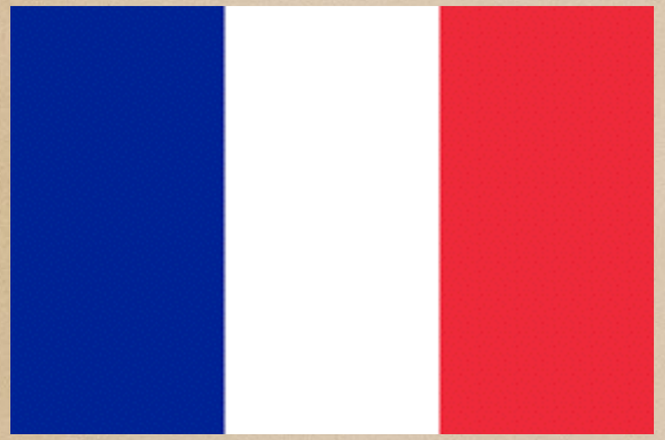
Thermal DM beyond 10-100 TeV



Yann Gouttenoire
DESY - Hamburg
Supervised by Geraldine Servant

J+2 after WC 2018

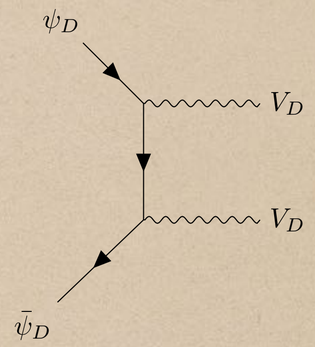
20 year after WC 1998

With the collaboration of Filippo Sala, Kallia Petraki and Marco Cirelli.

Cargèse 2018

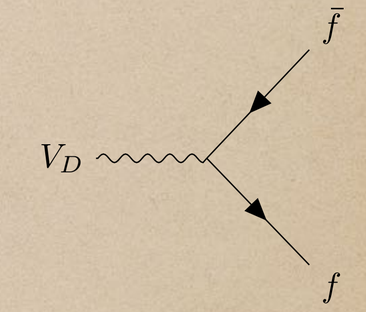
The Dark U(1) model

Dark Matter: $\bar{\psi}_D i \left(\not{\partial} + i g_D \not{V}_D \right) \psi_D - m_{DM} \bar{\psi}_D \psi_D$



Dark photon: $-\frac{1}{4} F_{D\mu\nu} F_D^{\mu\nu} - \frac{1}{2} m_{V_D}^2 V_{D_\mu} V_D^\mu$

Kinetic coupling to SM: $\frac{\epsilon}{c_w} B_{\mu\nu} F_D^{\mu\nu}$

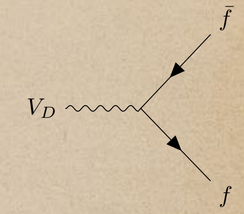


4 parameters: $m_{DM},\ m_{V_D},\ \alpha_D,\ \epsilon$

Motivation: current and planned telescopes have the ability to constrain Thermal DM with mass O(100 TeV) and beyond.

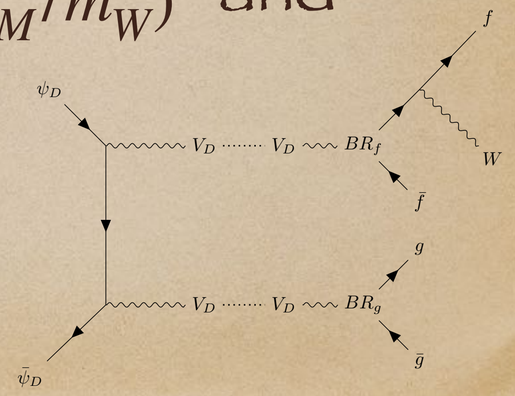
Challenges:

1. Unitarity bound constrains DM mass to be lower than O(100 TeV)



Solution: entropy dilution due to mediator decay

2. Electroweak radiations corrections scales as $\frac{\alpha_W}{2\pi}\log^2(m_{DM}^2/m_W^2)$ and are non-perturbative when $m_{DM} > 100$ TeV.

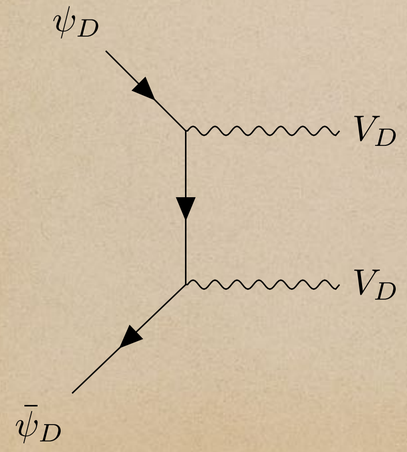


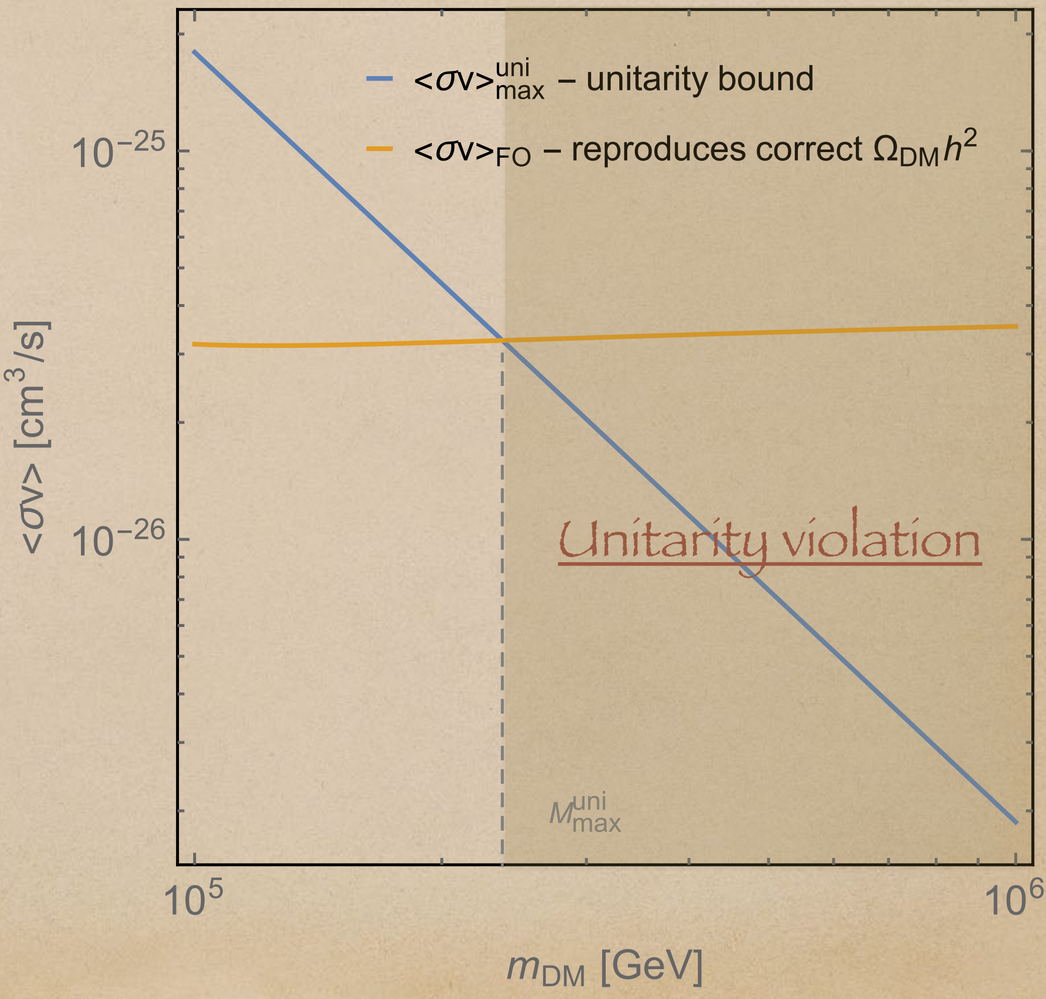
Solution: With a mediator it scales as $\frac{\alpha_W}{2\pi}\log^2(m_{V_D}^2/m_W^2)$

The Unitarity Bound

$$SS^{\dagger} = 1 \quad \rightarrow \quad \left\langle \sigma_{ine} v_{rel} \right\rangle_J < \frac{4\pi(2J+1)}{m_{DM}^2 v_{rel}}$$

$$\rightarrow \quad m_{DM}^{max} \approx 140\ TeV$$





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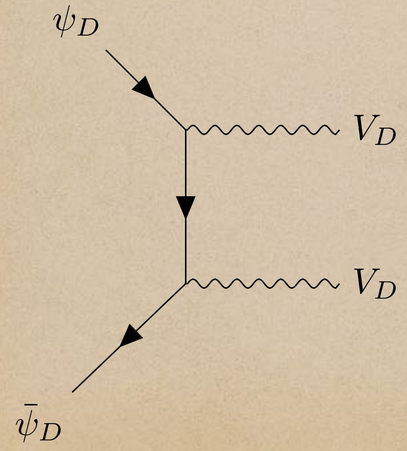
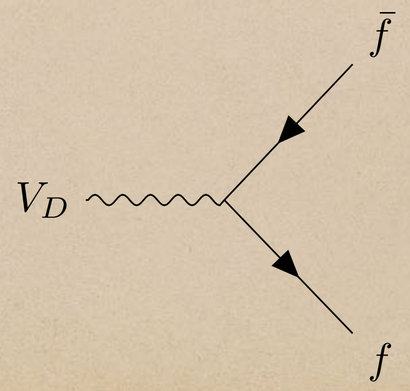
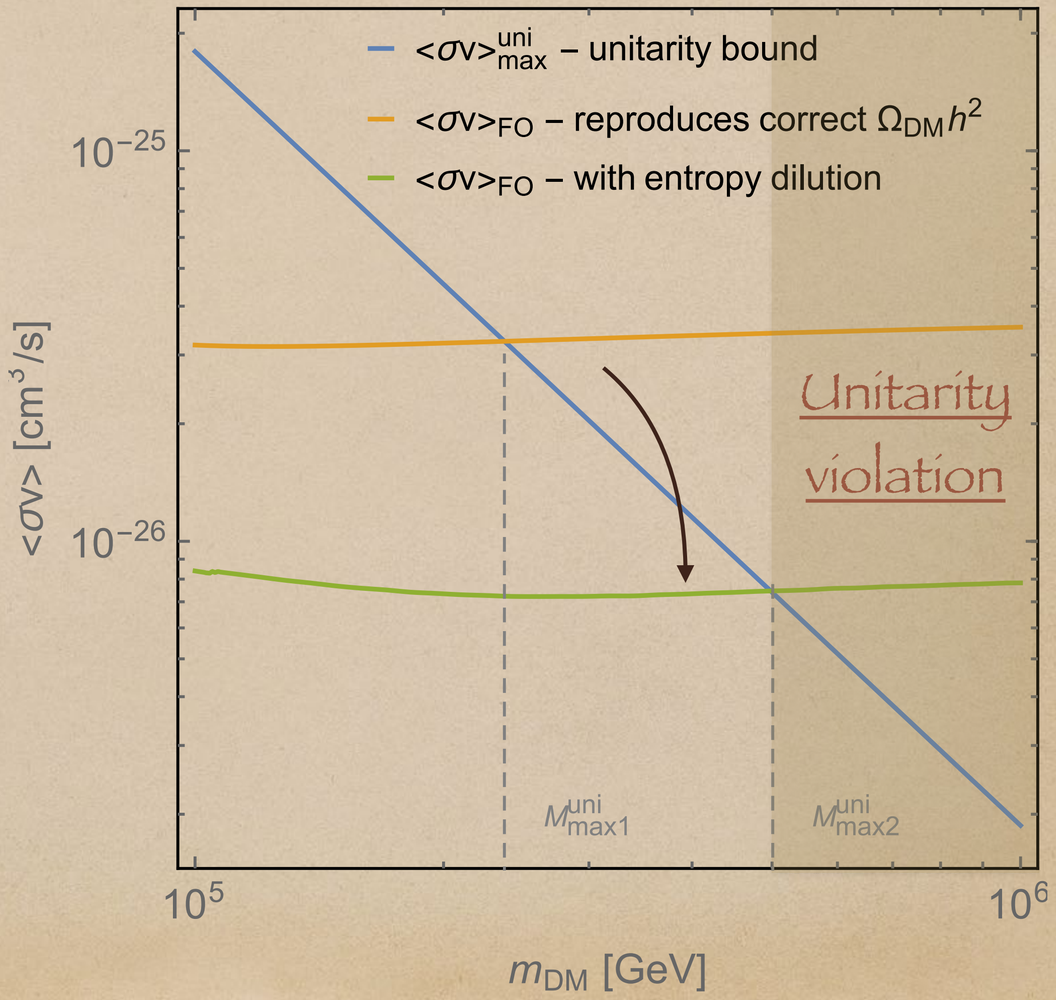
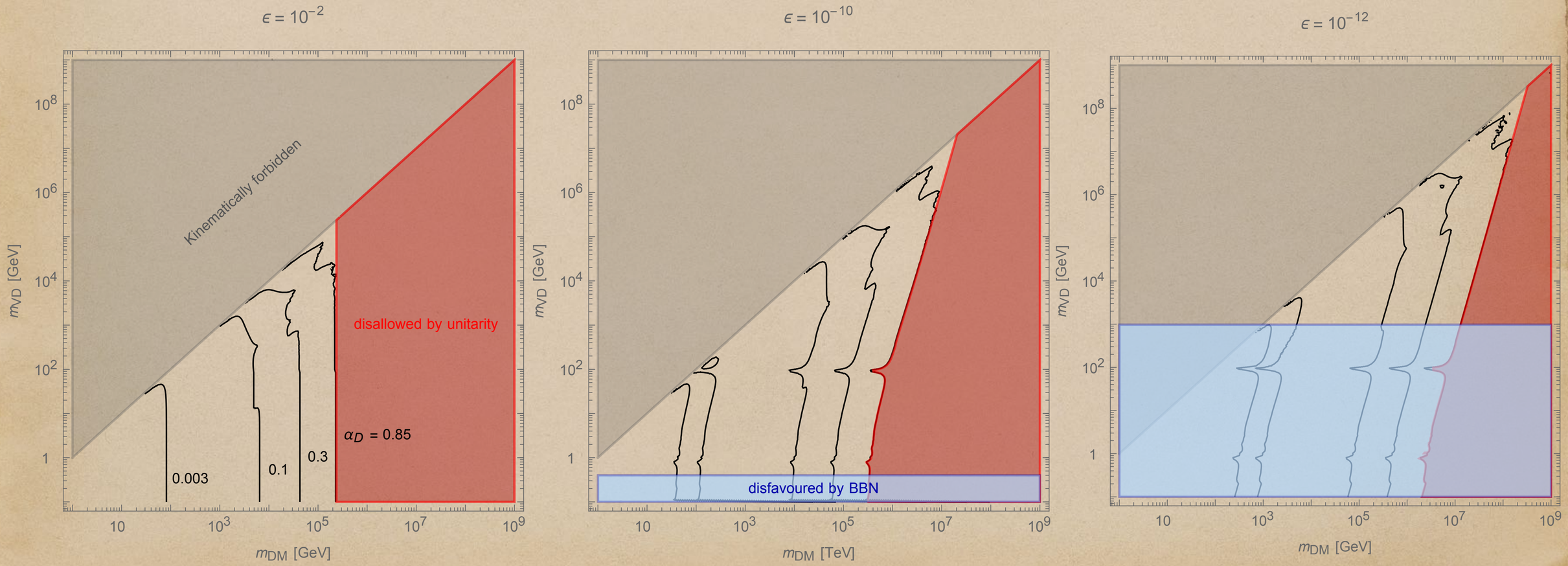
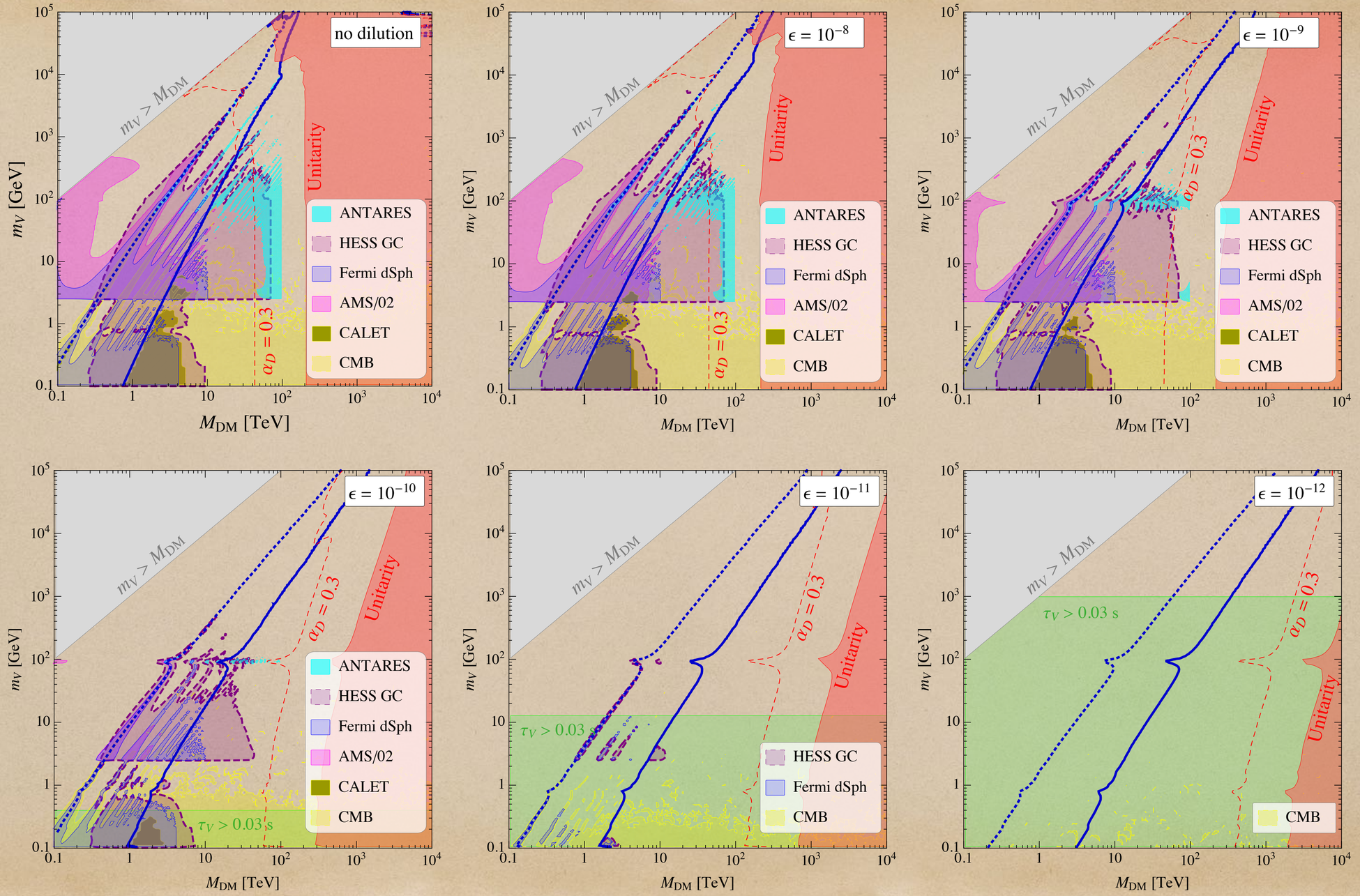






Consequences of the entropy dilution

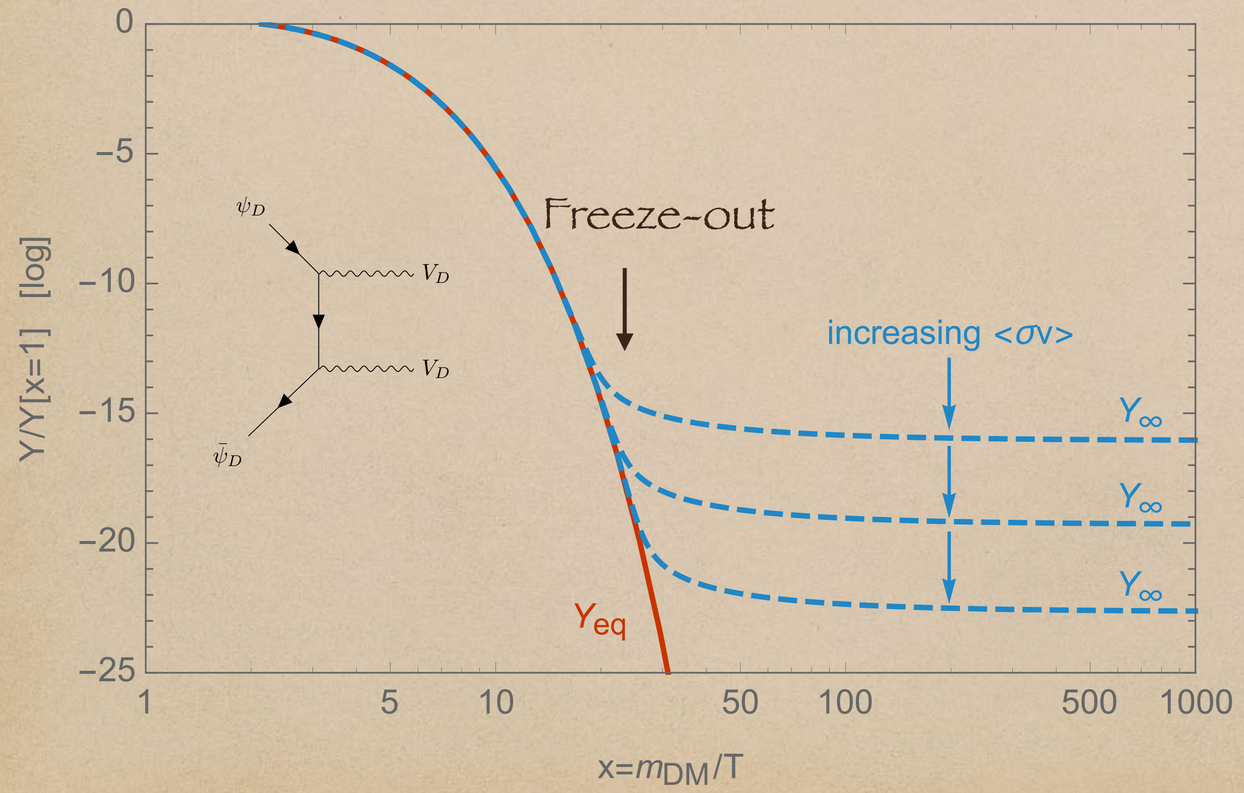



no dilution
$\epsilon = 10^{-8}$
$\epsilon = 10^{-9}$
$\epsilon = 10^{-10}$
$\epsilon = 10^{-11}$
$\epsilon = 10^{-12}$
$m_V > M_{DM}$
Unitarity
$\alpha_D = 0.3$
$\tau_V > 0.03$ s
ANTARES
HESS GC
Fermi dSph
AMS/02
CALET
CMB
m_V [GeV]
M_{DM} [TeV]

Back-up slides

Thermal Dark Matter

Assume thermal equilibrium between DM and SM at Early times

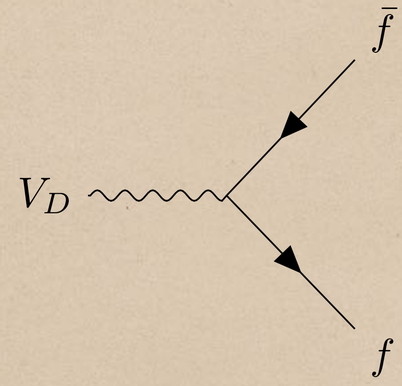


DM relic abundance today:

$$\Omega_{DM}h^2 = 0.1186 \qquad \text{(Planck)}$$

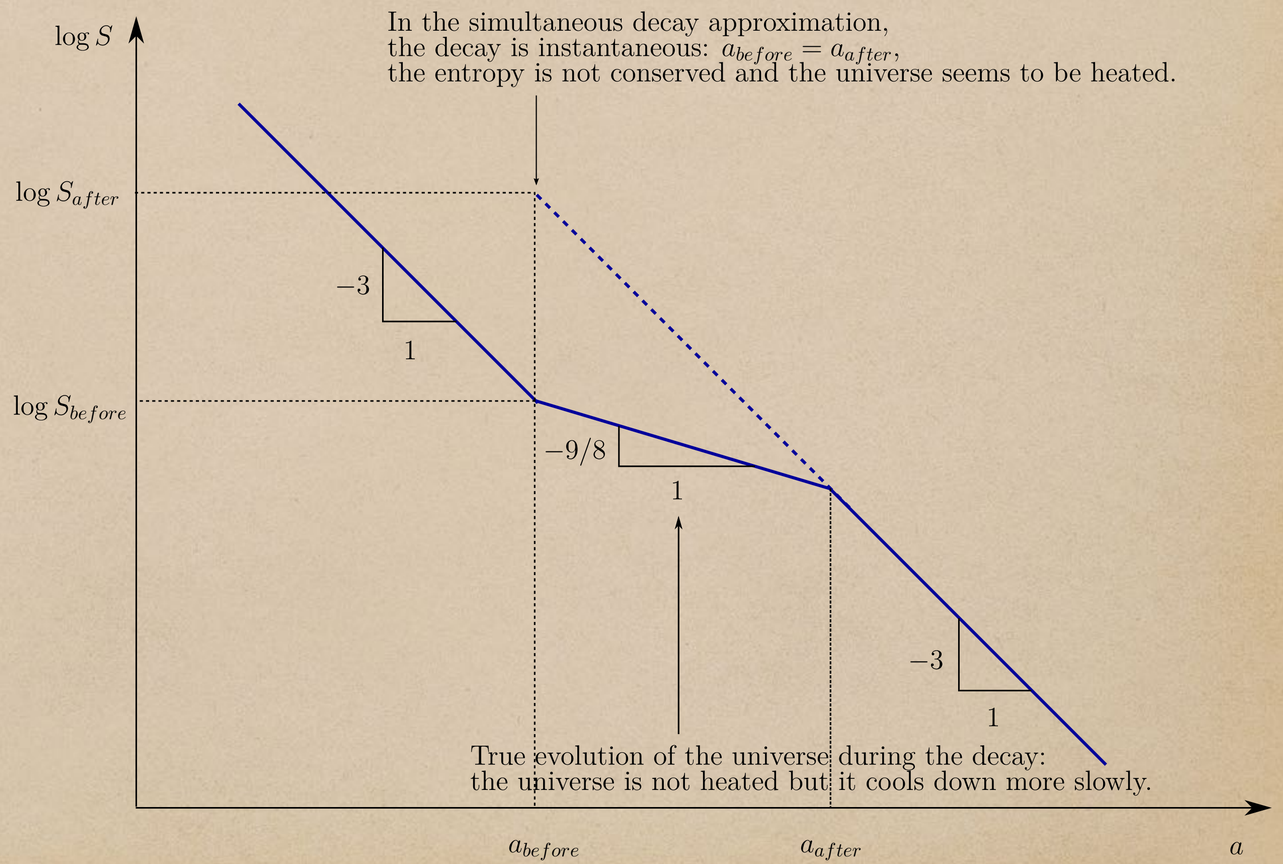
$$\rightarrow \quad \langle \sigma_{ann} v \rangle \sim 3 \times 10^{-26}\ cm^3/s$$

The entropy dilution



$$\underbrace{\rho_{NR}^{V_D}}_{\text{non-contributing to S}} \rightarrow \underbrace{\rho_{rel}^{SM}}_{\text{contributing to S}}$$

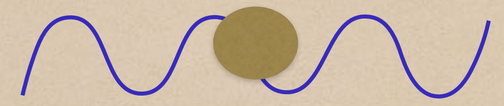
$$S_{SM} \rightarrow D\, S_{SM} \quad \rightarrow \quad m_{DM}^{max} \rightarrow \sqrt{D}\, m_{DM}^{max}$$



The Sommerfeld enhancement

With short range potential:

$$\psi_0(\vec{r}) = e^{i\vec{k}\cdot\vec{r}}$$

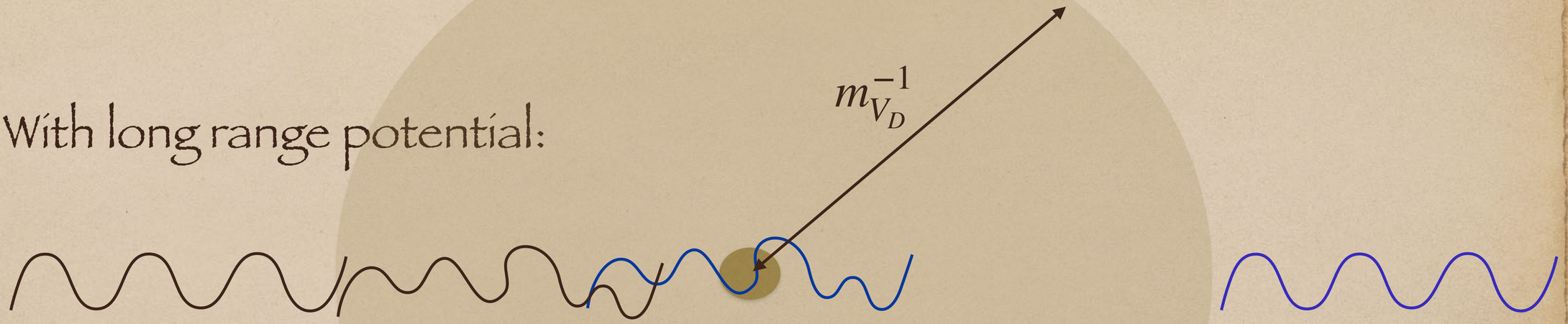


$$H_{ann} = U_{ann}\delta(\vec{r})$$

Interaction rate proportional to: $|\psi_0(0)|^2 = 1$

The Sommerfeld enhancement

With long range potential:



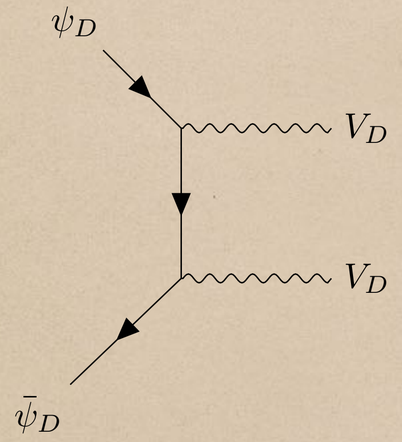
$$\psi(\vec{r}) \neq e^{i\vec{k}\cdot\vec{r}}$$

$$H = H_{ann} - \alpha\frac{e^{-m_{V_D}r}}{r}$$

Interaction rate proportional to: $|\psi(0)|^2 > 1$

Annihilation cross-section: $\sigma_{ann} \to \sigma_{ann} S_{ann}$ with $S_{ann} = \left|\frac{\psi(0)}{\psi_0(0)}\right|^2$

The Sommerfeld enhancement



$$\sigma_{ann} \to \sigma_{ann} S_{ann}$$

with $$S_{ann} = 2\pi \frac{\alpha}{v} \frac{1}{1 - e^{-2\pi \frac{\alpha}{v}}} \quad \underset{\frac{\alpha}{v} \to 0}{\longrightarrow} 1 \quad \underset{\frac{\alpha}{v} \gg 1}{\longrightarrow} 2\pi \frac{\alpha}{v}$$

After freeze-out: $v \sim 0.3 \to 0.01$

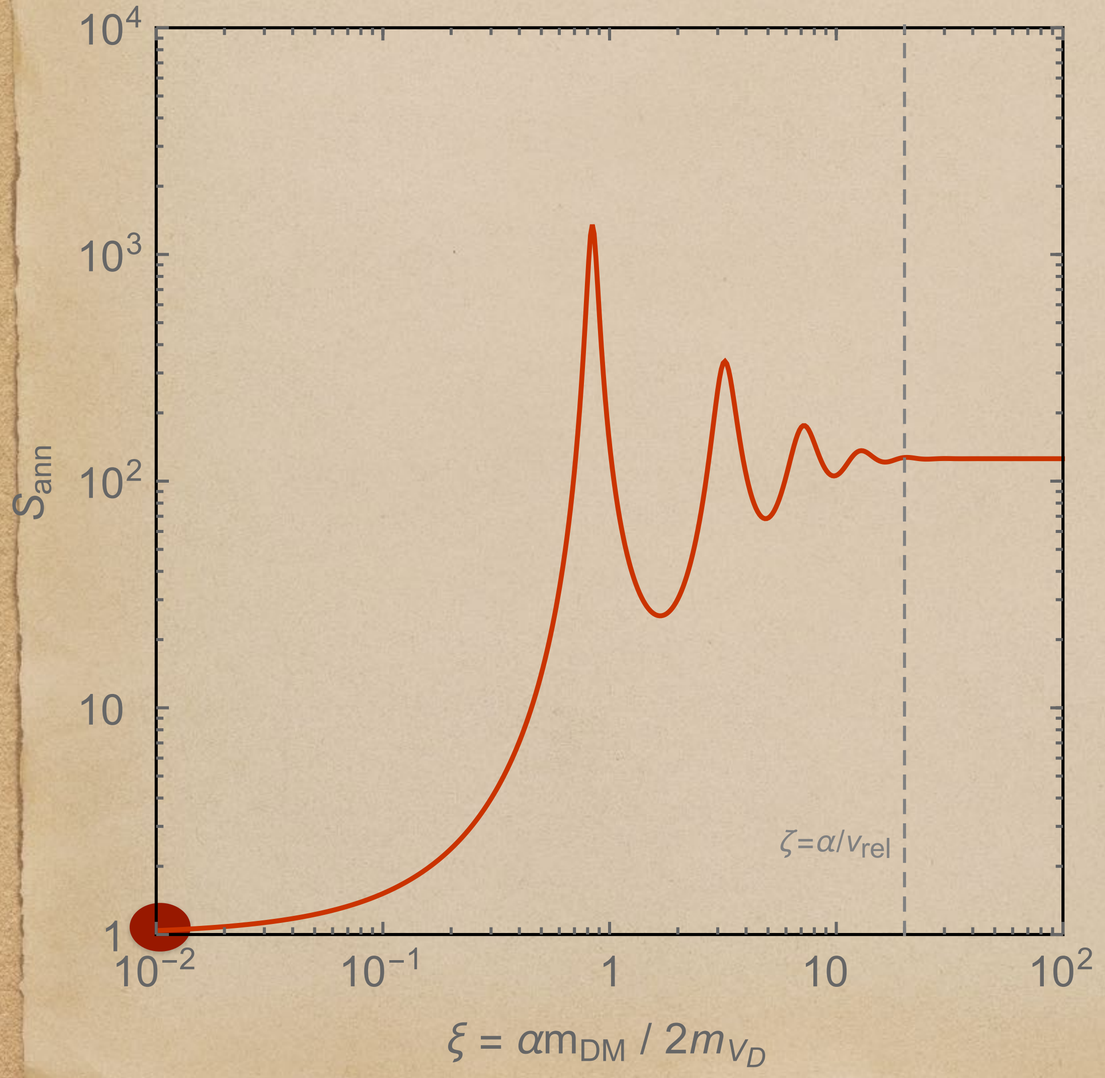
In Milky-Way: $v \sim 10^{-3}$

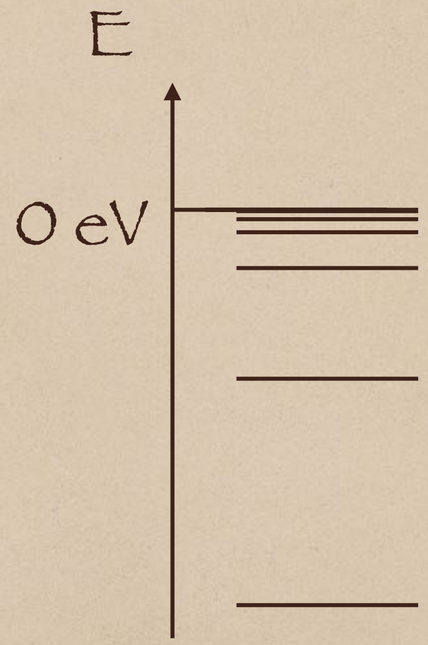
In Dwarf: $v \sim 5 \times 10^{-5}$

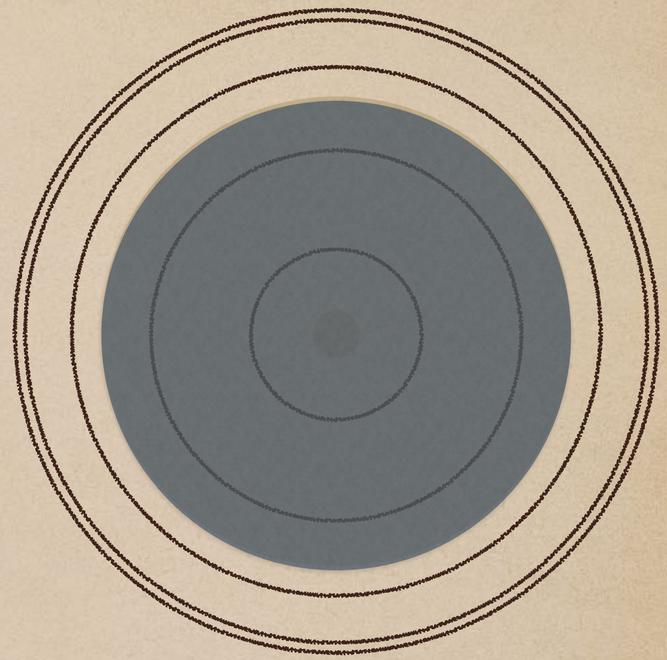
Extend DM annihilation after standard freeze-out

Boost collected cosmic rays fluxes on Earth

Resonance structures







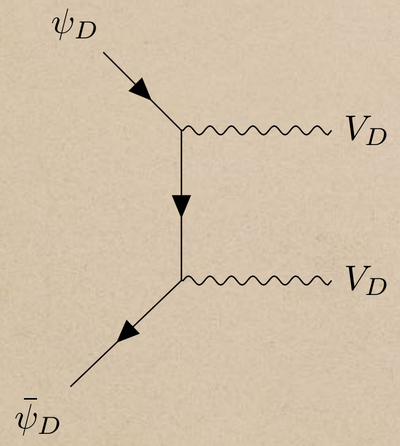
Bound state size αm_{DM}^{-1}:

Yukawa sphere m_{VD}^{-1}:

De Brogglie sphere $m_{DM} v_{rel}^{-1}$:

Bound State Formation

If the mediator range $m_{V_D}^{-1}$ is bigger than the size of the would-be bound state $(\alpha_D m_{DM})^{-1}$, we can form DM bound state



$$\sigma_{ann} = \sigma_{ann} S \qquad \text{with} \qquad S = S_{ann} + S_{BSF}$$

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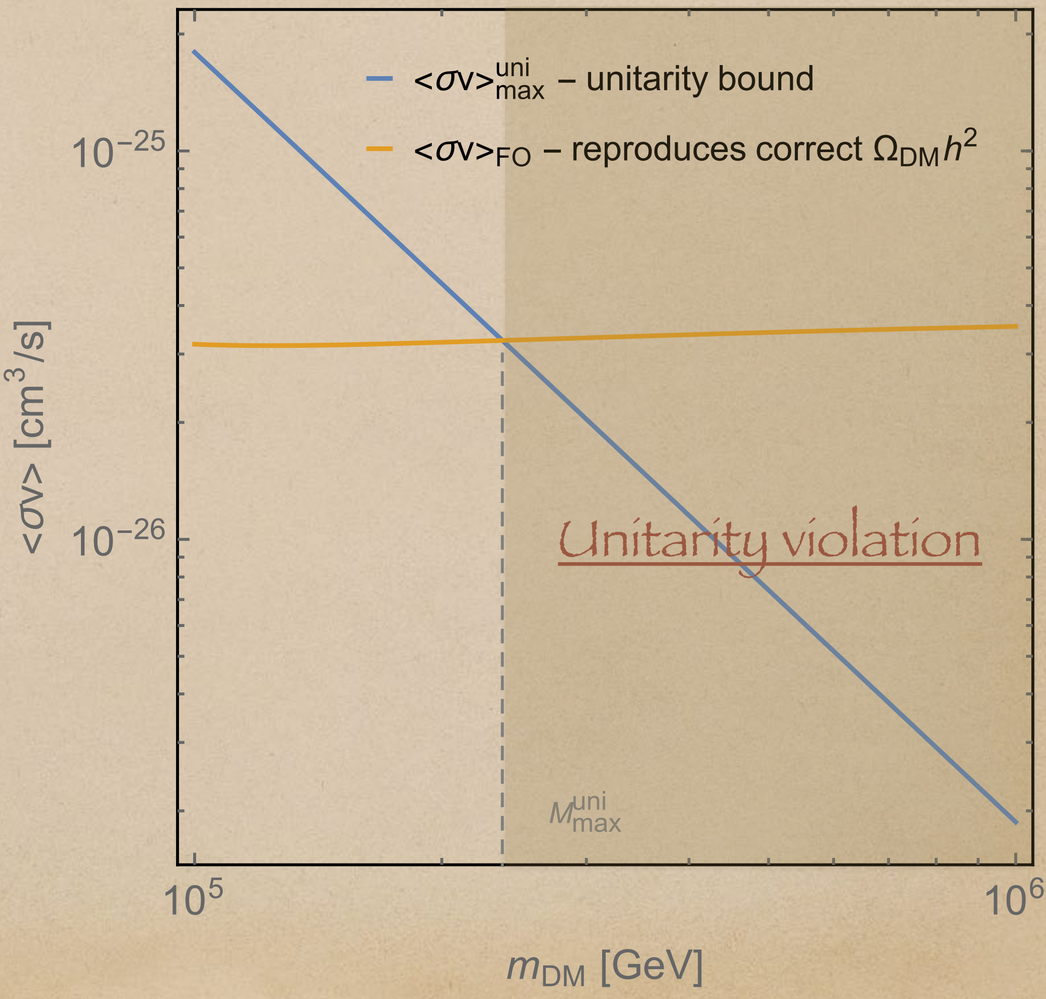

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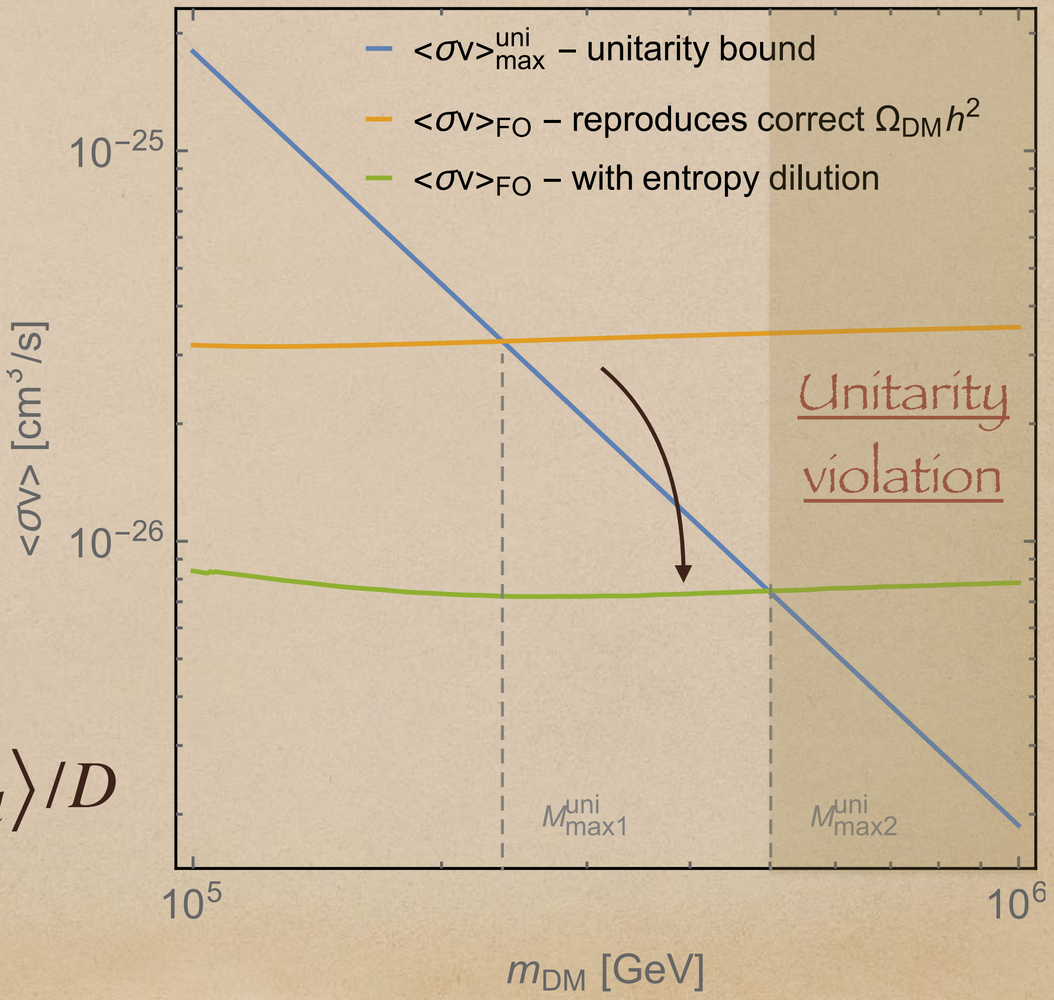
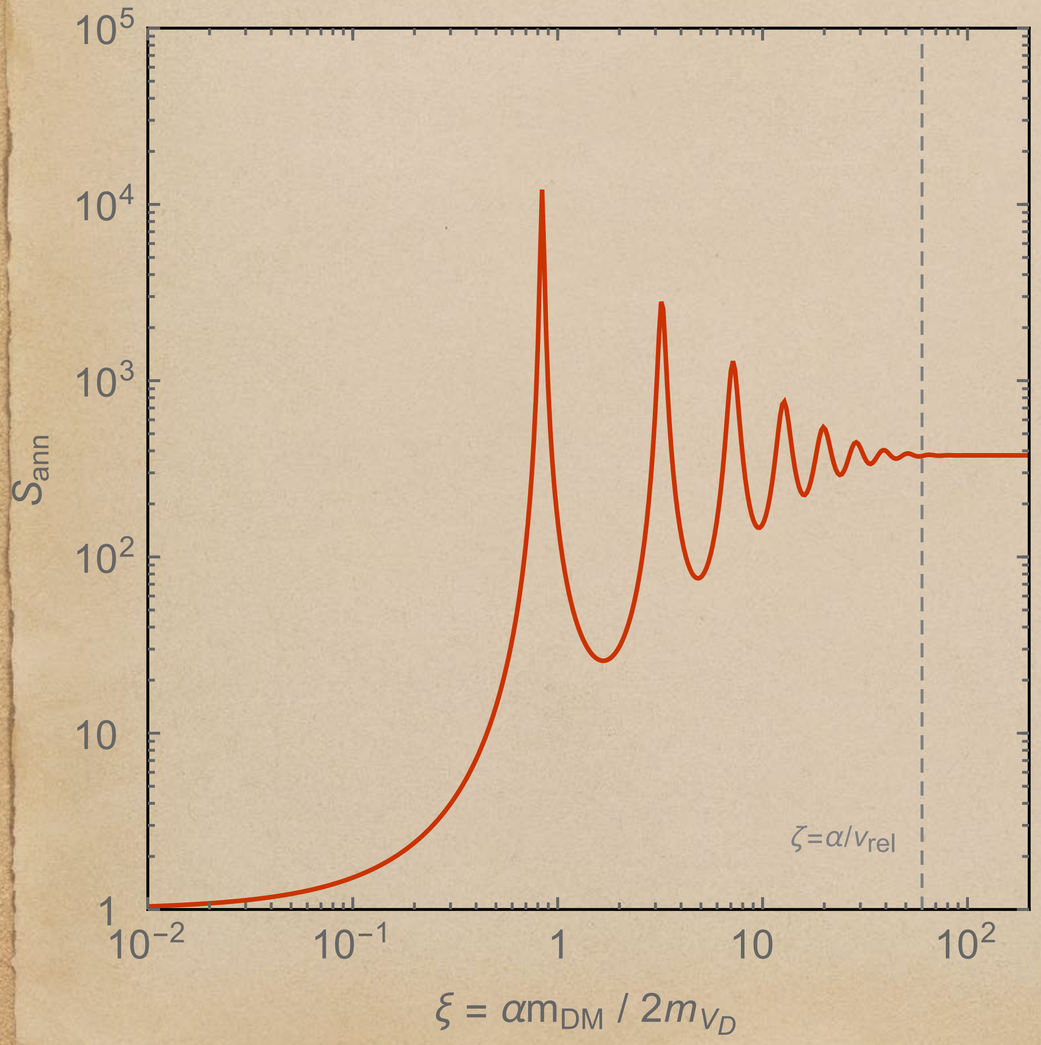
With entropy dilution:

$$S_{SM} \rightarrow D\, S_{SM} \quad \rightarrow \quad Y_\infty \rightarrow Y_\infty / D$$

$$\rightarrow \quad \langle \sigma_{ann} v_{rel} \rangle \rightarrow \langle \sigma_{ann} v_{rel} \rangle / D$$

$$\rightarrow \quad m_{DM}^{max} \rightarrow \sqrt{D} m_{DM}^{max}$$




10^5
10^4
10^3
10^2
10
1
S_{ann}
10^{-2}
10^{-1}
1
10
10^2
$\zeta=\alpha/v_{rel}$
$\xi = \alpha m_{DM} / 2m_{V_D}$