2018 Blaise Plascal Chair Lecture 1

A Brief History of the Cosmos

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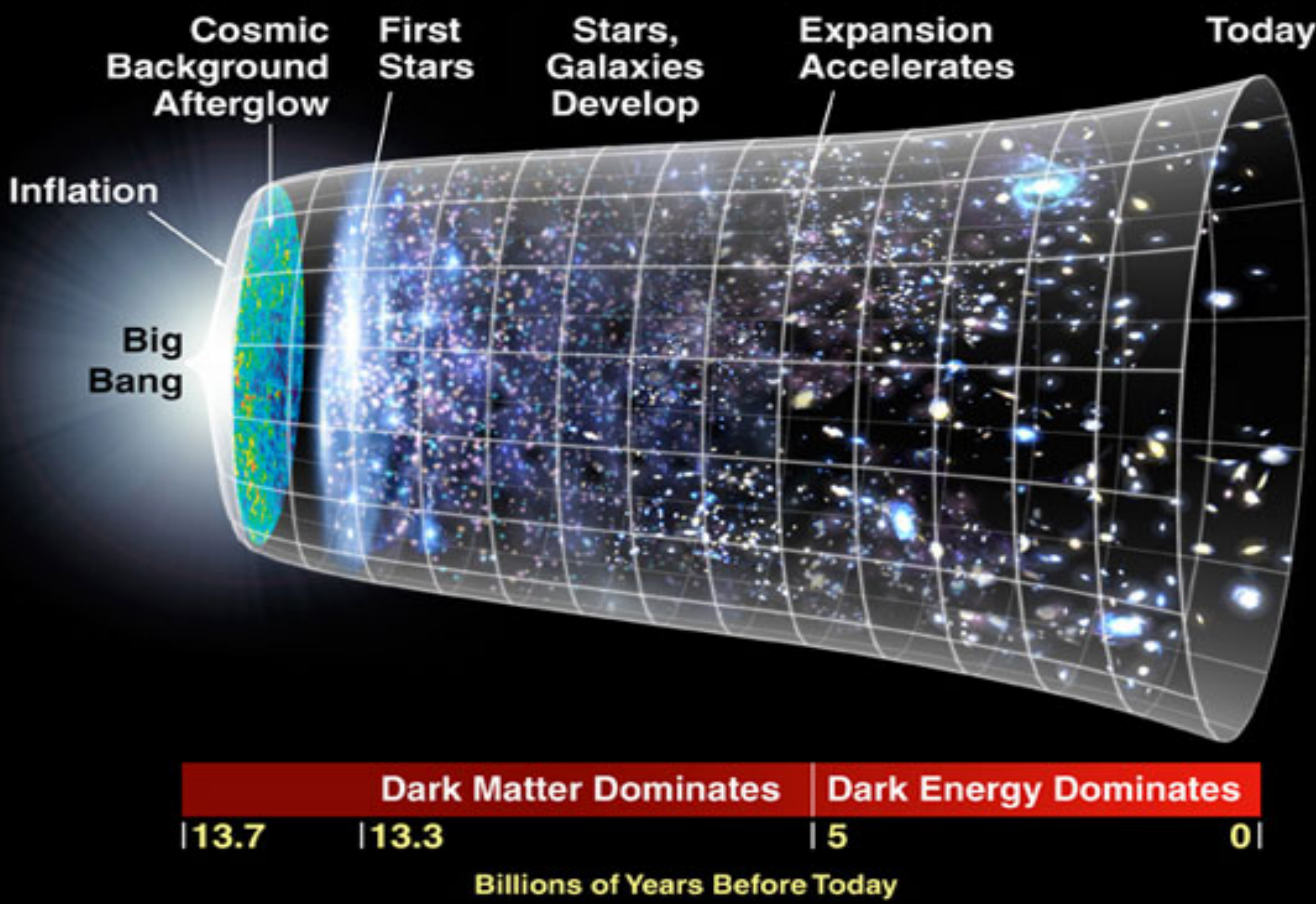
LLR, Ecole Polytechniqque, Jan. 21, 2019

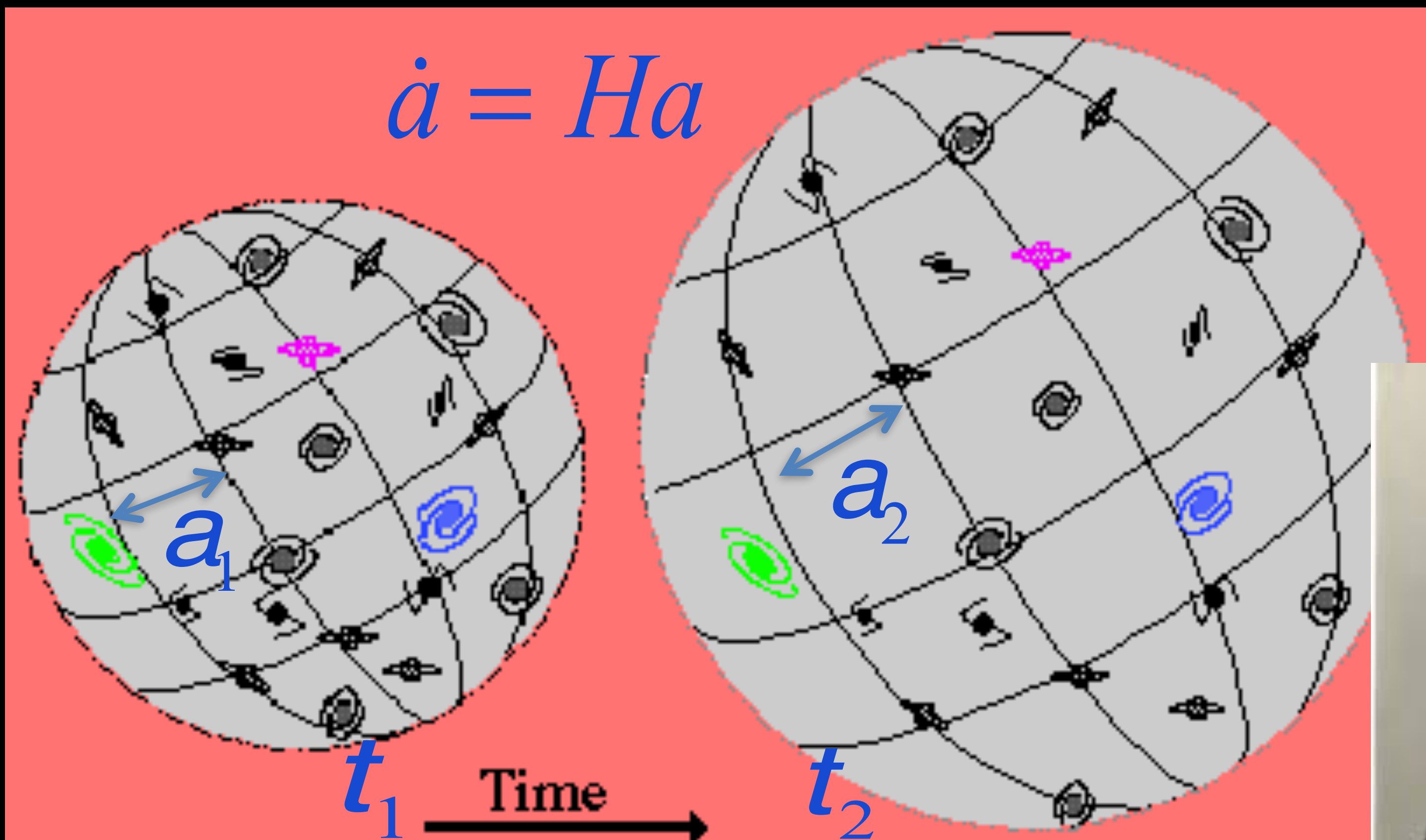
THE EXPANDING UNIVERSE: A CAPSULE HISTORY



Big Bang

Hubble's great discovery: Universe is expanding!

→ The universe must have a beinning

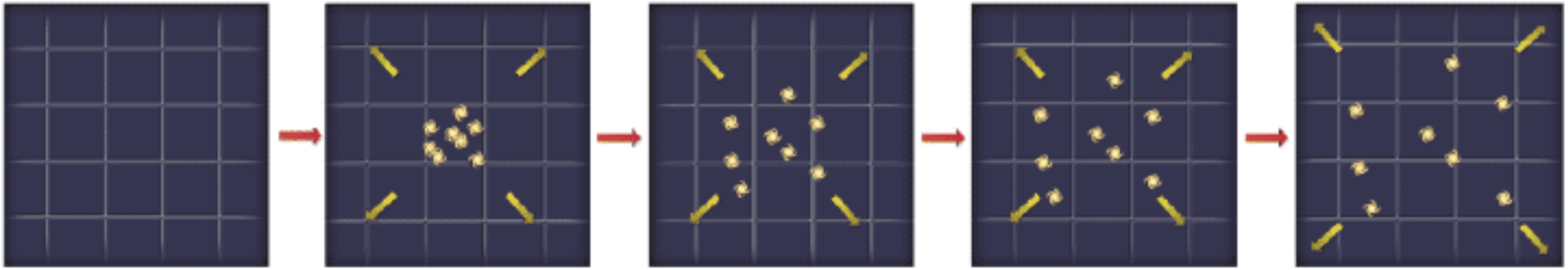


Edwin Hubble (1889–1953)

WHAT KIND OF EXPLOSION WAS THE BIG BANG?

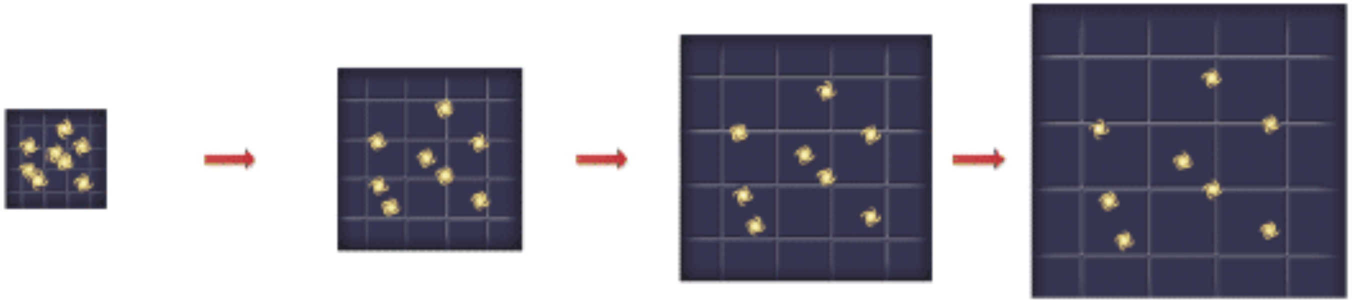
WRONG: The big bang was like a bomb going off at a certain location in previously empty space.

In this view, the universe came into existence when matter exploded out from some particular location. The pressure was highest at the center and lowest in the surrounding void; this pressure difference pushed material outward.



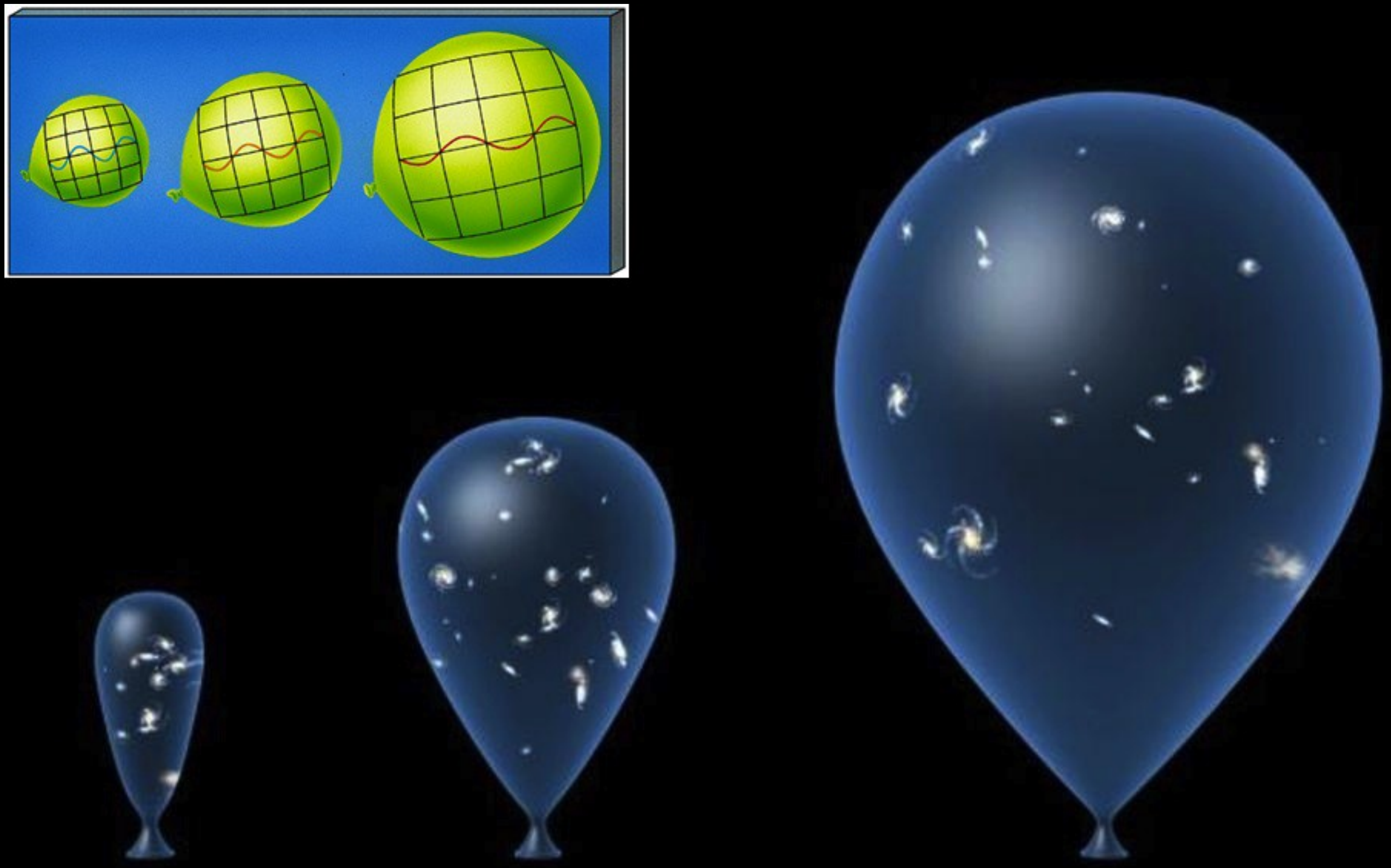
RIGHT: It was an explosion of space itself.

The space we inhabit is itself expanding. There was no center to this explosion; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.



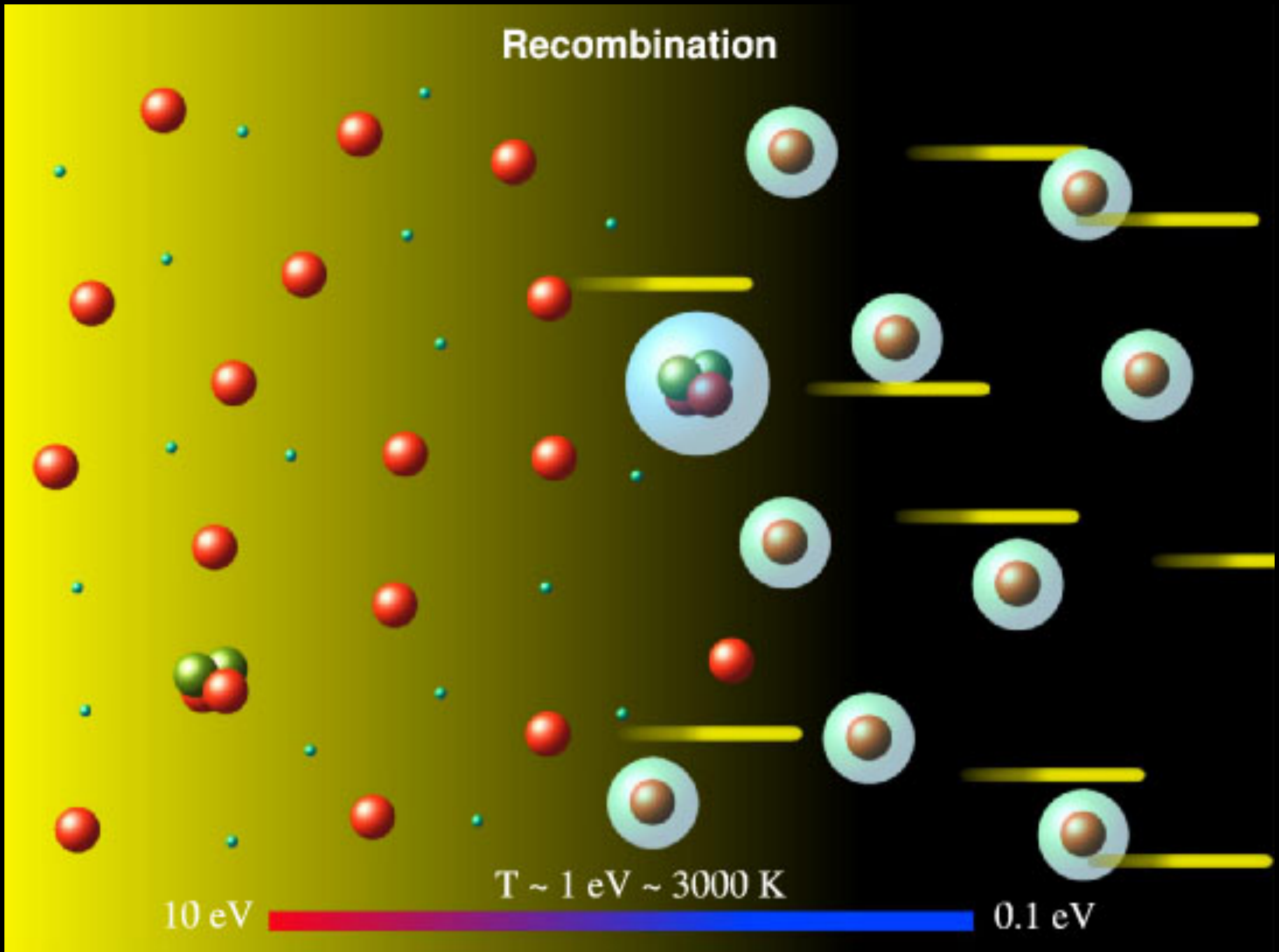
ALFRED T. KAMAJIAN

Light has a unique property. Its wavelength stretches as the universe expands.

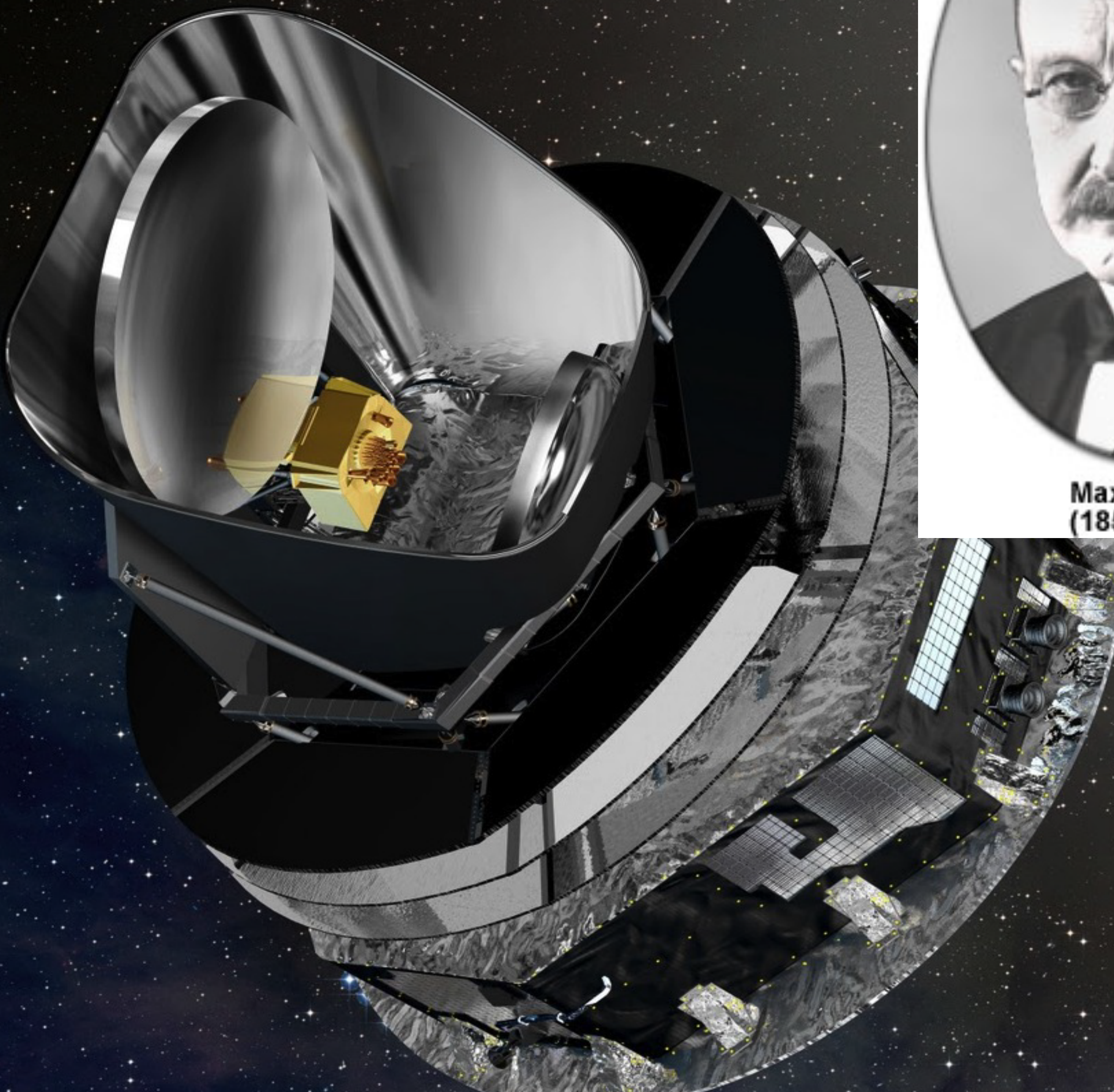


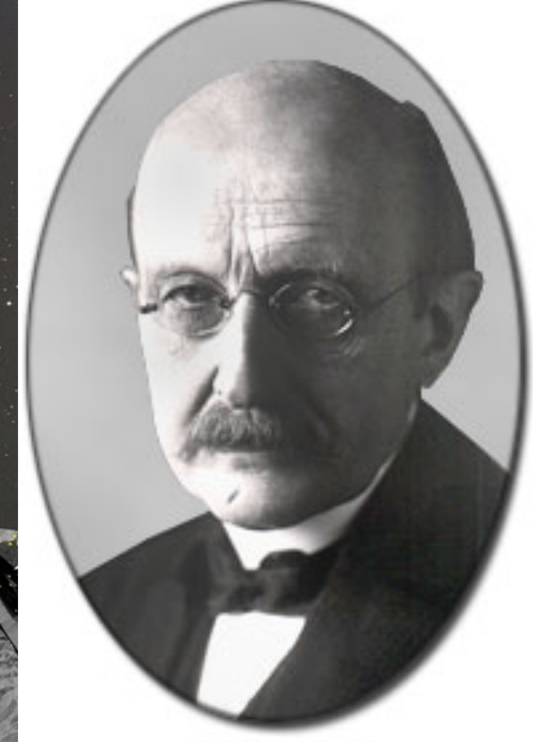
The longer the wavelength, the lower the temperature.

As the universe expands, it cools down.
Eventually electrons and nuclei formed atoms.
Cosmic microwave background detached



The Planck Mission

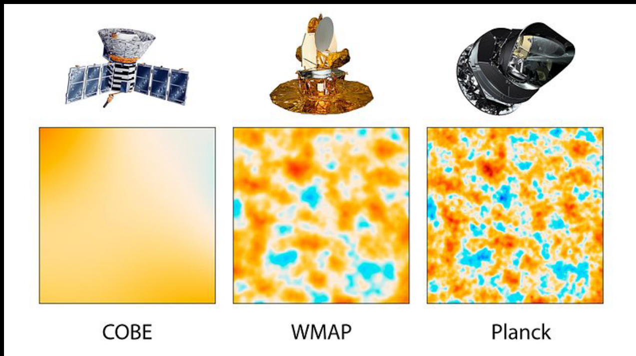




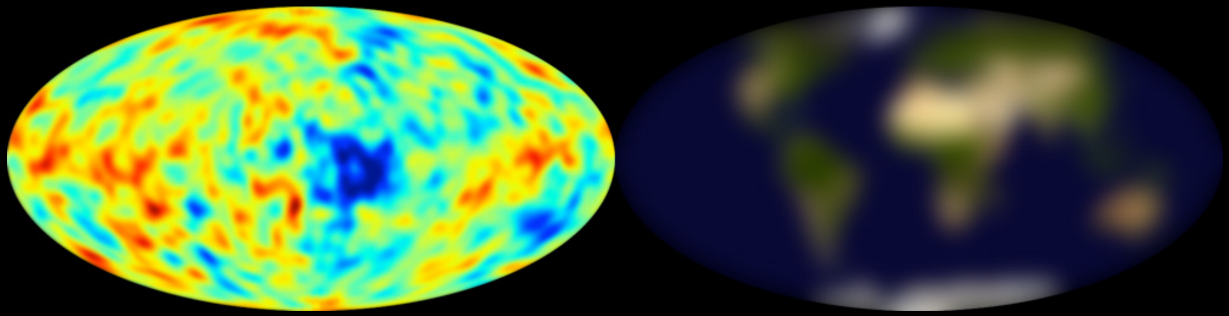
Max Planck
(1858-1947)

CMB Anisotropy

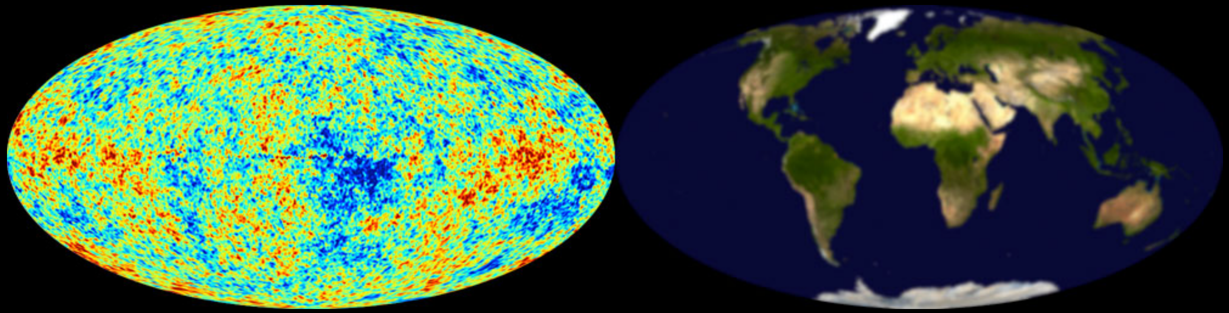
at the level of ~1/100,000



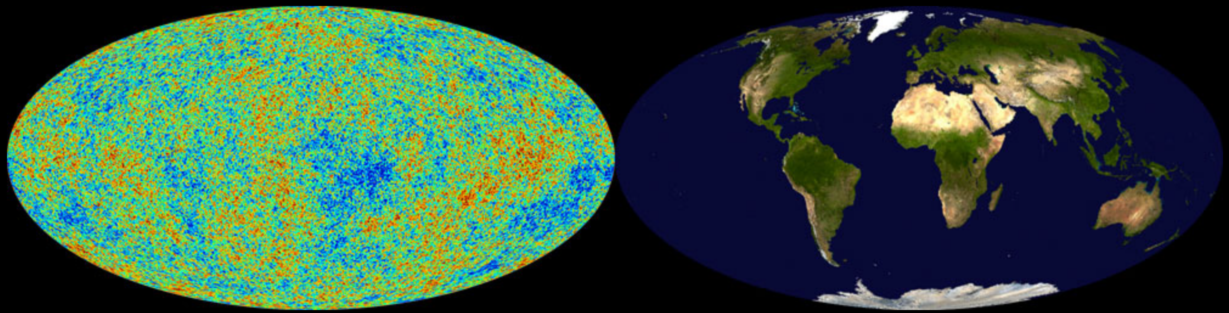
COBE



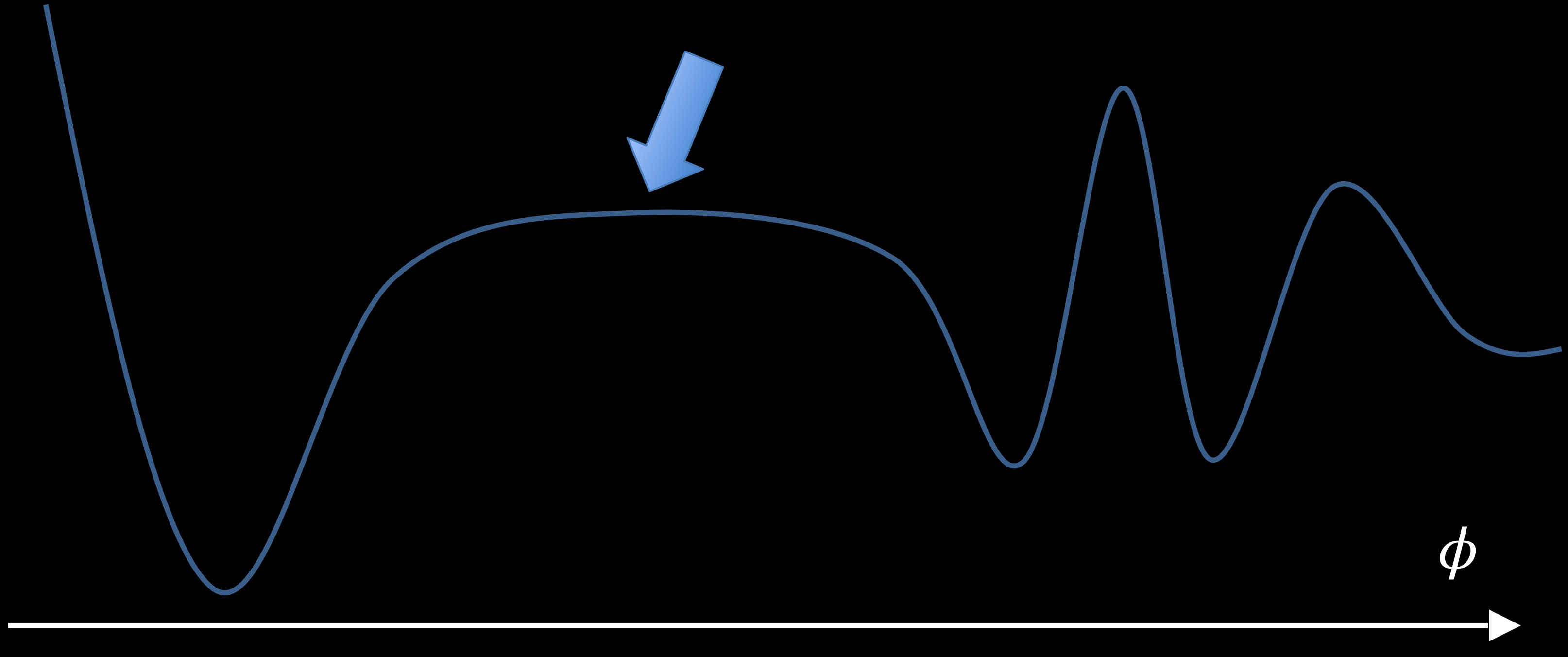
WMAP



Planck

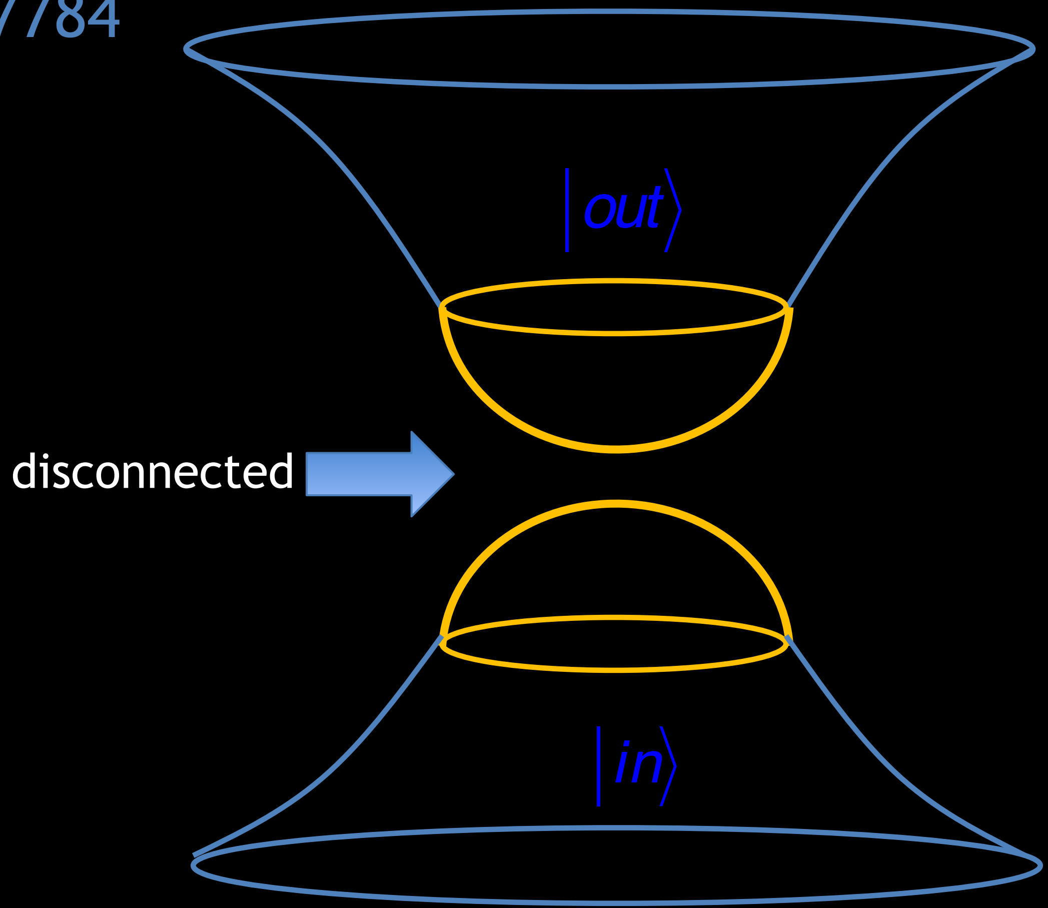


Why did our universe start from here, where the potential is concave?



Euclidean wormholes in dS

PC, Hu and Yeom, 1611.08468; PC and D-h Yeom, 1706.07784



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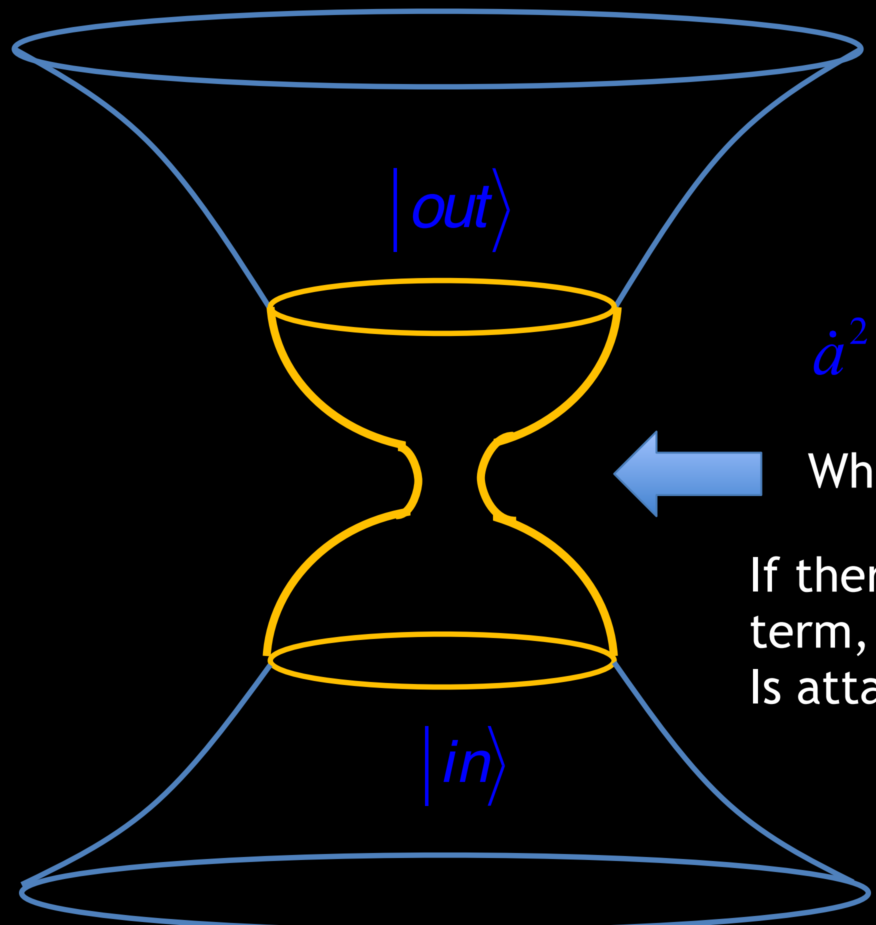


$$\dot{a}^2 = 1 - \frac{\Lambda}{3a^2} - \frac{C}{a^n}$$

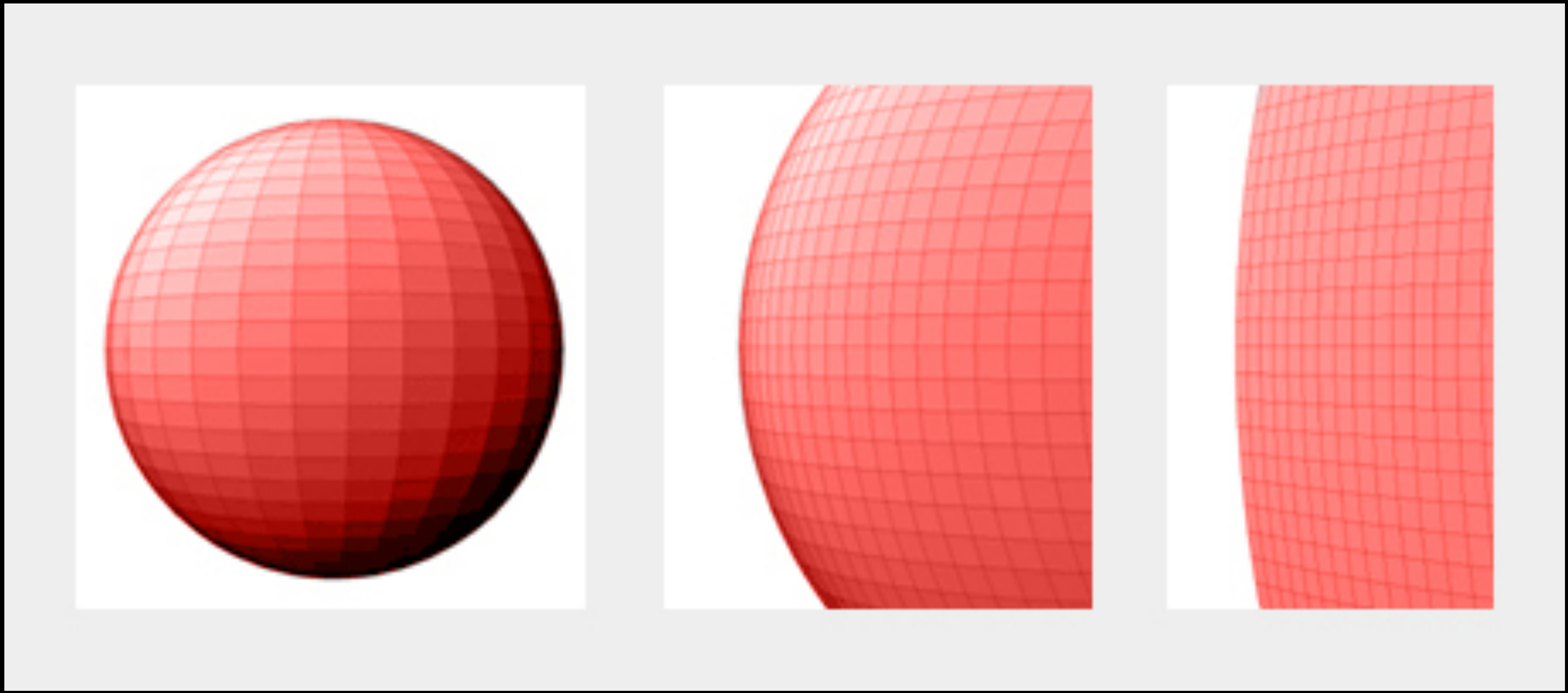
What if connected?

If there exists such a correctio
term, then a wormhole solutio
Is attainable.

Inflation

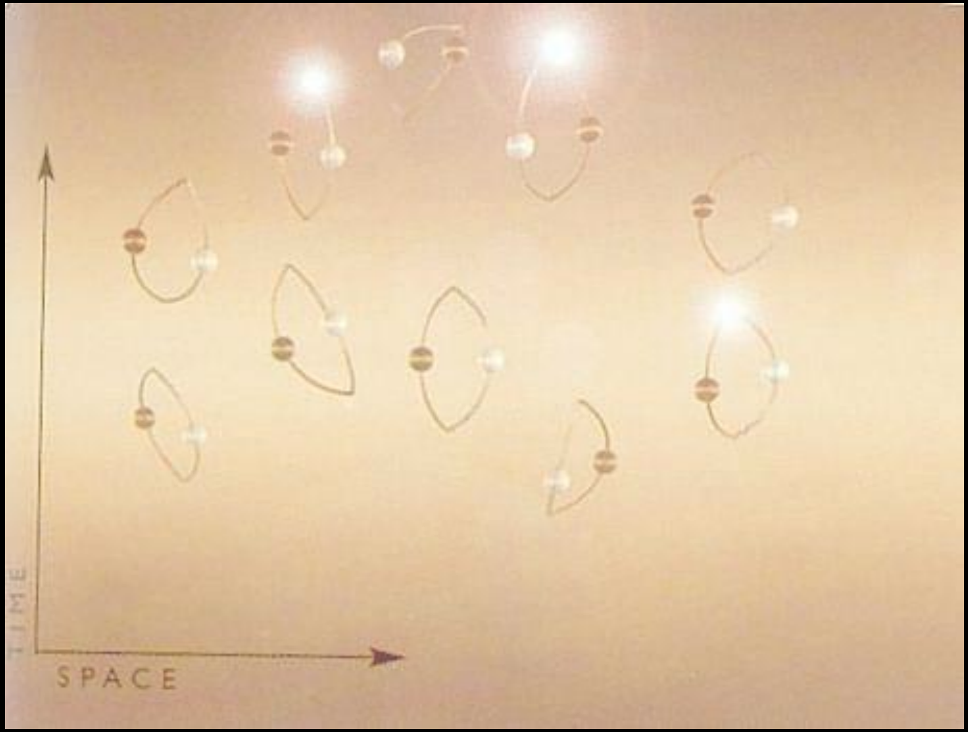
Q: Why is the universe so uniform and flat?
A: Inflation

Within 10^{-35} sec. the size of the universe expanded 10^{26} times!



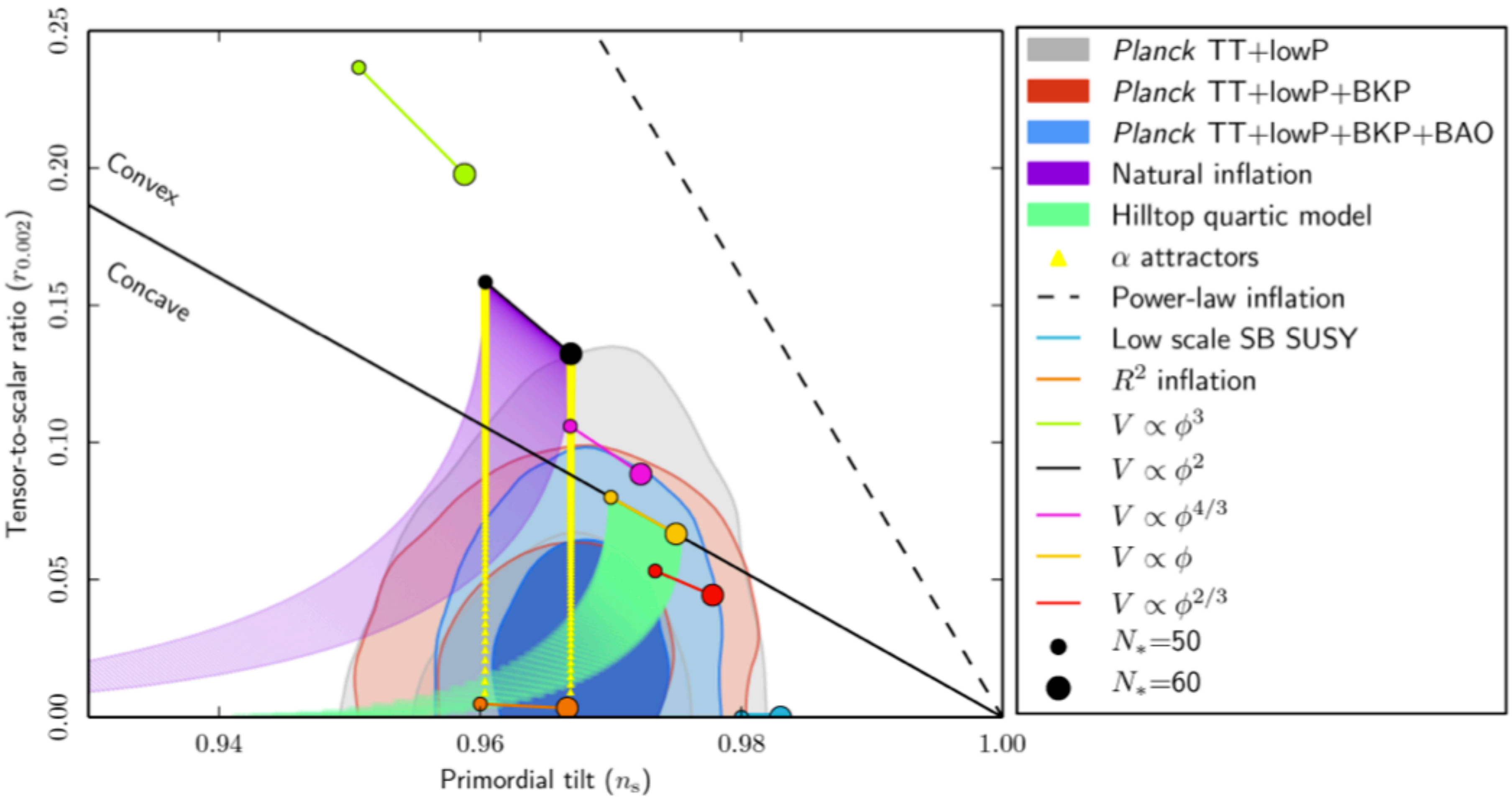
Q: But why is it slightly non-uniform?
A: Quantum fluctuations

According to QM, vacuum is filled with particles randomly emerged and disappeared dictated by Heisenberg's uncertainty principle.

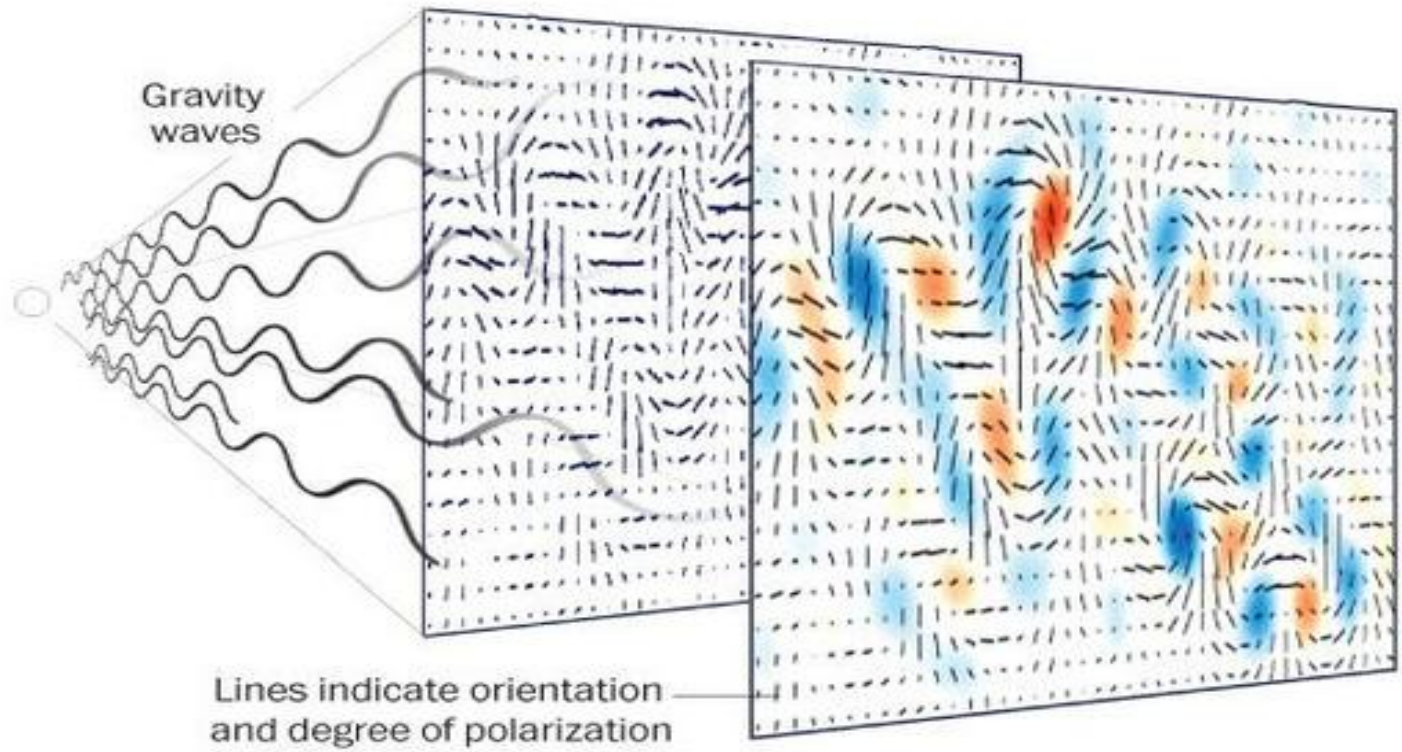


$\Delta x \cdot \Delta p \geq$ [illegible] $\longleftrightarrow$ $\Delta t \cdot \Delta E \geq$ [illegible]

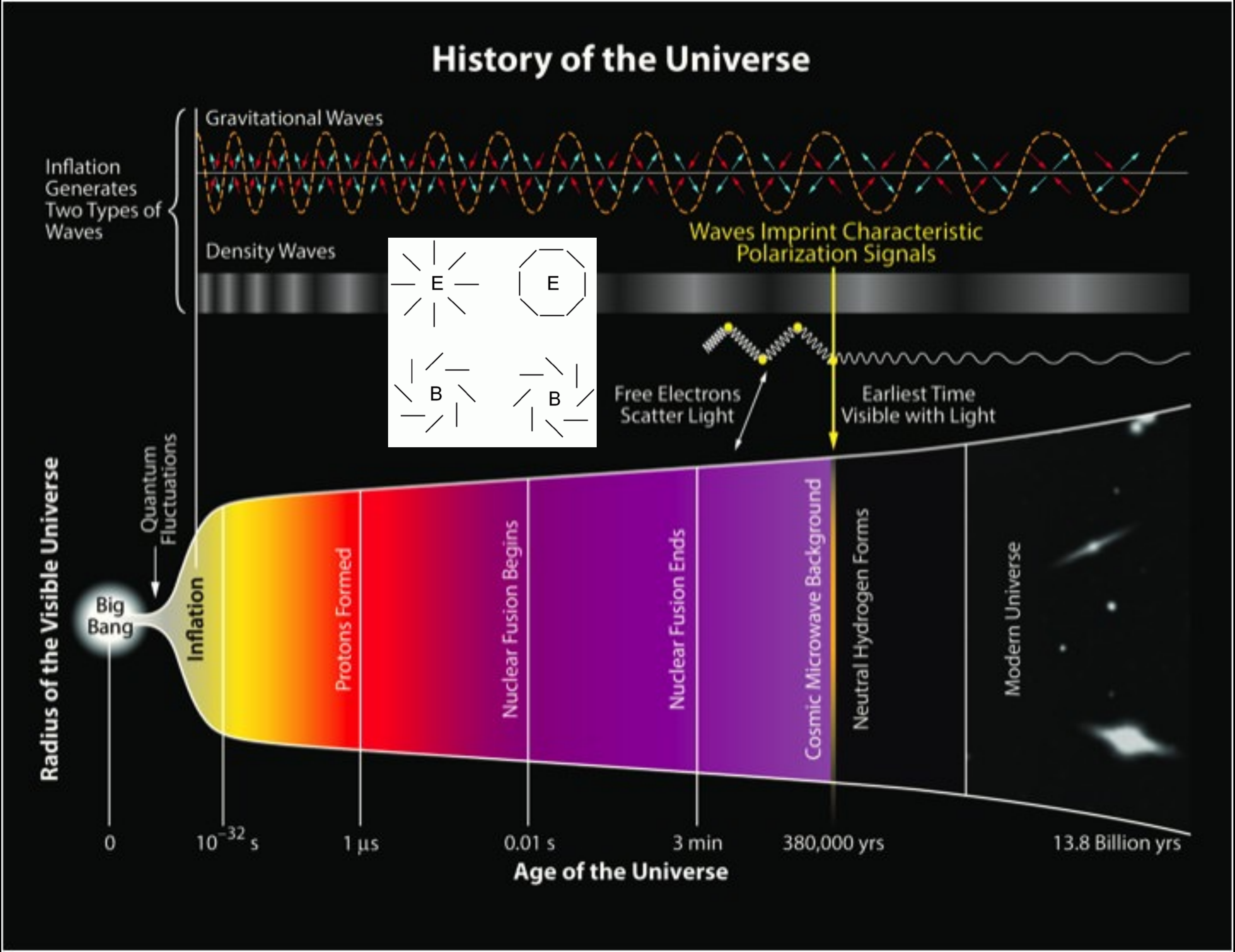
Starobinsky R^2 Model Favored



Primordial Gravitational Waves: The holy grail of inflation

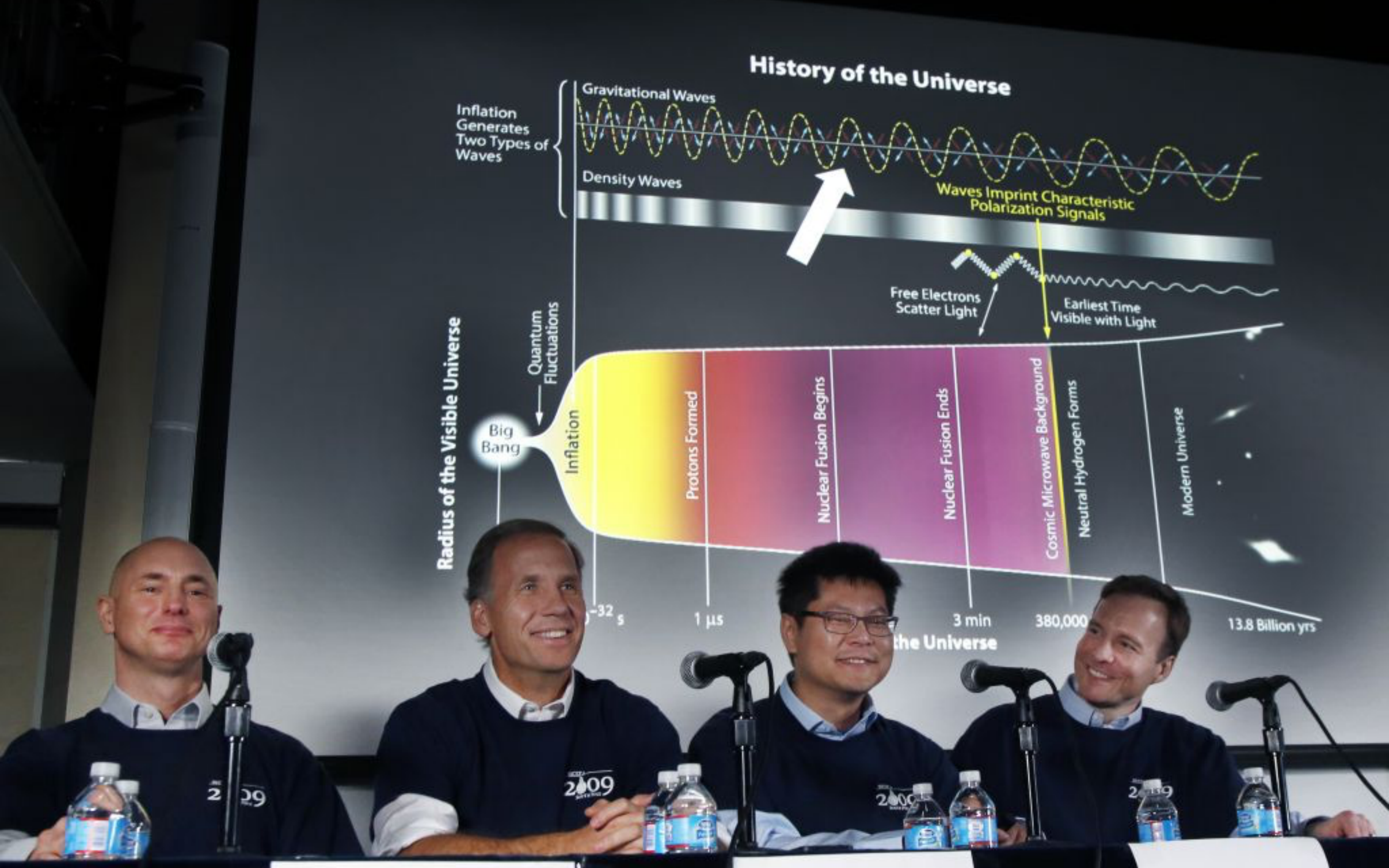


In the 1990s, physicists theorized that rapid inflation during the big bang would also generate **gravity waves**, which would leave their mark by polarizing light in the cosmic afterglow. Extremely sensitive telescopes at the South Pole have detected such skewed light waves, but scientists have spent almost a decade ensuring that the phenomenon was not the result of other factors.



History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
E
E
B
B
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10^-32 s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe

The 2015 BICEP-2 false alarm

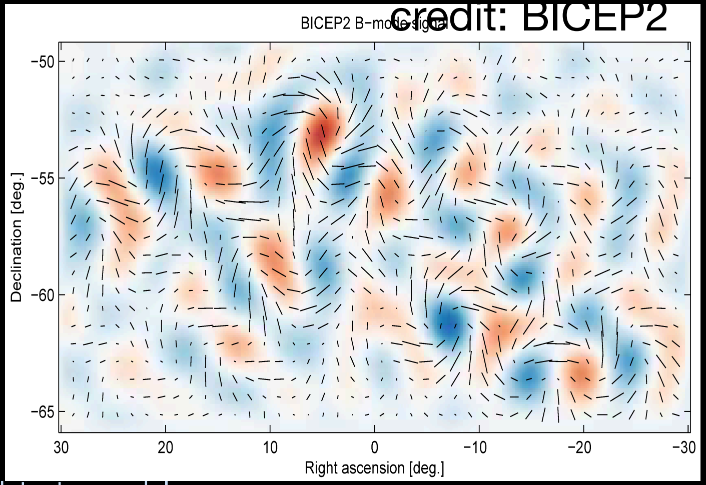


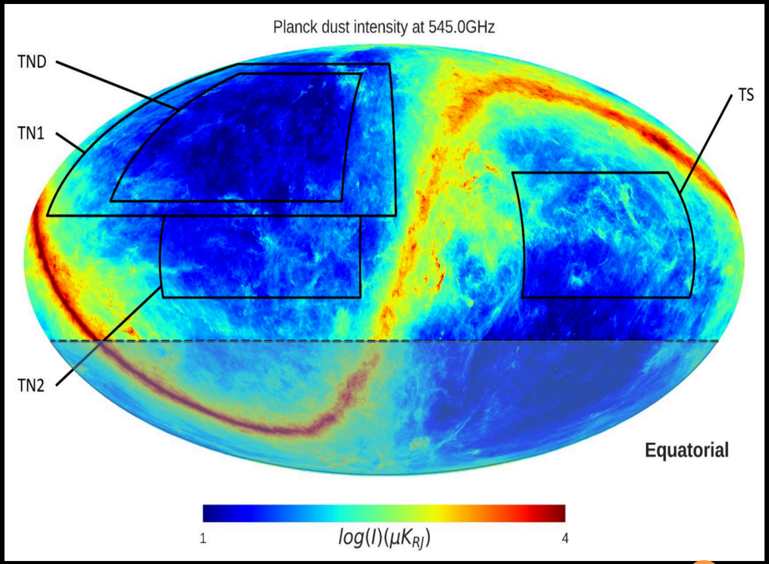
AliCPT (Ali CMB Polarization Telescope)

IHEP-NTU-Stanford/SLAC-ASU Collaboration

- A two-phase CMB polarization experiment in Ali, Tibet.

- Primary science goals
  - Inflation: tensor to scalar ratio ***r***
  - CPT violation: CMB rotation angle
  - Reionization: E-mode polarization





Planned survey region of AliCPT

- Based on BICEP3 detector module.

- AliCPT-1 (95 &150 GHz; survey up to ~10% sky)
  - Provides cutting edge E-mode measurement;
  - Suggests survey region for AliCPT-2.

Complementary northern hemisphere measurement / Large sky coverage / Ideal site

Status of AliCPT

AliCPT-1 (5,250m site)

- 4 detector modules (~ 6,800 detectors) for 90, 150 GHz.
- Design to be fixed by 2018; Calibration and test during 2019. Data taking from 2020.

July 2017

July 2018

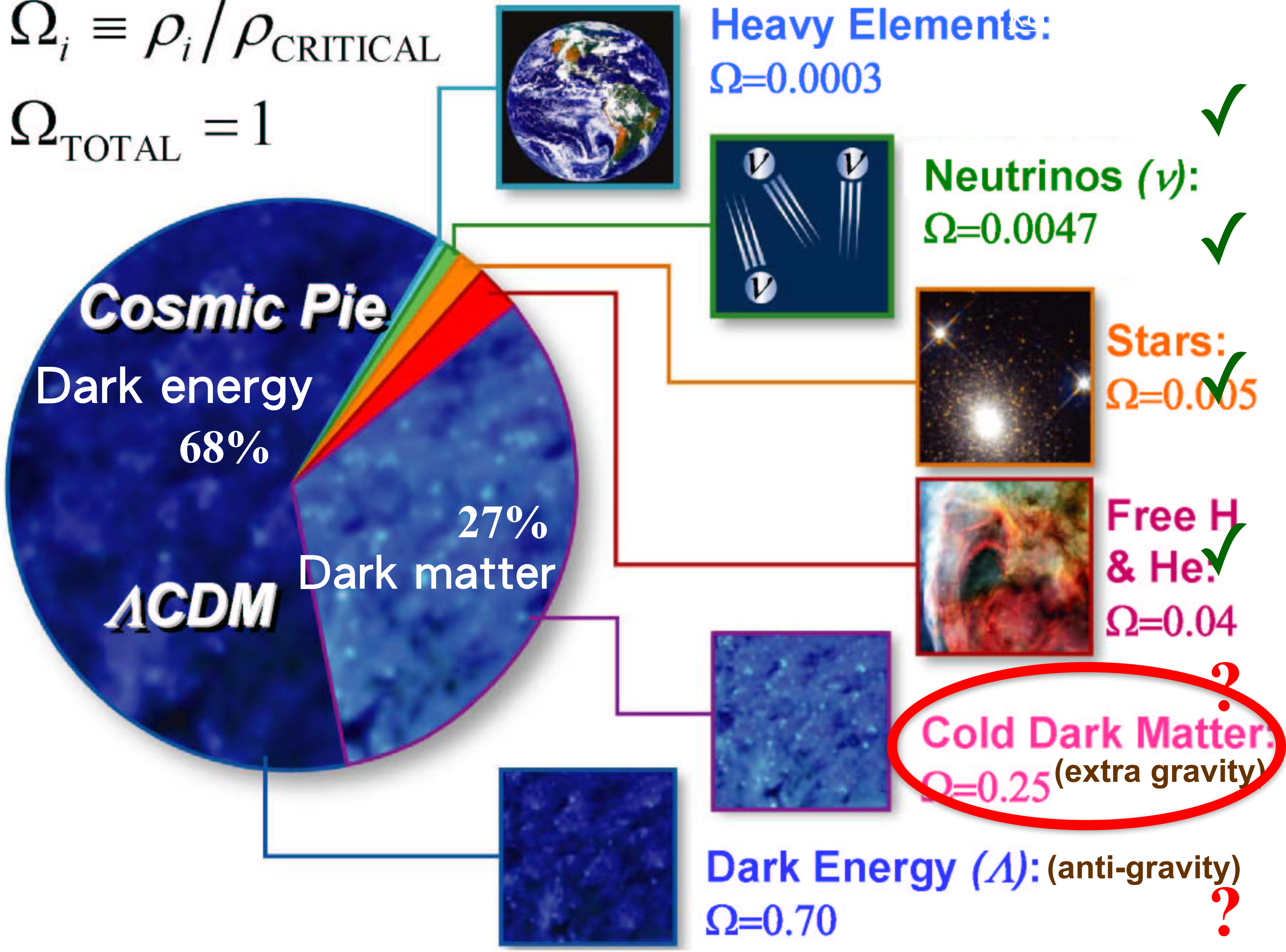
AliCPT-2 (6,000m site)

- Preliminary site survey in July 2017. Planned survey in the near future.
- Two weather stations installed. Data will b compared to NASA MERRA-2 satellite.
- Expected to be deployed in 2022.

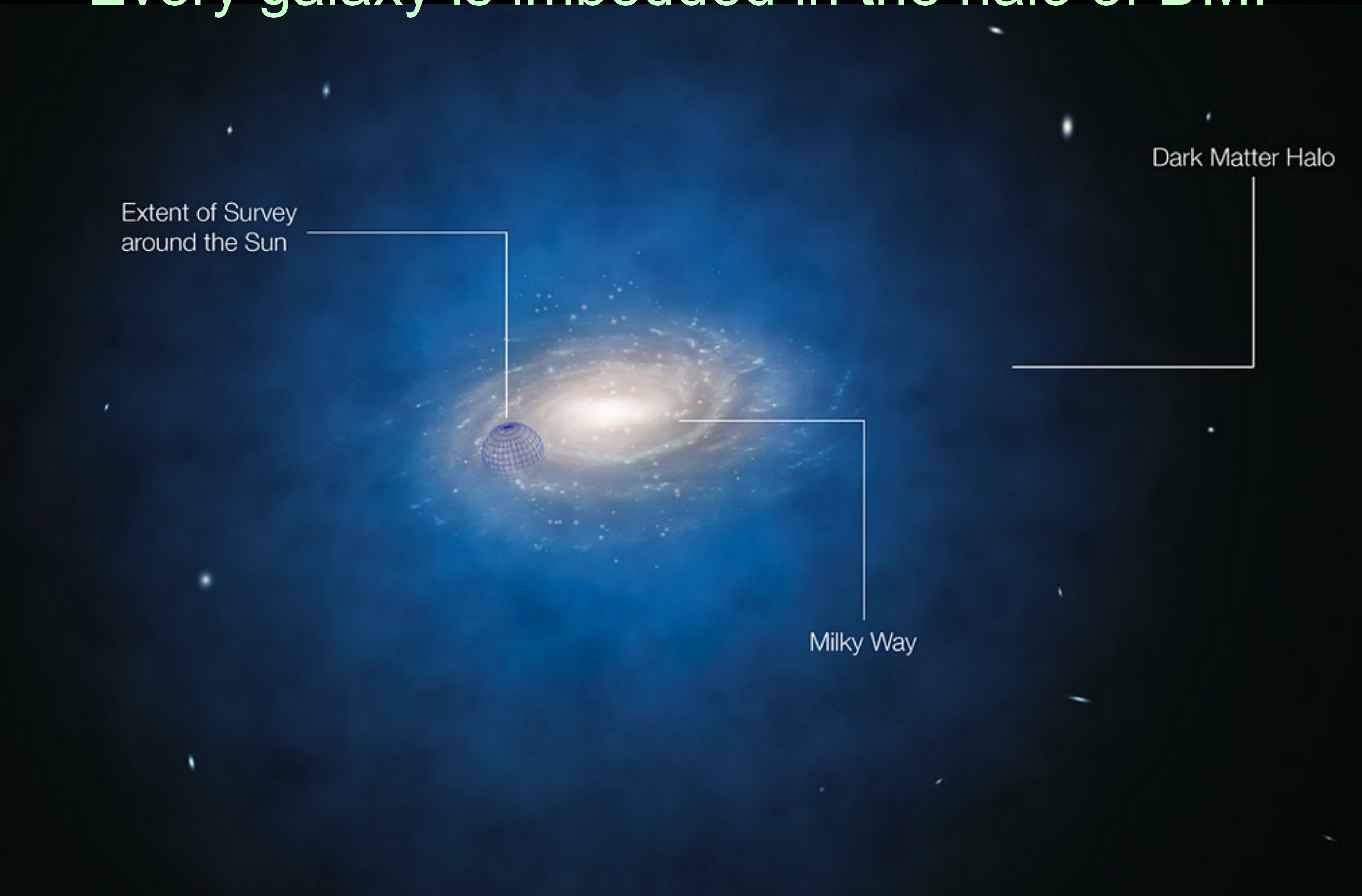
Dark Matter

$$\Omega_i \equiv \rho_i / \rho_{\text{CRITICAL}}$$

$$\Omega_{\text{TOTAL}} = 1$$

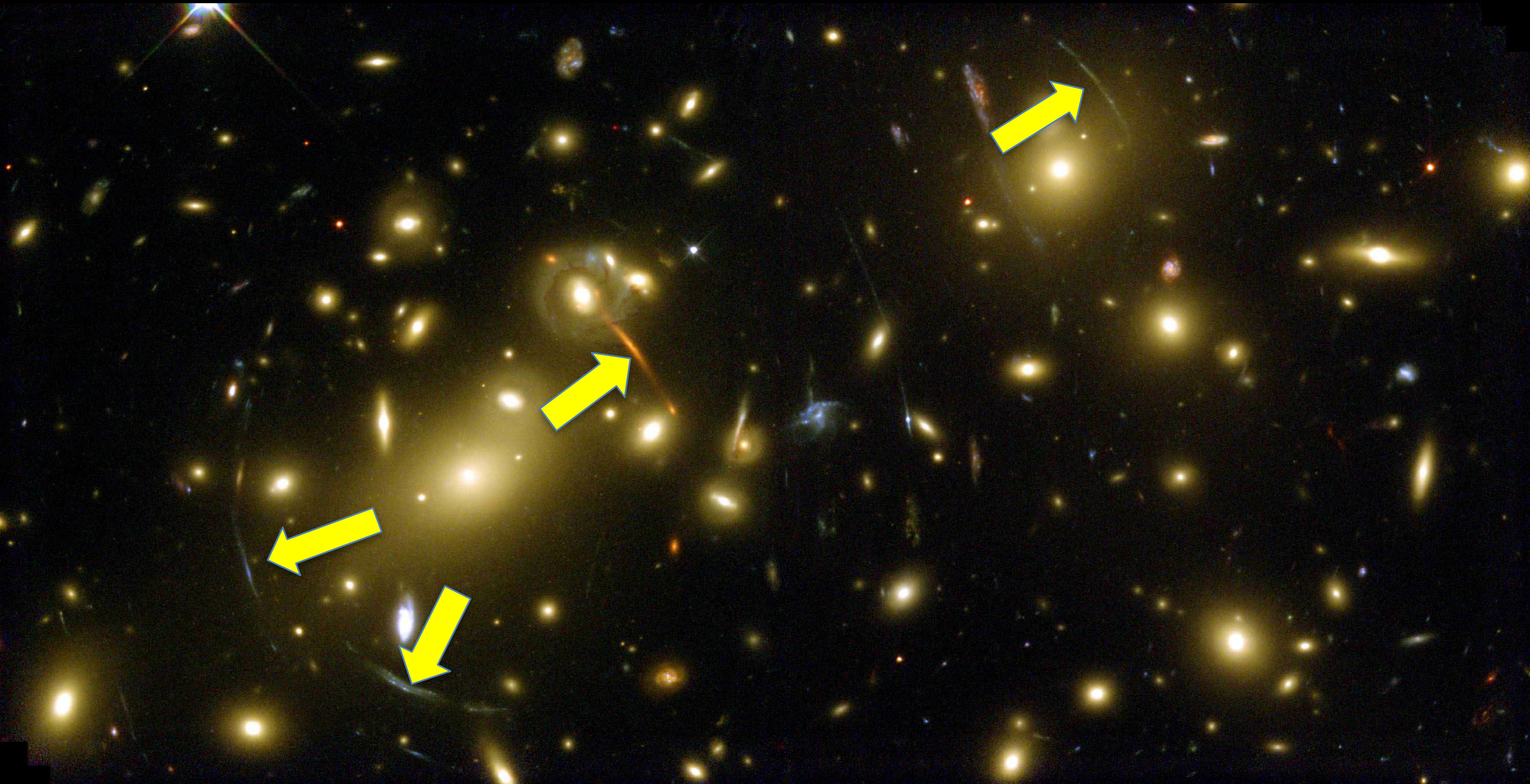


Every galaxy is imbedded in the halo of DM.

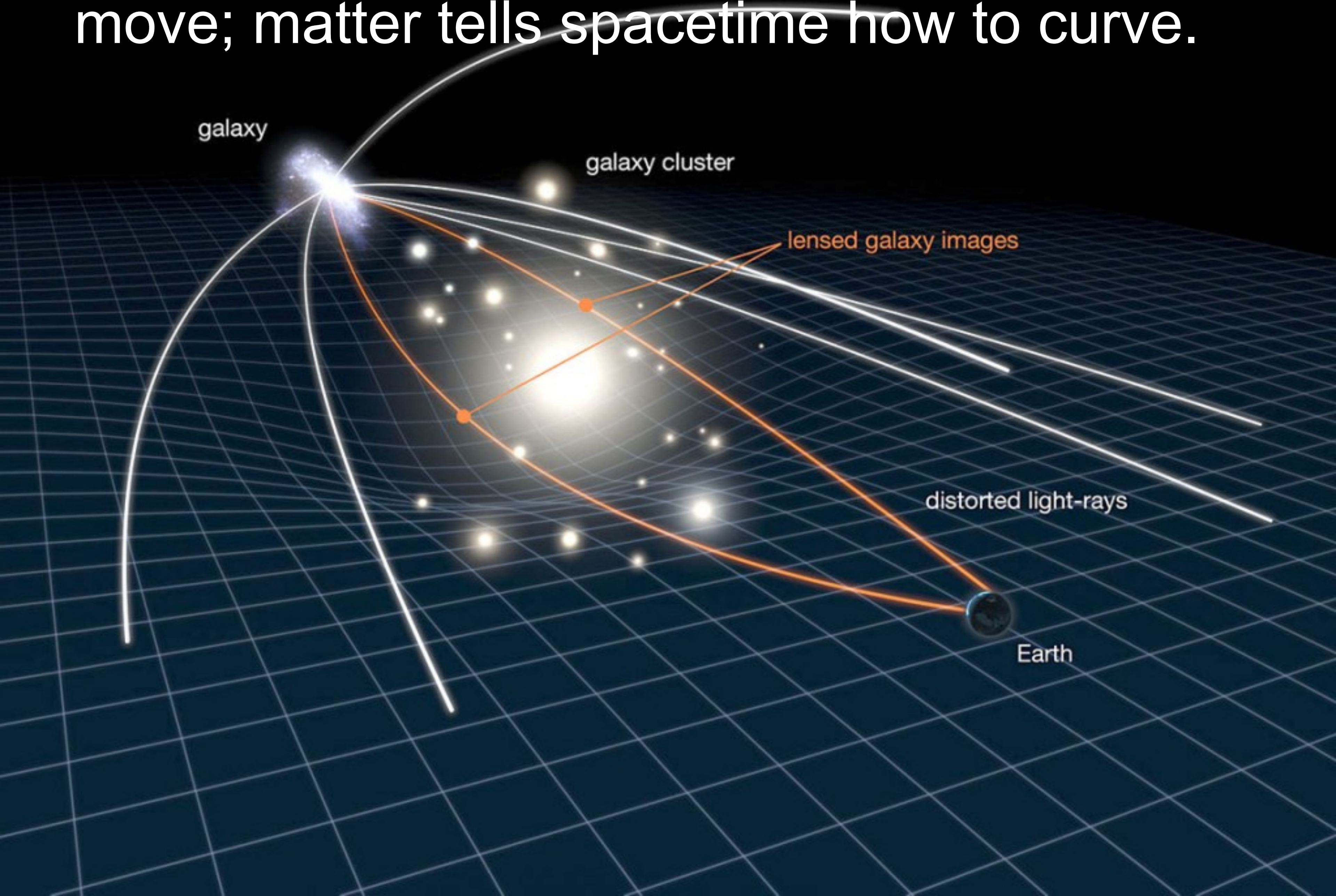


Abell Cluster viewed from Hubble Telescope

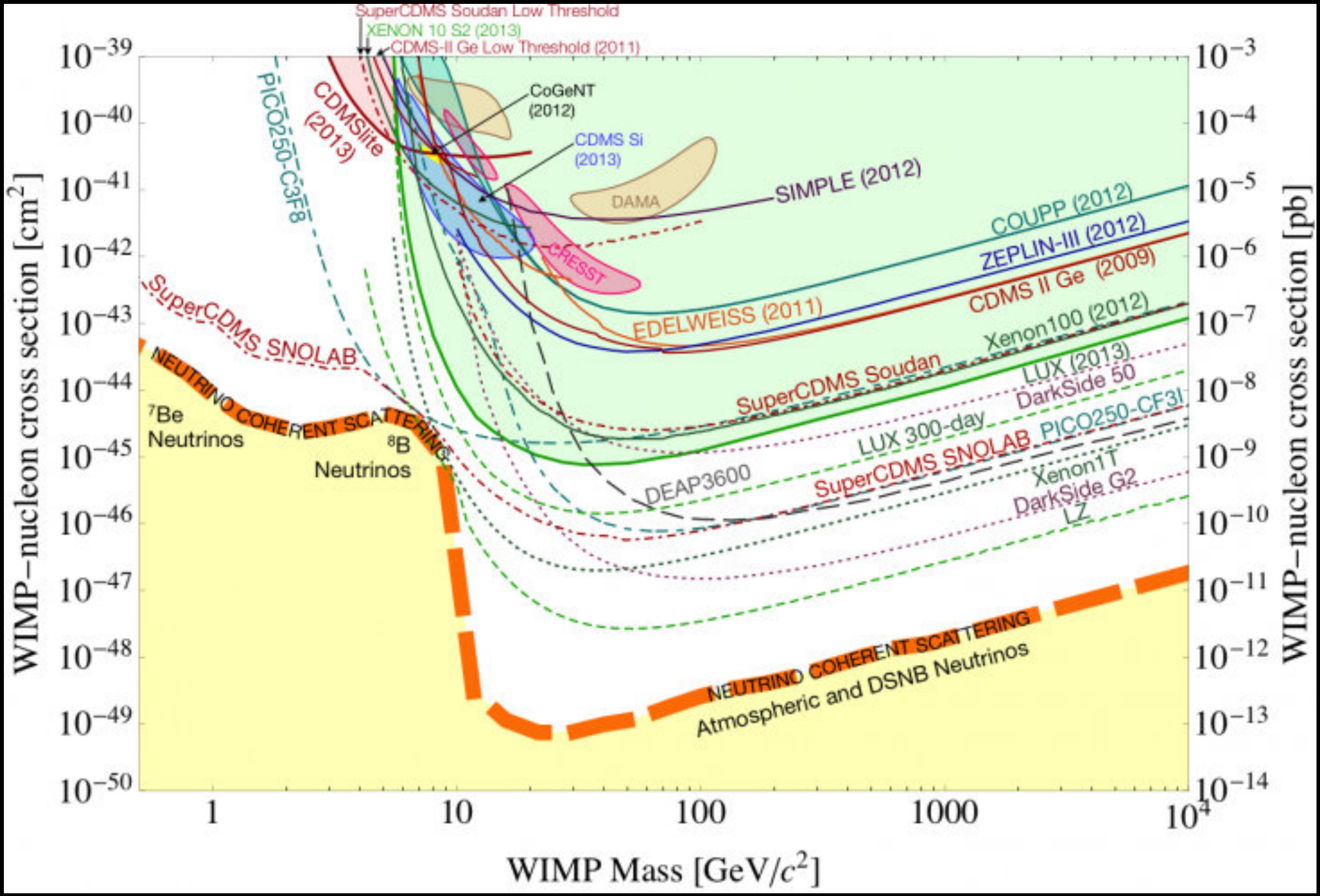
The visible gravitational lensing effect cannot be explained unless there exists additional gravity provided by invisible matter.



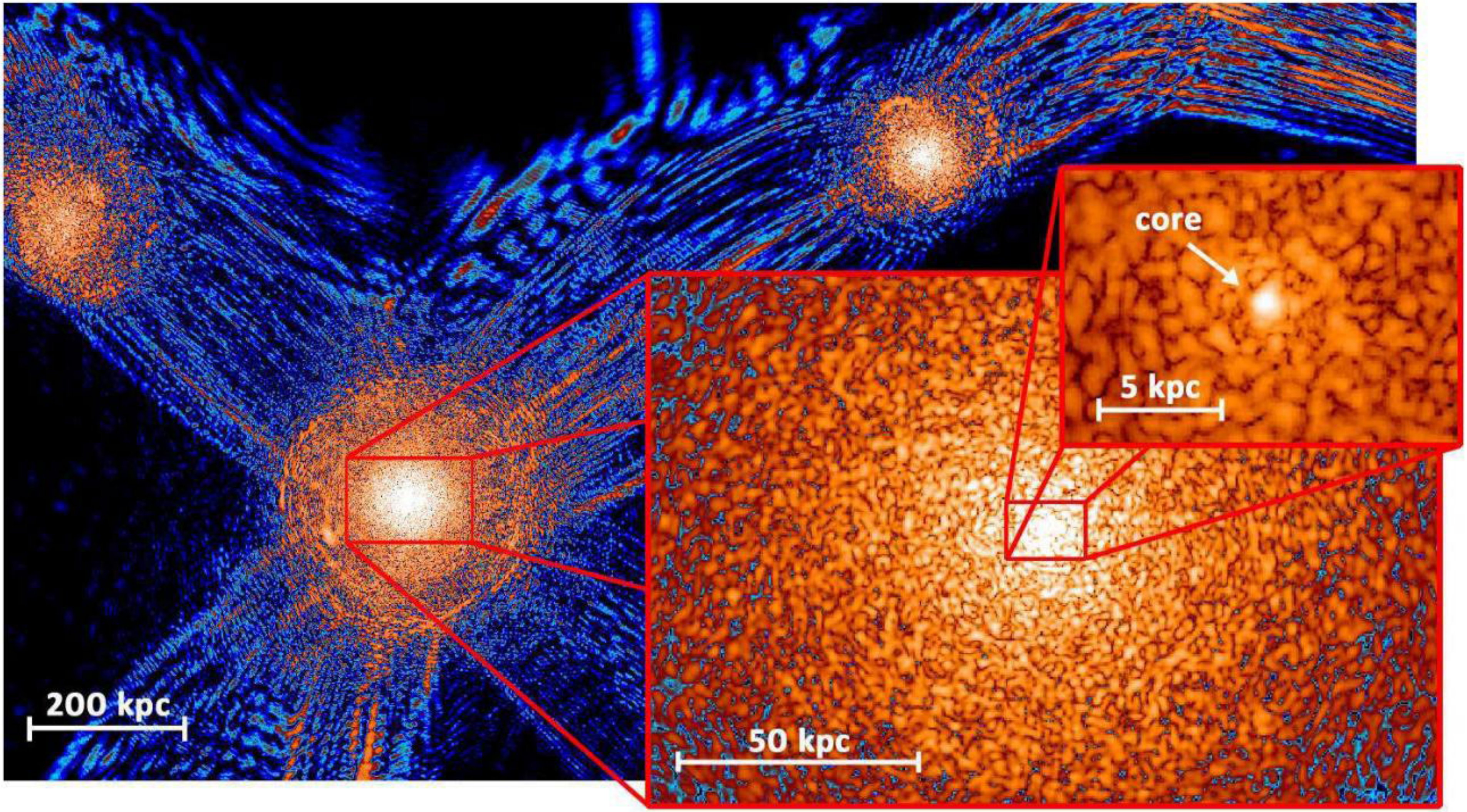
John Wheeler: Spacetime tells matter how to move; matter tells spacetime how to curve.



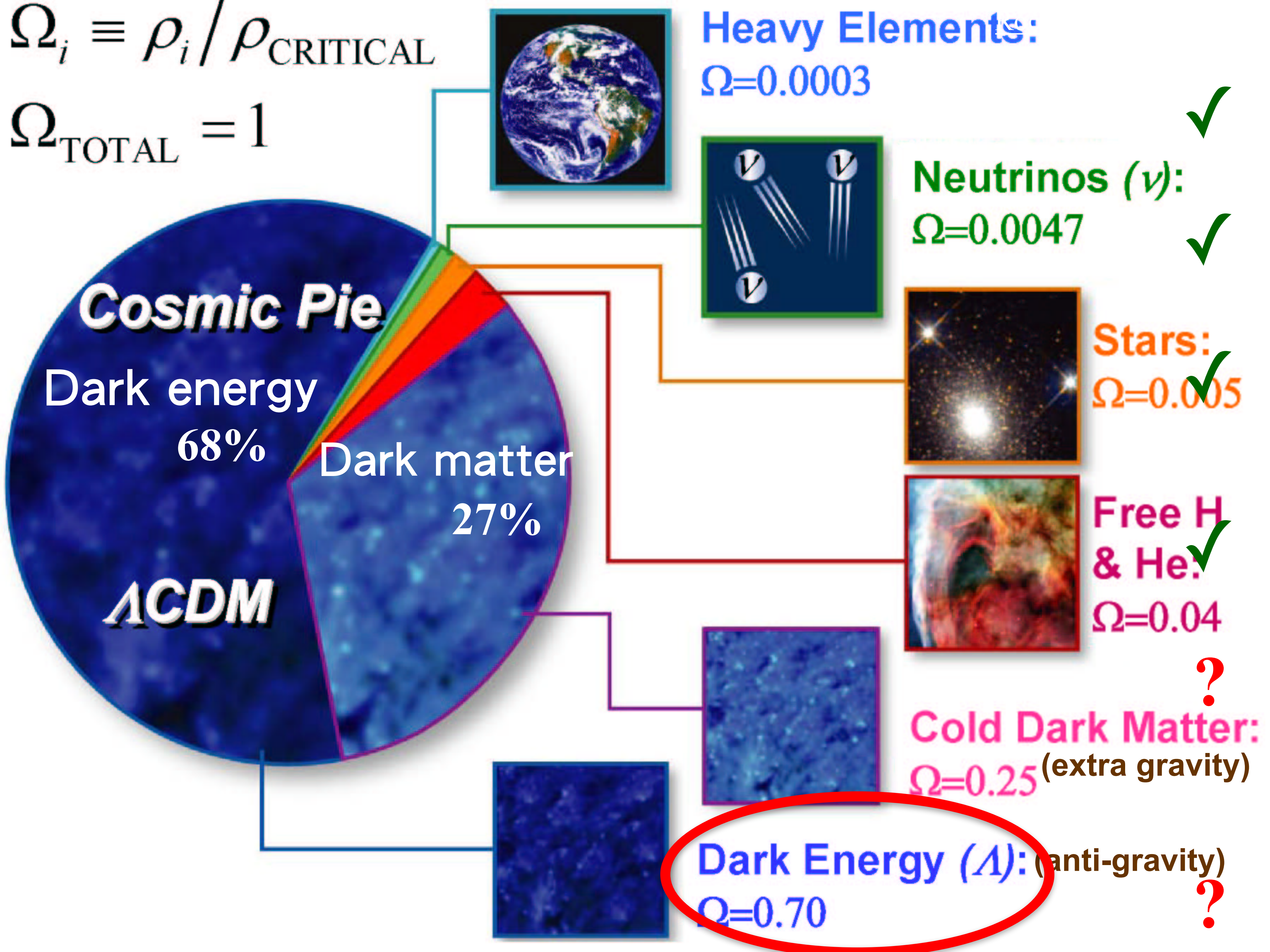
WIMP Dark Matter Not Found!



Axion-like BEC Dark Matter?

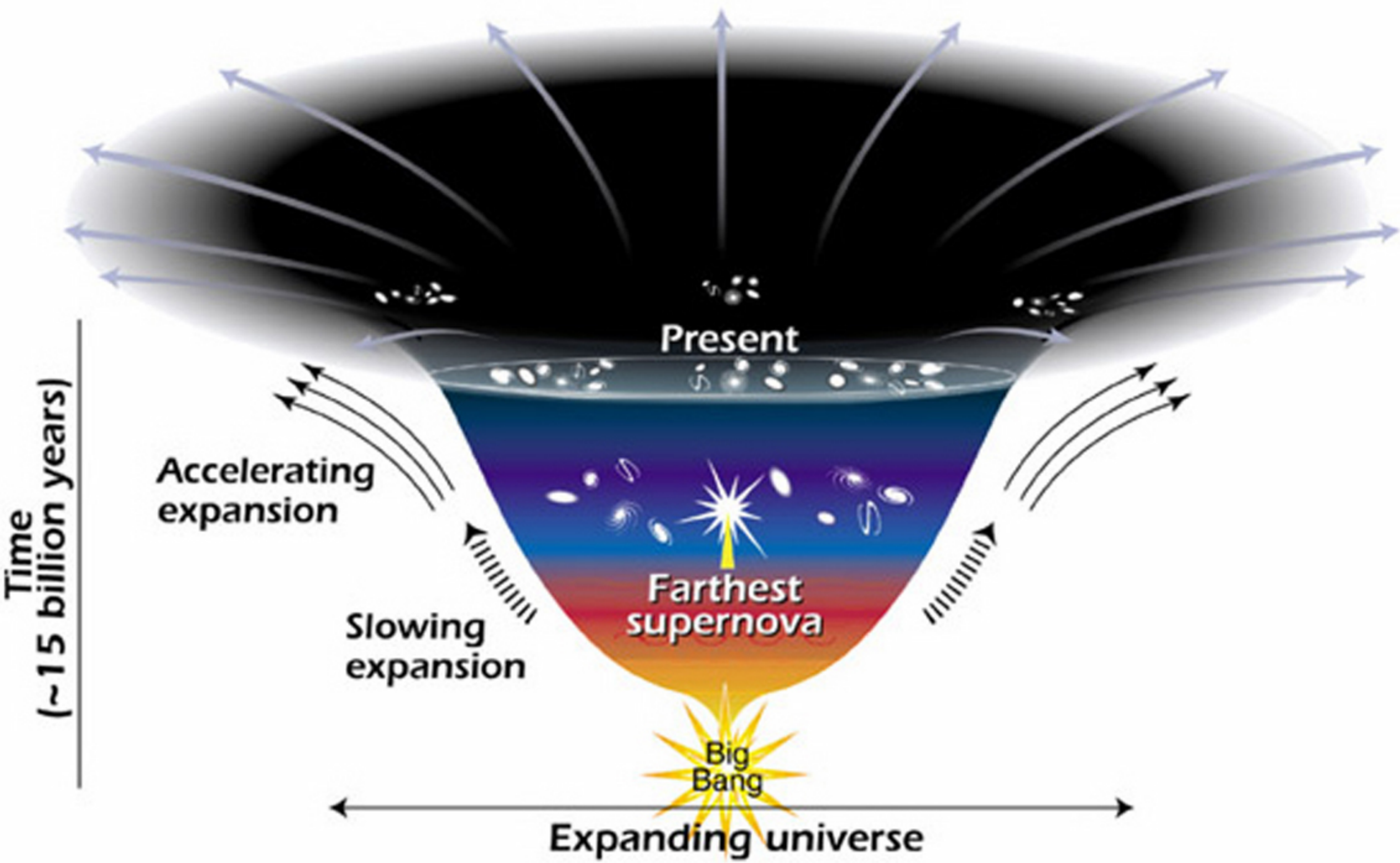


Dark Energy



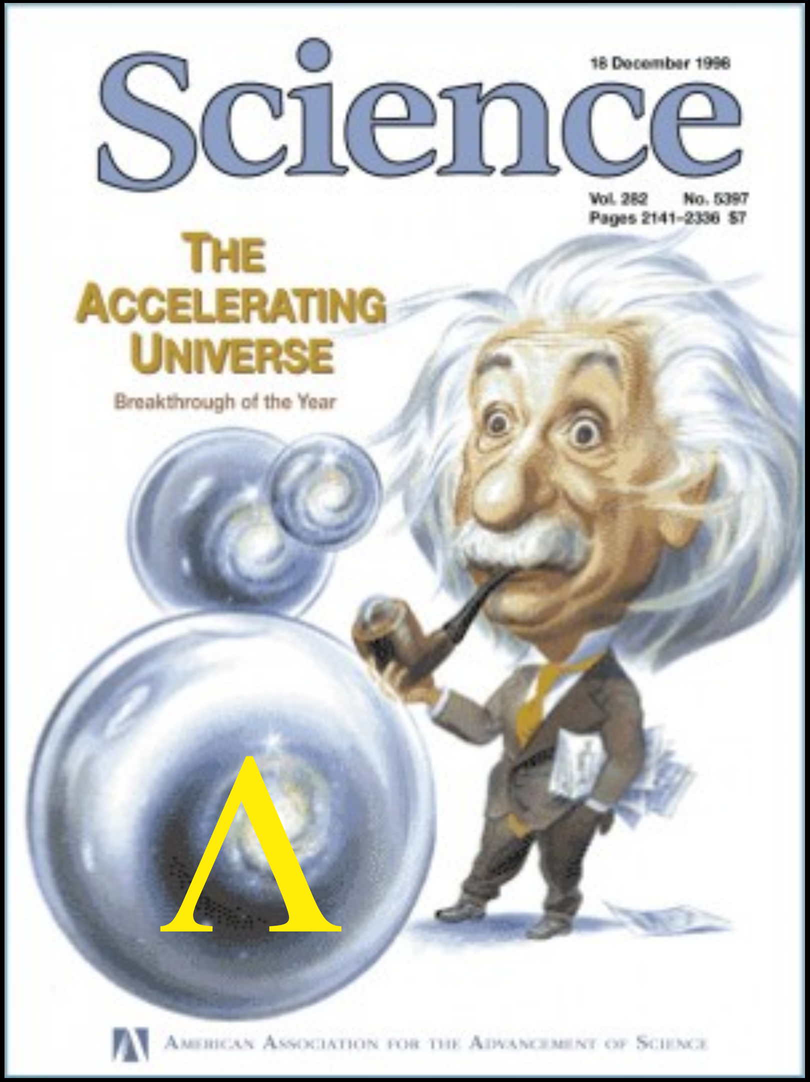
$\Omega_i \equiv \rho_i / \rho_{\mathrm{CRITICAL}}$
$\Omega_{\mathrm{TOTAL}} = 1$
Cosmic Pie
Dark energy
68%
Dark matter
27%
ΛCDM
Heavy Elements:
Ω=0.0003
Neutrinos (ν):
Ω=0.0047
Stars:
Ω=0.005
Free H
& He:
Ω=0.04
Cold Dark Matter:
Ω=0.25 (extra gravity)
Dark Energy (Λ): (anti-gravity)
Ω=0.70
?
?

“New” discovery (1998): Accelerating expansion of the universe
Requires the existence of a new substance – dark energy.



Einstein's cosmological constant a natural candidate for dark energy

Once Einstein knew the universe was expanding, he discarded the **cosmological constant,** which he introduced in his general relativity theory to prevent the gravitational collapse of a galaxy, as an unnecessary **fudge factor**. He later called it the "biggest blunder of his life," according to his fellow physicist George Gamow. Today astronomers refer to one theory of dark energy as Einstein's **cosmological constant**



Dark Energy: Dynamical Field vs. Cosmological Constant

DE eq. of state: $p = w\rho, \quad w = w_0 + w_a(1-a).$

$w_0 = -1.04^{+0.72}_{-0.69}, \quad w_a < 1.32.$ (95%; Planck+WP+BAO)

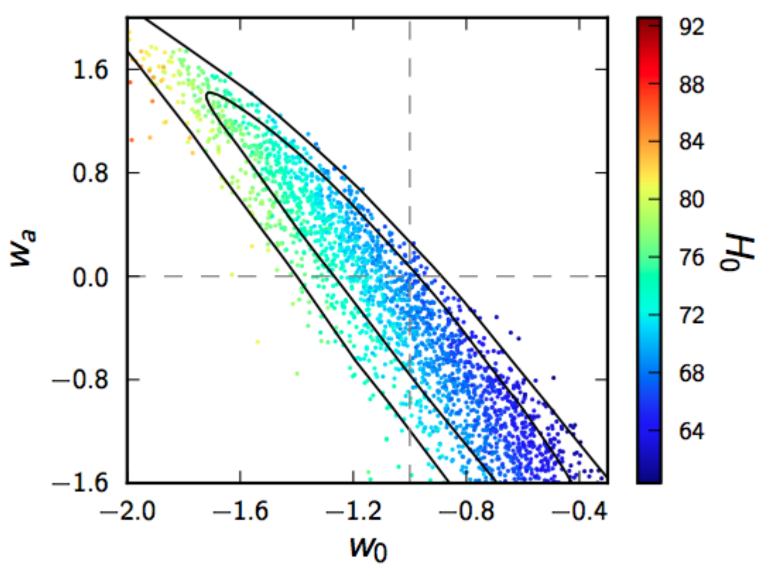


Fig. 35. 2D marginalized posterior distribution for w_0 and w_a for *Planck*+WP+BAO data. The contours are 68% and 95%, and the samples are colour-coded according to the value of H_0. Independent flat priors of $-3 < w_0 < -0.3$ and $-2 < w_a < 2$ are assumed. Dashed grey lines show the cosmological constant solution $w_0 = -1$ and $w_a = 0$.

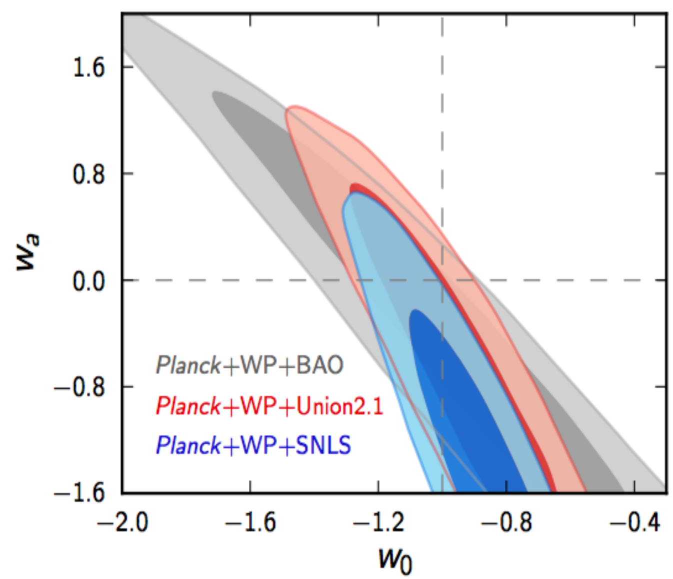
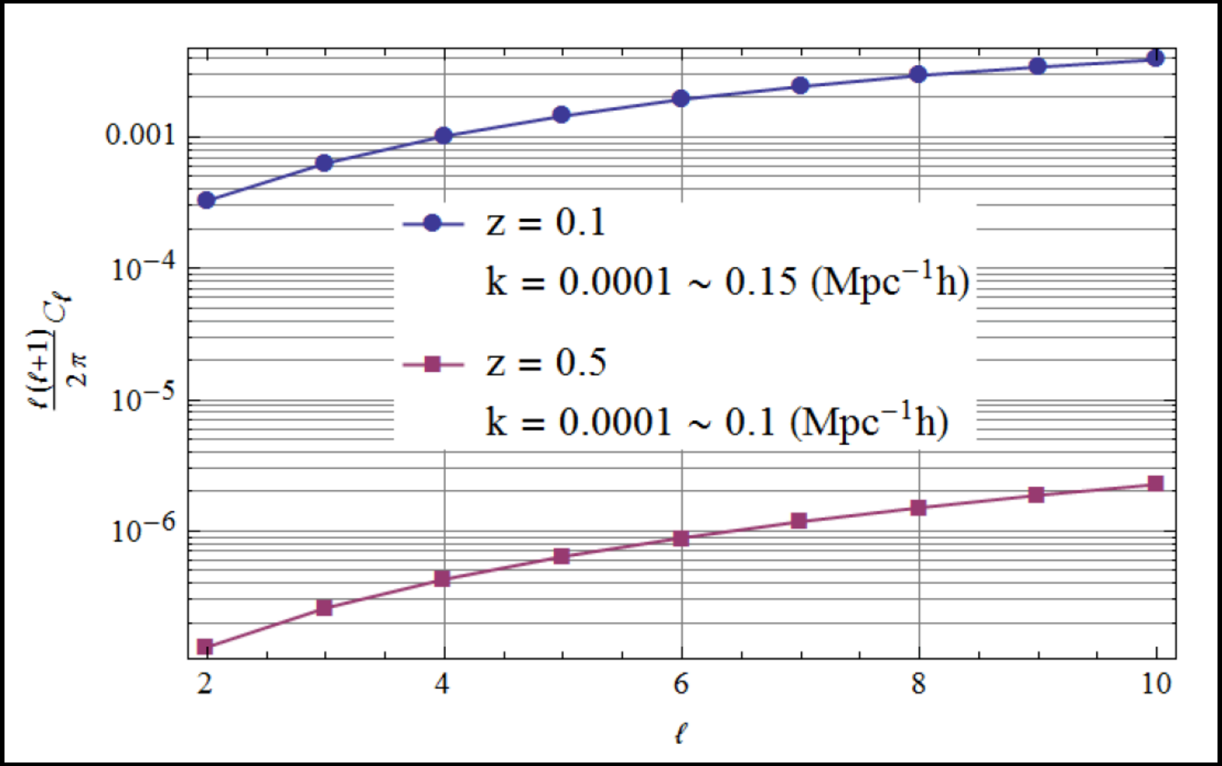


Fig. 36. 2D marginalized posterior distributions for w_0 and w_a, for the data combinations *Planck*+WP+BAO (grey), *Planck*+WP+Union2.1 (red) and *Planck*+WP+SNLS (blue). The contours are 68% and 95%, and dashed grey lines show the cosmological constant solution.

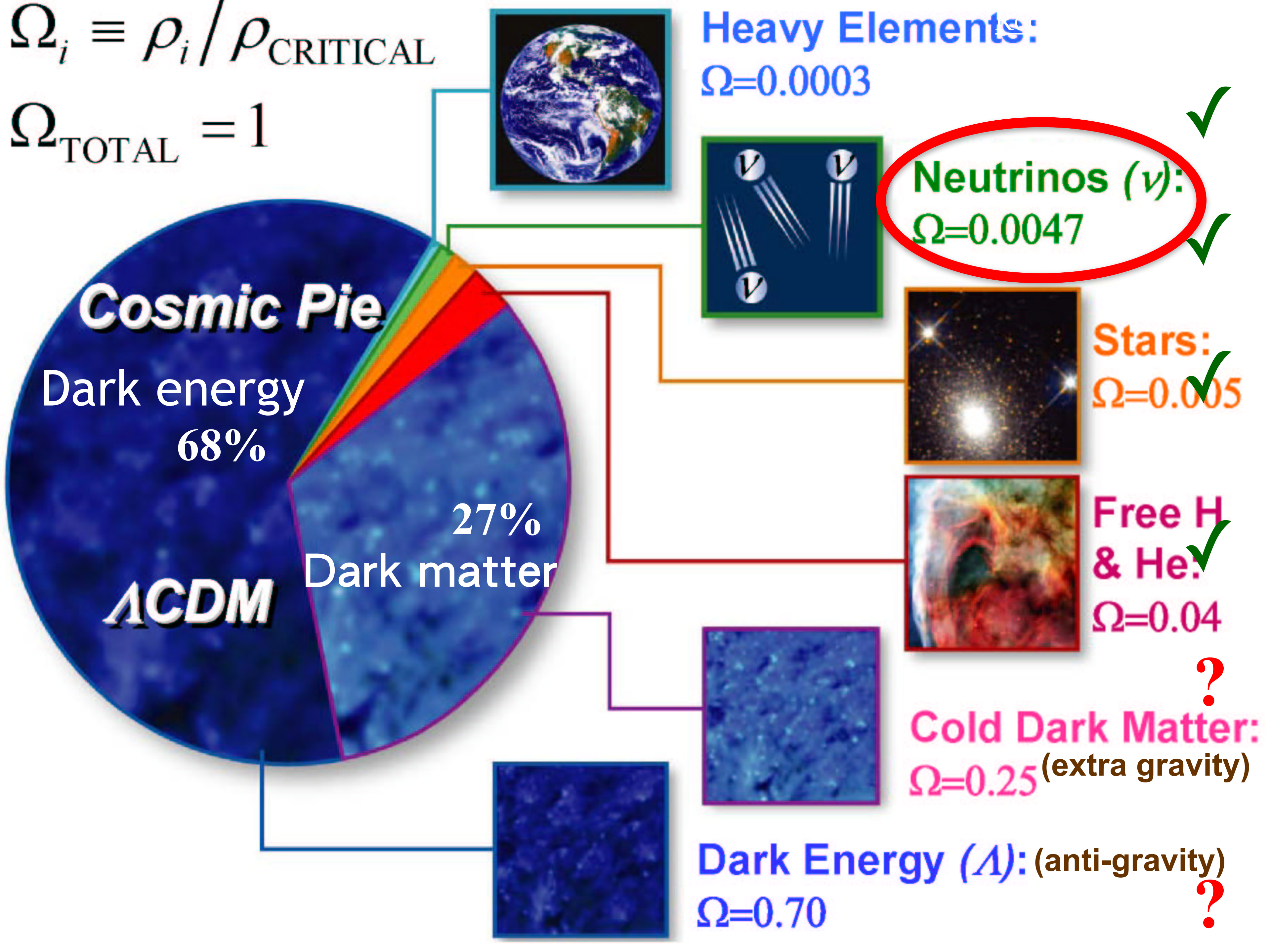
Dark Energy Induced Anisotropy in Cosmic Expansion

Chien-Ting Chen & PC, arXiv:1704.06797



The total luminosity distance power spectrum for ℓ = 2 to 10 at z = 0.1 with the integration range from k = 0.0001 to 0.15 Mpc^{-1}h (blue) and at z = 0.5 with the integration range from k = 0.0001 to 0.1 Mpc^{-1}h (purple).

Neutrinos



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$\Omega_{\mathrm{TOTAL}} = 1$
Cosmic Pie
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68%
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Heavy Elements:
Ω=0.0003
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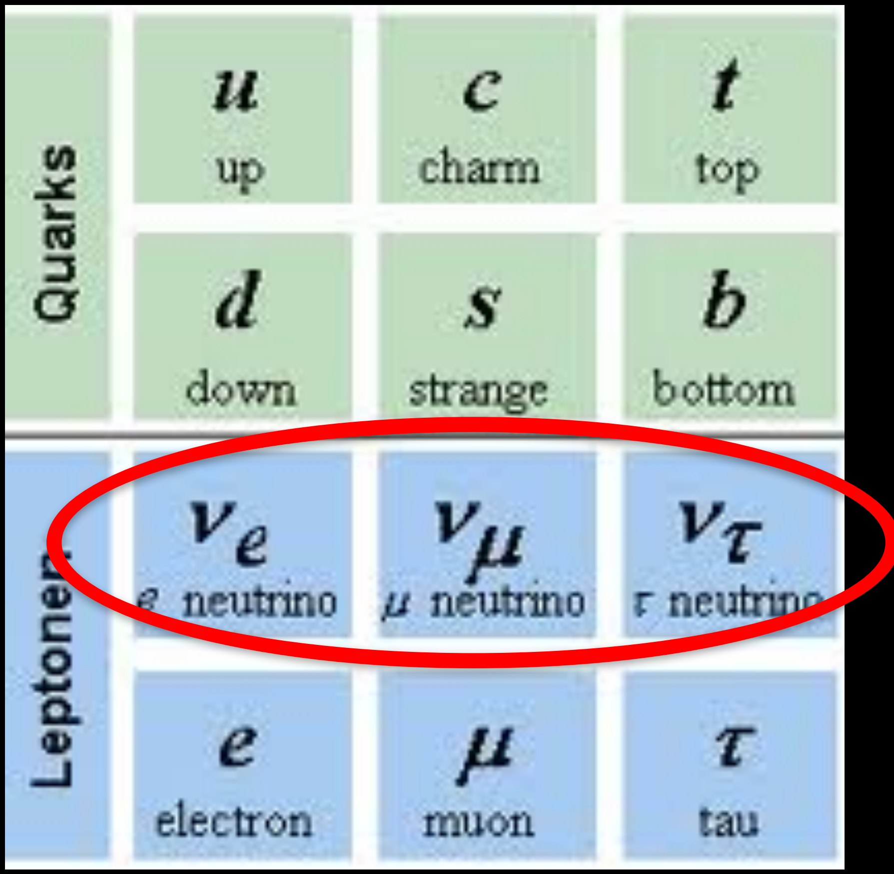
Ω=0.005
Free H
& He:
Ω=0.04
?
Cold Dark Matter:
Ω=0.25 (extra gravity)
Dark Energy (Λ): (anti-gravity)
Ω=0.70
?

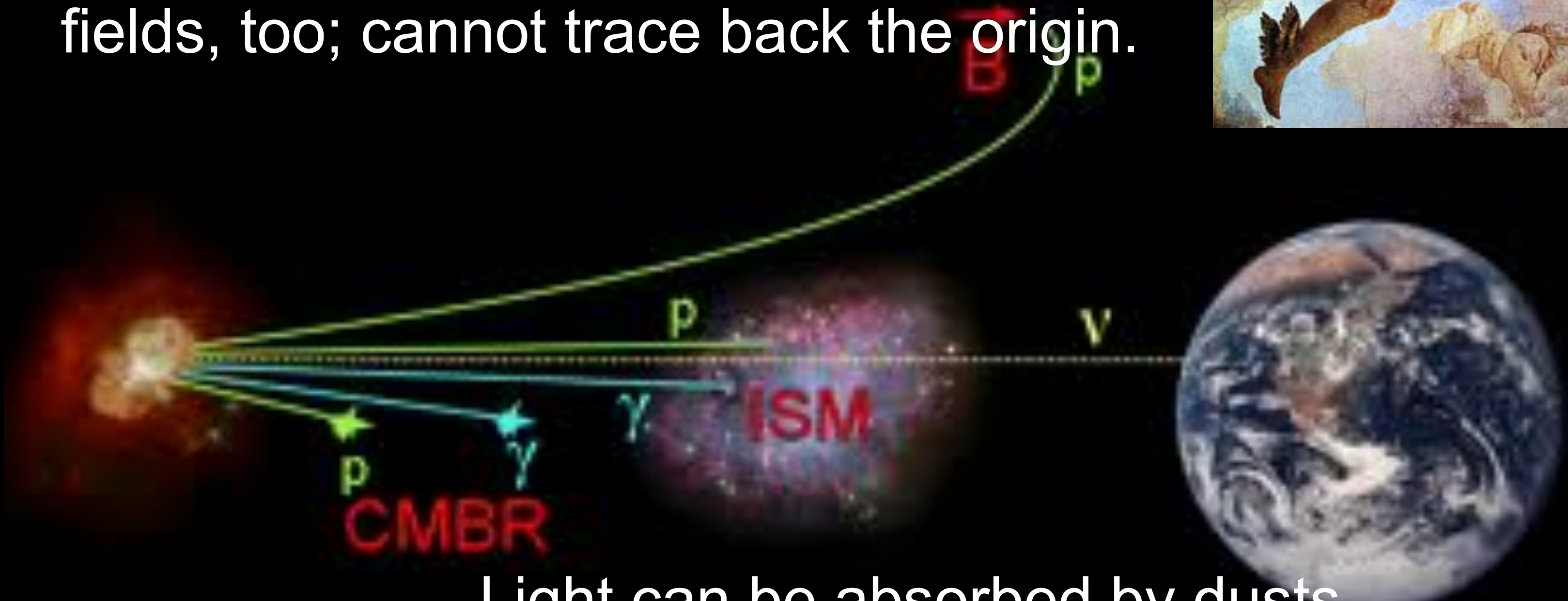
Standard model of particle physics
12 building blocks, each with a different “flavor”.



Neutrinos contribute ¼, yet they are least understood.

Neutrinos: The longest distance messenger in the universe

Protons would interact with CMB and be lost; bent by inter-galactic magnetic fields, too; cannot trace back the origin.

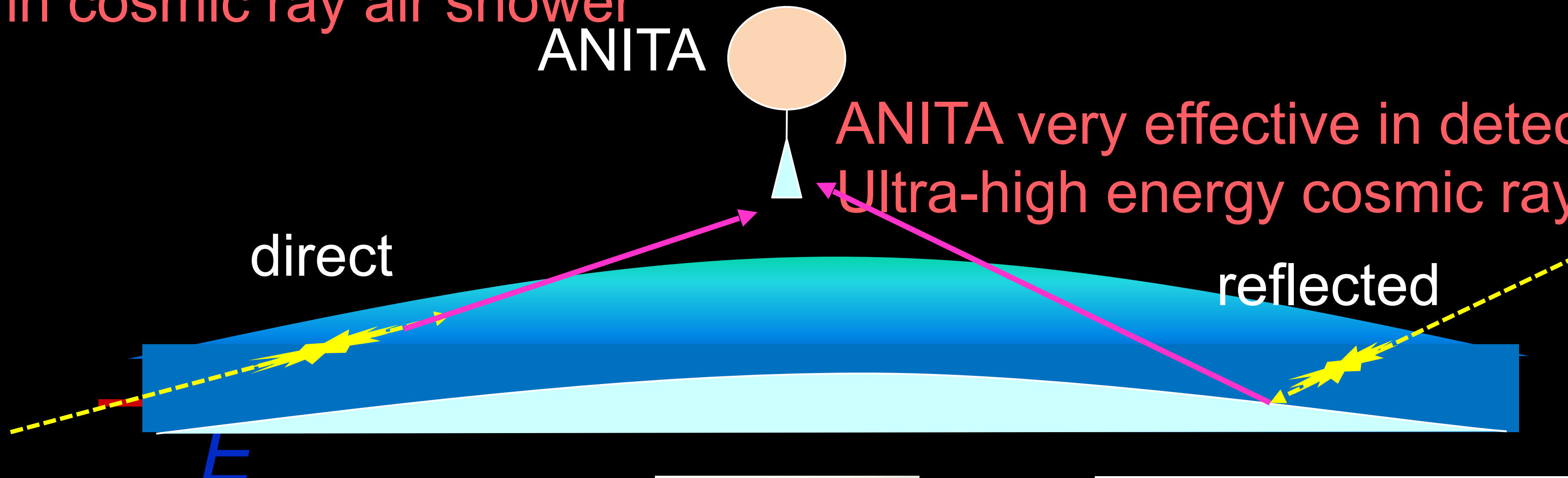


Light can be absorbed by dusts.

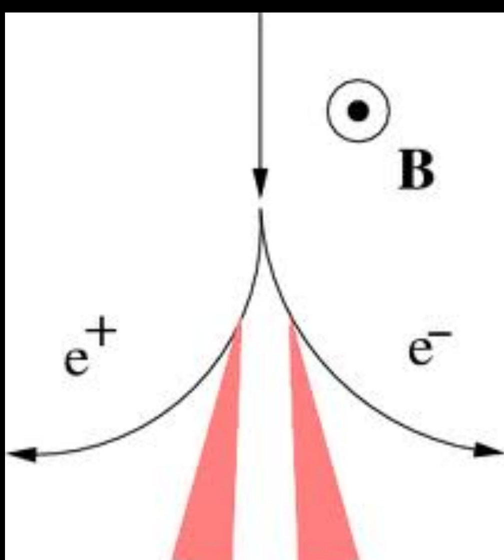
ANITA-I, II, III, IV (2006-2018)

Accidental discovery made by the NTU team

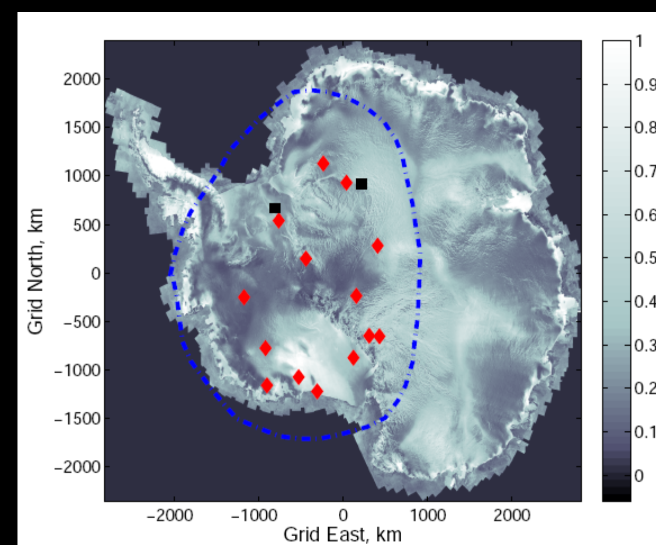
Geomagnetic field induced synchrotron radiation by e+e- paris in cosmic ray air shower



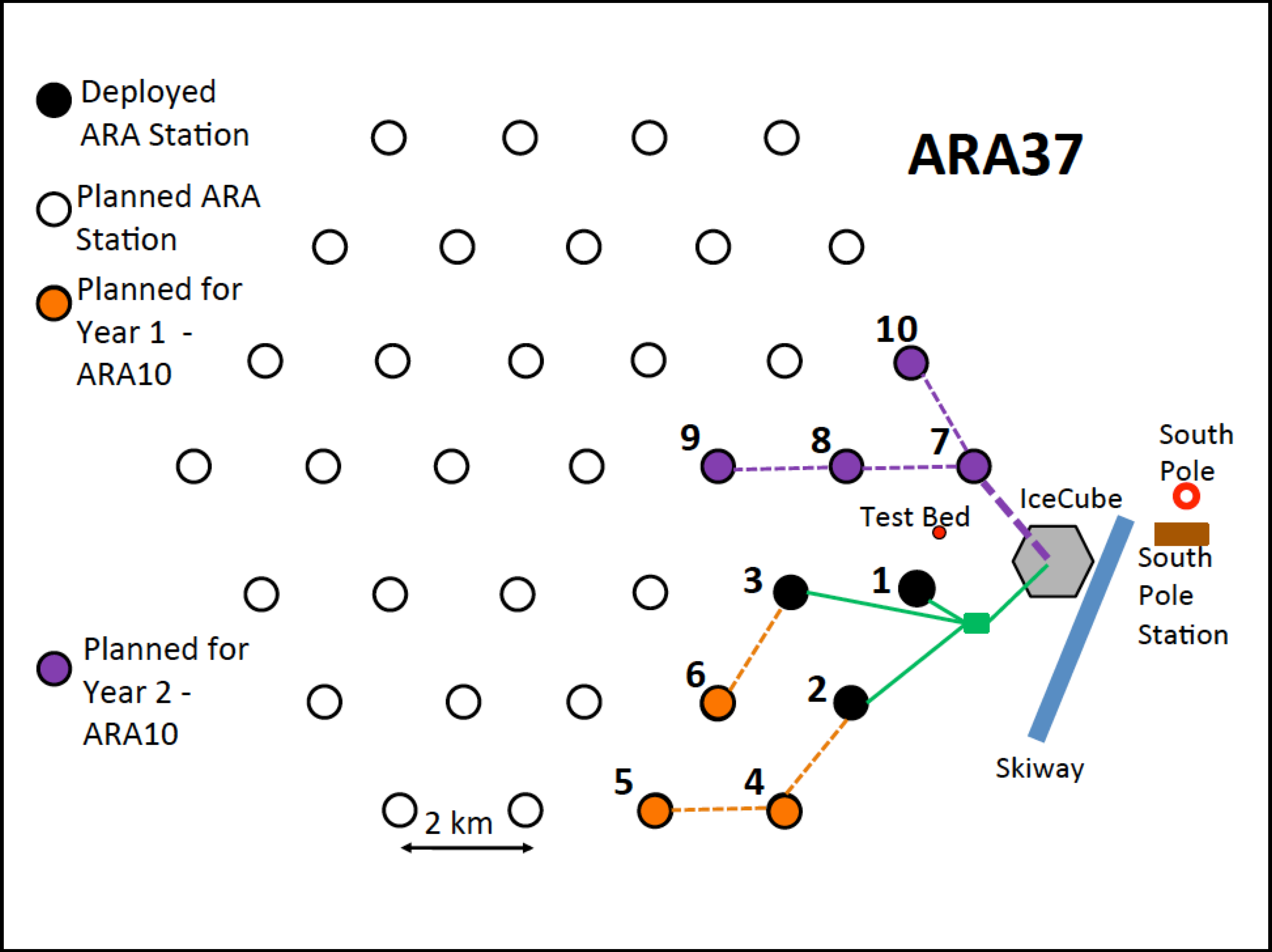
ANITA very effective in detecting Ultra-high energy cosmic rays



NTU Prof. Jiwoo Nam
First discovered this.



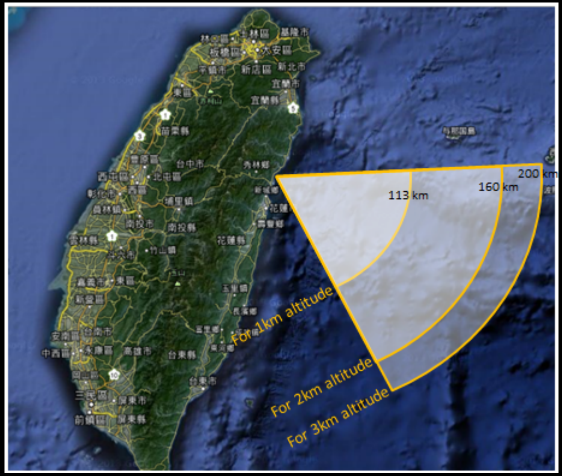
ARA Cosmic Neutrino Observatory

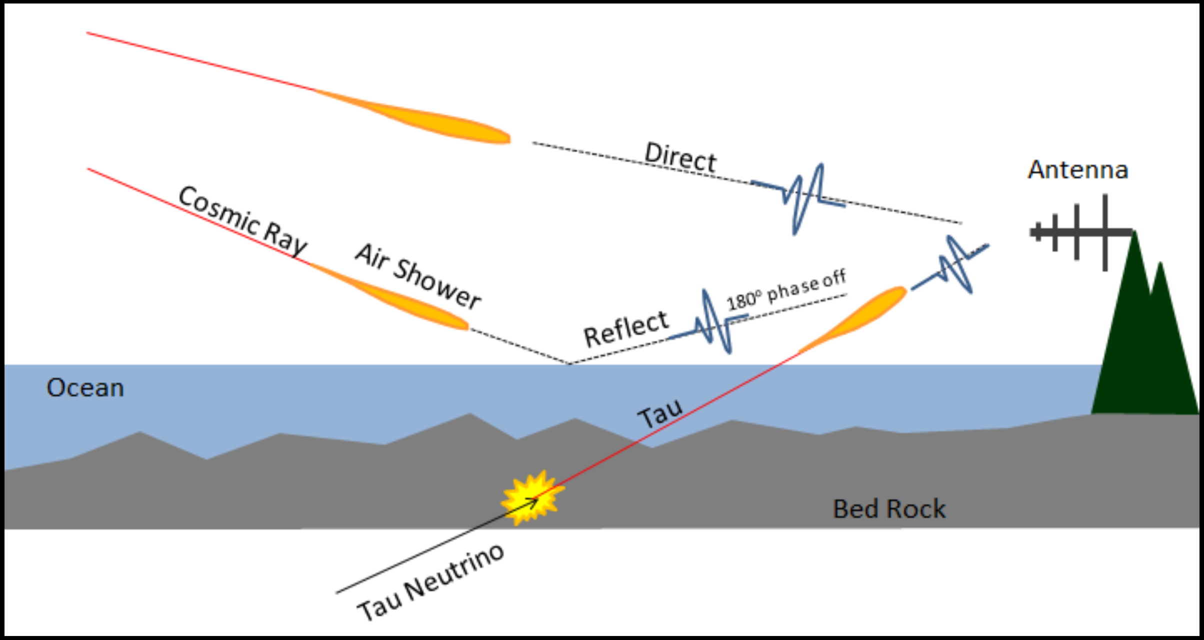


ROC's first major science project at South Pole

TAROGE Observatory

(Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emission)

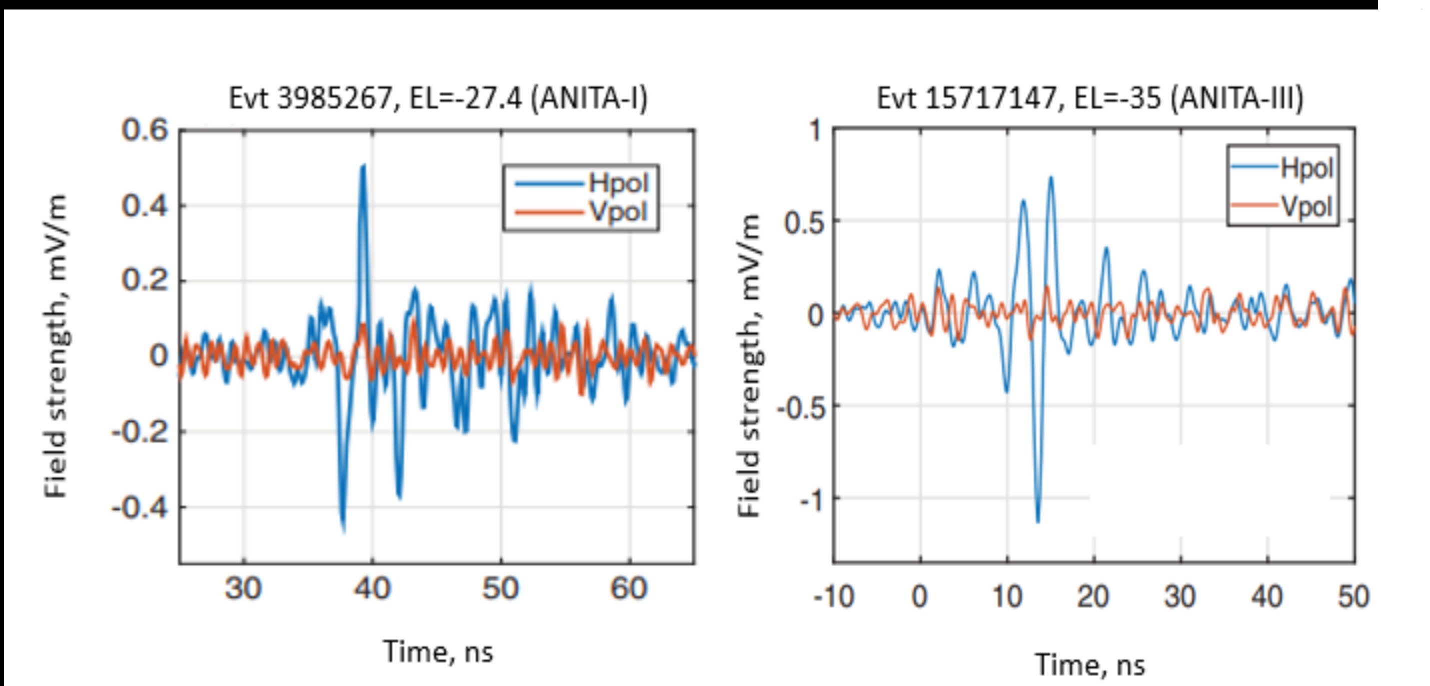


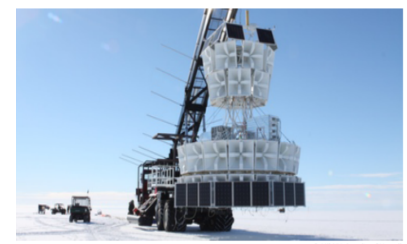


Installation of TAROGE-3, July 2018

ANITA discovered two anomalous up-pointing shower events:

Cannot be explained by Standard Model





APS physics | Physics

Synopsis: ANITA Spots Another Inverted Cosmic-Ray-Like Event

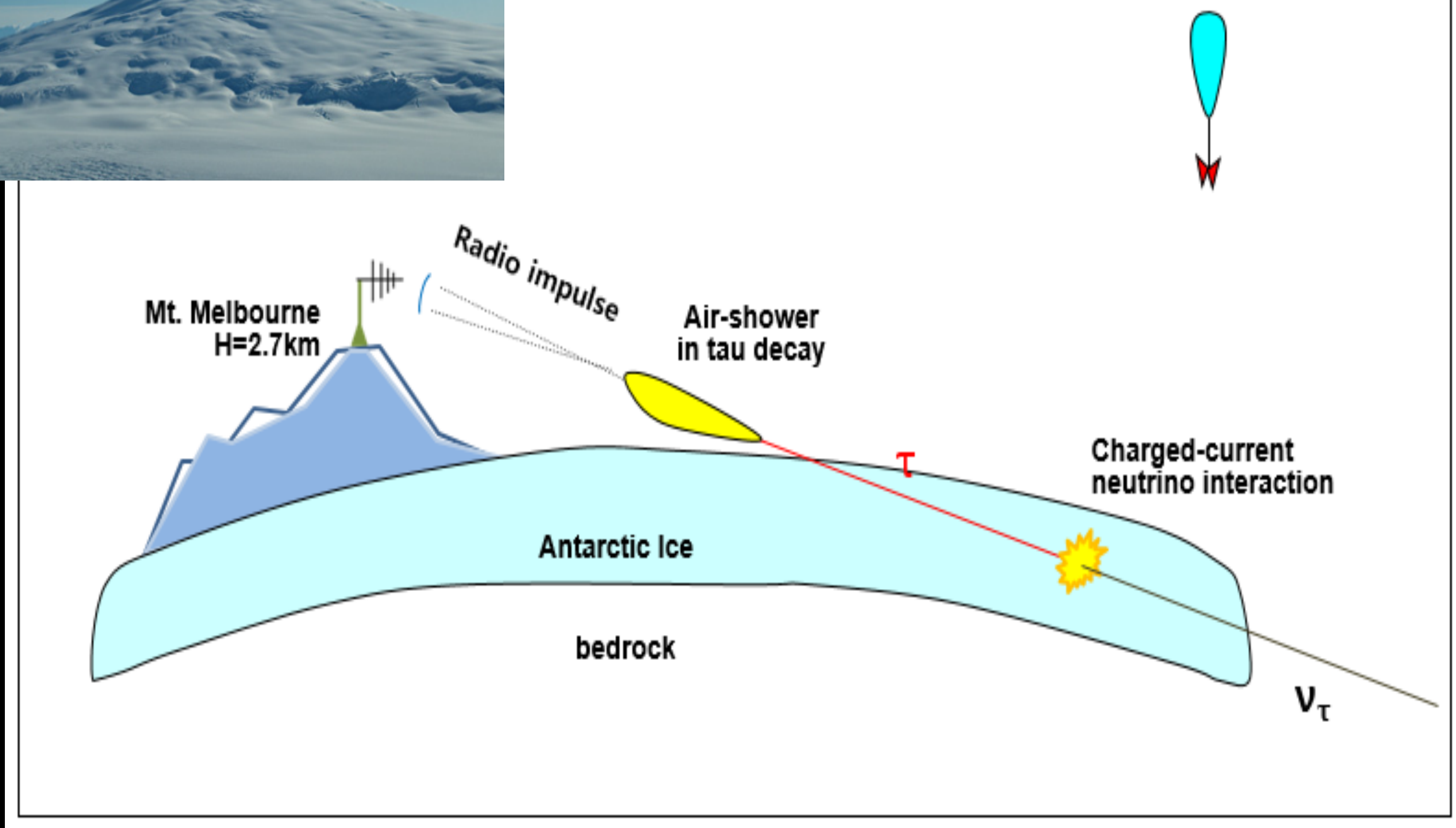
October 18, 2018

A fountain of high-energy particles that resembles an upside-down cosmic-ray ...er is detected for the second time by the Antarctic Impulsive Transient ...na.

C. Miki/University of Hawaii

...energy cosmic-ray particles constantly bombard Earth. When one of these ...les collides with molecules in our atmosphere, it triggers a cascade of secondary ...les, collectively known as a cosmic-ray air shower. But that isn't the only way ...energy particles interact with Earth. On 28 December 2006, the balloon-borne ...tic Impulsive Transient Antenna (ANITA) detected an "upward" air shower—a ...in of high-energy particles erupting from Antarctica's icy ground. The team now ...s the observation of a second such event, which occurred on 12 December 2014.

TAROGE-M: To nail down up-pointing events

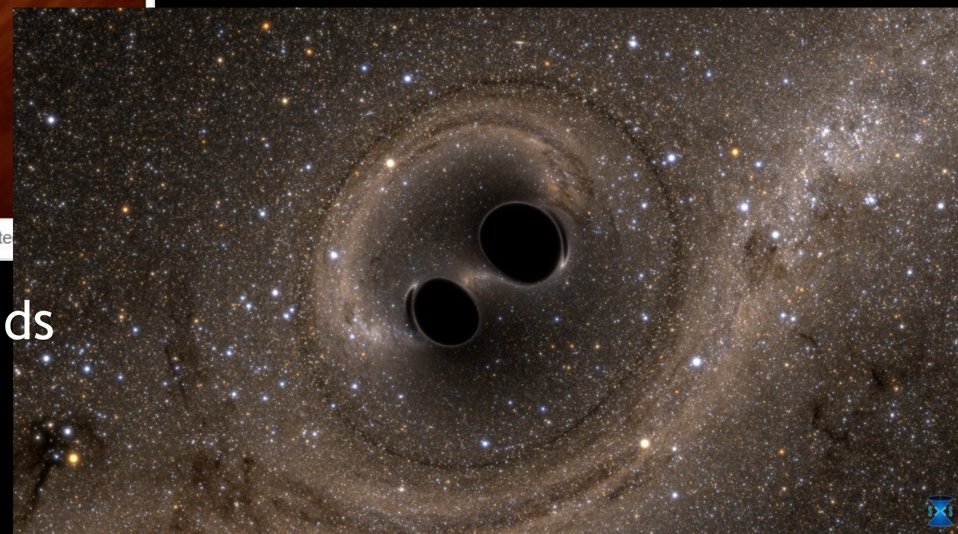


Black Holes

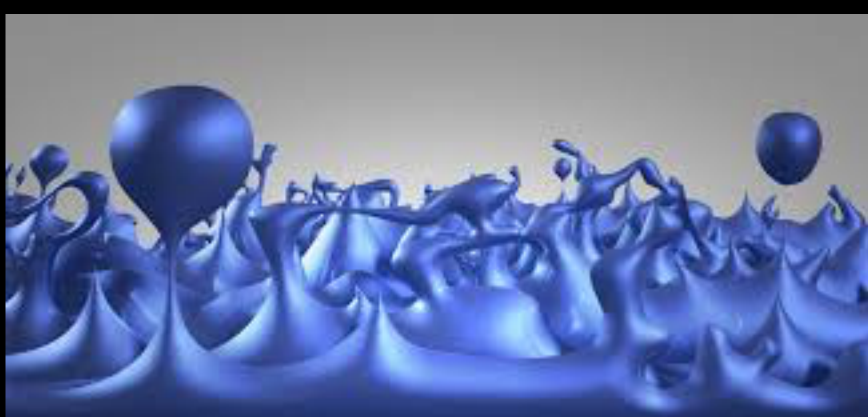
Three types of black holes

Artist's concept illustrating a supermassive black hole with millions to billions times the mass of our sun (Image: NASA/JPL-Calte

Supermassive BHs (hundreds of thousands to billions solar masses)



Stellar BHs (several to tens solar masse

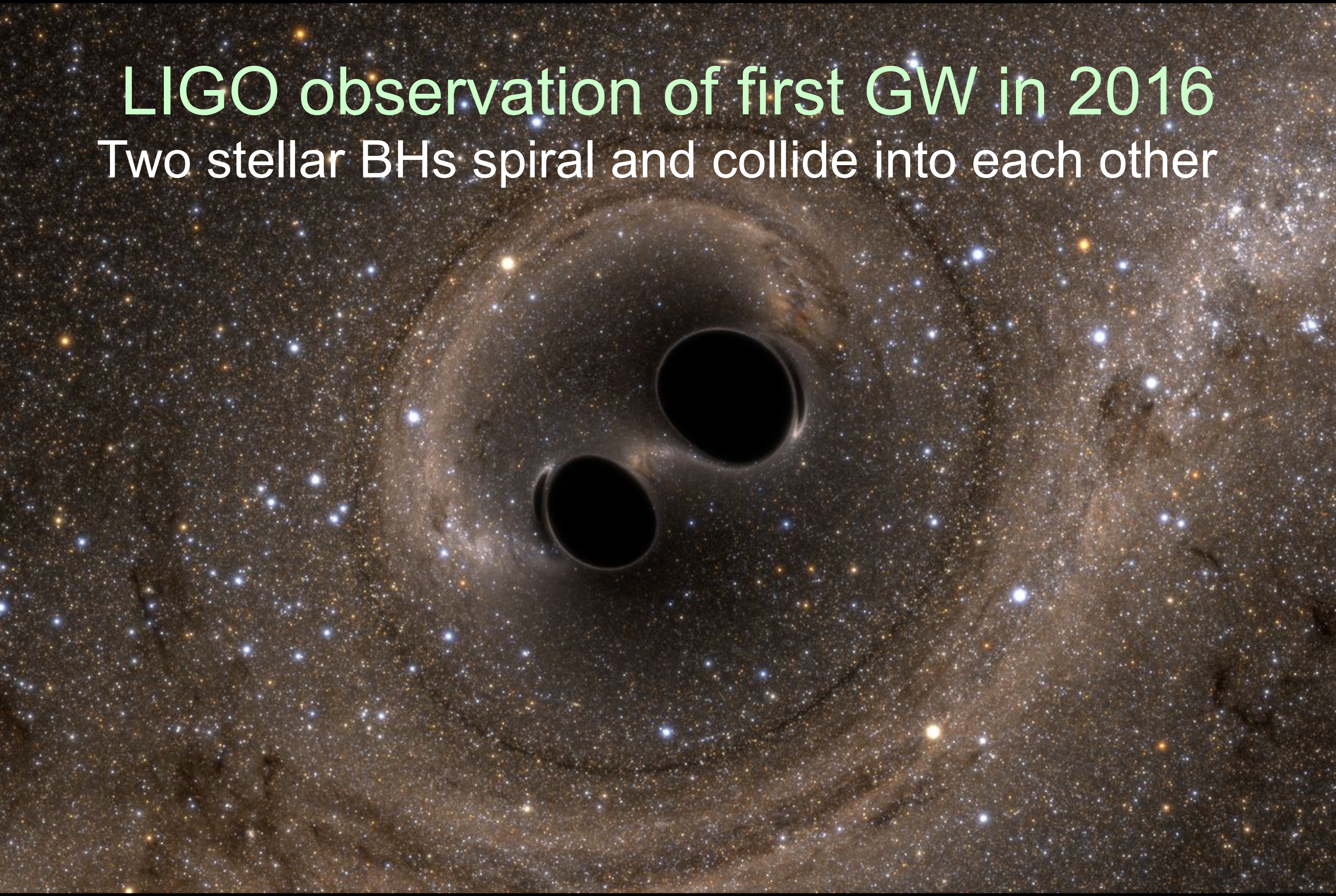


Primordial BHs (born around Big Bang era

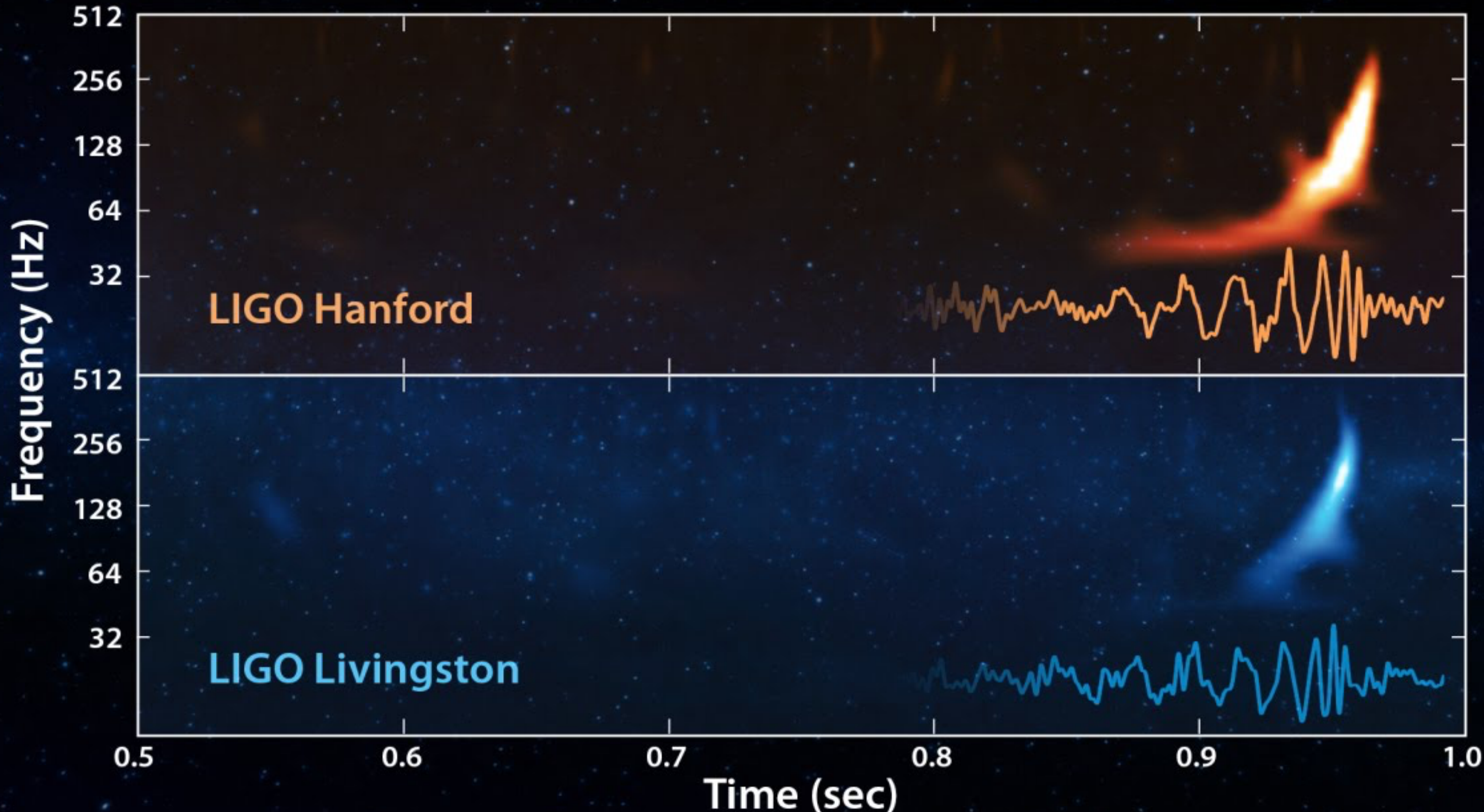
LIGO gravitational waves observatory

LIGO observation of first GW in 2016

Two stellar BHs spiral and collide into each other



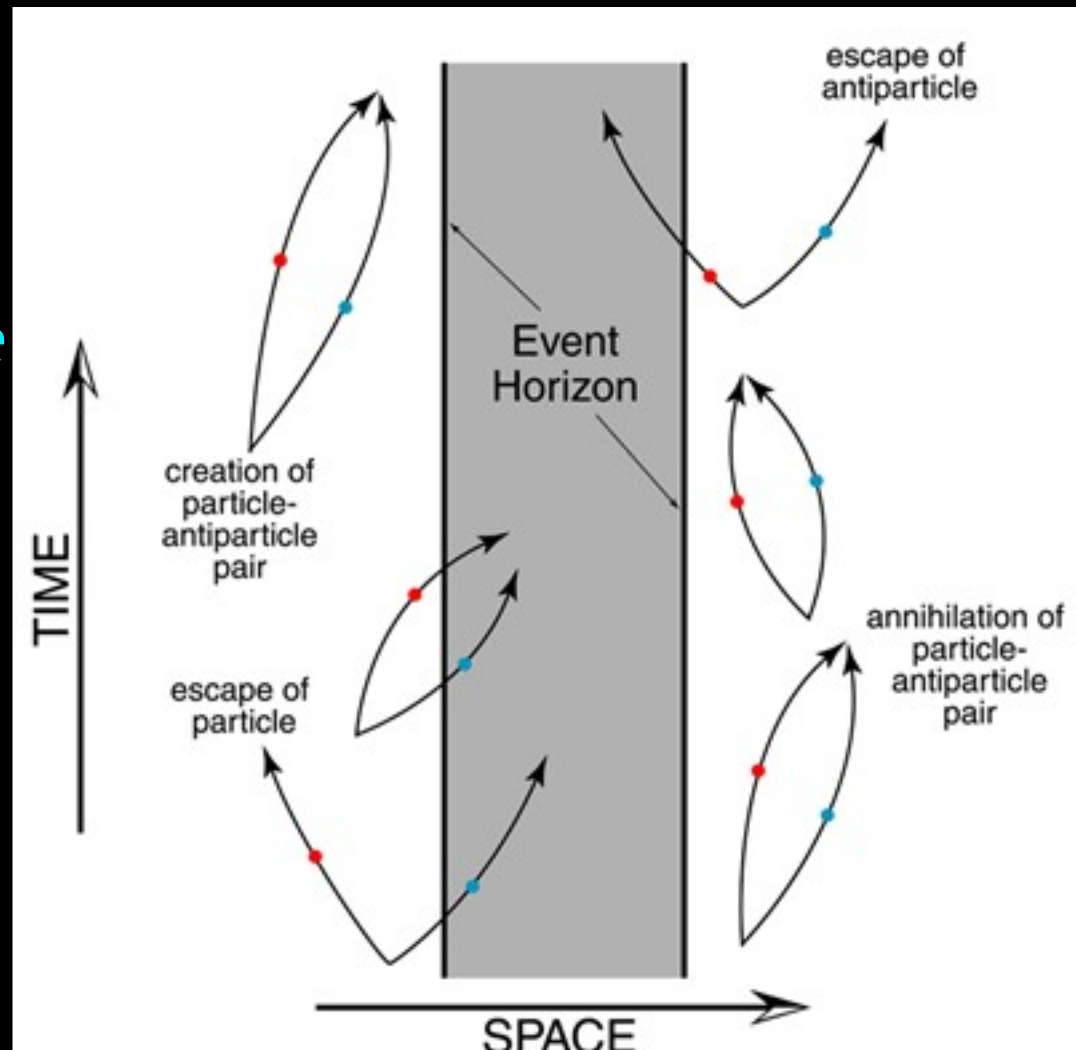
Simple algebra:
29+36=62+3



Black hole Hawking evaporation: Connecting gravity, QM, statistical mechanics in one stroke

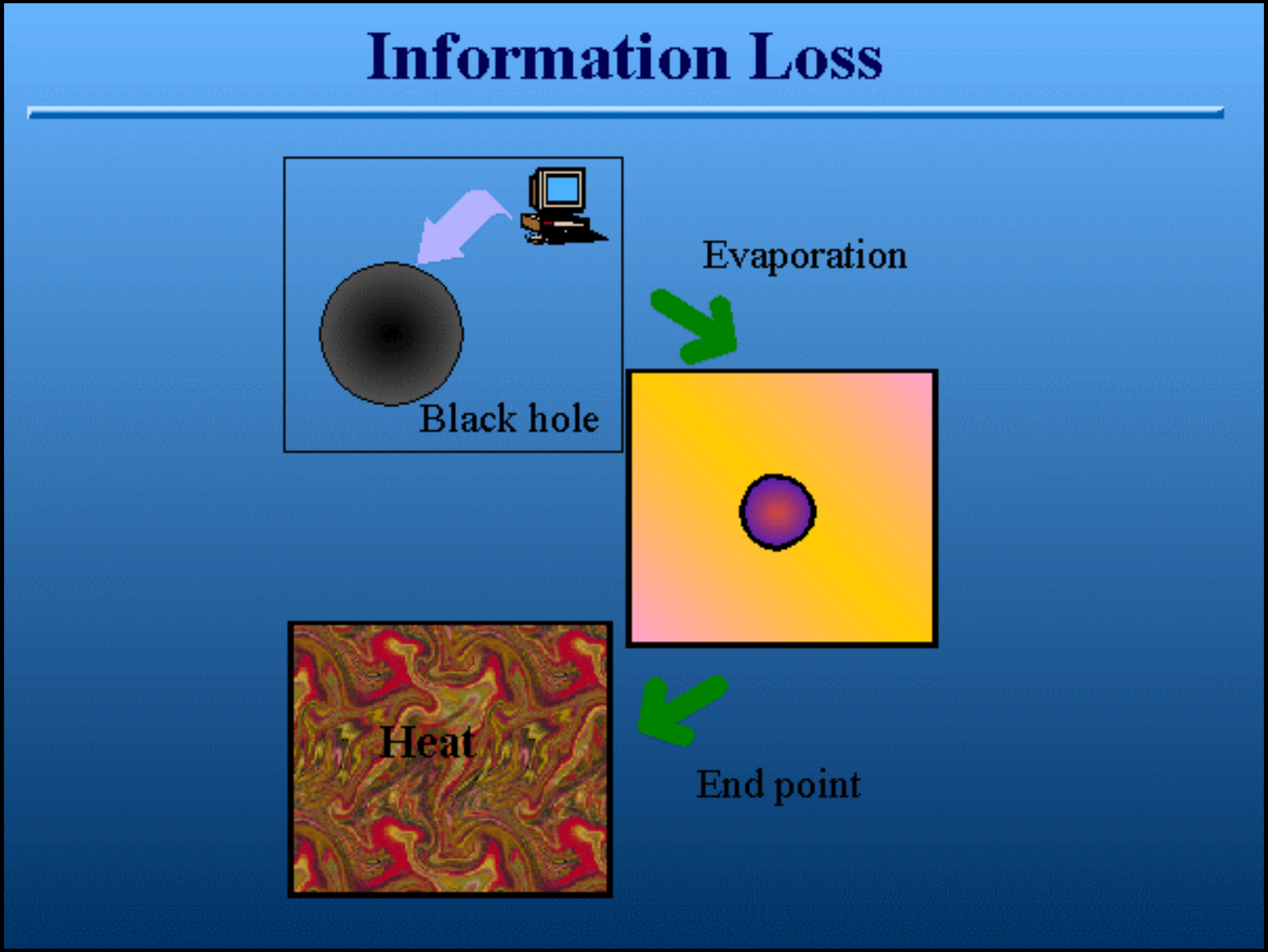
$$r_s = \frac{2GM}{c^2} \qquad g = \frac{GM}{r_s^2}$$

$$k_B T_H = \frac{\hbar c^3}{8\pi GM} = \frac{\hbar g}{2\pi c}$$



Information Loss

BH evaporation and information loss paradox



Investigations of ILP mostly theoretical. Astro black holes too cold and too young

Hawking lifetime of solar mass BH: 10^{67} years

Age of the universe: 1.38×10^{10} years

Analog Black Holes

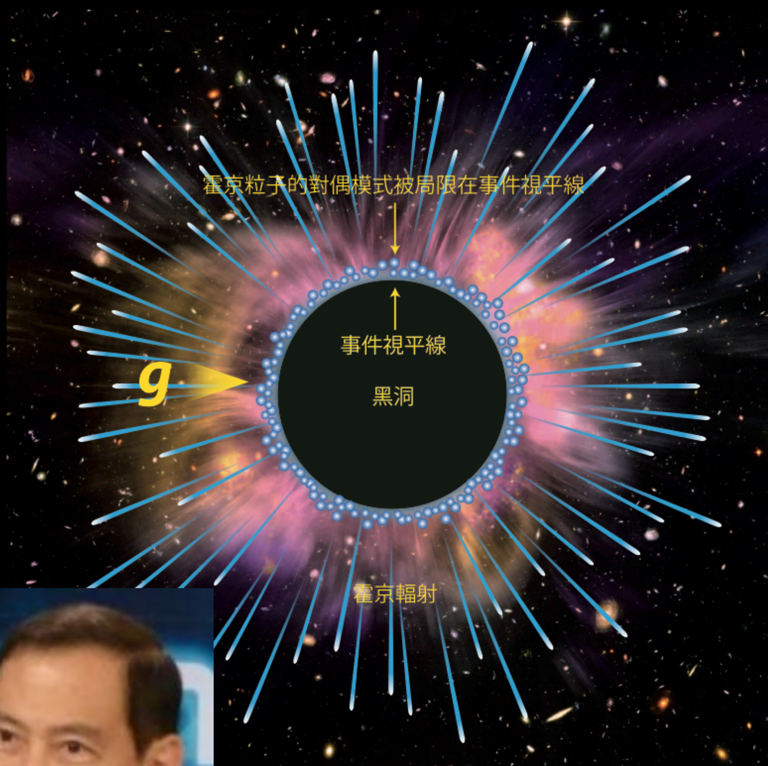
- Sound waves in moving fluids – "dumb holes"
  Unruh (1981, 1995)
- Traveling index of refraction in media
  Yablonovitch (1989)
- Violent acceleration of electron by lasers
  Chen-Tajima (1999)
- Electromagnetic waveguides
  Schutzhold-Unruh (2005)
- Bose-Einstein condensate
  Steinhauer (2014)
- Accelerating mirror
  Fulling-Davies (1976), Davies-Fulling-Unruh (1977), Birrell-Davies (1982), Carlitz-Willey (1987), Hotta-Schutzhold-Unruh (2015), Chen-Mourou (2016), Chen-Yeom (2017)

Flying plasma mirrors as analog black holes

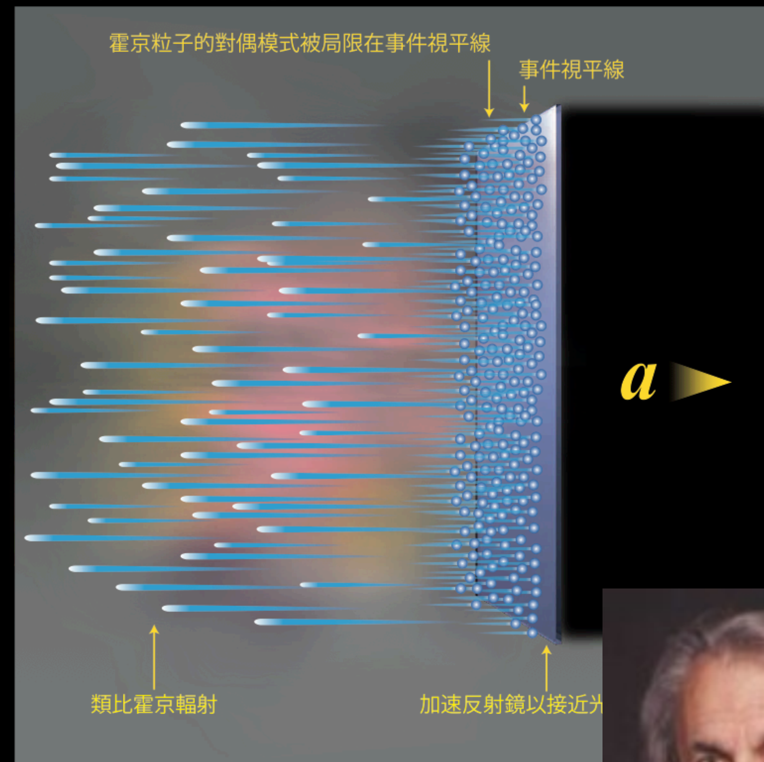
P. Chen and G. Mourou, Phys. Rev. Lett. **118**, 045011 (2017)

在實驗桌上模擬黑洞

新穎的類比黑洞構想可能解答一個基礎物理四十年未決的懸案

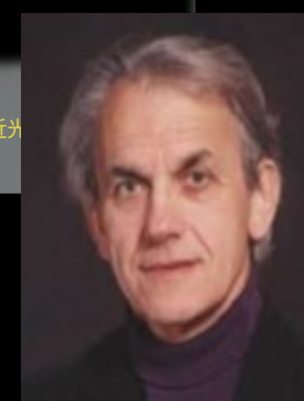


黑洞霍京蒸發

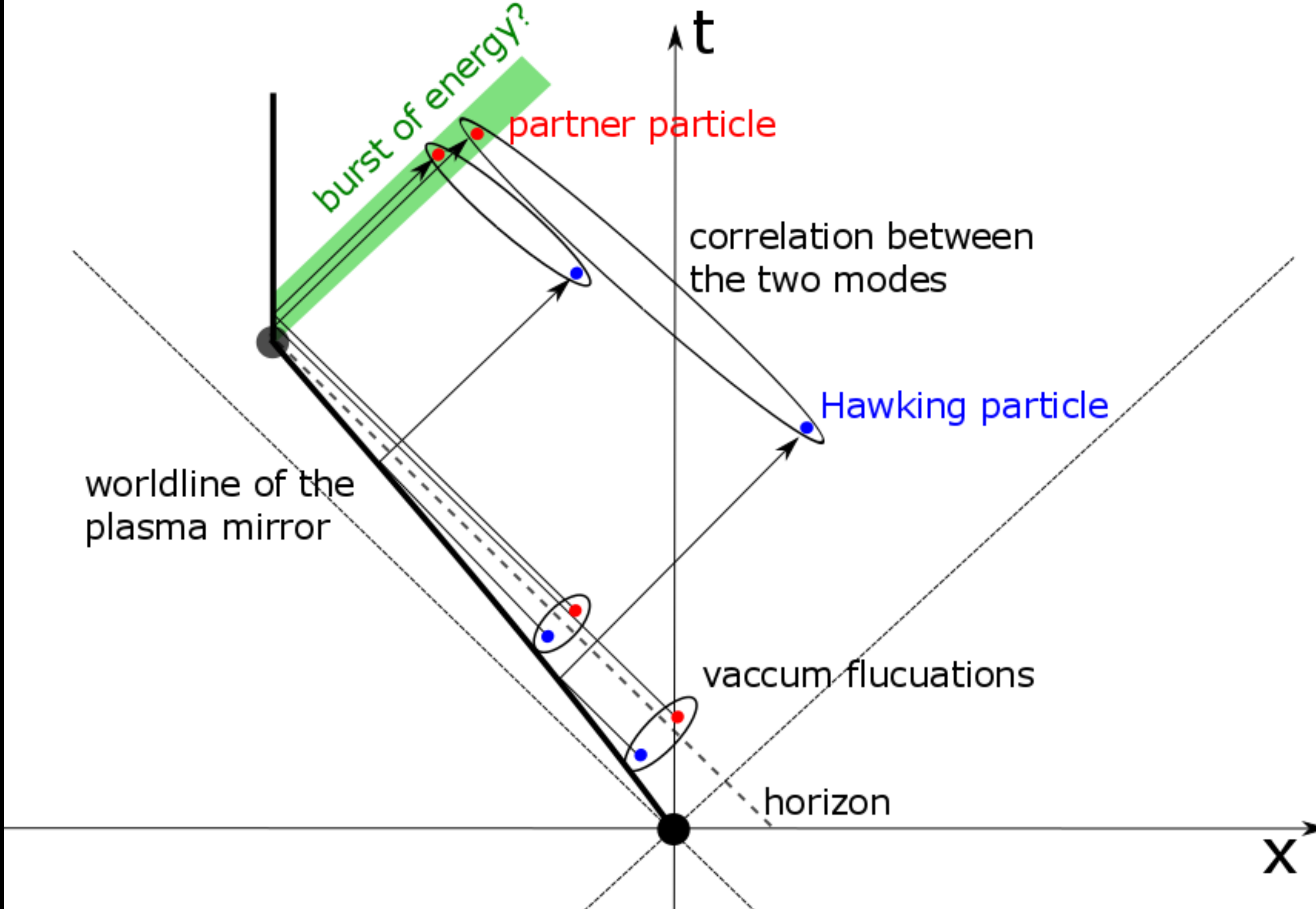


加速反射鏡可模擬黑洞霍京蒸發

Pisin Chen

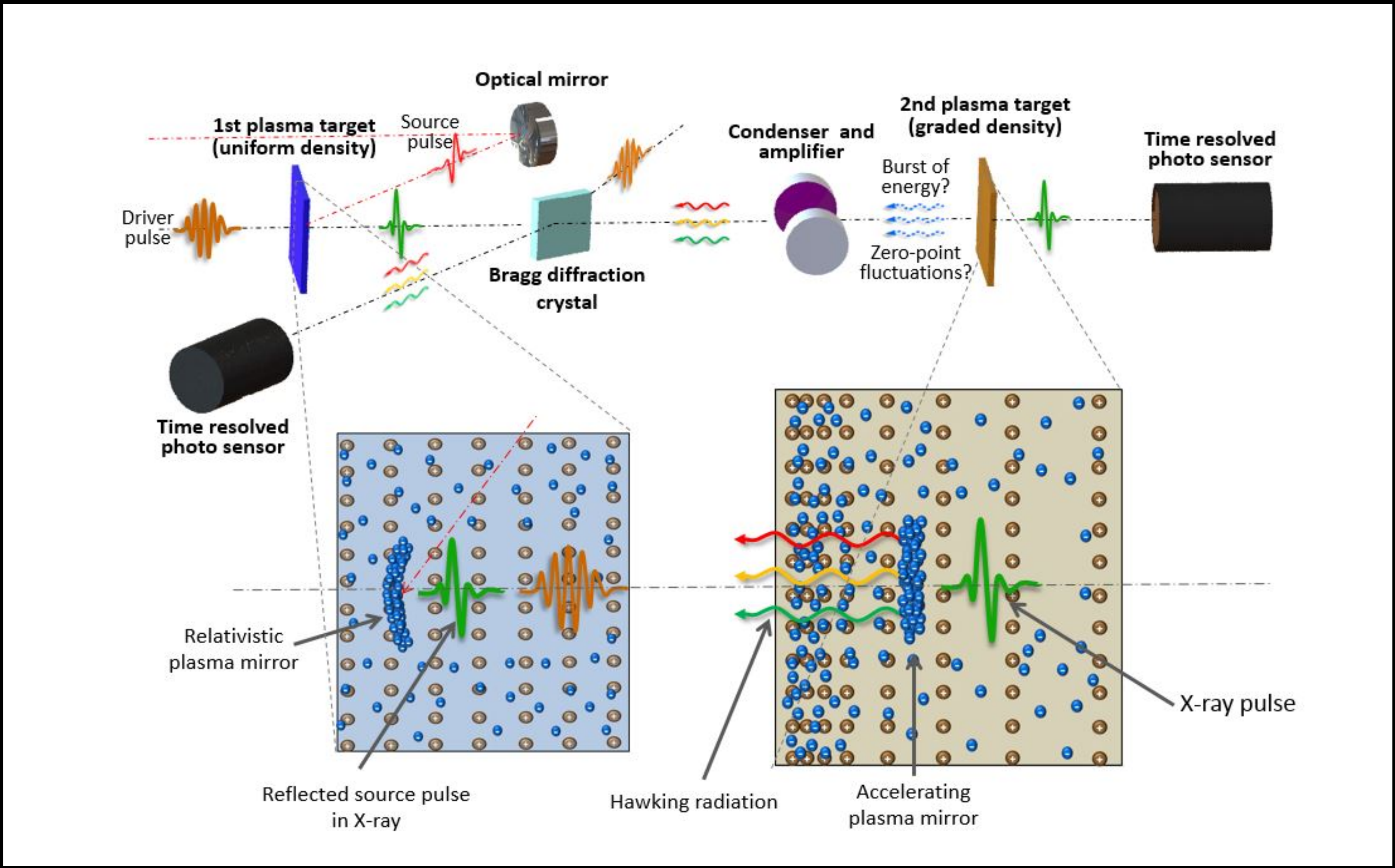


Gerard Mourou



How would AnaBHEL investigate information loss paradox?

Conceptual design of AnaBHEL experiment



AnaBHEL Collaboration formed (Analog Black Hole Evaporation via Lasers)

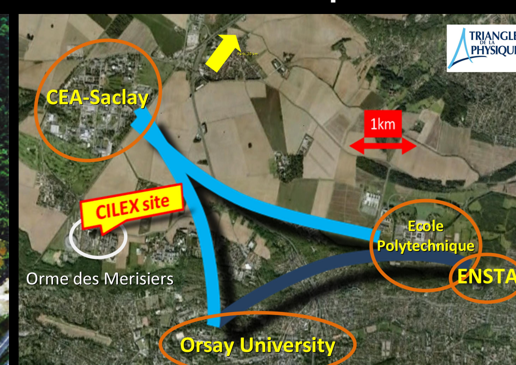
National Taiwan University + Ecole Polytechnique + CEA-Saclay + Kansai Photon Research Inst. + Shanghai Jiao Tong U.

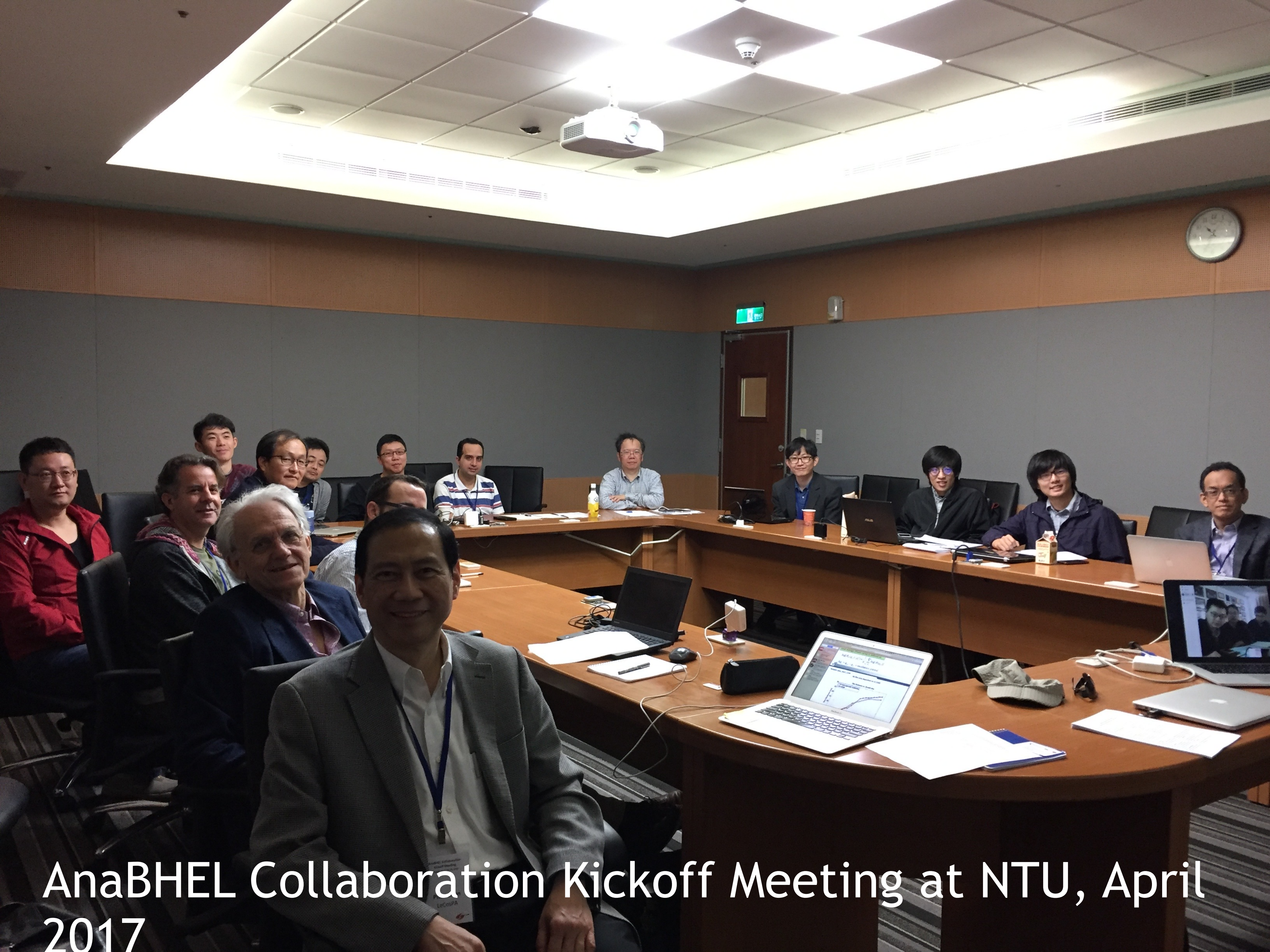
- Three stages:
  1. Proof of principle at NCU 100 TW Laser facility (Taiwan)
  2. Further tests at KPSI (Japan) with 1 PW laser
  3. Full scale expt. with 10PW Apollon Laser Facility, Saclay when completed in 2019

NCU 100 TW Laser Facility, Taiwan

KPRI 1 PW Laser, Japan

10 PW Apollon Laser, France



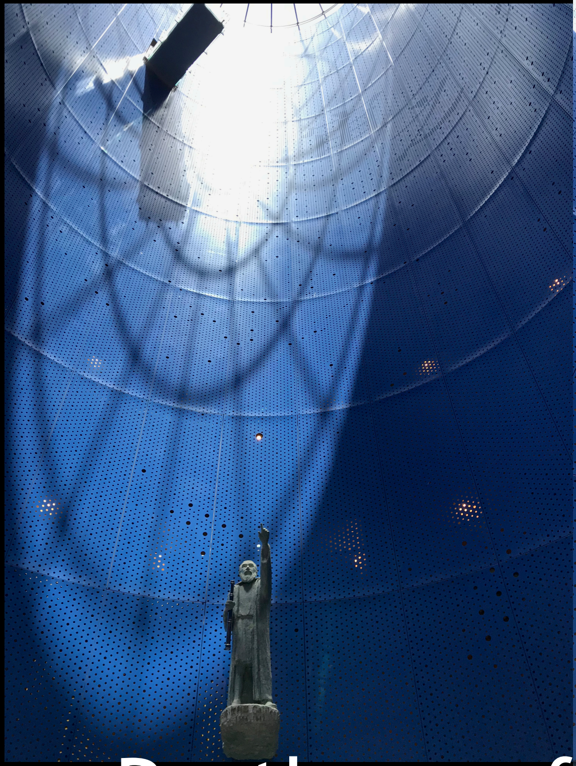


AnaBHEL Collaboration Kickoff Meeting at NTU, April 2017


LeCosPA

Chee-Chun Leung Cosmology Hall

2018 World Architecture Festival Award Finalist



Pantheon of Cosmology:
Zhang Heng, Galileo, Newton, Einstein