Dark Photons from Captured Dark Matter Annihilation

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arXiv: 1509.07525, 1602.01465, and 1701.03168

with J.L. Feng and P. Tanedo

Pheno Dark Matter Session III May 8, 2018

Dark Matter with Dark Photons

Hidden broken U(1)' symmetry.

Kinetically mixed to the SM Photon.

$$\alpha_X^{\rm th} = 0.035 \left(\frac{m_X}{\rm TeV}\right)$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_{\rm SM} \bar{f}\left(i\partial\!\!\!/ - q_f e A\!\!\!/ - m_f\right) f$$

$$-\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu + \bar{X}\left(i\partial\!\!\!/ - g_X A\!\!\!/' - m_X\right) X$$

$\epsilon \approx 10^{-9} - 10^{-7}$

100 GeV – 10 TeV

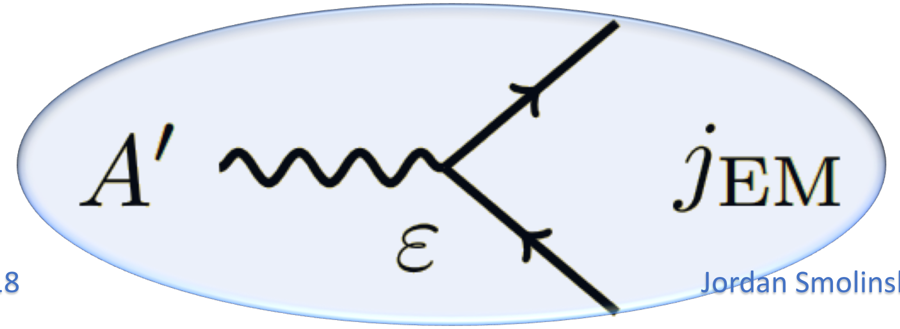
Dark Matter with Dark Photons

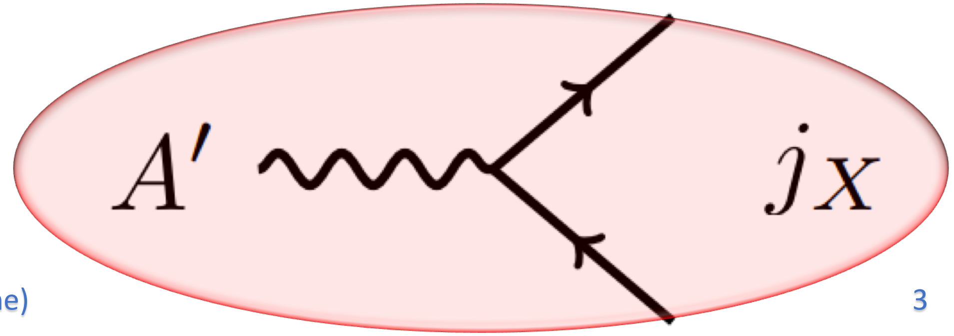
Standard model becomes dark "milli-charged."

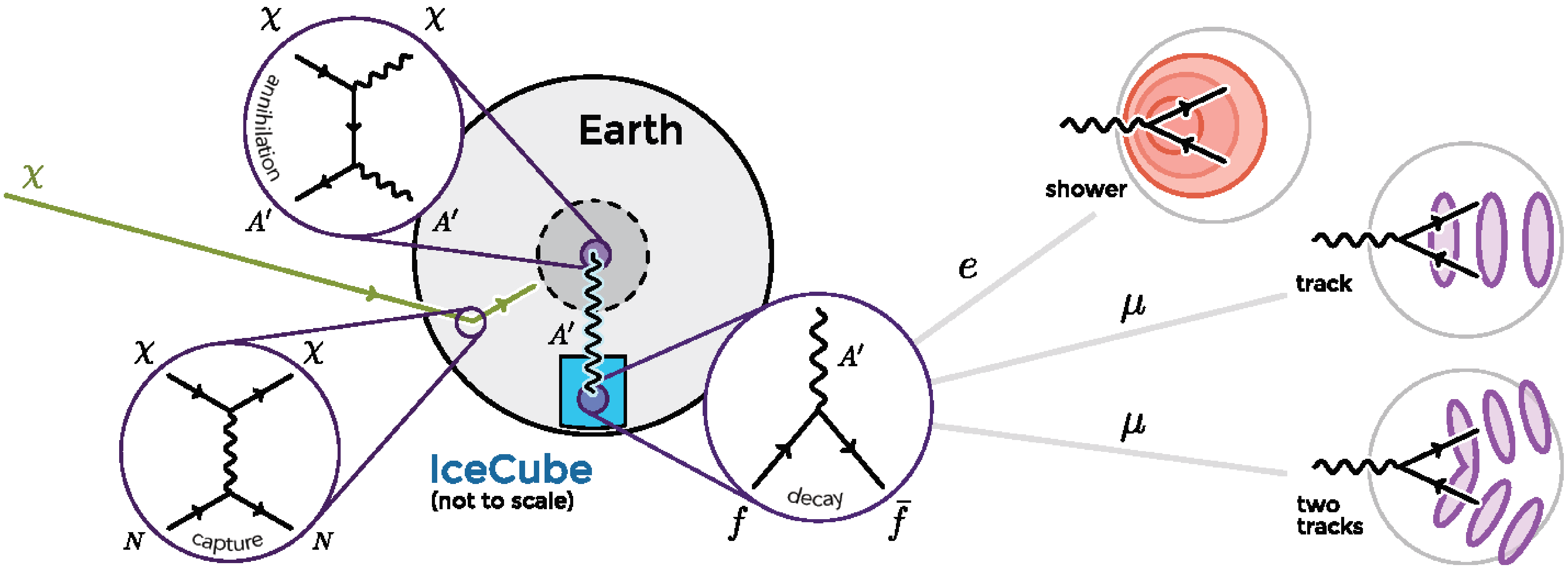
Dark sector doesn't become charged under QED (Feynman vertices).

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2$$

$$- \sum_f q_f e(A_\mu + \varepsilon A'_\mu)\bar{f}\gamma^\mu f - g_X A'_\mu \bar{X}\gamma^\mu X$$






χ
χ
χ
annihilation
A′
A′
Earth
χ
A′
χ
χ
N
capture
N
IceCube
(not to scale)
A′
decay
f
f̄
e
μ
μ
shower
track
two tracks

Dark Matter Capture

Dark matter population is described by

$$\frac{dN_X}{dt} = C_{\text{cap}} - C_{\text{ann}} N_X^2$$

Capture rate scales like $\frac{\varepsilon^2 \alpha_X}{m_X}$

Proportional to the thermal-averaged cross section

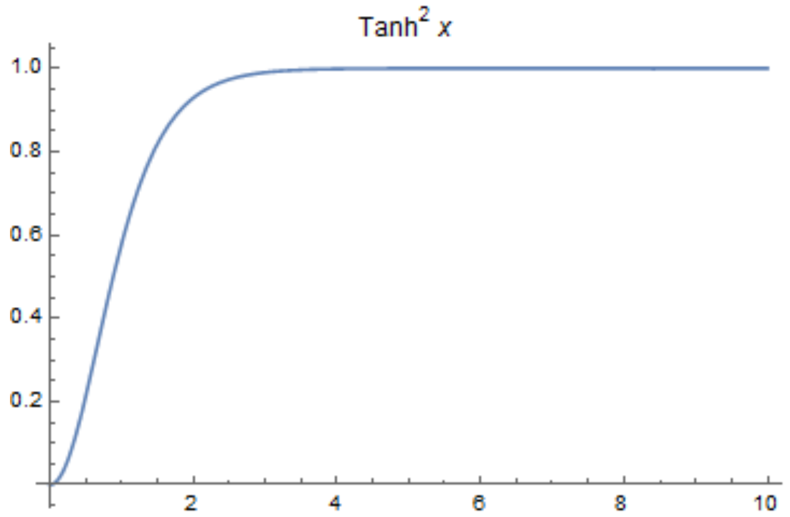
Dark Matter Capture

When a body is not in equilibrium, the rate of dark matter annihilation is extremely low.

For WIMPs, the Earth is not in equilibrium, but this is fixed in light mediator models.

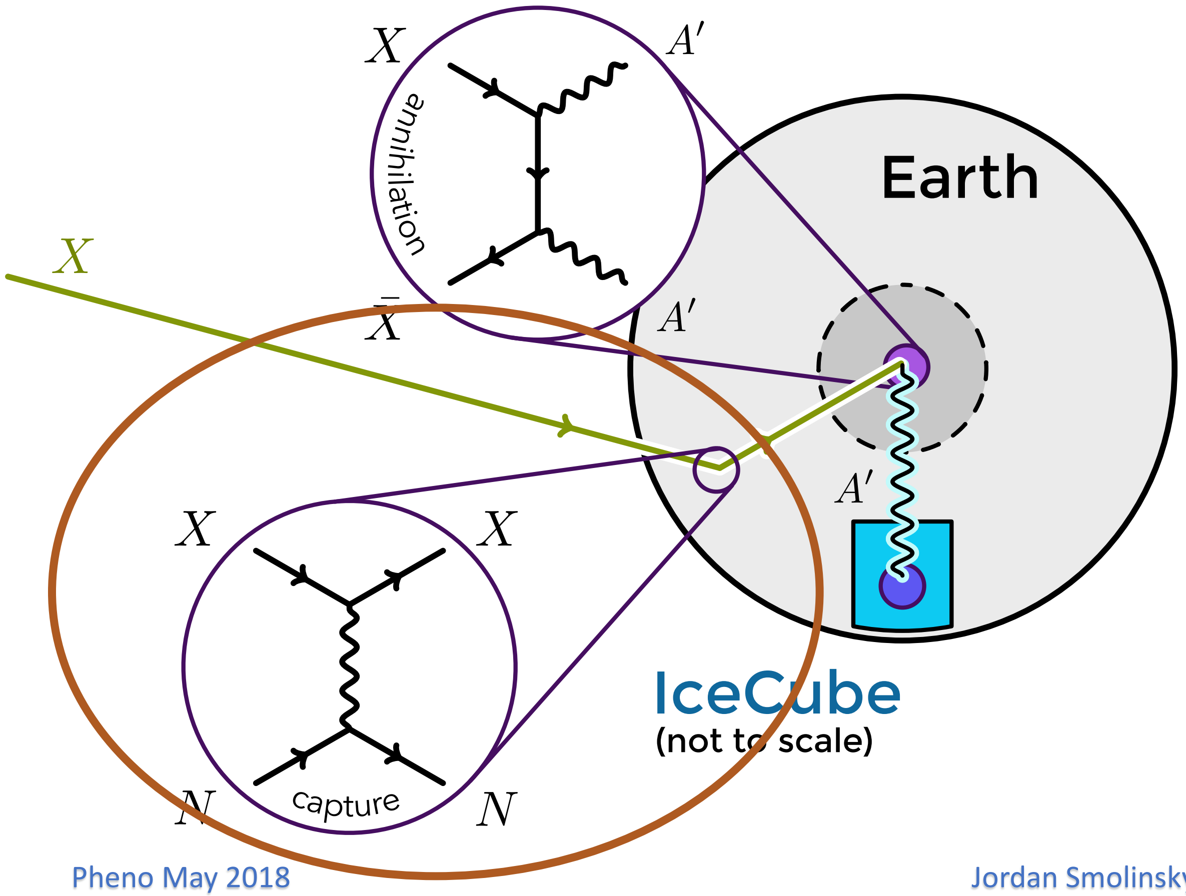
$$\tau = (C_{\text{cap}} C_{\text{ann}})^{-1/2}$$

$$\Gamma_{\text{ann}} = \frac{1}{2} C_{\text{cap}} \tanh^2 \left(\frac{\tau_\oplus}{\tau} \right)$$

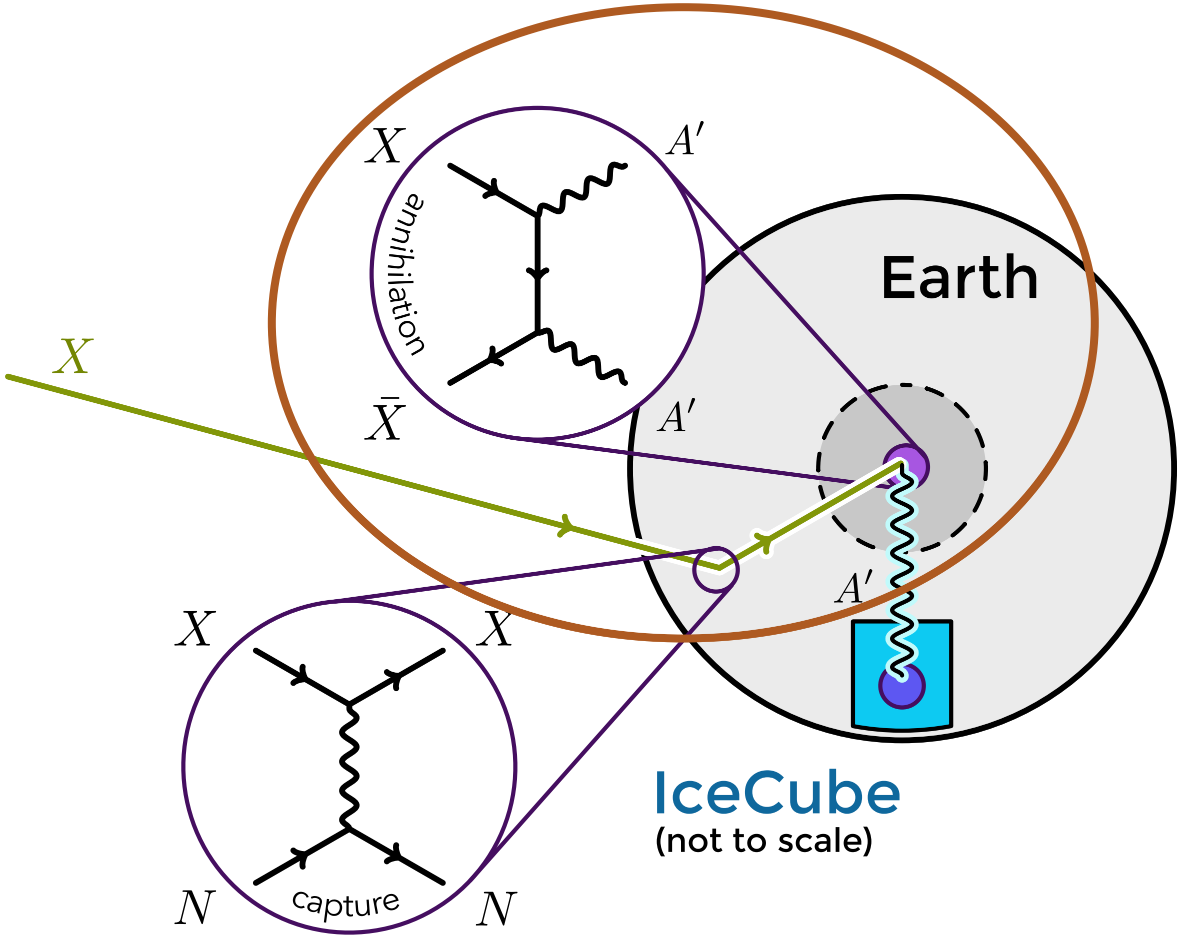


Dark Matter Capture

$$dC_{\rm cap} = n_X \sum_N n_N(r) \frac{d\sigma_N}{dE_R} w\, f_\oplus(w,r)\, d^3w\, d^3r\, dE_R$$



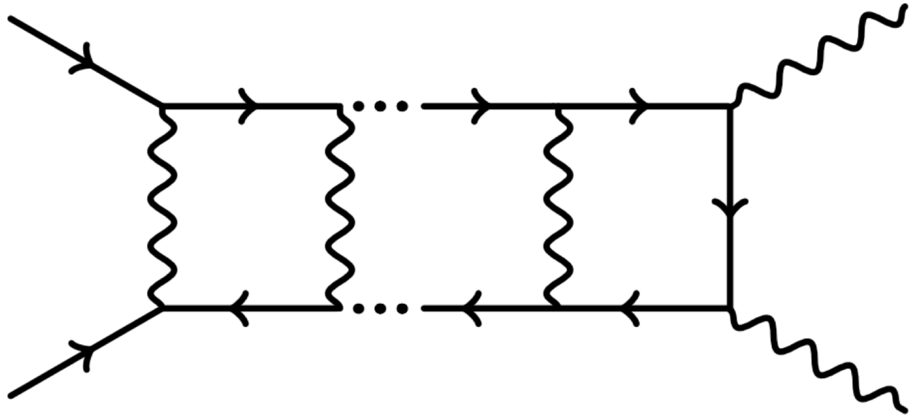
Dark Matter Annihilation



$$C_{\mathrm{ann}} = \langle \sigma_{\mathrm{ann}} v \rangle \left[\frac{G_N m_X \rho_\oplus}{3 T_\oplus} \right]^{3/2}$$

Sommerfeld Enhancement

At low temperature we need to consider ladder diagrams, or equivalently solve the SE

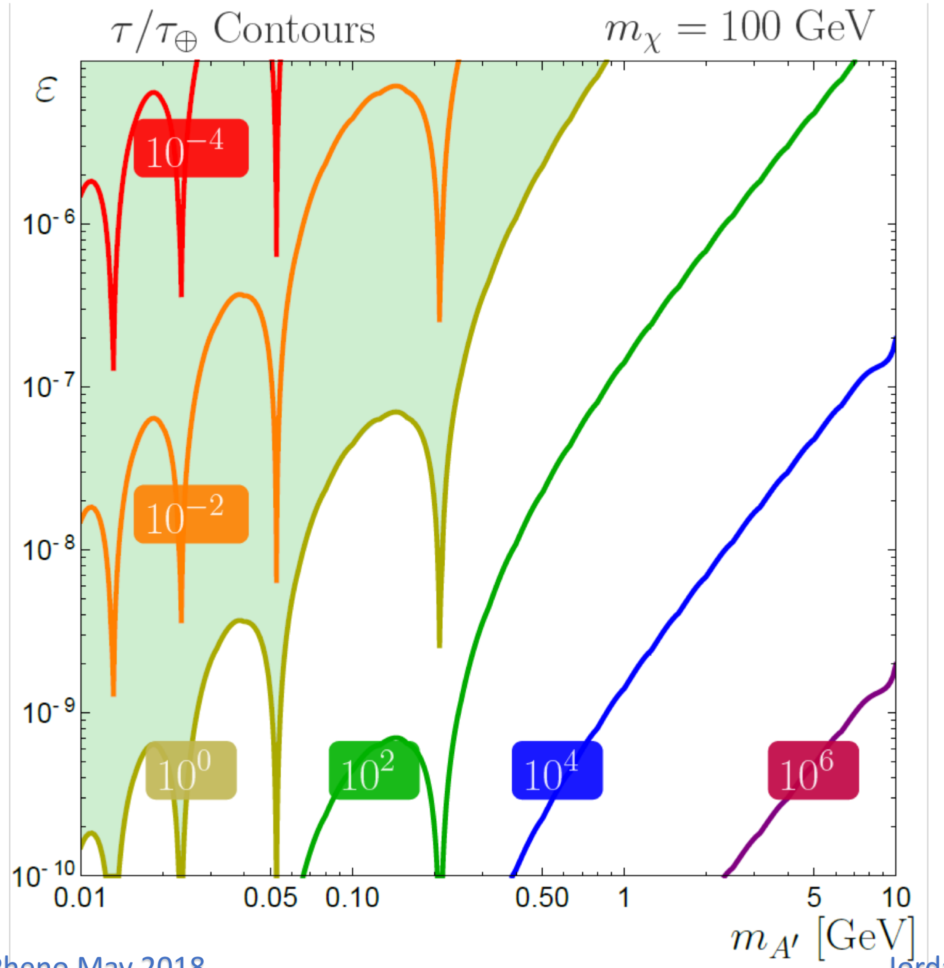


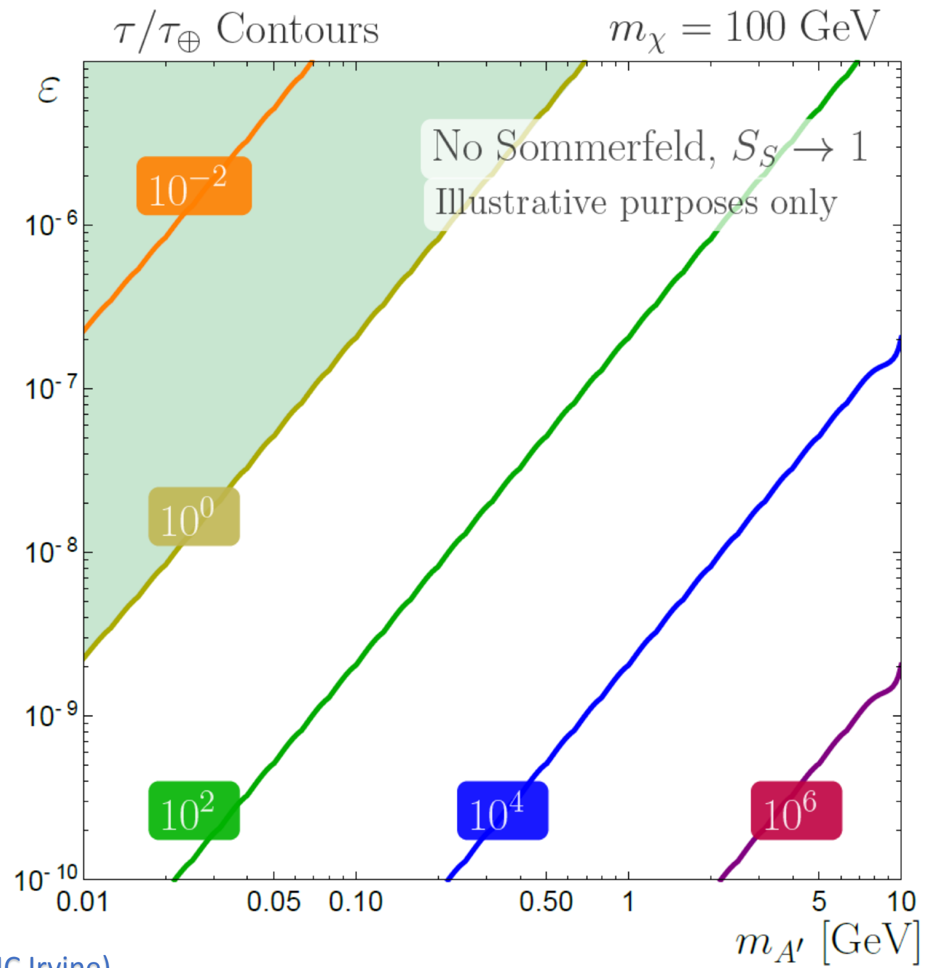
Increases the annihilation cross section

$$\langle \sigma_{\rm ann} v \rangle = (\sigma_{\rm ann} v)_{\rm tree} \langle S_S \rangle \qquad S_0 = \frac{2\pi\,\alpha_X/v}{1 - e^{-2\pi\alpha_X/v}}$$

Equilibrium Time

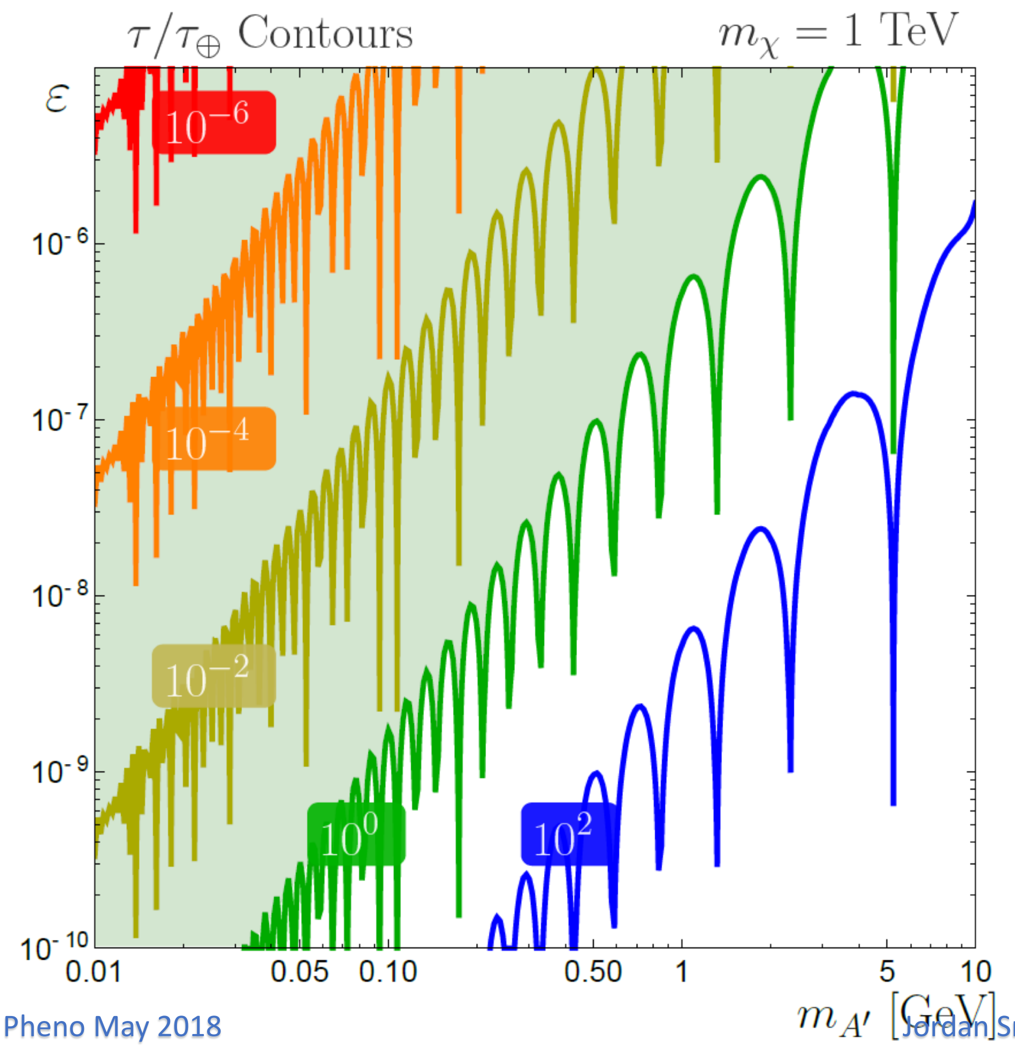
$$\tau = (C_{\text{cap}} C_{\text{ann}})^{-1/2}$$

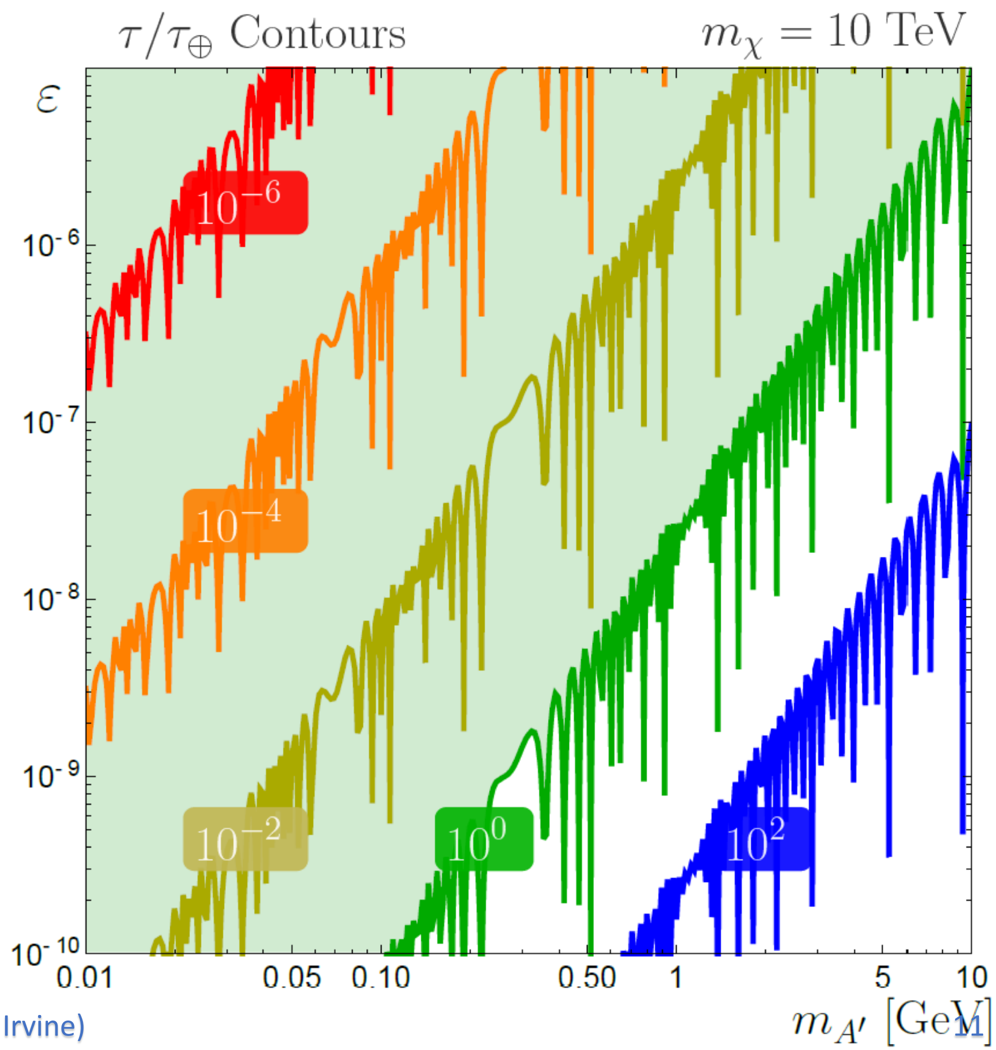




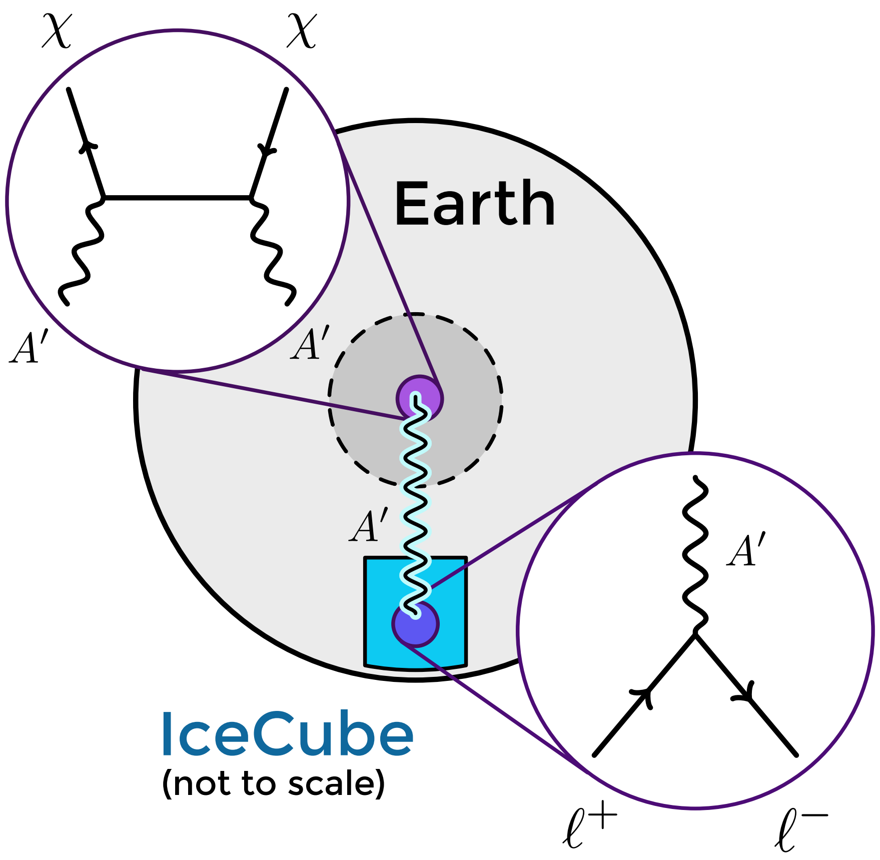
Equilibrium Time

$$\tau = (C_{\text{cap}} C_{\text{ann}})^{-1/2}$$





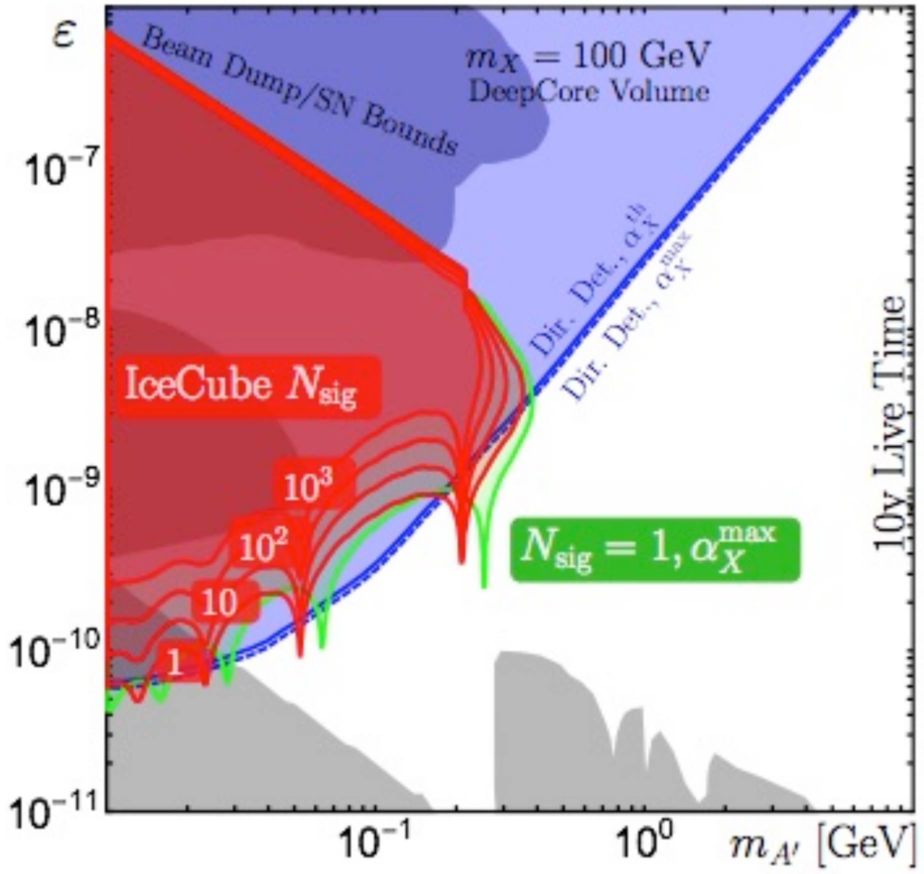
Detection



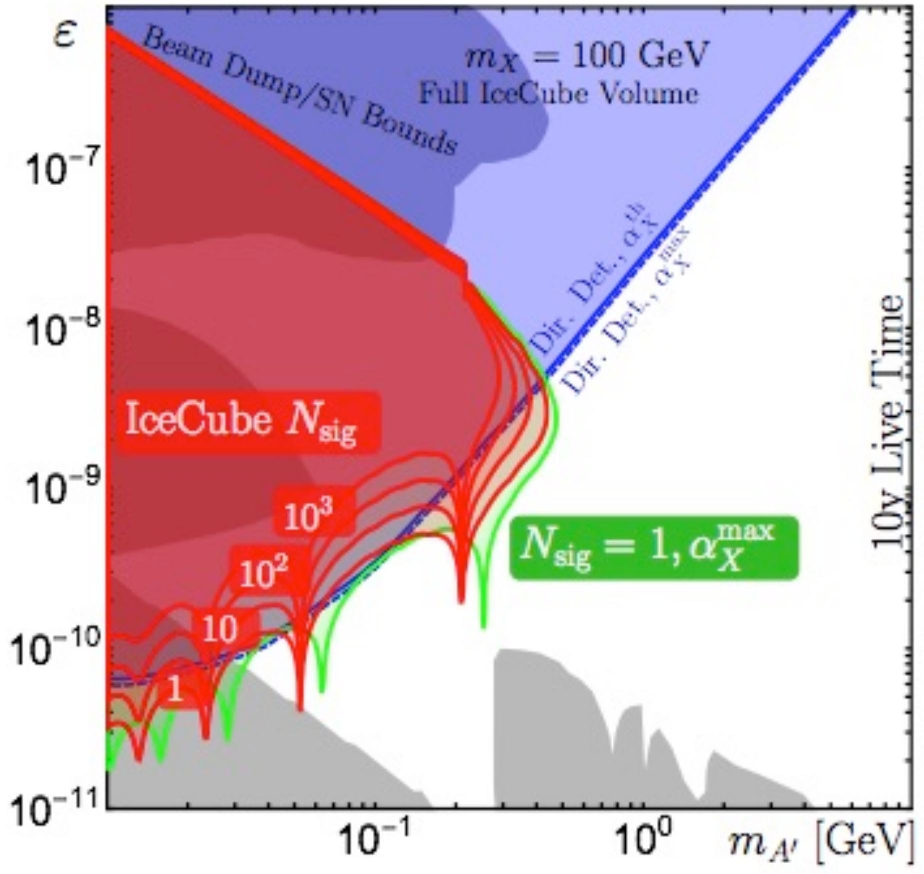
$$N_{\rm sig} = 2\,\Gamma_{\rm ann}\,\frac{A_{\rm eff}}{4\pi R_\oplus^2}\,\epsilon_{\rm decay}\,T$$

$$\epsilon_{\rm decay} = e^{-R_\oplus/L} - e^{-(R_\oplus+D)/L}$$

Detection

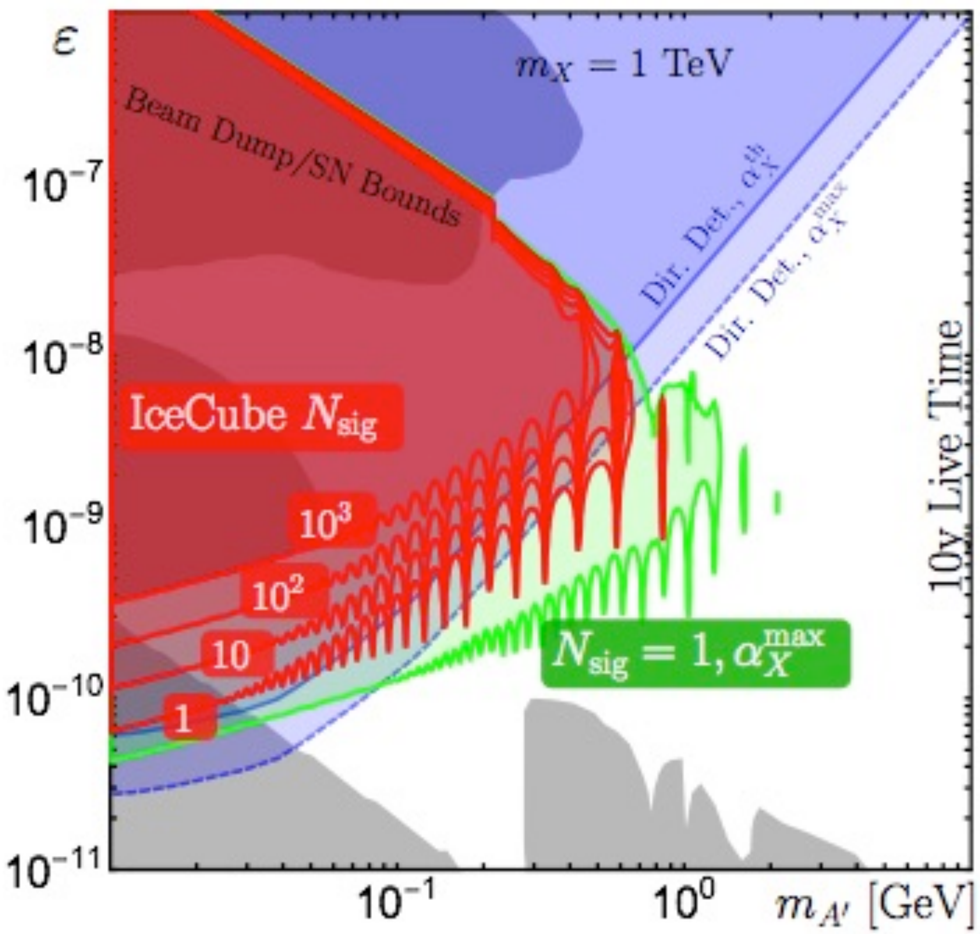


$m_X = 100$ GeV
DeepCore Volume
Beam Dump/SN Bounds
Dir. Det., α_X^{th}
Dir. Det., α_X^{max}
IceCube N_{sig}
10^3
10^2
10
1
$N_{sig} = 1, \alpha_X^{max}$
10y Live Time
ε
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-1}
10^0
$m_{A'}$ [GeV]

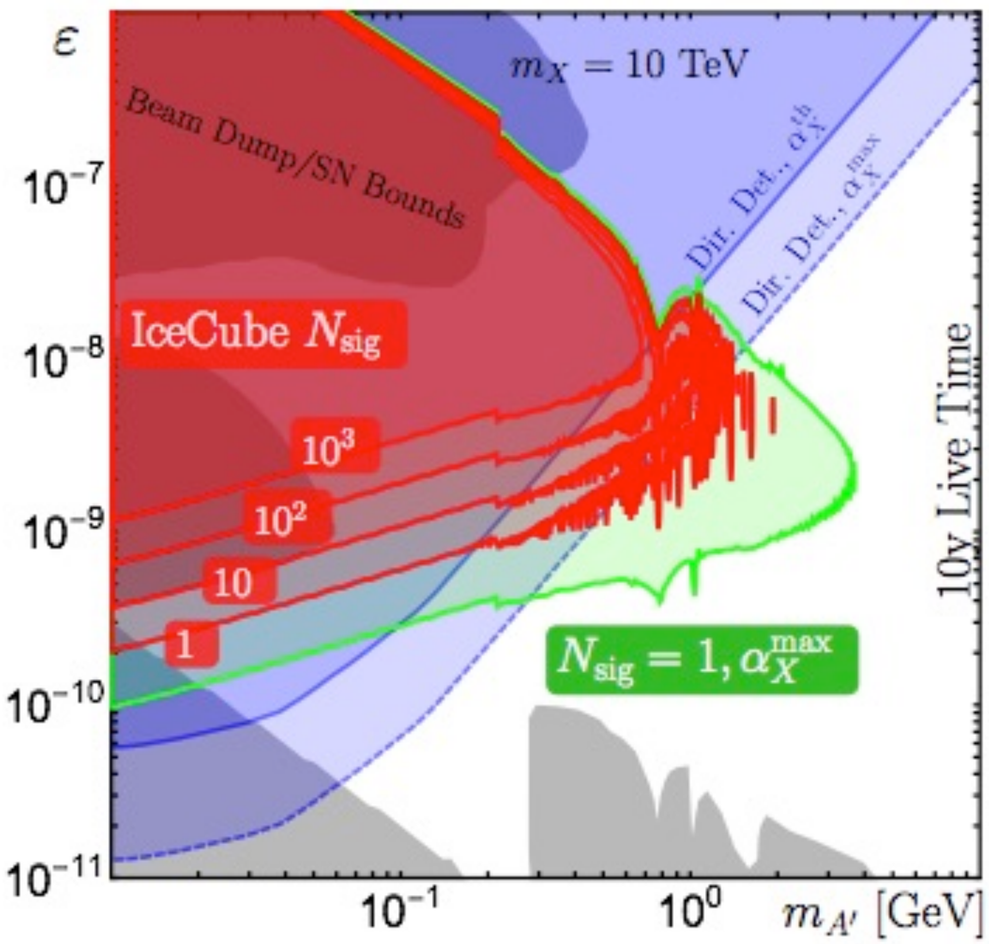


$m_X = 100$ GeV
Full IceCube Volume
Beam Dump/SN Bounds
Dir. Det., α_X^{th}
Dir. Det., α_X^{max}
IceCube N_{sig}
10^3
10^2
10
1
$N_{sig} = 1, \alpha_X^{max}$
10y Live Time
ε
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-1}
10^0
$m_{A'}$ [GeV]

Detection

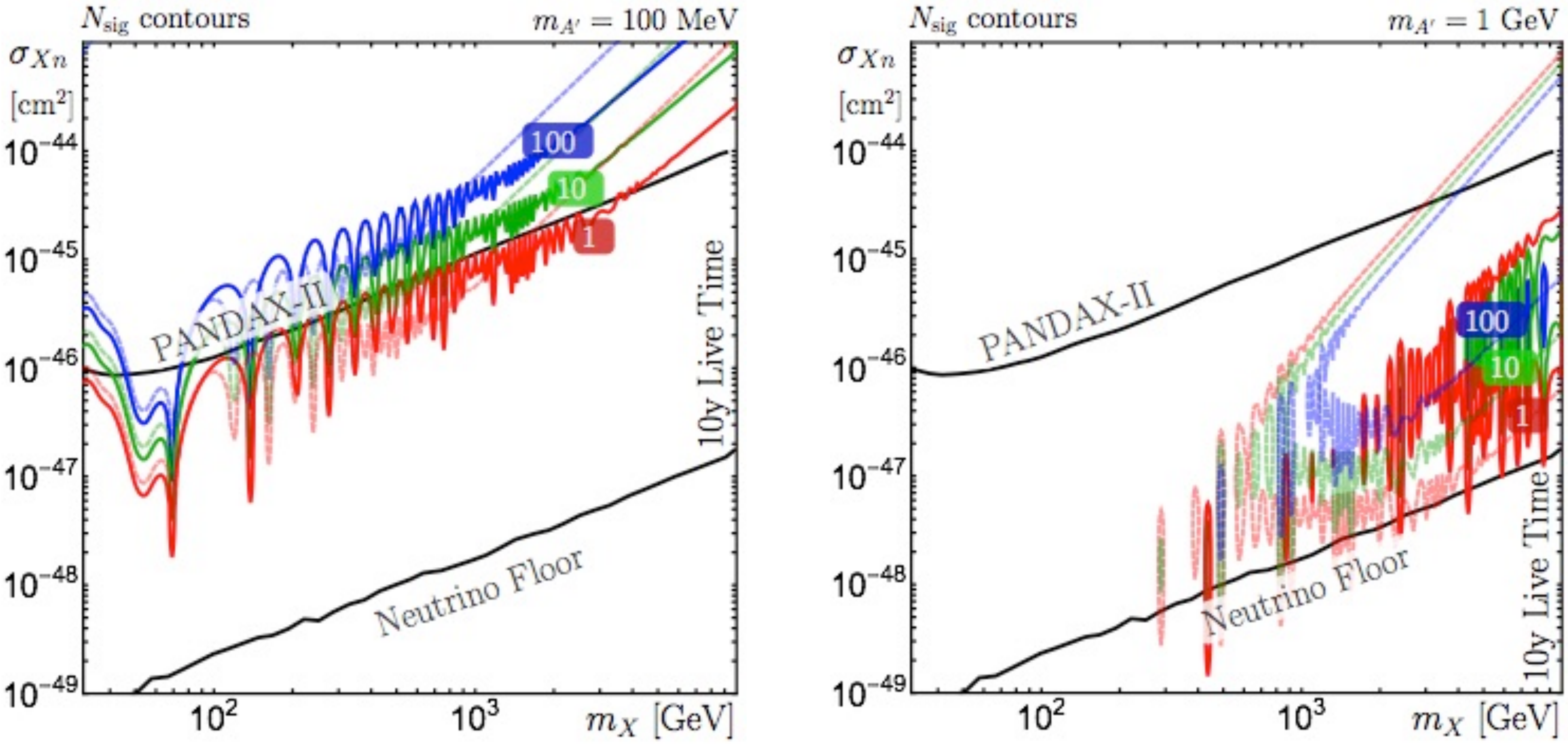


ε
$m_X = 1$ TeV
Beam Dump/SN Bounds
Dir. Det., α_X^{th}
Dir. Det., α_X^{max}
IceCube N_{sig}
10^3
10^2
10
1
$N_{sig} = 1, \alpha_X^{max}$
10y Live Time
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-1}
10^0
$m_{A'}$ [GeV]



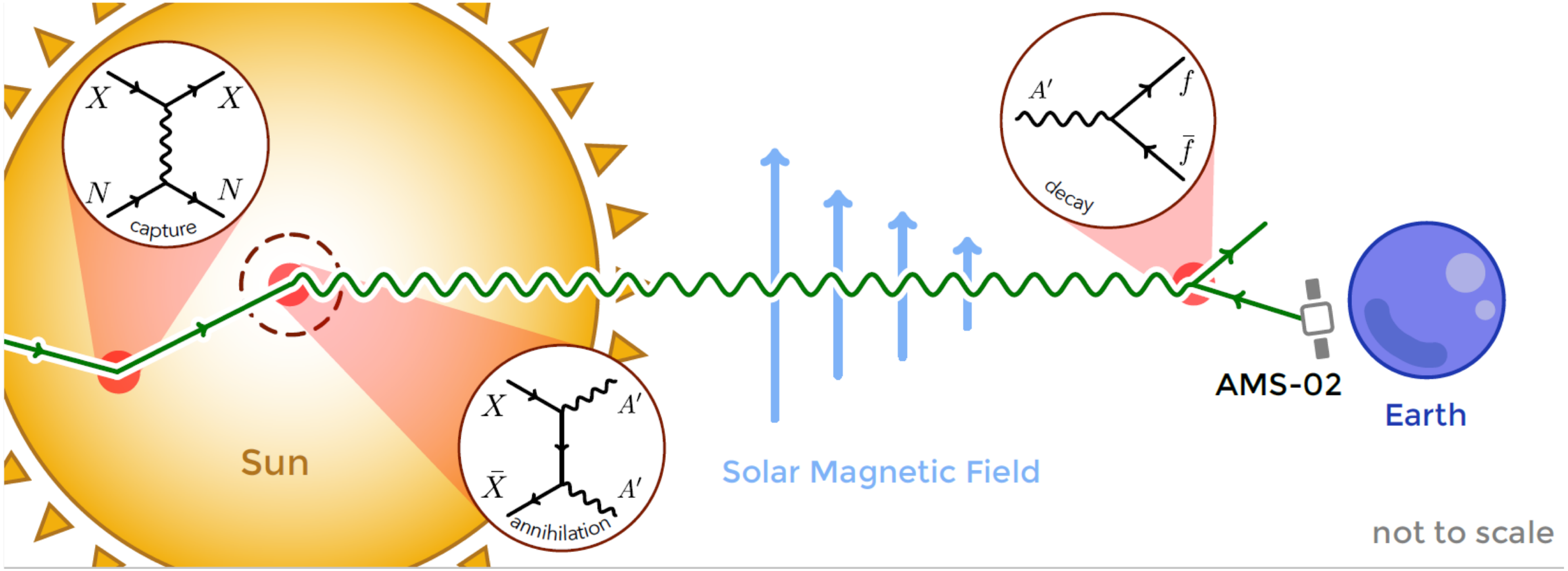
ε
$m_X = 10$ TeV
Beam Dump/SN Bounds
Dir. Det., α_X^{th}
Dir. Det., α_X^{max}
IceCube N_{sig}
10^3
10^2
10
1
$N_{sig} = 1, \alpha_X^{max}$
10y Live Time
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-1}
10^0
$m_{A'}$ [GeV]

Detection



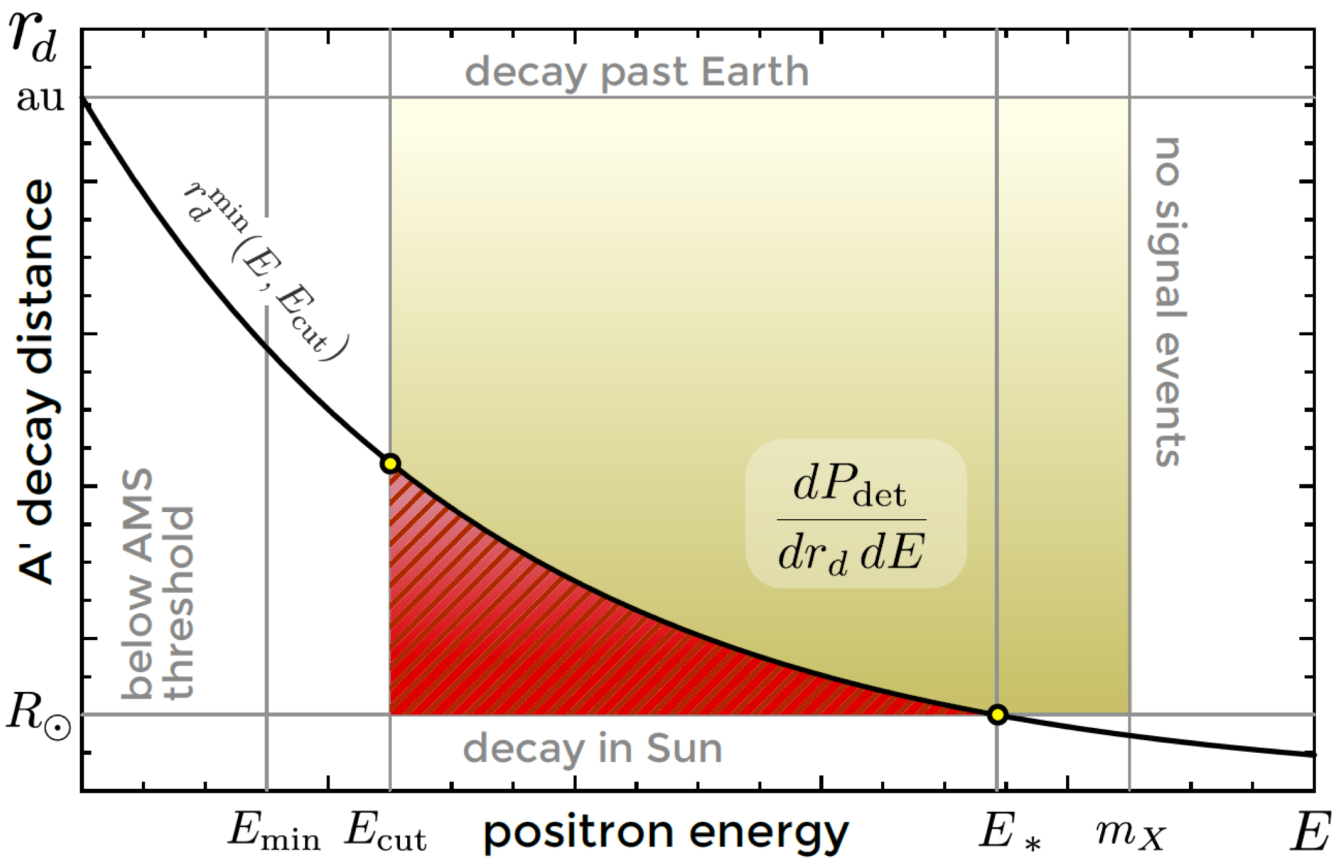
$N_{\rm sig}$ contours
$m_{A'} = 100$ MeV
σ_{Xn} [cm^2]
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
100
10
1
PANDAX-II
10y Live Time
Neutrino Floor
10^2
10^3
m_X [GeV]
$N_{\rm sig}$ contours
$m_{A'} = 1$ GeV
σ_{Xn} [cm^2]
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
PANDAX-II
100
10
1
Neutrino Floor
10y Live Time
10^2
10^3
m_X [GeV]

For the Sun



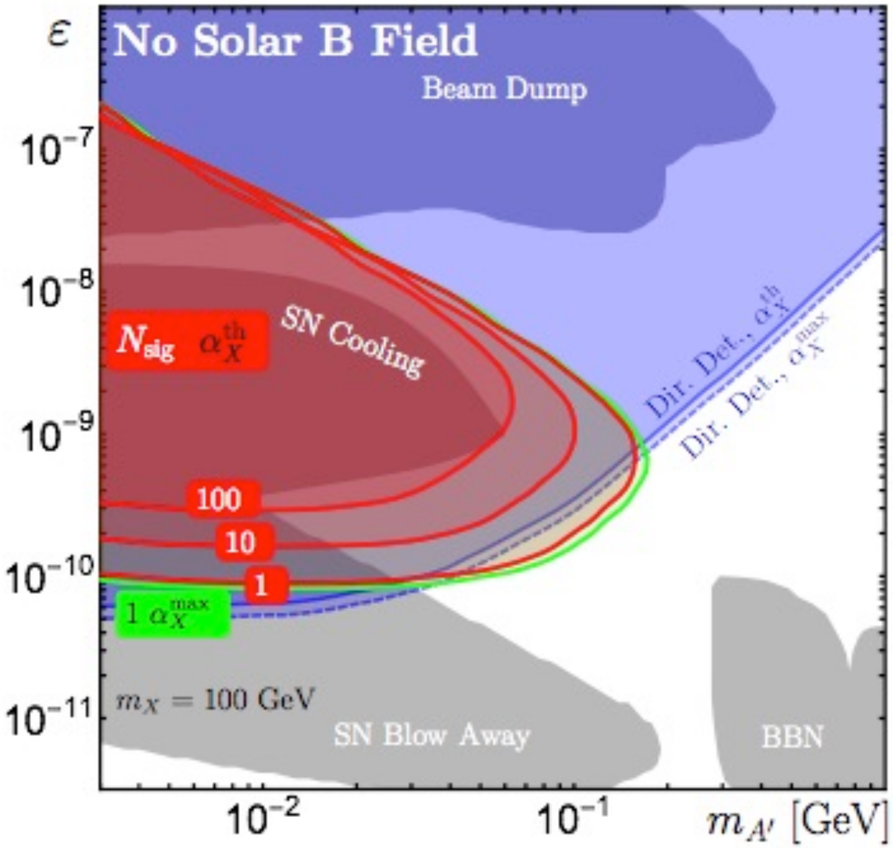
X
X
N
N
capture
X
A′
$\bar{X}$
A′
annihilation
Sun
Solar Magnetic Field
A′
f
$\bar{f}$
decay
AMS-02
Earth
not to scale

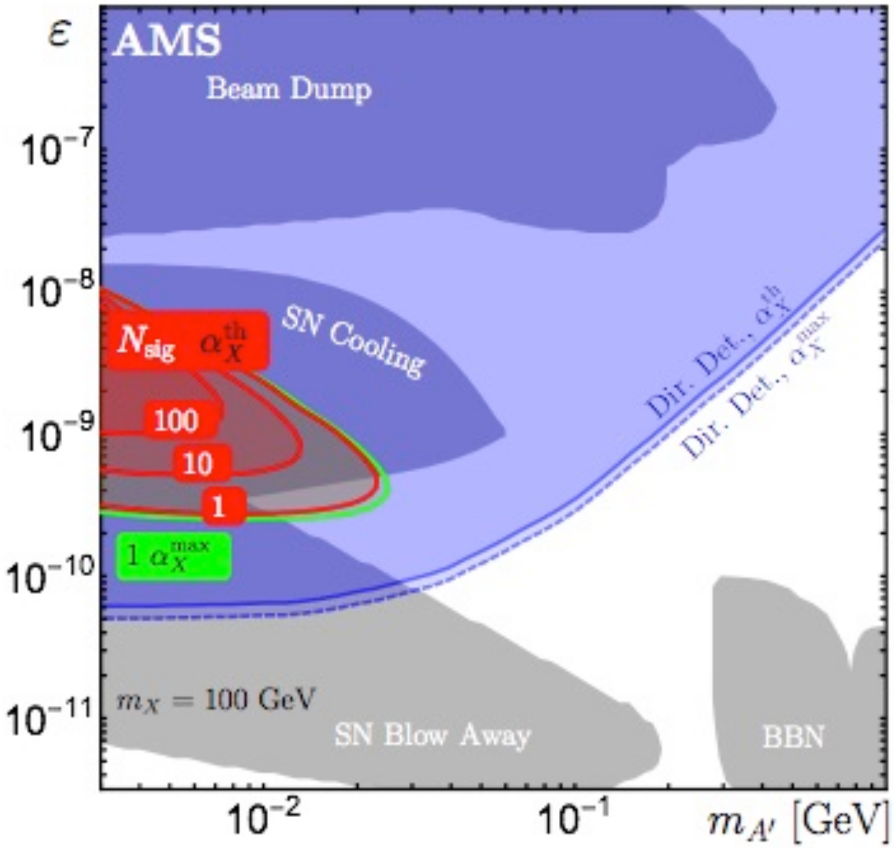
Magnetic Field Deflections



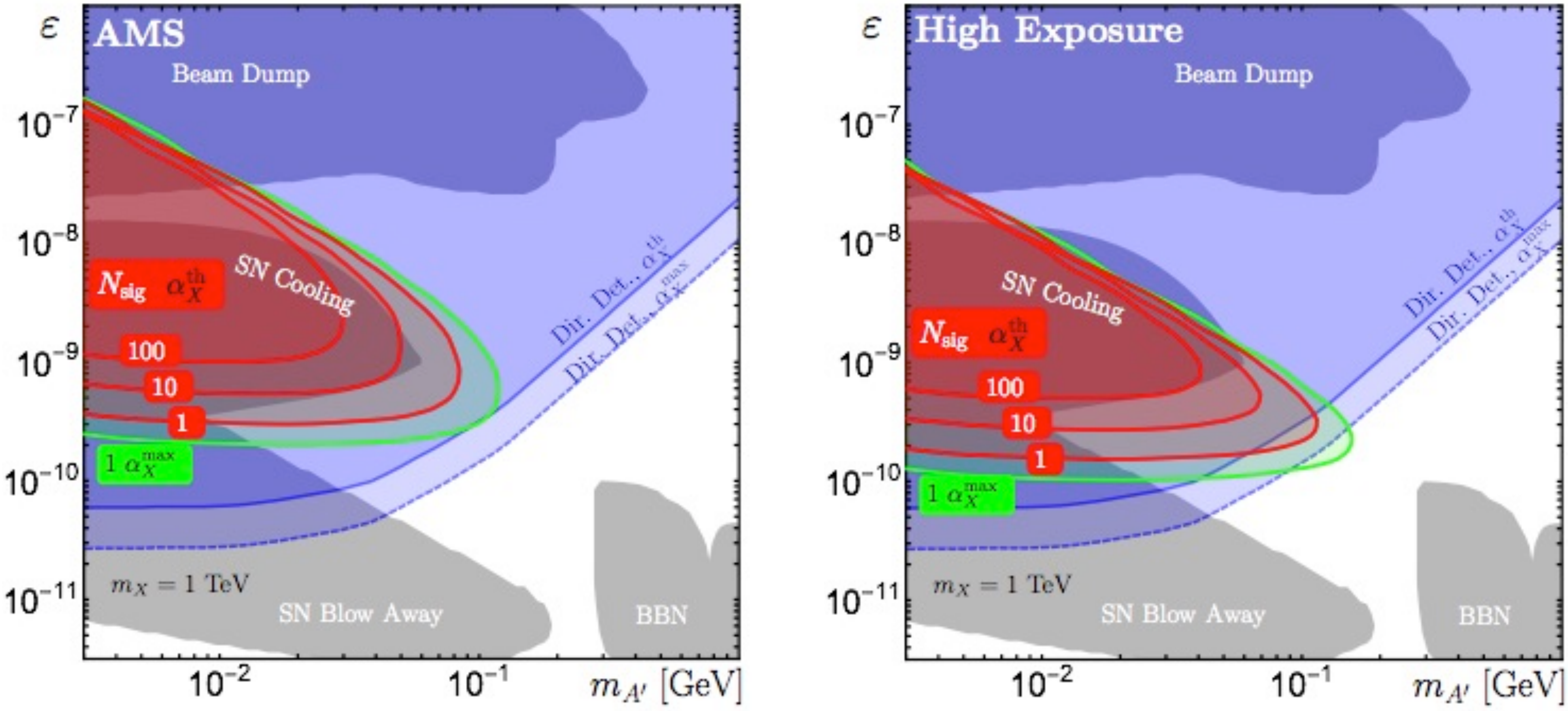
For the Sun

These cuts can make a dramatic impact on our region of sensitivity

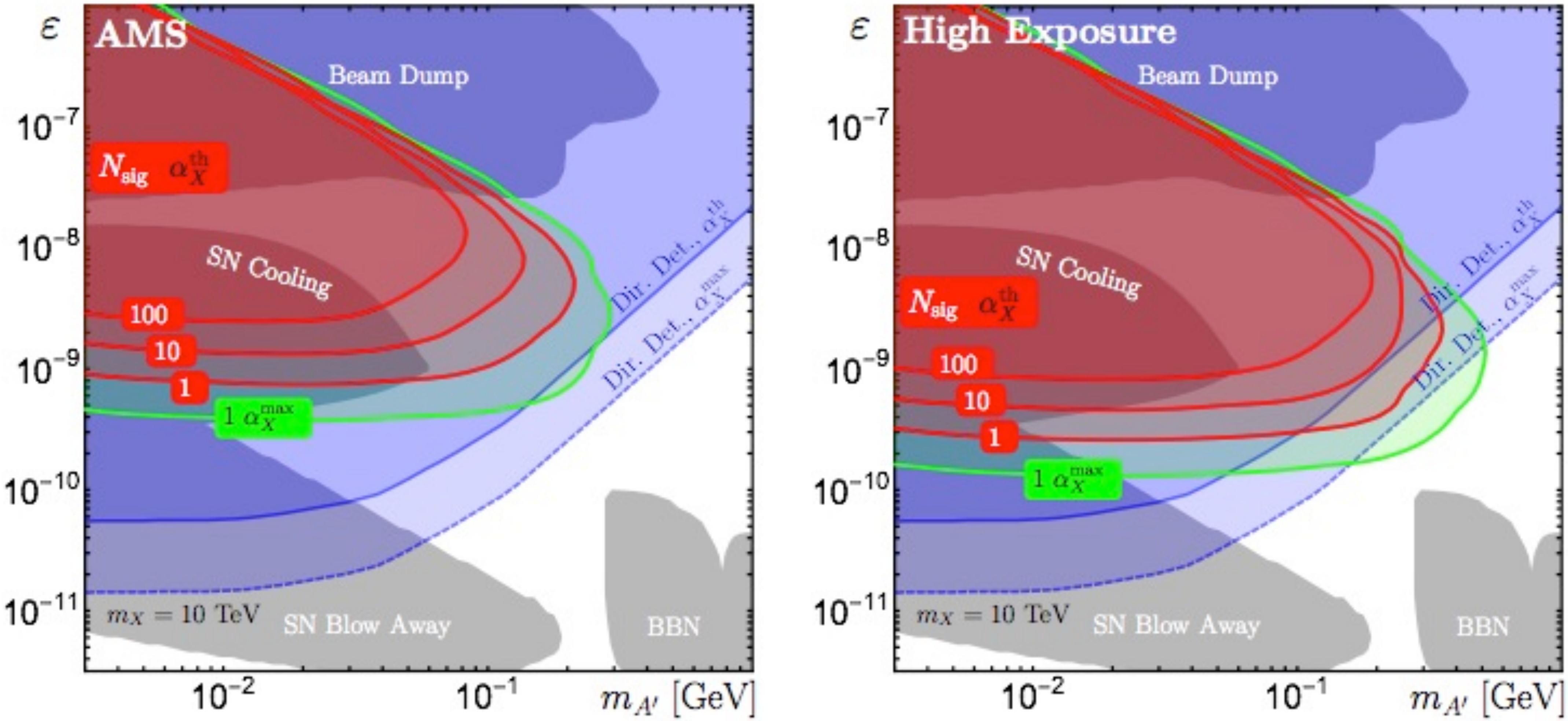




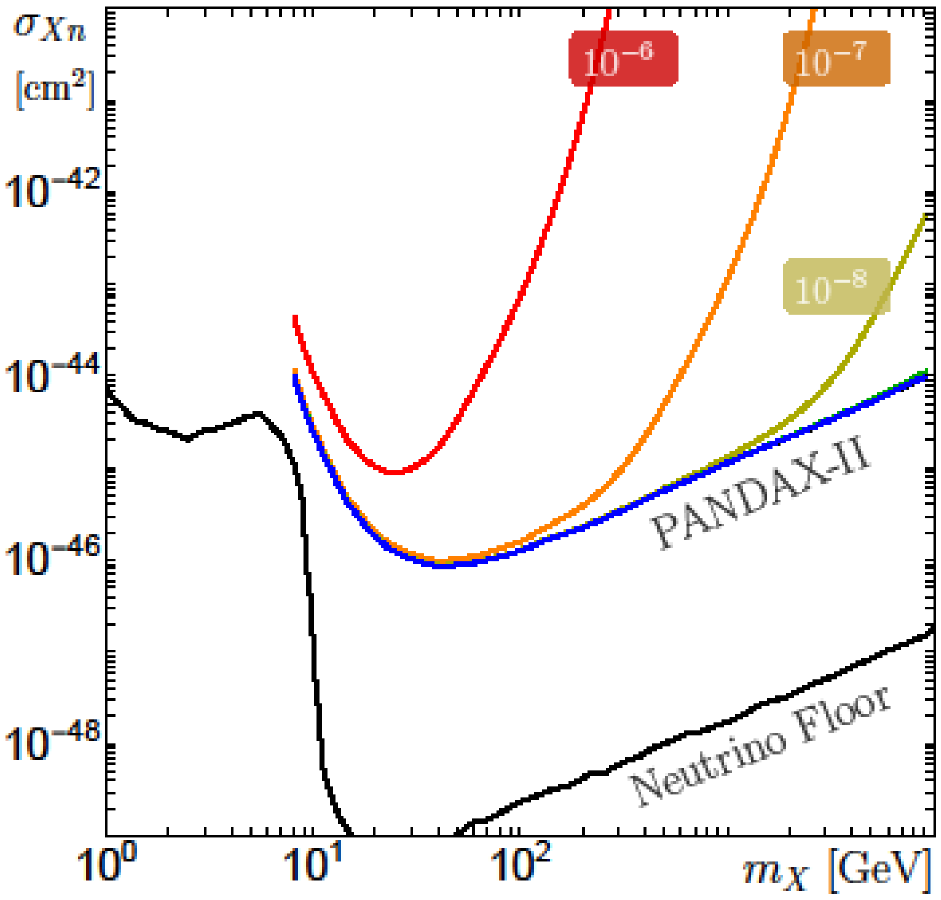
So what can we do?

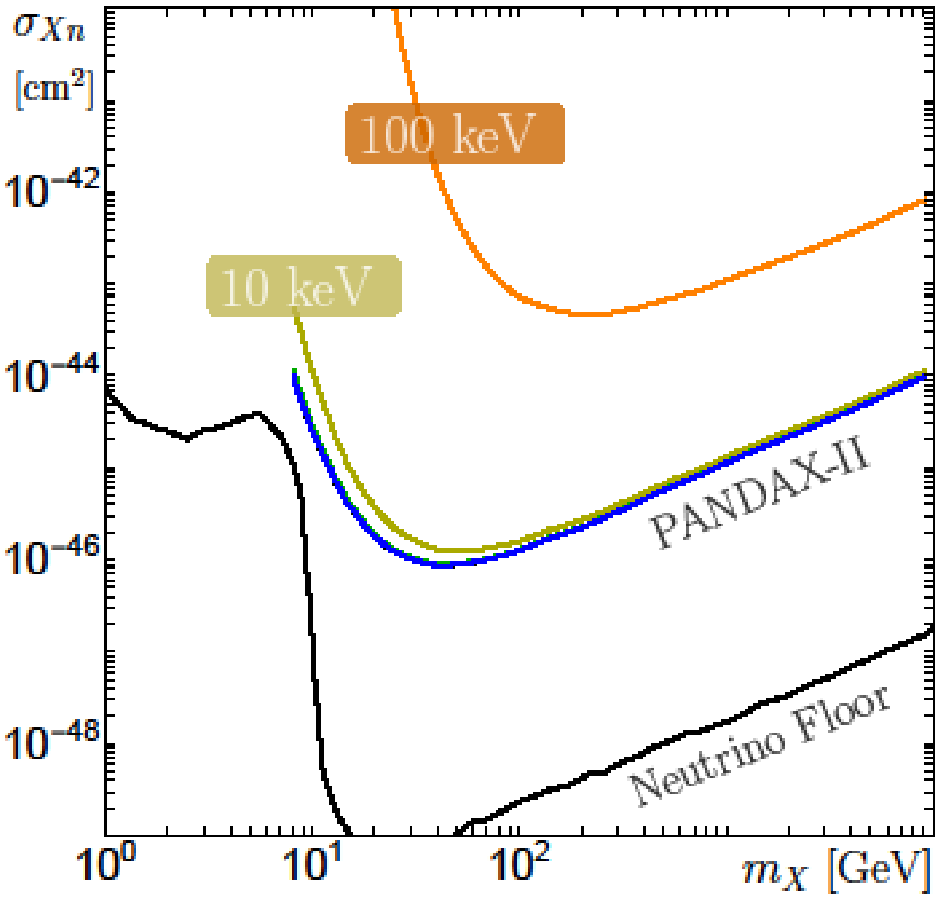


So what can we do?

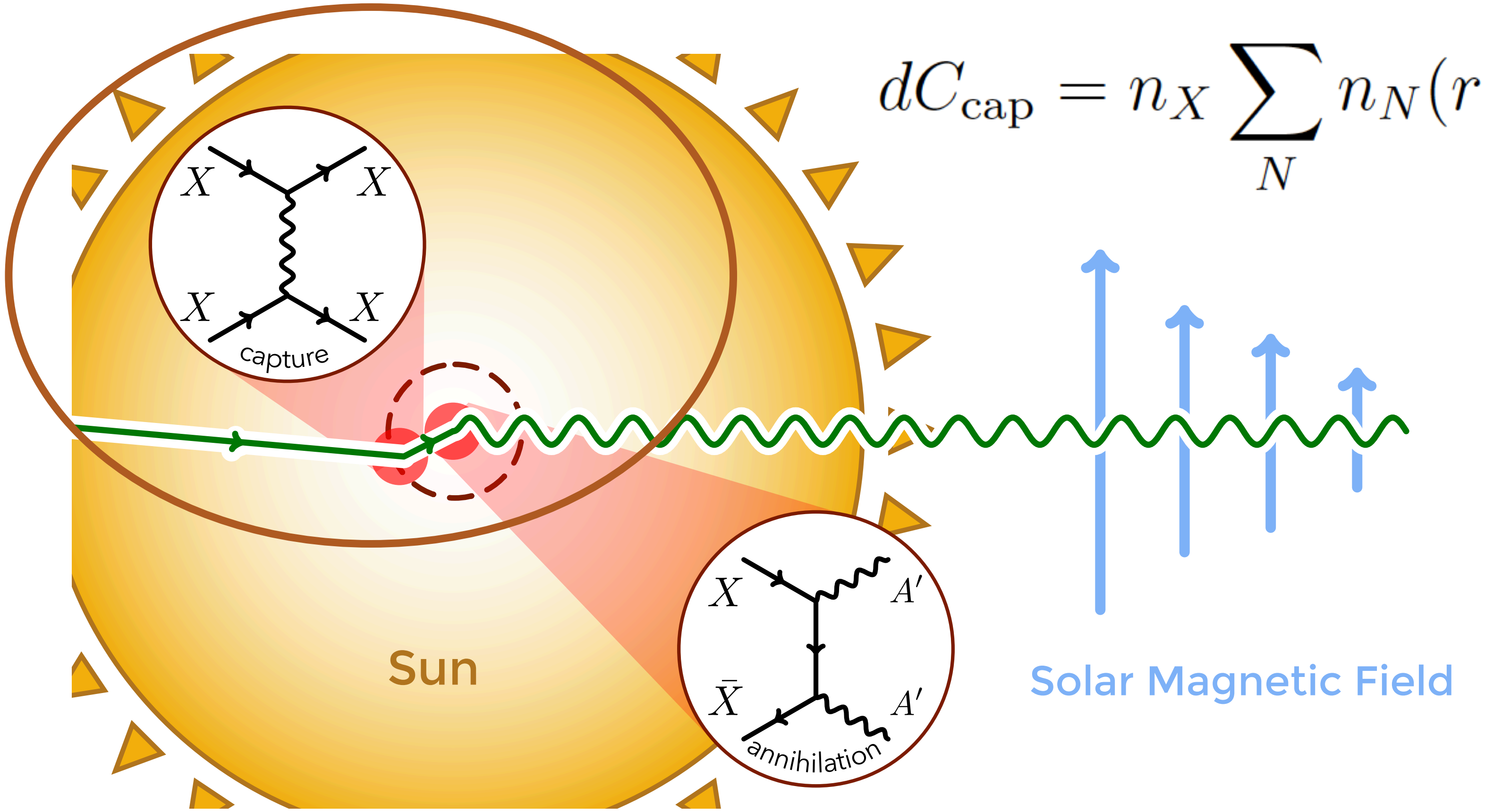


Inelastic Dark Matter





Dark Matter Capture

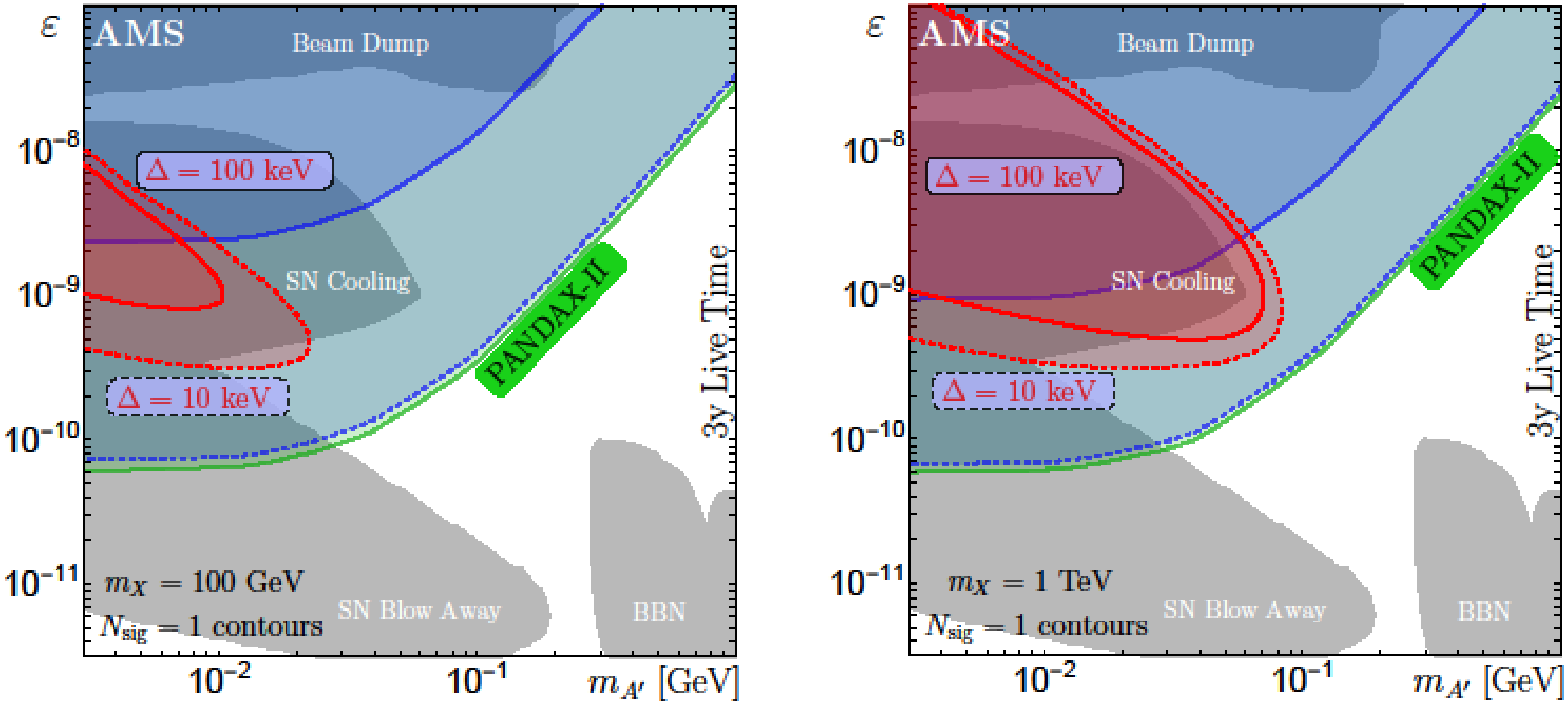


$$dC_{\text{cap}} = n_X \sum_N n_N(r) \frac{d\sigma_N}{dE_R} w\, f_{\oplus}(w, r)\, d^3w\, d^3r\, dE_R$$

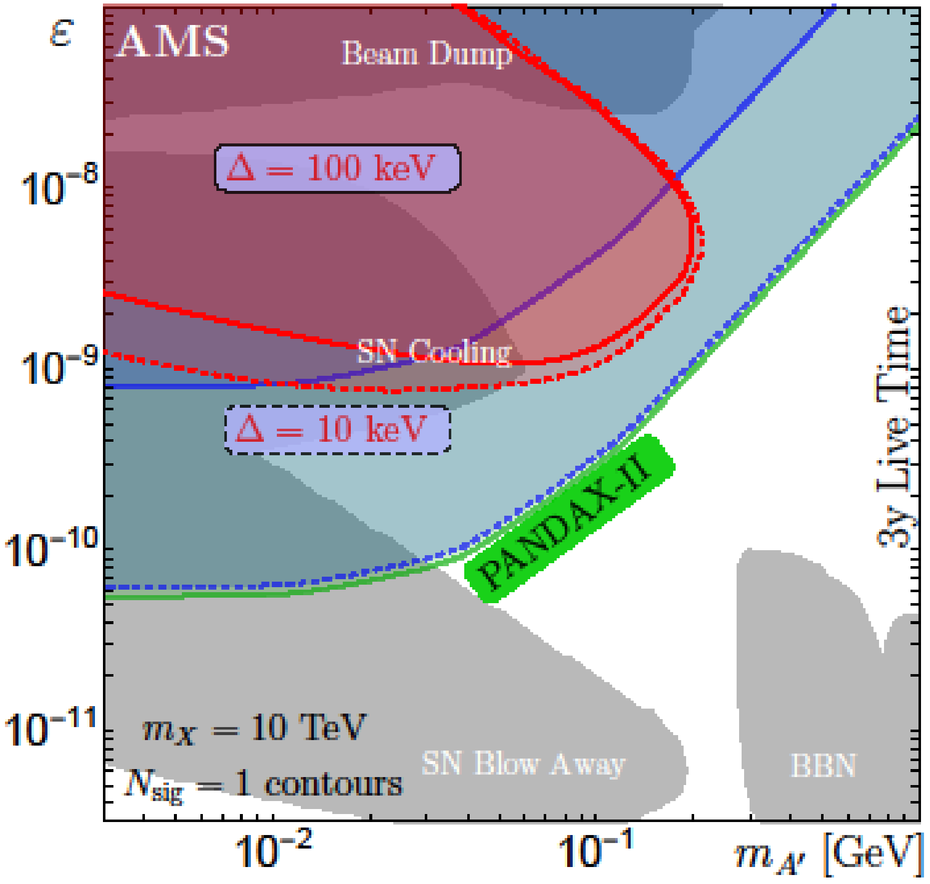
$$w_{\text{min}} = \sqrt{2\Delta\left(\frac{1}{m_N} + \frac{1}{m_X}\right)}$$

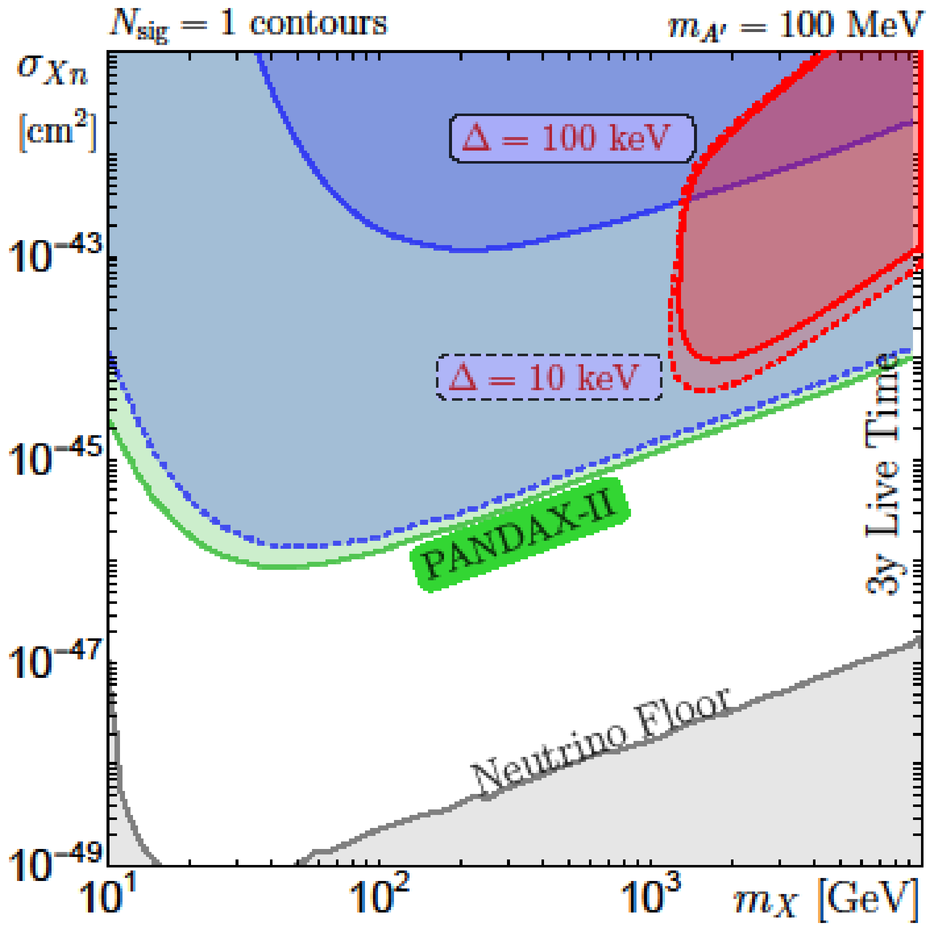
$$E_R^{\text{min}} = \frac{1}{2} m_X u^2 - \frac{1}{2}\Delta v_{\odot}^2(r)$$

Inelastic Dark Matter



Inelastic Dark Matter





Summary

Dark matter capture can be used to search for dark sectors

The Earth is a better capture target than expected

Existing experiments can already do these searches

Sommerfeld Enhancement

$$S_s = \frac{\pi}{a} \frac{\sinh(2\pi ac)}{\cosh(2\pi ac) - \cos(2\pi\sqrt{c - a^2c^2})}$$

$$a = v/(2\alpha_X)$$

$$c = 6\alpha_X m_X/(\pi^2 m_{A'})$$

Feng, Kaplinghat, Yu (1005.4678)

Magnetic Field Deflections

The Parker model gives for the azimuthal component of the magnetic field

$$B_\phi = \left(\frac{3.3\ \mathrm{nT}}{\sqrt{2}}\right)\frac{\mathrm{au}}{r}$$

So the deflection angle once the positron arrives at Earth is

$$\theta_{\mathrm{bend}}(r_d, E) = 8.9^\circ \left(\frac{\mathrm{TeV}}{E}\right)\int_{r_d}^{\mathrm{au}} \frac{B_\phi(r')\, dr'}{\mathrm{au}\,(3.3\ \mathrm{nT})} = 6.3^\circ \left(\frac{\mathrm{TeV}}{E}\right)\ln\frac{\mathrm{au}}{r_d}$$

Magnetic Field Deflections

AMS-02's positron background is fit by

$$N_B(E_{\rm cut}, \theta_{\rm cut}) = 0.051 \left(\frac{100\ {\rm GeV}}{E_{\rm cut}}\right)^{1.8} \left(\frac{\theta_{\rm cut}}{1^\circ}\right)^2 \left(\frac{T}{\rm yr}\right)$$

We set our acceptance window to allow one background event.

This allows us to place cuts on the decay distance as a function of energy

Inelastic Dark Matter

Weakens direct detection constraints

$$\sigma_{Xn}^{\text{upper}} \propto \left[\int dE_R\, dt\ F^2(E_R) \left(\frac{\text{erf}(y_{\text{min}}(\Delta) + \eta) - \text{erf}(y_{\text{min}}(\Delta) - \eta)}{\eta}\right)\right]^{-1}$$

$$\eta \equiv \frac{u_\oplus}{u_0} = \frac{V_\odot + V_\oplus \cos\gamma \cos(\omega(t - t_0))}{u_0} \qquad y_{\text{min}} \equiv \frac{1}{u_0}\sqrt{\frac{1}{2m_N E_R}}\left(\frac{m_N E_R}{\mu_N} + \Delta\right)$$