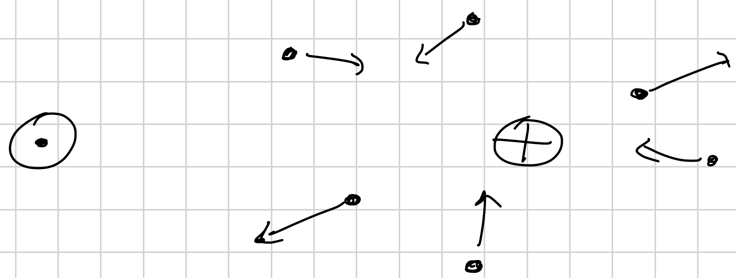
WIMP dark matter searches: Direct detection

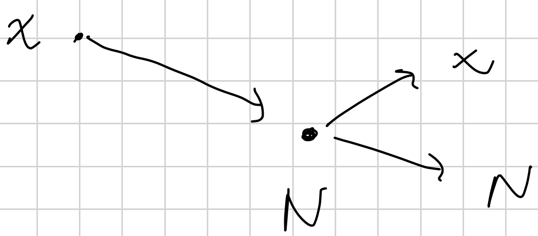
DM produced via freeze-out: it has to be in thermal eq with the SM $\Rightarrow$ there must be sizeable interactions. Can we test them?

Direct detection

Idea: Earth is constantly hitted by DM particles



Some of them (depending on the cross section) will scatter against some particle (nuclei) of the stuff Earth is made of. If we take a "target" and we equip it to see any recoil of the nuclei it is made of, we can hope to detect these scattering processes and measure the cross section.

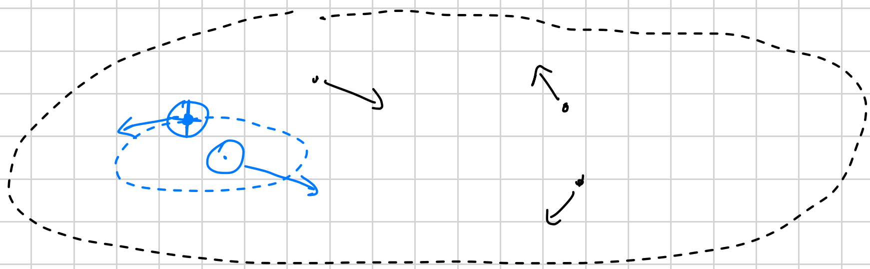


elastic scattering.

Typical numbers: $\rho_{DM} \sim 0.3\ \mathrm{GeV\ cm^{-3}}$ $\quad v \sim 220\ \mathrm{km\ s^{-1}}$

$v/c \sim 10^{-3}$

Earth is moving $\left(v_\oplus \simeq 30\ \mathrm{km\ s^{-1}} \sim \frac{v_\chi}{10} \right)$



The Sun moves in the galaxy, Earth moves around the Sun

$\Rightarrow$ Expect annual modulation of the incoming flux (and hence of the signal)

Estimate the flux

$$n_\chi = \frac{\rho_\chi^{local}}{m_\chi}$$

ρ_χ^{local} fixed $\Rightarrow$ n_χ decreases for larger m_χ

heavier χ harder to detect (there are fewer around)

Typical flux: $\quad \phi_\chi = n_\chi v_\chi = \frac{\rho_\chi^{local}}{m_\chi} v_\chi$

for $m_\chi = 100$ GeV:

$$\phi_\chi = \frac{0.3\ \mathrm{GeV\ cm^{-3}} \quad 220\ \mathrm{km\ s^{-1}}}{100\ \mathrm{GeV}} \approx 10^5\ \mathrm{cm^{-2}\ s^{-1}}$$

For comparison: the flux of solar neutrinos is $\sim 10^{11}\ \mathrm{cm^{-2}\ s^{-1}}$

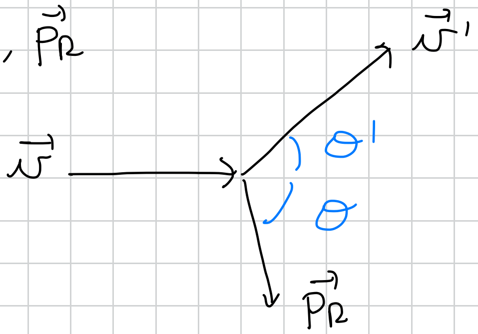
Background: - cosmic rays (and their secondary products)
- natural radioactivity
- ν's

Setup: specify the target (mass and spin of the nucleus) and the detection method (electrons emitted from ionization, heat and phonons from vibrations ($\to$ temperature increase), light emitted by scintillating cristals ...)

Kinematics

$$\chi \, N \to \chi \, N$$

In the plane of $\vec{v}'$, $\vec{p}_R$



$$\begin{cases} \frac{1}{2} m_\chi v^2 = \frac{1}{2} m_\chi v'^2 + \frac{1}{2} m_N v_R^2 \\ m_\chi \vec{v} = m_\chi \vec{v}' + m_N \vec{v}_R \end{cases} \Rightarrow \begin{cases} v'^2 = v^2 - \frac{m_N}{m_\chi} v_R^2 & (1) \\ \vec{v}' = \vec{v} - \frac{m_N}{m_\chi} \vec{v}_R & (2) \end{cases}$$

$$(2) \Rightarrow \quad v'^2 = v^2 + \left(\frac{m_N}{m_R}\right)^2 v_R^2 - 2 v v_R \frac{m_N}{m_\chi} \cos\theta \qquad (3)$$

$$(1),(3) \Rightarrow \quad \cancel{v^2} - \cancel{\frac{m_N}{m_\chi}} \cancel{v_R^2} = \cancel{v^2} + \left(\frac{m_N}{m_\chi}\right)^{\cancel{2}} \cancel{v_R^2} - 2 v \cancel{v_R} \cancel{\frac{m_N}{m_\chi}} \cos\theta$$

$$v_R \left(\frac{m_N}{m_\chi} + 1\right) = 2 v \cos\theta$$

$$\Rightarrow \quad v_R = 2 \frac{m_\chi}{m_N + m_\chi} v \cos\theta$$

$$\Rightarrow \quad E_R = \frac{1}{2} m_N v_R^2 = 2 \frac{\mu^2}{m_N} v^2 \cos\theta$$

where $\quad \mu = \dfrac{m_\chi m_N}{m_\chi + m_N}$

Energy thresholds

Maximal velocity: $E_{max} = 2 \frac{\mu^2}{m_N} v^2$

This needs to impose some detector thresholds:

$$E_{max} > E_{th} \Rightarrow v > v_{th} = \sqrt{\frac{m_N E_{th}}{2\mu^2}}$$

$$\mu \approx \begin{cases} m_N & m_\chi \gg m_N \\ m_\chi & m_\chi \ll m_N \end{cases}$$

$$\Rightarrow v_{th} = \begin{cases} \frac{E_{th}}{2m_N} & m_\chi \gg m_N \\ \frac{m_N E_{th}}{2m_\chi^2} & m_\chi \ll m_N \end{cases}$$

$\Rightarrow$ detection becomes problematic for $m_\chi \ll m_N$

Typical recoil energy: $m_\chi \sim 100\,\text{GeV}$, $m_N \sim 100\,\text{GeV}$ (Xenon atoms) ^{54}Xe

$v \sim 10^{-3}$

$$E_{max} \sim \frac{2\,(100\,\text{GeV})^2\, 10^{-6}}{100\,\text{GeV}} \approx 200\,\text{keV}$$

Minimal recoil energy in an experiment: $\sim \mathcal{O}(\text{keV})$

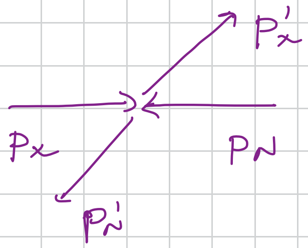
$\rightsquigarrow$ corresponds to mass $\quad (m_\chi \ll m_N \Rightarrow \mu \approx m_\chi)$

$$m_\chi \approx \left(\frac{m_N E_{th}}{v^2}\right)^{1/2} \approx \frac{(100\,\text{GeV}\; 1\,\text{keV})^{1/2}}{10^{-3}} \approx 10\,\text{GeV}$$

Center of mass kinematics

You can work out the kinematics and get $E_R = \frac{\mu^2 v_{rel}^2}{m_N}(1-\cos\theta_x)$

Solution:



$$p_x' = p_N' \qquad p_N = p_x$$

$$\frac{p_N^2}{2m_N} + \frac{p_x^2}{2m_x} = \frac{p_N'^2}{2m_N} + \frac{p_x'^2}{2m_x} \qquad \Rightarrow p_x = p_N = p_x' = p_N'$$

$$p_N = m_N v_N = m_x v_x \quad \Rightarrow \quad v_{rel} = v_x + v_N = p_N\left(\frac{1}{m_N} + \frac{1}{m_x}\right) = \frac{p_N}{\mu}$$

$$\Rightarrow p = \mu v_{rel}$$

define $\vec{q} = \vec{p}' - \vec{p} \quad \Rightarrow \quad q^2 = 2\mu^2 v_{rel}^2 (1+\cos\theta_x)$

q^2 is a Lorentz invariant! $\quad Q = P_x' - P_x \Rightarrow Q^2 = -q^2$

$$P_x = \begin{pmatrix} E_p \\ \vec{p} \end{pmatrix} \qquad P_x' = \begin{pmatrix} E_p' \\ \vec{p}' \end{pmatrix} = \begin{pmatrix} E_p \\ \vec{p}' \end{pmatrix} \qquad Q = \begin{pmatrix} 0 \\ \vec{p}' - \vec{p} \end{pmatrix}$$

In the lab frame instead:

$$P_x' - P_x = P_N - P_N' = \begin{pmatrix} m_N \\ \vec{0} \end{pmatrix} - \begin{pmatrix} \sqrt{m_N^2 + p_R^2} \\ \vec{p}_R \end{pmatrix}$$

$$\Rightarrow Q^2 = \left(\sqrt{m_N^2 + p_R^2} - m_N\right)^2 - p_R^2 = m_N^2 + p_R^2 - p_R^2 + m_N^2 - 2m_N\sqrt{m_N^2 + p_R^2}$$

$$= 2m_N^2 - 2m_N^2\left(1 + \frac{1}{2}\frac{p_R^2}{m_N^2}\right) = -p_R^2$$

$$\Rightarrow |\vec{p}_R| = |\vec{q}| \quad \text{and} \quad E_R = \frac{q^2}{2m_N} = \frac{\mu^2 v_{rel}^2}{m_N}(1-\cos\theta_x)$$

$$\Rightarrow \frac{d}{dE_R} = \frac{m_N}{\mu^2 v_{rel}^2} \frac{d}{d\cos\theta_*}$$

Scattering rate

Event rate: $\Gamma \equiv \frac{dN_T}{dV\,dt} \equiv n_\chi n_N v \sigma$ → in general, v_{rel}, but we can write it as v_{rel} because the two are equal in frames in which $v_\chi \parallel v_N$

Γ is Lorentz invariant

Differential rate:

$$\frac{d^2\Gamma}{dE_R\,d\varphi} = \frac{m_N}{\mu^2 v_{rel}^2}\frac{d^2\Gamma}{d\varphi\,d\cos\theta_*} = \frac{m_N}{\mu^2 v_{rel}^2} n_N n_\chi v_{rel} \underbrace{\frac{d^2\sigma}{d\varphi\,d\cos\theta_*}}_{\frac{d\sigma}{d\Omega_*} \text{ or } \sigma(\varphi,\theta_*)}$$

For NR relativistic scattering

$$\frac{d\sigma}{d\Omega_*} = \frac{1}{(m_\chi + m_N)^2}\frac{|\mathcal{M}|^2}{64\pi^2}$$

$\mathcal{M}$ depends on how does DM interact with the nucleus.

NB: here we fixed a velocity, but DM actually has a distribution. On Earth, this is not the simple maxwellian distribution, because 1) I have to boost it to the Earth frame ($\oplus$ is moving around $\odot$ which moves around the galaxy) and 2) there is an escape velocity.

$$\int_0^{v_{esc}} f_\chi(v_{rel})\,dv_{rel} = 1$$

and

$$\frac{d\Gamma}{dE_R\,d\varphi} = \frac{n_N n_T n_\chi}{\mu^2 v_{rel}} \frac{d\sigma}{d\Omega_*\,dv}\,dv$$

$n_\chi \to \frac{\rho_\chi}{m_\chi}$ and $\rho_\chi = 0.3$ GeV cm^{-3} is purely astro

Non-relativistic operators

How does DM interact w/ nuclei?

Two observations:

1) $q \sim \mu v_{rel} \sim 10^{-3} \dfrac{m_N m_\chi}{m_N + m_\chi} \sim 10^{-3}\, 100\,\text{GeV} \sim 100\,\text{MeV}$

$\Delta x \sim 10^{-2}\,\text{MeV}^{-1}$ where $\hbar = 1 = 197.3\,\text{MeV fm}$

$\sim 2\,\text{fm} \gtrsim$ proton size

$\Rightarrow \chi$ doesn't see quarks and gluons, it sees protons and neutrons!

2) $v \ll 1$ thus the scattering is non relativistic $\Rightarrow$ use the tools of non relativistic QM rather than QFT.

Procedure:

1) consider an operator mediating the χ - quarks (gluon) interaction, eg

$$\mathcal{O}_5^q = \bar{\chi} \gamma^\mu \chi \; \bar{q} \gamma_\mu q$$
$$\mathcal{O}_8^q = \bar{\chi} \gamma^\mu \gamma_5 \chi \; \bar{q} \gamma_\mu \gamma_5 \chi$$

2) Derive what operators does this induce at the nucleon level

$$\mathcal{O}_5^q \longrightarrow \mathcal{O}_5^N = \bar{\chi} \gamma_\mu \chi \, \bar{N} \gamma^\mu N$$

(with an appropriate coefficients)

$$\mathcal{O}_8^q \longrightarrow \mathcal{O}_8^N = \bar{\chi} \gamma^\mu \gamma_5 \chi \, \bar{N} \gamma_\mu \gamma_5 N$$

3) Consider the non-relativistic limit. Limits of fermion bilinears are of the form

$$u^s(p) = \begin{pmatrix} \sqrt{p^\mu \sigma_\mu}\ \xi^s \\ \sqrt{p^\mu \bar\sigma_\mu}\ \xi^s \end{pmatrix} \approx \frac{1}{\sqrt{4m}} \begin{pmatrix} (2m - \vec{p}\cdot\vec{\sigma})\,\xi^s \\ (2m + \vec{p}\cdot\vec{\sigma})\,\xi^s \end{pmatrix}$$

$$\bar u(p')\gamma^\mu u(p) \approx \begin{pmatrix} 2m \\ \vec{P} + 2i\,\vec{q}\times\vec{s} \end{pmatrix}$$

$$\bar u(p')\gamma^\mu \gamma_5\, u(p) \approx \begin{pmatrix} 2\vec{P}\cdot\vec{s} \\ 4m\vec{s} \end{pmatrix}$$

$$\vec{P} = \vec{p} + \vec{p}\,' \qquad \vec{q} = \vec{p} - \vec{p}\,' \qquad \vec{s} = \xi'\,\frac{\vec{\sigma}}{2}\,\xi$$

We obtain

$$O_5^N \longrightarrow O_1^{NR} = \mathbb{1} \qquad \text{"SI: spin-independent"}$$

$$O_8^N \longrightarrow O_4^{NR} = \vec{s}_\chi \cdot \vec{s}_N \qquad \text{"SD: spin-dependent"}$$

Where the non rel operators are "used" with non-rel fields containing only creation or annihilation ops

$$\mathcal{L}_{int} = \sum_{N=n,p} \sum_i c_i^N\, O_i\, \chi^+ \chi^- N^+ N^-$$

$$N^-(x) = \int \frac{d^3k}{(2\pi)^3} \frac{1}{\sqrt{2m_N}}\, e^{-ik\cdot y}\, a_k^+ \qquad N^+(x) = \left(N^-(x)\right)^+$$

4) Compute the χ-nucleus cross section. SI scattering wins a factor $A^2 \sim O(10^4)$ because the matrix elements with individual nuclei add opp coherently.

Example : SI

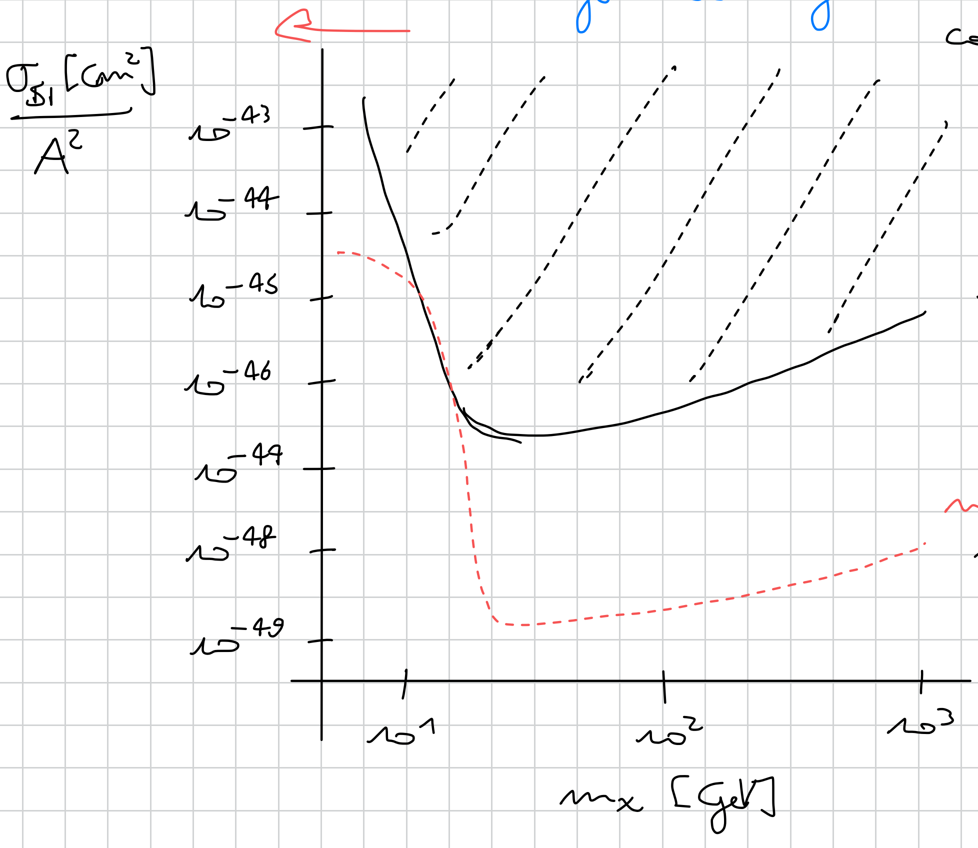
$$\mathcal{M}^{SI}_{\chi N} = F(E_R)\left[Z f_p + (A-Z) f_n\right]$$

"nucleon form factor" obtains from matching the quark operator onto the nucleus

$$\frac{d\sigma}{d\Omega_*} = \frac{\sigma}{4\pi} = \frac{\sigma(E_R=0)}{4\pi} F(E_R)^2$$

$$\frac{d\Gamma}{dE_R} = \underbrace{(N_N m_N)}_{\text{target}} \underbrace{\left(\frac{\sigma^{SI}_{\chi N}(E_R=0)}{\mu^2 m_\chi}\right)}_{\text{microscopic DM model}} \underbrace{F(E_R)^2}_{\text{nuclear physics: from } q,\, g \text{ to nucleons}} \underbrace{\left(\rho_\chi \int_{v_{min}(E_R)}^{v_{esc}} \frac{f_\chi(v_{rel})}{2 v_{rel}}\, dv_{rel}\right)}_{\text{astrophysics}}$$

how to go below GeV? scattering off electrons, collective scatterings.



Xenon 1T
(1t of Xenon × 1 yr)

neutrino floor : at this sensitivity the experiment starts to see νs from the sun (very rare at these energies)

→ a nightmare background

need directional detection?

Low mass limit: - below ~ 10 GeV $\Rightarrow$ scattering w/ electrons

- below ~ MeV: $q \sim$ keV $\Rightarrow \Delta\lambda \sim$ Å

$\Rightarrow$ DM interacts with many nuclei at the same time, Excites collective modes of the target

3. Indirect detection

General idea

Thermal DM production $\Rightarrow$ DM particles can annihilate into pairs of SM ones.

Thermal freeze-out benchmark: $\langle \sigma v_{rel} \rangle \simeq 3 \times 10^{-26}\ cm^3 s^{-1}$

Is this a big number? Number of annihilations in our solar system, since when the galaxy exists:

$$N^{local}_{ann} \sim (n_\chi^{loc})^2 \langle \sigma v \rangle V \tau \sim \left(\frac{\rho_\chi^{loc}}{m_\chi}\right)^2 \langle \sigma v \rangle R^3_{sol\,sys}\, \tau$$

$$\sim \left(\frac{0.3\ GeV\ cm^{-3}}{100\,GeV}\right)^2 3 \times 10^{-26}\ cm^3 s^{-1} \ (10^5\,AU)^3 \left(5 \times 10^9\ yr\right)$$

$$\sim 10^{41}$$

We need to point our telescope at regions with high DM density

- galactic centre: large ρ, but large / complicated bkg from stellar processes
- dwarf-galaxies: most precise signal because DM-dominated

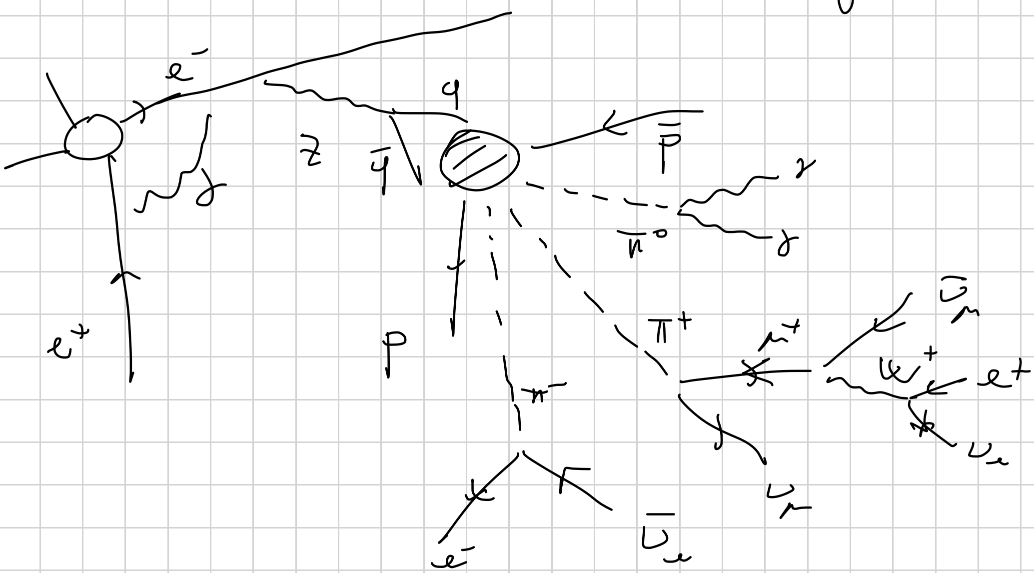
Final states

main channel : pair annihilation

$$\chi\chi \to q\bar{q},\ e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ \nu\nu,\ \gamma\gamma,\ W^+W^-,\ ZZ,\ Zh,\ hh$$

- quarks hadronize $\to p, n, \pi$'s, ...
- unstable particles decay
- EW corrections are important: emission of a soft/collinear W boson is enhanced by $\log \frac{m_\chi}{m_W}$, $\log\log \frac{m_\chi}{m_W}$ and can alter the spectrum.

⇒ the emitted W/Z induces production of other particles



Propagation

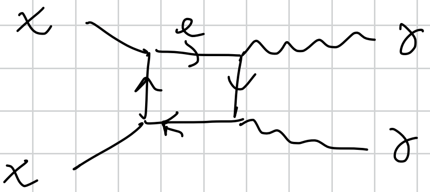
neutral stuff (γ and ν) : travel undisturbed on a straight line

charged stuff ($e^\pm$, $p^\pm$) : scattered and bended by galactic fields in the galaxy : need some propagation model (w/ uncertainties)

ID w/ photons

Two channels:

$\chi\chi \to \gamma\gamma$ eg via a box diagram

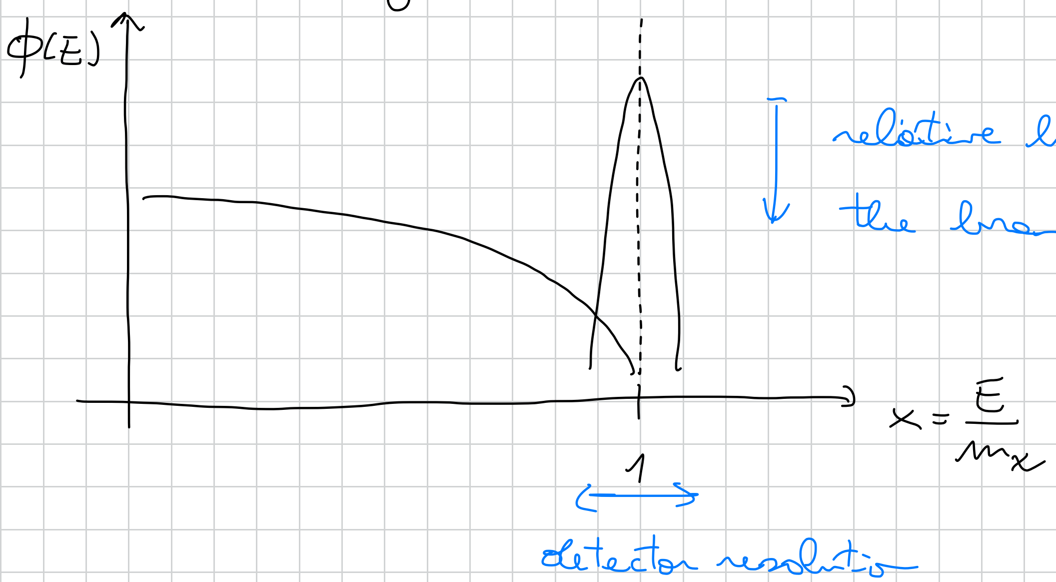


$$s = (p_1 + p_2)^2 \approx 4 m_\chi^2 \qquad (v \ll 1)$$

$\Rightarrow E_\gamma = m_\chi \quad \Rightarrow$ X-ray line

Final state radiation / decay : continuous spectrum

We expect something like

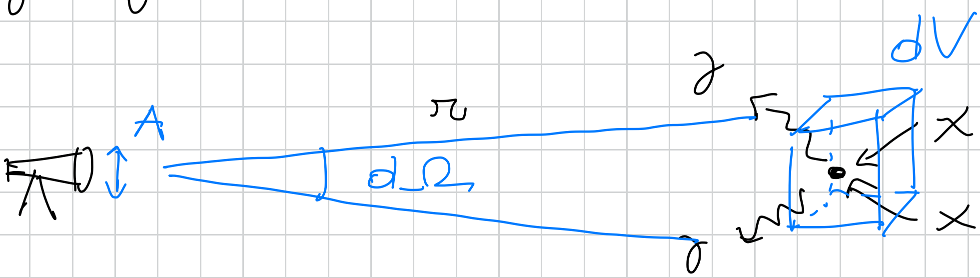


relative height depends on the branching fraction

$\chi\chi \to W^+W^-$ is the same as $e^+e^- \to W^+W^-$, as long as FSR is corrected. $\Rightarrow$ we can use all the machinery developed for collider experiments (hadronization, radiative corrections, etc)

Photon flux

Consider photons produced at one particular location in the galaxy



$$\frac{dN_\gamma}{dE\, dV} = \frac{1}{4\pi r^2} \; \frac{dn_\gamma(m_\chi)}{dE_\gamma} \; \frac{1}{2} n_\chi^2 \langle \sigma v \rangle \quad A\, \Delta t$$

spectrum of produced photons

avoid double counting in the number of distinct DM pairs

Integrate over the volume w/ $dV = r^2\, dr\, d\Omega$

$$\frac{dN_\gamma}{dE_\gamma\, d\Omega} = \underbrace{(A\,\Delta t)}_{\text{detector}} \underbrace{\left(\frac{\langle \sigma v_{rel} \rangle}{m_\chi^2}\right)}_{\text{particle physics}} \underbrace{\left(\frac{dn_\gamma(m_\chi)}{dE_\gamma}\right)}_{\text{SM}} \underbrace{\left(\frac{1}{8\pi}\int \rho_\chi^2 \, dr\right)}_{\text{astrophysics}}$$

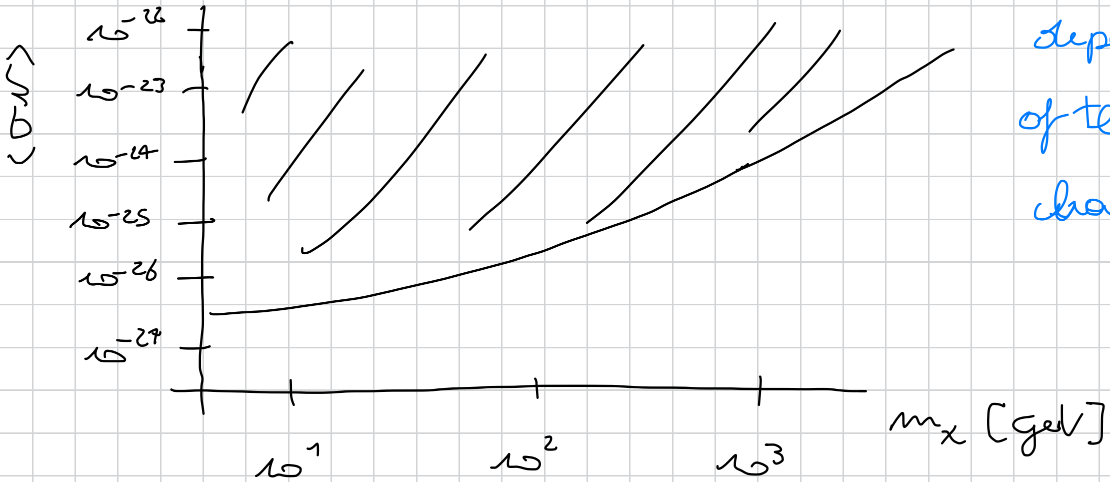
$\equiv J$ "J-factor"

Main uncertainty : J-factor (up to 2 orders of magnitude)

We do not know whether the distribution is peaked or cored

Results

Typical bound looks like



depends on the assumption of the dominant annihilation channel

Decaying DM

$\chi \to$ SM stuff w/ $\tau_\chi > \tau_U$

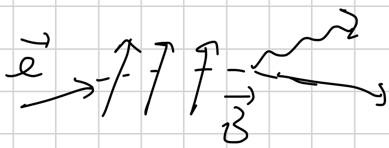
Same as above, w/ $m_\chi^2 \langle\sigma v\rangle$ replaced by $m_\chi \Gamma_\chi$ w/ $\Gamma_\chi = \tau_\chi^{-1}$

$$\Rightarrow \quad J_{decay} = \frac{1}{8\pi}\int dl\, \rho_\chi \quad \Rightarrow \text{less uncertainty}$$

Other photon sources (DM related)

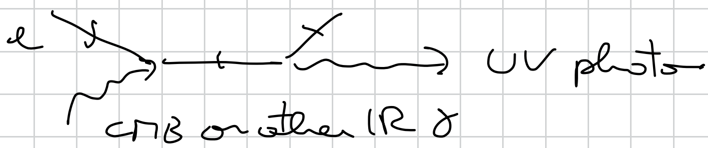
- synchrotron emission in the galactic magnetic field $\vec{B}$

$\chi\chi \to e^+e^-$ +



- Inverse Compton scattering

$\chi\chi \to e^+e^-$ +



Again, for $v \to 0$, Sommerfeld enhancement & bound state formation can be very important

Ambient excesses [2109.02696]

Background estimation + statistics is a nasty business

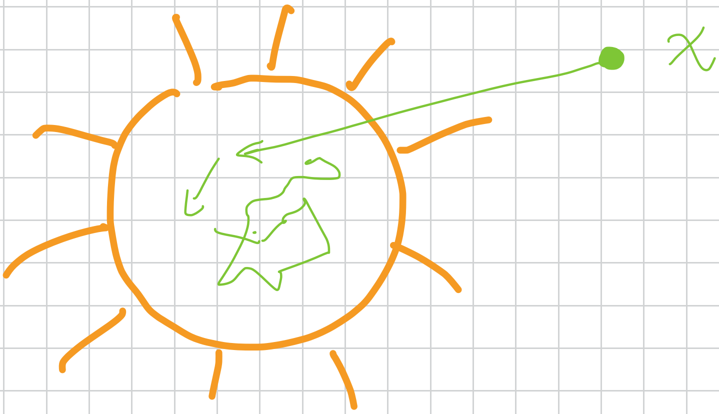
If any signal is seen, 2 questions:

1) is it really there? Or is it just some statistical fluctuation? Or maybe there is just no excess?

2) if an excess is found, is it due to DM? Or do I need to remodel my bkg?

- cosmic rays positrons, antiprotons, at high energy
- anti-^4He
- 3.5 keV line in galaxy clusters (decay of 7 keV sterile neutrinos)
- 21 cm absorption
- 1–3 GeV γ-ray excess around the galactic centre,

Neutrinos from the Sun



Scatterings slow down χ that is trapped in the Sun

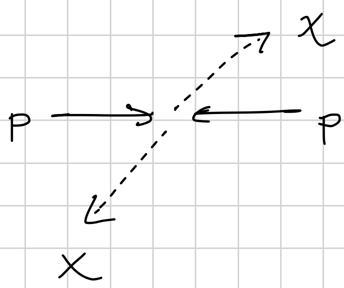
$$\Gamma_{ann} = \Gamma_{capture} \propto \langle \sigma v \rangle \big|_{scattering}$$

$$\chi\chi \to \nu\bar{\nu}$$

put bounds on $\sigma v|_{scatt}$ (strong also for SD)

Collider searches

Produce DM at colliders. χ leave the detector without being detected



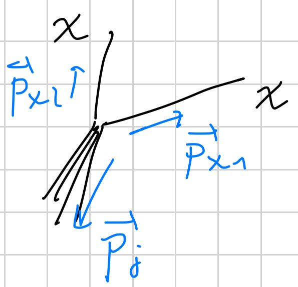
Such a event is useless because I cannot detect it. Need to have some recoiling SM particle.

Eg $\quad q\bar{q} \to \chi\chi g \rightsquigarrow$ mono-jet + missing energy

in general "mono-X + MET" searches

$(X = \text{jet}, \gamma, Z, h, \ldots)$

MET = missing $E_T = -\sum \vec{p}_T$ momentum in the transverse plane is imbalanced

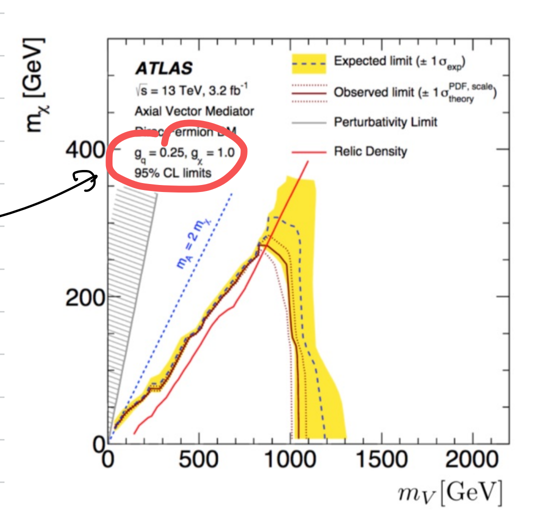


$\vec{p}_j + \vec{p}_{\chi 1} + \vec{p}_{\chi 2} = 0$ but I don't see $\vec{p}_{\chi 1,2}$

At a proton collider the longitudinal momentum is not 0

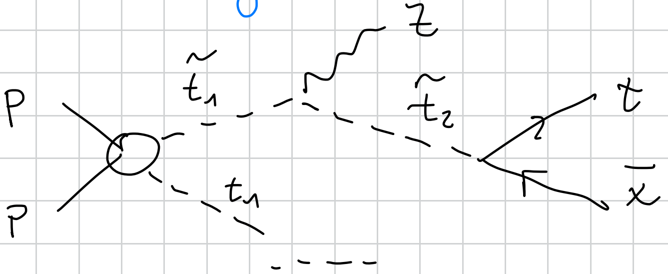
Typical result:

couplings are fixed



Other search channels:

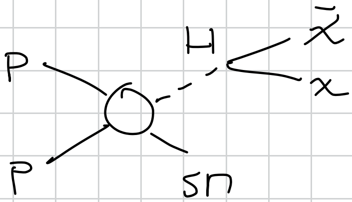
- cascade decays



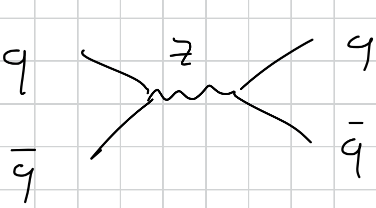
t quark is the least constrained

top partners such as $\tilde{t}$ are well motivated (SUSY) and less constrained

- $H \to$ invisible



- Mediator searches (this is what LHC does best)



dijet channel

$m_{Z'} \gtrsim 2 - 2.5 \text{ TeV}$ for $g \simeq 0.1$

Early Universe bounds

DM annihilation can be dangerous if they deposit too much energy into the plasma around the time of nucleosynthesis or CMB.

Energy injected in the plasma after freeze-out:

$$\frac{dE}{dV\,dt} = m_x\, n_x^2 \langle \sigma v \rangle \qquad\qquad n_x = \left(\frac{a_f}{a}\right)^3 n_x^f = \left(\frac{T}{T_f}\right)^3 n_x^f$$

$$= m_x\, n_x \left(\frac{T}{T_f}\right)^3 n_x^f \langle \sigma v \rangle$$

$$= m_x\, n_x \left(\frac{T}{T_f}\right)^3 H_f$$

$$= \rho_x \left(\frac{T}{T_f}\right)^3 H_f$$

In one Hubble time, for each baryon I inject an energy

$$\frac{E}{N_b} = \left(\rho_x \left(\frac{T}{T_f}\right)^3 H_f\right) \frac{a^3}{n_b a^3} H^{-1} \qquad\qquad H \propto T^{-2}$$

$$= \frac{\rho_x}{\rho_b / 1\,\text{GeV}} \left(\frac{T}{T_f}\right) \qquad m_x \approx 100\ \text{GeV} \quad x_f \approx 25 \quad T_f \approx 4\ \text{GeV}$$

$$\approx 5\ \text{GeV}\ \frac{T}{4\ \text{GeV}} \approx T$$

BBN: $T \sim \text{MeV} \Rightarrow \frac{E}{N_b} \approx \text{MeV} \approx$ binding energy of nuclei
$\Rightarrow$ dangerous!

CMB: $T \sim \text{eV} \Rightarrow \frac{E}{N_b} \approx \text{eV} \lesssim$ binding energy of H atom
$\Rightarrow$ dangerous

For the actual bound I have to go back to the expression for the energy deposit and evolve it in time over the duration of BBN or CMB:

$$\frac{dE}{dV\,dt} = m_\chi \, n_\chi^2 \langle \sigma v \rangle = \frac{\rho_\chi^2}{m_\chi} \langle \sigma v \rangle = (1+z)^6 \, \rho_{\chi,0}^2 \, \frac{\langle \sigma v \rangle}{m_\chi}$$

Strongest bound from CMB: $\langle \sigma v \rangle < 3 \times 10^{-27} \frac{cm^3}{s} \left(\frac{m_\chi}{1\,GeV} \right)$

$\Rightarrow$ $m_\chi \gtrsim 10\,GeV$ for thermal fo production (unless the dominant channel is into neutrinos, that decouple around BBN (way before CMB))