Direct Detection Signals from Absorption of Fermionic Dark Matter

Jeff A. Dror, Gilly Elor, & RM 1905.12635, 1908.10861
+= Tien-Tien Yu (in prep.)

Berkeley Week @ IPMU, 1/17/20

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BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Thank You!

I have absorbed a lot!

Robert McGehee

I have absorbed a lot!

anomalies, asymmetric dark matter,

Robert McGehee

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anomalies, asymmetric dark matter,

axions/ALPs, baryogenesis, black holes,

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bounces, cosmic strings, gravitational waves,

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Robert McGehee

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axions/ALPs, baryogenesis, black holes,

bounces, cosmic strings, gravitational waves,

large Q expansions, leptogenesis,

neutron star BSM bounds, novel direct detection,

Q-balls, strong CP solutions, supernovae, superradiance, weak value

Robert McGehee

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The WIMP Paradigm

Fermion

~10 GeV-10 TeV

Stable

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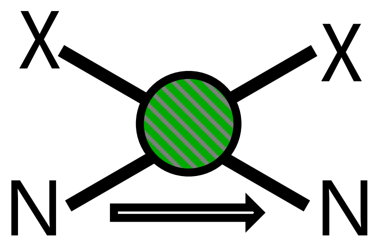
Stable



$$E_R \sim \frac{\mu^2 v^2}{2M_N}$$

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The WIMP Paradigm

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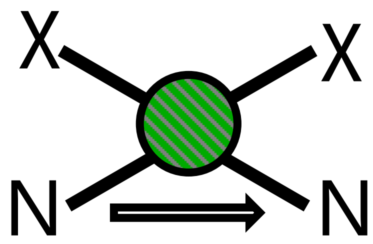

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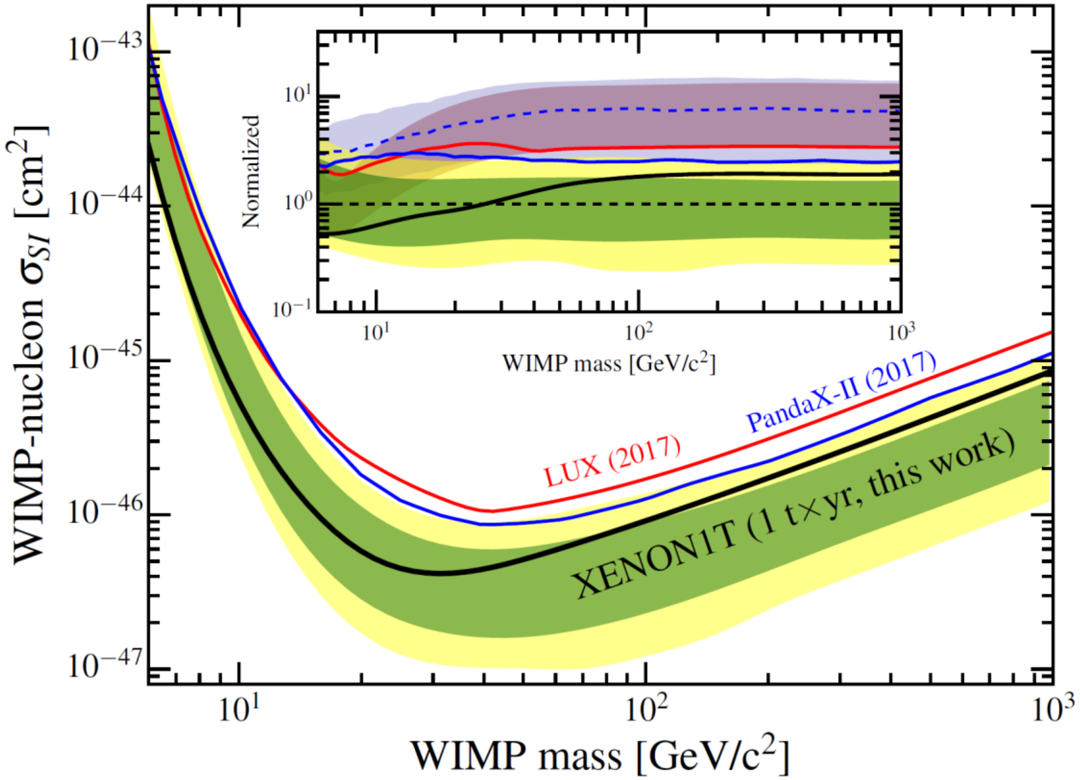

XENON Collaboration, E. Aprile *et al.*, “Dark Matter Search Results from a One Ton-Year Exposure of XENON1T”, *Phys. Rev. Lett.* **121** (2018), no. 11, 111302

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~~The WIMP Paradigm~~

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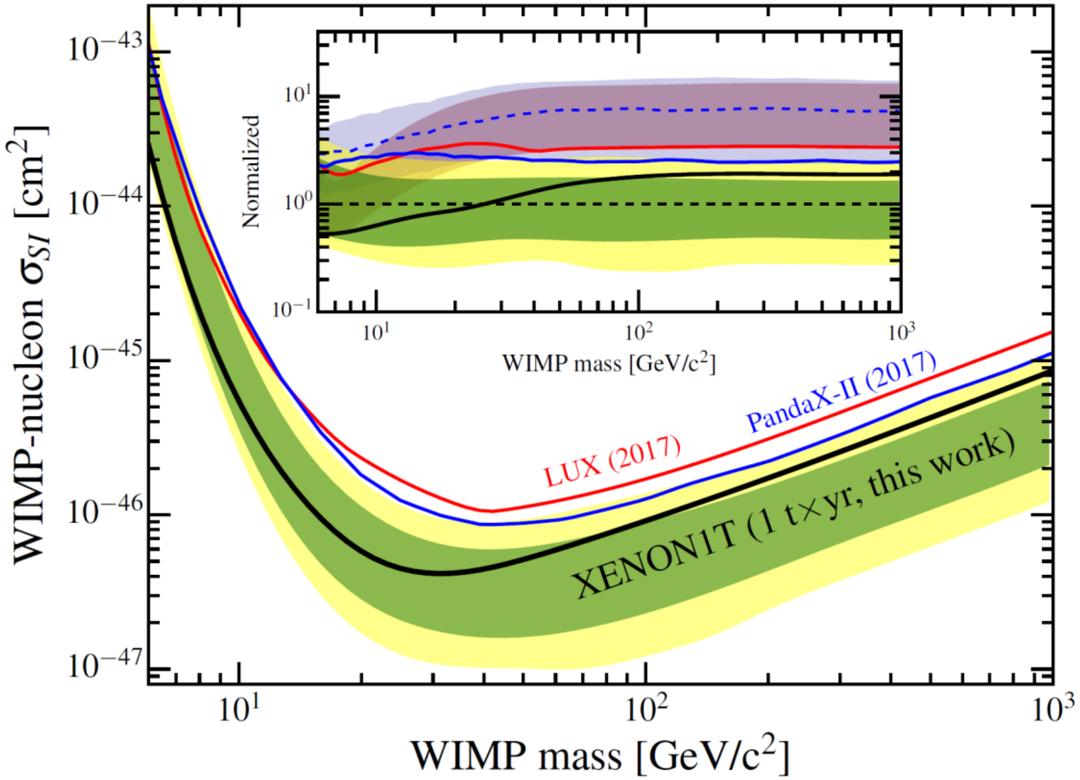
Stable

Eleanor Hall, Shin Kobayashi, David Dunsky, Zhengkang (Kevin) Zhang



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~~The WIMP Paradigm~~

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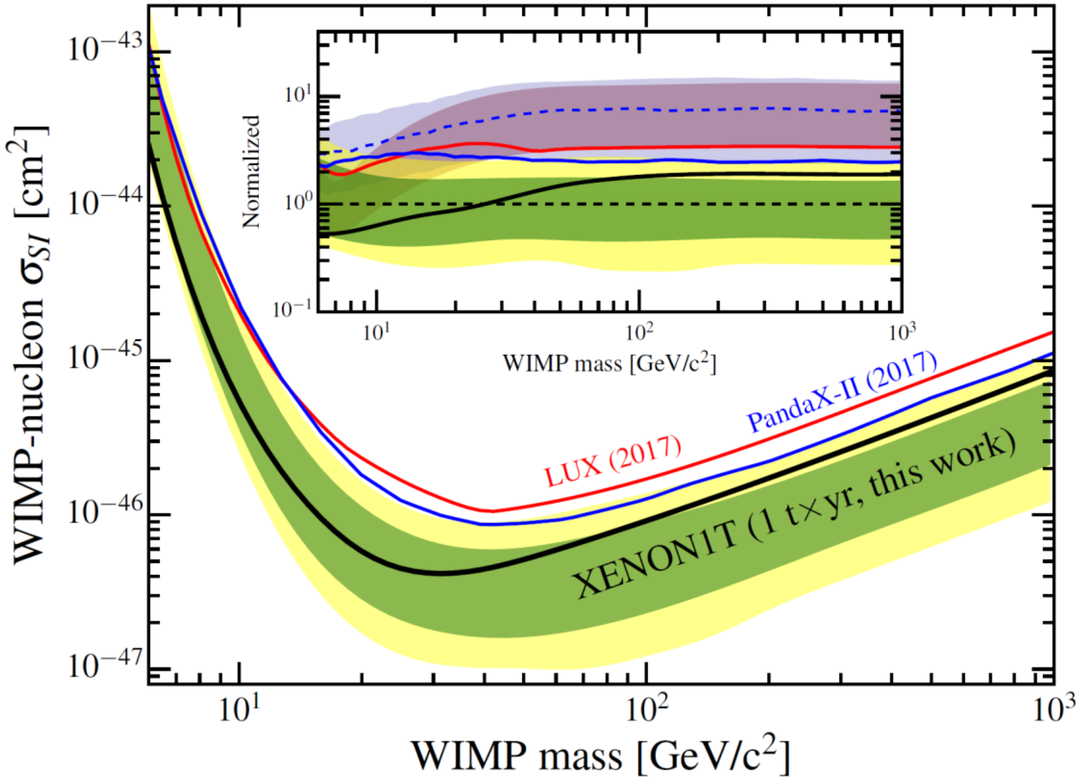
Stable

Jacob Leedom, Hiromasa Nakatsuka, Ippei Obata



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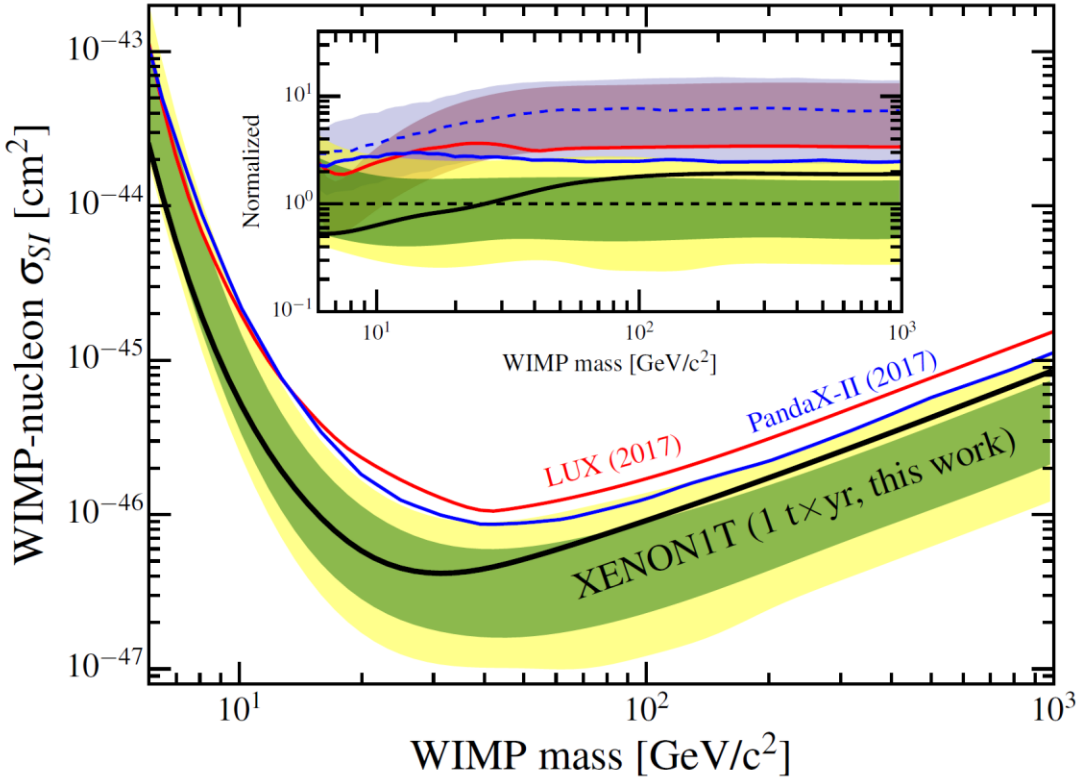
The WIMP Paradigm

Fermion

~10 GeV-10 TeV

Stable

Robert McGehee, right now!



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Leave No Stone Unturned

Requiem for a WIMP

Robert McGehee

Leave No Stone Unturned

Requiem for a WIMP

1. Theory: everyone’s alternatives (*future*)
2. Experiment: larger or lighter (*future*)

Robert McGehee

Leave No Stone Unturned

Requiem for a WIMP

1. Theory: everyone’s alternatives (*future*)
2. Experiment: larger or lighter (*future*)
3. Both: new DM & signals (*present*)
   i. DM scattering off electrons (Essig, Mardon, Volansky [1108.5383])
   ii. Boosted DM (Agashe, Cui, Necib, Thaler [1405.7370])
   iii. Self-Destructing DM (Grossman, Harnik, Telem, Zhang [1712.00455])
   iv. Fermionic Absorption DM

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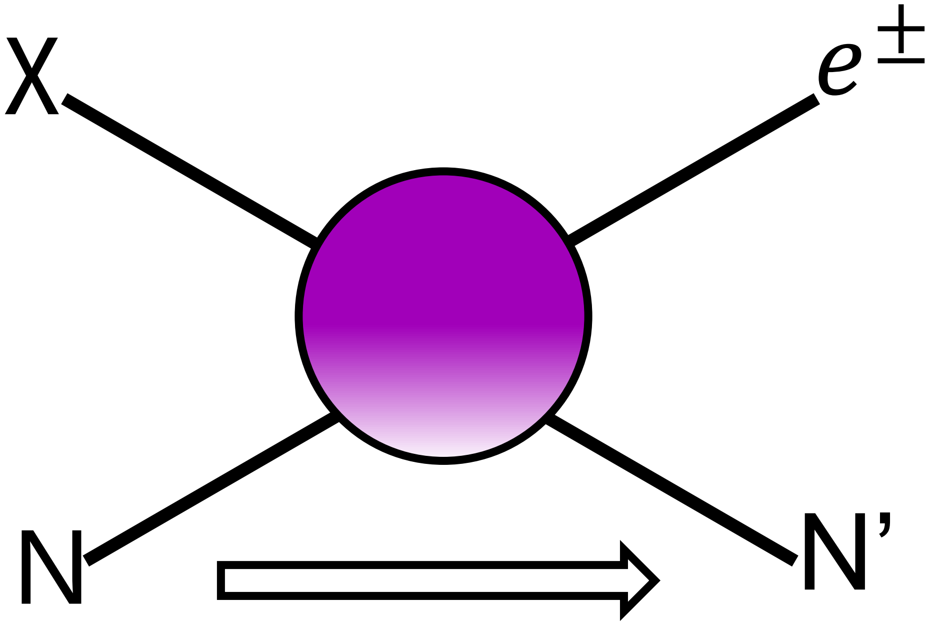
Fermionic "Absorption"



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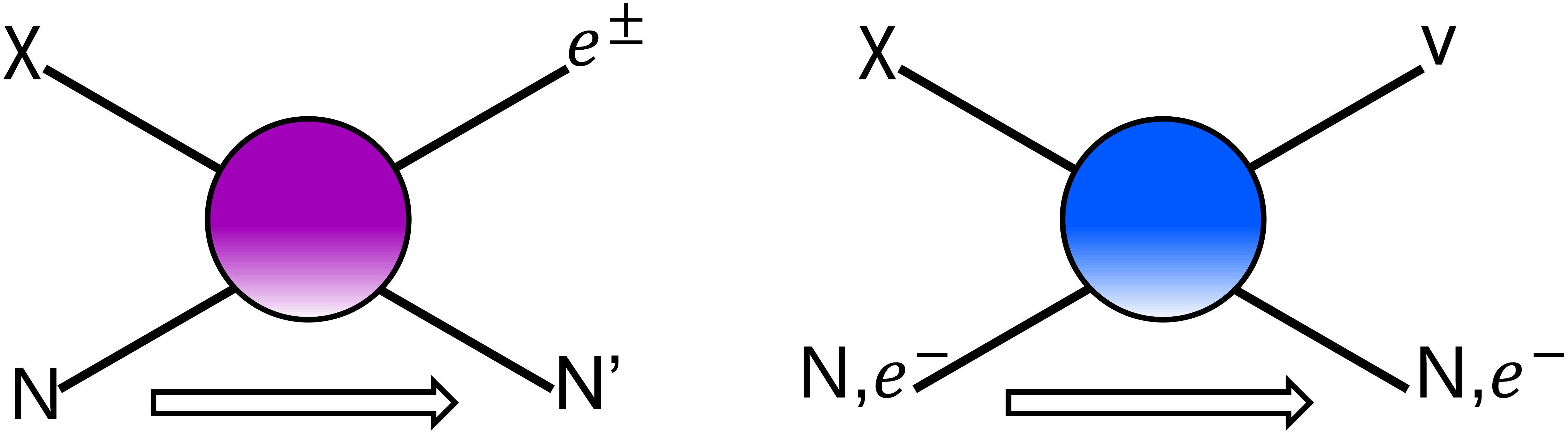

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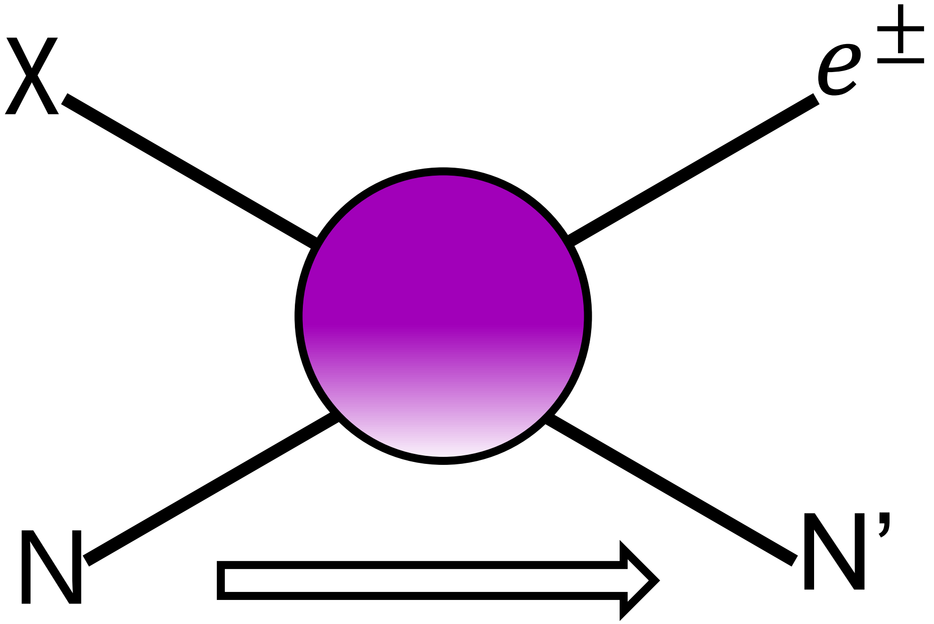
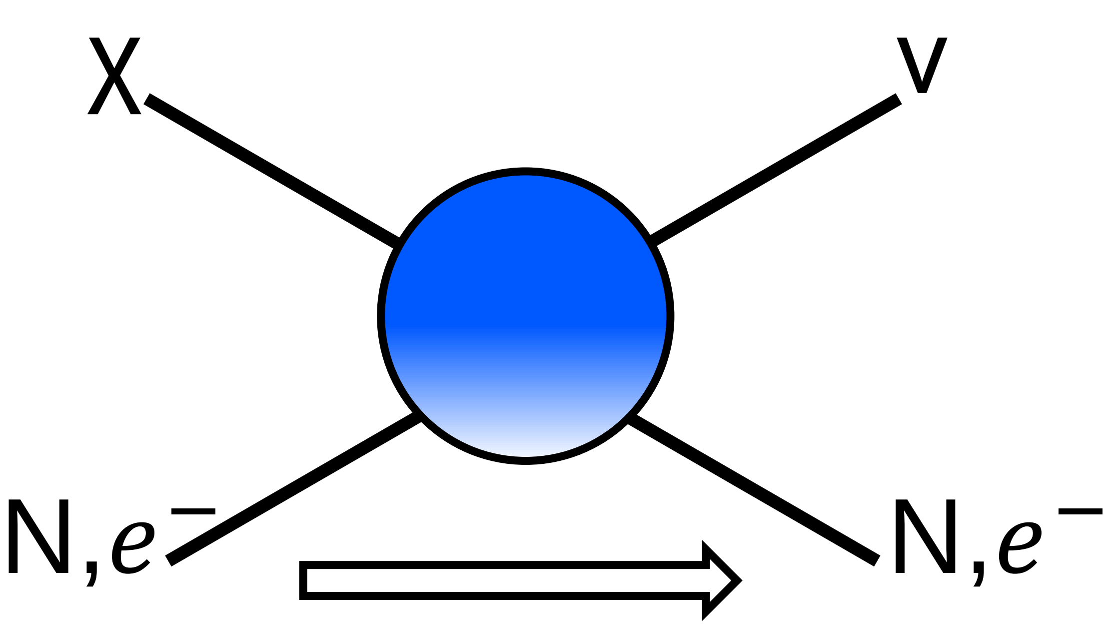
Fermionic "Absorption"





$$\frac{1}{\Lambda^2}[\bar{\chi}\Gamma_\mu e][\bar{n}\Gamma^\mu p] + \text{h.c.}$$

$$\frac{1}{\Lambda^2}[\bar{\chi}\Gamma_\mu \nu]\left[\bar{\psi}_T\Gamma^\mu \psi_T\right] + \text{ h.c.}$$

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Outline

Motivation

Charged Current

Neutral Current

Fermionic Absorption by Nuclear Targets

Jeff A. Dror, Gilly Elor, & RM

1905.12635, 1908.10861

Robert McGehee

Charged Current

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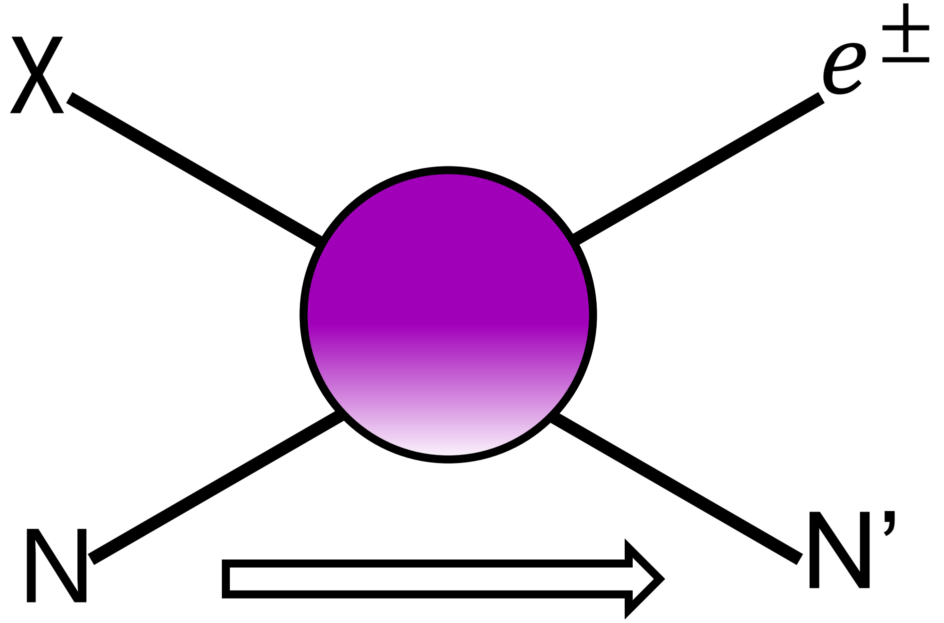
$$\frac{1}{\Lambda^2}\left[\bar{p}\gamma_\mu(1+\lambda\gamma_5)n\right]\left[\bar{e}\gamma^\mu P_R\chi\right] + \mathbf{h.c.}$$

$$\chi + {}^{A}_{Z}\mathbf{X} \rightarrow e^\pm + {}^{A}_{Z\mp 1}\mathbf{X}^{(*)}$$



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Target Isotope Dependence

Stable $\rightarrow$ “Induced” Beta Decay

$$m_\chi > m_{\text{th}}^{\beta^\mp} \equiv M_{A,Z\pm1}^{(*)} + m_e - M_{A,Z}$$

Threshold ~ MeV

Large Experiments

“Direct” Constraints

“Direct” $\rightarrow$ don’t rely on X being DM

LHC constrains mediator $\Lambda \gtrsim 3\ \mathrm{TeV}$

(Belyaev et al [1807.03817])

Operator + Model dependent

$$m_\chi \lesssim 100\ \mathrm{MeV}\ \text{and}\ \Lambda \gtrsim 3\ \mathrm{TeV}$$

Decay Constraints

$$\chi \to e^+ e^- \nu$$

$$\chi \to \nu\nu\nu$$

$$\chi \to \gamma\nu$$

$$\chi \to \gamma\gamma\nu$$

$$\chi \to \gamma\gamma\gamma\nu$$

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Decay Constraints

$$\chi \to e^+ e^- \nu$$

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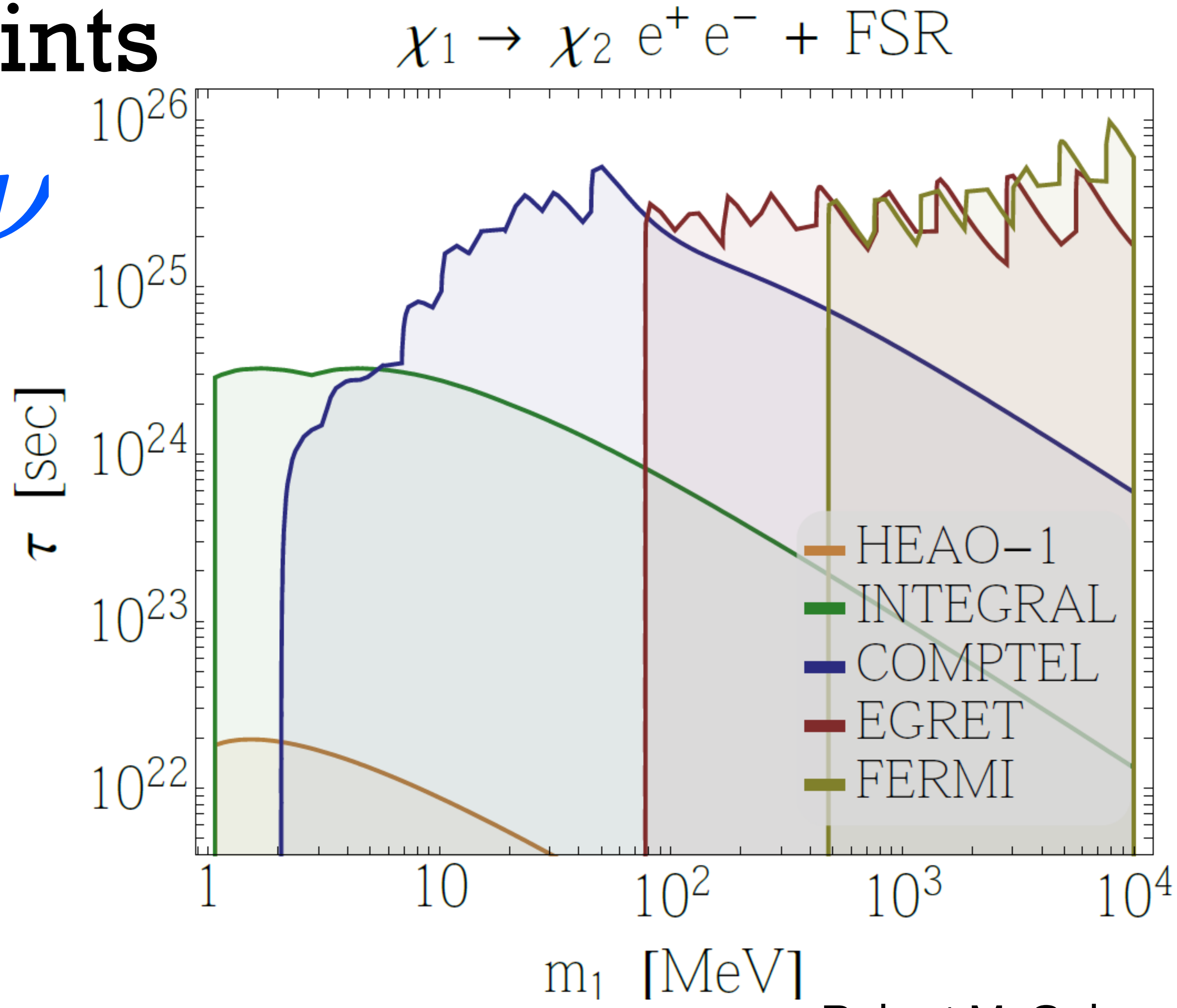
Essig, Kuflik, McDermott, Volansky, Zurek [1309.4091]



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Decay Constraints

$$\chi \to e^+ e^- \nu$$

$$\chi \to \nu\nu\nu$$

$$\chi \to \gamma\nu$$

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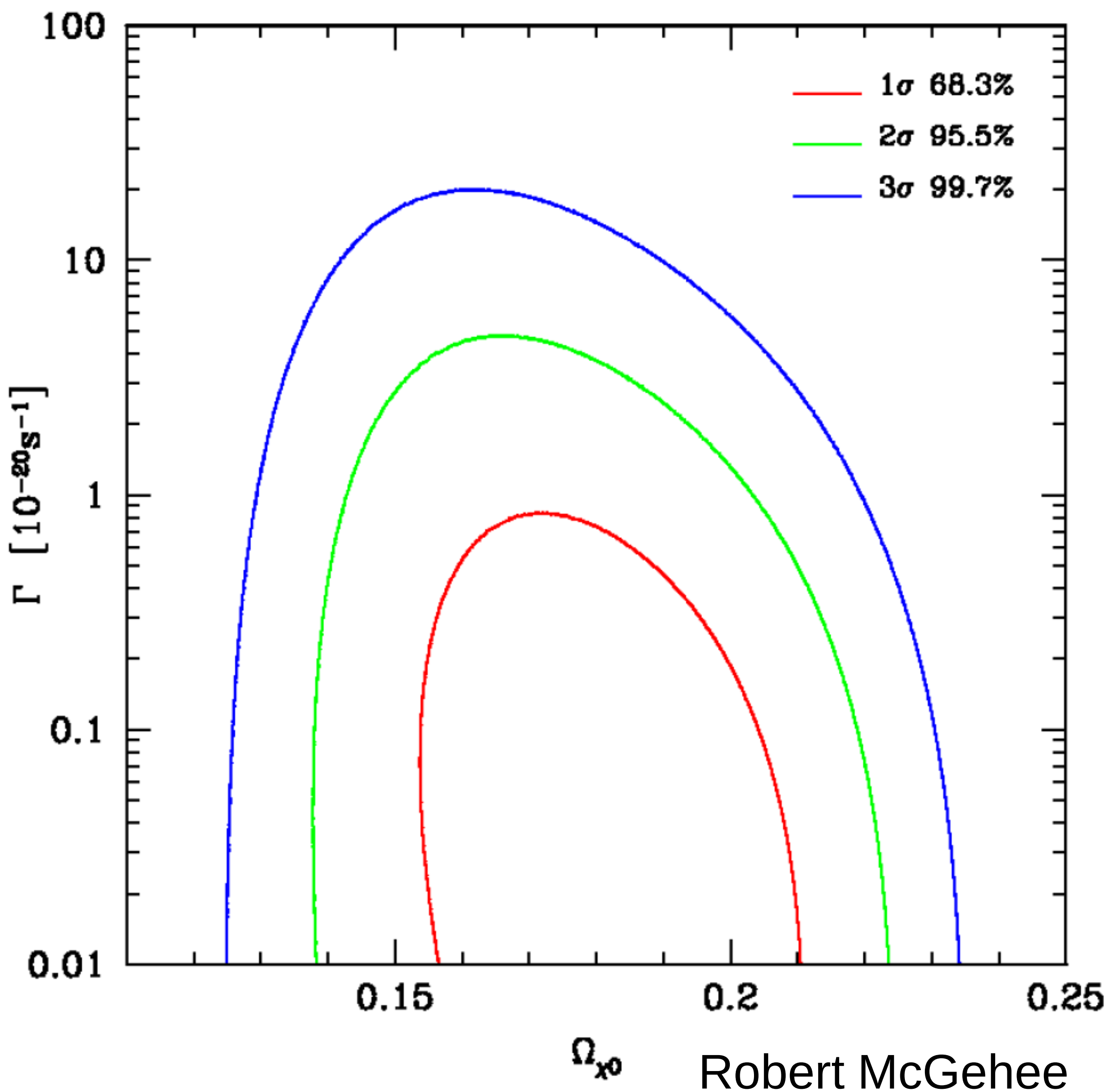
$$\chi \to \gamma\gamma\gamma\nu$$

Gong, Chen [0802.2296]



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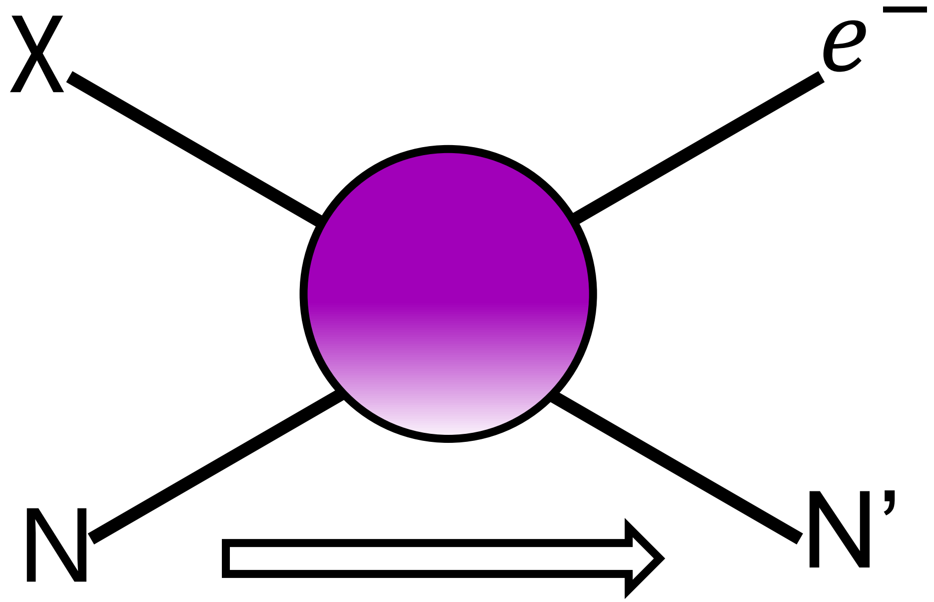
Induced β^- Decays



- e^-!
- NR!
- γ!
- N' Decay!

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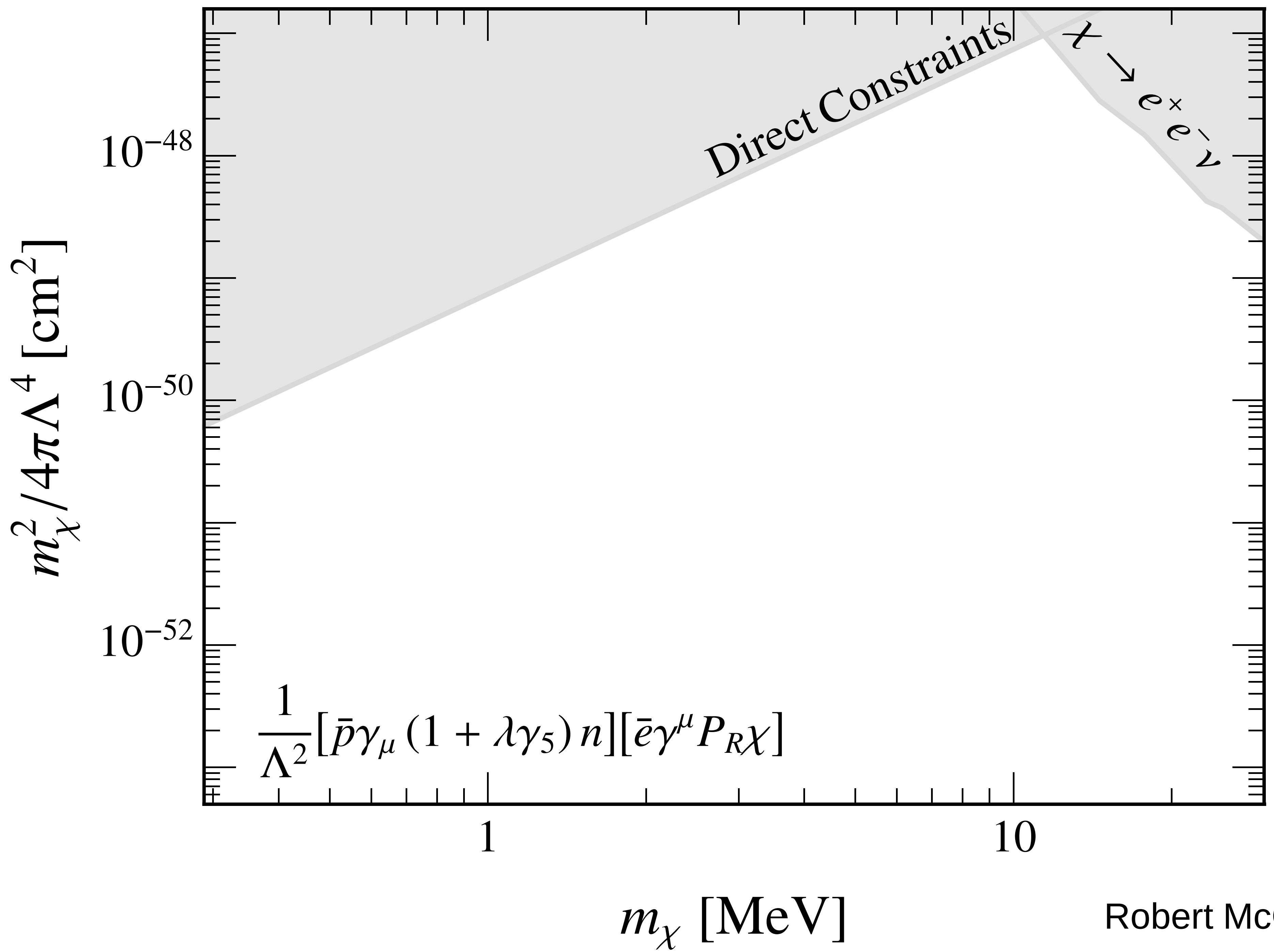

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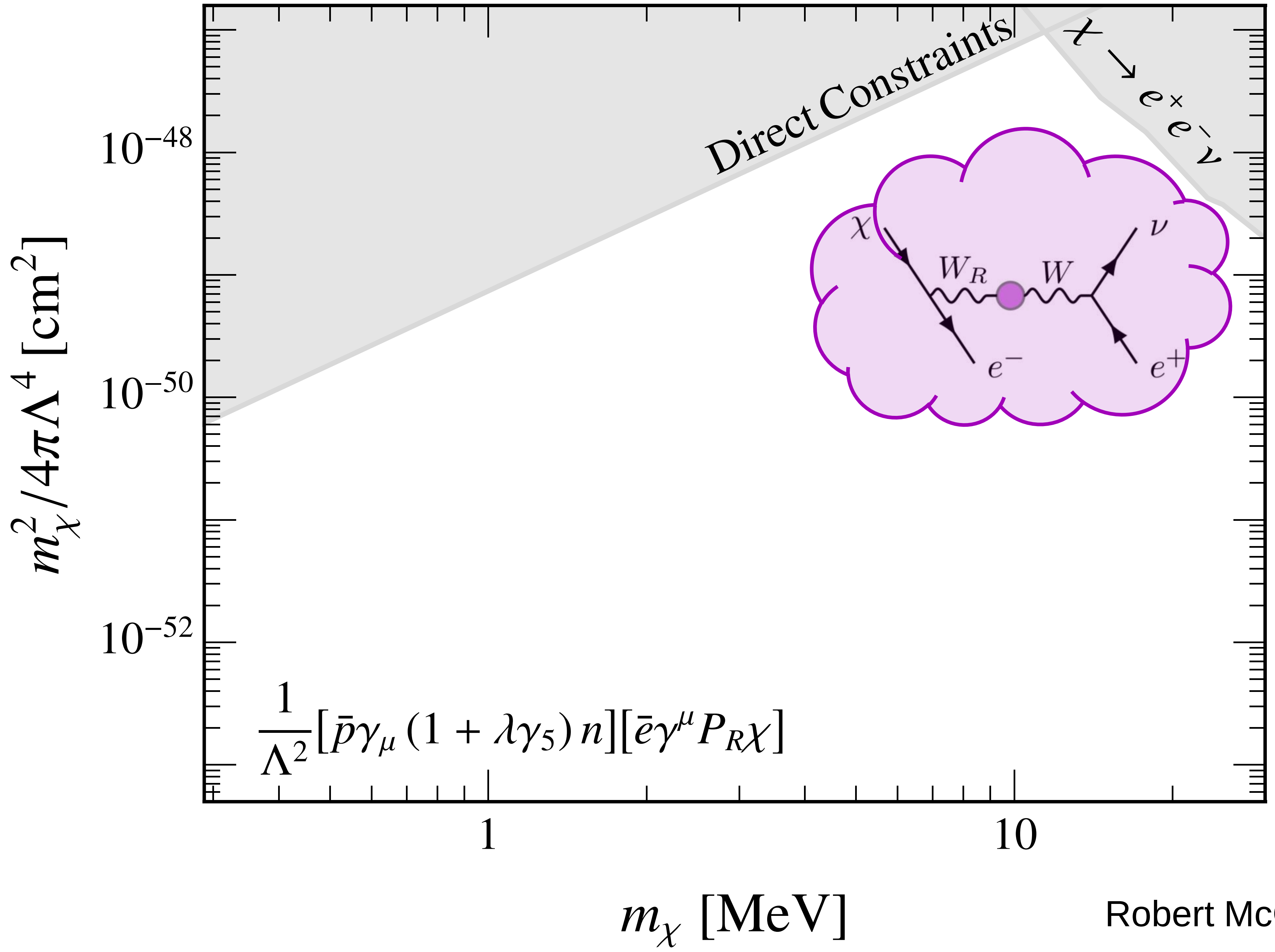

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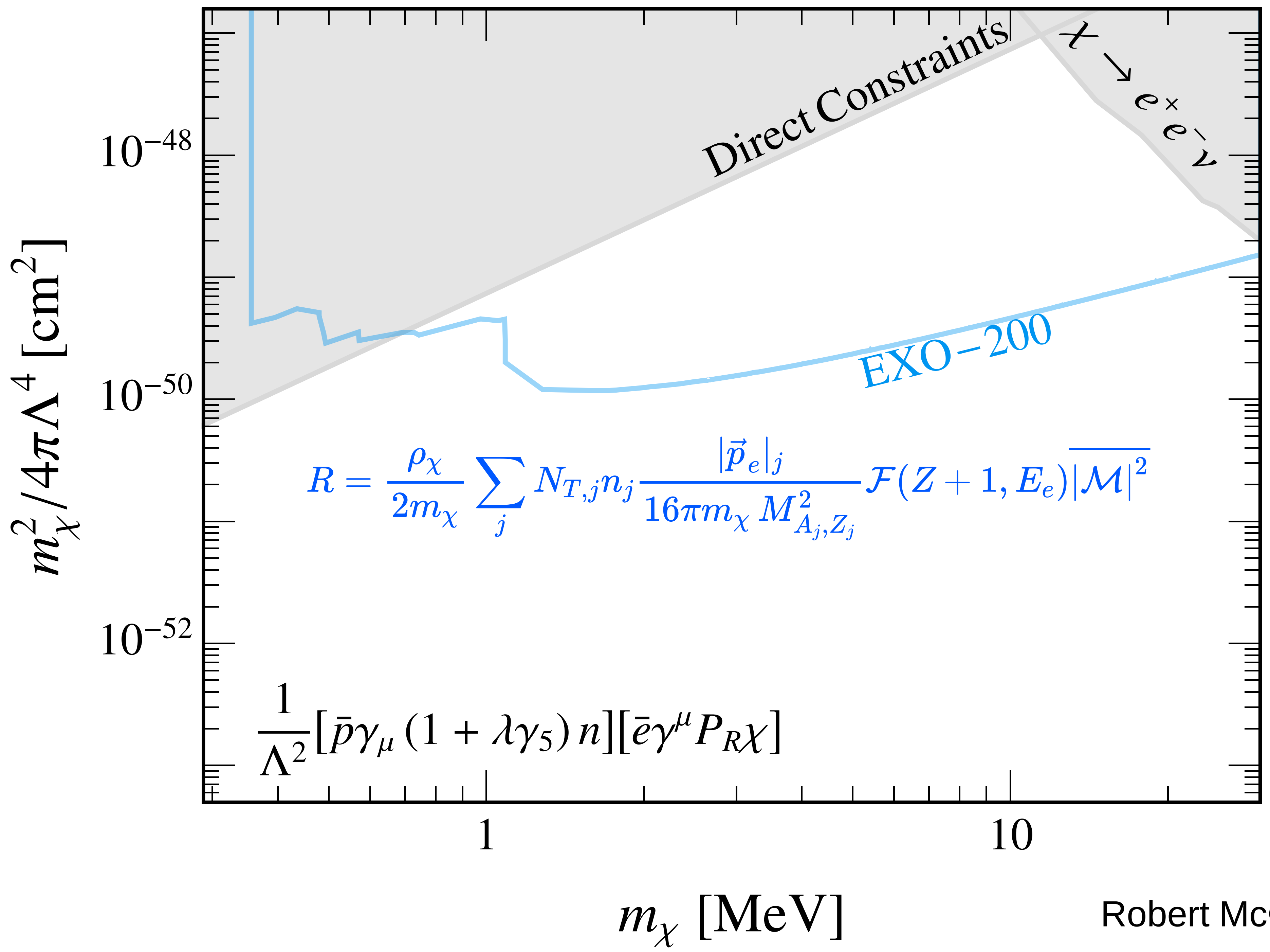

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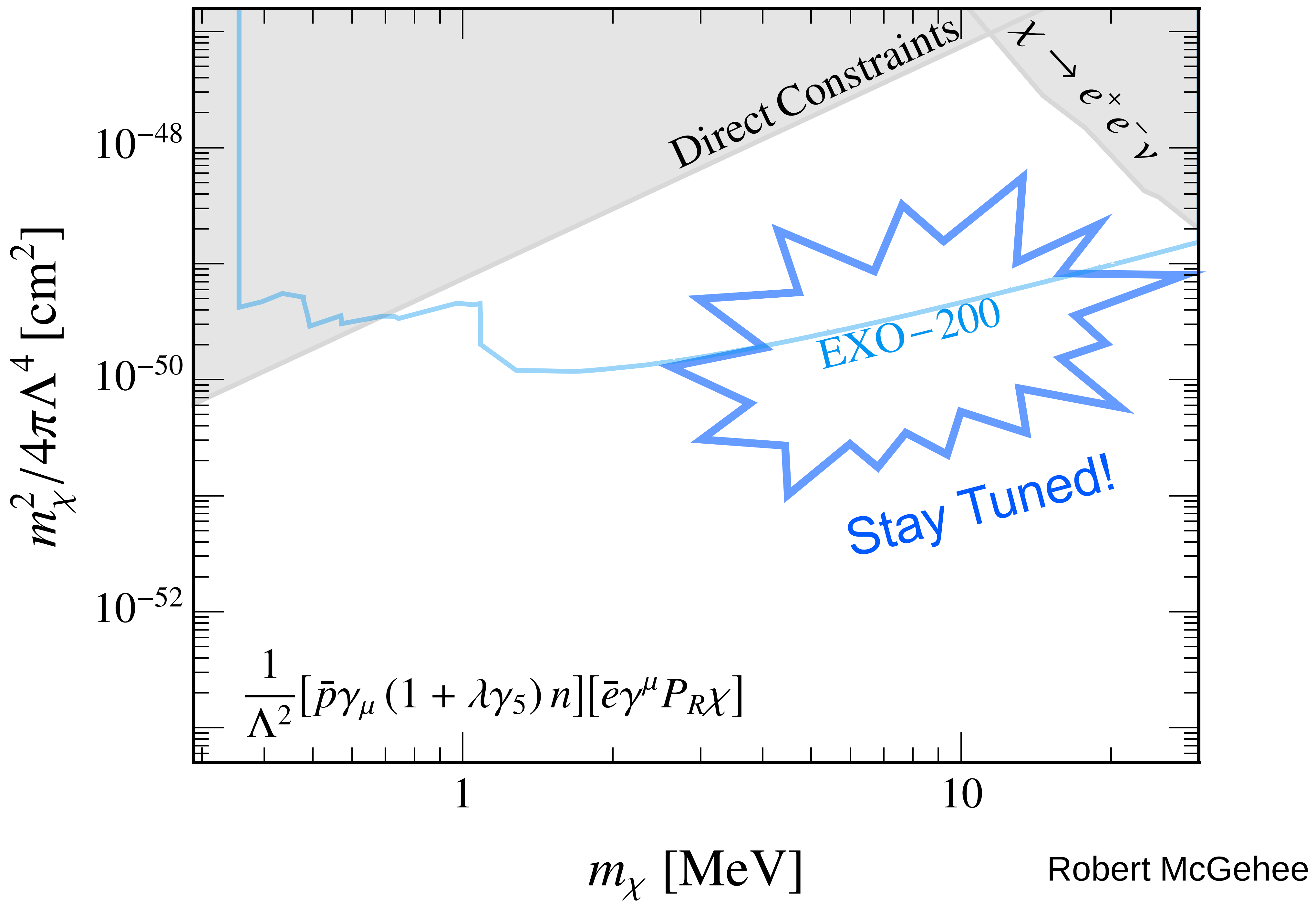

Direct Constraints
$\chi \to e^+ e^- \nu$
EXO−200
Stay Tuned!
10^{-48}
10^{-50}
10^{-52}
1
10
$m_\chi^2 / 4\pi\Lambda^4$ [cm^2]
m_χ [MeV]
$\frac{1}{\Lambda^2}[\bar{p}\gamma_\mu(1+\lambda\gamma_5)n][\bar{e}\gamma^\mu P_R \chi]$
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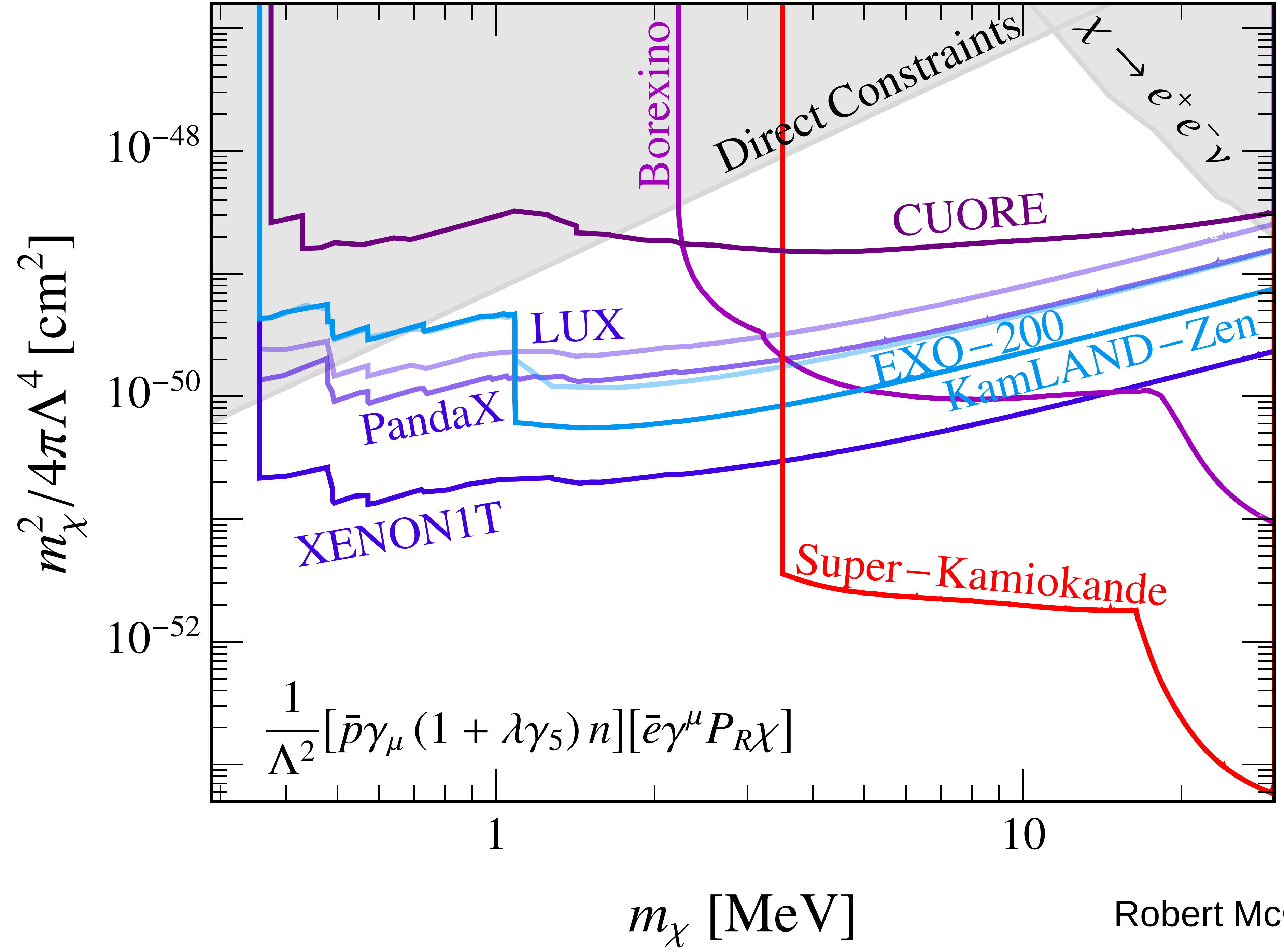

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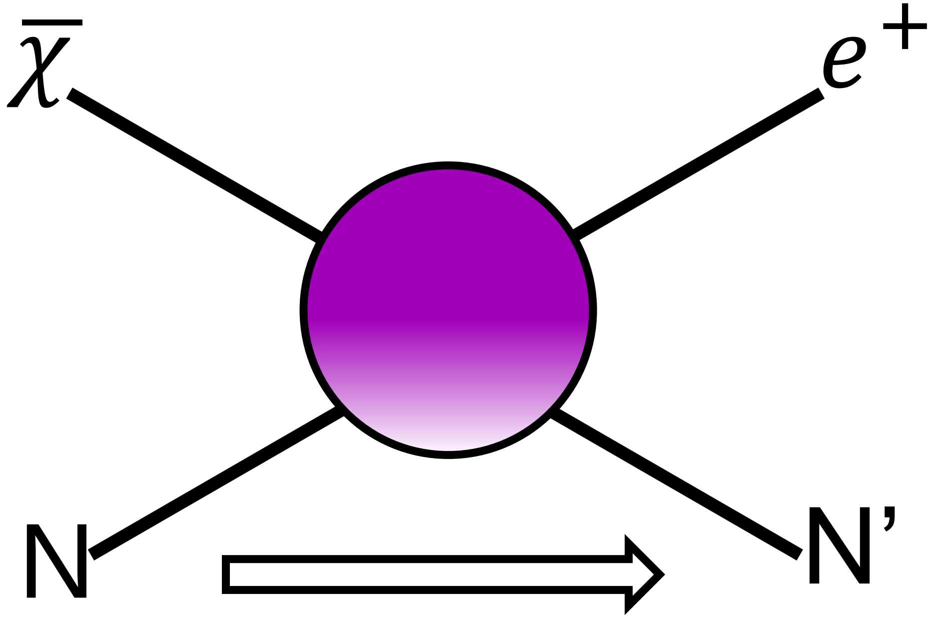
Induced β^+ Decays



- May be only signal (ADM)
- Focus on Hydrogen

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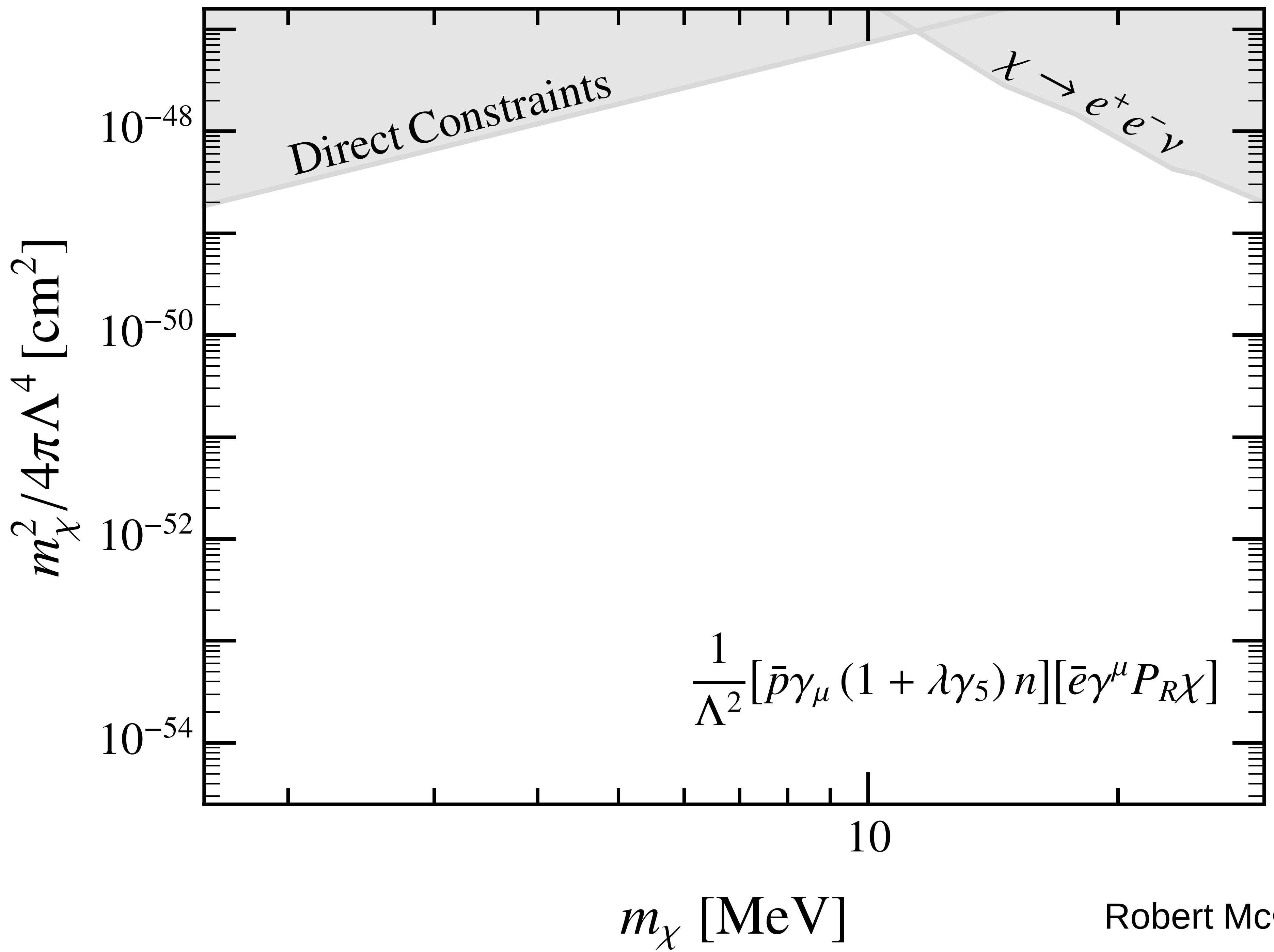

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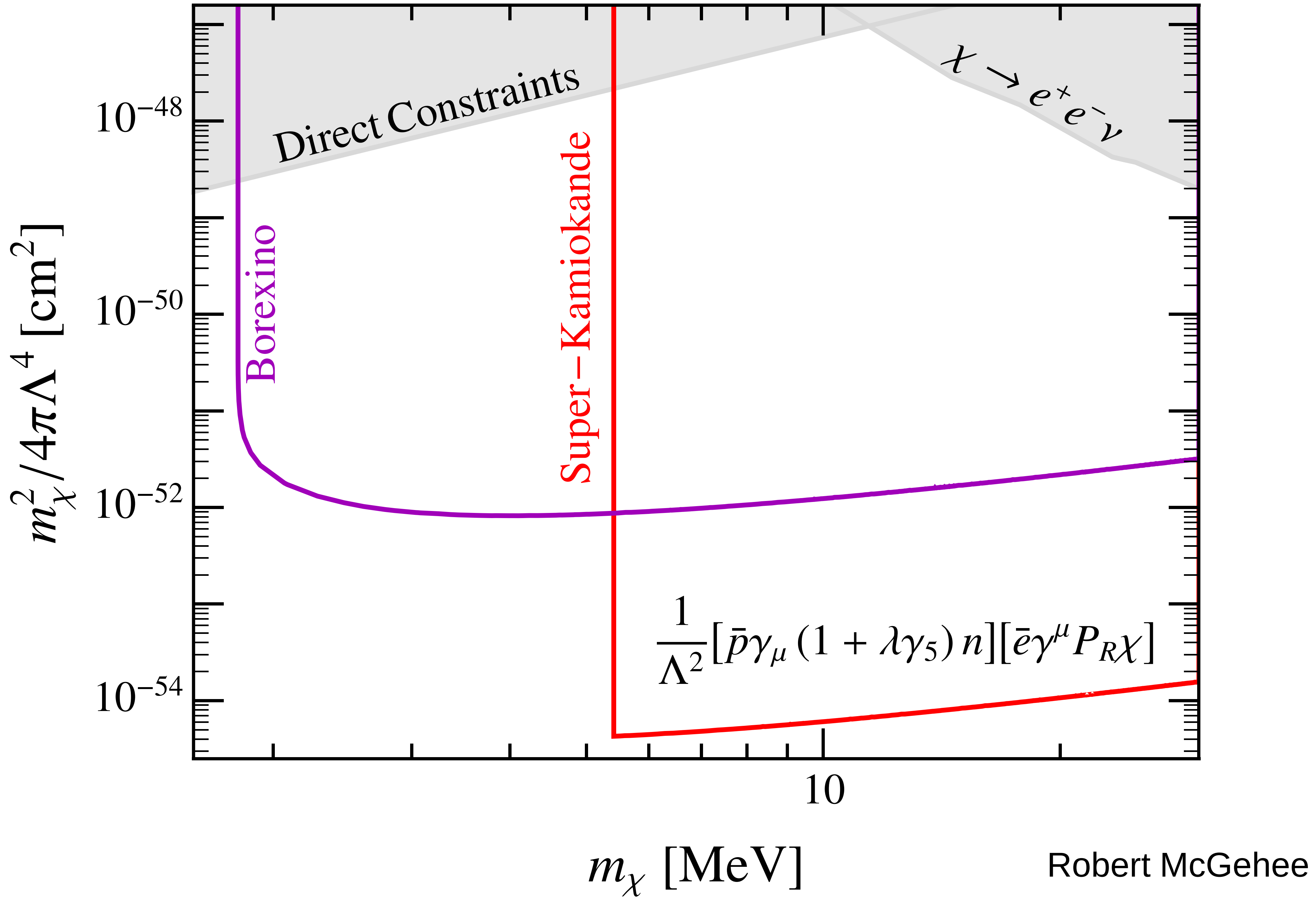

Direct Constraints
$\chi \to e^+ e^- \nu$
Borexino
Super−Kamiokande
$\frac{1}{\Lambda^2}[\bar{p}\gamma_\mu(1+\lambda\gamma_5)n][\bar{e}\gamma^\mu P_R\chi]$
10^{-48}
10^{-50}
10^{-52}
10^{-54}
10
$m_\chi^2/4\pi\Lambda^4$ [cm^2]
m_χ [MeV]
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Neutral Current

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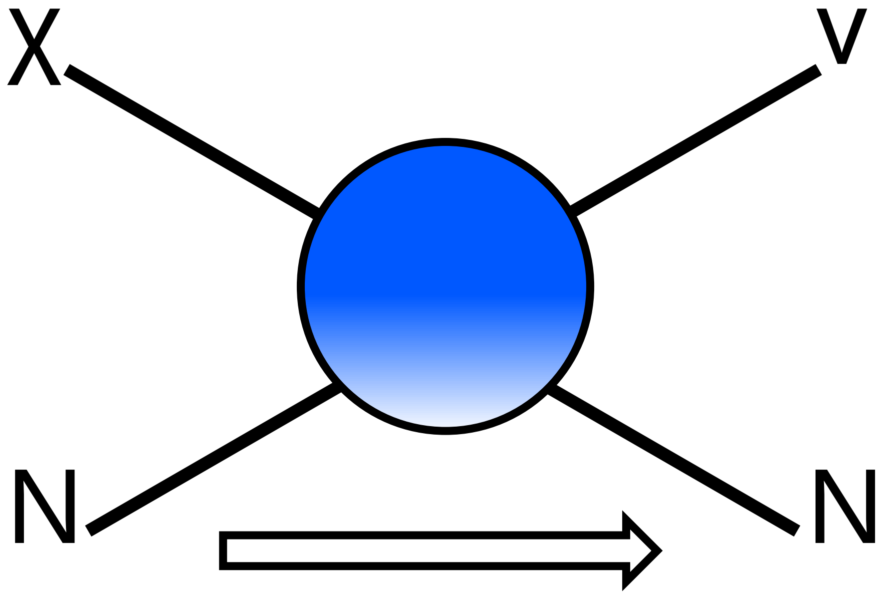
$$\frac{1}{\Lambda^2}(\bar{n}\gamma^\mu n + \bar{p}\gamma^\mu p)\bar{\chi}\gamma_\mu P_R \nu + \text{h.c.}$$



$$\chi + {}^A_Z\text{X} \rightarrow \nu + {}^A_Z\text{X}$$

$$q \sim m_\chi$$

$$E_R \sim \frac{m_\chi^2}{2M_N}$$

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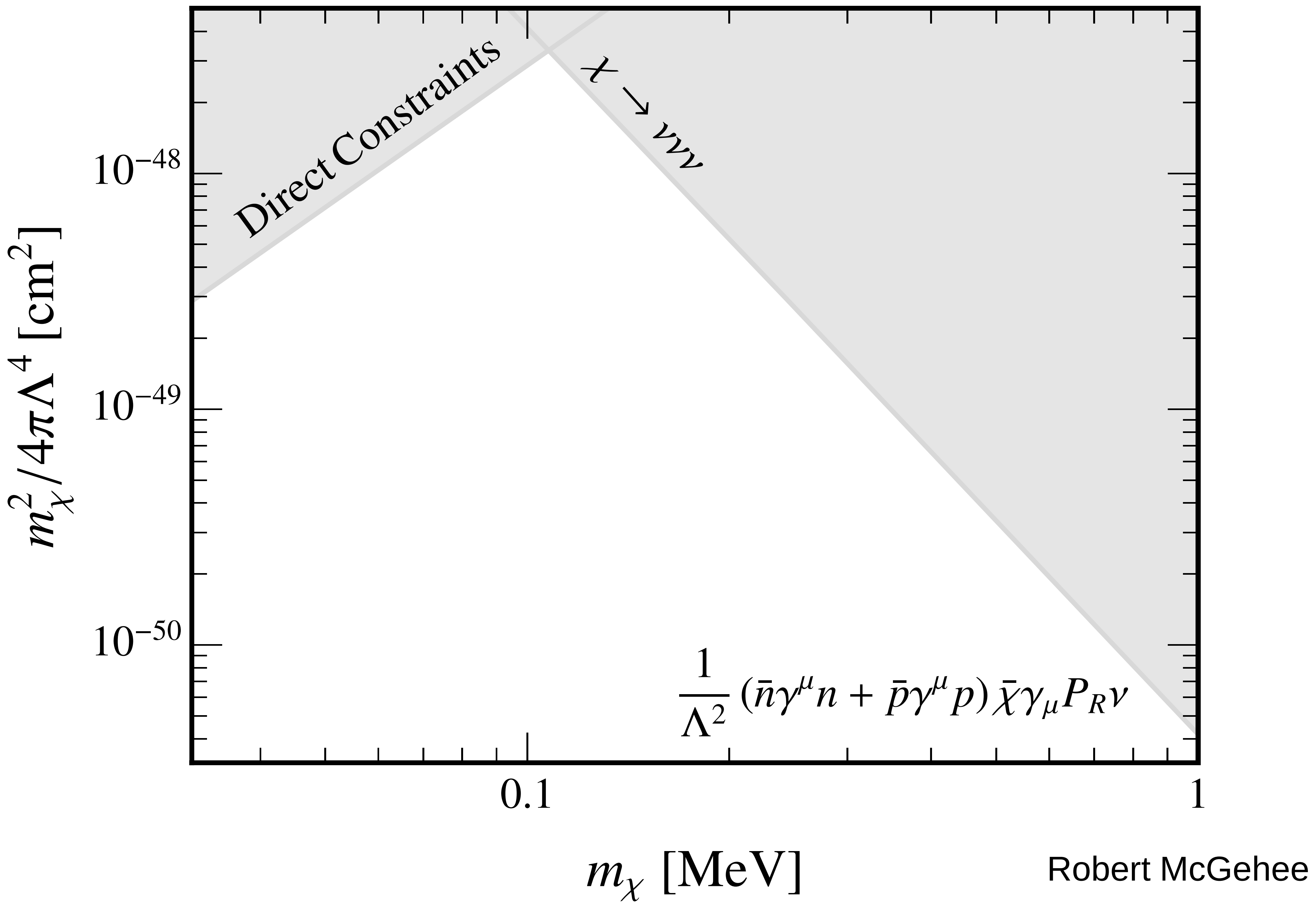
Direct Constraints
$\chi \to \nu\gamma\gamma$
$\frac{1}{\Lambda^2}(\bar{n}\gamma^\mu n + \bar{p}\gamma^\mu p)\,\bar{\chi}\gamma_\mu P_R \nu$
10^{-48}
10^{-49}
10^{-50}
$m_\chi^2/4\pi\Lambda^4$ [cm^2]
0.1
1
m_χ [MeV]
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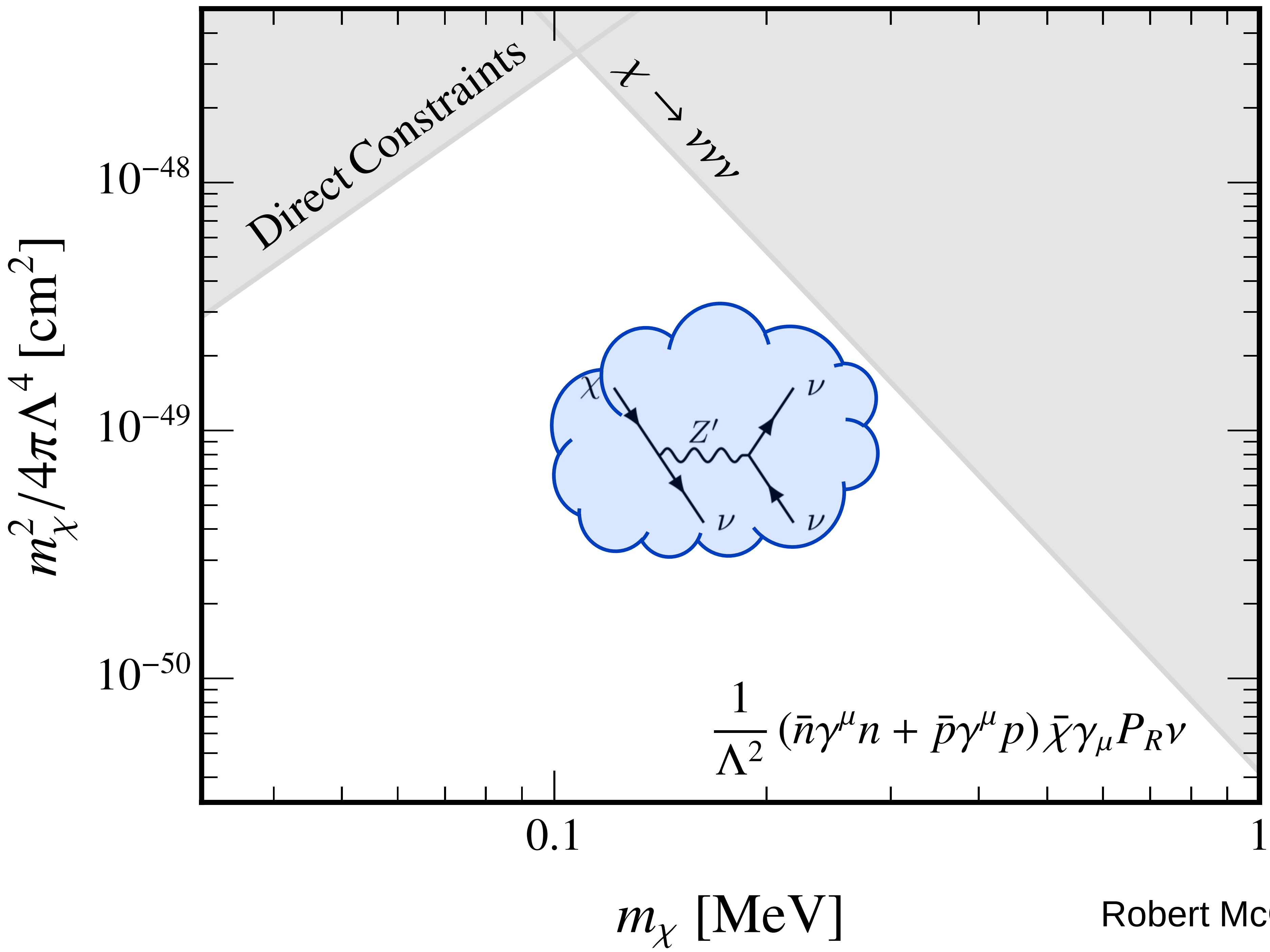

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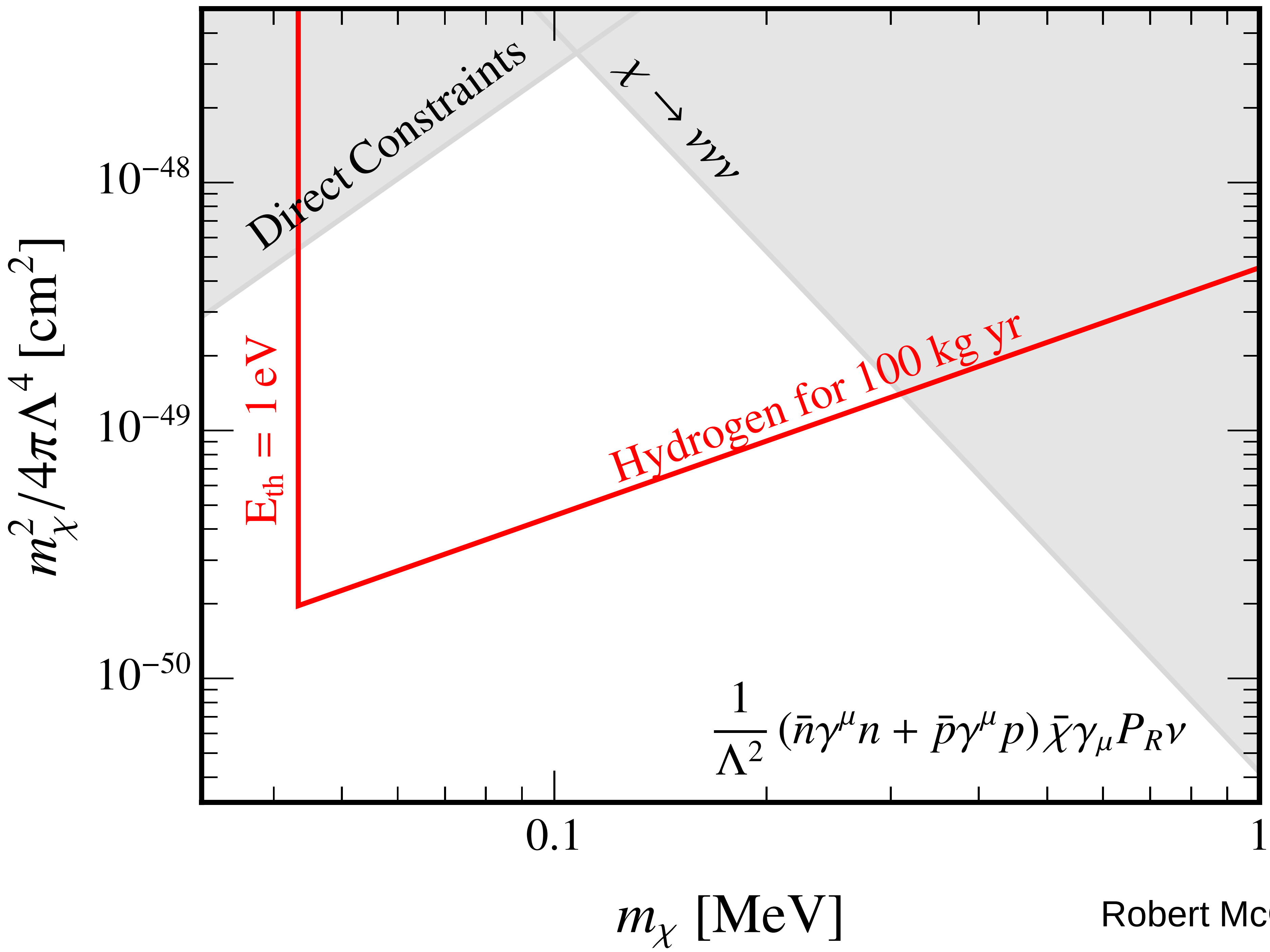

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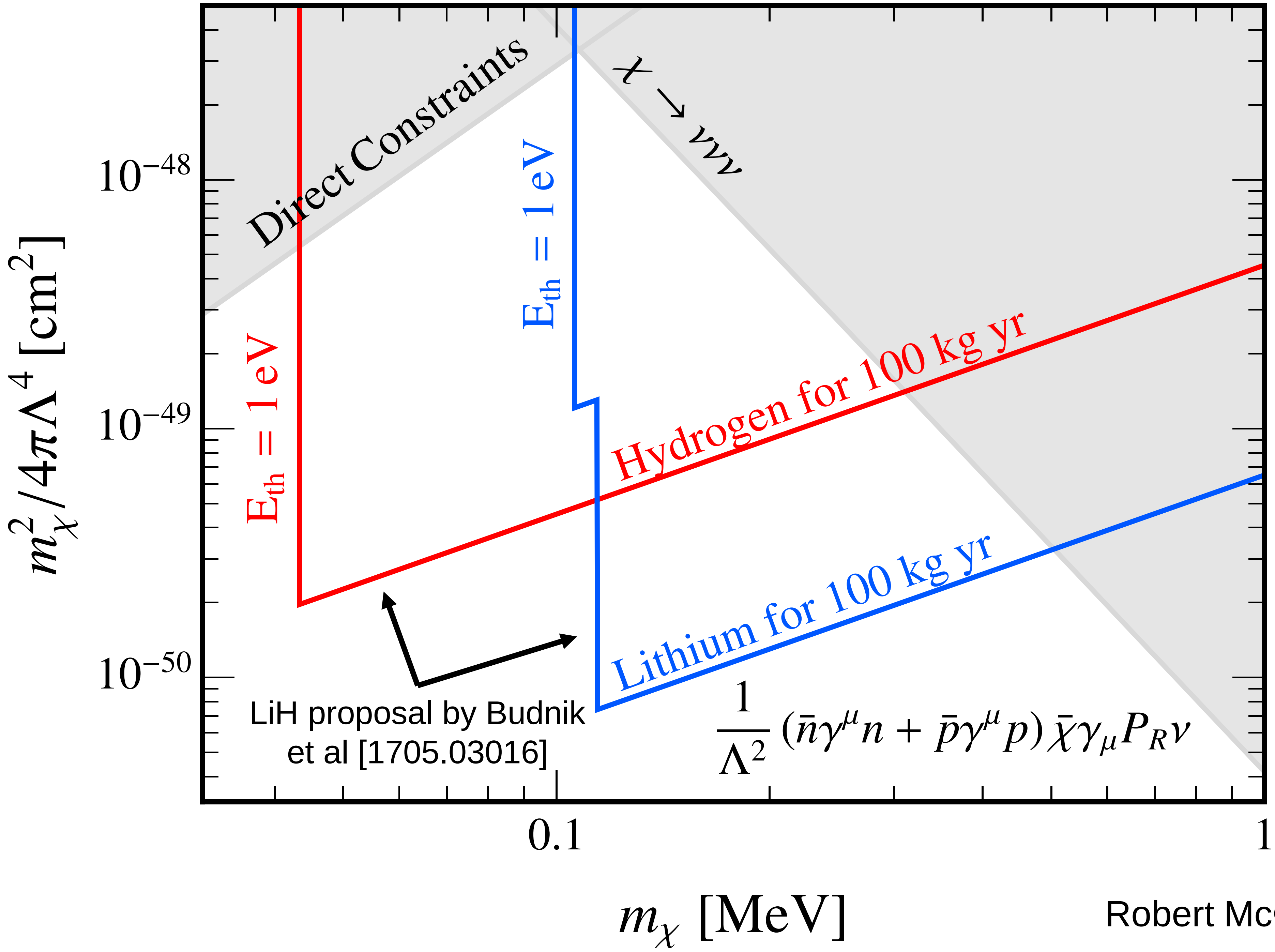

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Summary

Relaxing DM stability assumptions allows for novel signals and operators.

Charged current operators induce $\beta^{\pm}$ decays with NR, $e^{\pm}$, and γ signals.

Neutral current operators yield peaked, correlated nuclear recoil (NR) signals.

New searches at *existing* experiments can probe both neutral and charged current operators.

Stay tuned for absorption by electrons!

Backup Slides

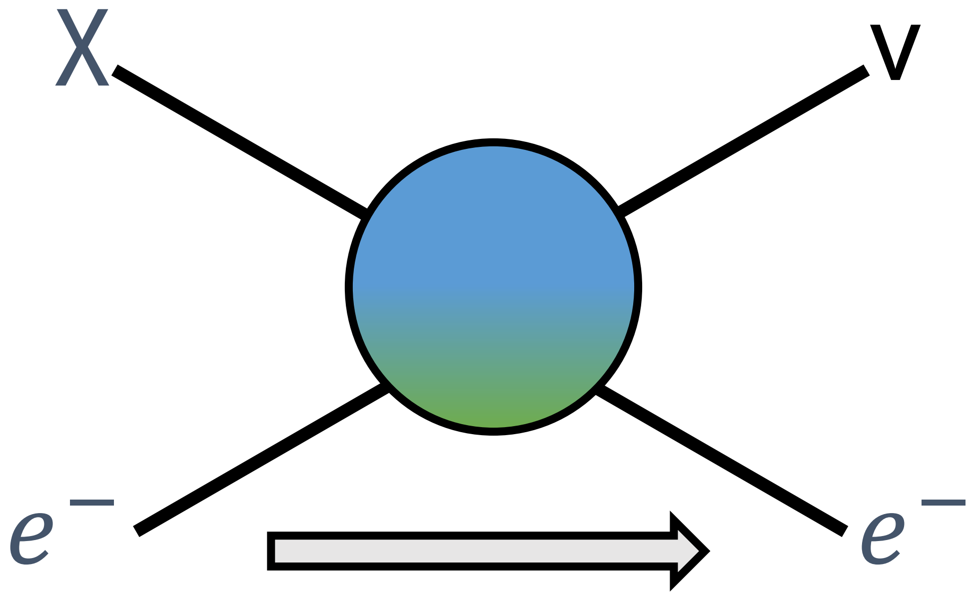
Fermionic Absorption by Electron Targets

Jeff A. Dror, Gilly Elor, RM, & Tien-Tien Yu

(in preparation)

Robert McGehee

$$\frac{1}{\Lambda^2}\bar{e}\gamma^{\mu}e\bar{\chi}P_R\nu + \text{h.c.}$$



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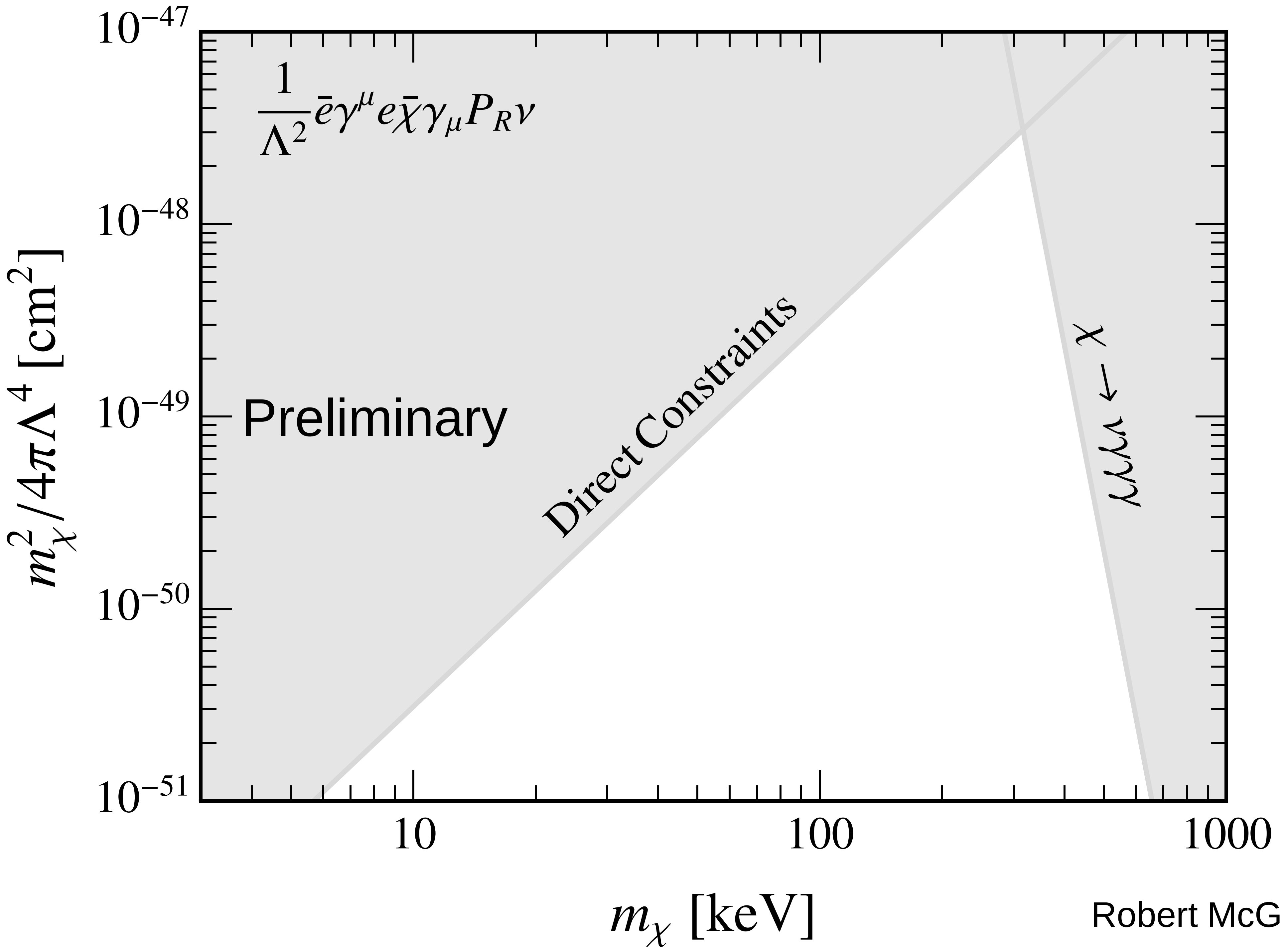

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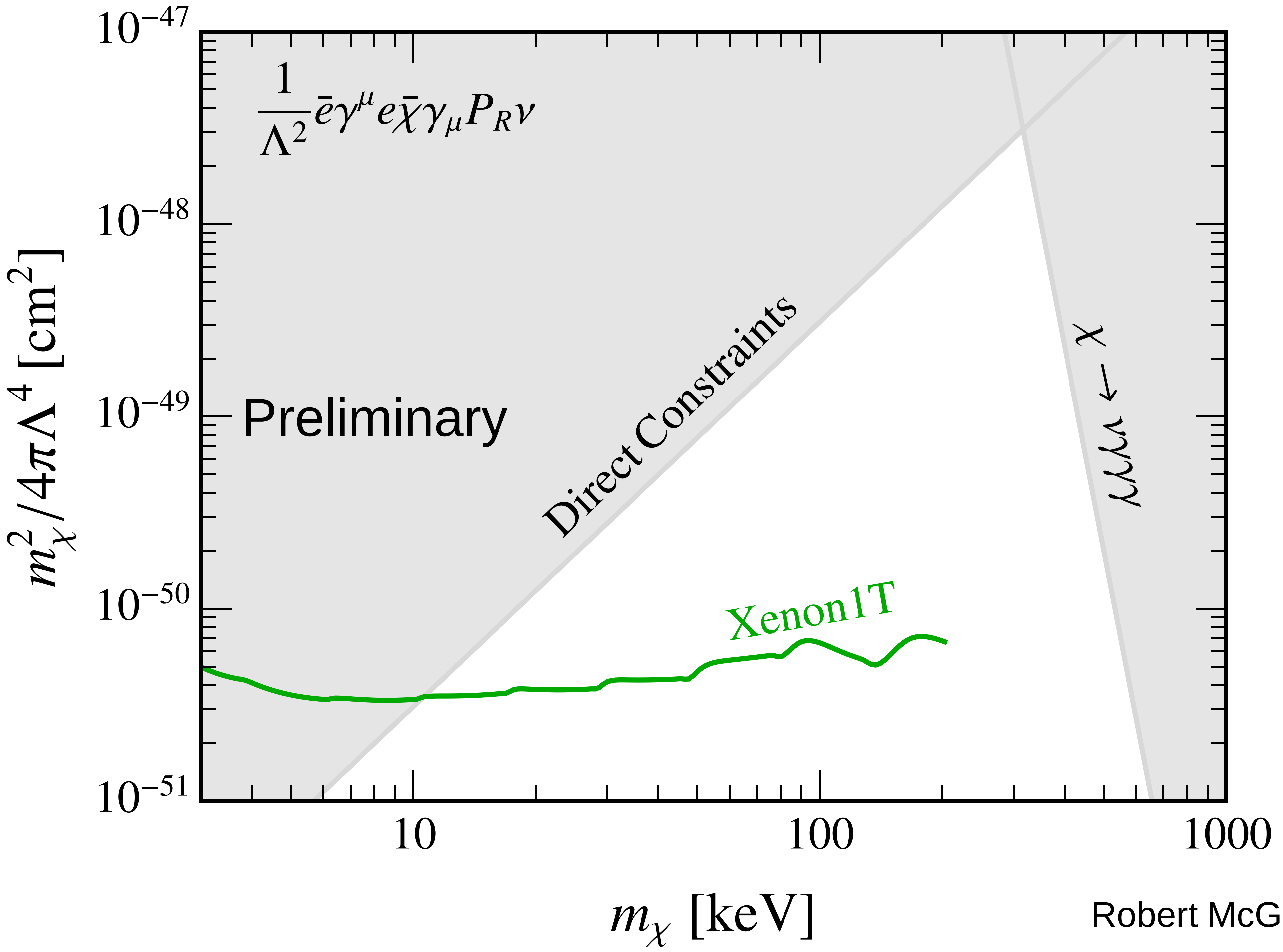

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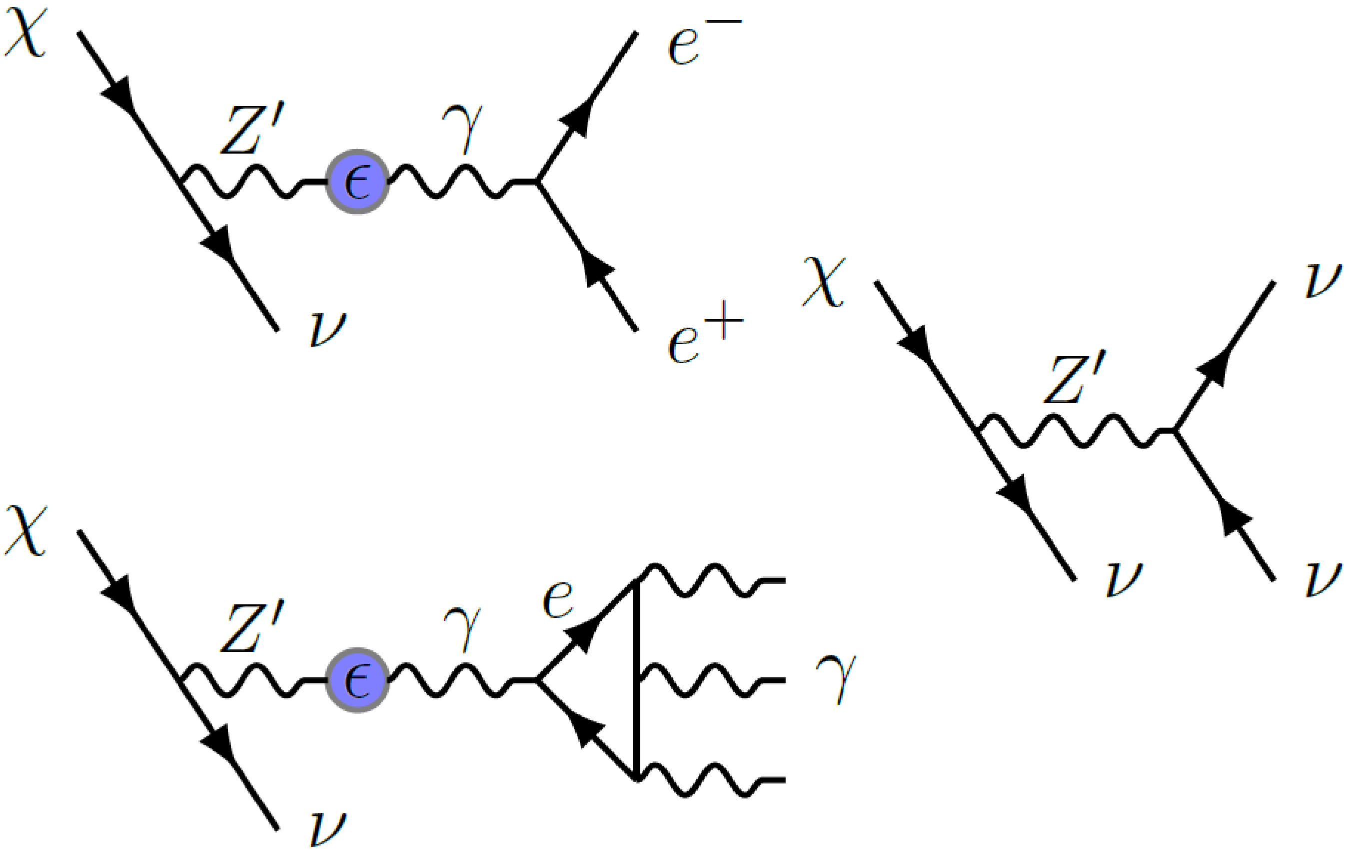
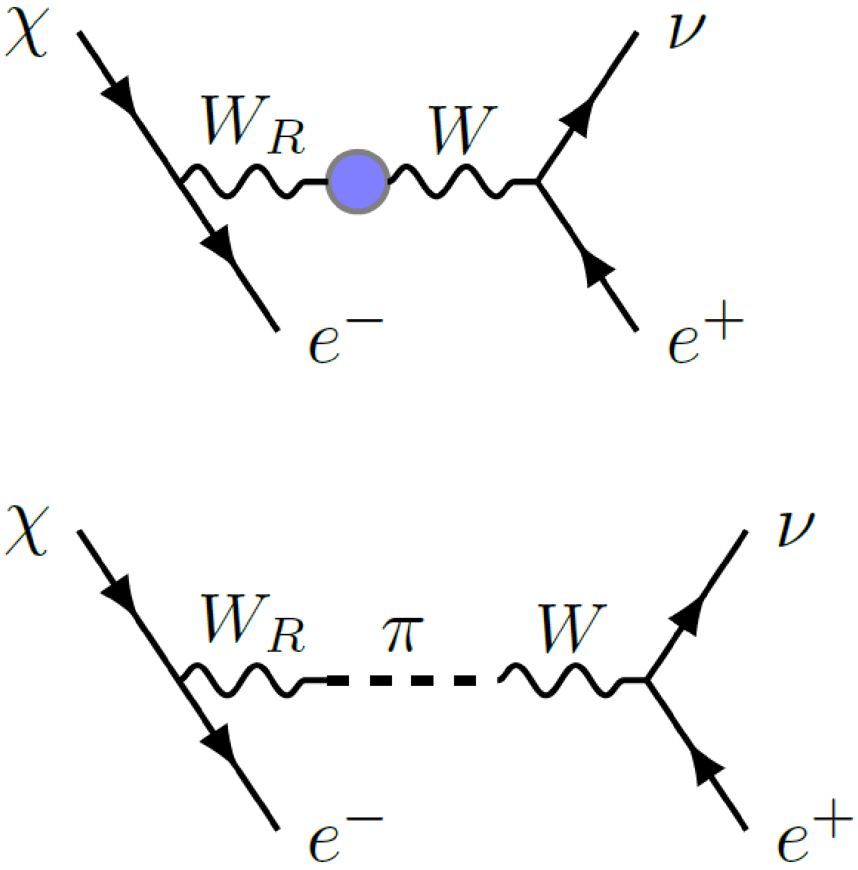
Decay details

Z' - Model



W_R - Model



Decay details: Charged current model

$$\Gamma^{(1-\text{loop})}_{\chi\to e^+e^-\nu} = (16\log 2 - 11)\,\frac{m_\chi^5}{512\pi^3}\left(\frac{g_L^2 g_R^2 m_u m_d}{(4\pi)^2 M_{W_R}^2 M_W^2}\log\frac{m_u}{\Lambda_{\mathrm{QCD}}}\right)^2$$

$$\Gamma^{(\pi)}_{\chi\to e^+e^-\nu} = \left(\log 4 - \frac{31}{24}\right)\frac{m_\chi^7 m_e^2}{256\pi^3}\left(\frac{g_L^2 g_R^2 f_\pi^2}{8m_\pi^2}\frac{1}{M_{W_R}^2 M_W^2}\right)^2.$$

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Decay details: Neutral current model

$$\Gamma_{\chi\to\nu e^+e^-} = \left(16\log 2 - \frac{31}{3}\right)\frac{m_\chi^5}{512\pi^3}\left(\frac{\epsilon e Q_\chi g_\chi s_{\theta_R} c_{\theta_R}}{m_{Z'}^2}\right)^2$$

$$\Gamma_{\chi\to\nu\nu\nu} = (16\log 2 - 11)\frac{m_\chi^5}{128\pi^3}\left(\frac{Q_\chi^2 g_\chi^2 s_{\theta_R}^3 c_{\theta_R}}{m_{Z'}^2}\right)^2$$

$$\Gamma_{\chi\to\nu\gamma} = 0 + \mathcal{O}\left(\frac{m_\chi^{13}}{(4\pi)^{13} m_{Z'}^{12}}\right), \qquad \Gamma_{\chi\to\nu\gamma\gamma} = 0 + \mathcal{O}\left(\frac{m_\chi^9}{(4\pi)^{11} m_{Z'}^8}\right)$$

$$\Gamma_{\chi\to\nu\gamma\gamma\gamma} \simeq 10^{-7} m_\chi^{13}\left(\frac{(8Q_\chi g_\chi \epsilon) s_{\theta_R} c_{\theta_R}\alpha^2}{360 m_e^4 m_{Z'}^2}\right)^2$$

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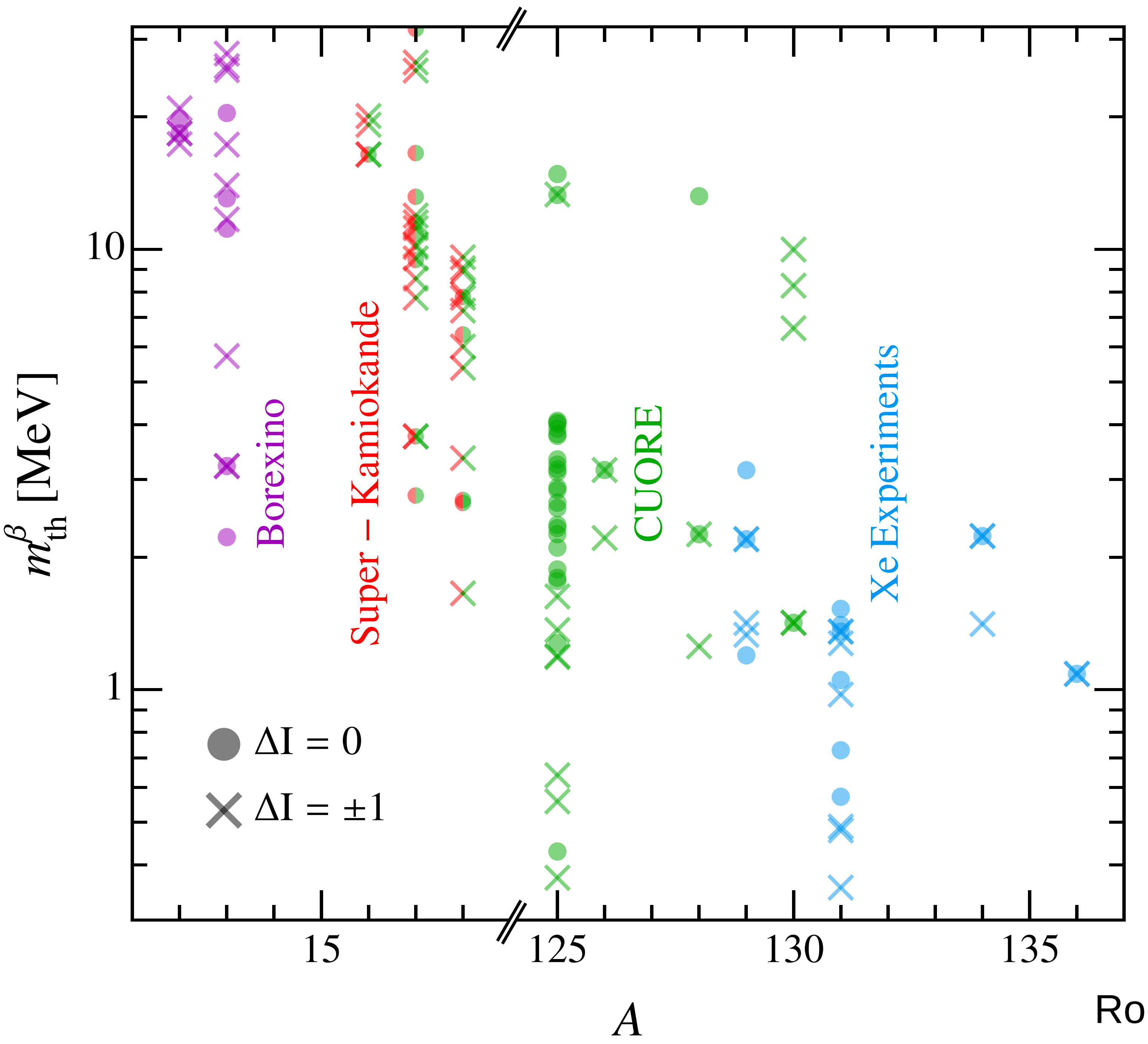

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	Process	Isotope (Threshold $\Delta I = 0$, $\Delta I = \pm 1$)
β^-:	${}^{A}_{6}C \rightarrow {}^{A}_{7}N$	${}^{12}_{6}C$(18.3 MeV, 17.3 MeV), ${}^{13}_{6}C$(2.22 MeV, 5.7 MeV)
	${}^{A}_{8}O \rightarrow {}^{A}_{9}F$	${}^{16}_{8}O$(16.4 MeV, 16.4 MeV), ${}^{17}_{8}O$(2.76 MeV, 3.75 MeV),
		${}^{18}_{8}O$(2.70 MeV, 1.65 MeV)
	${}^{A}_{52}Te \rightarrow {}^{A}_{53}I$	${}^{130}_{52}Te$(1.42 MeV, 6.62 MeV), ${}^{128}_{52}Te$(2.25 MeV, 1.25 MeV),
		${}^{126}_{52}Te$(3.1 MeV, 1.41 MeV), ${}^{125}_{52}Te$(430 keV, 374 keV)
	${}^{A}_{54}Xe \rightarrow {}^{A}_{55}Cs$	${}^{129}_{54}Xe$(1.19 MeV, 1.33 MeV), ${}^{131}_{54}Xe$(570 keV, 355 keV),
		${}^{134}_{54}Xe$(2.23 MeV, 490 keV), ${}^{136}_{54}Xe$(1.09 MeV, 1.06 MeV)
β^+:	${}^{1}_{1}H \rightarrow n$	${}^{1}_{1}H$(1.8 MeV)

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Experiment	Goal	Exposure	Target	E_{NR}^{th}
CRESSTII	DM	52 kg day	$CaWO_4$ crystals	307 eV
CRESSTIII	DM	2.39 kg day	$CaWO_4$ crystals	100 eV
DAMIC	DM	0.6 kg day	Si CCDs	0.7 keV
DarkSide-50	DM	6786 kg day	Liquid Ar	0.6 keV
EDELWEISS	DM	.0334 kg day	Ge	0.06 keV
LUX	DM	91.8 kg yr	Liquid Xe	4 keV
NEWS-G	DM	9.7 kg day	Neon	720 eV

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Experiment	Goal	Exposure	Target	E_{NR}^{th}
PandaX-II	DM/$0\nu2\beta$	150 kg yr	Liquid Xe	3 keV
PICO-60	DM	3420 kg day	Superheated CF_3I	13.6 keV
PICO-60	DM	1167 kg day	Superheated C_3F_8	3.3 keV
SuperCDMS	DM	577 kg day	Ge crystals	1.6 keV
CDMSlite	DM	70 kg day	Ge crystals	0.4 keV
XENON1T	DM	1.0 t yr	Liquid Xe	3 keV

Experiment	Goal	Exposure	Target	E_{NR}^{th}
CUORE	$0\nu2\beta$	86.3 kg yr	TeO_2 crystals	100 keV
EXO-200	$0\nu2\beta$	233 kg yr	Liquid $^{136}_{54}Xe$	—
KamLAND-Zen	$0\nu2\beta$	504 kg yr	$^{136}_{54}Xe$ in LS	—
Borexino	solar ν	817 t yr	$C_6H_3\,(CH_3)_3$	500 keV
COHERENT	CEνNS	6726 kg day	CsI[Na]	6.5 keV
Super-Kamiokande	ν	171,000 t yr	H_2O	—

Target Isotope Dependence

Stable $\rightarrow$ “Induced” Beta Decay

$$m_\chi > m_{\text{th}}^{\beta^\mp} \equiv M_{A,Z\pm1}^{(*)} + m_e - M_{A,Z}$$

Threshold ~ MeV

Large Experiments

Target Isotope Dependence

Unstable → Beta Endpoint Shifts

$$m_\chi > m_{\rm th}^{\beta^\mp} \equiv M_{A,Z\pm1}^{(*)} + m_e - M_{A,Z}$$

Threshold ~ MeV

Large Experiments

Target Isotope Dependence

Unstable → Beta Endpoint Shifts

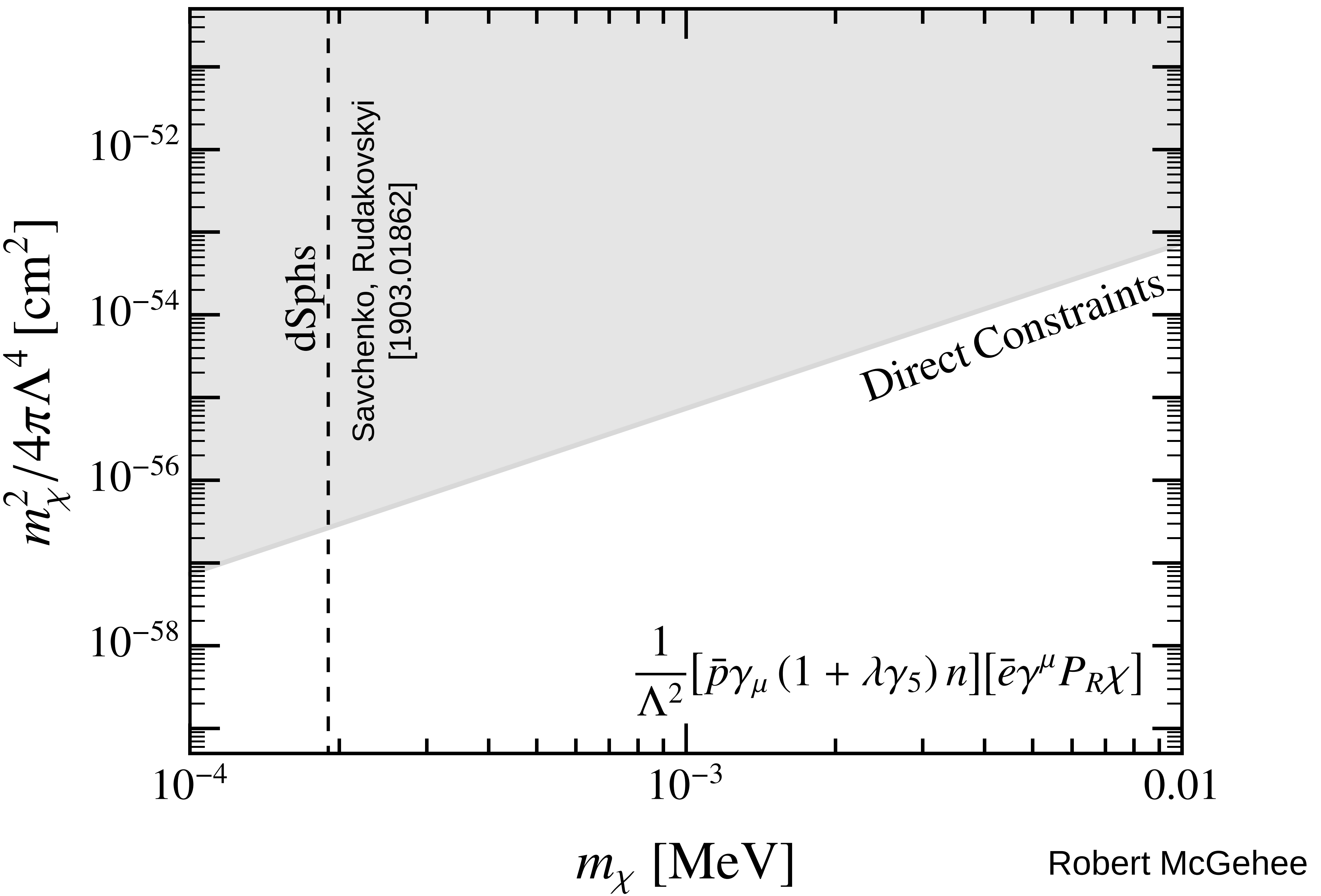
$$m_\chi > m_{\rm th}^{\beta^\mp} \equiv M^{(*)}_{A,Z\pm1} + m_e - M_{A,Z}$$

Threshold ~ MeV

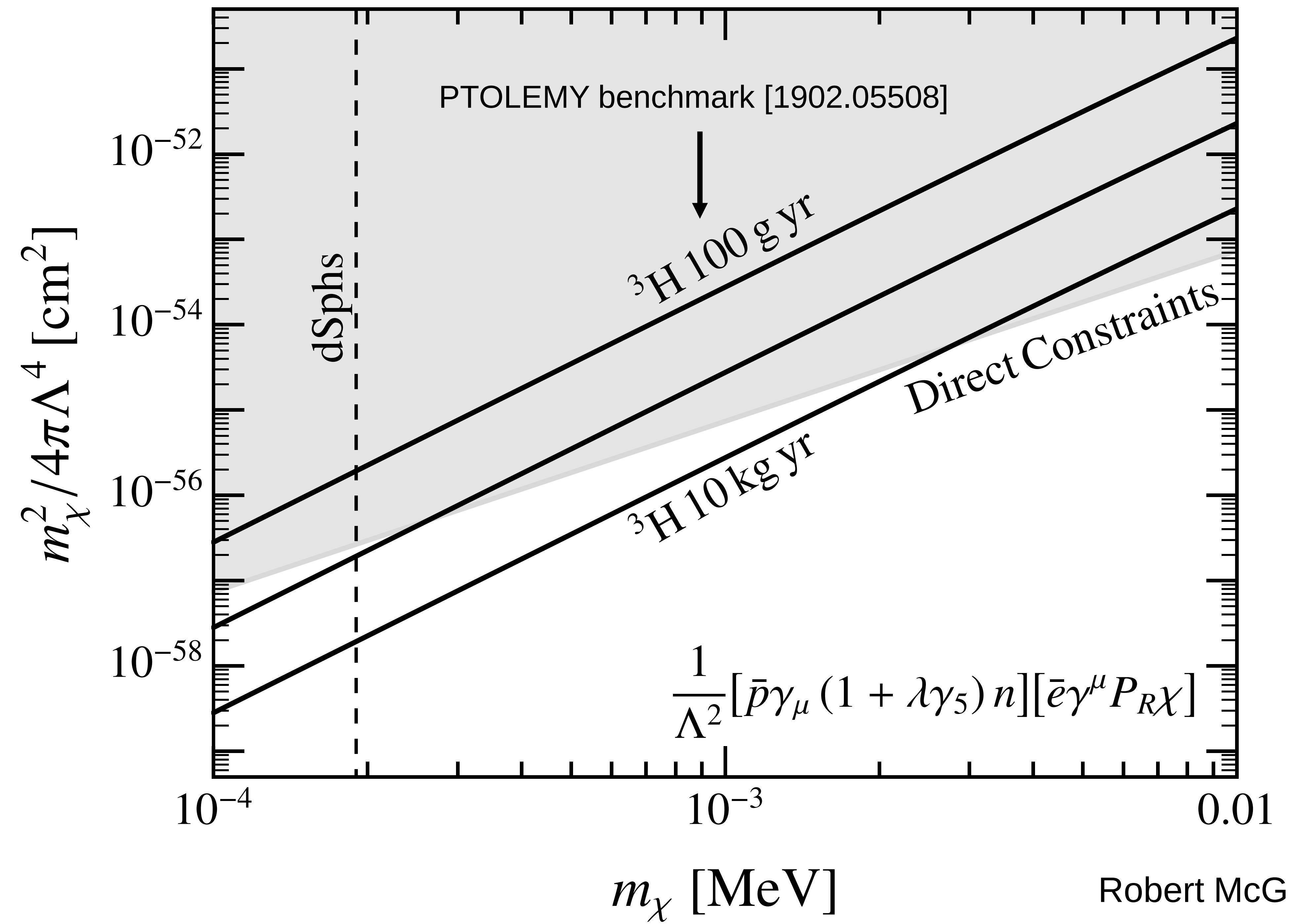
Large Experiments

Sufficient exposure *hard*

Best bet: tritium beta decay

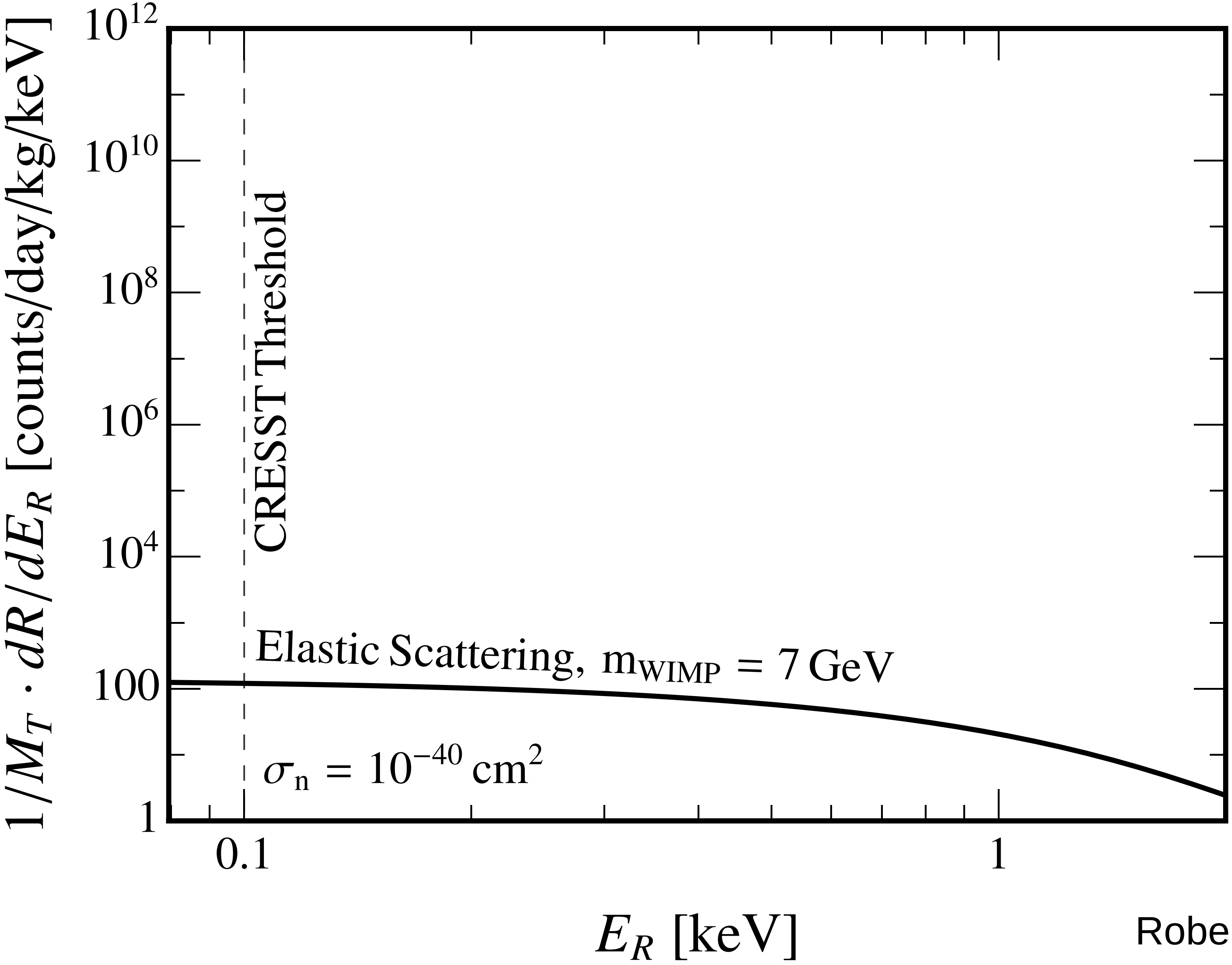


10^{-52}
10^{-54}
10^{-56}
10^{-58}
10^{-4}
10^{-3}
0.01
$m_\chi^2/4\pi\Lambda^4$ [cm^2]
m_χ [MeV]
dSphs
Savchenko, Rudakovskyi
[1903.01862]
Direct Constraints
$\frac{1}{\Lambda^2}[\bar{p}\gamma_\mu(1+\lambda\gamma_5)n][\bar{e}\gamma^\mu P_R\chi]$
Robert McGehee



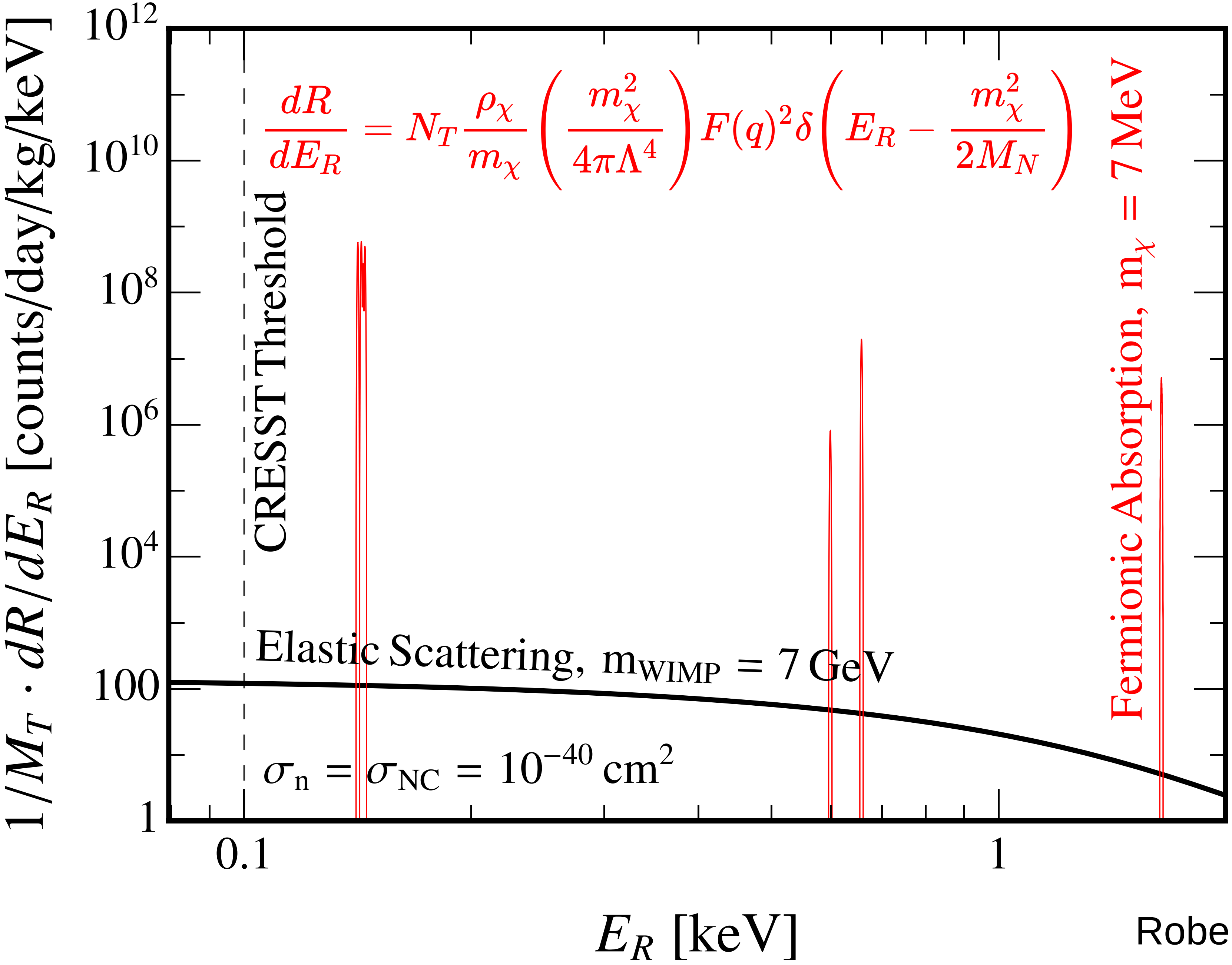
Robert McGehee

Scattering in CRESST



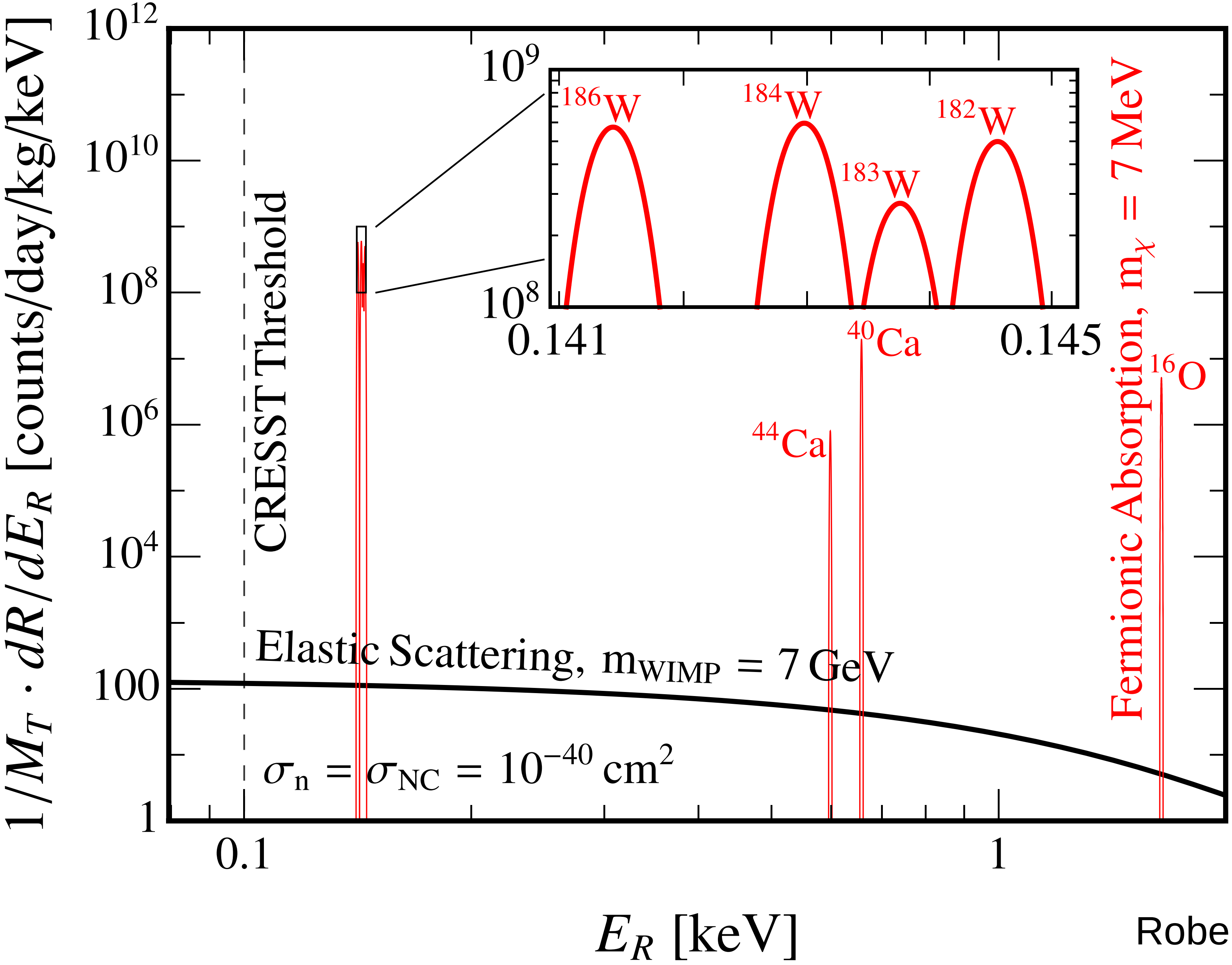
Robert McGehee

Scattering in CRESST

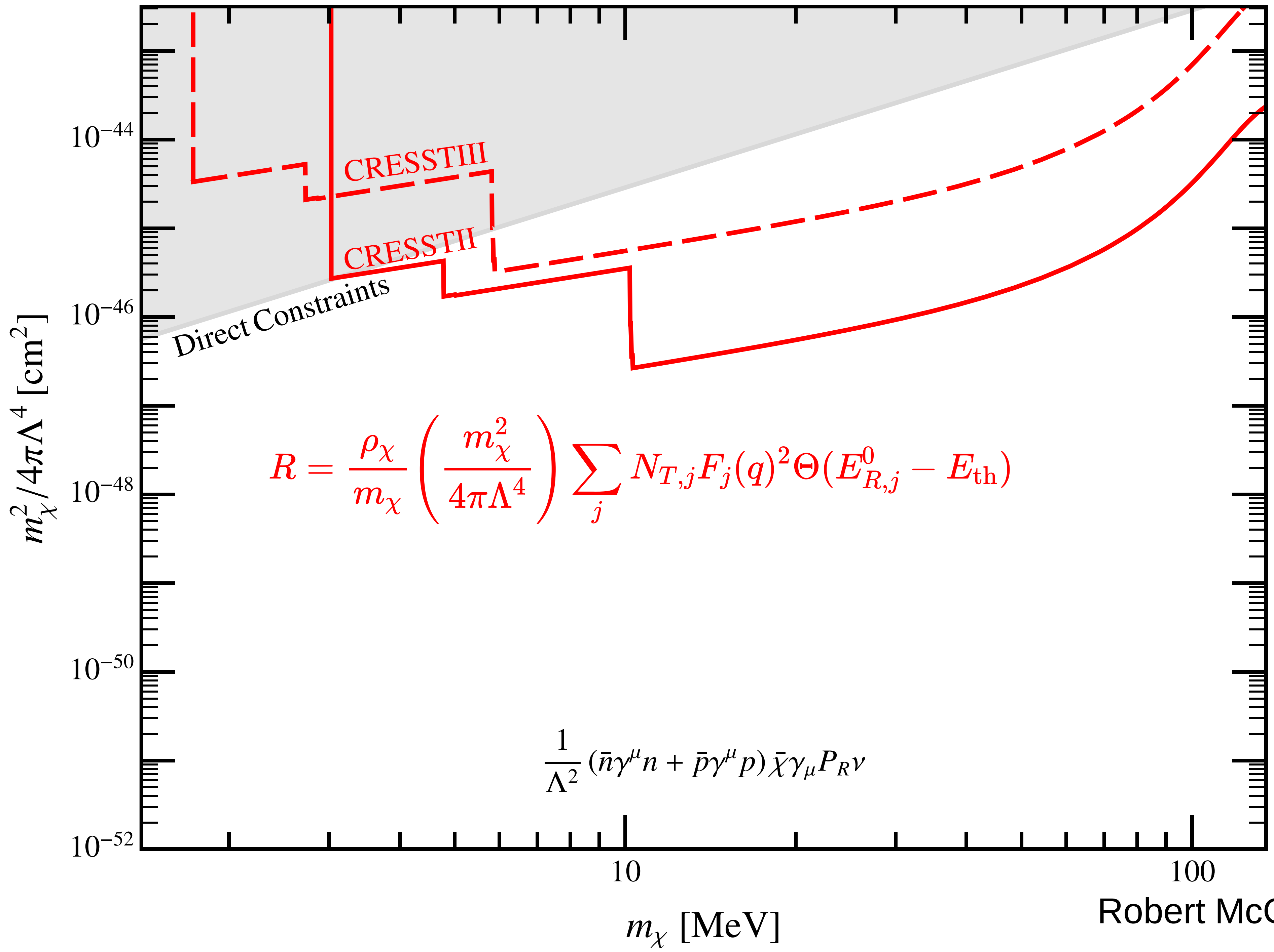


Robert McGehee

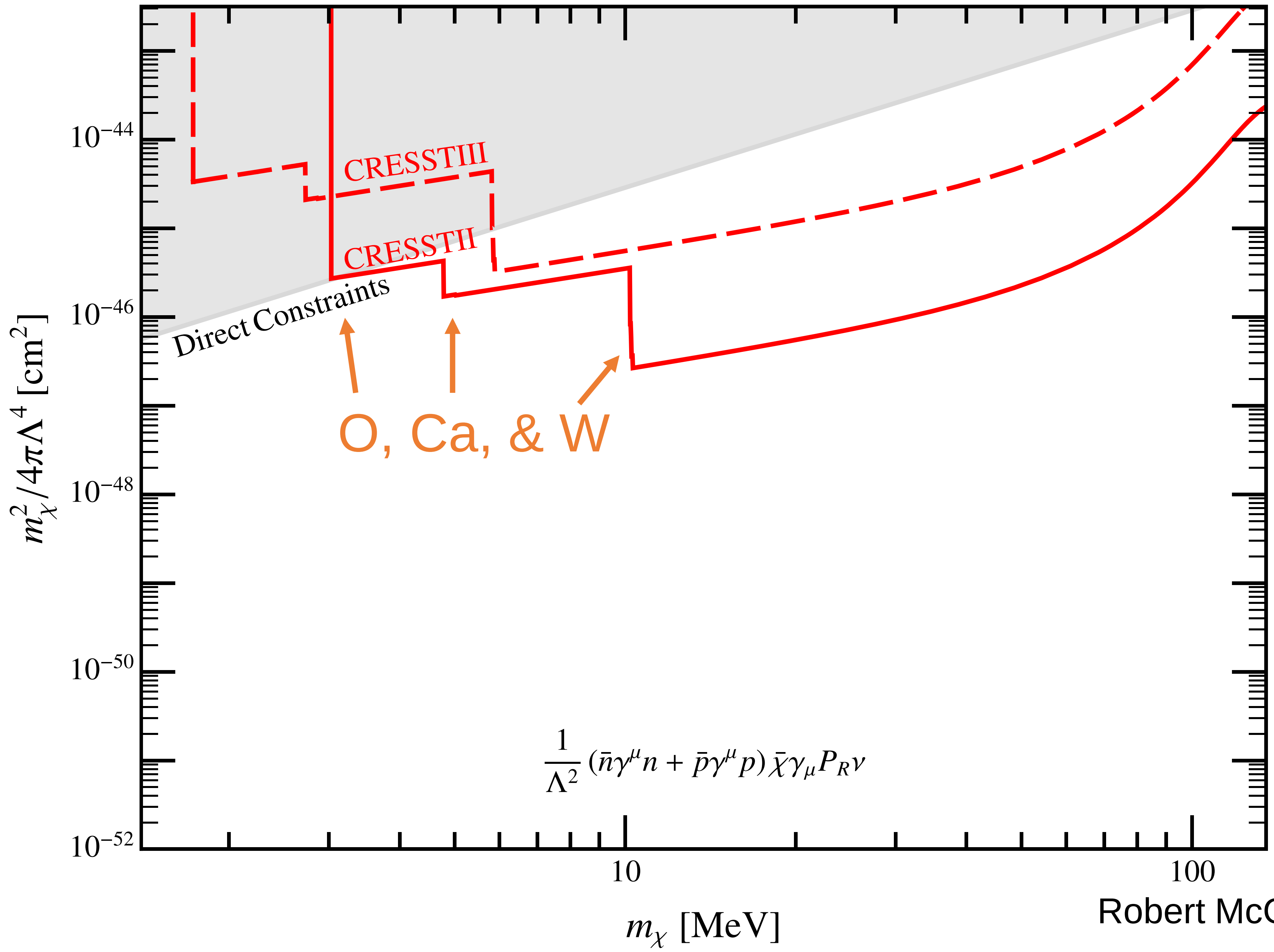
Scattering in CRESST



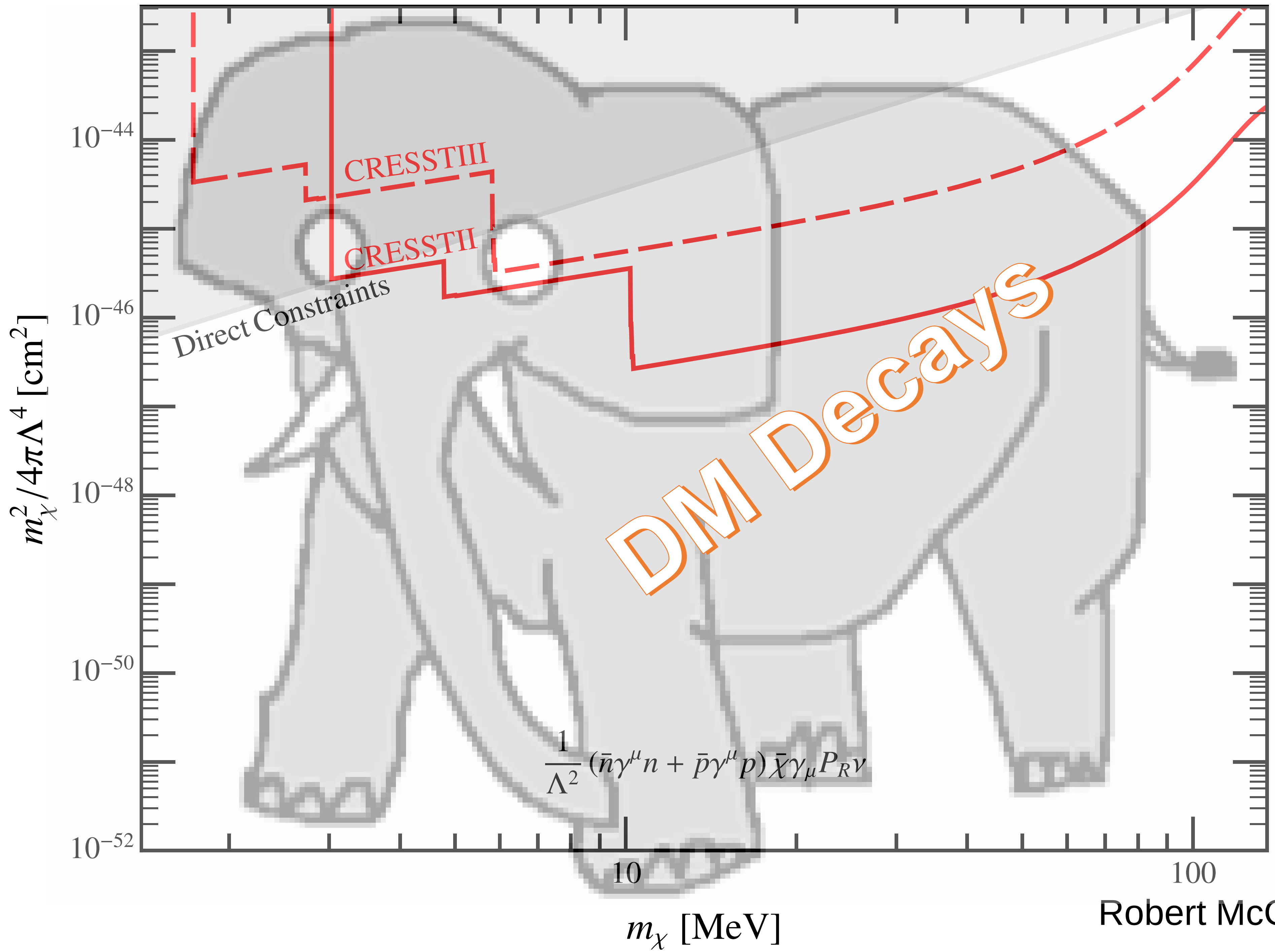
Robert McGehee



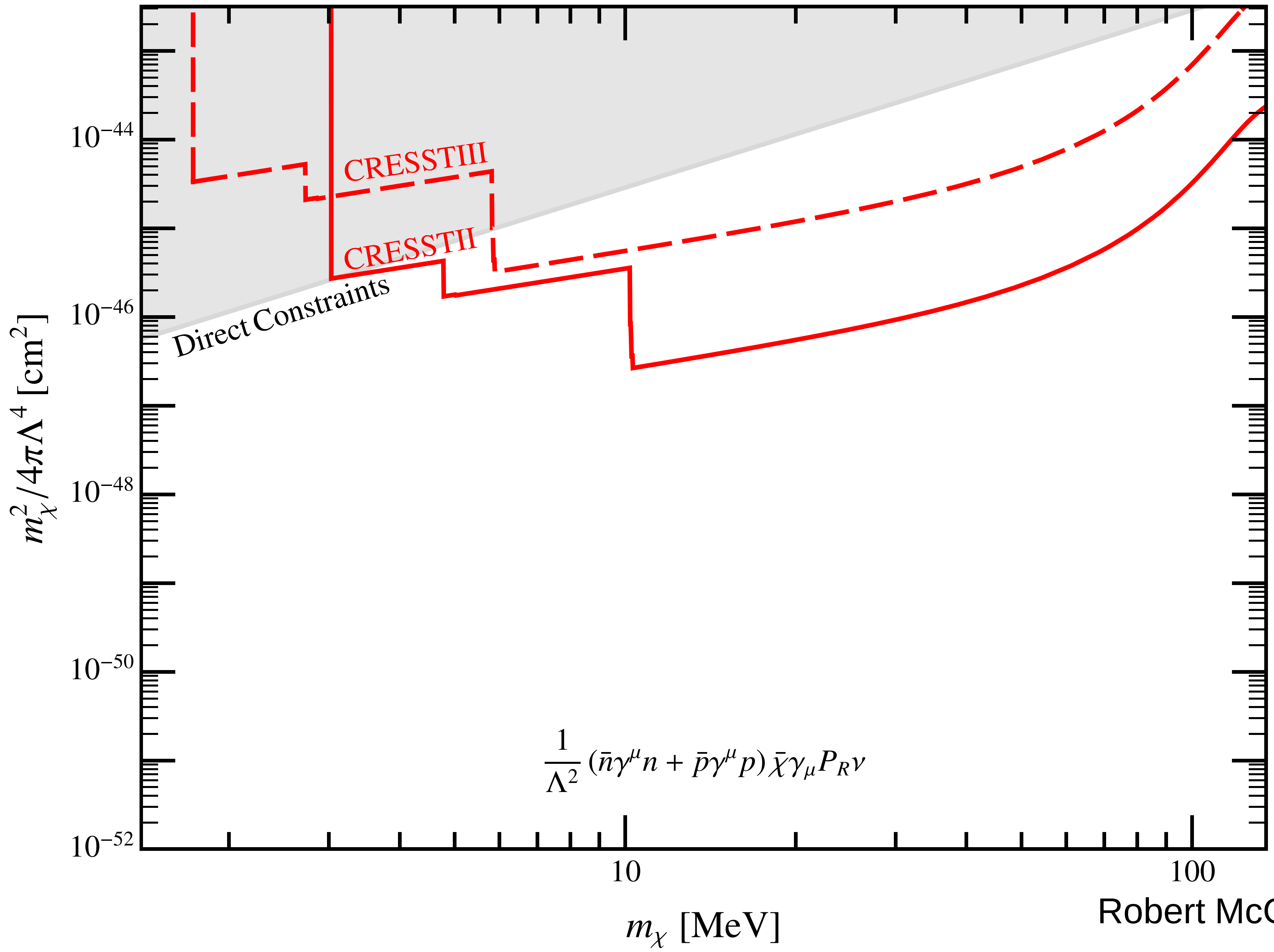
Robert McGehee



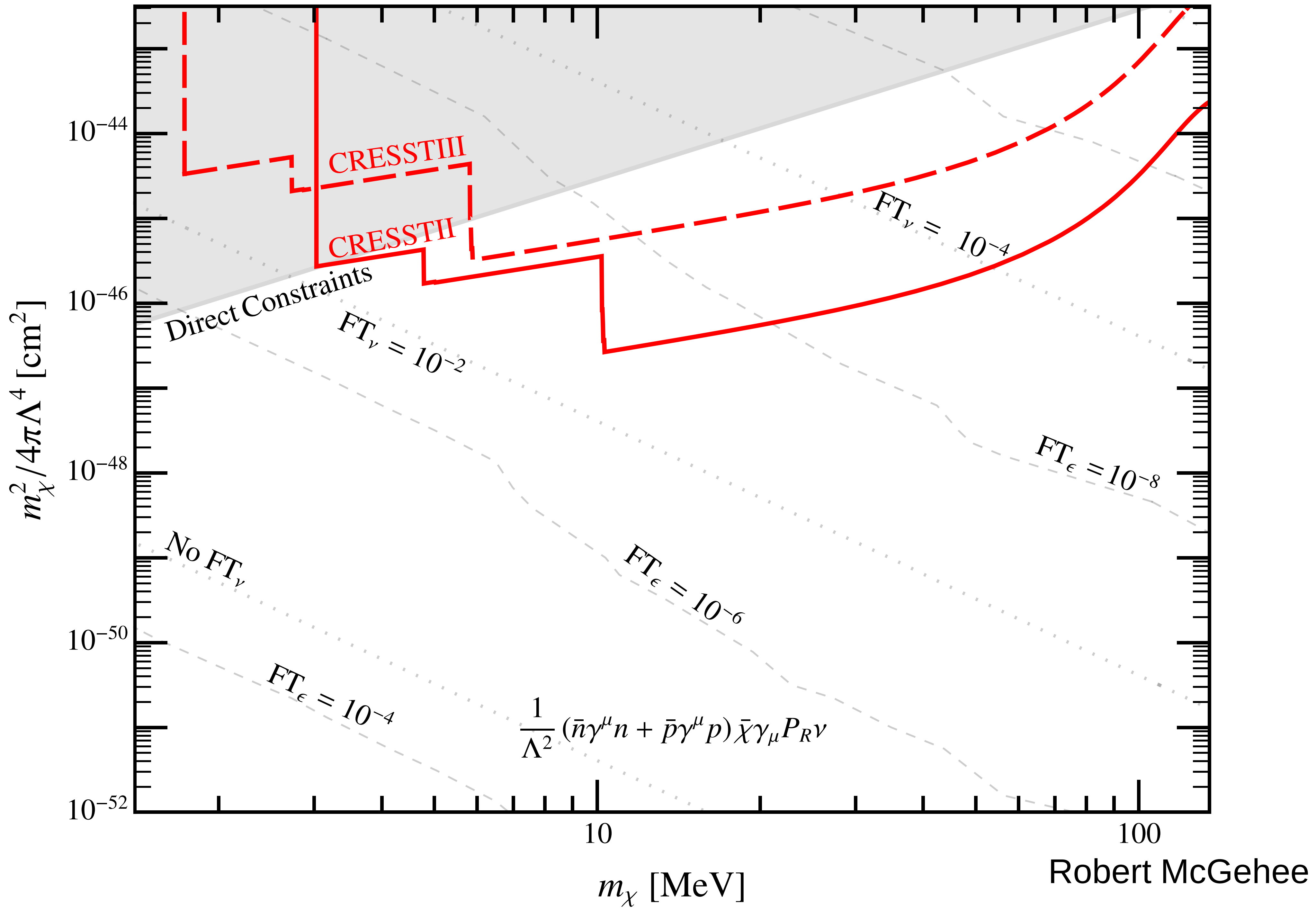
Robert McGehee



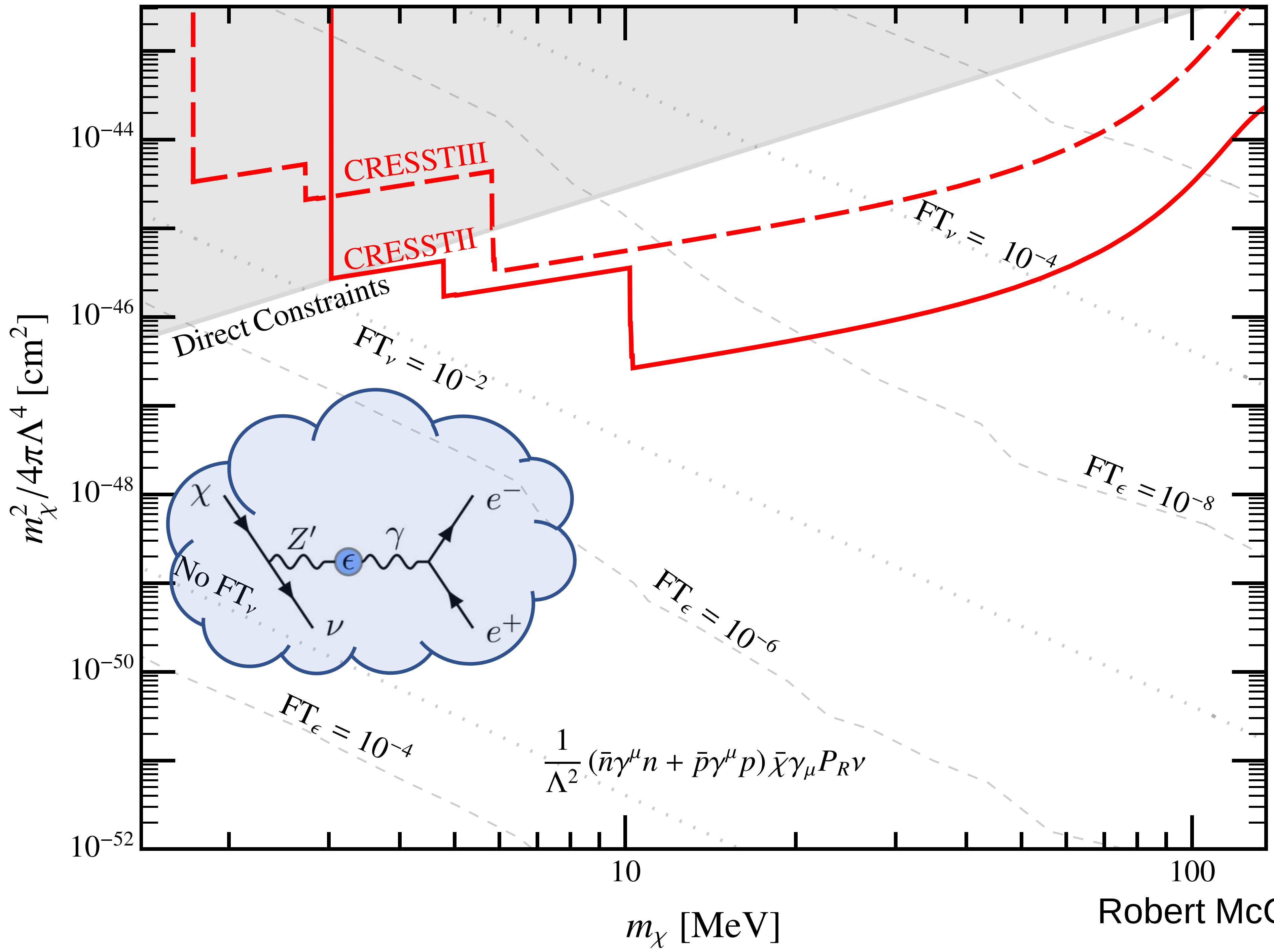
Robert McGehee



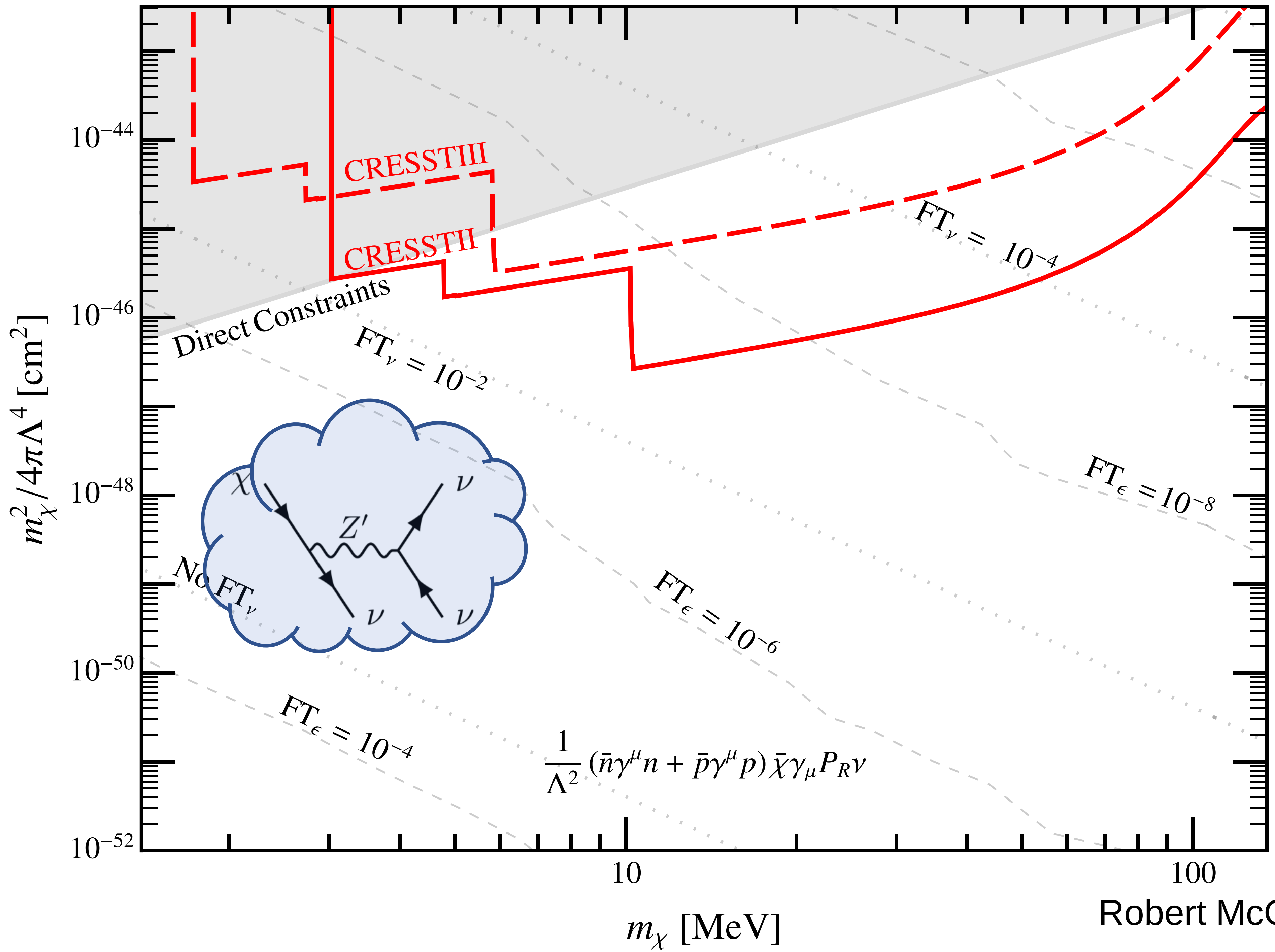
Robert McGehee



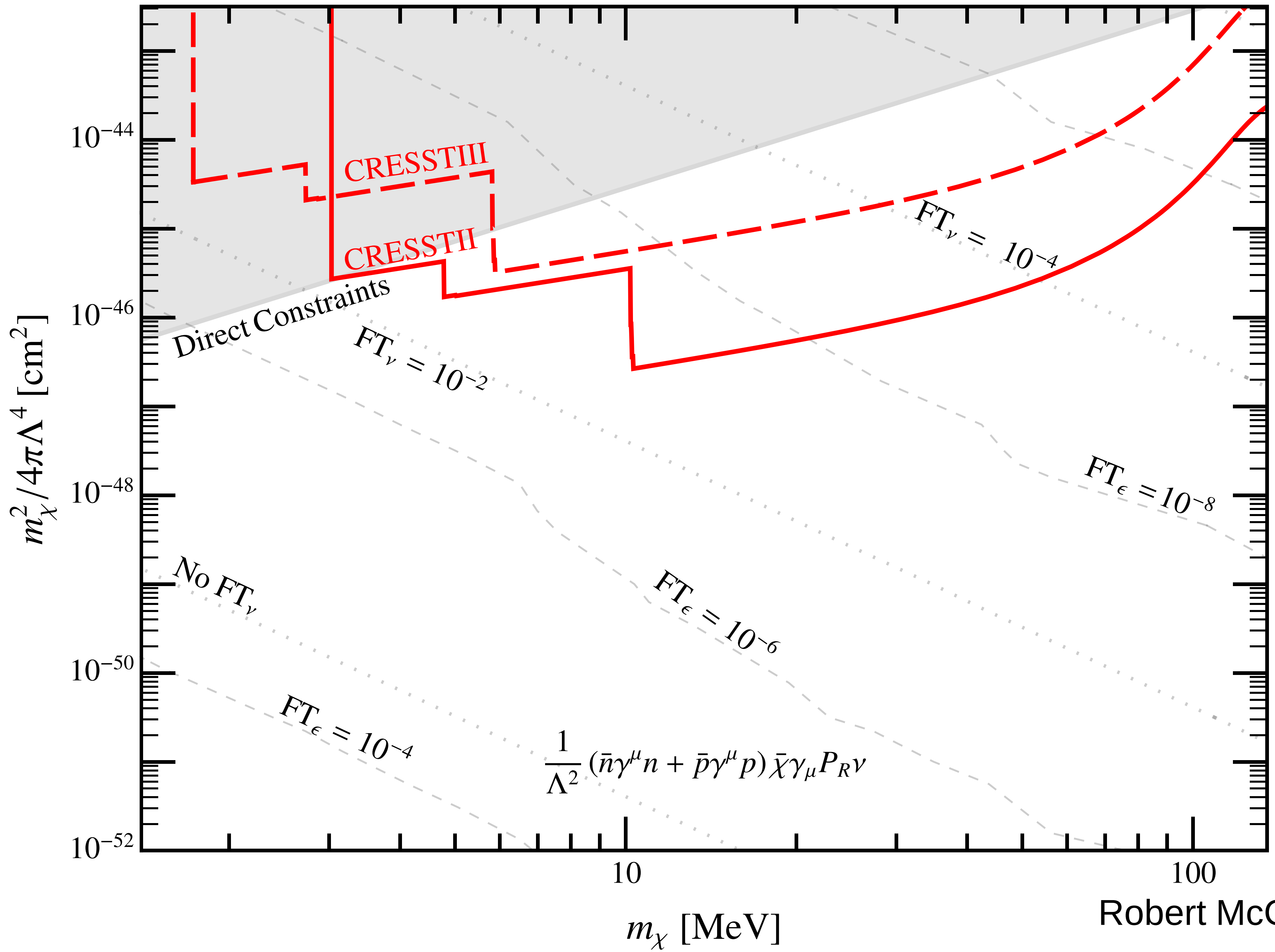
CRESSTIII
CRESSTII
Direct Constraints
$\mathrm{FT}_\nu = 10^{-2}$
$\mathrm{FT}_\nu = 10^{-4}$
$\mathrm{FT}_\epsilon = 10^{-8}$
$\mathrm{FT}_\epsilon = 10^{-6}$
No FT_ν
$\mathrm{FT}_\epsilon = 10^{-4}$
$\frac{1}{\Lambda^2}(\bar{n}\gamma^\mu n + \bar{p}\gamma^\mu p)\bar{\chi}\gamma_\mu P_R \nu$
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-52}
$m_\chi^2/4\pi\Lambda^4$ [cm^2]
10
100
m_χ [MeV]
Robert McGehee



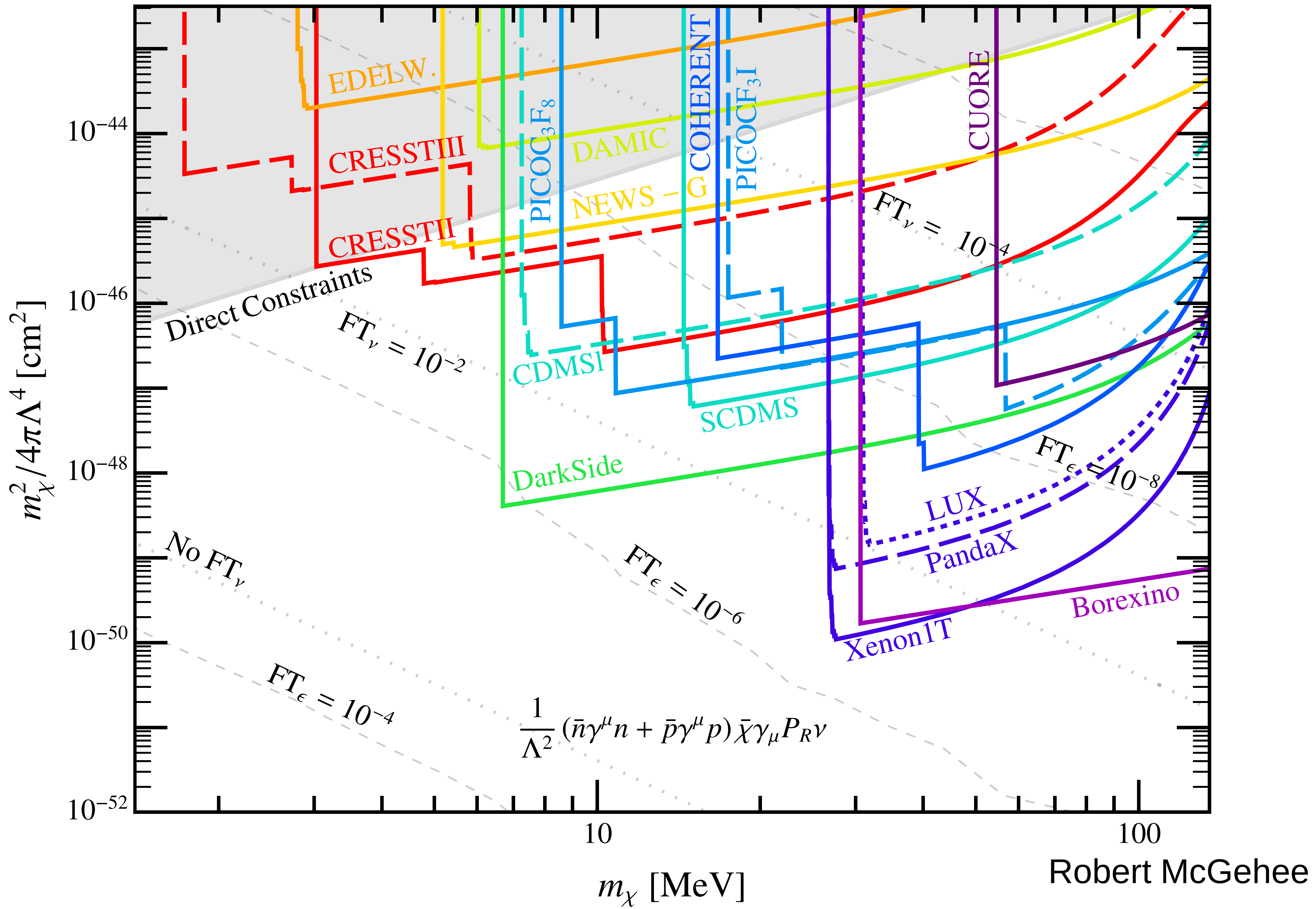
Robert McGehee



Robert McGehee



Robert McGehee



EDELW.
CRESSTIII
CRESSTII
Direct Constraints
PICOC$_3$F$_8$
DAMIC
NEWS − G
COHERENT
PICOCF$_3$I
CUORE
FT$_\nu$ = 10^{-4}
FT$_\nu$ = 10^{-2}
CDMSI
SCDMS
DarkSide
FT$_\epsilon$ = 10^{-8}
LUX
PandaX
No FT$_\nu$
FT$_\epsilon$ = 10^{-6}
Borexino
Xenon1T
FT$_\epsilon$ = 10^{-4}
$\frac{1}{\Lambda^2}(\bar{n}\gamma^\mu n + \bar{p}\gamma^\mu p)\bar{\chi}\gamma_\mu P_R \nu$
$m_\chi^2/4\pi\Lambda^4$ [cm^2]
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-52}
10
100
m_χ [MeV]
Robert McGehee