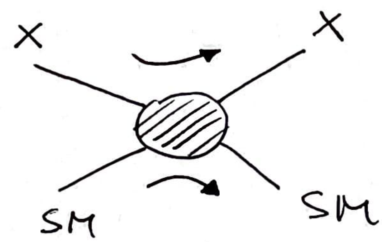
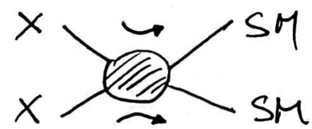
# Hunting For Dark Matter

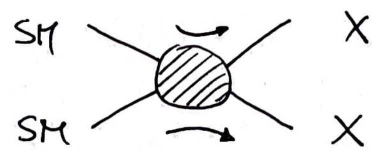
i) Direct Detection




ii) IN-Direct Detection




iii) Colliders



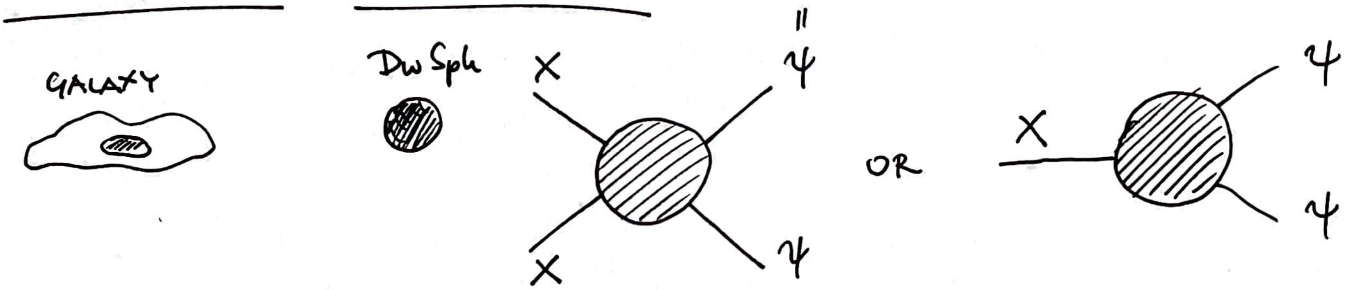

Cosmologically, the production of DM is related to microscopic interactions via $\langle \sigma v \rangle$. How does this translate to observables? We will go (briefly) through the above options and quantify the relations to the existing and upcoming experiments.

This year, we will discuss indirect detection only.

# INDIRECT DETECTION

TASI lectures by T. Slatyer

SM [1710.05137]




DM ANNIHILATION

DM DECAY

- The idea here is to look at astrophysical objects (galaxies, dwarf spheroidals, ...) and search for either <u>annihilation</u> or <u>decay</u> of DM into SM. These final states may include ($e^\pm$, $p$, $\bar{p}$, $n$, $\gamma$, $q$, ...).

- <u>Upshot</u>: plenty of DM $\rho_0 \gg \rho_{DM}$ ($\Omega_{DM} \simeq 5\Omega_b$) to produce an observable signal.

- <u>Challenges</u>: a) DM might be very weakly coupled to SM (perhaps even only gravitationally)

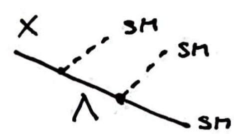
  b) Many astrophysical backgrounds (pulsars) make it hard to claim a DM signal.

  c) Charged final states ($e$, $p$, light nuclei) get deflected by intergalactic $B$ fields. Tools like GALPROP can propagate the charged finals states, but in general it's hard to back-trace a signal to the origin.

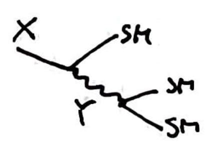
- Neutral final states $(\gamma, \nu)$ travel unimpeded $(\theta, \varphi, z)$.
- Our task is to estimate the number of events on Earth and relate them to $\langle \sigma v \rangle$ for annihilation and $\Gamma_x$ for decays.

## INDIRECT SIGNALS FROM DM DECAY

- Dimensional analysis of $\Gamma$ for DM with $m_x$, $\Lambda \sim M_{GUT} \sim 10^{16}\,\text{GeV}$

a) $D=5$ operator : $\Gamma = \dfrac{m_x^3}{\Lambda^2}$ ,  $= 1\,s^{-1}$,



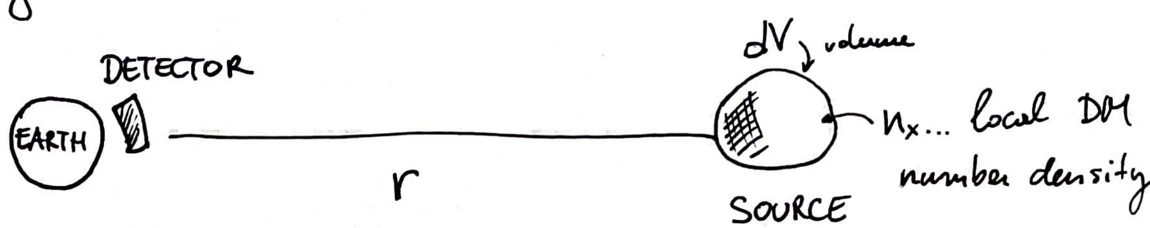
b) $D=6$ operator : $\Gamma = \dfrac{m_x^5}{\Lambda^4}$ ,  $= 10^{26}\,s^{-1}$.

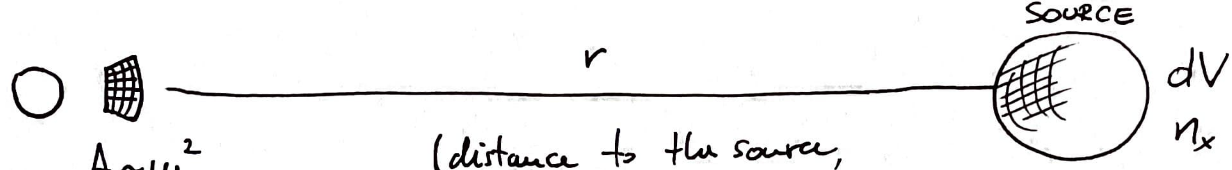


- Taking $O(1)$ couplings a) is too fast, but b) can give a viable (unstable) DM candidate:

$$\tau_{DM} \sim 10^{26}\,s = 10^{19}\,\text{yrs} \gtrsim t_u .$$

- Estimating the number of events on the earth






$A \sim m^2$ (detector surface)

(distance to the source, center of MW, to DwSph)

- Number of events per unit of time:

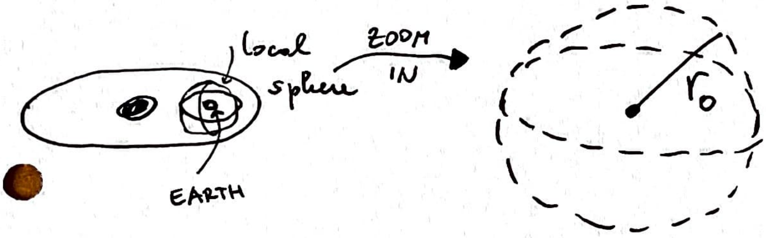
$$\frac{dN}{dt} = \underbrace{\left(\frac{n_x dV}{\tau_x}\right)}_{\text{}}\underbrace{\left(\frac{A}{4\pi r^2}\right)}_{\text{}} , \quad dV = r^2 dr\, d\Omega$$

$\propto$ source volume and $\Gamma_x$ size, strength of the DECAY SIGNAL

geometric acceptance of our detector setup

$$= A\, n_x \left(\frac{d\Omega}{4\pi}\right)\frac{dr}{\tau_x} . \quad (\text{the } r^2 \text{ cancelled out})$$

EXAMPLE #1 : local source in our neighborhood




$r_0 \leq 1\,\text{kpc}$ is limited by $e^{\pm}$ with $E \sim M_W$ attenuation

$r_0 \sim 1\,\text{kpc}$

$\rho_0 \sim 0.4\ \text{GeV cm}^{-3}$ (from DM mass profiles)

$d\Omega \sim 4\pi$ , we look at the entire surrounding, not a distant point source

Then : $\dfrac{dN}{dt} = \dfrac{A\, n_x r_0}{\tau_x} = \dfrac{A \rho_0 r_0}{m_x \tau_x}$ , where we used $\rho_0 = m_x n_x$ .

So, the first example of a local homogeneous sphere around the earth with a limited radius, gives:

$$\frac{dN}{dt} = 10^{-4}\, s^{-1} \left(\frac{A}{m^2}\right)\left(\frac{\rho_0}{0.4\,\frac{GeV}{cm^3}}\right)\left(\frac{r_0}{kpc}\right)\left(\frac{TeV}{m_X}\right)\left(\frac{10^{26}\, sec}{\tau_X}\right).$$

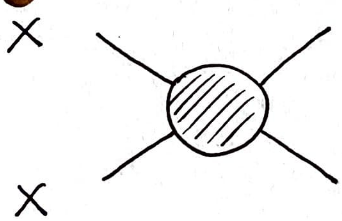
We get $\sim \pi \times 10^7$ sec in one year, so this would give us around $10^3$ events in a year.

- The sterile neutrino had $m_X \sim keV$ and $\theta \sim 10^{-7}$,

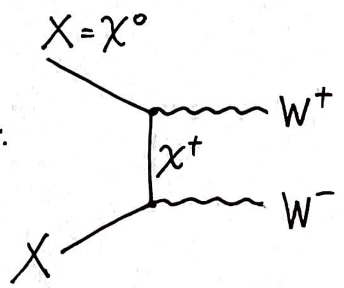
$$\tau_X \sim 10^{30}\, s \left(\frac{10^{-7}}{\theta^2}\right)\left(\frac{keV}{m_X}\right)^5.$$

We loose 4 orders in $\Gamma_X = \tau_X^{-1}$, but gain in $m_X$ 9 orders.

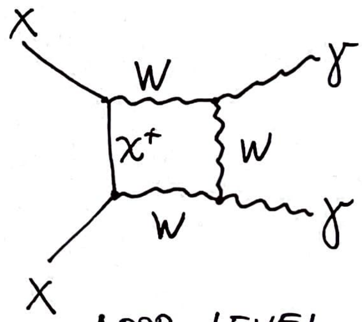
## INDIRECT SIGNALS FROM DM ANNIHILATION




, e.g.:



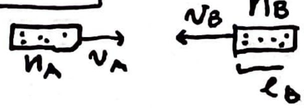

TREE




LOOP-LEVEL

Number of events per unit time & volume:

σ definition




$$\frac{dN}{dt} = n_A n_B\, dV_B\, \sigma\, \Delta v$$

cross-section   incident flux

$$\frac{dN}{dt\, dV} = \sigma \times n_X v \times n_X$$

density of the target

- Now we use the same example of a finite sphere with $r_0 = \text{kpc}$, replace $n_X^2 = (\rho_0/m_X)^2$, and we get:

$$\frac{dN}{dt} = A \langle \sigma v \rangle \left(\frac{\rho_0}{m_X}\right)^2 \frac{r_0}{3}$$

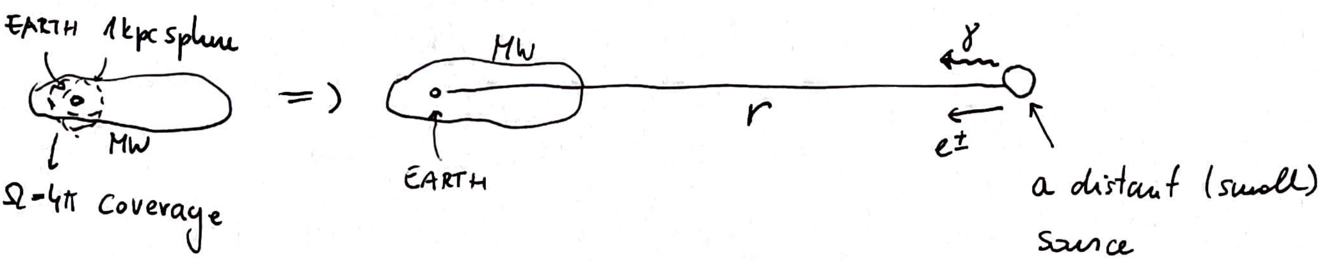
$$= 5 \times 10^{-8}\, s^{-1} \left(\frac{A}{m^2}\right)\left(\frac{\rho_0}{0.4\, \text{GeV}\,\text{cm}^{-3}}\right)^2 \left(\frac{r_0}{\text{kpc}}\right)\left(\frac{\text{TeV}}{m_X}\right)^2 \left(\frac{\langle \sigma v \rangle}{10^{-26}\, \text{cm}^3 s^{-1}}\right)$$

$$\simeq 1 \text{ event}/\text{year}.$$

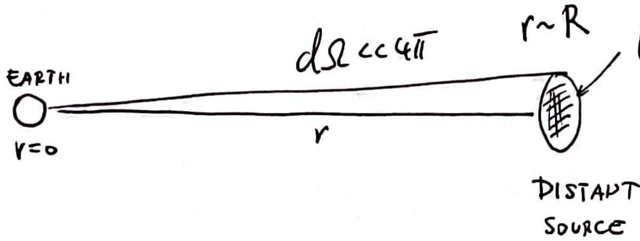
- Here $\langle \sigma v \rangle$ might be T-independent if $m_X \gg M_W$, which would be exactly the same quantity one would use in thermal freeze-out: $\langle \sigma v \rangle \simeq \frac{\alpha_2^2}{m_X^2}$

## EXAMPLE #2: DISTANT POINT SOURCES & J-FACTORS

- Previously we considered a finite kpc sphere around the earth. Now we consider a distant extragalactic source, another galaxy (Andromeda, ...) or dwarf spheroidal



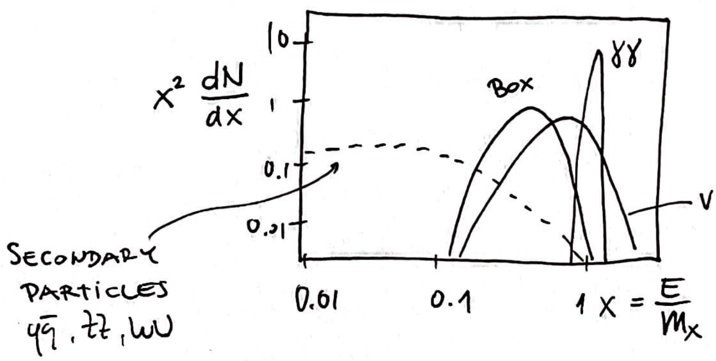
- J-factors: a common practice is to factorize all the astrophysical uncertainties into the J-factor.




local DM density profile

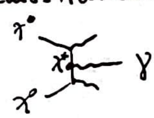
$\rho = m_\chi n(\vec{r})$

- Within the source, the DM may annihilate ($\chi\chi \to \gamma\gamma$, $e^+e^-$, $W^+W^-, \dots$) or decay ($\chi \to \nu\gamma, \dots$). The microscopic models give us the energy distribution at the source




[1208.5481]

VIB = virtual internal bremsstrahlung




- With sufficient resolution, we would be able to distinguish different models.

- The rate distribution is then given by

units: $m^2 \cdot \frac{m}{s} \cdot \left(\frac{1}{m^3}\right)^2$ ✓

$$\frac{dN}{dE\,dt\,\underbrace{dV}_{r^2 dr\, d\Omega}} = \left.\frac{dN}{dE}\right|_{\text{source}} \left(\frac{\overset{\text{surface of the experiment}}{A}}{4\pi r^2}\right) \begin{cases} \langle \sigma v \rangle \dfrac{n_\chi^2}{2} & \text{, annihilations,} \\ \dfrac{n_\chi}{\tau_\chi} & \text{, decays.} \end{cases}$$

$$\frac{dN}{dE\,dt\,d\Omega} = \left.\frac{dN}{dE}\right|_s \frac{A}{4\pi} \begin{cases} \dfrac{\langle\sigma v\rangle}{2m^2} \displaystyle\int_0^\infty \rho^2 dr \\ \dfrac{1}{m} \displaystyle\int_0^\infty \rho\, dr \end{cases}$$

- Again, we use $n_X = \frac{\rho(\vec{r})}{m_X}$ and get:

the annihilation J-factor

$$\langle\sigma v\rangle \int \frac{n_X^2}{2} \cong \frac{\langle\sigma v\rangle}{2m_X^2} \int_0^\infty \int \rho^2(r)\, dr\, d\Omega = \frac{\langle\sigma v\rangle}{2m_X^2} \cdot 8\pi J_{ann}$$

$$\int \frac{n_X}{\tau_X} \cong \frac{1}{m_X \tau_X} \underbrace{\int_0^\infty \int \rho(r)\, dr\, d\Omega}_{\sim \frac{1}{R^2} \int \rho\, dV \sim \frac{M}{R^2}} \simeq \frac{M}{m_X \tau_X R^2}.$$

integrate over the line of sight and the size of the source

## ANNIHILATIONS

$$\frac{1}{A} \frac{dN}{dE dt} = \frac{\langle\sigma v\rangle}{m_X^2} \left(\frac{dN}{dE}\right)_s J_{ann},$$

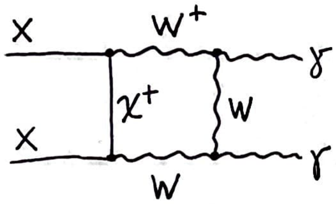
$\boxed{\text{ANNIHILATION}}$

- The J-factors can be obtained from $\rho$ profiles, e.g. the NFW $\rho = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$, which can be evaluated for MW ($1°$ center) and for the DwSph.

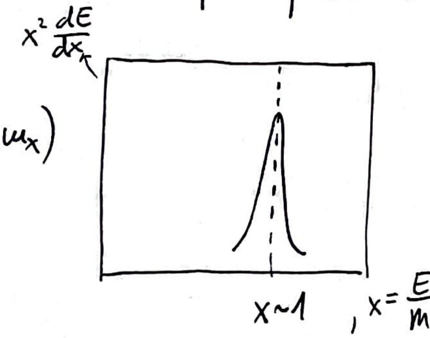
$$J_{ann} = \begin{cases} 10^{17-20} \frac{GeV^2}{cm^5}, & \text{DwSph}, \\ 10^{22} \frac{GeV^2}{cm^5}, & \text{MW}. \end{cases}$$

The $\rho^2$ dependence gives sensitivity to overdensities and varies across profiles and may lead to enhancements.

- The energy spectrum depends on the microscopic picture

e.g.: 


$$\left.\frac{dN}{dE}\right|_{\text{Source}} = 2\,\delta(E-m_x)$$




## DECAYS

- In this case, the line of sight integral (the J-factor) is very simple, because $R \gg$ size of the source


$$\frac{d\rho}{dr} \simeq \frac{M}{V}\,\delta(\rho - R),$$

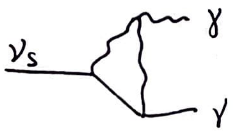
- all the mass is concentrated at one point @ $r = R$.

$$\int \rho \, dr \, d\Omega \sim \frac{1}{R^2} \int \rho \, dV = \frac{M}{R^2}.$$

- Then the rate distribution becomes:

$$\frac{1}{A}\frac{dN}{dE\,dt} = \frac{1}{4\pi}\frac{1}{m_x \tau_x}\left(\frac{dN}{dE}\right)_{\text{Source}} \frac{M}{R^2}, \qquad \boxed{\text{DECAYS}}$$

For two body decays, the source E distribution is particularly simple (e.g. for $\nu_s \to \nu \gamma$)

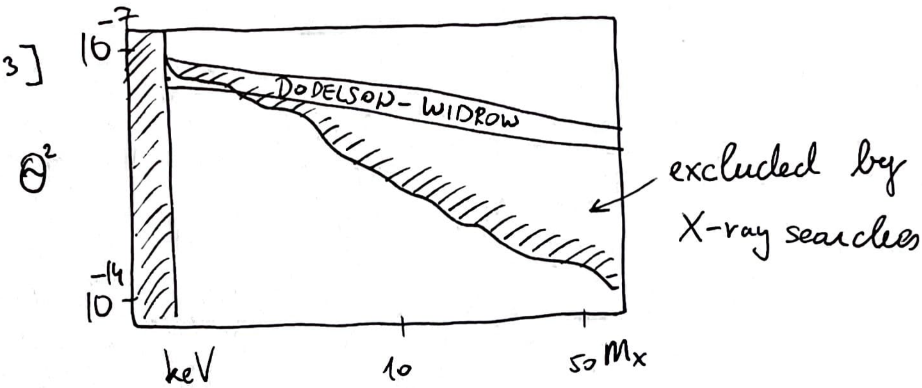



$$: \frac{dN}{dE} \simeq \delta\left(E - \frac{m_x}{2}\right),$$

# EXPERIMENTAL SEARCHES / CONSTRAINTS

- **DECAYS**, X-ray searches for mono-chromatic photon lines, ranging from keV → MeV

[2102.10183]

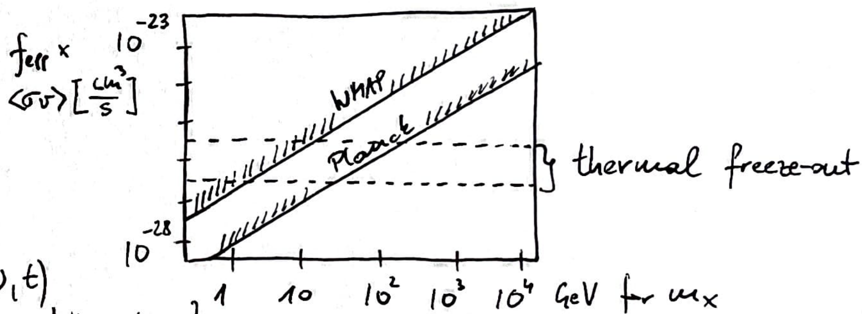



- **ANNIHILATIONS**: The limit on $\langle\sigma v\rangle$ depends on the final state (electron, protons, $\gamma$'s, $\nu$'s, ...)

a) Early universe

bound from CMB, recombination

$f_{eff} = \{0.4, 0.2, 0\}$ for $\{(e, W, t), \text{therm}, 0\}$




b) AMS'02 satellite

- more stringent for $e^+e^-$ $m_X \in [10-100]$ GeV

c) FERMI Satellite

$\langle\sigma v\rangle_{XX\to\gamma\gamma} \leq 10^{-28}\,\frac{cm^3}{s}$ @ $m_X = 10$ GeV, but typically loop suppressed by $\frac{\alpha^2}{4\pi}$ or more.