ダークユニバース宇宙論 研究拠点

Research Center for Dark Universe Cosmology

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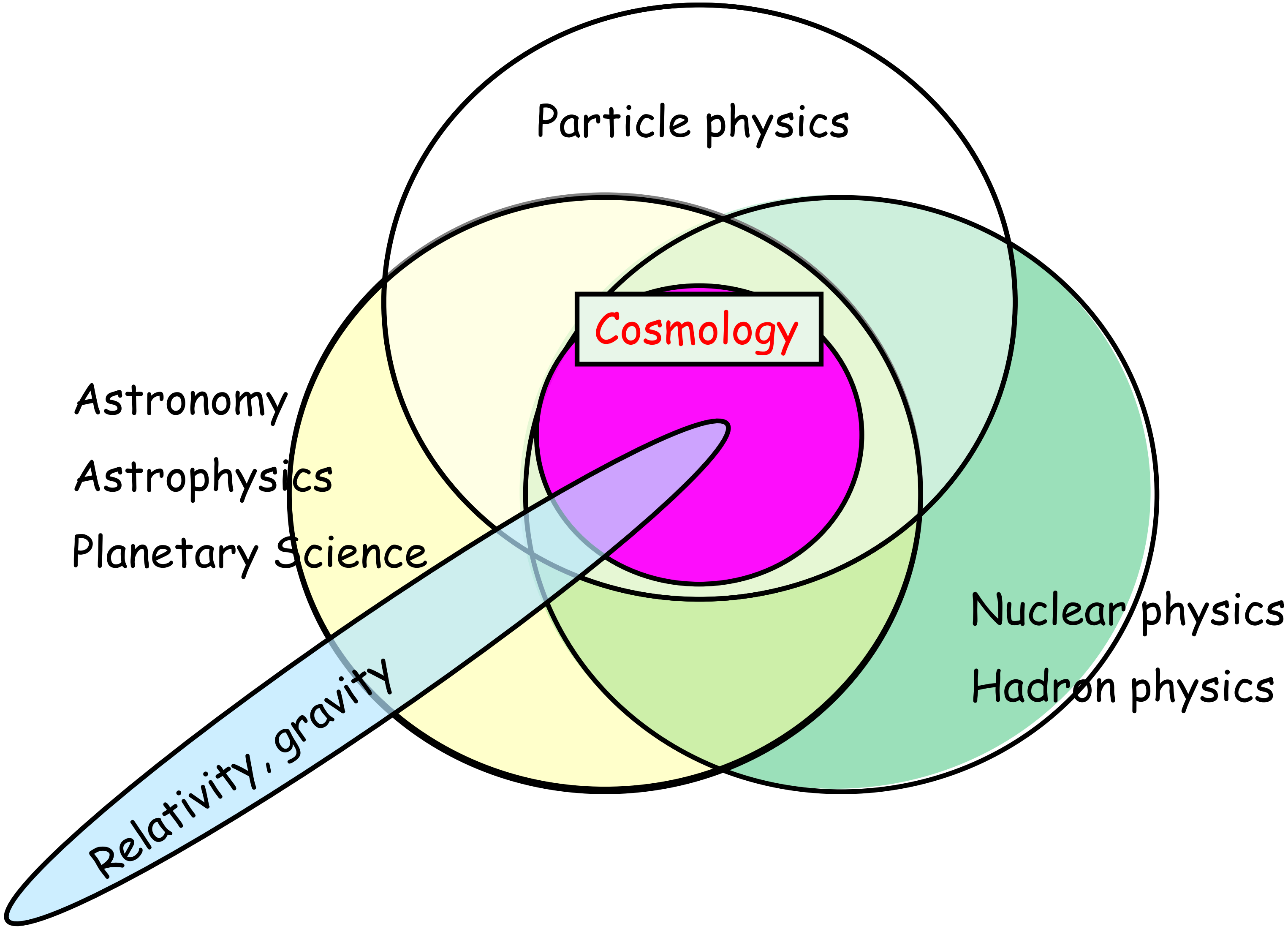
Interdisciplinary Subjects in Fundamental Physics and Astronomy

COSMOLOGY: An academic field to discuss evolutions of the whole Universe



History of the Universe

Birth of the Universe

Cosmic time	Energy		
10^{-43} sec	10^{19} GeV	Planck scale	Inflation?
10^{-38} sec	10^{16} GeV	GUT phase transition	Neutrino mass?
10^{-11} sec	10^{2} GeV	Electroweak phase transition	Baryogenesis? WIMP? DM?
10^{-5} sec	200 MeV	QCD phase transition	axion DM? PBH DM?
0.1 sec	3 MeV	Neutrino decoupling	Big-bang Nucleosynthesis (BBN)
1 sec	0.5 MeV	Electron-positron annihilation	
10^{10} sec	1 eV	Matter-radiation equality	
10^{12} sec	0.3 eV	Last scatting of CMB	
13.7 Gyr ($\sim 10^{17}$ sec)	2.7°K (-454°F)	dark energy? Present	

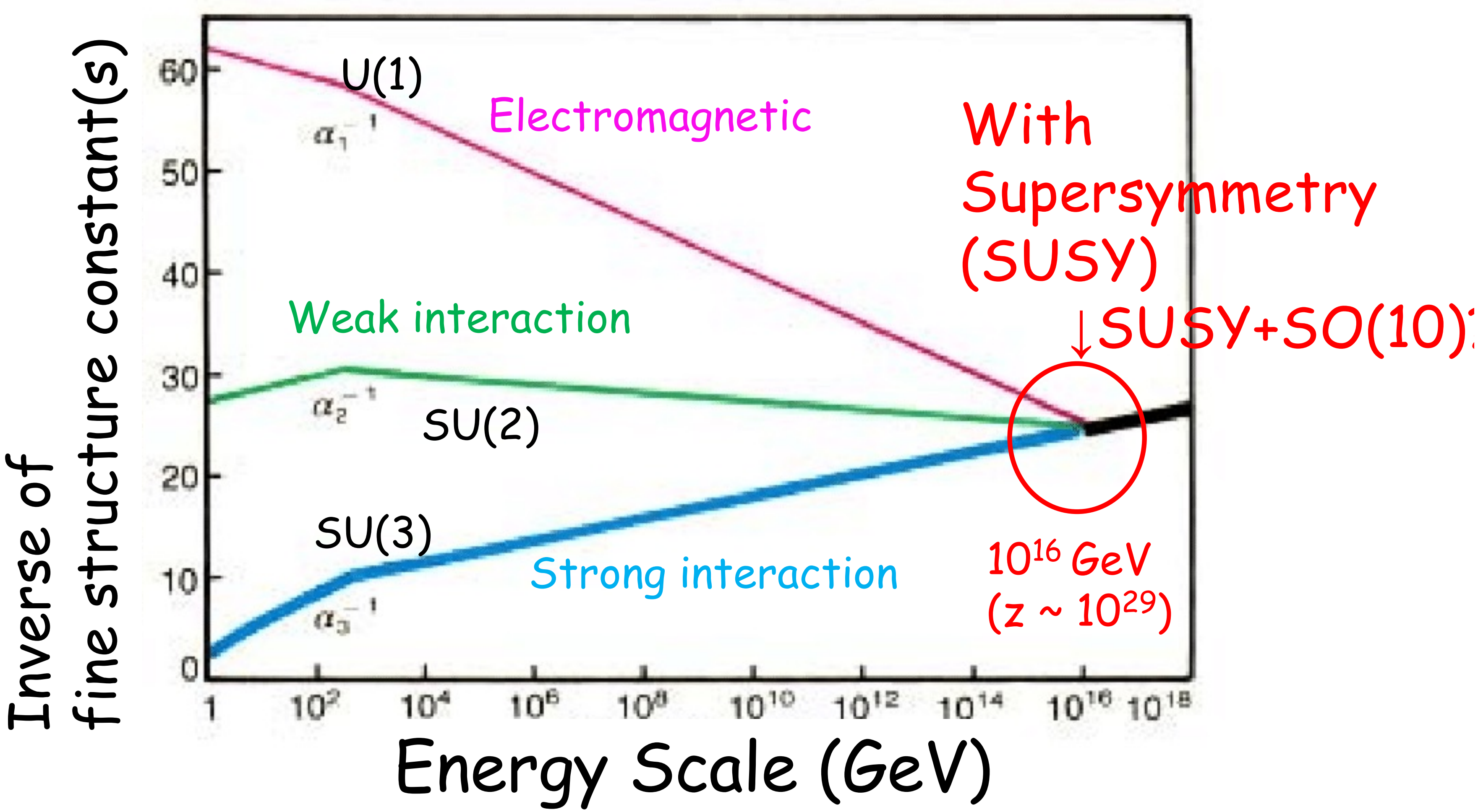


GUT (Grand Unified Theory)

Unification of three coupling constants at 10^{16} GeV

Ugo Amaldi, Wim de Boer, Hermann Furstenau, 1991

Can we confirm it observationally/experimentally?



Concepts of values in particle physics

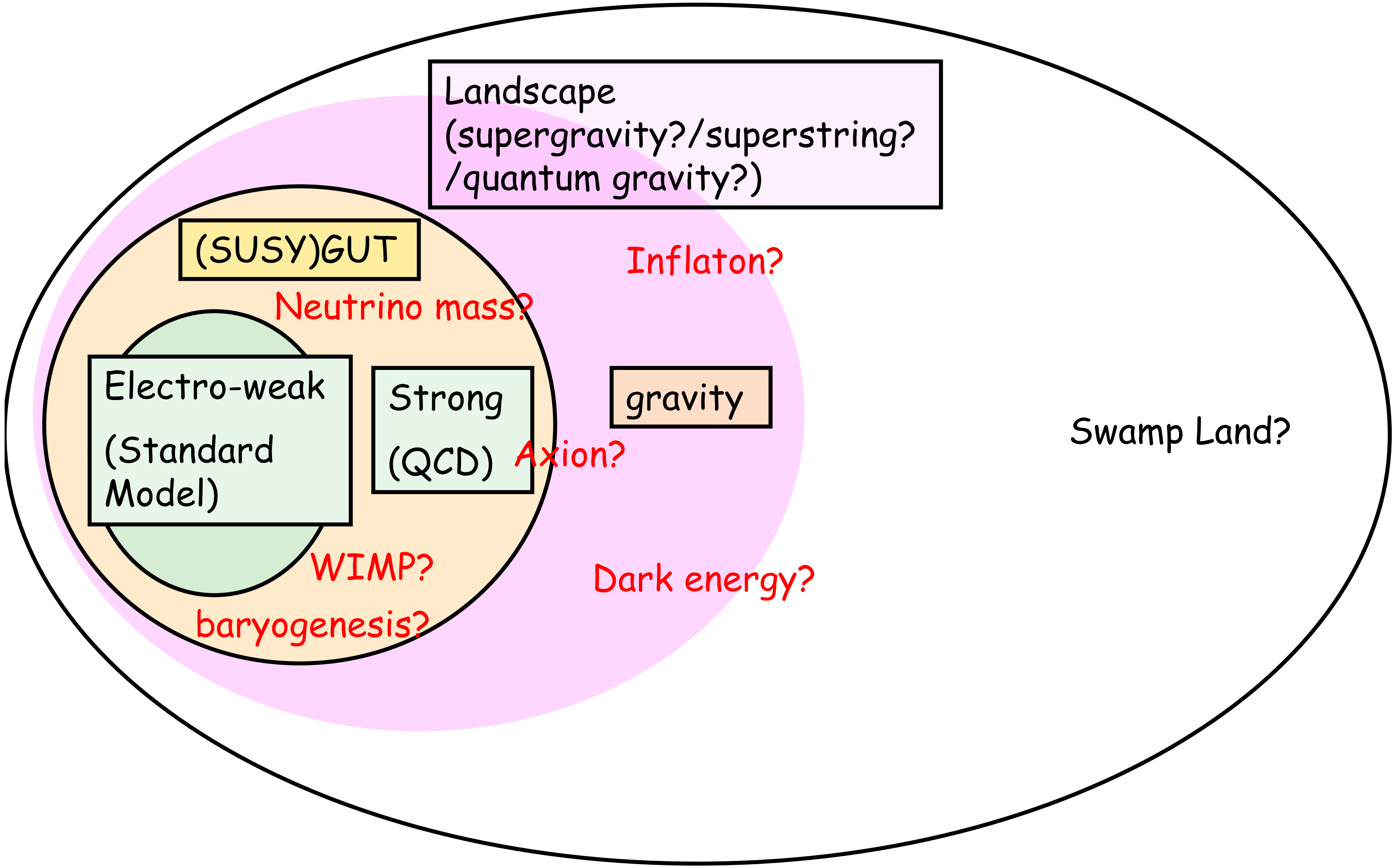
- The ultimate dream: Unifying three forces (electromagnetic, weak and strong interactions, i.e., GUT) and gravity under a symmetry such as SU(3)xSU(2)xU(1), SU(5), SO(10), SUSY, E(8)xE(8) etc.

- Looking for new physics beyond the standard model (the electroweak theory)

- Finding a new physical law by which the current physical law of particle physics must be rewritten

定義により、常に新しい物理学理論を追い求めることを意味する
プロジェクト主義ではなく、目的主義

Further Unification?



New Physics beyond the Standard Model

- Inflation
- Dark matter
- Neutrino masses/hierarchy and CP violation
- Dark energy
- Matter-antimatter asymmetry
- …

2. Science Goal: Solving the problems

- How did the Universe begin (Inflation)?

  Kohri, Tomaru

- What is dark matter?

  Kohri, Hamana, Dainotti, Aoki, Miyazaki , Iguchi, Akahori, Gouda, Kano

- What is dark energy?

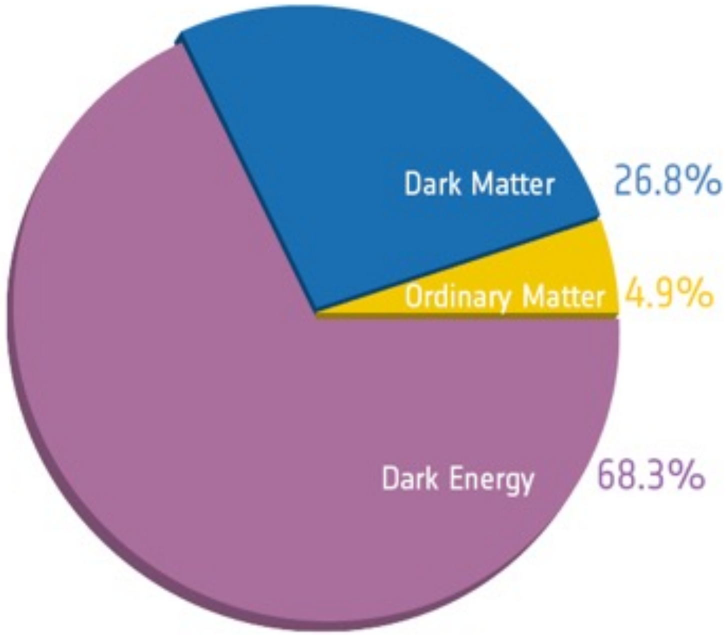
  Kohri, Dainotti, Miyazaki, Iguchi, Akahori

- Why are visible matters much less than photons (by neutrino mass/CP violation)?

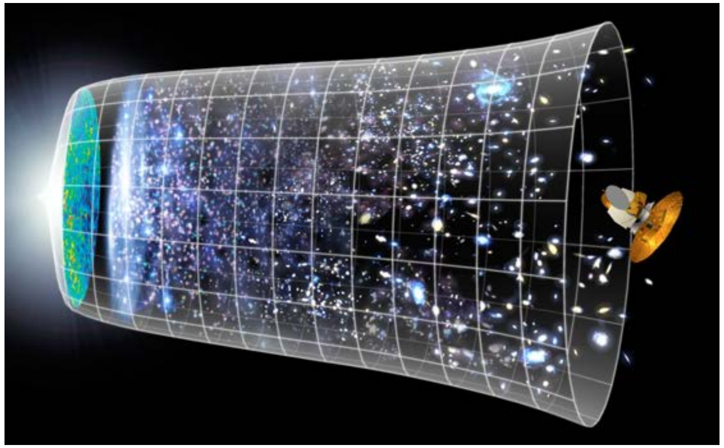
  Kohri, Takiwaki

- What's the role of black holes in the evolution of the Universe?

  Kohri, Ouchi, Tomaru, Gouda, Kano

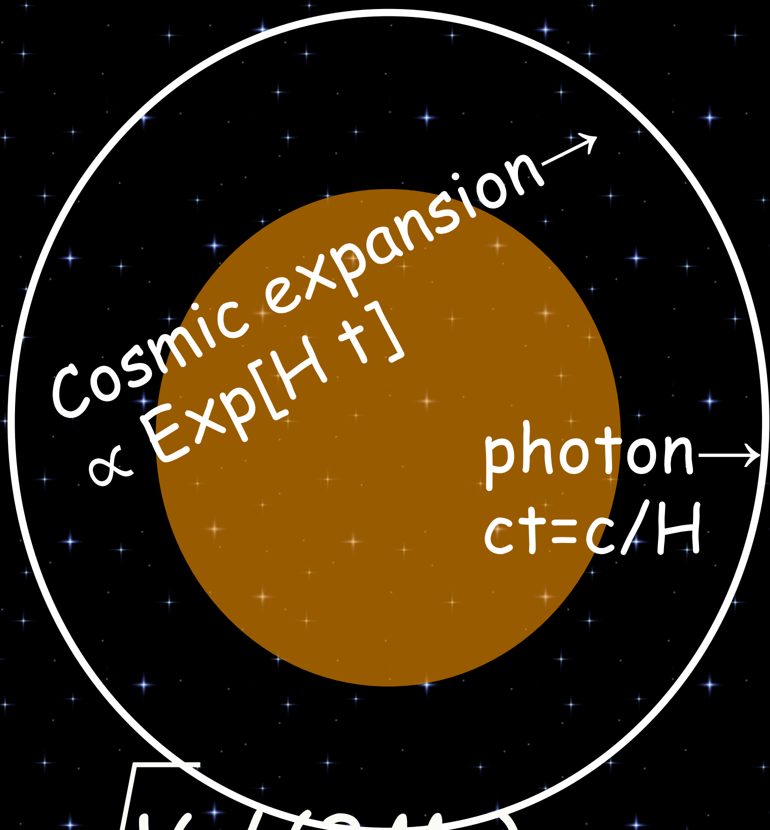


https://sci.esa.int/web/planck



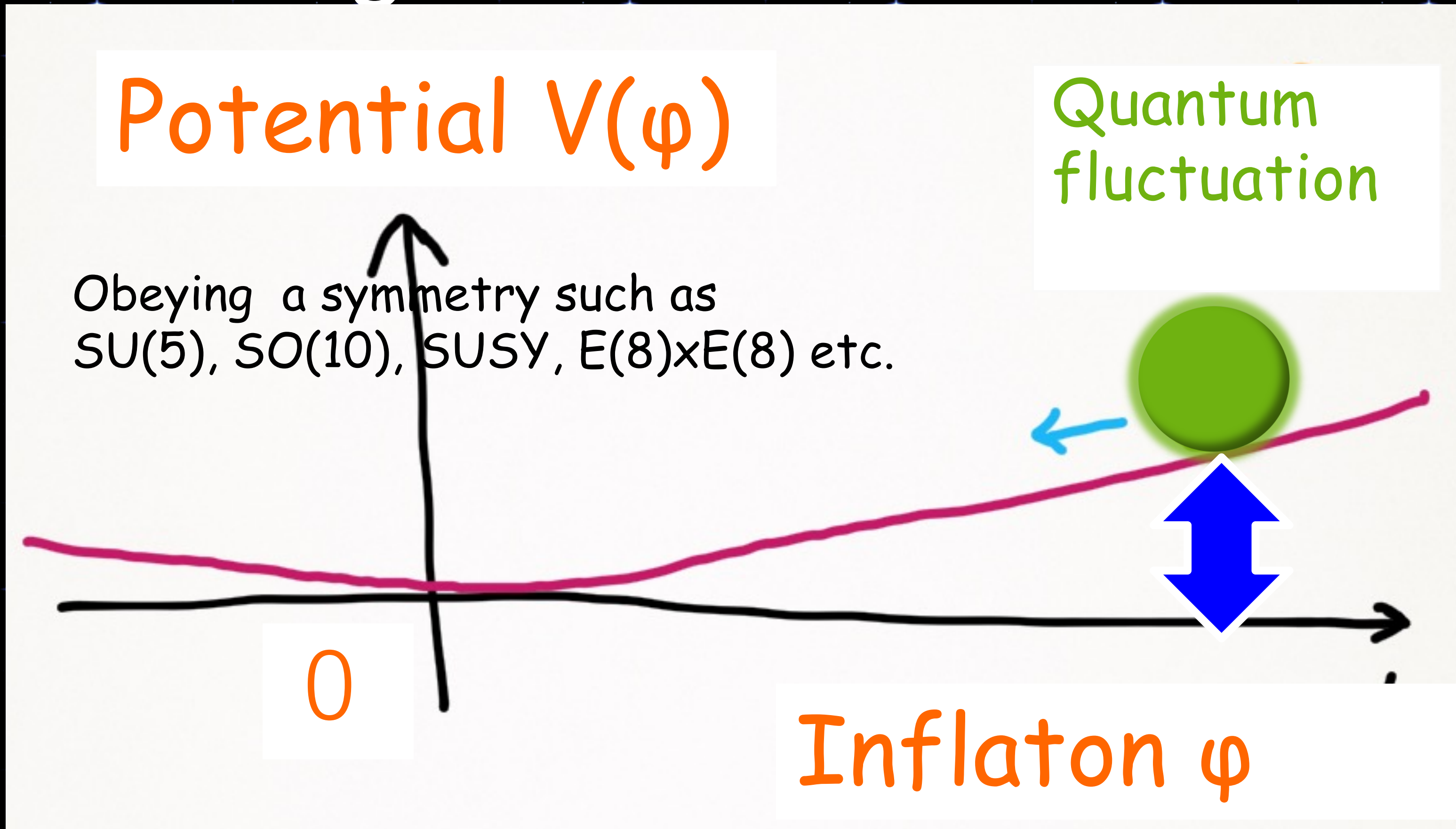
http://map.gsfc.nasa.gov

We need inflation



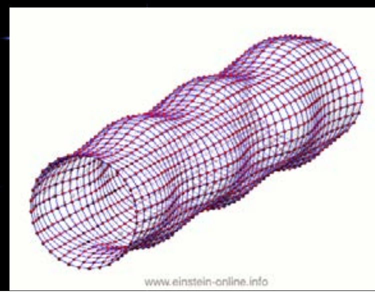
$$H = \dot{a}(t) / a(t) = \sqrt{V} / (3M_G)$$

Inflation produces density perturbation and gravitational wave



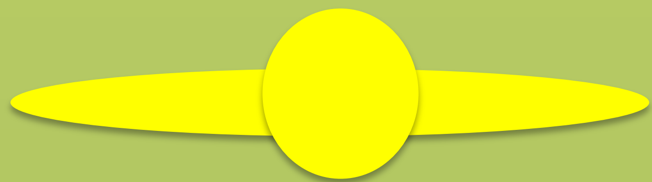
Density fluctuation

GWs (B-mode)



We need Dark Matter

First, dark matter halo was produced in the early Universe ($1 < z < 3400$)



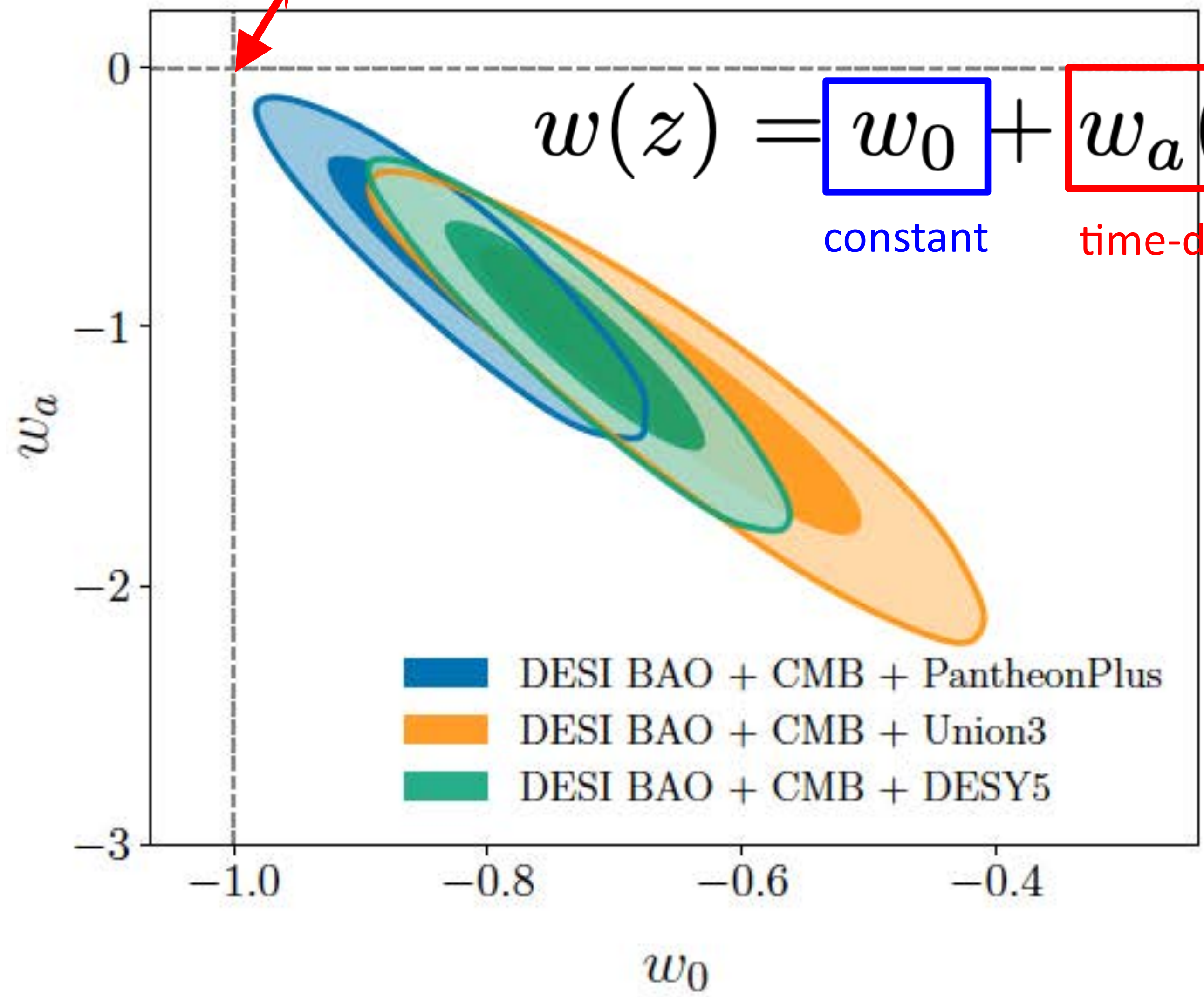
Then a galaxy (made by visible matter) is produced inside the dark matter halo due to the gravity of dark matter

$$\text{We see } \frac{\rho_{DM}}{\rho_{baryon}} \sim 5$$

We need Dark Energy

DESI Collaboration: A. G. Adame et al, arXiv:2404.03002 [astro-ph.CO]

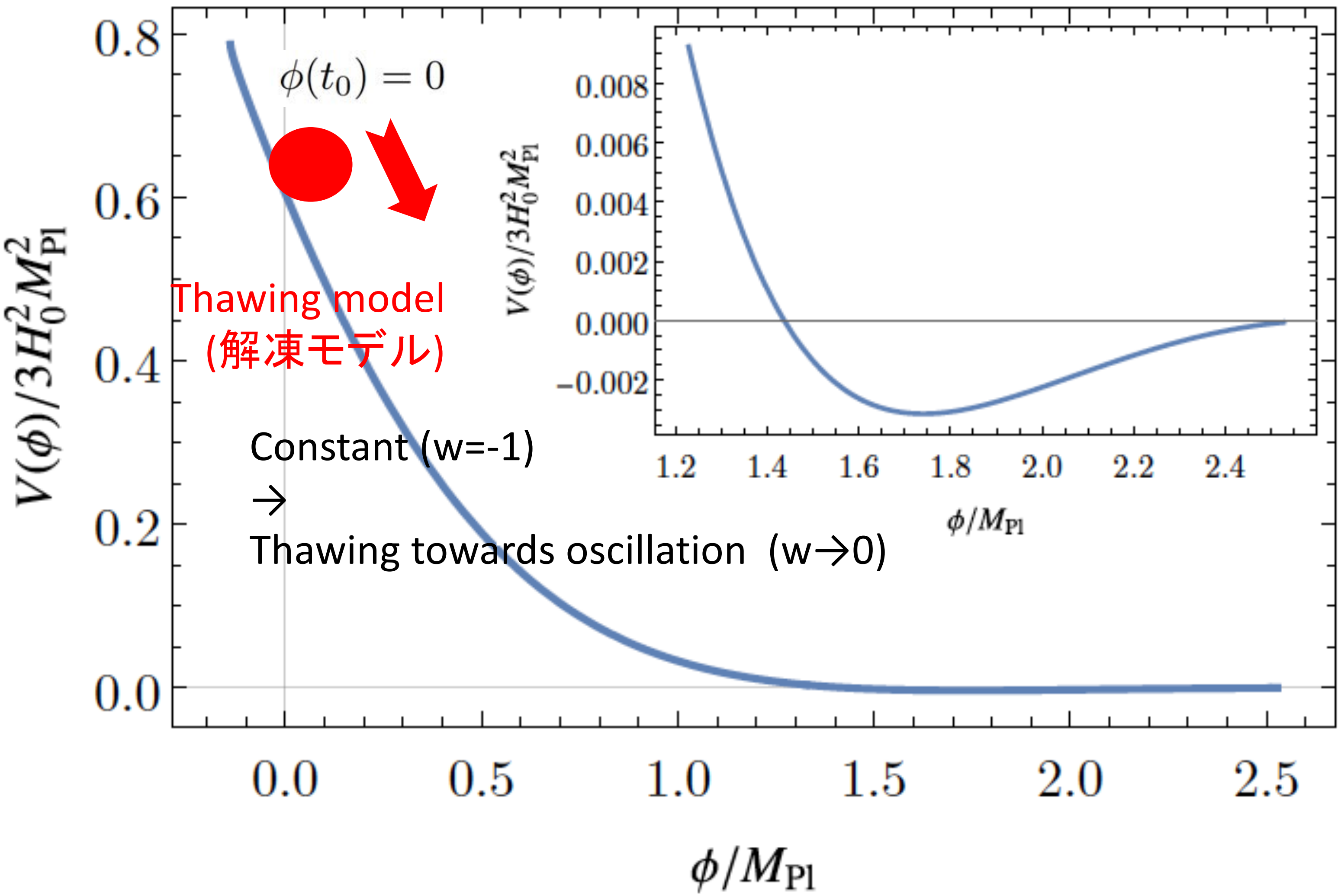
Non-zero ω_a



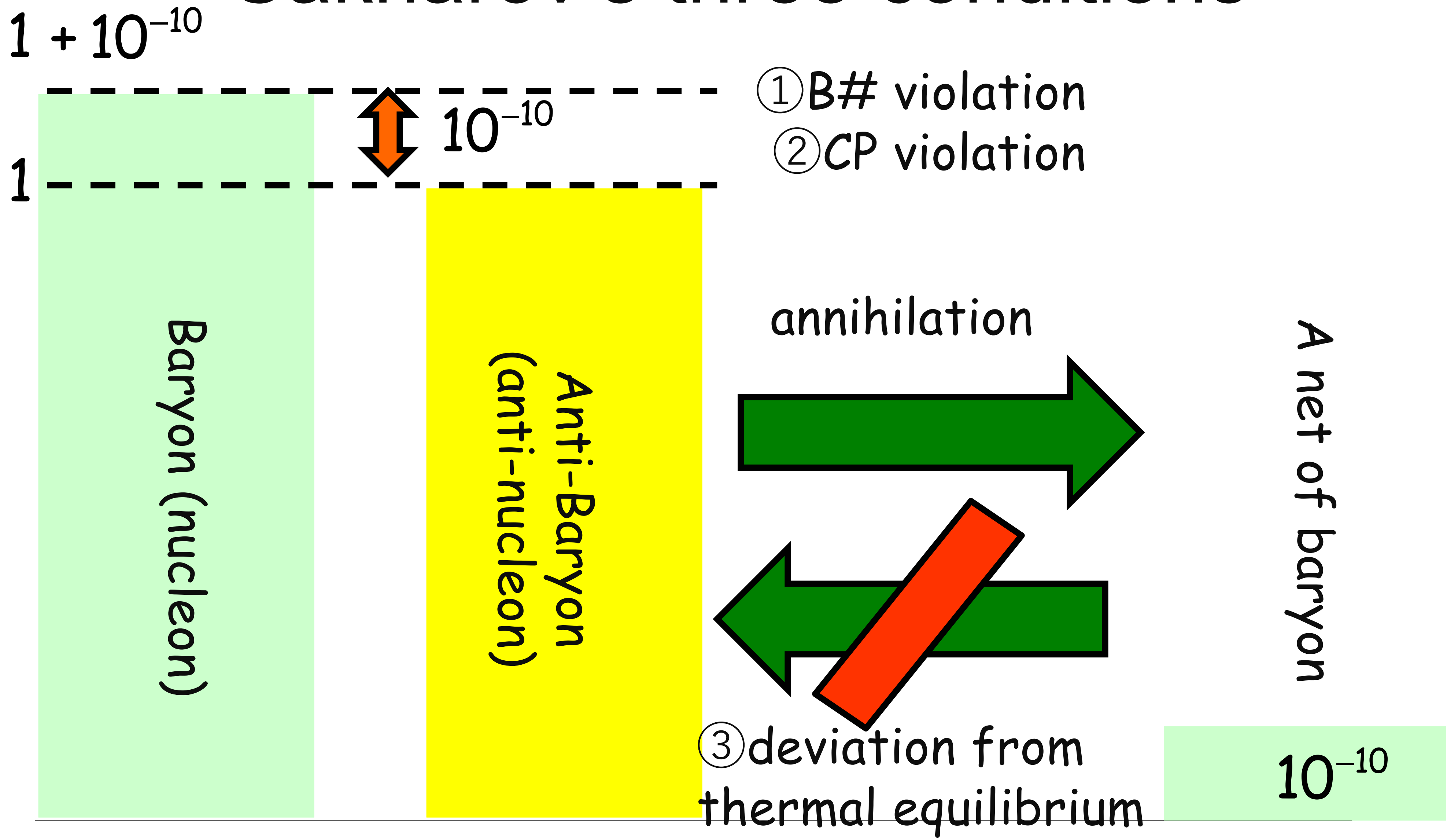
$$w(z) = \underbrace{\boxed{w_0}}_{\text{constant}} + \underbrace{\boxed{w_a(1 - a(t))}}_{\text{time-dependent terms}}$$

Quintessential interpretation of the evolving dark energy in light of DESI

Yuichiro Tada and Takahiro Terada, arXiv:2404.05722v2



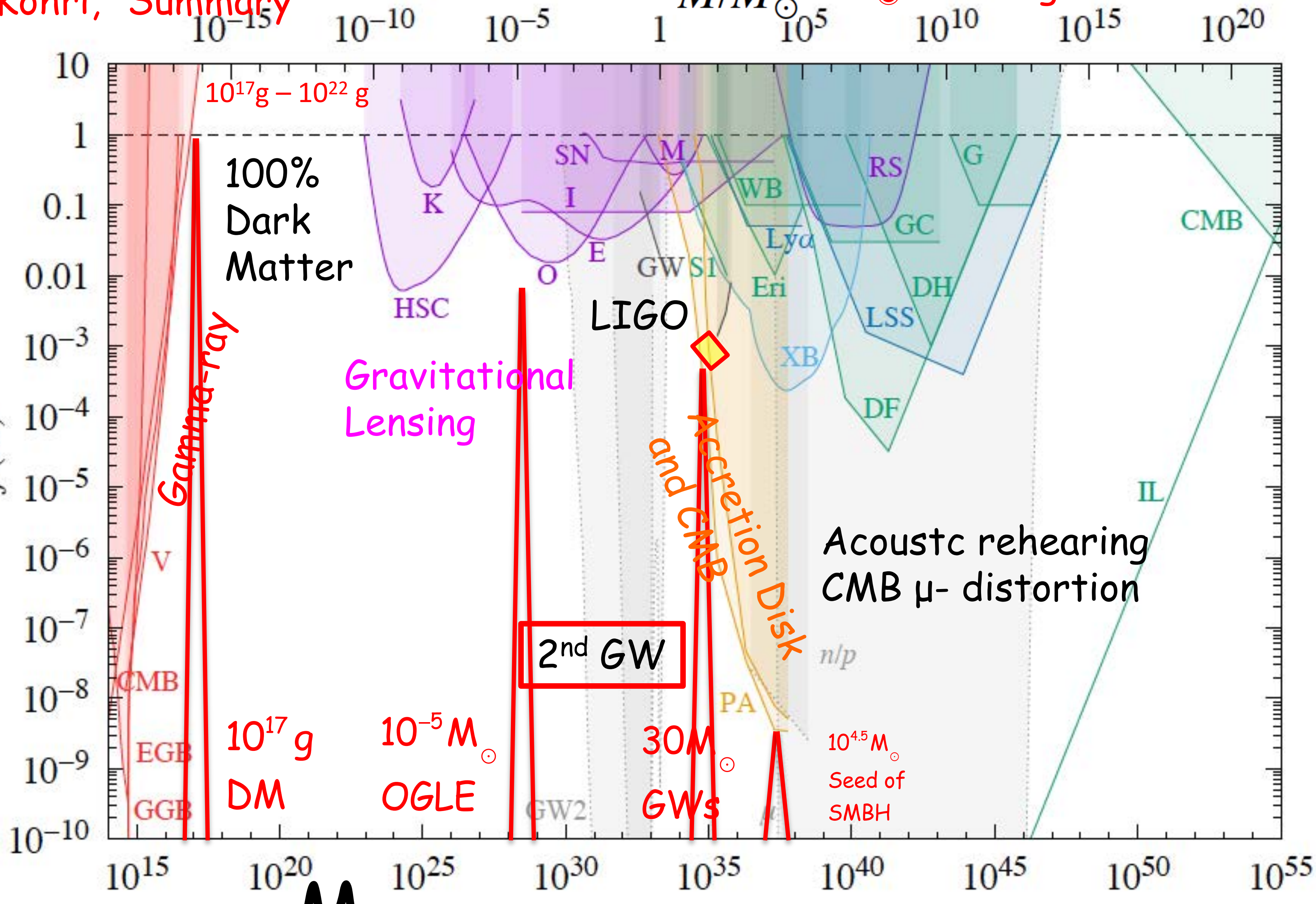
Baryogenesis/Leptogenesis and Sakharov's three conditions



Primordial Black Holes

See Springer Book, "PBH" (2025)
§ 20, K. Kohri, "Summary"

Carr, Kohri, Sendouda, J.Yokoyama (2009)(2020)



$f_{PBH} = \Omega_{PBH}/\Omega_{CDM}$

M_{PBH}

Mass in gram

3. Scientific objectives

- So far, observations reported only the ratios of radiation, baryon, dark matter and dark energy to the total.
- The next step in astronomy/astrophysics is 1) to uncover the true nature of dark matter and dark energy, 2) solve the mystery of the origin of visible matter, and complete the ultimate physical law that describes the birth of the Universe, and 3) rewrite the astronomy textbook.
- We will create a research base that promotes theoretical cosmological research to solve these mysteries.
- Multi-messenger astronomy is completely complementary to cosmology in that it targets the evolution of the whole Universe

4-0. Science investigations

- Mainly we promote theoretical/scientific research and act as a hub connecting researchers in other institutions
- We use observations
    - Optical/IR (Subaru/Roman/TAO/JASMINE/TMT)
    - Radio (ALMA/SKA/ngVLA/TSUKUYOMI)
    - GW (KAGRA/ET/LISA/DECIGO)
    - CMB(LiteBIRD/SO/S4)
    - Neutrino (IceCube/KM3NeT)
    - X-ray (XRISM/Athena/JEDI)
    - Gamma-ray (Fermi/Magic/ HiZ-GUNDAM
    - /CTA/SMILE/COSI)
    - Cosmic rays (CALET/Auger/TA)

4-1. Science investigations (for (4.3) Threshold Science)

- (4.1)Before 2033, we will mainly advocate for a place at NAOJ for collaborations led by a newly-employed young faculty.
- (4.2) After 2033, we will propose future projects with applying for big grants (such as Transformative Research Areas A or WPI) under the leadership of the employed faculty.

- Using future observations, narrowing down the most likely candidates for dark matter, (i) WIMP, (ii) axion, (iii) primordial black hole, (iv) right-handed neutrino, etc.

- Resolve the Hubble tension through detailed theoretical analyses of data for distance indicators such as Type Ia supernovae and gamma-ray bursts, we will determine whether the nature of dark energy is a cosmological constant or a scalar field (such as a light axion).

- We will solve the problem of σ_8 by comparing future large-scale galaxy surveys with detailed theoretical calculations This will provide insights into dark matter models.

- We will determine the abundances of light elements such as D, He4, Li7 with high precision, and compare them with Big Bang nucleosynthesis theory to obtain hints for new physics (e.g. baryon/lepton number violation, modified gravity theory, etc)

- Compare future CMB observations of B-mode with theoretical predictions for inflation to select a theoretical model and solve the mystery of the beginning of the Universe.

6. Originality and international competitiveness

- In Japan, research institutes such as Institute for Cosmic Ray Research (ICRR), the University of Tokyo, which has groups conducting observations measuring gravitational waves, gamma rays, cosmic rays, optical and infrared, and directly-detecting dark matter, are searching dark matter. In addition, the High Energy Accelerator Research Organization (KEK) is conducting research to produce dark matter using accelerators. The Kavli IPMU at the University of Tokyo is conducting research into dark matter and dark energy using the Subaru telescope, as well as direct detection experiments for dark matter.

- The NAOJ's strength lies in the fact that most of the researchers have their office rooms on one main campus (Mitaka). it hosts original observation equipment for radio astronomy, differentiating it from these research institutions. In addition, the Division of Science has many theorists of supernova explosions and gamma-ray bursts, and also has theorists of cosmology and astroparticle physics. In other words, the NAOJ is the best research institution in Japan to be a research base that solves the fundamental mysteries of astronomy/astrophysics, such as dark matter, dark energy, the birth of the universe, and the origin of visible matter, from both the observation and theoretical perspectives.

- The CfA in the US is a research institution with a large number of observers and theorists, but it does not host gravitational wave observations. CERN in Switzerland, SLAC and Fermilab in the US, and DESY in Germany all have a large number of particle physicists and theorists, but they do not host optical or infrared observations. The research targets of the Max Planck Institute in Germany and the Chinese Academy of Sciences (CAS) are extremely broad, covering astronomical observation, particle physics and cosmology with larger numbers of researchers than that of NAOJ, but their campuses are separate. The Paris Observatory (IAP + Paris University) in France and the University of Oxford (BIPAC + Physics Department) in the UK are carrying out projects of a similar scale to the National Astronomical Observatory of Japan.

7. Current Status

- We are in the process of organizing joint research groups for five themes.

8. Cost assessments, budget line and status

- Budget scale for the entire project (total amount or amount per year): 12M JPY/year

- National Astronomical Observatory funding (total amount or amount per year):): 10 M JPY/year

- We are hoping to receive 10 M JPY /year in Unkou-Kin funding. This will cover the personnel costs of hiring a new associate professor (successor staff) to carry out this programme, as well as research expenses. The Department of Science does not have any associate professors with expertise in cosmology, and we would like this person to be responsible for the practical work of establishing the centre.
- By applying for some grants, e.g., Grant-in-Aid for Scientific Research, we will add 2M JPY/year into the total amount.

9. Members (with junior faculties)

NAOJ

- Kazunori Kohri (PI), T. Hamana, M. G. Dainotti, T. Takiwaki, M. Ouchi (DoS), W. Aoki (TMT), S. Miyazaki (SUBARU), S. Iguchi (ALMA/ngVLA/TSUKUYOMI), T. Akahori (SKA1/VLBI), T. Tomaru (KAGRA), N. Gouda (JASMINE), R. Kano(JASMINE), etc.

Others

- R. Takahashi (Hirosaki), F. Takahashi (Tohoku, Physics), K. Hayashi (Sendai Coll), T. Matsubara (KEK), M. Takada, T. Matsumura (IPMU), S. Matsumoto (IPMU), N. Yoshida (Hongo, Physics), T. Suyama (Science Tokyo), N. Hiroshima (Yokohama), K. Ichiki (Nagoya), A. Taruya (YITP), K. T. Inoue (Kindai), K. Nagamine (Osaka), T. Takahashi (Saga), K. Takahashi (Kumamoto), etc.

10. Why NAOJ ?

- In terms of the research of cosmology, the NAOJ hosts Subaru, TMT, Roman, ALMA, KAGRA and JASMINE, and has excellent observers.

- In addition, there are many theorists of cosmology, supernova explosions and gamma-ray bursts. The characteristics of the NAOJ are that it can become a top research base for uncovering the true nature of dark matter and dark energy, verifying the theory of inflation, and solving the mystery of the origin of matter and the birth of the universe.

- Unravelling these mysteries is an astronomical challenge that the NAOJ should take the lead in tackling.

- On the other hand, it is rather strange that these themes have not been systematically researched until now.