DARK MATTER CANDIDATES

DARK MATTER:

- BEHAVES LIKE ORDINARY MASSIVE PARTICLES TODAY, MAKES CLUMPS
- COLD DARK MATTER: NON-RELATIVISTIC AT PRETTY EARLY STAGE OF THE EVOLUTION OF THE UNIVERSE
  STANDARD OPTION
- DOES NOT PARTICIPATE IN ELECTROMAGNETIC OR STRONG INTERACTIONS
  OTHERWISE WE WOULD HAVE OBSERVED IT
- IF THESE ARE PARTICLES, THEY MUST BE RATHER HEAVY

* COLD: NON-RELATIVISTIC AT THE TIME THE SHORTEST INTERESTIN MODES CROSS IN THE HORIZON.

LET ℓ_0 BE PRESENT WAVELENGTH OF SUCH A MODE. THEN (UP TO FACTORS ~ 1) TEMPEATURE T AT WHICH IT CROSSED IN THE HORIZON IS FOUND FROM

$$\ell_0 (1+z)_T = \underset{\Uparrow\; M_{Pl}^*/T^2}{H^{-1}(T)} \Rightarrow \ell_0 \cdot \frac{T_0}{T} \simeq \frac{M_{Pl}^*}{T^2}$$

$$T \simeq \frac{M_{Pl}^*}{\ell_0 T_0}$$

REQUIRE $M > 3T$

$\ell_0 \sim 10\ \text{kpc} = 3\cdot 10^{22}\ \text{cm}$ $\Longrightarrow$ $M > 10\ \text{keV}$

$T_0 \sim 10^{-1}\ \text{cm}$; $M_{Pl}^* \simeq 10^{19}\ \text{GeV}$

PARTICLES OF MASS $\gtrsim 10$ keV, if DECOUPLED BEFORE $T \sim 10$ keV, CAN MAKE CDM. LIFETIME $\gtrsim 10^{10}$ yrs.

NB: $M \sim$ a few keV $\Rightarrow$ WARM DARK MATTER STILL AN OPTION

NB: "CDM BEHAVES LIKE ORDINARY MASSIVE PARTICLES" DOES NOT NECESSARILY MEAN THAT IT IS MADE OF PARTICLES.

WIMP dark MATTER.

BEST GUESS : Weakly Interacting Massive Particles, WIMPs.

- ASSUME:
  - THERE EXIST NEW PARTICLES (WIMPs) X OF mass M. Lifetime $\gtrsim 10^{10}$ yrs.

    STRONG ASSUMPTION. NEED NEW FUNDAMENTAL CONSERVATION LAW.

PROTON IS STABLE BECAUSE OF CONSERVATION OF BARYON NUMBER; ELECTRON STABILITY $\Leftrightarrow$ CONSERVATION OF CHARGE.

  - X CAN DISAPPEAR ONLY THROUGH ITS INTERACTION WITH ANTIPARTICE $\bar{X}$.

VERSION (VALID IN SUSY THEORIES): X CARRIES "INTRINSIC PARITY" (−1); disappears THROUGH

$X + X \longrightarrow e^+e^-, q\bar{q}, \ldots$

IN SUSY, R-parity does THE JOB.

  - $X, \bar{X}$ ARE IN THERMAL EQUILIBRIUM (WITH OUR MATTER) AT $T \gtrsim 0.1\,M$.
  - No ASYMMETRY BETWEEN $X, \bar{X}$

$\bar{X} = X \Rightarrow$ LAST REQUIREMENT IRRELEVANT.

- REQUIRE $\Omega_X = \Omega_{CDM} \sim 0.25$ TODAY

  $\Downarrow$

  FIND PROPERTIES OF X.

- BEGIN WITH $n_X = n_{eq}$, EQUILIBRIUM NUMBER DENSITY FOR MASS M
- n_X REMAINS EQUAL TO n_{eq} DUE TO

$$X + \bar{X} \leftrightarrow e^+e^-, q\bar{q}, \ldots$$

- ONCE n_{eq} BECOMES SMALL ENOUGH, ANNIHILATION STOPS: X CANNOT FIND $\bar{X}$ IN HUBBLE TIME. n_X FREEZES IN. THEN GETS DILUTED AS $\frac{1}{a^3}$.

- CONVENIENT QUANTITY: X TO ENTROPY RATIO,

$$\boxed{\Delta_X = \frac{n_X}{s}}$$

$s = \frac{4\pi^2}{90} g_* T^3$

CONSTANT IN comoving volume.

STAYS CONSTANT AFTER FREEZE-IN.

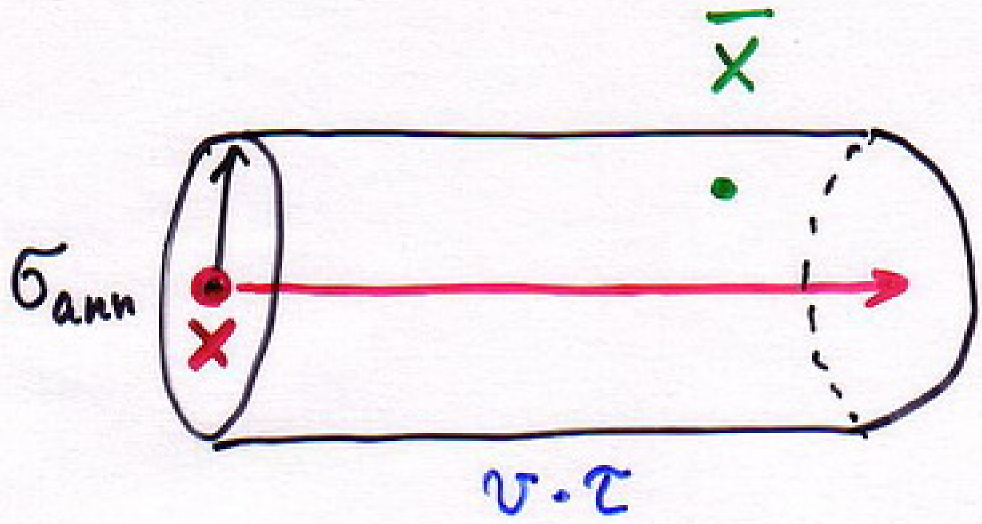
„TODAY" $s_0 = \frac{4\pi^2}{90}\left[2 T_\gamma^3 + 2 \cdot 3 \cdot \frac{7}{8} T_\nu^3\right]$

$$\boxed{s_0 = 2.8 \cdot 10^3 \frac{1}{cm^3}}$$

MASS DENSITY OF X-PARTICLES TODAY

$$\rho_X = M \cdot s_0 \cdot \Delta_X$$

WANT TO CALCULATE Δ_X.



one $\bar{X}$ in volume $\sigma_{ann} \cdot v\tau$

ANNIHILATION PROBABILITY, WHEN FLUX OF X FALLS ON $\bar{X}$:

$$\mathcal{P} \simeq a^3 \, |\psi_X(a)|^2 \cdot \text{const}$$ $\Leftarrow$ independent of v as $v \to 0$.

a = SIZE OF interaction region around $\bar{X}$.

$$\sigma_{ann} = \frac{\mathcal{P}}{\text{FLUX}} = \frac{\mathcal{P}}{v|\psi|^2} \propto \frac{1}{v}$$

$$g_x \left(\frac{M T_d}{2\pi} \right)^{3/2} \cdot e^{-\frac{M}{T_d}} \cdot \sigma_0 = \frac{T_d^2}{M_{pl}^*}$$ AT DECOUPLING

MUST BE SMALL

SMALL

$\Downarrow$

$T \ll M$, NON-RELATIVISTIC TREATMENT

- DECOUPLING TEMPERATURE, in log approximation

$$\frac{M}{T_d} = - \ln \left[\frac{T_d^2}{M_{pl}^*} \cdot \frac{1}{\sigma_0 \left(\frac{M T_d}{2\pi} \right)^{3/2}} \right]$$

$T \sim M$ here, FORGET 2π

$$\boxed{T_d = \frac{M}{\ln \left[\frac{M_{pl}^*}{M} \cdot \sigma_0 M^2 \right]}}$$

SOMEWHAT SMALLER THAN M:
FOR $M \sim 100$ GeV, $\sigma_0 M^2 \sim 1$, $T \sim 3$ GeV

$$n_x \sigma_0 = H \Rightarrow n_x = \frac{T_d^2}{M_{pl}^* \sigma_0}$$

$$\Rightarrow \Delta_x = \frac{n_x}{s} = \frac{T_d^2}{M_{pl}^* \sigma_0} \cdot \frac{1}{0.44 \cdot g_* T_d^3}$$

$$\Delta_X = \frac{\ln\left(\frac{M_{Pl}^*}{M}\cdot\sigma_0 M^2\right)}{M}\cdot\frac{1}{\sigma_0}\cdot\frac{1}{0.44\,g_* M_{Pl}^*}$$

$$\Downarrow$$

Presently

$$\rho_X = M s_0 \Delta_X =$$

$$s_0\cdot\frac{1}{\sigma_0}\cdot\frac{1}{0.44\,g_* M_{Pl}^*}\ln\left(\frac{M_{Pl}^*}{M}\sigma_0 M^2\right)$$

Main unknown parameter!

$$\Downarrow$$

$$\Omega_X = \frac{\rho_X}{\rho_c} = 0.3\cdot\left[\frac{1\cdot 10^{-8}\,\mathrm{GeV}^{-2}}{\sigma_0}\right]\times\frac{1}{\sqrt{g_*/10}}$$

$$\times\frac{1}{2h^2}\times 30\ln\left[\frac{g_* M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right]$$

Need annihilation cross-section

$$\sigma_{ann} = \frac{\sigma_0}{v}, \quad \boxed{\sigma_0 \sim 10^{-8}\,\mathrm{GeV}^{-2}}$$

Larger/smaller $\sigma_{ann} \Leftrightarrow$ under/over production of X.

Annihilation cross section $\sigma_0 \sim 10^{-8}\ \mathrm{GeV}^{-2}$

$$\Downarrow$$

BALLPARK OF ENERGY SCALES INVOLVED

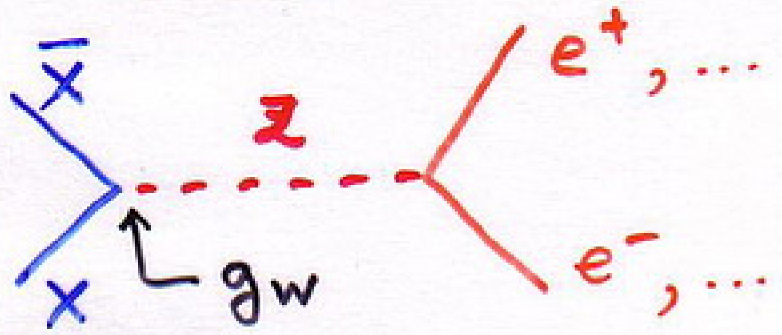
* FOR ELEMENTARY X

$$\sigma_0 < \frac{1}{M_X^2}$$

$$\Downarrow$$

$$M_X < 10^4\ \mathrm{GeV} = 10\ \mathrm{TeV}$$

* Annihilation via Z-exchange, $M_X \ll m_Z$



Decay amplitude

$$\propto \frac{1}{m_Z^2} \cdot \underbrace{\alpha_W^2}_{\frac{g_W^2}{4\pi}}$$

$$\sigma_0 \sim \underbrace{(\#\text{ of channels})}_{\sim 10} \cdot \underbrace{\alpha_W^4}_{\alpha_W \simeq \frac{1}{30}} \cdot \underbrace{\frac{1}{m_Z^4}}_{m_Z \simeq 100\ \mathrm{GeV}} \cdot M_X^2$$

$$\Downarrow$$

$$\sigma_0 \sim 10^{-6} \left(\frac{M_X}{100\ \mathrm{GeV}}\right)^2 \mathrm{GeV}^{-2}$$

$$\sigma_0 \sim 10^{-8}\ \mathrm{GeV}^{-2} \iff M_X \sim 10\ \mathrm{GeV}$$

* $M_X \gg m_Z$

$$\sigma_0 = (\#\text{ of channels}) \cdot \alpha_W^4 \cdot \frac{1}{M_X^2}$$

$$\Downarrow$$

$$M_X \sim 1 \text{ TeV}$$

- $M_X = 10 \text{ GeV} \div 1 \text{ TeV}$

INTERACTION CROSS SECTIONS SIMILAR TO THOSE OF WEAK INTERACTIONS

Hence the name.

MINIMUM ASSUMPTIONS $\Rightarrow$ ENCOURAGING RESULT.

SEARCHES:
- COLLIDERS
  EXCELLENT CHANCE FOR LHC
- Underground: SCATTERING OFF NUCLEI

- Small CROSS SECTIONS
- Small ENERGY DEPOSIT

- Indirect

$X + \bar{X} \to \nu + \bar{\nu}$ in the center of SUN OR EARTH

$$\Downarrow$$

FLUX of high energy neutrinos

Underground, Underwater (Baikal), Underice (AMANDA, Icecube)

DISCOVERY OF WIMPs

$\Downarrow$

WINDOW INTO UNIVERSE AT $T \sim$ a few GeV
TO (a few)$\cdot$10 GeV

$t \sim 10^{-8}$ s

UNTIL NOW: NUCLEOSYNTHESIS, $T \sim 1$ MeV
$t \sim 1$ s

WHAT IS NEW PHYSICS BEHIND WIMPs?
LIKELY CANDIDATE: SUPERSYMMETRY @ 100 GeV - 1 TeV

SUSY: SYMMETRY BETWEEN BOSONS AND FERMIONS HINTS FROM PARTICLE PHYSICS

$e^- \leftrightarrow \tilde{e}^-$, "SELECTRON"

$q \leftrightarrow \tilde{q}$, "squark"

$\gamma \leftrightarrow \tilde{\gamma}$, "photino"

$Z \leftrightarrow \tilde{Z}$, "zino"

$h \leftrightarrow \tilde{h}$, "higgsino".

R-parity +1 $\quad$ -1

CONSERVATION OF R-parity $\Leftrightarrow$ sparticles CAN ONLY BE PRODUCED/DISAPPEAR IN PAIRS

LSP = LIGHTEST SUSY particle
EXCELLENT CANDIDATE FOR WIMP

WHOLE NEW SWORLD AT ACCESSIBLE ENERGIES.

MANY MORE DARK MATTER CANDIDATES

- GRAVITINO $\Leftarrow$ INDIRECT SEARCH AT COLLIDERS
- Massive GRAVITON $\Leftarrow$ UNDETECTABLE
- AXION $\Leftarrow$ EXTREMELY DIFFICULT TO DETECT.
- STERILE NEUTRINO ν_R

WARM DM $\quad m_{\nu_R} \simeq 4\,\mathrm{keV}$ $\Leftarrow$ UNDETECTABLE

$\Omega_{CDM} \simeq 1$ IS A COINCIDENCE.

"HOMEWORK"

WHY $\Omega_{CDM} \approx \Omega_{BARYON}$ WITHIN A FACTOR OF A FEW?

COMPELLING ANSWER: MORE THAN A THESIS.

PROBLEM

CONSIDER SCINTILLATION DETECTOR OF DARK MATTER WHOSE MATERIAL HAS ATOMIC WEIGHT $A \sim 50$.

- ESTIMATE ENERGY DEPOSIT IN THE DETECTOR DUE TO ELASTIC SCATTERING OF A WIMP OFF A NUCLEUS IN THE DETECTOR, ASSUMING $M_{WIMP} \gg 50$ GeV.
- ASSUMING CONVERSION FACTOR 1% OF THIS ENERGY INTO LIGHT, ESTIMATE THE NUMBER OF PHOTONS (VISIBLE LIGHT) PRODUCED IN THE DETECTOR.

HINT WIMPs NEAR US ROTATE AROUND THE CENTER OF OUR GALAXY AT ABOUT THE SAME VELOCITY AS THE SUN DOES.