The WIMP dark matter paradigm and beyond

Jia Liu (刘佳)
Peking University

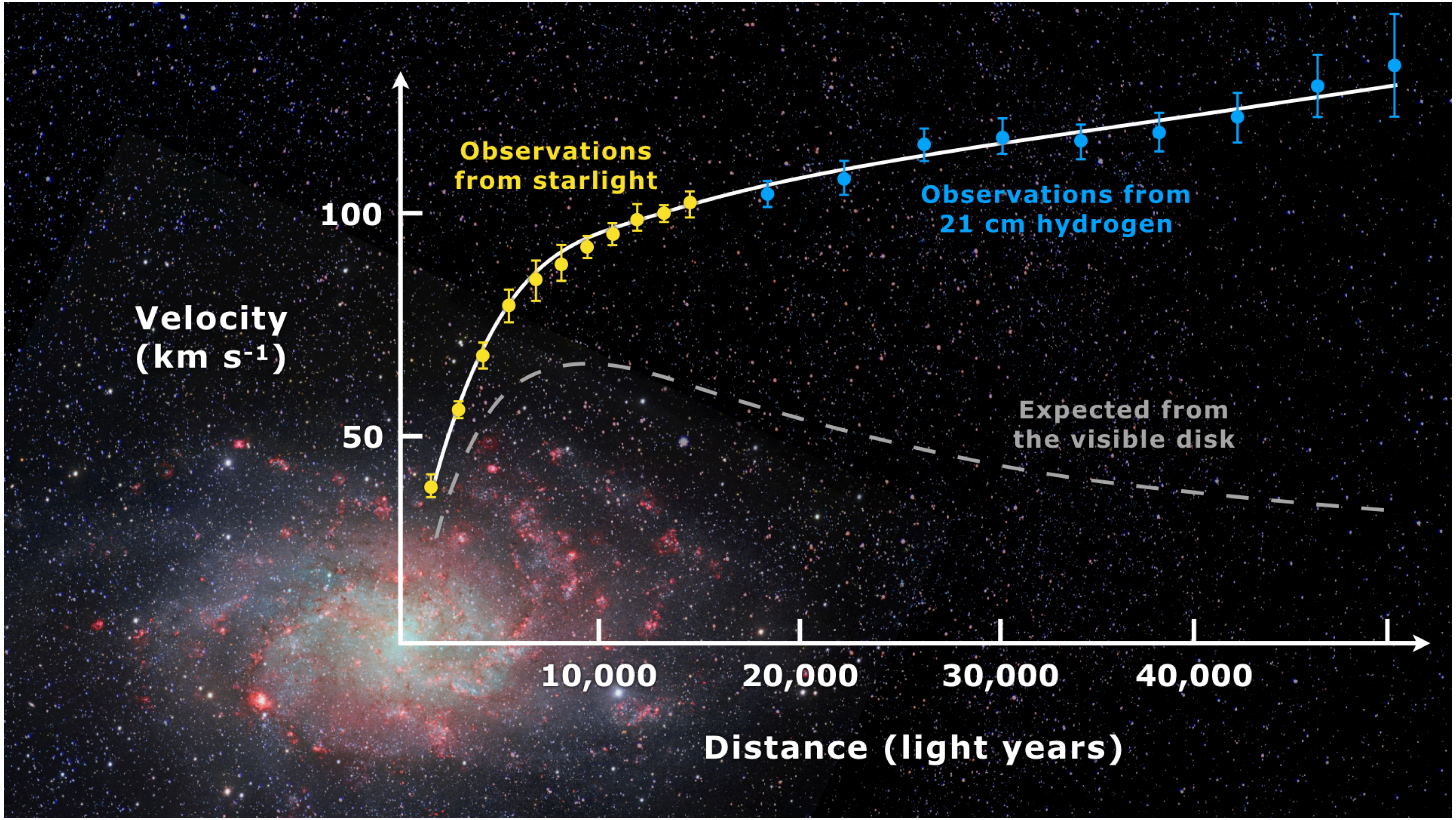
高能理论论坛 (High Energy THeory Forum)@IHEP
2021-10-19

Outlines

- The dark matter in astrophysics perspective
- The dark matter in particle physics perspective
  - The WIMP crisis from direct detection
  - The DM limits from indirect detection
  - A WIMP variant from cosmological evolution
- Summary

Observational evidence for DM

- Galaxy rotation curves
- Bullet cluster
- Gravitational Lensing
- Structure formation
- Cosmic Microwave Background



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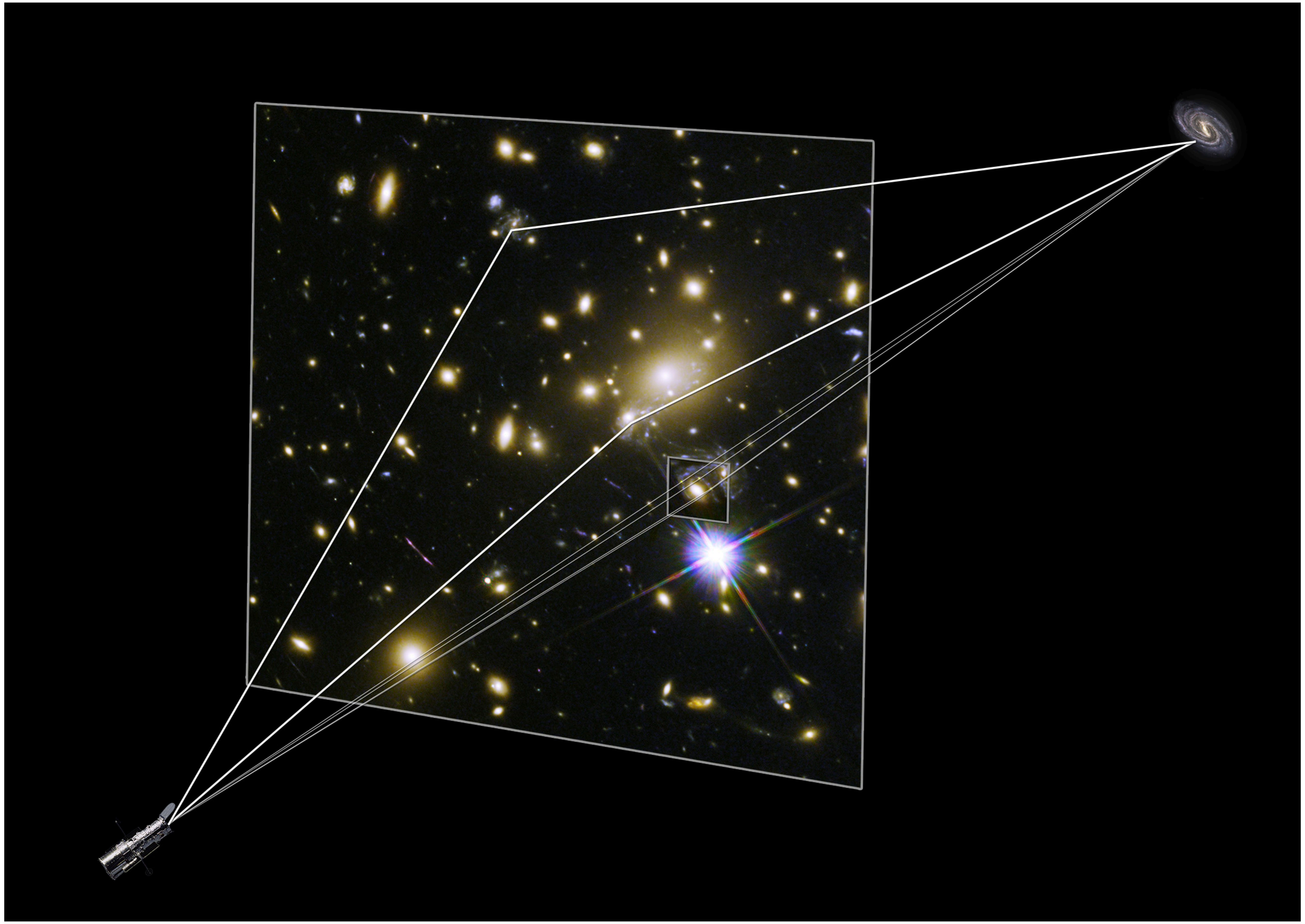

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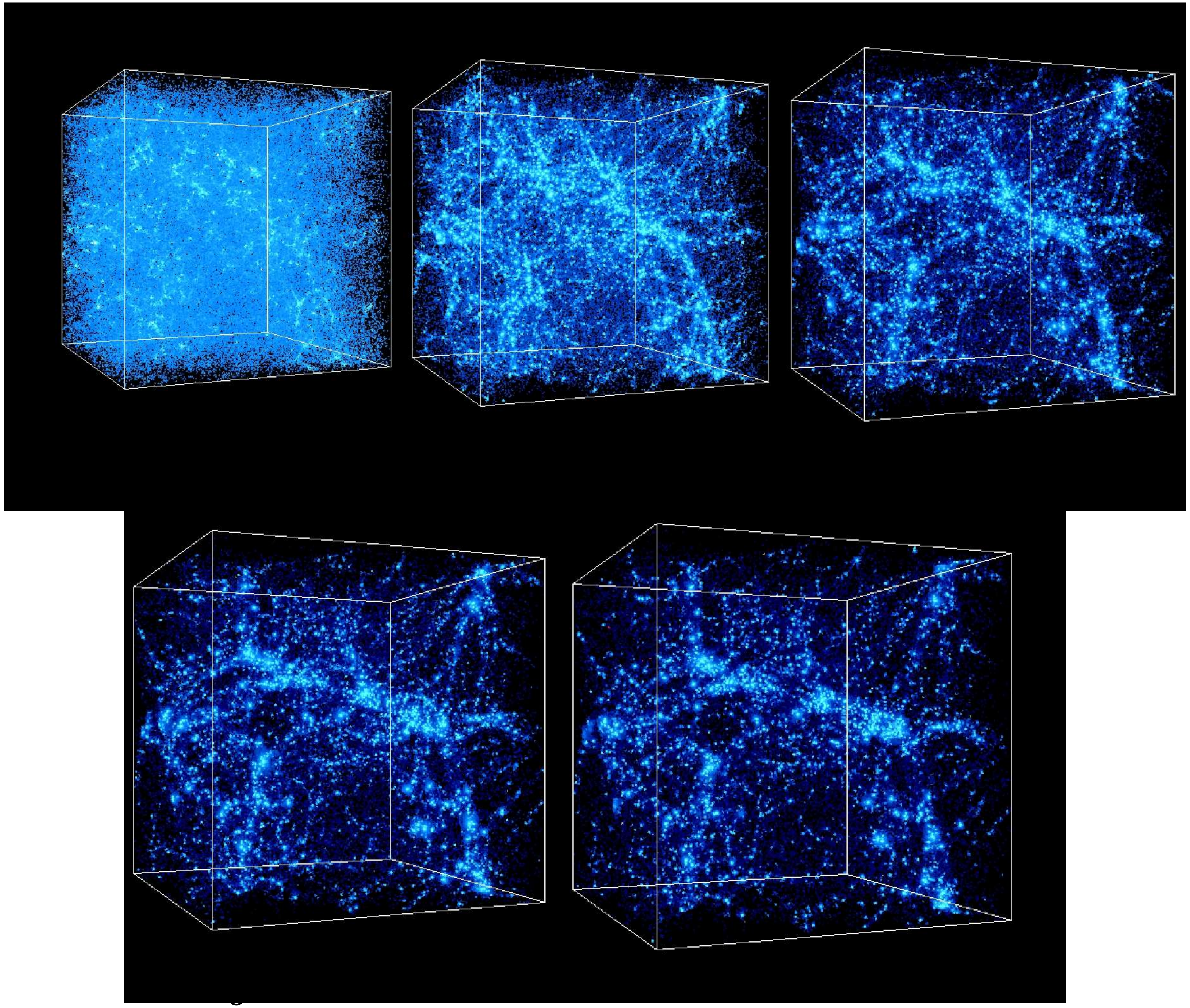

Observational evidence for DM

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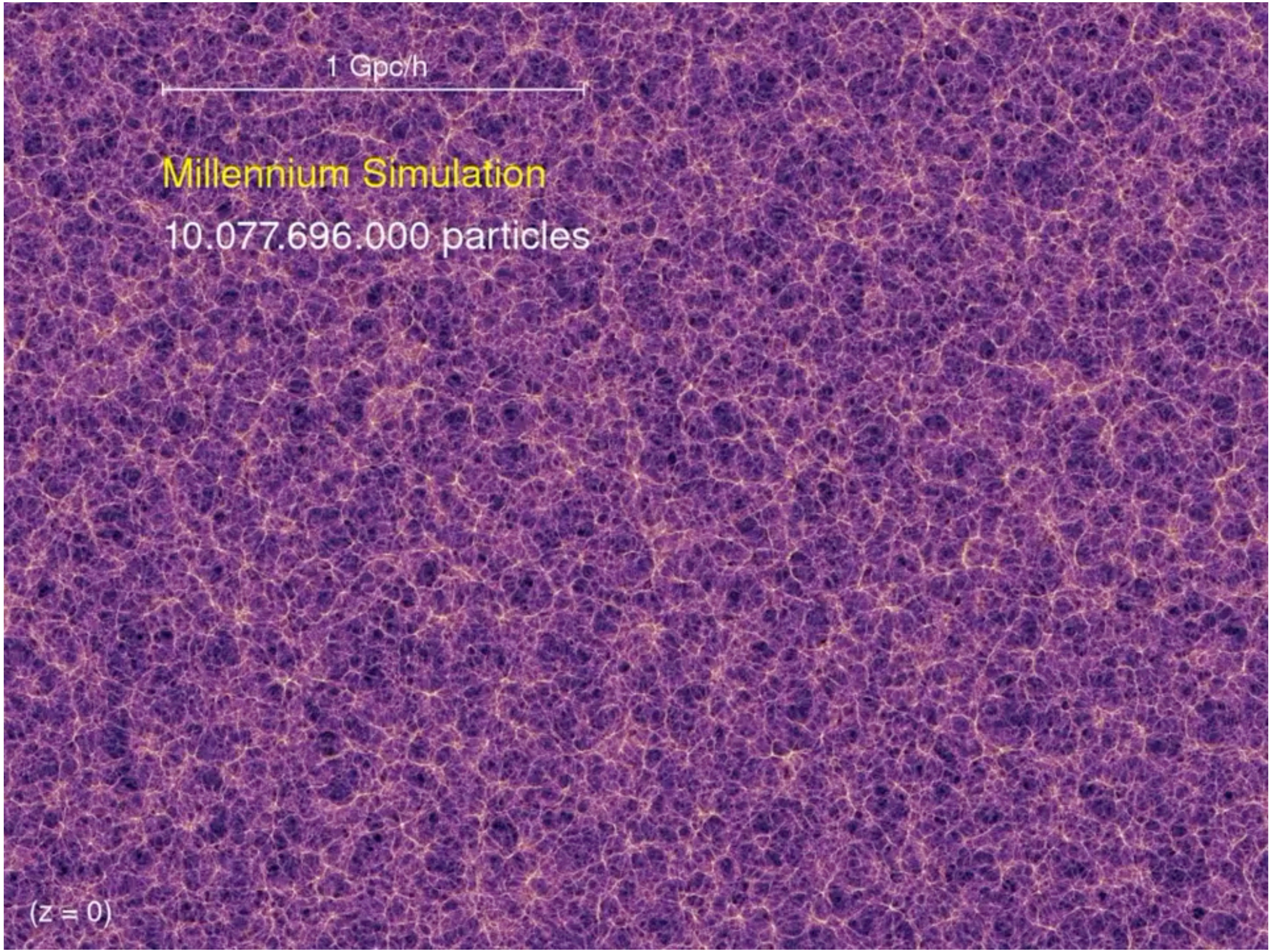
The *Millennium Run* used more than 10 billion particles to trace the evolution of the matter distribution in a cubic region of the Universe over 2 billion light-years on a side.



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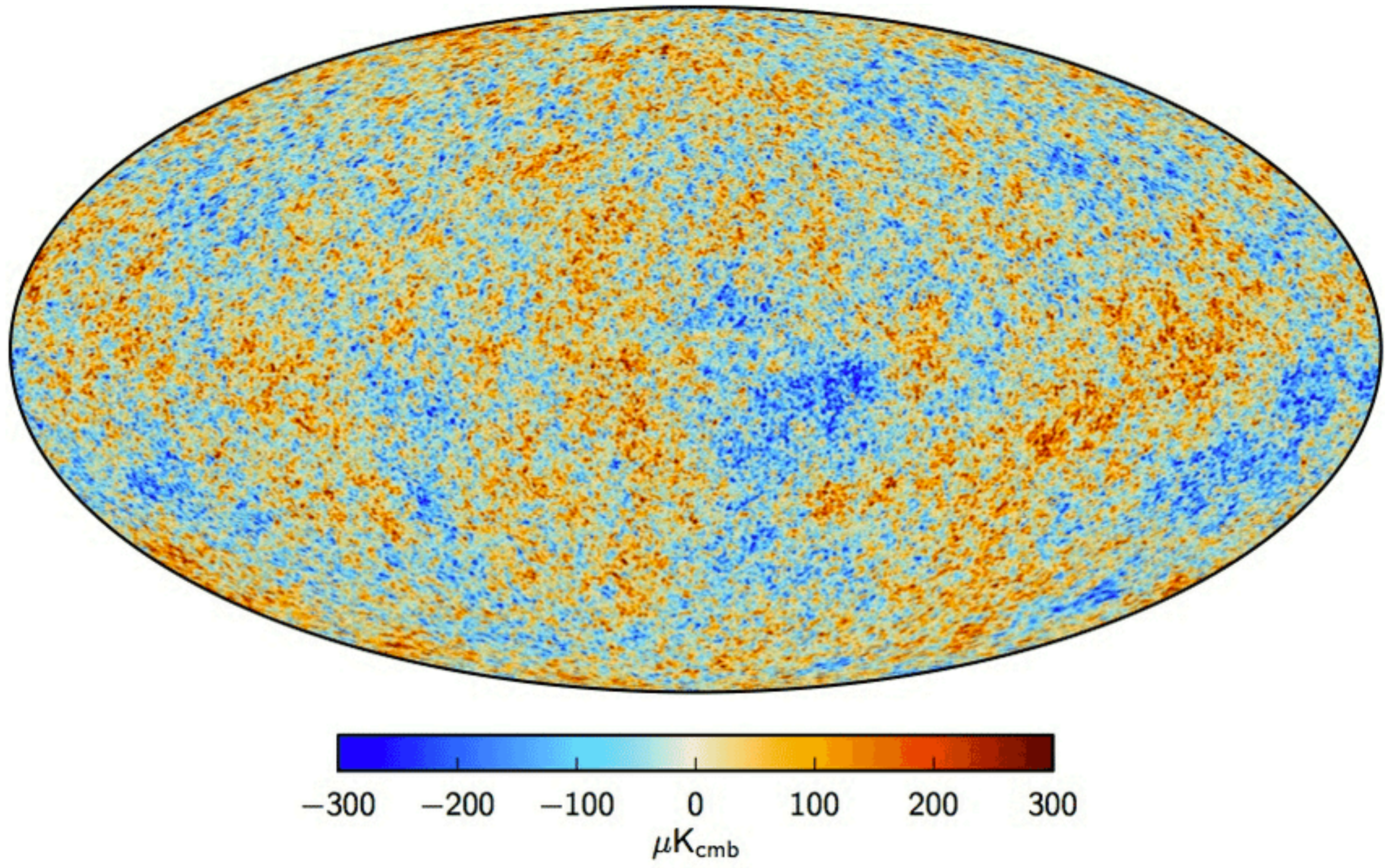
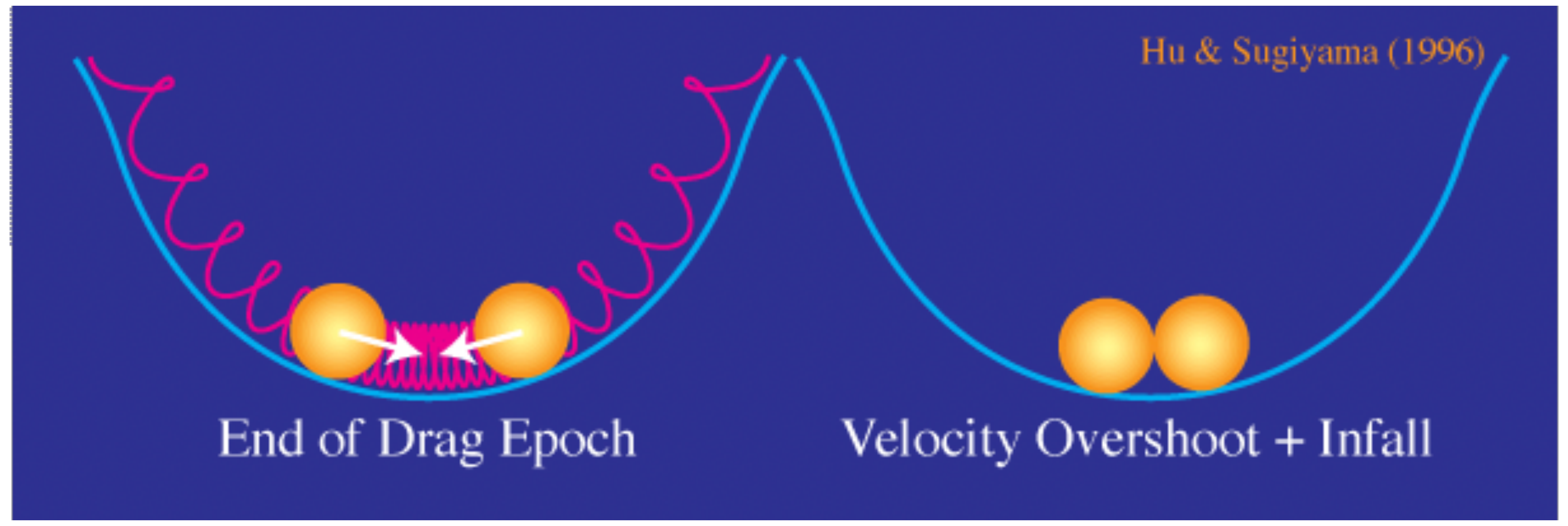
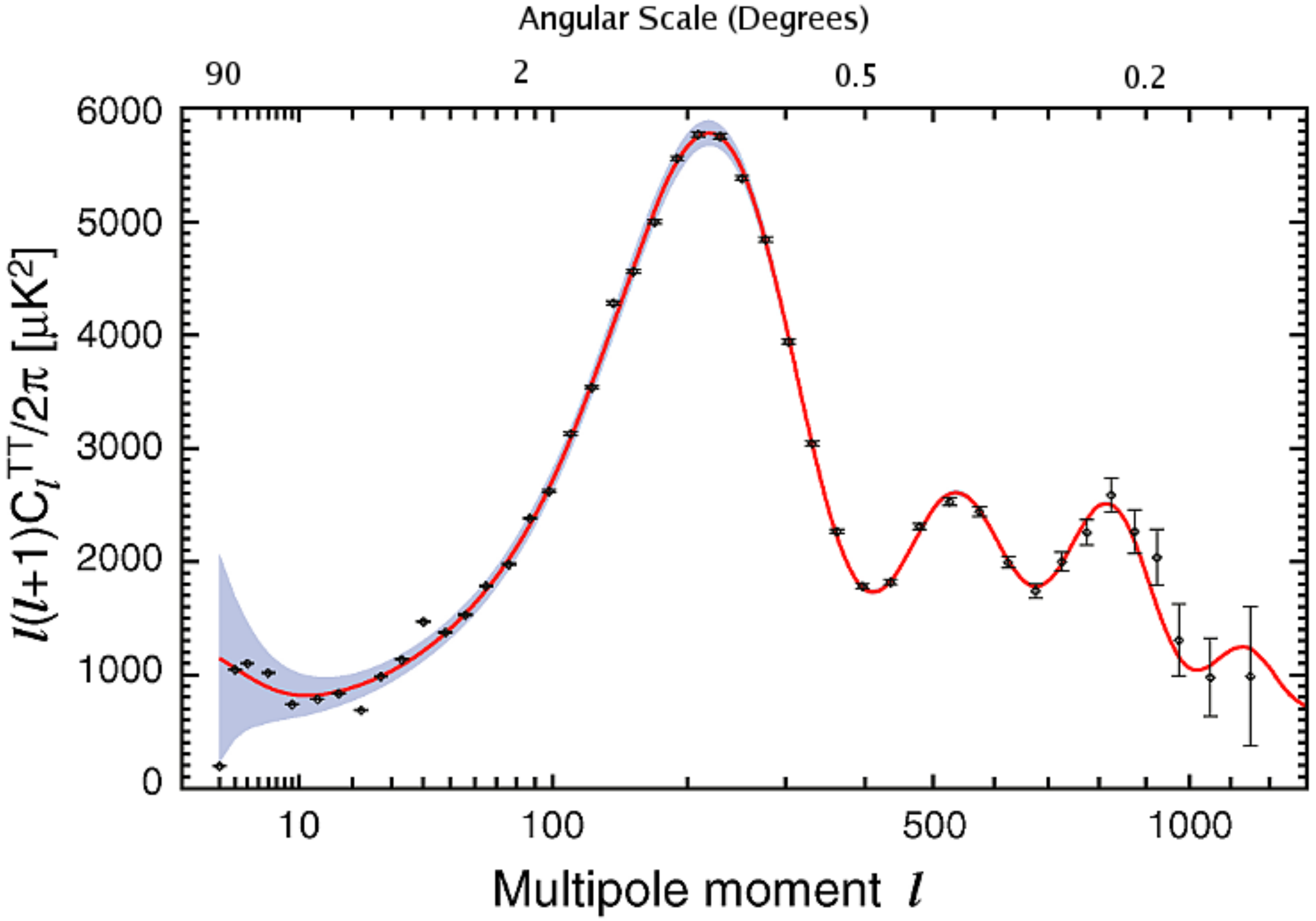
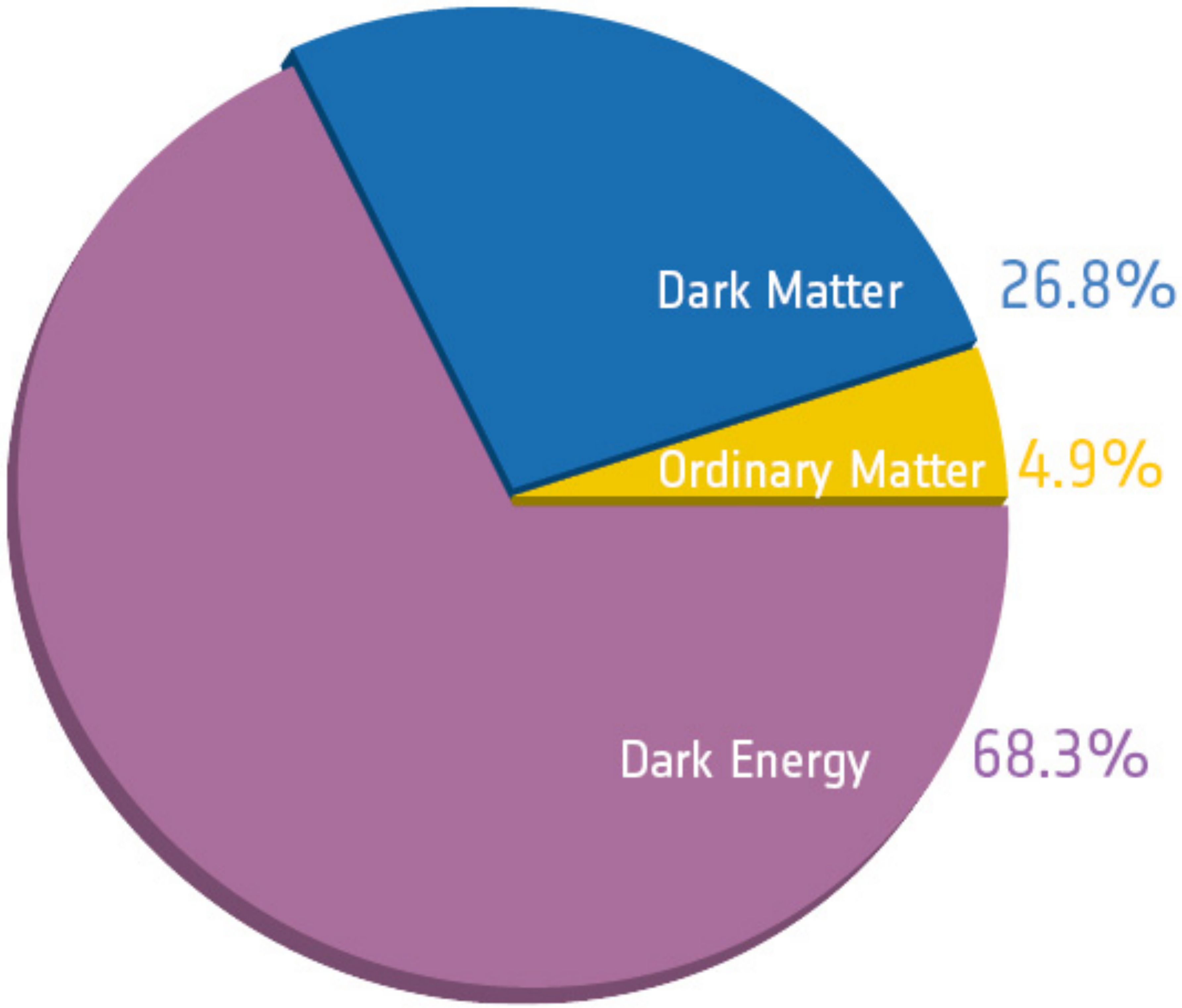






The success of the Lambda cold dark matter Model

- The standard model of Big Bang cosmology
  - Λ, dark energy; CDM, cold dark matter; Matter, SM particles



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  - Large-scale structure in the distribution of the galaxies
  - The observed abundance of H, D, He and Li
  - Accelerating expansion of the Universe

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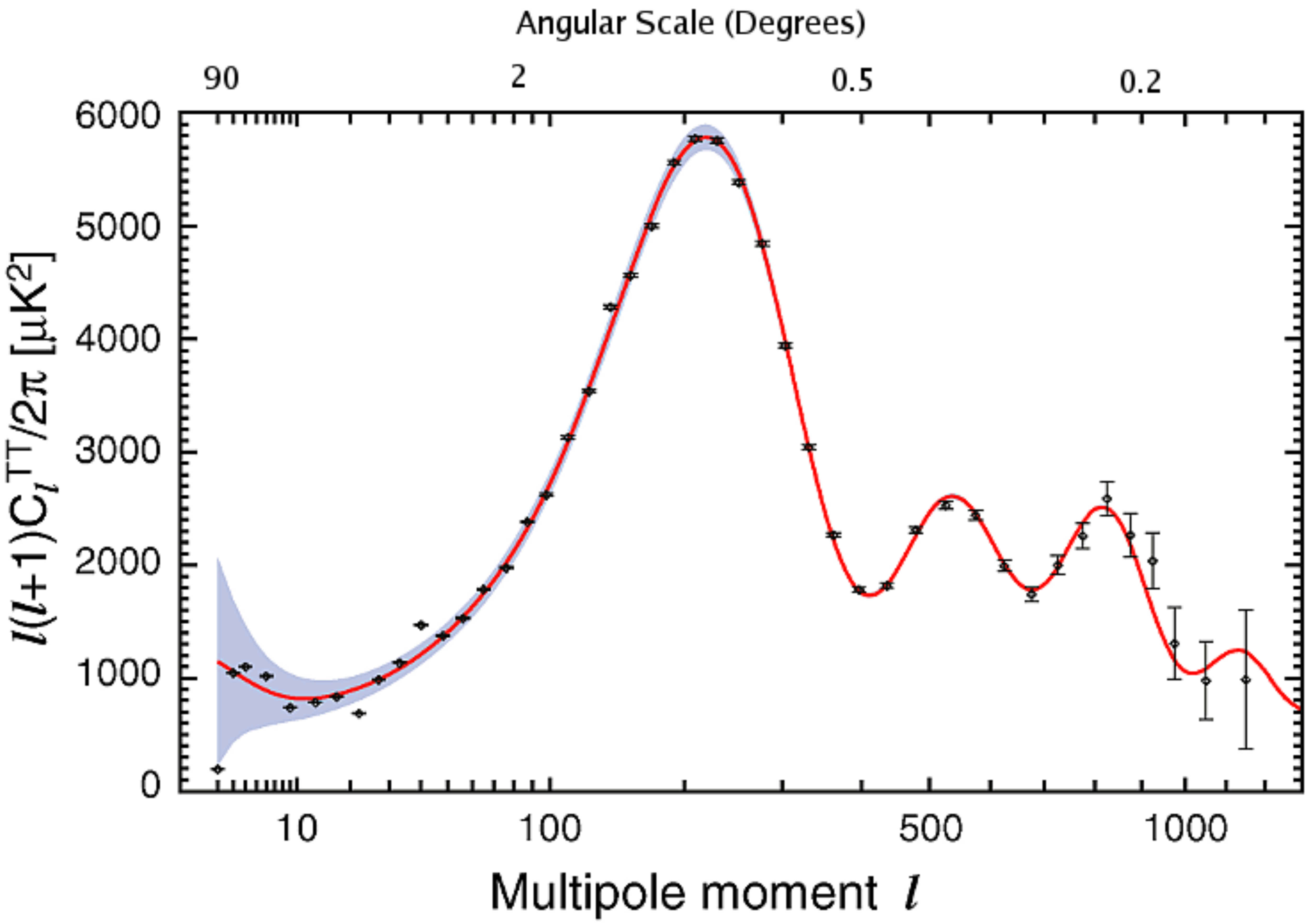

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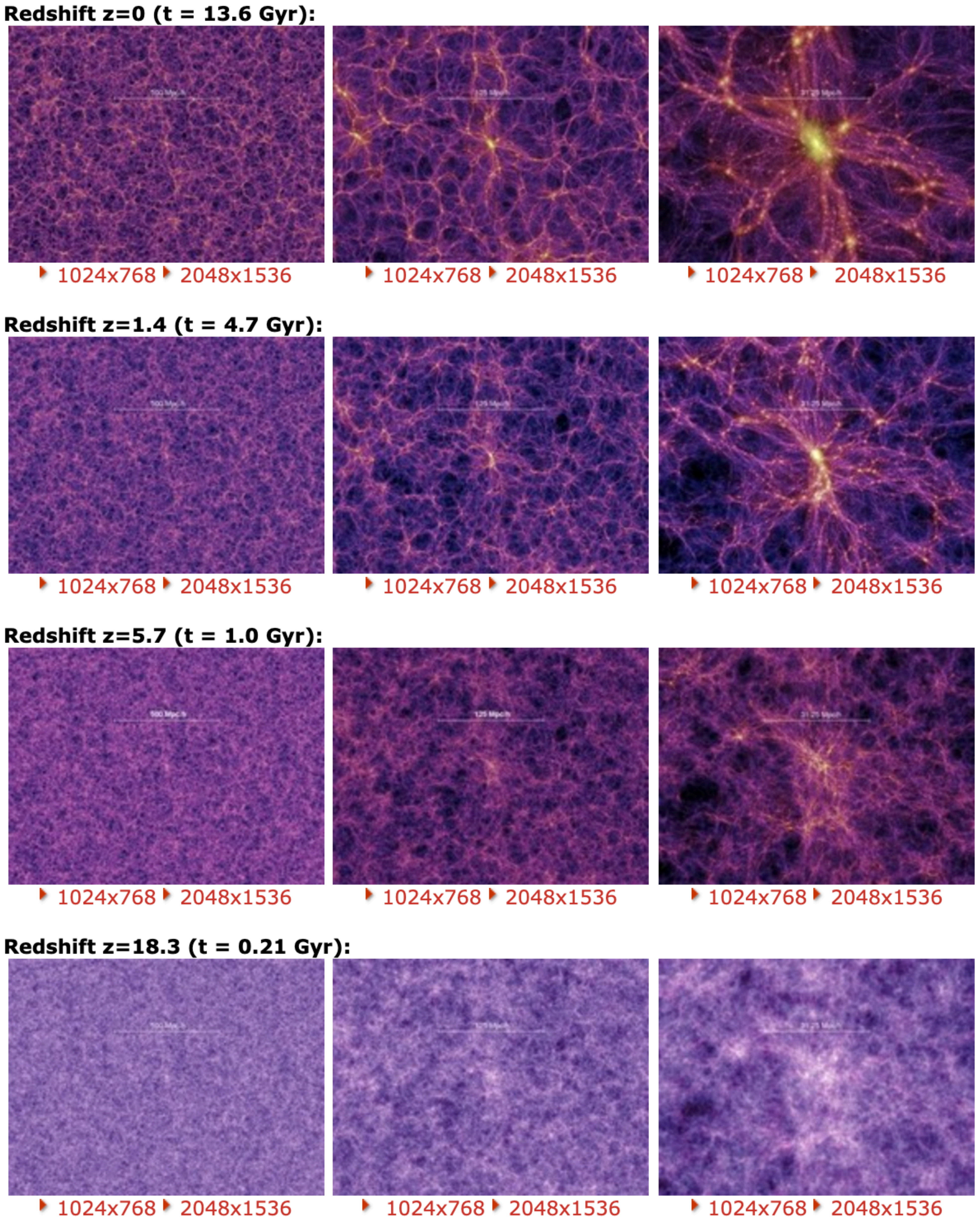

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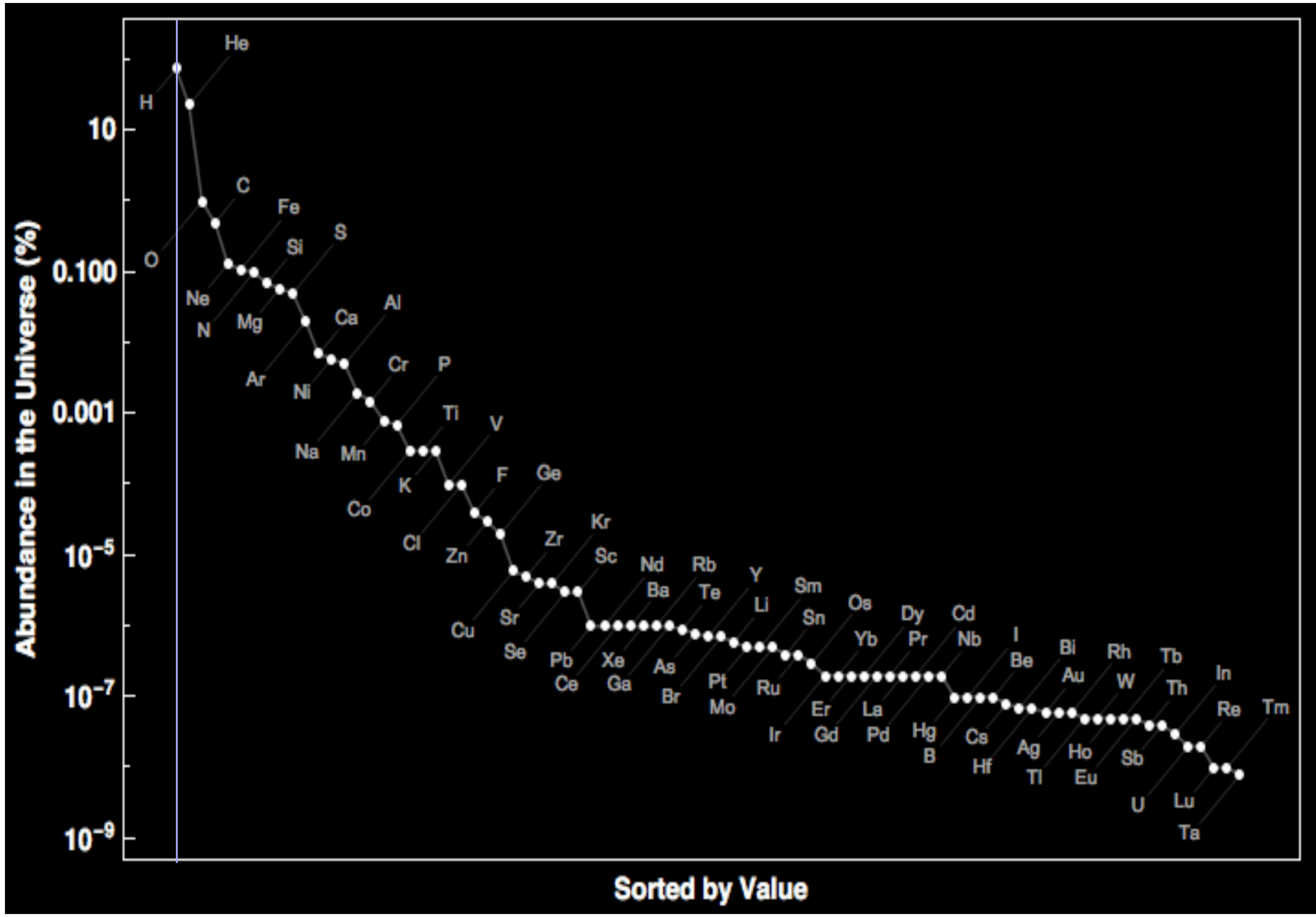

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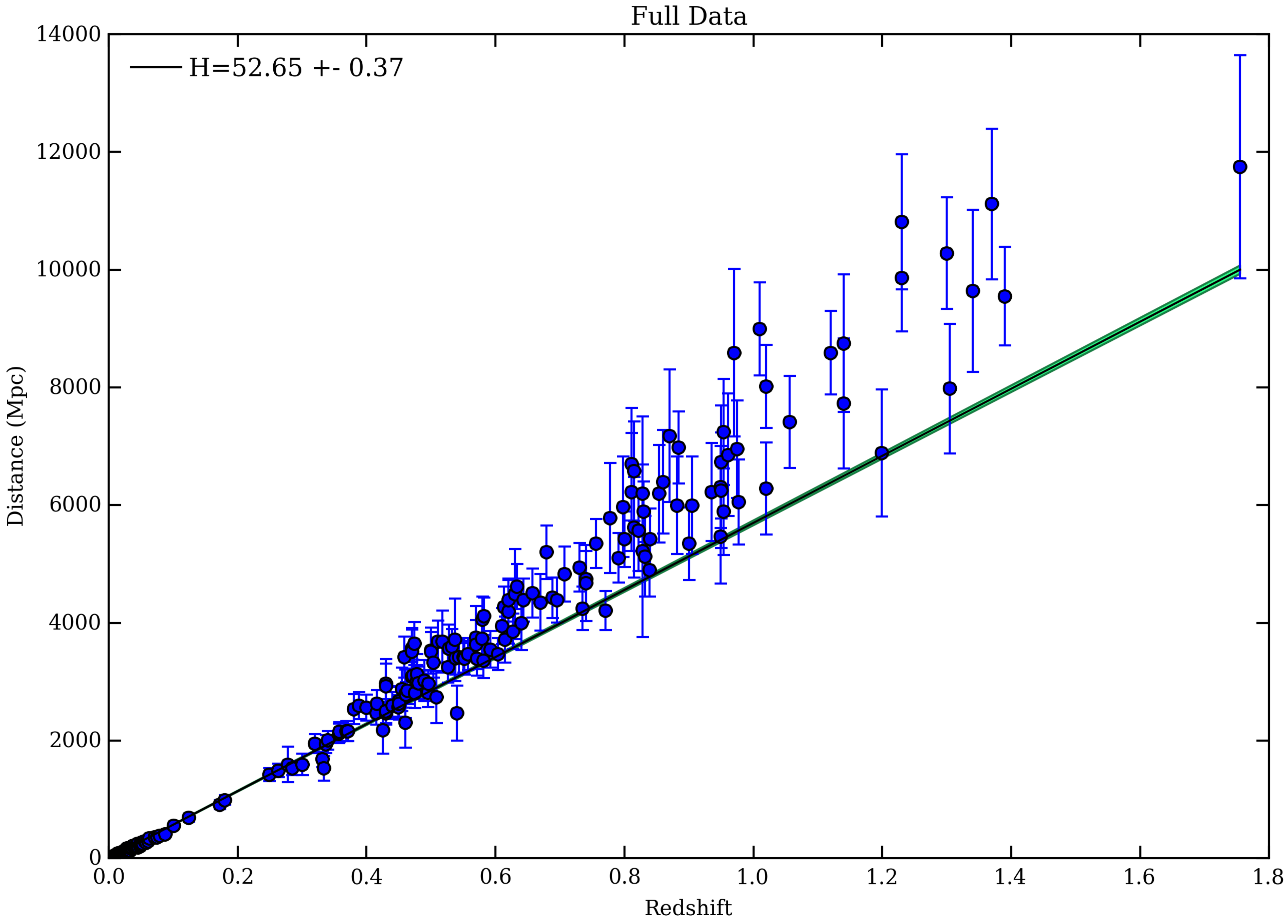

(Re)Discovering Dark Energy and the Expanding Universe

Credit: 2016, Adam Dempsey. CIERA, Northwestern University

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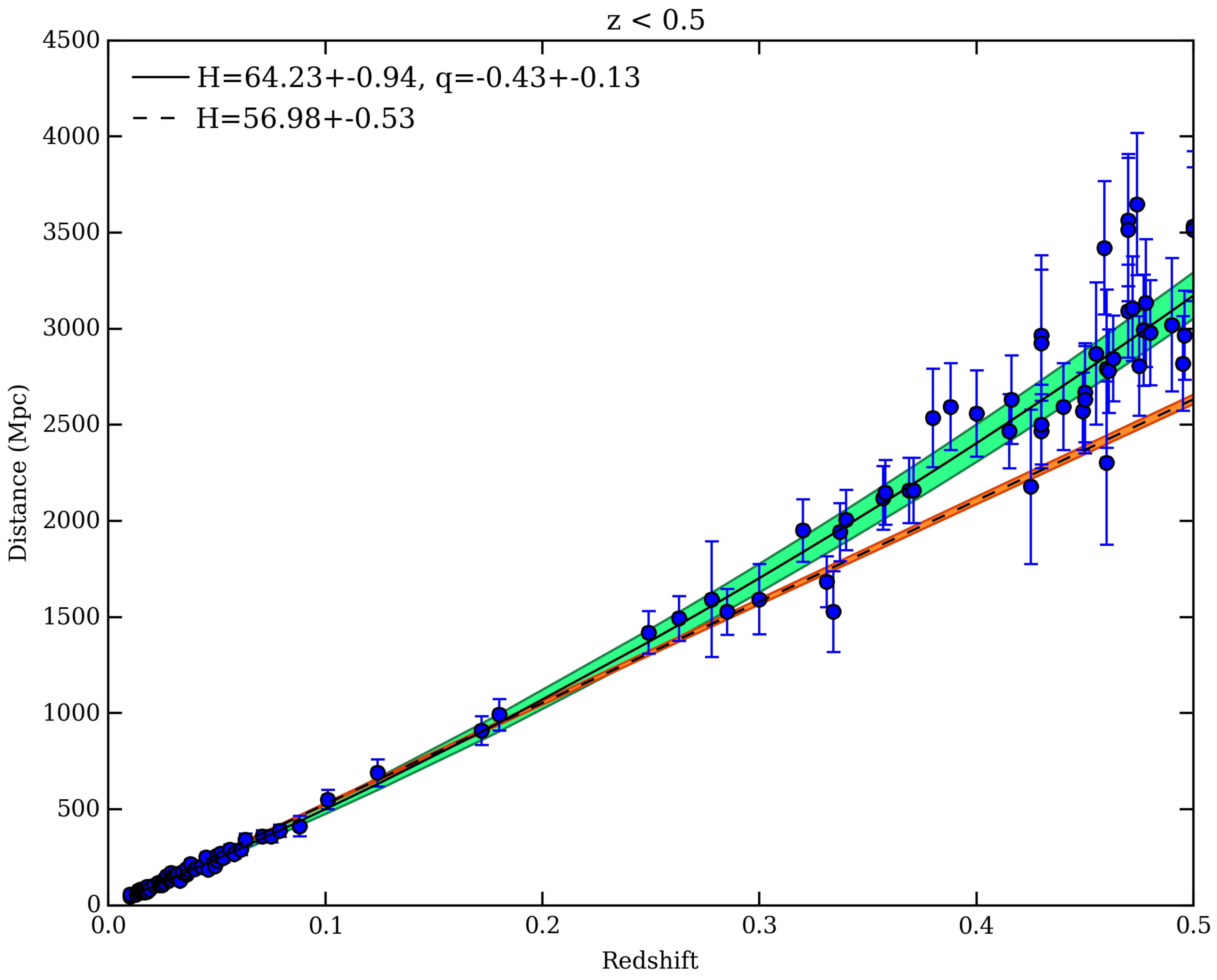

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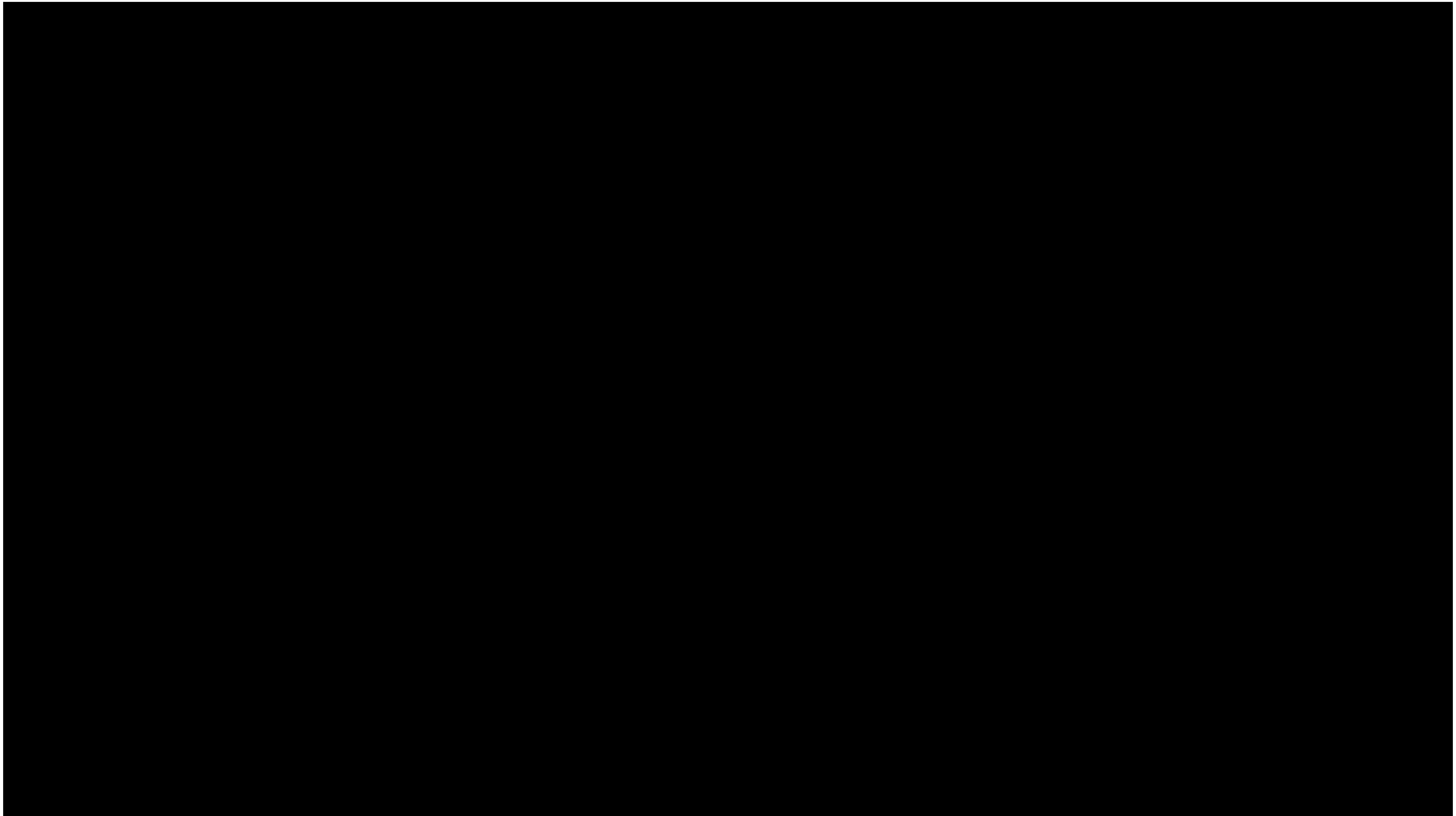
The cosmology frontier of Particle Physics



The dark matter in astrophysics/cosmology

- Energy density scales as $\rho \propto a^{-3}$, others $\rho_r \propto a^{-4}$, $\rho_{cc} \propto a^0$
- Massive, interacting gravitationally
- Neutral, not quite interacting with others, collision-less
- Stable

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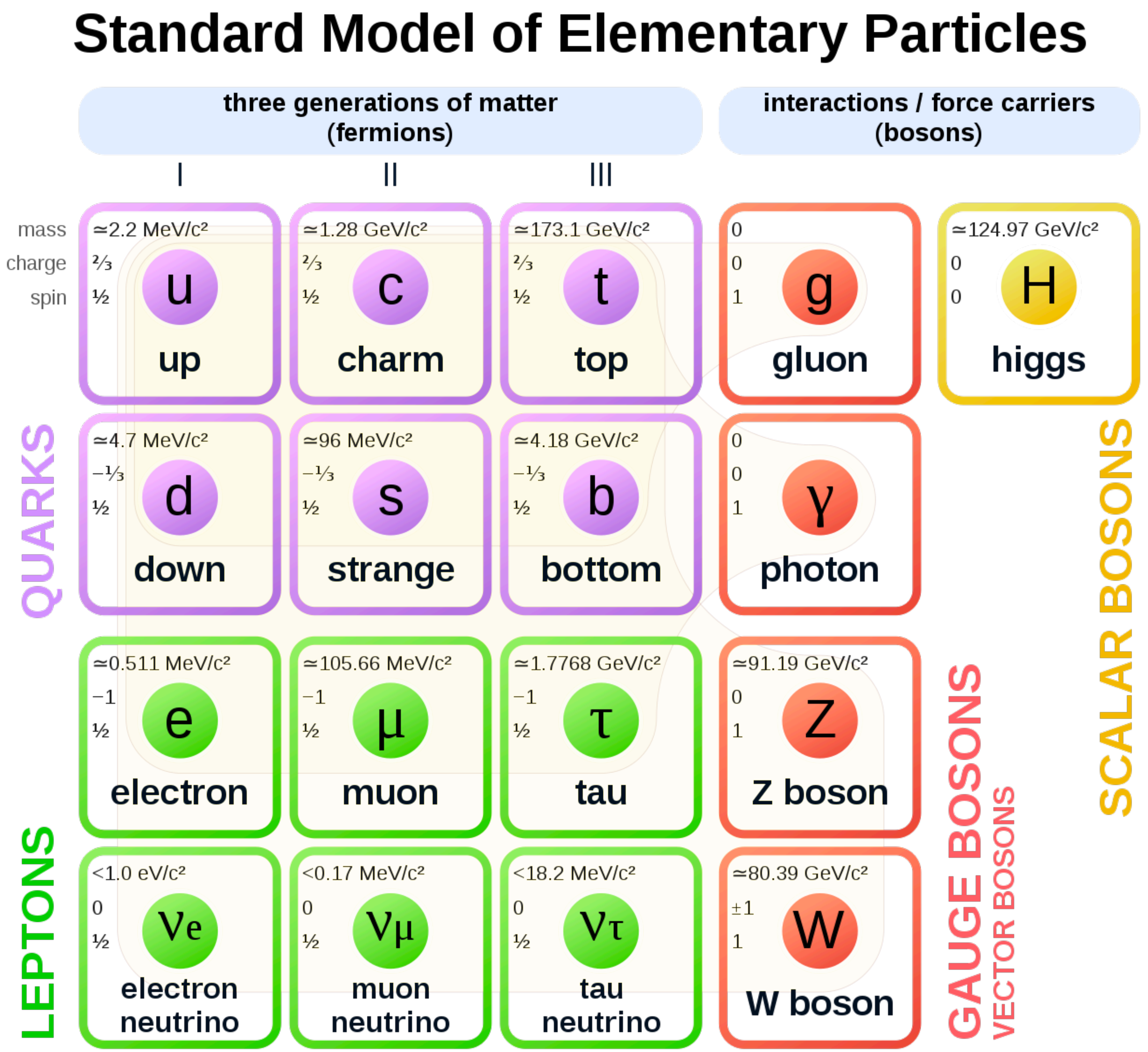
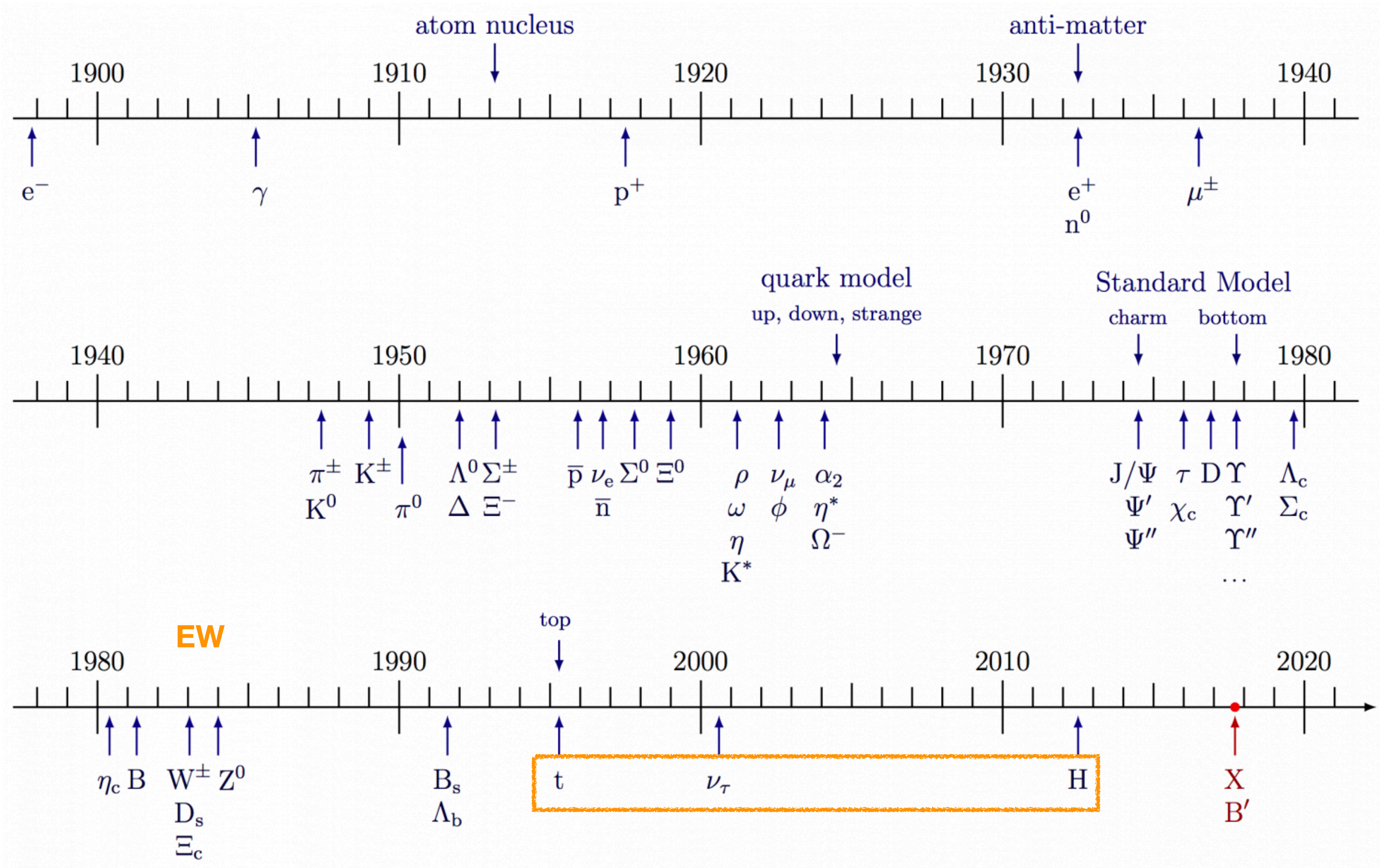
The dark matter in particle physics perspective

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



Chronicle of particle discoveries



The menu of the Standard Model

Top quark
The heaviest fermion
3rd gen up-type quark
1995

Tau neutrino
The last discovered neutrino
3rd gen neutrino
2000

Higgs
It gives masses to other particles
The heaviest scalar particle
2012

- We always hold a menu
- What about next?

The new menu from Supersymmetry

- SUSY model MSSM guided the phenomenology study for a long time
  - Sizable coupling to SM sector
    - Collider searches
    - Direct searches
    - Indirect searches
- Neutralino DM is well-motivated
  - A role-model for Weakly Interacting Massive Particle

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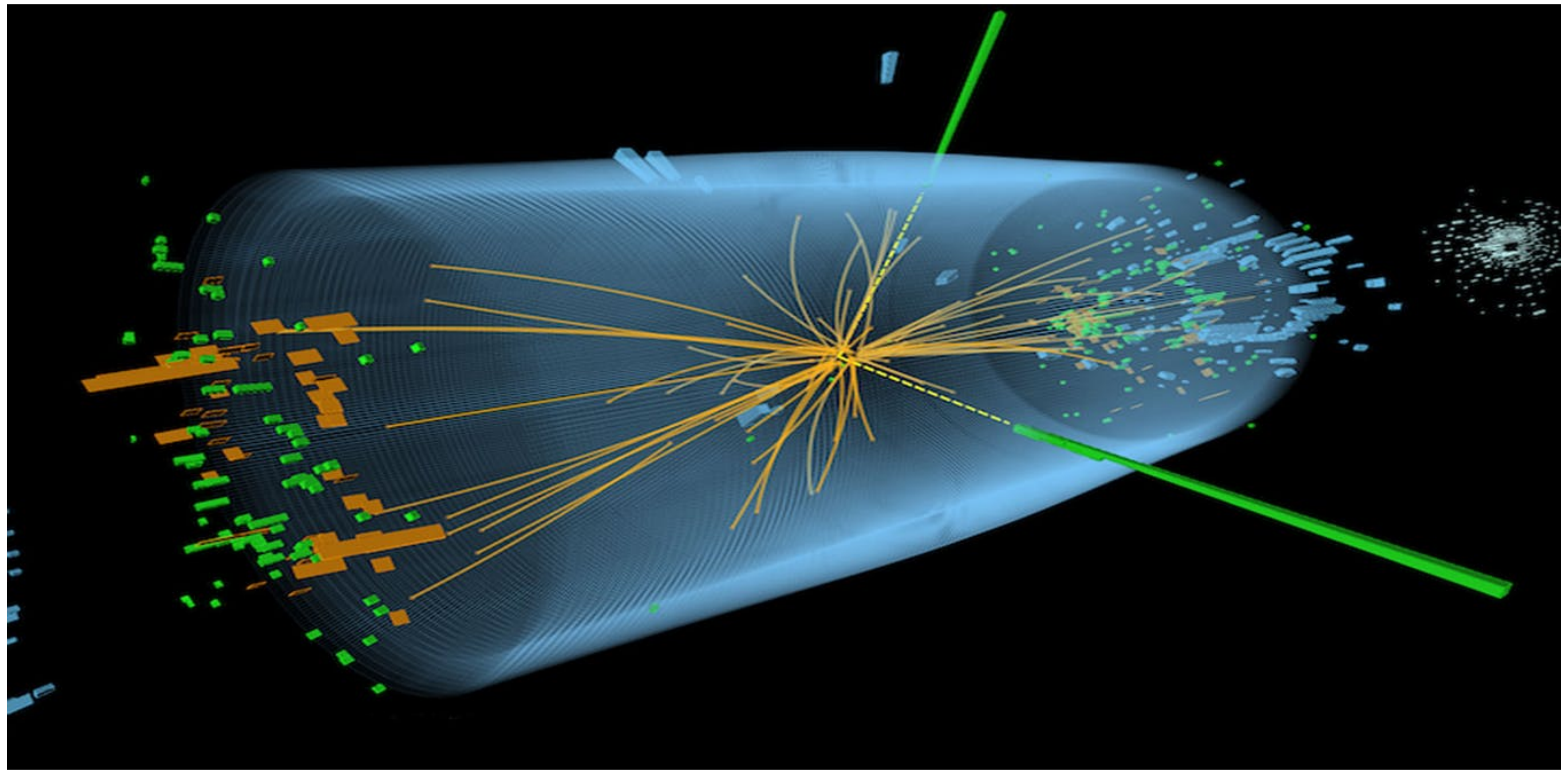
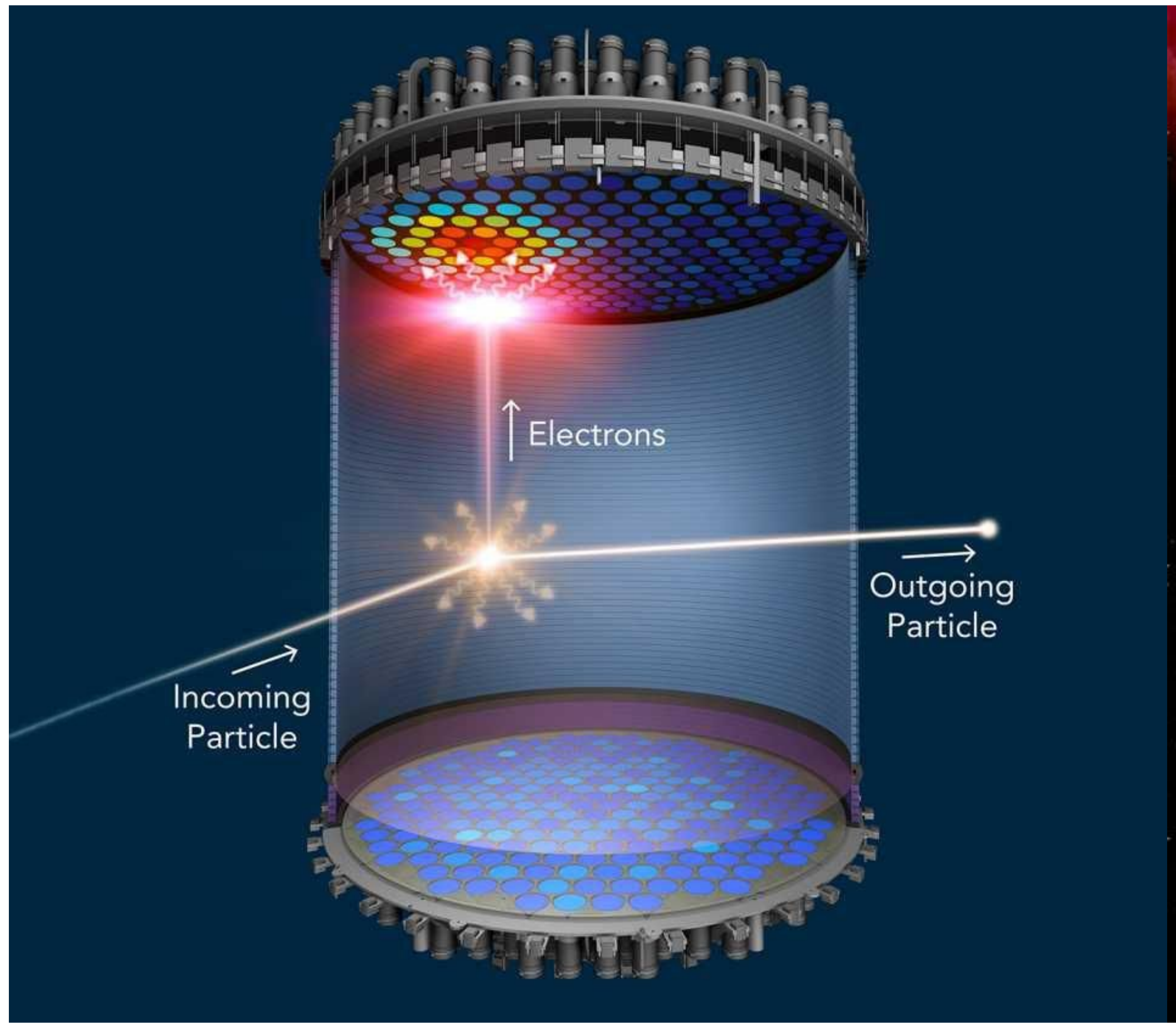
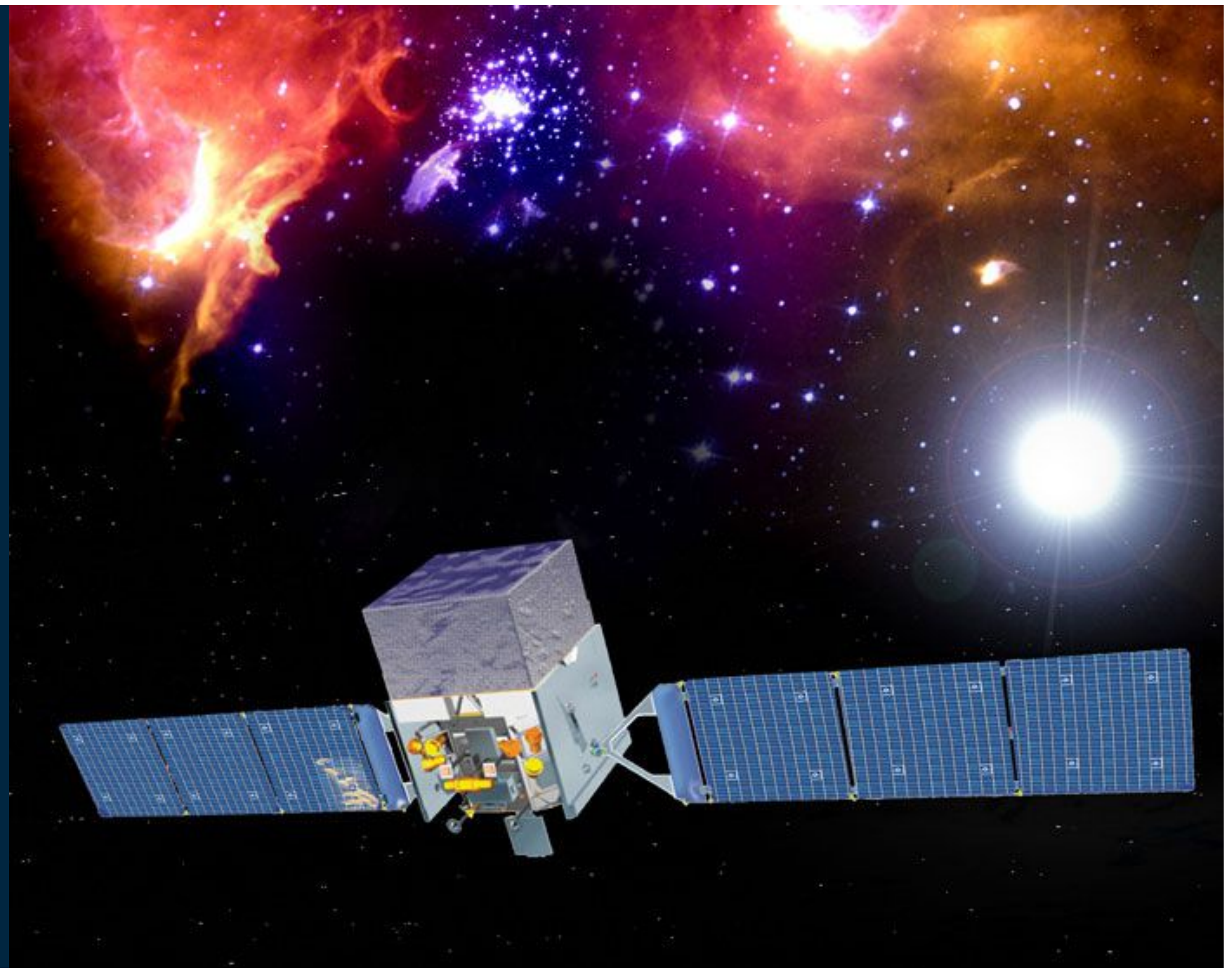
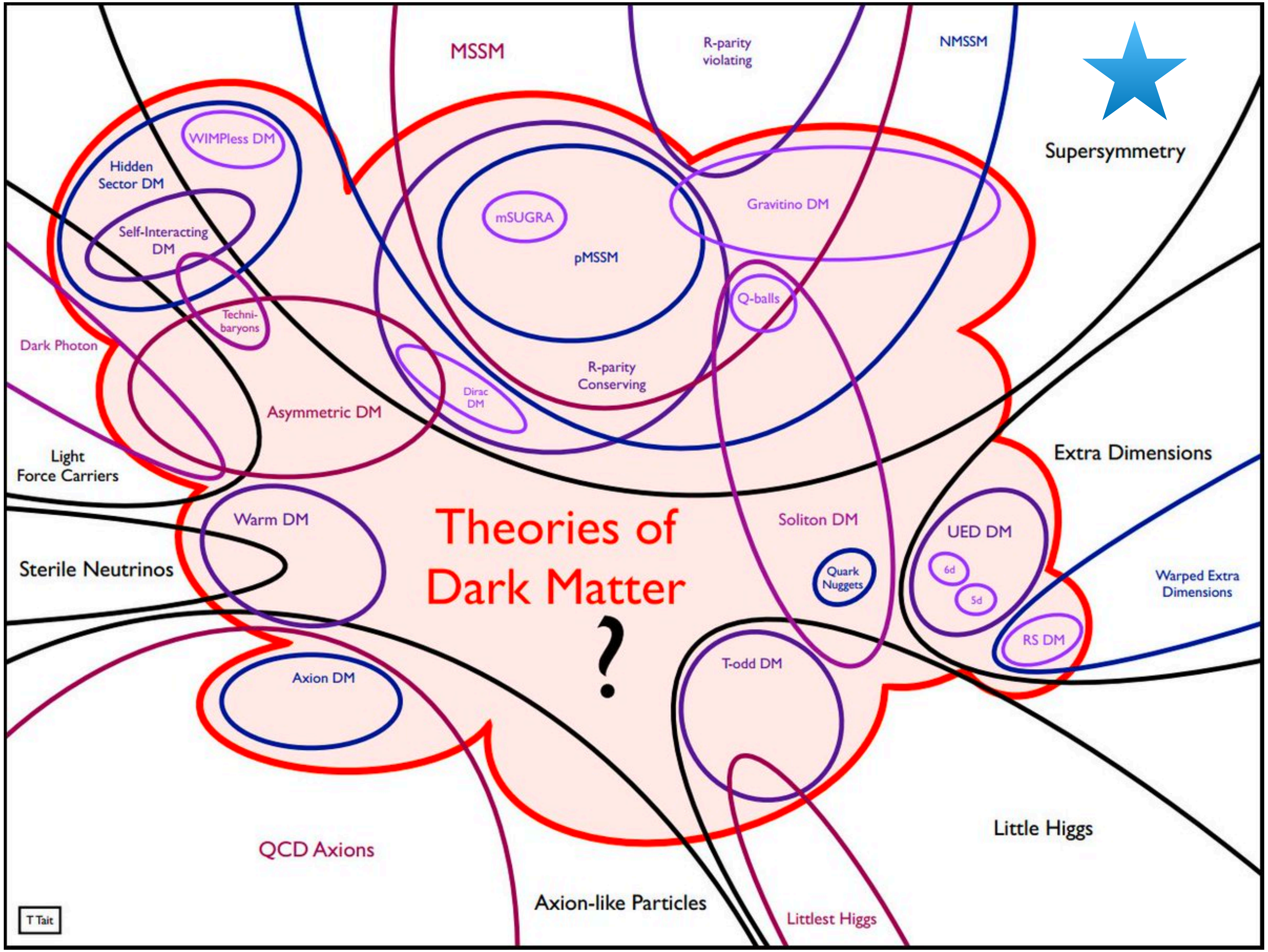




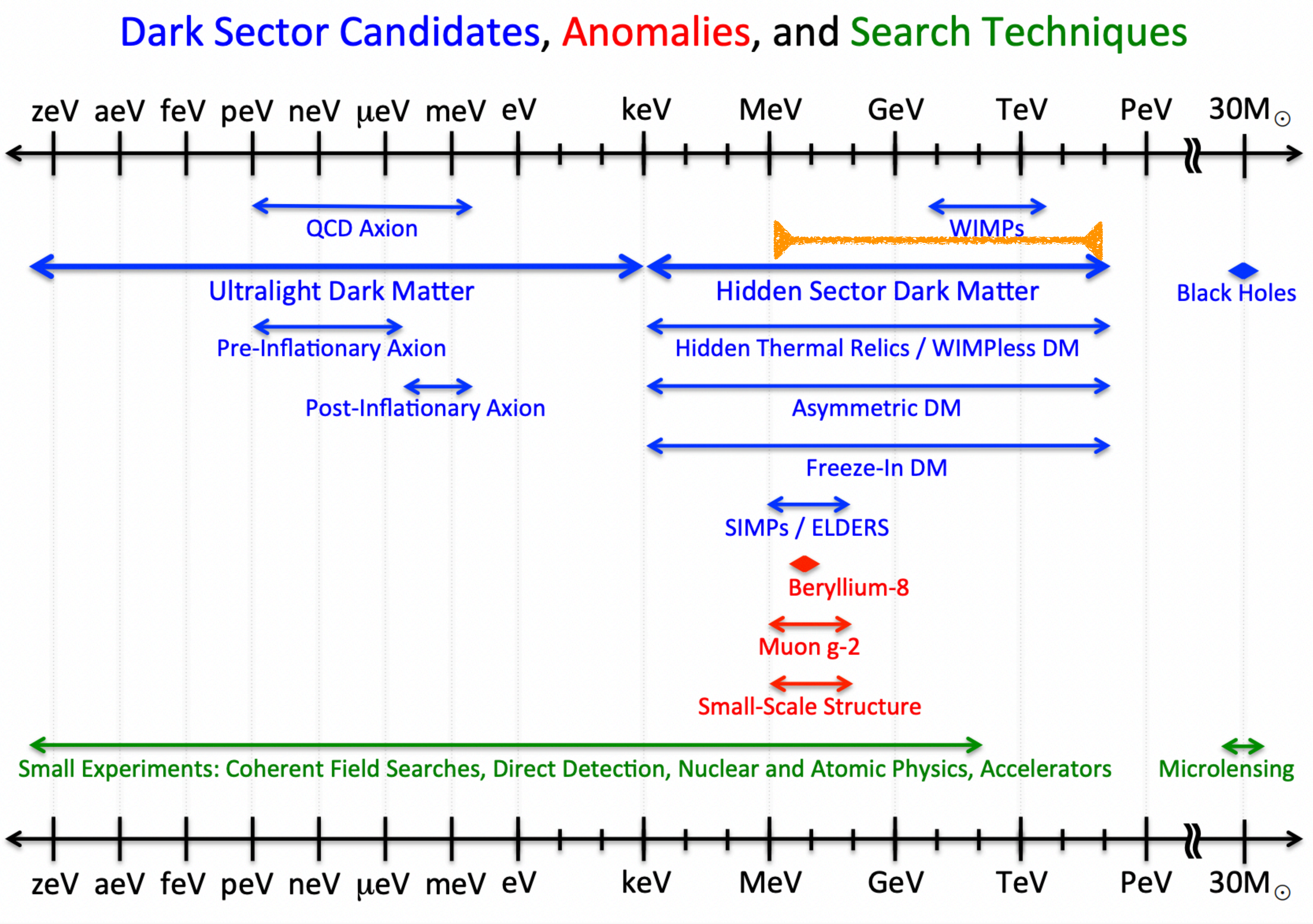


The menu for dark matter models



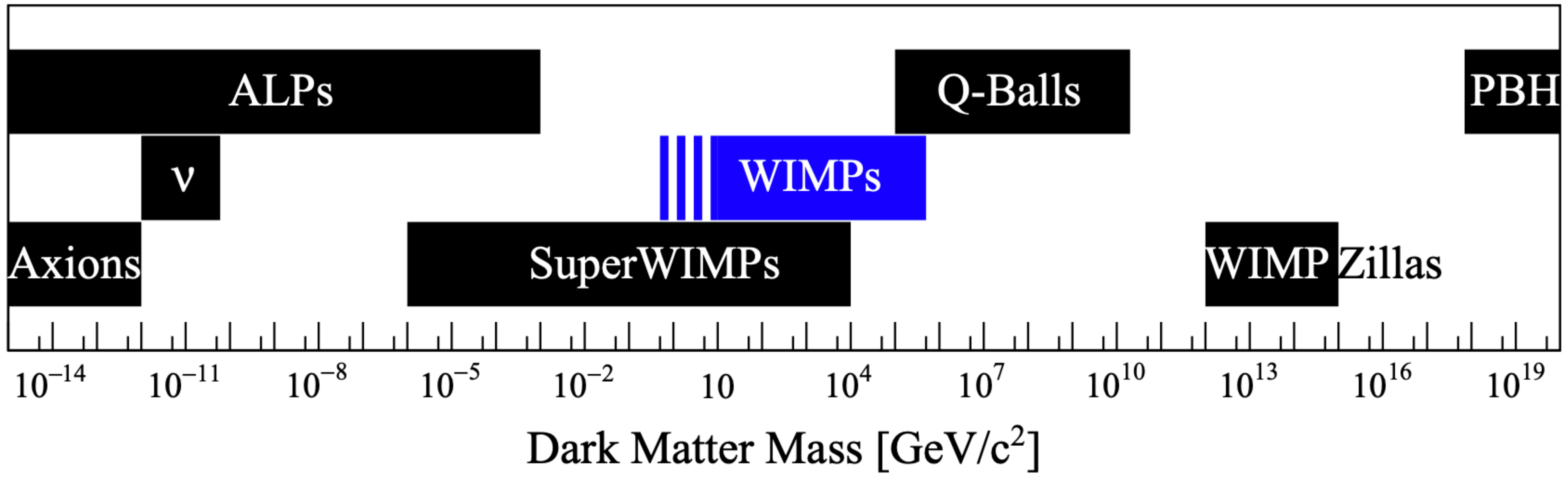
The wide ranges of dark matter searches

- In this talk:
  - Skip very small mass: DM is wave-like rather than particle like
  - Skip very small interaction rate: DM is accumulated through thermal leakage of SM fields
  - We focus on mass range ~[MeV (Neff bound), 100 TeV (unitary bound)]
- DM starts in thermal equilibrium

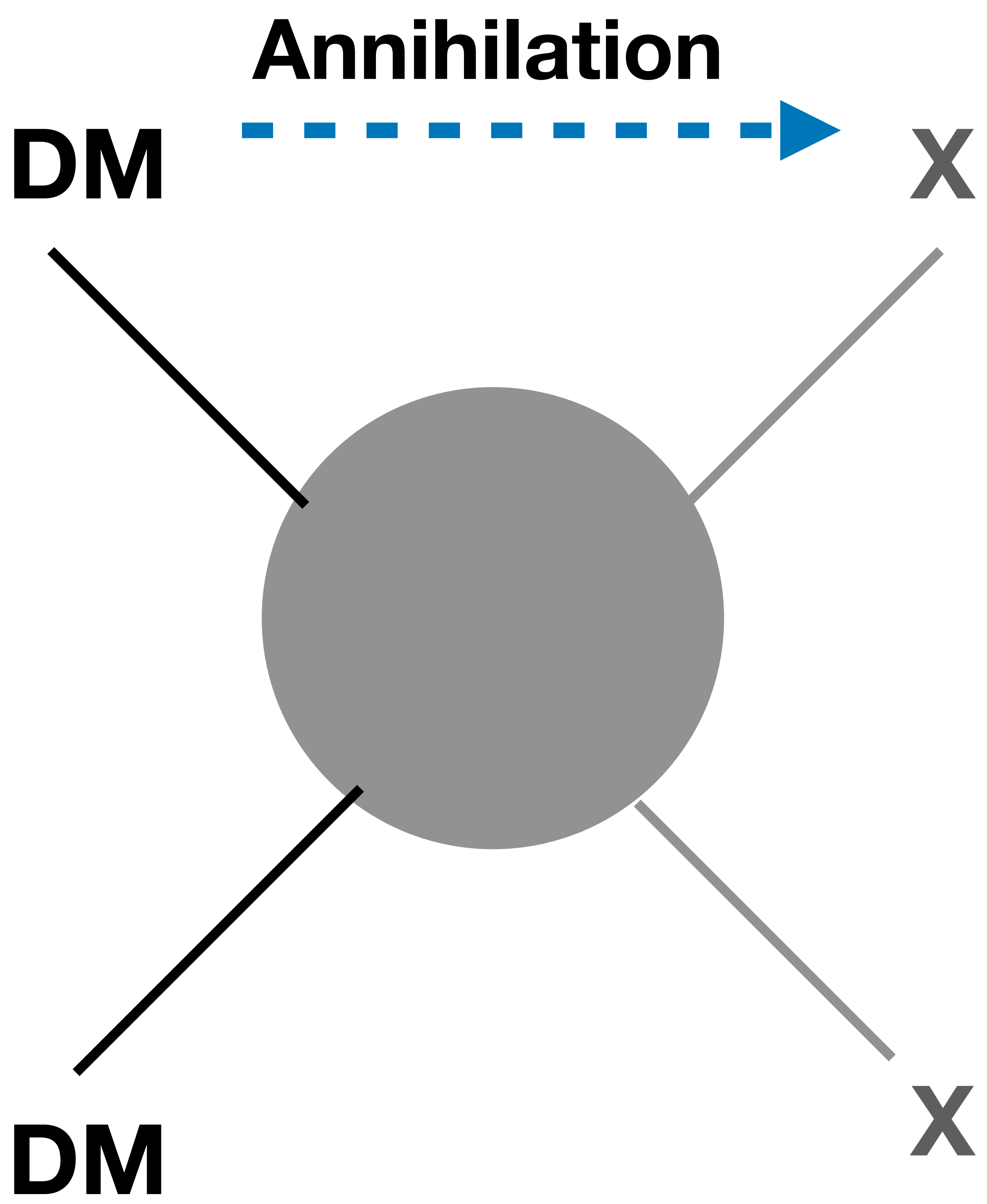


Cosmic Visions [arXiv:1707.04591]

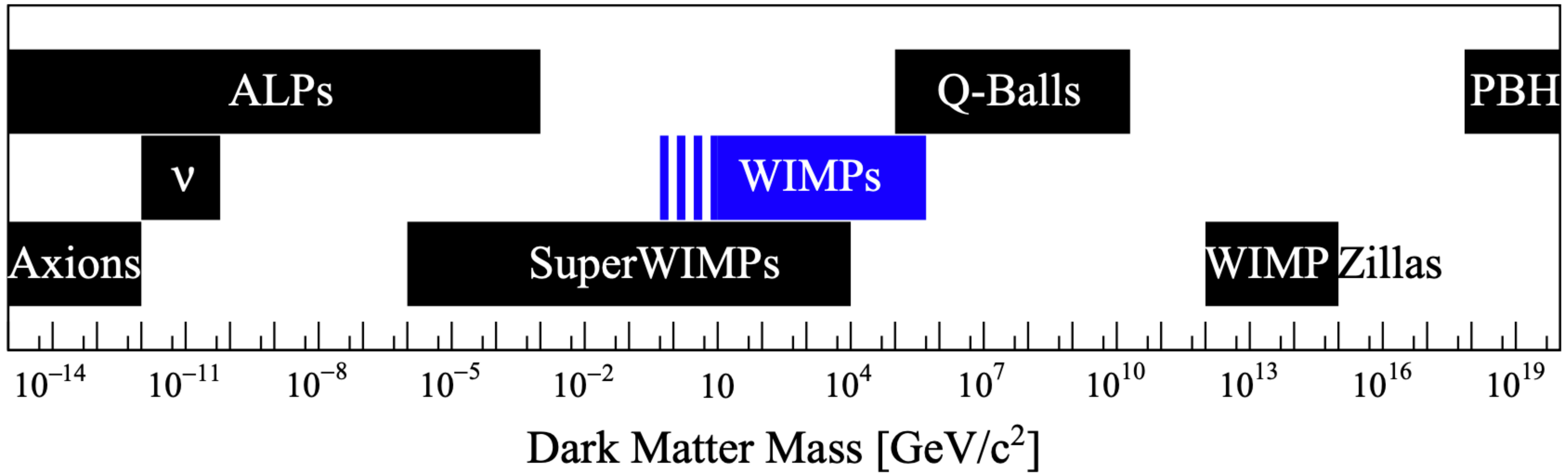
The Weakly Interacting Massive Particle paradigm



- 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

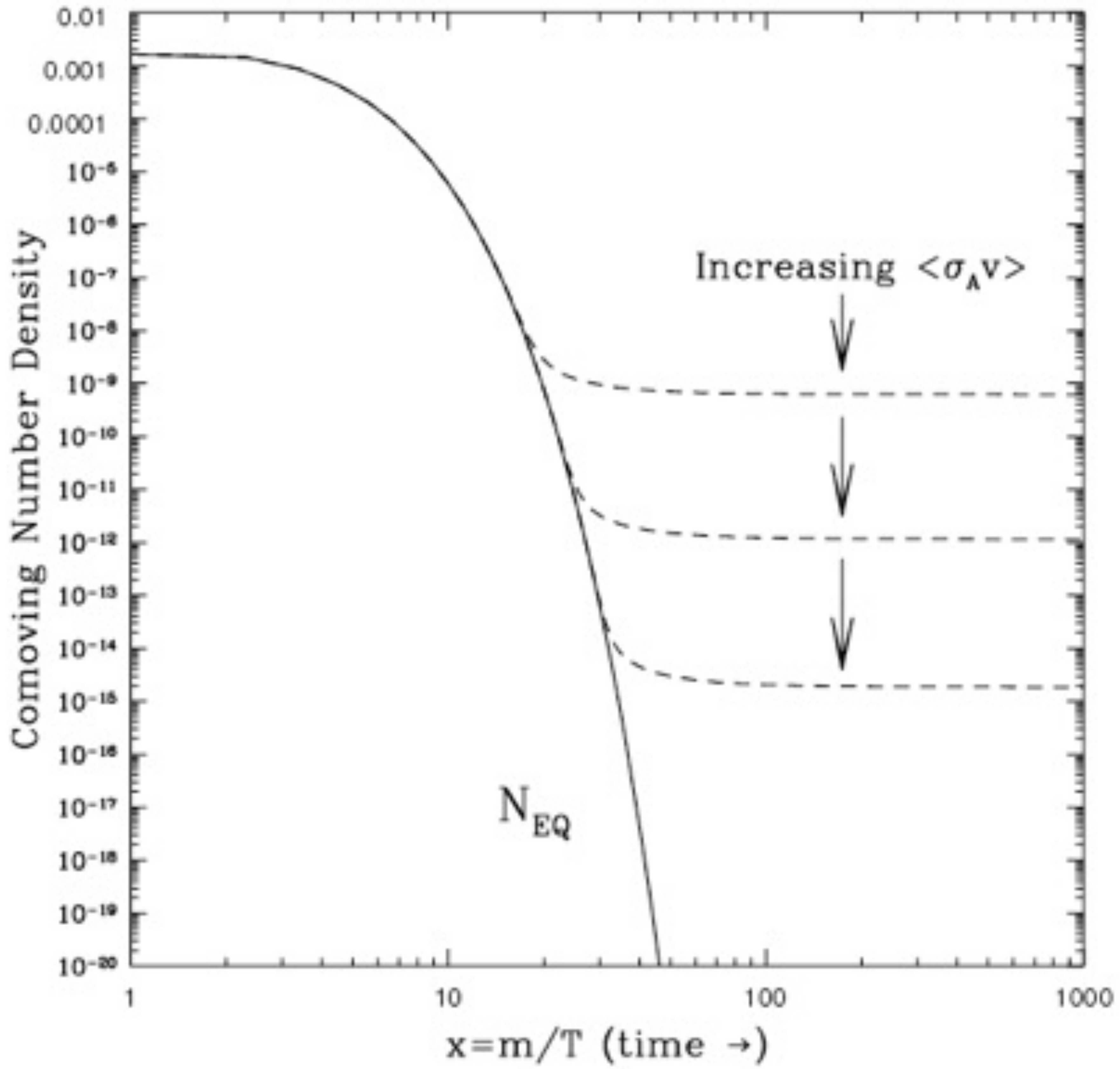


- Thermal cross-section

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

- 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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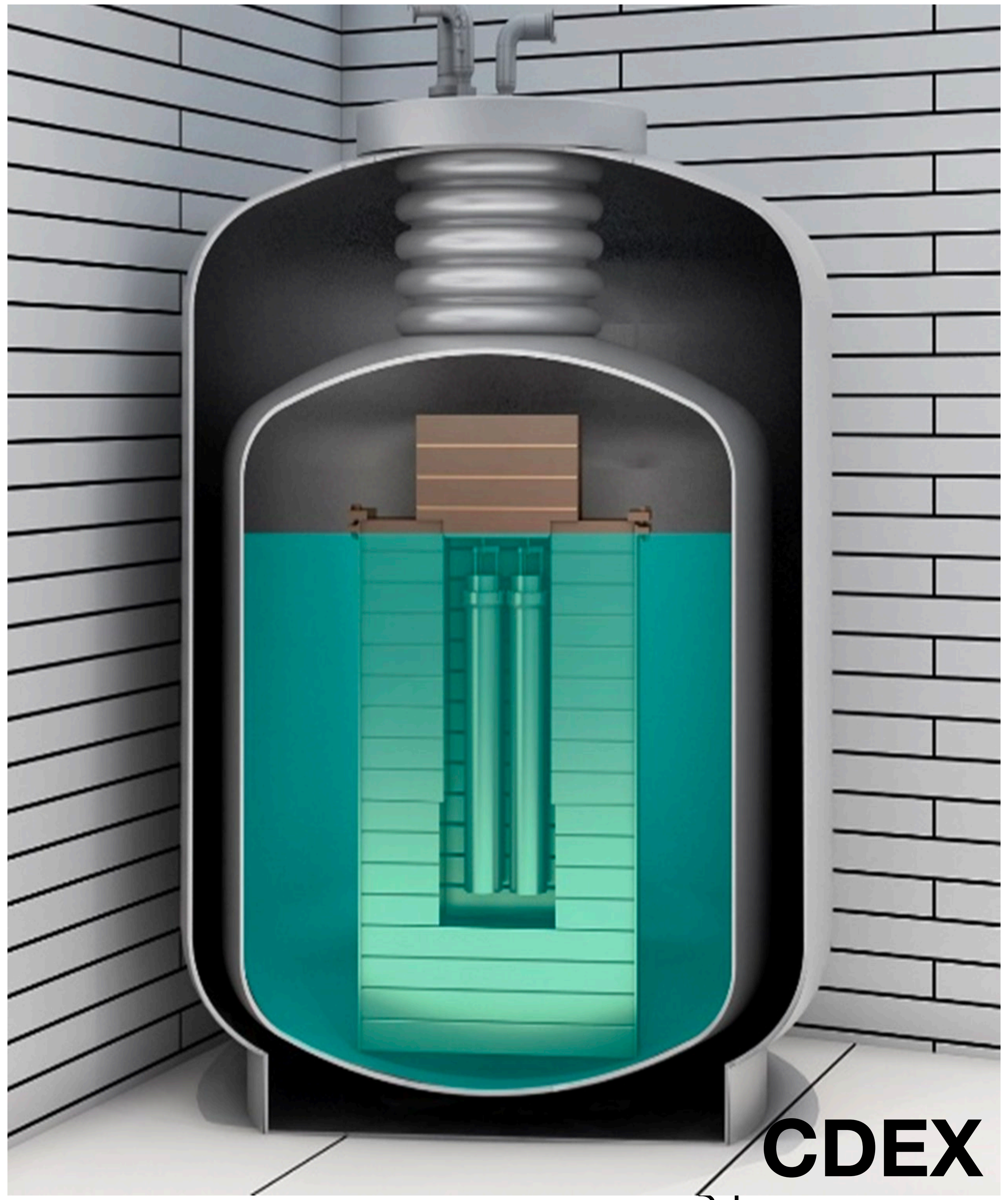
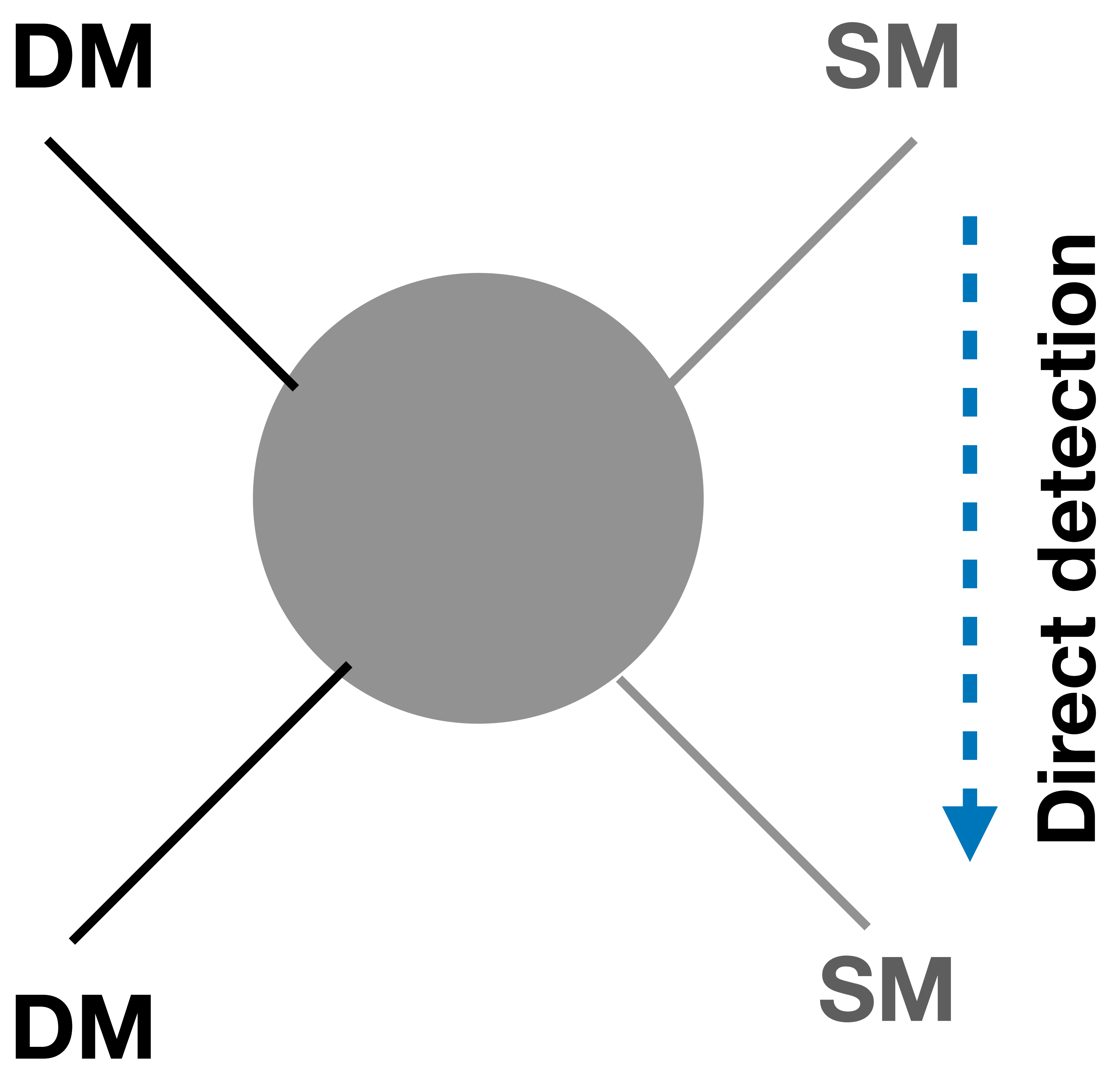
The WIMP crisis from direct detection

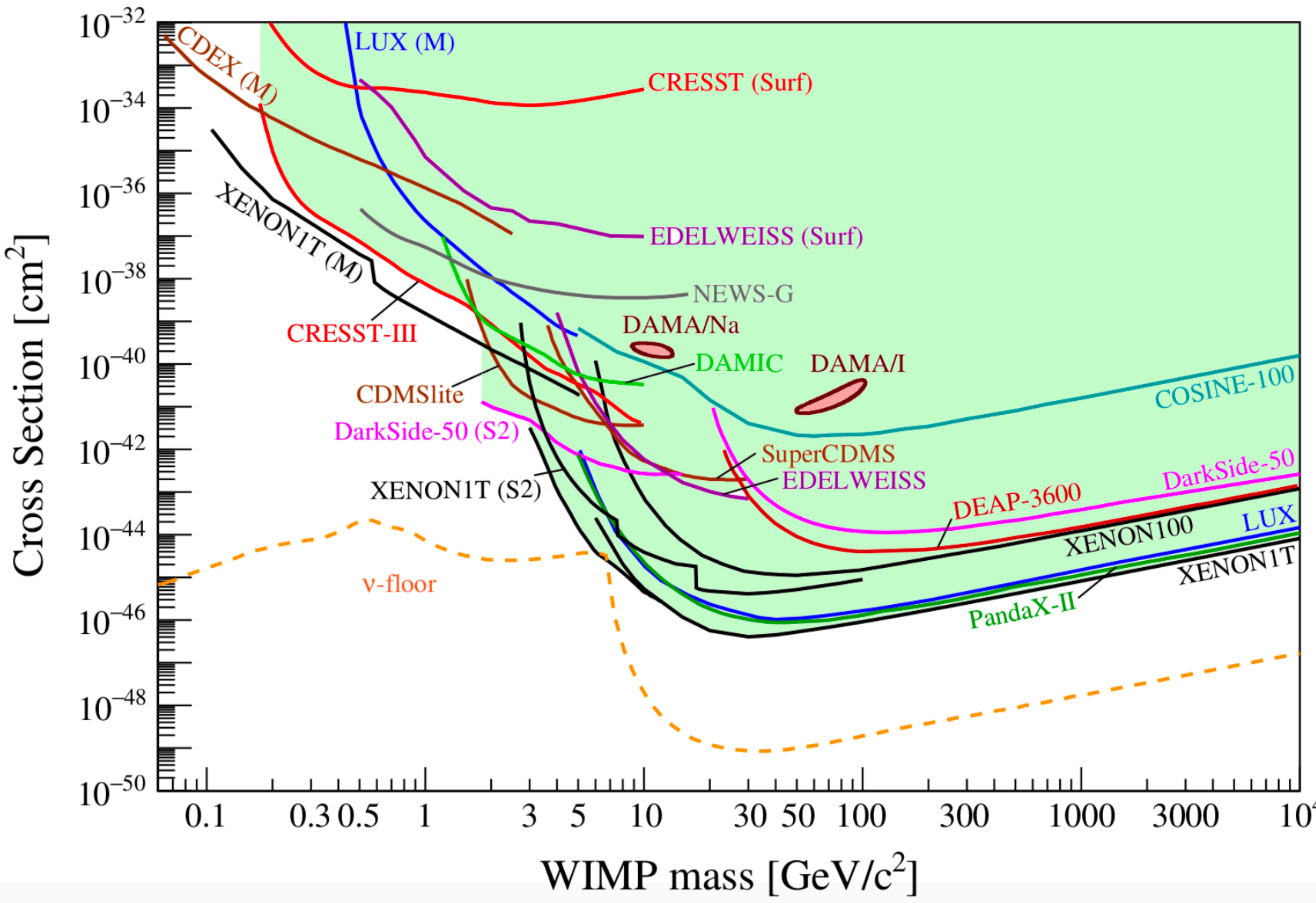
- Weakly Interacting Massive Particle
- The sizable coupling of DM to SM particles predicts sizable scattering cross-section





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)
  - We focus on EW scale ($\gtrsim$ 10 GeV)



山雨欲来风满楼

APPEC Committee Report: 2104.07634

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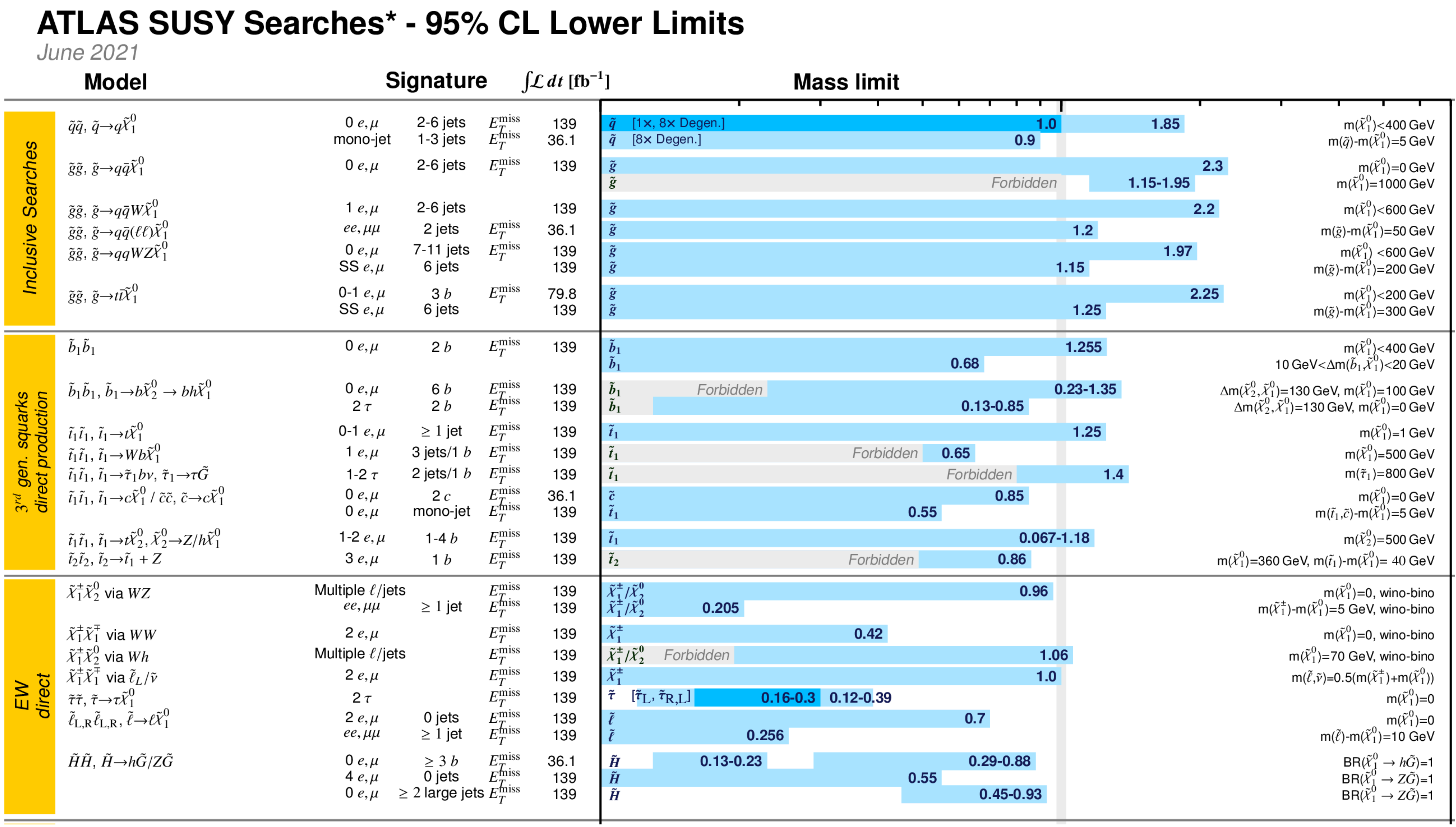
Together with the fact that, we have not seen SUSY either.

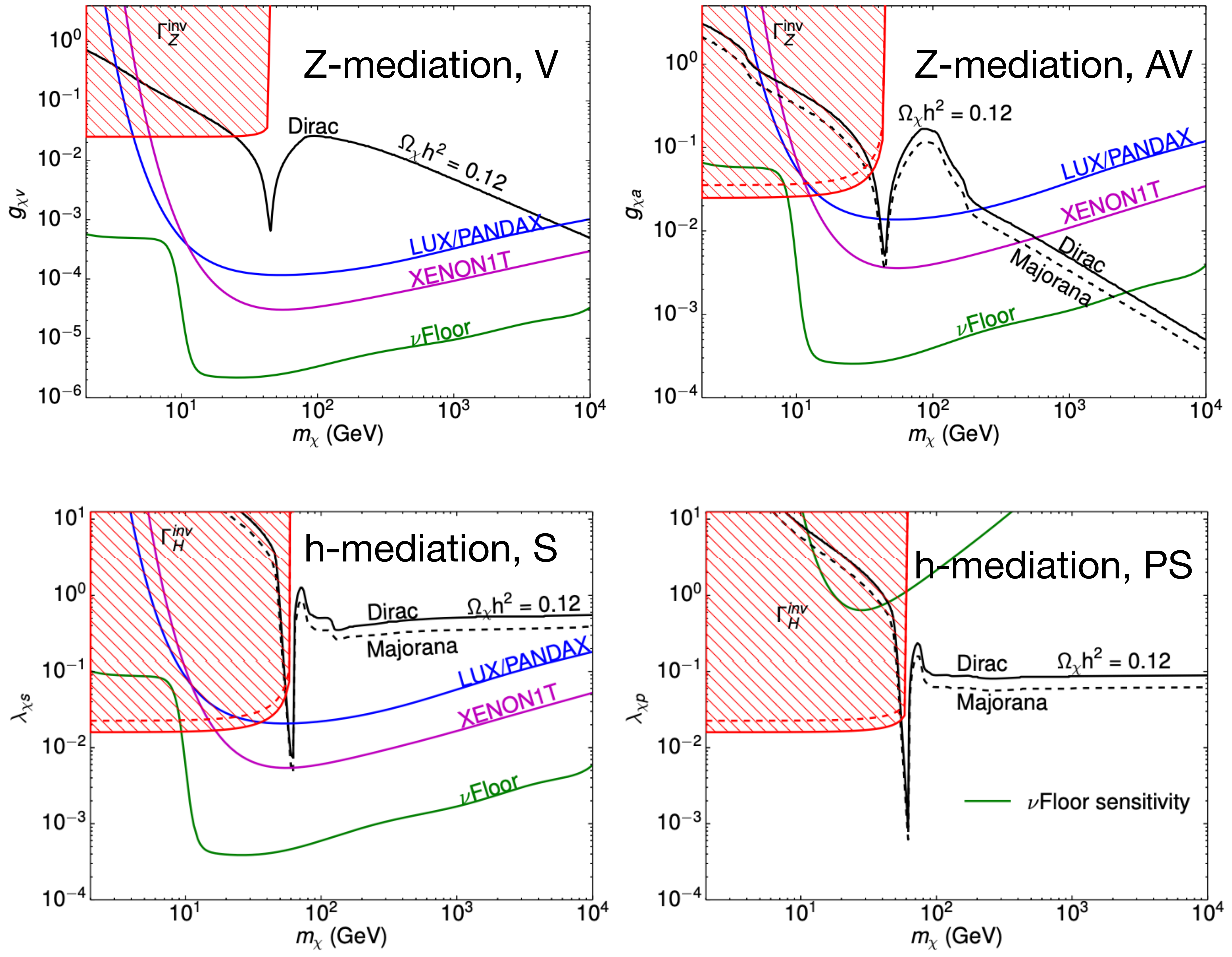


屋漏偏逢连夜雨

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



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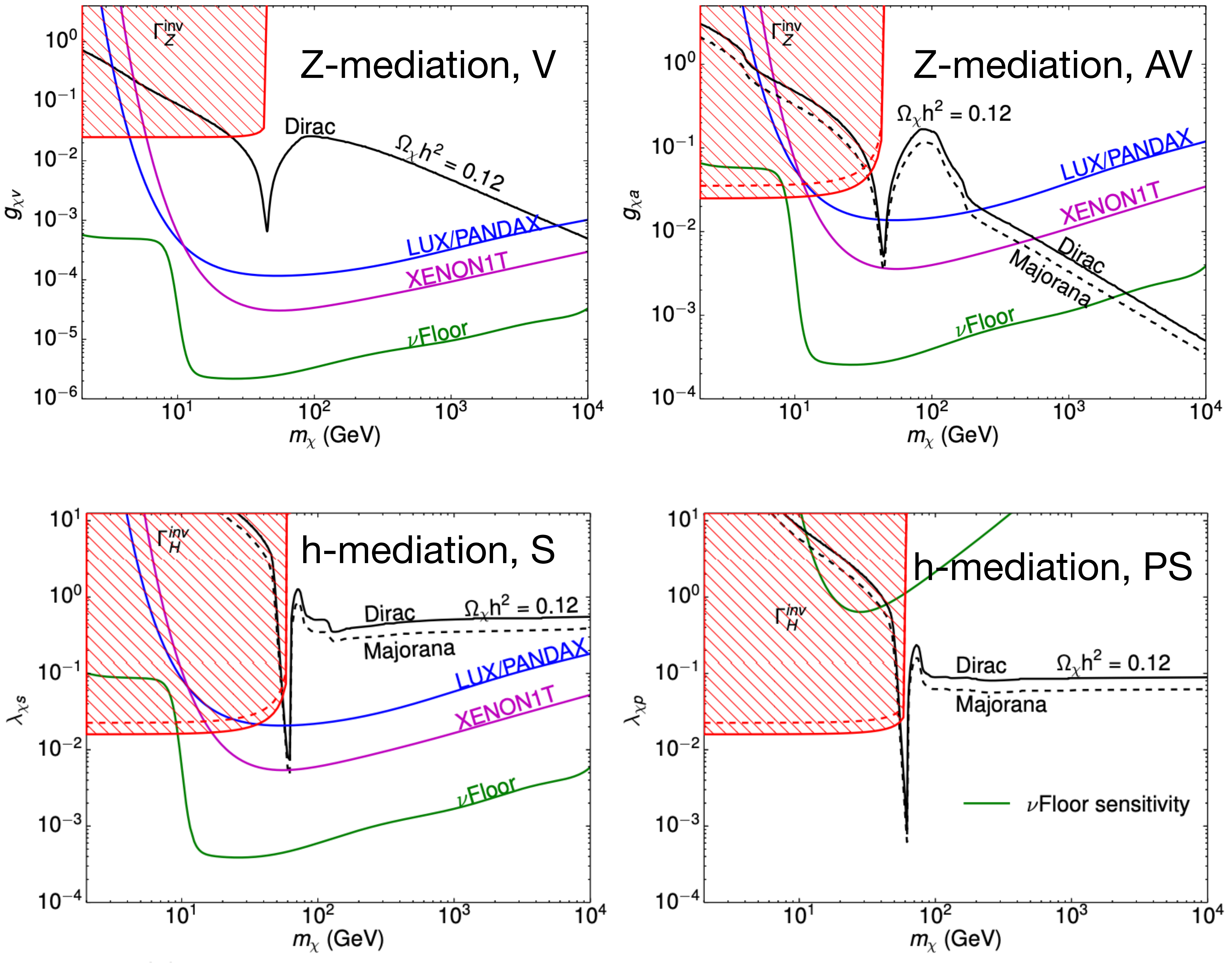
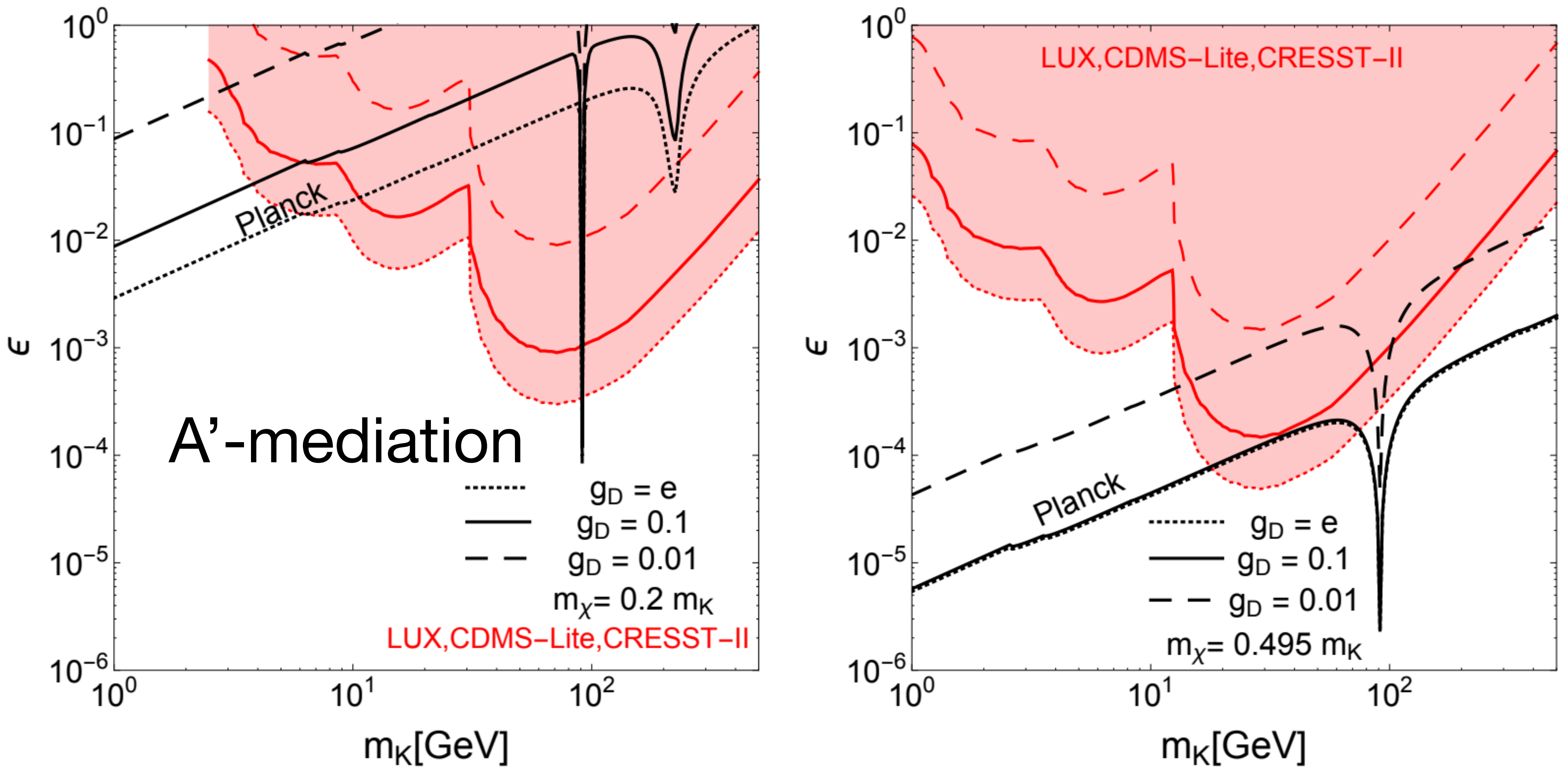
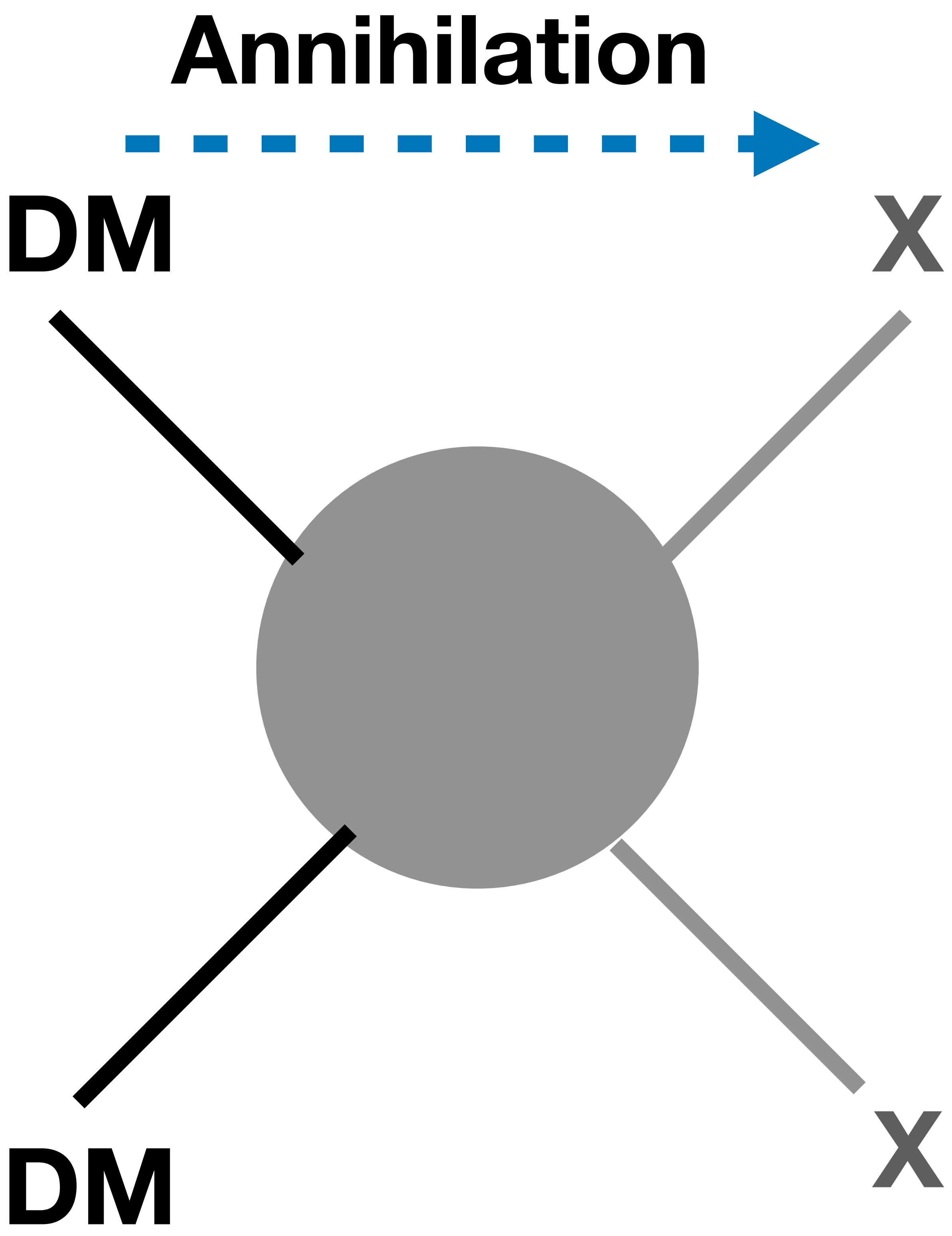


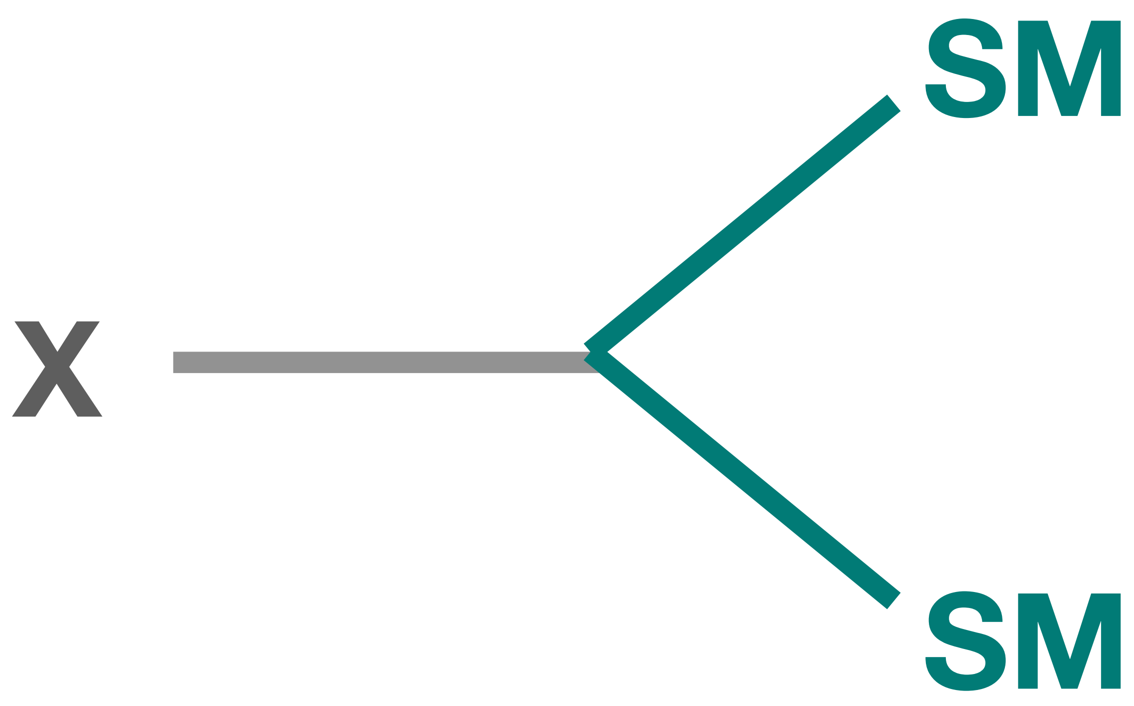
JL, X.P. Wang, F. Yu, 1704.00730, JHEP



The way-out from direct detection limits

- 1. Very small coupling:
  - 1.1 Secluded dark matter (dark sector)





Dark mediator with very small coupling to SM

The way-out from direct detection limits

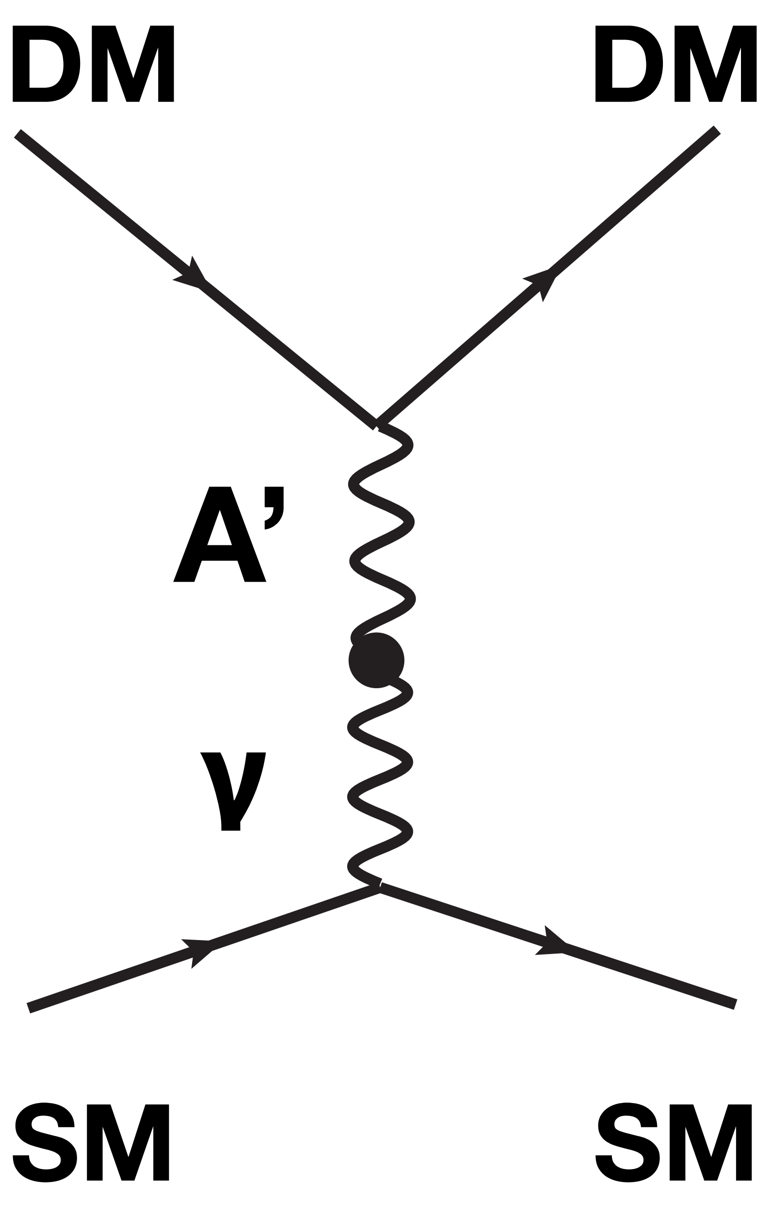
- 1.1 Secluded dark matter (dark sector)

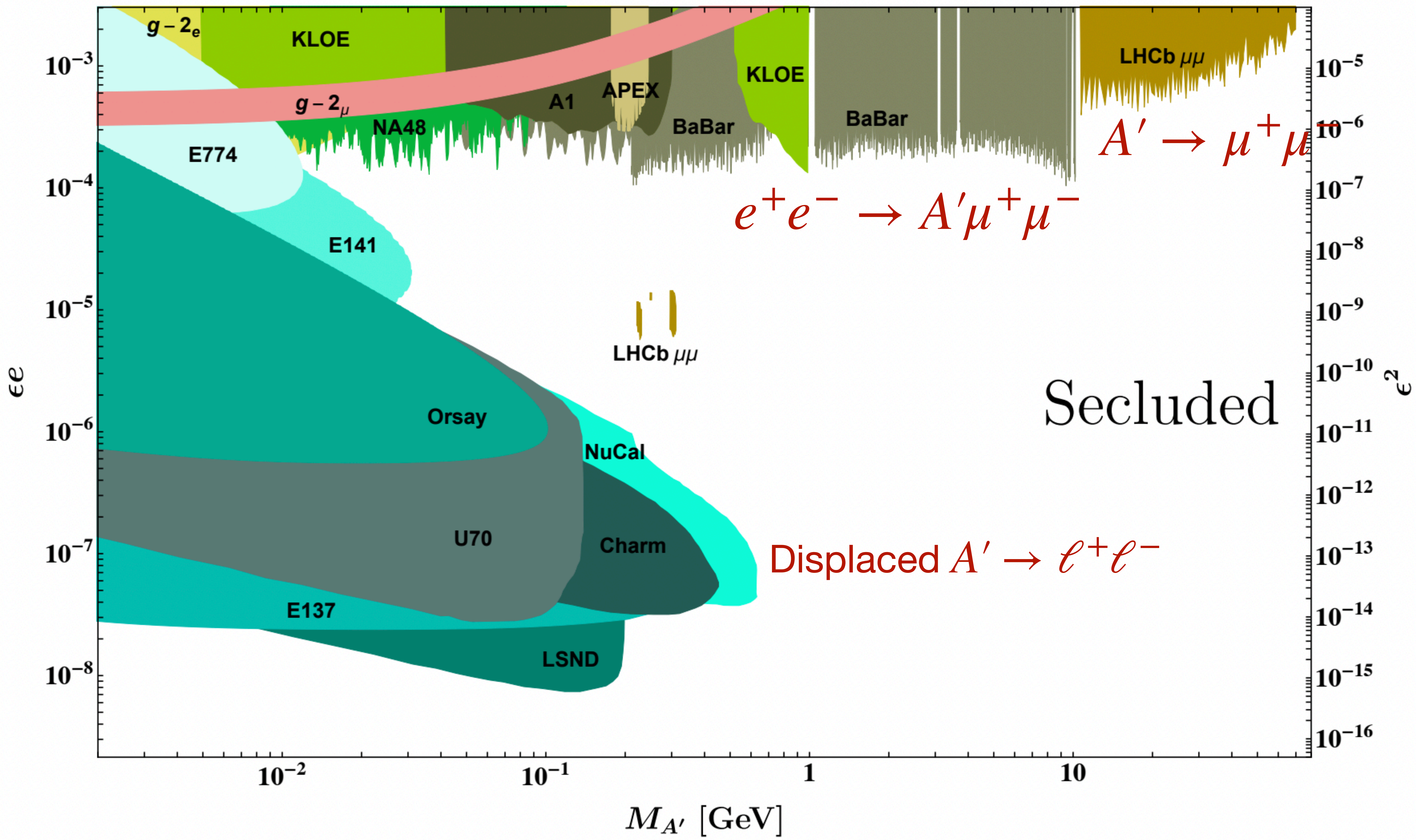
  - Looking for mediator X is easier than DM

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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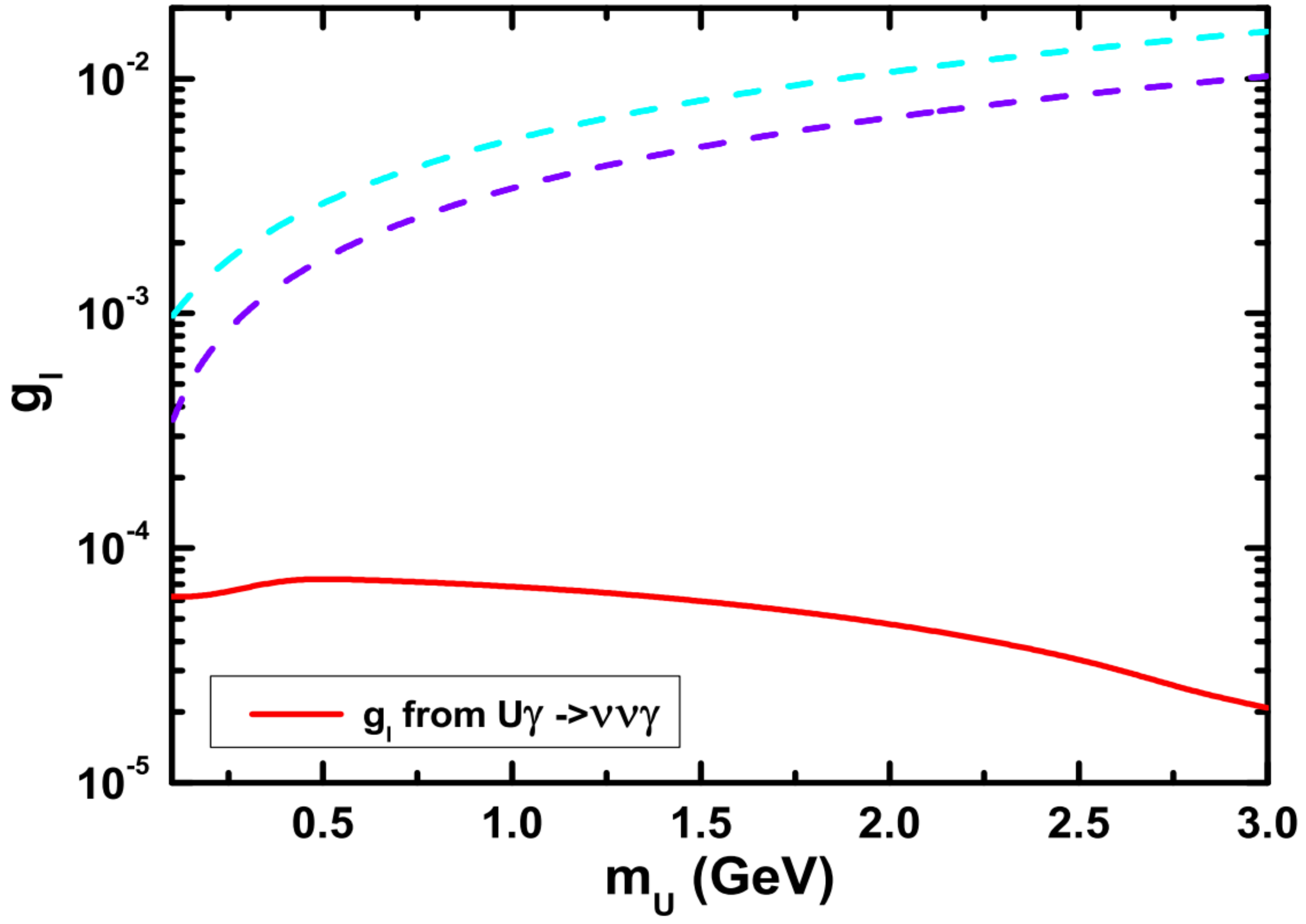
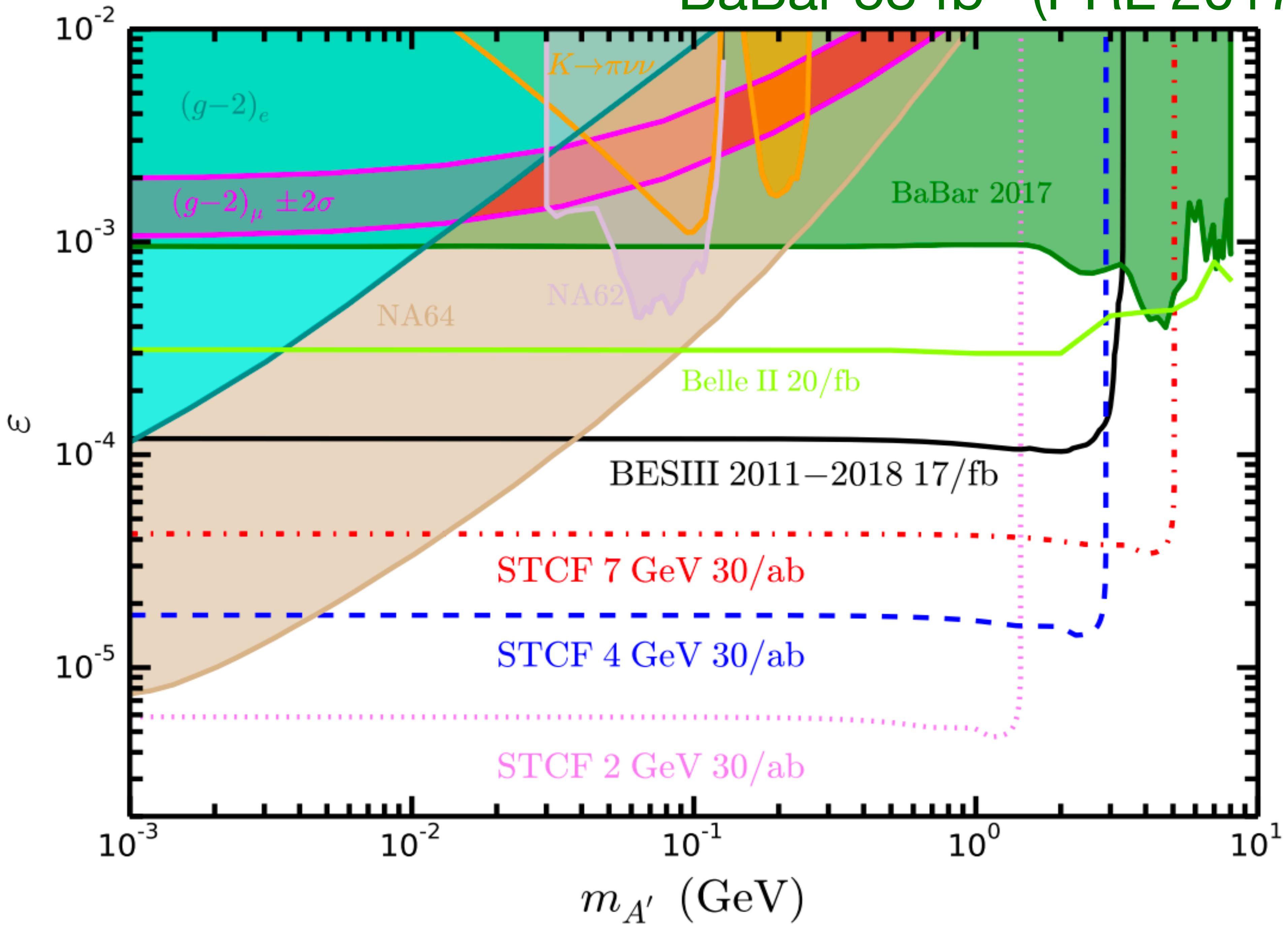
Dark photon A' example: invisible $A' \to \bar{\nu}\nu, \bar{\chi}\chi$

NA64: e beam dump, but for invisible final states

BaBar 53 fb^{-1} (PRL 2017)



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

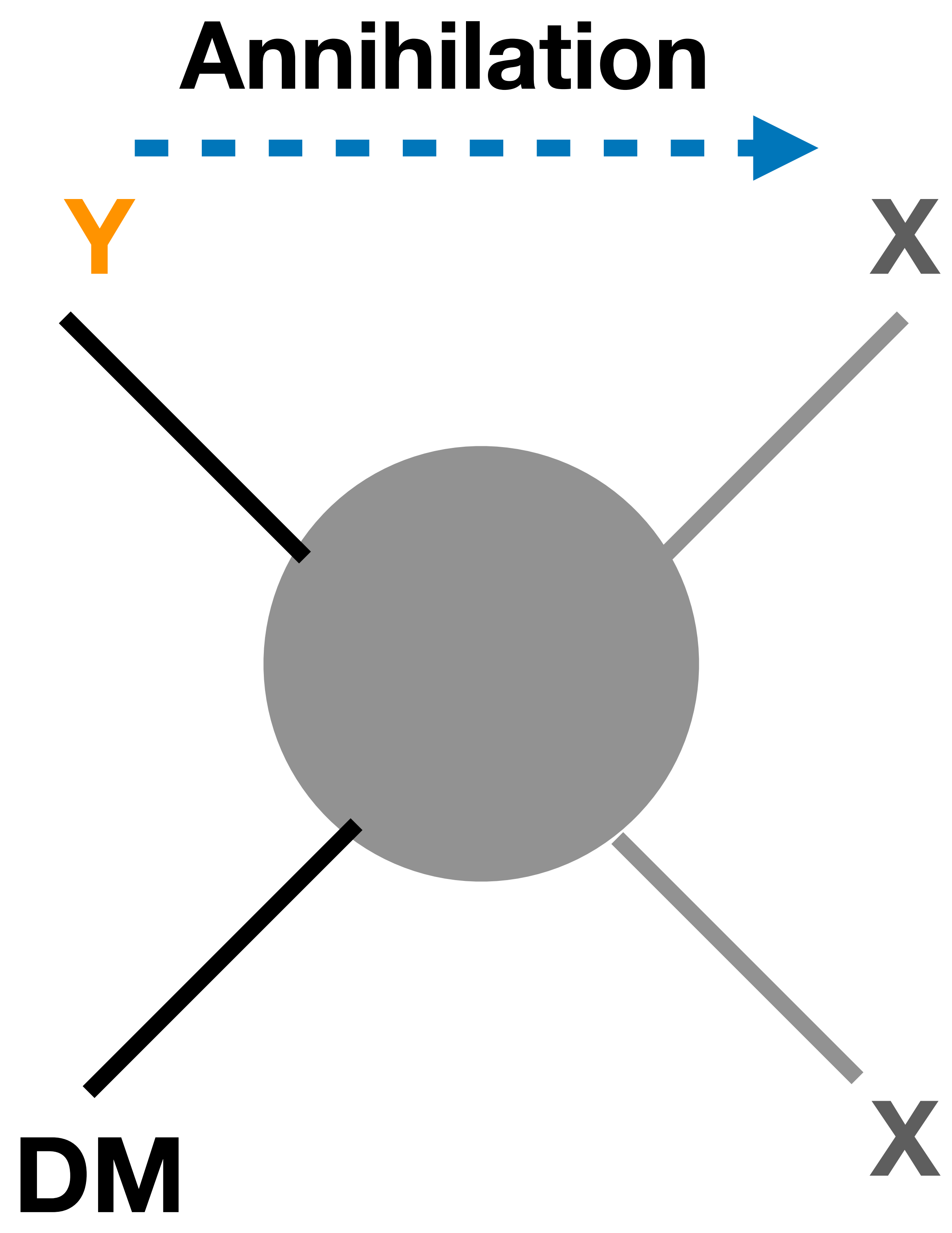
Case for Fermionic DM

Kumar & Marfatia:1305.1611 (PRD)

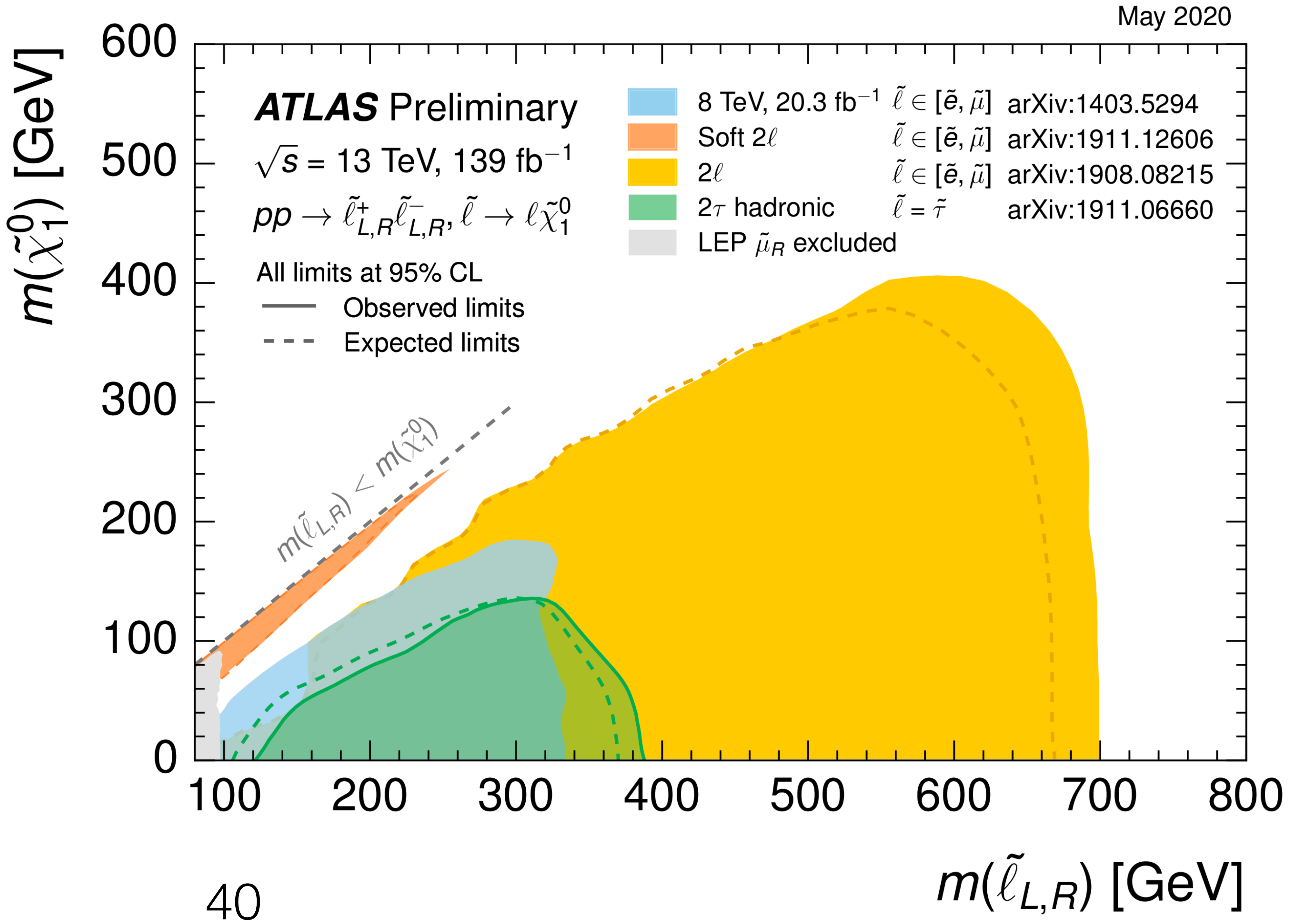
	Name	Interaction Structure	$\sigma_{\rm SI}$ suppression	$\sigma_{\rm SD}$ suppression	s-wave?
Scalar	F1	$\bar{X}X\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	No
	F2	$\bar{X}\gamma^5 X\bar{q}q$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
	F3	$\bar{X}X\bar{q}\gamma^5 q$	0	q^2 (SM)	No
Pseudoscalar	F4	$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	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



- Y has a close mass with DM
  - Y is not populated today due to decay
  - Charged Y: near degenerate spectrum of SUSY, AMSB; EW multiplet DM (2n+1, 0) ($\delta m \sim$ 166 MeV)



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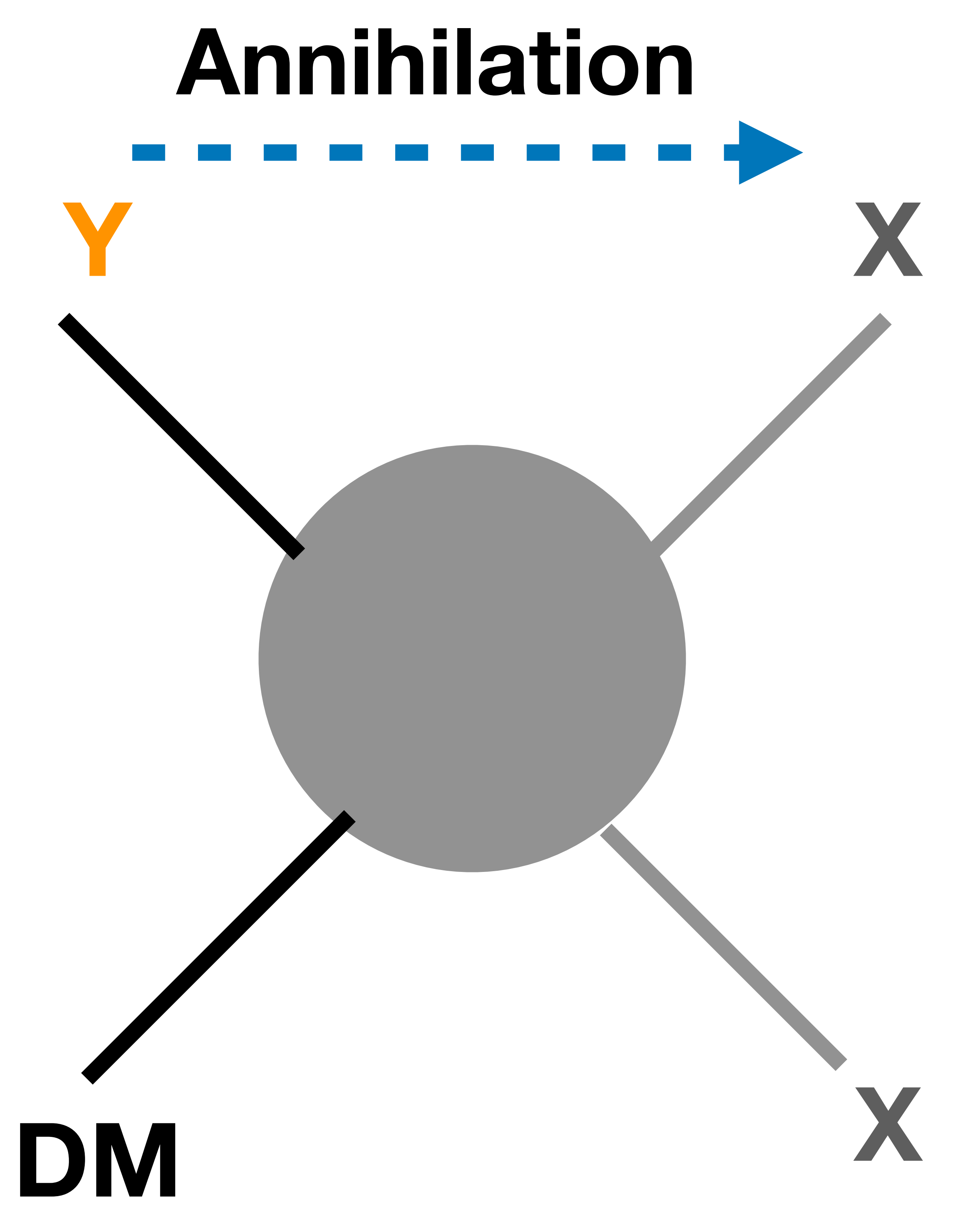

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  - Y is not populated today due to decay
  - Charged Y: near degenerate spectrum of SUSY, AMSB
  - Neutral Y: Inelastic Dark Matter

Fermionic DM with kinetic mixing A' mediator

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

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

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

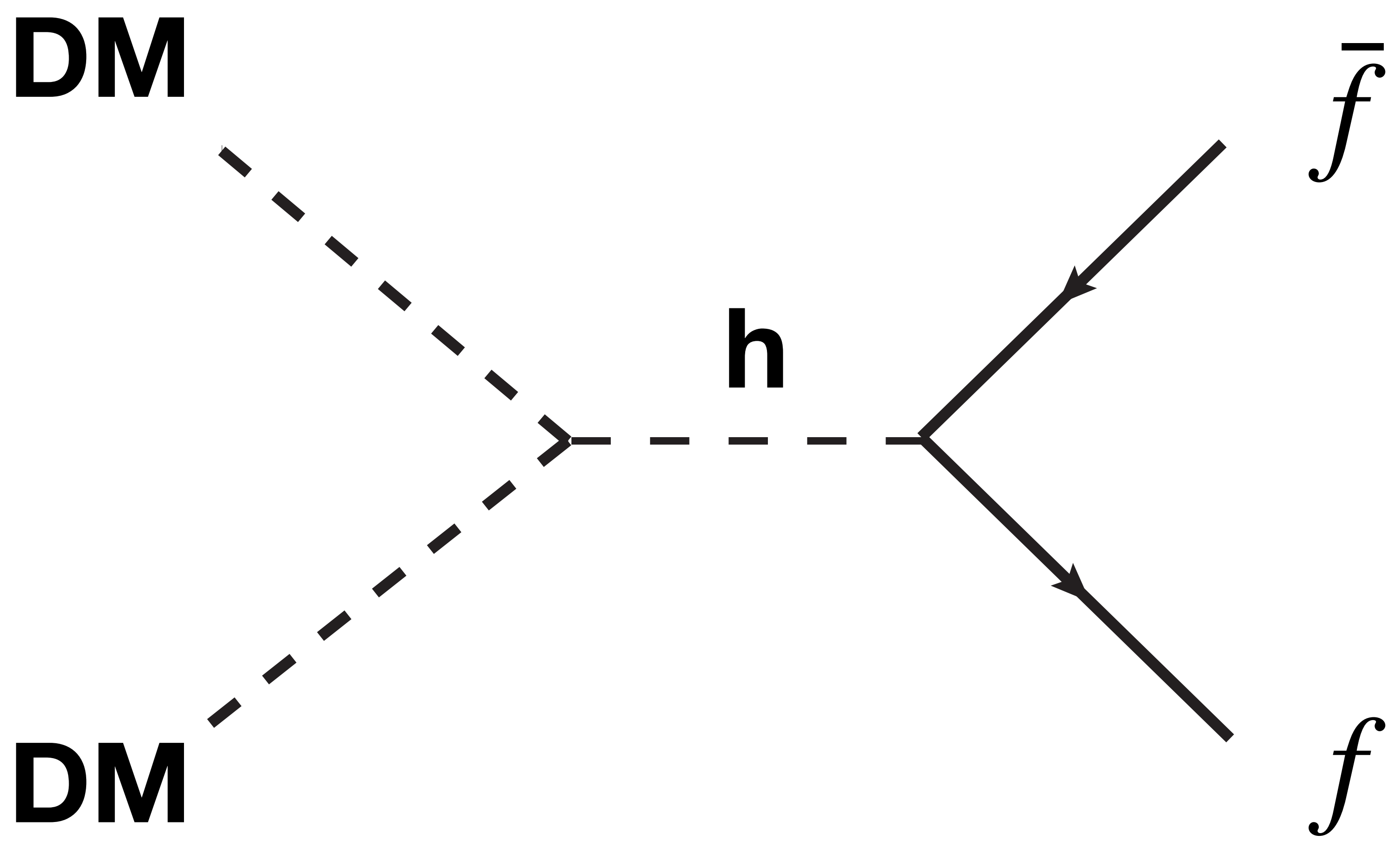
Smith, Weiner: hep-ph/0101138 (PRD)

The way-out from direct detection limits

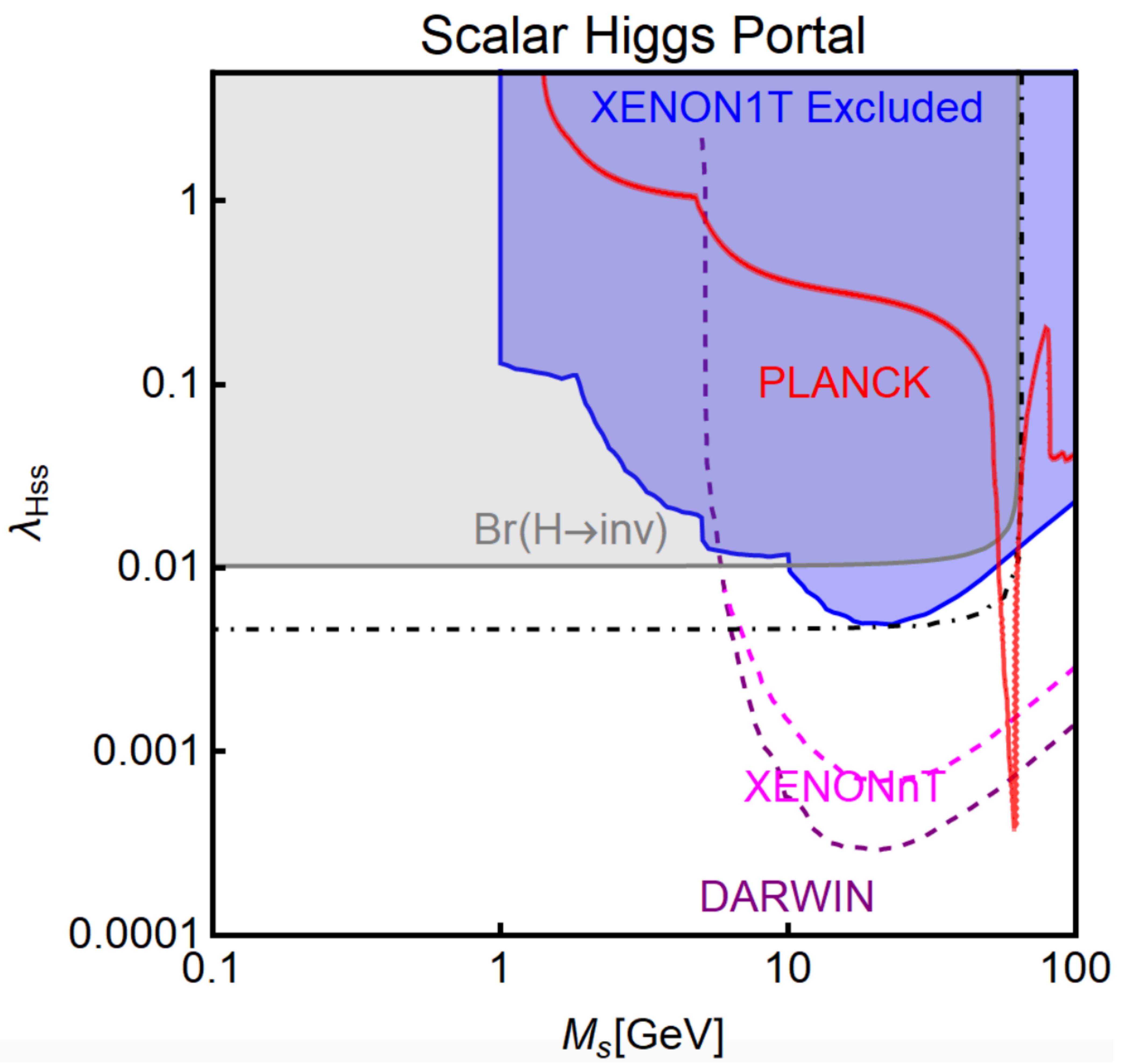
- 4. Resonant annihilation
  - $2m_{\rm DM} \approx m_X$

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

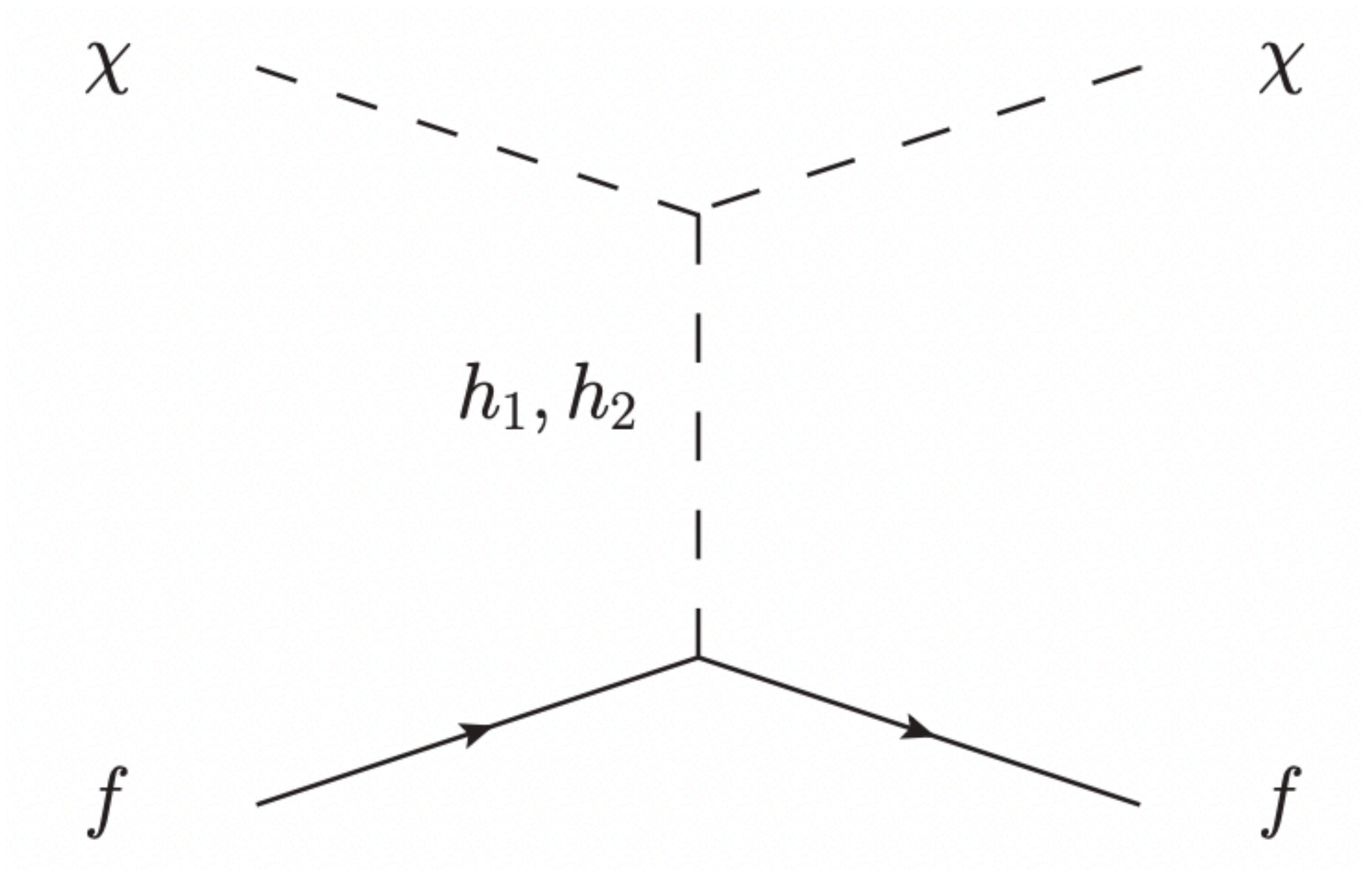
See also WL Guo, LY Wu et al 2010; B Li, YF Zhou 2015

The way-out from direct detection limits

- 5. Cancellation effect in scattering cross-section

  - SM Higgs - Dark scalar mediator cancellation

Gross, Lebedev1, 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) $\rightarrow (h_1,\ h_2)$

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

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

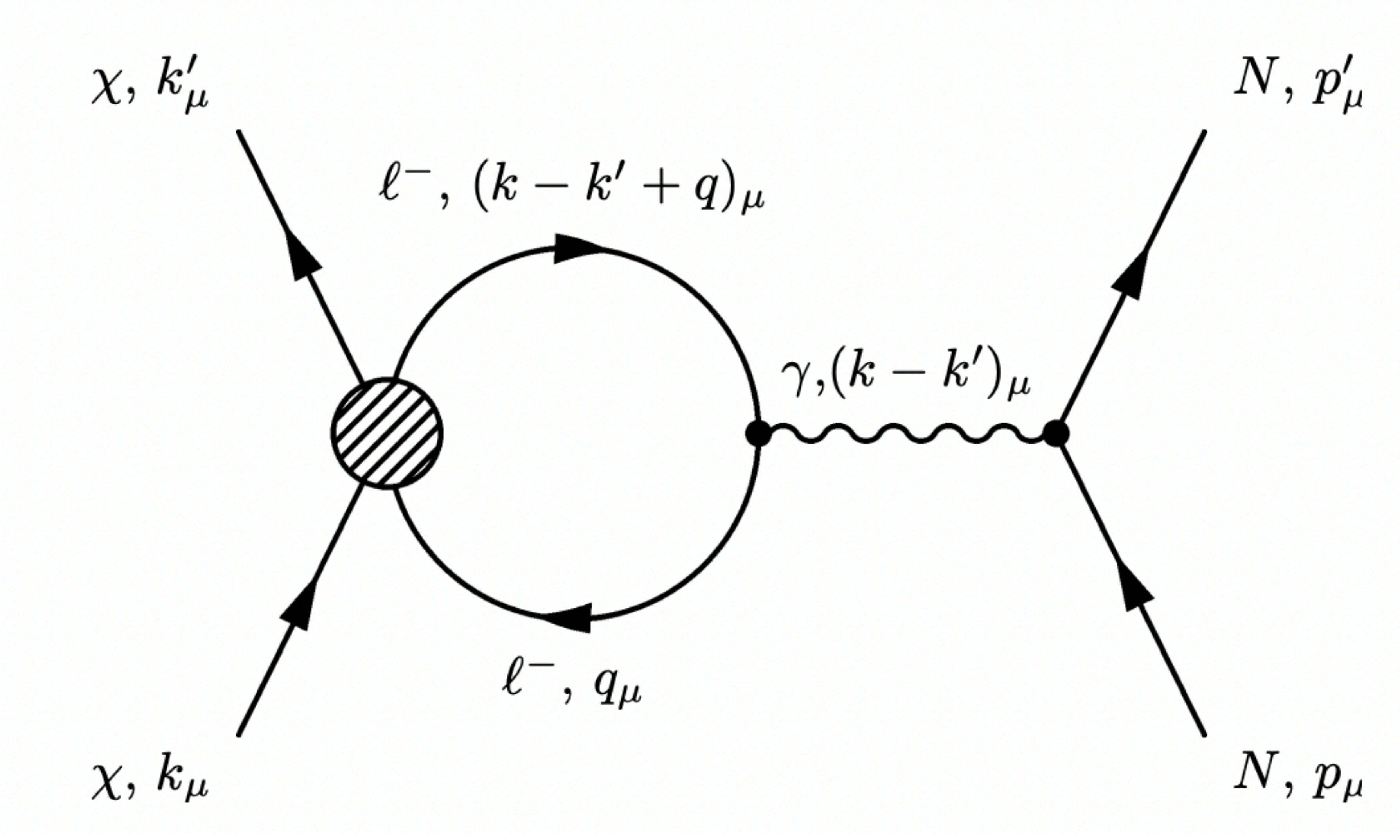
See JL, XP Wang and F Yu 1704.00730 (JHEP), for cancellation between A' - Z boson in kinetic mixing dark photon model

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

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)
    - 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

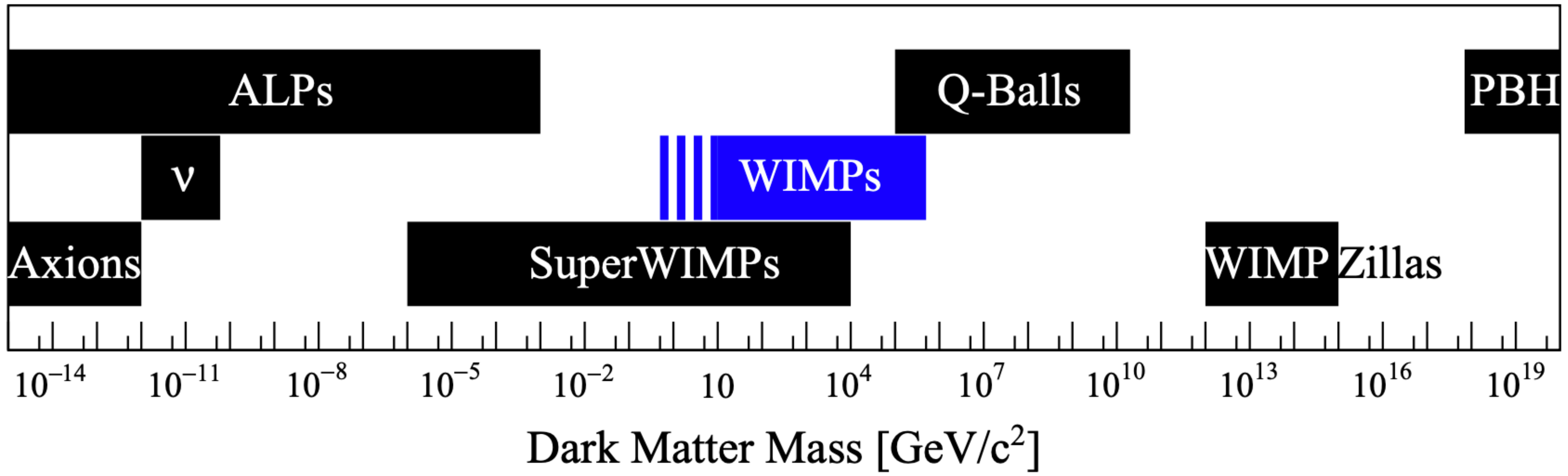
The probability to find a high p electron
in the wave function is highly suppressed!

Kopp et al: 0907.3159 (PRD)

Outlines

- The dark matter in astrophysics perspective
- The dark matter in particle physics perspective
    - The WIMP crisis from direct detection
    - The DM limits from indirect detection
    - A WIMP variant from cosmological evolution
- Summary

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!

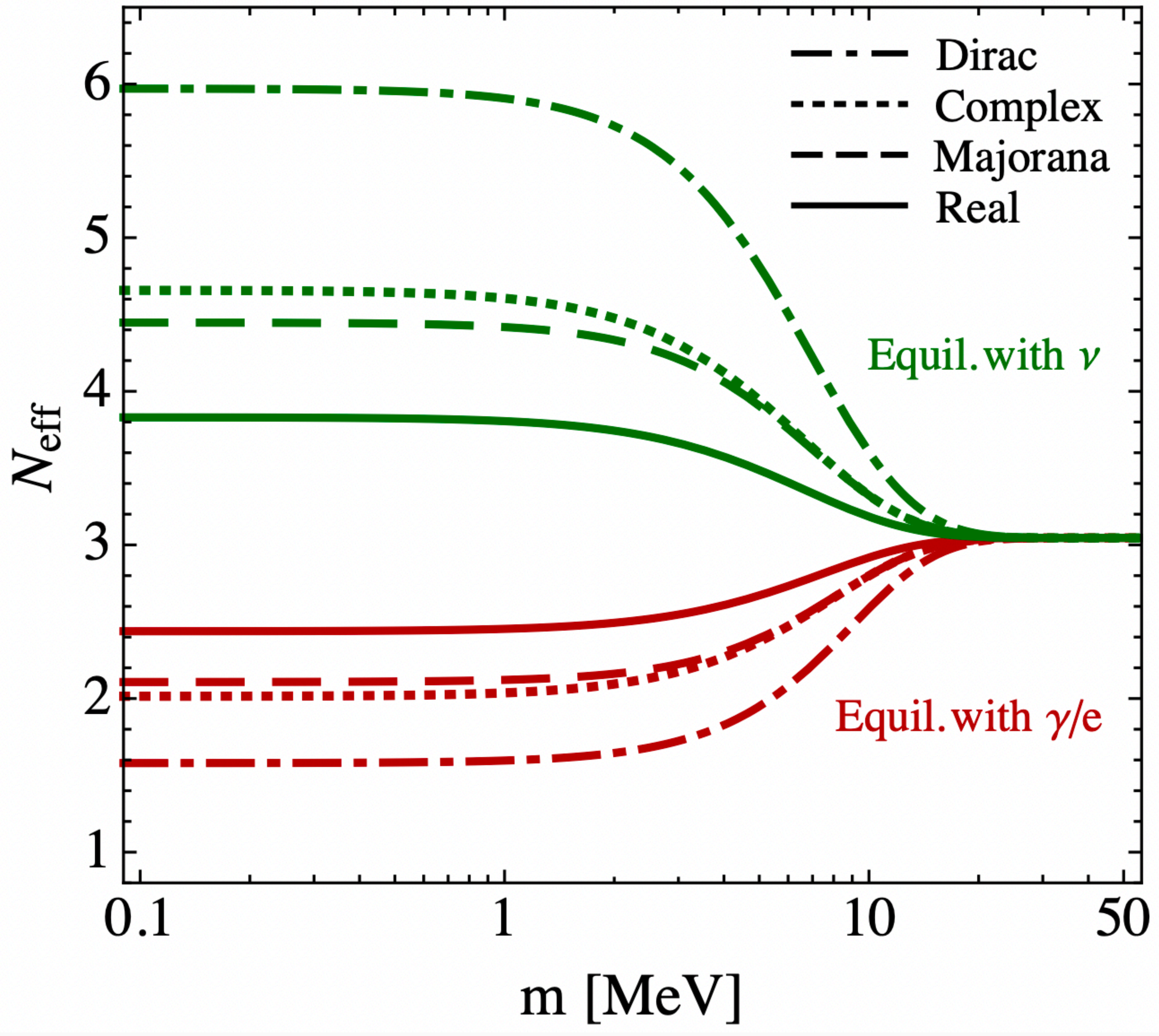
(Secluded X → SM + SM)

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 $T_{fo} \sim m_{\text{DM}}/20$
  - DM entropy goes into neutrinos or e/γ, will modify T_ν/T_γ

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.



Boehm et al: 1303.6270 (JCAP)

The annihilation cross-section expansion

- Expansion over velocity
  - S-wave
  - P-wave (L=1)
  - D-wave (L=2), due to extra chiral suppression

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

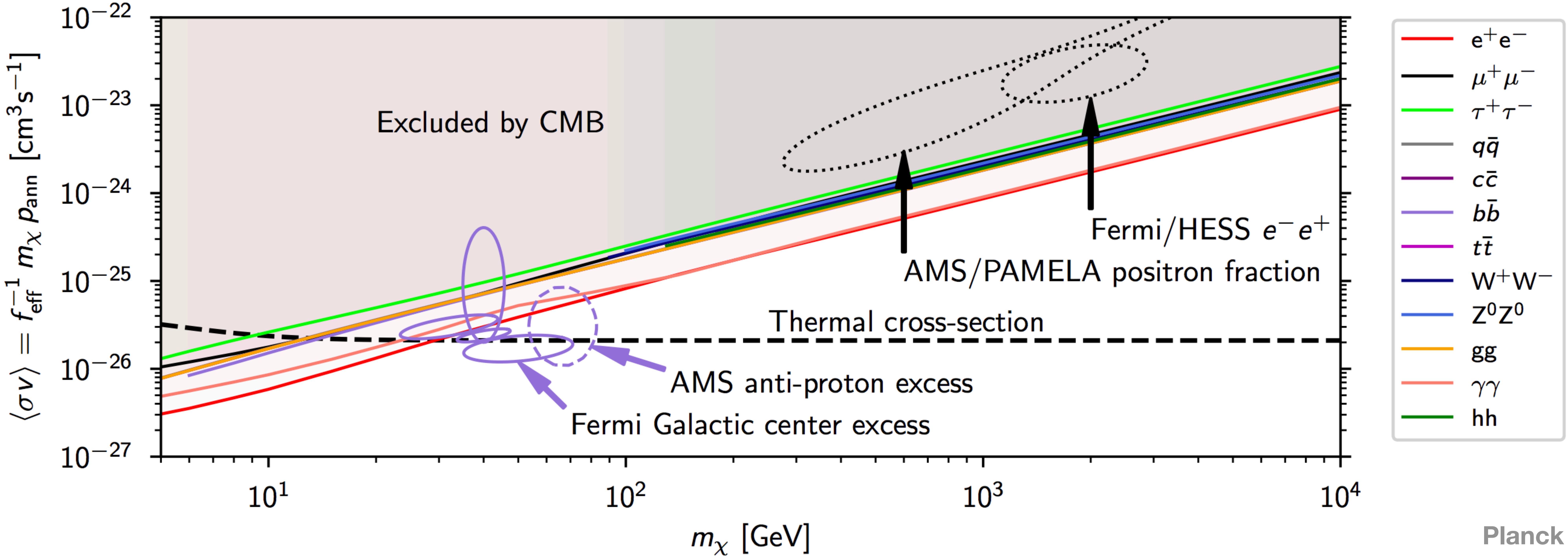
- The value of velocities at different time
  - Freeze-out: $v^2 \sim 0.25$
  - CMB: $v^2 \sim \mathrm{eV}/m_{\mathrm{DM}} \sim 10^{-5}$
  - Today: $v \sim 10^{-3} c$

Annihilation constraints from CMB

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

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

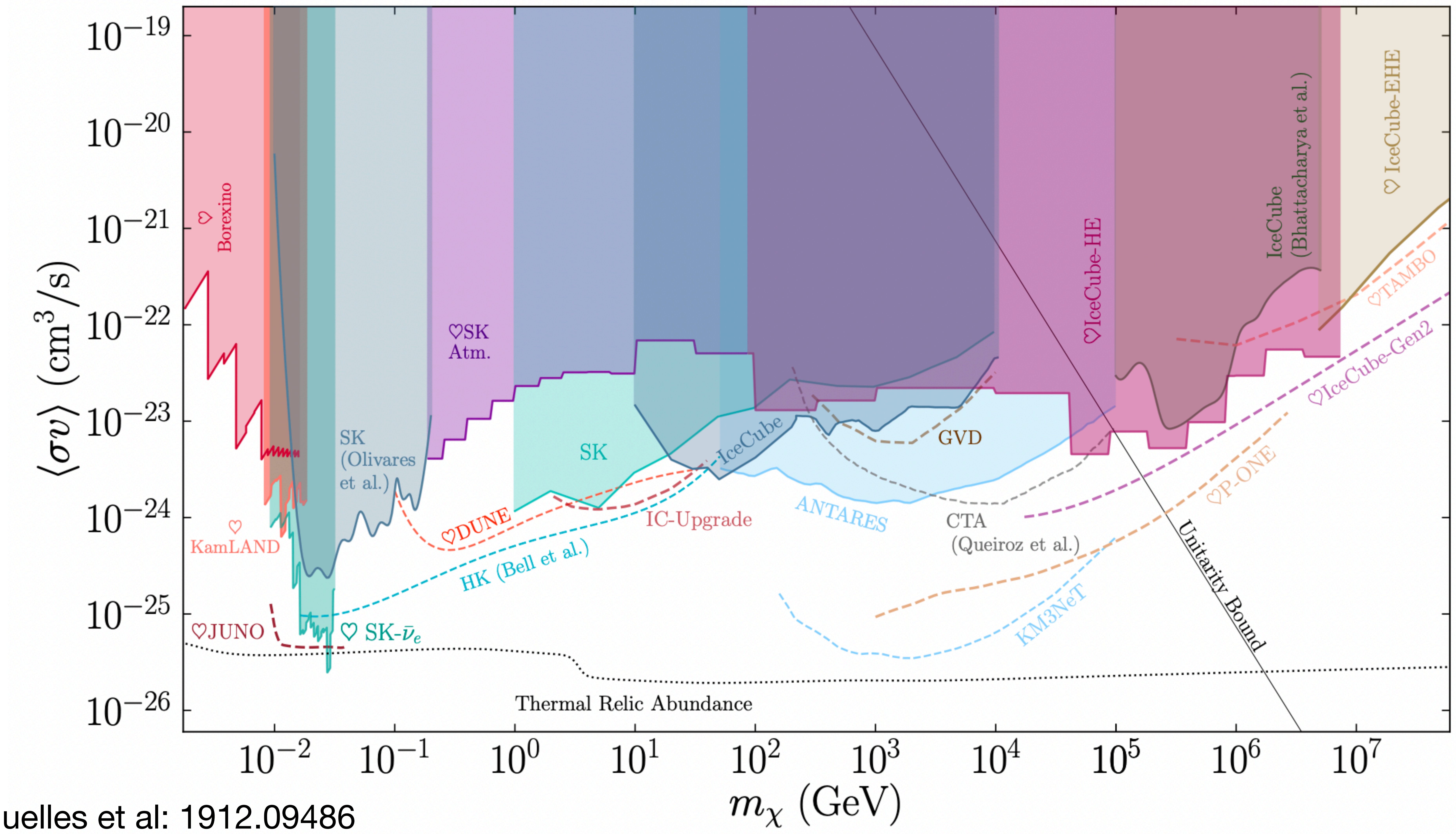
- f_{eff} : the efficiency with which the energy released in DM annihilation is absorbed by the primordial plasma



Planck 2018

How to escape CMB constraints?

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



Arguelles et al: 1912.09486

How to escape CMB constraints?

- 2. 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)

How to escape CMB constraints?

- 2+. Linear v suppression
  - How about cross-section linear in v? ($\sigma v \propto v$)
    - For CMB, linear v is enough to be safe
    - For indirect detection
      - Cluster, v ~ 1000 km/s ~ 3 x 10^{-3}
      - Galaxy, v ~ 220 km/s ~ 1 x 10^{-3}
      - Dwarfs, v ~ 10 km/s ~ 3 x 10^{-5}
    - Detectable in Cluster and Galaxy, not in Dwarfs

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

Linear v to escape CMB limits

- Cross-section linear in v

$$\mathrm{DM} + \mathrm{DM} \to \mathrm{X} + \mathrm{X} \qquad \langle \sigma v \rangle = \frac{1}{4m_{DM}^2} \int dPS_2 |\mathbf{M}|^2$$

- If $m_{MD} = m_X$, then the two-body phase space

$$\int dPS_2 = \frac{1}{8\pi} v$$

- For s-wave annihilation, this gives

$$\langle \sigma v \rangle \approx \frac{1}{2} \sigma_0 v$$

- In practice, not exact degenerate

$$\boxed{\begin{array}{c} \Delta = m_{\mathrm{DM}} - m_{\mathrm{X}} \\ \langle \sigma v_{\mathrm{rel}} \rangle \simeq \sigma_0 \sqrt{\frac{v_{\mathrm{rel}}^2}{4} + \frac{2\Delta}{m_{\mathrm{DM}}}} \end{array}}$$

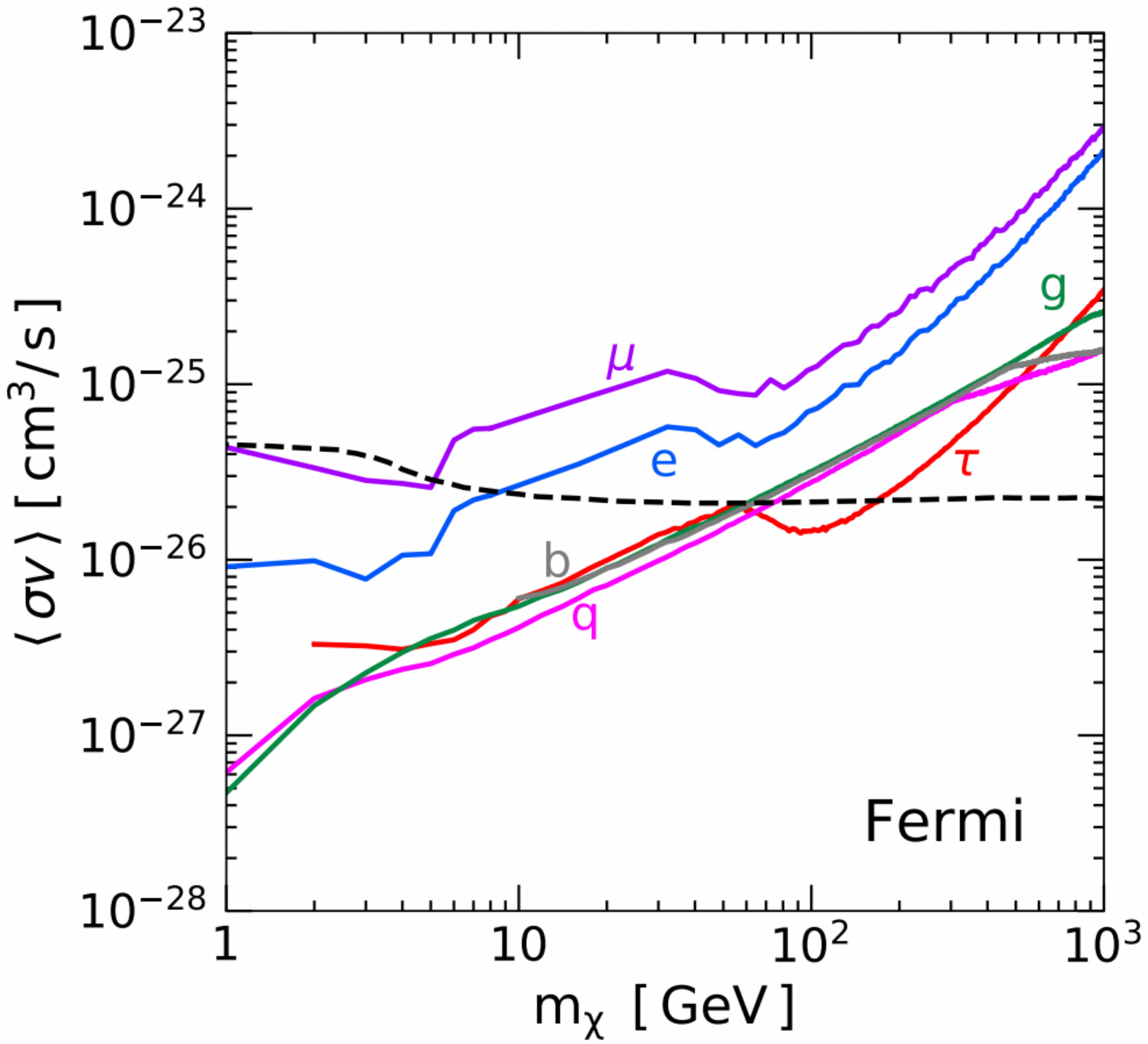
- Model building for $\Delta \ll m_{DM}$

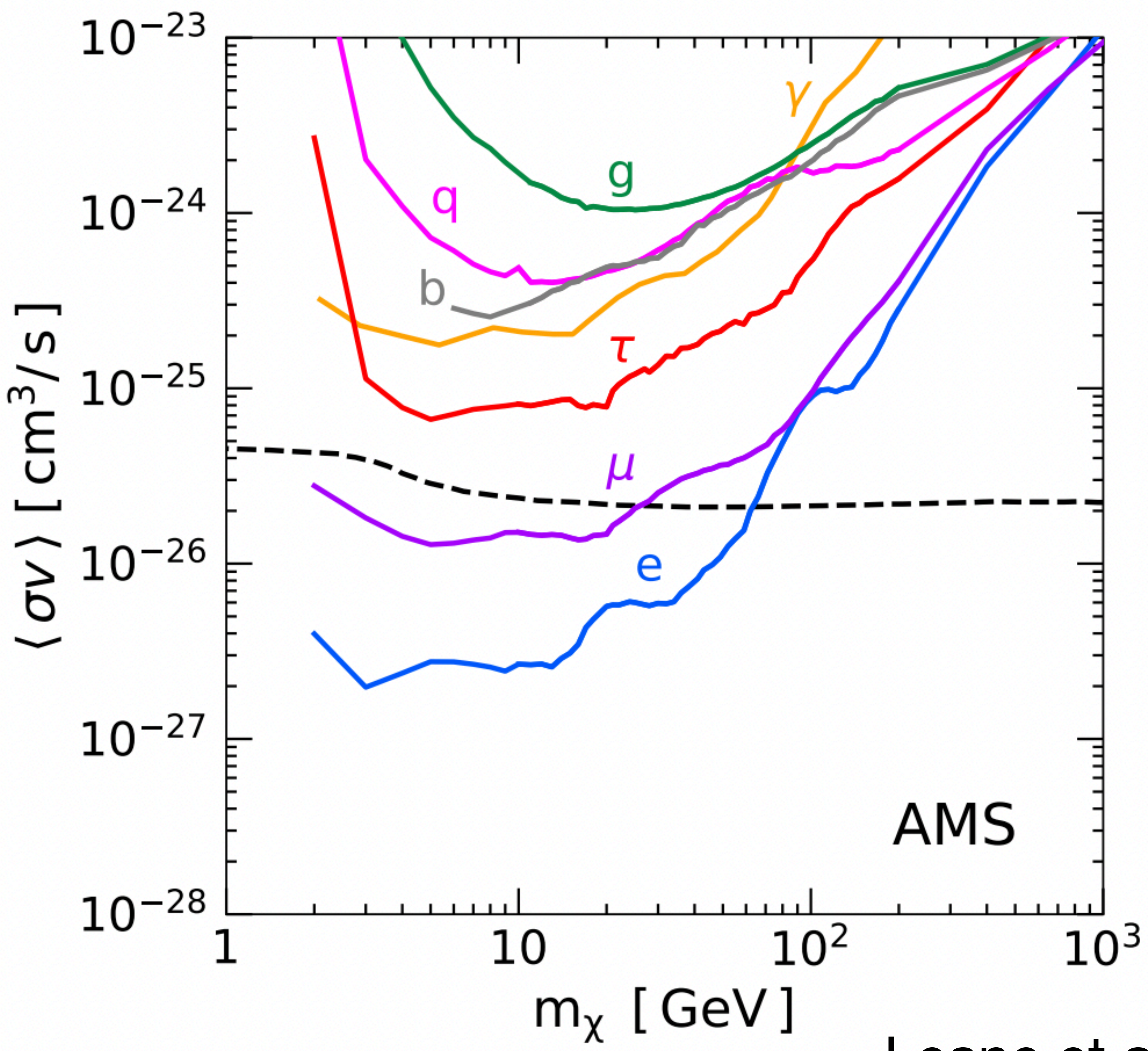
- Symmetry reason
  - Custodial symmetry: dark SU(2) vector DM $\Delta < 0$
  - Chiral symmetry: dark pion DM $\Delta > 0$
  - Supersymmetry: NMSSM setup 1901.02018

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

Other indirect limits

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

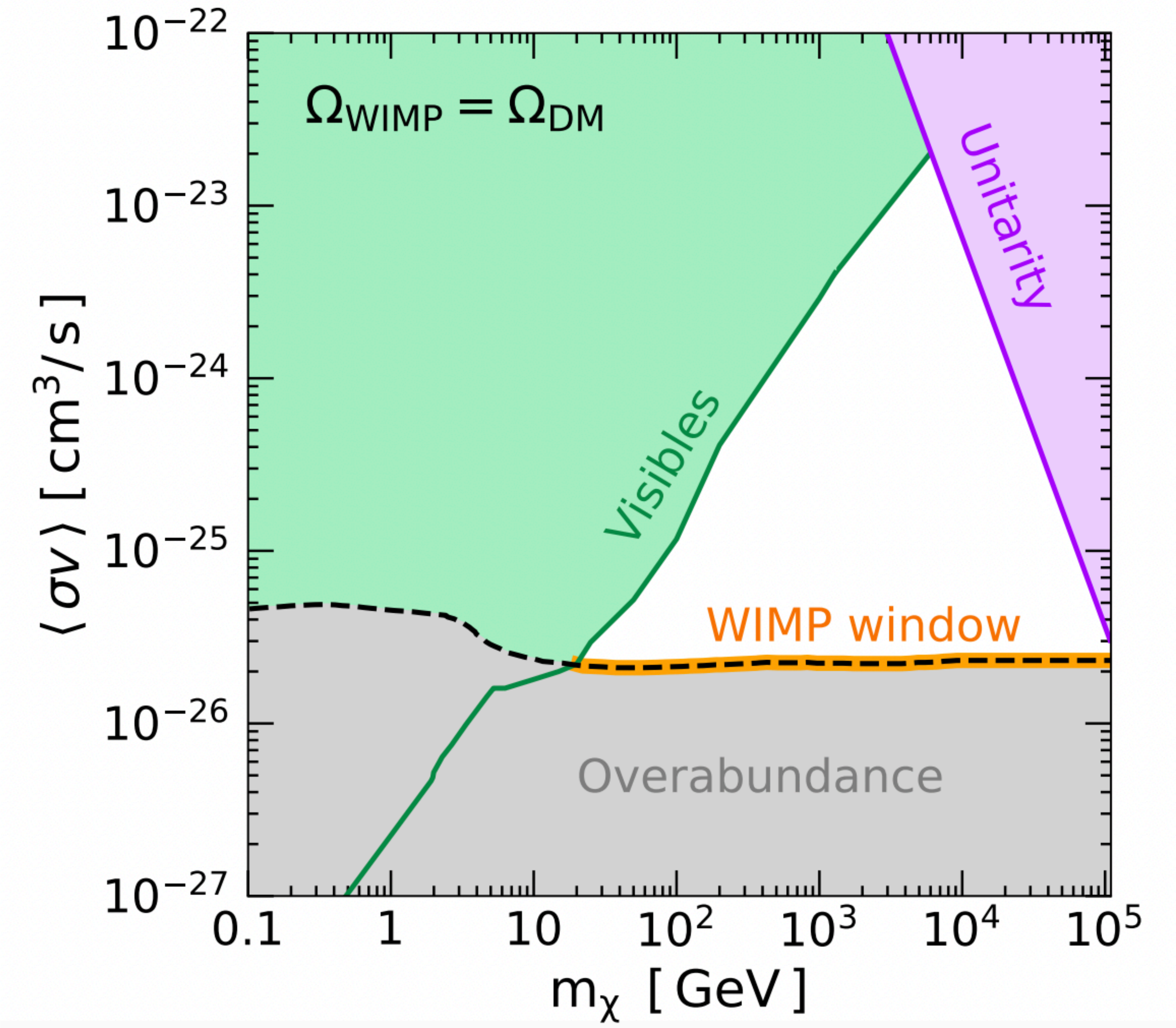




Leane et al: 1805.10305 (PRD)

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)

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Dark matter transient annihilations in the early Universe

Katsuya Hashino, Jia Liu, Xiao-Ping Wang, and Ke-Pan Xie

ArXiv: 2109.07479

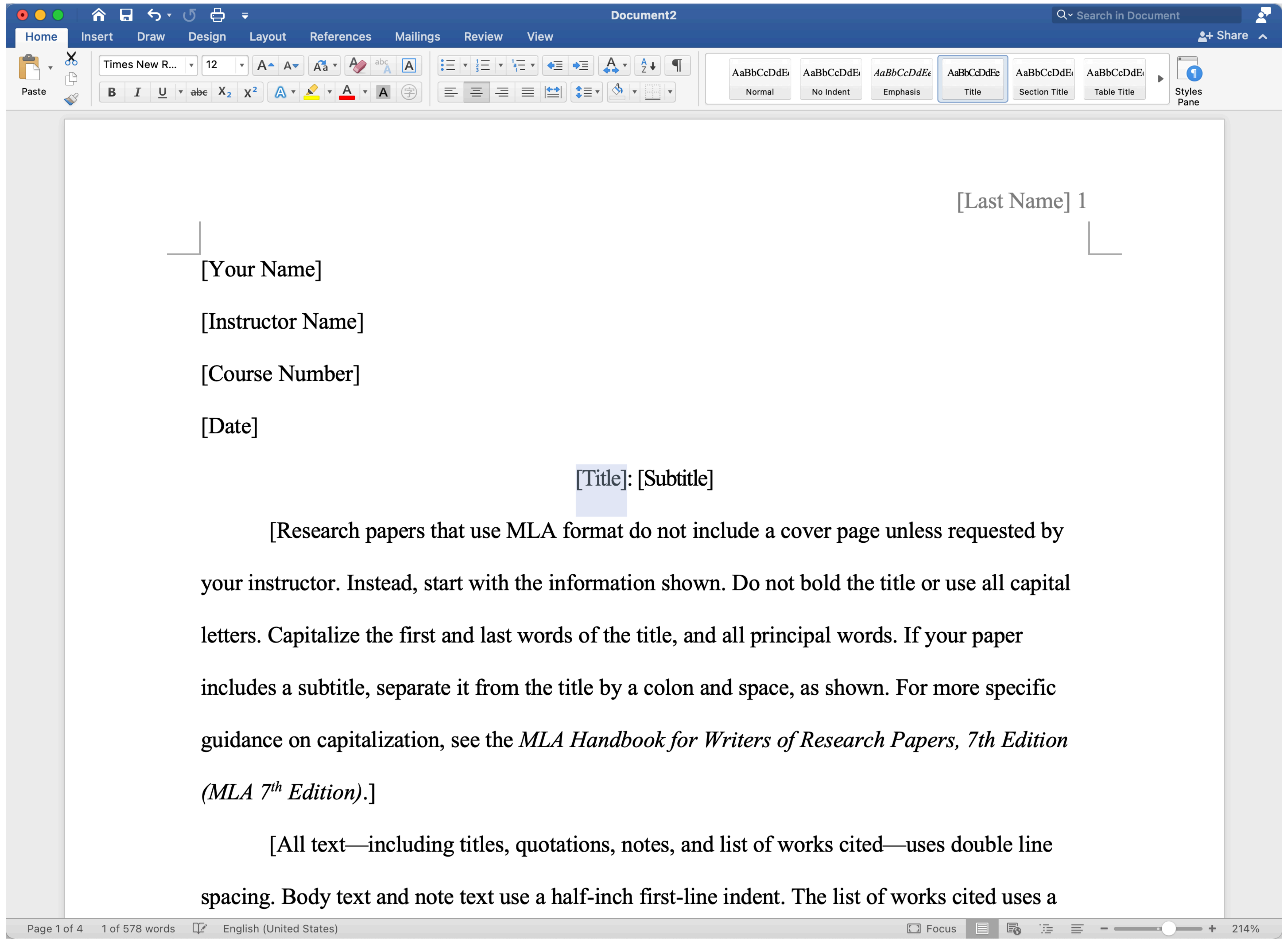
DM properties and cosmological evolution

- 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
…



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[All text—including titles, quotations, notes, and list of works cited—uses double line spacing. Body text and note text use a half-inch first-line indent. The list of works cited uses a

Word, WPS 等办公软件符合“所见即所得”
WYSIWYG，“What You See Is What You Get”

A WIMP variant: DM with transient annihilations

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

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

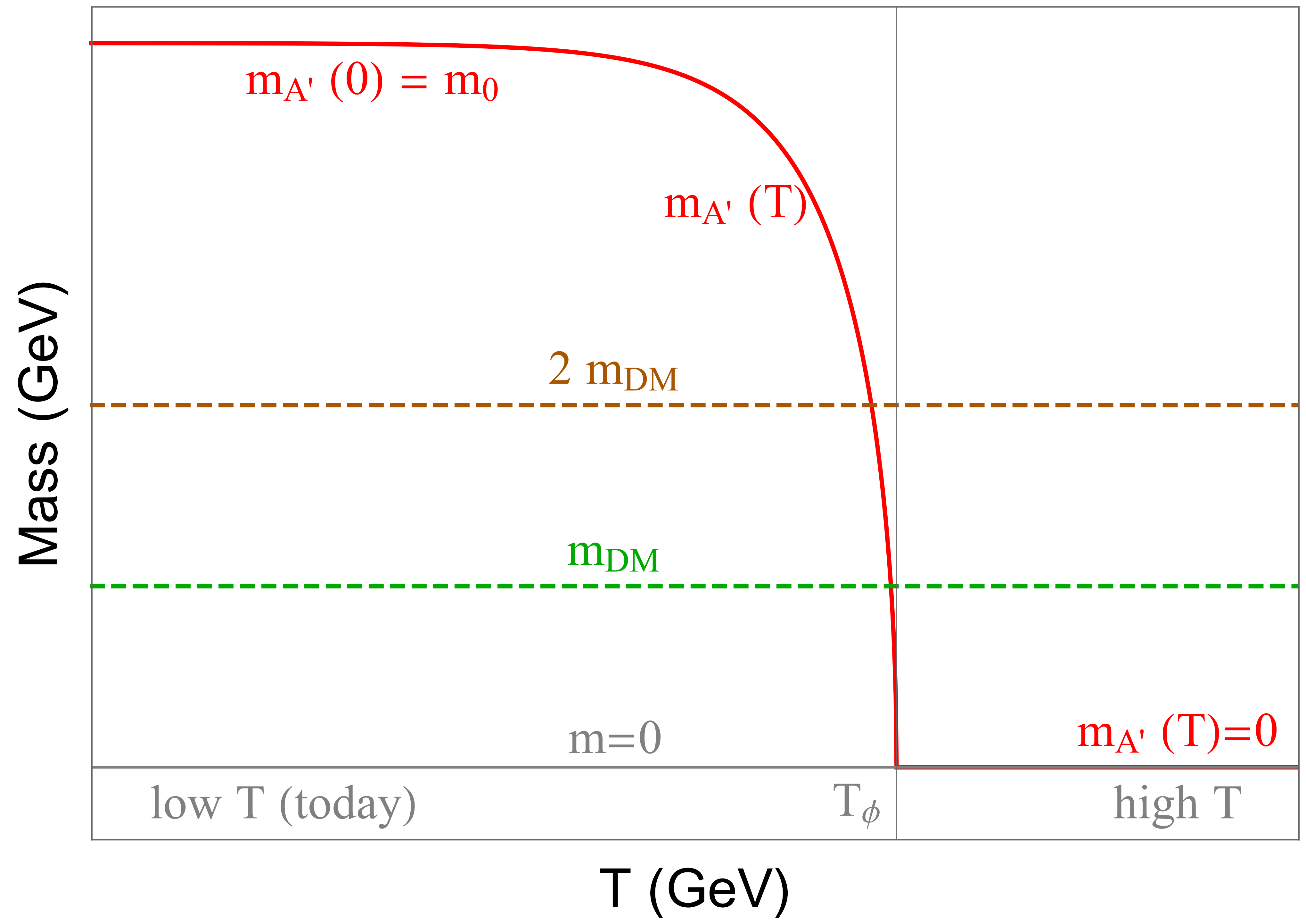
- 2. If it is the DM-SM mediator, and the mass variation happens near DM freeze-out, what happens?

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

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

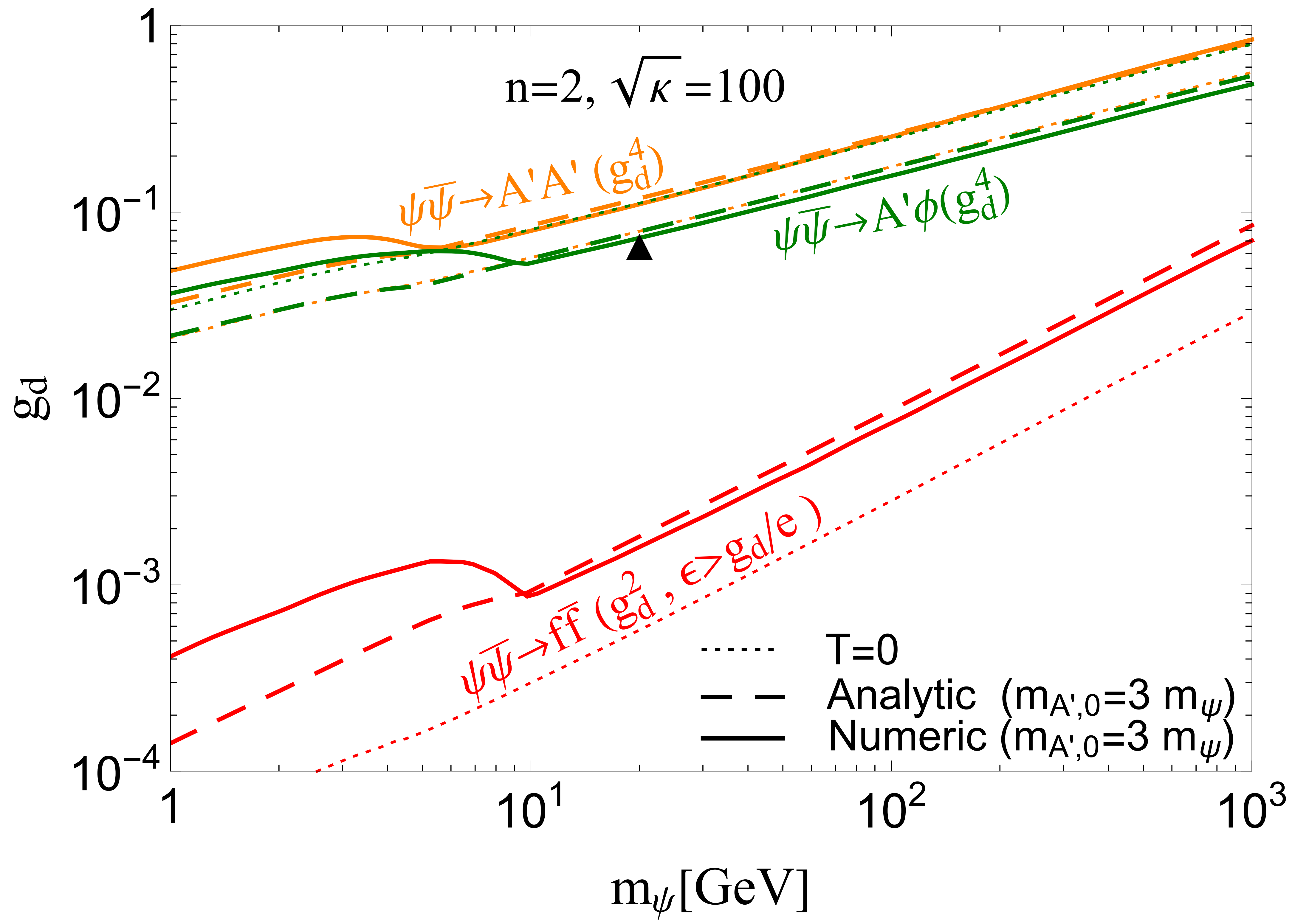
$(\bar{\psi}\psi \to A'\phi)$ $\quad m_{A'} = 2m_\psi - m_\phi,$

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

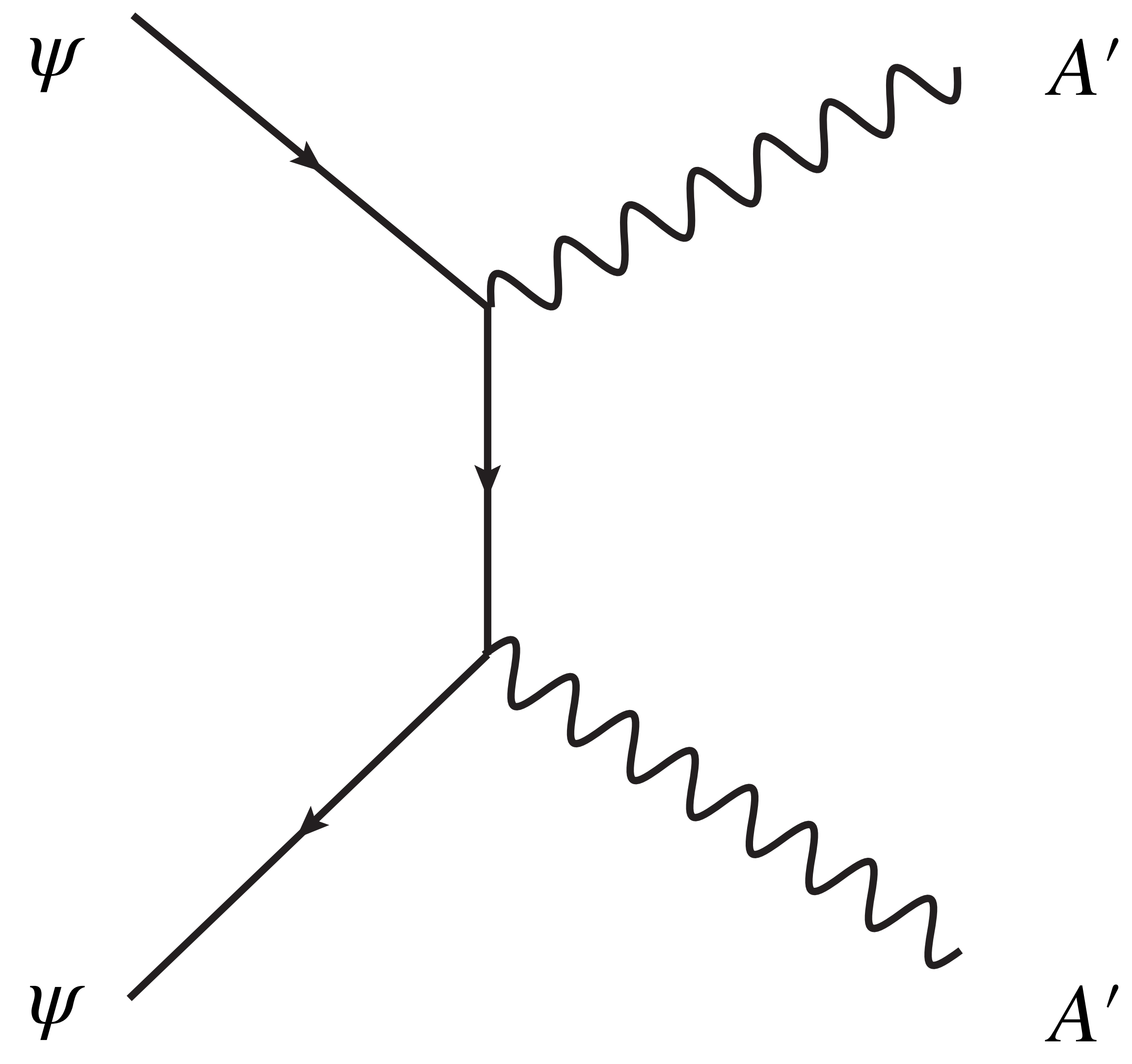


Features for DM with transient annihilations

- Transient secluded annihilation only happens in the early universe
  - is forbidden today
  - No indirect constraints



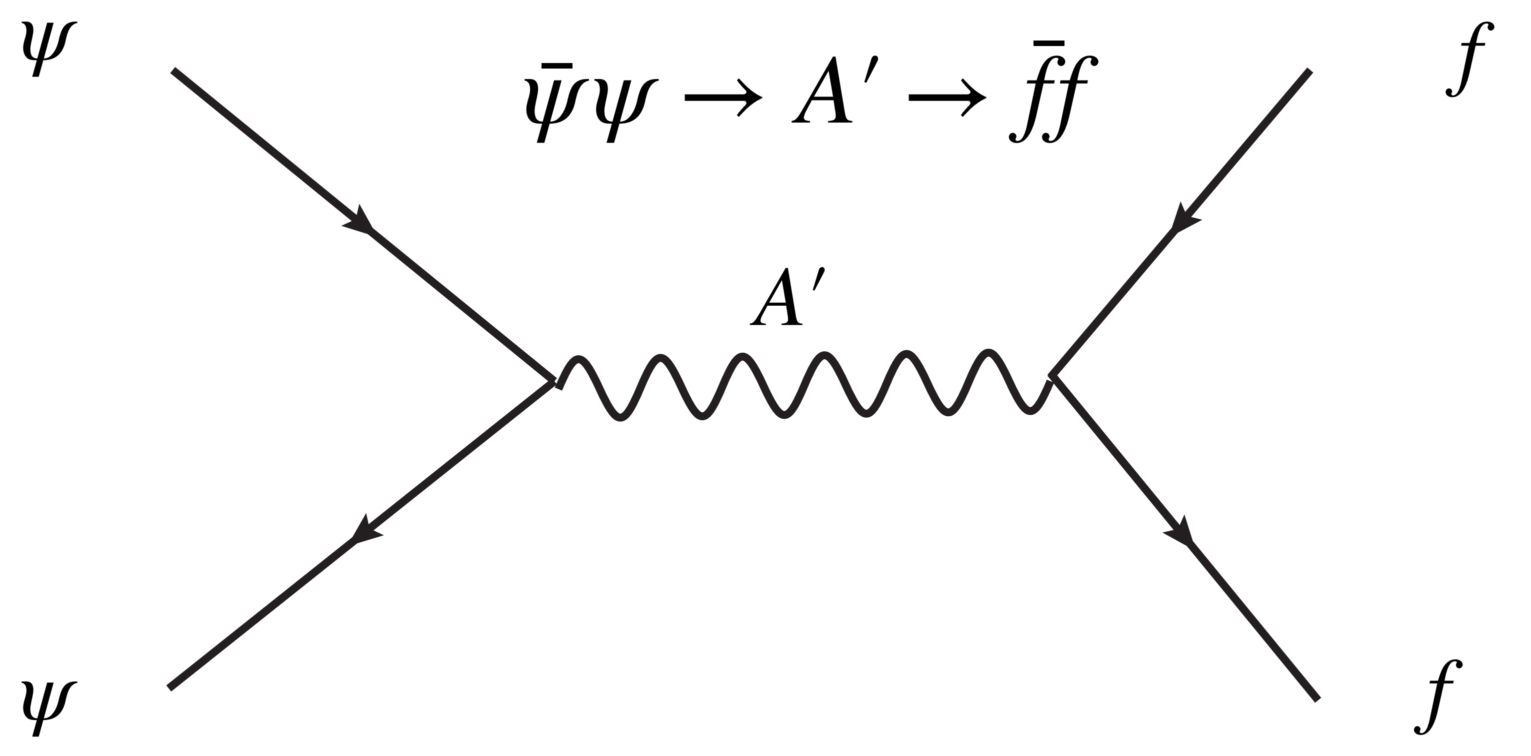
$\bar{\psi}\psi \to A'A'$

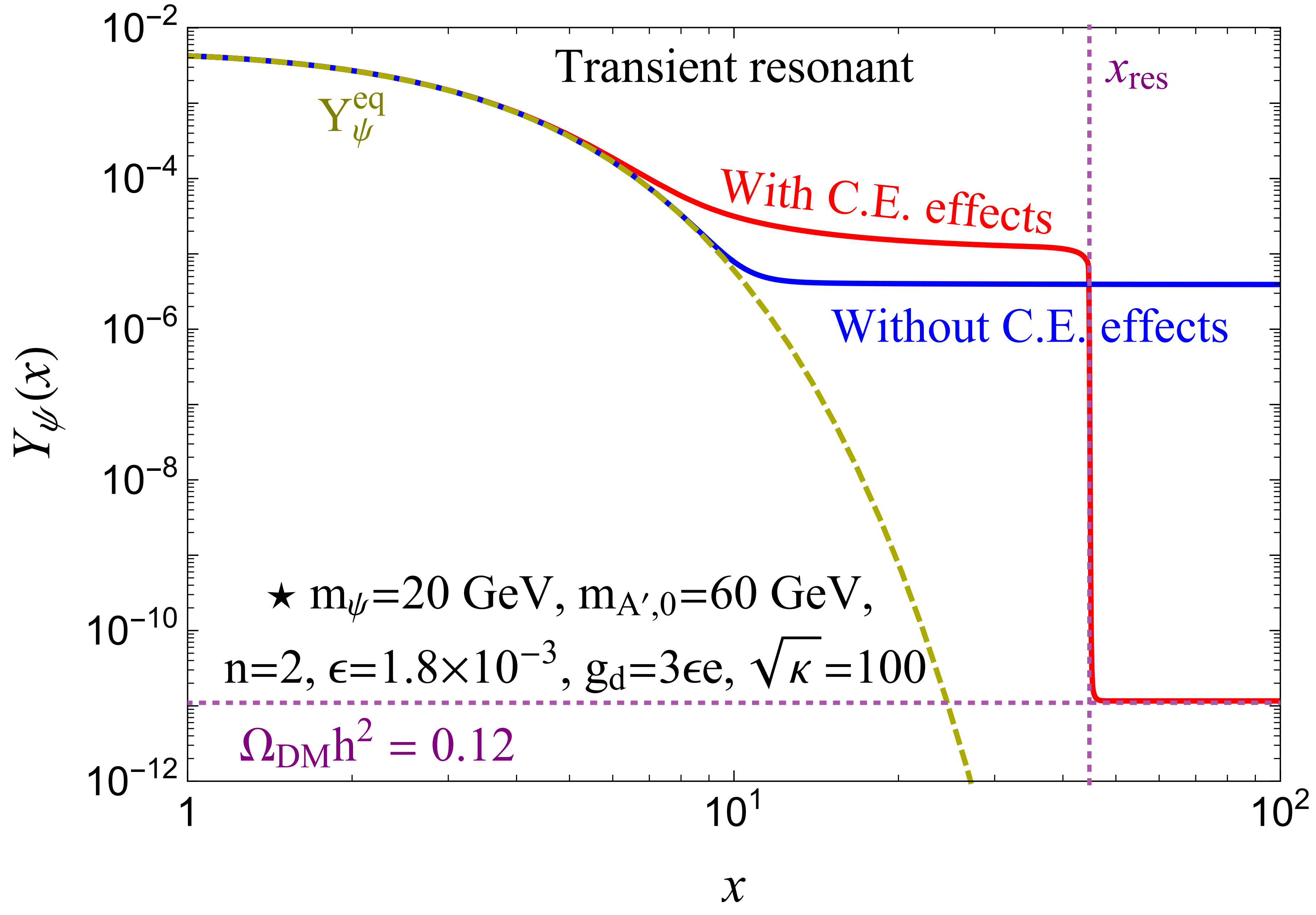


$$\langle \sigma v_{A'A'} \rangle \approx \frac{g_d^4}{16\pi m_\psi^2} \left(1 - r^2\right)^{3/2} \left(1 - r^2/2\right)^{-2}$$

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

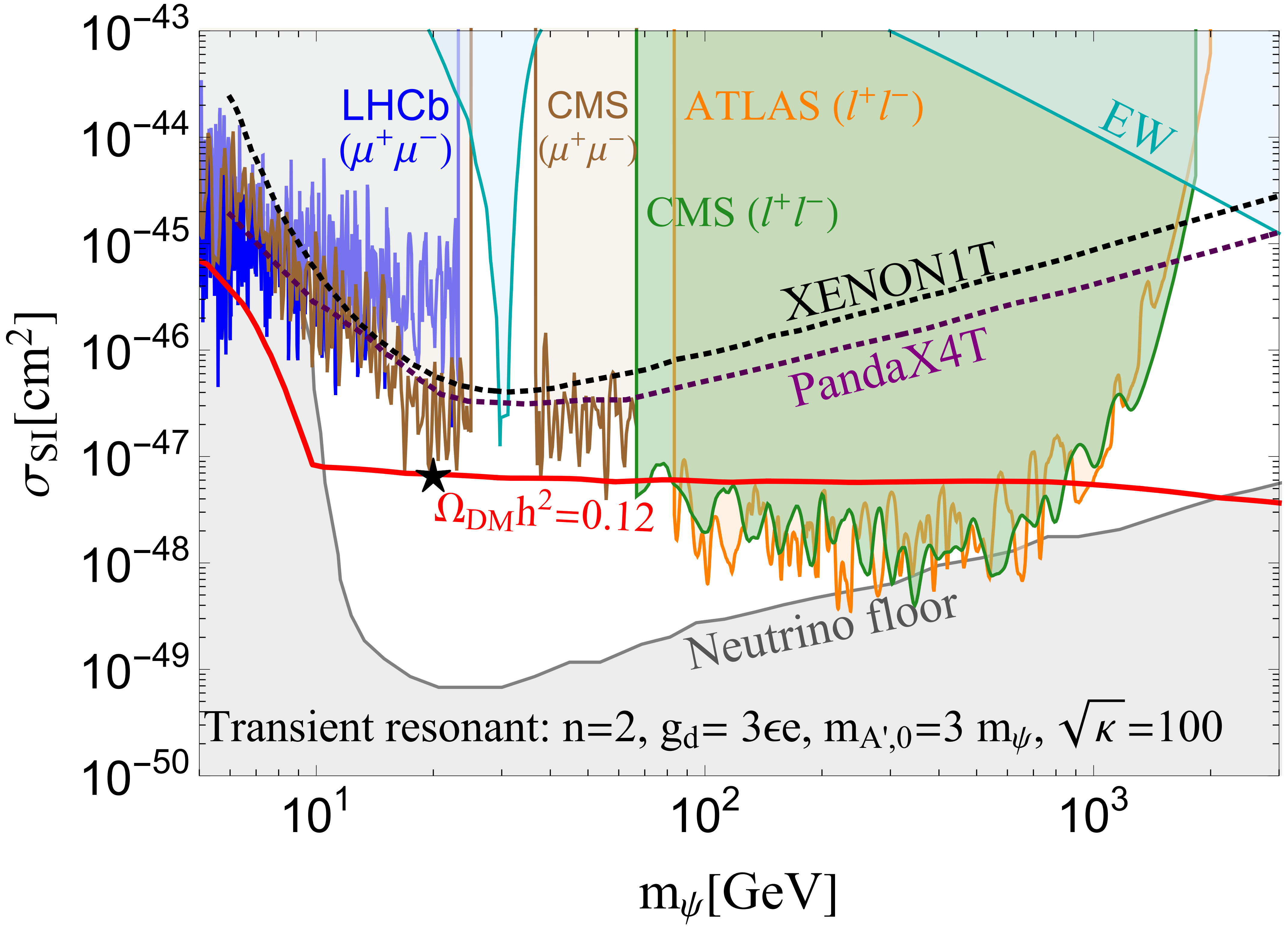
Features for DM with transient annihilations





$$\langle \sigma v \rangle_{\bar{f}f}^{\rm res} \approx \frac{g_d^2 \epsilon^2 e^2 (2 + r^2) x}{48\sqrt{2\pi} m_\psi \Gamma_{A'}} \sqrt{r(r^2-4)x e^{-(r-2)x}}$$

- 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



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