Dark Matter

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2023 CTPU-PTC Summer School on Cosmology & Particle Physics

Lecturer?

- 박종철 (Park, Jong-Chul)
  충남대 (Chungnam National University)

- Particle Physics – Phenomenology:
  Dark Matter, Neutrino, Cosmic Rays,
  Early Universe Cosmology, …

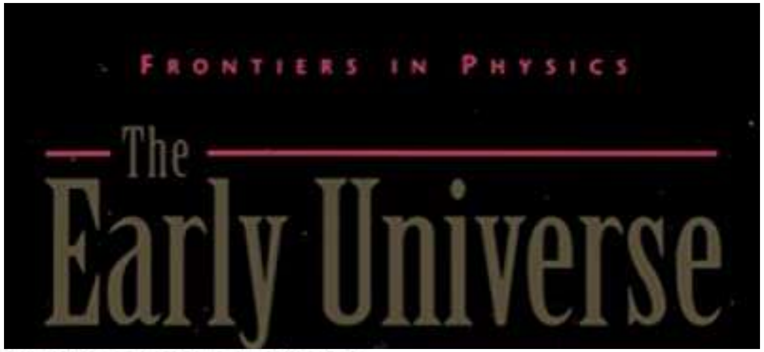
- log1079@gmail.com or jcpark@cnu.ac.kr

- https://inspirehep.net/literature?sort=mostrecent&size=25&page=1&q=a%20j.%20c.%20park%20and%20d%20%3E%202002&ui-citation-summary=true

References: Reviews/Lecture Notes

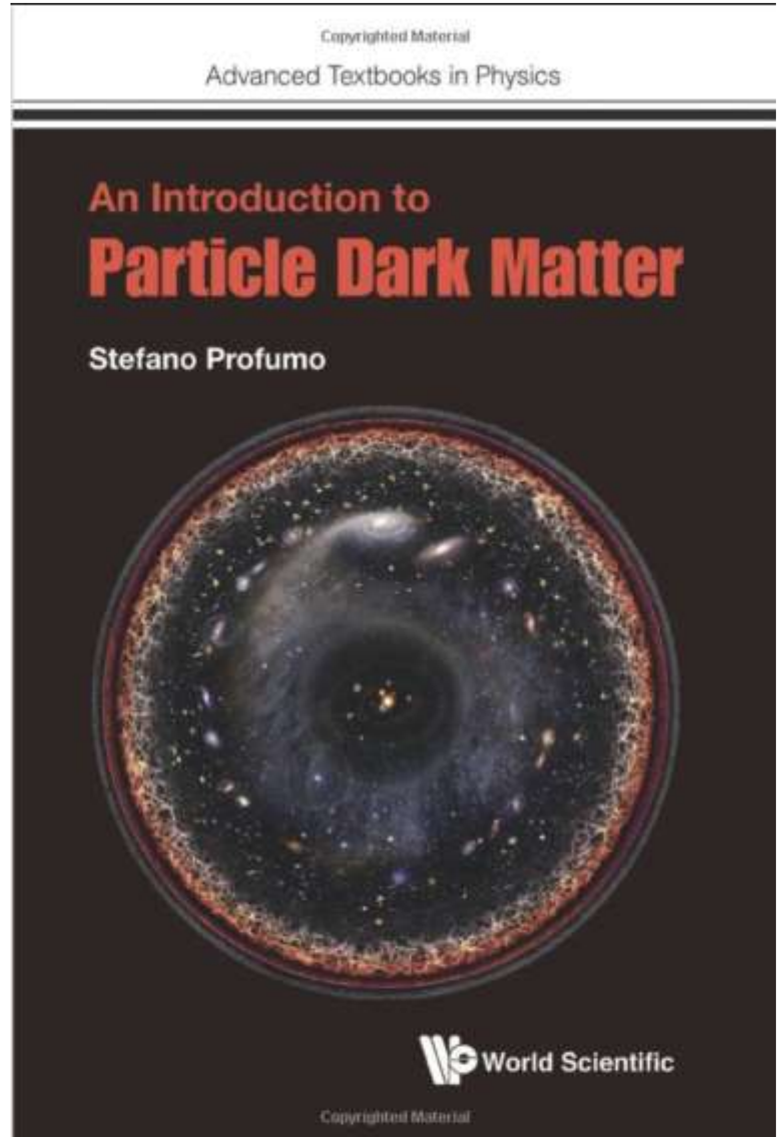
1. https://arxiv.org/abs/1605.04909 ➔ History
2. https://arxiv.org/abs/1703.07364 ➔ General w/ Models
3. https://arxiv.org/abs/1705.01987 ➔ General
4. https://arxiv.org/abs/1910.05610 ➔ General
5. https://arxiv.org/abs/1903.03026 ➔ Direct Detection
6. https://arxiv.org/abs/1904.07915 ➔ Direct Detection
7. https://arxiv.org/abs/1710.05137 ➔ Indirect Detection
8. https://arxiv.org/abs/1812.02029 ➔ Indirect Detection
9. https://arxiv.org/abs/2109.02696 ➔ Indirect Detection (Extension of 7)
10. https://arxiv.org/abs/1912.04727 ➔ Cosmology
11. ...

References: Books



3. STANDARD COSMOLOGY

5. THERMODYNAMICS IN THE EXPANDING UNIVERSE



References: Simulation Tools

1. WimPyDD (https://wimpydd.hepforge.org/)
2. PPPC 4 DM ID (http://www.marcocirelli.net/PPPC4DMID.html)
3. MicrOMEGAs (https://lapth.cnrs.fr/micromegas/)
4. MadDM (https://launchpad.net/maddm)
5. …

Things You Should Have Known ...

- Classical Mechanics, Thermal Physics
- Quantum Mechanics, Special Relativity
- General Relativity ???
- Quantum Field Theory… ????

Outline

0. Very Short Summary of the Standard Model
1. Observational Evidence of Dark Matter
2. Relic Abundance of Dark Matter
3. Direct Detection of DM – Target particle recoil
4. Indirect Detection of DM – Cosmic rays
5. Direct production of DM – Collider
6. New Approaches

0. Very Short Summary of the Standard Model

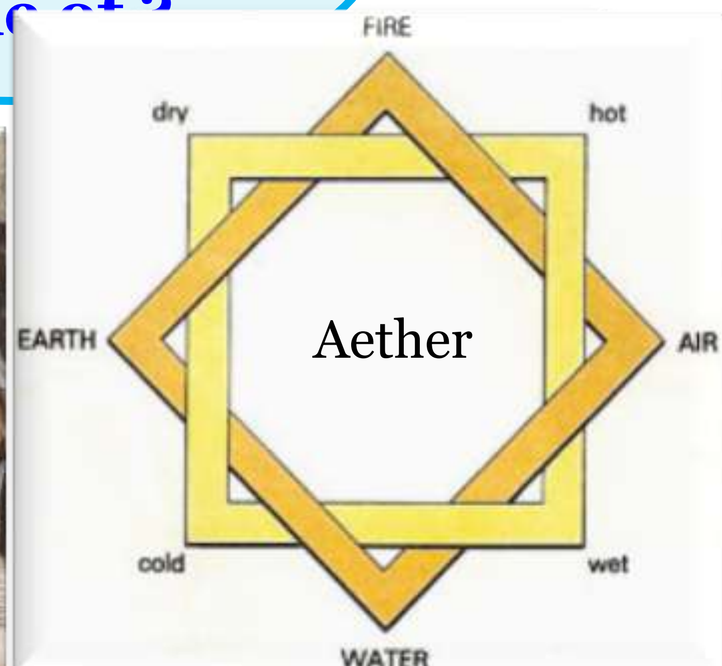
Eternal Questions

What is the Universe made of ?

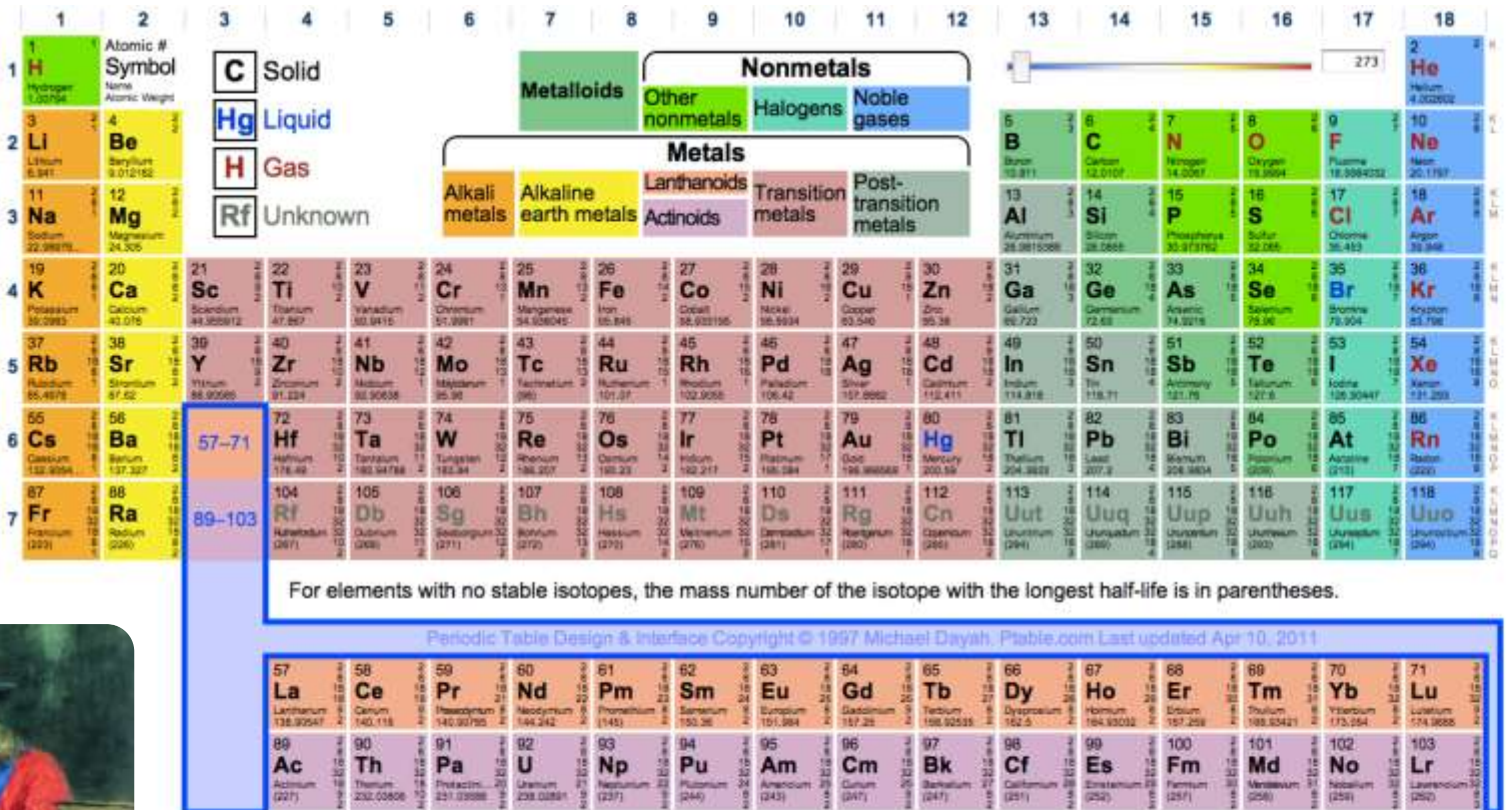
Eternal Questions

What is the Universe made of ?

- Ancient Greek: 4 basic elements

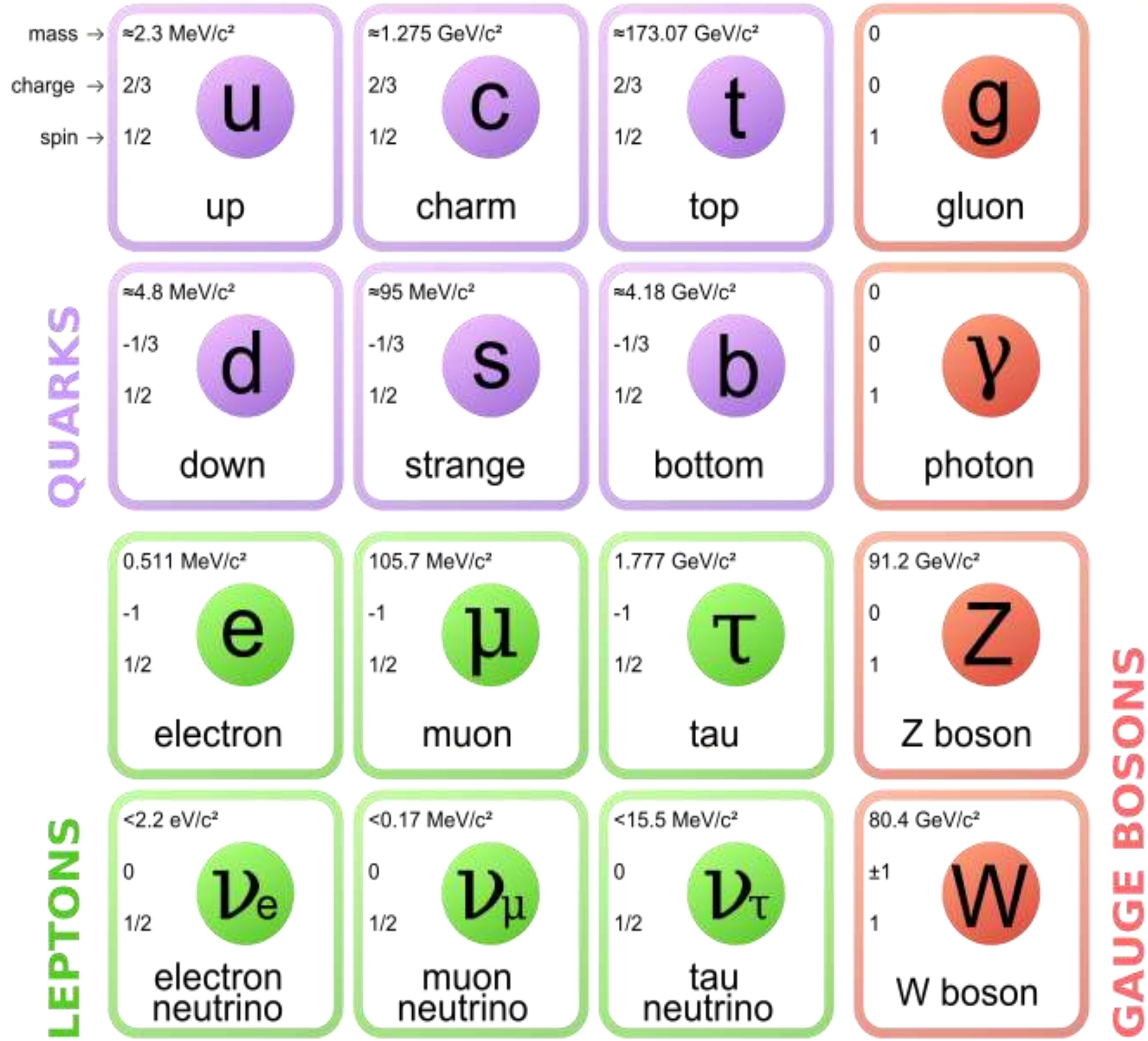


19th c: Periodic Table



Dmitri Mendeleev
(1869)

20^{th} c: Standard Model (SM)



GeV ~ m_p

Lectures by Prof. Eung Jin Chun

Higgs (1964)!

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

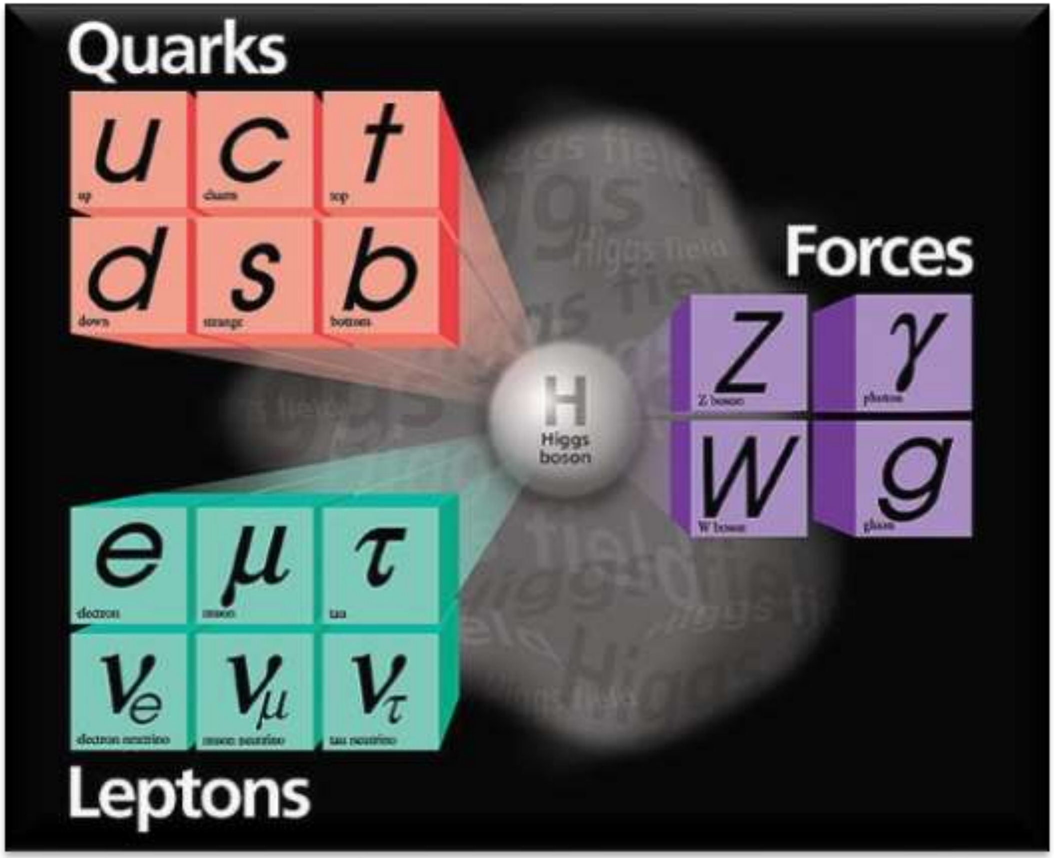
Chicago (USA)

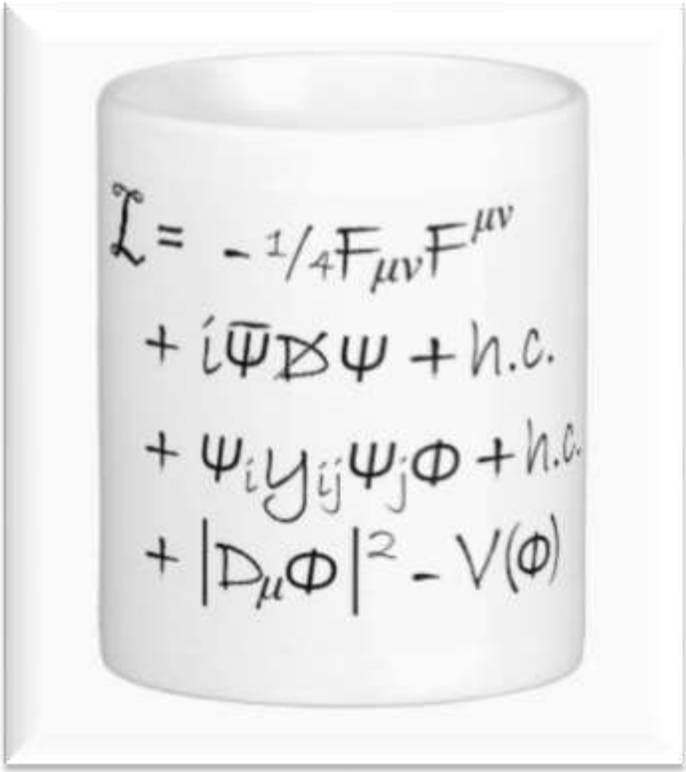
Geneva (Europe)

Higgs (2012)!

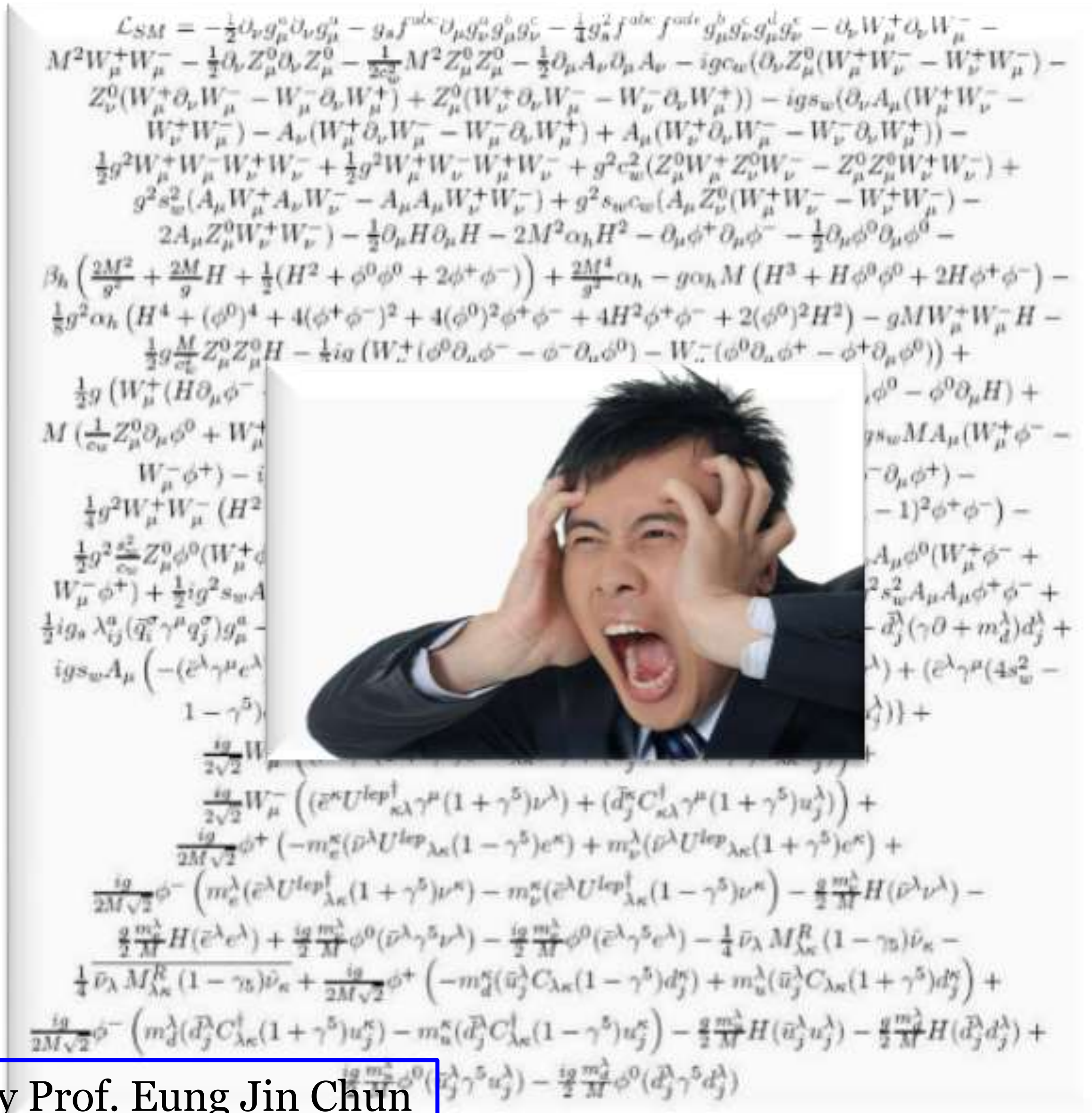
Higgs is discovered!

Now: Standard Model (SM)





Now: Standard Model (SM)



Probably NOT by Prof. Eung Jin Chun

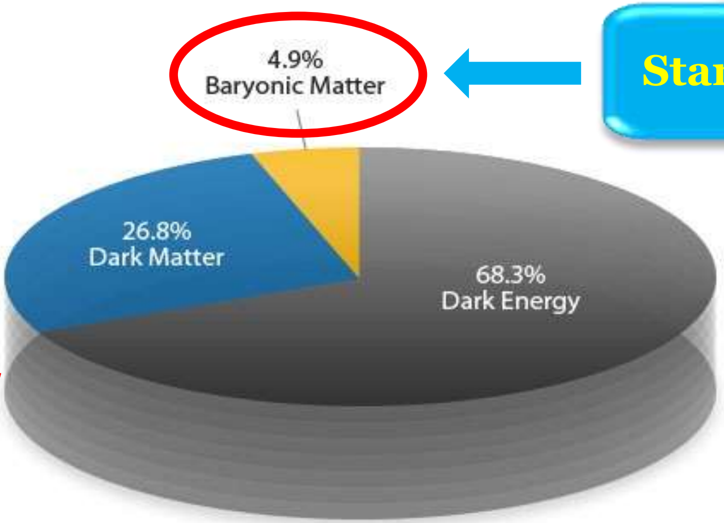

EIN ROLAND EMMERICH FILM
2012


NEED WORK!

Message from Cosmology

- Modern cosmology ➔ Cosmic pie

Stars, Galaxies, H, …



Supernova

CMB

- The Standard Model explains only ~5% of the total E of the Universe.

Question in the 20th Century!!

What's
the matter?

⬇

What's
Dark Matter?

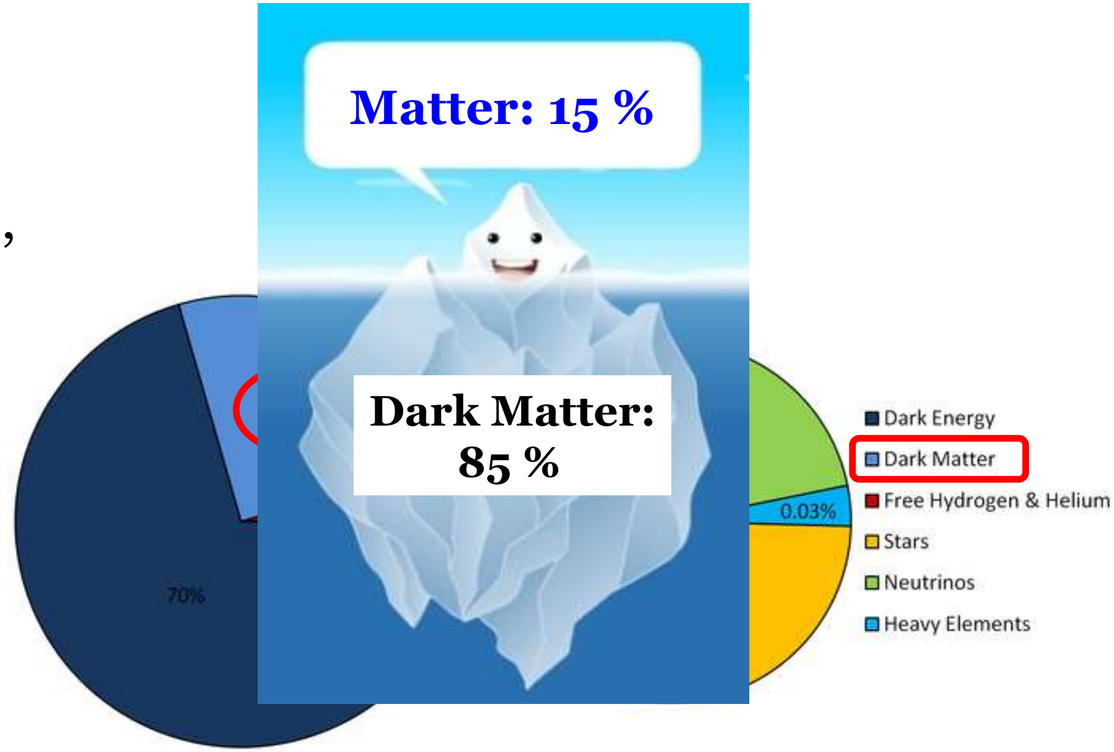
Dark Matter (DM)

❖ Postulated by Fritz Zwicky in early 1930's

❖ Rediscovered by Vera Rubin in 1970

❖ **Compelling paradigm**:

- ✓ massive,
- ✓ non-relativistic (→ $v \ll c$),
- ✓ non-luminous (no/tiny EM interaction),
- ✓ stable particles
- ✓ ~1/4 of the Universe



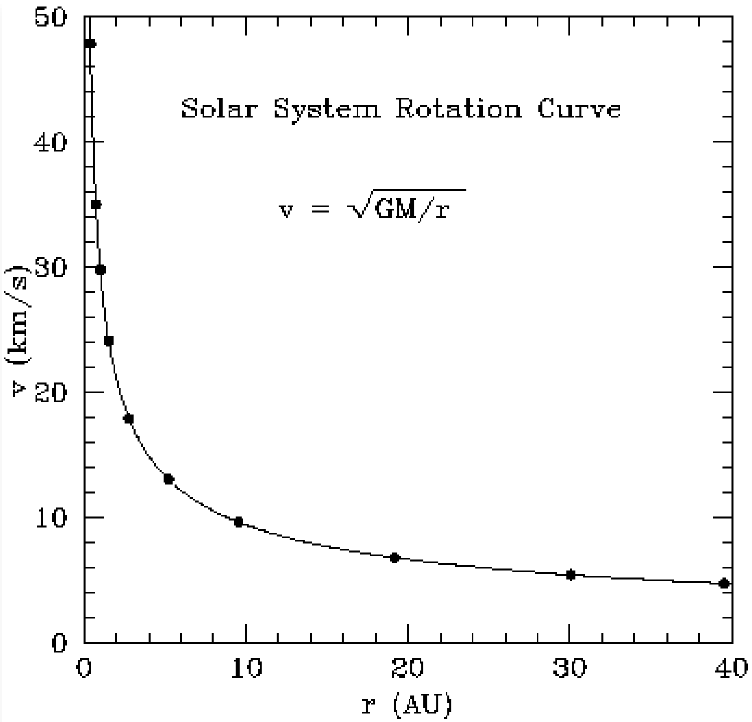

Existence of
Dark Matter?

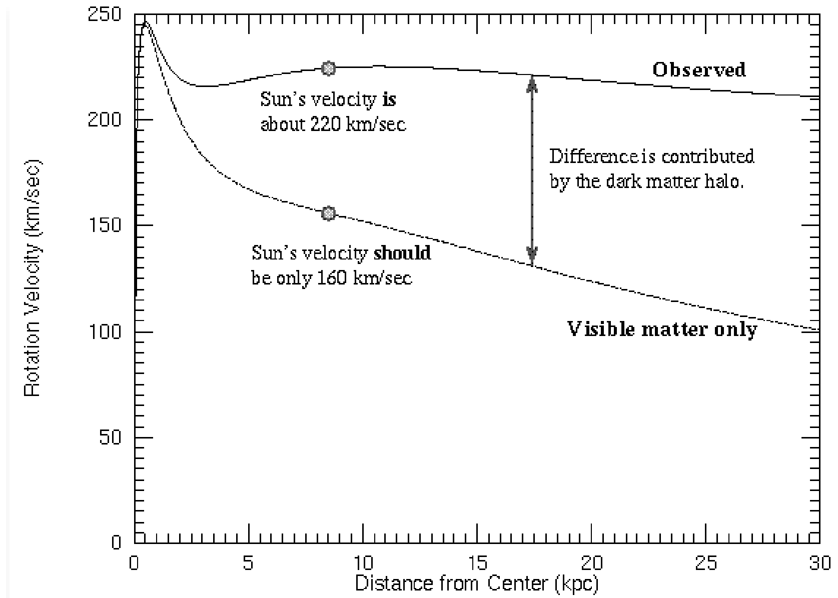
1. Observational Evidence of Dark Matter

Observational Evidence of DM

- ✓ Galaxy rotation curve
- ✓ Coma cluster
- ✓ Gravitational lensing
- ✓ Bullet cluster
- ✓ Structure formation
- ✓ Cosmic microwave background radiation (CMBR)
- ✓ Sky surveys
- ✓ Type Ia supervovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ …

Galaxy Rotation Curve

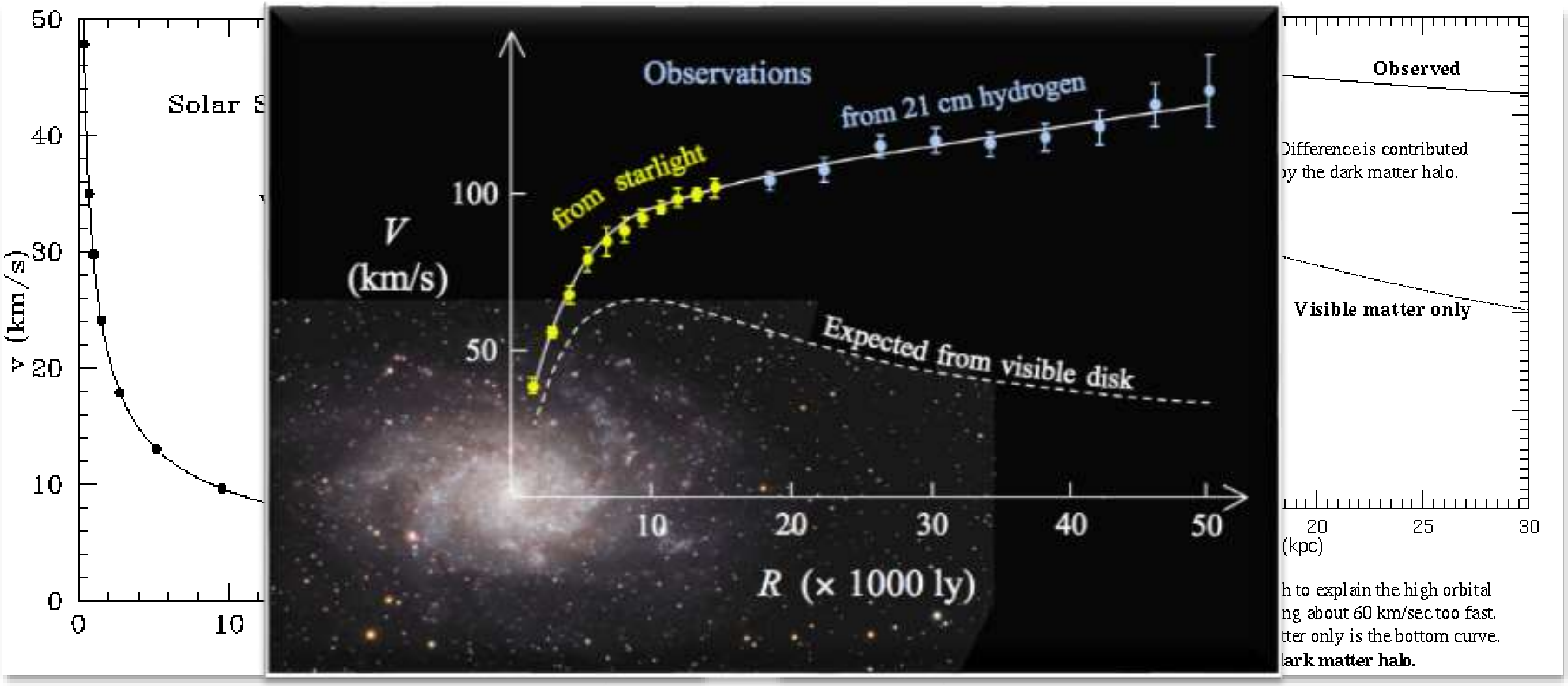




The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**

Vera Rubin

Galaxy Rotation Curve



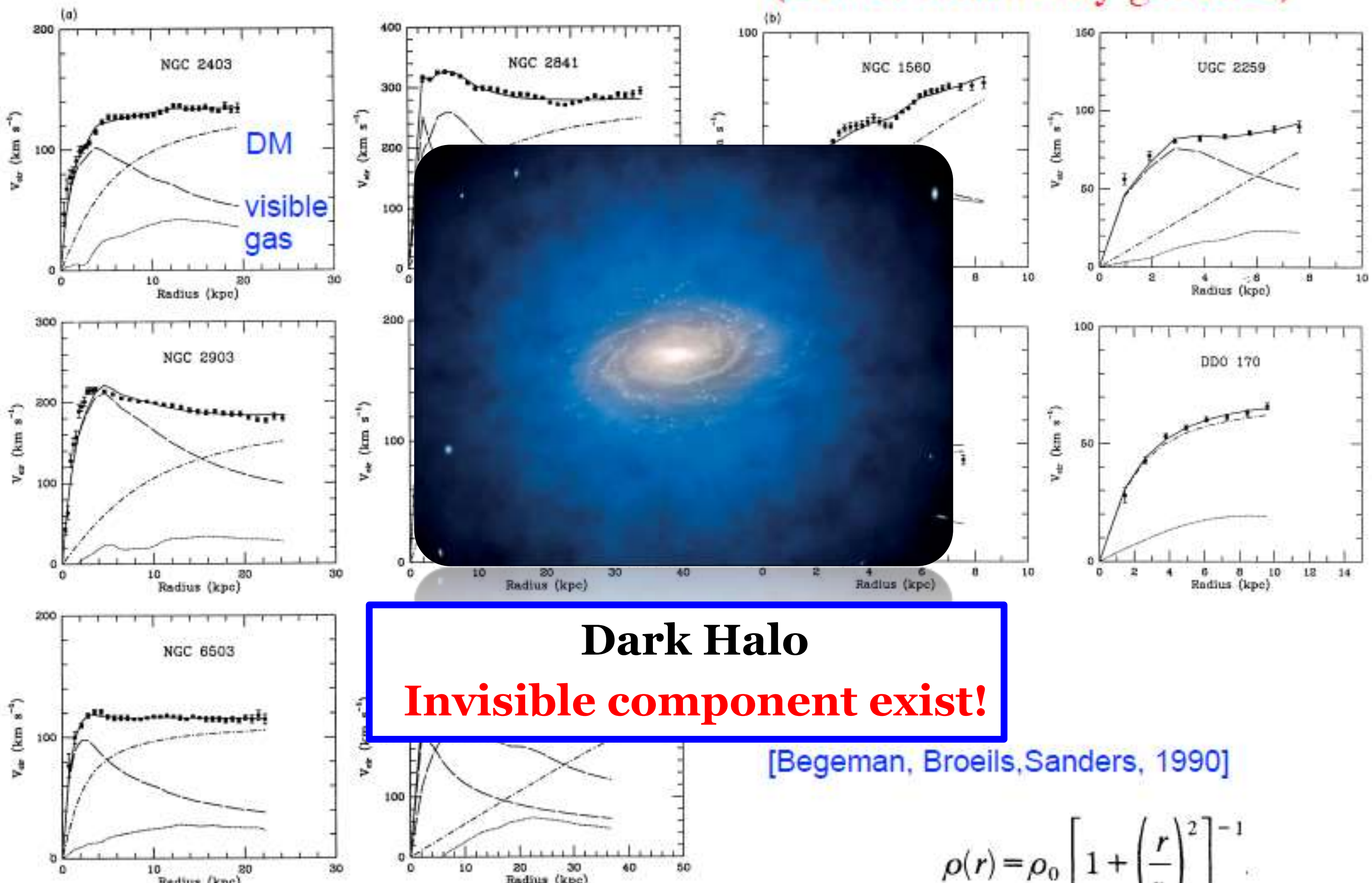

Vera Rubin

$$\frac{GMm}{r^2} = \frac{mv^2}{r} \rightarrow v \propto \sqrt{\frac{GM}{r}}$$

$$v \sim \text{constant} \rightarrow M(r) \propto r$$

❖ Much more galaxies

(Lower luminosity galaxies)



Dark Halo

Invisible component exist!

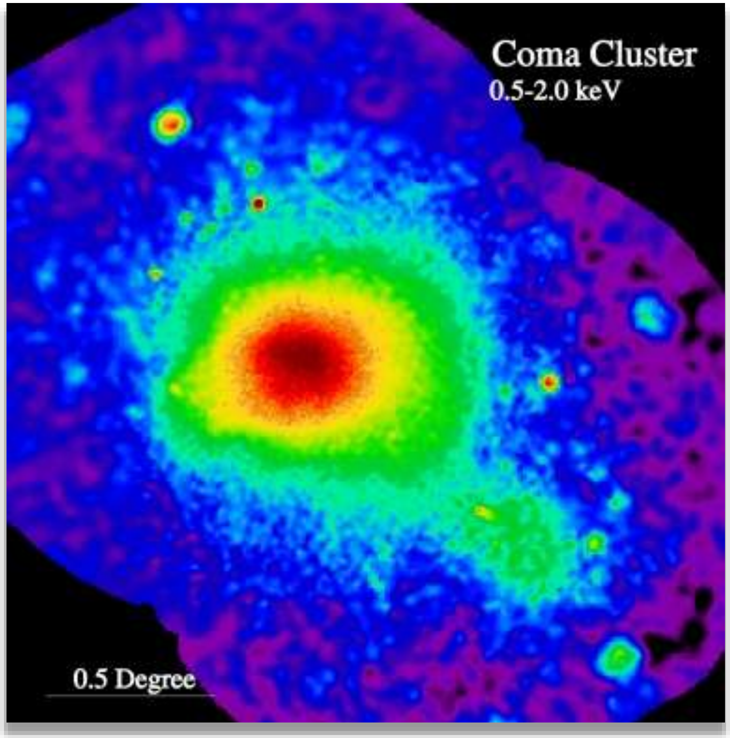
[Begeman, Broeils,Sanders, 1990]

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-1}$$

Figure 1. Three-parameter dark-halo fits (solid curves) to the rotation curves of sample galaxies. The rotation curves of the individual components are also shown: the dashed curves are for the visible components, the dotted curves for the gas, and the dash-dot curves for the dark halo. The fitting parameters are the mass-to-light ratio of the disc (M/L), the halo core radius (r_c), and the halo asymptotic circular velocity (V_∞). The galaxies from the sample of Begeman are shown in (a) and the lower luminosity galaxies in (b). Best-fit values for the free parameters are given in columns 2, 3 and 4 of Table 2.

Coma Cluster

❖ The gravity of the cluster: too weak to contain the hot gas.
→ It would evaporate!: $T \propto v^2 \Leftrightarrow v^2 \propto GM/r$

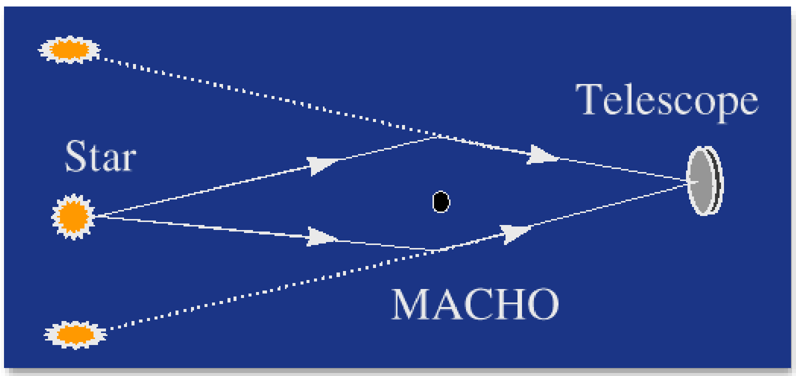


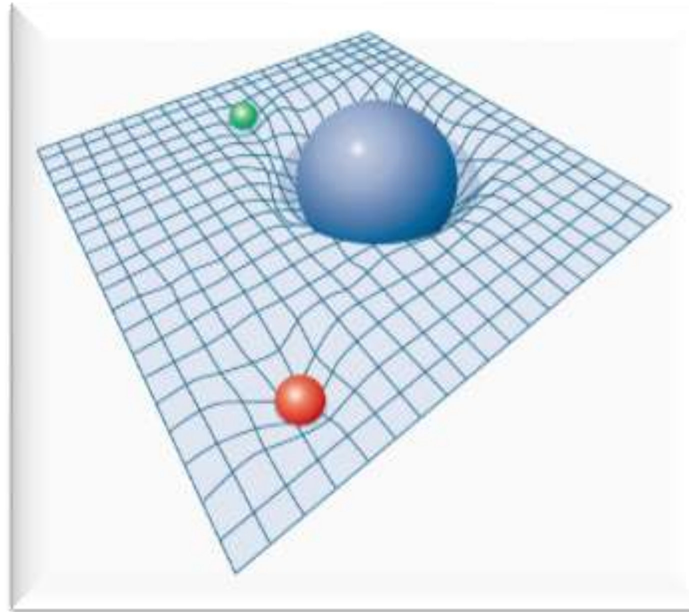
x-ray image from the ROSAT satellite

Gravitational Lensing

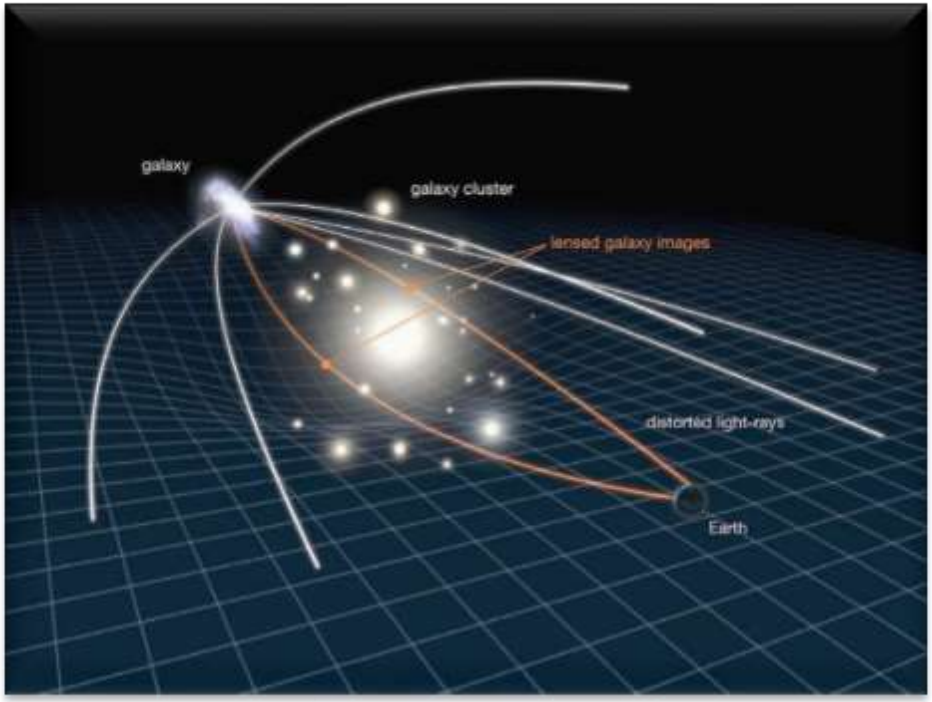
- General relativity: M distorts space-time

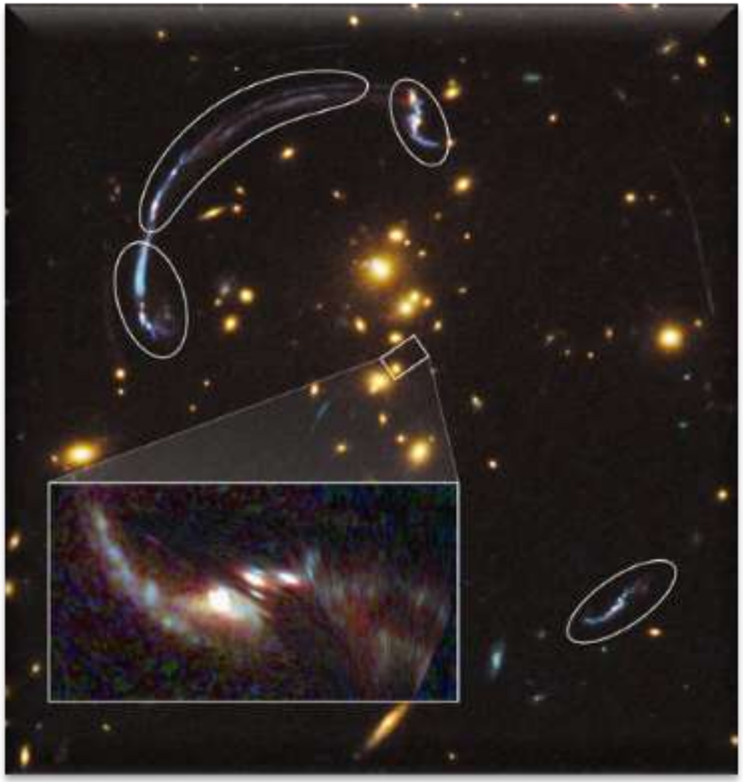
  ➔ When light passes around a massive object, it is bent!





Gravitational Lensing





➢ Stars and hot gas:

too small to bend the light from the background galaxies so much

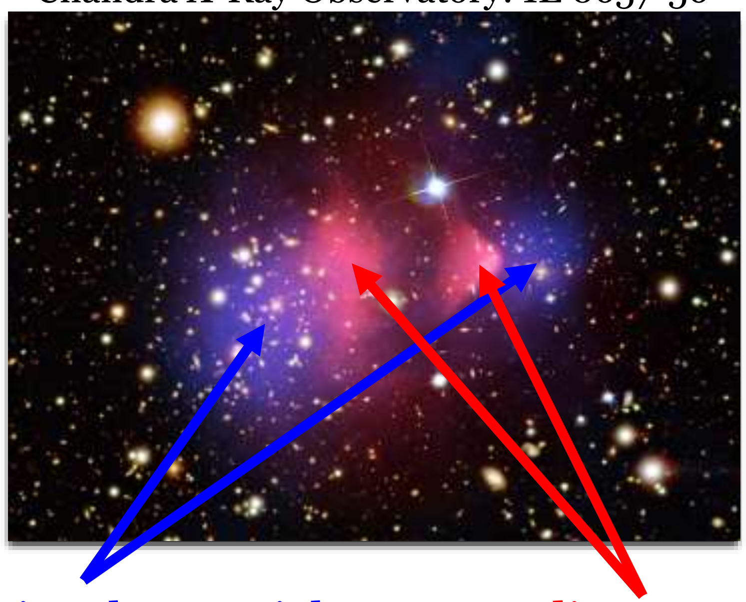
→ **Great concentration of invisible matter: Dark Matter !!**

Bullet Cluster

- Two colliding galaxy clusters

  → significant displacement between their center of visible matter & gravitational potential

Chandra X-Ray Observatory: 1E 0657-56

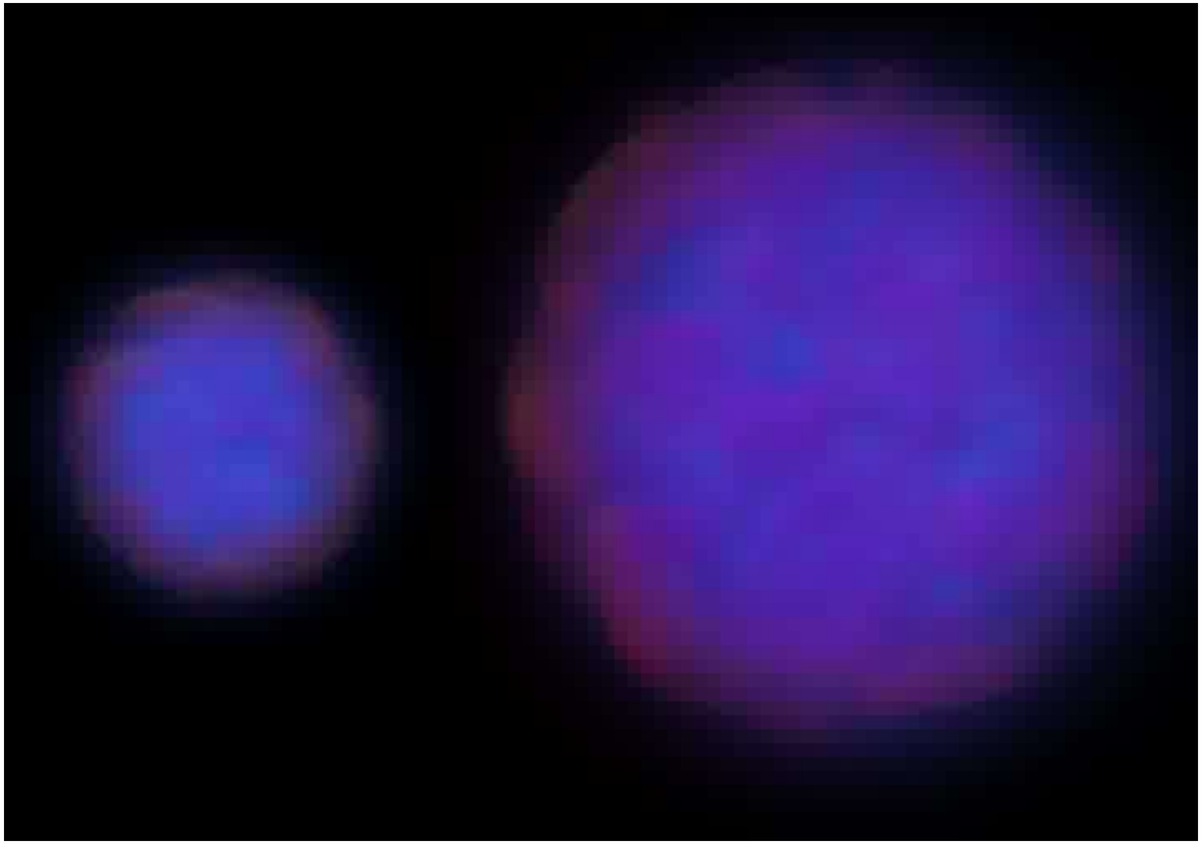


Gravitational potential (lensing)

Ordinary matter (X-ray)

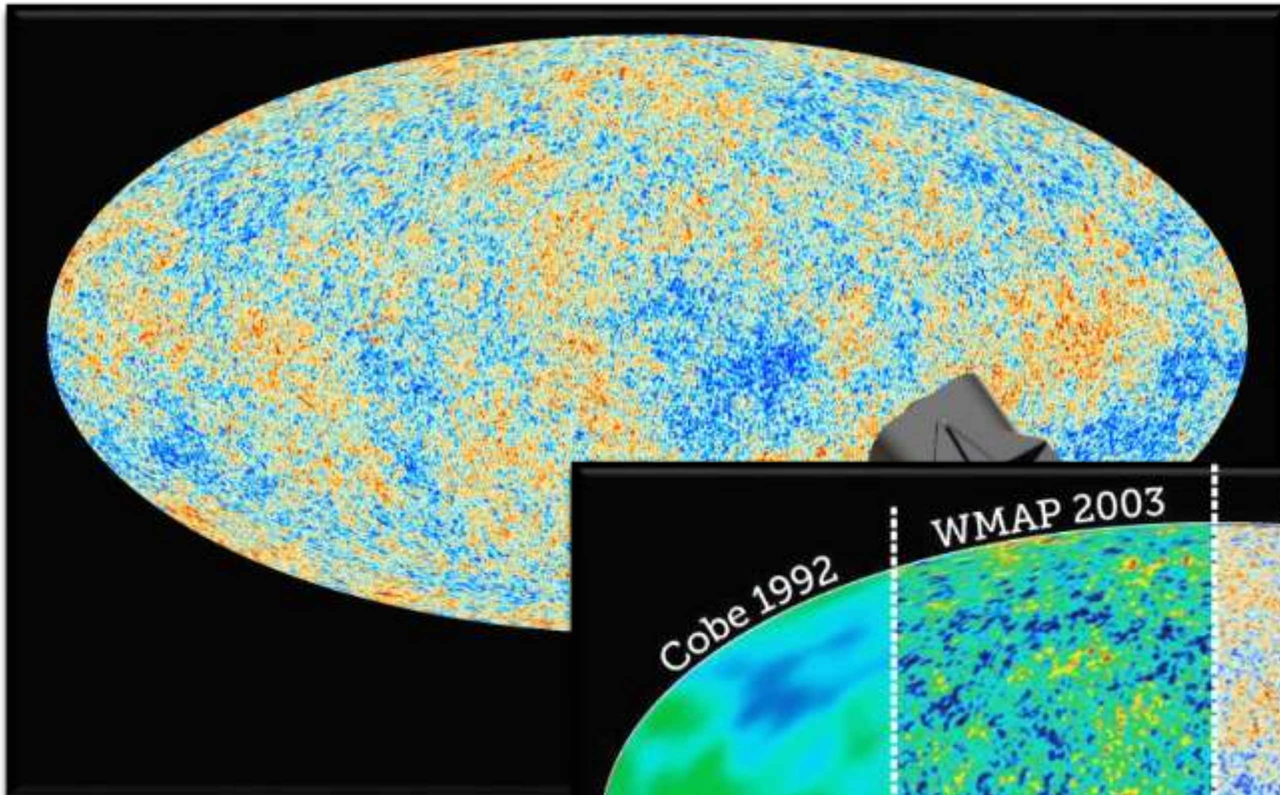
Bullet Cluster

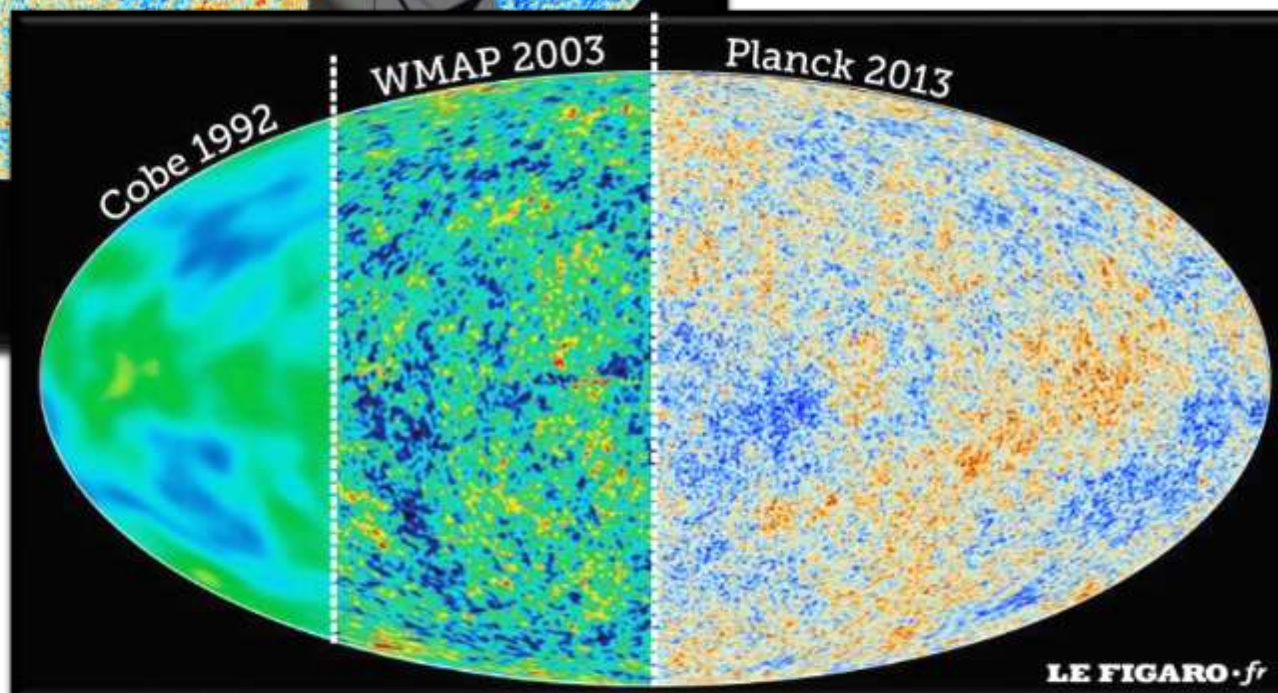
❖ Simulation of two colliding galaxy clusters



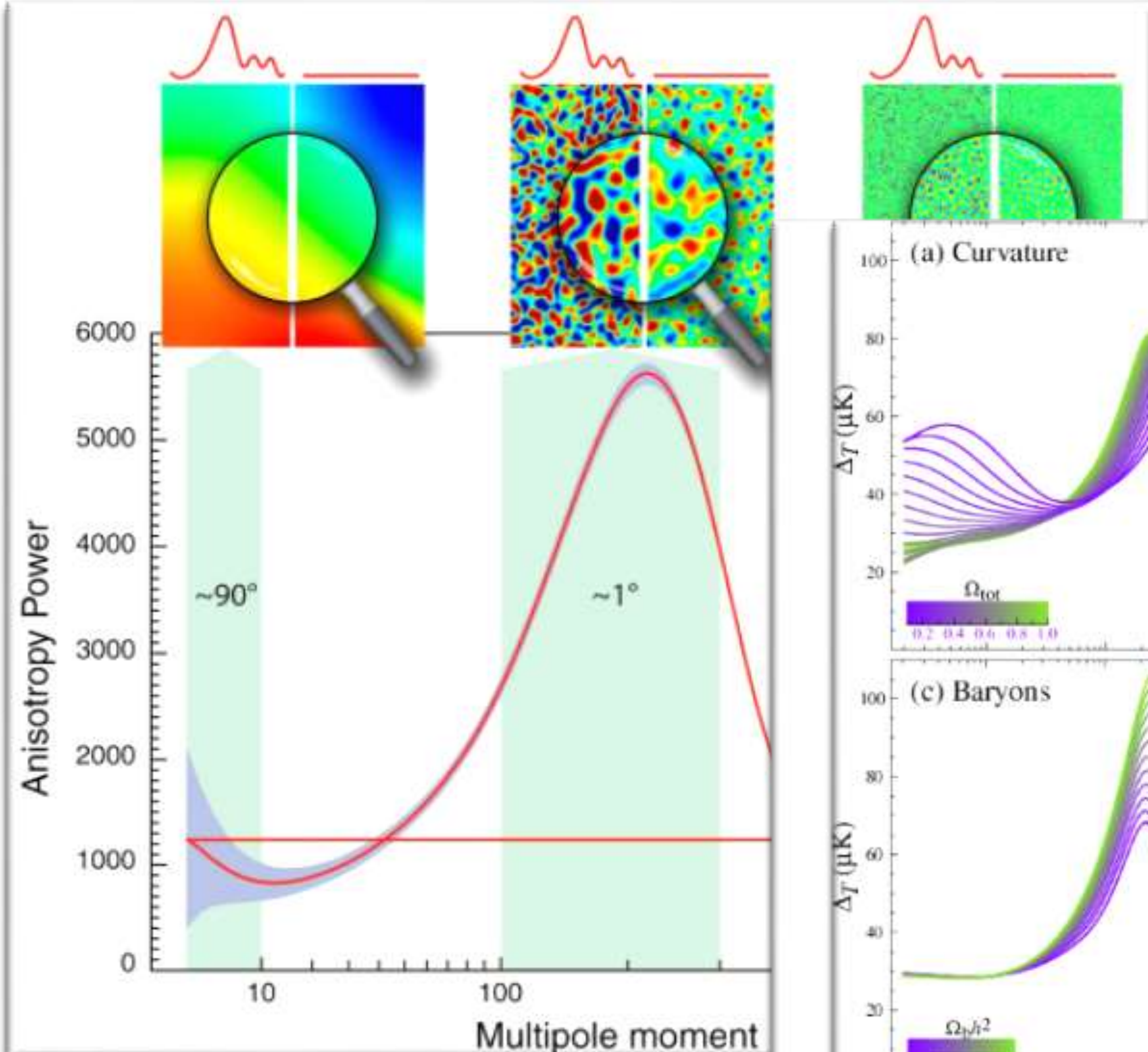
http://chandra.harvard.edu/photo/2006/1e0657/1e0657_bullett_anim_lg.mpg

CMB

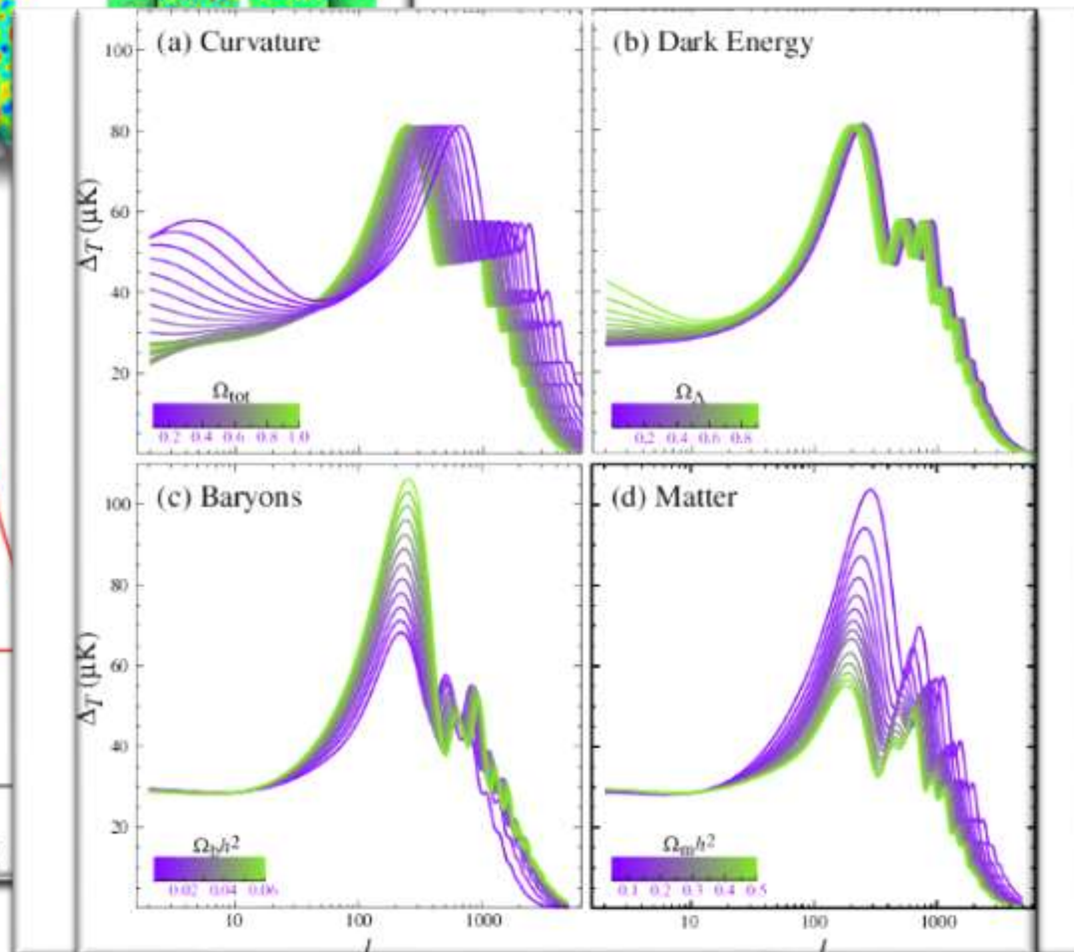




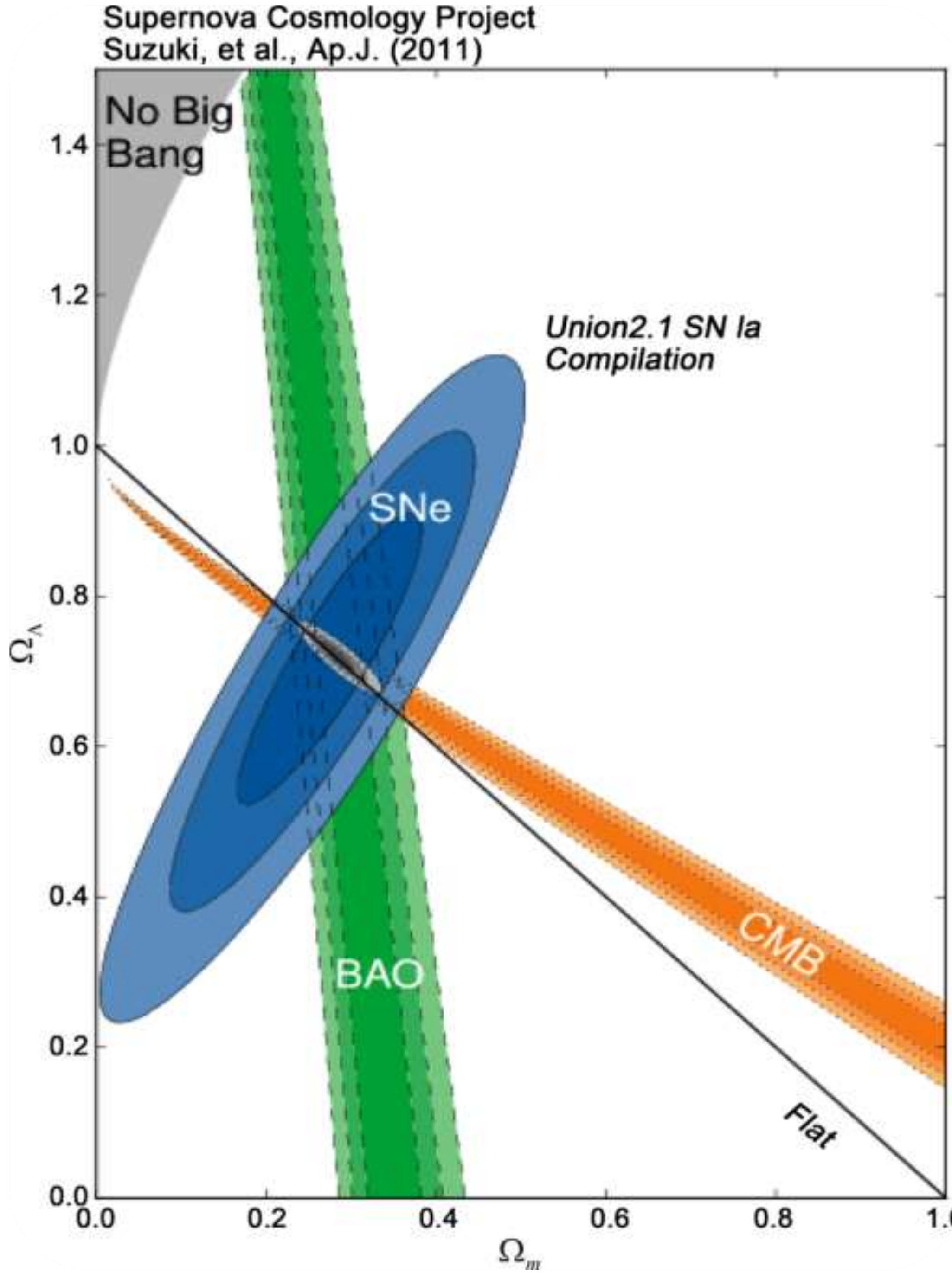
CMB



6000
5000
4000
3000
2000
1000
0
Anisotropy Power
~90°
~1°
10
100
Multipole moment

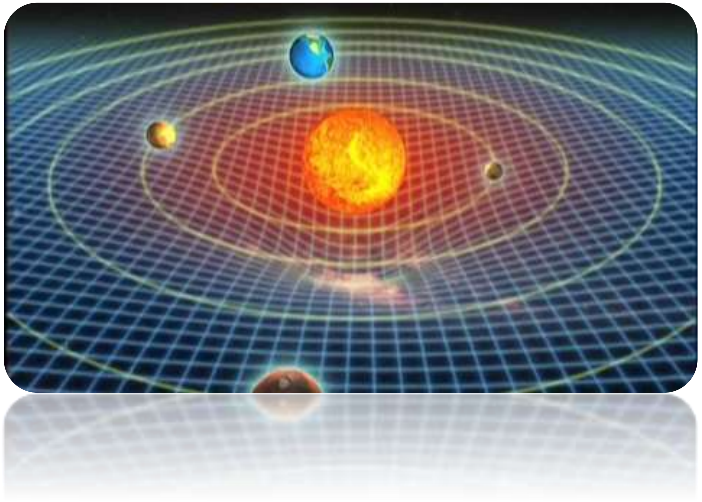


(a) Curvature
(b) Dark Energy
(c) Baryons
(d) Matter
Δ_T (μK)
Ω_{tot}
Ω_Λ
$\Omega_b h^2$
$\Omega_m h^2$
10
100
1000
l



Supernova Cosmology Project
Suzuki, et al., Ap.J. (2011)
No Big Bang
Union2.1 SN Ia Compilation
SNe
BAO
CMB
Flat
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
Ω_Λ
Ω_m

Observational Evidence of DM



- ✓ Galaxy rotation curve
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- ✓ Baryonic acoustic oscillation (BAO)
- ✓ ...

Exercises

1. DM vs Modified gravity/MOND (MOdified Newtonian Dynamics):

(a) What are Modified gravity and MOND?

(b) Compare DM & Modified gravity/MOND: pros and cons

2. DM candidates among SM particles:

(a) Which ones?

(b) Why not? (If possible, Relic density of neutrino)

2. Relic Abundance of Dark Matter

Thermal Freeze-out

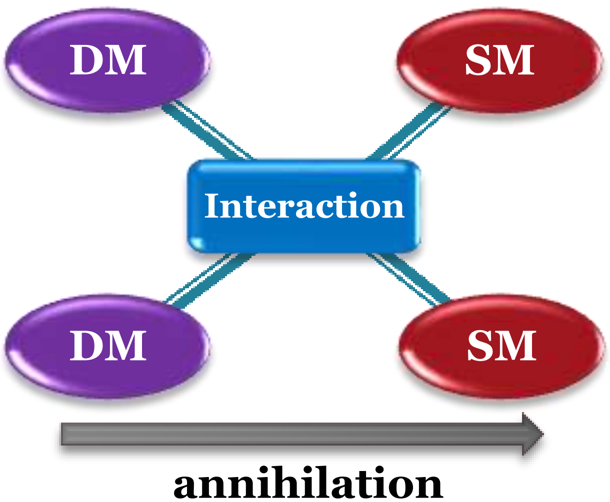
Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.



Basics of Freeze-out

- Boltzmann equation: the statistical behavior of a thermodynamic system not in a state of equilibrium ➔ time evolution of # density:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_A v\rangle[(n_\chi)^2 - (n_\chi^{eq})^2]$$

- Decoupled when $\Gamma_{int} = \langle\sigma v\rangle n_\chi < H$
- Comoving number density ➔ Scale out the expansion effect:

$$(n_\chi/s)_0 = (n_\chi/s)_f \simeq 100/(m_\chi m_{Pl} g_*^{1/2}\langle\sigma_A v\rangle)$$
$$\simeq 10^{-8}/[(m_\chi/\mathrm{GeV})(\langle\sigma_A v\rangle/10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1})]$$

- Relic density in units of the critical density:

$$\Omega_\chi h^2 = m_\chi n_\chi/\rho_c \simeq (3\times10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}/\langle\sigma_A v\rangle)$$

For more details, please see e.g., Ch. 5.1 & 5.2 of "The Early Universe"