# Exercises

3. Nuclear recoil spectrum in DM direct detection:

(a) $v_{\min} = \sqrt{E_R m_N / 2\mu_{\chi N}^2} = \frac{m_\chi + m_N}{m_\chi} \sqrt{E_R / 2m_N}$

(b) Shape of nuclear recoil spectrum (dependence on $m_\chi$)

➔See e.g., [Lewin & Smith, Astroparticle Physics 6 (1996) 87]

4. Fluxes of DM annihilation products, e.g., $e^{\pm}, \bar{p}$:

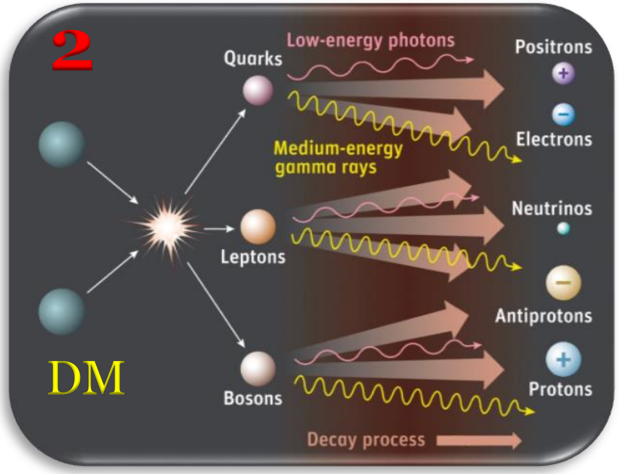
(a) Annihilation cross section dependence

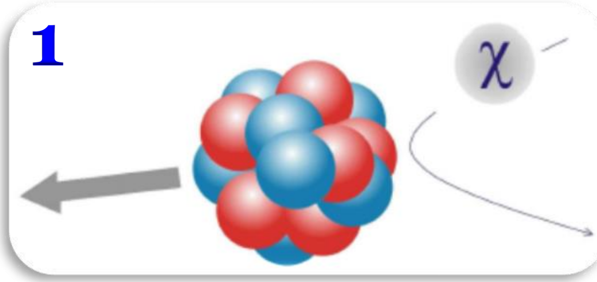
(b) $m_\chi$ dependence

# 4. Indirect Detection

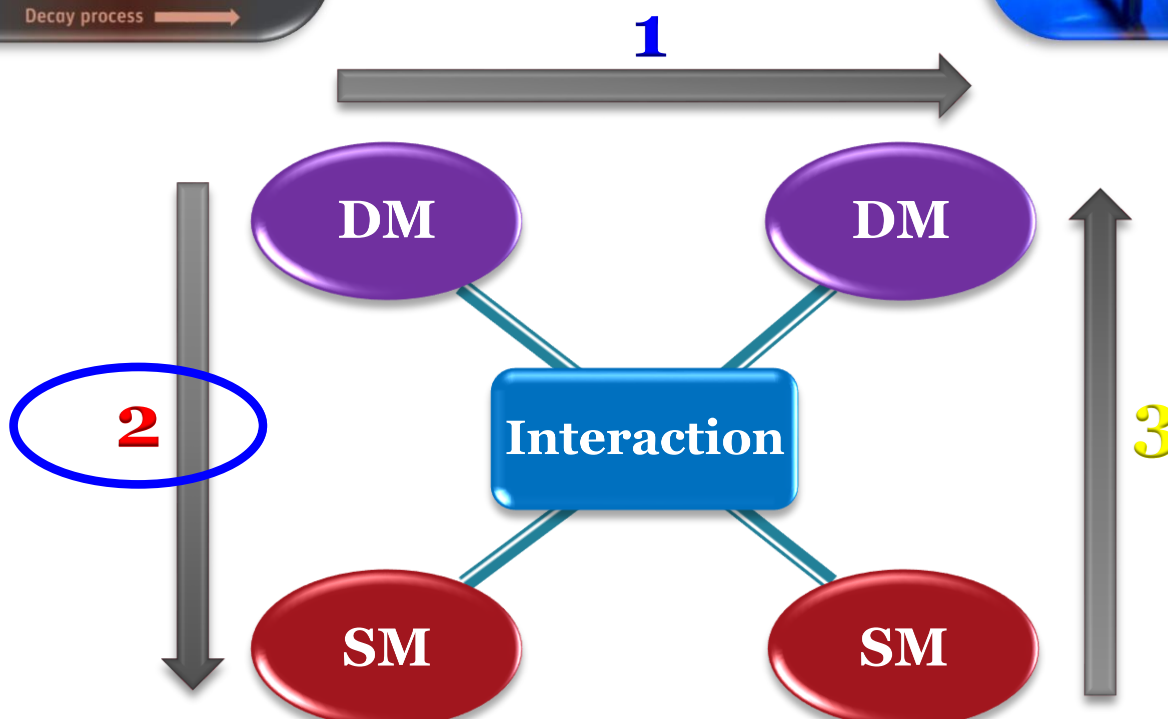
# Cosmic Rays

# DM Indirect Detection



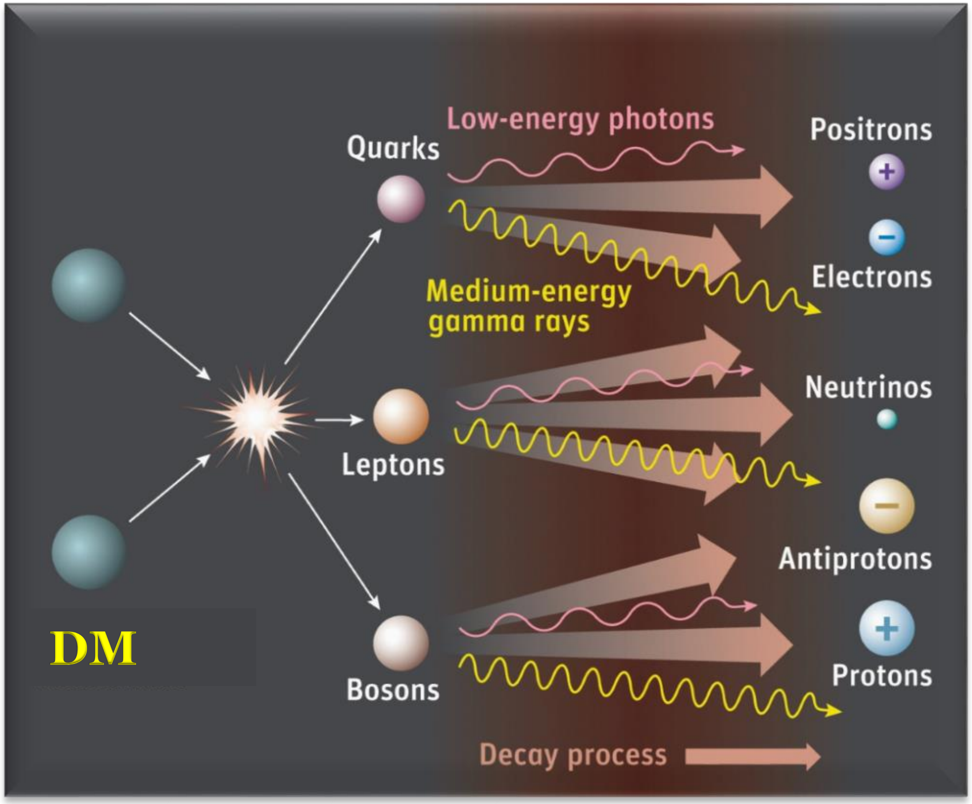







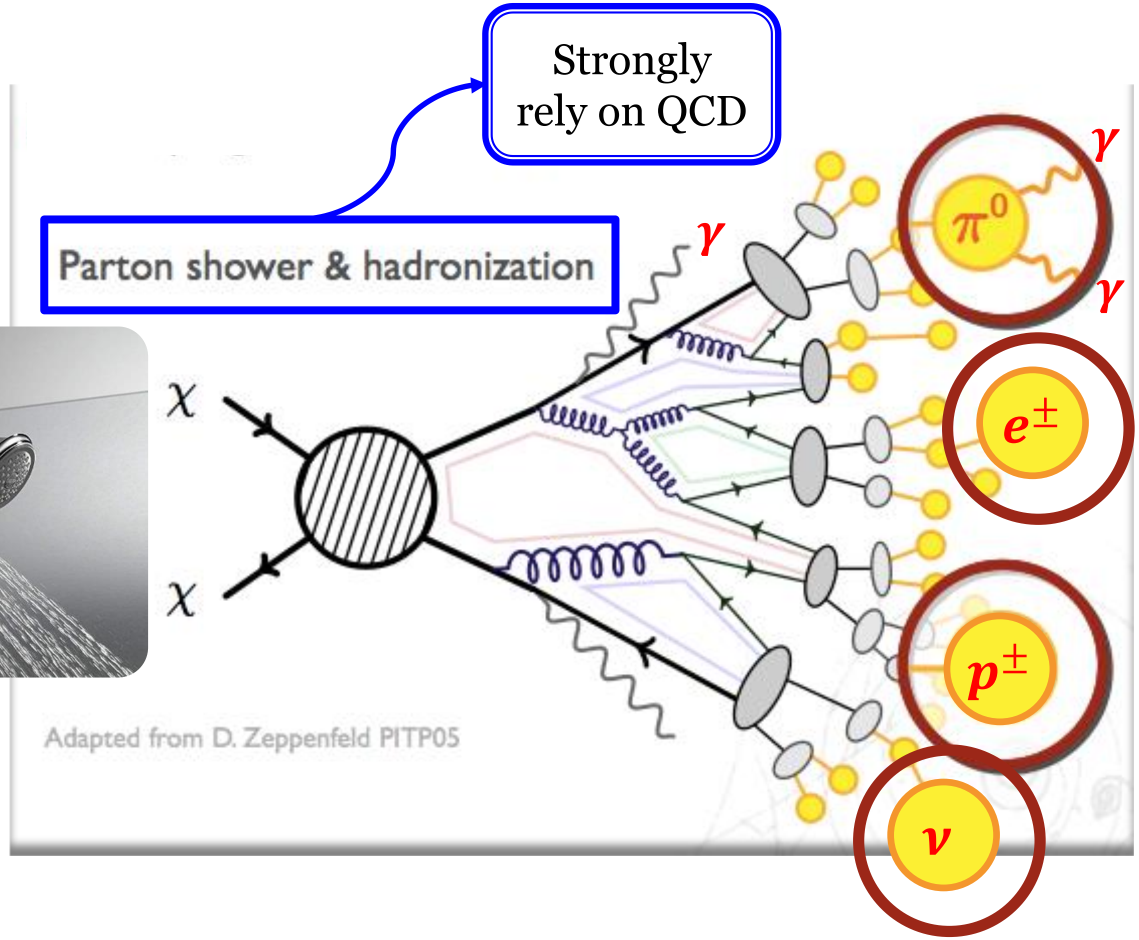
# Cosmic Rays from DM

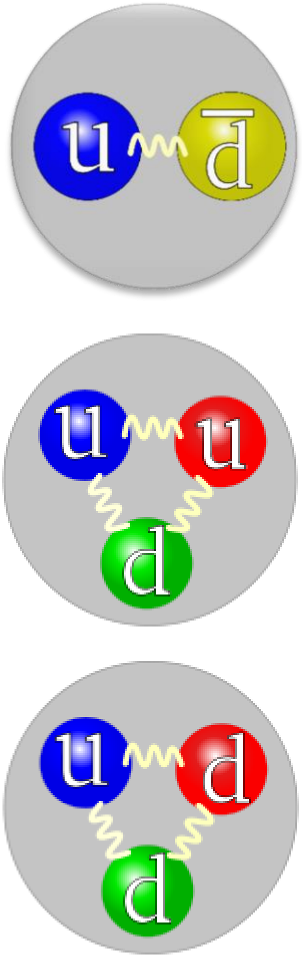
❖ Search for the products of DM annihilation and/or decay: $\gamma$, $\nu$, $e^{\pm}$, p, ...



# Cosmic Rays from DM: Showering

❖ Final states from DM annihilation and/or decay: γ, e±, p±, ν, …



# Cosmic Ray Experiments

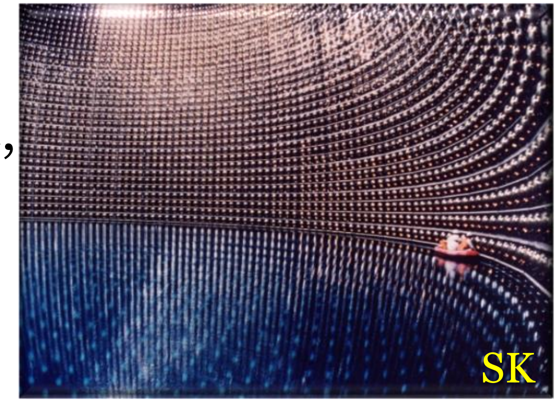
- Ground-based
  MAGIC, HESS, CTA, IceCube,
  Super-K, Hyper-K, DUNE, …

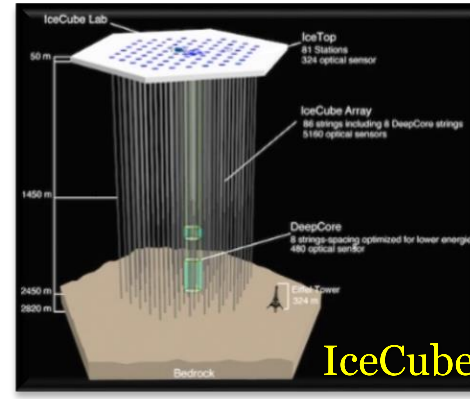
- Balloon-based:
  ATIC, PPB-BETS, …

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

  ✓ Great sensitivity to cosmic-ray signals

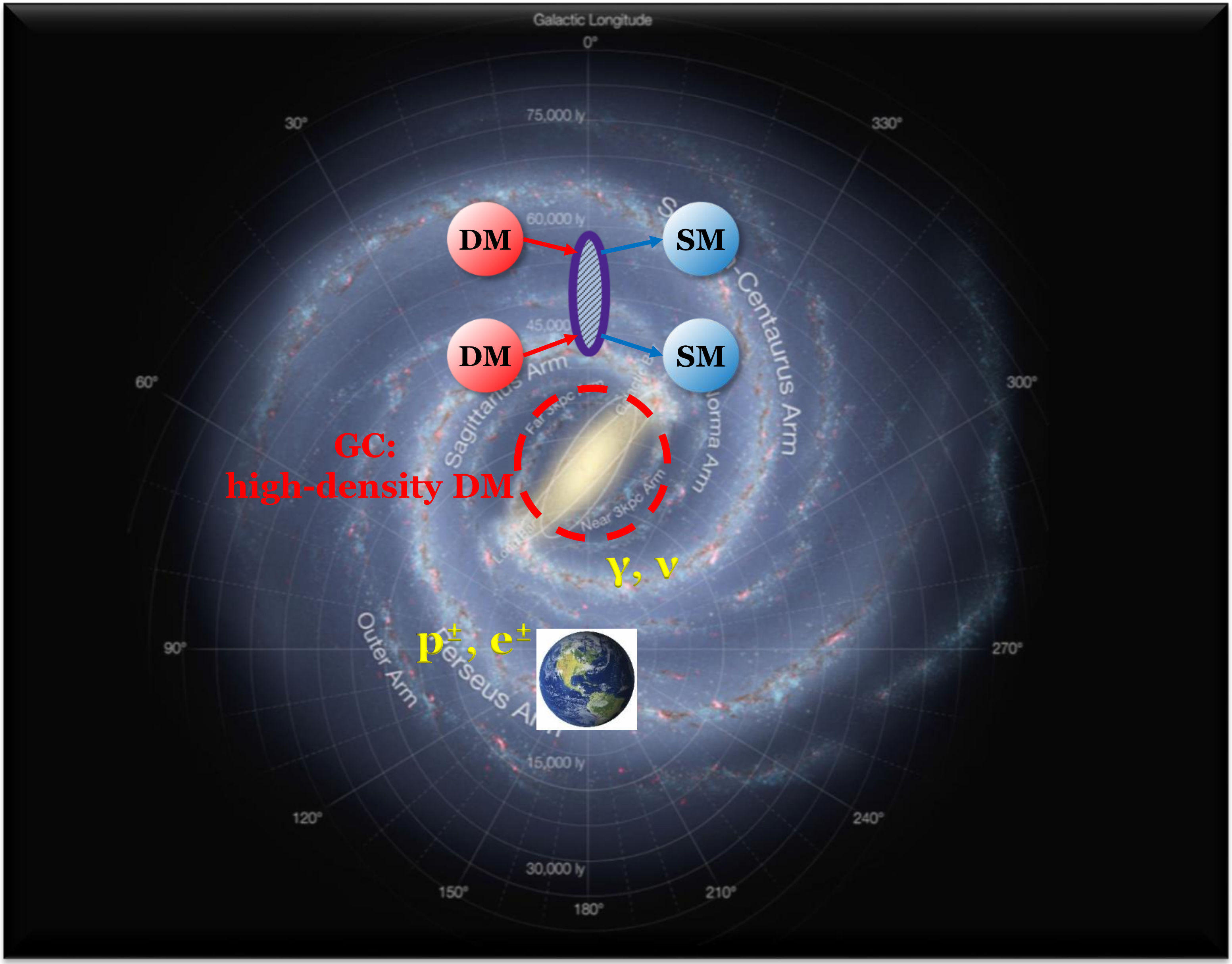
  ✓ Better chance to have the information for extracting DM properties



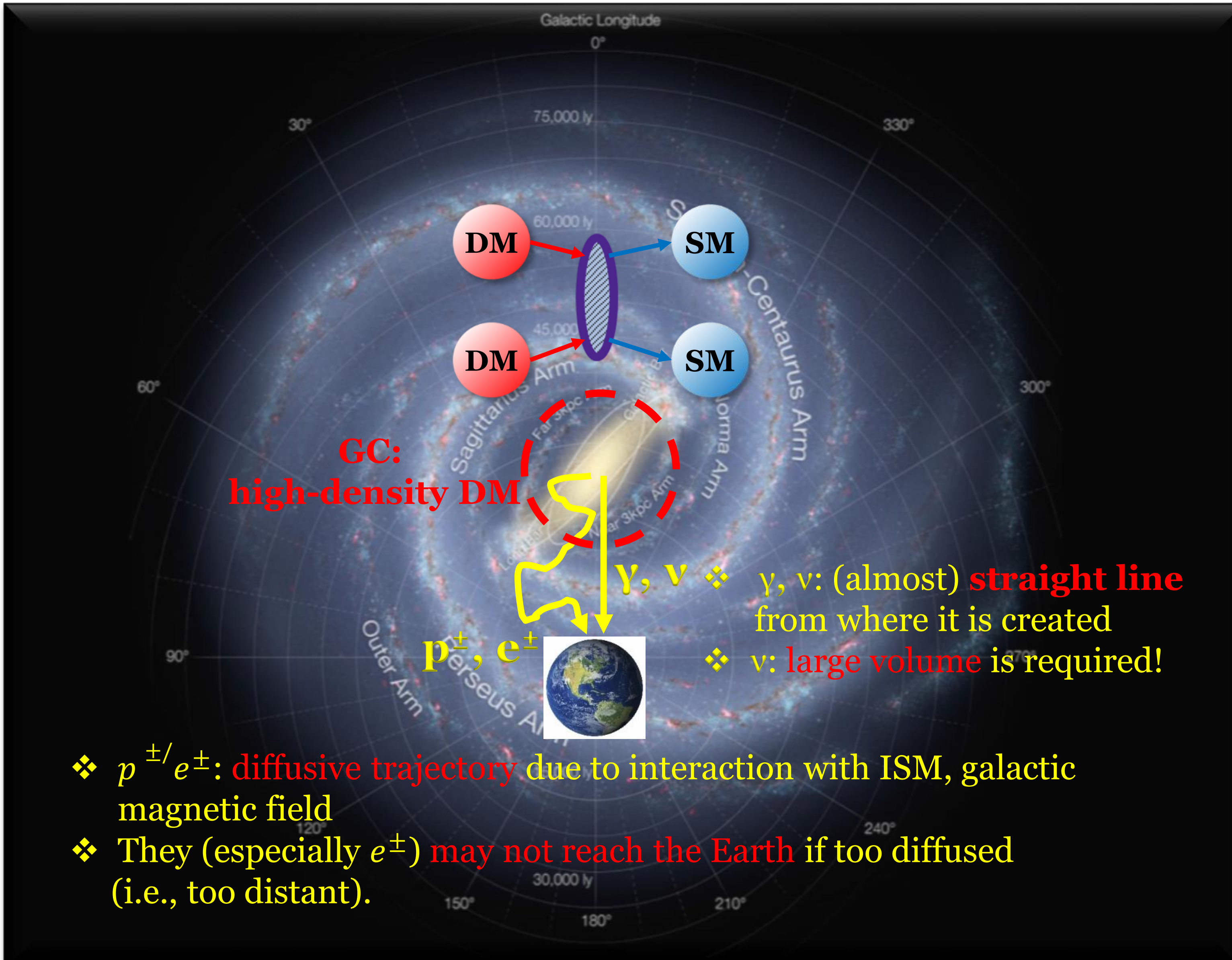





# Indirect Detection: Cosmic Rays

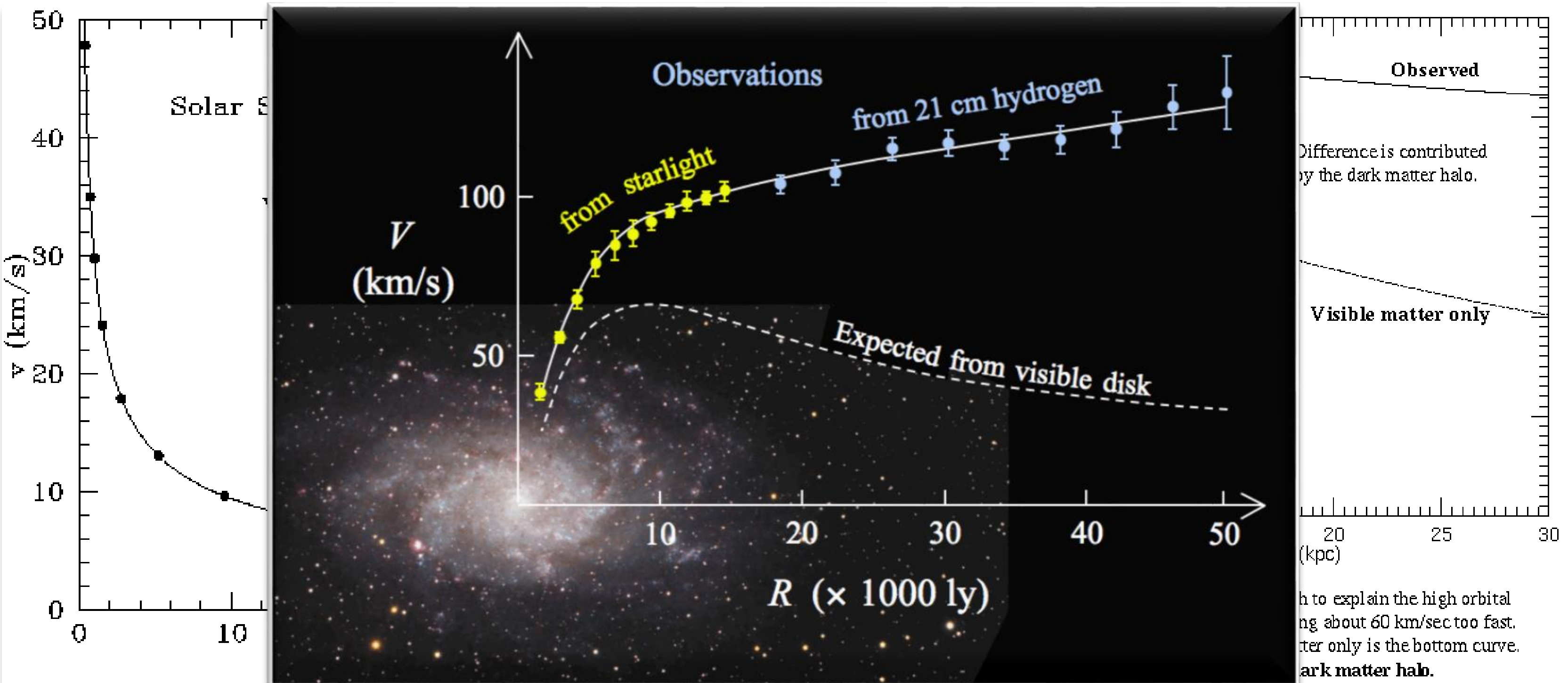


# Indirect Detection: Cosmic Rays




- γ, ν: (almost) **straight line** from where it is created
- ν: large volume is required!
- $p^{\pm}/e^{\pm}$: 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).

# Galaxy Rotation Curve

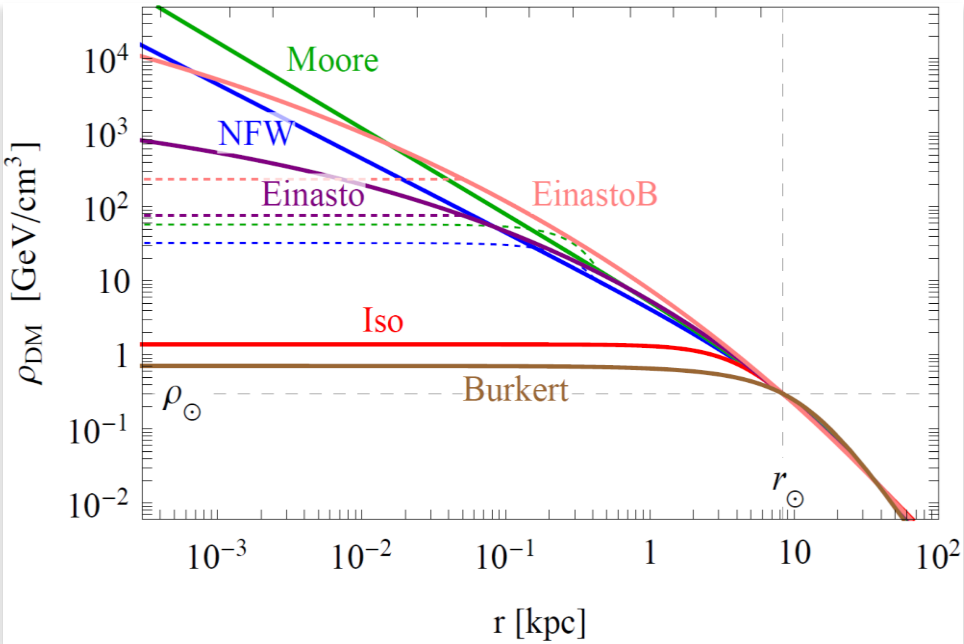



Vera Rubin

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

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

# DM Halo Profiles




$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

| DM halo | $\alpha$ | $r_s$ [kpc] | $\rho_s$ [GeV/cm$^3$] |
|---|---|---|---|
| NFW | – | 24.42 | 0.184 |
| Einasto | 0.17 | 28.44 | 0.033 |
| EinastoB | 0.11 | 35.24 | 0.021 |
| Isothermal | – | 4.38 | 1.387 |
| Burkert | – | 12.67 | 0.712 |
| Moore | – | 30.28 | 0.105 |

# Fluxes at Production: Primary Channels

DM + DM $\Rightarrow$

$$e_L^+e_L^-,\ e_R^+e_R^-,\ \mu_L^+\mu_L^-,\ \mu_R^+\mu_R^-,\ \tau_L^+\tau_L^-,\ \tau_R^+\tau_R^-,$$

$$q\bar{q},\ c\bar{c},\ b\bar{b},\ t\bar{t},\ \gamma\gamma,\ gg,$$

$$W_L^+W_L^-,\ W_T^+W_T^-,\ Z_LZ_L,\ Z_TZ_T,$$

$$hh,$$

$$\nu_e\bar{\nu}_e,\ \nu_\mu\bar{\nu}_\mu,\ \nu_\tau\bar{\nu}_\tau,$$

$$VV\to 4e,\ VV\to 4\mu,\ VV\to 4\tau,$$

- Primary channels (including annihilation amplitudes, relative ratios → $\sigma v_i$): determined by particle physics

- Flux of DM annihilation products: $\Phi \propto \sigma v\, n^2(r)$

  $n(r)$: the number density of a DM particle

# Fluxes at Production: Secondary Channels

DM+DM → Primary channel → Secondary channel

Theoretical model
(+ CalcHEP/MadGraph)

Simulation:
HERWIG/PYTHIA

$e_L^+ e_L^-$, $e_R^+ e_R^-$, $\mu_L^+ \mu_L^-$, $\mu_R^+ \mu_R^-$, $\tau_L^+ \tau_L^-$, $\tau_R^+ \tau_R^-$

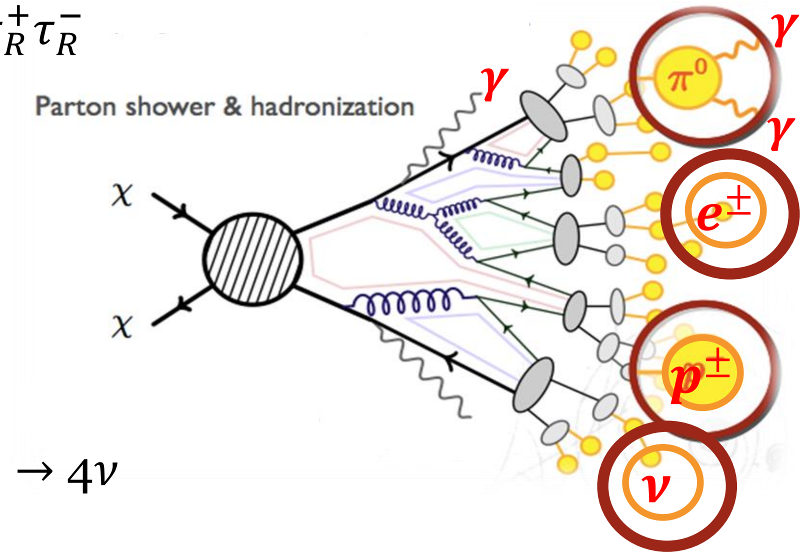
$q\bar{q}$, $c\bar{c}$, $b\bar{b}$, $t\bar{t}$, $\gamma\gamma$, $gg$,

$Z_L Z_L$, $Z_T Z_T$, $W_L^+ W_L^-$, $W_T^+ W_T^-$,

$hh$,

$\nu\bar{\nu}_e$, $\nu\bar{\nu}_\mu$, $\nu\bar{\nu}_\tau$,

$VV \to 4e$, $VV \to 4\mu$, $VV \to 4\tau$, $VV \to 4\nu$



# Final Fluxes

- Cosmic rays from DM annihilation is described by

$$\Phi_i(\psi, E) = \sigma v \frac{\mathrm{d}N_i}{\mathrm{d}E} \frac{1}{8\pi m_{\mathrm{DM}}^2} \int_{\text{line of sight}} \mathrm{d}s\, \rho^2(r(s, \psi))$$

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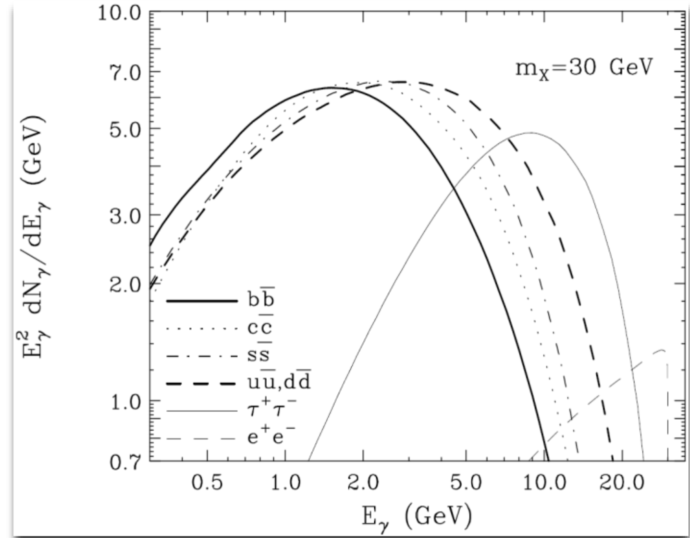
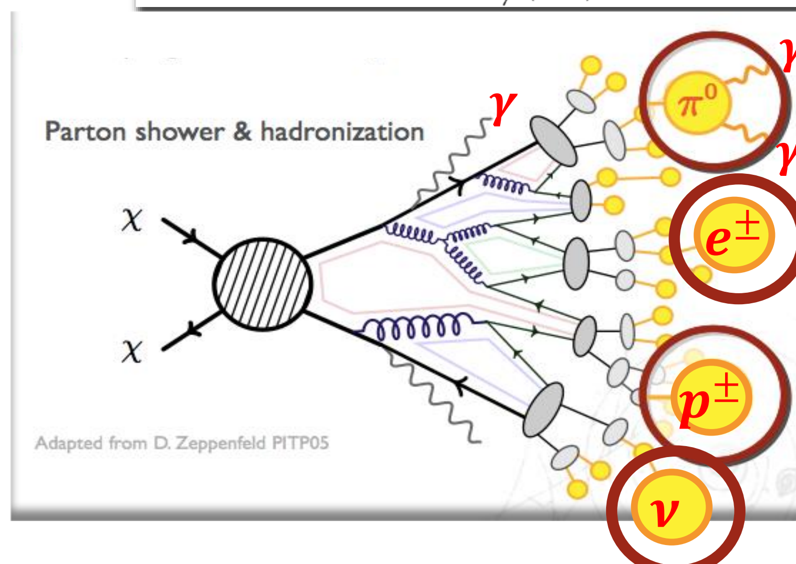
γ, ν, (e±, p±)

γ, ν, e±, p±

1) Shape of spectrum



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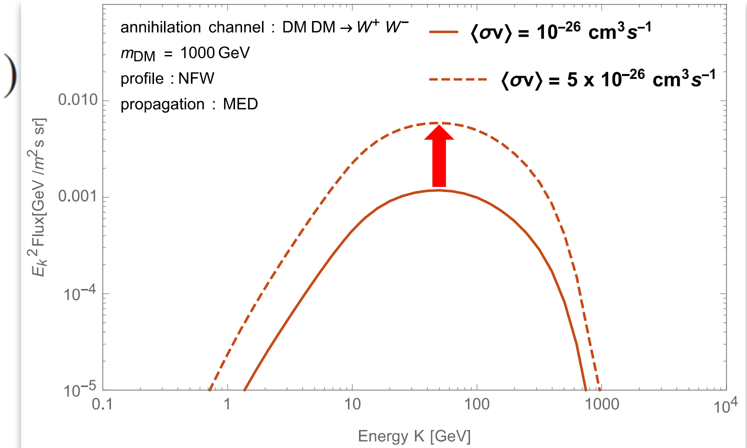
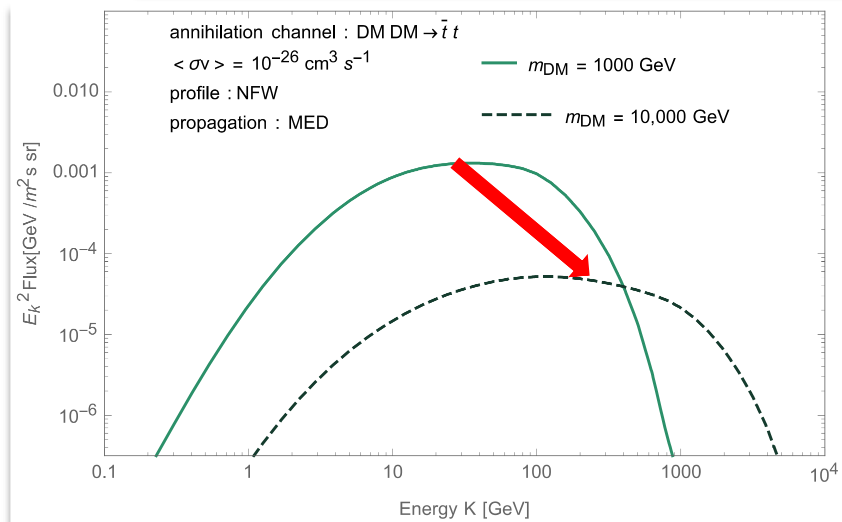
number density of DM
$n_{DM} = \rho_{DM} / m_{DM}$

1) Shape of spectrum

2) Normalization of the signal



# Final Fluxes: $\gamma, \nu$

❖ Cosmic rays from DM annihilation is described by

$$\Phi_i(\psi, E) = \sigma v \frac{\mathrm{d}N_i}{\mathrm{d}E} \frac{1}{8\pi m_{\mathrm{DM}}^2} \int_{\text{line of sight}} \mathrm{d}s\, \rho^2(r(s,\psi))$$

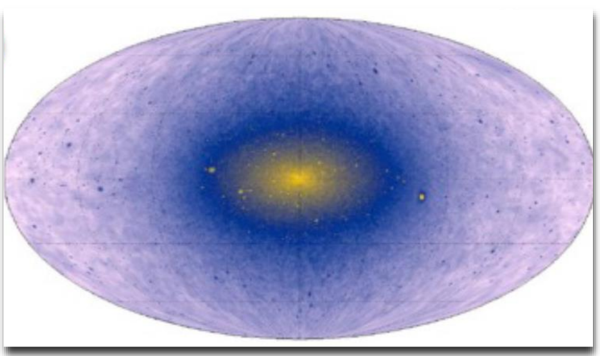
number density of DM
$n_{\mathrm{DM}} = \rho_{\mathrm{DM}}/m_{\mathrm{DM}}$

1) Shape of spectrum

2) Normalization of the signal

$\gamma, \nu$

3) $\gamma, \nu$: Signal concentrated around the GC, Spherical symmetry, Morphology determined by the DM distribution



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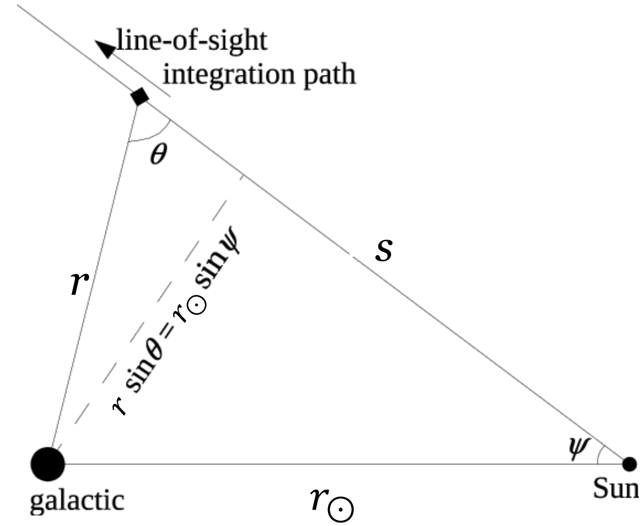


number density of DM
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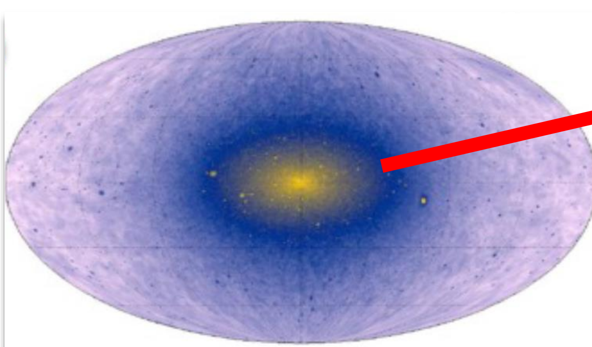
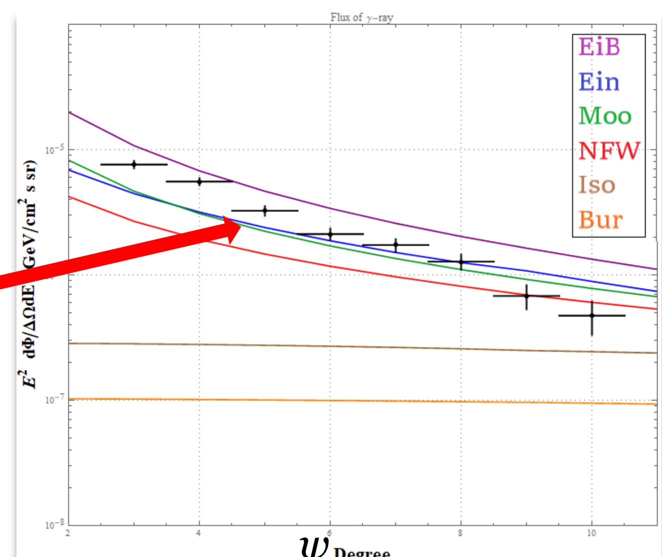
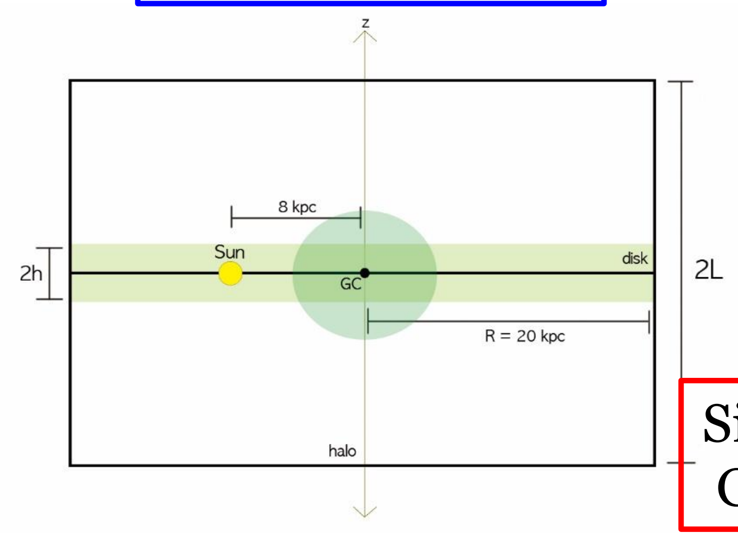




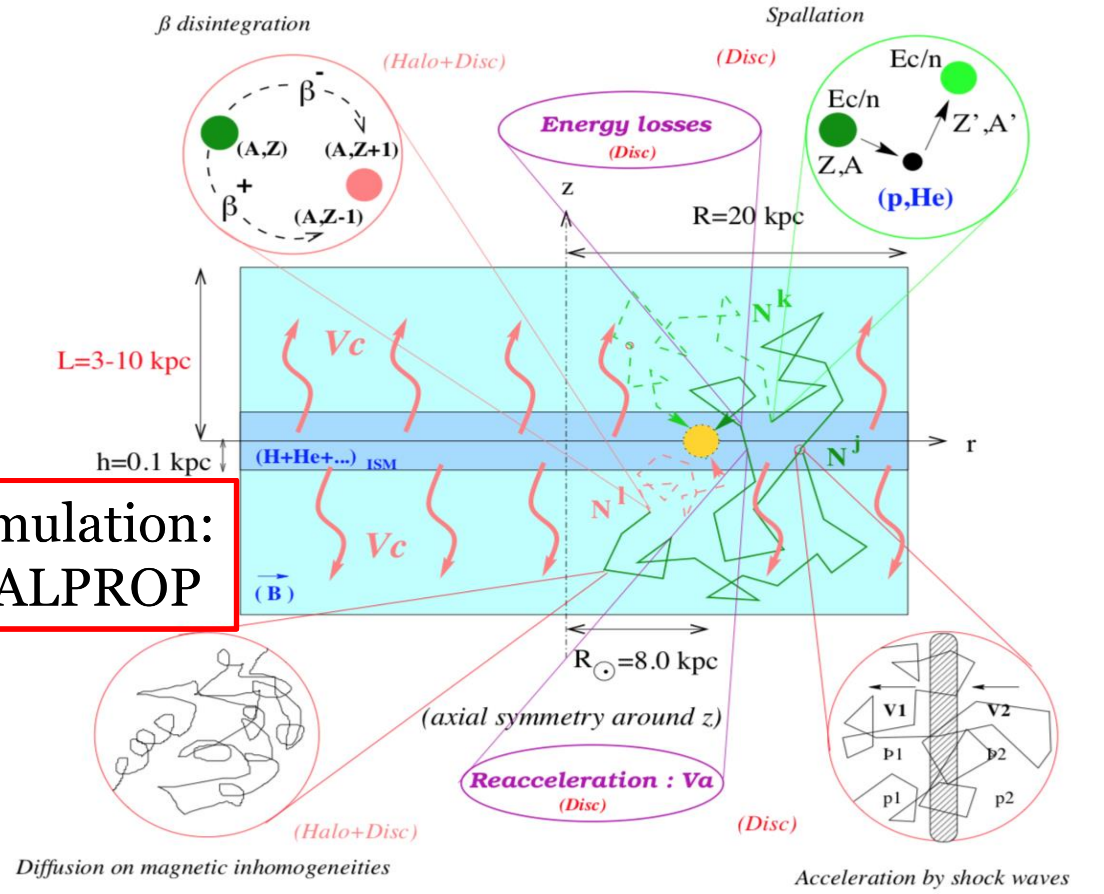

Life is not easy for
any for us.
Marie Curie
quotefancy

# Propagation of Charged Particles

Diffusion zone




Simulation: GALPROP



# Hints from Cosmic-Rays?

❖ DM signatures in cosmic-ray observations?

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

# Hints from Cosmic-Rays?

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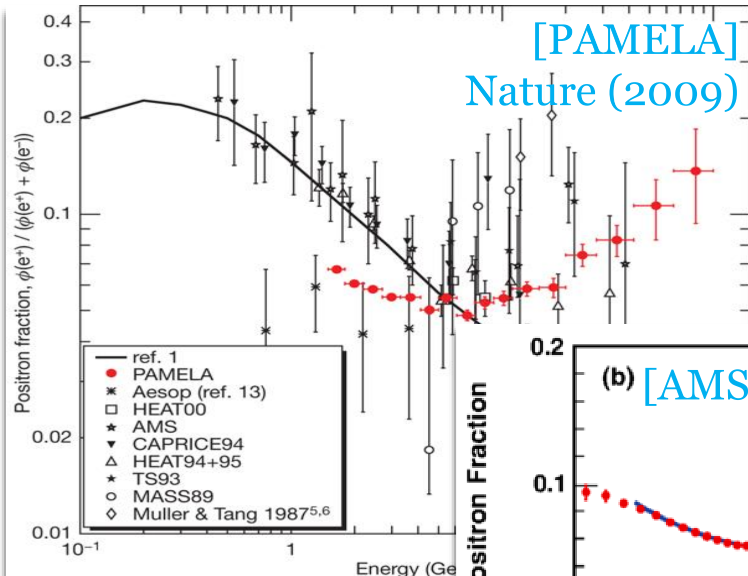
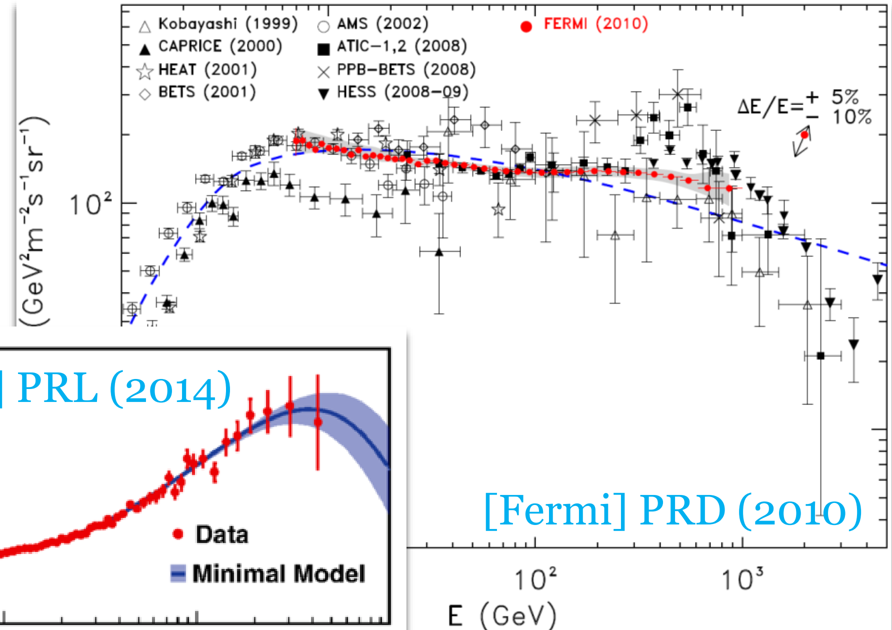
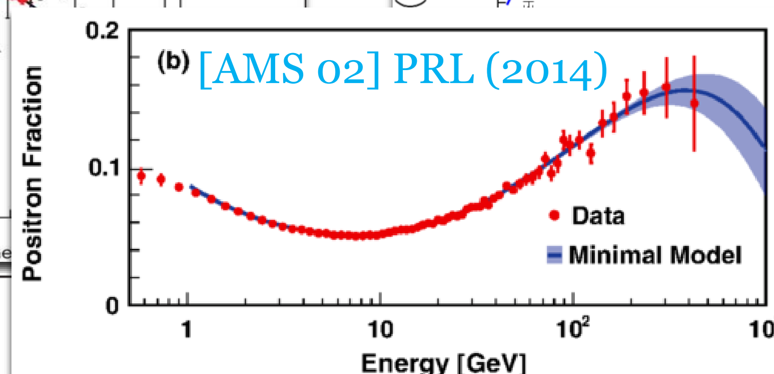
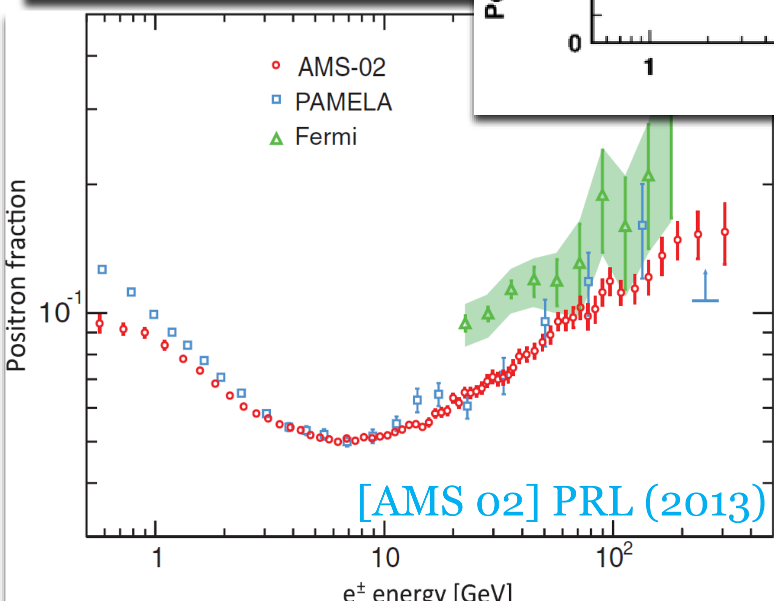
- XMM-Newton (X-ray): 3.5 keV line
- IceCube ($\nu$): PeV events
- …

# DM Indirectly Detected? ($e^{\pm}$)



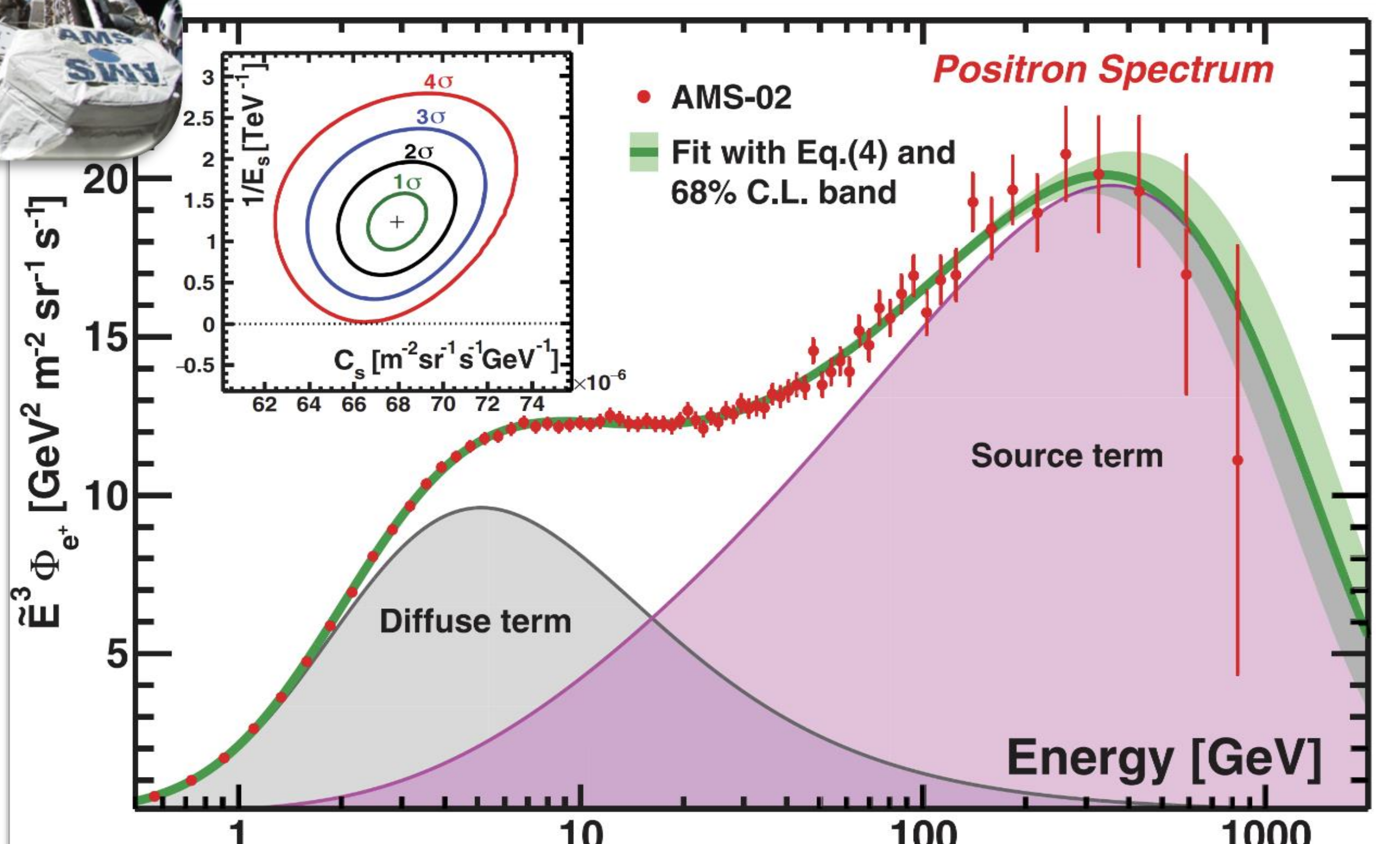




❖ PAMELA, Fermi-LAT, AMS-02:

➔ Excess in $e^{+}/e^{-}$ fraction and $e^{+}+e^{-}$ flux

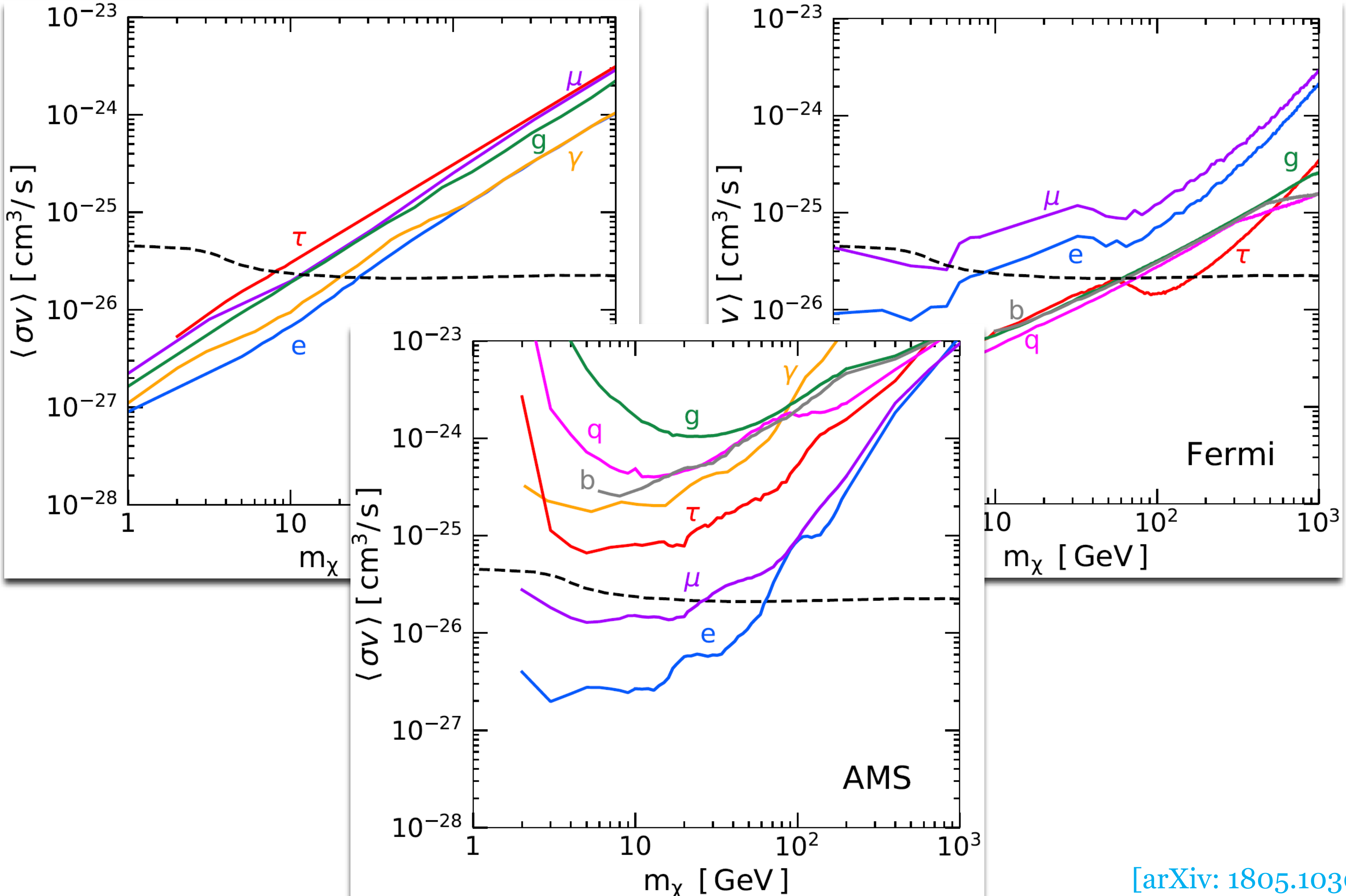
❖ Require new sources of $e^{+}$ & $e^{-}$

# e+ Excesses: AMS-02


[AMS 02] PRL (2019)

# Status of Indirect Searches

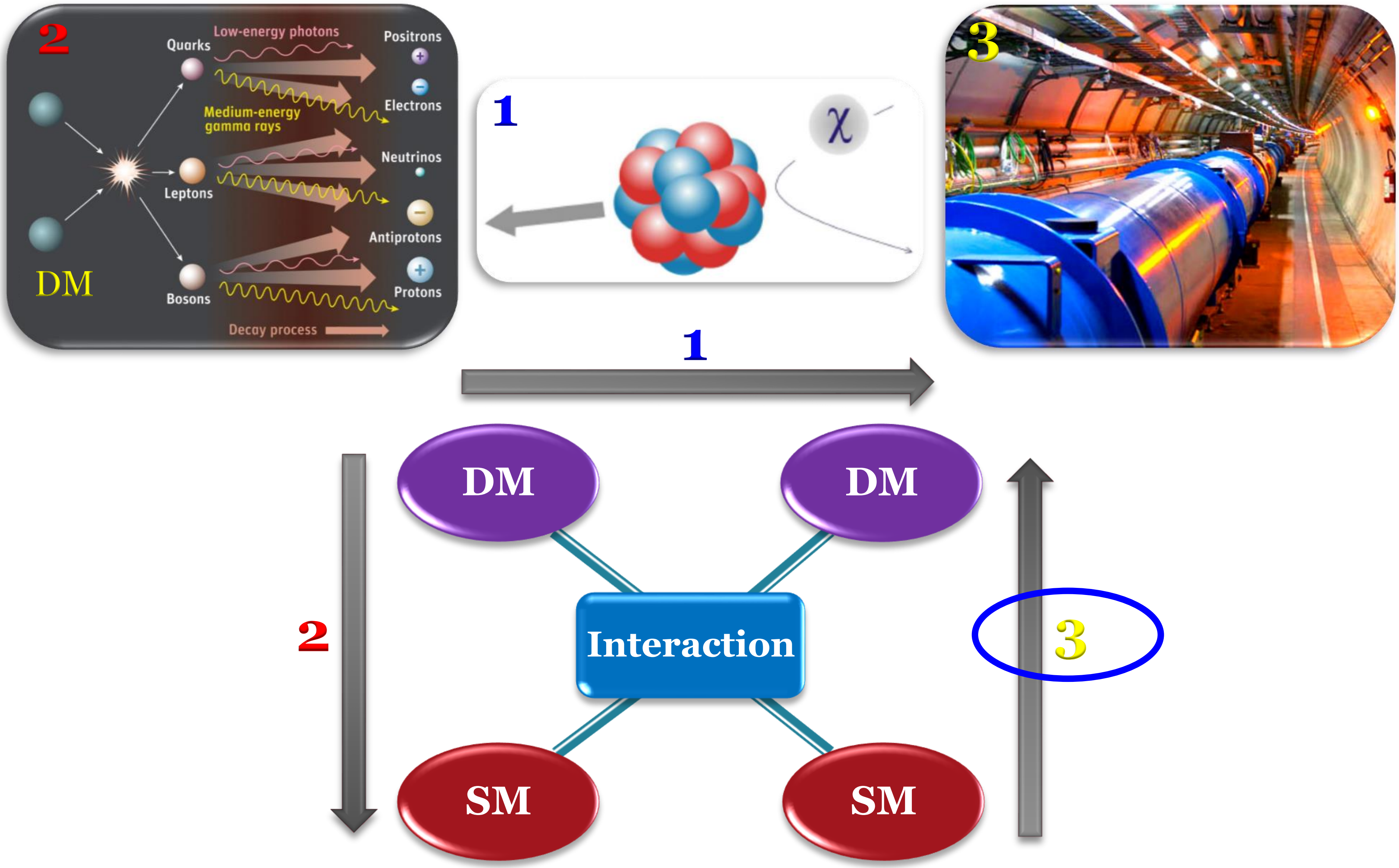



[arXiv: 1805.10305]

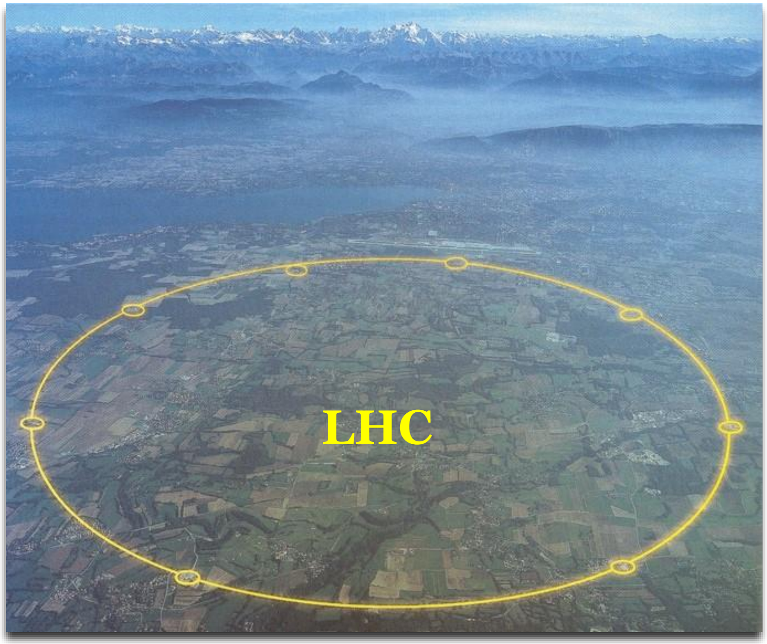
# 5. Collider

# Direct Production

# DM Production @ Colliders



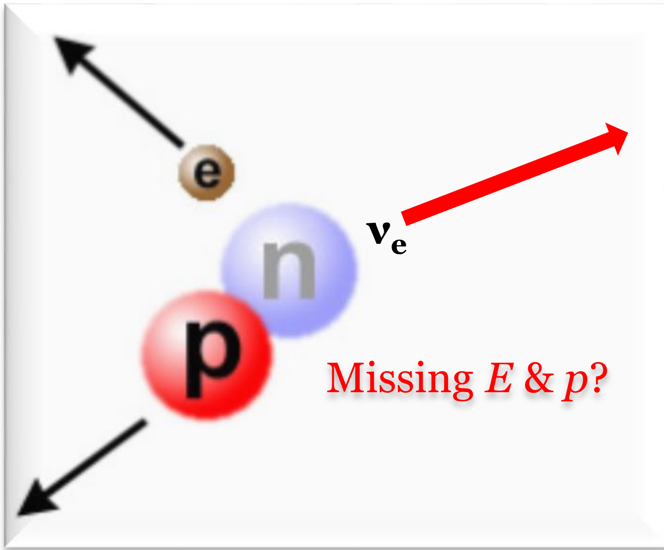
# Collider Physics

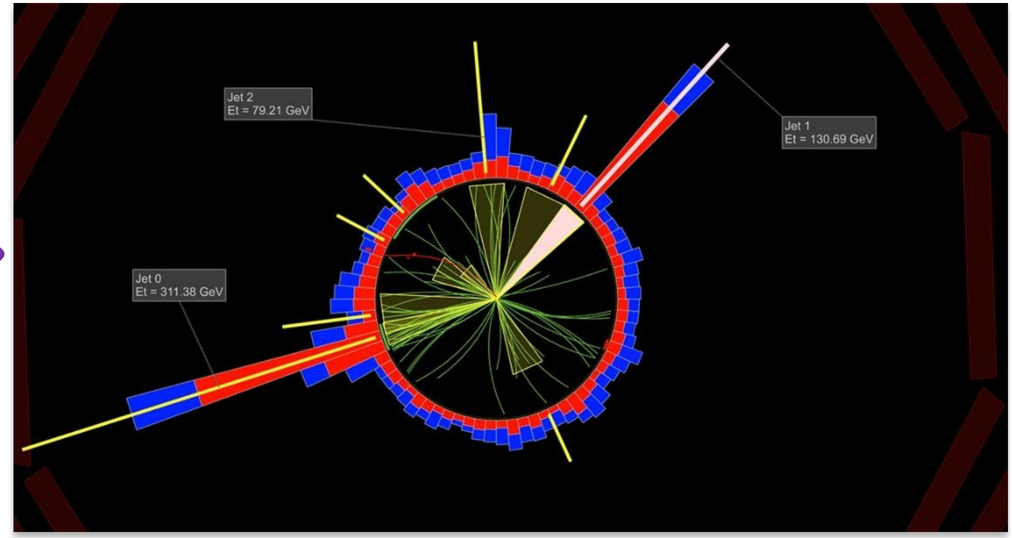




- Production of heavy particles (e.g. super-partner, *Z'*, *t'*, B, ...) ← E=mc²
- LHC Run I, Belle I: no conclusive evidence of DM yet
- LHC Run II (13 TeV), Belle II (high luminosity): have been upgraded & now running!

# DM at Colliders

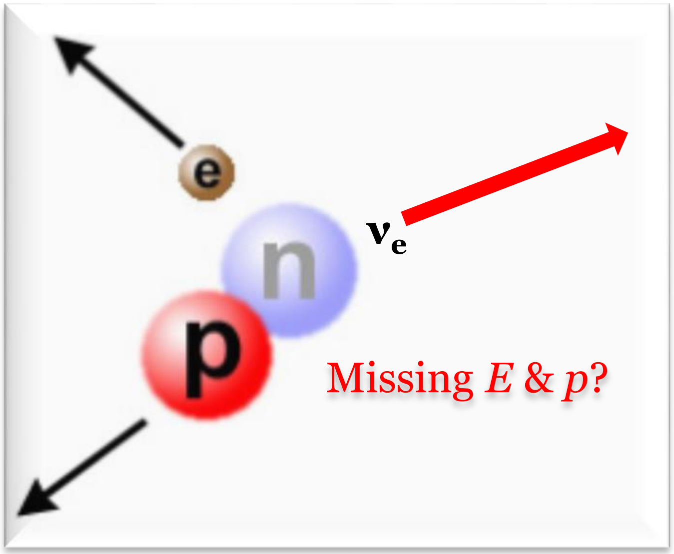


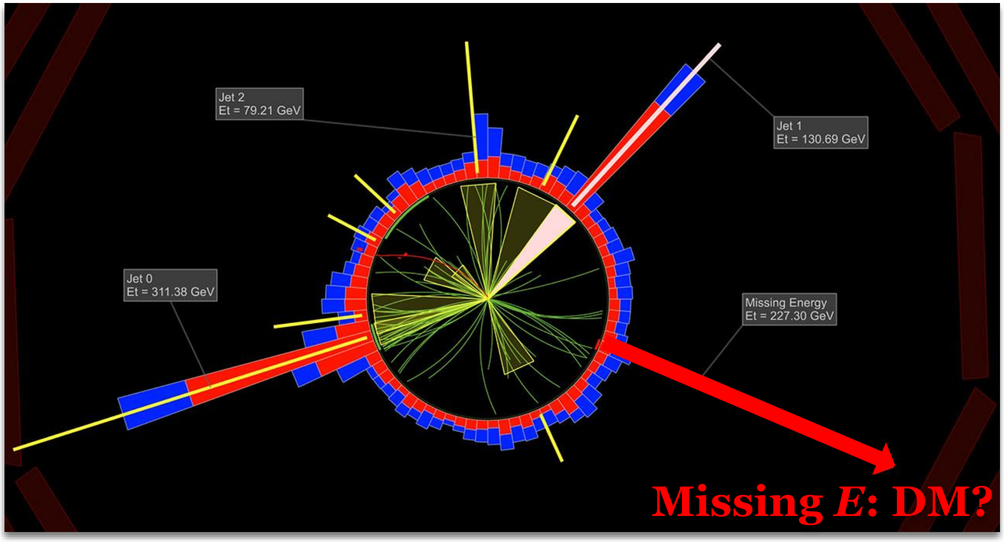



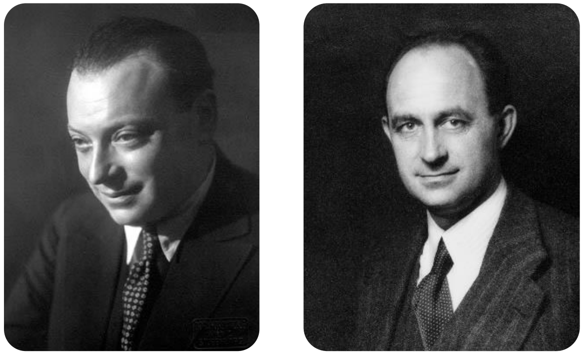

Pauli(1930) Fermi(1932)

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

# DM at Colliders



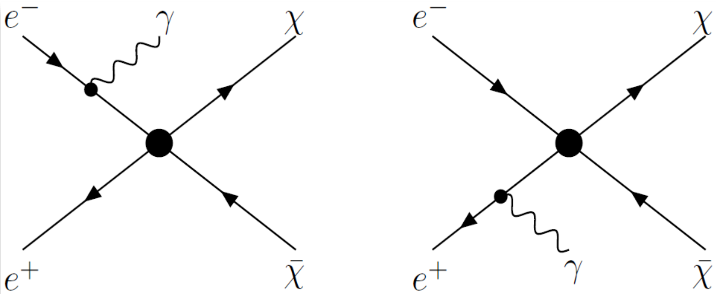



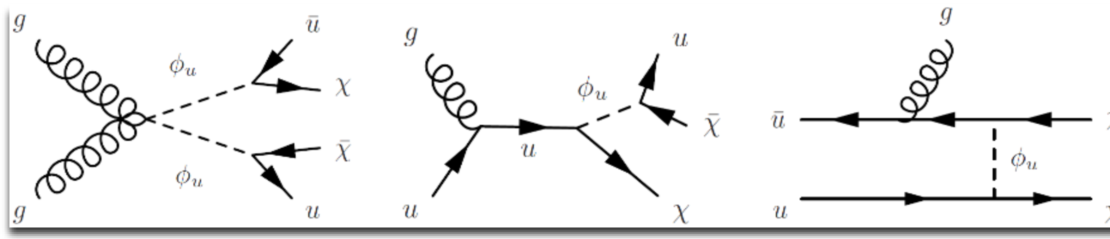
Pauli(1930) Fermi(1932)

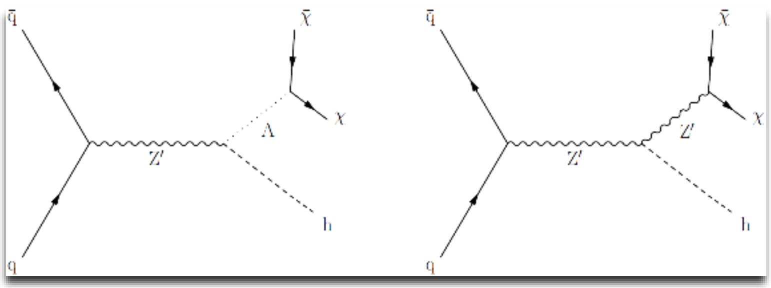
- ν: to explain Missing *E*, *p*, *S* in the beta decay
- Nature(1934): "Too remote from reality!"
- DM cannot be directly detected

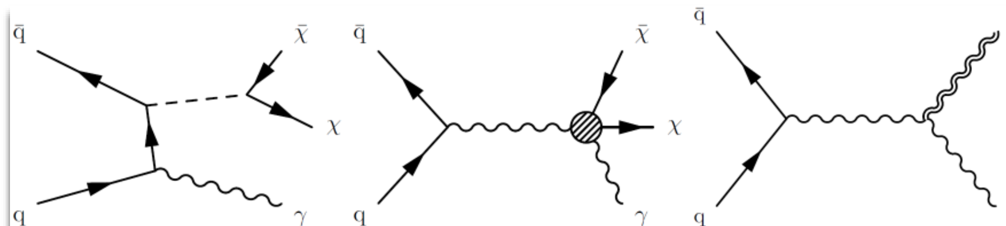
  → regarded as Missing *E*

# Collider Searches



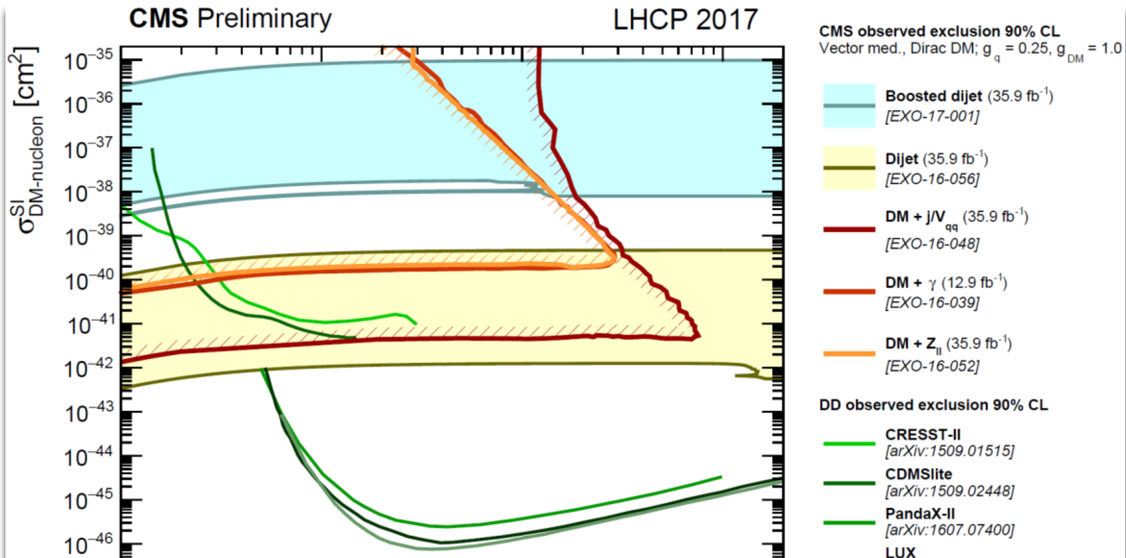



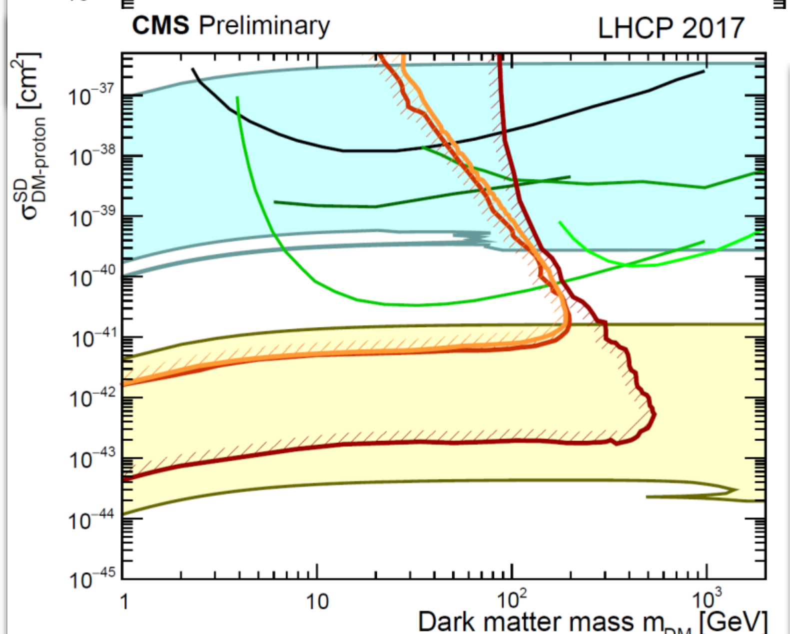



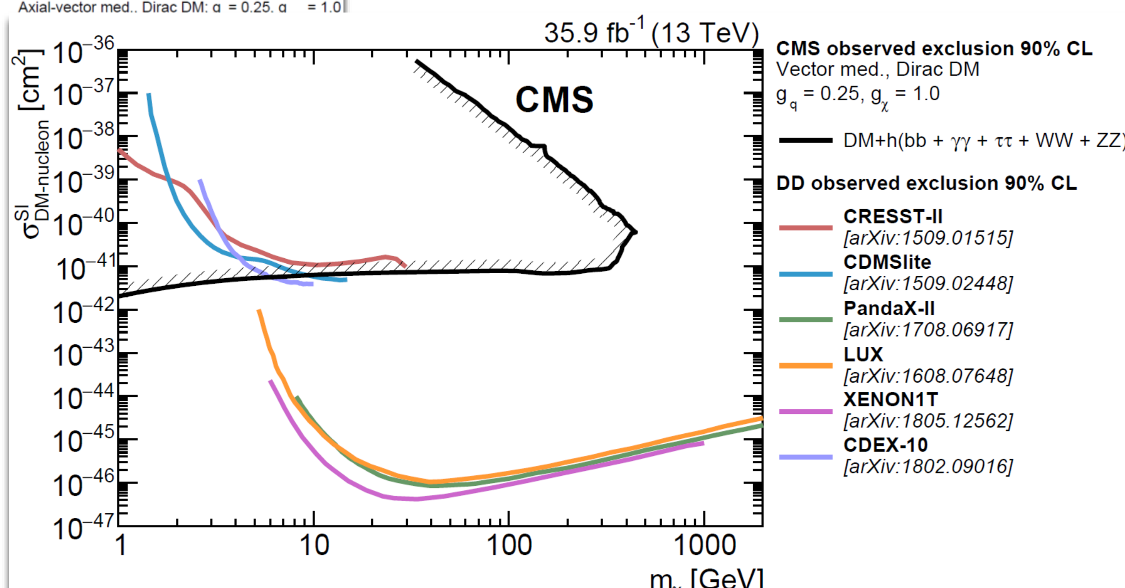

- LEP/ILC/Belle II/LHC/…: mono-X+$E_T$
  → limits on $\sigma_{\chi\text{-}e/N}$ & $\langle\sigma v\rangle_{\chi\chi\to ll,\, qq,\, \ldots}$

**Constraints on DM models**

# Current Status of LHC Searches



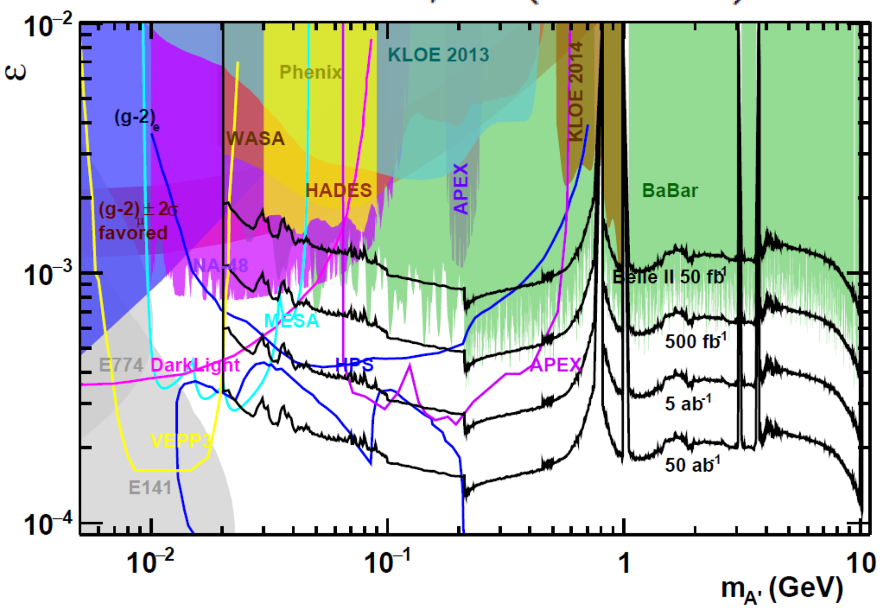



# Dark Photon in Belle II

## Prospects with Belle II

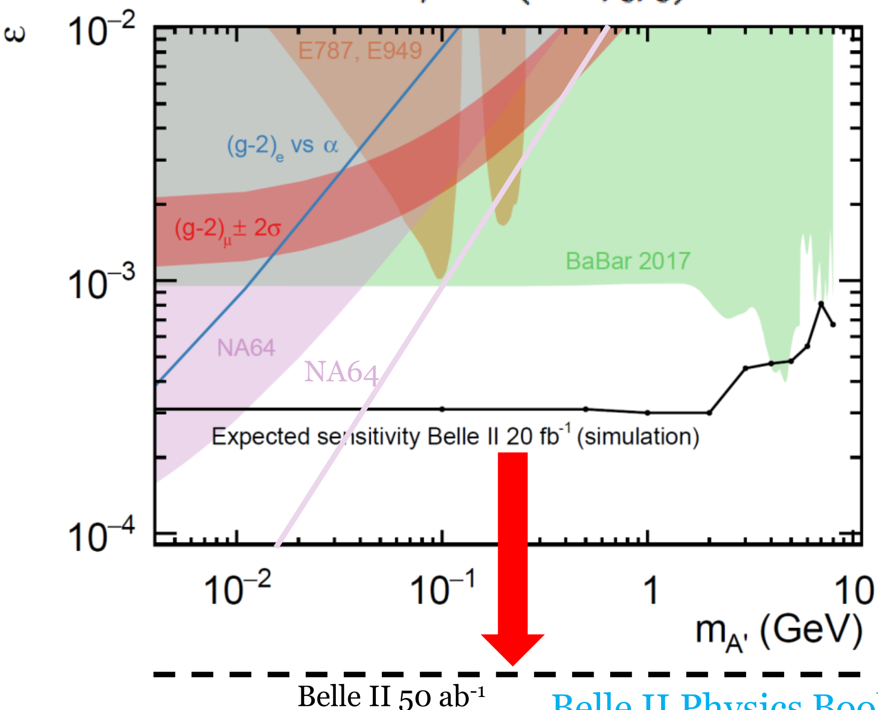
$m_X < 2m_{DM}$

$e^+e^- \to \gamma\, A'(\to \ell^+\ell^-)$




$m_X > 2m_{DM}$

$e^+e^- \to \gamma\, A'(\to \chi\bar{\chi})$




Belle II Physics Book
[arXiv: 1808.10567]

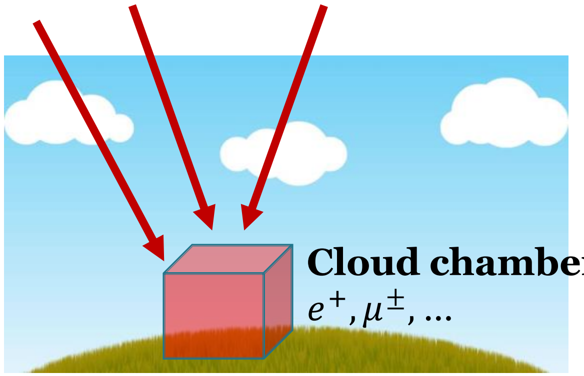
Something New?

# 6. New Approaches

# Fixed Target
# (Beam Dump)

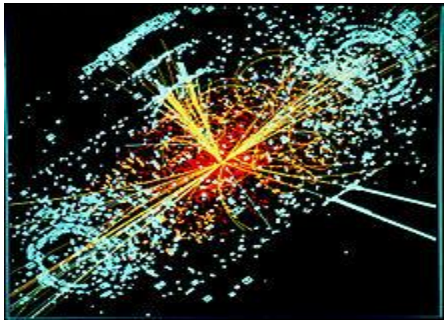
# Particle Searches: Passive → Active

~5% visible sector



**Cloud chamber:**
$e^+, \mu^\pm, \ldots$

**Collider:** controlled environment

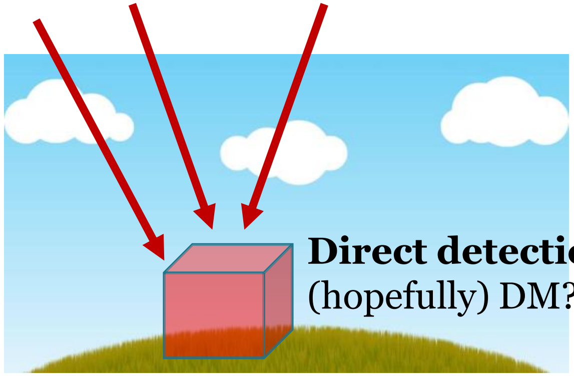


**Conventional colliders**

- ❑ Head-on collision of light SM-sector (stable) particles
- ❑ to produce heavier SM states
- ❑ and study resulting pheno.

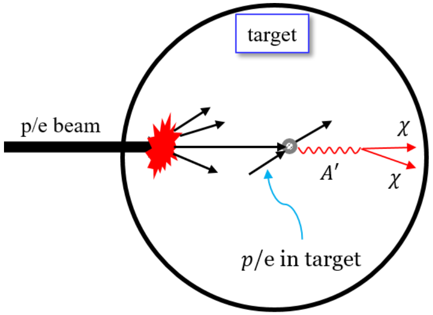
**Passive searches** **Active searches**

~25% dark sector



**Direct detection:**
(hopefully) DM?

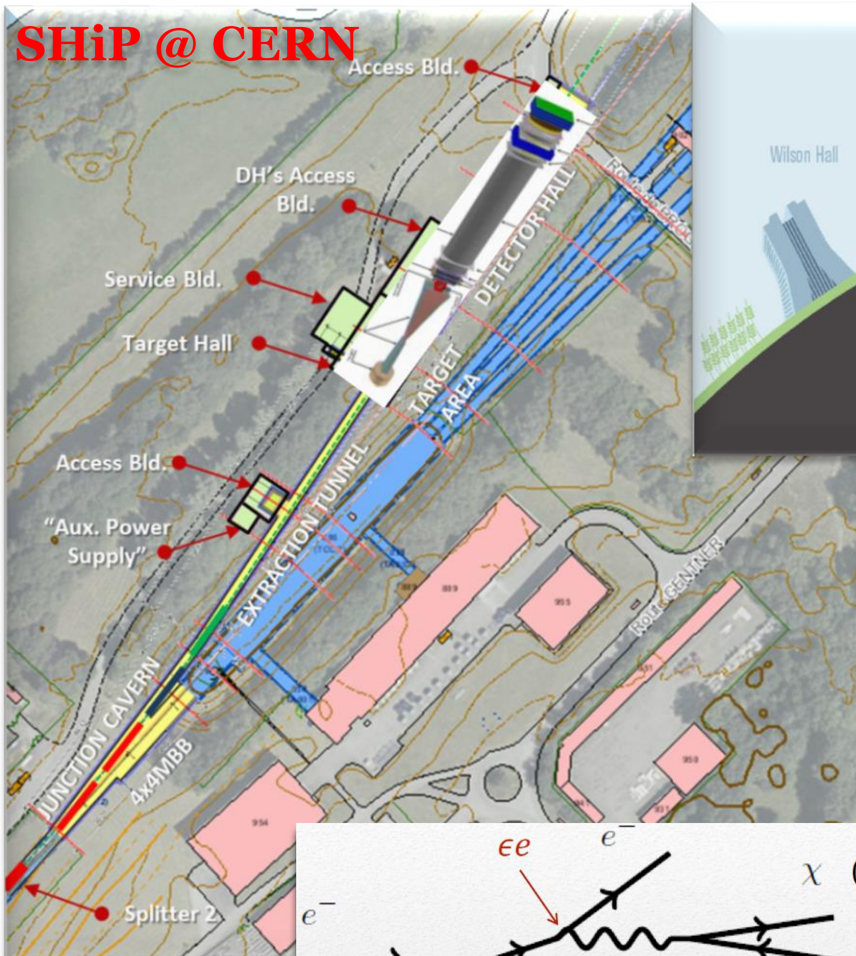
**DM "Production"** (e.g. fixed target exp.)
**:** controlled environment

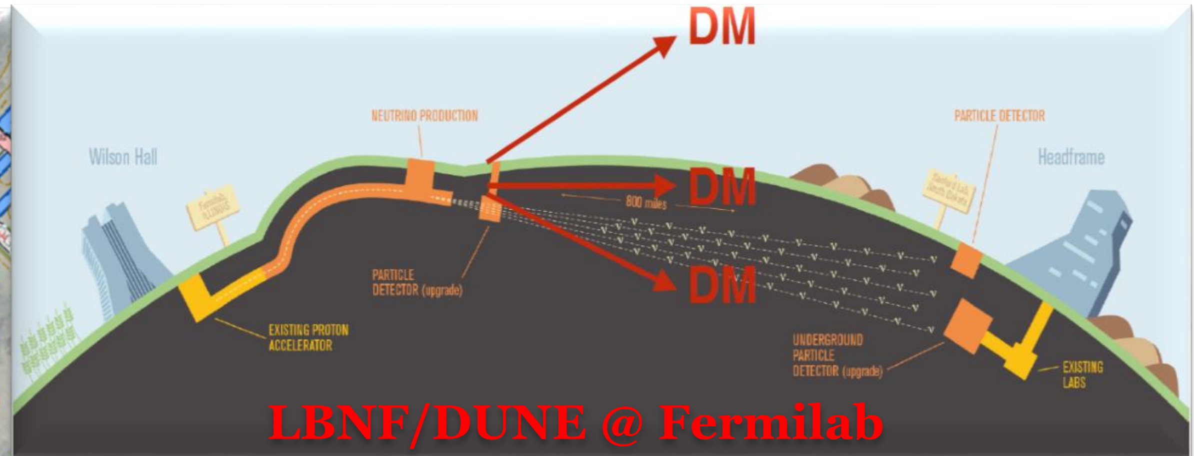


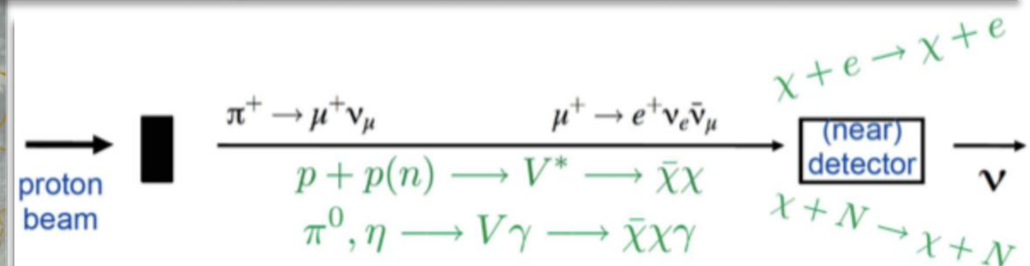

**Dark matter productions**

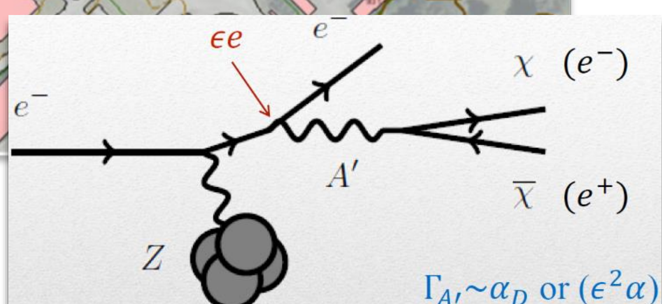
- ❑ Dump of SM-sector (stable) particles onto a target
- ❑ to produce dark-sector states
- ❑ and study resulting pheno.

# DM @ Fixed Target Experiments



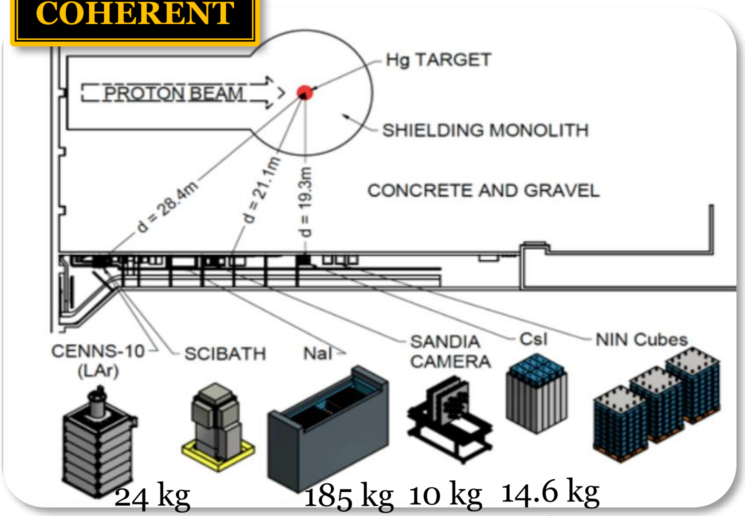




- p/e beam dump ➔ $Z'$, DM production
- Original purpose: $\nu$ production (not all)
- Exps.: JSNS²/T2HK(J-PARC), NOVA/MicroBooNE/DUNE(Fermilab), PEX/HPS/DarkLight/BDX (J-Lab), COHERENT, CCM, SHiP(CERN), ...

# Benchmark Experiments

Low E, High luminosity, Pulsed beam

**COHERENT**



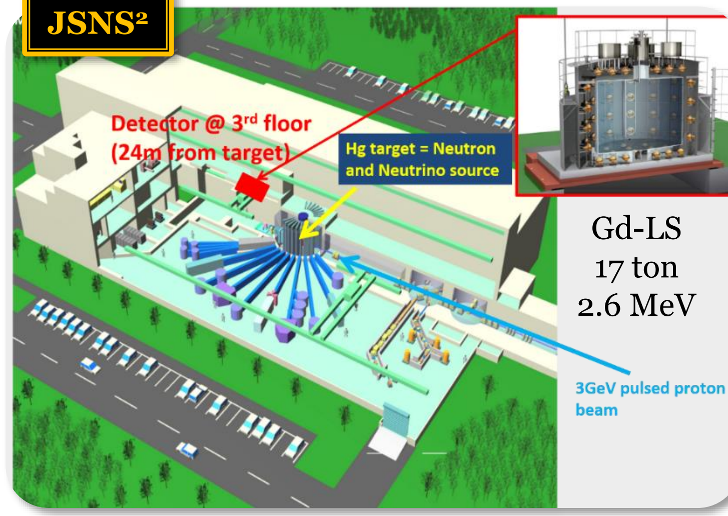

24 kg
20 keV

185 kg
13 keV

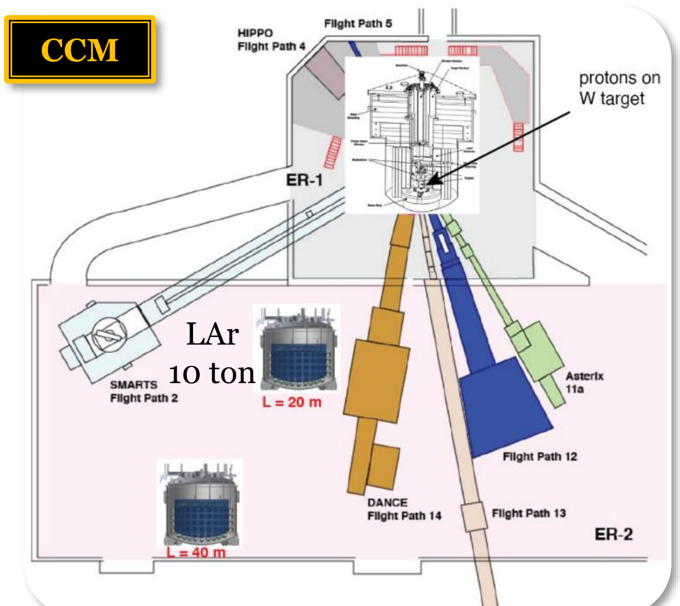
10 kg
5 keV

14.6 kg
6.5 keV

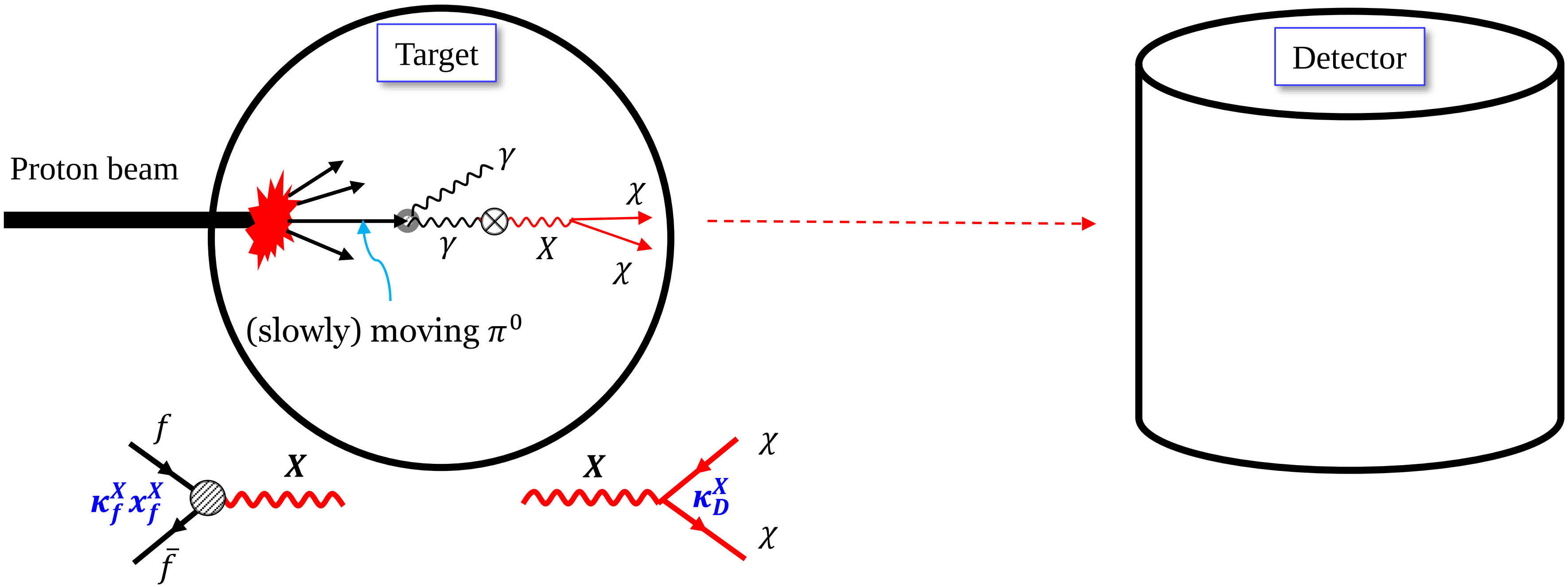
**JSNS²**




**CCM**



# Dark Matter Production I



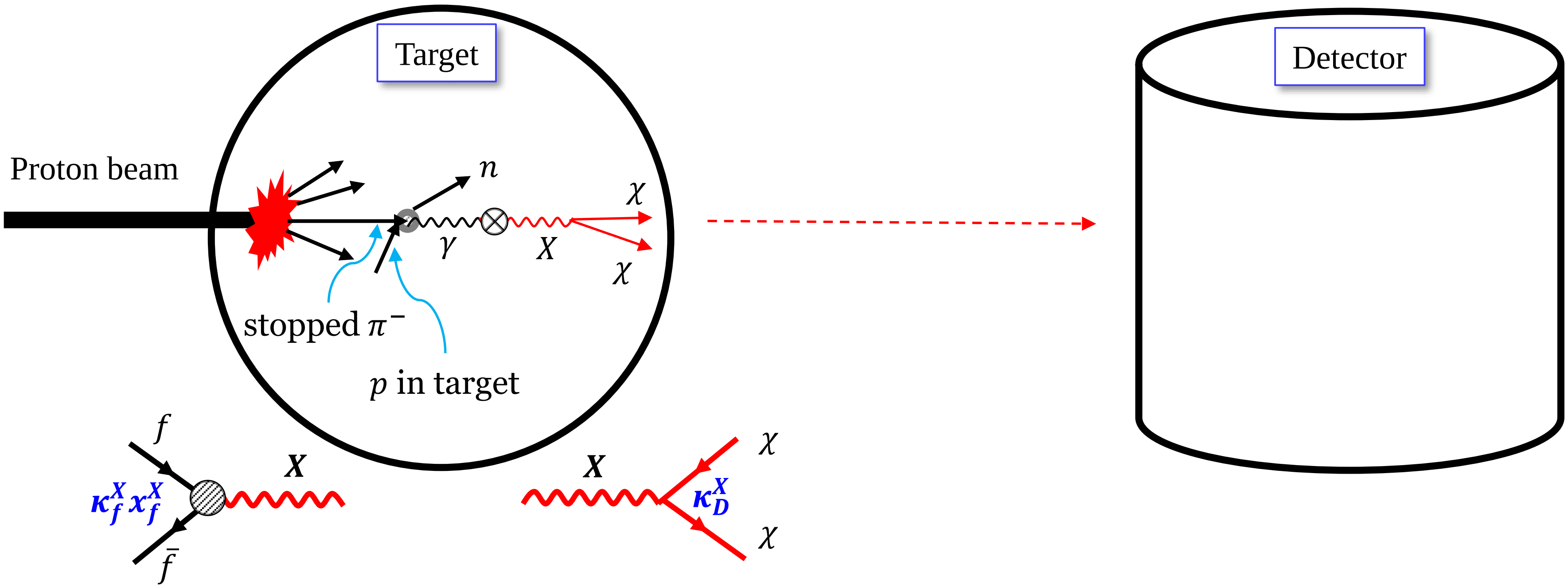

$$\mathcal{L}_{X,\text{prod}} \supset \sum_f \kappa_f^X x_f^X X_\mu \bar{f}\gamma^\mu f + \kappa_D^X X_\mu \bar{\chi}\gamma^\mu \chi$$

❖ Meson decays (P1): $\pi^0(\eta) \to \gamma + \gamma/\boldsymbol{X}$

✓ For example,

$\kappa_f^X x_f^X \to Q_f\ e\epsilon$ for the dark photon scenario

# Dark Matter Production II

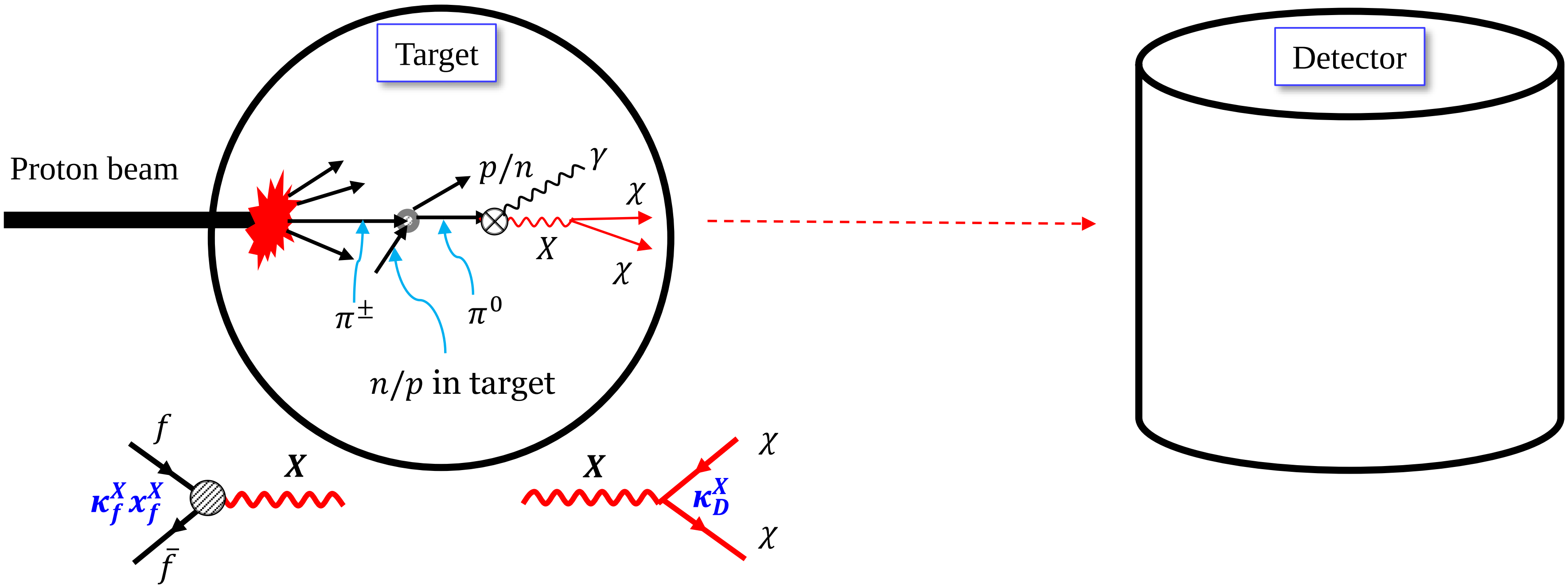



$$\mathcal{L}_{X,\mathrm{prod}} \supset \sum_f \kappa_f^X x_f^X X_\mu \bar{f} \gamma^\mu f + \kappa_D^X X_\mu \bar{\chi} \gamma^\mu \chi$$

- $\pi^-$ capture (Panofsky) process (P2): $\pi^- + p \to n + \gamma/\boldsymbol{X}$ ($X$: single-valued E)

> ✓ For example,
>
> $\kappa_f^X x_f^X \to Q_f\ e\epsilon$ for the dark photon scenario

# Dark Matter Production III



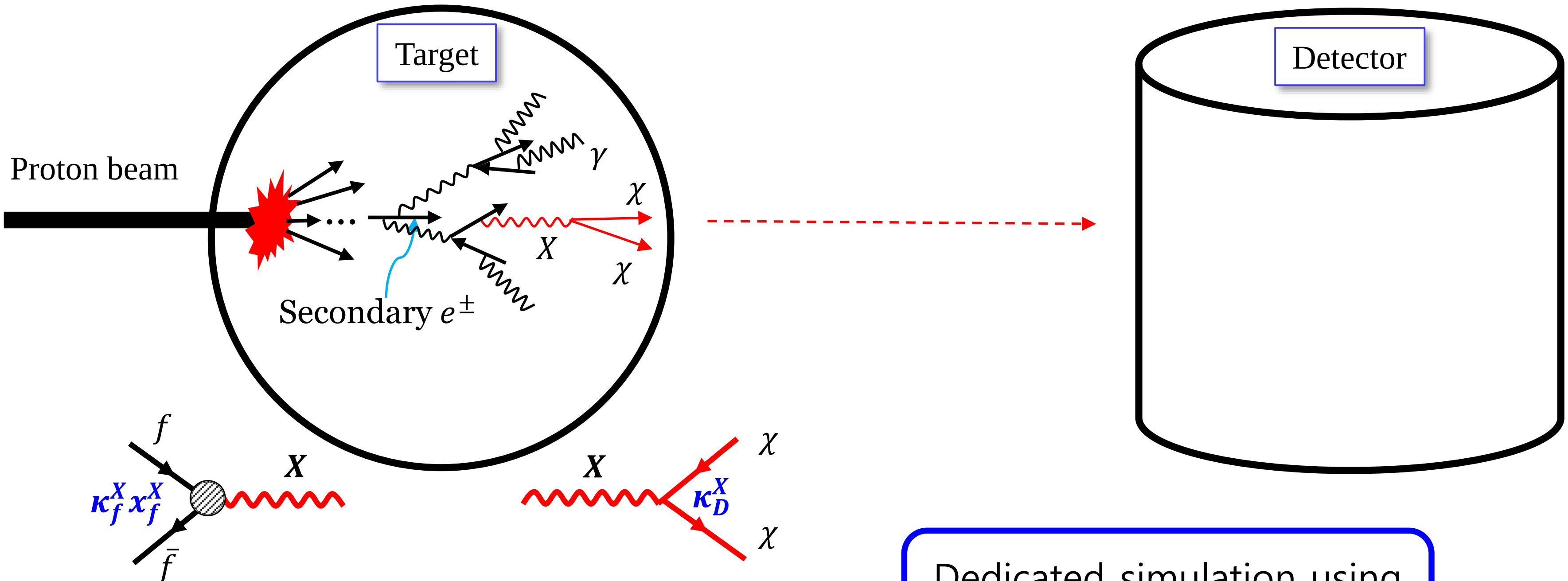

$$\mathcal{L}_{X,\mathrm{prod}} \supset \sum_f \kappa_f^X x_f^X X_\mu \bar{f}\gamma^\mu f + \kappa_D^X X_\mu \bar{\chi}\gamma^\mu \chi$$

❖ Charge exchange processes (P3): $\pi^{-(+)} + p(n) \to n(p) + \pi^0$ & $\pi^0 \to \gamma + \gamma/\boldsymbol{X}$

✓ For example,

$\kappa_f^X x_f^X \to Q_f\ e\epsilon$ for the dark photon scenario

# Dark Matter Production IV




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

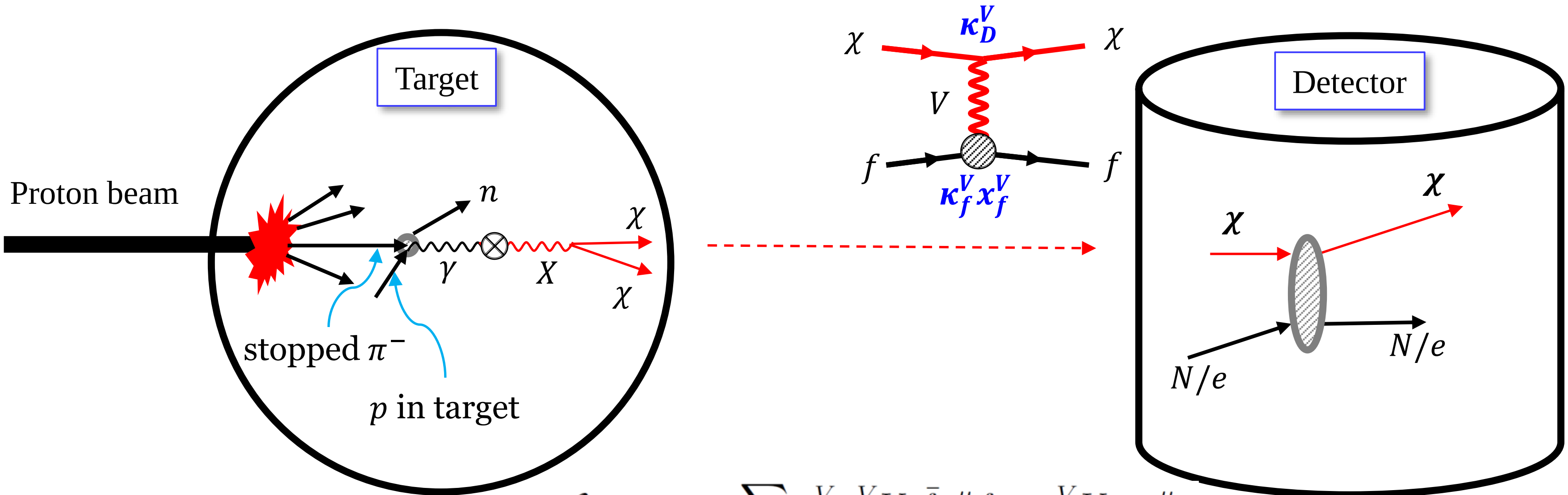
Dedicated simulation using e.g. GEANT4 is needed!

- $e^{\pm}$-induced cascade (P4): electromagnetic cascade showering & $\gamma \to \boldsymbol{X}$

✓ For example,

$\kappa_f^X x_f^X \to Q_f\ e\epsilon$ for the dark photon scenario

# Dark Matter Detection




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

❖ Nucleus scattering (D1): small $E_r$ (< MeV) ➔ COHERENT, CCM

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

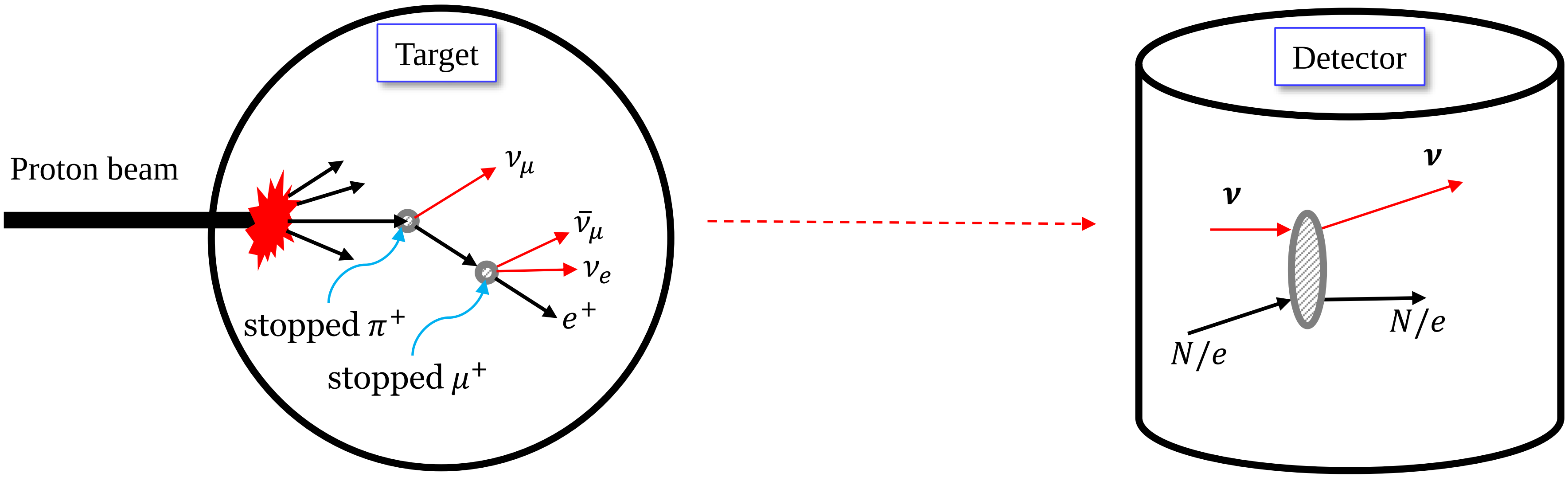
$F_V$: form factor, $E_\chi$: E of incoming DM, $E_{r,N}$: recoil kinetic E of target nucleus
$m_N$: mass of target nucleus, $m_V$: mass of a mediator

❖ Electron scattering (D2): large $E_r$ (> MeV) ➔ JSNS2

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

$E_{r,e}$: recoil kinetic E of target electron
$m_e$: mass of target electron
$Z$: atomic number
$s = m_e^2 + 2E_\chi m_e + m_\chi^2$
$\lambda(x,y,z) = (x-y-z)^2 - 4yz$

# Backgrounds?




❖ Prompt neutrinos from the decay of stopped (positively)-charged pions (kaons → minor)

✓ Mean life time of $\pi^+ = 2.6 \times 10^{-8}$s $\ll \mu$s.

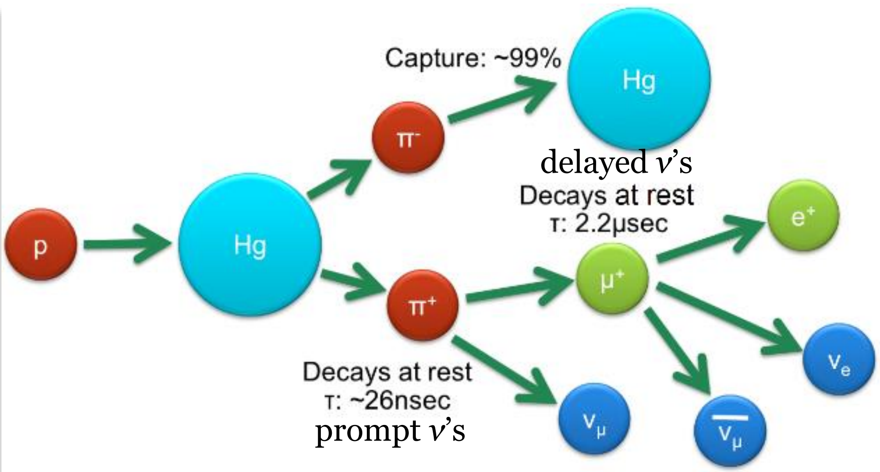
✓ Neutrino E is single-valued ($E_\nu = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$~30 MeV) → ***E*-cut**

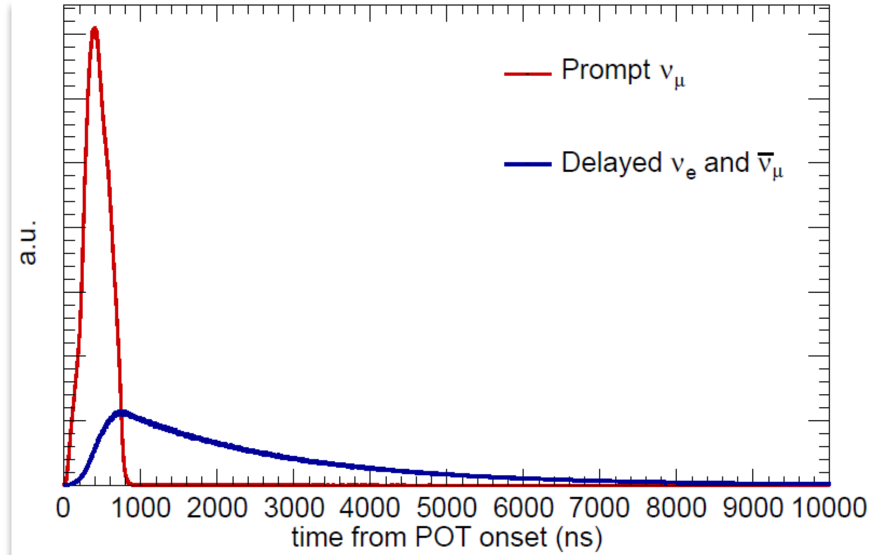
❖ Delayed neutrinos from the decay of stopped muons

✓ Mean life time of $\mu^+ = 2.2 \times 10^{-6}$s $> \mu$s → ***t*-cut**

✓ Neutrinos are more energetic than prompt neutrinos ($E_\nu^{\max} = \frac{m_\mu^2 - m_e^2}{2m_\mu}$).

# Backgrounds: $E/t$-Spectra of $\nu$



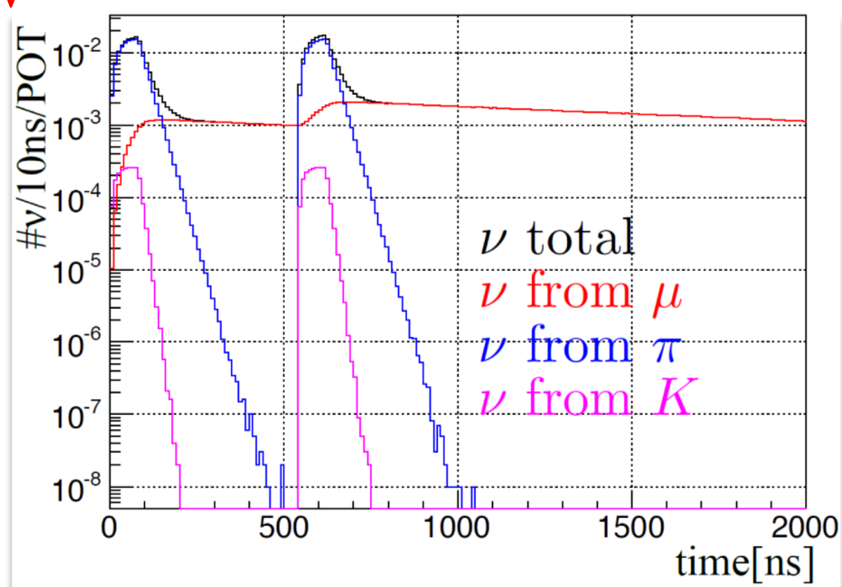




- ✓ **Prompt** $\nu$'s: prompt & narrow $t$, $E_\nu = 29.8$ MeV
- ✓ $\nu$'s from $K$: shorter $t$, larger $E_\nu$, lower flux
- ✓ **Delayed** $\nu$'s: delayed & broad $t$,

  $E_\nu = 0 - 53$ MeV

$$E_{r,N}^{\max} = \frac{2E_\nu^2}{m_N + 2E_\nu}$$

$$E_{r,e}^{\max} = \frac{2E_\nu^2 + 2E_\nu m_e + m_e^2}{m_e + 2E_\nu}$$

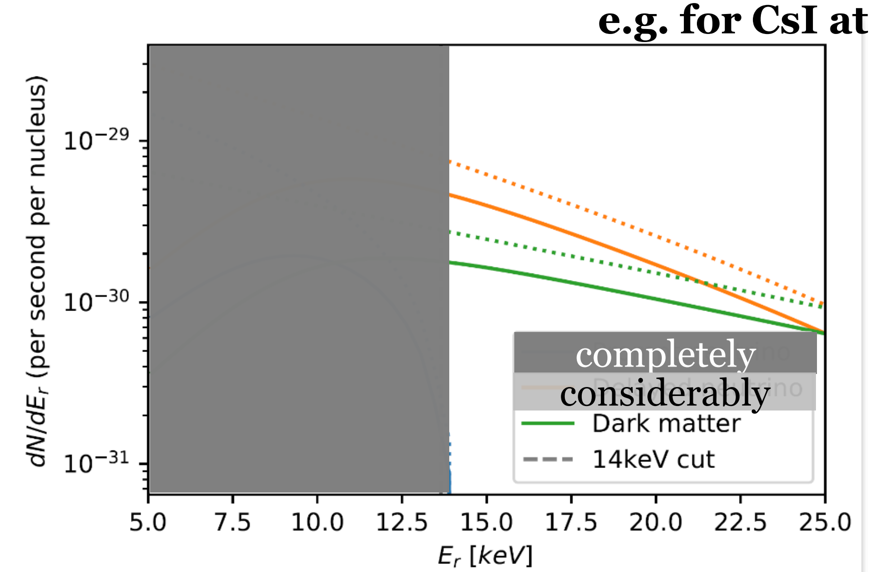


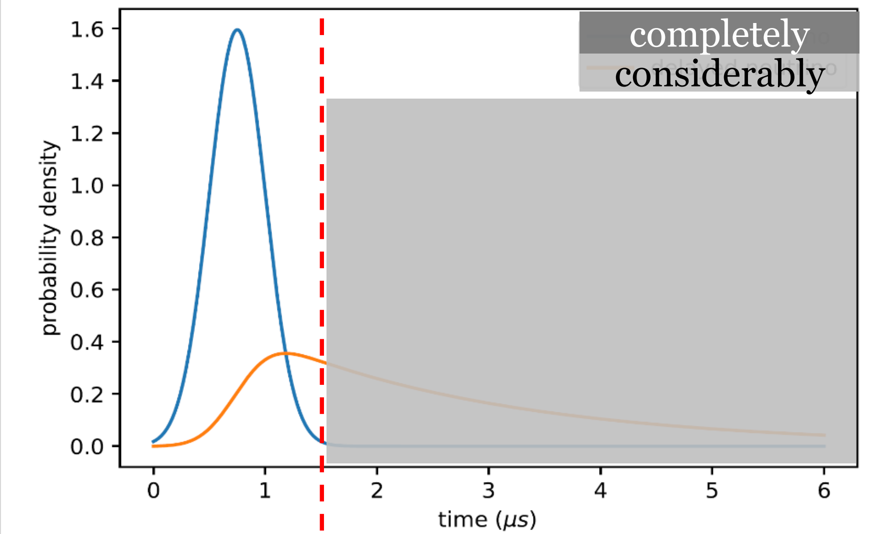

COHERENT [1803.09183 & 1804.09459], JSNS2 [1705.08629]

# Proposed Search Strategy: *E* & *T*-cuts

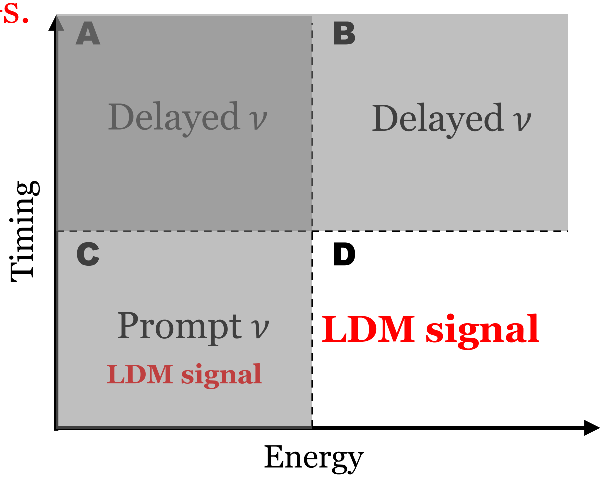
[Dutta, Kim, Liao, **JCP**, Shin, Strigari, PRL (2020)

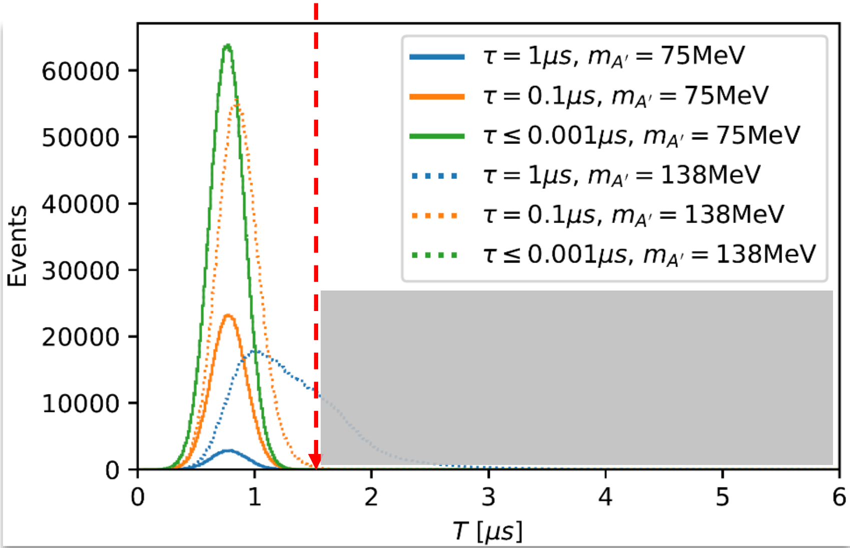
**e.g. for CsI at COHERENT**



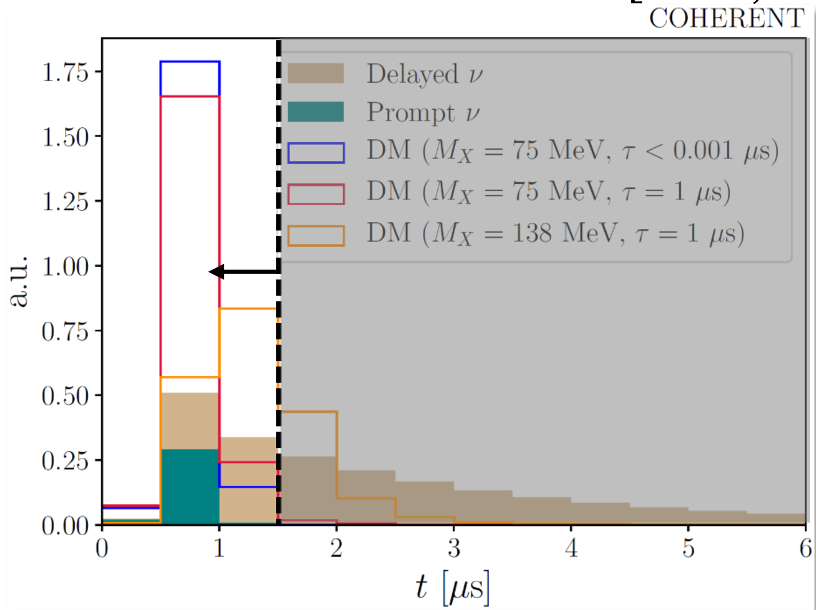

❖ **A combination of *E* & *t* cuts** can remove SM/NSI $\nu$ BGs.

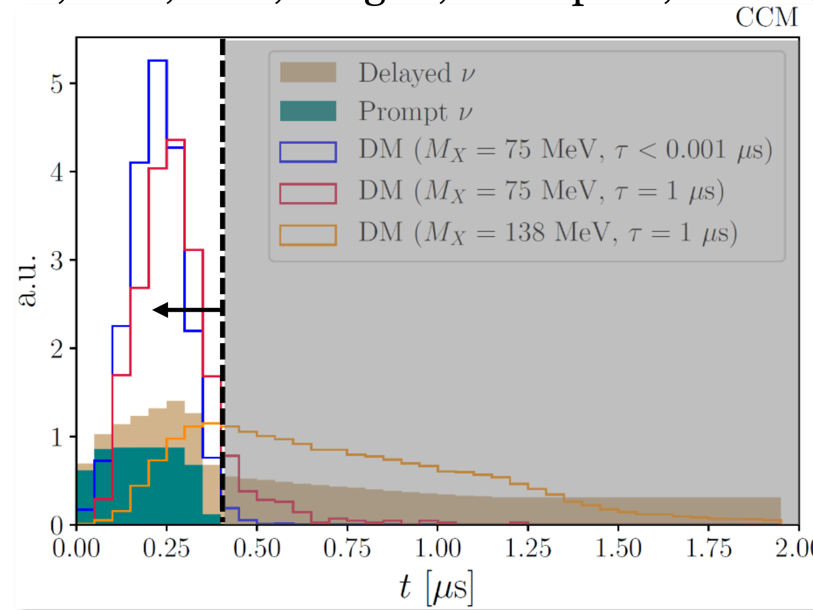


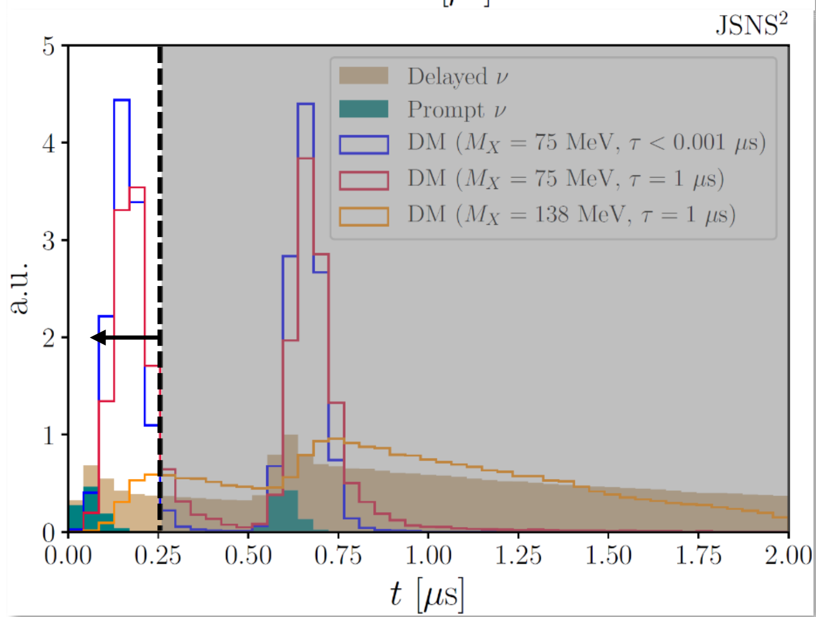



# Various Timing Spectra of DM & $\nu$

[Dutta, Kim, Liao, **JCP**, Shin, Strigari, Thompson, JHEP (2021)]




- ✓ Expected unit-normalized *t*-distributions of DM & $\nu$ scattering events
- ✓ $\nu$ events: $\nu$ scattering cross sections convolved and stacked & collectively unit-normalized.
- ✓ With appropriate *t*-cuts, **delayed $\nu$** can be significantly removed while a large portion of **DM events** are retained.

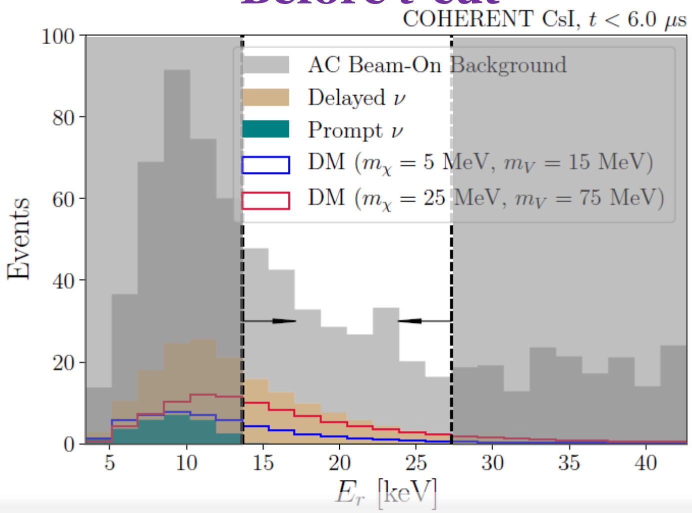
# $E_r$ Spectra of DM & $\nu$: COHERENT

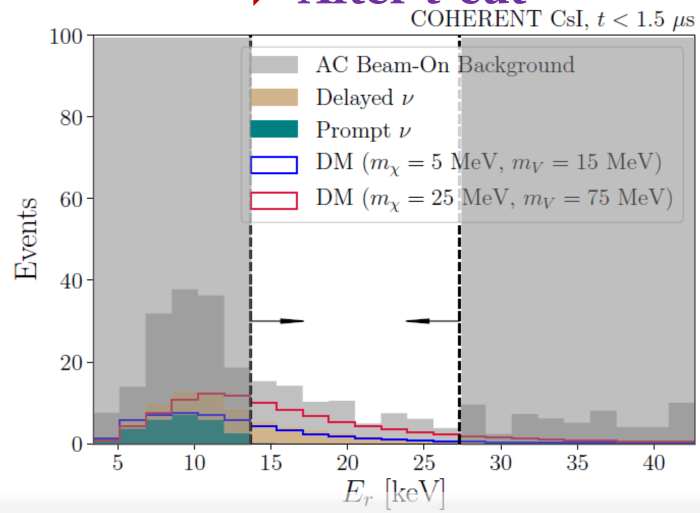
[Dutta, Kim, Liao, **JCP**, Shin, Strigari, Thompson, JHEP (2021)]

***t*-cuts**: delayed $\nu$ significantly removed & DM events almost retained.

**Before *t*-cut** → **After *t*-cut**

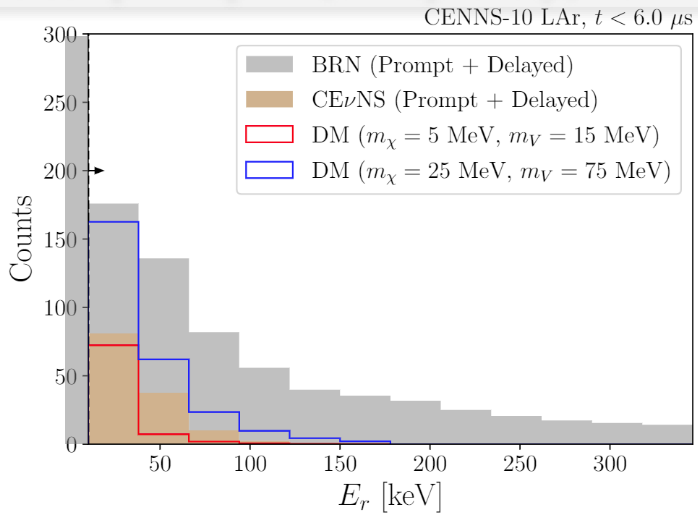
**CsI**

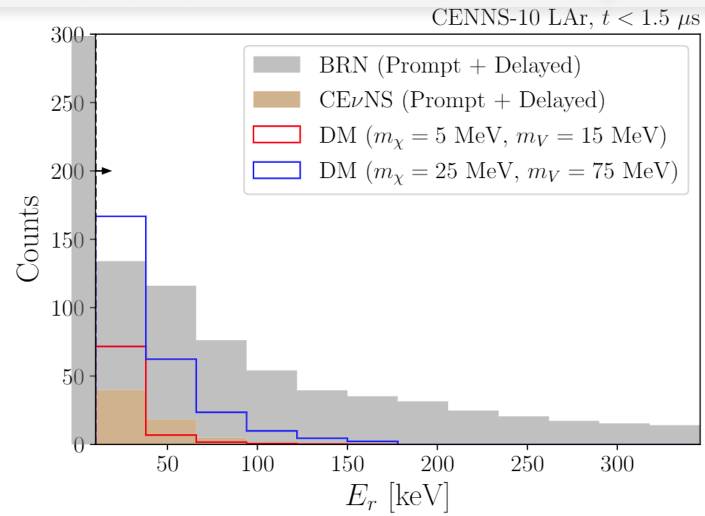



***E*-cuts**: prompt $\nu$ (completely) removed & DM events considerably retained.

**LAr**



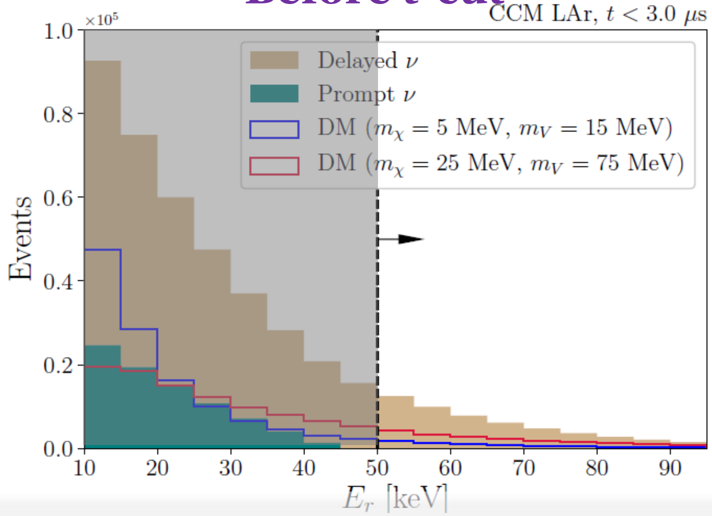
# $E_r$ Spectra of DM & $\nu$: CCM, JSNS²

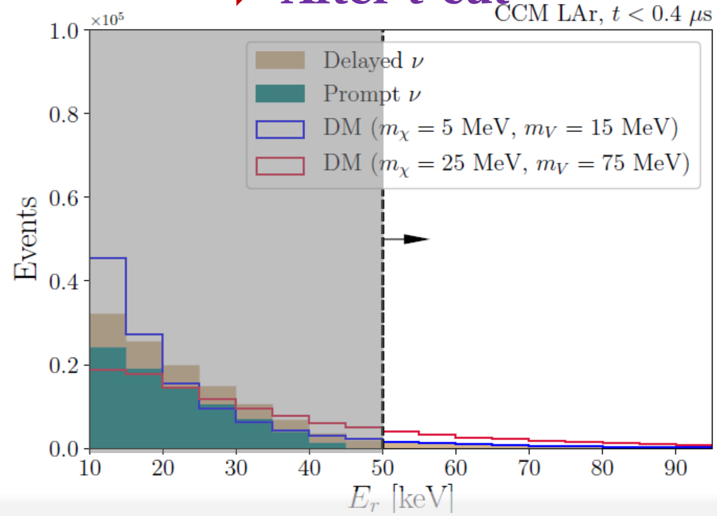
[Dutta, Kim, Liao, **JCP**, Shin, Strigari, Thompson, JHEP (2021)]

***t*-cuts**: delayed $\nu$ significantly removed & DM events almost retained.

**Before *t*-cut** → **After *t*-cut**

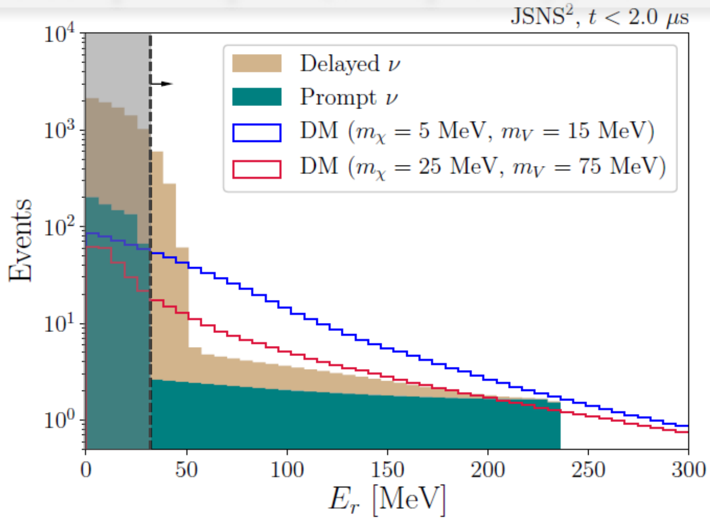
**CCM LAr**

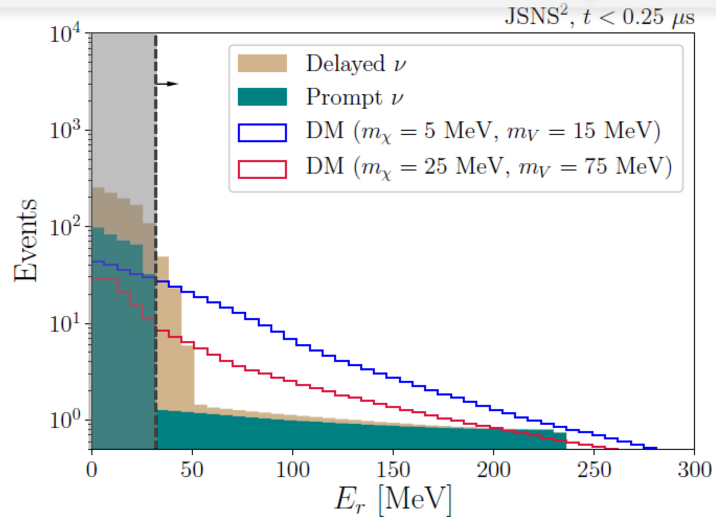



***E*-cuts**: prompt $\nu$ (completely) removed & DM events considerably retained.

**JSNS² Gd-LS**

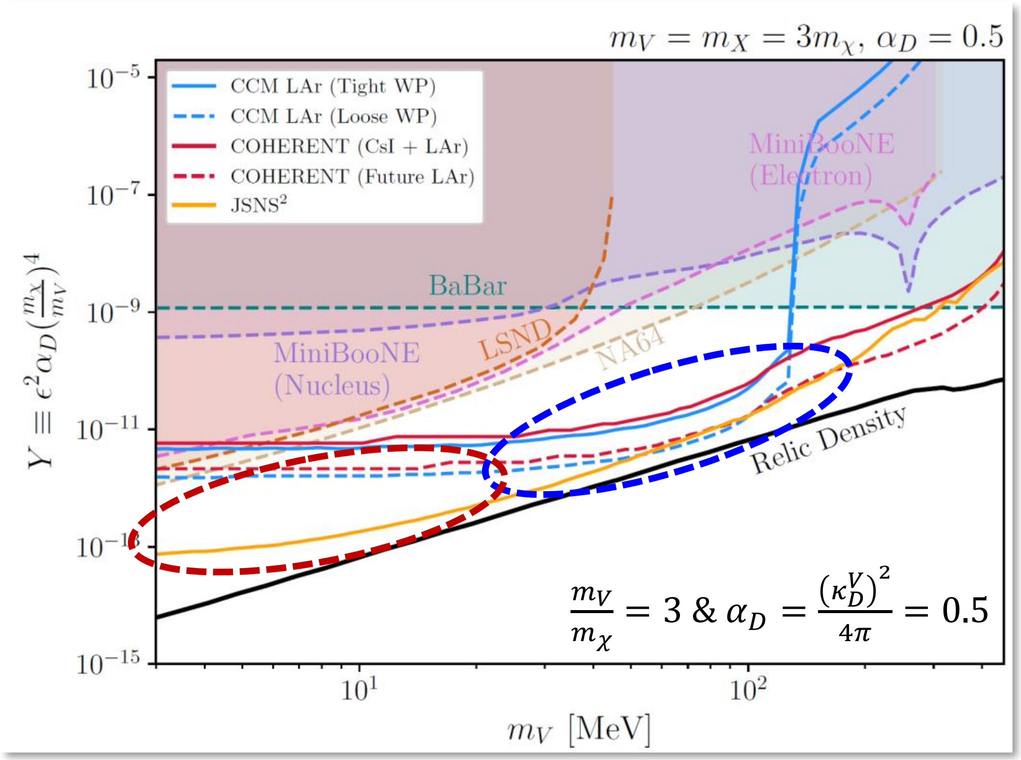


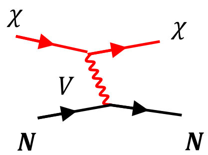
# No Excess: Constraining Parameter Space

[Dutta, Kim, Liao, **JCP**, Shin, Strigari, Thompson, JHEP (2021)]

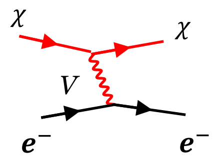
❖ Assuming no excess is observed, we can constrain parameter space.




- ✓ Projected sensitivity (3-year exposure) for the dark photon mediator scenario
- ✓ 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 $E_T$




For COHERENT & CCM




For JSNS²

❖ COHERENT & CCM ⇔ JSNS² : Complementary!

# Boosted Dark Matter

# (BDM)

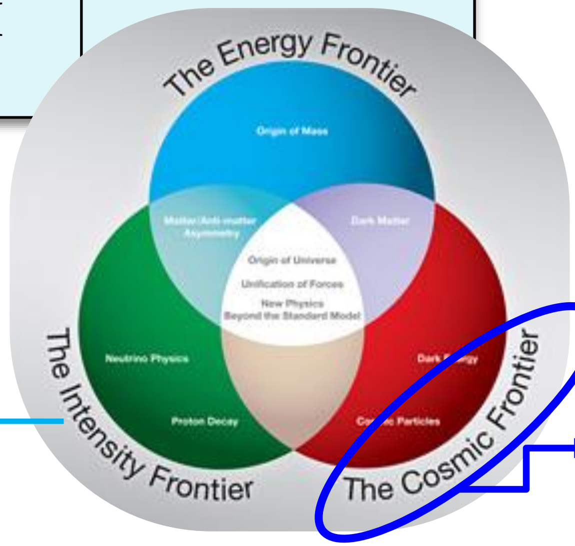
# DM Search Schemes (via Scattering)

| Scattering \ $v_{DM}$ | ***non*-relativistic (<< c)** |
|---|---|
| **elastic** | Direct detection |
| ***in*elastic** | inelastic DM (iDM) |

Very well-studied

# DM Search Schemes (via Scattering)

| Scattering \ $v_{DM}$ | ***non*-relativistic (<< c)** | **relativistic (~c)** |
|---|---|---|
| **elastic** | Direct detection | Boosted DM (BDM) |
| ***in*elastic** | inelastic DM (iDM) | |

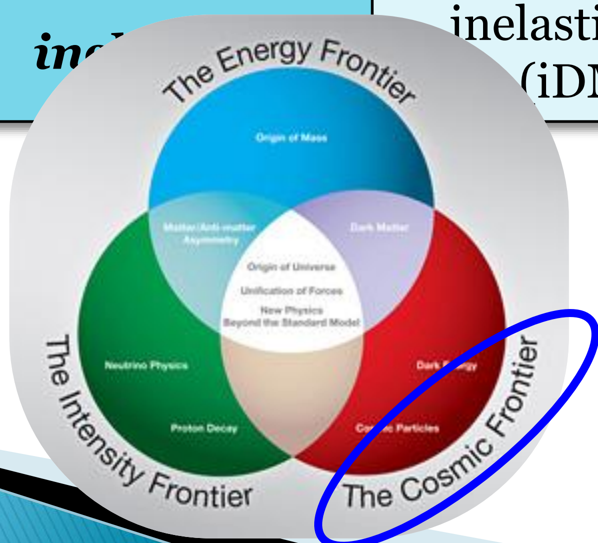



Beam dump Experiments

**This Idea**

# DM Search Schemes (via Scattering)

| Scattering \ $v_{DM}$ | ***non*-relativistic (<< c)** | **relativistic (~c)** |
|---|---|---|
| **elastic** | Direct detection | Boosted DM (eBDM) |
| ***ine*[illegible]** | inelastic DM (iDM) | inelastic BDM (*i*BDM) |



# DM Boosting Scenarios

## *Boosted DM coming from the universe*

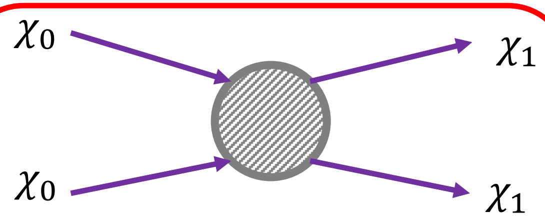
❖ Various scenarios: requirements ➔ right DM relic abundance & DM boosting mechanism

- ✓ Multi-component model: [Belanger & **JCP**, 1112.4491; Kong, Mohlabeng, **JCP**, 1411.6632;
  Kim, **JCP**, Shin, 1702.02944; Aoki & Toma, 1806.09154; more]
- ✓ Semi-annihilation model: [D'Eramo & Thaler, 1003.5912]
- ✓ Decaying multi-component DM: [Bhattacharya et al., 1407.3280; Kopp, Liu, Wang, 1503.02669;
  Cline et al., 1904.13396; Heurtier, Kim, **JCP**, Shin, 1905.13223; more]
- ✓ High velocity (semi-relativistic) DM
  - Anti-DM from DM-induced nucleon decay in the Sun: [Huang & Zhao, 1312.0011]
  - Charged cosmic-ray induced BDM: [Bringmann & Pospelov, 1810.10543; Ema, Sala & Sato, 1811.00520;
    Cappiello & Beacom, 1906.11283; Dent et al., 1907.03782;
    Jho, **JCP**, Park & Tseng, 2006.13910; Cho, Choi & Yoo, 2007.04555; more]
  - **Cosmic-Neutrino-Boosted DM ($\nu$BDM)**: [Jho, **JCP**, Park & Tseng, 2101.11262]
- ✓ More ideas~

# DM Boosting Scenarios: Dark Sector

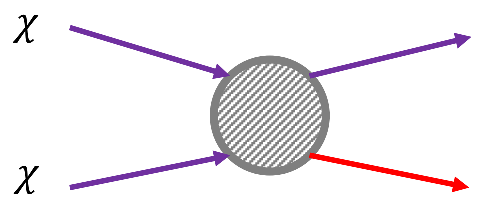
## ***Boosted DM** coming from the universe*

$E_k^{\chi_1} = m_0$




✓ Multi-component model

$m_0 \gg m_1$



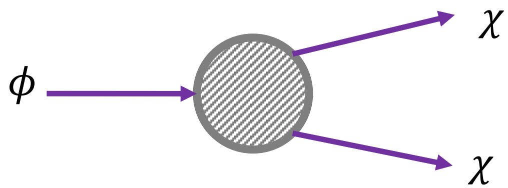

$$E_k^{\chi} = \frac{5m_\chi^2 - m_X^2}{4m_\chi}$$

✓ Semi-annihilation model

$m_\chi \gg m_X$

**Large $E_k^{\mathrm{DM}}$** (monochromatic) due to **mass gap**

- ❖ Relic component DM: non-relativistic!
- ❖ BDM signal: detectable at large Vol. DM & neutrino detectors




$E_k^{\chi} = m_\phi /2$

✓ Decaying multi-component DM

$m_\phi \gg m_\chi$

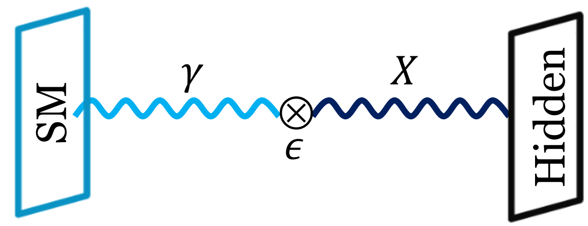
These scenarios need extension of dark sector.

# Boosted DM (BDM) Models

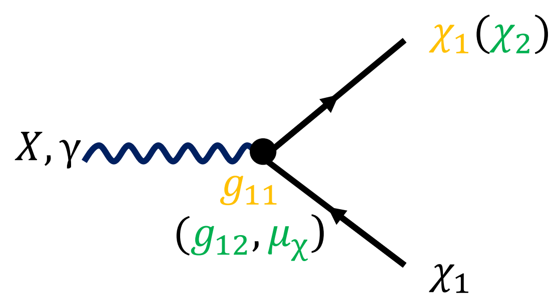
[Kim, **JCP** & Shin, PRL (2017)
Giudice, Kim, **JCP**, Shin, PLB (2018)]

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

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



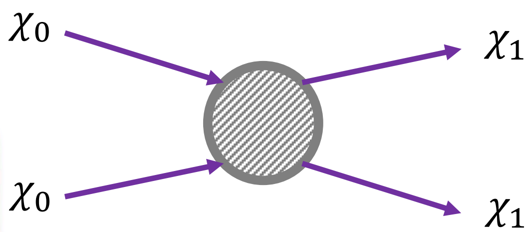

- ✓ $\chi_2$: a heavier (unstable) dark-sector state
- ✓ Flavor-conserving ➔ elastic scattering (eBDM)
- ✓ Flavor-changing ➔ inelastic scattering (*i*BDM)




❖ 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.

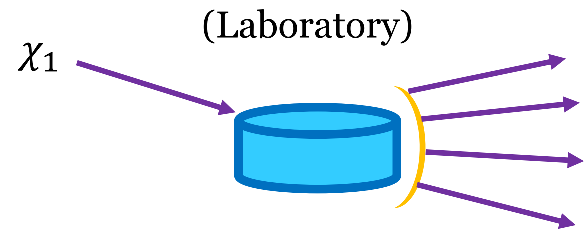
# BDM: Production & its Signatures




(cf. $\chi\chi \to \gamma\gamma$, $\nu\nu$)

becomes boosted

$(\gamma_1 = m_0/m_1)$



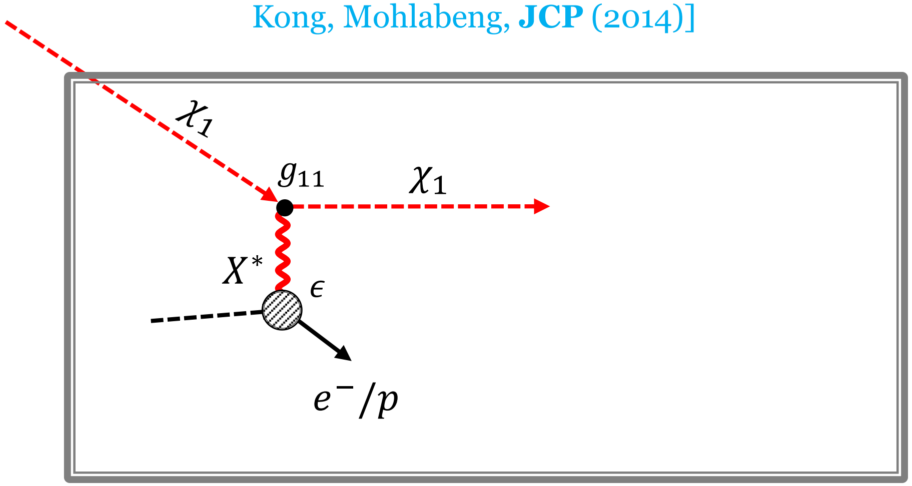

$$\frac{d\Phi_1}{dE_1} = \frac{1}{4}\cdot\frac{1}{4\pi}\int d\Omega \int_{\rm l.o.s.} ds \langle\sigma v\rangle_{\chi_0\bar{\chi}_0\to\chi_1\bar{\chi}_1}\frac{dN_1}{dE_1}\left(\frac{\rho(\mathbf{r}(s,\theta))}{m_0}\right)^2$$
$$= 8.0\times10^{-5}\ {\rm cm^{-2}s^{-1}}\times\left(\frac{\langle\sigma v\rangle_{\chi_0\bar{\chi}_0\to\chi_1\bar{\chi}_1}}{5\times10^{-26}\ {\rm cm^3\,s^{-1}}}\right)\left(\frac{\rm GeV}{m_0}\right)^2\frac{dN_1}{dE_1}$$

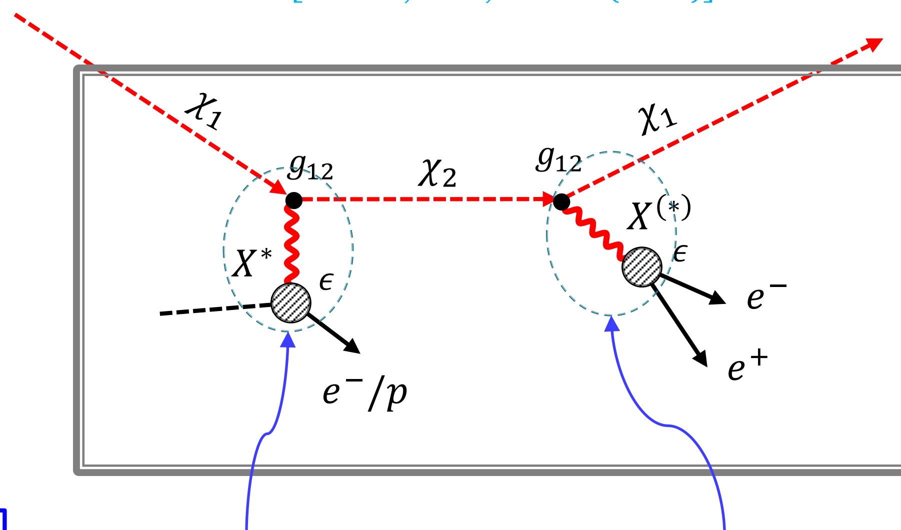
**elastic scattering (eBDM)**

[Agashe, Cui, Necib, Thaler (2014); Kong, Mohlabeng, **JCP** (2014)]

**inelastic scattering (*i*BDM)**

[D. Kim, **JCP**, S. Shin (2016)]




✓ *i*BDM: 1~3 tracks depending on $E_{\rm th}$ & $l_{\chi_2}$

*p*- or *e*-scattering (primary)

Decay (secondary)

# Boosted DM Searches @ SK/COSINE-100

***Boosted DM (BDM) models:***
***Receiving rising attention as an alternative scenario***

PHYSICAL REVIEW LETTERS **120,** 221301 (2018)

Editors' Suggestion

**Search for Boosted Dark Matter Interacting with Electrons in Super-Kamiokande**

PHYSICAL REVIEW LETTERS **122,** 131802 (2019)

Editors' Suggestion

**First Direct Search for Inelastic Boosted Dark Matter with COSINE-100**

- ✓ Not restricted to primary physics goals
- ✓ Opened to other (unplanned) physics opportunities

# e-Recoil @ XENON1T/nT by BDM

[G. Giudice, D. Kim, **JCP**, S. Shin, 1712.07126]

- We, for the first time, pointed out that **DM direct detection experiments** including XENON1T would be **sensitive enough to energetic e-recoils induced by BDM** by pumping up the BDM flux: e.g. $\mathcal{F}_{\chi_1} \propto \frac{\langle \sigma v \rangle_{\chi_0 \chi_0 \to \chi_1 \chi_1}}{m_0^2}$.
- COSINE-100: First official direct search for *i*BDM [COSINE-100, 1811.09344]

**The First Direct Search for Inelastic Boosted Dark Matter with COSINE-100**

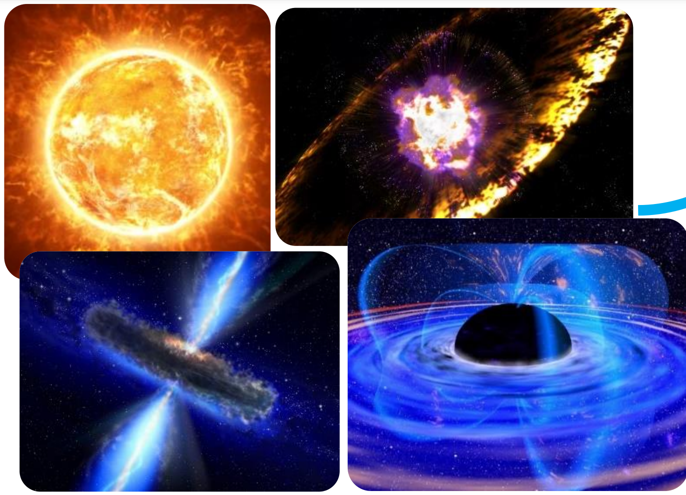
C. Ha,[1] G. Adhikari,[2] P. Adhikari,[2] E. Barbosa de Souza,[3] N. Carlin,[4] S. Choi,[5] M. Djamal,[6] A. C. Ezeribe,[7] I. S. Hahn,[8] E. J. Jeon,[1] J. H. Jo,[3] H. W. Joo,[5] W. G. Kang,[1] W. Kang,[9] M. Kauer,[10] G. S. Kim,[11] H. Kim,[1] H. J. Kim,[11] K. W. Kim,[1] N. Y. Kim,[1] S. K. Kim,[5] Y. D. Kim,[1,2] Y. H. Kim,[1,12] Y. J. Ko,[1] V. A. Kudryavtsev,[7] H. S. Lee,[1,*] J. Lee,[1] J. Y. Lee,[11] M. H. Lee,[1] D. S. Leonard,[1] W. A. Lynch,[7] R. H. Maruyama,[3] F. Mouton,[7] S. L. Olsen,[1] B. J. Park,[13] H. K. Park,[14] H. S. Park,[12] K. S. Park,[1] R. L. C. Pitta,[4] H. Prihtiadi,[6] S. J. Ra,[1] C. Rott,[9] K. A. Shin,[1] A. Scarff,[7,†] N. J. C. Spooner,[7] W. G. Thompson,[3] L. Yang,[15] and G. H. Yu[9]
(COSINE-100 Collaboration)

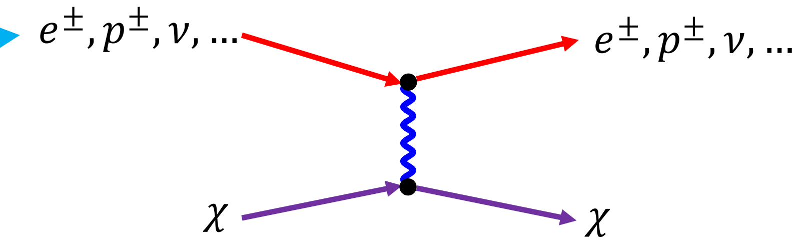
**ACKNOWLEDGMENTS**

We thank Jong-Chul Park for encouraging this analysis and for insightful discussions. We also acknowledge Seodong Shin for insightful discussions. We thank

# DM Boosting Scenarios: Cosmic Rays

## *Cosmic-Ray-Induced BDM*



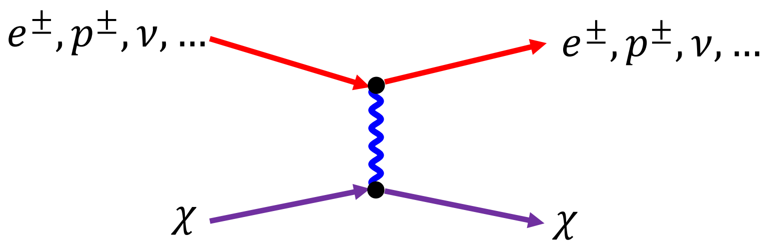



- Energetic cosmic-ray-induced BDM: energetic cosmic-rays kick DM (large $E_{e^{\pm},p^{\pm},\nu,\ldots}$ ➔ large $E_{\chi}$)

  ➔ Efficient for Light DM

# Cosmic-ray-induced BDM

❖ Energetic cosmic-ray-induced BDM: <u>cosmic-rays kick DM</u> (large $E_{e^\pm,p^\pm,\nu,\ldots}$ )




**Large $E_k^\chi$** due to **$E_k^{CR}$ transfer**

❖ Interactions between DM & SM particles

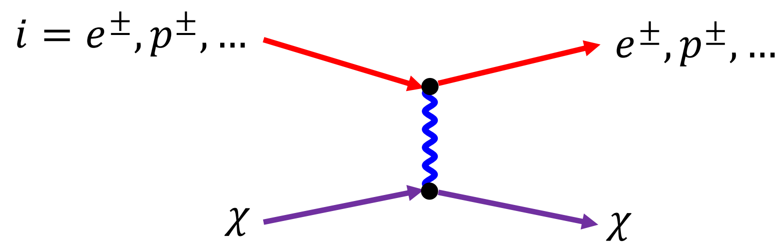
- ✓ Couplings to proton: [Bringmann & Pospelov, 1810.10543; Dent et al., 1907.03782]
- ✓ Couplings to electron: [Ema, Sala & Sato, 1811.00520]
- ✓ Couplings to p & e: [Cappiello & Beacom, 1906.11283; Cho, Choi & Yoo, 2007.04555]
- ✓ Couplings to leptons (e & <u>***ν***</u>): [Jho, **JCP**, Park & Tseng, 2006.13910 & 2101.11262]

Calculation of BDM E-spectrum: quite similar even with different types of cosmic rays

**<u>Except the neutrino-induced case</u>**!

# Cosmic-ray-induced BDM: $e^{\pm}, p^{\pm}$, …

❖ Charged-cosmic-ray-induced BDM: charged cosmic-rays kick DM (large $E_{e^{\pm},p^{\pm},\ldots}$ )




**Large $E_k^{\chi}$ due to $E_k^{CR}$ transfer**

✓ DM-$i$ interaction ➔ Non-relativistic halo DM can be boosted by high E charged cosmic-rays.

✓ BDM flux: by convolution of charged cosmic-ray fluxes & DM-$i$ differential cross section

(charged cosmic-ray fluxes: AMS-02, DAMPE, Fermi-LAT, Voyager, …)

$$\frac{d\Phi_\chi}{dK_\chi} = \frac{1}{4\pi}\int d\Omega \int_{\text{l.o.s.}} ds \left(\frac{\rho_\chi(r(s,\theta))}{m_\chi}\right) \int_{K_i^{\min}}^{\infty} dK_i \frac{d\sigma_{i\chi\to i\chi}(K_i)}{dK_\chi}\frac{d\Phi_i^{\text{LIS}}}{dK_i}$$

$\rho_\chi$: the relic density of $\chi$ in the galaxy

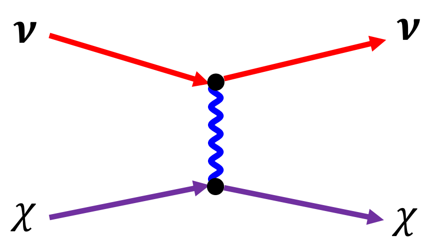
$d\Phi_i^{\text{LIS}}/dK_i$: the local interstellar differential flux of the cosmic-ray particle $i$

$K_i^{\min}$: the minimum kinetic energy of the cosmic-ray particle $i$

# Cosmic-ray-induced BDM: $\nu$BDM

[Jho, **JCP**, Park & Tseng, 2101.11262]

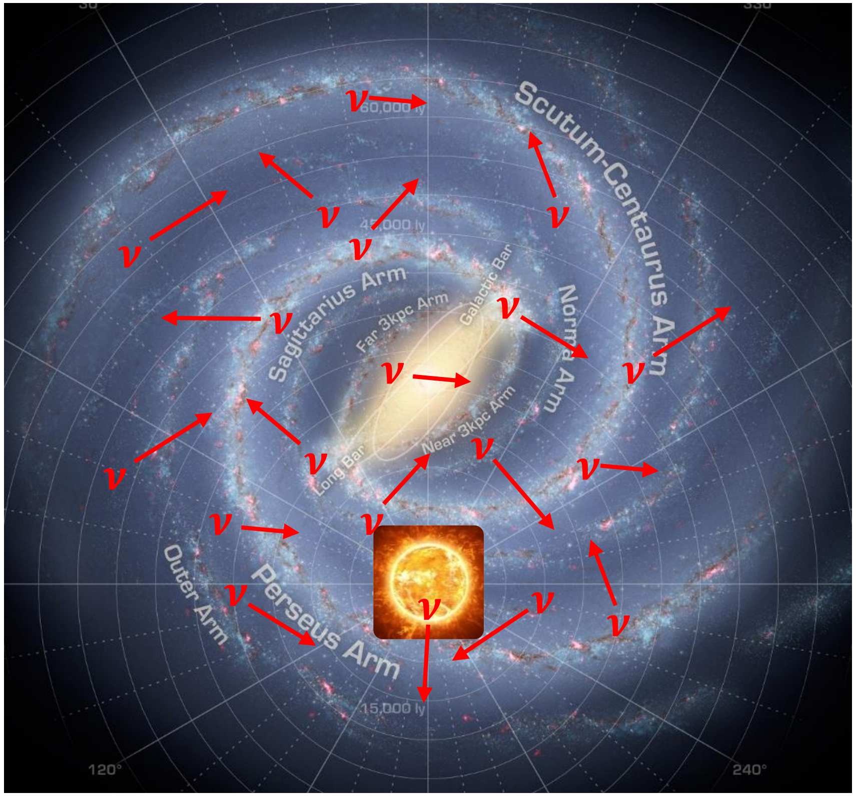
❖ **Cosmic-$\nu$**-induced BDM (**$\nu$BDM** ): <u>cosmic neutrinos kick DM</u> (large $E_\nu$)




**Large $E_k^\chi$** due to **$E_k^\nu$ transfer**

✓ DM-$\nu$ interaction ➔ Non-relativistic halo DM can be boosted by <u>***ν*'s from stars in the galaxy**</u>.

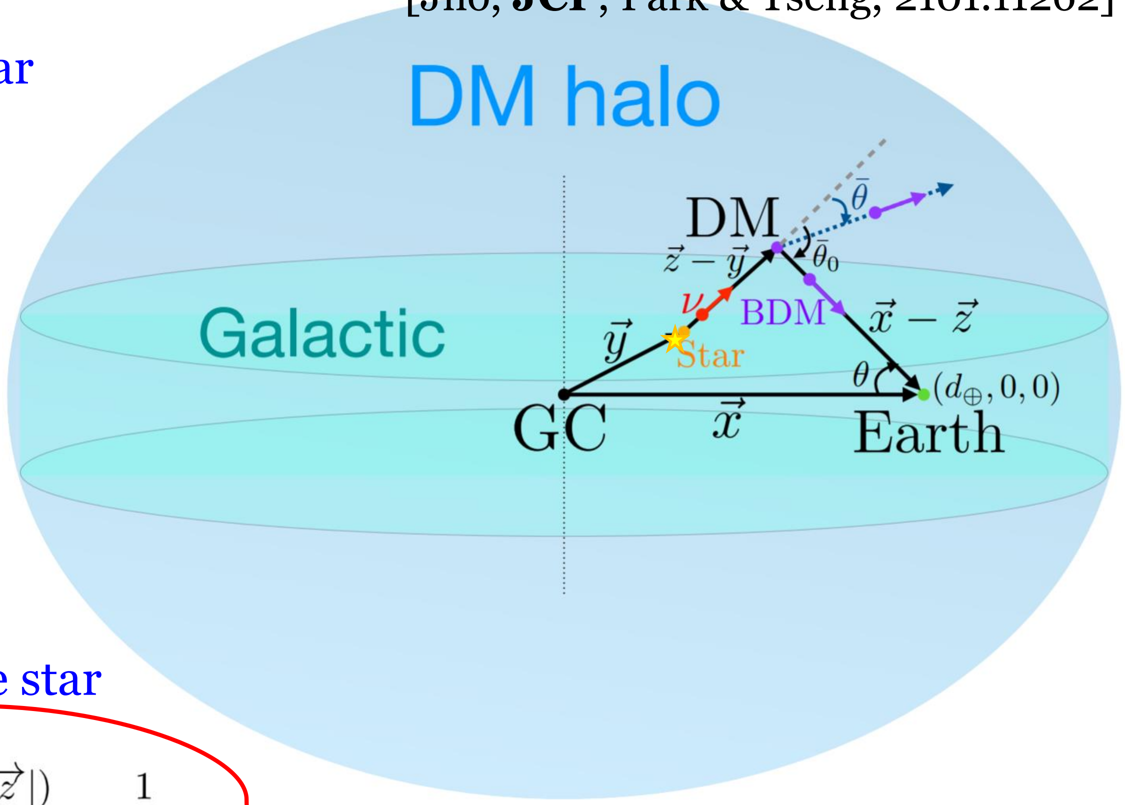
$$\boldsymbol{\Phi_\nu \gg \Phi_{e,p}}$$



# Cosmic-ray-induced BDM: $\nu$BDM

[Jho, **JCP**, Park & Tseng, 2101.11262]

❖ BDM production by $\nu$ from a star




❖ BDM flux by $\nu$'s from a Sun-like star

$$\frac{d\Phi^{(1)}_{\rm DM}(\vec{y})}{dK_{\rm DM}} \simeq \frac{\mathcal{F}}{8\pi^2}\left(\tilde{f}_1 \frac{d\dot{N}^{\rm Sun}_\nu}{dK_\nu}\right)\int d^3\vec{z}\,\frac{\rho_{\rm DM}(|\vec{z}|)}{m_{\rm DM}}\frac{1}{|\vec{x}-\vec{z}|^2} \times \left(\frac{dK_\nu}{d\bar{\theta}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right)\left(\frac{d\sigma_{\nu{\rm DM}}}{dK_{\rm DM}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right) \times \frac{1}{\sin\bar{\theta}_0}\frac{1}{|\vec{z}-\vec{y}|^2}\times\exp\left(-\frac{|\vec{z}-\vec{y}|}{d_\nu}\right)$$

Neutrino emission rate for a Sun-like star

Variances of stellar properties from Sun

Scattering angle via kinematic relations

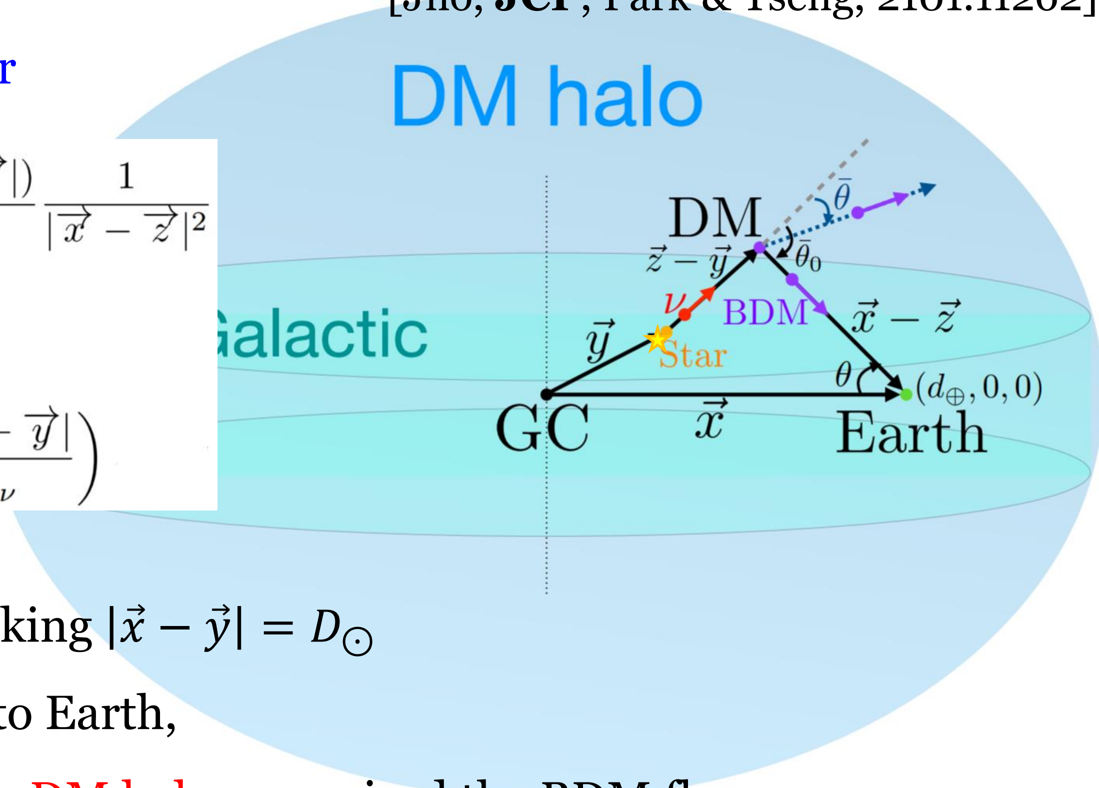
Attenuation due to propagation

# Cosmic-ray-induced BDM: $\nu$BDM

[Jho, **JCP**, Park & Tseng, 2101.11262]

❖ BDM production by $\nu$ from a star

$$\frac{d\Phi^{(1)}_{\rm DM}(\vec{y})}{dK_{\rm DM}} \simeq \frac{\mathcal{F}}{8\pi^2}\left(\tilde{f}_1 \frac{d\dot{N}^{\rm Sun}_\nu}{dK_\nu}\right)\int d^3\vec{z}\,\frac{\rho_{\rm DM}(|\vec{z}|)}{m_{\rm DM}}\frac{1}{|\vec{x}-\vec{z}|^2} \times \left(\frac{dK_\nu}{d\bar{\theta}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right)\left(\frac{d\sigma_{\nu\rm DM}}{dK_{\rm DM}}\bigg|_{\bar{\theta}=\bar{\theta}_0}\right) \times \frac{1}{\sin\bar{\theta}_0}\frac{1}{|\vec{z}-\vec{y}|^2}\times\exp\left(-\frac{|\vec{z}-\vec{y}|}{d_\nu}\right)$$




✓ BDM flux by $\nu$'s from Sun by taking $|\vec{x}-\vec{y}| = D_\odot$

Sun provides the largest $\nu$ flux to Earth,

but only small volume of nearby DM halo comprised the BDM flux.

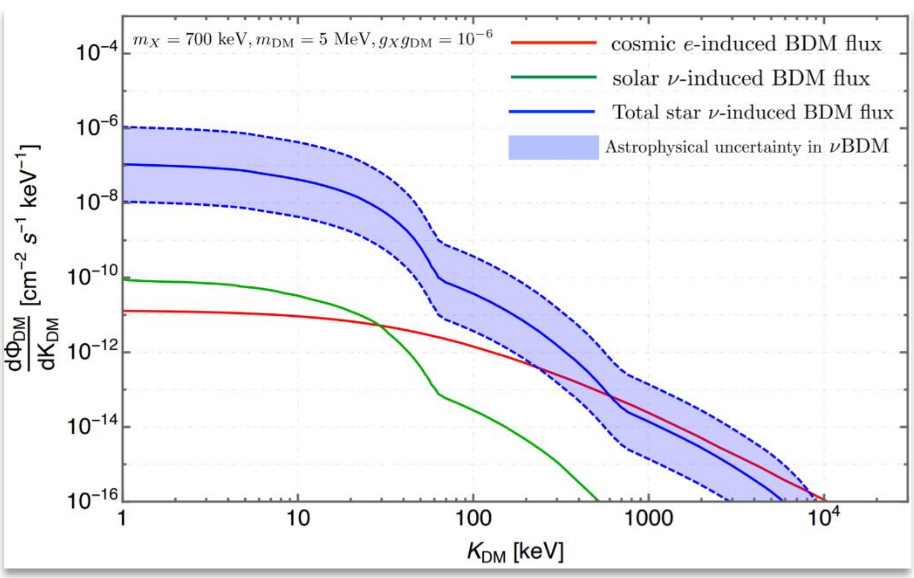
✓ Entire stellar contributions in the galaxy:

$$\frac{d\Phi_{\rm DM}}{dK_{\rm DM}} = \int d^3\vec{y}\, n_{\rm star}(\vec{y})\frac{d\Phi^{(1)}_{\rm DM}(\vec{y})}{dK_{\rm DM}}$$

# Cosmic-ray-induced BDM: $\nu$BDM

[Jho, **JCP**, Park & Tseng, 2101.11262]

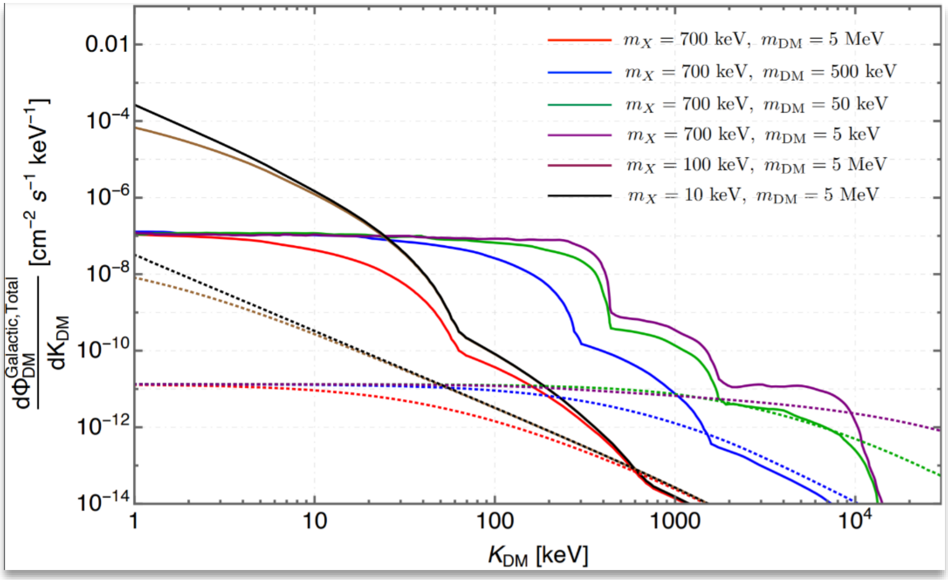
❖ BDM fluxes by solar/star neutrinos & cosmic electrons




✓ **$\nu$BDM** ~ $10^3$ ×BDM by solar $\nu$

✓ **$\nu$BDM** ~ $10^{2-4}$ ×CeBDM for $K_{DM} \lesssim$ 50 keV

❖ BDM fluxes for different mediator & DM masses




✓ **$\nu$**BDM (**solid**) vs. **Ce**BDM (**dashed**)

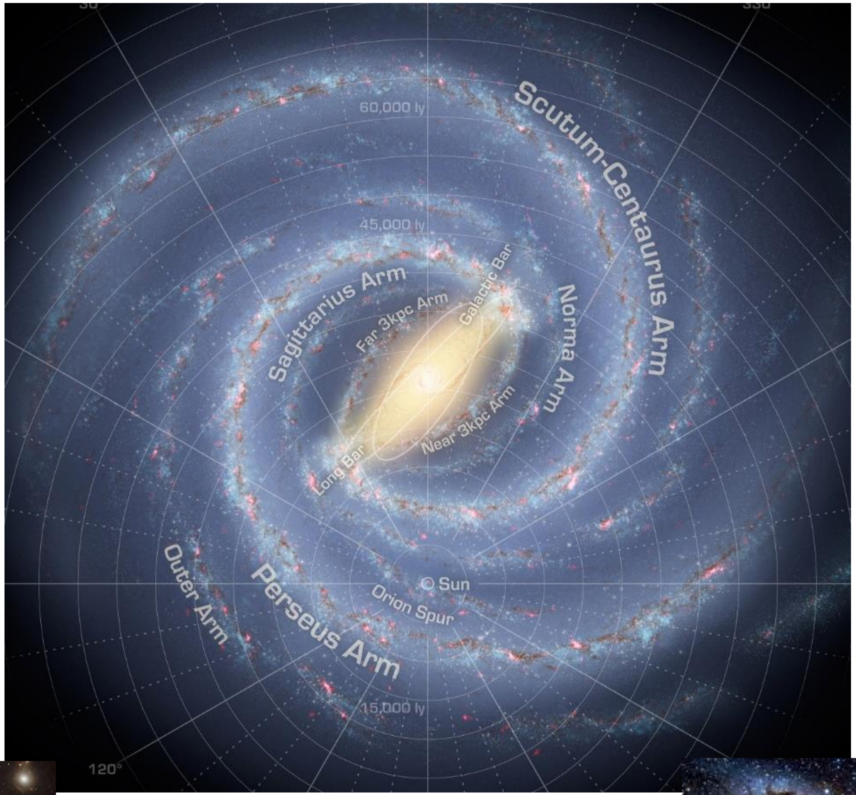
Solar/star neutrinos can very efficiently boost light DM ($\lesssim$ 10 MeV)!

# Cosmic-ray-induced BDM: $\nu$BDM

[Jho, **JCP**, Park & Tseng 2101.11262 & In preparation]

❖ **Extra-galactic(EG) contribution** to the $\nu$BDM flux

**Dominant contribution:**
**$\nu$ & DM populated regions**
**➔ e.g., Galactic Center**

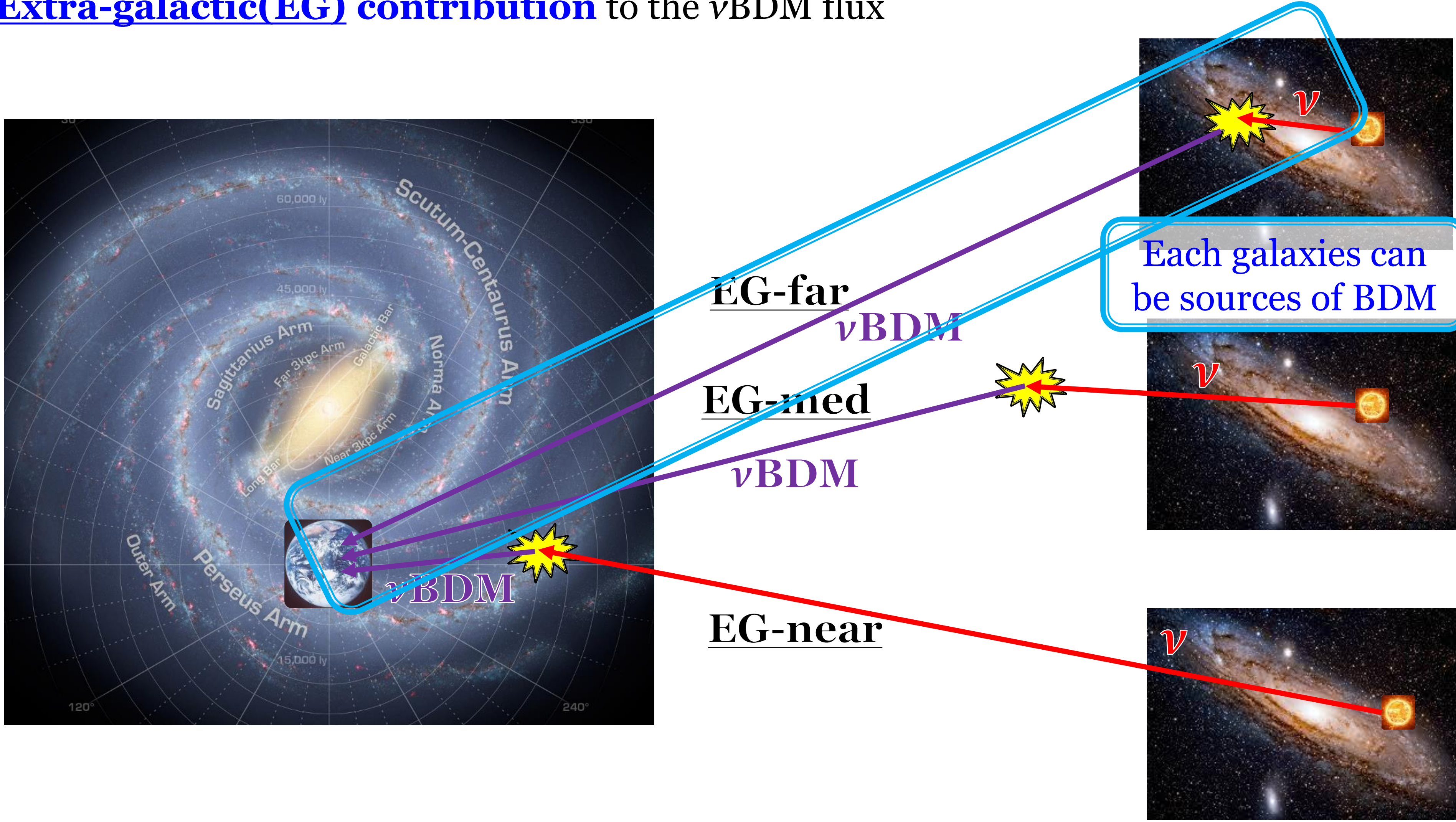



# Cosmic-ray-induced BDM: $\nu$BDM

[Jho, **JCP**, Park & Tseng 2101.11262 & In preparation]

❖ **Extra-galactic(EG) contribution** to the $\nu$BDM flux

**Extra-galactic(EG) contribution** to the $\nu$BDM flux

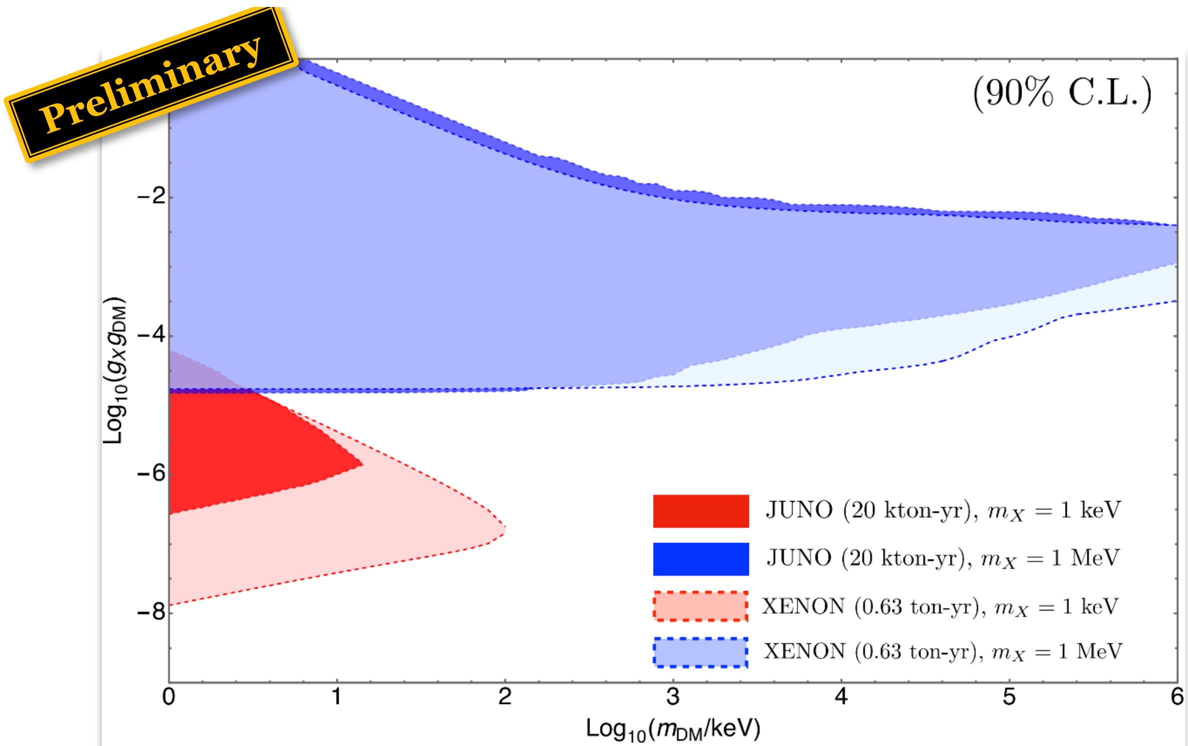


# Cosmic-ray-induced BDM: Limits - Coupling

[Jho, **JCP**, Park & Tseng 2101.11262 & In preparation]

❖ Experimental status

$$\mathcal{L} \supset -g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_e \bar{e}\gamma^\mu e X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$$




✓ XENON1T: mostly better limits (lower $E_{\rm th}$)

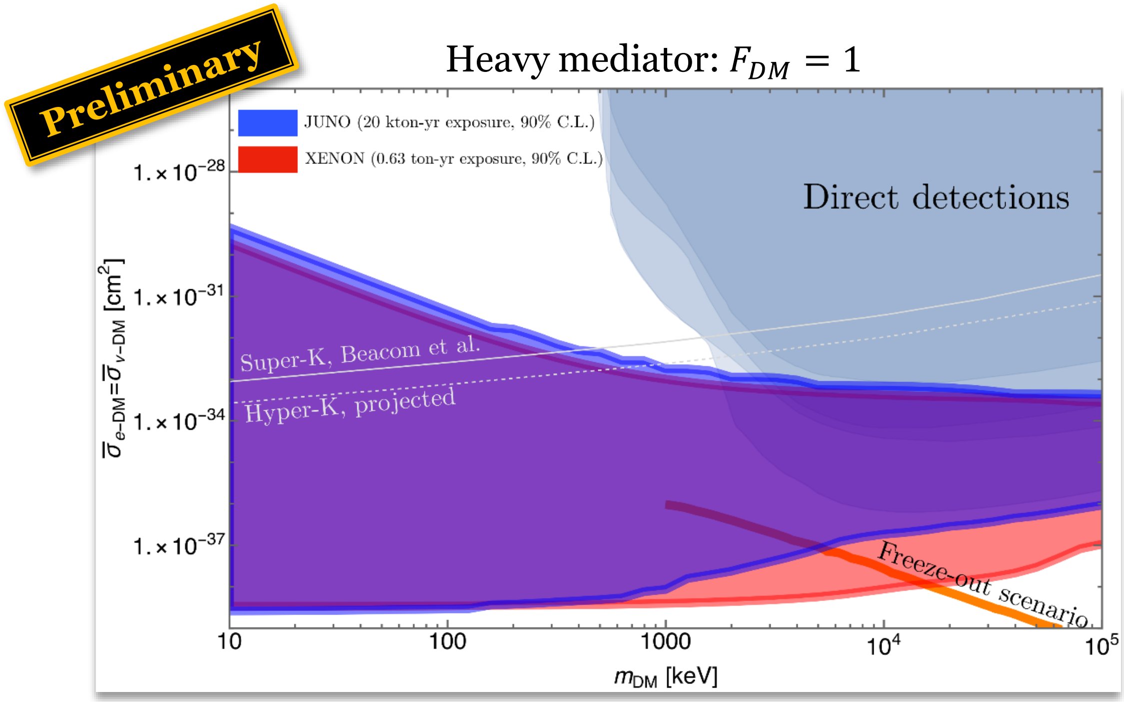
✓ JUNO: competitive upper limits (less attenuation) & better limits for heavier $m_X$ with lighter $m_{\rm DM}$ (high flux even for $K_{\rm DM}$~$O(100\ {\rm keV})$)

# Cosmic-ray-induced BDM: Limits - Coupling

[Jho, **JCP**, Park & Tseng 2101.11262 & In preparation]

❖ Experimental status

$$\mathcal{L} \supset -g_\nu \bar{\nu}\gamma^\mu P_L \nu X_\mu - g_e \bar{e}\gamma^\mu e X_\mu - g_{\rm DM}\bar{\chi}\gamma^\mu \chi X_\mu$$




✓ $\nu$BDM+CRe-BDM contributions to XENON1T/JUNO e-recoils

✓ Expected sensitivities for sub-GeV DM from various current & future detectors: the $\nu$BDM provides stringent constraints on unexplored parameter space for light DM ($\lesssim$ MeV)

# e/*i*BDM Searches in Various Exps.

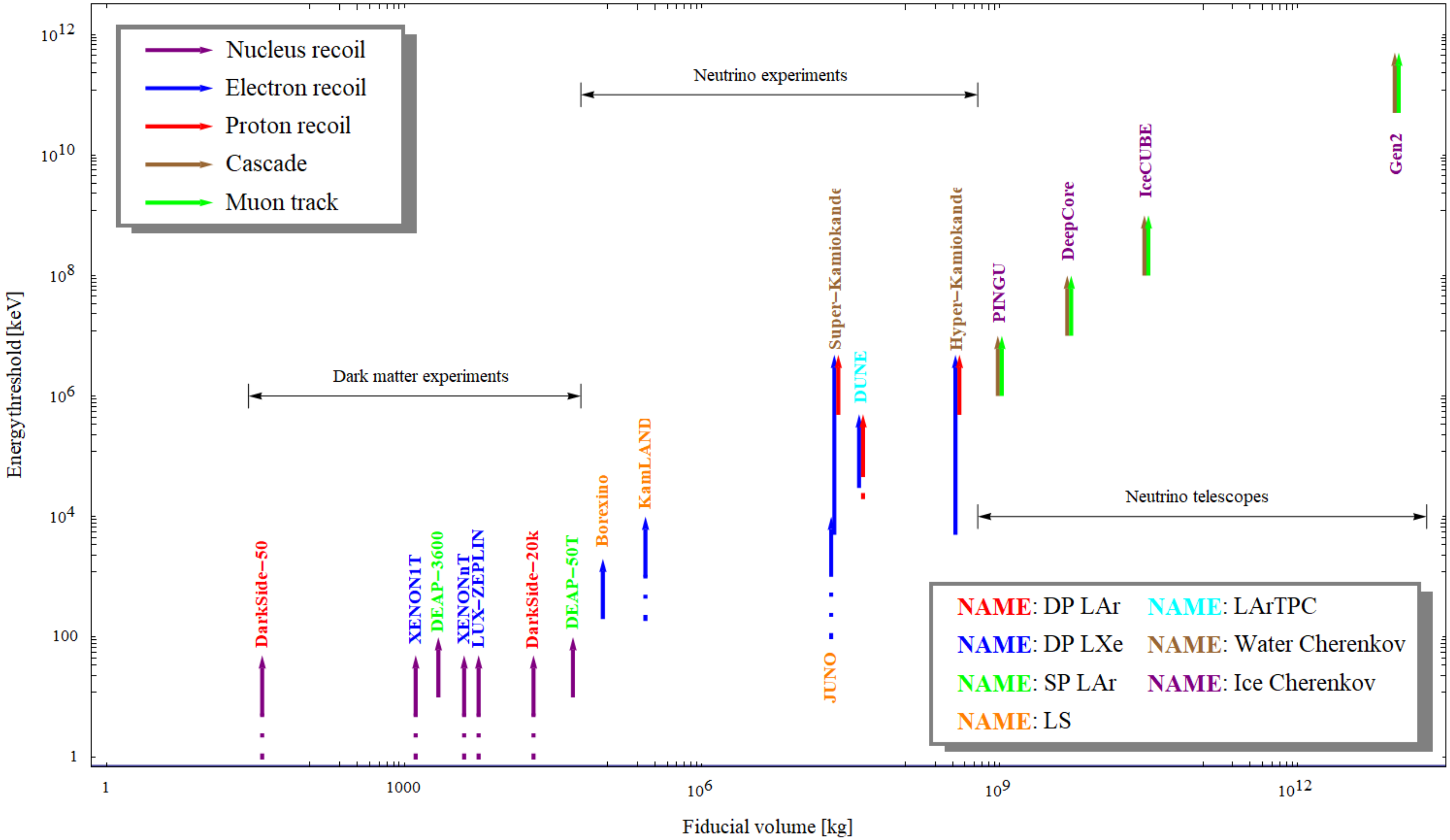
P. Machado, D. Kim, **JCP** & S. Shin [2003.07369]

| **Dark Matter Experiments** | Target Material | Volume [t] Active | Fiducial | Depth [m] | $E_{\rm th}$ [keV] | Resolution Position [cm] | Angular [°] | Energy [%] | PID | Run Time | Refs. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DarkSide −50 | LAr DP-TPC | 46.4 kg | 36.9 kg | 3,800 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | $\lesssim 10$ | – | 2013- | [112] |
| DarkSide −20k | LAr DP-TPC | 23 | 20 | 3,800 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | $\lesssim 10$ | – | goal: 2021– | [79] |
| XENON1T | LXe DP-TPC | 2.0 | 1.3 | 3,600 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | – | – | 2016 –2018 | [113, 114] |
| XENONnT | LXe DP-TPC | 5.9 | $\sim 4$ | 3,600 m.w.e. | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | – | – | goal: 2020– | [113] |
| DEAP -3600 | SP LAr S1 only | 3.26 | 2.2 | 2,000 | $\mathcal{O}(10)$ | $< 10$ | – | $\sim 10-20$ | – | 2016- | [99–101] |
| DEAP −50T | SP LAr S1 only | 150 | 50 | 2,000 | $\mathcal{O}(10)$ | 15 | – | – | – | – | [99] |
| LUX-ZEPLIN | LXe DP-TPC | 7 | 5.6 | 1,500 | $\mathcal{O}(1)$ | $\sim 0.1-1$ | – | 2.5 MeV: 2 | – | goal: 2020– | [115, 116] |
| **Neutrino Experiments** | Target Material | Volume [kt] Active | Fiducial | Depth [m] | $E_{\rm th}$ [MeV] | Resolution Vertex [cm] | Angular [°] | Energy [%] | PID | Run Time | Refs. |
| Borexino | organic LS | 0.278 | 0.1 | 3,800 m.w.e. | $\sim 0.2$ | ~9-17 | – | $\frac{5}{\sqrt{E\,(\rm MeV)}}$ | – | > 5.6 year | [117] |
| KamLAND | LS | 1 | 0.2686 | 1,000 | 0.2–1 | $\frac{12-13}{\sqrt{E\,(\rm MeV)}}$ | – | $\frac{6.4-6.9}{\sqrt{E\,(\rm MeV)}}$ | – | $\sim 10$ year? | [118, 119] |
| JUNO | LS | – | 20 | 700 | $< 1$, goal: 0.1 | $\frac{12}{\sqrt{E\,(\rm MeV)}}$ | $\mu$: $L > 5$ m: $< 1$, $L > 1$ m: $< 10$ | $\frac{3}{\sqrt{E\,(\rm MeV)}}$ | $\mu^\pm$ vs $\pi^\pm$, $e^\pm$ vs $\pi^0$: difficult | goal: 2021– | [120–122] |
| DUNE | LArTPC | Total: 17.5 ×4 | $\gtrsim 10$ ×4 | 1500 | $e: 30$, $p$: 21-50 | $\lesssim 1-2$ | $e,\mu: 1$, $\pi^\pm, p, n: 5$ | $e: 20$ ($E < 0.4$ GeV), 10 ($E < 1.0$ GeV), $2 + \frac{8}{\sqrt{E/\rm GeV}}$ ($E > 1.0$ GeV) $p: 10$ ($E < 1.0$ GeV), $5 + \frac{5}{\sqrt{E/\rm GeV}}$ ($E > 1.0$ GeV) | good $e,\mu,\pi^\pm,p$ separation | 10 kt: 2026-, 20 kt: 2027– | [77, 80–84] |
| SK | Water Cherenkov | Total: 50 | 22.5 | 1,000 | $e: 5$, $p: 485$ | 5 MeV: 95, 10 MeV: 55, 20 MeV: 40 | 10 MeV: 25, 0.1 GeV: 3, 1.33 GeV: 1.2 | 10 MeV: 16, 1 GeV: 2.5 | $e,\mu$: good | $\gtrsim 14$ year | [123–125] |
| HK | Water Cherenkov | Total: 258 ×2 | 187 ×2 | Japan: 650, Korea: 1,000 | $e: < 5$, $p: 485$ | 5 MeV: 75, 10 MeV: 45, 15 MeV: 40, 0.5 GeV: 28 | similar to SK | better than SK | $e,\mu$: good, $\pi^0,\pi^\pm$: mild | goal: 2027– | [85–87] |
| **Neutrino Telescopes** | Target Material | Effective Volume [Mt] | | Depth [m] | $E_{\rm th}$ [GeV] | Resolution Vertex [m] | Angular [°] | Energy [%] | PID | Run Time | Refs. |
| IceCube | Ice Cherenkov | 100 GeV: $\sim 30$, 200 GeV: $\sim 200$ | | 1,450 Ice | $\sim 100$ | vertical: 5, horizontal: 15 | $\mu$-track: $\sim 1$, shower: $\sim 30$ | 100 GeV: 28, 1 TeV: 16 | only $\mu$ | 2011– (2008) | [89, 126] |
| DeepCore | Ice Cherenkov | 10 GeV: $\sim 5$, 100 GeV: $\sim 30$ | | 2,100 Ice | $\sim 10$ | better | $\mu$-track: ~1, shower: $\gtrsim 10$ | – | only $\mu$ | 2011– (2010) | [88, 89] |
| IceCube Upgrade | Ice Cherenkov | – | | 2,150 Ice | $\mathcal{O}(1)$ | much better | 5 GeV: $\sim 20$, 10 GeV: $\sim 15$ | – | only $\mu$ | goal: 2023 | [127] |
| PINGU | Ice Cherenkov | 1 GeV: $\gtrsim 1$, 10 GeV: $\sim 5$ | | 2,100 Ice | $\sim 1$ | much better | 1 GeV: 25, 10 GeV: 10 | 1 GeV: 55, 10 GeV: 25 | only $\mu$ | > 2023 | [128, 129] |
| Gen2 | Ice Cherenkov | $\sim 10$ Gt | | 1,360 Ice | $\sim 50$ TeV | worse | $\mu$-track: $< 1$ shower: $\sim 15$ | – | only $\mu$ | – | [130] |

- ❖ Many existing/upcoming experiments are potentially capable of testing models conceiving BDM
- ❖ Additional physics opportunity on top of the main mission of each experiment

# e/*i*BDM Searches in Various Exps.

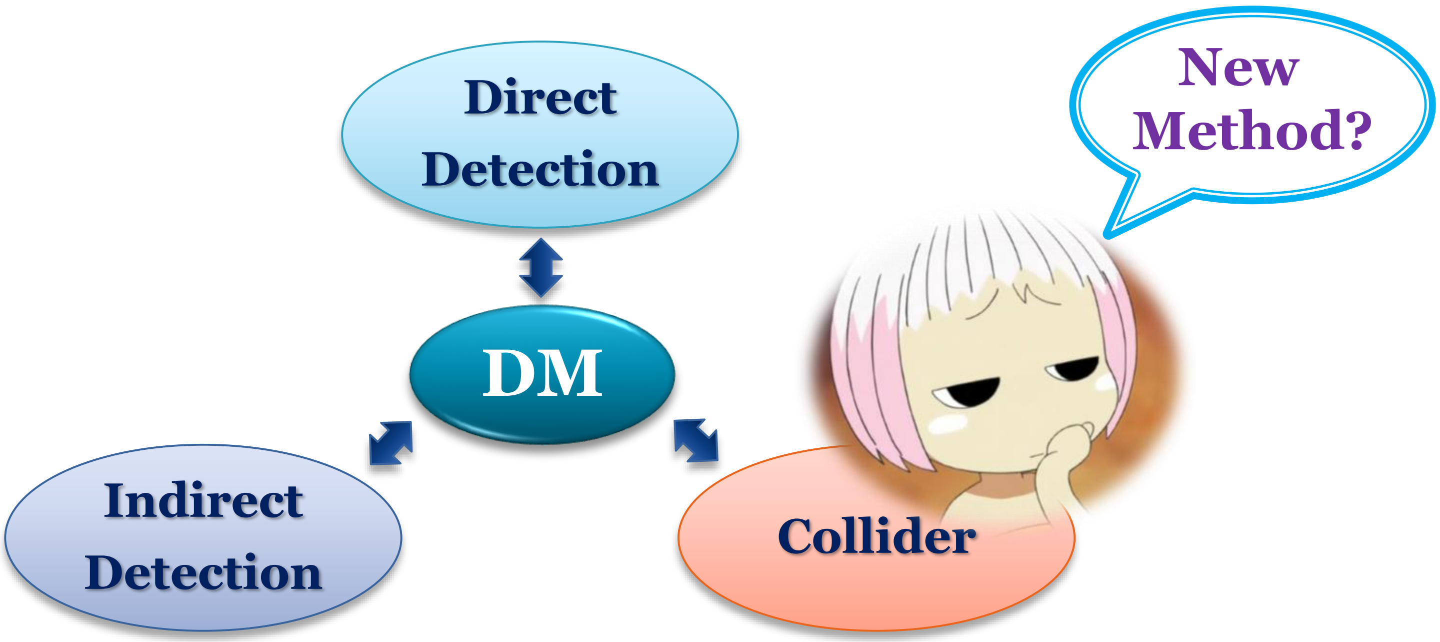
P. Machado, D. Kim, **JCP** & S. Shin [2003.07369]




Detectors are complementary to one another rather than superior to the other!

# 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!




**Thank you~!!**