Thermal Evolution of the Secluded Dark Matter

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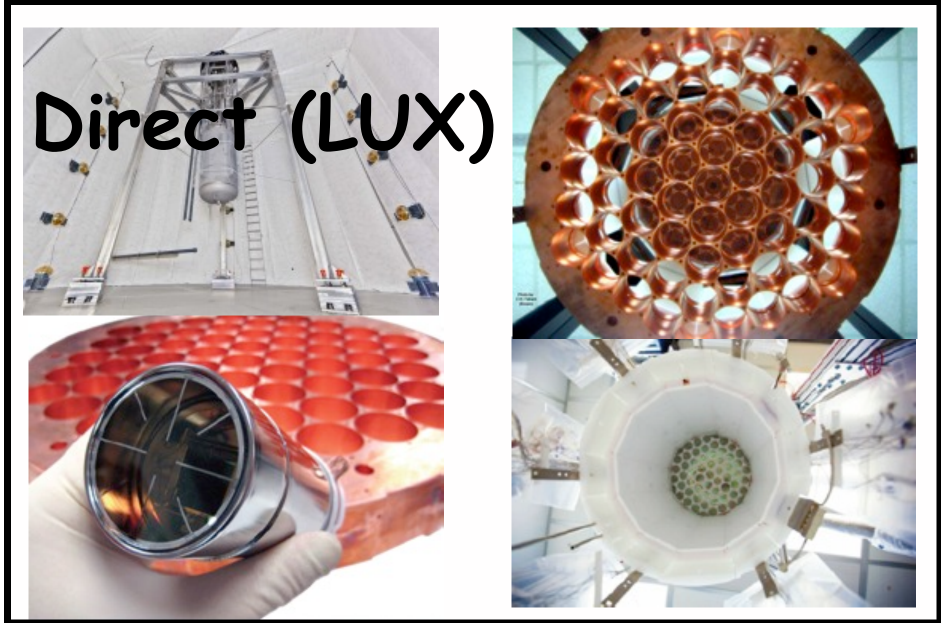
Work is in preparation

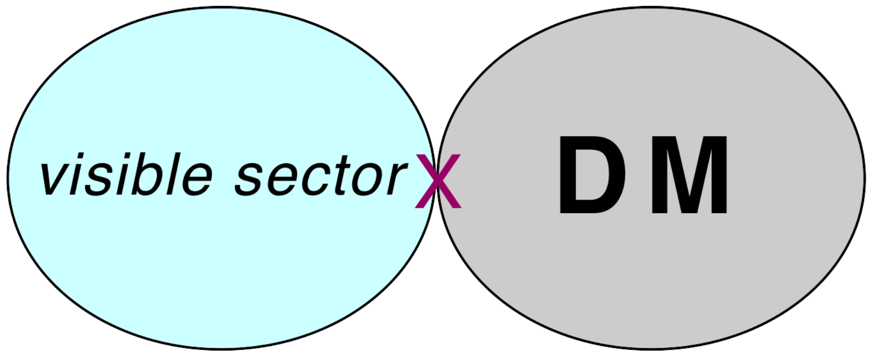
Outline

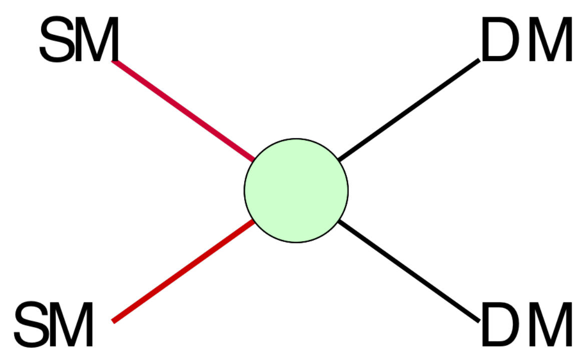
- Introduction :
- Motivation
- Taking a simplest secluded vector dark matter model as an example
- Theoretical and experimental constraints (partially)
- Thermal evolution of the hidden sector
- Summary

Four roads to Dark Matter



Weakly Interacting Massive Particles

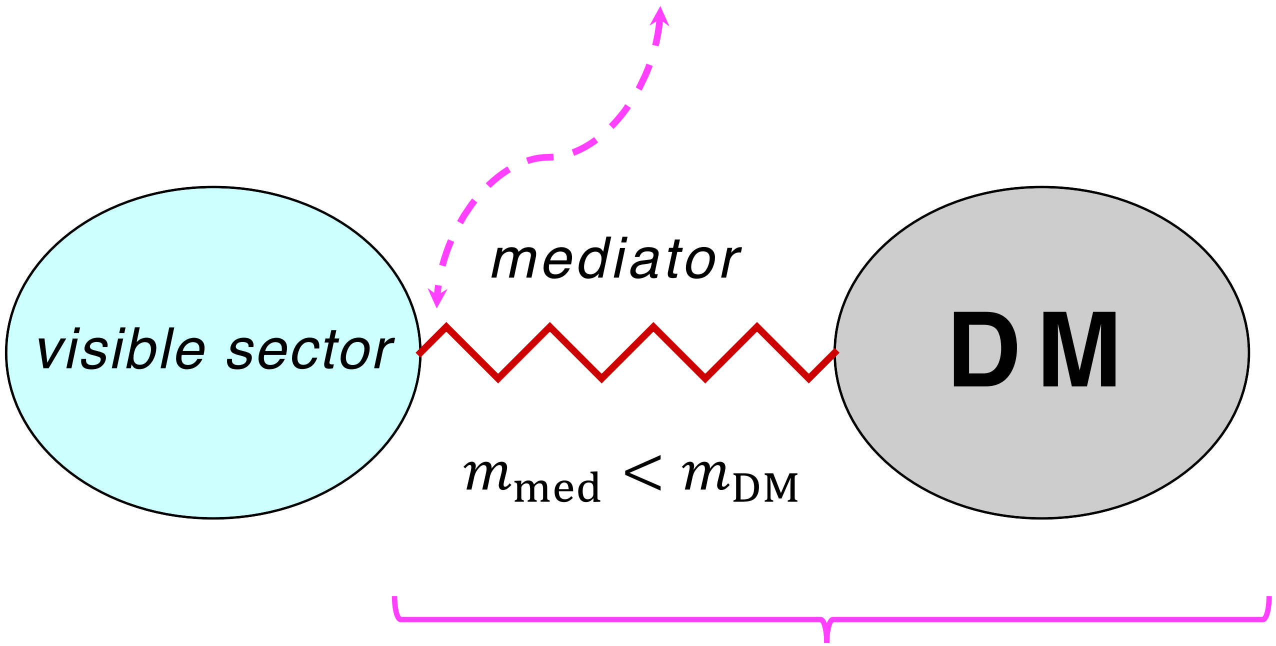




$$\langle \sigma_{ann} v \rangle \simeq \frac{\alpha^2}{m_{\mathrm{DM}}^2}$$

Correct relic abundance for $m_{DM} \sim \frac{\alpha}{0.01} \times 100 \text{ GeV}$

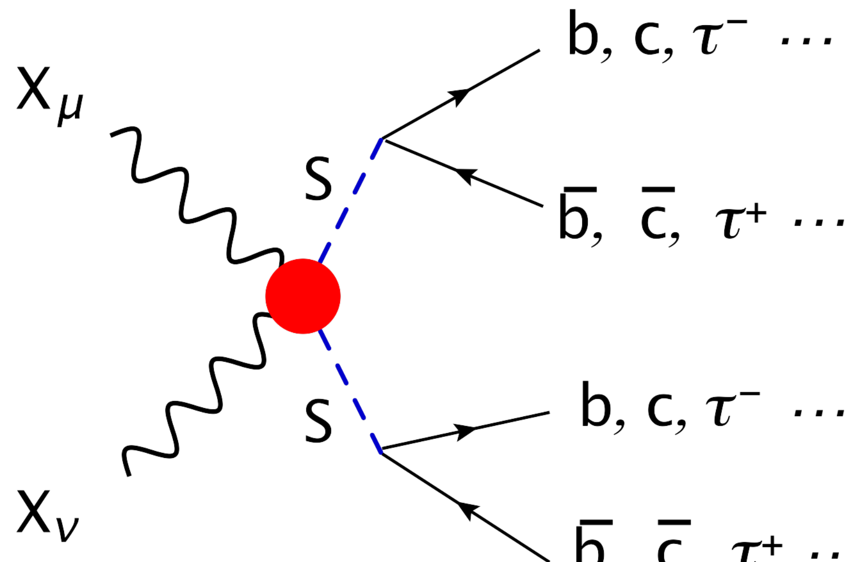
A very small coupling is allowed



Hidden sector
in which dark matter is secluded

The simplest secluded vector dark matter model

Diagram relevant to the galactic center gamma-ray emission



Vector dark matter

Hidden scalar decay

The relevant kinetic terms in the dark sector are

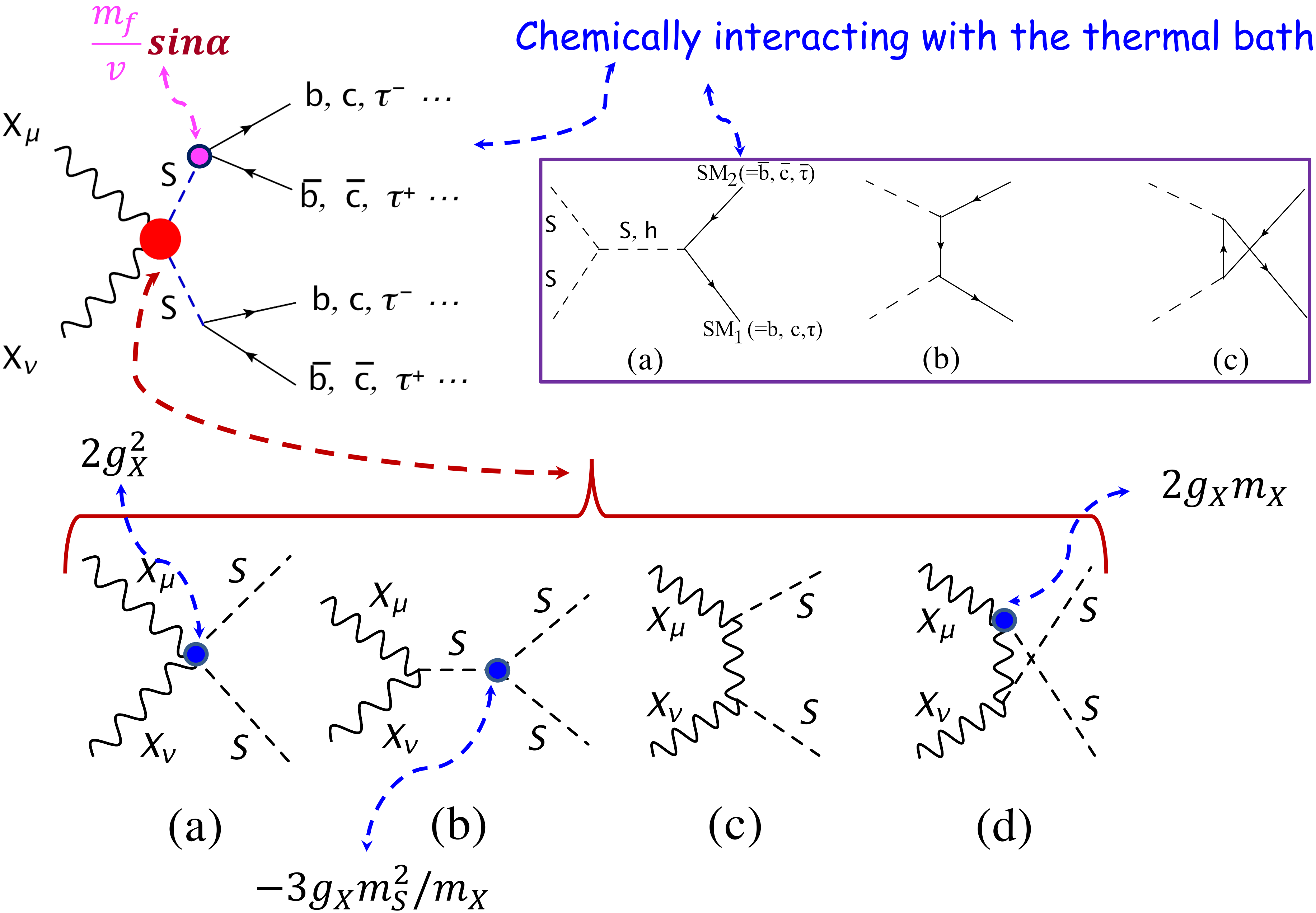
$$\mathcal{L}_{\rm DM} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi_S)^\dagger (D^\mu \Phi_S)$$

$$D_\mu \Phi_S = (\partial_\mu + i g_X Q_{\Phi_S} X_\mu) \Phi_S,$$

$$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$$

$U_{dm}(1)$ charge of Φ_S

$$\begin{pmatrix} \phi_h \\ \phi_s \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

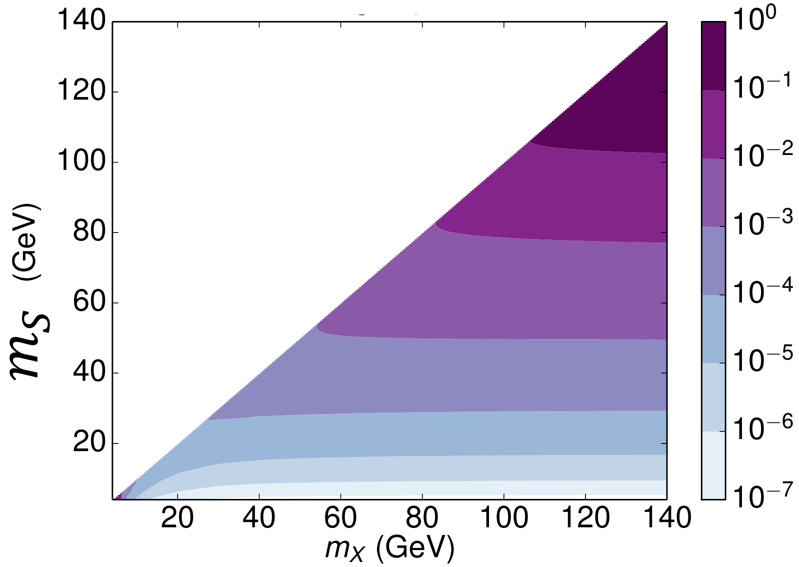


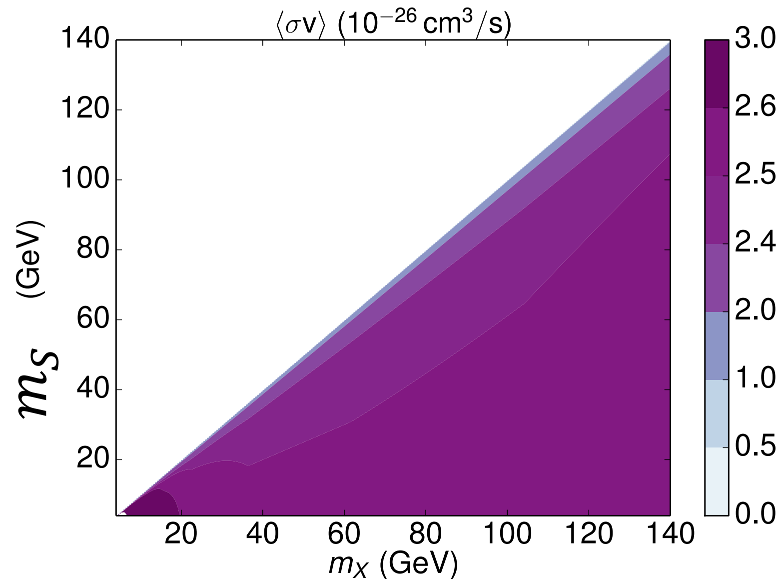
Also relevant to dark matter relic density

Mixing angle α:

constraint by spin-independent scattering cross section with nuclei

$\sin^2 \alpha$





From 1709.07002, by Escudero, Witte, Hooper

Data:
XENON 1T (2017)

$\sin \alpha \lesssim 0.05$ for $m_X \sim 80$ GeV, $m_S = 0.8\, m_X$

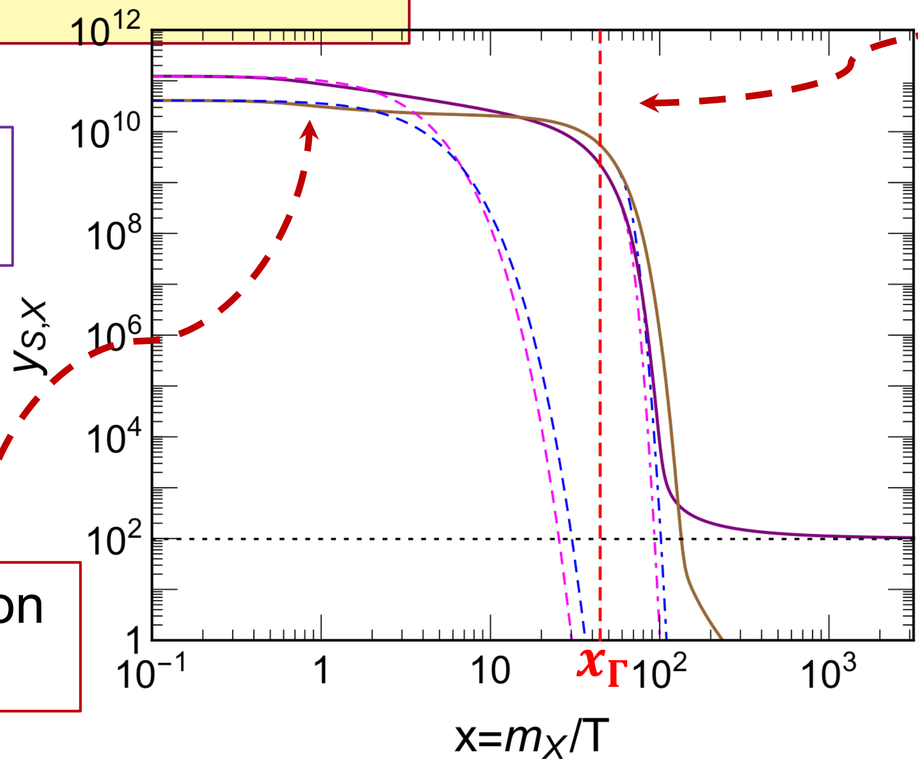
LUX-ZEPLIN(LZ)
projected limit:
$\sin \alpha \sim 0.005$

$$\sigma_{nucleon} = \frac{g_X^2 f_N^2}{4\pi} \mu_{XN}^2 \frac{m_N^2}{v_H} \left[\sin 2\alpha \left(\frac{1}{m_S^2} - \frac{1}{m_h^2} \right) \right]^2$$

$$\simeq 2\times 10^{-45} cm^2 \left(\frac{g_X c_\alpha s_\alpha}{10^{-2}} \right)^2 \left(\frac{80\text{ GeV}}{m_S} \right)^4 \left(1 - \frac{m_S}{m_h} \right)^2$$

$m_X \sim 80$ GeV, $m_S = 0.8\, m_X$, $g_x = 0.16$

$\alpha = 1.\times 10^{-7} > 1.9\times 10^{-11}$ **BBN bound**



$y_{S,X} \propto n_{S,X}/s$
normalized yield

3 → 2 annihilation
(cannibalism)

$x_\Gamma = \dfrac{m_X}{T_\Gamma}$

$$\frac{y_S(x_\Gamma)}{y_S^{\rm in}(1)} \simeq e^{-\frac{C}{2}(x_\Gamma^2-1)} \stackrel{\rm def}{=} \frac{e^{-1}}{4}$$

$y_S^{in}(1) = y_X(1) + y_S(1) \simeq 4 y_S(1)$

$y_X^\infty = x_f = \dfrac{m_X}{T_f} \simeq 90$

$$\Omega_{\rm DM} h^2 \simeq \frac{1.04\times 10^9\ {\rm GeV}^{-1}}{J\sqrt{8\pi g_*} M_{\rm pl}} = 0.1198 \pm 0.0026$$

$$J = \int_{x_f}^{\infty} \frac{\langle\sigma v\rangle_{XX\to SS}}{x^2} dx \approx \frac{\langle\sigma v\rangle^{(0)}_{XX\to SS}}{x_f}$$

That is $\langle\sigma v\rangle^0_{XX\to SS} \propto x_f$

It hints that $\langle\sigma v\rangle^0_{XX\to SS}$ could be 4 times larger than the WIMP case

THERMAL EVOLUTION: Boltzmann Equation

In the homogeneous isotropic Friedmann-Robertson-Walker Universe

$$\frac{df}{dt} = C[f_h]$$

$$\frac{df}{dt} = \frac{\partial f_h}{\partial t} + \cancel{\boxed{\frac{dx^i}{dt}\frac{\partial f_h}{\partial x^i}}} + \boxed{\frac{dp}{dt}\frac{\partial f_h}{\partial p}} + \cancel{\boxed{\frac{d\hat{p}^i}{dt}\frac{\partial f_h}{\partial \hat{p}^i}}}$$

$$\frac{\partial f_h}{\partial t} - Hp\frac{\partial f_h}{\partial p} = \boxed{C[f_h]}$$

Boltzmann Equation

Collision term

Moment of Boltzmann Equation

Taking the moment integral

$$n_X(T_h) = g_X \int \frac{d^3p}{(2\pi)^3} f_X(T_h), \qquad n_S(T_h) = g_S \int \frac{d^3p}{(2\pi)^3} f_S(T_h)$$

we get the evolution of the number densities

$$\frac{dn_X}{dt} + 3Hn_X = \mp (XX \rightleftharpoons SS)$$
$$\boxed{\pm(XXX \rightleftharpoons SS) \quad \mp(XXS \rightleftharpoons SS) \quad \pm(SSS \rightleftharpoons XX)}$$

$$\frac{dn_S}{dt} + 3Hn_S = \mp(S \rightleftharpoons SM\,SM) \quad \mp (SS \rightleftharpoons SM\,SM) \pm (XX \rightleftharpoons SS)$$
$$\boxed{\begin{array}{l}\pm(XXX \rightleftharpoons SS) \quad \pm(XXS \rightleftharpoons SS) \quad \mp(SSS \rightleftharpoons XX) \\ \mp(XSS \rightleftharpoons XS) \quad \mp(SSS \rightleftharpoons SS)\end{array}}$$

cannibal annihilations

Temperature evolution of the hidden scalar

Taking the moment integral $\int \frac{d^3p}{(2\pi)^3} E_S$ to the Boltzmann eq. of the hidden scalar, we get

$$\rho_S = g_S \int \frac{d^3p}{(2\pi)^3} E_S f_S \simeq g_S n_S \left(m_S + \frac{3}{2} T_h \right)$$

where $$T_h = \frac{2}{3} \int \frac{d^3p}{(2\pi)^3} \frac{p_S^2}{2m_S} f_S$$

…, and the temperature evolution of the hidden scalar

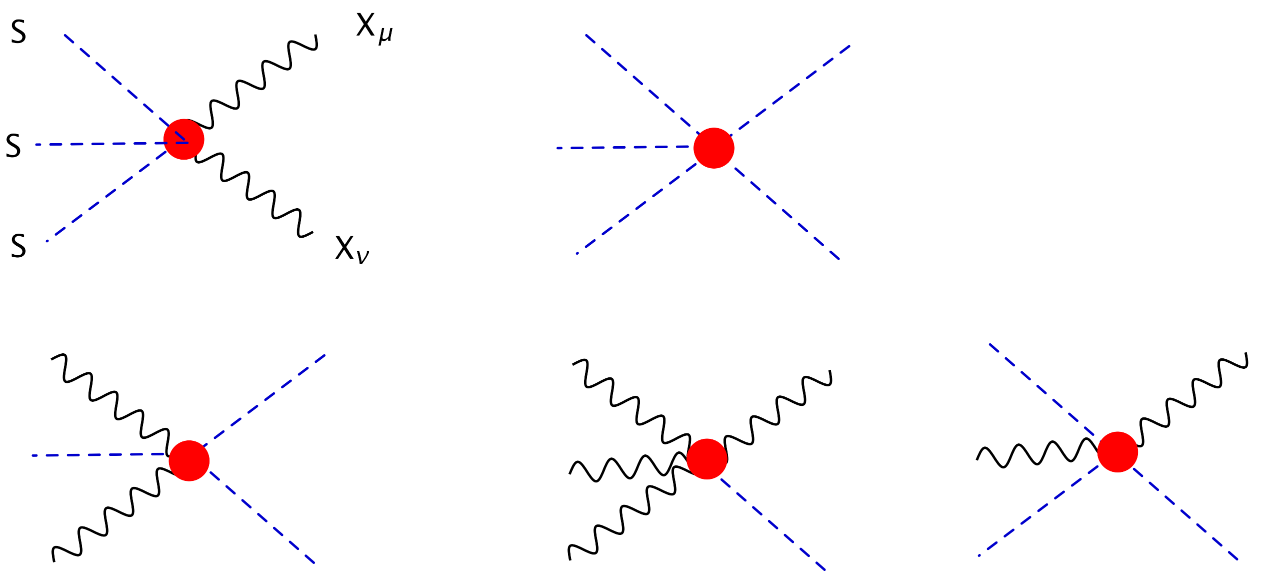
$$\frac{dT_h}{dt} + 2HT_h = \frac{2}{3n_S(T_h)} \left[- \left(\frac{dn_S(T_h)}{dt} + 3Hn_S(T_h) \right) \left(m_S + \frac{3}{2} T_h \right) + C[f_S \cdot E_S] \right]$$

In this model, $m_X \sim m_S \sim O(10\ GeV)$ and the elastic scattering χS ↔ χS can keep the X and S particles in thermal equilibrium ($T_X = T_S$) until the dark matter freezes out.

Cannibal annihilations:

Total entropy of the hidden sector is still conserved

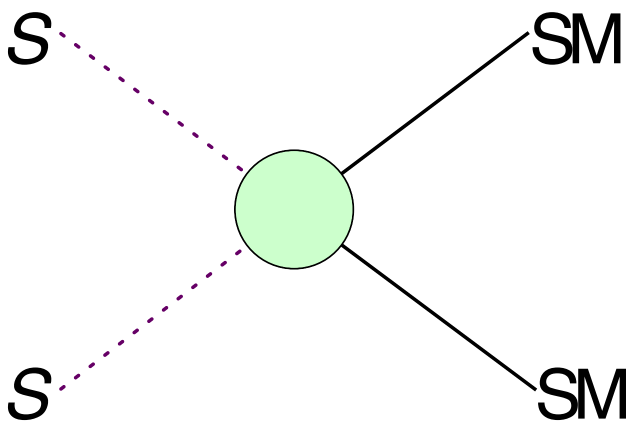
Temperature of hidden sector is thus heated



$$\left(n_h^{eq}(T_h)\right)^2 \langle \sigma\, v^2 \rangle_{3\to 2} \sim H\,(T)$$

Set the time scale T_h^c corresponding to decoupling of $m \leftrightarrow n$ process, $m \neq n$

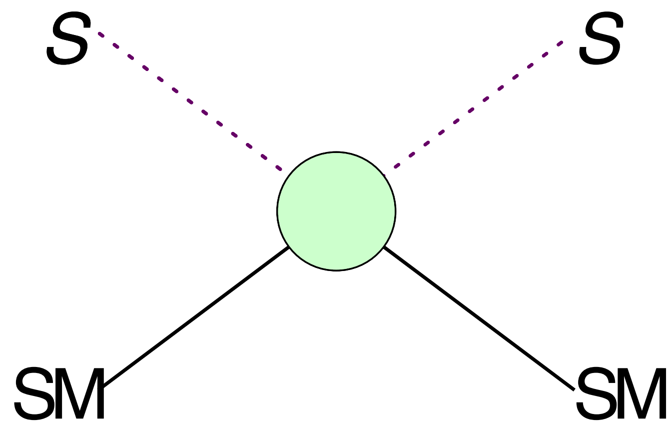
After T_h^c, $n_h(T_h)$ does not follow up $n_h^{eq}(T_h)$



annihilation

$$\left(n_S^{eq}(T)\right)^2 \langle \sigma v \rangle \sim H\, n_S(T)$$

Set decoupling temperature for this annihilation



Elastic scattering with SM

$$\left(n_{SM}^{eq}(T)\right)\langle \sigma_{el}\, v \rangle \sim H\,(T)$$

Set kinetic decoupling temperature

Hidden sector: thermal equilibrium with the bath

Chemical equilibrium keeping $\mu = 0$ when $m_{X,S} \lesssim T$:

Annihilation to SM, $S\,S \to \mathrm{SM\,SM}$: decoupling quickly when $T < m_S$

$\left(n_S^{eq}(T)\right)^2 \langle \sigma\, v \rangle \gtrsim H\,(T)\, n_S(T_h)$ ➡ $n_S(T_h) \to n_S^{eq}(T)$ & $T_h \to T$

Decay to SM, $S \to \mathrm{SM\,SM}$:

$\Gamma_S\, n_S^{eq}(T) \gtrsim H\, n_S\,(T_h)$ ➡ $n_S(T_h) \to n_S^{eq}(T)$ & $T_h \to T$

Cannibalization: $3 \to 2$ for hidden sector (comoving entropy density conserved)

$\left(n_h^{eq}(T_h)\right)^2 \langle \sigma\, v^2 \rangle_{3\to 2} \gtrsim H\,(T)$ ➡ $n_S(T_h) \to n_S^{eq}(T_h)$, $\mathrm{T_h}$ may be heated

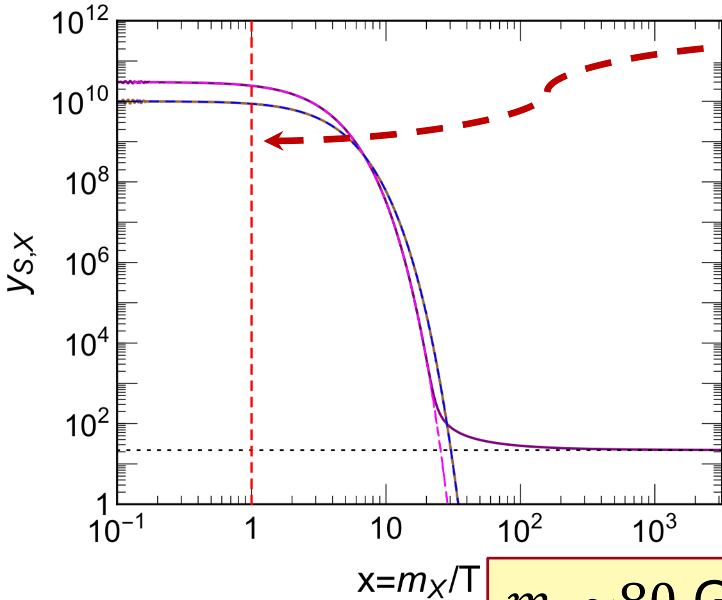
Boltzmann suppression

Kinetic equilibrium

Elastic scattering, $S\,\mathrm{SM} \to S\,\mathrm{SM}$:

$\left(n_{SM}^{eq}(T)\right)\langle \sigma_{el}\, v \rangle \gtrsim H\,(T)$ ➡ $T_h \to T$

WIMP

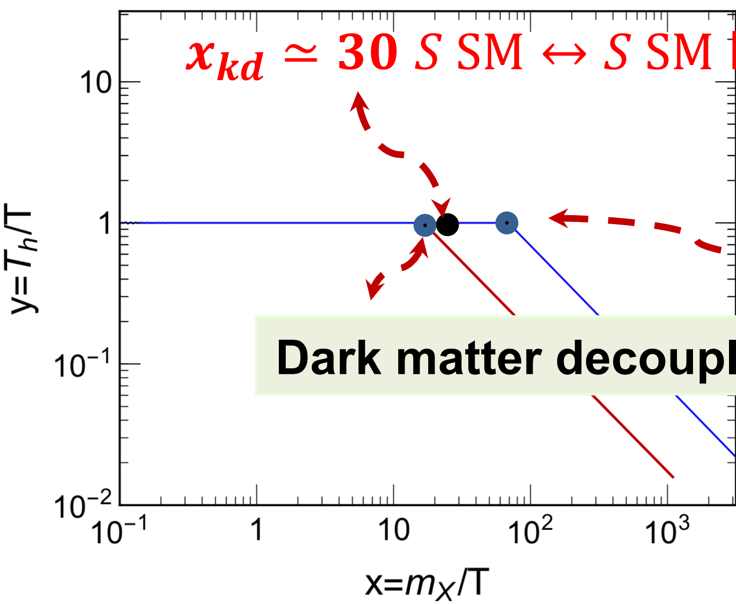


$x_\Gamma = \frac{m_X}{T_\Gamma}$, $S \to$ SM SM becomes significant

$y_X^\infty = x_f \simeq 22$

m_X~80 GeV, $m_S = 0.8\, m_X, g_X = 0.16$

$\alpha = 0.0001$



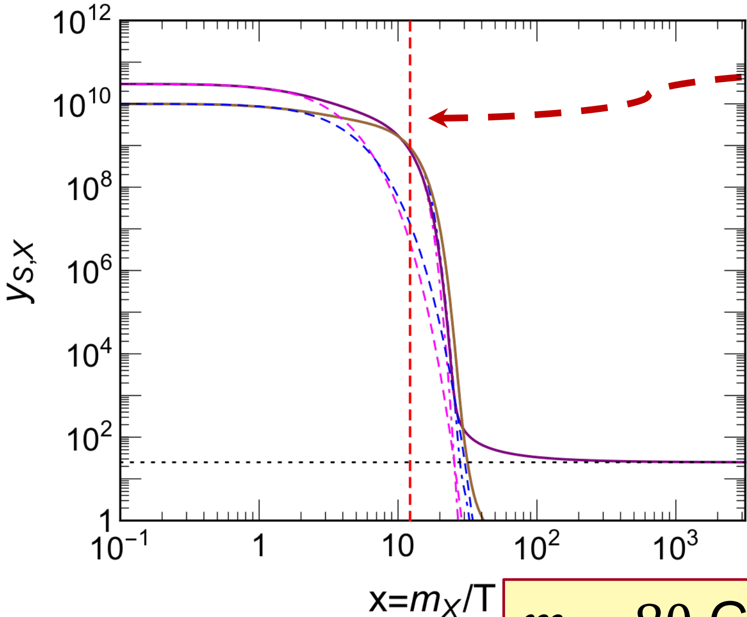
$x_{kd} \simeq 30$ S SM $\leftrightarrow$ S SM kinetic decoupling

x_{dd}, $S \to$ SM SM chemical decoupling

Dark matter decouples from S kinetically and chemically

After decoupling, $\frac{\mathrm{T_h}}{\mathrm{T_h^D}} \simeq \left(\frac{T}{T^D}\right)^2$, i.e., $\mathrm{T_D} \propto T^2$

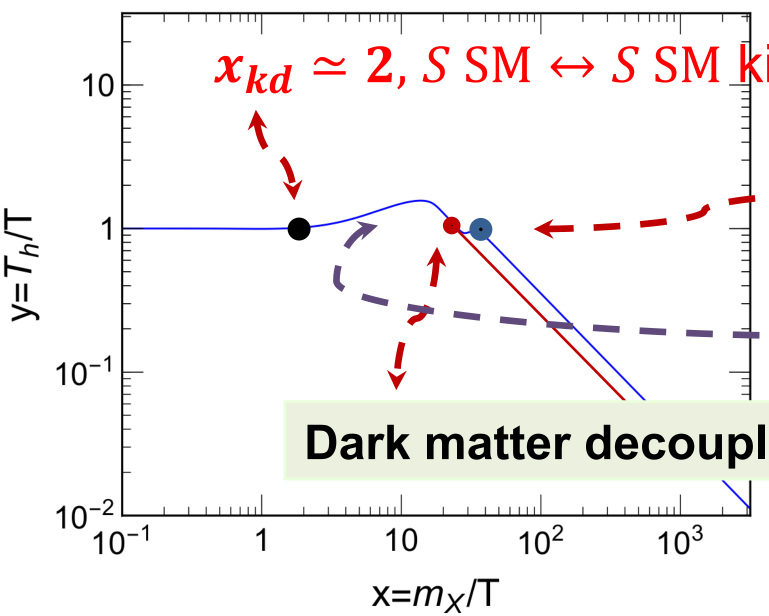
Non-WIMP



$x_\Gamma = \frac{m_X}{T_\Gamma}$, $S \to$ SM SM becomes significant

$y_X^\infty = x_f \simeq 25 \quad \propto \langle \sigma v \rangle^0_{XX \to SS}$

$m_X \sim 80$ GeV, $m_S = 0.8\, m_X, g_X = 0.1645$ $\alpha = 5 \times 10^{-7}$



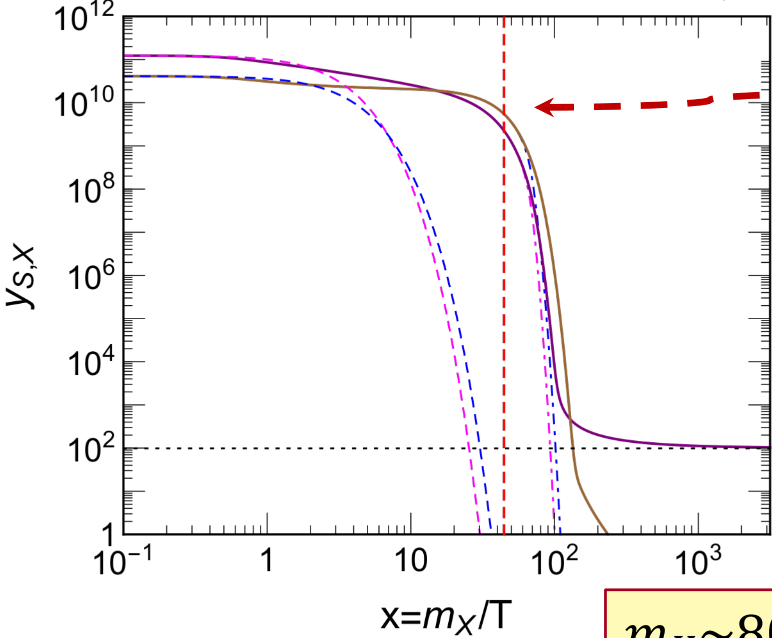
$x_{kd} \simeq 2$, S SM $\leftrightarrow$ S SM kinetic decoupling

x_{dd}, $S \to$ SM SM chemical decoupling

cannibalization

Dark matter decouples from S kinetically and chemically

Non-WIMP



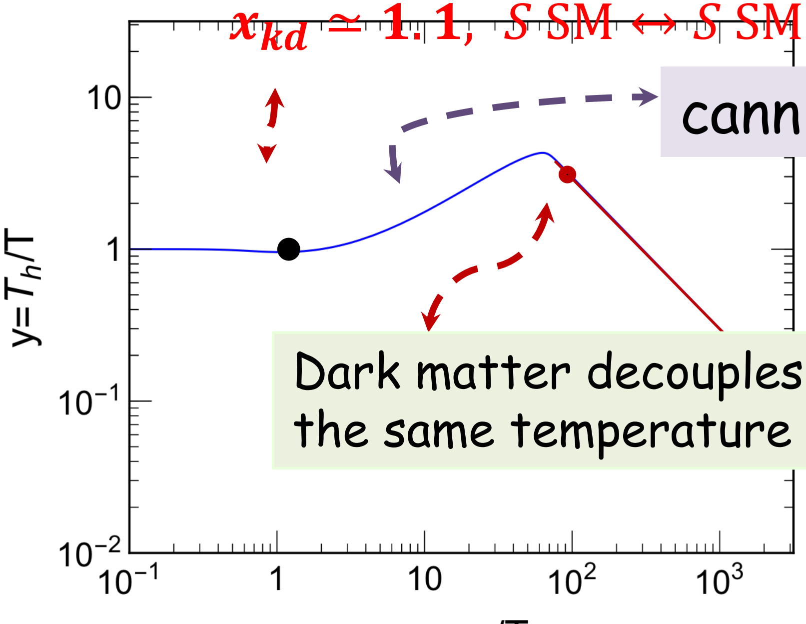
$x_\Gamma = \frac{m_X}{T_\Gamma}$, $S \to$ SM SM becomes significant

$y_X^\infty = x_f \simeq 98 \;\; \propto \langle \sigma v \rangle^0_{XX\to SS}$

$m_X \sim 80$ GeV, $m_S = 0.8\, m_X, g_X = 0.24$

$\alpha = 1\times 10^{-7}$

$x_{kd} \simeq 1.1$, S SM $\leftrightarrow$ S SM kinetic decoupling



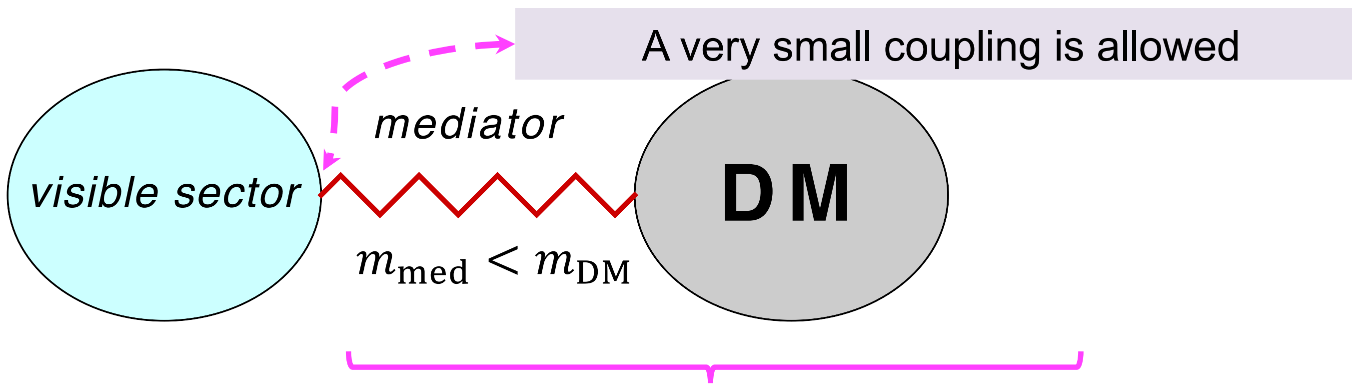
cannibalization

$S \to$ SM SM does not play a roller for the thermal equilibrium

Dark matter decouples from S kinetically and chemically, but follows the same temperature with S

Summary

Using the simplest secluded vector dark matter model, I have given the thermal evolution results of the hidden sector



Hidden sector in which dark matter is secluded

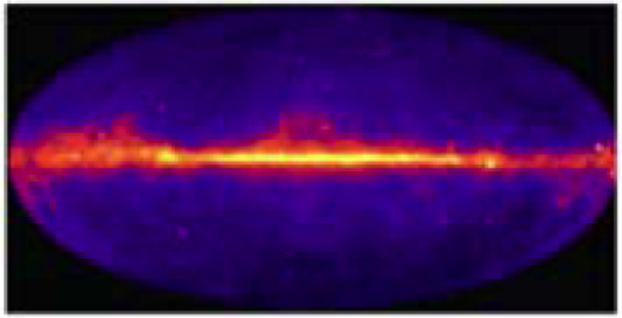
Summary

1. cascade DM annihilation can well account for GC gamma-ray emission.

2. We have discussed a simplest secluded vector dark matter model

3. The mechanism resulting in the **cannibally co-decaying** vector dark matter can explain the GC gamma-ray emission, the relic density simultaneously, and other constraints.

Fermi sky



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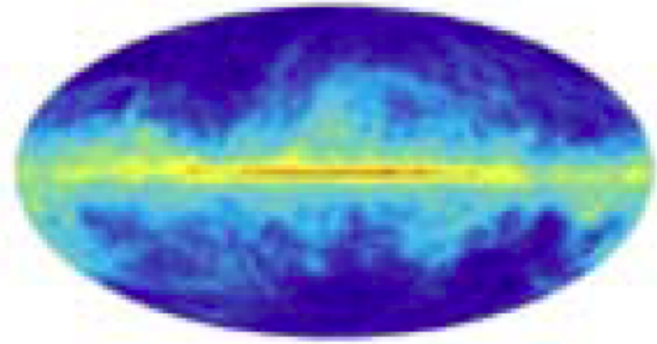
Galactic diffuse



Isotropic gamma-ray background

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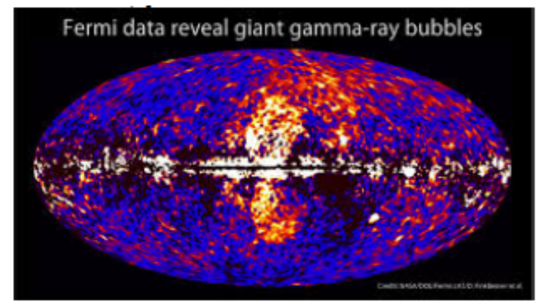
Fermi bubbles



point

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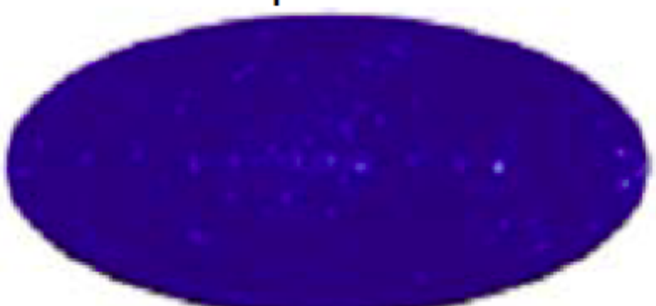

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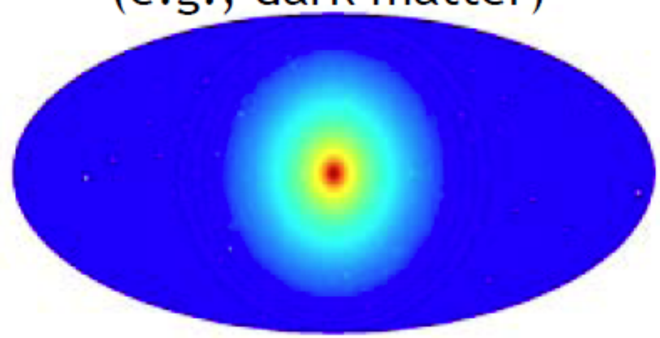
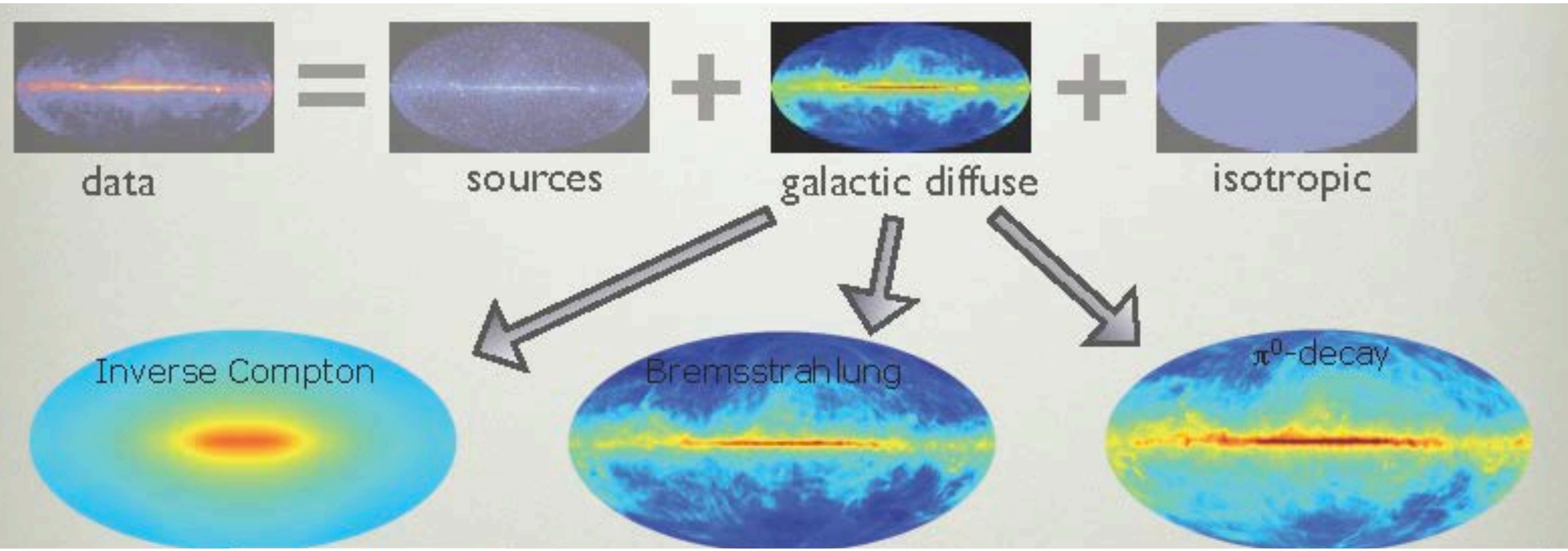
residual
(e.g., dark matter)

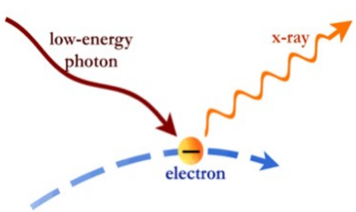


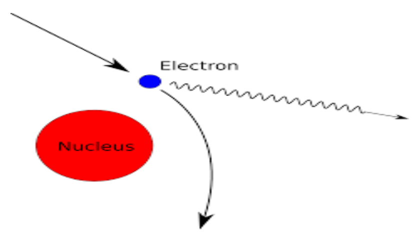
From Satya's Talk @ LHCDM, 2015

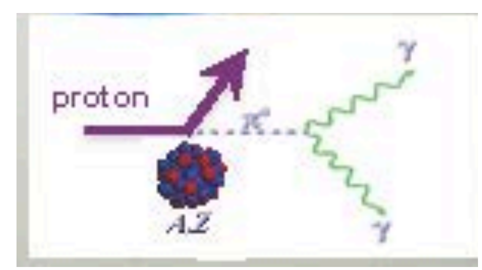
Sources of Galactic Diffuse Emission (GDE)

1. Inverse Compton: CR electrons up-scattering low-energy photons
2. Neutral pion decays: CR protons inelastic collision with nuclei (gas)
3. Bremsstrahlung : CR electrons interacting with interstellar gas









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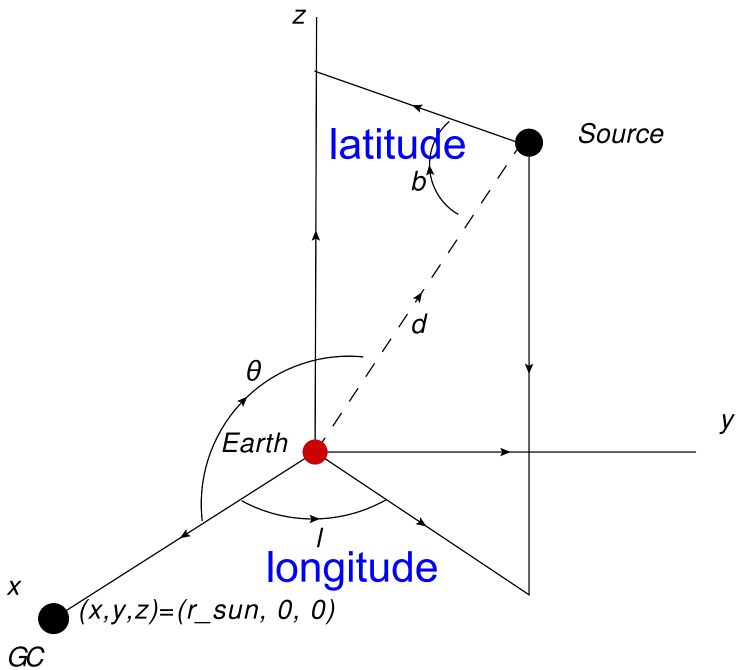
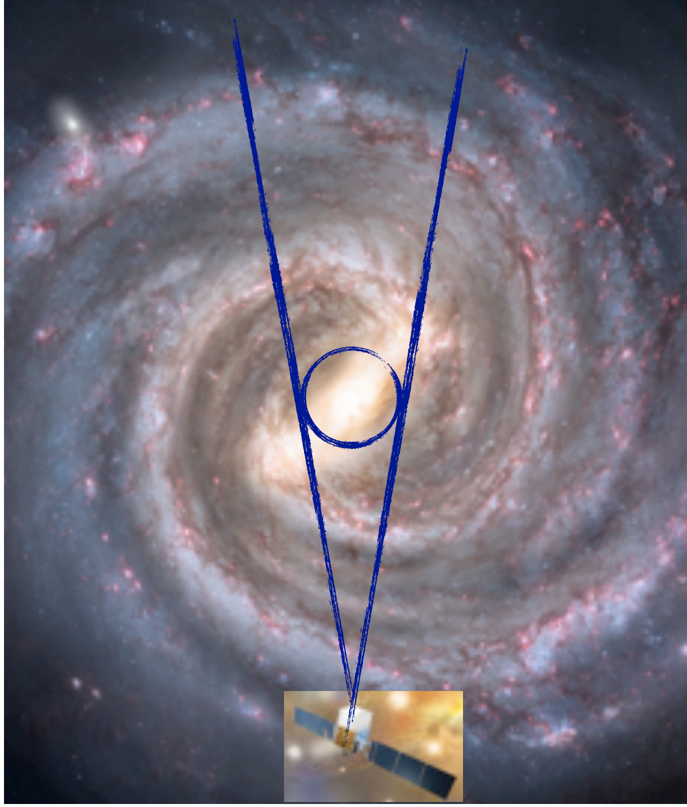


From Satya

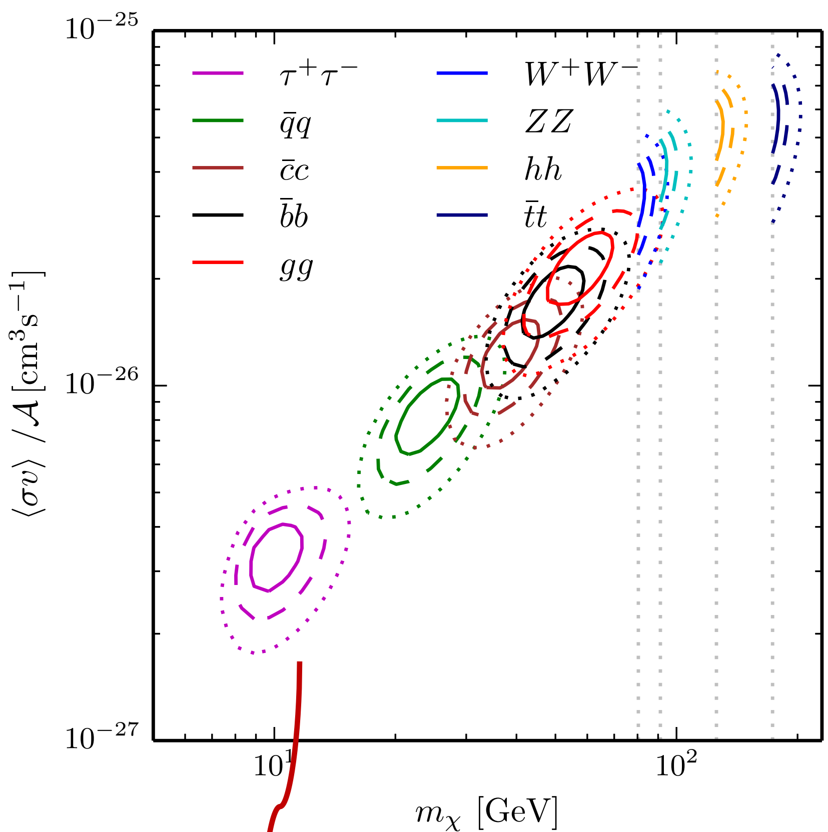


The differential flux of gamma-ray

DM prompt γ-ray spectrum per annihilation

$$\frac{d\Phi_\gamma}{dE} = \frac{1}{8\pi m_X^2} \sum_f \langle \sigma v \rangle_f \boxed{\left(\frac{dN_\gamma^f}{dE} \right)_X} \frac{1}{\Delta\Omega} \underbrace{\int_{\Delta\Omega} \int_{\mathrm{l.o.s.}} ds \rho^2(r(s,\psi)) d\Omega}_{\text{J-factor}},$$

depend on the observational region of interest (ROI) in a particular analysis



CCMW: Annihilation into gluons, $\bar{q}q, \bar{c}c, \bar{b}b, hh$ provides a good fit

Channel	$\langle\sigma v\rangle$ $(10^{-26}\ \mathrm{cm^3\ s^{-1}})$	m_χ (GeV)	$\chi^2_{\rm min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\boxed{\tau^+\tau^-}$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
$[\,\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	$0.0036]_{\cancel{\mathrm{ICS}}}$

Low p-value; is not excluded with 95% CL significance

This is for self-conjugate DM