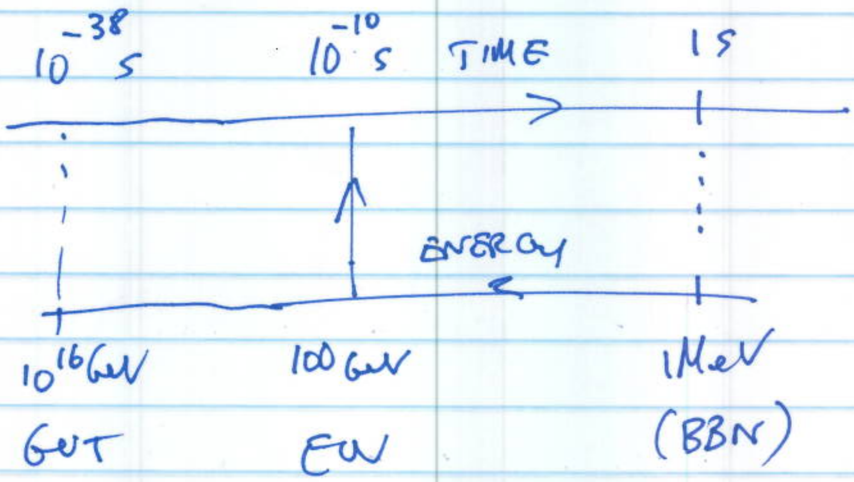
INTRODUCTIONS

— WHAT I WILL NOT TALK ABOUT TODAY

BARYOGENESIS : WHY $\dfrac{n_p - n_{\bar{p}}}{n_\gamma} \sim 10^{-10}$



TESTED BY LHC, ED, GW...

— WHAT I WILL TELL YOU A BIT ABOUT TODAY

SEARCHING FOR DM WITH ASTRO-PARTICLE EXPERIMENTS

-- SELF-SERVING / PROMOTING REF: TASI 2012 LECTURES 1301.0952

EVIDENCE FOR DARK MATTER IS ENTIRELY GRAVITATIONAL!

NO NO-GO THEOREMS ASSURE US WE COULD <u>EVER</u> DETECT DM!

- ROTATION CURVES IN SPIRALS
- STAR MOTION IN dSph
- GALAXY MOTION IN CLUSTERS
- $\underbrace{\Omega_B}_{\text{BBN, CMB}} \ll \underbrace{\Omega_M}_{\text{CLUSTERS, CMB}}$
- STRUCTURE FORMATION

WHAT COULD DM BE?

... REVIEW <u>SM OF PARTICLE PHYSICS</u>

EM $\rightarrow$	γ	$U(1)$	
WEAK $\rightarrow$	W, Z	$SU(2)$	$\rightarrow$ UNSTABLE
STRONG $\rightarrow$	g	$SU(3)$	

MATTER FERMIONS

HIGGS BOSON H

$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$ — STRONGLY INT.

$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$ — EM. INT / ?

NEUTRINOS: <u>MASSLESS</u> IN SM

... BUT, FROM ASTROPARTICLE EXP, WE KNOW THEY <u>MUST</u> HAVE MASS! (PONTECORVO)
└ ADVISOR OF ADVISOR OF MY ADVISOR

- $\bar{\nu}_e$ DISAPP. $\longrightarrow$ $\Delta m^2_{SOLAR} \sim 7.9\ eV^2$
- ATM NEUTRINOS (UP VS DOWN GOING)

$\longrightarrow$ NEED AT LEAST 2 $\neq 0$ MASSES!

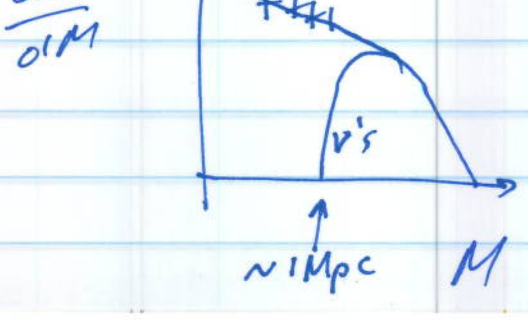
$\longrightarrow$ EVIDENCE FOR PHYSICS BSM!

... BACK TO DM: CAN NEUTRINOS BE DM?

WE KNOW FROM DIRECT SEARCHES THAT ν's MUST BE VERY LIGHT $\lesssim 1\ eV$

$\longrightarrow$ ARE <u>RELATIVISTIC</u> WHEN STRUCTURES FORM (HOT DARK MATTER)

FREE STREAMING LENGTHS CUTOFF STRUCTURE FORMATION



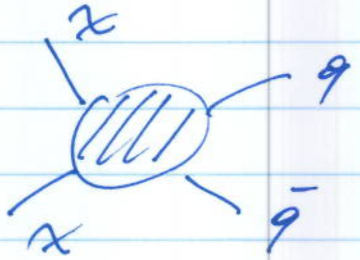
ALSO: TOP-DOWN FORMATION DOESN'T WORK!

... SO: NEED <u>NEW</u> PARTICLE INGREDIENT

COULD WE LEARN ANYTHING ABOUT THIS NEW PARTICLE WITH ASTRONOMICAL, OR COSMIC-RAY OBSERVATIONS?

KEY ASSUMPTION: DM SHARES INTERACTION (i.e. QUANTUM NUMBERS) WITH ORDINARY MATTER.

e.g.:



$\updownarrow$ SCATTERING (DIRECT DETECTION)

$\longrightarrow$

ANNIHILATION (TODAY + EARLY UNIVERSE)

$\longleftarrow$

PRODUCTION

CAN WE <u>ESTIMATE</u> DETECTION RATES TODAY FOR DM, BASED ON WHAT WE KNOW RE: DM?

— WE KNOW THAT $\Omega_{DM} h^2 \sim 0.2$

$$\text{or } \bar{\rho}_{DM} \simeq 0.23\, \rho_{crit} \sim \begin{cases} 3\times 10^{10} \dfrac{M_\odot}{Mpc} \\ 10^{-6} \dfrac{GeV}{cm^3} \end{cases}$$

MAYBE WE CAN EXPLAIN ρ_{DM} VIA THERMAL DECOUPLING

(SAME LANGUAGE AS
- RECOMBINATION ($H\gamma \leftrightarrow pe^-$)
- BBN ($e^+ n \leftrightarrow p + \bar{\nu}$)
- ν DECOUPLING

IN SHORT $\underbrace{\Gamma}_{\substack{\text{INT.}\\ \text{RATE}}} \sim \underbrace{H}_{\substack{\text{EXP}\\ \text{RATE}}}$

$\Gamma \sim n \cdot \sigma$

$$\underset{\substack{\text{(STAT}\\ \text{MECH)}}}{n \sim} \begin{cases} T^3 & m \ll T \quad \text{(REL. LIMIT)} \\ (mT)^{3/2} \exp\left(-\frac{m}{T}\right) & m \gg T \quad \text{(NON-REL)} \end{cases}$$

$$H \sim \frac{T^2}{M_p}$$

(FROM FRIEDMANN EQ $H^2 = \frac{8\pi G_N}{3} \rho$

$\rho \simeq \rho_{RAD} = \frac{\pi^2}{30} \cdot 2 \cdot T^4$

$M_p = \frac{1}{\sqrt{8\pi G_N}} \sim 10^{18}\,\text{GeV}$)

e.g. HOT RELIC

$\sigma \sim G_F^2 T^2$ → ON DIM. GROUNDS

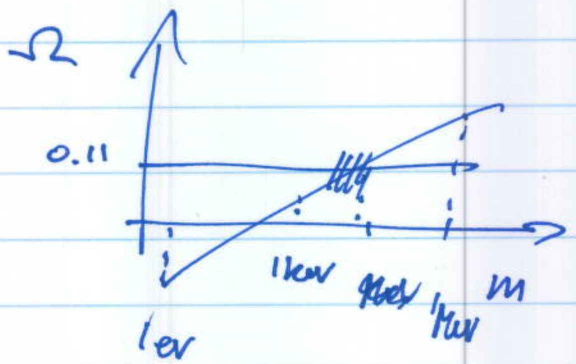
σ → DIM OF E^{-2}

G_F → $G_F \sim 10^{-5}\,\text{GeV}^{-2}$

$$\Gamma \sim H \quad \text{FOR} \quad \underbrace{T_\nu^3}_{n} \cdot \underbrace{G_F^2 T_\nu^2}_{\sigma} \sim \overbrace{\frac{T_\nu^2}{M_p}}^{H} \rightarrow T_\nu \sim \underbrace{\left(G_F^2 M_p\right)^{-1/3}}_{\sim 1\,\text{MeV}}$$

... DENSITY FROM ASSUMPTION OF ISOENTROPIC UNIVERSE

$$\Omega_\nu \sim \frac{m_\nu}{91.5\,\mathrm{eV}\; h^2}$$

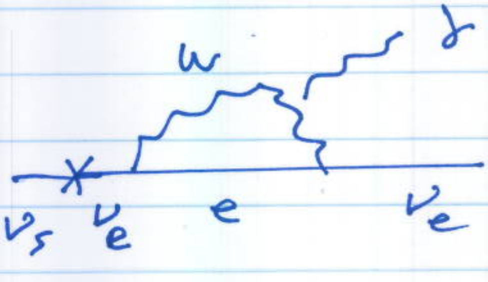


$\longrightarrow$ GETTING WARM

$\longrightarrow$ ν'S SUBDOMINANT

$\longrightarrow$ MAYBE STERILE NEUTRINOS ? (WARM DM).

$$\nu_s \longrightarrow \nu + \gamma$$



few keV

$\longrightarrow$ LINE IN X-RAYS

SIGNAL FROM DWARF ?

CONSTRAINTS FROM M31, CLUSTERS

$$\text{SIGNAL} \sim \frac{1}{4\pi D^2} \underbrace{\int \frac{\rho}{m_\nu}\, dV}_{\#\ \text{PARTICLES}} \times \underbrace{\frac{1}{\tau}}_{\text{DECAY RATE}}$$

$$\frac{M_{TOT}}{m_\nu}$$

WIMP "MIRACLE"

WE WANT A COLD RELIC $\longrightarrow n \sim (m_\chi T)^{3/2} \exp\left(-\frac{m}{T}\right)$

$n\sigma \sim H$ AT freeze-out $\longrightarrow n_{f.o.} \sim \dfrac{T_{f.o.}^2}{M_p \cdot \sigma}$

CALL: $\dfrac{m}{T} = x \quad \left(T = \dfrac{m}{x}\right)$ WE ARE IN $x \gg 1$ REGIME

FREEZE-OUT: $\left(m \cdot \dfrac{m}{x}\right)^{3/2} \exp(-x) = \dfrac{m^2}{x^2 \cdot M_p \sigma}$

$$\longrightarrow \quad \sqrt{x}\, e^{-x} = \frac{1}{m_\chi M_p \sigma}$$

SUPPOSE $\sigma \sim G_F^2 m_\chi^2 \longrightarrow 10^{-6}$
$m \sim 100$ GeV

$$e^{-x_{f.o.}} \sqrt{x_{f.o.}} \sim \frac{1}{10^2 \cdot 10^{18} \cdot 10^{-6}} \sim 10^{-14} \rightarrow x_{f.o.} \sim 30$$

NOW $\Omega_{DM} = \dfrac{m \cdot \overbrace{n(T=T_0)}^{n_0}}{\rho_c} \times \left[\dfrac{T_0^3}{T_0^3}\right]$

$T_0 \longrightarrow 2.7K \sim 10^{-4}$ eV

NOW, ISO-ENTROPIC UNIVERSE: $\dfrac{n_0}{T_0^3} \simeq \dfrac{n_{f.o.}}{T_{f.o.}^3}$

So $\Omega_{DM} = \frac{m}{\rho_c} \cdot T_0^{\,3} \cdot \frac{n_{f.o.}}{T_{f.o.}^3} = \frac{T_0^{\,3}}{\rho_c} \cdot X_{f.o.} \underbrace{\left(\frac{n_{f.o.}}{T_{f.o.}^2}\right)}_{\frac{1}{M_p \cdot \sigma}}$

So $\Omega_{DM} = \left(\frac{T_0^{\,3}}{\rho_c M_p}\right) \frac{X_{f.o.}}{\sigma}$

AND $\left(\frac{\Omega_{DM}}{0.2}\right) \approx \frac{X_{f.o.}}{30} \cdot \frac{10^{-8}\ \text{GeV}^{-2}}{\sigma}$

So for a "WIMP" to work $\sigma \sim 10^{-8}\ \text{GeV}^{-2}$

OR $\sigma \sim 10^{-8}\ \text{GeV}^{-2} \cdot \underbrace{(\hbar c)^2}_{\sim 0.1\ \text{GeV}^2\ \text{mbarn}} \sim \cancel{3} \times 10^{-9}$ mbarn

$10^{-27}\ \text{cm}^2$

$\sim 10^{-36}\ \text{cm}^2$

... THIS IS KEY TO ESTIMATE DM FLUXES!

USUALLY QUOTED IS $\sigma \cdot v \sim 3 \times 10^{-26}\ \frac{\text{cm}^3}{\text{s}}$

SO: $m \sim 100\ \text{GeV} \longrightarrow$ WEAK SCALE

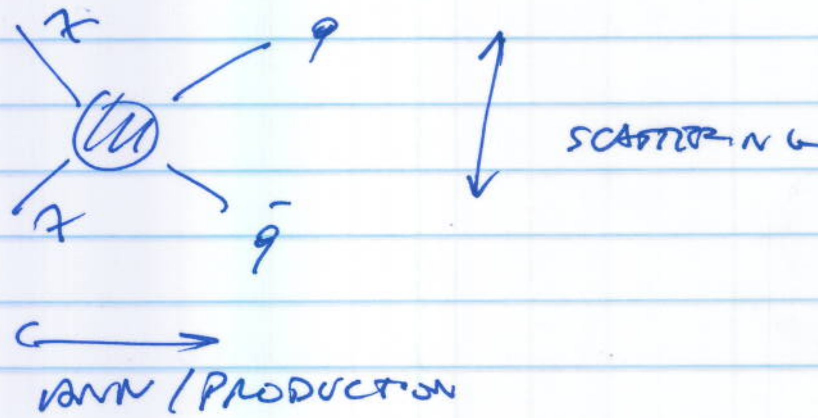
$\sigma \sim 10^{-36}\ \text{cm}^2$ OR $10^{-8}\ \text{GeV}^{-2}$

$\hookrightarrow$ WEAK INTERACTIONS!

$$G_F^2 \cdot m_W^2 \sim 10^{-8}\ \text{GeV}^{-2}$$

... WE HAVE SOMETHING TO SHOOT FOR!

BACK TO



SCATTERING: DIRECT DETECTION

CURRENT LIMITS: $\sigma_{\chi N} \gtrsim 10^{-44}\ \text{cm}^2$ (!)

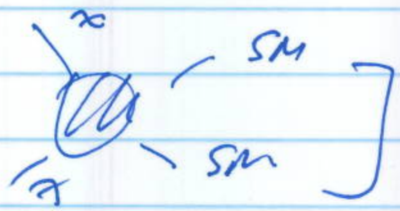
$$\sigma_{\chi N} \sim \left(\frac{m_{red}}{m}\right)^2 \sigma_{\chi\chi} \sim 10^{-4} \cdot 10^{-36}\ \text{cm}^2 \sim 10^{-40}\ \text{cm}^2$$

$$\frac{m_\chi m_p}{m_p + m_\chi} \sim m_p$$

VERY COMPETITIVE

STRONG CONSTRAINTS ETC.

~~aug:~~ CONSIDER PAIR ANNIHILATION



WHAT CAN WE HOPE TO DETECT?

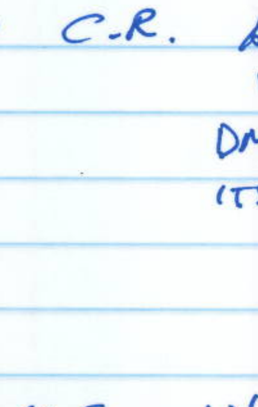
(3) → PHOTONS!

(2) → C.R. $\underbrace{\text{ANTIMATTER}}$ (BCKG: POWER-LAW)

DM USUALLY
ITS OWN ANTIPARTICLE, AS MANY p AS $\bar{p}$
e^- AS e^+
...

(1) → H.E. ν's

(1): BEST STRATEGY: ν'S FROM SUN

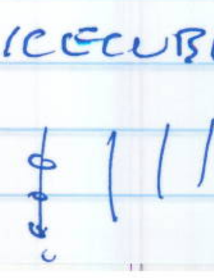


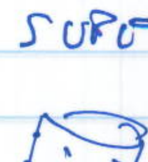
CAPTURE ⟶ DIR DET
$\chi p \to \chi p$

ANNIHILATION ⟶ EQUILIBRIUM?

SIGNAL: HE ν's FROM SUN!

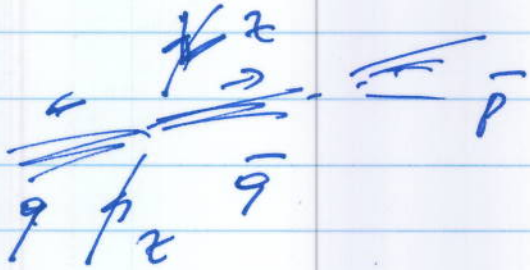
ICECUBE, ANTARES, SUPER K



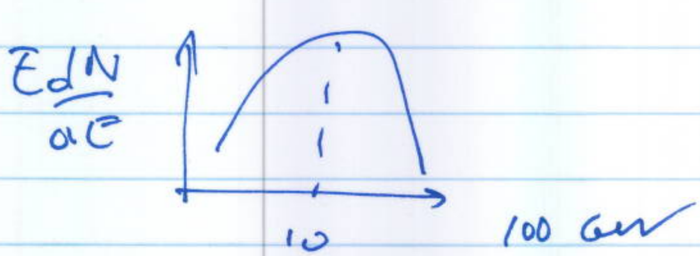


C.R. ANTIMATTER: $\bar{p}$, e^+, $\bar{D}$ ...

$\bar{p}$: • PRODUCED IN HADRONIZATION OF JETS:



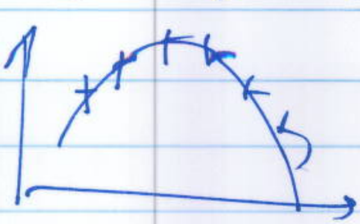
• "SOFT" SPECTRUM, PEAKED ~ $\frac{m_\chi}{10}$



• PRODUCED THROUGHOUT GALAXY
→ PROPAGATION
→ ENERGY LOSSES

• RESULTS: NO DISAGREEMENT WITH SECONDARY $\bar{p}$ FROM SPALLATION

$p \longrightarrow \bullet \Longrightarrow p, p, \bar{p}, p$



$\Rightarrow$ PUT CONSTRAINTS ON DM

e^+: SIMILAR, **BUT** ANOMALOUS RISE IN POSITRON FRACTION!

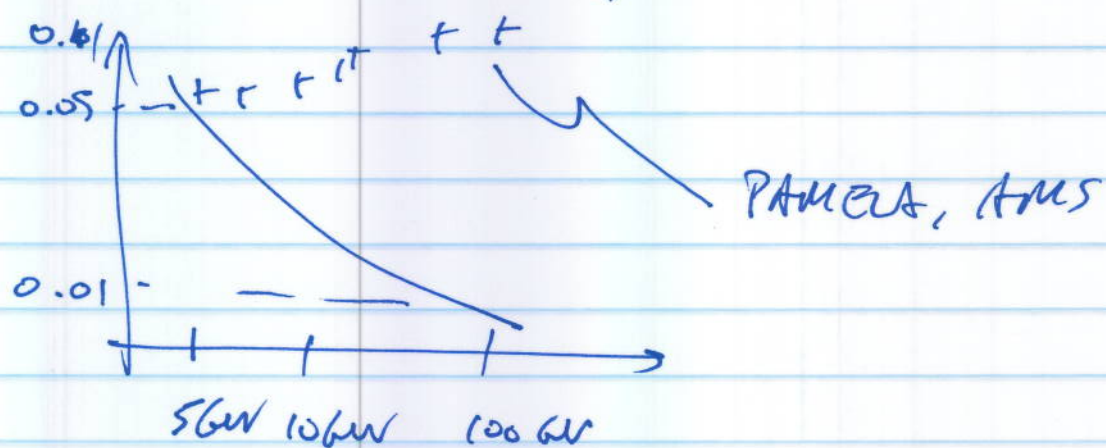
$$PP \to \pi\text{'s}, n\text{'s} \ldots$$

e^+ FROM $\pi^+ \to \mu^+ \nu_\mu$

$$\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$$

e^+ SPECTRUM SOFTER THAN e^- (SECONDARY)

$\to \dfrac{e^+}{e^+ + e^-}$ SHOULD DECLINE WITH ENERGY



IF DM, $E_{max} = M_{DM}$, THEN CUTOFF

BUT! SIMILAR FROM PSR!

$$\frac{dE}{dt} = -bE^2$$

IC + SYNC $\quad b \sim 10^{-16}\,\frac{1}{\text{GeV}}\,\frac{1}{s}$

$$\int_{E_0}^{E} \frac{dE}{E^2} = -bT \qquad -\frac{1}{E} + \frac{1}{E_0} = -bT$$

E_0: INITIAL

T: INJECTION EPOCH

$$E = \frac{E_0}{1+bE_0 T} \qquad E_{MAX} = \lim_{E_0 \to \infty} \frac{E_0}{1+bE_0T} = \frac{1}{bT}$$

e.g. FOR $T \sim 1\,\text{Myr}$ PSR, $T \sim 10^6 \cdot 3\,10^7 = 3\,10^{13}\,s$

$$E_{MAX} = \frac{1}{10^{-16}\,3\,10^{13}}\ \text{GeV} \simeq 300\ \text{GeV}\ !$$

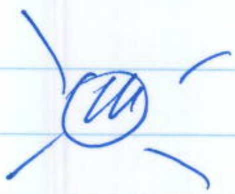
SO SIMILAR CUTOFF! PROBLEM: HOW TO DISCRIMINATE.

- ANISOTROPY!

  DONE WITH FERMI, AMS 02
  BUT INCONCLUSIVE

- ACT! 1304.1791 (LINDEN, PROFUMO)

NOW ... PHOTONS! $\longrightarrow$ HADRONIZATION
BREMS



$\longrightarrow$
PAIR ANN

$$N_{events} = \underbrace{\left(\frac{\Delta\Omega}{4\pi}\right)\phi_\chi}_{\text{FLUX} \ \frac{1}{cm^2 \cdot s}} \cdot A_{eff} \cdot T_{exp}$$

A_{eff} — FERMI $\sim 1 m^2$ / γ's
ACT $\sim 10^5 m^2$

ICECUBE $\sim 1 km^2$ / ν's

AMS-02 $\sim 0.1 m^2$ / COSMIC RAY ANTIMATTER

T_{exp} — SATELLITES $\sim$ yr $\sim \pi \cdot 10^7 s$
V-TEL $\sim$ yr

TELESCOPES $\sim 100 hr \sim 10^5 s$
(BUT SMALL FIELD OF VIEW!)

$$\phi_\chi \sim \#_\gamma \int \underbrace{n_{DM}}_{\text{TARGET}} \cdot \underbrace{n_{DM} \cdot v}_{\text{INCIDENT FLUX}} \cdot \underbrace{\sigma}_{\text{CROSS SECTION}} \, dl \longrightarrow \langle \sigma v \rangle \int \left(\frac{\rho_{DM}}{m_{DM}}\right)^2 dV$$

$J \sim \int \rho_{DM}^2 \, dl$ SELECTS TARGETS FOR OBSERVATIONS... UNITS: $\frac{GeV^2}{cm^5}$

e.g.:

$$\frac{J}{GeV^2/cm^5}$$

$GC \longrightarrow 10^{22} \div 10^{25}$

$dSph \longrightarrow 10^{20}$

$\cancel{M31} \longrightarrow 10^{20}$

$G\,Clusters \longrightarrow 10^{18}$ (FORNAX)

10^{17} (COMA)

ANY HOPE?

WE NEED, e.g. FOR FERMI $A_{eff} \cdot T_{exp} \sim 10^4\ cm^2 \times 3\times10^7\ s$

$$\sim 3\times10^{11}\ cm^2\,s$$

NOW $\phi_\chi = \underbrace{J}_{?} \cdot \underbrace{\langle\sigma v\rangle}_{3\times10^{-26}} \cdot \underbrace{\#_\gamma}_{\sim 10 \text{ IN FERMI RANGE}}$

WE WANT e.g. 10 events:

$$N_{events} = \underbrace{\phi_\chi}_{J \cdot \frac{3\times10^{-25}}{\left(\frac{m}{GeV}\right)^2} \frac{cm^3}{s}} \cdot \underbrace{A_{eff} \cdot T_{exp}}_{3\times10^{11}\ cm^2 s} \cdot \frac{\Delta\Omega}{4\pi} \sim 10$$

$$\text{SO } J \sim \frac{\cancel{10}}{\underbrace{\cancel{10} \cdot 10^{11} \cdot 10^{-25} \cdot 10^{-4} \cdot 10^{-4}}_{10^{-22}}} \frac{GeV^2}{cm^5} \sim 10^{22} \frac{GeV^2}{cm^5}$$

ALSO! SECONDARIES

$\longrightarrow$ SYNC : $\frac{\nu_{sync.}}{MHz} \simeq 2\left(\frac{E_e}{GeV}\right)\left(\frac{B}{\mu G}\right)^{1/2}$

$\longrightarrow$ IC : $\langle E_0{}' \rangle \sim \frac{4}{3}\gamma_e{}^2 E_0$