暗物质理论综述

刘佳 (Jia Liu)
北京大学物理学院

中国物理学会高能物理分会
第十一届全国委员代表大会暨学术年会
2022-08-09

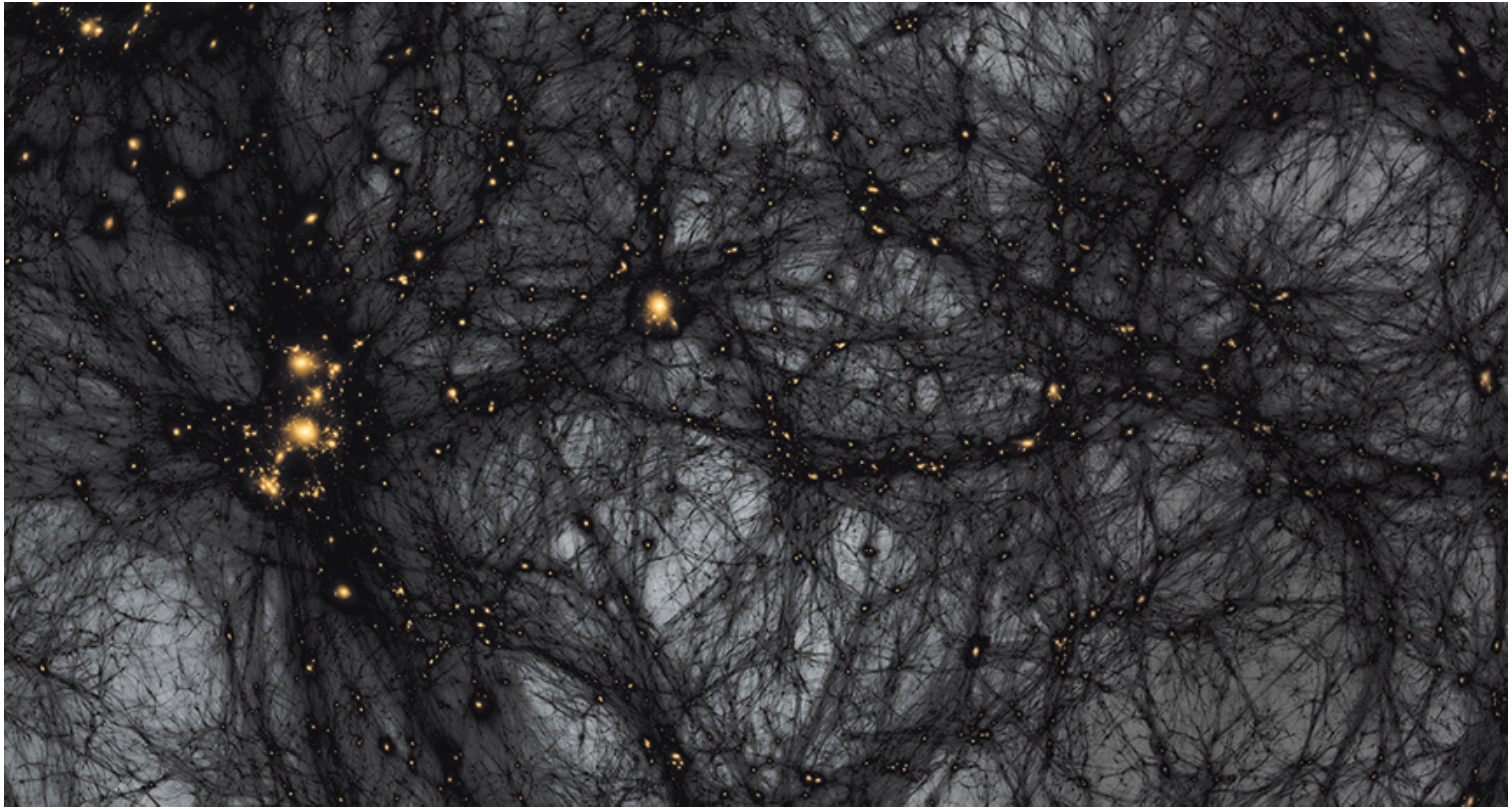
Outlines

- 暗物质的天文观测证据
- 暗物质的物理模型
  - 可能的暗物质候选模型
    - 超轻波动型暗物质
    - WIMP暗物质
- WIMP暗物质
  - WIMP暗物质的直接探测危机
    - 解决危机的多种办法
  - 暗物质对撞机探测的互补性
  - 暗物质的间接探测限制
    - 避开限制的办法
- 总结

什么是暗物质?

- 暗物质是理论上提出的可能存在于宇宙中的一种不可见的物质，它可能是宇宙物质的主要组成部分，但又不属于构成可见天体的任何一种已知的物质。

- 中性不带电
- 和可见物质相互作用小的
- 稳定
- 有质量的
- 冷的



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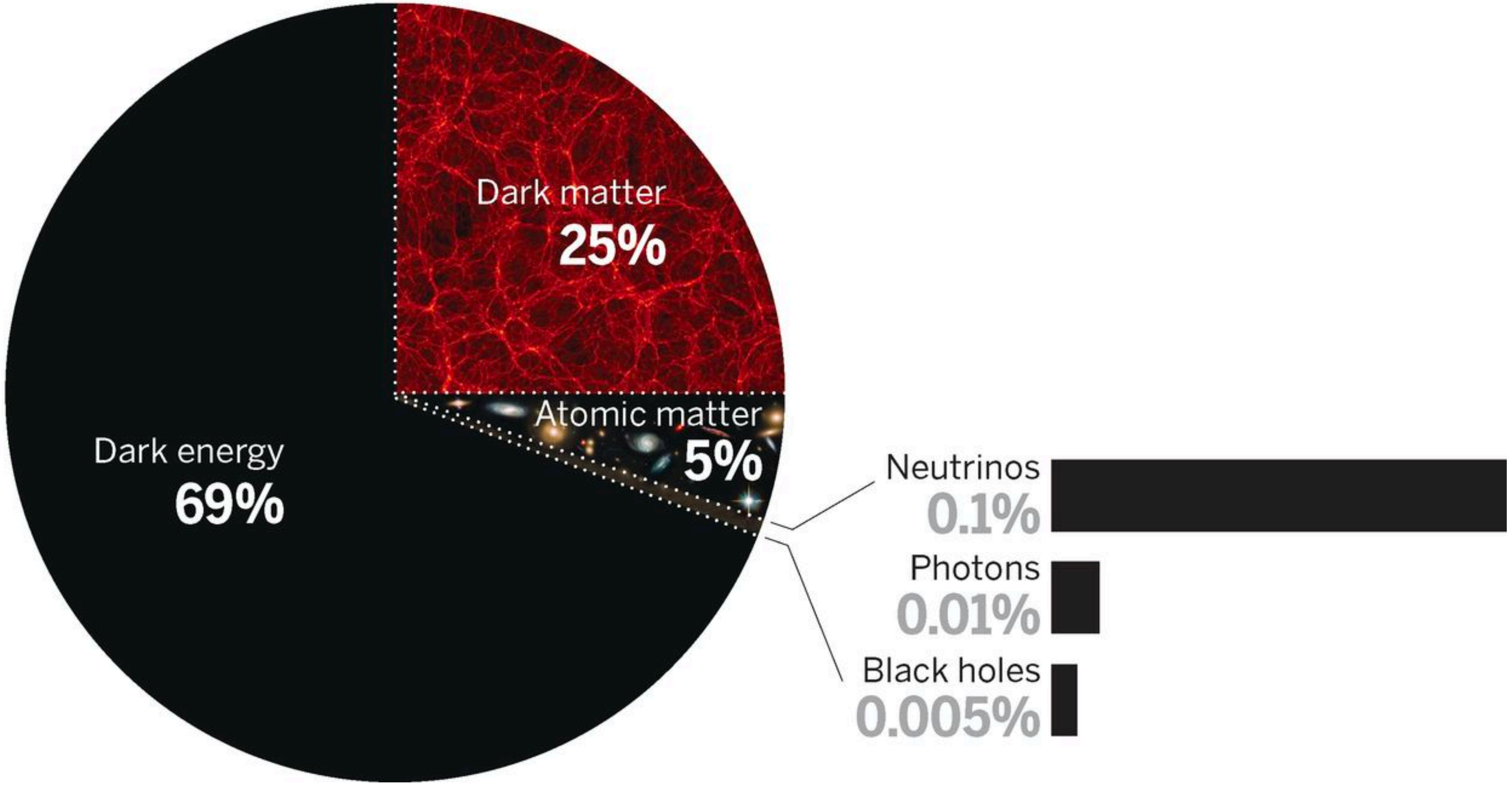
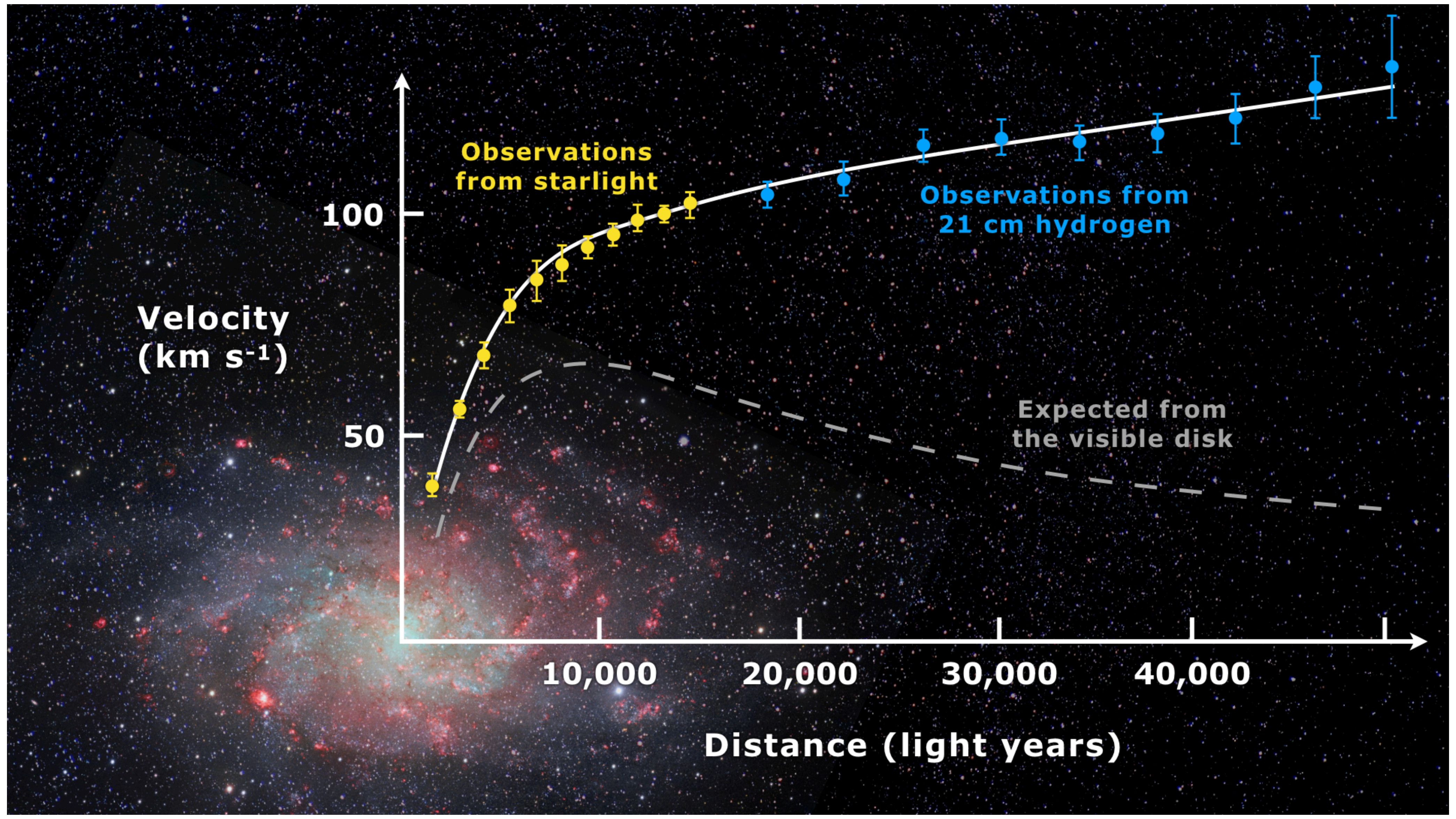
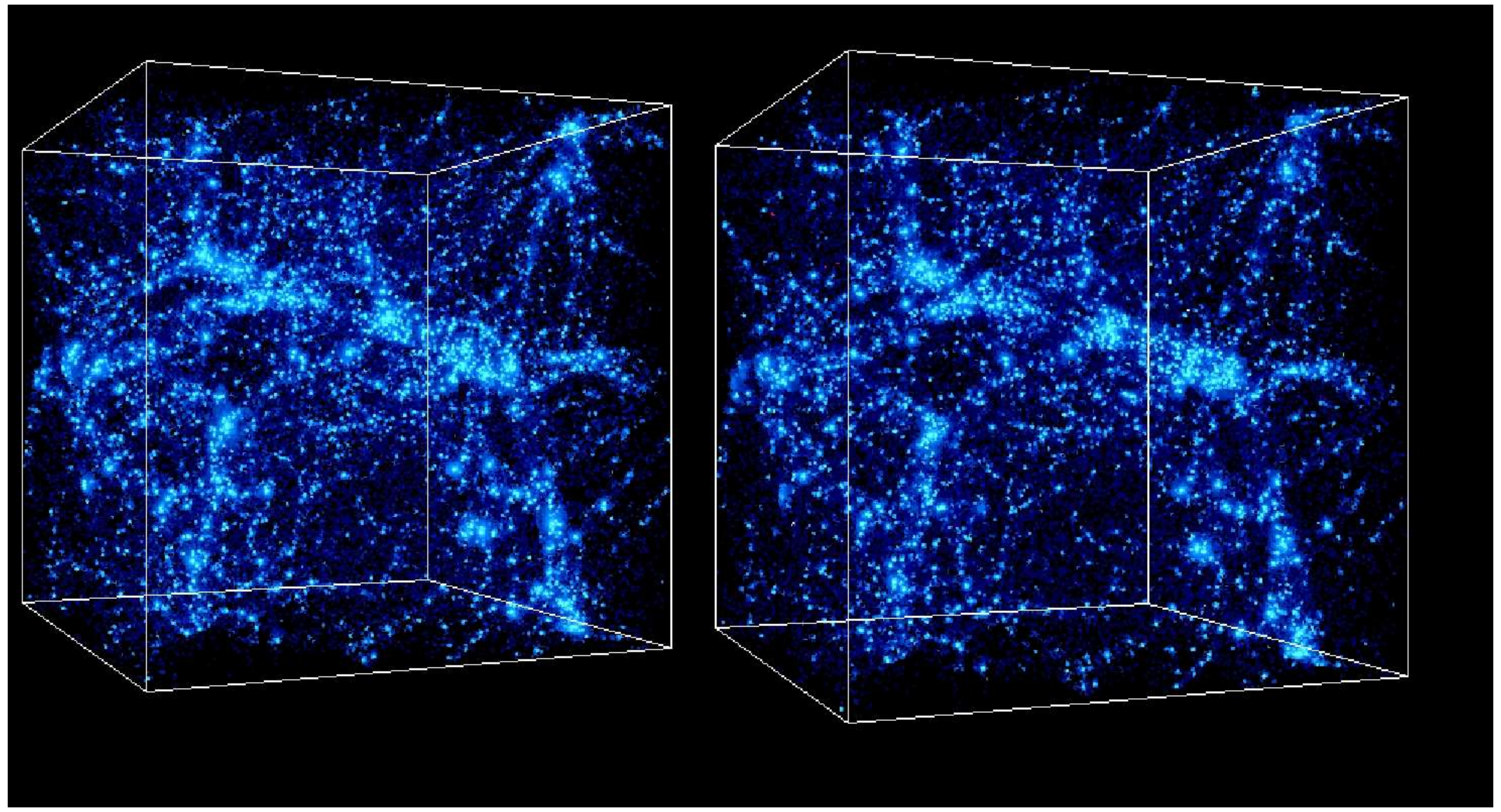
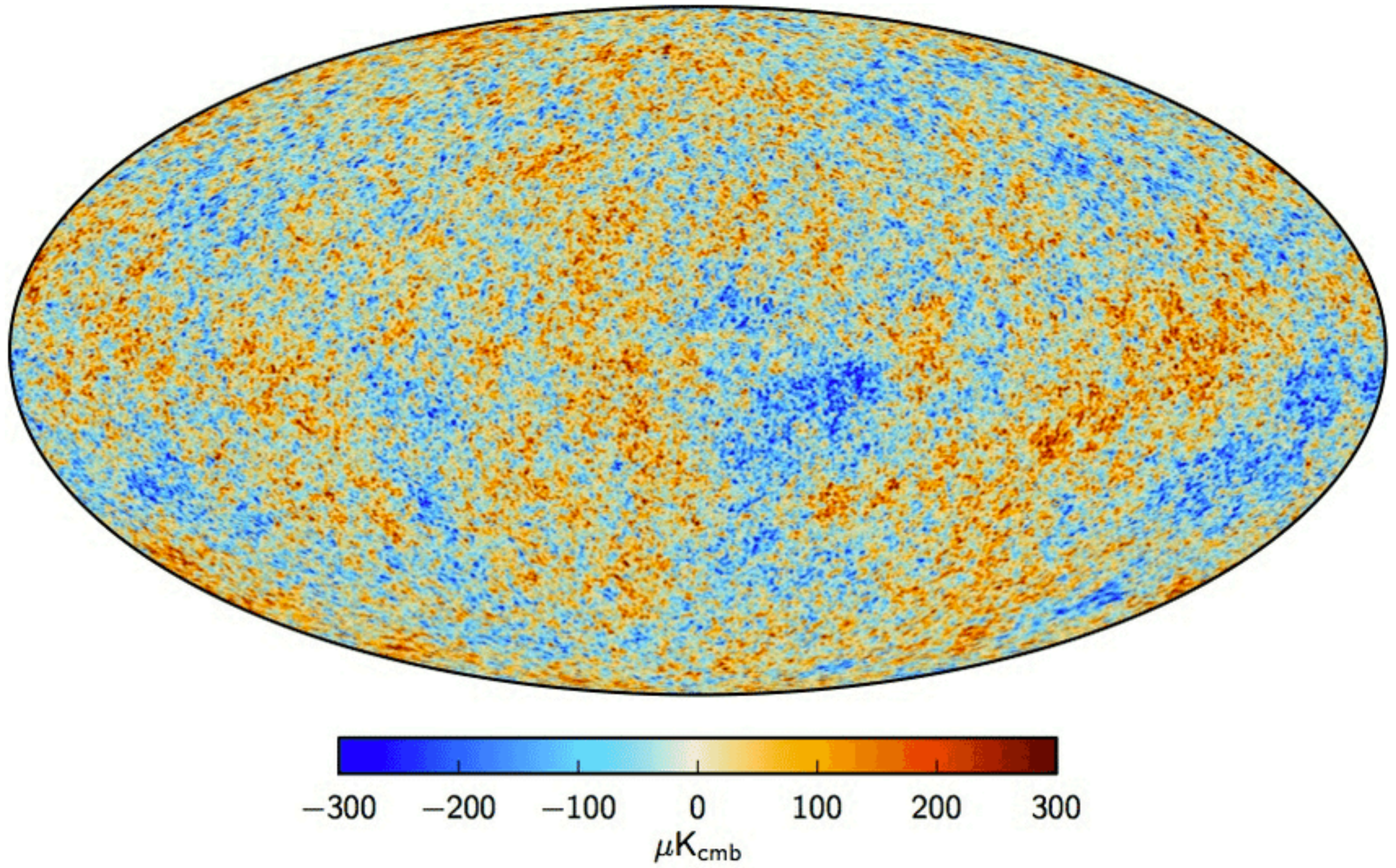


暗物质的观测证据



Observations from starlight
Observations from 21 cm hydrogen
Velocity (km s⁻¹)
100
50
Expected from the visible disk
10,000
20,000
30,000
40,000
Distance (light years)





−300
−200
−100
0
100
200
300
μK_cmb

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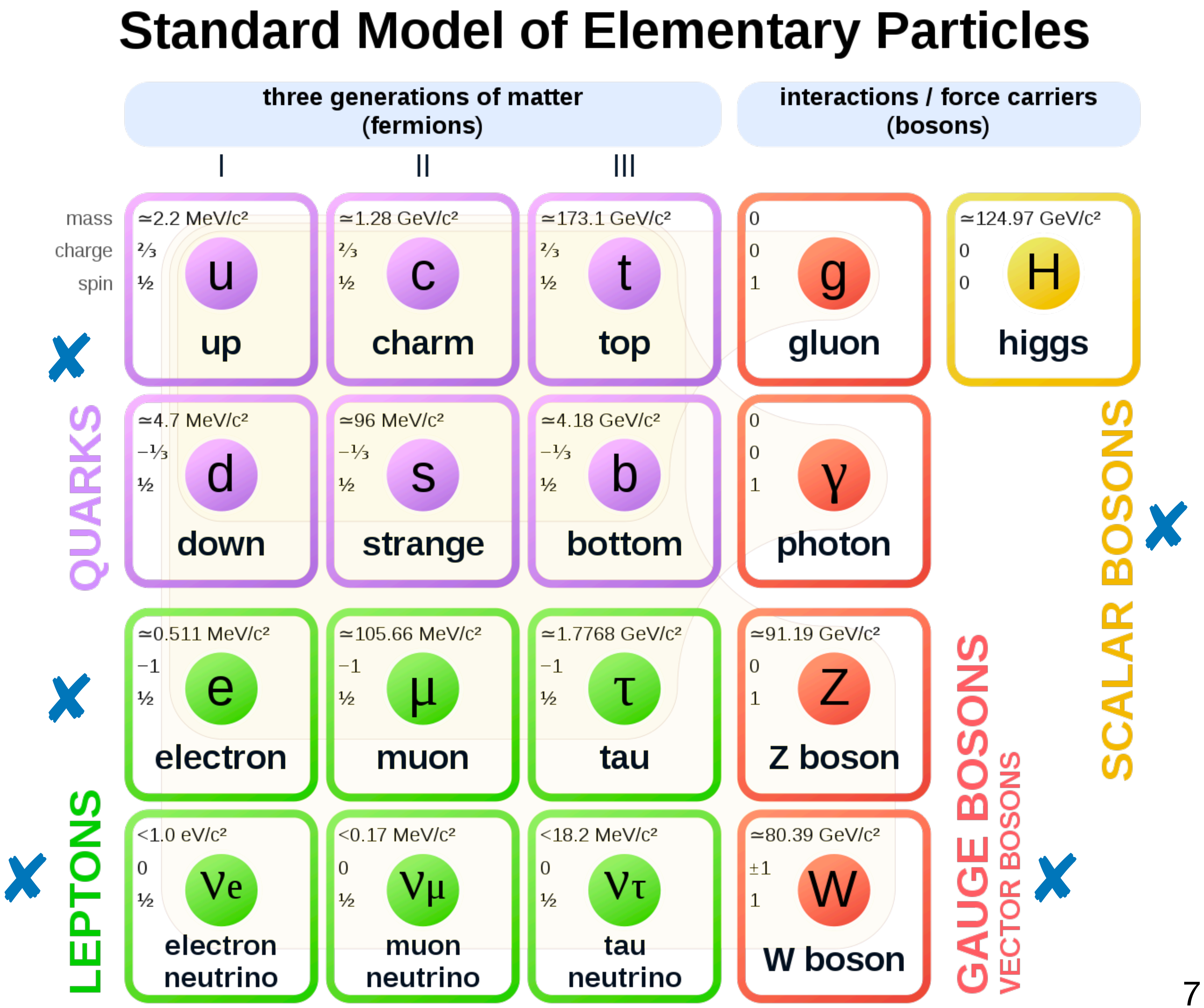
粒子物理标准模型与暗物质

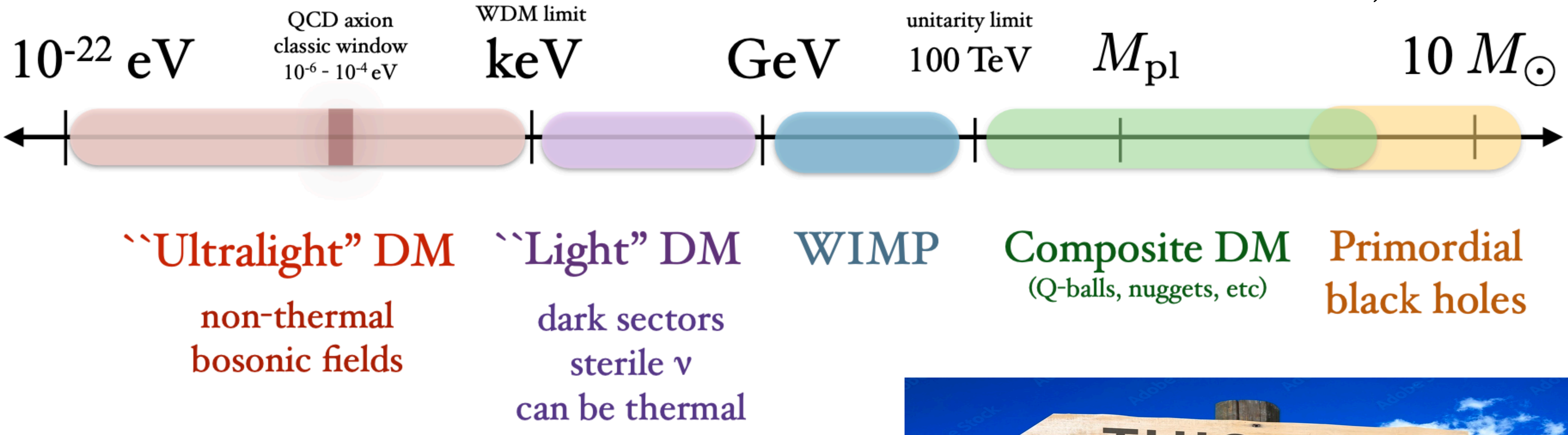
- No body knows what DM is
- Not in Standard Model
- There are good guesses



Not neutrinos ✗

暗物质的候选者模型

1904.07915，TASI lecture



HEP at a cross-road: explore all directions!

- 超轻波动型暗物质 (Ultralight Dark Matter)
- 具有弱相互作用的有质量粒子 (WIMP)
- …… 原初黑洞 (Primordial Black Hole, PBH)、(Freeze-in) 冻结暗物质、(Asymmetric) 不对称暗物质等

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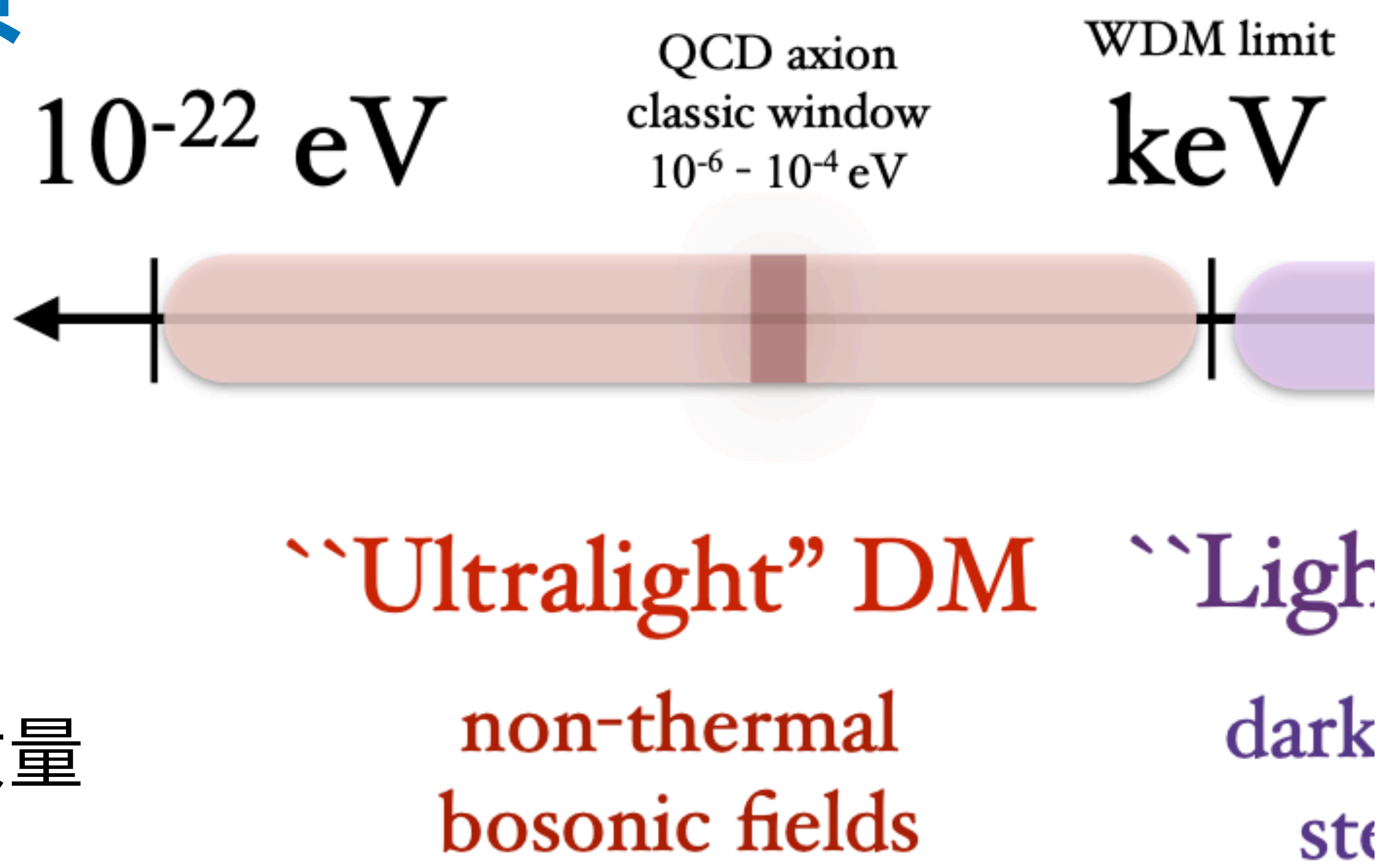
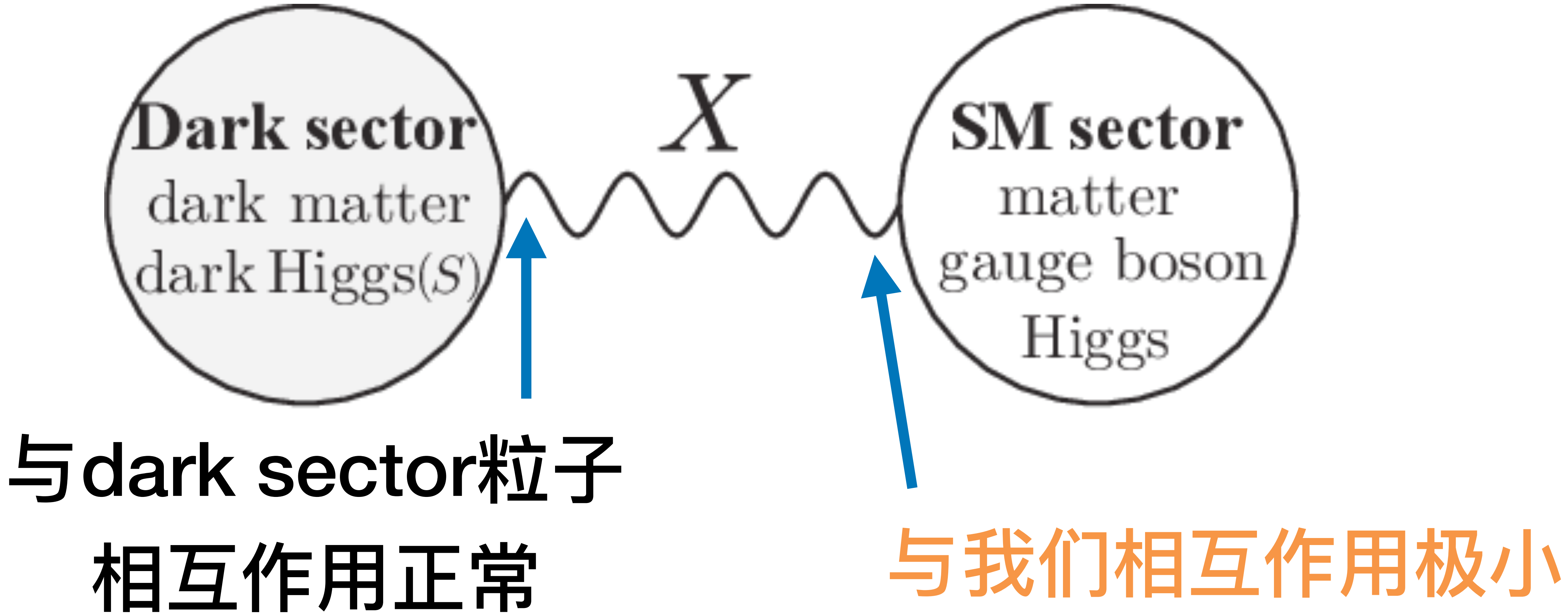
超轻波动型暗物质

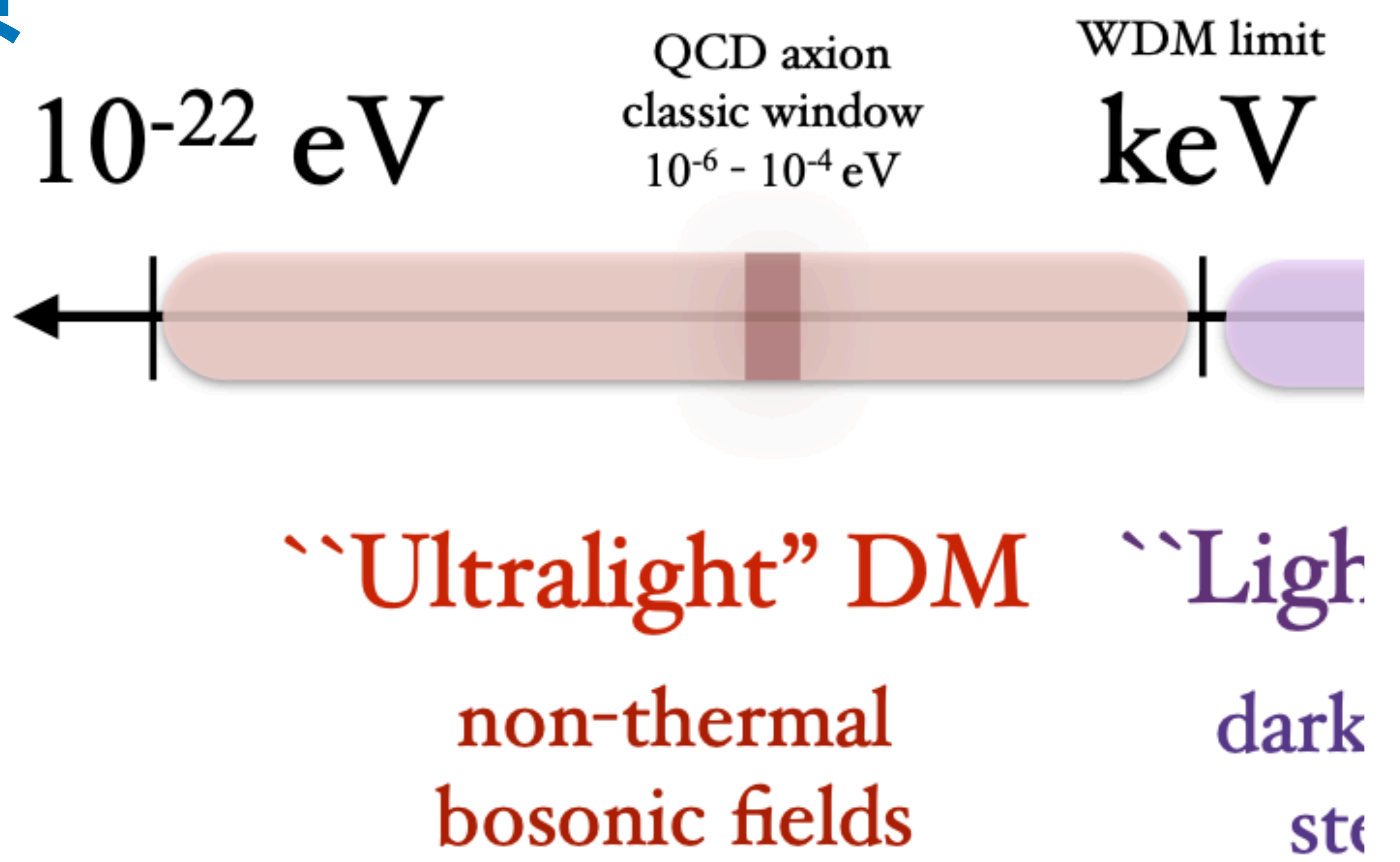
- 超轻波动型暗物质 (Ultralight Dark Matter)
  - 轴子和类轴子: 和费米子自旋耦合，随时间变化的EDM
  - 暗光子 (Dark photon)：和电磁流耦合，随时间变化的电场
  - 暗标量粒子 (Dark scalar)：和费米子质量项耦合，随时间变化的质量
  - 残余丰度：Misalignment机制等
  - 物理动机：
    - 冷暗物质小尺度结构问题
    - 暗物质世界和我们世界的媒介粒子
    - 暗物质稳定性：全局对称性 V.S. 极小质量
      - 典范模型：QCD 轴子

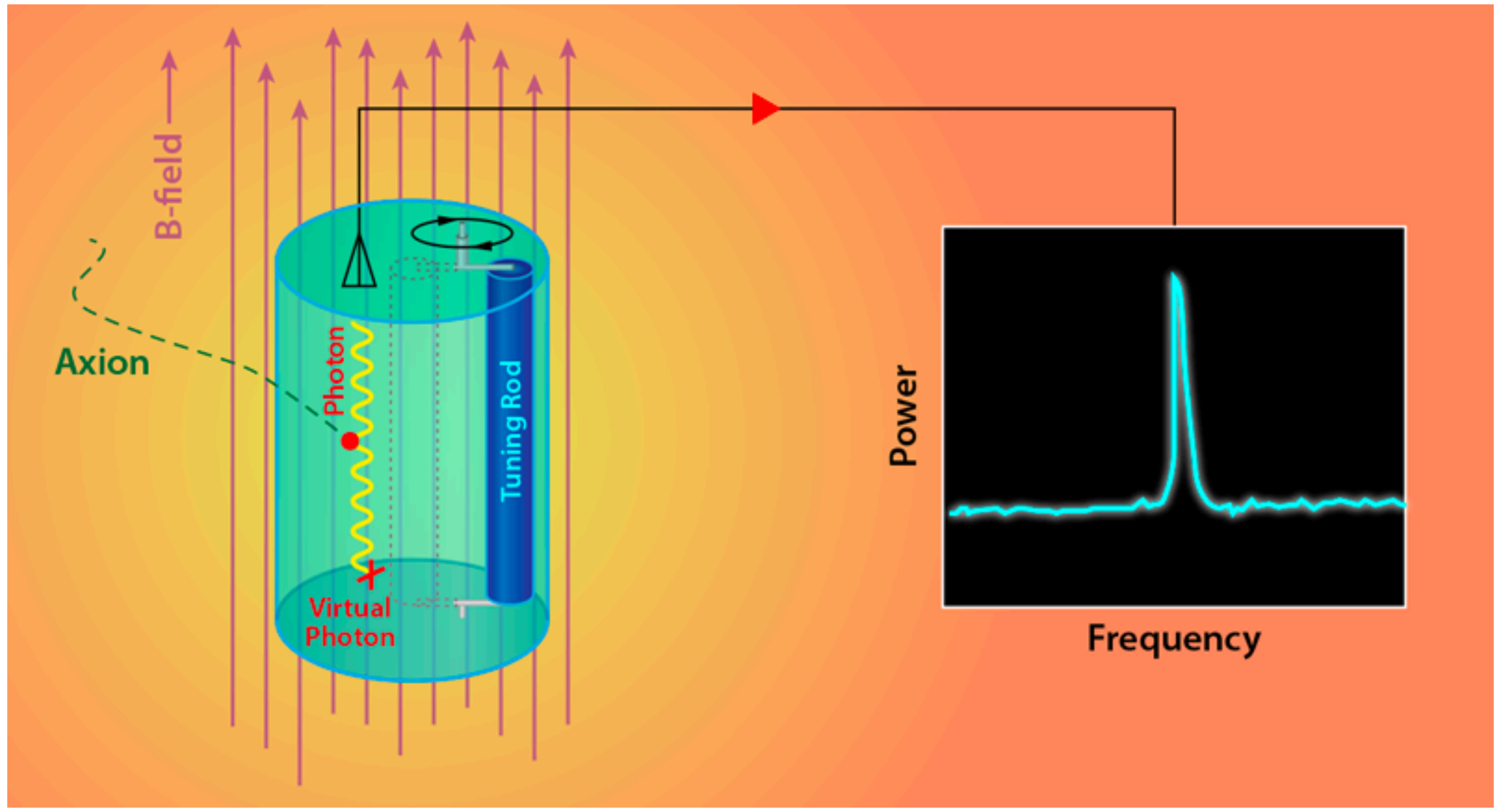




超轻波动型暗物质

- 超轻波动型暗物质 (Ultralight Dark Matter)
  - 超轻波动型暗物质质量范围$[10^{-22}, 10^{3}]$ eV，以经典振荡场的形式存在；$[10^{-6},10^{-4}]$ eV 是QCD 轴子的经典区间
  - 并且与光和物质有微弱相互作用，探测需要和其它物理学科，如原子分子、光学、天文学、天体物理学和宇宙学进行交叉与合作
  - 探测方式丰富多彩：
    - 天体行星作为实验室：限制异常能量流失 （A’, ALP, S）
    - 早期宇宙CMB、高能伽马光、黑洞照片偏振 (ALP、A’)
    - 实验室谐振腔共振探测（ADMX, HAYSTAC …）(ALP, A’)
    - 实验室宽频谱搜寻（WISPDMX，Dark E-field …） （A’）
    - 第五种力、等效原理 （S, A’）
    - 暗物质直接探测实验 (XENONnT, PANDAX-4T, CDEX) (ALP, A’)
    - 射电天文学 (ALP, A’)
    - ……

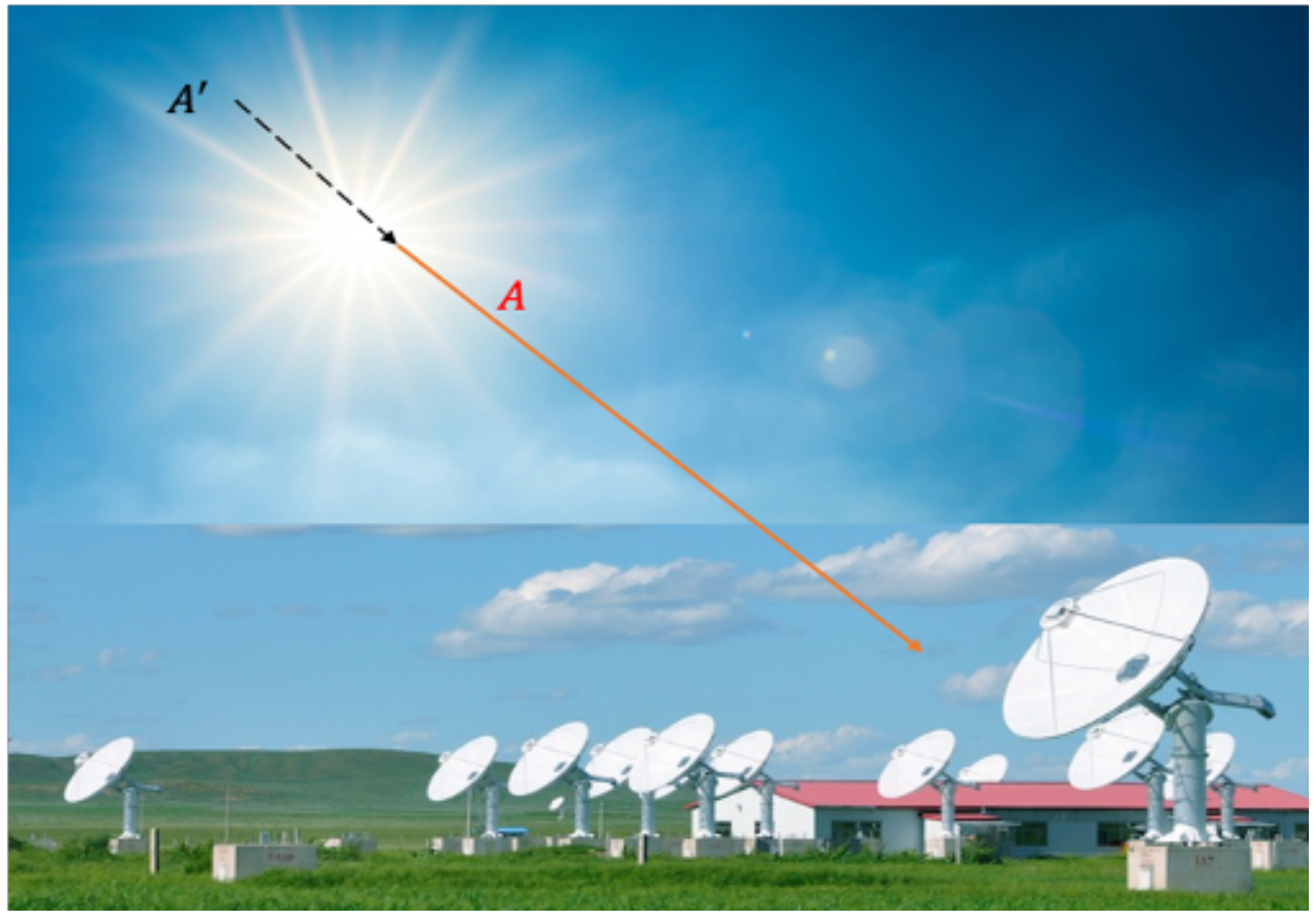




学科交叉：量子探测器、量子传感器、单光子探测器…

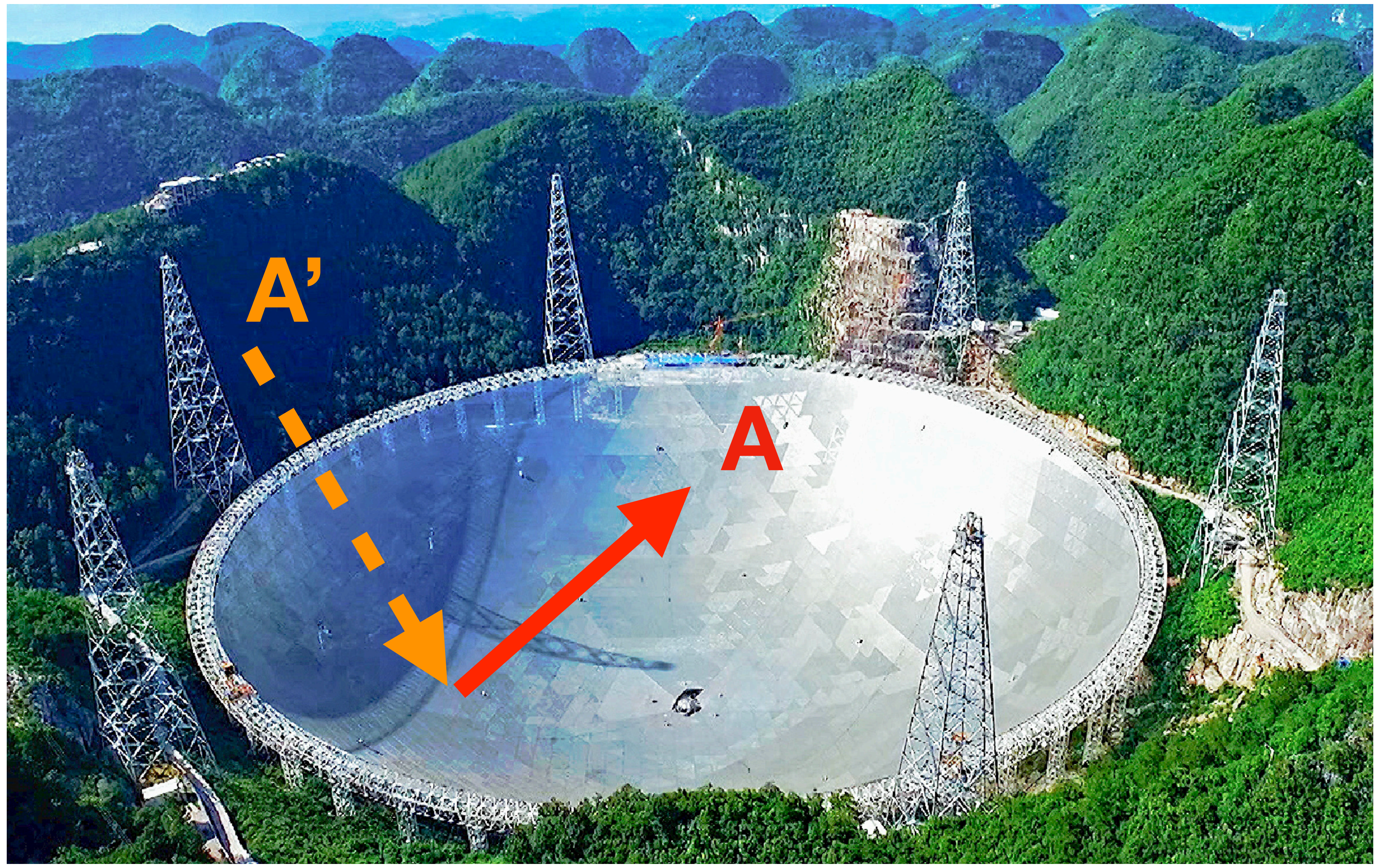
利用天文学的观测手段探测粒子物理模型: 与射电天文学的交叉

- 超轻波动型暗物质 (Ultralight Dark Matter): 超轻暗光子暗物质
  - 经典振荡场的形式存在；相互作用类似弱化的背景电磁场；振荡频率与质量相关



太阳日冕层等离子体中的暗光子-光子共振转化

An, Huang, JL, Xue 2010.15836 (PRL)



射电天文望远镜镜面或天线上暗光子-光子的转化

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

利用天文学的观测手段探测粒子物理模型: 与射电天文学的交叉

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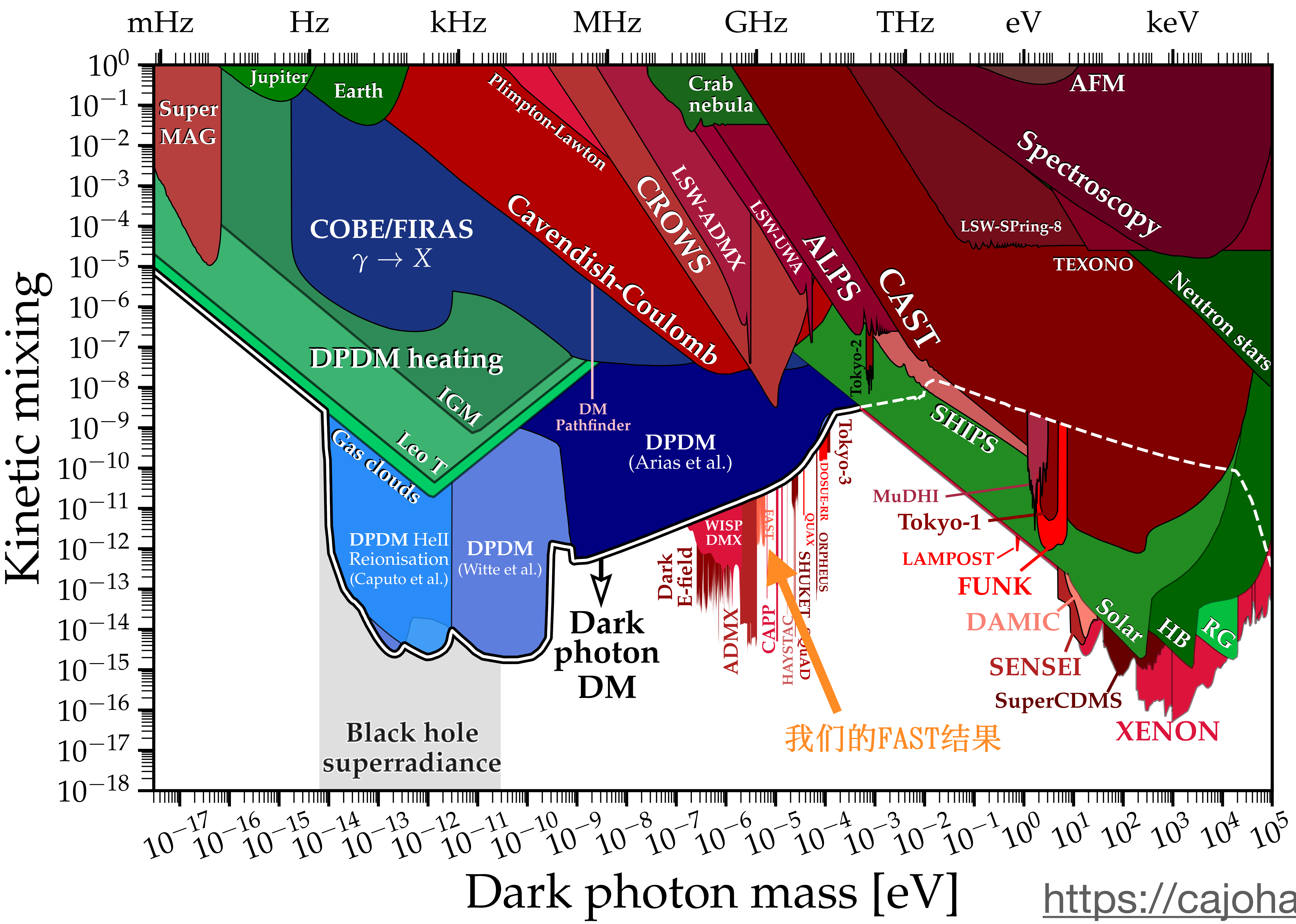

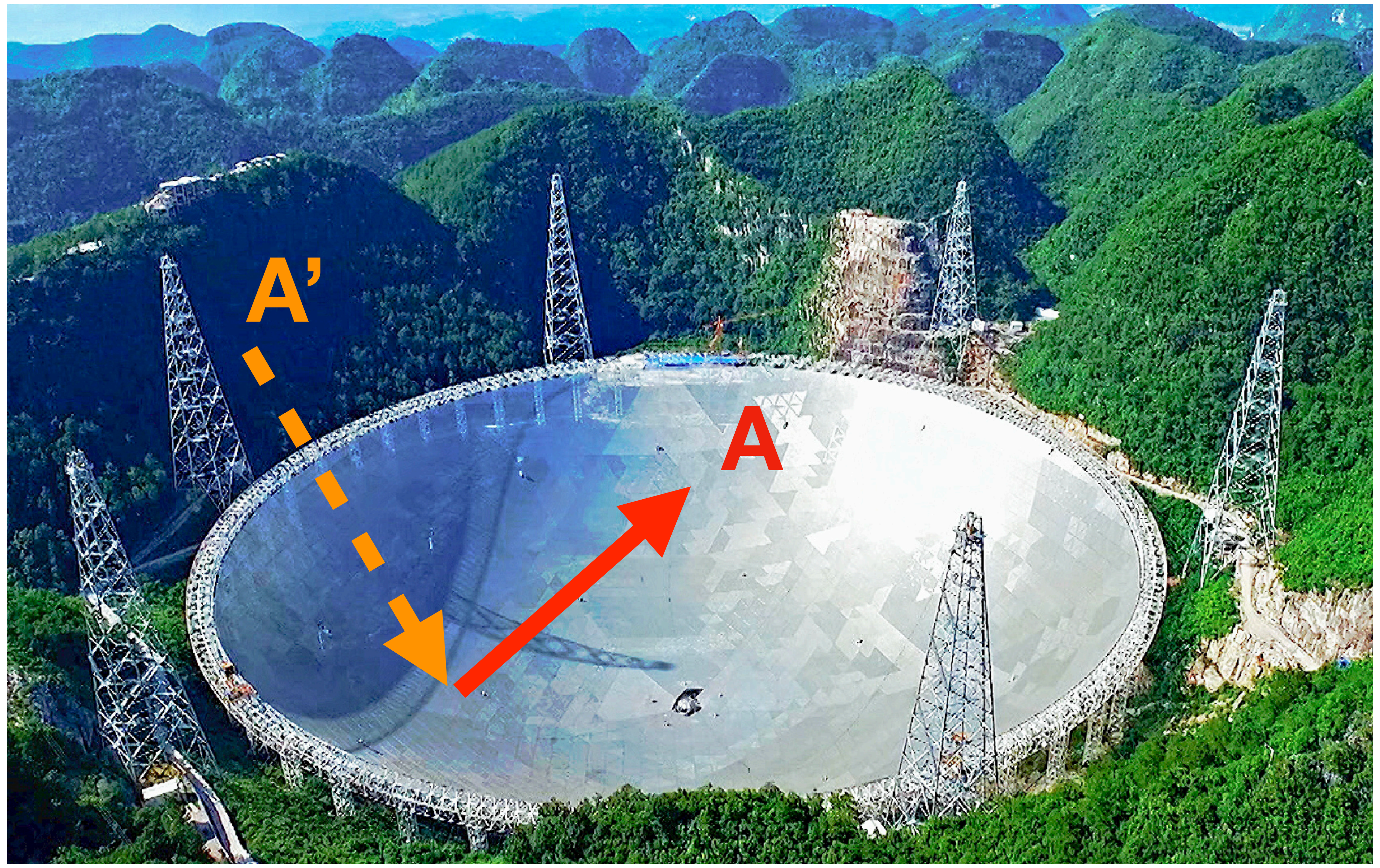

射电天文望远镜镜面或天线阵列上暗光子-光子的转化

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

https://cajohare.github.io/AxionLimits/docs/dp.html

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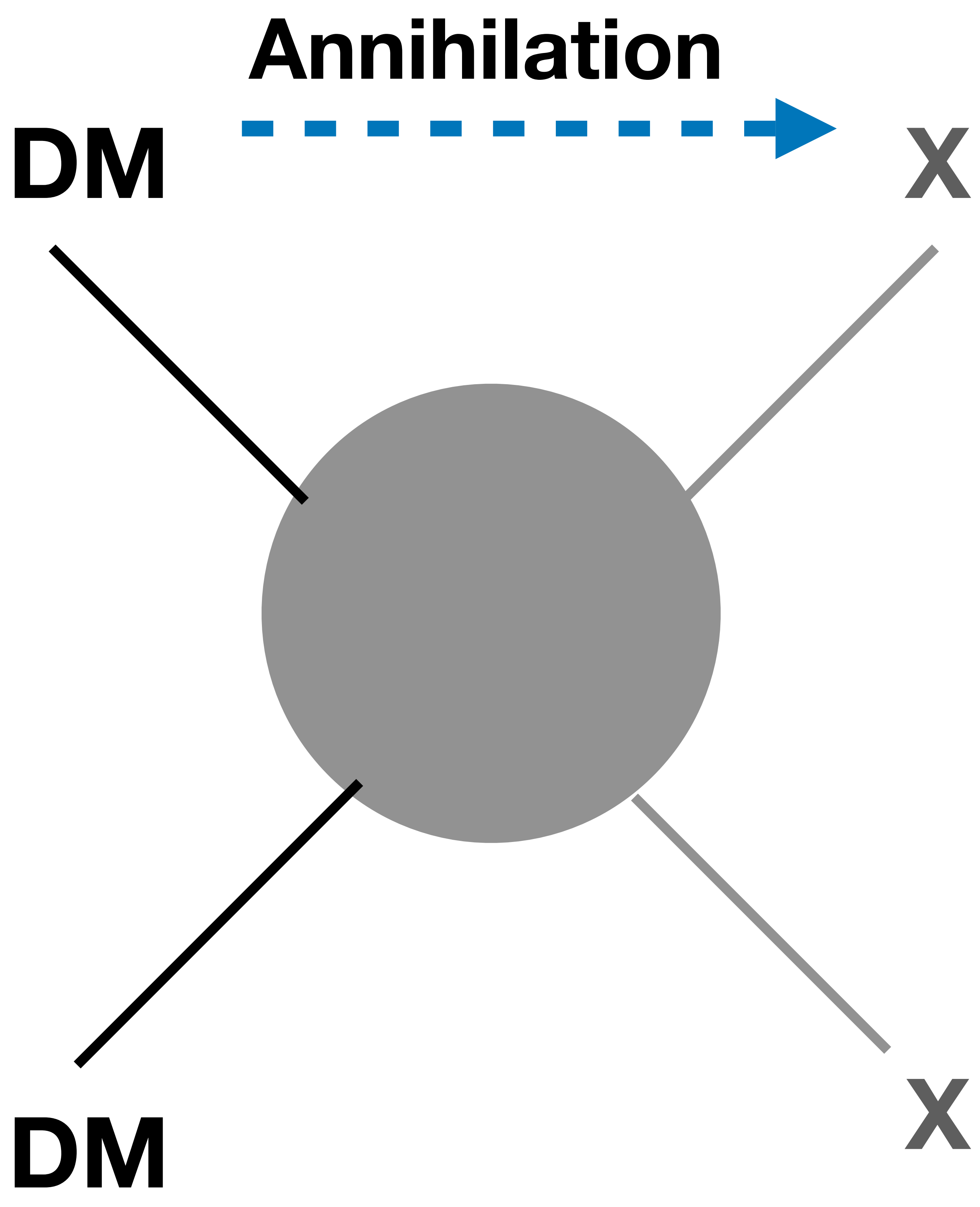
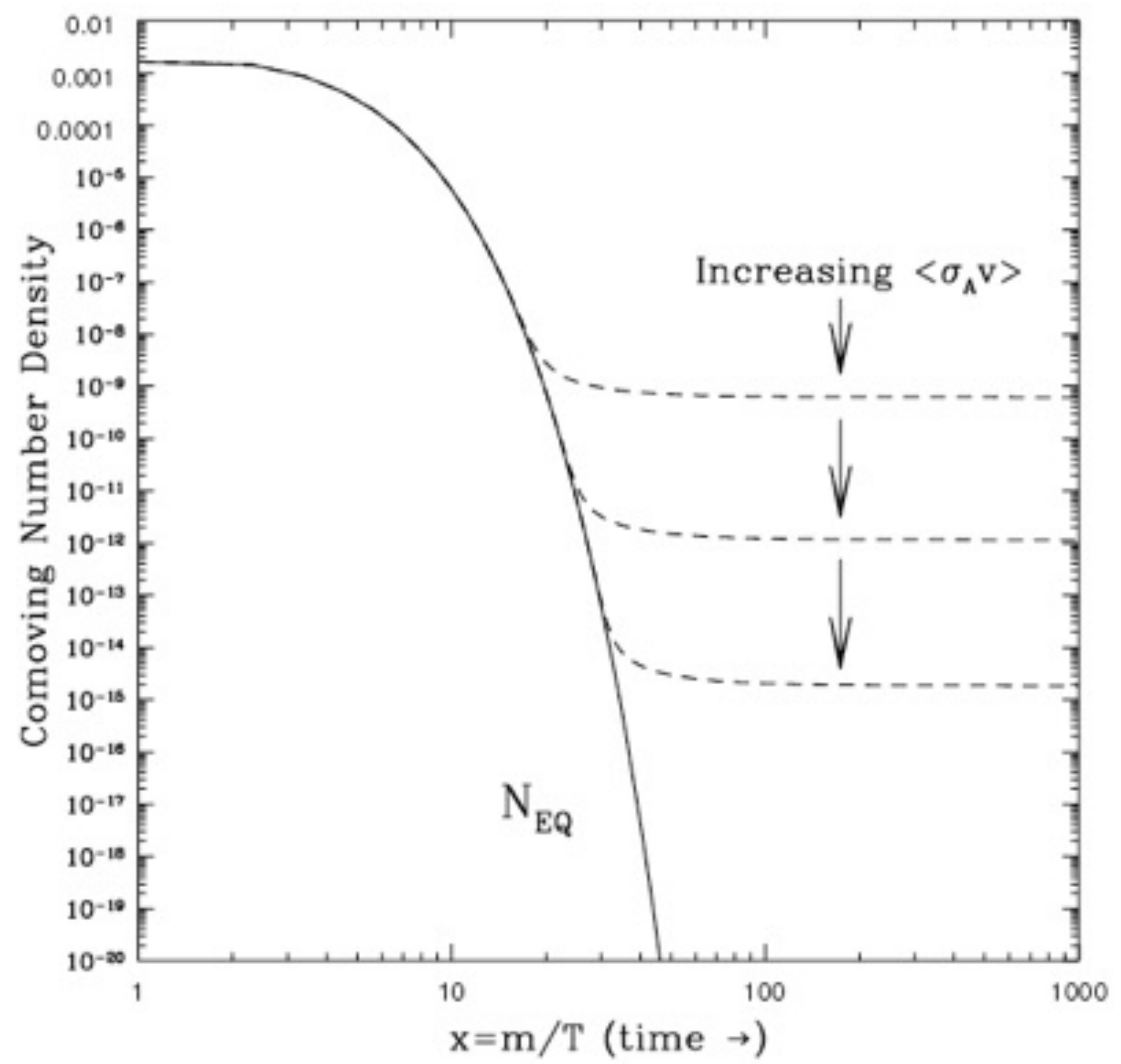
WIMP暗物质的热退耦合机制

- 热退耦合湮灭截面与电弱相互作用强度和能标吻合 $\langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2} \sim 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$



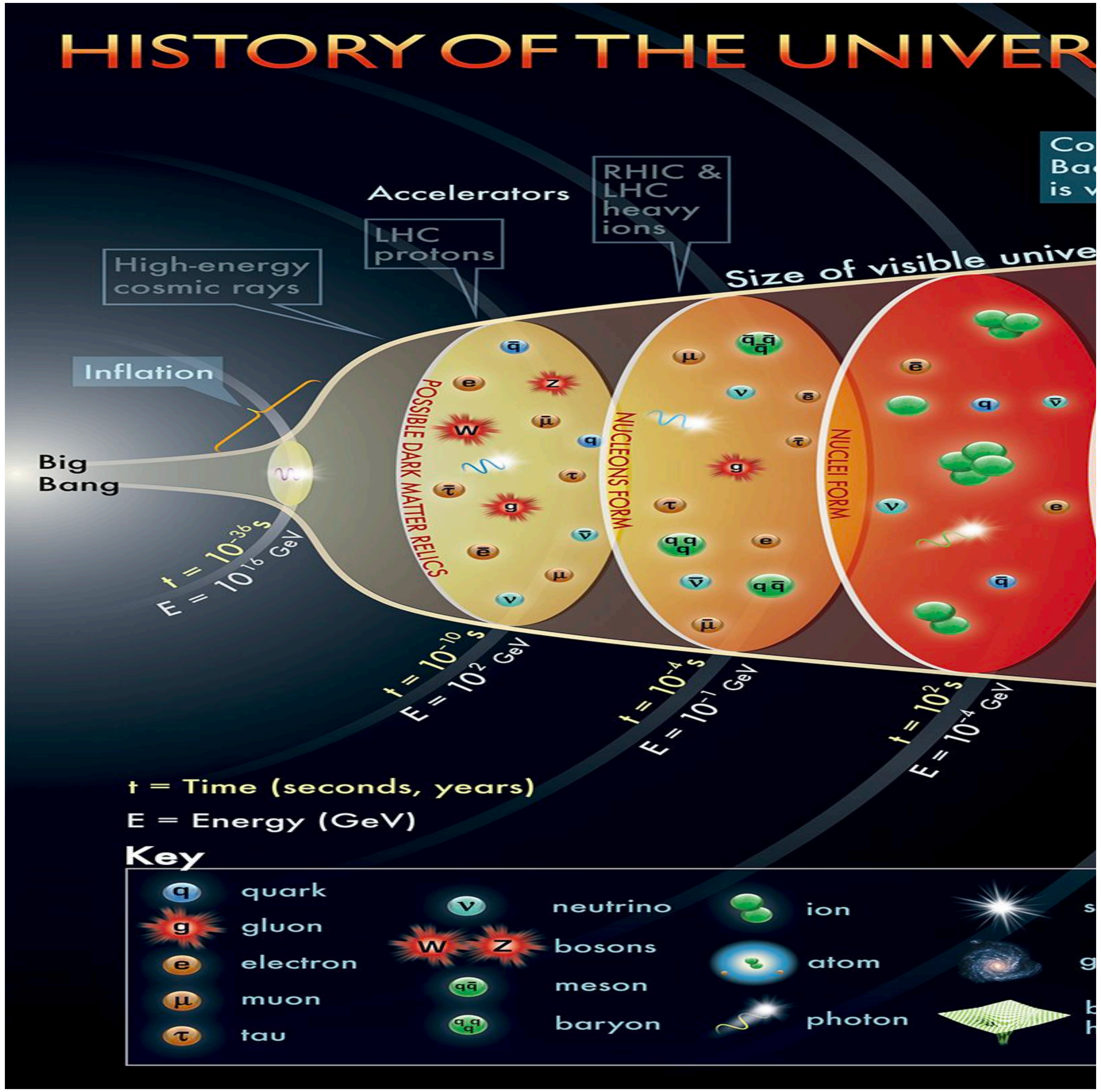
人们称该吻合为 **WIMP miracle**



Jungman *et al* hep-ph/9506380

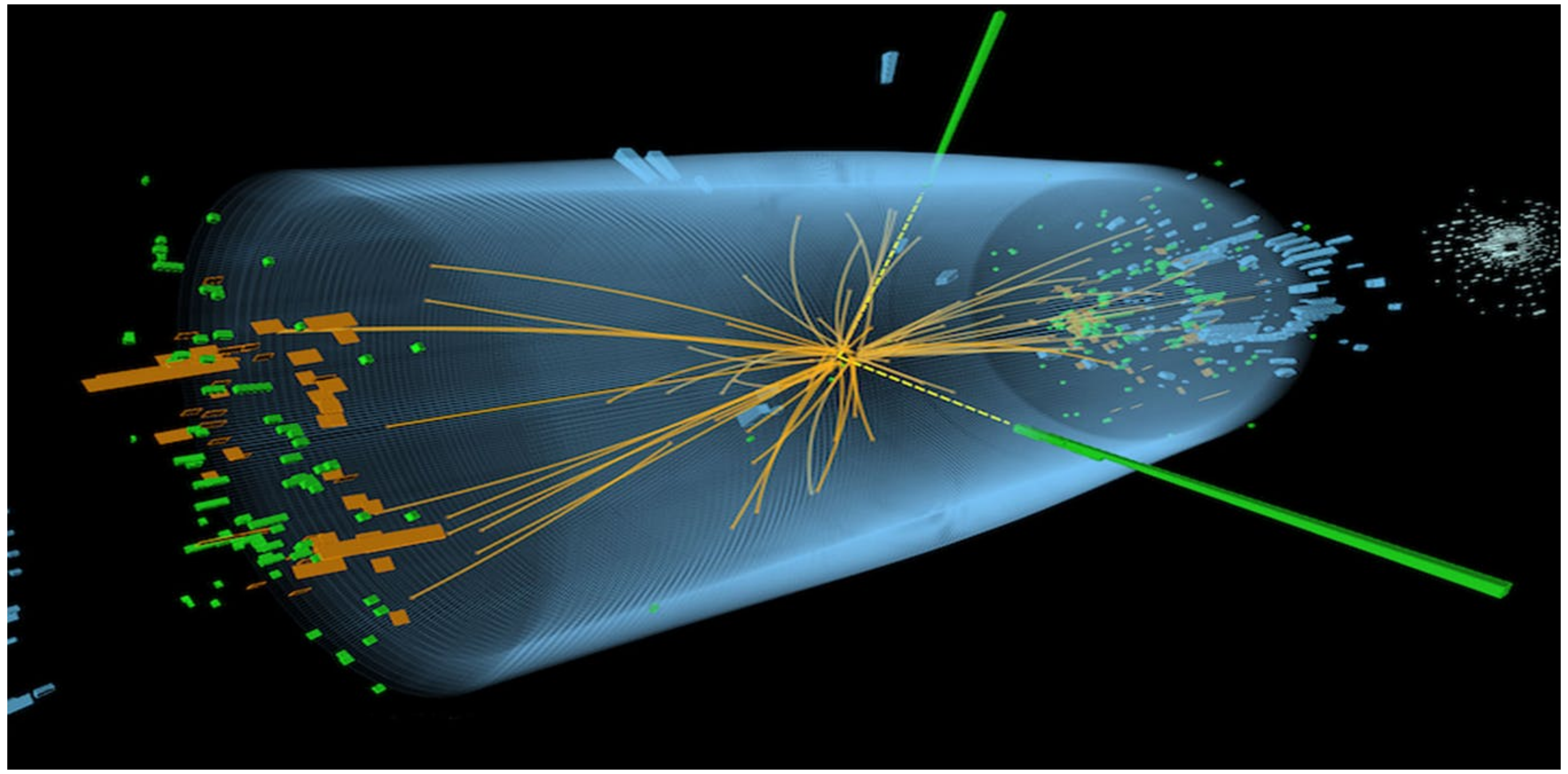
热退耦合机制

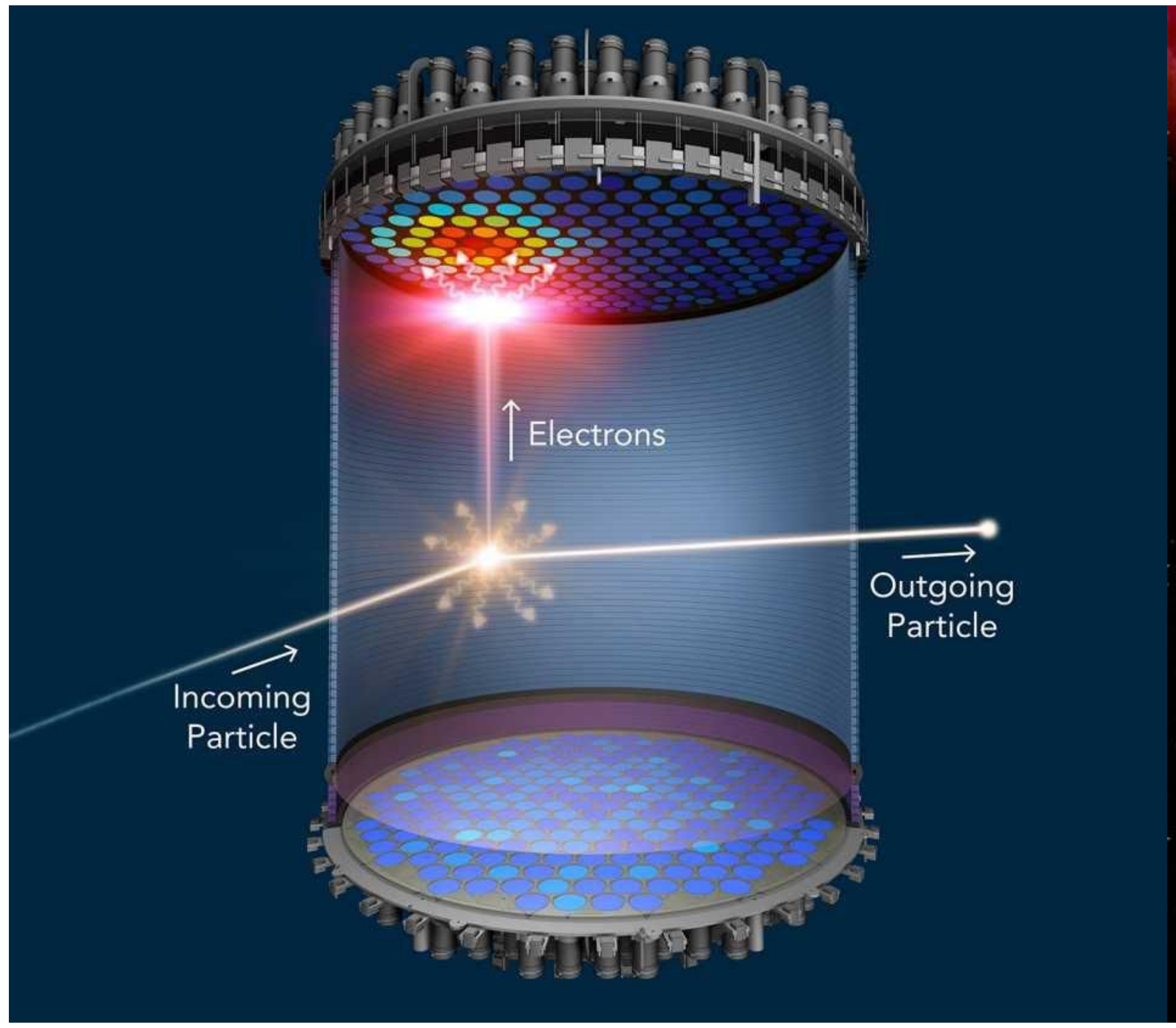
- 自然的得到暗物质残余丰度
  - 不需要UV信息 (以热平衡分布开局)
  - 电弱能标的湮灭截面
  - 与标准模型其他粒子相似的故事
    - (ν decoupling, n_p/n_n ratio, nuclear elements)
  - 预言了直接/间接/对撞机的实验信号

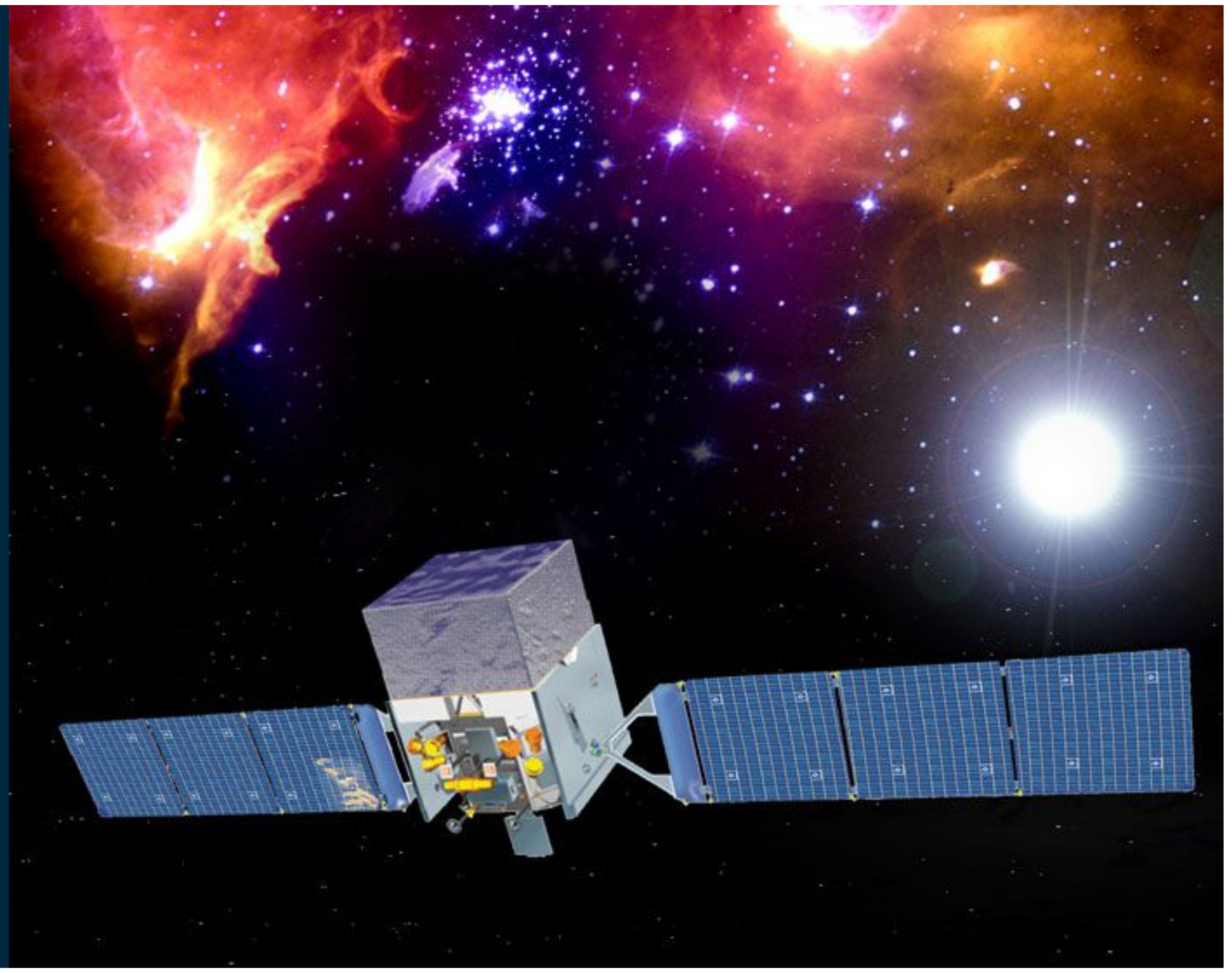


优秀的实验信号预期

- WIMP暗物质和标准模型有较大的相互作用
  - 直接探测实验 SM + DM > SM + DM
  - 间接探测实验 DM + DM > SM + SM
  - 对撞机实验 SM + SM > DM + DM

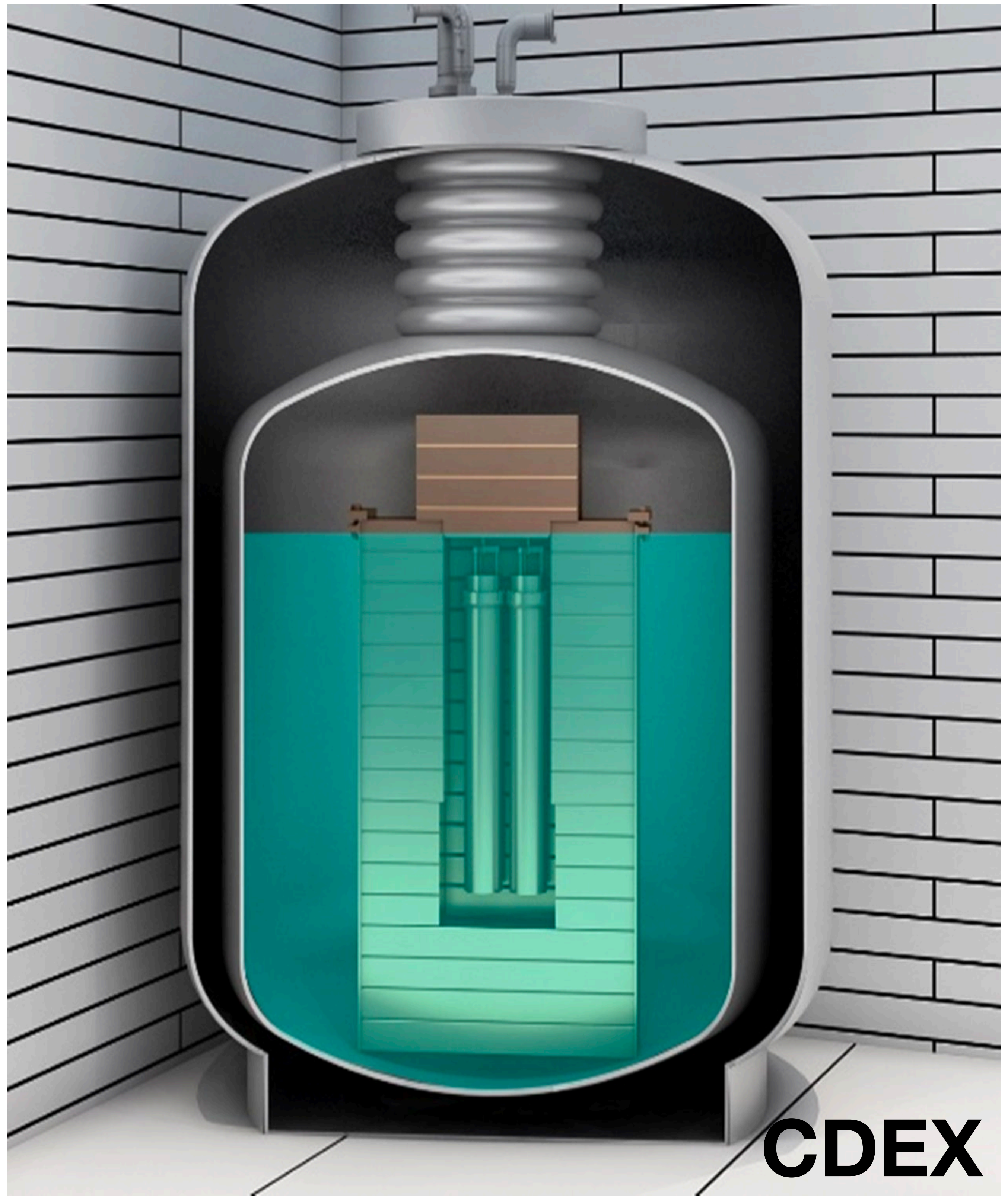


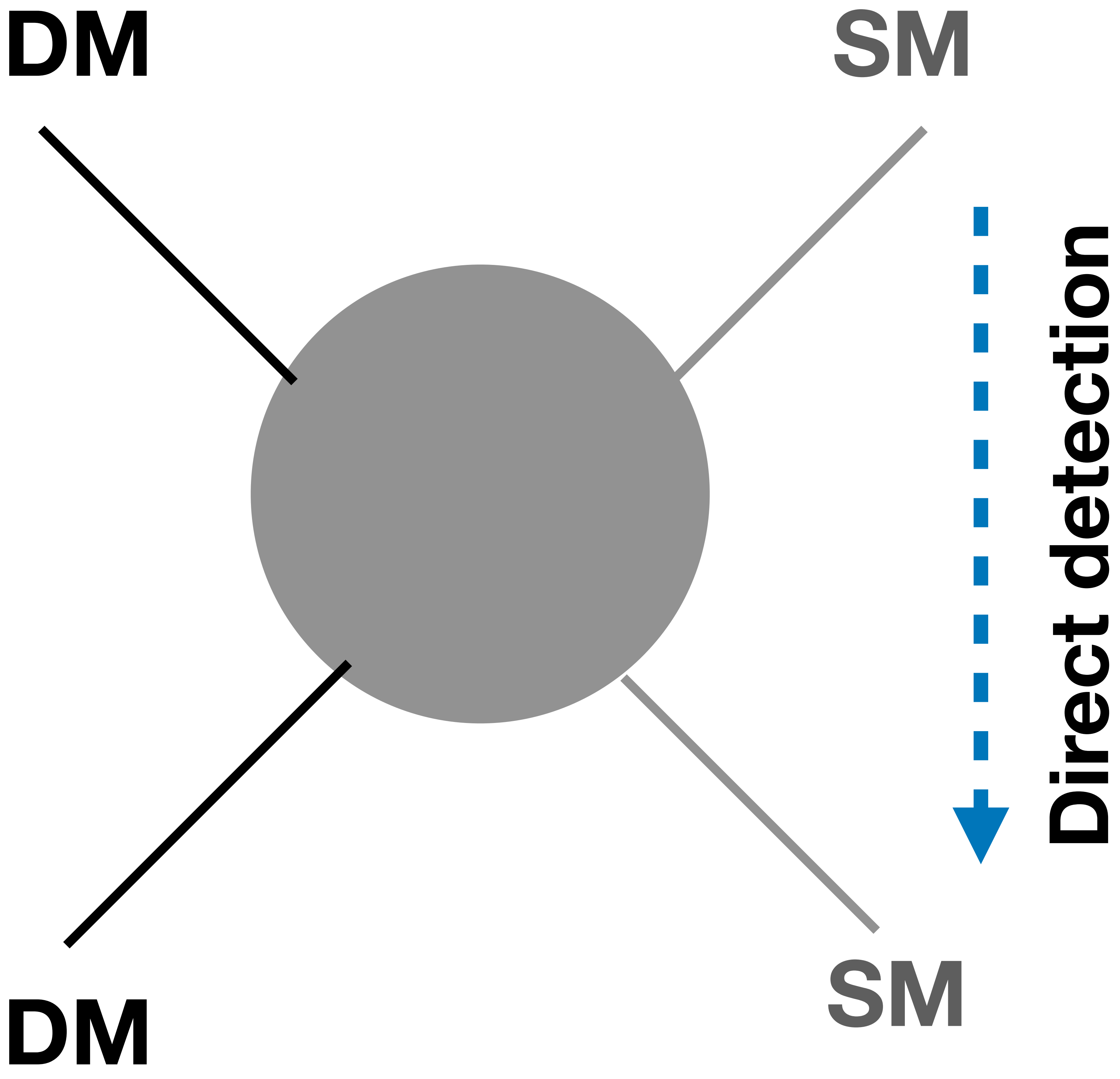




The WIMP crisis from direct detection

- Weakly Interacting Massive Particle
- The sizable coupling of DM to SM particles predicts sizable scattering cross-section





我国暗物质直接探测实验
CDEX： Ge， 低质量
PANDAX： Xe， 高质量

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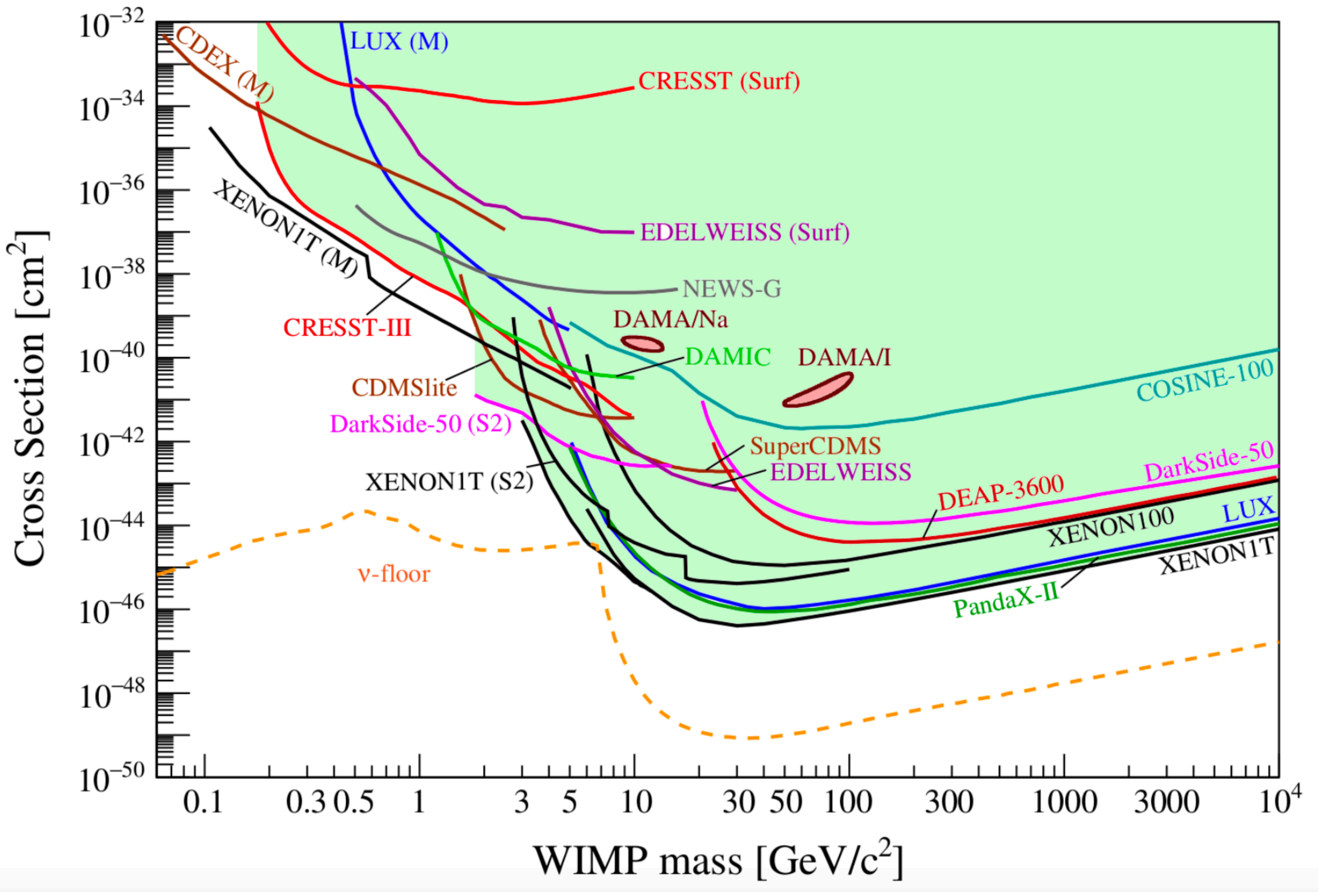
The WIMP crisis from direct detection

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

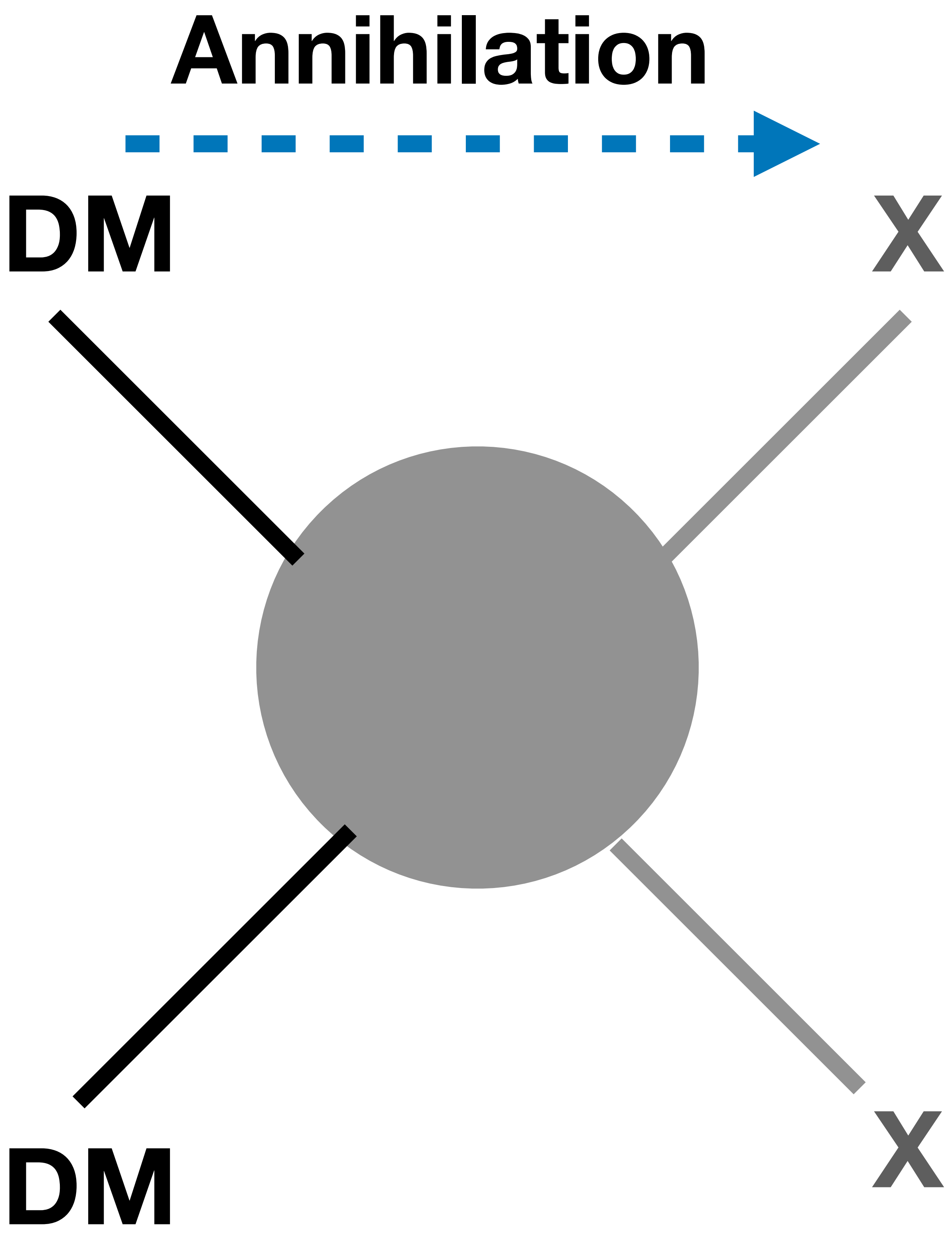


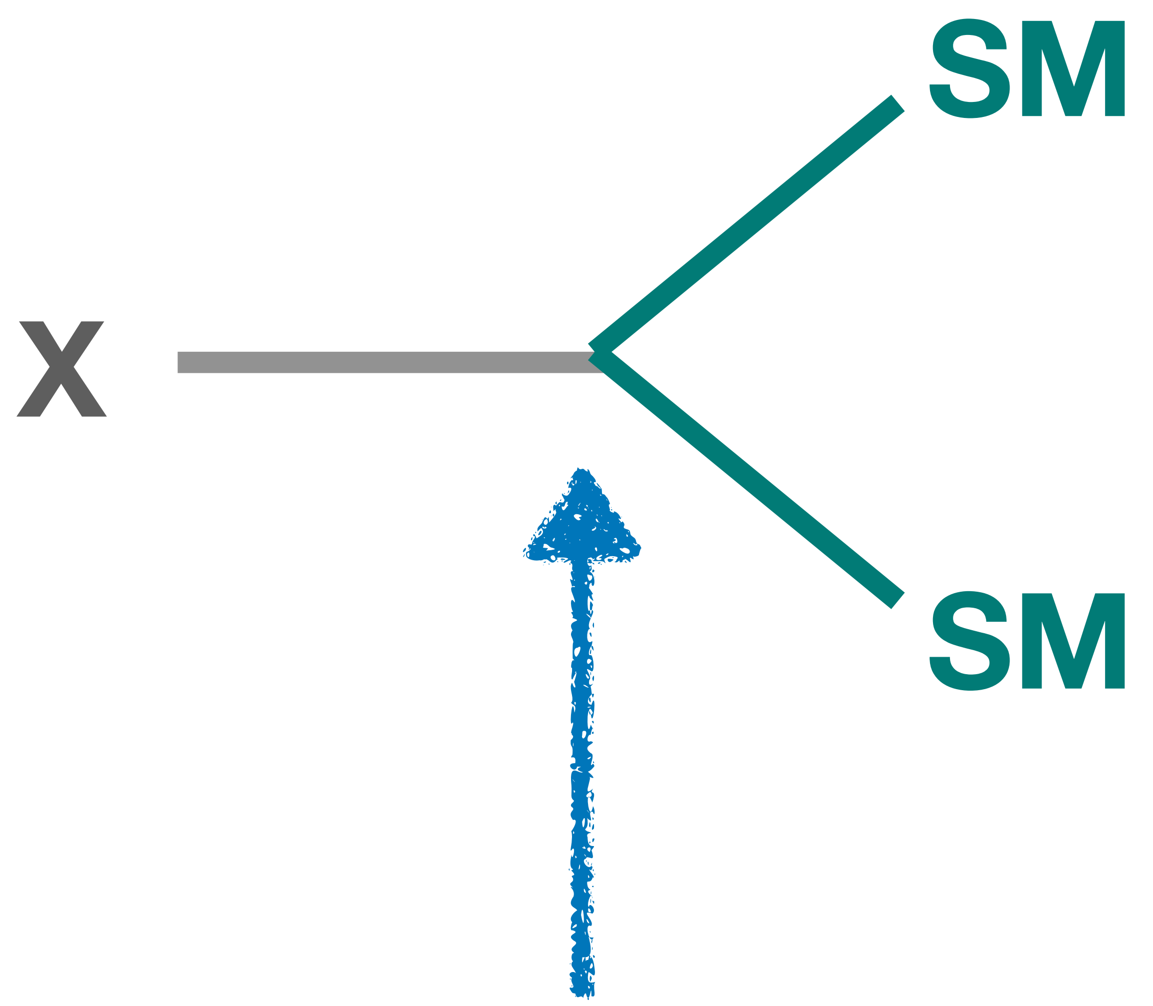
APPEC Committee Report: 2104.07634

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**

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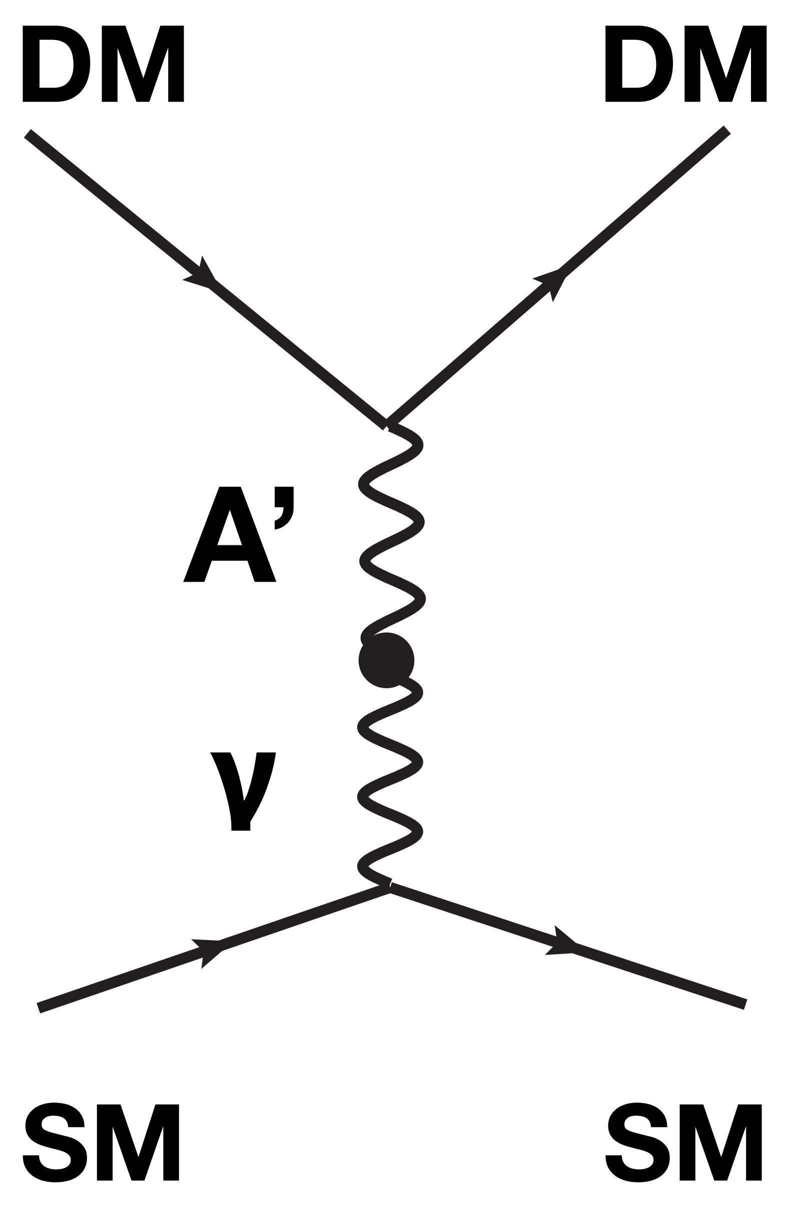
The way-out from direct detection limits

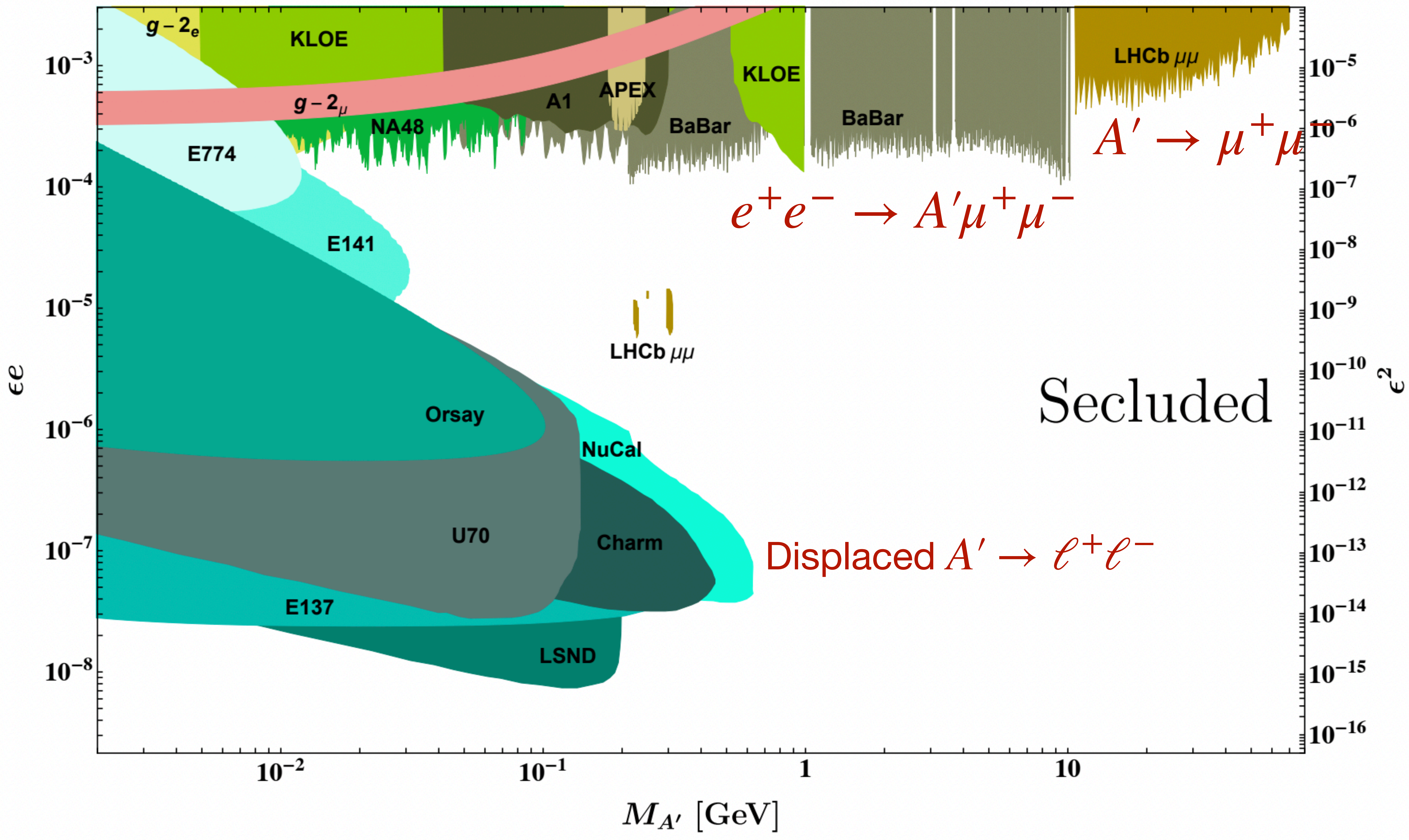
- 1. Secluded dark matter (dark sector)
  - Looking for mediator X is easier than DM

Bauer et al: 1803.05466 (JHEP)

Dark photon A' example: visible

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





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The way-out from direct detection limits

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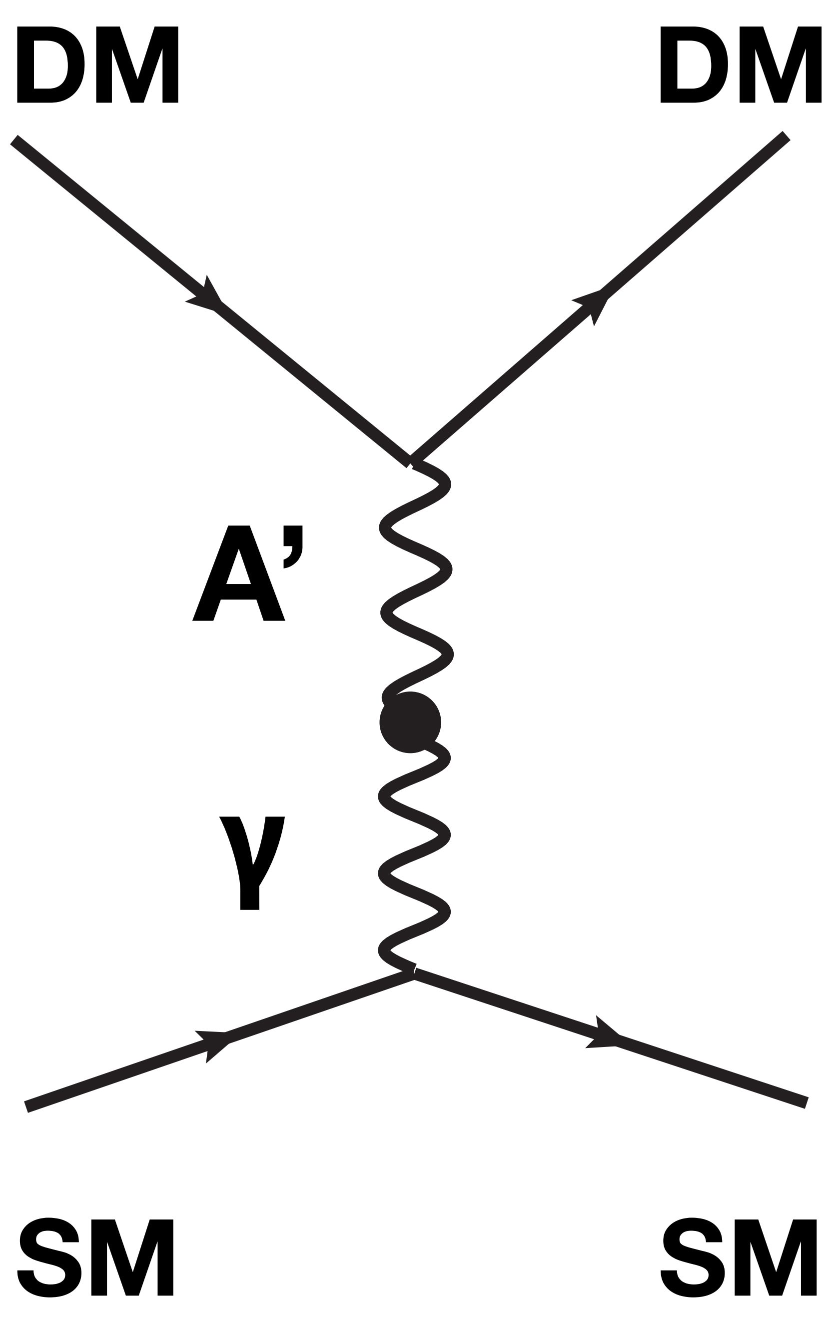
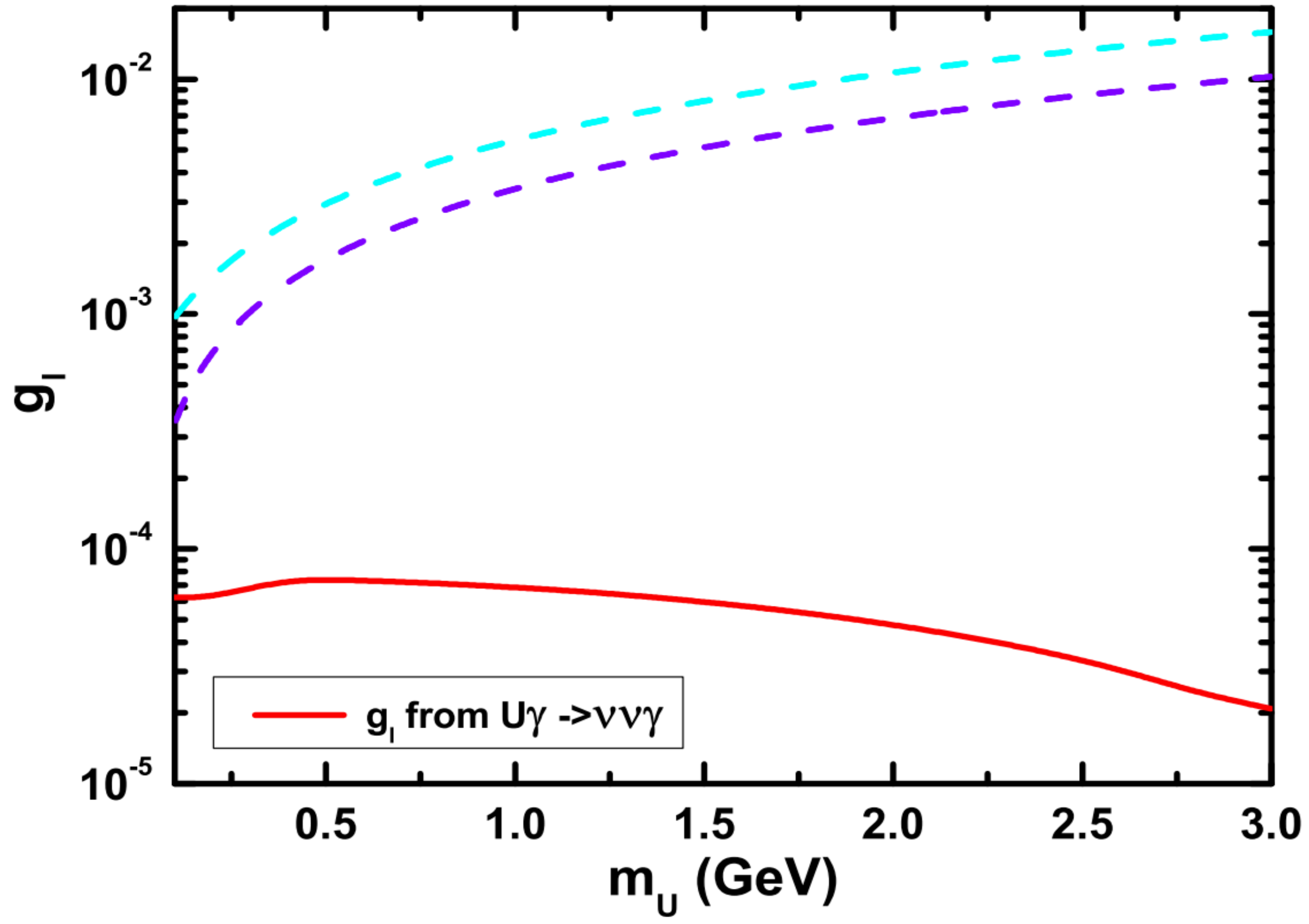
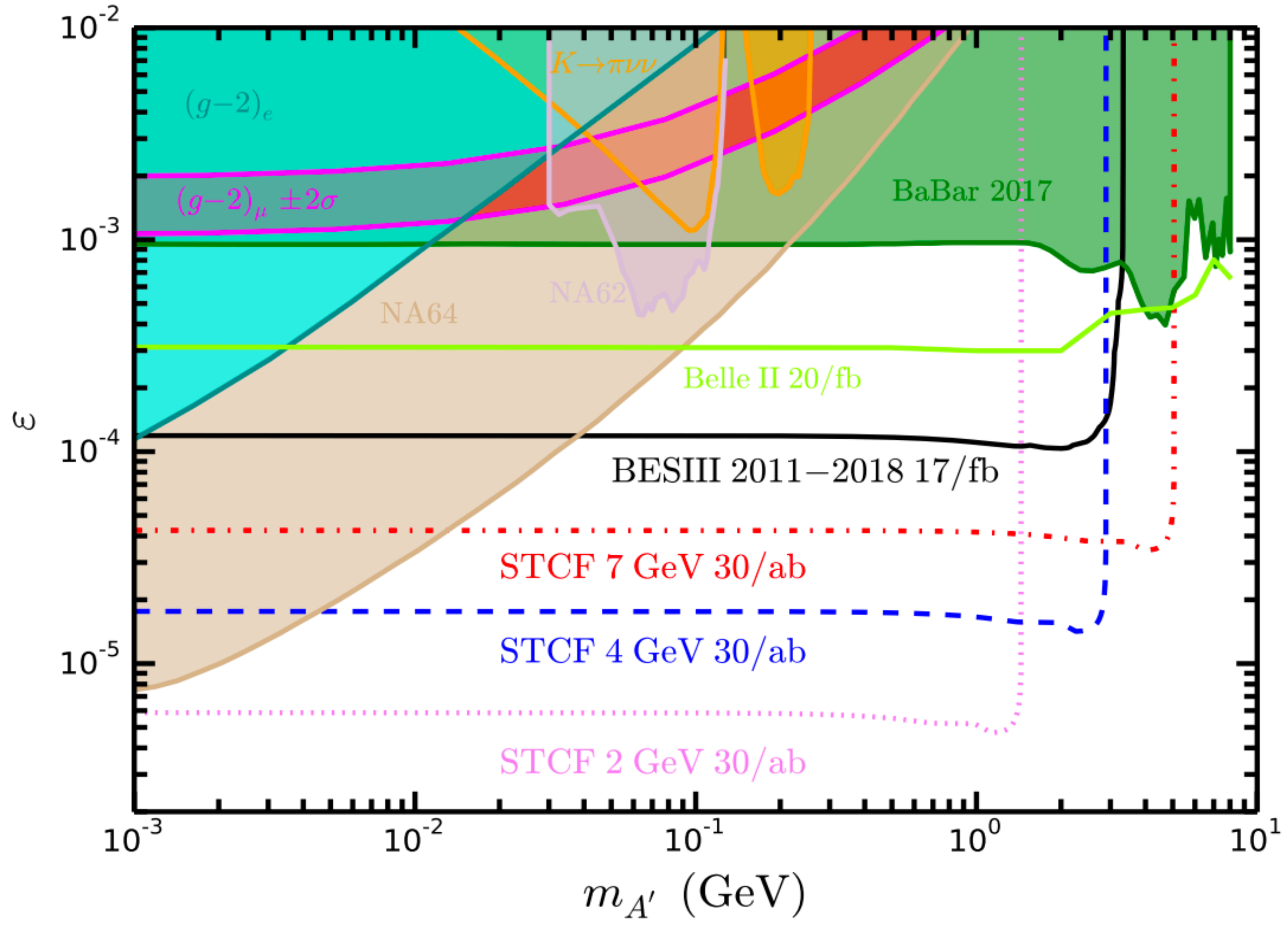
  - Looking for mediator X is easier than DM

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

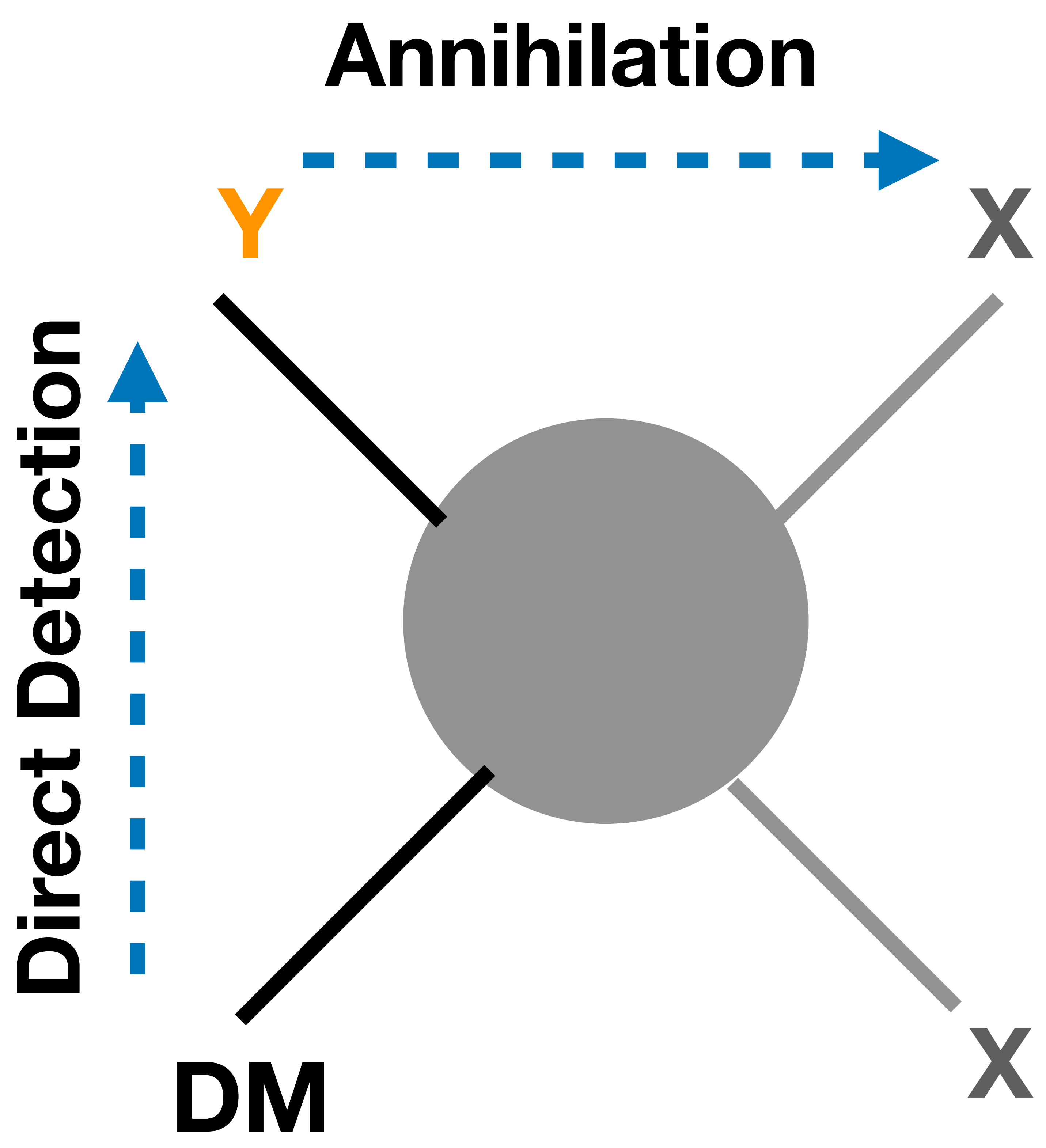
Case for Fermionic DM

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	$q^2 v^{\perp 2}$ (SM)	No
	F2	$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
	F3	$\bar{X}X\bar{q}\gamma^5 q$	0	q^2 (SM)	No
Pseudoscalar	F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	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	$q^2 v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
Anapole	F6	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
	F7	$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
	F8	$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (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) $q^2 v^{\perp 2}$ (SM)	1	Yes
	F10	$\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu} q$ (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



$m_{\mathrm{DM}} \lesssim m_Y$

- 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

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

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

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

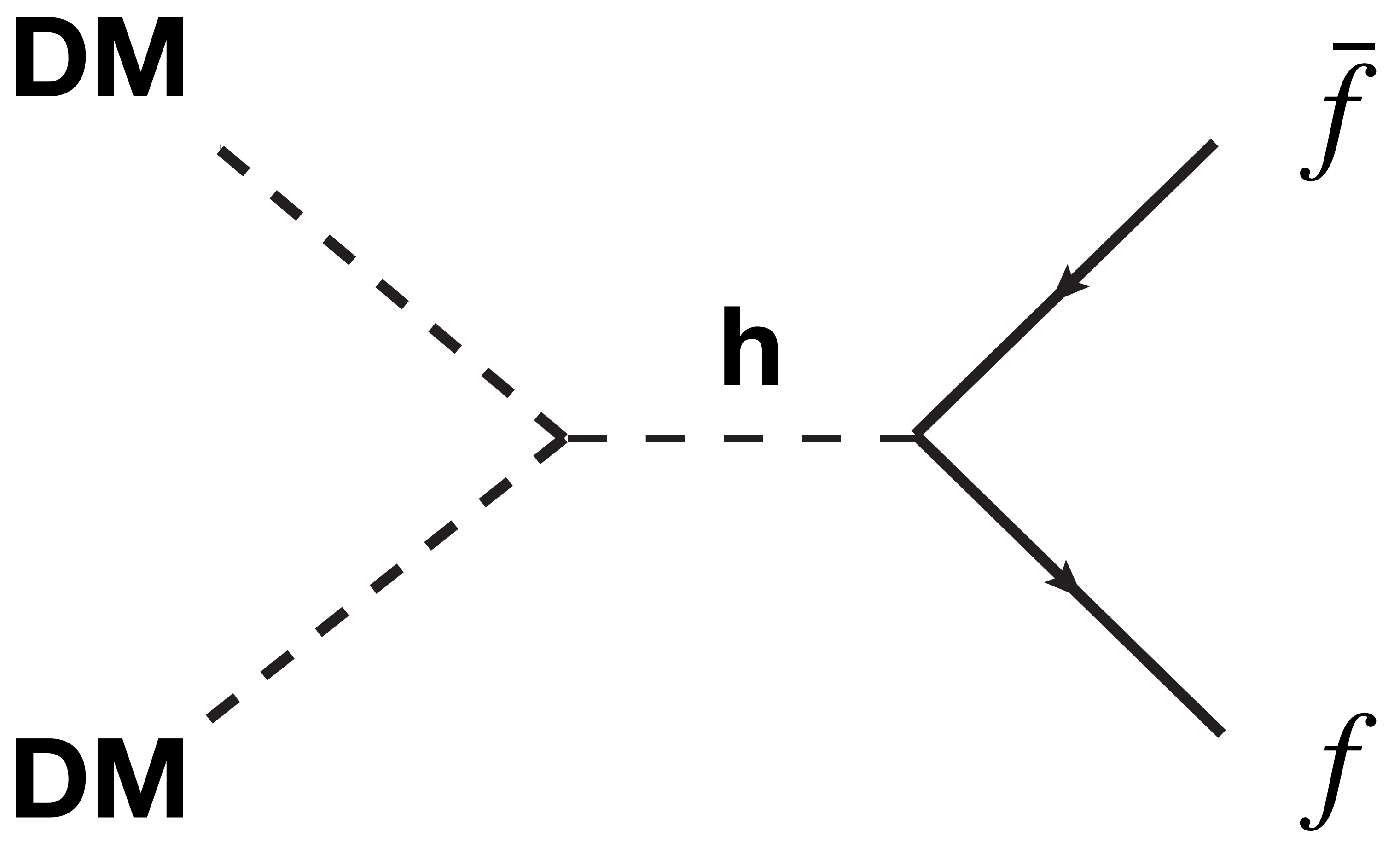
Smith, Weiner: hep-ph/0101138 (PRD)

The way-out from direct detection limits

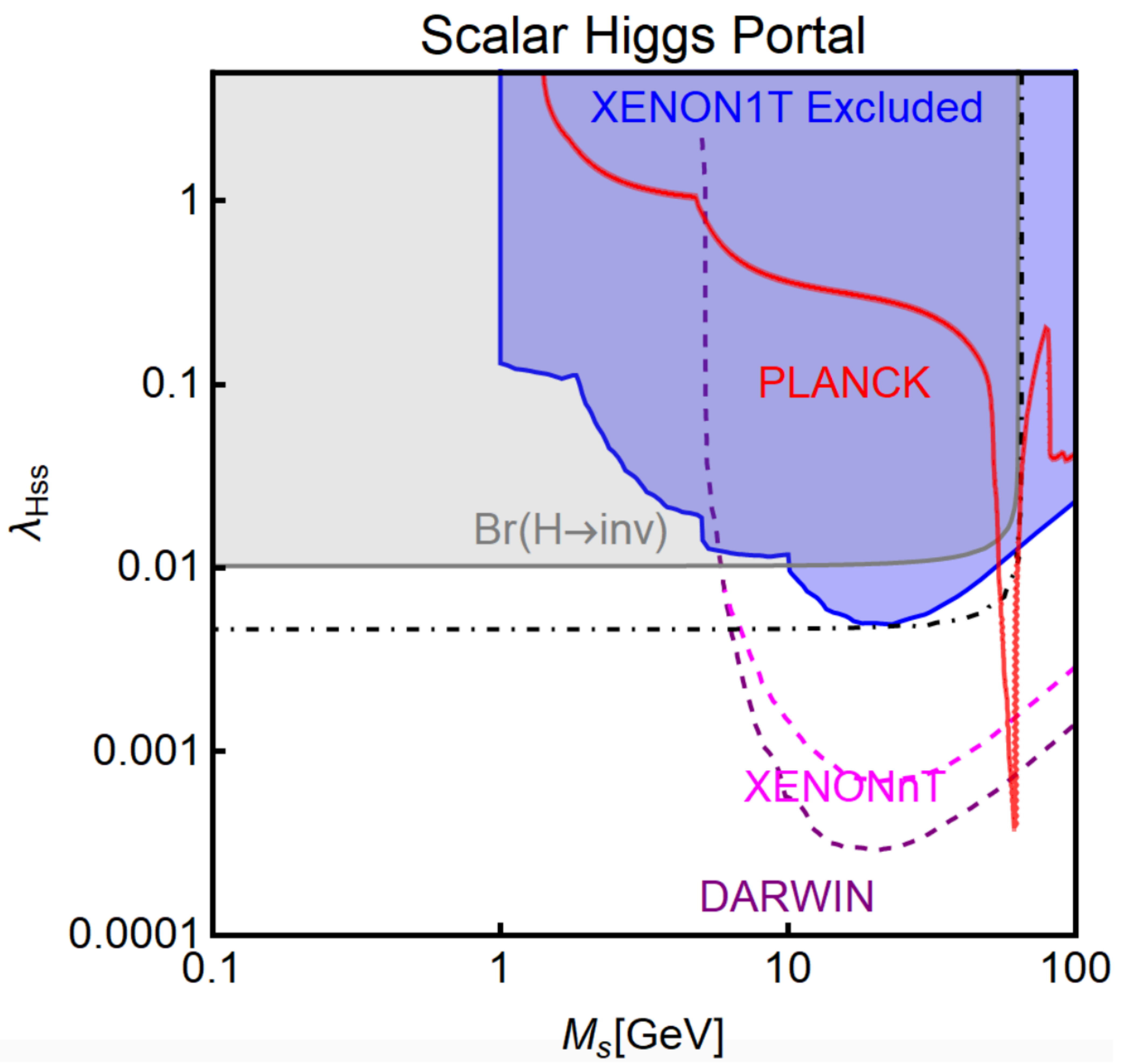
- 4. Resonant annihilation
  - $2m_{\rm DM} \approx m_X$

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

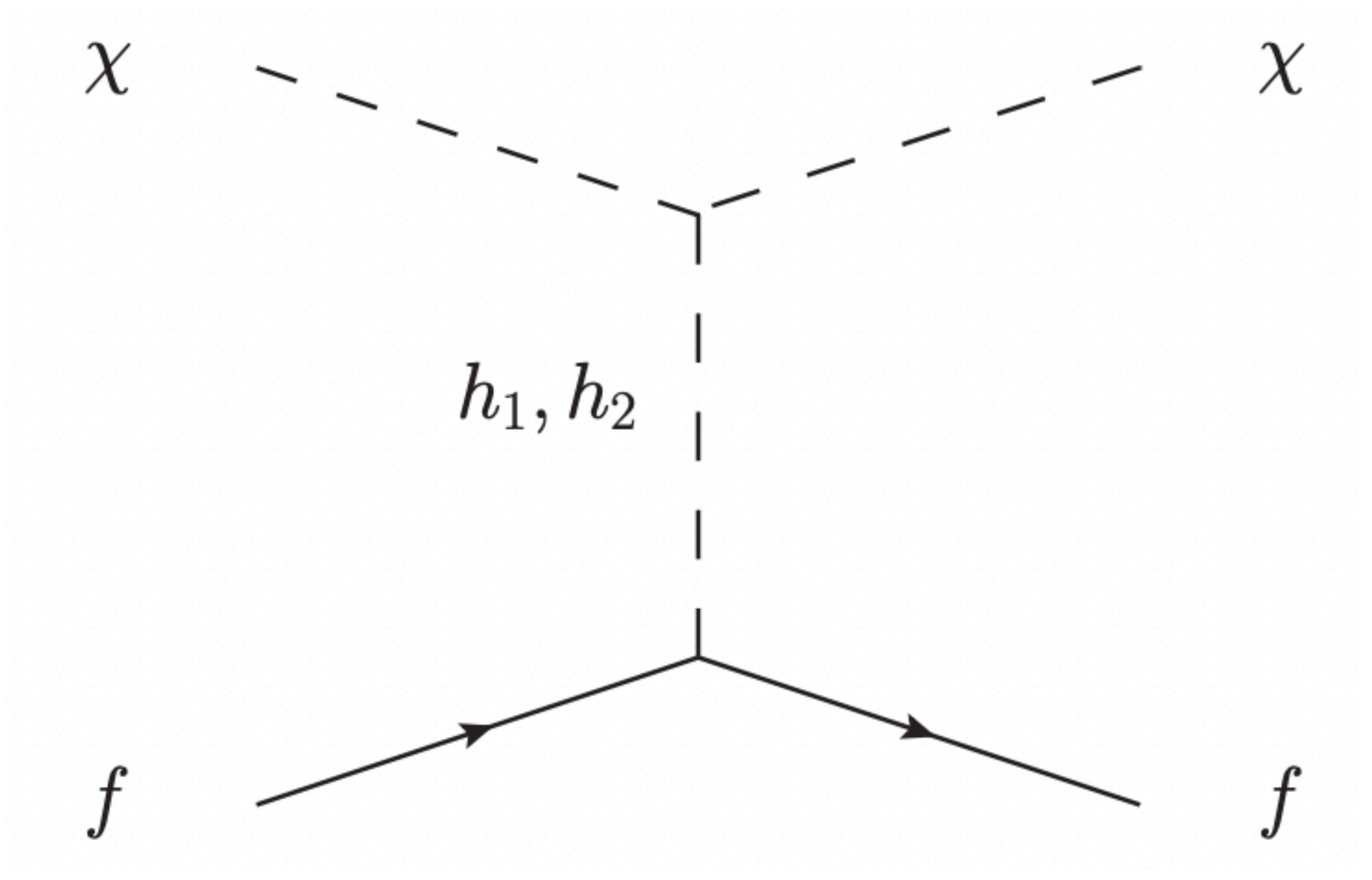
  - SM Higgs - Dark scalar mediator cancellation

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) $\rightarrow (h_1,\ h_2)$

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

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

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

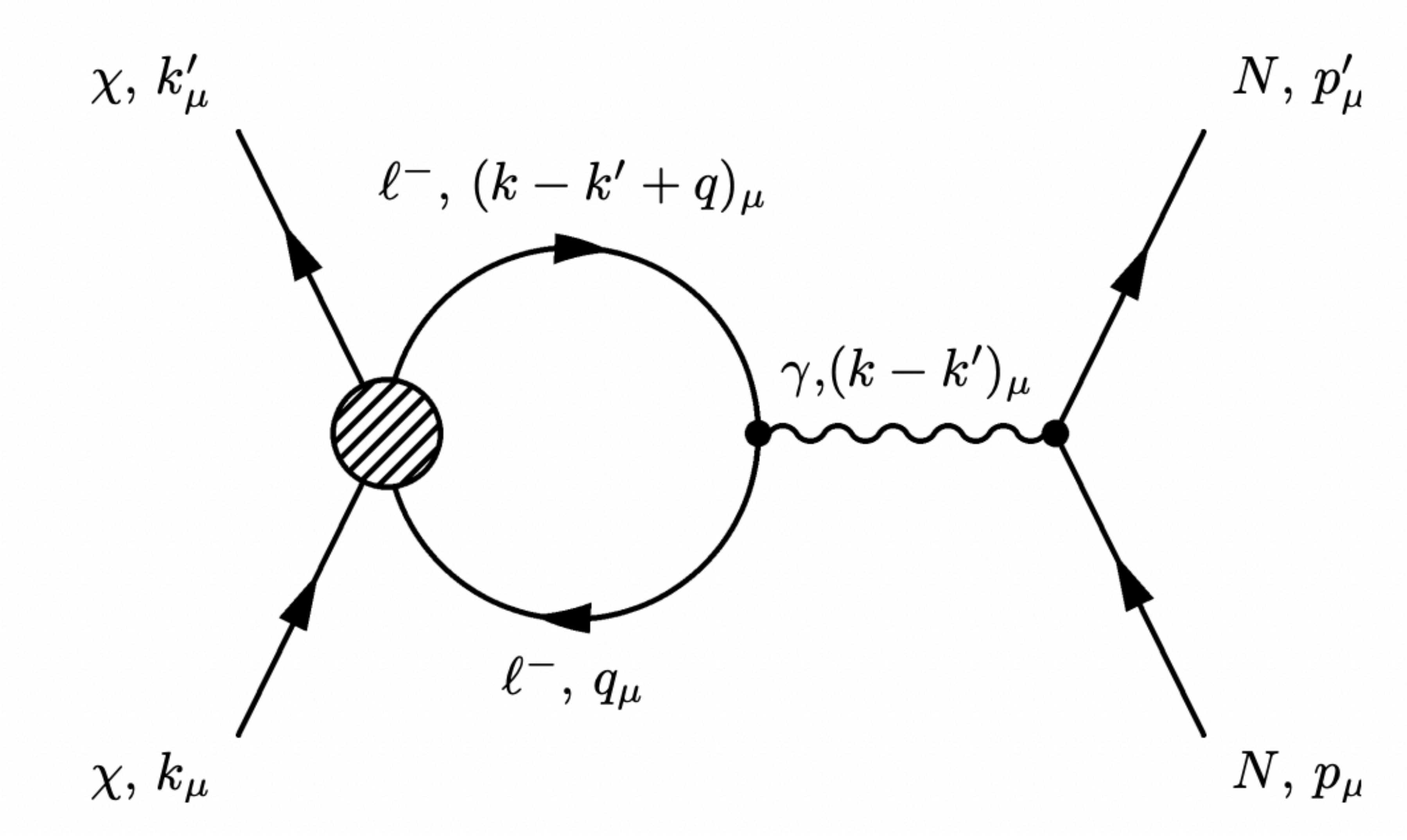
See JL, XP Wang and F Yu 1704.00730 (JHEP), for cancellation between A' - Z boson in kinetic mixing dark photon model

刘佳

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)

Outlines

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  - 可能的暗物质候选模型
    - 原初黑洞
    - 超轻波动型暗物质
    - WIMP暗物质
- WIMP暗物质
  - WIMP暗物质的直接探测危机
    - 解决危机的多种办法
  - 暗物质对撞机探测的互补性
  - 暗物质的间接探测限制
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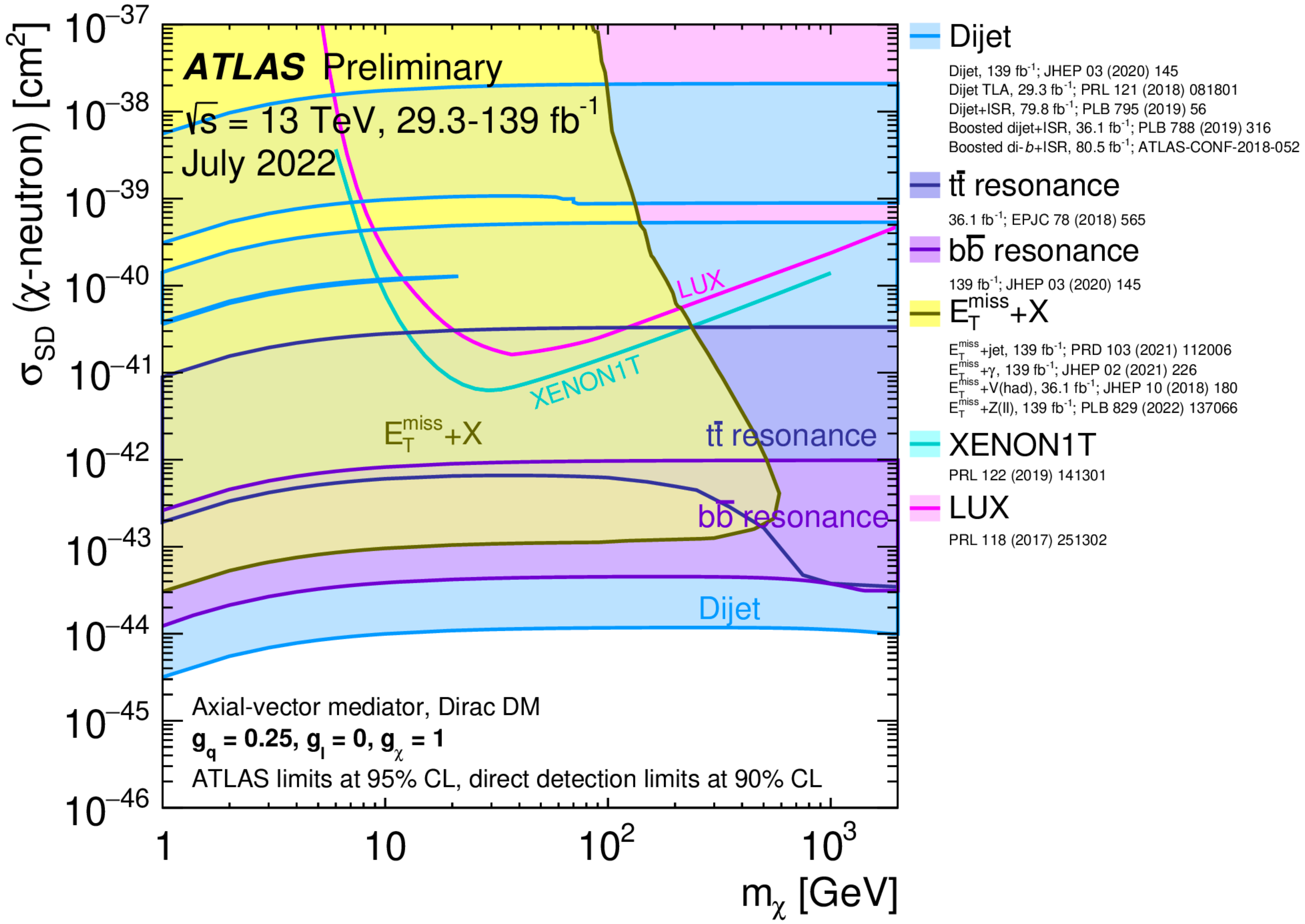
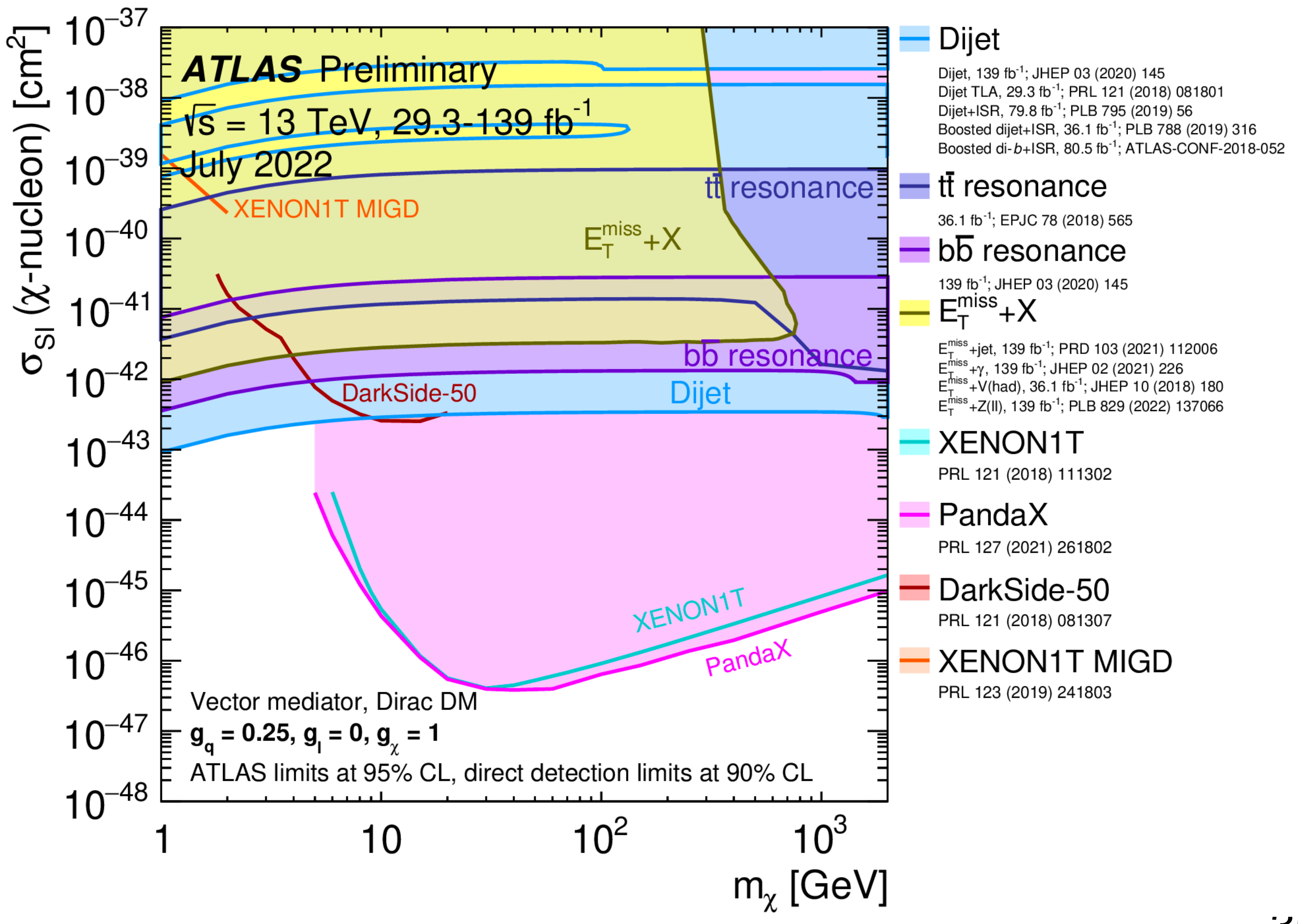
- 总结

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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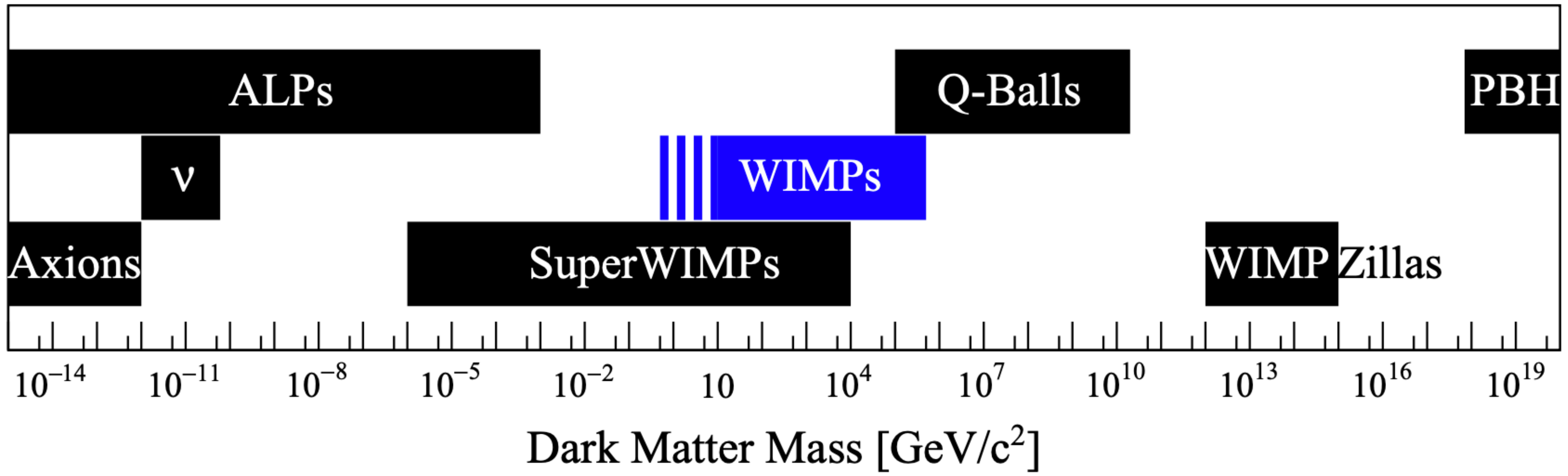
The indirect detection limits from DM annihilation



- DM starts with thermal distribution
- DM has electroweak-scale coupling
- 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 entropy of DM goes into SM sector most of the time!
(Secluded X → SM + SM)

Lower mass bound for thermal DM

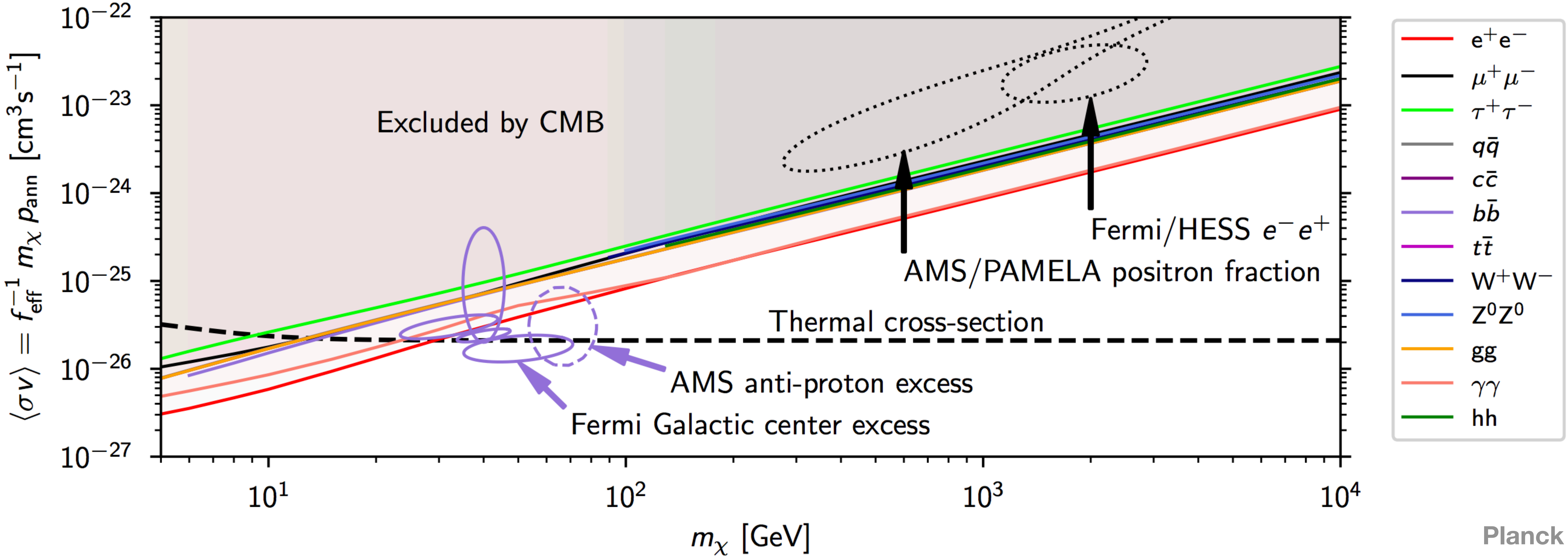
- Lower bound from N_{eff} at CMB
  - Light DM freeze-out after neutrino decoupling at $T_D \approx 2.3$ MeV
  - Normally $T_{fo} \sim m_{\rm DM}/20$
  - DM entropy goes into neutrinos or e/γ, will modify T_ν/T_γ
  - DM mass $\gtrsim 5$ MeV, depending on d.o.f.

Annihilation constraints from CMB

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

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

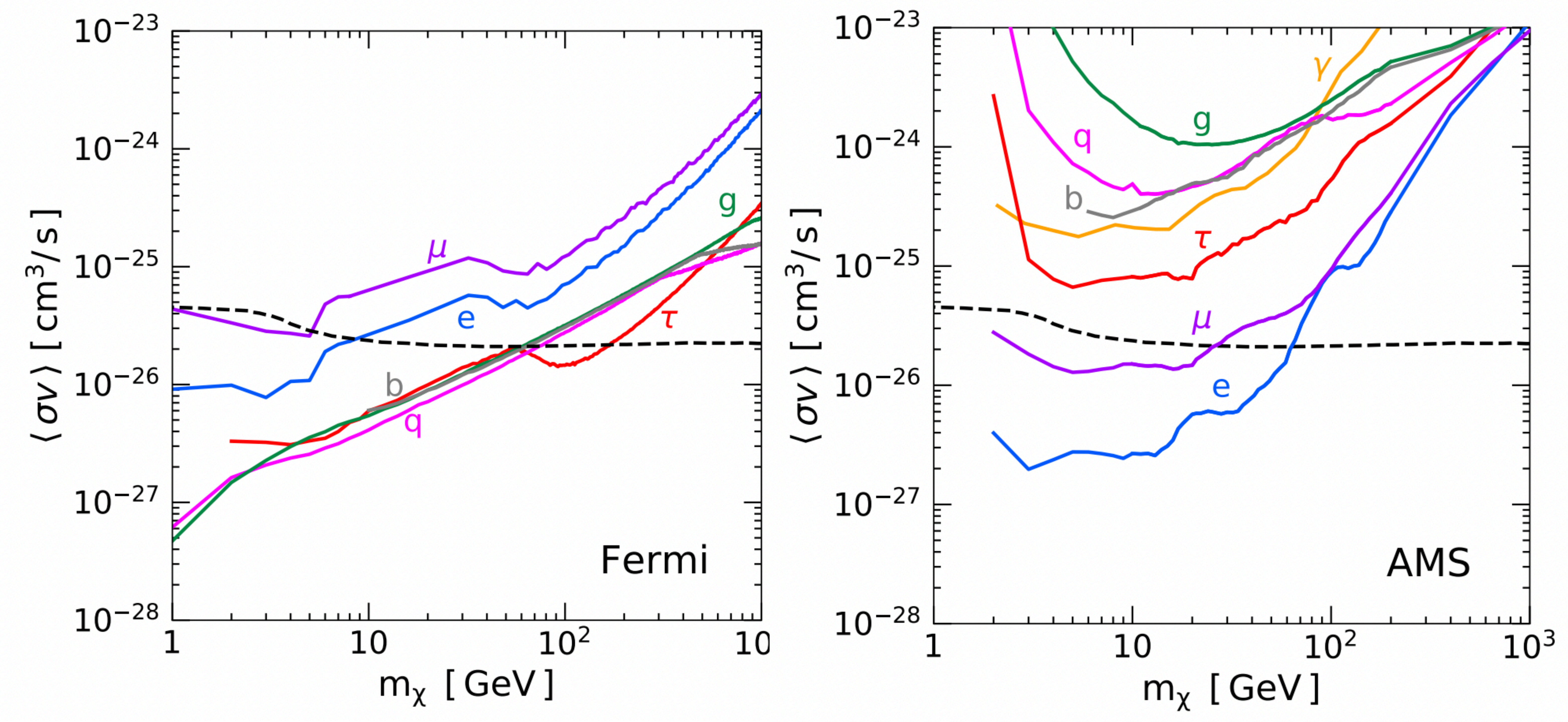
- $f_{\rm eff}$: the efficiency with which the energy released in DM annihilation is absorbed by the primordial plasma



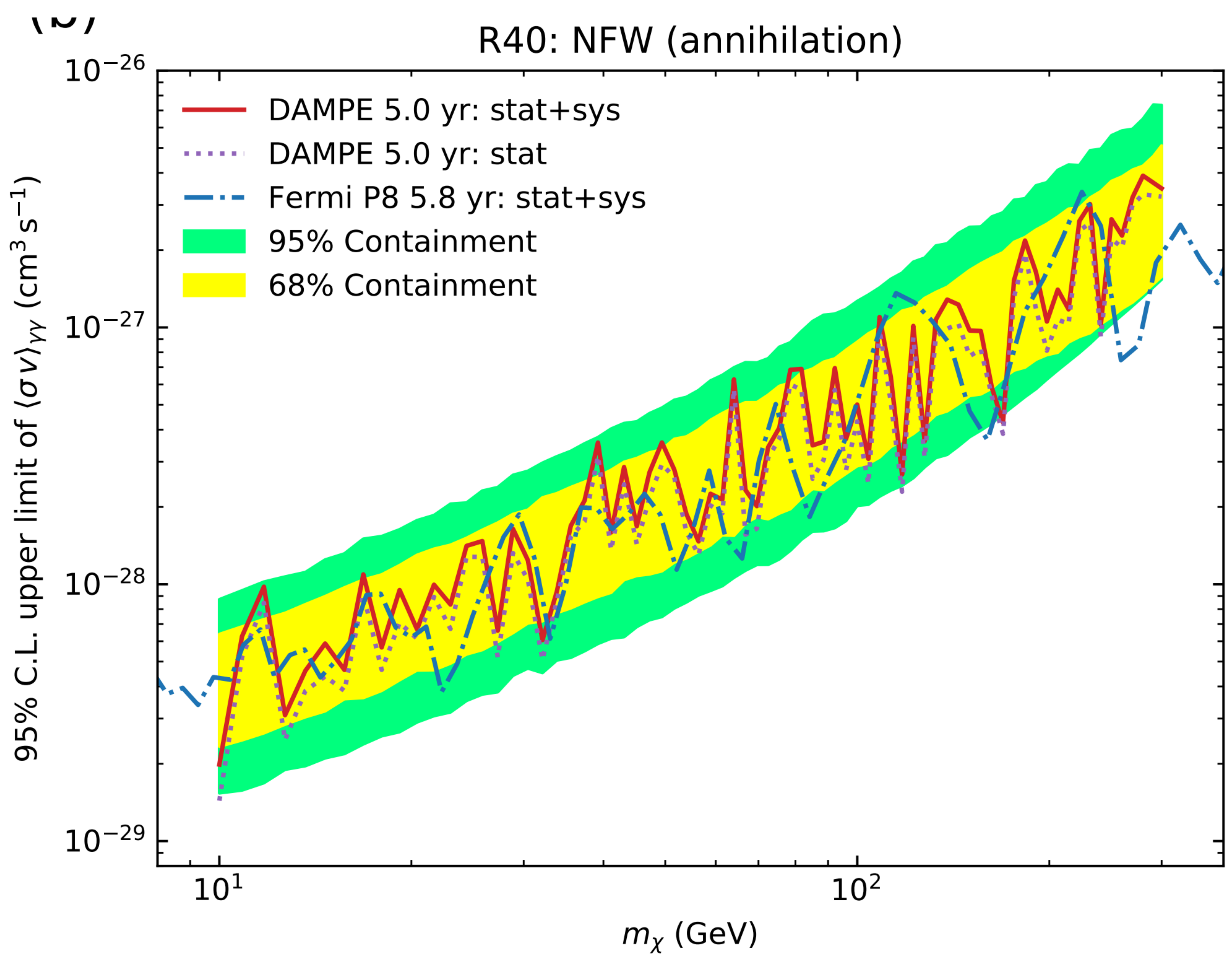
Planck 2018

卫星间接探测实验限制

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



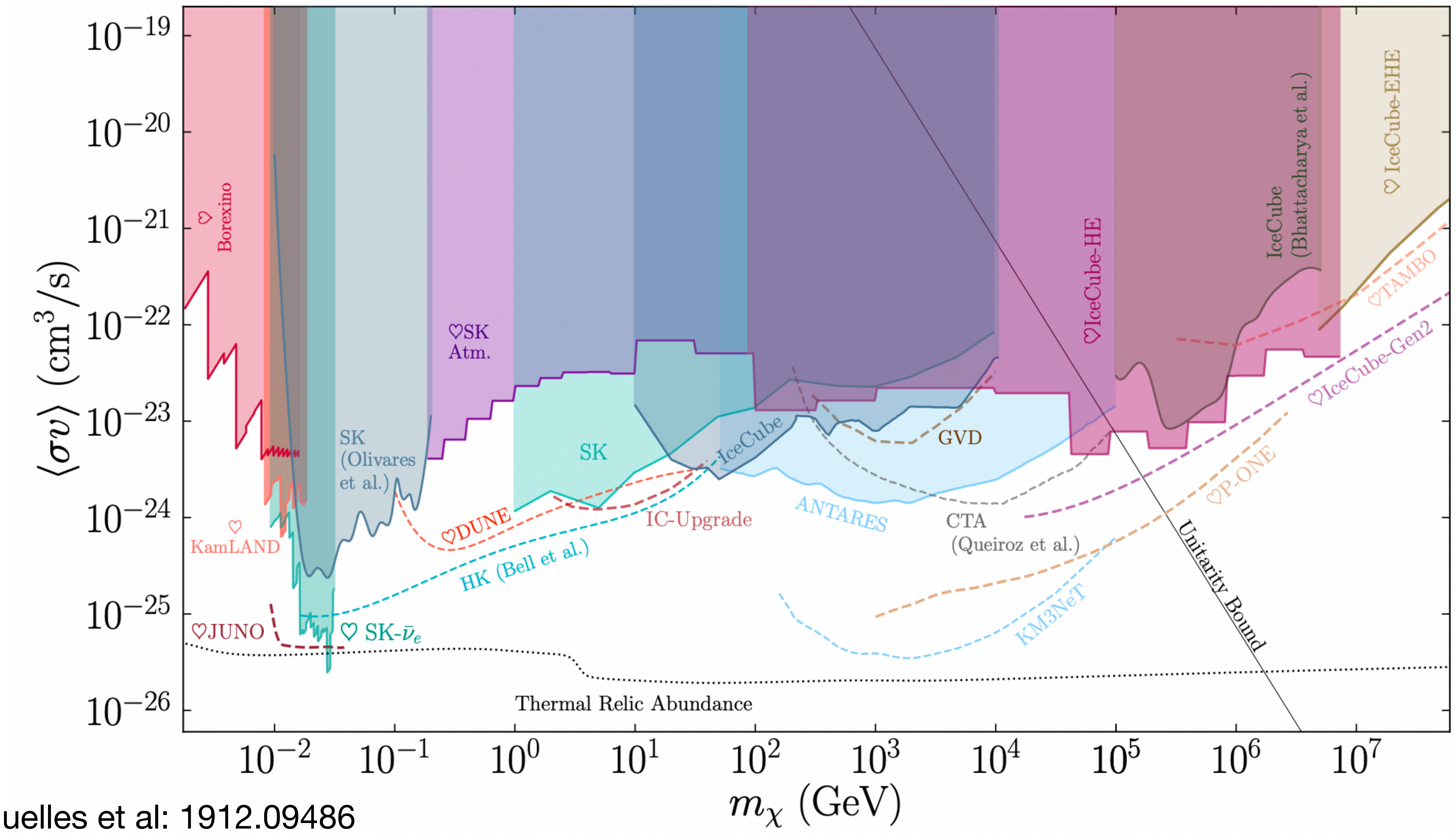
Leane et al: 1805.10305 (PRD)



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: $v^2 \sim {\rm eV}/m_{\rm DM} \sim 10^{-5}$
  - Today: $v \sim 10^{-3} c$

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

Summary

- 暗物质是粒子物理急需解决的重大问题，它有很多候选者模型
  - 超轻波动型暗物质是以经典场形式存在的低质量玻色子暗物质
    - 粒子类型、物理动机、探测方式、多学科交叉
  - WIMP暗物质是电弱能标的具有极强竞争力的模型
    - 直接探测限制使得人们非常焦虑，开始思考其它的暗物质模型
      - （模型依赖）多种方式避免直接探测限制
    - 对撞机探测+直接探测互补性强：LHC未来15年数据+搜寻至中微子地板
    - 间接探测限制，需要暗物质质量 $\gtrsim \mathcal{O}(10)$ GeV
      - 低质量暗物质避免限制：p波湮灭截面、湮灭产物不参与电磁相互作用
    - WIMP暗物质模型的变种：早期宇宙瞬时共振湮灭
  - WIMP暗物质依然存活

Thank you!

Backup slides

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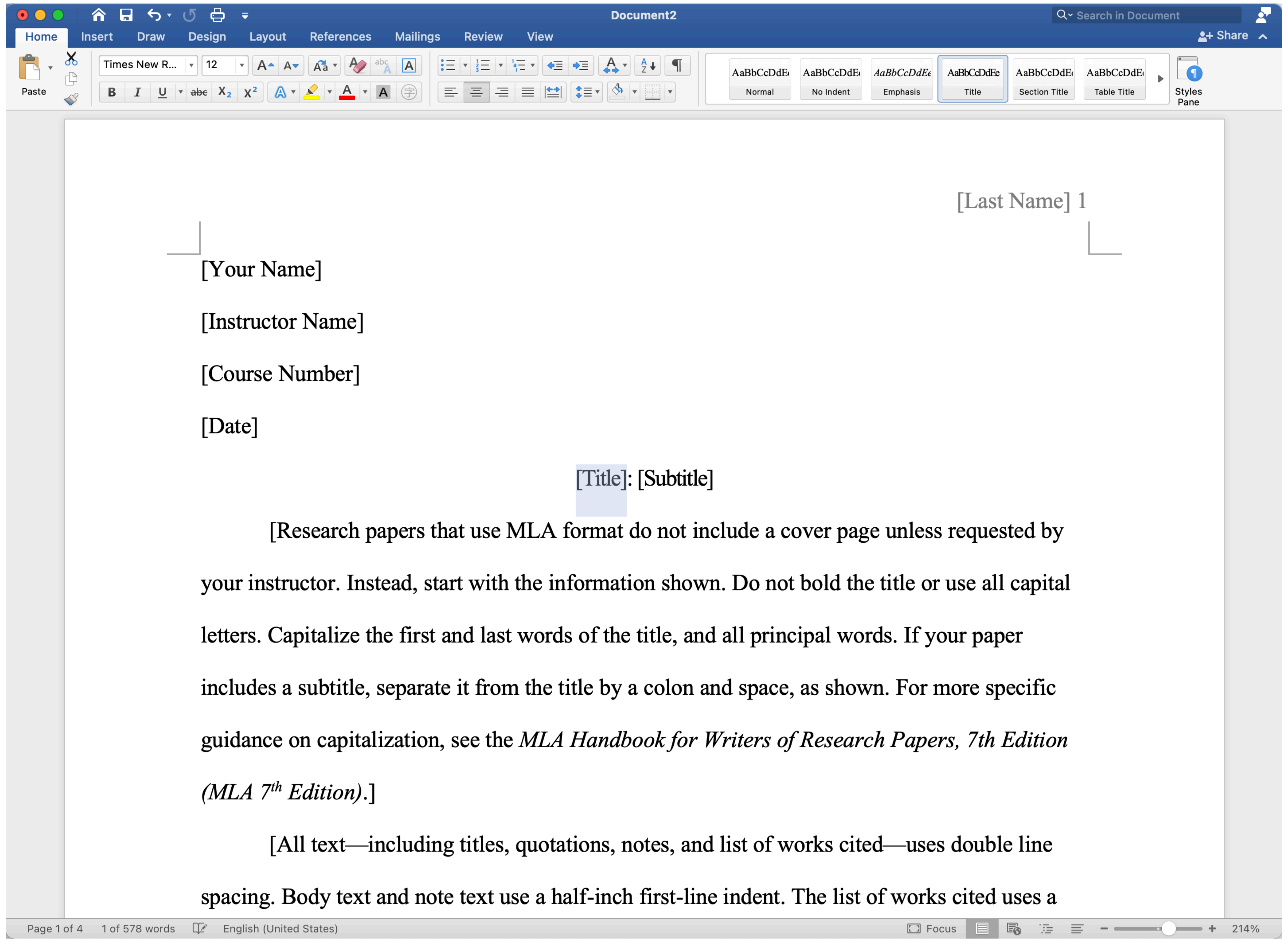
DM properties and cosmological evolution

- 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 等办公软件符合"所见即所得"
WYSIWYG，"What You See Is What You Get"

Variant: transient annihilations

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

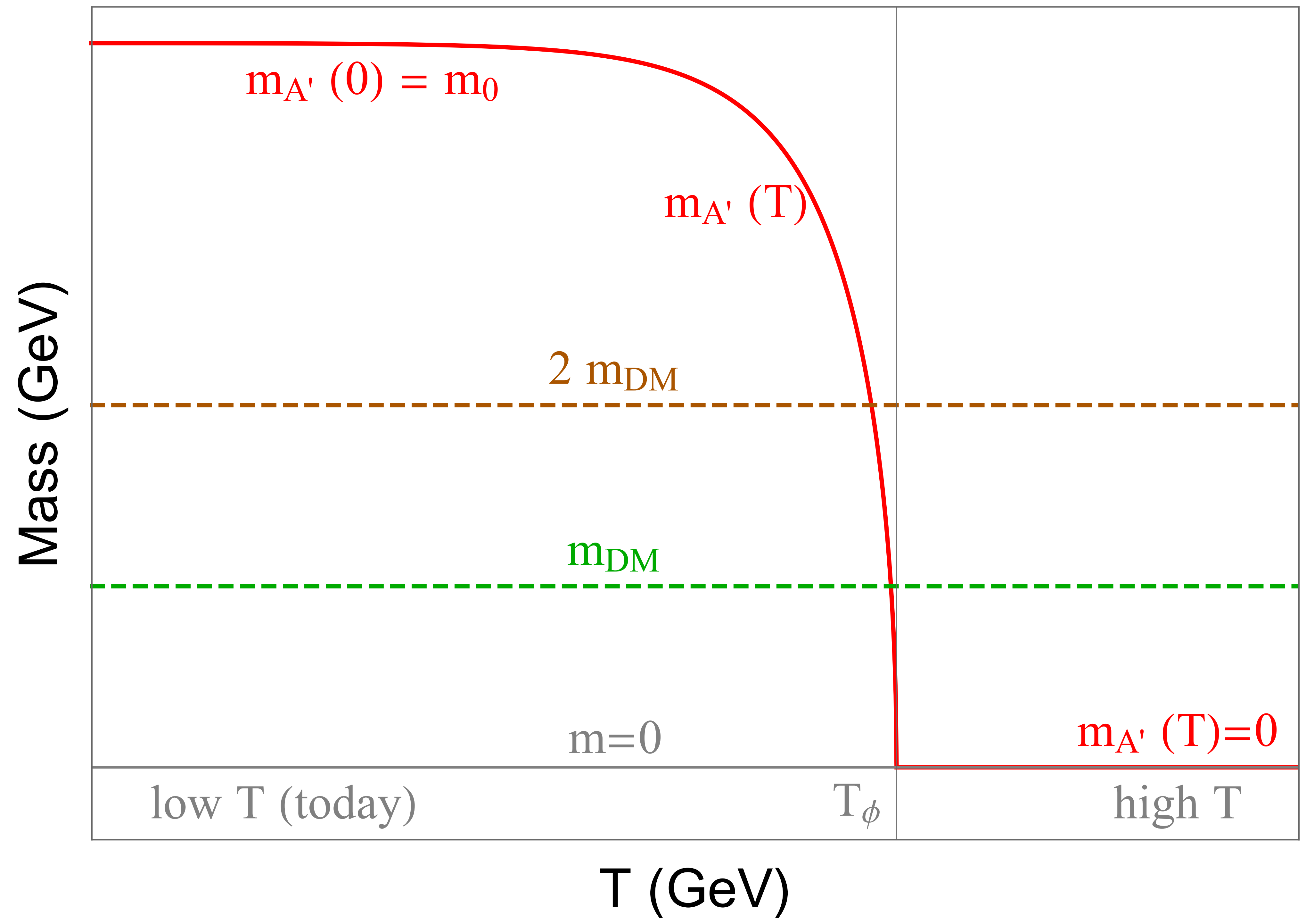
- If it is the DM-SM mediator, and the mass variation happens near DM freeze-out, what happens?

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

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

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

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



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

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

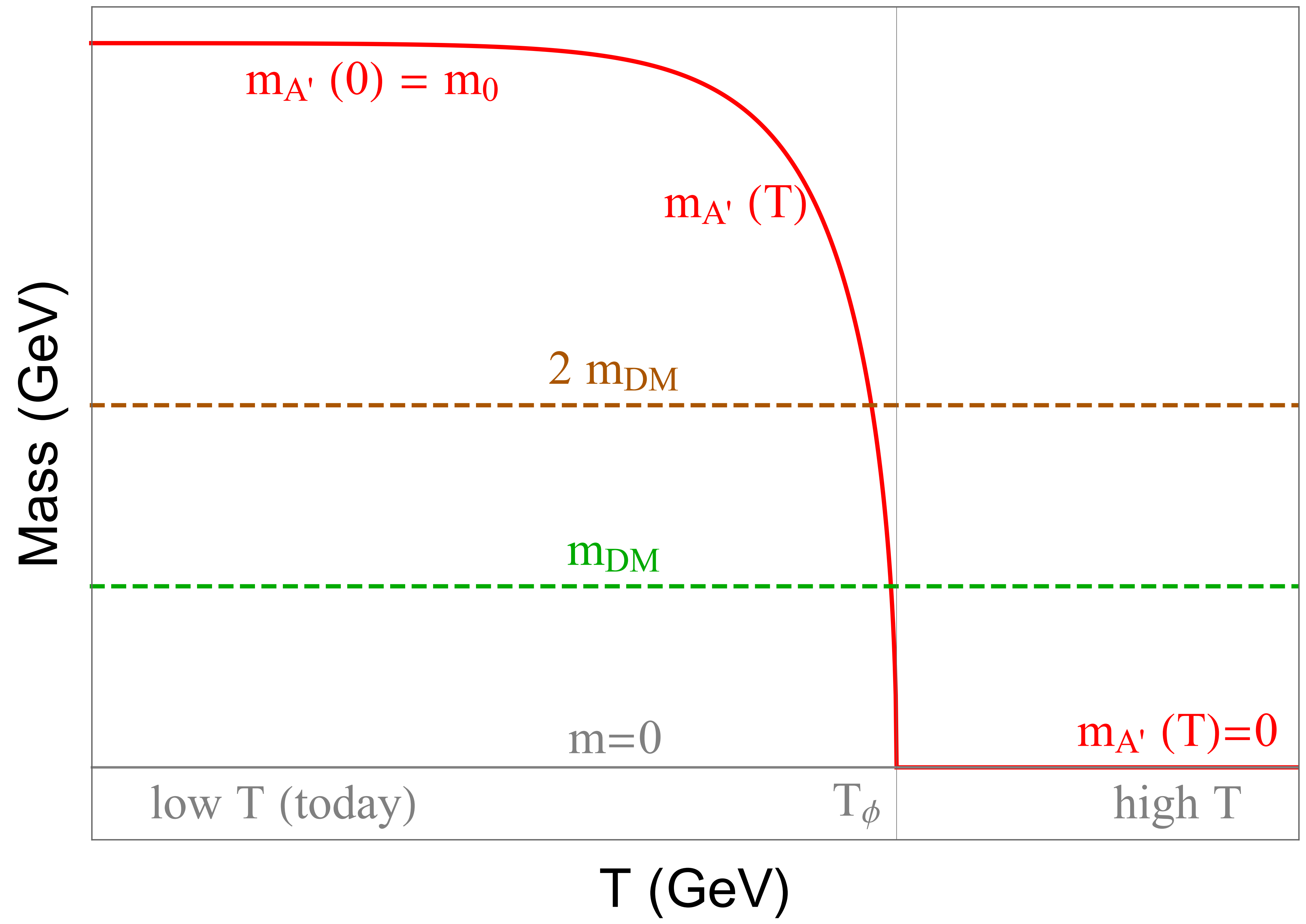
$$m^2_{A'}(T) = \begin{cases} 0 & T > T_\phi, \\ m^2_{A',0} - \kappa m^2_\psi \left(\frac{T}{m_\psi}\right)^n & T < T_\phi \end{cases}$$

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



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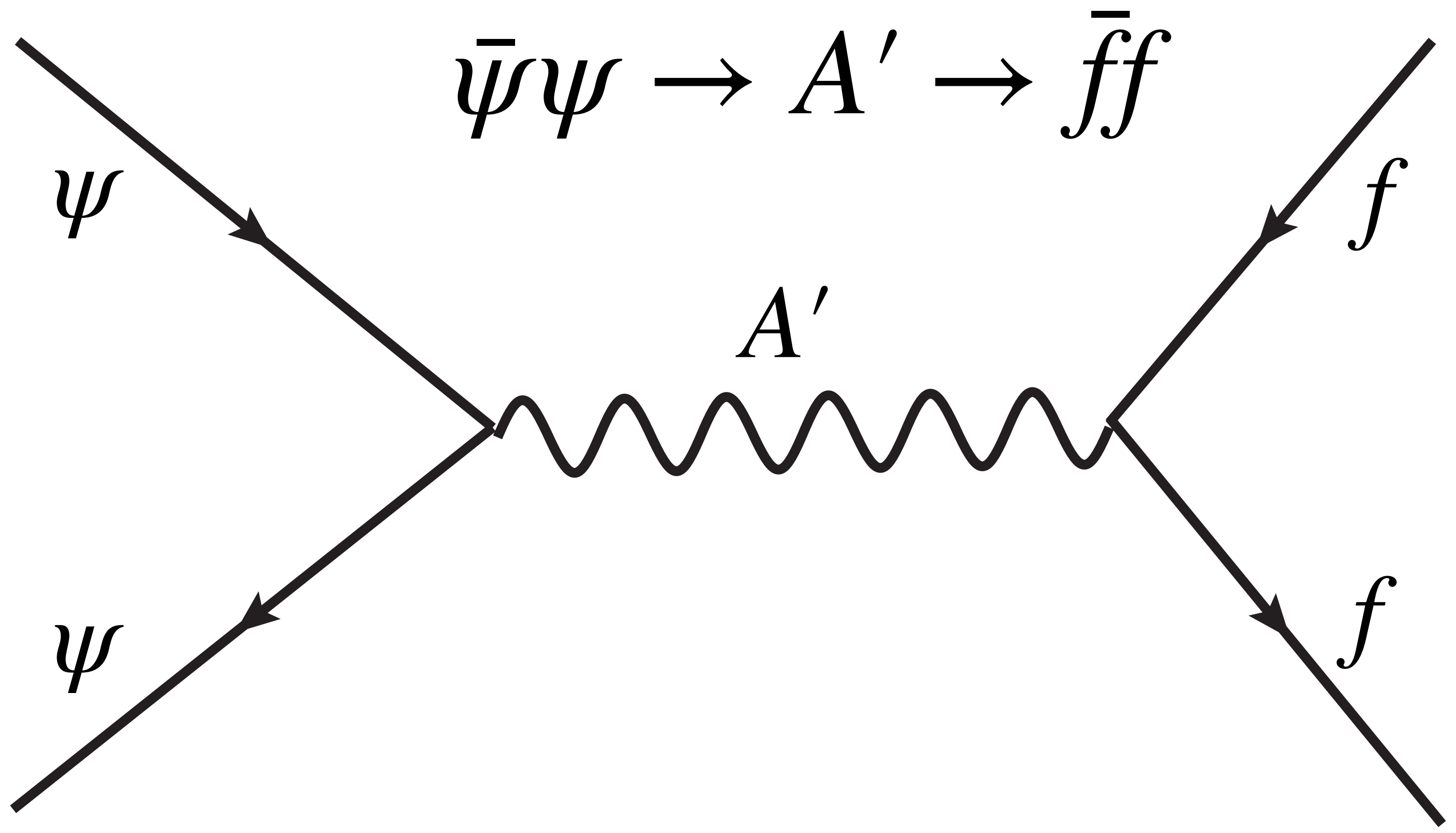
Transient resonant annihilation

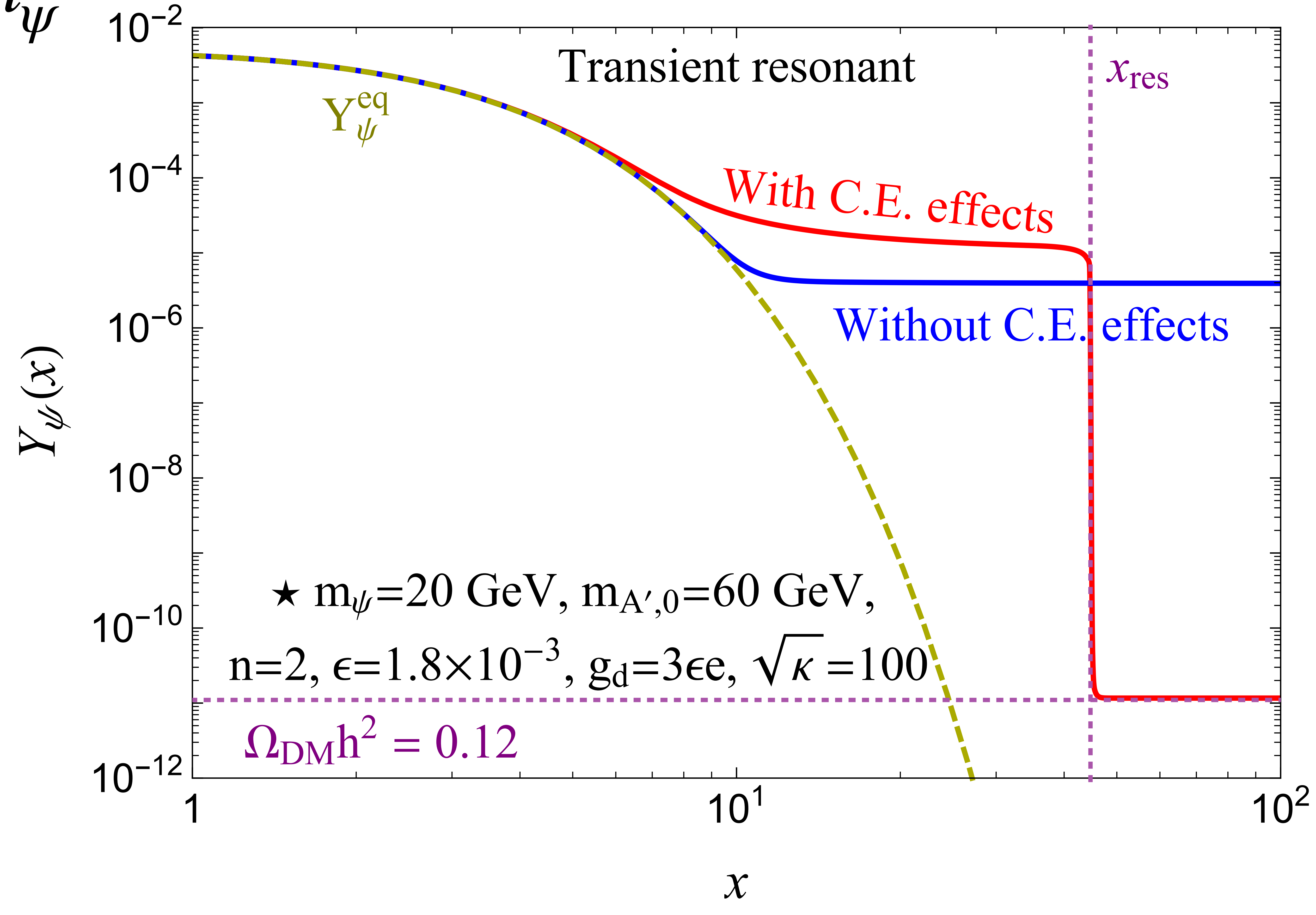


$\bar{\psi}\psi \to \bar{f}f$

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

- 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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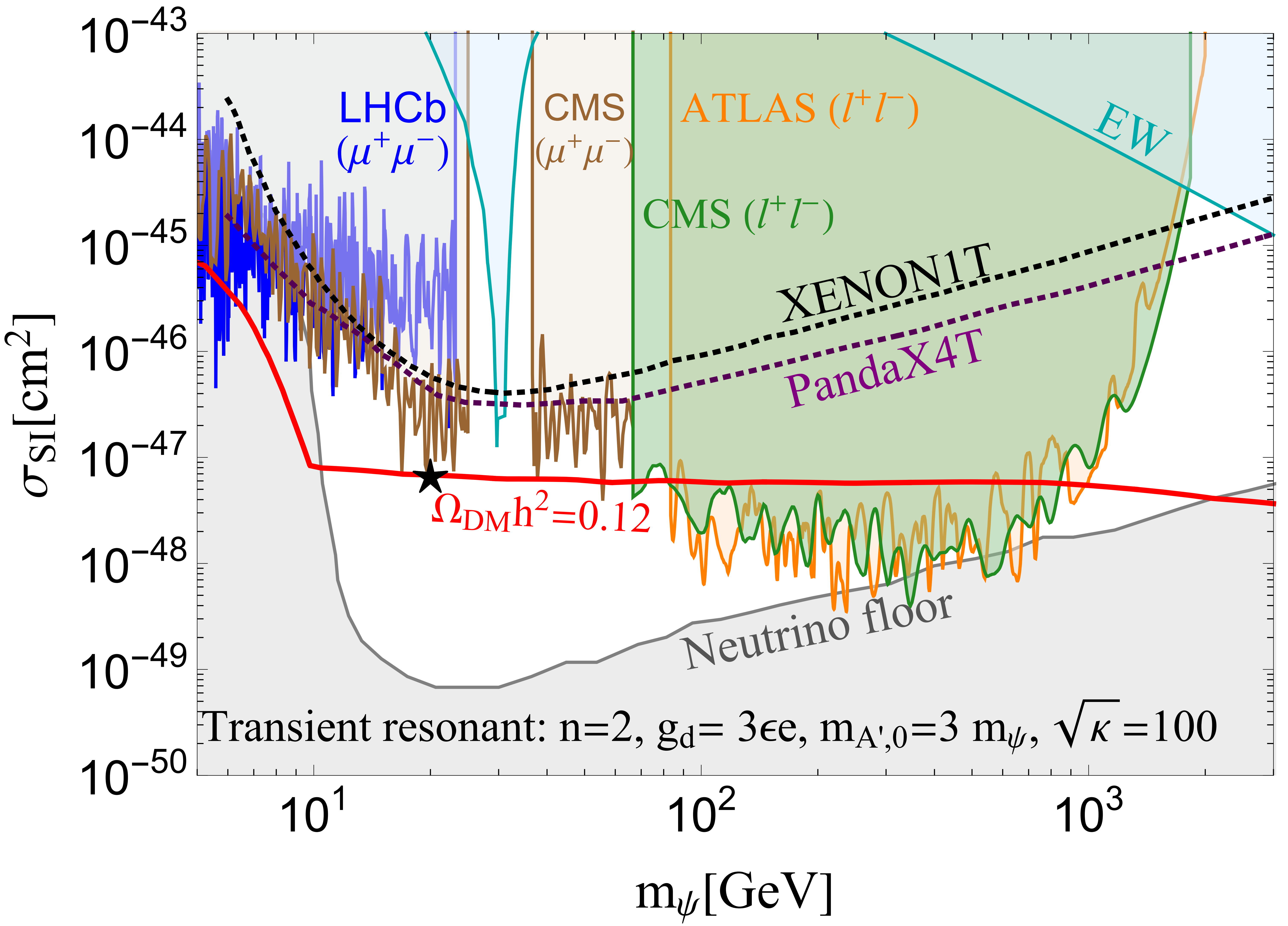
Transient resonant annihilation

- 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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