

MIRROR DARK MATTER

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98, 99

WHAT IS THE DARK
MATTER PARTICLE ?

- SUSY LSP
- AXION
- ?

? = MIRROR MATTER

VERY WELL MOTIVATED

BY:

- SUPERSTRING THEORIES

i.e. $E_8 \otimes E_8'$

- ν -PHYSICS

(STERILE ν 's)

DARK MATTER PUZZLES:

(i) $\Omega_B \sim \Omega_{DM} ?$

(ii) WHAT ARE THE MACHOS?

• MICROLENSING \Rightarrow MACHO, EROS

13-17 OBJECTS, $\bar{M}_{MACHO} \sim \frac{1}{2} M_{\odot}$
 $f \sim 20\%$

• CANNOT BE BARYONIC

(FREESE, FIELDS, GRAFF '98)

(iii) HALO CORE DENSITY PROBLEM
MAY BE SUGGESTING
COLLISIONAL DARK MATTER

(SPERGEL, STEINHARDT)

• $\rho \xrightarrow{r \rightarrow 0} r^{\alpha}$

$\alpha \approx -1.5$ (NFW)

$\alpha \approx -0.5$ (HD OBSERV.)

• # DWARF GALAXIES IN LOCAL GROUP (10^4)

SPERGEL, STEINHARDT :

$$\lambda_x \sim \frac{1}{n \sigma_x} \quad \begin{array}{l} \sim 100 \text{ Kpc} \\ \sim \text{Mpc} \end{array}$$

$$\Rightarrow M_x \sim \text{GeV}$$

$$\sigma \sim 10^{-23} - 10^{-24} \text{ cm}^2$$

\Rightarrow ELECTRICALLY NEUTRAL
"STRONGLY" SELF INTERACTING
DARK MATTER. (SIDM)

\Rightarrow AXION AND NEUTRALINO
ARE NOT VIABLE CANDIDATES!!

TWO POSSIBILITIES:

- (i) GLUINO LSP (X)
- (ii) MIRROR MATTER

(i) GLUINO LSP (OR SIMP) (\tilde{X} OR \tilde{G})

UNLIKELY!!

CONSTRAINTS FROM

a) UNDERGROUND DETECTORS:
STARKMAN et. al.

FOR $M_X > 100$ GeV,
CAN PENETRATE THRU EARTH
SHIELD.

b) COLLIDER:

• $p\bar{p} \rightarrow \tilde{G} + \dots$

ENERGY DEPOSITE IN THE HADRON
CALORIMETER

• α_s EVOLUTION

(CSIKOS, FODOR, ...)

BAER, CHUNG, GUNION
MAFI, RABY

c) SEARCH FOR ANOMALOUS
LIGHT NUCLEI (R.N.M., TEPLITZ)

AT BBN, X BINDS \Rightarrow ${}^9\text{Be}^*$
(NO ${}^9\text{Be}$ FORMS)

\Downarrow
ANOMALOUS

NOT SEEN IN SEARCHES (HEMMICK et. al.)

CONSTRAINTS ON SIMPS: $G_{\text{eff}} \leq M_X \lesssim \text{TeV}$

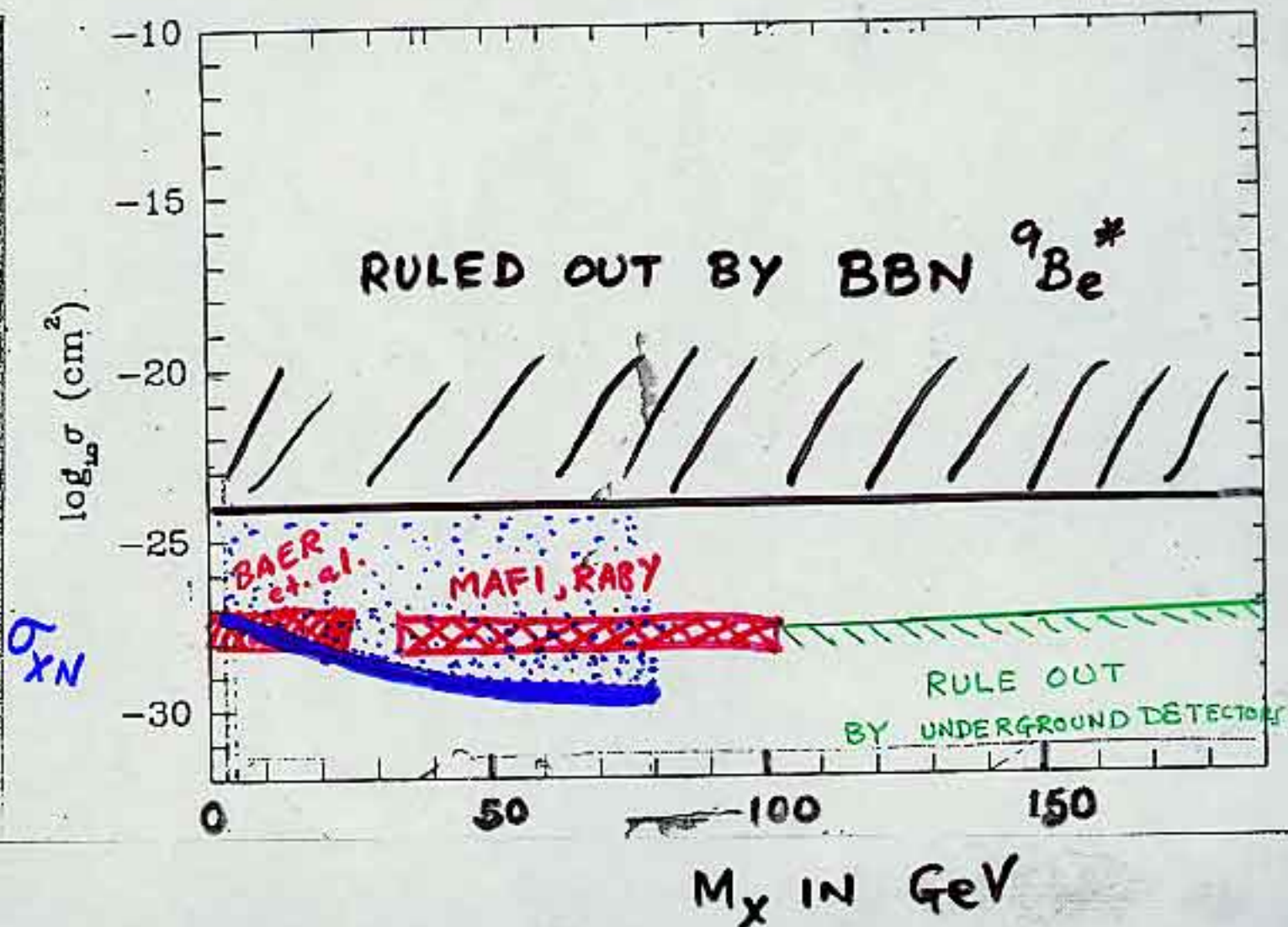
~~|||||~~ : ${}^9\text{Be}^*$ FORMATION AT BBN EPOCH.

~~|||||~~ : $M_X > 100 \text{ GeV}$: RULED OUT BY UNDERGROUND DETECTORS.

~~.....~~ : CAN BE PROBED BY PURDUE GOLD EXPT.

~~XXXXX~~ : 35 GeV TO 115 GeV : CDF RUN I;
 (\tilde{G})
 3 GeV TO 20 GeV : LEP,

FISHBACH et al.



ii) MIRROR MATTER:

DUPLICATION OF STANDARD
MODEL: (E.G. IN SUPERSTRING THEORIES)

STD. MODEL:

$$SU(2)_L \times U(1)_Y \times SU(3)_C$$

$$W^\pm, Z, \gamma, G$$

Q, L

MIRROR SECTOR

$$SU(2)'_L \times U(1)'_Y \times SU(3)'_C$$

$$W'^{\pm}, Z', \gamma', G'$$

Q', L'



: MIRROR SYMMETRY:

TWO VERSIONS

(i) SYMMETRIC (FOOT, VOLKAS '95)

$$M_W = M_{W'}; \Lambda = \Lambda', m_Q = m_{Q'}, \dots$$

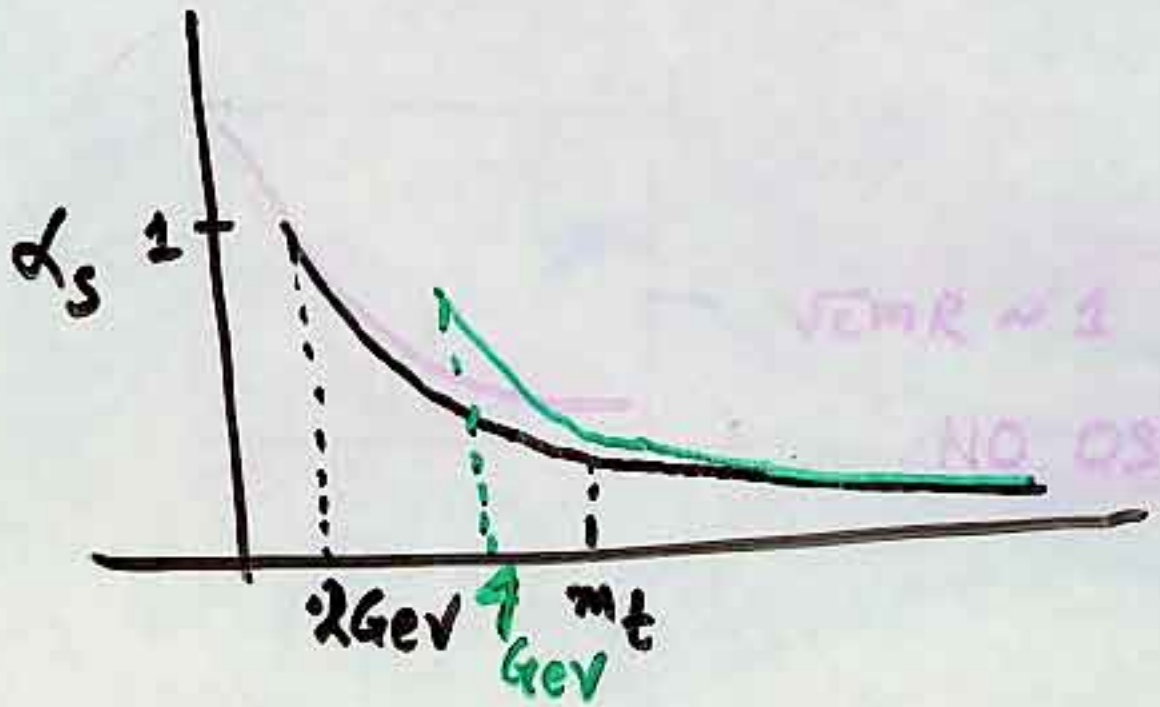
(ii) ASYMMETRIC (BEREZHIANI, R.N.M. '95) W/TEPH

$$M_{W'} = \zeta_c M_W; \Lambda' = \zeta_c \Lambda, m_{Q'} = \zeta_c m_Q$$

($\zeta \gg 1$)

WEAK SCALE ASYM.

$$\Rightarrow \Lambda'_{QCD} \gg \Lambda_{QCD}$$



$$m_{p'} \approx 20 m_p$$

$$\text{FOR } V_{WK}' \approx 20 V_{WK}$$

MIRROR MATTER MODEL AND ν 's

ν_e, ν_μ, ν_τ

$\nu'_e, \nu'_\mu, \nu'_\tau$

STD MODEL: B-L SYM. KEEPS ν_e, ν_μ, ν_τ
VERY LIGHT

MIRROR SECTOR HAS B'-L'
 \Rightarrow KEEPS $\nu'_{e,\mu,\tau}$ LIGHT.

$$\nu'_{e,\mu,\tau} \equiv \nu_{\text{STERILES}}$$

- IF SOLAR, ATMOSPHERIC & LSND
ARE CORRECT, A STERILE
 ν IS NEEDED !!

CALDWELL, R.N.M '93
PELTONIEMI, VALLE '93

HOW DO ν , ν' MIX?

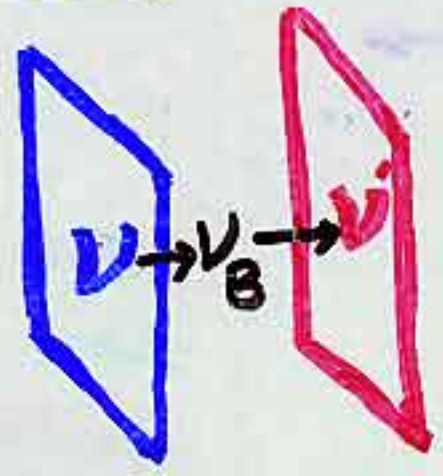
- GRAVITY CAN MIX NEUTRINOS
ONLY

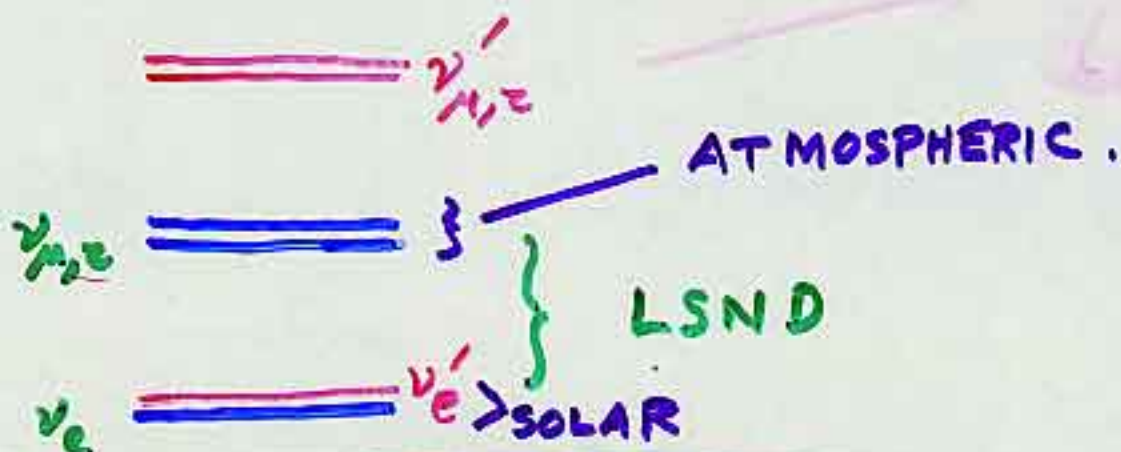


$$\theta_{\nu_e \nu'_e} \sim \zeta^{-1} \quad \zeta = \frac{V_{WK}'}{V_{WK}}$$

SOLAR $\nu \Rightarrow \zeta \sim 20$

B) BRANE PICTURE





BBN CONSTRAINT

APRIORI: $3\nu, \gamma, e^+e^-$
 $+ 3\nu', \gamma', e^+e'^-$ $\Rightarrow N_\nu \sim 9$

PRESENT LIMIT: $N_\nu \sim 4$

SOLUTION: ASYMMETRIC INFLATION
 $\Rightarrow T_R' < T_R$

+ SMALL MIXINGS $\leftarrow (\xi \gg 1)$

$\Rightarrow \eta_{\nu', \gamma', \dots} \ll \eta_{\nu, \gamma, \dots}$ + NO REGENERATION

(SEARCH FOR SYM. MIRROR MODELS)

MIRROR WORLD

- MASSES HEAVIER
BY A FACTOR $\xi = 15-20$
- COOLER, BY A FACTOR
 $\beta = T_R'/R$
(2-PARAMETER THEORY)
- INTERACTIONS WEAKER
(WEAK, EM) BY ξ^{2n} ($n > 0$)

1. MIRROR DARK MATTER: (MIM)

$$\text{BBN} \Rightarrow \left(\frac{T_{R'}}{T_R} \right)^3 < 1$$

$$\Rightarrow \frac{\Omega_{B'}}{\Omega_B} = \frac{\eta_{B'}}{\eta_B} \frac{m_{B'}}{m_B} = \zeta \frac{\eta_{B'}}{\eta_B}$$

$$\frac{\eta_{B'}}{\eta_{\gamma'}} = \frac{\eta_B}{\eta_{\gamma}} \quad \text{SINCE DYNAMICS IS SAME !!}$$

$$\frac{\Omega_{B'}}{\Omega_B} = \zeta \left(\frac{T_{R'}}{T_R} \right)^3 \approx (15-20) \times \left(\frac{T_{R'}}{T_R} \right)^3$$

$$\Rightarrow \Omega_{B'} \approx \Omega_B \times (\text{few})$$

$$\text{SPECIFICALLY, } \Omega_B = 0.05, \Omega_{B'} = 0.2$$

$$\Rightarrow \zeta = 15 \Rightarrow \delta N_{\nu}^{\text{BBN}} = 1.05$$

$$\zeta = 20 \Rightarrow \delta N_{\nu}^{\text{BBN}} = 0.718$$

CAN BE TESTED!! δN_{ν} CANNOT BE LOWER!!

MACHOS ARE MIRROR STARS:

$$m_{e'} = \zeta m_e$$

$$m_{p'} = \zeta m_p$$

HOW DO STELLAR PARAMETERS CHANGE?

$$1. \quad M_{\max}^{\odot'} (\text{MIRROR}) = A \frac{M_{\text{PR}}^3}{m_{p'}^2} = \zeta^{-2} M_{\max}^{\odot}$$

$$M_{\max}^{\odot} \sim (70 - 100) M_{\odot}$$

$$\Rightarrow \zeta \sim 15, \quad M_{\max}^{\odot'} \sim \frac{1}{2} M_{\odot}$$

(\approx MACHO MASS)

HYDRODYNAMICS \Rightarrow

$$\bullet \quad P = \left(\frac{4\pi}{3}\right)^{1/3} G M^{2/3} \rho^{4/3}$$

$$\bullet \quad P = P_{\text{gas}} + P_{\text{rad}} + P_{\text{deg.}}$$

$$P_{\text{gas}} \sim P_{\text{rad}} \Rightarrow \text{MAX } M_{\odot}$$

CORE DENSITY PROBLEM:

MIRROR MATTER HAS ITS OWN SELF INTERACTION BUT NO INTERACTION WITH OUR MATTER.

IDEAL SIDM CANDIDATE !!

$$SS \Rightarrow \sigma_{XX} \approx 8 \times 10^{-25} \text{ cm}^2 \left(\frac{m_X}{\text{GeV}} \right) \left(\frac{\lambda}{\text{Mpc}} \right)^{-1}$$

$$m_X \sim 30 \text{ GeV}, \quad \lambda \sim \text{kpc}$$

$$\Rightarrow \sigma_{XX} \sim 3 \times 10^{-20} \text{ cm}^2.$$

IS THIS CONDITION SATISFIED BY MIRROR HYDROGEN ?

MIRROR H'-H' COLLISION:

ELASTIC CROSS SECTION: (W/NUSSIMOV)

$$\sigma_{H'H'} \sim \frac{\sigma_{HH}}{\xi^2} \sim 10^{-19} \text{ cm}^2$$

$$E_{H'} \sim \frac{1}{2} m_{H'} v^2 \approx 20 \text{ keV}$$

$$R \equiv Rp \sim 1000$$

⇒ SCATTERING MOSTLY FORWARD

$$\Delta\theta / \text{COLLISION} \sim \frac{\frac{1}{2} m_e \alpha^2}{E_{H'}} \sim \frac{1}{20}$$

$$\begin{aligned} \sigma_{\text{TRANSPORT}} &\sim \frac{1}{4\pi} \int \frac{d\sigma}{d\Omega} (1 - \cos\theta) d\Omega \\ &\sim \sigma_{H'H'} (\overline{\Delta\theta})^2 \sim 10^{-22} \text{ cm}^2 \end{aligned}$$

SINCE MIRROR DARK MATTER
SO SIMILAR TO NORMAL MATTER,
WHY GALACTIC HALO IS NOT
DISC SHAPED ?

KEY POINT :

DISC SHAPE OF VISIBLE MATTER
GALAXY DUE TO BREHMSTRAHLUNG



$\tau_{RELAX}^B \sim \text{AGE OF THE UNIV.}$

MIRROR MATTER :

$$\sigma_{H'}^B \sim \frac{1}{5^2} \sigma_H^B$$
$$\Rightarrow \tau_{RELAX}^{B'} \sim 1000 \times t_U .$$

CONCLUSION

1. ν -PHYSICS \Rightarrow STERILE ν_s :

⊕ SUPERSTRINGS

MOTIVATE "MIRROR WORLD".

2. ASYMMETRIC MIRROR MODEL

i.e. $\frac{\Lambda'}{\Lambda} = \frac{M_{W'}}{M_W} = 5$ EXPLAINS

QUALITATIVELY :

i) ν -PUZZLES

ii) WHY $\Omega_B \sim \Omega_{B'}$

iii) WHY $M_{\text{macro}} \sim \frac{1}{2} M_0$

iv) CAN ADDRESS CORE DENSITY PROBLEM !

3. δN_ν TEST .

STRUCTURE SIZES IN MDM:

SILK DAMPING SCALE :

$$\lambda_{\gamma'} = \frac{1}{n_e \sigma_T'} = \frac{\zeta^3 m_p}{\Omega_b \rho_c \zeta^3 \sigma_T}$$

SD NOT EFFECTIVE IF $\lambda_{\gamma'} > \frac{1}{3} ct$

$$\Rightarrow z_{SD} \approx 8 \zeta^3$$

$$\Rightarrow \lambda_{SD} \sim 10^{27} \zeta^{-6} \text{ cm}$$

$$M_{SD} \sim 10^{54} \zeta^{-9} \text{ gm}$$

} $\sim R_{GALAXY}$
} $\sim M_{GALAXY}$
FOR $\zeta \sim 15$

COOLING \Rightarrow BREAK UP TO
GIVE MIRROR STARS

DARK MATTER

= GAS + STARS

(MACHOS).

CONSIDER 3 TeV SIMP AS HALO DM.

$$\Rightarrow E_x \sim \text{MeV}$$

• EACH COLLISION, $\frac{\Delta E}{E} \sim \frac{m_{\text{nuc.}}}{M_x} \sim 10^{-3}$

MEAN FREE PATH ~ 1 meter

PENETRATION DEPTH $\sim \text{km}$

SHOULD HAVE BEEN SEEN IN UNDERGROUND DETECTORS.

(STARKMAN et. al.)

SECOND SET OF CONSTRAINTS:

AT BBN EPOCH, X-SHOULD BIND & FORM He^4^* & Be^9^*

(R.N.M., TEPLITZ '98)

$$\frac{n_{\text{Be}^9^*}}{n_{\text{Be}}}$$

ESTIMATE BY (DICUS, TEPLITZ '82)
FOR $V_{\text{XN}} \sim 20 \text{ MeV}$.

ESTIMATE OF $n(^9\text{Be}^*)/n(\text{Be})$ NOW!

$$\frac{n_{^9\text{Be}^*}}{n_{\text{Be}}}\Big|_{\text{now}} = \left(\frac{n_{^9\text{Be}^*}}{n_{^5\text{He}^*}}\right)_{\text{BSN}} \left(\frac{n_{^5\text{He}^*}}{n_{\text{B}}}\right)_{\text{BSN}} \left(\frac{n_{\text{B}}}{n_{\text{Be}}}\right)_{\text{now}}$$

a) $\frac{n_{^5\text{He}^*}}{n_{\text{B}}} = P C_X$

$$P = n_{^4\text{He}} v t \sigma_{X + ^4\text{He} \rightarrow ^5\text{He}^* + \gamma}$$

BLATT-WEISKOPF :



$$\sigma(A, Z, k) \approx \frac{8\pi\alpha Z^2}{3} \gamma^{-2} \left(\frac{k\gamma}{k^2 + \gamma^2}\right)^3 \approx \left(\frac{B}{k}\right)^2$$

$$\Rightarrow \boxed{P \approx 10^{-3}} \quad (M_X \text{ INDEP.})$$

b) $\frac{n_{^9\text{Be}^*}}{n_{^5\text{He}^*}} = 10^{-6}$

(DICUS, TEPLITZ '80)

$$n_x \approx \Omega_x \frac{\rho_c}{m_x} > 10^{-9} \quad \text{FOR } m_x < 10 \text{ TeV}$$

$$\Rightarrow \frac{n_{\text{Be}^9 x}}{n_{\text{Be}}} \approx 1 \quad \text{FOR } m_x < 10 \text{ TeV}$$

$$\text{HEMMICK et. al.} \Rightarrow \frac{n_{\text{Be}^9 x}}{n_{\text{Be}}} \lesssim 10^{-12} - 10^{-8}$$

FOR $M_x \lesssim 10 \text{ TeV}$

CONTRADICTION !!

V_{XN} WEAKER ?

SEARCH FOR ANOMALOUS GOLD!

FISHBACH et. al.