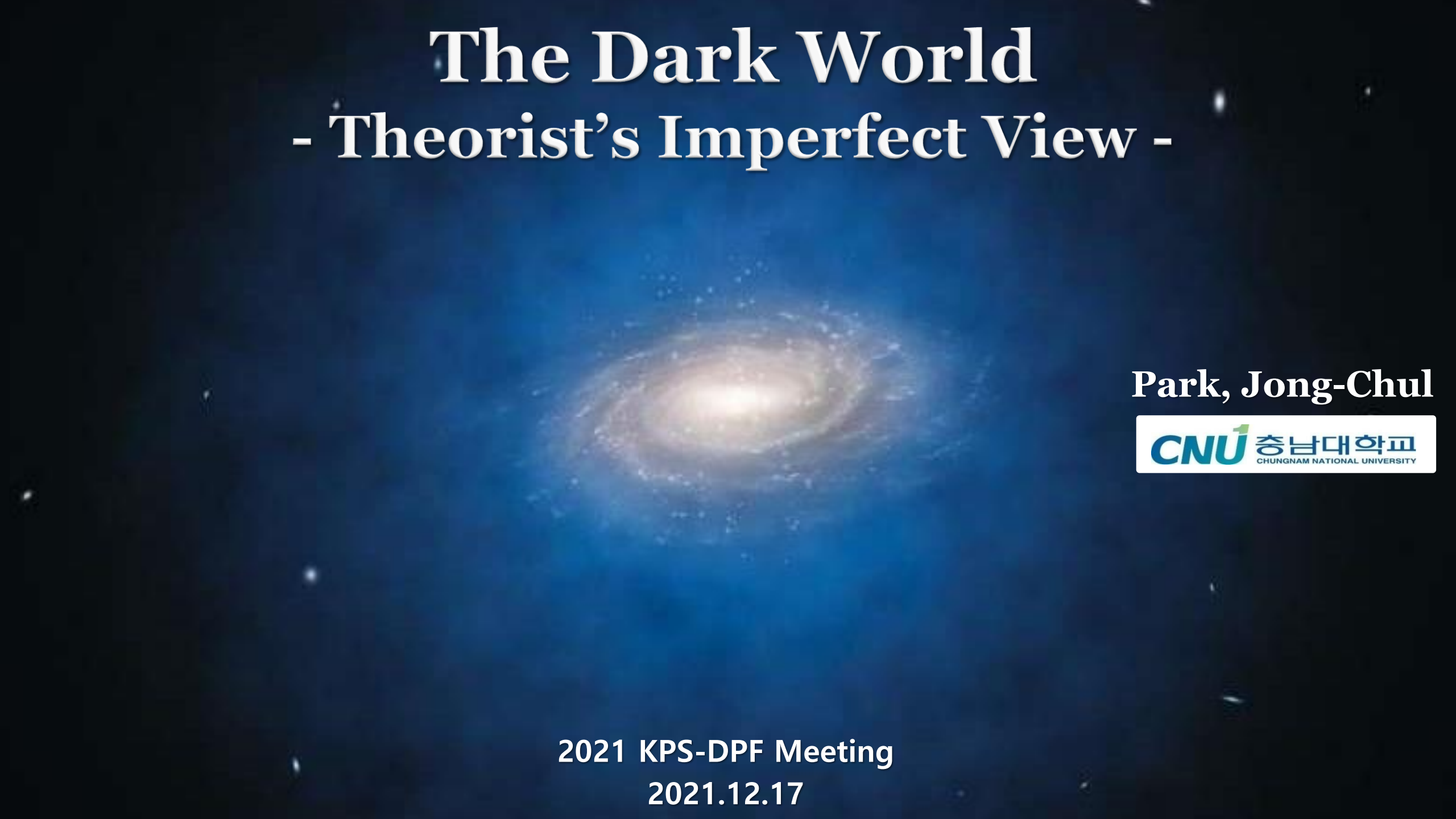
The Dark World
- Theorist's Imperfect View -

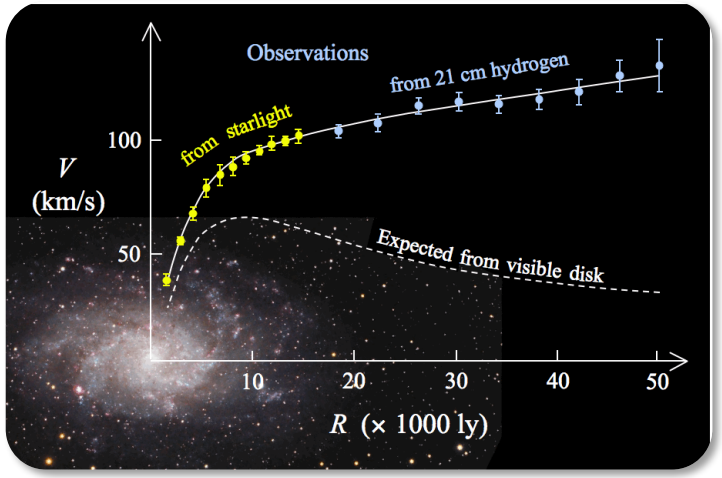


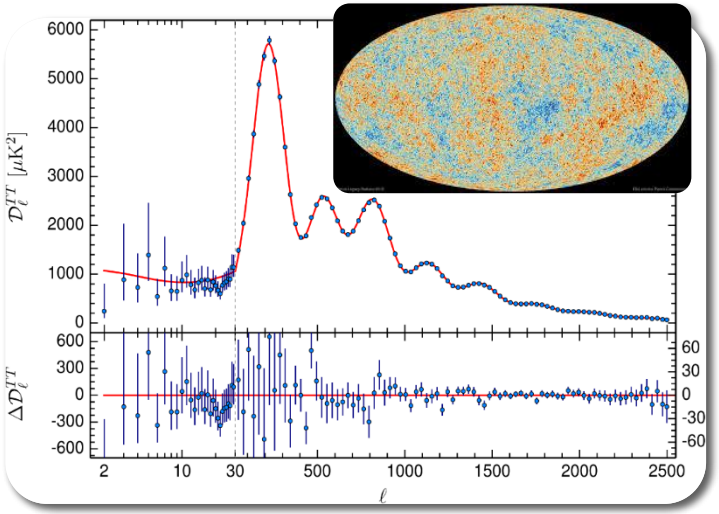
Park, Jong-Chul

CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

2021 KPS-DPF Meeting
2021.12.17

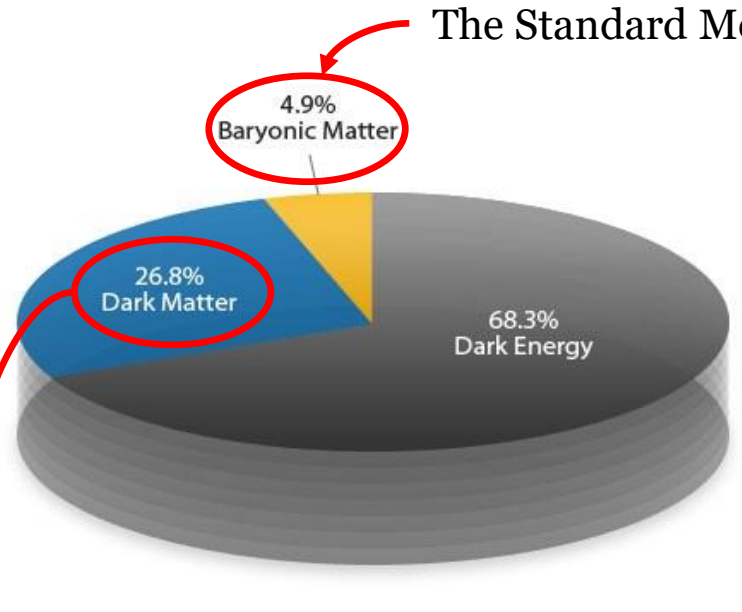
Message from Cosmology: Dark Matter (DM)





❖ **Evidence**: Galactic rotation curve, Bullet cluster, Coma cluster, Gravitational lensing, Structure formation, CMB, …

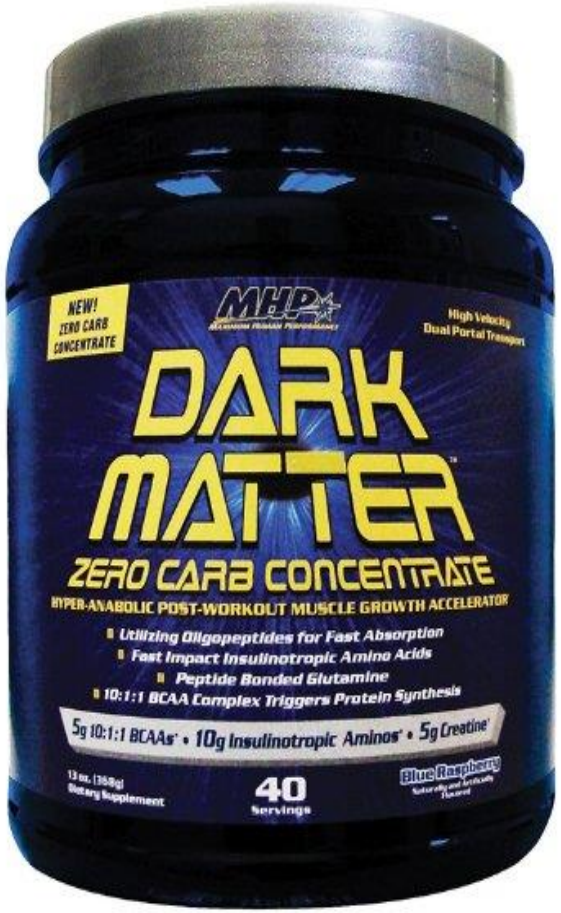
❖ **Modern cosmology**:



❖ **Compelling paradigm**:

- ✓ Massive,
- ✓ Non-relativistic ($v \ll c$),
- ✓ Non-luminous (no/tiny EM interaction),
- ✓ Stable particles

One of the Big Questions in the 21st Century



What's Dark Matter?

Weakly Interacting Massive Particle (WIMP)

Classic Solution*: WIMP

Cosmological Lower Bound on Heavy-Neutrino Masses

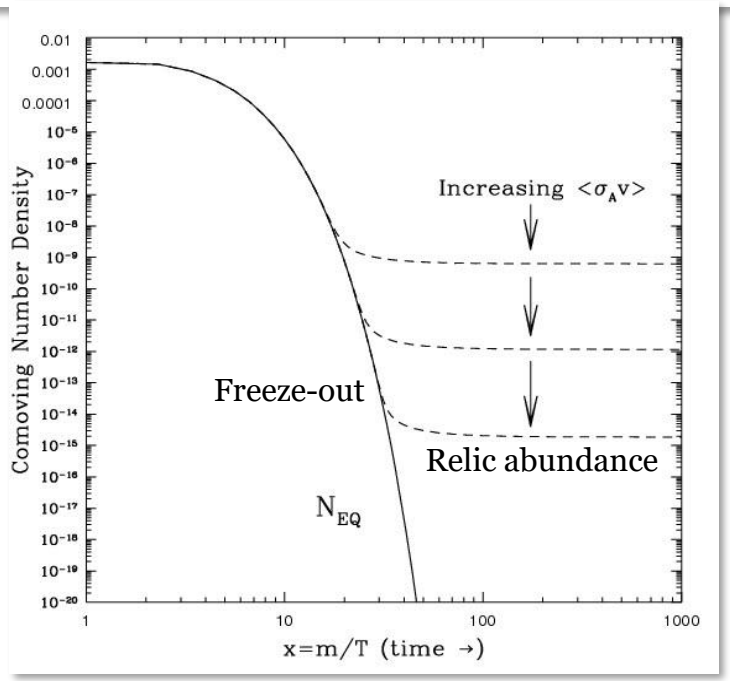
Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

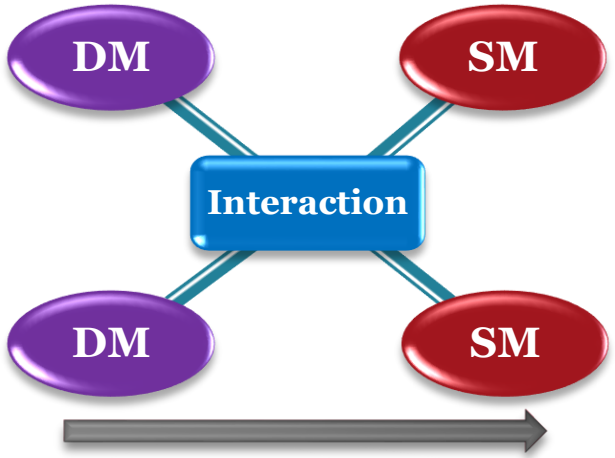
and

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

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

PRL (1977)





annihilation

- Correct thermal relic abundance:

  $\Omega h^2 \sim \frac{0.1\,pb}{\langle\sigma v\rangle}$ with $\langle\sigma v\rangle \sim \frac{\alpha_X^2 m_X^2}{M^4}$ (M: dark scale/mediator)

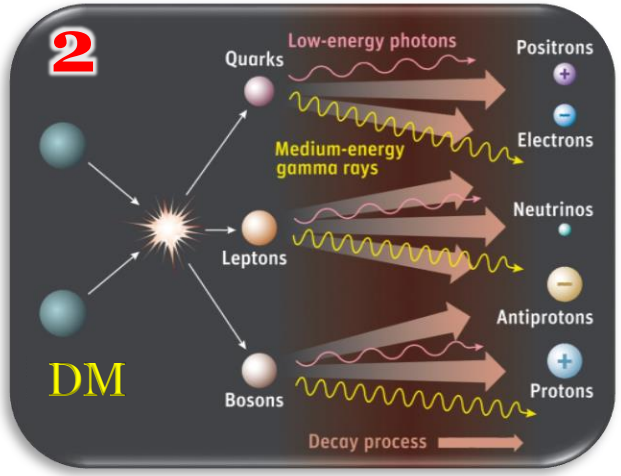
- Weak coupling ➔ naturally weak scale mass:

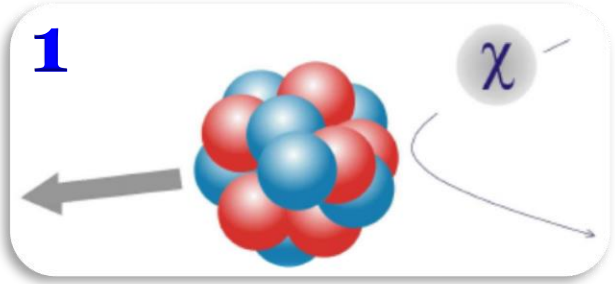
  ~ 1 GeV – 100 TeV mass range favored

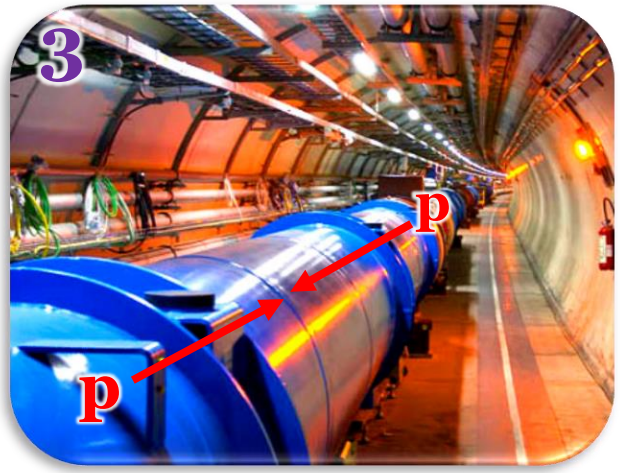
  ➔ weak scale (new) physics

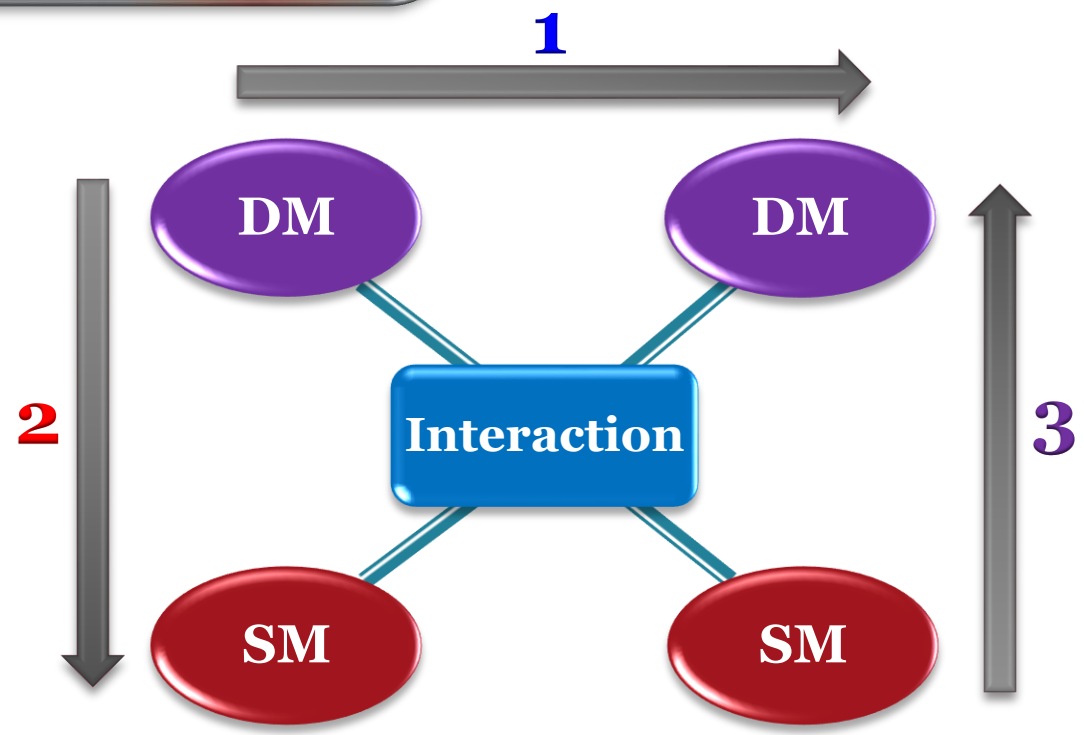
* Of course also **axion**: **Woohyun's talk**

Conventional DM Search Strategies









❖ Based on the WIMP paradigm.

Cosmological Lower Bound on Heavy-Neutrino Masses

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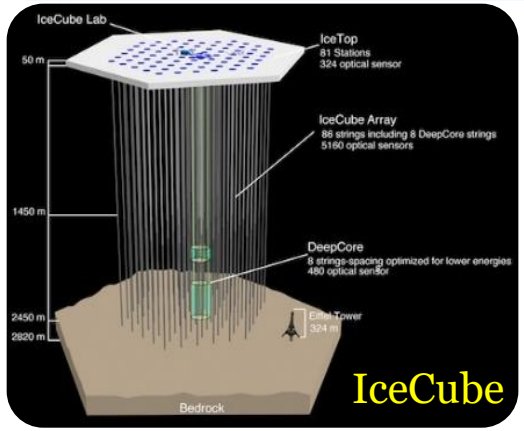
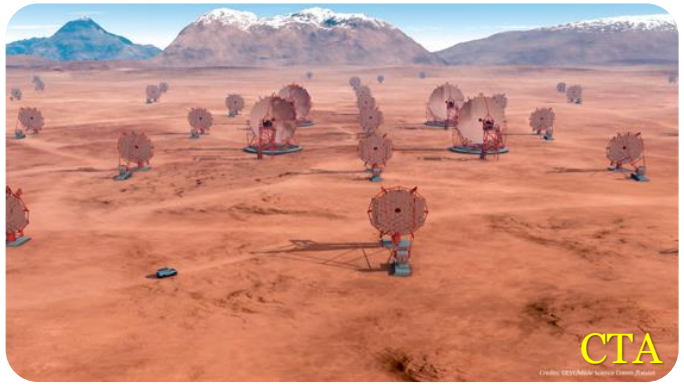
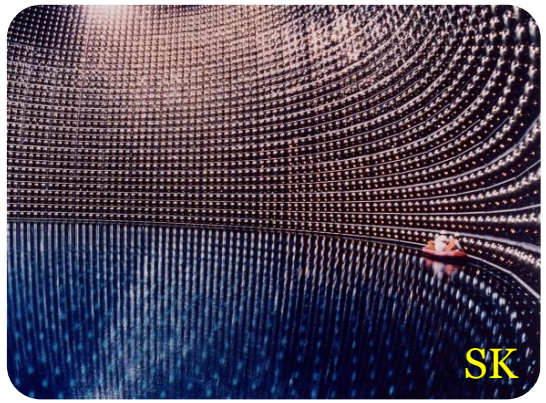
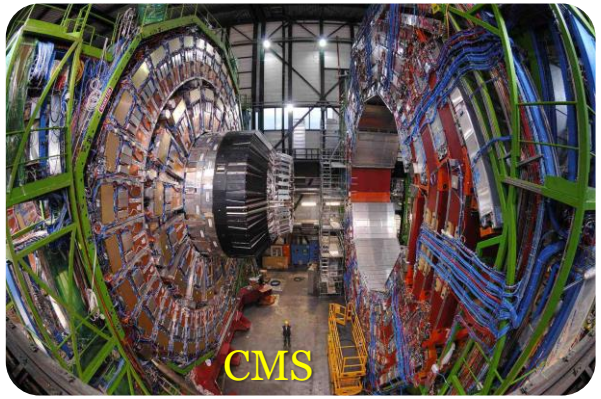
[PRL (1977)]

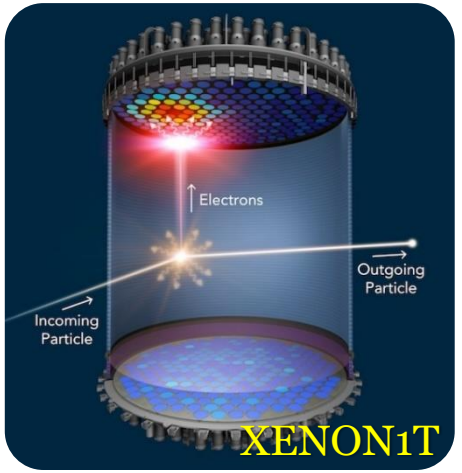
Diverging Efforts for WIMP Searches

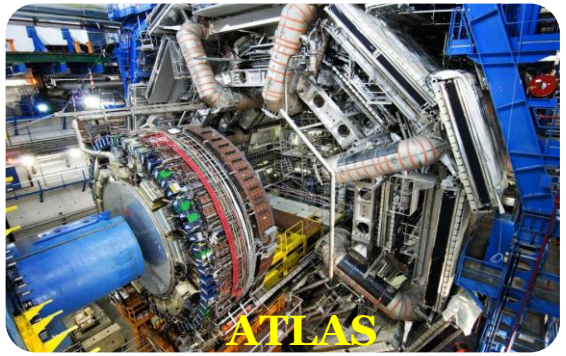


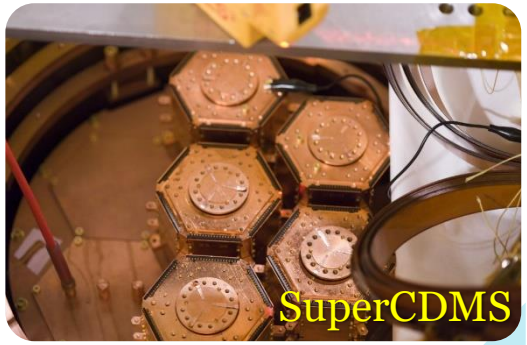






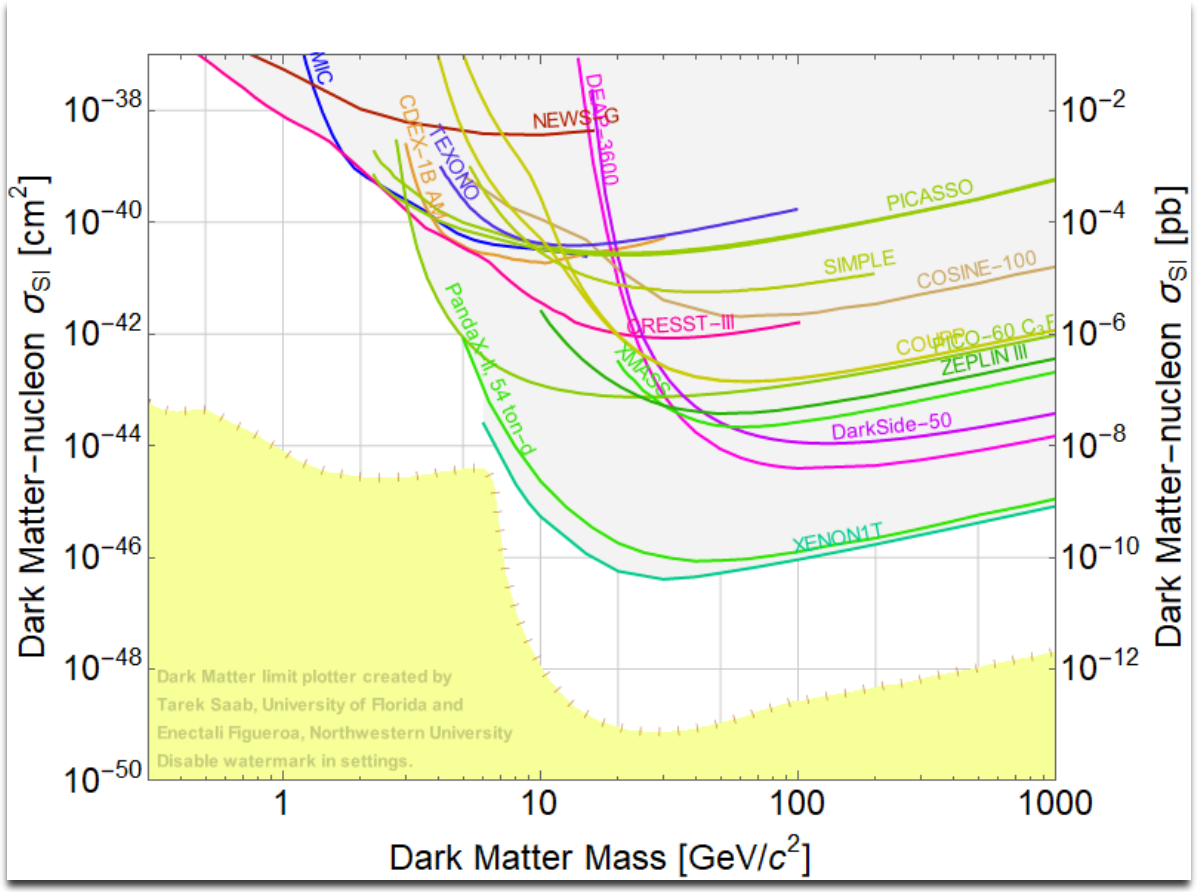


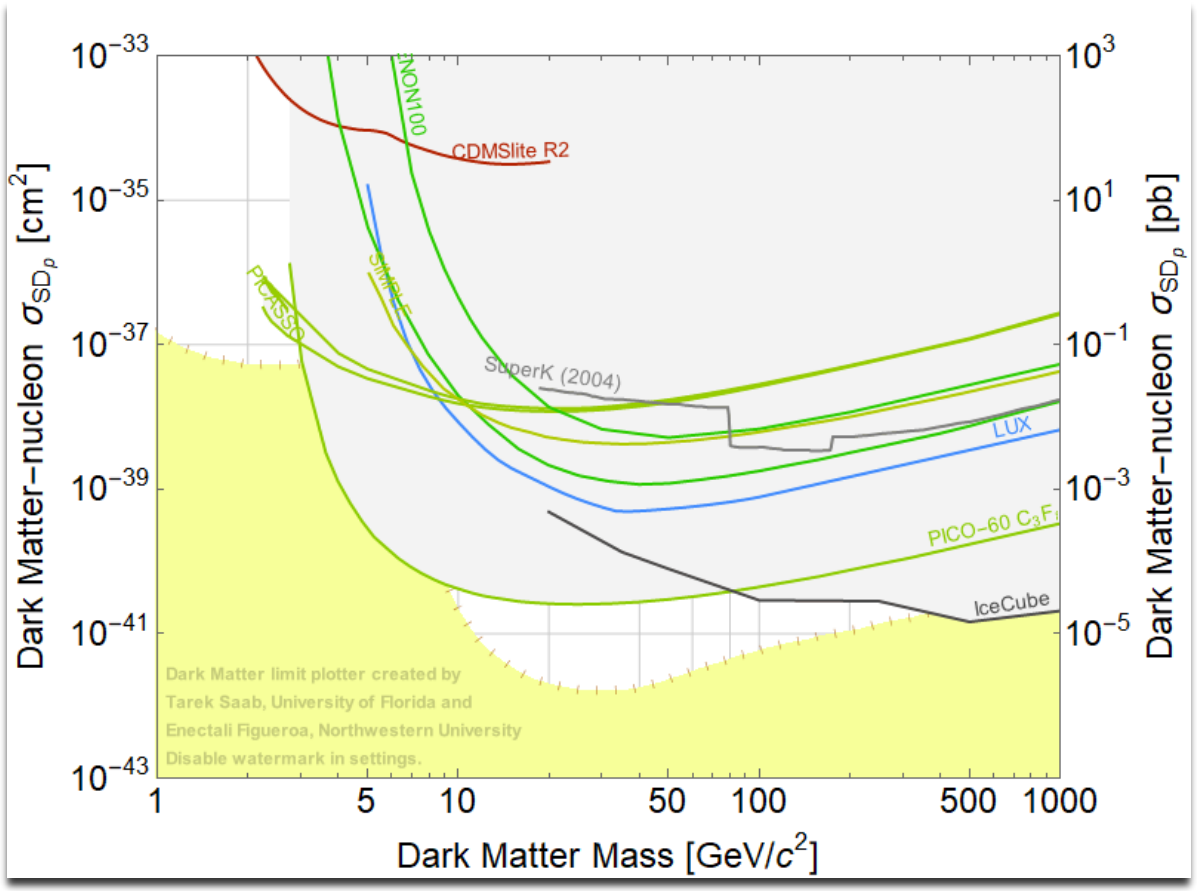




Current Search Status: Direct

❖ Stringent constraints on WIMP.

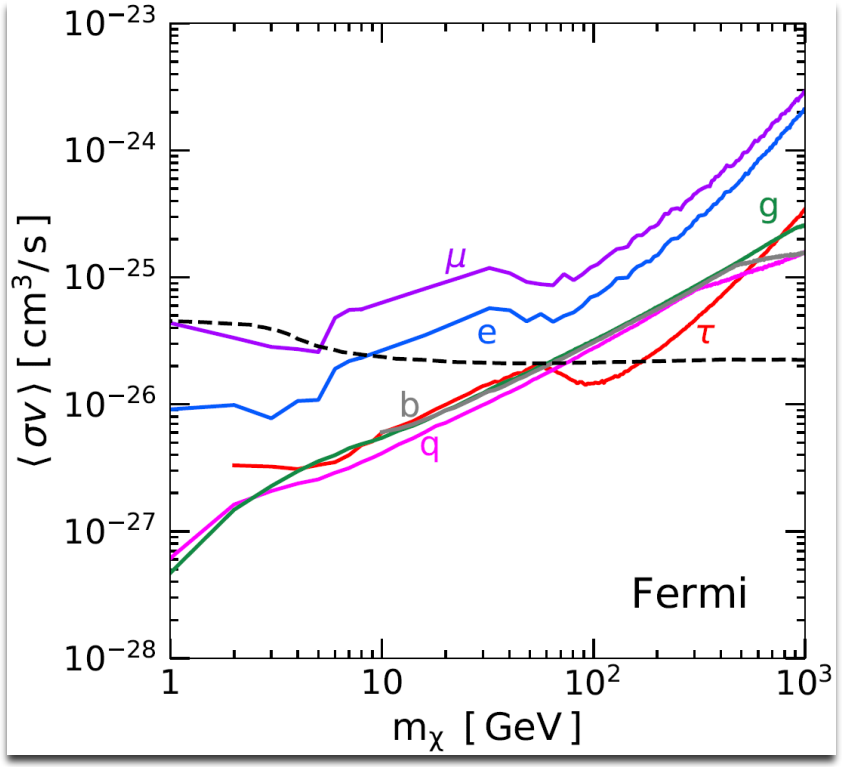


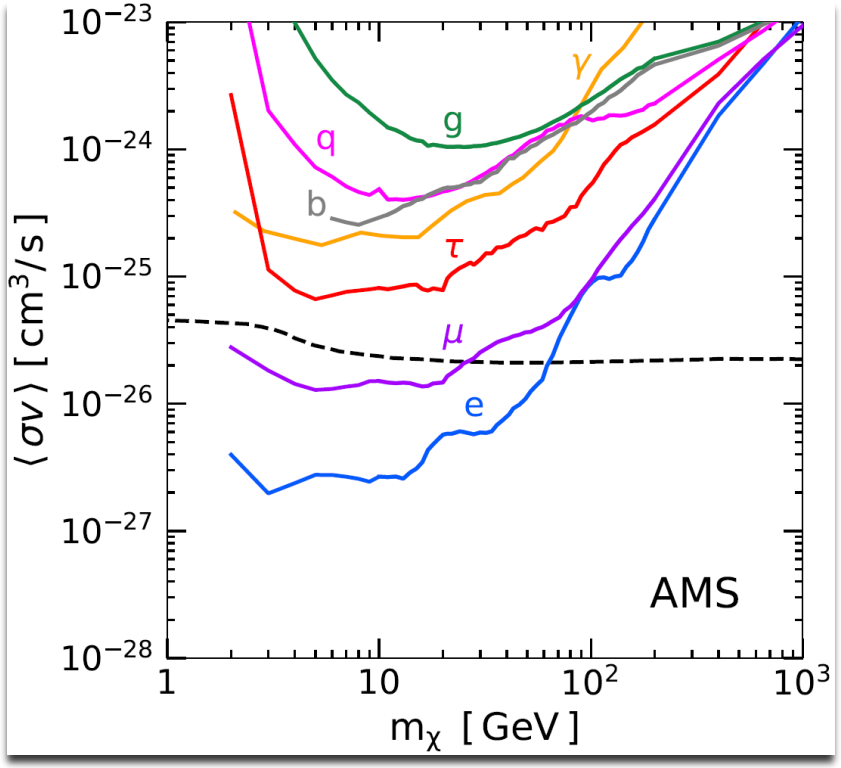


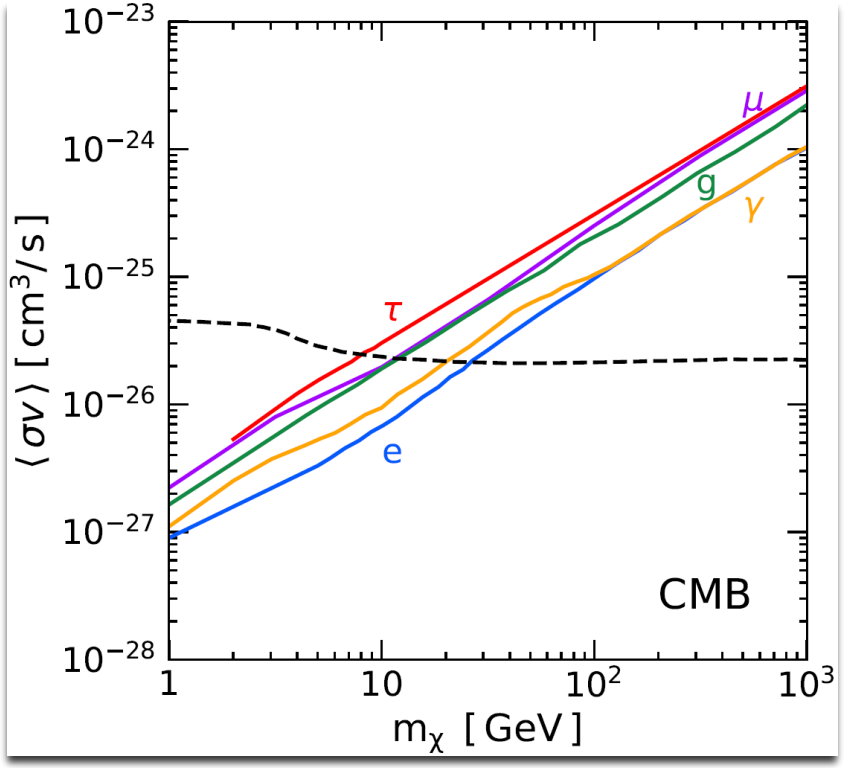
Dark Matter Limit Plotter v5.16, updated September 03, 2021

Current Search Status: Indirect

❖ Stringent constraints on WIMP, too.



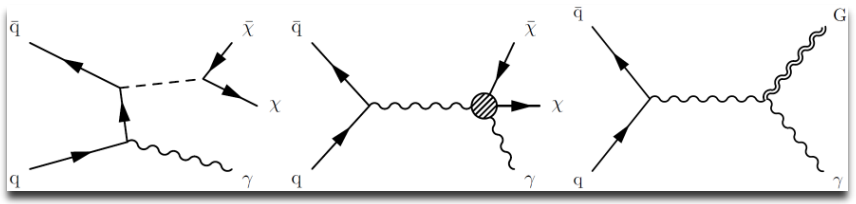


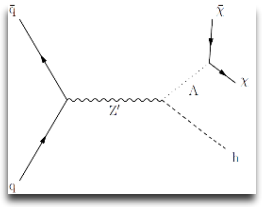


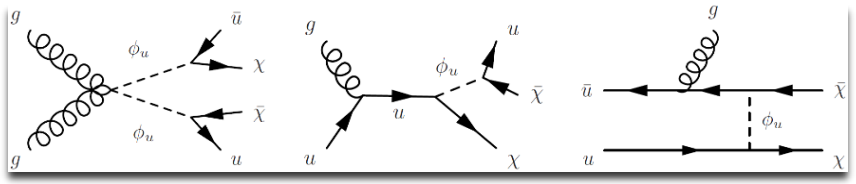
[1805.10305]

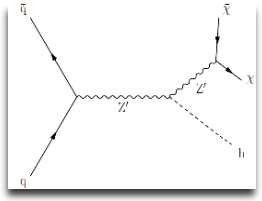
Current Search Status: LHC

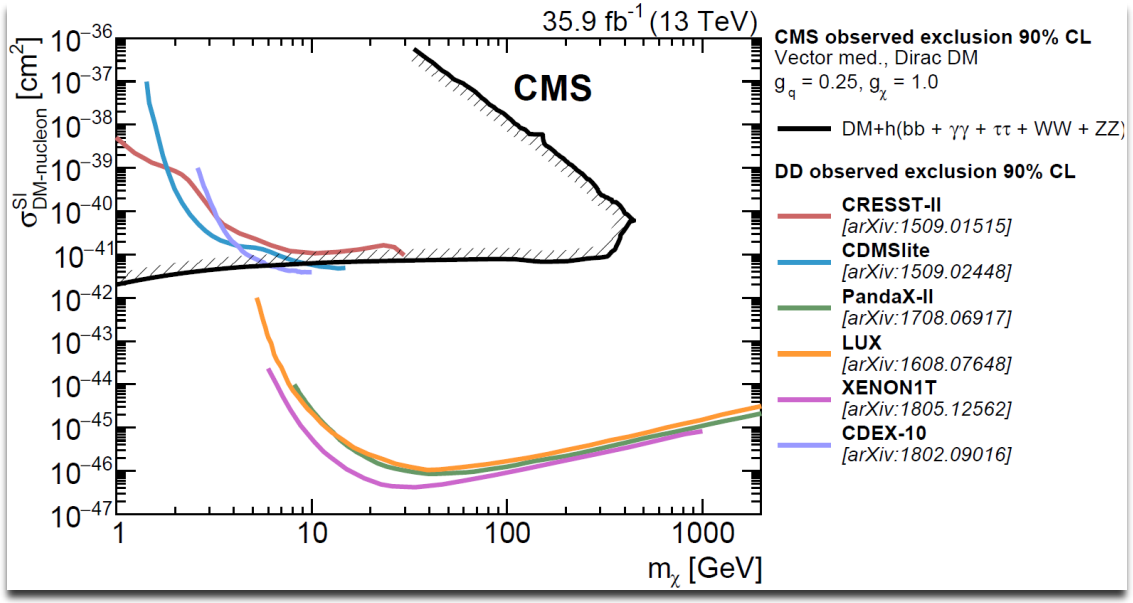
❖ Stringent constraints on WIMP, again.

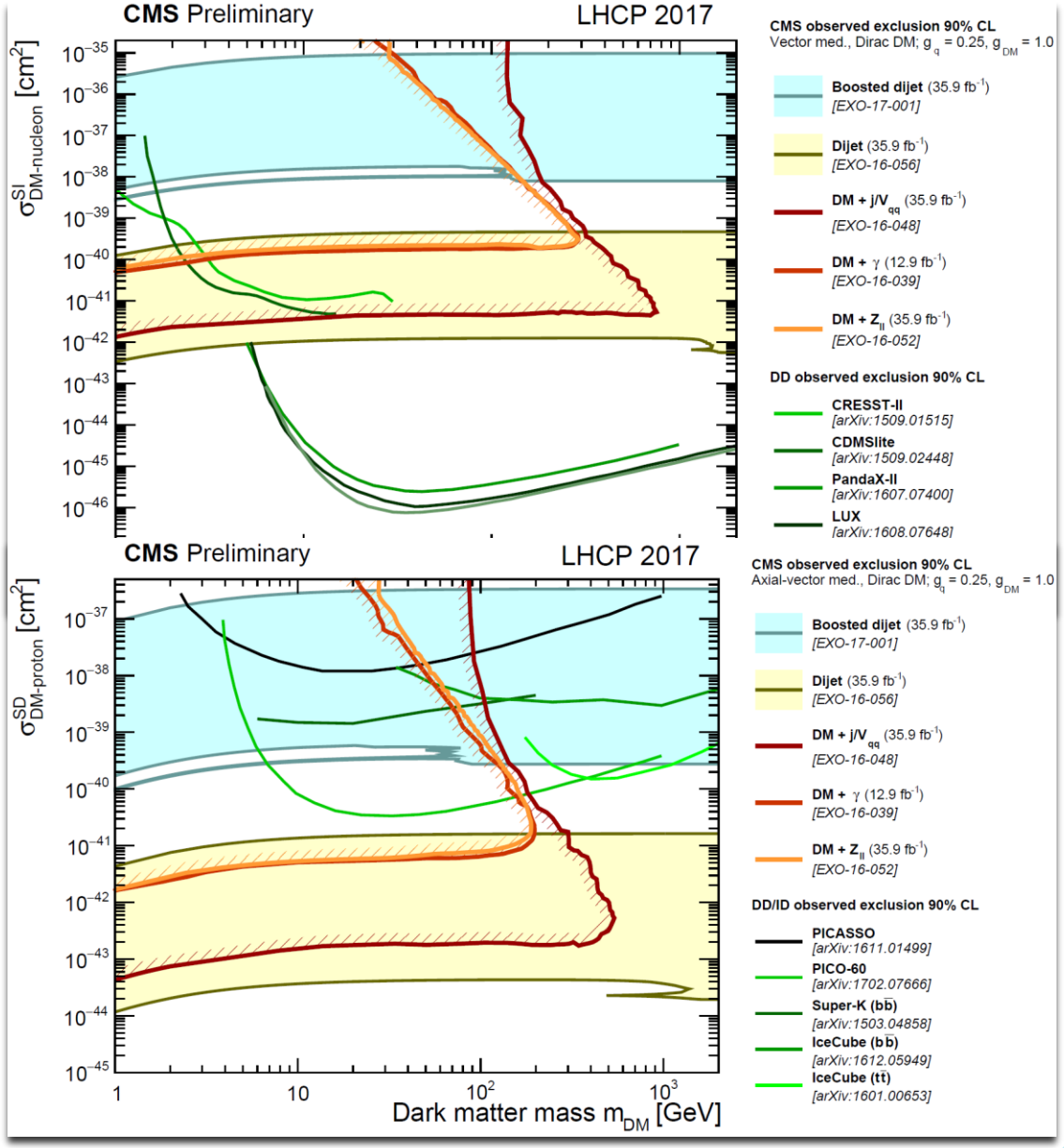




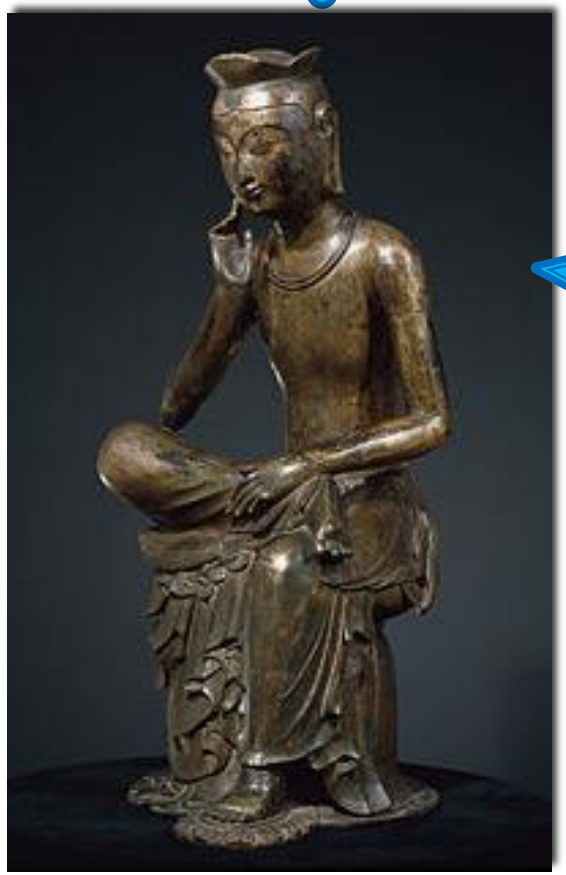








Hmm...
WIMP Dead?



No
Alive!

WIMP: Thermal Relic ➔ Constraints?

❖ WIMP models can get around experimental constraints.

- ✓ Correct relic from thermal freeze-out:

$$\Omega_{\rm DM}h^2 \approx 0.1\left(\frac{2\times10^{-26}\ {\rm cm}^3/{\rm s}}{\langle\sigma v\rangle}\right)$$

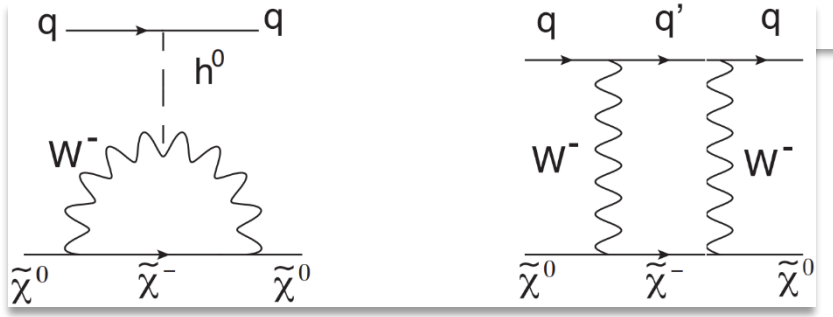
- ✓ This is usually translated into direct/indirect/collider event rates.

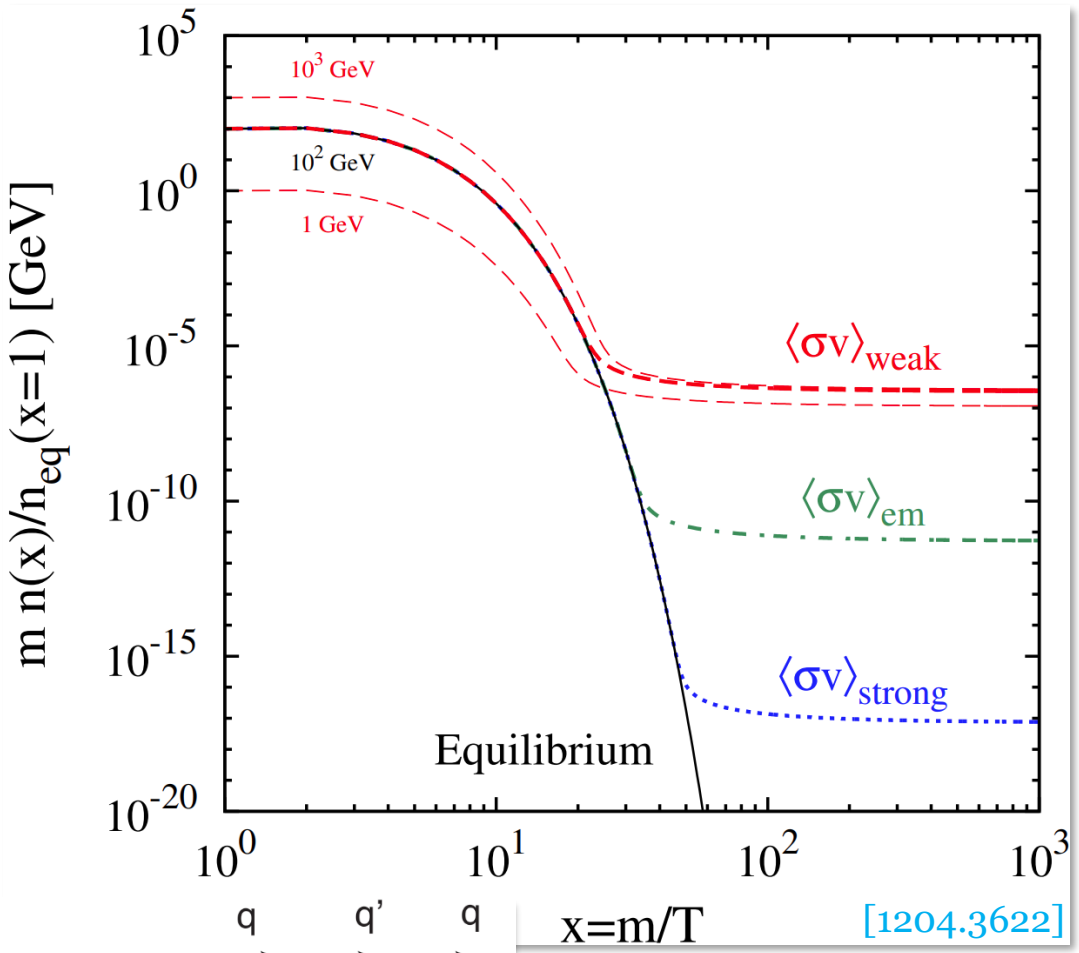
However, It's <u>Not So Simple</u>!

❖ <u>Loopholes</u>: generic, e.g. for fermion DM

- ✓ Scalar coupling: p-wave annihilation
- ✓ Pseudoscalar coupling: momentum-suppressed scattering
- ✓ SU(2) multiplets (EWDM): loop-level scattering

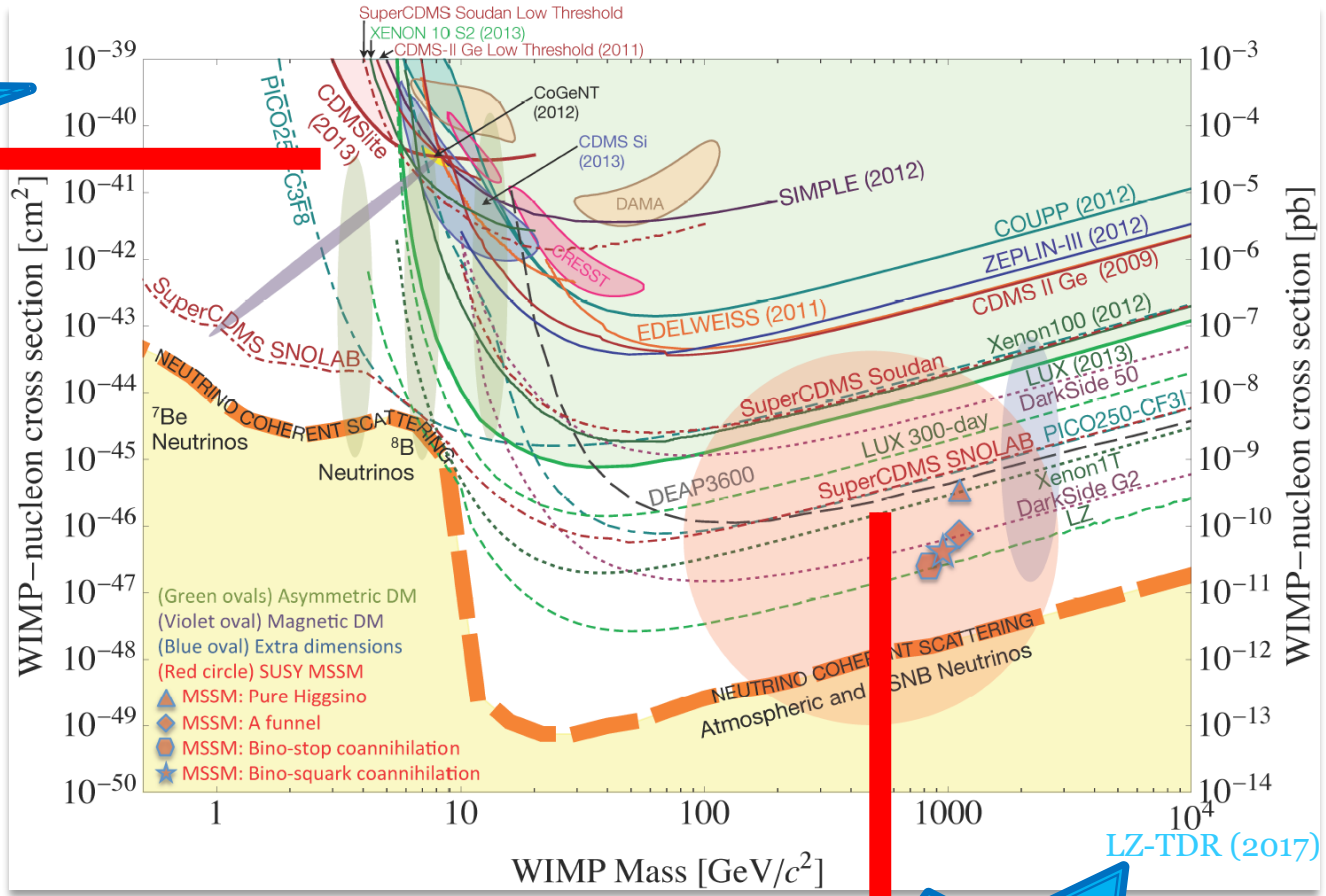
  + Destructive interference! [0710.1668; 1004.4090; 1309.4092]





Direct Search: Past, Present, and Future

Lower mass



- Z exchange
- h exchange
- W-loop (wino-like)
- W-loop (higgsino-like)

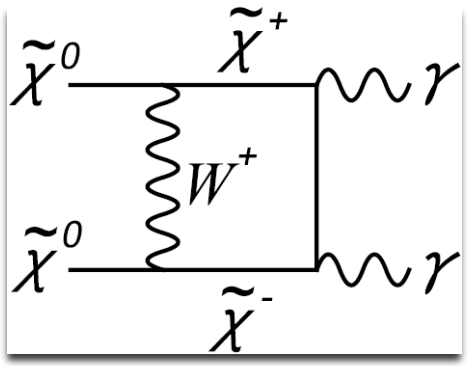
✓ Ideas to overcome BGs: e.g. annual modulation (COSINE), directionality (NEWSdm) ➔ **Chang Hyon's talk**!

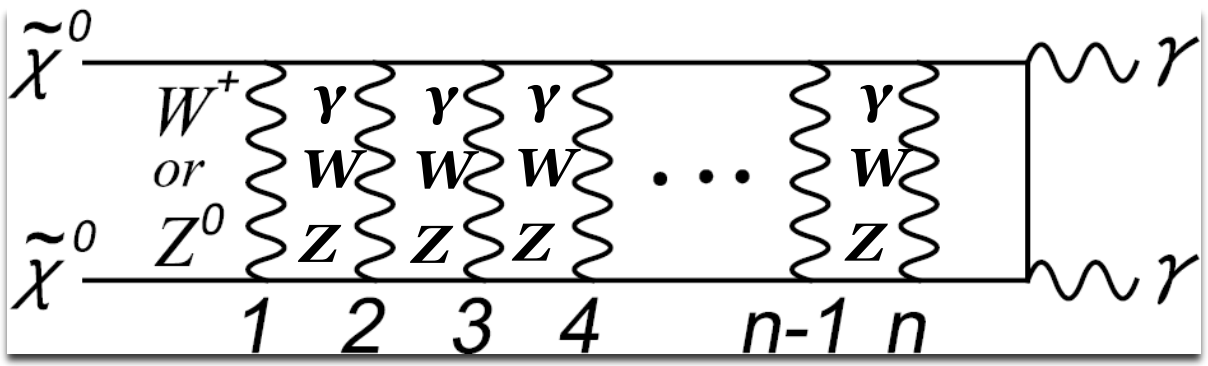
Lower X-section

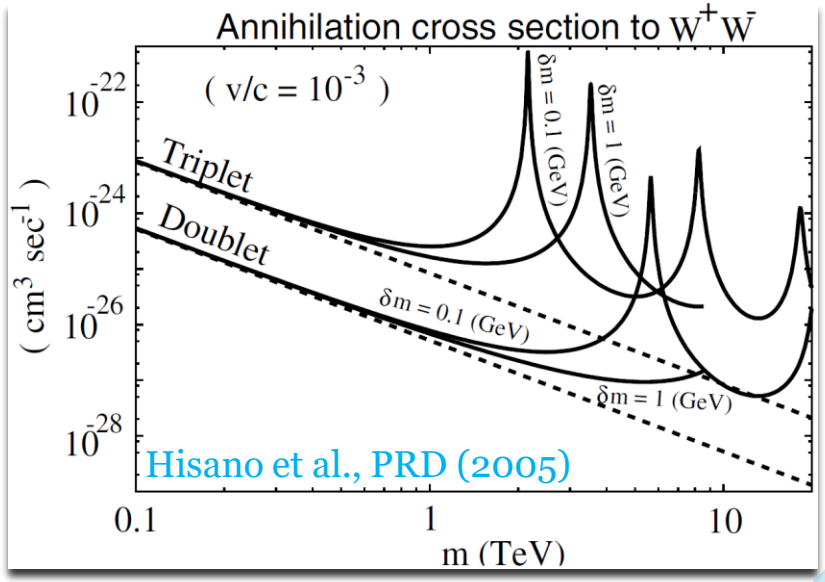
Sommerfeld-Ramsauer-Townsend Effect for EWDM

EJ Chun, **JCP**, S Scopel (2012)

- Intrinsic in non-relativistic pair-annihilation, production, or scattering Sommerfeld (1931); Ramsauer (1921); Townsend (1921)
- In the non-relativistic pair annihilation of EWDM, the non-perturbative effect due to the exchange of EW gauge bosons mixes together the two-body states of the multiplet components.
- Sommerfeld effect ➔ enhancement, but Ramsauer-Townsend effect ➔ suppression
- In DM annihilation, this happens when the Coulomb (Yukawa) force generated by massless (massive) particle exchange becomes strong at small relative velocities: $v<\alpha$, $\alpha m_\chi > m_\varphi$



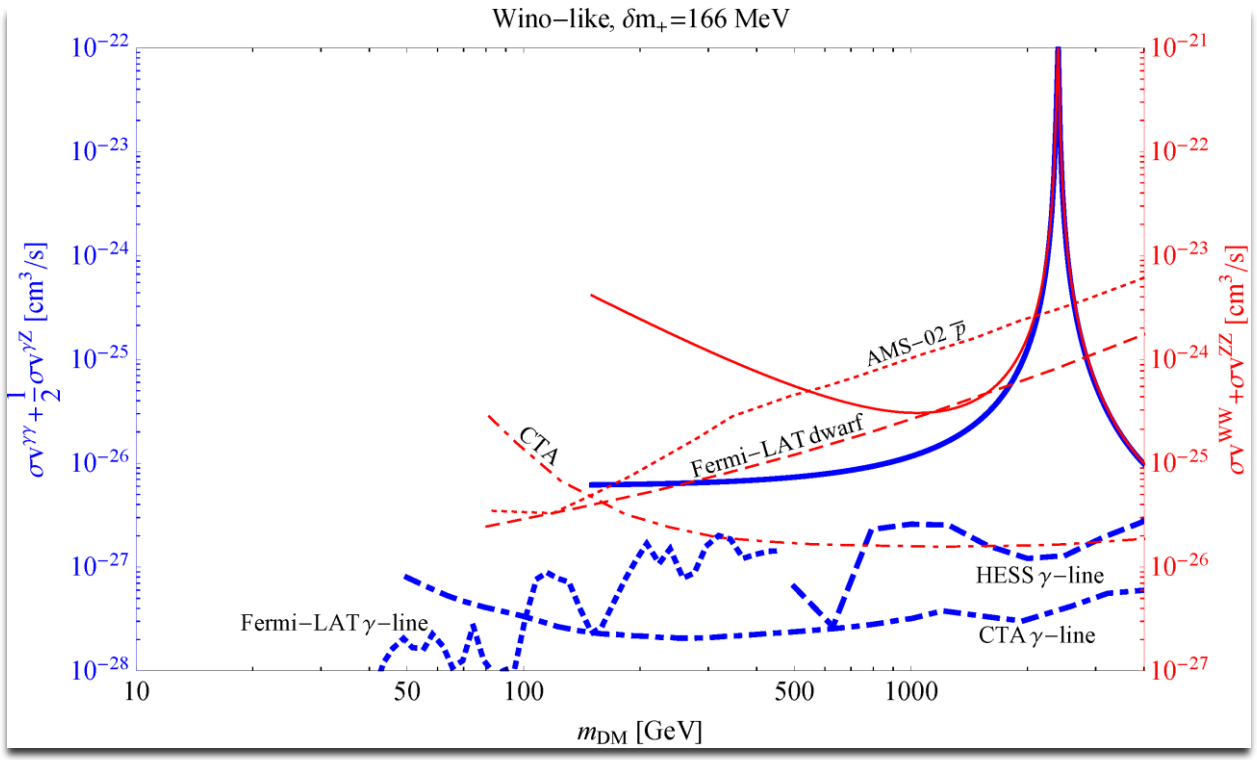


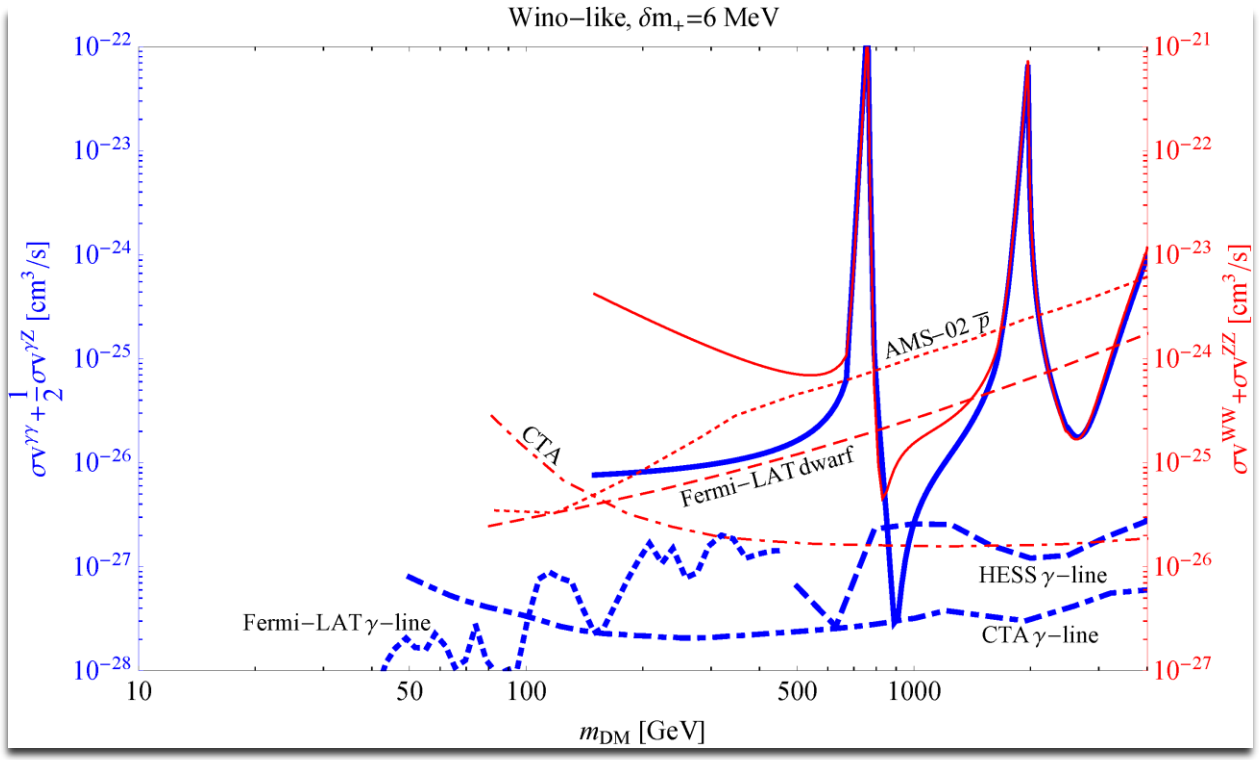


Wino-like EWDM

EJ Chun & **JCP** (2015)

- Stringently constrained by gamma-ray searches
- Could be evaded around RT dips for a small mass splitting

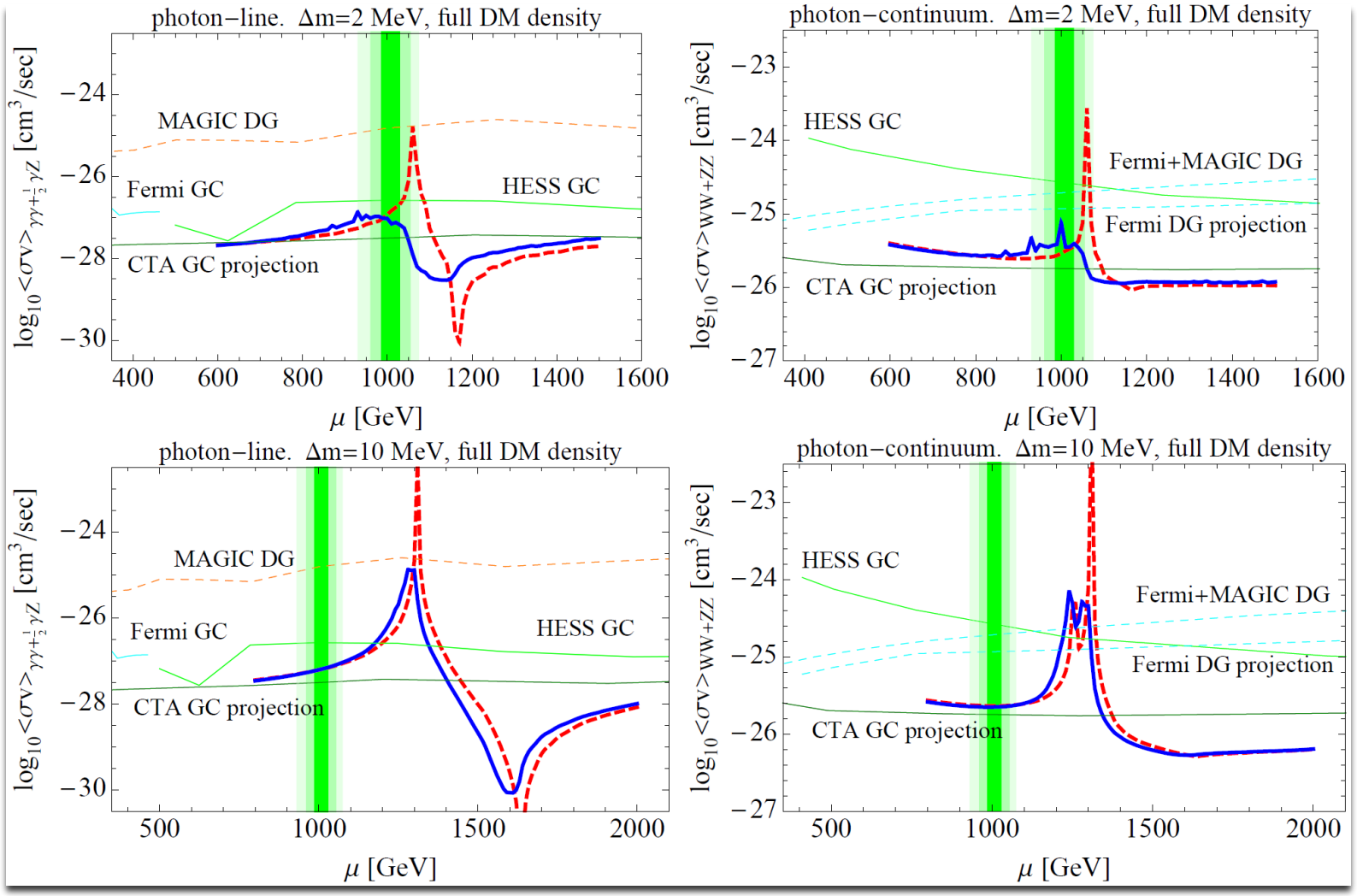




Higgsino-like EWDM

EJ Chun, **JCP**, S. Jung (2016)

- Pure Higgsino LSP: difficult to test up to 1-2 TeV at colliders
- A very degenerate Higgsino DM w/ $\Delta m << \Delta m_{loop} \sim 350$ MeV: realized in the limit $\mu << M1$ & $M2$ admitting slight gaugino mixtures ➔ Produce distinct features in cosmic-ray signals
- Currently, DG (GC) searches constrain Sommerfeld peaks ($\Delta m = 10$ MeV).



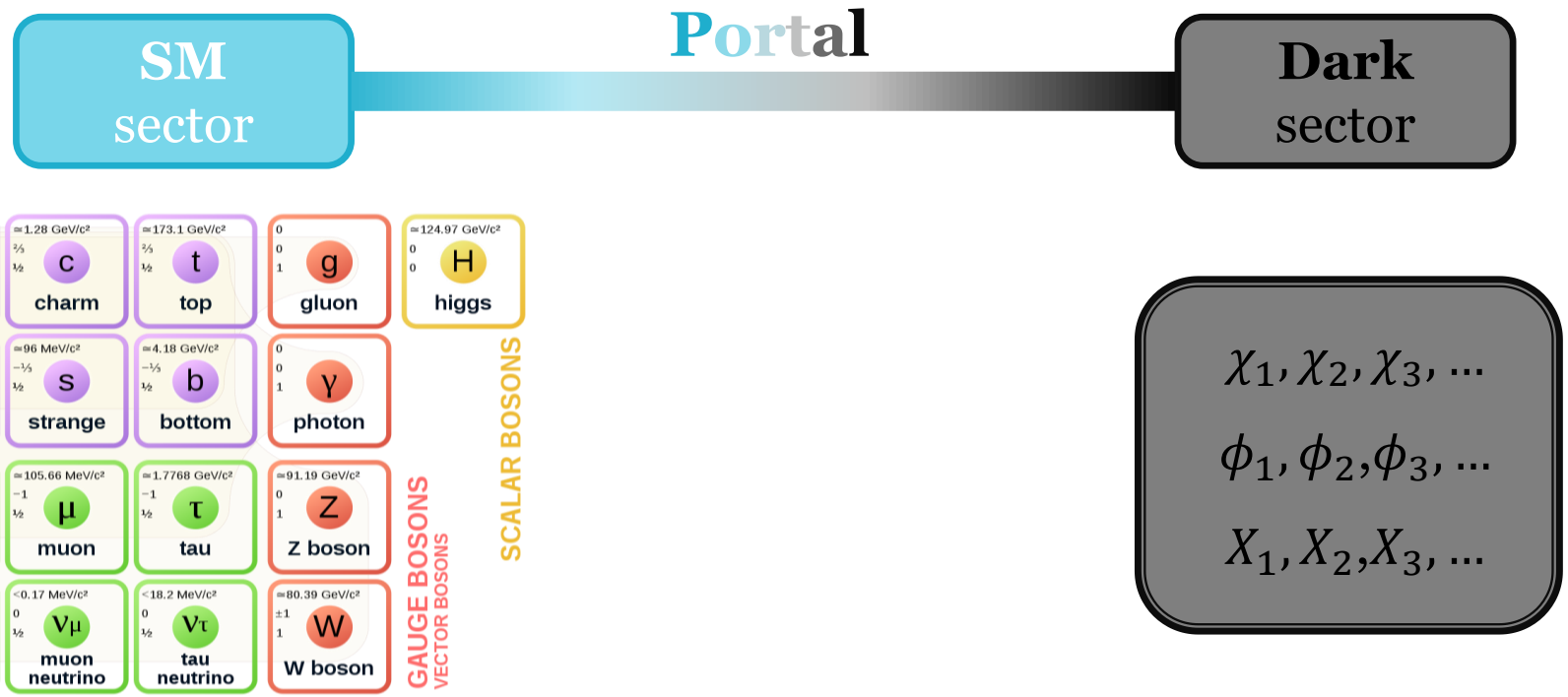
Dark Sector

Dark Sector: Hidden/Secluded

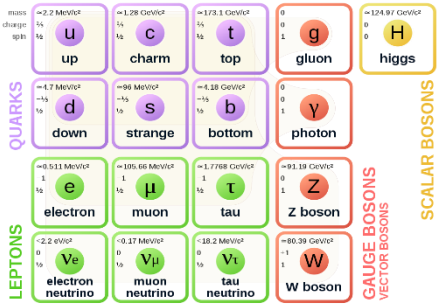
❖ SM mediated WIMP processes & light ($\lesssim$ GeV) SM-charged particles: strongly constrained by experiments

➔ SM-neutral DM (Hidden/Secluded sector) & Need new particles beyond the SM which can mediate interactions between the dark sector & the SM (Portal).

❖ Portal couplings: strongly constrained by Lorentz invariance & SM symmetries.



Dark Sector: Dark Particles & Portals



❖ Portals

- ✓ Vector portal (kinetic mixing): $\frac{\sin\epsilon}{2} B_{\mu\nu} X^{\mu\nu}$
- ✓ Scalar (Higgs) portal: $\lambda_{H\phi} |H|^2 |\phi|^2$
- ✓ Fermion (neutrino) portal: $\lambda_\chi H L \chi$
- ✓ Pseudo-scalar (axion) portal: $\frac{1}{f_{a\gamma/ag}} a F_{\mu\nu} \tilde{F}^{\mu\nu}$

  $\frac{1}{f_{af}} \partial_\mu a (\bar{\psi} \gamma^\mu \gamma^5 \psi)$
- ✓ Gauged SM global #: B-L, L_μ-L_τ, …
- ✓ Dark axion portal: $G_{a\gamma\gamma'} a F_{\mu\nu} \tilde{X}^{\mu\nu}$
- ✓ Double portal: a combination of ≥ 2 portals
- ✓ ???

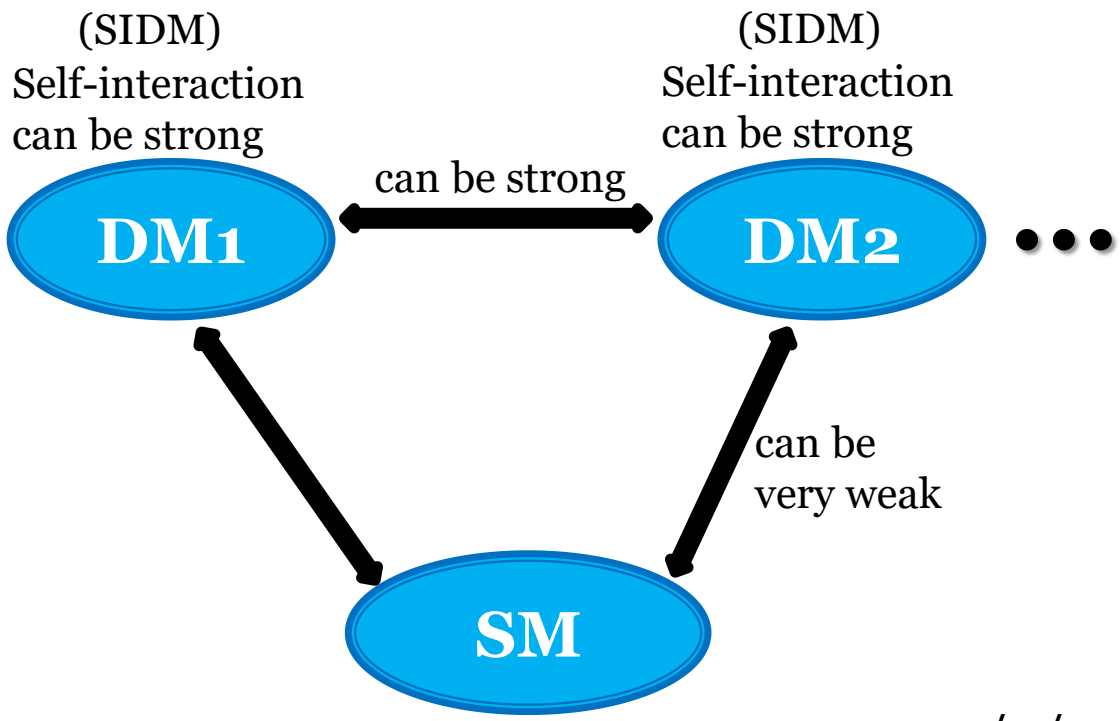
❖ Dark sector

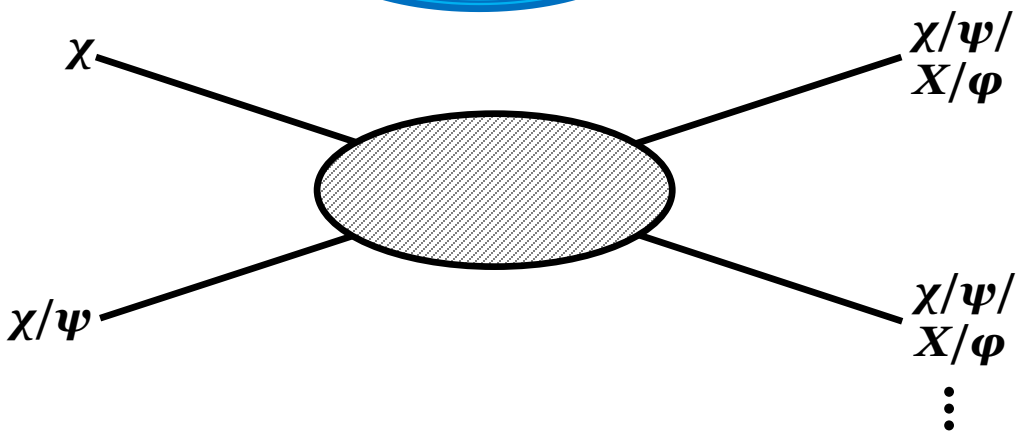
- ✓ DM spin: fermion, scalar, vector
- ✓ DM species: single-/two-/multi-component
- ✓ DM mass: light, heavy, light & heavy
- ✓ DM interaction: flavor-conserving (elastic), flavor-changing (inelastic)
- ✓ ???

New Ideas for DM Relic Abundance

❖ Alternative mechanisms for DM relic determination:

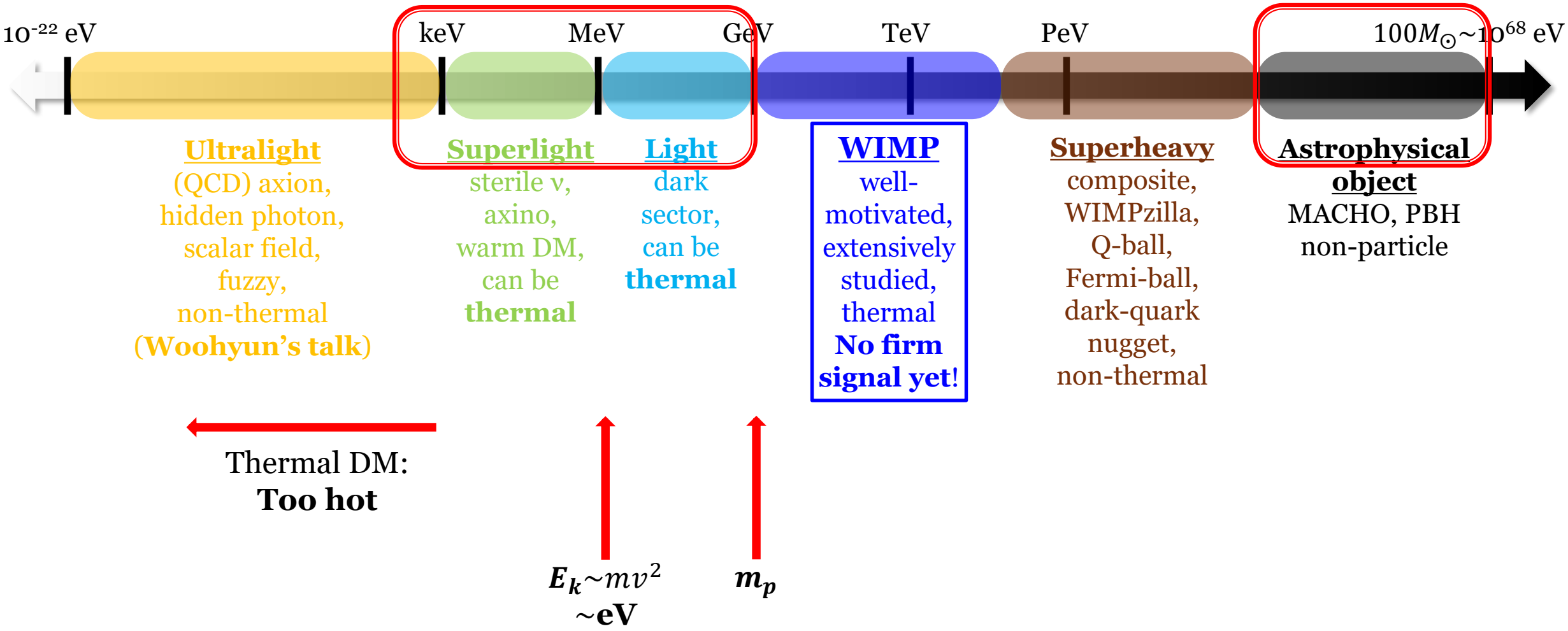
- ✓ Assisted freeze-out [1112.4491]
- ✓ Asymmetric dark matter [0901.4117]
- ✓ Cannibal dark matter [1602.04219, 1607.03108]
- ✓ Co-annihilation [PRD43 (1991) 3191]
- ✓ Co-decaying dark matter [1105.1652, 1607.03110]
- ✓ Continuum dark matter [2105.07035]
- ✓ Co-scattering mechanism [1705.08450]
- ✓ Dynamical dark matter [1106.4546]
- ✓ ELastically DEcoupling Relic (ELDER) [1512.04545]
- ✓ Freeze-in [0911.1120]
- ✓ Forbidden channels [PRD43 (1991) 3191 , 1505.07107]
- ✓ Inverse decay dark matter [2111.14857]
- ✓ Pandemic dark matter [2103.16572]
- ✓ Semi-annihilation [0811.0172, 1003.5912]
- ✓ Strongly Interacting Massive Particle (SIMP) [1402.5143, 1702.07860]
- ✓ …



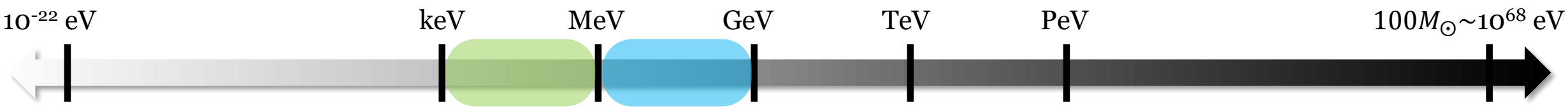


Not WIMP: Other Scales

DM Landscape: A Very Wide Mass Range

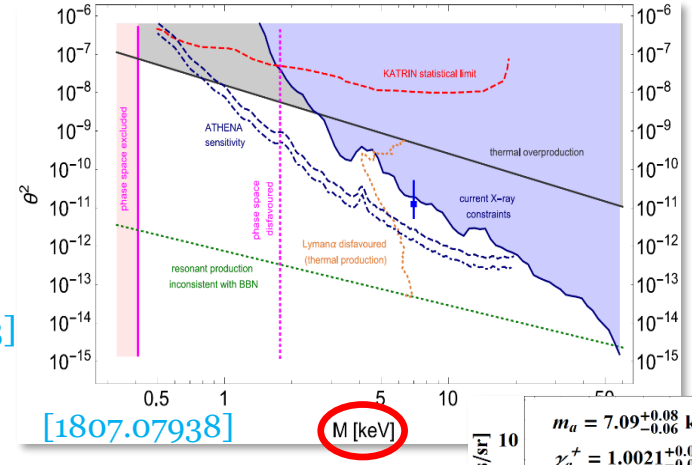


(Super-)Light DM



❖ Various well-motivated super-light DM pheno.:

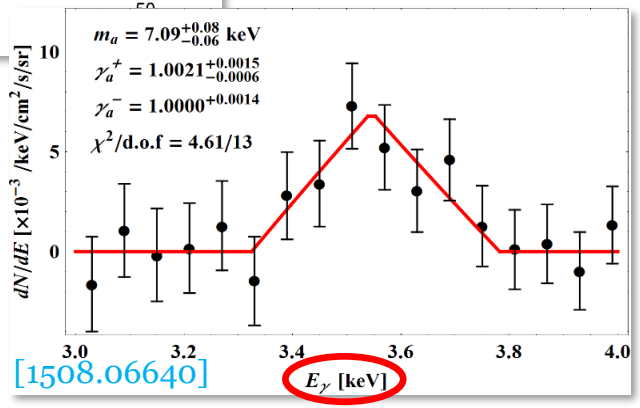
- ✓ Sterile neutrinos [hep-ph/9303287, astro-ph/9810076]
- ✓ Mirror ν DM [hep-ph/9505385]
- ✓ Axino/gravitino [0902.0769, 1407.0017]
- ✓ Axion-like particles [0912.0015, 1407.0017, 1510.07633]
- ✓ Super-light dark gauge bosons [1105.2812, 1201.5902]
- ✓ Decaying DM for 3.5 keV line [1403.0865, 1403.1536]
- ✓ keV DM for XENON1T, … [2006.10035, 2006.16252]



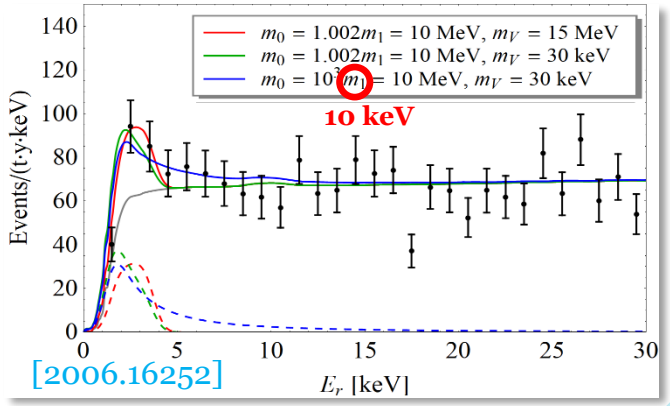
[1807.07938]

❖ Various light DM/mediator scenarios:

- ✓ MeV DM for GC 511 keV line observation [astro-ph/0309686]
- ✓ Secluded MeV DM [0711.3528, 0711.4866]
- ✓ Sommerfeld enhancement for e^+ excess [0810.0713]
- ✓ $(g-2)_{e,\mu}$: $\sim 2-5\sigma$ discrepancy [1806.10252]
- ✓ New ν interactions for the MiniBooNE excess [1807.09877]
- ✓ Solutions of Yukawa coupling hierarchy prob. [1905.02692]
- ✓ …

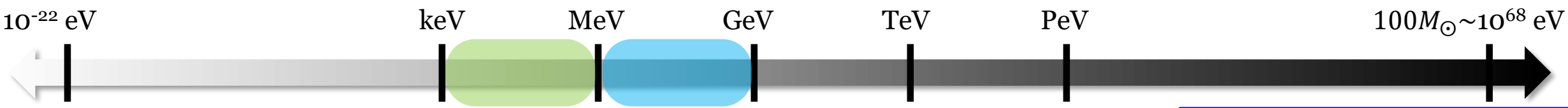


[1508.06640]



[2006.16252]

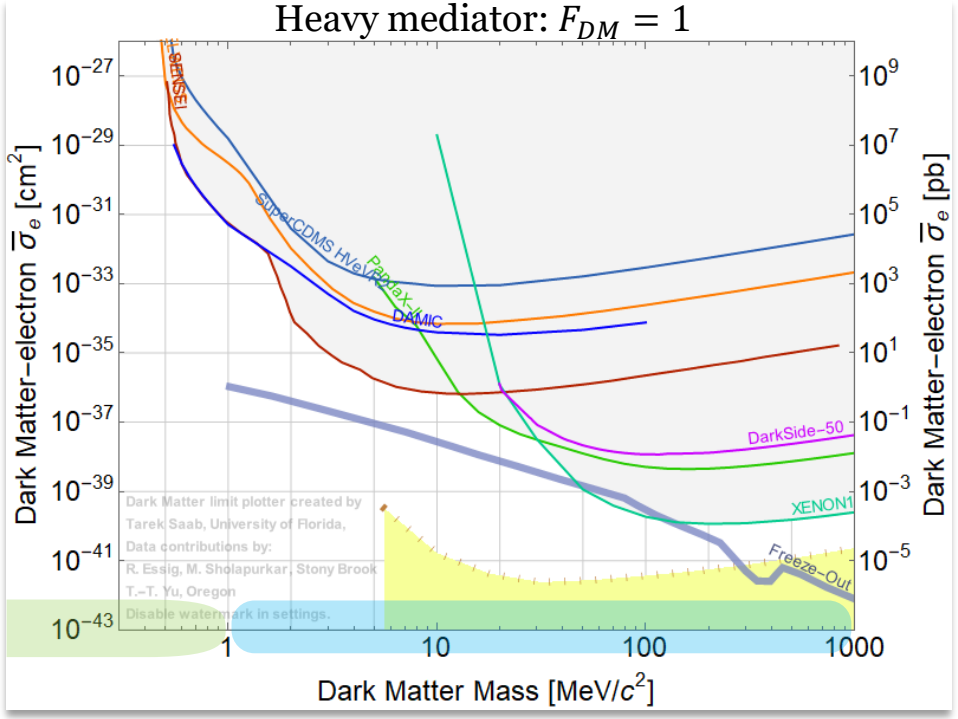
(Super-)Light DM Direct Search



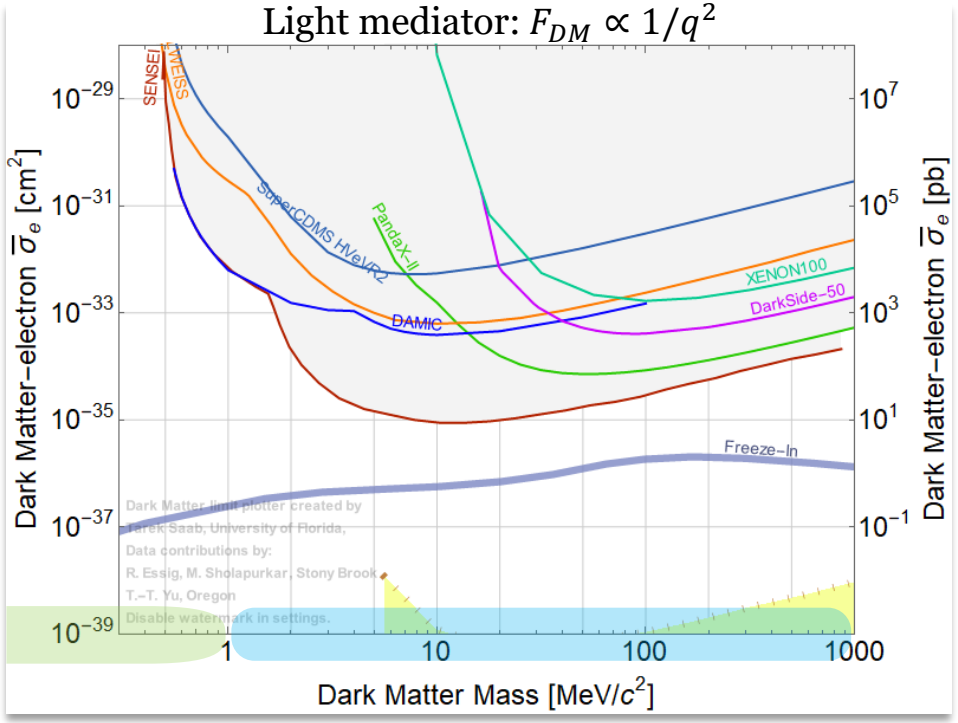
- $E_k \sim mv^2$, $\Phi_\chi = n_\chi v_{rel}$ & $n_\chi = \rho_\chi / m_\chi$ ➔ smaller mass: smaller E_r but **lager flux**
  ➔ **low E_{th}** preferred even with **small target mass**

✓ Ideas for super-light DM
Sehwook's talk!

Heavy mediator: $F_{DM} = 1$



Light mediator: $F_{DM} \propto 1/q^2$

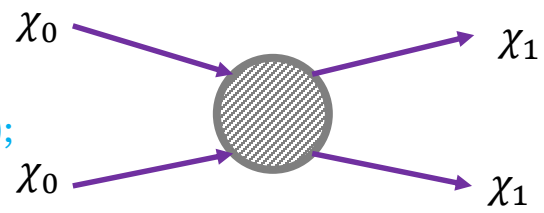


Dark Matter Limit Plotter v5.16, updated September 03, 2021

DM Boosting Mechanisms

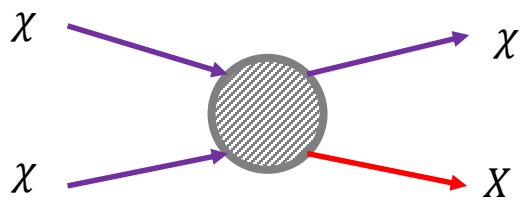

Boosted DM (BDM) coming from the Universe

[Belanger & **JCP**, JCAP (2012);
Agashe et al., JCAP (2014);
Kong, Mohlabeng, **JCP**, PLB (2015);
Berger et al., JCAP (2015);
Kim, **JCP**, Shin, PRL (2017);
more]



✓ Multi-component model

$m_0 \gg m_1$



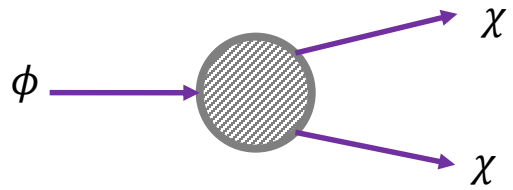
[D'Eramo & Thaler, JHEP (2010);
Berger et al., JCAP (2015)]

✓ Semi-annihilation model

$m_\chi \gg m_X$

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

- BDM signal: detectable at large Vol.
  DM & neutrino detectors
- Need extension of dark sector
- Relic component DM: non-relativistic!



✓ Decaying multi-component DM

$m_\phi \gg m_\chi$

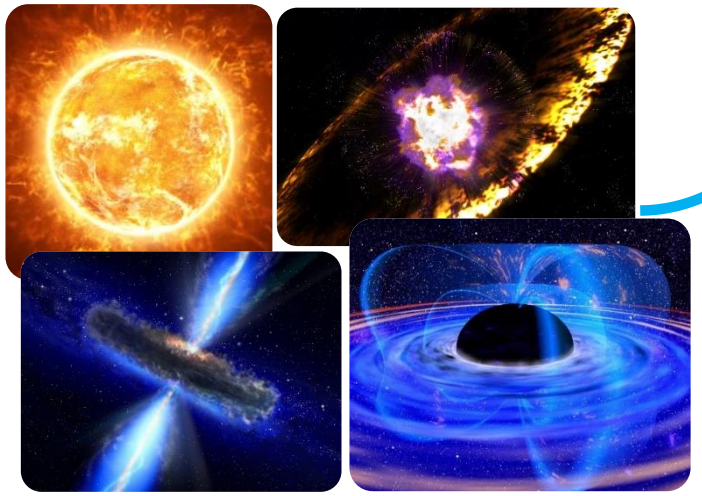
[Bhattacharya et al., JCAP (2015);
Kopp et al., JHEP (2015);
Cline et al., PRD (2019);
Heurtier, Kim, **JCP**, Shin, PRD (2019);
more]

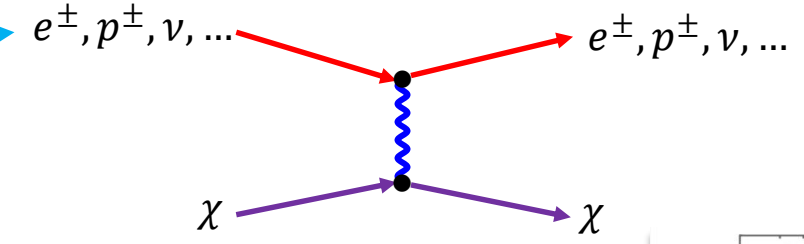
- Heating via sizable self-scattering (natural for LDM) ➔ affect the thermal evolution of DM

[Kamada, Kim, Kim & Sekiguchi, PRL (2018); Kamada, Kim, **JCP** & Shin, 2111.06808]

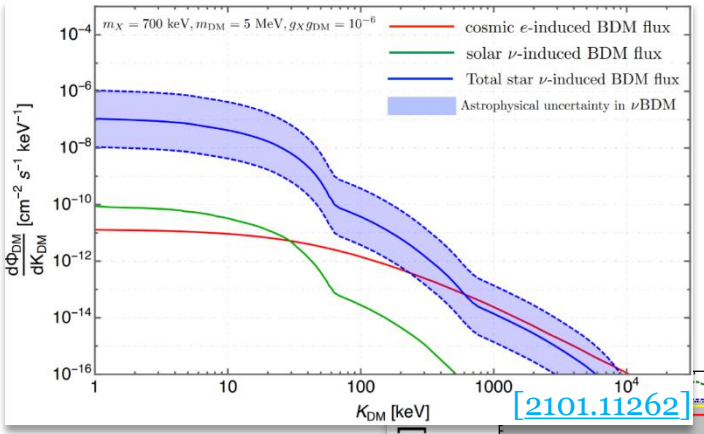
DM Boosting Mechanisms

Cosmic-Ray-Induced BDM

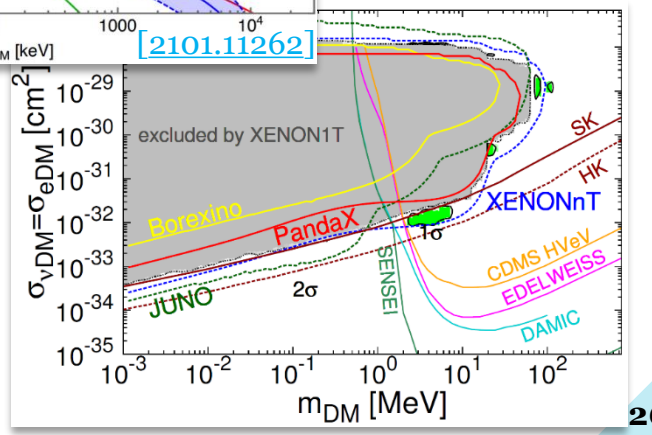




- ✓ Charged cosmic-ray: [Bringmann & Pospelov, PRL (2019); Ema et al., PRL (2019); Cappiello & Beacom, PRD (2019); Dent et al., PRD (2020); Jho, **JCP**, Park & Tseng, PLB (2020); Cho, Choi & Yoo, PRd (2020); more]
- ✓ Cosmic- ν (νBDM): [Jho, **JCP**, Park & Tseng, PRL submitted; Das & Sen, 2104.00027]



[2101.11262]

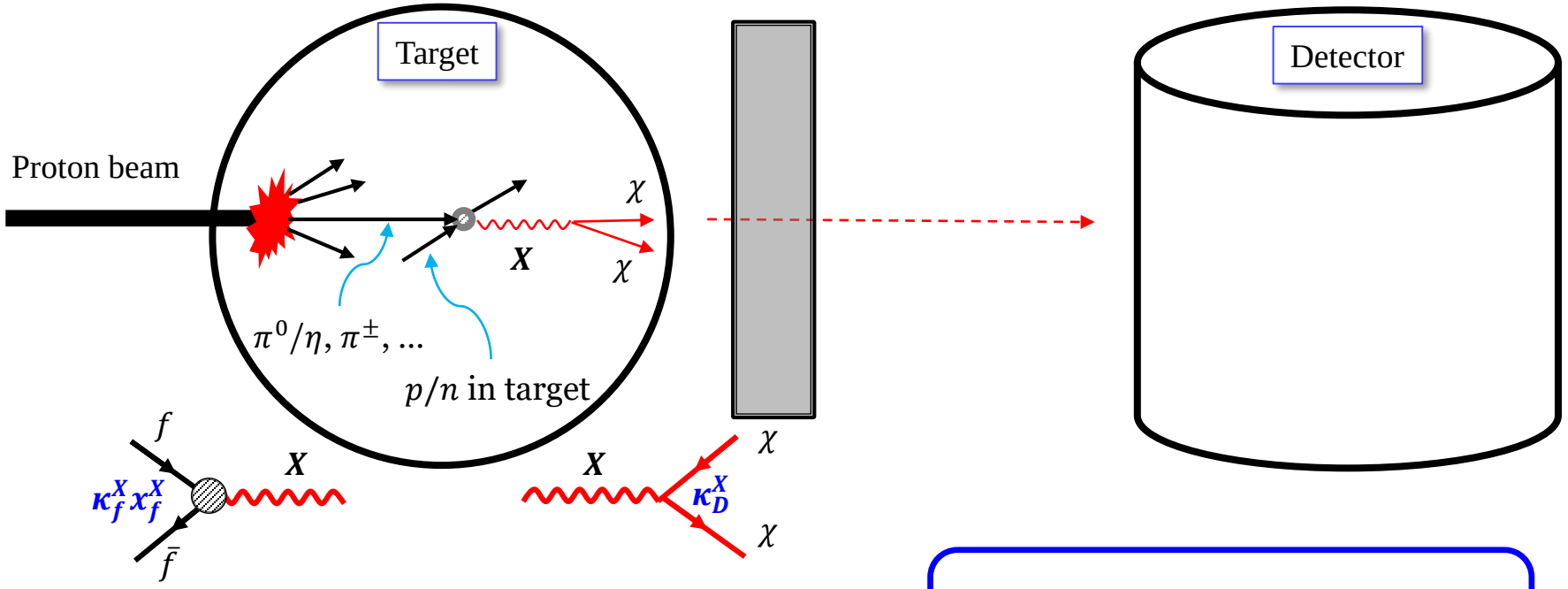


❖ Energetic cosmic-ray-induced BDM: cosmic-rays kick DM

(large $E_{e^{\pm},p^{\pm},\nu,\ldots}$ ➔ large E_χ)

➔ Efficient for Light DM

Passive ➔ Active: Direct Production

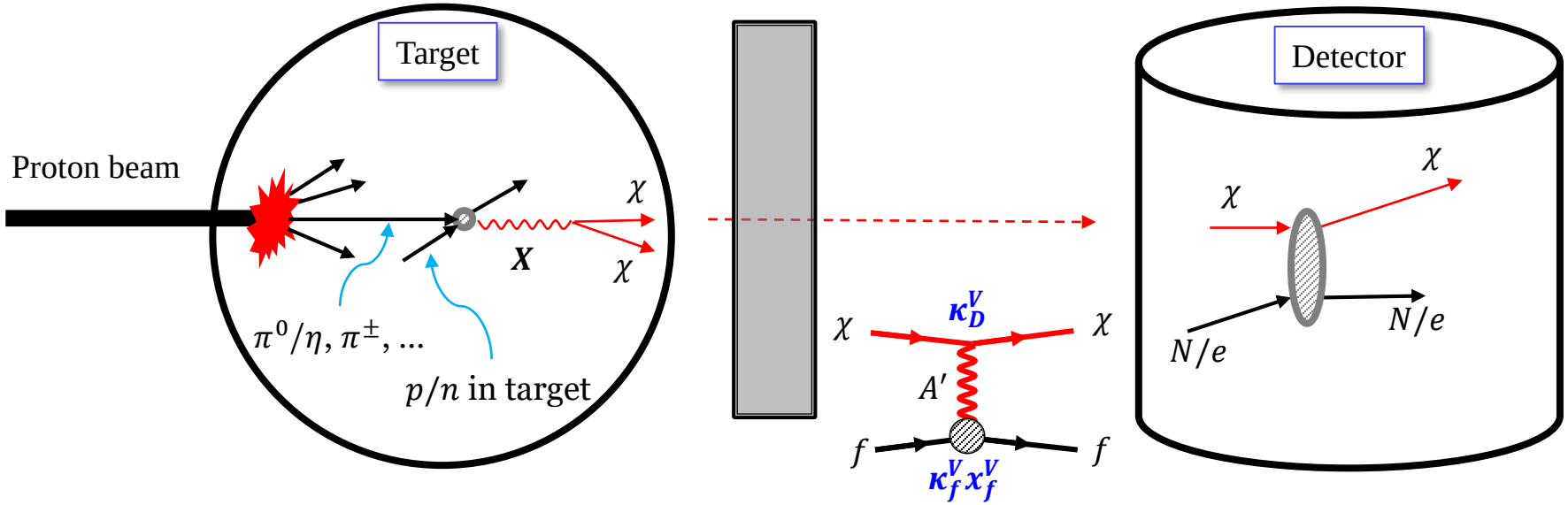


$$\mathcal{L}_{X,\text{prod}} \supset \sum_f \kappa_f^X x_f^X X_\mu \bar{f}\gamma^\mu f + \kappa_D^X X_\mu \bar{\chi}\gamma^\mu \chi$$

Dedicated simulation using e.g. GEANT4 & BdNMC are needed!

- 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 & $\gamma \to \boldsymbol{X}$

Passive ➔ Active: Direct Production & 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 for LDM)

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

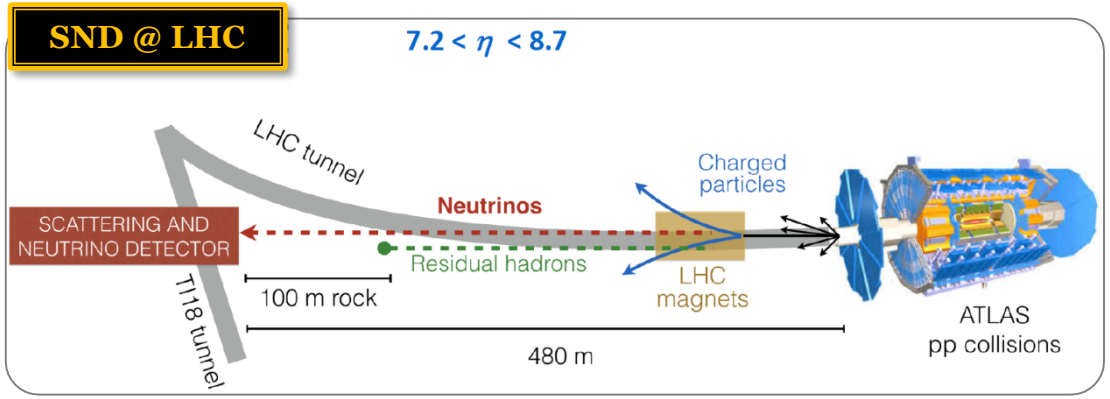
❖ Electron scattering (D2): (large E_r even for LDM)

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

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

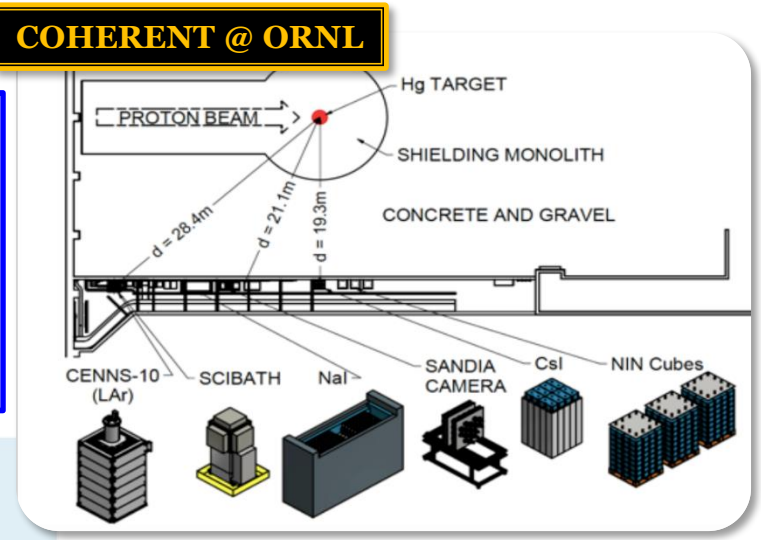
Passive ➔ Active: Direct Production & Detection

SND @ LHC

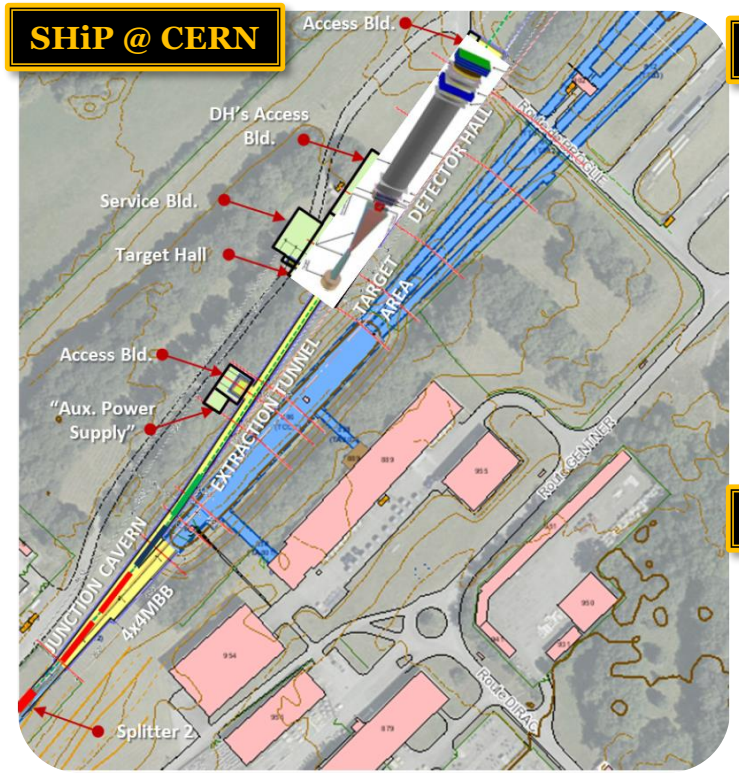


- ✓ See also **Chang Hyon's / Intae's / Kang Young's talks!**

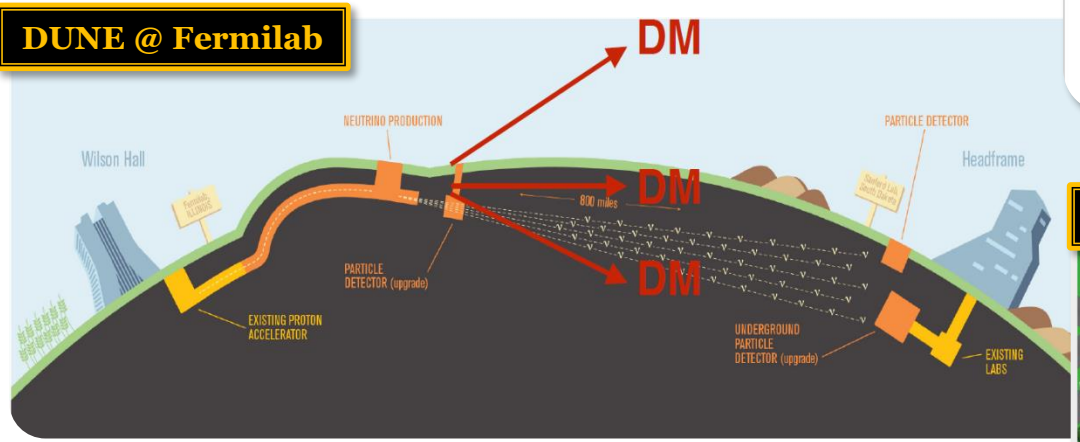
COHERENT @ ORNL



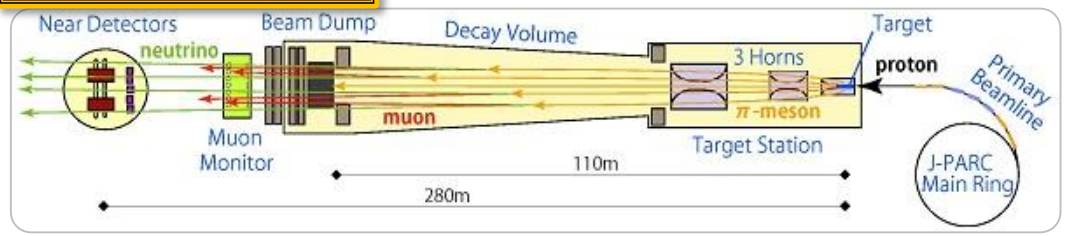
SHiP @ CERN



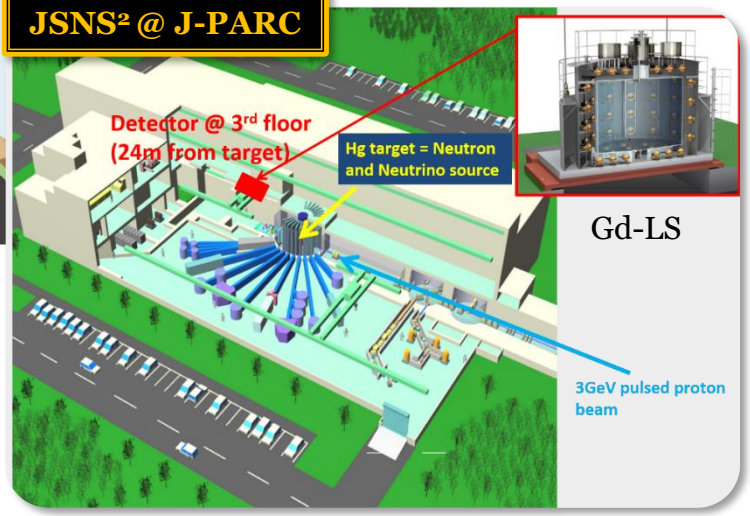
DUNE @ Fermilab



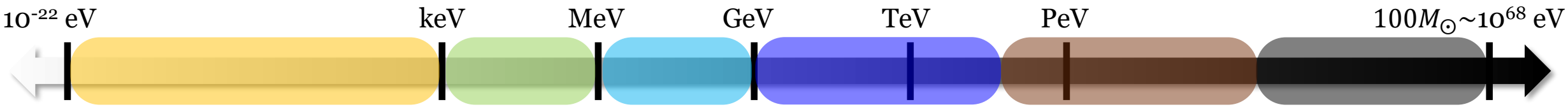
T2SK/HK @ J-PARC



JSNS² @ J-PARC

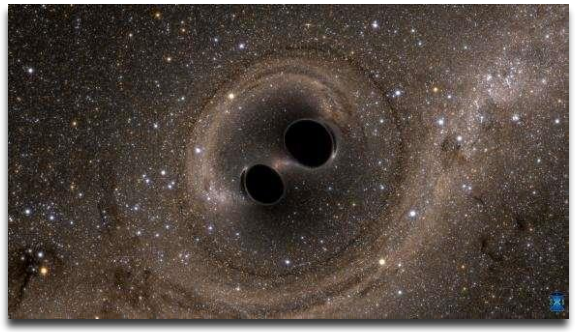


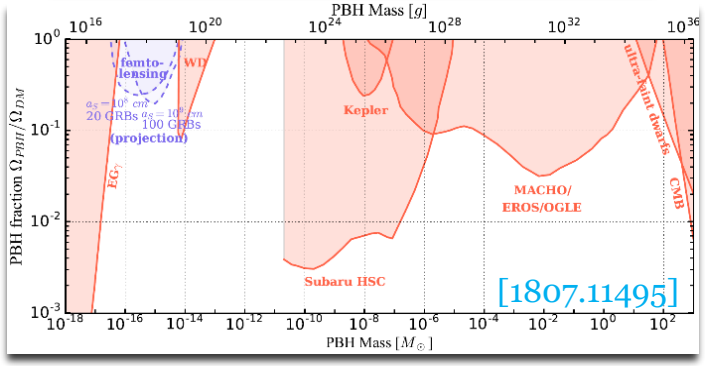
Astrophysical Object

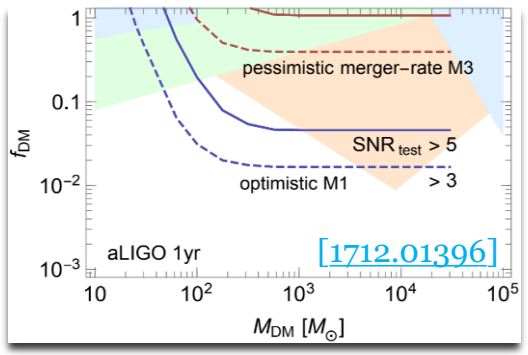


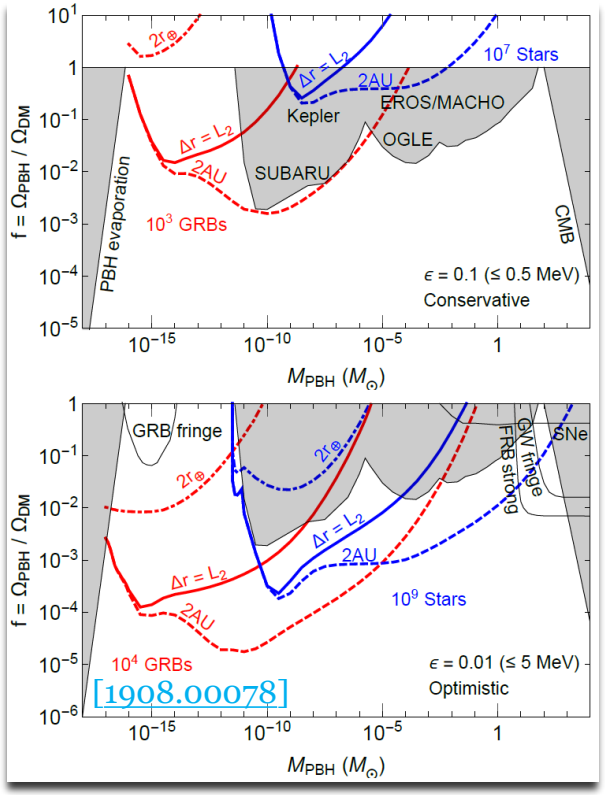
- ✓ MACHO (massive astrophysical compact halo object): black holes, neutron stars, brown dwarfs, unassociated planets, …
- ✓ PBHs (primordial black holes): formed in the early universe, receiving rising attention
- ✓ Experimental searches: gravitational lensing, gravitational wave, CMB, …

Astrophysical object
MACHO, PBH
non-particle

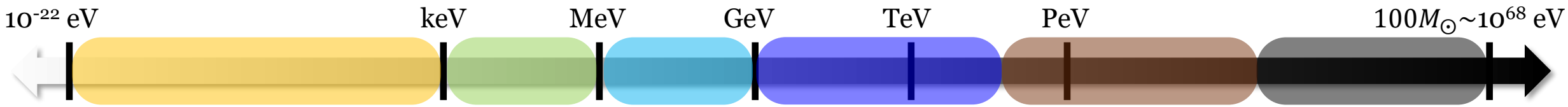






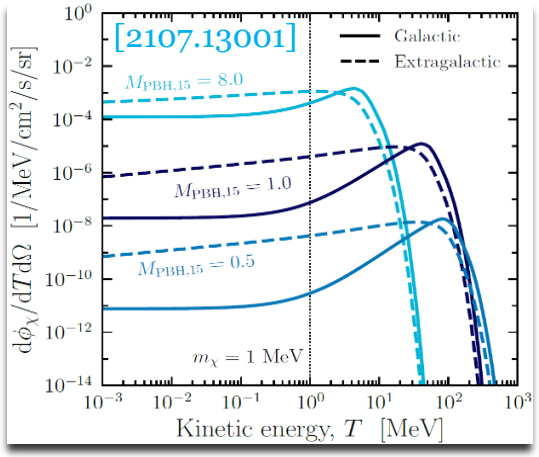


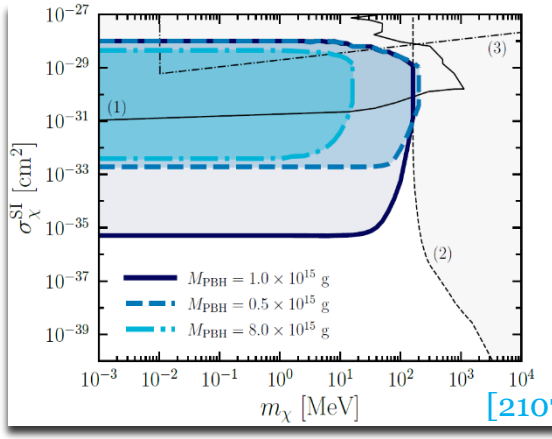
Astrophysical Object

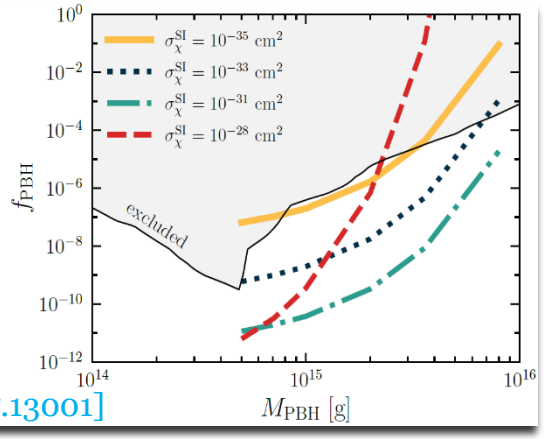


✓ PBH evaporation: various experimental considerations ➔ BBN, CMB, γ-ray, neutrino, LDM, …

Astrophysical object
MACHO, PBH
non-particle

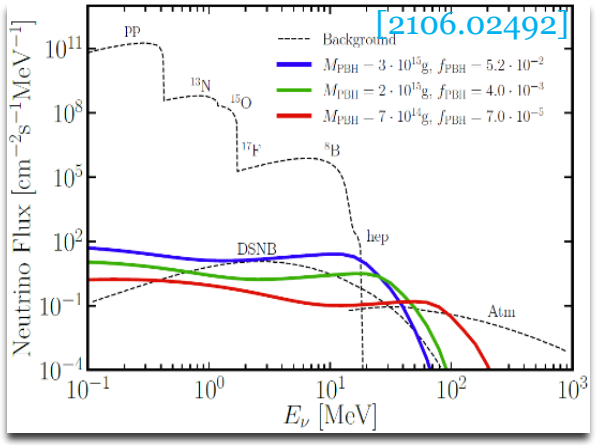


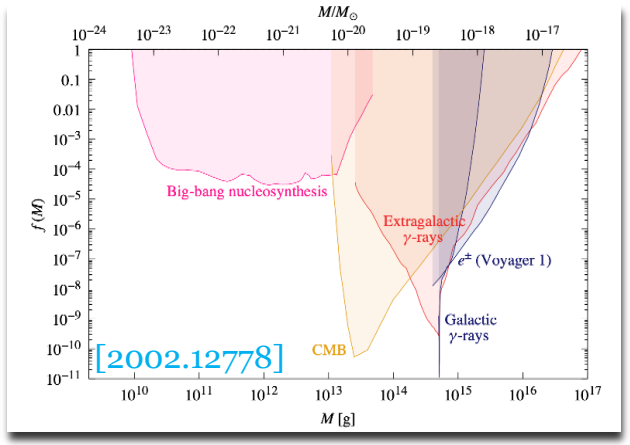


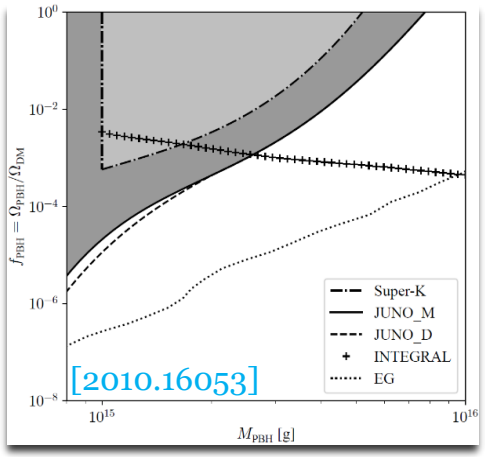


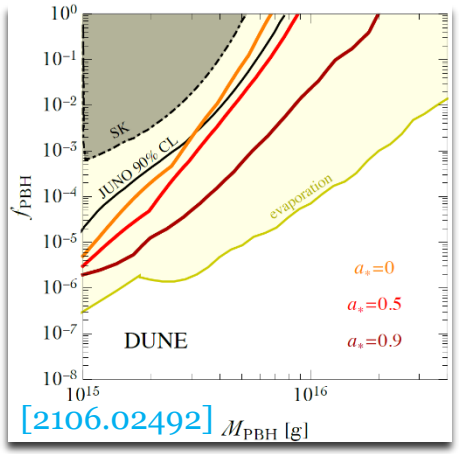
[2107.13001]

➔ LDM from PBH evaporation & its detection









➔ SM from PBH evaporation & its detection

Experimental Anomalies & Issues

- Direct detection
  - ✓ Annual modulation signals by DAMA
  - ✓ Lowering E_{th}, Neutrino floor ➔ directionality?
- Indirect detection (cosmic ray)
  - ✓ Photon: 3.5 keV line (XMM-Newton), GC 511 keV line (SPI/INTEGRAL), GC ~GeV excess (Fermi-LAT)
  - ✓ e^+e^-: O(10 – 1000 GeV) excess (PAMELA, Fermi-LAT, AMS-02)
  - ✓ $\bar{p}$: O(10 GeV) excess (AMS-02)
  - ✓ ν: PeV events (IceCube), EeV events (ANITA → observed: EM shower)
- Direct production or Particle beam
  - ✓ e-like event excess (MiniBooNE)
  - ✓ an excess in the timing-spectra (COHERENT)
- Precision
  - ✓ Muon g-2 ➔ On Kim's talk
  - ✓ B-anomaly (Belle, LHC) ➔ Youngjoon's talk
  - ✓ ATOMKI anomaly
- Cosmology
  - ✓ Core vs Cusp, Missing satellite, Too-big-to-fail
  - ✓ H_0 tension

???

Summary

- WIMP: well-motivated & well-studied

  ➔ numerous stringent constraints, but still alive & various anomalies

- Dark sector: can be flavorful & secluded ➔ multi-species, masses, spins, interactions, …

  ➔ New ideas for portals between DM-SM sectors & DM relic abundance

- Other mass scale DM: rising interest ➔ super-/ultra-light DM, superheavy DM

  ➔ extended dark sector, energetic/boosted DM, … ➔ New search ideas

- PBH: rising attention ➔ search strategies: gravitationally, evaporation, …