THE DARK SIDE OF THE EARTH

DIRECTIONAL INDIRECT DETECTION

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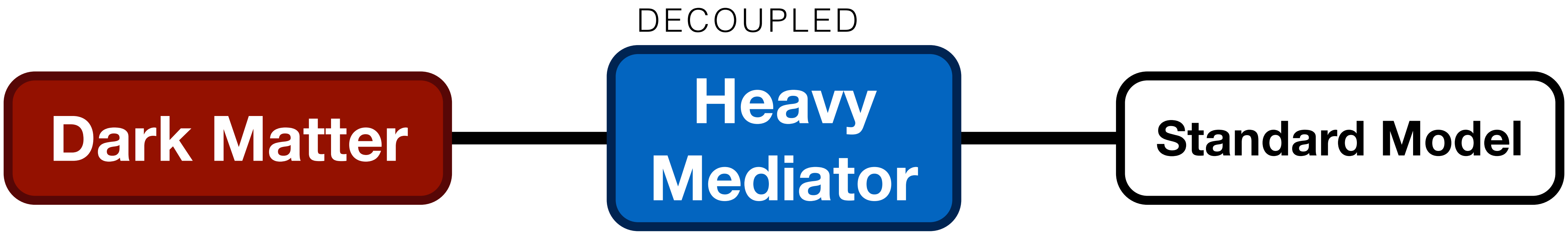
1509.07525 & 1602.01465

Phys. Rev. D93, 015014

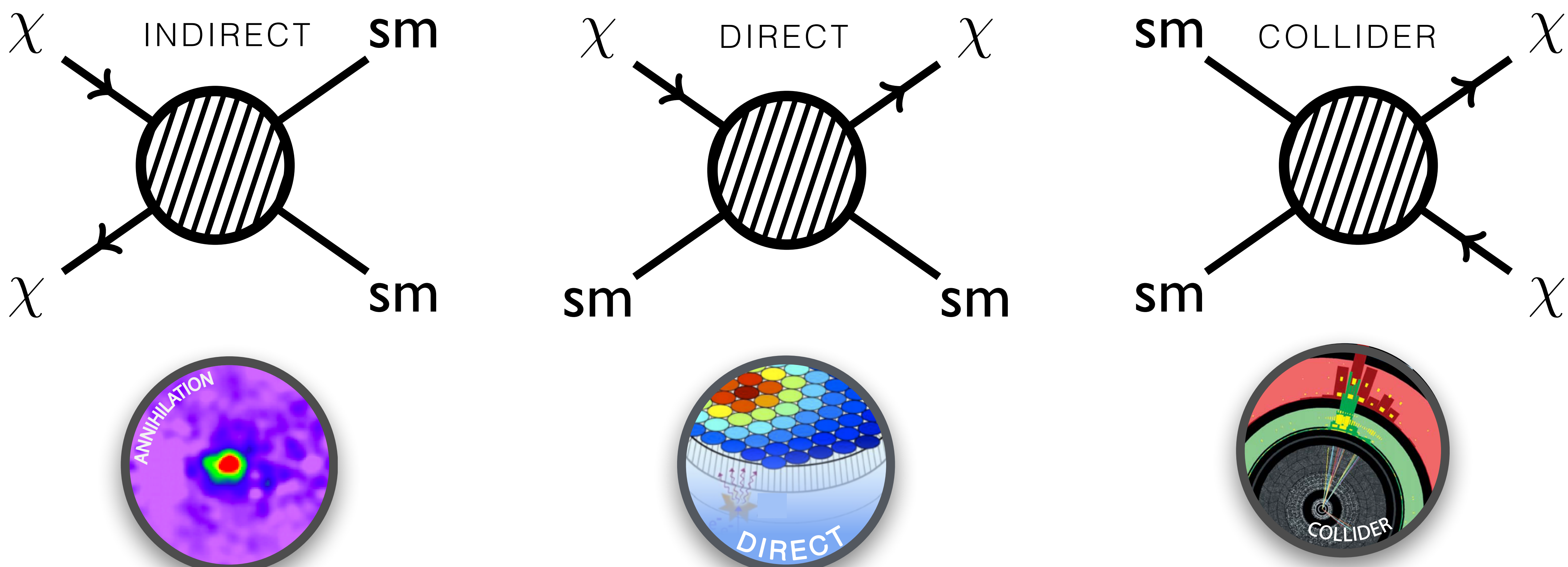
with J. Feng and J. Smolinsky

SLAC, 5 February 2016

A Hidden Sector

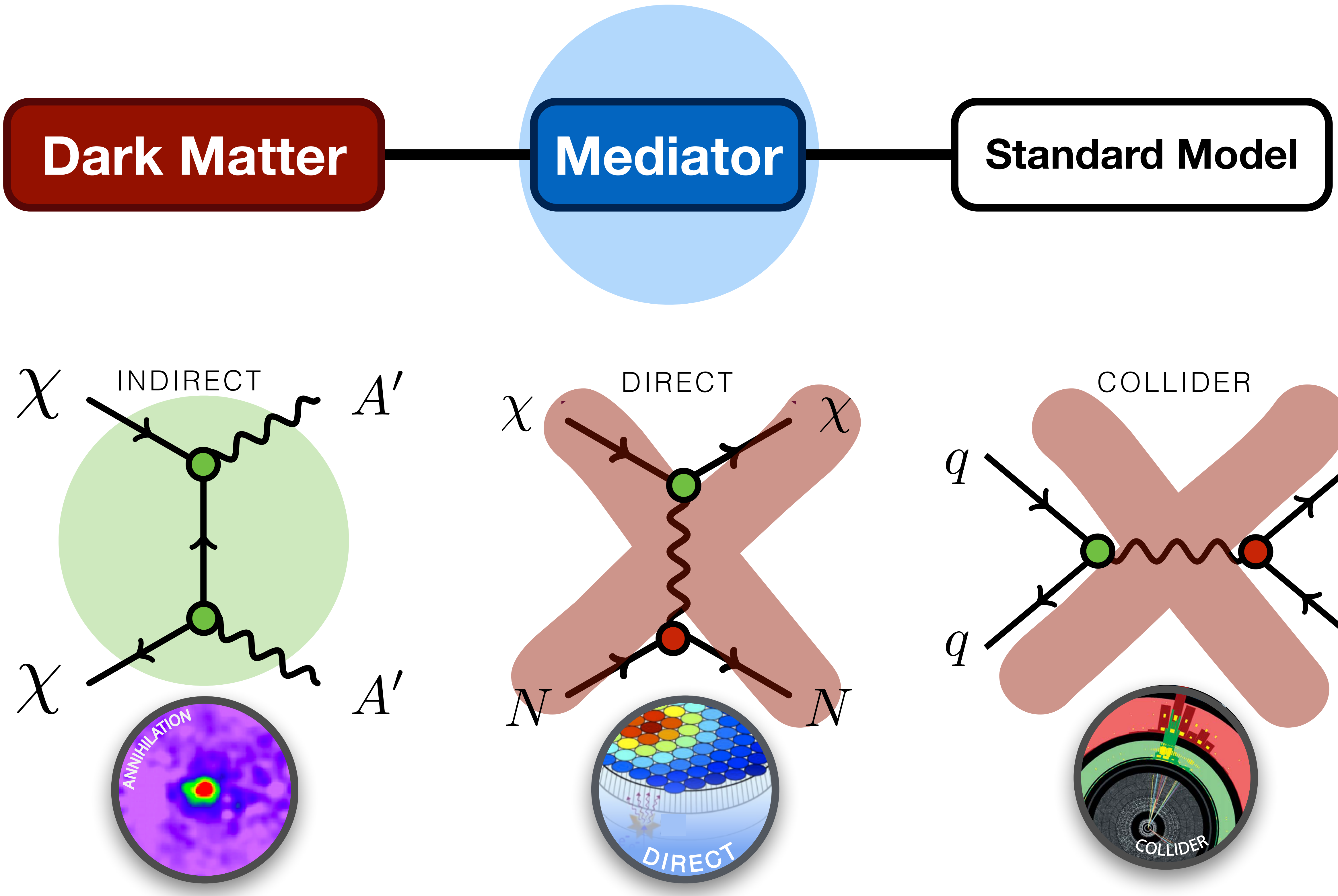


Dark matter searches related by crossing symmetry:

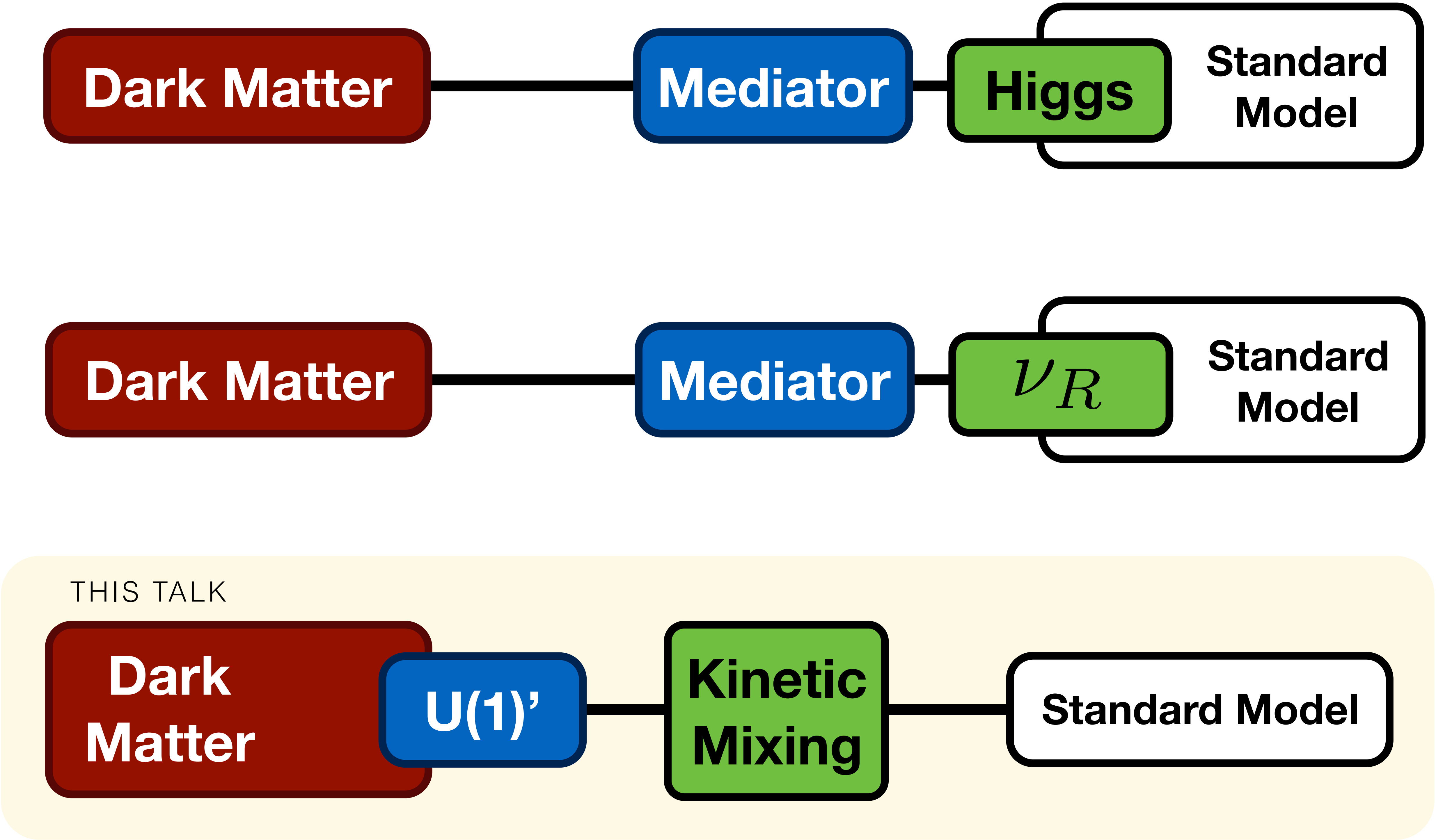


See no [dark matter], hear no [dark matter], speak no [dark matter]

Dark Portals with Light Mediators



Renormalizable Portals



MAD LIBS™ (UCI Version)

Indirect detection of dark matter is:

Dark Matter annihilates in **the Earth (or the Sun)** to
A PLACE

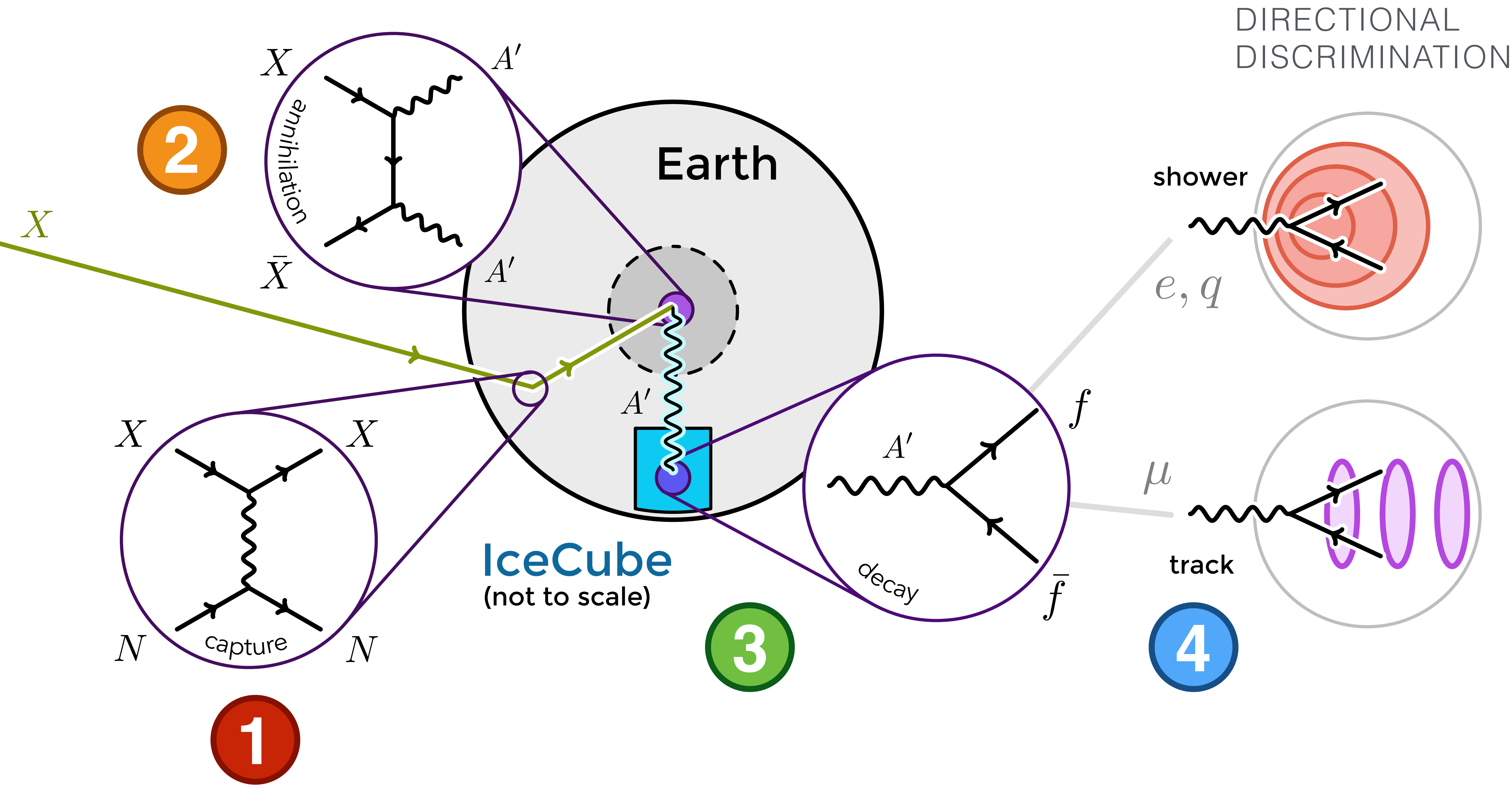
dark photons, which are detected by **IceCube (or AMS)**.
SOME PARTICLE(S) — AN EXPERIMENT

Adapted from J. Feng

CAPTURE& ANNIHILATION: Press & Spergel '85; Krauss, Srednicki, Wilczek '86; Freese '86; Griest & Seckel '87; Gaisser, Steigman, Tilav '86; Gould ('87,'88,'92)

DARK PHOTONS: Holdom (PLB 178, 65 '86); Batell, Pospelov, Ritz, Shang (0910.1567) Delaunay, Fox, Perez (0812.3331); Schuster, Toro, Yavin (0910.1602, 0910.1839); Meade, Nussinov, Papucci, Volansky (0910.4160); …

DM Capture, annihilation to A'



Minimal Model of *Faux-tons*

dark U(1)

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ig_\chi A\!\!\!/') \chi$$

$$+ m_{A'}^2 A'^2 - m_\chi \bar{\chi}\chi$$

~GeV

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2} F_{\mu\nu}F'^{\mu\nu}$$

Kinetic Mixing

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

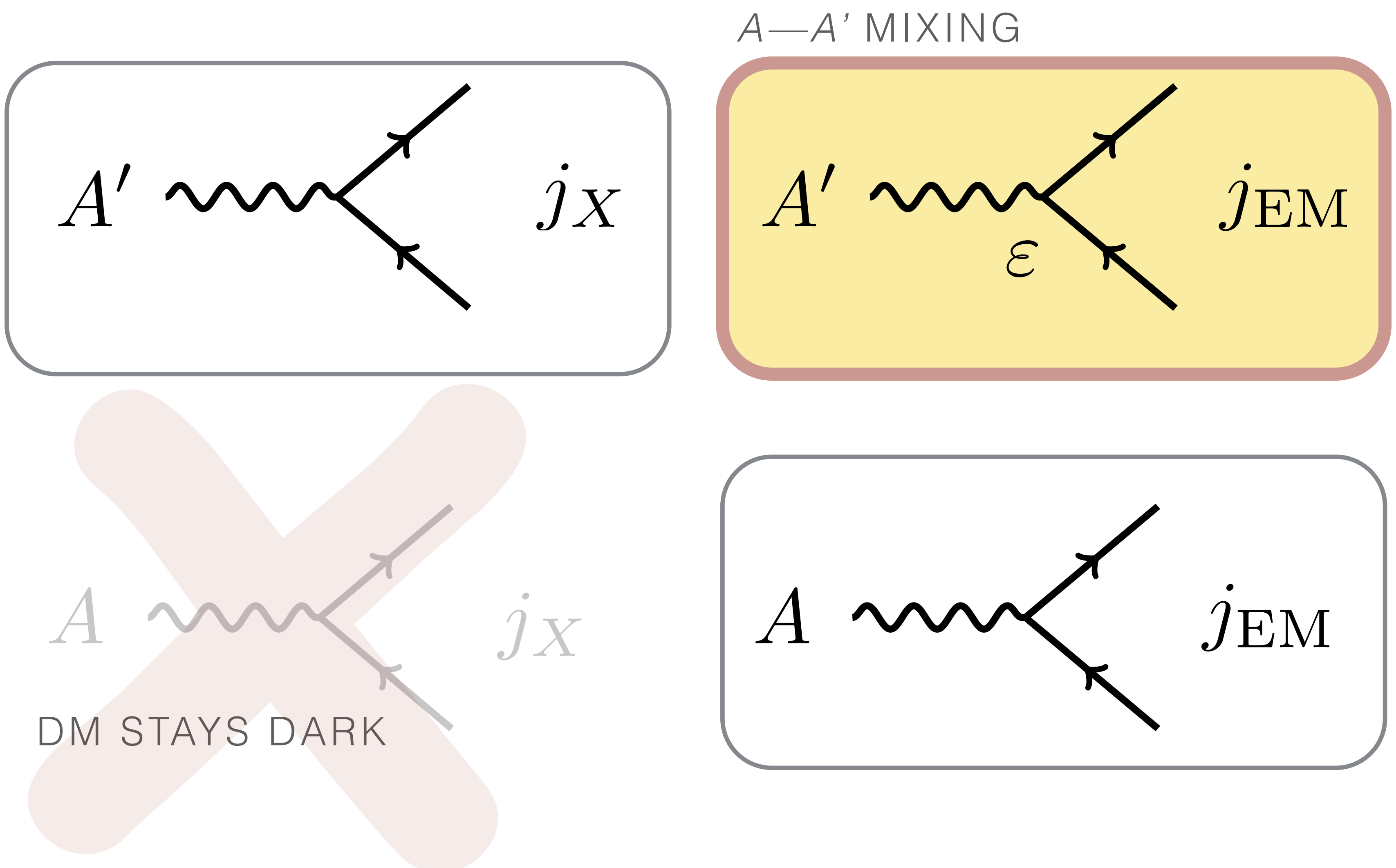
THERMAL RELIC

α_χ s.t. $\langle \sigma v \rangle_{\text{ann}} = 2.1 \times 10^{-26}\ \text{cm}^3/\text{s}$

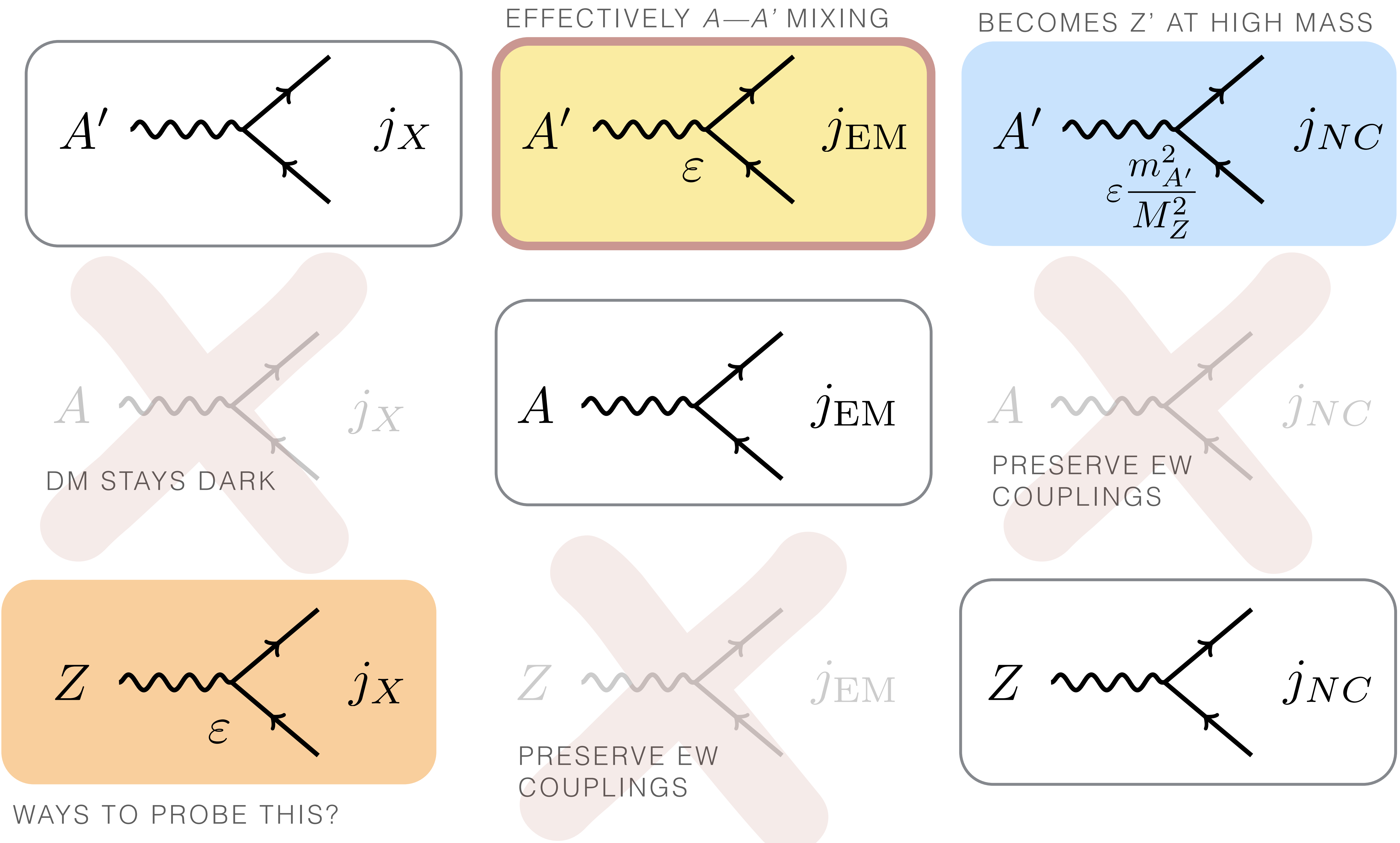
$100\ \text{GeV} \lesssim m_\chi \lesssim 10\ \text{TeV}$

WEAK-SCALE DM MASSES

Results of Diagonalization



Mixing with Hypercharge



Dark Photon Bounds

dark U(1)

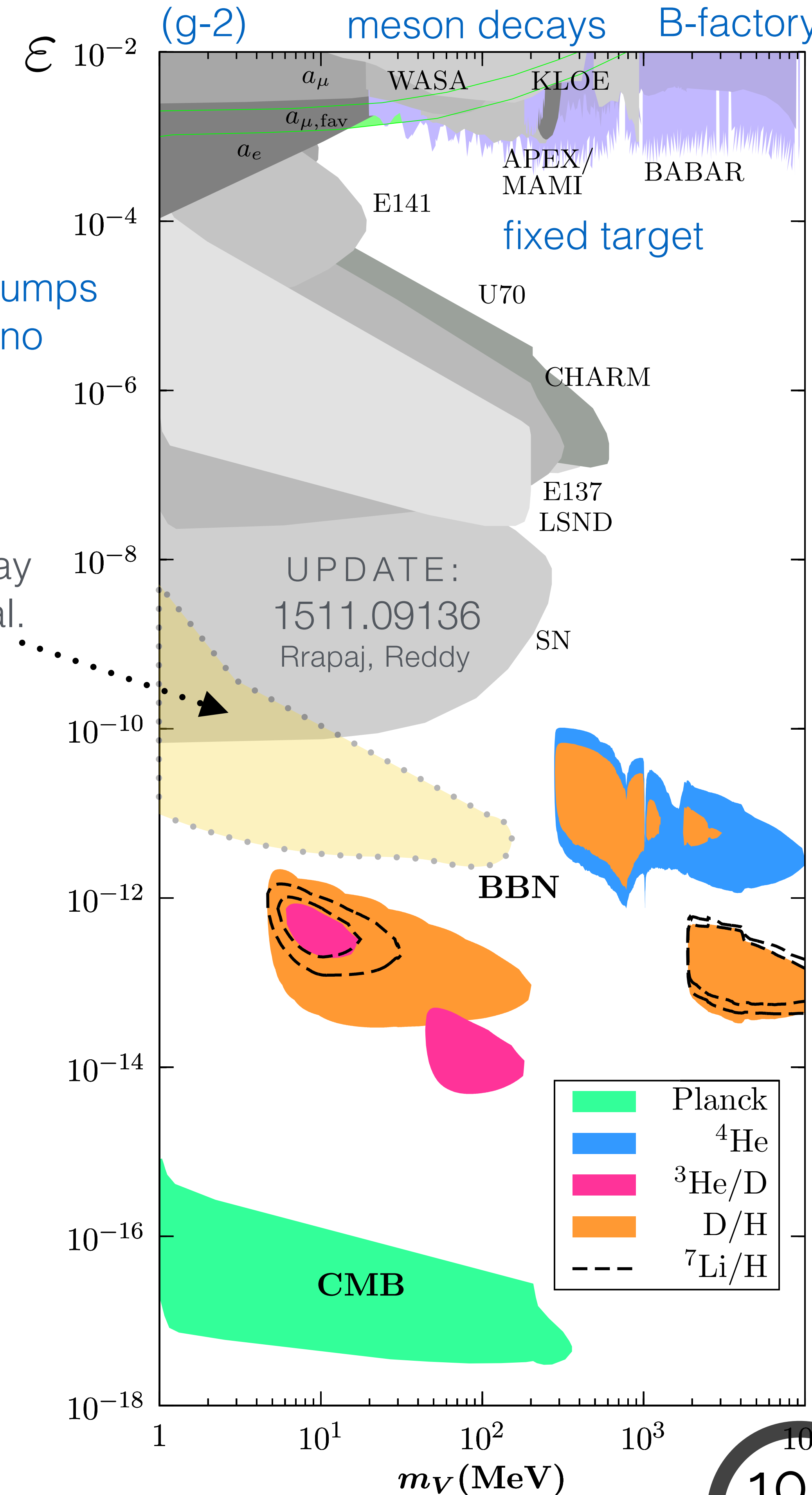
$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2_{A'}A'^2$$

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

Kinetic Mixing

beam dumps & neutrino

SN Blow Away
Kazanas et al.
1410.0221



Fradette et al. 1407.0993

Dark Photon Minimal Model

dark U(1)

$$\mathcal{L}_{\text{dark}} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ig_\chi A\!\!\!/')\chi - m_{A'}A'^2 - m_\chi\bar{\chi}\chi$$

$$\mathcal{L}_{\text{mix}} = \frac{\epsilon}{2}F^{(0)}_{\mu\nu}F'^{(0)\mu\nu}$$

Kinetic Mixing

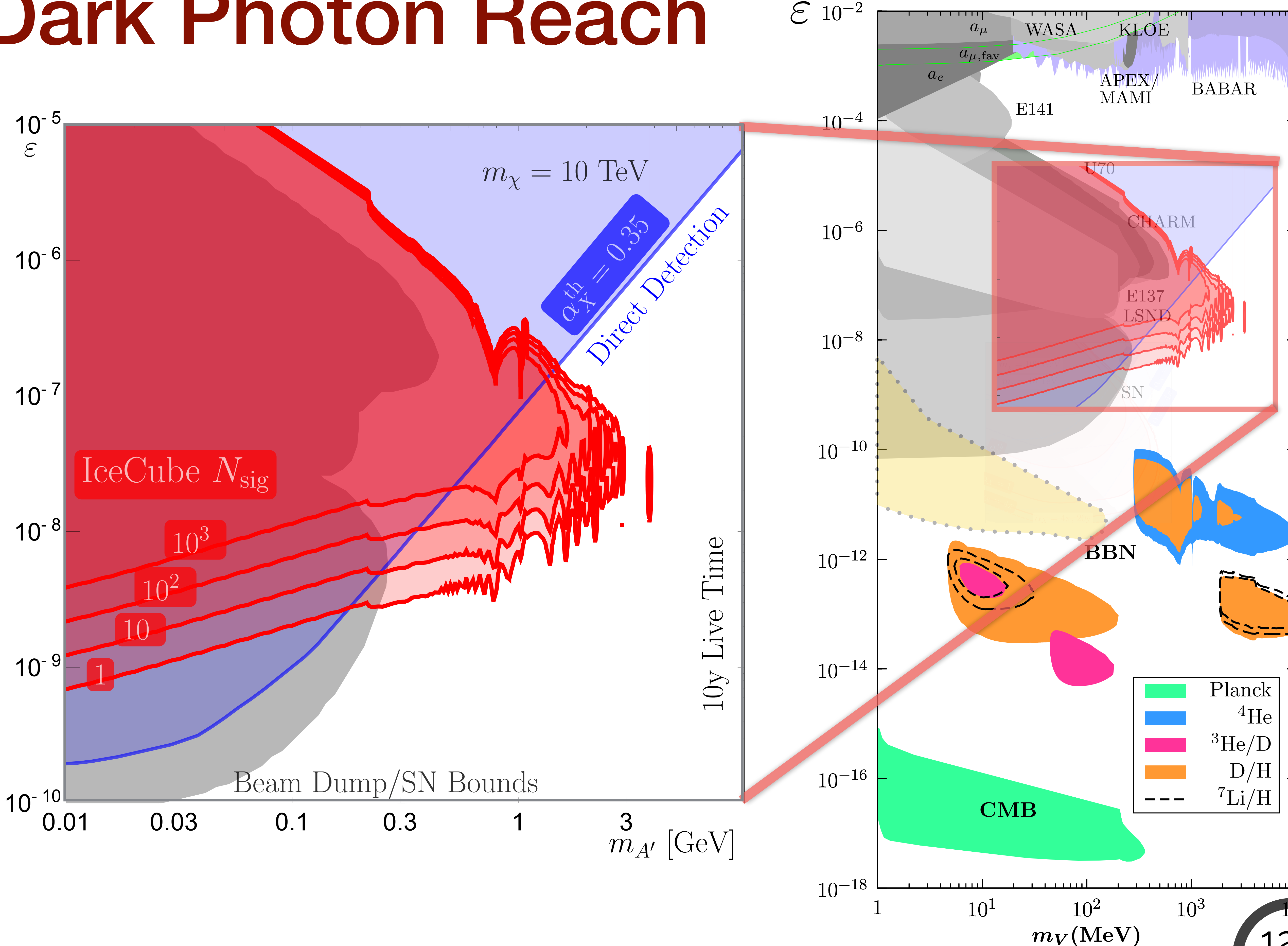
$100\text{ GeV} \lesssim m_\chi \lesssim 10\text{ TeV}$

dark coupling

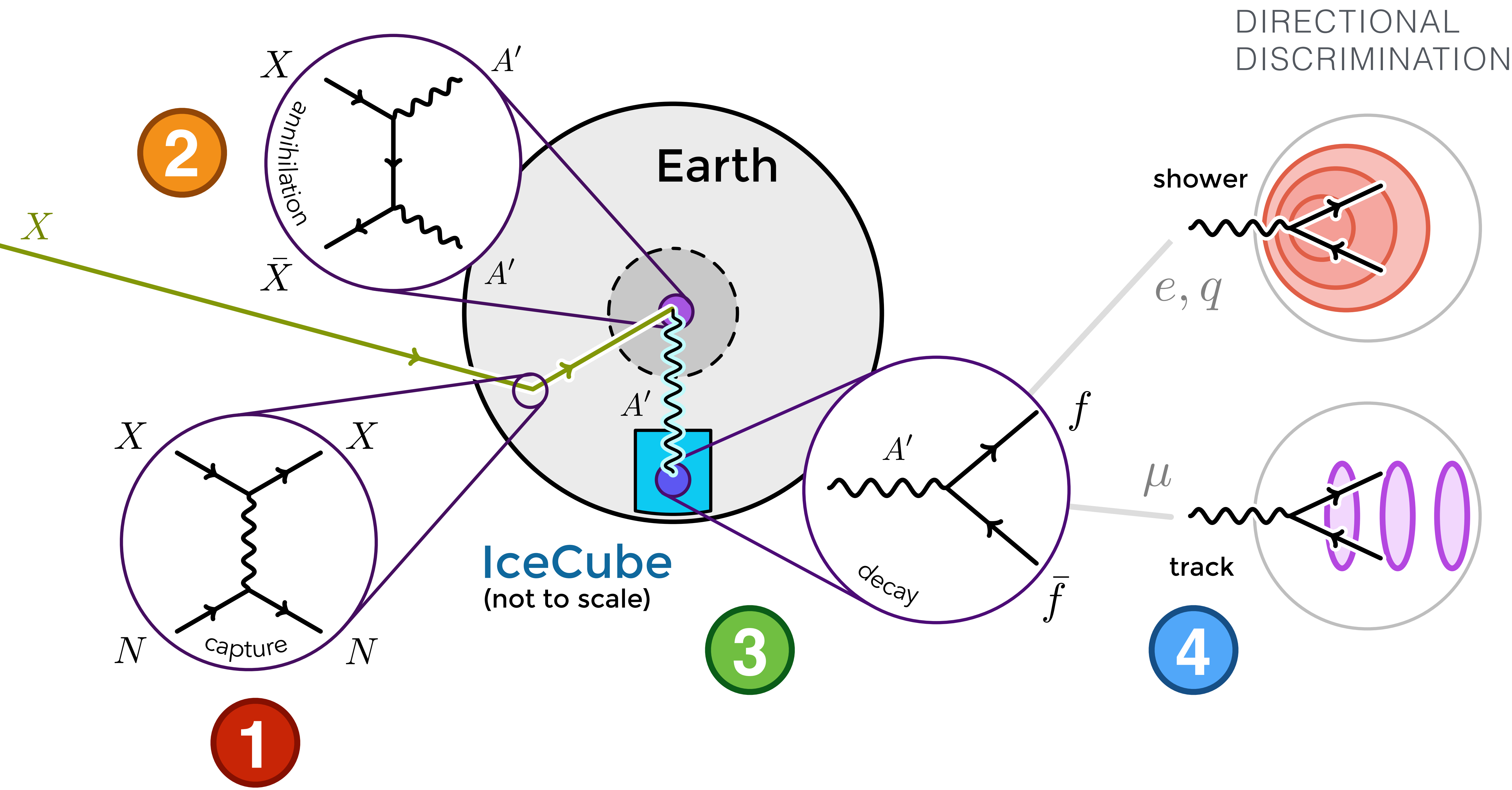
α_χ s.t.

$\langle\sigma v\rangle_{\text{ann}} = 2.1\times 10^{-26}\text{ cm}^3/\text{s}$

Dark Photon Reach



DM Capture, annihilation to A'

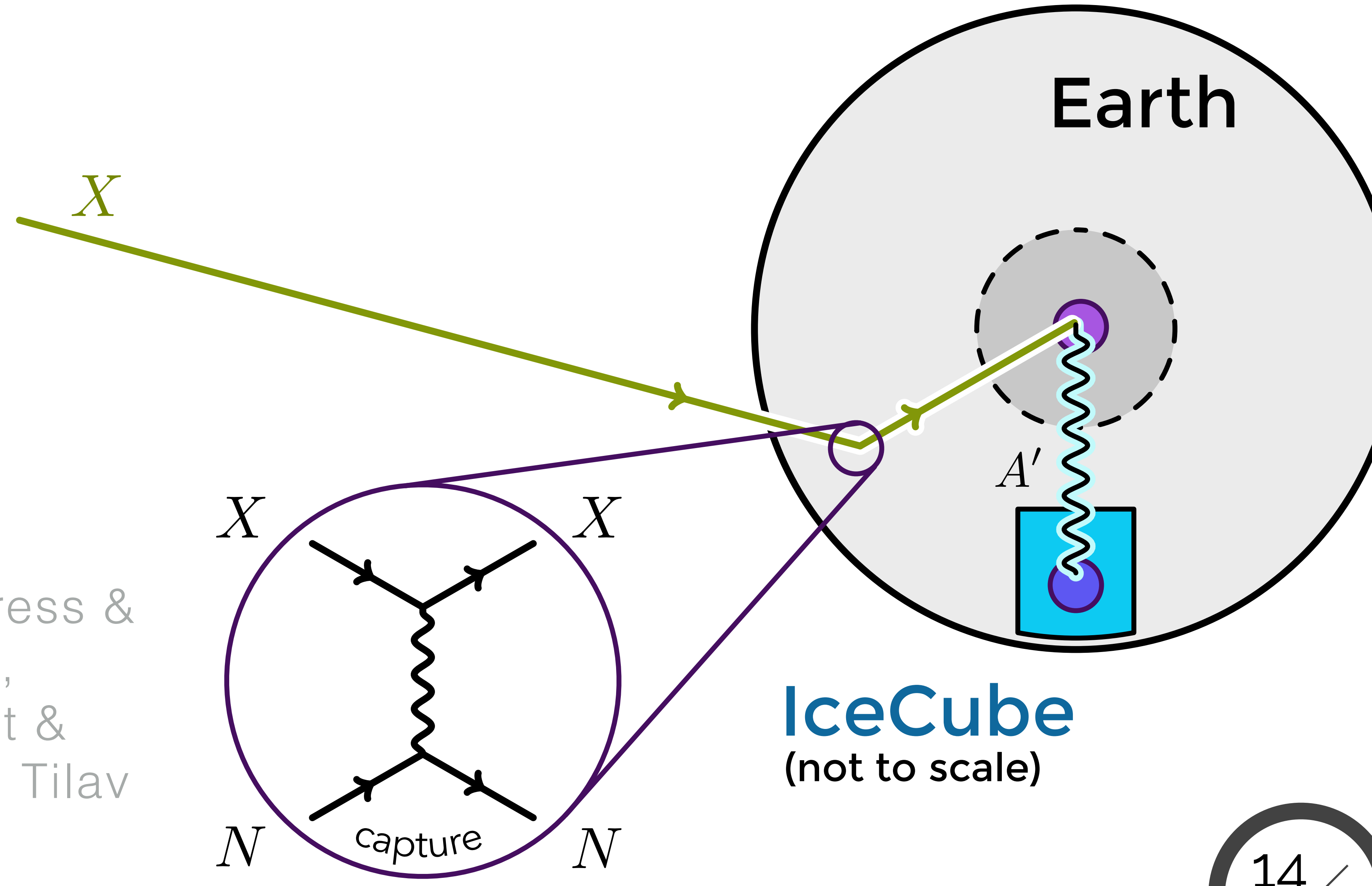


EARLIER WORK: Holdom (PLB 178, 65 '86); Batell, Pospelov, Ritz, Shang (0910.1567) Delaunay, Fox, Perez (0812.3331); Schuster, Toro, Yavin (0910.1602, 0910.1839); Meade, Nussinov, Papucci, Volansky (0910.4160); …

Dark Matter Capture

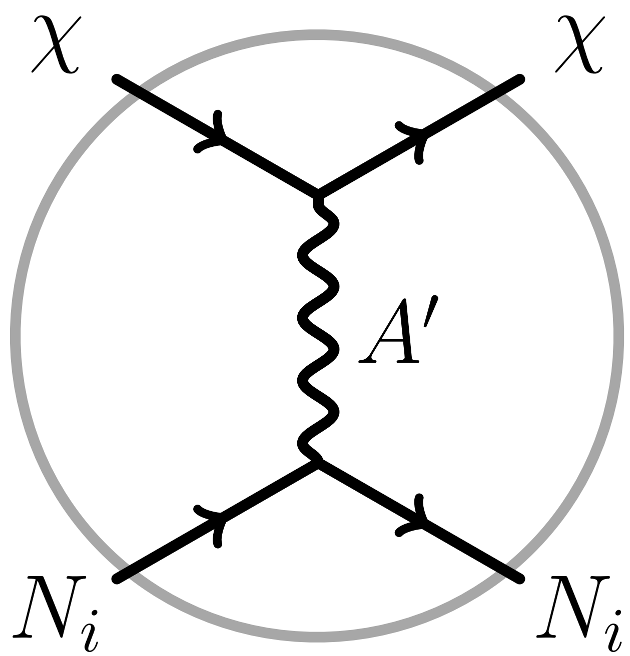
DM is captured when elastically scattered dark matter has velocity less than the Earth's escape velocity

CAPTURE PROCESS ~ DIRECT DETECTION



CAPTURE& ANNIHILATION: Press & Spergel '85; Krauss, Srednicki, Wilczek '86; Freese '86; Griest & Seckel '87; Gaisser, Steigman, Tilav '86; Gould ('87,'88,'92)

Capture of Dark Matter



DM capture when $v_\chi < v_{esc}$

"Direct Detection" in space

EARTH

VELOCITY

ESCAPE VELOCITY

ASYMP. VELOCITY

RECOIL ENERGY

KINEMATICS

$$\Gamma^i_{\text{cap}} = n_\chi \int d^3r\, n_i(r) \times \int d^3u\, f(u) \frac{u^2+v^2}{u} \times \int dE_R \frac{d\sigma_i}{dE_R} F(E_R)\Theta$$

$$\frac{d\sigma_i}{dE_R} = \frac{8\pi m_i^2 E_X^2 \alpha_x \varepsilon^2 Z^2 \alpha}{m_i p_X^2 (2m_i E_R + m_{A'}^2)^2}$$

Press & Spergel (85), Krauss, Srednicki, Wilczek (86), Gould (87, 92), PPPCv (1312.6408)

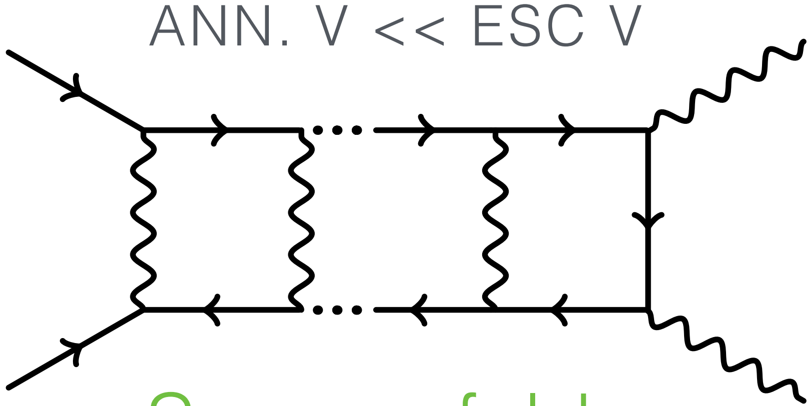
Dark Matter Capture

$$\dot{N}_\chi = C_\text{cap} - C_\text{ann} N_\chi^2$$

EQUILIBRIUM TIME

$$\tau = \frac{1}{\sqrt{C_\text{cap} C_\text{ann}}}$$

ANN. V << ESC V

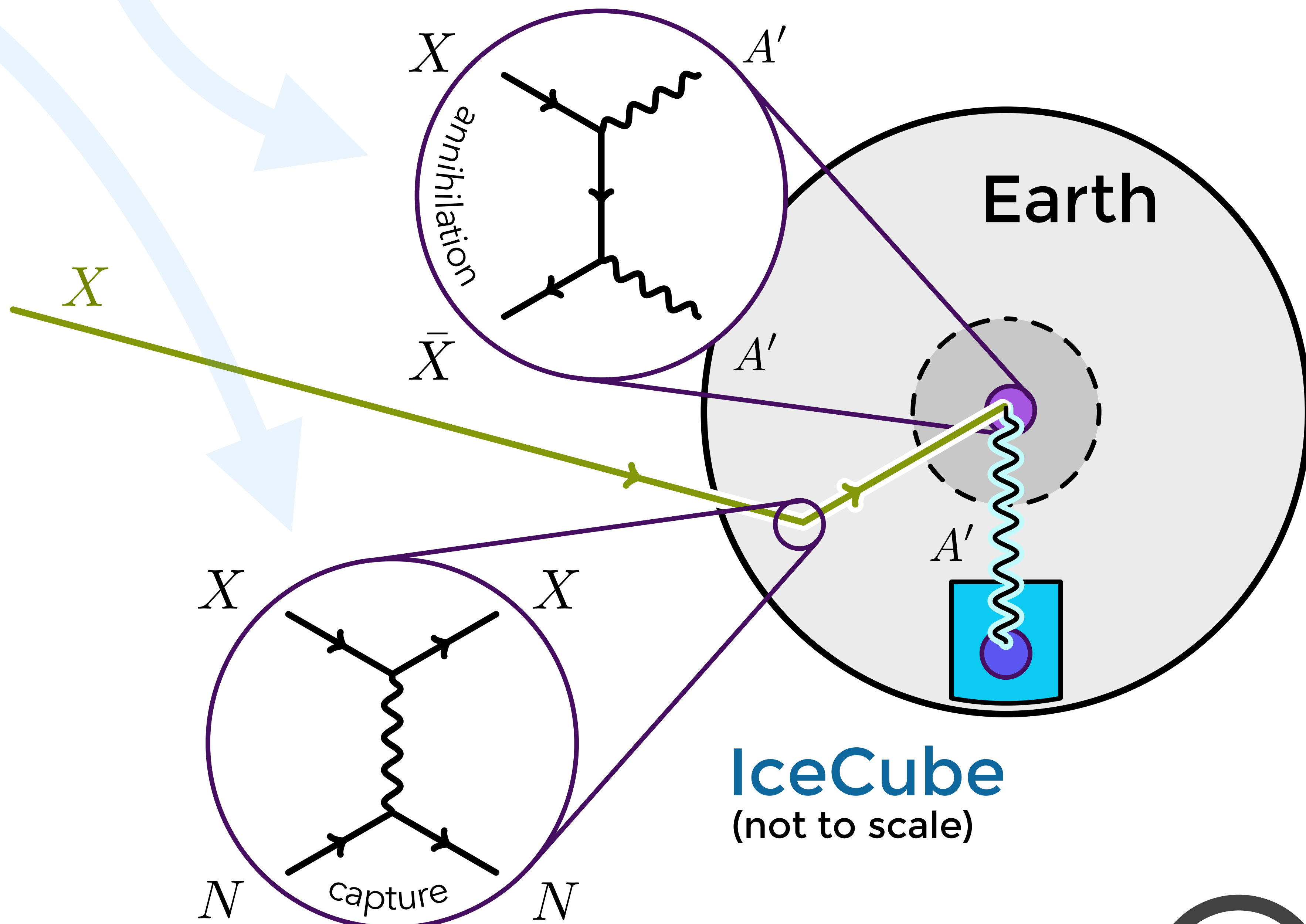


Sommerfeld

HAS RESONANCES
see, e.g. 1302.3898

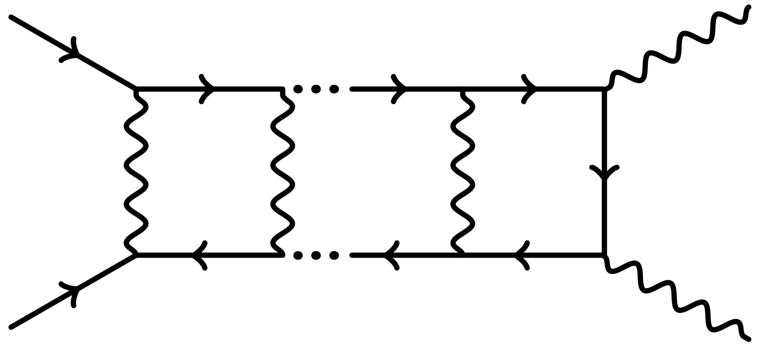
$$v_0 \approx 10^{-6}\sqrt{\frac{\text{TeV}}{m_X}}$$

5700 K



Sommerfeld Enhancement

$$S_0 = \frac{2\pi\,\alpha_X/v}{1 - e^{-2\pi\alpha_X/v}}$$



$m_{A'} \ll \alpha_X m_X$

GENERAL, valid for finite mediator mass

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

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

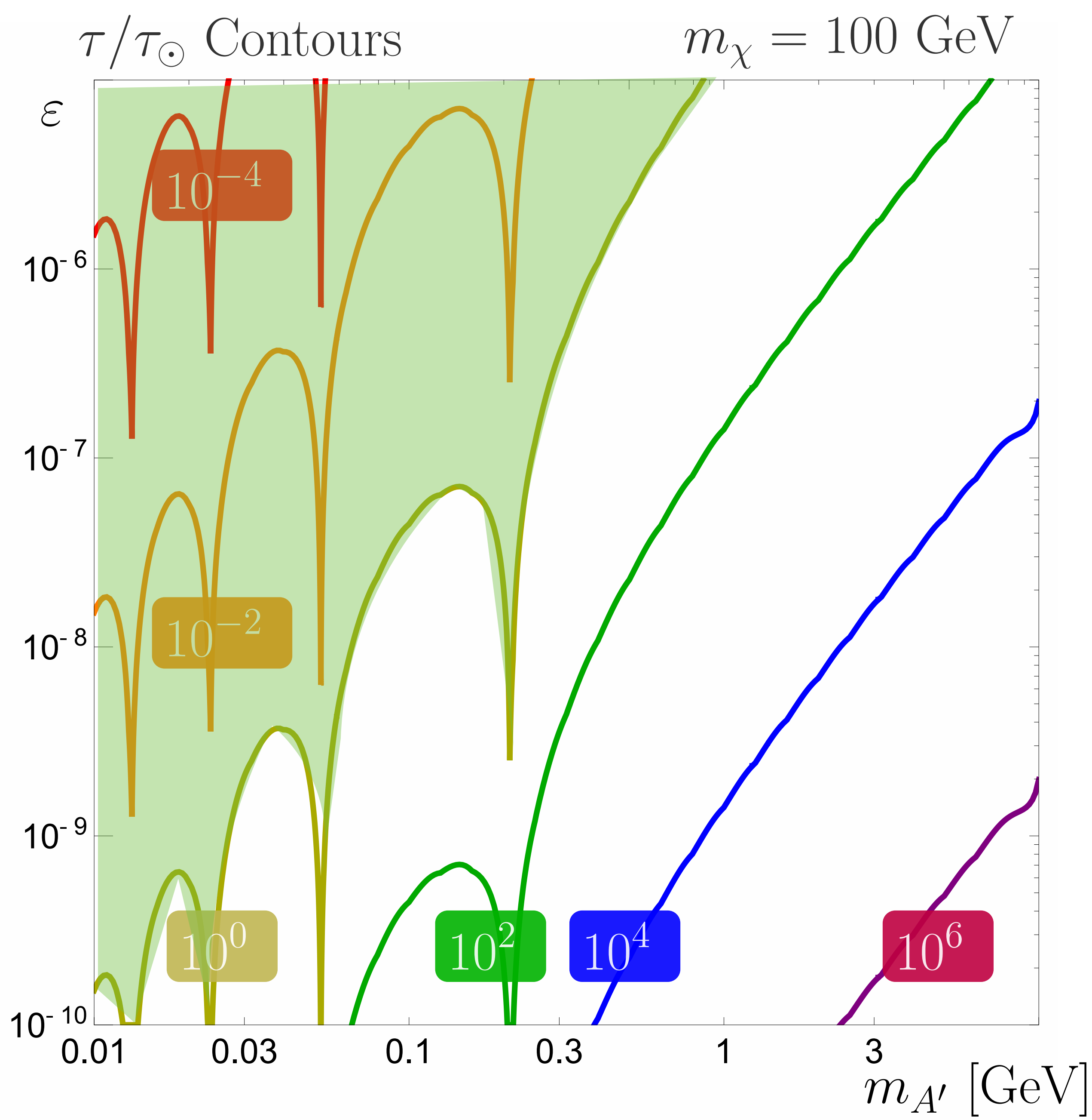
$$\langle S_S\rangle = \int \frac{d^3v}{(2\pi v_0^2)^{3/2}}\, e^{-\frac{1}{2}v^2/v_0^2}\, S_S$$

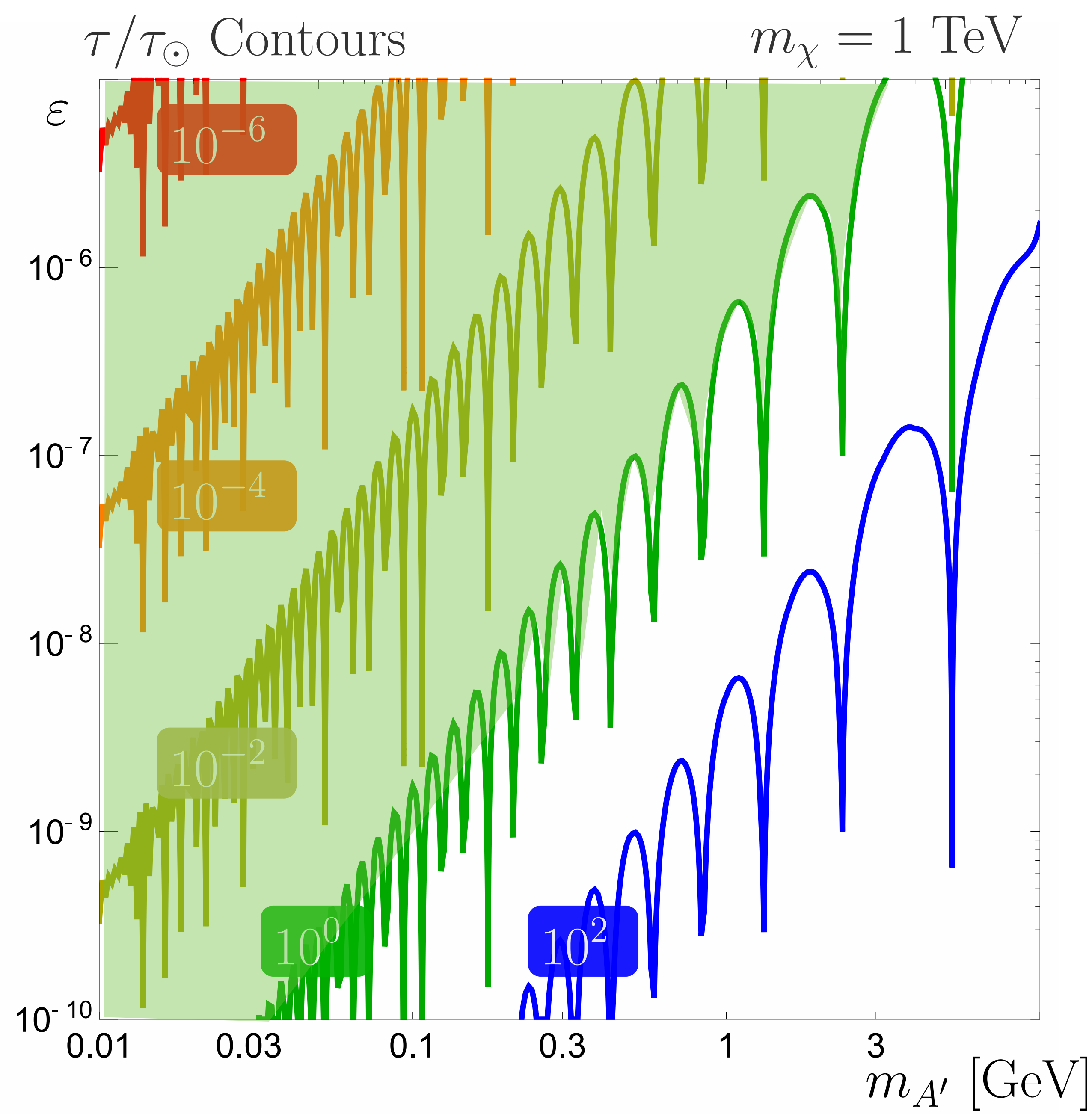
$$v_0 \approx 10^{-6}\sqrt{\frac{\text{TeV}}{m_X}}$$

5700 K

Feng, Kaplinghat, Yu (1005.4678)

Filling the Earth with Dark Matter





Shaded: Earth is DM saturated

Annihilation from Capture

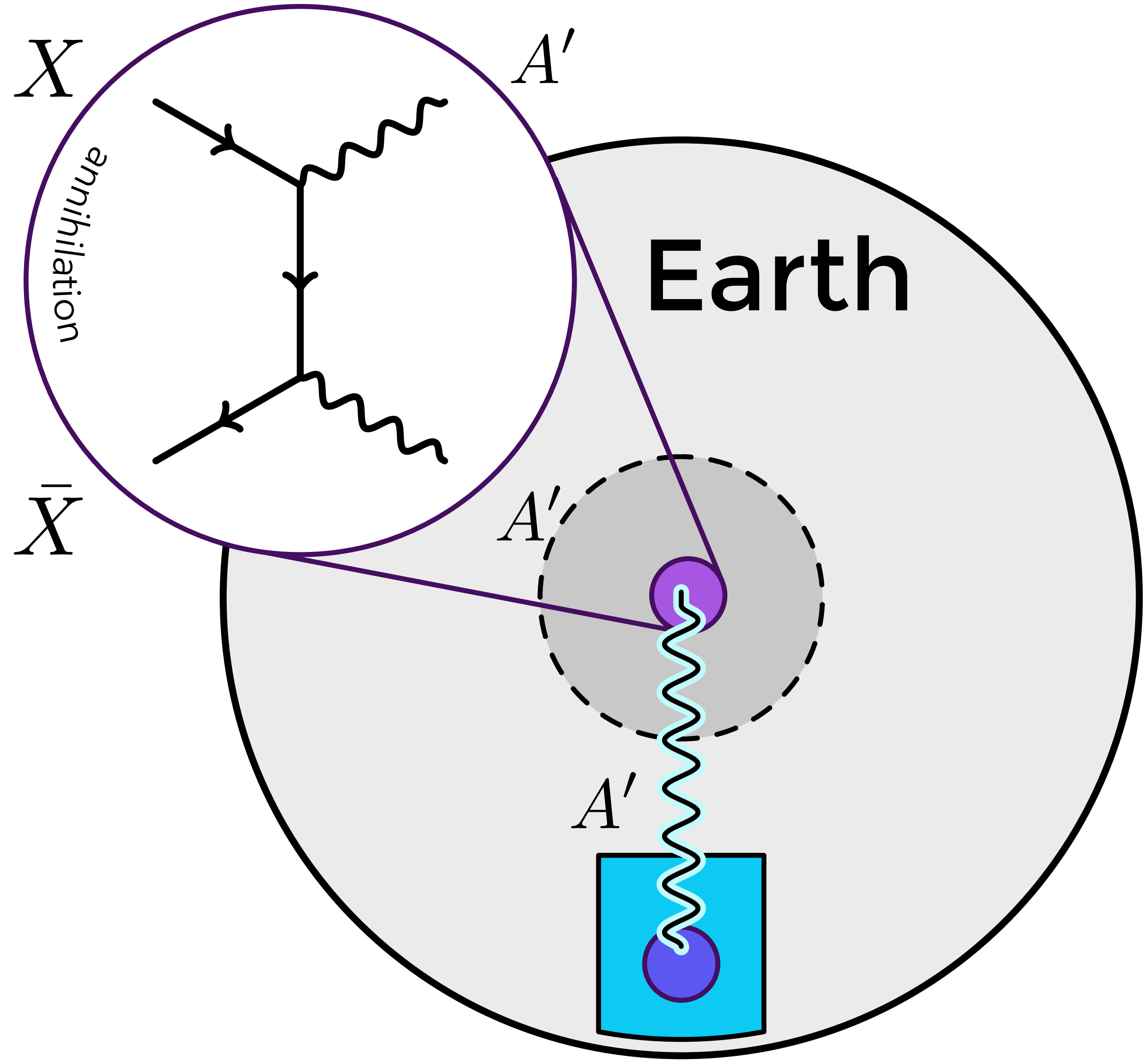
$$\Gamma_{\text{ann}} = \frac{\Gamma_{\text{cap}}}{2} \tanh^2\left(\frac{t_\odot}{\tau}\right)$$

Indirect detection, but no J factors.

EQUILIBRIUM TIME

$$\tau = \frac{1}{\sqrt{C_{\text{cap}} C_{\text{ann}}}}$$

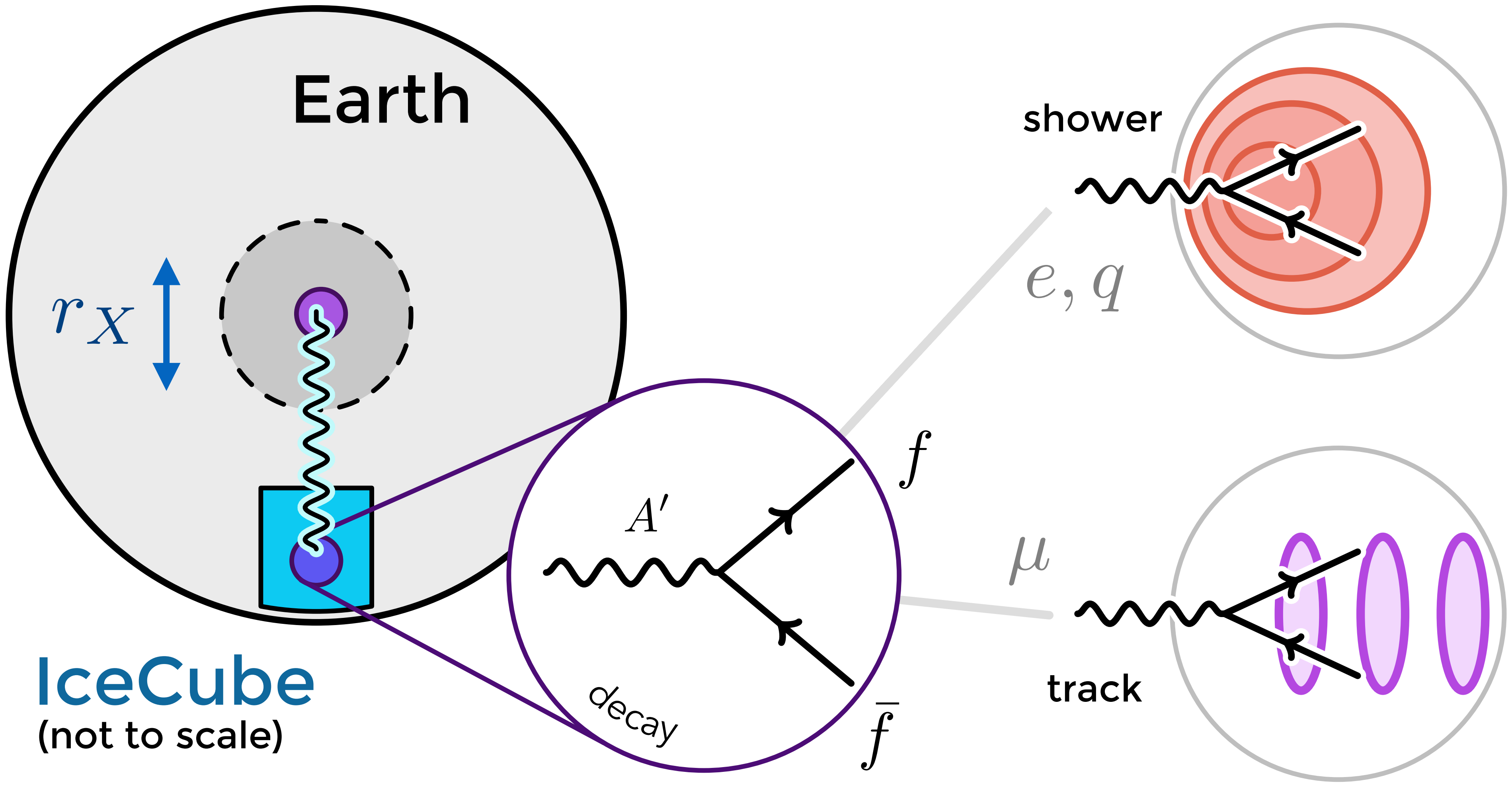
$$\dot{N}_\chi = C_{\text{cap}} - C_{\text{ann}} N_\chi^2$$



Detection in IceCube

$$r_X = \left(\frac{3T_\oplus}{2\pi G_N \rho_\oplus m_X}\right)^{1/2} \approx 150\ \text{km}\sqrt{\frac{\text{TeV}}{m_X}}$$

DIRECTIONAL DISCRIMINATION



km²

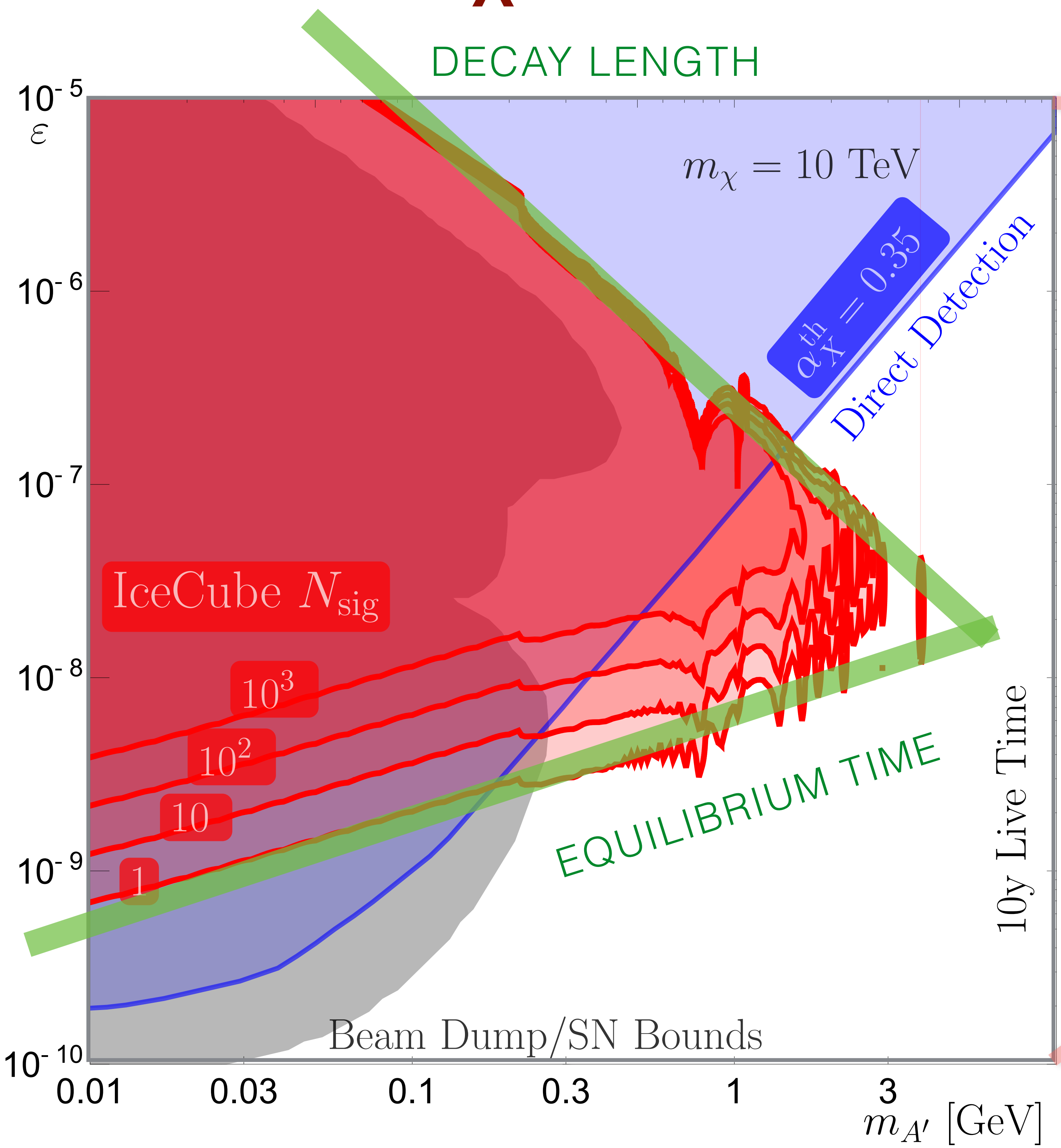
$$e^{-R_\oplus/L} - e^{-(R_\oplus + D)/L}$$

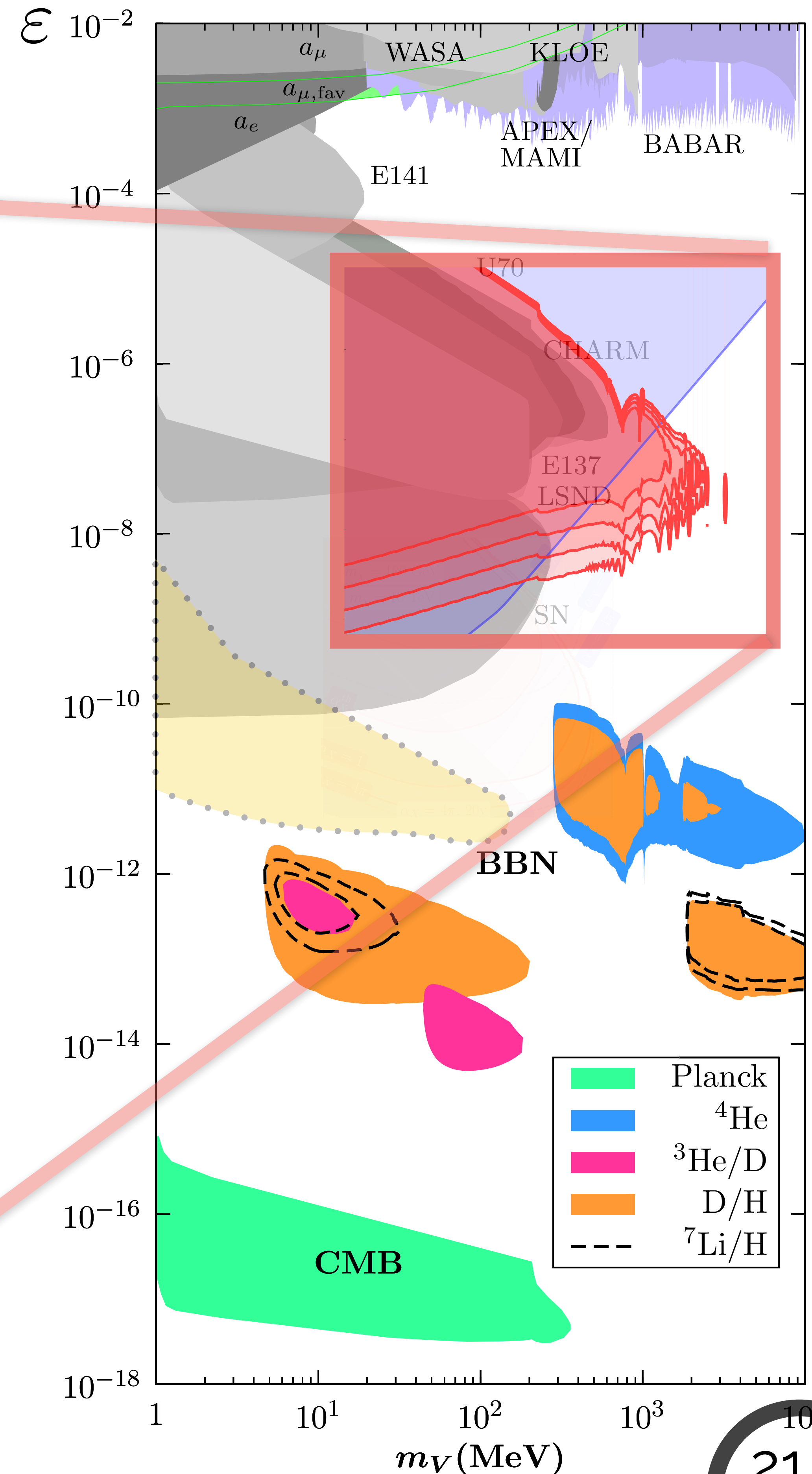
$$N_{\text{sig}} = 2\,\Gamma_{\text{ann}}\,\frac{A_{\text{eff}}}{4\pi R_\oplus^2}\,\epsilon_{\text{decay}}\,T$$

6400 km

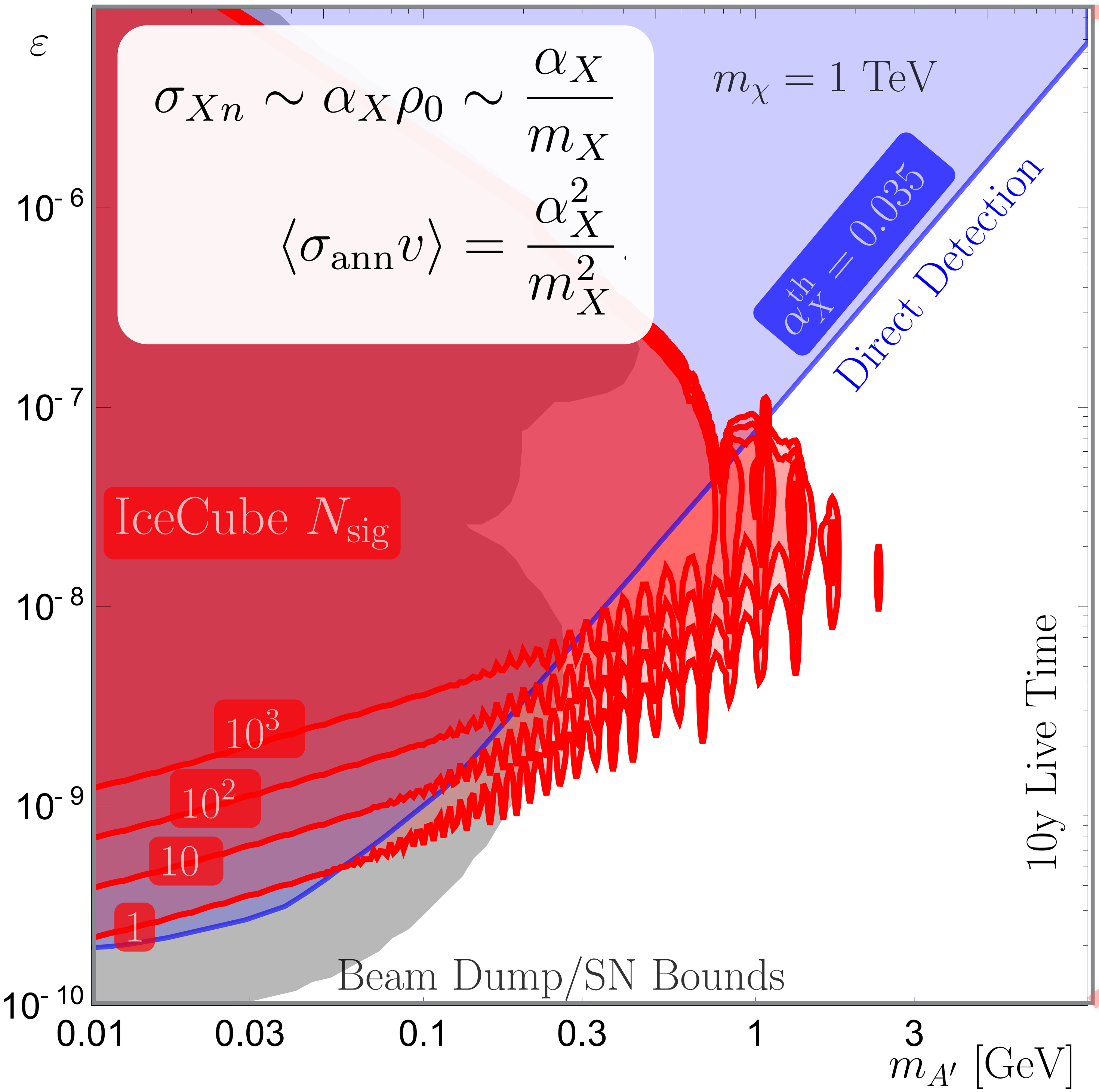
10 y

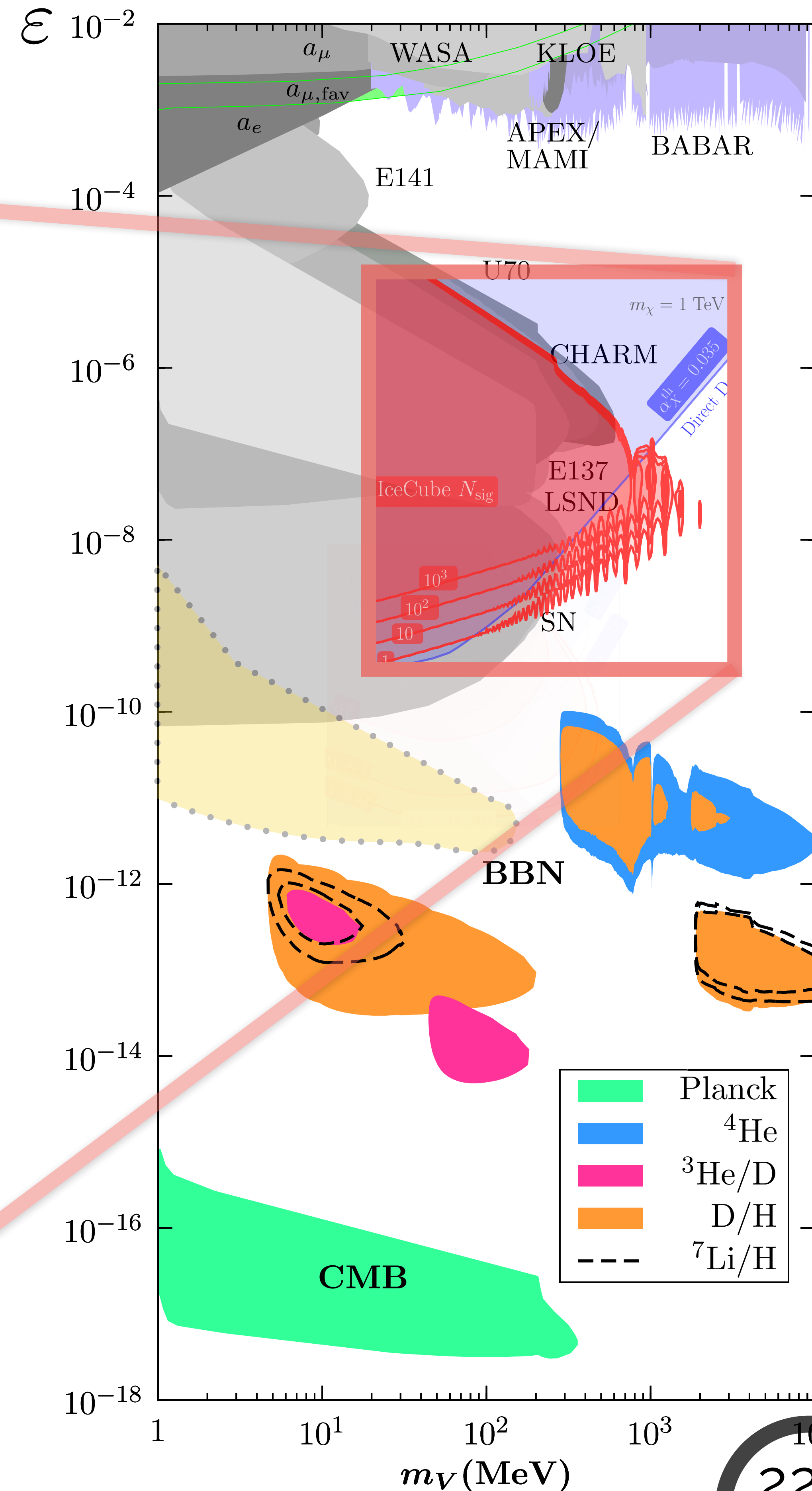
Reach: m_χ = 10 TeV



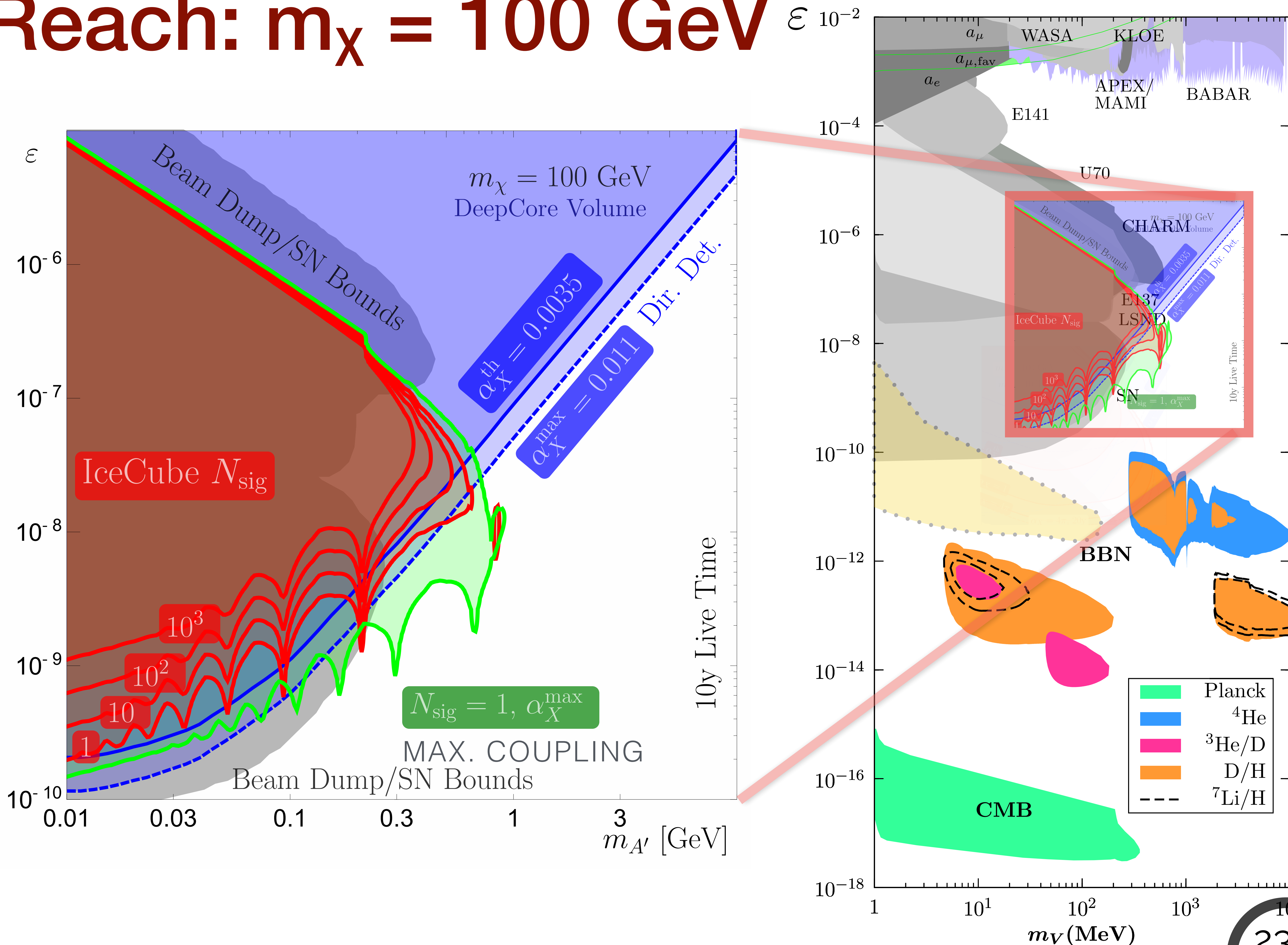


Reach: m_X = 1 TeV

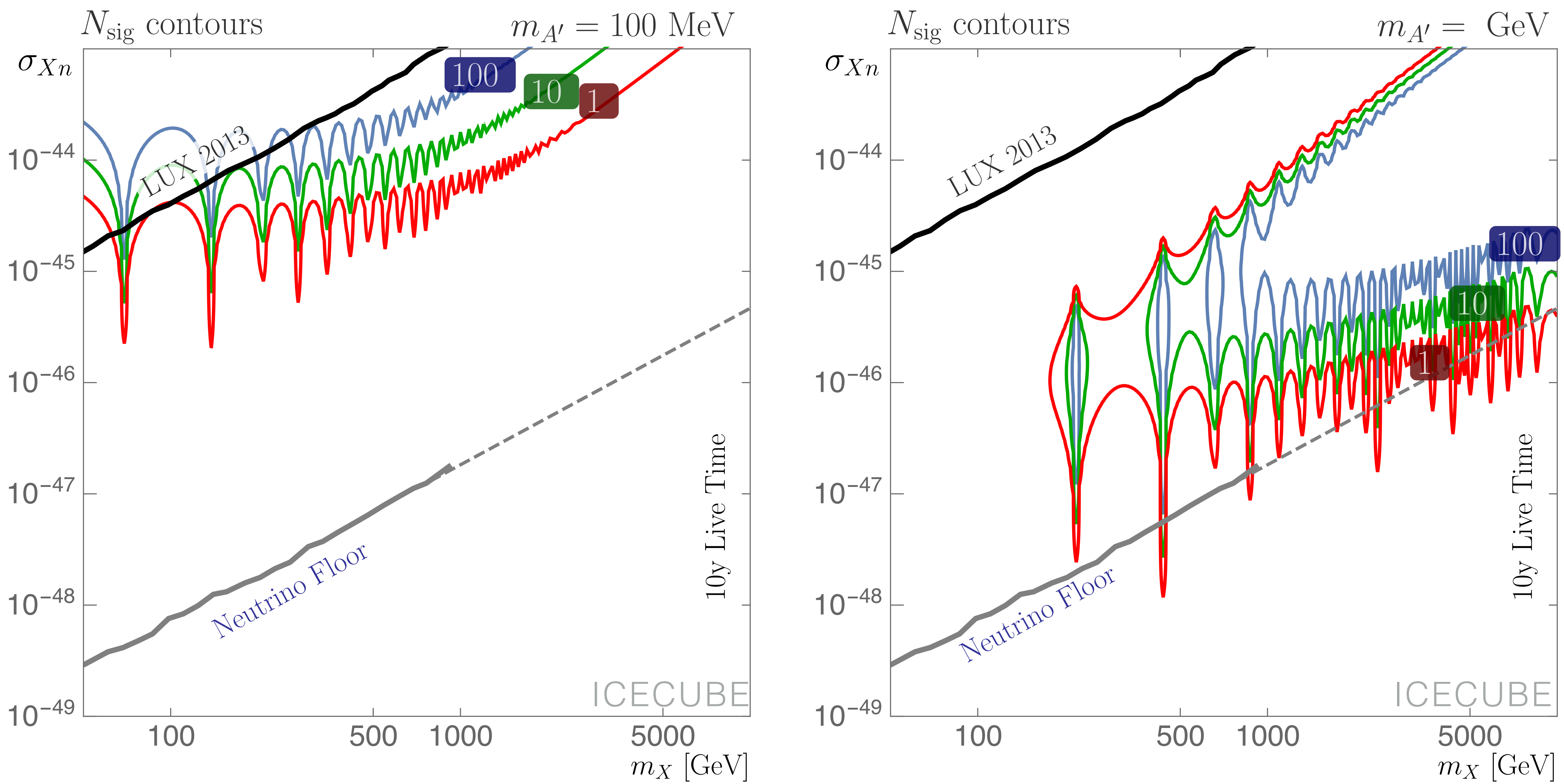




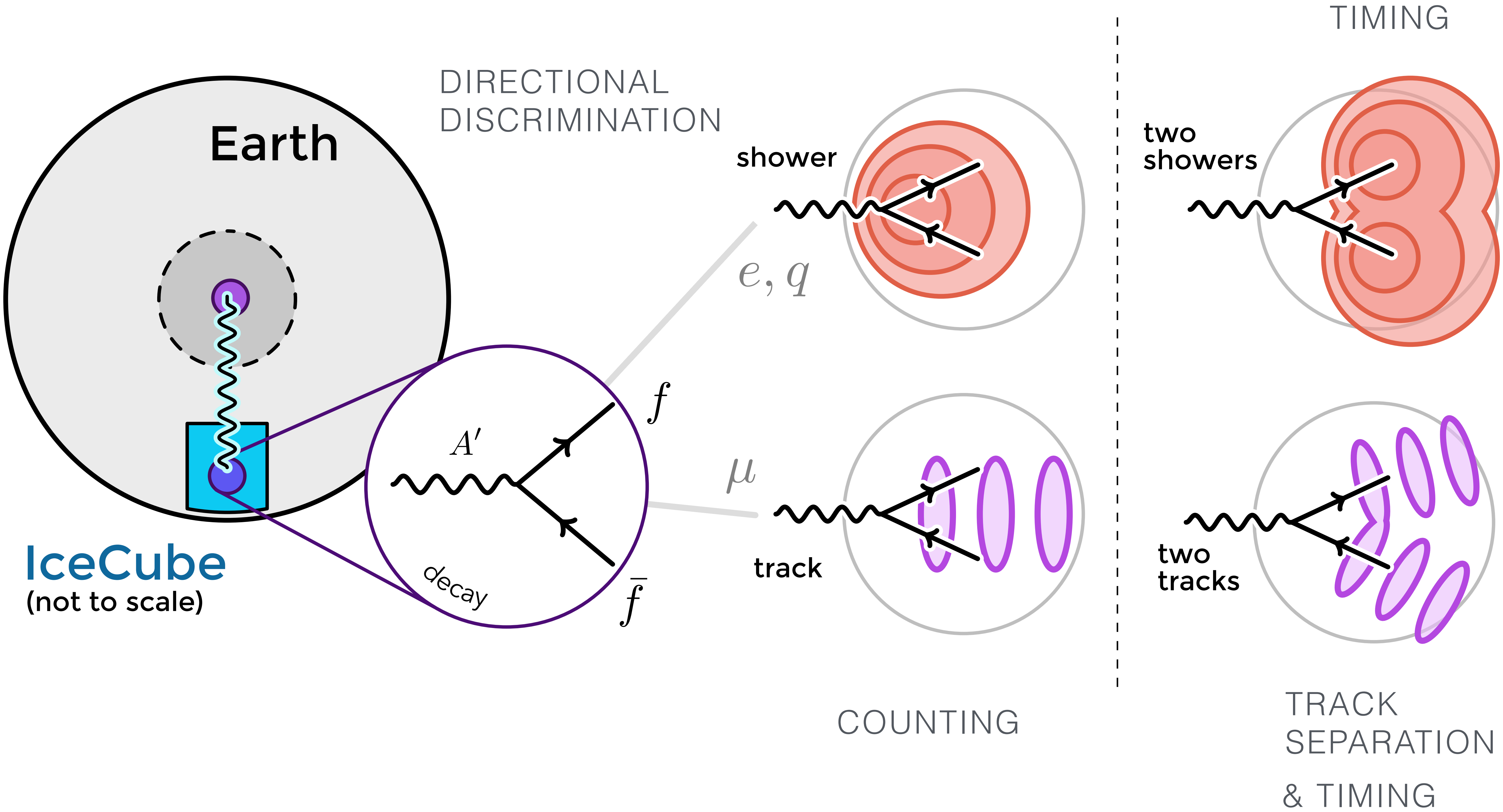
Reach: m_χ = 100 GeV



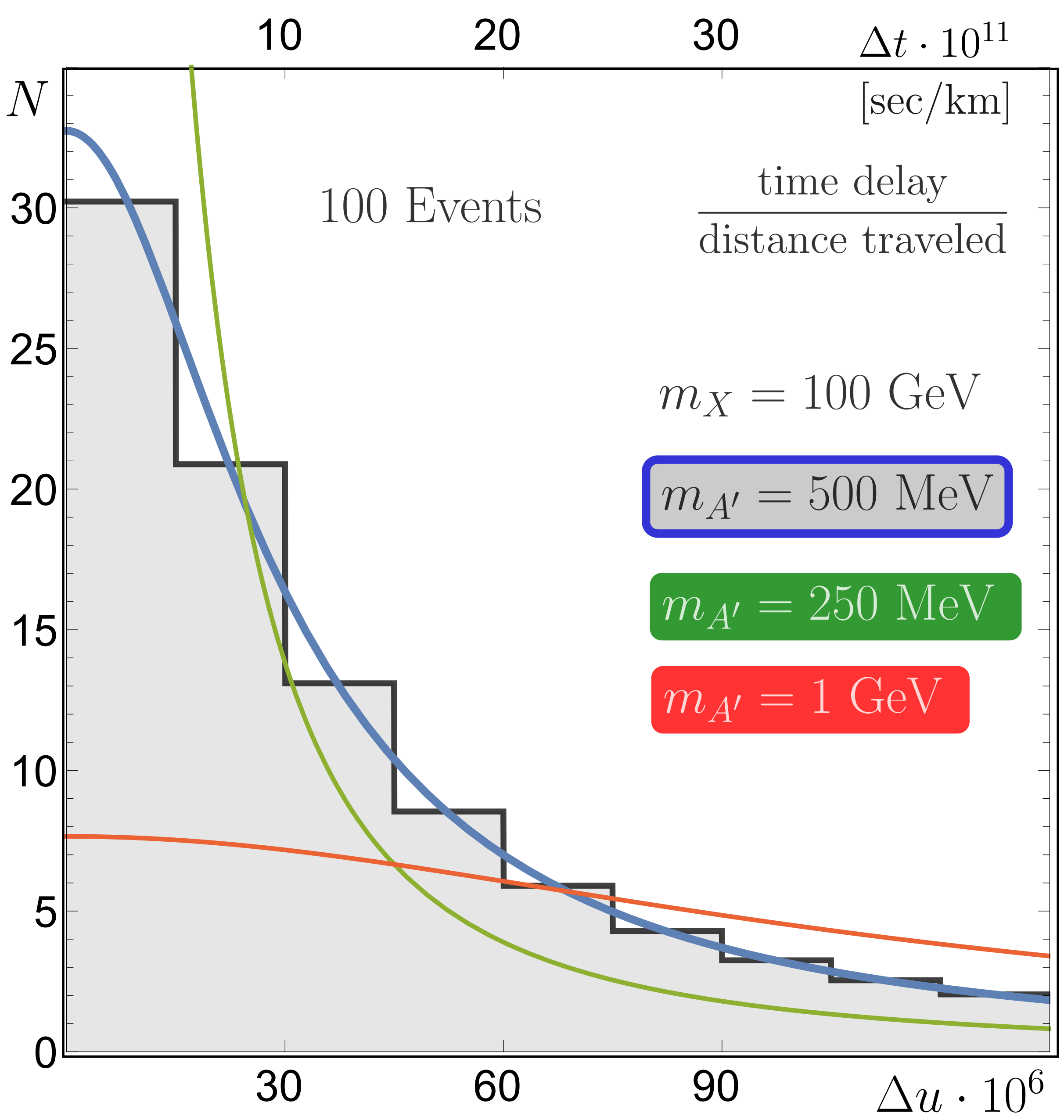
Direct Detection Plane

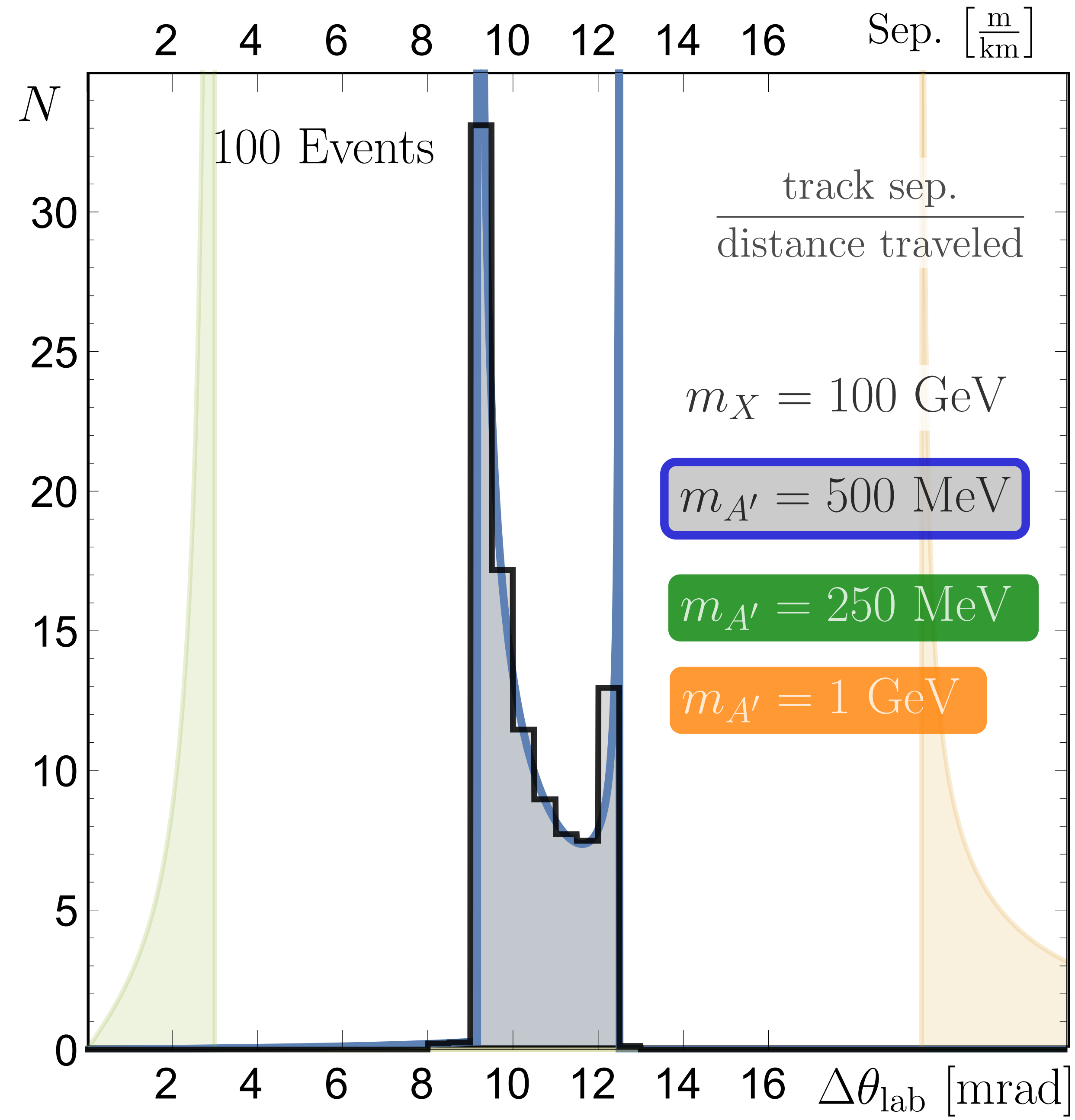


Detection in IceCube



Kinematic Distributions

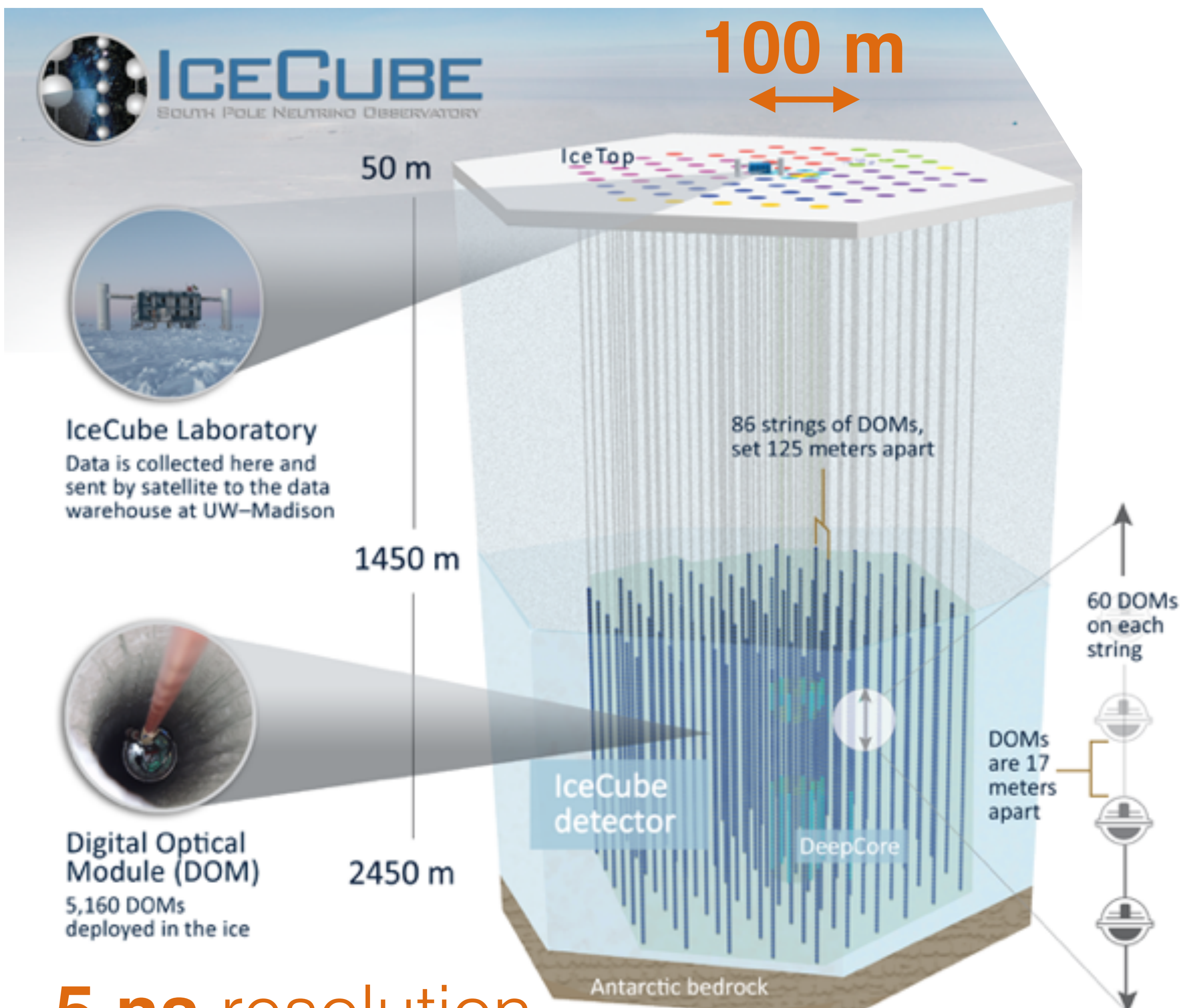




time delay ~ 0.1 ns

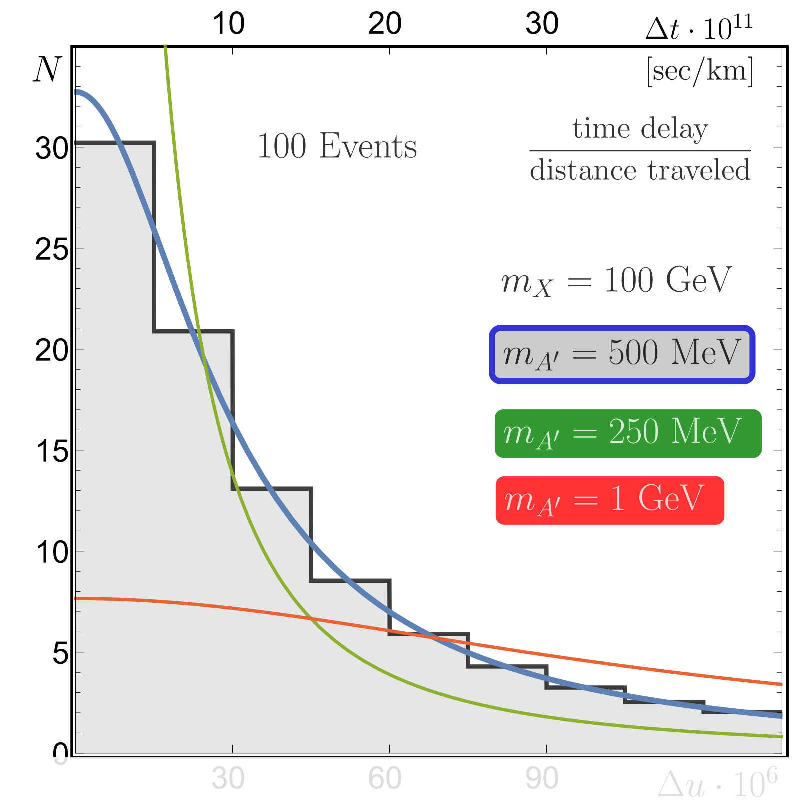
track separation ~ 10 m

Just out of reach

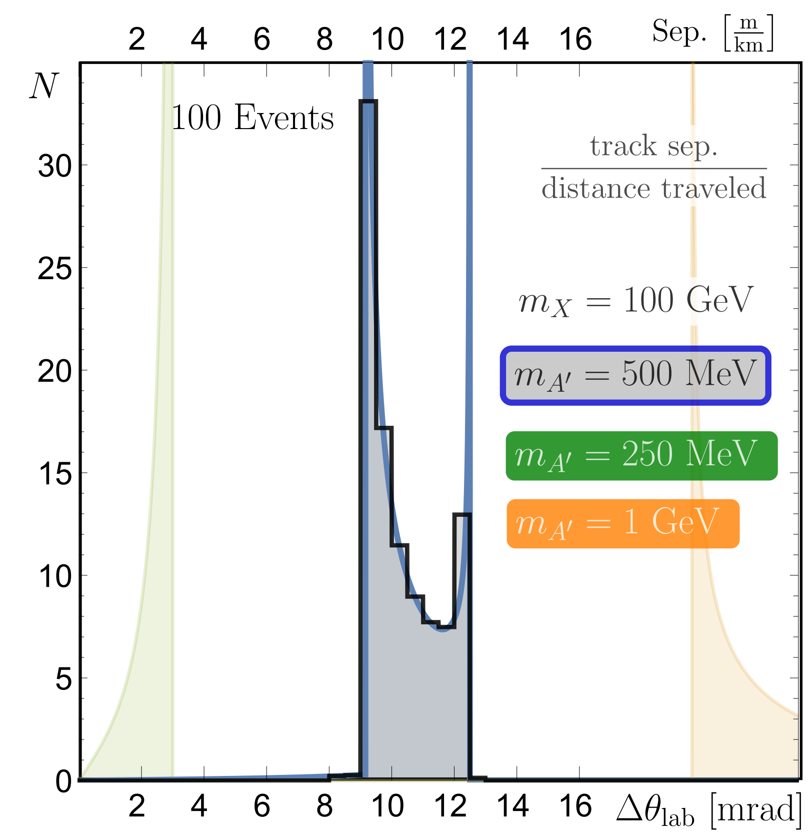


5 ns resolution

IceCube Collaboration website



time delay ~ 0.1 ns

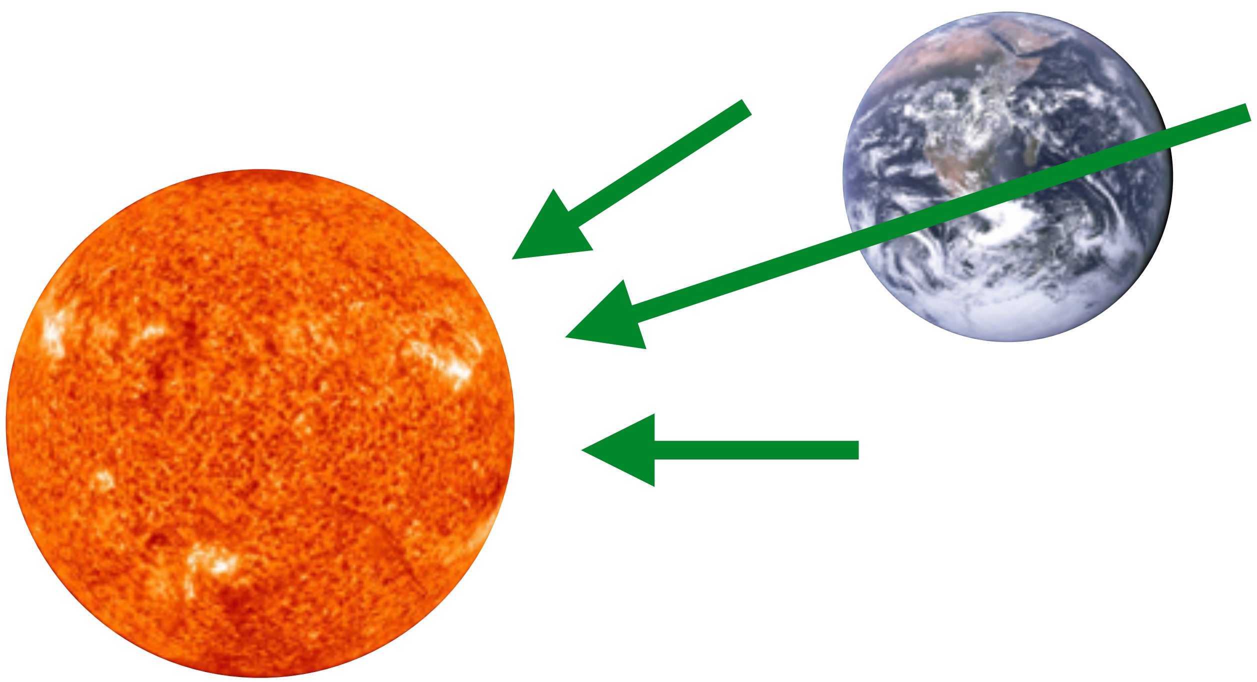


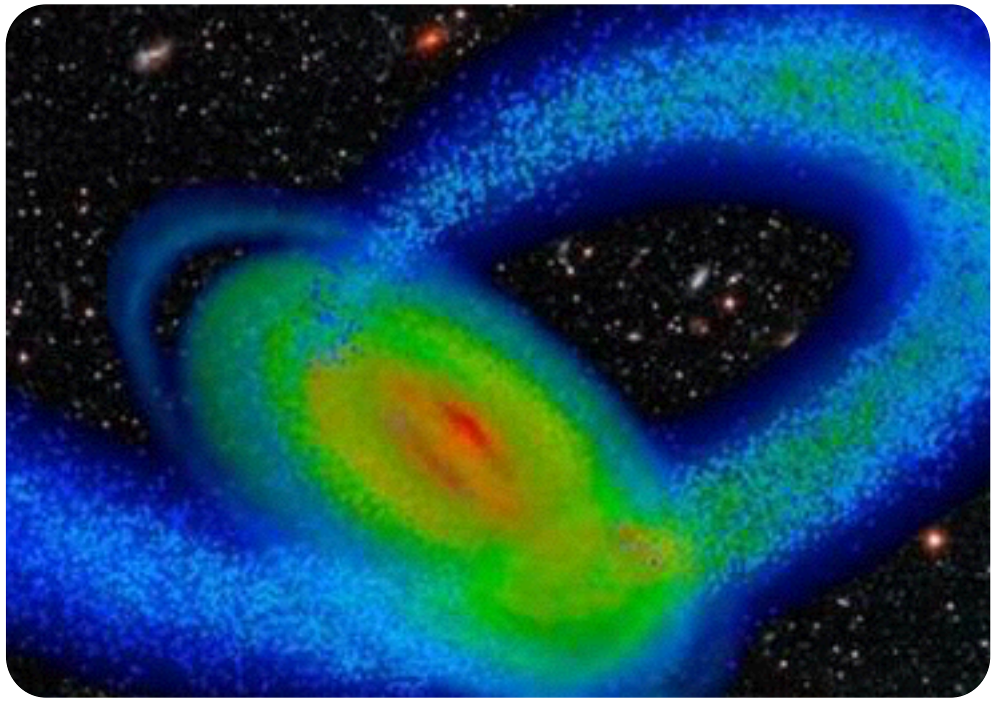
separation ~ 10 m

Astrophysical Opportunities

- Acceleration from gravitational pull of the sun
  COMPENSATED BY JUPITER, VENUS? (Gould 1992)
  (More recent simulations: Edsjo et al 2004, Peter 2009)

- Dark Disk of the Milky Way, Stellar Streams?
  ENHANCEMENT FROM LOW VELOCITY SUBHALOS?
  (Read, et al. 0803.2714, 0902.0009; Purcell, Bullock, Kaplinghat 0906.5348)





Other targets?

Dark Matter annihilates in **[other places?]** to
A PLACE

dark photons, which are detected by **IceCube / Fermi**.
SOME PARTICLE(S) AN EXPERIMENT


EARTH

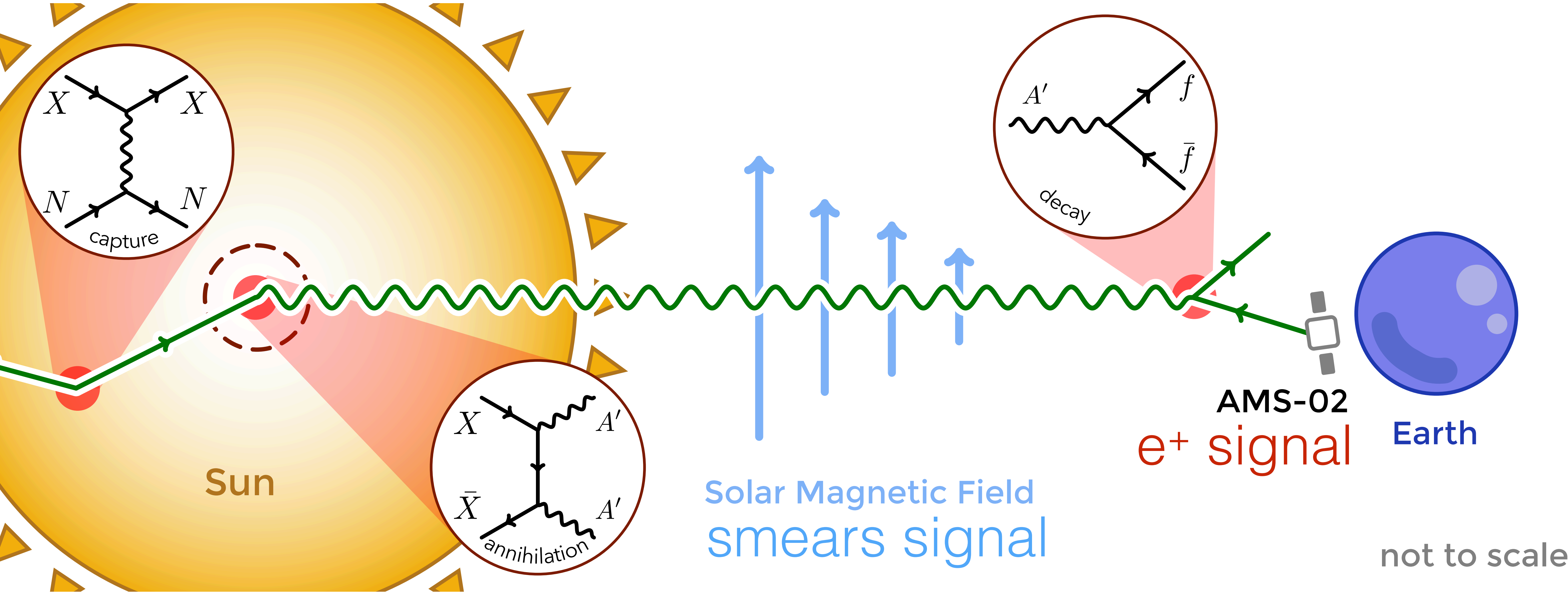

MOON


SUN


JUPITER

Images: Wikipedia

Accumulation in the Sun



Capture & Annihilation

ANALOGOUS TO EARTH

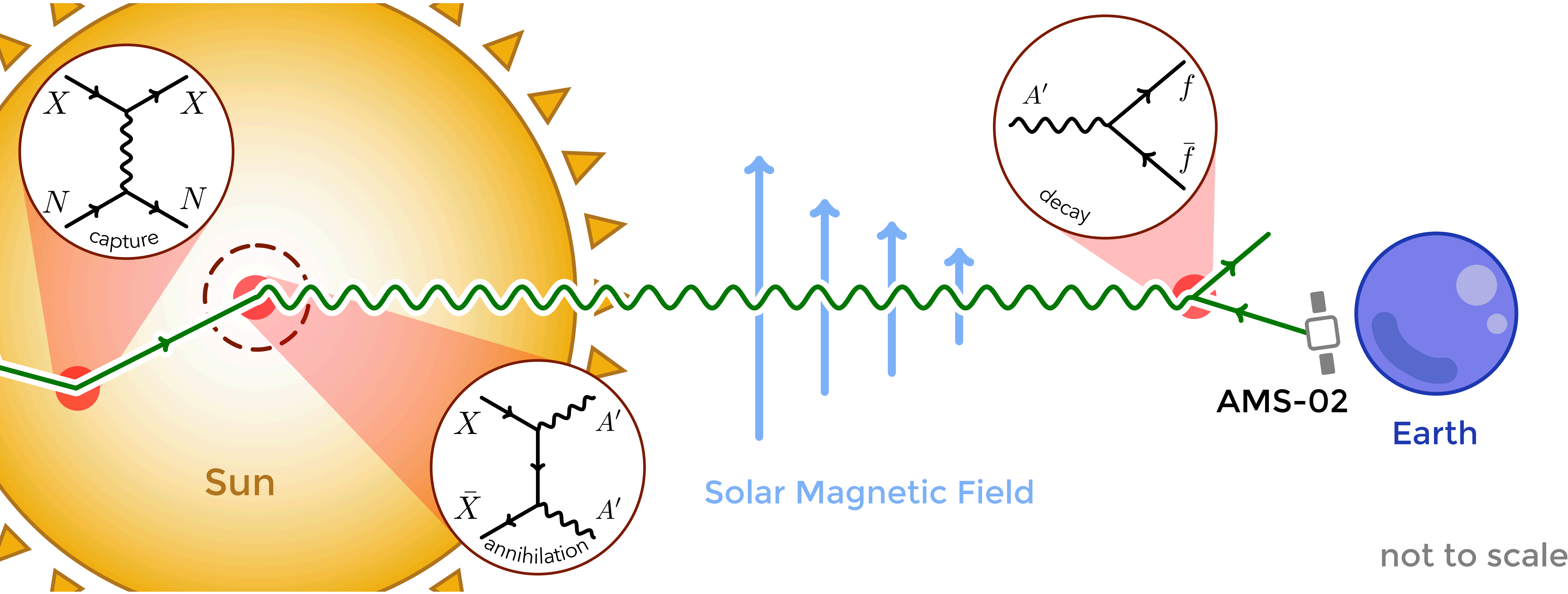
Rule of thumb: sun is always in equilibrium.

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

PARKER SPIRAL

J. Feng, J. Smolinsky, FT 1602.01465

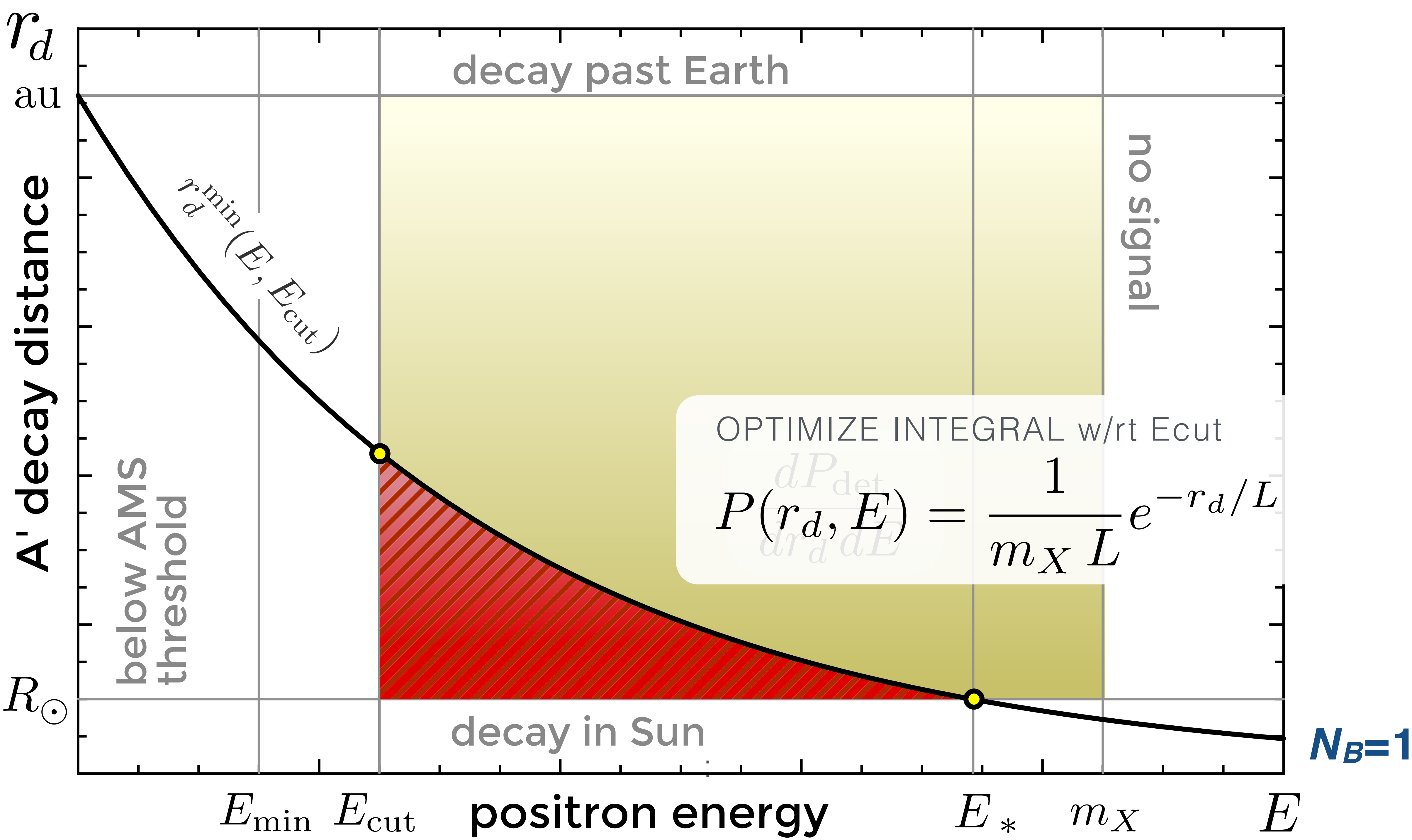
Optimizing for Signal



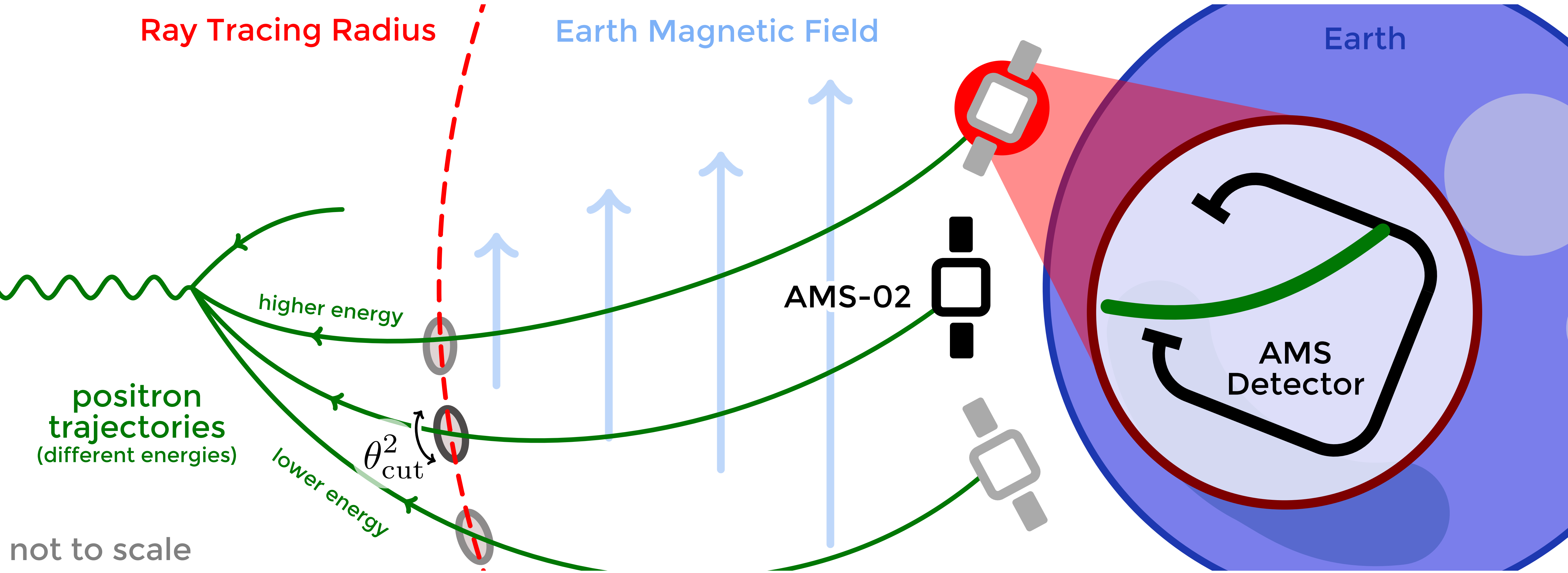
Choose:

1. **maximum e^+ solid angle from sun**
   TO MINIMIZE BACKGROUND (N_B= 1)
2. **minimum e^+ energy**
   TO MAXIMIZE SIGNAL

Signal and Background



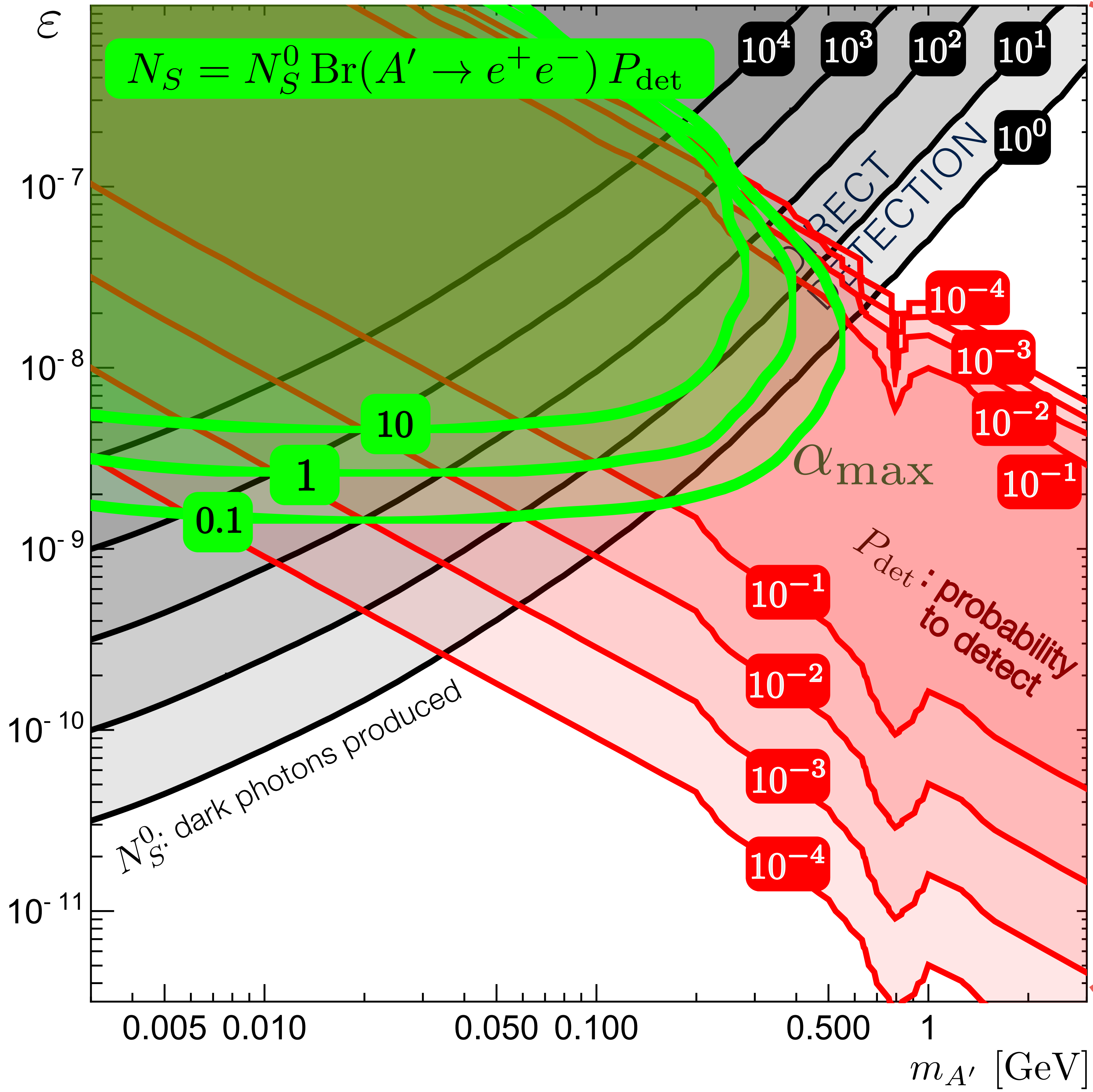
Earth's Magnetic Field

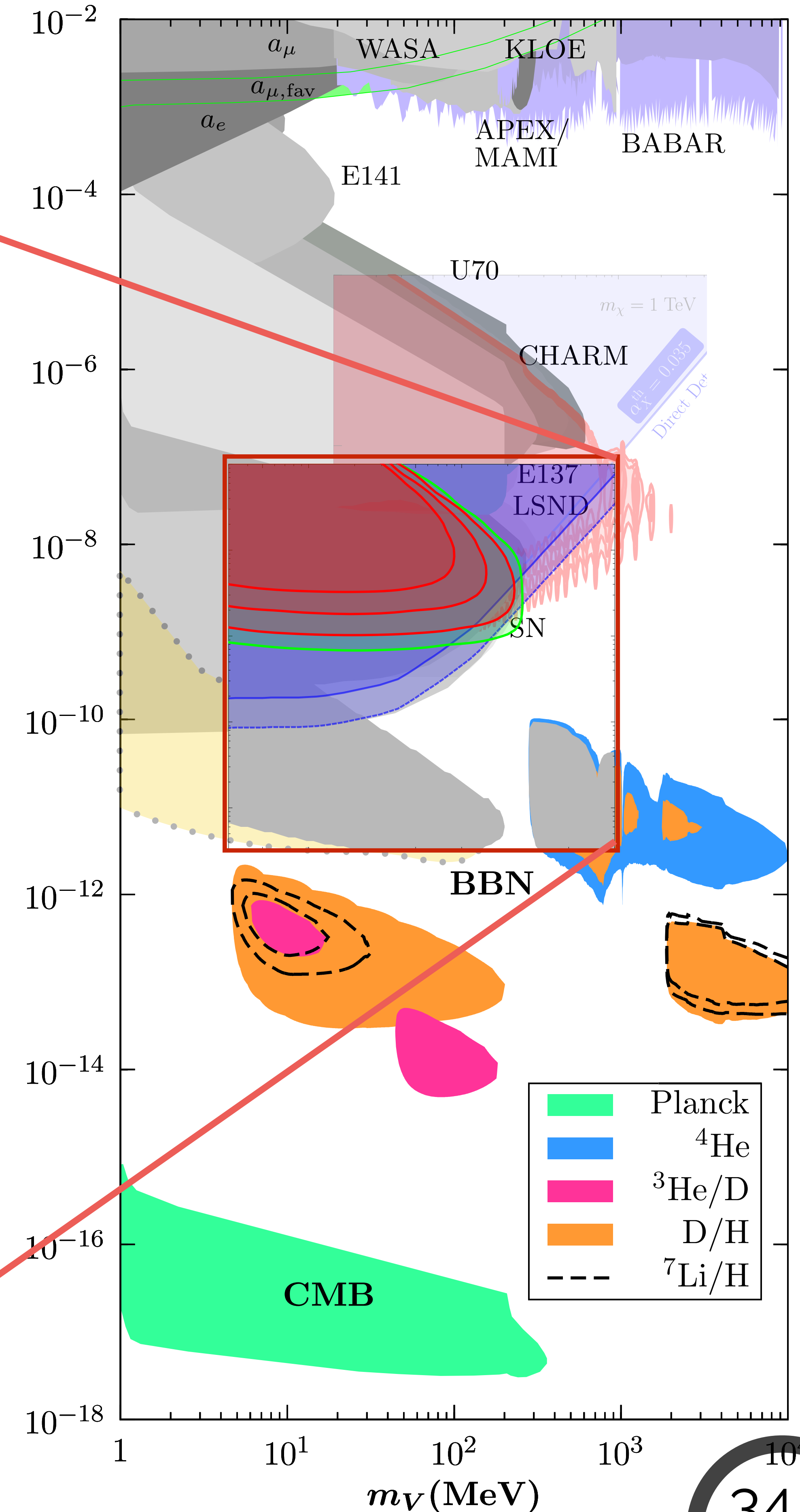


Assumption: Earth's magnetic field is mapped and trajectories can be traced back

AMS-02 Reach

3 year live time, 1 BG event

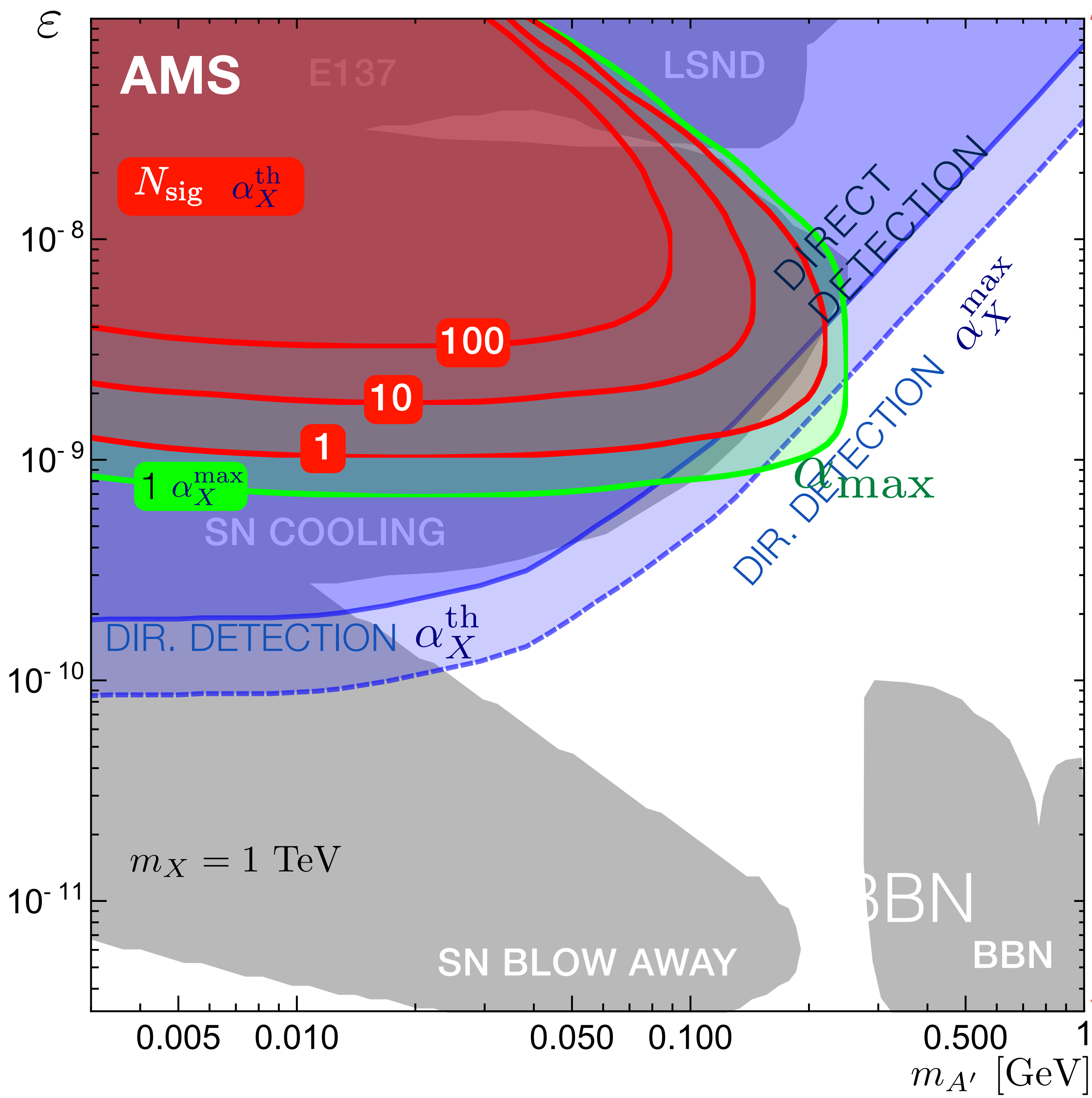


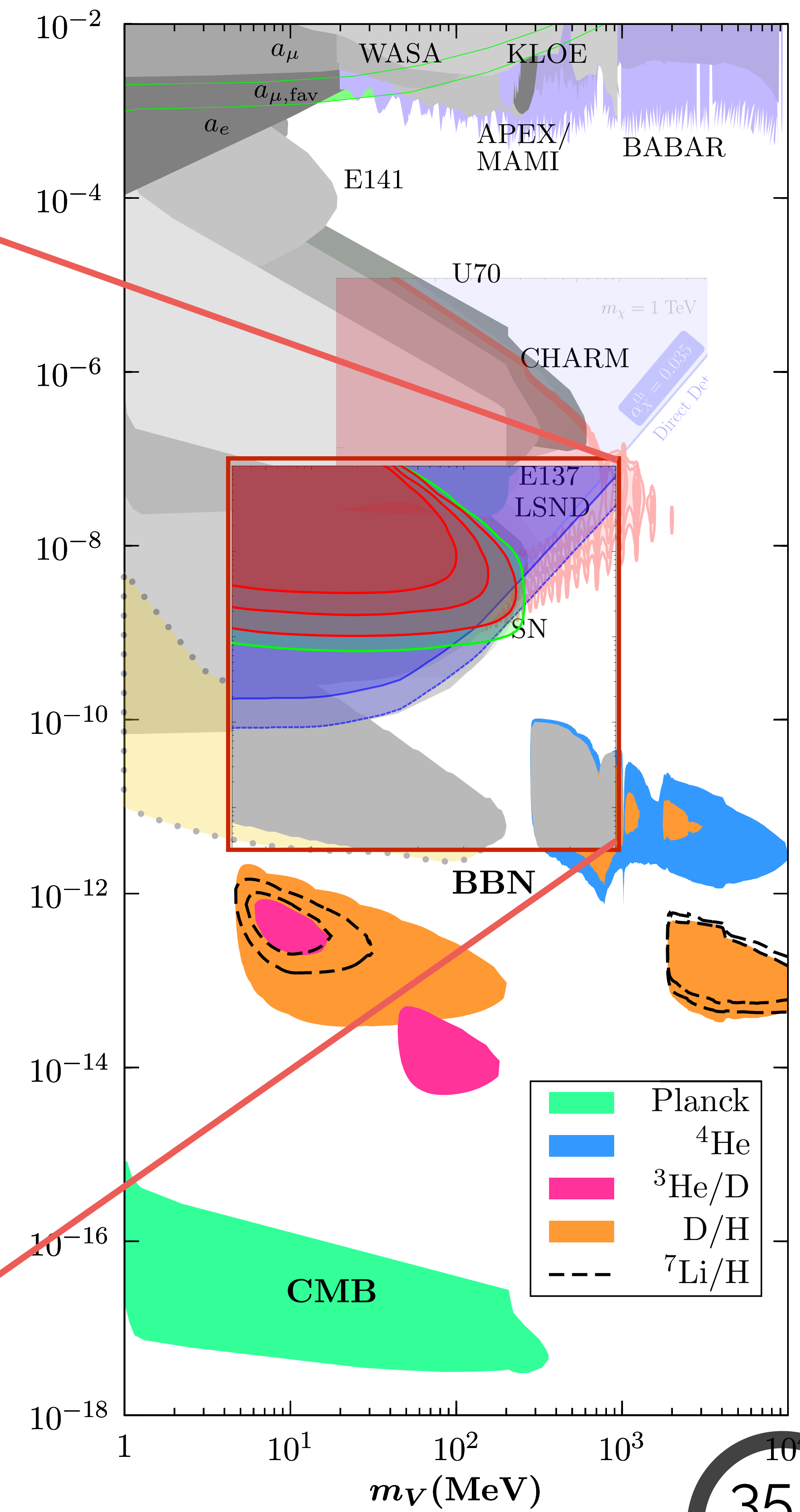


Feng, Smolinsky, FT (1602.01465)

AMS-02 Reach

3 year live time, 1 BG event

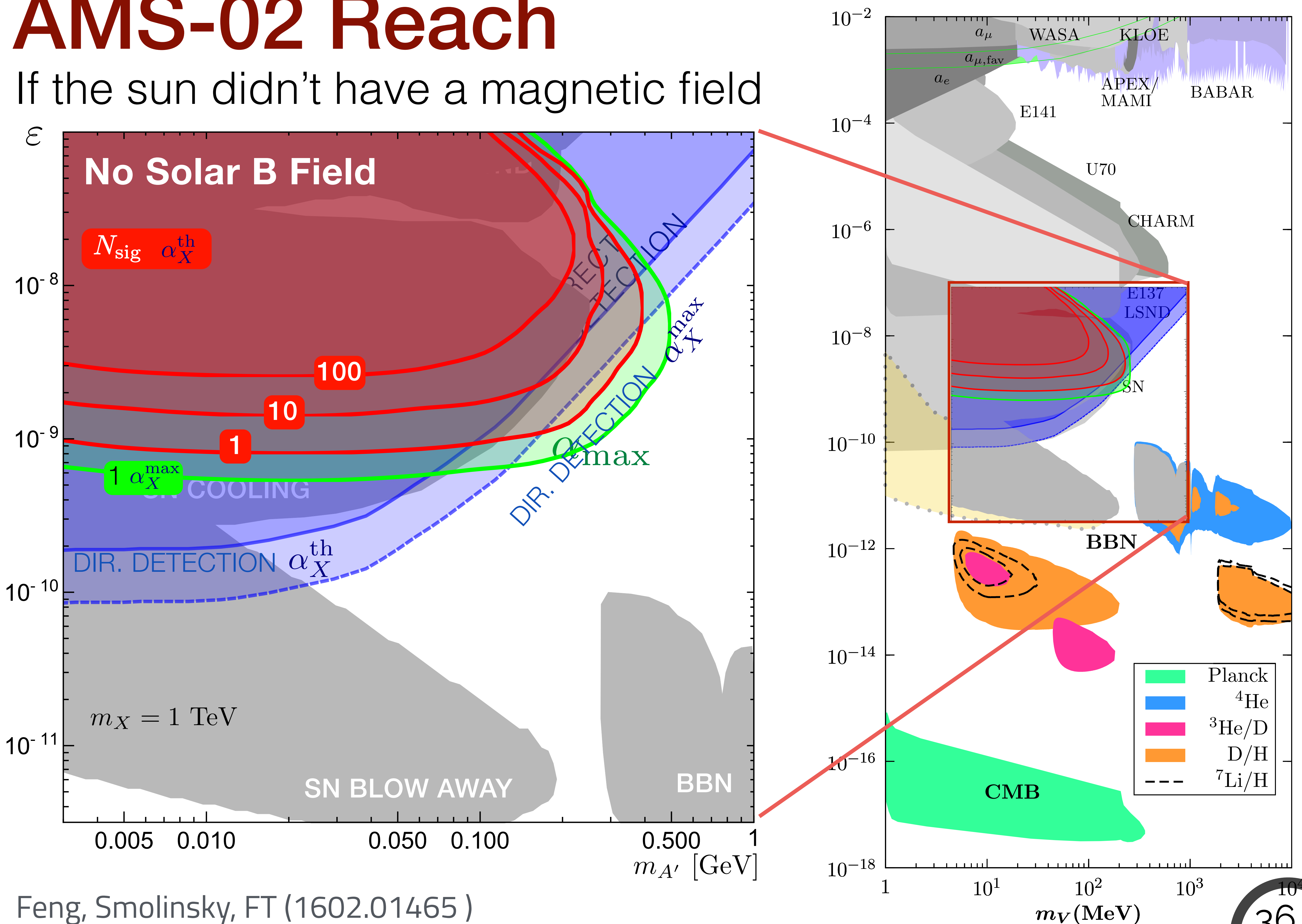




Feng, Smolinsky, FT (1602.01465)

AMS-02 Reach

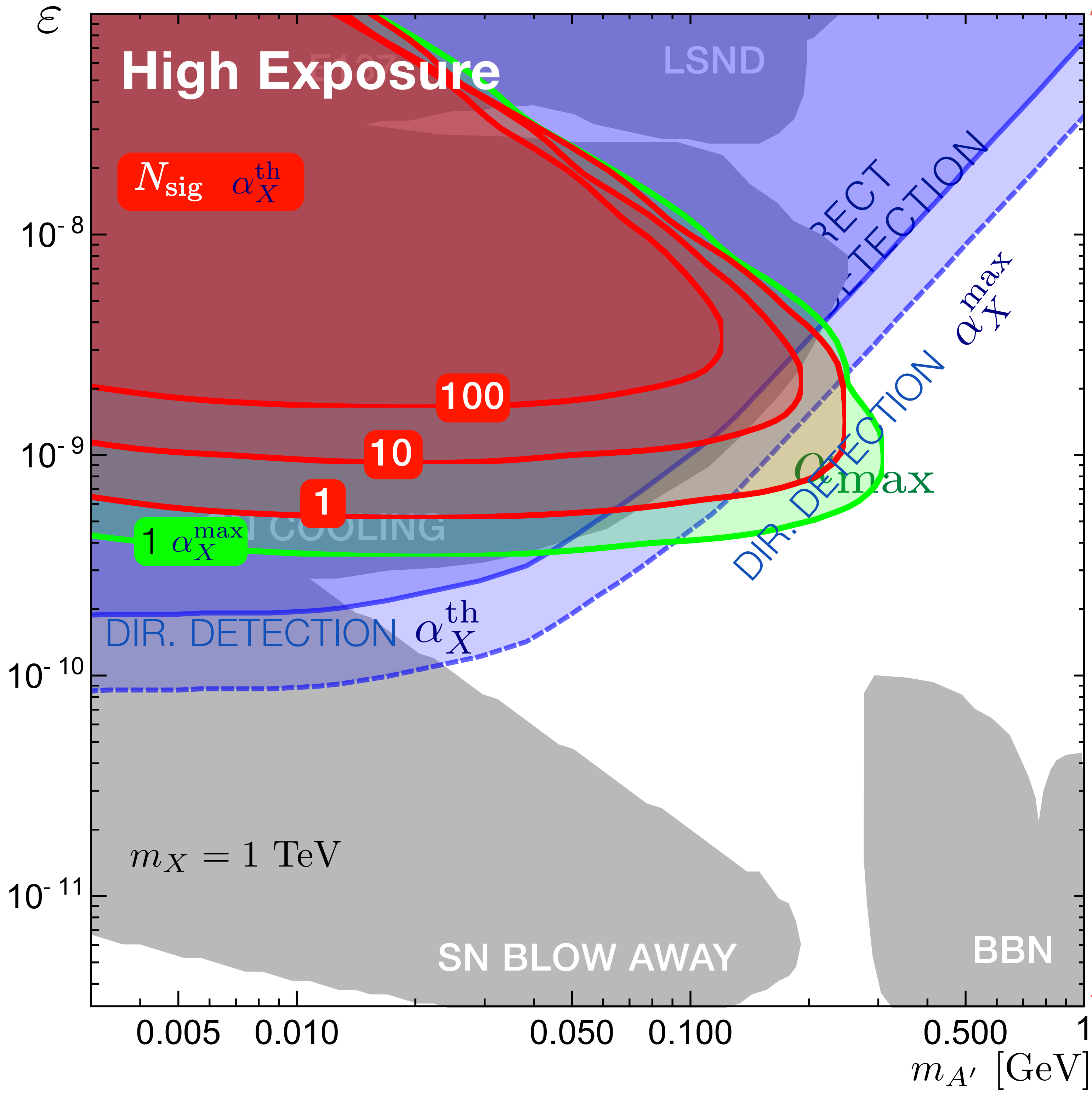
If the sun didn't have a magnetic field

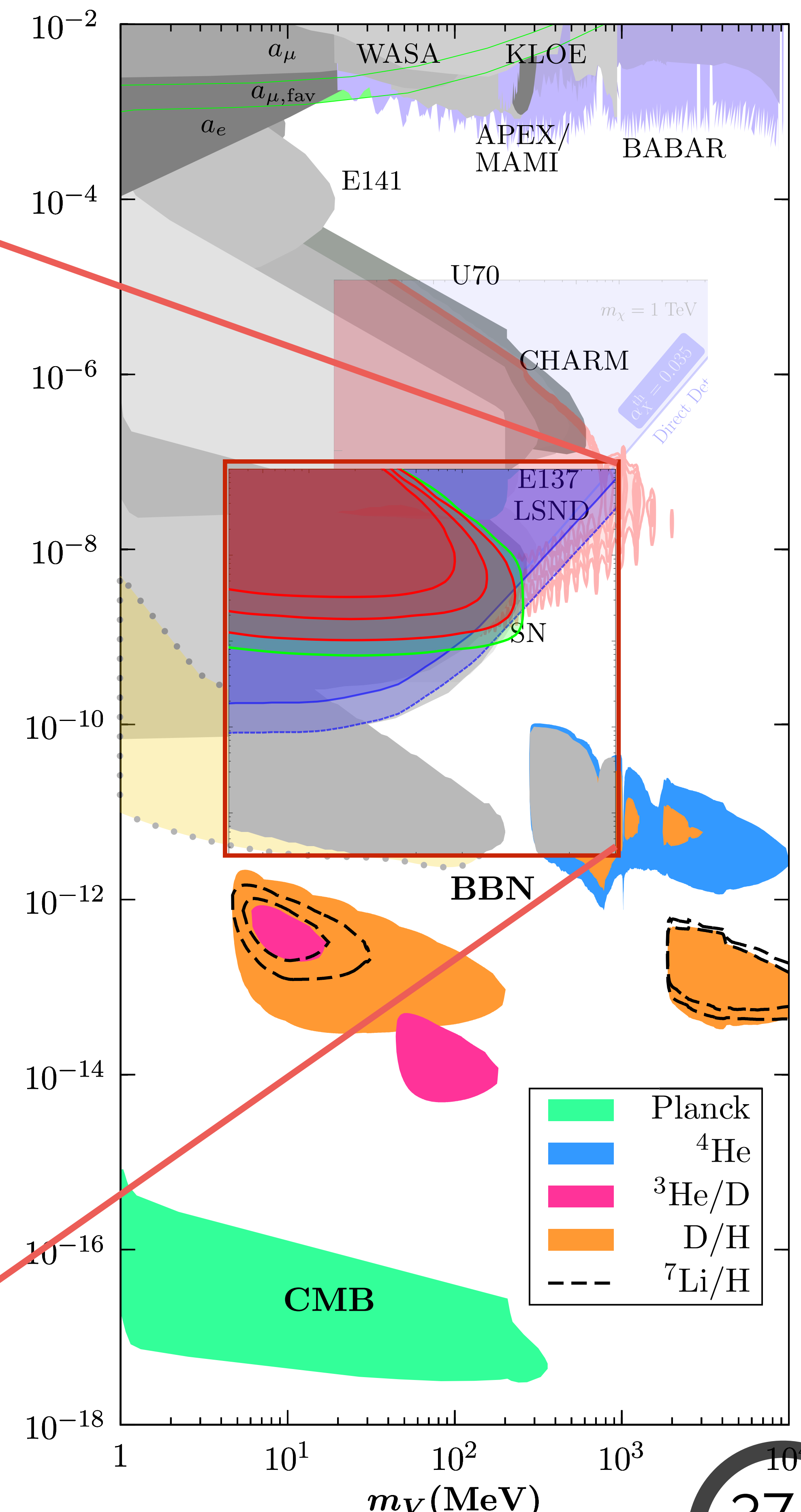


Feng, Smolinsky, FT (1602.01465)

AMS-02 Reach

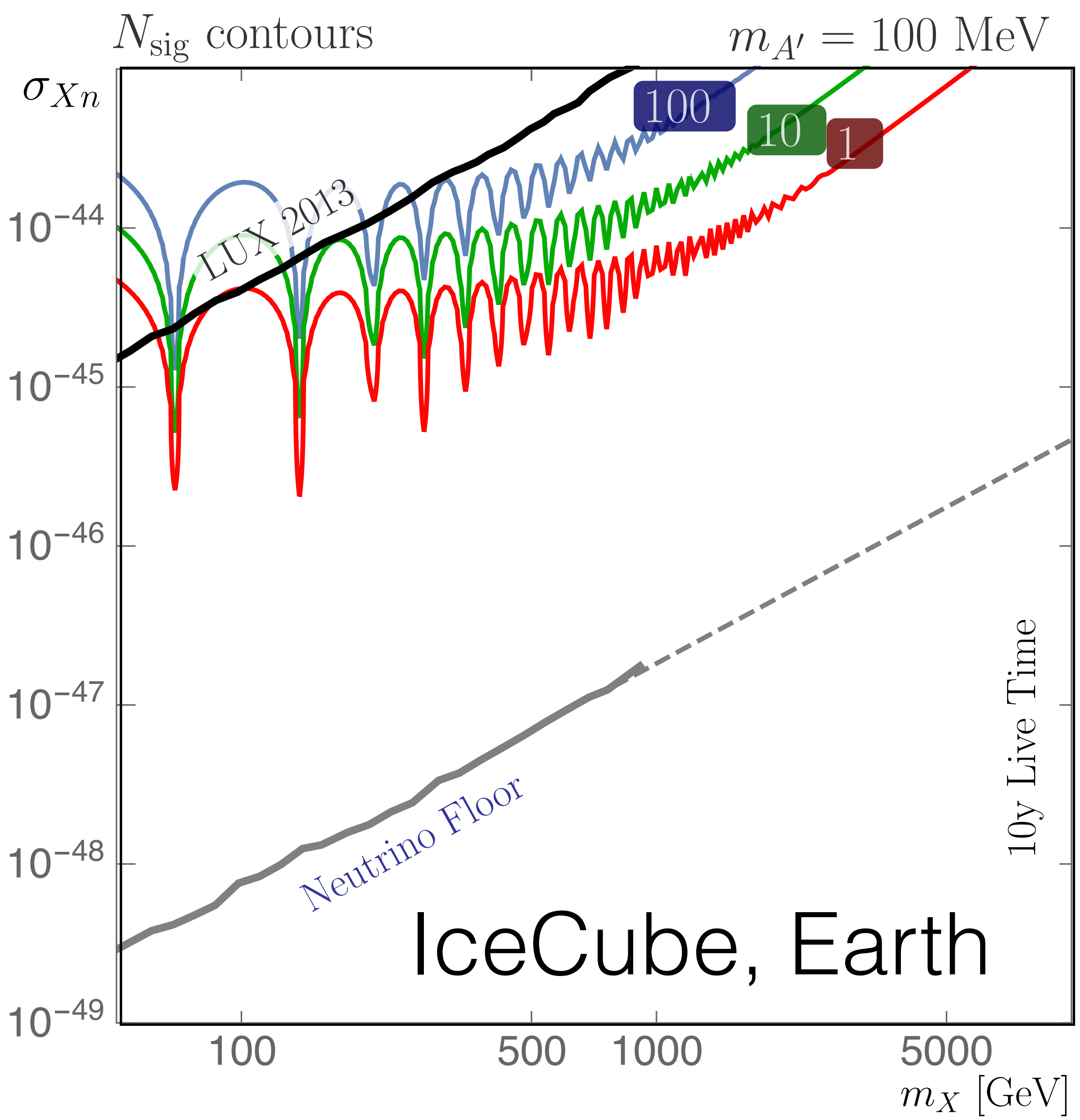
If AMS only pointed at the Sun

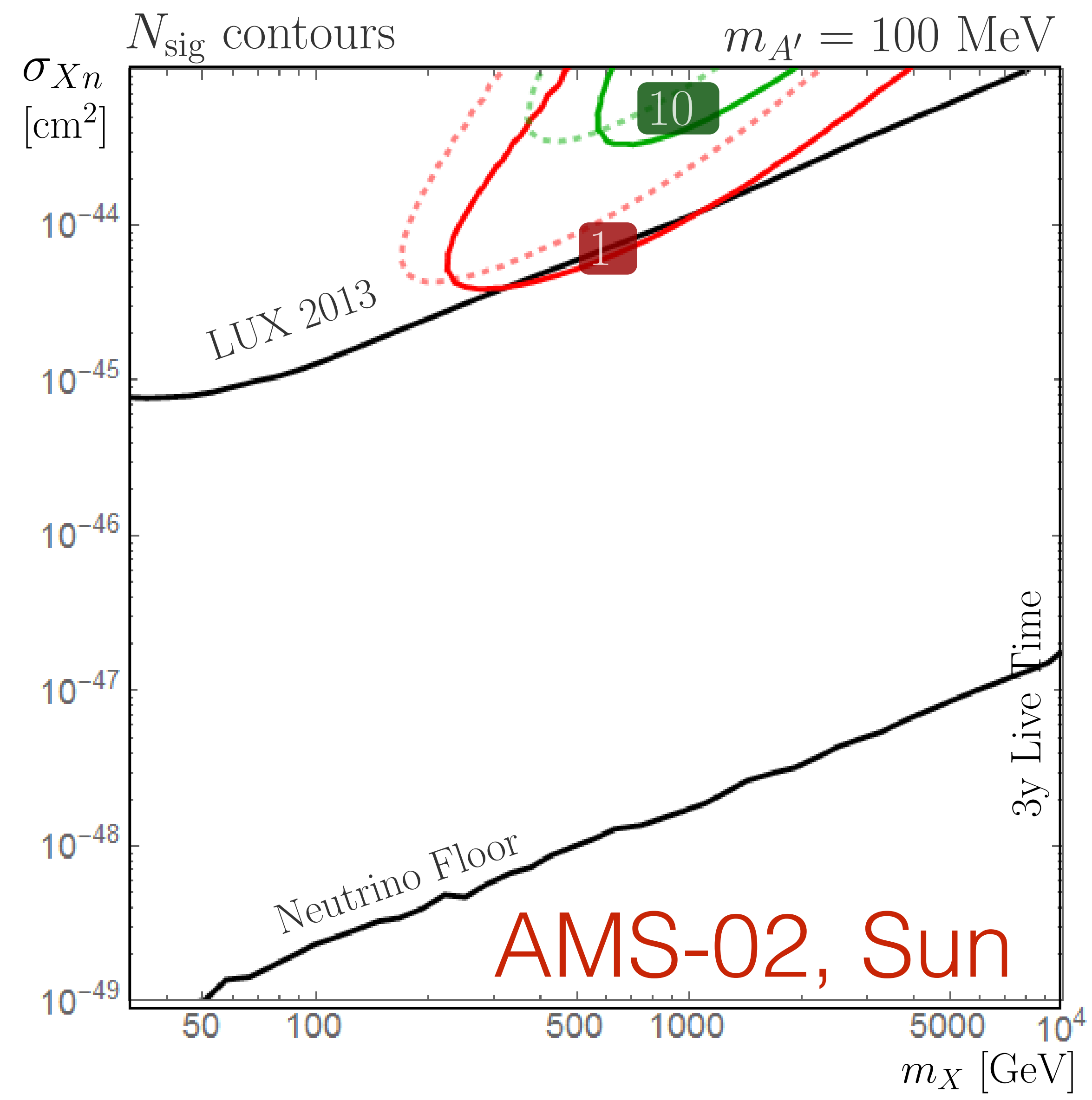




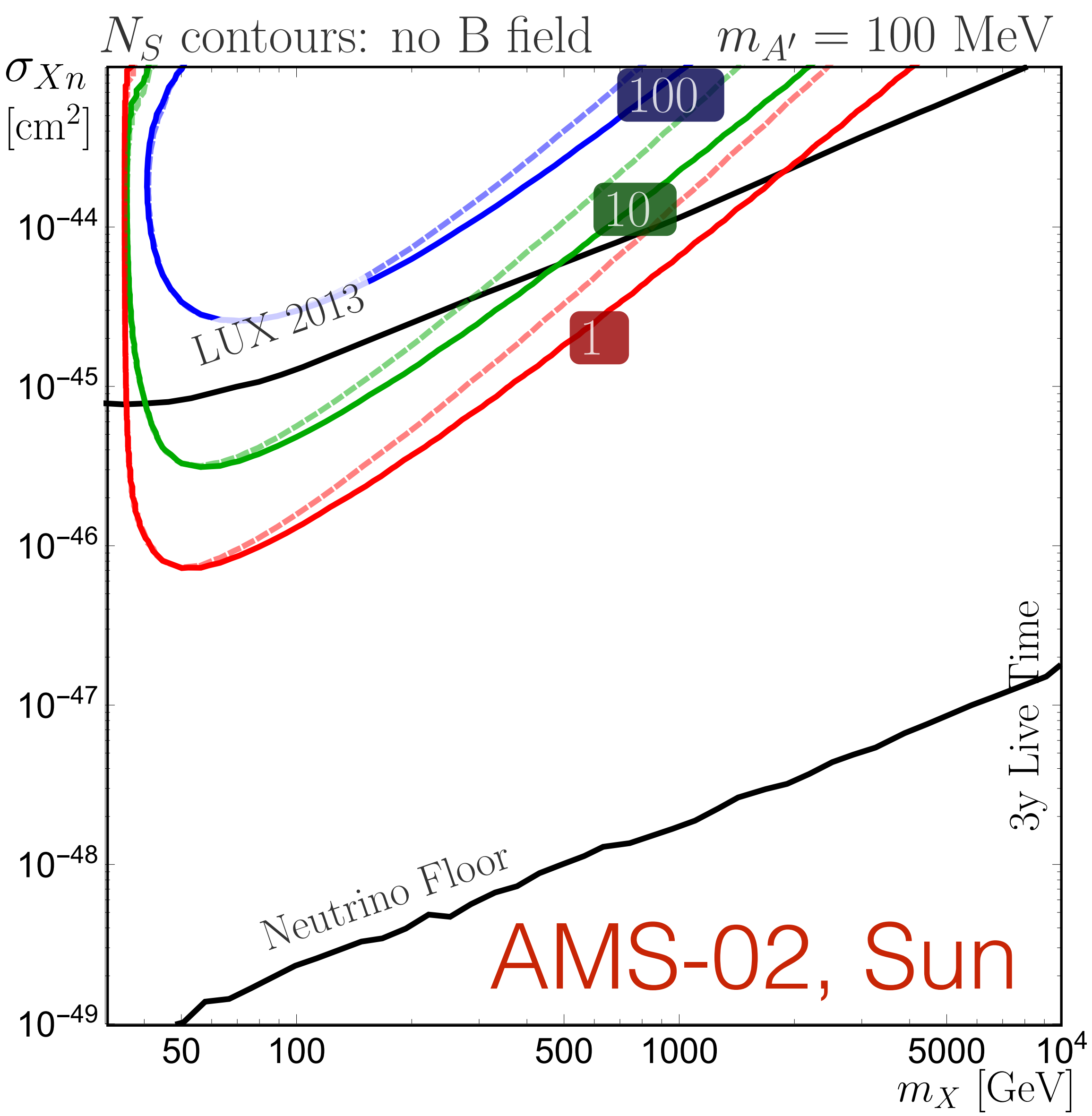
Feng, Smolinsky, FT (1602.01465)

Reach on direct detection plane

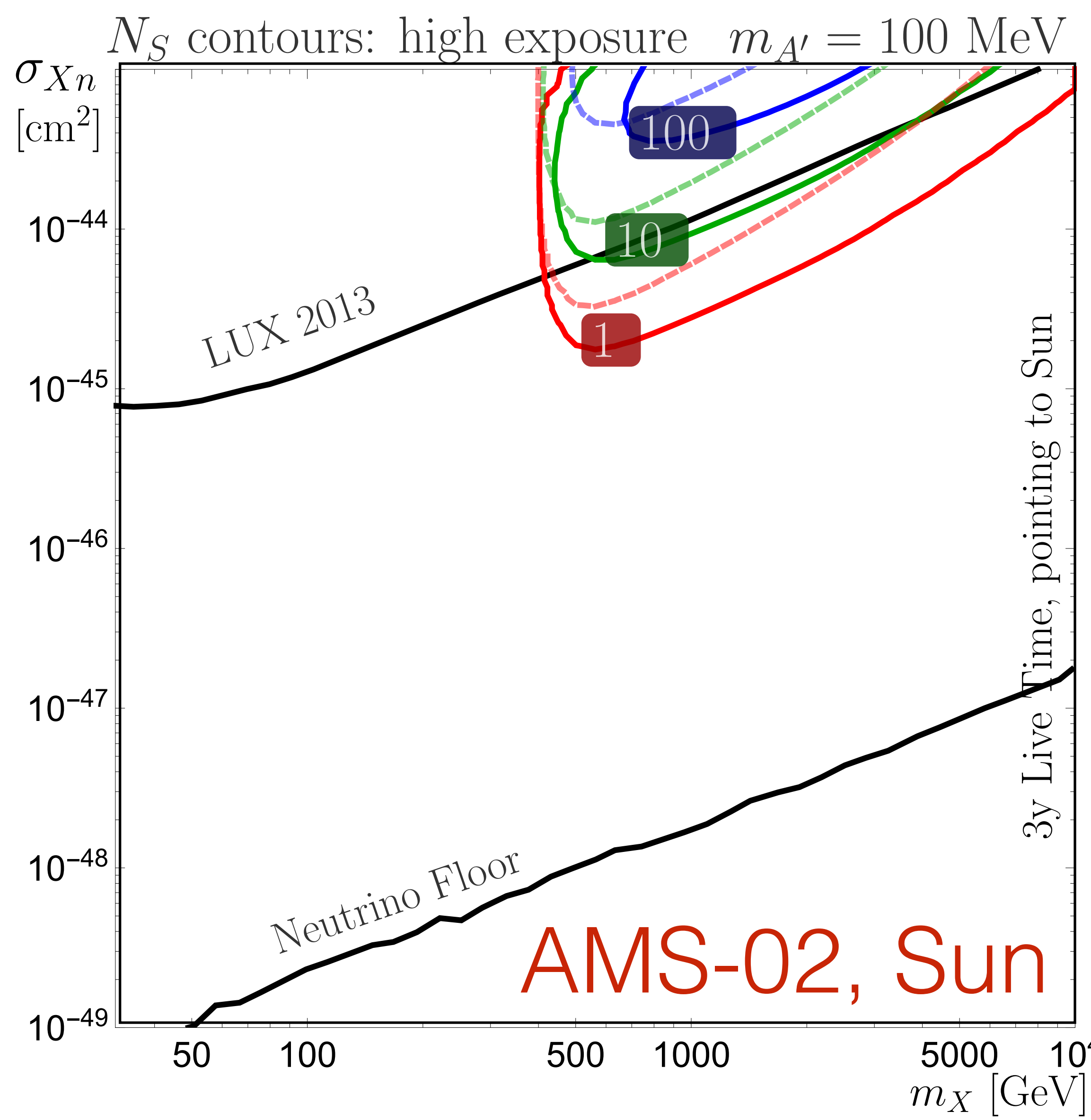




Reach on direct detection plane



no solar B field

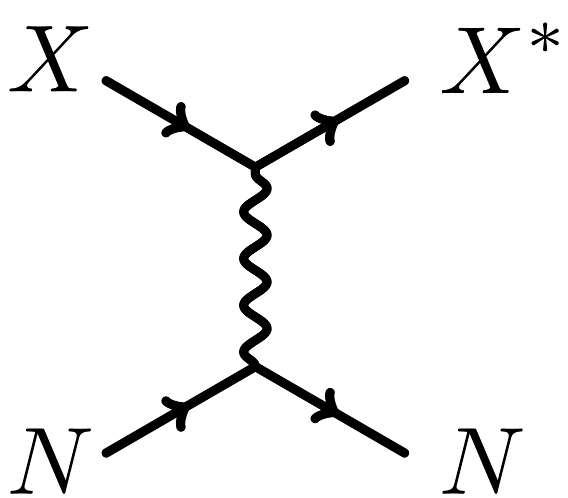


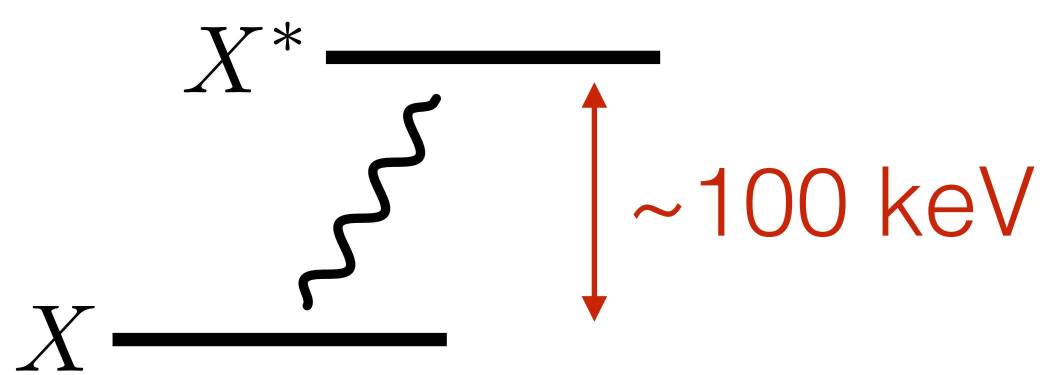
pointed at Sun 100%

Some Interesting Questions

What would it take for the moon to capture?

Example: inelastic dark matter





MOON

GENERIC IN DARK PHOTON MODEL
ALSO AVOIDS DIRECT DETECTION BOUNDS

Some Interesting Questions

Can we hack a better detector?
… probably not, but curious!

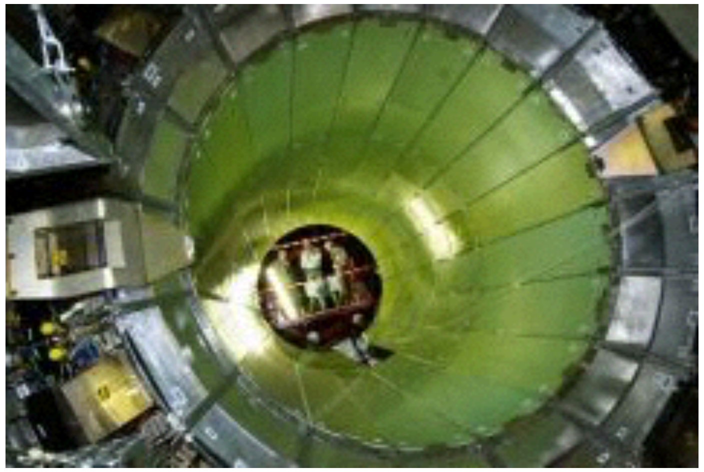
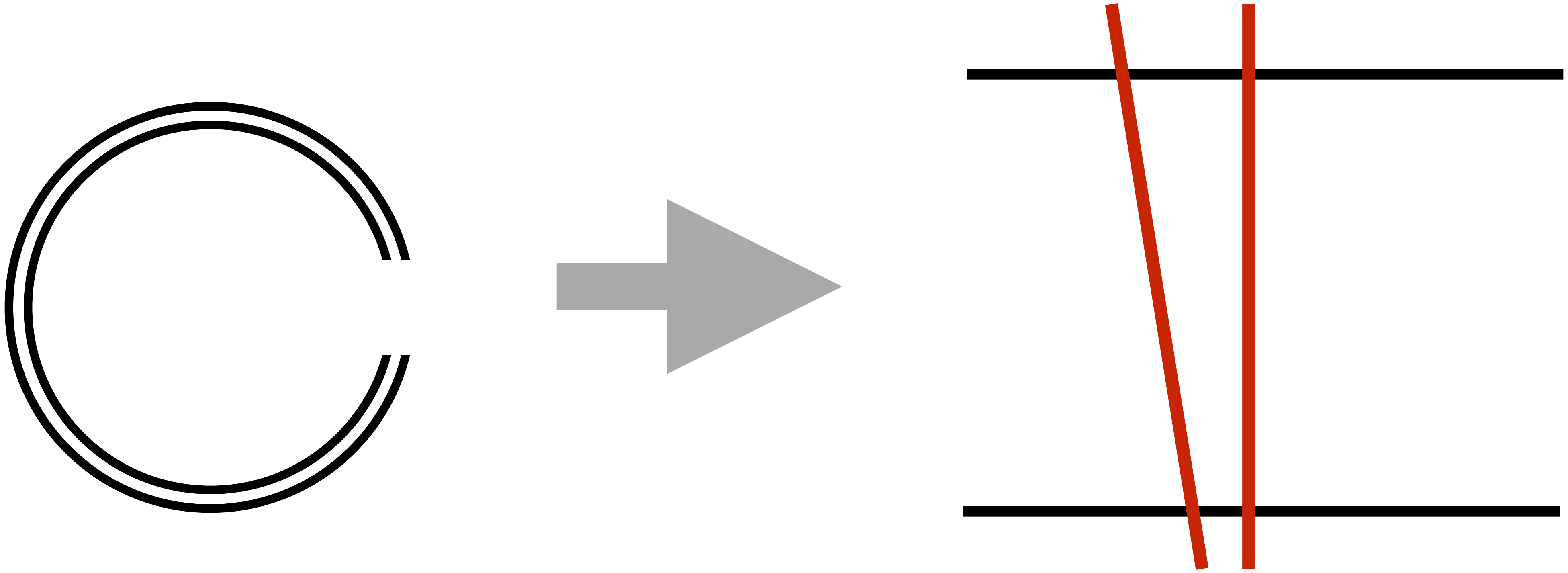


Image: CMS e-cal public page

Use CMS tracker to build μ detector
200m^2 = 2 stations x 3 layers of 33m^2
Optimistically, about O(10) too small



Summary

Dark Matter annihilates in the Earth (or the Sun) to
A PLACE

dark photons, which are detected by IceCube (or AMS).
SOME PARTICLE(S) AN EXPERIMENT

- Directional information for background rejection
- Earth/Sun is cold: Sommerfeld resonances
- Interesting but difficult to reach:
  Double track events, Solar *A'* decays