Dark Matter Theory circa 2022

Hyun Min Lee

이 현 민

Chung-Ang University

2022 Meeting of Division of Particles and Fields

Korean Physical Society

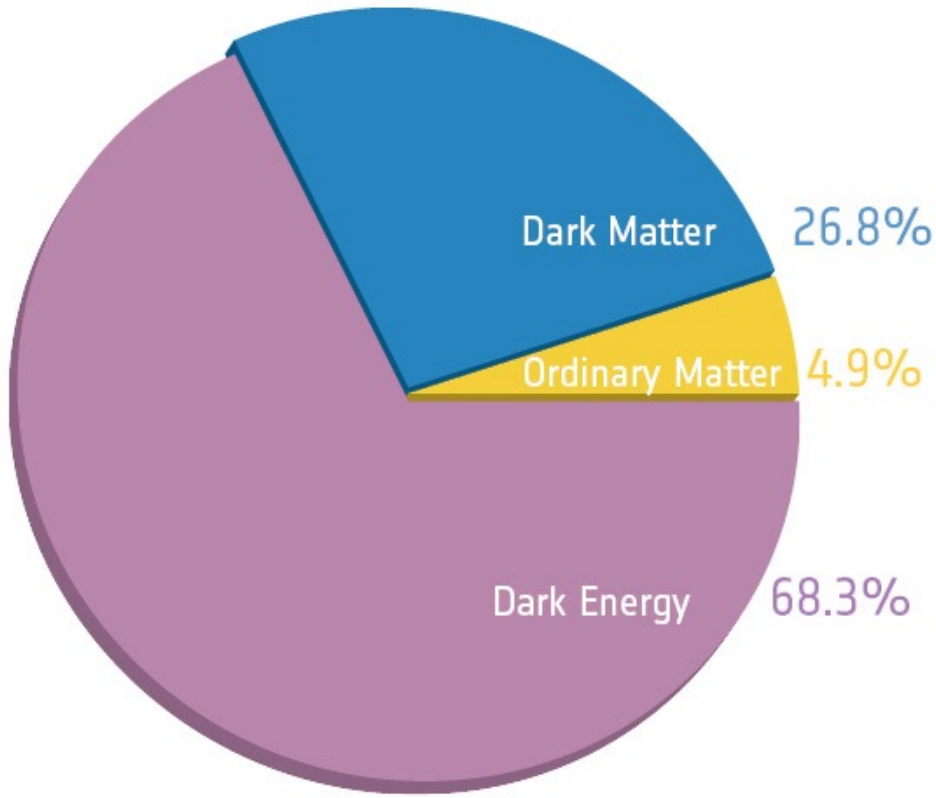
Sungkyunkwan Univ, Dec 17, 2022

Outline

- WIMP and (new) portals
- Small-scale crisis and beyond WIMP
- Non-perturbative dark matter
- Conclusions

WIMP and (new) portals

We know about dark matter



CMB (+ flat Universe)
+ SN1a + BAO

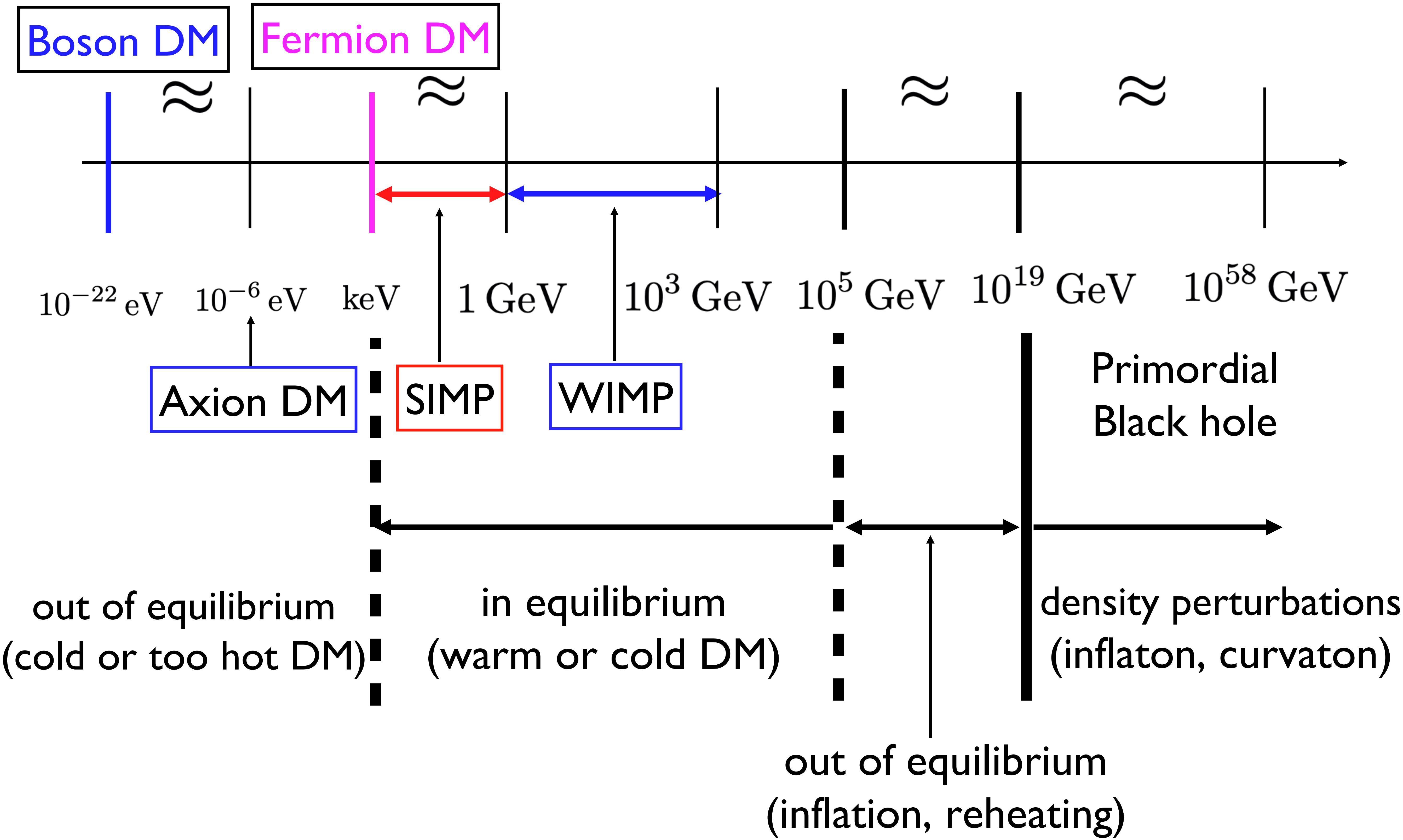
$$\Rightarrow \quad 1 = \Omega = \sum_i \Omega_i,$$

$$\Omega_b = 0.05, \quad \Omega_c = 0.27, \quad \Omega_\Lambda = 0.68.$$

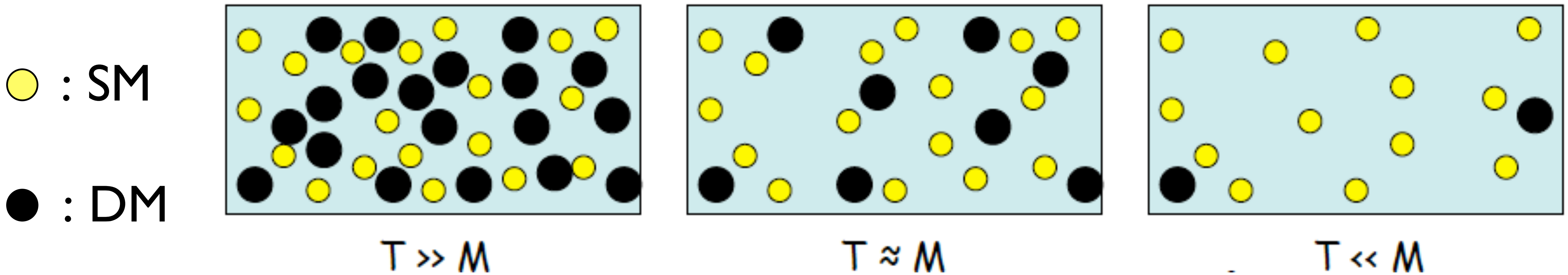
- Gravitational interactions to matter.
- Almost charge-neutral and cold.
- Occupies 85% of total matter (non-relativistic).
- Not in the Standard Model.

cf. neutrinos: $\Omega_\nu = 0.001(m_\nu/0.2\,\mathrm{eV})$

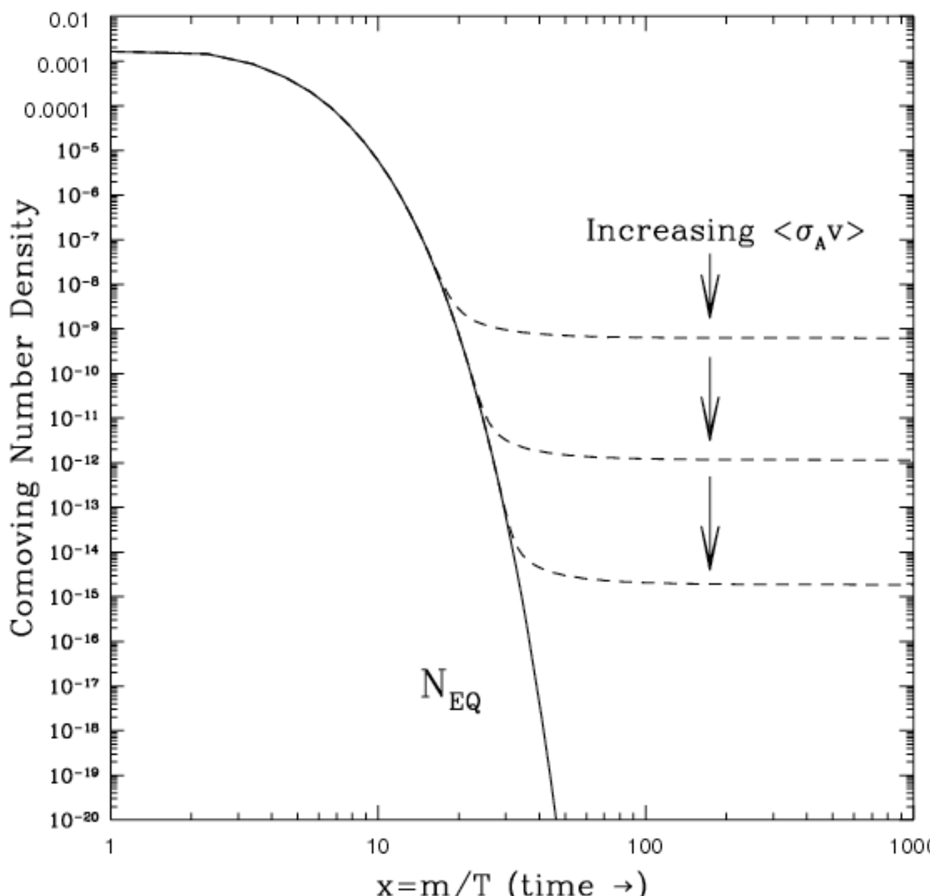
Dark matter by production



WIMP paradigm



DM abundance



time

[Lee,Weinberg(1977)]

Weakly Interacting Massive Particles(WIMP)

Once in equilibrium: $\chi\chi \leftrightarrow \mathrm{SM\ SM}$

"Freeze-out" condition

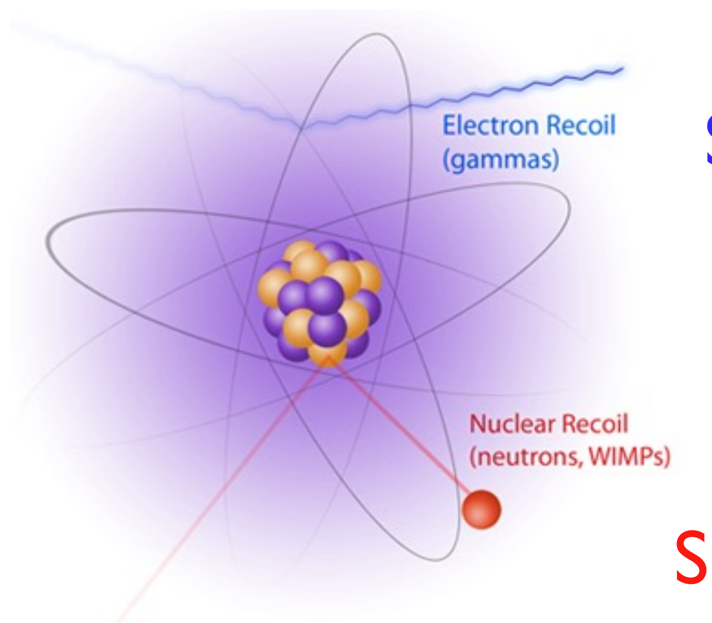
$$t = H^{-1} < t_{\rm int} = (n_{\rm DM}\sigma_A v)^{-1}$$

Expansion time　　Annihilation time

$$\Rightarrow \quad \Omega_{\rm DM} = 0.3\left(\frac{1\,\mathrm{pb}}{\langle\sigma_A v\rangle}\right)$$

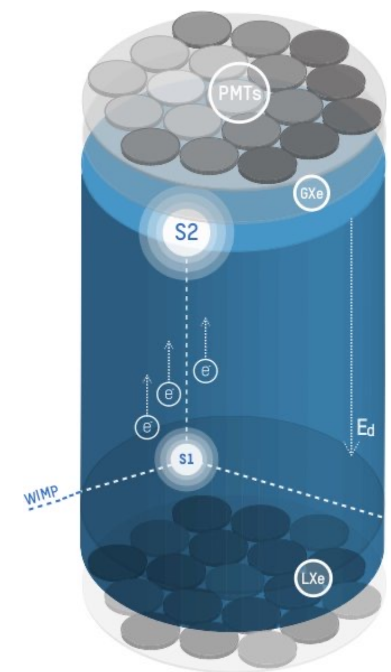
: insensitive to initial history.

WIMP direct detection



S2

S1



e.g. XENON1T

S1: Scintillation (photons)

S2: Ionization (electrons)

WIMP: $S1/S2 \gg (S1/S2)_\gamma$

60~600M DM particles per sec go through our body.

Nucleus recoil E:

$$E_R = \frac{\vec{q}^2}{2m_N} = \frac{(\mu v)^2}{m_N} \lesssim 50\mathrm{keV}$$

Event rate:

$$\frac{dR}{dE_R} = \frac{\rho_\odot}{m_{\rm DM}} \left\langle \frac{d\sigma}{dE_R} v \right\rangle$$

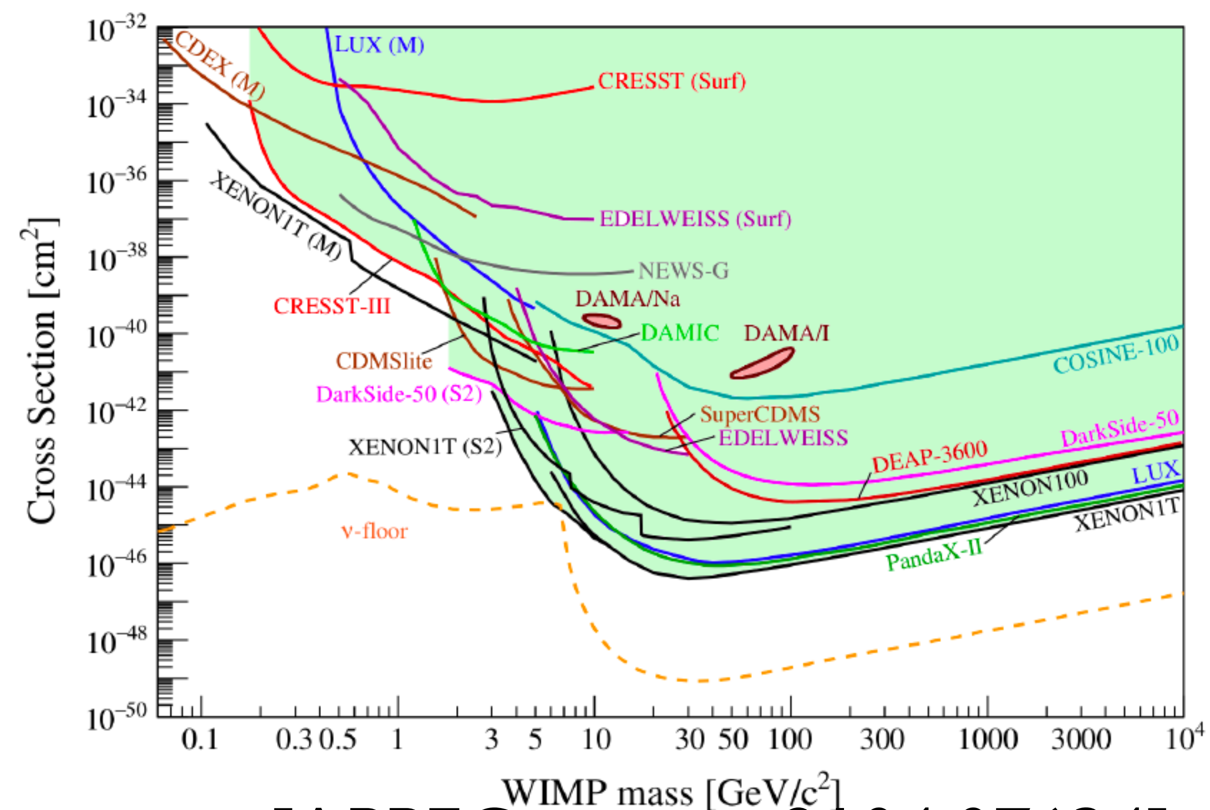
~1event/kg/day

Astrophysics

$$\rho_\odot = 0.3\,\mathrm{GeV/cm^3}$$
$$v_{\rm ave} = 220\,\mathrm{km/s}$$

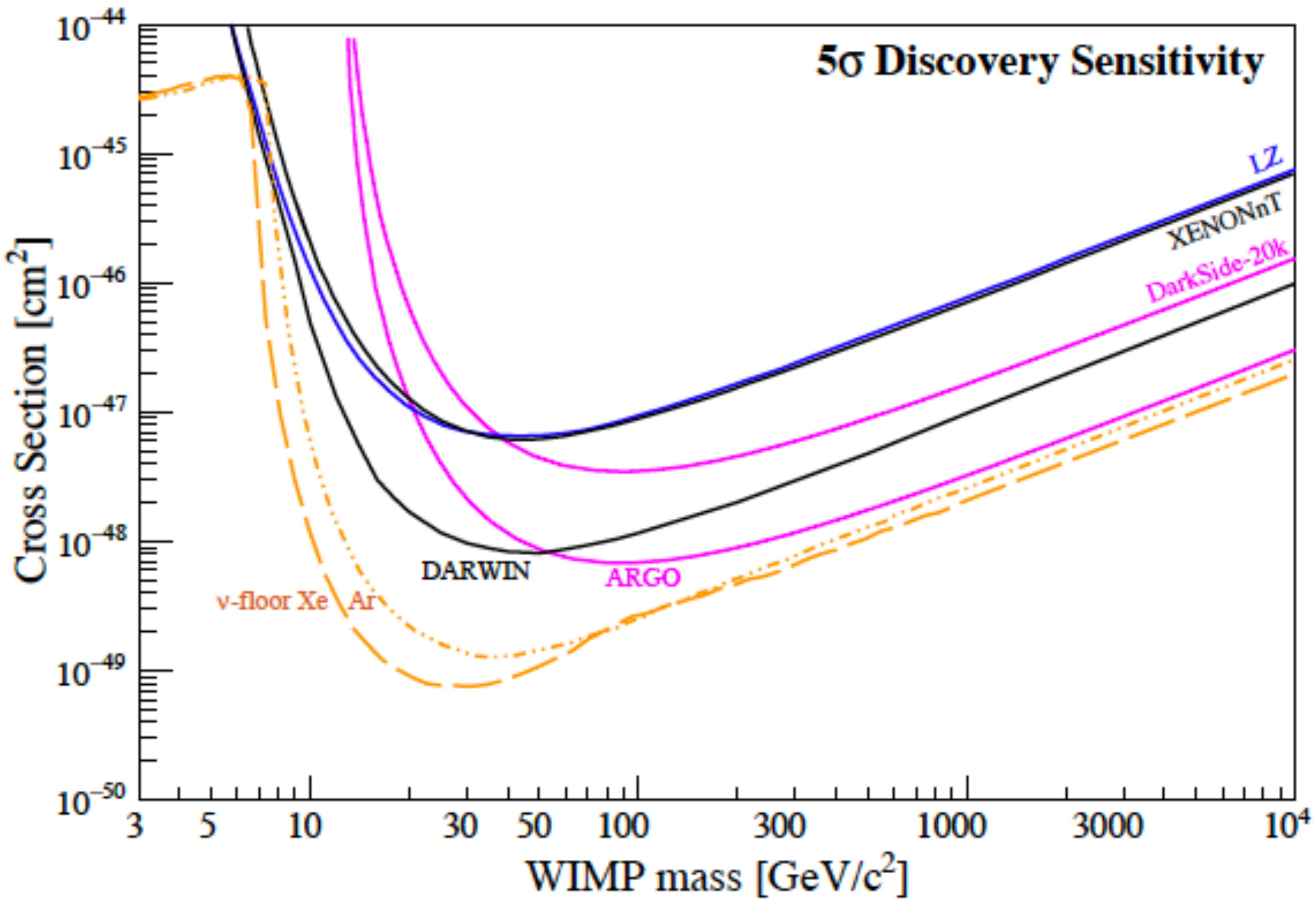
Particle Physics

DM spin, mass, interactions

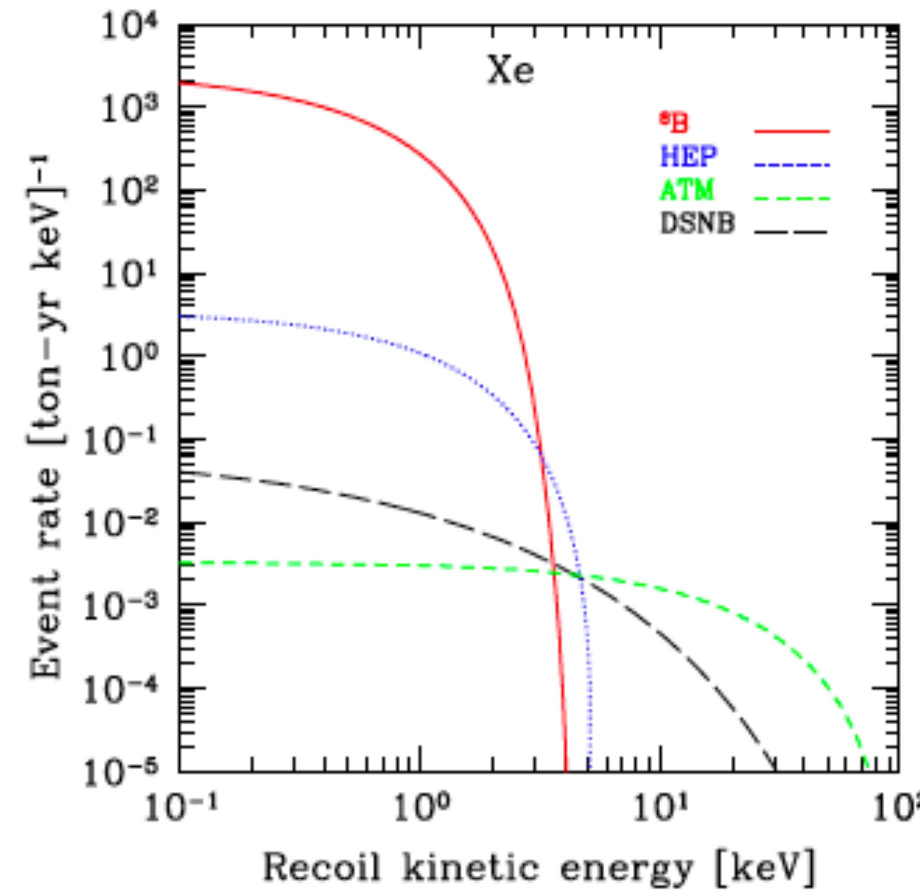


[APPEC report, 2104.07634]

Challenge for WIMP



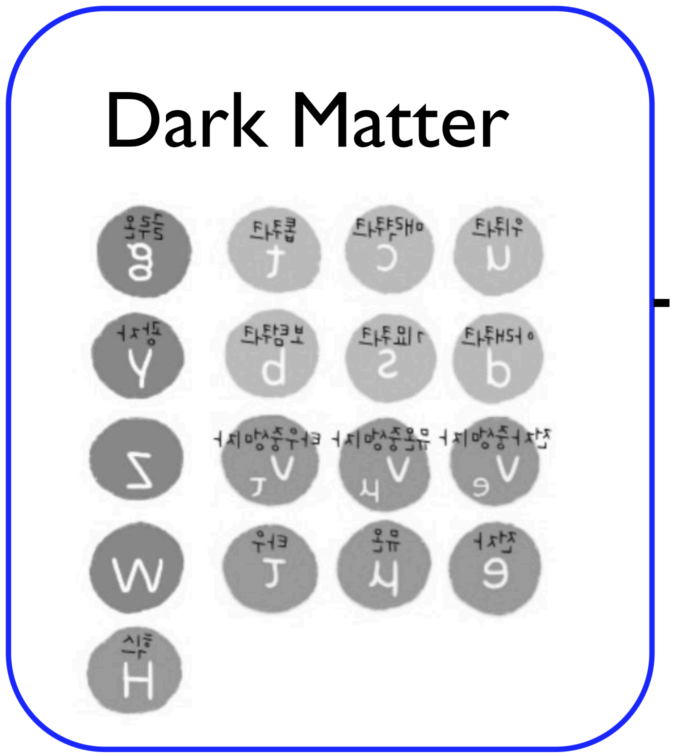
[APPEC report, 2104.07634]



[L. Strigari, 2009]

- Future searches: XENONnT, LZ & DARWIN, etc.
- Challenging to distinguish from the background signals of solar, atmospheric and SN neutrinos.

WIMP via portals



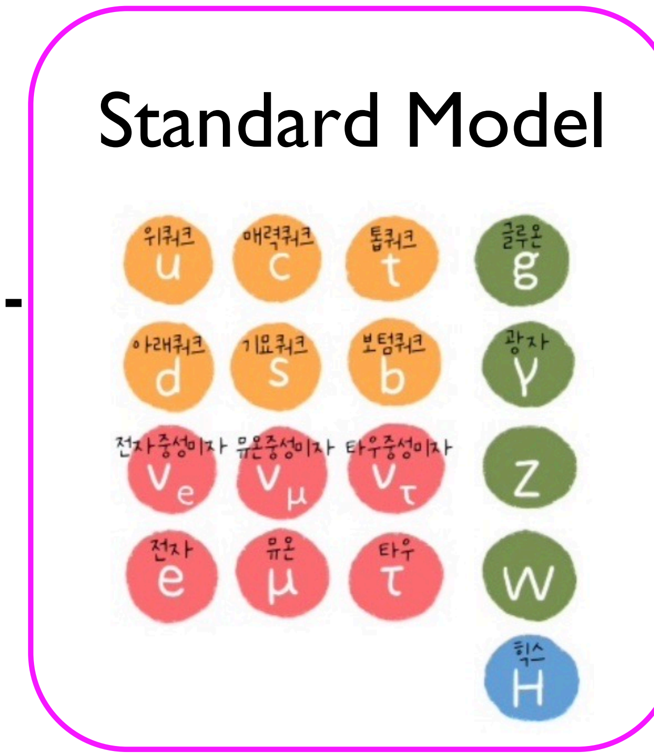
$$|H|^2 \mathcal{O}_{\rm dark}$$

$$B_{\mu\nu} \mathcal{O}^{\mu\nu}_{\rm dark}$$

$$N(HL + \mathcal{O}_{\rm dark})$$

$$\frac{a}{f}(\mathcal{O}_{\rm dark} + \mathcal{O}_{\rm SM})$$

$$\frac{G^{\mu\nu}}{M}(T^{\mu\nu}_{\rm dark} + T^{\mu\nu}_{\rm SM}) \ldots$$

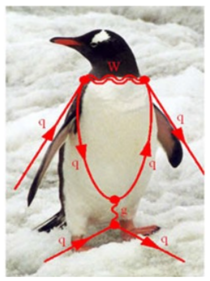


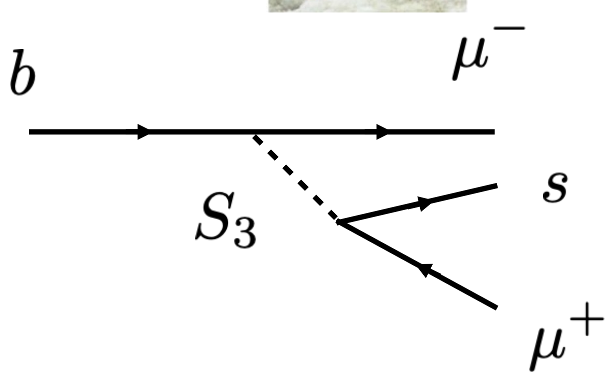
- Dark matter are neutral under SM gauge group, so their interactions are dictated by mediator particles.
- Higgs portal, Z' portal, neutrino-portal, axion portal, graviton portal, and new types of portals: leptoquark, four-form, etc.

Leptoquark portals

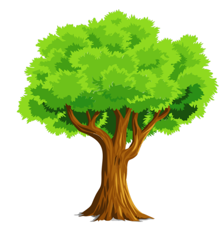
B-meson and muon g-2 anomalies favor leptoquark interactions.

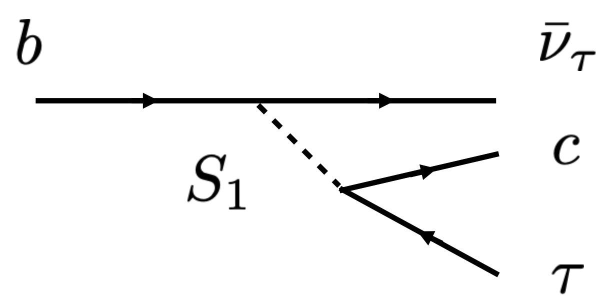
$R_K^{(*)}$



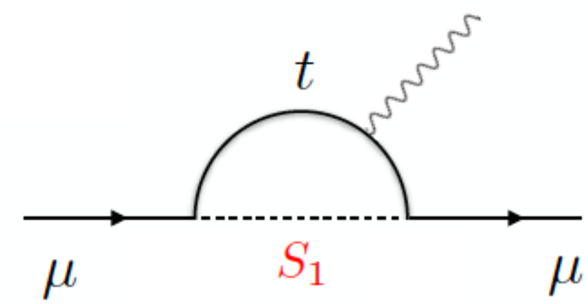


$R_D^{(*)}$



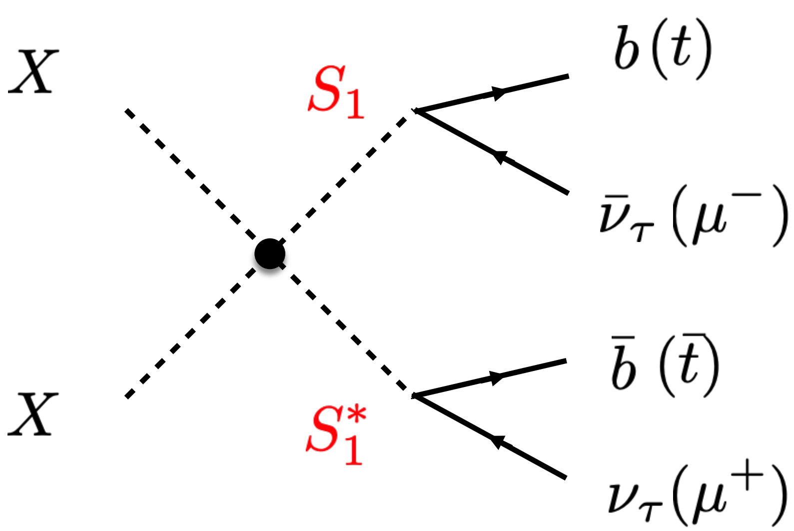


$(g\text{-}2)_\mu$

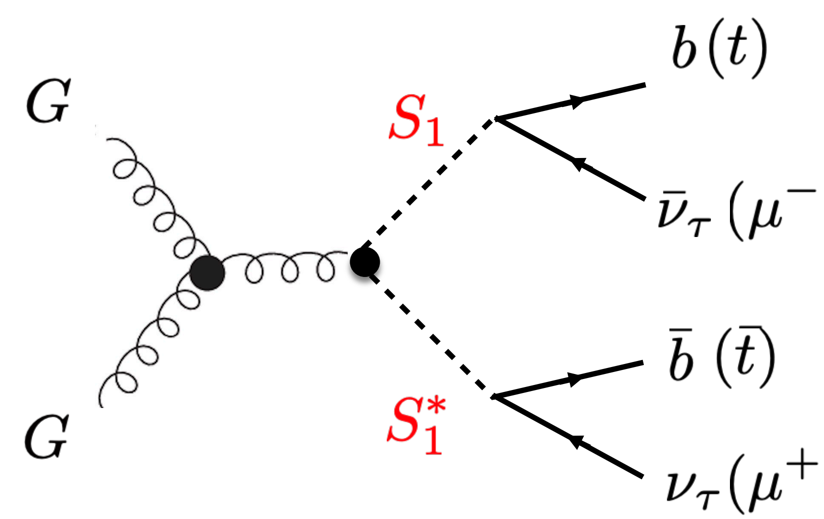


+ W boson mass anomaly

Leptoquark production from DM

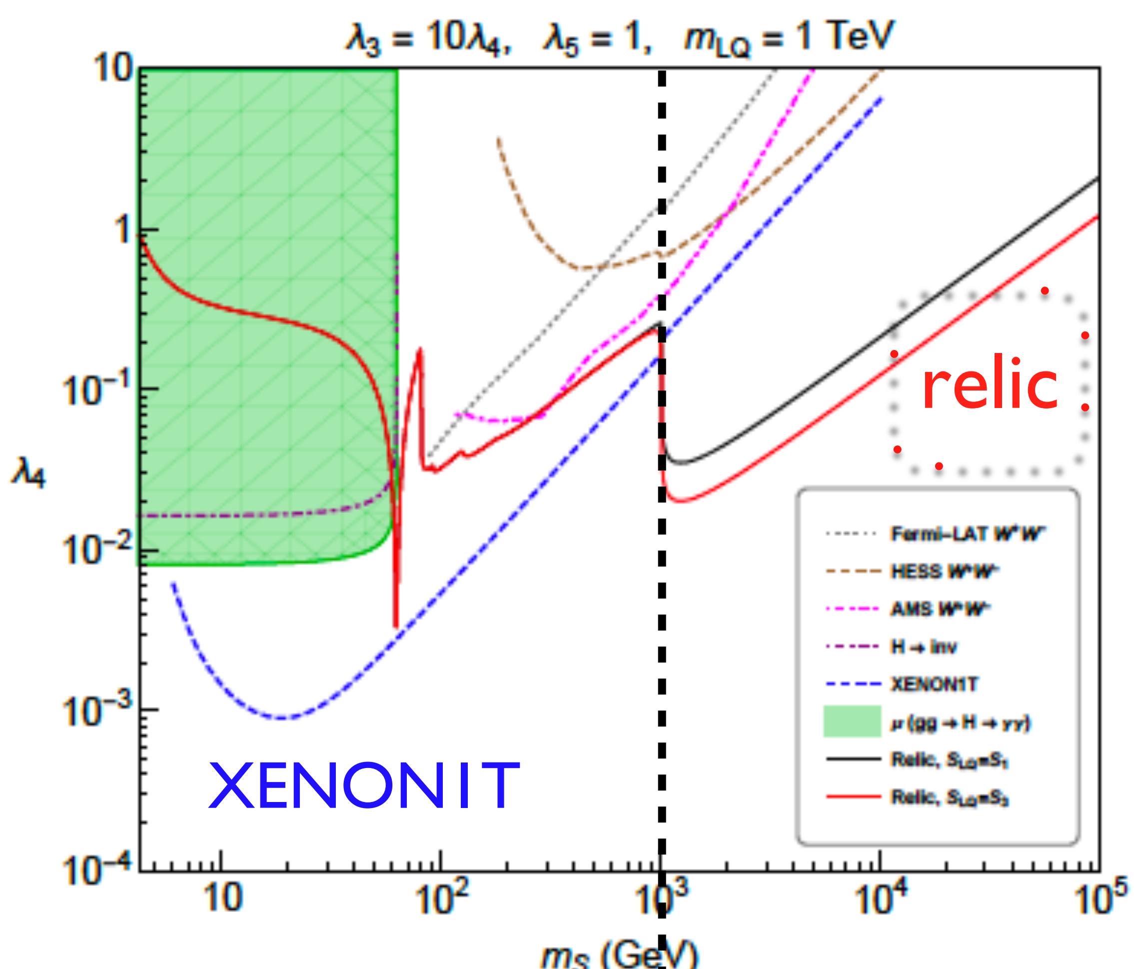


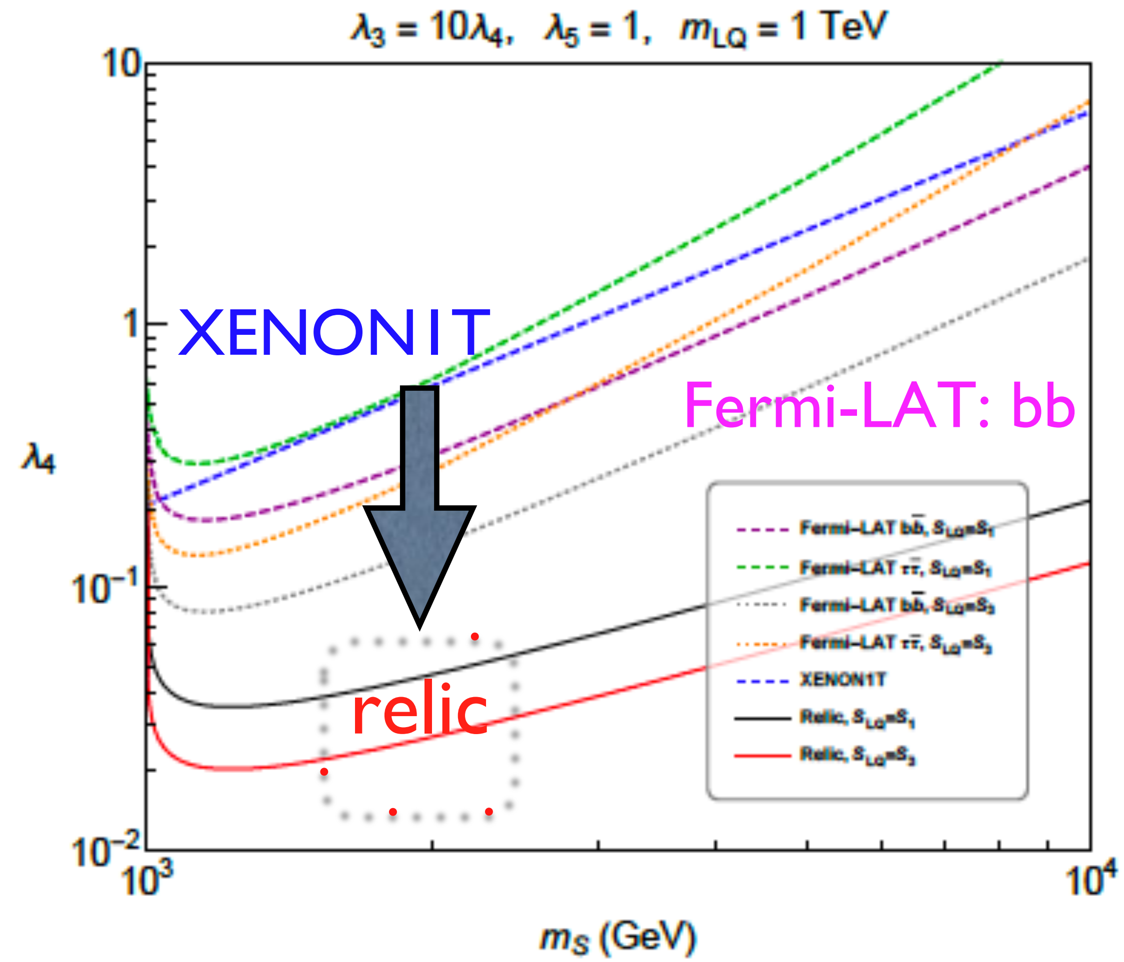
Leptoquark production @ LHC



B-decays, LHC & cosmic rays

[Choi, Kang, HML, Ro, 2018]





TeV-scale DM beyond LHC, XENON1T bounds.

B-anomalies & cosmic ray fractions

$R_{D^{(*)}}$: $\quad \mathrm{B}(\bar{t}t\,\bar{\tau}\tau) : \mathrm{B}(\bar{b}b\,\bar{\nu}_\tau\nu_\tau) : \mathrm{B}(\bar{t}b\,\bar{\tau}\nu_\tau + \mathrm{h.c.}) = \frac{1}{2} : \frac{1}{2} : 1$

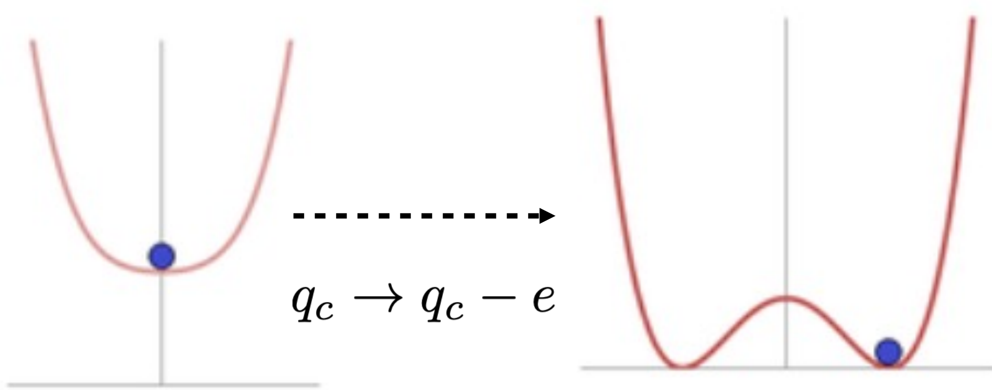
$R_{K^{(*)}}$: $\quad \mathrm{B}(\bar{b}b\,\bar{\mu}\mu) : \mathrm{B}(\bar{t}t\,\bar{\mu}\mu) : \mathrm{B}(\bar{b}b\,\bar{\nu}_\mu\nu_\mu) : \mathrm{B}(\bar{t}b\,\bar{\mu}\nu_\mu + \mathrm{h.c.}) : \mathrm{B}(\bar{t}t\,\bar{\nu}_\mu\nu_\mu)$

$$= 1 : \frac{1}{4} : \frac{1}{4} : \frac{1}{2} : 1.$$

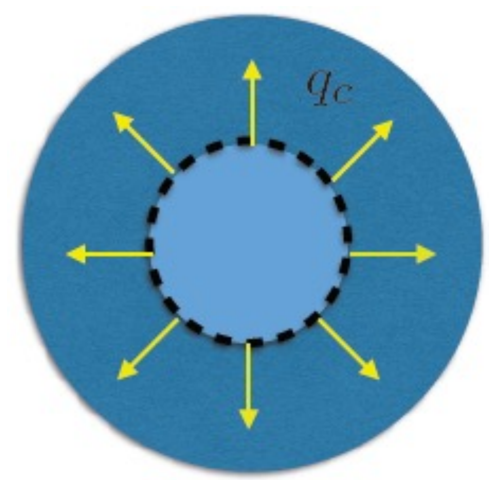
Flux-mediated dark matter

- Four-form flux portal for Higgs mass & cosmological constant as well as dark matter.

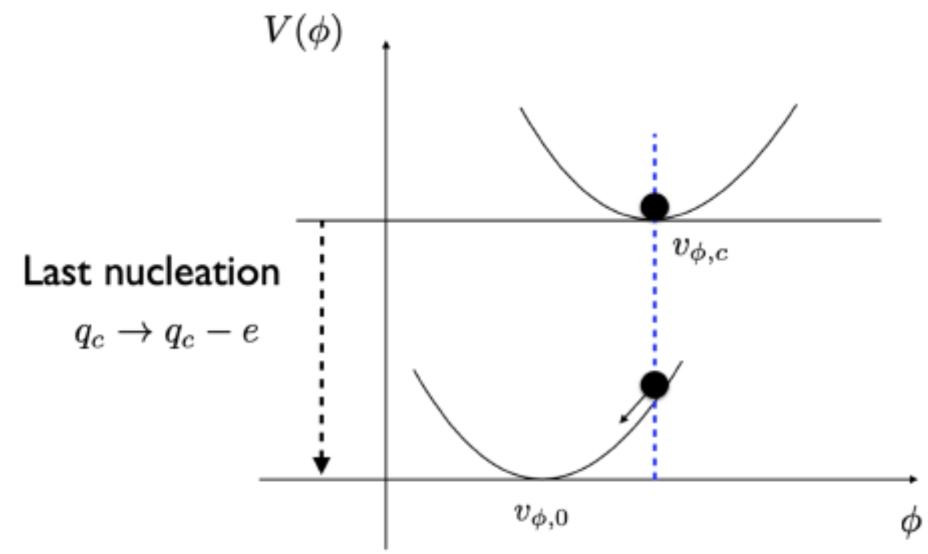
[HML, 2019; Y. Kang, HML, A. Menkara, J. Song, 2021]



Higgs mass & C.C.

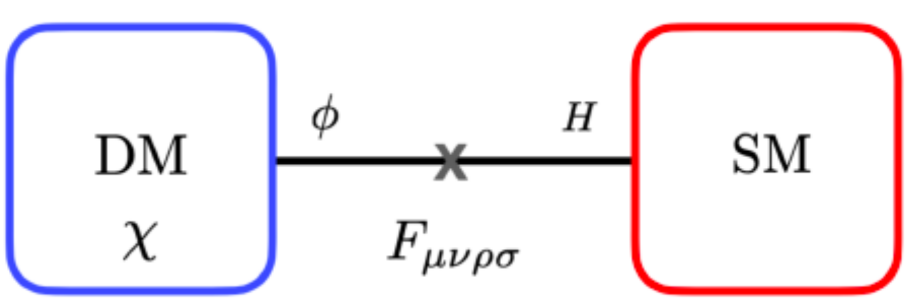


Membrane nucleation



Reheating field

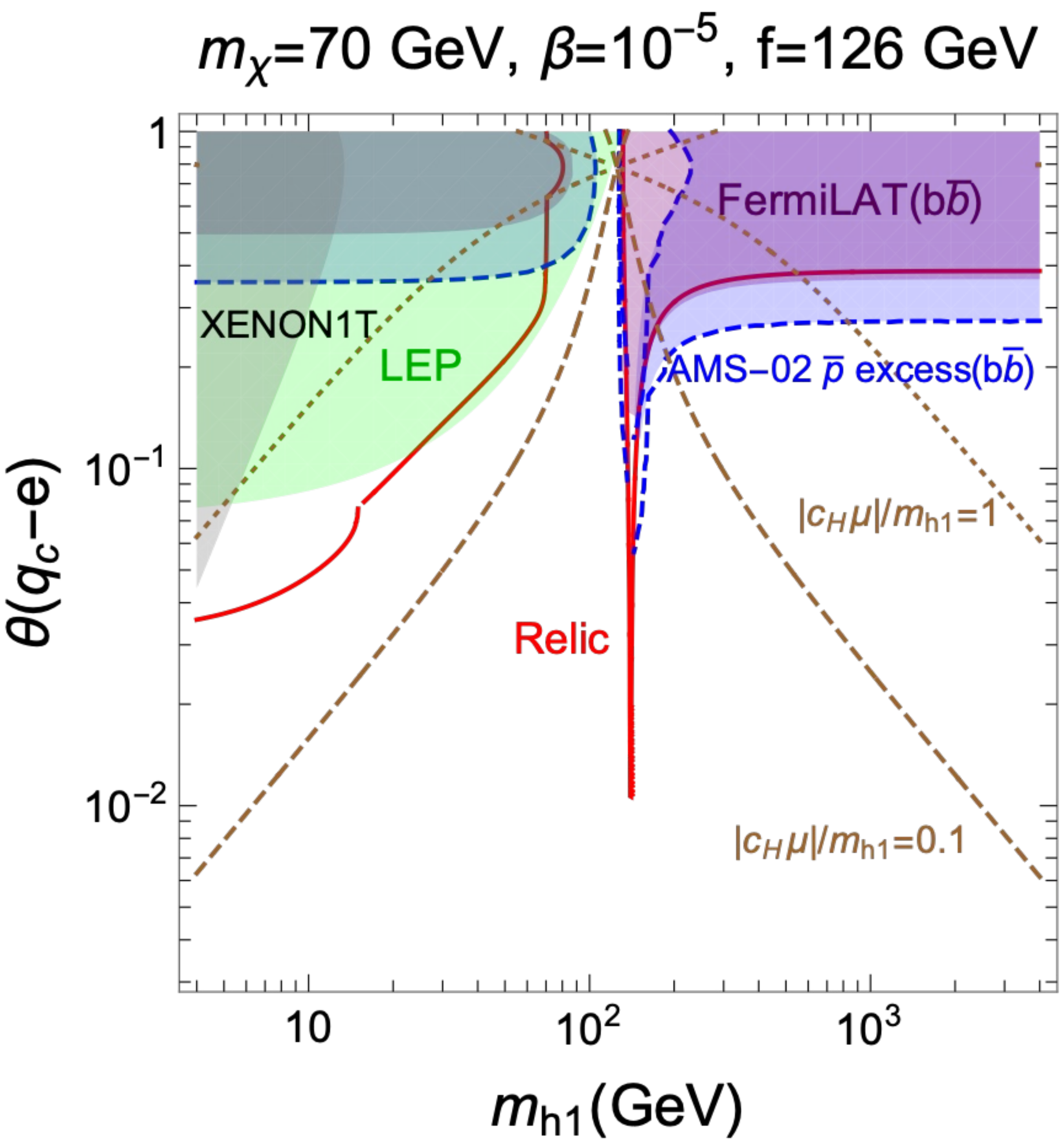
$$\mathcal{L} = -\frac{1}{4!}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma} + \frac{1}{4!}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu\rho\sigma}\left(\mu\phi + c_H|H|^2\right) + \frac{im_\chi}{f}\,\phi\bar{\chi}\gamma^5\chi$$

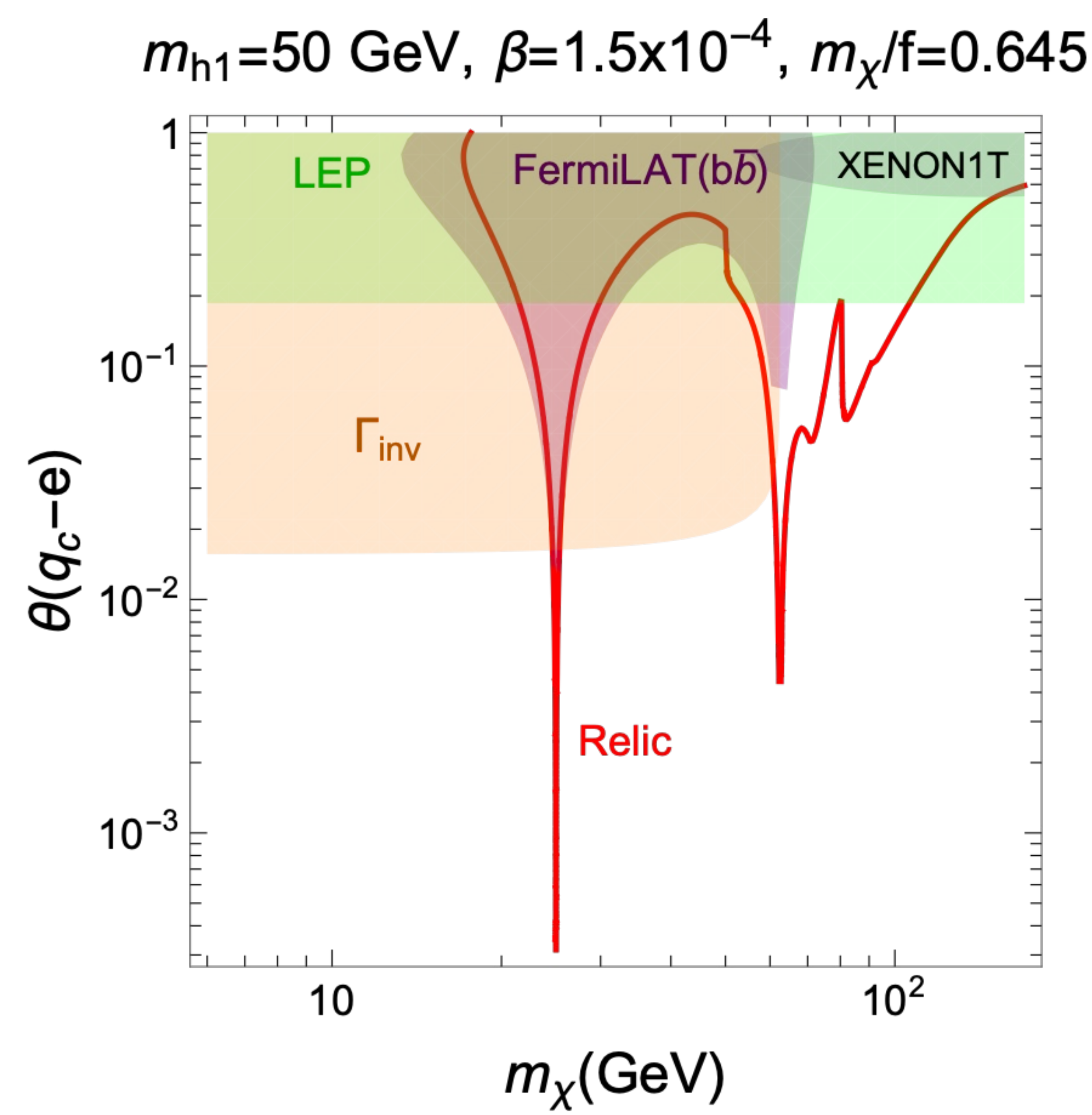


CP violation by Higgs mixing.

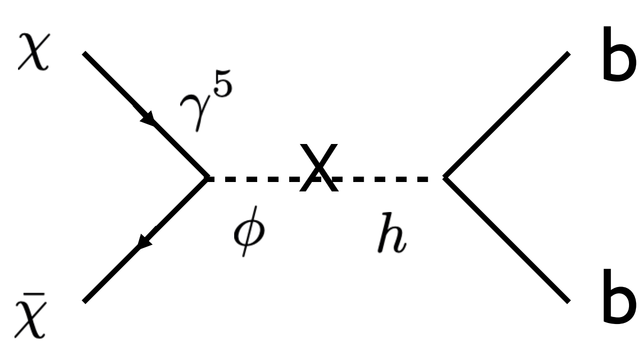
"New Higgs-portal"

Bounds on four-form portals

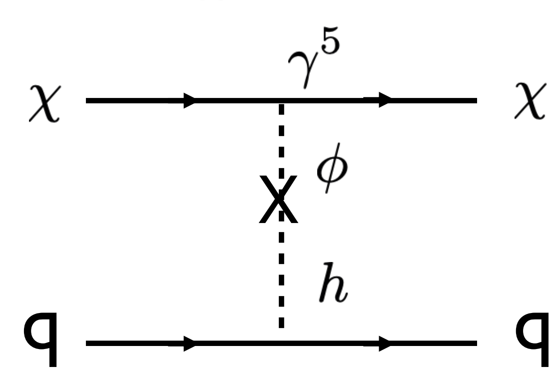




−10−



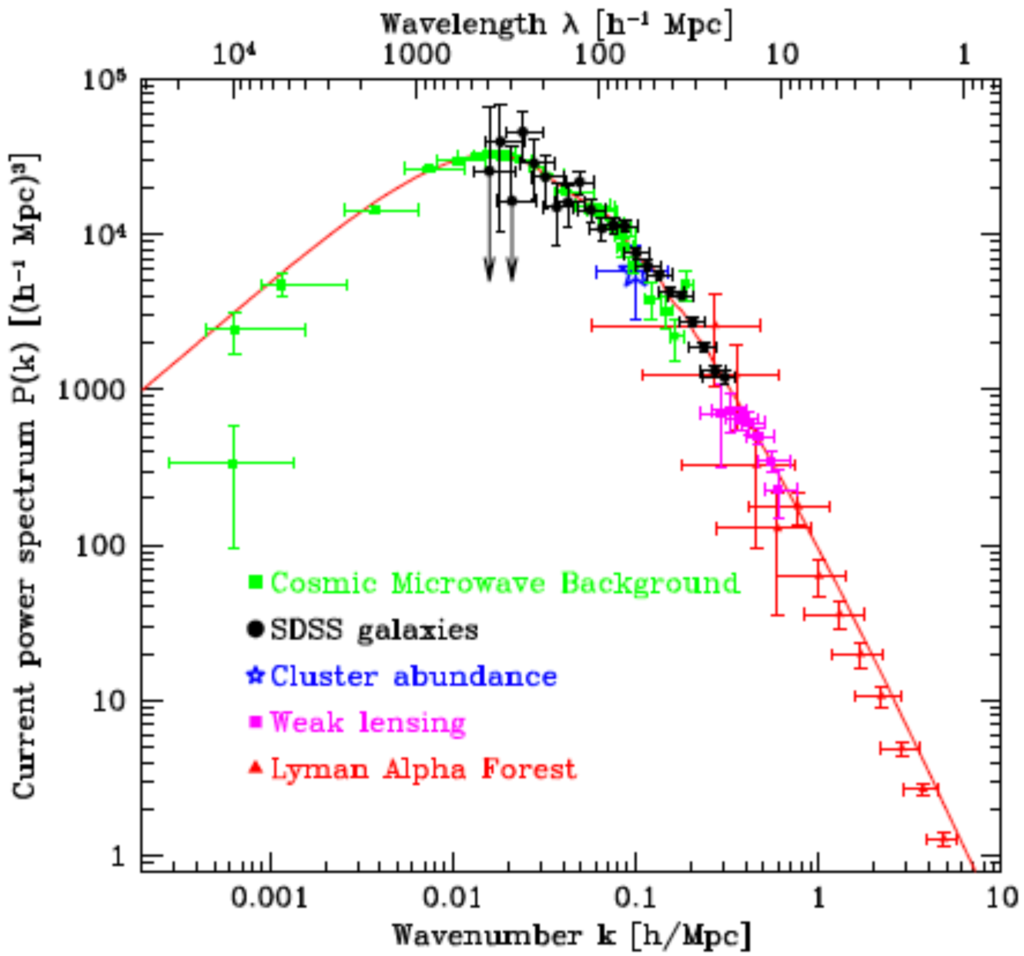
Fermi-LAT γ-ray & AMS-02 anti-p



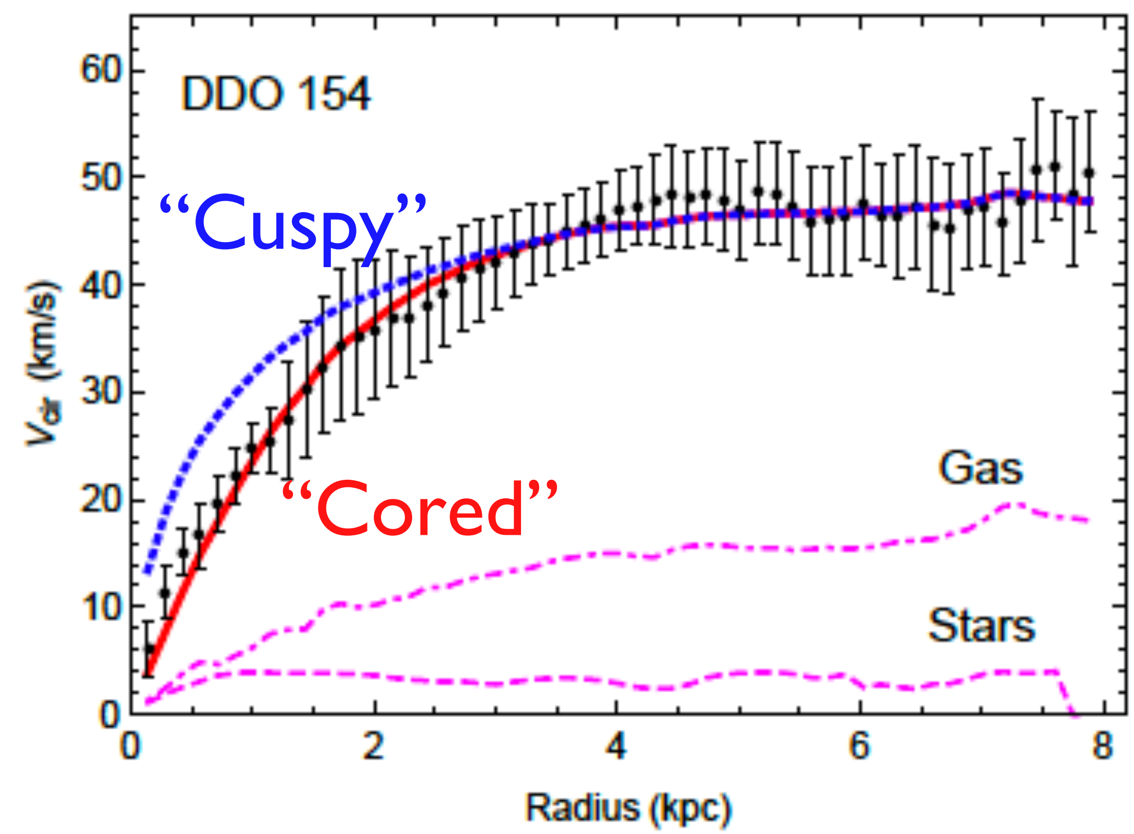
Suppressed DM-nucleon scattering

Small-scale crisis and beyond WIMP

Small-scale crisis



WIMP works well at >Mpc



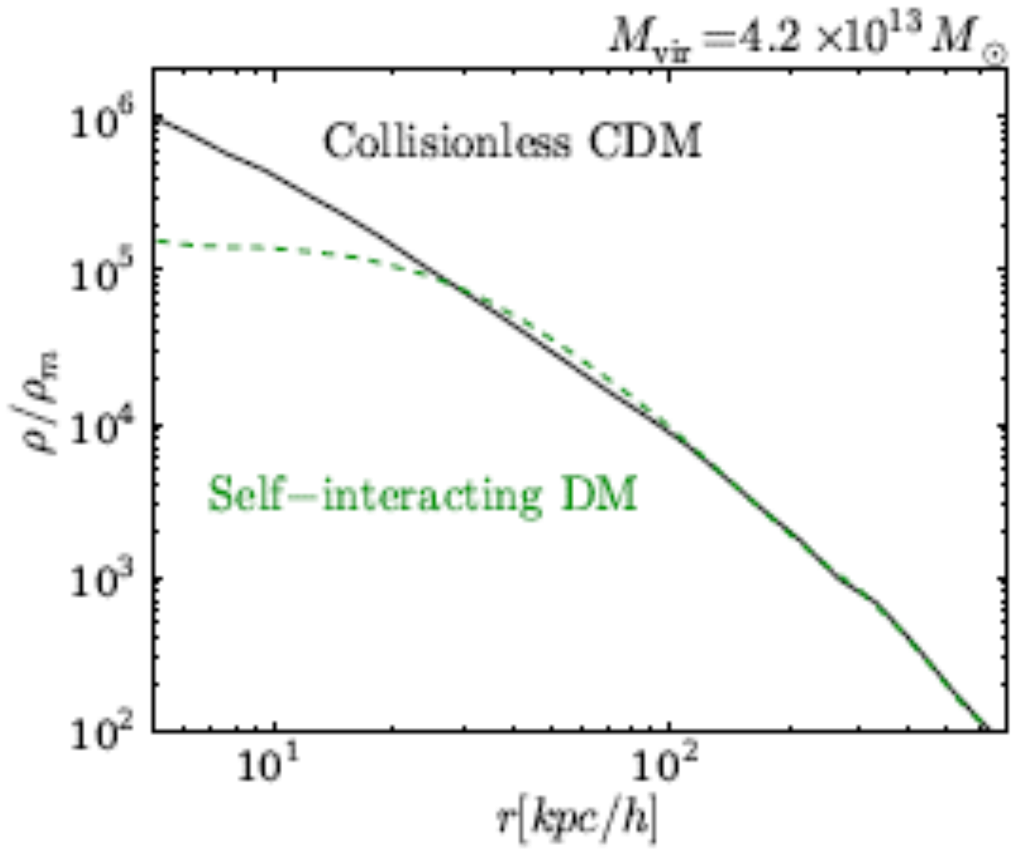
Galaxy rotation curves at <1kpc
[Spergel, Steinhardt, 2000; Tulin, Yu, 2017]

- WIMP N-body simulation predicts cuspy DM profile (NFW), making rotation velocities overshooting at small scales.

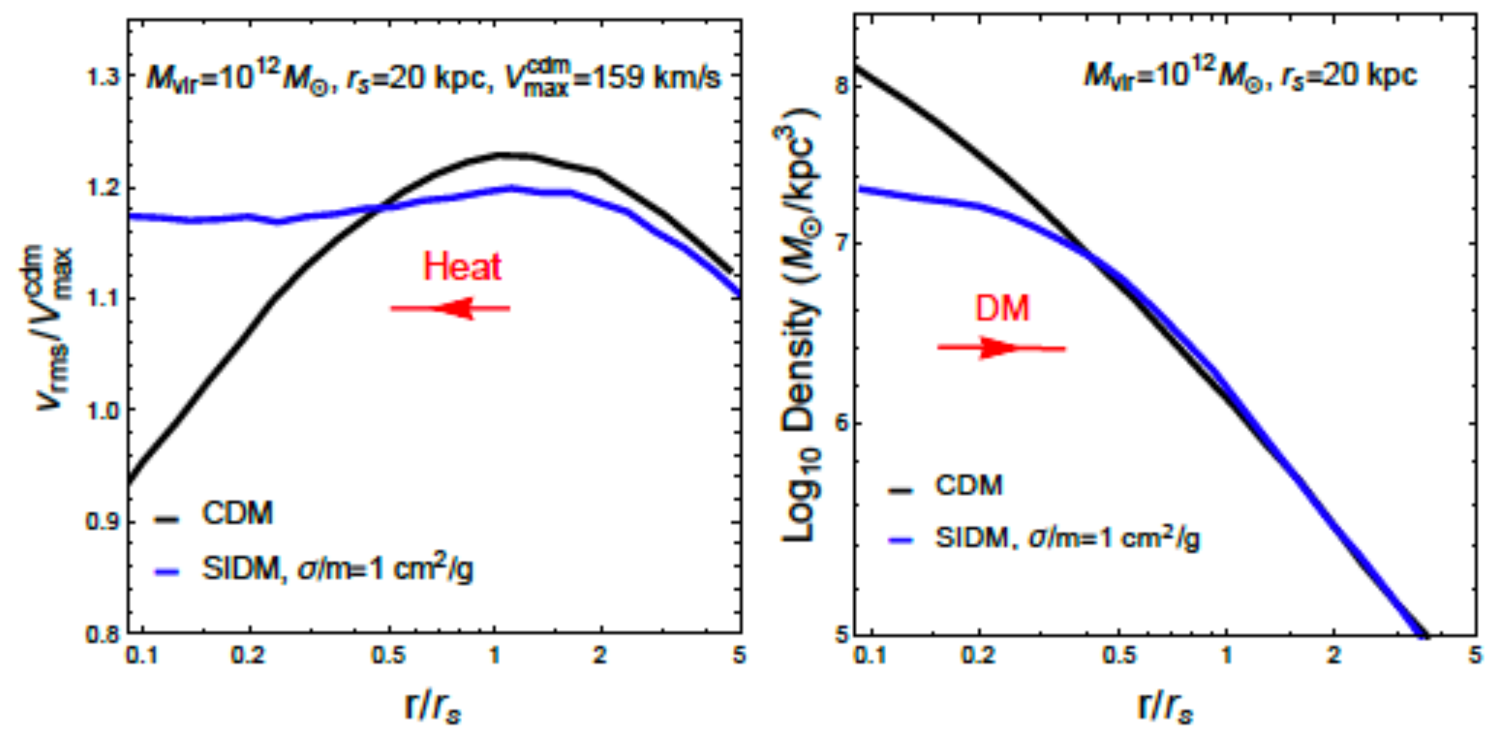
$$v_{\rm cir} \sim \sqrt{r}, \quad \rho_{\rm dm} \sim r^{-1} \quad \text{"Cuspy"}$$

$$v_{\rm cir} \sim r, \quad \rho_{\rm dm} \sim r^{0} \quad \text{"Cored"}$$

Self-Interacting Dark Matter



[Weinberg et al, 2013]



[Tulin, Yu, 2017]

Transport heat by self-interactions makes DM scatter and cored.

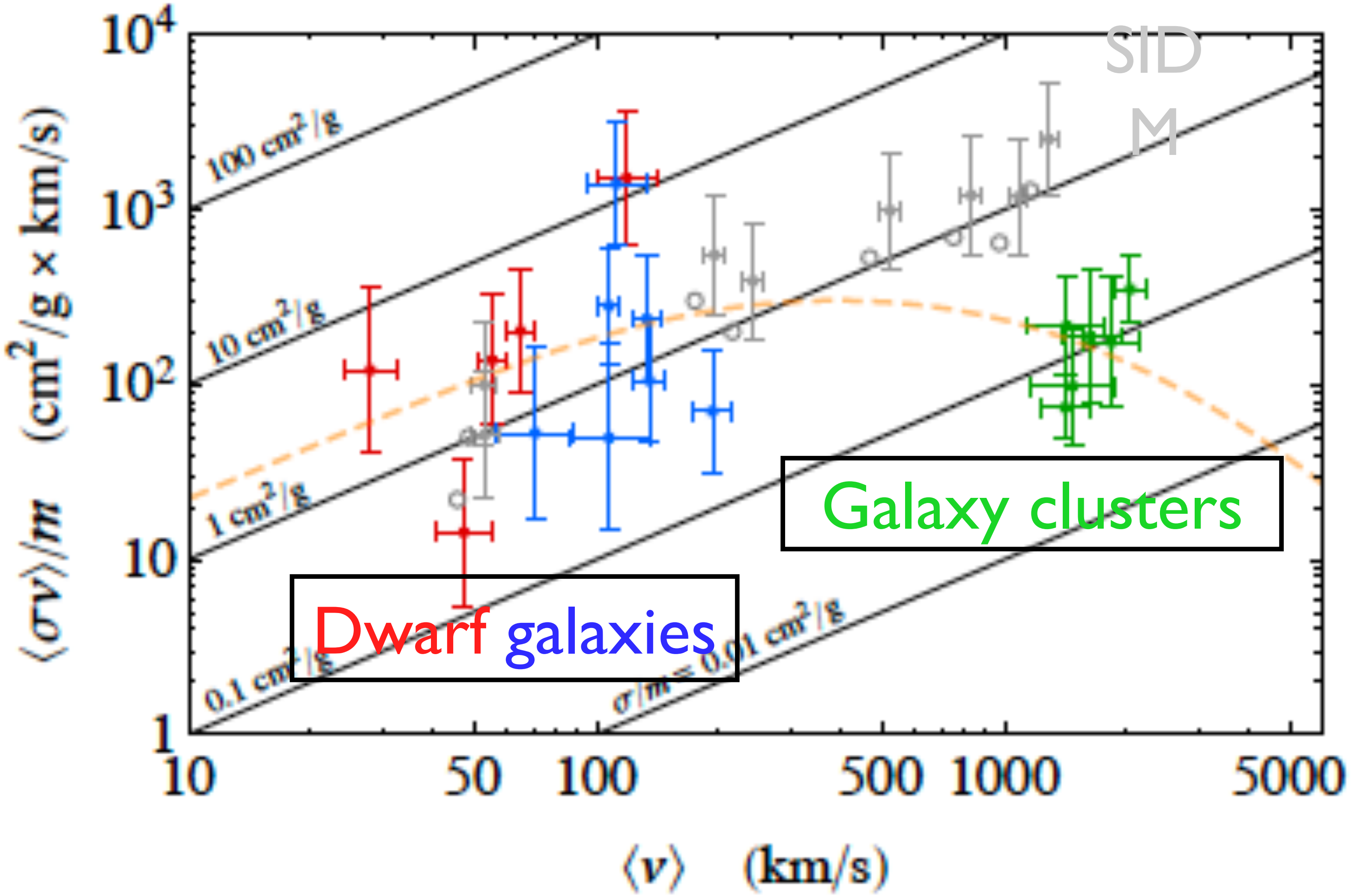
$$\sigma_{\rm self}/m_{\rm DM} \sim 0.1 - 10{\rm cm}^2/{\rm g}$$

DM scattering rate: $R_{\rm scat} = \sigma v_{\rm rel}\rho_{\rm dm}/m \approx 0.1\ {\rm Gyr}^{-1} \times \left(\frac{\rho_{\rm dm}}{0.1\ {\rm M_\odot/pc^3}}\right)\left(\frac{v_{\rm rel}}{50\ {\rm km/s}}\right)\left(\frac{\sigma/m}{1\ {\rm cm^2/g}}\right)$

Self-interaction+ baryons explains diversity of rotation curves.

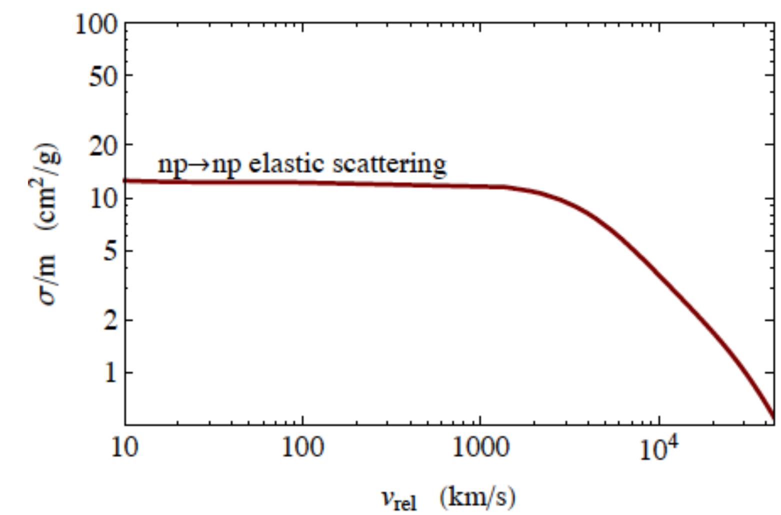
[A. Kamada et al, 2016]

Cosmological colliders



THINGS dwarf galaxies (red), LSB galaxies (blue), and clusters (green).

SIDM N-body simulations, with $\sigma/m = 1\,\mathrm{cm}^2/\mathrm{g}$, *(gray)*



$\langle \sigma v \rangle$=constant

$\Rightarrow \sigma \propto \frac{1}{\langle v \rangle}$

velocity suppressed at clusters

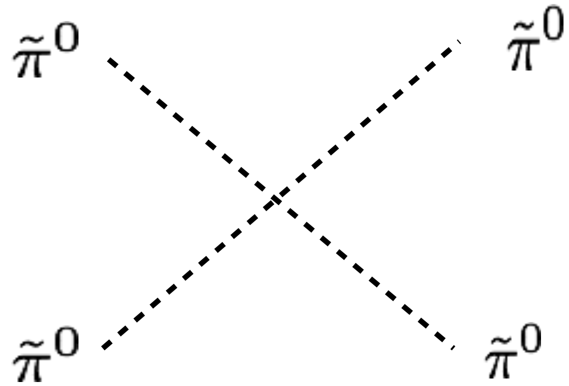
[M. Kaplinghat et al, 2015]

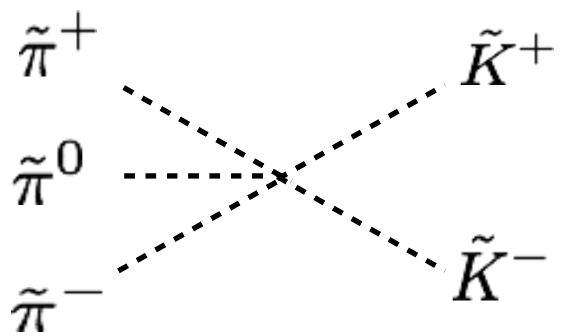
- Self-scattering is suppressed for large velocities at clusters.

cf. Bound from Bullet cluster: $\sigma/m \lesssim 0.7\,\mathrm{cm}^2/\mathrm{g}$

SIMP paradigm

Self-interactions





Strongly Interacting Massive Particle (SIMP)

[Hochberg et al, 2014; M.-S. Seo, HML, 2015;
S.-M. Choi, P. Ko, HML, A. Natal, 2018]

Self-scattering ⟶ Solve small-scale problems

$$\sigma_{\rm self} = \frac{\alpha_{\rm eff}^2}{m_\pi^2}$$

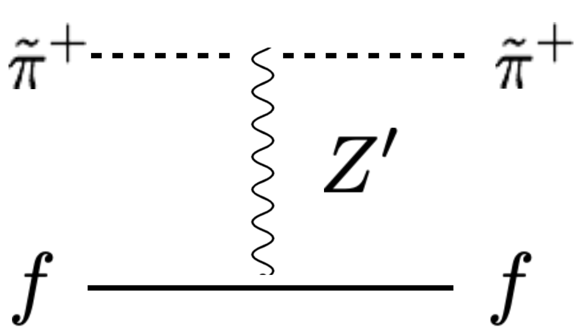
3→2 processes ⟶ Freeze-out $\Omega_{\rm DM}h^2 \propto \frac{1}{(\langle\sigma v^2\rangle)^{1/2}}$

$$\langle\sigma v^2\rangle = \frac{\alpha_{\rm eff}^3}{m_\pi^5}$$

$$\alpha_{\rm eff} \lesssim 10, \;\; m_\pi \lesssim 1\,{\rm GeV}$$

"Natural candidates for sub-GeV dark matter"

Mediator couplings



$$\frac{\partial f_{\rm DM}}{\partial t} \sim \frac{1}{E_{\rm DM}} C[f_{\rm DM}] \longrightarrow T_{\rm DM} = T_\gamma$$

[M.-S. Seo, HML, 2015]

Heat from 3→2 processes equilibrated
by mediator interactions with $m_{Z'} > m_{\rm DM}$.

Testable by direct detection, collider/beam dump

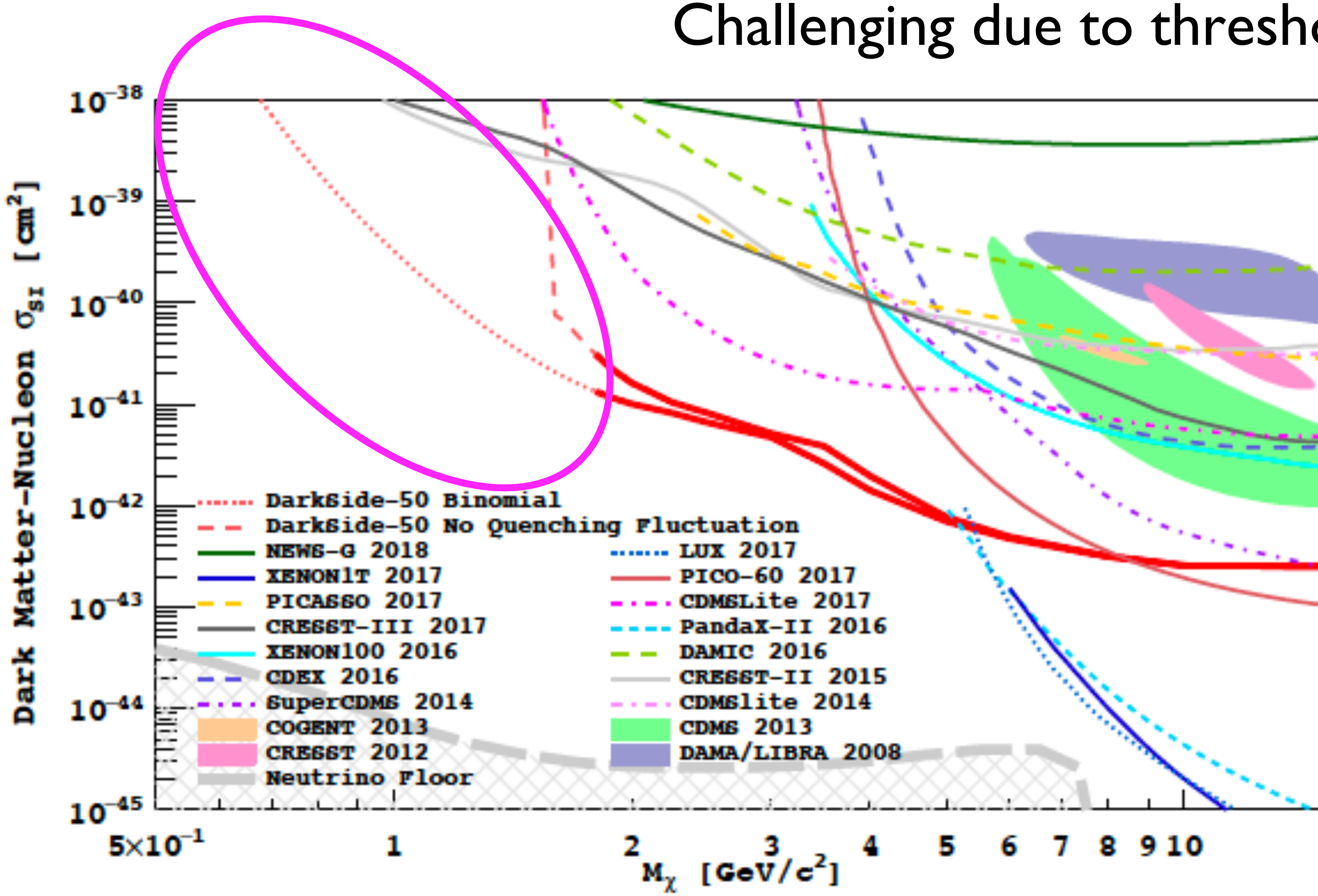
Challenge for light dark matter

Light dark matter: $1\,\mathrm{keV} \lesssim m_{\mathrm{DM}} \lesssim 10\,\mathrm{GeV}$

(Fermion DM)

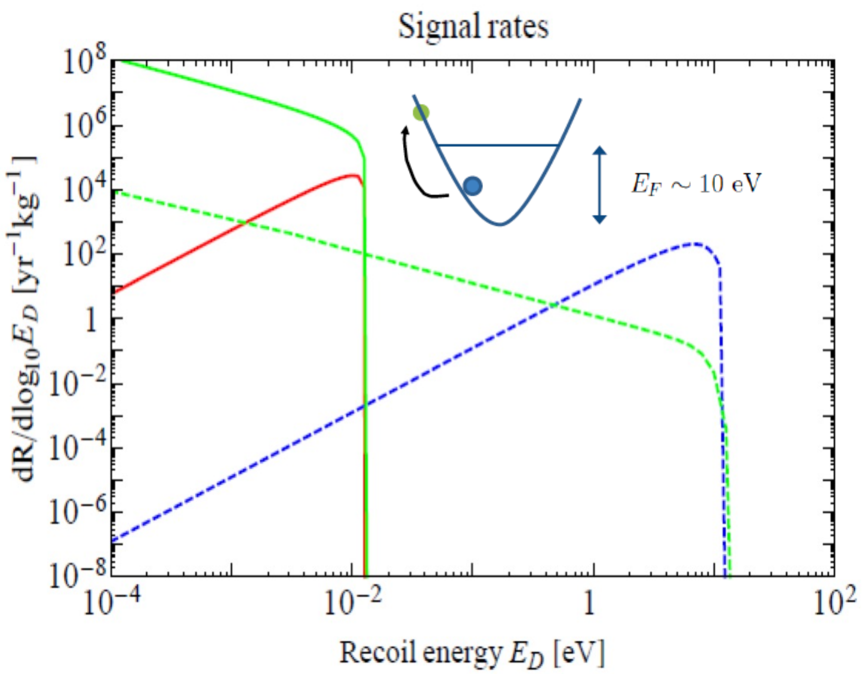
$$E_R = \frac{\vec{q}^2}{2m_N} = \frac{(m_{\mathrm{DM}} v)^2}{2m_N} \lesssim \mathrm{keV}$$: small nucleus recoil energy

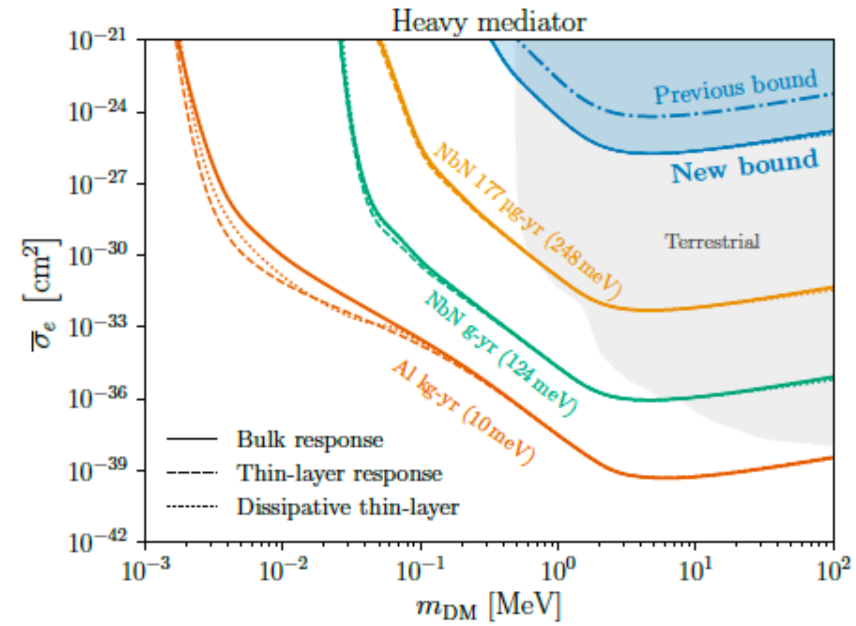
Challenging due to threshold energy!



Light DM in interplay

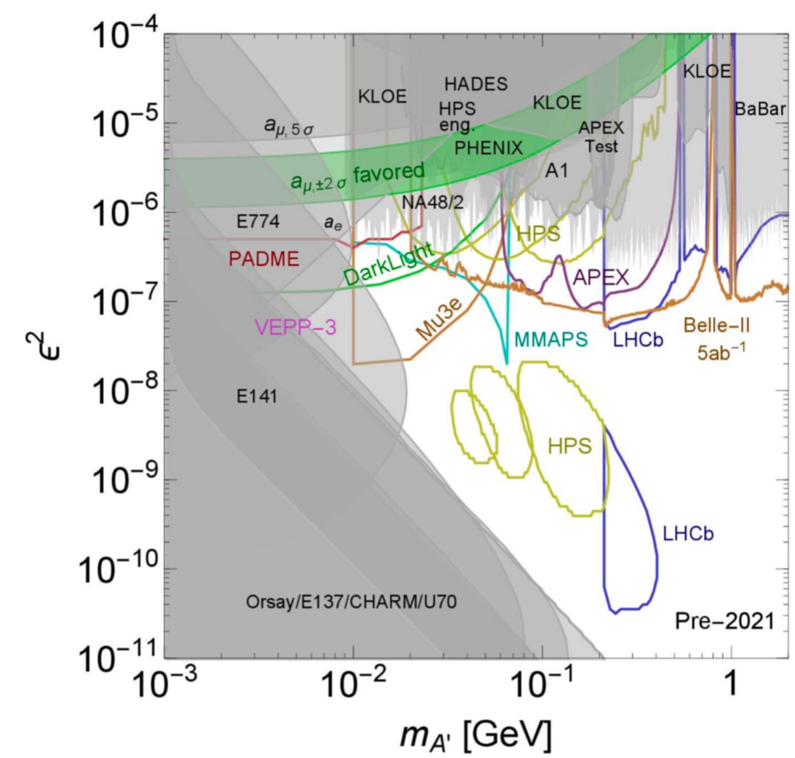
DM-electron scattering

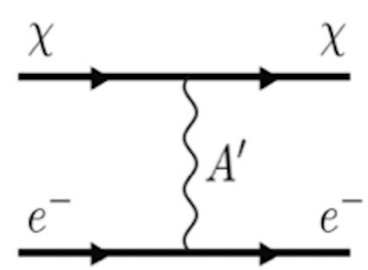




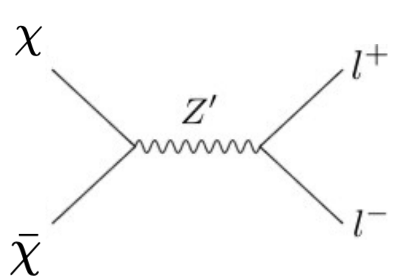
Superconductor(Al)/semi-conductor(Ge)
[Y. Hochberg et al, 2015, 2021]

[US Cosmic Visions, 2017]

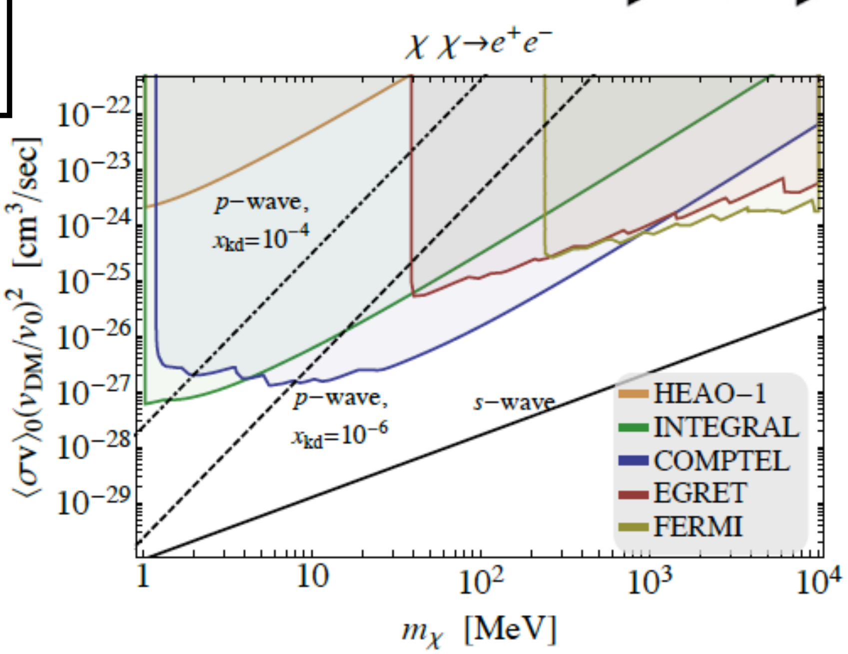




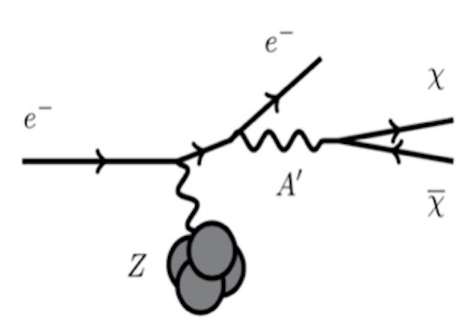
Gamma-ray/CMB

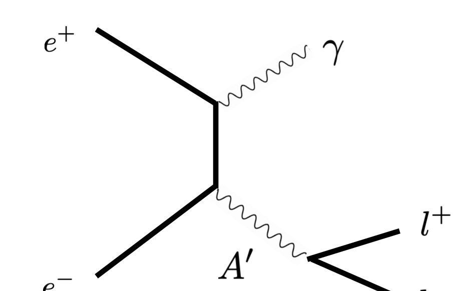


[Essig et al, 2013;
Cirelli et al, 2021]



Beam-dump/colliders





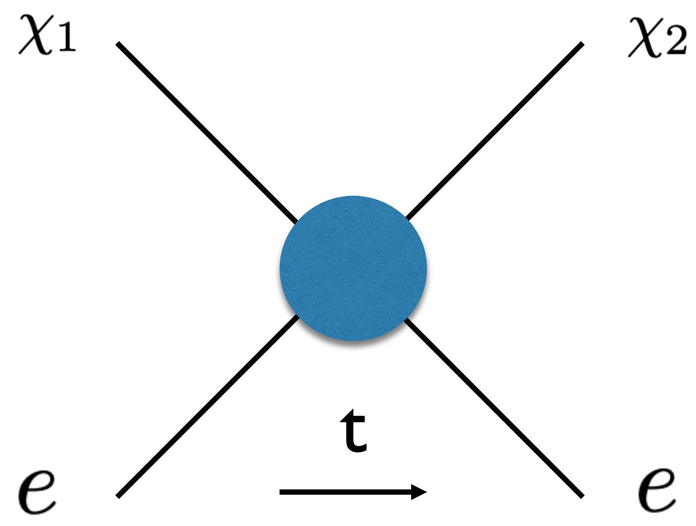
Exothermic dark matter

- Elastic scattering between light DM & electron.

$$E_R \sim \frac{\mu^2 v^2}{m_e} \sim m_e v^2 \sim 0.3\,\mathrm{eV} - 20\,\mathrm{eV}$$: small recoil energy.

$$m_\chi \gtrsim m_e, \quad v \sim 220\,\mathrm{km/s} - 10^{-2}c$$

- Down scattering with electron for small mass splitting.

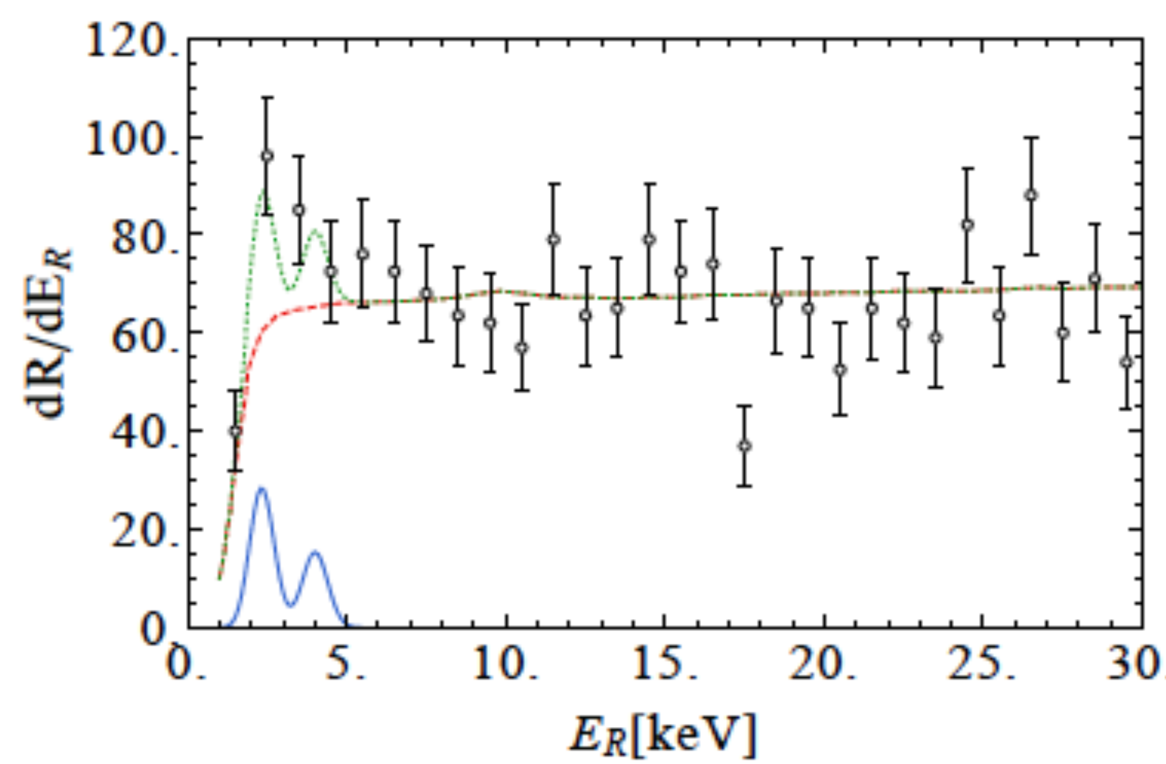


[K. Harigaya et al 2020; HML 2020; S.-M. Choi, HML, B. Zhu, 2020
J. Bramante et al 2020; Essig et al, 2020]

$$\Delta m = m_{\chi_1} - m_{\chi_2} \gg m_e v^2$$

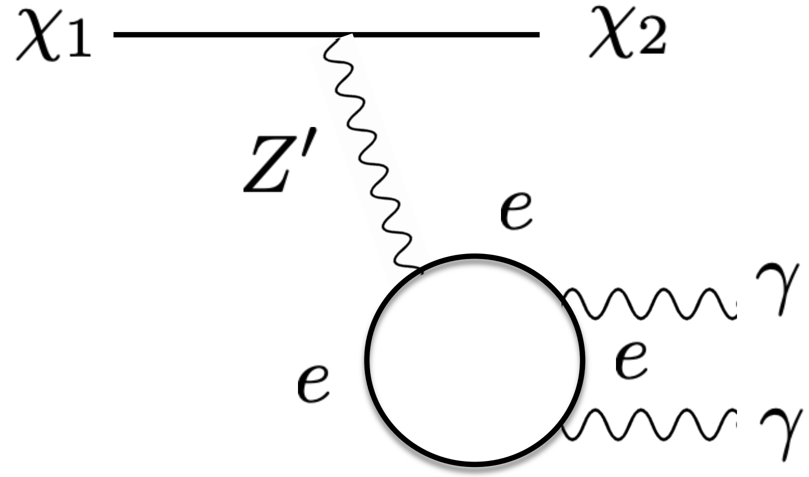
$$E_R \sim \Delta m \sim 2.5\,\mathrm{keV}$$

"Large electron recoil energy"



Bounds on Z' portal

- The axial vector Z' coupling for electron makes the heavier state decaying into two photons:

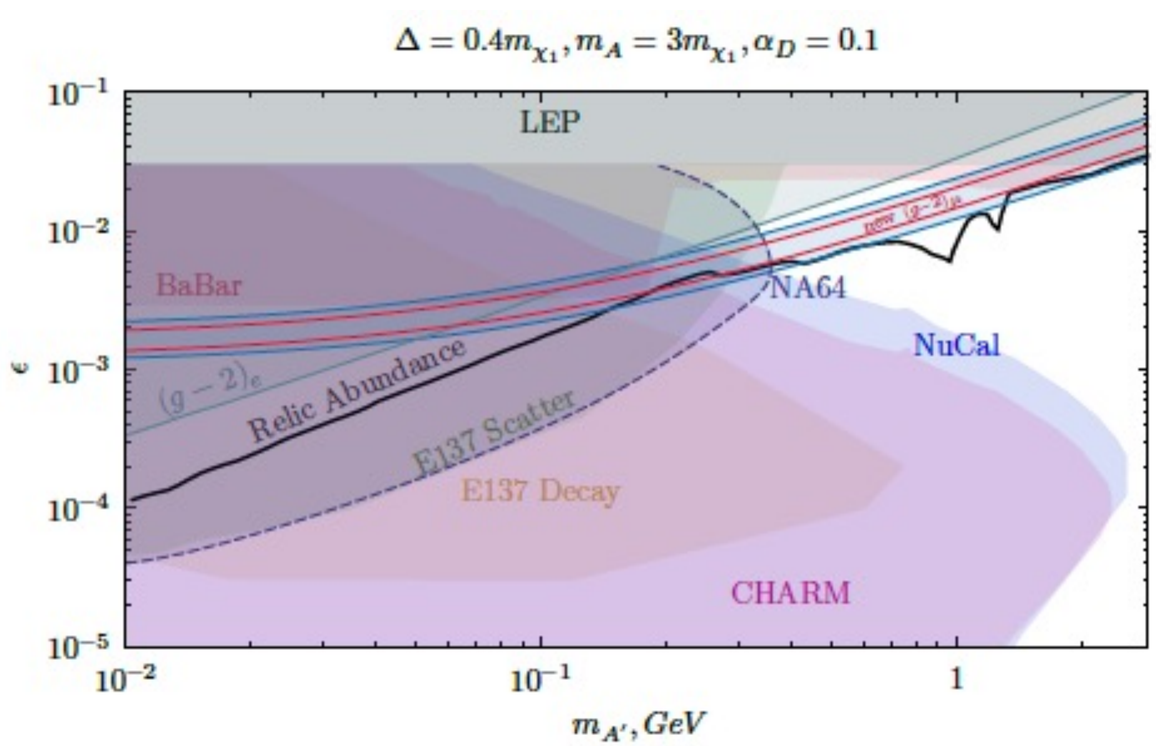


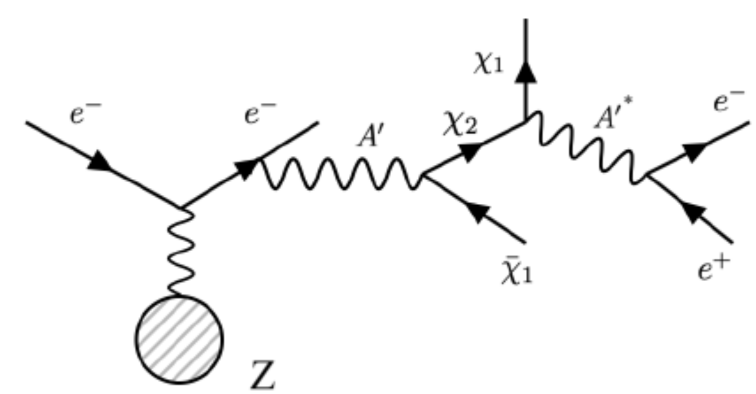
$$\Gamma(\chi_1 \to \chi_2\gamma\gamma) \simeq \frac{a_e^2(v_\chi^2 + a_\chi^2)e^4 g_{Z'}^2}{2560\pi^7}\frac{(\Delta m)^5}{m_{Z'}^4}$$

Diffuse X-ray bound: $\tau_{\chi_1} \gtrsim 10^{24}\,\mathrm{sec}$

$$|a_e| g_{Z'}\sqrt{v_\chi^2 + a_\chi^2} < 2.5 \times 10^{-6}\left(\frac{2.5\,\mathrm{keV}}{\Delta m}\right)^{5/2}\left(\frac{m_{Z'}}{1\,\mathrm{GeV}}\right)^2$$

- Sizable mass splitting => long-lived neutral particles



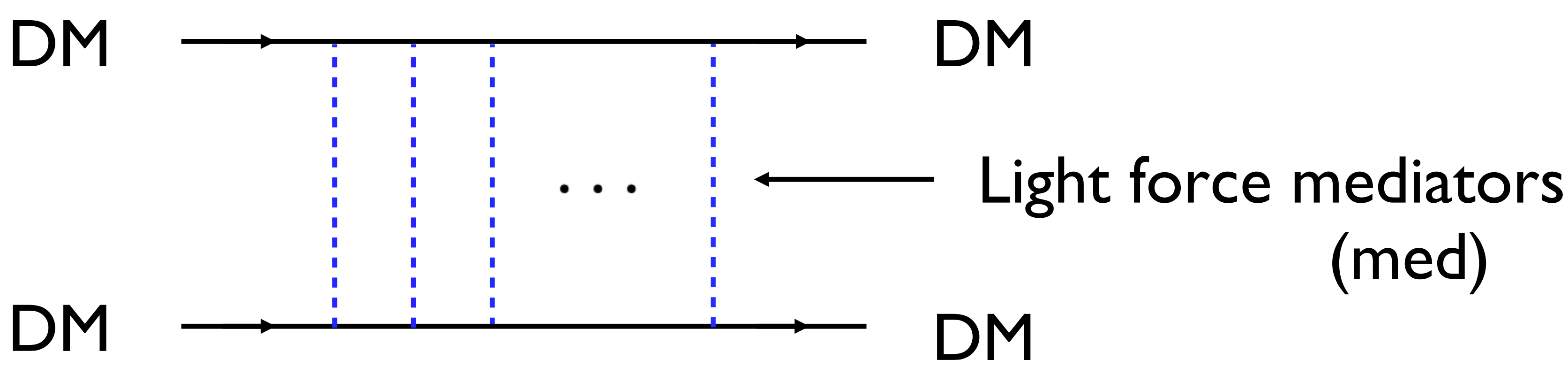


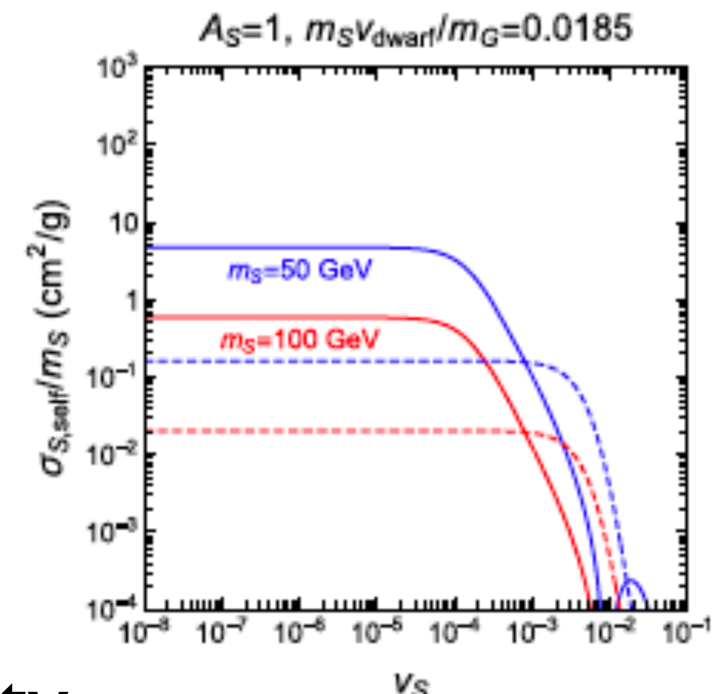
Invisible+visible displaced signals (NA64, LHCb, Belle-II, etc)

Non-perturbative dark matter

T-channel forces in challenge

Light mediators for dark matter self-scattering

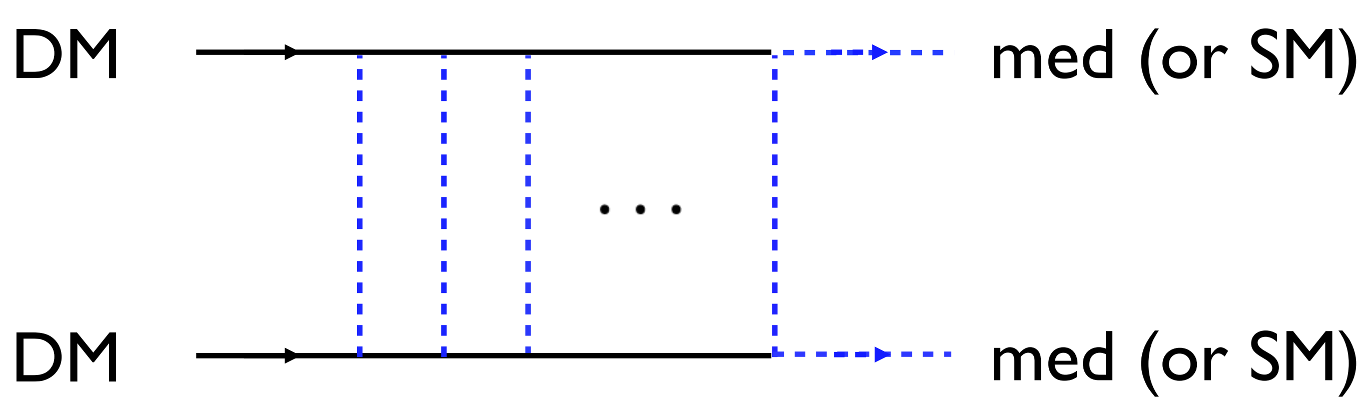


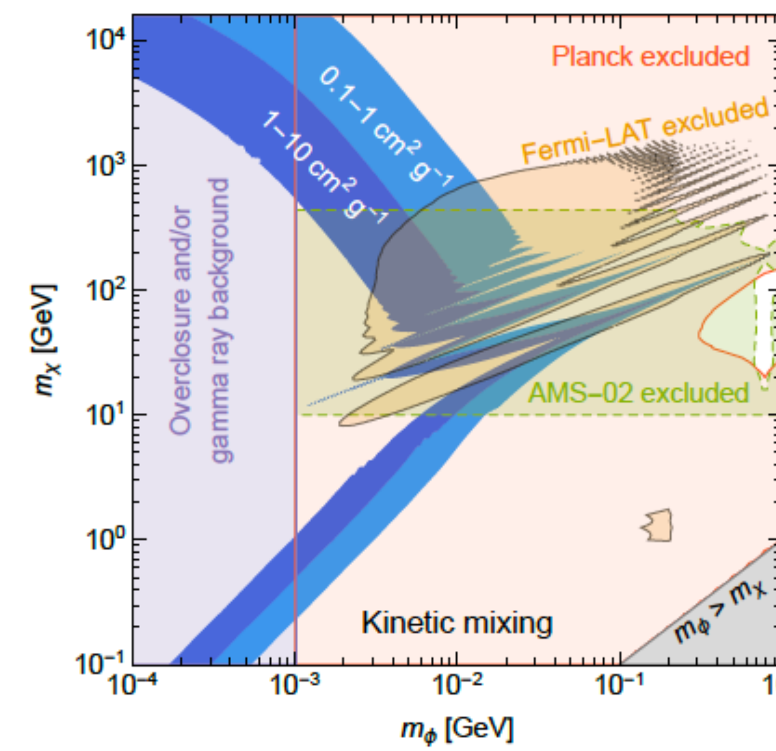


[Kang, HML, 2020]

Self-interaction enhanced at small velocity.

Sommerfeld effect enhances dark matter annihilations at small velocity.





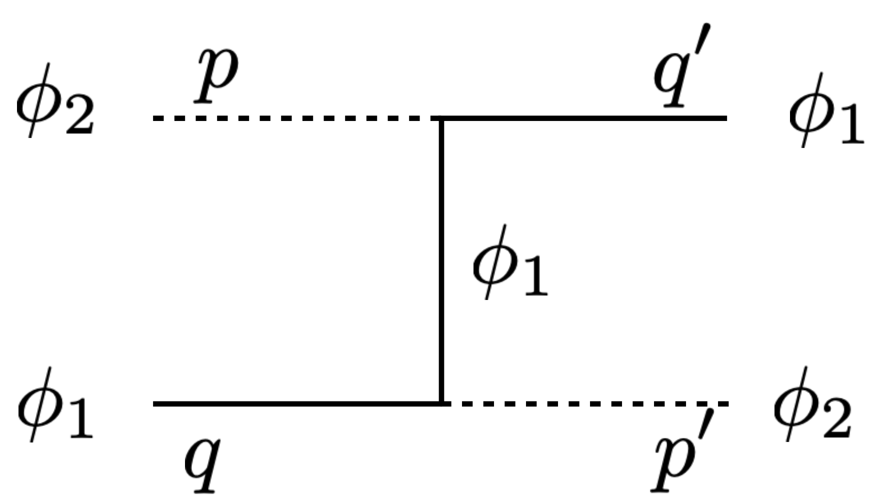
Annihilation product almost ruled out by CMB and cosmic rays.

[Bringmann et al, 2016]

U-channel resonances

- U-channel for 2→2 co-scattering dark matter

[S. Kim, HML, B. Zhu, 2021, 2022]



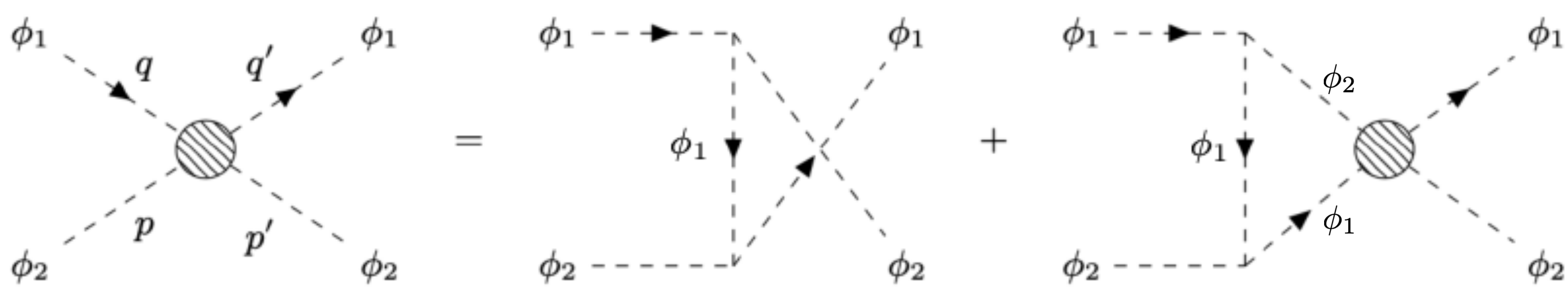
$$\mathcal{L}_{\rm int} = -2g\, m_1 \phi_2 |\phi_1|^2$$

$$\tilde{\Gamma}_u(p,q;p',q') = \frac{4g^2 m_1^2}{|\vec{p}-\vec{q}'|^2 + m_1^2 - \omega^2}$$

$$\omega = p_0 - q_0' \approx m_2 - m_1 \neq 0$$

$m_2 = 2m_1$ "Effectively massless"

Resummation of u-channel ladder diagrams is needed.



Effective u-channel forces

Bethe-Salpeter equation for co-scattering dark matter

$$\left(-\frac{1}{2\mu}\nabla^2 - E\right)\psi_{BS}(\vec{x}) = -V(\vec{x})\psi_{BS}\left(-\frac{m_2}{m_1}\vec{x}\right)$$

[S. Kim, HML, B. Zhu, 2021, 2022]

$$\begin{cases} V(\vec{x}) = -\dfrac{\alpha}{r}e^{-Mr} \\ \alpha \equiv \frac{g^2}{4\pi} \qquad M \equiv m_2\sqrt{2-\dfrac{m_2}{m_1}} \end{cases}$$

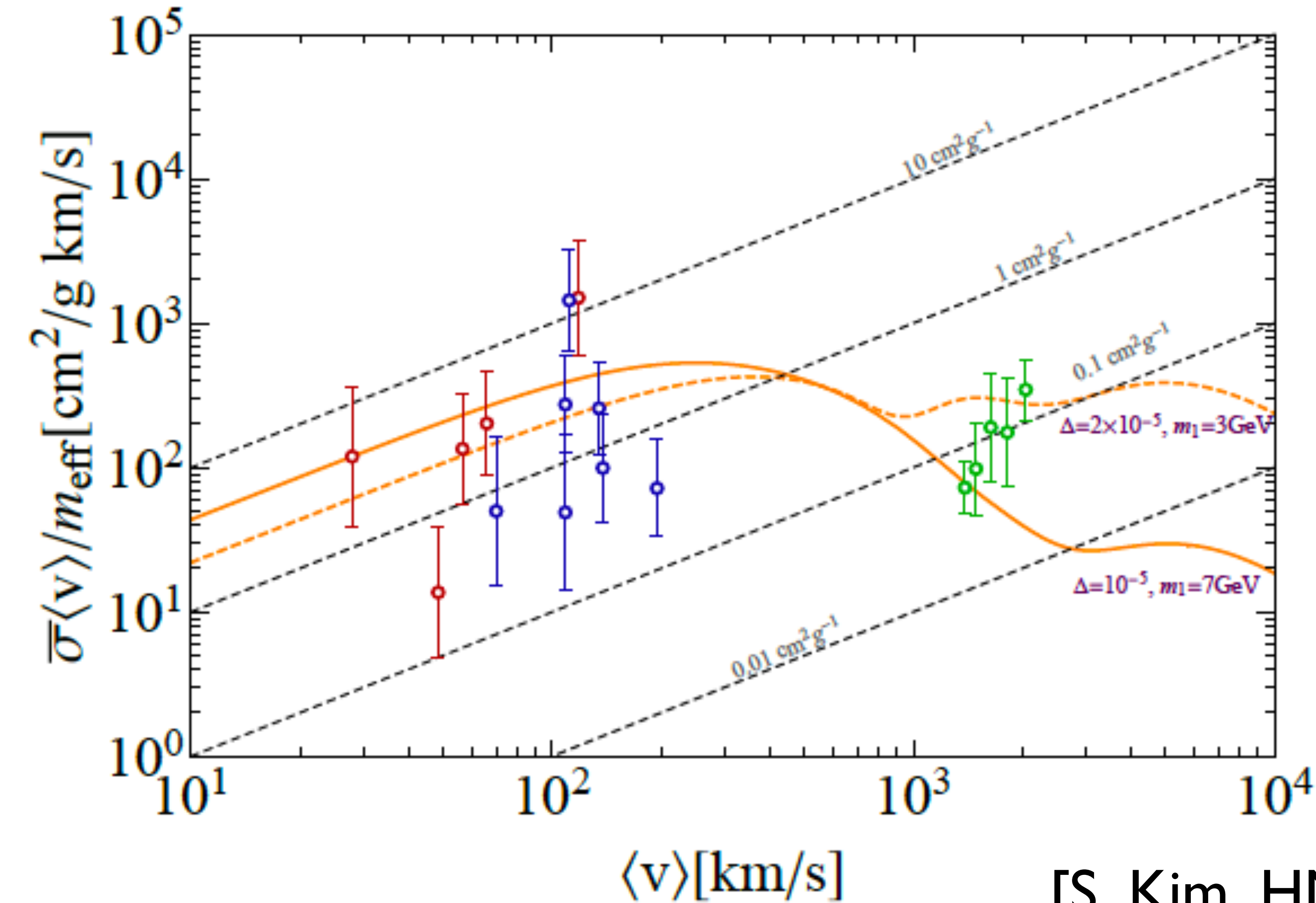
➡ Effective Yukawa interaction

BS wave function in spherical coordinates:

$$\psi_{\rm BS}(\vec{x}) = R_l(r)Y_l^m(\theta,\phi) \longrightarrow \psi_{\rm BS}\left(-\frac{m_2}{m_1}\vec{x}\right) = (-1)^l R_l\left(\frac{m_2}{m_1}r\right)Y_l^m(\theta,\phi)$$

- Effective potential depends on angular momentum: attractive for l=even ; repulsive for l=odd.
- Effective mediator mass: $M \equiv m_2\sqrt{2-\frac{m_2}{m_1}} \to 0, \quad m_2 \to 2m_1.$

SIDM from co-scattering



$\alpha = g^2/(4\pi) = 0.1$

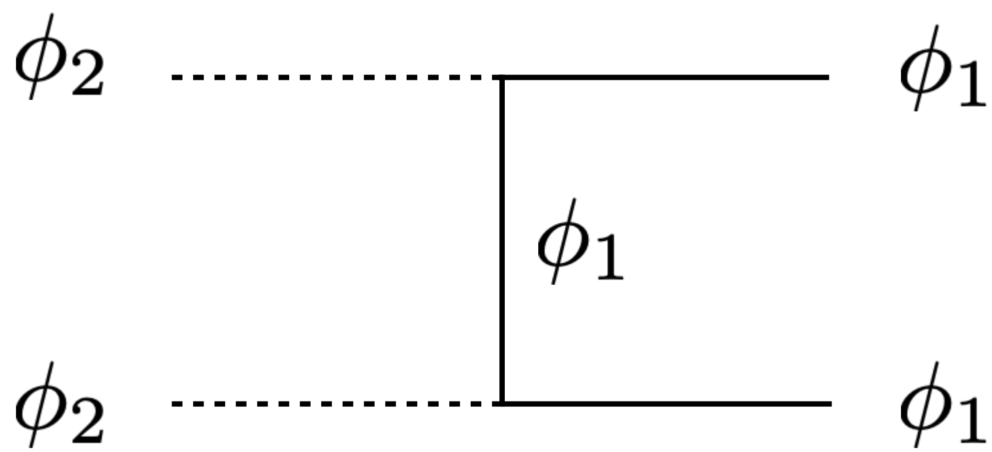
[S. Kim, HML, B. Zhu, 2021]

$\phi_1\phi_2 \to \phi_1\phi_2$: $\sigma = \frac{4\pi}{k^2}\sin^2\delta_0$, total cross section

$\bar{\sigma} = \langle \sigma v_{\rm rel}^3\rangle/(24/\sqrt{\pi}v_0^3)$: energy-transfer average

➡ u-channel force for dark matter is velocity-dependent.

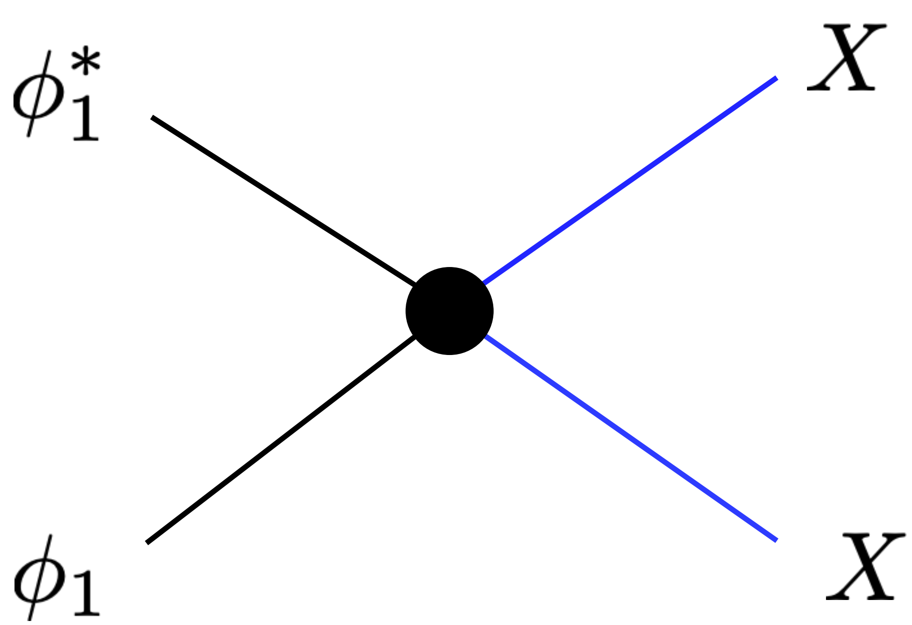
DM annihilation

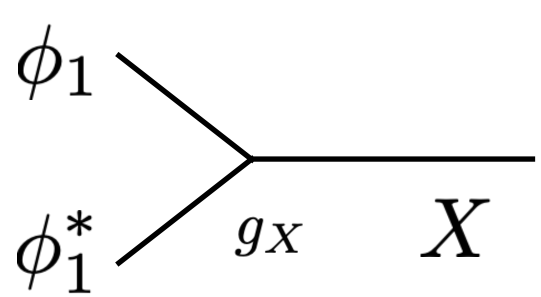


Heavier DM always annihilates into lighter DM, but no freeze-out.

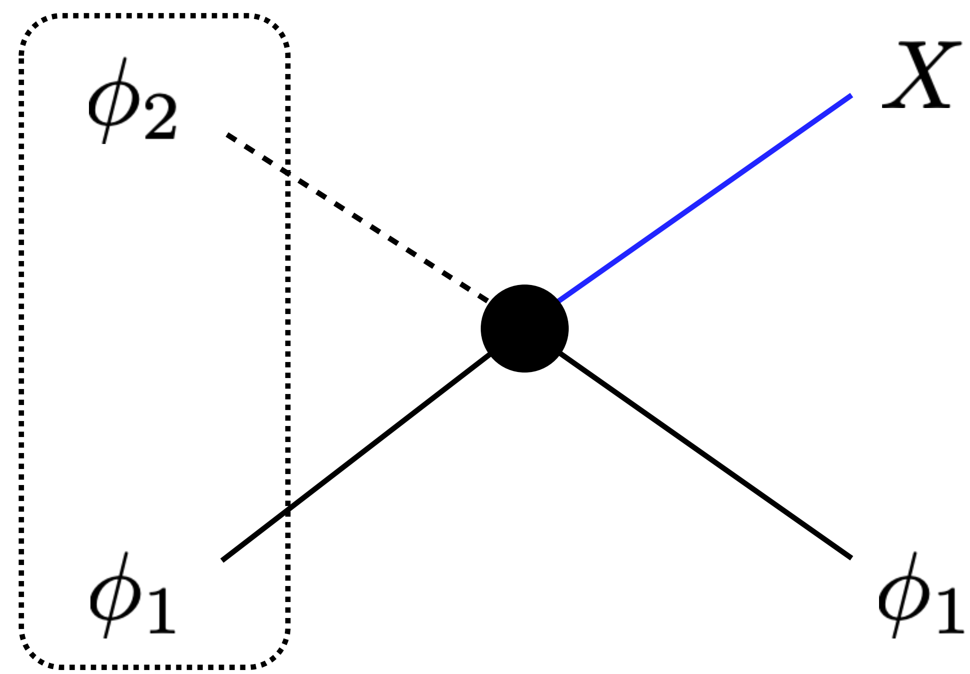
→ extra 2→2 annihilation

e.g. dark photon portal



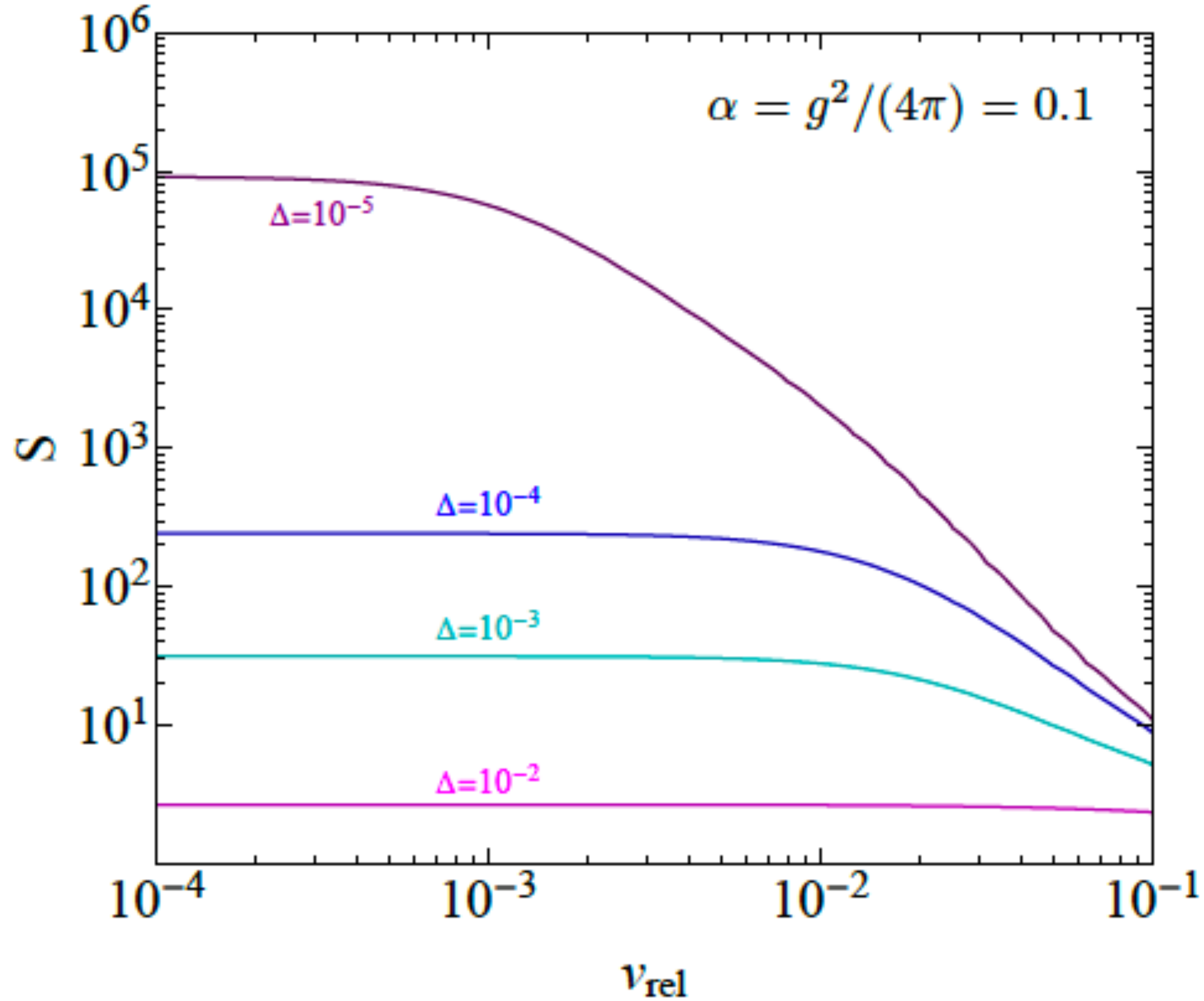


BS w.f.



u-channel
Sommerfeld enhancement

Sommerfeld factor



Sommerfeld factor (s-wave):

$$S = \frac{|\psi_{\rm BS}(0)|^2}{|\psi_{\rm pert}(0)|^2} = A^2$$

Effective mediator mass

$$\longleftrightarrow \quad \Delta = 1 - \frac{m_2}{2m_1} \geq 0$$

[S. Kim, HML, B. Zhu, 2021]

Boundary conditions (s-wave):

$$\tilde{u}_0(\rho) \longrightarrow \frac{1}{a}\sin(a\,e^{-\rho} + \delta_0), \qquad \rho \to -\infty, \qquad \text{“plane-wave”}$$

$$\tilde{u}_0(\rho) \longrightarrow A\,e^{-\rho}, \qquad \rho \to +\infty \qquad \text{“constant R”}$$

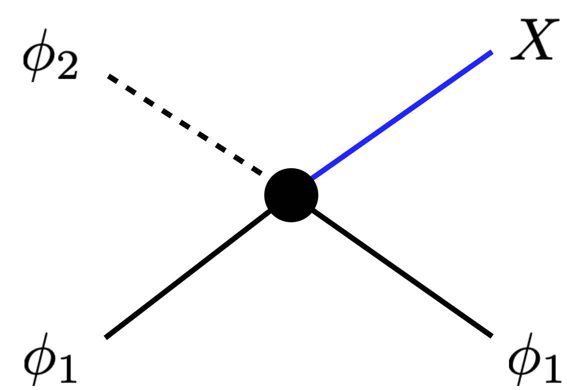
Indirect detection

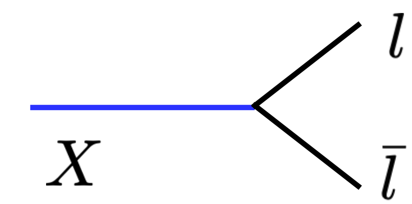
Cosmic ray (from semi-annihilation): [S. Kim, HML, B. Zhu, 2022]

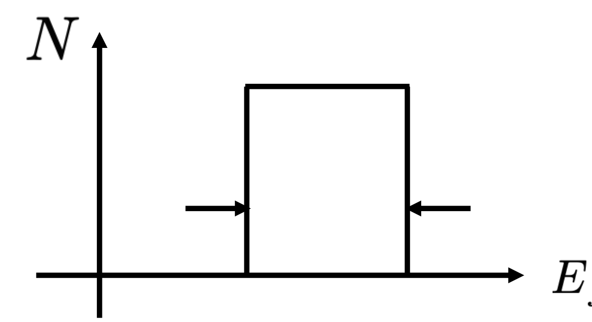
Leptons boosted in galactic center frame

$$E_f = \frac{1}{\gamma_X}\,\bar{E}_f\,(1 - v_X\ \cos\theta)^{-1},$$

$$\bar{E}_f = \frac{m_X}{2}$$







$\Delta E_f = v_X \gamma_X\, m_X$

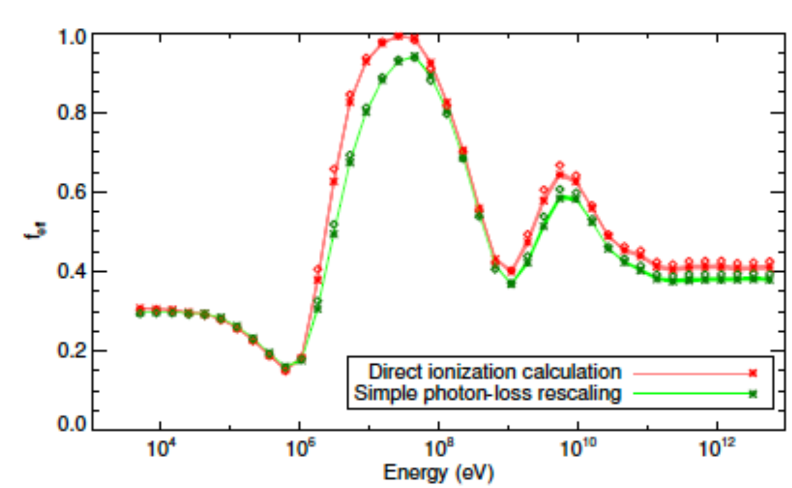
CMB (from semi-annihilation):

Leptons injects energy to CMB photons

$$\langle\sigma v\rangle_{\phi_1\phi_2\to\phi_1 X} < 4\times 10^{-25}\,\mathrm{cm^3/s}\left(\frac{f_{\rm eff}}{0.1}\right)^{-1}\cdot\frac{1}{r_1(1-r_1)}\cdot\left(\frac{m_2}{100\,\mathrm{GeV}}\right)$$

Efficient factor: $f_{\rm eff}(m_2) = \frac{\int_0^{m_2/2} dE_e\, E_e\, 2 f_{\rm eff}^{e^+e^-}\, \frac{dN_e}{dE_e}}{m_2}, \quad r_1 = \Omega_1/\Omega_{\rm DM}$

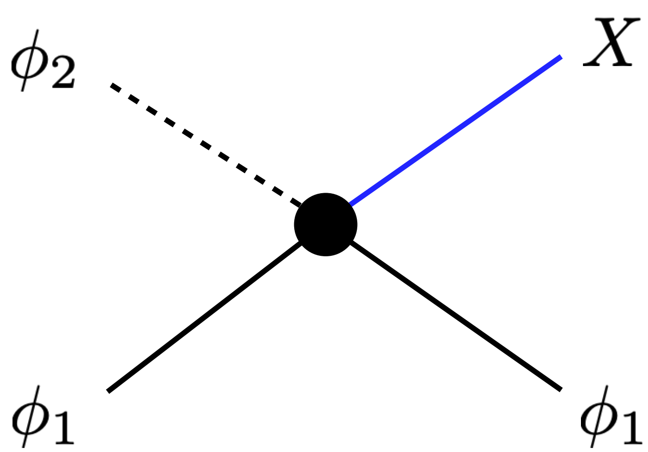
	$m_2 \simeq 2m_1$ [GeV]	m_X [GeV]	$\alpha = \frac{g^2}{4\pi}$	$\alpha_X = \frac{g_X^2}{4\pi}$	$\langle\sigma v\rangle^0_{\phi_1\phi_2\to\phi_1 X}$ [cm^3/s]	$r_1 = \frac{\Omega_1}{\Omega_{\rm DM}}$	S_0	$\Delta = 1 - \frac{m_2}{2m_1}$	$\sigma_{\rm self}/m_{\rm eff}$ [cm^2/g]
B1	200	50	0.05	0.0045	9.9×10^{-27}	0.5	444.7	7.75×10^{-4}	0.014
B2	400	100	0.1	0.009	9.9×10^{-27}	0.5	889	10^{-4}	0.002
B3	26	5	0.00032	0.04	2.0×10^{-26}	0.005	1336	5×10^{-10}	0.003
B4	240	60	0.0032	0.03	2.9×10^{-27}	0.075	7379	$10^{-7.7}$	0.086



[T. Slatyer, 2015]

Direct detection

Boosted DM from semi-annihilation: [S. Kim, HML, B. Zhu, 2022]

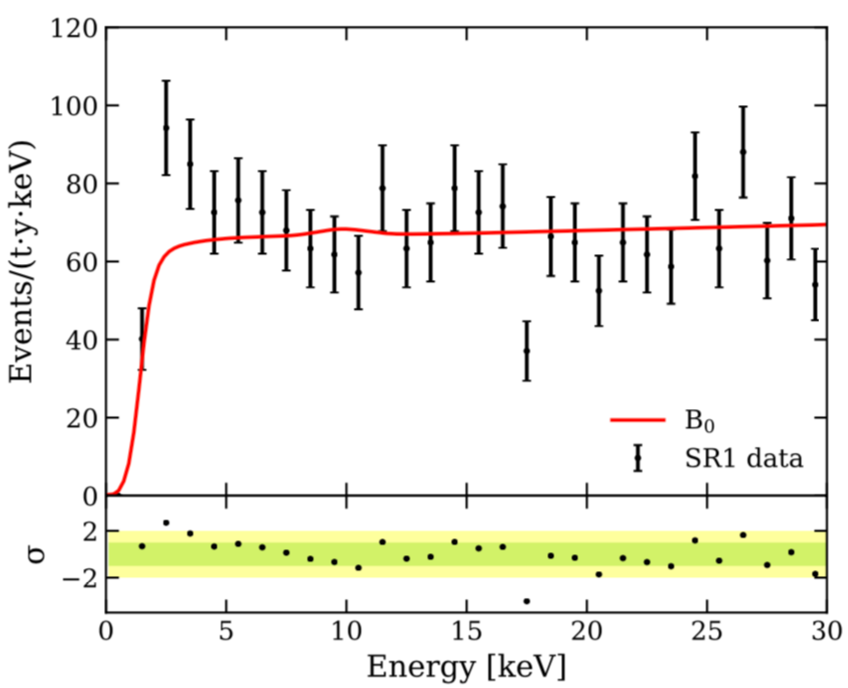


Gamma factor for boosted DM

$$\gamma_1 = (10m_1^2 - m_X^2)/(6m_1^2) \qquad m_2 \simeq 2m_1$$

DM flux from galactic center (NFW)

$$\Phi_1^{\rm G.C.} = 1.6\times 10^{-4}{\rm cm}^{-2}{\rm s}^{-1}\left(\frac{\langle\sigma v\rangle_{\phi_1\phi_2\to\phi_1 X}}{5\times 10^{-26}{\rm cm}^3/{\rm s}}\right)\left(\frac{(1\,{\rm GeV})^2}{m_1 m_2}\right) r_1(1-r_1)$$



XENON1T (old) excess

Large electron-recoil in XENON

$$\sigma_e = 10^{-33}\,{\rm cm}^2\left(\frac{10^{-1}{\rm cm}^{-2}{\rm s}^{-1}}{\Phi_1^{\rm G.C.}}\right)\left(\frac{N_{\rm sig}}{10}\right)$$

$$E_e = 2m_e v_1^2 = 3.6\,{\rm keV}, \quad m_1 = 2m_2 \sim 1\,{\rm GeV} \text{ and } r_1 \simeq \tfrac{1}{2}$$

$$\longrightarrow \quad m_X = 1.99729 m_1$$

XENON sensitive to u-channel forces

Conclusions

- There is a room to probe (new) portal models for WIMP and there is a wide parameter space for dark matter beyond WIMP by new techniques, such as DM-electron scattering, high-intensity beams, etc.

- SIMP is a new paradigm beyond WIMP or axion: small-scale problems and diversity problem are solved; distinguishable by self-interactions and couplings with relatively heavy dark photons.

- New non-perturbative effects of multi-component dark matter are identified, giving rise to boosted signatures for self-interactions and indirect/direct detections.