The Weakly Interacting Massive Particle dark matter and beyond

刘佳 (Jia Liu)
Peking University

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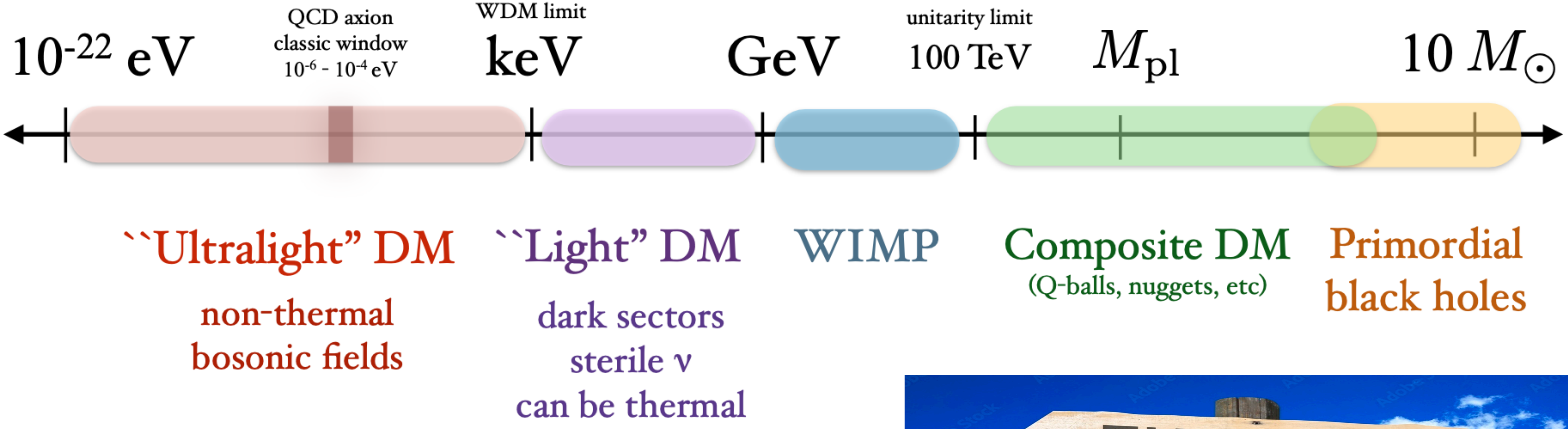
2022-11-18

Outlines

- Various DM models
  - Ultralight bosonic DM
  - WIMP DM
    - Direct detection crisis
    - Complementarity with collider detection
    - DM indirect constraints
  - A WIMP variant from cosmological evolution
- Summary

Dark matter candidate models

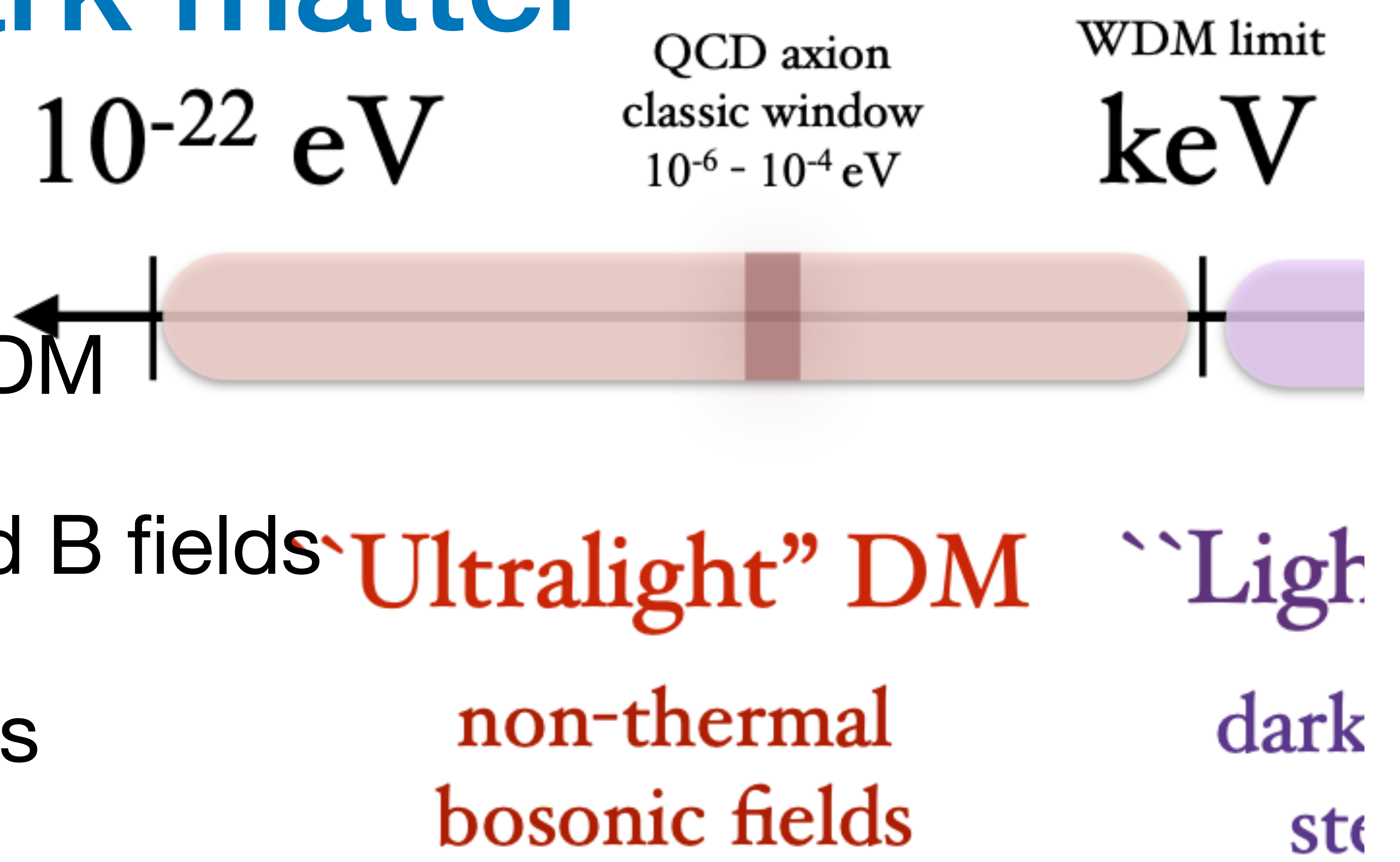
1904.07915， TASI lecture



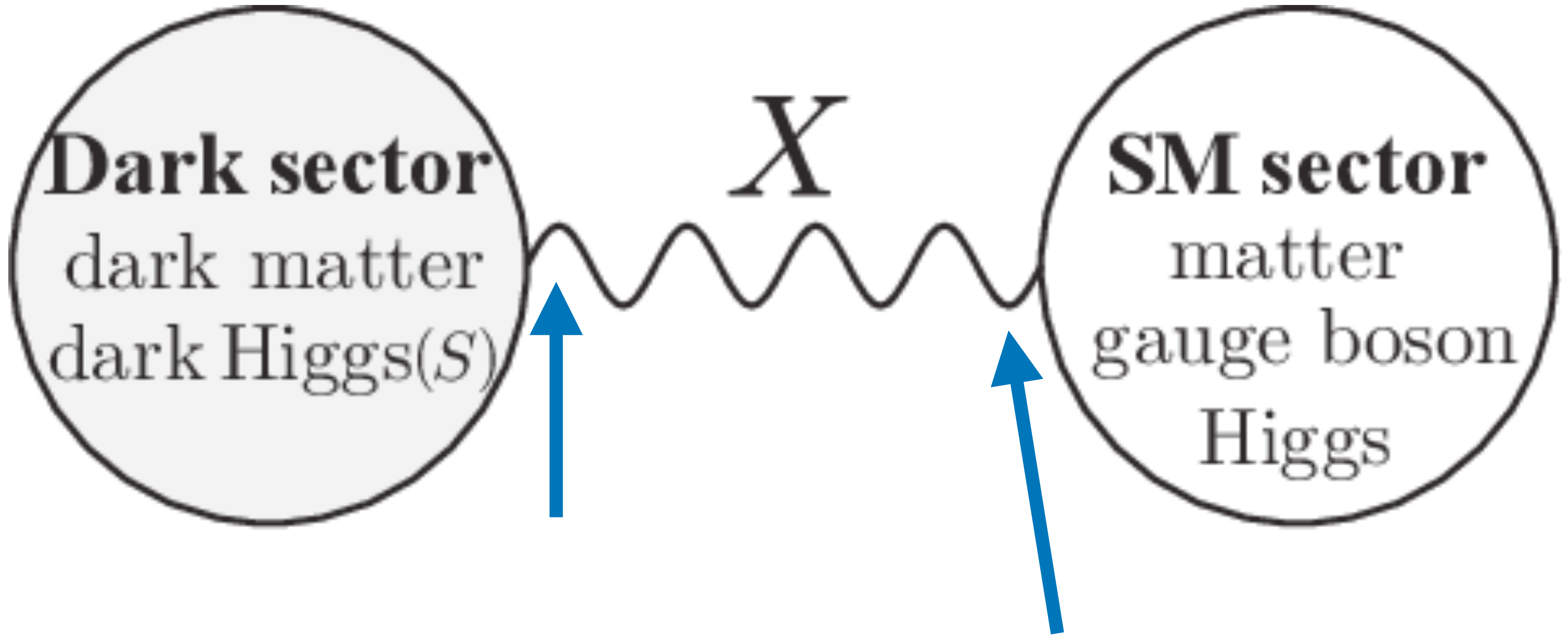
- Ultralight light bosonic dark matter
- Weakly Interacting Massive Particles
- …… Primordial Black Hole, Freeze-in DM, Asymmetric DM

HEP at a cross-road: explore all directions!

Ultralight light bosonic dark matter



- Ultralight Dark Matter
  - Axion and ALPs: coupling to spins, inducing time varying EDM
  - Dark photon: coupling to EM currents, leading to dark E and B fields
  - Dark scalar： coupling to fermion mass, time varying masses
  - Relic abundance： Misalignment etc …
  - Motivations：
    - Small structure problems from CDM
    - Dark sector and dark matter
    - Very small mass from
      - pseudo-Nambu-Goldstone, QCD axion

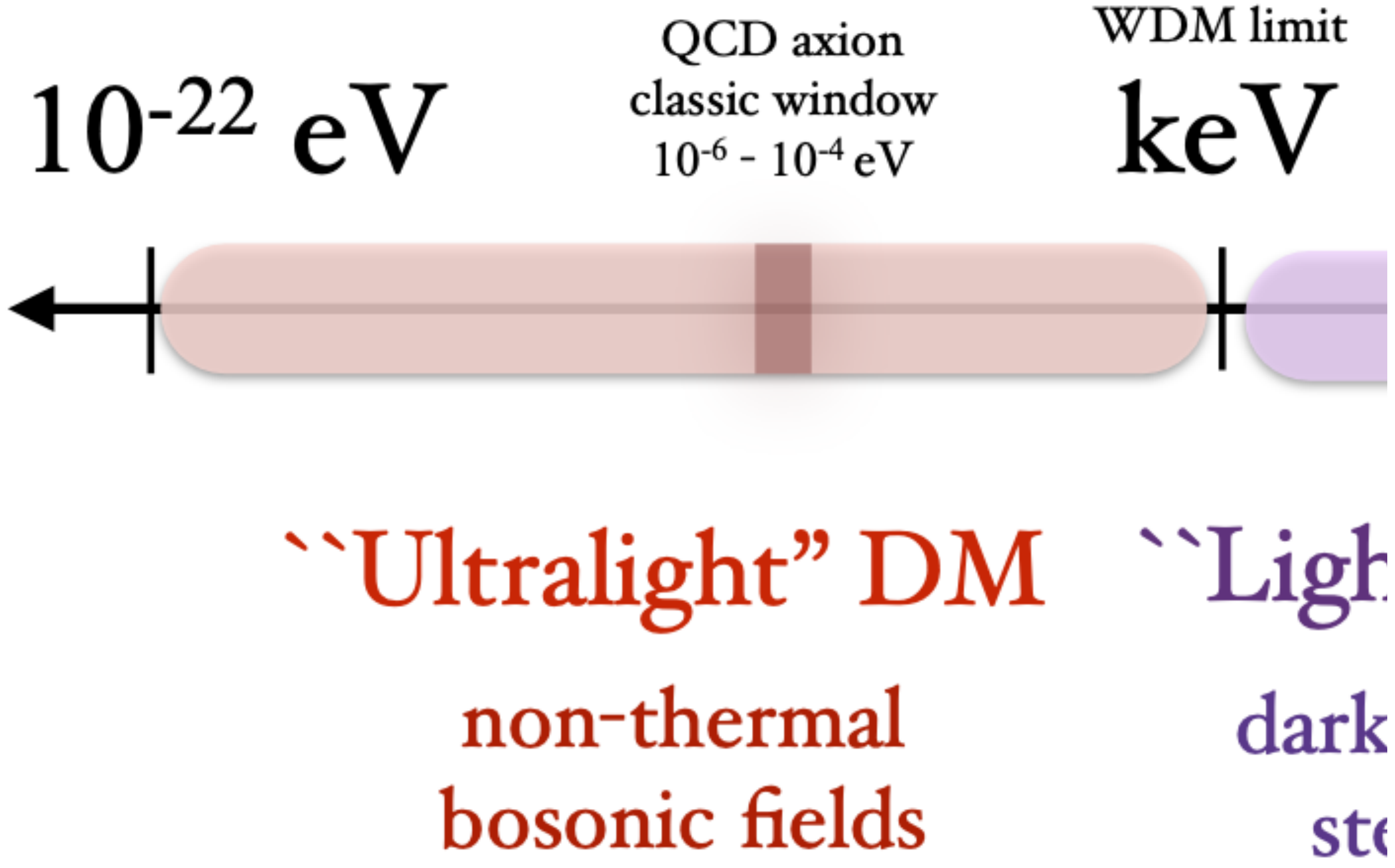


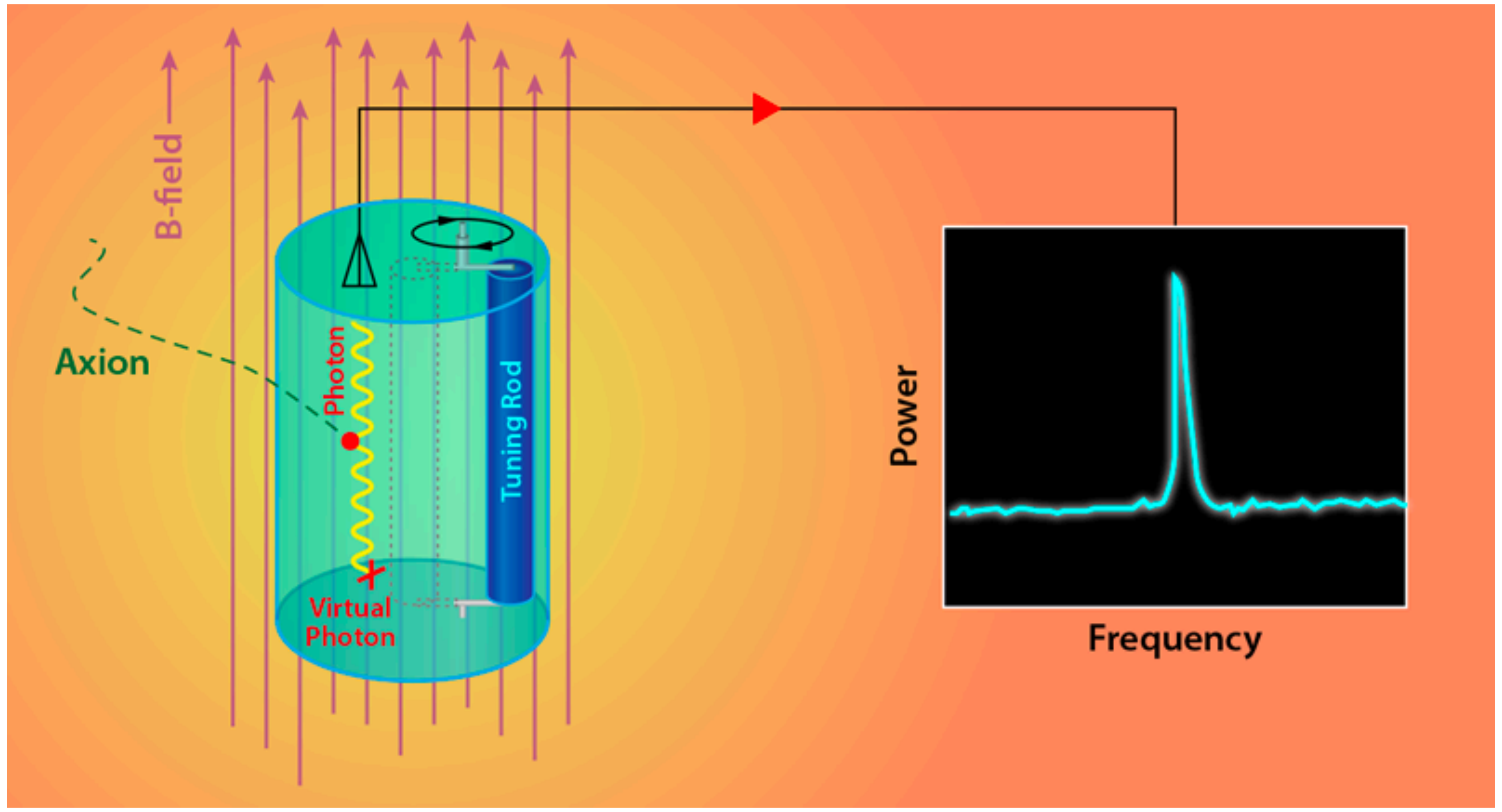
Normal couplings

Very small couplings

Ultralight light bosonic dark matter

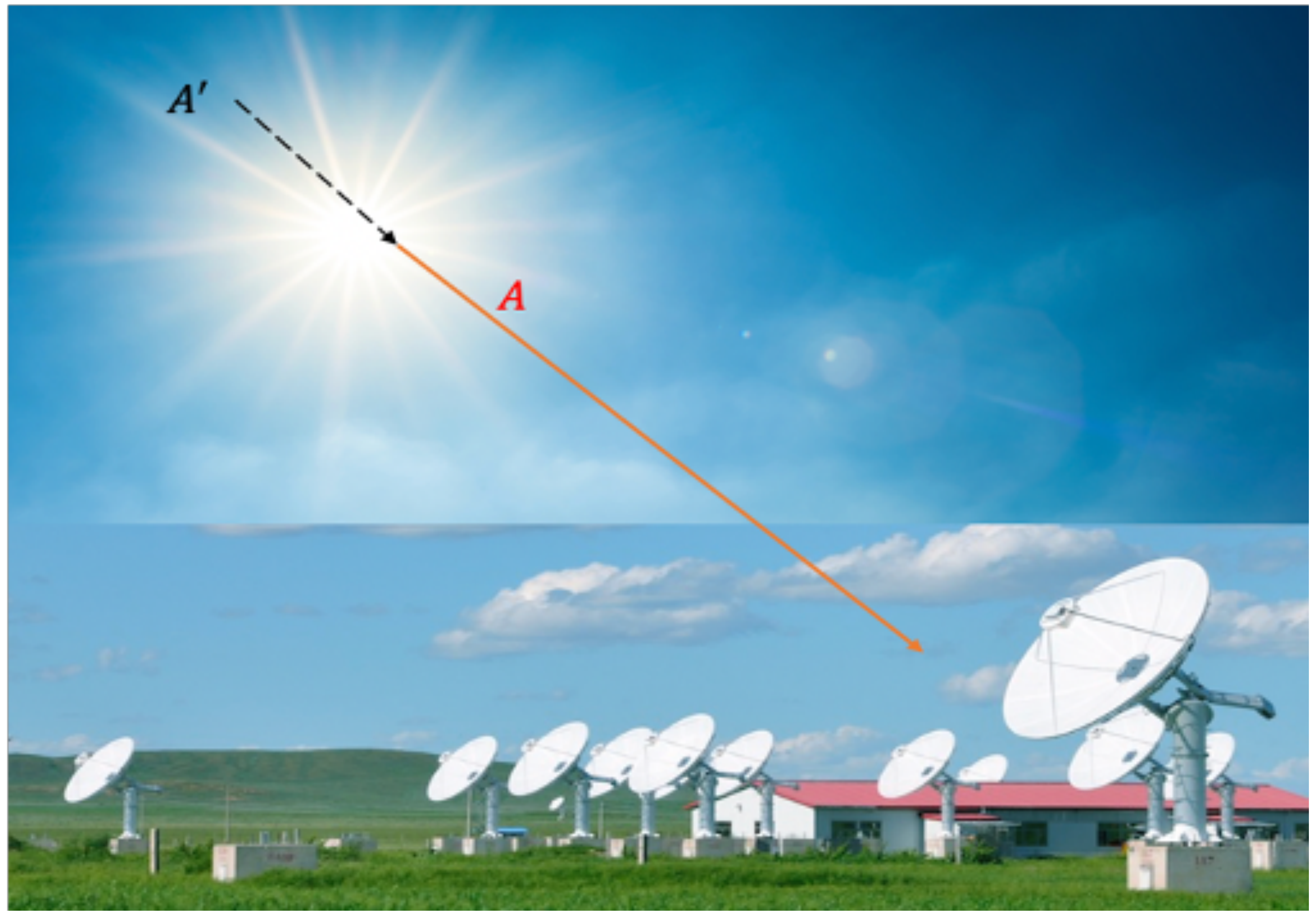
- Mass in $[10^{-22}, 10^{3}]$ eV, exists as classical fields
- Feeble couplings and low energies: interplay with AMO, astrophysics and cosmology
- Various detection methods
  - Cavity resonant experiment（ADMX, HAYSTAC …）(ALP, A’)
  - Broadband searches（WISPDMX，Dark E-field …）（A’）
  - Fifth force、Equivalence Principle （S, A’）
  - DM direct detection (XENONnT, PANDAX-4T, CDEX) (ALP, A’)
  - Astrophysical observations
    - Stars as laboratories：exotic energy loss （A’, ALP, S）
    - CMB, High energy γ, BH polarization (ALP、A’)
    - Radio astronomy (ALP, A’) …





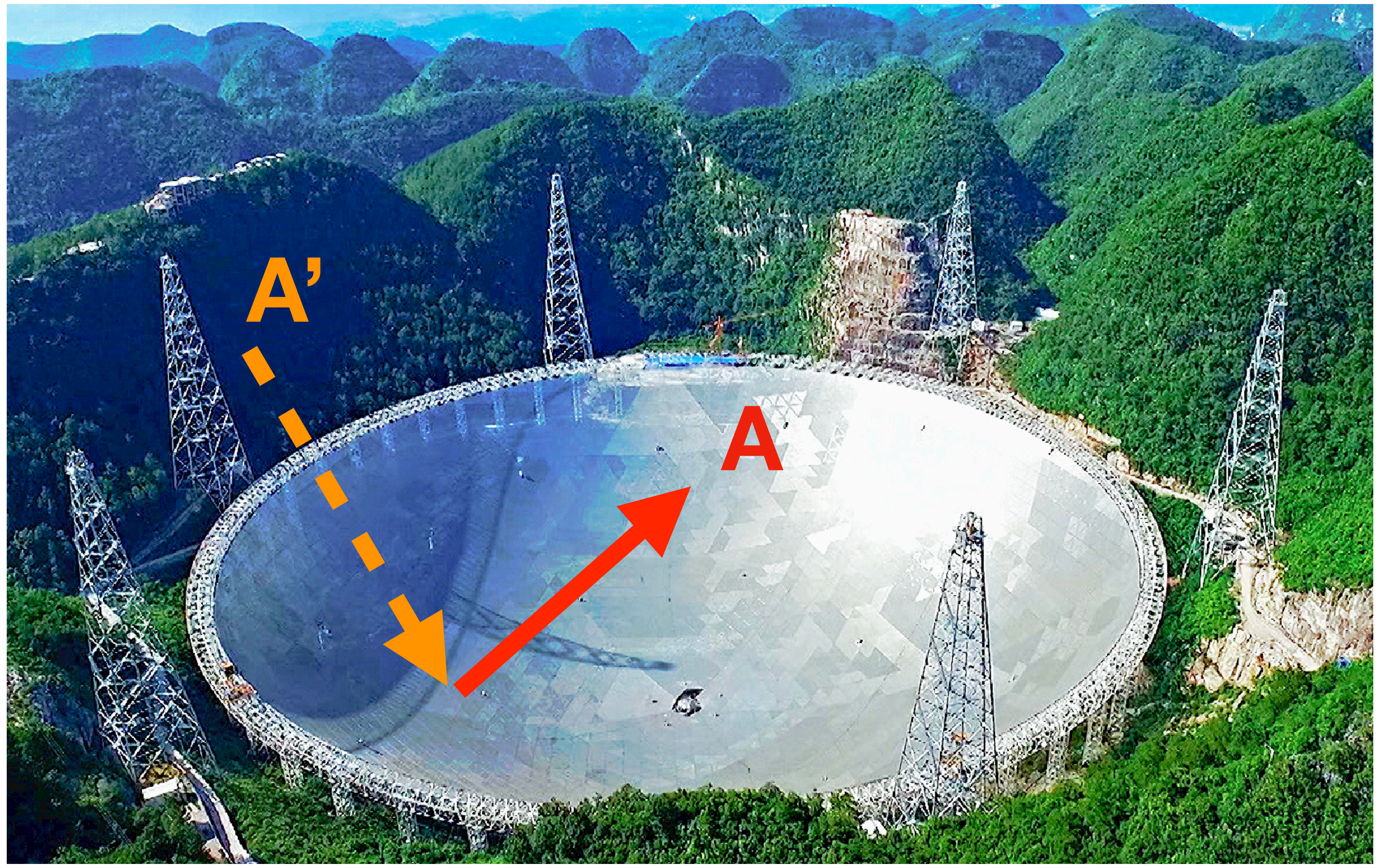
Complementarity from radio astronomy

- Ultralight bosonic dark matter : dark photon DM
  - Classical fields； dark electric and magnetic fields； oscillating frequency fixed by dark photon mass



DPDM-photon resonant conversion in the Solar Corona

An, Huang, JL, Xue 2010.15836 (PRL)



DPDM-photon resonant conversion at the reflecting mirror
Or antenna at radio telescopes

An, Ge, Guo, Huang, JL, Lu, ArXiv:2207.05767

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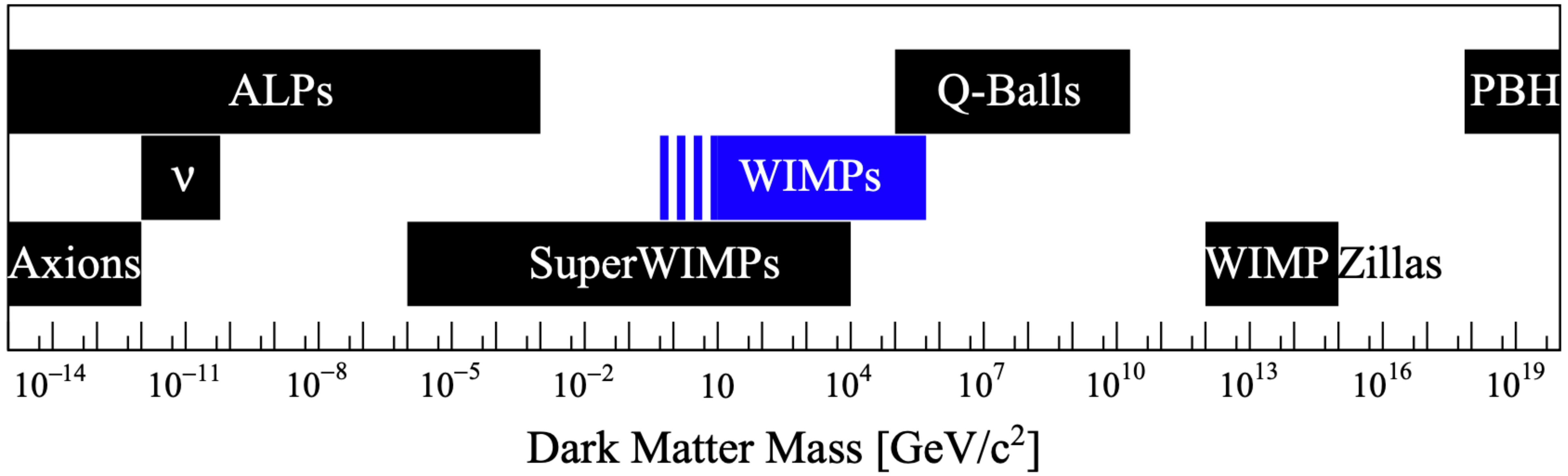
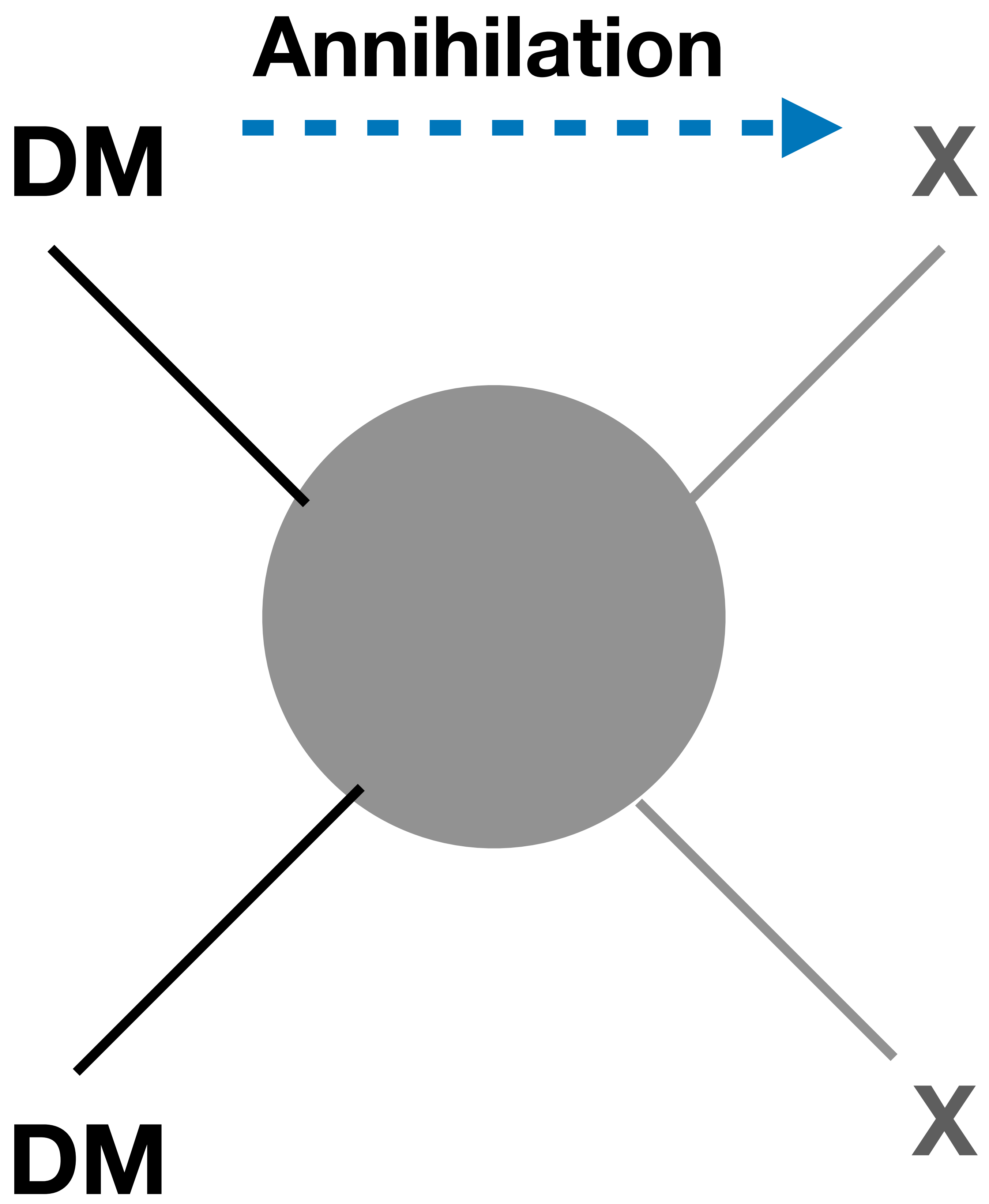
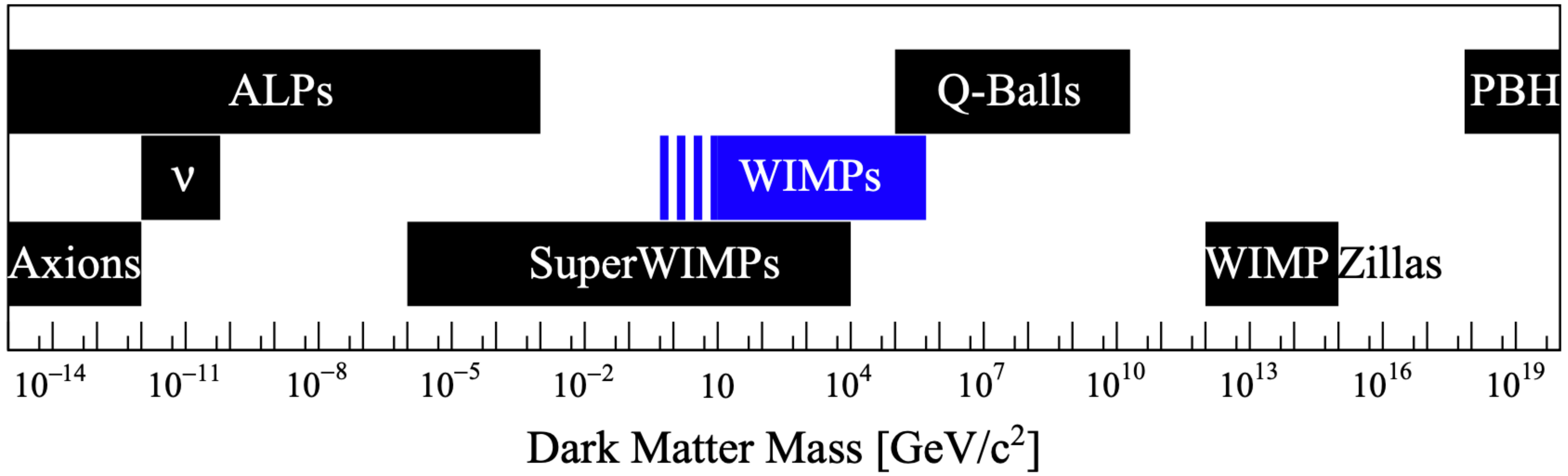
The Weakly Interacting Massive Particle paradigm



- DM is a massive elementary particle
- DM has an electroweak-scale coupling
  - DM starts with thermal distribution
  - Relic abundance is determined by freeze-out mechanism
  - DM Annihilation into
    - X = Standard Model particles (direct coupling)
    - X = Dark Sector particles (secluded DM models)



The freeze-out of WIMP DM

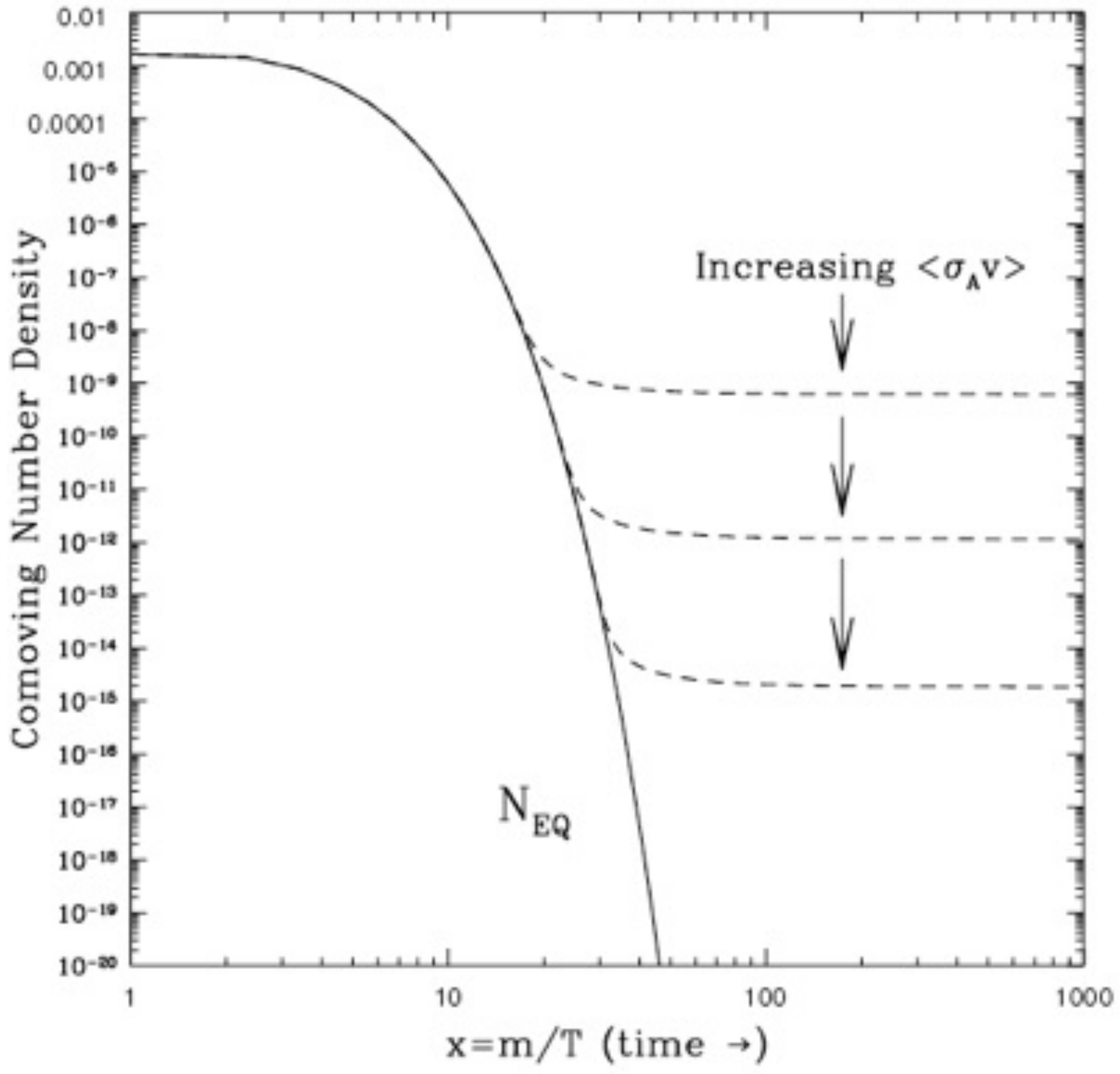


- Thermal cross-section

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- DM Annihilation cross-section

$$\langle \sigma v \rangle \sim \frac{g^4}{m_{\mathrm{DM}}^2} \Rightarrow g \sim \sqrt{\frac{m_{\mathrm{DM}}}{10\mathrm{TeV}}}$$



Jungman *et al* hep-ph/9506380

This is called WIMP miracle!

The WIMP DM and freeze-out

- DM relic abundance
  - No further UV info needed (started with a thermal distribution)
  - Electroweak scale annihilation cross-section
  - Similar stories in SM (ν decoupling, n_p/n_n ratio, nuclear elements)
  - Leads to collider/direct/indirect signal as well

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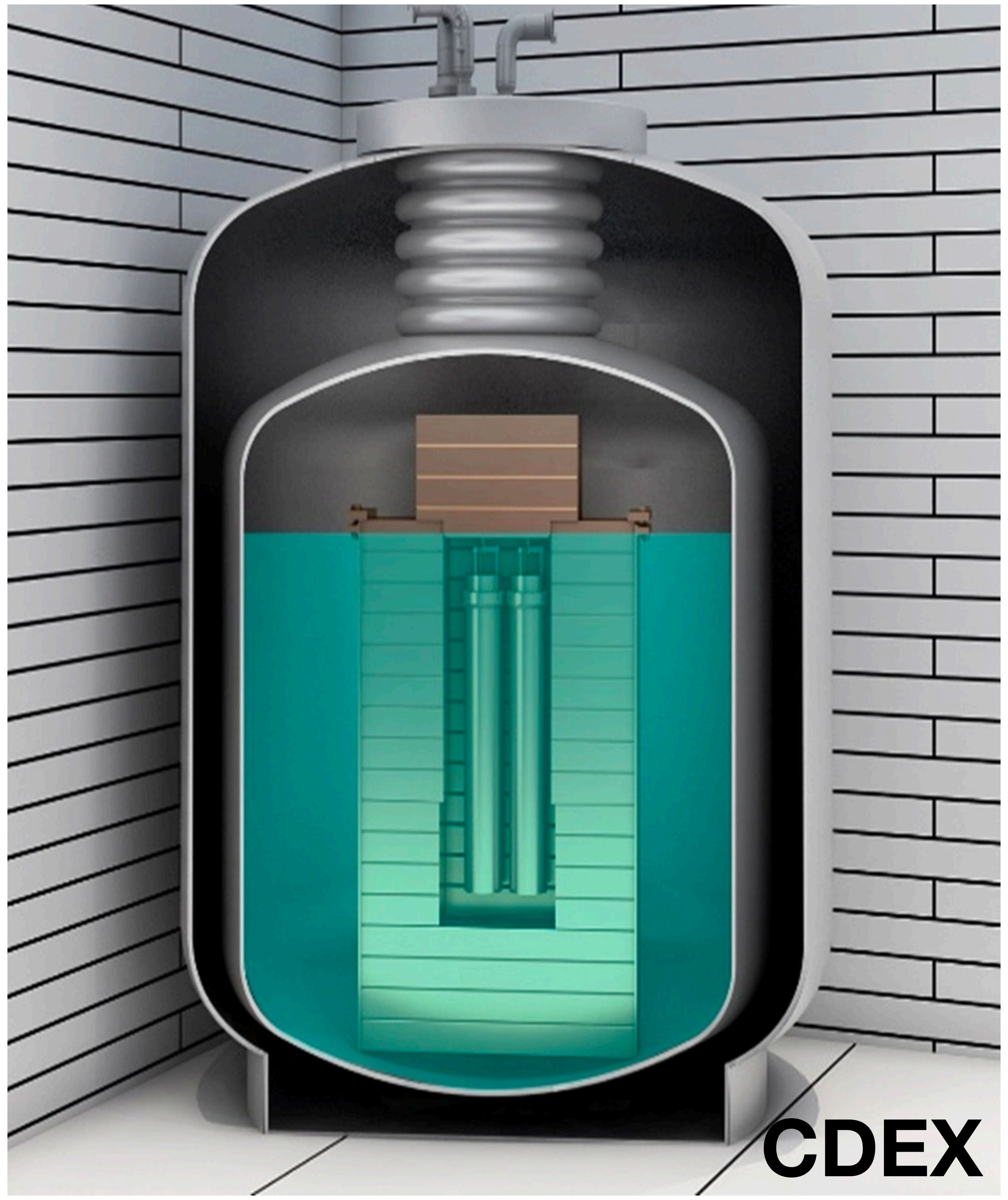
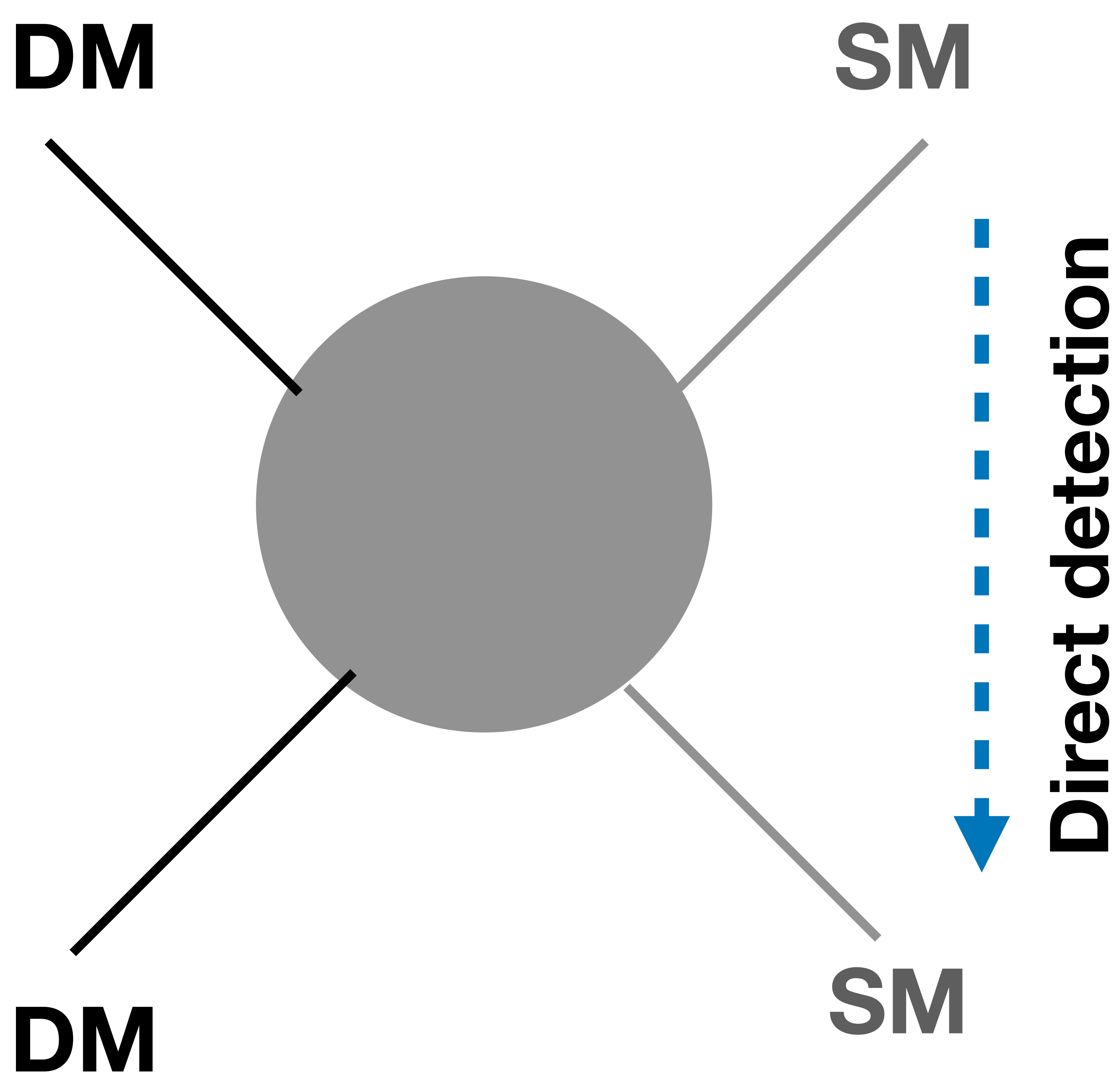
The WIMP crisis from direct detection

- Weakly Interacting Massive Particle

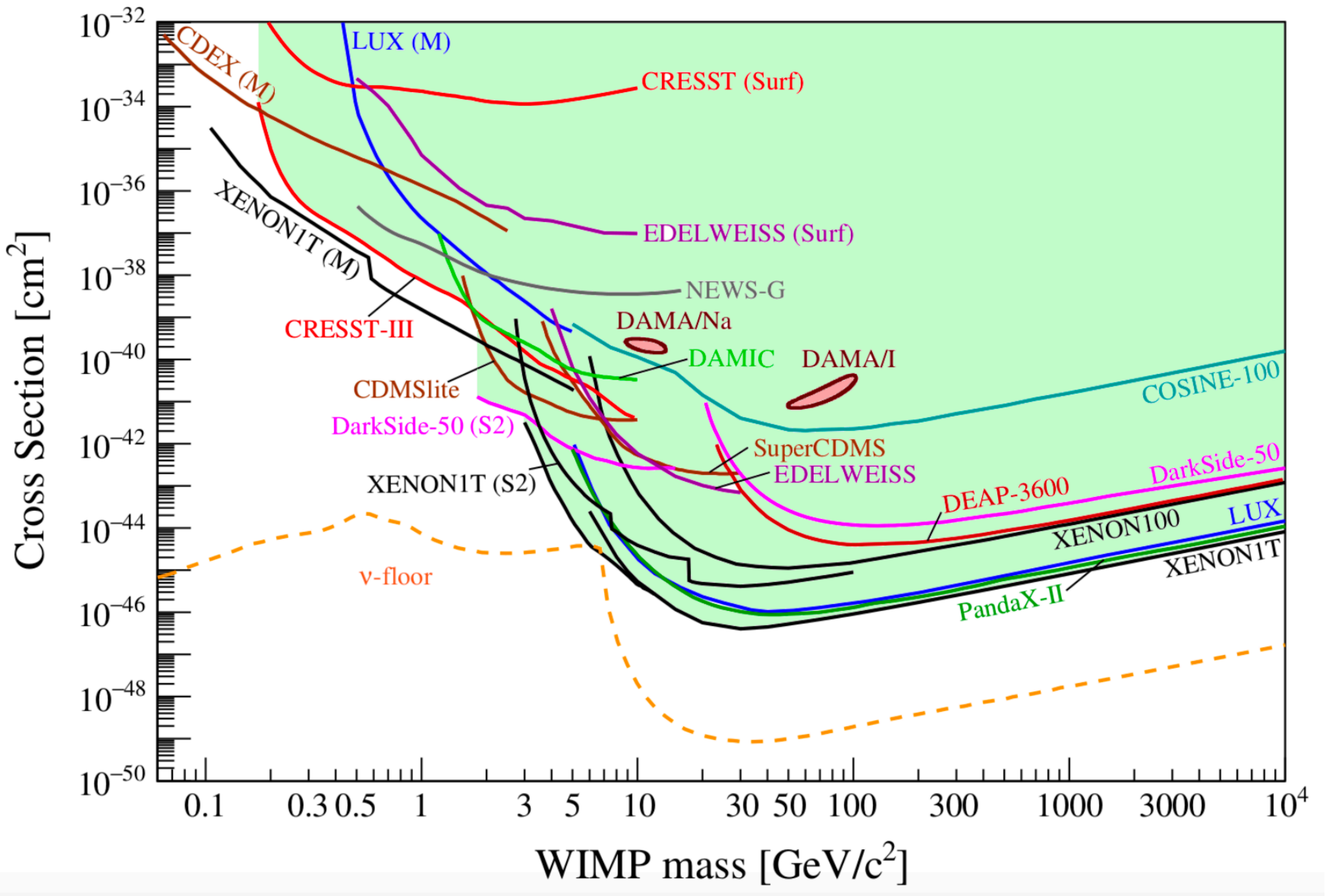
- The sizable coupling of DM to SM particles predicts sizable scattering cross-section





The WIMP crisis from direct detection

- Null result from direct detection
  - Maybe discovery in the corner?
  - Neutrino floor and beyond: directional ..
  - The rise of light dark matter ($\lesssim$ 10 GeV)
    - High velocity DM: Cosmic-Ray DM, Boosted DM …
  - We focus on EW scale ($\gtrsim$ 10 GeV)

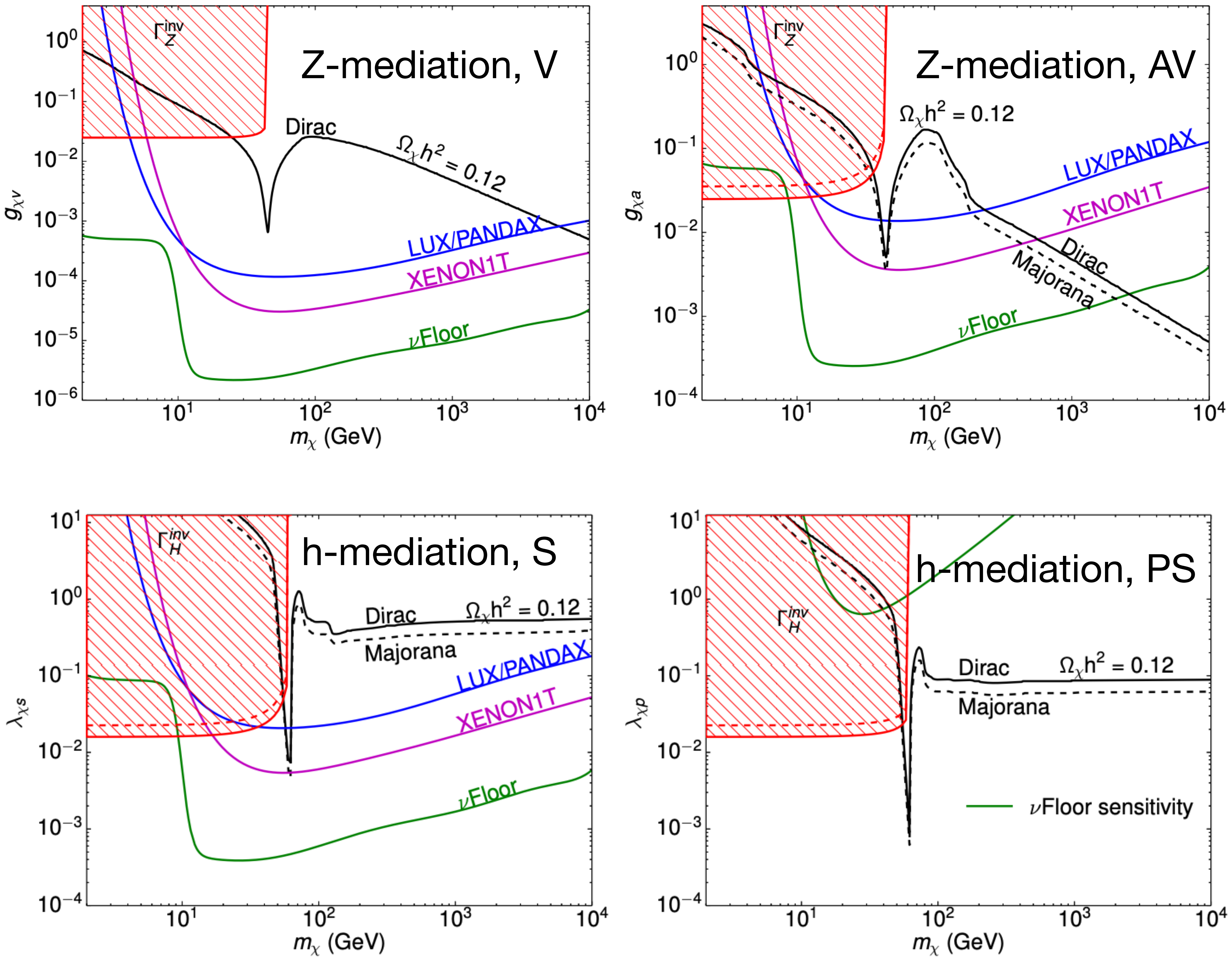


APPEC Committee Report: 2104.07634

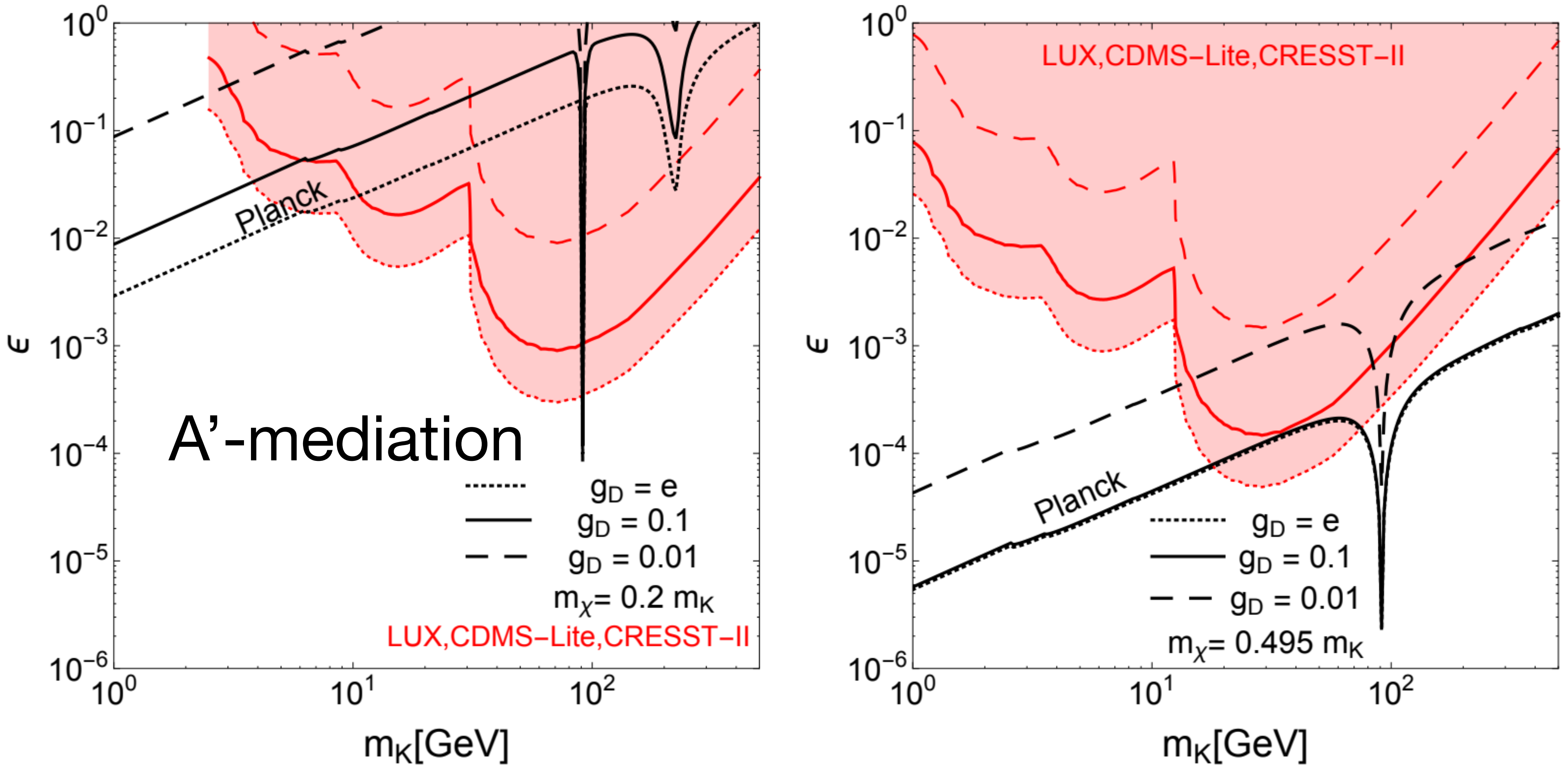
The WIMP crisis from direct detection

- SM Higgs and Z mediated scenario are highly constrained
- Other mediators without DD suppression is also highly constrained, e.g. A’
    - Unless in the resonant region

Toward (Finally!) Ruling Out Z and Higgs Mediated Dark Matter Models
Hooper et al, ArXiv: 1609.09079, JCAP



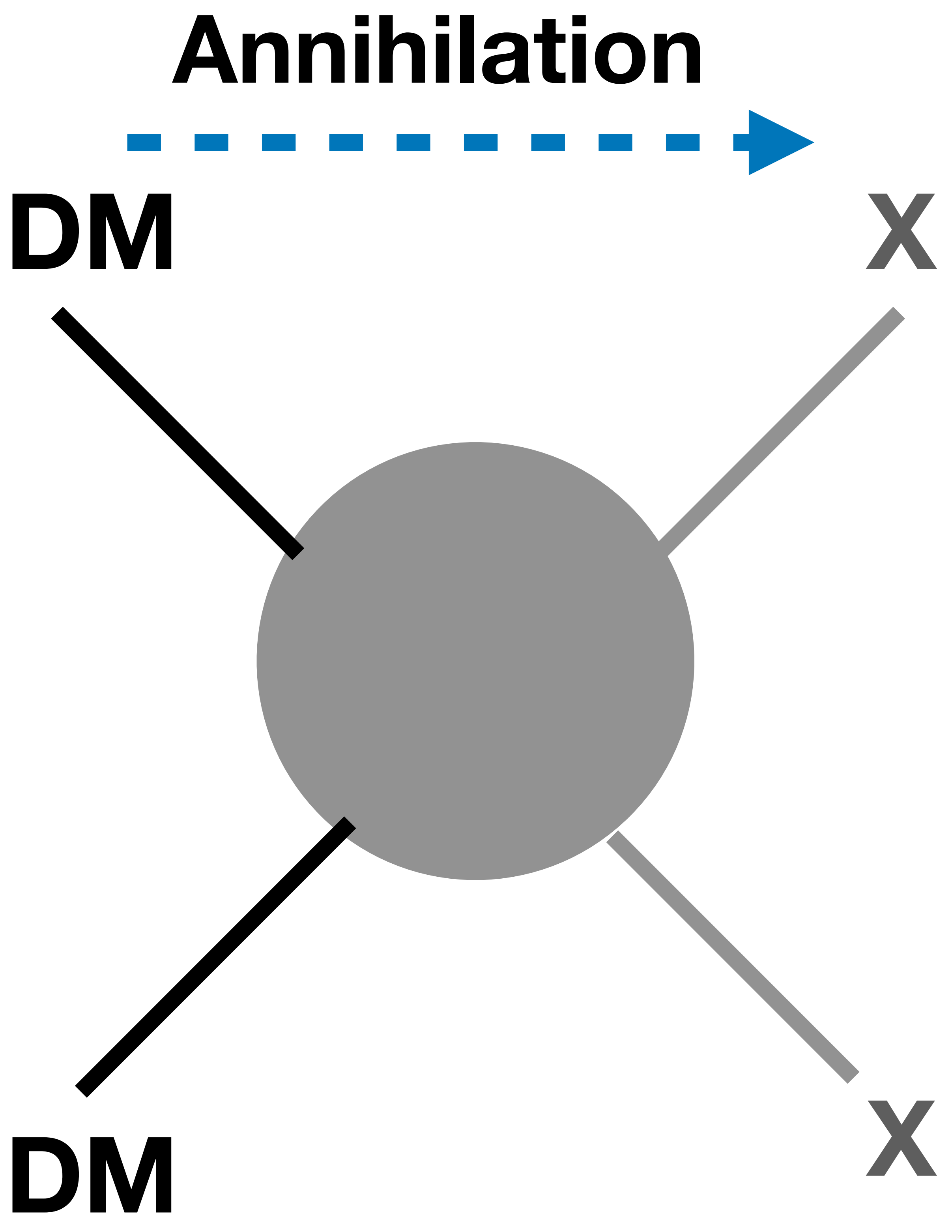
JL, X.P. Wang, F. Yu, 1704.00730, JHEP

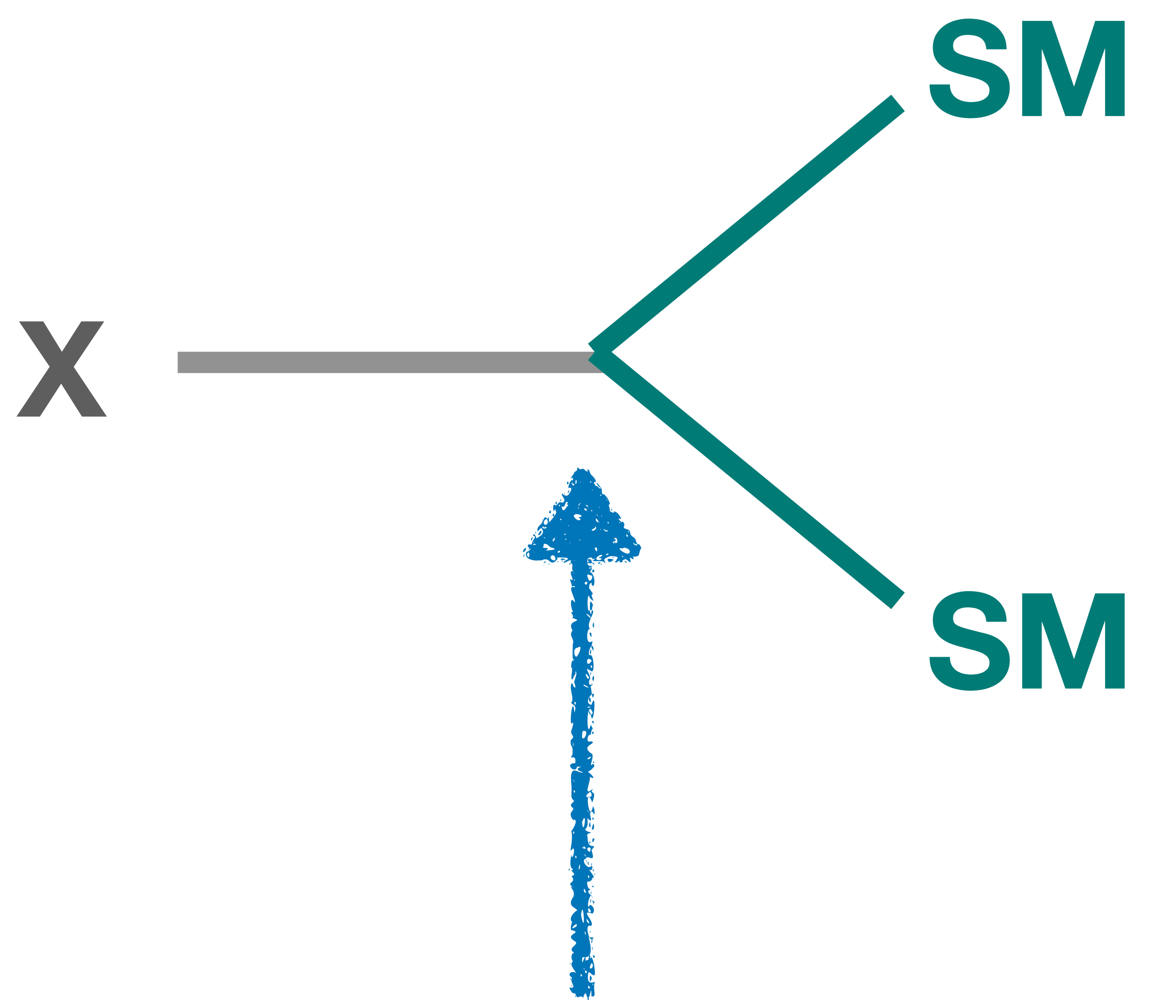


The way-out from direct detection limits

- 1. Secluded dark matter (dark sector)

  - Very small coupling to SM sector





Dark mediator
with very small coupling to SM
$\epsilon \gtrsim 10^{-7}$ **to thermalize dark sector**

Pospelov, Ritz, Voloshin, 0711.4866 [PLB]
Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 0810.0713 [PRD]

The way-out from direct detection limits

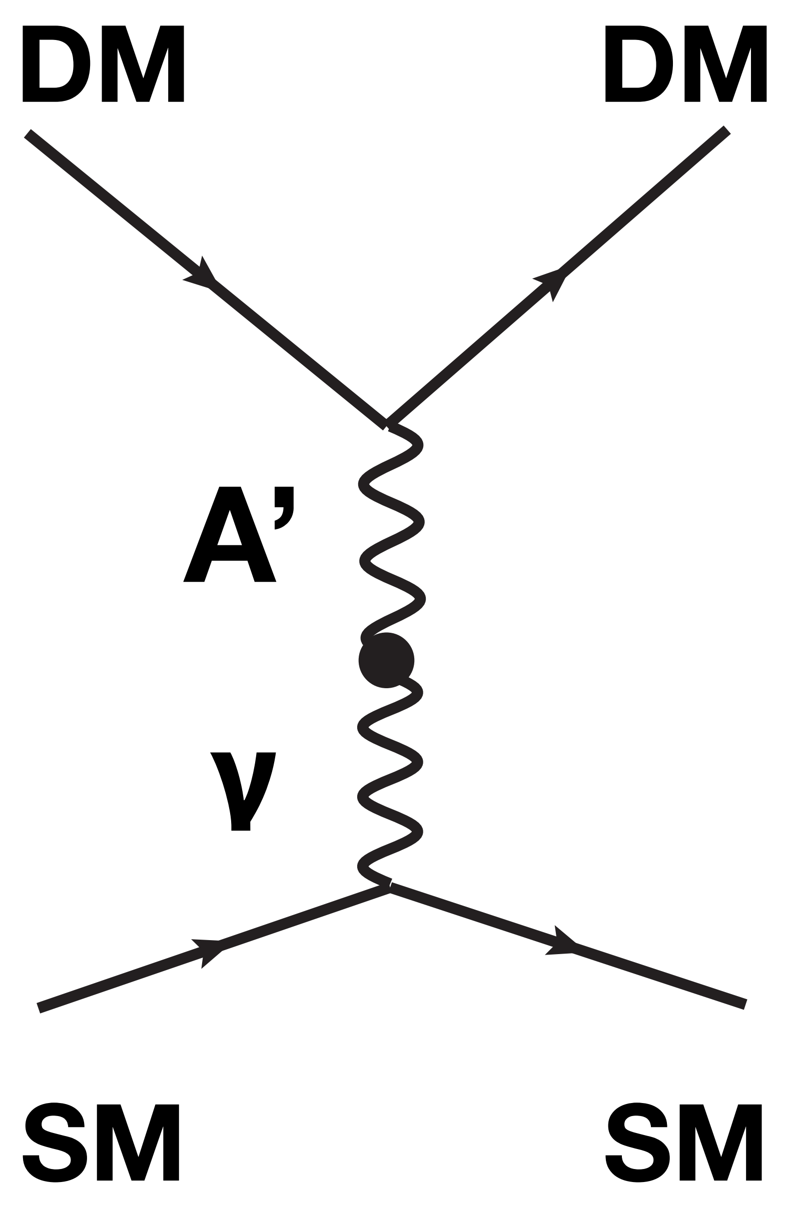
- 1. Secluded dark matter (dark sector)

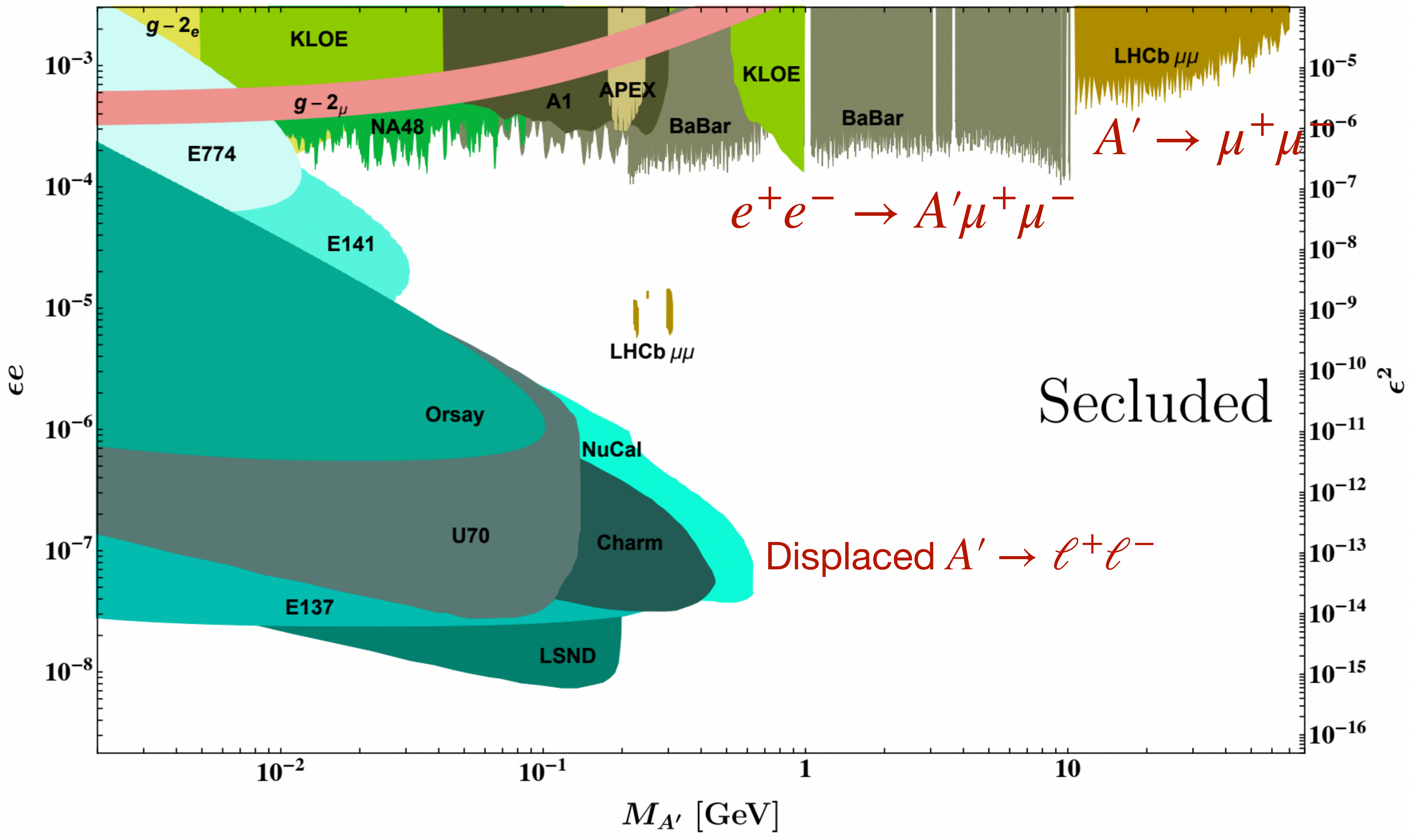
  - Looking for mediator X is easier than DM

Bauer et al: 1803.05466 (JHEP)

Dark photon A' example: visible

$$\epsilon F'_{\mu\nu}B^{\mu\nu}: \; A' \to \ell^+\ell^-$$



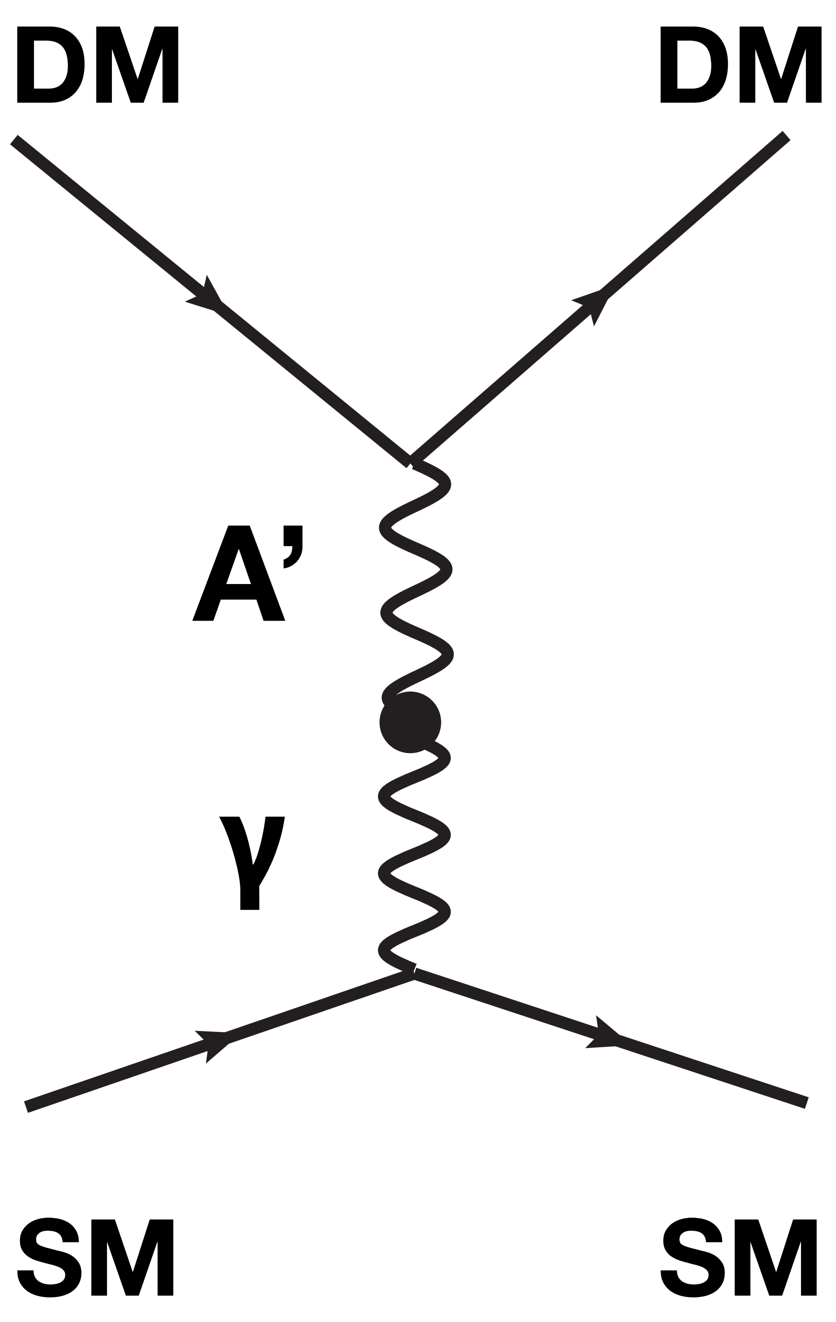


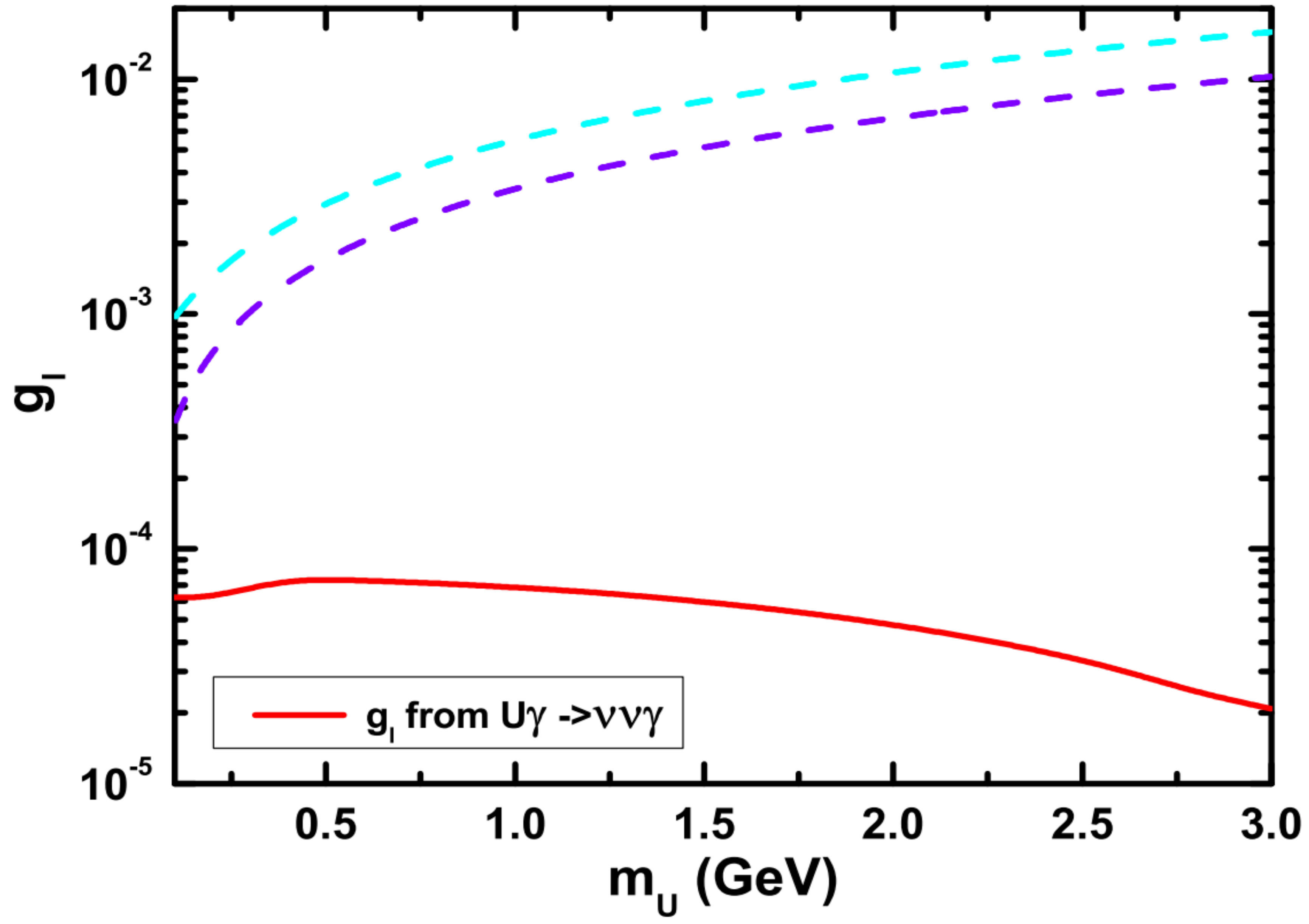
The way-out from direct detection limits

- 1. Secluded dark matter (dark sector)

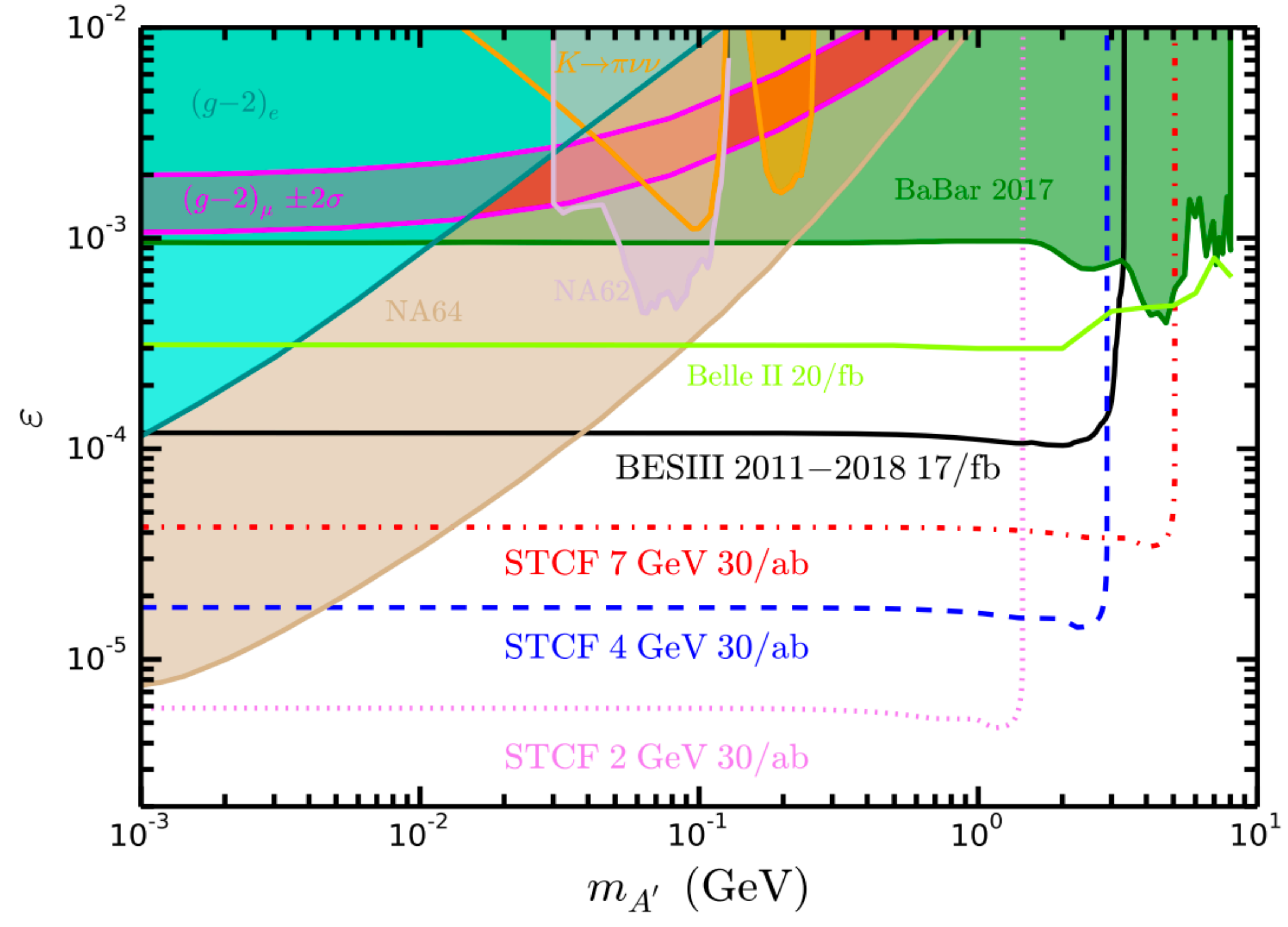
  - Looking for mediator X is easier than DM

Dark photon A' example: invisible $A' \to \mathrm{DM} + \mathrm{DM},\ \bar{\nu}\nu$





PF Yin, JL, SH Zhu: 0904.4644 (PRD)



BESIII: 1907.07046 (PRD)

The way-out from direct detection limits

- 2. Suppressed scattering cross-section:

  - By velocity or momentum transfer

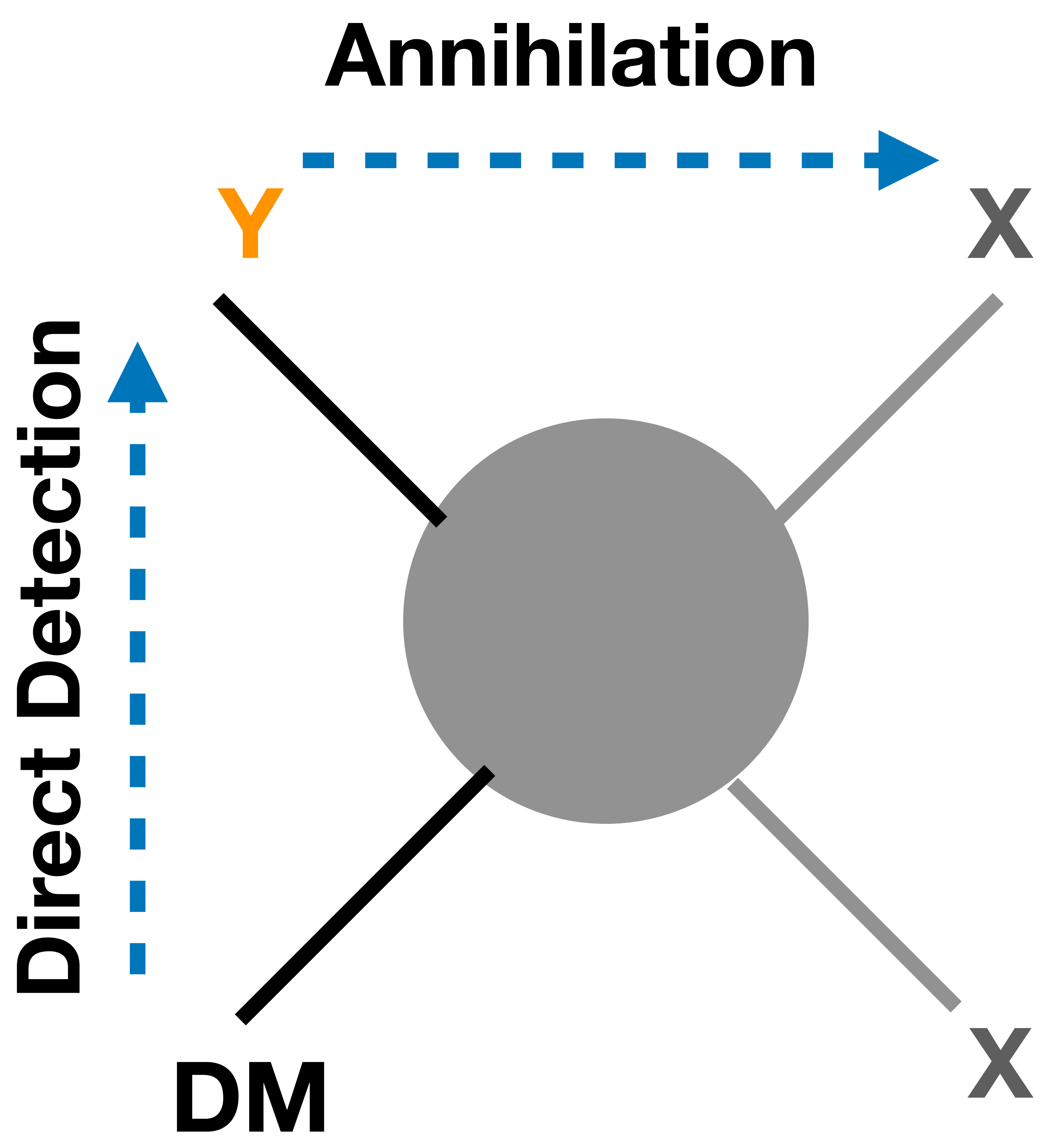
Case for Fermionic DM

Kumar & Marfatia:1305.1611 (PRD)

	Name	Interaction Structure	σ_{SI} suppression	σ_{SD} suppression	s-wave?
Scalar	F1	$\bar{X}X\bar{q}q$	1	$q^2v^{\perp 2}$ (SM)	No
	F2	$\bar{X}\gamma^5X\bar{q}q$	q^2 (DM)	$q^2v^{\perp 2}$ (SM); q^2 (DM)	Yes
	F3	$\bar{X}X\bar{q}\gamma^5q$	0	q^2 (SM)	No
Pseudoscalar	F4	$\bar{X}\gamma^5X\bar{q}\gamma^5q$	0	q^2 (SM); q^2 (DM)	Yes
Vector	F5	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	$q^2v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
Anapole	F6	$\bar{X}\gamma^\mu\gamma^5X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
	F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5q$ (vanishes for Majorana X)	$q^2v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
	F8	$\bar{X}\gamma^\mu\gamma^5X\bar{q}\gamma_\mu\gamma^5q$	$q^2v^{\perp 2}$ (SM)	1	$\propto m_f^2/m_X^2$
	F9	$\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2v^{\perp 2}$ (SM)	1	Yes
	F10	$\bar{X}\sigma^{\mu\nu}\gamma^5X\bar{q}\sigma_{\mu\nu}q$ (vanishes for Majorana X)	q^2 (SM)	$v^{\perp 2}$ (SM) q^2 or $v^{\perp 2}$ (DM)	Yes

The way-out from direct detection limits

- 3. Coannihilation mechanism



$m_{\rm DM} \lesssim m_Y$

- Y has a close mass with DM
  - Y is not populated today due to decay
  - Charged Y: near degenerate spectrum of SUSY, AMSB
  - Neutral Y: Inelastic Dark Matter

Fermionic DM with kinetic mixing A' mediator

$$\mathscr{L} = \bar{\psi} i \gamma_\mu D^\mu \psi + m \bar{\psi} \psi + \delta \overline{\psi^c} \psi / 2$$

$$\overline{\psi} \gamma_\mu \psi \simeq i(\overline{\chi}_1 \overline{\sigma}_\mu \chi_2 - \overline{\chi}_2 \overline{\sigma}_\mu \chi_1) + \frac{\delta}{2m} (\overline{\chi}_2 \overline{\sigma}_\mu \chi_2 - \overline{\chi}_1 \overline{\sigma}_\mu \chi_1).$$

$$m_{\chi_1} = m - \delta;\ \ m_{\chi_2} = m + \delta$$

Smith, Weiner: hep-ph/0101138 (PRD)

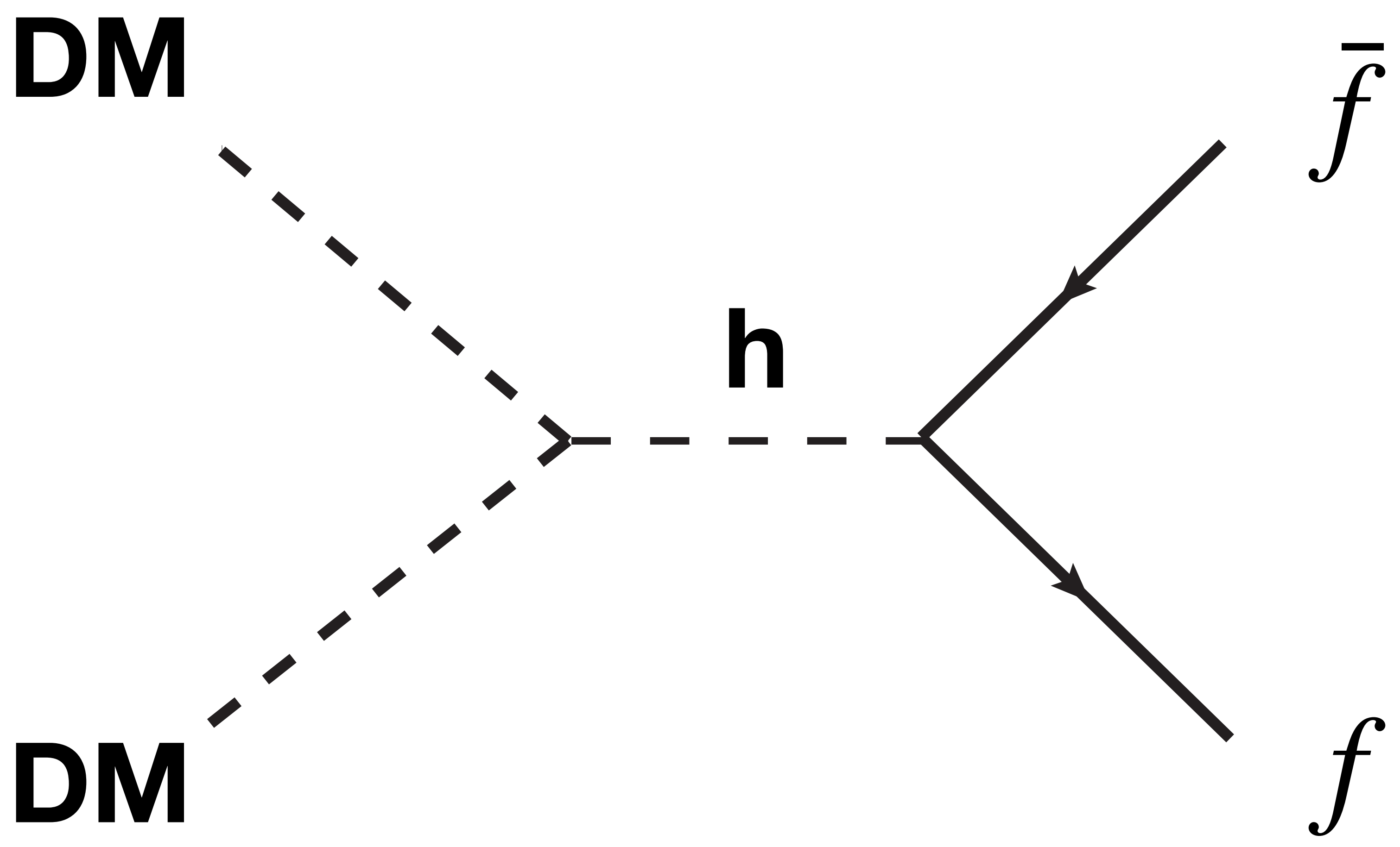
The way-out from direct detection limits

- 4. Resonant annihilation

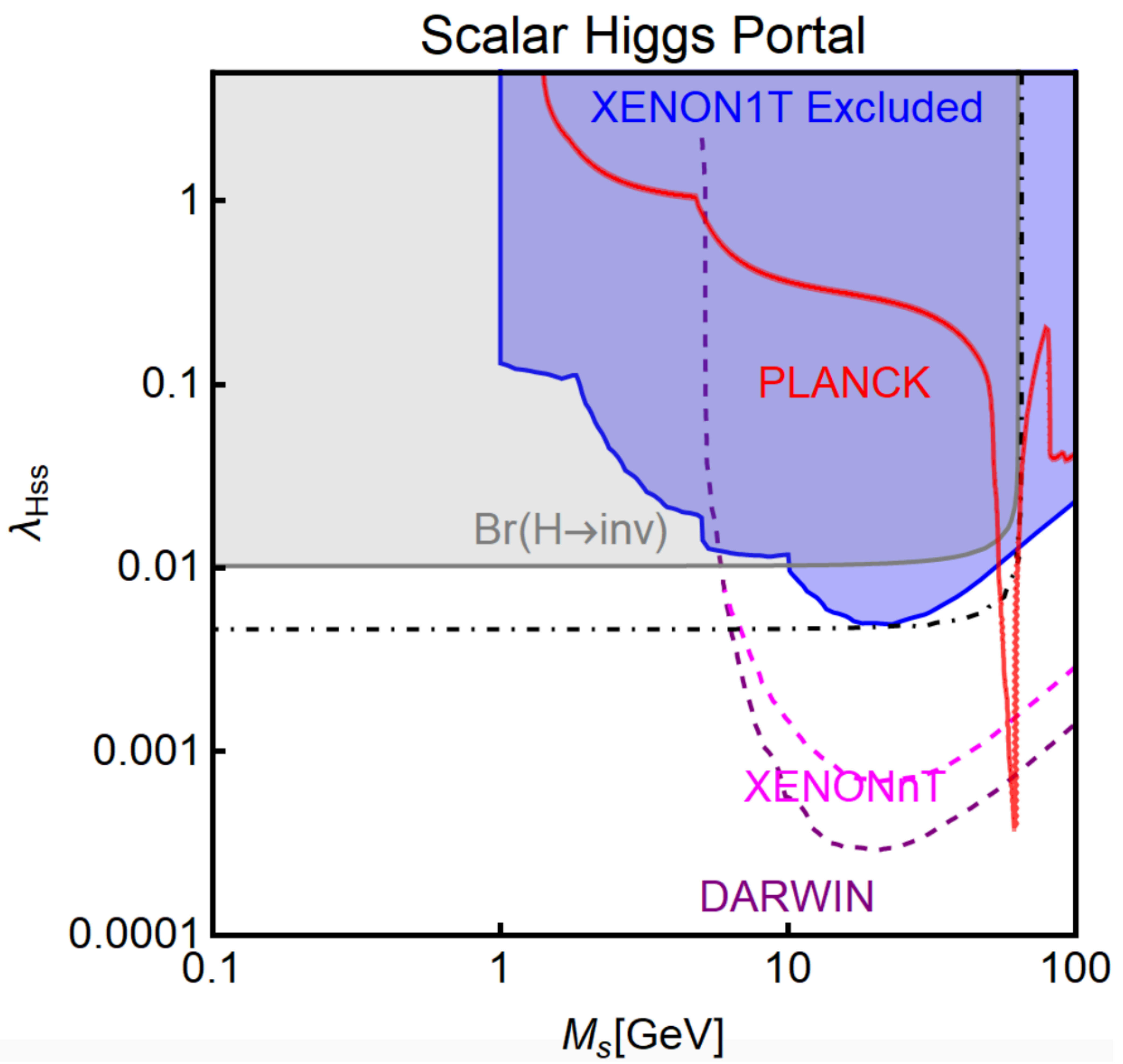
  - $2m_{\mathrm{DM}} \approx m_X$

Scalar DM (s) with a Higgs portal coupling

$$\Delta\mathcal{L}_s = -\frac{1}{2}m_s^2 s^2 - \frac{1}{4}\lambda_s s^4 - \frac{1}{4}\lambda_{Hss}\phi^\dagger\phi s^2$$



+ 2 diagrams to hh



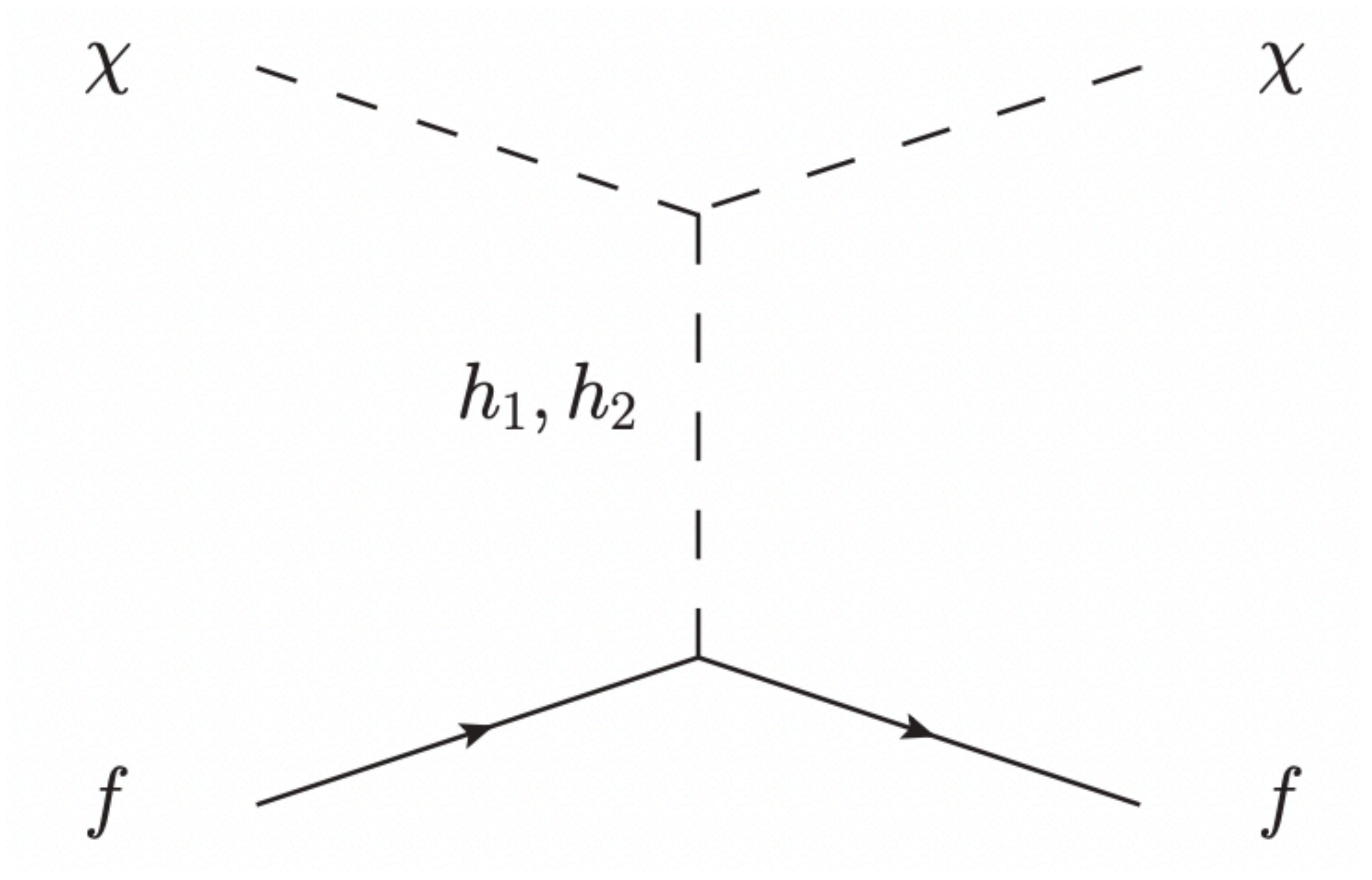
Arcadi et al: 2101.02507

See also WL Guo, LY Wu et al 2010; B Li, YF Zhou 2015

The way-out from direct detection limits

- 5. Cancellation effect in scattering cross-section
  - SM Higgs - Dark scalar mediator cancellation

Gross, Lebedev, Toma: 1708.02253 (PRL)



$$V_0 = -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4$$

$$V_{\rm soft} = -\frac{\mu_S'^2}{4} S^2 + \text{h.c.} \qquad \text{symmetry} : S \leftrightarrow S^*$$

$$S = (v_s + s + i\chi)/\sqrt{2}$$ Pseudoscalar DM

CP-even scalar mixing (s, h) $\to (h_1,\ h_2)$

$$\mathcal{L} \supset -(h_1 \cos\theta + h_2 \sin\theta) \sum_f \frac{m_f}{v} \bar{f} f \qquad \mathscr{L} \supset \frac{\chi^2}{2v_s}\left(m_{h_1}^2 \sin\theta h_1 - m_{h_2}^2 \cos\theta h_2\right)$$

$$\boxed{\mathcal{A}_{dd}(t) \propto \sin\theta\cos\theta \left(\frac{m_{h_2}^2}{t - m_{h_2}^2} - \frac{m_{h_1}^2}{t - m_{h_1}^2}\right) \simeq \sin\theta\cos\theta\, \frac{t\,(m_{h_2}^2 - m_{h_1}^2)}{m_{h_1}^2\, m_{h_2}^2} \simeq 0}$$

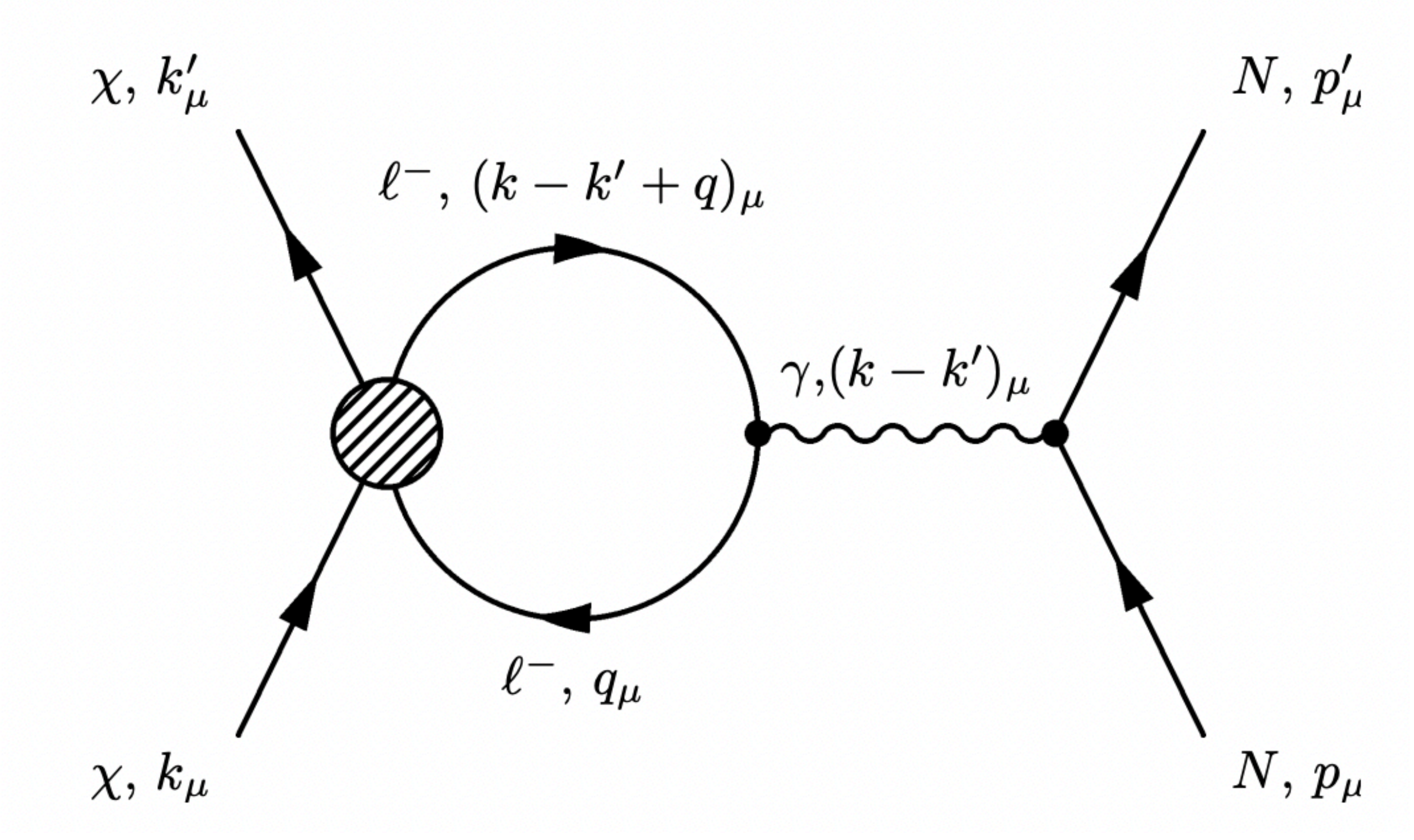
The amplitude is suppressed by q^2 from pseudo-goldstone nature

See JL, XP Wang and F Yu 1704.00730 (JHEP), for cancellation between A' - Z boson in kinetic mixing dark photon model

See an extension from Honghao Zhang et al, 2109.11499

The way-out from direct detection limits

- 6. Leptophilic models
  - Only couples to electrons, couples to nucleons at 1-loop
    - For light DM, e-DM recoils can have stringent limits (e.g. XENON1T, PANDAX, CDEX, LZ)
    - For heavy DM, neucleus-DM recoils wins over e-DM recoil



$$R^{\rm WAS} : R^{\rm WES} : R^{\rm WNS} \sim \epsilon_{\rm WAS} : \epsilon_{\rm WES}\,\frac{m_e}{m_N} : \left(\frac{\alpha_{\rm em} Z}{\pi}\right)^2 \sim 10^{-17} : 10^{-10} : 1$$

WAS = e kicked out

WES = e to higher energy level

WNS = nucleus recoil

The probability to find a high p electron in the wave function is highly suppressed!

Kopp et al: 0907.3159 (PRD)

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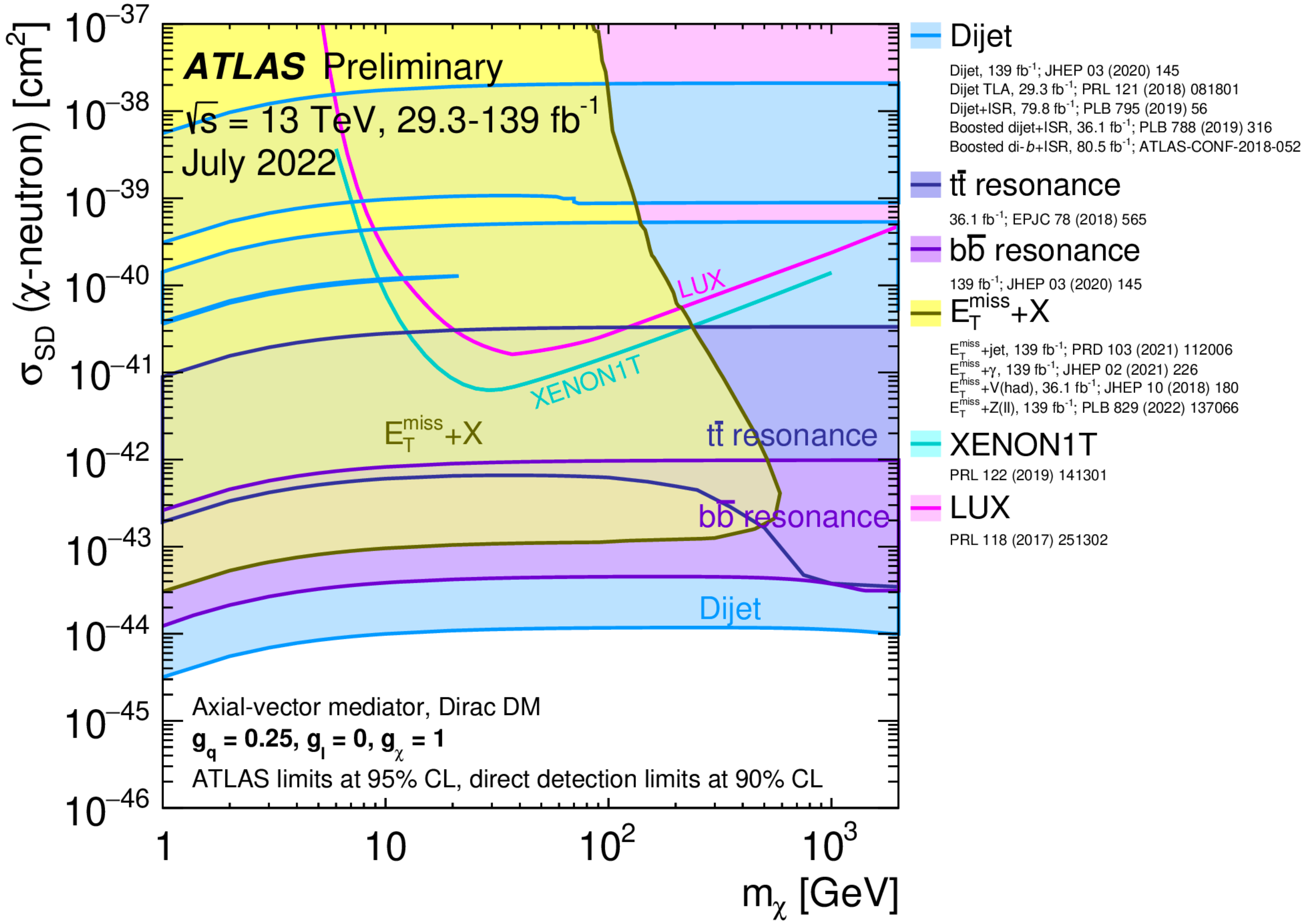
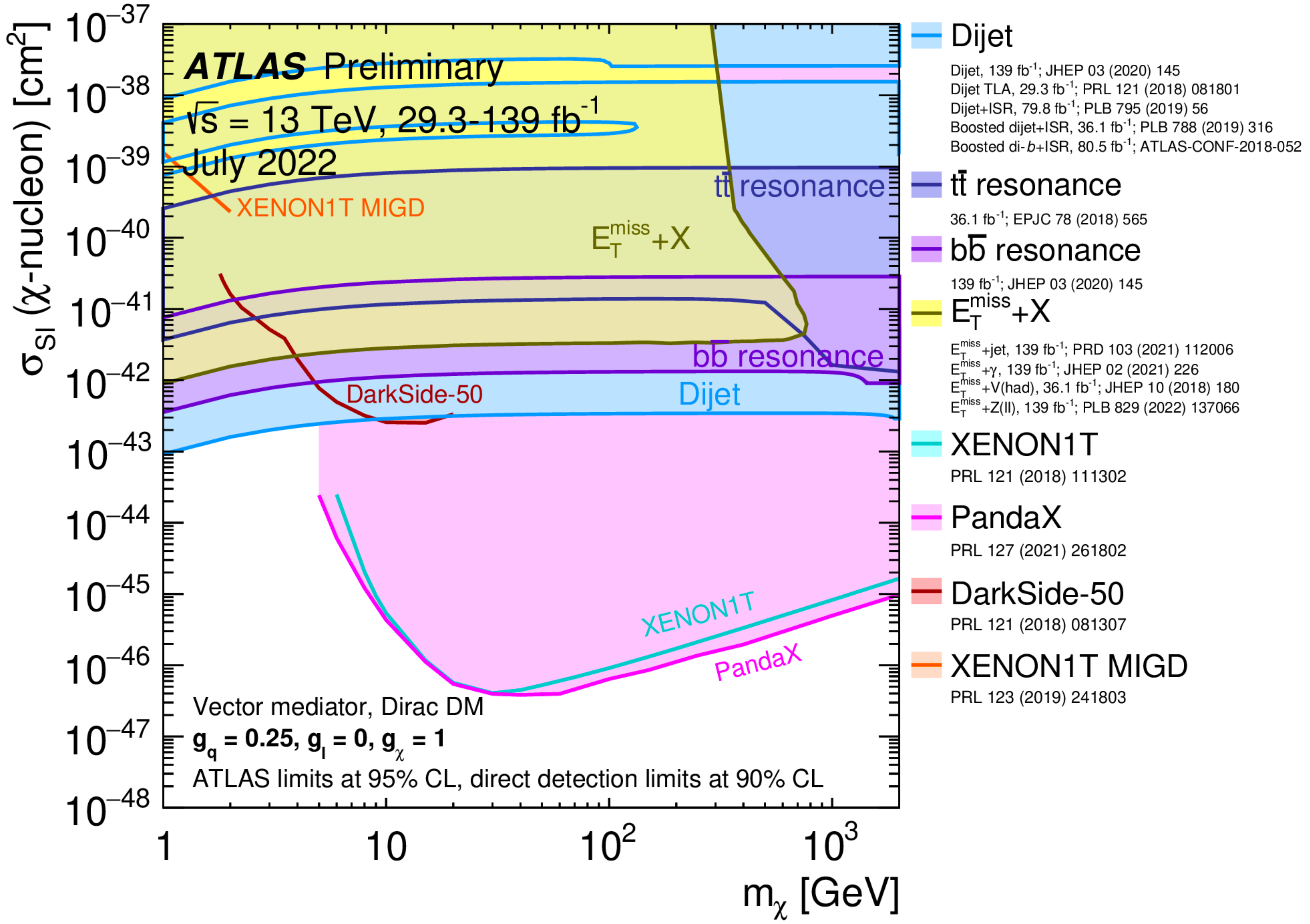
The complementarity between direct detection and collider searches

- Collider searches
  - Not suppressed by small velocity or small momentum transfer
  - Not suppressed by small dark matter mass



- Future: Collider + Direct detection searches
  - 15 years data from LHC
  - All the way down to neutrino floor



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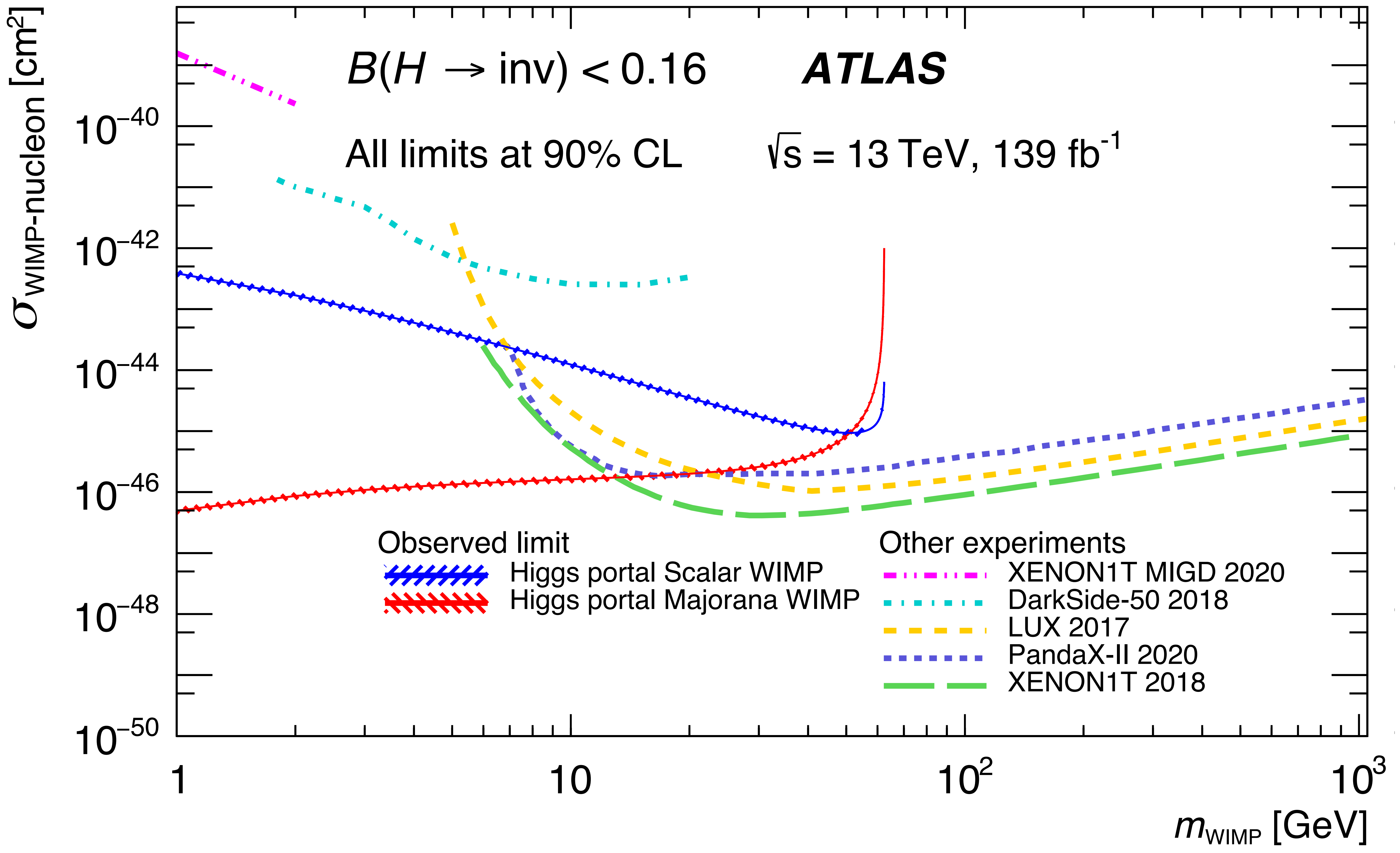

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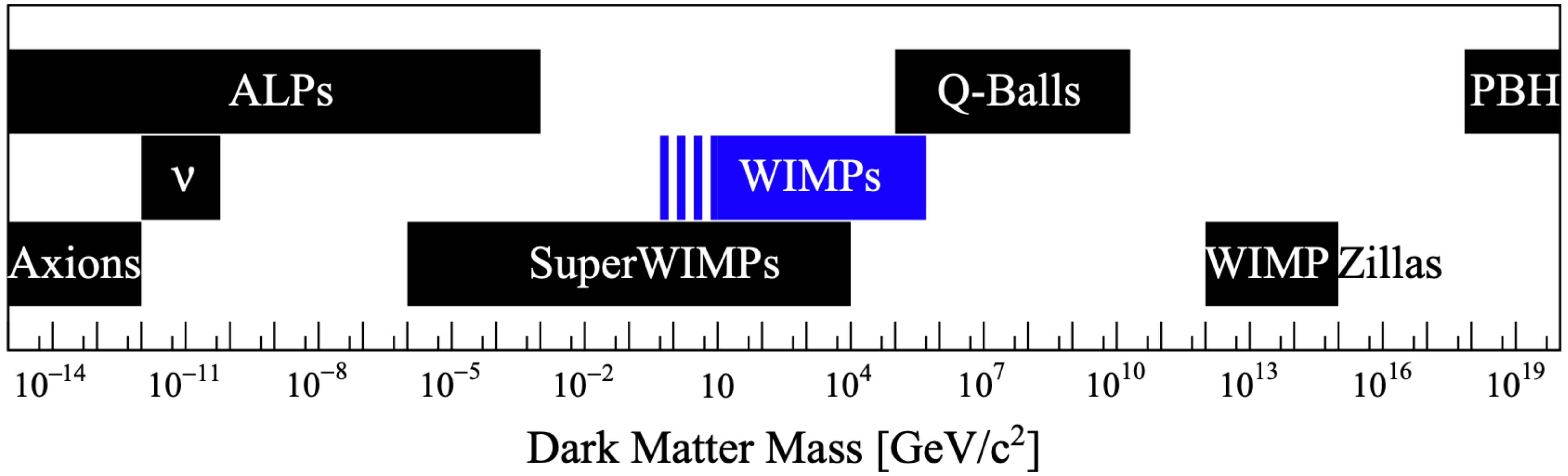
The indirect detection limits from DM annihilation



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  - X = Dark Sector particles (secluded DM models)

}

The entropy of DM goes into SM sector most of the time!

(Secluded X → SM + SM)

Lower mass bound for thermal DM

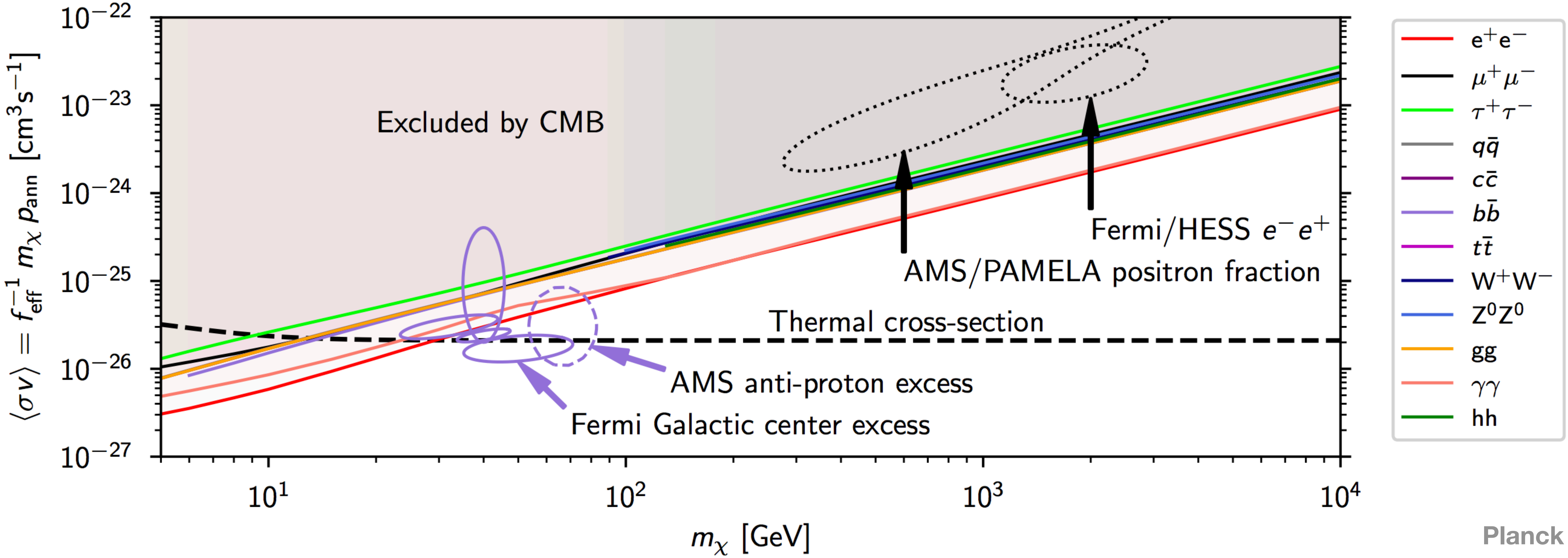
- Lower bound from N_{eff} at CMB
  - Light DM freeze-out after neutrino decoupling at $T_D \approx 2.3$ MeV
  - Normally $T_{fo} \sim m_{\mathrm{DM}}/20$
  - DM entropy goes into neutrinos or e/γ, will modify T_ν / T_γ
  - DM mass $\gtrsim 5$ MeV, depending on d.o.f.

Annihilation constraints from CMB

- The annihilation: $\mathrm{DM} + \mathrm{DM} \to \mathrm{SM} + \mathrm{SM}$
- The rate DM energy density converted into EM energy

$$\frac{d\rho_{\mathrm{DM}}}{dt} = m_{\mathrm{DM}} n_{\mathrm{DM}}^2 \langle \sigma v \rangle \times f_{\mathrm{eff}}$$

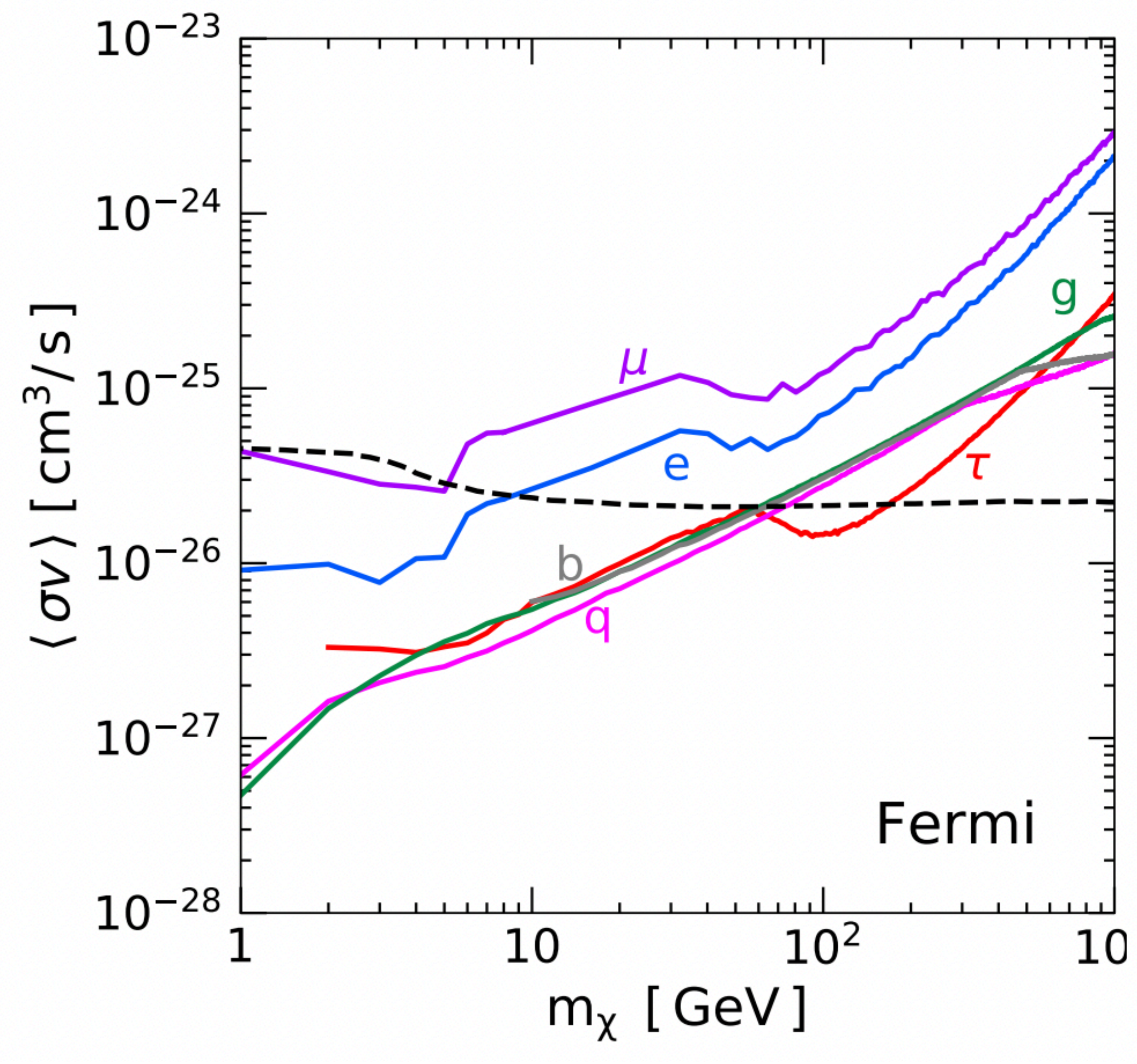
- f_{eff} : the efficiency with which the energy released in DM annihilation is absorbed by the primordial plasma

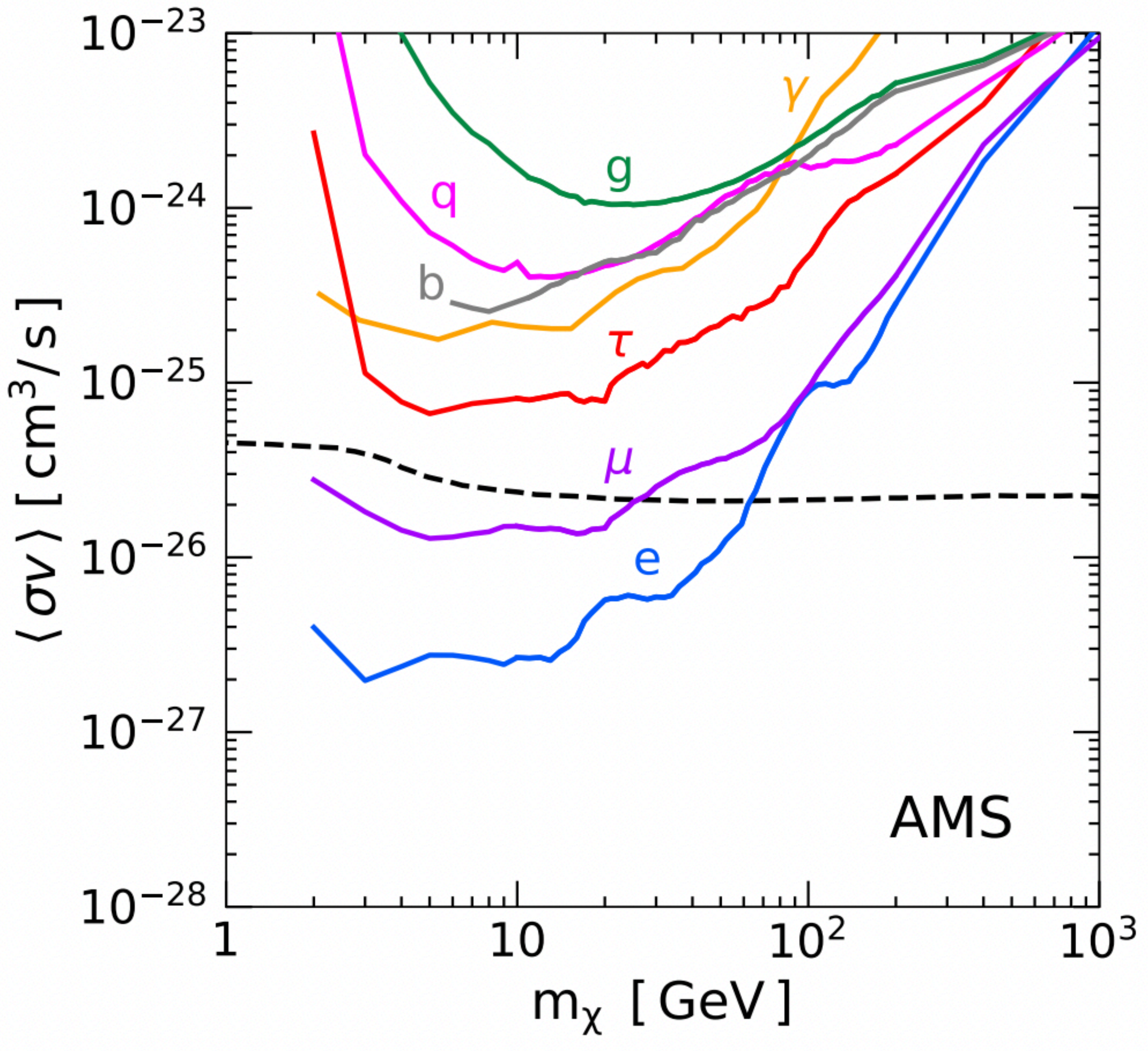


Planck 2018

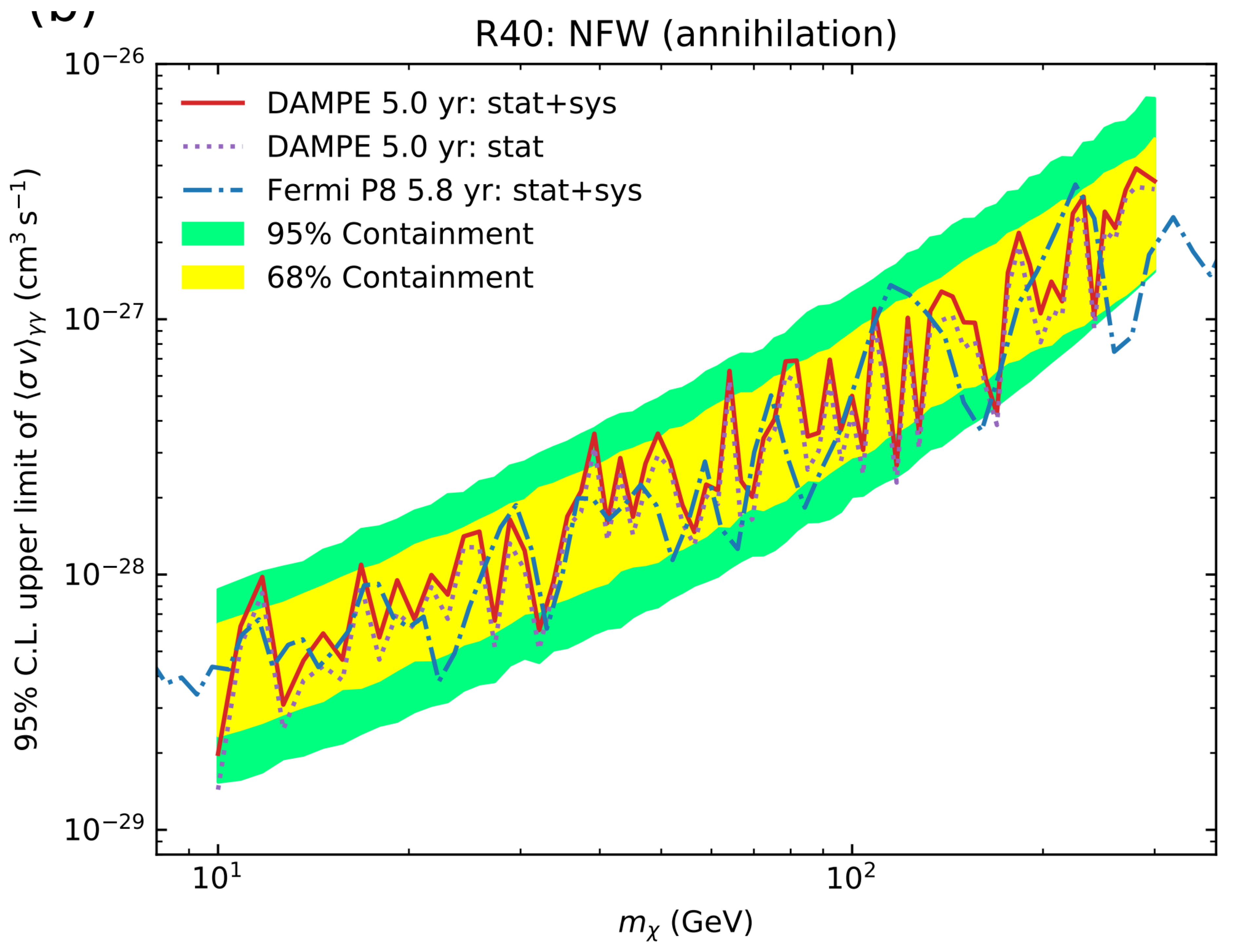
Indirect limits from satellite experiments

- CMB limits only works for DM mass $\lesssim 10$ GeV
- Indirect limits from AMS-02, DAMPE(悟空卫星), Fermi-LAT





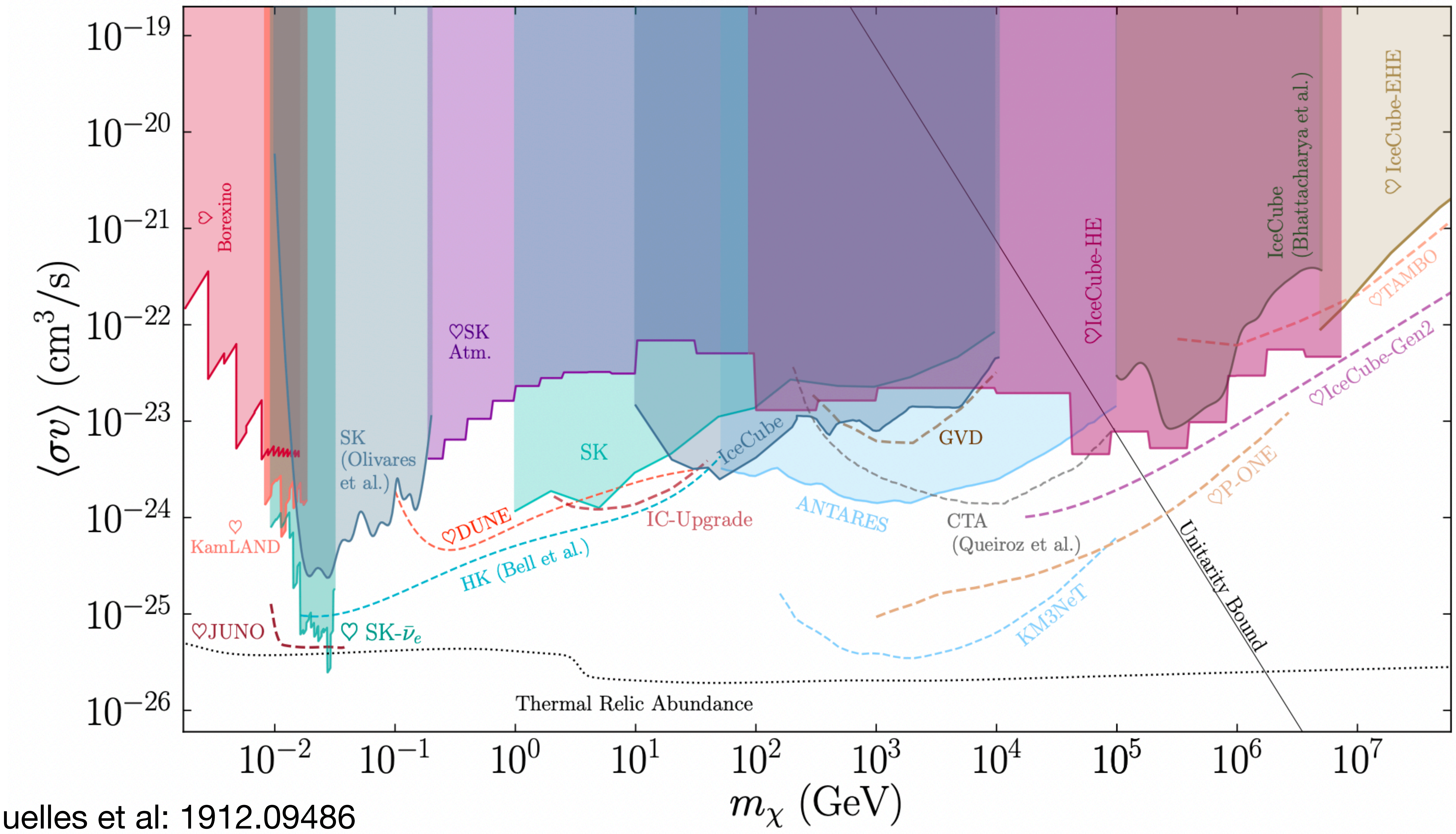
Leane et al: 1805.10305 (PRD)



悟空卫星: 2112.08860 (Science Bulletin)

How to escape CMB constraints?

- Annihilation to neutrinos ($2\mathrm{DM} \to \bar{\nu}\nu$): $f_{\mathrm{eff}} = 0$



Arguelles et al: 1912.09486

How to escape CMB constraints?

- P-wave annihilation or no annihilation (asymmetric DM) but no indirect detection signal

- Expansion over velocity
  - S-wave
  - P-wave (L=1)
  - D-wave (L=2), due to extra chiral suppression
  - Linear v dependence?
    - Final state phase space suppression ($m_{\rm DM} \approx m_X$) from symmetry reason

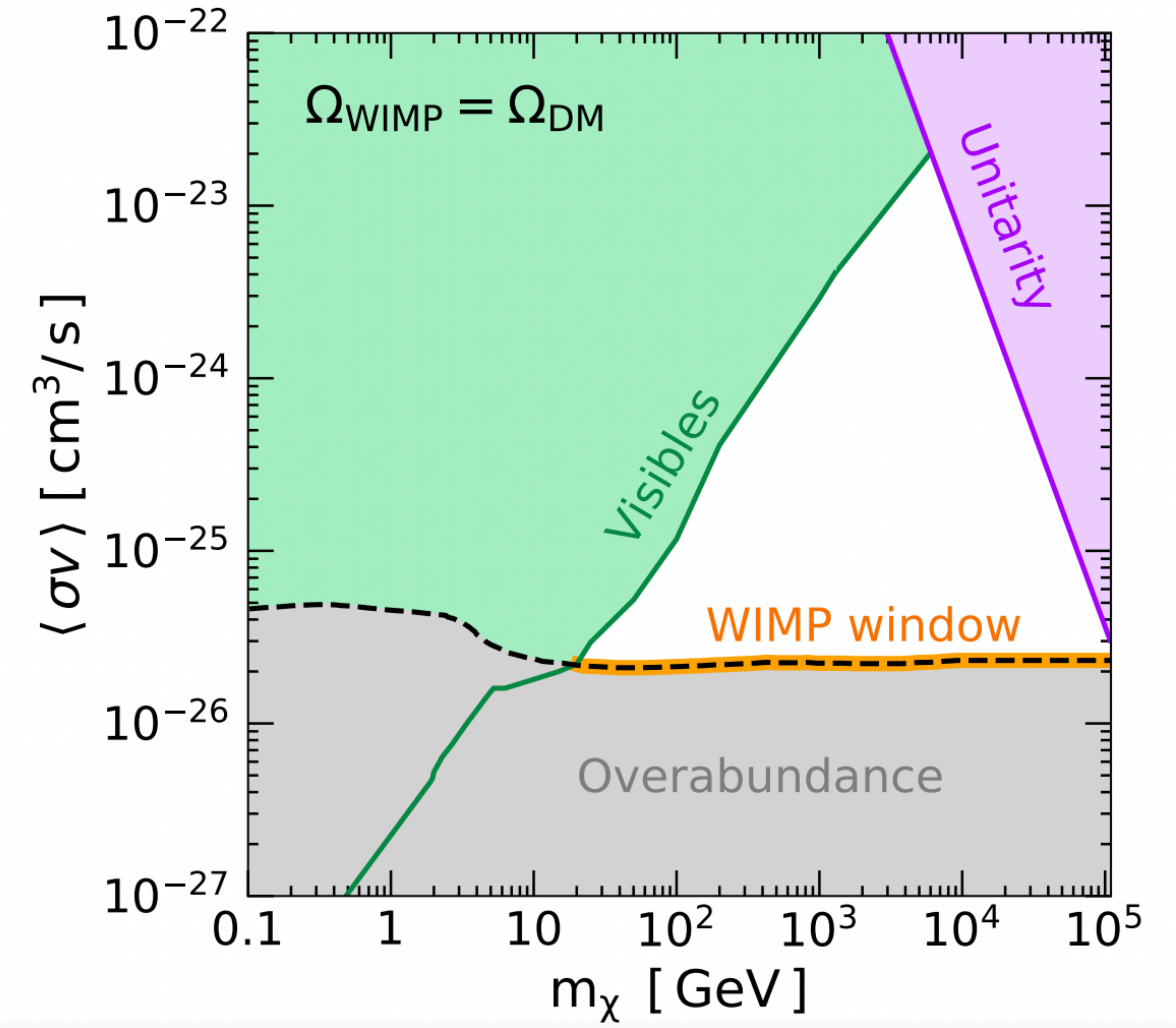
$$\sigma v \sim \sigma_s + \sigma_p v^2 + \sigma_d v^4 + \ldots$$

- The value of velocities at different time
  - Freeze-out: $v^2 \sim 0.25$
  - CMB: $v^2 \sim \mathrm{eV}/m_{\rm DM} \sim 10^{-5}$
  - Today: $v \sim 10^{-3} c$

J Kopp, JL, T Slatyer, XP Wang, W Xue: 1609.02147 (JHEP)

The WIMP limits from indirect detection

- WIMP mass $\gtrsim 10$ GeV is still viable



GeV-Scale Thermal WIMPs: Not Even Slightly Dead

Leane et al: 1805.10305 (PRD)

Outlines

- Various DM models
  - Ultralight bosonic DM
  - WIMP DM
    - Direct detection crisis
    - Complementarity with collider detection
    - DM indirect constraints
  - A WIMP variant from cosmological evolution
- Summary

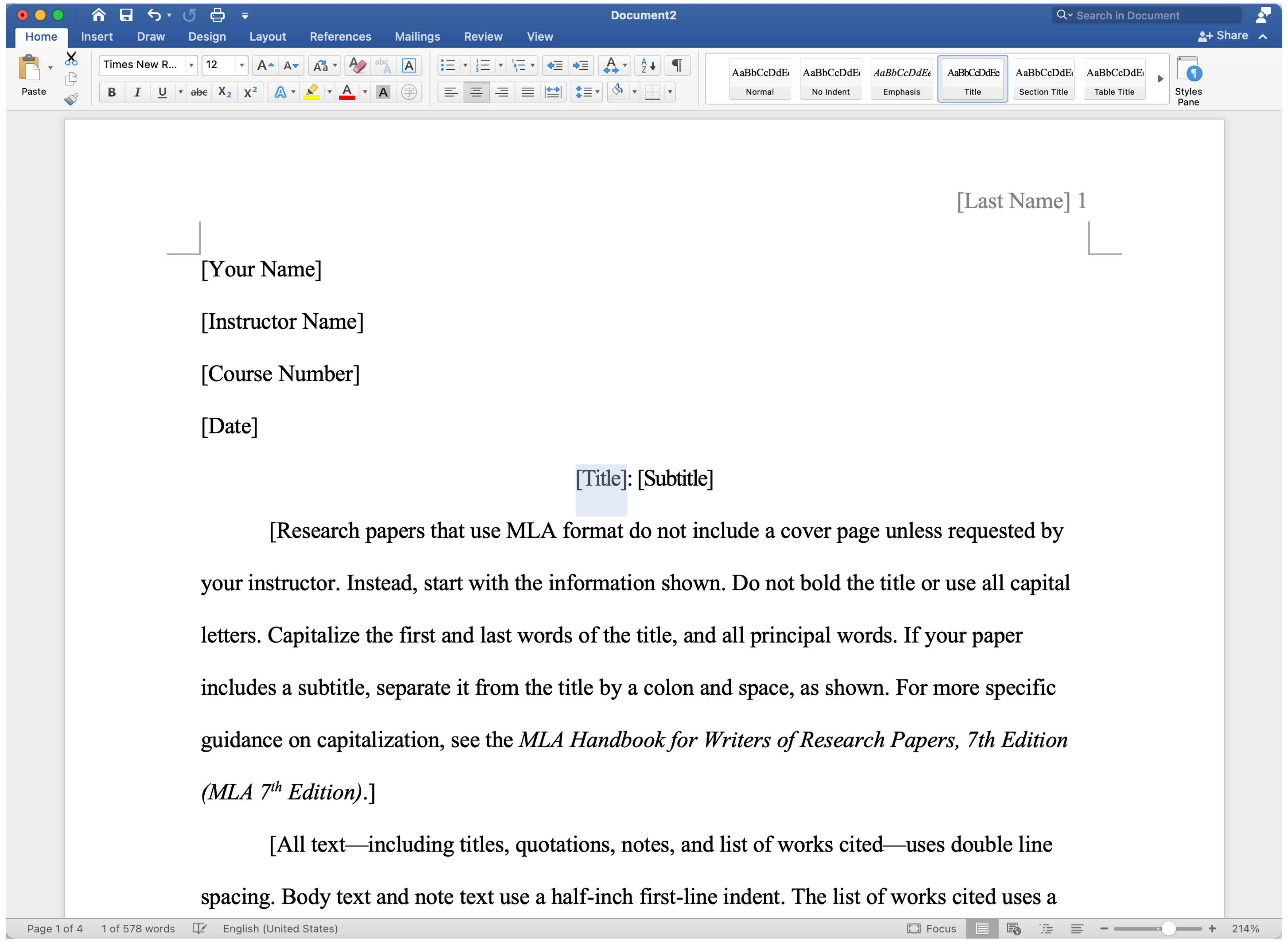
DM properties and cosmological evolution

- DM evolution can be deeply affected by the thermal history of the Universe

  - DM properties at freeze-out may be different from today

  - DM mass, stability, interaction couplings, decay and annihilation channels, rates

T. Cohen et al, 0808.3994
M. Baker, J. Kopp et al, 1608.07578, 1712.03962, 1811.03101
Kobakhidze and Schmidt et al, 1712.05170, 1910.01433
Hektor et al, 1801.06184
L. Bian and Y.L. Tang, 1810.03172
L. Bian and X. Liu, 1811.03279
L. Heurtier et al, 1912.02828
H. Murayama et al, 2012.15284
B. Batell et al, 2109.04476
…



Word, WPS etc …
WYSIWYG, “What You See Is What You Get”

Variant: transient annihilations

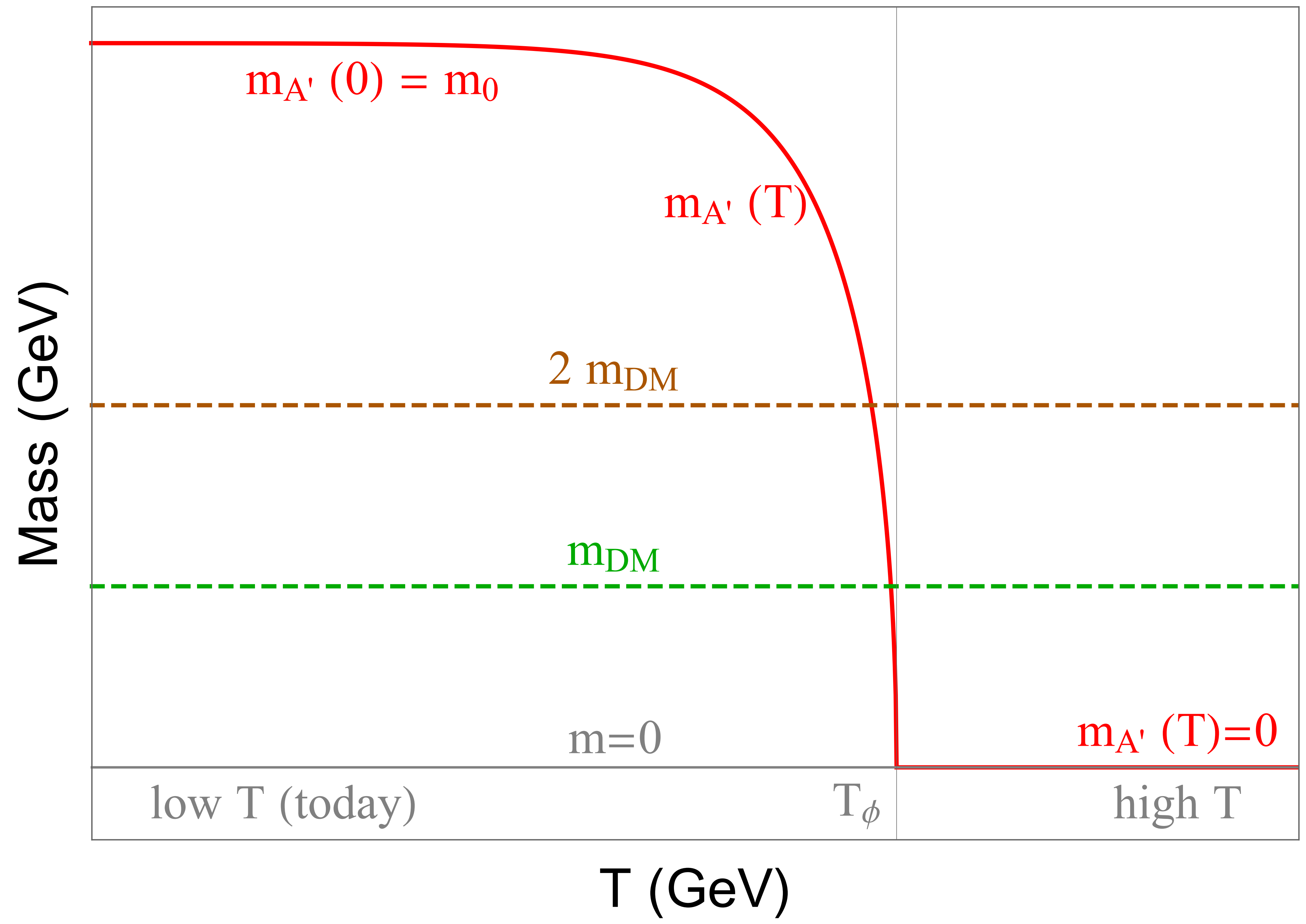
- Massive gauge boson has a varying mass in the early universe

$$m^2_{A'}(T) = \begin{cases} 0 & T > T_\phi, \\ m^2_{A',0} - \kappa m^2_\psi \left(\frac{T}{m_\psi}\right)^n & T < T_\phi \end{cases}$$

- If it is the DM-SM mediator, and the mass variation happens near DM freeze-out, what happens?

$$\mathcal{L}_d = \bar{\psi}\left(i\not{D} - m_\psi\right)\psi - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \epsilon e A'_\mu J^\mu_{\rm em}$$

$$V(\Phi) = \mu_d^2|\Phi|^2 + \lambda_d|\Phi|^4$$



- Today, $m_{A'}$ is much larger than $m_{\rm DM}$

K. Hashino, JL, X.P. Wang, K.P. Xie 2109.07479 PRD

Variant: transient annihilations

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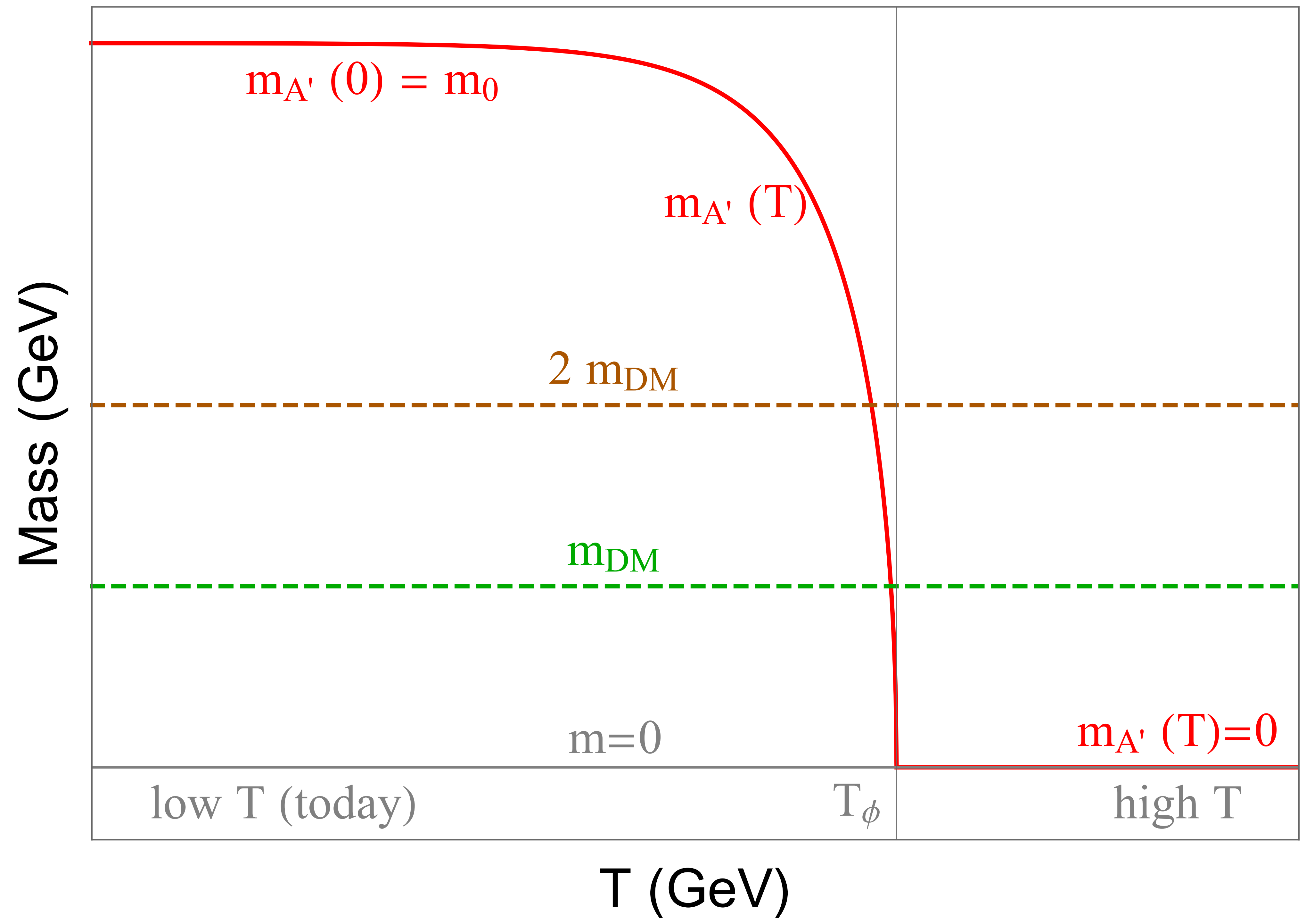
$$m^2_{A'}(T) = \begin{cases} 0 & T > T_\phi, \\ m^2_{A',0} - \kappa m^2_\psi \left(\frac{T}{m_\psi}\right)^n & T < T_\phi \end{cases}$$

- The annihilation channels divided into two categories:

Transient secluded: $(\bar\psi\psi \to A'A')$ $\quad m_{A'} = m_\psi,$

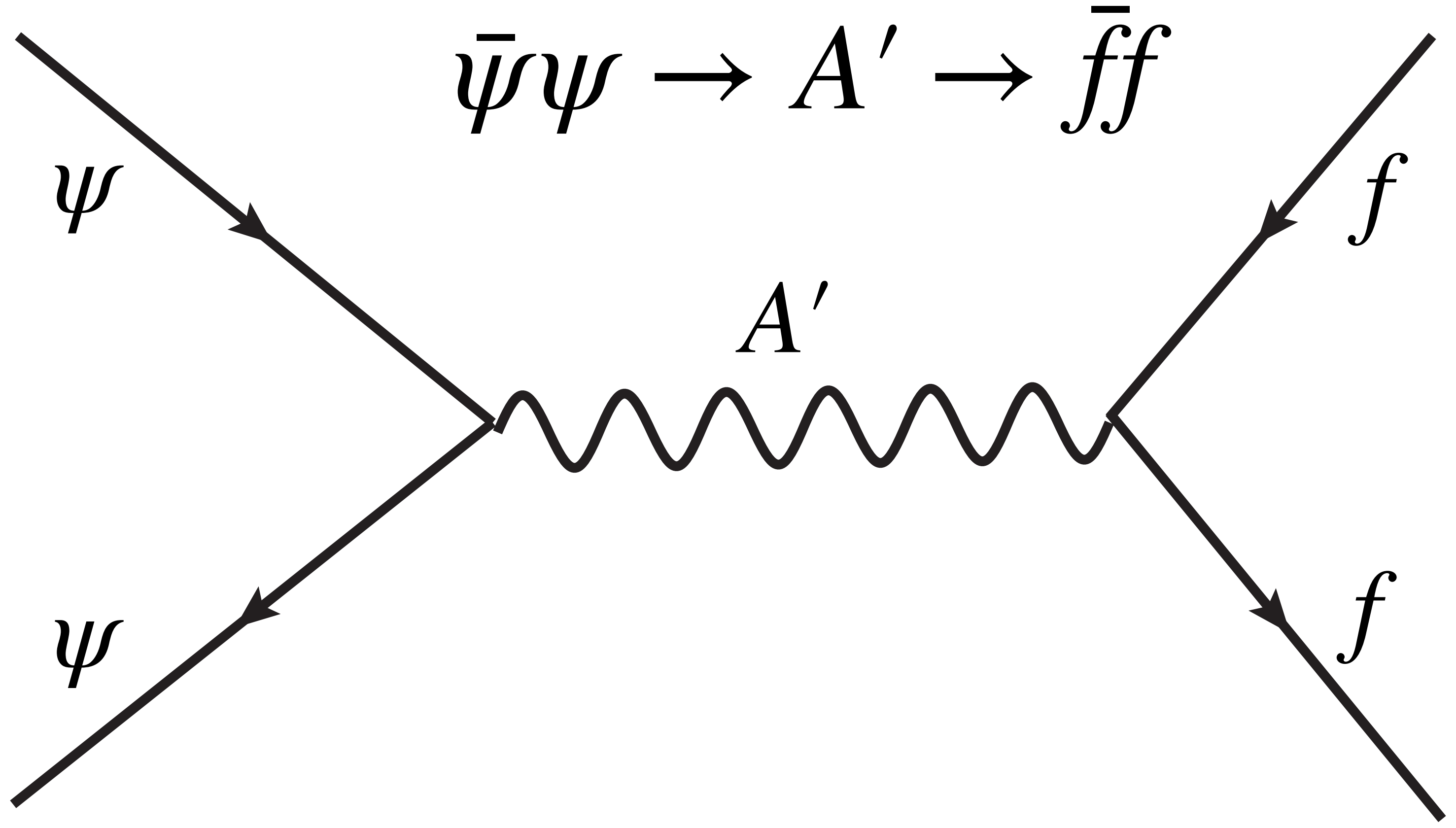
$(\bar\psi\psi \to A'\phi)$ $\quad m_{A'} = 2m_\psi - m_\phi,$

Transient resonant: $(\bar\psi\psi \to \bar f f)$ $\quad m_{A'} = 2m_\psi\,.$



K. Hashino, JL, X.P. Wang, K.P. Xie 2109.07479 PRD

Transient resonant annihilation

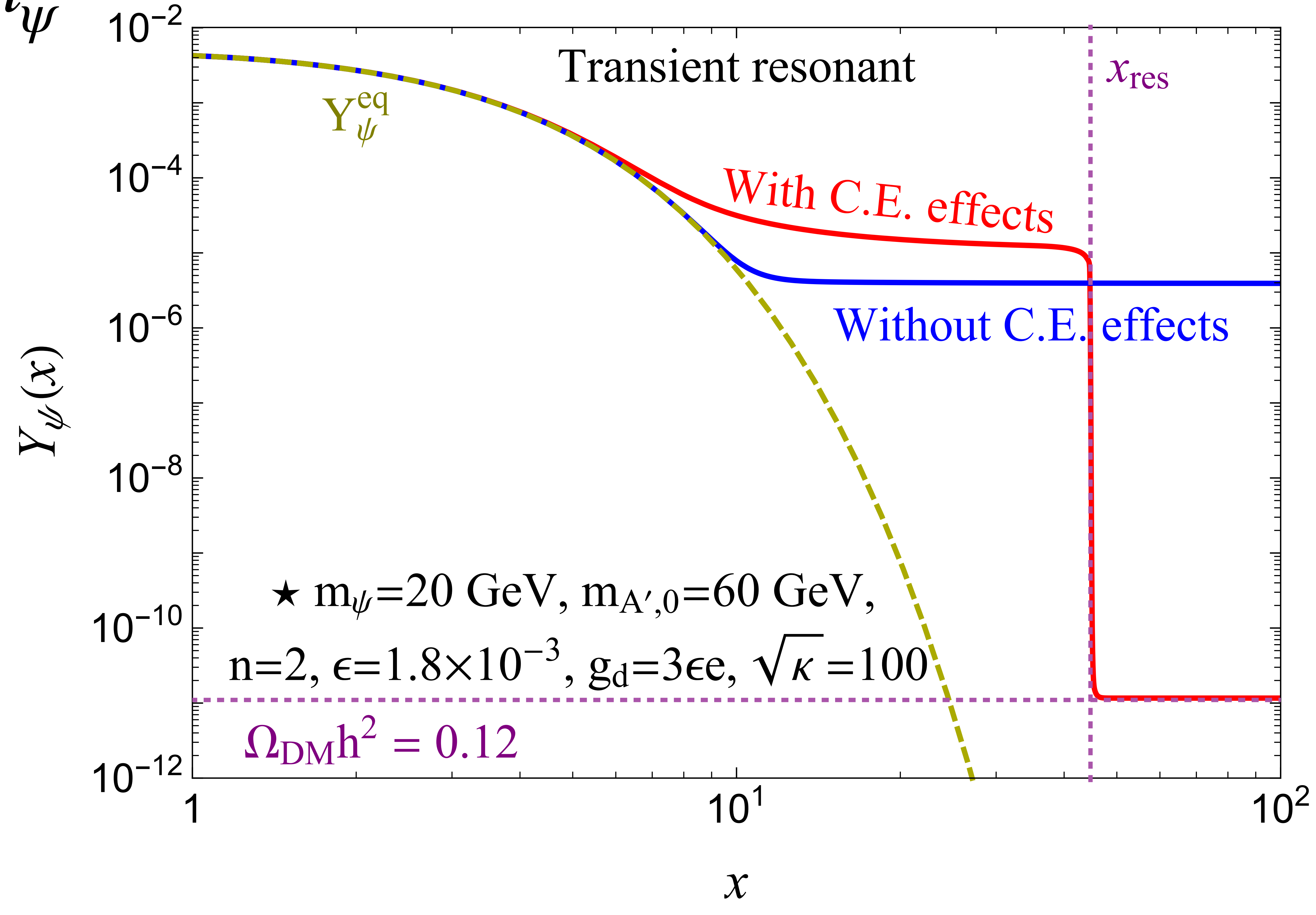


$\bar{\psi}\psi \to \bar{f}f$

$r \equiv m_{A'}/m_\psi$

- Relic abundance

$$Y_{\rm res}^{-1} \approx \sqrt{\frac{\pi^3 g_*}{5}} \frac{g_d^2 m_{\rm pl}}{n m_\psi} \left(r_0^2 - 4\right)^{\frac{1-n}{n}} \kappa^{-1/n}$$



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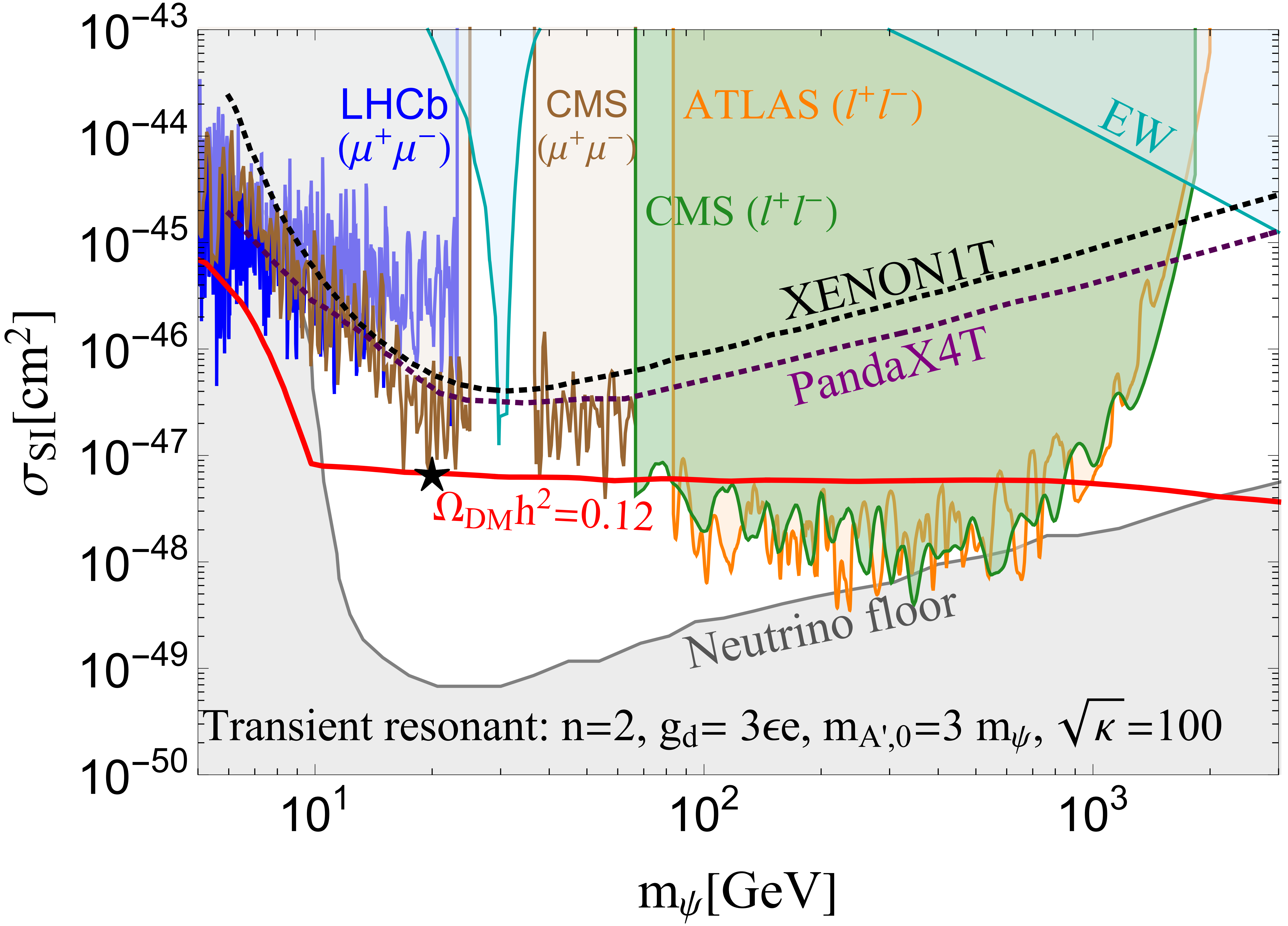
Transient resonant annihilation

- Transient resonant annihilation only happens in the early universe
  - No indirect constraints
  - Collider and direct detection constraints are evaded
  - Can be soon tested in the future



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Summary

- WIMP DM has significant coupling to SM model
  - Direct detection sets strong limits, but there are at least six ways to escape the limits
  - Indirect detection sets strong limits, less way to escape the limits. But it leaves open for DM mass $\gtrsim 10$ GeV
  - GeV-Scale Thermal WIMPs: Not Even Slightly Dead
- A variant of WIMP model from cosmic evolution: transient annihilation DM, evading DD, collider and indirect searches but can be tested soon

Thank you!

Backup slides