Break it: Annihilating & Decaying Dark Matter

Dark matter needs to be stable in order to survive to today, but is it absolutely stable?

A la Tien-Tien, WIMPs will have $\langle\sigma v\rangle_{ann.} \sim 10^{-26}\,cm^3/s$ (s-wave)

rate of annihilations per unit volume will be $\sim \langle\sigma v\rangle n_x^2$

$\therefore$ for fixed mass-density $\rho_x = m_x n_x$, rate $\sim 1/m_x^2$ (power $\sim 1/m_x$)

$\Rightarrow$ weaker effect at higher masses

Let's plug in some #s: ρ_x nearby is $\sim 0.01\, M_\odot/pc$

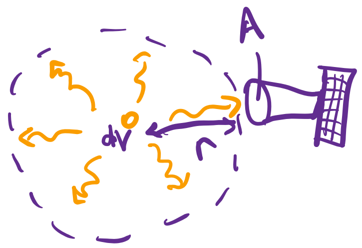
TeV-scale WIMP $n_x \sim 1000/m^3 \Rightarrow \langle\sigma v\rangle n_x^2 \sim 10^{-27}/m^3 s$

over age of universe, $\tau\langle\sigma v\rangle n_x^2 \sim 10^{-9}/m^3$ (one in a trillion WIMPs annihilate!)

Ok, so no way we'd notice gravitationally, what about detecting annihilation end products w/ spectrum $\left(\frac{dN}{dE}\right)_0$? Yes!

(I'll focus on photons)

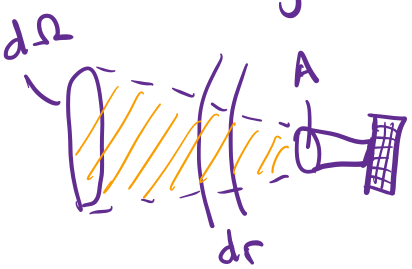
Let's assume we have a telescope w/ area A.



$$\left(\frac{dN}{dE\,dV\,dt}\right)_{obs} = \left(\frac{dN}{dE}\right)_0 \times \frac{A}{4\pi r^2} \times n_x^2(r)\langle\sigma v\rangle$$

$\left(\frac{dN}{dE}\right)_0$: intrinsic spectrum; $\frac{A}{4\pi r^2}$: fraction of products entering telescope; $n_x^2(r)\langle\sigma v\rangle$: annihilation rate per DM volume

now let's imagine we want to consider all decays along line of sight in a particular direction $dV = dr\, d\Omega$



integrate over r:

$$\left(\frac{dN}{dE\,d\Omega\,dt}\right)_{obs} = \left(\frac{dN}{dE}\right)_0 \times \frac{A\langle\sigma v\rangle}{4\pi m_x^2} \int \cancel{r^2}\,dr\, \frac{\rho_x^2(r)}{\cancel{r^2}}$$

if the dark matter is localized (e.g. to a dwarf galaxy) it makes sense to integrate over solid angle of source

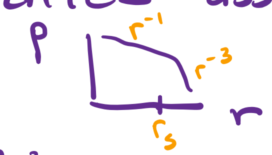
$$\frac{1}{A}\left(\frac{dN}{dE\,dt}\right)_{obs} = \left(\frac{dN}{dE_0}\right) \times \frac{\langle \sigma v \rangle}{m_\chi^2} \times \int \rho_\chi^2(r)\, dr \frac{d\Omega}{4\pi}$$

stuff happening at telescope — particle physics — astrophysics of DM density (related to "J-factor" up to factors of 2)

The spectrum depends on the SM state produced and how that state subsequently decays or interacts e.g. $\chi\chi \to b\bar{b}$ vs. $\chi\chi \to \mu^+\mu^-$ look different

prompt radiation can be computed w/ event generators such as PYTHIA. Then the spectrum dictates what telescope you want to use <slides of telescope options>

The J-factor is helpful in deciding the "best" targets as determined by stellar kinematics assuming a density smooth density profile e.g. NFW



e.g. dwarf galaxies have $J \sim 10^{17-20}\ \mathrm{GeV^2/cm^5}$

MW galactic centre (within 1°) have $J \sim 10^{22}\ \mathrm{GeV^2/cm^5}$

you'd therefore expect the MW galactic centre to be great for searches... however, lots of astrophysical "background" in that region. Currently there is an excess of GeV-scale gamma rays observed in the GC spectrum & morphology are consistent w/ DM annihilation but also pulsars... currently a hot topic of debate!

Some other caveats:

↳ the prompt spectrum isn't necessarily what is observed due to:
- redshifting (for extragalactic sources)
- attenuation/scattering (extragalactic $e^{-\tau(E,z)}$ in J)
- $e^{\pm}$ produced make extra photons due to inverse compton & synchrotron (usually radio freq.)

this can be accounted for with e.g. PPPC4DMID "poor particle physicicists cookbook for DM indirect detection"

↳ $\langle \rho \rangle^2 \neq \langle \rho^2 \rangle$ in general, so substructure can possibly really enhance J. This "boost factor" is hard to determine accurately, need really good simulations...

With all this, we can see how well we can constrain DM annihilation <break for slides>

We can basically repeat a lot of the above for DM decay, which is interesting for candidates like e.g. sterile neutrinos

what changes in above?

↳ rate per volume is $\frac{n_\chi}{\tau}$ instead of $n_\chi^2 \langle \sigma v \rangle$ so we end up using "D-factor" $D \sim \int \rho(r)\, dr\, d\Omega$ ← not sensitive to substructure

which can affect which systems are optimal

e.g. "blank sky" D-factor is the same as Perseus galaxy cluster where 3.5 keV line was thought to be a DM signal from ν_s

Instead of looking "directly" for annihilation/decay products in our telescopes ("direct indirect detection"), we can look for the influence in other environments ("indirect indirect detection") notably the neutral intergalactic medium between recombination & reionization

Q: how much dark matter would have to annihilate/decay in order to ionize the whole universe?

$\Omega_{DM} \sim 5\,\Omega_b$ so for every ~GeV mass atom there is 5 GeV worth of energy stored in DM mass but it only takes ~ 10 eV to ionize $\Rightarrow \frac{10\text{ eV}}{5\text{ GeV}} \sim 10^{-9}$

∴ if one in a billion DM particles annihilates/decays we reionize the whole universe (crazy!)