암흑 물질 탐색의 새로운 접근법

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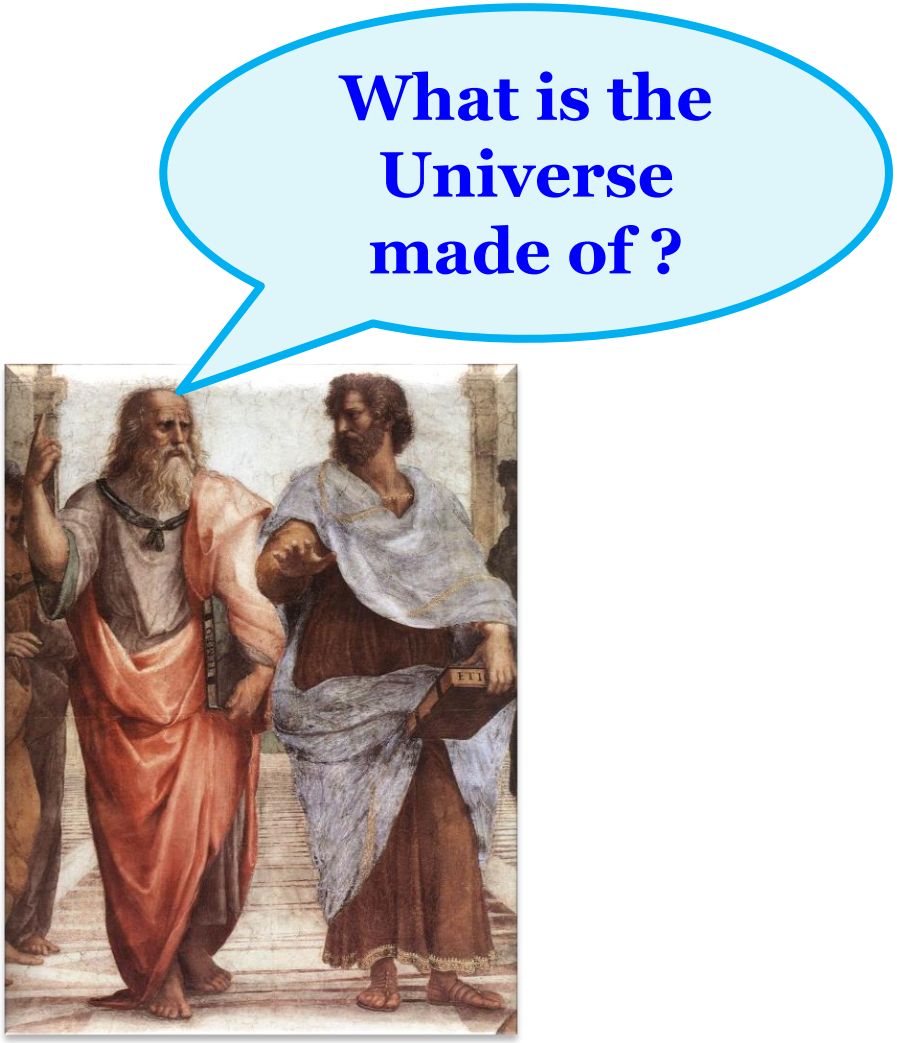
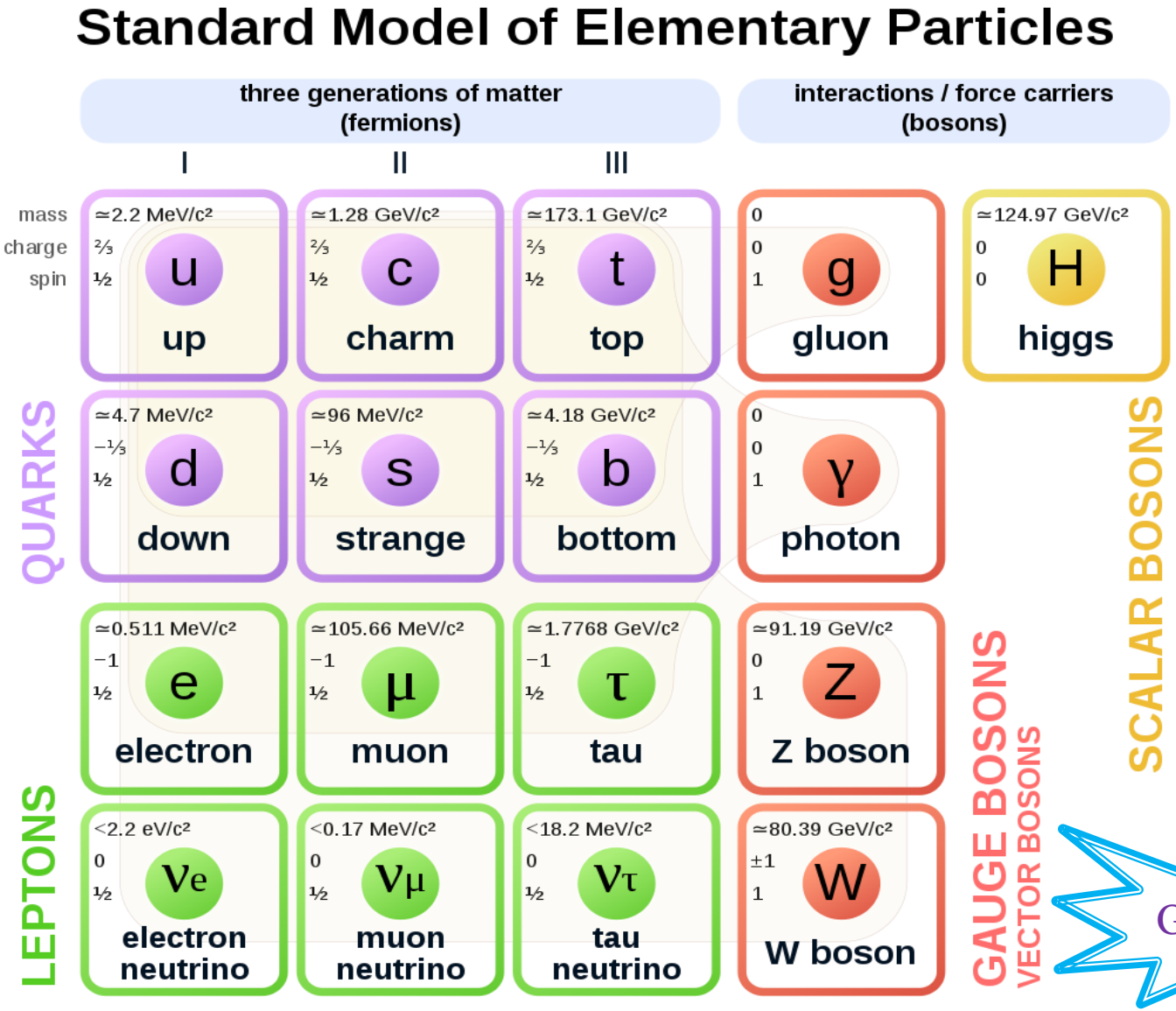
Eternal Questions

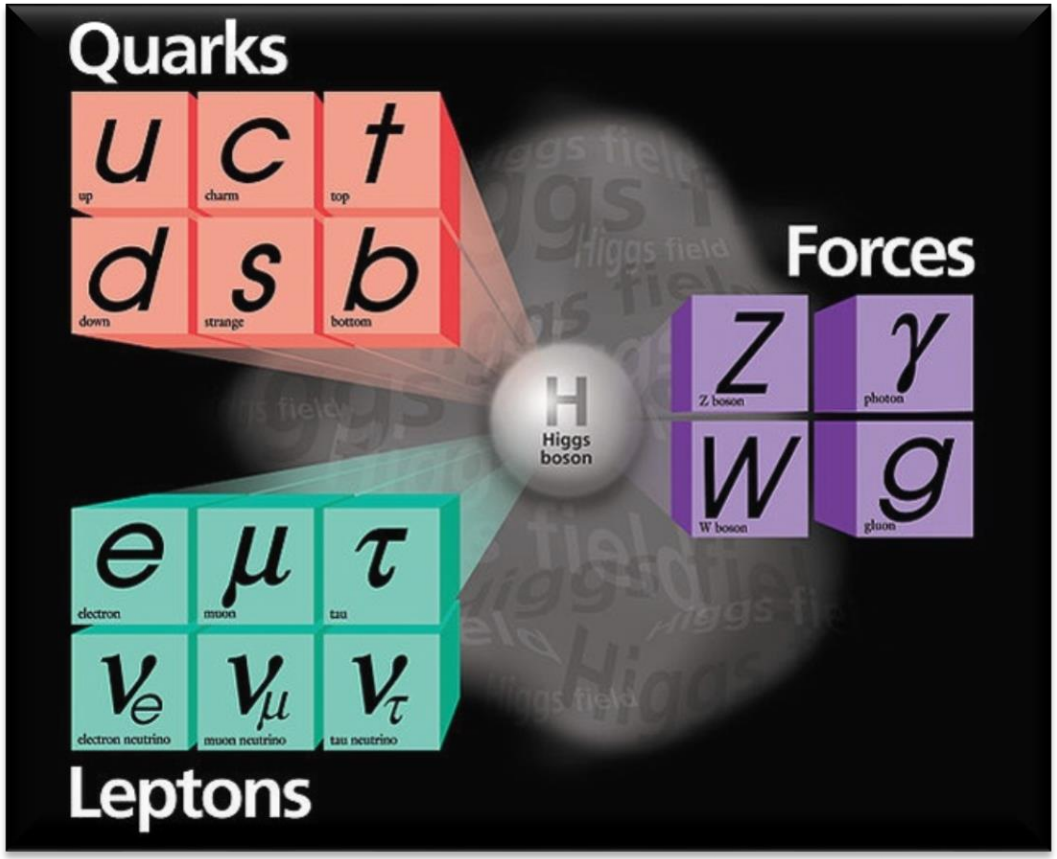


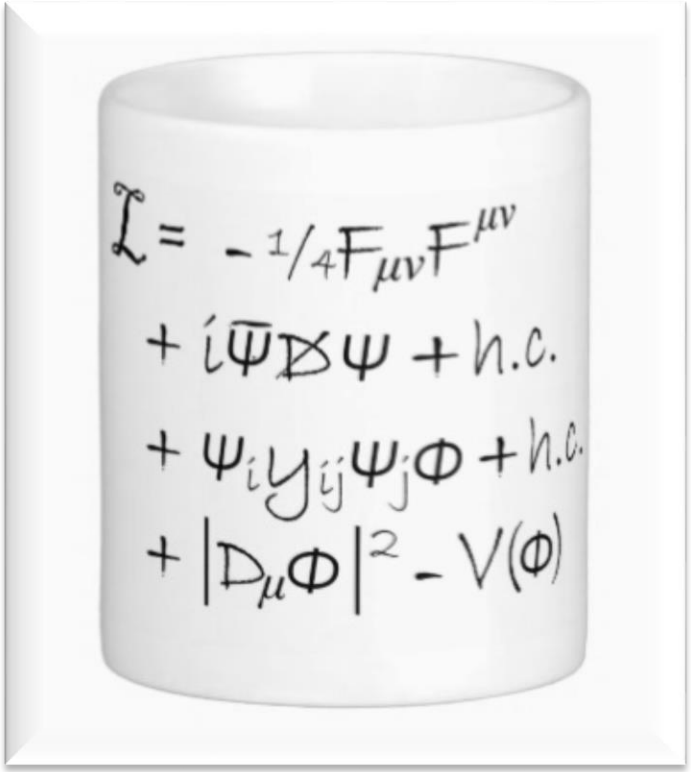
Standard Model (SM)



Wikipedia, https://en.wikipedia.org/wiki/Standard Model.

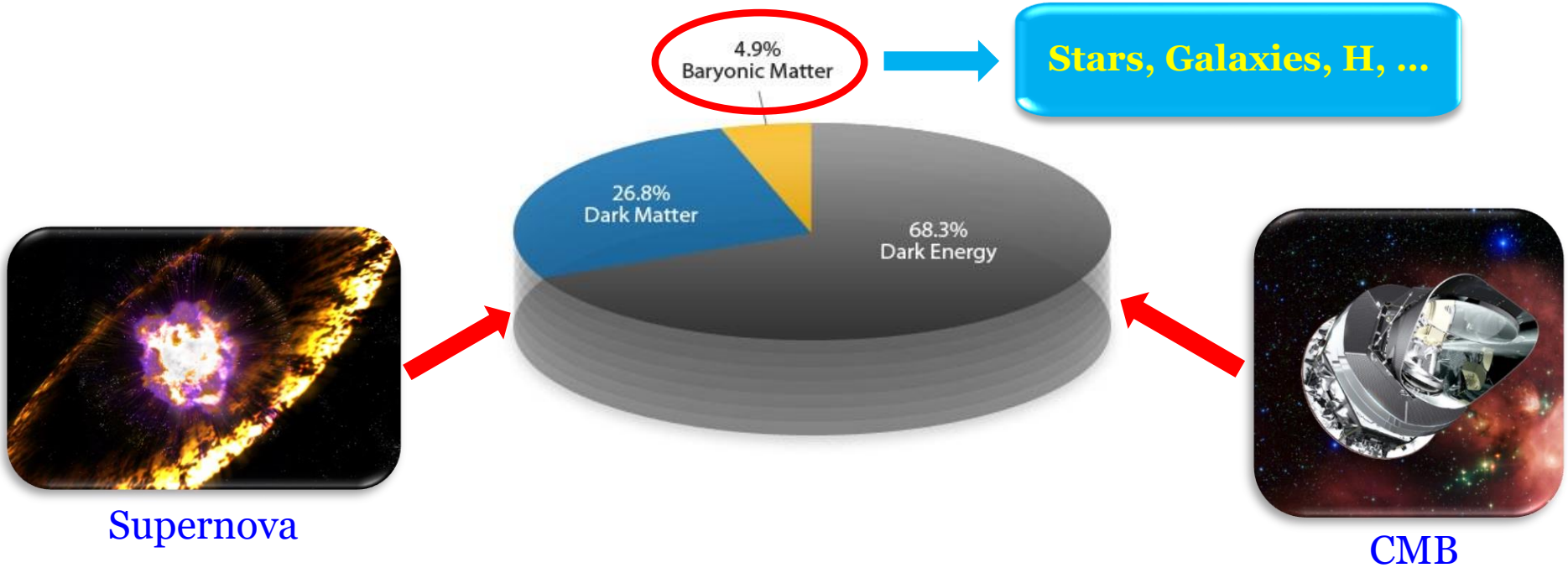
Standard Model (SM)





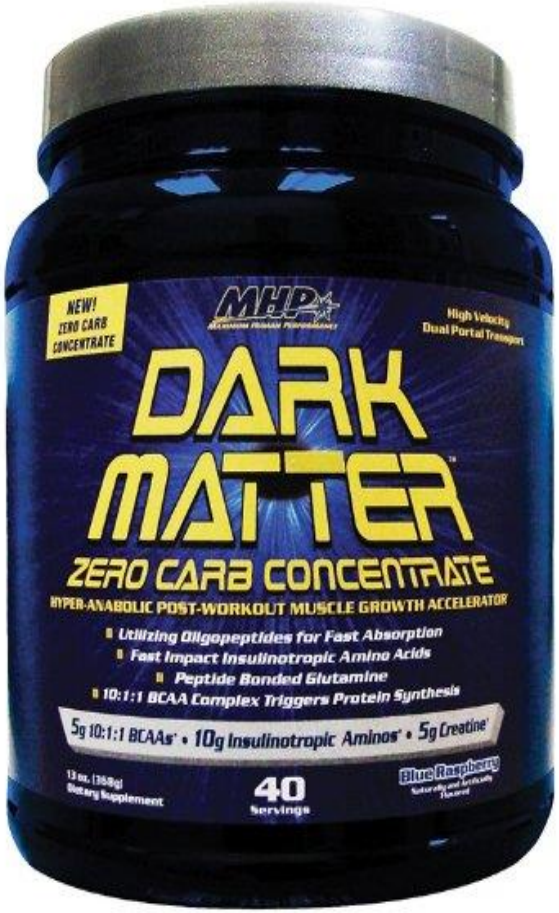
Message from Cosmology

- Modern cosmology ➔ Cosmic pie



- The standard model explains only ~5% of the M-E of the Universe.

Question in the 20th Century!!



What's the matter?

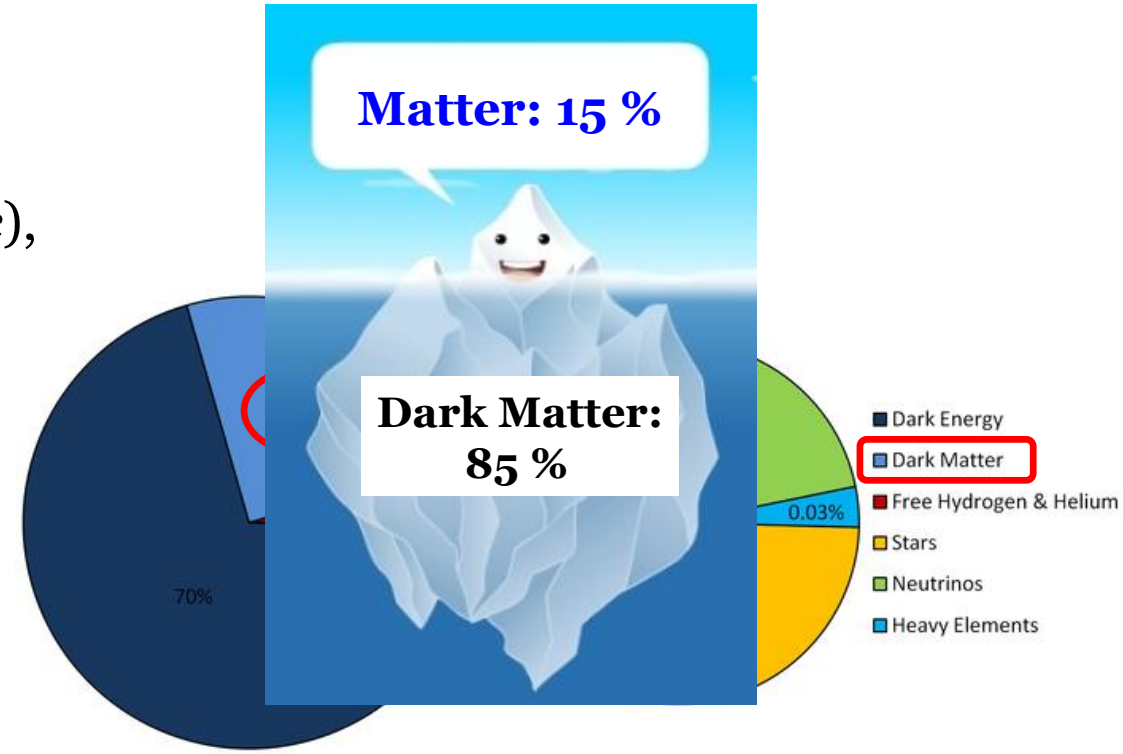
⬇

What's Dark Matter?

Dark Matter (DM)

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

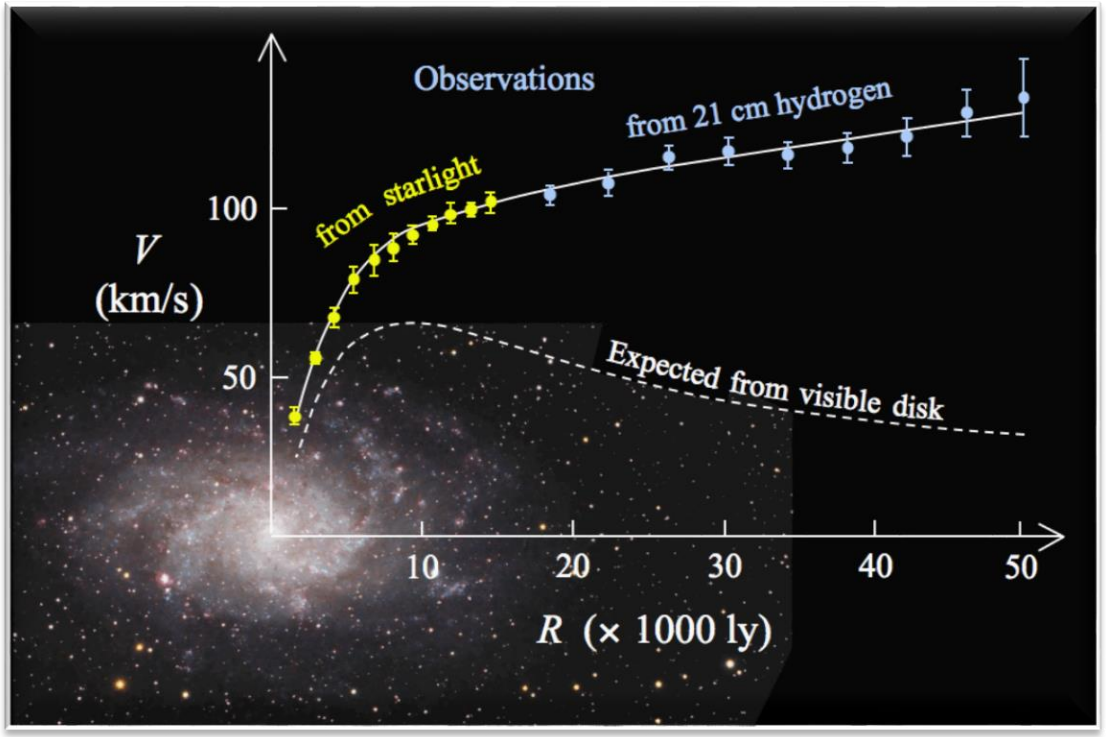
- **Compelling paradigm**:
  - ✓ massive,
  - ✓ non-relativistic ($\rightarrow v << c$),
  - ✓ non-luminous (no/tiny EM interaction),
  - ✓ stable particles
  - ✓ ~1/4 of the Universe



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

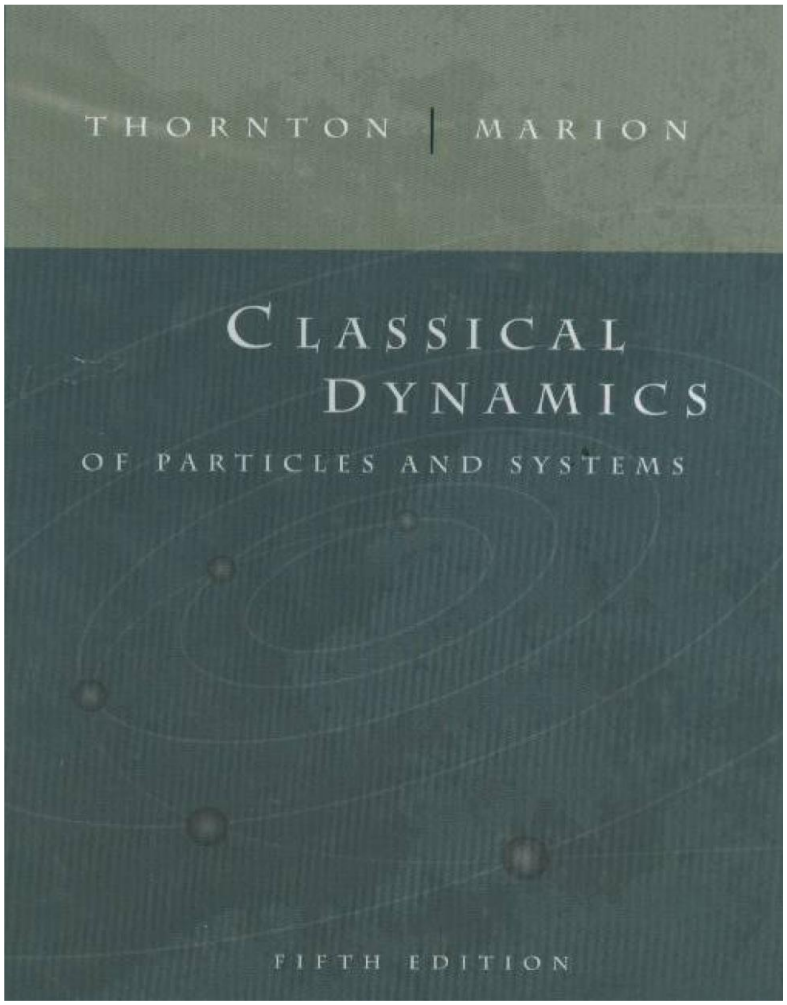


Vera Rubin

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

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

Galaxy Rotation Curve



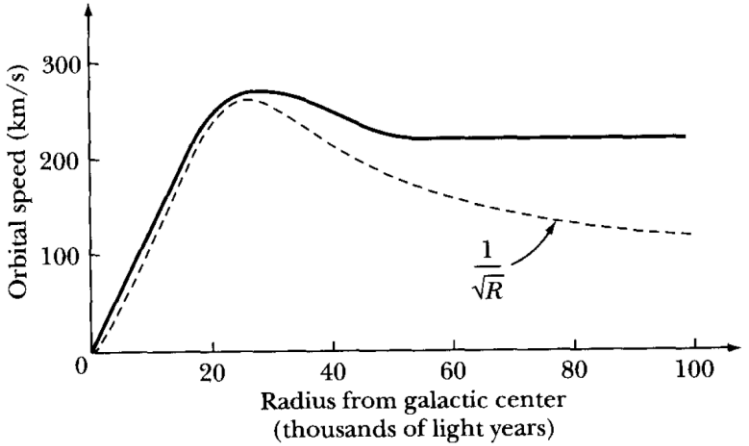
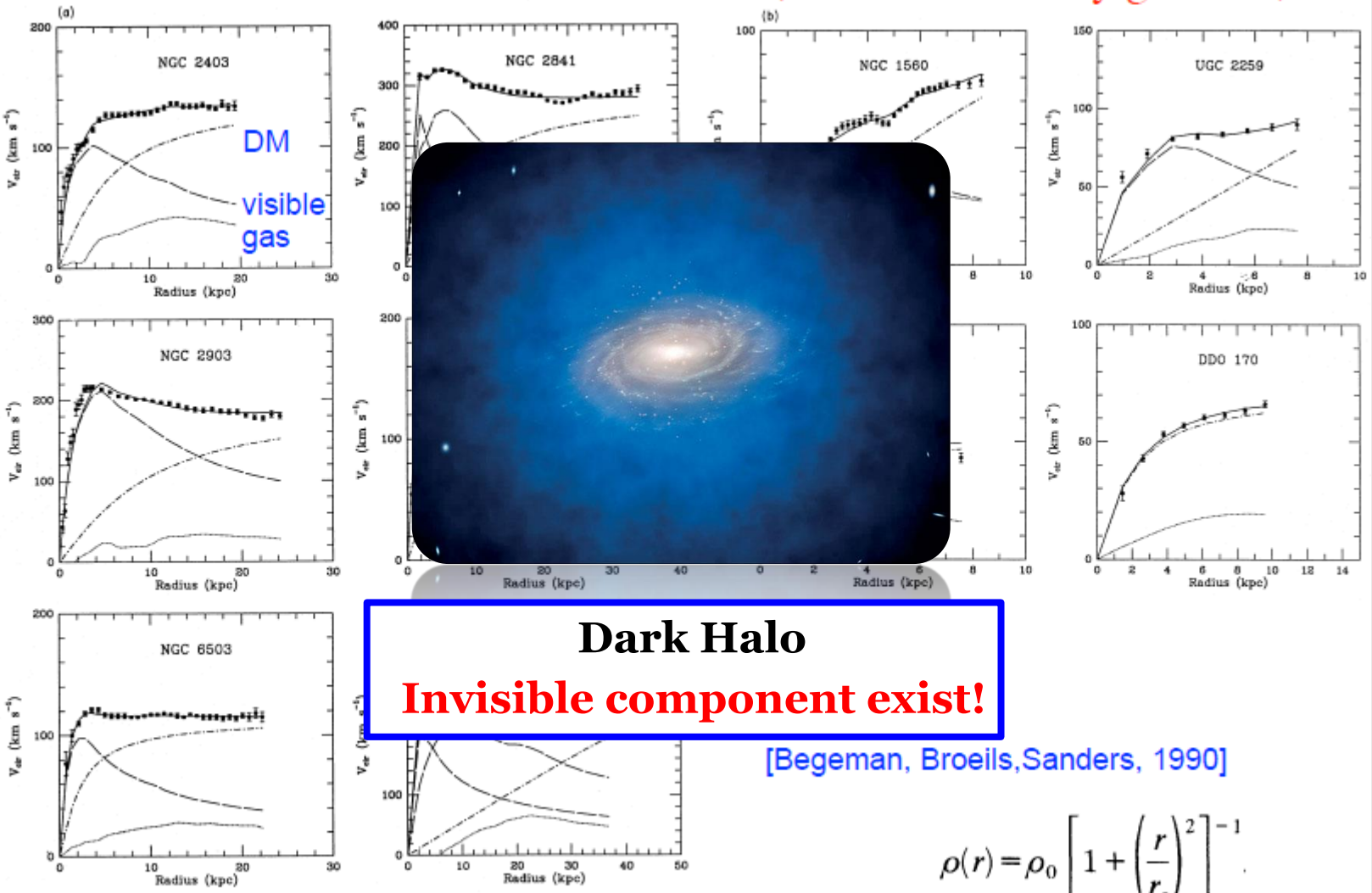


FIGURE 5-5 Example 5.2. The solid line represents data for the orbital speed of mass as a function of distance from the center of the Andromeda galaxy. The dashed line represents the $1/\sqrt{R}$ behavior expected from the Keplerian result of Newton's laws.

❖ Much more galaxies

(Lower luminosity galaxies)



Dark Halo

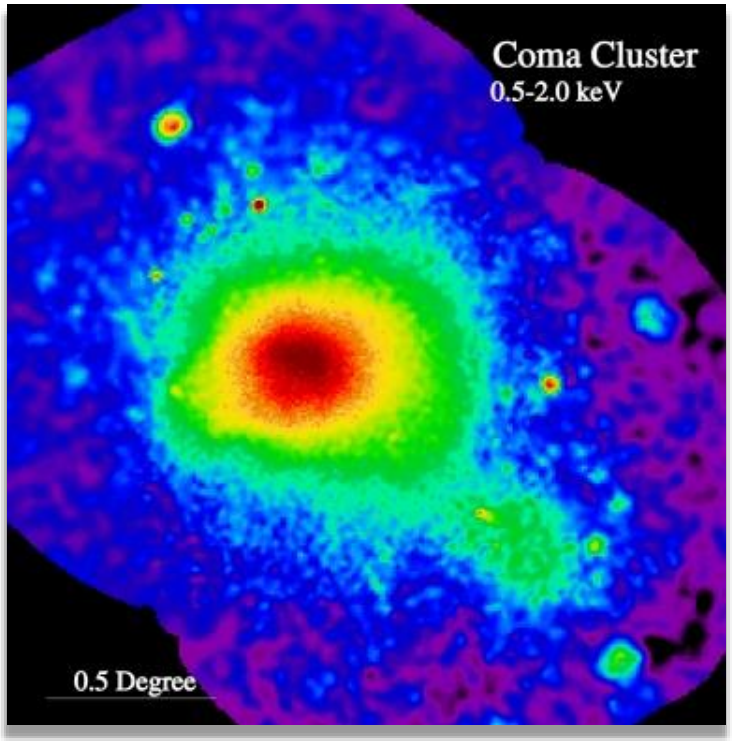
Invisible component exist!

[Begeman, Broeils,Sanders, 1990]

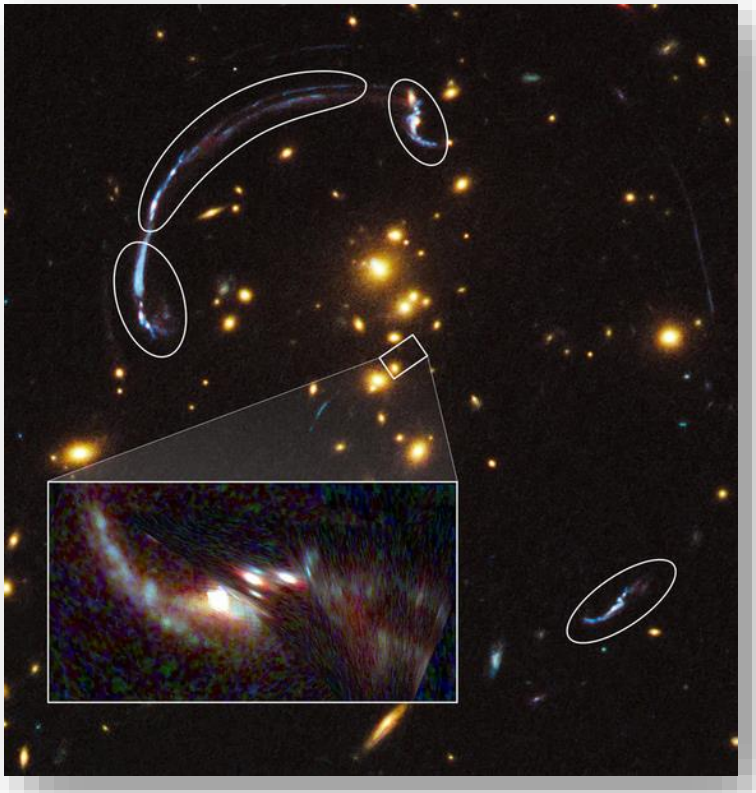
$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1}$$

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 / Gravitational Lensing



x-ray image from the ROSAT satellite



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

❖ Stars and hot gas: **not enough** to bend the light from the background galaxies so much

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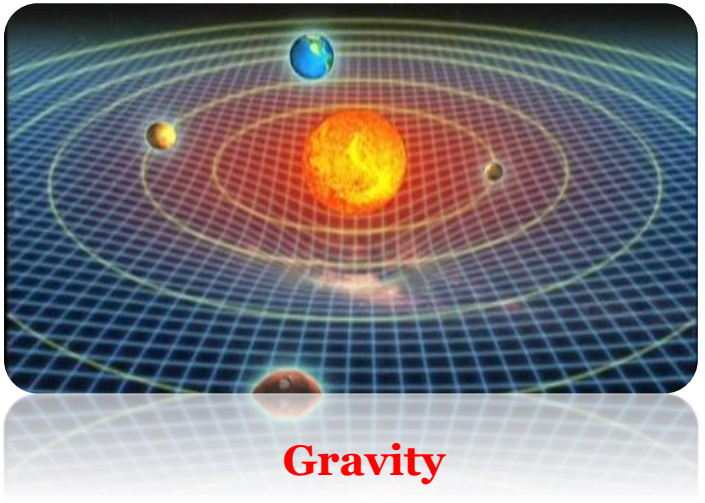
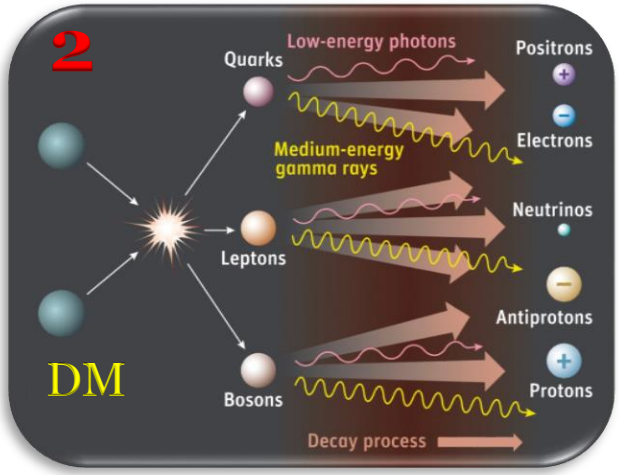
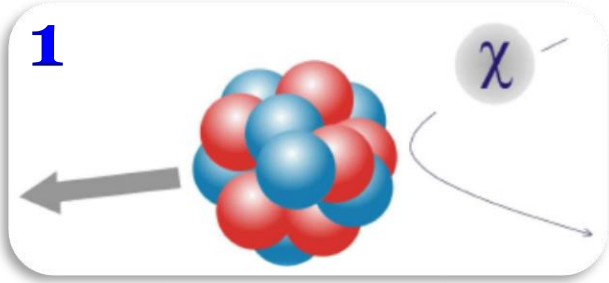
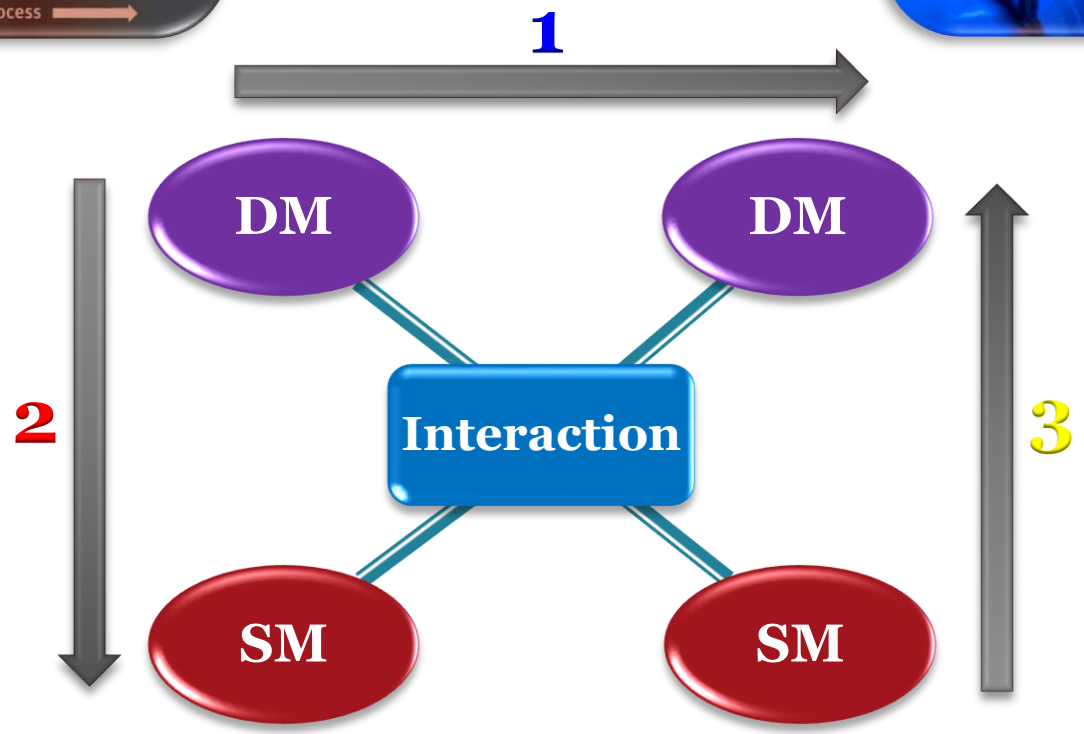


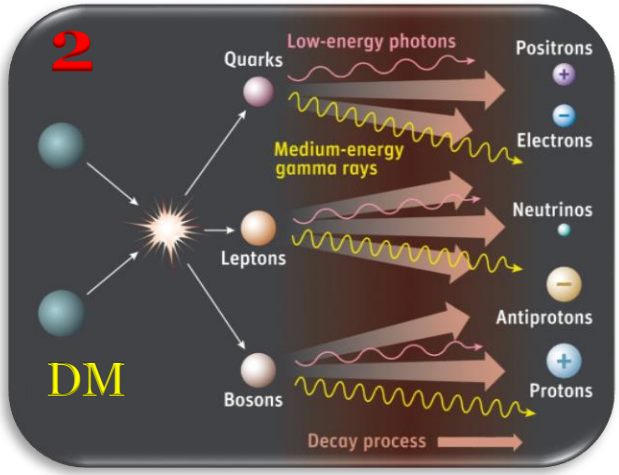
DM Search Strategies

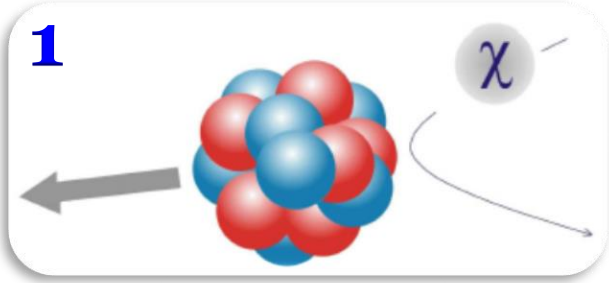


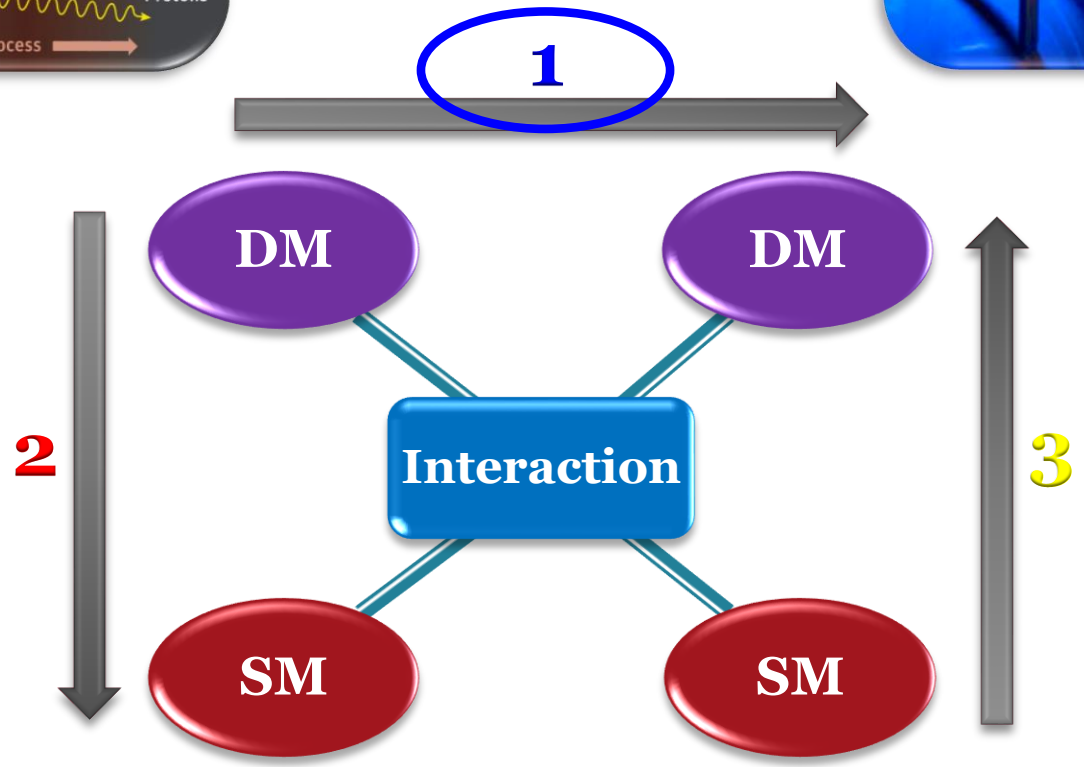




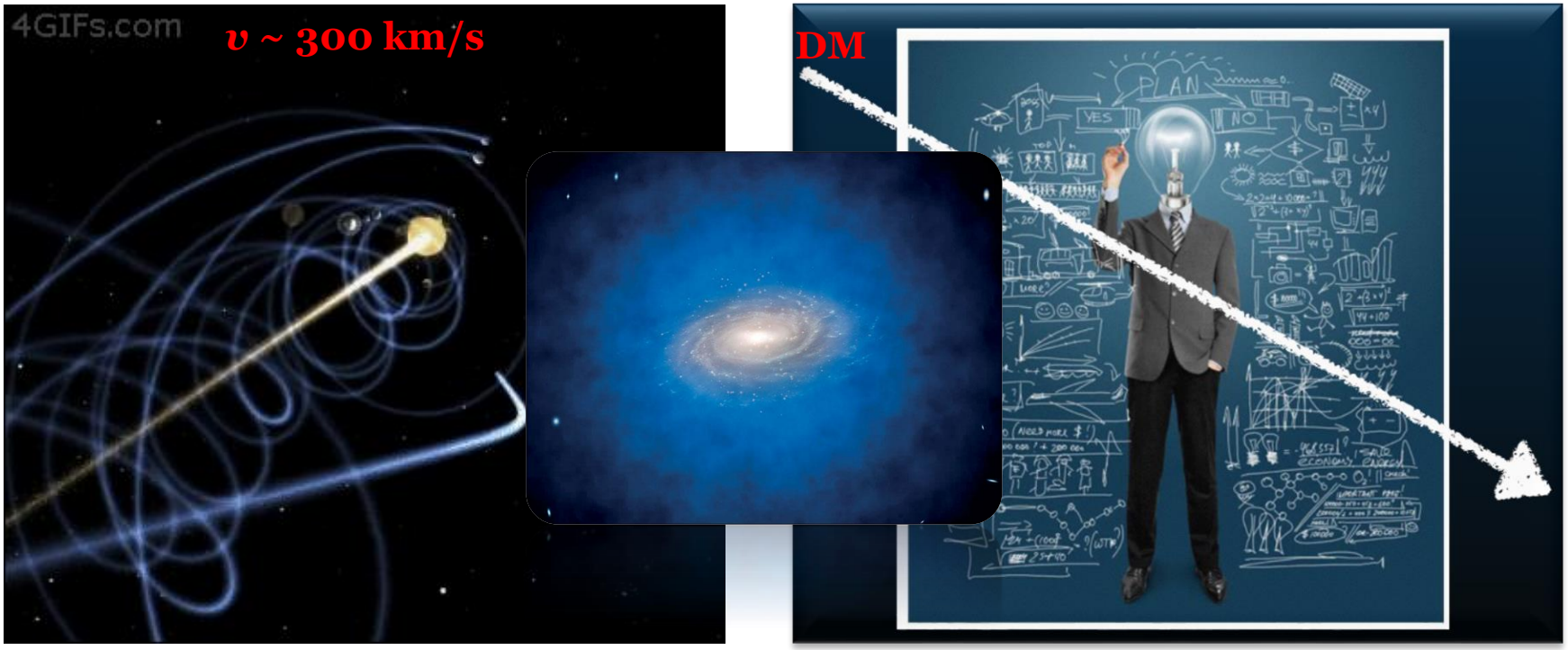
DM Direct Detection







Dark Matter vs Human

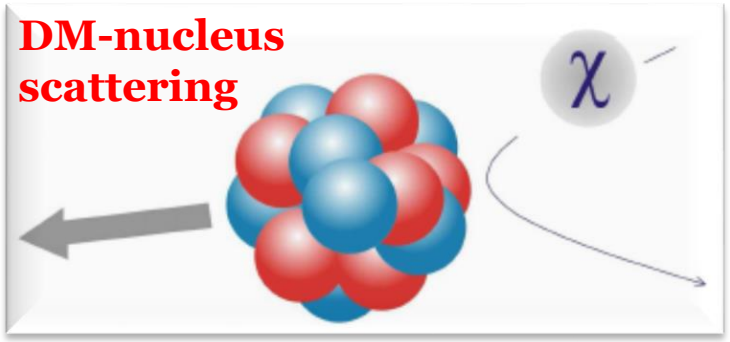


- When $m_{\rm DM} \sim m_{\rm p} \sim 0.94$ GeV: $300\ \text{km/s} \times \dfrac{0.4\ \text{GeV/cm}^3}{0.94\ \text{GeV}} \times 60\ \text{cm} \times 170\ \text{cm}$

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

- ~10^{11}/s DM's penetrate our body for $m_{\rm DM} \sim m_{\rm p}$!

DM Direct Detection



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

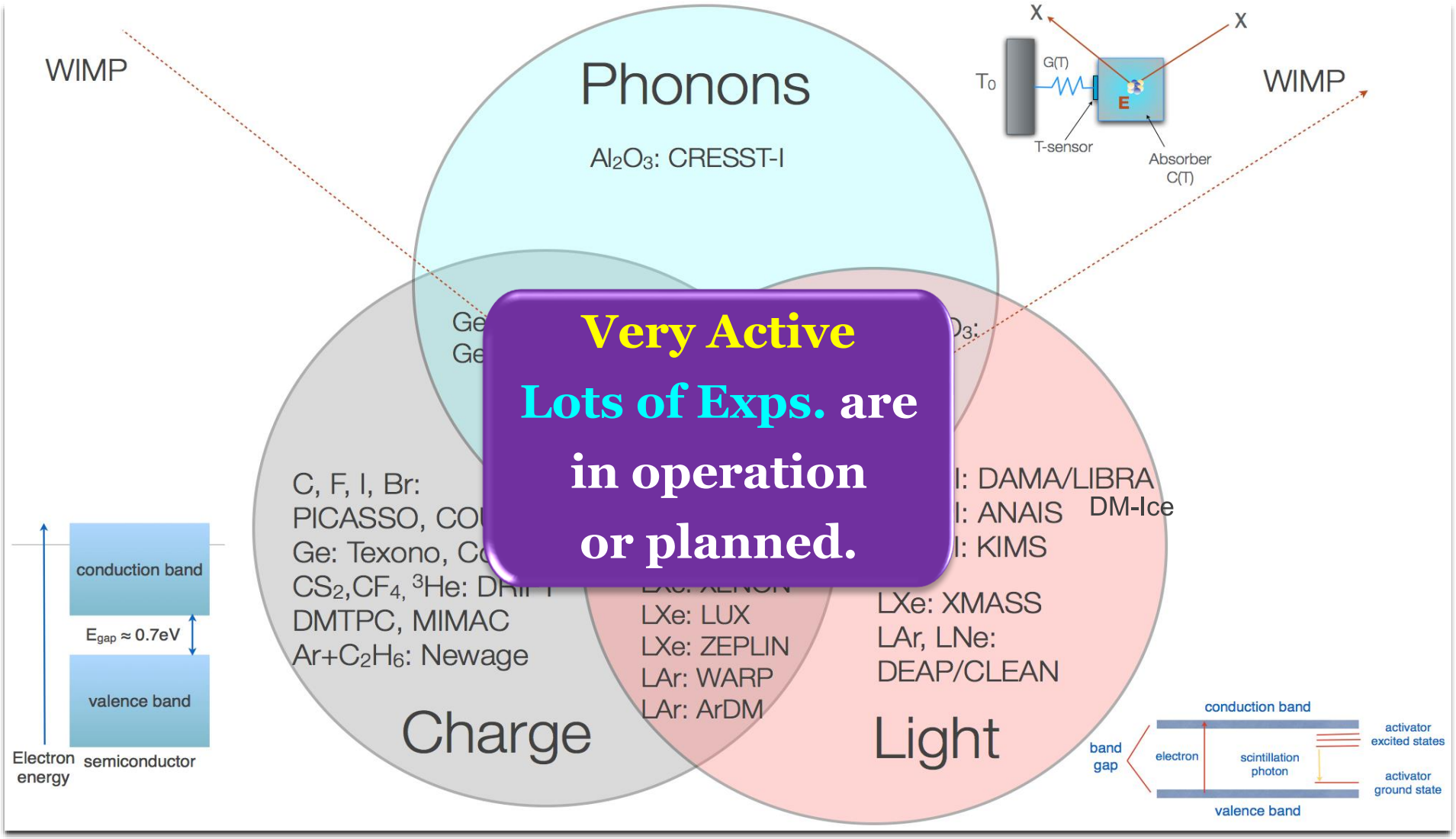
  based on *E* & *p* conservation!

- What is measure: *E* of recoiling nucleus ~ 1-10^3 keV for m_{DM} ~ 1-10^3 GeV

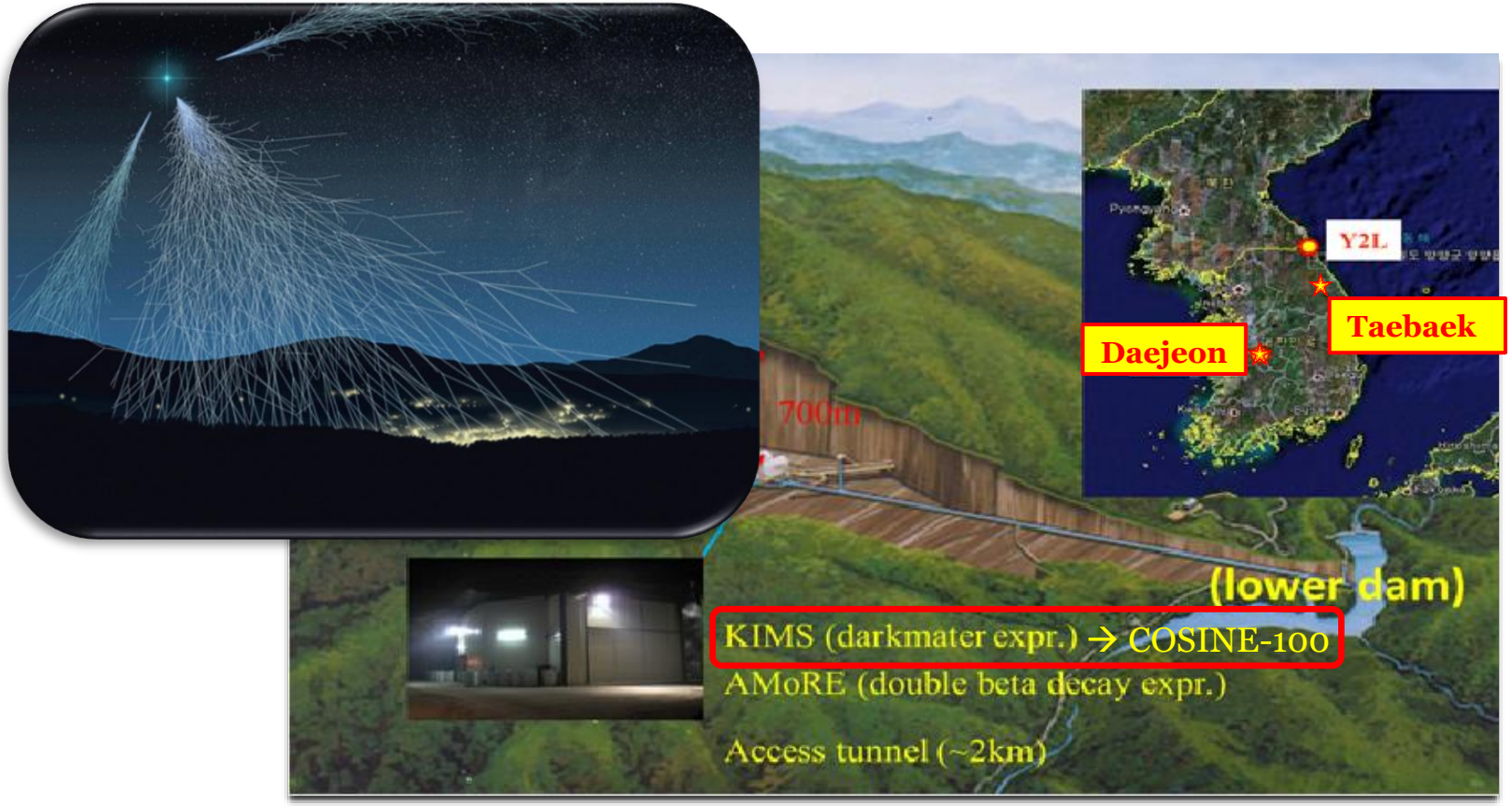
  ($E_k \sim mv^2$ with $v/c \sim 10^{-3}$)

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

Detection Techniques

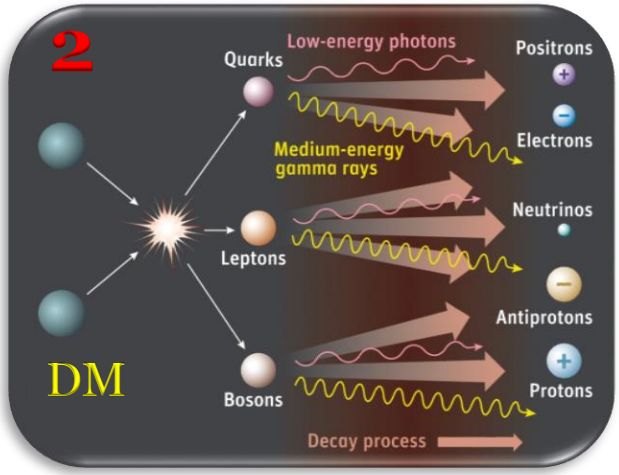


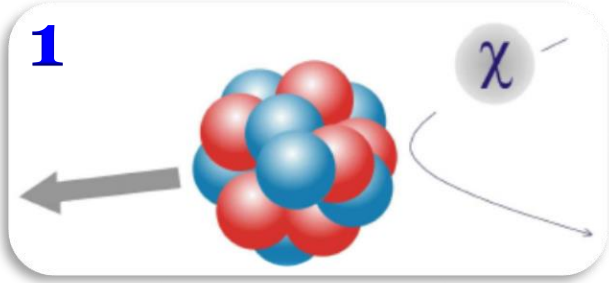
Direct Detection in Korea

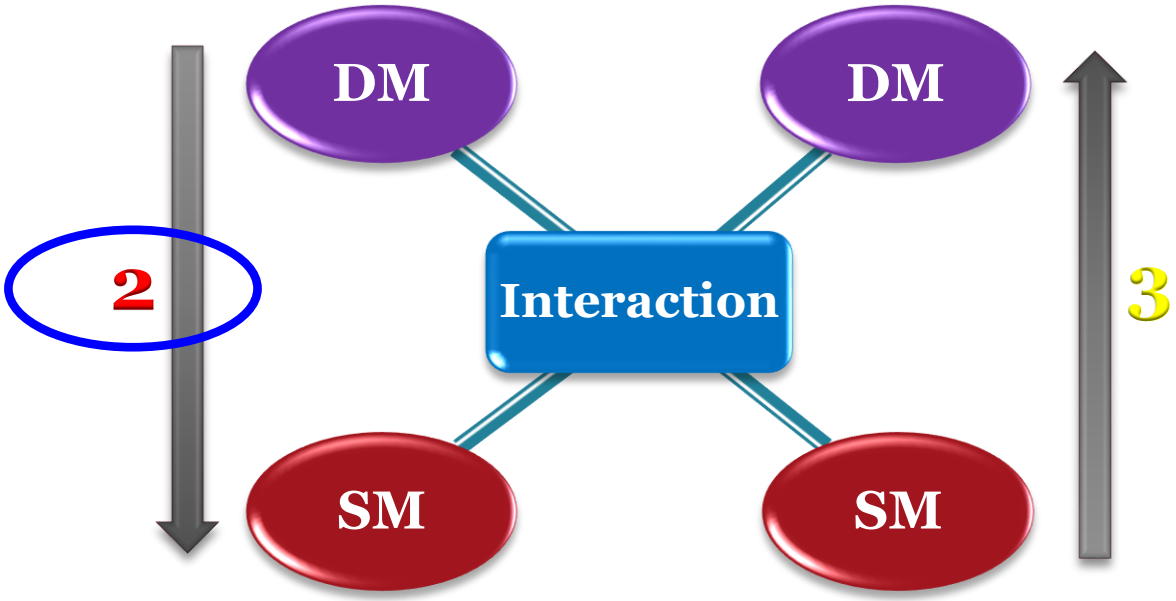


- Center for Underground Physics (CUP) of IBS (Daejeon): Yangyang & Taebaek

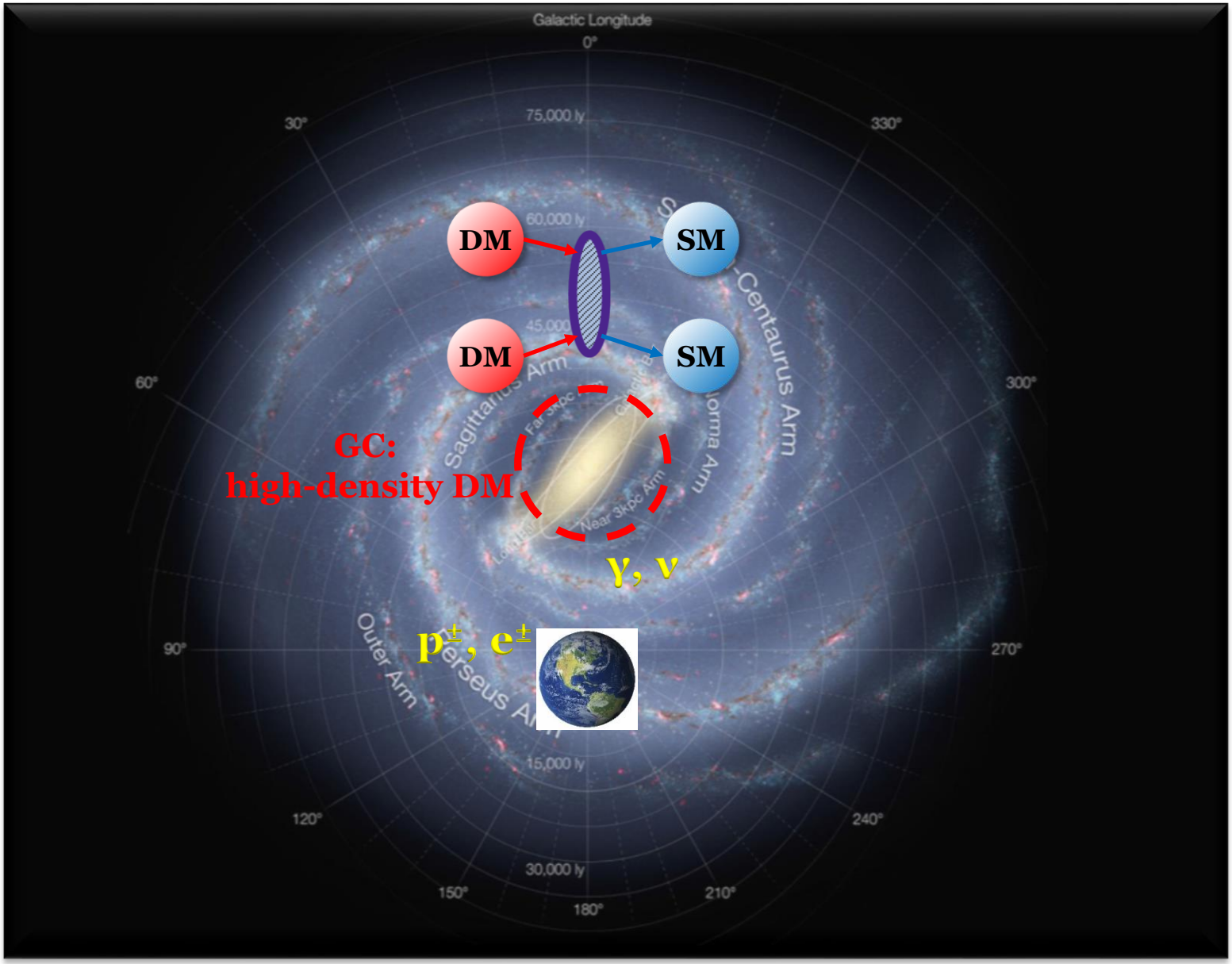
DM Indirect Detection



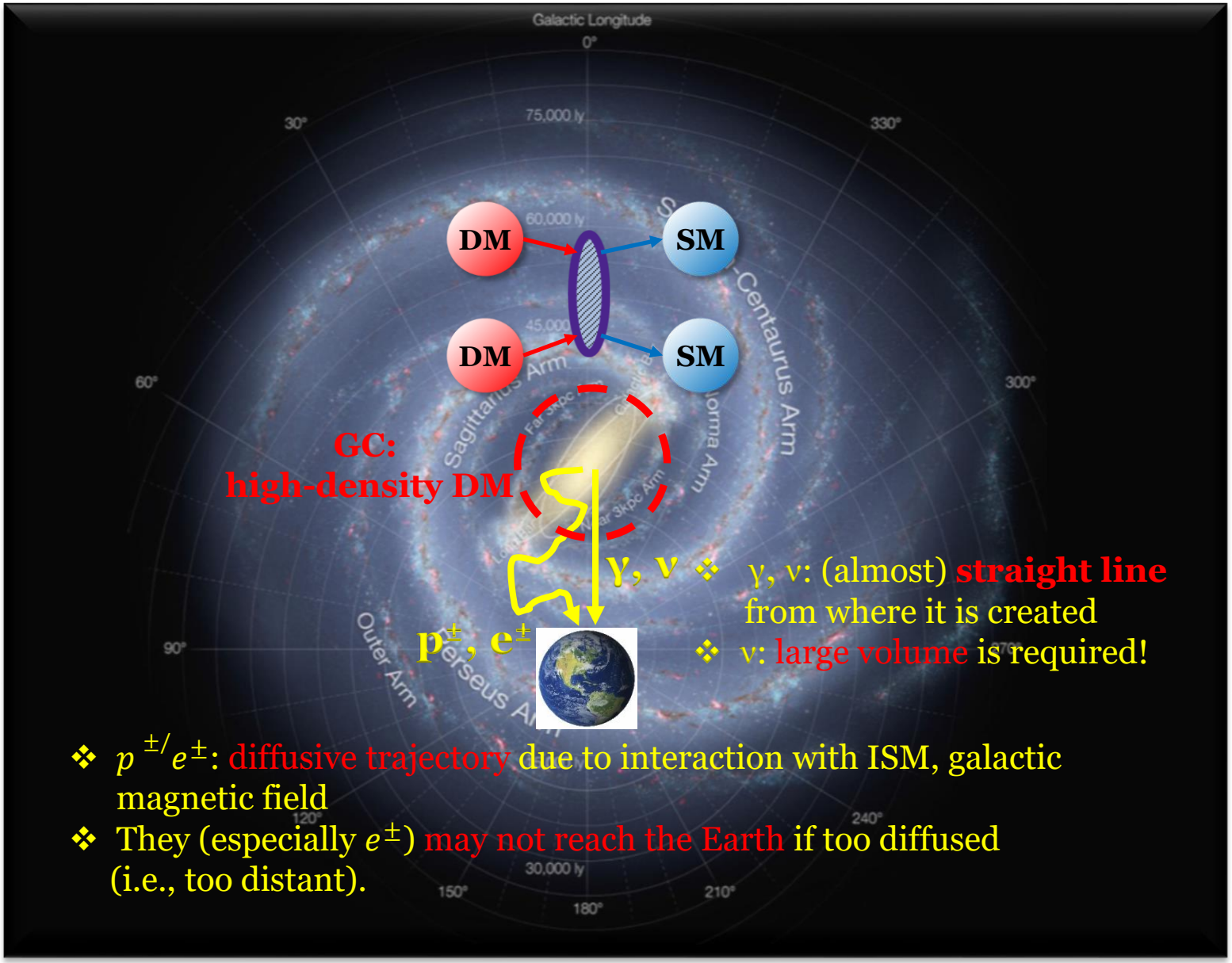




Indirect Detection: Cosmic Rays



Indirect Detection: Cosmic Rays



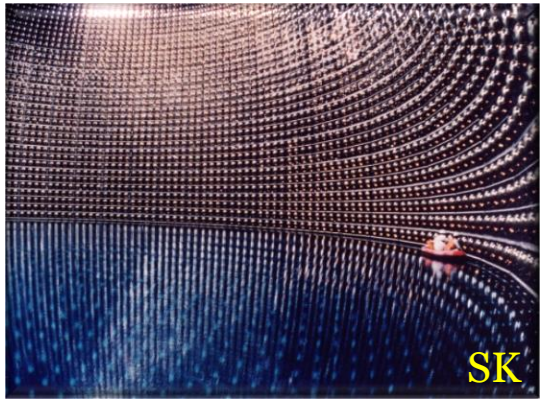
Cosmic-Ray Experiments

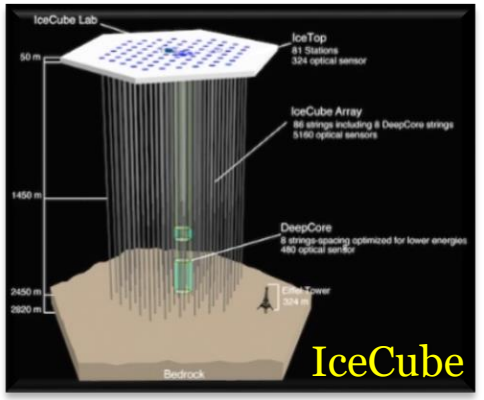
- Ground-based
  MAGIC, HESS, CTA, IceCube,
  Super/Hyper-K/KNO, DUNE, …

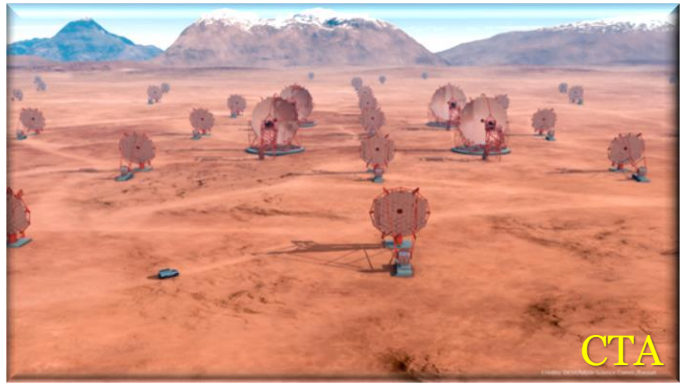
- Balloon-based:
  ATIC, PPB-BETS, …

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

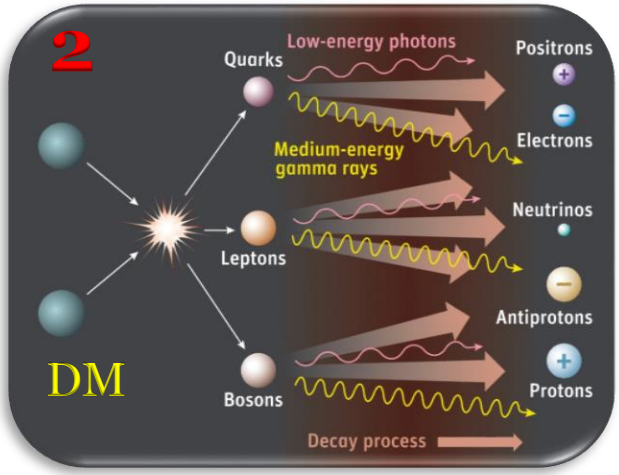
  - ✓ Great sensitivity to cosmic-ray signals
  - ✓ Better chance to have the information for extracting DM properties

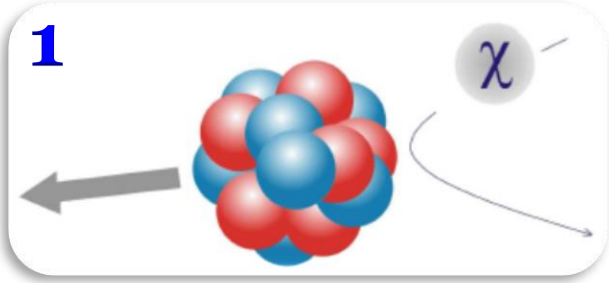


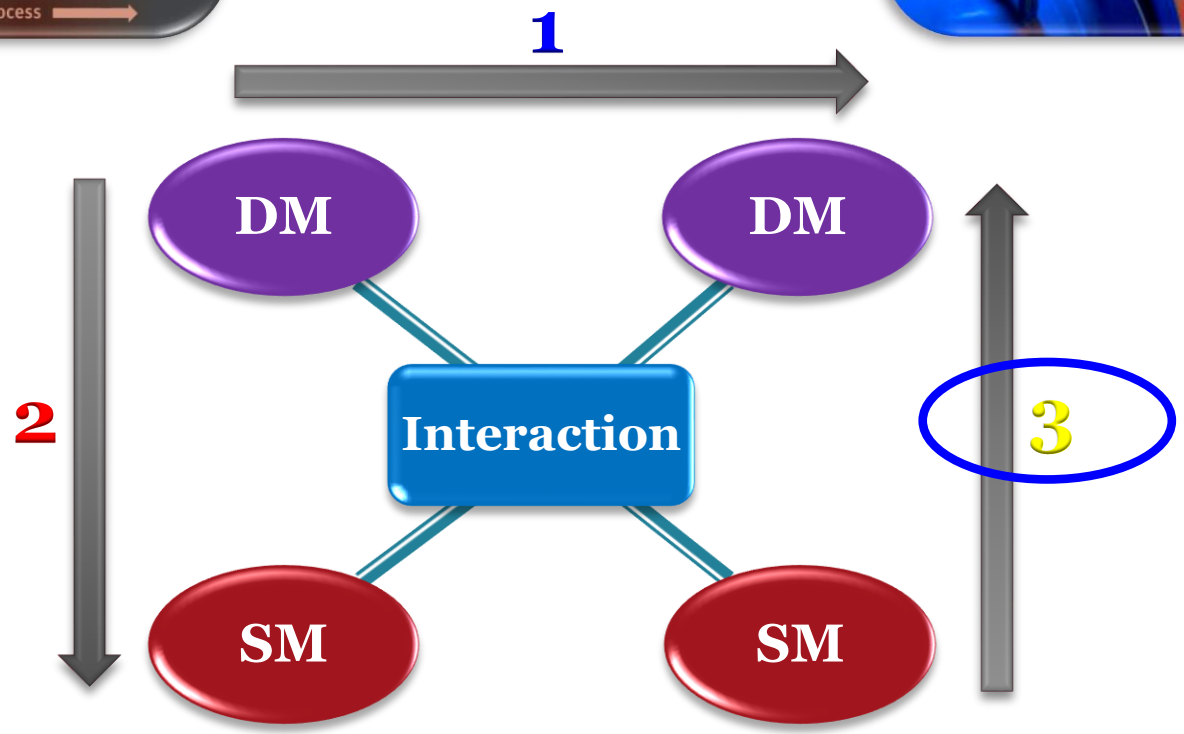




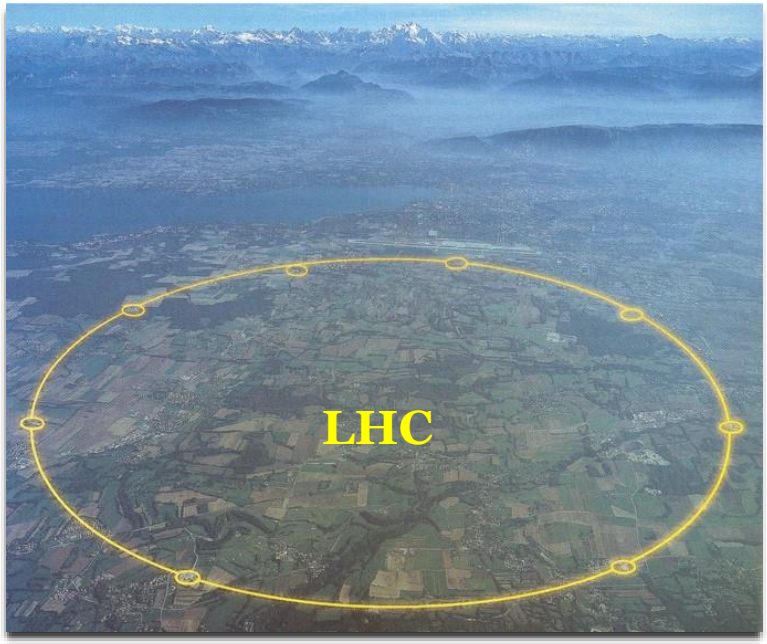
DM Production @ Colliders





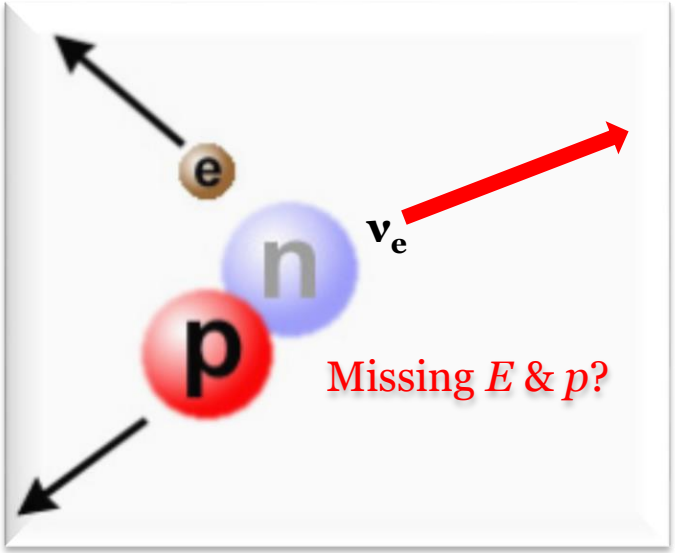


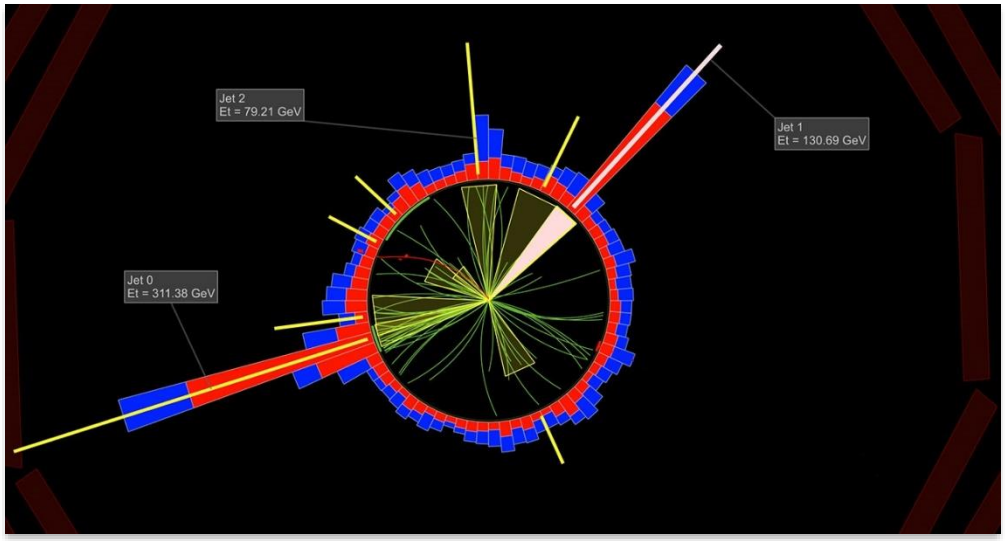
Collider Physics



- 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



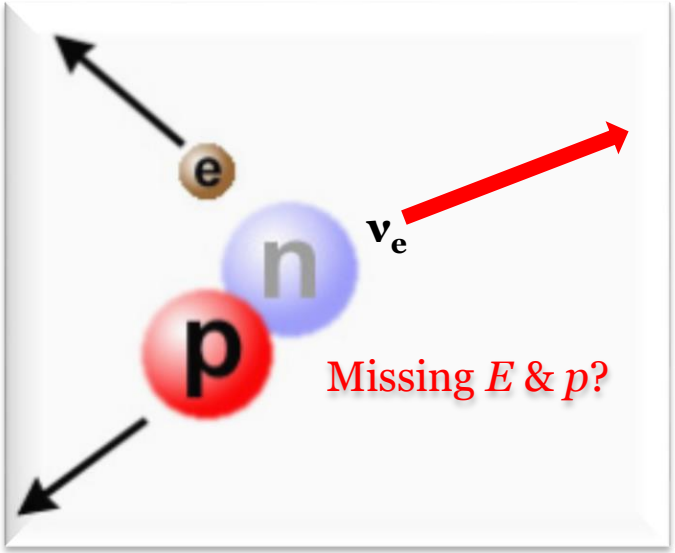


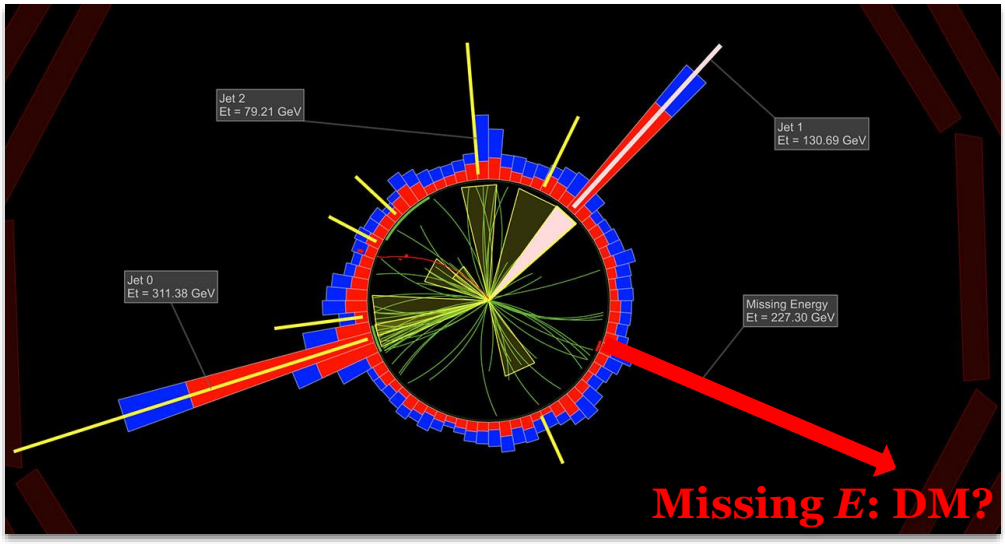
Pauli(1930)

Fermi(1932)

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

DM at Colliders





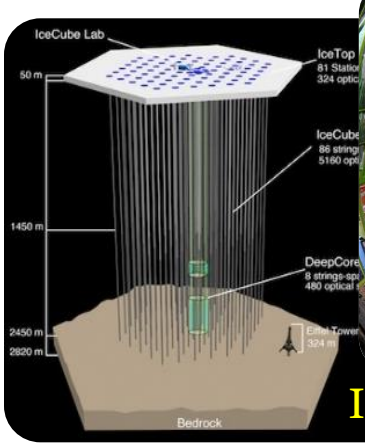
Pauli(1930)

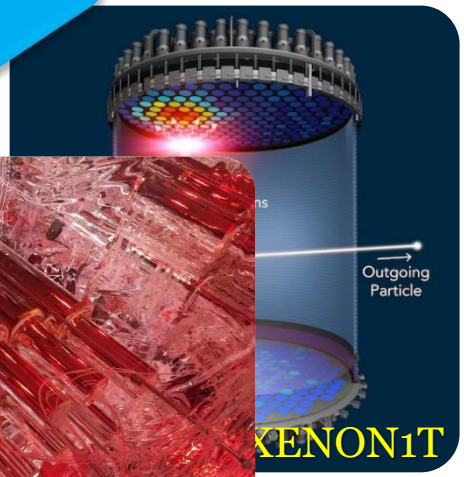
Fermi(1932)

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

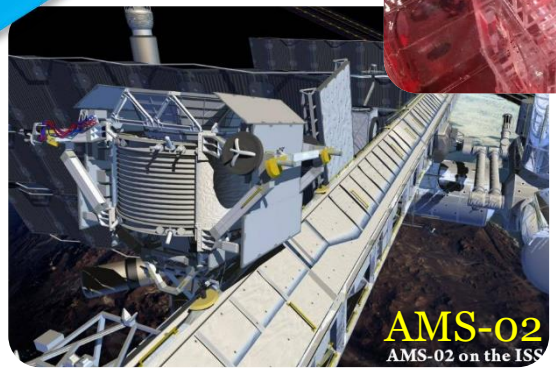
  → regarded as Missing E

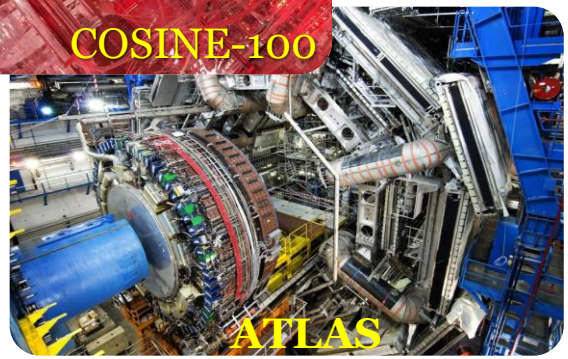
Diverging Efforts for DM Searches





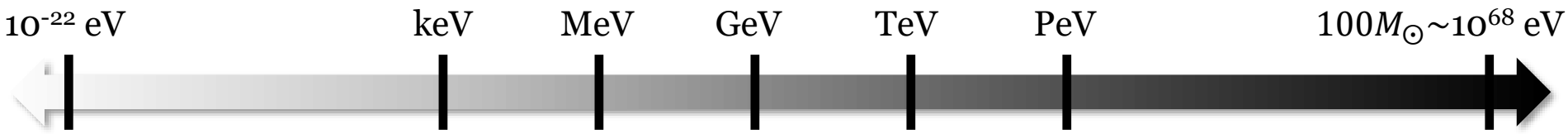
No Firm Signal!





뭔가 다른
방법은 없을까?

DM Landscape: A Very Wide Mass Range



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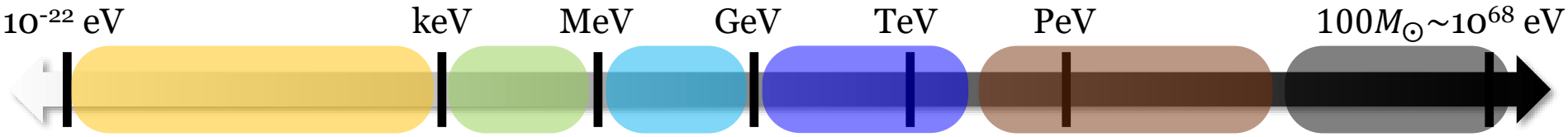


Ultralight
Scalar field
(QCD) Axion
Hidden photon
Fuzzy
non-thermal

Superlight
WDM
Sterile ν
axino
may be
thermal

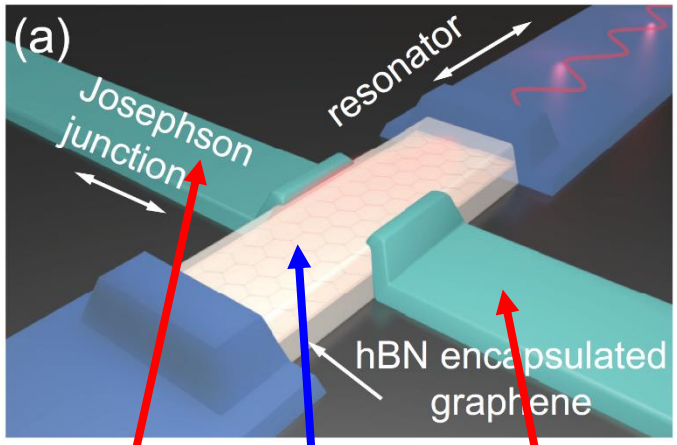
Light
particle
DM
can be
thermal
➔ e
recoil

WIMP
well-
motivated
extensively
studied
thermal
➔ N recoil

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

MACHO / Primordial BHs
non-particle

Graphene Josephson Junction Device



Superconductor-Graphene-Superconductor (SGS)

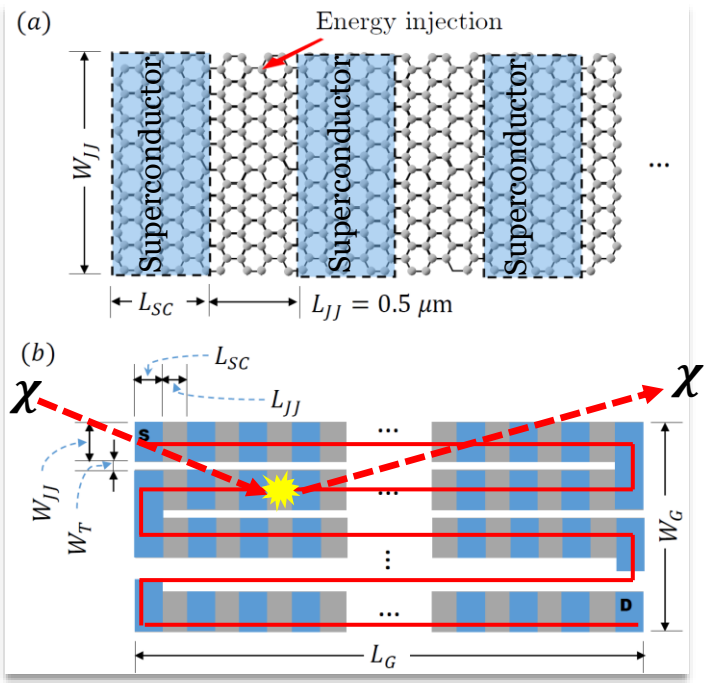
The device consists of a sheet of mono-layer graphene two sides of which are joined to superconductor, forming a superconductor-normal metal-superconductor Josephson junction.

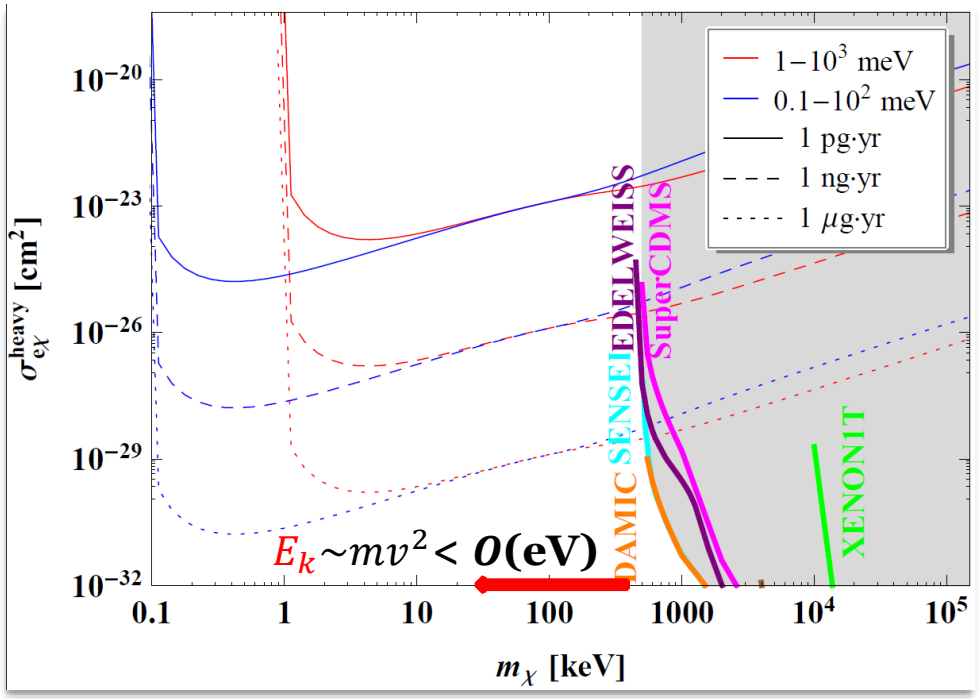
- A GJJ single-photon detector was proposed, covering from near-IR to microwave. [Phys. Rev. Applied (2017)]
- K.C. Fong, G.-H. Lee & their collaborators have **demonstrated experimentally** that the GJJ microwave bolometer can have **sensitivity to E~0.1 meV energy deposit**. [Nature (2020)]
- Currently, a GJJ single-photon detector is under testing in the laboratory.

Super-Light DM: Detection Using GJJ

D. Kim, **JCP**, K. C. Fong & G.-H. Lee, [arXiv:2002.07821]

❖ Detector using graphene Josephson junction





✓ GJJ: sensitivity to $E \sim 0.1$ meV energy deposit demonstrated experimentally [Nature (2020)]

✓ Scattering between DM moving in 3D space & free electrons confined in 2D graphene layer

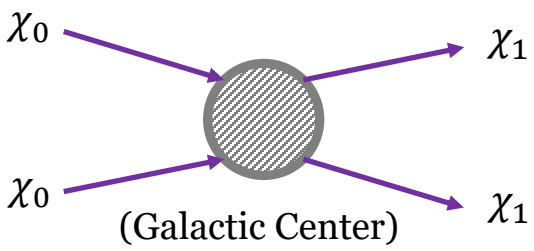
➔ signal rate depending on the DM direction

✓ GJJ DM detector improving the minimum detectable DM mass ($m_{\mathrm{DM}} \sim 0.1$ keV) by more than 3 orders of magnitude over the ongoing/existing experiments

"Relativistic" DM (BDM)

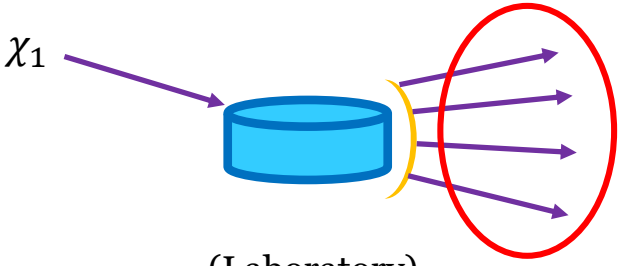
G. Belanger, **JCP**, JCAP (2012)
Agashe, Cui, Necib, Thaler, JHEP (2014)
K. Kong, G. Mohlabeng, **JCP**, PLB (2015)

❖ Need for alternative approaches

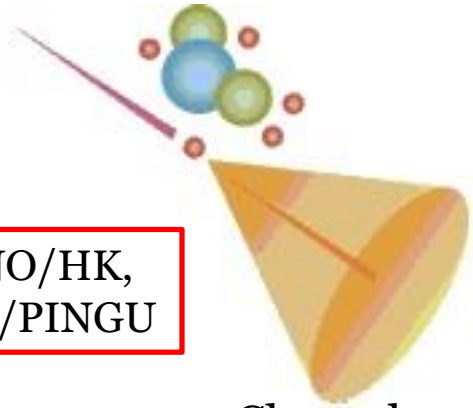


(Galactic Center)

energetic
$\gamma = m_0/m_1 > 1$

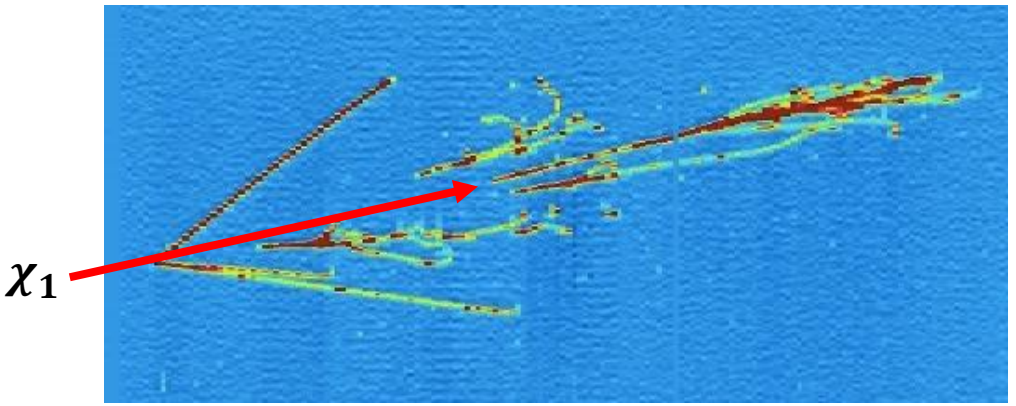


(Laboratory)



SK, KNO/HK, IceCube/PINGU

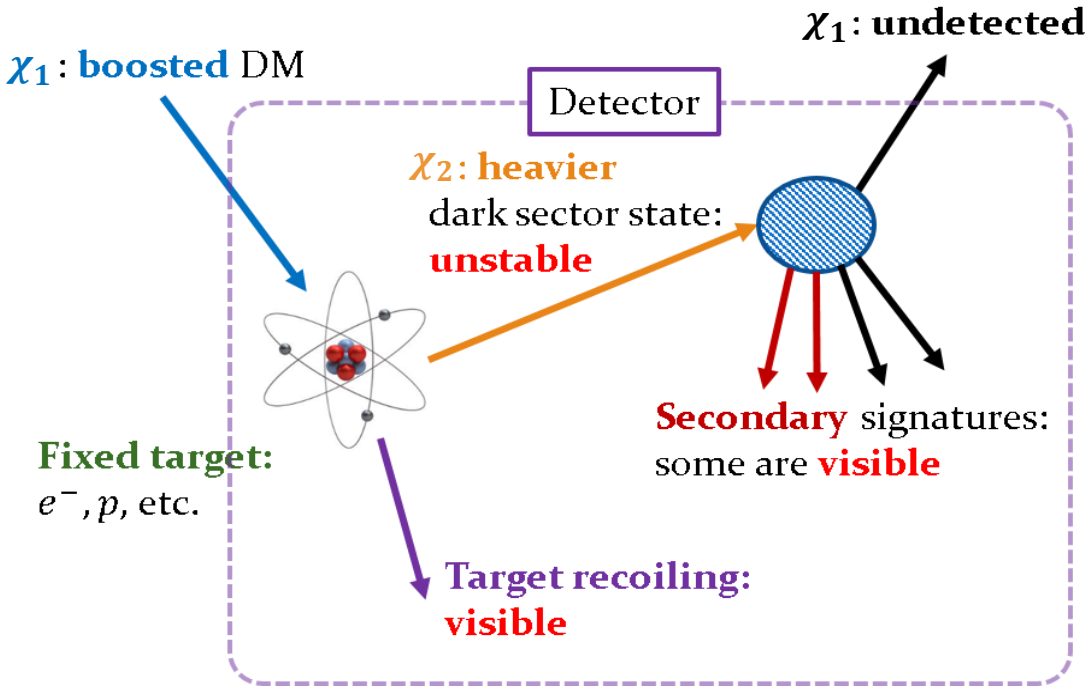
Cherenkov light



DUNE: LArTPC

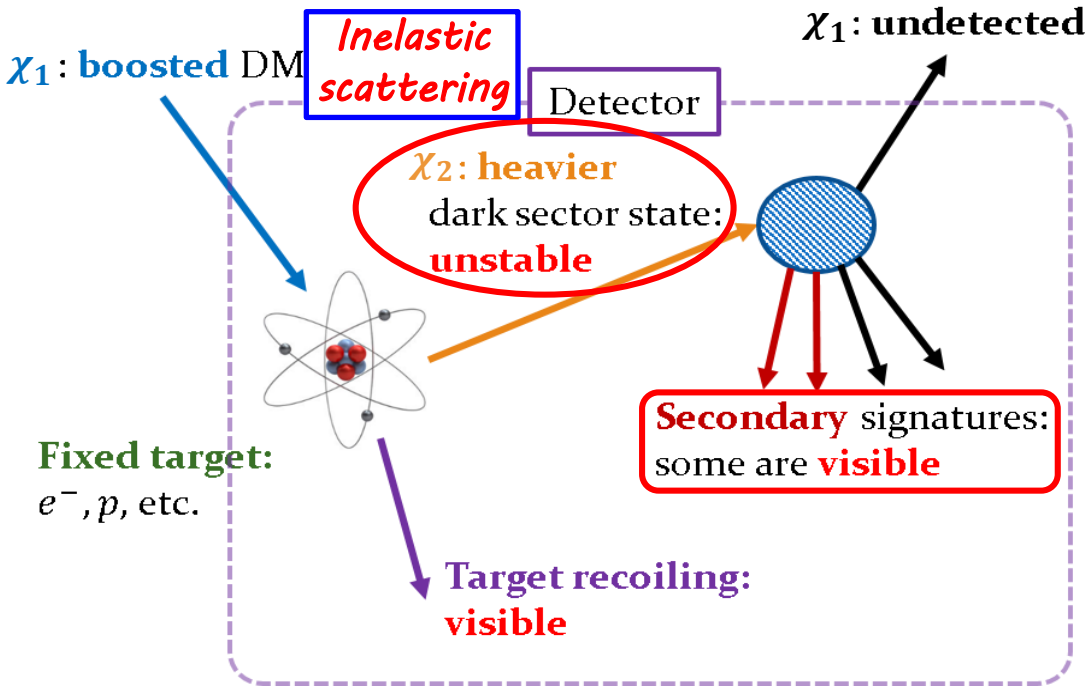
iBDM: DM "Collider"

D. Kim, **JCP** & S. Shin, PRL (2017)



iBDM: DM "Collider"

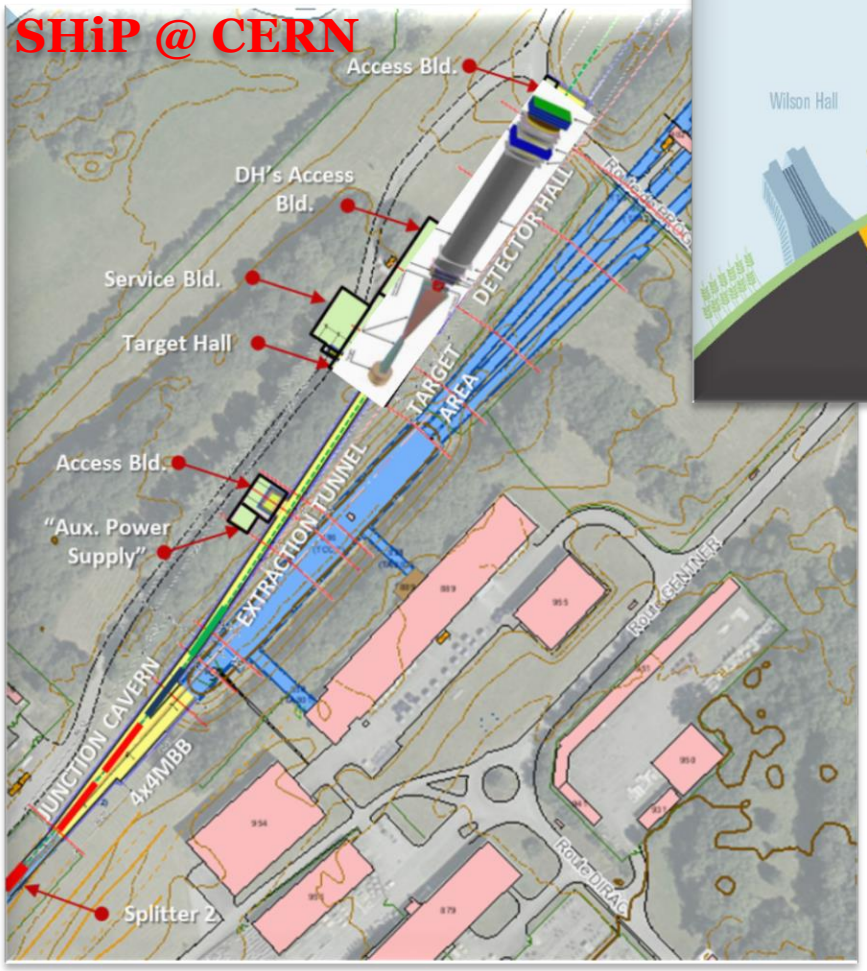
D. Kim, **JCP** & S. Shin, PRL (2017)

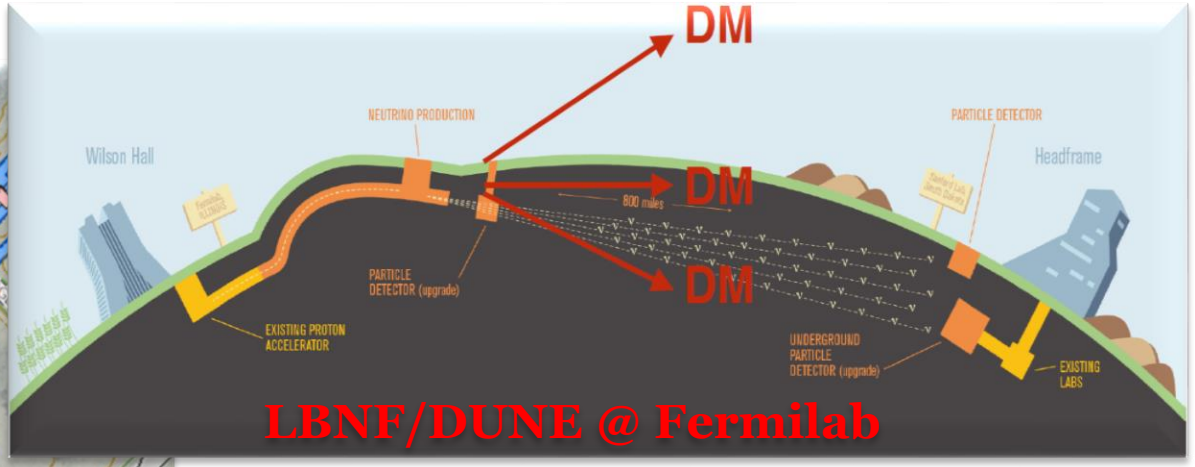


- Target recoil (like in typical DM direct detection exp.) + secondary visible signatures ➔ **more** handles, (relatively) **background-free**
- **Complementary** to standard DM direct searches
- **Boosted DM sources** needed: BDM scenarios, fixed target experiments, etc.

Follow-ups in collaborations with experimentalists (COHERENT, DUNE, SK/HK, ...)

Fixed Target Experiments

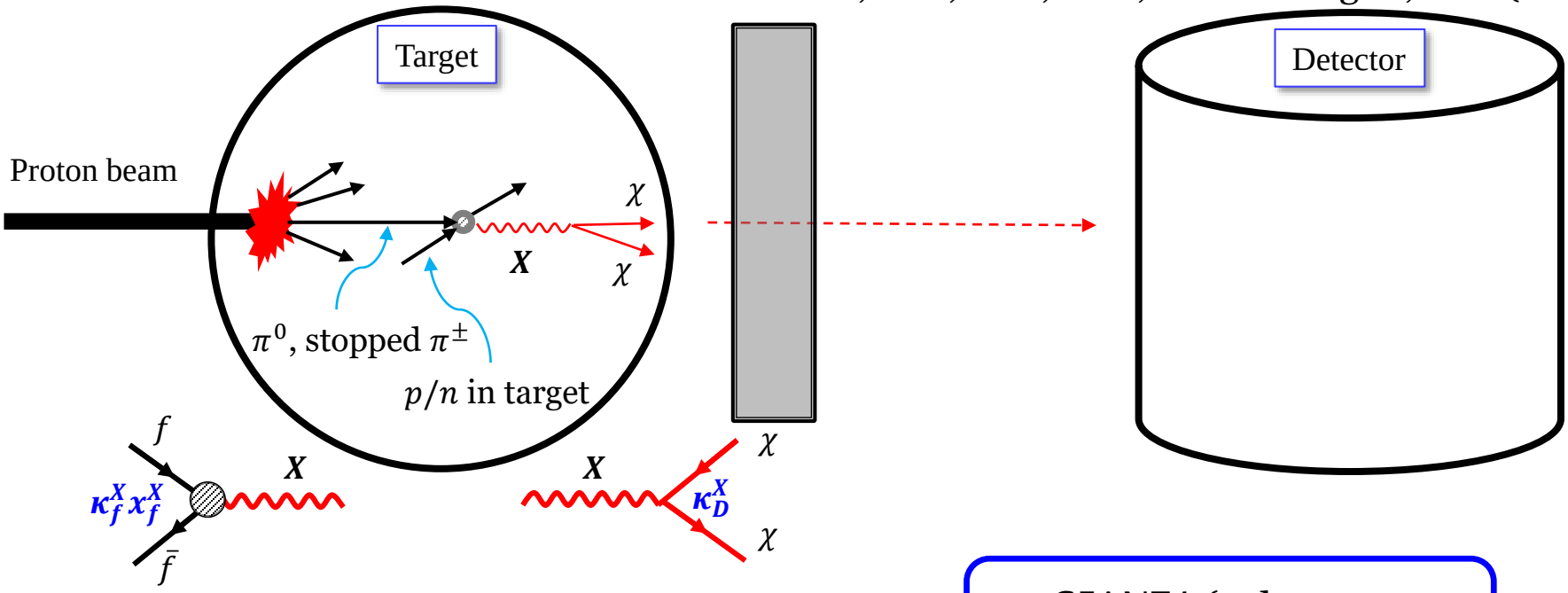




- p/e beam on fixed target ➔ Z', DM production
- Original purpose: ν production (not all)
- Upcoming Exps.: JSNS2, T2HK(J-PARC), NOVA/MicroBooNE/DUNE(Fermilab), PEX/HPS/DarkLight/BDX (J-Lab), SHiP(CERN), COHERENT (Oak Ridge), CCM (LANL), …

Fixed Target Exps.: DM Production

Dutta, Kim, Liao, **JCP**, Shin & Strigari, PRL (2020)



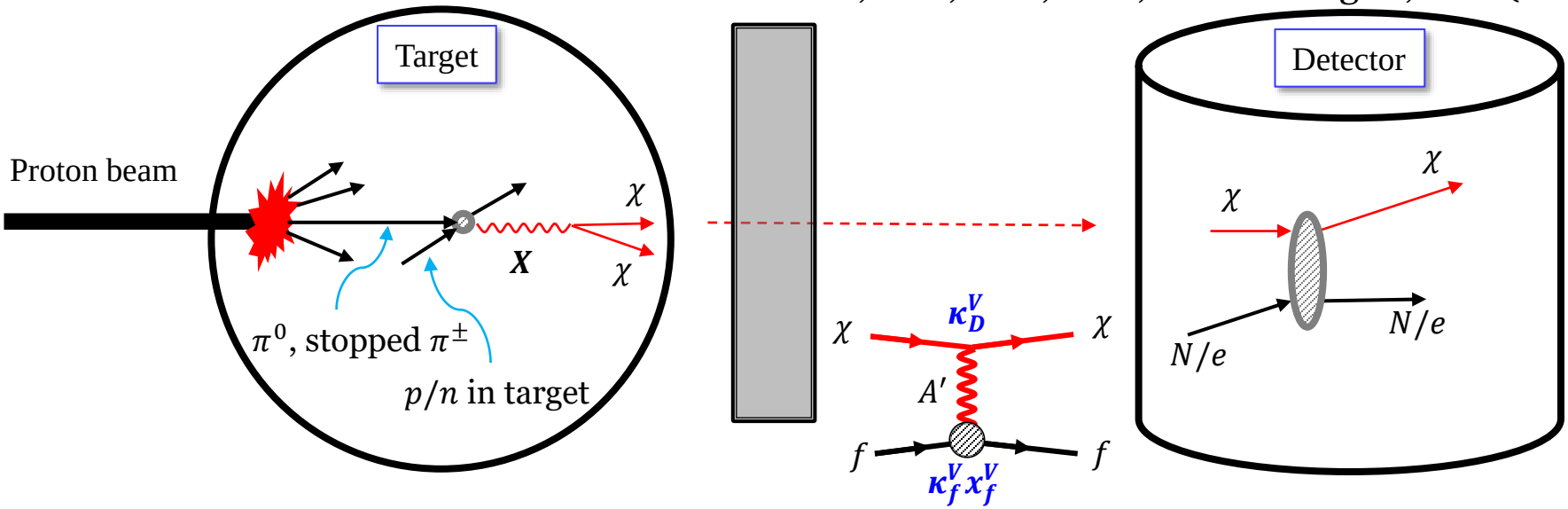
$$\mathcal{L}_{X,\text{prod}} \supset \sum_f \kappa_f^X x_f^X X_\mu \bar{f}\gamma^\mu f + \kappa_D^X X_\mu \bar{\chi}\gamma^\mu \chi$$

GEANT4 (p dump ~ γ production) + our own code

- Meson decays (P1): $\pi^0(\eta) \to \gamma + \gamma/\boldsymbol{X}$
- π^- absorption (capture) process (P2): $\pi^- + p \to n + \gamma/\boldsymbol{X}$ (X: single-valued E)
- Charge exchange processes (P3): $\pi^{-(+)} + p(n) \to n(p) + \pi^0$ & $\pi^0 \to \gamma + \gamma/\boldsymbol{X}$
- $e^\pm$-induced cascade (P4): electromagnetic cascade showering & $\gamma \to \boldsymbol{X}$

Fixed Target Exps.: DM Detection

Dutta, Kim, Liao, **JCP**, Shin & Strigari, PRL (2020)



$$\mathcal{L}_{V,\text{scatter}} \supset \sum_f \kappa_f^V x_f^V V_\mu \bar{f}\gamma^\mu f + \kappa_D^V V_\mu \bar{\chi}\gamma^\mu \chi$$

❖ Nucleus scattering (D1): (small E_r)

$$\frac{d\sigma}{dE_{r,N}} = \frac{(\kappa_f^V \kappa_D^V)^2 (Q_{\text{eff}}^V)^2 \cdot |F_V|^2}{4\pi p_\chi^2 (2m_N E_{r,N} + m_V^2)^2} \left\{ 2E_\chi^2 m_N \left(1 - \frac{E_{r,N}}{E_\chi} - \frac{m_N E_{r,N}}{2E_\chi^2}\right) + m_N E_{r,N}^2 \right\}$$

❖ Electron scattering (D2): (large E_r)

$$\frac{d\sigma}{dE_{r,e}} = \frac{Z(x_f^V \kappa_f^V \kappa_D^V)^2 m_e^2}{\pi\lambda(s, m_e^2, m_\chi^2)\left\{2m_e(m_e - E_{r,e}) - m_V^2\right\}^2} \times \left[m_e\left\{E_\chi^2 + (m_e + E_\chi - E_{r,e})^2\right\} + \left(m_e^2 + m_\chi^2\right)(m_e - E_{r,e})\right]$$

$$s = E_\chi^2 + 2E_\chi m_e + m_\chi^2$$

$$\lambda(x, y, z) \equiv (x - y - z)^2 - 4yz$$

Application to the Existing CsI Data

Dutta, Kim, Liao, **JCP**, Shin & Strigari, PRL (2020)

❖ Data released by COHERENT: CsI detector ➔ 14.57 kg×308.1 days [arXiv:1804.09459]

❖ Analysis scheme

✓ Fix the average rms radius of the neutron distribution to $R_n = 4.7$ fm

✓ $14\ \text{keV} < E_r < 28\ \text{keV}$ & $T < 1.5\ \mu\text{s}$

$$F_N^{\text{Helm}}(q^2) = \frac{3j_1(qR_0)}{qR_0}\exp(-\frac{q^2s^2}{2})$$
$$R_n^2 = 3R_0^2/5 + 3s^2$$

97 : total events

– 49 : classified as steady-state (SS) backgrounds

– 3 : beam-related neutron (BRN) backgrounds

– 19 : identified as delayed (SM) ν events (due to E_r/t-cuts)

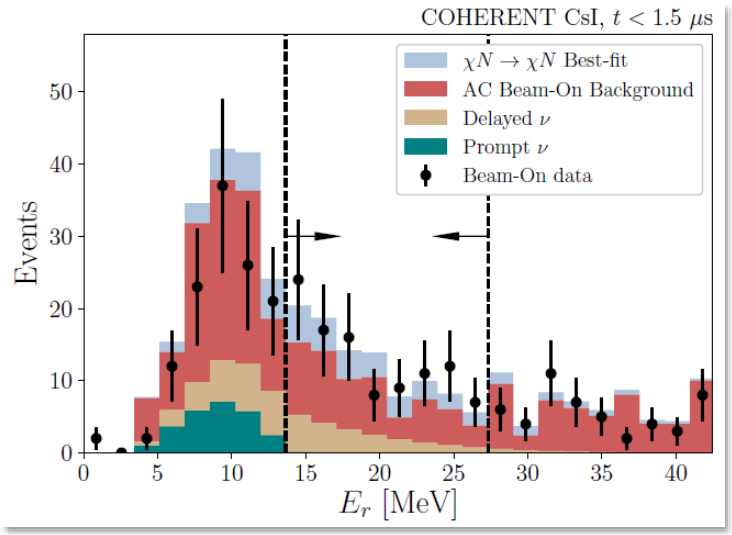
– 0 : identified as prompt (SM) ν events (due to E_r-cut)

26 : "Excess!!"

Significance ($R_n = 4.7$ fm): **2.4 σ**

Significance ($R_n = 5.5$ fm): **3.0 σ**

[arXiv:1801.05546]



"Alex... ...in, this time try Alexa $10 credit Learn more

‹ Back to search results for "dark matter"

MHP Dark Matter Post-Workout Muscle ...celerator, Blue Raspberry, 3.22 Pound

Maximum Human Pe...

★★★½☆ 63 customer reviews

Price: $36.09 ($11.21 / Pound) & **FREE Shipping**. Details

In Stock. Ships from and sold by Amazon.com. Gift-wrap available.

2 Flavors: Blue Raspberry

Blue Raspberry	Fruit Punch
$36.09 ($11.21 / Pound)	from 2 sellers

Want it tomorrow, Aug. 9? Order within **3 hrs 35 mins** and choose **One-Day Shipping** at checkout. Details

Ship to: Select a shipping address:

Yes, I want **FREE Two-Day Shipping** with Amazon Prime

Qty: 1 Turn on 1-click ordering

Add to Cart

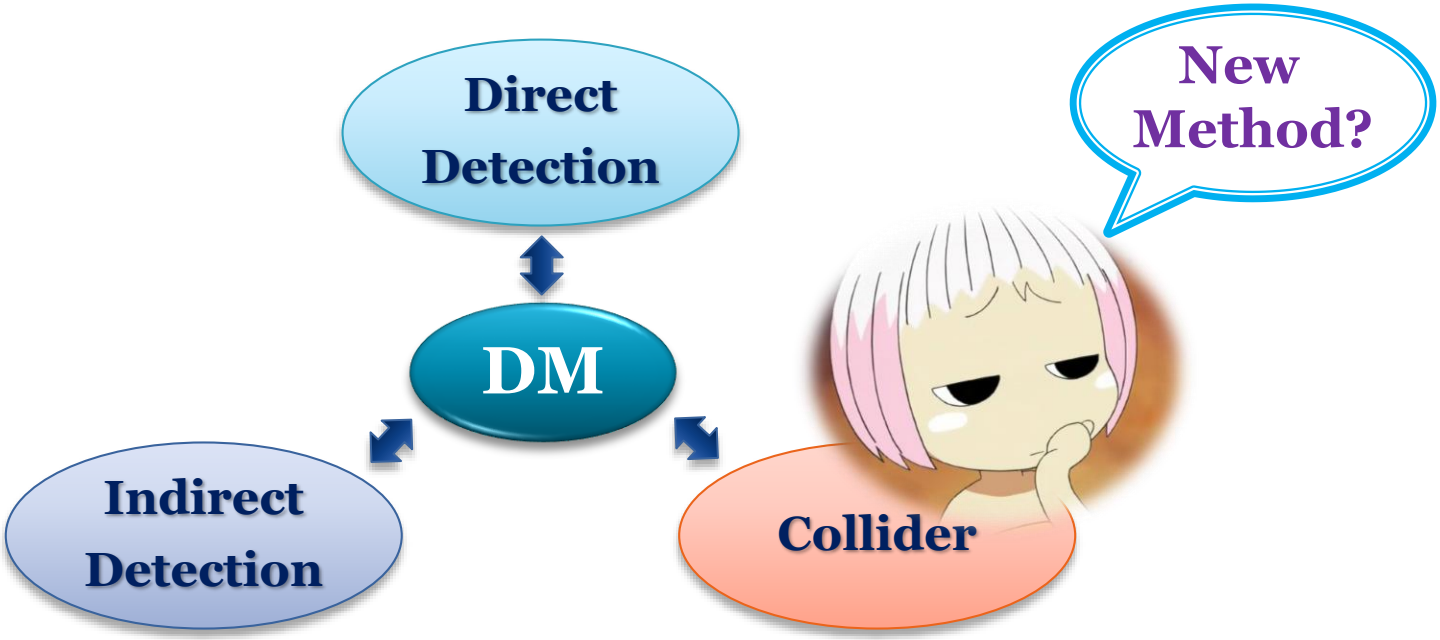
Add to List

About the product

- The ultimate post workout muscle growth accelerator
- 600 % increase in protein synthesis
- Absorbs faster than whey isolate

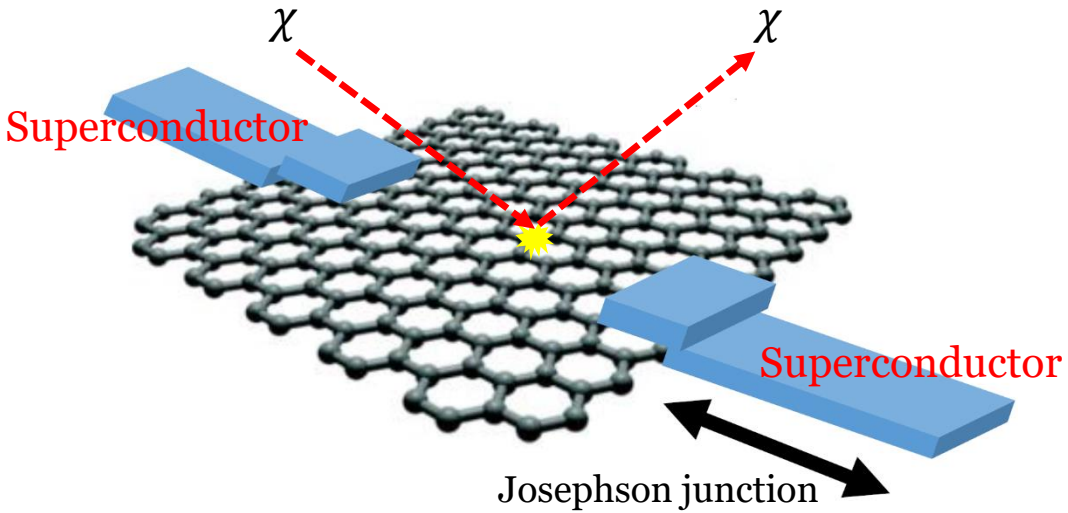
Summary

- Particle physics: to find fundamental interactions and elements
- DM: clear sign of new physics (particle) beyond the Standard Model
- Nature of DM: one of the most important problems in the 21th century!



Back-Up

Detection Principle of GJJ-Detector



I. DM scatters off (π-bond) free electrons, transferring some fraction of its incoming E_k.

II. The recoiling e heats up & thermalizes with nearby e's rapidly via e-e interactions.

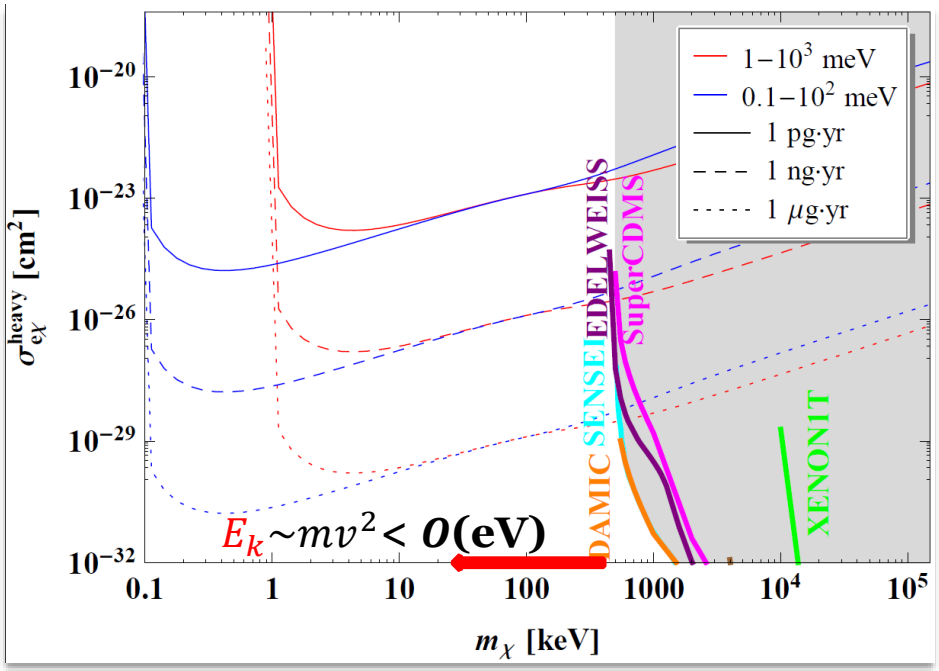
III. The JJ is triggered: the temperature rise switches the zero-voltage of JJ to resistive state.

❖ $E_k \sim mv^2 \sim 1$ meV for $m_{DM} = 1$ keV

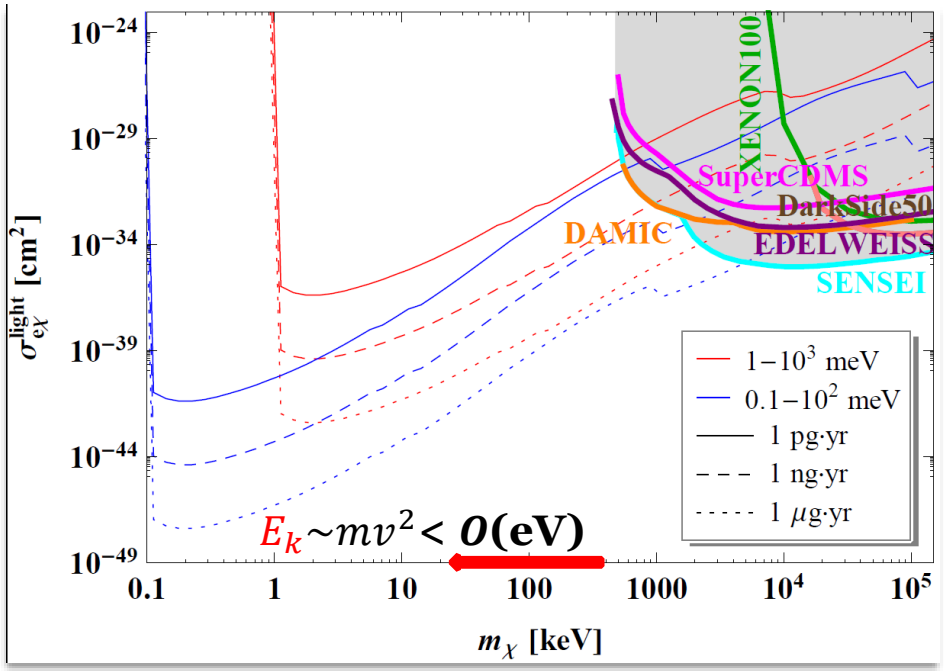
➔ The GJJ device can posses the sensitivity to the signal induced even by sub-keV DM.

Expected Sensitivities: Near Future

Heavy mediator: $F_{DM} = 1$



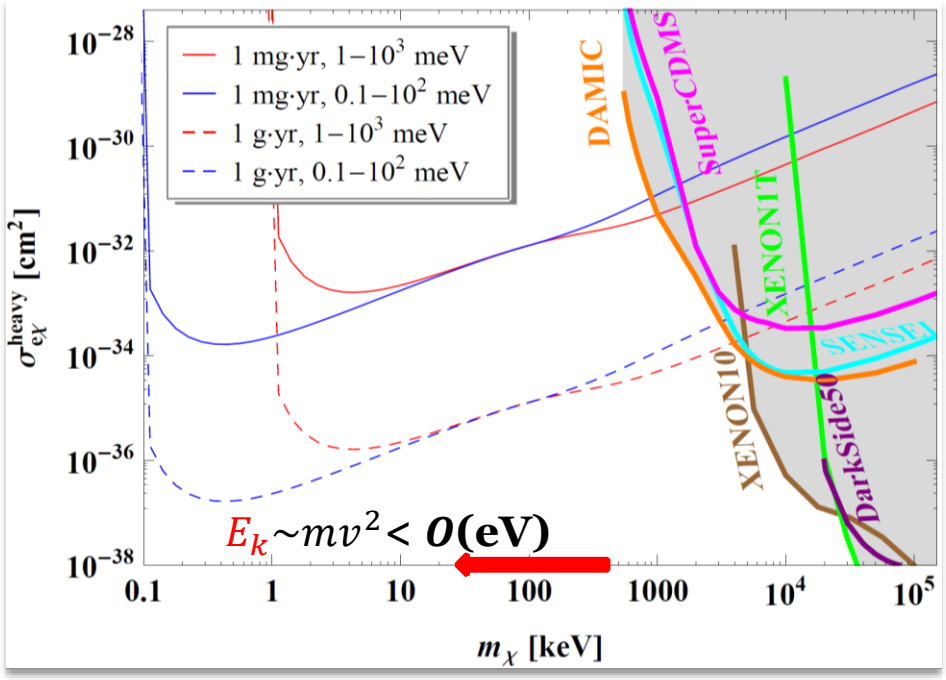
Light mediator: $F_{DM} \propto 1/q^2$ with $q_{\mathrm{ref}} = \alpha_e m_e$



- ✓ We required N_{eve}=3.6 under the negligible background assumption.
- ✓ The proposed GJJ DM detector can improve the minimum detectable DM mass (m_{DM}~0.1 keV) by more than 3 orders of magnitude over the ongoing/existing experiments.
- ✓ Even capable of probing sub-keV DM with great expected reaches.

Expected Sensitivities: (Far) Future

Heavy mediator: $F_{DM} = 1$



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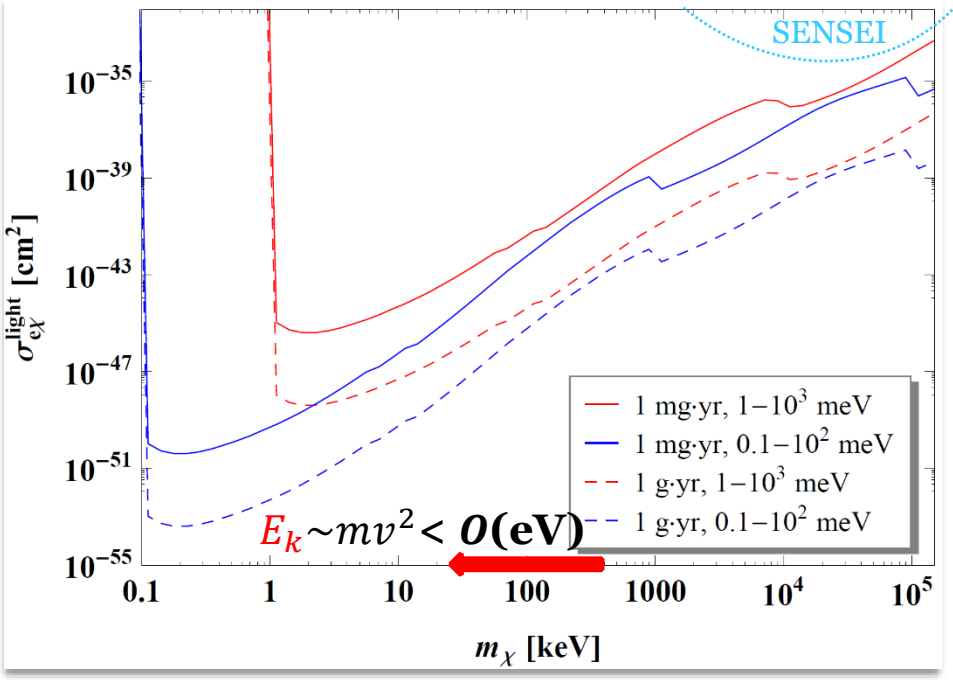

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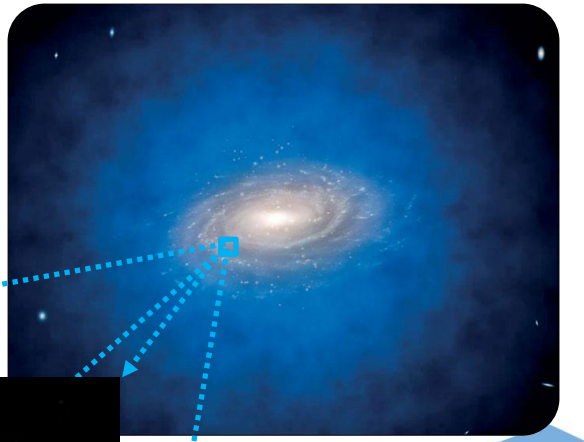
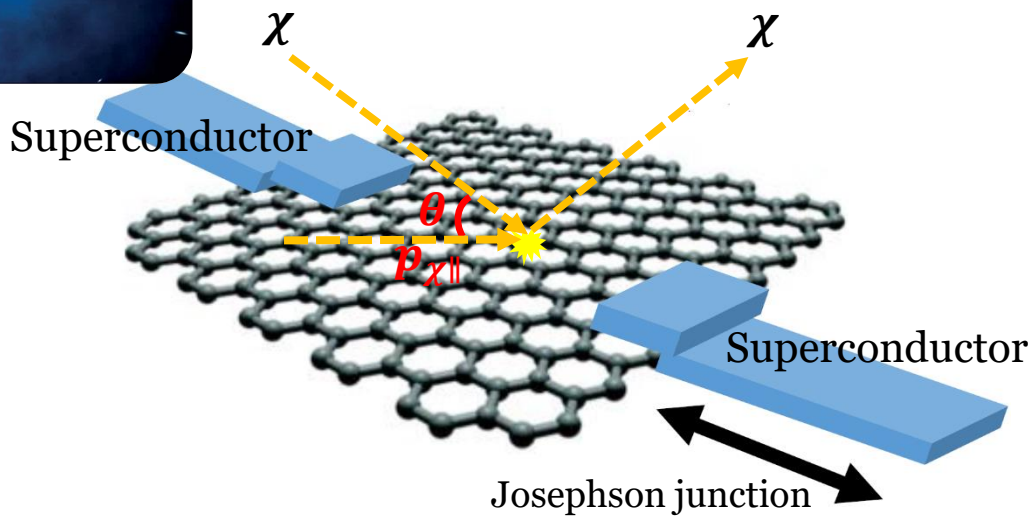
- ✓ The proposed GJJ DM detector can improve the minimum detectable DM mass (m_{DM}~0.1 keV) by more than 3 orders of magnitude over the ongoing/existing experiments.
- ✓ Even capable of probing sub-keV DM with great expected reaches.

Signal Rate: Directional Dependence

❖ Electron: **confined** in the **2D graphene sheet** even after the collision.

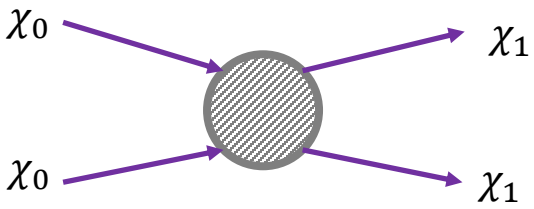
➔ The momentum transfer is determined by the **change of $p_{\chi\parallel}$**. ➔ Signal rate depends on the **DM incident direction**! ➔ DM signal would be validated by rotating the graphene sheet: aligned with the direction parallel/perpendicular to the overall DM flux.





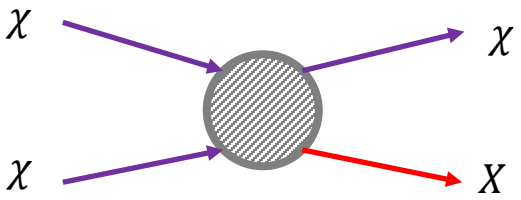
Energetic/Boosted Dark Matter (DM)

Boosted DM coming from the universe



✓ Multi-component model

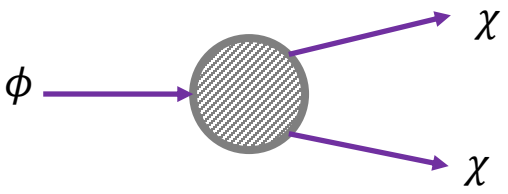
$m_0 \gg m_1$



✓ Semi-annihilation model

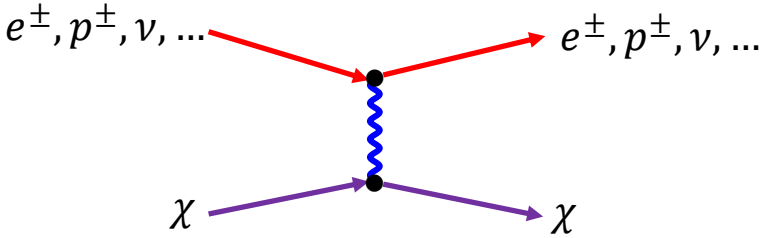
$m_\chi \gg m_X$

Large E_k^{DM} due to **mass gap** or **E_k^{CR} transfer**



✓ Decaying multi-component DM

$m_\phi \gg m_\chi$



✓ Energetic cosmic-ray induced DM

$E_{e^{\pm},p^{\pm},\nu,\ldots} \gg m_\chi$

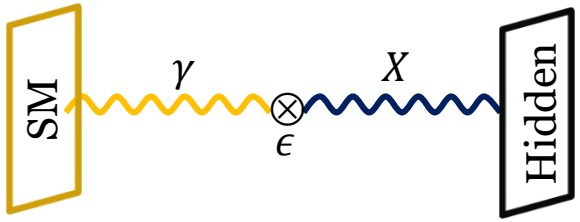
❖ Some scenarios need extension of dark sector, but others just need couplings between DM & SM.

BDM Models

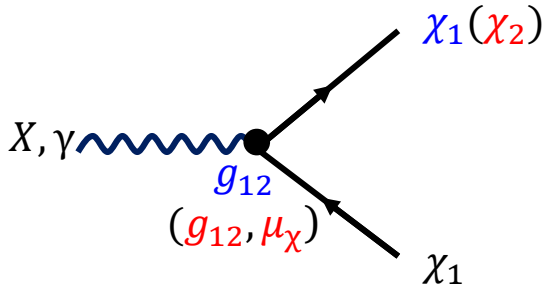
$$\mathcal{L}_{\text{int}} \ni -\frac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{11} \bar{\chi}_1 \gamma^\mu \chi_1 X_\mu + g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + h.c.$$

$$\mathcal{L}_{\text{int}} \ni (\mu_\chi/2) \bar{\chi}_2 \sigma^{\mu\nu} \chi_1 F_{\mu\nu} + h.c.$$

Kim, **JCP** & Shin, PRL (2017)
Giudice, **JCP**, et al., PLB (2018)



- ✓ χ_2: a heavier (unstable) dark-sector state
- ✓ Flavor-conserving ➔ elastic scattering (eBDM)
- ✓ Flavor-changing ➔ inelastic scattering (*i*BDM)

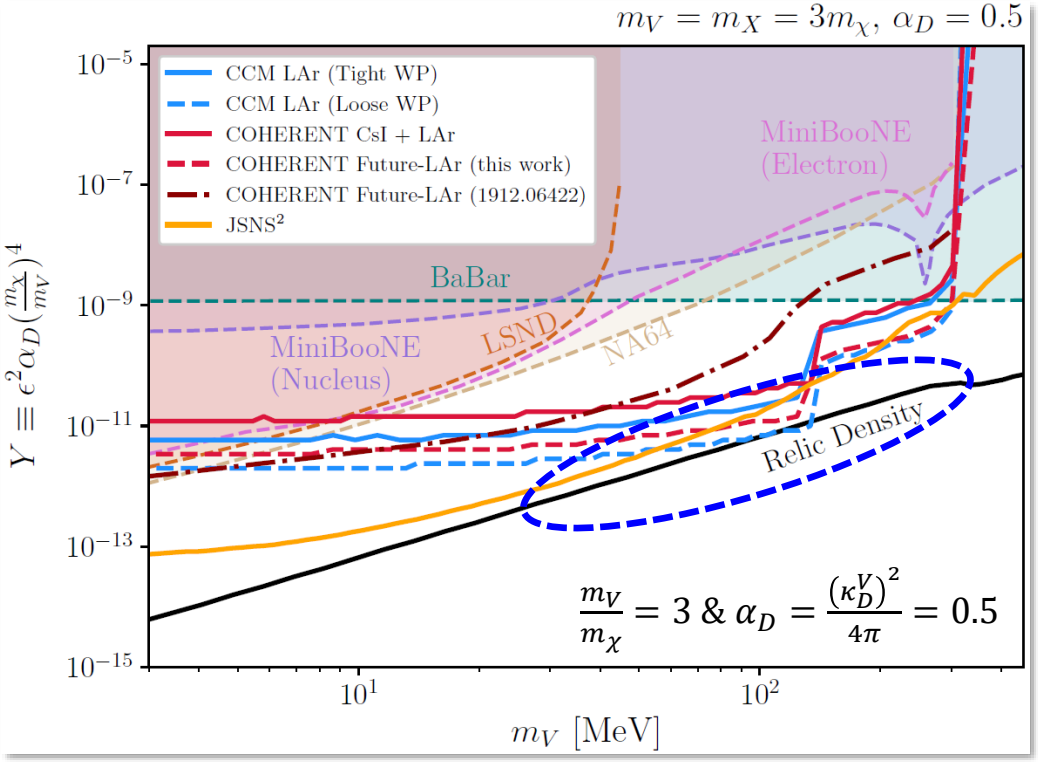


❖ Various models conceiving BDM signatures

- ✓ Source: GC, Sun (capture), dwarf galaxies, etc.
- ✓ Mechanism: assisted freeze-out, semi-annihilation, decaying, cosmic-ray induced DM, etc.
- ✓ Portal: vector portal, scalar portal, etc.
- ✓ DM spin: fermionic DM, scalar DM, etc.
- ✓ *i*BDM-inducing operators: two chiral fermions, two real scalars, dipole moment interactions, etc.

Beam Produced DM Search Limits

❖ Assuming no excess is observed, we can constrain parameter space.



- ✓ Projected sensitivity in the single-mediator scenario: a dark photon mediator
- ✓ Data & information about BGs are available for COHERENT, but not for CCM &JSNS²
- ✓ A different curvature of JSNS²: due to $m_e \ll m_V$, but $m_N \gg m_V$ for others
- ✓ NA64, BaBar: missing E_T