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neutrinos, dark matter & dark energy physics

elusives
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Neutrino Portals to Dark Matter

Salvador Rosauro-Alcaraz

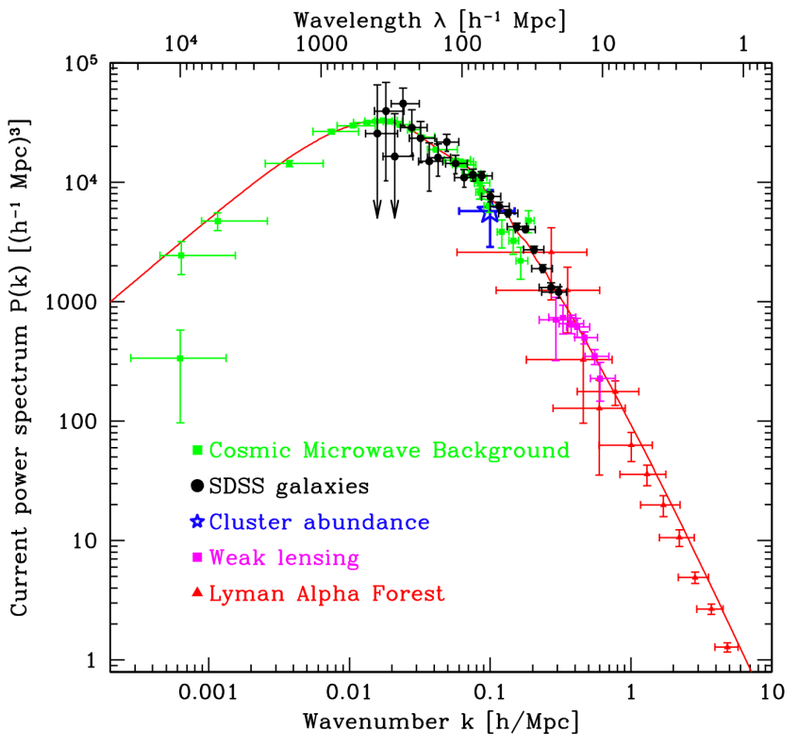
In collaboration with M. Blennow, E. Fernández-Martínez, A. Olivares-Del Campo, S. Pascoli and A. Titov
Based on Eur.Phys.J. **C79** (2019) 55

Instituto de Física Teórica
UAM-CSIC

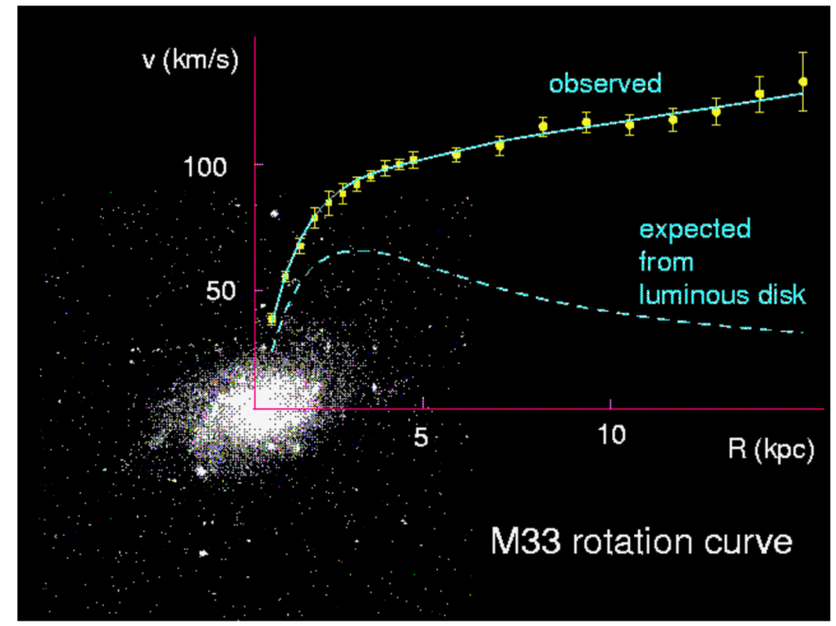
Topics in Cosmic Neutrino Physics
9-11 October 2019, Fermilab

UAM
Universidad Autónoma de Madrid

Dark Matter

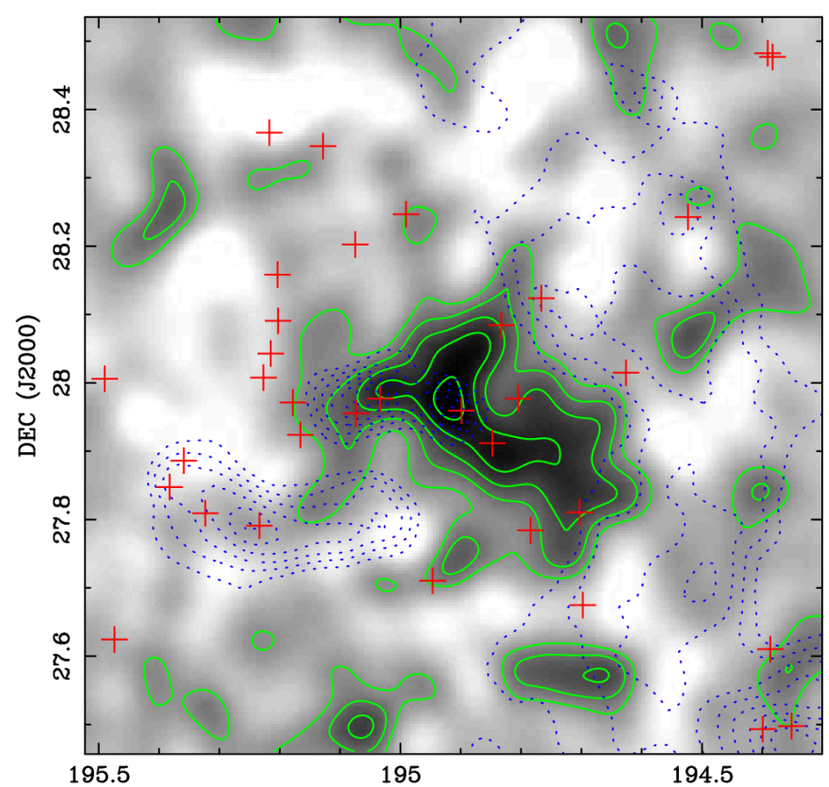


M. Tegmark *et al.*
arXiv:0310725



D. P. Roy, arXiv:physics/0007025

R. Gavazzi *et al.*
arXiv:astro-ph/0904.0220



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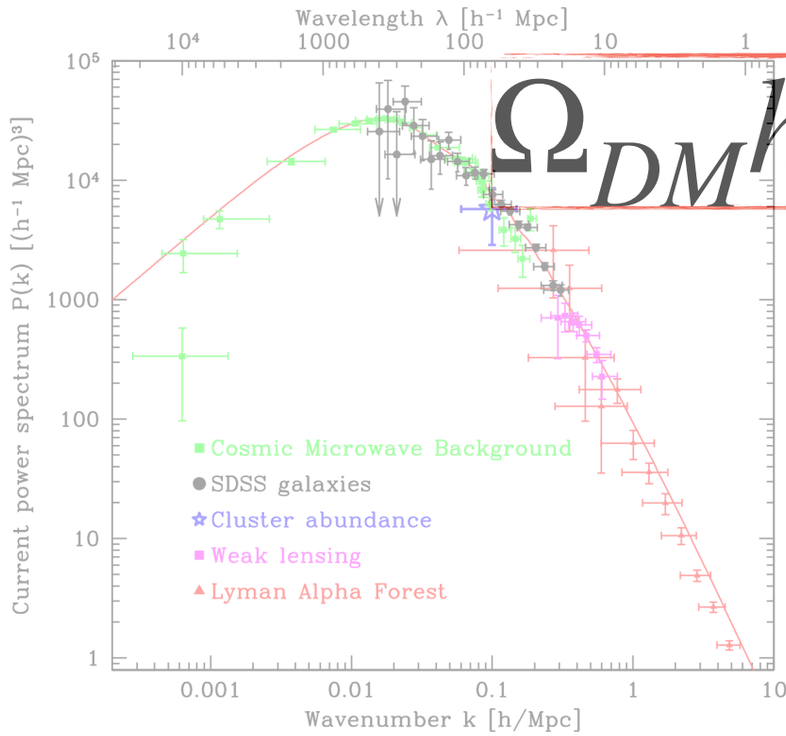
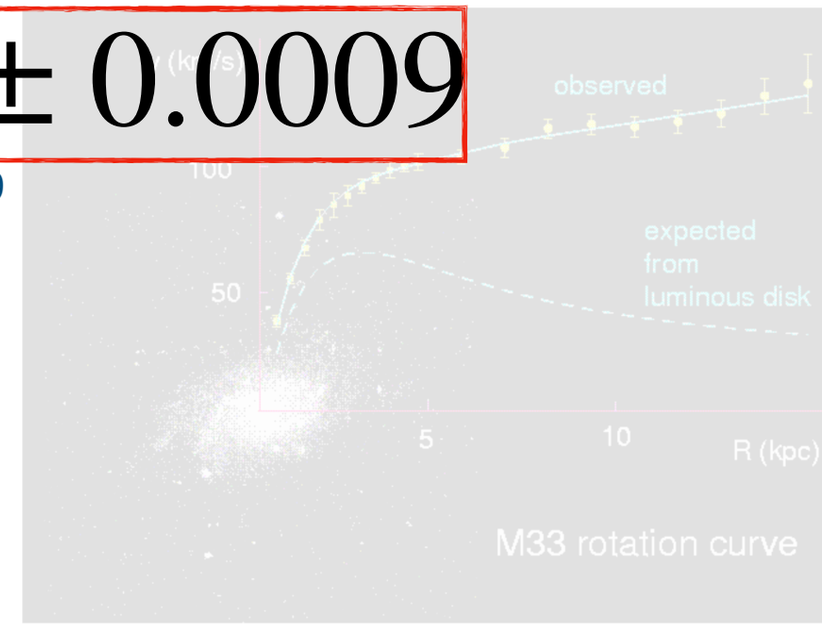
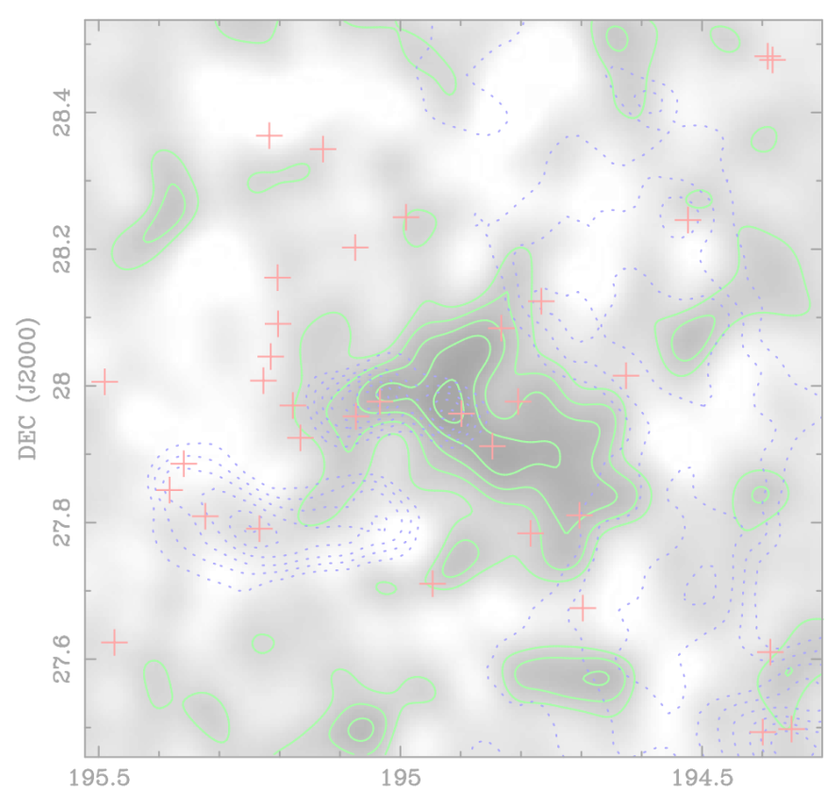


$$\Omega_{DM} h^2 = 0.1193 \pm 0.0009$$

Planck Collaboration, arXiv:1807.06209





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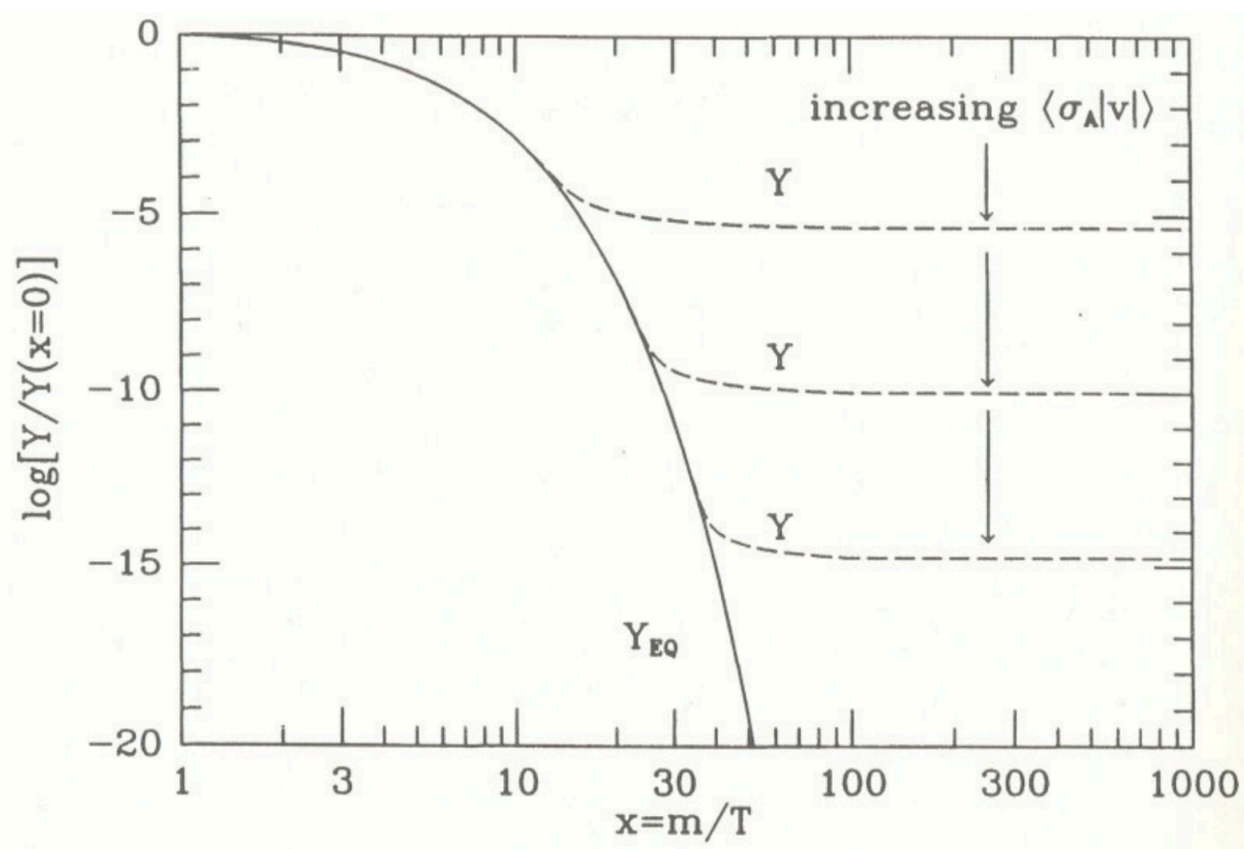
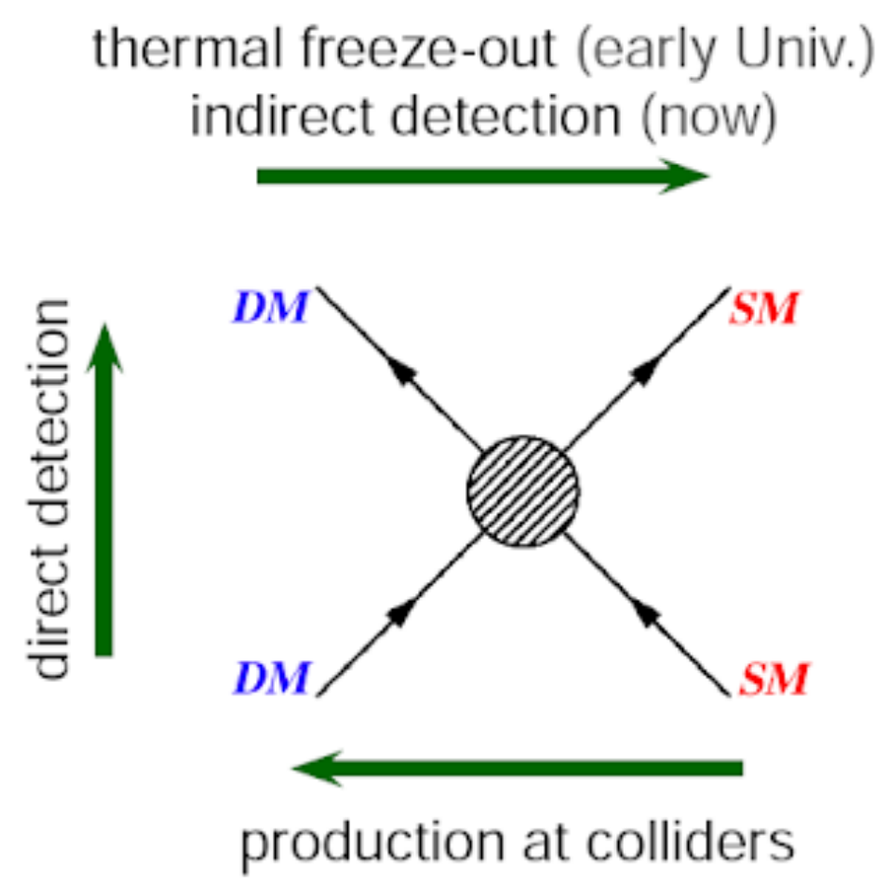
Thermal freeze-out



The Early Universe, E. Kolb & M. Turner



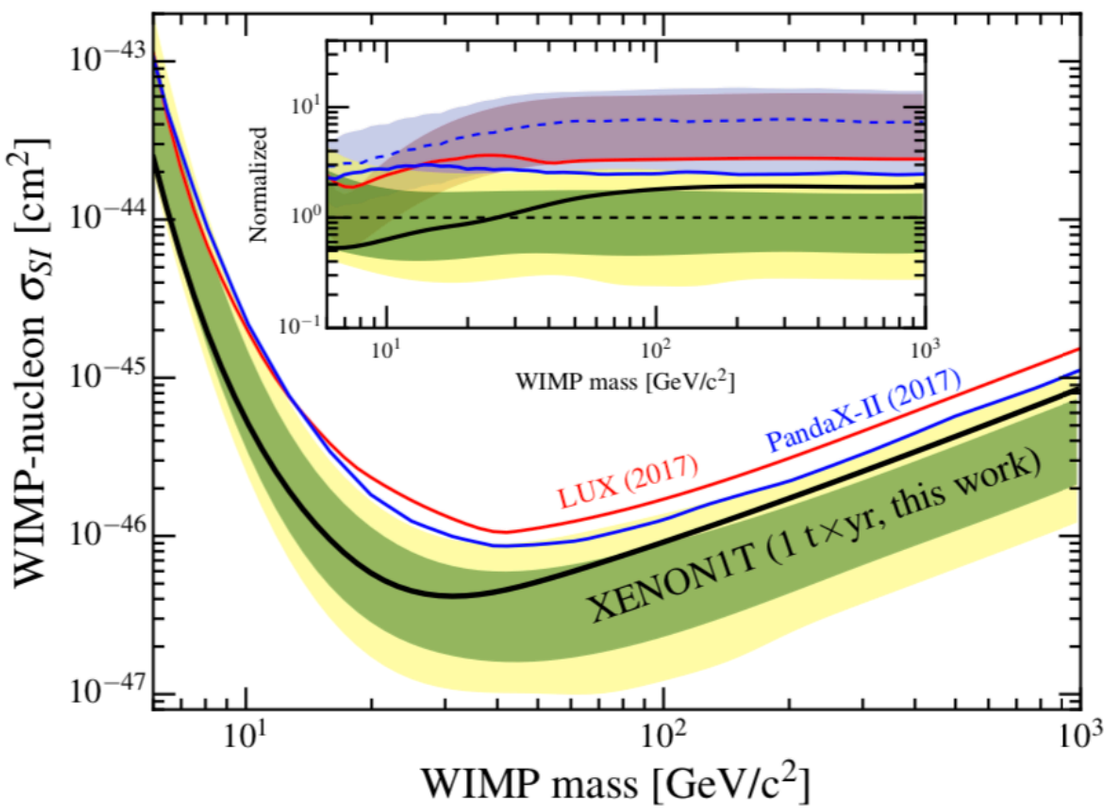
J. Feng, MPIK webpage
https://www.mpi-hd.mpg.de/lin/research_DM.en.html

What about direct detection?

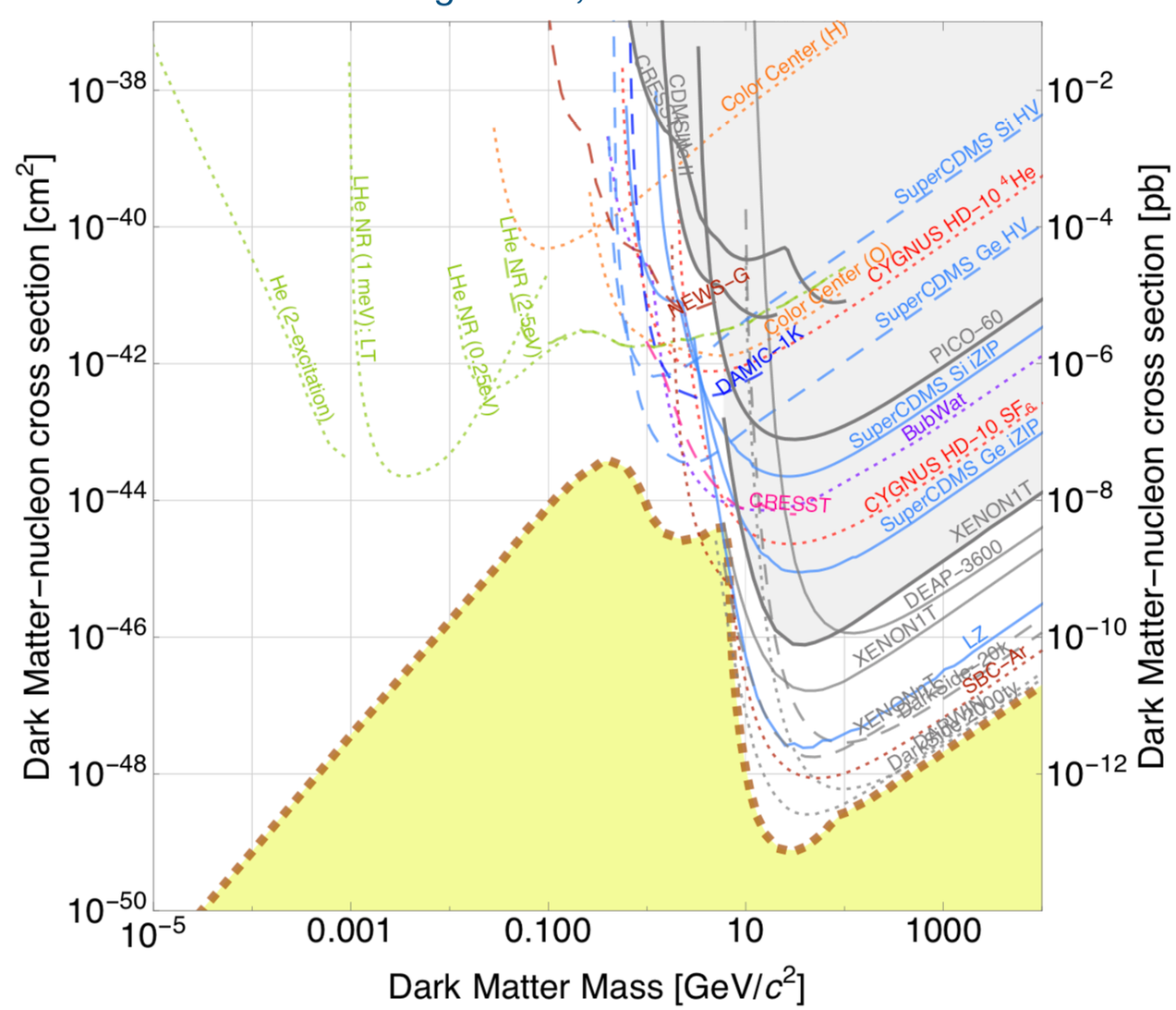
$$\Omega_{DM}h^2 = 0.1193 \pm 0.0009$$

Planck Collaboration, arXiv:1807.06209

XENON Collaboration, arXiv:1805.12562



E. Adelberger *et al.*, arXiv:1701.04591



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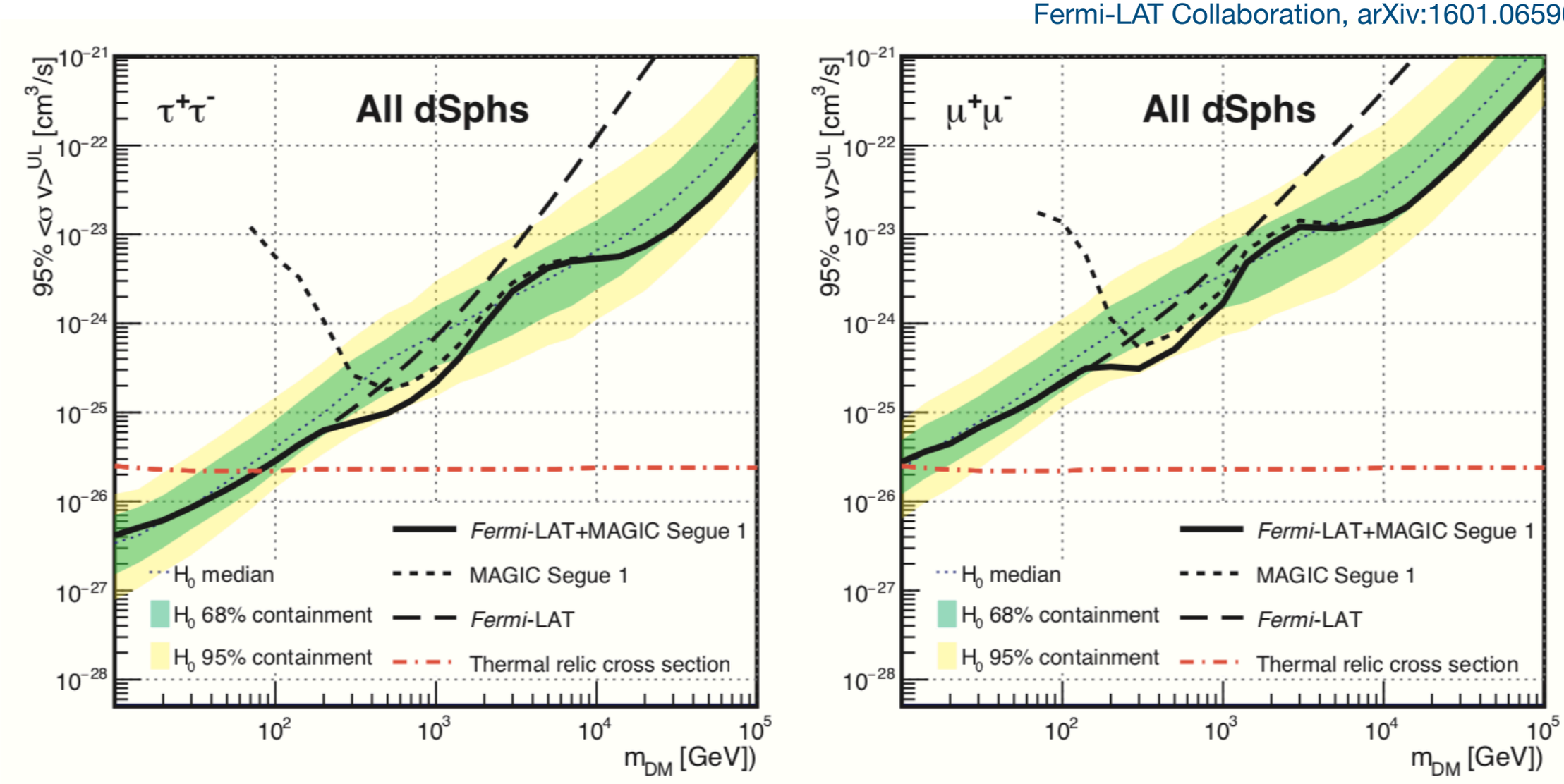
Planck Collaboration, arXiv:1807.06209

Fermi-LAT Collaboration, arXiv:1601.06590

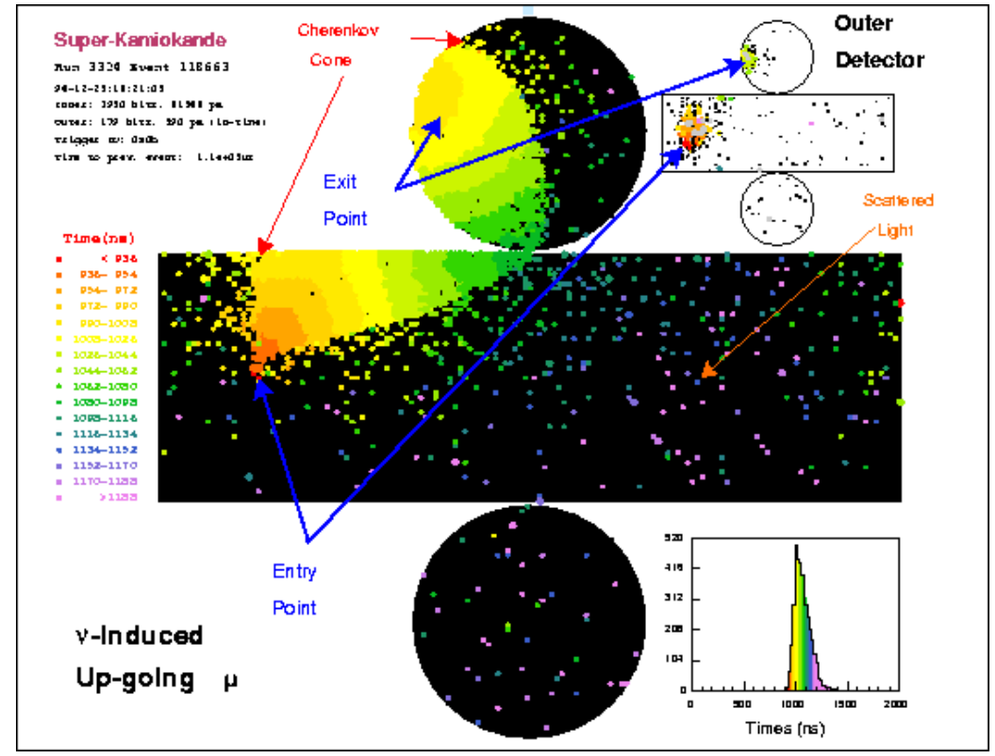


Neutrino-dark matter interactions

In the Standard Model

$$\mathscr{L}_{\nu\ int} \supset \frac{g}{\sqrt{2}}\bar{\nu}_\alpha \gamma^\mu P_L l_\alpha W_\mu^+ + \frac{g}{2\cos\theta_W}\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha Z_\mu$$

Dark matter shares its elusive nature with neutrinos



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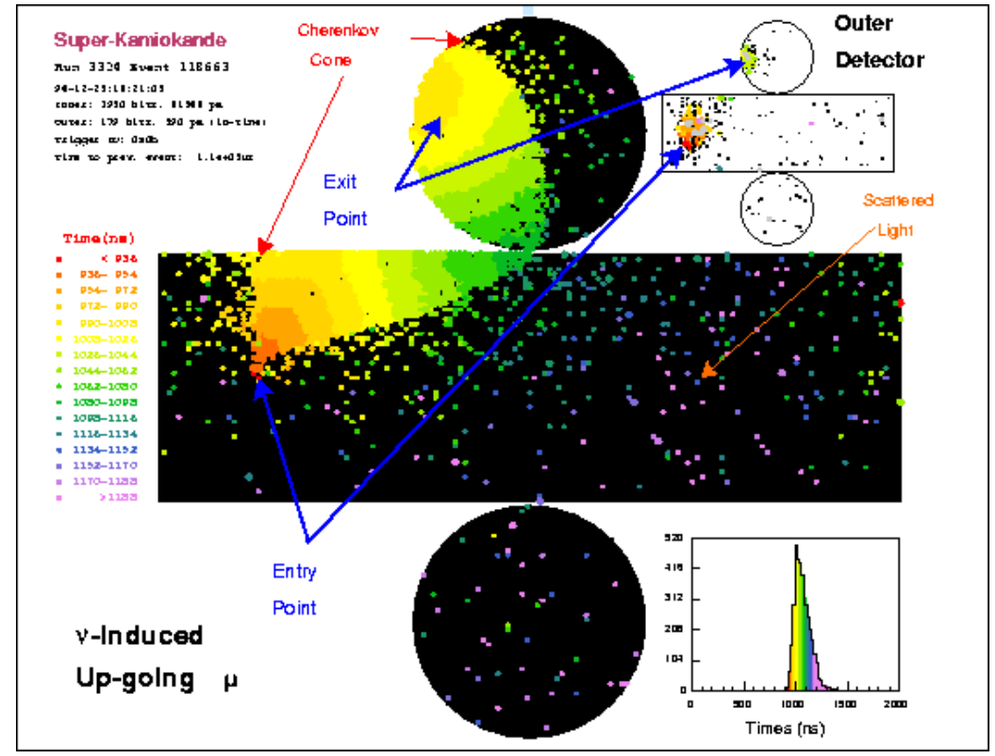

Could dark matter be primarily interacting with neutrinos?

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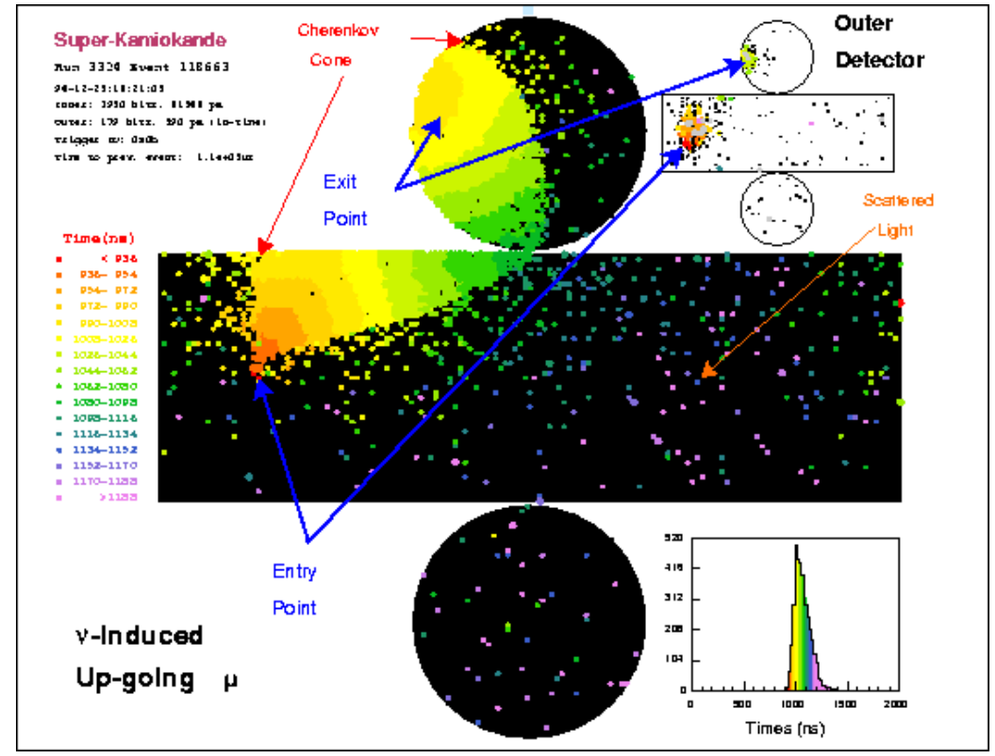
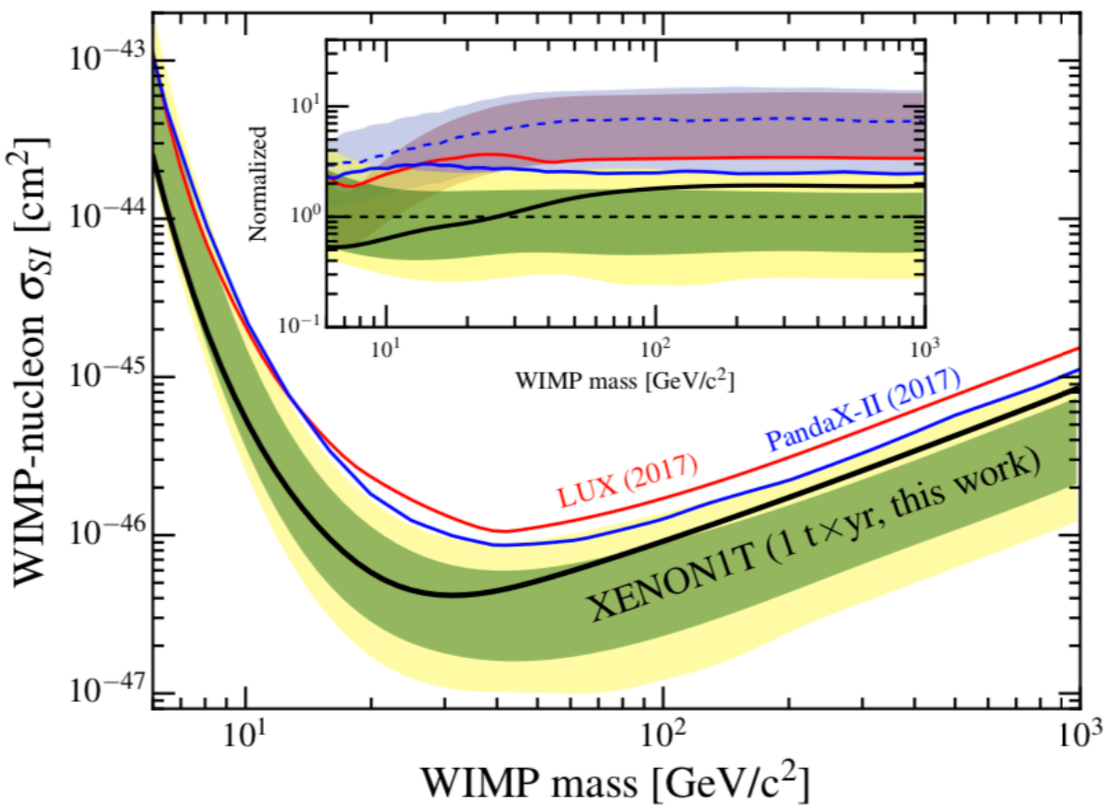


Could dark matter be primarily interacting with neutrinos?

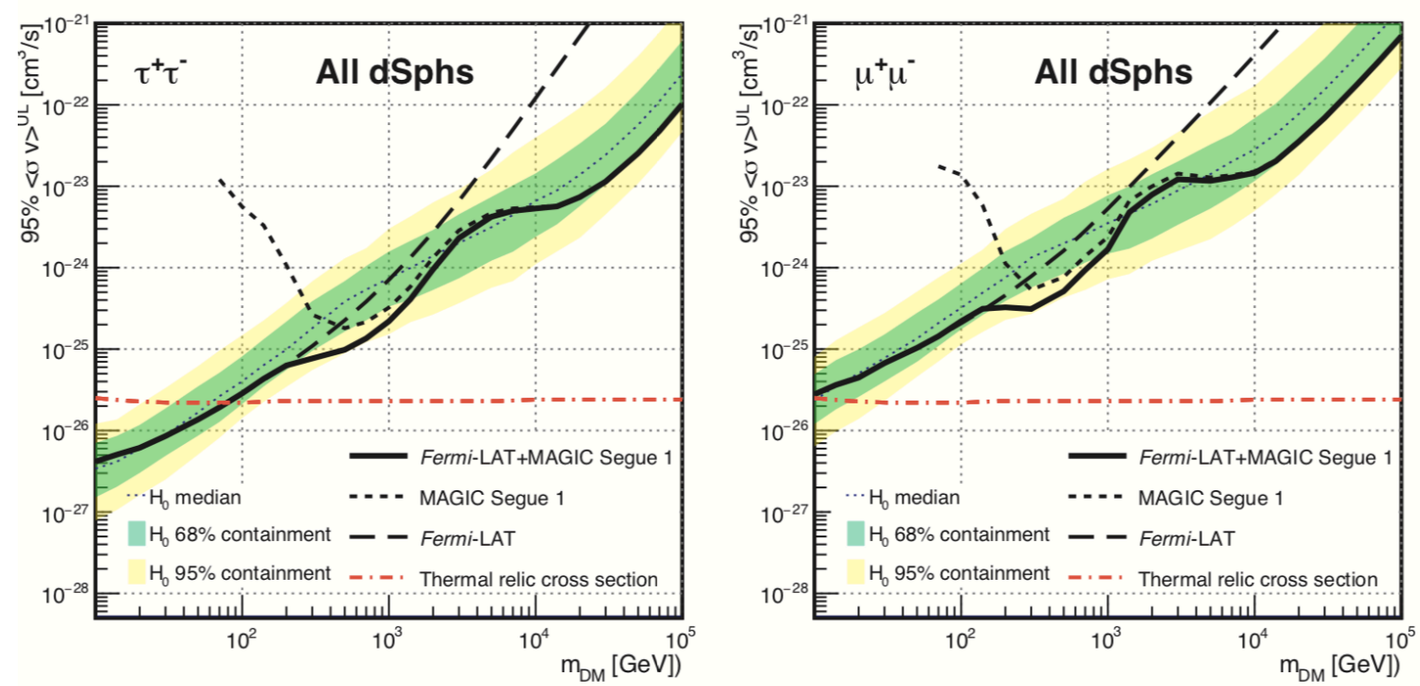
Can we detect such interaction?

Constraints on DM-SM interactions

Direct detection



Indirect detection with charged leptons



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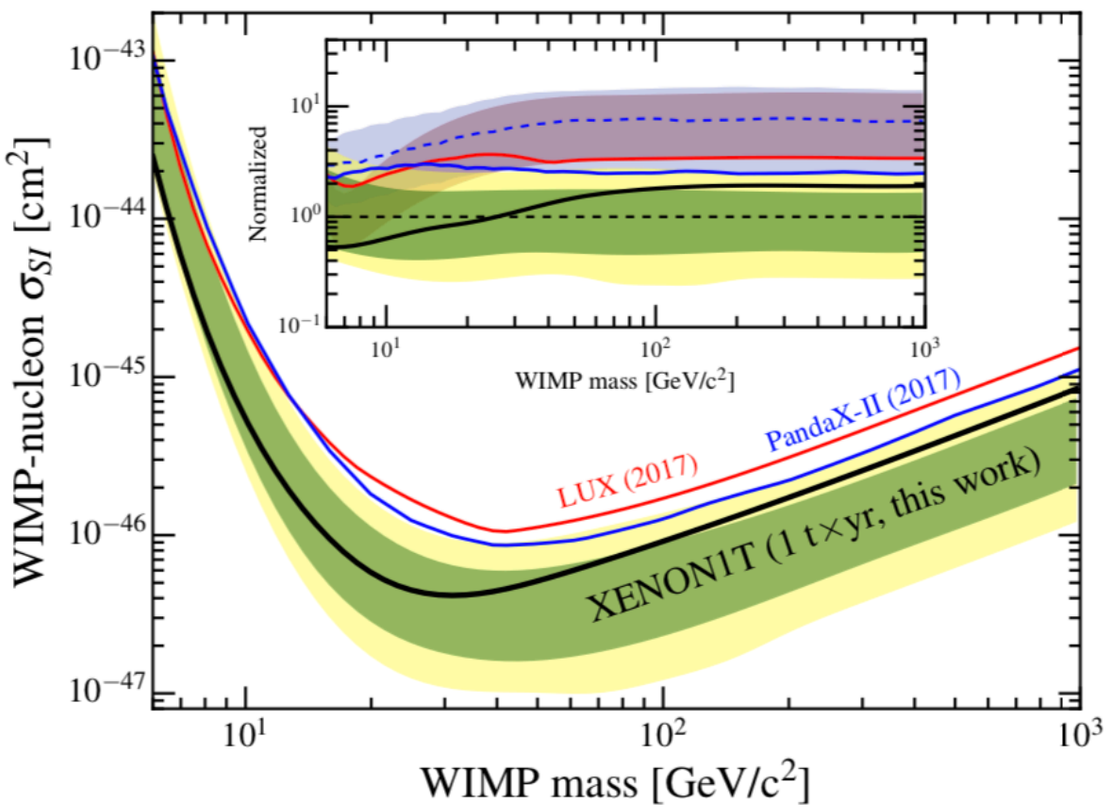

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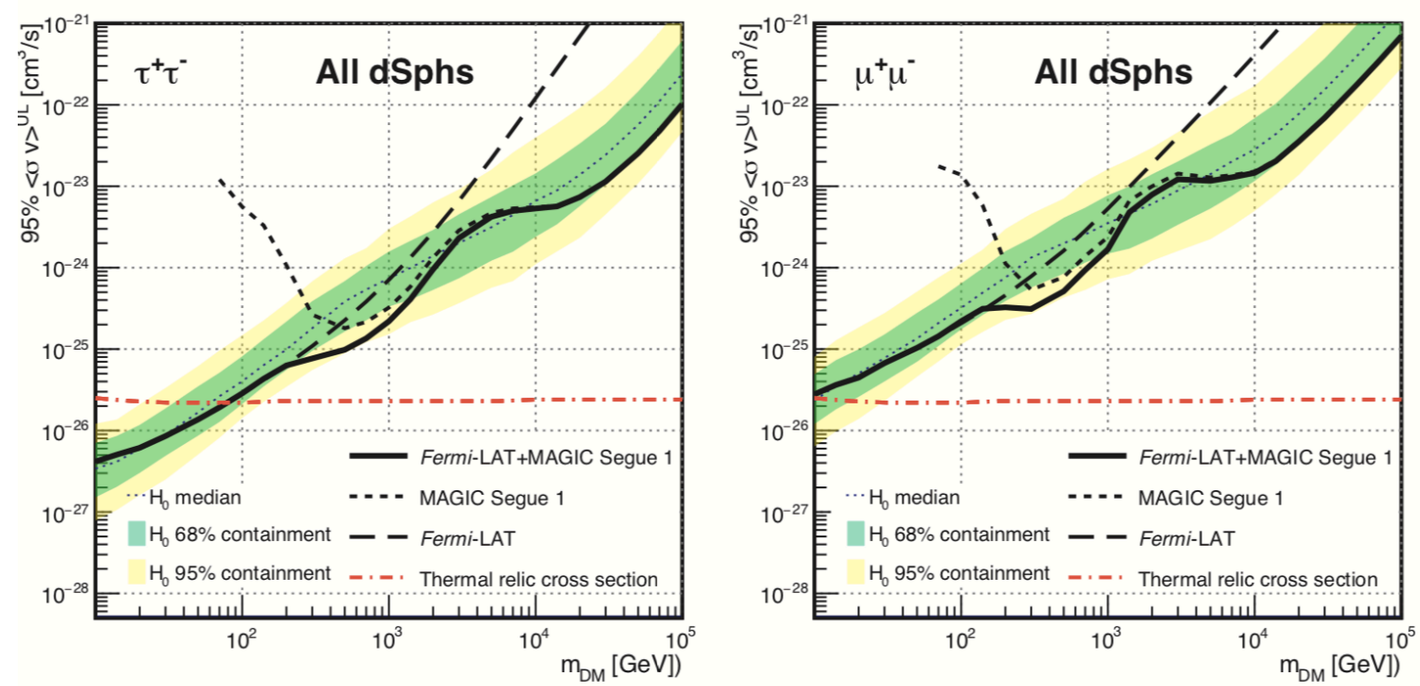


Cosmology

P. D. Serpico & G. G. Raffelt, arXiv:0403417
F. Iocco *et al.*, arXiv:0809.0631
C. Bohem *et al.*, arXiv:1303.6270
K. M. Nollet & G. Steigman, arXiv:1411.6005

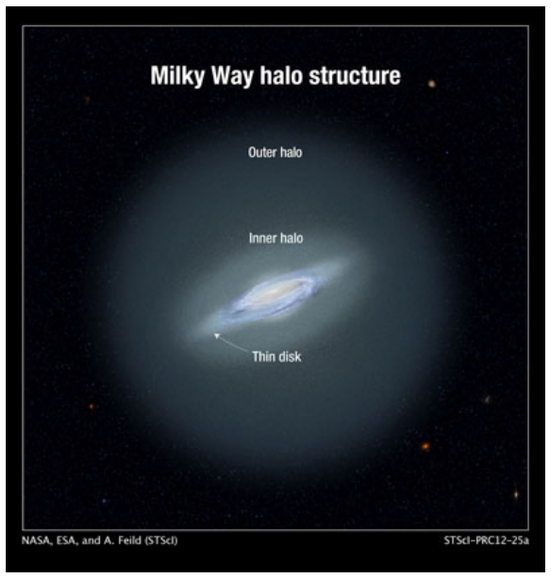
N_{eff}

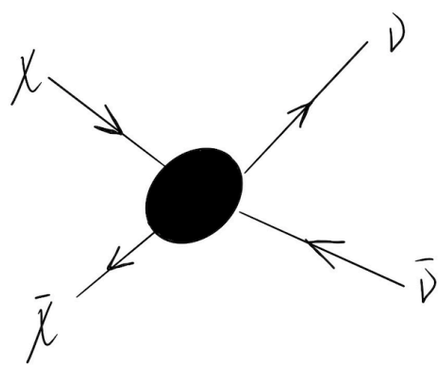
$m_\chi > 10\ MeV$

p_{ann}

$$p_{ann} \equiv f_{eff} \frac{\langle \sigma v_r \rangle}{m_\chi} < 3.2 \times 10^{28}\ cm^{-3}\ s\ GeV$$

Constraints on DM-SM interactions





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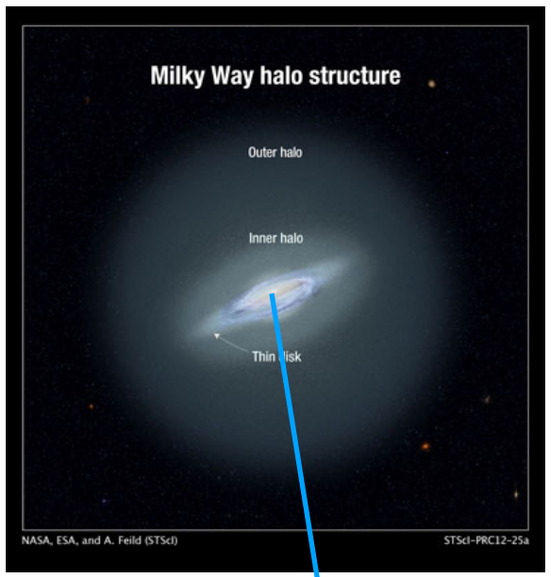
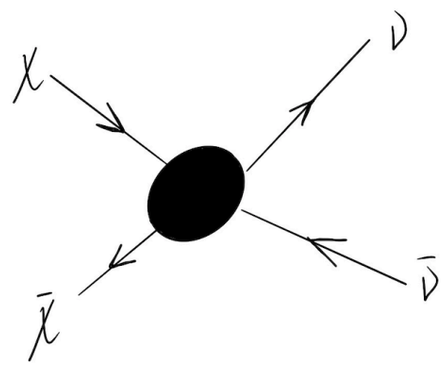
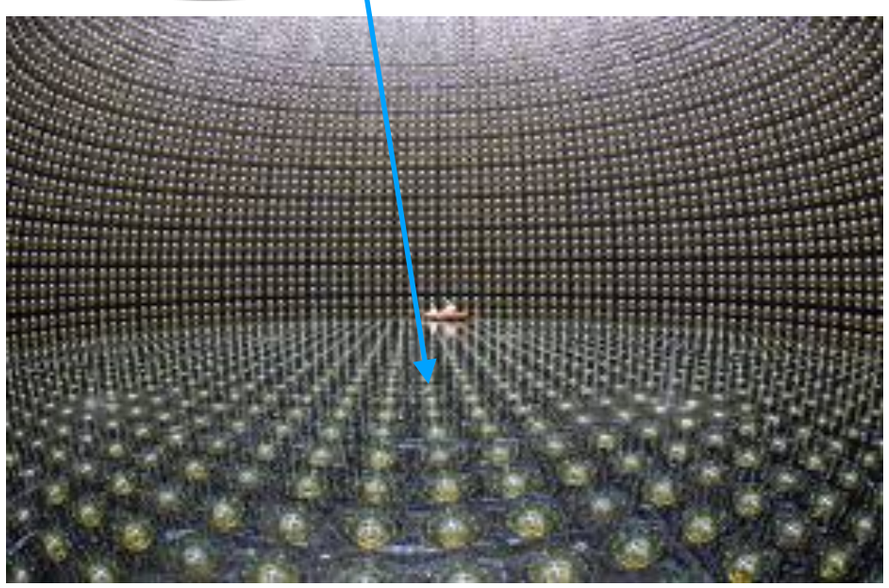




$$E_\nu = m_\chi$$



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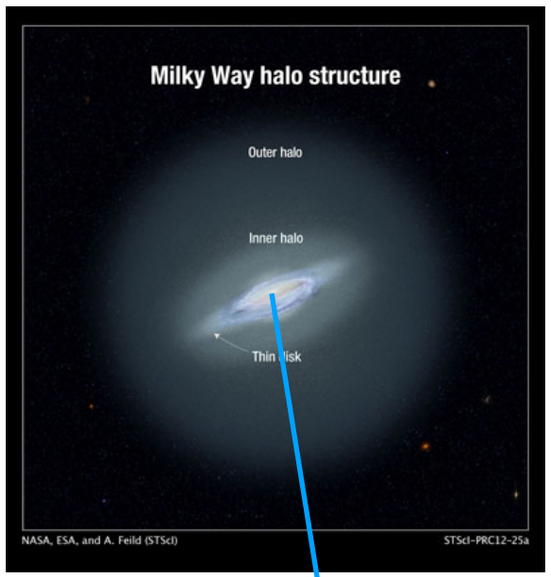

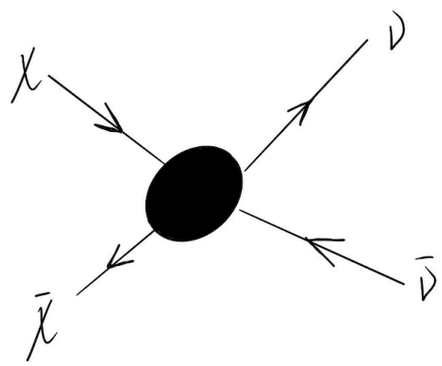

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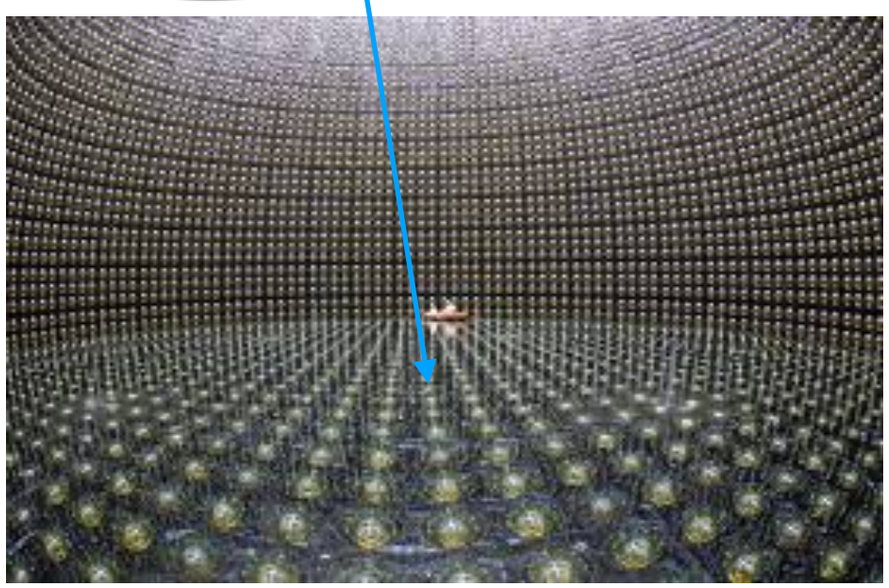
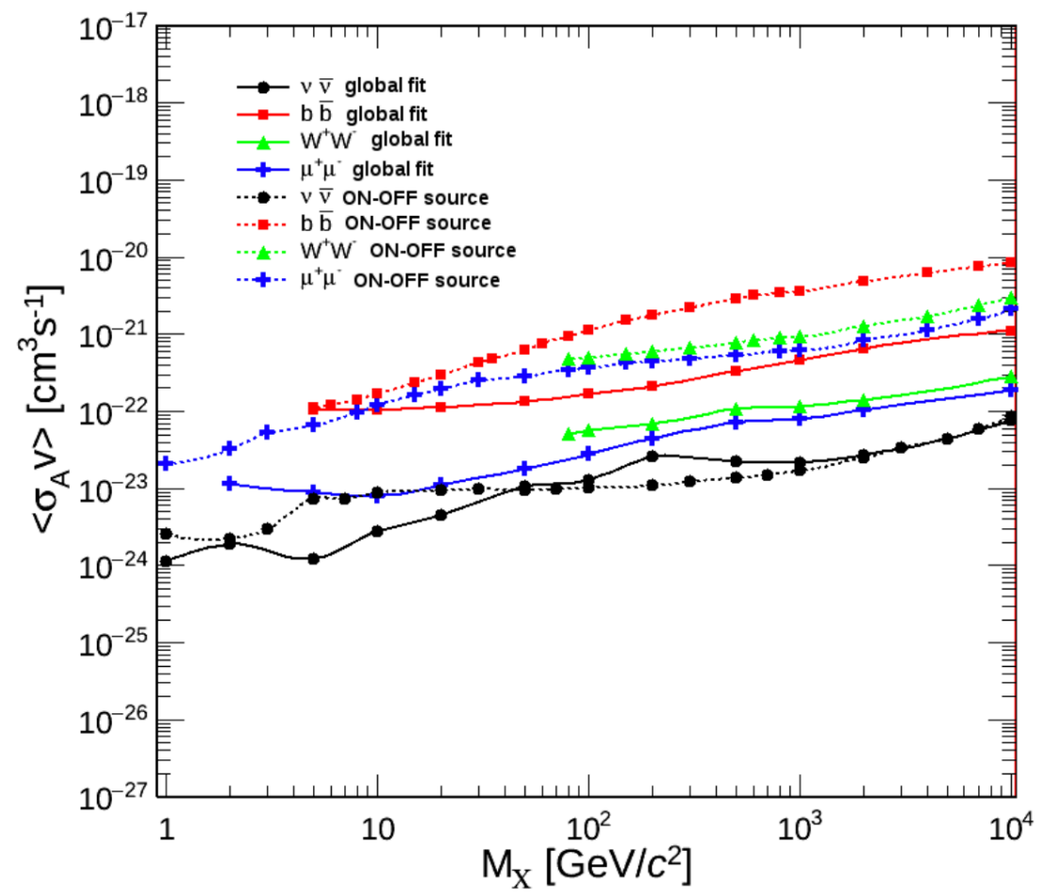


Indirect detection with neutrinos



Super-Kamiokande Collaboration, arXiv:1510.07999
H. Yüksel *et al.*, arXiv:0707.0196
A. Olivares-Del Campo *et al.*, arXiv:1711.05283

Coupling to lepton doublet

Gauge invariance

$$L_{L\alpha} = \begin{pmatrix} \nu_{L\alpha} \\ l_{L\alpha} \end{pmatrix}$$

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Dark matter couples to charged leptons as strongly as to neutrinos

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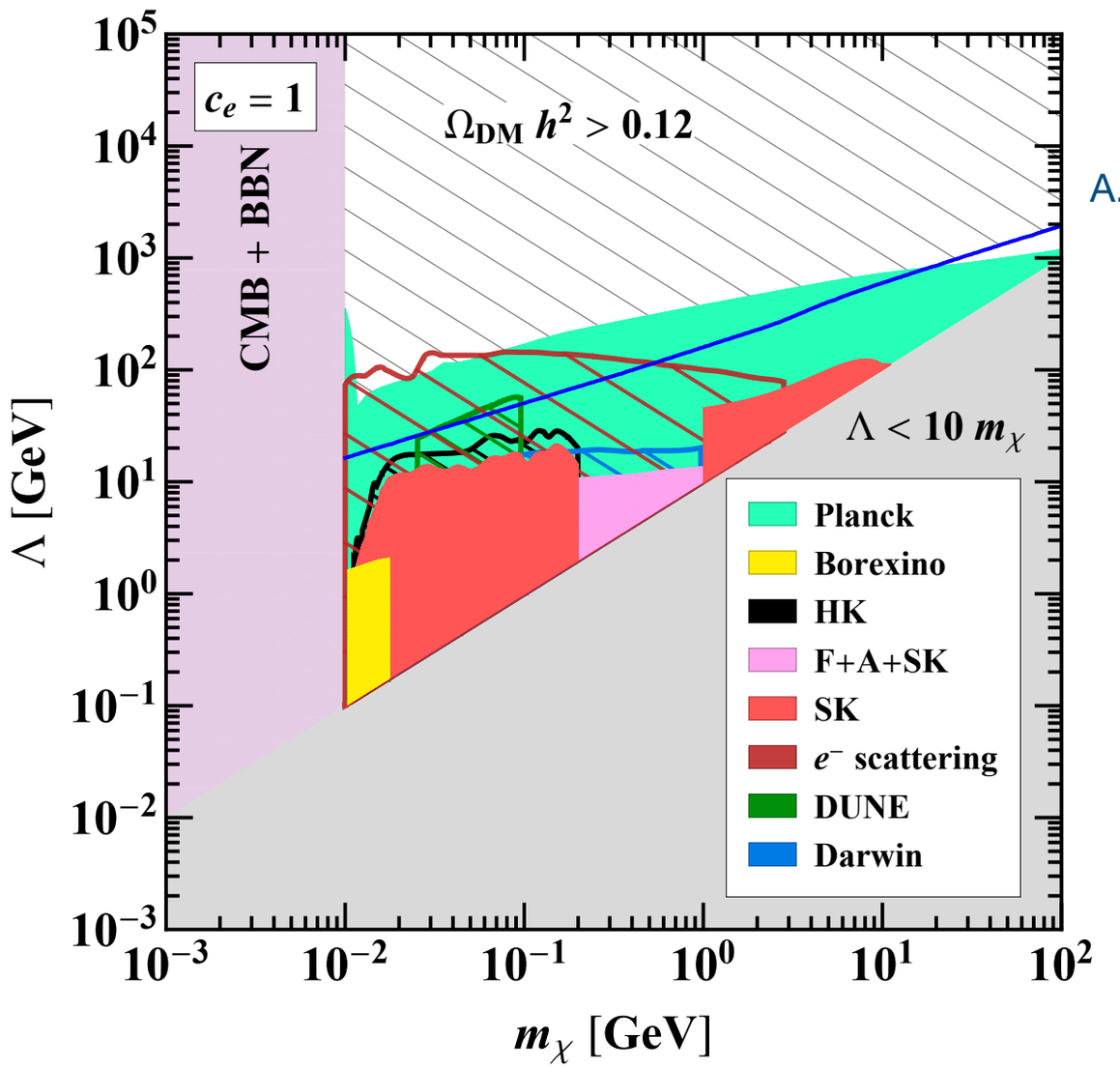
Dark matter couples to charged leptons as strongly as to neutrinos

$$\langle\sigma v_r\rangle \approx \frac{c_\alpha^2 m_\chi^2}{2\pi\Lambda^4}\left(1 - \frac{m_\alpha^2}{4m_\chi^2}\right)\sqrt{1 - \frac{m_\alpha^2}{m_\chi^2}}$$

Coupling to lepton doublet



D. McKeen & N. Raj, arXiv:1812.0512
N. Klop & S. Ando, arXiv:1809.00671
R. Essig *et al.*, arXiv:1801.10159
A. Olivares-Del Campo *et al.*, arXiv:1805.09830

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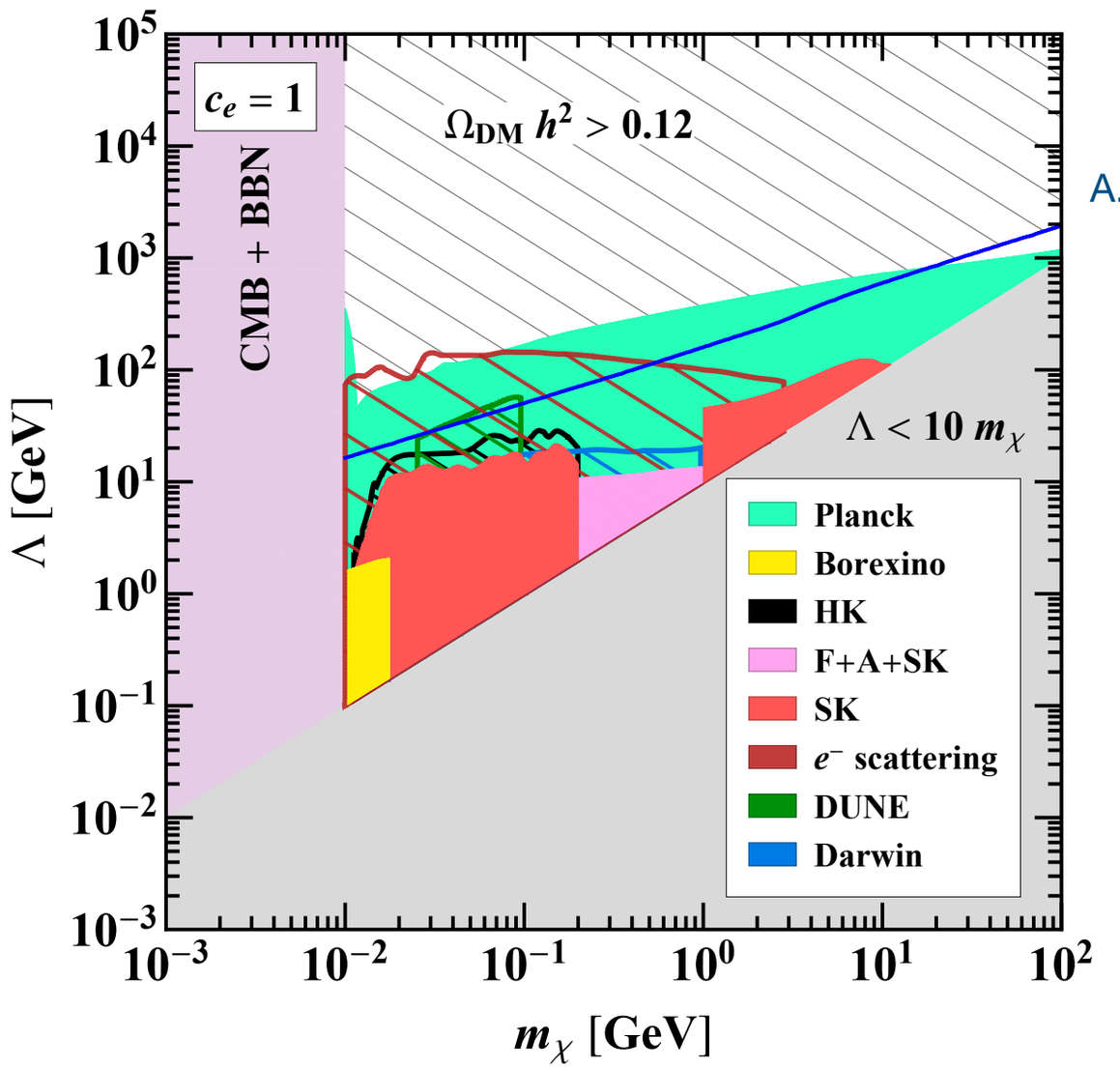

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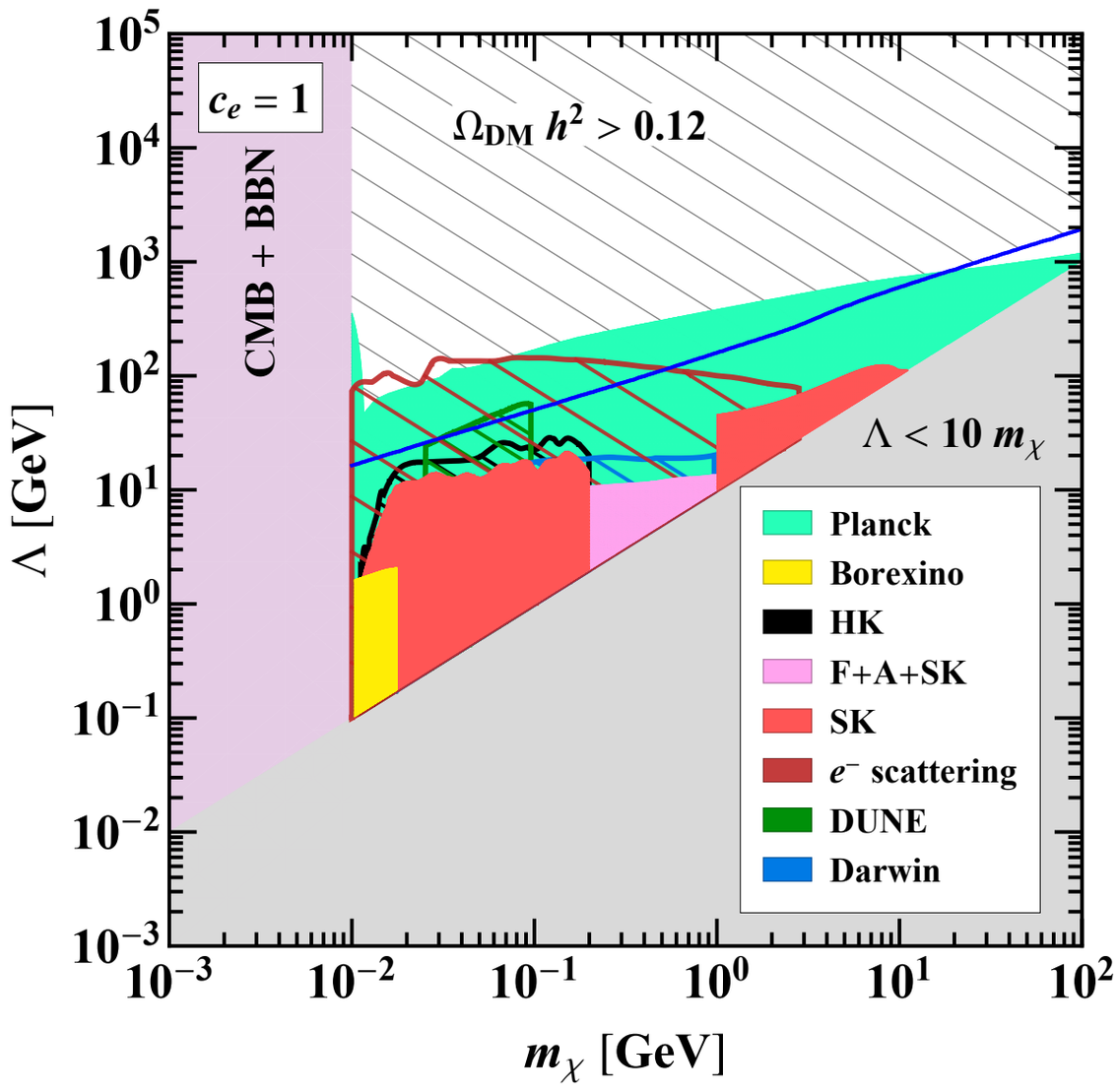
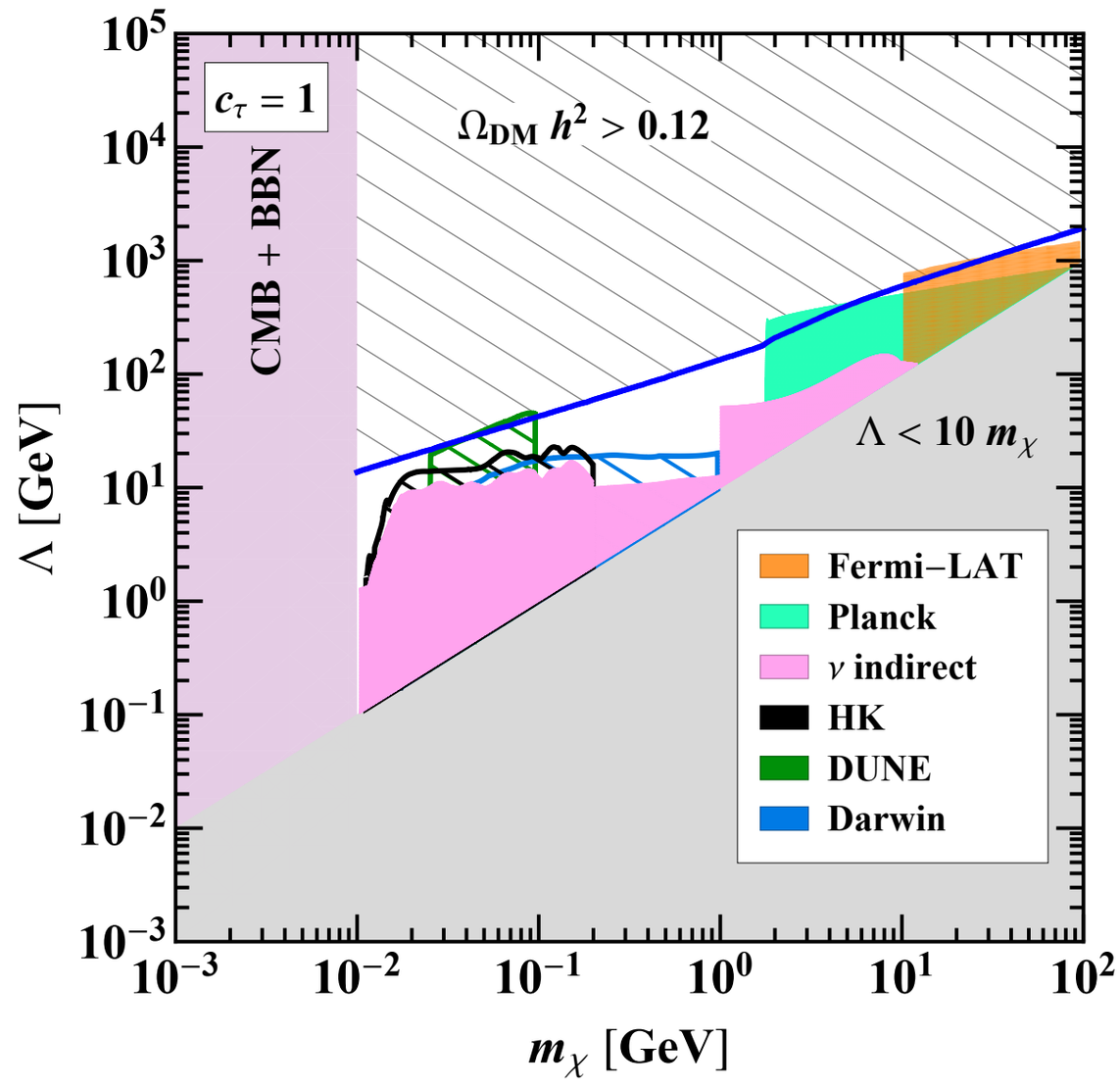
Planck and Fermi-LAT place the strongest bounds

Coupling to lepton doublet



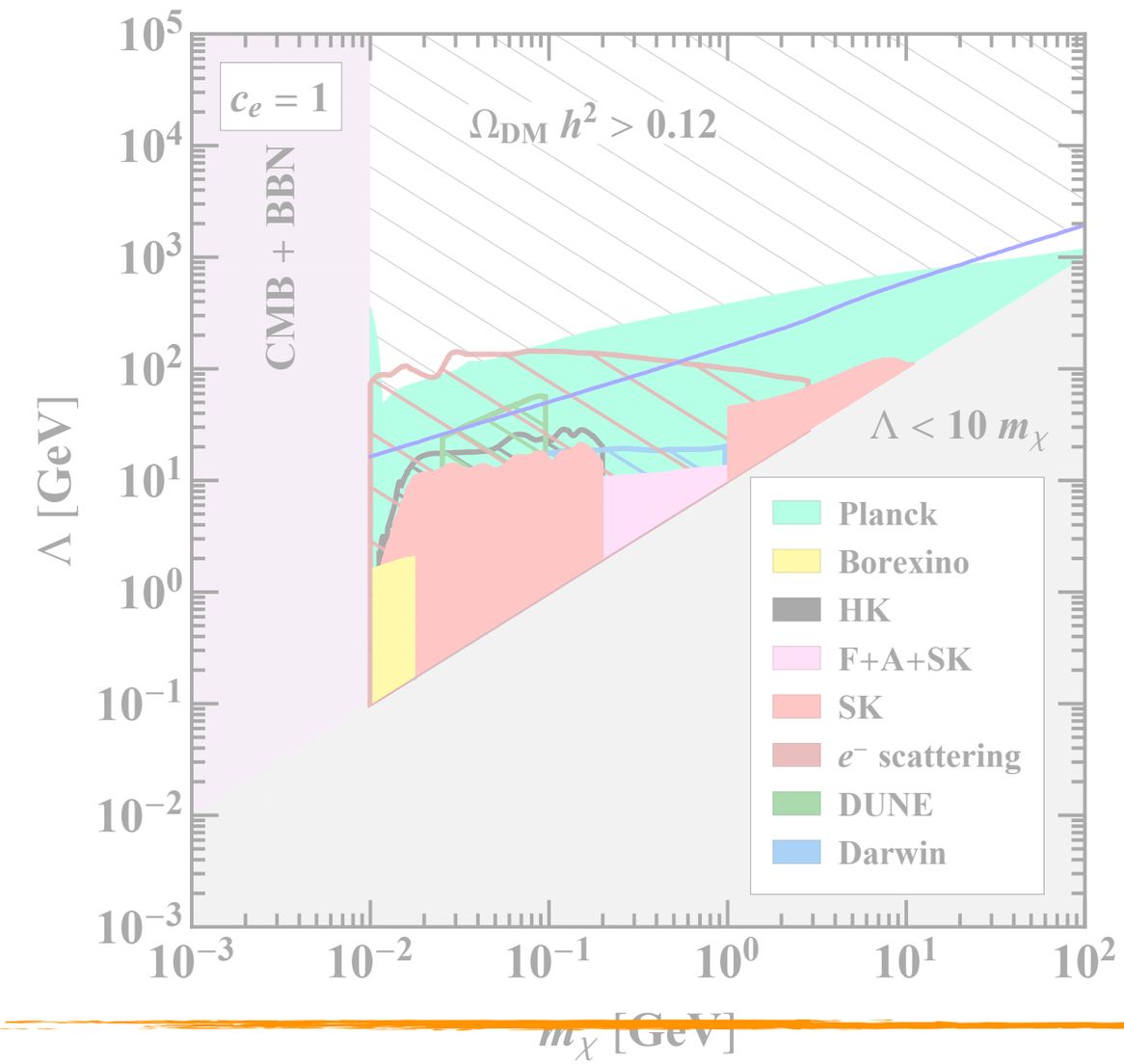


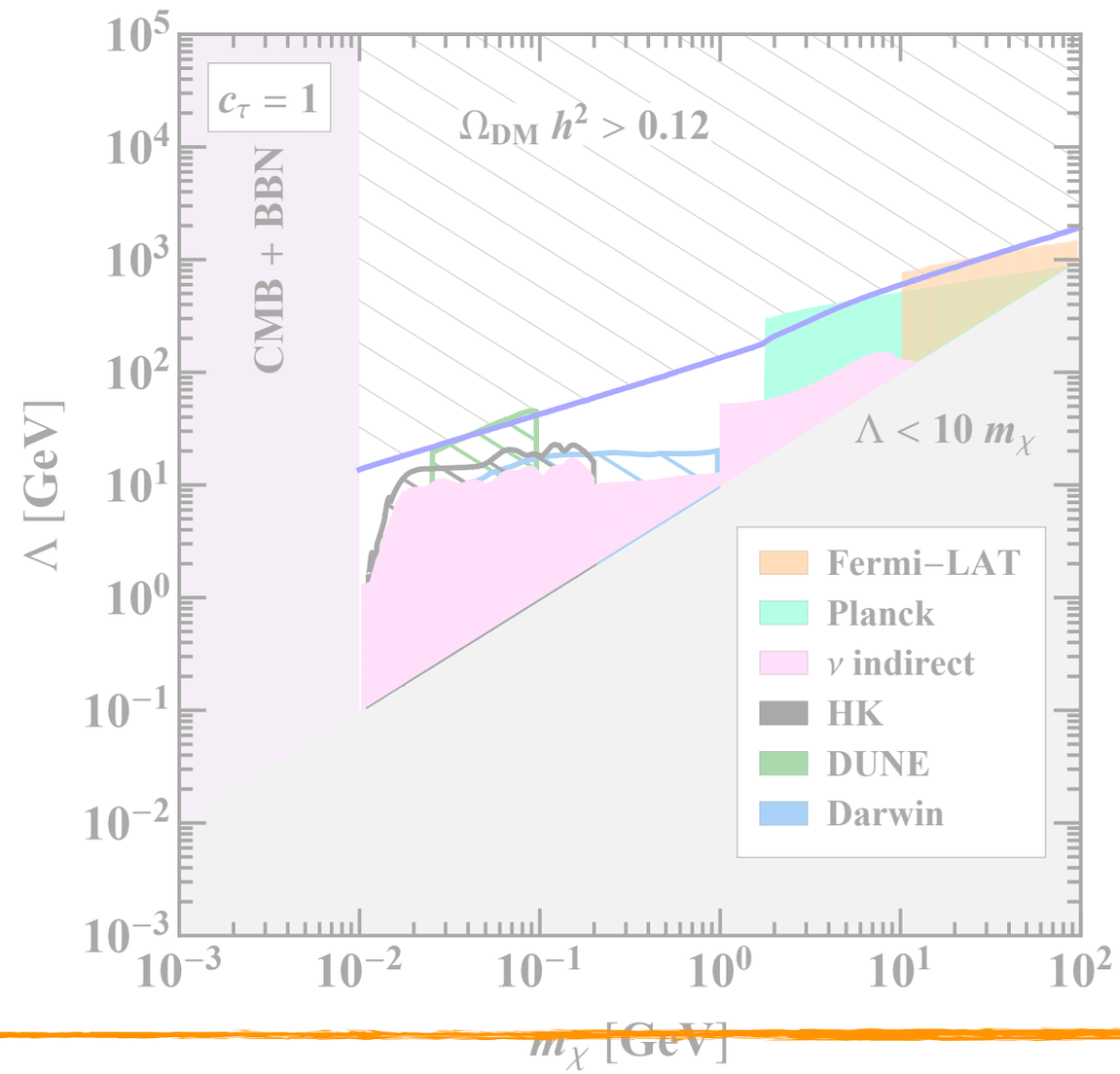
Planck and Fermi-LAT place the strongest bounds

$m_\chi < m_{\tau(\mu)} \quad c_e \sim 0$

Neutrino detectors are our only window to the dark sector

Coupling to lepton doublet

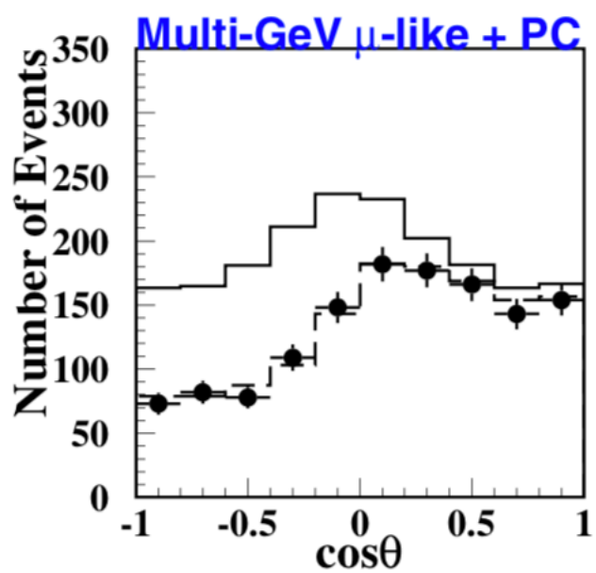




Is it possible to avoid the coupling to charged leptons?

Neutrino masses

Super-Kamiokande collaboration,
arXiv:0105023



Neutrino oscillations

↓

Massive neutrinos

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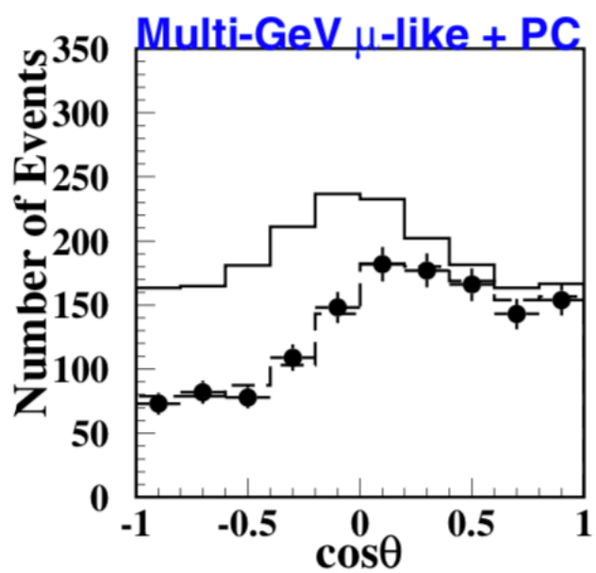

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P. Minkowsky, Phys.Lett. **B67** (1977) 421
T. Yanagida, 1979
M. Gell-Mann, P. Ramon and R. Slansky,
arXiv:1306.4669
S. L. Glashow, NATO Sci.Ser. B **61** (1980) 687
R. N. Mohapatra and G. Senjanovic,
Phys. Rev. Lett. **44** (1980) 912

$$\mathscr{L} \supset -\bar{L}_L Y_\nu \tilde{H} N_R - \frac{1}{2}\bar{N}_R^c M_M N_R + h.c.$$

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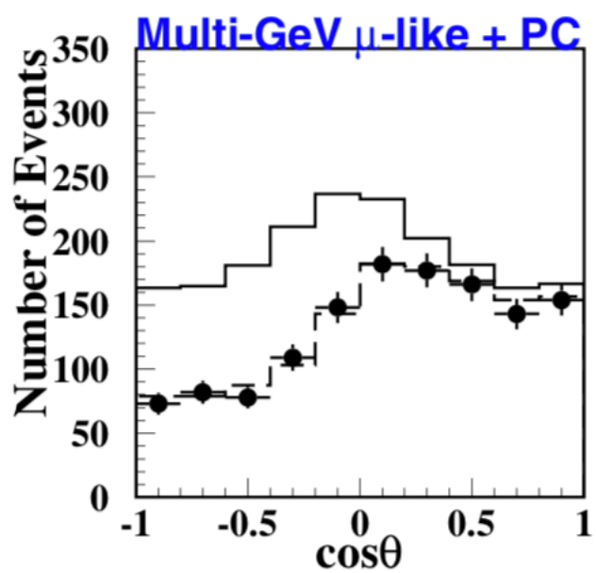

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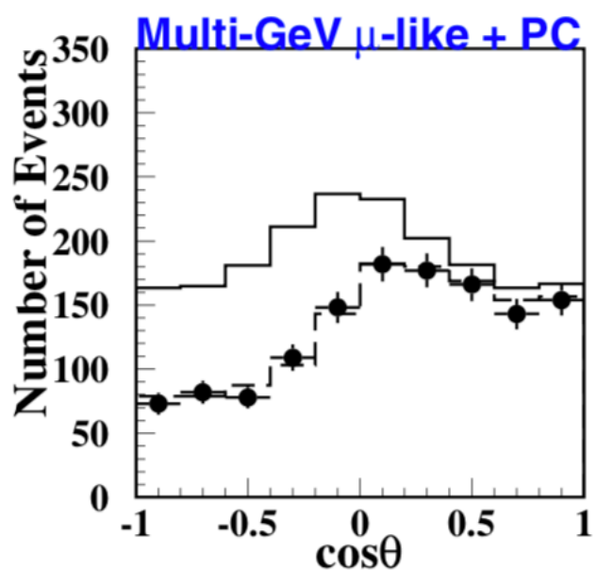

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$$Y_\nu \sim 1, m_\nu \sim 0.01 eV \rightarrow M_M \sim 10^{15} GeV, \theta \sim 10^{-13}$$

Neutrino masses

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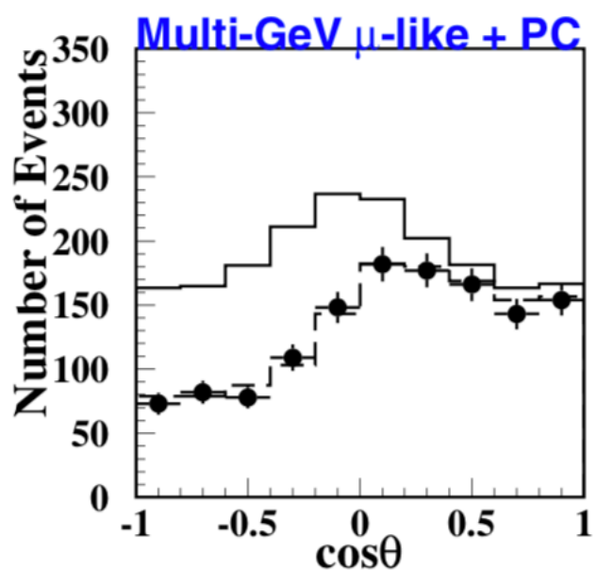

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No hope to have
any experimental signature

Neutrino masses

Approximate L conservation

Neutrino masses

Approximate L conservation → **Inverse Seesaw**

M. Malinsky *et al.*, arXiv:0506296

Neutrino masses

Approximate L conservation → **Inverse Seesaw**

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Neutrino masses

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M. Malinsky *et al.*, arXiv:0506296

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Neutrino masses

Approximate L conservation → **Inverse Seesaw**

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One Dirac singlet neutrino

$$m_{1,2,3} = 0,\ m_4 = \sqrt{M_D^2 + \frac{1}{2}\sum_{\alpha=e,\mu,\tau} |Y_{\nu\alpha}|^2 v^2}, \quad \theta_\alpha = \frac{v}{\sqrt{2}}\frac{Y_{\nu\alpha}}{M_D}$$

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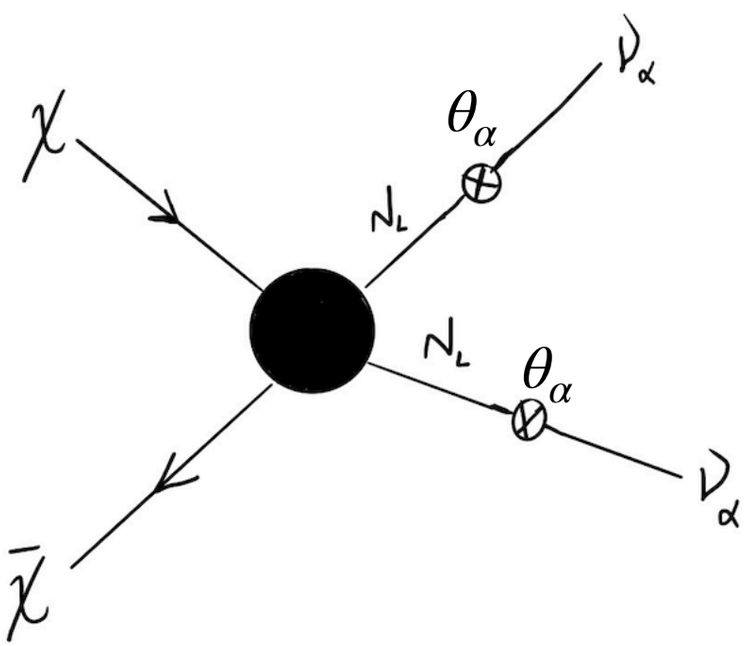
$$\nu_\alpha = \sum_i U_{\alpha i}^* \nu_i, \quad U = \begin{pmatrix} U_{\alpha i} & U_{\alpha 4} \\ U_{si} & U_{s4} \end{pmatrix}, \quad U_{\alpha 4} = \frac{\theta_\alpha}{\sqrt{1 + \sum_\alpha |\theta_\alpha|^2}}$$

Neutrino Portal to Dark Matter

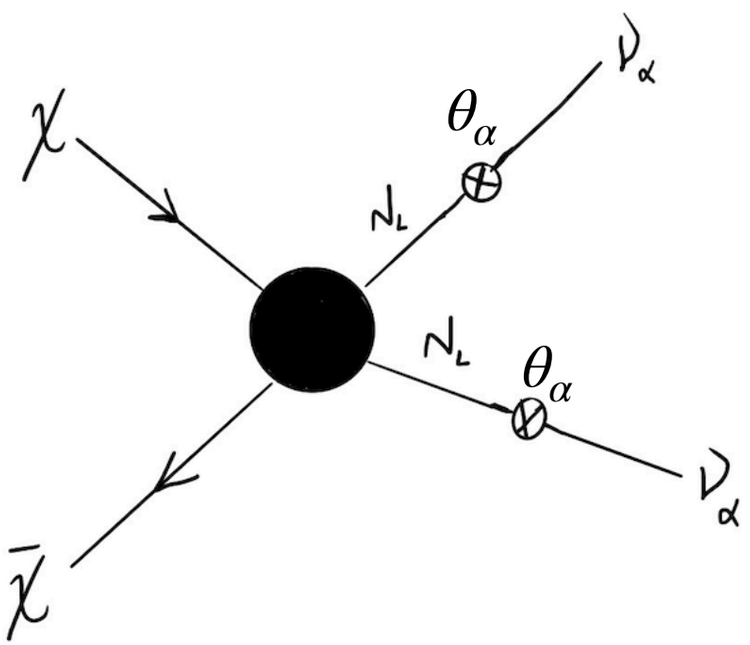


Couple dark matter to singlet neutrinos

↓

Coupling to active neutrinos through large mixing

Neutrino Portal to Dark Matter



Couple dark matter to singlet neutrinos

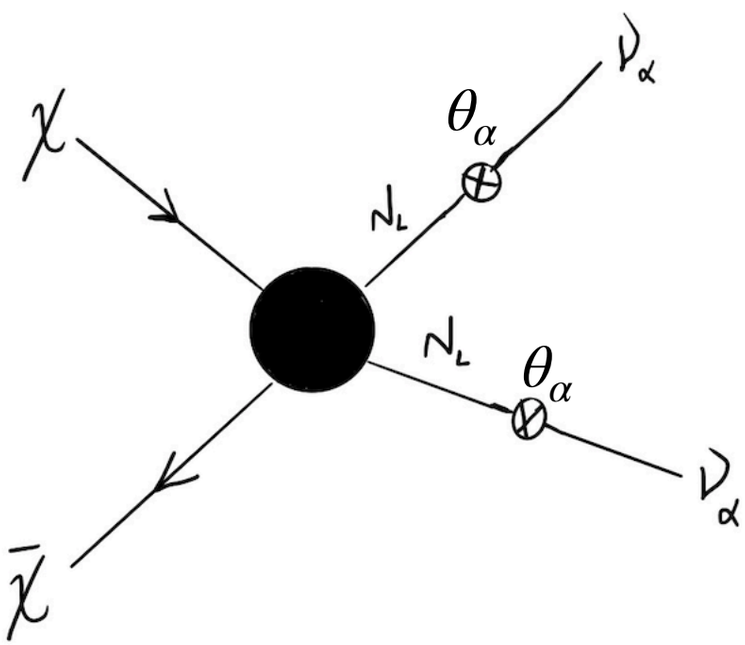
Coupling to active neutrinos through large mixing

Two possible mediators

Scalar mediator

$$\mathscr{L}_{int} \supset -y_L \bar{\chi} S N_L + h.c.$$

Neutrino Portal to Dark Matter



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Scalar mediator

$$\mathscr{L}_{int} \supset -y_L \bar{\chi} S N_L + h.c.$$

Vector mediator

$$\mathscr{L}_{int} \supset g' \bar{\chi}_R \gamma^\mu \chi_R Z'_\mu + g' \bar{N}_L \gamma^\mu N_L Z'_\mu$$

Scalar mediator

$$\mathscr{L}_{DM} = \mathscr{L}_{\nu} + \bar{\chi}\left(i\partial_{\mu}\gamma^{\mu} - m_{\chi}\right)\chi - y_L\bar{\chi}SN_L + h.c.$$

B. Bertoni *et al.*, arXiv:1412.3113
B. Batell *et al.*, arXiv:1709.07001

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Coupling between DM and light neutrinos

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$$\langle\sigma v_r\rangle \approx \frac{y_L^4}{32\pi}\left(\sum_{\alpha=e,\mu,\tau}|U_{\alpha 4}|^2\right)^2 \frac{m_\chi^2}{(m_\chi^2+m_S^2)^2}$$

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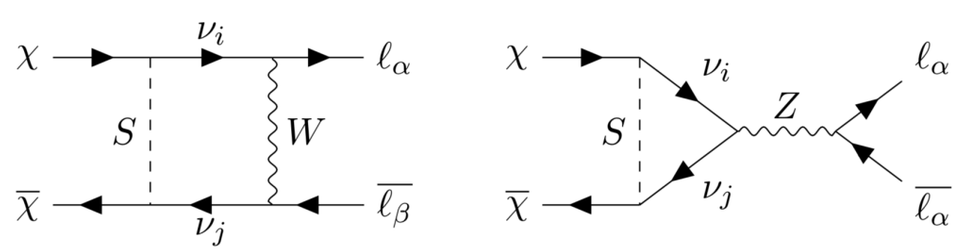
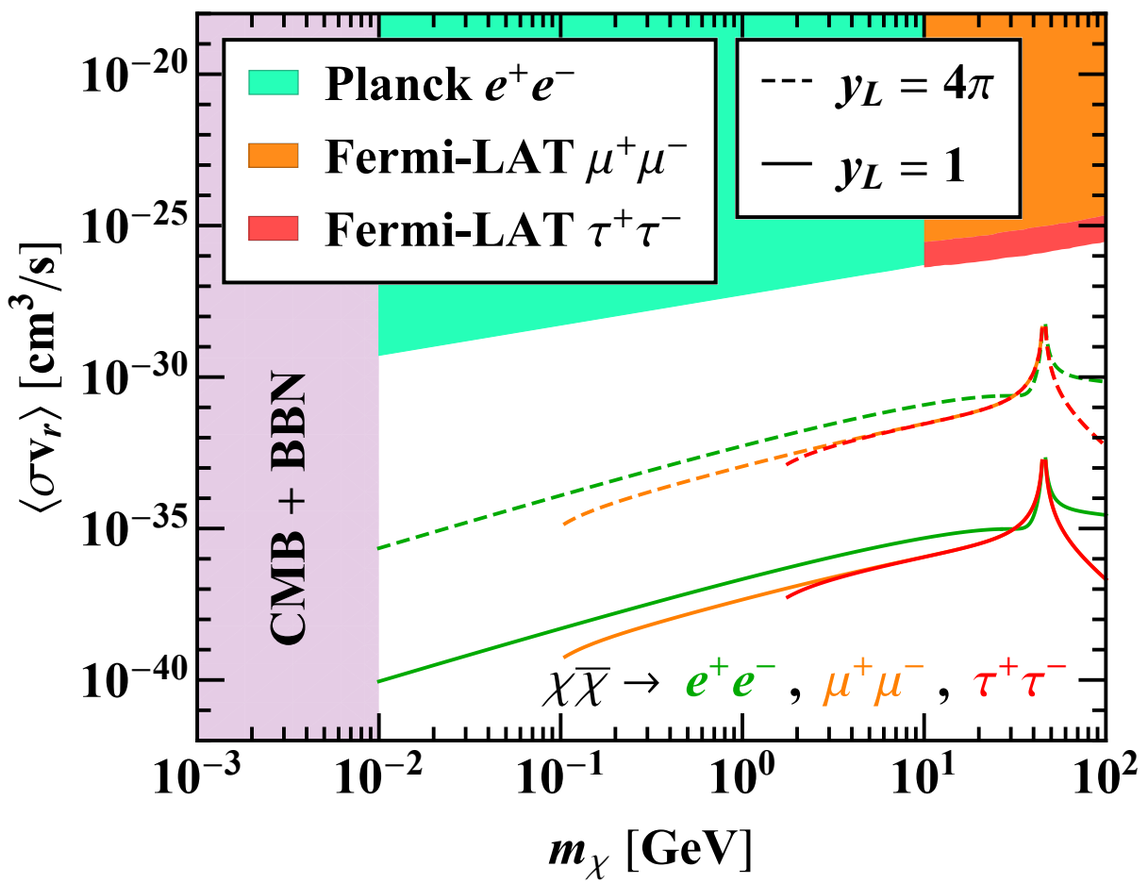
At one loop

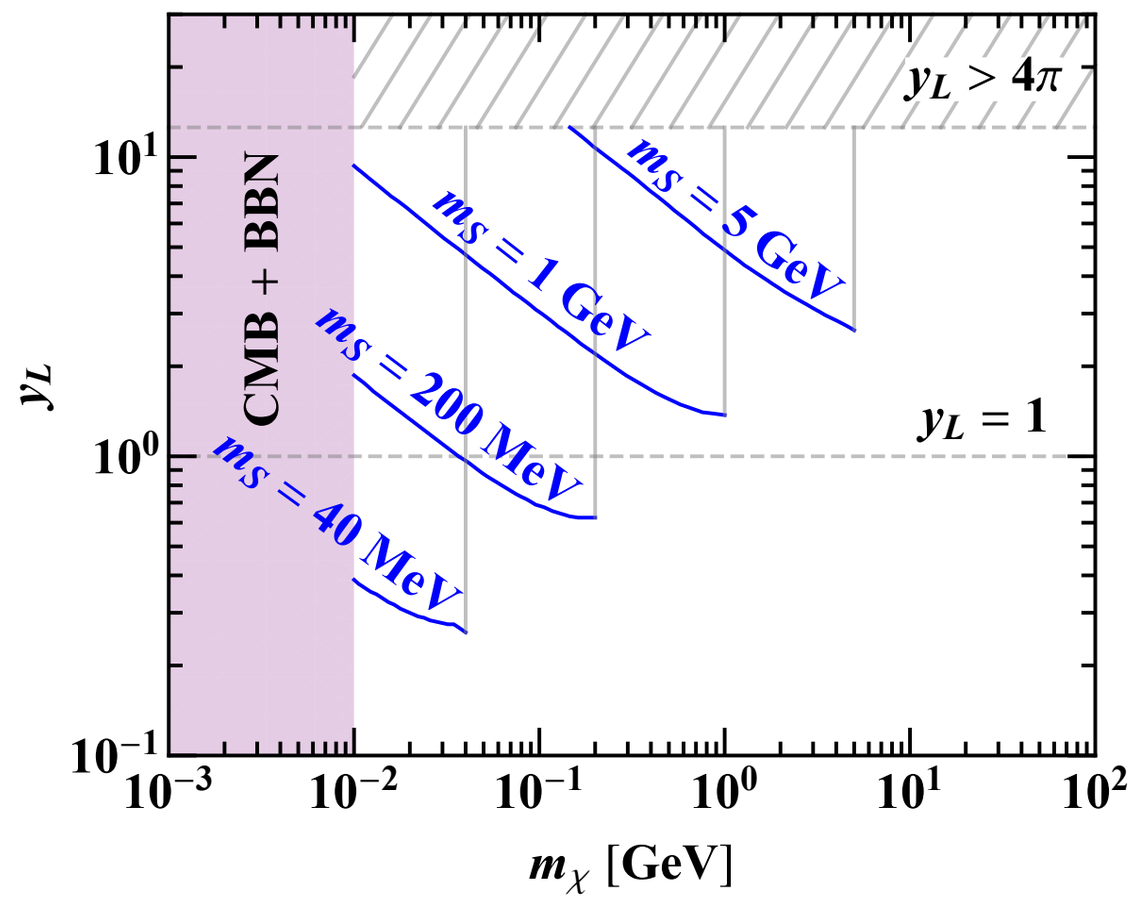


$$\mathscr{L} \supset -a_{SW}\frac{g^2}{m_W^2}\bar{\chi}\gamma^{\mu}P_R\chi\bar{l}_{\alpha}\gamma_{\mu}P_Ll_{\beta} - a_Z\frac{g}{\cos\theta_W}\bar{\chi}\gamma^{\mu}P_R\chi Z_{\mu} + h.c.$$

Coupling between DM and charged leptons/quarks

Scalar mediator

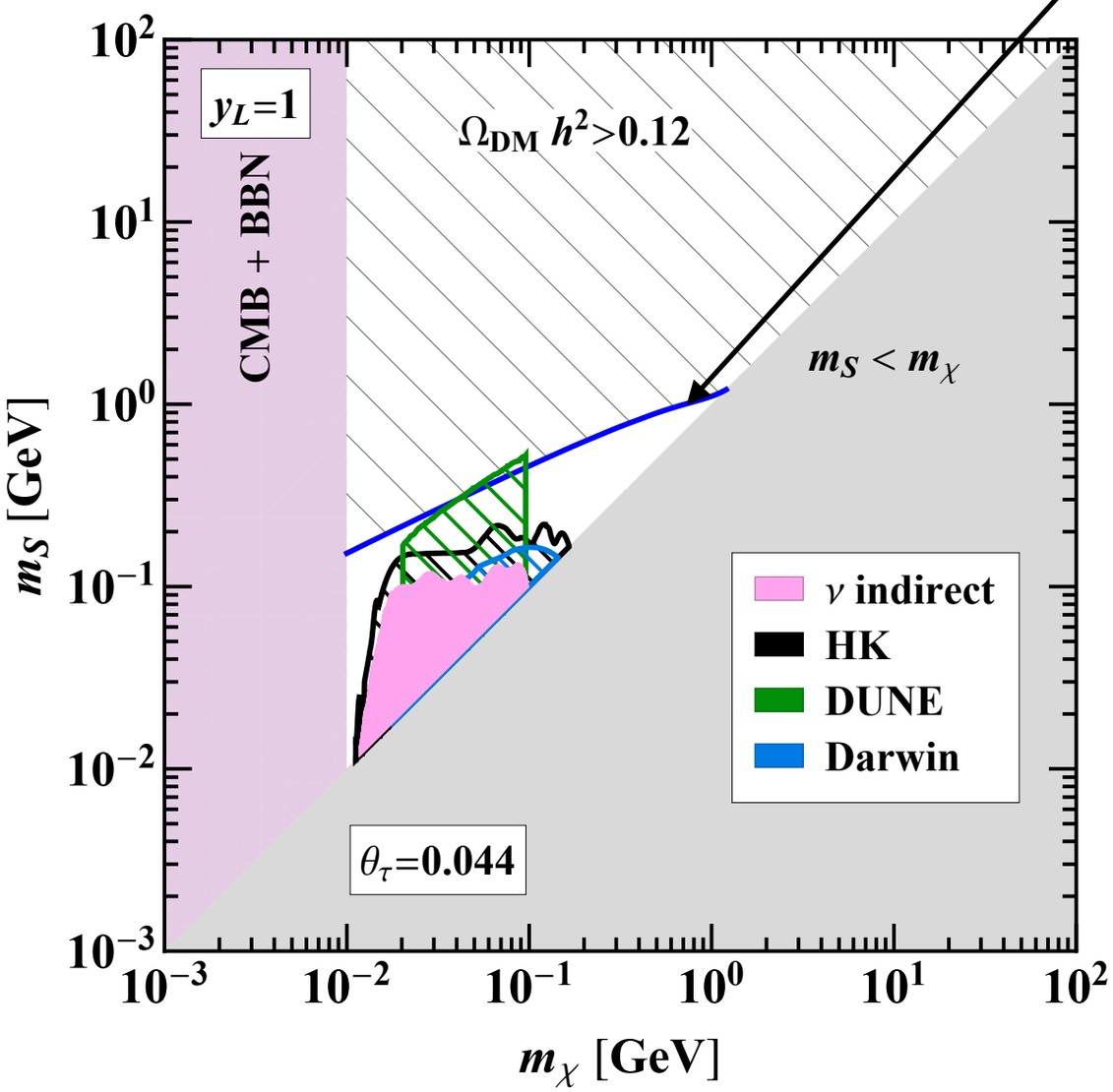


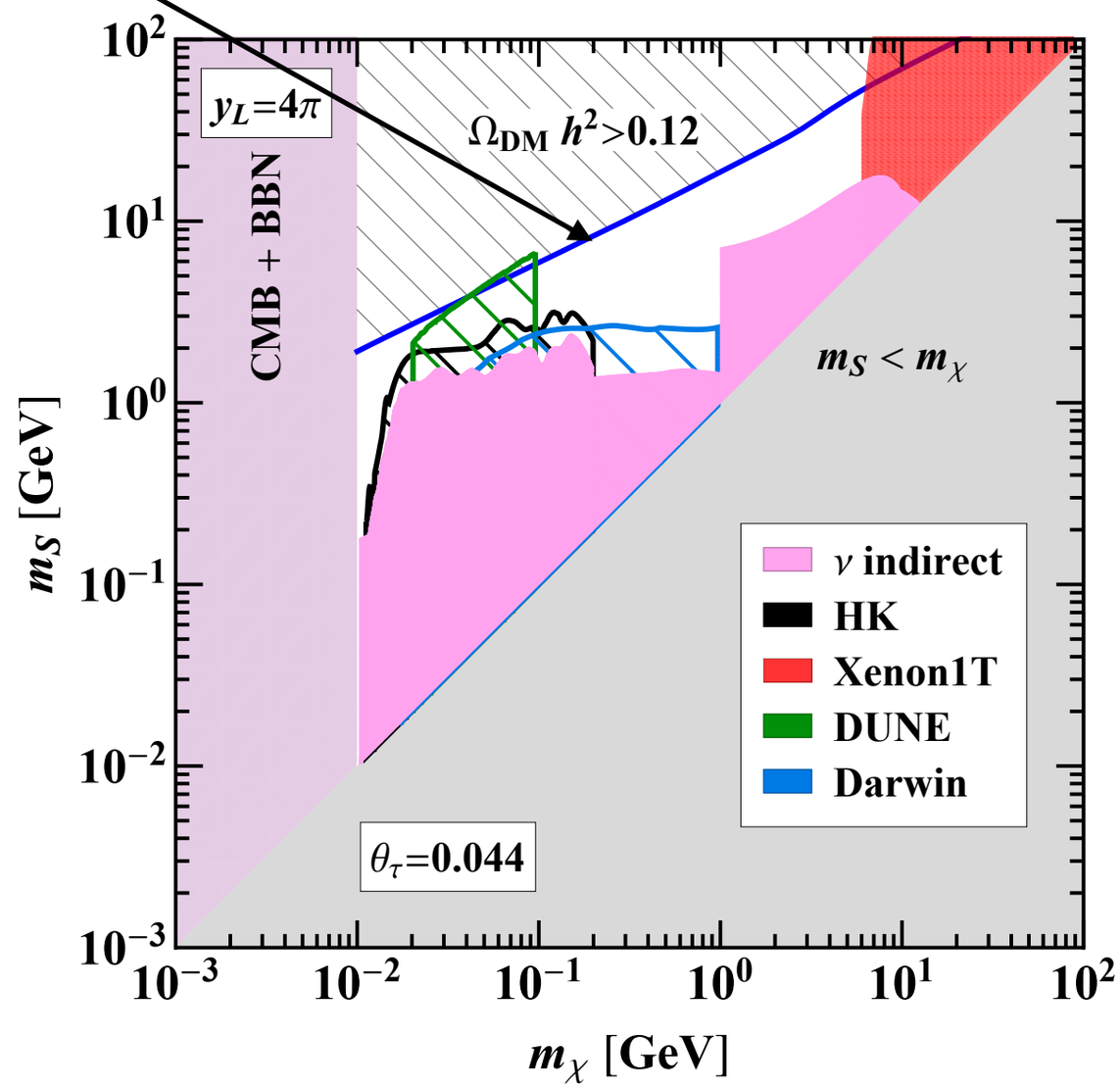


Bounds from charged leptons avoided

Scalar mediator

$$\Omega_{DM}h^2 = \Omega_{DM}h^2|_{Planck}$$





Only neutrino detectors can probe the parameter space

Vector mediator

$$\mathscr{L}_{DM} = \mathscr{L}_{\nu} + g'\bar{\chi}_R\gamma^{\mu}\chi_R Z'_{\mu} + g'\bar{N}_L\gamma^{\mu}N_L Z'_{\mu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}m^2_{Z'}Z'_{\mu}Z'^{\mu}$$

Coupling between DM and light neutrinos

$$\mathscr{L}_{int} \supset g' \sum_{i,j} U_{si}U^*_{sj}\bar{\nu}_i\gamma^{\mu}P_L\nu_j Z'_{\mu}$$

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$$\langle \sigma v_r \rangle \approx \frac{g'^4}{8\pi}\left(\sum_{\alpha=e,\mu,\tau} |U_{\alpha 4}|^2\right)^2 \frac{m^2_{\chi}}{(4m^2_{\chi} - m^2_{Z'})^2}$$

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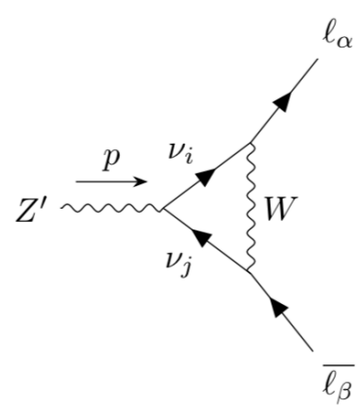
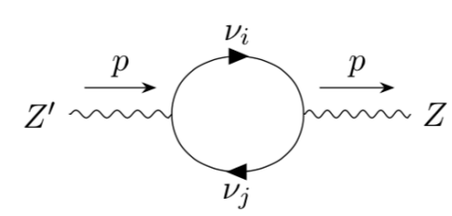
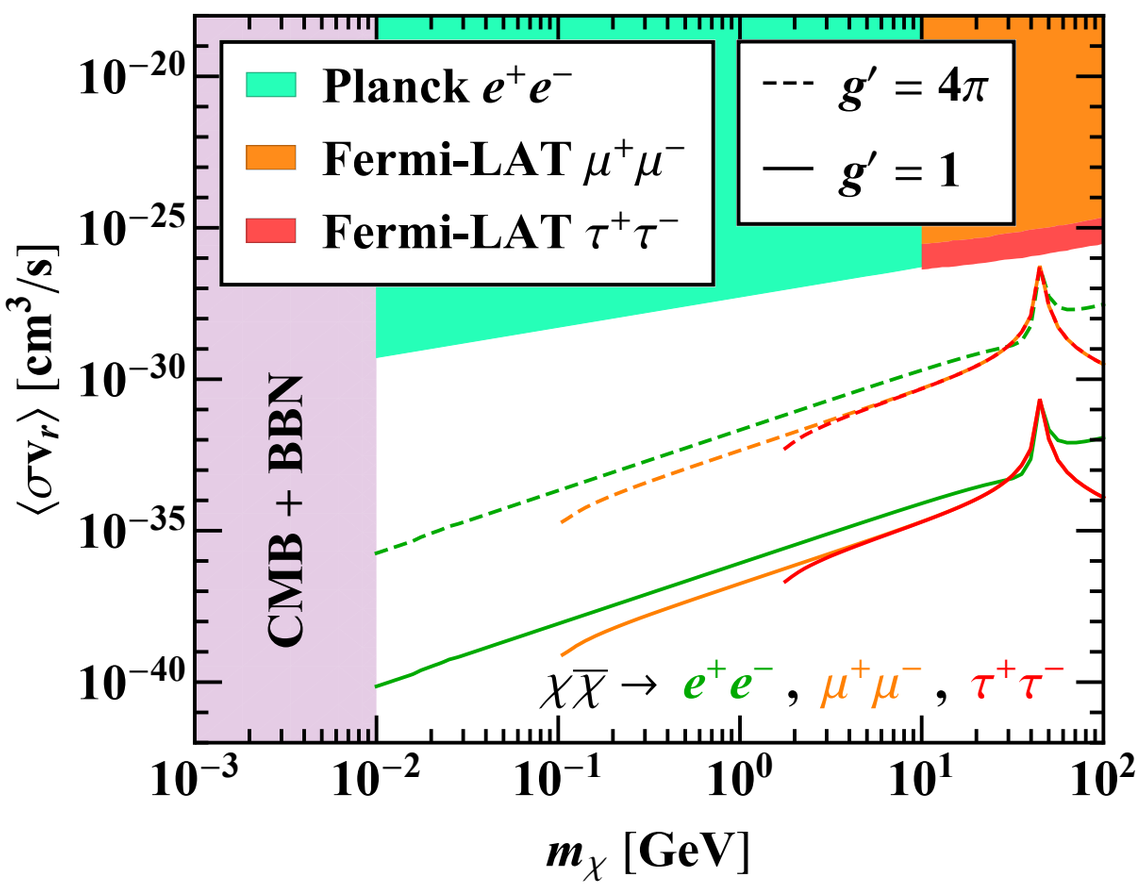
Coupling to charged leptons and quarks

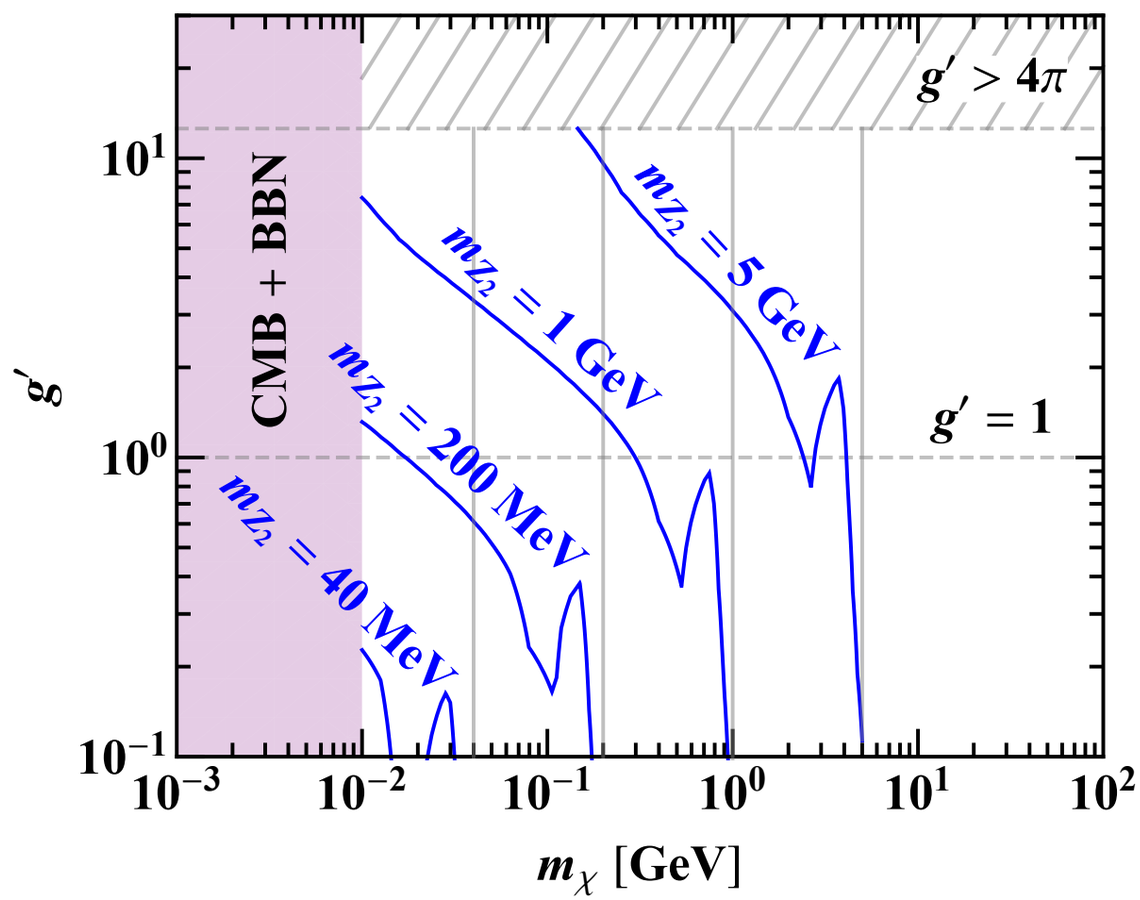




$$\mathscr{L} \supset -a_W g'\bar{l}_{\alpha}\gamma^{\mu}P_L l_{\beta}Z'_{\mu} - \frac{\sin\epsilon}{2}Z'_{\mu\nu}Z^{\mu\nu} + \delta m^2 Z'_{\mu}Z^{\mu} + h.c.$$

Vector mediator





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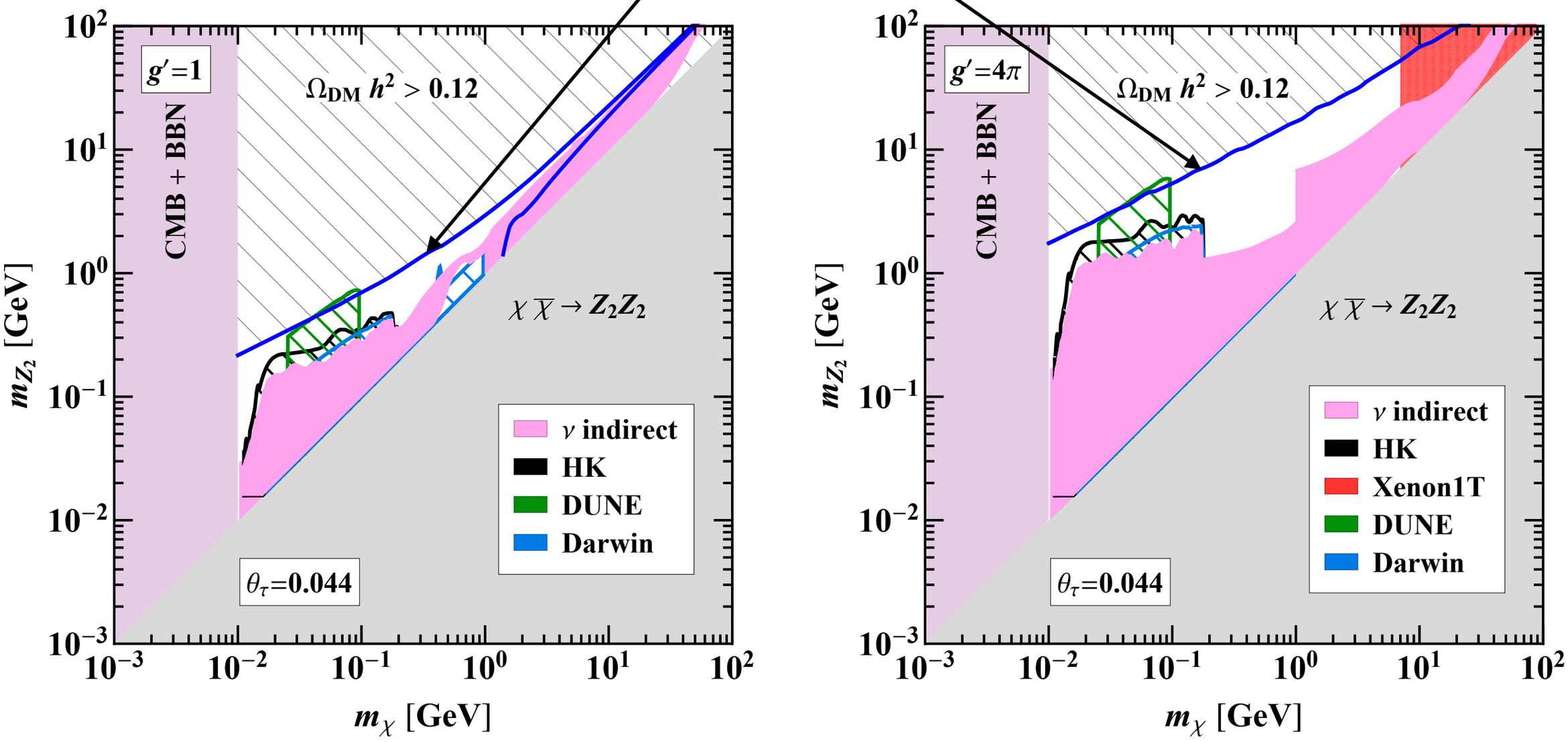

Most parameter space already probed by neutrino experiments

Conclusions

No signal for DM-SM interactions other than gravitationally

↓

DM-neutrino interactions

Avoid all direct and indirect searches?

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Coupling to lepton doublet ← **Gauge invariance**

Planck and FERMI-LAT

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$m_\chi < m_{\tau(\mu)}, \quad c_e \sim 0$

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Thank you!