Viable Indirect Detection For sub-GeV Thermal DM

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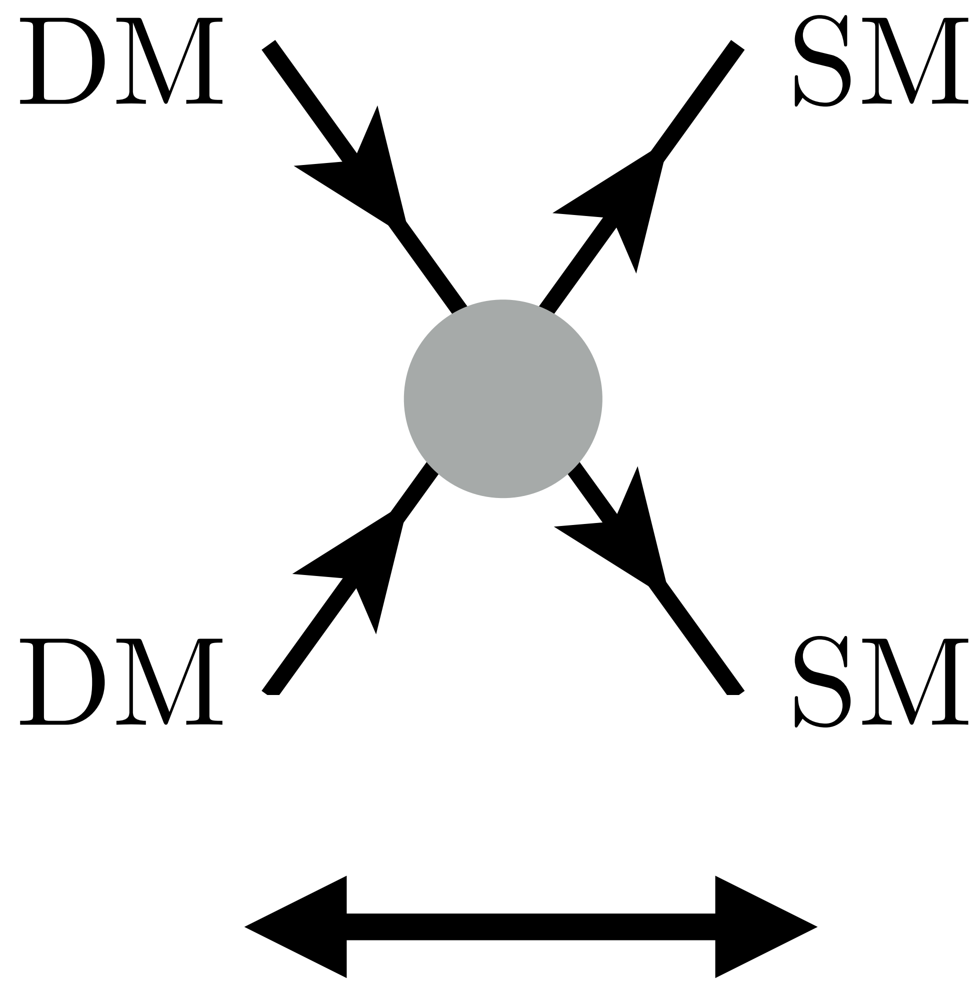
arXiv:2309.XXXXX

PADUA Workshop, Sept 7, 2023

Image: Volker Springel

Was DM ever in equilibrium with SM?



Chemical equilibrium: DM production = annihilation just after the big bang when $T \gg m_{\rm DM}$

Was DM ever in equilibrium with SM?

NO

How was it populated?

Was DM ever in equilibrium with SM?

NO

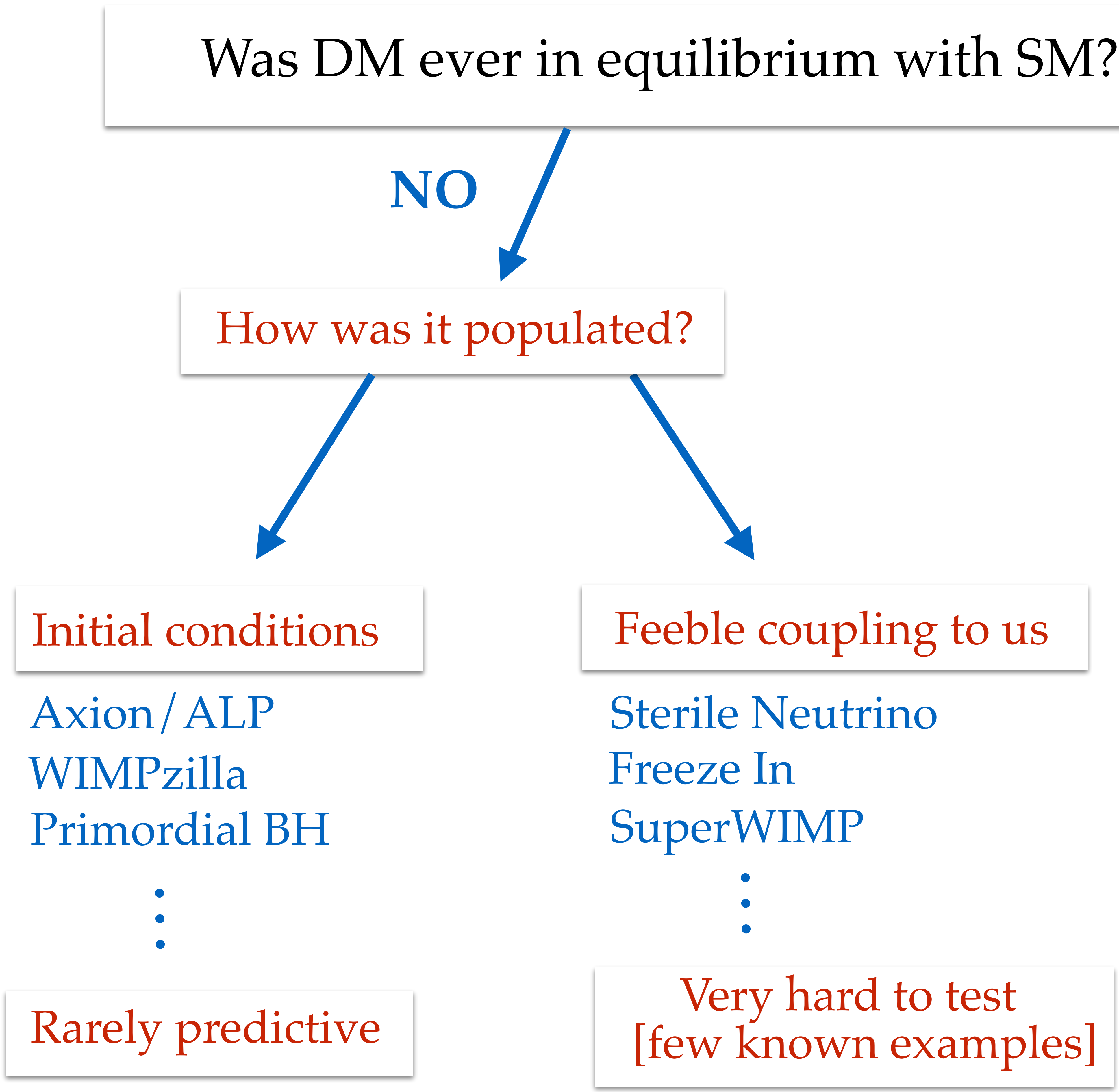
How was it populated?

Initial conditions

Axion / ALP
WIMPzilla
Primordial BH

⋮

Rarely predictive


Was DM ever in equilibrium with SM?
NO
How was it populated?
Initial conditions
Feeble coupling to us
Axion / ALP
WIMPzilla
Primordial BH
Sterile Neutrino
Freeze In
SuperWIMP
Rarely predictive
Very hard to test
[few known examples]

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

$$n_i^{\rm eq} = \int \frac{d^3p}{(2\pi)^3} \frac{g_i}{e^{E/T} \pm 1} \propto T^3 \qquad (T \gg m)$$

In equilibrium, number density set by temperature

All relativistic species have comparable numbers

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Stayed the same

We've measured the DM mass density
so equilibrium predicts particle mass

$$m_\chi \approx \rho_\chi / n_\chi \sim 10\,\mathrm{eV}$$

Too hot, ruled out!

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Other dark states

Heavy

too much DM

Light

spoils BBN/CMB

Requires nonstandard cosmology

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

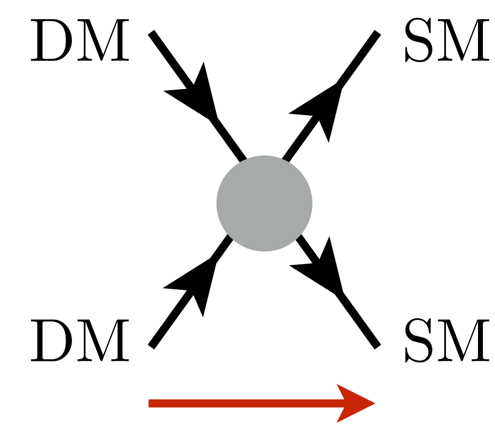
Where did its density go?

Visible matter

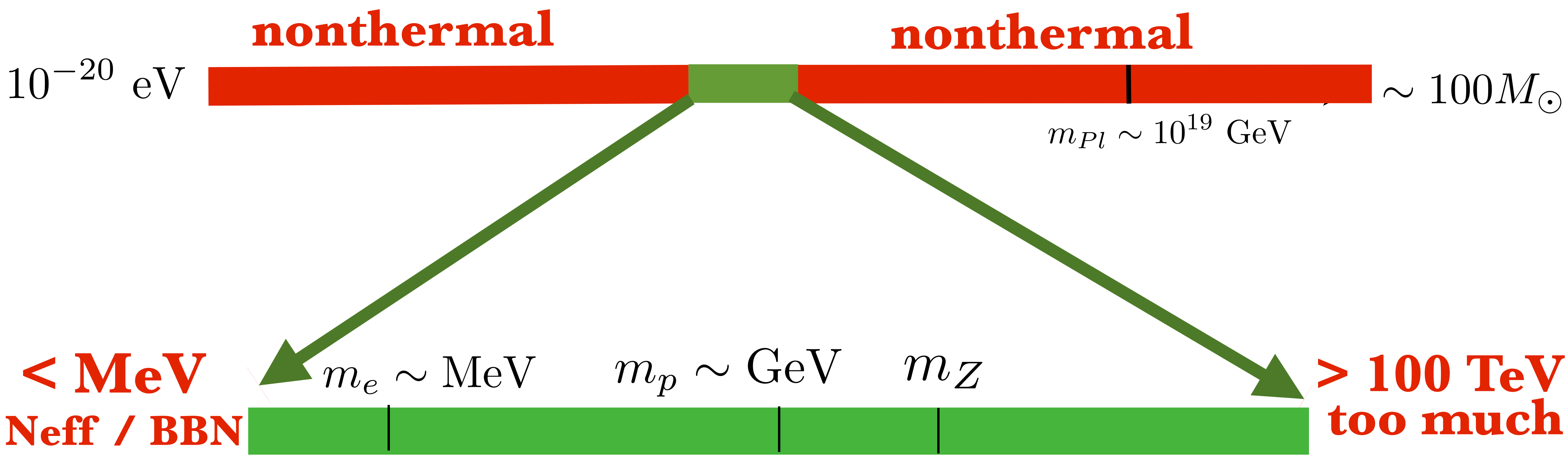
Direct Annihilation

1) Predicts ***minimum*** SM coupling

2) The **only** production scenario that is insensitive to unknown cosmic epochs

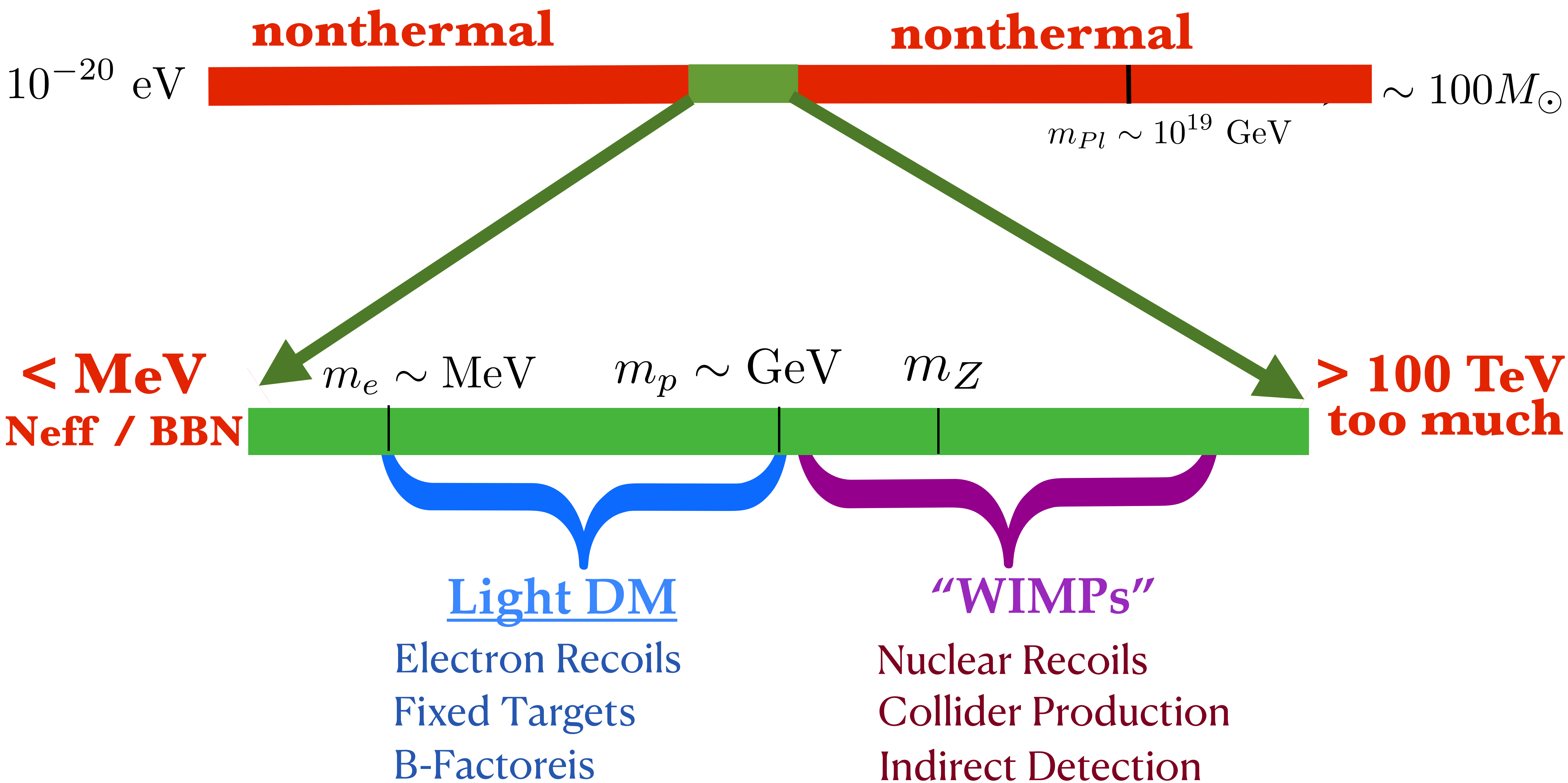


Equilibrium Narrows Mass Range!

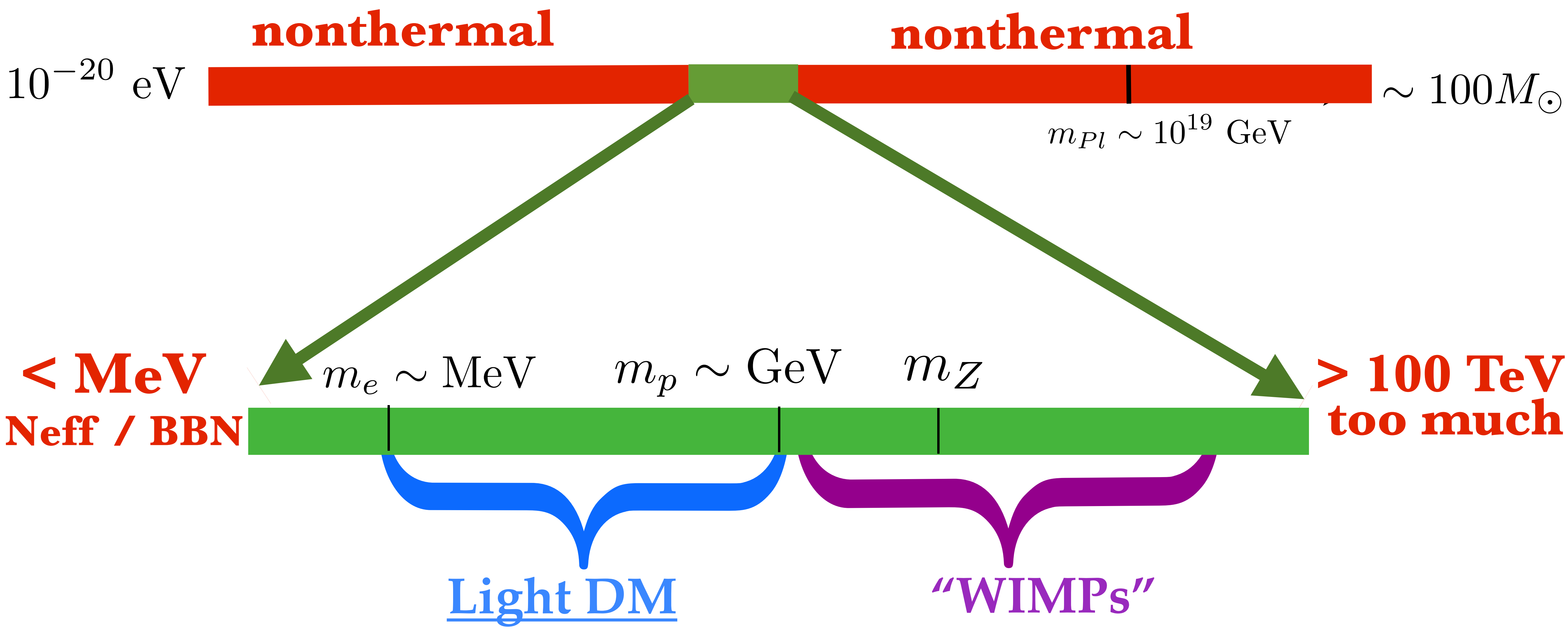


Any DM candidate outside this range is ruled out if theory allows thermalization with the SM

Equilibrium Narrows Mass Range!



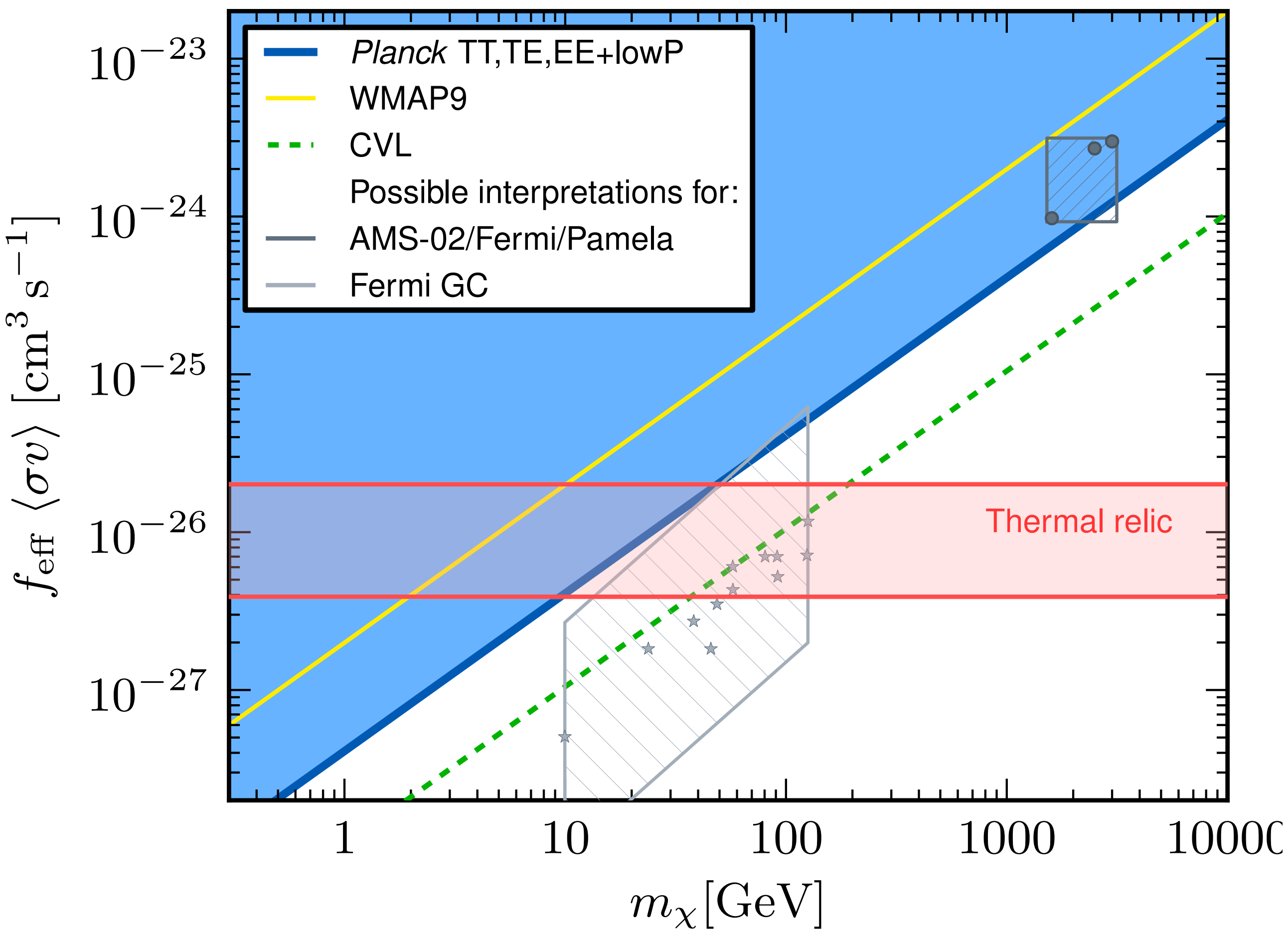
Equilibrium Narrows Mass Range!

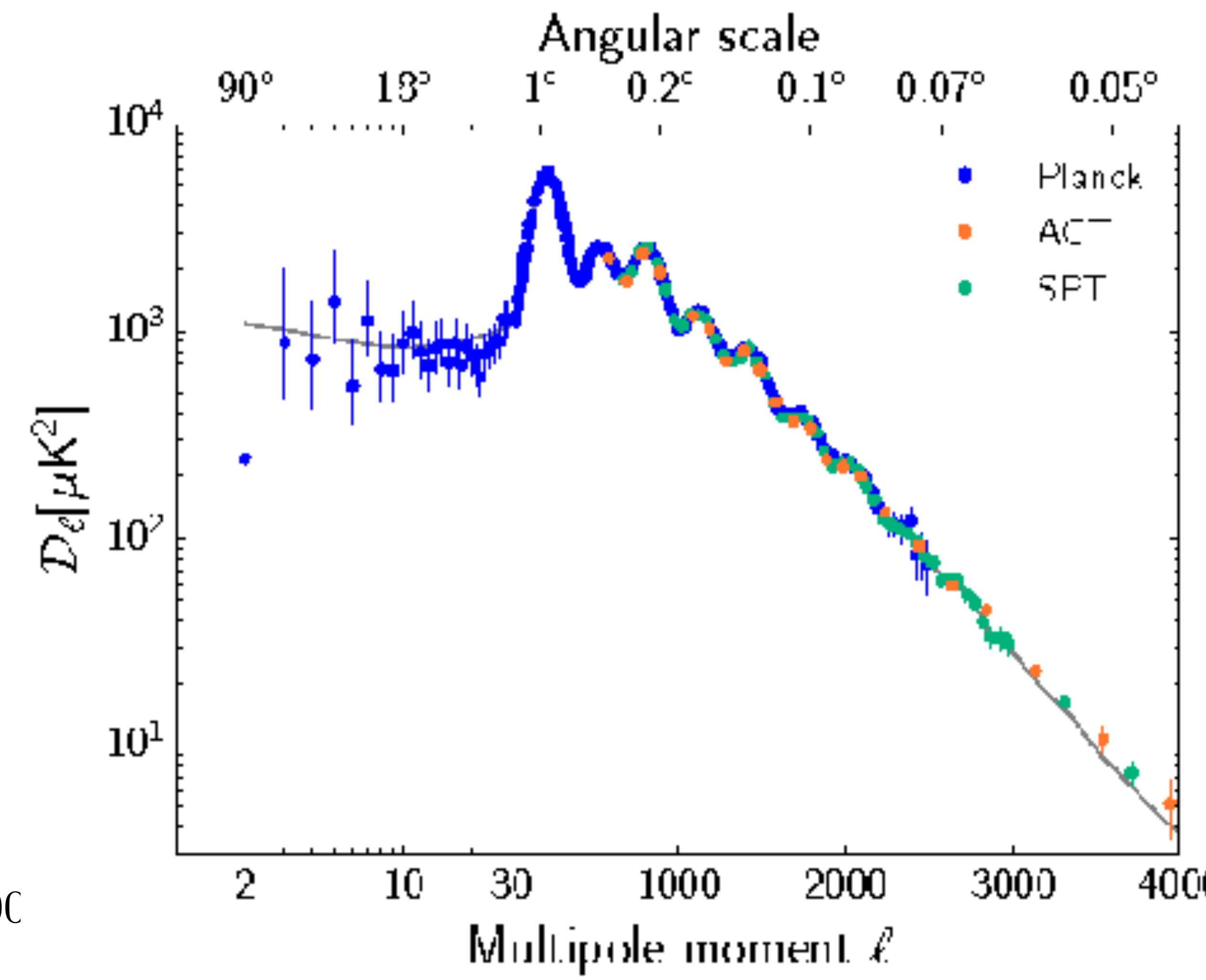


What about sub-GeV Indirect Detection??

Indirect Detection

Generic Issue: CMB Limits





Planck Collaboration 1502.01589

Rare out-of-equilibrium DM annihilation ionizes hydrogen

CMB photons encounter more plasma

Naively out thermal relic cross section for DM < 20 GeV…

CMB Safety: Two Strategies

Strategy 1: p-wave annihilation $\sigma v \propto v^2$ $v^2 \sim 0.1 \,\mathrm{at}\; \mathrm{FO}$

Suppressed CMB annihilation

$$\langle \sigma v \rangle_{\mathrm{CMB}} \ll \langle \sigma v \rangle_{\mathrm{FO}}$$

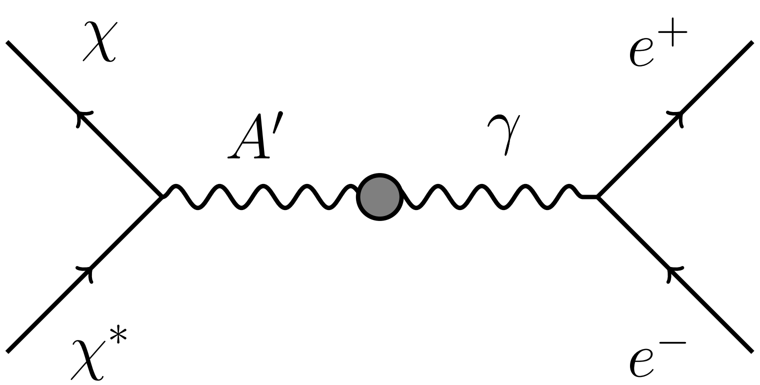
Also suppresses annihilation today

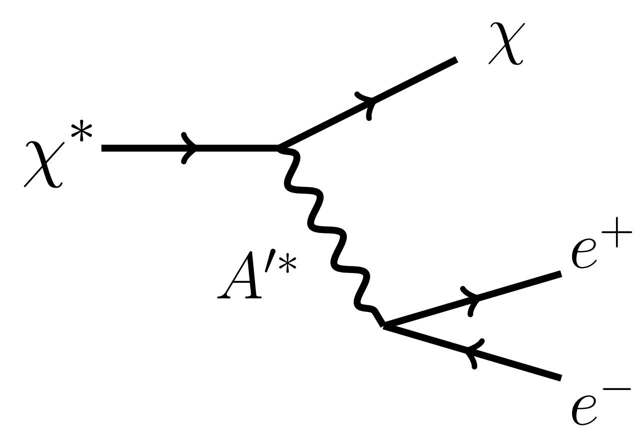
$$\langle \sigma v \rangle_{\mathrm{today}} \sim 10^{-6} \langle \sigma v \rangle_{\mathrm{FO}}$$

CMB Safety: Two Strategies

Strategy 2: Change the DM population

Example — coannihilation with heavier unstable partner χ^*





Equal initial abundances

Heavier state depleted before CMB

Same qualitative conclusion: CMB safe…
but no indirect detection today

Gonzalez, Toro 2108.13422

Overall Assessment?

Hard to have < GeV thermal freeze out and preserve indirect detection signals

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Hard to have < GeV thermal freeze out and preserve indirect detection signals

Clever variation: two components with different histories

Stable thermal subcomponent →

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\chi\chi} v_{\rm rel} \rangle_{\rm (F.O.)} \left[n_\chi^2 - n_\chi^{\rm eq\,2} \right]$$

Only annihilating species $\langle \sigma_{\chi\chi'} v_{\rm rel} \rangle \gg \langle \sigma v \rangle_{\rm thermal}$

D'Eramo Profumo:1806.04745

Overall Assessment?

Hard to have < GeV thermal freeze out and preserve indirect detection signals

Clever variation: two components with different histories

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\chi\chi} v_{\rm rel} \rangle_{\rm (F.O.)} \left[n_\chi^2 - n_\chi^{\rm eq\,2} \right]$$

$$\frac{dn_\psi}{dt} + 3Hn_\psi = \mathcal{C}_\psi \ ,$$

Dominant species
Non-thermal production

Doesn't annihilate, but decays
$\psi \to \chi$

D'Eramo Profumo:1806.04745

Overall Assessment?

Hard to have < GeV thermal freeze out and preserve indirect detection signals

Clever variation: two components with different histories

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{\chi\chi} v_{\rm rel} \rangle_{\rm (F.O.)} \left[n_\chi^2 - n_\chi^{\rm eq\,2} \right]$$
$$\frac{dn_\psi}{dt} + 3Hn_\psi = \mathcal{C}_\psi \ ,$$

Subdominant χ population = CMB safe

Dominant population decays at later times $\psi \to \chi \cdots$

Increases χ abundance after CMB era = indirect detection

D'Eramo Profumo:1806.04745

Lingering Question

Is there a predictive freeze-out model of sub-GeV DM with indirect detection signatures?

Goal: use only the ingredients required for freeze out

Representative Model

Four component fermion + dark photon

$$\mathcal{L} \supset g_D A'_\mu \bar{\psi} \gamma^\mu \psi + M \bar{\psi} \psi + H_D \bar{\psi}^c \psi$$

Vector current

Dirac mass

Charge 2 dark Higgs

Representative Model

Four component fermion + dark photon

$$\mathcal{L} \supset g_D A'_\mu \bar{\psi}\gamma^\mu\psi + M\bar{\psi}\psi + H_D\bar{\psi}^c\psi$$

Break dark U(1) with dark Higgs VEV

$$\mathcal{L}_{\rm mass} = M\bar{\psi}\psi + \langle H_D\rangle\bar{\psi}^c\psi$$

Dirac Majorana

Representative Model

Four component fermion + dark photon

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Break dark U(1) with dark Higgs VEV

$$\mathcal{L}_{\text{mass}} = M\bar{\psi}\psi + \langle H_D \rangle \bar{\psi}^c \psi$$

Diagonalizing to mass basis splits Dirac components

$$\psi \equiv (\xi, \eta^\dagger) \longrightarrow (\chi, \chi^\star)\ ,\ \delta \equiv m_{\chi^\star} - m_\chi$$

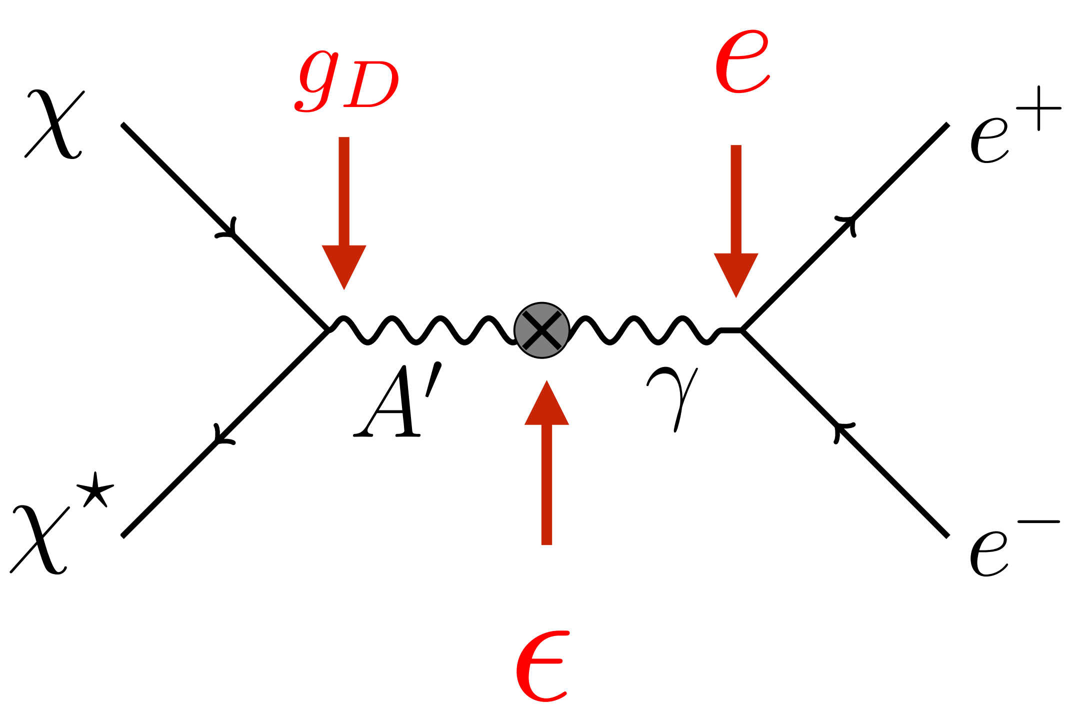
int. eigenstates → mass eigenstates

Representative Model

Vector current off-diagonal in mass basis

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi}^\star \gamma^\mu \chi + h.c.$$

Dominant process for relic abundance



Direct Coannihilation

$$m_{A'} > m_\chi + m_{\chi^\star}$$

Opposite regime is not predictive or CMB safe

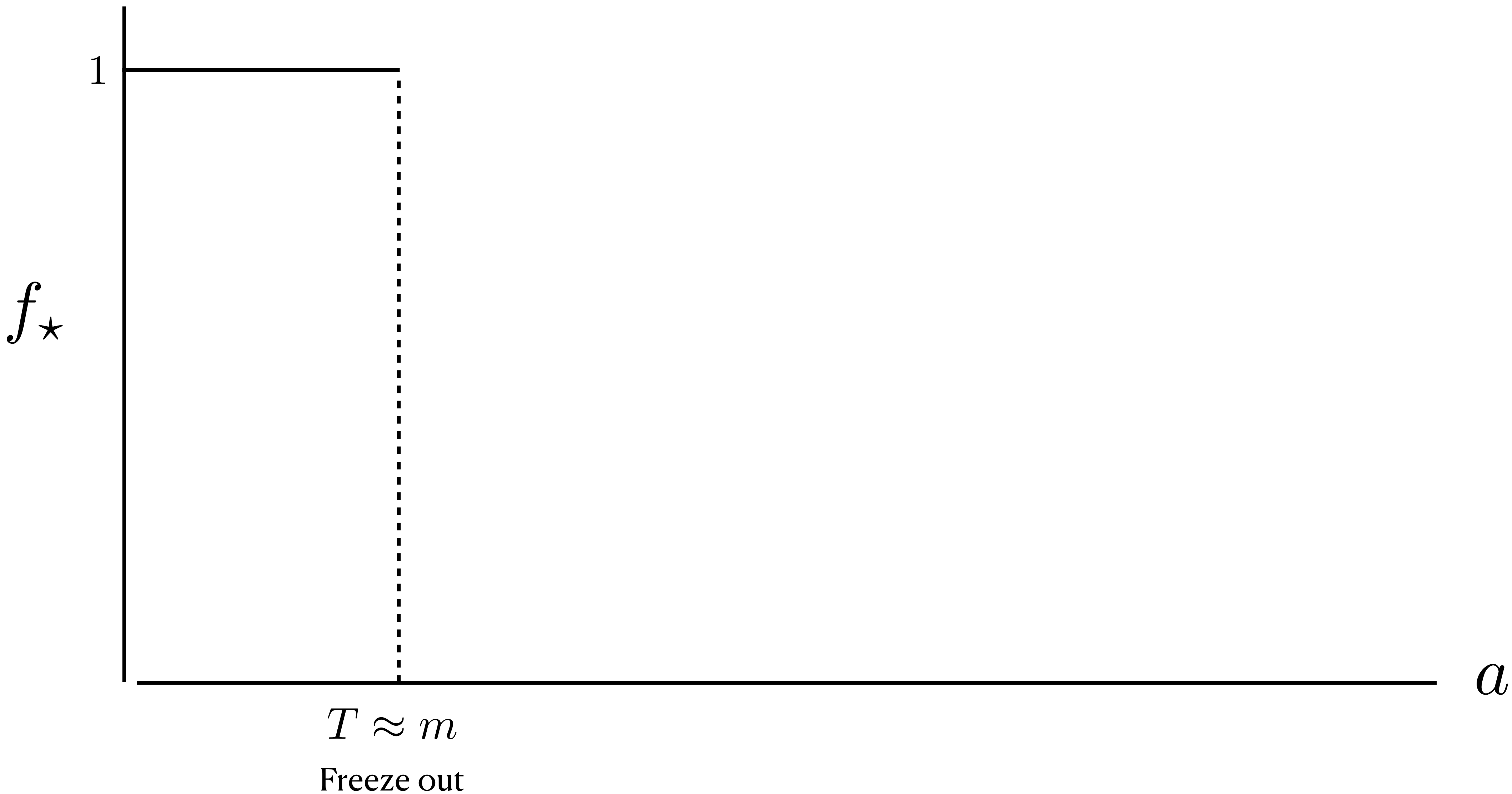
$$\chi\chi \to A'A'$$

$$\alpha_D \equiv \frac{g_D^2}{4\pi}$$

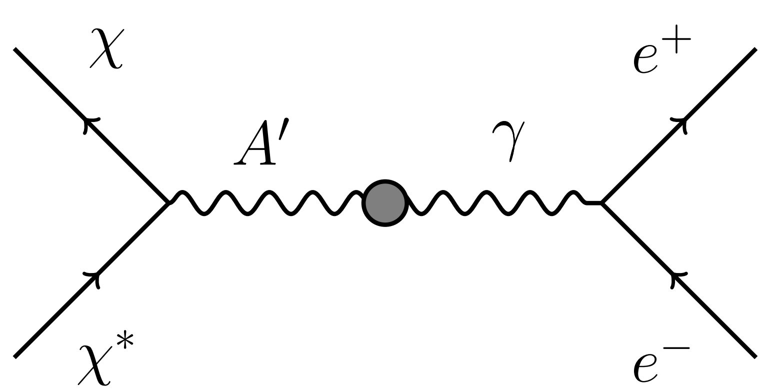
Cosmological History

$$f_\star \equiv \frac{n_{\chi^\star}}{n_\chi}$$

Thermal Freeze Out



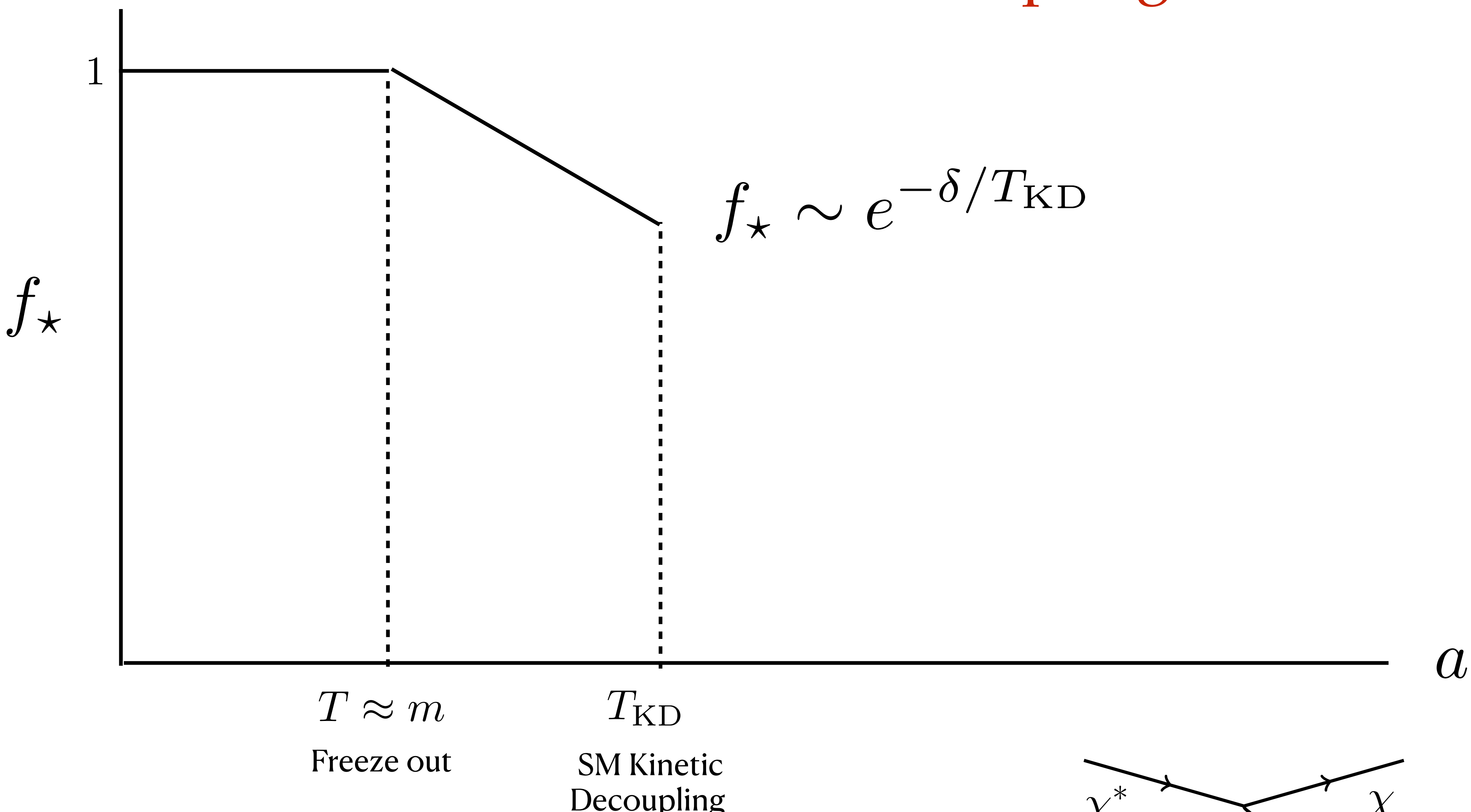
$$T_\chi = T_\gamma \propto a^{-1}$$

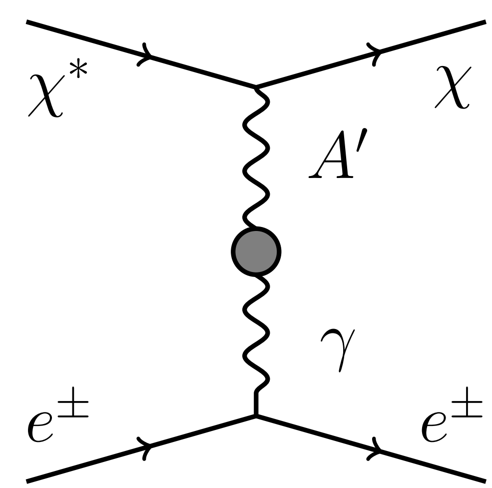


Cosmological History

$$f_\star \equiv \frac{n_{\chi^\star}}{n_\chi}$$

Dark-SM Kinetic Decoupling





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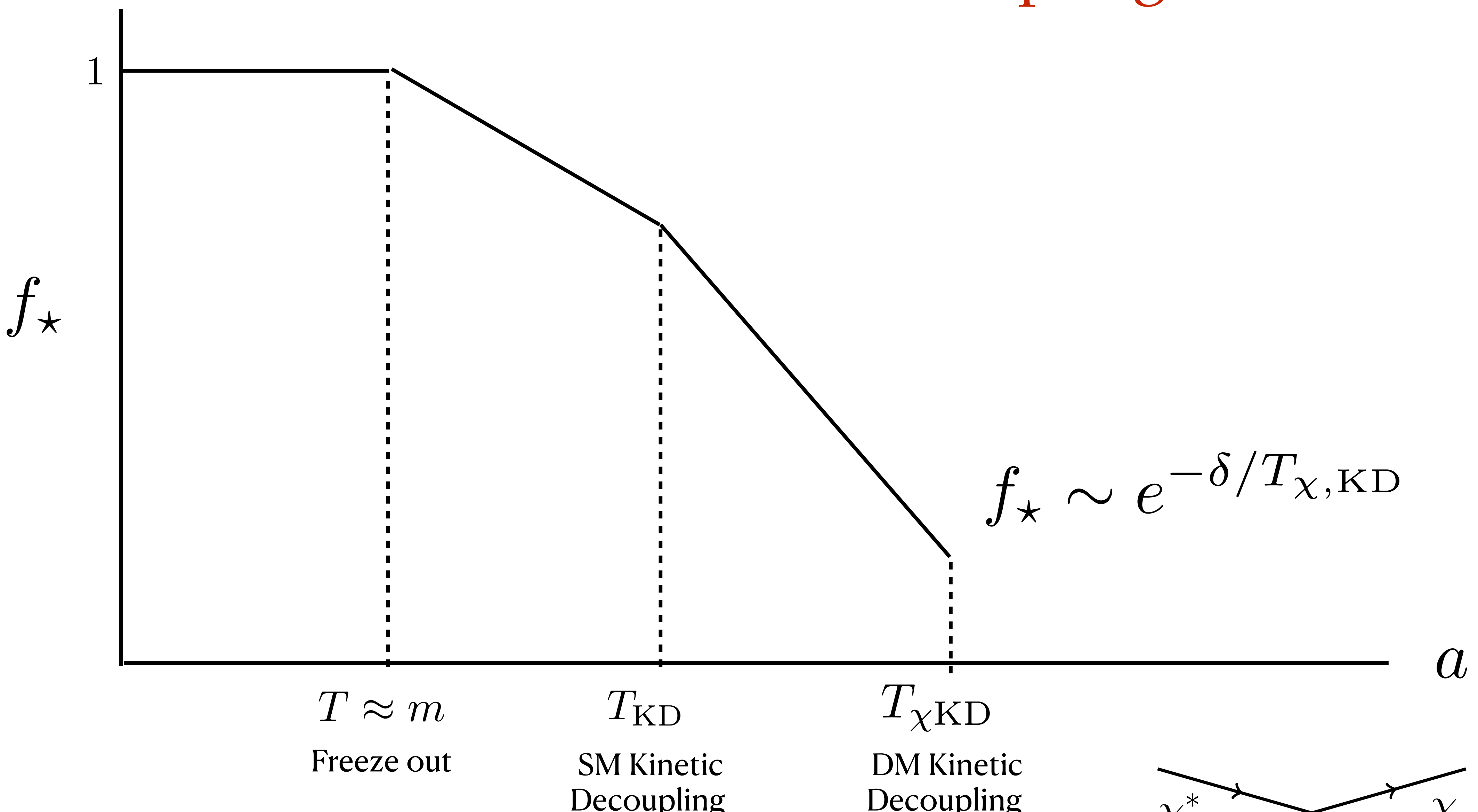
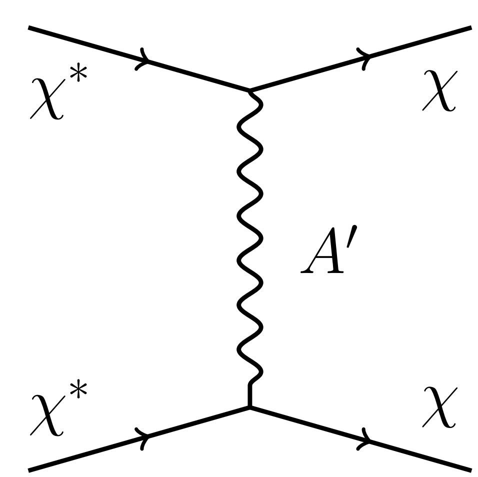
Dark-Dark Kinetic Decoupling



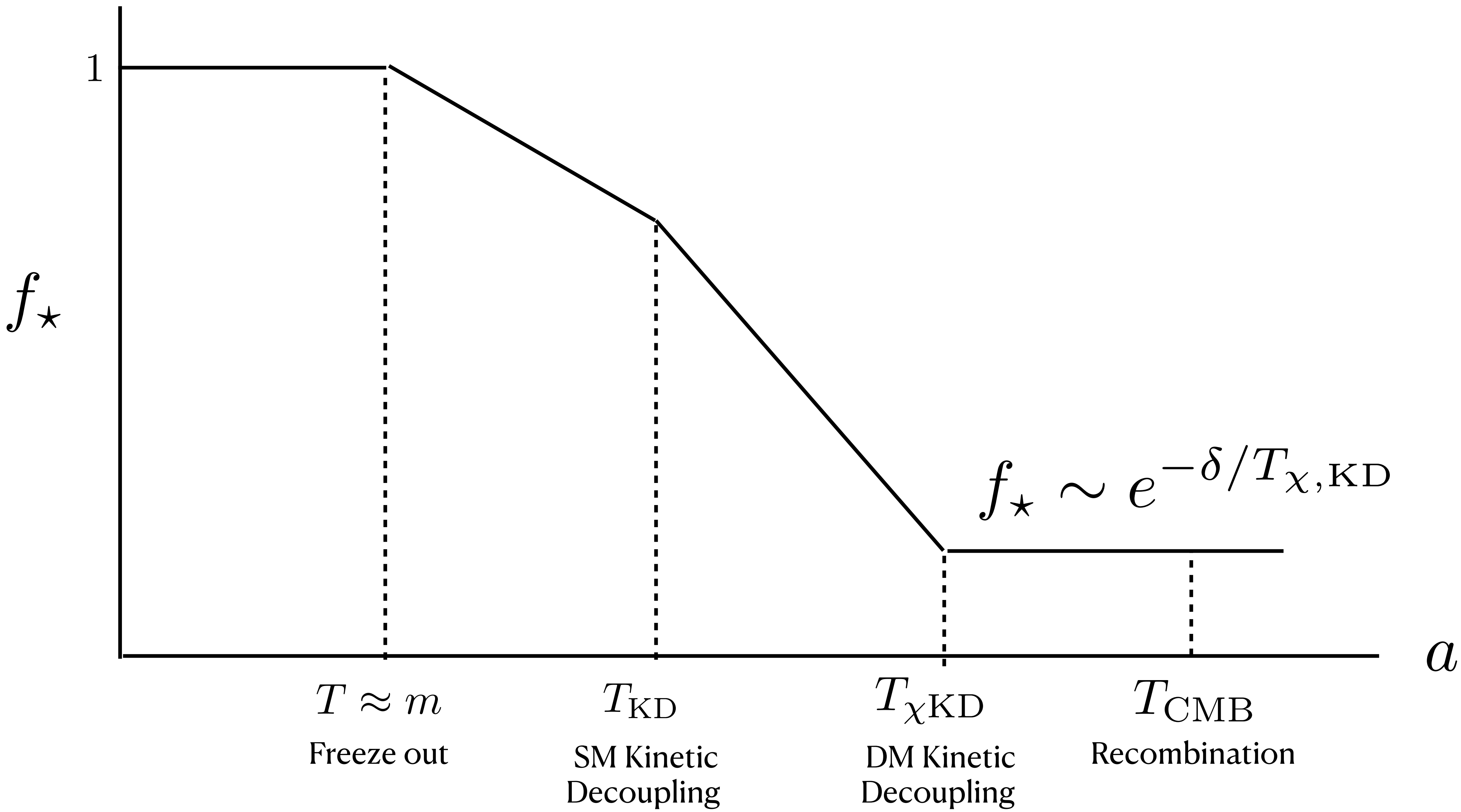
$$T_\chi \propto a^{-2}$$



Cosmological History

$$f_\star \equiv \frac{n_{\chi^\star}}{n_\chi}$$

Recombination Annihilation

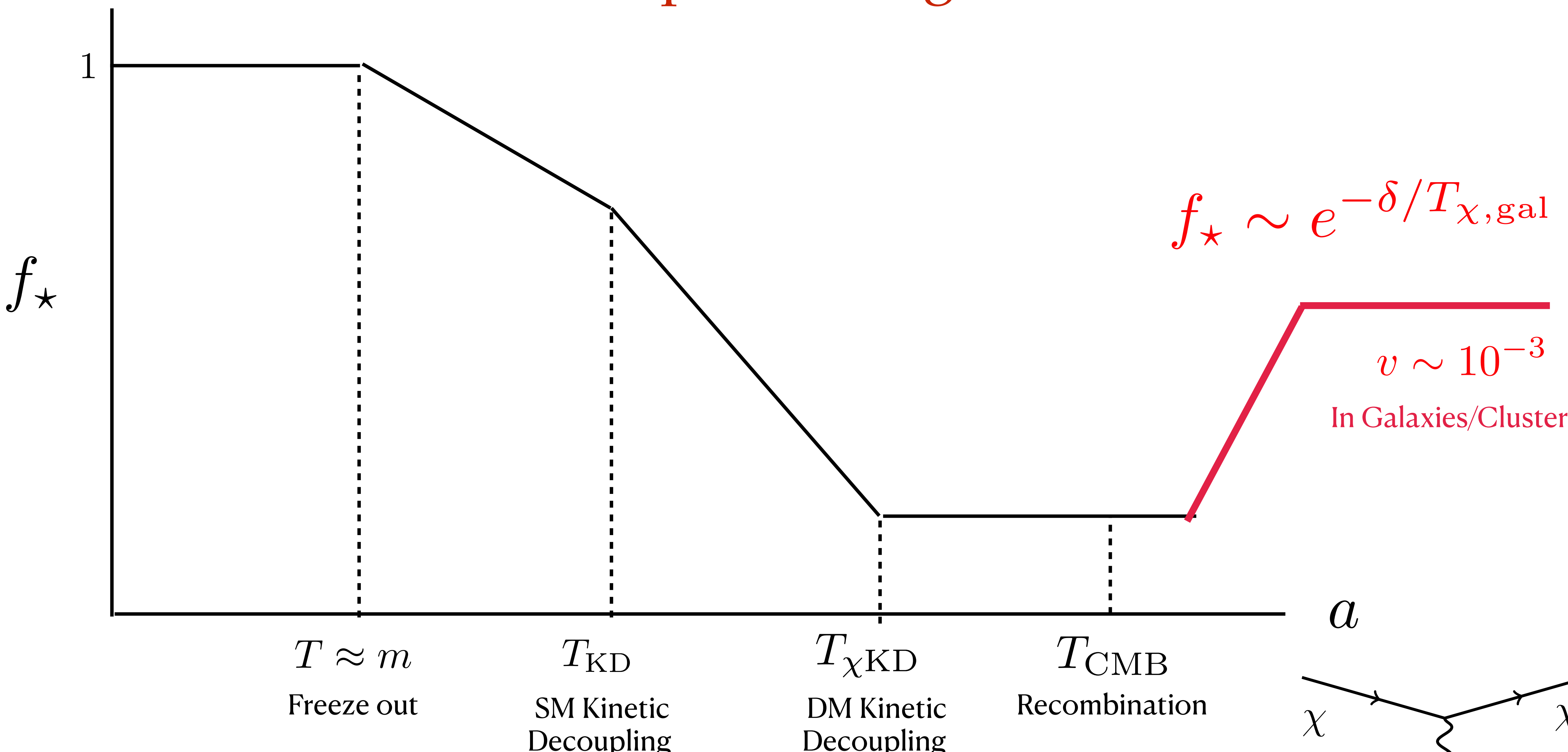


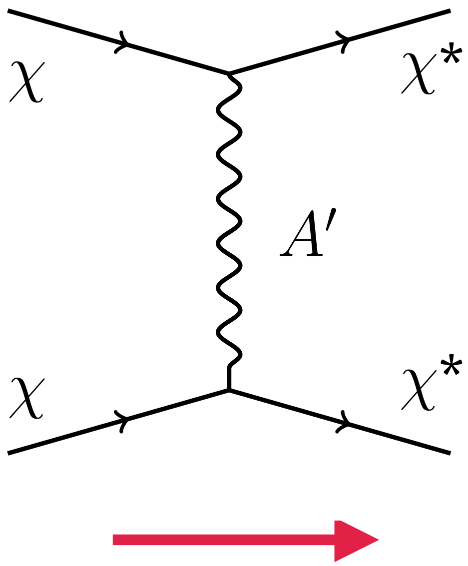
$$\text{power injected into CMB} \propto f_\star \langle \sigma v \rangle, \quad f_\star \ll 1$$

Cosmological History

$$f_\star \equiv \frac{n_{\chi^\star}}{n_\chi}$$

Galactic Upscattering

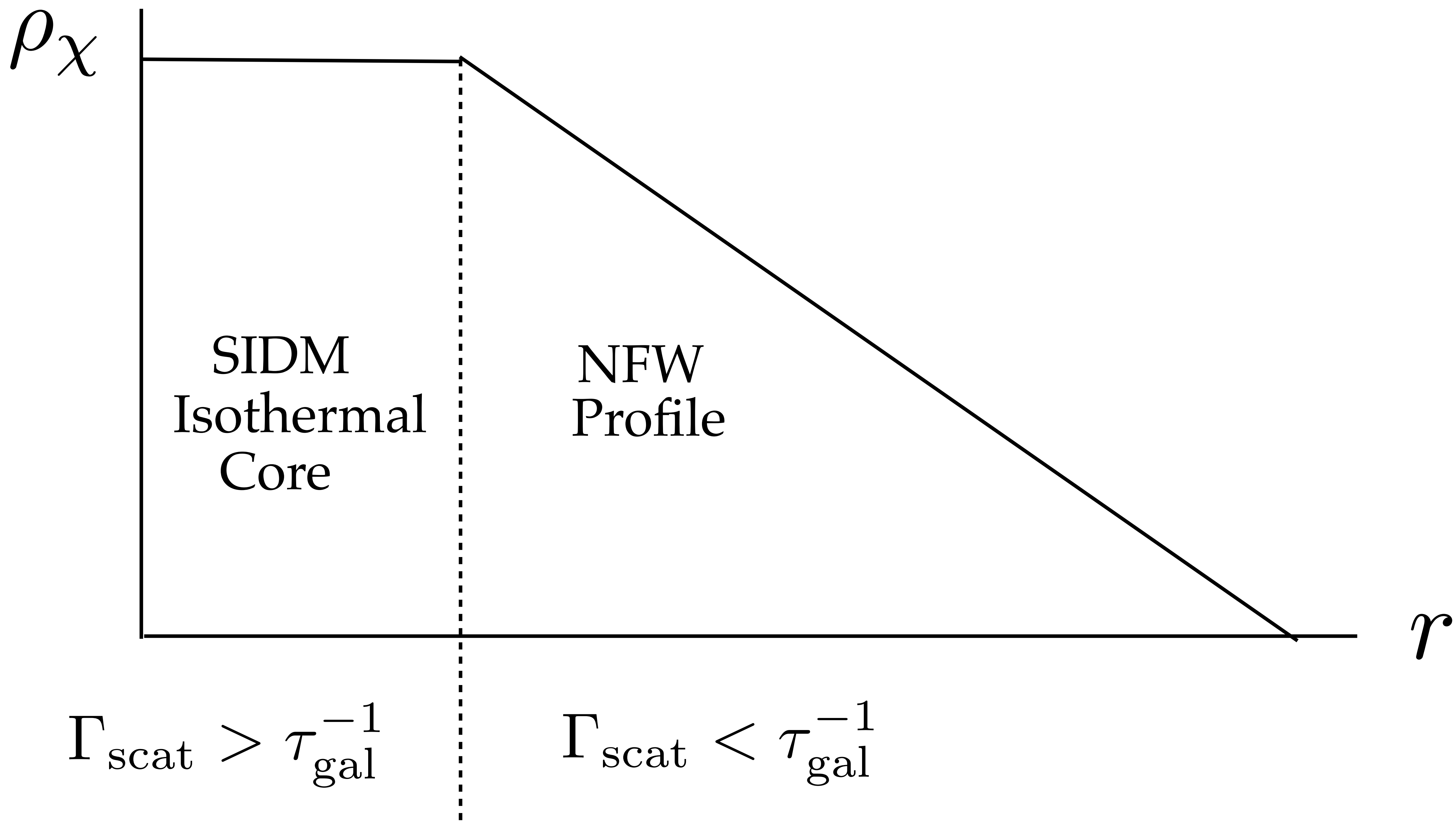




Faster DM in galaxies upscaters to revive heavier state for $T_{\chi,\mathrm{gal}} > \delta$

Compare with SIDM Halo

For canonical self-interacting DM (SIDM) halo profile gets cored



Kaplinghat, Tulin, Yu 1508.03339

Inelastic Halo Dynamics

Thermally averaged scattering rate to make heavy state

$$\Gamma^{\rm gal}_{\chi\chi\to\chi^*\chi^*} \equiv n_\chi \int d^3v_1 f(v_1,r) \int d^3v_2 f(v_2,r) |\vec{v}_1 - \vec{v}_2|\, \sigma_{\chi\chi\to\chi^*\chi^*}$$

Inelastic Halo Dynamics

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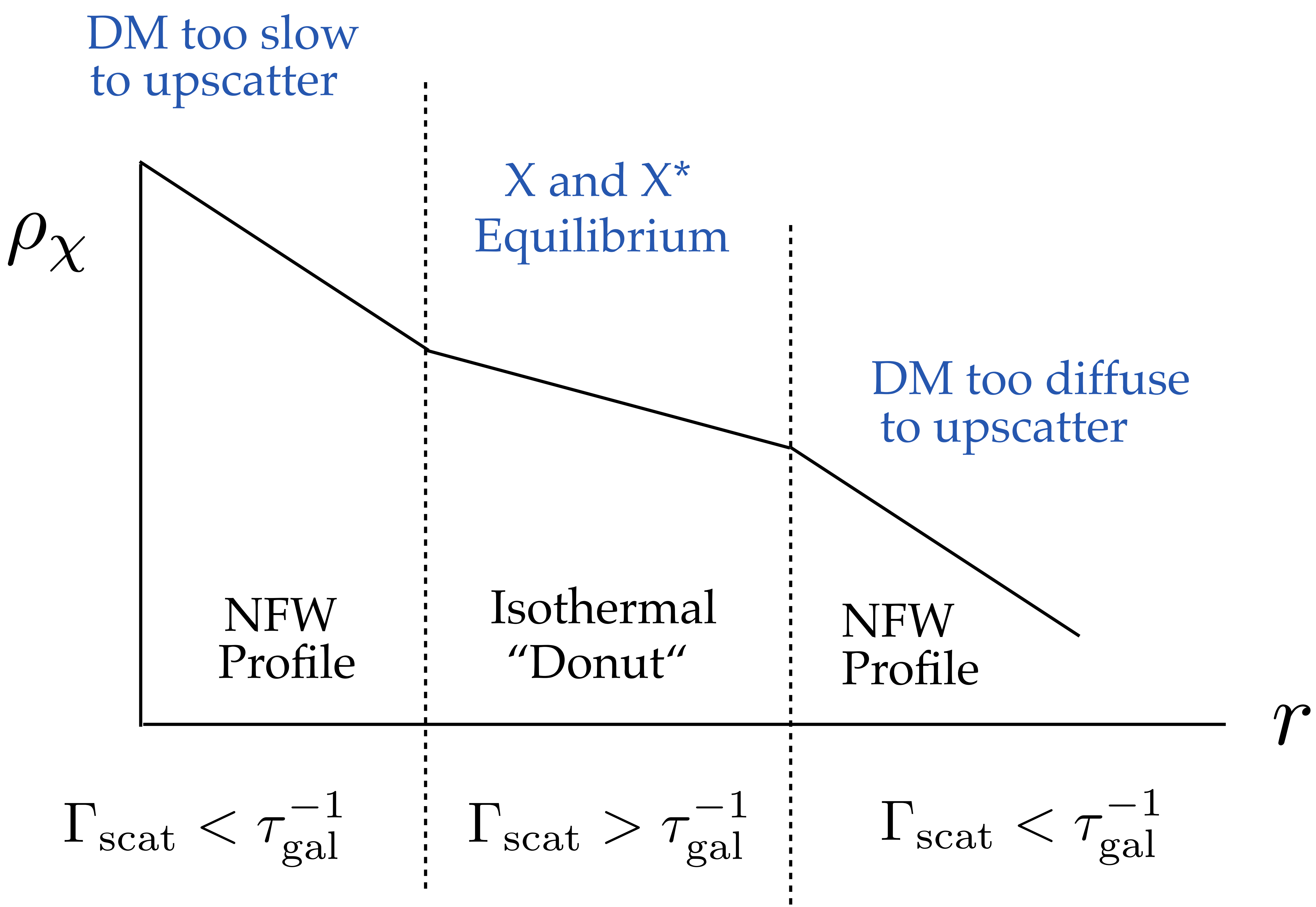
Two regimes for heavy state production in the Galaxy

$$n_{\chi^*} \approx n_\chi \min\left(e^{-\delta/T_\chi}, \tau\Gamma^{\rm gal}_{\chi\chi\to\chi^*\chi^*}\right)$$

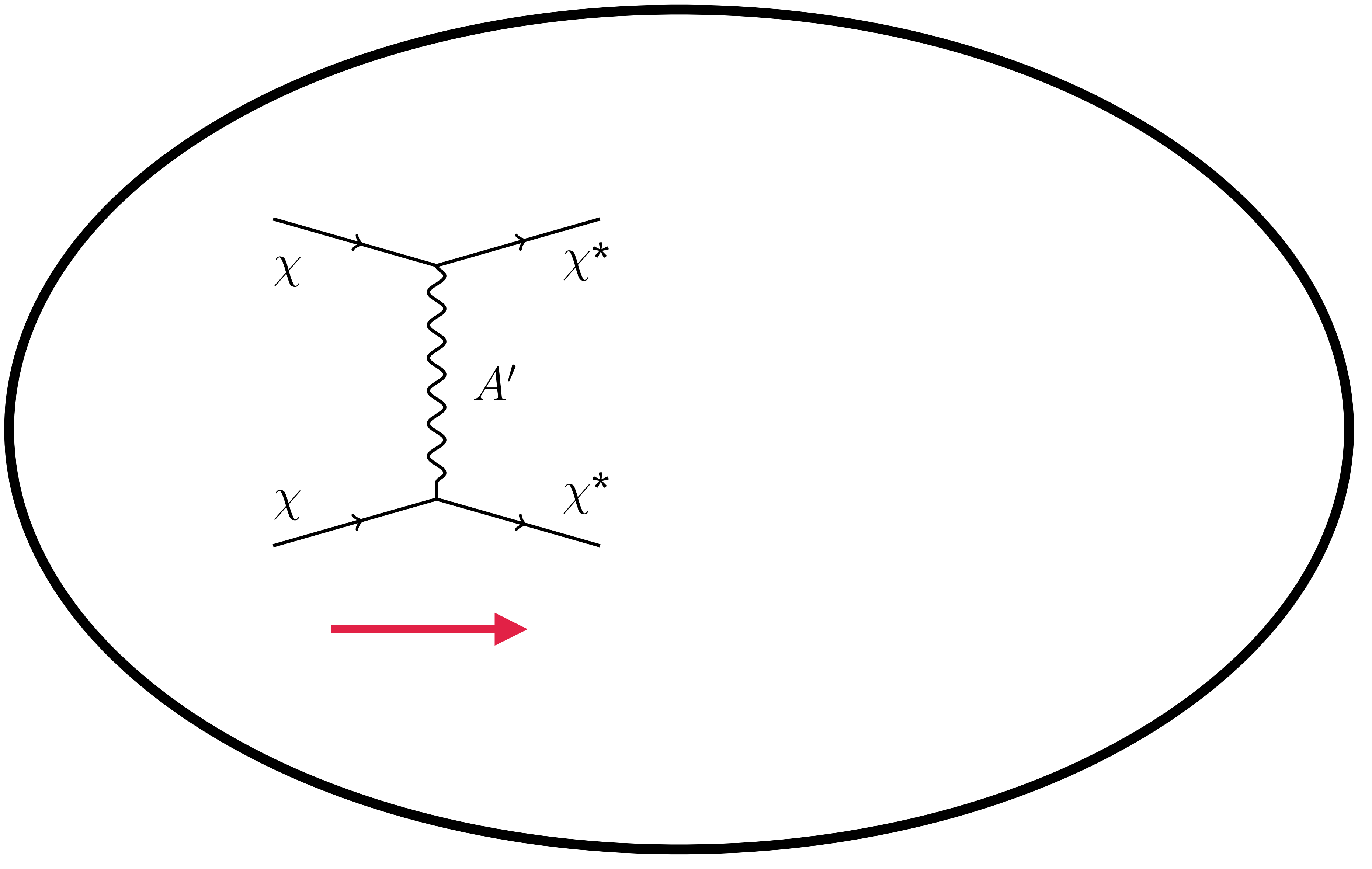
$$\Gamma^{\rm gal}_{\chi\chi\to\chi^*\chi^*} > \tau_{\rm gal}^{-1}$$

$$\Gamma^{\rm gal}_{\chi\chi\to\chi^*\chi^*} < \tau_{\rm gal}^{-1}$$

Inelastic Halo Dynamics

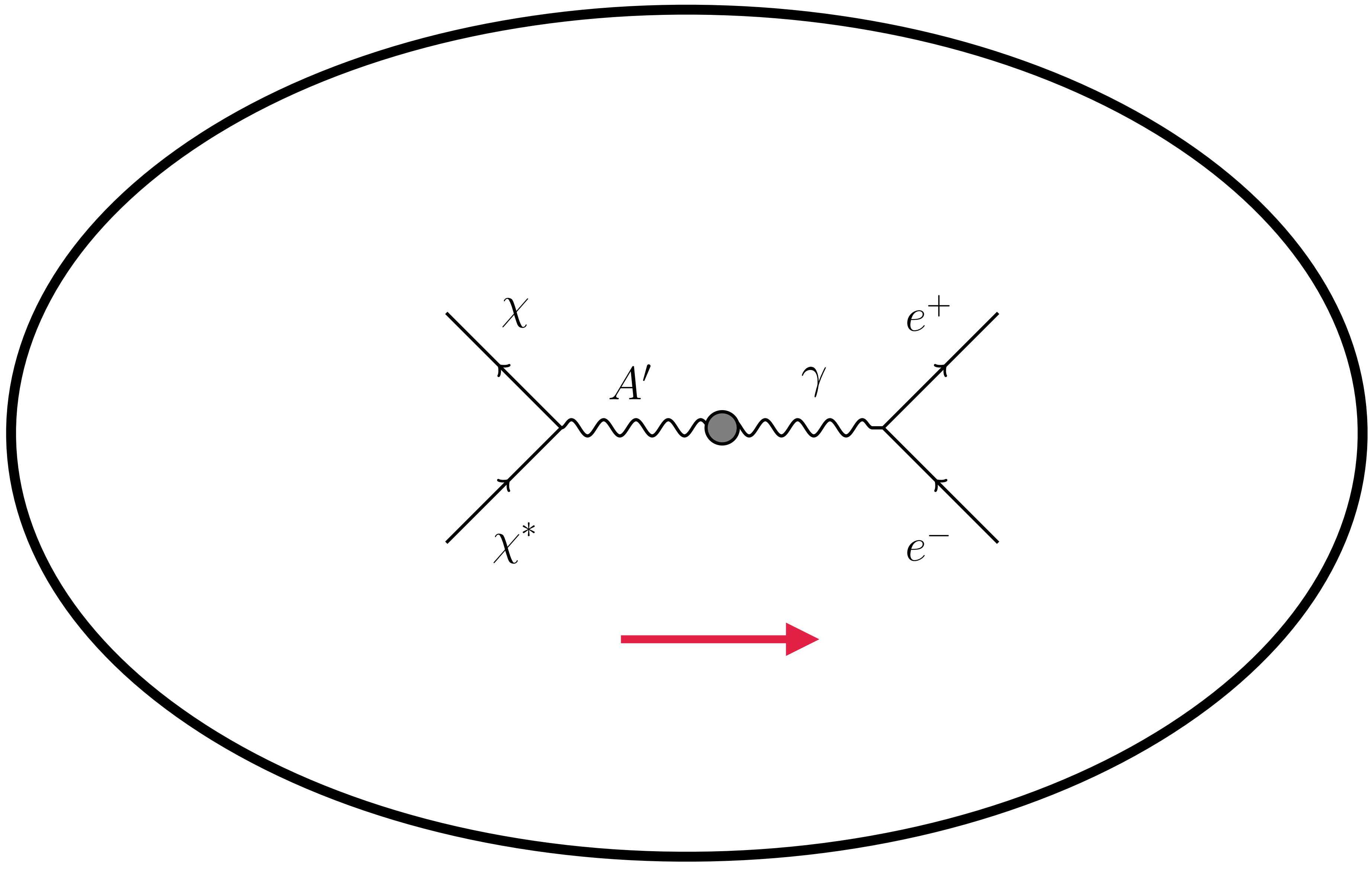


Indirect Detection



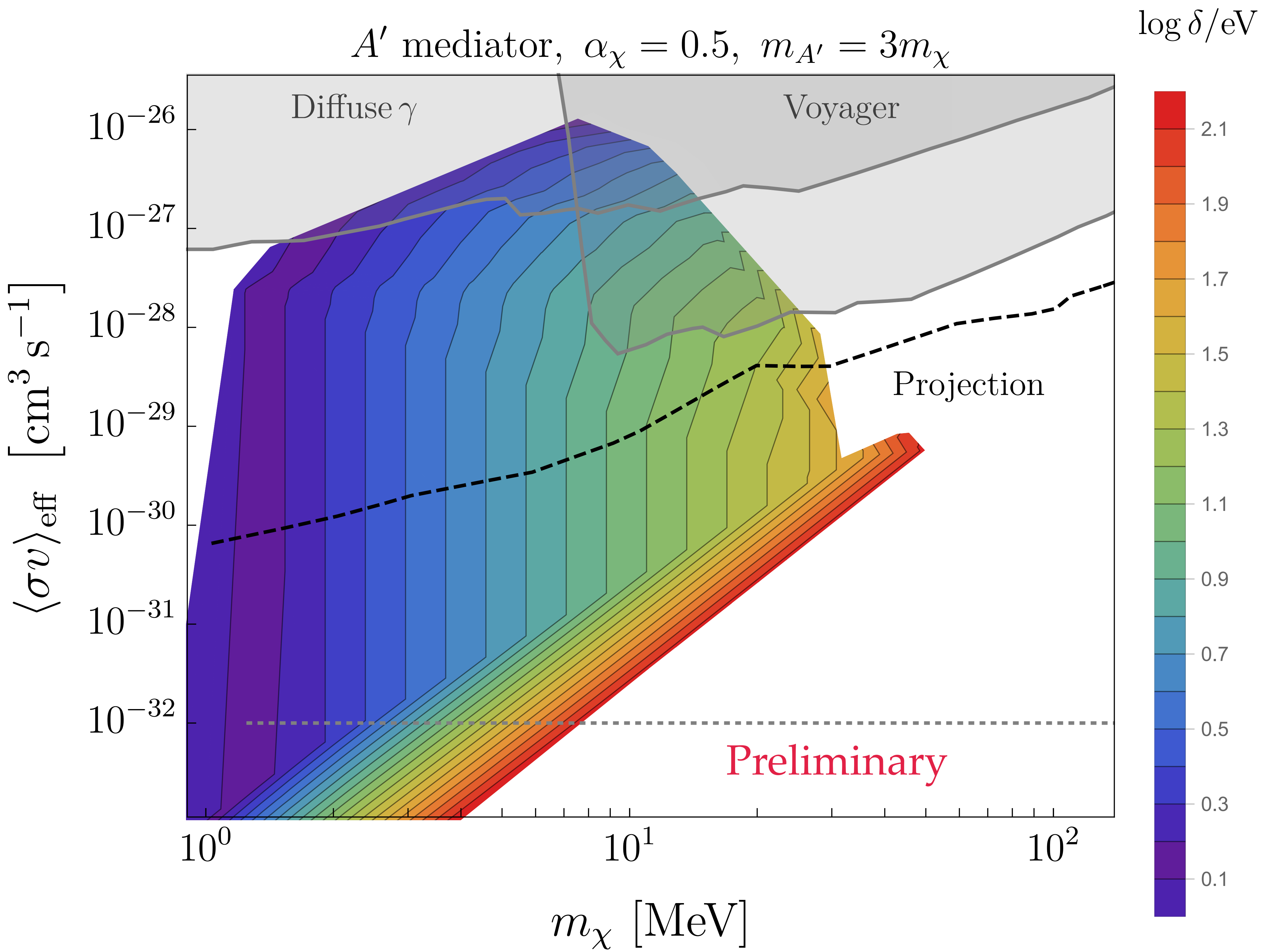
Step 1: revive heavier state

Indirect Detection



Step 2: coannihilation in the galaxy

Indirect Detection

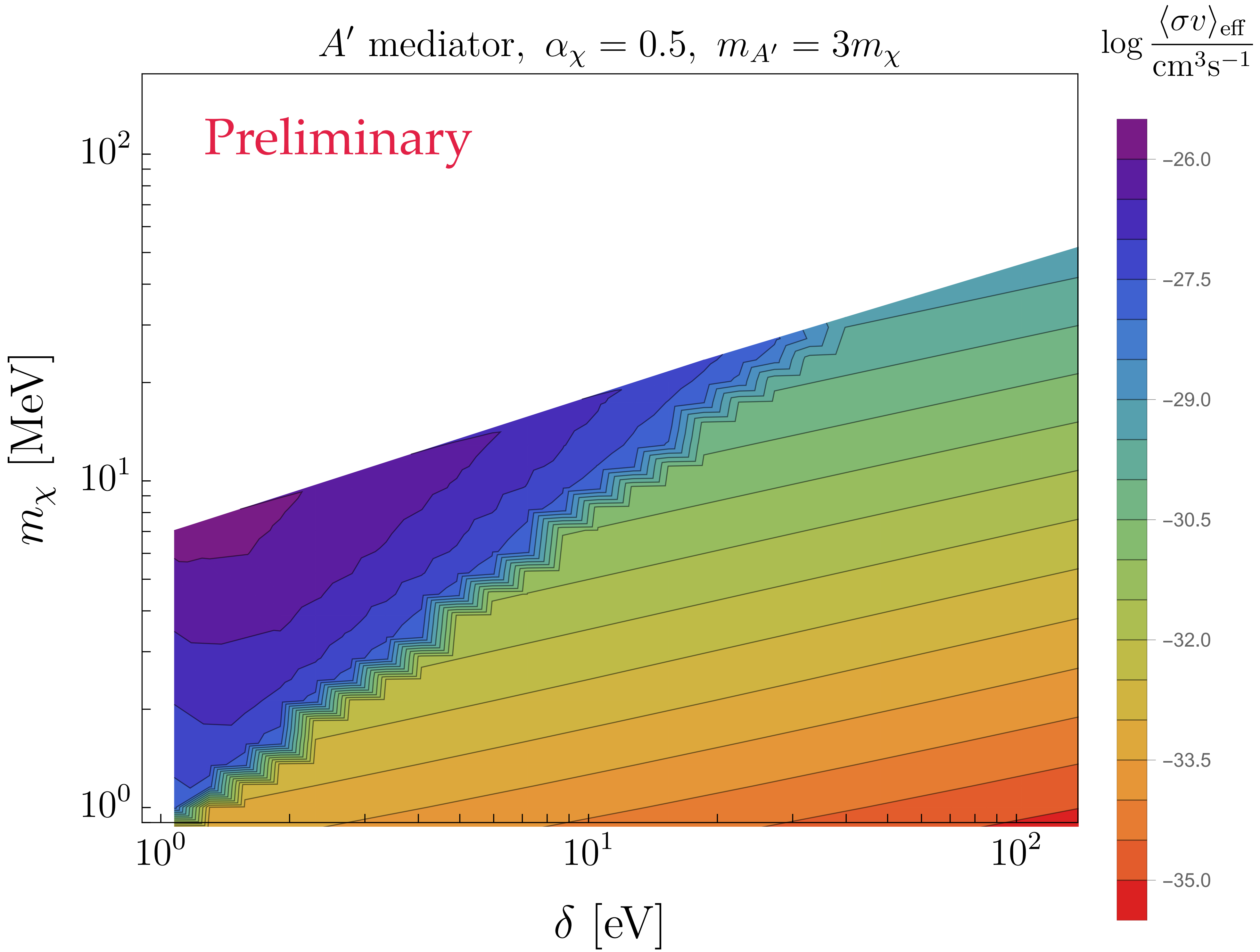


eAstrogam / AMEGO projection

Bartels Gaggero Weniger 1703.02546

Berlin, GK, Pinetti 2309.XXXX

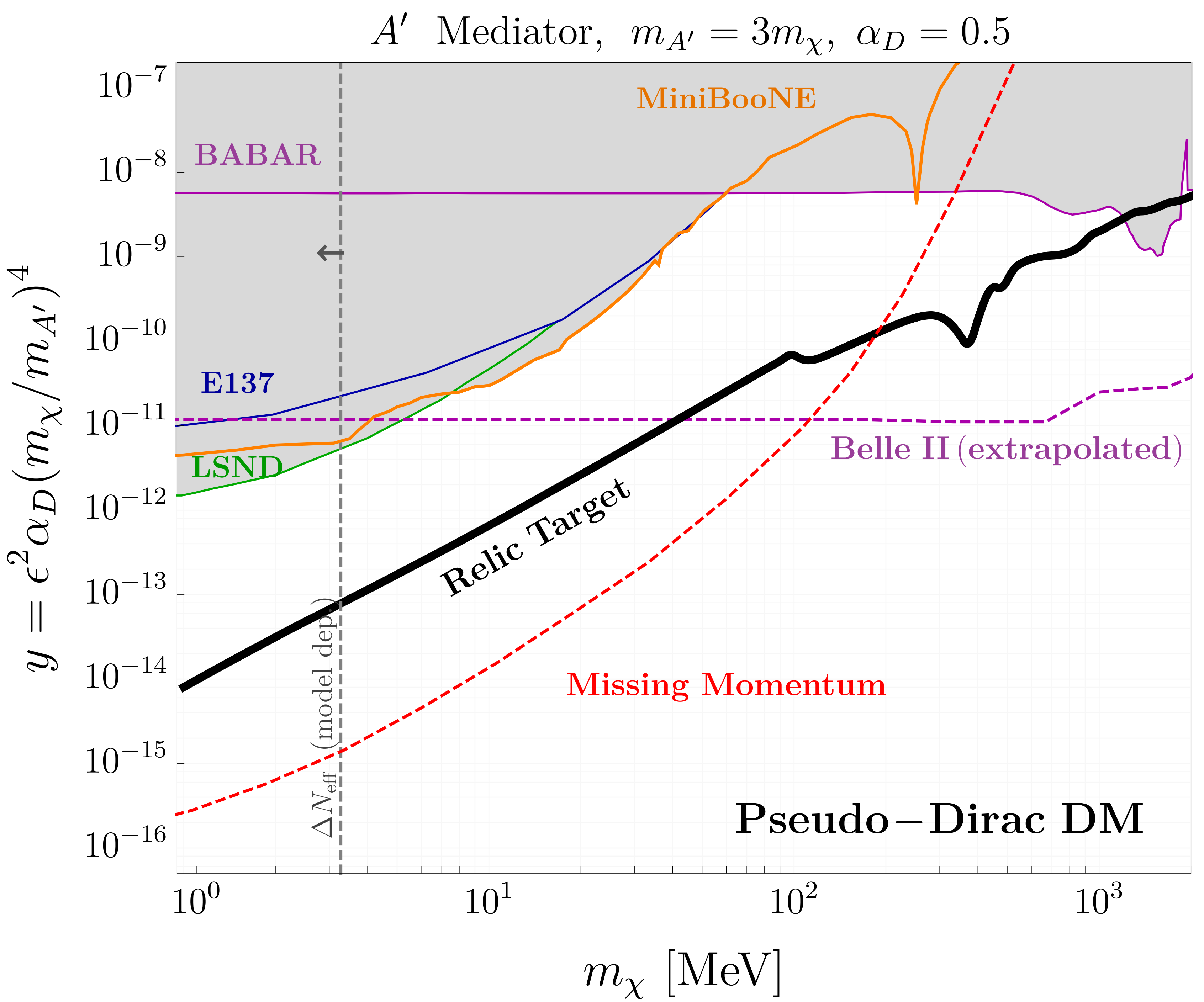
Indirect Detection



All points correspond to predictive thermal freeze out origin via $\chi\chi^* \to \mathrm{SM}$

Berlin, GK, Pinetti 2309.XXXX

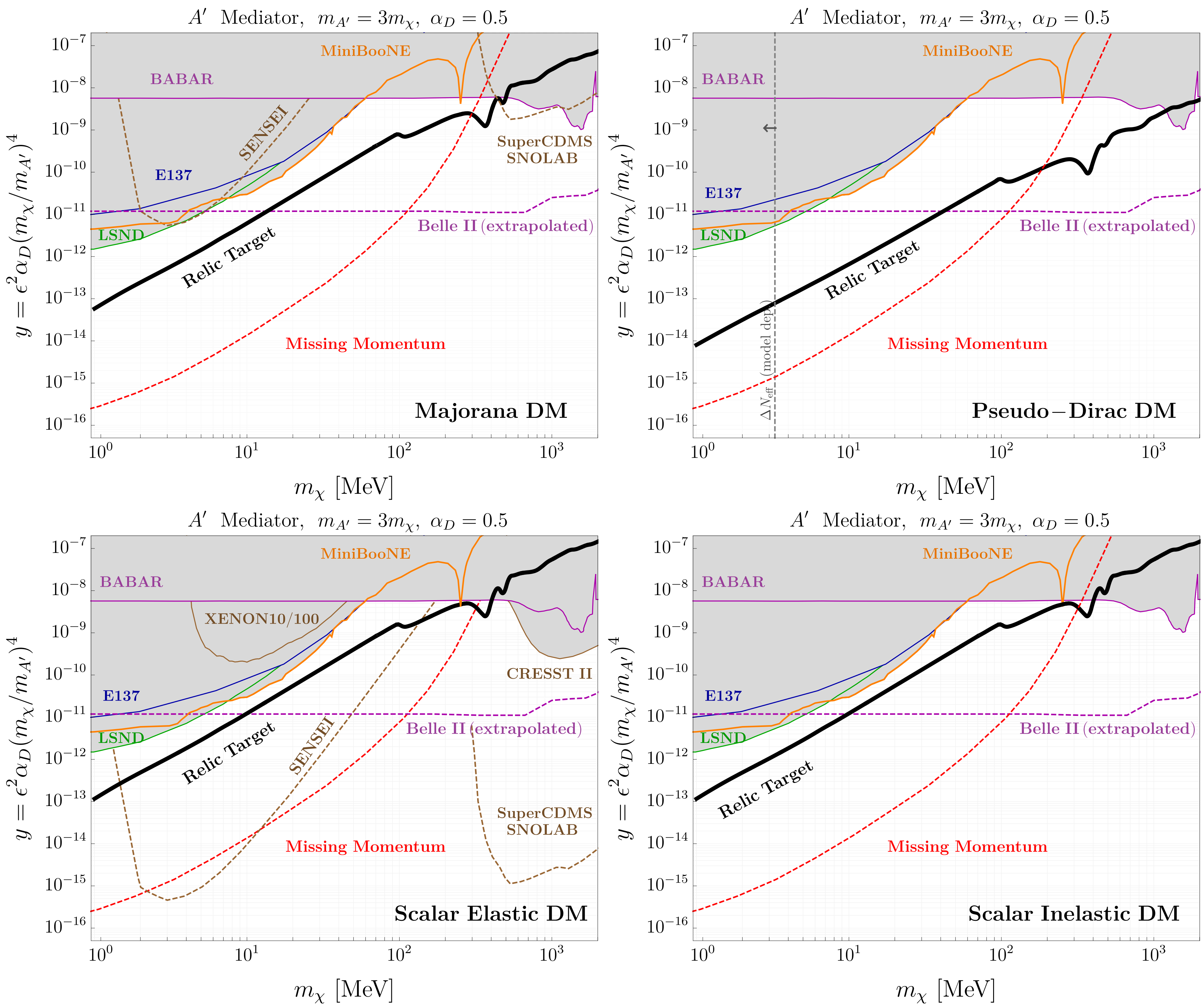
Accelerator Complementarity



Our indirect detection results use parameters along the relic curve
This is the same reference model for accelerator benchmarks

Berlin, Blinov, GK, Schuster, Toro 1808.05219

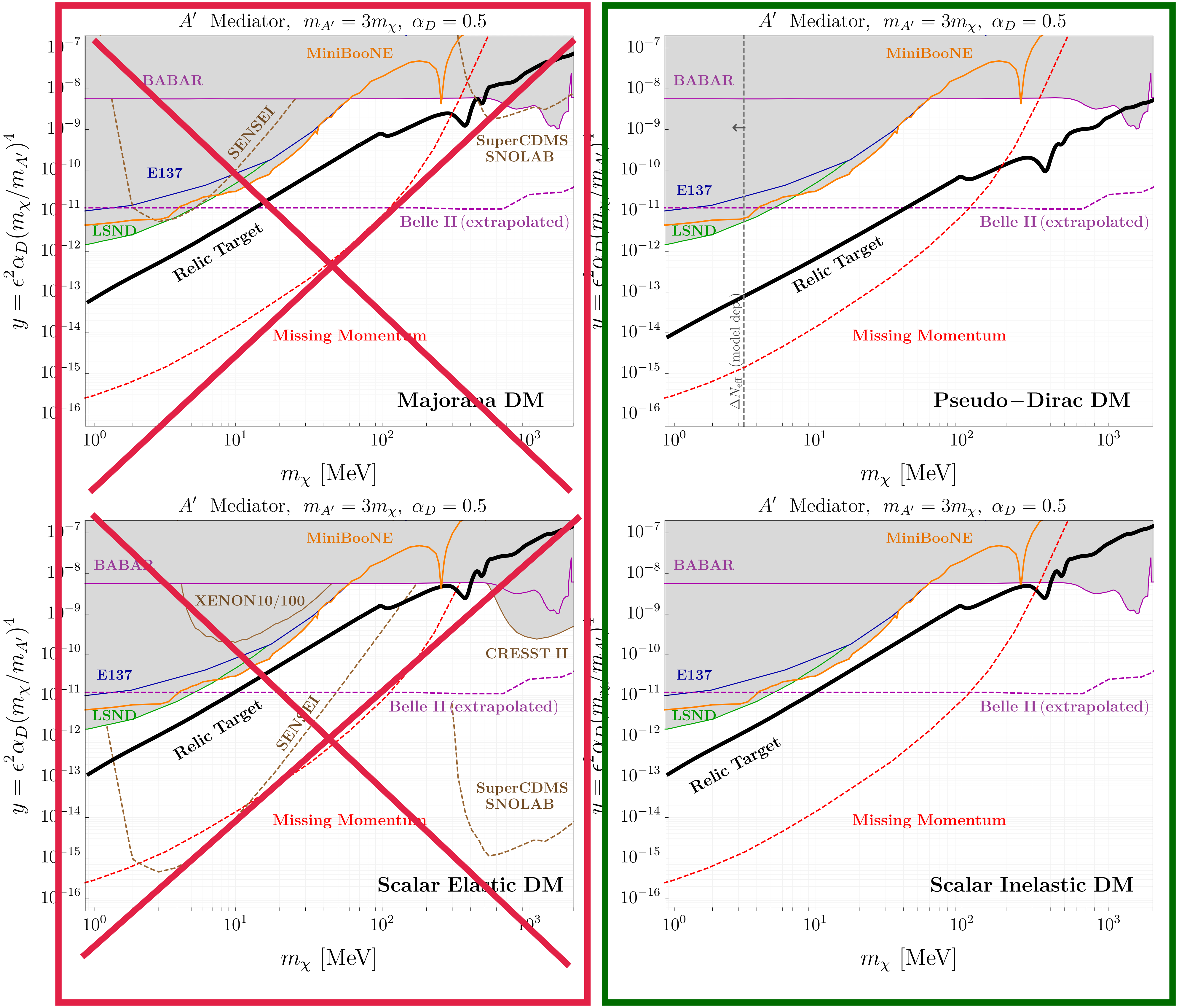
Model Discrimination?



Berlin, Blinov, GK, Schuster, Toro 1808.05219

No Indirect detection

MeV Indirect detection



No DD

No DD

Yes DD

No DD

Concluding Remarks

Conventional Wisdom: no indirect detection for sub-GeV annihilation

Planck limits require little annihilation during recombination

Pseudo-Dirac DM w/ coannihilation is naturally CMB safe

Heavier state is cosmologically depleted by CMB

Heavier state revived by Galactic upscahttering

This population co-annihilates to yield MeV indirect signal

Unique halo profile

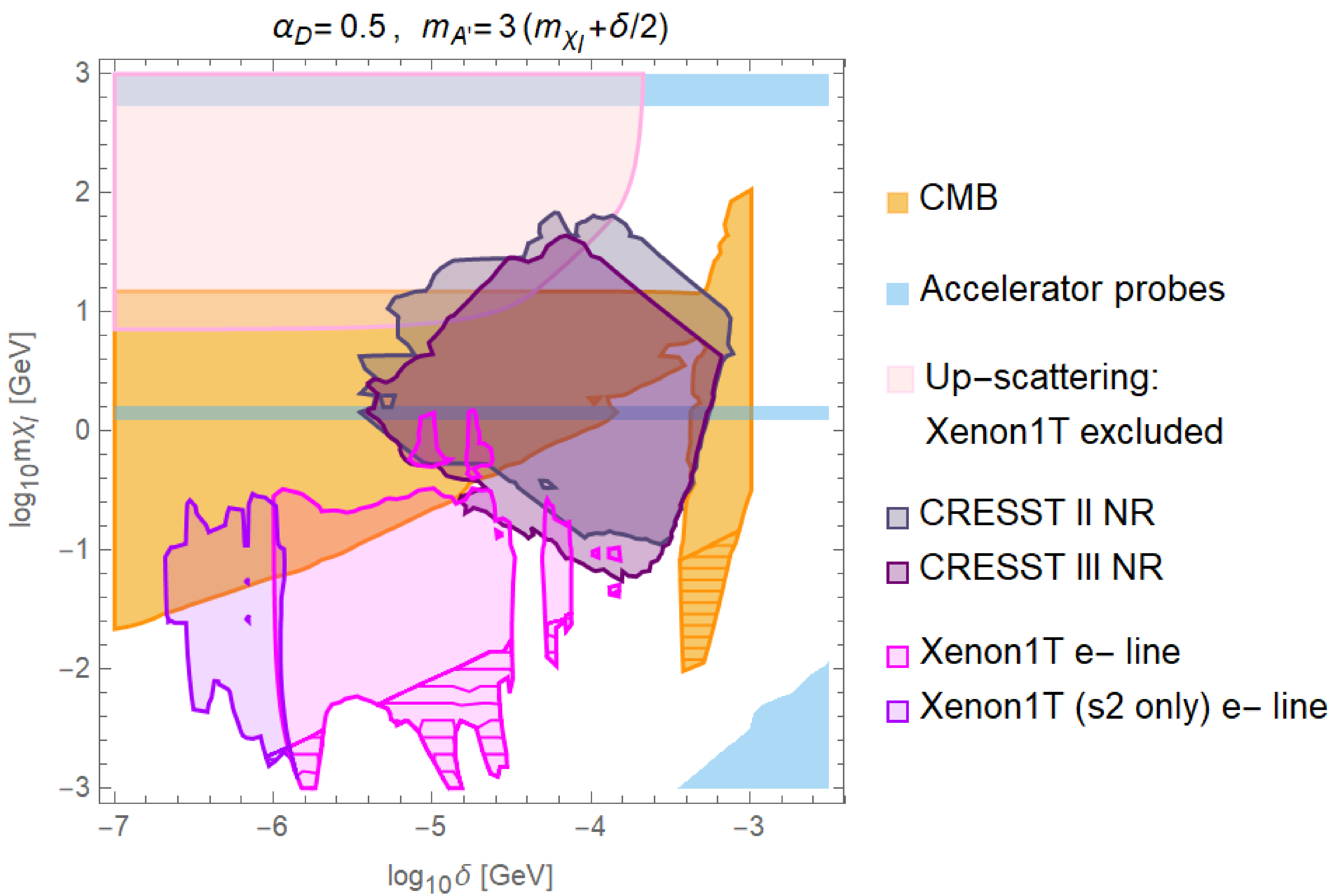
Isothermal profile for intermediate radial region (“donut”)

Requires numerical N-body simulation to fully characterize

Potential gain from slower heavier state

Might drift to smaller radii, enhance J-factor in Galactic center

Direct Detection?



Gonzalez, Toro 2108.13422