LEcTUrE # 4

(1) ν-Telescopes

SPECIFICS OF 3 INdIR. DET. METHOdS: (2) γ-RAYS

(3) CR AntIMAtTER

(1): ν's: Point-sOurce DETeCTION HARD
    (IN FACT ONLY 2 ν ASTRo SOURCeS OBSERVED)
    sn 1987A, SUN

BUT! can be CAPTUrEd in sOn (earth

Sink In
Pair AnnIHILate
Produce Distinctive SIGNAL (VirIc

M ost PromIscIng case: sOn

# of DM PartIcles in sUn

LET'S ESTIMATe This process: \( \frac{dN(t)}{dt} = C^0 - A^0 \left( \frac{N(t)}{E^0} \right) \)

CAPTUrE RATE: \( C^0 \sim \phi_x \left( \frac{M_0}{m_p} \right)^{\frac{m_p}{v_{DM}}} \)

\( \phi_x \sim h_x \cdot v_x = \frac{\phi_{DM}}{m_x} \cdot v_{DM} \)

\( M_0 \sim 10^{-20} \text{ kg} \sim 10^{-52} \text{ GeV} \)

\( \Gamma_{\nu} \)  

\( \left\{ \begin{array}{l}
\text{Spin Dep} \leq 10^{-39} \text{ cm}^2 \quad \text{most relevant for Sun (} > 90\% \text{ H)}
\text{Spin indip} \leq 10^{-44} \text{ cm}^2
\end{array} \right. \)
So \( C^0 \sim 10^{23} \left( \frac{\sigma_{\text{DM}}}{3.3 \text{ GeV/cm}^2} \right) \left( \frac{\sqrt{V_{\text{DM}}}}{100 \text{ GeV}} \right) \left( \frac{100 \text{ GeV}}{M_X} \right) \left( \frac{a_{\text{exp}}}{10^{-39} \text{ cm}^2} \right) \)

\[ A^0 < \frac{\langle \sigma v \rangle}{V_{\text{eff}}} \rightarrow 10^{-8} \text{ cm}^3 \left( \frac{M_X}{100 \text{ GeV}} \right)^{3/2} \]

"WIMP-Sphere" \( N(t) = n_0 \exp\left( -\frac{m_X^2}{2 g_{\text{eff}}} \right) \)

\( N(t) \) without evaporation can be solved exactly

\[ N(t) = \sqrt{C^0 \cdot A^0 \cdot \tanh(\sqrt{C^0 A^0} t)} \]

\[ \frac{1}{t_{\text{eq}}} \quad \text{if} \quad t < t_{\text{eq}} \]

Then the annihilation rate \( \Gamma_A = \frac{1}{2} A^0 \left( N(t) \right)^2 \)

Reduces to \( \Gamma_A \sim \frac{C^0}{2} \)

Do we reach capture-annihilation equilibrium? If so, \( \frac{M_X}{g_{\text{eff}}} \) is not too big

\( C^0 \sim 10^{23} \text{ s}^{-1} \left( \frac{\sigma_{\text{exp}}}{10^{-39} \text{ cm}^2} \right) \)

\( A^0 \sim \left( \frac{\langle \sigma v \rangle}{3 \cdot 10^{-26} \text{ cm}^3} \right) \frac{3 \cdot 10^{-26}}{10^{28}} \text{ s}^{-1} \)

\( \text{Vanilla WIMP} \)

\( \sim 3 \cdot 10^{-54} \text{ s}^{-1} \)

We want \( C^0 A^0 \gg \left( \frac{t_3}{t_0} \right)^2 \)

4.5 byr \( \sim 10^{17} \text{ s} \)

\( \frac{\sigma_{\text{exp}}}{10^{-39} \text{ cm}^2} \Rightarrow \frac{10^{-39}}{3 \cdot 10^{-54} \cdot 10^{23}} \Rightarrow 10^{-34} \)

So \( \sigma_{\text{exp}} > 10^{-41} \text{ GeV cm}^2 \)
should then see stream of HE U's (up from W+/W- \mu \rightarrow \mu^+ \mu^- ... but currently, no events!

Problem: energy threshold is high!

\begin{itemize}
  \item IceCube \approx 100 \text{ GeV} \text{ for CC-conversion of muons}
  \item Dz=3 \approx 10 \text{ cm}
  \item PINGU \approx 0.1 \text{ GeV}
\end{itemize}

Matroska

\underline{gamma rays}
GAMMA RAYS

LIGHT FROM DM

(i) PROMPT (ANNIHILATION EVENT)

(ii) SECONDARY (FROM RADIATIVE PROCESSES ASSOCIATED WITH STABLE, CHARGED PARTICLES FROM ANN.)

(i) \( \pi^0 \) FROM HADRONTIZATION, \( \pi^0 \to \gamma \gamma \)

\[ \frac{dN_{\gamma\gamma}}{dE_{\gamma}} \text{ symmetric around } \frac{m_{\pi^0}}{2} \text{ on log scale!} \]

- PHOTONS FROM "INTERNAL BREMSSTRAHLUNG"

- PHOTONS FROM "EXTERNAL BREMSSTRAHLUNG"

(ii) KEY ENERGY LOSES FOR \( e^\pm \): (a) INVERSE COMPTON

(b) SYNCHROTRON

(a) IC

- \( E_\gamma \)

- \( E_0 \)

- \( \frac{1}{3} \gamma_e^2 E_0 \)

- AMBIENT PHOTON

- CMB: \( E_0 \sim 2 \times 10^{-4} \text{ eV} \)

- STARLIGHT: \( E_0 \sim 1 \text{ eV} \)

- DUST: \( E_0 \sim 0.01 \text{ eV} \)
So for \( E_e \sim \frac{m_X}{10} \), \( \gamma_e = \frac{m_X}{10 \cdot 0.6 \cdot 10^{-3}} = \frac{(m_X)}{(100 \text{ GeV}) \cdot 2 \cdot 10^6} \)

So \( E_{\text{CMB}}^1 \sim \frac{4}{3} \cdot 4 \cdot 10^8 \left( \frac{m_X}{100 \text{ GeV}} \right)^2 \cdot 2 \cdot 10^{-4} \text{ eV} \sim 10 \text{ eV} \left( \frac{m_X}{100 \text{ GeV}} \right)^2 \gamma_e^2 \). \( E_e \)

So IC produces **hard X-ray photons \( \sim 100 \text{ keV} \)**

**[GREAT NEWS: NUSTAR JUST LAUNCHED!]**

Starlight \( \sim 10 \text{ GeV} \)

Dust \( \sim 0.1 \text{ GeV} \)

\[ \}
\text{\( \gamma \)-ray regime} \]

\((b)\) Synchrotron, in monochromatic approximation

\[ \frac{L^2_{\text{sync}}}{\text{MHz}^2} \sim 2 \cdot \left( \frac{E_e}{\text{GeV}} \right) \left( \frac{B}{\mu G} \right)^{1/2} \]

And synchrotron power \( \sim B^2 \)

\[ \]

\[ E^2 dN \]

\[ \frac{dN}{dE} \]

\[ \text{MHz to GHz} \]

\[ \text{MeV to GeV} \]

\[ \text{IC} \]

\[ \text{Sync} \]

\[ 11^\circ, 185 \]

[Slide Fig. 1]
\[ \phi = \frac{\Delta \Omega}{4 \pi} \left\{ \frac{1}{\Delta \Omega} \int d\Omega \int dE \langle \sigma v \rangle \frac{(p_{DM})^2}{2m_{\chi}^2} dE \right\} \frac{dN^0}{dcE} \sum \frac{dN^0}{dE} \]

\[ J(\Delta \Omega, \phi) \]

UNIT: \( \frac{GeV^2}{cm^5} \)

\[ \Delta \Omega: ANGULAR REGION, OPTIMIZED FOR SIGNAL / NOISE \]

FOR GIVEN DETECTOR, TARGET, FIELD OF VIEW, ANGULAR...

TYPICALLY, \( \Delta \Omega \sim 1.0 \text{deg} \rightarrow 10^{-3} \text{sr} \) (FERMI @ 1 GeV)

\( \sim 0.1 \text{deg} \rightarrow 10^{-5} \text{sr} \) (ACT, PAMELA)

LAUNDRY LIST

MINI-CODE GALAXIES

- o/Sph
- M31
- UMi: \( \sim 10^{10} \) ± 1.5
- Segue: \( \sim 10^{20} \) ± factor 3

MINI-CODE CLUSTERS

- Fornax Cluster \( \sim 10^{18} \)
- Coma \( \sim 10^{17} \)
- Bullet \( \sim 10^{14} \)

GALACTIC CENTER

\( 0.1^\circ: 10^{22} \div 10^{25} \)

\( 1^\circ: 10^{22} \div 10^{24} \)

(CURRENT BEST LIMIT: \( 2.5 \times 10^{-28} \text{cm}^3 / \text{s} / \text{GeV} \))
COSMIC RAYS

\( \bar{P}, \bar{D} : \) Key idea
- Mostly produced in spallation processes:

\[ P + P \rightarrow P + P + P + \bar{P} \]

\[ \text{interstellar} \]

\[ \text{Hi}^{+} \]

\[ \left( (E, \vec{P}) + (m_p, \vec{0}) \right)^2 \sim (4m_p)^2 \]

\[ E^2 + 2m_p c + m_p^2 - E^2 \approx 16 m_p^2 \]

\[ E \sim 7.5 m_p \]

\[ \Rightarrow \langle E \rangle \sim \text{few GeV} \]

\[ \Rightarrow \frac{dN_p}{dE} \sim E^{-2.7} \] steeply falling \( \Rightarrow \) compared to CR flux at 1 eV

\[ \left( \frac{0.1}{7.5} \right)^{2.7} \sim 10^{-5} \text{ suppression of } \bar{P} \text{ flux} \]

\( \bar{D} : \) Even more extreme:

\[ p + p \rightarrow p + p + p + \bar{p} + n + n \]

\[ E_{\text{kin}} \sim 17.5 \text{ GeV} \]
CHARGED SPECIES UNDERGO "RANDOM-WALK" (i.e. DIFFUSIVE) PROPAGATION, DESCRIBED BY A DIFF EQ LIKE

(1) \[ \frac{\partial}{\partial t} \phi = D(E) \Delta \phi + \frac{\partial}{\partial E} \left( b(E) \phi \right) + \phi (x, t) \]

**Diffusion** \hspace{2cm} **Energy Loss** \hspace{2cm} **Source**

(PLUS: CONVECTION, DIFFUSIVE REACC., Fragmentation, Decay...)

\[ D(E) \sim D_0 \left( \frac{E}{E_0} \right)^q \]

\[ \text{for } "\text{corridor radius}" \]

\[ \text{few } \times 10^{28} \text{ cm}^2 \text{ s}^{-1} \]

IN STEADY STATE (1) REDUCES TO

\[ 0 = - \frac{\phi}{\tau_{\text{diff}}} - \frac{\phi}{\tau_{\text{loss}}} + \phi \]

\[ \tau_{\text{diff}} \sim \frac{R^2}{D_0} E^{-q} \]

\[ \tau_{\text{loss}} \sim \frac{E}{b(E)} \rightarrow b(E) \sim 10^{-16} \left( \frac{E}{\text{GeV}} \right)^2 \text{ GeV s}^{-1} \]

\[ \phi \approx \min \left[ \frac{\tau_{\text{diff}}}{\tau_{\text{loss}}} \right] \]
... apply this to sec. to prim. ratio

- Protons:
  - Primary source: SNR, \( Q \sim E^{-2} \) (FERMI accelerator)
  \[ \frac{\phi}{E^2} \cdot \frac{E^{-s}}{E^{-2.7}} = E^{-2.7} \quad \checkmark \]
  \[ T_{\text{diff}} < T_{\text{loss}} \]

- Primary electrons:
  \[ Q \sim E^{-2} \]
  \[ E^{-2} \]  \[ E^{-3} \]
  \[ T_{\text{loss}} \sim T_{\text{diff}} \]

- Secondary \( (e^+) \):
  \( Q \sim \text{primary protons}, E^{-2.7} \)
  \[ E^{-3.4} \]
  \[ E^{-3.7} \]

So generically
\[ \frac{\Phi_{e^+}}{\Phi} \sim E^{-8} \sim E^{-0.7} \quad \text{not observed!} \]
WHAT COULD PRODUCE $E \sim 100$ GeV POSITRONS?

**TIMESCALE:** $t \sim \frac{E}{b(E)} \sim \frac{100 \text{ GeV}}{10^{-16} \cdot 100^2 \text{ GeV s}} \sim 10^5$ sec

100 GeV of co-esc energy in ABOUT 1 Myr

$\text{PSR age}$

**DISTANCE:** $\leq \sqrt{D(E) \cdot t_{\text{loss}}} \sim \sqrt{10^{28} \cdot (10^2)^{3/2} \cdot 10^{14} \text{ cm}}$

$\sim 10^{22} \text{ cm} \sim 3 \text{ kpc}$

So,

- MATURE, LOCAL PSR (Myr, $\sim$ kpc)
- LOCAL ($< 3 \text{ kpc}$) DM

MANY ISSUES... SEE MY TALK ON MONDAY!