어두운 세상

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2019.12.27

The Dark World

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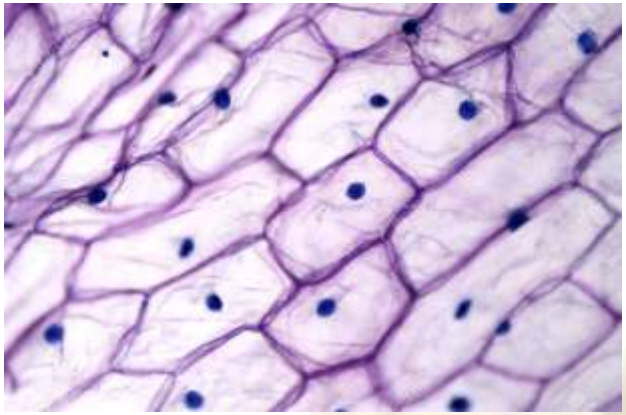
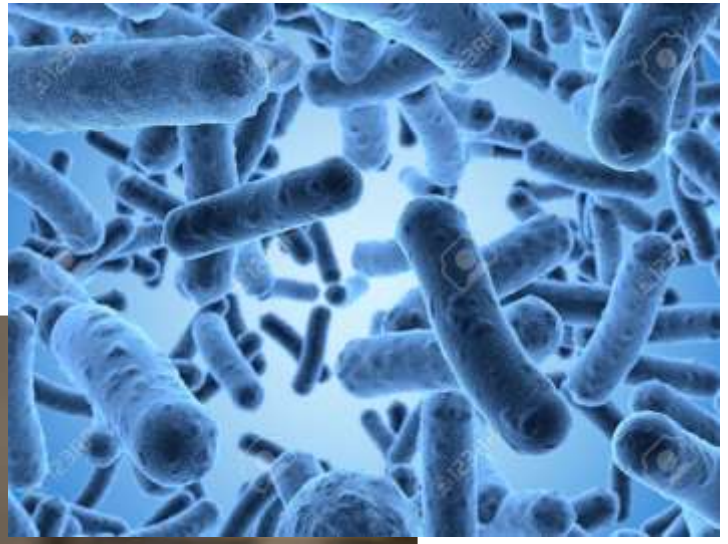
MARVEL
THOR
THE DARK WORLD

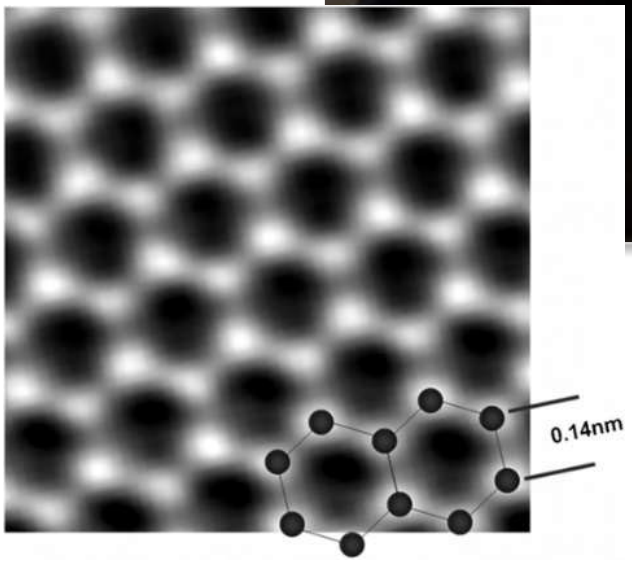
Search for the Dark World

2019.12.27

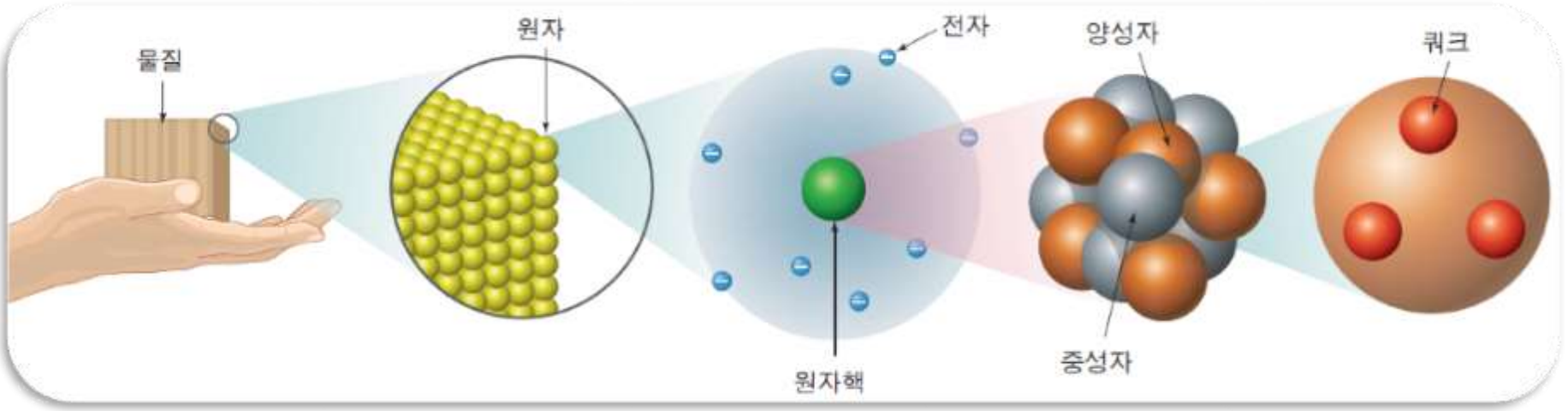

"본다"라는
말의 의미?






0.14nm

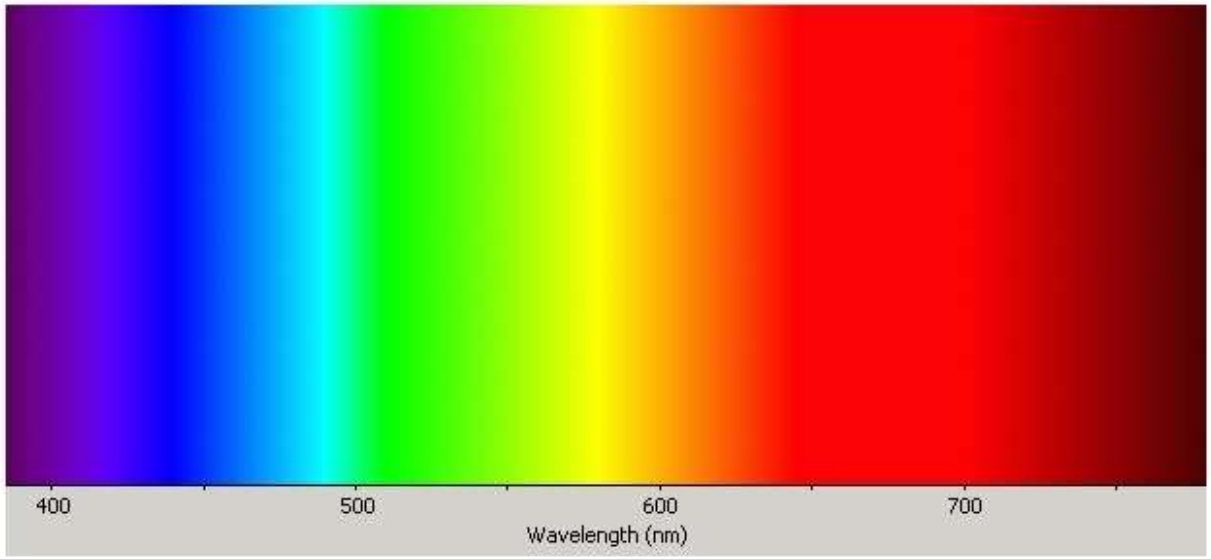
더 작은 세상(기본 존재)을 찾아서~



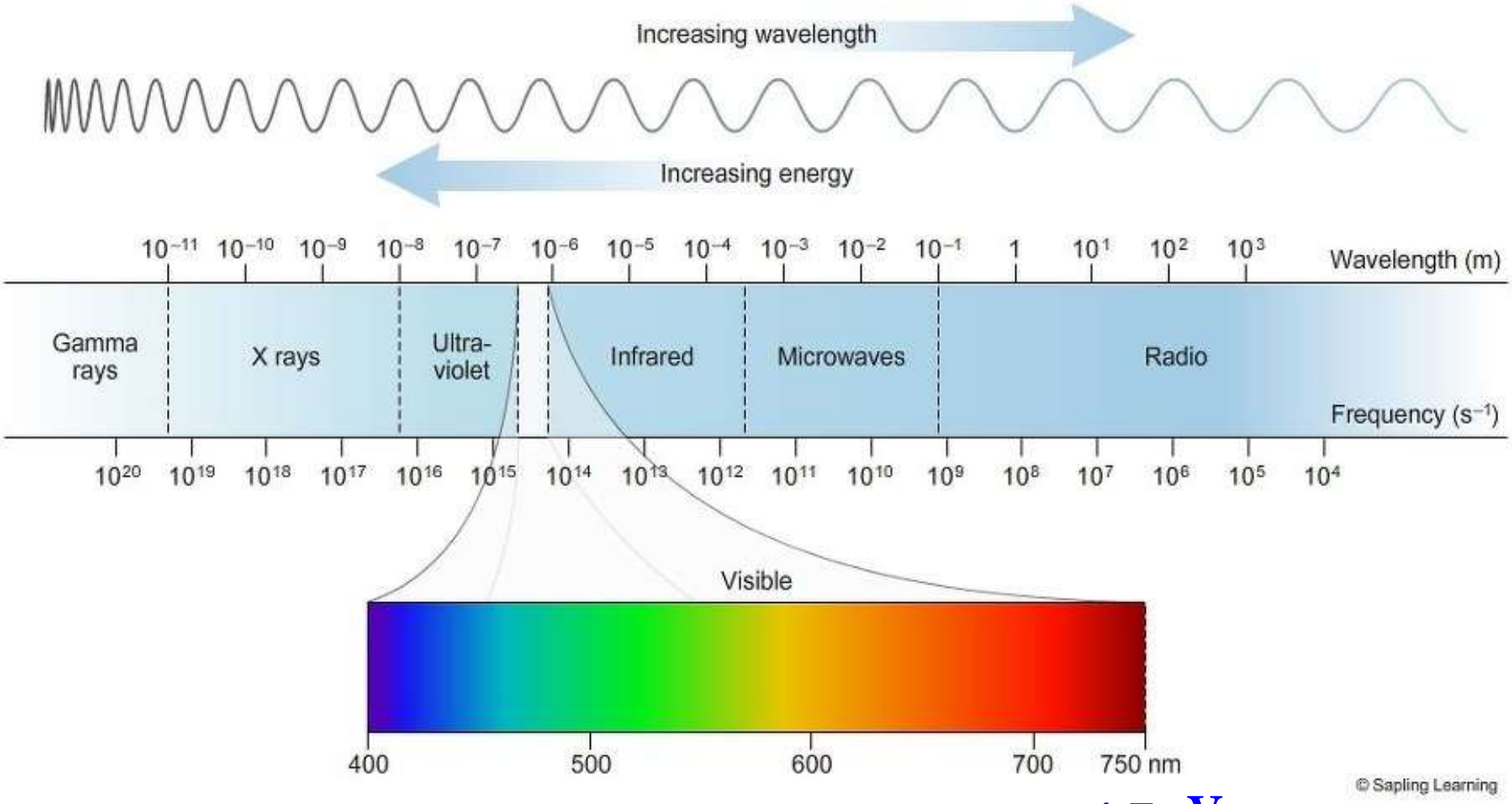
- 존 돌턴 (John Dalton): 현대적 의미의 원자론(1808년)
- 조지프 존 톰슨 (Joseph John Thomson): 전자(1896년)
- 어니스트 러더퍼드 (Ernest Rutherford): 원자핵(1909년), 양성자(1919년)
- 제임스 체드윅 (James Chadwick): 중성자(1932년)
- 머리 겔만 (Murray Gelman): 쿼크 모형(1964년)

"본다"의
다른 의미?

좁은 의미의 본다: 눈으로 ➔ 가시광선

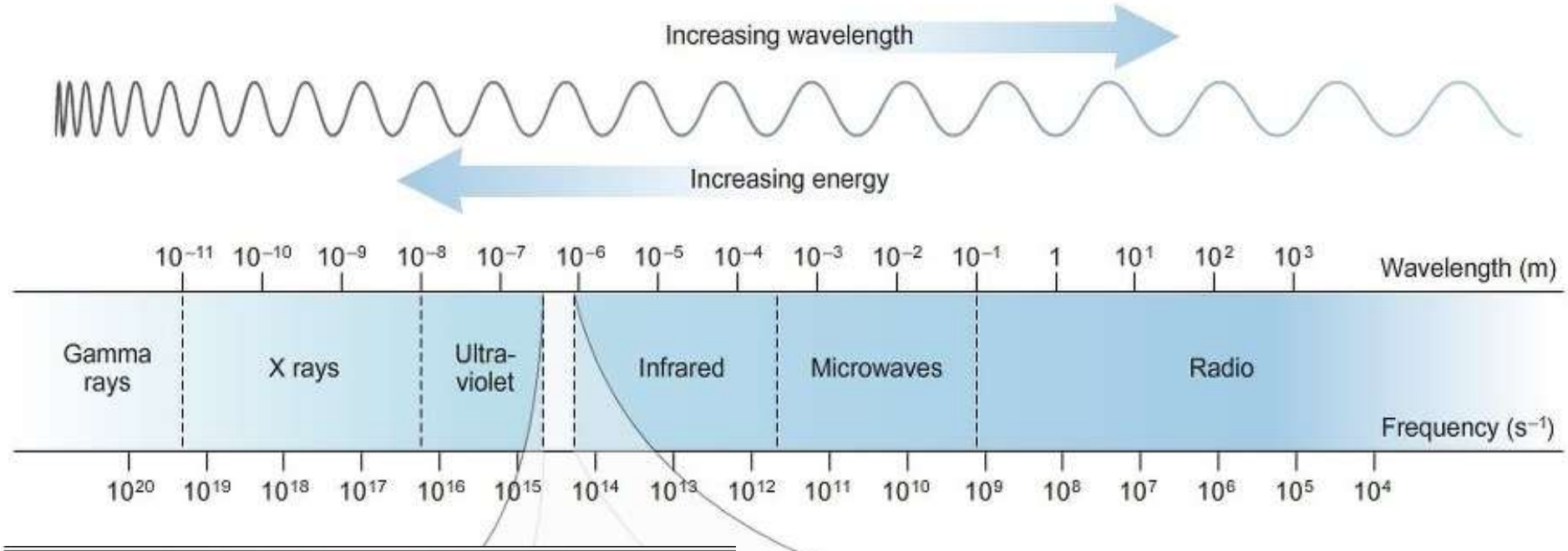


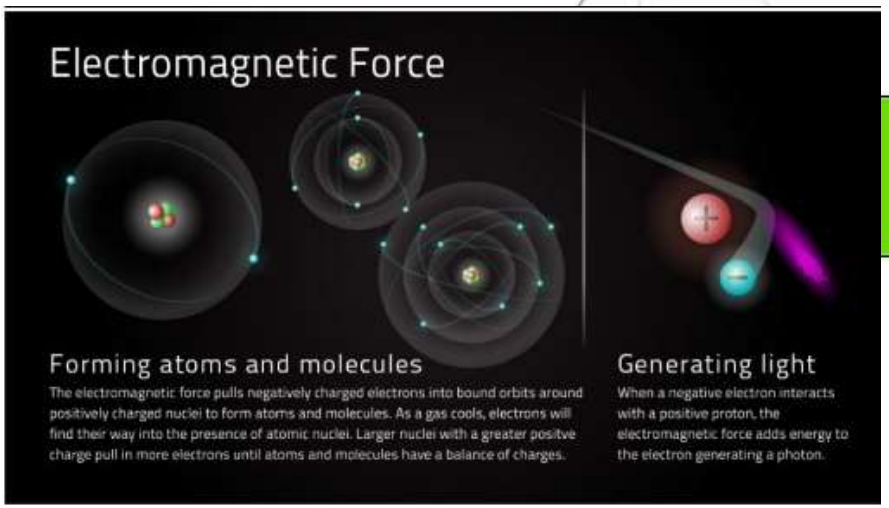
더 넓은 의미의 본다: 다른 파장으로도~

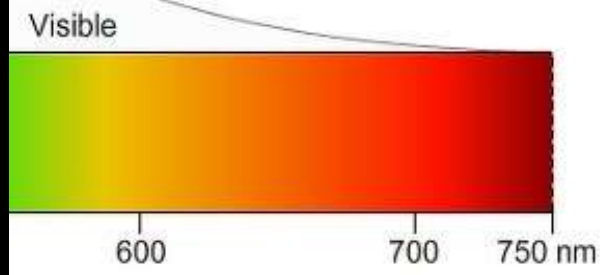


~1.7 eV

더 넓은 의미의 본다: 다른 파장으로도~



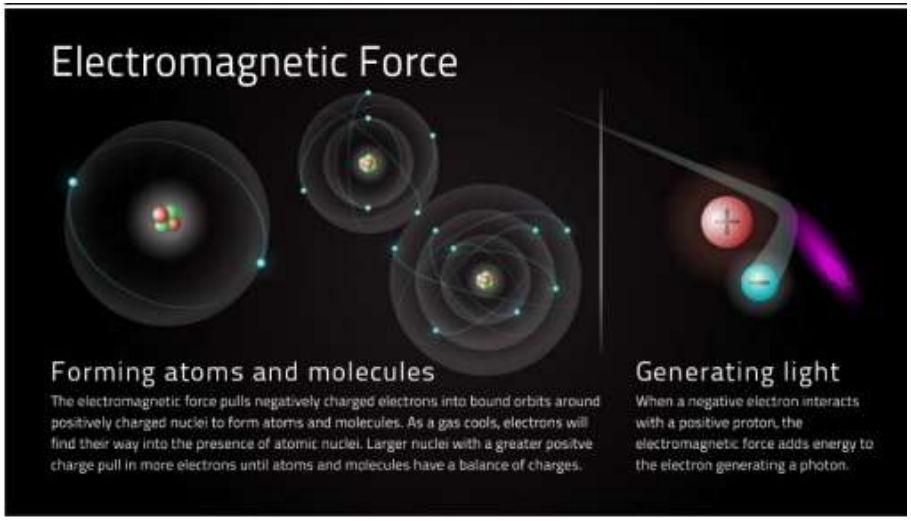


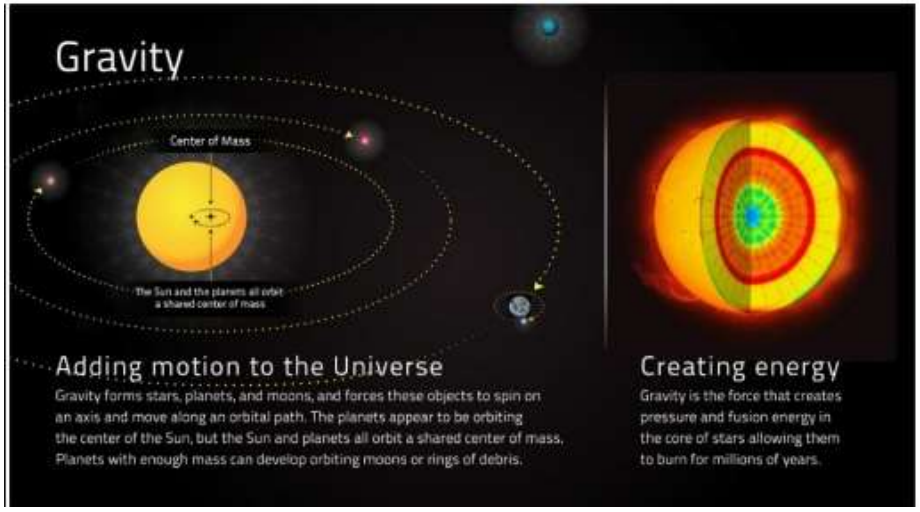


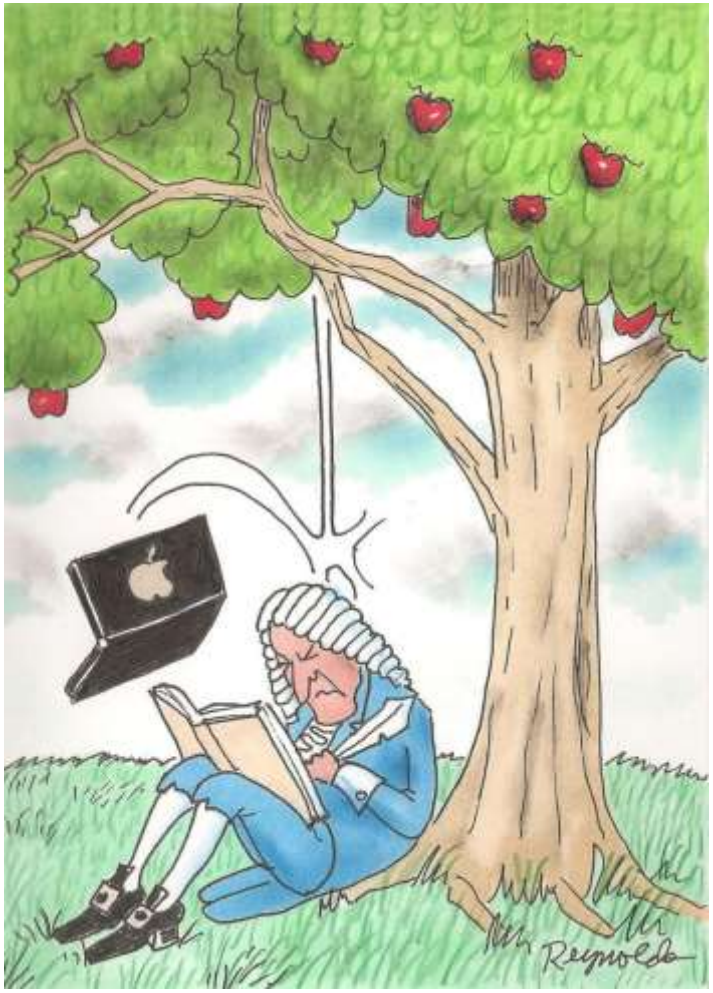
~1.7 eV

"본다"라는
개념의 확장?

본다 = 상호 작용을 통해 느낀다/안다!







다른 상호 작용으로도 볼 수 있음!

Electromagnetic Force

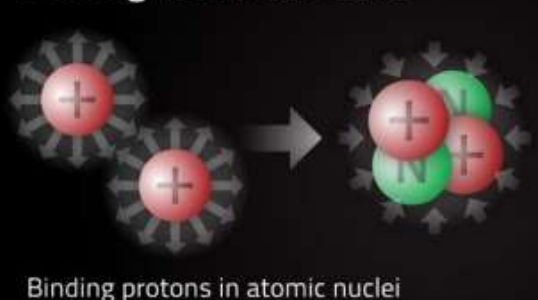
Forming atoms and molecules

The electromagnetic force pulls negatively charged electrons into bound orbits around positively charged nuclei to form atoms and molecules. As a gas cools, electrons will find their way into the presence of atomic nuclei. Larger nuclei with a greater positve charge pull in more electrons until atoms and molecules have a balance of charges.

Generating light

When a negative electron interacts with a positive proton, the electromagnetic force adds energy to the electron generating a photon.

Strong Nuclear Force



Binding protons in atomic nuclei

Positively charged particles naturally repel each other, it takes an extreme amount of force to hold protons together. The strong nuclear force overcomes the repulsion between protons to hold together atomic nuclei. Without the strong nuclear force, complex nuclei cannot form.

Breaking the bond

Enormous energy is released as gamma rays and nuetrinos when the strong nuclear force is broken between protons and neutrons.

Gravity

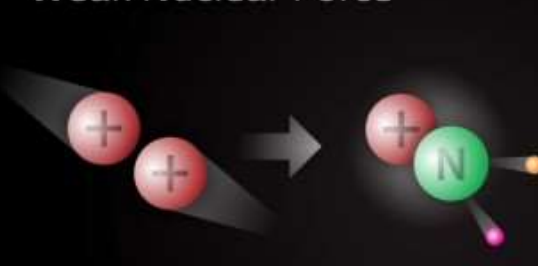
Adding motion to the Universe

Gravity forms stars, planets, and moons, and forces these objects to spin on an axis and move along an orbital path. The planets appear to be orbiting the center of the Sun, but the Sun and planets all orbit a shared center of mass. Planets with enough mass can develop orbiting moons or rings of debris.

Creating energy

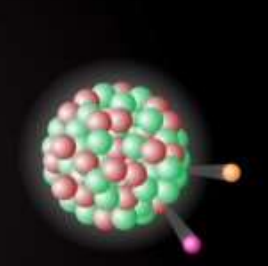
Gravity is the force that creates pressure and fusion energy in the core of stars allowing them to burn for millions of years.

Weak Nuclear Force



Converting protons into neutrons

When two protons collide and fuse, a disruption in the weak nuclear force emits a positron and neutrino, which converts one of the positively charged proton to a neutrally charged Nuetron. Without the weak nuclear force converting protons into nuetrons, certain complex nuclei cannot form.



Releasing radiation

Heavy atoms have an imbalance of protons and nuetrons, so the weak nuclear force converts protons to nuetrons releasing radiation.

우리가 볼 수 있는
세상(우주)의 구성 성분

가장 많은 성분? 얼마나?

가장 많은 성분? 얼마나?

우주에서 물질의 구성 비율

어떻게 구별?

물질 vs 암흑 물질

어떻게 구별?

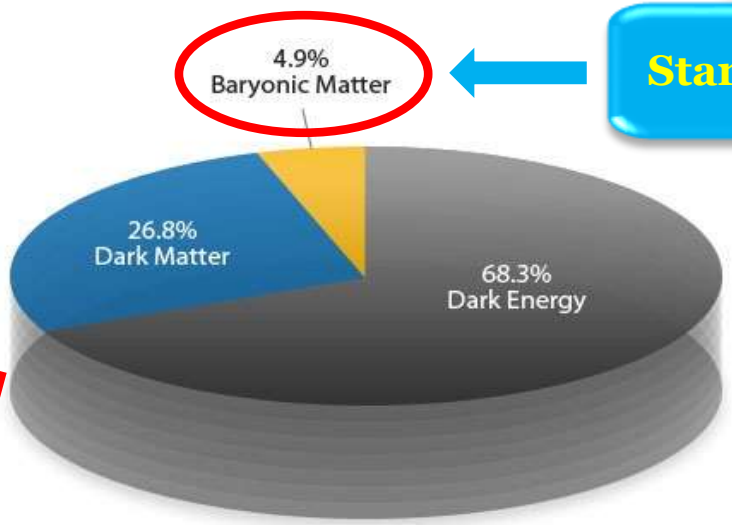
- ❖ 공통점: 질량이 있어 중력을 통해 서로 당긴다.
- ❖ 차이점: 물질은 보이지만, 암흑 물질은 안보인다.

우리가 볼 수 있는
우주의 최종(?) 구성 성분

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?

Question in the 21th Century!

What's the matter?

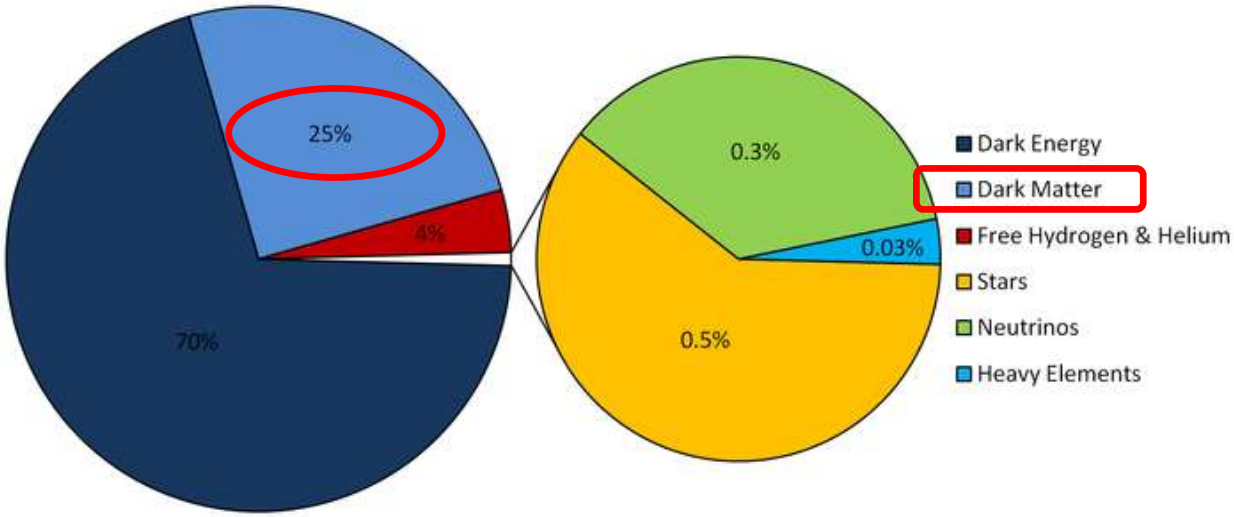
⬇

What's Dark Matter?

암흑 물질: Dark Matter (DM)

- Postulated by Fritz Zwicky in early 1930's
- Rediscovered by Vera Rubin in 1970

- **Compelling paradigm**:
  - ✓ massive, non-luminous, non-relativistic (→ $v << c$), stable particles
  - ✓ ~1/4 of the Universe

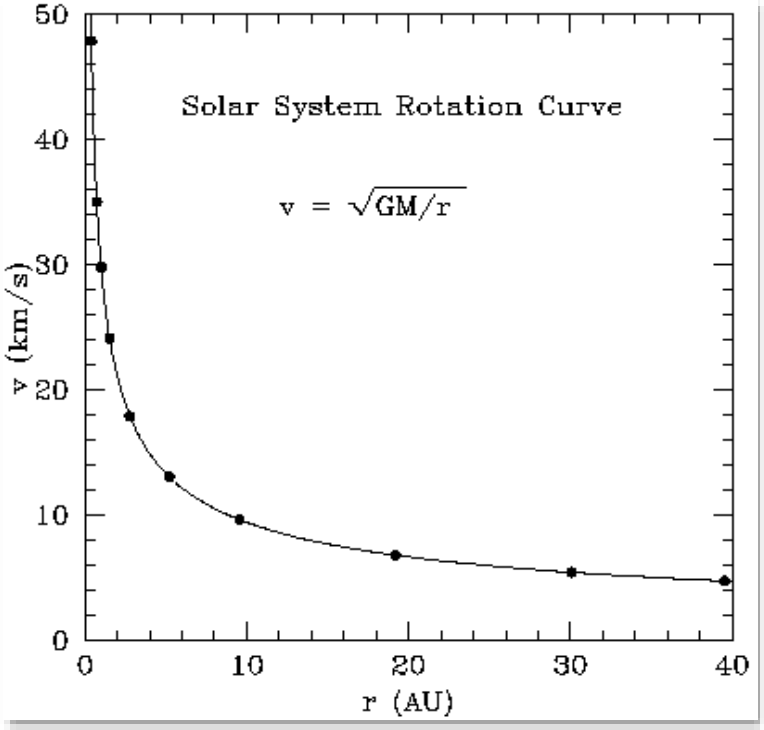


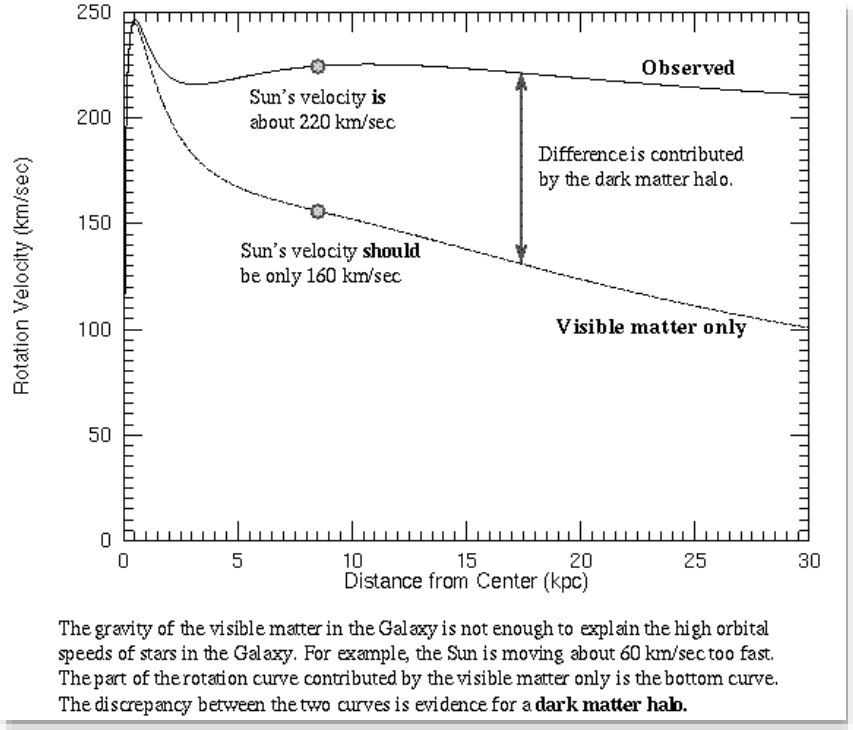
암흑 물질 존재
어떻게 알아요?

암흑 물질의 존재에 대한 관찰 증거들~

- ✓ 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

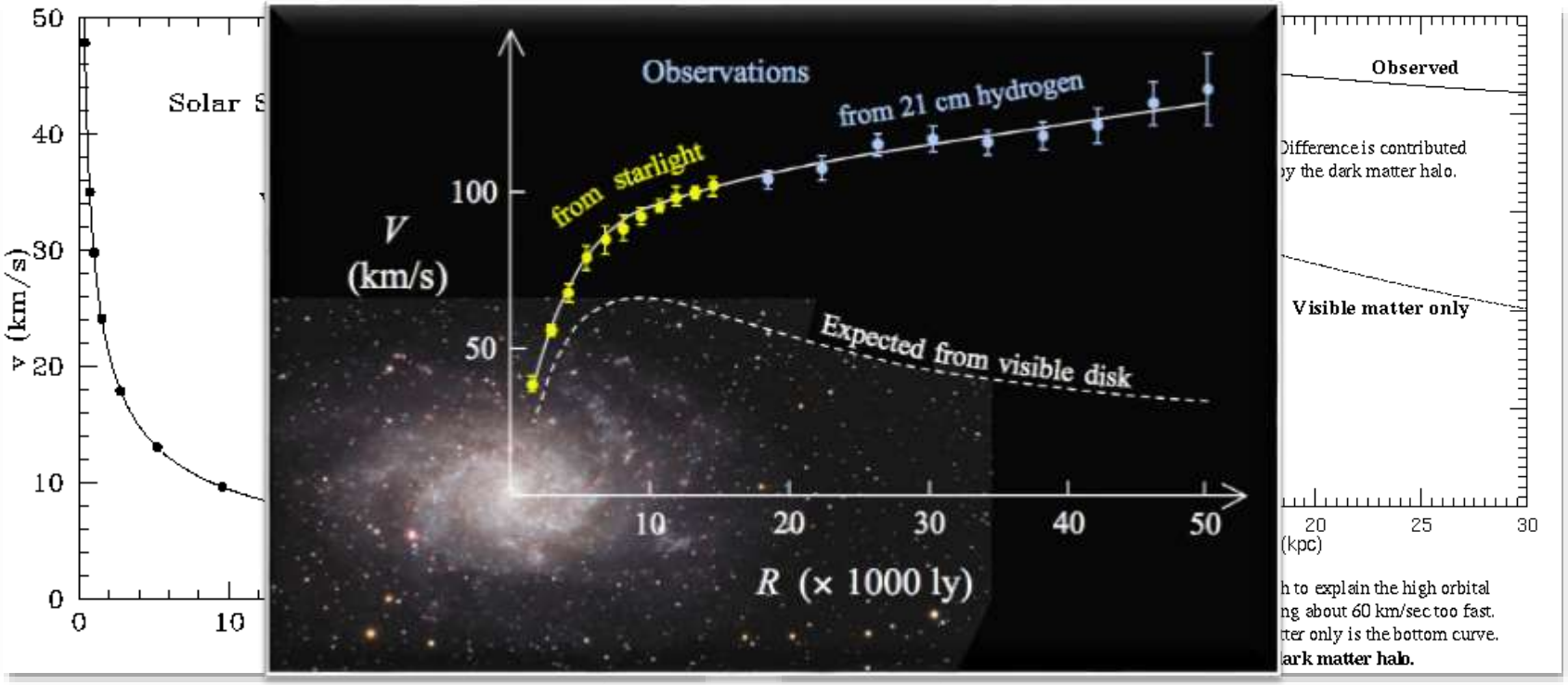




The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two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

Vera Rubin

Galaxy Rotation Curve



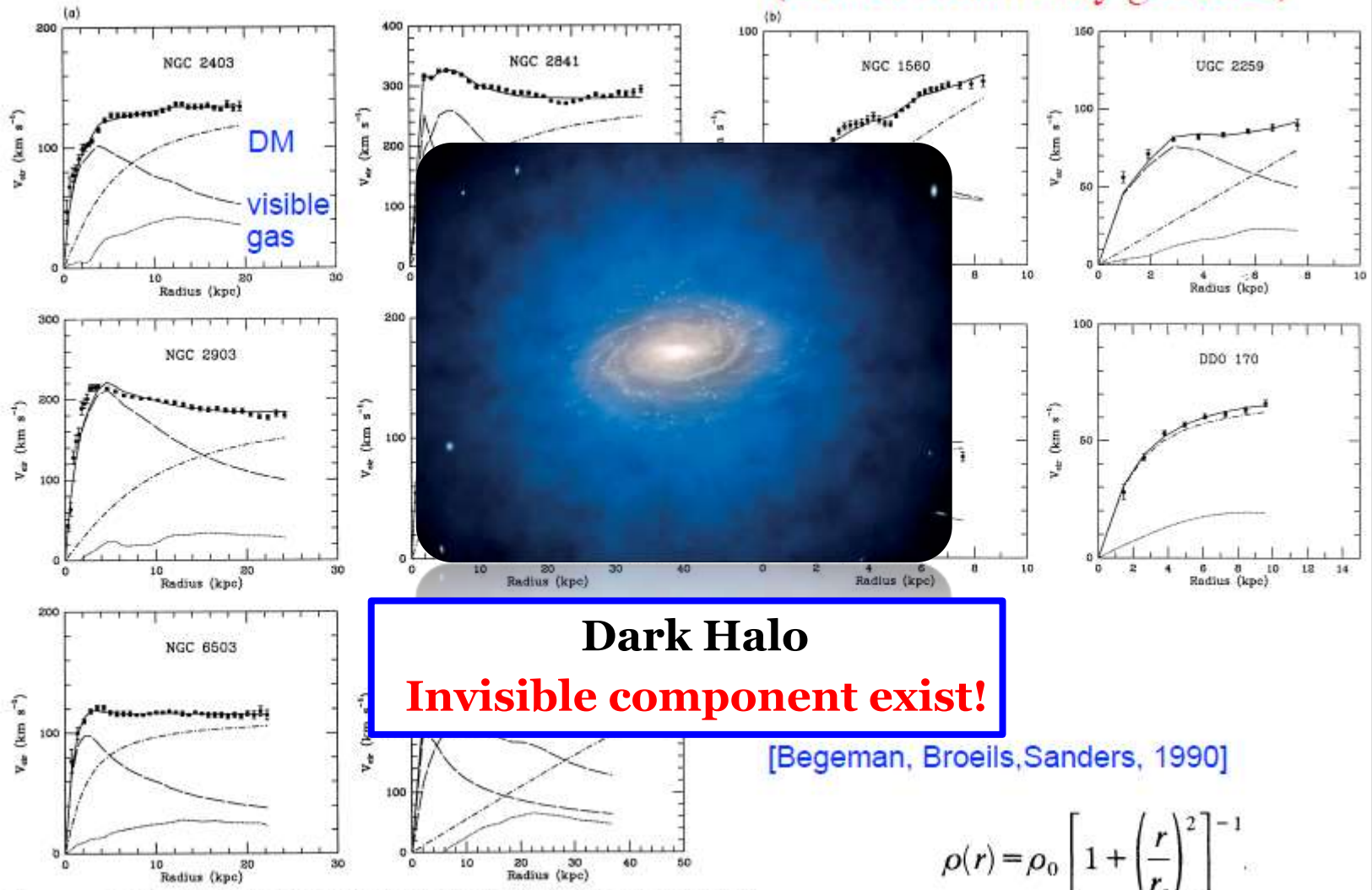
Vera Rubin

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

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

❖ Much more galaxies

(Lower luminosity galaxies)



Dark Halo

Invisible component exist!

[Begeman, Broeils,Sanders, 1990]

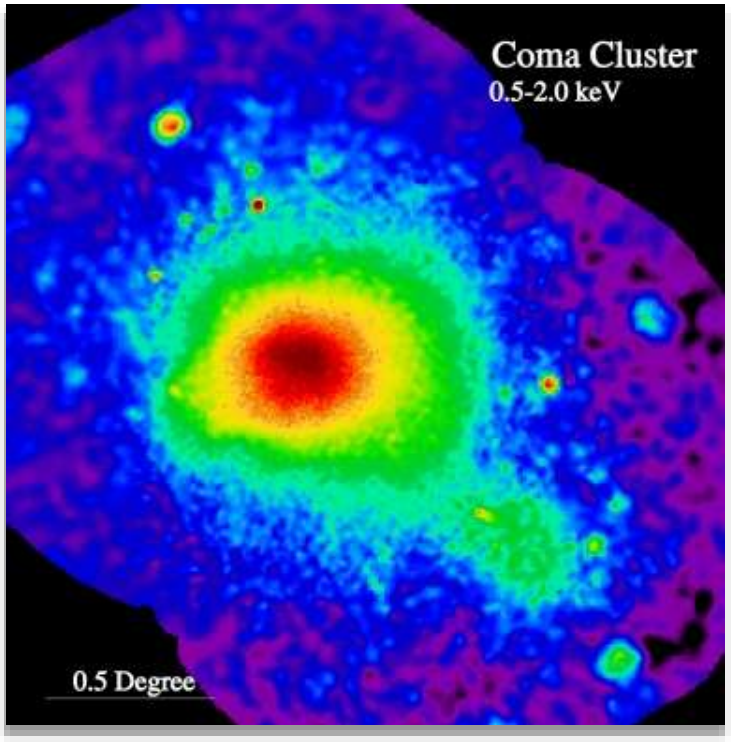
$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1}$$

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_h). 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!: $T \propto v^2 \Leftrightarrow v^2 \propto GM/r$

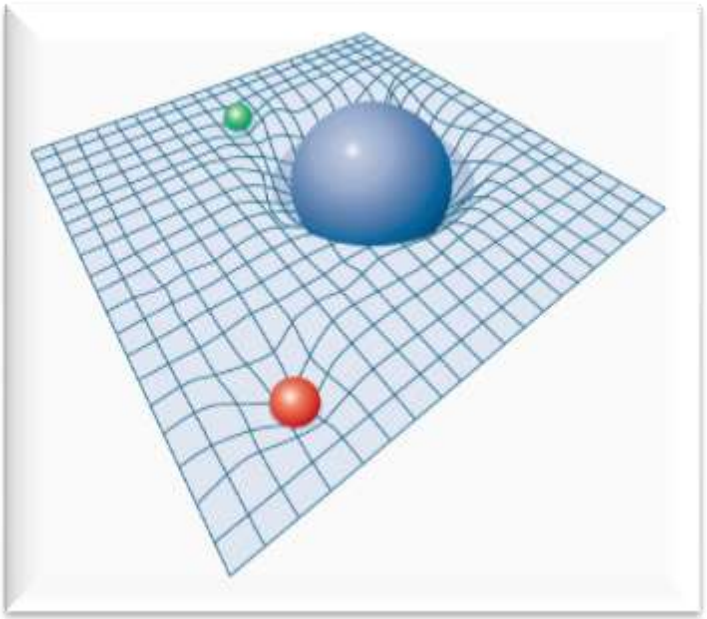


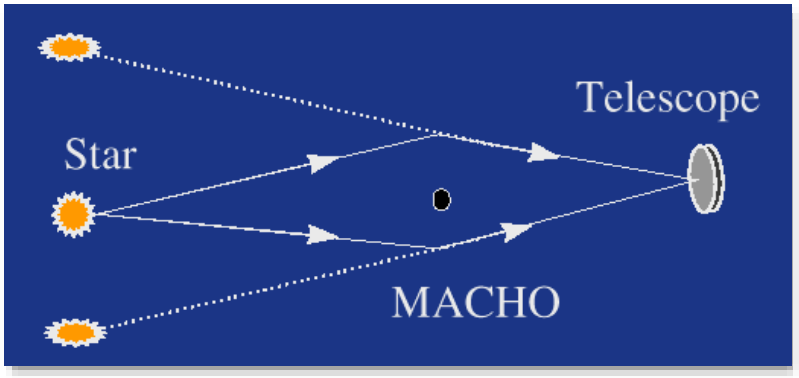
x-ray image from the ROSAT satellite

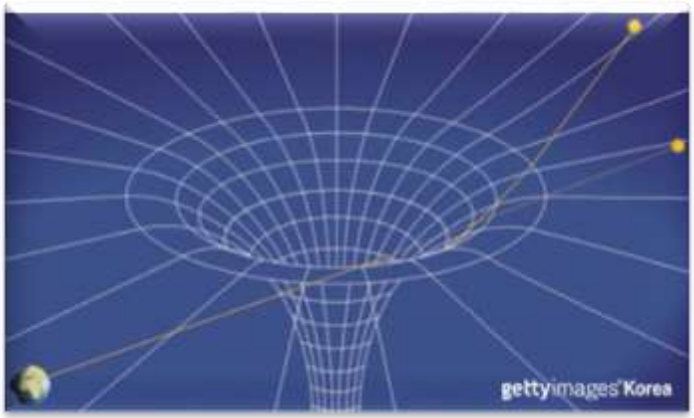
Gravitational Lensing

- General relativity: M distorts space-time

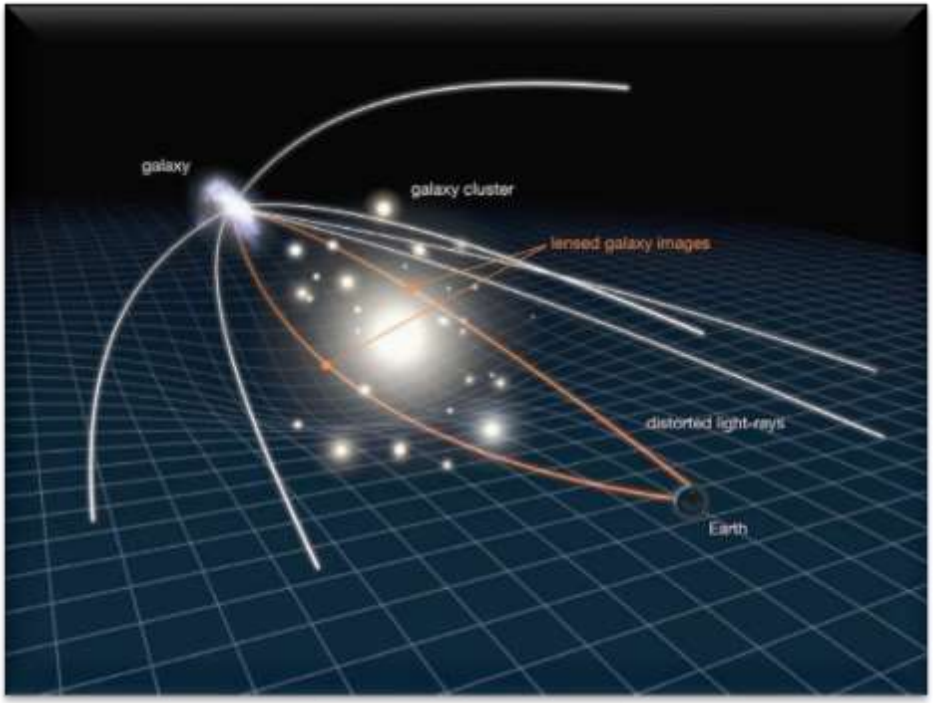
  ➔ When light passes around a massive object, it is bent!

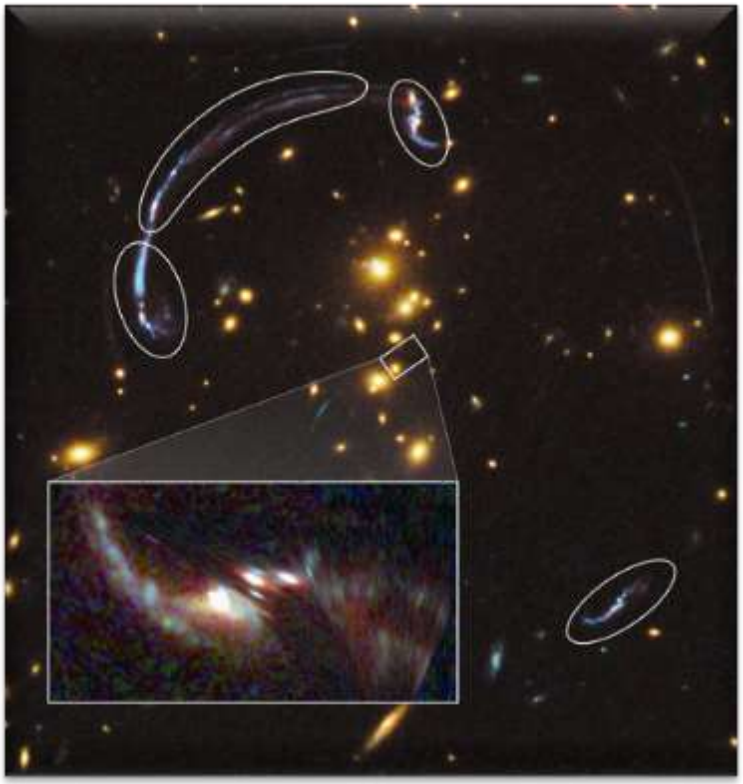






Gravitational Lensing



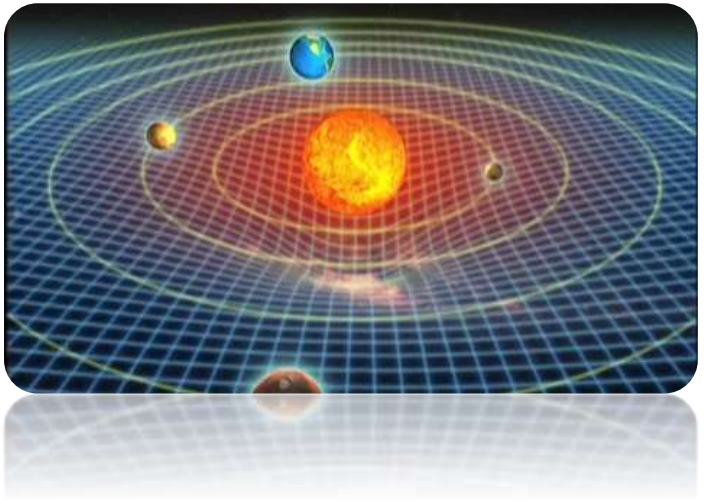


- Stars and hot gas:

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

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

암흑 물질의 존재에 대한 관찰 증거들~



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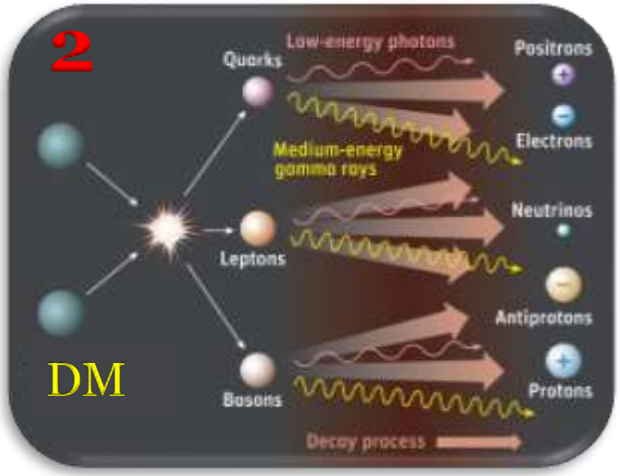
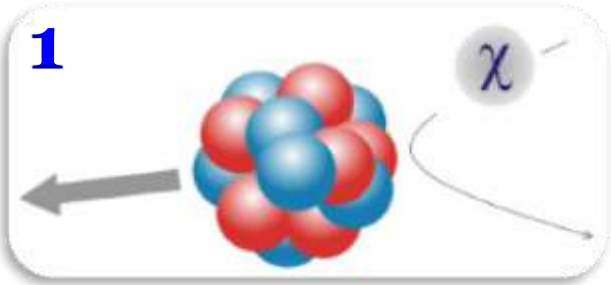
- ✓ …

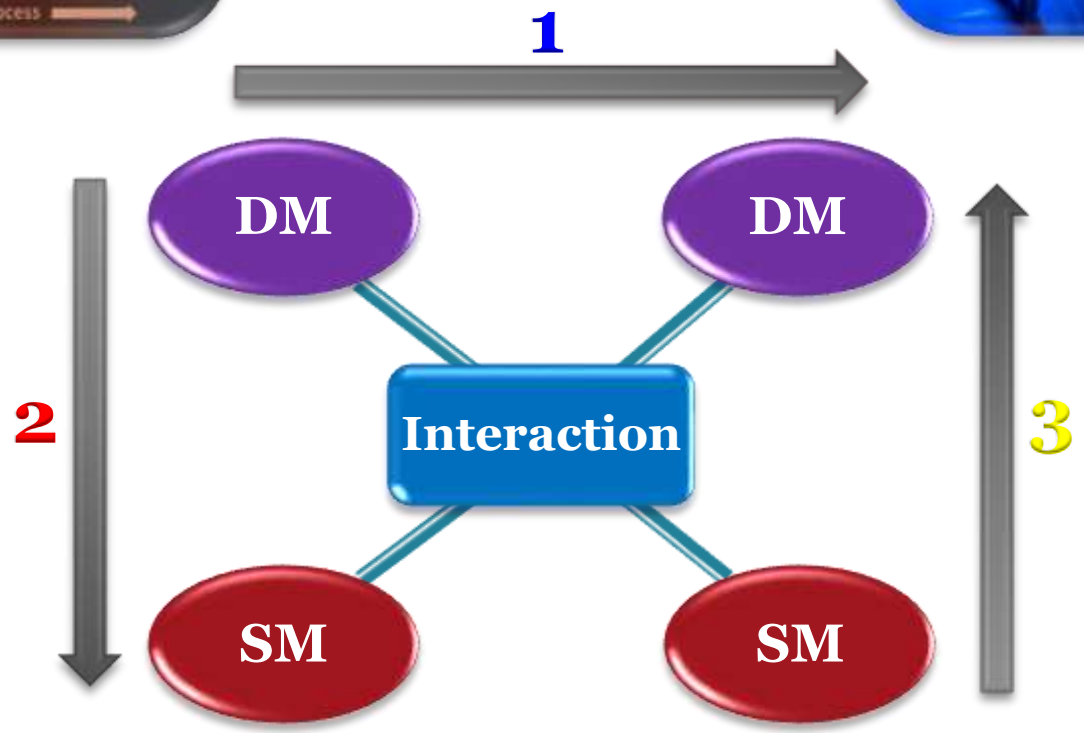
암흑 물질 정체
어떻게 알아요?

암흑 물질 탐색 방법

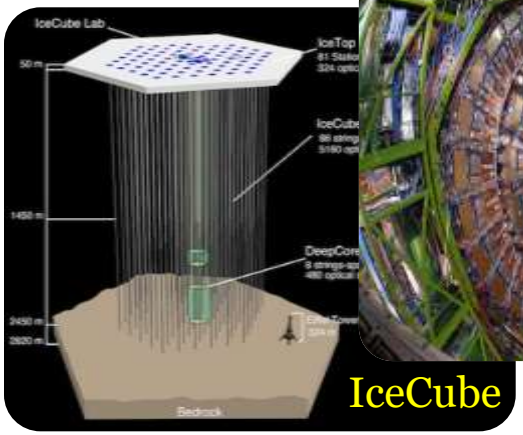

2
Quarks
Low-energy photons
Positrons
Electrons
Medium-energy gamma rays
Neutrinos
Leptons
Antiprotons
DM
Bosons
Protons
Decay process

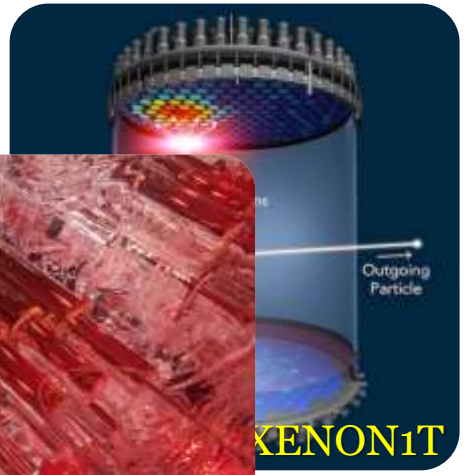

1
χ


3

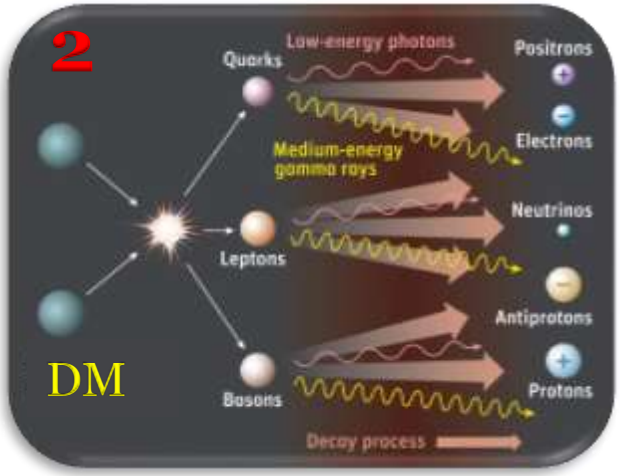

1
DM
DM
2
Interaction
3
SM
SM

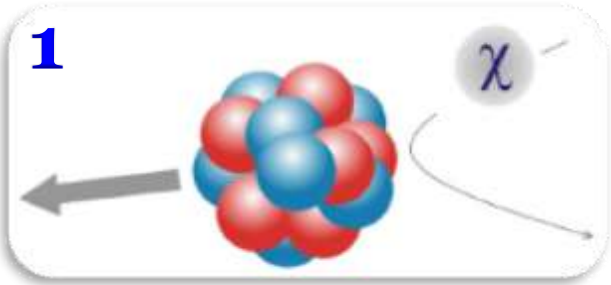
Diverging Efforts for DM Searches

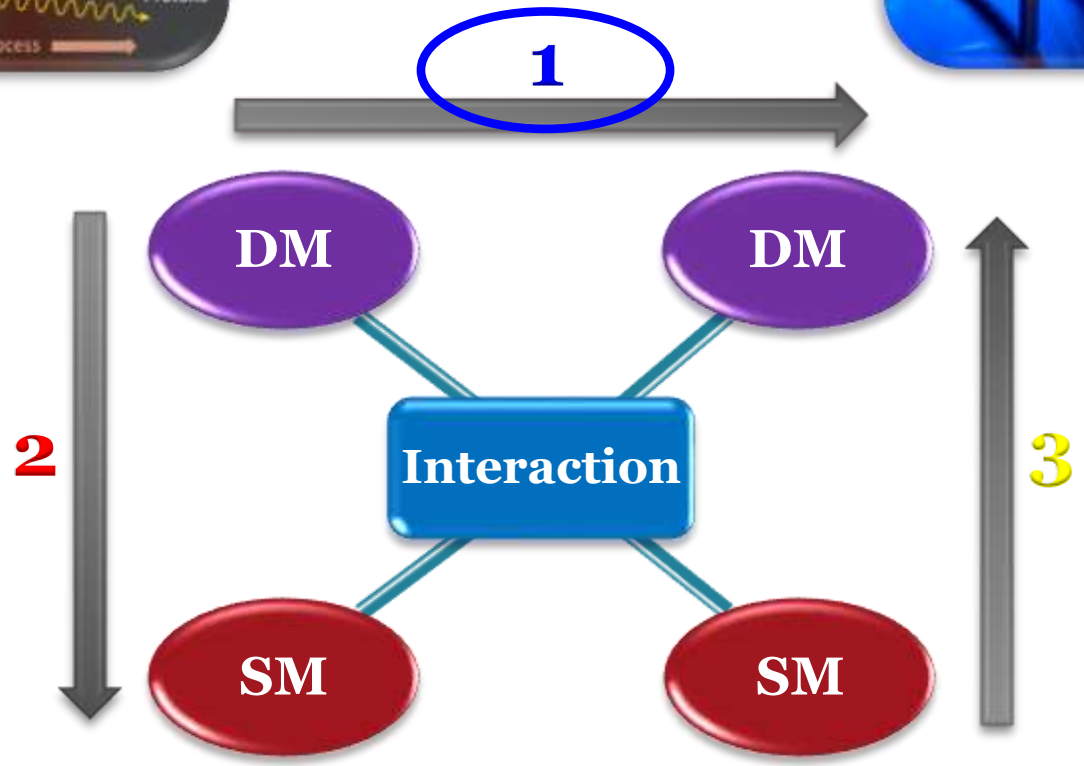




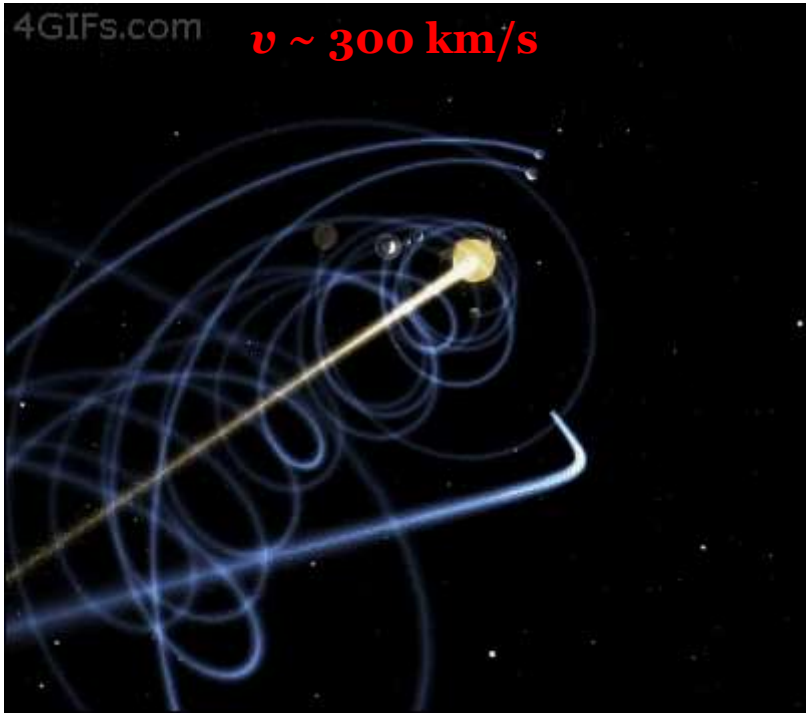
직접 탐색: DM Direct Detection







암흑 물질 vs 인간



- When $m_{DM} \sim m_p \sim 0.94$ GeV: $300\ \mathrm{km/s} \times \dfrac{0.4\ \mathrm{GeV/cm^3}}{0.94\ \mathrm{GeV}} \times 60\ \mathrm{cm} \times 170\ \mathrm{cm}$

$$\approx\ 10^{11}/\mathrm{s}$$

- ~10^{11}/s DM's penetrate our body for $m_{DM} \sim m_p$!
  - ✓ Solar ν: ~10^{11} /cm^2/s

DM Direct Detection

- DM: all around us! → recoil of DM-nucleus scattering

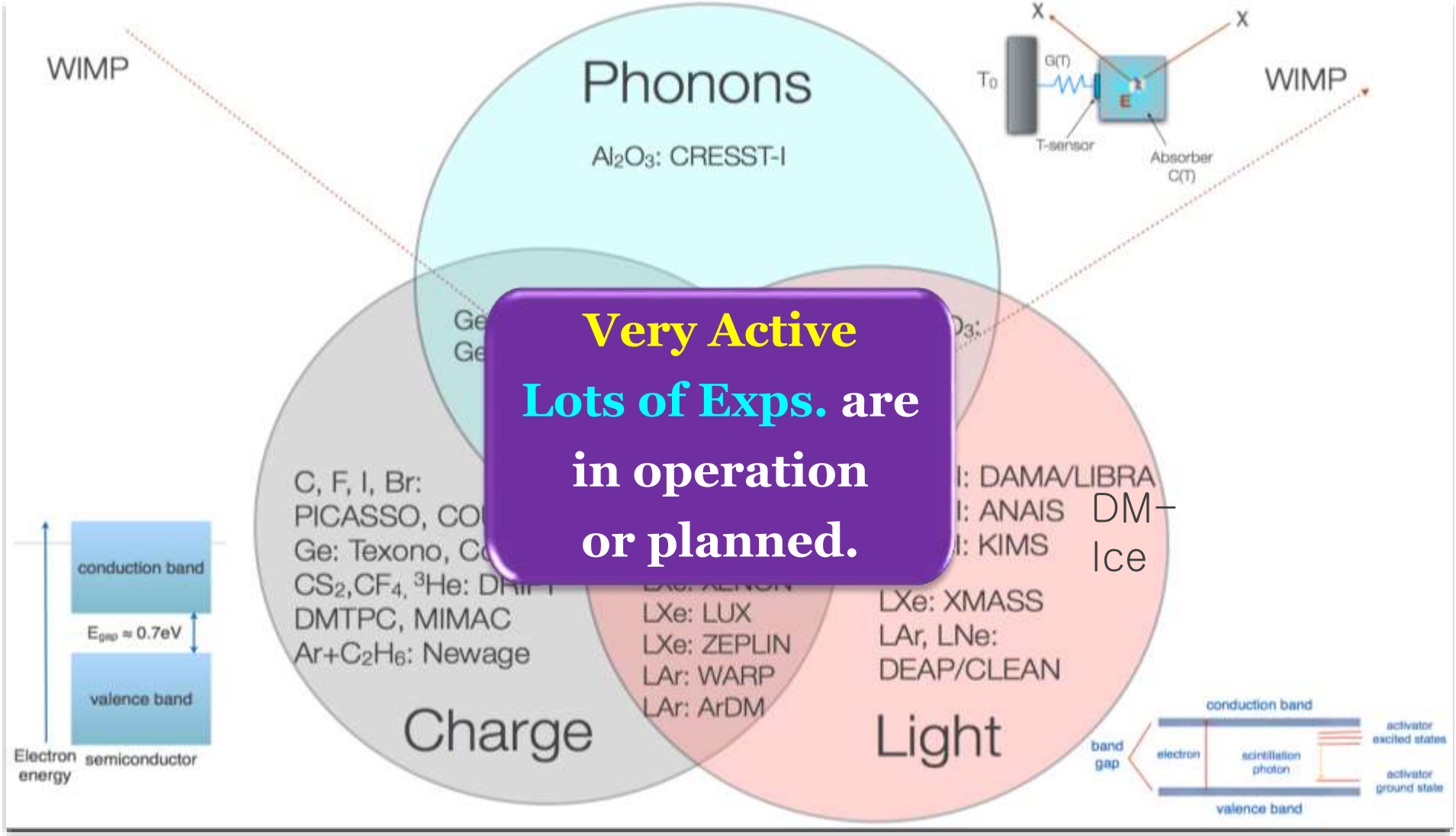
  based on ***E* & *p* conservation**!

- What is measure: E of recoiling nucleus ~ 1-100 keV for m_{DM} ~ 1-100 GeV

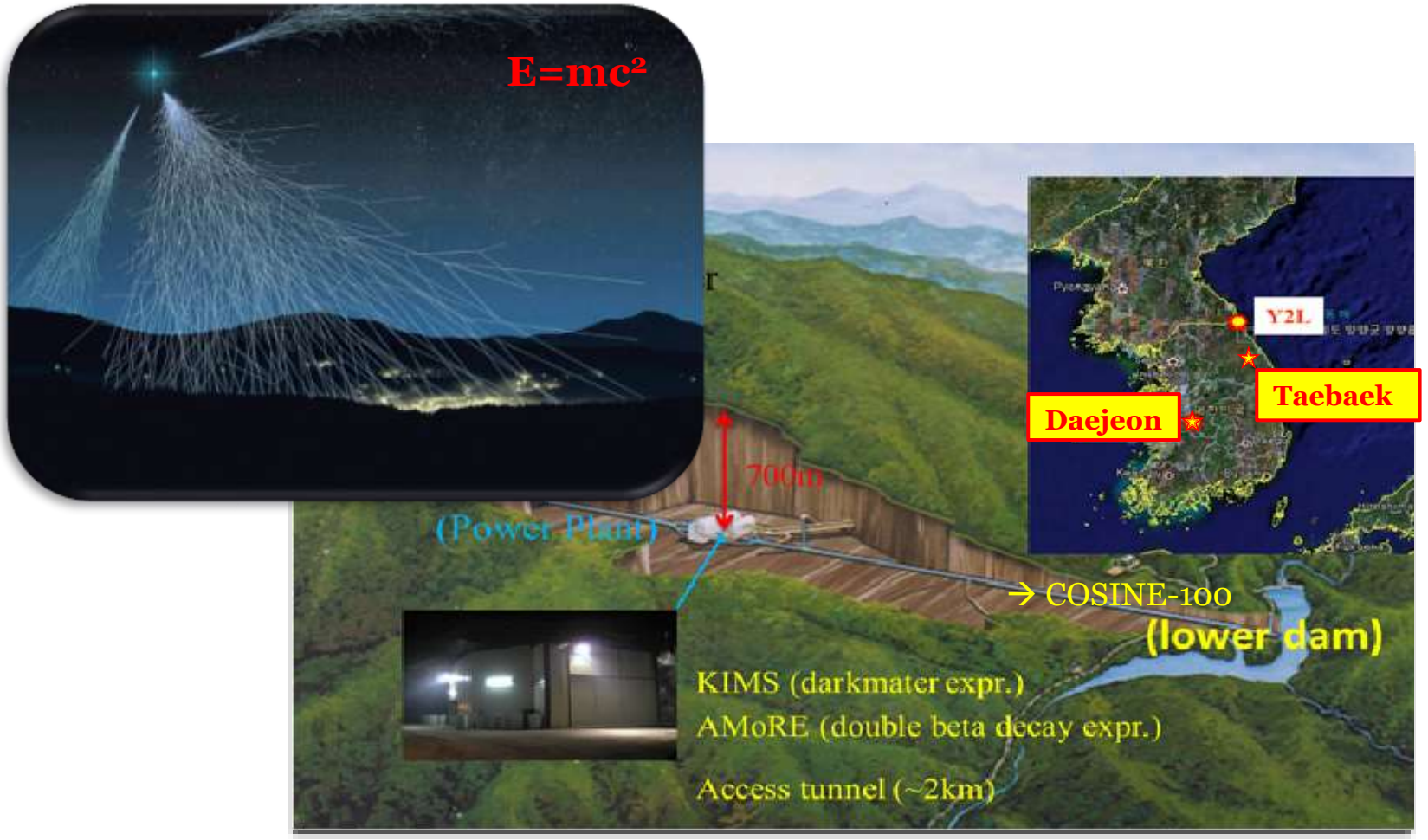
  ($E_k \sim mv^2$ with $v/c \sim 10^{-3}$)

- Challenges: very small E, small event rate, large backgrounds

Detection Techniques

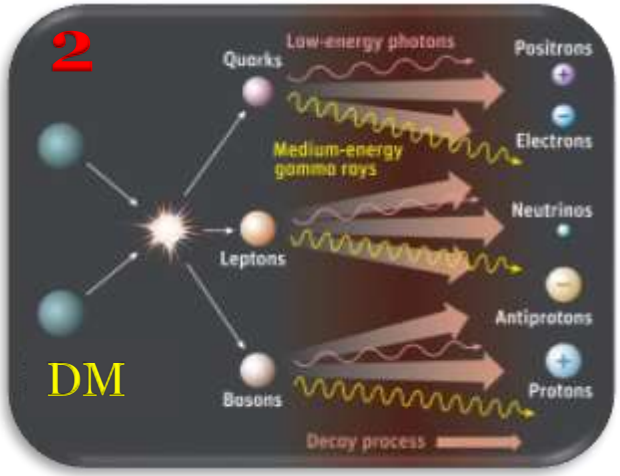


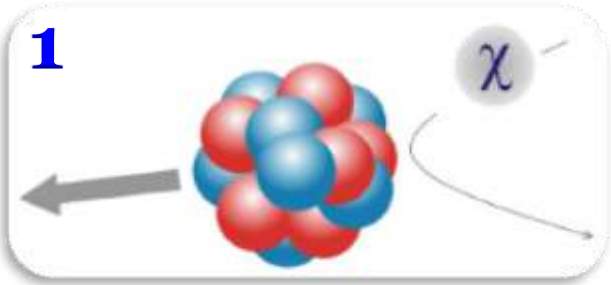
Direct Detection in Korea

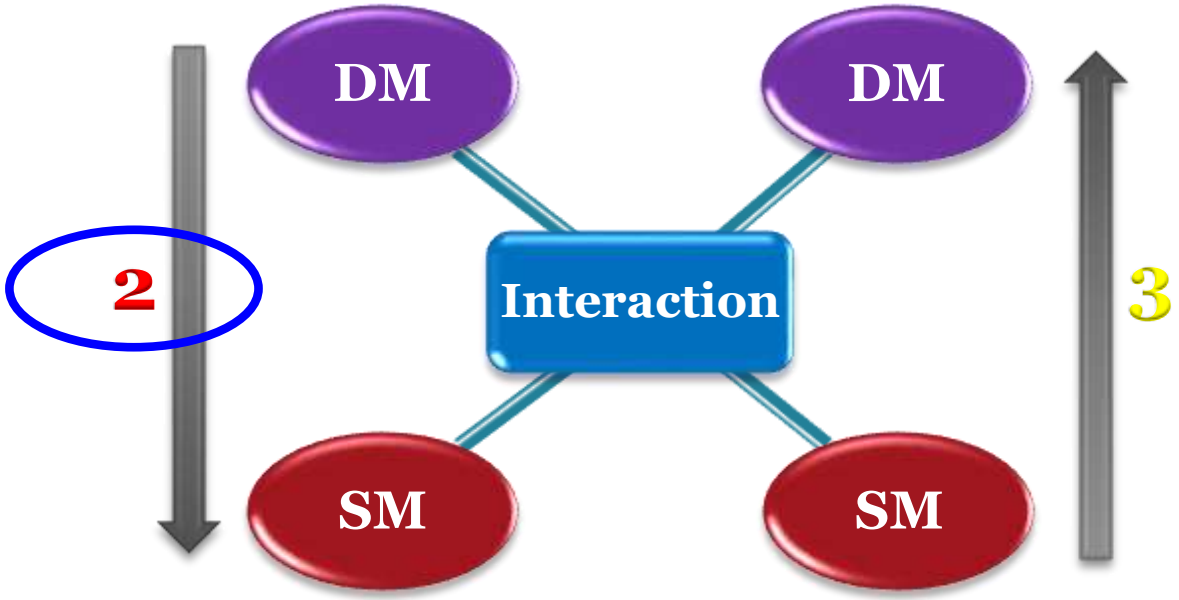


- Center for Underground Physics (CUP) of IBS (Daejeon): Yangyang & Taebaek

간접 탐색: DM Indirect Detection

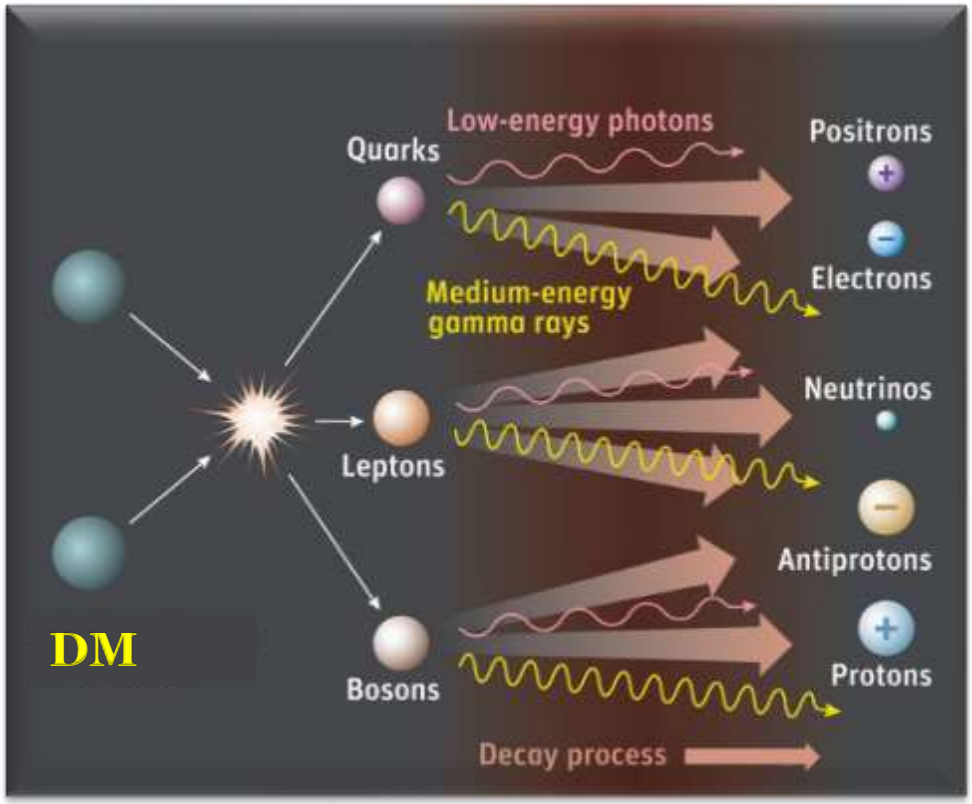






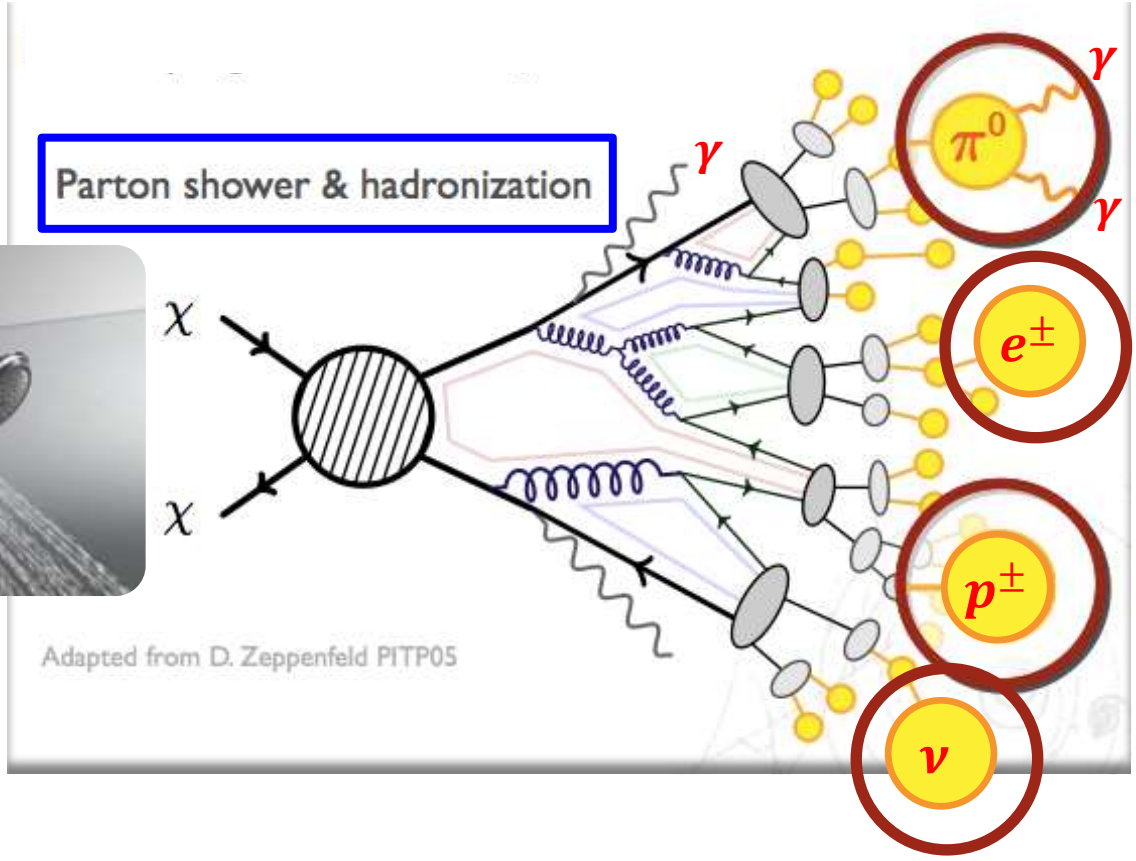
Cosmic Rays from DM

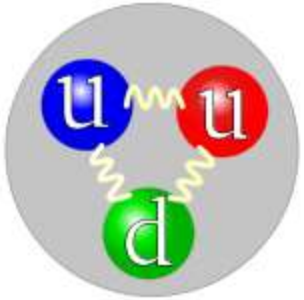
❖ Search for the products of DM annihilation and/or decay: γ, ν, $e^{\pm}$, p, …

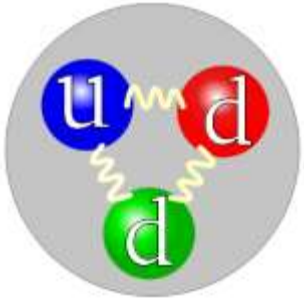


Cosmic Rays from DM: Showering

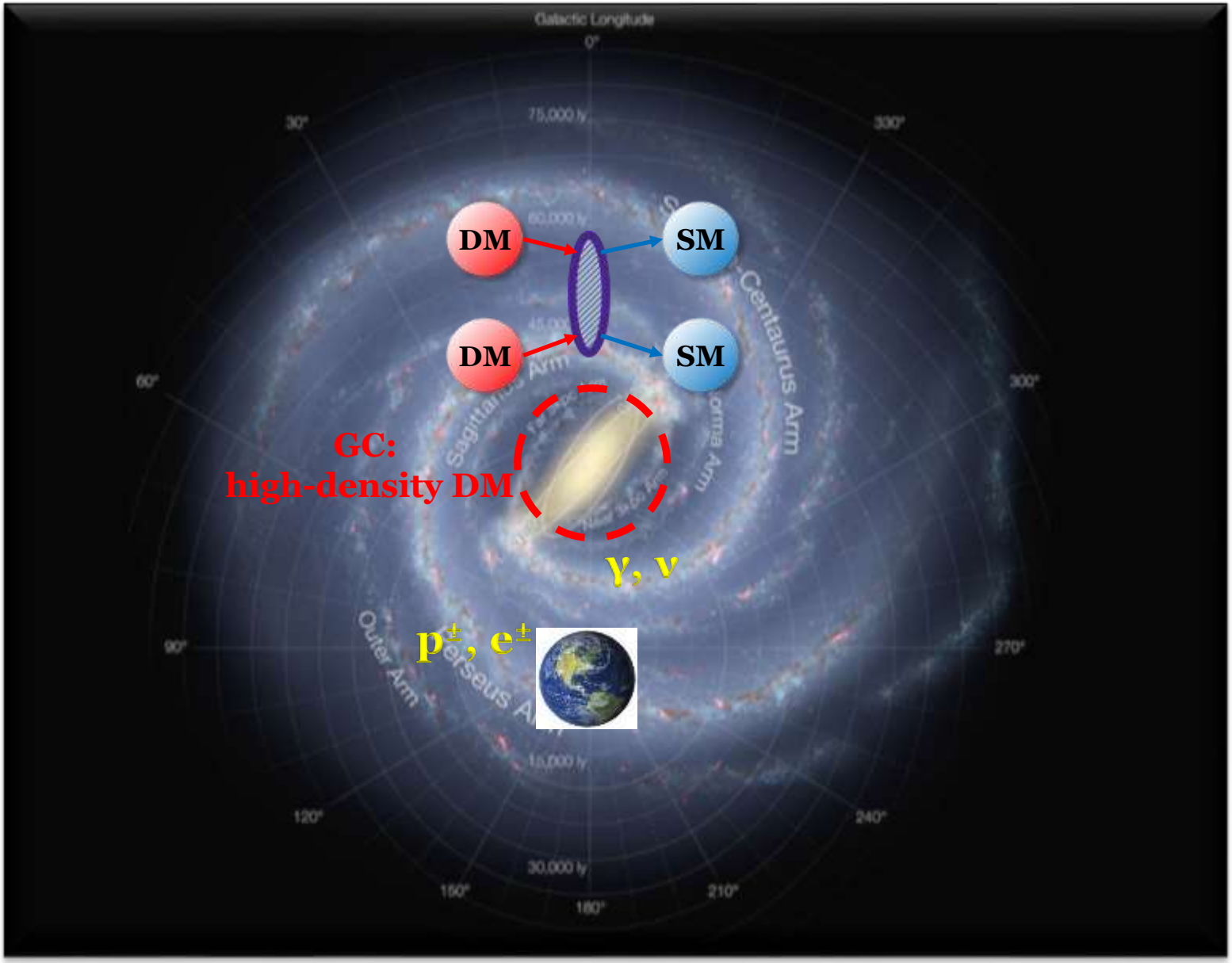
❖ Final states from DM annihilation and/or decay: γ, $e^{\pm}$, $p^{\pm}$, ν, …



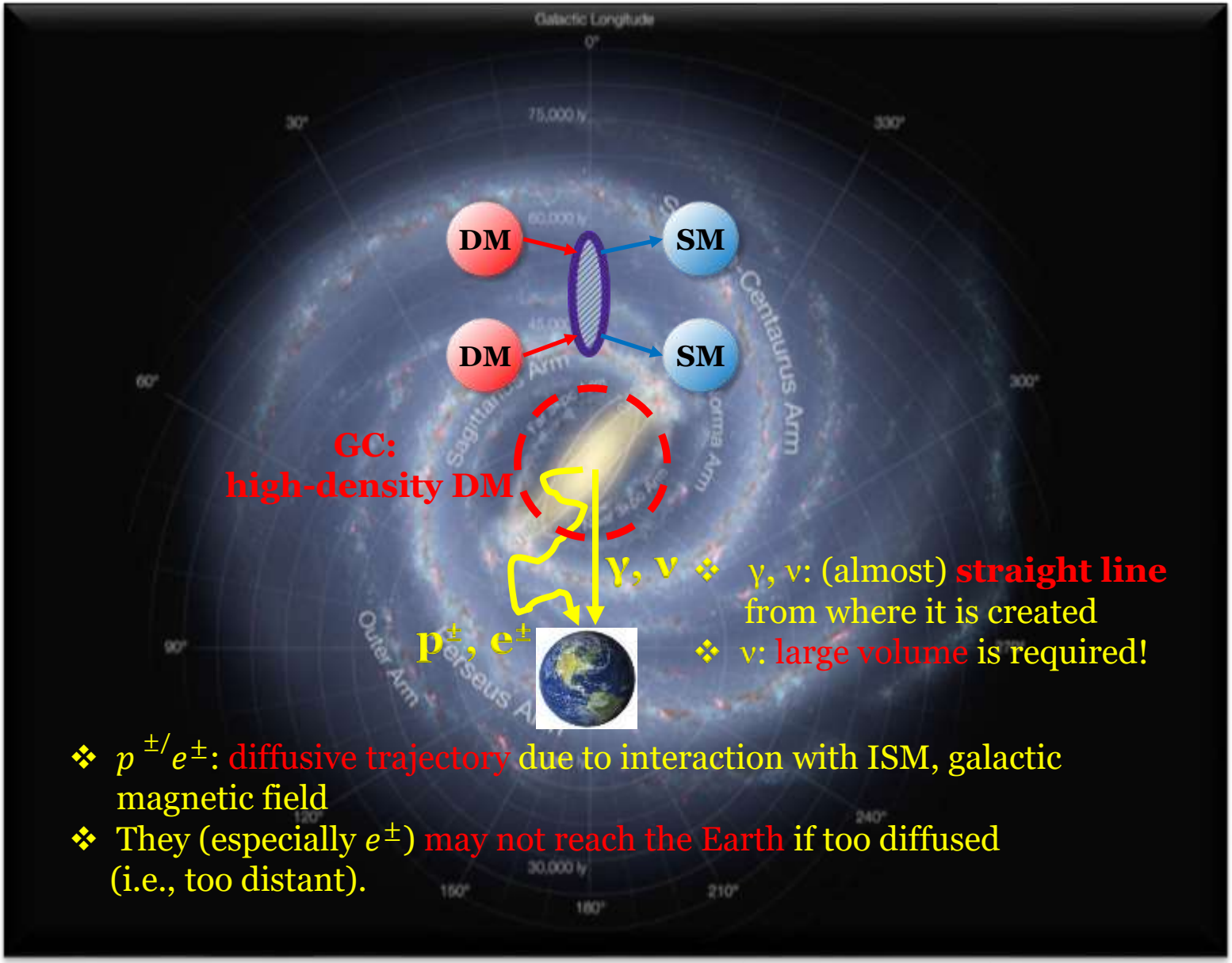




Indirect Detection: Cosmic Rays



Indirect Detection: Cosmic Rays



- $p^{\pm}/e^{\pm}$: diffusive trajectory due to interaction with ISM, galactic magnetic field
- They (especially $e^{\pm}$) may not reach the Earth if too diffused (i.e., too distant).

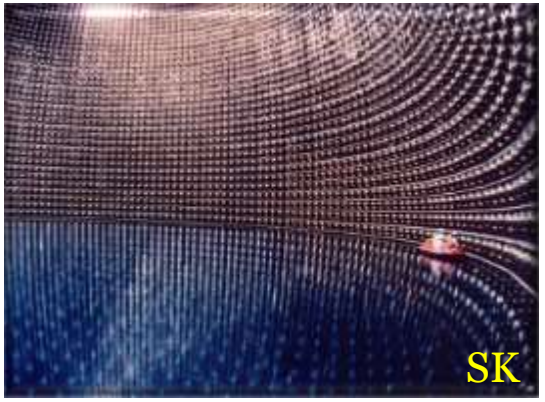
Cosmic Ray Experiments

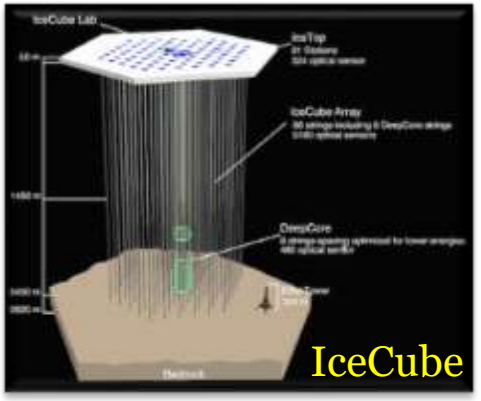
- Ground-based
  MAGIC, HESS, CTA, IceCube,
  Super-K, Hyper-K, DUNE, …

- Balloon-based:
  ATIC, PPB-BETS, …

- Satellite-based:
  AMS, Chandra, Fermi-LAT, PAMELA,
  XMM-Newton, DAMPE, ASTROGAM, …

  - ✓ Great sensitivity to cosmic-ray signals
  - ✓ Better chance to have the information for extracting DM properties



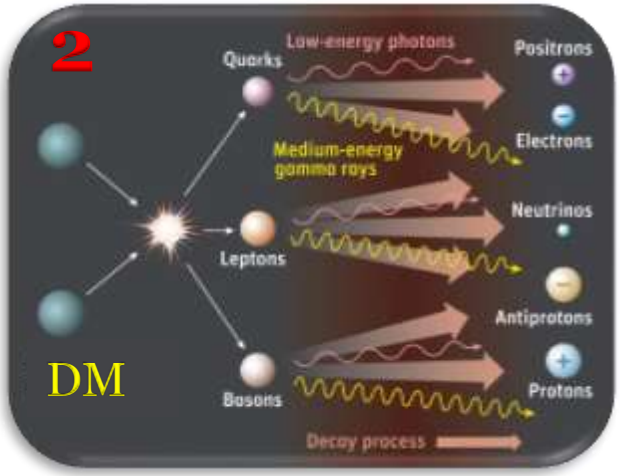


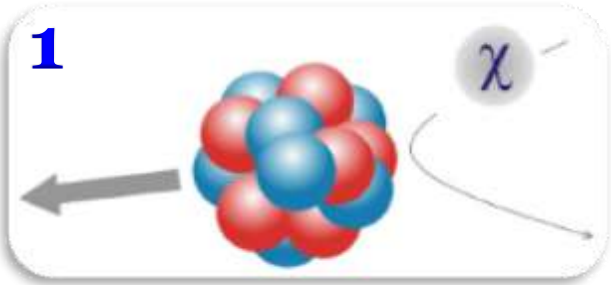
Hints from Cosmic-Rays?

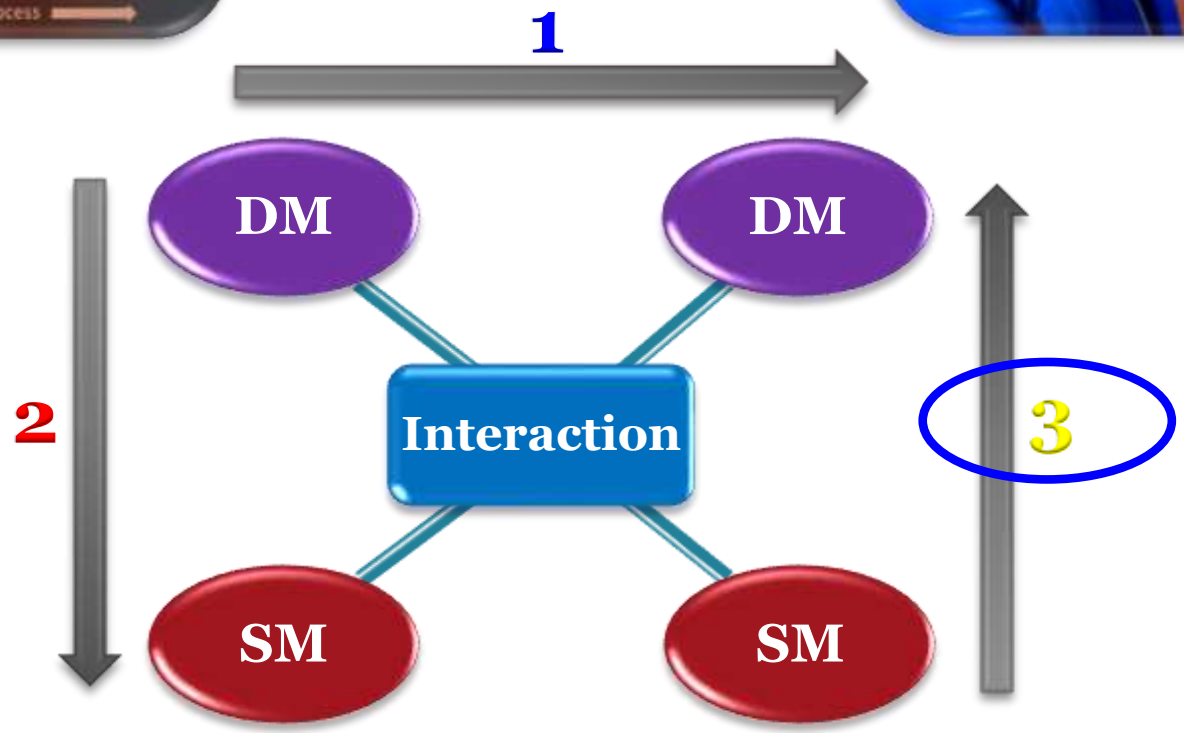
❖ DM signatures in cosmic-ray observations?

- XMM-Newton (X-ray): 3.5 keV line
- SPI/INTEGRAL ($\gamma \rightarrow e^+$): 511 keV line
- Fermi-LAT (γ , e^-+e^+): GeV excess, 130 GeV line, e^-e^+ excess
- PAMELA ($e^\pm$, $p^\pm$, ...): e^+ excess
- ATIC (e^-+e^+): e^-e^+ excess
- AMS-02 ($e^\pm$, $p^\pm$, ...): e^+ ($\bar{p}$) excess
- IceCube (ν): PeV events
- ANITA (ν): EeV events
- ...

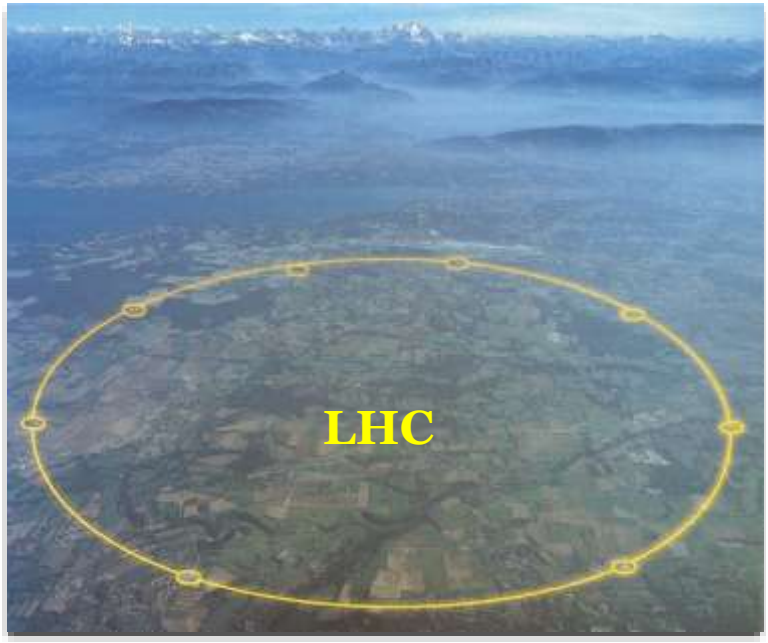
직접 생성: DM Production @ Colliders





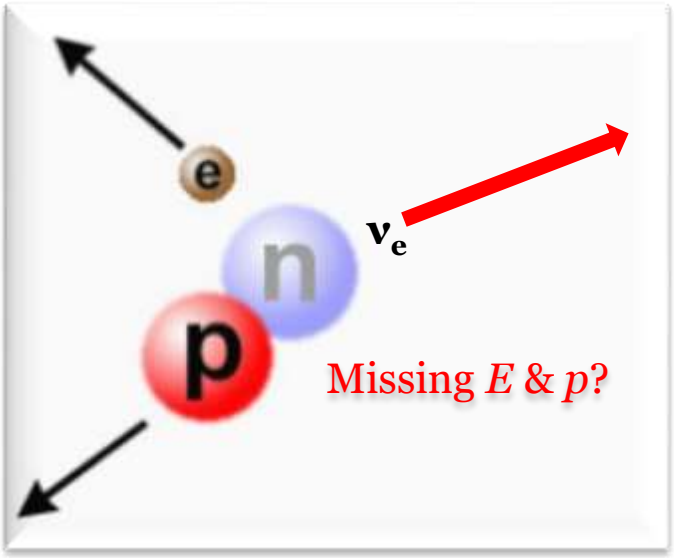


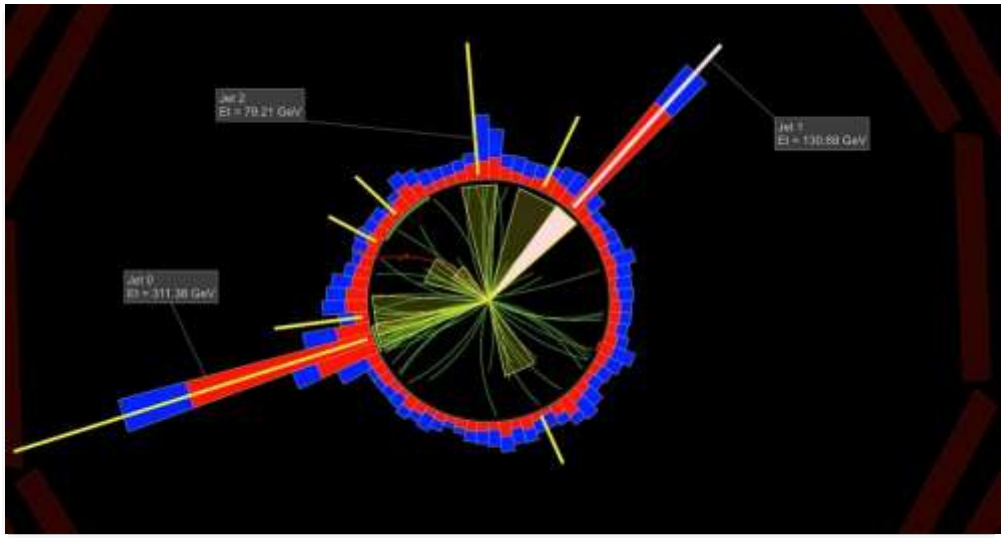
Collider Physics



- Production of heavy particles (e.g. super-partner, Z', t', B, …) ← $E=mc^2$
- LHC Run I & II, Belle I: no conclusive evidence of DM yet
- Belle II (high luminosity): have been upgraded & is running!
- LHC Run III: in the upgrade phase (2021)

DM at Colliders

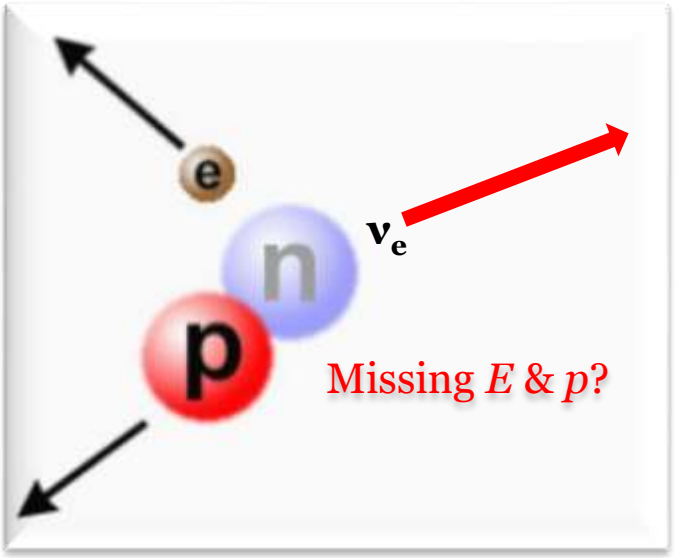


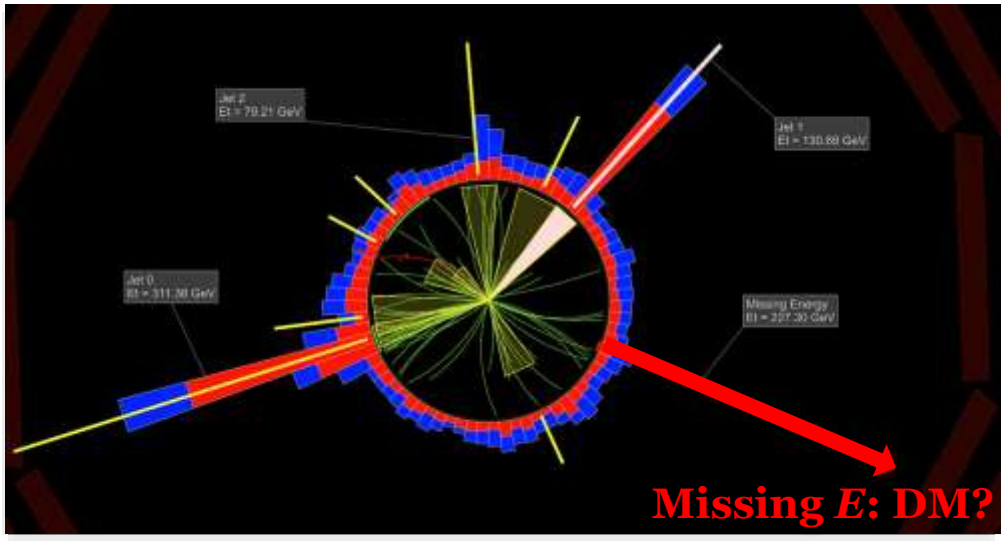


Pauli(1930) Fermi(1932)

- ν: to explain Missing E, p, S in the beta decay
- Nature(1934): "Too remote from reality!"

DM at Colliders





Pauli(1930)

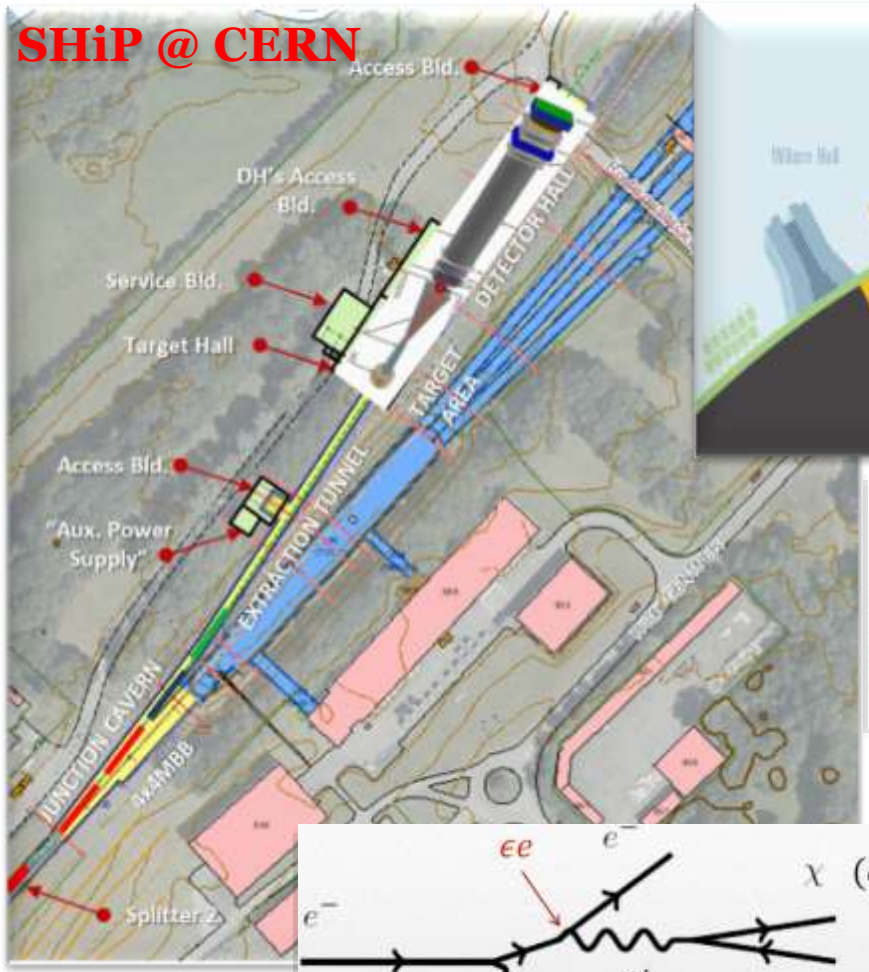
Fermi(1932)

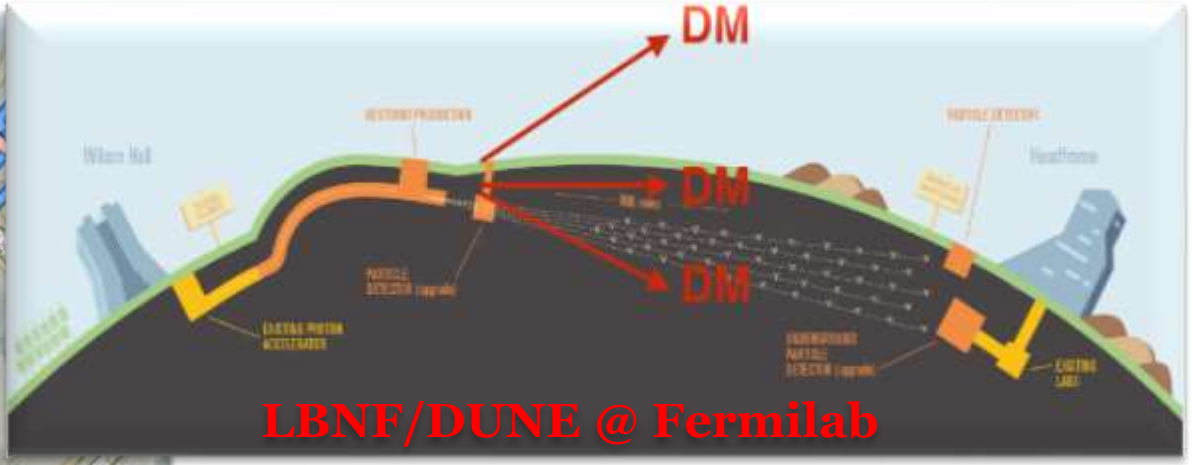
- ν: to explain Missing E, p, S in the beta decay
- Nature(1934): "Too remote from reality!"
- DM cannot be directly detected

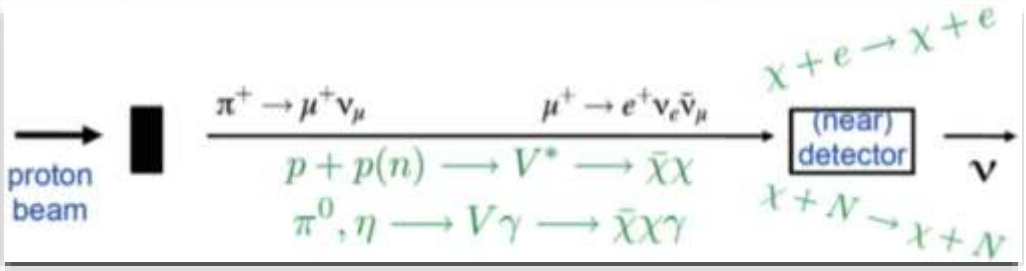
  → regarded as Missing E

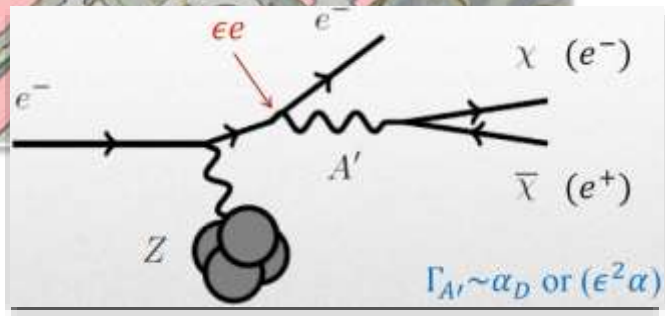
다른 방법은
안되나요?

DM @ Fixed Target Experiments









- p/e beam dump ➔ Z', DM production
- Original purpose: ν production (not all)
- Upcoming Exps.: T2HK(J-PARC), NOVA/MicroBooNE/DUNE(Fermilab), PEX/HPS/DarkLight/BDX (J-Lab), SHiP(CERN),

암흑 물질의 질량?

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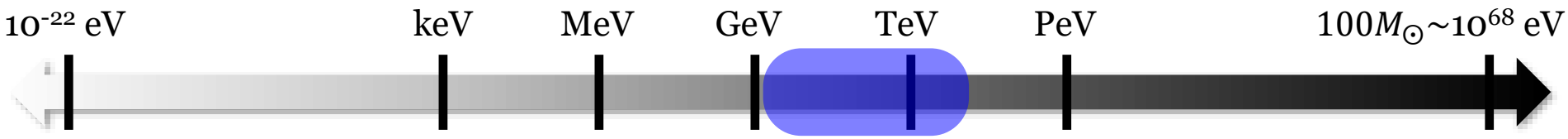
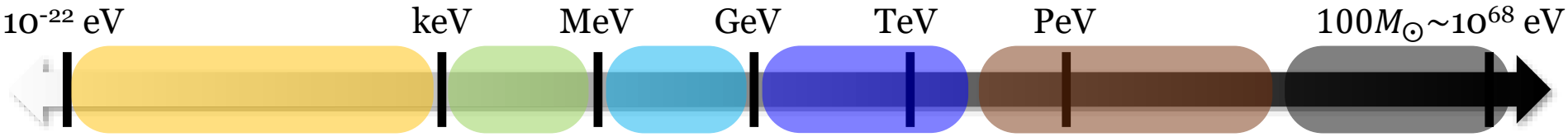


WIMP
well-
motivated
extensively
studied
thermal

암흑 물질의 질량: 아주 다양한 가능성~!!



Ultralight
Scalar field
(QCD) Axion
Hidden photon
non-thermal

Superlight
WDM
Sterile ν
may be
thermal

Light
particle
DM
can be
thermal

WIMP
well-
motivated
extensively
studied
thermal

Superheavy / Composite
WIMPzilla
Q-ball
Dark-quark
nugget
non-thermal

MACHO / Primordial BHs
non-particle

요약 정리

- **본다**: 더 넓은 개념 ➔ 대상의 크기, 빛의 파장, 다른 상호 작용
- **암흑 물질**: 봤지만, 보지 못하는 존재 …
- **암흑 물질의 정체**: 21세기 과학계의 가장 중요한 문제 중 하나!