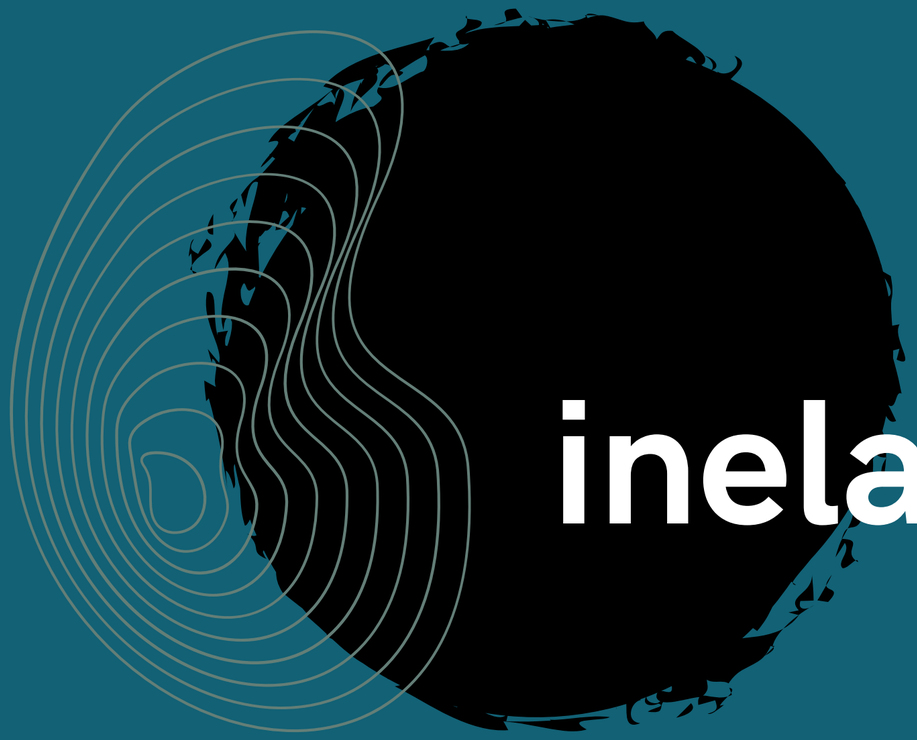


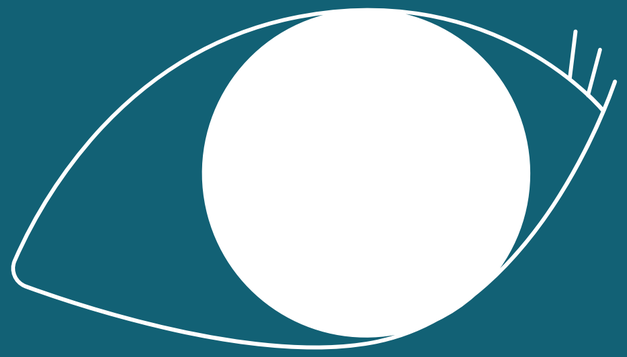
News directions in inelastic Dark Matter

arXiv:2405.08081 & arXiv:2411.02147
GDVG et al. GDVG

Giovani Dalla Valle Garcia, Felix Kahlhoefer,
Maksym Ovchynnikov and Thomas Schwetz

DAAD KIT KSETA HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

10.07.2025
EPS-HEP 2025



OUTLINE

introduction to
(inelastic) Dark Matter

a model to be searched:
not-so-inelastic Dark Matter
collider searches

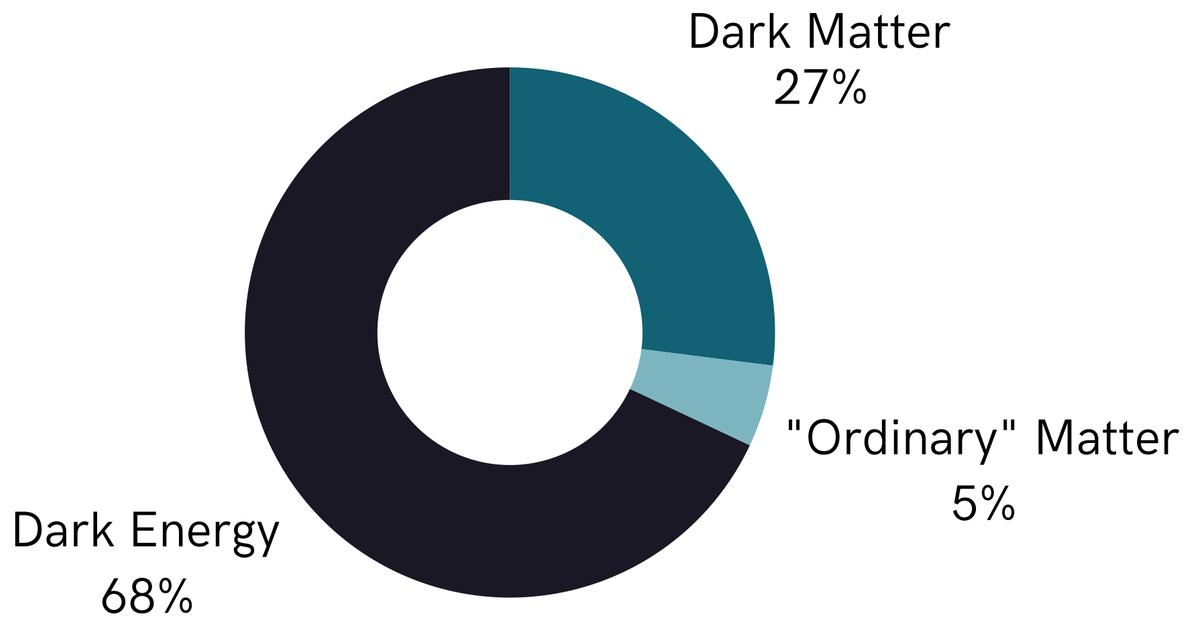
a simpler model:
minimal-inelastic Dark Matter

Conclusion

not-so-inelastic Dark Matter (niDM)

~~not-so-inelastic~~ Dark Matter (~~ni~~DM)

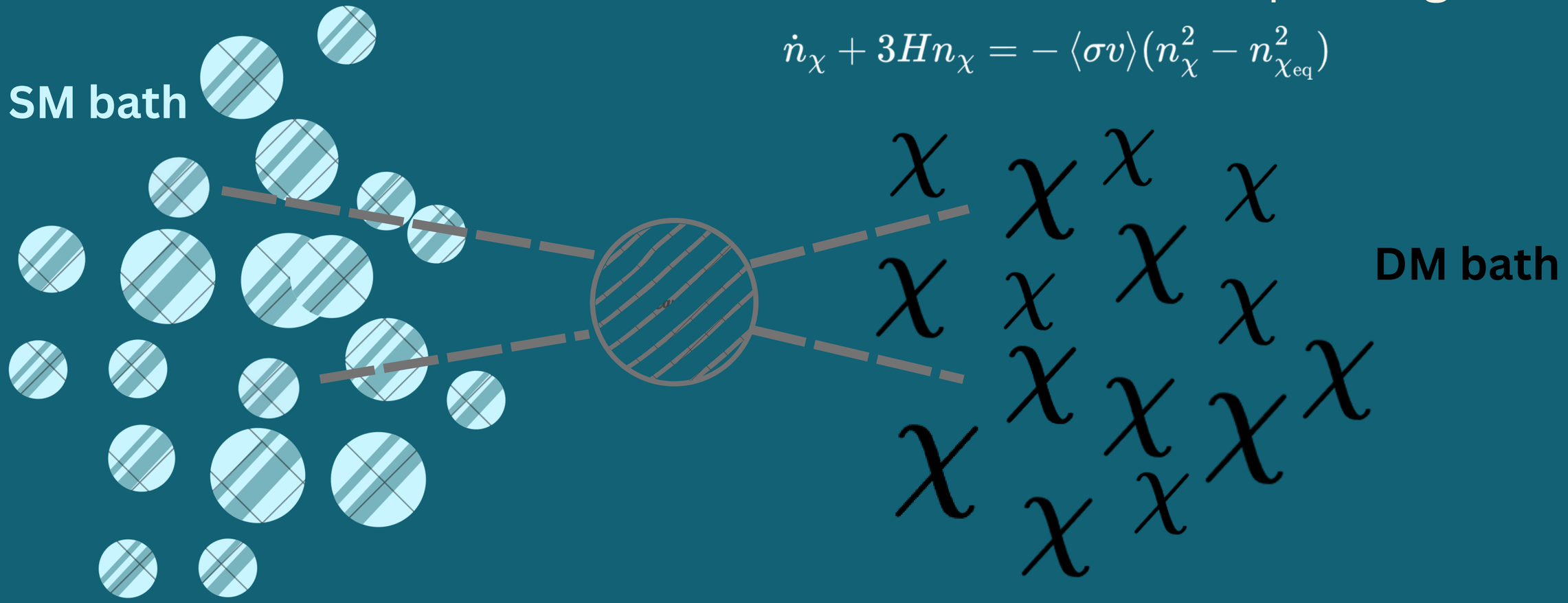
- **Most of the matter in the Universe**
- Non-baryonic
- Cold (structure formation)
- “Stable” (13.7 billion years)
- *Weak* interactions with SM particles
- **All evidences from gravity**



~~not-so-inelastic~~ Dark Matter (~~ni~~DM)

Freeze-out and the WIMPs paradigm

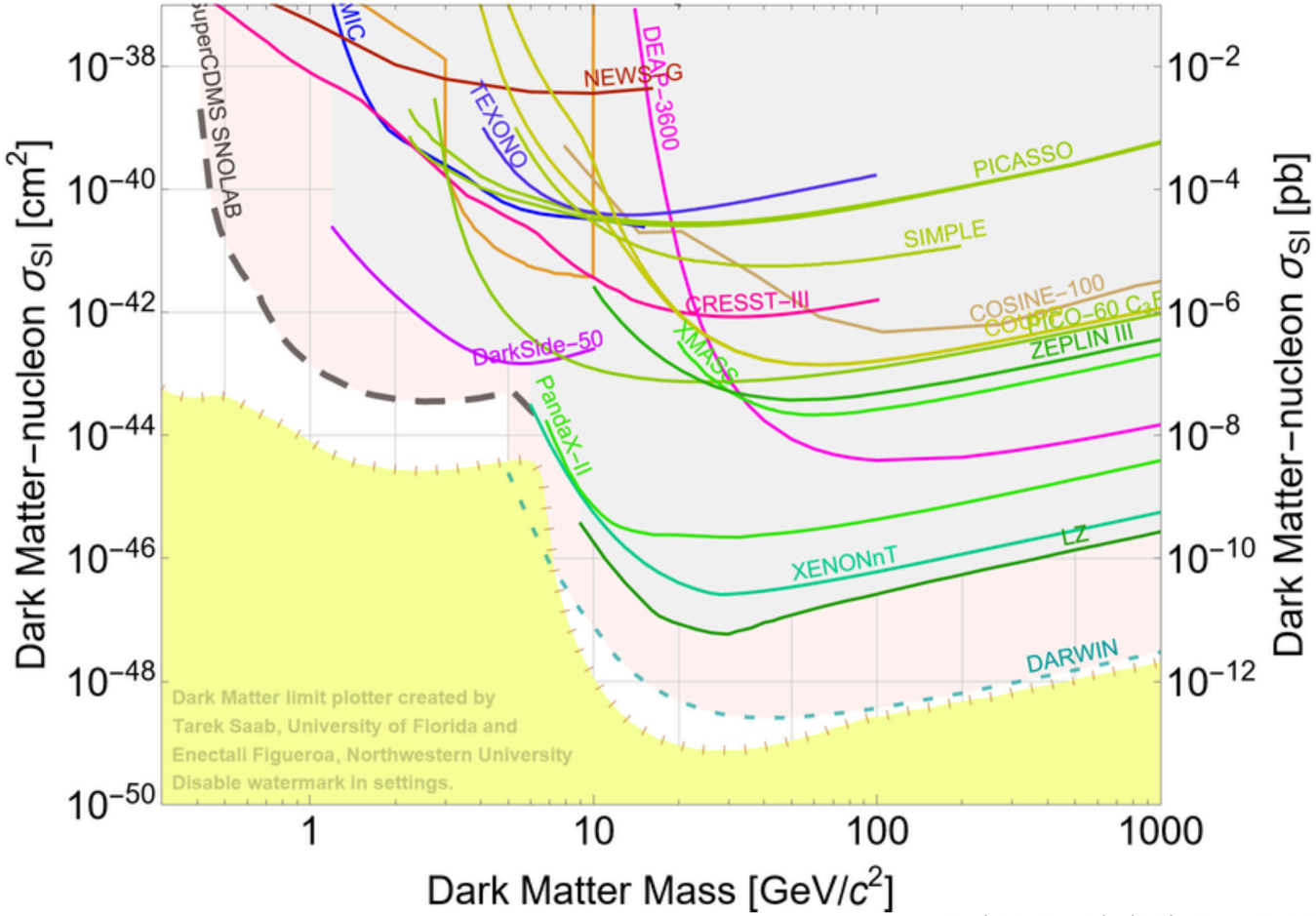
$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\chi_{\rm eq}}^2)$$



~~not-so-inelastic~~ Dark Matter (~~ni~~DM)

Direct detection

- Nuclear recoil
- Pushes DM to light masses

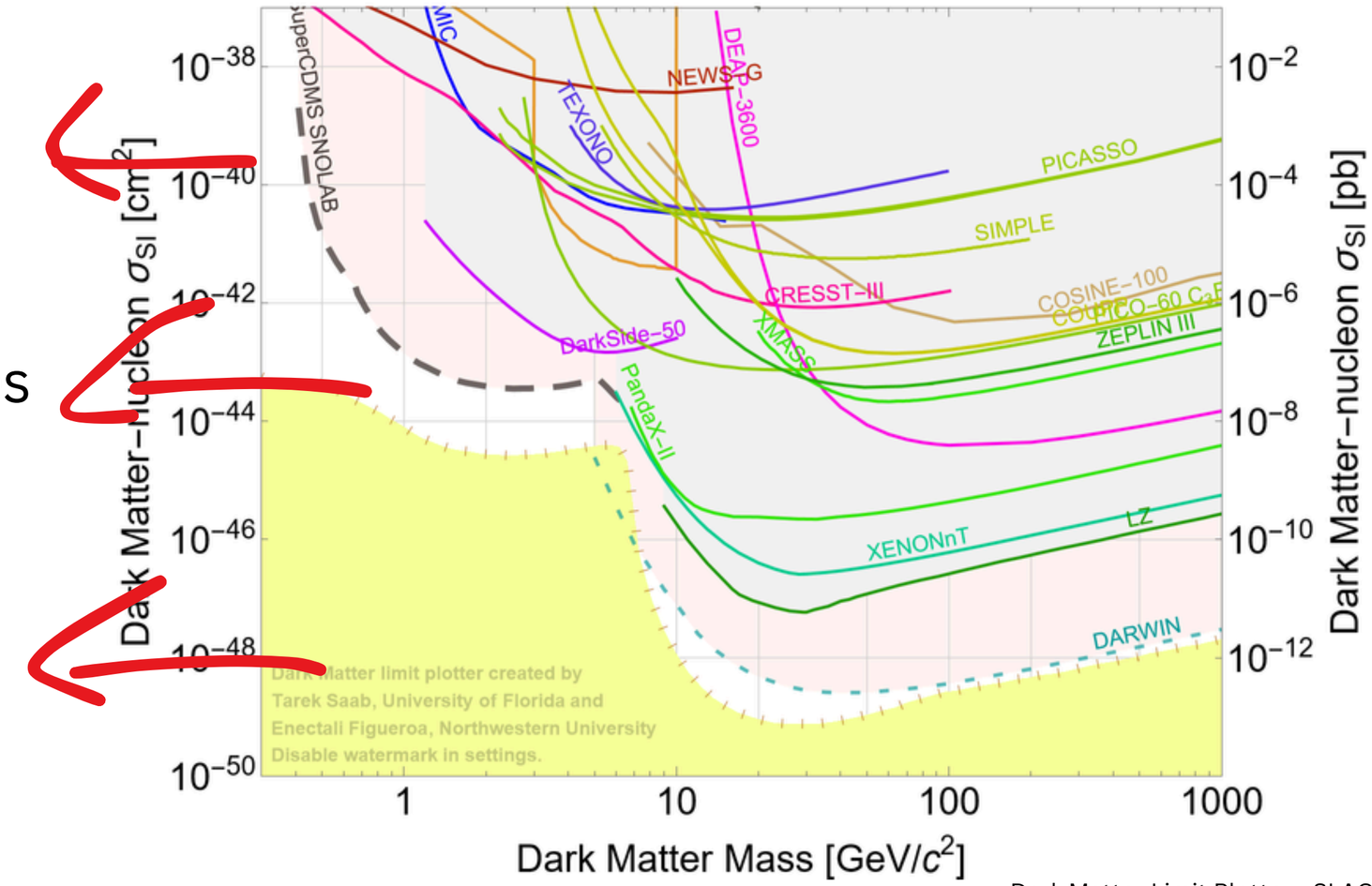


Dark Matter Limit Plotter - SLAC

~~not-so-inelastic~~ Dark Matter (~~ni~~DM)

Direct detection

- Nuclear recoil
- Pushes DM to light masses

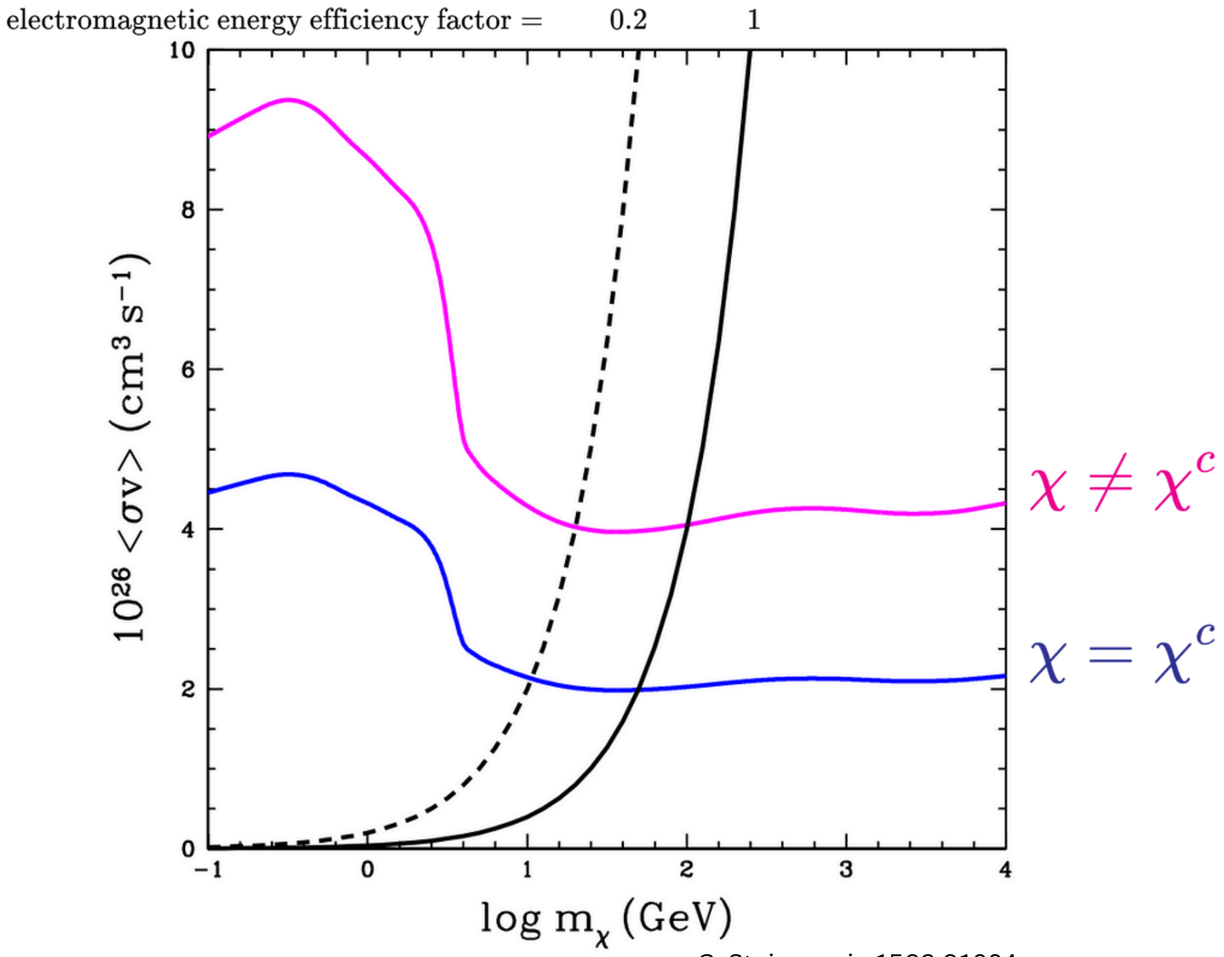


Dark Matter Limit Plotter - SLAC

~~not-so-inelastic~~ Dark Matter (~~ni~~DM)

Indirect detection

- cosmic microwave background
  - frequency
  - power spectrum
- Pushes DM to heavy masses



G. Steigman in 1502.01884

~~not-so-inelastic~~ Dark Matter (~~ni~~DM)

Indirect detection

- cosmic microwave background
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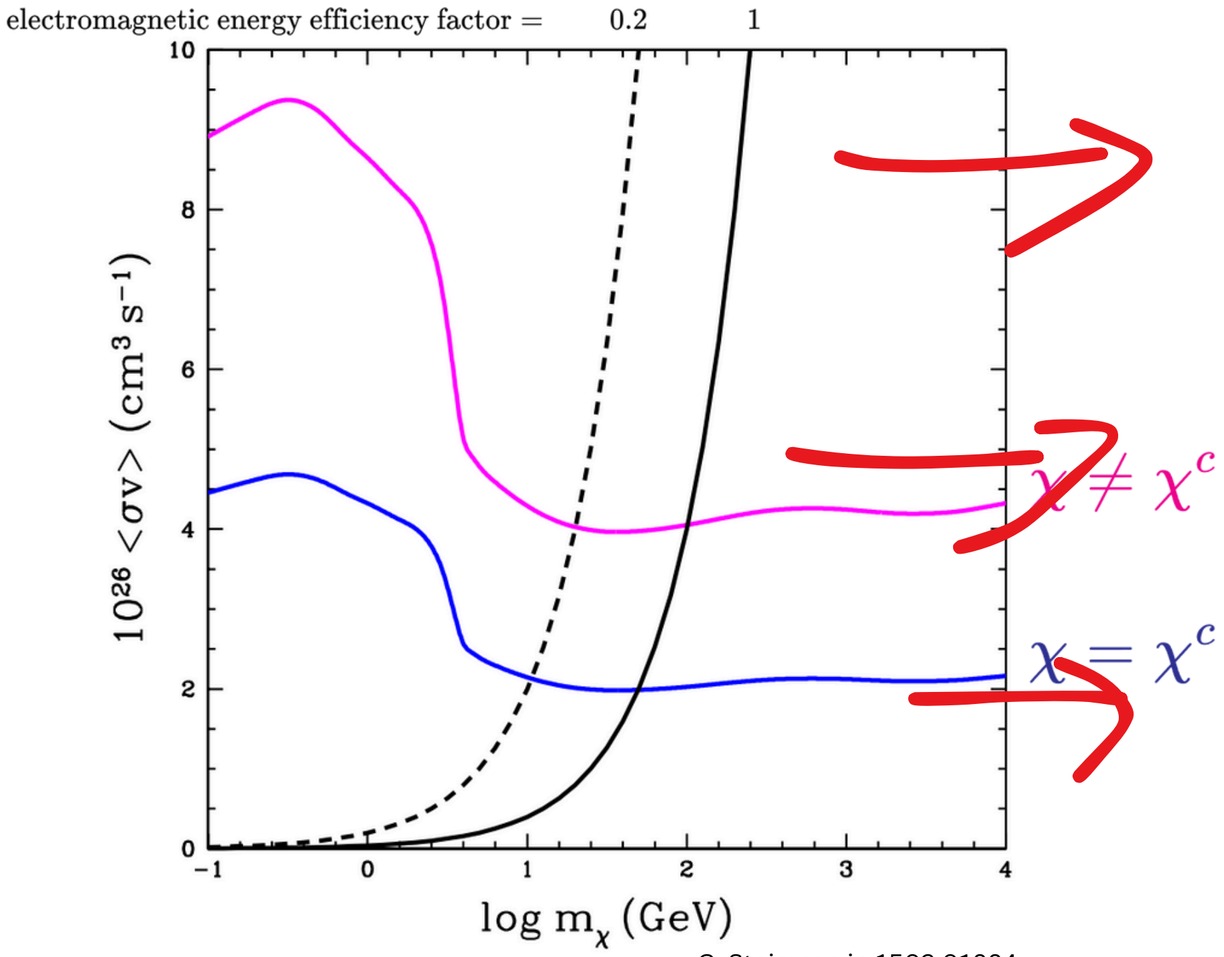


G. Steigman in 1502.01884

~~not-so~~ inelastic Dark Matter (niDM)

Indir

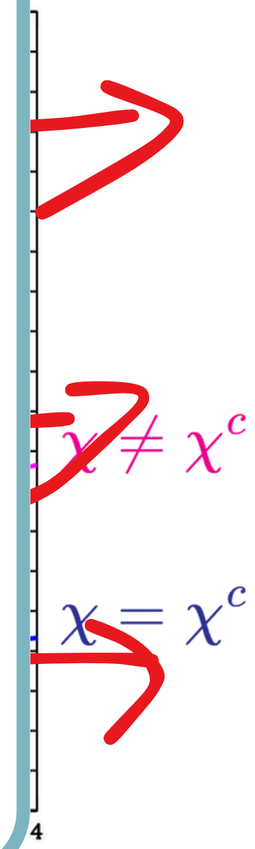
- co
- Pr

FEW OPTIONS

for thermal DM

- velocity-suppressed annihilating DM $\langle \sigma v \rangle \propto v^2$
- assymetric DM $\chi\bar{\chi} \to XX$
  - inelastic DM
  - coannihilating DM
- $\chi\chi \to \nu\nu$ or $\chi\chi \to XX(X \to \nu\nu)$

$$T_{\rm DM} \ll T_{\rm SM}$$



G. Steigman in 1502.01884

~~not so~~ inelastic Dark Matter (~~ni~~DM)

Basic principles

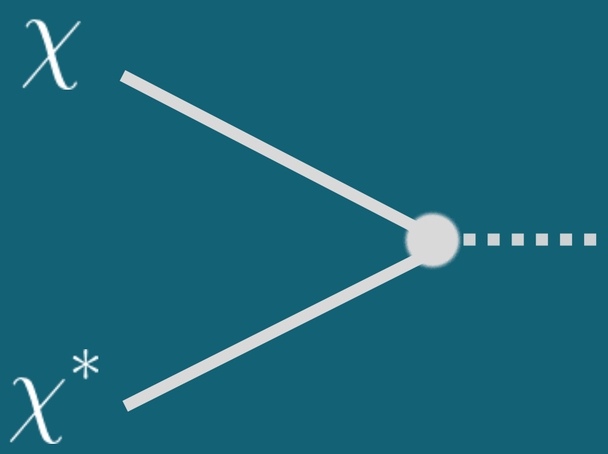
dark matter states with only off-diagonal couplings

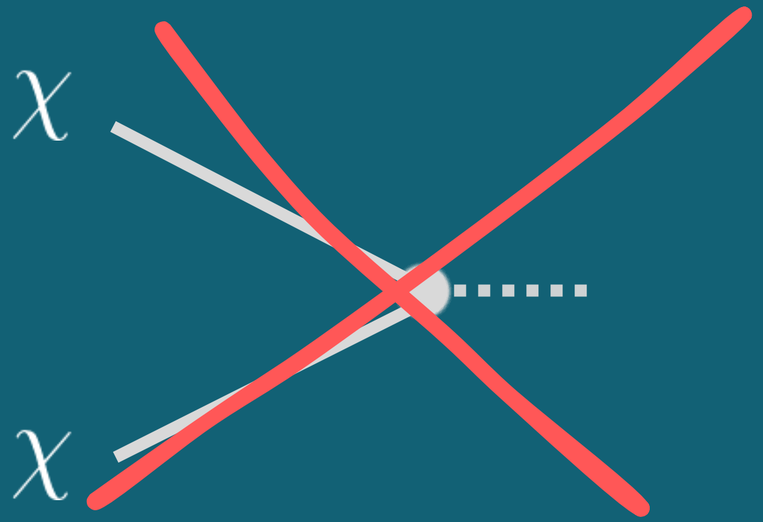
Two DM states

$$\chi \quad \chi^*$$

with a mass splitting

$$\frac{m_{\chi^*} - m_\chi}{m_\chi} = \Delta_m$$





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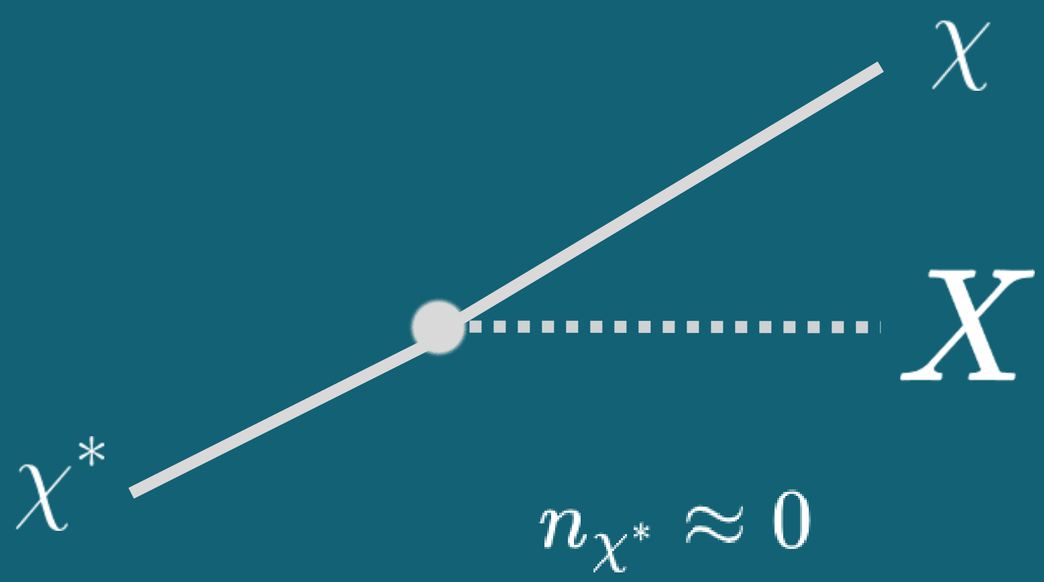

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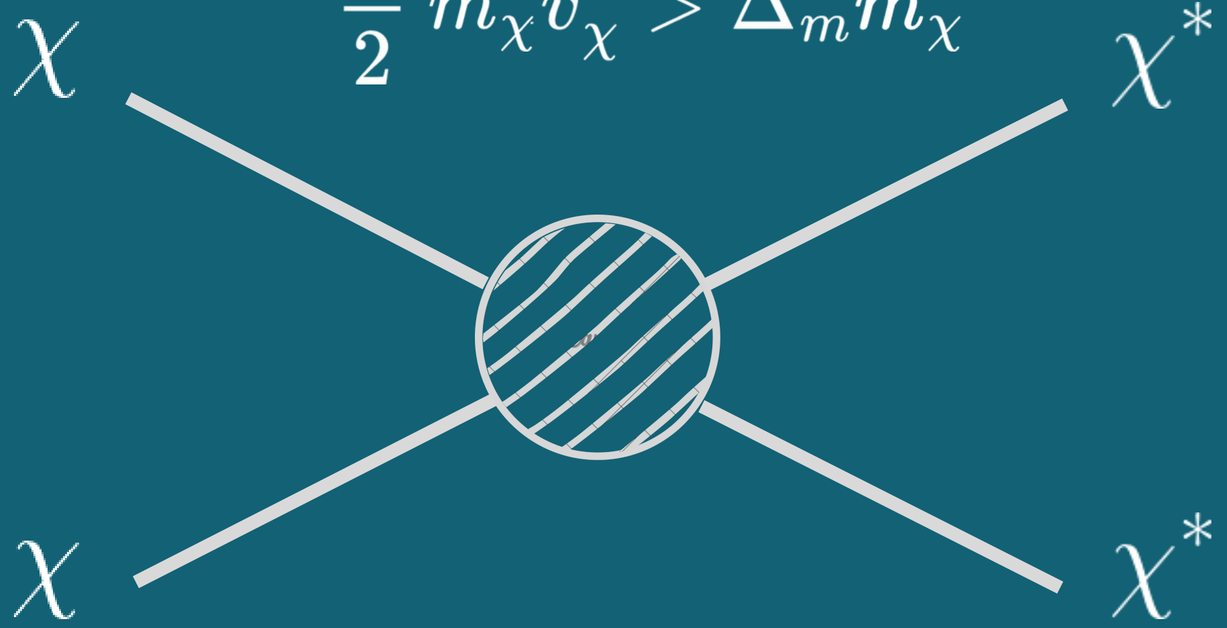
Indirect Detection

$$\frac{1}{2} m_\chi v_\chi^2 > \Delta_m m_\chi$$



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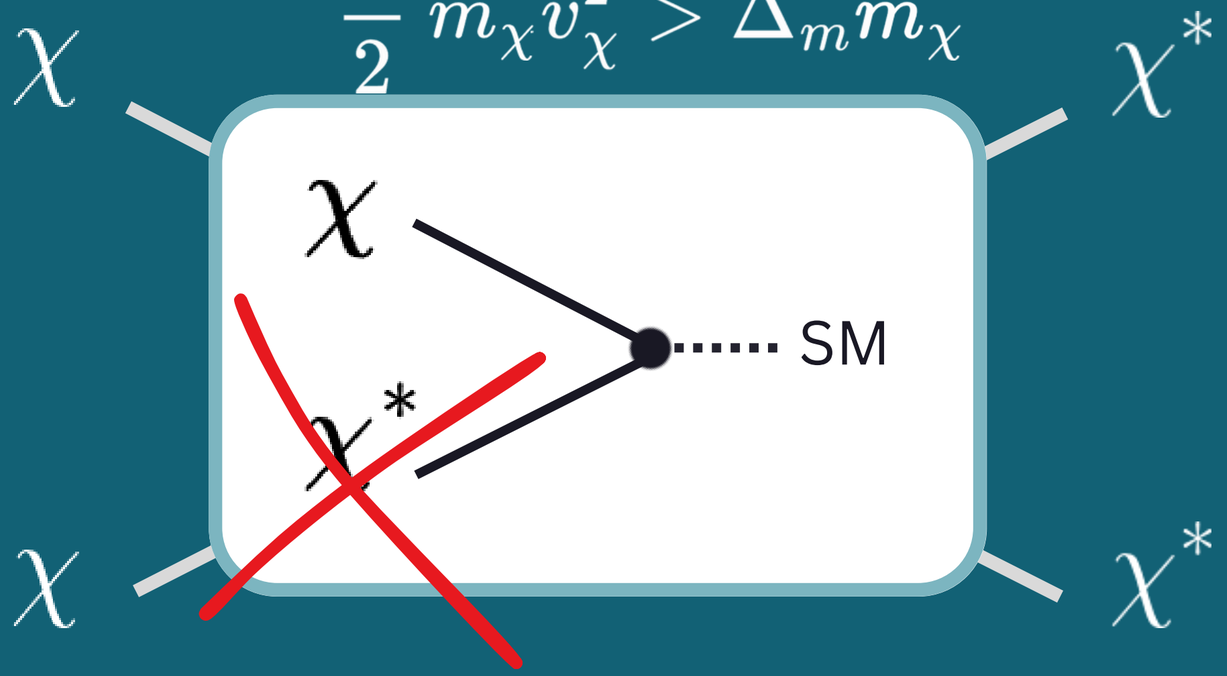


~~not so~~ inelastic Dark Matter (~~ni~~DM)

Two DM states

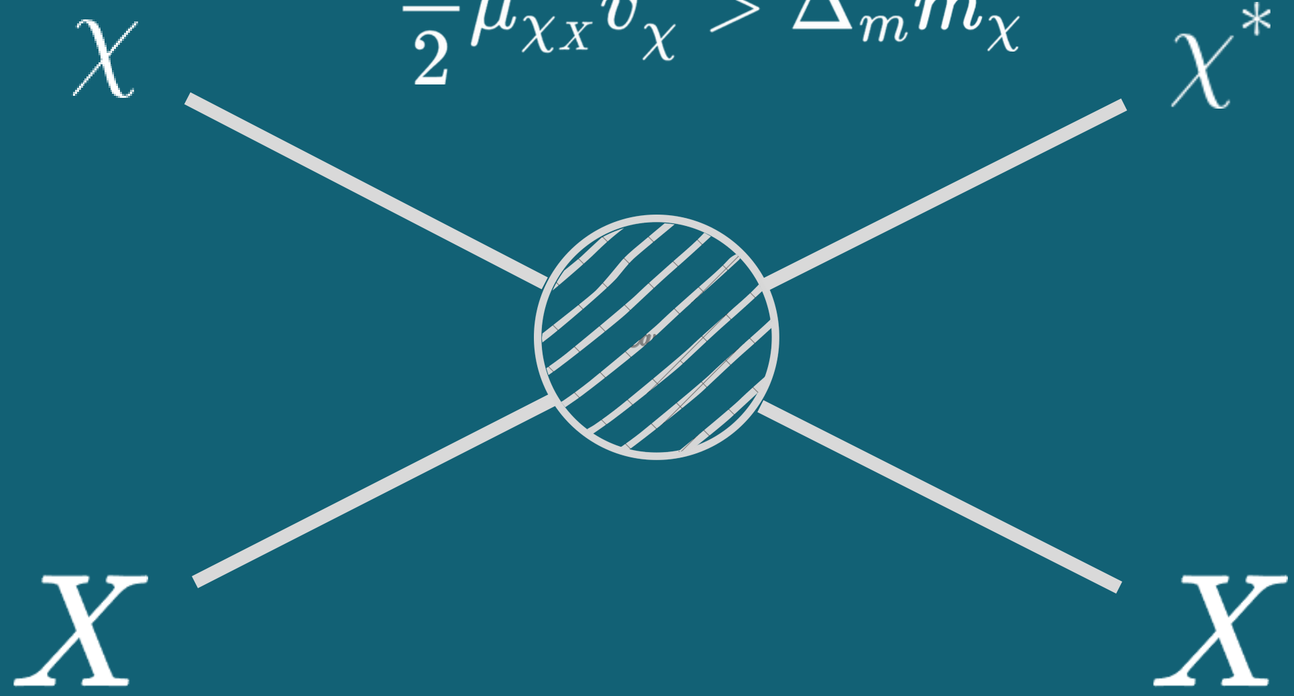
$$\chi \quad \chi^*$$

with a mass splitting

$$\frac{m_{\chi^*} - m_\chi}{m_\chi} = \Delta_m$$

Direct Detection

$$\frac{1}{2}\mu_{\chi X} v_\chi^2 > \Delta_m m_\chi$$

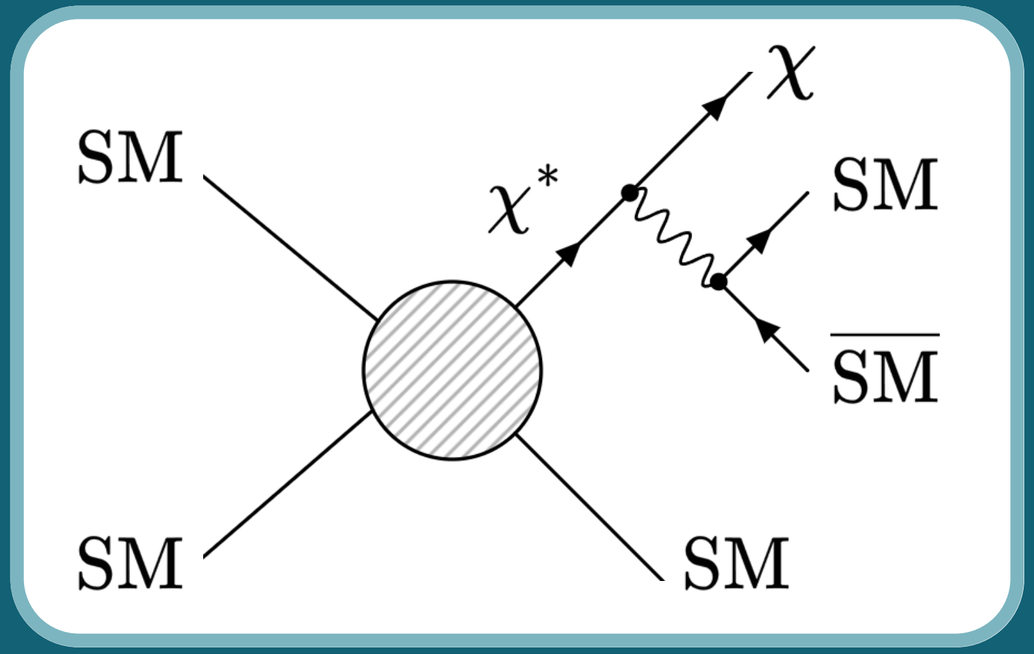


~~not so~~ inelastic Dark Matter (~~ni~~DM)

A sub-GeV DM candidate

Non-trivial dark sector $\Longrightarrow$

- long-lived particles
- new signatures: displaced vertices



not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Dirac Fermion DM

$\chi = \chi_L + \chi_R$

NEW FORCE: $U'(1)$

a Dark Photon

A'

SSB: $V(H')$

Dark Higgs

H'

$$\mathcal{L}_\chi^I \supset ie' A'_\mu \bar{\chi} \gamma^\mu \chi \quad - \quad H' \bar{\chi^c} (y_L P_L \chi + y_R P_R) \chi$$

not-so-inelastic Dark Matter (niDM)

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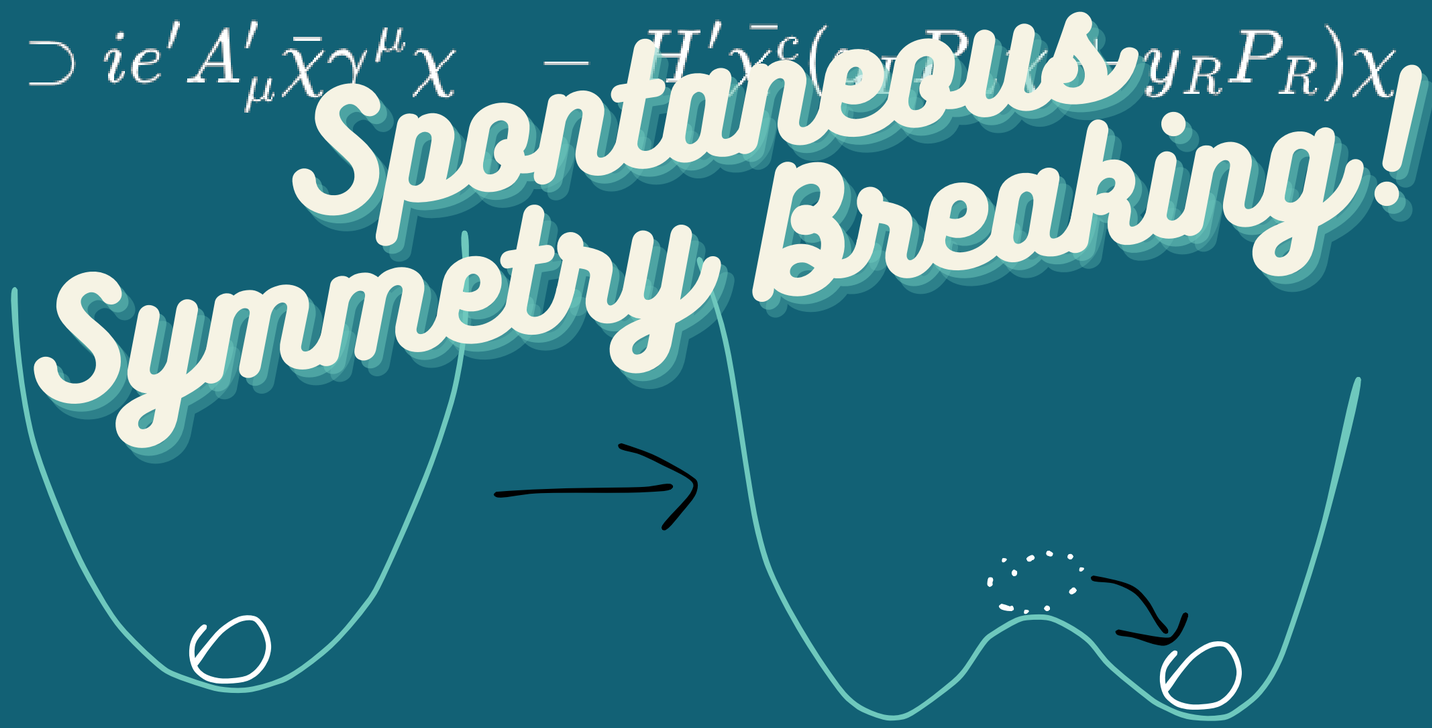

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a massive Dark Photon

$$A'$$

SSB: $V(H')$

Dark Higgs

$$h'$$

$$\mathcal{L}_\chi^I \supset ie' A'_\mu \bar{\chi} \gamma^\mu \chi - (h' + w)\bar{\chi}^c (y_L P_L \chi + y_R P_R)\chi$$

$$\mathcal{L}_\chi \supset -m_D^* \bar{\chi}_L \chi_R - \frac{1}{2} m_L \bar{\chi}_L^c \chi_L - \frac{1}{2} m_R \bar{\chi}_R^c \chi_R$$

$$\Psi = \begin{pmatrix} \chi_L \\ \chi_R^c \end{pmatrix} \qquad M_\chi = \begin{pmatrix} y_L w & m_D/2 \\ m_D/2 & y_R w \end{pmatrix}$$

requires a mass diagonalization $\Psi \to \Psi' = U^\dagger \Psi$

not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: ~~$U(1)$~~

a massive Dark Photon

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Dark Higgs

h'

$$\mathcal{L}_\chi^I \supset e' A'^\mu \, \bar{\chi}_i (i\alpha_{ij} + \beta_{ij}\gamma^5)\gamma_\mu \chi_j - y_L h' \, \bar{\chi}_i (\hat{\alpha}_{ij} + i\hat{\beta}_{ij}\gamma^5)\chi_j$$

LIKE WEAK INTERACTIONS

$Q, d_R, u_R \to Q', d'_R, u'_R$ and $U^\dagger \leftrightarrow V_{\rm CKM}$

flavor changing interactions

not-so-inelastic Dark Matter (niDM)

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: ~~$U(1)$~~

a massive Dark Photon

A'

SSB: ~~$V(H')$~~

Dark Higgs

~~h'~~

a simple UV-complete sub-GeV WIMP model

$$\mathcal{L}_\chi^I \supset e' A'^\mu \bar{\chi}_i (i\alpha_{ij} + \beta_{ij}\gamma^5)\gamma_\mu \chi_j - y_L h' \bar{\chi}_i (\hat{\alpha}_{ij} + i\hat{\beta}_{ij}\gamma^5)\chi_j$$

sub-GeV DM masses

$$e, \mu, \pi, K, p, n, \ldots$$

$$m_{h'} > m_{A'}, m_{\chi^{(*)}}$$

see later...

not-so-inelastic Dark Matter (niDM)

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $U'(1)$

a massive Dark Photon

A'

a simple UV-complete sub-GeV WIMP model

$$\Delta_m \equiv \frac{m_{\chi^*} - m_\chi}{m_\chi}$$

$$\delta_y \equiv \frac{y_R - y_L}{y_L} = \frac{m_R - m_L}{m_L}$$

Parity breaking

not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$$\chi \quad \chi^*$$

NEW FORCE: $U'(1)$

a massive Dark Photon

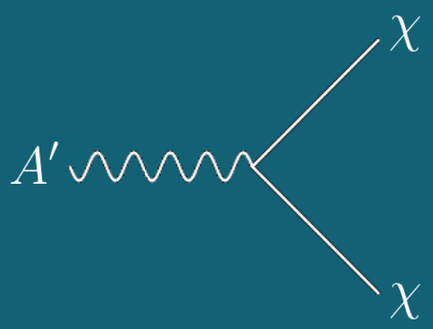
$$A'$$

Parameters

$$m_{\chi^*} = (1 + \Delta_m) m_\chi$$

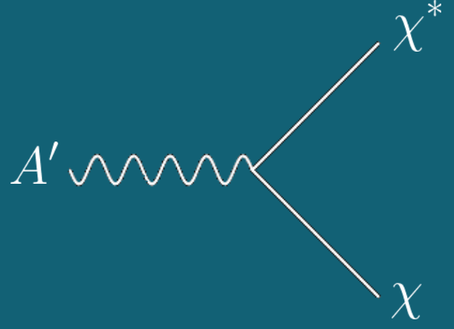
$$m_R = (1 + \delta_y) m_L$$

elastic



$$\alpha'_{\text{el}} = \alpha' \cos^2 2\theta$$

inelastic



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not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

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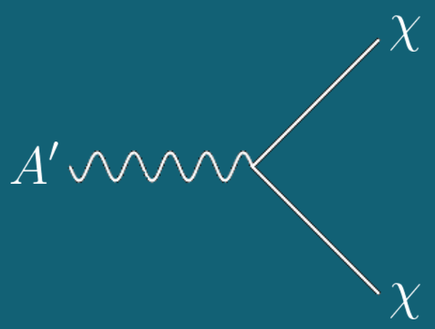

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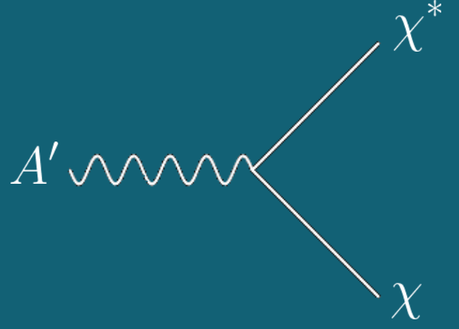
inelastic



$\alpha'_{\text{inel}} = \alpha' \sin^2 2\theta$

$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

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Parameters

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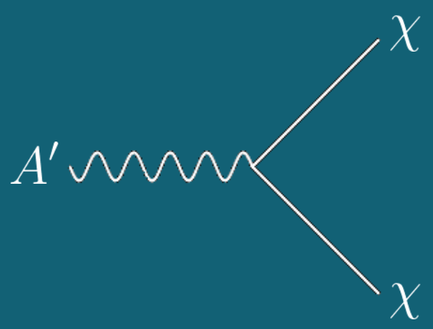
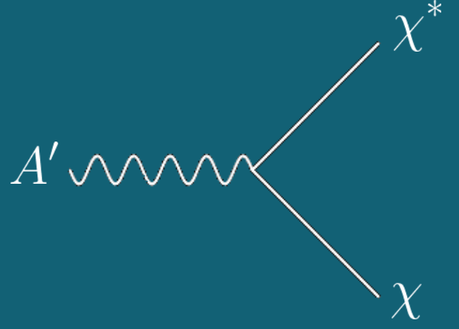
elastic



$\alpha'_{\rm el} = \alpha' \cos^2 2\theta$

inelastic



$\alpha'_{\rm inel} = \alpha' \sin^2 2\theta$

$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

iDM: $\delta_y = 0$

not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

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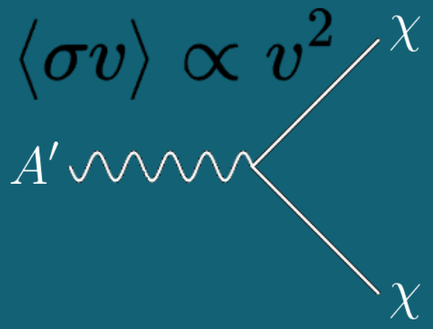
elastic

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



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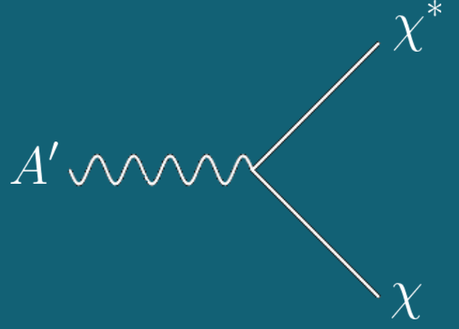
inelastic



$\alpha'_{\rm inel} = \alpha' \sin^2 2\theta$

$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

iDM: $\delta_y = 0$

niDM: $\delta_y \neq 0$

not-so-inelastic Dark Matter (niDM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$$\chi \quad \chi^*$$

NEW FORCE: $U'(1)$

a massive Dark Photon

$$A'$$

Parameters

$$m_{\chi^*} = (1 + \Delta_m) m_\chi$$

$$m_R = (1 + \delta_y) m_L$$

$$Q'^{\mathrm{SM}} = -\epsilon Q_{\mathrm{em}}$$

not-so-inelastic Dark Matter (niDM)

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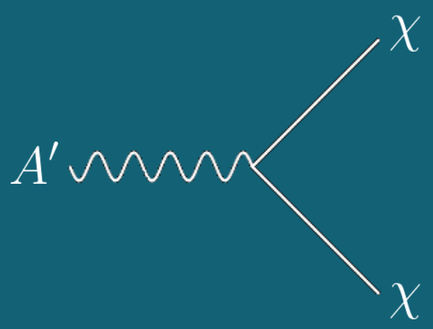

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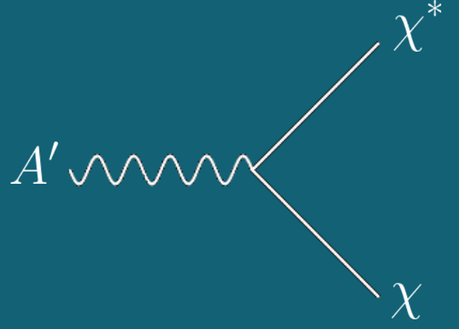
inelastic



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$$\cos 2\theta = -\frac{\delta_y \Delta_m}{(2 + \delta_y)(2 + \Delta_m)}$$

SM-DM mediation

iDM: $\delta_y = 0$

niDM: $\delta_y \neq 0$

not-so-inelastic Dark Matter (niDM)

Majora

model

NEV

a mas

DM
ation

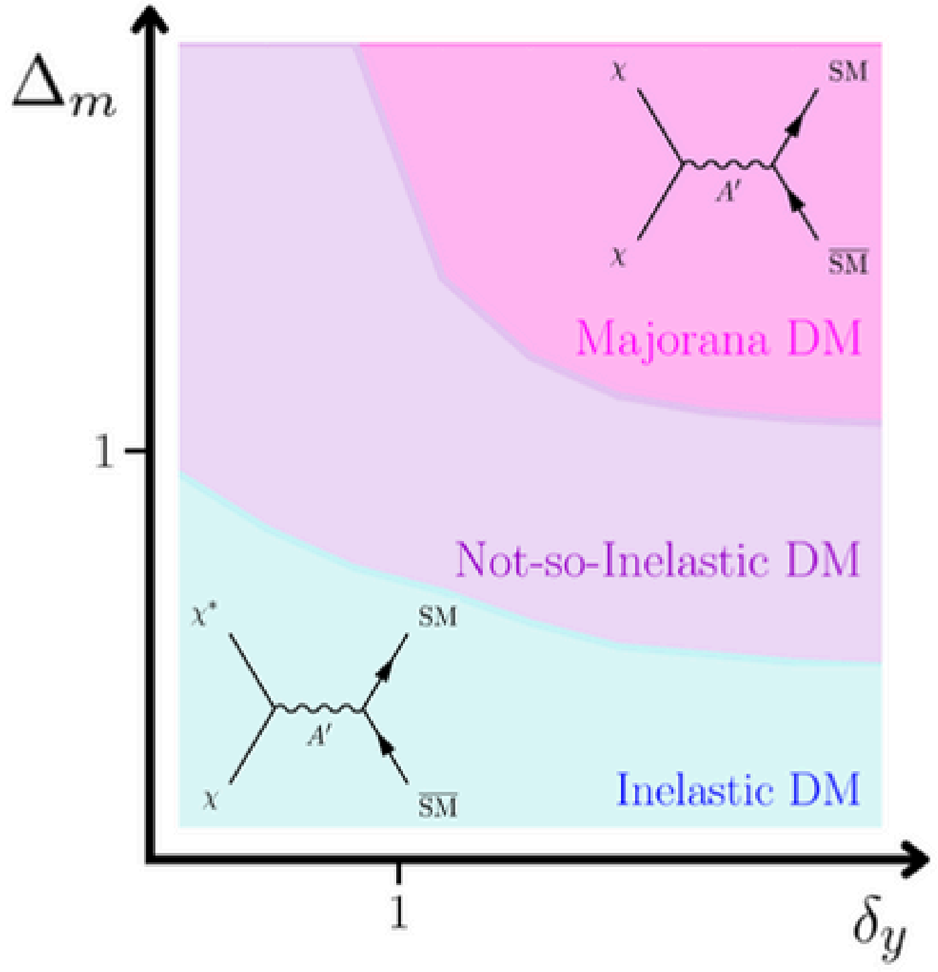
A'

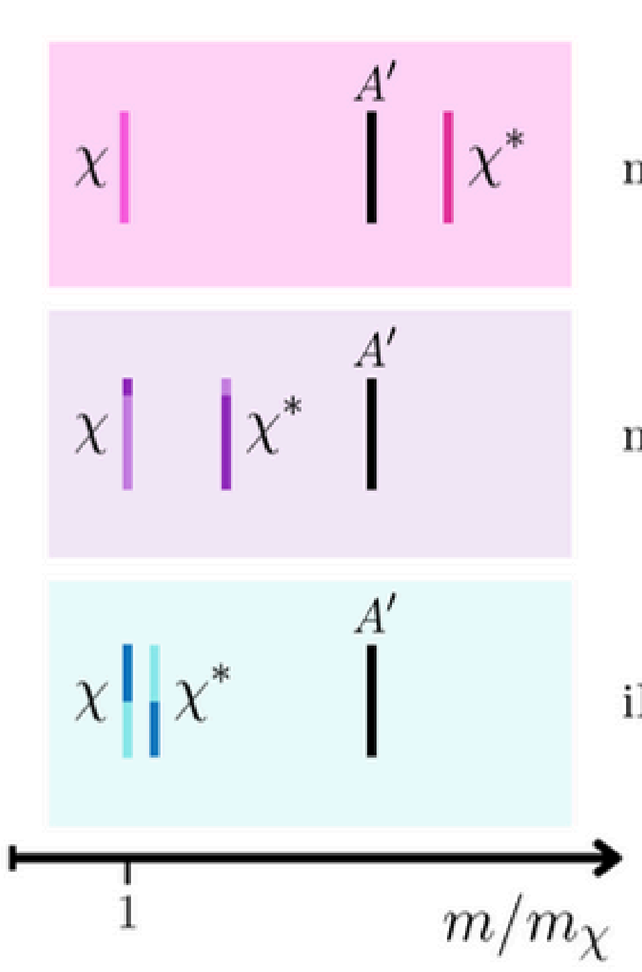
m_{χ^*} =

m_R

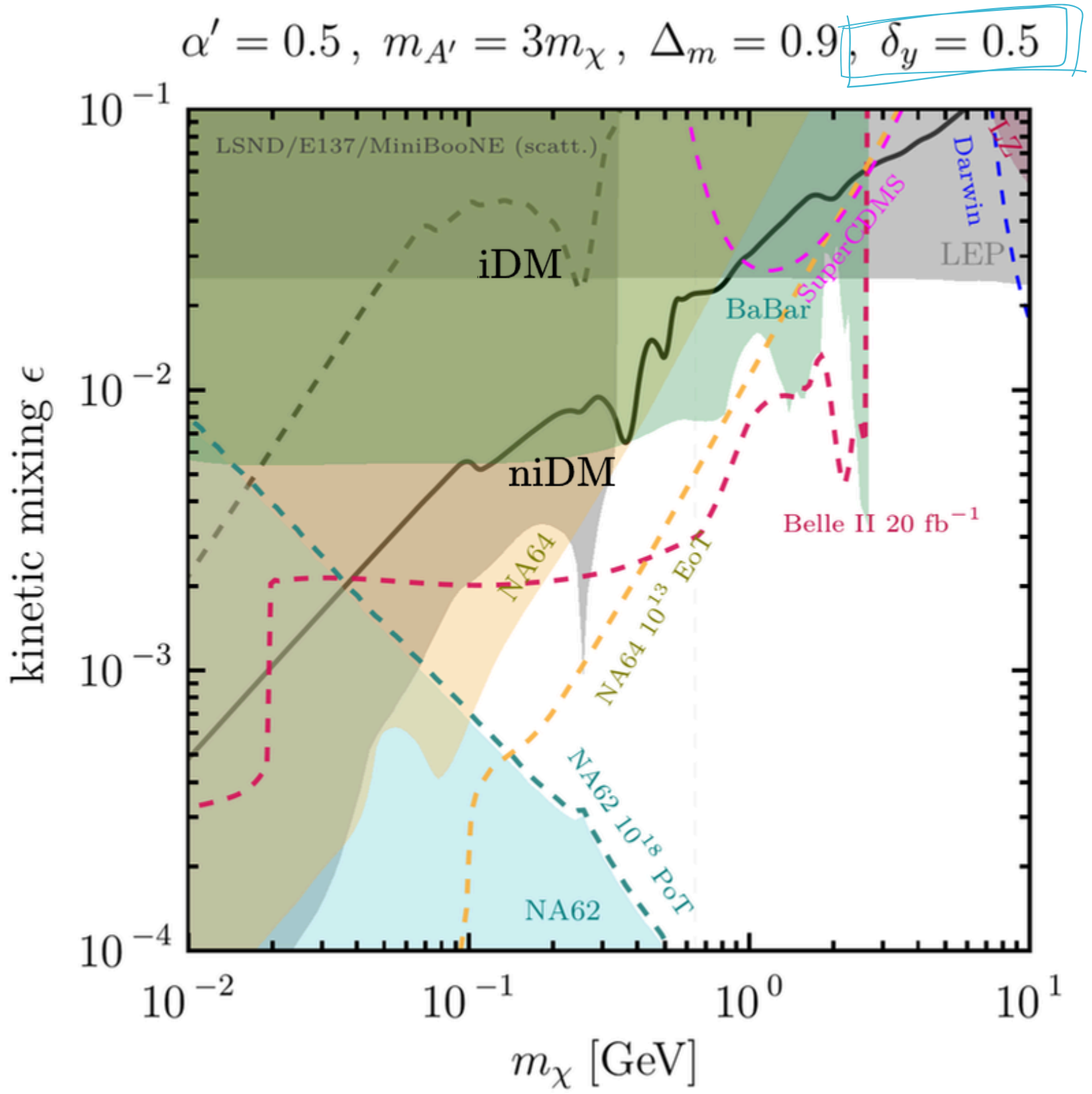
$\delta_y = 0$

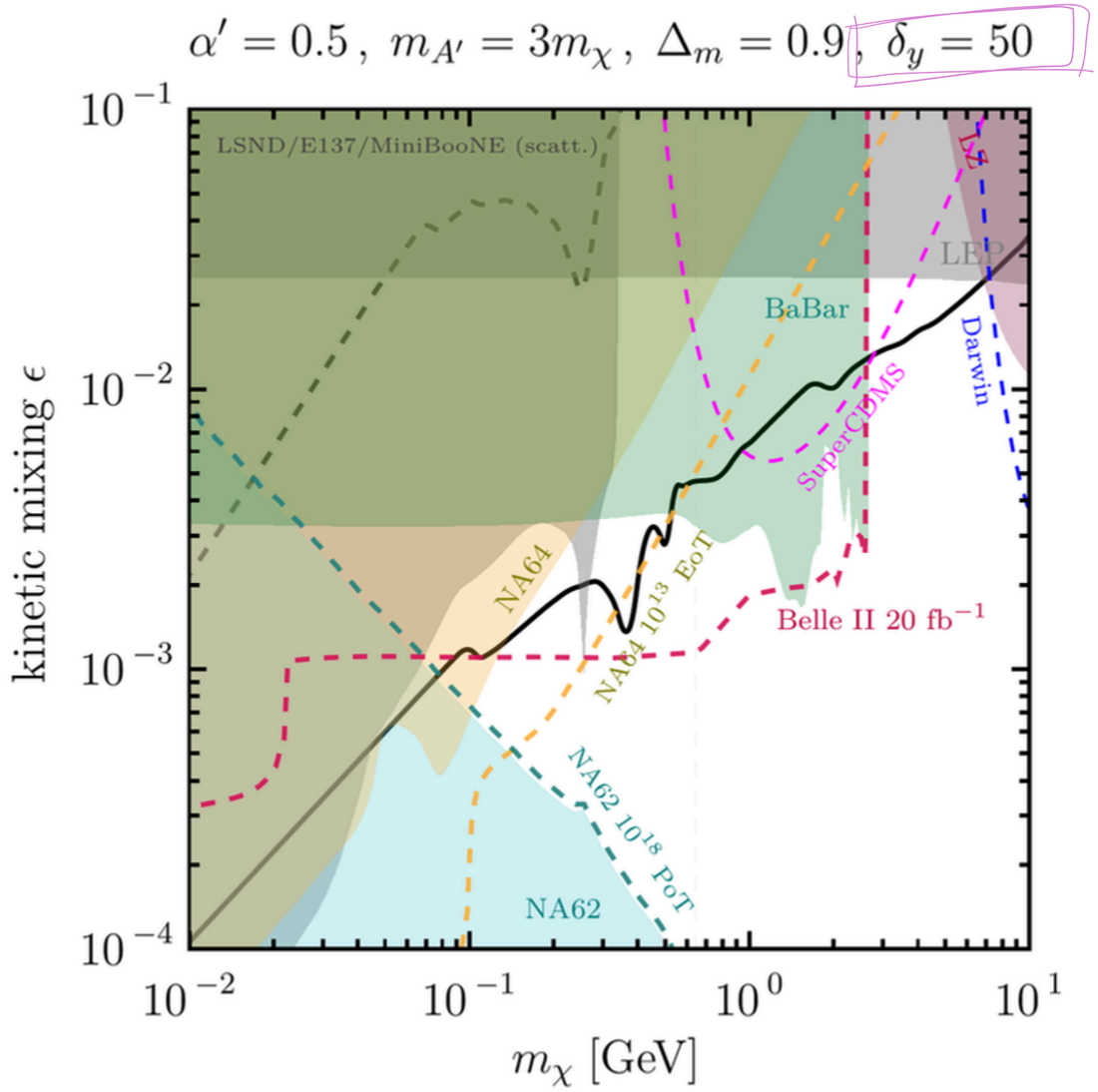
$\delta_y \neq 0$





RESULTS


$\alpha' = 0.5\,,\ m_{A'} = 3m_\chi\,,\ \Delta_m = 0.9,\ \delta_y = 0.5$
LSND/E137/MiniBooNE (scatt.)
iDM
niDM
BaBar
SuperCDMS
Darwin
LEP
LZ
Belle II 20 fb^{-1}
NA64
NA64 10^{13} EoT
NA62 10^{18} PoT
NA62
kinetic mixing ϵ
m_χ [GeV]


$\alpha' = 0.5\,,\ m_{A'} = 3m_\chi\,,\ \Delta_m = 0.9,\ \delta_y = 50$
LSND/E137/MiniBooNE (scatt.)
BaBar
SuperCDMS
Darwin
LEP
LZ
Belle II 20 fb^{-1}
NA64
NA64 10^{13} EoT
NA62 10^{18} PoT
NA62
kinetic mixing ϵ
m_χ [GeV]

~~not so~~ inelastic Dark Matter (~~ni~~DM)

a simple UV-complete sub-GeV WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: $\cancel{U(1)}$

a massive Dark Photon

A'

SSB: $V(H')$

Dark Higgs

h'

$$\mathcal{L}_\chi^I \supset e' A'^\mu \, \bar{\chi}_i (i\alpha_{ij} + \beta_{ij}\gamma^5)\gamma_\mu \chi_j - y_L h' \, \bar{\chi}_i (\hat{\alpha}_{ij} + i\hat{\beta}_{ij}\gamma^5)\chi_j$$

what is

essential?

~~not so~~ inelastic Dark Matter (~~ni~~DM)

Majorana Fermions DM

$\chi \quad \chi^*$

NEW FORCE: ~~$U(1)$~~

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A'

SSB: $V(H')$

Dark Higgs

h'

$e, \mu, \pi, K, p, n, \ldots$

a simple UV-complete ~~sub GeV~~ WIMP model

$$\mathcal{L}_\chi^I \supset e' A'^\mu \, \bar{\chi}_i (i\alpha_{ij} + \beta_{ij}\gamma^5)\gamma_\mu \chi_j - y_L h' \, \bar{\chi}_i (\hat{\alpha}_{ij} + i\hat{\beta}_{ij}\gamma^5)\chi_j$$

$$m_D = i m_d \text{ with } m_d \in \mathbb{R} \text{ or } h' \to a \, (\text{pseudoscalar})$$

minimal inelastic Dark Matter (miDM)

a simple UV-complete WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

SSB: $V(a)$

a real pseudoscalar

a

$$\mathcal{L}_\chi^I \supset y_L a\, \bar{\chi}_i(\hat{\alpha}_{ij} + i\hat{\beta}_{ij}\gamma^5)\chi_j$$

$$\delta_d \equiv \frac{m_L}{m_d} \propto \frac{w}{m_d} \ll 1 \qquad \delta_y \approx 2\delta_P \ll 1$$

Parameters

$$m_{\chi^*} = (1 + \Delta_m) m_\chi$$
$$m_R = (1 + \delta_y) m_L$$

minimal inelastic Dark Matter (miDM)

a simple UV-complete WIMP model

Majorana Fermions DM

$\chi \quad \chi^*$

SSB: $V(a)$

a real pseudoscalar

a

Parameters

$\Delta_m \, , \, \delta_y \to \delta_d \, , \, \delta_P$

$$\mathcal{L}_\chi^I \supset y_L a \, \bar{\chi}_i (\hat{\alpha}_{ij} + i\hat{\beta}_{ij}\gamma^5)\chi_j$$

$$\delta_d \equiv \frac{m_L}{m_d} \propto \frac{w}{m_d} \ll 1 \qquad \delta_y \approx 2\delta_P \ll 1$$

$$\Delta_m = 2\delta_d \delta_P \ll 1$$

minimal inelastic Dark Matter (miDM)

Majorana Fermions DM

$$\chi \quad \chi^*$$

SSB: $V(a)$

a real pseudoscalar

$$a$$

Parameters

$$\delta_d \ , \ \delta_P$$

a simple UV-complete WIMP model

$$\mathcal{L}_\chi^I \supset y_L a\, \bar{\chi}_i (\hat{\alpha}_{ij} + i\hat{\beta}_{ij}\gamma^5)\chi_j$$

$$\hat{\alpha}_{ii} \approx 2(\delta_d \pm \delta_P) + \mathcal{O}(\delta^2)$$

$$\hat{\beta}_{\_*} \approx 2 + \mathcal{O}(\delta)$$

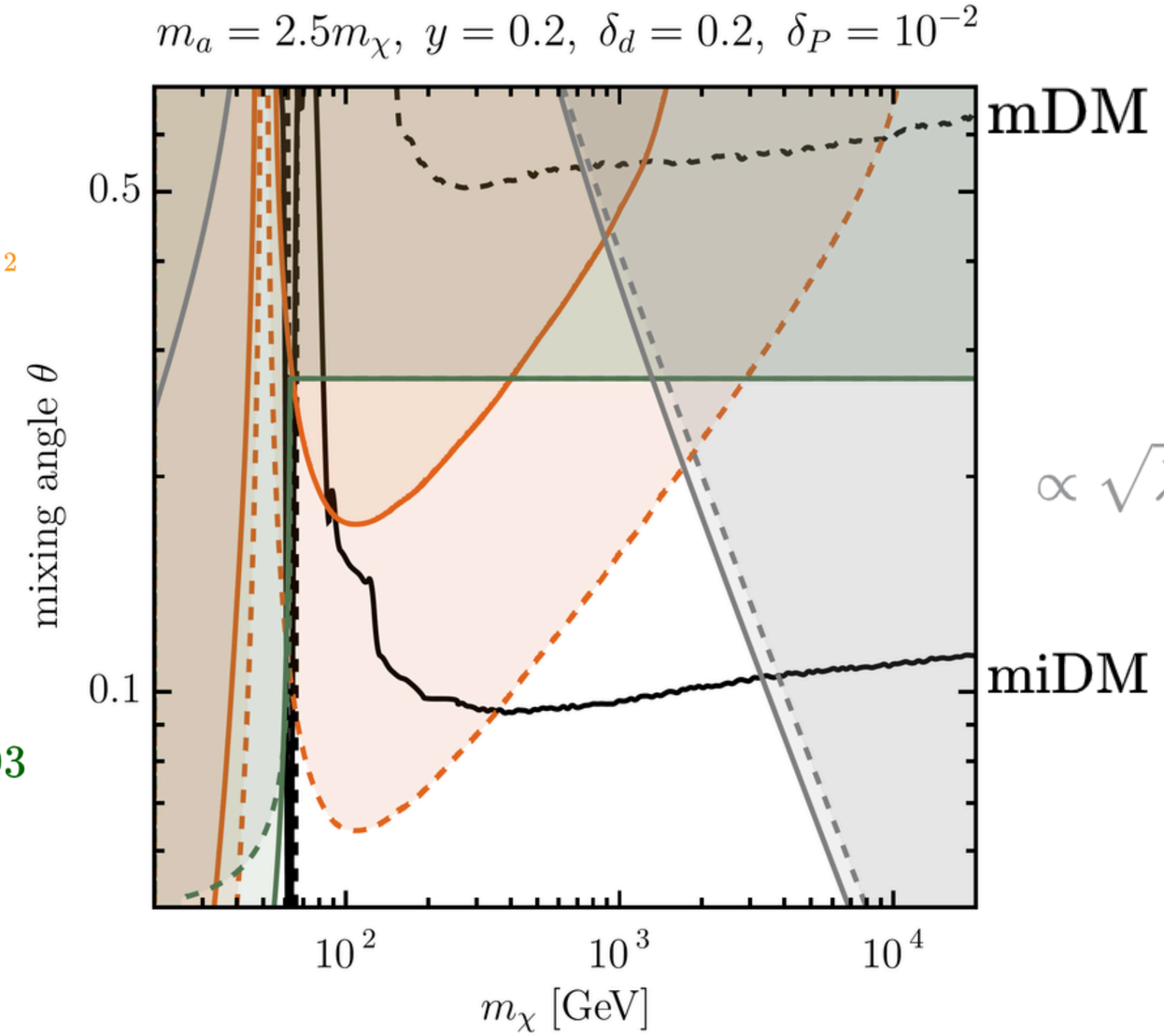
SSB generates a Higgs mixing

$$\lambda_{ah} A^2 H^2 \rightarrow \begin{pmatrix} \hat{a} = a\cos\theta - h\sin\theta \\ \hat{h} = h\cos\theta + a\sin\theta \end{pmatrix}$$

RESULTS

$$\sigma^{\mathrm{SI}} \propto y^2 \sin^2 2\theta \left(\frac{1}{m_h^2} - \frac{1}{m_a^2} \right)^2 (\delta_d - \delta_P)^2$$

$$\mu = \cos^2\theta \frac{\cos^2\theta \Gamma_h}{\cos^2\theta \Gamma_h + \Gamma_{\mathrm{dark}}} > 0.93$$

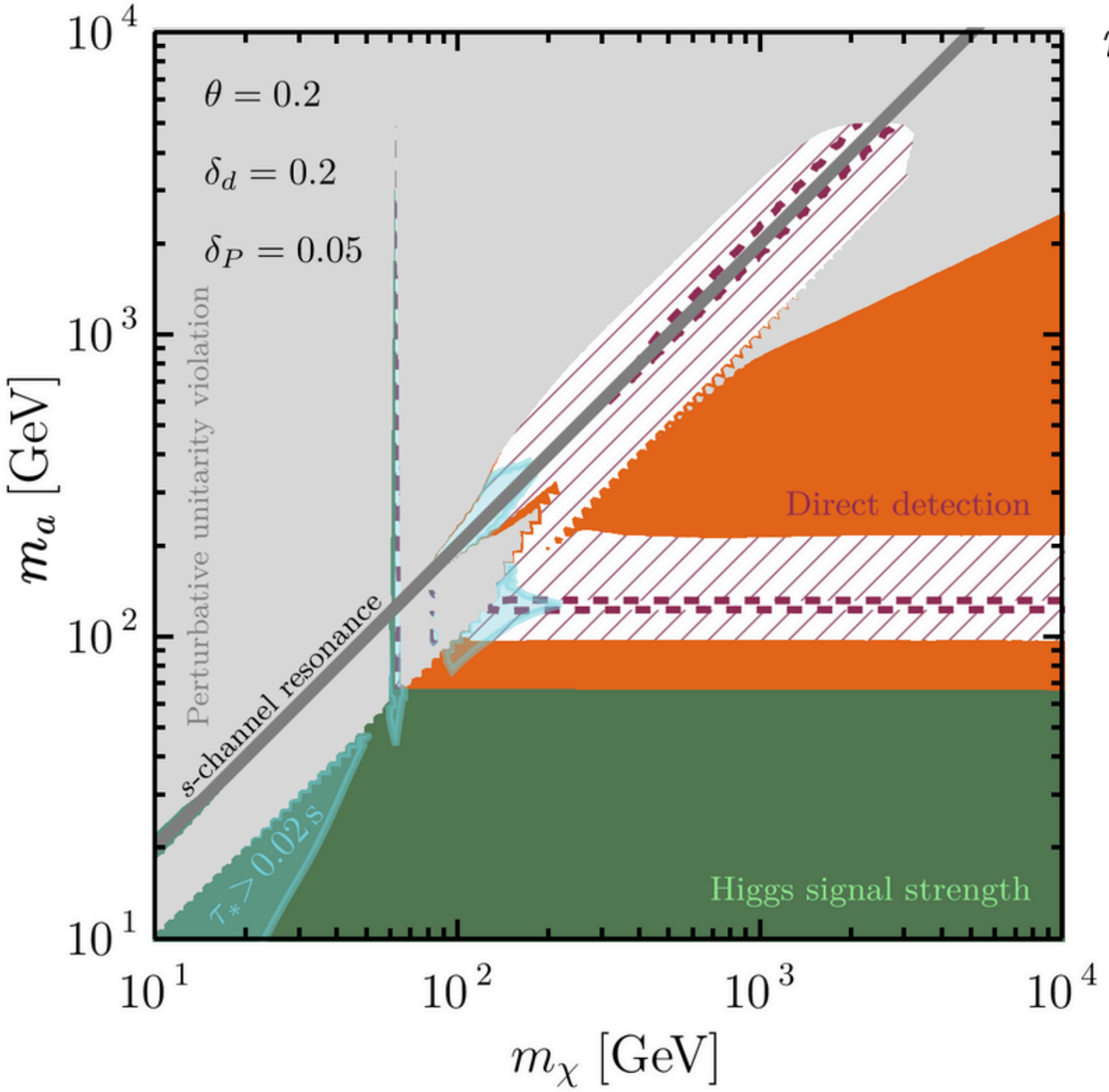


$$m_a \approx \sqrt{2\lambda_a} w$$

$$\propto \sqrt{\lambda_a} \delta_d m_d > m_\chi \approx m_d$$

$$\implies \lambda \gg 1$$

RESULTS

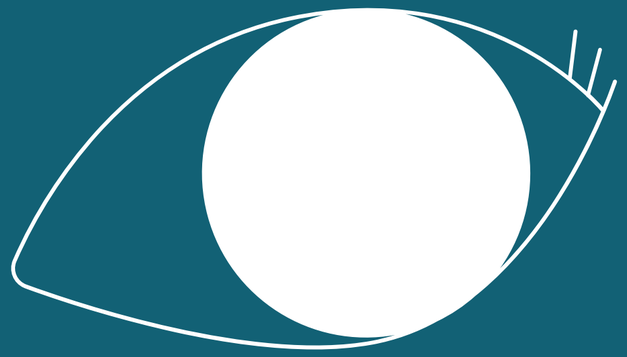


$m_a \in (2 \pm 10\%) m_\chi$

χ^* lifetime > 0.02 s
may alter BBN

$\theta \ll 1$

$\delta_d \ll 1$



FUTURE SEARCHES

Future exploration

niDM: DM masses around 5 GeV with future colliders and direct detection experiments
miDM: compute relative DM abundance and BBN/CMB bounds in detail

New signatures

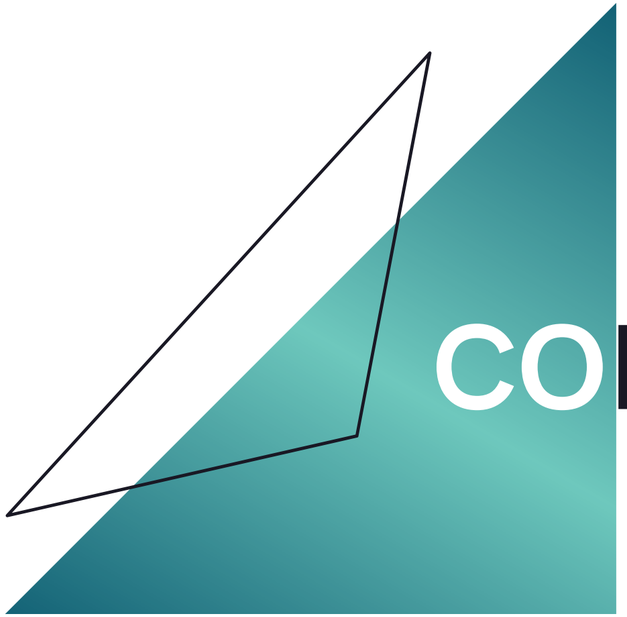
displaced vertices

double-bang

New experiments

niDM: NA64 muons

miDM: FCC



CONCLUSION

New directions explored

parity violation also in the dark sector

inelastic Dark Matter with **large** mass spliting

inelastic Dark Matter with **only** a (pseudo)**scalar** mediator

Thank you!

Questions?

BACKUP SLIDES

not-so-inelastic Dark Matter (niDM)

SUMMARY

Majorana Fermions DM

$$\chi \quad \chi^*$$

NEW FORCE: $U'(1)$

a massive Dark Photon

$$A'$$

Parameters

$$\epsilon$$

$$\alpha' = \frac{e'^2}{4\pi}$$

$$m_{A'}$$

$$m_\chi$$

$$\Delta_m$$

$$\delta_y$$

Giovani Dalla Valle Garcia

inelastic Dark Matter (iDM)

A sub-GeV DM candidate

The WIMP miracle revisited:

$$n_\chi \langle\sigma v\rangle \sim H(x_f)$$
$$\implies \Omega_{\rm DM} h^2 \propto \langle\sigma v\rangle^{-1}$$

$$n_{\chi'} \langle\sigma v\rangle = e^{-\Delta_m x_f} n_\chi \langle\sigma v\rangle \sim H(x_f)$$
$$\implies \Omega_{\rm DM} h^2 \propto e^{\Delta_m x_f} \langle\sigma v\rangle^{-1}$$

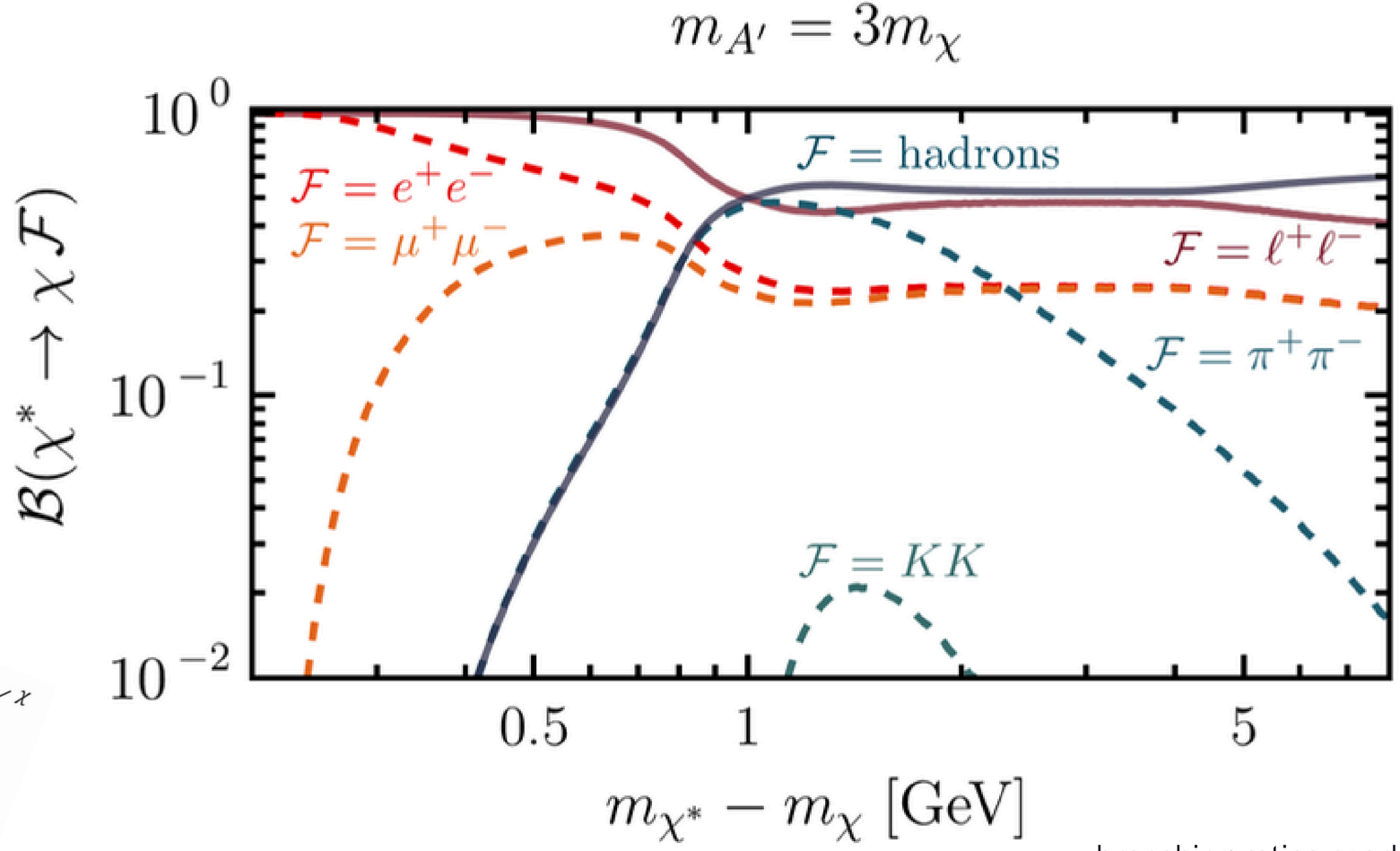
$$\langle\sigma v\rangle \sim \frac{\alpha_{\rm DM}^2}{m_\chi^2}$$

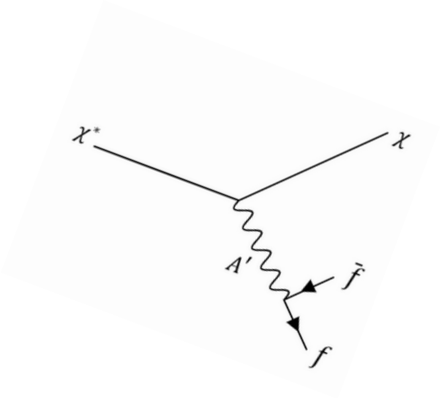
$$\Omega_{\rm DM} h^2 = \frac{e^{\Delta_m x_f} m_\chi^2}{\alpha_{\rm DM}'^2}$$

↑ linearly

↓ exponentially

niDM - Excited states decays

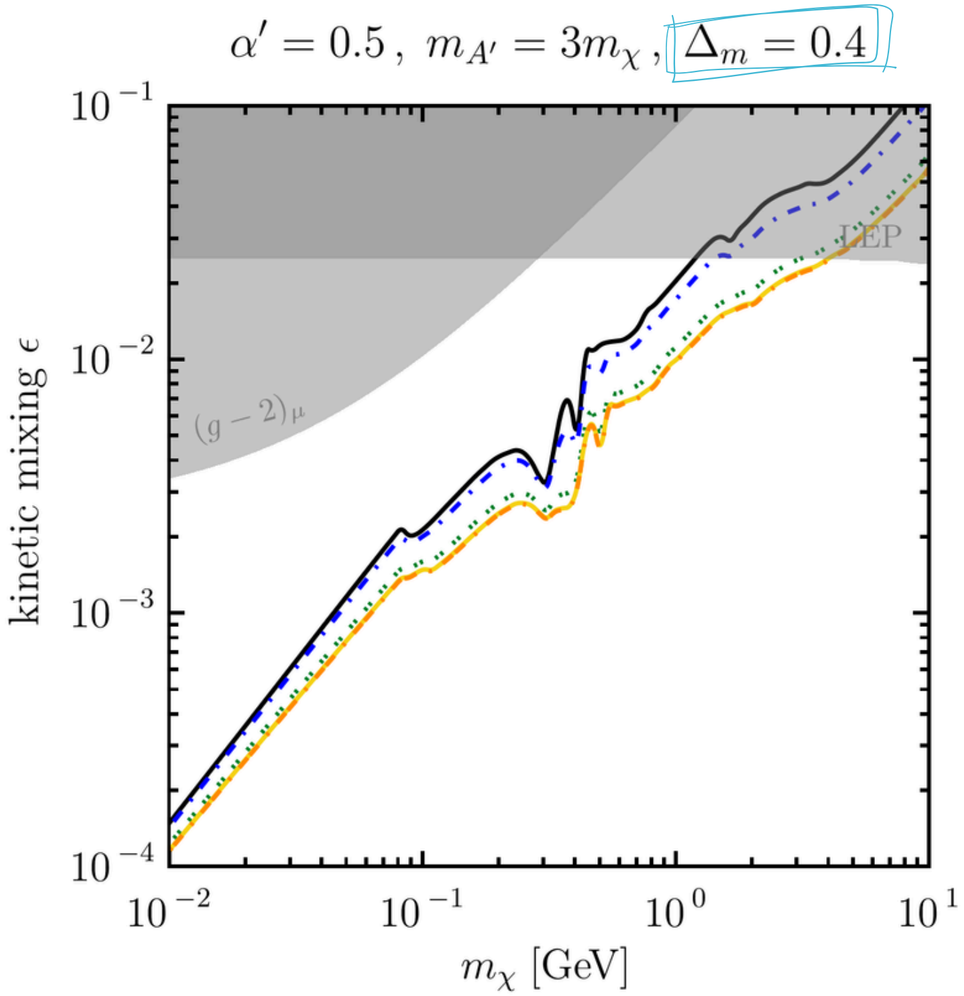


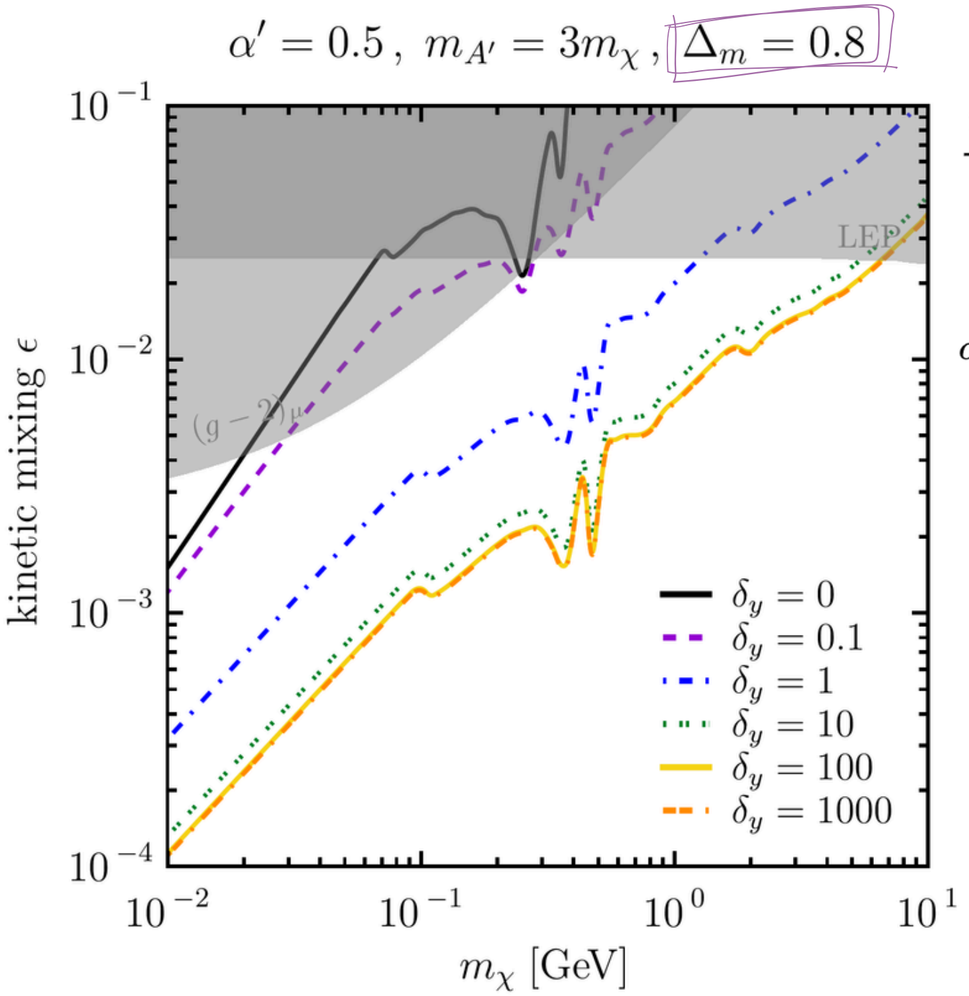


branching ratios nearly independent of $m_{A'}$

niDM - Relic abundance

Standard Freeze-out

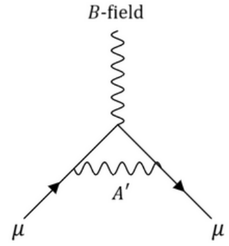




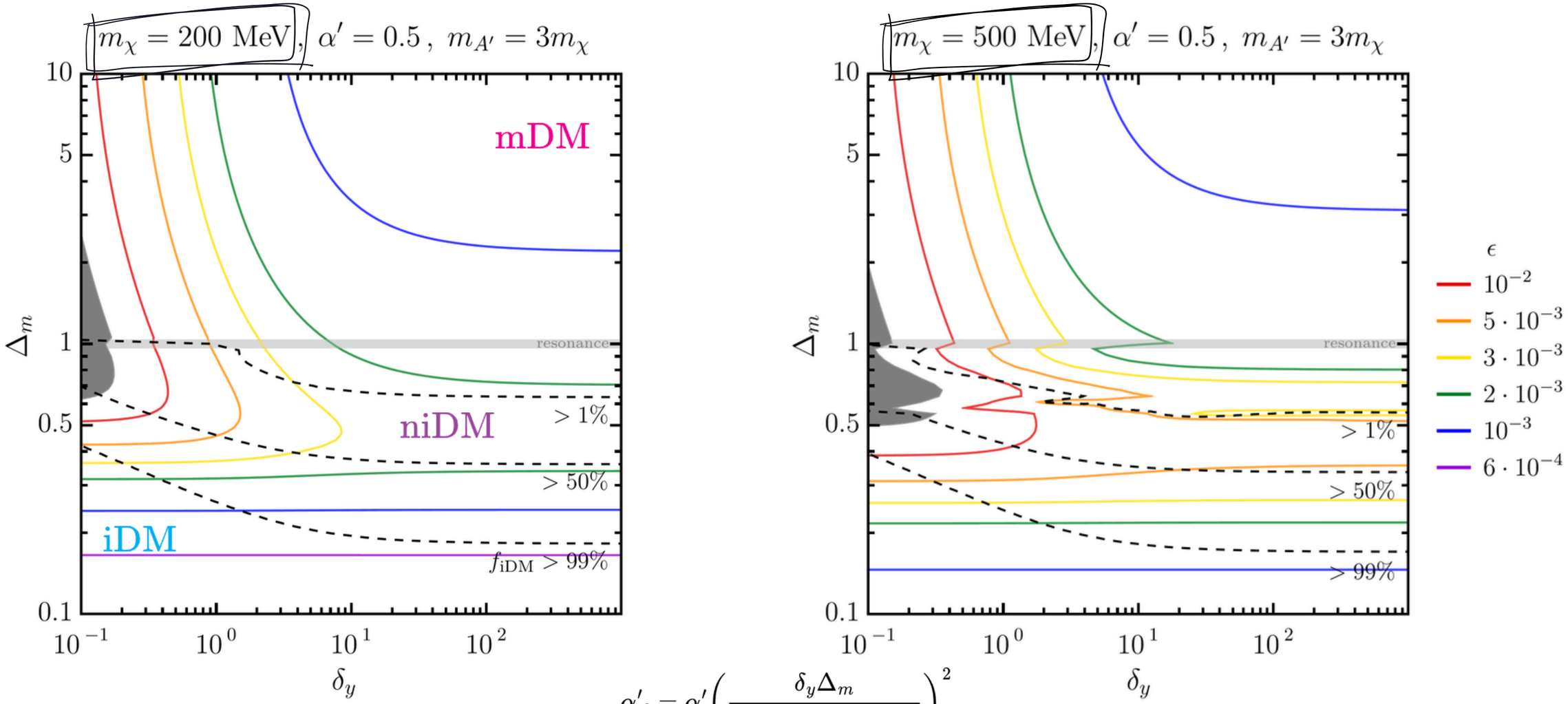
$$\frac{n_{\chi^*}}{n_\chi} \propto e^{-\Delta_m x_f}\,, x_f \approx 20$$

$$\alpha'_{\text{el}} = \alpha' \left(\frac{\delta_y \Delta_m}{(2+\delta_y)(2+\Delta_m)} \right)^2$$

$(g-2)_\mu$:

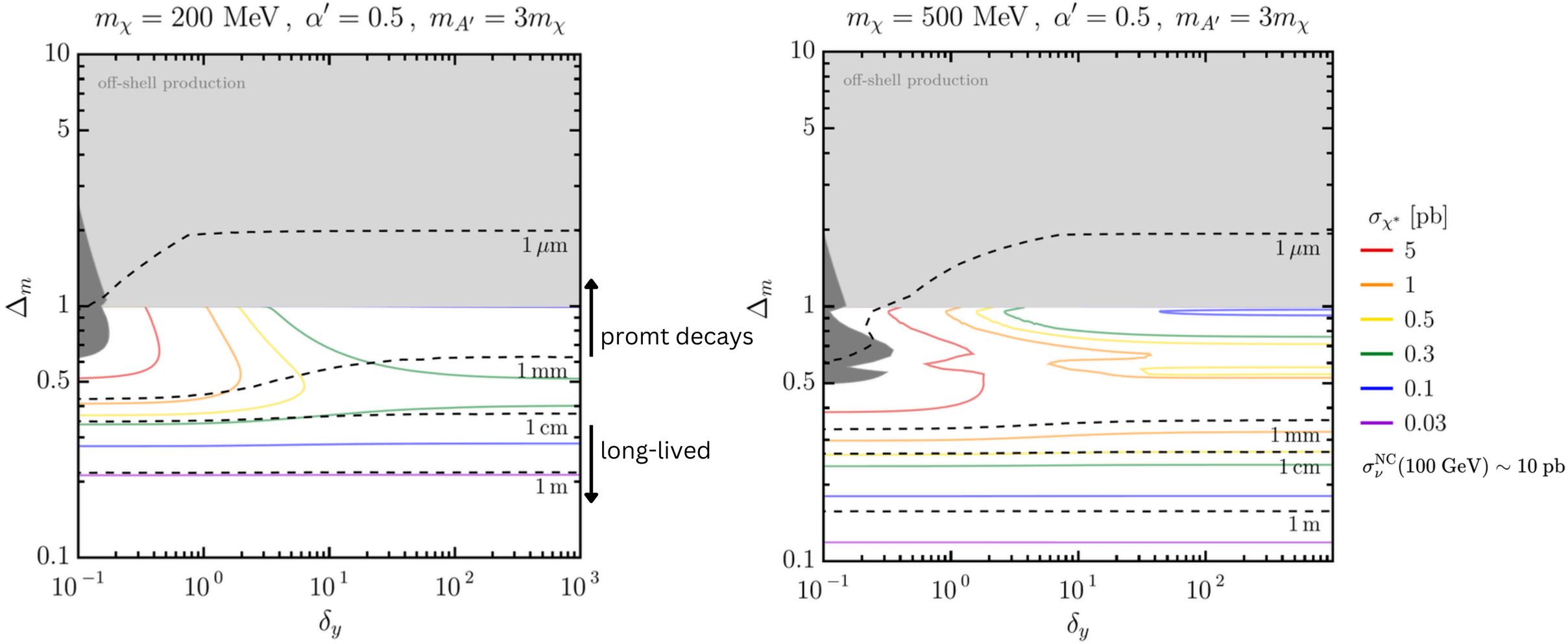


niDM - Relic abundance

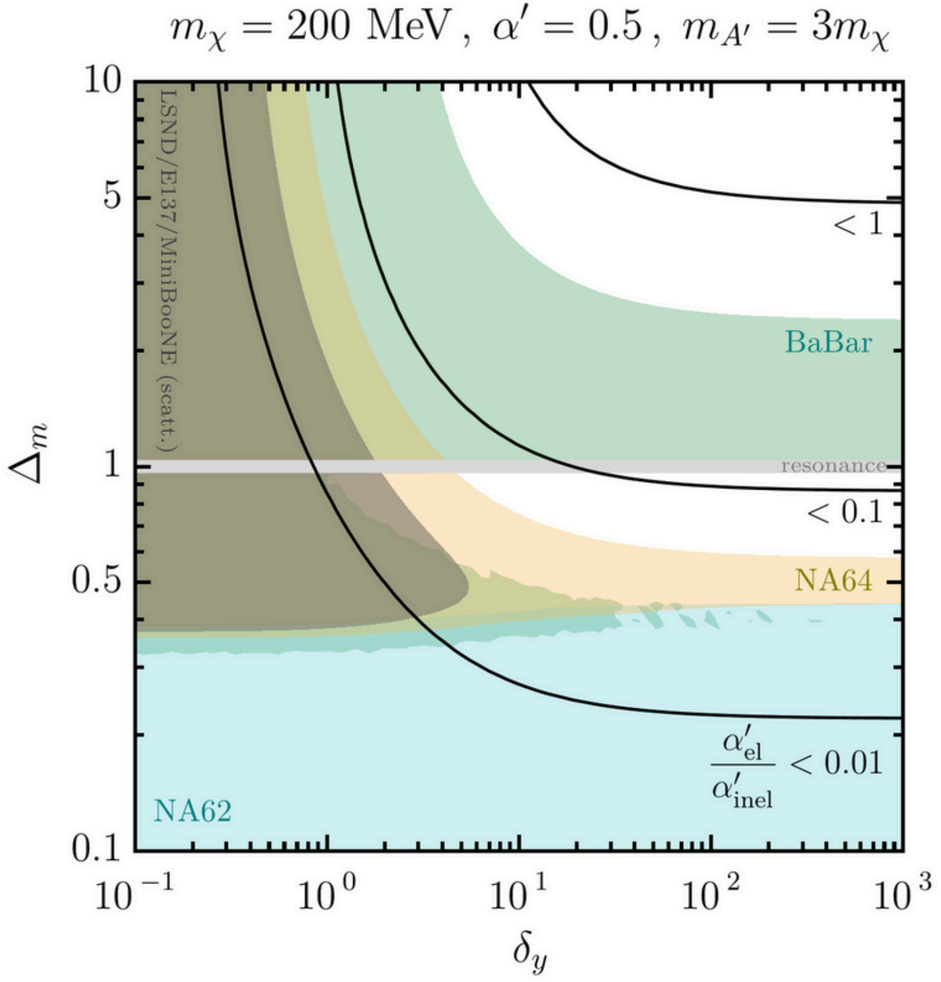


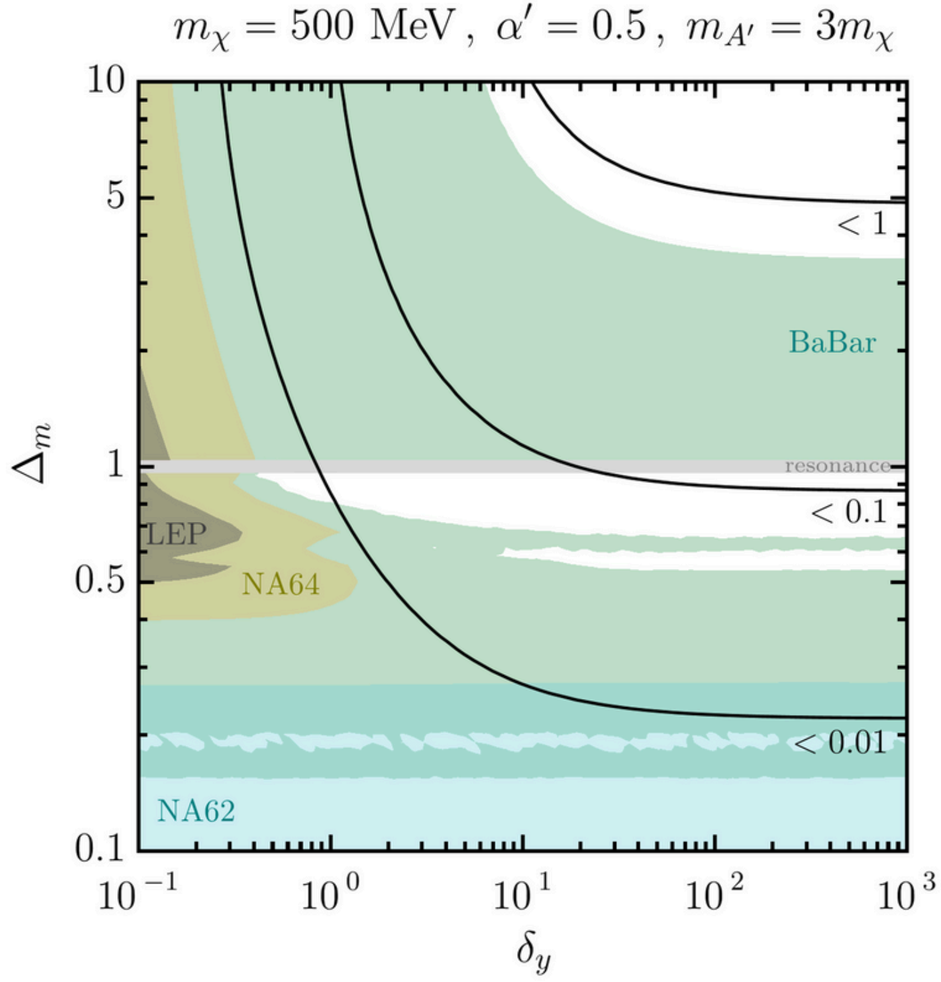
$$\alpha'_{\rm el} = \alpha' \left(\frac{\delta_y \Delta_m}{(2+\delta_y)(2+\Delta_m)} \right)^2$$

COLLIDER SEARCHES

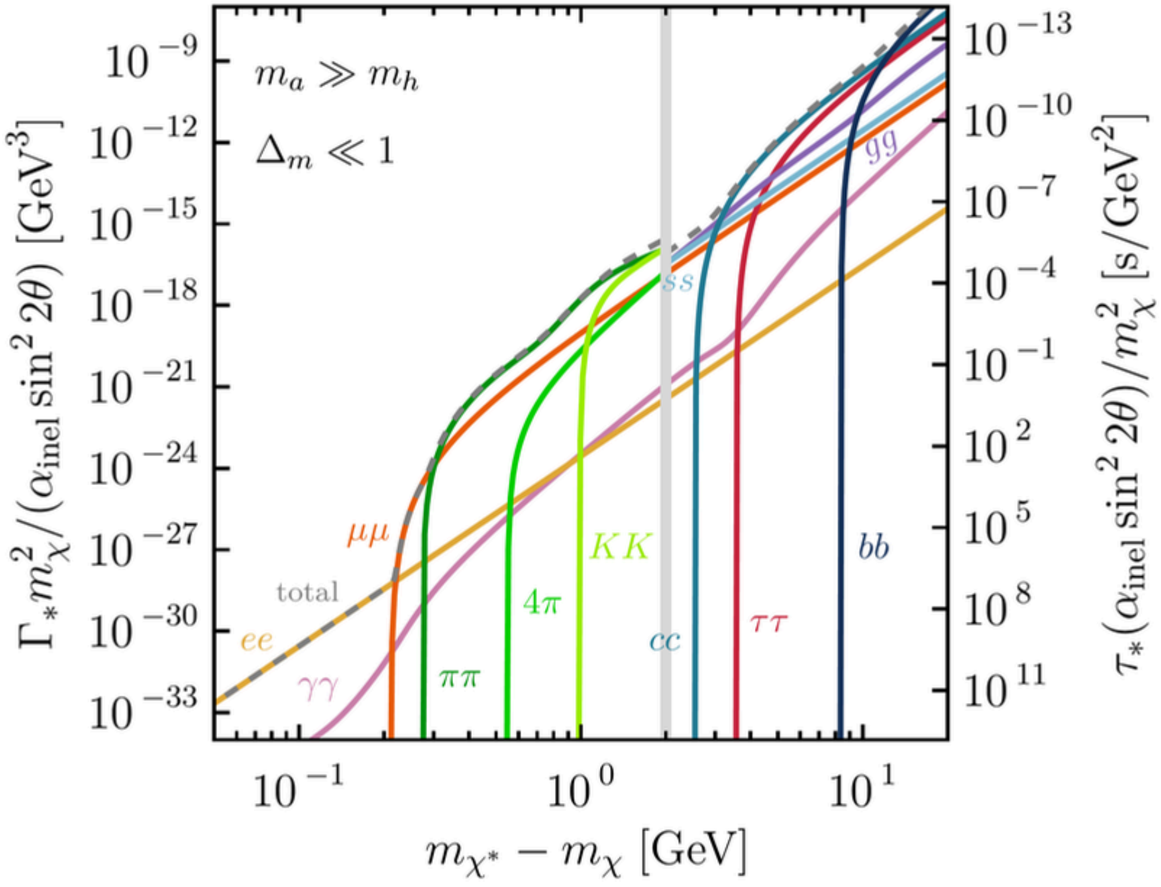


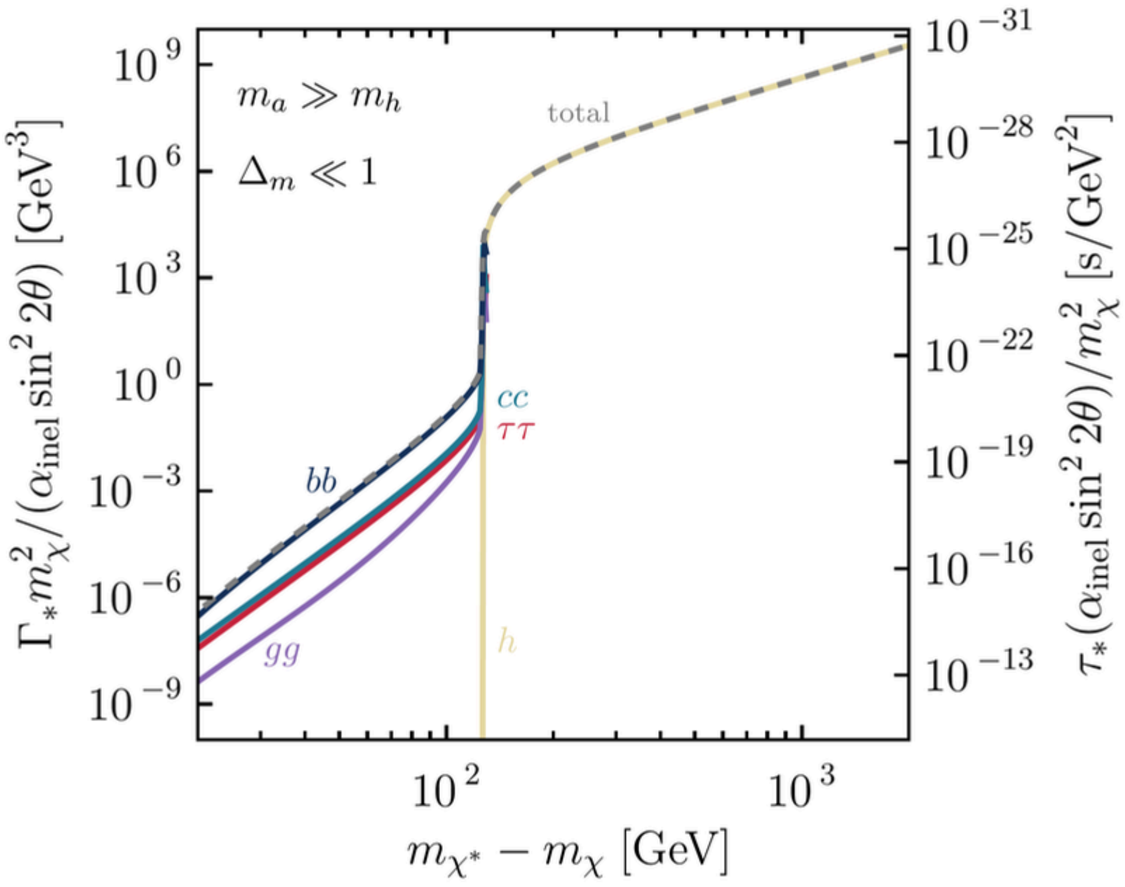
COLLIDER SEARCHES



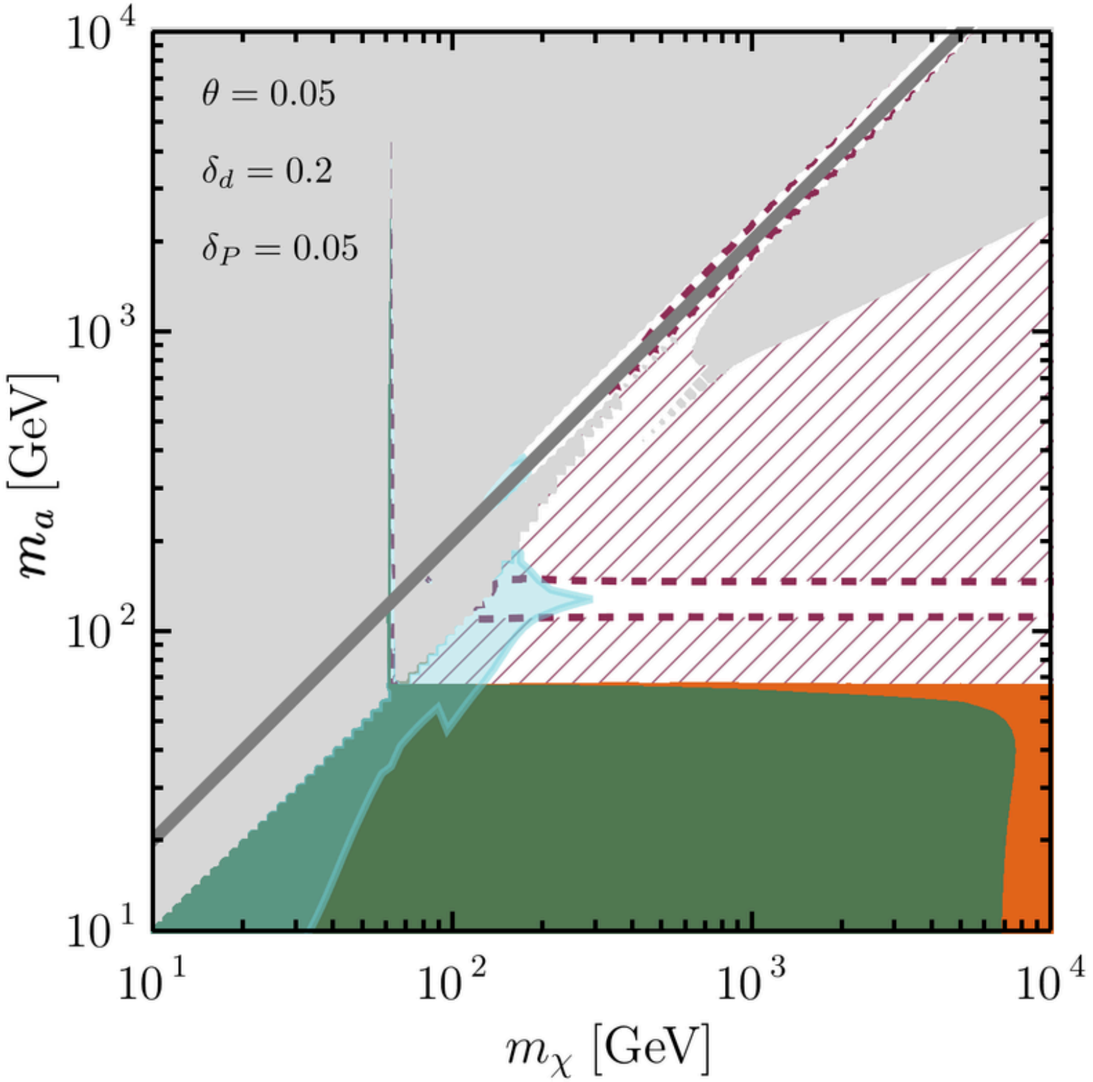


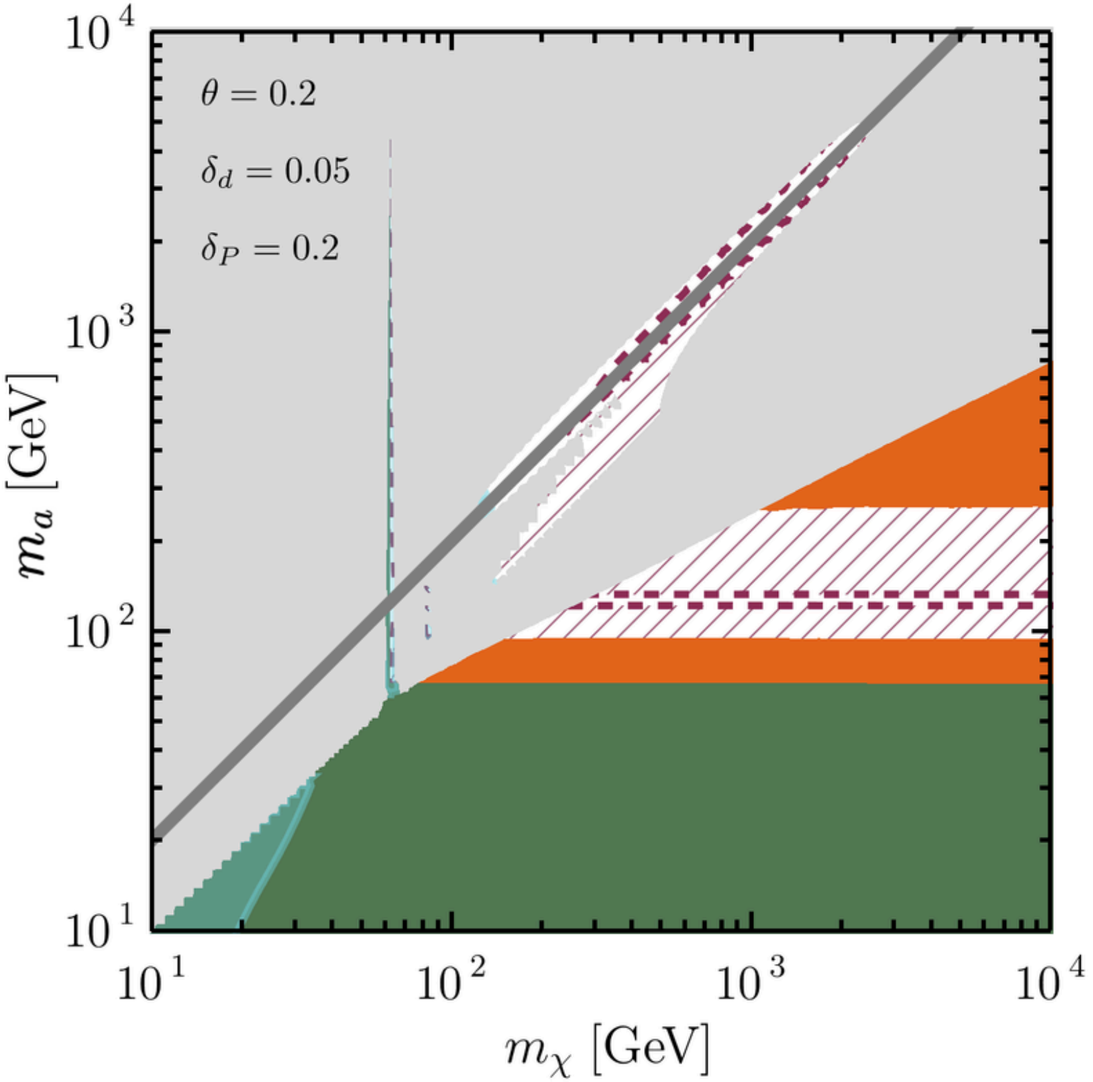
miDM - Excited states decays



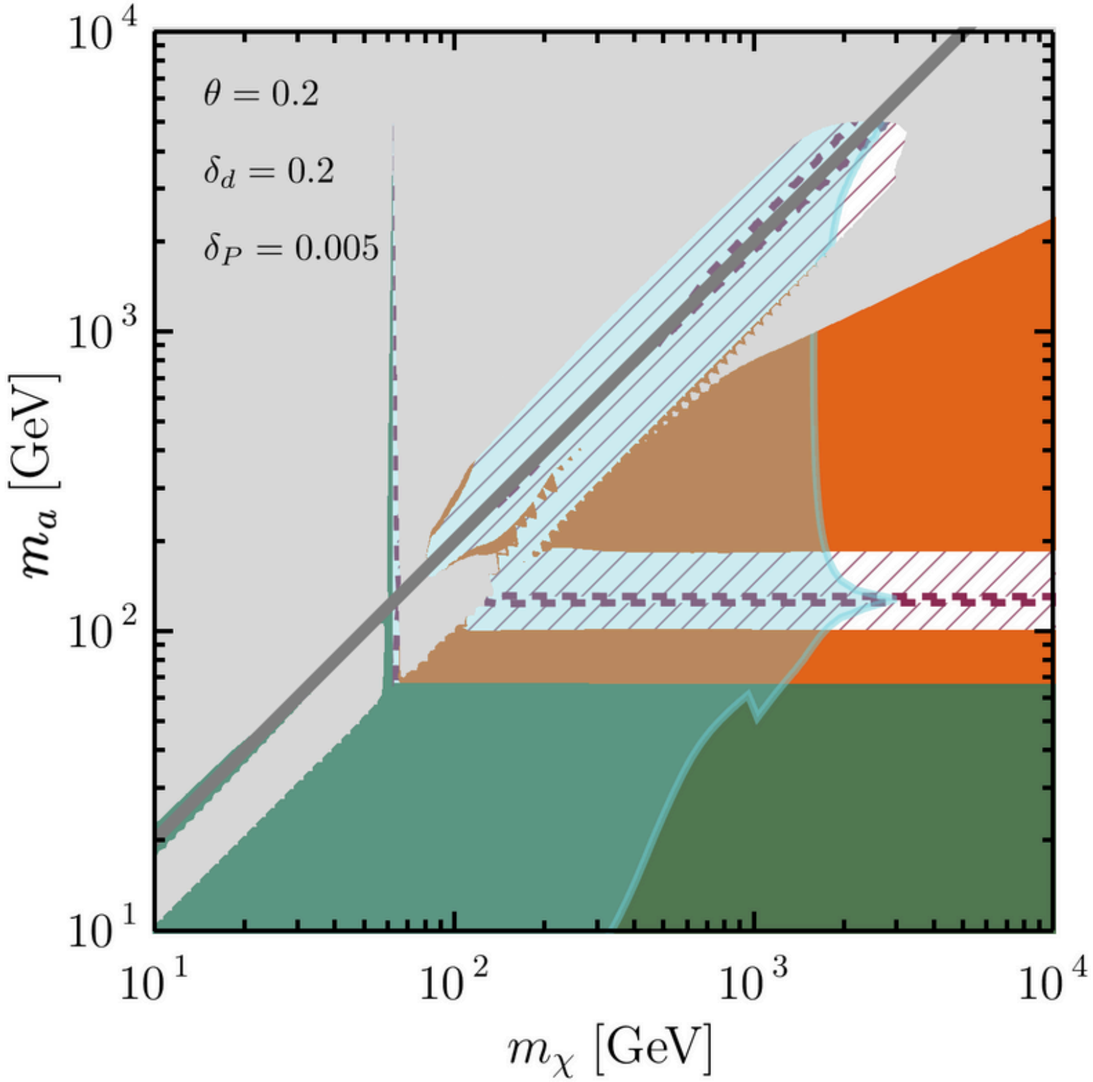


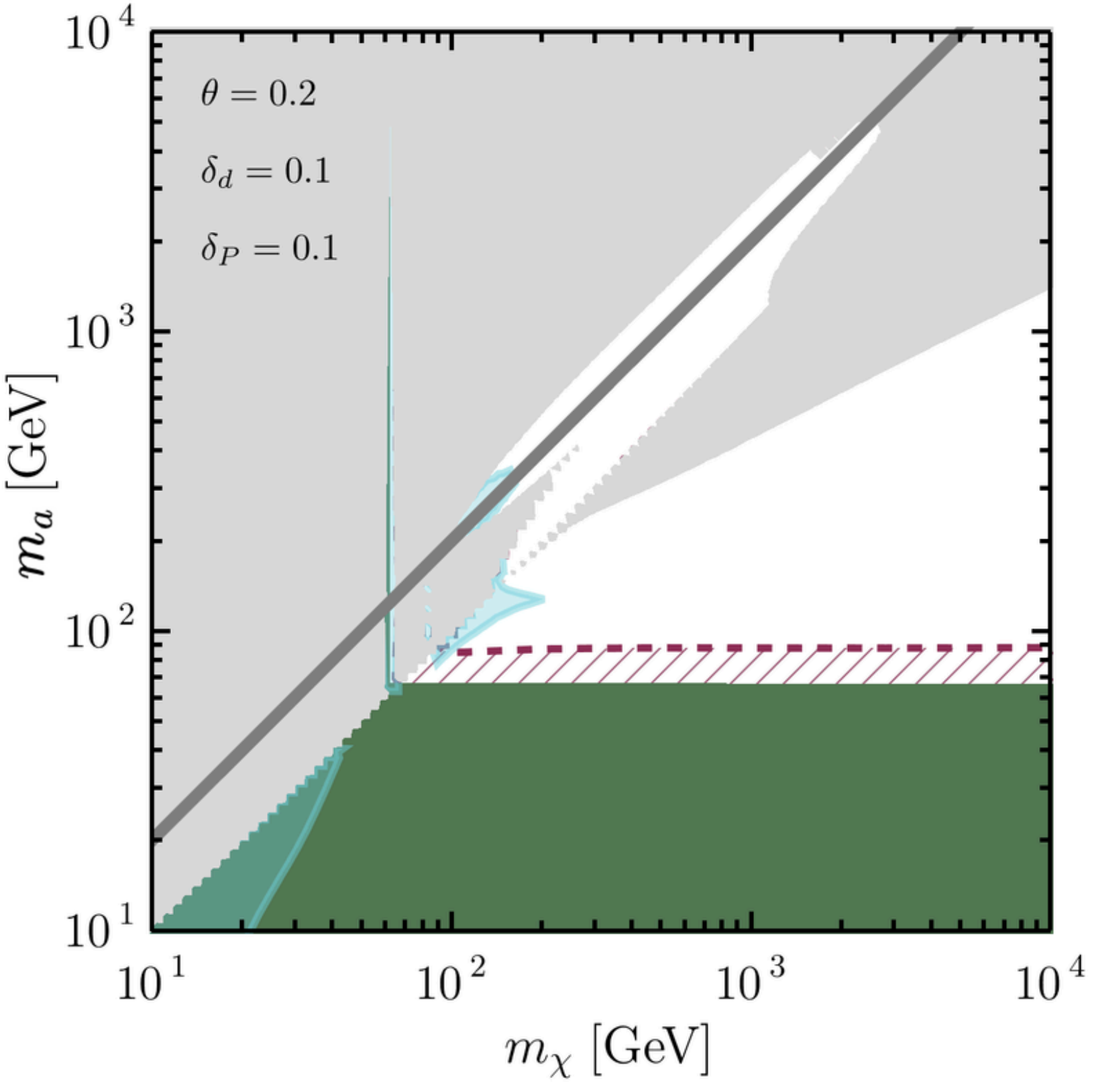
RESULTS


$\theta = 0.05$
$\delta_d = 0.2$
$\delta_P = 0.05$
m_a [GeV]
m_χ [GeV]
10^1
10^2
10^3
10^4


$\theta = 0.2$
$\delta_d = 0.05$
$\delta_P = 0.2$
m_a [GeV]
m_χ [GeV]
10^1
10^2
10^3
10^4

RESULTS


$\theta = 0.2$
$\delta_d = 0.2$
$\delta_P = 0.005$
m_a [GeV]
m_χ [GeV]
10^1
10^2
10^3
10^4


$\theta = 0.2$
$\delta_d = 0.1$
$\delta_P = 0.1$
m_a [GeV]
m_χ [GeV]
10^1
10^2
10^3
10^4

not-so-inelastic

Dark Matter (DM)

A simplified sub-GeV WIMP model

Dirac Fermion DM
$\chi = \chi_L + \chi_R$

NEW FORCE: $U'(1)$
a massive Dark Photon
A'

SSB: $V(H')$
Dark Higgs
H'

$$\mathcal{L}_\chi^I \supset ig_\chi A'_\mu \bar{\chi}\gamma^\mu\chi - \sqrt{2}y_L S\bar{\chi^c}P_L\chi - \sqrt{2}y_R S\bar{\chi^c}P_R\chi + \text{h.c.}$$

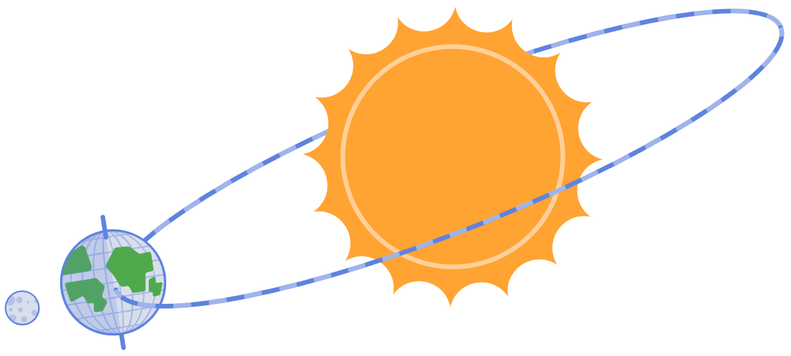
$$g_\chi A'_\mu \bar{\Psi} R_{A'}\gamma^\mu\Psi + \Psi^T C^{-1}(M_\chi + h' R_{H'})\Psi + \text{h.c.}$$

$$\Psi = \begin{pmatrix}\chi_L \\ \chi_R^c\end{pmatrix} \quad R_{A'} = \begin{pmatrix}1 & 0 \\ 0 & -1\end{pmatrix} \quad M_\chi = \begin{pmatrix}y_L w & m_D/2 \\ m_D/2 & y_R w\end{pmatrix} \quad R_{H'} = y_L\begin{pmatrix}1 & 0 \\ 0 & 1+\delta\end{pmatrix}$$

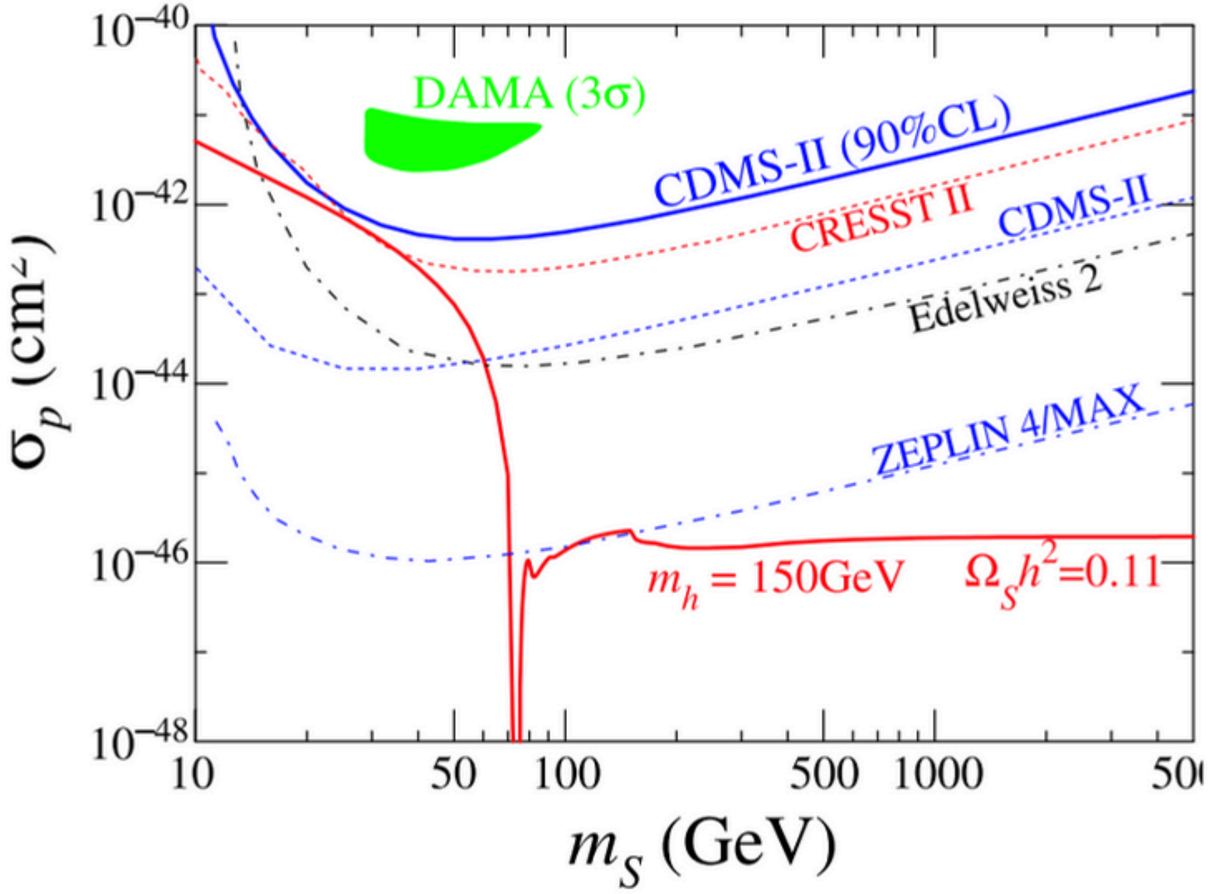
Historical interlude: the DAMA anomaly

- Annual modulation

$$\approx 7\%$$



exclusion plot for the spin-independent DM parameter space

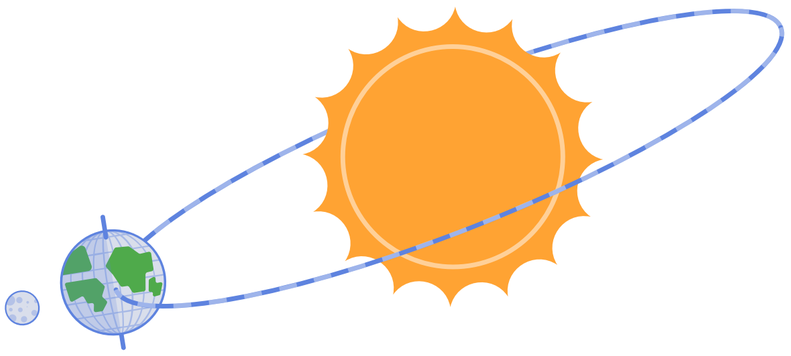


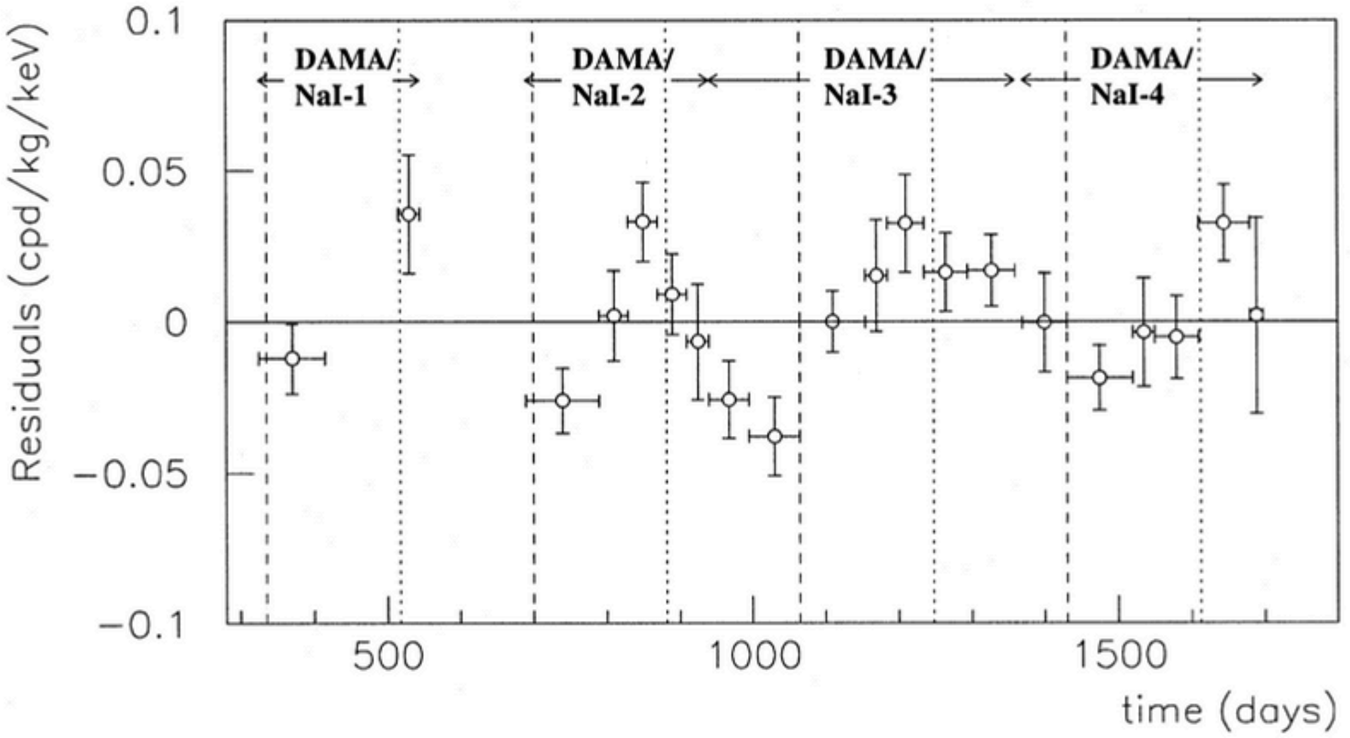
G. D'Amico, M. Kamionkowski, K. Sigurdson in 0907.1912

The DAMA anomaly

- Annual modulation

$$\approx 7\%$$





model independent residual rate for the cumulative 2–6 keV energy interval as a function of the time

inelastic Dark Matter

as solution to the DAMA anomaly

- CDMS is composed of Germanium (73 u)
- DAMA is composed of Iodine (127 u)

For a typical DM particle

$$v_\chi \approx 220\ \mathrm{km/s}$$

assuming

$$m_\chi \approx 100\ \mathrm{GeV}$$

PROPER CALCULATION

use a velocity distribution

$$f(v_\chi)$$

- in CDMS $\Delta_m m_\chi \lesssim 11\ \mathrm{keV}$
- in DAMA $\Delta_m m_\chi \lesssim 15\ \mathrm{keV}$

D. Smith, N. Weiner in 0101138

inelastic Dark Matter

-
-

For

ass

F. Kahlhoefer in *Annual modulation of dark matter signals: Experimental results and new ideas - IDM22, Vienna*