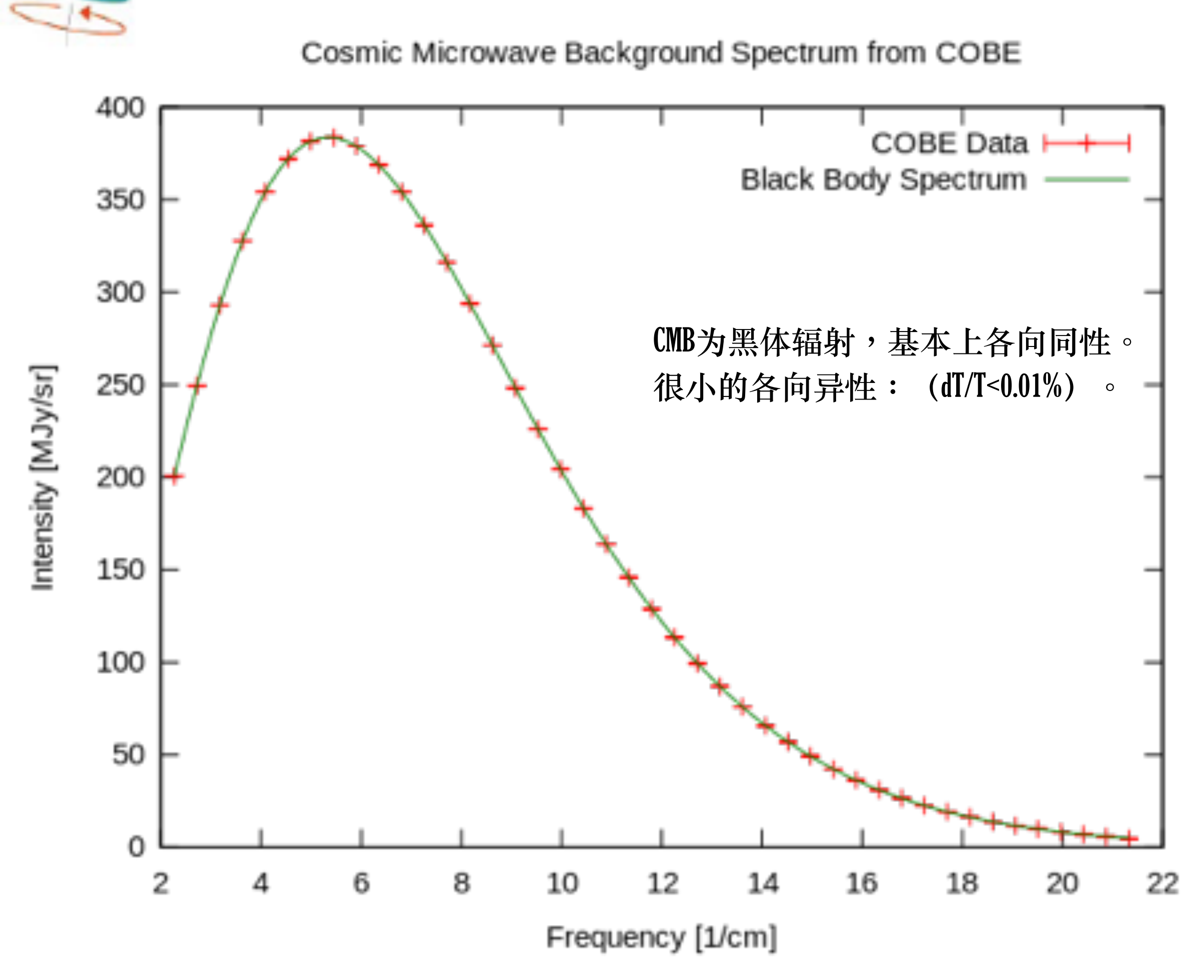
The COBE satellite (1992) enabled measurement of the CMB in all directions.



If you had microwave eyes:







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

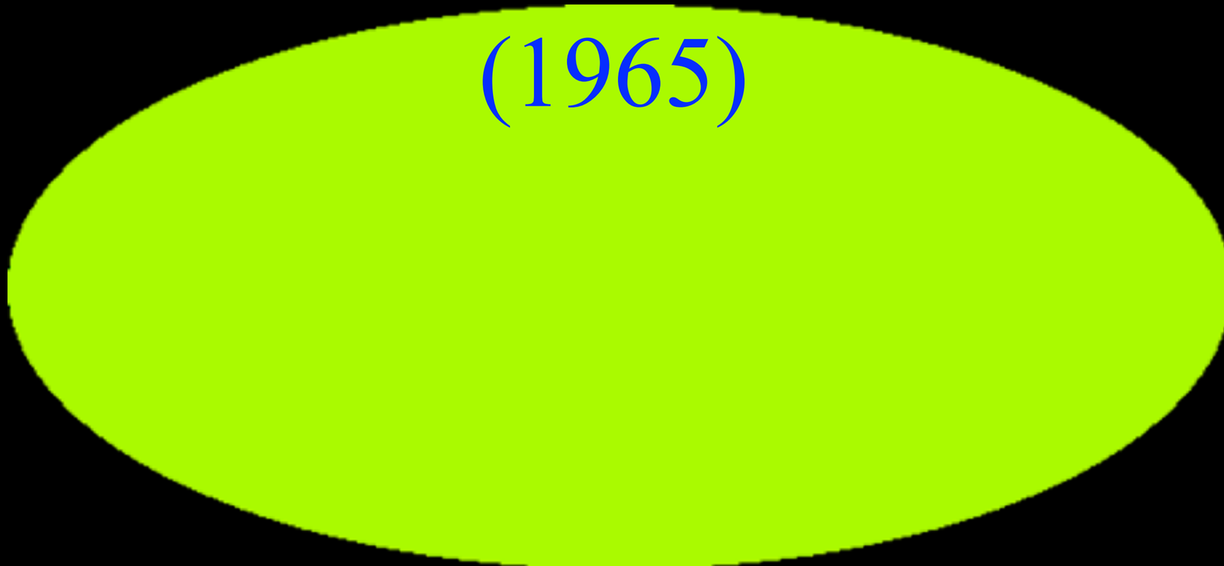
The Nobel Prize in Physics 2006

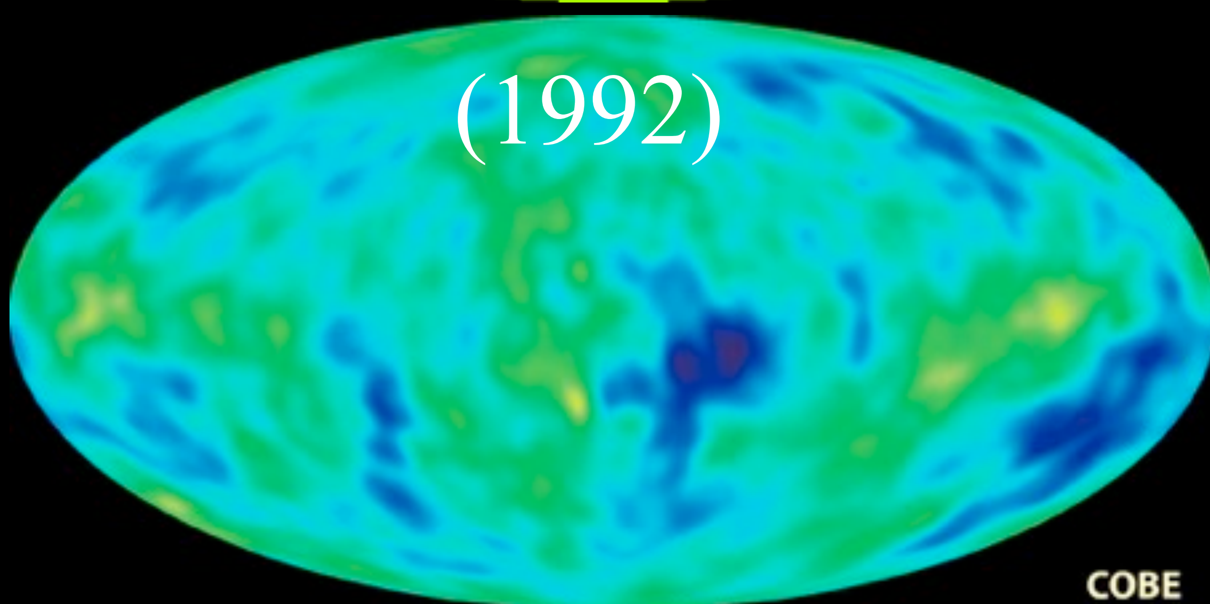
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

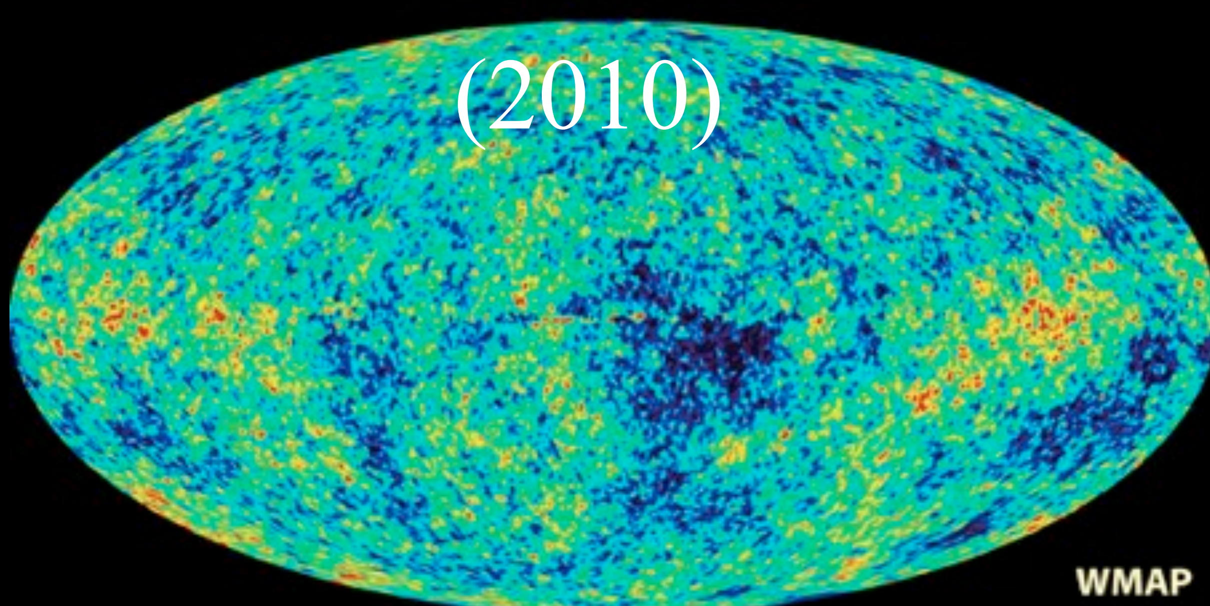
John C. Mather
NASA

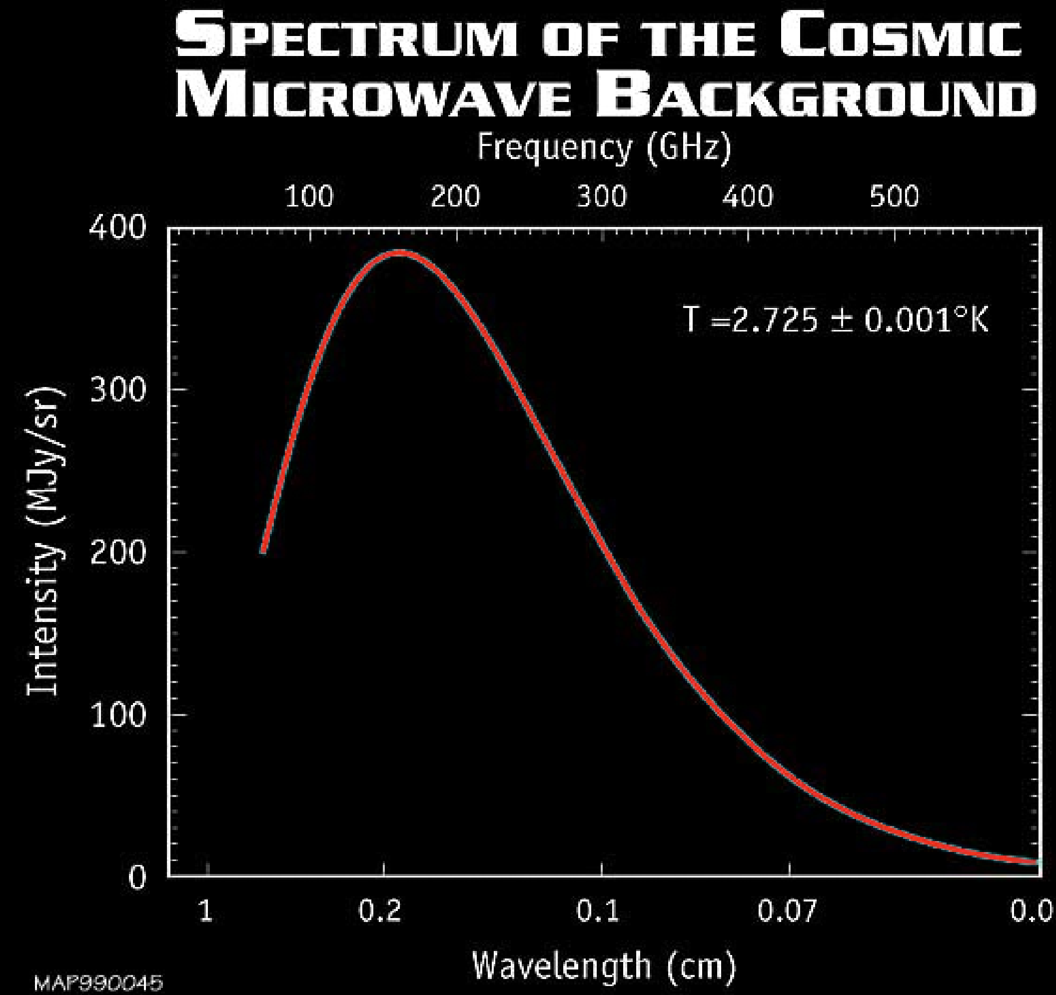
George F. Smoot
University of California, Berkeley

If you had microwave eyes:

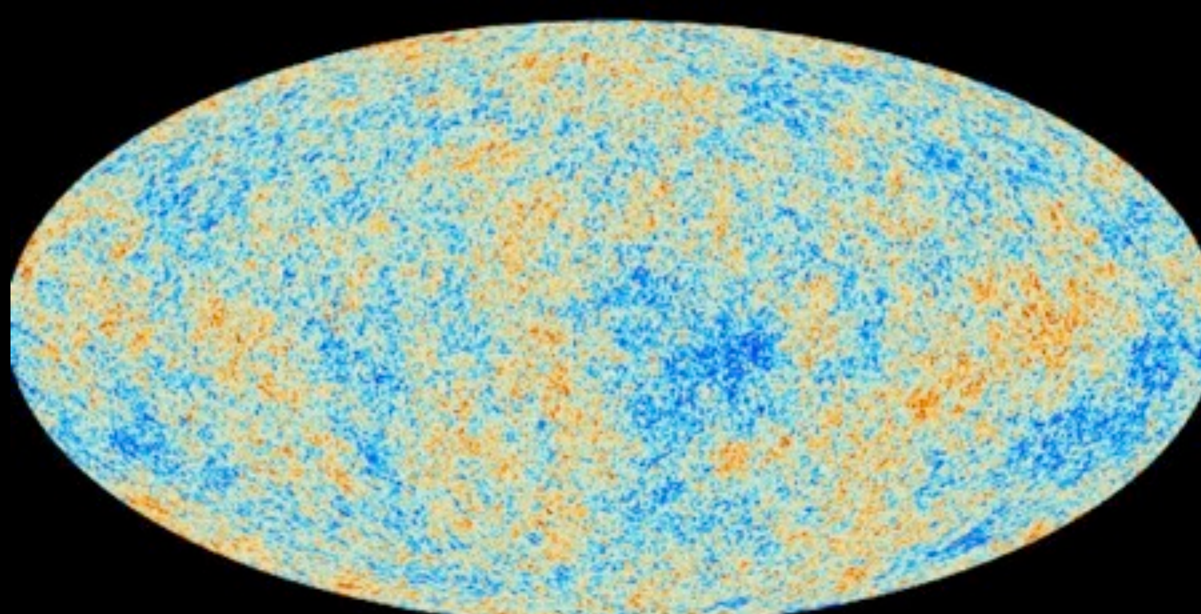


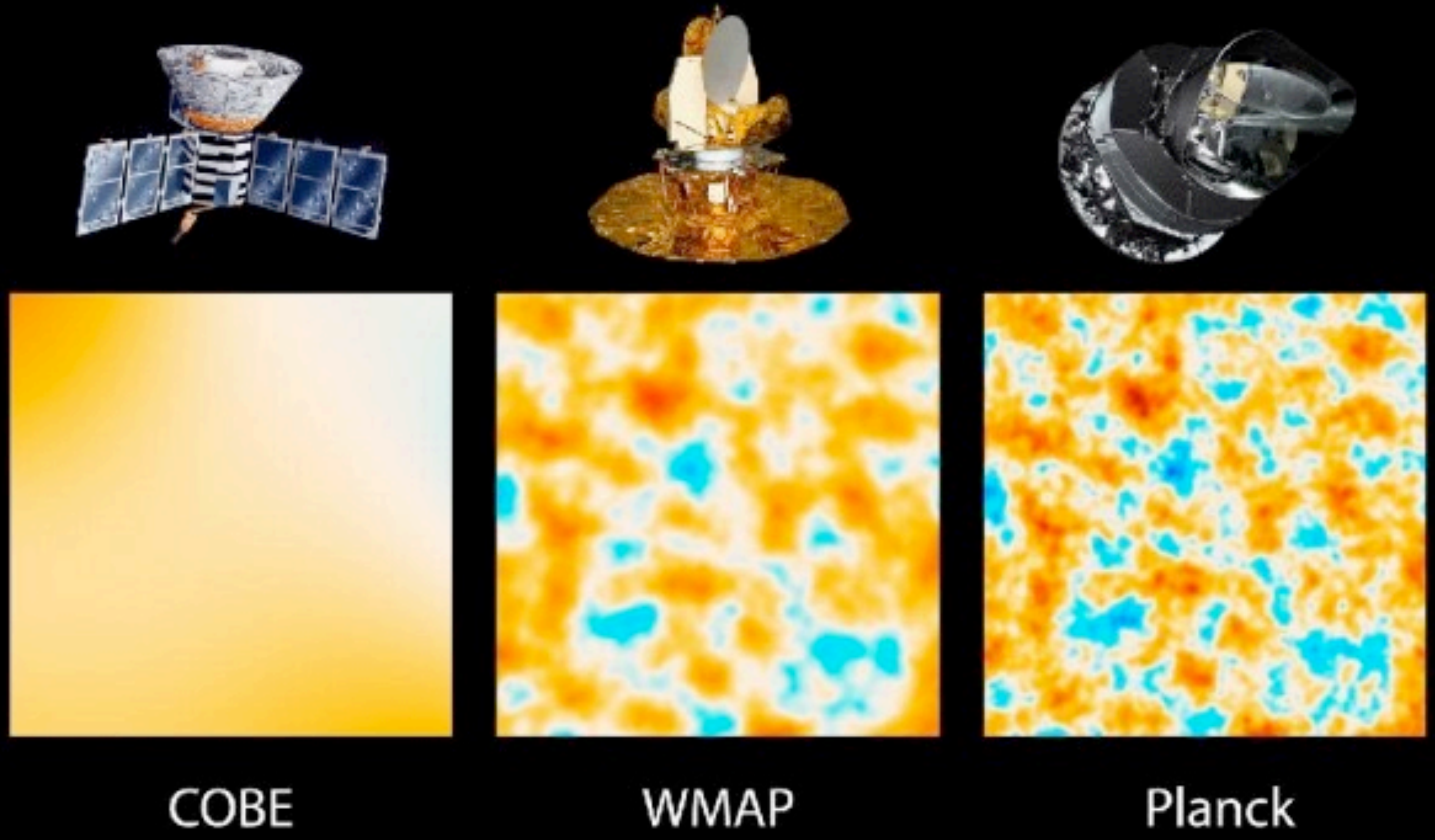




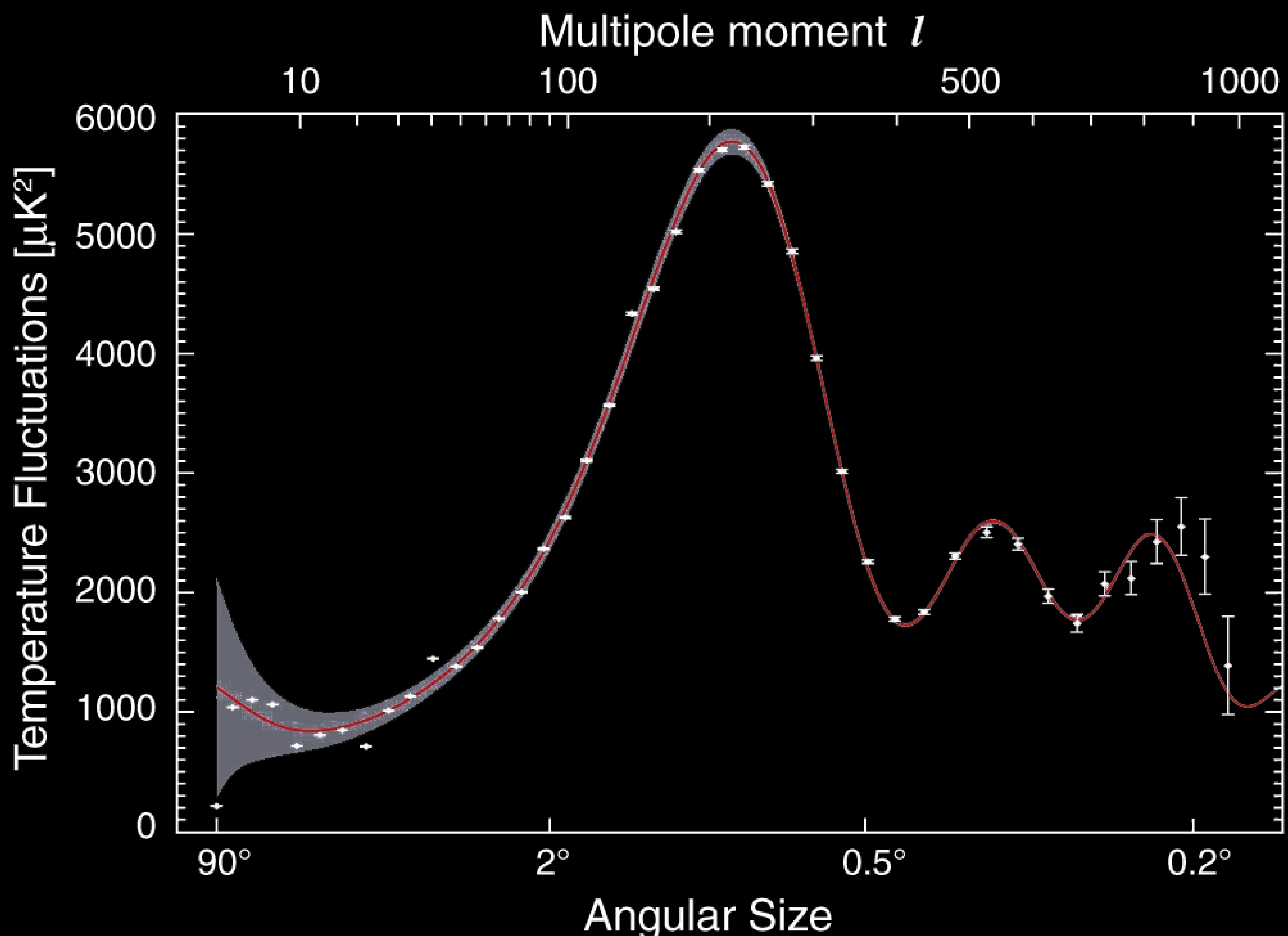


Planck (2013)





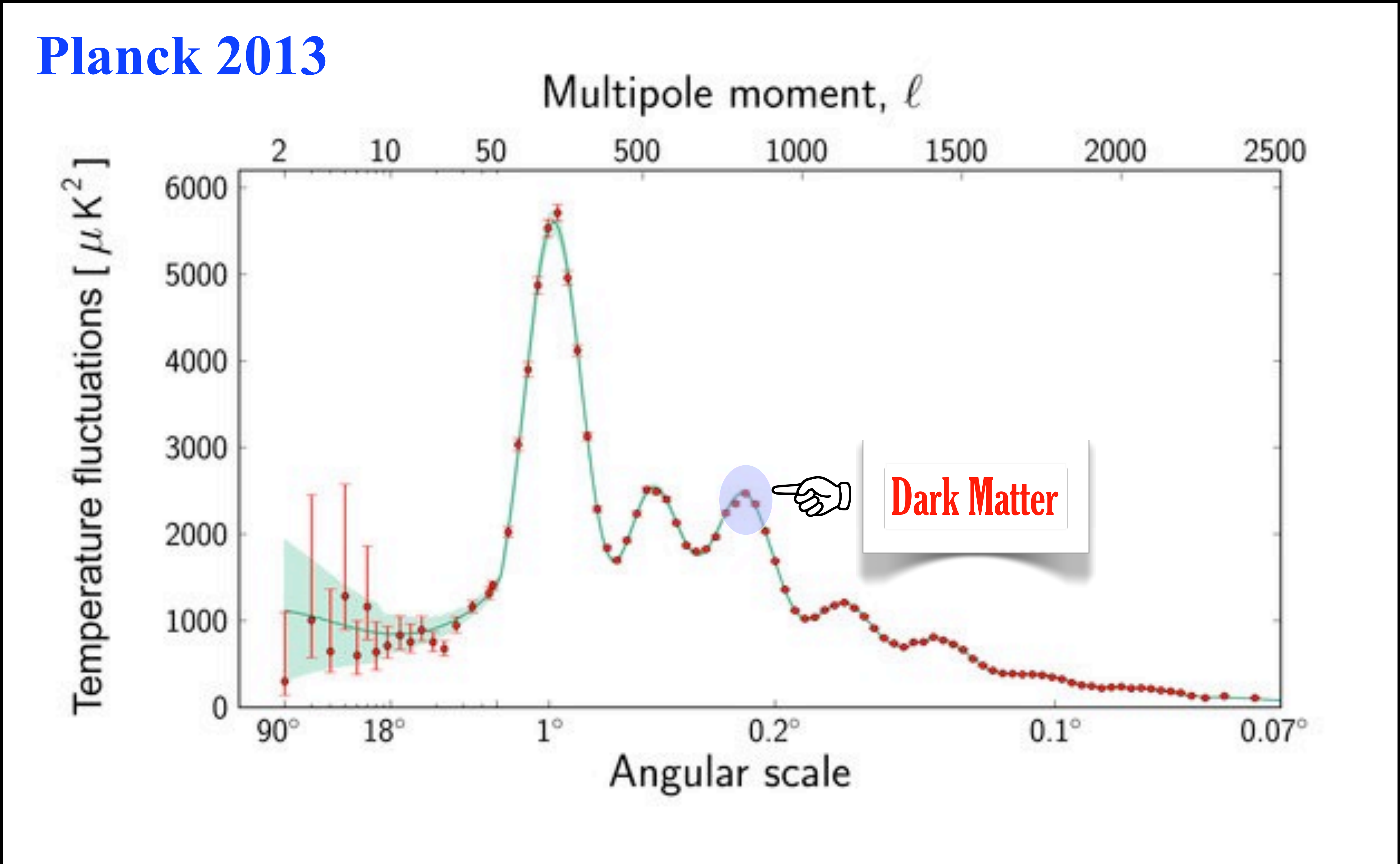
1992 2003 2013



White points:
WMAP (2010)
7-year data

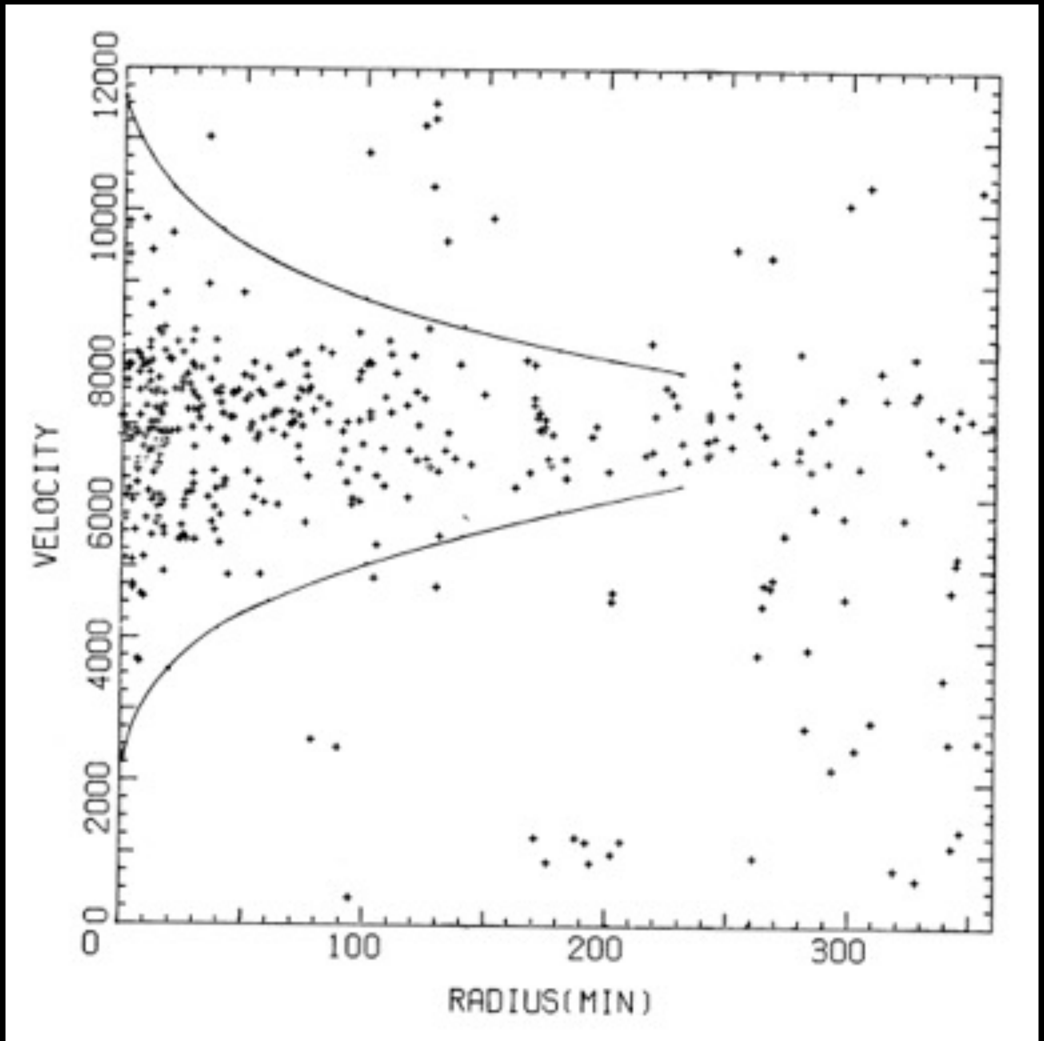
Red curve: Theoretical prediction for a universe made of
70% dark energy, 25% dark matter, 5% atoms

Cosmic Microwave Background (CMB)



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

Other Evidences for Dark Matter



COMA cluster

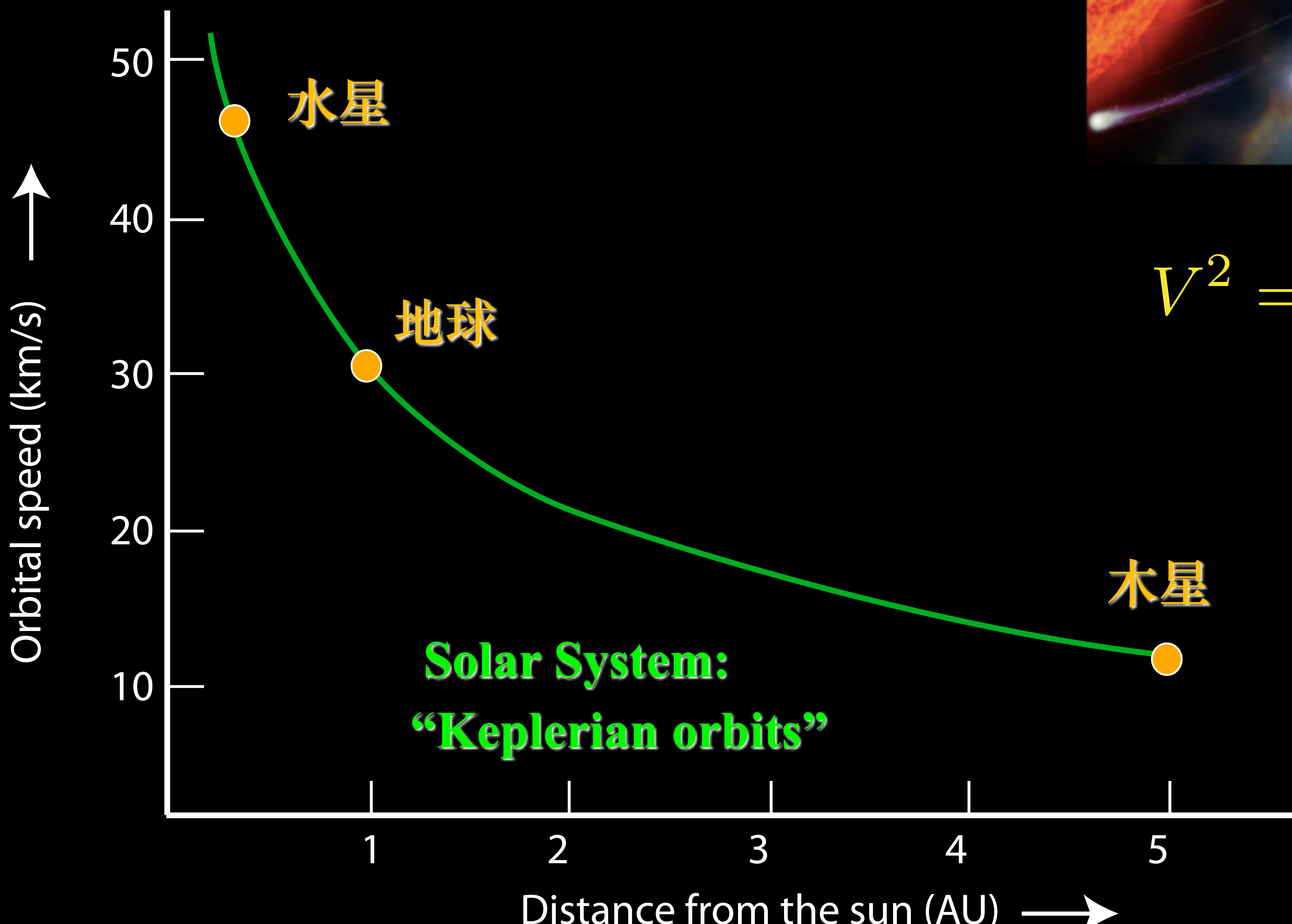
Zwicky (1933) used the radial velocity dispersion in the Coma cluster to conclude that the mass of luminous matter ~ 10% Gravitational mass .

F. Zwicky 1933

Cluster would be unstable if there were only luminous matters

Solar System:

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



1970 ApJ 159, 379

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

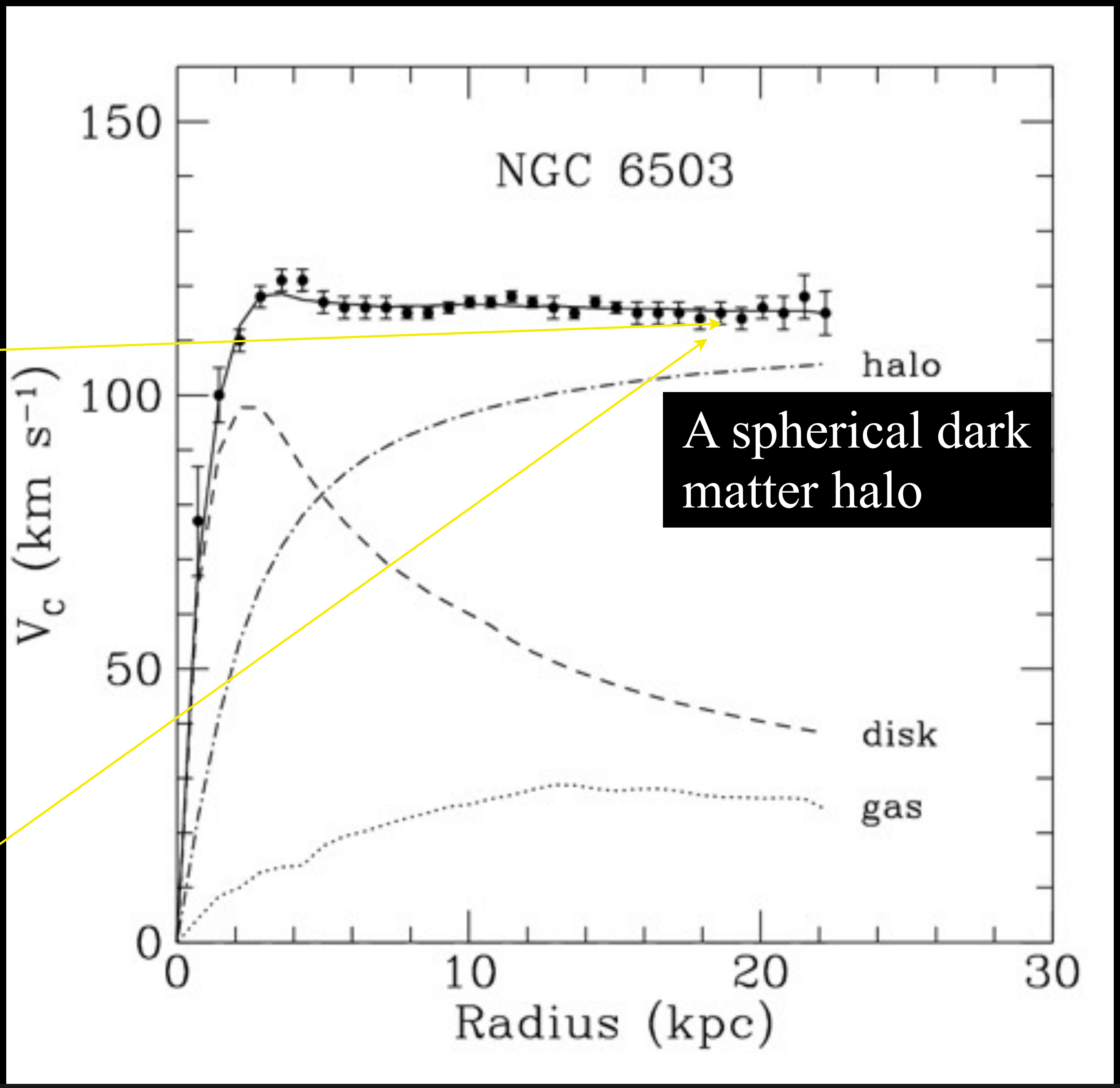
VERA C. RUBIN† AND W. KENT FORD, JR.†

Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

2016年12月25日
去世，88歲。

Spiral galaxy

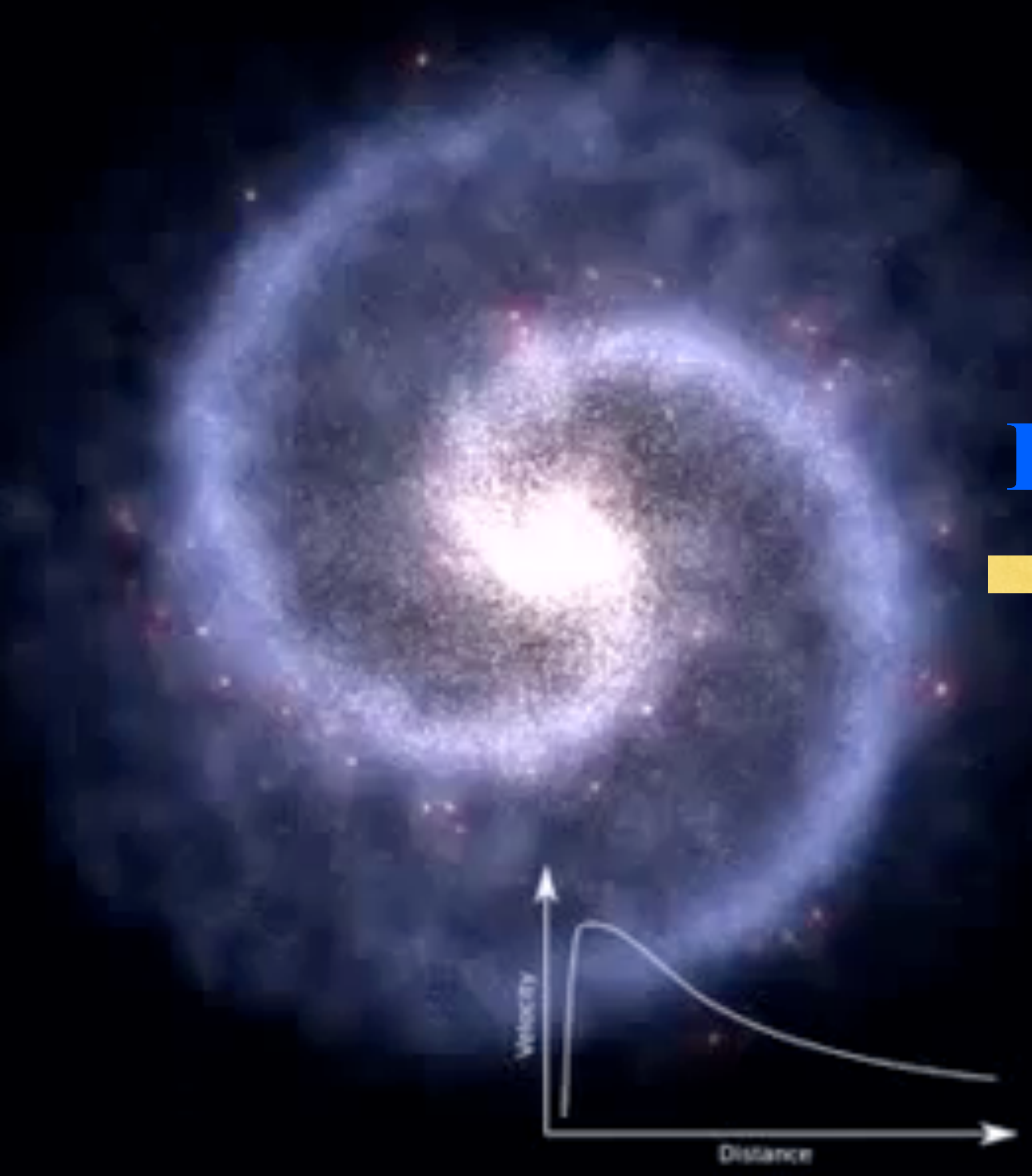
DM



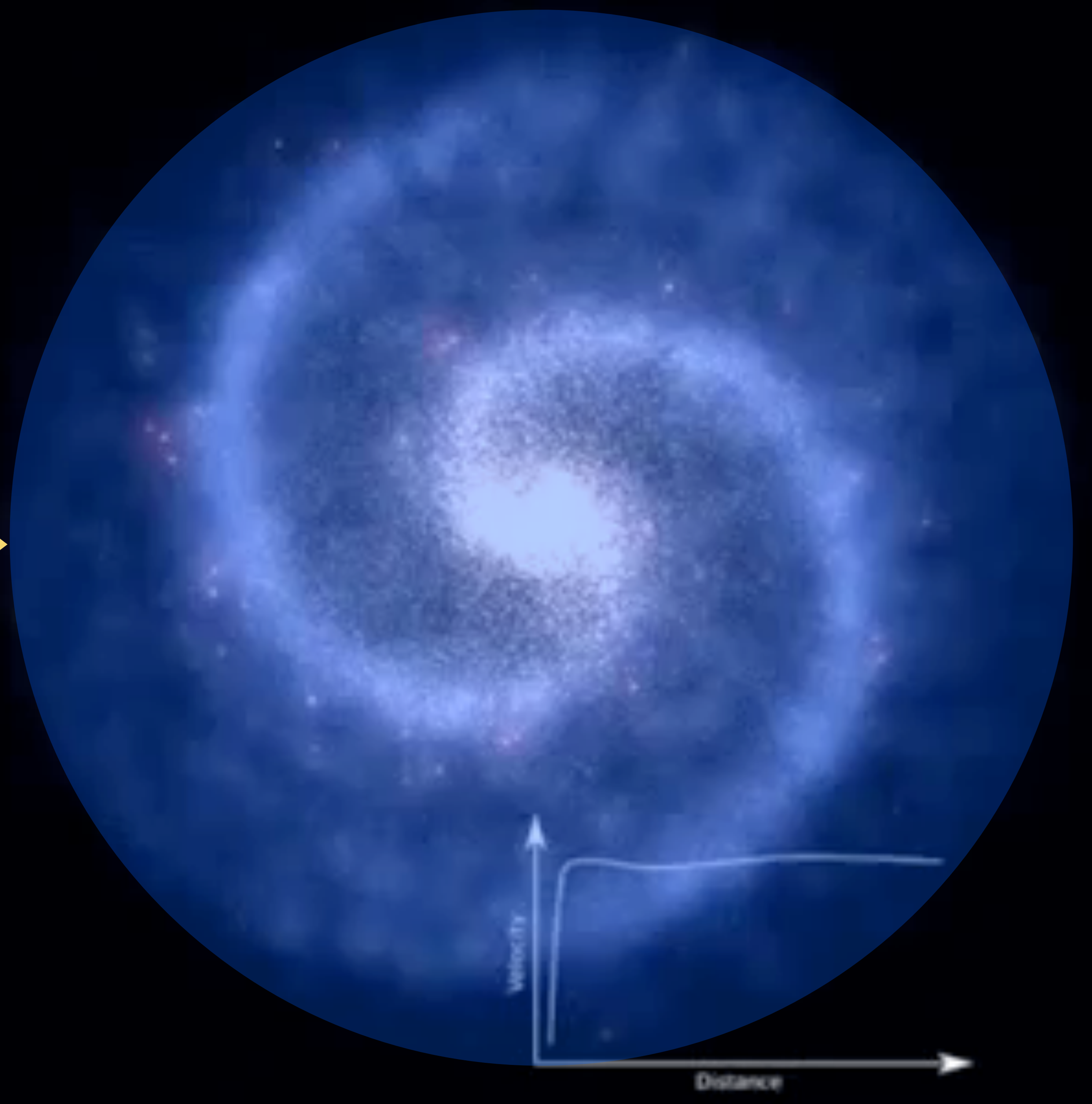
$$\frac{G\,M_{DM+OM}}{r^2} = \frac{v^2}{r}$$

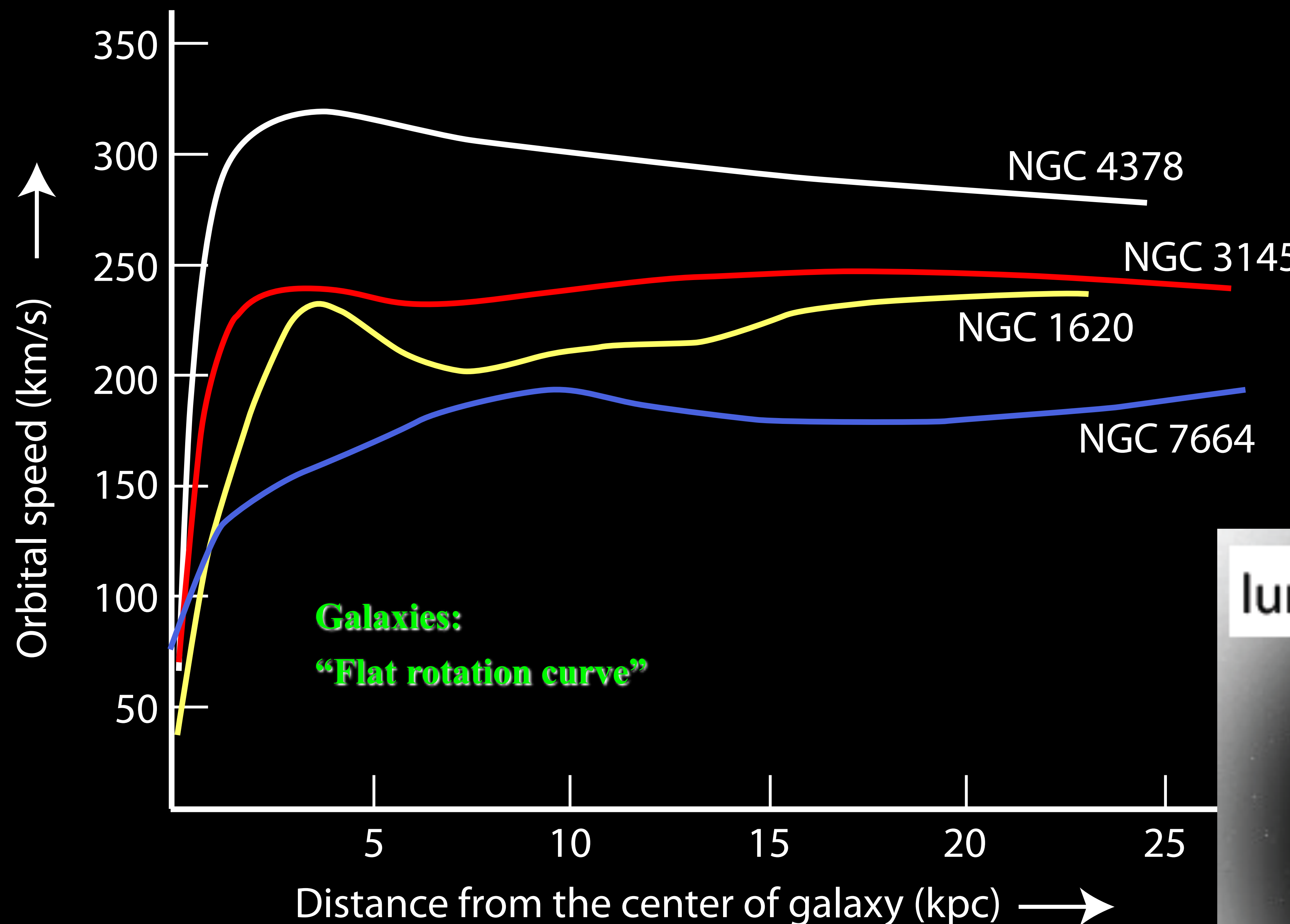
Stars would be moving too fast if there were only luminous matters

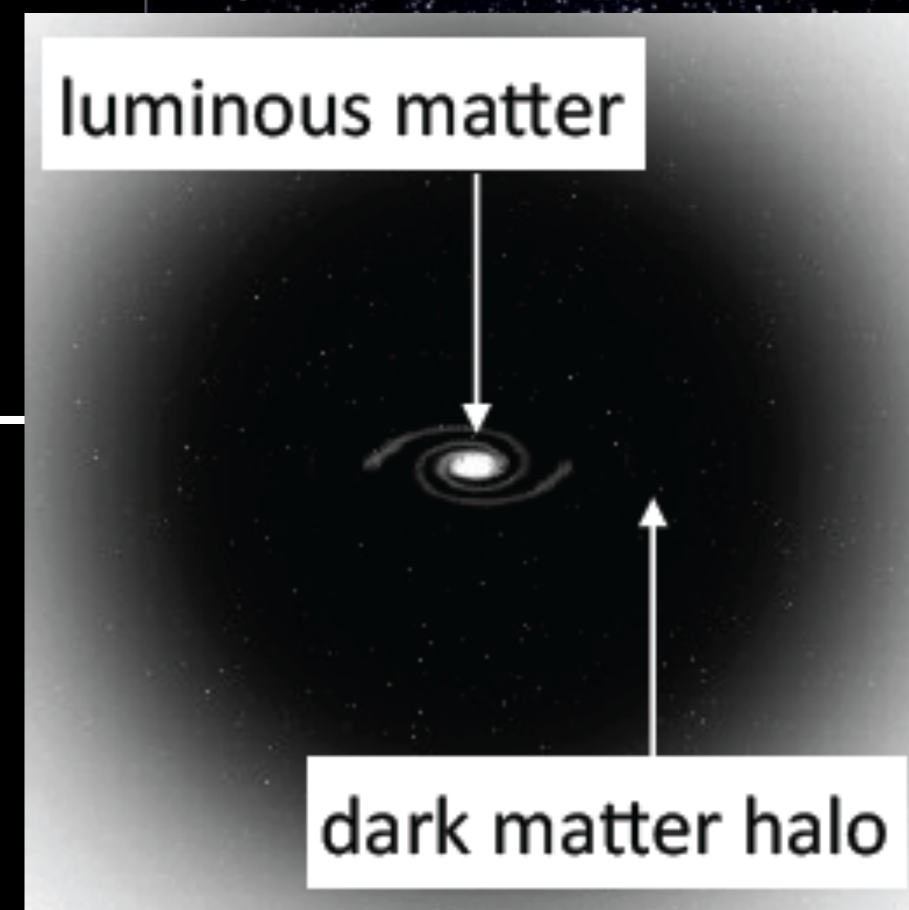
Spiral galaxy



DM



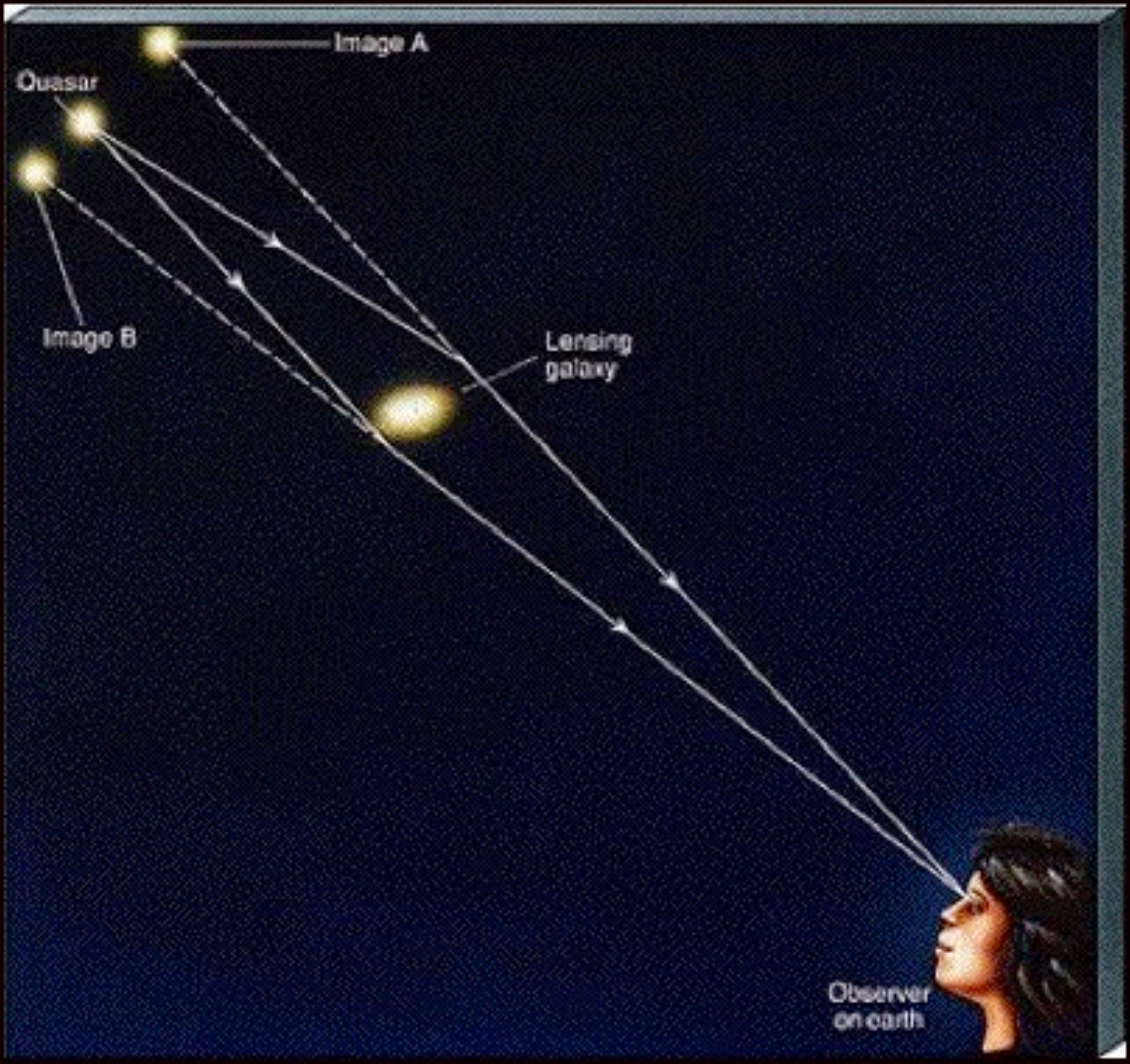

Orbital speed (km/s)
350
300
250
200
150
100
50
5
10
15
20
25
Distance from the center of galaxy (kpc)
NGC 4378
NGC 3145
NGC 1620
NGC 7664
Galaxies:
"Flat rotation curve"


luminous matter
dark matter halo

Most -72%- large galaxies have spiral structures

One way to "weigh" things in the universe:

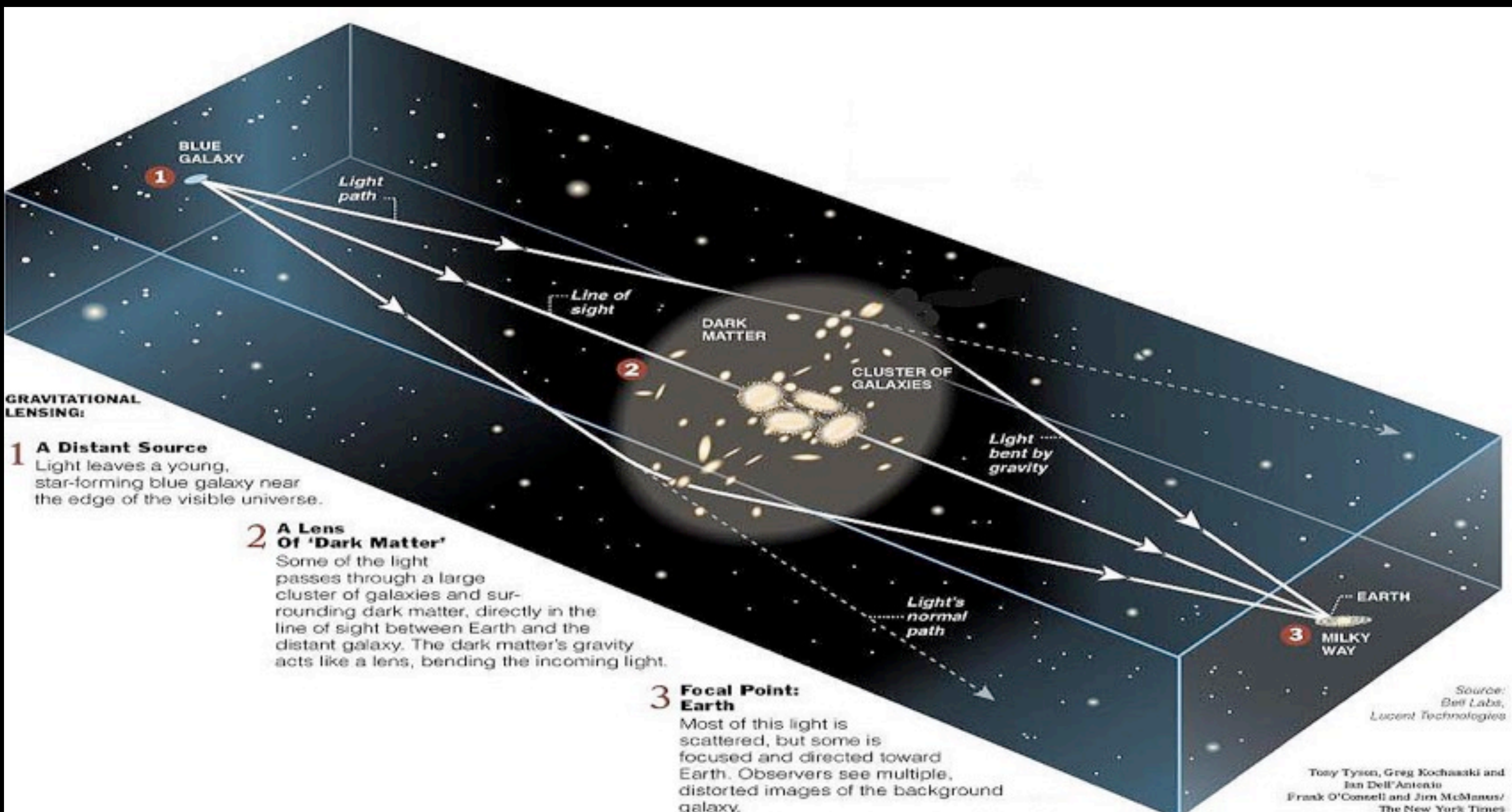
Gravitational lensing.

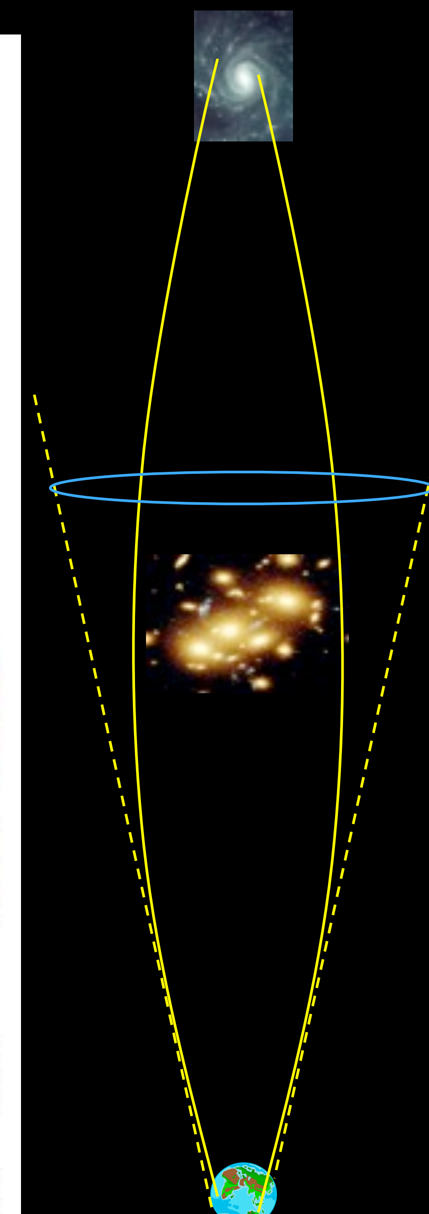


The gravitational field of a galaxy (or cluster of galaxies) deflects passing light; the more mass, the greater deflection.

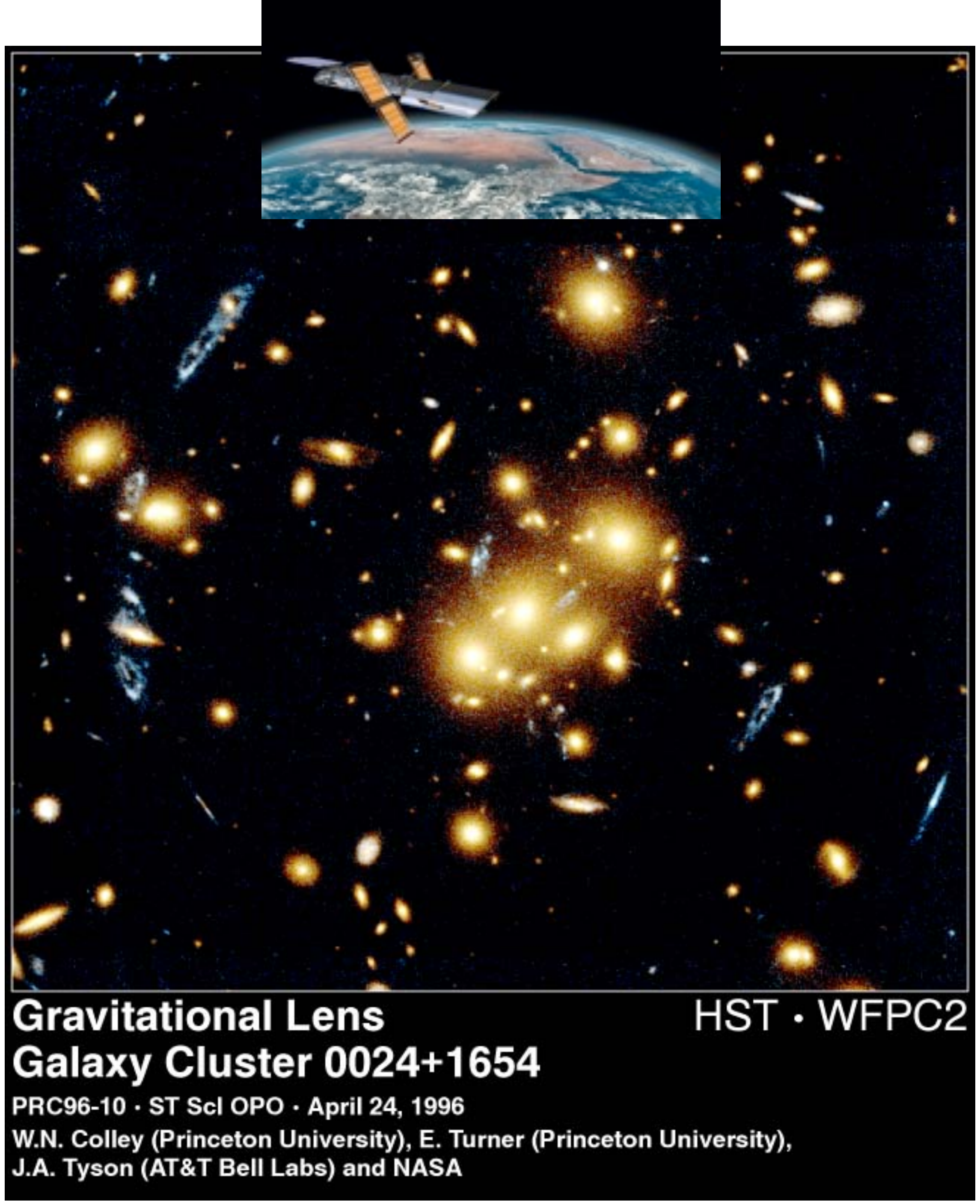
So we can infer the existence of matter even if we can't see it.

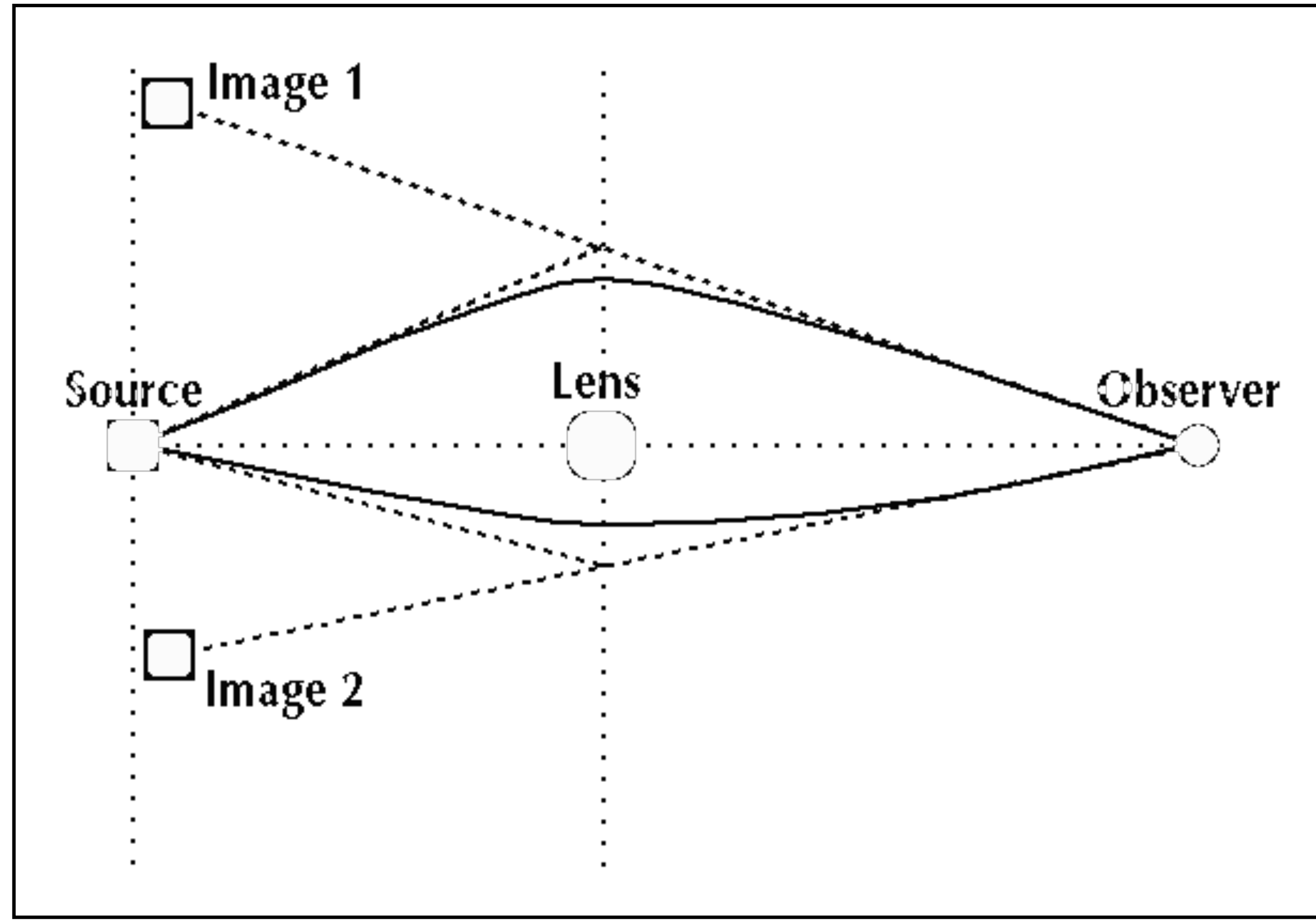
Gravitational Lensing

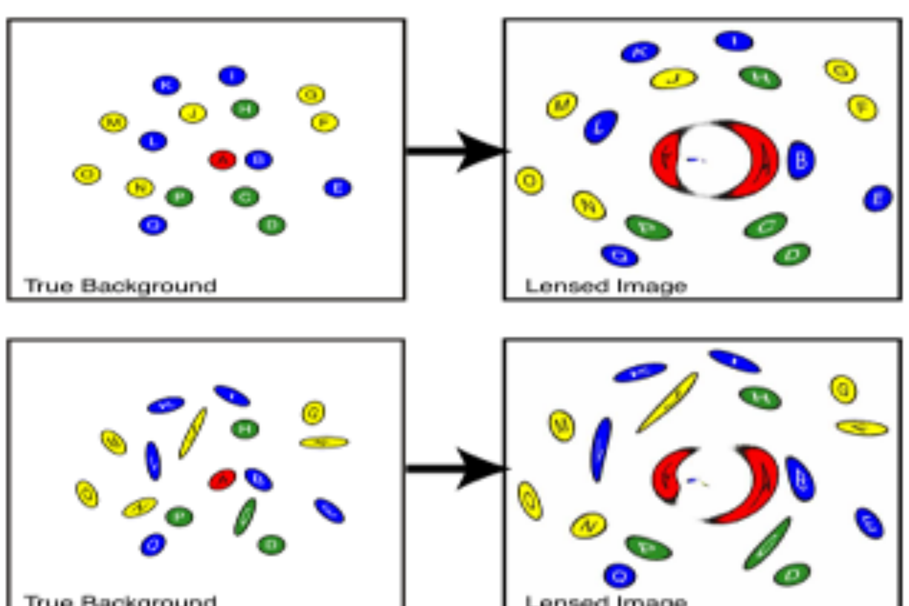




Gravitational Lensing







➢ **Clusters & Superclusters**

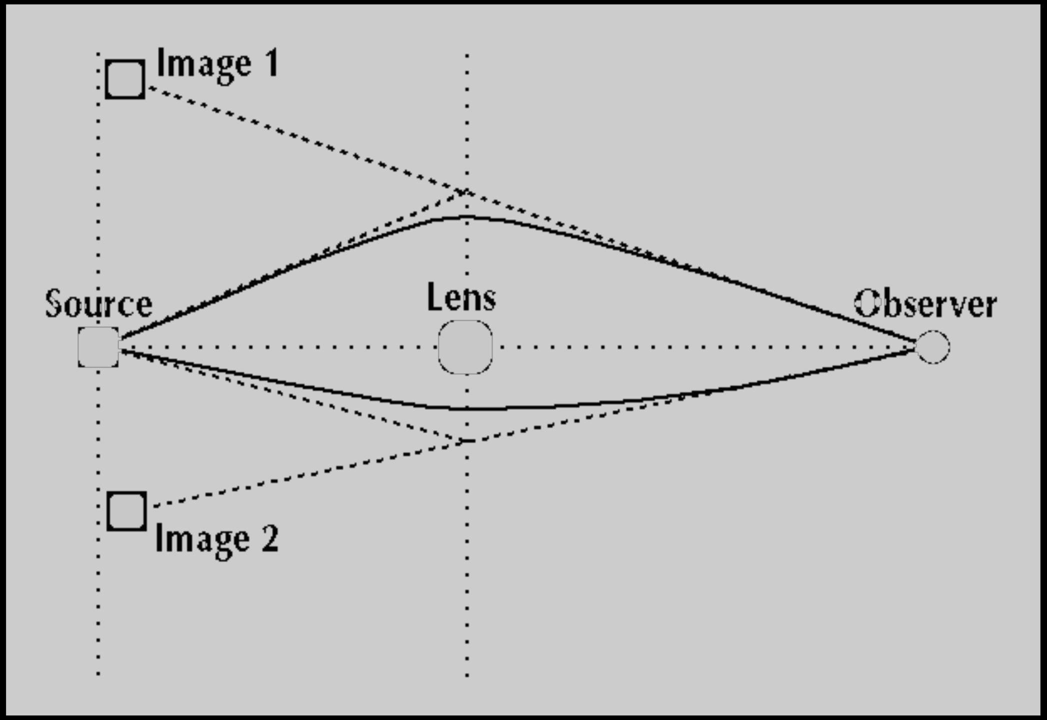
↳ **Gravitational Lensing**

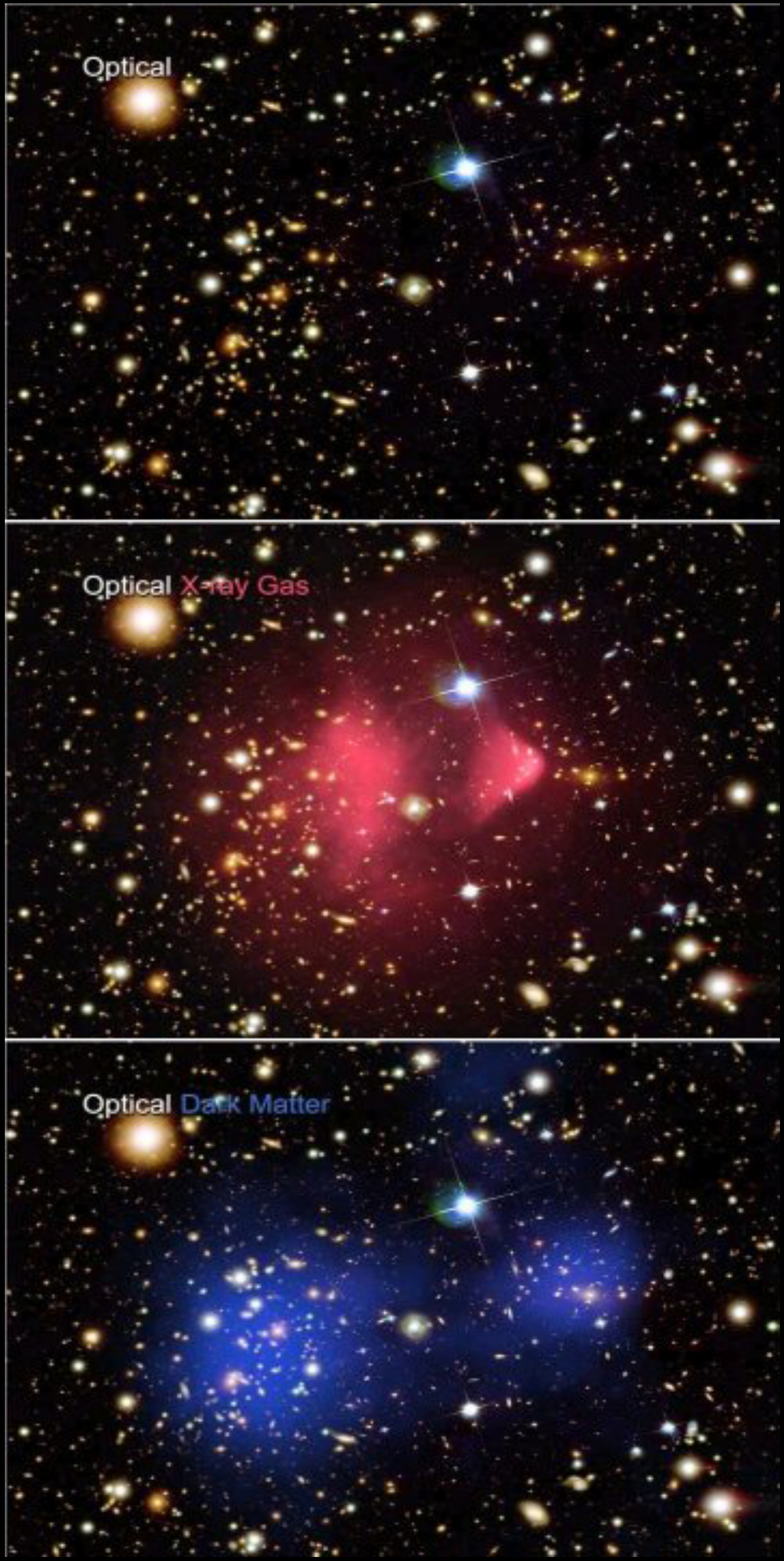
⇒ **Grav. Mass > Lum. Mass**

☞ Dark Matter

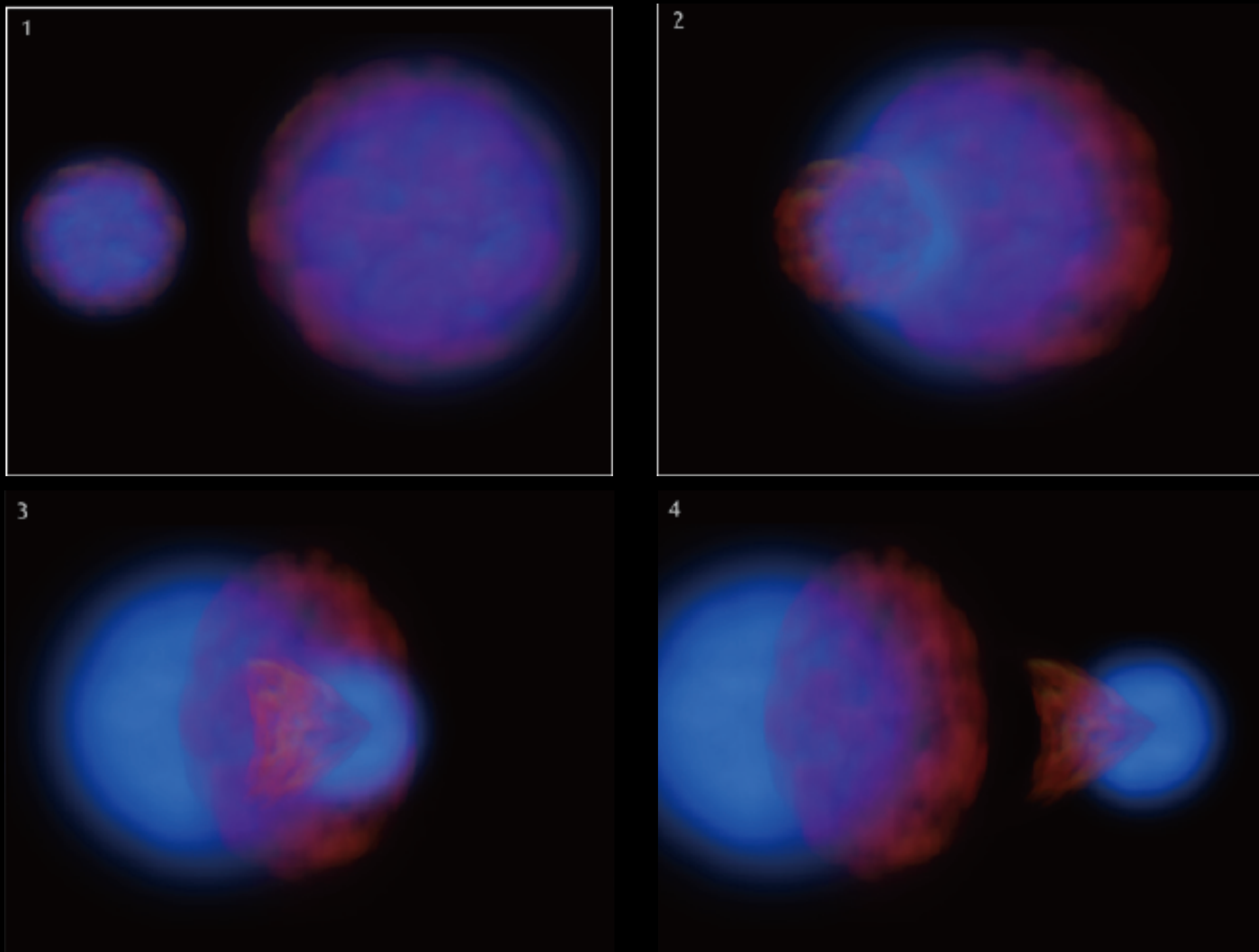
Bullet Cluster

Gravitational Lensing

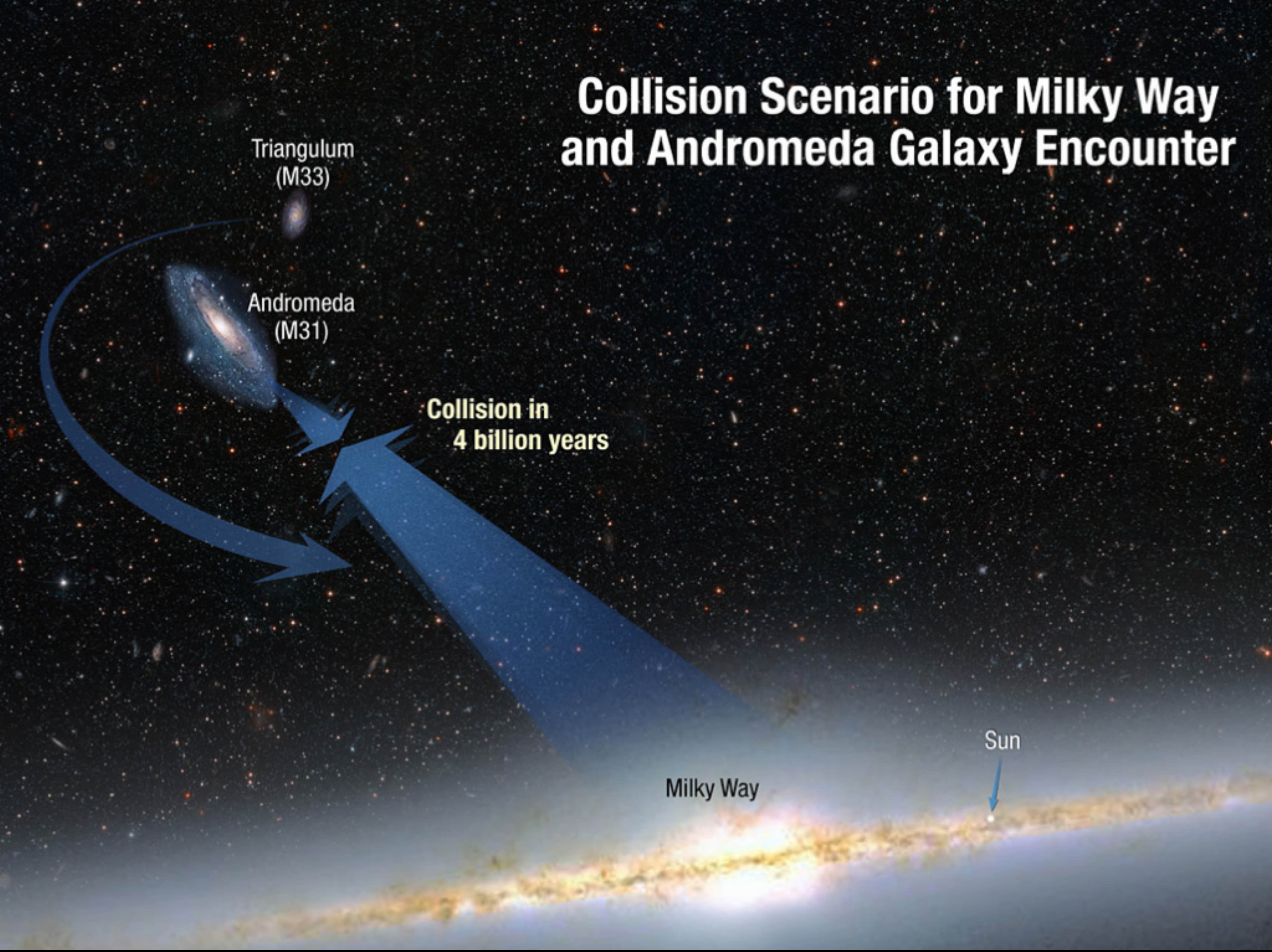




Merging Clusters artists' rendition




仙女座
Andromeda
銀河系
Milky Way


Collision Scenario for Milky Way
and Andromeda Galaxy Encounter
Triangulum
(M33)
Andromeda
(M31)
Collision in
4 billion years
Sun
Milky Way

DC2. Dark Energy

The Acceleration Universe

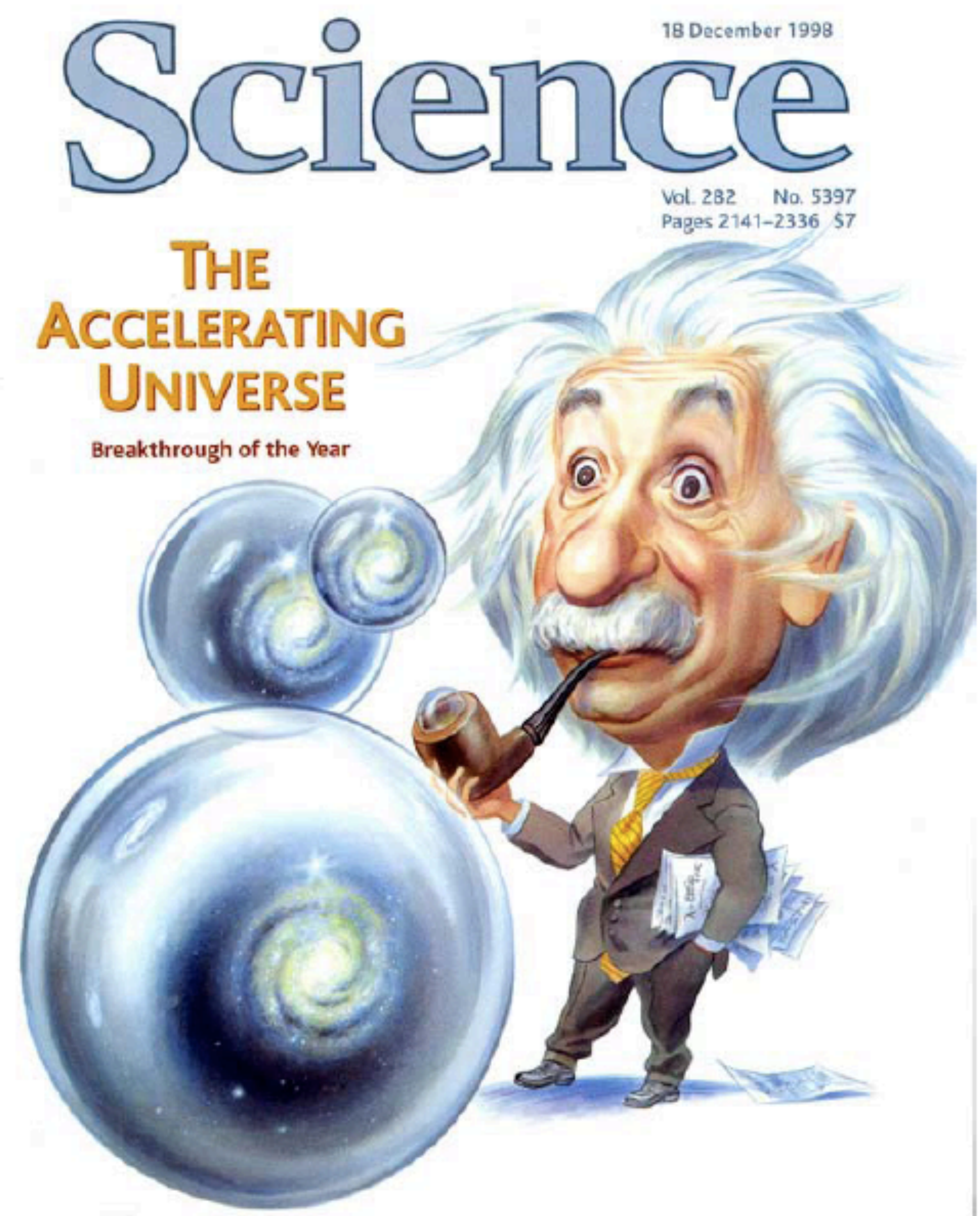
Big News in 1998!

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

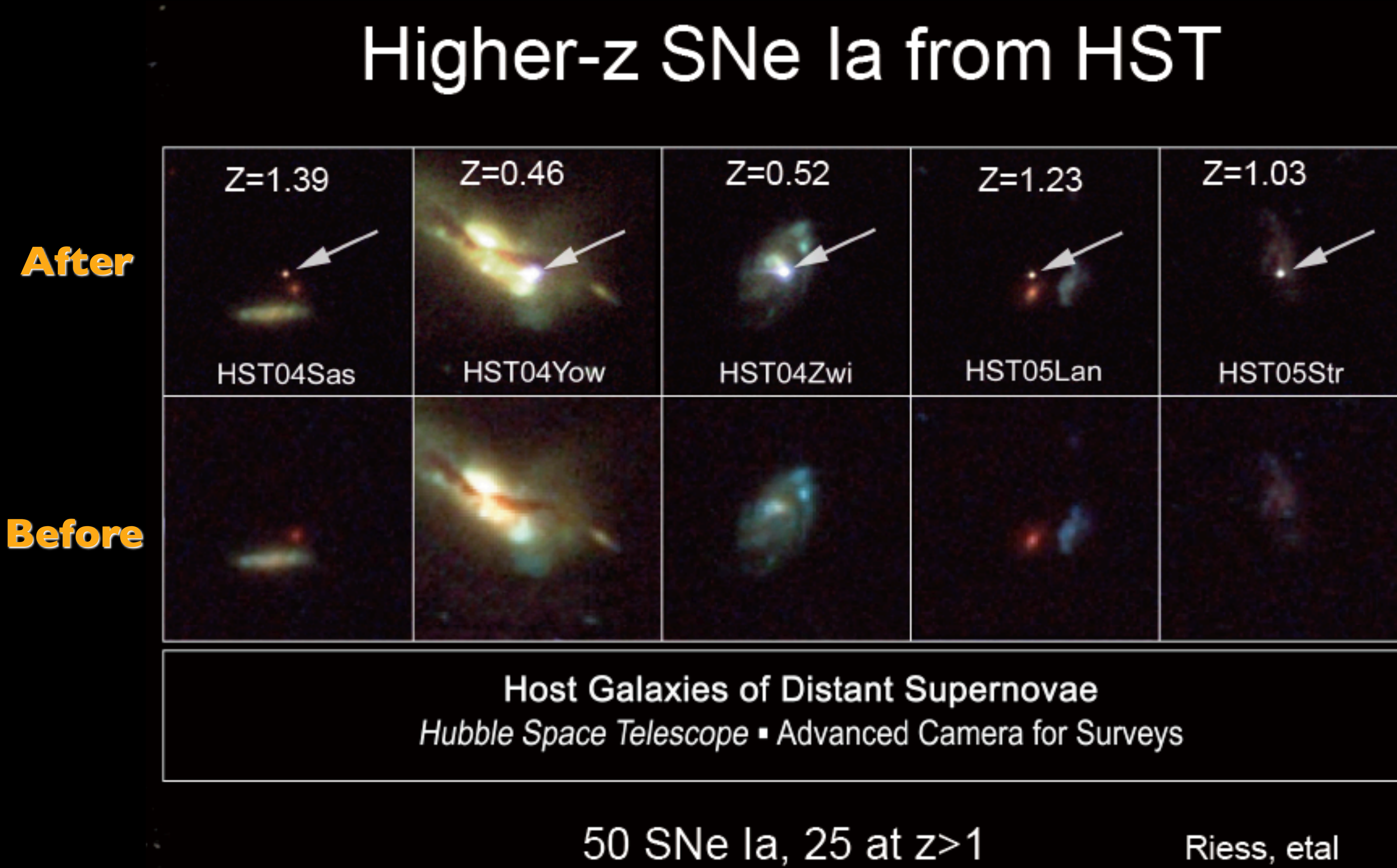
Brian P. Schmidt

Photo: Homewood Photography

Adam G. Riess

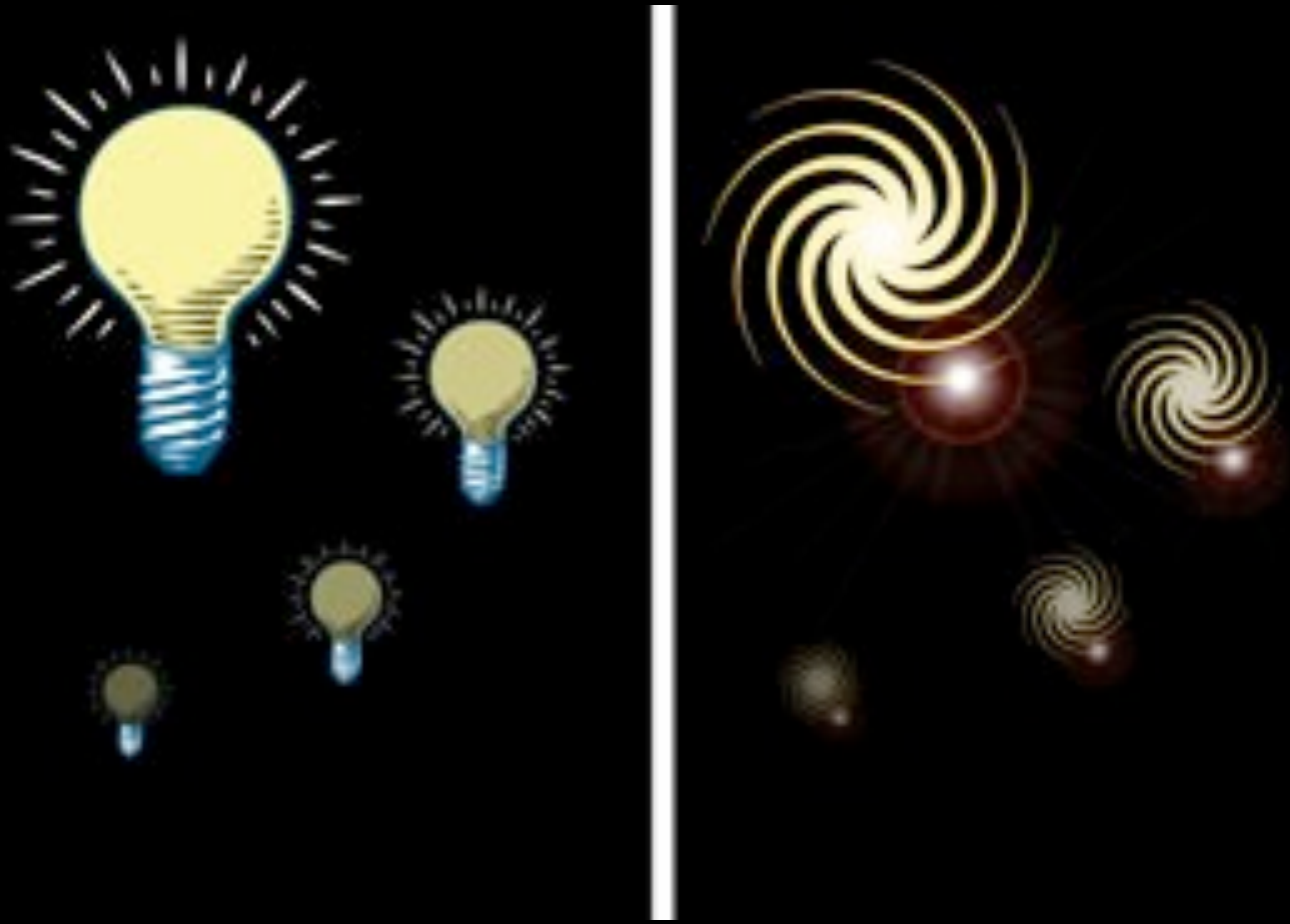
2015 Breakthrough Prize in Fundamental Physics: 51 members splitting the $3 million

Distant supernovae

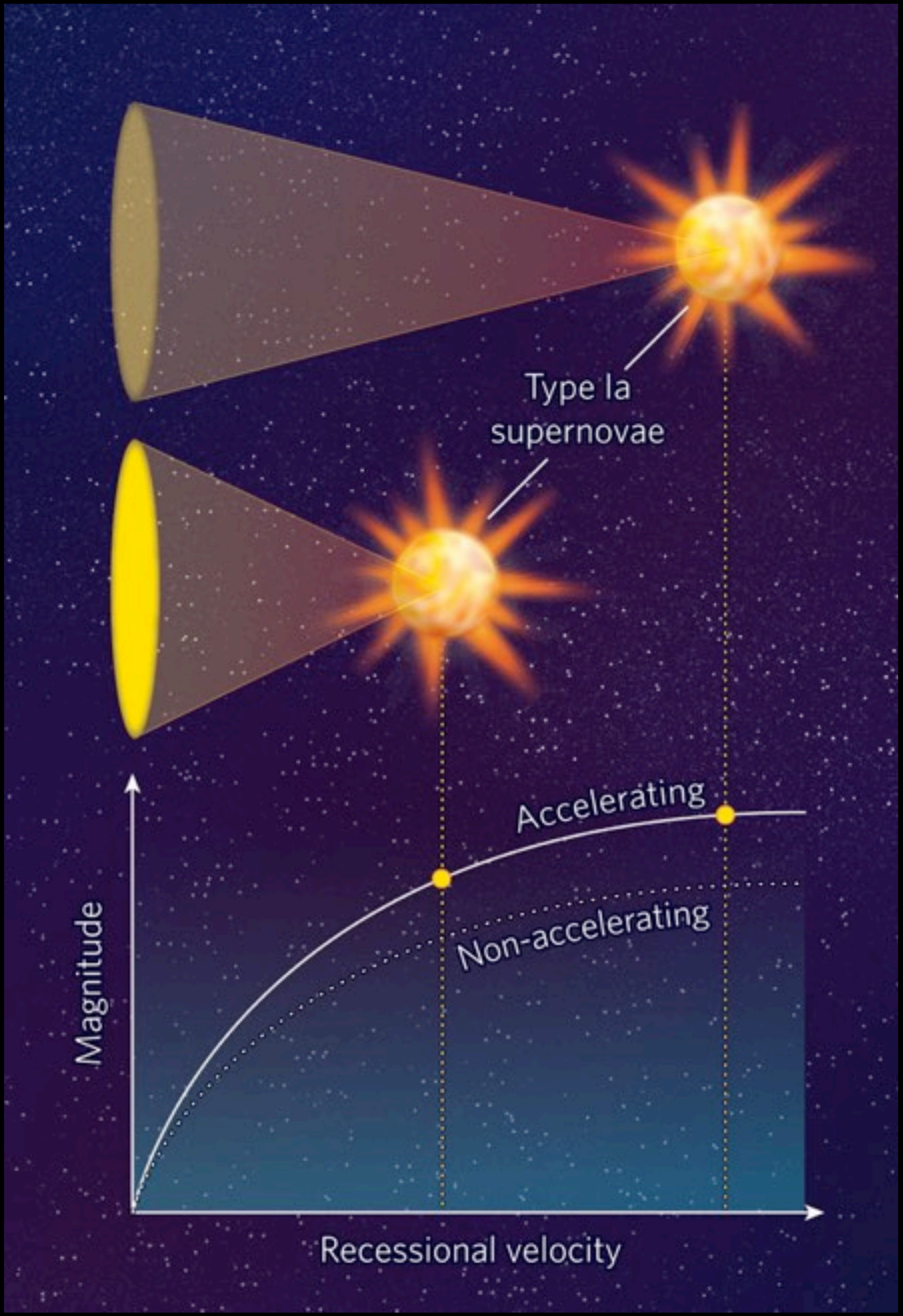


Distant supernovae

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



Distant SN as standard candles



Luminosity distance:

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

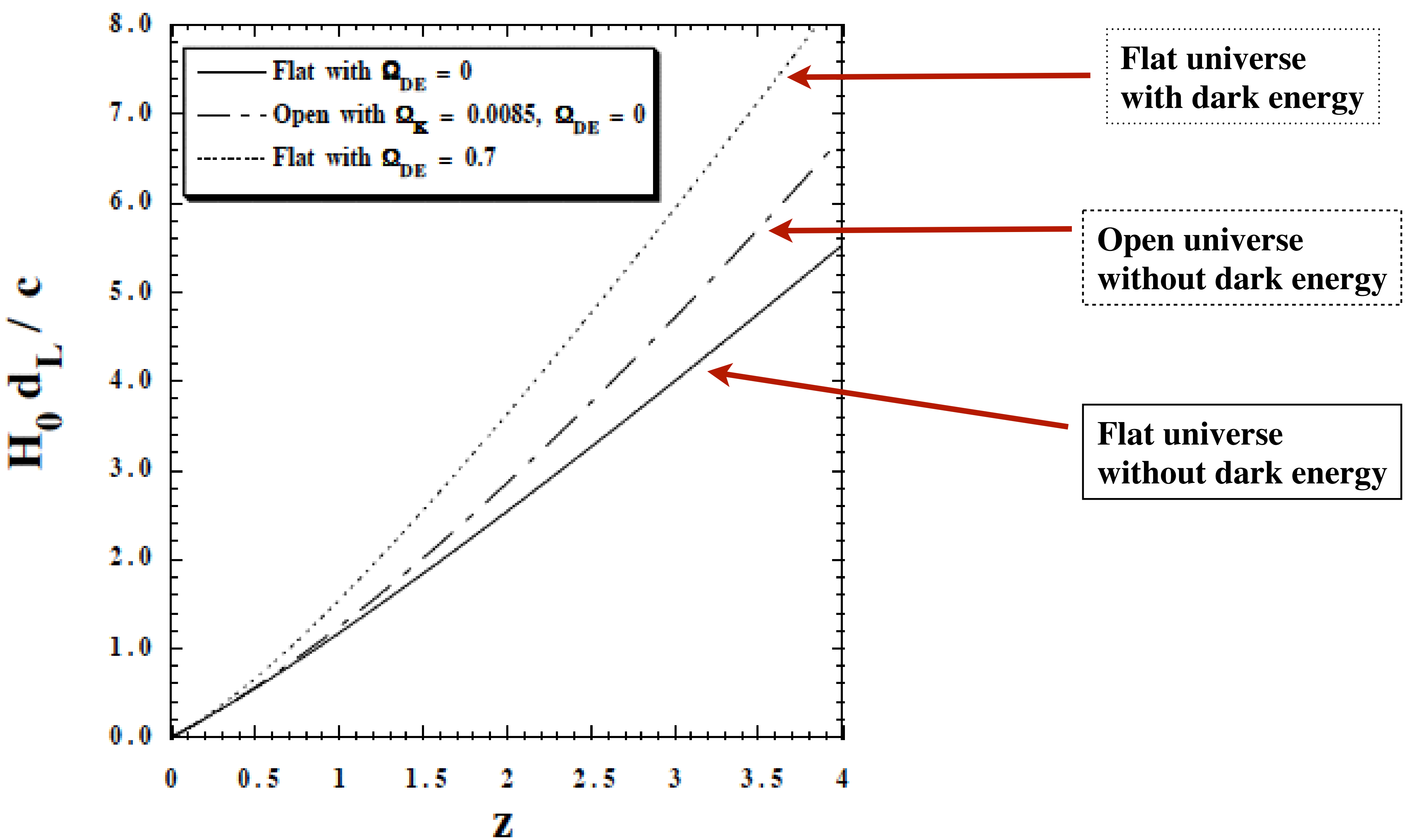
L_s the absolute luminosity of the source
F observed flux

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

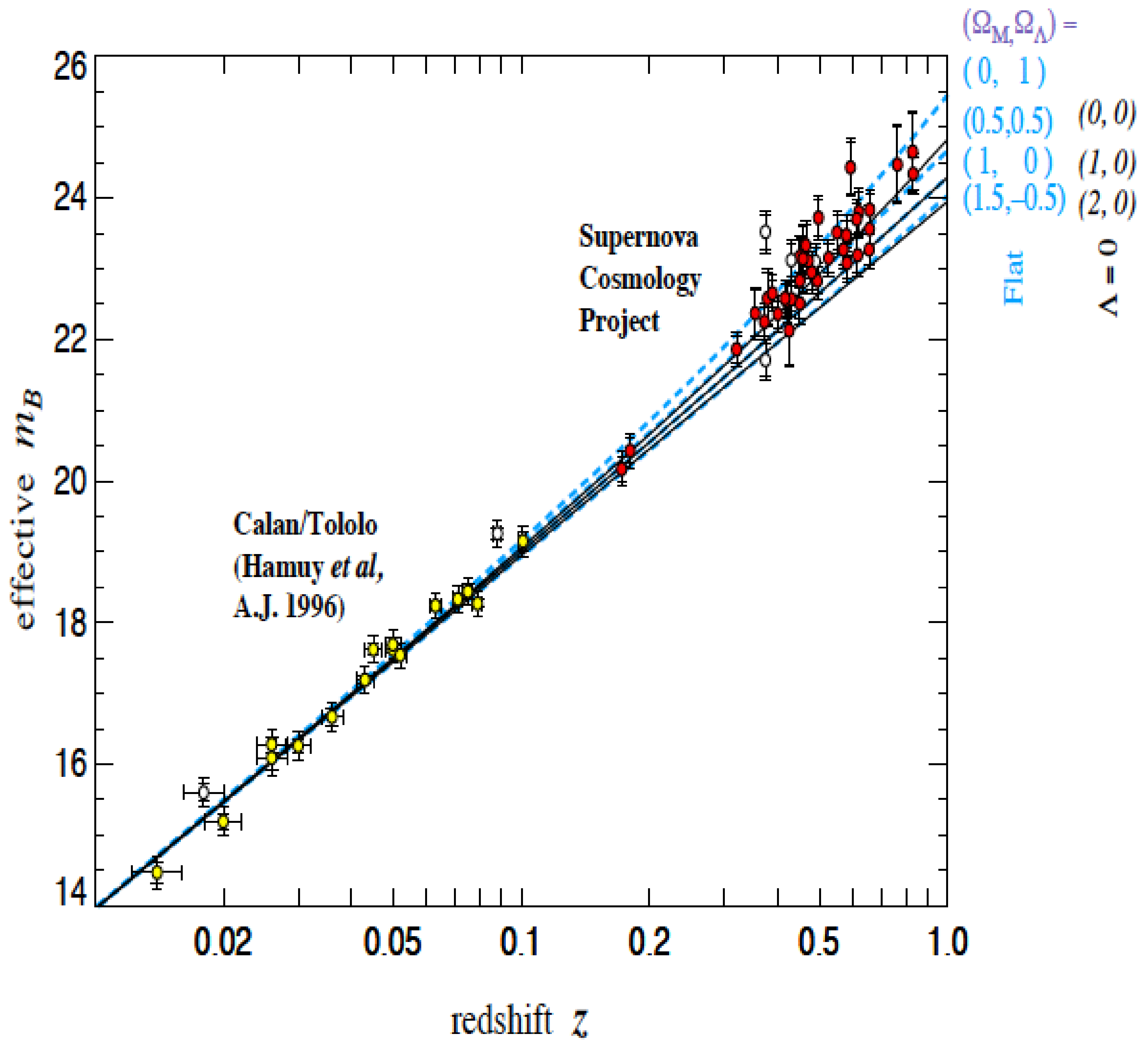
K>0: closed
K=0: flat
K<0: open

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

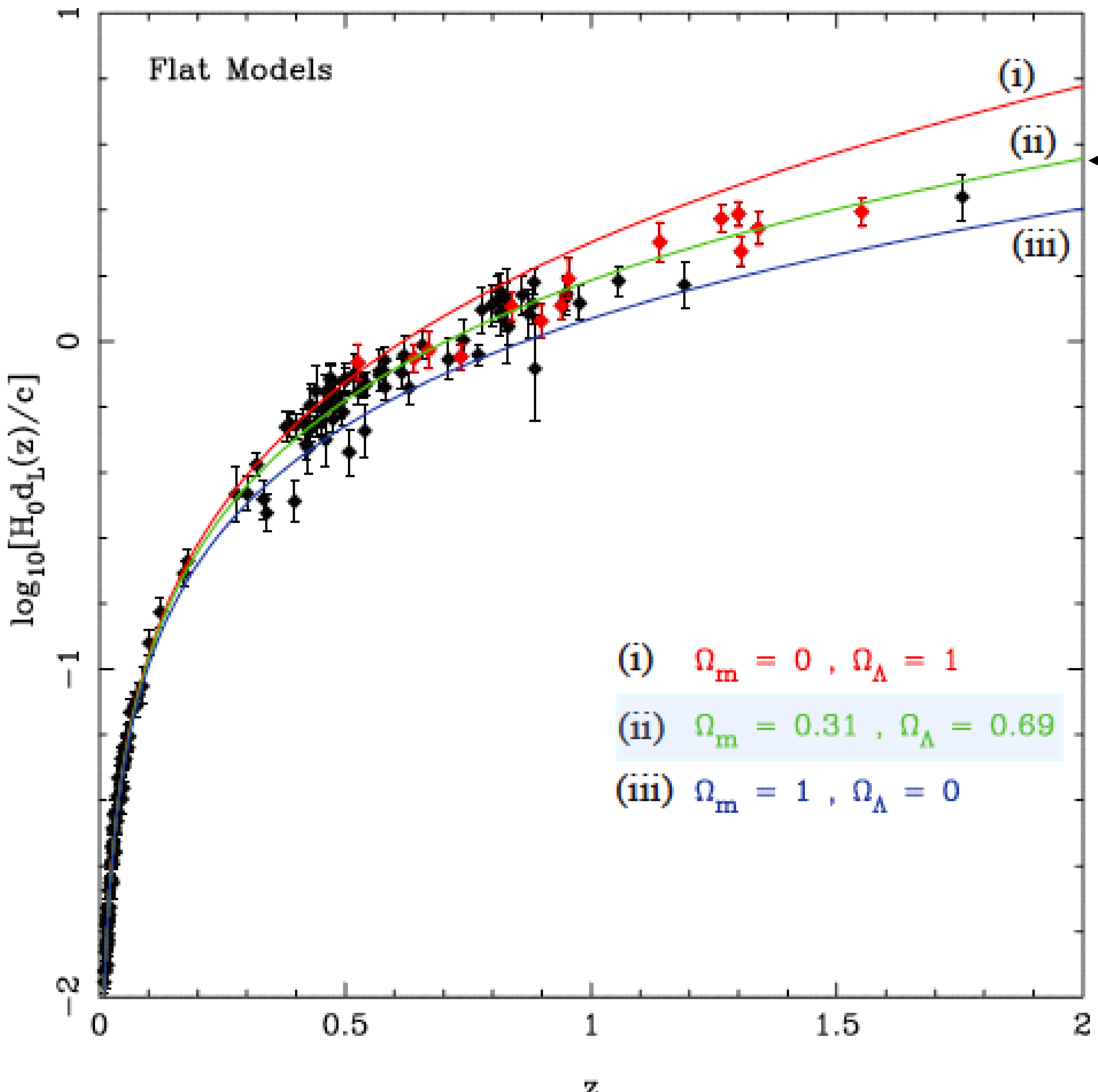
$$E(z) = \left[\Omega_m^{(0)}(1+z)^3 + \Omega_K^{(0)}(1+z)^2 + \Omega_{DE}^{(0)}\exp\left\{\int_0^z \frac{3(1+w_{DE})}{1+z'}dz'\right\}\right]^{1/2}$$



Perlmutter et al and Riess et al (1998)



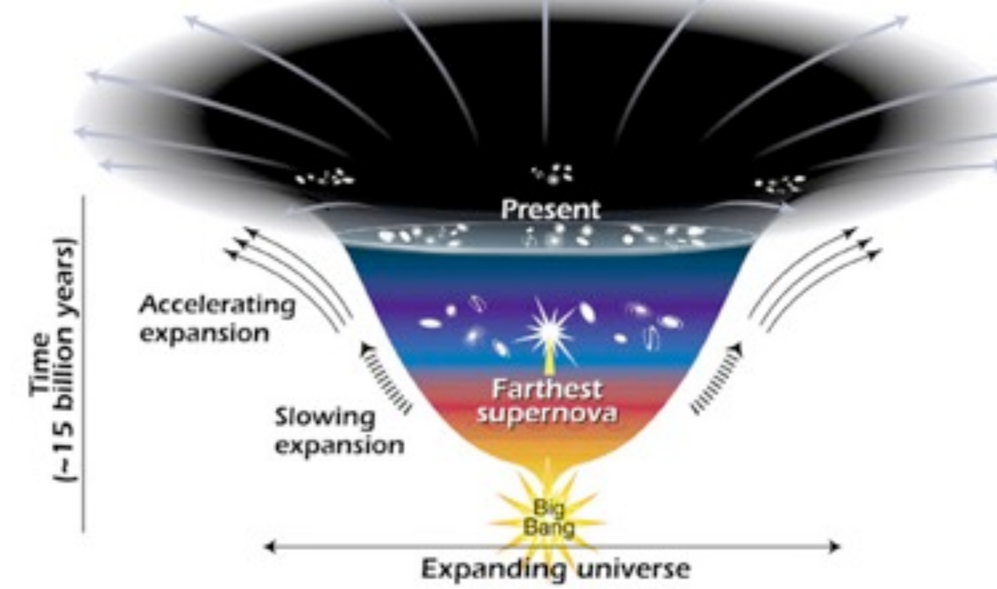
More data over the past 10 years



~ 70%
Dark Energy

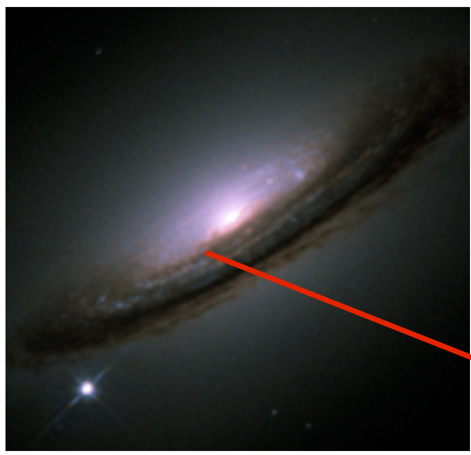
暗能量

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

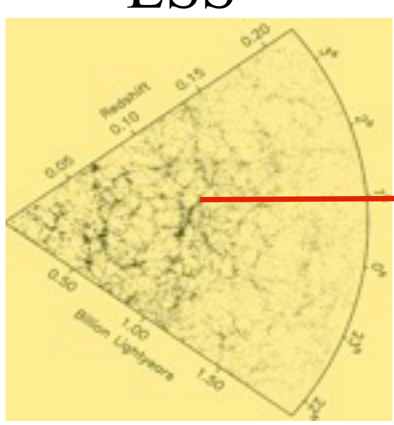


This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers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

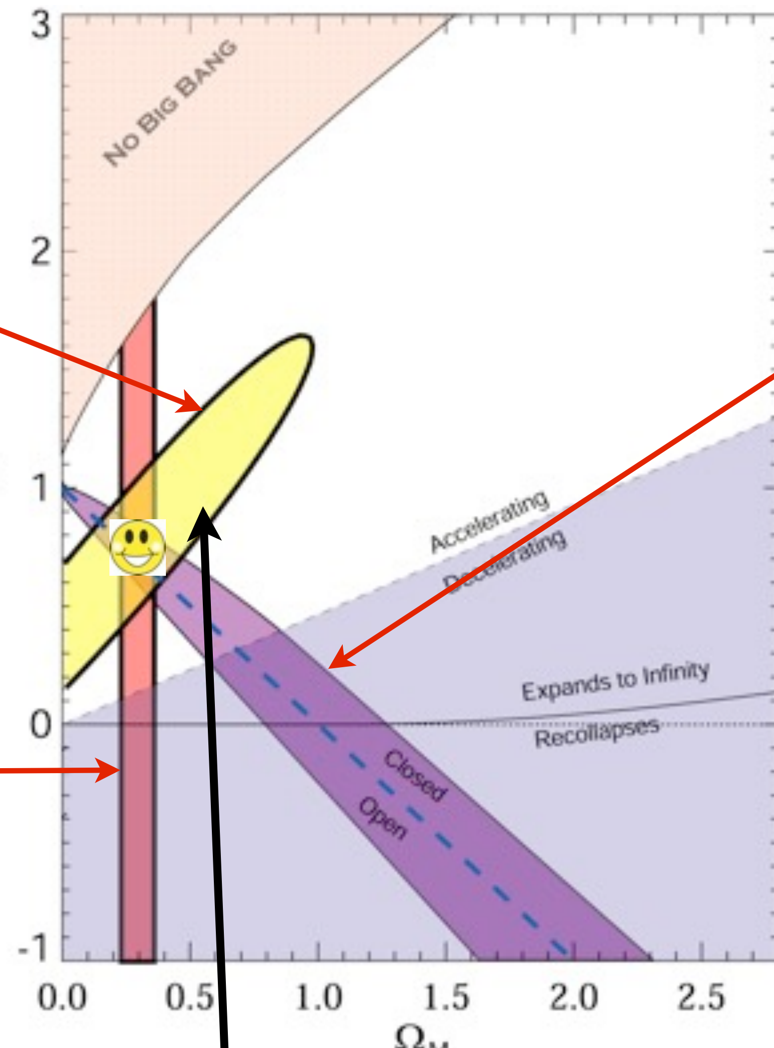
SNe Ia



LSS



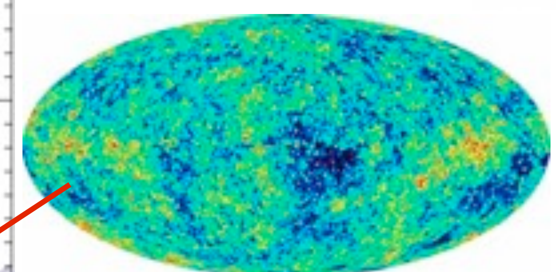
暗能量



物質

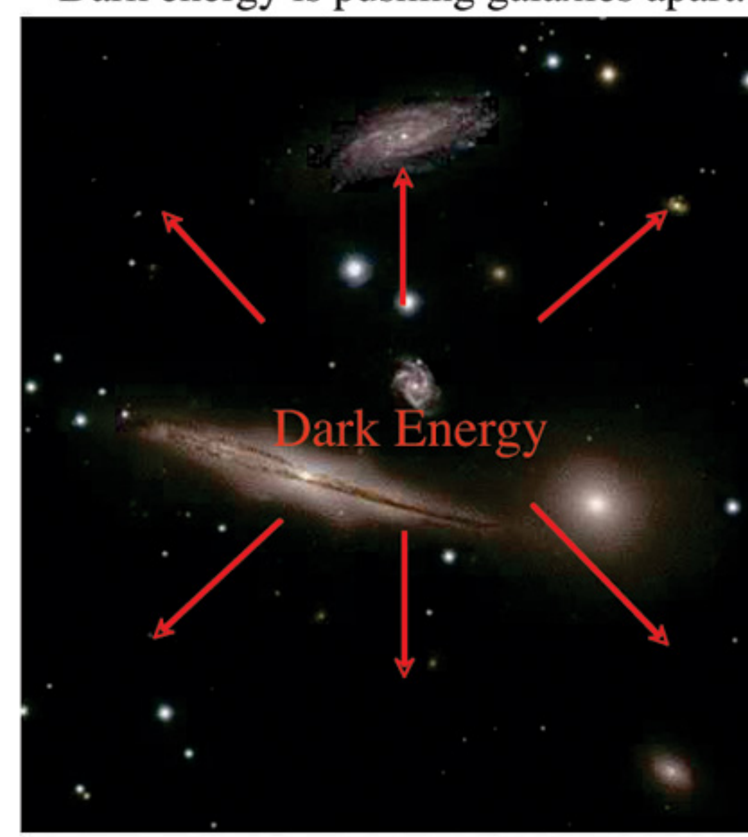
2011 N.P. in Physics

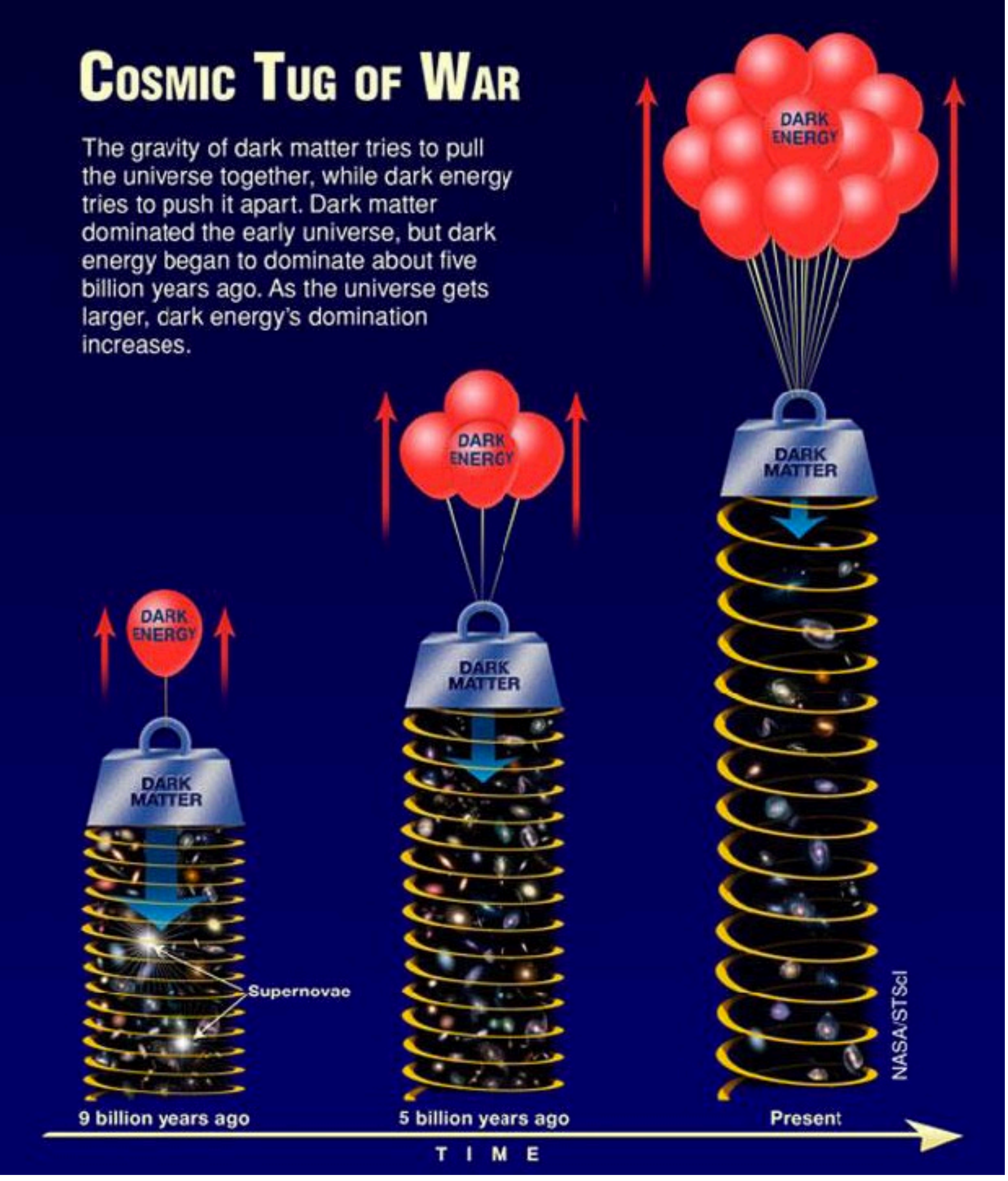
CMB



The current universe is accelerating!

Dark energy is pushing galaxies apart.





COSMIC TUG OF WAR
The gravity of dark matter tries to pull the universe together, while dark energy tries to push it apart. Dark matter dominated the early universe, but dark energy began to dominate about five billion years ago. As the universe gets larger, dark energy's domination increases.
DARK ENERGY
DARK MATTER
Supernovae
DARK ENERGY
DARK MATTER
DARK ENERGY
DARK MATTER
NASA/STScI
9 billion years ago
5 billion years ago
Present
TIME

Edward Witten

IAS, Princeton

W

W

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

W

M

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.

The Nobel Prize in Physics 2015

Takaaki Kajita

Arthur B. McDonald

The Nobel Prize in Physics 2015

Takaaki Kajita
Born 1959, Japan

Arthur B. McDonald
Born 1943, Canada

The Nobel Prize in Physics 2015

Takaaki Kajita
Born 1959, Japan
Prize share: 1/2

Arthur B. McDonald
Born 1943, Canada
Prize share: 1/2

Prize amount:
SEK 8 million
(1USD=8.5SEK;
1SEK=3.83NT)
～3100NTD

Fajita

McDonald

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Fajita

McDonald

Kajita: Spokesman of the Super-Kamiokande neutrino detector in Kamioka, Japan

McDonald: Spokesman of the Sudbury Neutrino Observatory in Sudbury, Ontario, Canada

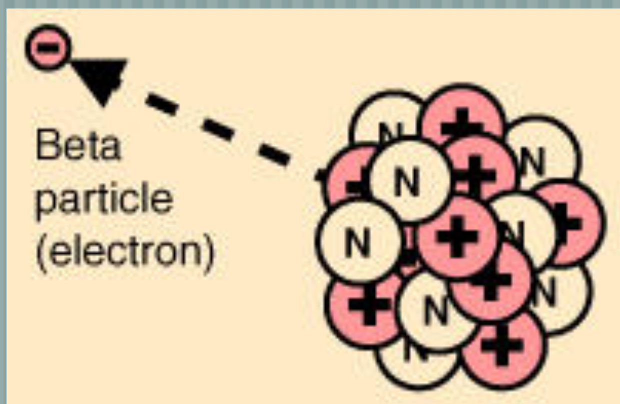
What is Neutrino?

什麼是中微子?

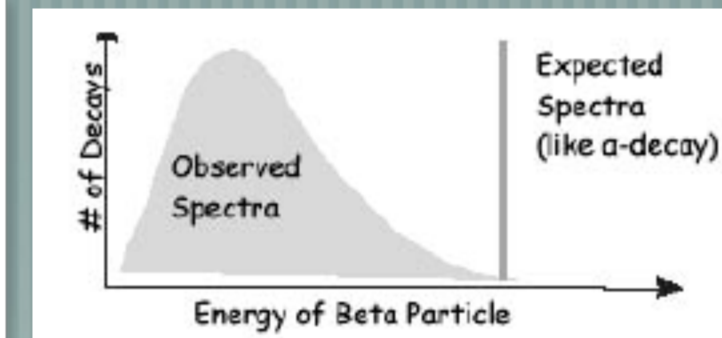
基本粒子
微小質量
自旋 1/2
電中性
與其它粒子相互作用微弱

Matter spontaneously emits penetrating radiation
(Becquerel, 1896; the Curies, 1898)

β decay:



beta Energy Spectrum:



Wolfgang Pauli (1900-1958)

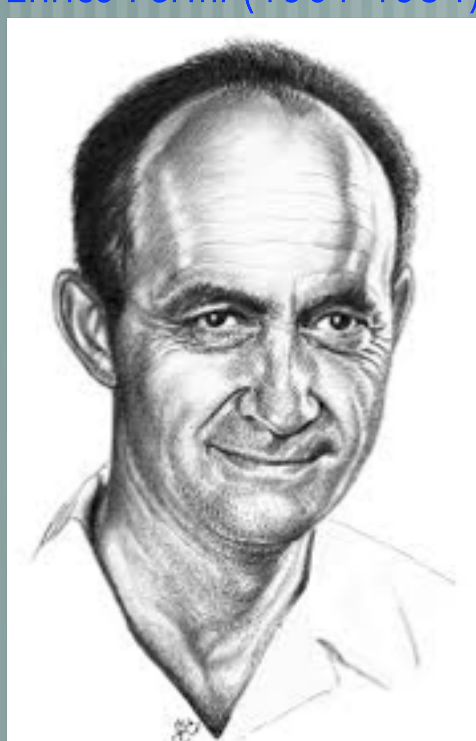
A missing neutral particle

Neutron (Chadwick 1932) → ``neutron" (Pauli, 1930)

Neutri´no: Little neutral object (Fermi, 1933)

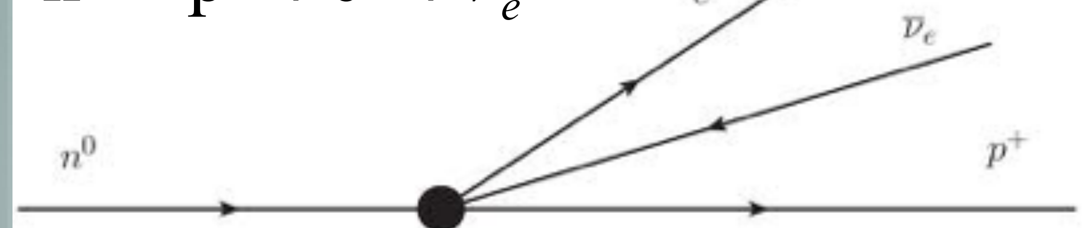
``*I have done a terrible thing, I have postulated a particle that cannot be detected.*"

Enrico Fermi (1901-1954)



β-theory of weak interaction (1934)

$$n \rightarrow p^{+} + e^{-} + \bar{\nu}_e$$



$$H_{weak} \propto G\,(\overline{\Psi}_p\ \gamma_\mu\ \Psi_n)\,(\overline{\Psi}_e\ \gamma^\mu\ \Psi_\nu)$$

Neutrino cross-section / Electron cross-section ~10^{-10} → No detection for 23 years

← 1953 Reines&Cowan

中微子(neutrino)

- Number density

At present $112\,(\nu+\bar{\nu})\,\mathrm{cm}^{-3}$ per flavour

T=1.95K

- Energy density

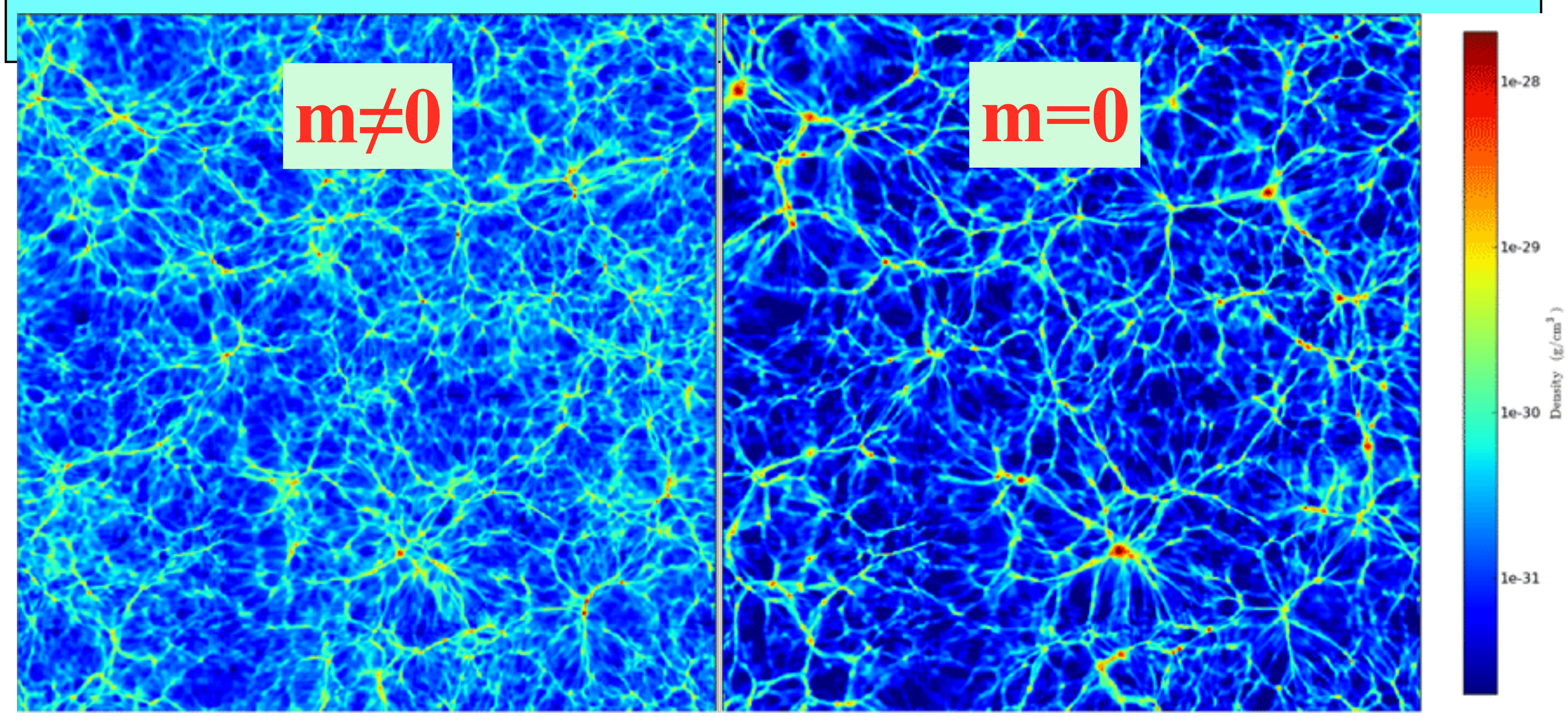
Contribution to the energy density of the Universe

$$\Omega_\nu h^2 = 1.7\times10^{-5}$$ Massless

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{94.1\ \mathrm{eV}}$$ Massive $m_\nu \gg T$

There are some 10^{90} neutrinos and anti-neutrinos left over from the Big Bang, making them the second most abundant particle in the Universe (after photons).

中微子的數目10^{90}是宇宙中第二多的粒子僅次於光子。



Highlights of Neutrino History

1930 ν existence postulated (Pauli)

1953 ν_e interaction observed (Reines & Cowan)

Nobel 1995 Reines (Cowan died in 1974)

1957 ν oscillation predicted (Pontecorvo)

1962 ν_μ observed (Lederman, Schwartz & Steinberger)

Nobel 1988 Lederman, Schwartz & Steinberger

1968 Solar ν observed (Davis)

1987 Supernova ν observed (Koshiba)

Nobel 2002 Davis & Koshiba

1989 Only three light ν generations (LEP experiments)

1998 ν_{atm} oscillation observed by Super-K (Kajita)

2001 ν_{sol} oscillation observed by SNO (MaDonald)

Nobel 2015 Kajita & MaDonald

2000 ν_τ observed (DONUT experiment)

2016 Breakthrough Prize in Fundamental Physics

7 leaders and 1370 members of 5 experiments on

Neutrino Oscillation

splitting 3 million USD (Nov. 8, 2015)

? ☜

Daya Bay (China): Yifang Wang 王貽芳  and Kam-Biu Luk 陸錦標 

中山大學王為 

KamLand (Japan): Atsuto Suzuki 

K2K/T2K (Japan): Koichiro Nishikawa 

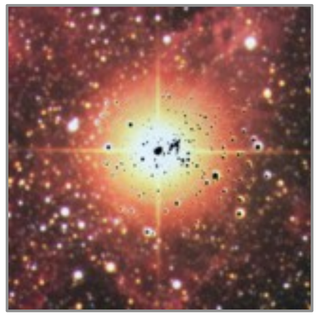
Sudbury Neutrino Observatory (Canada): Arthur B. McDonald 

Super-Kamiokande (Japan): Takaaki Kajita  and Yoichiro Suzuki 

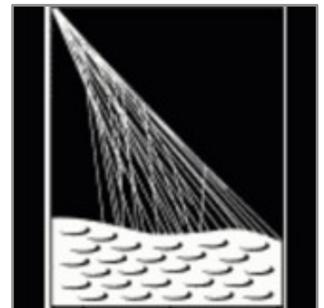
 2015 Noble Physics Prize (Oct. 6, 2015)

There are neutrinos everywhere!!!

Supernova

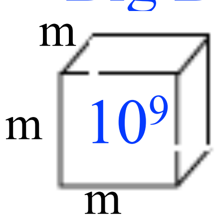


1987a (168,000 light yrs)
~3×10^{14} m^{-2} with 24 observed!

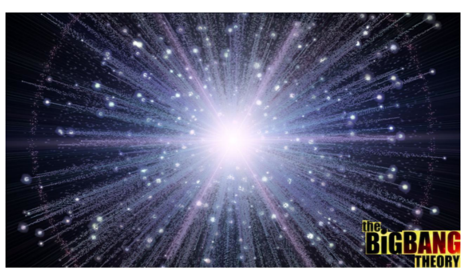


Cosmic Ray Showers

Relic ν from Big Bang



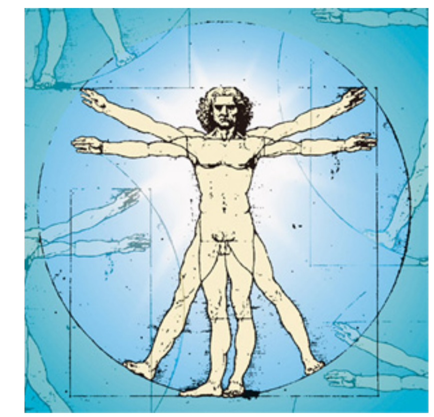
or billion per m^3



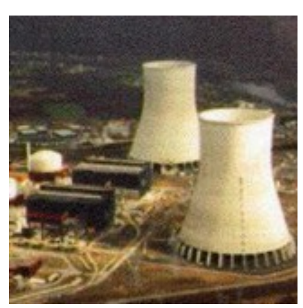
66 billion ν s cm^{-2} s^{-1}

(6.6×10^{14} m^{-2} s^{-1})

Potassium(鉀): ^{40}K



Neutrino Beams made from Reactors and Particle Accelerators



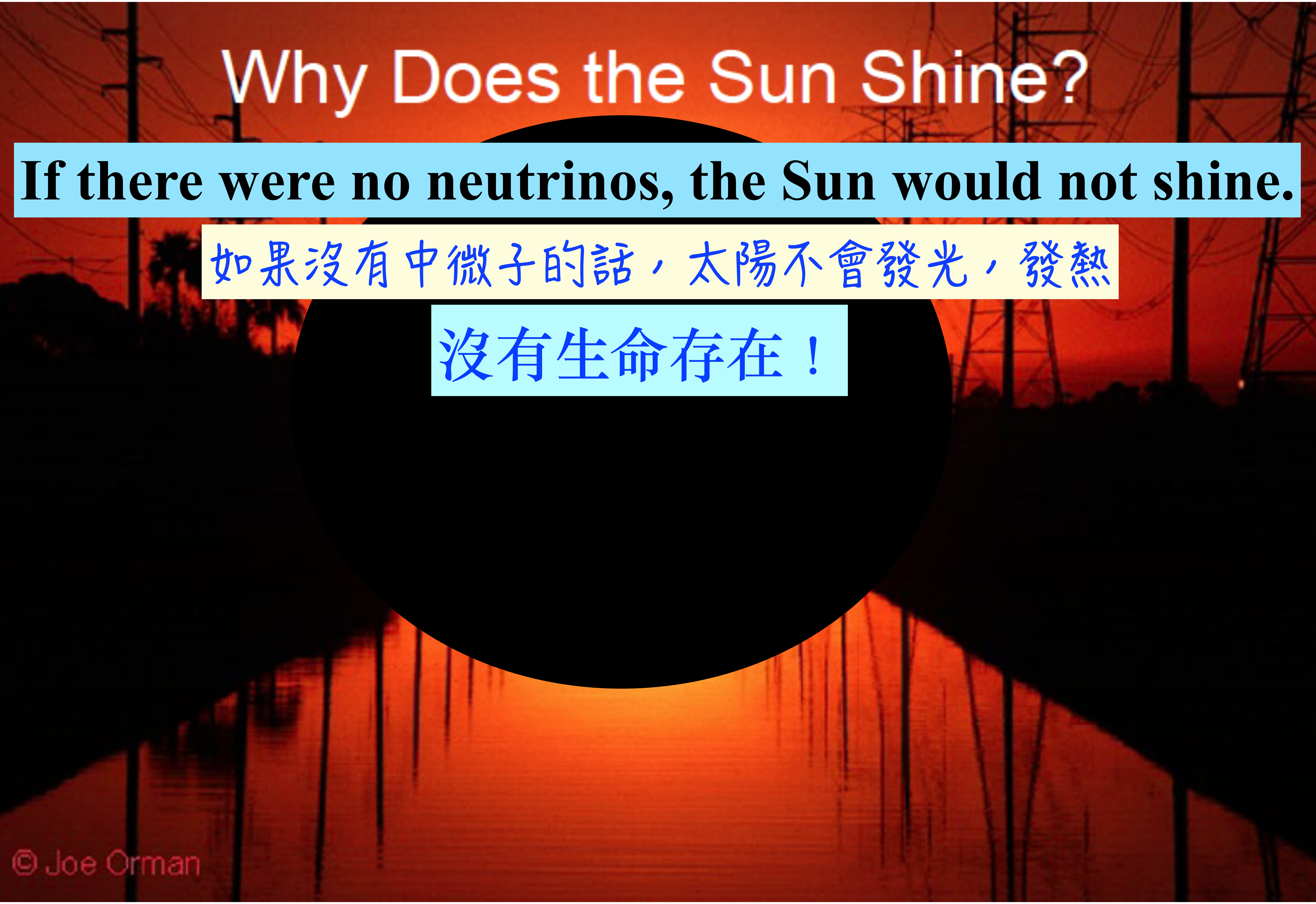
為什麼我們都沒感覺到呢？

ν

A neutrino has a good chance of traveling through 3000 light years of water (or human) before interacting at all!

5000 neutrinos will collide a human body in lifetime; ~1ν/week!

Are Neutrinos Important to Our Lives?

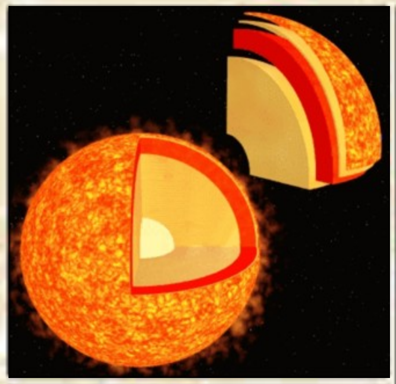


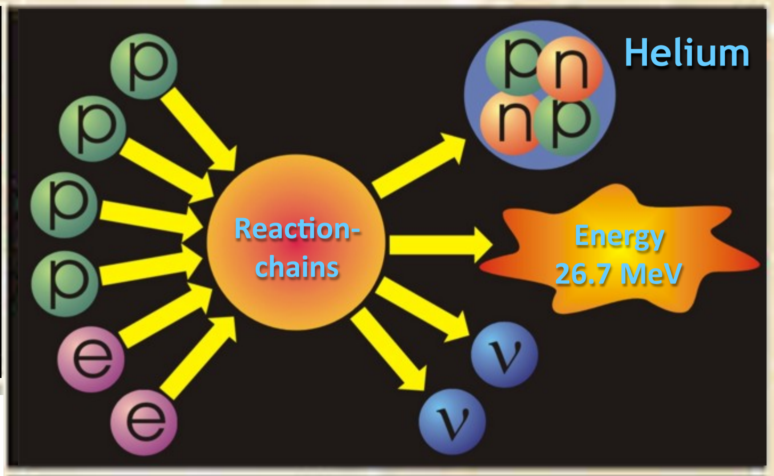
If there were no neutrinos, the Sun would not shine.

如果沒有中微子的話，太陽不會發光，發熱

沒有生命存在！

Neutrinos from the Sun





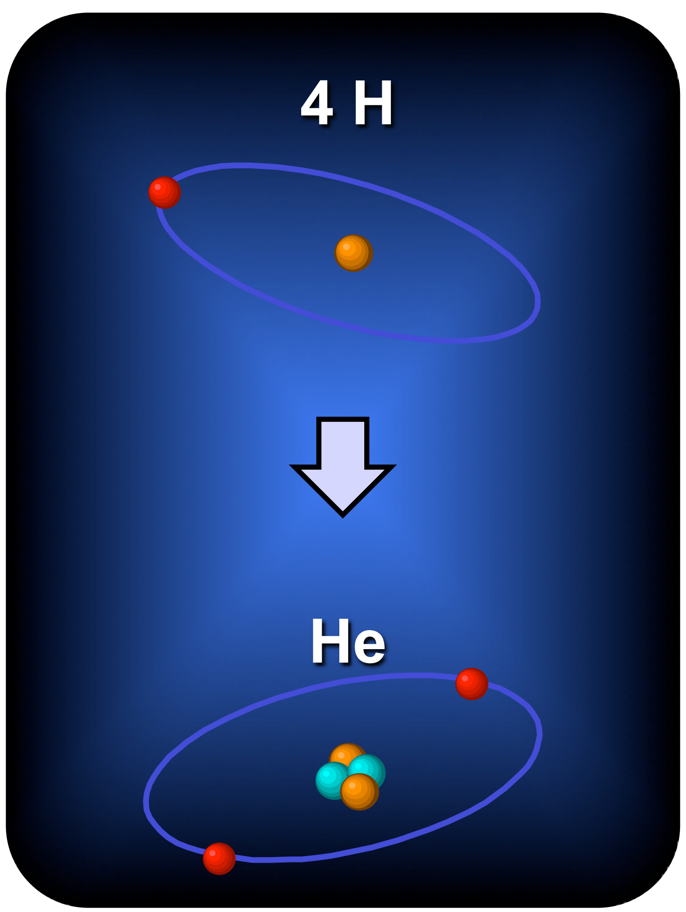
Solar radiation: 98% light
2% neutrinos

At Earth 66 billion neutrinos/cm^2 sec

Hans Bethe (1906-2005, Nobel 1967)
Thermonuclear reaction chain (1938)

Nuclear Fusion

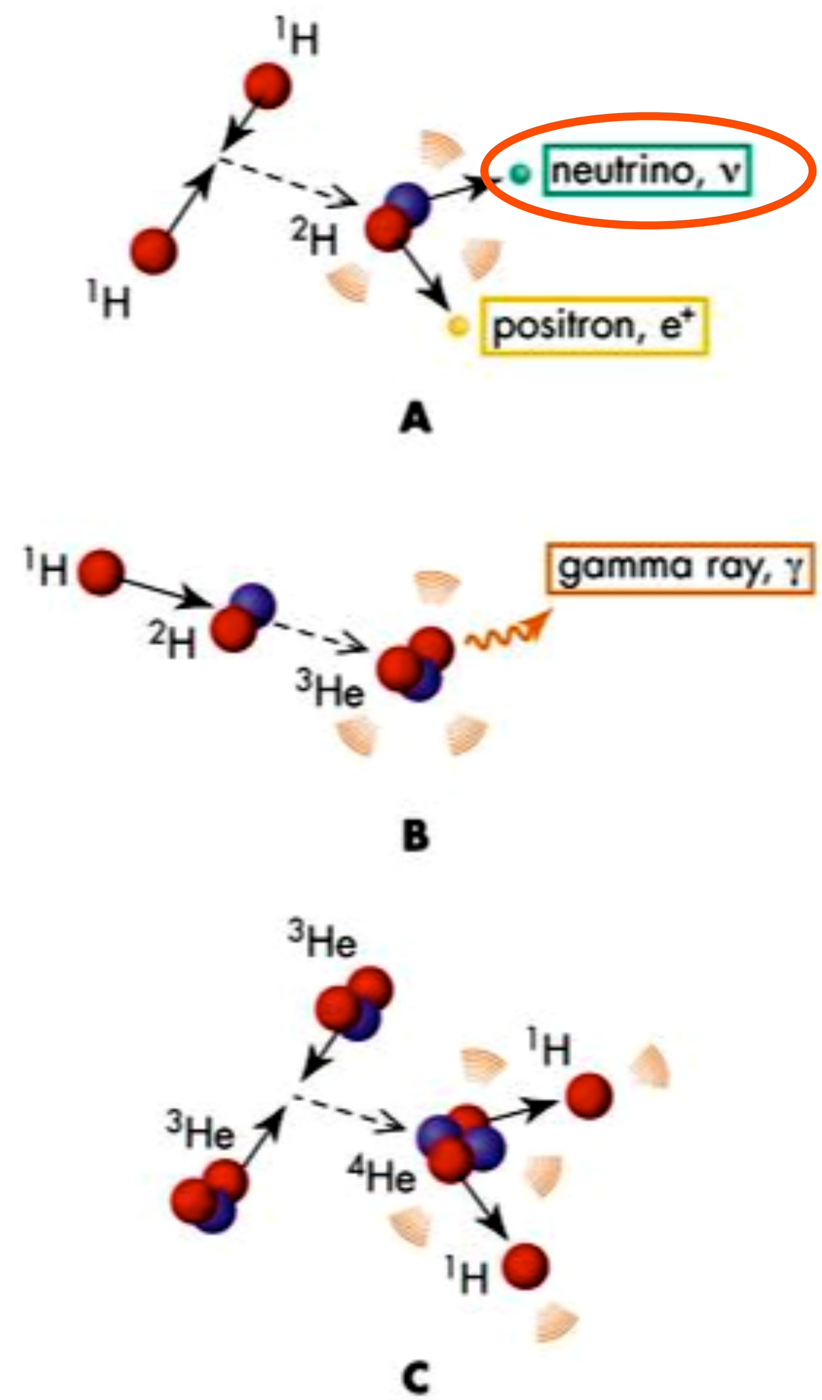
核聚變



Energy production in the Sun: cycles of nuclear reactions

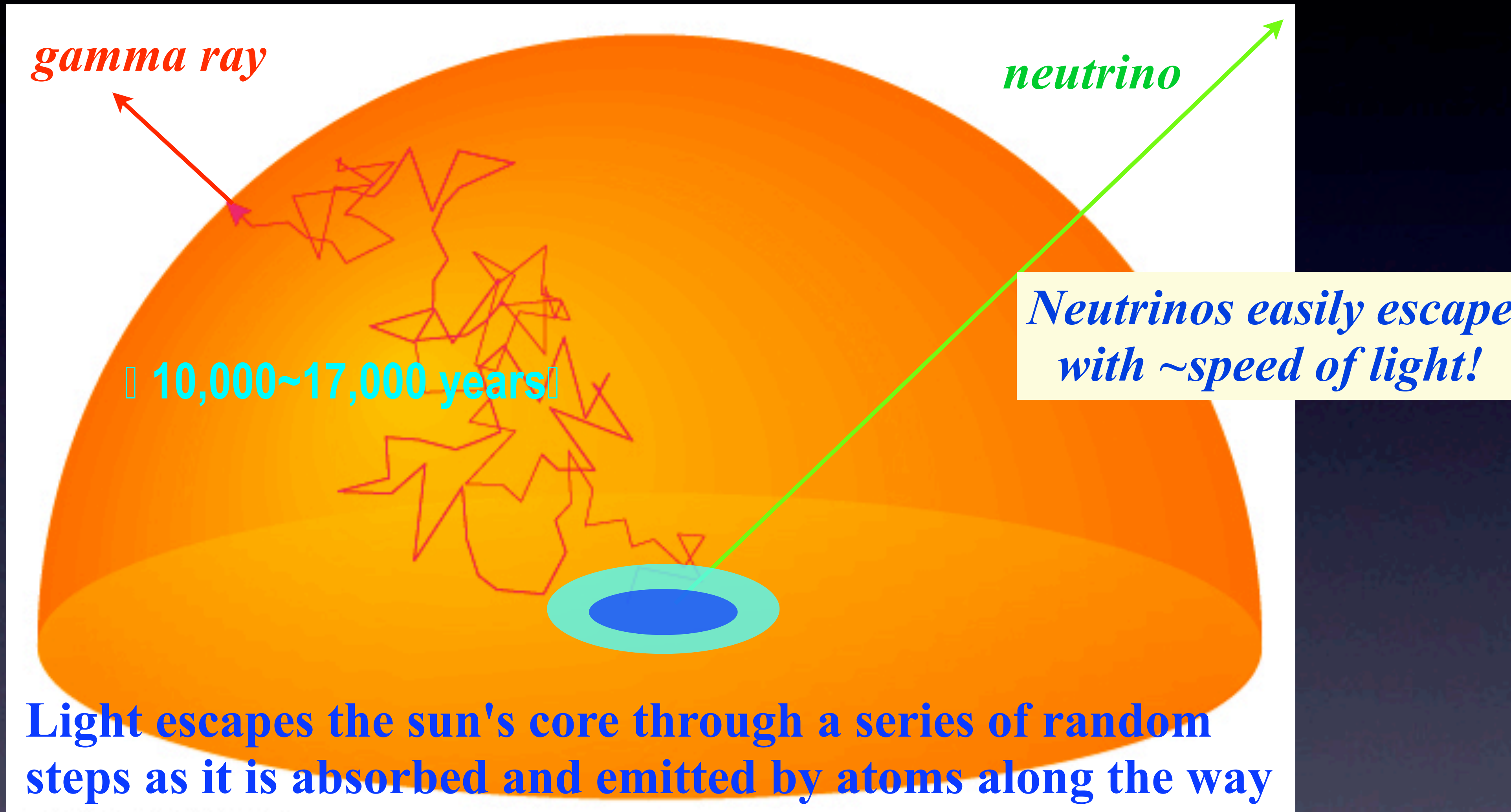
$$4p + 2e \rightarrow {}^4He + 2\nu_e + 26.7 \text{ MeV}$$

Only ν_e are produced in the pp chain



The energy output from *the core of the Sun* is in the form of gamma rays. There are transformed into visible and IR light by the time they reach the surface (after interacting with particles in the Sun).

The 8-minute travel time to Earth by sunlight hides more than a 10-thousand-year journey that actually began in the core.



Light escapes the sun's core through a series of random steps as it is absorbed and emitted by atoms along the way

太陽中微子是太陽核心之信息唯一的直接傳遞者!

To understand our universe
We must understand neutrinos

Neutrino Oscillations

中微子振盪

一種巨觀可測量的量子相關效應
證明中微子有質量

Solar Neutrino Problem 太陽中微子問題

Davis experiment

1960s~1994

- Raymond Davis used this tank of cleaning fluid (615 ton) C_2Cl_4
- Location: Homestake, SD, USA (1478 m underground)
- Operated for 3 decades between 1960s~1994
- $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ (E_ν>0.814 MeV) （氯→氬）
- Only ~1/3 of the expected number found (1968)

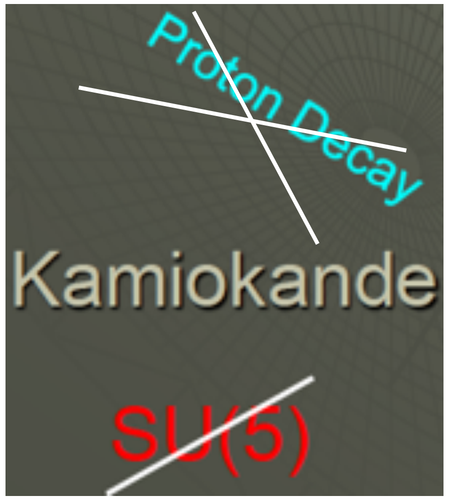
Solar Neutrino Deficit

Atmospheric Neutrino Problem 大氣中微子問題

Kamioka Nucleon Decay Experiment=Kamiokande

大統一場理論: SU(5)

Proton lifetime ~ 10^{29} yrs



Masatoshi Koshiba

1982~1995

- 3,000 tons of pure water
- 1,000 (50 cm diameter) PhotoMultiplier tubes (PMTs)

Solar Neutrinos: found the solar neutrino flux to be ~1/2 that predicted by solar models

Atmospheric neutrinos: indicated a deficit of muon neutrinos **Atmospheric Neutrino Deficit**

Supernova 1987A: observed 11 events from 160,000 light years away （大麥哲倫星云的超新星）

The Nobel Prize in Physics 2002

One half jointly to Raymond Davis Jr. and Masatoshi Koshiba "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos" and the other half to Riccardo Giacconi "for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources".

太陽中微子

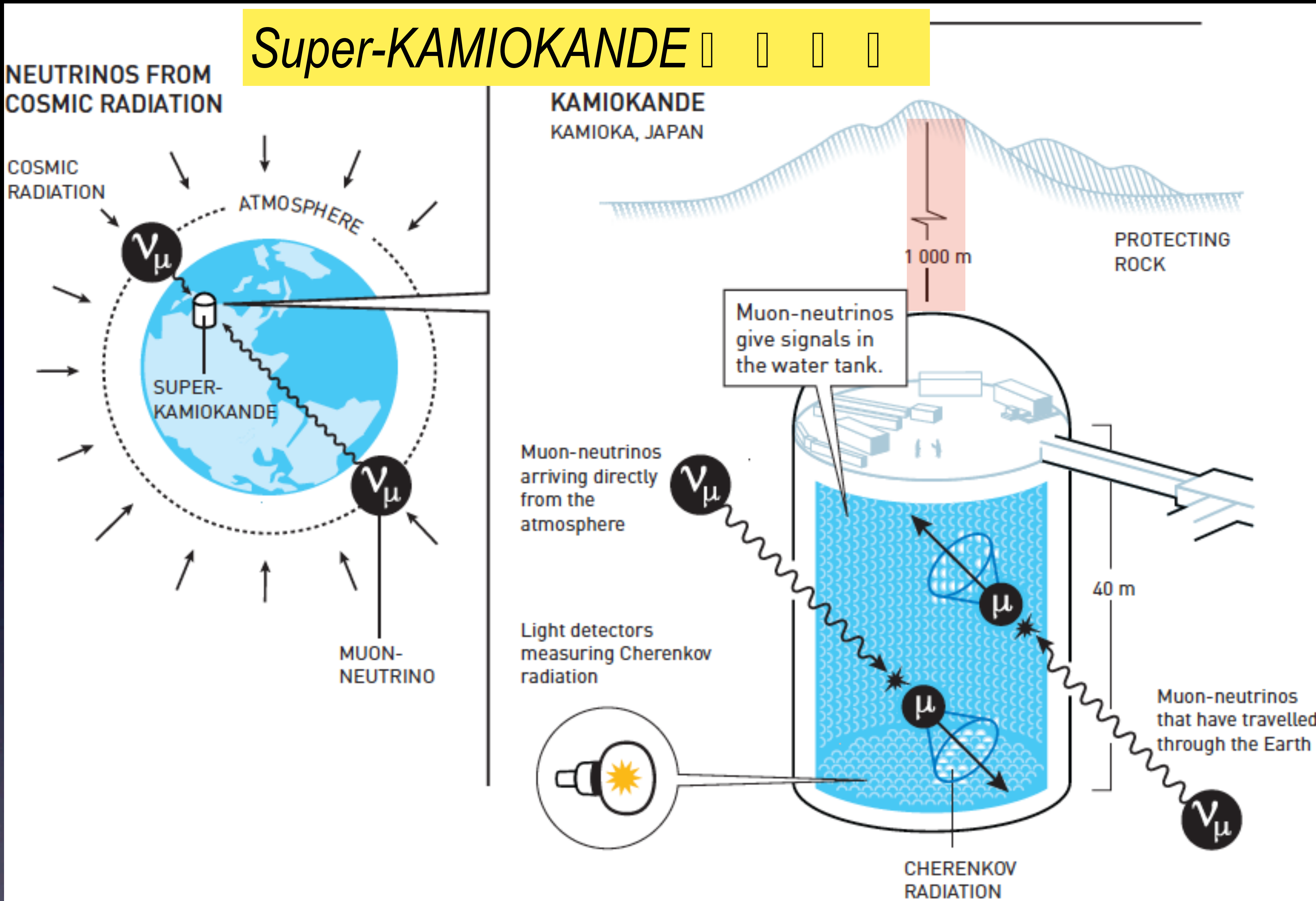
超新星中微子

Raymond Davis Jr.
1914－2006

Masatoshi Koshiba
1926－

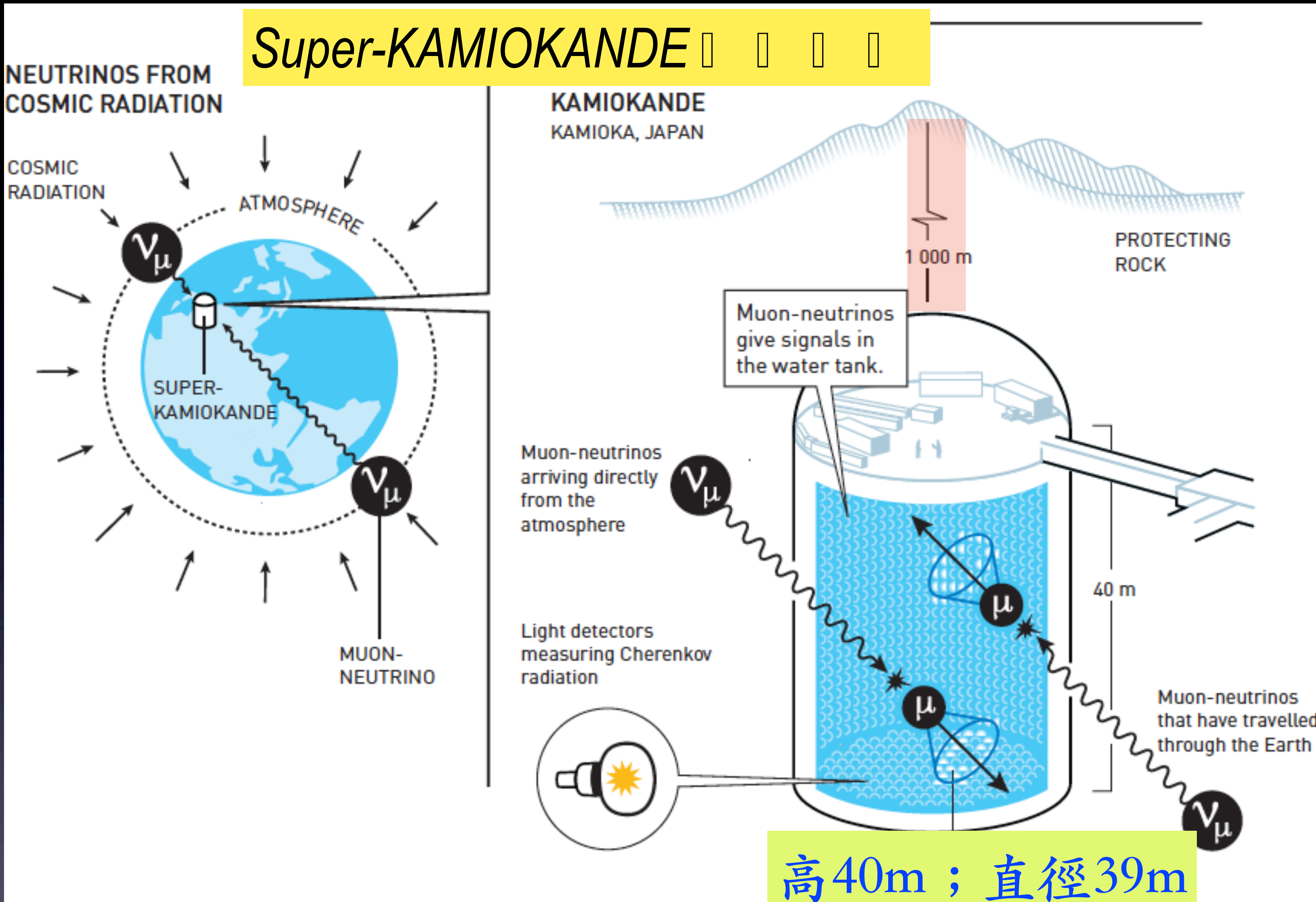
Riccardo Giacconi

Super-KAMIOKANDE



Super-Kamiokande is a gigantic detector built 1,000 metres below the Earth's surface. It consists of a tank, 40 metres high and as wide, filled with 50,000 tonnes of water. The water is so pure that light beams can travel 70 metres before their intensity is halved, compared to just a few metres in an ordinary swimming pool. More than 11,000 light detectors are located in the tank's top, sides and bottom, with the task to discover, amplify and measure very weak light flashes in the ultra-pure water.

Super-KAMIOKANDE



高40m；直徑39m

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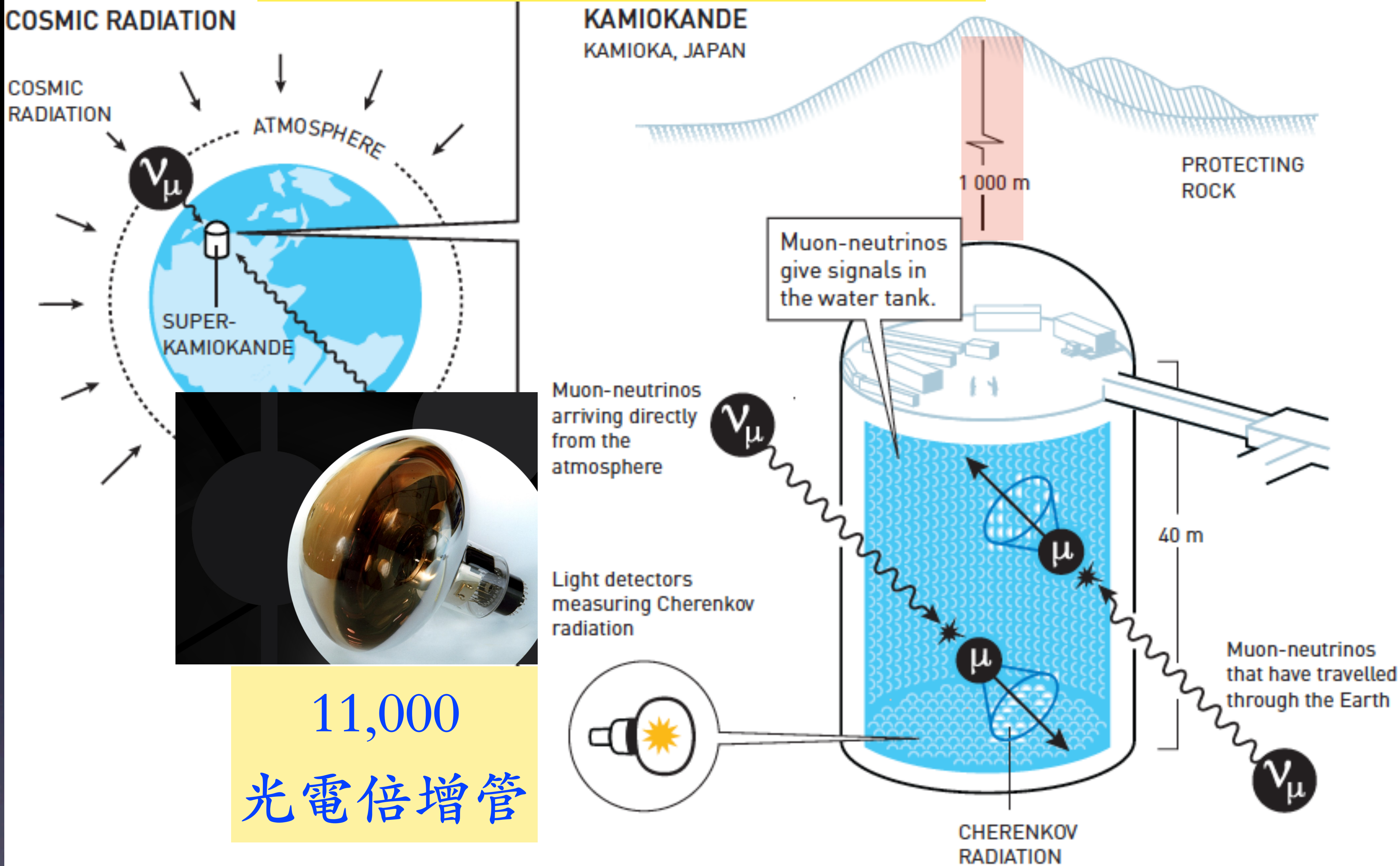

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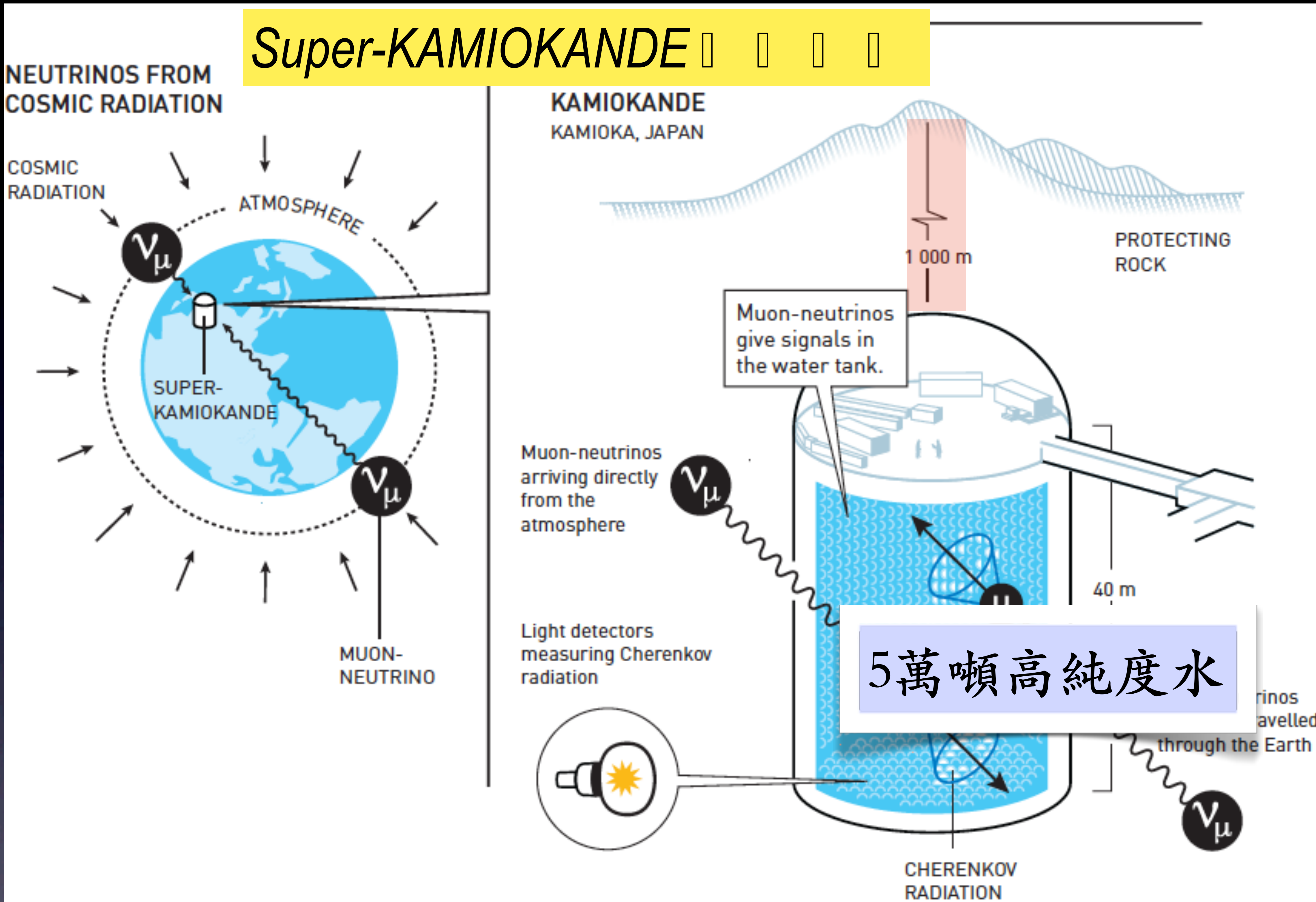

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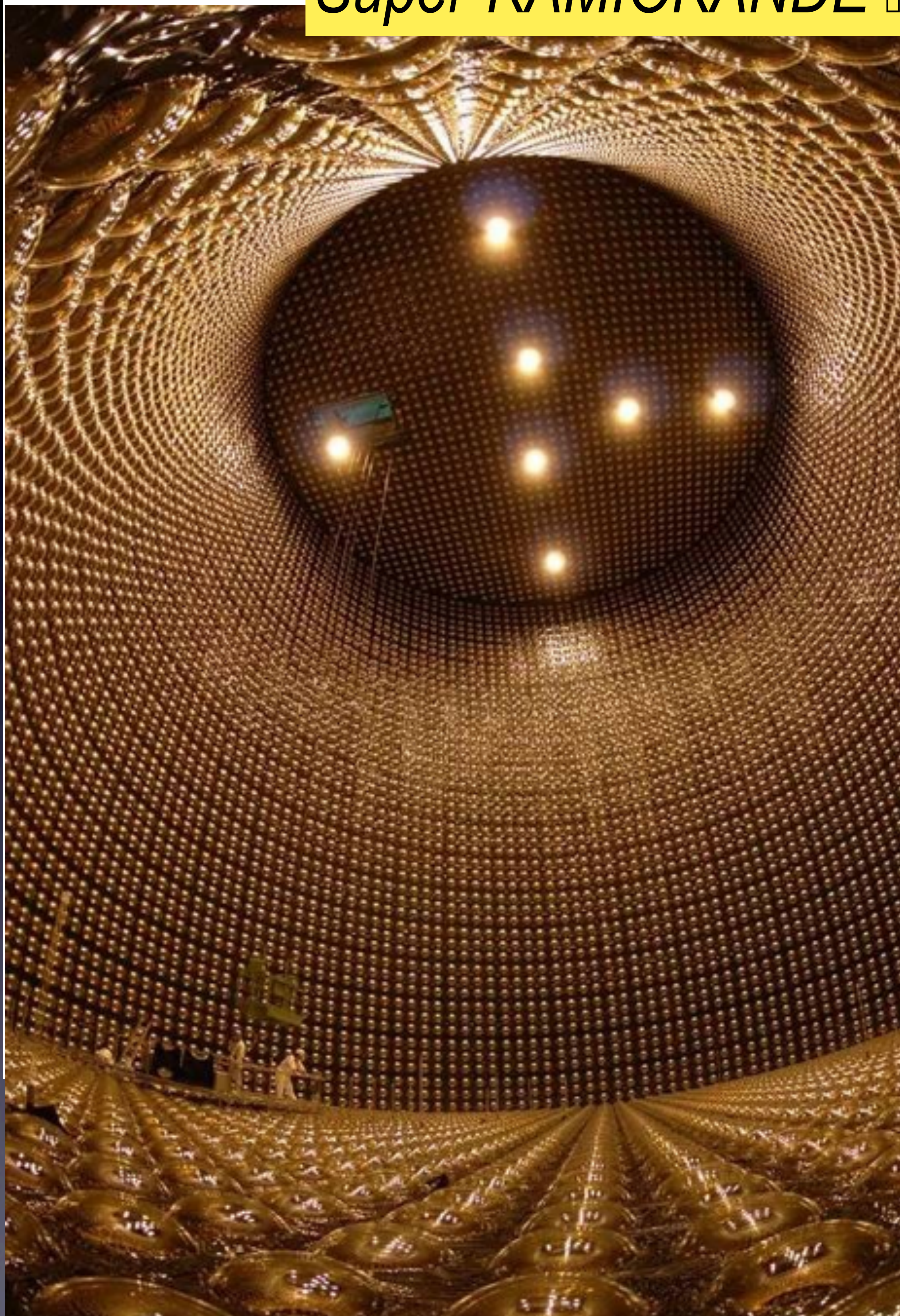

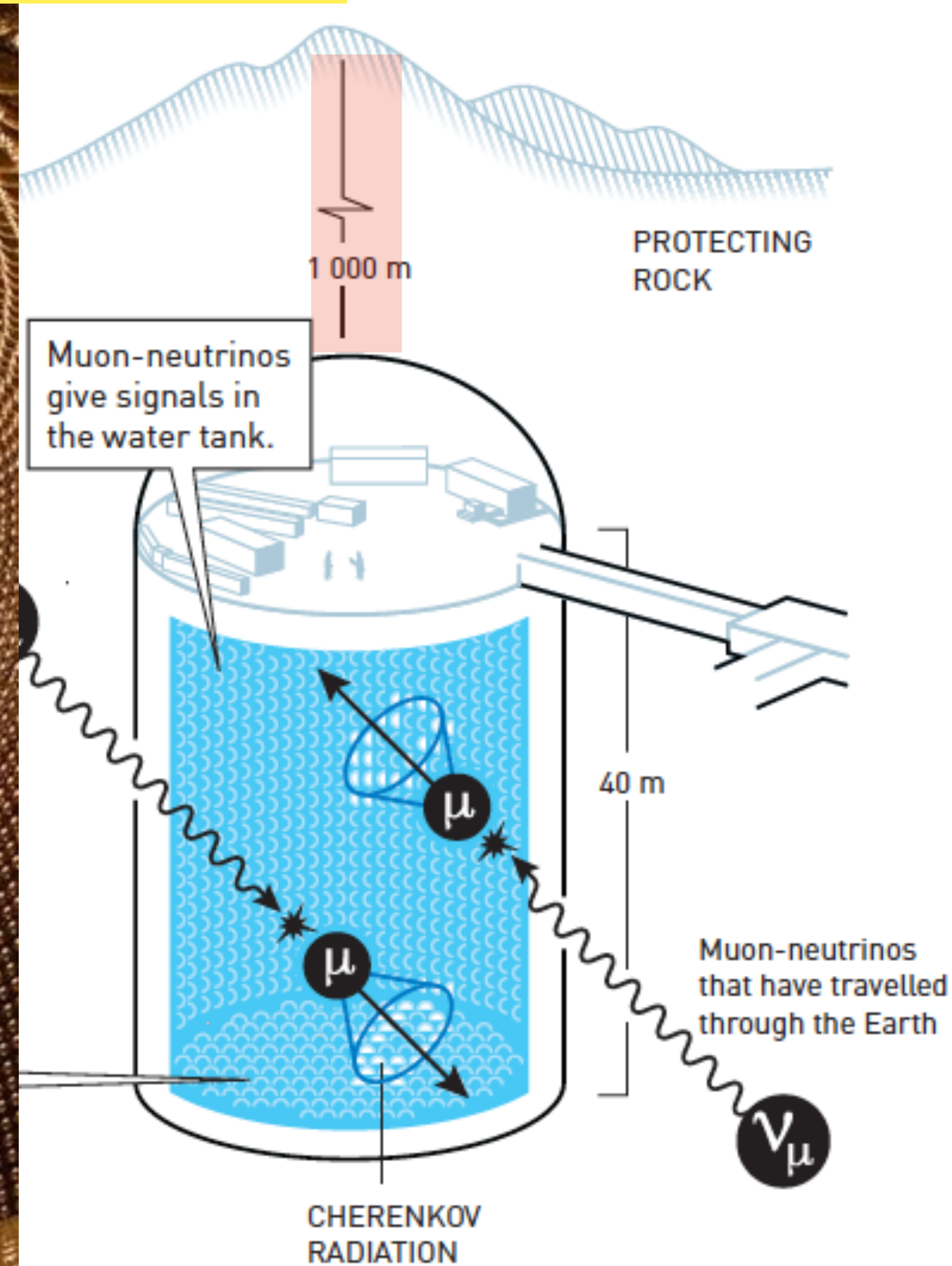

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water. The water is so pure that light beams can
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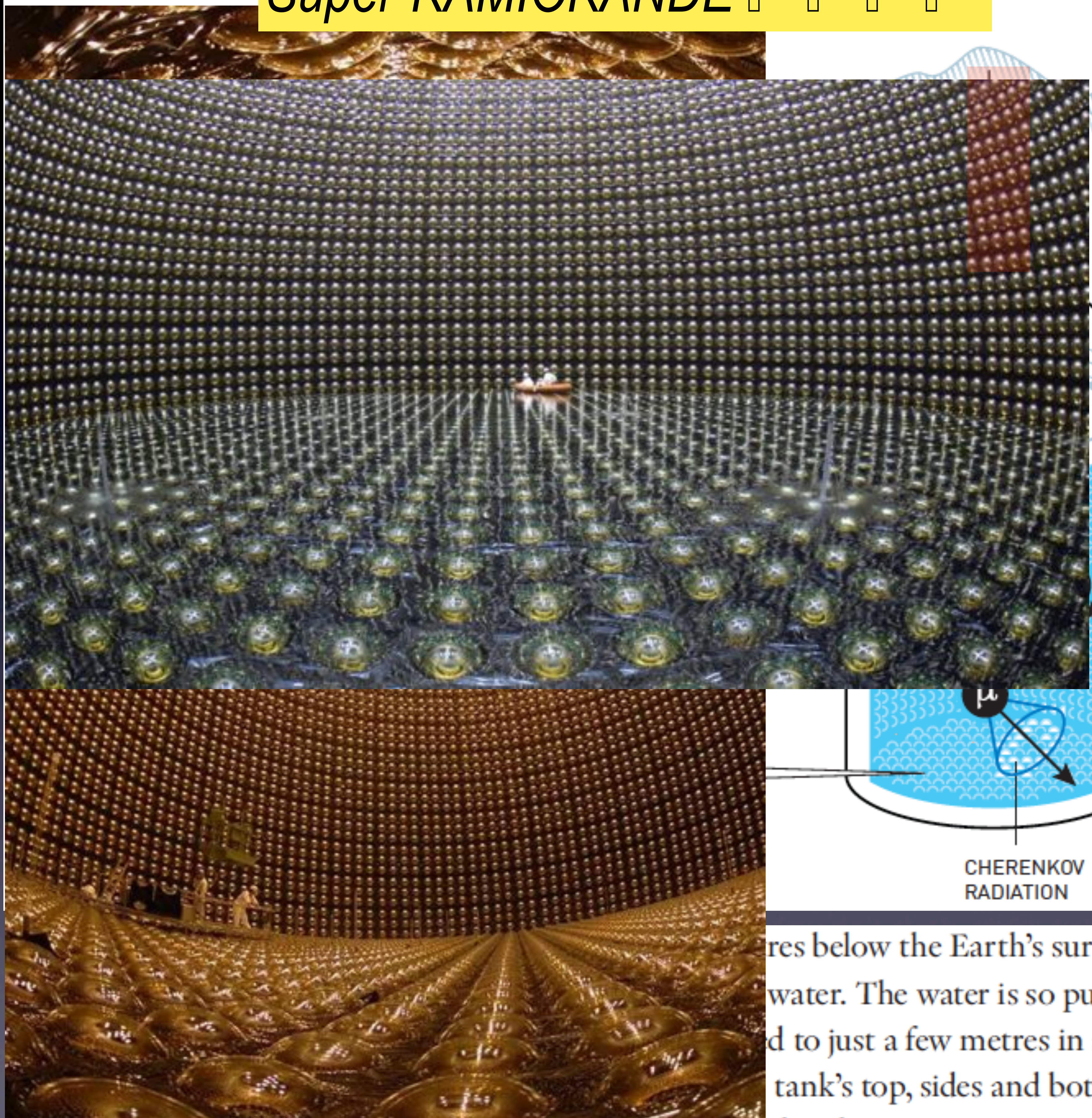

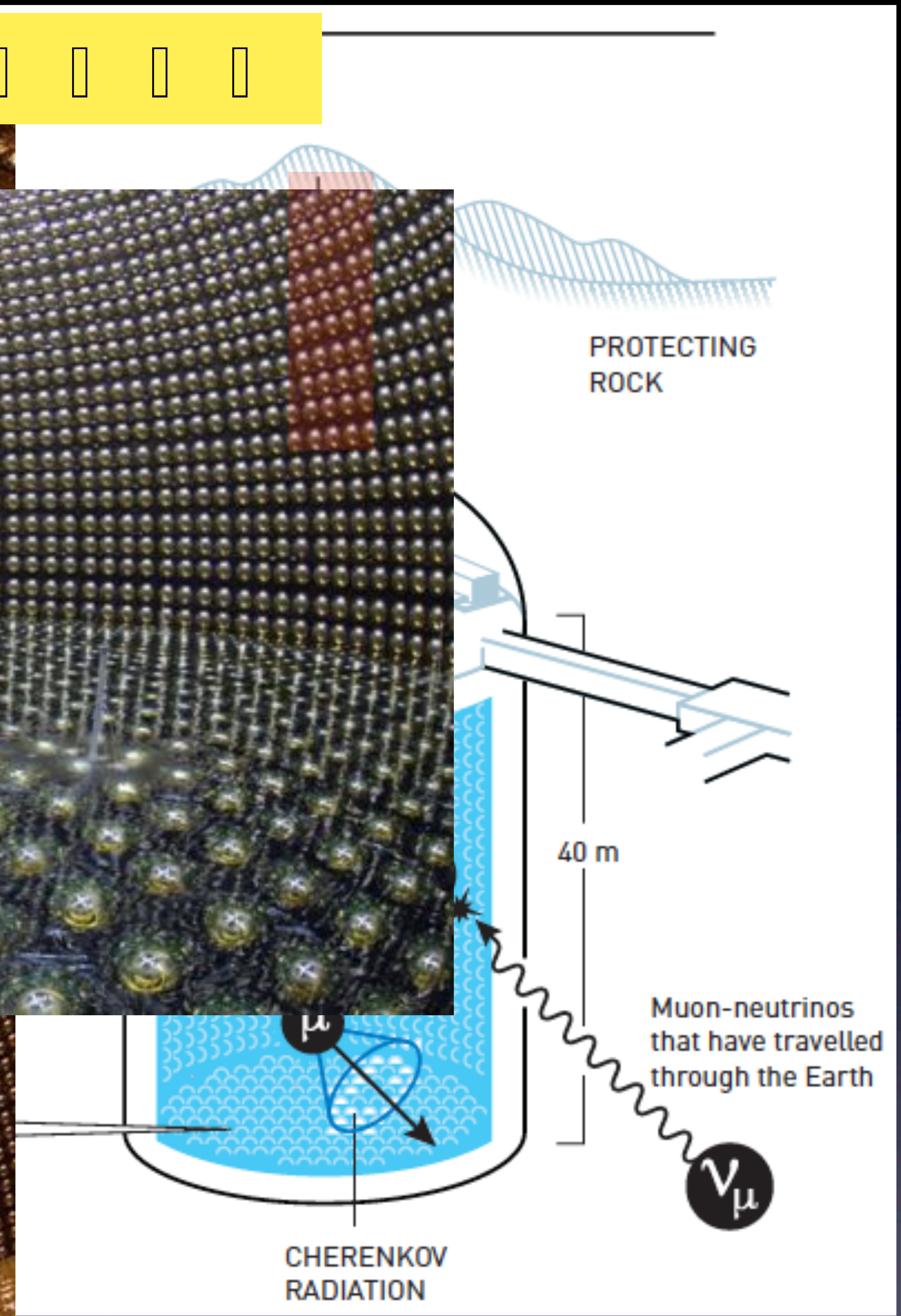

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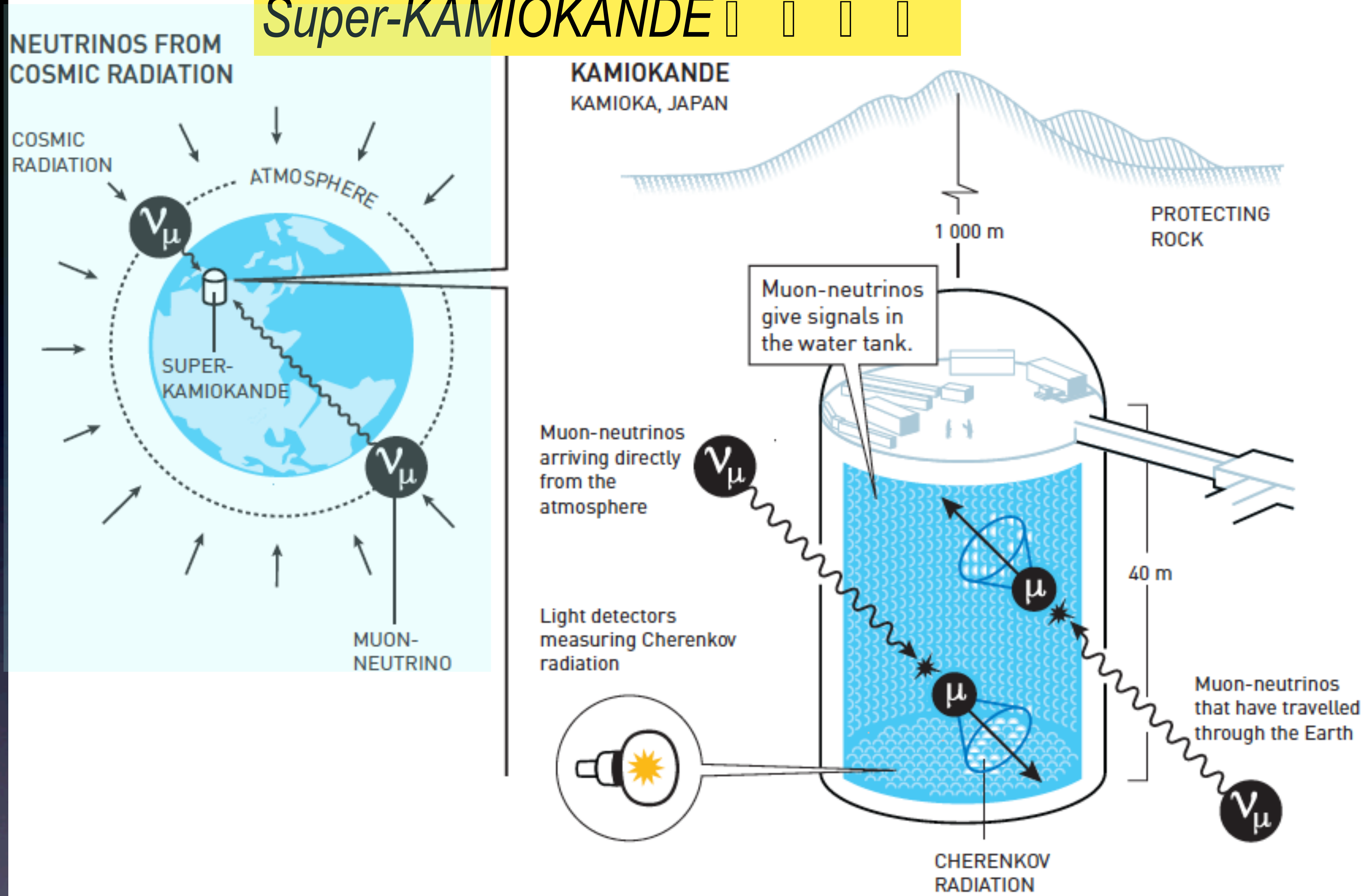

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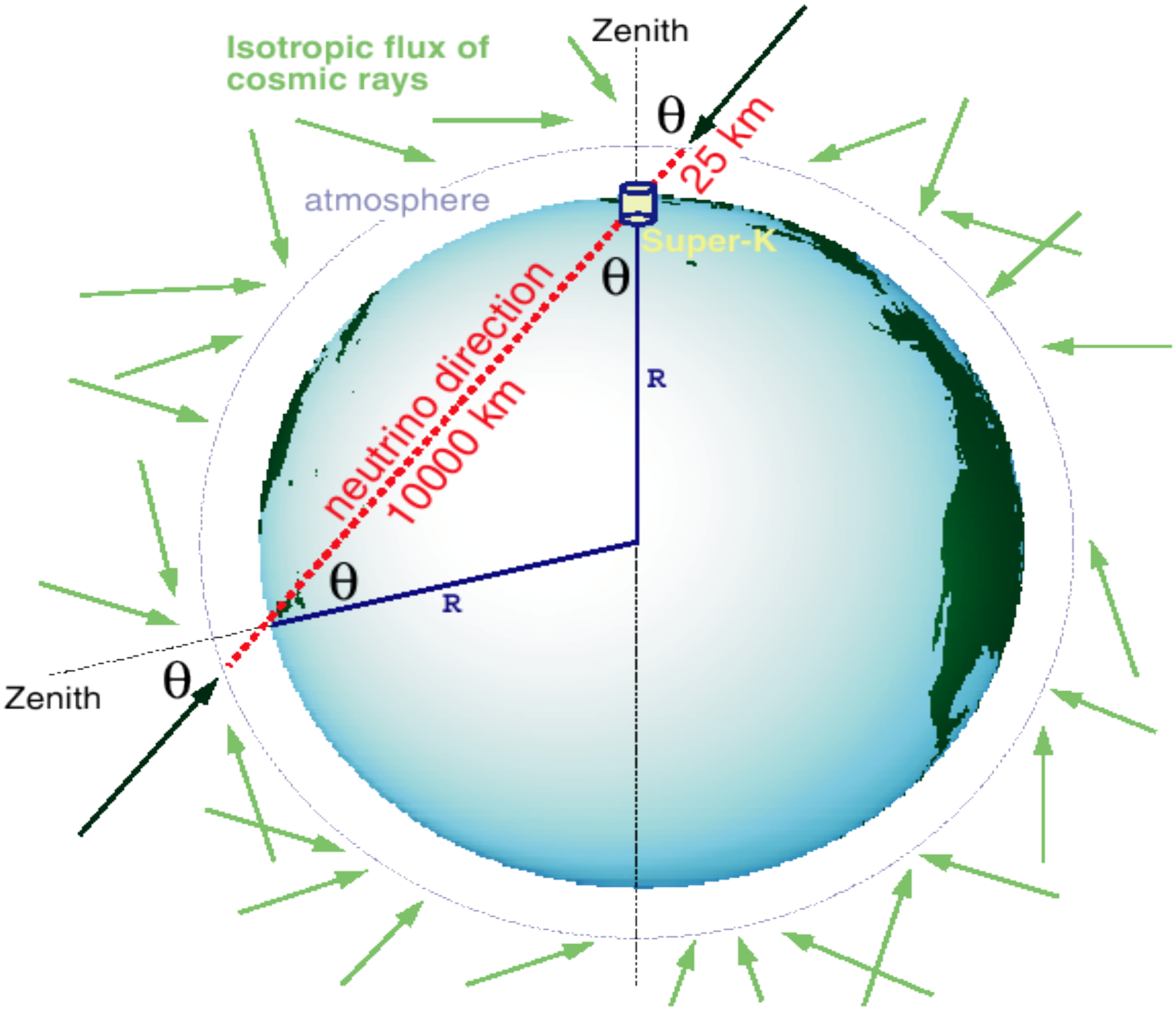

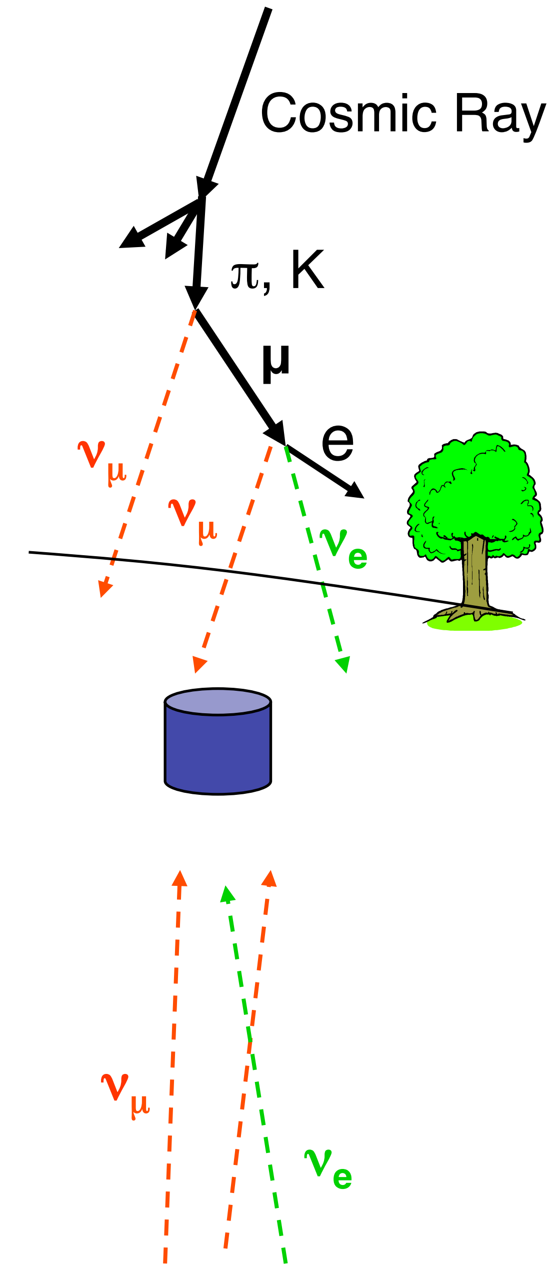

Cosmic rays come from all directions at the same rate.
So atmospheric neutrinos are produced all around the earth at the same rate.

But Number (ν_μ Up) / Number (ν_μ Down) = 1/2.

$\nu_\mu \rightarrow \nu_\tau$

Half the ν_μ that travel to the detector from the far side of the earth disappear!

Who is Super-K?

T. Kajita 第二任掌門人

Y. Suzuki 目前掌門人

Y. Totsuka 第一任掌門人

~140位科學家

~35個研究所

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J. Kameda, K. Kaneyuki, K. Kobayashi, Y. Koshio, M. Miura,
S. Moriyama, M. Nakahata, S. Nakayama, T. Namba,
Y. Obayashi, A. Okada, K. Okumura, N. Sakurai,
M. Shiozawa, Y. Suzuki, H. Takeuchi,
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W. Wang,

Brookhaven National Laboratory
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D.W. Liu, S. Mine, M. Smy, H.W. Sobel, M.R. Vagins

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University of Maryland
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D. Turcan

University of Minnesota Duluth
A. Habig

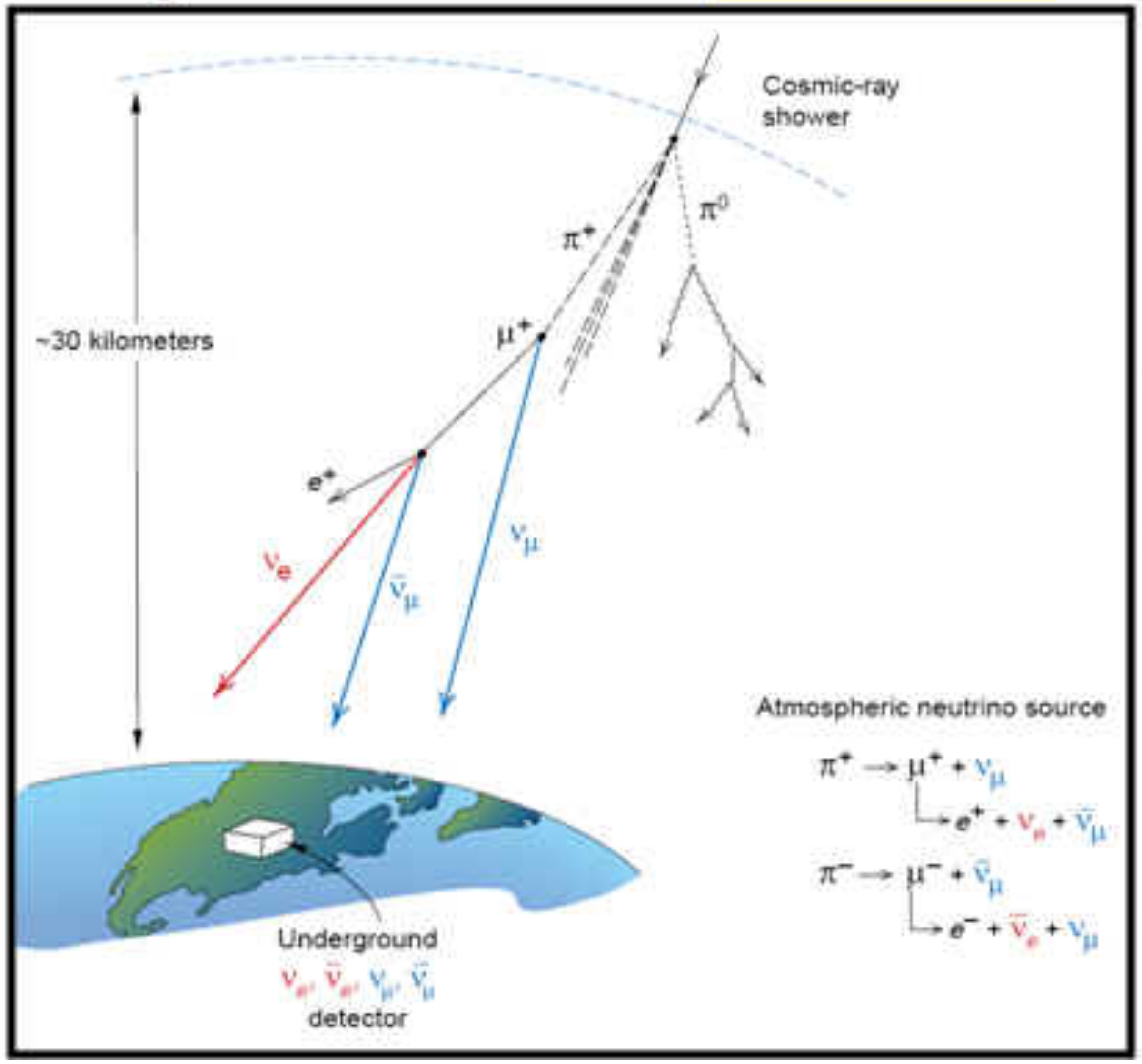
State University of New York, Stony Brook
J. Hill, C.K. Jung, K. Martens, M. Malek, C. Mauger,
C. McGrew, E. Sharkey, B. Viren, C. Yanagisawa

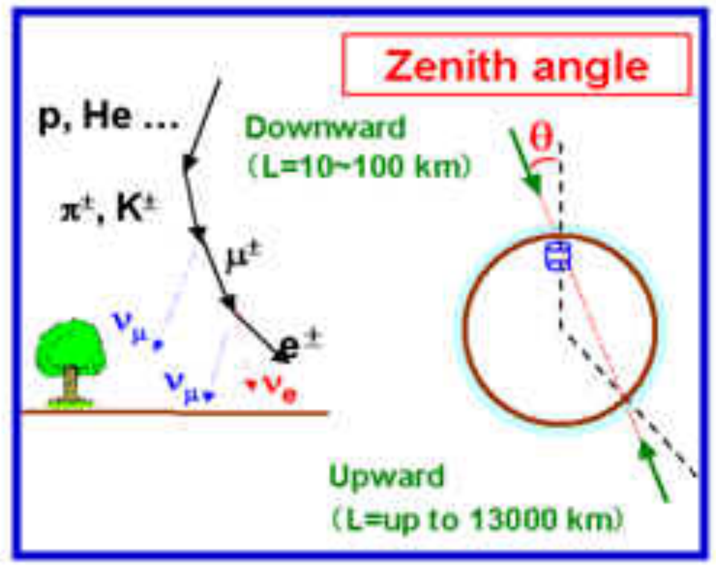
University of Warsaw
D. Kielczewska, U. Golebiewska

University of Washington
S.C. Boyd, A.L. Stachyra, R.J. Wilkes, K.K. Young

Department of Physics, Seoul National University
H.I. Kim, S.B. Kim, J. Yoo

Atmospheric muon neutrino deficit was firmly established at Super-Kamiokande (Y. Totsuka & T. Kajita 1998).





Yoji Totsuka (1942-2008)

當時SuperK
的掌門人

Their doctoral advisor:

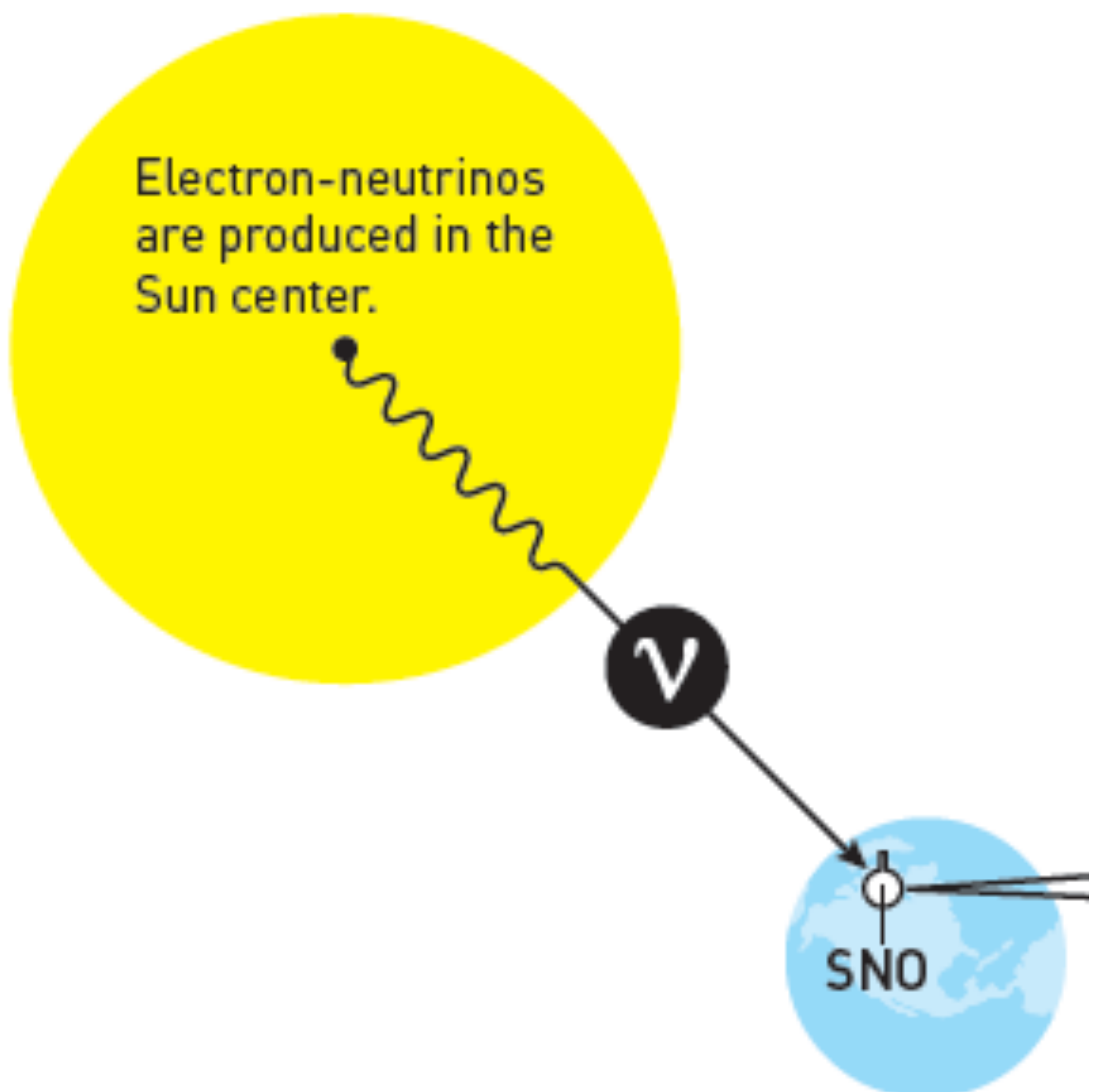
M. Koshiba (Nobel 2002)

``if Totsuka can extend his lifespan by eighteen months, he must receive the Nobel prize."

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	ongoing

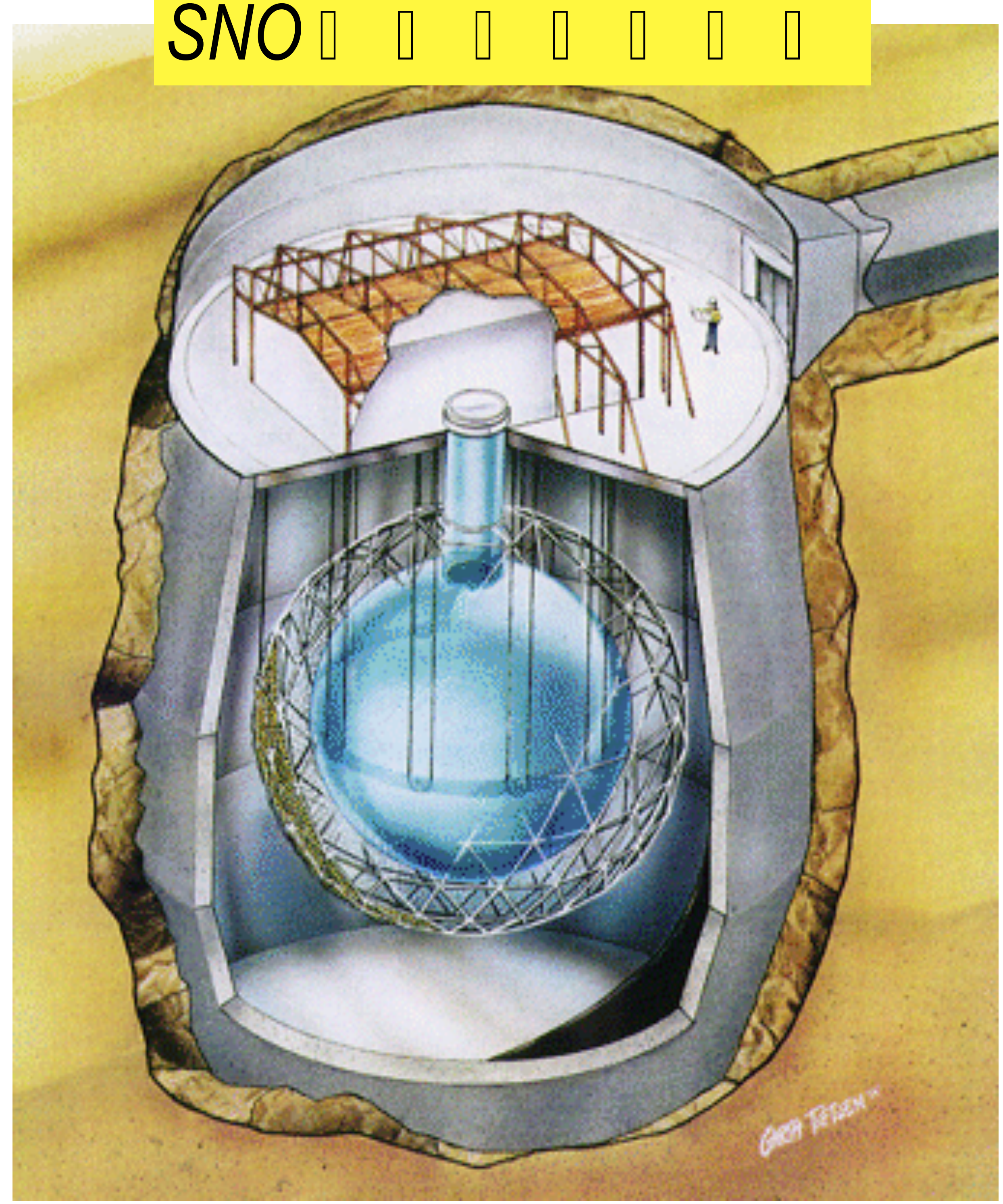
SK-I (1996-2001) — accident (2001) — SK-II (2003-2005) — SK-III (2006-2008)

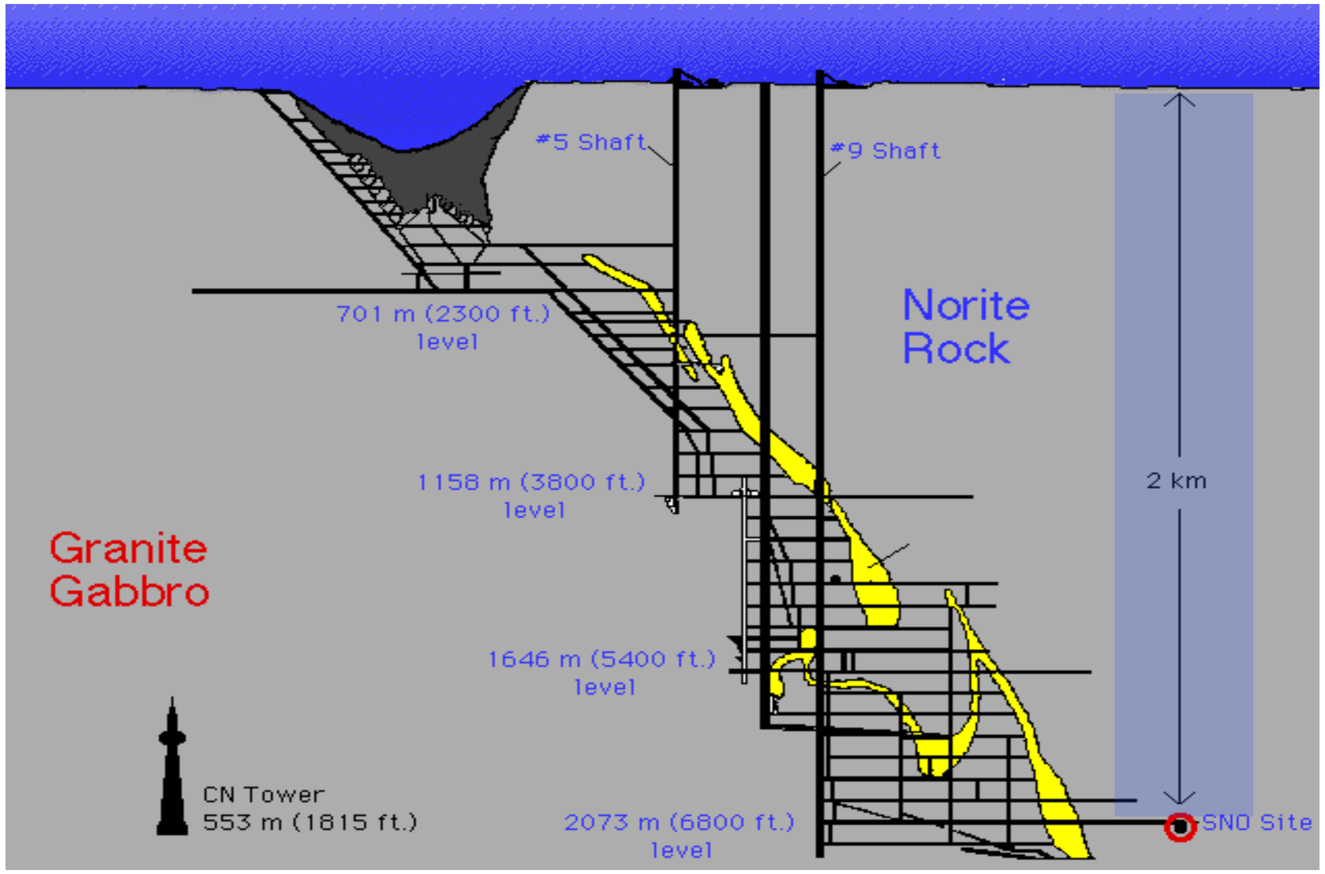
NEUTRINOS FROM THE SUN



Sudbury Neutrino Observatory

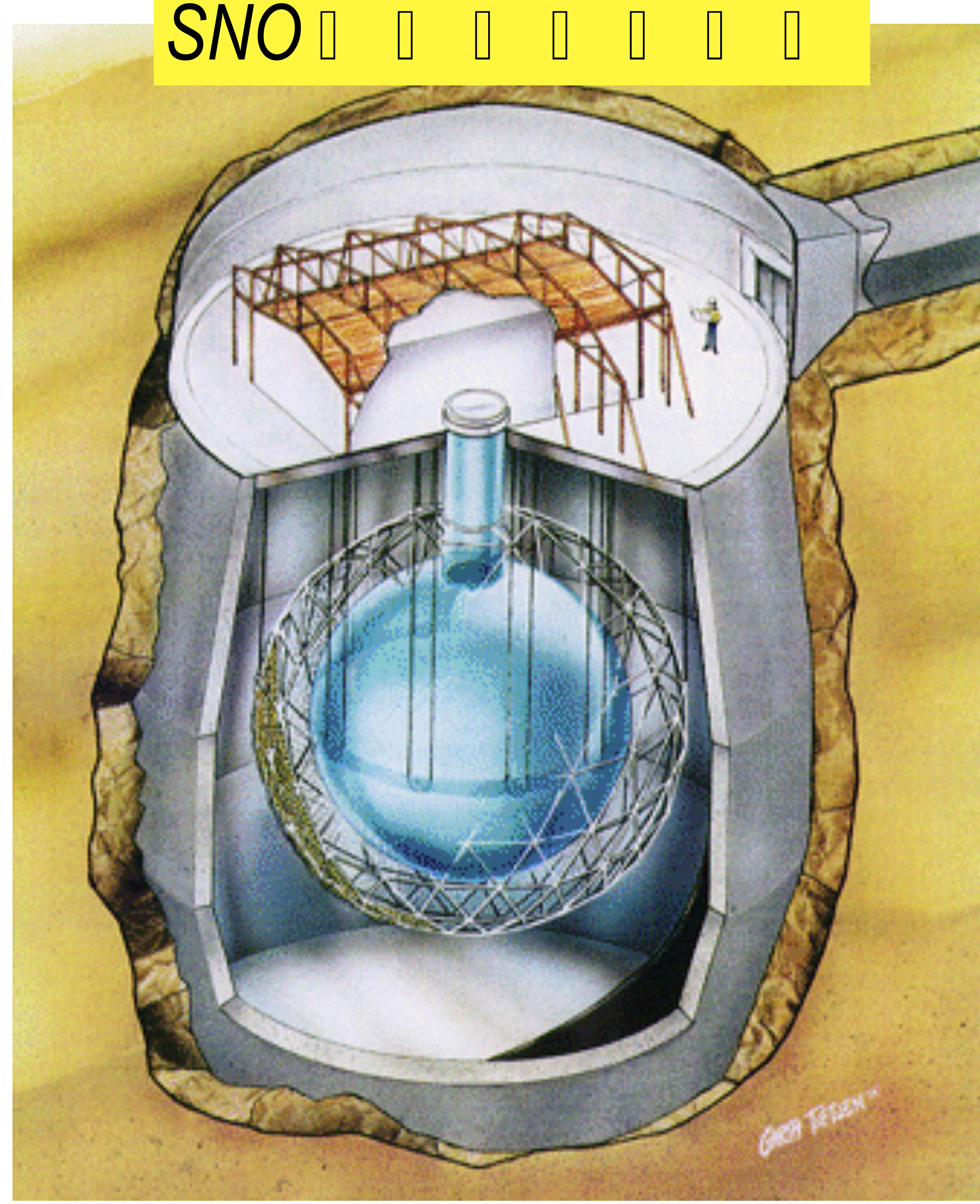
SNO





Sudbury
Neutrino
Observatory

SNO



1000 tonnes D_2O

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs
(~60% photocathode coverage)

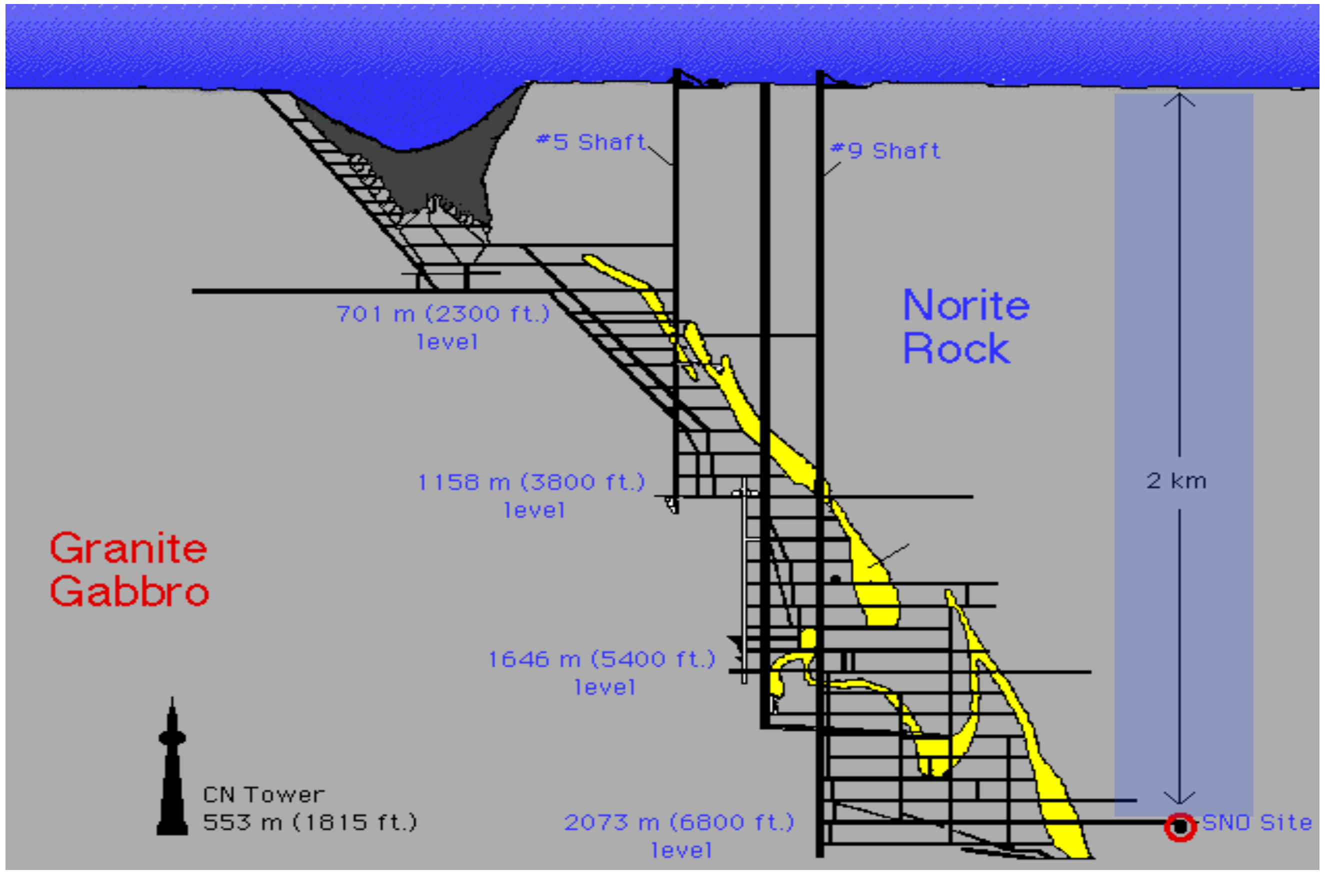
1700 tonnes inner shielding H_2O

5300 tonnes outer shielding H_2O

Urylon liner radon seal

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

Sudbury Neutrino Observatory



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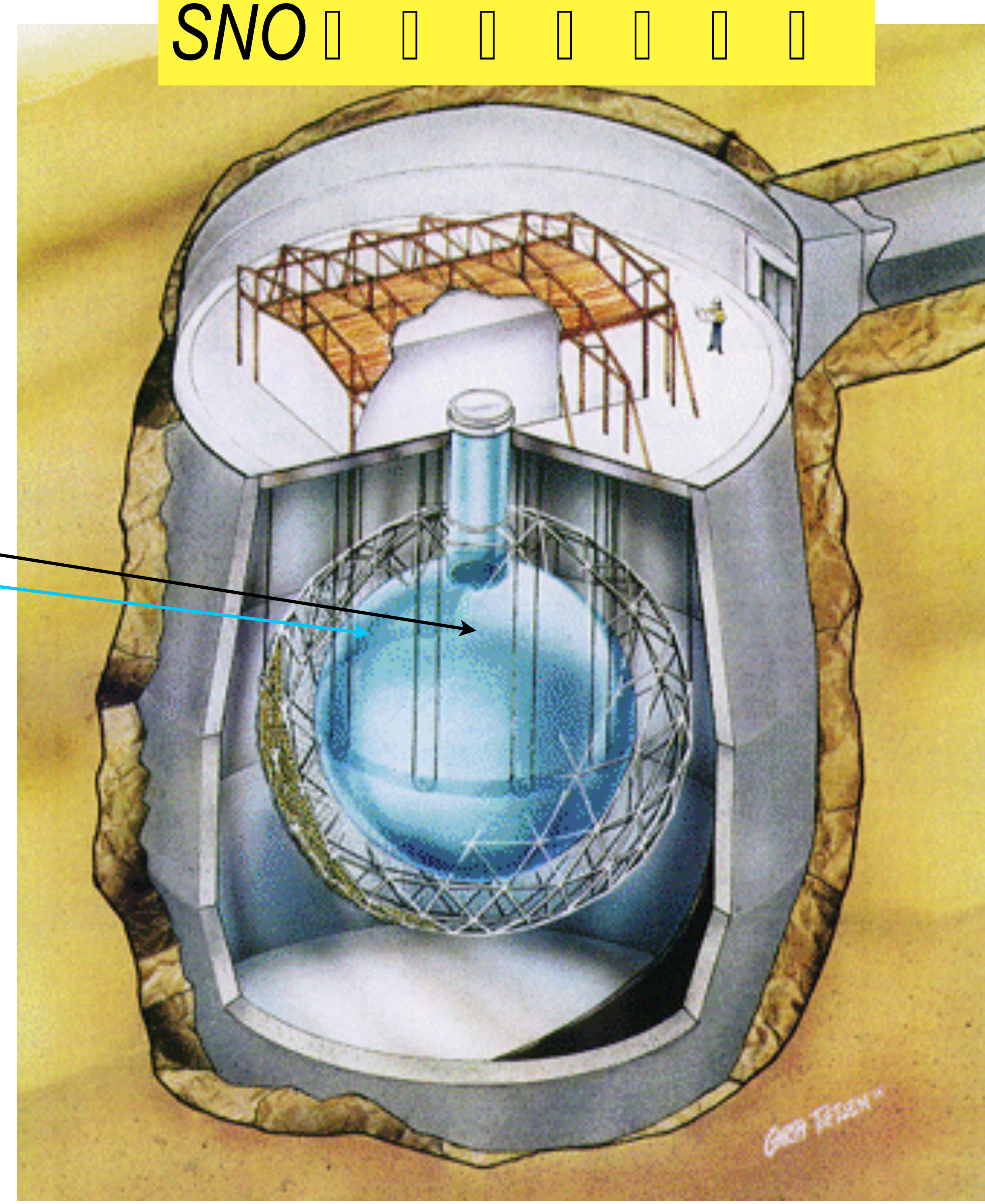

1000噸重水 D_2O

直徑12米的有機玻璃容器

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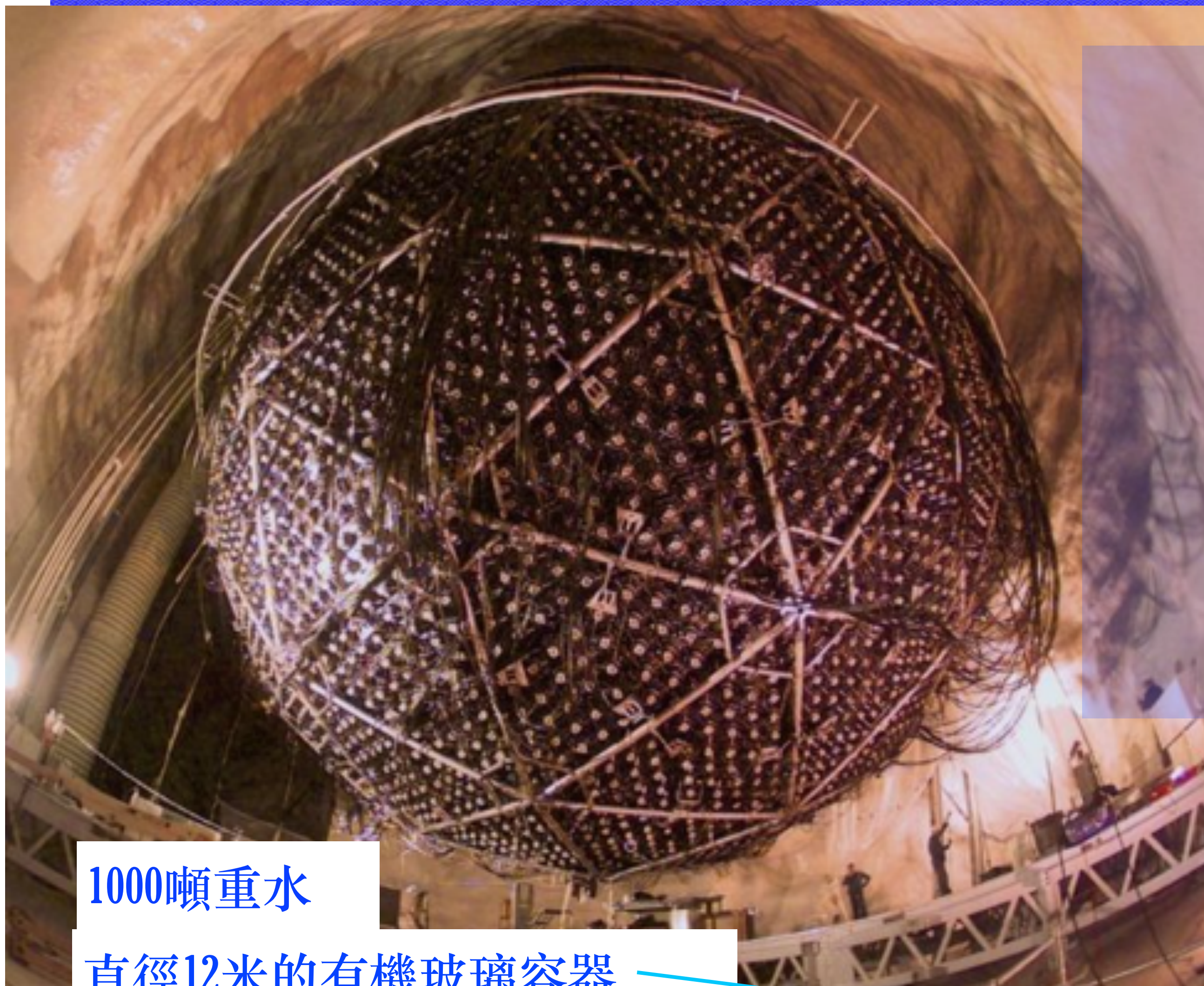

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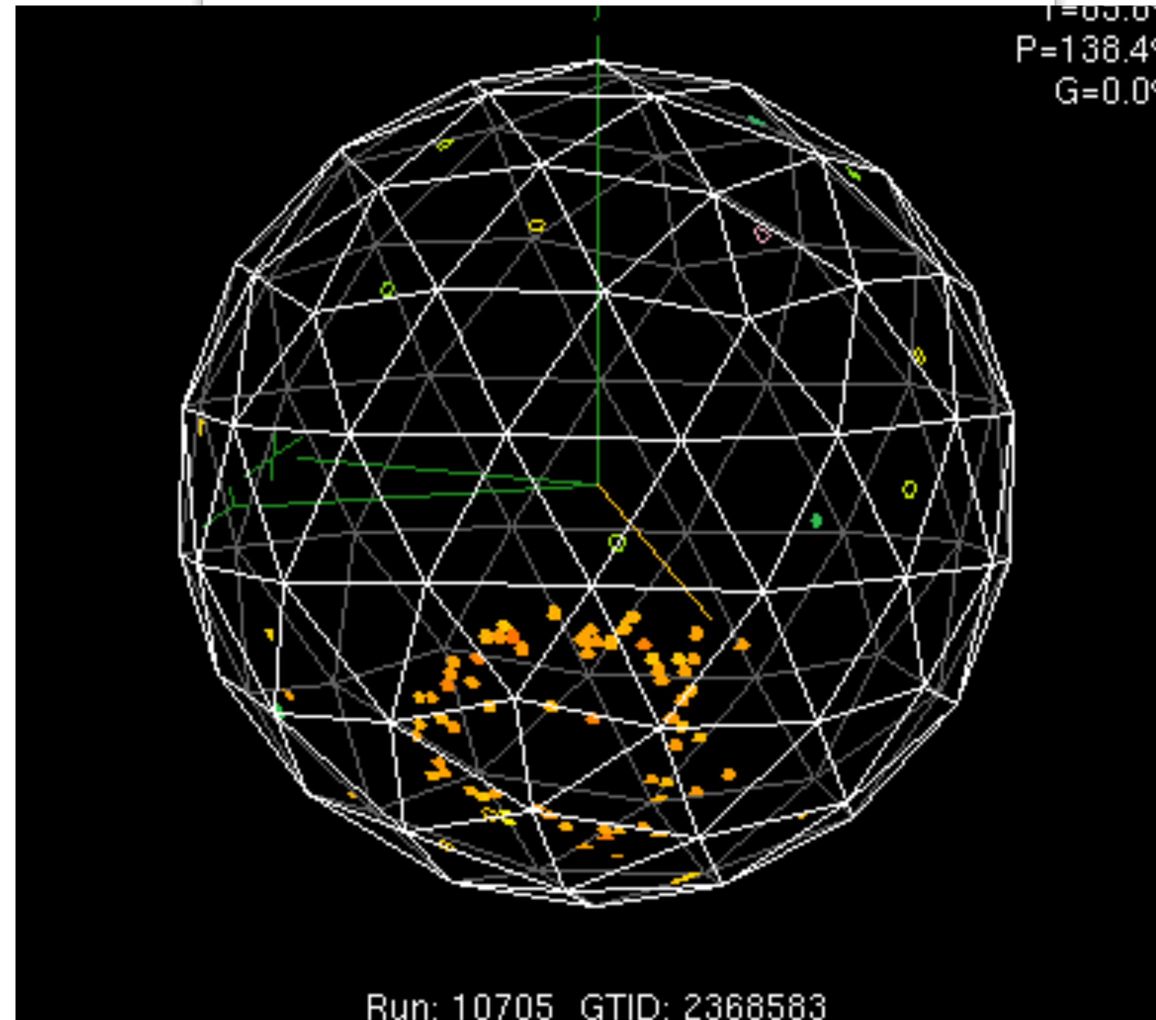

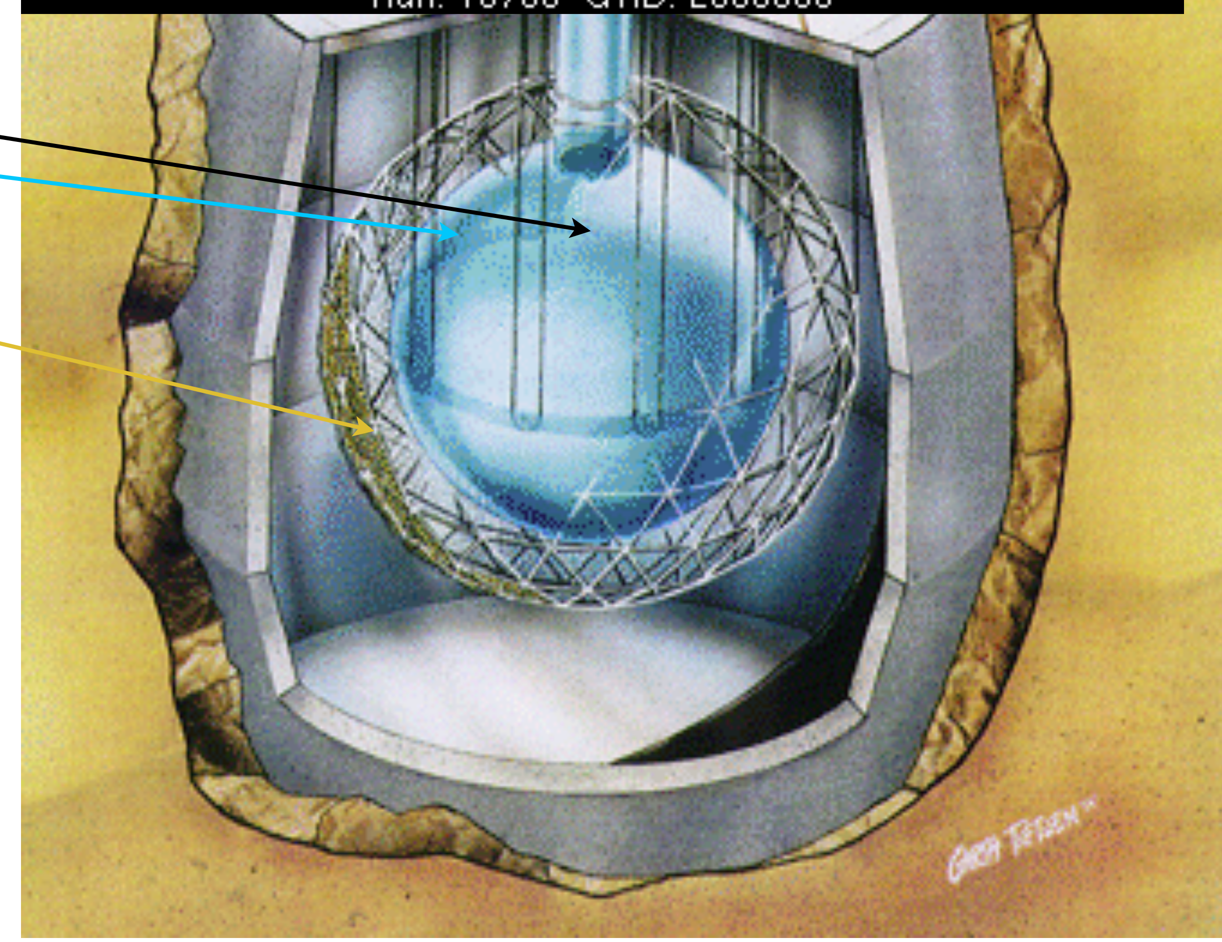

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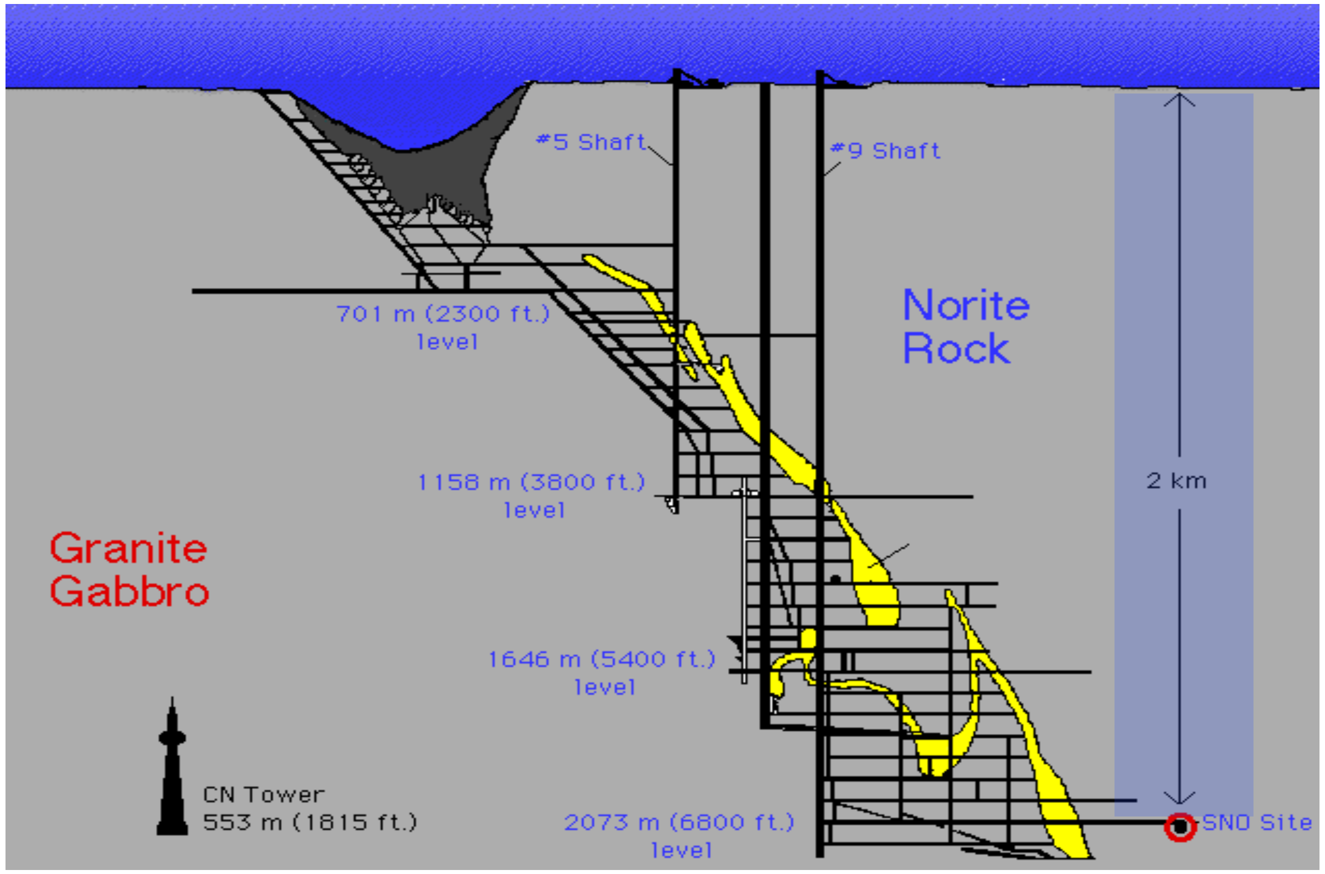

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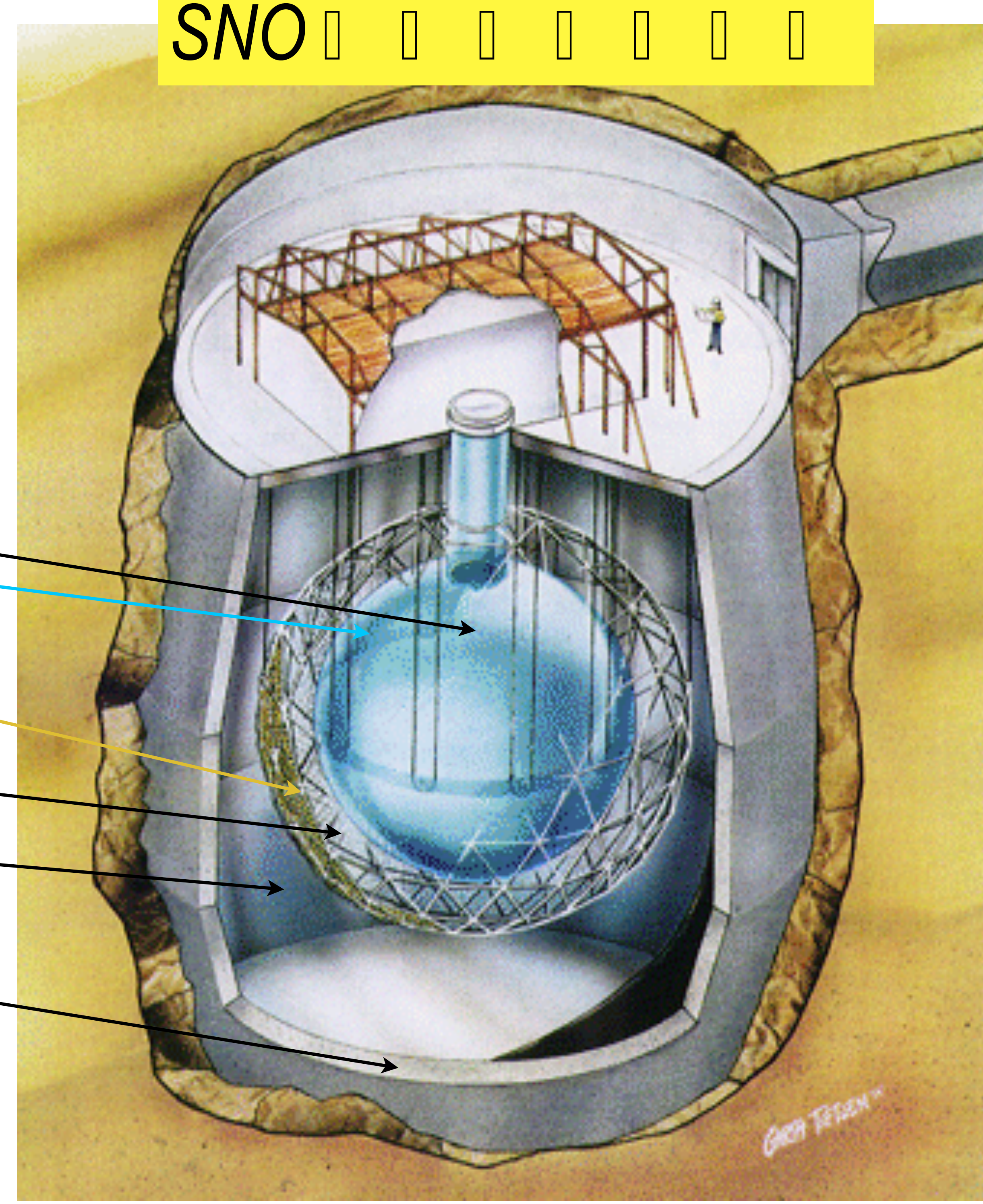

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The SNO Collaboration

May 1999 – Nov. 2006

S. Gil, J. Heise, R.L. Helmer, R.J. Komar, T. Kutter,
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J.V. Germani, A. A. Hamian, R. Hazama, K. M. Heeger, M. A. Howe,
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T. D. Steiger, L. C. Stonehill, B. L. Wall, J. F. Wilkerson.
University of Washington

1st spokesman from the US side

G. Milton, B. Sur, AECL, Chalk River

*deceased

~238位科學家

~18個研究所

加州大學爾灣分校的華人物理學家陳華森

1942-1987

VOLUME 55, NUMBER 14 PHYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

Direct Approach to Resolve the Solar-Neutrino Problem

PRL 55, 1534 (1985)

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

An experiment which directly addresses the solar neutrino problem should be sensitive to all neutrino species equally. Such a measurement could determine the *total solar neutrino flux* even if neutrinos oscillate.

SNO detects solar neutrinos in several different ways.

加州大學爾灣分校的華人物理學家陳華森 1942-1987

VOLUME 55, HYSICAL REVIEW LETTERS 30 SEPTEMBER 1985

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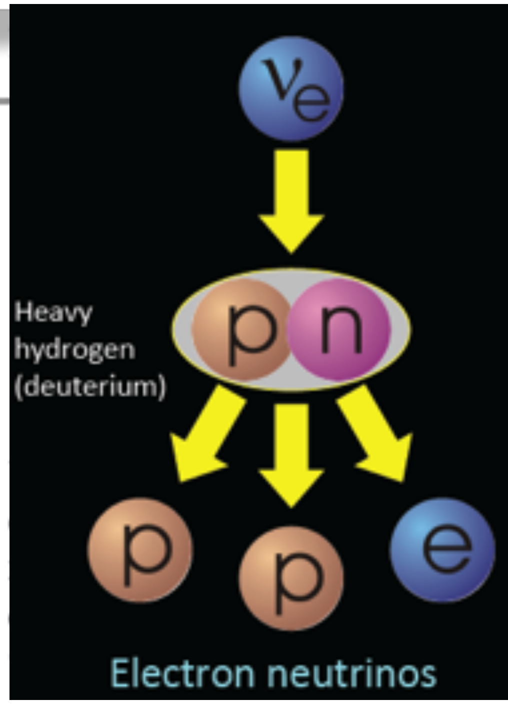

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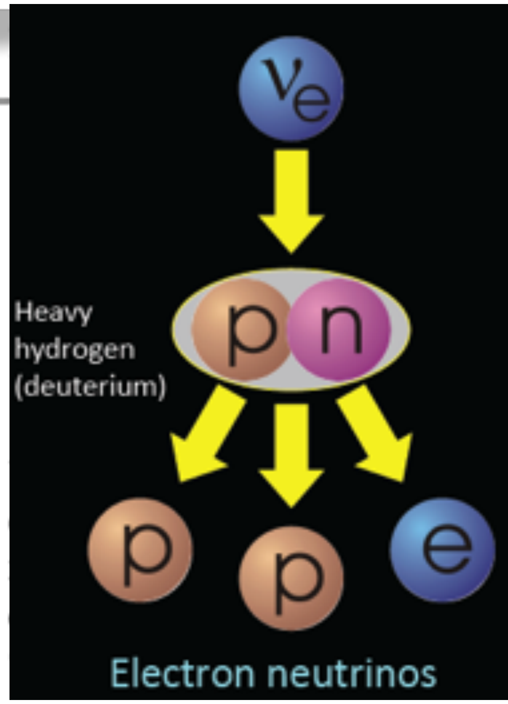

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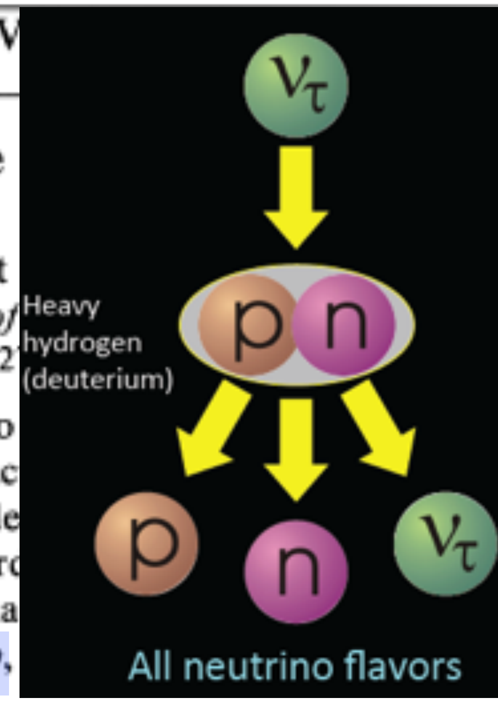

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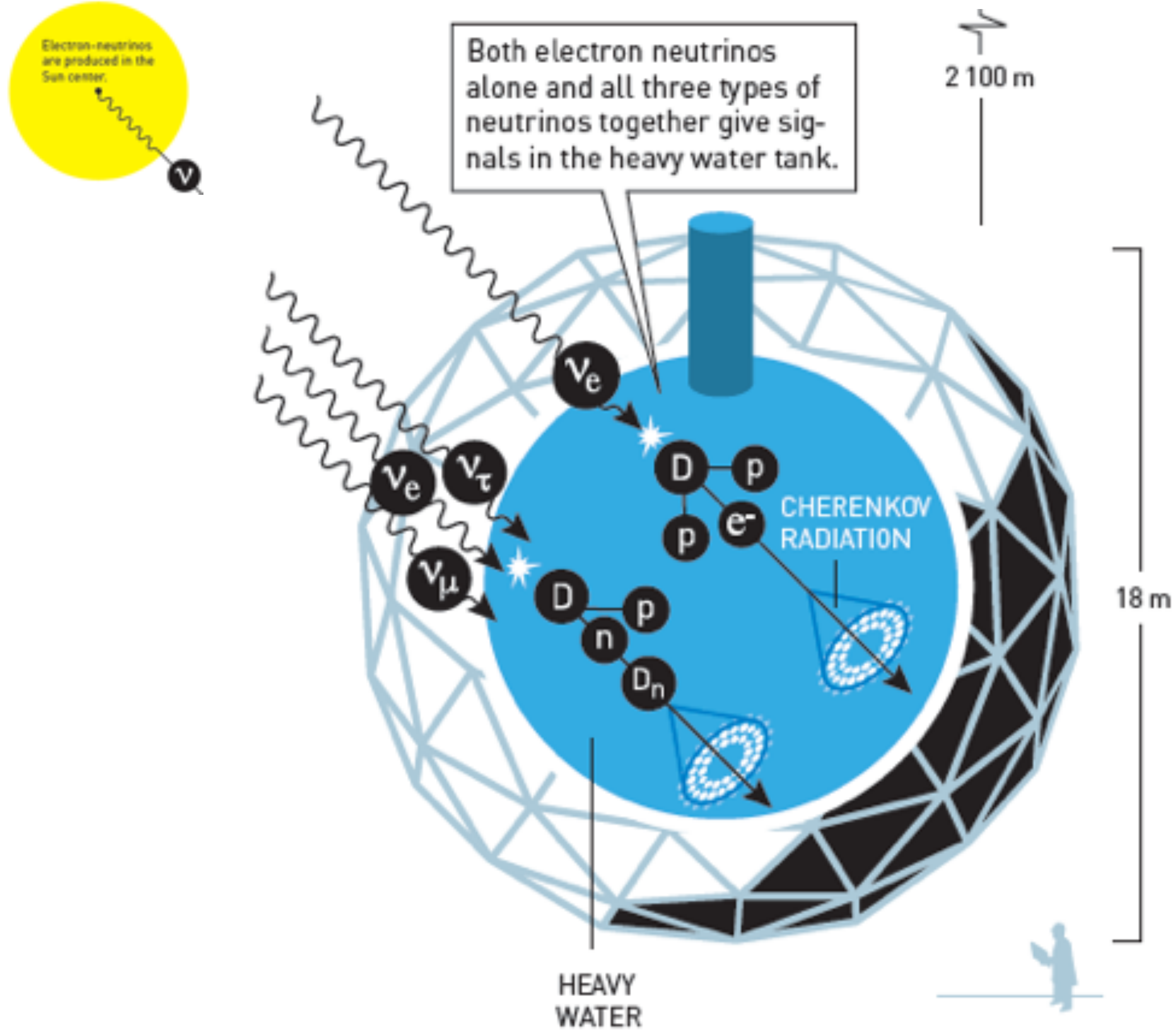

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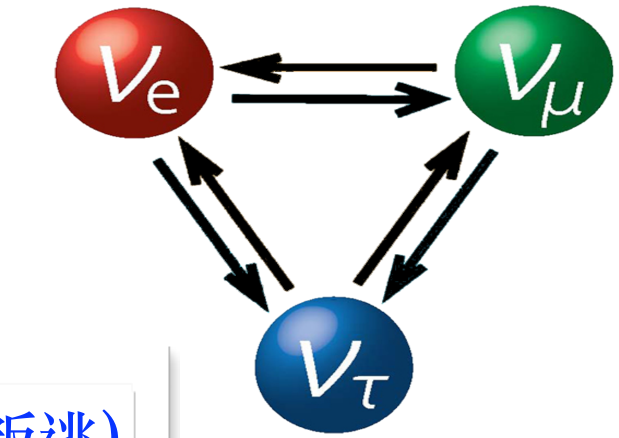
$$\text{SNO:} \quad \frac{\text{Number}(\nu_e)}{\text{Number}(\nu_e) + \text{Number}(\nu_\mu) + \text{Number}(\nu_\tau)} = \mathbf{1/3}$$

All the solar neutrinos are born as ν_e

But 2/3 of them morph into ν_μ or ν_τ → **Solar Neutrino Problem**

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)

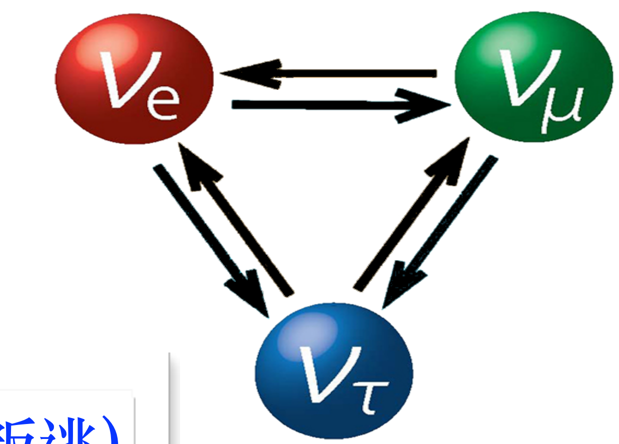
The Atlantic

SCIENCE

The Communist Spy (Maybe) Behind This Year's Nobel Prize in Physics

How neutrino research stems from—and validates—a physicist who defected to the Soviet Union in the 1950s

Solution to Solar and Atmospheric Neutrino Problems



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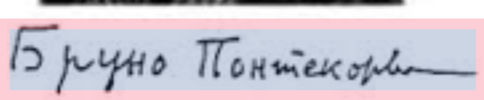
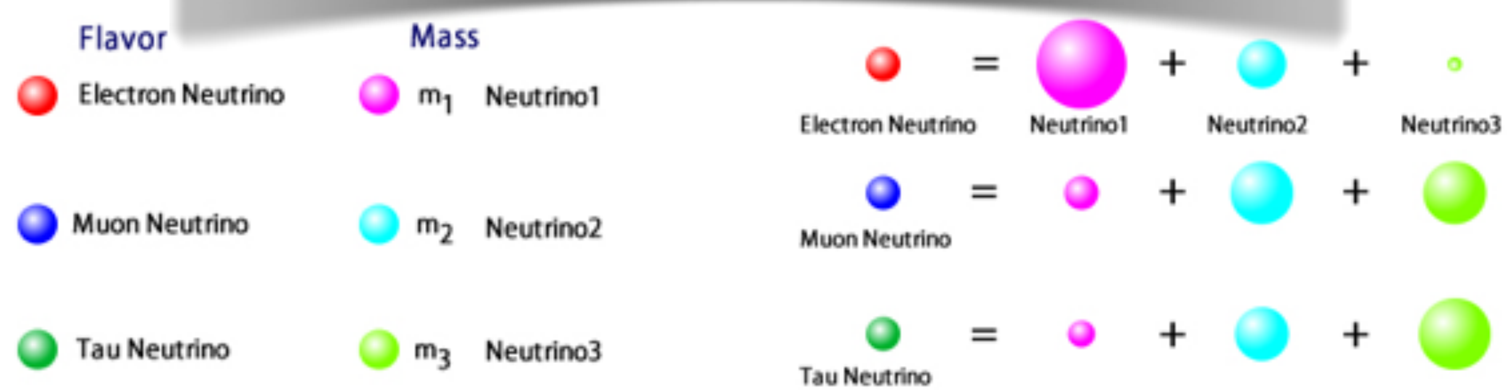
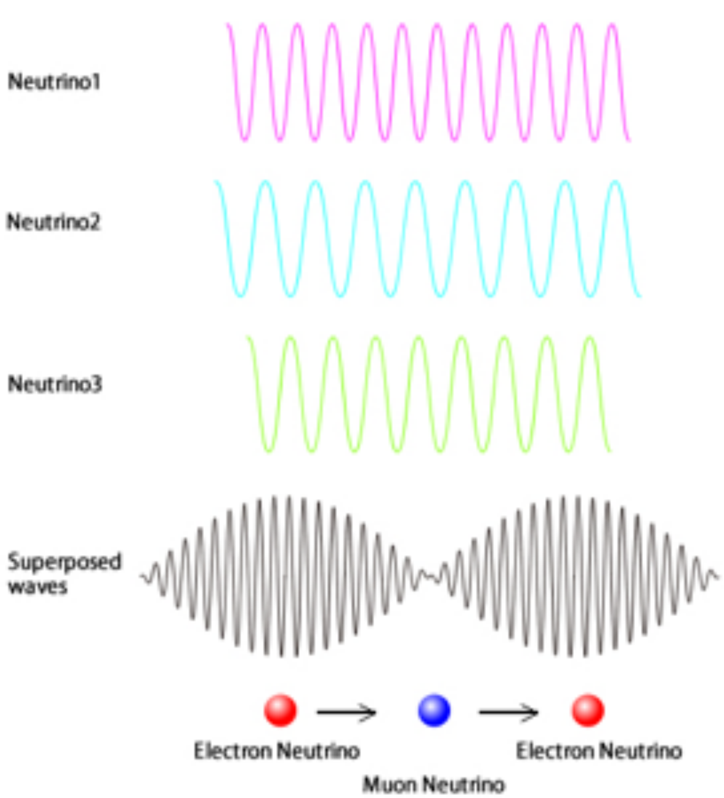
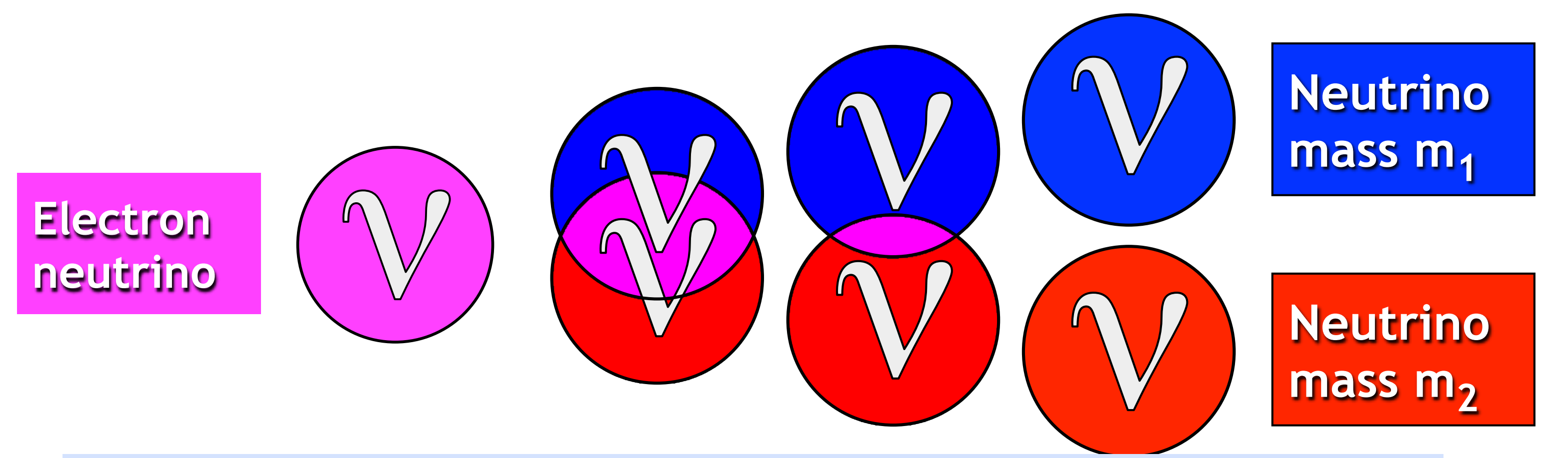


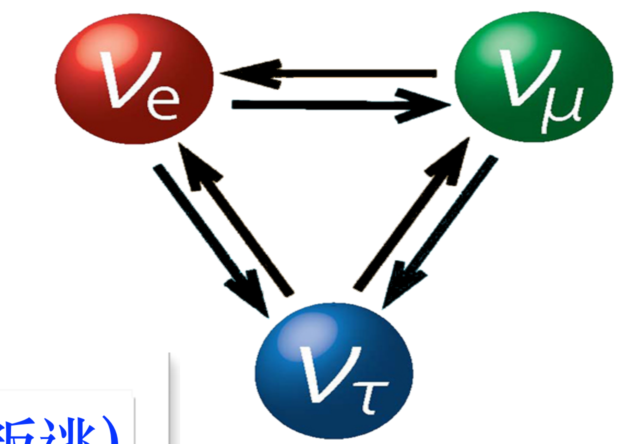






Neutrino propagation as a wave phenomenon

Solution to Solar and Atmospheric Neutrino Problems



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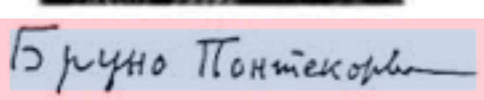
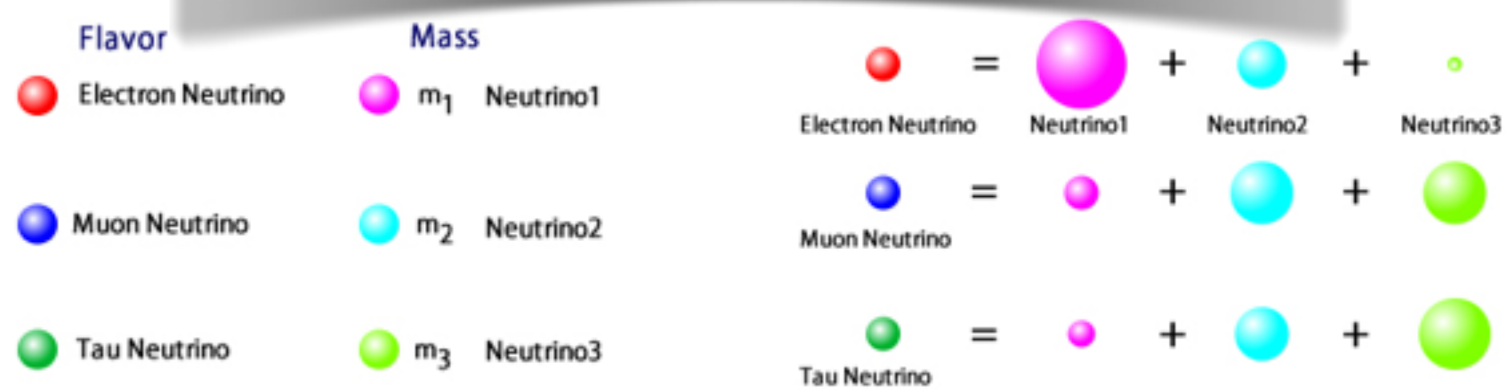
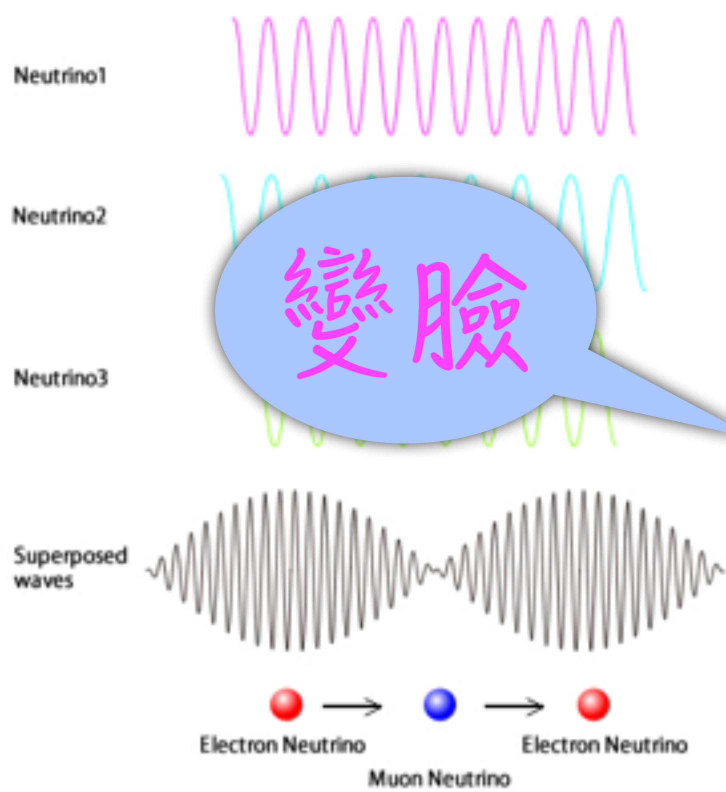
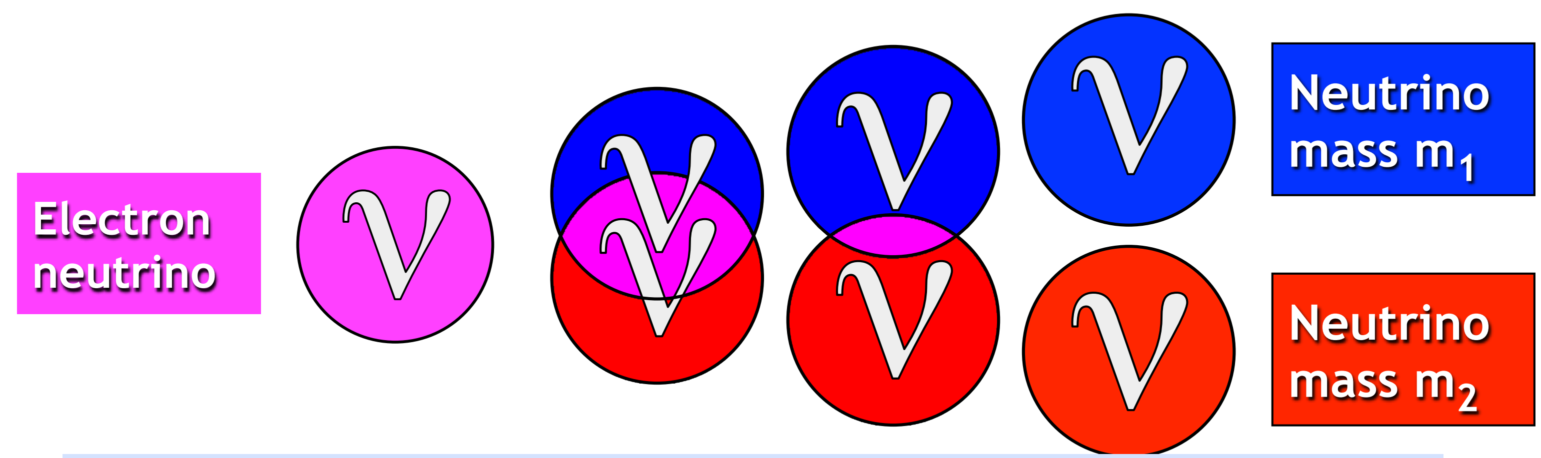




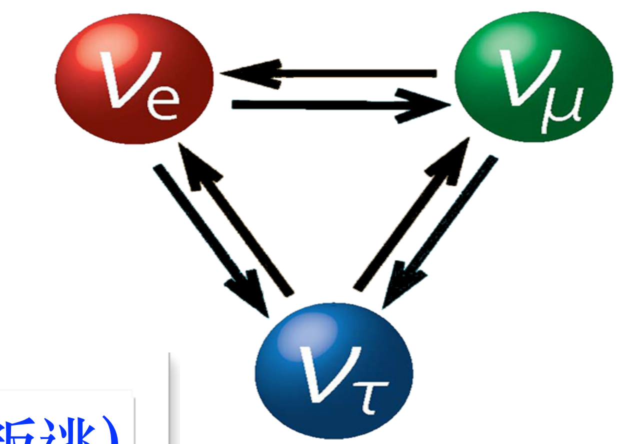




Neutrino propagation as a wave phenomenon

Neutrinos have mass!

Solution to Solar and Atmospheric Neutrino Problems



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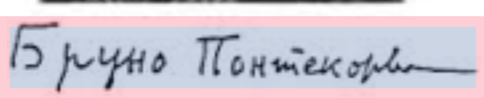
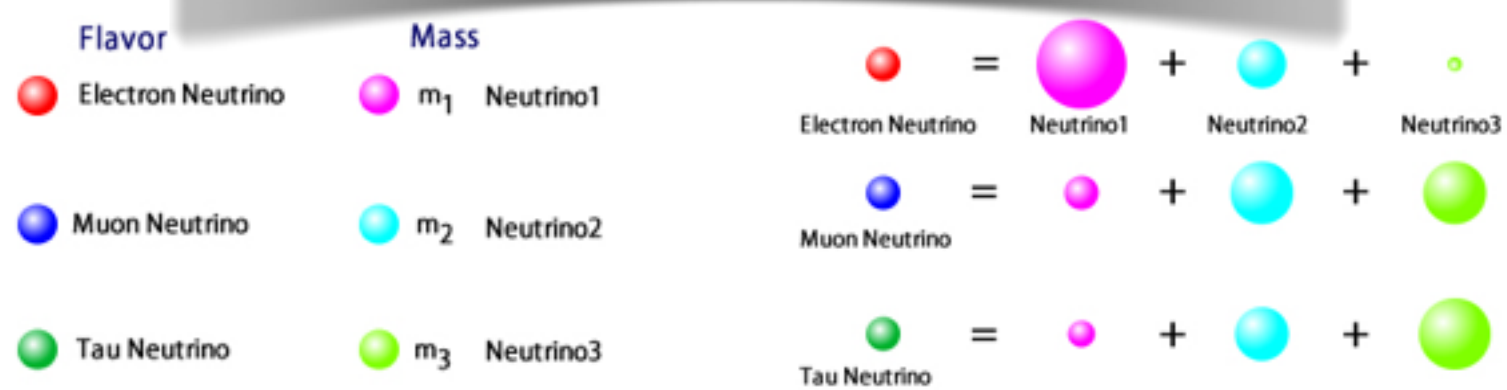
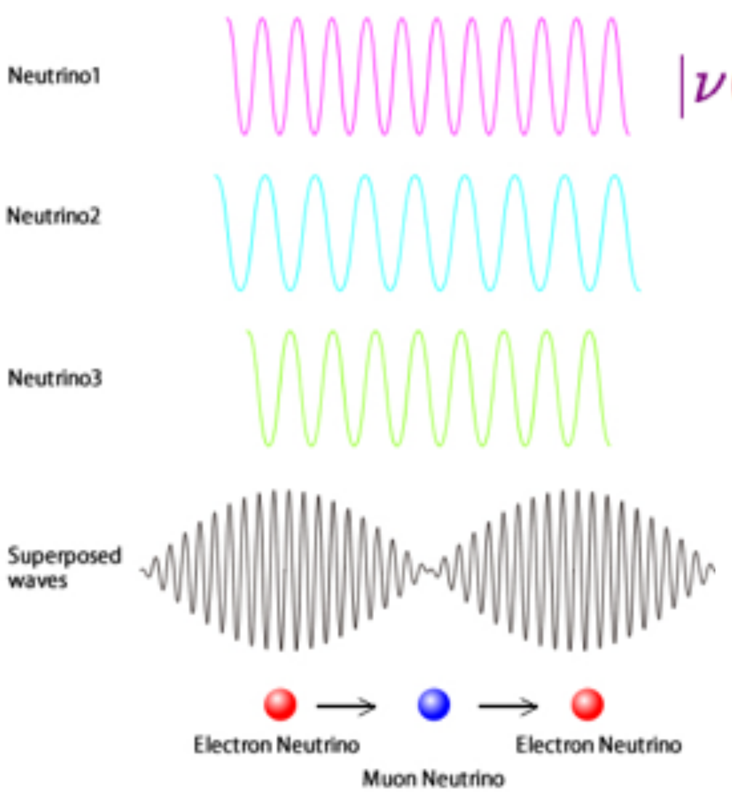
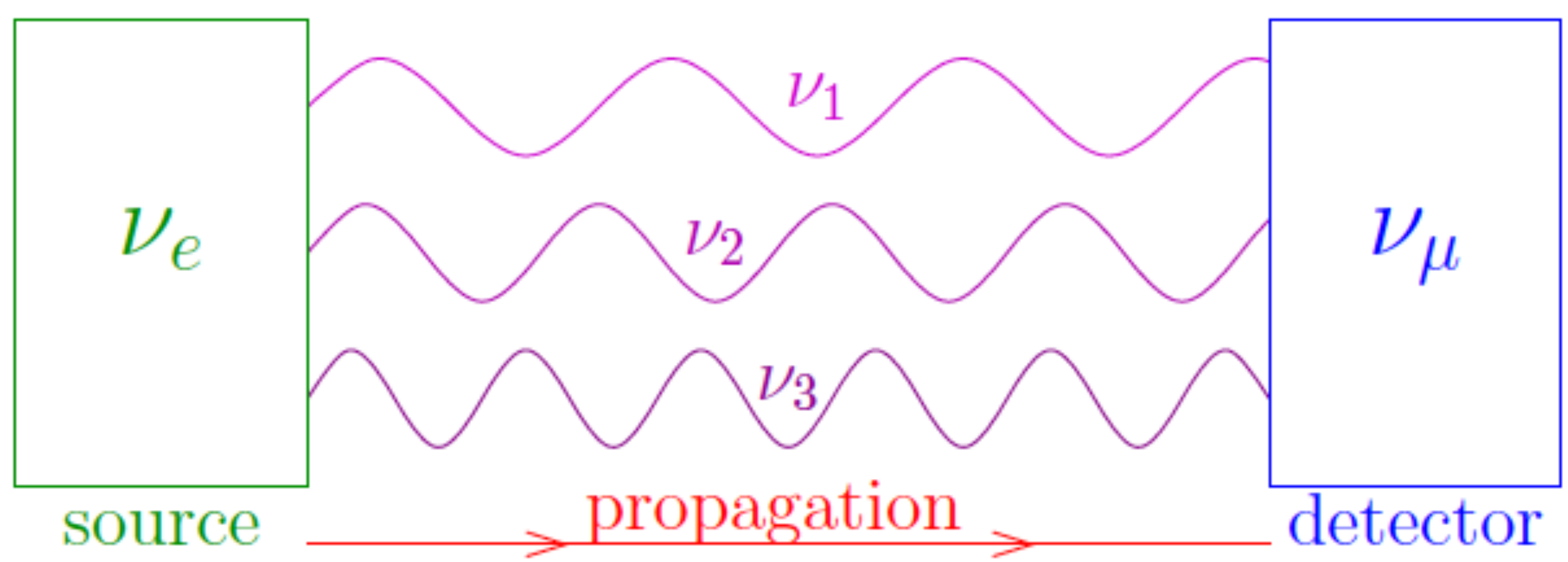




$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

$$|\nu(t>0)\rangle = U_{e1}\, e^{-iE_1 t}|\nu_1\rangle + U_{e2}\, e^{-iE_2 t}|\nu_2\rangle + U_{e3}\, e^{-iE_3 t}|\nu_3\rangle \neq |\nu_e\rangle$$





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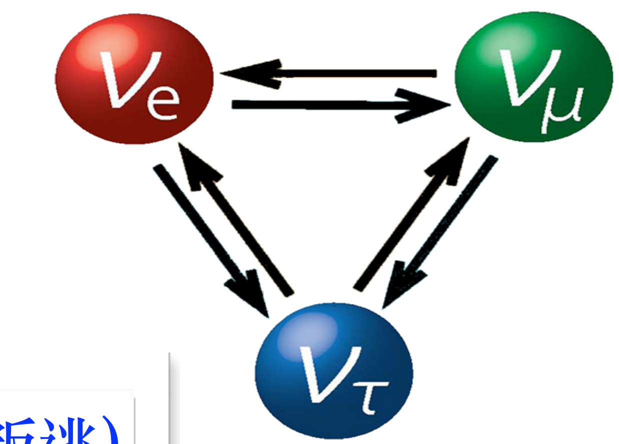

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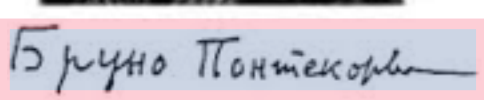
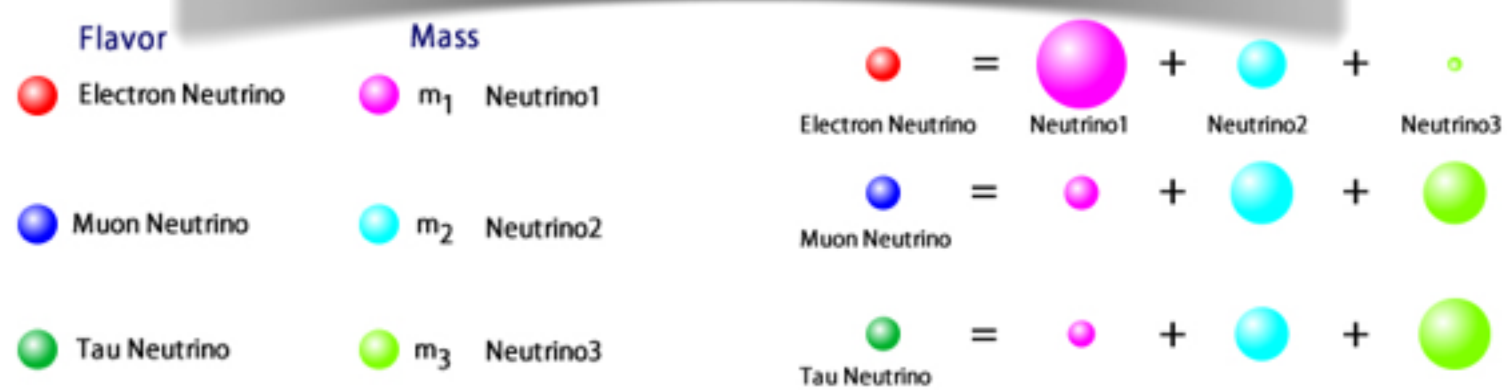
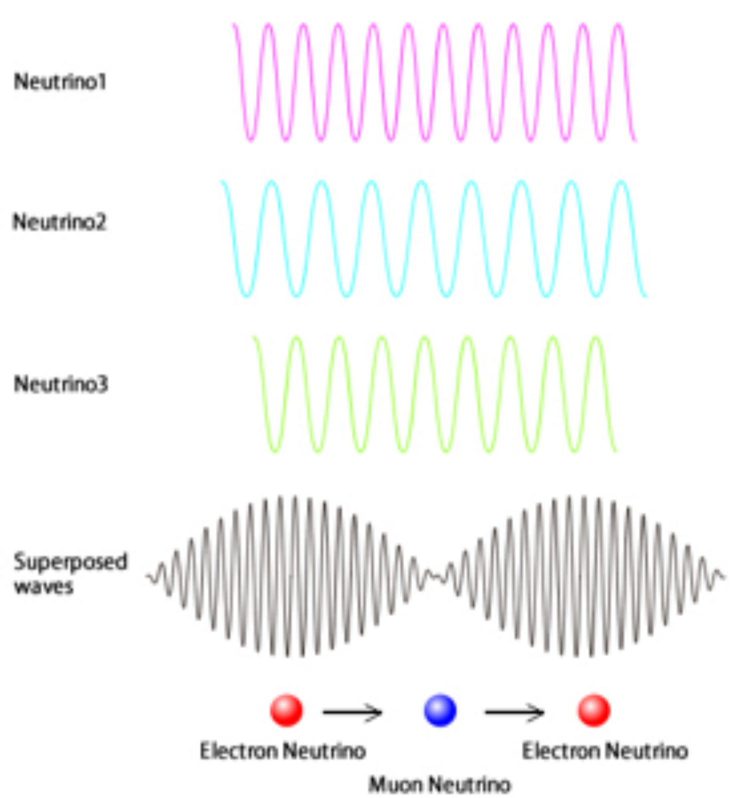






Solar neutrino oscillation

$$\Delta m^2 \sim 7.5 \times 10^{-5}\,\mathrm{eV}^2$$

SNO →

$\mathbf{m}(\nu_e) \neq 0$ **or/and**

$\mathbf{m}(\nu_\mu) \neq 0$

Atmospheric neutrino oscillation

$$\Delta m^2 \sim 2.4 \times 10^{-3}\,\mathrm{eV}^2$$

SK →

$\mathbf{m}(\nu_\mu) \neq 0$ **or/and**

$\mathbf{m}(\nu_\tau) \neq 0$

At least, two neutrinos have non-zero mass!

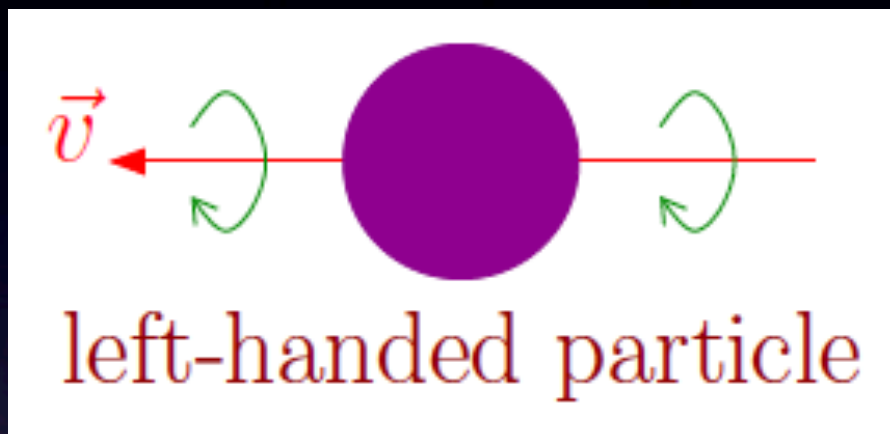
Origin of Neutrino Masses

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

Why does the Standard Model require MASSLESS neutrinos?

- All neutrinos left-handed ⇒ massless



Strictly left-handed neutrinos ⟺ Massless Neutrinos

~~Fermi theory of weak interaction (1934)~~

V-A theory of weak interaction (1957)

R.Marshak, G.Sudarshan

$m_\nu \neq 0$

⇒ **New Physics beyond the Standard Model (BSM)!**

Origin of the neutrino masses: Dirac or Majorana?

Paul Dirac (1902-1984)

$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \overline{\nu}_\downarrow \\ \overline{\nu}_\uparrow \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

Ettore Majorana (1906-???)

Disappeared in 1938 during a boat trip from Palermo to Naples without his body found

On February 4, 2015 Rome Attorney's Office released a statement declaring that Majorana was alive between 1955 and 1959, living in Valencia, Venezuela.

Dirac neutrino mass (1928):

$$\mathcal{L}_D = -m_D \overline{\nu_L} \nu_R + \text{h.c.}$$

☺ the lepton number L is conserved

☞ **Introduce ν_R (not in the SM)**

Majorana neutrino mass (1937):

$$\mathcal{L}_M = -m_M \overline{\nu^c} \nu \quad + \text{h.c.} \qquad \nu \leftrightarrow \bar{\nu}$$

- the lepton number L is violated

☞ **FORBIDDEN IN THE SM.**

Origin of the neutrino masses: Dirac or Majorana?

Paul Dirac (1902-1984)

$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \overline{\nu}_\downarrow \\ \overline{\nu}_\uparrow \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

Ettore Majorana (1906-???)

Disappeared in 1938 during a boat trip from Palermo to Naples without his body found

On February 4, 2015 Rome Attorney's Office released a statement declaring that Majorana was alive between 1955 and 1959, living in Valencia, Venezuela.

Dirac neutrino

$\mathcal{L}_D = -m_D \overline{\nu_L}$

☺ the lepton nu

There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these.

— (Enrico Fermi about Majorana, Rome 1938)

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VOLUME 58, NUMBER 10 PHYSICAL REVIEW LETTERS 9 MARCH 1987

Naturally Small Dirac Neutrino Masses in Superstring Theories

G. C. Branco and C. Q. Geng
Physics Department, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
(Received 8 December 1986)

We show that a $Z_2 \otimes Z_3$ symmetry leads to the radiative generation of naturally small Dirac neutrino masses in a class of superstring theories. This model realizes in a simple and consistent way a recent suggestion by Masiero, Nanopoulos, and Sanda.

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Modern Physics Letters A
Vol. 30, No. 24 (2015) 1530018 (7 pages)

DOI: 10.1142/S0217732315300189

World Scientific
www.worldscientific.com
Brief Review

Generating Majorana neutrino masses with loops

Chao-Qiang Geng

Chongqing University of Posts & Telecommunications, Chongqing, 400065, China
Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
Physics Division, National Center for Theoretical Sciences, Hsinchu, Taiwan

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The Nobel Prize in Physics 2015

Takaaki Kajita, Arthur B. McDonald

Selected Articles on Neutrino Physics

Free-to-Read until 30th April 2016

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Particles and Fields; Gravitation; Cosmology

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E. Witten—Opening Talk at *Neutrino 00* [hep-ph/0006332]

For neutrino masses, the considerations have always been qualitative, and, despite some interesting attempts, there has never been a convincing quantitative model of the neutrino masses.

當今公認的
genius

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當今公認的 genius

What was said in 2000 by Witten is also true TODAY (2017)

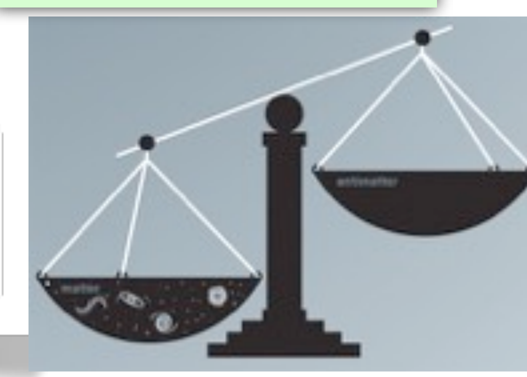
如同2000年，17年後的今天(2017年)也是如此：

至今也還沒有一個令人信服的定量微中子質量模型

Neutrino Masses?

Matter-antimatter asymmetry

物質－反物質不對稱性



Family problem

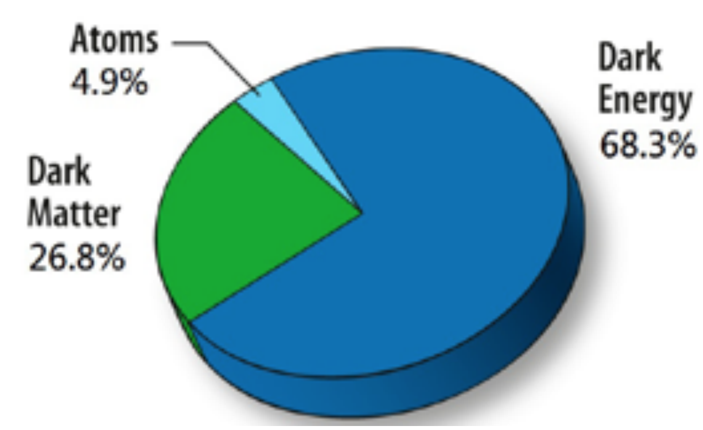
為什麼自然界僅有三代

Dark Matter

暗物質

Dark Energy

暗能量



☞ New Physics beyond the SM

Future prospects

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)***

超英雄歲月

+ something unexpected?

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

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

Future prospects

Heroic Period (1960 -- 1975):

Nobel Prizes in Particle Physics & Cosmology: [work done]

20xx: ?

2013: Englert, Higgs □ Higgs particle [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]

1993: Hulse,Taylor – pulsar (indirect detection of GW [1974]

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]

1978: Penzias,Wilson – cosmic microwave background radiation [1965]

1976: Richter,Ting–charm quark (J/Psi) [1974]

1969: Gell-Mann–classification of elementary particles [1964]

more?

英雄歲月

=13

7. Super-Heroic Period (2020--2035)

超英雄歲月

LHC: ...

+ something unexpected?

GW: LISA，太極，天琴 *2030*

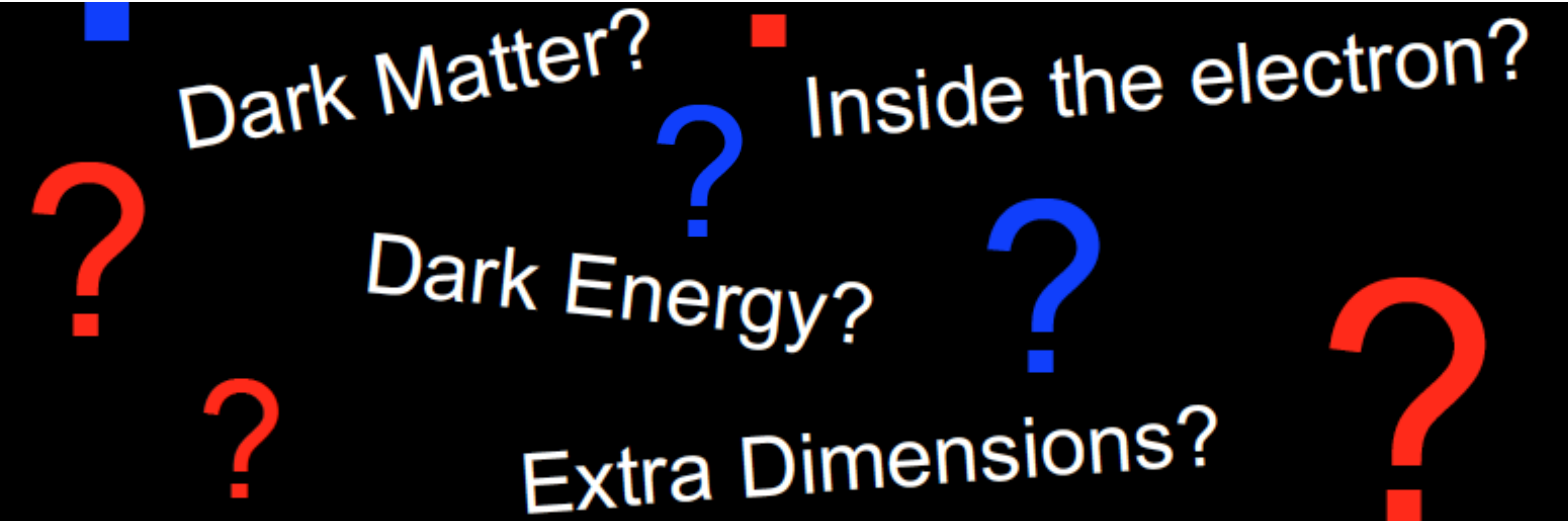
100 TeV Collider *2030*

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

>10

很多尚未解決之問題

- *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?*



美國《科学》杂志（2012.06) 盘点的八大宇宙未解之谜分别是：

1、暗能量，构成现存宇宙的73%但从未被观察到或测量过。暗能量的存在是“应需而生”的，它能平衡关于宇宙的数学公式，但可能永远不会被观测到；
2、暗物质，与暗能量紧密相关，被描述为将宇宙万物粘合在一起的“胶水”。为《科学》杂志撰写相关论文的阿德里安·丘认为，与暗能量不同，科学家们很可能有朝一日能切实观测到这种物质；
3、重子哪里去了？重子是一种能构成特殊物质的颗粒，但出于某些原因，当研究人员把暗能量、暗物质相加并把其它归于重子时，研究者所得的结果竟不是100%；
4、为什么恒星会爆炸？人们已经对有关恒星形成以及太阳系形成的许多过程有了初步认知，但科学家们承认，他们仍不能完全理解当一个恒星爆炸时其内部情况到底是怎样的，只知道爆炸后会形成超新星；
5、是什么使宇宙再电离？自宇宙大爆炸后数十万年，电子被从原子上剥离，但目前尚不知这是为什么；
6、各种能量充沛的宇宙射线的源头是什么？尽管地球的大气层能帮助我们抵挡住大多数宇宙射线，但我们每天仍会受到这些射线的“轰击”，科学家们至今无法就这些射线的源头达成共识；
7、为什么我们的太阳系如此独特？我们所在的太阳系是按照逻辑逐步形成的，还是误打误撞罢了？没人真正知晓。
8、为什么日冕那么热？专研太阳的科学家们始终想不明白。日冕是太阳的最外层部分，但其温度之高仍超乎想象。距离我们最近的这颗恒星所拥有的这层奇怪“分层”仍旧是个谜。

International Workshop on

Dark Matter, Dark Energy

Matter-antimatter Asymmetry

暗物質、暗能量及物質-反物質不對稱

Nov. 20-21, 2009 Phys. Dept. National Tsing Hua Univ., Hsinchu, Taiwan

2nd International Workshop on

Dark Matter, Dark Energy

Matter-antimatter Asymmetry

暗物質、暗能量及物質-反物質不對稱

November 5~6, 2010 Dept. of Phys., National Tsing Hua Univ., Hsinchu, Taiwan

3rd International Workshop on

Dark Matter, Dark Energy and Matter-Antimatter Asymmetry

暗物質、暗能量及物質-反物質不對稱

December 28-29, 2012 - Lecture Room 4A, NCTS, General 3rd Building, NTHU, Hsinchu, Taiwan
December 30-31, 2012 - Room 812, LeCosPA, Astronomy-Mathematics Building, NTU, Taipei, Taiwan

4th International Workshop on

Dark Matter, Dark Energy and Matter–Antimatter Asymmetry

暗物質、暗能量及物質-反物質不對稱

December 29–31, 2016 – Lecture Room 4A, NCTS, General 3rd Building, NTHU, Hsinchu, Taiwan

Just the beginning of the story

Key to the Universe

中微子質量，暗物質和暗能量等問題
或許是人類了解
宇宙歷史、結構和未來的鑰匙

謝謝！