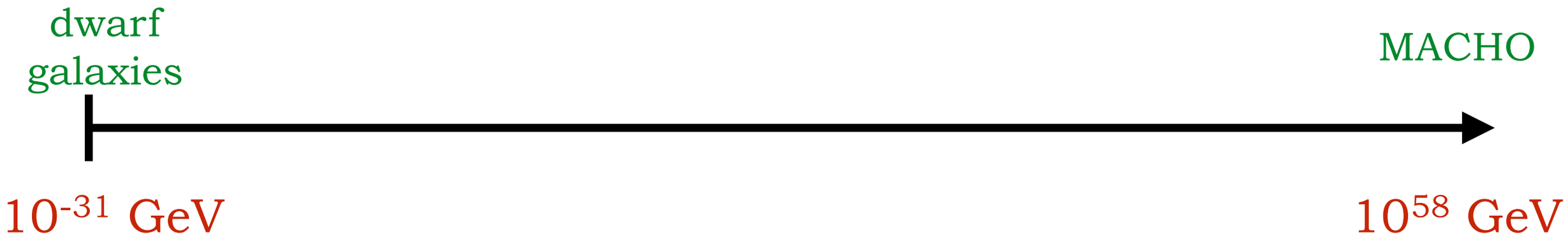
Dark Sector Overview

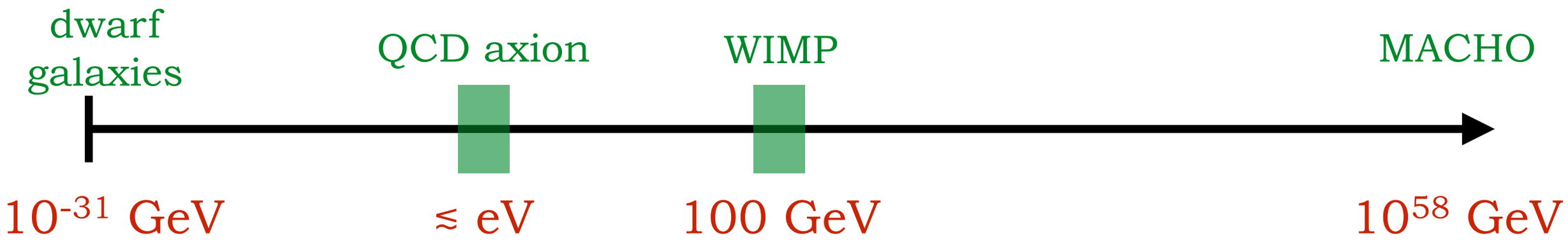
ASHER BERLIN, SLAC

HPS Collaboration Meeting, Newport News, VA
May 22, 2018

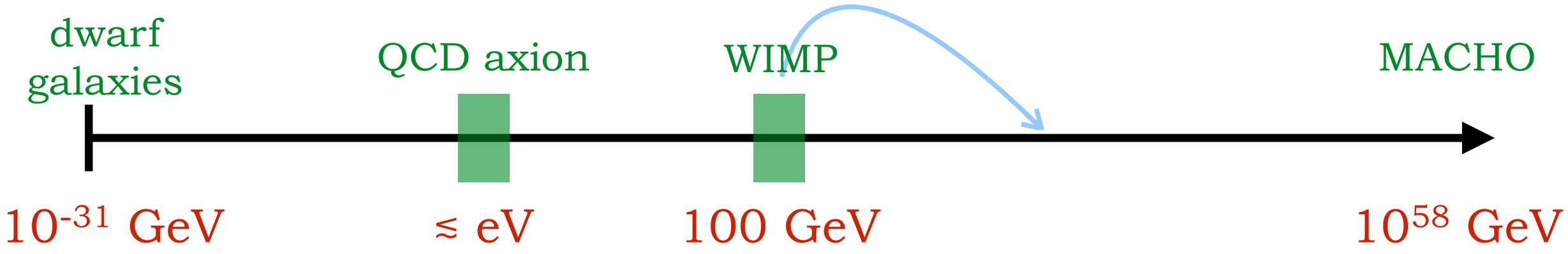
Dark Matter Mass



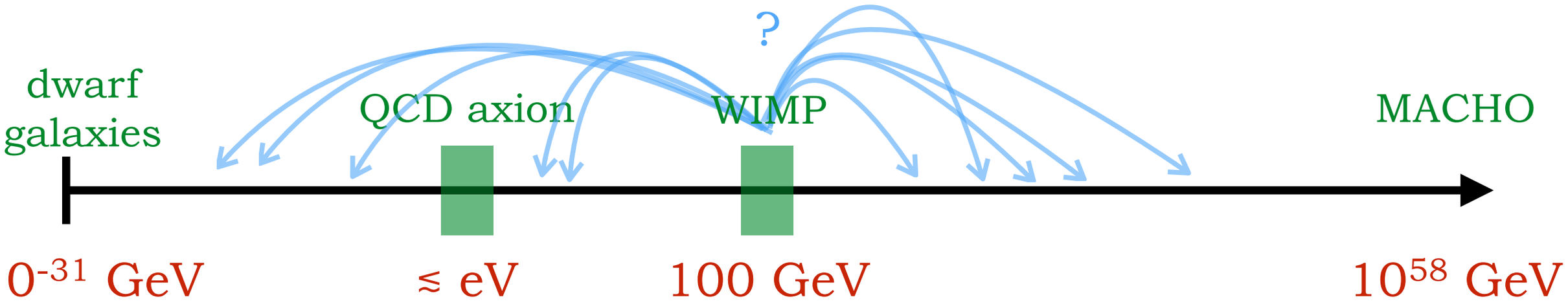
Dark Matter Mass



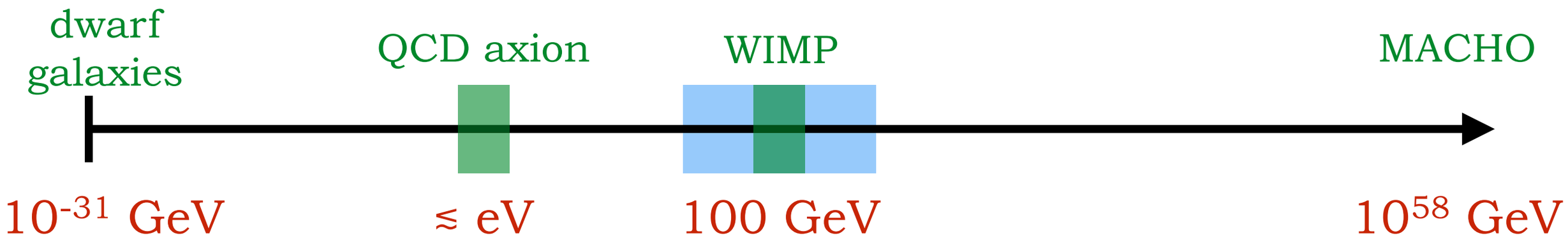
Dark Matter Mass



Dark Matter Mass

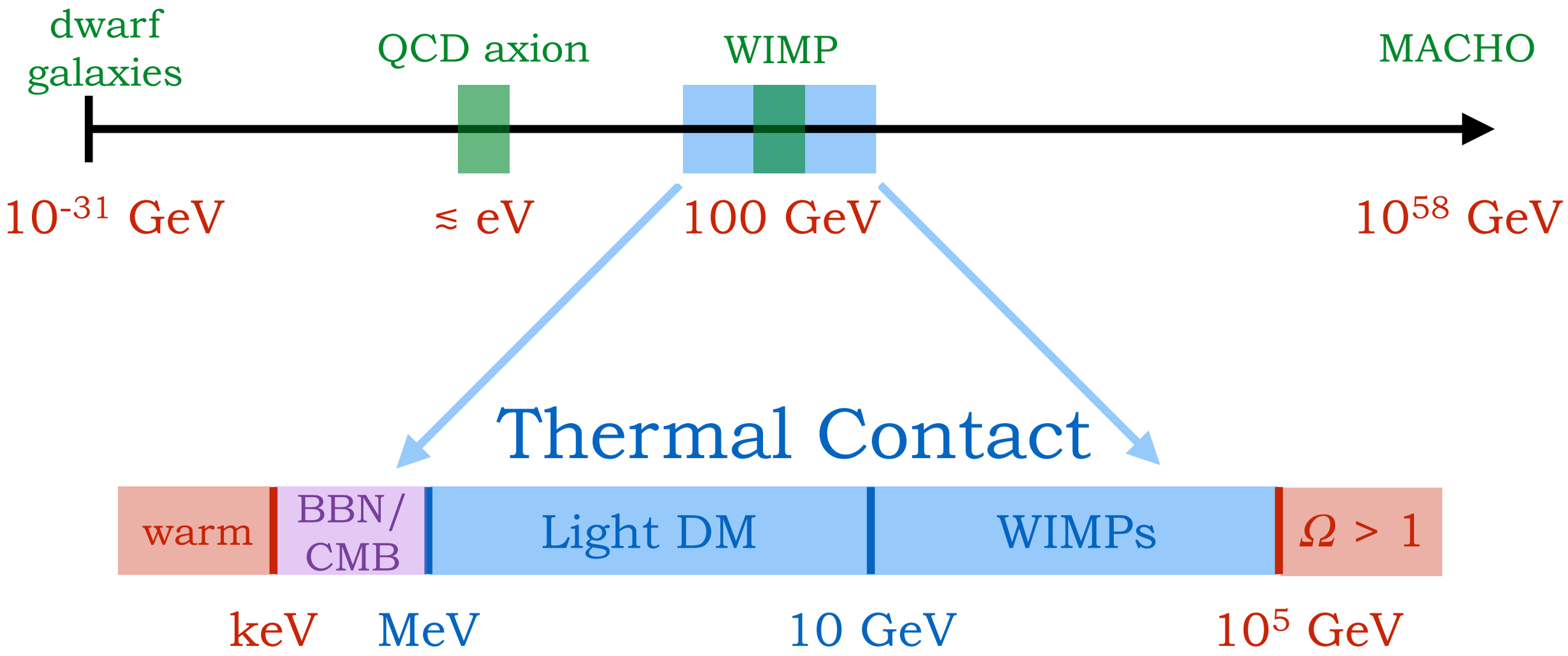


Dark Matter Mass

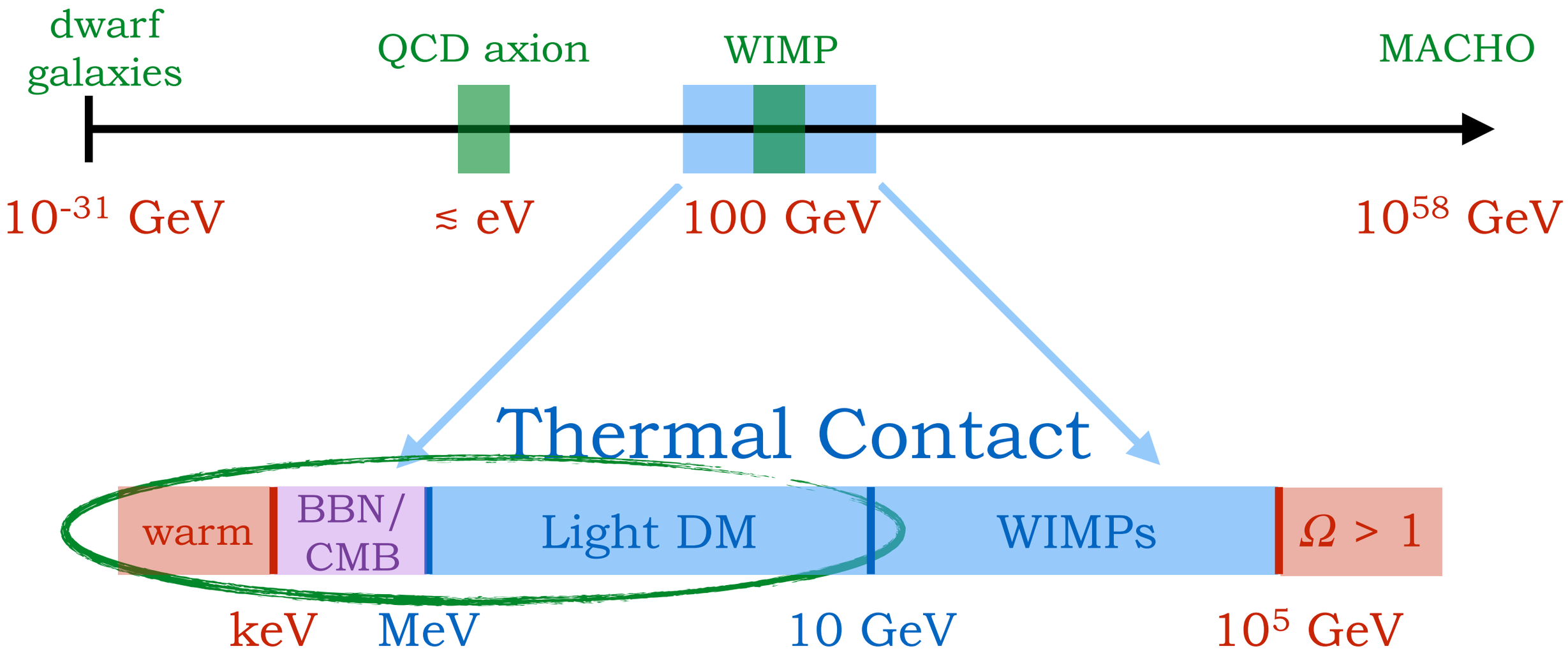


Thermal Contact

Dark Matter Mass

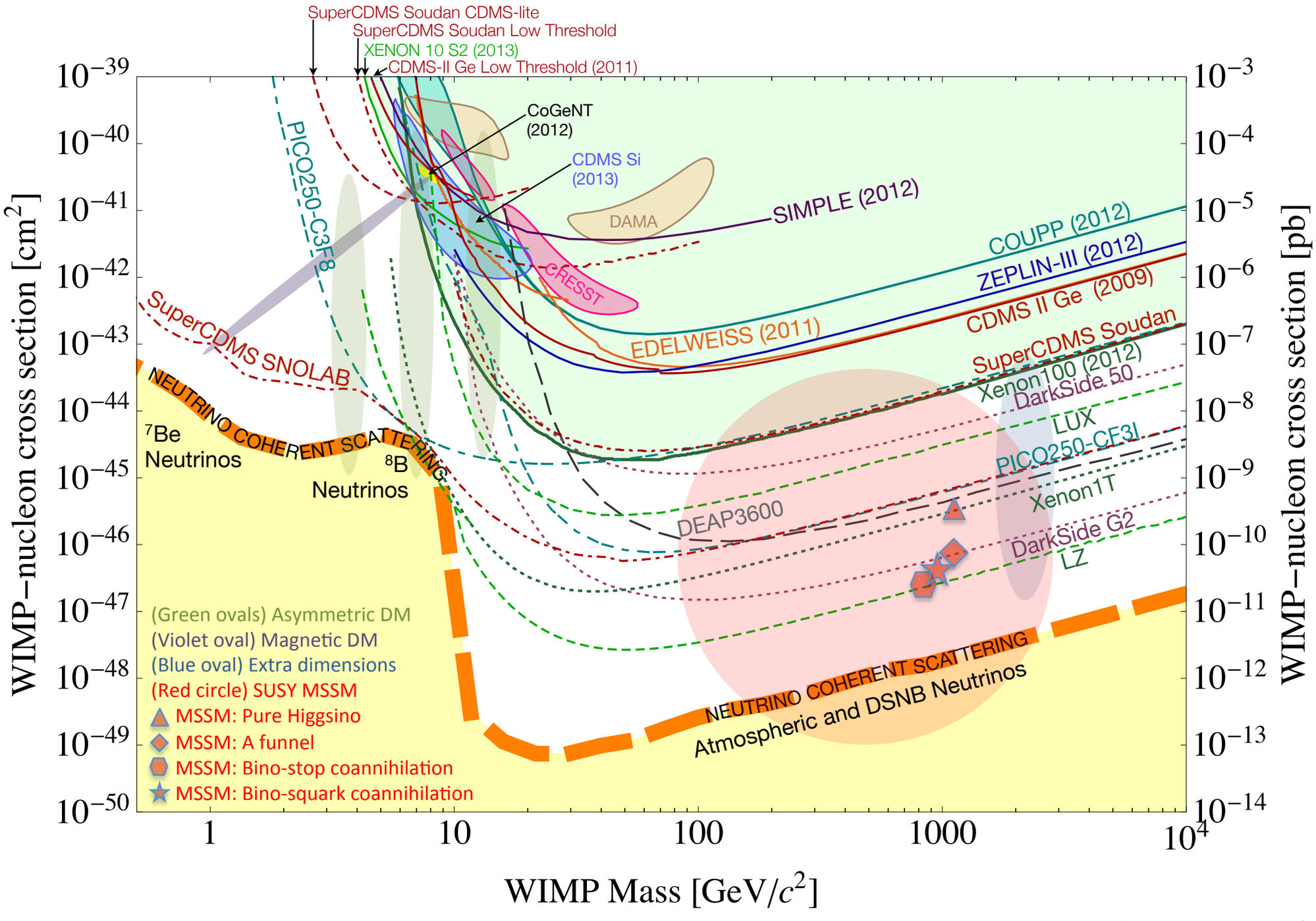


Dark Matter Mass



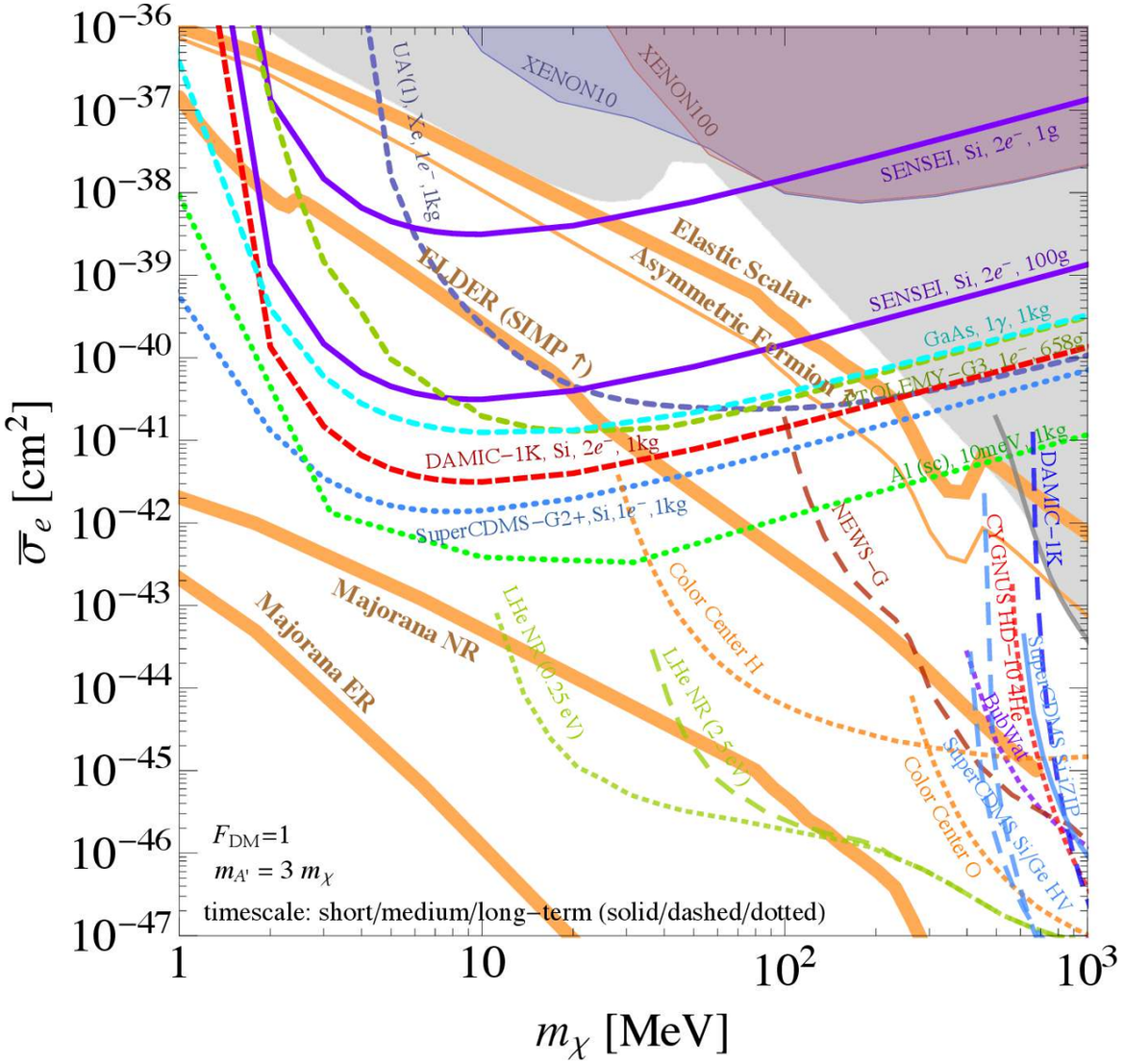
Experiments proposed: What models live here?

Moore's Law



Snowmass arXiv:1310.8327

Cosmic Visions



US Cosmic Visions Community Report
arXiv: 1707.04591

Outline

I. Very Thermal

II. Pretty Thermal

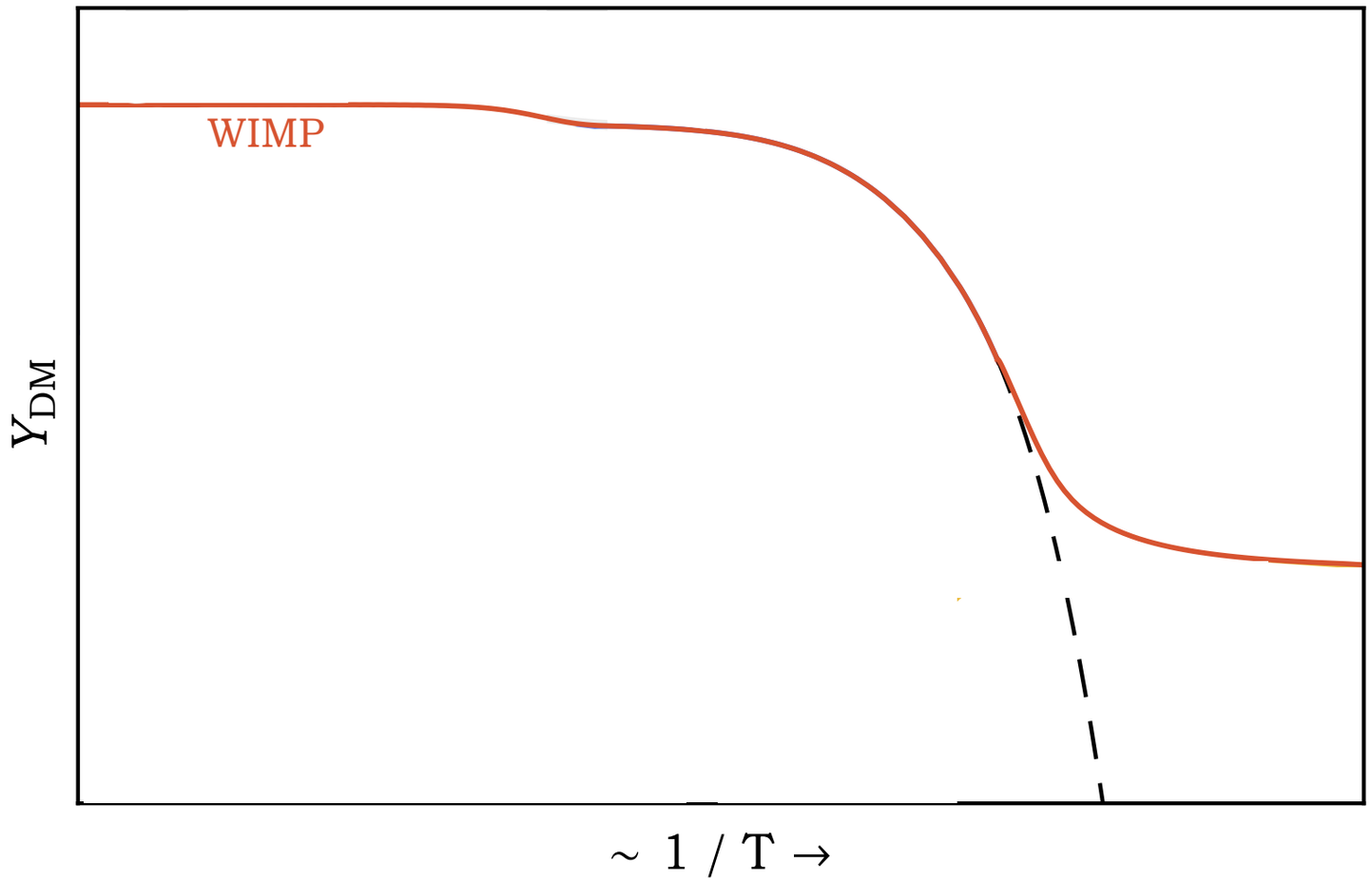
III. Almost Thermal

III. Not Thermal

larger coupling to visible sector

smaller coupling to visible sector

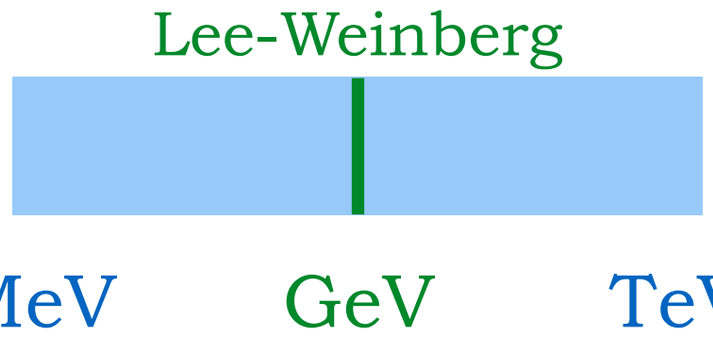
WIMP-Like

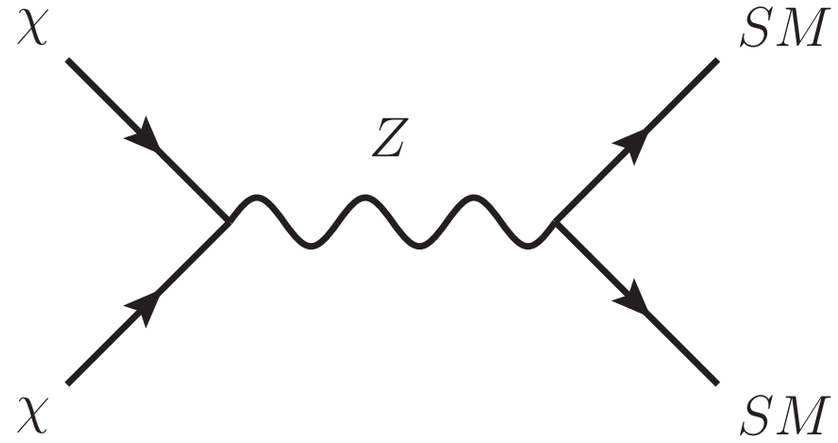


Light Thermal Dark Matter

- ☑ cold
- ☑ light mediator
- ☑ suppressed annihilations at late times

Light Mediators





$$\sigma v \lesssim \frac{m_\chi^2}{m_Z^4} \implies m_\chi \gtrsim \frac{m_Z^2}{(T_{\rm eq}\, m_{\rm pl})^{1/2}} \sim \text{GeV}$$

Sub-GeV thermal DM requires light mediators: $m_\varphi \sim m_\chi$

B. Lee and S. Weinberg,
Phys.Rev.Lett. 39 (1977) 165-168

C. Boehm and P. Fayet
arXiv: hep-ph/0305261

CMB

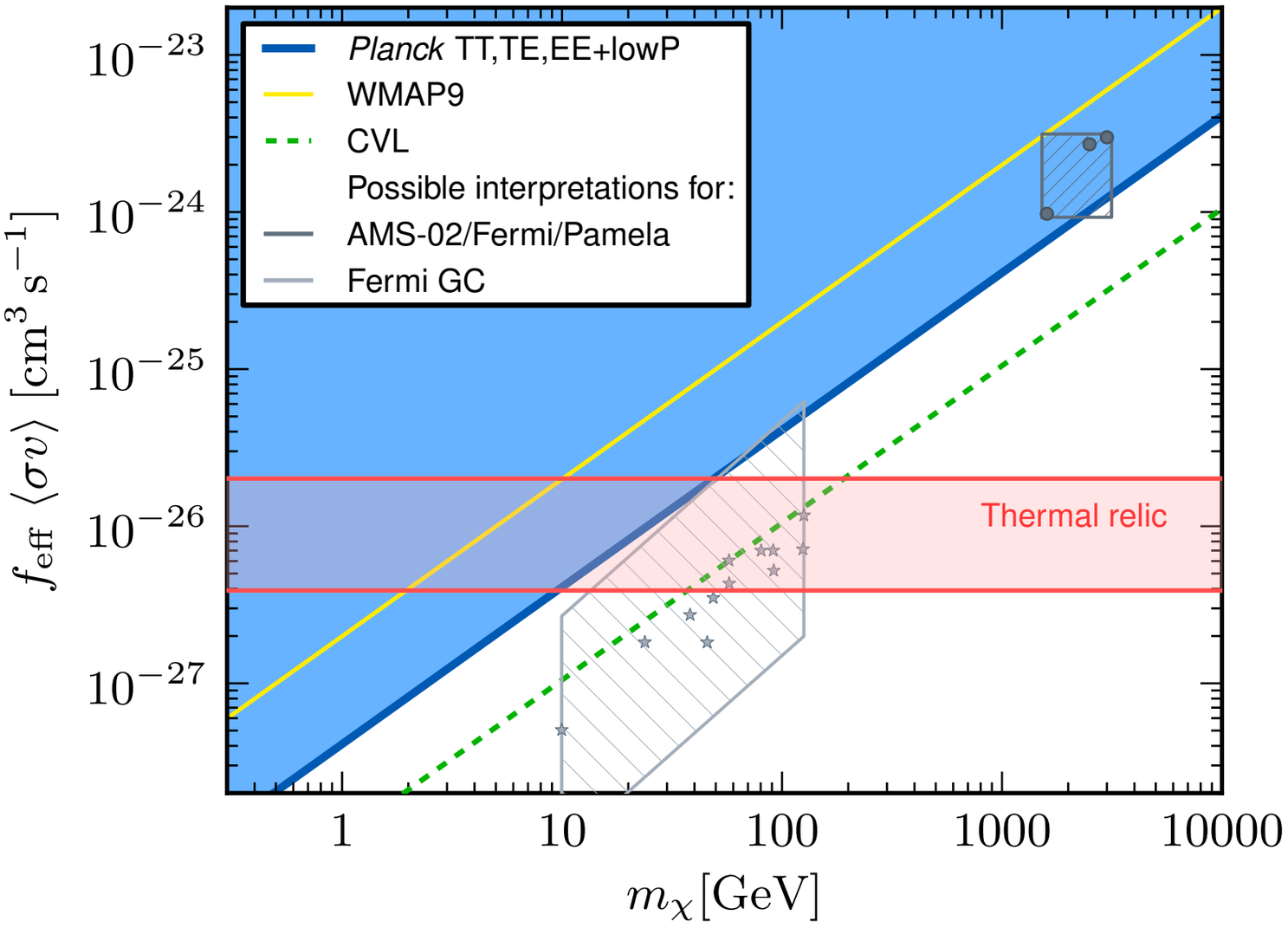
(DM < 10 GeV has suppressed visible annihilations at late times)

energy injection

$$m_\chi \, n_\chi^2 \, \langle \sigma v \rangle \sim m_\chi \left(\frac{\rho_\chi}{m_\chi} \right)^2 \langle \sigma v \rangle \lesssim \# \implies \langle \sigma v \rangle \lesssim m_\chi \times \#$$

CMB

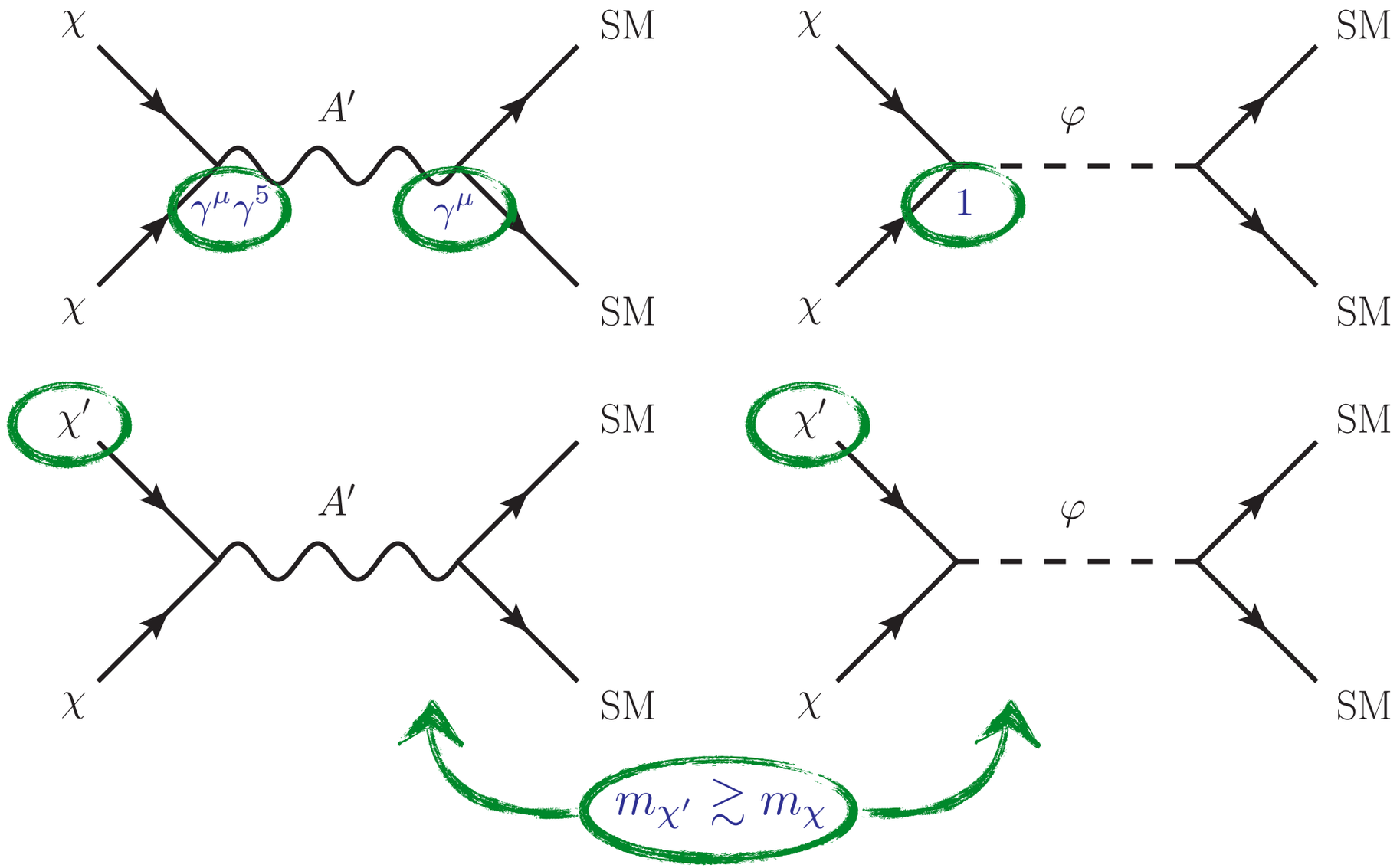
(DM < 10 GeV has suppressed visible annihilations at late times)



arXiv:1502.01589

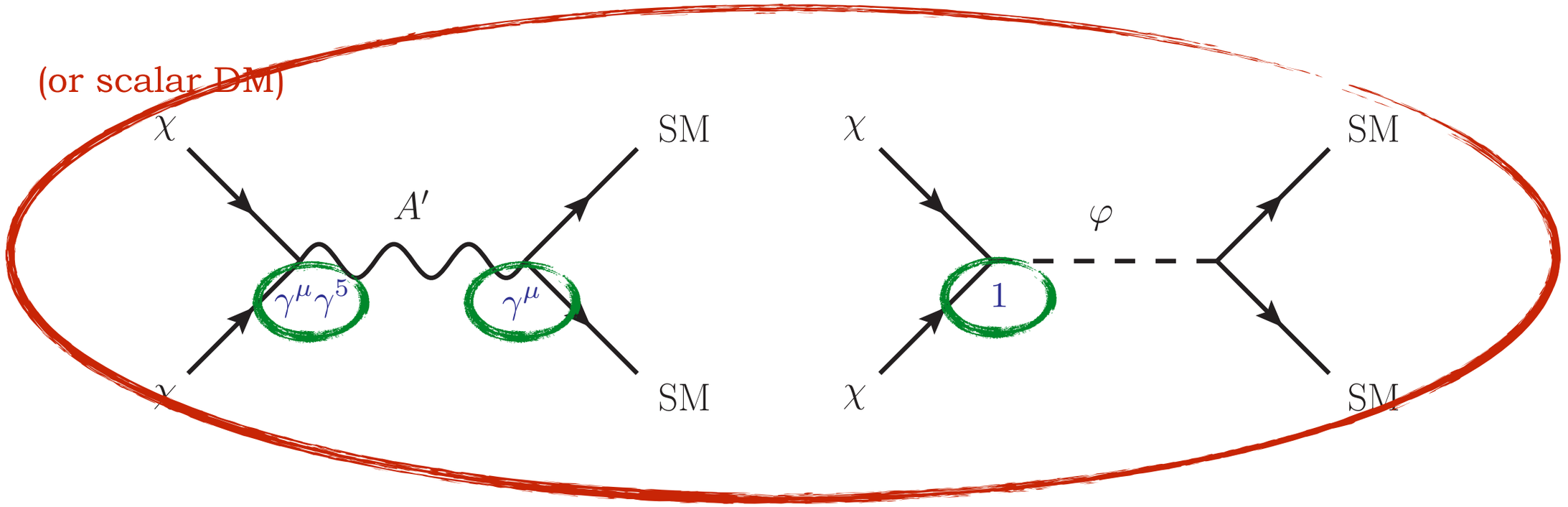
Visible and Direct Annihilations

(or scalar DM)



Visible and Direct Annihilations

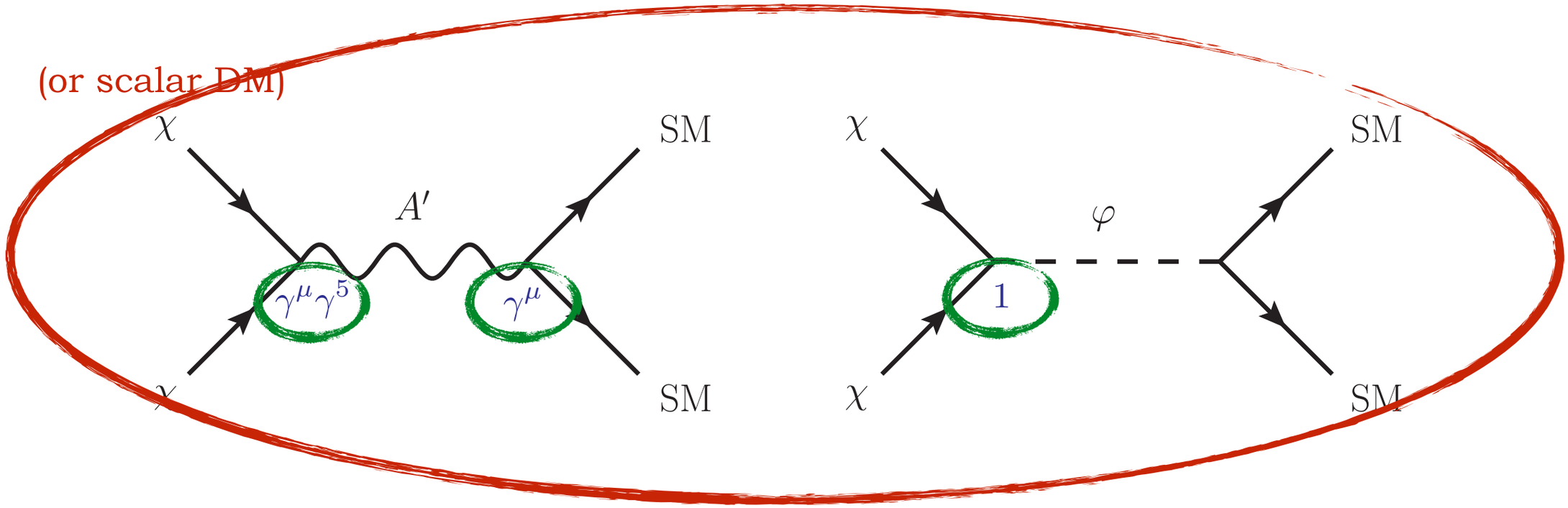
(or scalar DM)



$\langle \sigma v \rangle \propto v^2$ (p-wave)

Visible and Direct Annihilations

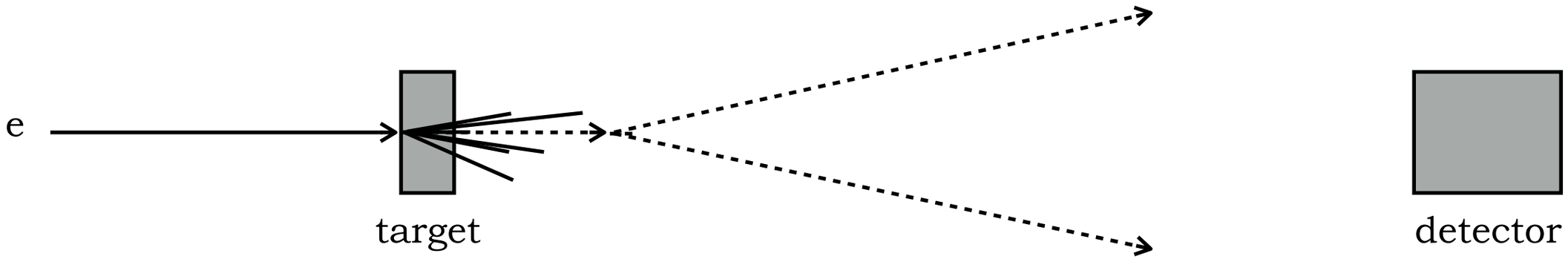
(or scalar DM)

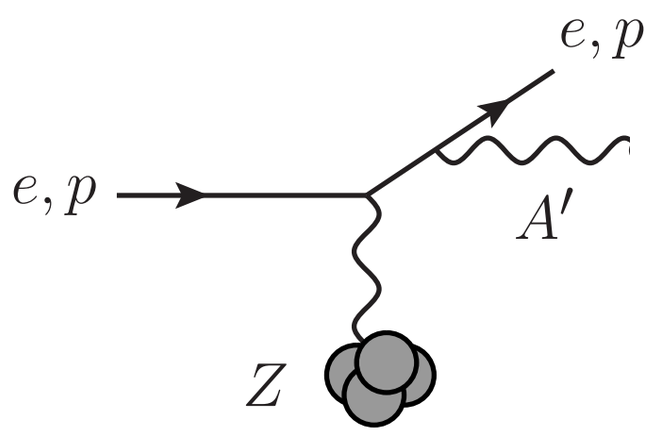


$\langle \sigma v \rangle \propto v^2$ (p-wave)

invisible mediator decays

Fixed-Target Search

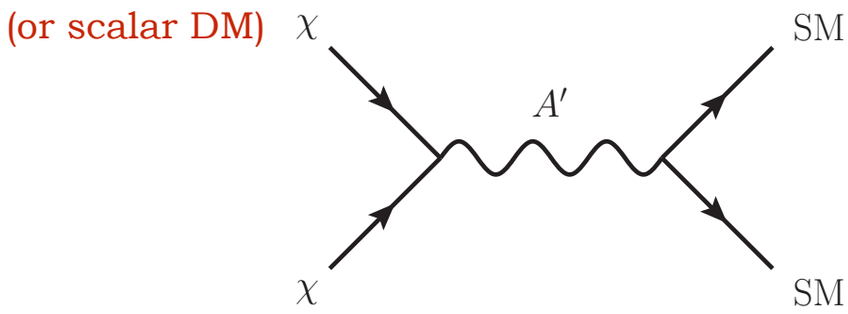




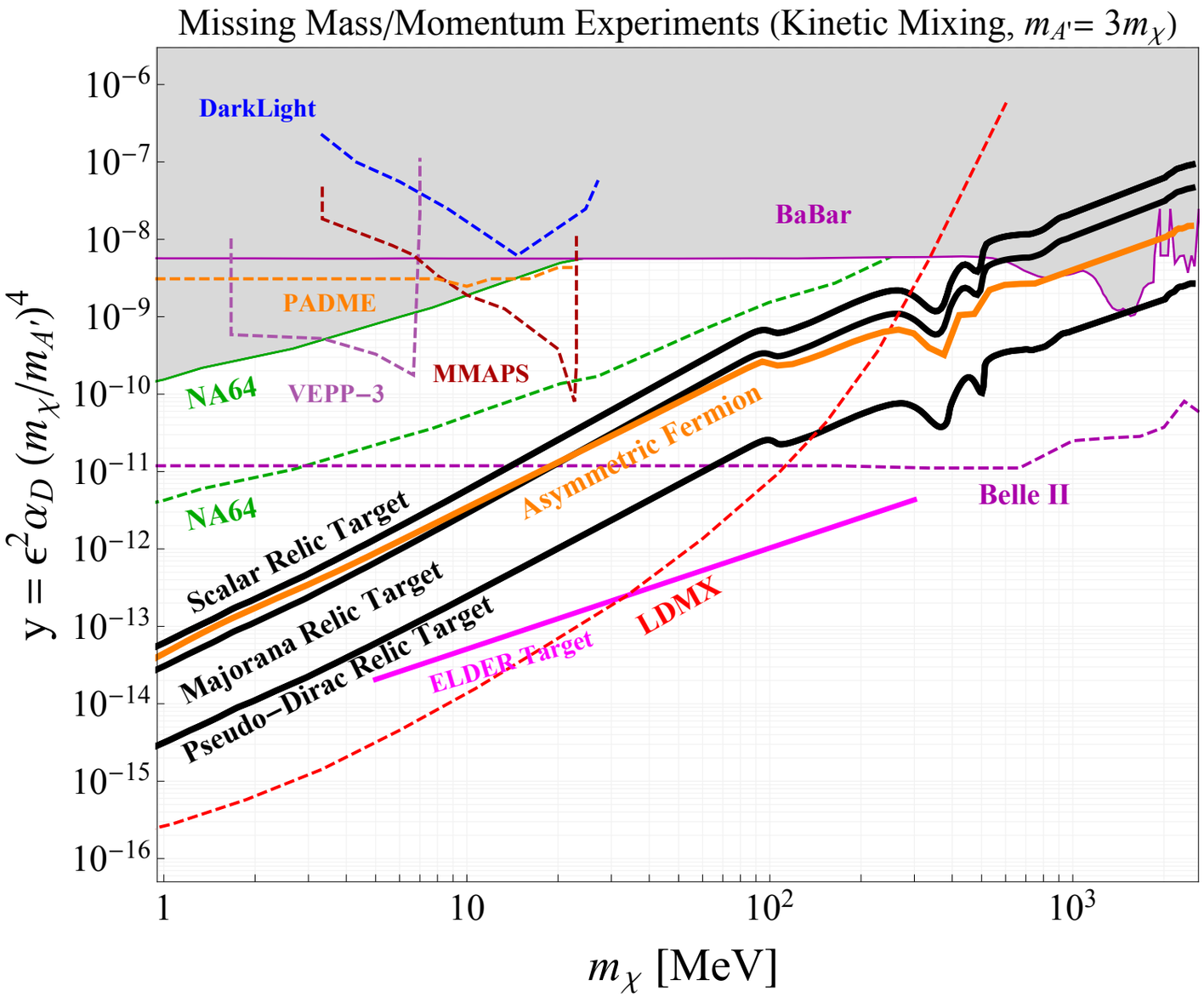
Visible and Direct Annihilations

invisible mediator decays

(p-wave)



$$\frac{\epsilon}{2\,\cos\theta_W}\,A'_{\mu\nu}\,B^{\mu\nu}$$

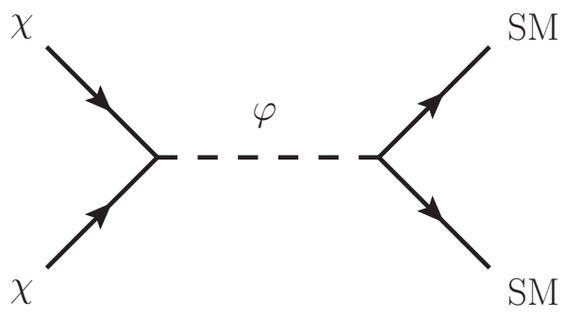


arXiv:1707.04591

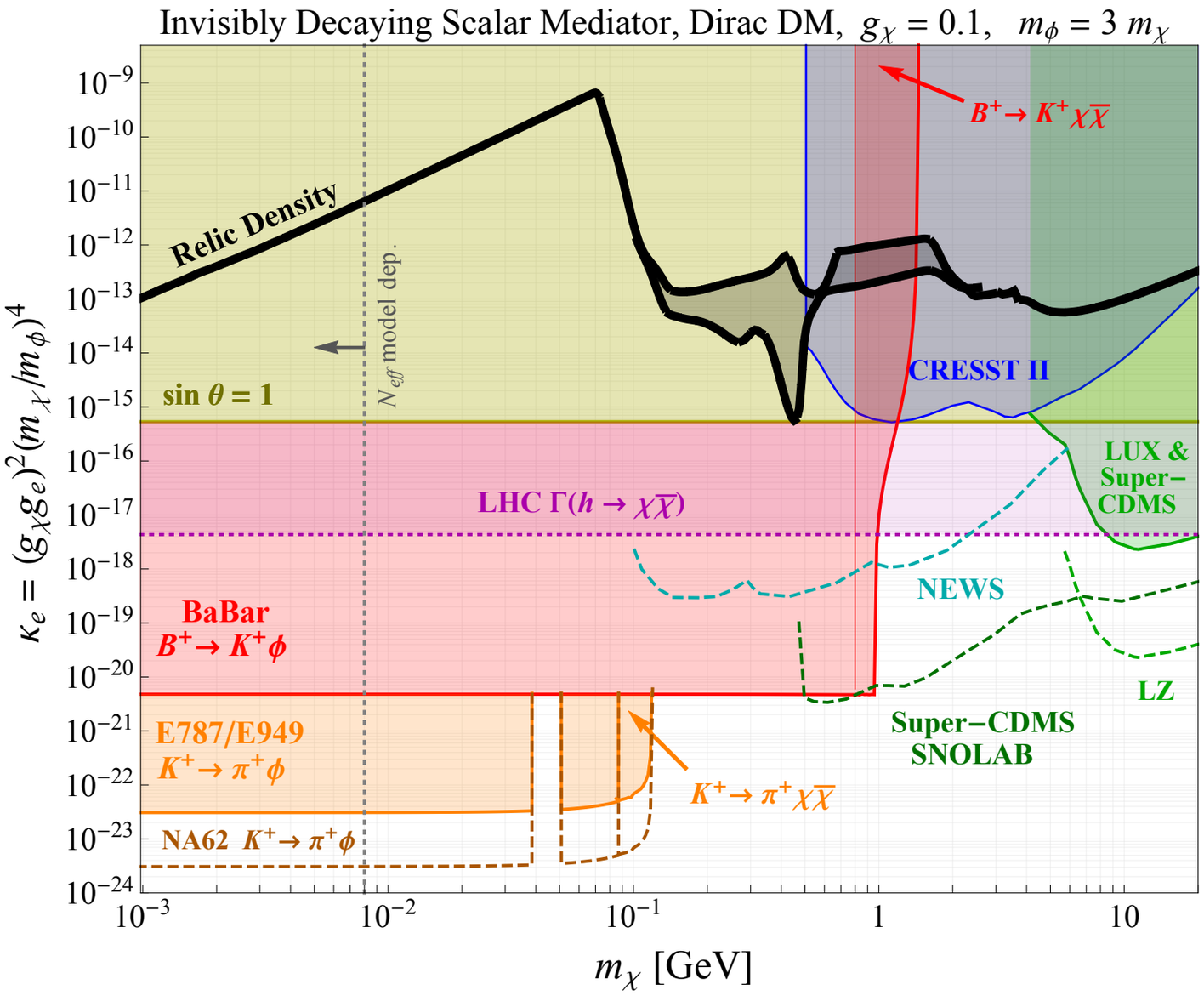
Visible and Direct Annihilations

invisible mediator decays

(p-wave)

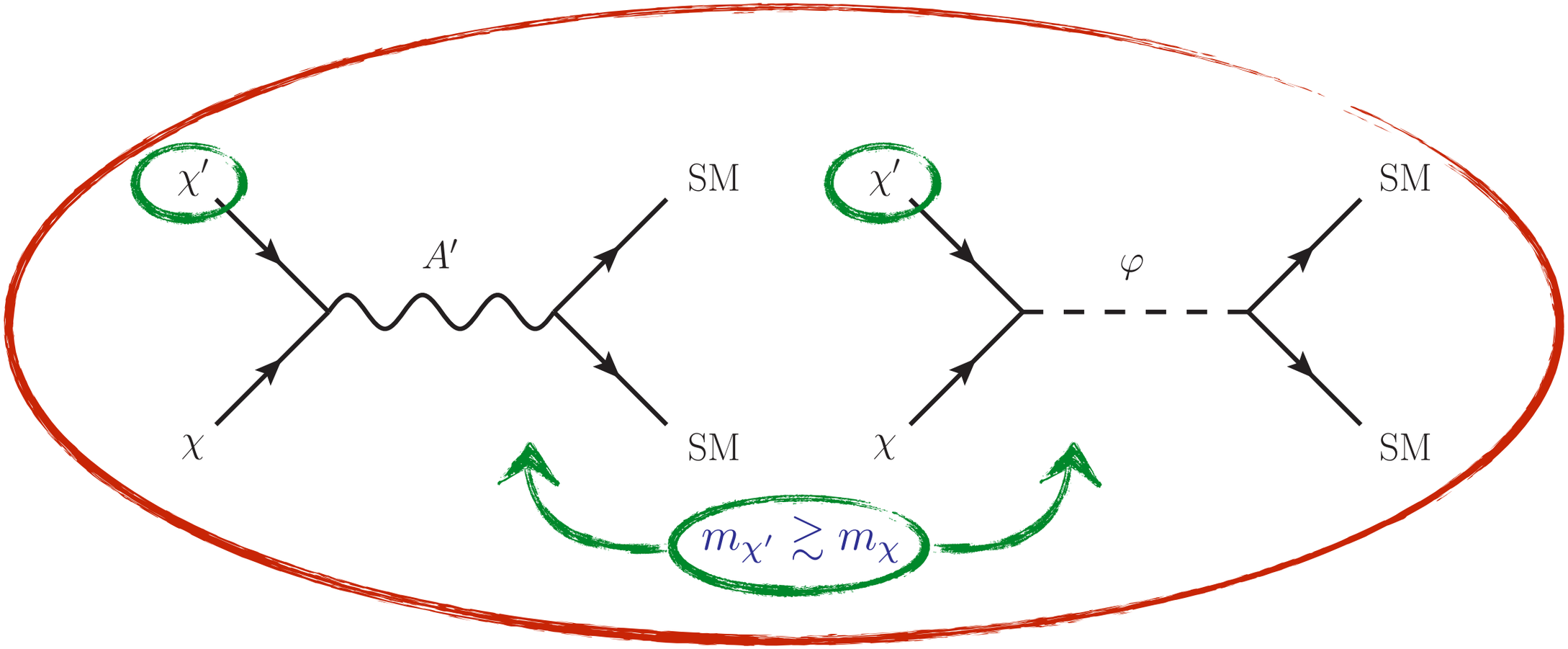


$$\sin\theta \; \frac{m_f}{v} \; \phi \; \bar{f} f$$



arXiv:1512.04119

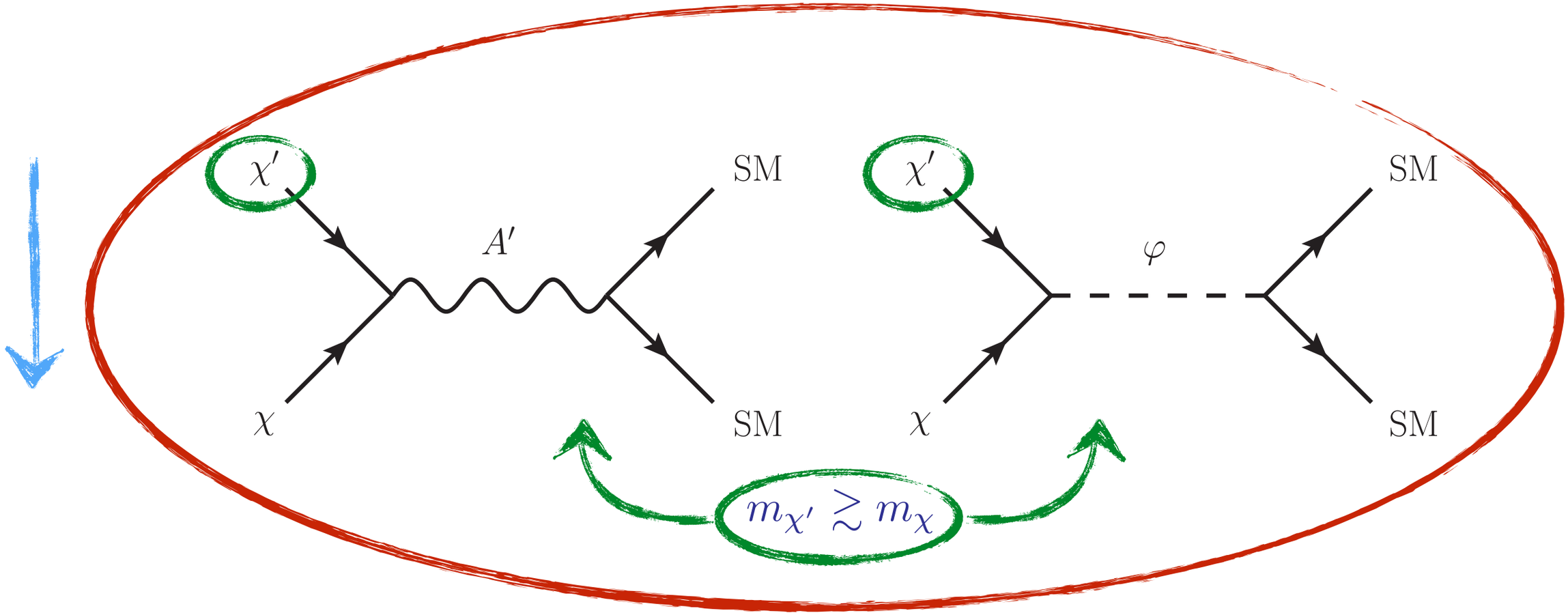
Visible and Direct Annihilations



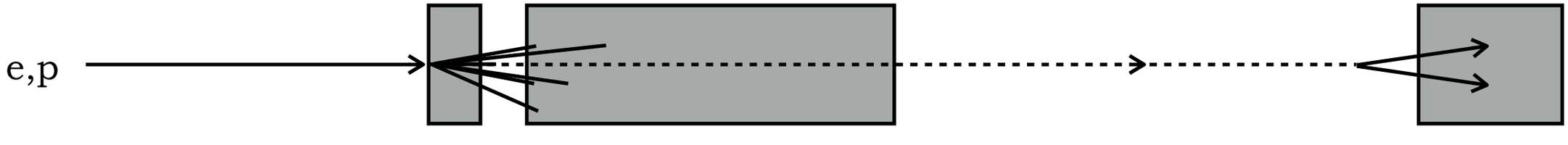
Visible and Direct Annihilations

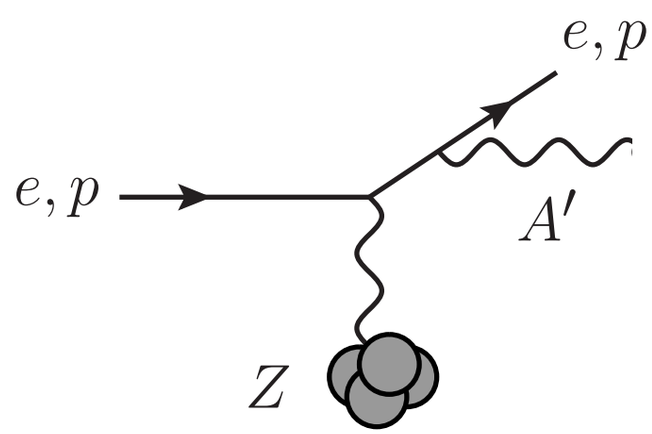
$\langle \sigma v \rangle \propto e^{-(m_{\chi'} - m_\chi)/T}$ (coannihilation)

visible χ' decays



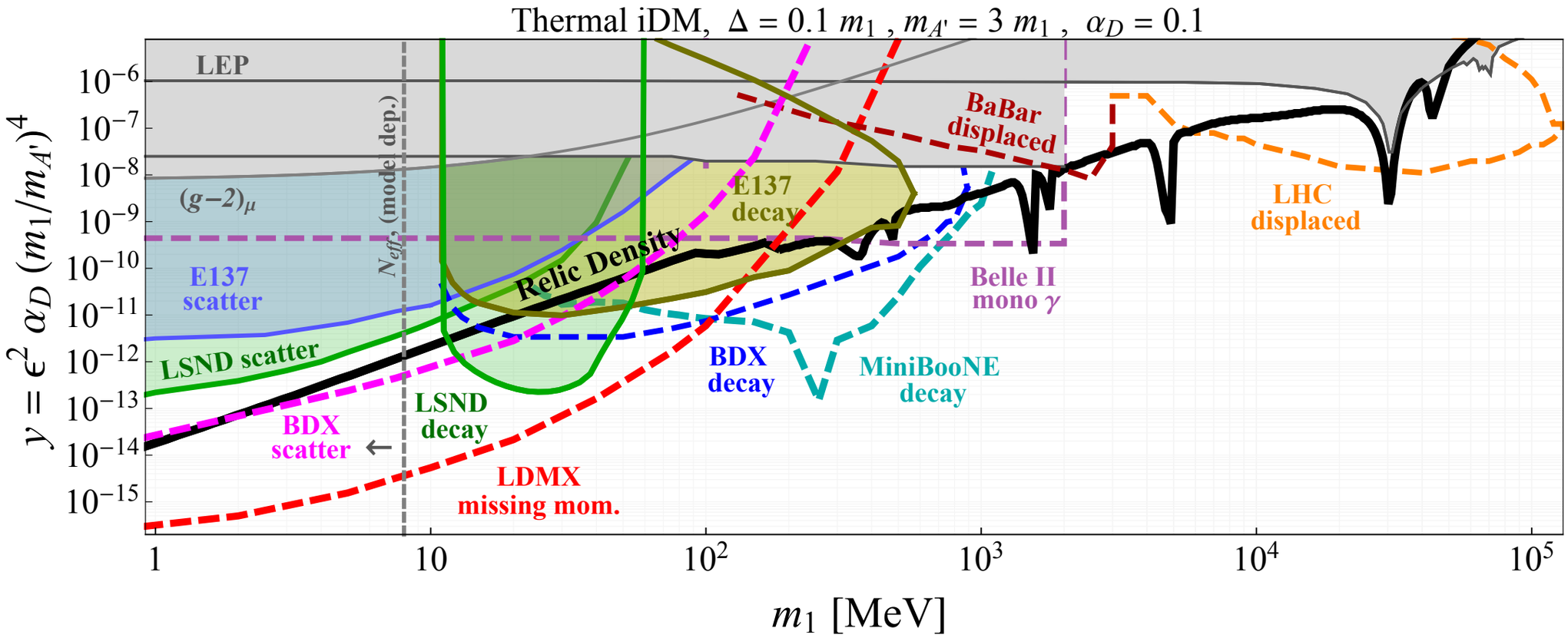
Fixed-Target Search





Visible and Direct Annihilations

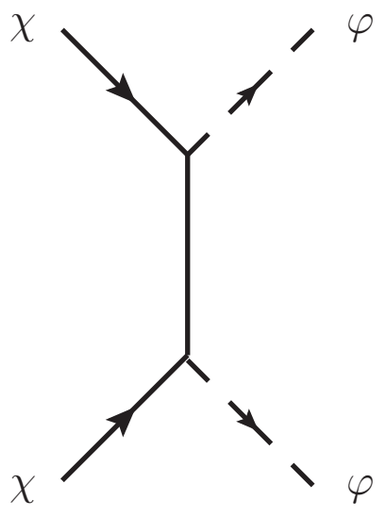
visible χ' decays

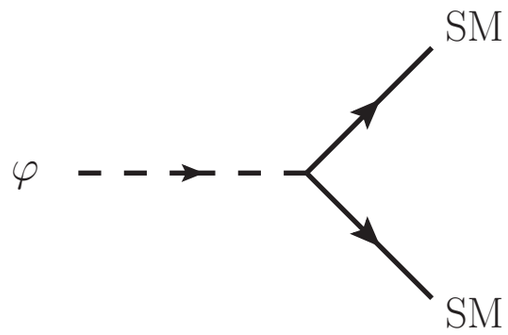


$$\frac{\epsilon}{2\ \cos\theta_W}\ A'_{\mu\nu}\ B^{\mu\nu}$$

arXiv:1703.06881

Visible and Secluded Annihilations

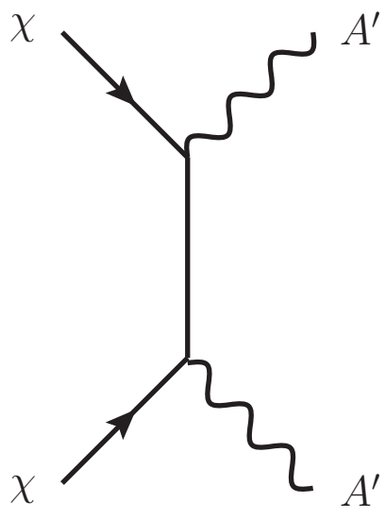


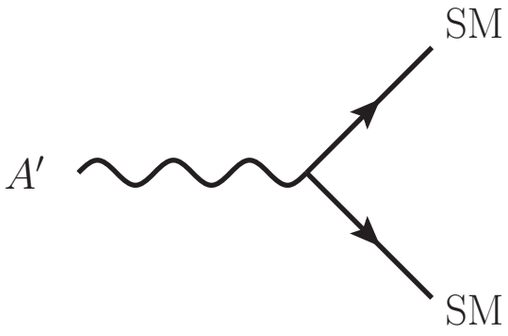


$$\langle \sigma v \rangle \propto v^2$$

(p-wave)

(or scalar DM)





$$m_{A'} \gtrsim m_\chi$$

$$\langle \sigma v \rangle \propto \left(e^{-(m_{A'} - m_\chi)/T} \right)^2$$

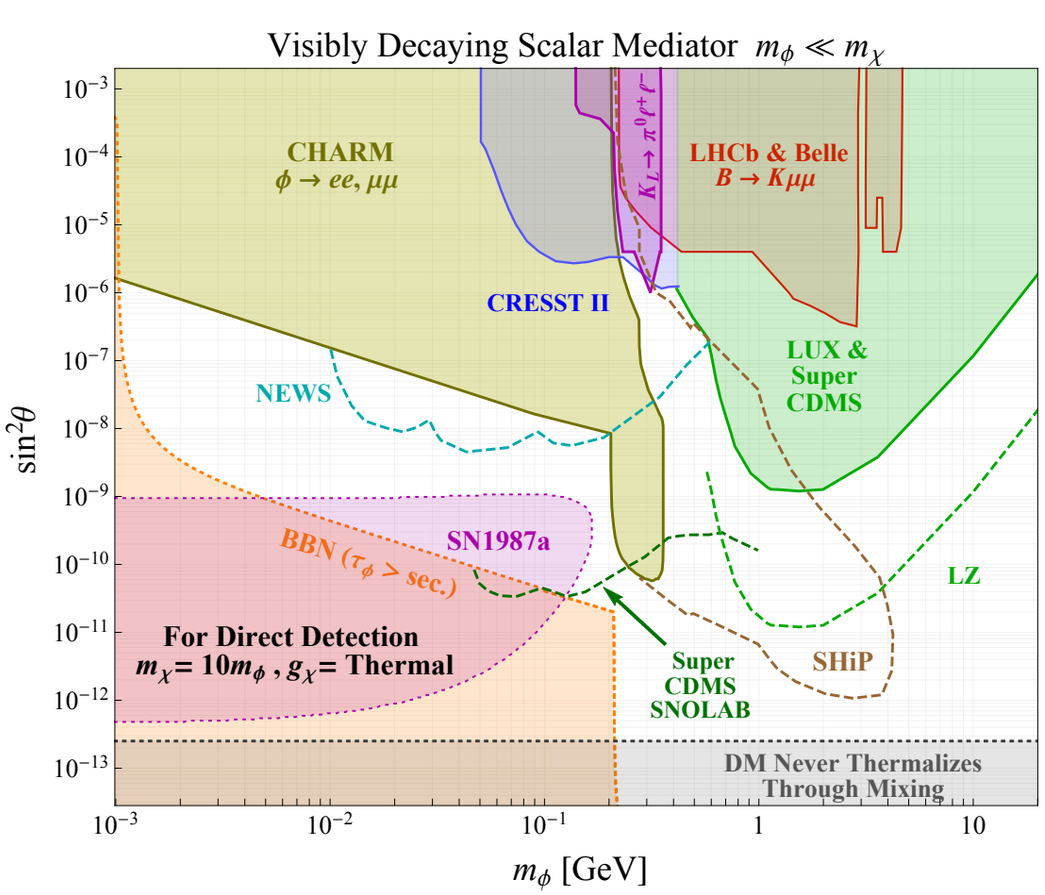
(Boltzmann suppressed)

arXiv:0711.4866

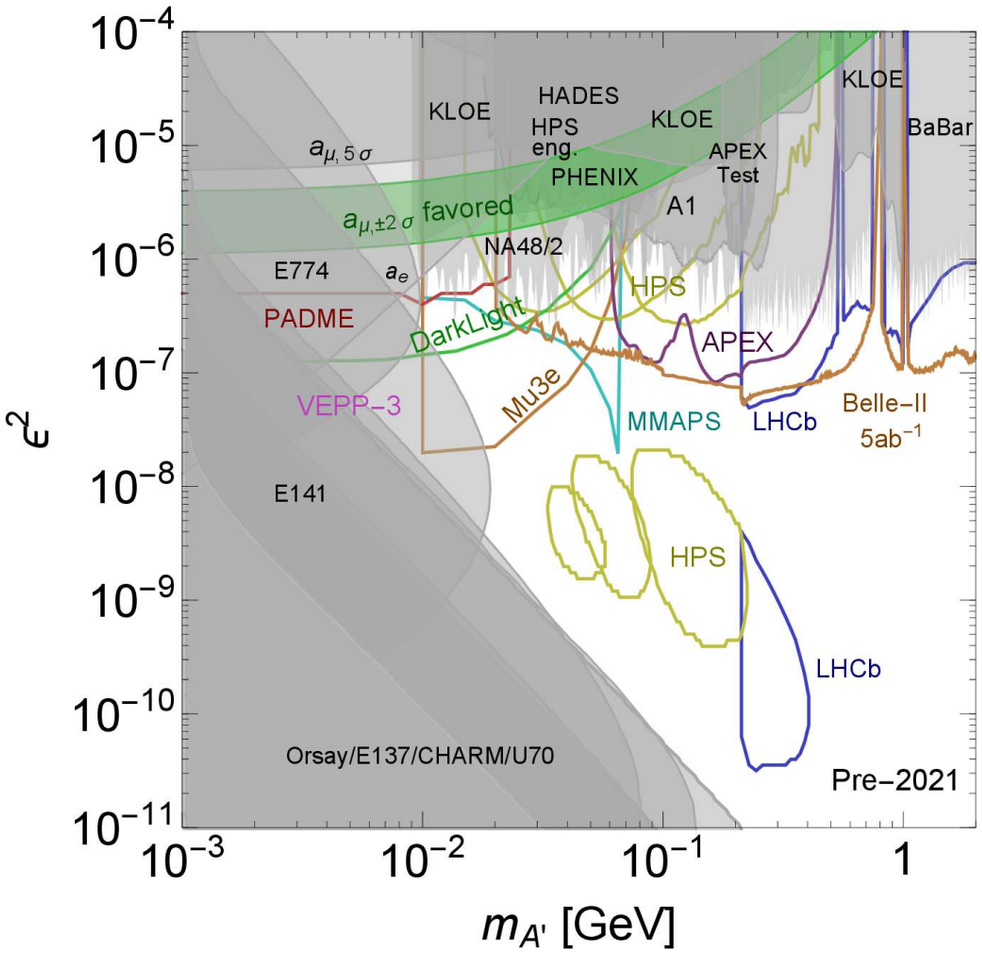
arXiv:1505.07107

Visible and Secluded Annihilations

visible mediator decays



$$\sin\theta \, \frac{m_f}{v} \, \phi \, \bar{f} f$$

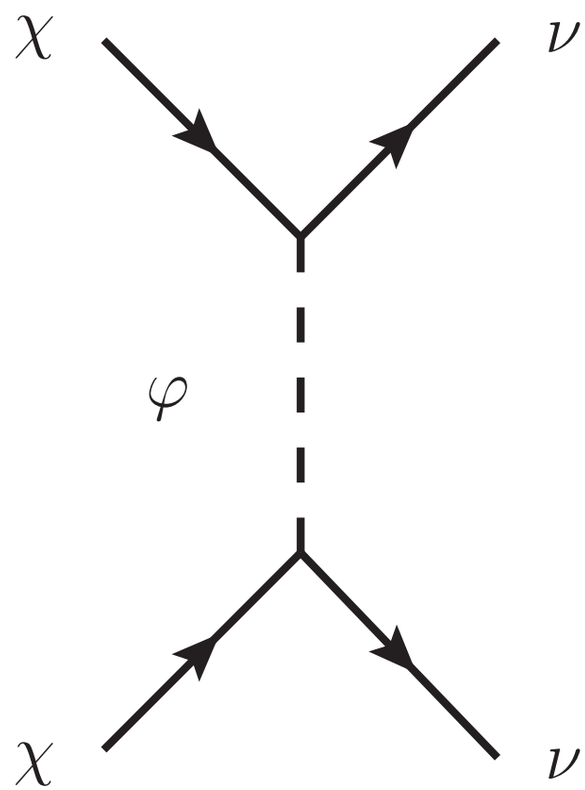


$$\frac{\epsilon}{2\,\cos\theta_W} \, A'_{\mu\nu} \, B^{\mu\nu}$$

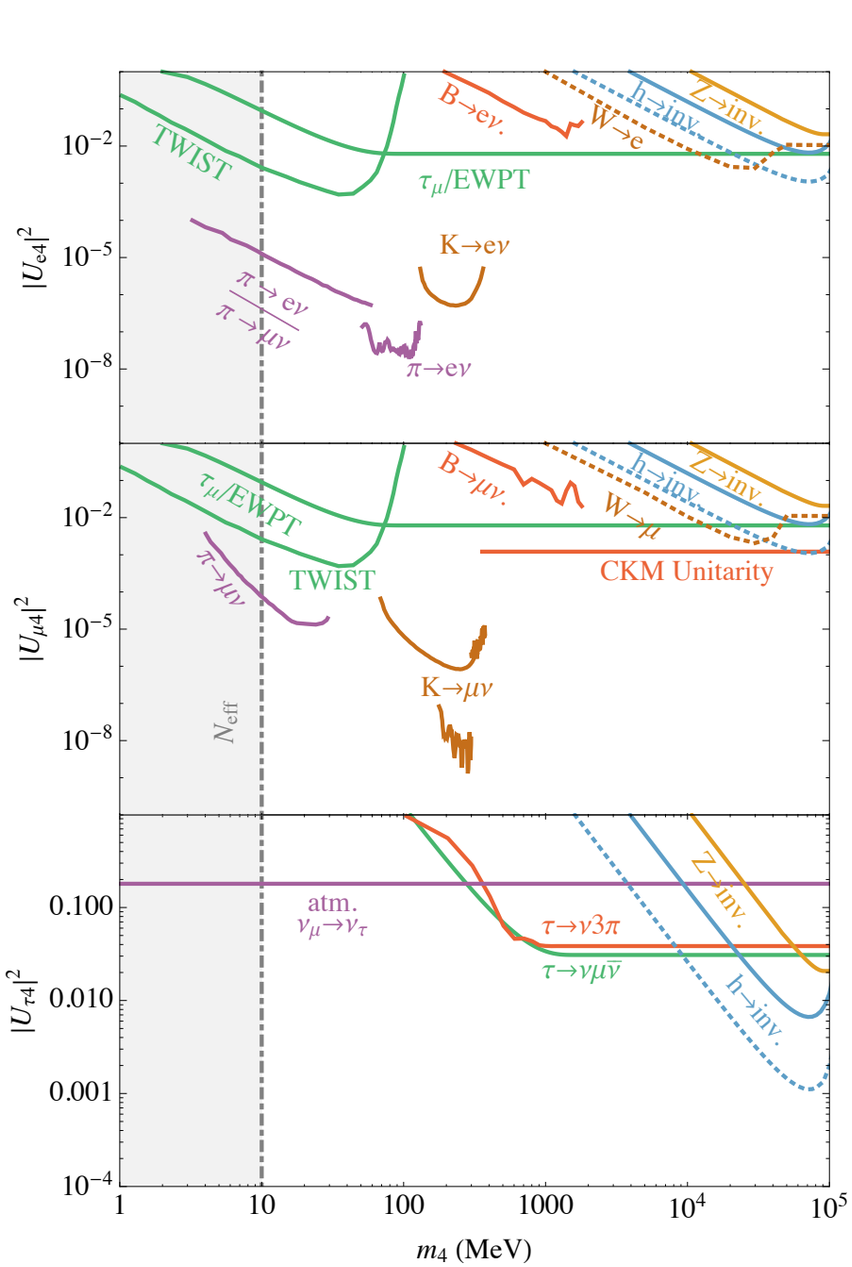
arXiv:1512.04119

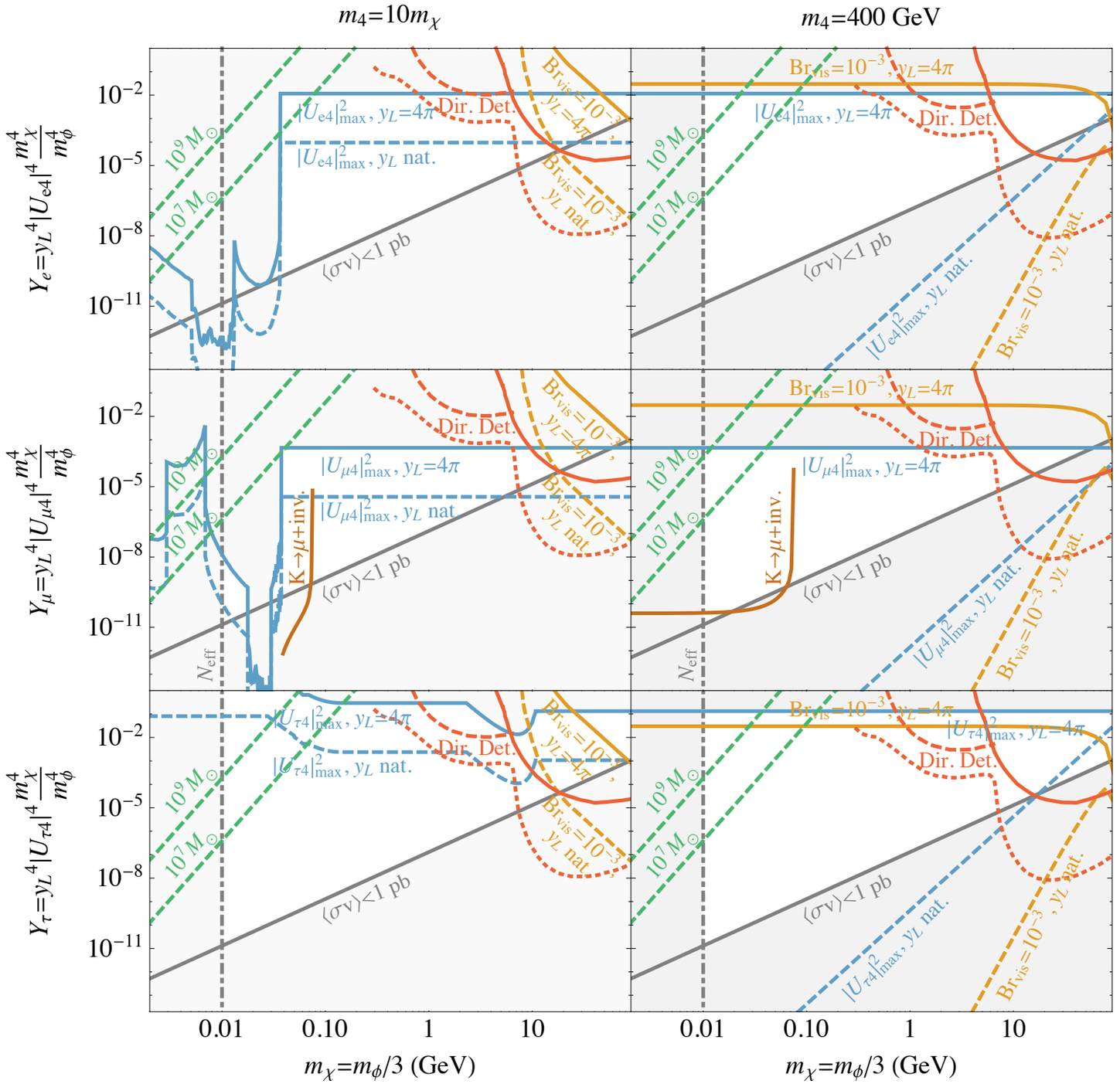
arXiv:1707.04591

Invisible Annihilations



Invisible Annihilations

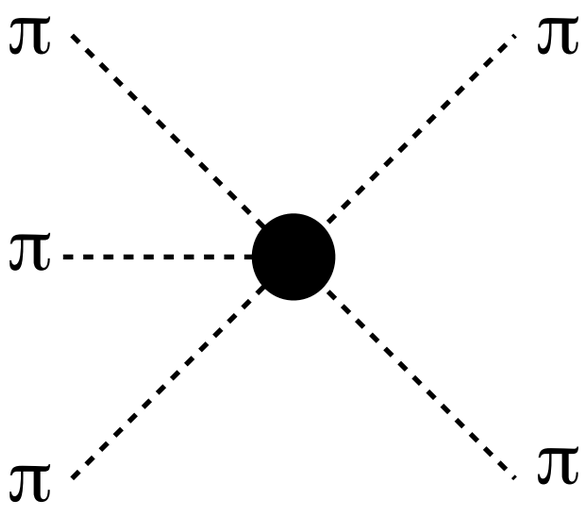


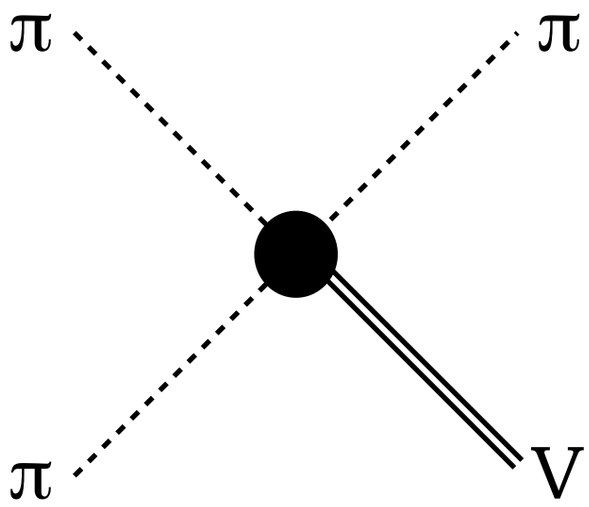


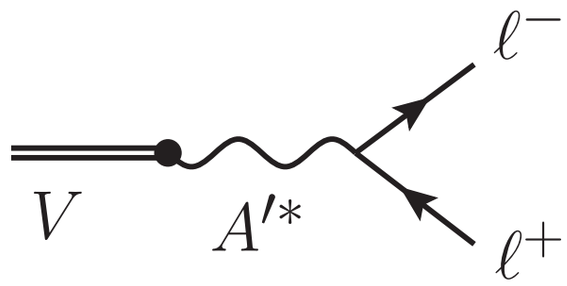
arXiv:1709.07001

Hidden Sector Dynamics

(π = Dark Matter)

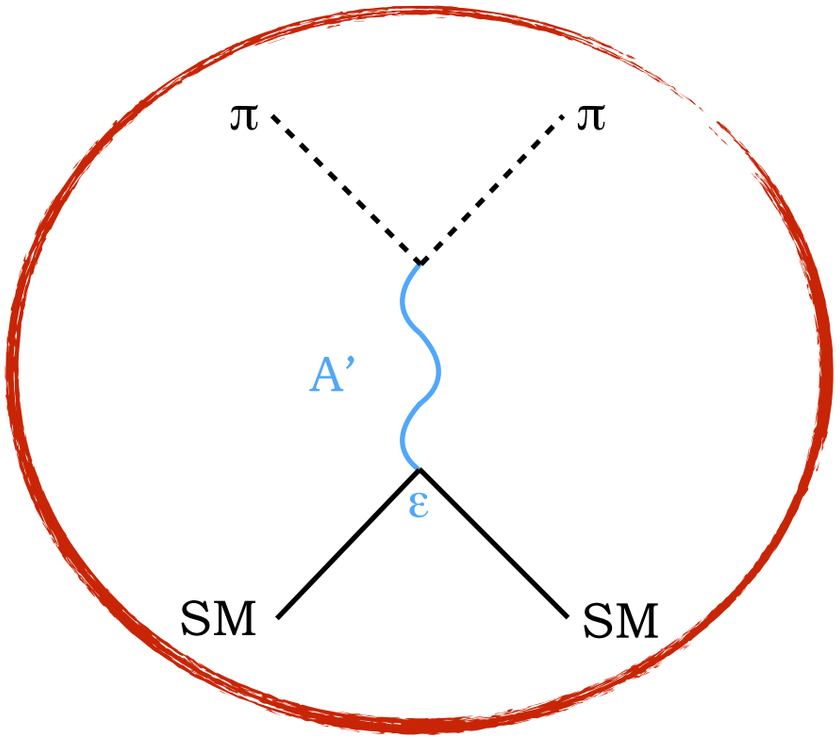






$m_V < 2\ m_\pi$

to keep dark matter cold



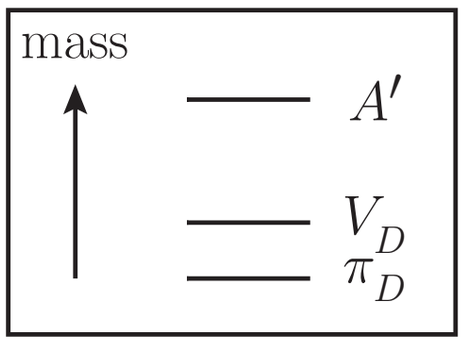
Carlson, Machacek and Hall (1992)

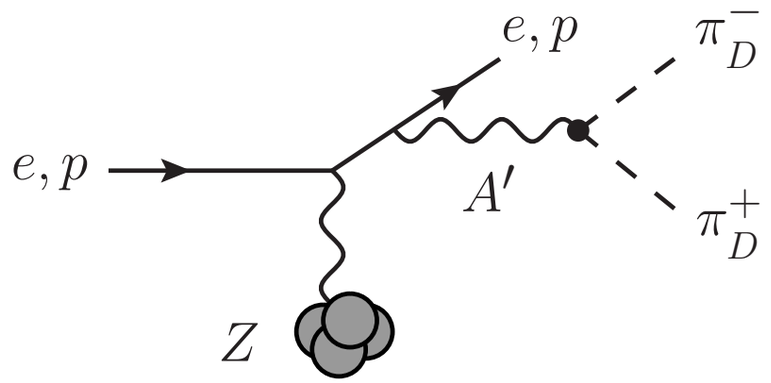
arXiv: 1402.5143

arXiv: 1801.05805

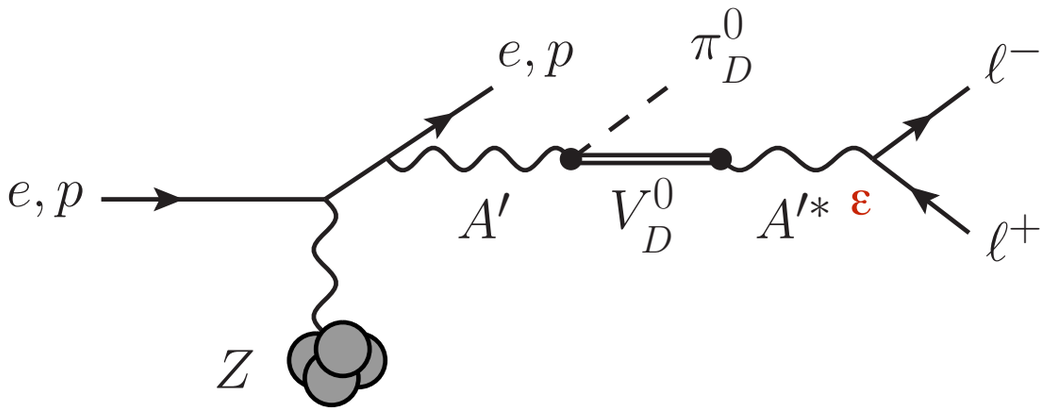
Hidden Sector Dynamics

(vector mesons are long-lived)

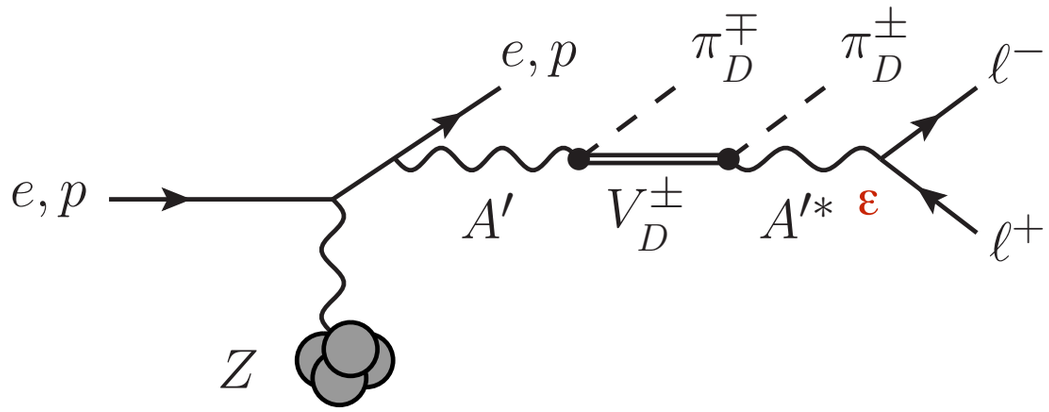




invisible decay



2-body V^0 decay

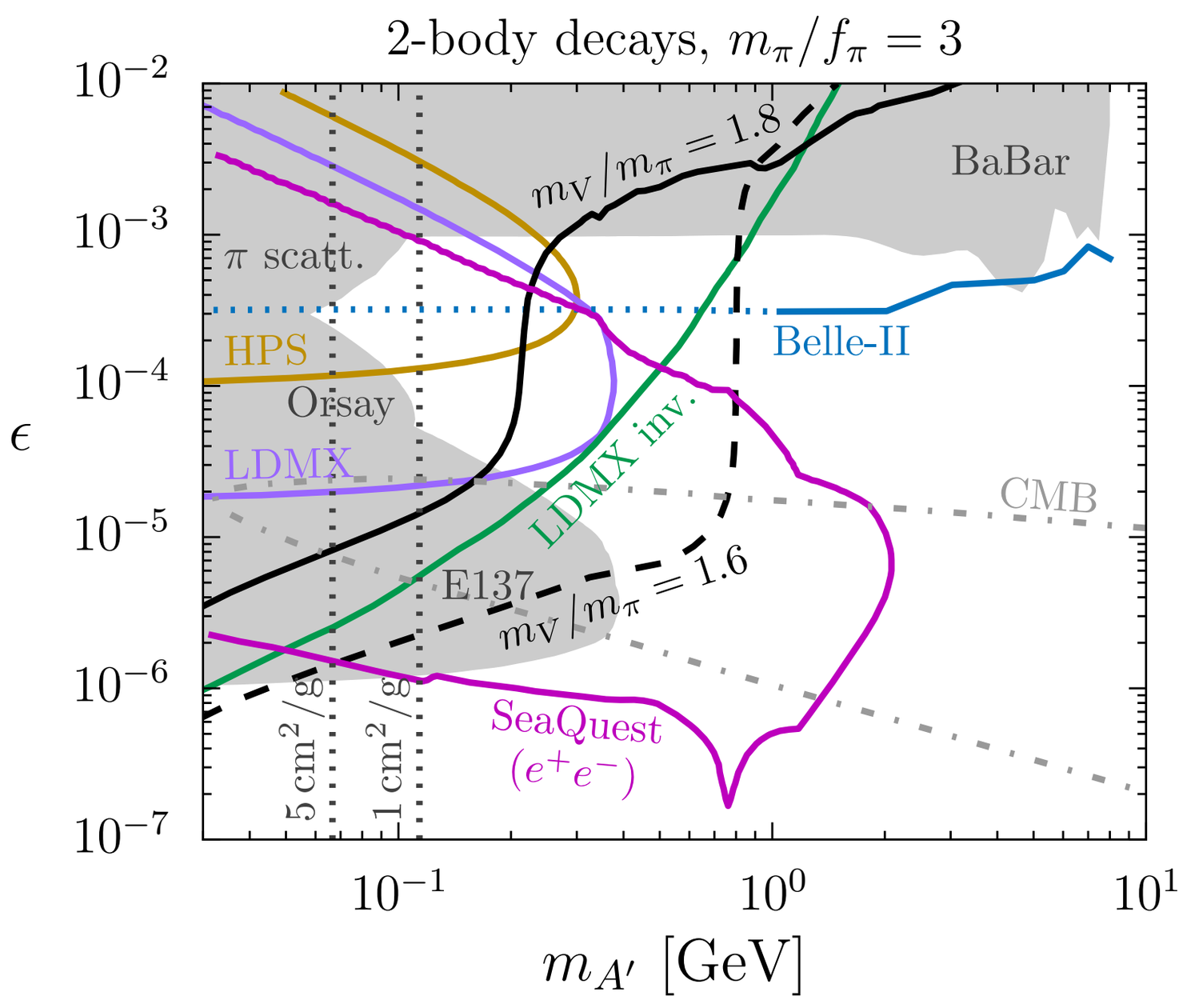


3-body $V^\pm$ decay

arXiv: 1801.05805

Hidden Sector Dynamics

($m_{A'}$ / m_π = 3)



arXiv: 1801.05805

Outline

I. Very Thermal

II. Pretty Thermal

III. Almost Thermal

III. Not Thermal

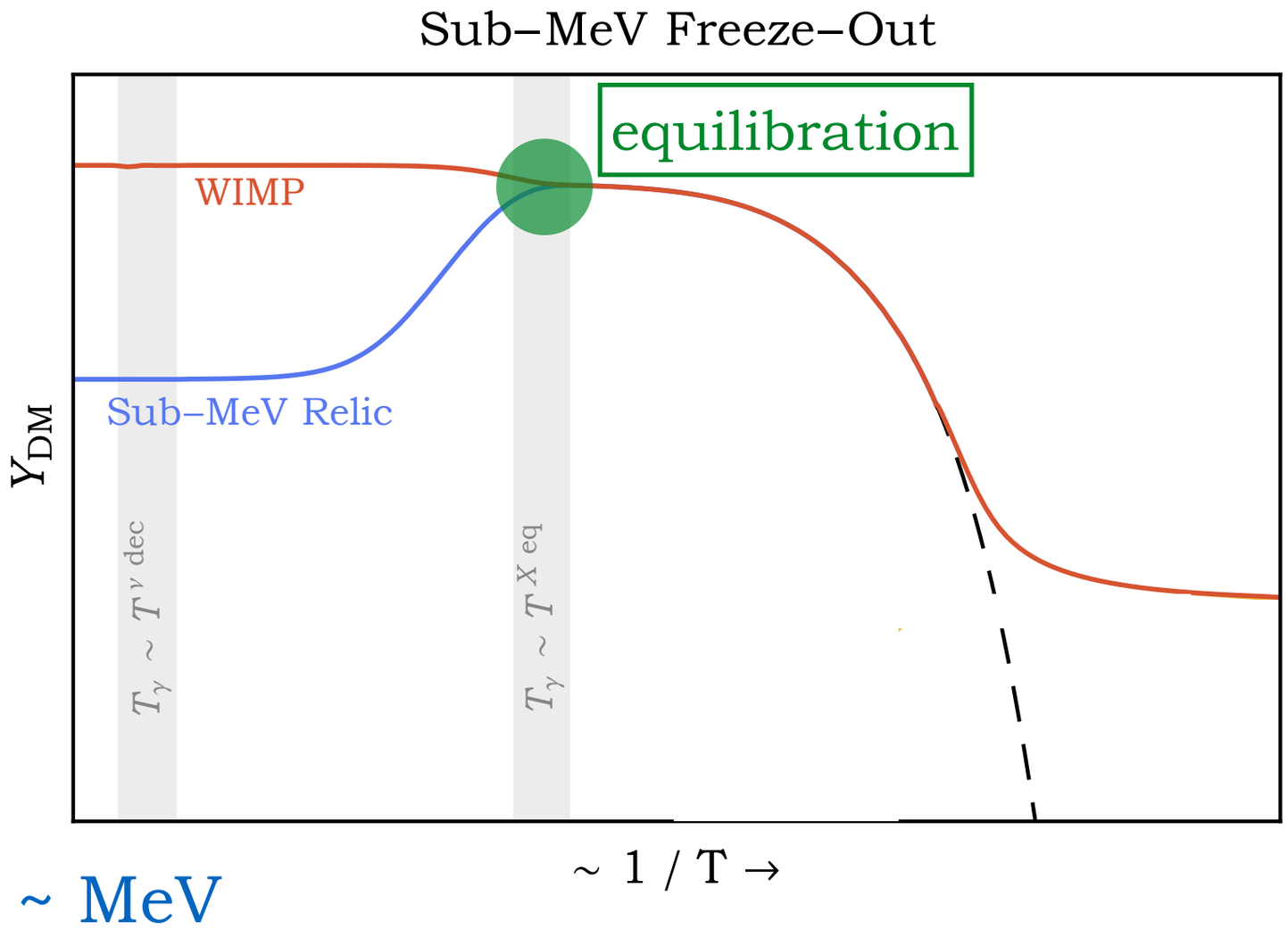
larger coupling to visible sector

smaller coupling to visible sector

Dark Matter Mass

N_{eff} Thermal Contact

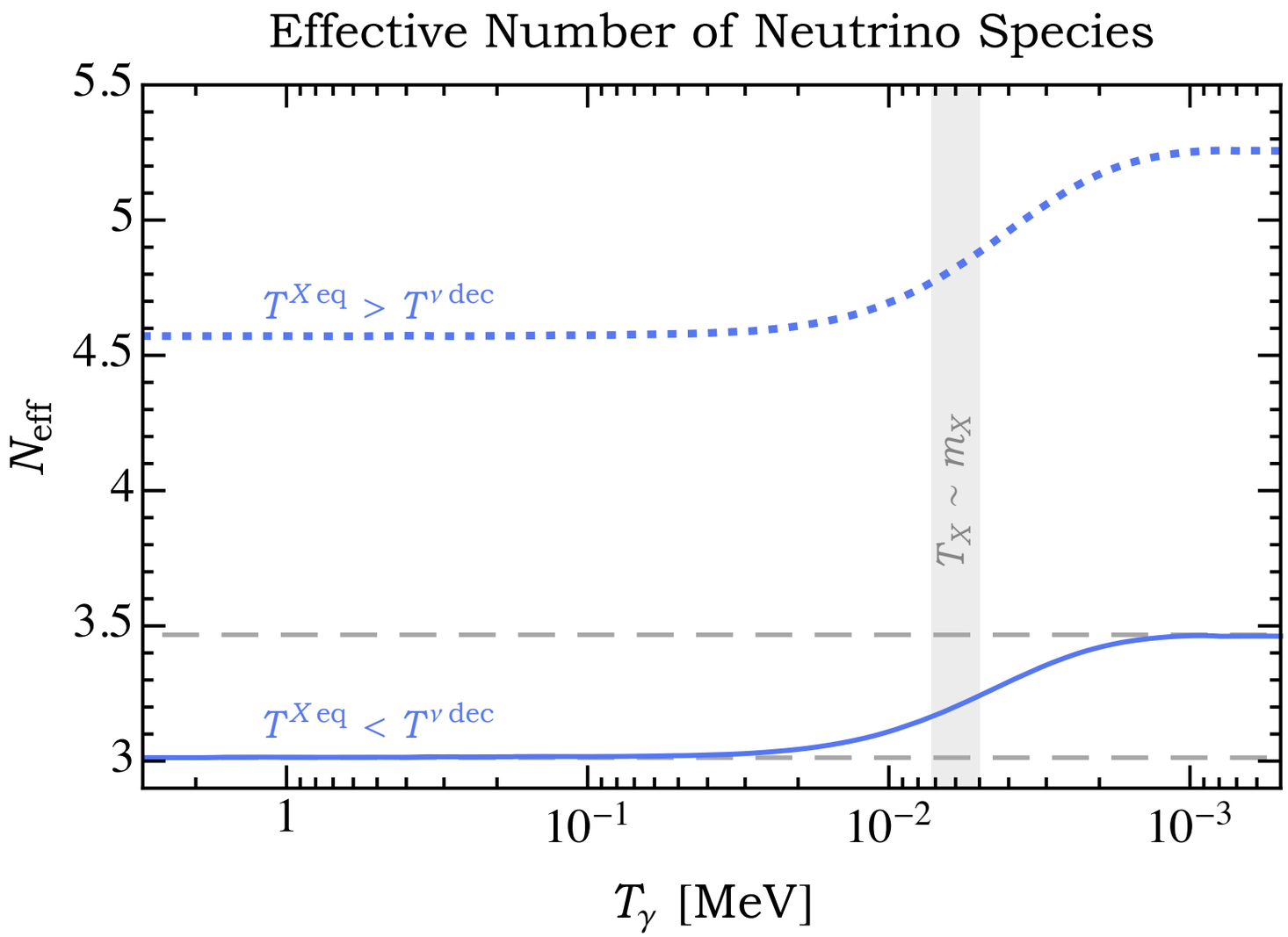
Delayed Equilibration



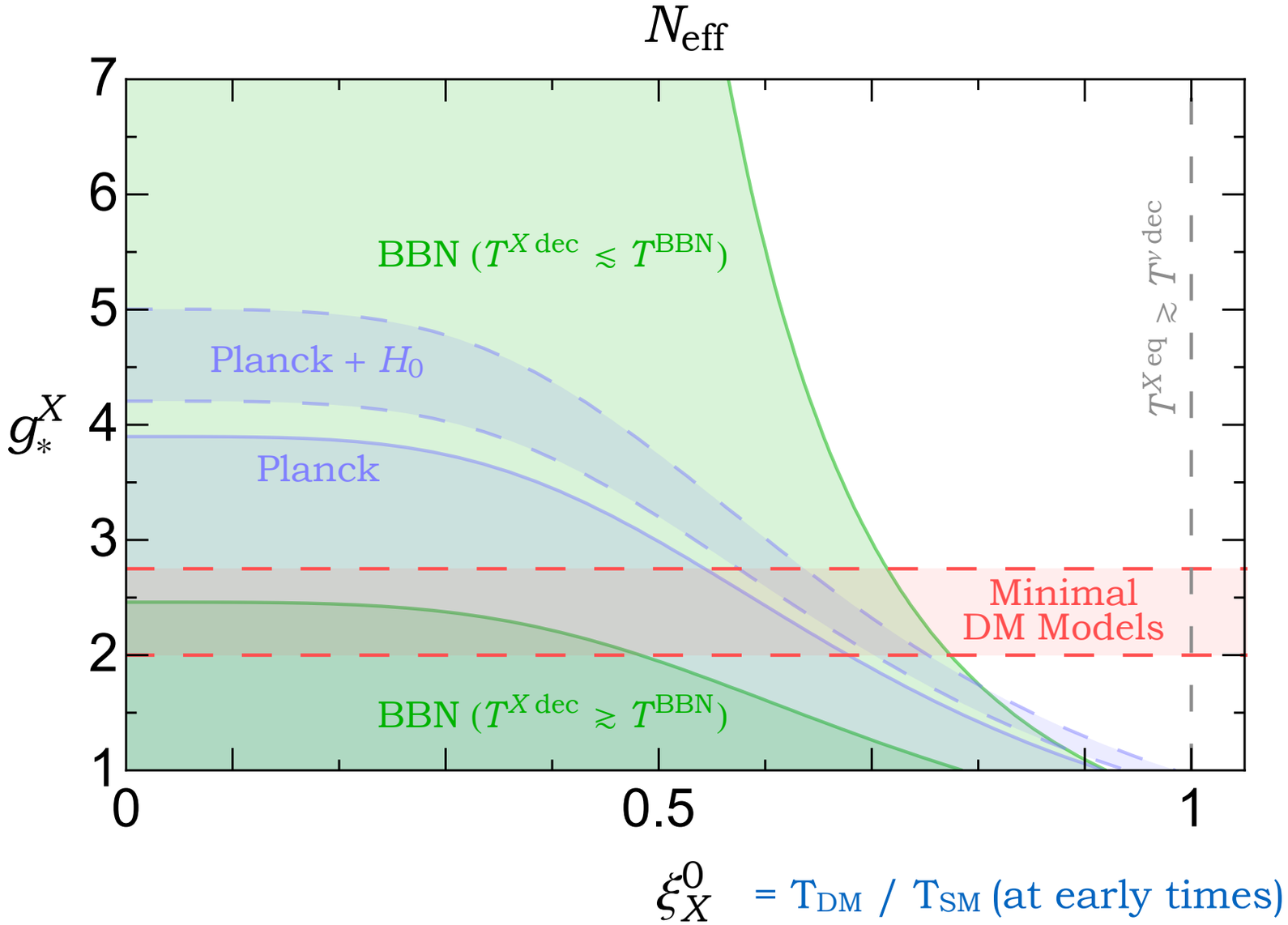
~ MeV

arXiv:1706.07046

Delayed Equilibration



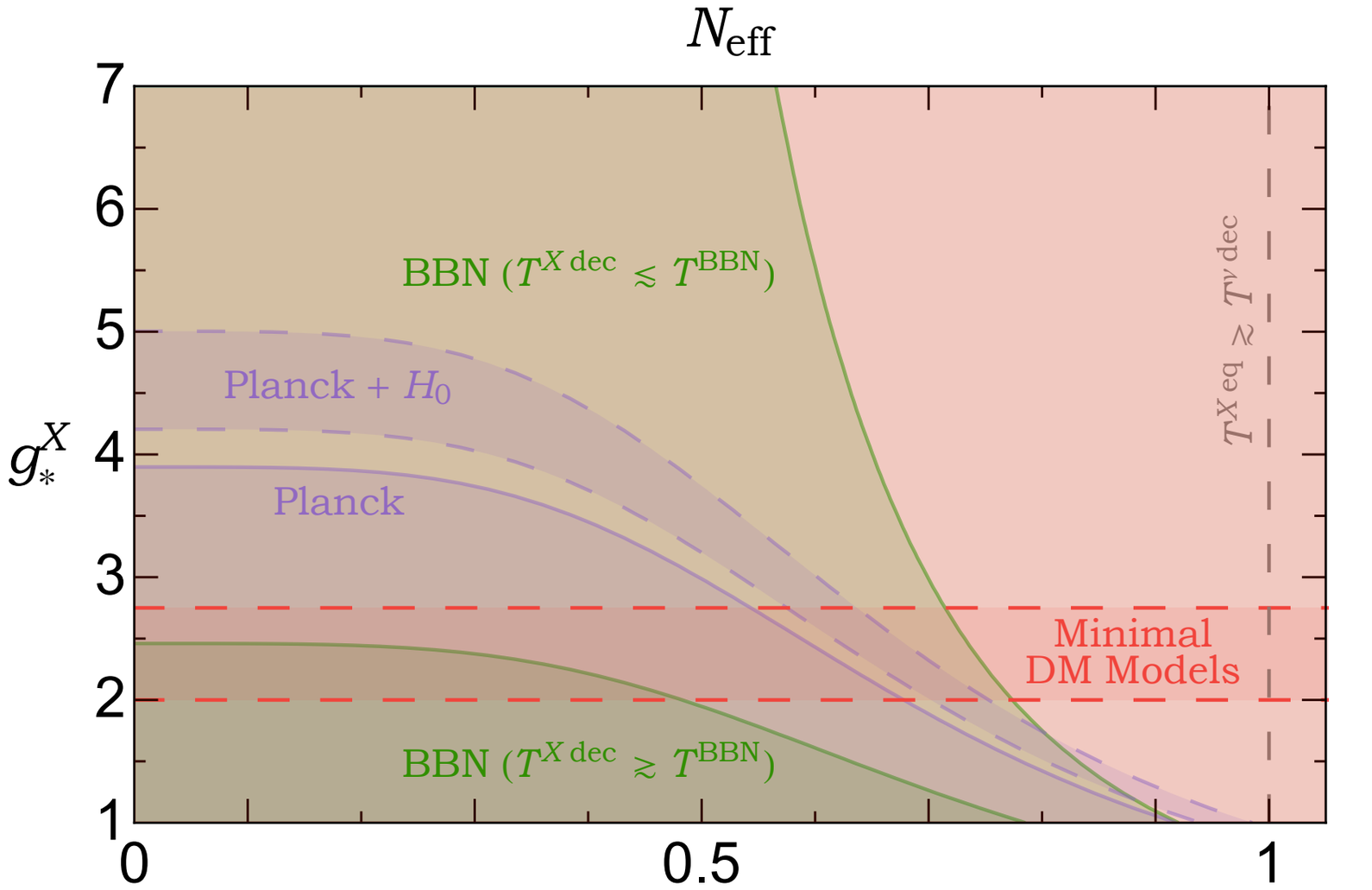
Delayed Equilibration



ξ_X^0 = T_{DM} / T_{SM} (at early times)

arXiv:1706.07046

Delayed Equilibration



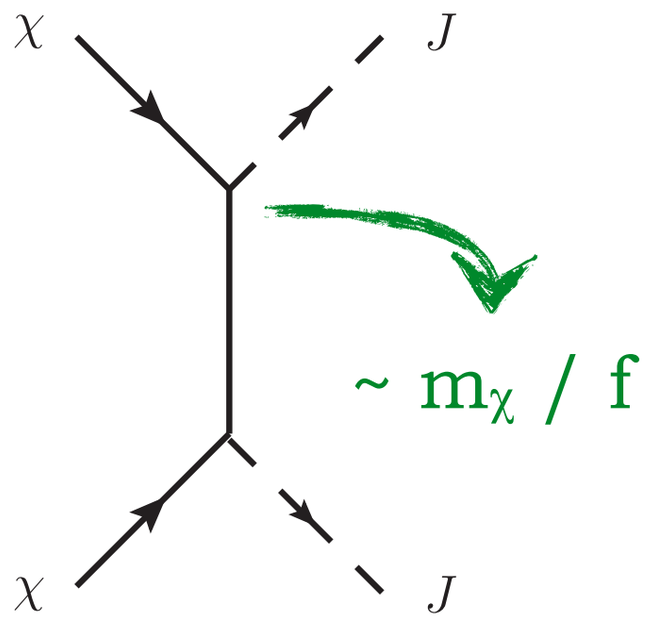
ξ_X^0 = T_{DM} / T_{SM} (at early times)

$\Delta N_{\rm eff}(\text{CMB-S4}) \simeq \pm 0.027$

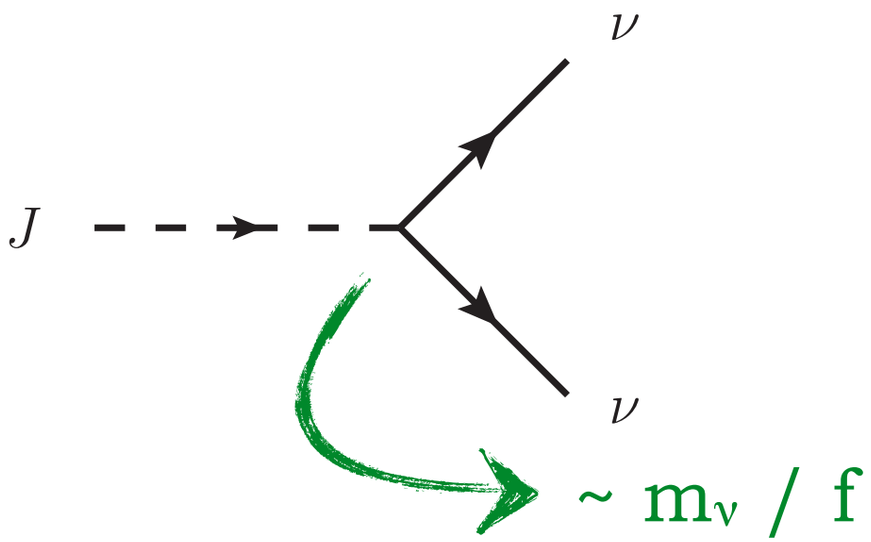
arXiv:1706.07046

Delayed Equilibration

Freeze-Out



Equilibration



freeze-out + equilibration $\Longrightarrow$ $m_\chi \sim \left(\frac{m_{\rm Pl}}{T_{\rm eq}}\right)^{1/4}$ $m_\nu \sim {\rm MeV}$

arXiv:1706.07046

Outline

I. Very Thermal

II. Pretty Thermal

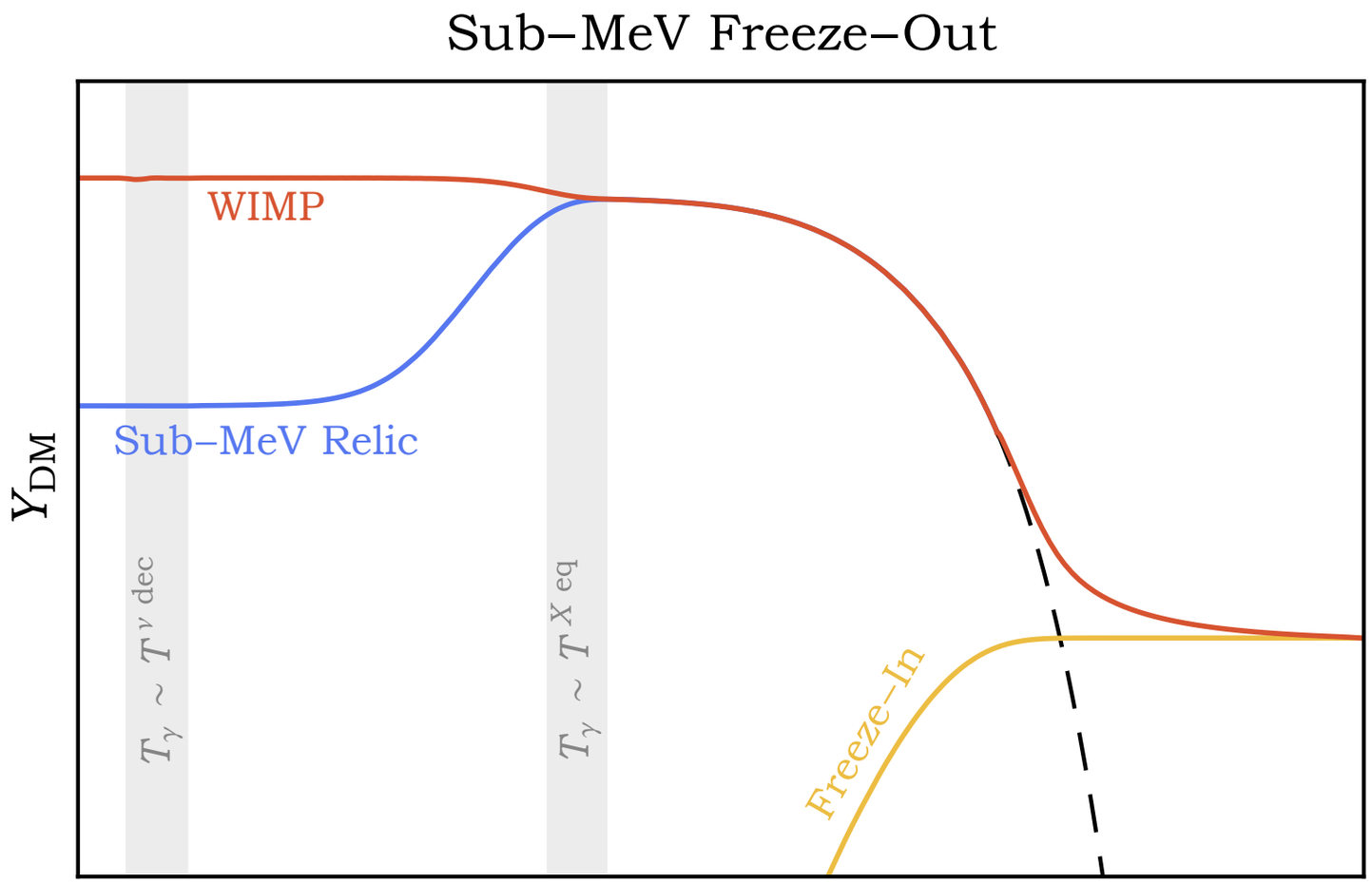
III. Almost Thermal

III. Not Thermal

larger coupling to visible sector

smaller coupling to visible sector

Freeze-in



~ MeV

arXiv:1707.04591

Freeze-in: Sterile Neutrino

$$-\mathcal{L} \supset y_\nu \, N \, L \, H + \frac{1}{2} \, M_N \, N^2 + \text{h.c.}$$

$$\nu \simeq i \, \nu_{\text{SM}} - \theta \, \nu_s \ , \ N \simeq \nu_s + i \, \theta \, \nu_{\text{SM}}$$

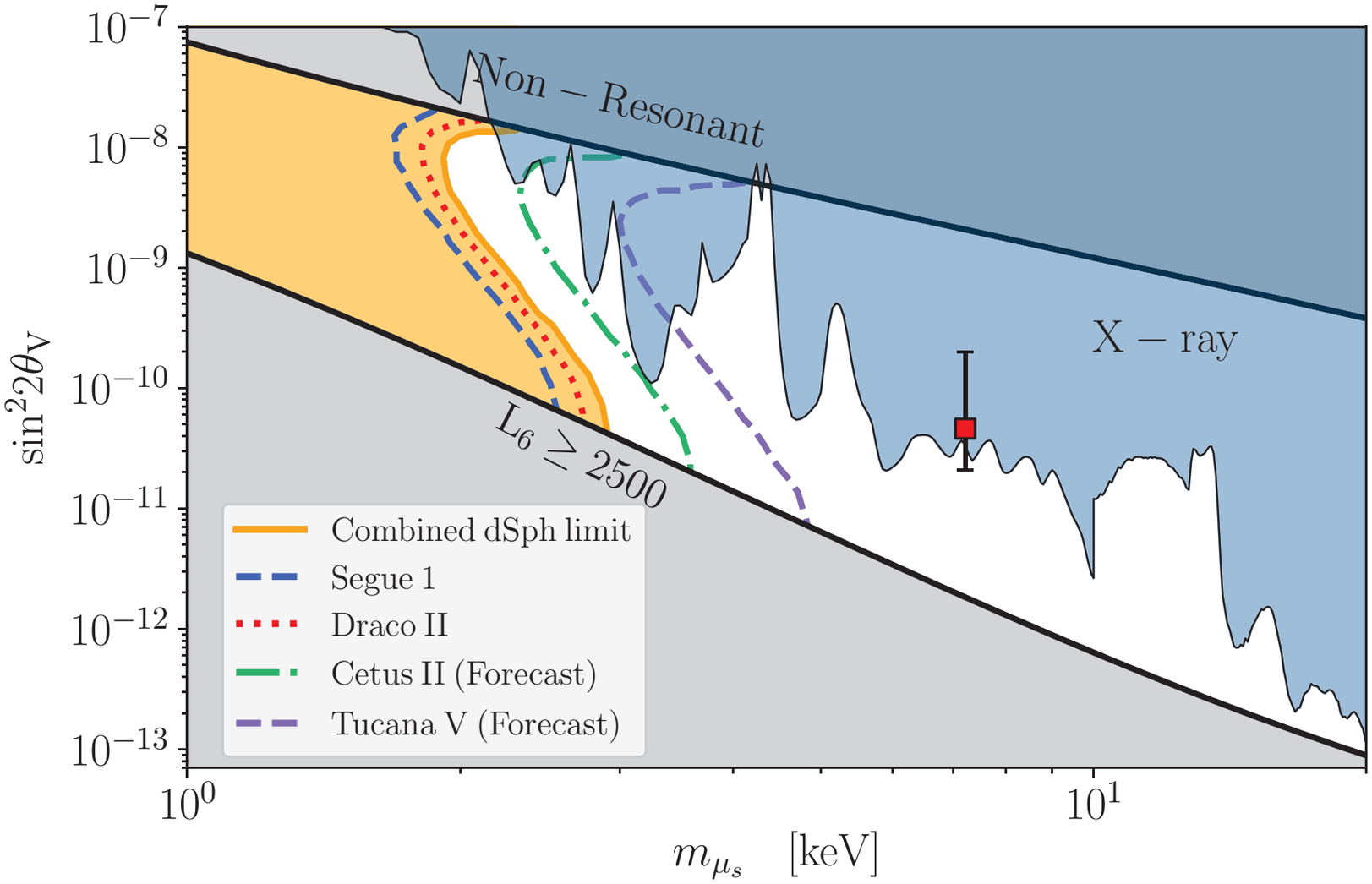
$$\theta = \frac{y_\nu \, v}{\sqrt{2} \, M_N} \simeq \left(\frac{m_{\nu_{\text{SM}}}}{m_{\nu_s}} \right)^{1/2}$$

$$\Omega_{\nu_s} \simeq \Omega_{\text{DM}} \times \left(\frac{\theta}{10^{-5}} \right)^2 \ \left(\frac{m_{\nu_s}}{30 \text{ keV}} \right)^2$$

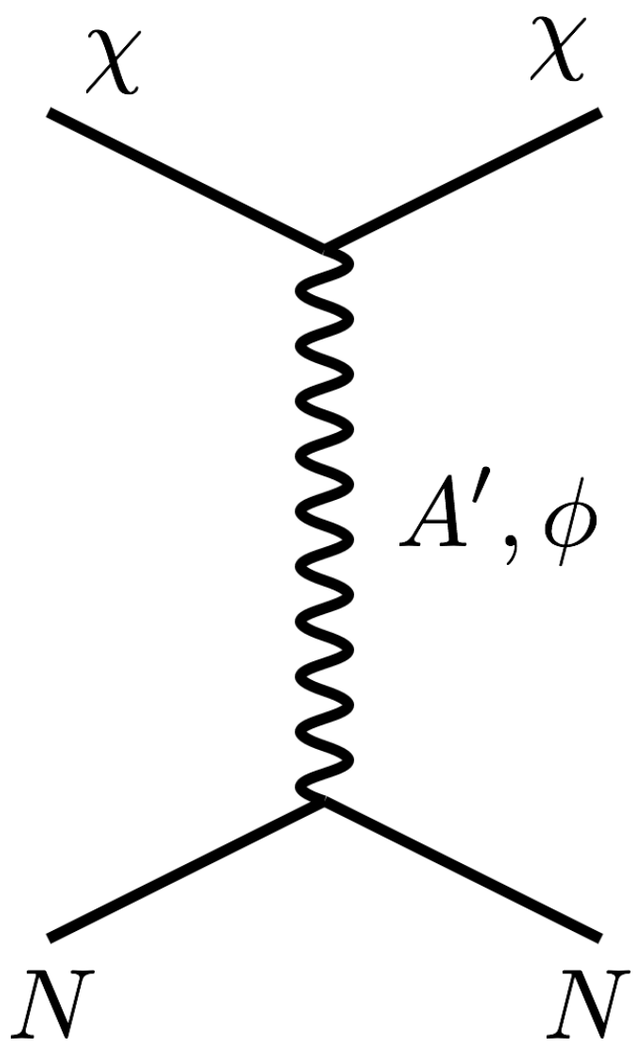
arXiv:hep-ph/9303287

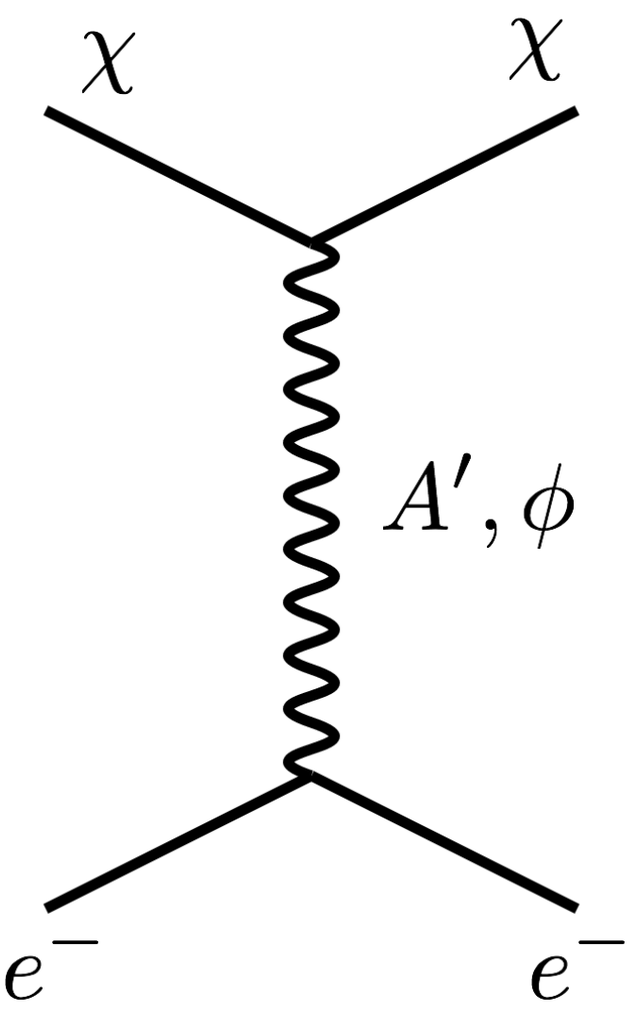
Freeze-in: Sterile Neutrino

$\nu_s \rightarrow \nu\ \gamma$

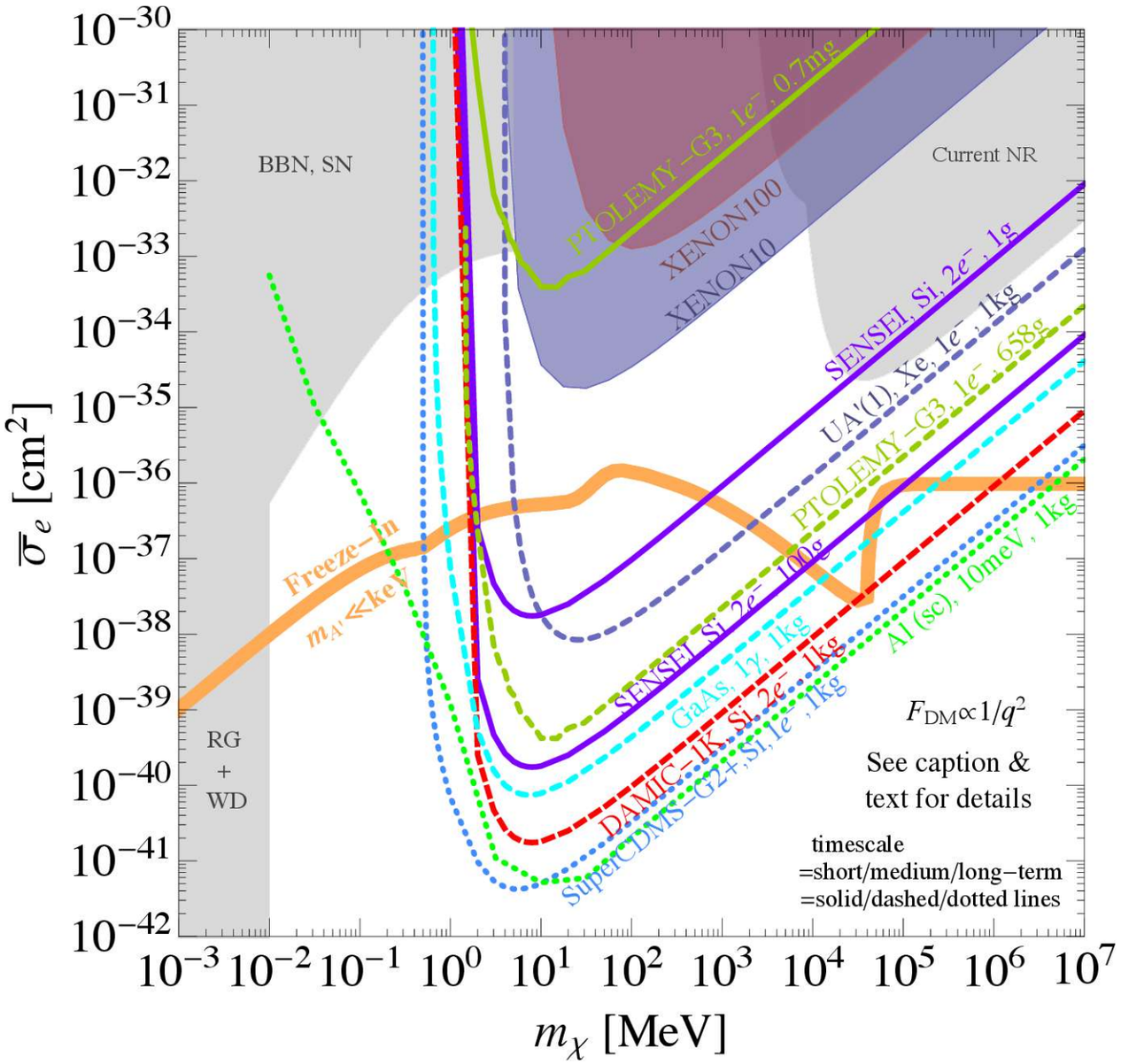


Freeze-in: Light Mediator





Freeze-in: Light Mediator



Outline

I. Very Thermal

II. Pretty Thermal

III. Almost Thermal

III. Not Thermal

(QCD axion, ultralight scalars and vectors)

larger coupling to visible sector

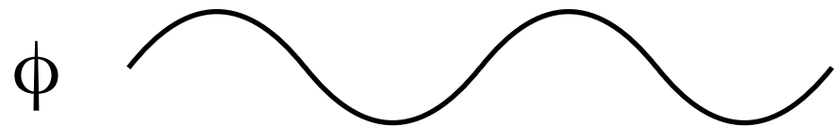
smaller coupling to visible sector

Ultralight Bosons

see relevant sections in
arXiv:1707.04591

QCD axion, ultralight scalars and vectors

Field-Like

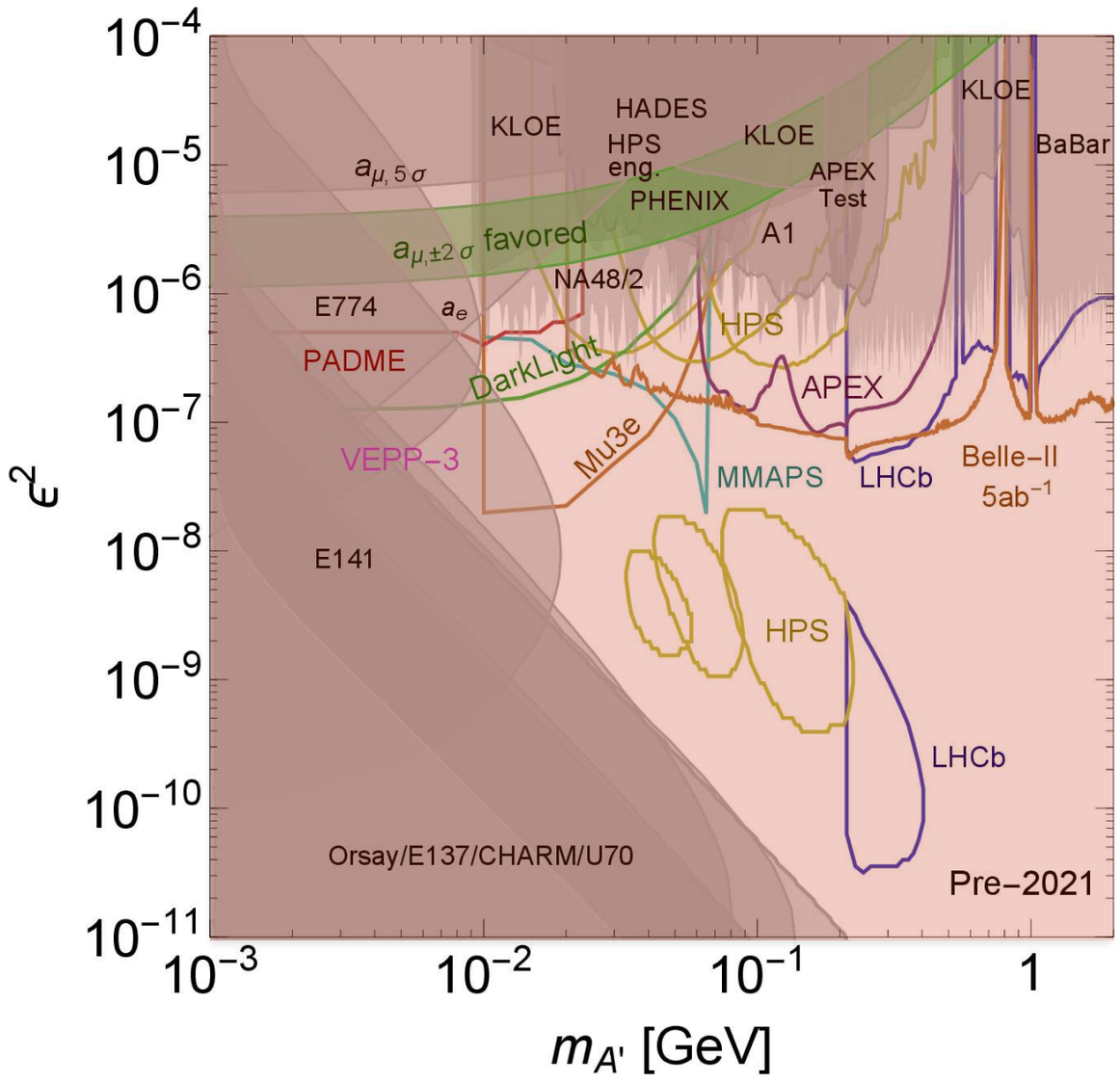


$$n_{\rm DM}\ \lambda^3 \simeq \left(\frac{2\pi}{v}\right)^3\ \frac{\rho_{\rm DM}}{m^4}$$

$$\simeq \mathcal{O}(100) \times \left(\frac{10^{-3}}{v}\right)^3\ \left(\frac{\rho_{\rm DM}}{0.4\ {\rm GeV}\ /\ {\rm cm}^3}\right)\ \left(\frac{10\ {\rm eV}}{m_\phi}\right)^4$$

$$\phi \simeq \frac{\sqrt{2\,\rho_{\rm DM}}}{m_\phi}\ \cos m_\phi\, t$$

Measurement of the Fine-Structure Constant



$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_{\mathrm{At}}}{m_{\mathrm{e}}}\frac{h}{m_{\mathrm{At}}}$$

"A model consisting of the Standard Model and dark photons of any m_V or ϵ is now incompatible with the data at up to a 99% confidence level (CL)."

Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and Holger Müller
Science 360, 191-195 (2018)

Measurement of the Fine-Structure Constant

SM predicts $X = 0$

SM + BSM predicts $X = 10^{-6}$

Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and Holger Müller
Science 360, 191-195 (2018)

Measurement of the Fine-Structure Constant

SM predicts $X = 0$

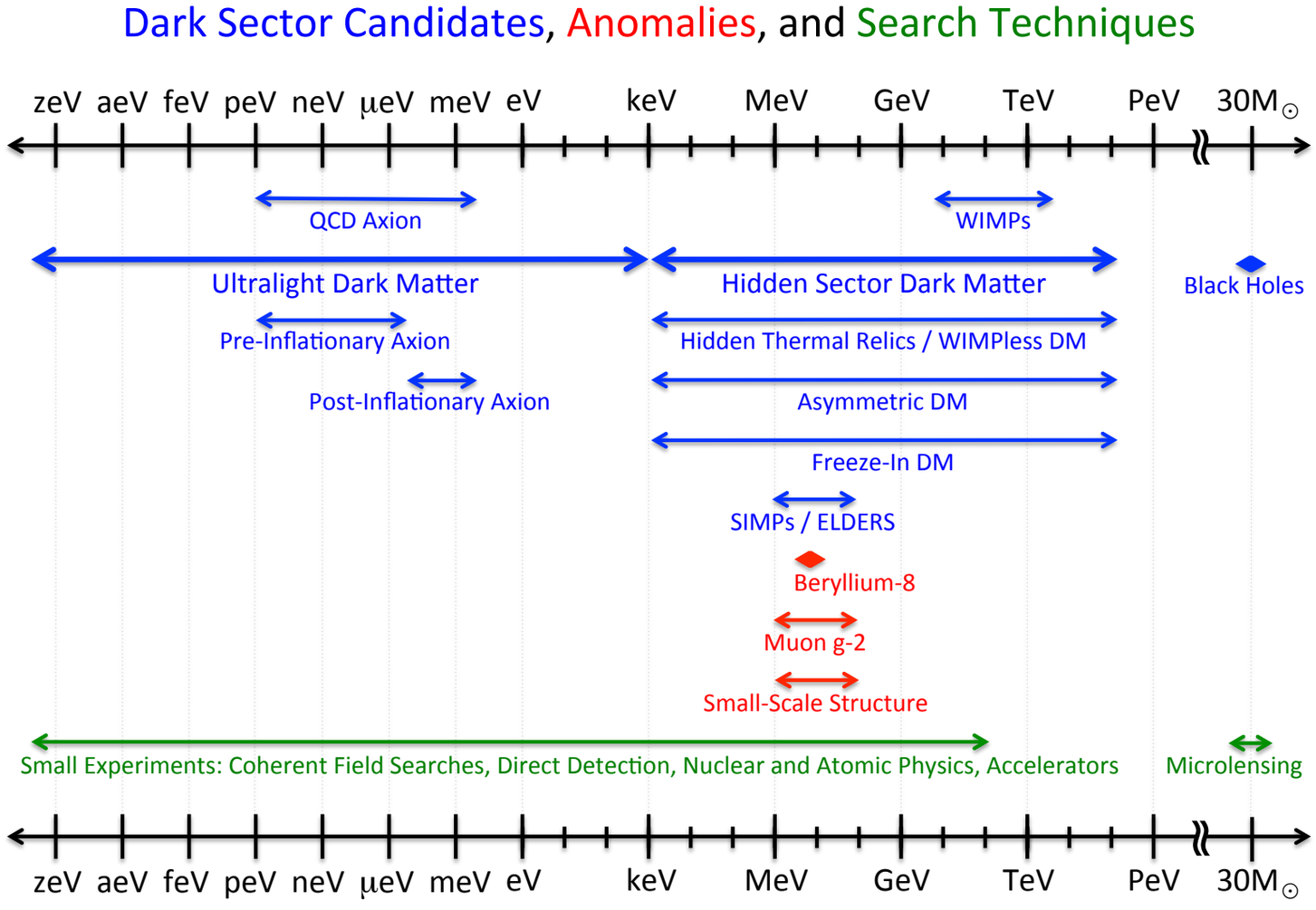
SM + BSM predicts $X = 10^{-6}$

Experiment measures $X = -1 \pm 0.333$

Experiment excludes SM + BSM at 3σ ?

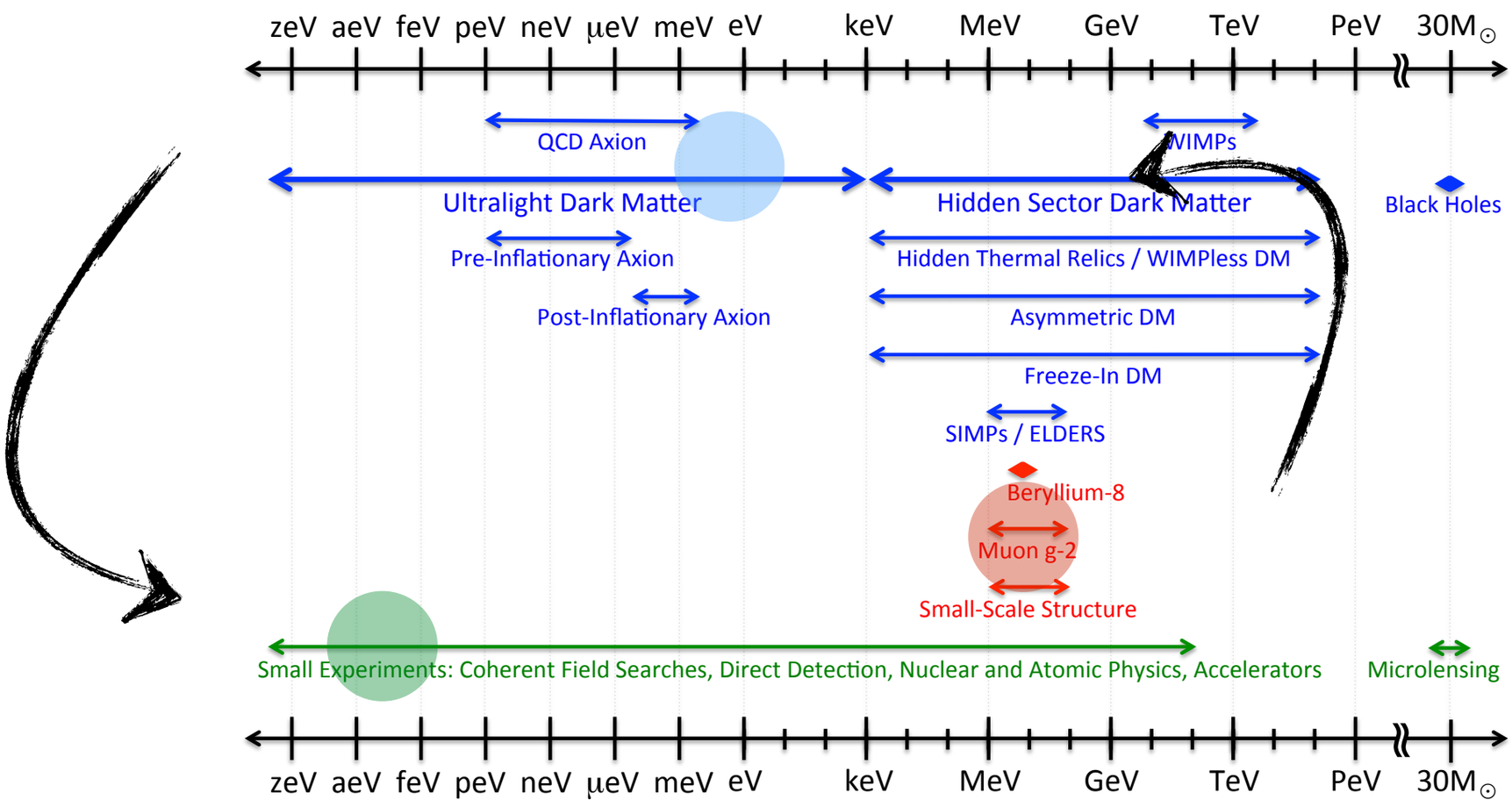
Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and Holger Müller
Science 360, 191-195 (2018)

Summary



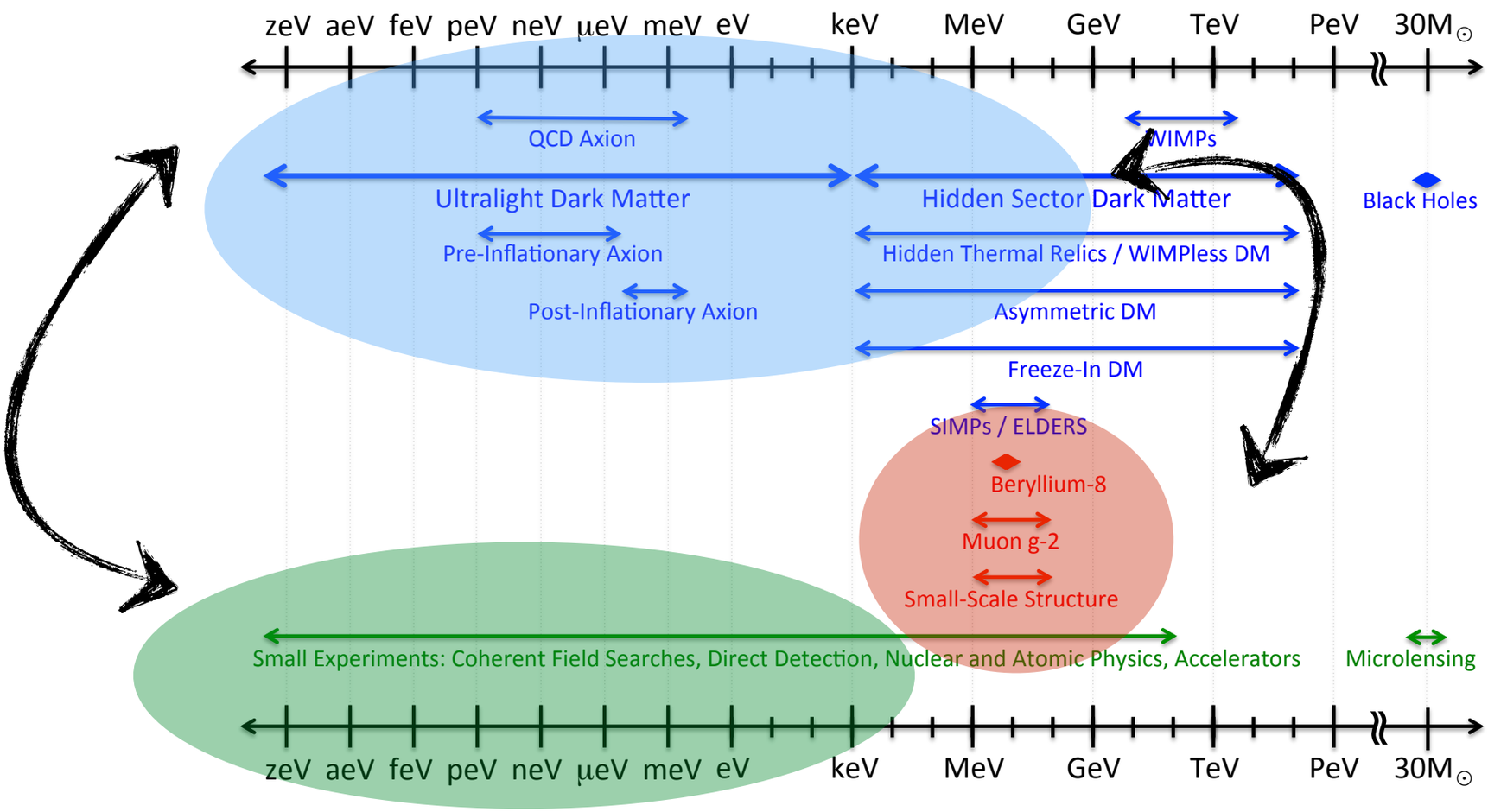
Summary

Anomalies ⇒ Models ⇒ Signals



Summary

Anomalies $\Longleftrightarrow$ Models $\Longleftrightarrow$ Signals



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